13th IDPASC SCHOOL

PALERMO, 17-27 SEPTEMBER, 2024

STANDARD MODEL COSMOLOGY
&
DARK MATTER

Antonio Masiero

Univ. of Padova and INFN, Padova

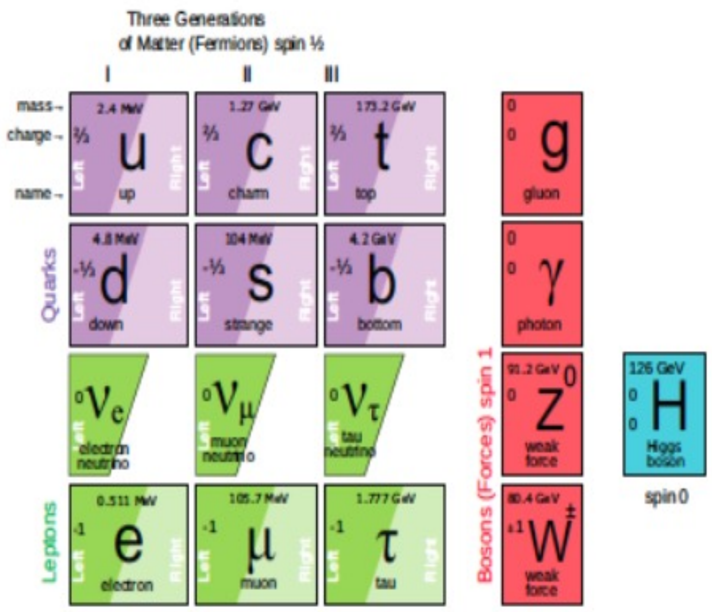
- By the end of the 20th century … **we have a comprehensive, fundamental theory of all observed forces of nature which has been tested and might be valid from the Planck length scale [10^{-33} cm.] to the edge of the universe [10^{+28} cm.]**

D. Gross 2007

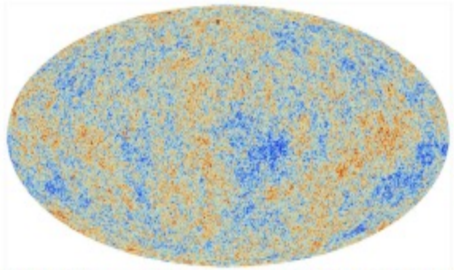
In this last decade → the triumph of the

STANDARD

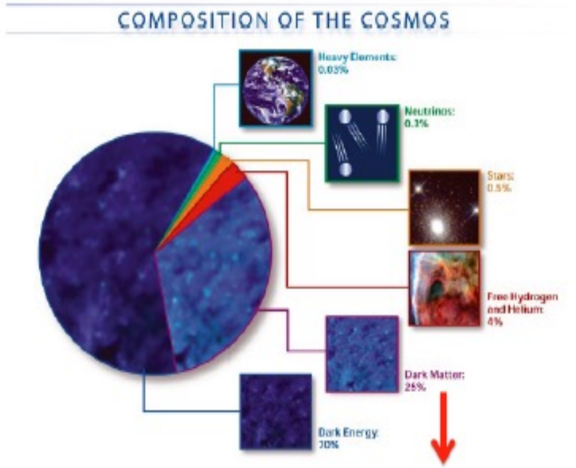
- **PARTICLE STANDARD MODEL**



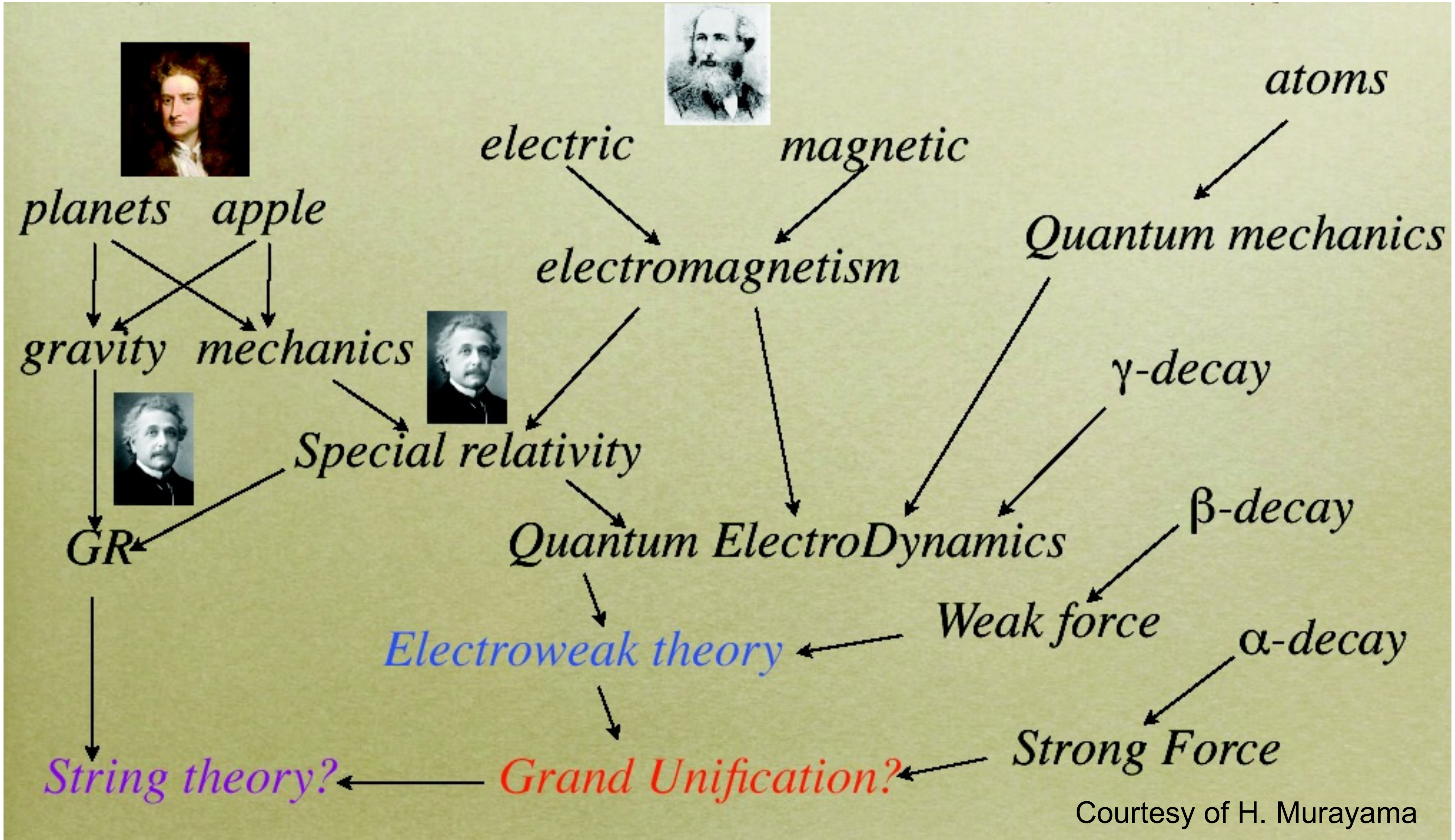
- **COSMOLOGY STANDARD MODEL**



ΛCDM + "SIMPLE" INFLATION



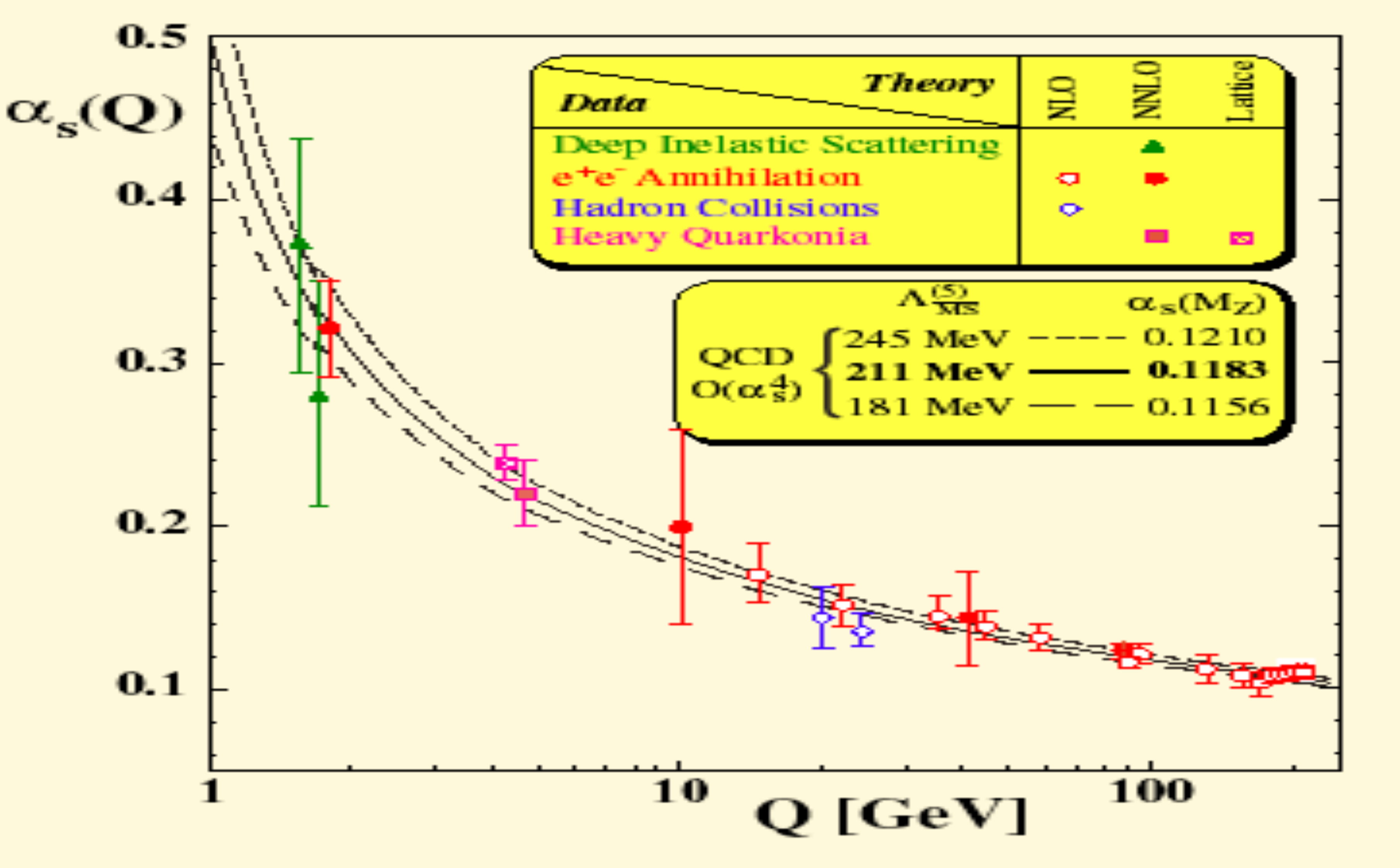
UNIFICATION of FUNDAMENTAL INTERACTIONS



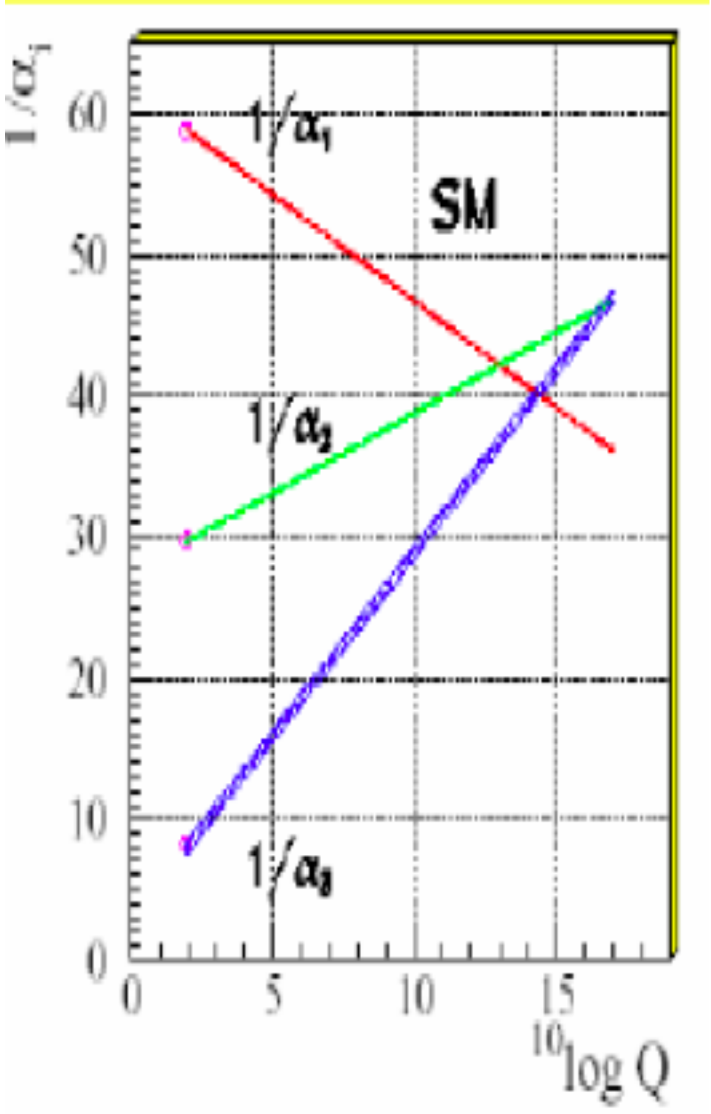
Courtesy of H. Murayama

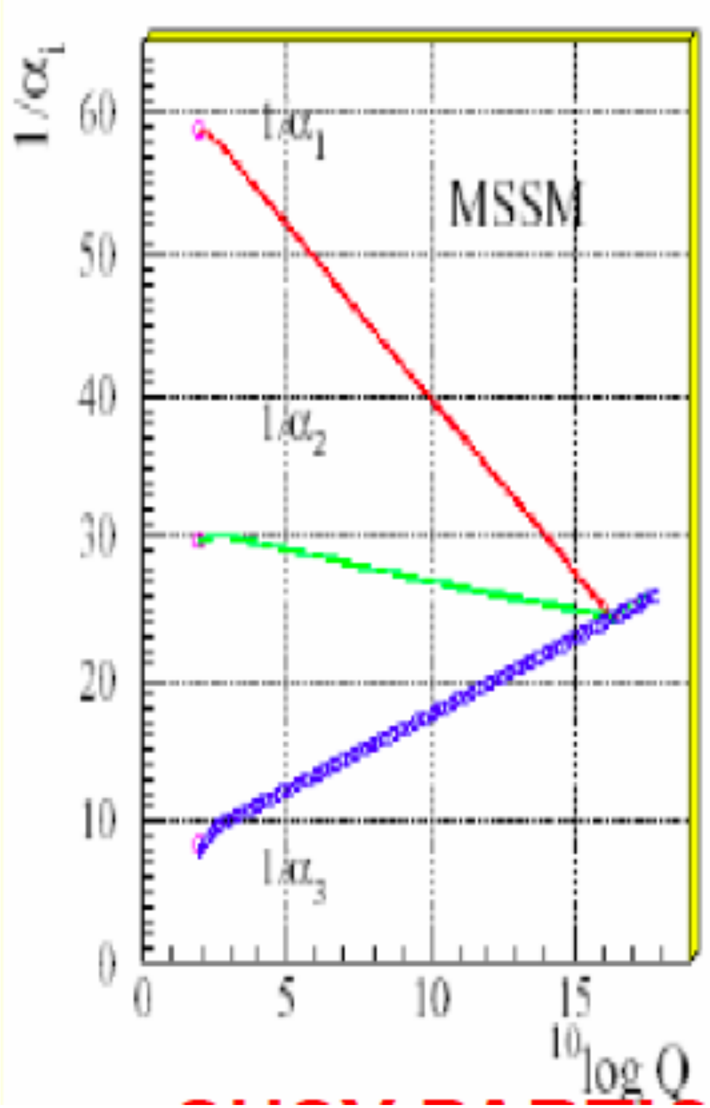
The **COUPLING CONSTANTS** of fundamental interactions are **NOT** constant, but

RUNNING COUPLING CONSTANTS



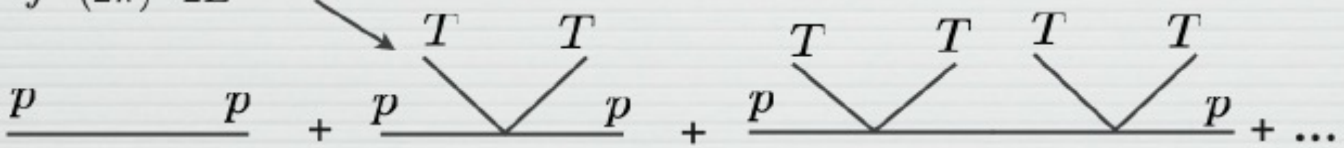
Only one fundamental interaction?





Symmetry Breaking/Restoration

$$-i\lambda \int \frac{d^3p}{(2\pi)^3} \frac{1}{2E} f(p) \propto -i\lambda T^2$$



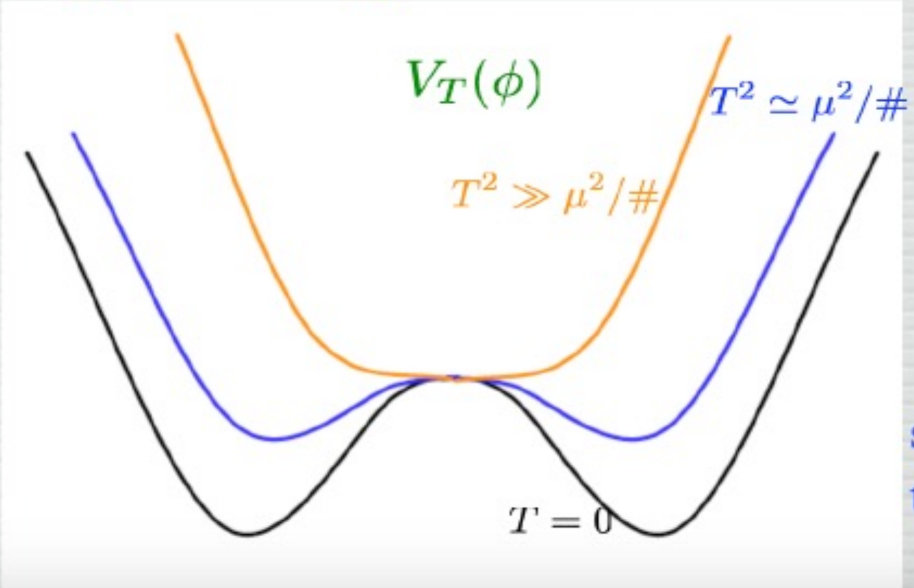
forward scattering

$$\frac{i}{p^2 - m^2} + \left(\frac{i}{p^2 - m^2}\right)^2 (-i\lambda T^2) + \left(\frac{i}{p^2 - m^2}\right)^3 (-i\lambda T^2)^2 + \ldots = \frac{i}{p^2 - m^2 - \lambda T^2}$$

thermal mass

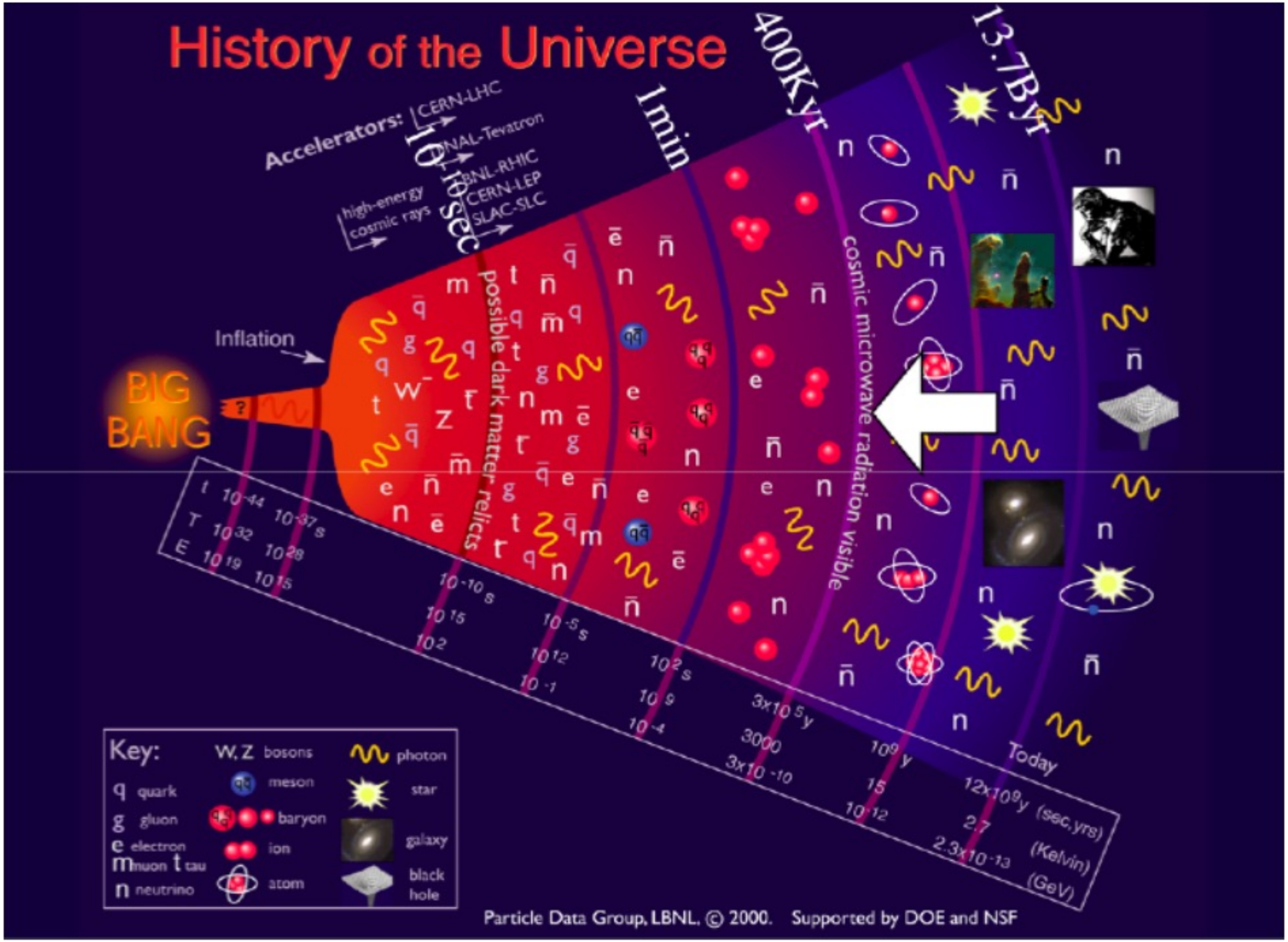
$$V(\phi) = -\frac{1}{2}\mu^2\phi^2 + \frac{1}{4!}\lambda\phi^4 \xrightarrow{T \gg \mu} \frac{1}{2}(-\mu^2 + \# T^2)\phi^2 + \frac{1}{4!}\lambda\phi^4$$

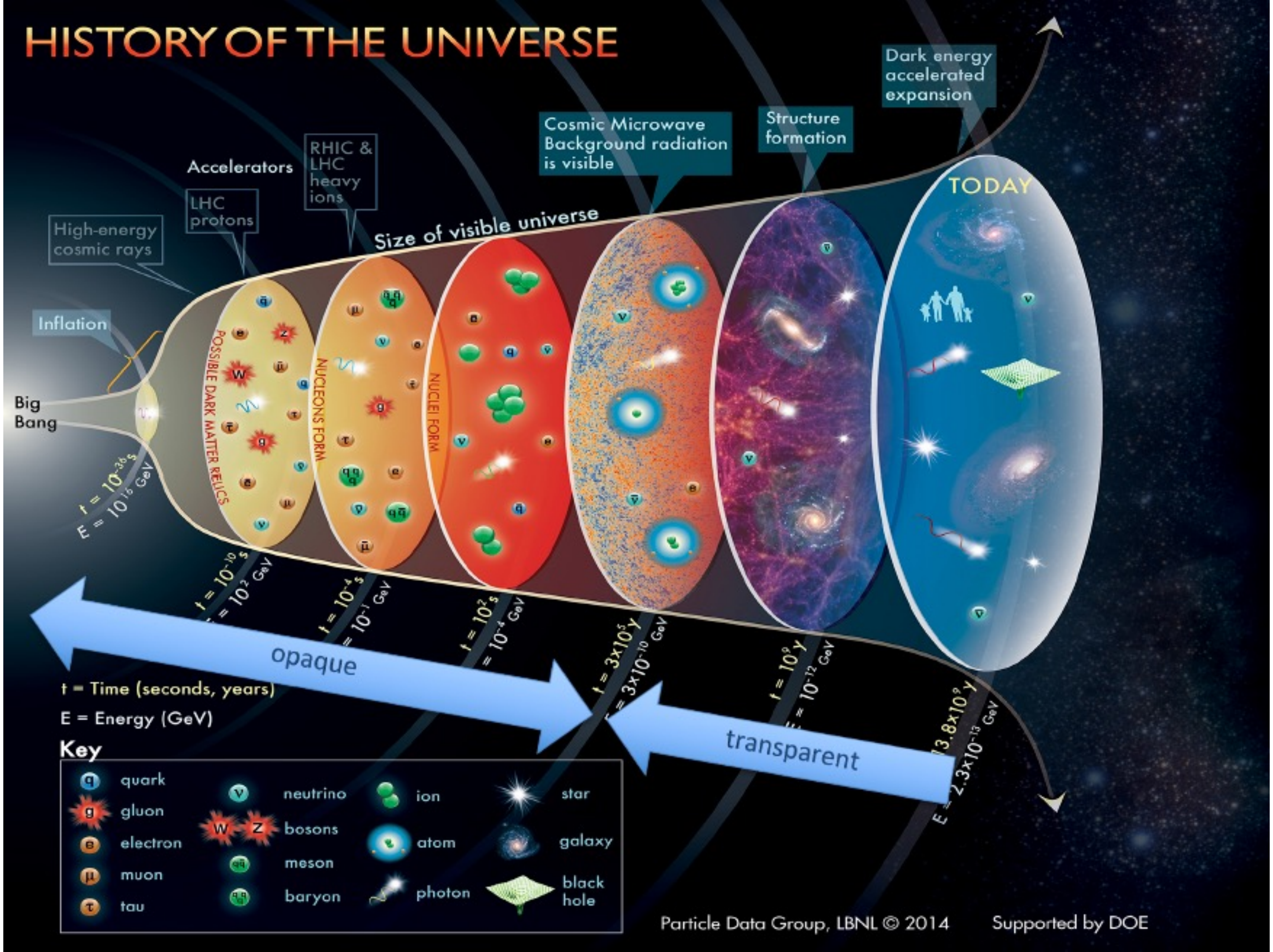
positive contributions from all relativistic particles coupled to ϕ



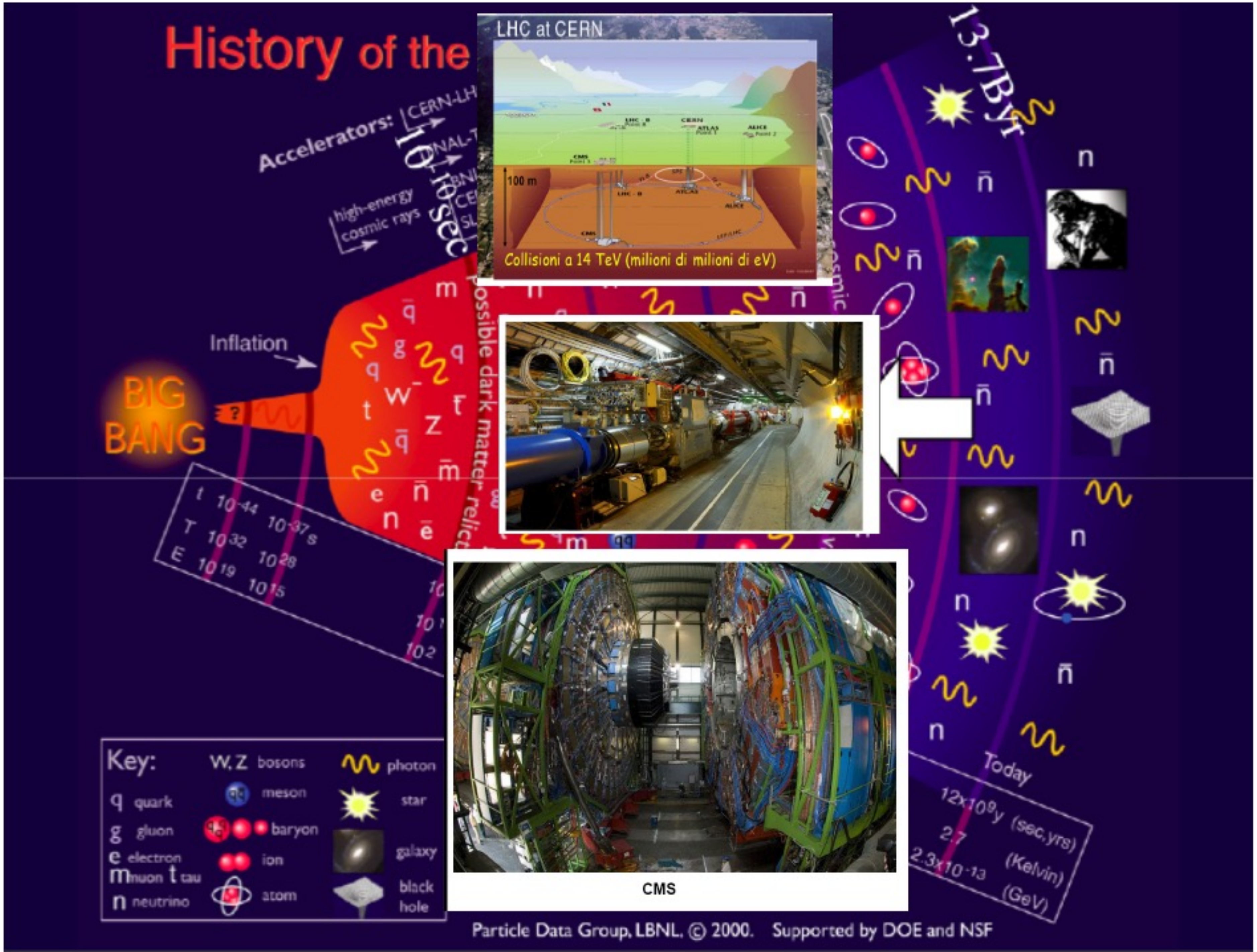
M. Pietroni, ISAPP – Padova, 2024

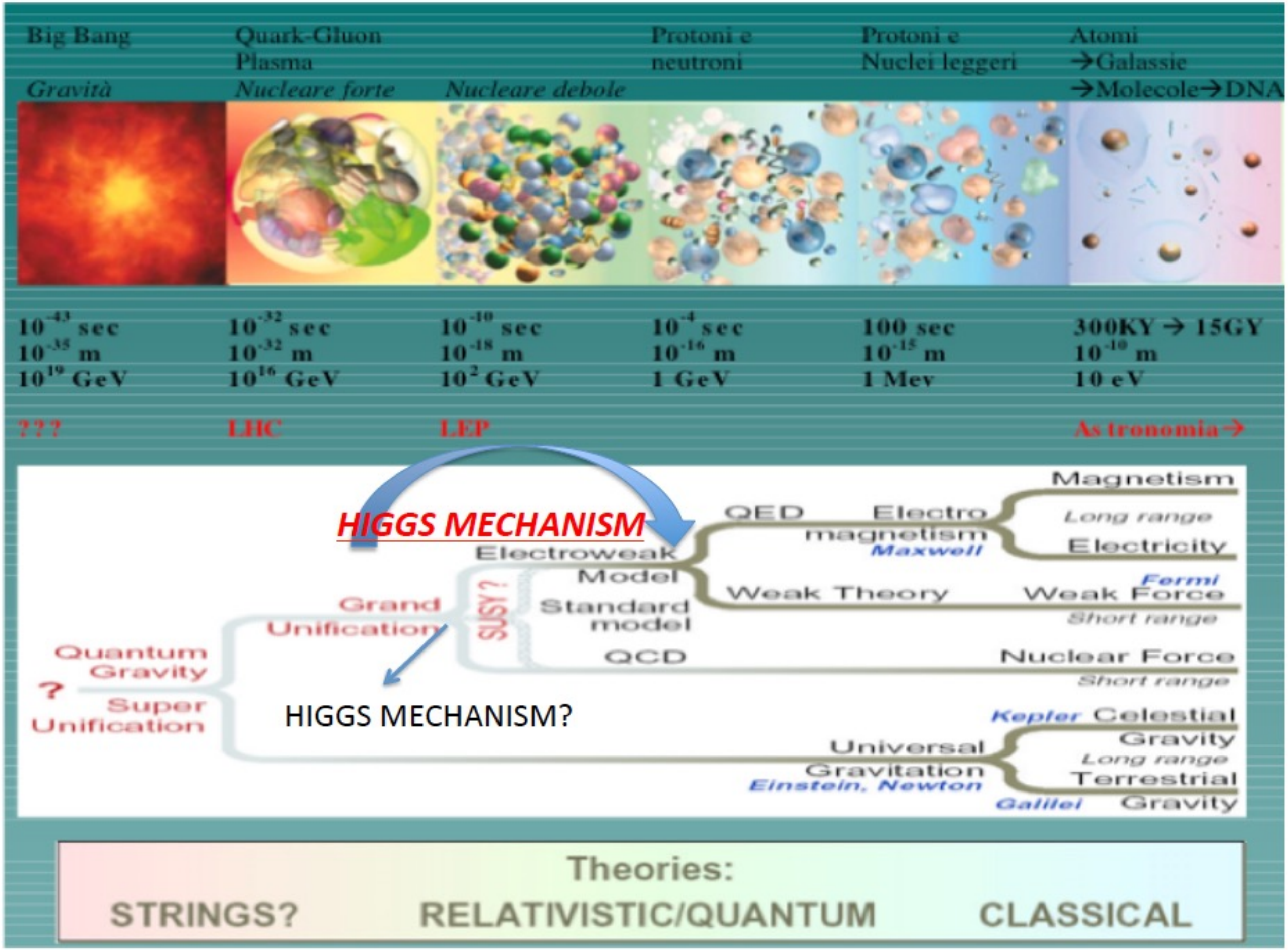
symmetry breaking phase transitions in the early Universe!


History of the Universe
Accelerators:
CERN-LHC
FNAL-Tevatron
BNL-RHIC
CERN-LEP
SLAC-SLC
high-energy cosmic rays
10^{-10} sec
1 min
400Kyr
13.7Byr
Inflation
BIG BANG
possible dark matter relicts
cosmic microwave radiation visible
t 10^{-44} 10^{-37} s
T 10^{32} 10^{28}
E 10^{19} 10^{15}
10^{-10} s
10^{15}
10^{2}
10^{-5} s
10^{12}
10^{-1}
10^{2} s
10^{9}
10^{-4}
3×10^{5} y
3000
3×10^{-10}
10^{9} y
15
10^{-12}
Today
12×10^{9} y (sec,yrs)
2.7 (Kelvin)
2.3×10^{-13} (GeV)
Key:
q quark
g gluon
e electron
m muon t tau
n neutrino
W, Z bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
Particle Data Group, LBNL, © 2000. Supported by DOE and NSF

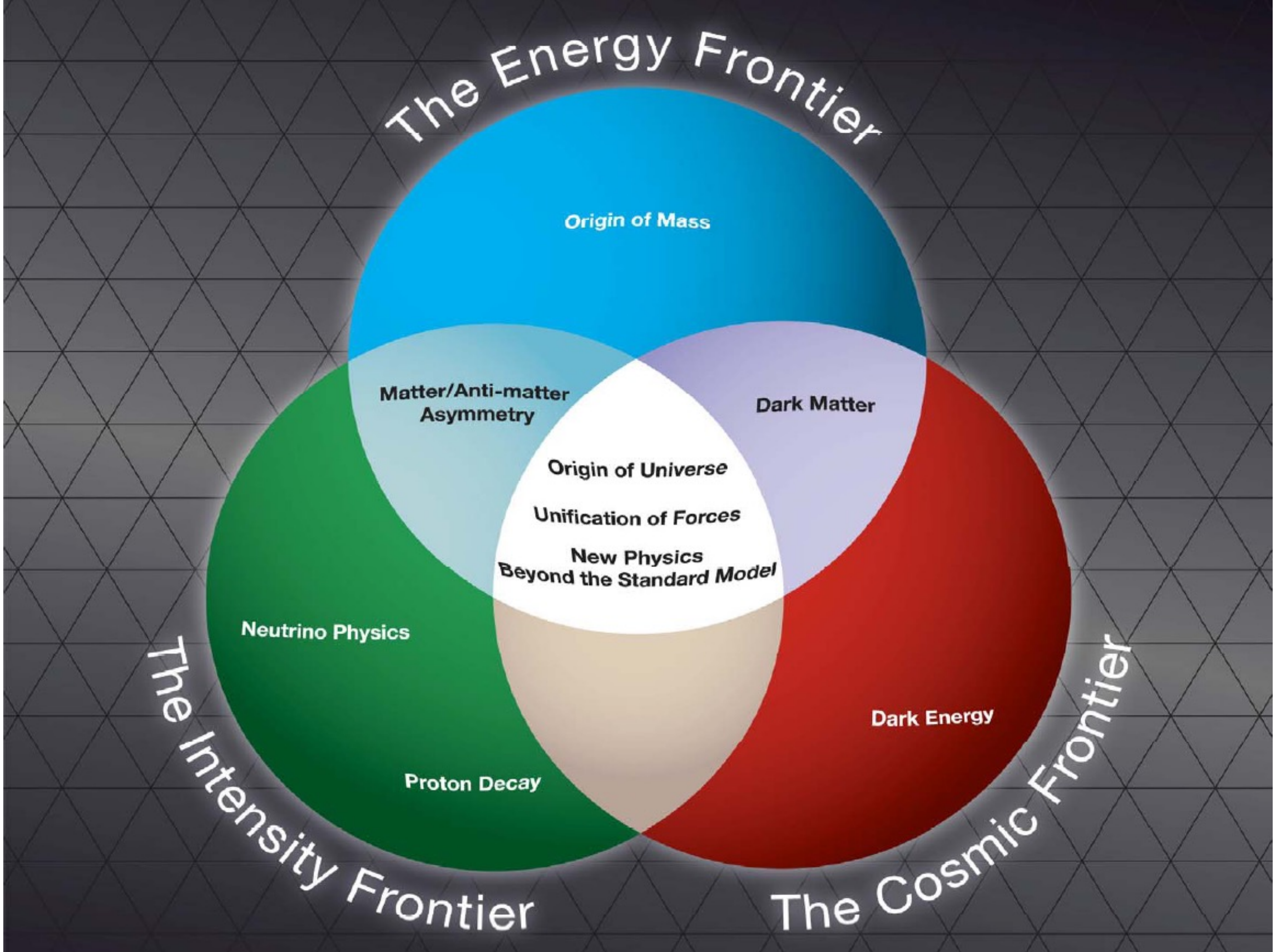


HISTORY OF THE UNIVERSE
Dark energy accelerated expansion
Cosmic Microwave Background radiation is visible
Structure formation
TODAY
Accelerators
RHIC & LHC heavy ions
LHC protons
High-energy cosmic rays
Size of visible universe
Inflation
Big Bang
POSSIBLE DARK MATTER RELICS
NUCLEONS FORM
NUCLEI FORM
t = 10⁻³⁶ s
E = 10¹⁶ GeV
t = 10⁻¹⁰ s
E = 10² GeV
t = 10⁻⁴ s
E = 10⁻¹ GeV
t = 10² s
E = 10⁻⁴ GeV
t = 3x10⁵ y
E = 3x10⁻¹⁰ GeV
t = 10⁹ y
E = 10⁻¹² GeV
t = 13.8x10⁹ y
E = 2.3x10⁻¹³ GeV
opaque
transparent
t = Time (seconds, years)
E = Energy (GeV)
Key
quark
gluon
electron
muon
tau
neutrino
bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
Particle Data Group, LBNL © 2014
Supported by DOE

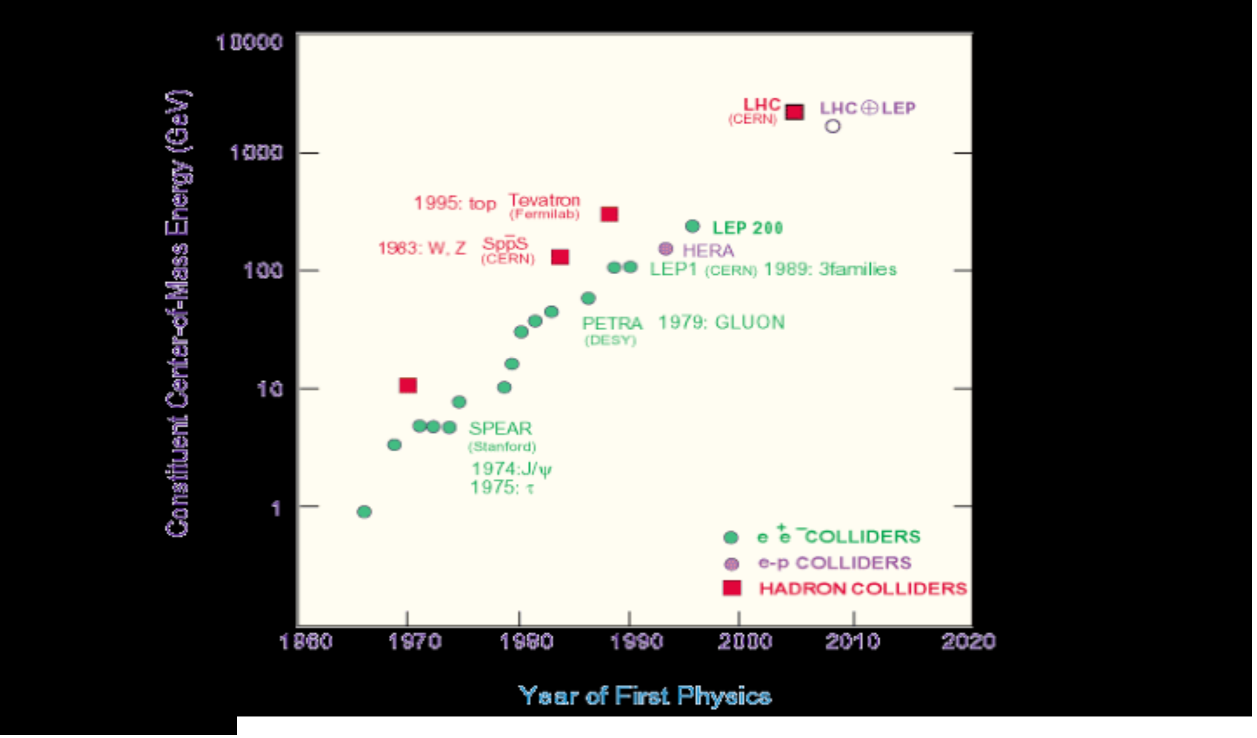

History of the
Accelerators:
high-energy cosmic rays
LHC at CERN
100 m
Collisioni a 14 TeV (milioni di milioni di eV)
13.7Byr
Inflation
BIG BANG
t 10-44 10-37 s
T 1032 1028
E 1019 1015
CMS
Today
12x109y (sec,yrs)
2.7 (Kelvin)
2.3x10-13 (GeV)
Key:
q quark
g gluon
e electron
m muon t tau
n neutrino
W,Z bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
Particle Data Group, LBNL, © 2000. Supported by DOE and NSF



Big Bang
Gravità
Quark-Gluon Plasma
Nucleare forte
Nucleare debole
Protoni e neutroni
Protoni e Nuclei leggeri
Atomi →Galassie →Molecole→DNA
10^{-43} sec
10^{-35} m
10^{19} GeV
10^{-32} sec
10^{-32} m
10^{16} GeV
10^{-10} sec
10^{-18} m
10^{2} GeV
10^{-4} sec
10^{-16} m
1 GeV
100 sec
10^{-15} m
1 Mev
300KY → 15GY
10^{-10} m
10 eV
???
LHC
LEP
As tronomia→
HIGGS MECHANISM
Magnetism
QED
Electro magnetism
Maxwell
Long range
Electricity
Electroweak
Model
Fermi
Weak Theory
Weak Force
Short range
Grand Unification
SUSY ?
Standard model
Quantum Gravity
QCD
Nuclear Force
Short range
?
Super Unification
HIGGS MECHANISM?
Kepler
Celestial Gravity
Long range
Universal Gravitation
Einstein, Newton
Terrestrial Gravity
Galilei
Theories:
STRINGS?
RELATIVISTIC/QUANTUM
CLASSICAL


The Energy Frontier
Origin of Mass
Matter/Anti-matter Asymmetry
Dark Matter
Origin of Universe
Unification of Forces
New Physics Beyond the Standard Model
Neutrino Physics
Proton Decay
Dark Energy
The Intensity Frontier
The Cosmic Frontier

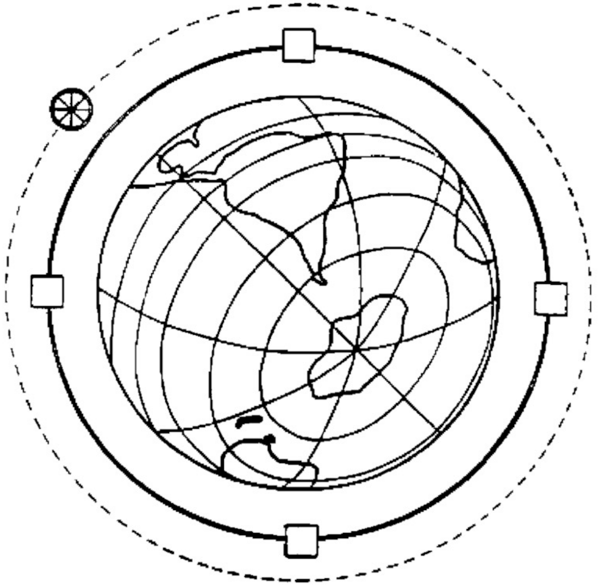
THE HIGH-ENERGY ROAD



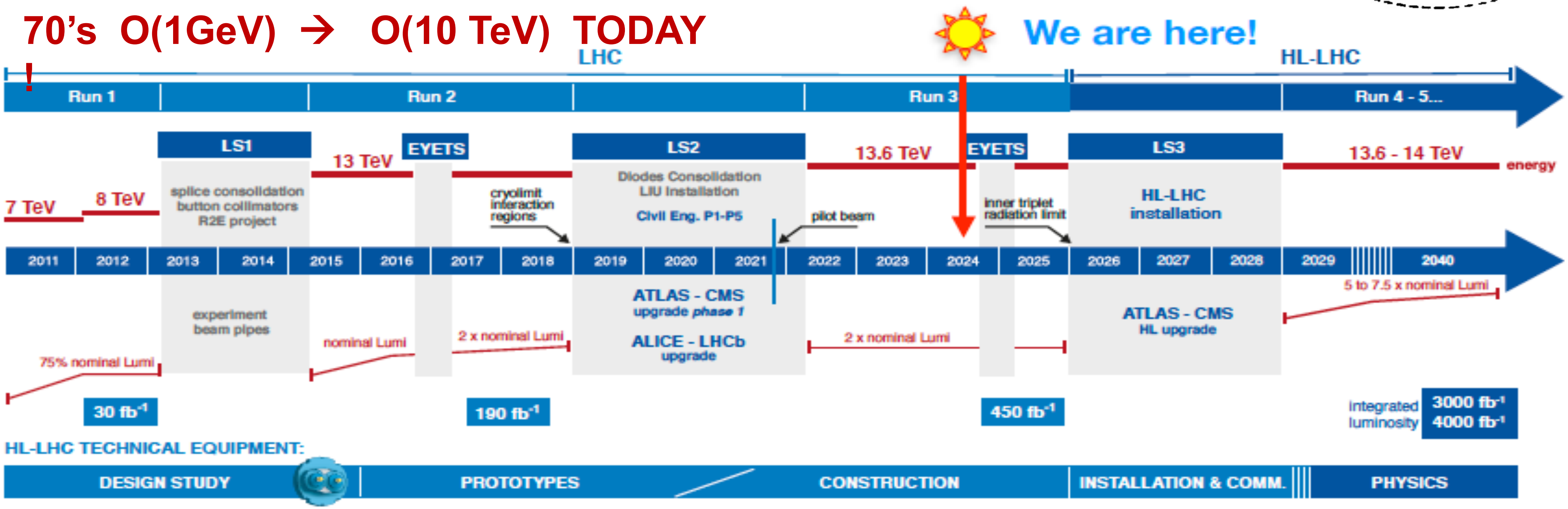
Ultimate Accelerator.

Drawn by Fermi in the '50 to reach 3 TeV.

The manifesto of HEP!



70's O(1GeV) → O(10 TeV) TODAY !



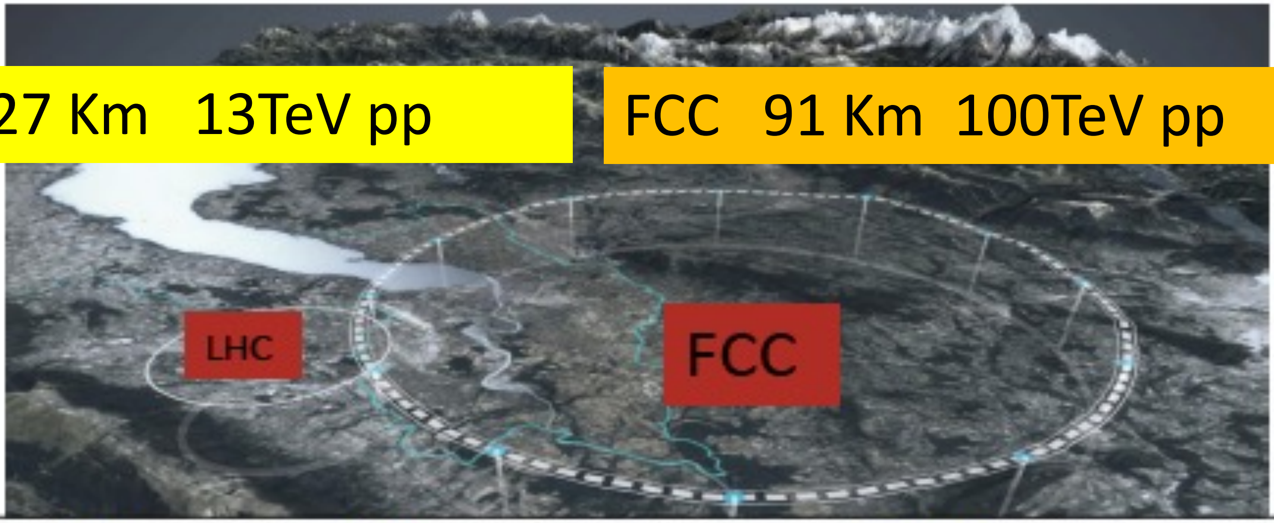
This leaves us with

the Future Circular Collider (e^+e^- followed by pp) – at CERN

or maybe a similar facility in China

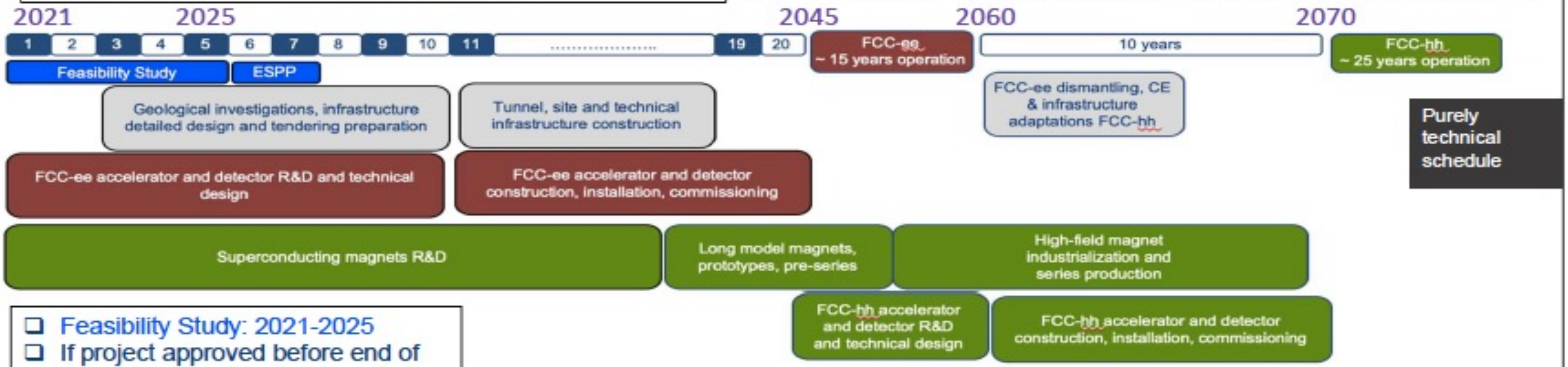
LHC 27 Km 13TeV pp

FCC 91 Km 100TeV pp



Reference https://indico.cern.ch/event/1202105/timetable/

I have drawn particularly on discussions with and slides provided by Fabiola Gianotti and Gavin Salam



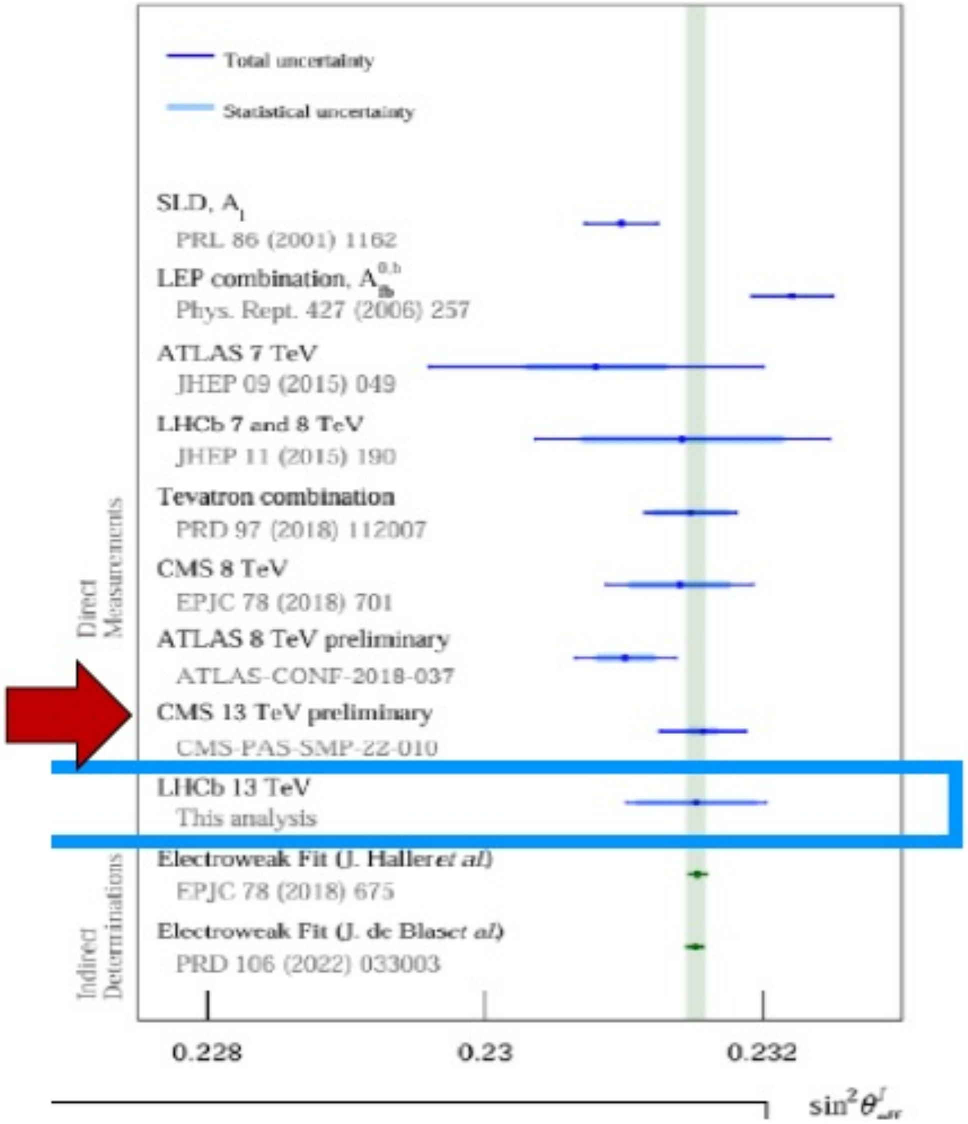
- Feasibility Study: 2021-2025
- If project approved before end of decade → construction can start beginning 2030s
- FCC-ee operation ~2045-2060
- FCC-hh operation 2070-2090++

For health of field:

imperative to minimise gap between Hi-Lumi LHC and FCC e^+e^-

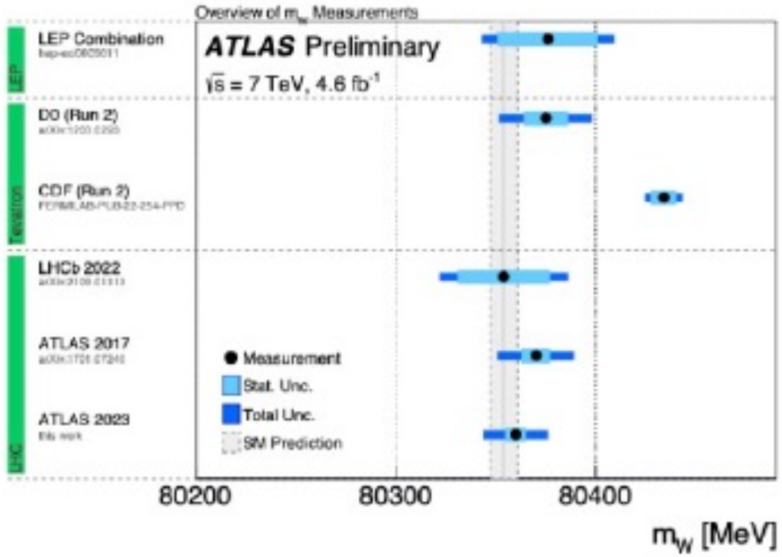
Testing the GAUGE part of the SM

LHC: from **DISCOVERY** to **PRECISION** physics machine

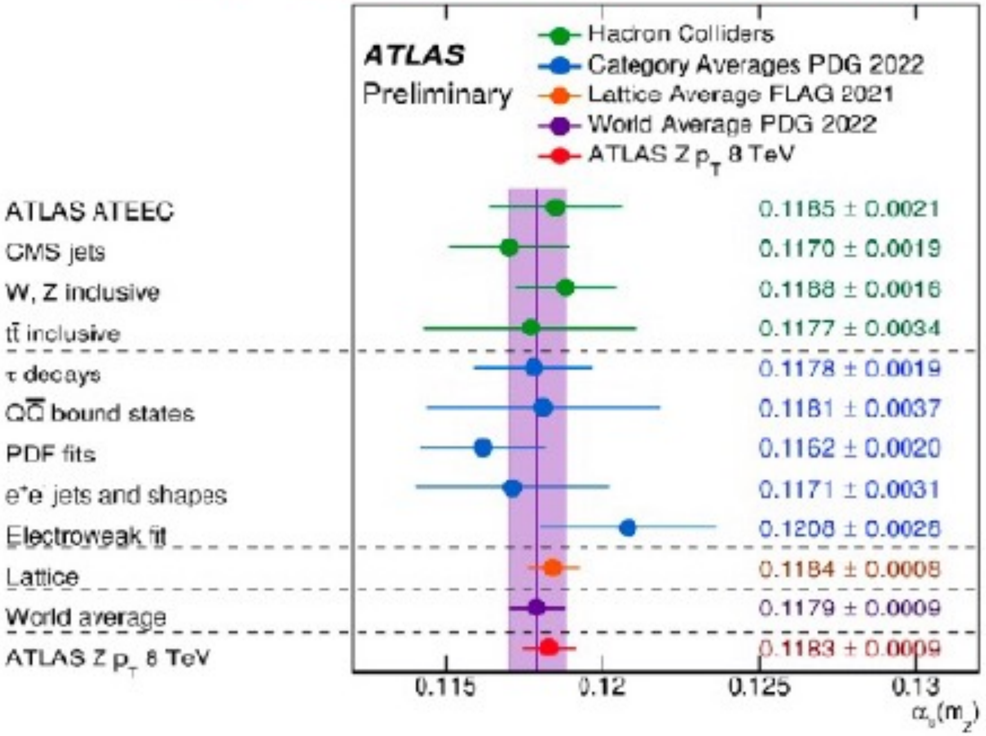


$\sin^2\theta^{l}_{eff}$

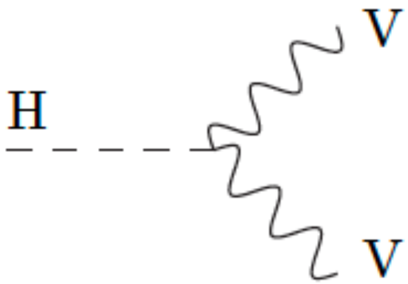
$$\sin^2 \theta^{\ell}_{eff} = 0.23152 \pm 0.00044 \pm 0.00005 \pm 0.00022$$



$m_W = 80360 \pm 5_{(stat.)} \pm 15_{(syst.)} = 80360 \pm 16$ MeV



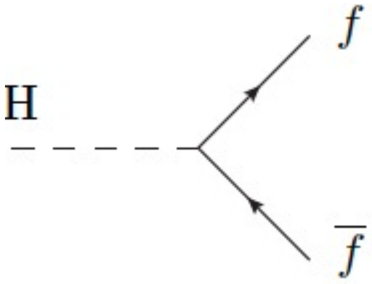
Testing the HIGGS part of the SM: present and future



$$\frac{2m_V^2}{v}$$

$$|D_\mu \phi|^2$$

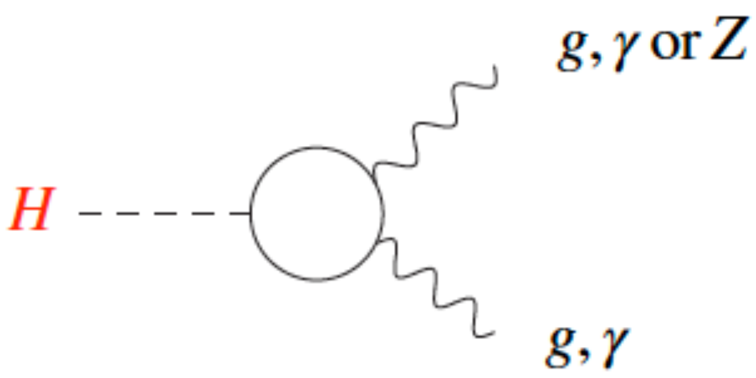
	Current	HL-LHC	FCC (ee)
$\kappa_{W,Z}$	6%	1.5%, 1.7 %	0.4%, 0.2 %

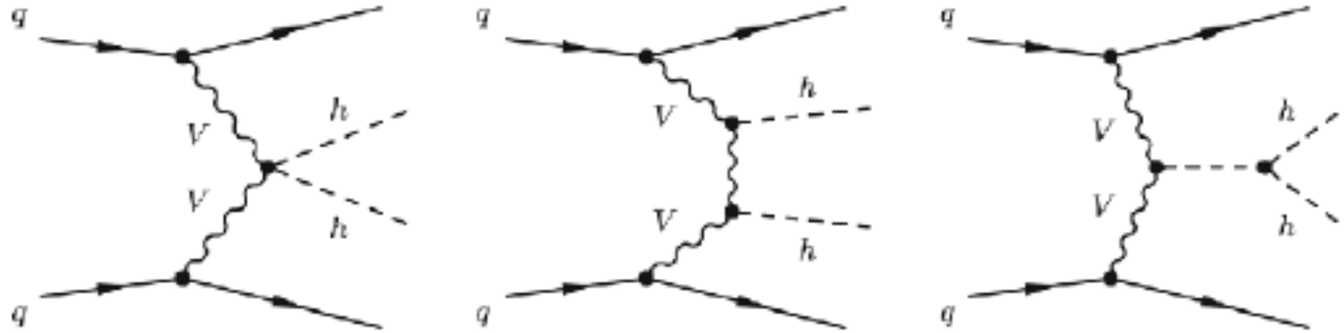


$$\frac{m_f}{v}$$

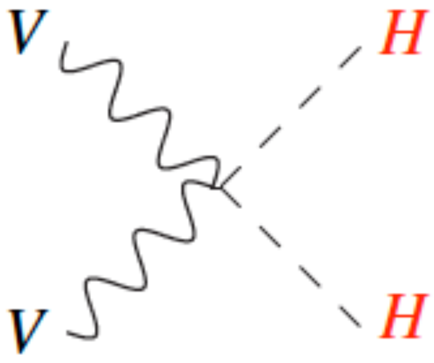
$$\bar{\psi}_i y_{ij} \psi_j \phi + h.c.$$

	Current	HL-LHC	FCC (ee)	FCC (hh)
κ_t	11%	3.4%	-	1%
κ_b	11%	3.7%	0.7%	-
κ_τ	8%	1.9%	0.7%	-
κ_μ	20%	4.3%	8.9%*	





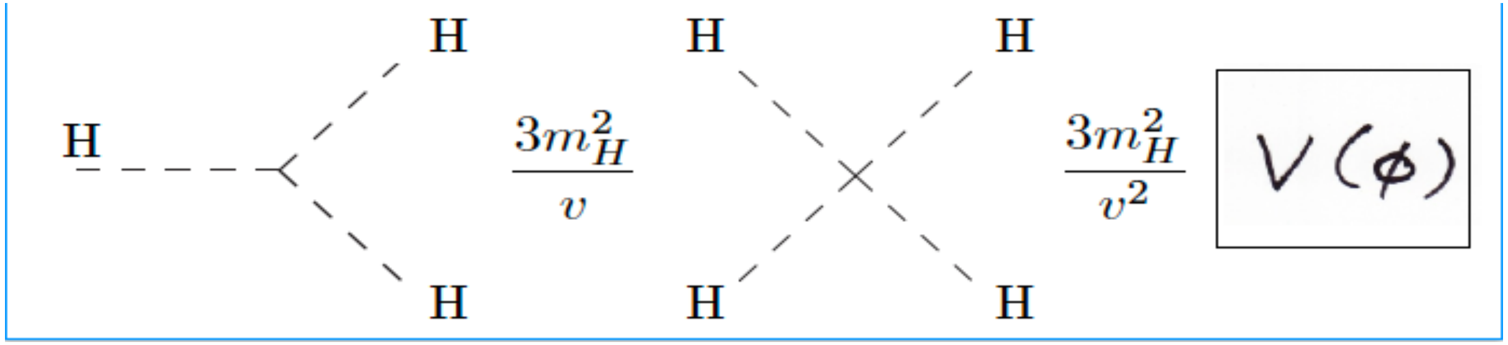
	Current	HL-LHC	FCC (ee)
κ_γ	6%	1.8%	3.9%
κ_g	7%	2.5%	1%
$\kappa_{Z\gamma}$	30%	9.8%	



$$g_{HHVV} \sim \frac{2M_V^2}{v^2}$$

$$\kappa_{2V} \in [0.67, 1.38]$$

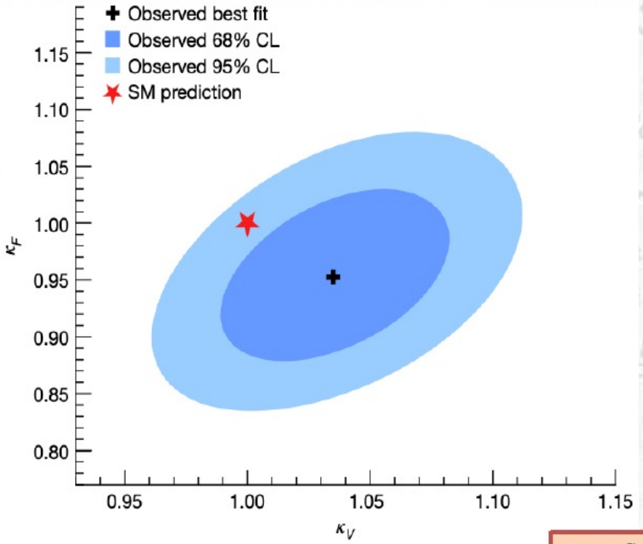
CMS result (ATLAS similar)



Large trilinear deviations are possible while deviations of the Higgs to Z coupling remain small

Status of Higgs Couplings

hat are experimental limits on modifications of
ouplings relative to Standard Model prediction?



ATLAS, Nature, 2022

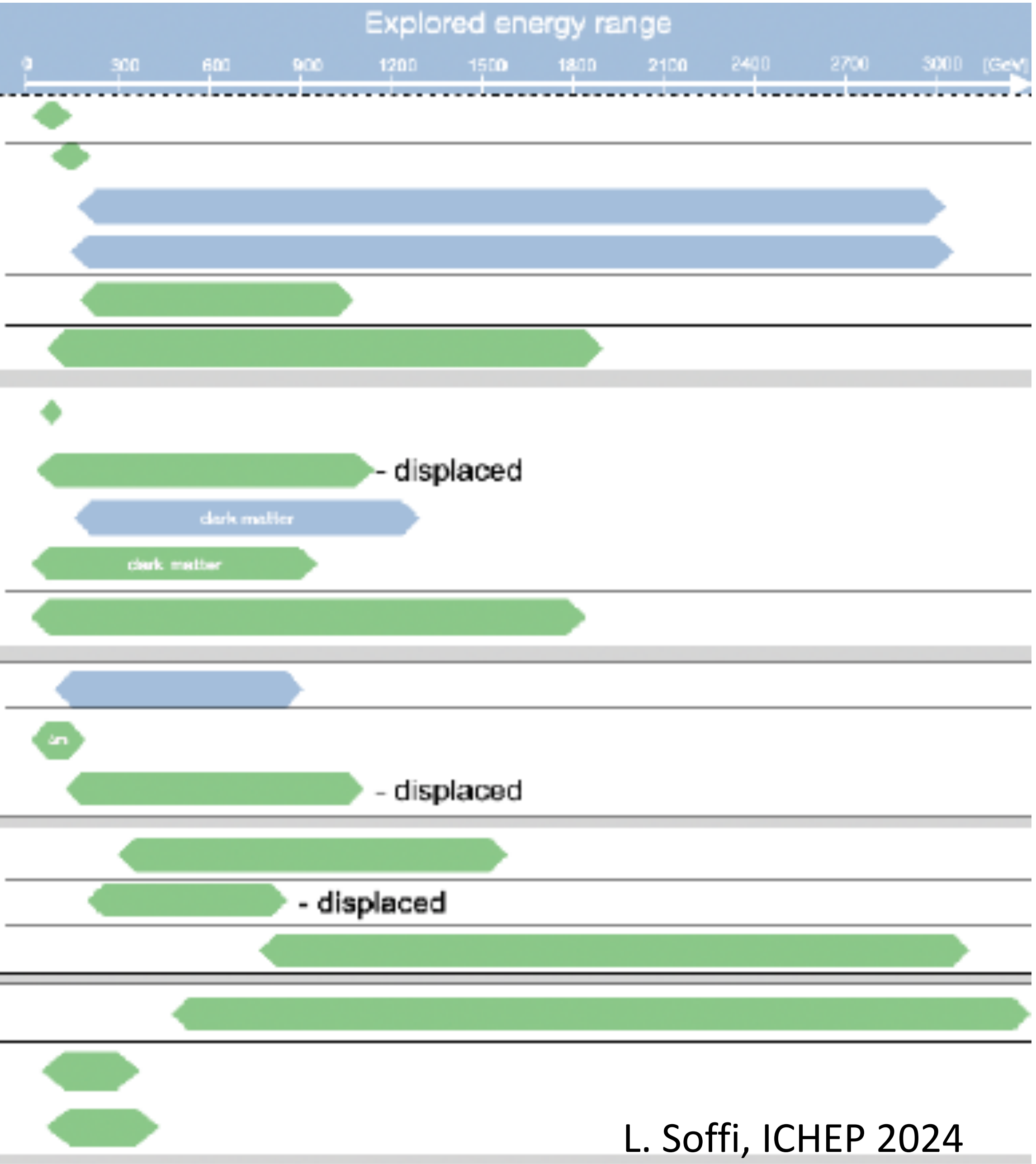
Higgs physics is still in its nascence. Pions were discovered in the early 1940's. Their fundamental origin, QCD, was developed theoretically in the early 1970's and only experimentally established in the late 1970's.

Twelve years since discovery of the Higgs boson.

As it stands, we don't know how it interacts with itself, or if it is composite; with far-reaching implications.

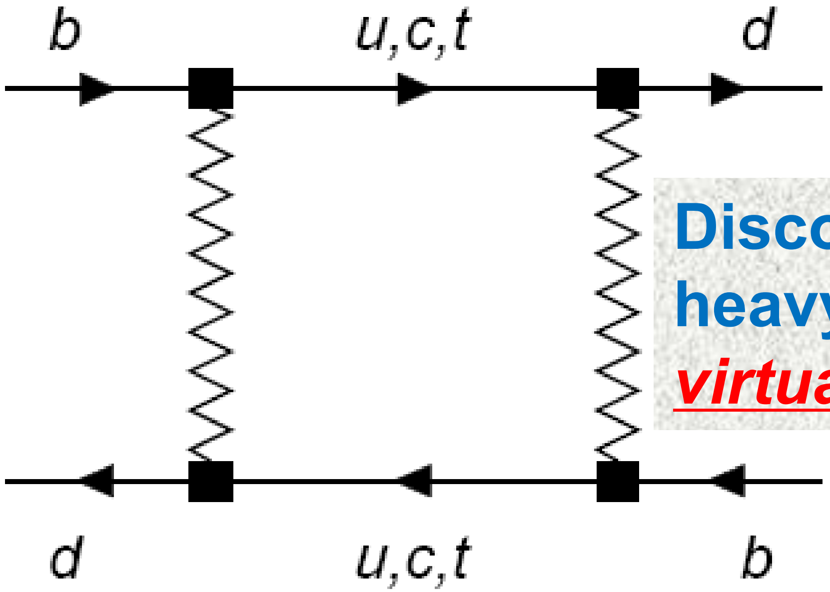
(Desperately) seeking SUSY particles or many other kinds of new particles beyond the SM particle spectrum

Reference	Topic	Experiment	Model
HDBS-2021-07	$H \to aa \to bb\tau\tau$	ATLAS	Extended Higgs Sector
HDBS-2020-11	$H^{\pm} \to cs$	ATLAS	
HDBS-2023-19	Combination of charged H	ATLAS	
HIG-24-002	$H \to ZZ \to 4l$	CMS	
HIG-22-004	$A \to Zh(\tau\tau)$	CMS	
SUS-24-001	$\phi \to b\bar{b}$	CMS	
EXOT-2018-55	Prompt Leptonjets	ATLAS	Dark Sector +ALPs
EXOT-2022-04	Neutral LLP into displaced jets	ATLAS	
SUS-23-004	$\mathrm{mono}-t$	CMS	
SUS-23-012	$\mathrm{mono}-h(\tau\tau)$	CMS	
SUS-23-018	$H \to Za \to ll\chi\chi$	CMS	
SUS-24-004	pMSSM	CMS	Supersymmetry
SUS-23-003	Compressed SUSY w/ RJR	CMS	
ATLAS-2024- 011	Run3 displaced leptons	ATLAS	
ATLAS-2024-008	$\mathrm{VLL} \to \tau b$	ATLAS	Heavy Fermions
EXO-23-015	$\mathrm{VLL} \to \tau a(\gamma\gamma)$	CMS	
B2G-22-005	$t^* \to tg$	CMS	
EXO-23-010	$ll + \mathrm{b-jets, non-resonant}$	CMS	EFT
EXO-24-007	Low mass dijet+ISR	CMS	Z' Mediator
EXO-22-006	$Z' \to \mu\mu + \mathrm{b-jets, resonant}$	CMS	

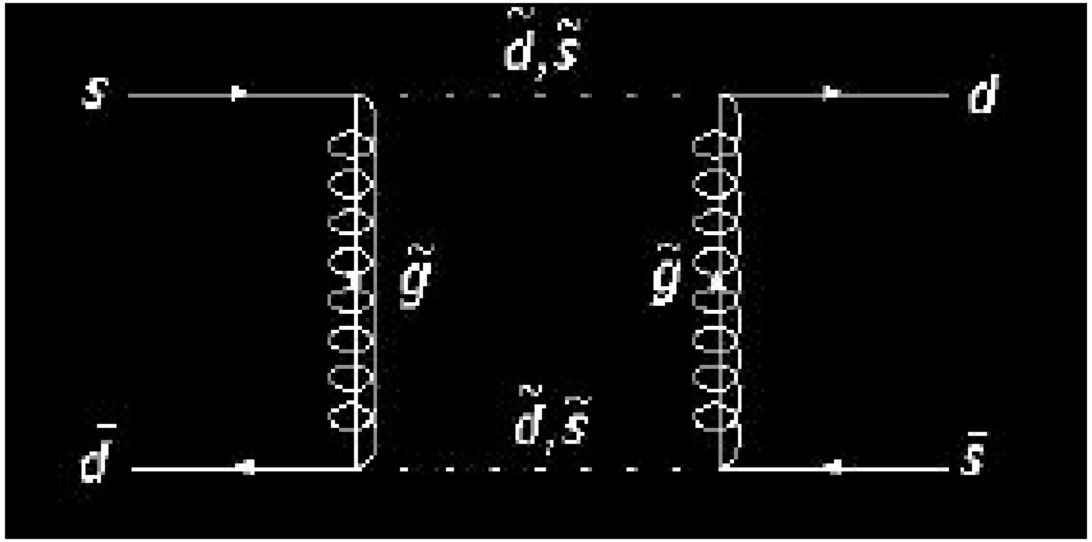


L. Soffi, ICHEP 2024

THE HIGH-INTENSITY ROAD



Discovering the presence of the heavy up-type quarks through their ***virtual*** effects on physical processes



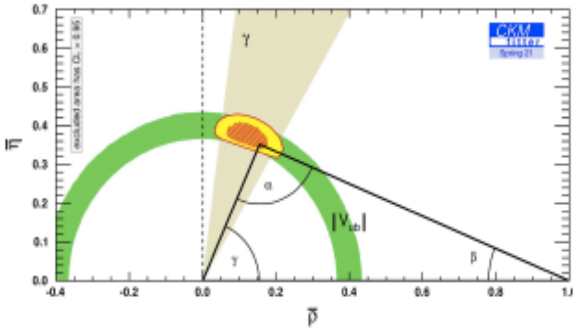
Looking for **NEW PARTICLES** through their virtual effects → **discrepancies** w.r.t. the **SM predictions**

Mixings and CP Violation in the SM quark sector (hadronic flavour physics):
the SM brilliantly passes unscathed all the extremely demanding flavour tests!

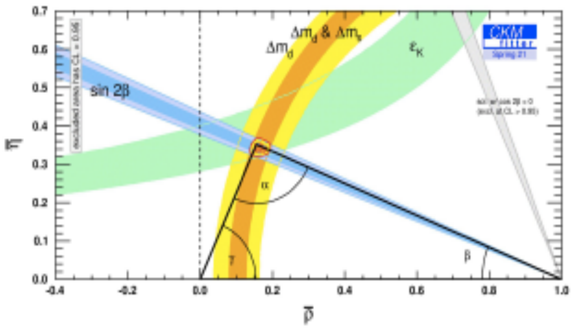
Consistency tests of the CKM matrix

- At the current level of precision (~%), all measurements are consistent and intersect in the apex of the UT
- What is particularly noteworthy is the consistency of the tree-level determinations of CKM elements, with those obtained from meson-anti meson mixing

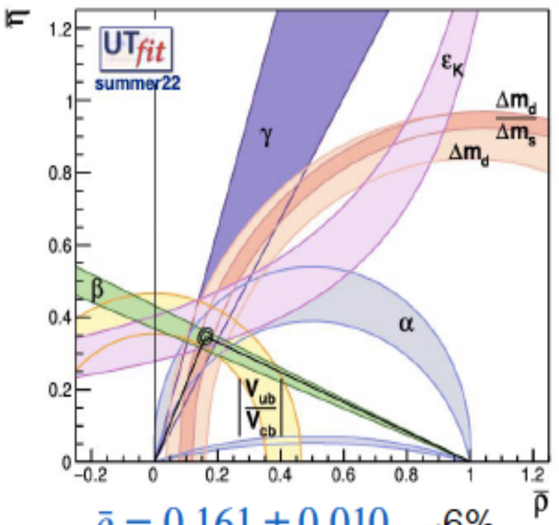
Tree-level observables



Loop observables



arXiv:2212.03894 UTfit,



$\bar{\rho} = 0.161 \pm 0.010$ ~6%

$\bar{\eta} = 0.347 \pm 0.010$ ~3%

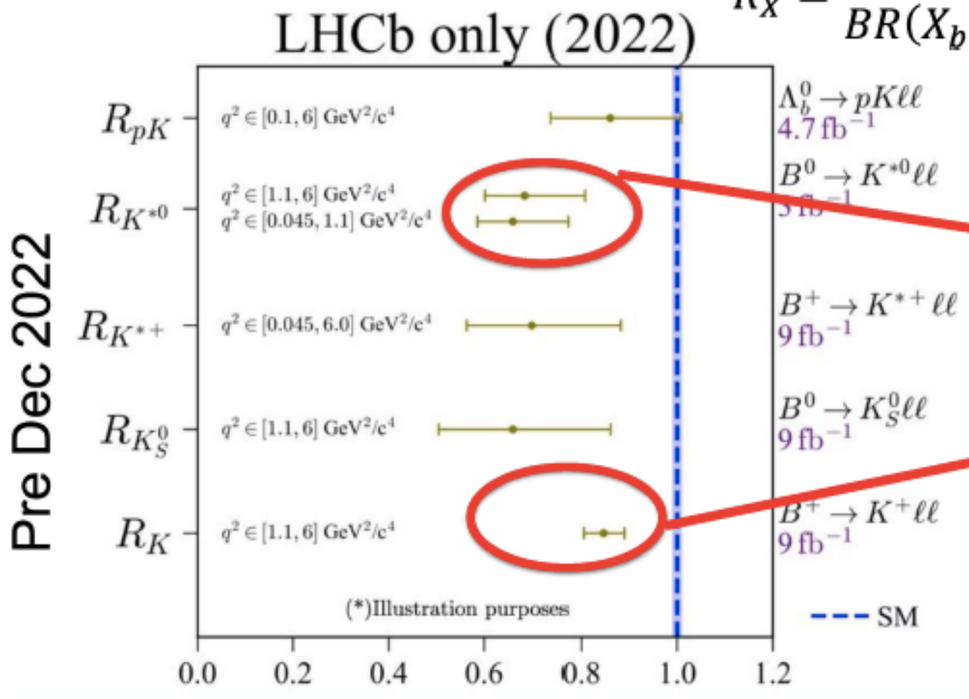
- New Physics effects (if there) are small!
- But… past examples show that it is unwise to think that few % is good enough

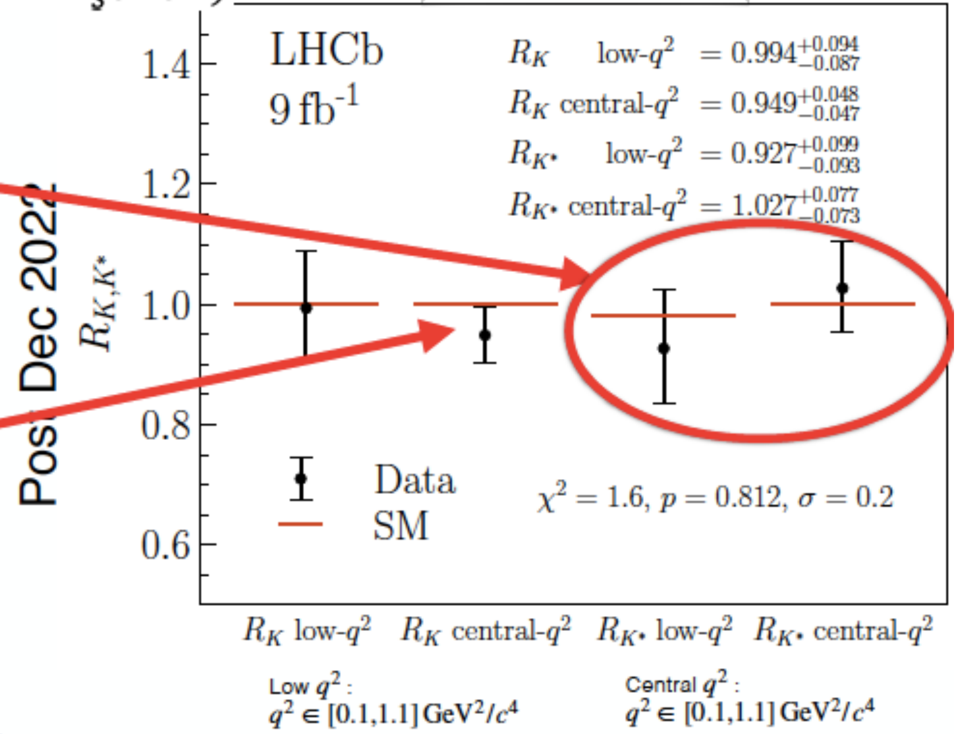
M. Pepe-Altarelli, Erice School, June 2023

Tests of Lepton Flavour Universality

$$R_X = \frac{BR(X_b \to X_s \mu^+ \mu^-)}{BR(X_b \to X_s e^+ e^-)}$$

arXiv:2212.09152
arXiv:2212.09153





A remaining flavor puzzle in B physics?

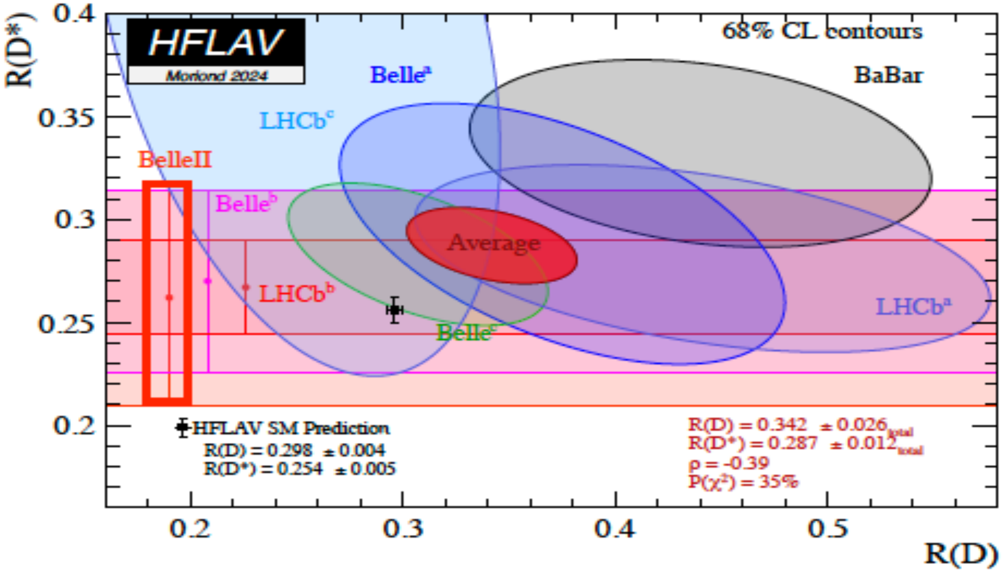
A puzzling result
in tree-level $b \to c$ transitions

First Belle II RD* measurement!

Both TH and EXP clean!

$$\mathcal{R}(D^{(*)}) = \frac{\mathcal{B}\left(B^0 \to D^{(*)-}\tau^+\nu_\tau\right)}{\mathcal{B}\left(B^0 \to D^{(*)-}\mu^+\nu_\mu\right)}$$

~3σ tension



$$R_D^* = 0.26 \pm 0.04^{+0.04}_{-0.03}$$

In conclusion, **NO firm hints for any discrepancy between SM expectations and experimental results in the many and accurate tests in FLAVOR PHYSICS** (FCNC, lepton flavor universality in K,D, B semileptonic decays, etc.)

<u>**Complementary**</u> (***not*** ALTERNATIVE!) approach → **HIGH-PRECISION EXPS. in SMALL/MID-SCALE RIs**

Low-energy high-precision exps. can exploit :

- many recent ***advances in experimental techniques and technologies*** + **(experimental as well as theoretical)** ***synergies*** with adjacent areas of particle physics (atomic, molecular, optical, nuclear, particle physics)
- the relevant impact of ***quantum mechanical virtual effects*** on physical phenomena → access to the exploration of BSM new physics areas (large energy scales, very feebly coupled new particles, hidden sectors, etc.) difficult to be probed by traditional HE particle physics

<u>**SYNERGY**</u> **between small/mid-scale & large-scale experiments → casting a wider and tighter net for possible effects of BSM physics**

Community Planning Exercise: Snowmass 2021 Blum, Winter et al. arXiv:2209.08041v2

→ 2023 P5 (Particle Physics Project Prioritization Panel) Report

Electric and Magnetic Dipole Moments of a fermion

Interaction of a fermion f with the photon field A_μ, $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$

$$-d_f \frac{\vec{S}}{|S|} \cdot \vec{E} \quad \rightarrow \quad d_f \frac{i}{2} (\bar{f} \sigma_{\mu\nu} \gamma_5 f) F^{\mu\nu}$$

$$-\mu_f \frac{\vec{S}}{|S|} \cdot \vec{B} \quad \rightarrow \quad e(\bar{f} \gamma_\mu f) A^\mu + a_f \frac{e}{4m_f} (\bar{f} \sigma_{\mu\nu} f) F^{\mu\nu}$$

the usual minimal coupling of fermions with the photon give rise to a magnetic moment with gyromagnetic factor $g = 2$

the dimension 5 operators induce an electric dipole moment d_f and an anomalous magnetic moment a_f

$$\mu_f = g_f \frac{e}{2m_f} \quad , \quad (g_f - 2) = 2a_f$$

$$\vec{\mu}_\ell = \frac{e}{2m}\vec{\ell}$$

$$\vec{\mu}_s = g\,\frac{e}{2m}\,\vec{s}$$

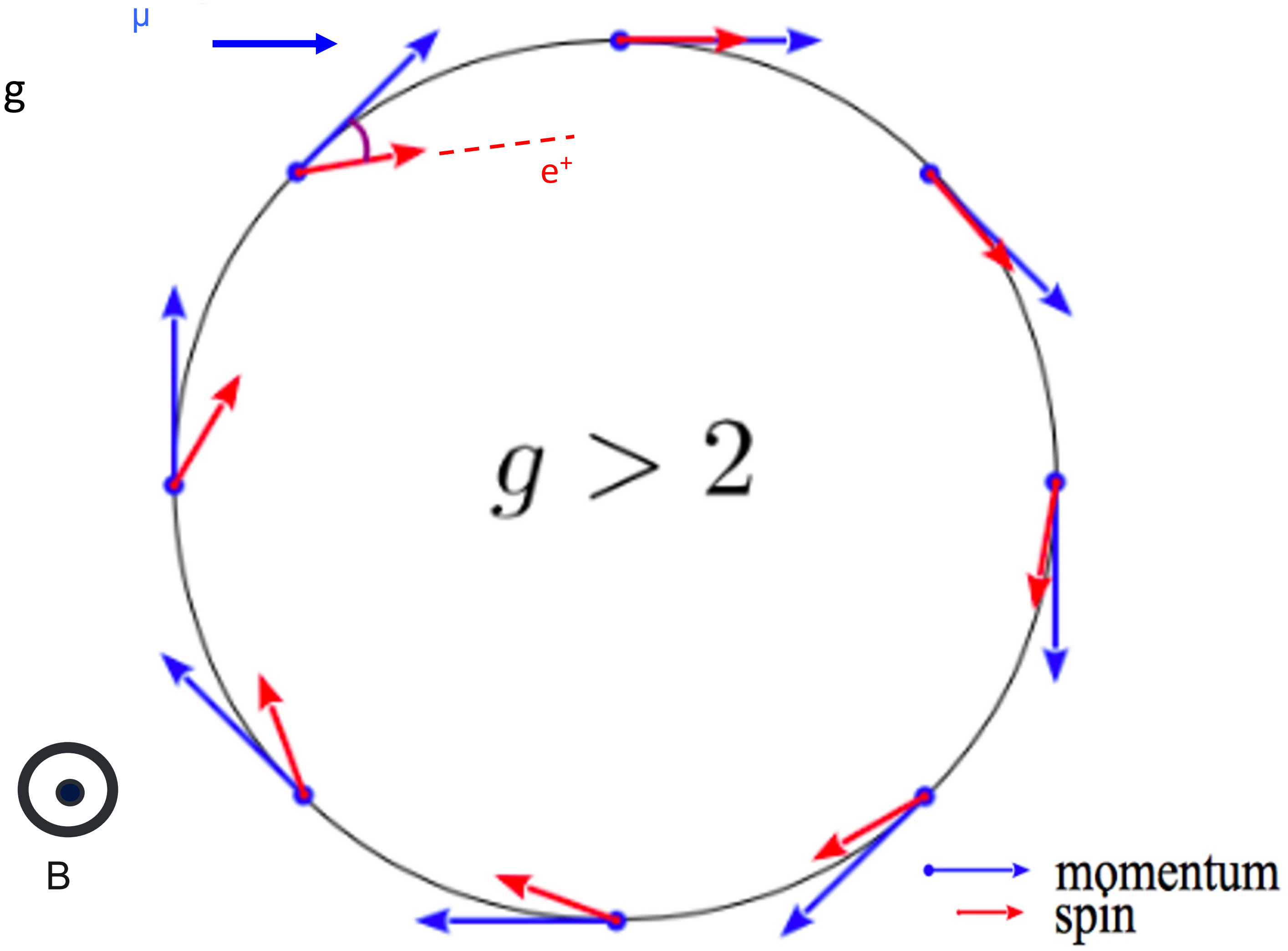
Put a beam of polarized muons into a storage ring

Both the muon spin and momentum precess

Because g is slightly greater than 2 the spin precesses faster than the momentum

$$a = (g-2)/2$$

$$a_\mu = \omega_a \frac{eB}{mc}$$

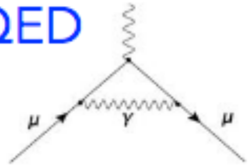


The 4 classes of SM contributions to the muon g-2

uncertainty largely dominated by the **hadronic contributions in Vacuum Polarization (HVP)**

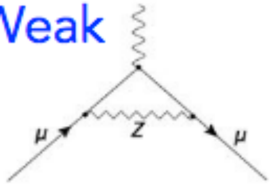
$$a_\mu(\mathrm{SM}) = a_\mu(\mathrm{QED}) + a_\mu(\mathrm{Weak}) + a_\mu(\mathrm{Hadronic})$$

QED



$+\ldots$ $\quad 116\,584\,718.9\,(1) \times 10^{-11}$ $\quad$ 0.001 ppm

Weak

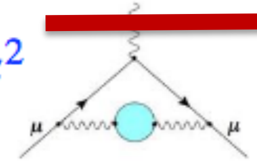


$+\ldots$ $\quad 153.6\,(1.0) \times 10^{-11}$ $\quad$ 0.01 ppm

Hadronic…

…Vacuum Polarization (HVP)

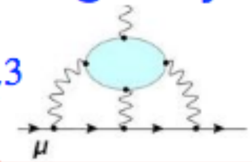
α^2



$+\ldots$ $\quad 6845\,(40) \times 10^{-11}$ [0.6%] $\quad$ 0.37 ppm

…Light-by-Light (HLbL)

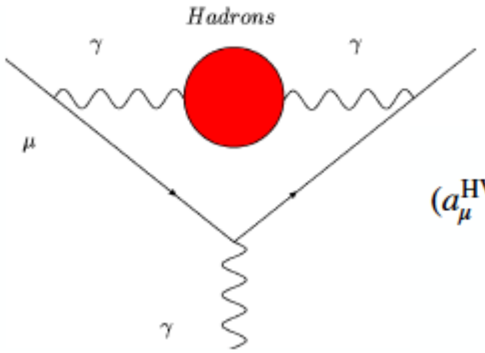
α^3



$+\ldots$ $\quad 92\,(18) \times 10^{-11}$ [20%] $\quad$ 0.15 ppm

Numbers from Theory Initiative Whitepaper

Hadronic Vacuum Polarization (HVP) contribution



Im  ~  ~ $\sigma(e^+e^- \to \gamma^* \to \text{hadrons})$

$$(a_\mu^{\mathrm{HVP}})_{e^+e^-} = \frac{\alpha}{\pi^2}\int_{m_{\pi^0}^2}^{\infty}\frac{\mathrm{d}s}{s}K(s)\,\mathrm{Im}\,\Pi_{\mathrm{had}}(s) = \frac{1}{4\pi^3}\int_{m_{\pi^0}^2}^{\infty}\mathrm{d}s\,K(s)\sigma_{\mathrm{had}}(s)$$

dispersion relations

optical theorem

kernel function

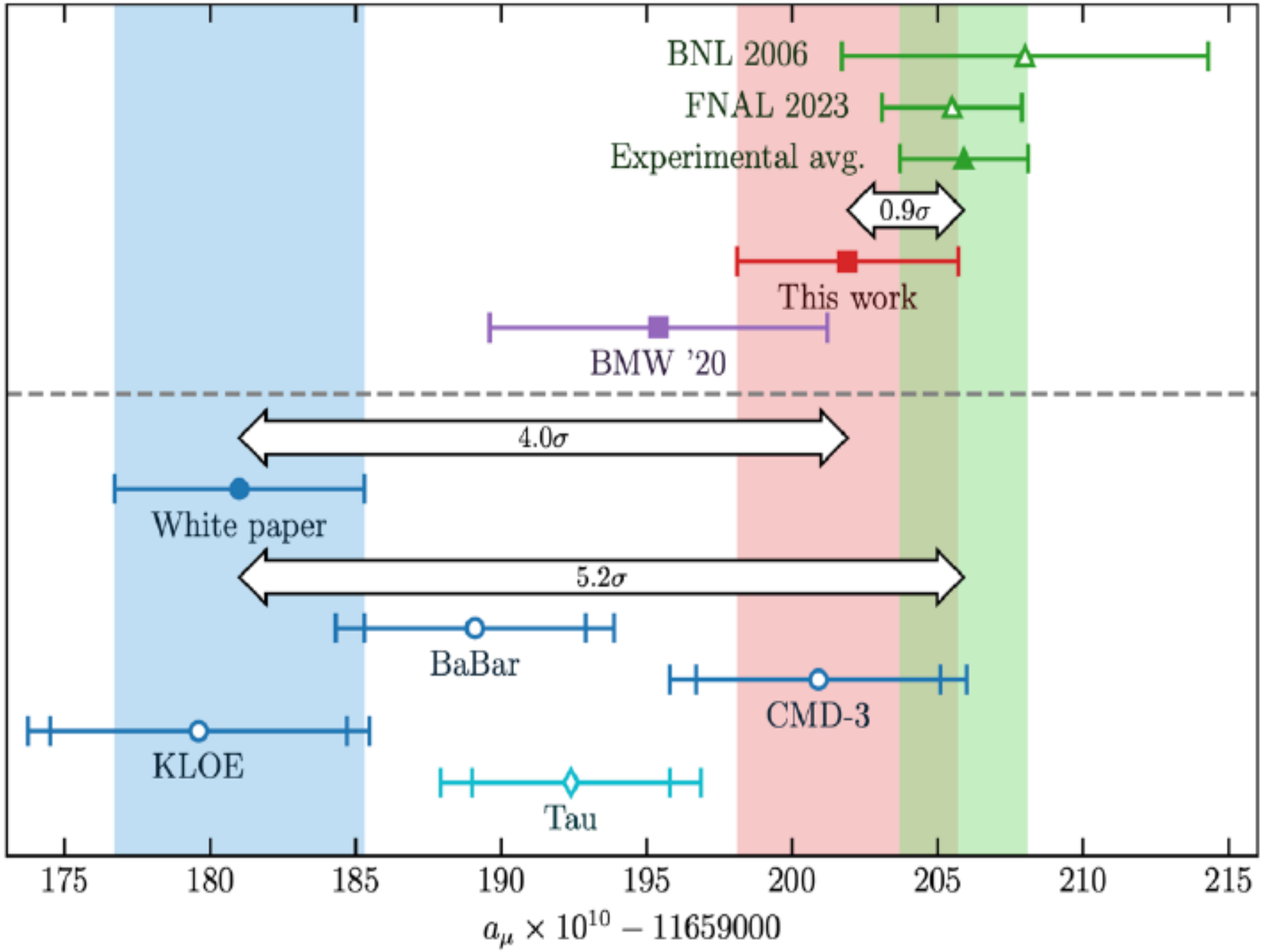
$K(s) \approx m_\mu^2/3s$ for $\sqrt{s} \gg m_\mu$

$$a_\mu^{\mathrm{HLO}} = \frac{\alpha^2}{3\pi^2}\int_{4m_\pi^2}^{\infty}\frac{ds}{s}K(s)\,R(s) \qquad R(s) = \frac{\sigma(e^+e^- \to had)}{\sigma(e^+e^- \to \mu^+\mu^-)}$$

$a_\mu^{\mathrm{HLO}} = 6895\ (33) \times 10^{-11}$	F. Jegerlehner, arXiv:1711.06089
$= 6939\ (40) \times 10^{-11}$	Davier, Hoecker, Malaescu, Zhang, arXiv:1908.00921
$= 6928\ (24) \times 10^{-11}$	Keshavarzi, Nomura, Teubner, arXiv:1911.00367
$= 6931\ (40) \times 10^{-11}$ (0.6%)	WP20 value

WP20 = White Paper of the Muon g-2 Theory Initiative: arXiv:2006.04822

Several important news from the front of $(g_\mu - 2)$ predictions from BaBar and Lattice in conjunction with data!



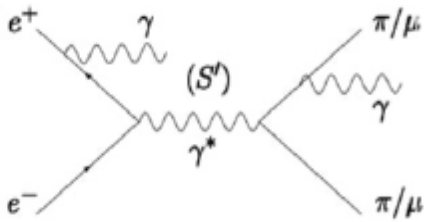
Scanning e+e– →π+ π – ECM = 0.32-2 GeV
CMD-3 at VEPP-2000 e+e- collider

Better detector performance Larger statistics (x30 CMD-2)

New BMW result including finer lattice and long distance effects from e^+e^- data!

New BaBar studies of higher order radiation and impact on the vacuum polarisation predictions of (g-2)!

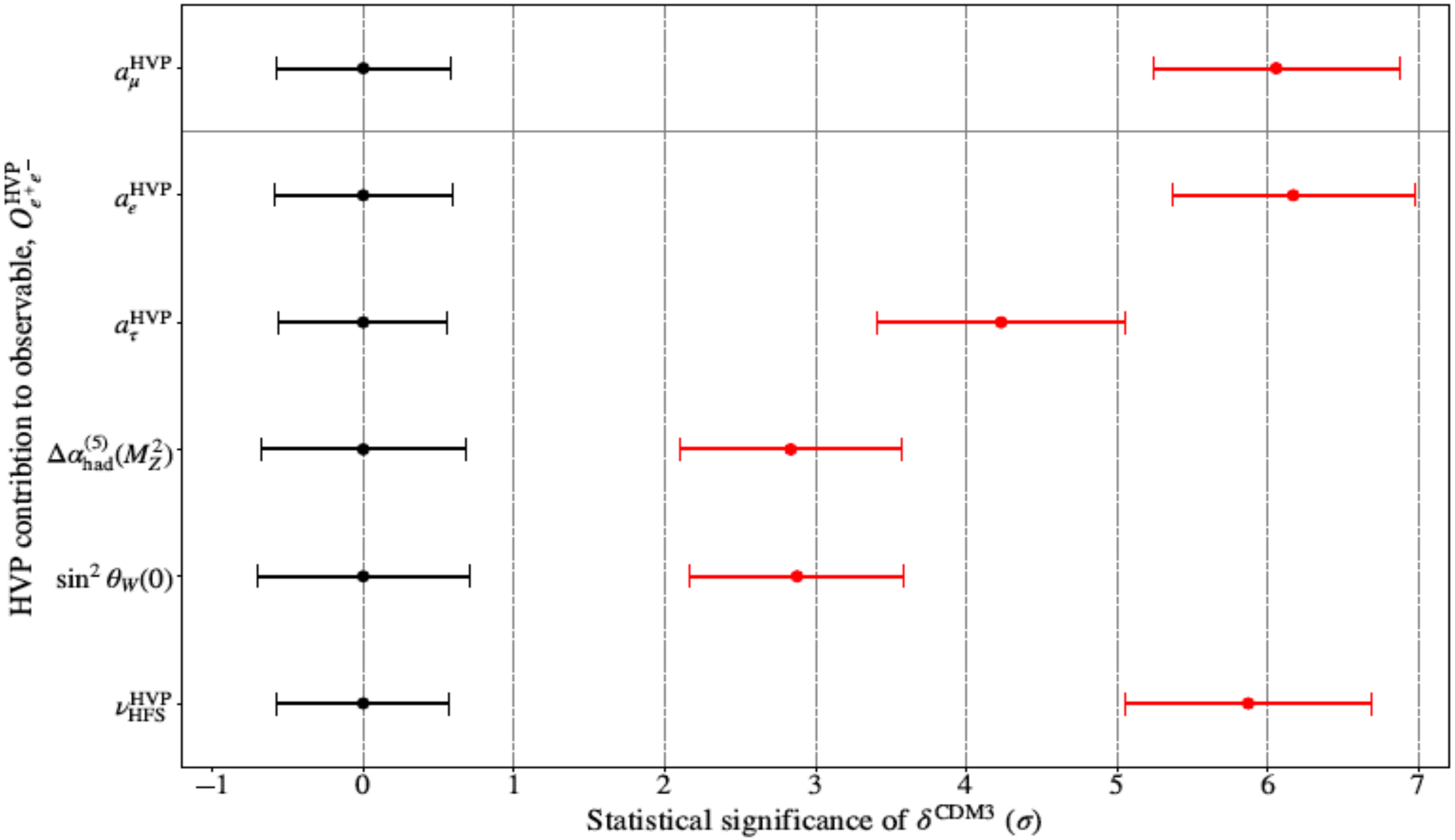
NNLO Radiative corrections need to be better understood and accounted in analyses!



BMW + DFZ Coll.; Z. Fodor, ICHEP 2024

Model independent tests of the HVP contribution to the muon g-2

New Observables providing independent tests of the current tensions observed in the muon g-2:
i) the **electron g-2;** **ii)** the **tau g-2**; **iii)** the **running of the QED coupling constant** α;
iv) the low-energy weak mixing angle **$\sin^2\theta_W(0)$**; **v)** the **Muonium hyperfine splitting** (HFS)



L. Di Luzio, A. Keshavarzi, A.M., P. Paradisi arXiv:2408.01123

Measurement of the Electron Magnetic Moment

X. Fan,[1,2,*] T. G. Myers,[2] B. A. D. Sukra,[2] and G. Gabrielse[2,†]

[1] *Department of Physics, Harvard University, Cambridge, Massachusetts 02138, USA*
[2] *Center for Fundamental Physics, Department of Physics and Astronomy, Northwestern University, Evanston, Illinois 60208, USA*

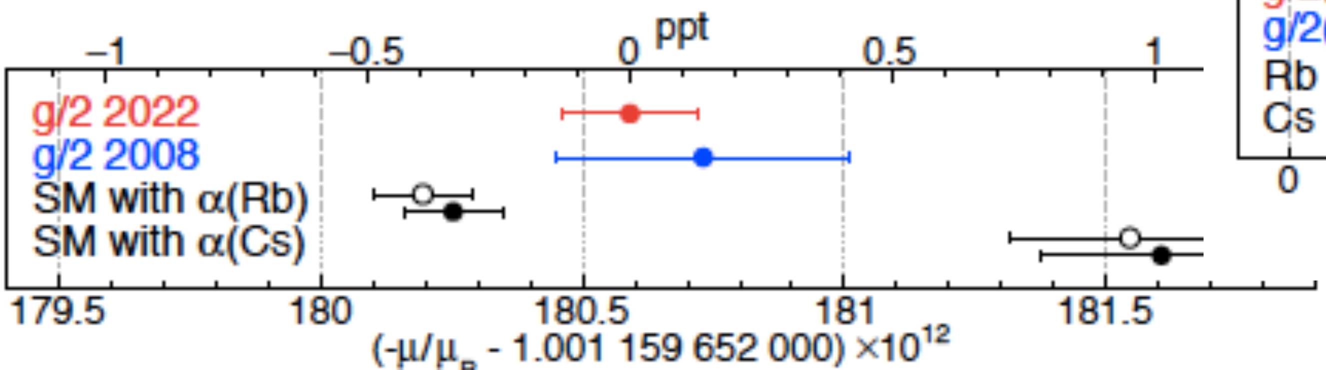
(Dated: December 8, 2022)

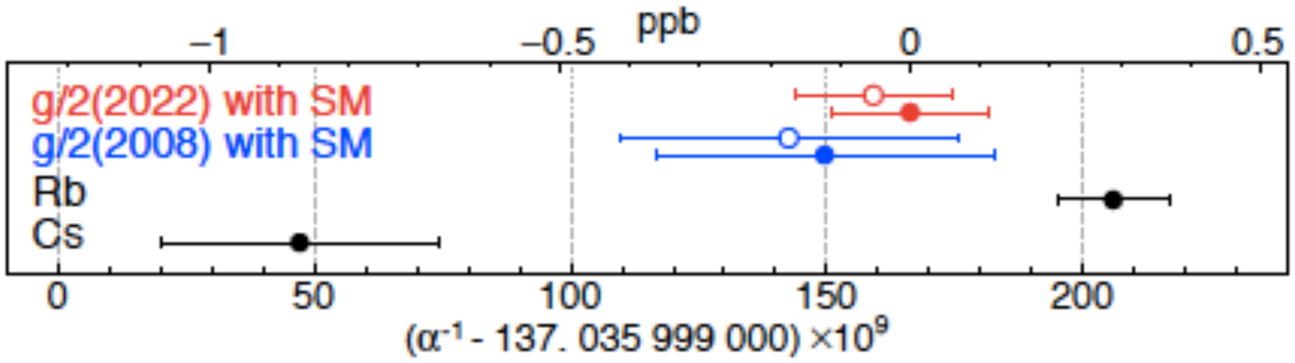
The electron magnetic moment, $-\mu/\mu_B = g/2 = 1.001\,159\,652\,180\,59\,(13)$ [0.13 ppt], is determined 2.2 times more accurately than the value that stood for 14 years. The most precisely determined property of an elementary particle tests the most precise prediction of the Standard Model (SM) to 1 part in 10^{12}. The test would improve an order of magnitude if the uncertainty from discrepant measurements of the fine structure constant α is eliminated since the SM prediction is a function of α. The new measurement and SM theory together predict $\alpha^{-1} = 137.035\,999\,166\,(15)$ [0.11 ppb] with an uncertainty ten times smaller than the current disagreement between measured α values.

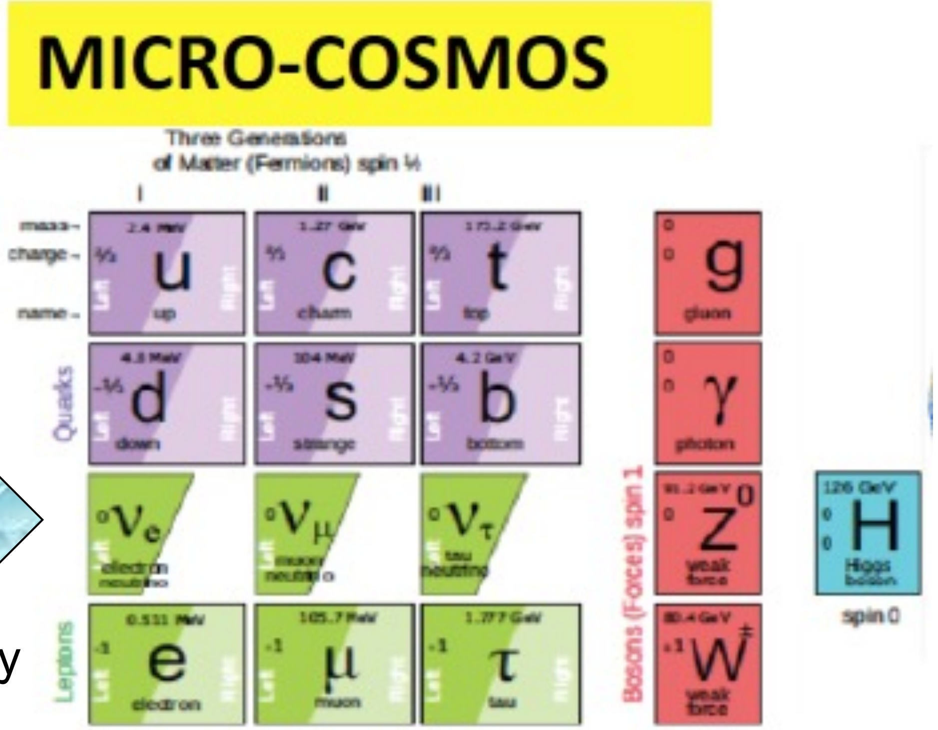
$$a_e^{\mathrm{EXP}} = 0.00115965218059(13)$$

$$\boxed{\delta a_e^{\mathrm{EXP}} = 1.3 \times 10^{-13}}$$

In **2008** Gabrielse et al. had obtained **$\delta a_e^{\mathrm{EXP}} = 2.8 \times 10^{-13}$**



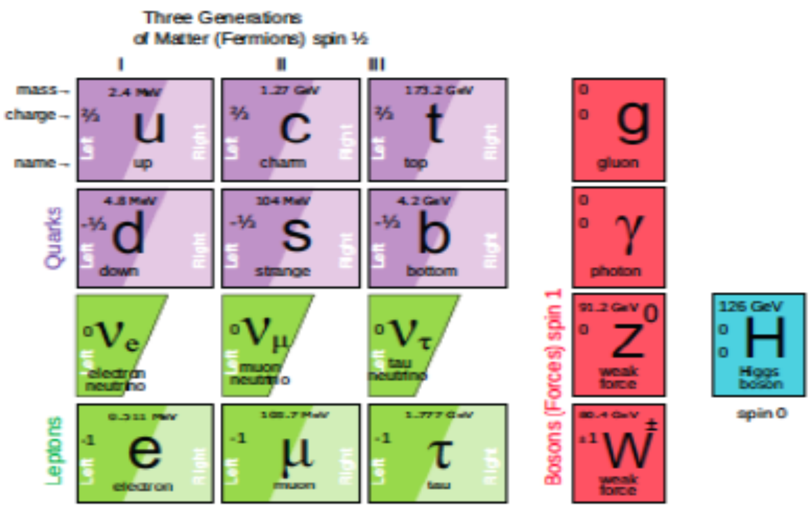




ν peculiarity: in the SM

ONLY LEFT-HANDED ν

i) **V– A** structure of the charged weak currents (i.e. the W boson couples only to the **LEFT-HANDED** fermions) ;
ii) ν doesn't couple to photons (no neutral currents observed at the time the SM was proposed);
iii) In any case, even **today no hint** of the presence of a **right-handed neutrino**
iv) Before observing neutrino oscillations, this (very light) particle was widely thought to be **massless** → **no need for the presence of its right-handed component**



- No DIRAC mass

$$\bar{\nu}_L \nu_R + \bar{\nu}_R \nu_L$$

Need of a new particle: the RH neutrino ν_R

NO MAJORANA mass

$$\nu^T_R \, \nu_R \ \text{or} \ \boxed{\nu^T_L \, \nu_L}$$

No SU(2)$_L$ and U(1)$_Y$ invariant

To obtain a neutrino mass in the renormalizable SM

--> need of new particles (**ν_R, Δ** scalar triplet of SU(2)$_L$)

$U(1)_B$: B(q) = 1/3 ; B(all other SM fields) = 0

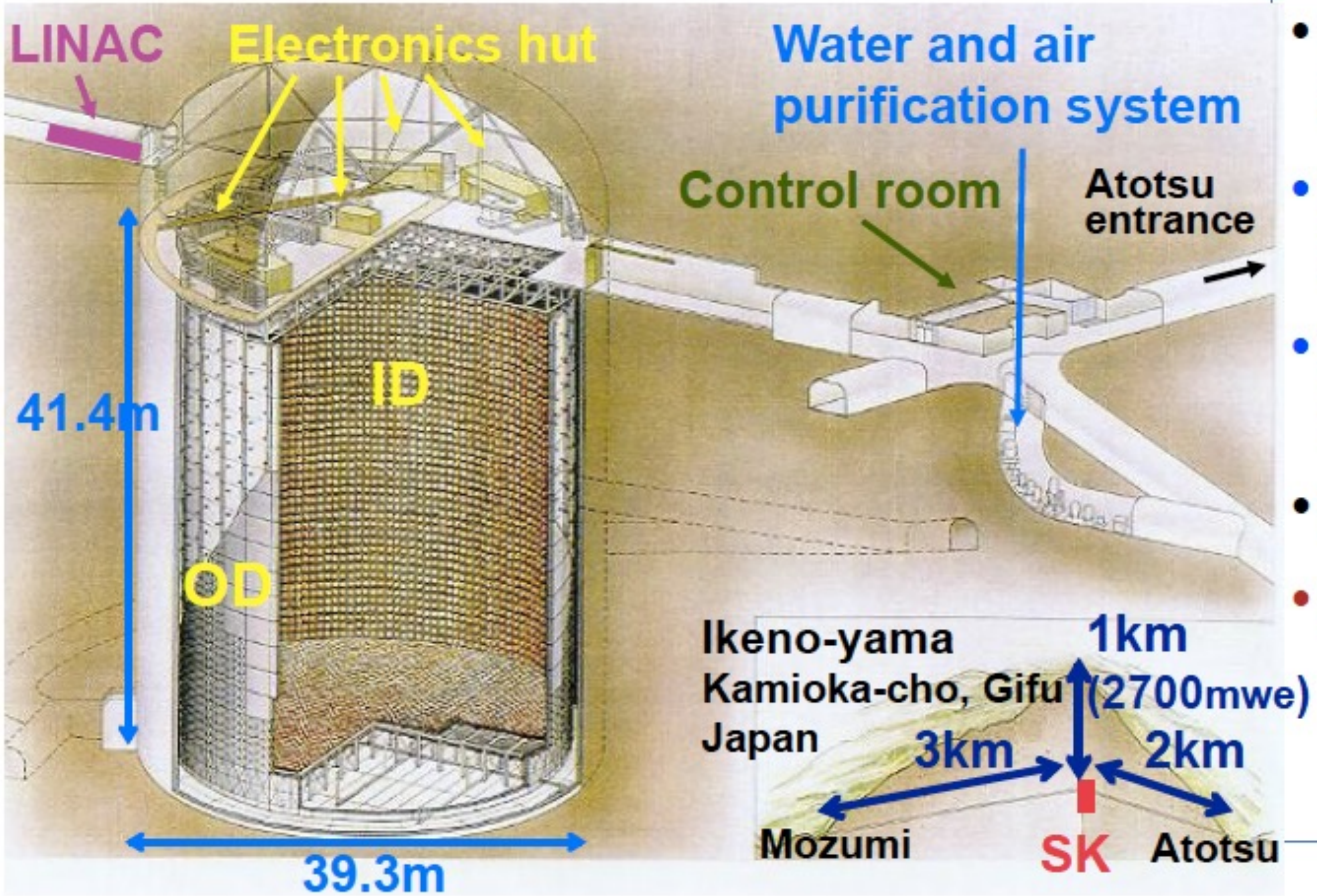
$U(1)_L$: L(leptons) = 1; L (all other SM fields) = 0

LEPTON NUMBER and *LEPTON FLAVOR NUMBERS* *CONSERVATION* in the ***SM***

- *BARYON (B) AND LEPTON (L) numbers are* ***AUTOMATICALLY*** *conserved in the SM* (at all orders of the perturbation expansion), i.e. with the fields of the SM particle spectrum it is not possible to write any **operator of dim. ≤ 4** which respects the SM gauge symmetry and violates B or L

Super-Kamiokande detector

M. Nakahata, Erice School, 2023



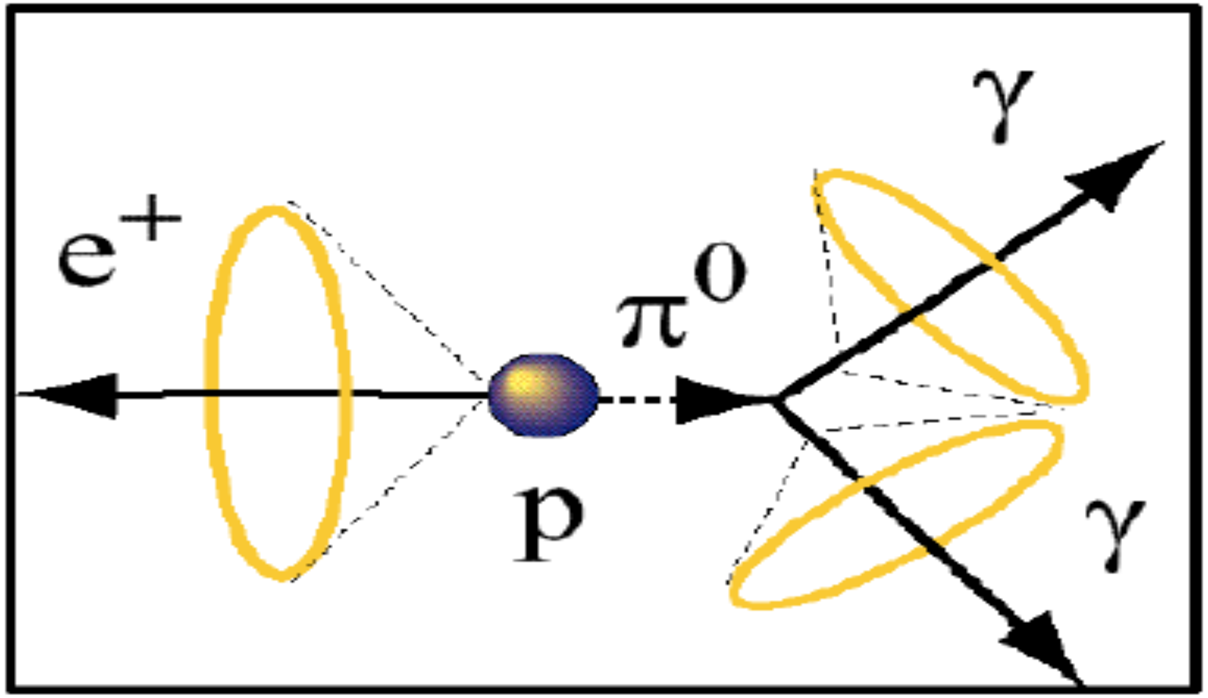
- 50 kton water Cherenkov
- 32kt photo-sensitive volume
- 22.5kt fid. vol. (2m from ID wall)
- SK-I: April 1996~
- SK-VII is running

Inner Detector (ID) PMT: ~11,000 20-inch PMTs
Outer Detector (OD) PMT: 1885 8-inch PMTs

MATTER STABILITY

are protons FOREVER ?

Search for $p \longrightarrow e^+\pi^0$



- Positron and π^0 run back-to-back
  - Momentum 459 MeV/c
- All particles in the final stable are visible with Super-K
  - Able to reconstruct p mass and momentum

Results on $p \rightarrow e^+\pi^0$ and $p \rightarrow \mu^+\pi^0$

	Eff(%)	Exp. BG (event)	Observed (event)
$p \rightarrow e^+\pi^0$			
Lower	18.1	0.02	0
Upper	19.5	058	0
$p \rightarrow \mu^+\pi^0$			
Lower	17.3	0.05	0
Upper	17.2	0.89	1

Lifetime limt (90% CL,450 kton・yrs data)

$p \rightarrow e^+\pi^{0:} > 2.4\text{x}10^{34}$ years

$p \rightarrow \mu^+\pi^{0:} > 1.6\text{x}10^{34}$ years

M. Nakahata, Erice School, 2023

Baryon number violation in the SM as an **Effective low-energy remnant** of a more fundamental theory at a **higher mass scale M**

qqql $\rightarrow$ es. $U_R\, U_R\, D_R\, E_R$ $\rightarrow$ $\mathbf{p \rightarrow e^+ \pi^0}$

B – L conserved

qqql dim 6 M^{-2} qqql

$\tau_p > 10^{34}$ years $\rightarrow$ $\mathbf{M > 10^{15}}$ **GeV**

NEUTRINO MASSES and a "NON-TRIVIAL" NEW PHYSICS

- **If no RH neutrino** → enlargement of the SM scalar sector (Higgs triplet) + introduction of a NEW ENERGY SCALE (some new mass parameter of the enlarged Higgs potential must give rise to a VEV of the higgs triplet several orders of magnitude smaller than the VEV responsible for the electroweak symmetry breaking
- **If RH neutrinos** are introduced
- A **pure neutrino DIRAC mass** (add to the gauge symmetry also a **global U(1) symmetry**, L, and then introduce Yukawa couplings 5-6 orders of magnitude smaller than the electron Yukawa coupling
- B **Dirac mass + Majorana mass of the RH neutrino** (**new parameter with dimension of a mass in the Lagrangian**; most natural choice **M>> electroweak scale** since neutrino masses come from LLHH/M effective terms

Choice A) → in this case $U(1)_L$ is **no longer an AUTOMATIC SYMMETRY** of the theory, rather it is a **NEW GLOBAL SYMMETRY** one imposes by hand **IN ADDITION** to the SM gauge symmetry.

THE FATE OF LEPTON NUMBER

L VIOLATED

υ Majorana ferm.

SMALLNESS of m_{υ}

PRESENCE OF A NEW PHYSICAL MASS SCALE

L CONSERVED

υ Dirac ferm.
(dull option)

$h\,\bar{\upsilon}_L H\,\upsilon_R \longrightarrow m_{\upsilon} = h\,\langle H \rangle$ $M_{\upsilon} < 5$ eV $\longrightarrow h < 10^{-11}$

EXTRA-DIM. ν_R in the bulk: small overlap?

NEW HIGH SCALE

NEW LOW SCALE

SEE - SAW MECHAN.

Minkowski; Gell-Mann, Ramond, SlansKy, Vanagida

ν_R ENLARGEMENT OF THE FERMIONIC SPECTRUM

$M\upsilon_R\,\upsilon_R + h\,\bar{\upsilon}_L\,\phi\,\upsilon_R$

	υ_L	υ_R
υ_L	~O	$h\langle\phi\rangle$
υ_R	$h\langle\phi\rangle$	M

LR Models?

MAJORON MODELS

Gelmini, Roncadelli; Glashow et al.

Δ ENLARGEMENT OF THE HIGGS SCALAR SECTOR

$h\,\upsilon_L\,\upsilon_L\,\Delta$

$m_{\upsilon} = h \langle \Delta \rangle$

ν mass in the

SM as an EFFECTIVE low-energy theory

LLHH dim 5 → $M^{-1} LL\langle H\rangle\langle H\rangle$

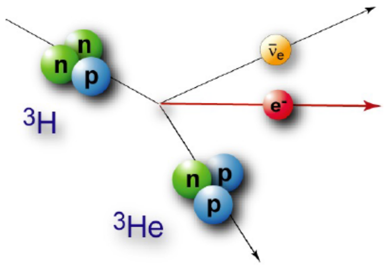
$$m_\nu \rightarrow \langle H\rangle^2 / M$$

$m_\nu < 100$ meV → $M > 10^{14}$ GeV

The signature

Neutrino Masses, Mixings and CP Violation

S. Mertens, ICHEP 2024

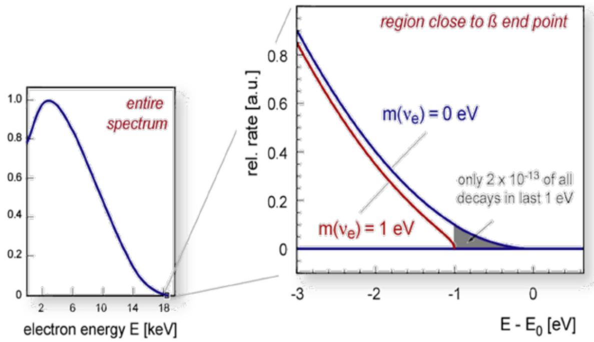


✓ Incoherent sum of neutrino masses

✓ Independent of neutrino nature (Dirac or Majorana)

KATRIN Experiment

$$m^2(\nu_e) = \sum_i |U_{ei}|^2 \cdot m_i^2$$



- New limit:
  $m_\nu < 0.45$ eV (90% CL)
  Neutrino-24 (2024), arXiv:2406.13516 (2024)

Final goal (in 2026):

- < 0.3 eV sensitivity

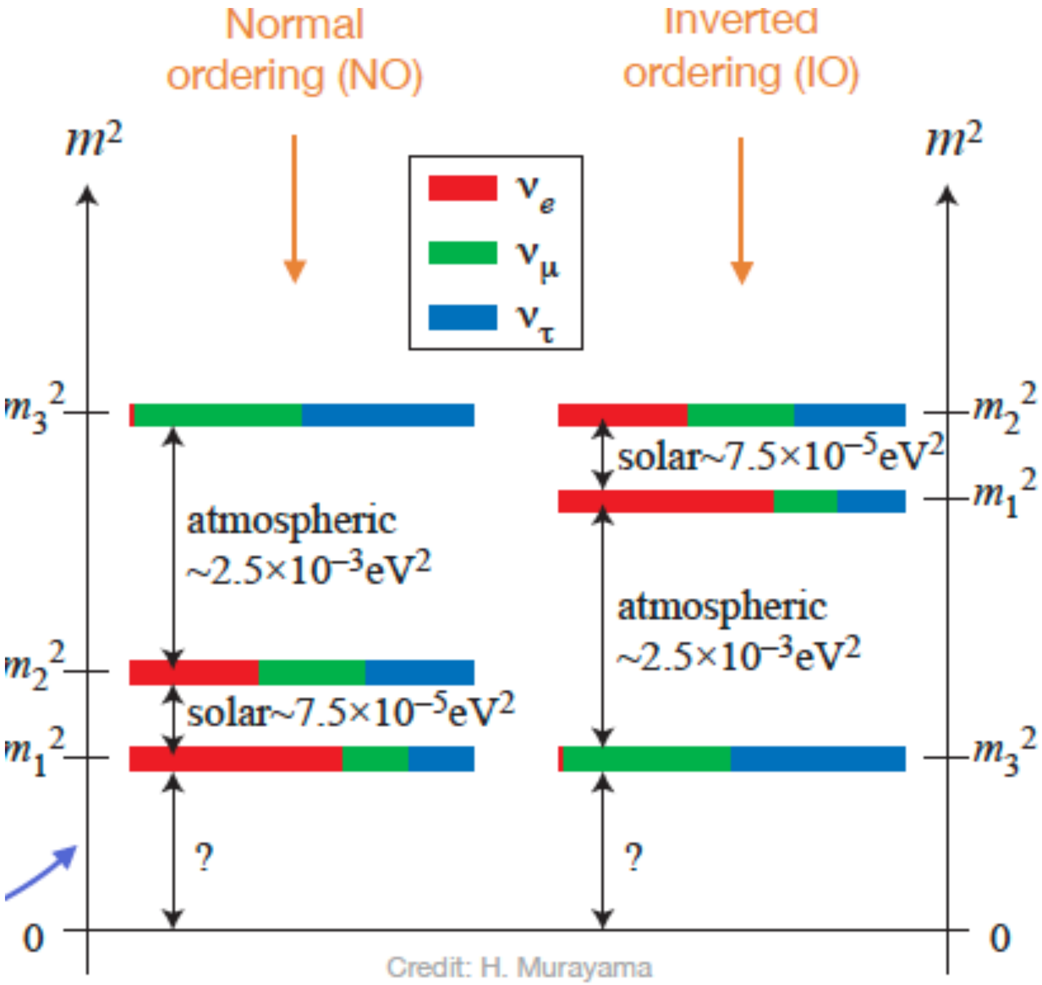
Constraints from COSMOLOGY

✓ With current cosmological observations, we can measure combinations of cosmological parameters with high precision. Still ΛCDM fits very well the data

✓ No evidence **yet** for nonzero neutrino masses or an enhanced radiation density (N_{eff}). Bounds $\Sigma m_\nu <$ **0.072-0.5 eV** (95% CL) and N_{eff}= **3.10±0.17** (68% CL), depending on data and model

✓ Cosmological constraints in non-standard neutrino physics

S. Pastor, Erice School 2024



Currently, we have some indications of what is the mass ordering but none above 3σ

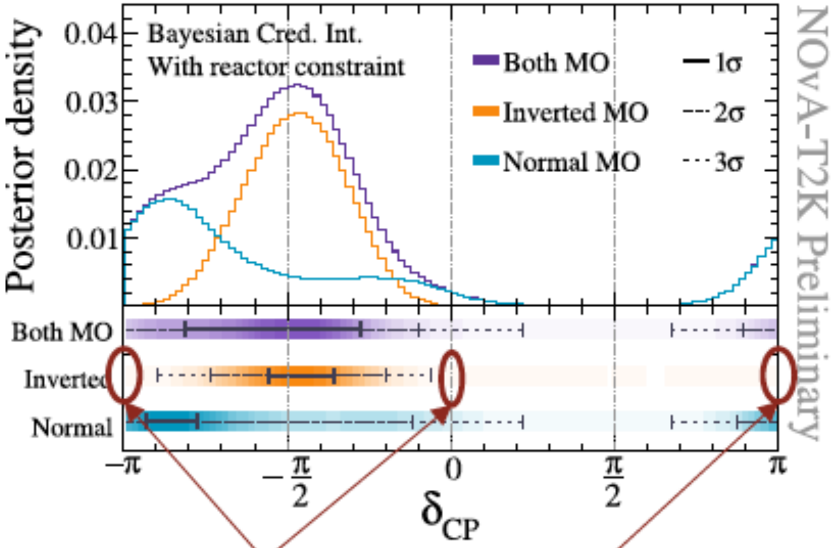
$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}1 & 0 & 0\\ 0 & \cos\theta_{23} & \sin\theta_{23}\\ 0 & -\sin\theta_{23} & \cos\theta_{23}\end{pmatrix}\begin{pmatrix}\cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta_{CP}}\\ 0 & 1 & 0\\ -\sin\theta_{13}e^{i\delta_{CP}} & 0 & \cos\theta_{13}\end{pmatrix}\begin{pmatrix}\cos\theta_{12} & \sin\theta_{12} & 0\\ -\sin\theta_{12} & \cos\theta_{12} & 0\\ 0 & 0 & 1\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

Atmospheric (+Accelerator) | Reactor (+Accelerator) | Solar (+Reactor)

Mild preference for Inverted Ordering but influenced by θ_{13} constraint

NOvA+T2K only	NOvA+T2K + 1D θ_{13}	NOvA+T2K + 2D (θ_{13}, Δm^2_{32})
IO (71%)	IO (57%)	NO (59%)

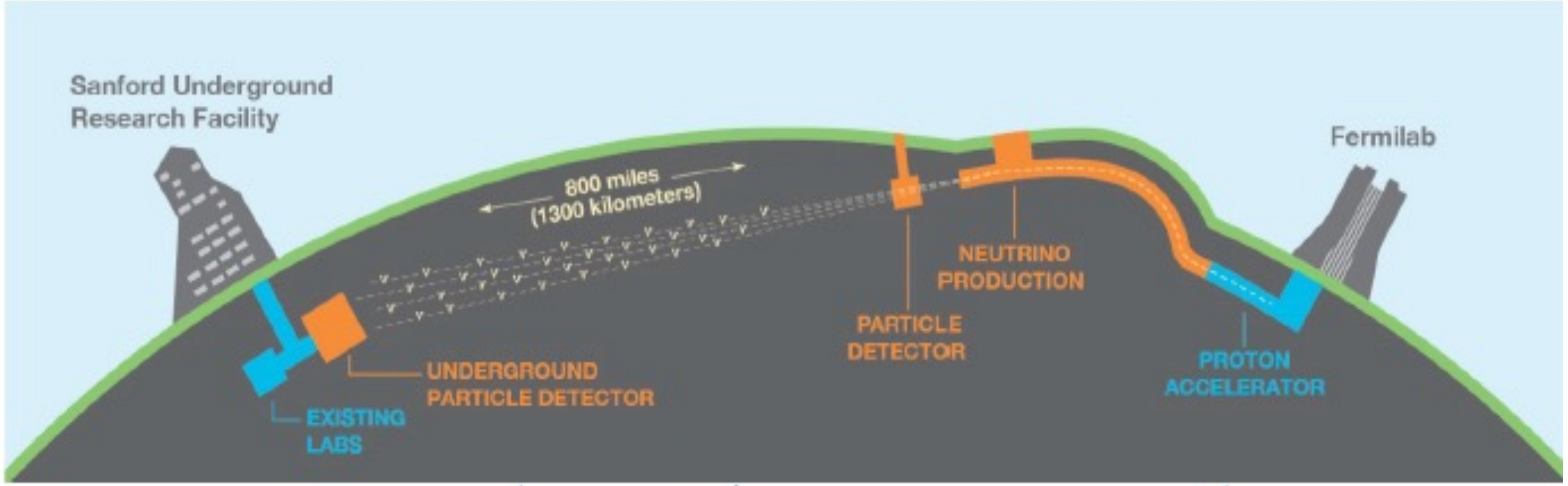
Strongly favor CP violation in Inverted Ordering scenario



CP-conserving points are *outside* 3σ intervals in IO

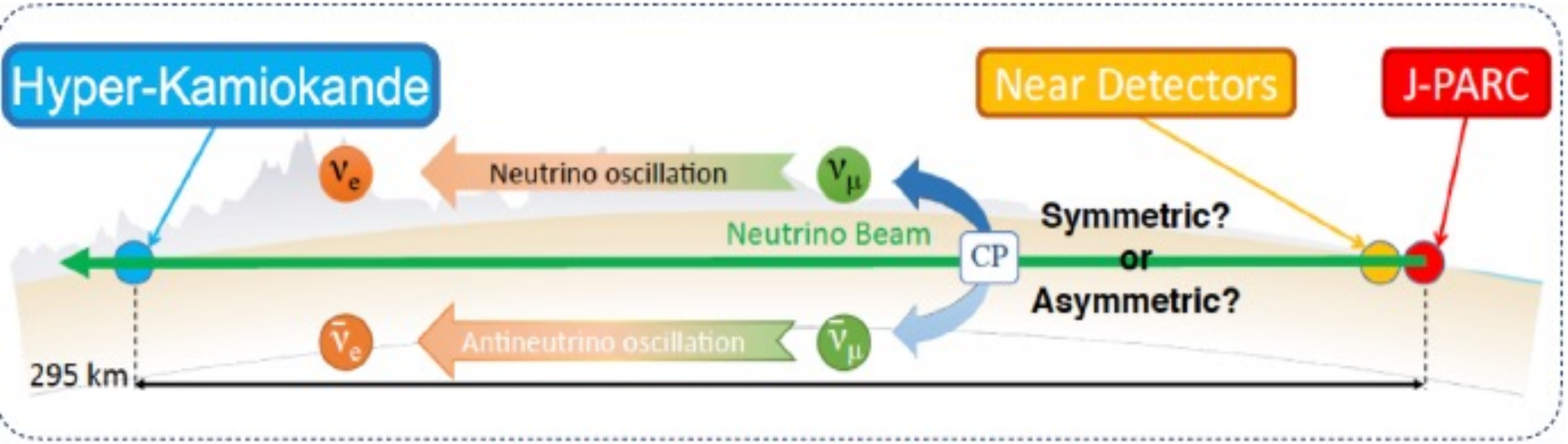
Expect CPV *if* ordering is inverted

Prospects



Large degree of complementarity:

large	wide band, higher energy	LArTPC
matter effects	energy spectrum	detection systematics
small	narrow band, lower energy	Water Cherenkov

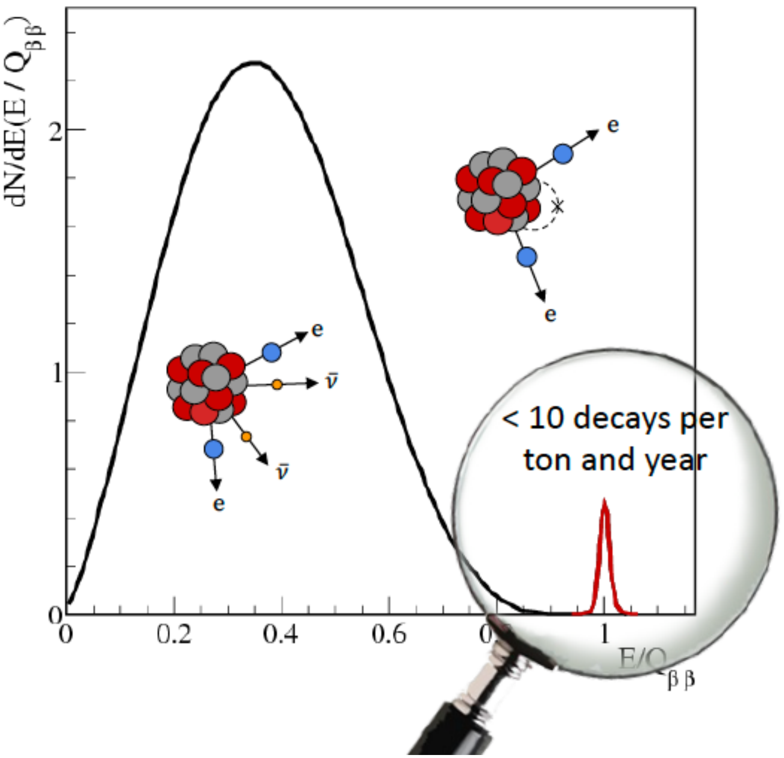


From T. Nakadaira's talk at ICHEP 2024

- Mass ordering:
  - DUNE: 5σ between 1 and 3 years (depending on how kind nature is)
- Precision measurement of oscillation parameters:
  - Long term high precision for Δm^2_{31} and θ_{13} sensitive to new physics in comparison with reactor measurements
- CP violation:
  - Long term establishment of CP violation at 3σ over 75% of δ_{CP} values
  - Similar 10-year precision of ~6-18° in δ_{CP} in both experiments

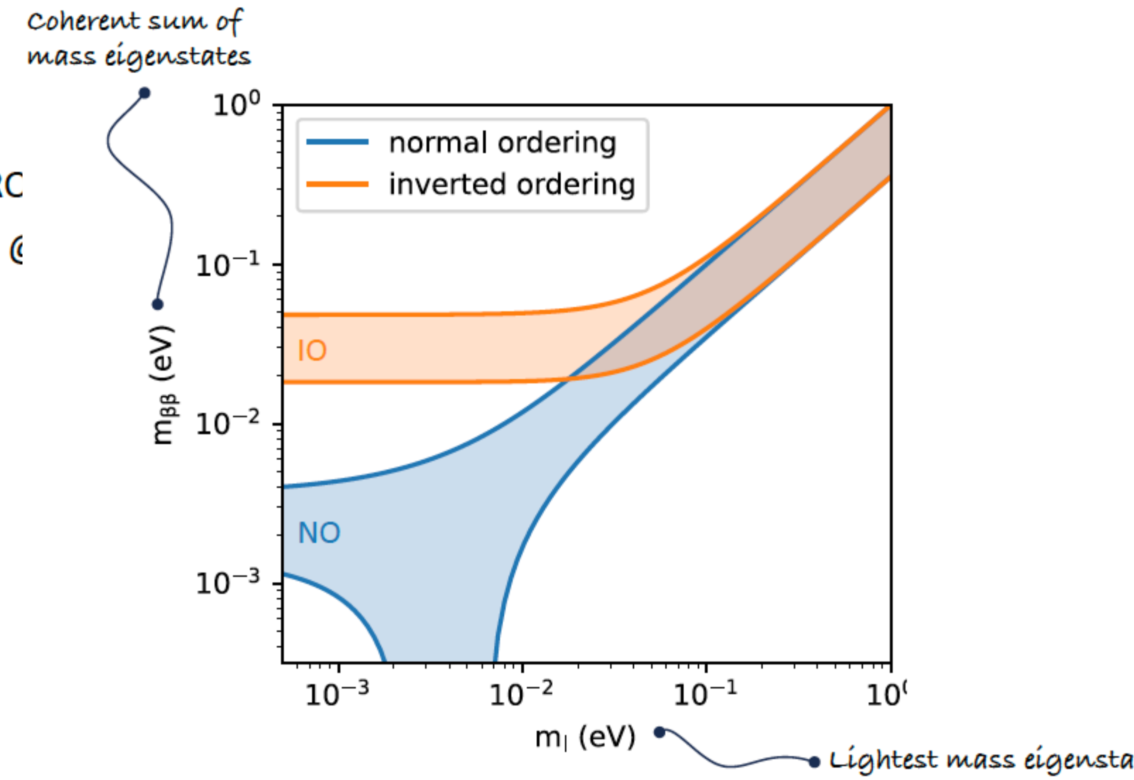
Is LEPTON Number a (global) symmetry of Nature?

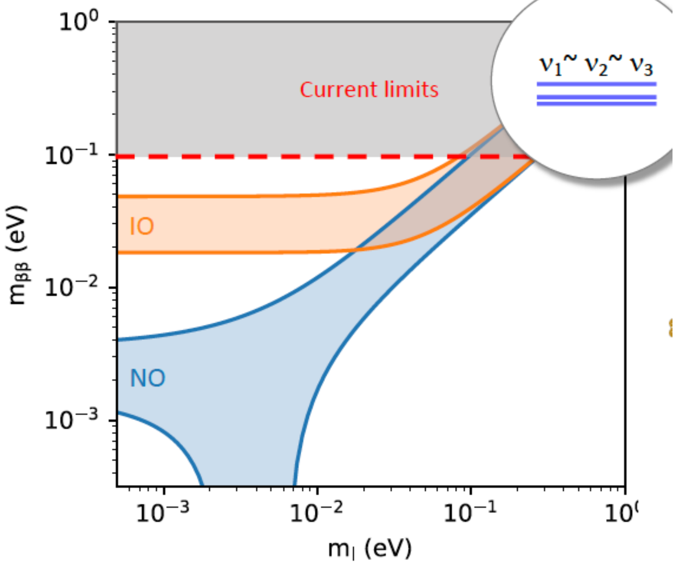
The **Neutrinoless Double Beta-Decay** to verify if the neutrino has a MAJORANA mass



Key requirements:

- Large exposure (ton-scale)
- Low background (< 1 cts/year/t/RC
- Excellent energy resolution (< 1% @





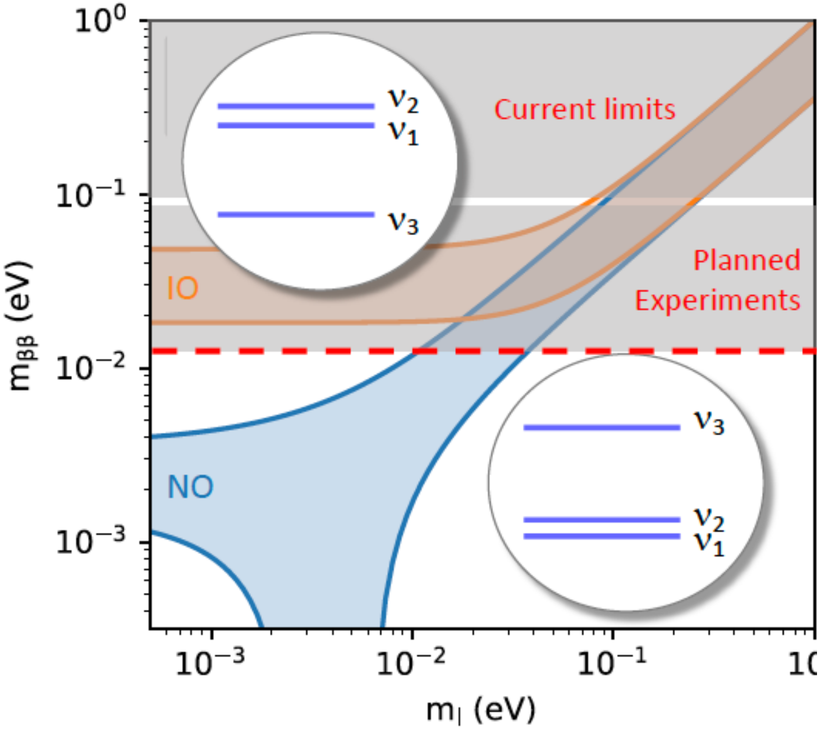
KamLAND-Zen Xe-loaded liquid scintillator

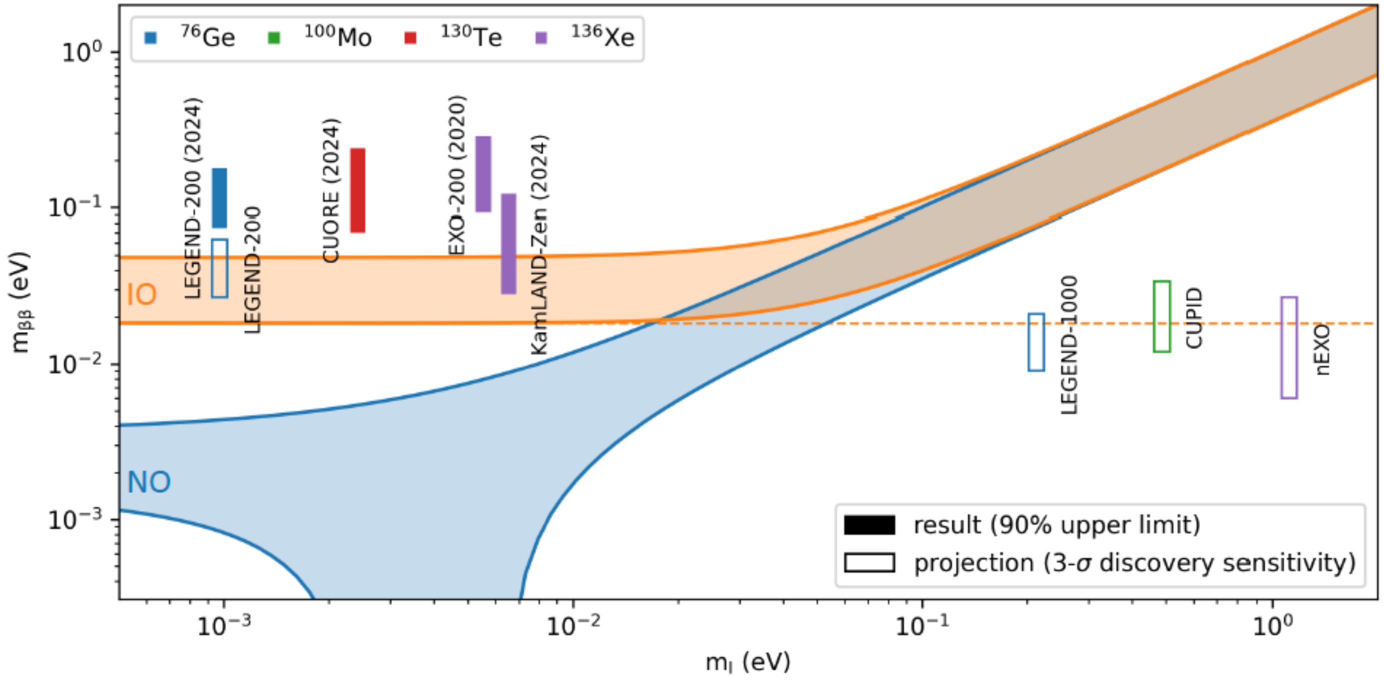
$m_{\beta\beta}$ < 122meV (90% CL)

arXiv:2406.11438 (2024)

Planned projects (e.g., LEGEND-1000, CUPID, nEXO) should **fully cover the inverted ordering range**

Overview $0\nu\beta\beta$





but *B and L are NOT conserved at the QUANTUM LEVEL in the SM*

- **B and L are NOT conserved at the quantum (non-perturbative) level.**
- **no visible implications (like proton decay) at zero (or low – like the Universe today)) temperature**
- **But at** early epochs when such temperature exceeded the electroweak energy scale (i.e. T > 100 GeV) the "tunneling toll" could be avoided so that **B and L violating transitions could proceed at large rates possibly larger than the expansion rate of the Universe at that time.**

Take-home message from the HIGH-ENERGY and HIGH-INTENSITY frontiers

- **No firm evidence (or at least strong hints) of new physics beyond the SM (BSM) from the High Energy and High Intensity (Flavour Physics) frontiers.**

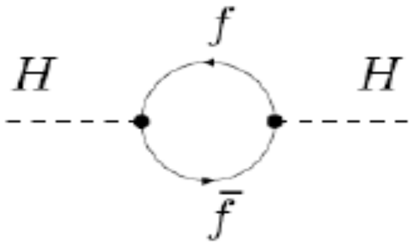
- Some **tensions** are present in **Low-Energy very high precision physics** (muon g-2) with interesting prospects for the further investigation of **magnetic and electric dipole moments**

- **Firm observable evidence for BSM physics**: **non-vanishing neutrino masses**. We don't know yet :
  i)whether such mass is linked to a **violation of the Lepton number symmetry** (neutrino Majorana mass);
  ii) how neutrino masses are ordered (**NO – Normal Ordering or IO – Inverse Ordering**); **if** and how much **CP is violated in the neutrino sector**.

ON THE RADIATIVE CORRECTIONS TO THE SCALAR MASSES

Free propagation: 

inverse propagator: $i(p^2 - M_H^2)$

Loop corrections: 

inverse propagator: $i(p^2 - M_H^2 + \Sigma_H^f)$

$$\Sigma_H^f \sim N_f\, \lambda_f^2 \int d^4k \left(\frac{1}{k^2 - m_f^2} + \frac{2m_f^2}{(k^2 - m_f^2)^2} \right)$$

for $\Lambda \to \infty$: $\Sigma_H^f \sim N_f\, \lambda_f^2 \left(\underbrace{\int \frac{d^4k}{k^2}}_{\sim \Lambda^2} + 2m_f^2 \underbrace{\int \frac{dk}{k}}_{\sim \ln \Lambda} \right)$

Notice that, on the contrary, for **fermion masses** the **radiative corrections are only logarithmically divergent**

QUADRATIC DIVERGENCE

DESTABILIZATION OF THE ELW. SYMMETRY BREAKING SCALE

For $\Lambda = M_{\mathrm{Pl}}$:

$$\Sigma_H^f \approx \delta M_H^2 \sim M_{\mathrm{Pl}}^2 \quad \Rightarrow \quad \delta M_H^2 \approx 10^{30}\, M_H^2$$

(for $M_H \lesssim 1$ TeV)

SCALAR MASSES ARE "UNPROTECTED" AGAINST LARGE CORRECTIONS WHICH TEND TO PUSH THEM UP TO THE LARGEST ENERGY SCALE PRESENT IN THE FULL THEORY

EX: Grand Unified Theory (GUT): $\delta M_H^2 \approx M_{\mathrm{GUT}}^2$

Naturalness or Un-naturalness?

- **New SYMMETRY** giving rise to a cut-off at

$$m_{NP} \ll M$$

Low-energy **SuperSymmetry**

- **Space-time modification (extra-dim., warped space)**

- **COMPOSITE HIGGS** : the Higgs is a pseudo-Goldstone boson (pion-like) → new interaction getting strong at $m_{NP} \ll M$

- **The scale at which the electroweak symmetry is spontaneously broken by <H> results from COSMOLOGICAL EVOLUTION**

- **H is a fundamental (elementary) particle → we live in a universe where the fine-tuning at M arises (anthropic solution, multiverse, Landscape of string theory)**

The most serious "fine –tuning problem":

the COSMOLOGICAL CONSTANT (or quantum vacuum energy density) PROBLEM

The value of the H field in the vacuum state , i.e. the H vacuum expectation value <H>, is of O(10^2 GeV) → V(<H>) ~ 10^8 GeV^4 .

On the other hand, the value of **the vacuum energy** (expected to be the value of the **Einstein cosmological constant** should correspond to:

dark energy density ~ critical energy density ~ (2.24 x 10^{-3} eV)^4

Notice that **any phase transition** we know - for instance also the O(1GeV) QCD quark-gluon phase transition, i.e. from free quarks and gluons to their confinement inside composite hadrons (protons, neutrons, etc. – corresponds to **energy scales >> cosmological constant energy scale**

2nd take home message:

theoretical reasons of dissatisfaction with the SM

$M_{HIGGS} / M_{PLANCK} \sim 10^{-16}$ **Gauge hierarchy problem**

COSM. CONST. PROBLEM

$E_{VACUUM} (DE) / M_{HIGGS} \sim 10^{-14}$

$\Theta_{CPV \text{ in STRONG INTERAC.}} < 10^{-9}$ **Strong CP problem**

THEOR. REASONS

+ lack of UNIFICATION of the ELW. and strong interactions

+lack of a physical "explanation" of the (largely different) masses and mixings of the fermions

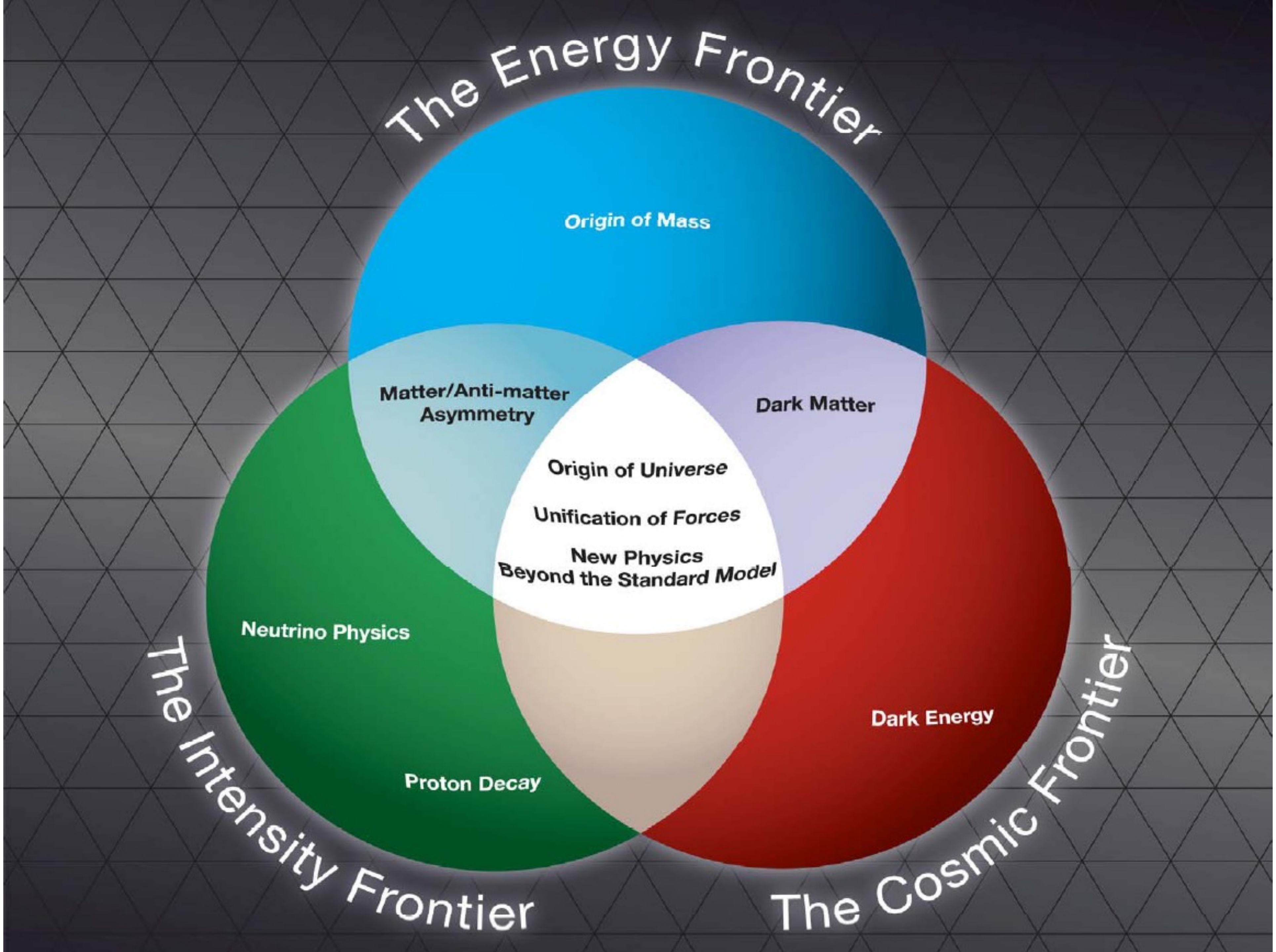
UNI- or MULTI- VERSE ?

- Gauge hierarchy, cosmological constant, DE – DM – Ordinary Matter energy densities, values of the running coupling constants, neutron-proton mass difference, … **FINE-TUNING of Fundamental Parameters,** a **Fundamental Theory** accounting for such apparent fine-tuning (maybe the Theory of Everything (**TOE**)), **Anthropic Principle** or ...?

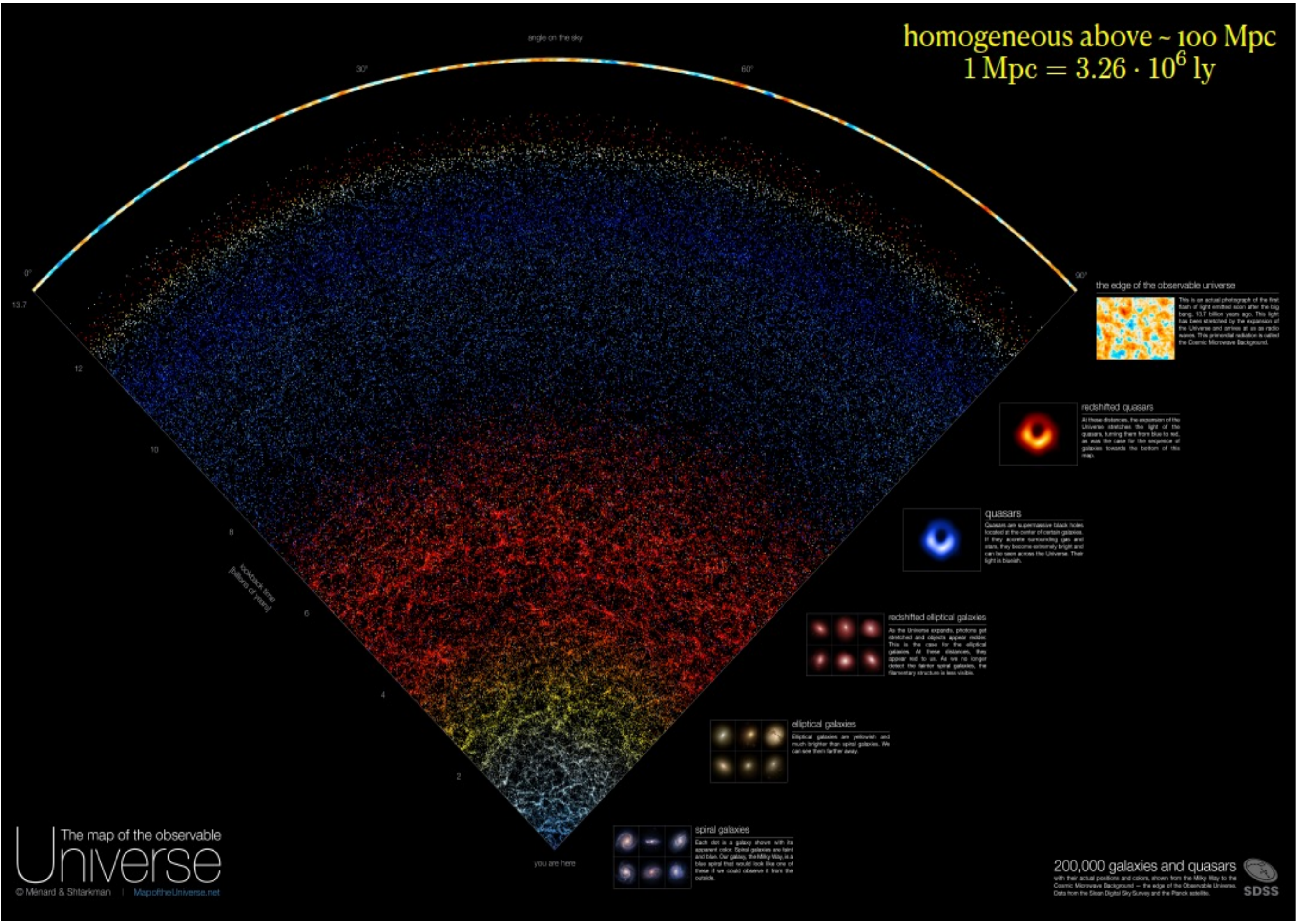
- **String Theory Landscape**: many (infinite?) **DEGENERATE VACUA** → each vacuum corresponds to a different universe, i.e. a universe with different values of the fundamental parameters → we live and study the ONLY universe where our life is allowed, i.e. just "OUR" universe where the fundamental parameters take the particular values allowing for our existence;

- In the **ETERNAL INFLATION** theory some regions of space stop stretching , form distinct bubbles – with different SSB and hence different physical constants

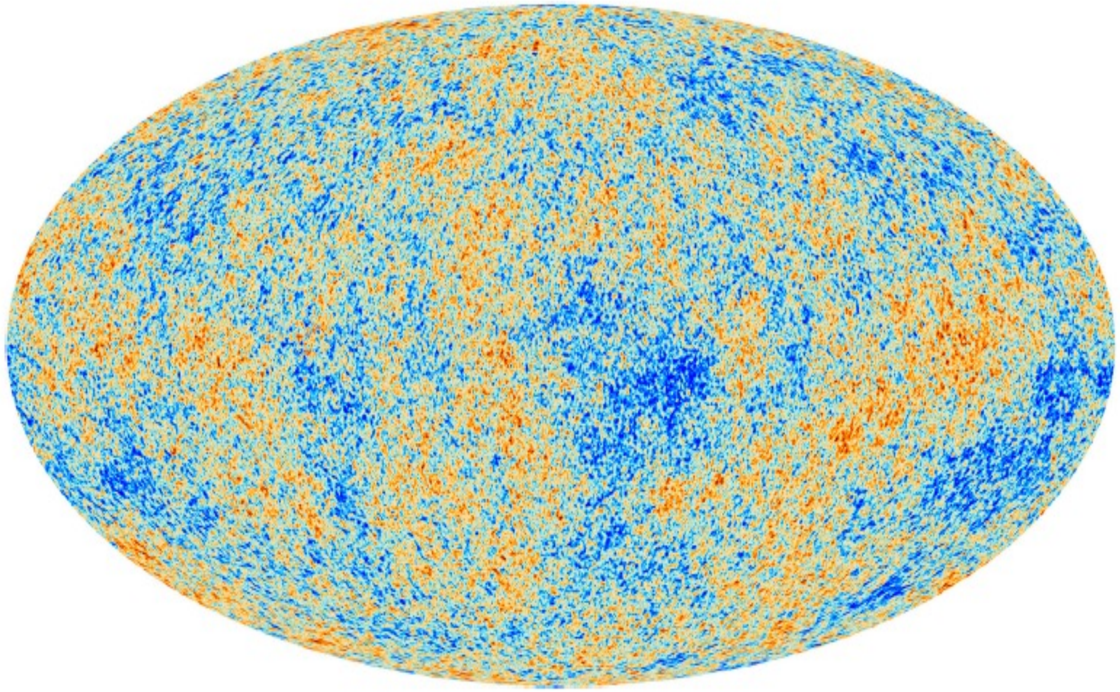
- **Weinberg's anthropic explanation** of the small (but not exactly zero) value of **the cosmological constant** (his paper was written in 1987 long before the exp. discovery of the accelerated expansion of the universe).


The Energy Frontier
Origin of Mass
Matter/Anti-matter Asymmetry
Dark Matter
Origin of Universe
Unification of Forces
New Physics Beyond the Standard Model
Neutrino Physics
Proton Decay
Dark Energy
The Intensity Frontier
The Cosmic Frontier

Our universe is ISOTROPIC and (very likely) HOMOGENEOUS



CMB temperature map from PLANCK
~ 380,000 years after the Bang



$$T \simeq 2.73\,K \qquad \frac{\Delta T}{T} \simeq 10^{-5}$$

The Standard Universe

- It is homogeneous and isotropic on large scales;
- It expands;
- It was hot and close to thermal equilibrium in the past;
- Light nuclei (D, ^{3}He, ^{4}He, ^{7}Li) formed < few seconds after the Bang;
- Photons decoupled ~ 380000 yrs after the Bang

Well accounted for by the
SM Cosmology
+
SM Particle Physics

Puzzles from the Universe

- The expansion accelerates;
- Normal matter makes up less than 5% of the present energy content;
- Structure formation is driven by ~25% of an unknown pressureless component;
- Initial conditions on density and velocities is extremely unlikely;
- Antimatter is missing.

NEW PHYSICS BEYOND THE SMs is needed!!

THE EARLY UNIVERSE

NATURAL UNITS

Units : $\hbar = c = k_B = 1$

k_B ← Boltzmann const.

$\Rightarrow$ M, E, T have the same dimension

$[E] = [mc^2]$, $[E] = [k_B T]$

$\boxed{1\,K \simeq 10^{-4}\,eV} = 10^{-13}$ GeV

dim. of t and L $\rightarrow \frac{1}{M}$

$[E] = [\hbar\omega]$; $[\omega] = [t^{-1}]$; $[L] = [ct]$

$\boxed{1\,GeV^{-1} \sim 10^{-14}\,cm = 10^{-16}\,m}$

$1\,GeV^{-1} \sim 10^{-24}$ sec.

$G_N = \frac{1}{M_{Pl}^2} \rightarrow M_{Pl} = 1.2 \cdot 10^{19}$ GeV

$\downarrow$

$V = -G\frac{m_1 m_2}{r}$ $[V] = M$ $[r^{-1}] = M$

Planck length: $\ell_{Pl} = \frac{1}{M_{Pl}} = 1.6 \cdot 10^{-33}$ cm

Planck time: $t_{Pl} = \frac{1}{M_{Pl}} = 5.4 \cdot 10^{-44}$ s.

Planck mass: $M_{Pl} = 2.2 \cdot 10^{-5}$ g.

1 Mpc $= 3.1 \cdot 10^{24}$ cm ; 1 year $= 3.16 \cdot 10^{7}$ s.

1 light year $\simeq 10^{18}$ cm

HOMOGENEOUS EXPANDING UNIVERSE

Homogeneity and isotropy: the metric tensor is invariant under translations (3) and rotations (3)

$$ds^2 = dt^2 - a^2(t) f(R) \delta_{ij}\, dx^i dx^j$$

(cartesian coordinates)
$R^2 = \delta_{ij} x^i x^j$

scale factor 3-dim line element

$$H \equiv \frac{\dot{a}}{a}$$

Hubble parameter

$$f(R) = \frac{1}{\left(1 + \frac{KR^2}{4}\right)^2}$$

K=0, flat (euclidean)
K>0, closed (finite volume)
K<0, open

$$\int_0^\infty \frac{dR}{1 + \frac{KR^2}{4}} = \pi/\sqrt{K}$$

Friedmann-Lemaître-Robertson-Walker Metric

Polar coordinates: $r = R\left(1 + \frac{KR^2}{4}\right)^{-1}$ $\quad dR\left(1 + \frac{KR^2}{4}\right)^{-1} \to dr/\sqrt{1 - Kr^2}$

$$ds^2 = dt^2 - a^2(t)\left[\frac{dr^2}{(1 - Kr^2)} - r^2\left(d\theta^2 + \sin^2\theta d\phi^2\right)\right] = dt^2 - a(t)^2 d\vec{l}^2$$

scale factor

curvature constant: [K]=[L]$^{-2}$
K=0, flat (euclidean)
K>0, closed (finite volume)
K<0, open

cosmological redshift

$$\boxed{1 + z \equiv \frac{\lambda^{\rm ph}(t_0)}{\lambda^{\rm ph}(t)} = \frac{1}{a(t)}}$$

Energy-Momentum tensor in FLRW

FLRW frame

Energy-momentum tensor: $T^\mu_\nu = -P g^\mu_\nu + (\rho + P) u^\mu u_\nu \to \mathrm{diag}(\rho, -P, -P, -P)$

4-velocity
of the observer

$\rho(t)$ energy density

$P(t)$ pressure

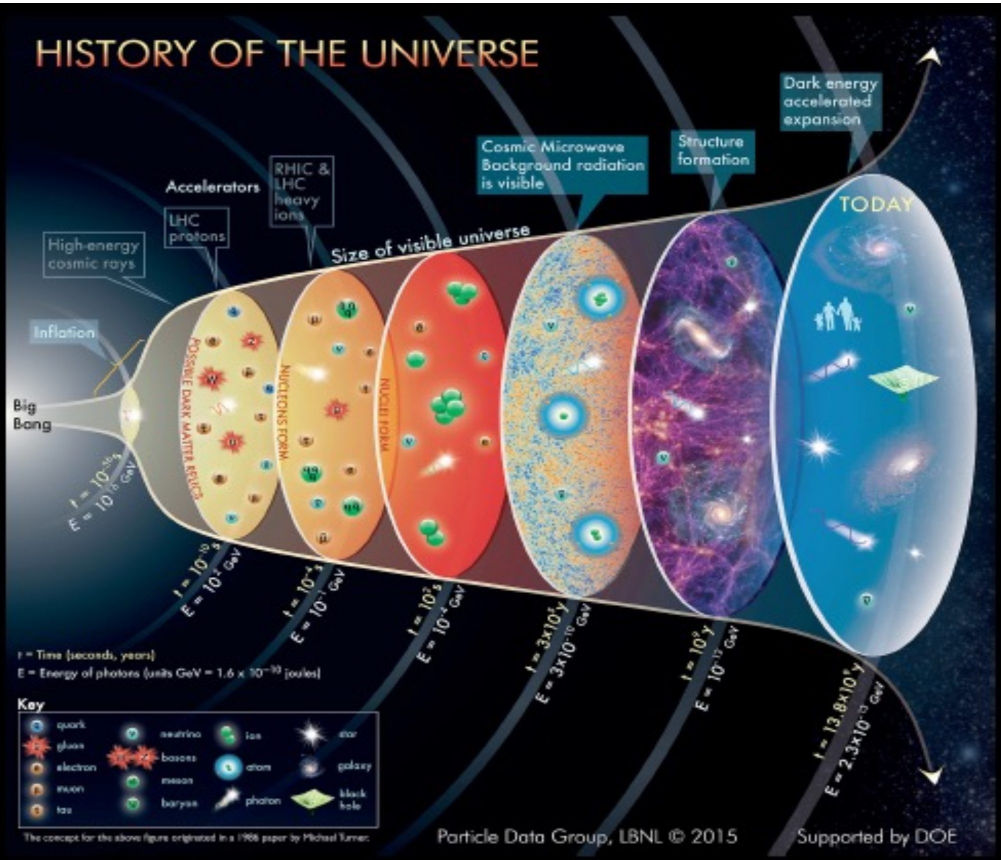
$$d\left(\rho a^3\right) = -P da^3$$

1st principle of thermodynamics
in an expanding universe

$\Downarrow$

$w(a) \equiv \dfrac{P(a)}{\rho(a)}$ $\boxed{\text{equation of state}}$ $\Rightarrow$ $\rho(a) = \rho_0 e^{-3\int_1^a \frac{da'}{a'}(1+w(a'))} \xrightarrow{\text{w constant}} \rho_0\, a^{-3(1+w)}$

K. Olive
Particle cosmology



scale factor a/a_0

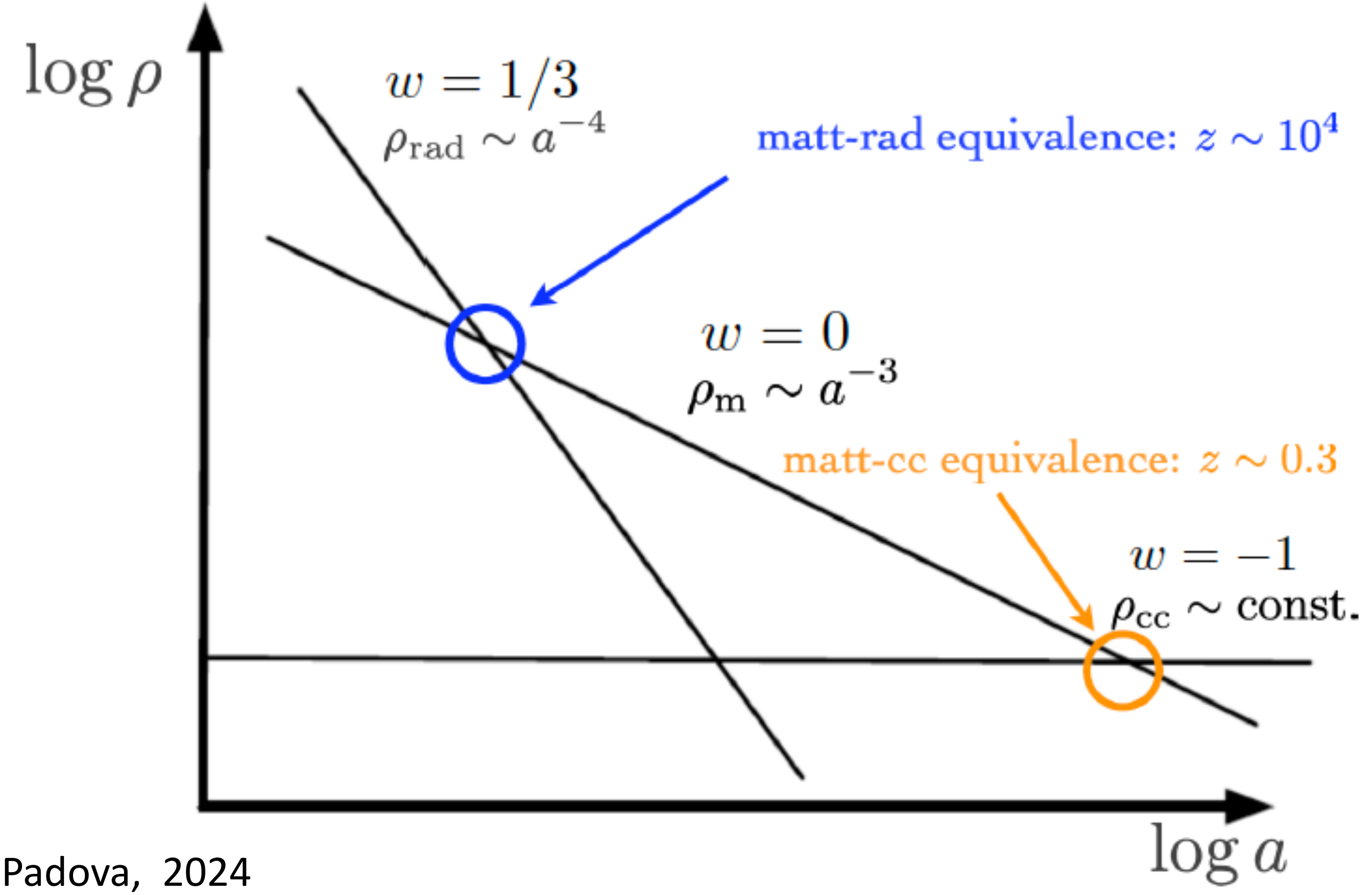
energy density: $\rho(a) = a^{-3(1+w)}$

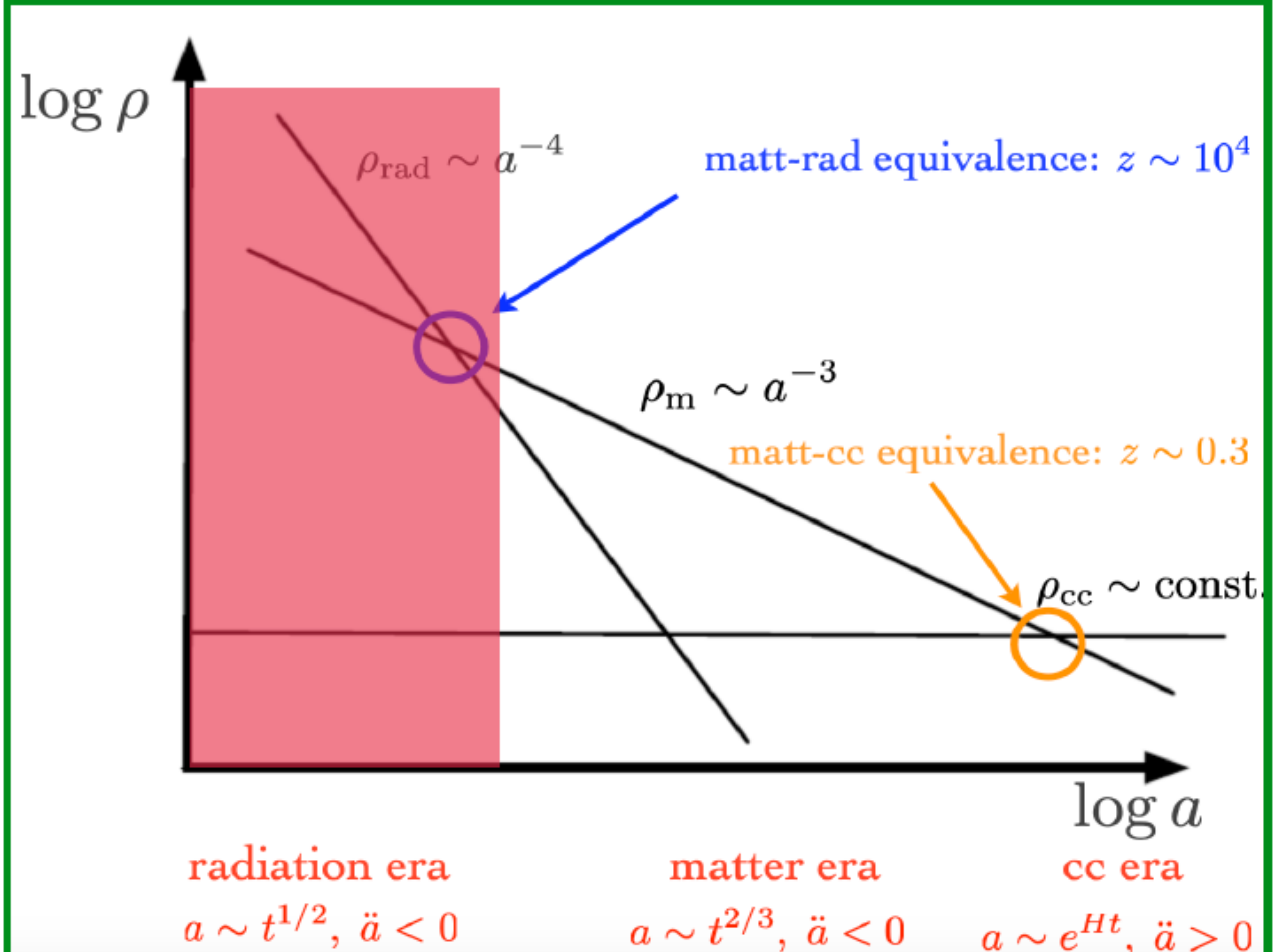
$$
\begin{array}{lll}
\rho_R \sim a^{-4} \quad , & w = 1/3 & \text{(Radiation)} \\
\rho_M \sim a^{-3} \quad , & w = 0 & \text{(Matter)} \\
\rho_\Lambda \sim \text{const.} \quad , & w = -1 & \text{(Cosmological constant)}
\end{array}
$$

Cosmological epochs

ΛCDM Model: $\rho = \rho_{\rm m} + \rho_{\rm rad} + \rho_\Lambda = \rho^0_{\rm m} a^{-3} + \rho^0_{\rm rad} a^{-4} + \rho_\Lambda$

different components dominate at different epochs




$\log\rho$
$\rho_{\rm rad} \sim a^{-4}$
matt-rad equivalence: $z \sim 10^4$
$\rho_{\rm m} \sim a^{-3}$
matt-cc equivalence: $z \sim 0.3$
$\rho_{\rm cc} \sim$ const.
$\log a$
radiation era
$a \sim t^{1/2}$, $\ddot{a} < 0$
matter era
$a \sim t^{2/3}$, $\ddot{a} < 0$
cc era
$a \sim e^{Ht}$, $\ddot{a} > 0$

Epoch of the RADIATION DOMINANCE

$\rho_R \gg \rho_M$ $\qquad$ $\rho_R > \rho_M$ for $t \lesssim 4 \cdot 10^{10}$ sec.

$\downarrow$

$\rho \simeq \rho_R$ $\qquad p_R = \rho_R/3$; $\qquad a(t) \propto \sqrt{t}$

$$\boxed{H \simeq 1.66 \sqrt{g_*} \, \frac{T^2}{M_{Planck}}}$$

$M_{Planck} = \frac{1}{\sqrt{G_N}} = 1.22 \times 10^{19}$ GeV

$\downarrow$ expansion rate of the Universe

Relation between T and t = age of the Universe at temperature T

$$t = \sqrt{\frac{90}{32\pi^3} \frac{1}{G_N g_*}} \frac{1}{T^2} \qquad t T^2 \simeq \frac{2.4}{\sqrt{g_*}}$$

$$\boxed{t \simeq \left(\frac{T}{\text{MeV}}\right)^{-2} \text{sec.}}$$

The “unbearable” acceleration of the expansion of the Universe

- Until the end of the past century the debate was if the universe was **open** (matter energy density < critical energy density) or **closed**, hence whether the universe would never end to expand or if its expansion was to stop at some point with the universe collapsing into a Big Crunch. **But no “reasonable” physicist was doubting that in any case the attractive force of gravity had to slow down the expansion of the universe** (indeed, a de-acceleration parameter was introduced to measure such slow down).
- **But**, on the contrary …

DARK ENERGY

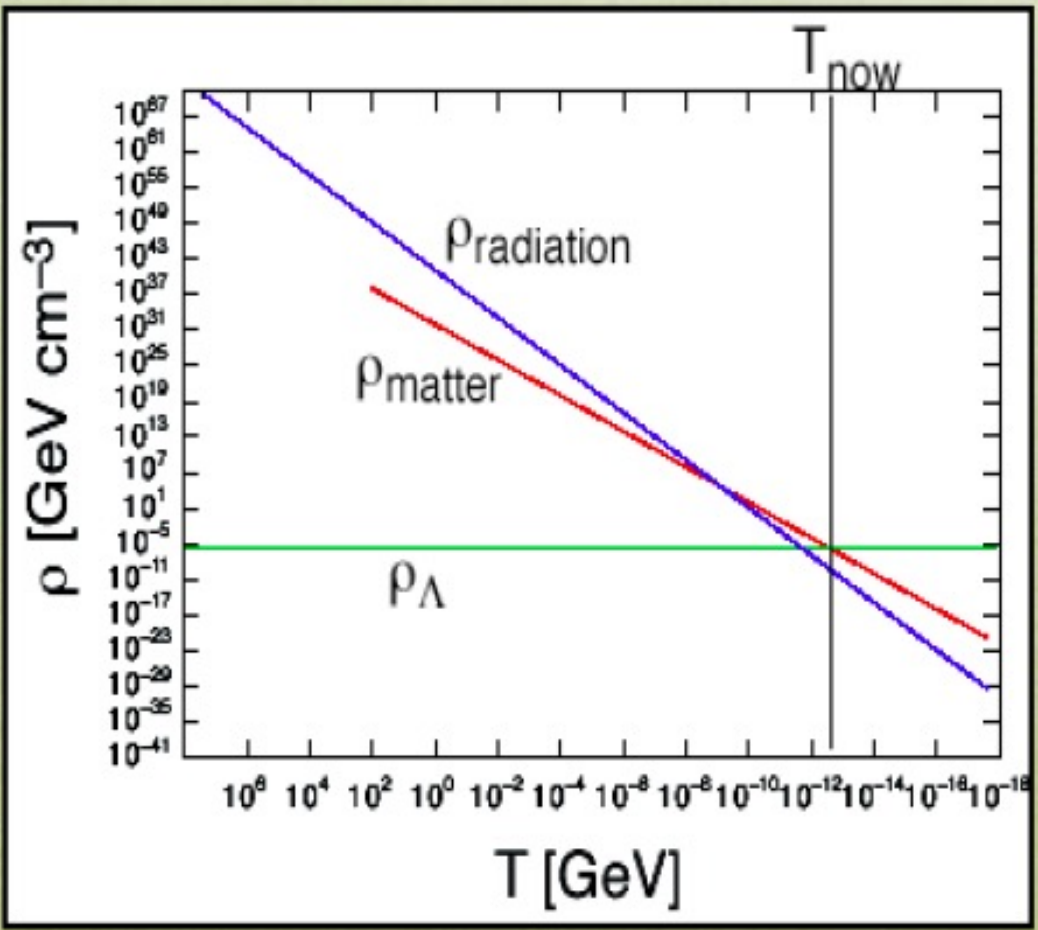
- What is causing the acceleration of the expansion of the universe?
  - Einstein's cosmological constant Λ?
  - Some new dynamical field ("quintessence," Higgs-like)?
  - Modifications to General Relativity?

  "Dark Energy"
- Dark energy effects can be studied in two main cosmological observables:
  - The history of the expansion rate of the universe: supernovae, weak lensing, baryon acoustic oscillations (BAO), cluster counting, etc.
  - The history of the rate of the growth of structure in the universe: weak lensing, large-scale structure, cluster counting, redshift-space distortions, etc.
- For all probes other than SNe, **large galaxy surveys are needed**:
  - **Spectroscopic**: 3D (redshift), medium depth, low density, selection effects
  - **Photometric**: "2.5D" (photo-z), deeper, higher density, no selection effects

Ramon Miquel

THE "WHY NOW" PROBLEM

- *Why do we see matter and cosmological constant almost equal in amount?*
- *"Why Now" problem*
- *Actually a triple coincidence problem including the radiation*
- *If there is a deep reason for $\rho_\Lambda \sim ((\mathrm{TeV})^2/M_{Pl})^4$, coincidence natural*



Arkani-Hamed, Hall, Kolda, HM

To be or not to be in THERMAL EQUILIBRIUM,

i.e. what are the conditions for a particle i to be in thermodynamical equilibrium in the primordial plasma of particles in the early universe

- Should the universe **not be expanding**, i.e. having particles in a box with fixed walls → after some time **each particle would realize the thermal equilibrium** with the other particles present in the plasma

- However **the universe IS EXPANDING** (box with sliding walls) at a certain **rate H** → the particle i is in equilibrium **only if it has some of its interactions with the other particles in the plasma proceeding with a rate larger than H**, i.e. some of its interactions should be (much) **faster** than time scale of the expansion

$$\text{interaction rate} \quad \Gamma \gg H \quad \text{expansion rate}$$

interaction rate $\Gamma \gg H$ expansion rate

$$f(\vec{x}, \vec{p}, t, \mu) \xrightarrow[\text{kinetic equilibrium}]{\text{homogeneity, isotropy}} f_T(p, \mu) = \frac{1}{e^{(E-\mu)/T} \pm 1}$$

distribution function

$$E = \sqrt{p^2 + m^2}$$

$$p = |\vec{P}| \sim 1/a$$

$$\rho = \boxed{g} \int \frac{d^3p}{(2\pi)^2} E\, f_T(p, \mu) = \begin{cases} \xrightarrow{T \gg m,\, \mu} \; g \dfrac{\pi^2}{30} T^4 \times \left\{ \begin{array}{ll} 1 & \text{boson} \\ \frac{7}{8} & \text{fermion} \end{array} \right. \\[2ex] \xrightarrow{T \ll m} \; m\, n = g\, m \left(\dfrac{mT}{2\pi} \right)^{3/2} e^{-(m-\mu)/T} \end{cases}$$

energy density

$$n = \boxed{g} \int \frac{d^3p}{(2\pi)^3} f_T(p, \mu) \underset{T \gg m, \mu}{\simeq} g \frac{2\zeta(3)}{\pi^2} T^3 \left[\frac{3}{4} \right]$$

[fermion]

number density

$$P = \boxed{g} \int \frac{d^3p}{(2\pi)^3} \frac{k^2}{3E} f_T(p, \mu) \underset{T \gg m, \mu}{\simeq} \frac{1}{3} \rho$$

pressure

Thermodynamical variables

EQUILIBRIUM THERMODYNAMICS

VARIABLE	RELATIVISTIC		NON REL.
	BOSE	FERMI	
n	$\frac{\zeta(3)}{\pi^2} g T^3$	$\frac{3}{4}\frac{\zeta(3)}{\pi^2} g T^3$	$g\left(\frac{mT}{2\pi}\right)^{3/2} e^{-m/T}$
ρ	$\frac{\pi^2}{30} g T^4$	$\frac{7}{8}\frac{\pi^2}{30} g T^4$	mn
p	$\frac{\rho}{3}$		$nT \ll \rho$
$\langle E \rangle$	$2{,}701T$	$3{,}151T$	$m + \frac{3}{2}T$

$$n = g_i \int \frac{d^2\vec{p}}{(2\pi)^3}\, f_i(p,T) \qquad \rho = g_i \int \frac{d^2\vec{p}}{(2\pi)^3}\, E_i\; f_i(p,T)$$

$$p = g_i \int \frac{d^2\vec{p}}{(2\pi)^3}\, \frac{p^2}{3E_i} f_i(p,T) \qquad \langle E \rangle = \rho/n$$

$$\rho_{\rm tot} = \sum_i \rho_i \simeq g_* \frac{\pi^2}{30} T^4$$

$$g_* = \sum_b g_b + \frac{7}{8} \sum_f g_f$$

sum over relativistic d.o.f.'s

$g_b \, (T_b / T)^4$ $\quad$ $g_f \, (T_f / T)^4$

g_* = total number of the EFFECTIVE RELATIVISTIC degrees of freedom

weighted by the temperature of each contributing d.o.f.
(if the corresponding particle is in thermal equilibrium, i.e. for a COUPLED particle, the temperature is the same as the T of thermal bath and, hence, no suppression factor is present

g_* is a function of the temperature T of the plasma of particles ➔ $g_*(T)$

ex. :

1) for $T \ll MeV \Rightarrow \begin{cases} \gamma \\ 3\,\nu \end{cases}$ $\quad T_\nu = \sqrt[3]{\frac{4}{11}}\, T_\gamma$ (see later) $\quad T_\gamma \downarrow T$

$$g_*\Big|_{T \ll MeV} = \underbrace{2}_{\gamma} + \frac{7}{8} \times 3 \times 2 \times \left(\frac{4}{11}\right)^{4/3} = \boxed{3.36}$$

2) for $1\,MeV < T < 100\,MeV$

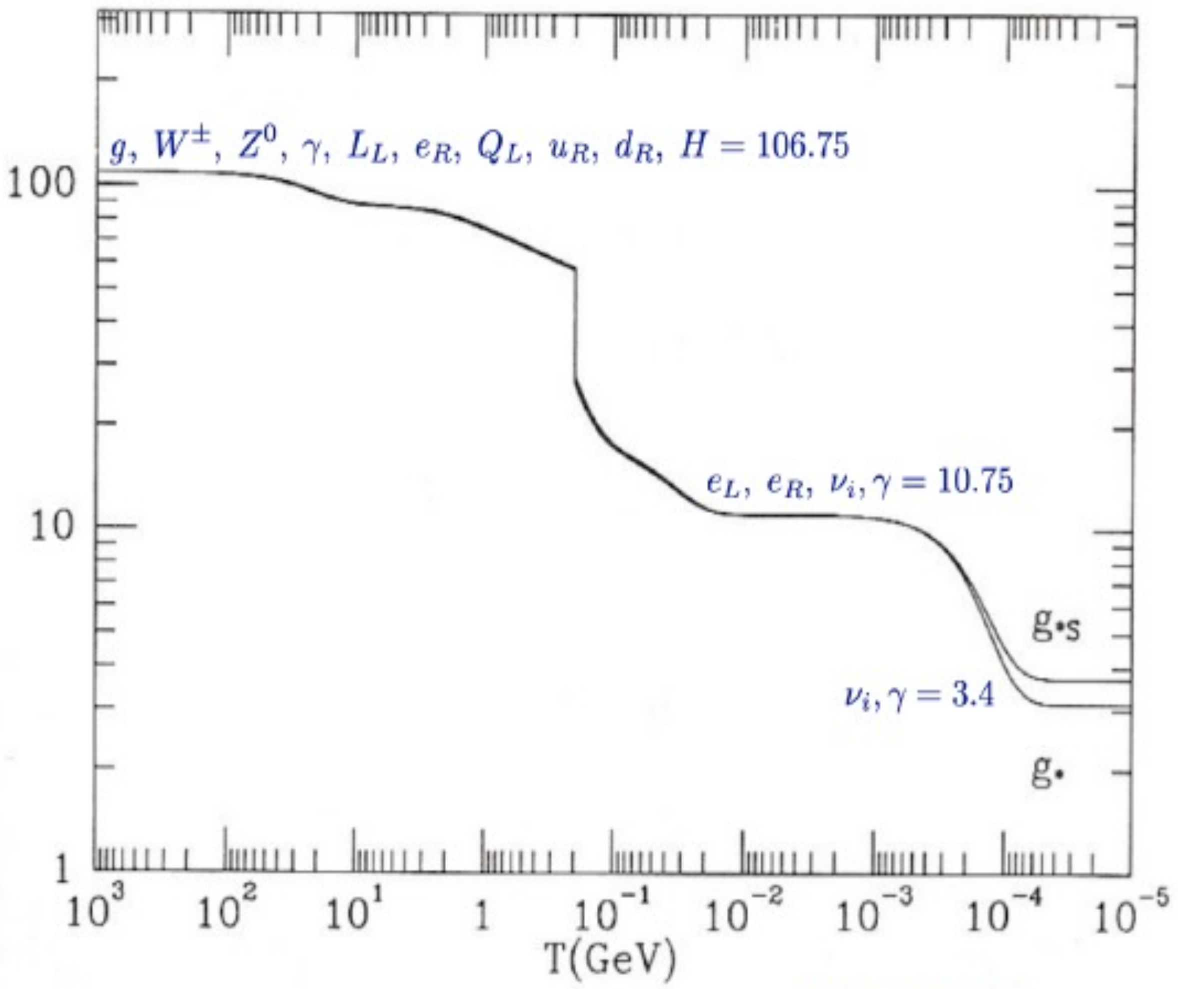
$$\begin{cases} \gamma \\ 3\,\nu \\ e^-, e^+ \end{cases} \qquad g_*\Big|_{1MeV<T<100MeV} = 2 + \frac{7}{8}\Big(\underbrace{3\times 2}_{3\,\nu_L \,\to\, 2\,d.o.f.} + \underbrace{1\times 4}_{e^+ e^- \,\to\, 4\,d.o.f.}\Big) = \boxed{10.75}$$

3) for $T > 200\,GeV$

all particles of the SM : 8 gluons, γ, $W^\pm$, Z^0, $6q$, e, μ, τ, 3ν, $H^0 \to$ Higgs boson

$$g_*\Big|_{T > 200\,GeV} \simeq \boxed{106.75}$$

If only the SM particles are present!

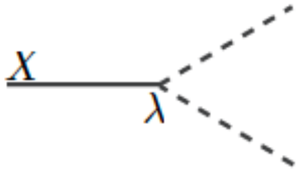


Kolb & Turner

Time-Scales

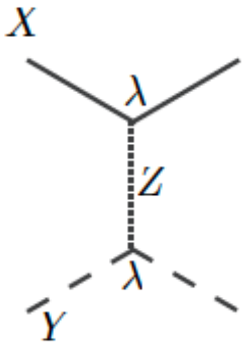
- expansion (rad. dom.): $$H = \sqrt{\frac{8\pi G}{3}\rho} \simeq 0.33\, g_*^{1/2}\frac{T^2}{M_p} \qquad [t/\mathrm{sec} \simeq (T/\mathrm{MeV})^{-2}]$$

- interactions:



decay $$\Gamma_D \sim \lambda^2 m_X \begin{cases} m_X/T & T \geq m_X \\ 1 & T \leq m_X \end{cases}$$

inv. decay $$\Gamma_{ID} \sim \Gamma_D \begin{cases} 1 & T \geq m_X \\ \left(\frac{m_X}{T}\right)^{3/2} e^{-\frac{m_X}{T}} & T \leq m_X \end{cases}$$



scattering (annihilation)

$$\Gamma_{S,X} \sim n_Y \lambda^4 \frac{T^2}{(T^2 + m_Z^2)^2} \sim \begin{cases} \lambda^4 T & T \gg m_{Y,Z} \\ \lambda^4 T^5/m_Z^4 & m_Y \ll T \ll m_Z \\ \propto e^{-m_Y/T} & T \ll m_Y \end{cases}$$

In or Out?

rule of thumb: in equilibrium if Γ » H

- gauge interactions: $\Gamma \sim \alpha^2 T \gg H$ ➡ $T \ll \alpha^2 M_p / 0.33 / g_*^{1/2} \simeq O(10^{15}\,\mathrm{GeV})$

- weak interactions: $\Gamma \sim G_F^2 T^5 \gg H$ ➡ $T \gg 1\mathrm{MeV}$

- baryon-photon coupling: $\Gamma \sim n_e\, \sigma_T \gg H$ ➡ $O(1\mathrm{eV}) \ll T \ll O(10^{15}\mathrm{GeV})$

  n_e: free-electron density; σ_T: Thomson cross-section

  $n_e \to 0$

- DM annihilations: $\Gamma \sim n_\chi \sigma_{\mathrm{ann}} \gg H$ ➡ $T \gg m_\chi$

NEUTRINO DECOUPLING (or NEUTRINO FREEZE-OUT)

Neutrino coupled to the thermal bath via weak interactions as

$$n\,\nu \leftrightarrow p\,e^-$$
$$n \leftrightarrow p\,e^-\,\bar{\nu}$$
$$n\,e^+ \leftrightarrow p\,\bar{\nu}$$
$$\nu\,\bar{\nu} \leftrightarrow e^-\,e^+$$

NEUTRINO MASSES << M_W

- New limit:
  $m_\nu < 0.45$ eV (90% CL)
  Neutrino-24 (2024), arXiv:2406.13516 (2024)

oscillations

$$|\Delta m^2_{12}| = (5.4 - 9.5) \times 10^{-5}\,\mathrm{eV}^2 \qquad \text{solar}$$
$$|\Delta m^2_{23}| = (1.2 - 4.8) \times 10^{-3}\,\mathrm{eV}^2 \qquad \text{atmosferic}$$

$$\Gamma_W \sim G_F^2 T^5 < H \sim 0.33\, g_*^{1/2} \frac{T^2}{M_p}$$

$$T < 0.8\mathrm{MeV}$$

weak interaction decoupling

RELIC NEUTRINOS

TODAY!

$m_\nu / T_W < 10^{-6}$ Neutrinos are relativistic at decoupling $\left.\frac{n_{\nu i}}{n_\gamma}\right|_{T_{\rm dec}} = \frac{2\times 3/4}{2} = \frac{3}{4}$

At $T \sim m_e < T_W$ electrons become non-relativistic: $e^+e^- \rightleftharpoons \gamma\gamma$ annihilate in photons (mostly)

Entropy conservation: $\left. g_*^s T^3 a^3 \right|_{\rm before} = \left. g_*^s T^3 a^3 \right|_{\rm after}$

$\Gamma_{\rm ann} \sim \alpha^2 m_e \gg H(T \sim m_e)$ annihilations are “instantaneous”: $a_{\rm before} = a_{\rm after}$

γ

Neutrinos are already decoupled: $\left(2 + 4\frac{7}{8}\right) T^3_{\rm before} = 2T^3_{\rm after}$

e^+, e^-

$$\boxed{\frac{T_\nu}{T_\gamma} = \frac{T_{\rm before}}{T_{\rm after}} = \left(\frac{4}{11}\right)^{1/3}} \qquad \boxed{\left.\frac{n_{\nu_i}}{n_\gamma}\right|_{\rm today} = \frac{3}{11}}$$

entropy of electrons transferred to photons
(% correction due to residual $e^+e^- \to \nu\bar{\nu}$)

TODAY: $T_\nu \sim T_\gamma / 1.4 \sim 1.96$ K and $n_\nu \sim O(100)$ cm^{-3} !!

- Number density

At present 112 $(\nu + \bar{\nu})$ cm^{-3} per flavour

- Energy density

Contribution to the energy density of the Universe

$$\Omega_\nu h^2 \simeq 1.7 \times 10^{-5}$$ Massless

$$\Omega_\nu h^2 = \frac{\sum_i m_i}{93.2 \text{ eV}}$$ Massive

$m_\nu >> T$

BBN – BIG BANG NUCLEOSYNTHESIS

- An astonishingly successful fruit of the **marriage between the TWO STANDARD MODELS of particle physics and cosmology**
- **TWO** crucial pieces of information on the universe:
  i) **how much "ordinary" matter** (i.e. baryonic matter, e.g. protons, neutrons) is present in the universe;
  ii) are there **new (non SM) light particles** other than neutrinos present in the early universe?

When did BBN start?

first nucleus. Deuterium: $n\,p \leftrightarrow D\,\gamma$ $\quad B_D = m_n + m_p - m_D = 2.2\,\mathrm{MeV}$

Equilibrium: $\mu_n + \mu_p = \mu_D$ $\quad \mu_\gamma = 0$ due to other processes, e.g. $e^+e^- \longleftrightarrow \gamma\gamma$

$$\frac{n_D}{n_n\,n_p} = \frac{n_D^{eq}}{n_n^{eq}\,n_p^{eq}} \simeq \frac{3}{4}\left(\frac{4\pi}{m_p T}\right)^{3/2} e^{B_D/T}$$

OUTPUT PARAMETER

$O(10^{-10})$

$$n_p \simeq n_n \simeq n_b, \quad n_\gamma \sim T^3 \qquad \frac{n_D}{n_b} \sim \frac{n_b}{n_\gamma}\left(\frac{T}{m_p}\right)^{3/2} e^{B_D/T}$$

The large entropy density (n_γ / n_b) delays D production from T~B_D to T~0.1 MeV

Helium abundance

When nucleosynthesis starts, all neutrons go to Helium-4 (excellent approximation)

How many neutrons are around at T~0.1 MeV ?

$$n\,\nu \leftrightarrow p\,e^-$$
$$n \leftrightarrow p\,e^-\,\bar{\nu}$$
$$n\,e^+ \leftrightarrow p\,\bar{\nu}$$

1.293 MeV

$$\frac{n_n}{n_p} = e^{-\Delta m/T}\, e^{(\mu_n-\mu_p)/T}$$

$$\frac{\mu_n}{T} \simeq \frac{\mu_p}{T} \sim \frac{n_b}{n_\gamma} \sim 10^{-10}$$

$\Gamma_W = H$

OUTPUT PARAMETER

$$T_W = \left(0.33\,\frac{g_*^{1/2}}{G_F^2 M_p}\right)^{1/3} \sim 0.8\,\mathrm{MeV}$$

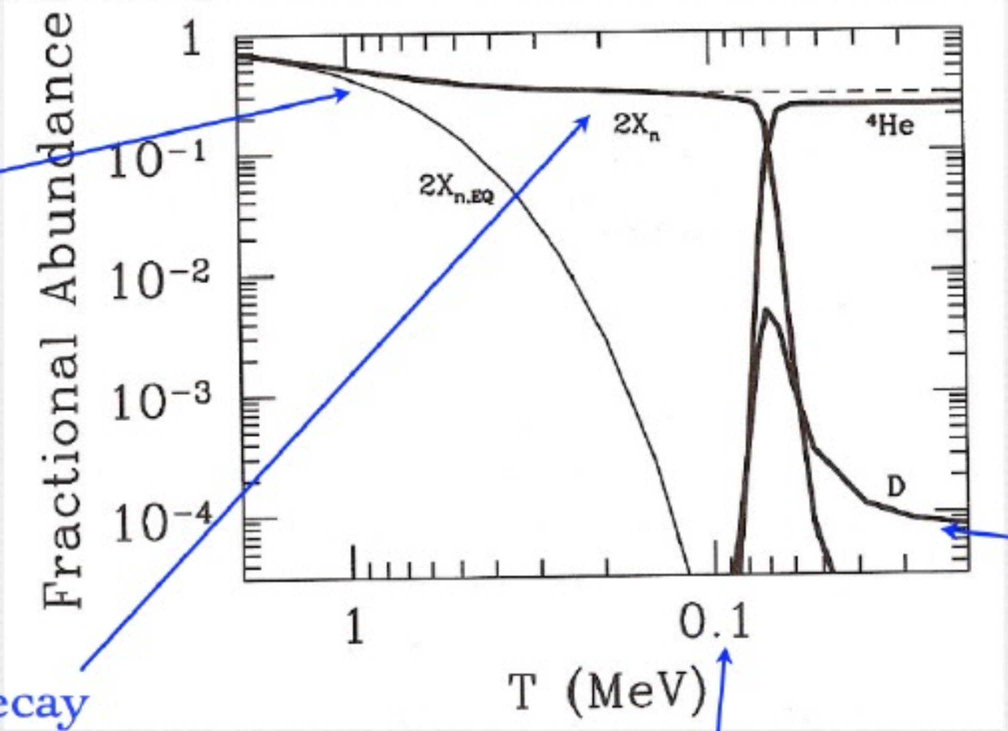
INPUT PARAMETER - if we extract the exp. value of G_F from the measurement of the neutron lifetime

$$\left.\frac{n_n}{n_p}\right|_{T=0.8\,\mathrm{MeV}} \simeq \frac{1}{6} \xrightarrow[\text{Boltzmann eq.}]{\text{n-decay}} \left.\frac{n_n}{n_p}\right|_{T=0.1\,\mathrm{MeV}} \simeq \frac{1}{8}$$

$\sim$ all neutrons finally go in ^{4}He

$$T_W = \left(0.33\,\frac{g_*^{1/2}}{G_F^2 M_p}\right)^{1/3} \sim 0.8\,\text{MeV}$$

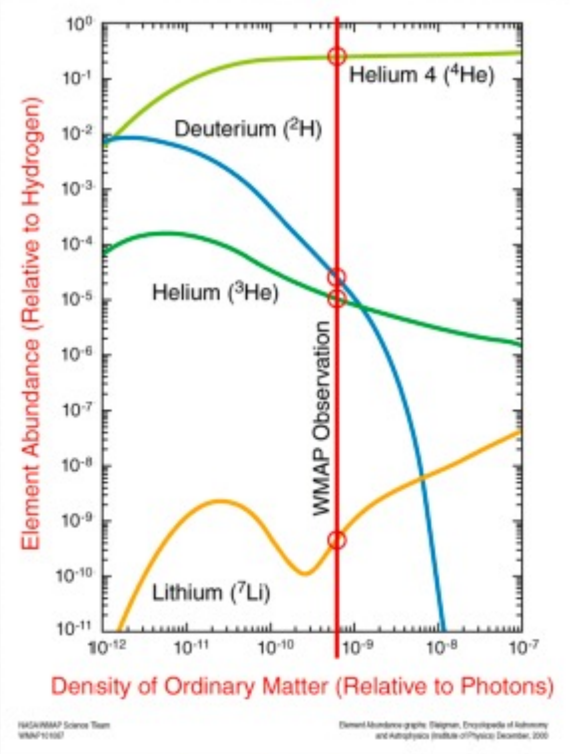
$$X_4 \equiv \frac{4\,n_{^4He}}{n_b} = \frac{2n_n}{n_n + n_p} \simeq 0.22$$



decoupling

n decay

BBN starts



residual D abundance

$D\,p \to {}^3He\,\gamma$

inefficient at low n_b/n_γ

$$g_* = g_*^{\text{standard}} + \Delta g_*$$

$$T_W = T_W^{\text{standard}} + \Delta T_W$$

$$\frac{n_n}{n_p} = \left.\frac{n_n}{n_p}\right|_{\text{standard}} + \Delta\frac{n_n}{n_p}$$

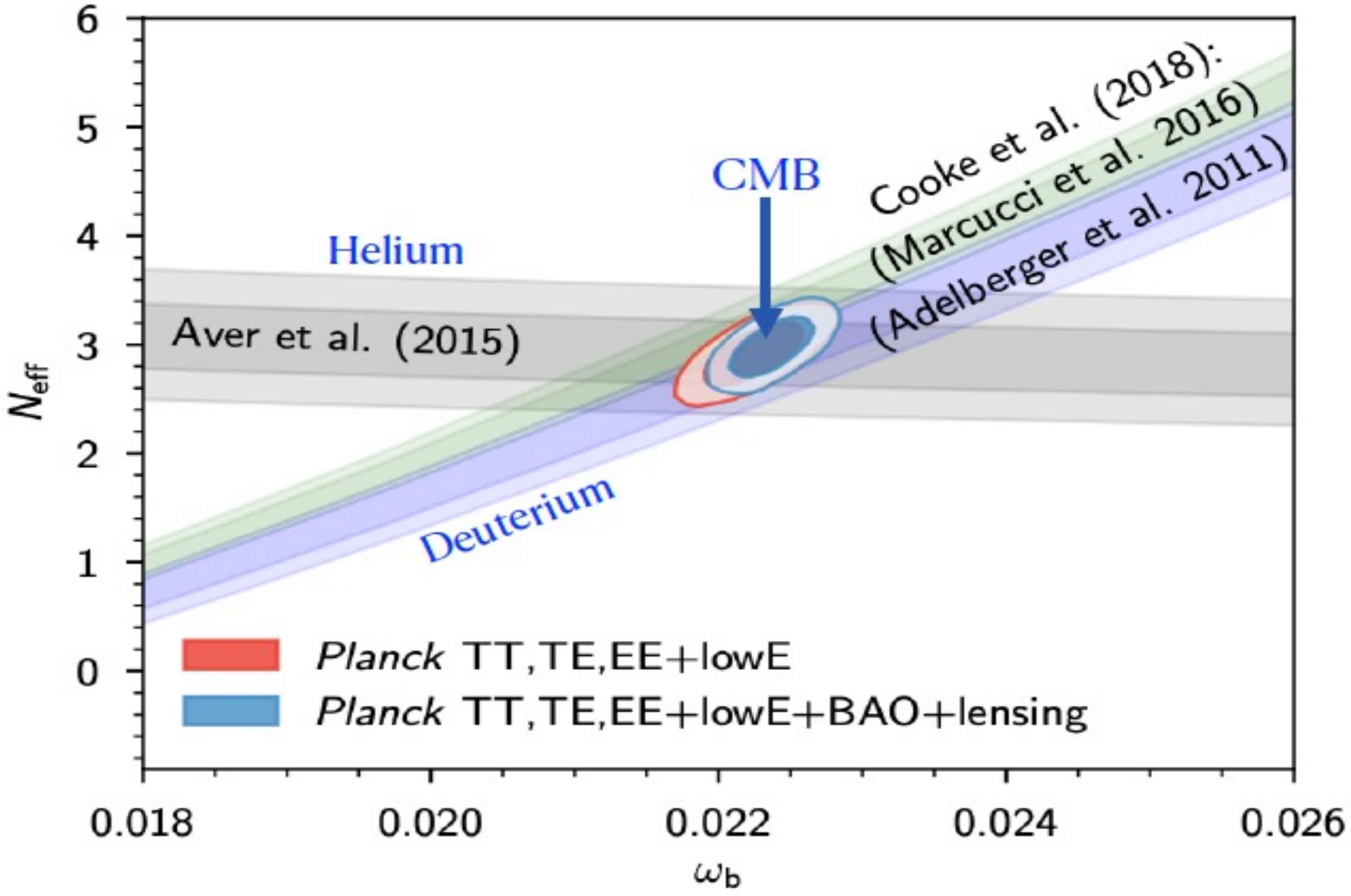
$$X_4 = X_{4,\,\text{st.}} + \Delta X_4$$

$$\Delta N_\nu < 0.1$$

bound on extra relativistic species

BBN is a powerful probe of n_b/n_γ and of $H(T \sim 1\text{MeV})$!

CMB+BBN: Baryons make up only ~ 4%



$$\omega_b = \Omega_b h^2$$

MICRO

GWS STANDARD MODEL

MACRO

HOT BIG BANG
STANDARD MODEL

UNIVERSE EXPANSION +
WEAK INTERACTIONS **NUCLEOYINTHESIS**
1 sec. after BB

NUMBER OF BARYONS and OF
NEUTRINO SPECIES →
CONFIRMED FROM CMB 350000
YEARS AFTER BB

BUT ALSO

FRICTION POINTS

Independent
confirmation from
the study of the CMB

New source(s) of CP violation

-COSMIC MATTER-ANTIMATTER ASYMMETRY

-INFLATION ???

New scalar potential

- DARK MATTER + DARK ENERGY

New particles and
interactions

OBSERVATIONAL EVIDENCE OF NEW PHYSICS

BEYOND THE STANDARD

THE COSMIC MATTER-ANTIMATTER ASYMMETRY PUZZLE:
-why only baryons
-why $N_{baryons}/N_{photon} \sim 10^{-10}$

- NO EVIDENCE OF ANTIMATTER WITHIN THE SOLAR SYSTEM
- ANTIPROTONS IN COSMIC RAYS: IN AGREEMENT WITH PRODUCTION AS SECONDARIES IN COLLISIONS
- IF IN CLUSTER OF GALAXIES WE HAD AN ADMIXTURE OF GALAXIES MADE OF MATTER AND ANTIMATTER $\longrightarrow$ THE PHOTON FLUX PRODUCED BY MATTER-ANTIMATTER ANNIHILATION IN THE CLUSTER WOULD EXCEED THE OBSERVED GAMMA FLUX
- IF $N_{ba.} = N_{antibar}$ AND NO SEPARATION WELL BEFORE THEY DECOUPLE WE WOULD BE LEFT WITH $N_{bar.}/N_{photon} << 10^{-10}$
- IF BARYONS-ANTIBARYONS ARE SEPARATED EARLIER $\longrightarrow$ DOMAINS OF BARYONS AND ANTIBARYONS ARE TOO SMALL SMALL TODAY TO EXPLAIN SEPARATIONS LARGER THAN THE SUPERCLUSTER SIZE

$\Downarrow$

- ONLY MATTER IS PRESENT
- HOW TO DYNAMICALLY PRODUCE A BARYON-ANTIBARYON ASYMMETRY STARTING FROM A SYMMETRIC SITUATION

$$\text{WMAP+BBN:} B = \frac{n_b - n_{\bar{b}}}{s} = (8.6 \pm 0.4) \times 10^{-11}$$

Evidences of a baryon-asymmetric Universe

Direct searches:

Cosmic rays at E > O(100 MeV) probe galactic scales, $r_{\rm Gal} \sim 30\ kpc$

$\frac{n_{\bar{p}}}{n_p} \sim 3\ 10^{-4}$ compatible with secondary production in $p\,p \to p\,p\,p\,\bar{p}$

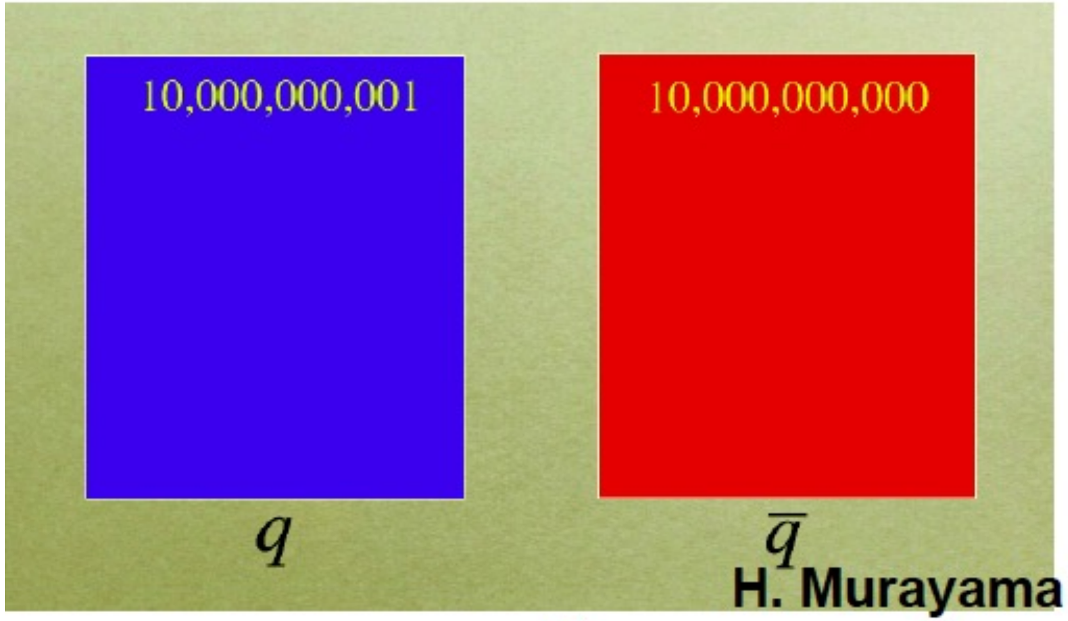
Indirect searches:

Look for: 1) γ's from $b\,\bar{b}$ annihilations;
2) CMB spectrum distortions due to Compton scattering.

no signal of galaxy-antigalaxy annihilation from Virgo cluster, or X-rays emitting clusters: $r_{\rm Clust} \sim 10\ Mpc$ (Steigman '76)

CMB+diffuse gamma ray background constrain matter-antimatter islands to be larger than ~ $O(10^3\ Mpc) \sim 1/H_0$ (Cohen, De Rujula, Glashow '98)

THE COSMIC MATTER-ANTIMATTER ASYMMETRY PUZZLE:
-why only baryons
-why $N_{baryons}/N_{photon} \sim 10^{-10}$



H. Murayama

Peculiar initial conditions?

Or is there a **dynamics** allowing for matter to prevail over antimatter starting from a perfectly **symmetric situation in matter – antimatter** content of the plasma after inflation?

Sakharov's conditions
necessary conditions for a dynamical baryogenesis

- **B-violating interactions** (the global symmetry B-number is NOT an exact symmetry of Nature

- **C and CP-violating interactions**

$$\text{C:} \quad \Gamma[i \to f] = \Gamma[\bar{i} \to \bar{f}]$$

$$\text{CP} \equiv \text{T:} \quad \Gamma[i \to f] = \Gamma[f \to i]$$

no net result: $n_b - n_{\bar{b}} = 0$

- the B-violating interactions giving rise to ΔB must **depart from thermal equilibrium** right after the the ΔB production

th. equilibrium: $$\begin{aligned} n_{b_i} &= n_{b_i}(E_i, \mu_i, T) \\ n_{\bar{b}_i} &= n_{\bar{b}_i}(E_i, -\mu_i, T) \end{aligned}$$ + B-violation + charge neutrality

$$\longrightarrow \boxed{\mu_i = 0 \qquad n_{b_i} = n_{\bar{b}_i}}$$

Standard Model: B-violation

B (and L) are **accidental symmetries** of the SM: $\partial_\mu J^\mu_{B(L)} = 0$

they are broken at the quantum level by **triangle anomalies**:

$$\partial_\mu J^\mu_B = \partial_\mu J^\mu_L = -\frac{3}{32\pi^2} g^2 F^a_{\mu\nu} \tilde{F}^{a\,\mu\nu} \quad (+\ \mathrm{U}(1)\ldots)$$

dual field strength tensor $\frac{1}{2}\varepsilon^{\mu\nu\lambda\rho} F^a{}_{\lambda\rho}$

$$\Delta B = 3\,\Delta N_{cs} = \Delta L$$

$$\left(N_{cs}(t) = \frac{g^2}{96\pi^2} \int d^3x\, \epsilon_{abc} \epsilon^{ijk} A^a_i A^b_j A^c_k \right)$$

$$B = \int d^3x\, J^0_B$$

in vacuum to vacuum transitions ΔN_{cs} is integer.

effective interaction: $O_{B+L} = \Pi_{i=1\cdots 3}(q_{L_i}\, q_{L_i}\, q_{L_i}\, l_{L_i})$

$$\boxed{\Delta(B+L) = 6\,, \quad \Delta(B-L) = 0}$$

Sphalerons

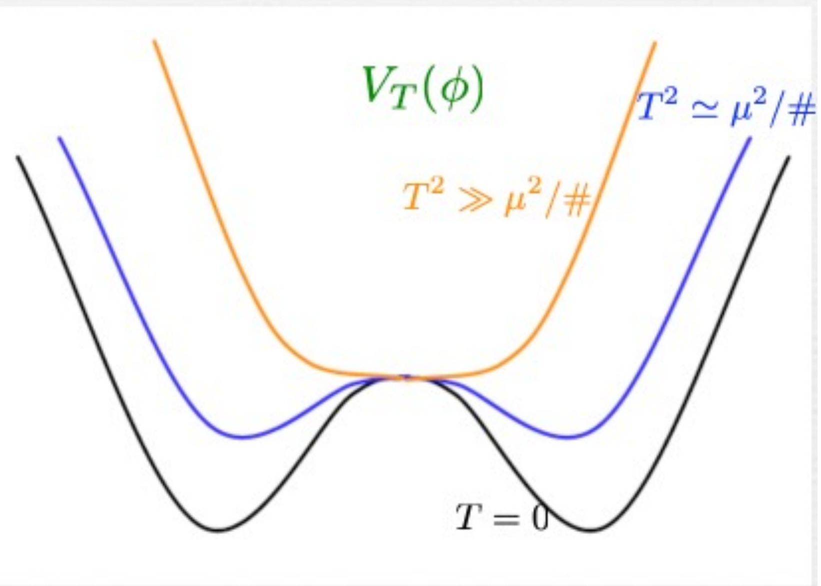
Higgs expectation value

different vacua are separated by an energy barrier $E_{sp} = \frac{4\pi v}{g} B(\lambda/g) = O(10\,\text{TeV})$

$T = 0$: vacuum tunnelling $\quad \Gamma \sim e^{4\pi/\alpha_w} = O(10^{-165})$

$T \neq 0$: thermal fluctuations $\quad \Gamma \sim e^{-\frac{E_{sp}(T)}{T}}$

$E_{sp}(T) \propto v(T) \to 0 \quad$ at high T!



in equilibrium for $T_{\text{EWPT}} \sim 100$ GeV $< T < O(10^{12})$ GeV

SM FAILS TO GIVE RISE TO A SUITABLE COSMIC MATTER-ANTIMATTER ASYMMETRY

- **NOT ENOUGH CP VIOLATION IN THE SM**

  NEED FOR ***NEW SOURCES OF CPV IN ADDITION TO THE PHASE PRESENT IN THE CKM MIXING MATRIX***

- FOR M_{HIGGS} > 80 GeV THE ELW. PHASE TRANSITION OF THE SM IS A SMOOTH CROSSOVER

NEED *NEW PHYSICS BEYOND SM*. IN PARTICULAR, FASCINATING POSSIBILITY: THE ENTIRE MATTER IN THE UNIVERSE ORIGINATES FROM THE SAME MECHANISM RESPONSIBLE FOR THE EXTREME SMALLNESS OF m_ν

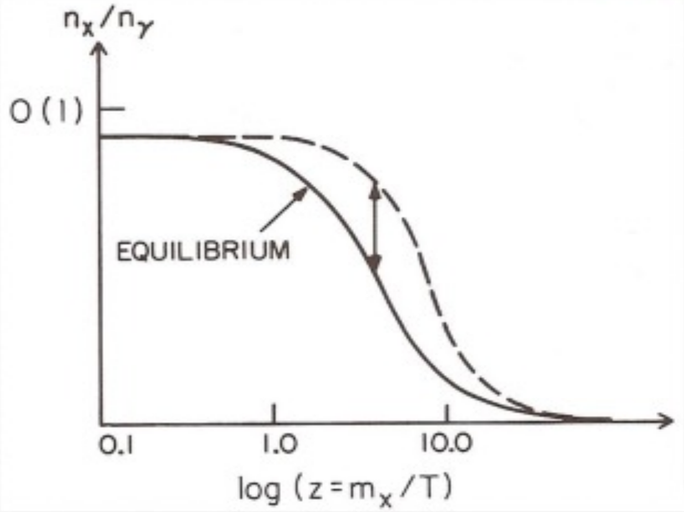
MATTER-ANTIMATTER ASYMMETRY ⟷ NEUTRINO MASSES CONNECTION: BARYOGENESIS THROUGH LEPTOGENESIS

- Key-ingredient of the SEE-SAW mechanism for neutrino masses: **large Majorana mass for RIGHT-HANDED neutrino**
- In the early Universe the heavy RH neutrino decays with Lepton Number violatiion; if these decays are accompanied by a new source of CP violation in the leptonic sector, then

VANILLA LEPTOGENESISIS !

→ it is possible to create a lepton-antilepton asymmetry at the moment RH neutrinos decay. Since SM interactions preserve Baryon and Lepton numbers at all orders in perturbation theory, but violate them at the quantum level, such **LEPTON ASYMMETRY** can be converted by these purely quantum effects into a BARYON-ANTIBARYON ASYMMETRY (**Fukugita-Yanagida mechanism for leptogenesis**)

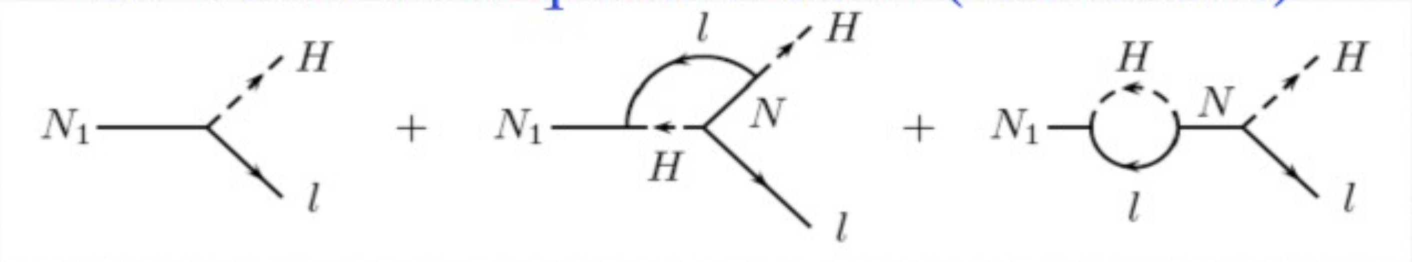
Out-of-equilibrium decay



$T_{\rm dec} < M$: inverse decays are out of eq.

$$\epsilon = \frac{\Gamma(N_1 \to H\, l) - \Gamma(\bar{N}_1 \to \bar{H}\, \bar{l})}{\Gamma(N_1 \to H\, l) + \Gamma(\bar{N}_1 \to \bar{H}\, \bar{l})}$$

CP-violation is a quantum effect (interference)



$$L = \frac{n_l - n_{\bar{l}}}{s} \sim \frac{\epsilon\, n_N}{g_* n_N} = \frac{\epsilon}{g_*}$$ (fully efficient)

$$B - L = -L = -K\frac{\epsilon}{g_*}$$ (realistic) K=efficiency factor <1 (need Boltz. eq.)

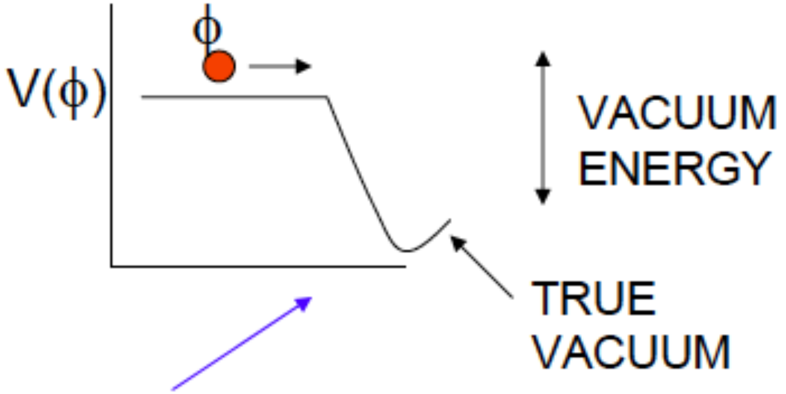
INFLATION

SEVERE COSMOGICAL PROBLEMS

- **CAUSALITY**
  (isotropy of CMBR)
- **FLATNESS**
  (Ω close to 1 today)
- **AGE OF THE UNIV.**
- **PRIMORDIAL MONOPOLES**

COMMON SOLUTION FOR THESE PROBLEMS

VERY FAST (EXPONENTIAL) EXPANSION IN THE UNIV.



Ω dominated by vacuum en.

For some inflationary models → large amount of primordial gravitational waves

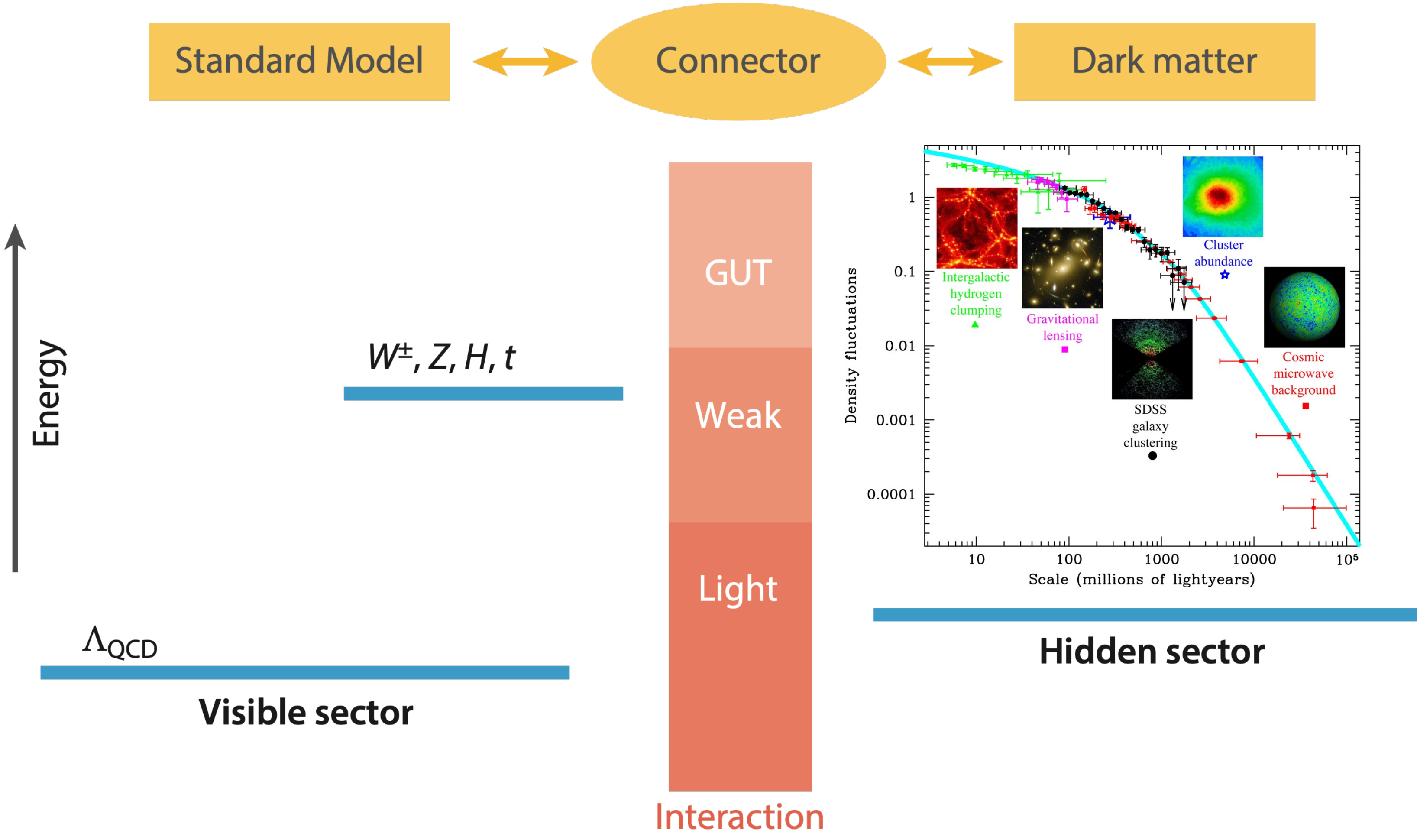
NO WAY TO GET AN INFLATIONARY SCALAR POTENTIAL IN THE SM, UNLESS THERE EXISTS A NON-MINIMAL COUPLING OF THE SM HIGGS FIELD TO GRAVITY

DARK MATTER
The Challenge.

All known properties of dark matter are via the gravitational interaction.

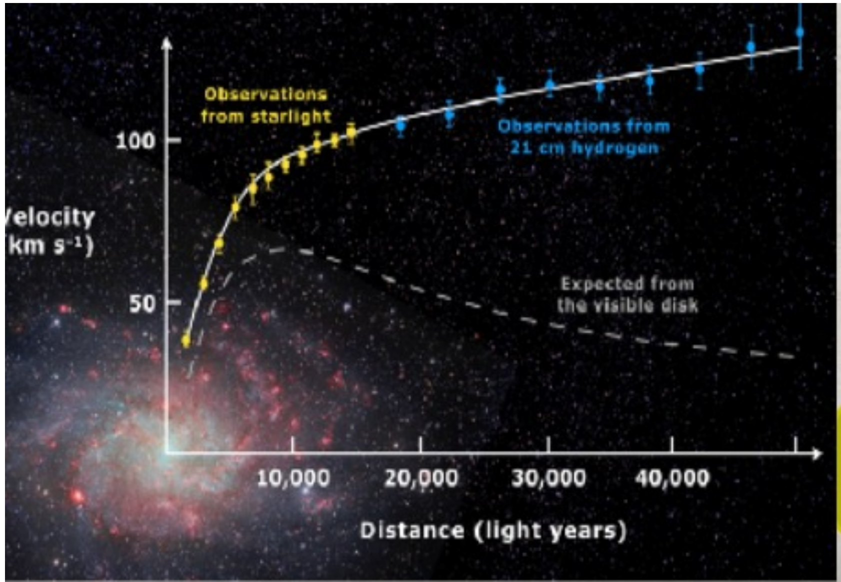
- Gravity is weak.
- Gravity gives the gross properties of dark matter — density and large-scale clustering.
- Learning about particle properties will require stronger-than-gravitational interactions.

K. Zurek, IDM 202



Inadequacy of the "ordinary" BARYONIC MATTER

- **CLUSTER SCALES**:
  i) Already ~90 years ago (1933) F. **Zwicky** pointed out that to account for the velocity dispersion of the galaxies in the COMA **cluster** some large amount of new non-shining "**DUNKLE MATERIE**" **DARK MATTER (DM)**, was needed; ii) **Nowadays**, from the observation of the **X-ray emission**, we infer that the temperature of the cluster gas is **TOO** high → it requires a **factor 5** more matter than the visible baryonic matter
- **GALACTIC SCALES**: but the existence of (a large amount of) NON-BARYONIC MATTER got firm credibility only ~40 years after Zwicky's claim → Vera RUBIN (with K. Ford et al) ~70's pointed out that stars in the outer part of galaxies are **faster** than expected



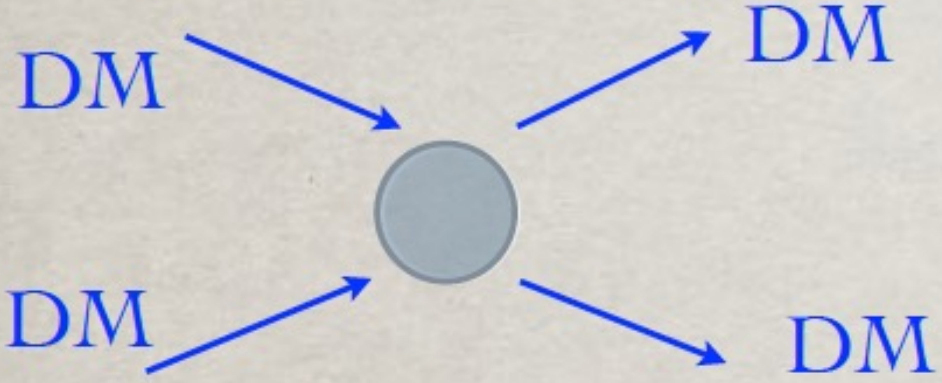
$$v_c^2 \propto G_N \frac{M(r)}{r} \propto \frac{M_{tot}}{r}$$

But instead it is constant ! Need

$$M(r) \propto r, \text{ i.e. } \rho_{DM} \propto r^{-2}$$

DM-DM INTERACTION

Self-interaction:



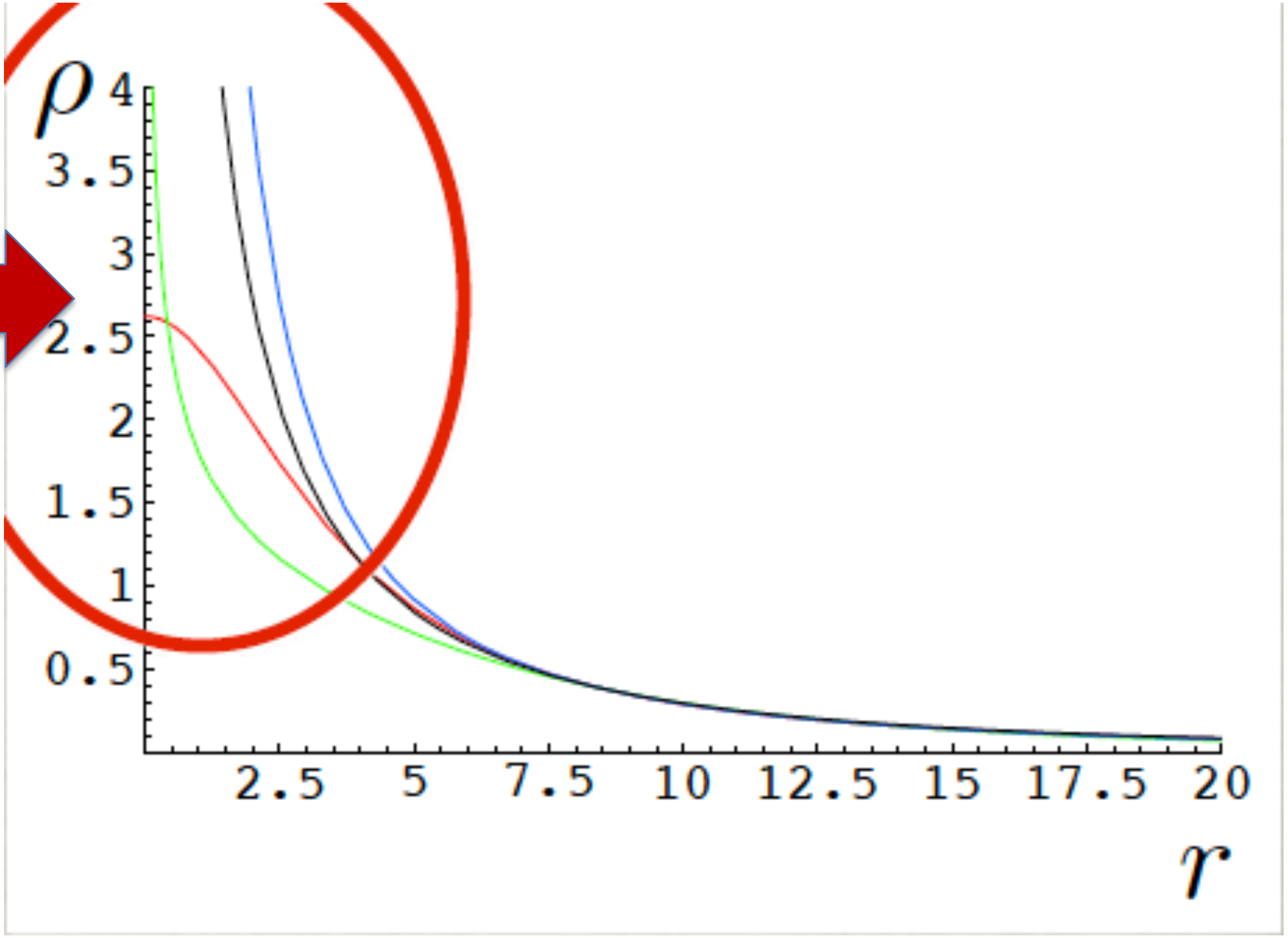
Bullett cluster bound on self-interaction:

$$\sigma \leq 1.7 \times 10^{-24} cm^2 \sim 10^9 pb \quad (m = 1\ \mathrm{GeV})$$

[Markevitch et al 03]

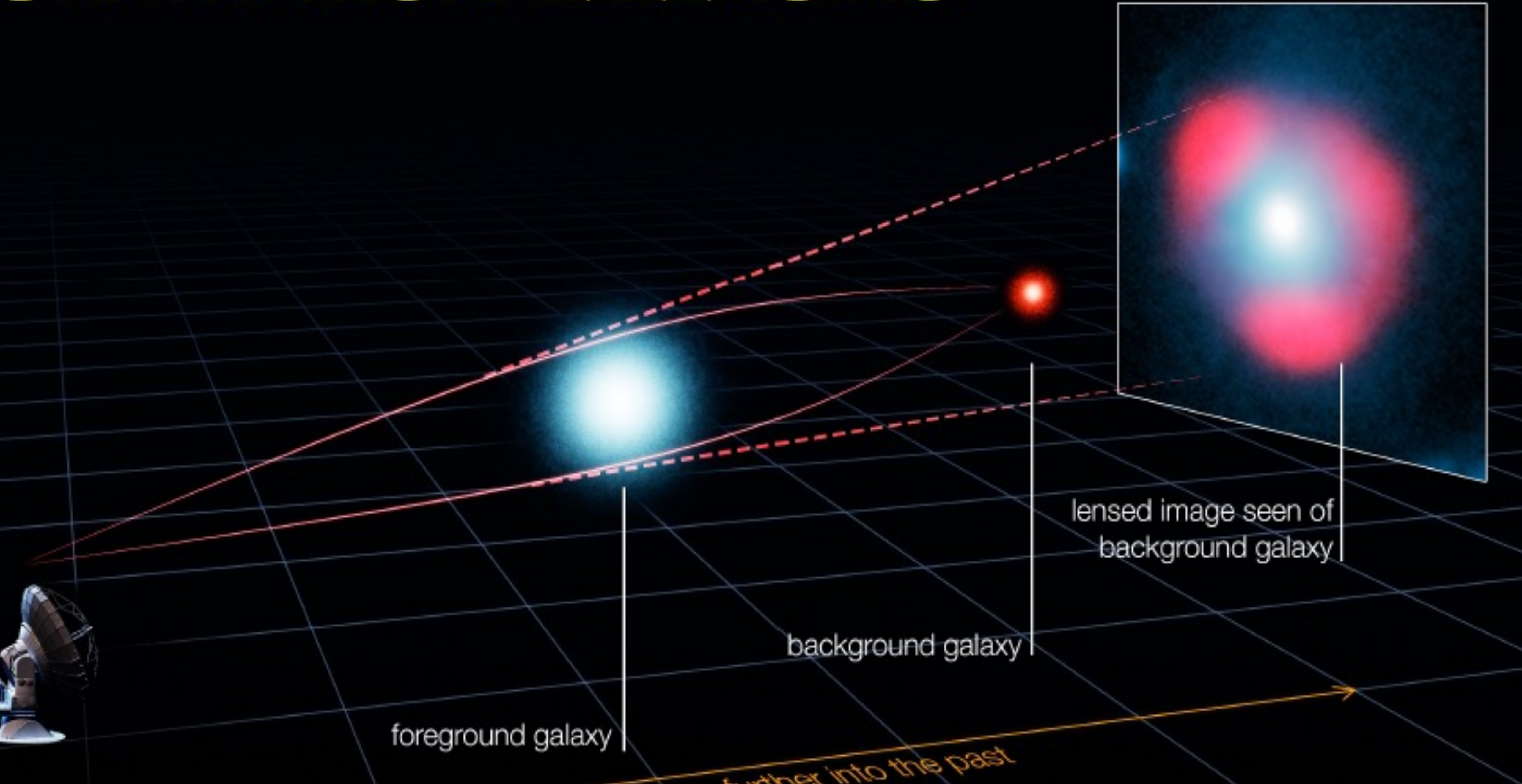
Galactic scales: DM density profiles

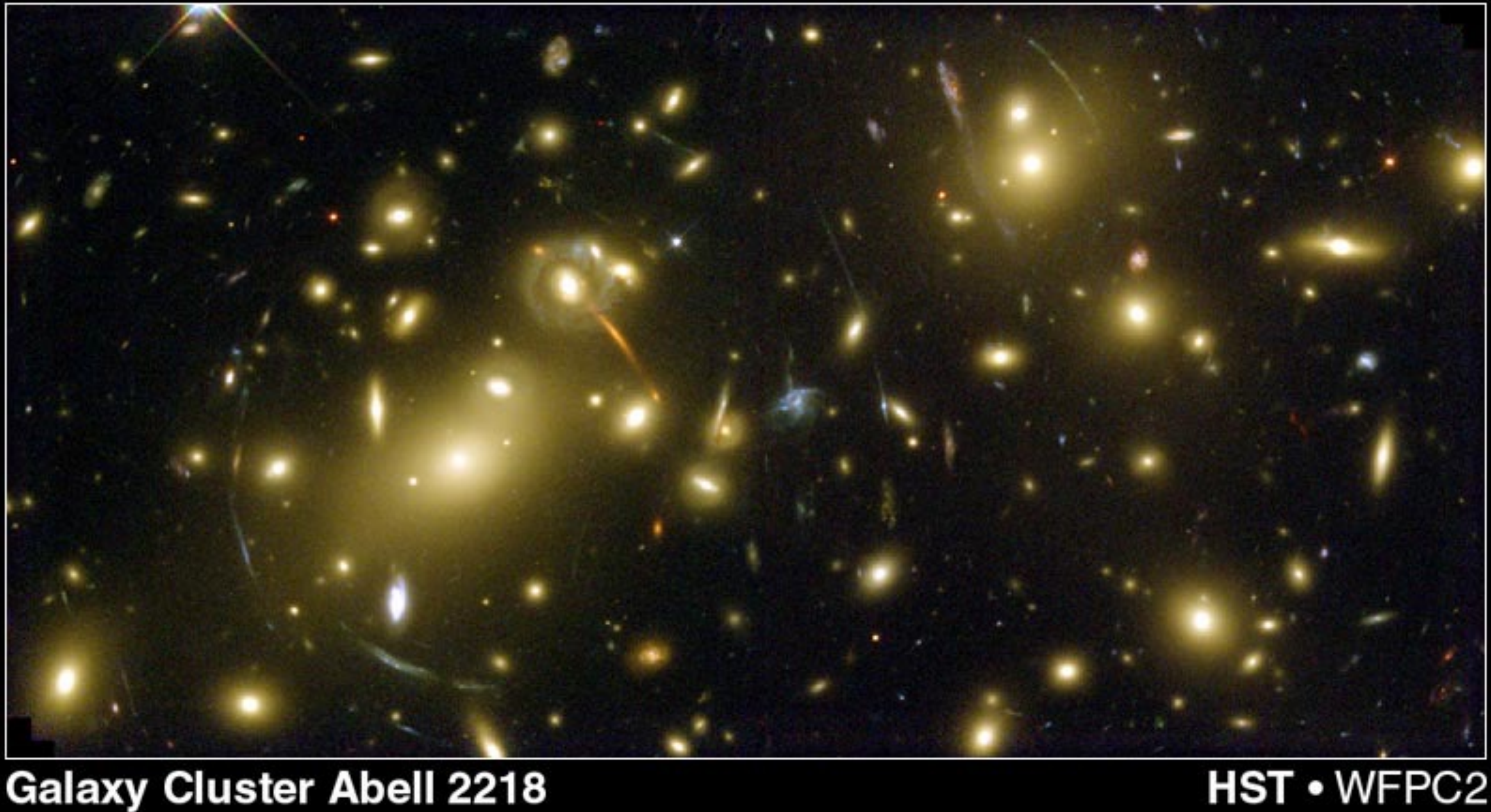
There exist **several DM density profiles** (related to data and/or numerical simulations) : Isothermal, NFW, Moore, Einasto, Kratsov, etc.



The **main difference** among such density profiles concerns the behaviour at the **centre** of the galaxy, either **cusped** or **cored**

GRAVITATIONAL LENSING





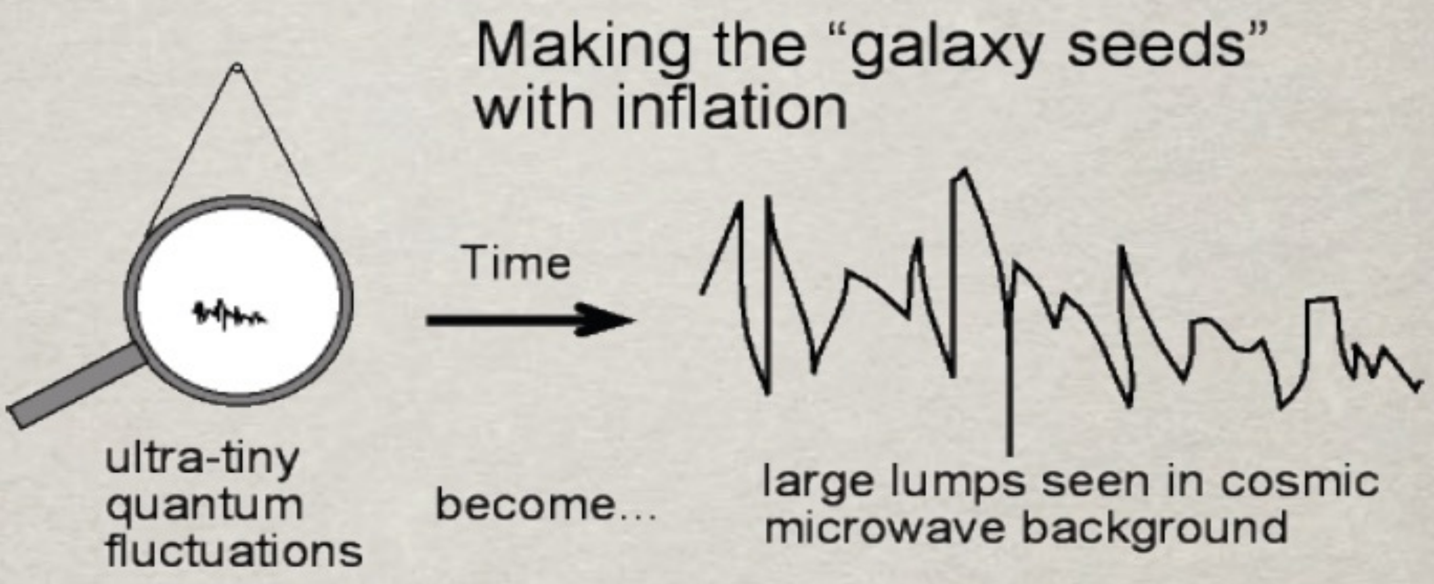
Gravitational lensing

A large amount of mass between the background galaxies and us can be inferred by the lensing effect

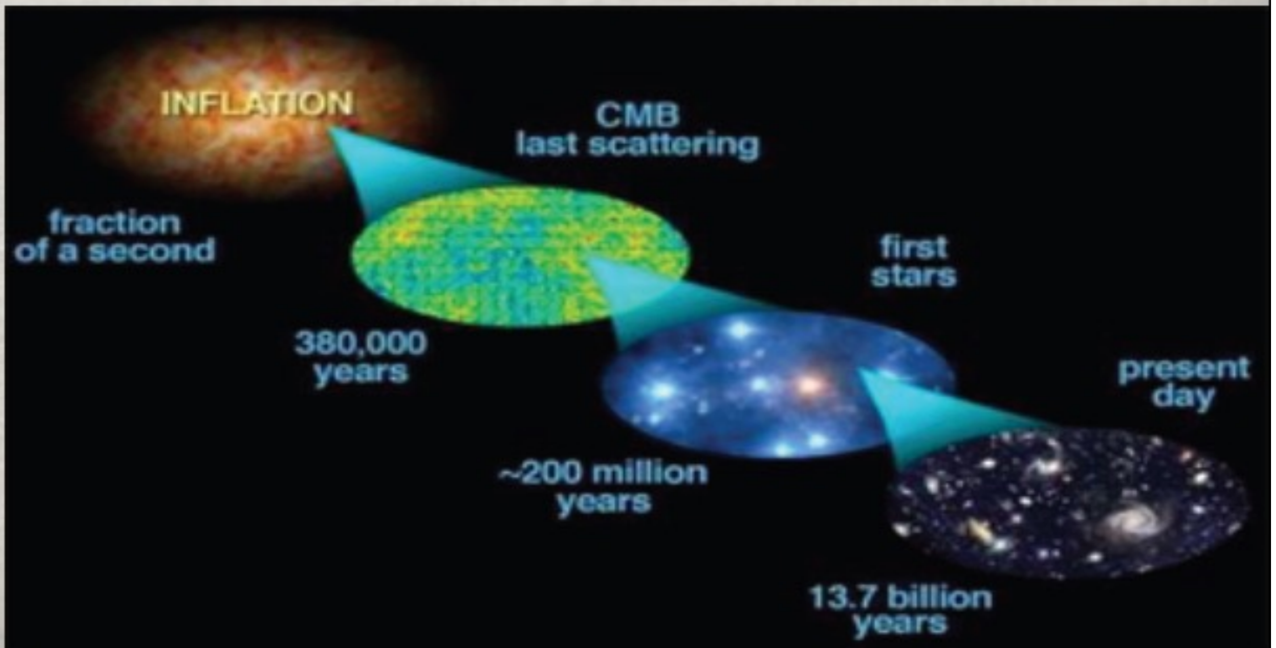
Quantum Fluctuation

$$\delta\varphi = \frac{H}{2\pi}$$

$$\Delta t \Delta E \geq \hbar$$



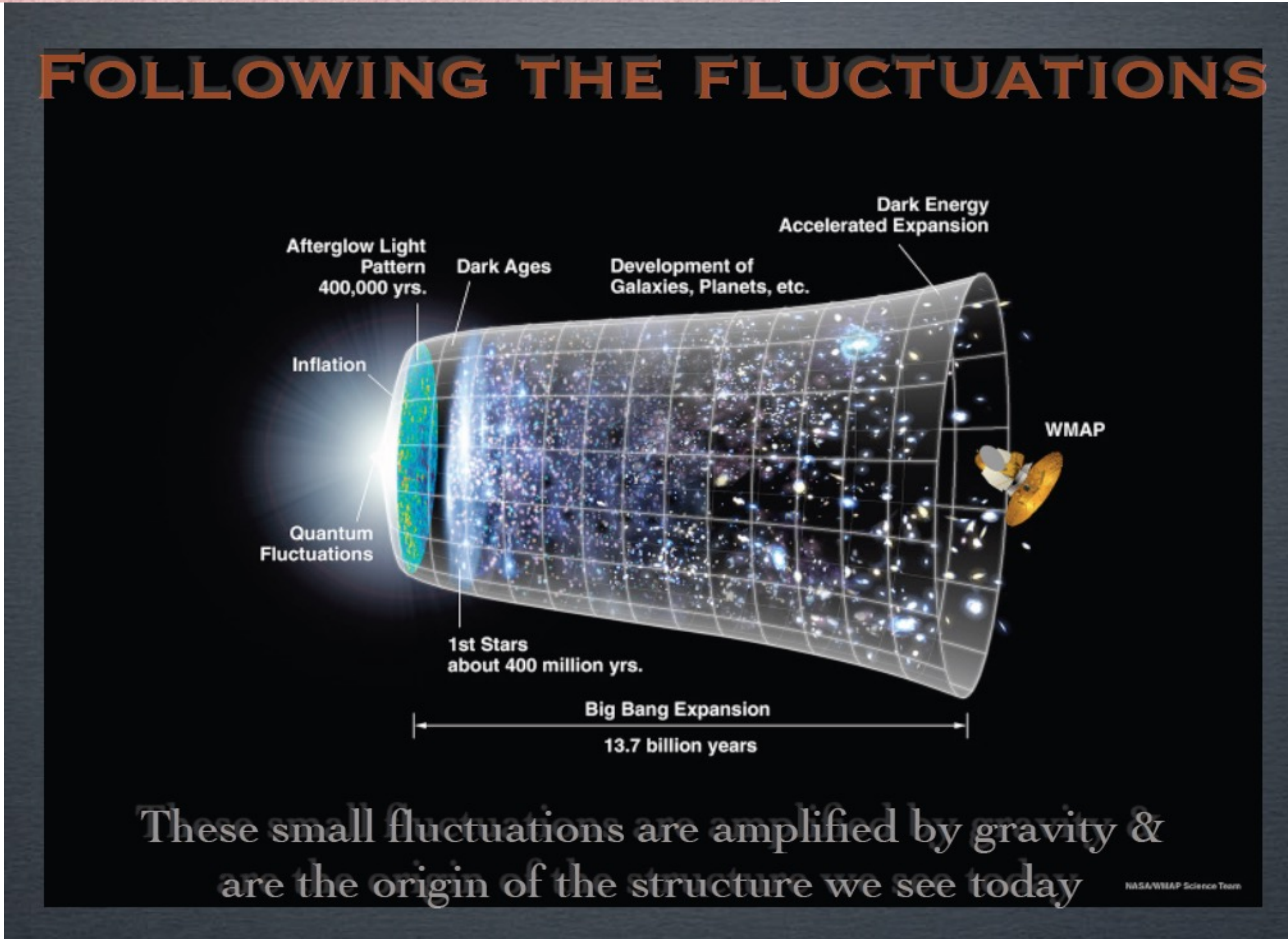
Gravity stretches
and amplifies
the microscopic
fluctuations to
macroscopic scales !!!



The need of NON-BARYONIC MATTER!

STRUCTURE FORMATION from **PRIMORDIAL DENSITY FLUCTUATIONS** requires the presence of a (large) amount of

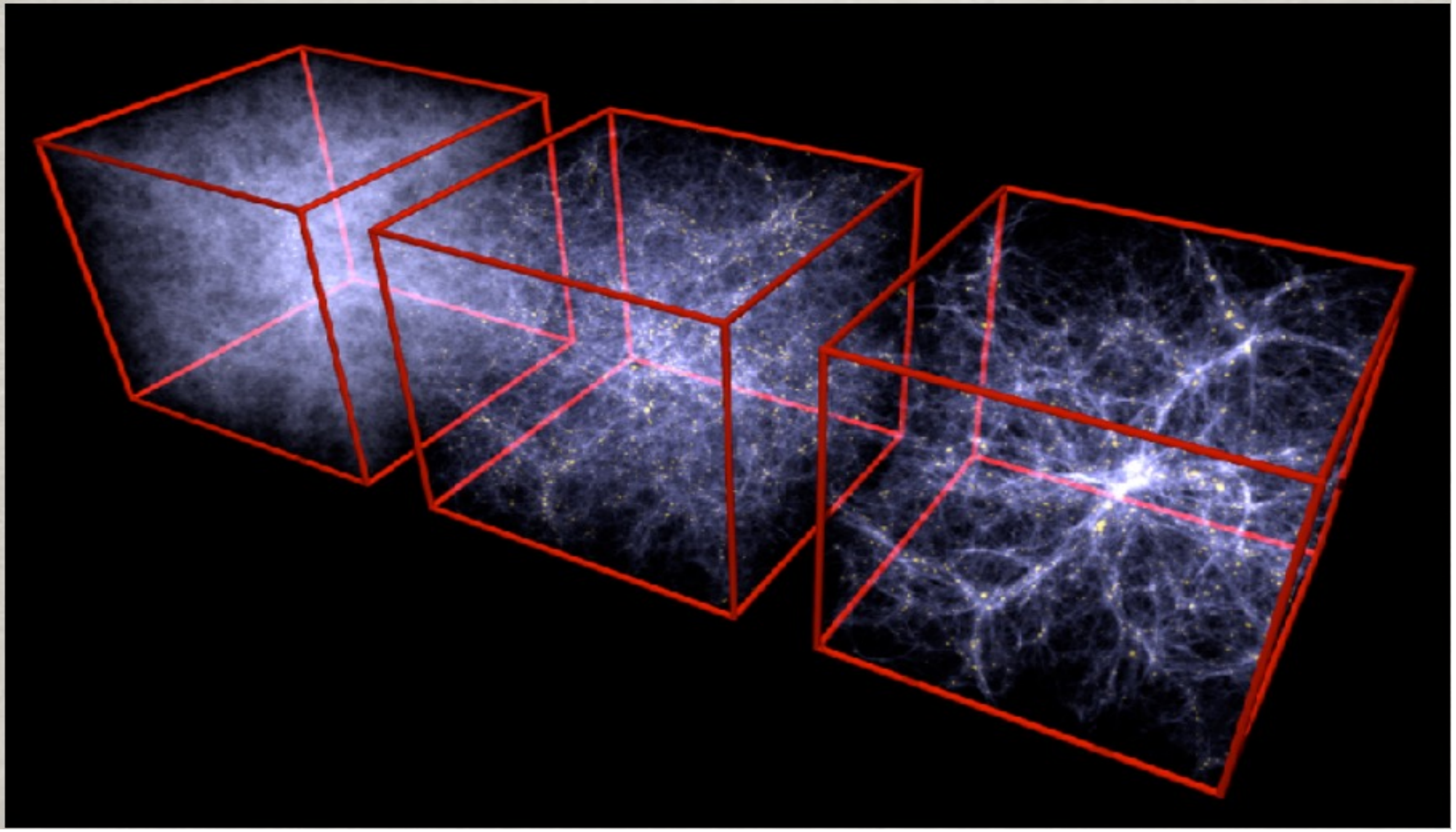
NON-BARYONIC MATTER

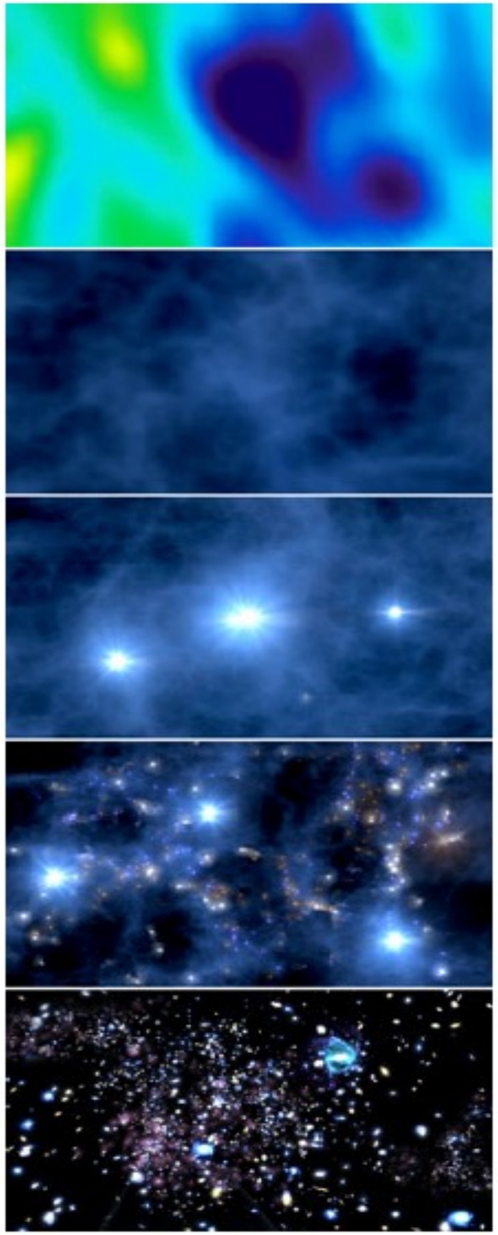


STRUCTURE FORMATION

V. Springel @MPA Munich

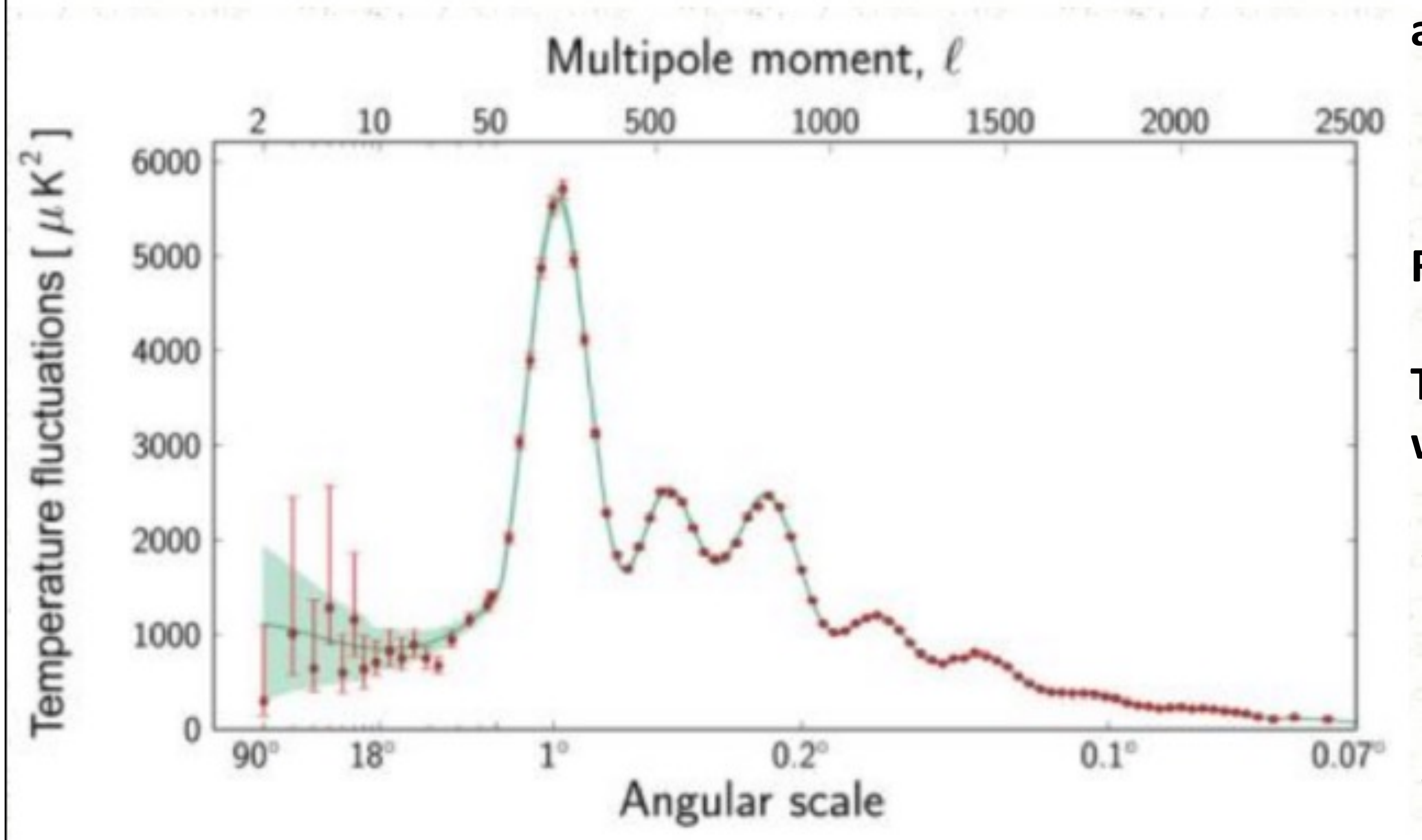
Yoshida et al 03





DM needs to be (mainly) cold
and (mainly) non-collisional

The need for a large amount of **NON-BARYONIC MATTER** from the study of the **Cosmic Microwave Background (CMB)**



Planck's power spectrum of temperature fluctuations in the CMB at different angular scales on the sky.

Red dots are the Planck data.

The peak at 1 degree is consistent with a flat geometry of the universe

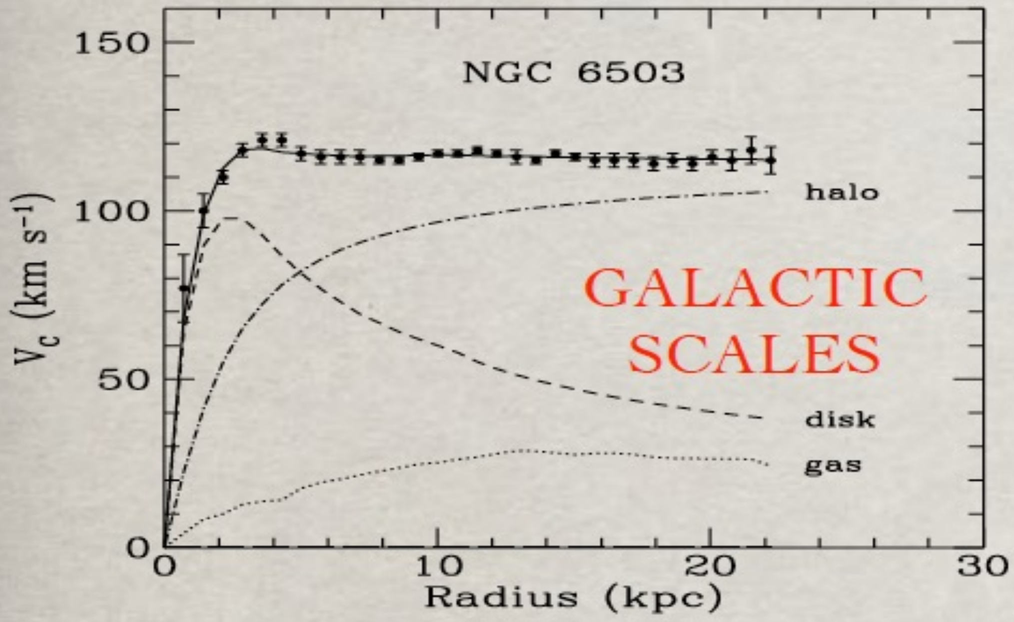
the height of the 2nd peak with

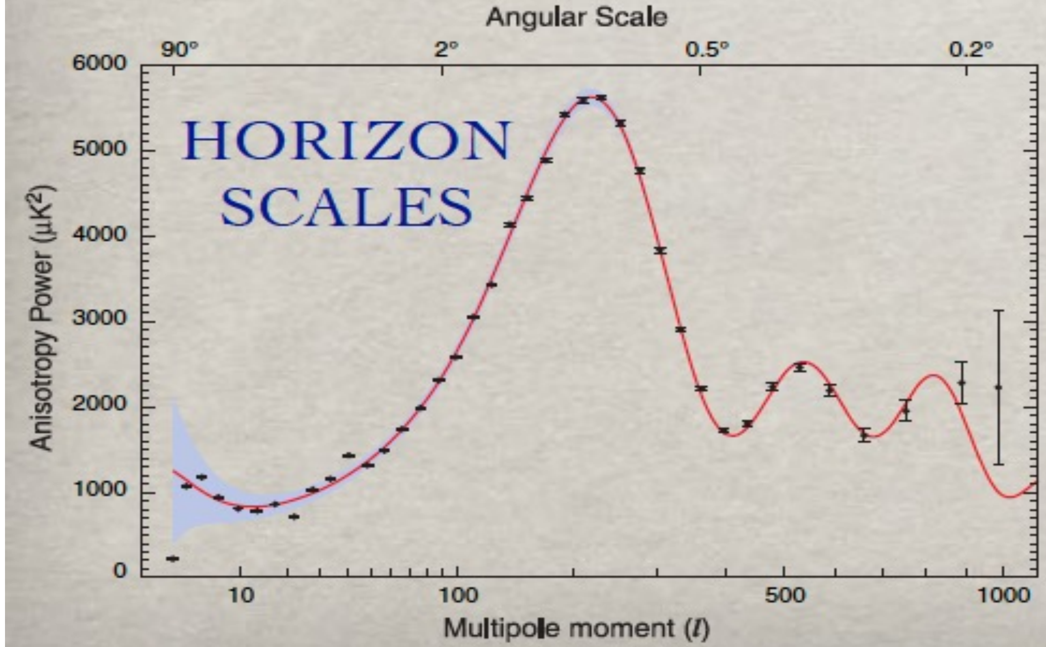
5% (baryonic matter)

the 2nd and 3rd peaks with

26% dark matter

DARK MATTER EVIDENCE





Particles	Ωh^2	Type
Baryons	0.0224	Cold
Neutrinos	< 0.01	Hot
Dark Matter	0.1-0.13	Cold

The ΛCDM Model

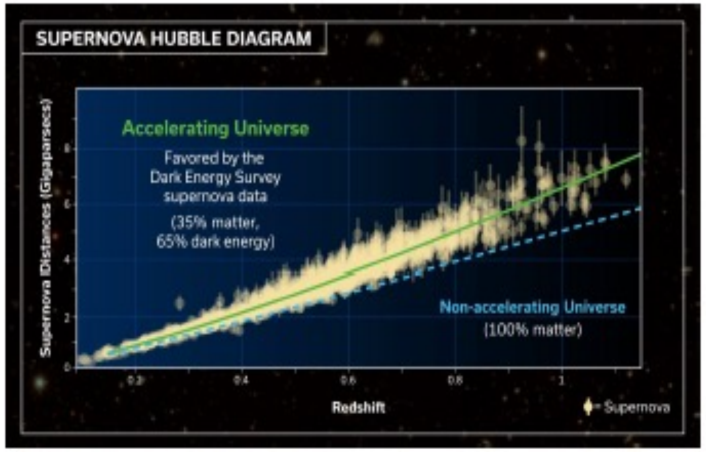
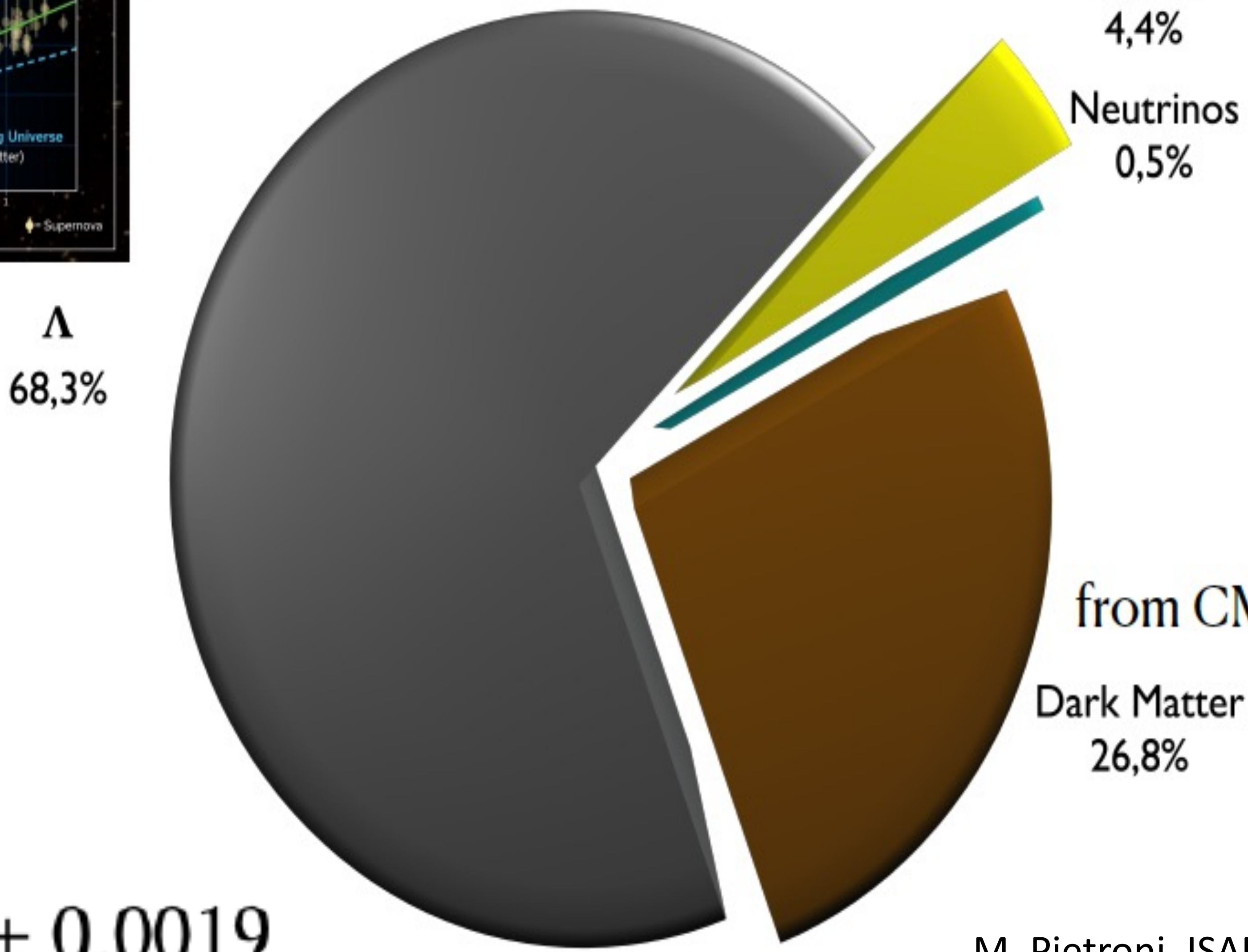


Image: DES collaboration

$d_L(z)$ from SNeIa

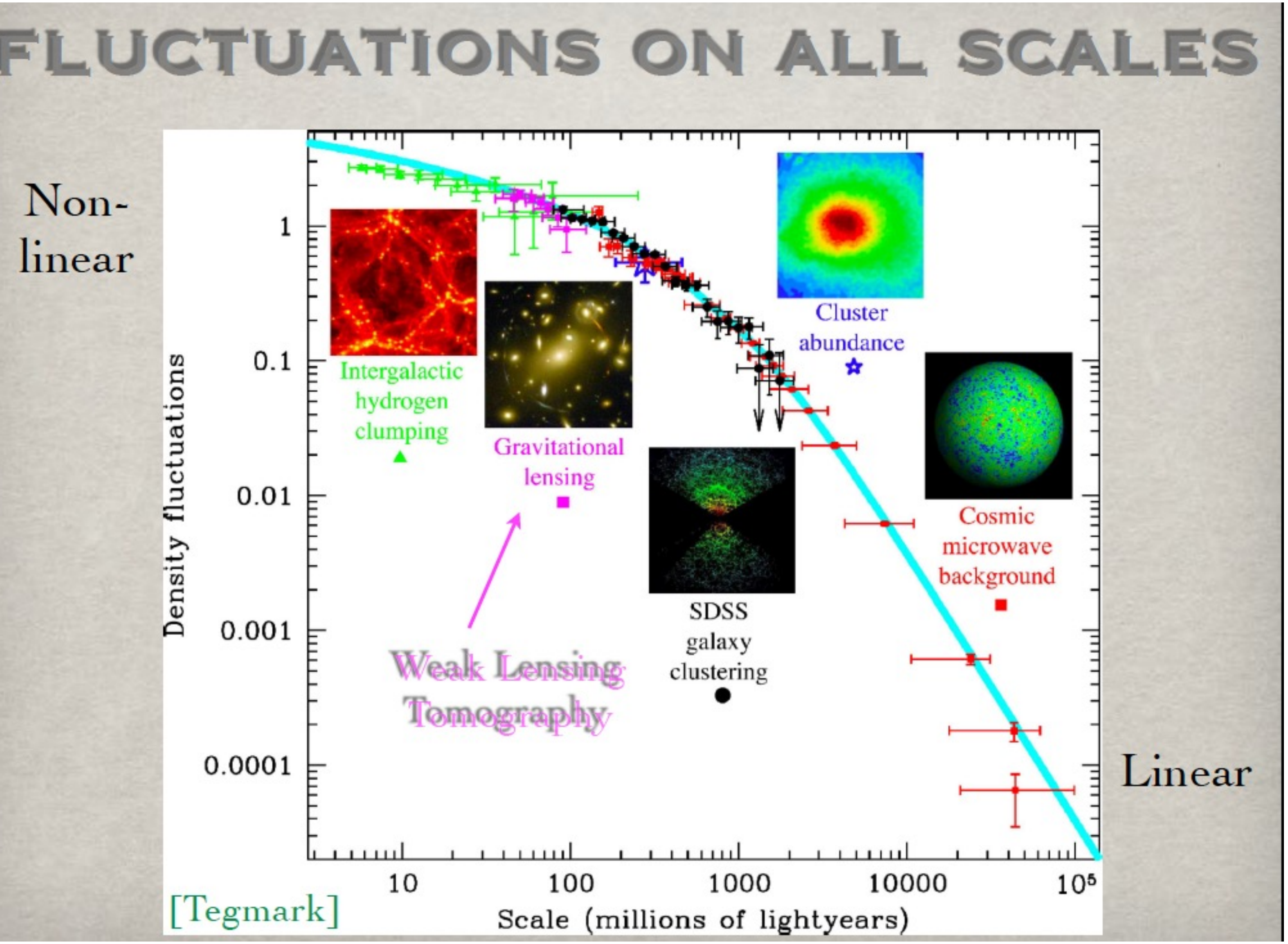
from Big Bang Nucleosynthesis and CMB



from CMB + LSS + ...

$$\Omega_K = 0.0007 \pm 0.0019$$

EVIDENCES FOR A CONSPICUOUS AMOUNT OF NON-BARYONIC DM AT SEVERAL (VERY) DIFFERENT LENGTH SCALES



Dynamics of galaxy clusters

Rotational curves of galaxies

Gravitational lensing

Structure formation from primordial density fluctuations

CMB spectrum → Energy density budget

What's dark matter?

"I can't tell you what's in the dark matter sandwich. No one knows what's in the dark matter sandwich."

But, at least , we know **what CANNOT BE in the DM sandwich:**

NO SM PARTICLE CAN BE THE DOMINANT SOURCE OF DM

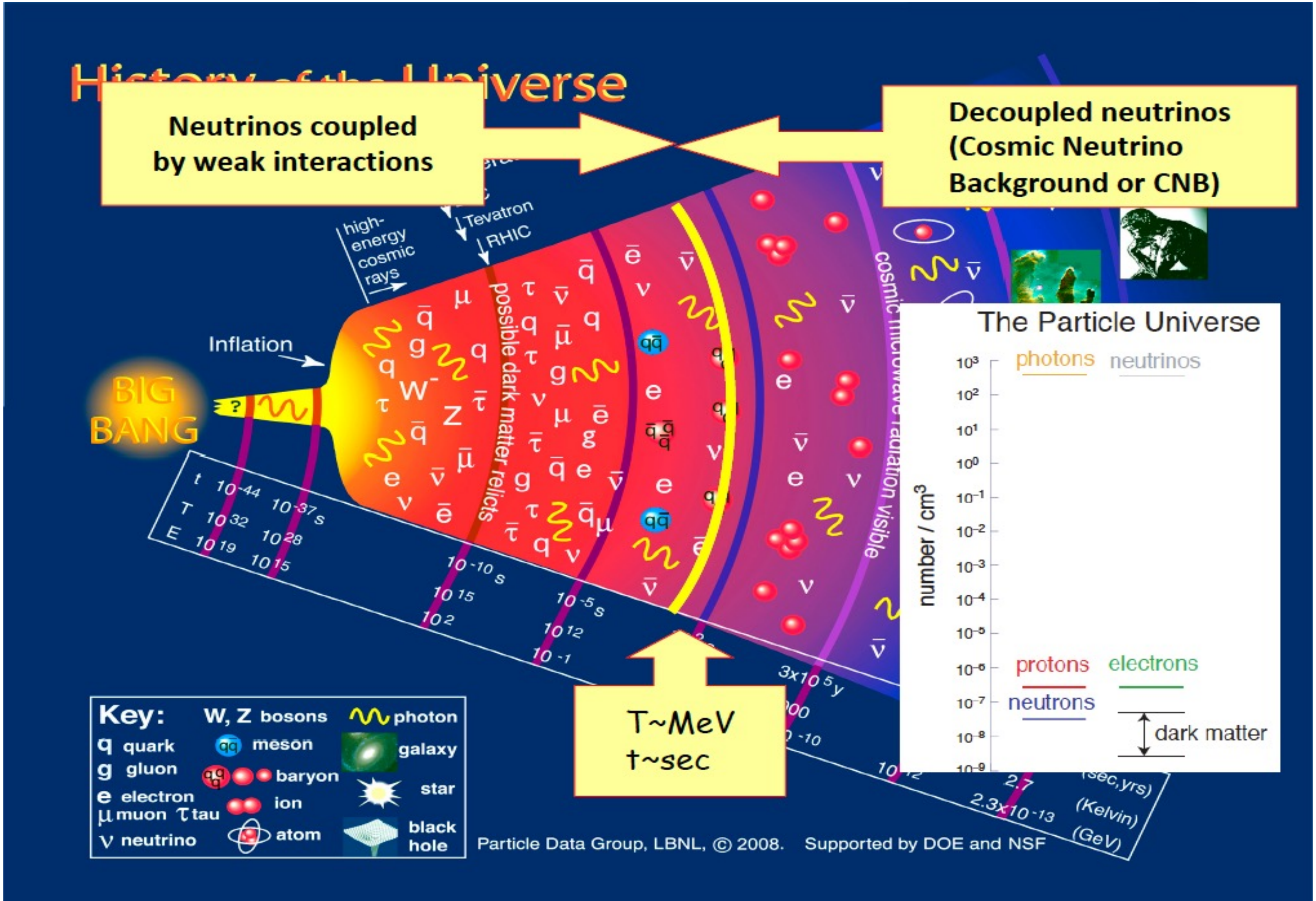
DARK MATTER PROPERTIES

- Interacts very weakly, but surely gravitationally (electrically neutral, non-baryonic and decoupled from the primordial plasma !!!)
- It must have the right density profile to "fill in" the galaxy rotation curves, i.e. non-dissipative.
- No pressure and negligible free-streaming velocity, it must cluster & cause structure formation.

COLD DARK MATTER

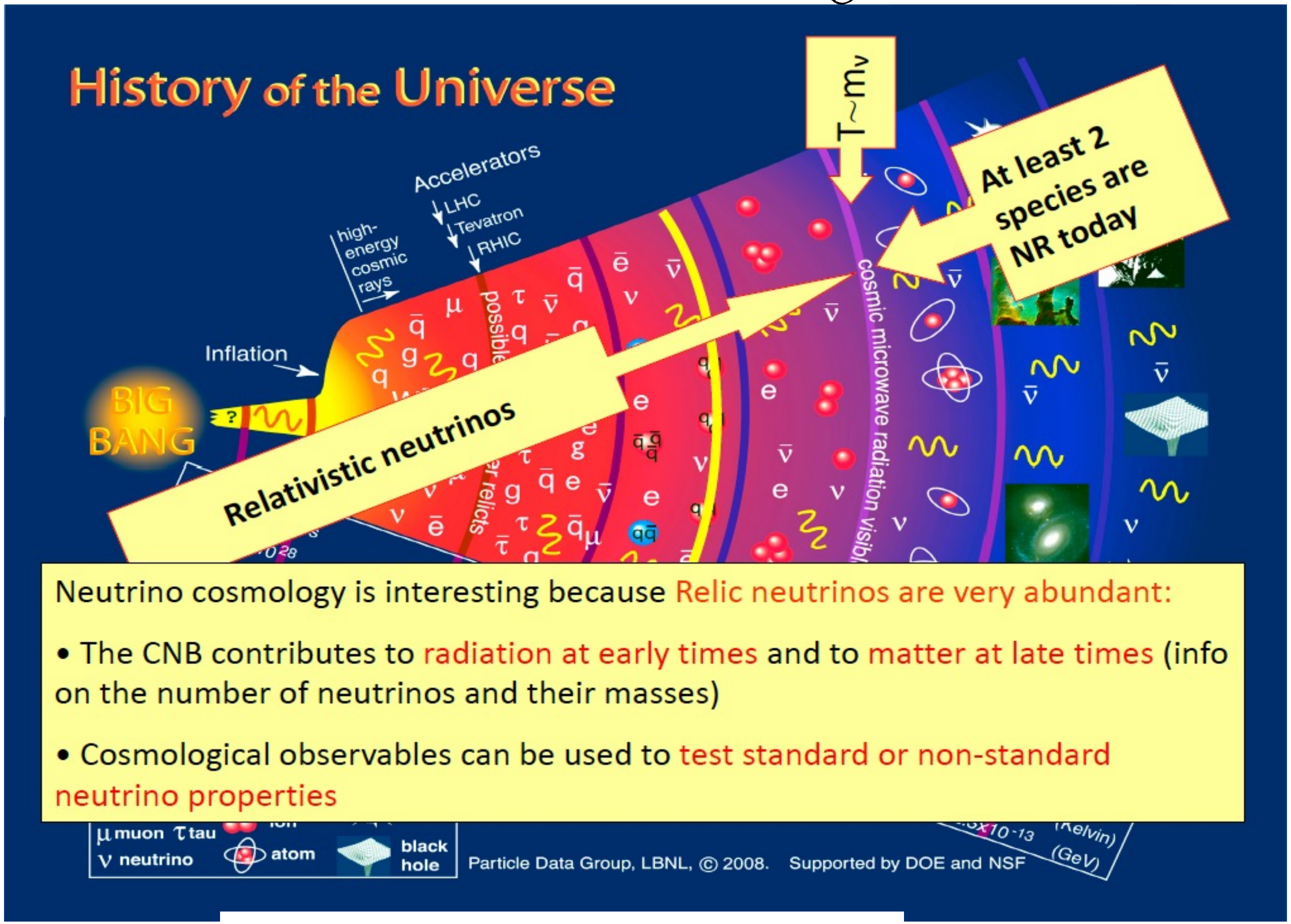
But unfortunately too many realizations !

The role of neutrinos in the Early Universe



S. Pastor, Erice School 2024

The role of neutrinos in the Early Universe



Neutrino cosmology is interesting because Relic neutrinos are very abundant:

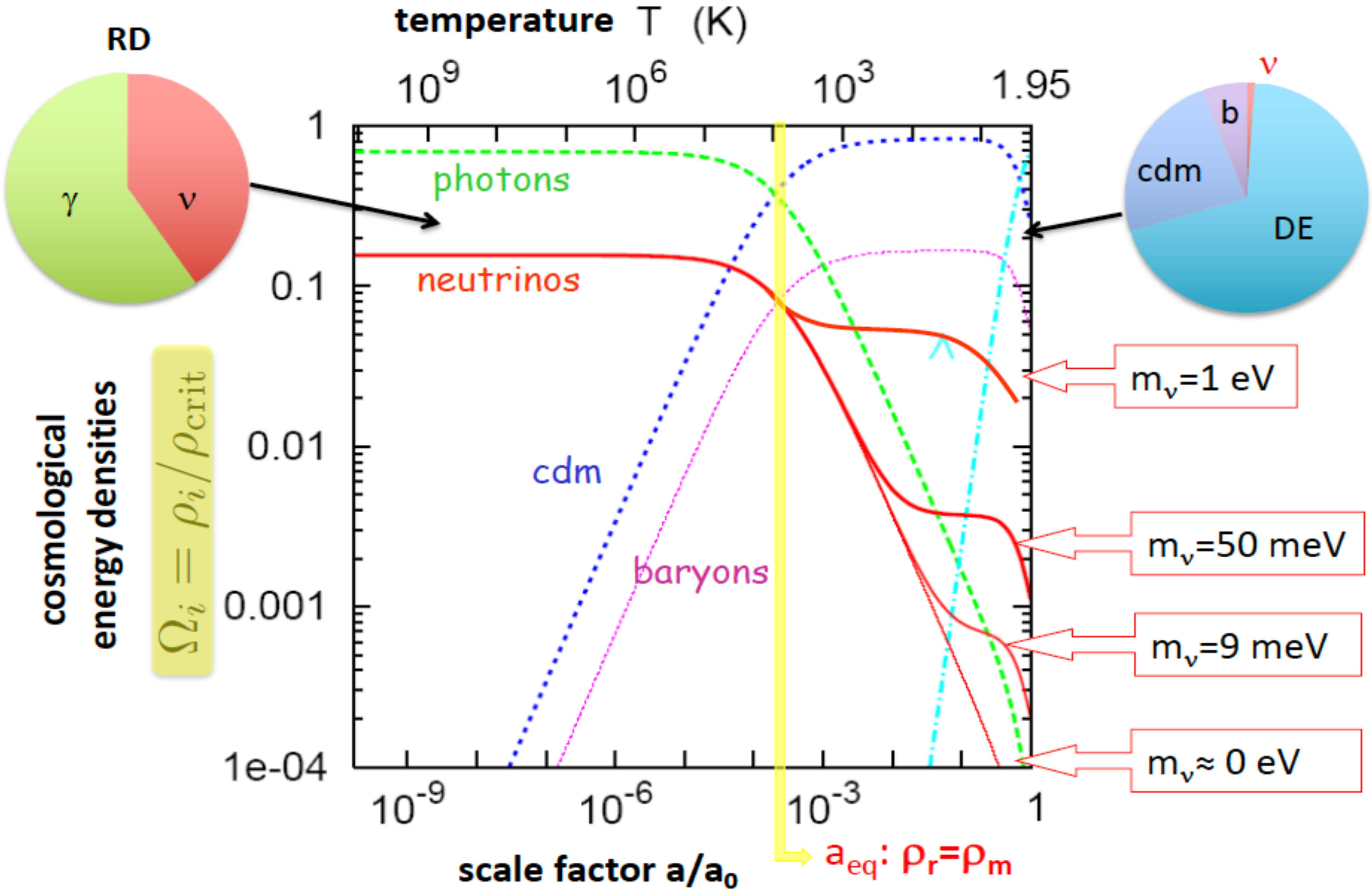
- The CNB contributes to radiation at early times and to matter at late times (info on the number of neutrinos and their masses)
- Cosmological observables can be used to test standard or non-standard neutrino properties

$$0.05(0.09)\ \mathrm{eV} \lesssim \sum_i m_i \lesssim 2.4\ \mathrm{eV}$$

oscillations KATRIN

S. Pastor, Erice School 2024

Evolution of the background densities: 1 MeV → now



Neutrinos as Dark Matter

S. Pastor Erice 2024

- Neutrinos are natural DM candidates

$$\Omega_\nu h^2 = \frac{\sum_i m_i}{93.2\ \mathrm{eV}} \qquad \Omega_\nu < 1 \rightarrow \sum_i m_i \lesssim 46\ \mathrm{eV}$$

$$\Omega_\nu < \Omega_m \simeq 0.3 \rightarrow \sum_i m_i \lesssim 15\ \mathrm{eV}$$

HOWEVER…

- They stream freely until non-relativistic (collisionless phase mixing) $\Rightarrow$ **Neutrinos are HOT Dark Matter** (large thermal motion)

- First structures to be formed when Universe became matter –dominated are very large

- Ruled out by structure formation $\Rightarrow$ CDM

Massive Neutrinos can still be subdominant DM: limits on m_ν from Structure Formation (combined with other cosmological data)

DM: THERMAL and NON-THERMAL RELICS

THERMAL $\rightarrow$ for some time in thermal equilibrium $\downarrow$ thermodynamic eq. distribution

NON-THERMAL $\rightarrow$ never in thermal eq. $\downarrow$ always decoupled, no info on their distrib.

DM: COLD and HOT THERMAL RELICS

X part. $\quad \xrightarrow{\quad M_X \qquad\qquad T_X^{\text{decoupling}} \quad} T\downarrow \quad$ COLD

" " $\quad \xrightarrow{\quad T_X^{\text{decoupl.}} \qquad\qquad M_X \quad} T\downarrow \quad$ HOT

ex. ν: $\quad \mathcal{O}(1\,\text{MeV}) \qquad m_\nu < 1\,\text{eV}$

MATTER-RADIATION EQUALITY at $T_{eq} \sim \mathcal{O}(1\,\text{eV})$

$\xrightarrow{\ 1\,\text{eV}\ (T_{eq}) \qquad M_X\ } T\downarrow$ HOT DM $\qquad \xrightarrow{\ M_X \qquad 1\,\text{eV} \qquad \text{COLD DM}\ } T$

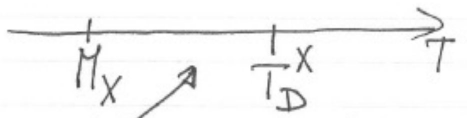
from large structures $\Longrightarrow$ strong bounds on the hot component of DM $\Rightarrow$ most of the DM must be COLD

HOT DM can be only a small component of the whole DM $\rightarrow$ ν cannot be the dominant source of DM !

THERMAL X (in thermal equil.)

case of STABLE HEAVY PARTICLE X

COMPUTATION OF $\Omega_X h^2$ under the assumption



at $T < M_X$ $\quad n_X^{eq} = g_X \left(\frac{M_X T}{2\pi}\right)^{3/2} e^{-M_X/T}$

number of X (in a comoving volume) changes only because of pair annihilation $\rightarrow$ light part.

or viceversa $\leftarrow$ pair creation

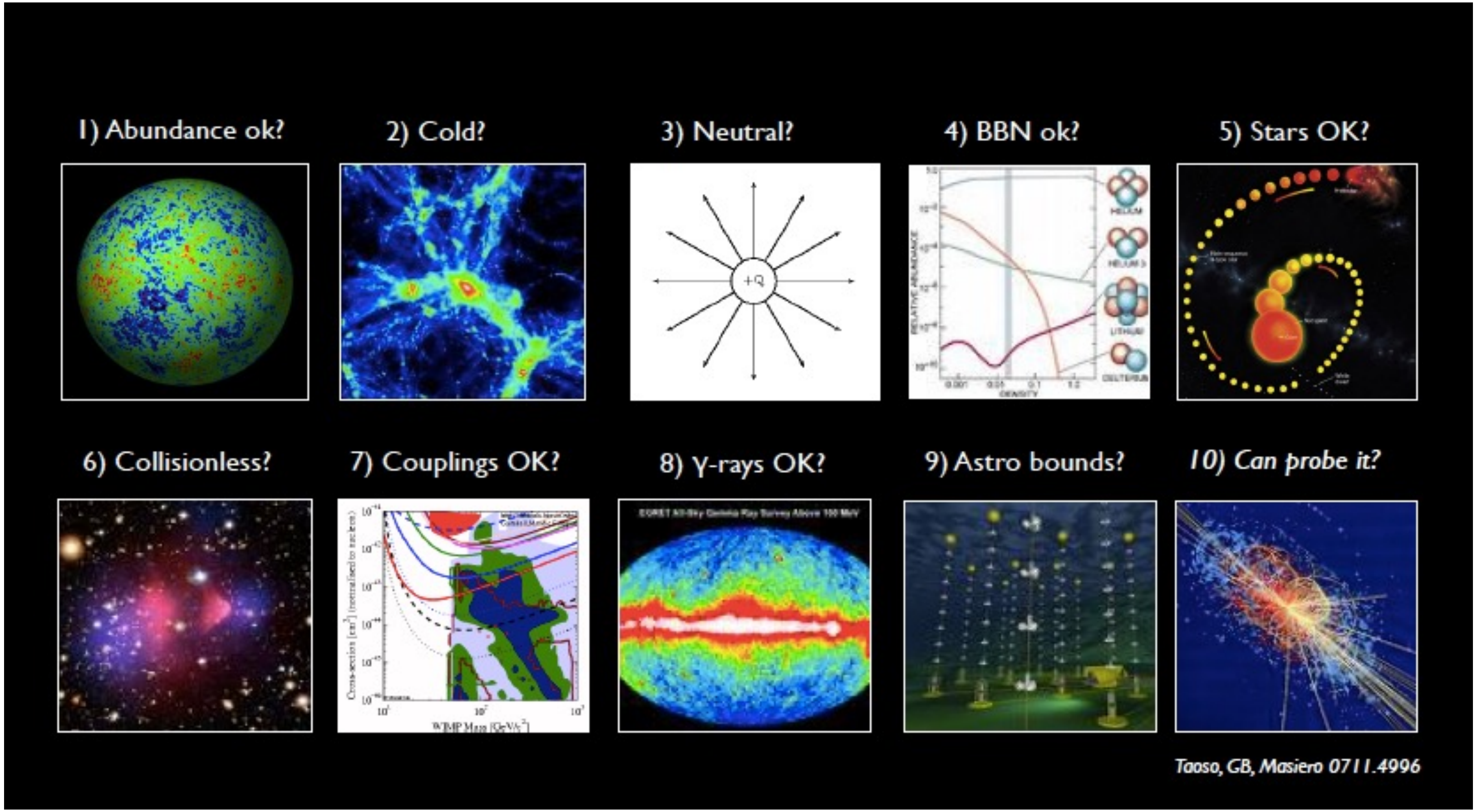
$X\bar{X} \rightarrow$ light part. $\qquad$ light part $\rightarrow X\bar{X}$

TEN COMMANDMENTS TO BE A "GOOD" DM CANDIDATE

BERTONE, A.M., TAOSO

- TO MATCH THE APPROPRIATE RELIC DENSITY
- TO BE COLD
- TO BE NEUTRAL
- TO BE CONSISTENT WITH BBN
- TO LEAVE STELLAR EVOLUTION UNCHANGED
- TO BE COMPATIBLE WITH CONSTRAINTS ON SELF – INTERACTIONS
- TO BE CONSISTENT WITH DIRECT DM SEARCHES
- TO BE COMPATIBLE WITH GAMMA – RAY CONSTRAINTS
- TO BE COMPATIBLE WITH OTHER ASTROPHYSICAL BOUNDS
- "TO BE PROBED EXPERIMENTALLY"

The Ten Commadments to respect to be a "good" DM candidate



NONE OF THE SM PARTICLES CAN BE A GOOD DM CANDIDATE !

DM: the most impressive evidence at the "quantitative" and "qualitative" levels of **New Physics beyond SM**

- QUANTITATIVE: Taking into account the latest WMAP data which in combination with LSS data provide stringent bounds on Ω_{DM} and Ω_B $\longrightarrow$ **EVIDENCE FOR NON-BARYONIC DM AT MORE THAN 10 STANDARD DEVIATIONS!! THE SM DOES NOT PROVIDE ANY CANDIDATE FOR SUCH NON-BARYONIC DM**

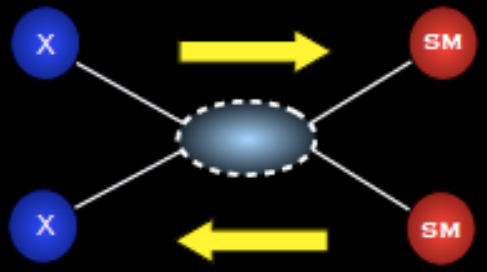
- QUALITATIVE: it is NOT enough to provide a mass to neutrinos to obtain a valid DM candidate; LSS formation requires DM to be COLD $\longrightarrow$ **NEW PARTICLES NOT INCLUDED IN THE SPECTRUM OF THE FUNDAMENTAL BUILDING BLOCKS OF THE SM !**

DM and ELW. SYMMETRY BREAKING

***THE DM ROAD TO NEW PHYSICS BEYOND THE SM*:**

IS **DM** A PARTICLE OF THE ***NEW PHYSICS AT THE ELECTROWEAK ENERGY SCALE*** **?**

The WIMP paradigm is based on a simple yet powerful idea:

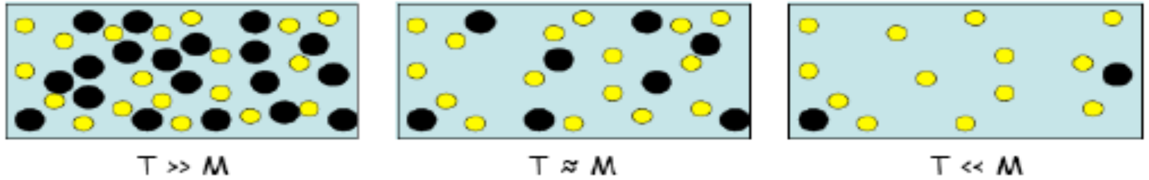


$$\frac{dn_\chi}{dt} - 3Hn_\chi = -\langle\sigma v\rangle \left[n_\chi^2 - (n_\chi^{eq})^2\right]$$

Weak-scale cross sections can reproduce observed relic density

$$\Omega h^2 \approx \frac{3 \times 10^{-27} cm^3 s^{-1}}{< \sigma v >}$$

'WIMP miracle': new physics at ~1TeV solves at same time fundamental problems of particle physics (*hierarchy problem*) AND DM



WIMPS (Weakly Interacting Massive Particles)

$\#\chi$ $\exp(-m\chi/T_\chi)$

$\#\chi \sim \#\gamma$ m_χ

$\#\chi$ does not change any more

$T_{decoupl.}$ typically ~ m_χ /20

Ω_χ depends on particle physics ($\sigma_{annih.}\chi$) and "cosmological" quantities (H, T_0, …

$$\Omega\chi\, h^2 \simeq \frac{10^{-3}}{\underbrace{<(\sigma_{annih.})\, V\chi>}_{\sim\, \alpha^2 / M^2_\chi}\ \mathrm{TeV}^2}$$

TeV² → From $T^0\, M_{Planck}$

COSMO – PARTICLE CONSPIRACY

$\Omega\chi h^2$ in the range 10^{-2} -10^{-1} to be cosmologically interesting (for DM)

$m\chi \sim 10^2 - 10^3$ GeV (weak interaction) $\Omega\chi h^2 \sim 10^{-2}$ -10^{-1} !!!

THERMAL RELICS (WIMP in thermodyn.equilibrium with the plasma until $T_{decoupl}$)

ROADS TO GO BEYOND THE STANDARD MODEL (I)

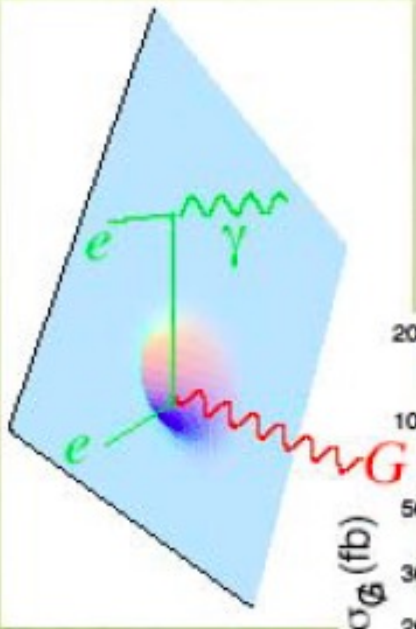
1) **THERE EXISTS NO NEW PHYSICAL ENERGY SCALE ABOVE THE ELW. SCALE**: gravity is an extremely weak force not because of the enormous value of the Planck scale, but because of the existence of **NEW DIMENSIONS** beyond the usual 3+1 space-time where (most of) the gravity flux lines get "dispersed"

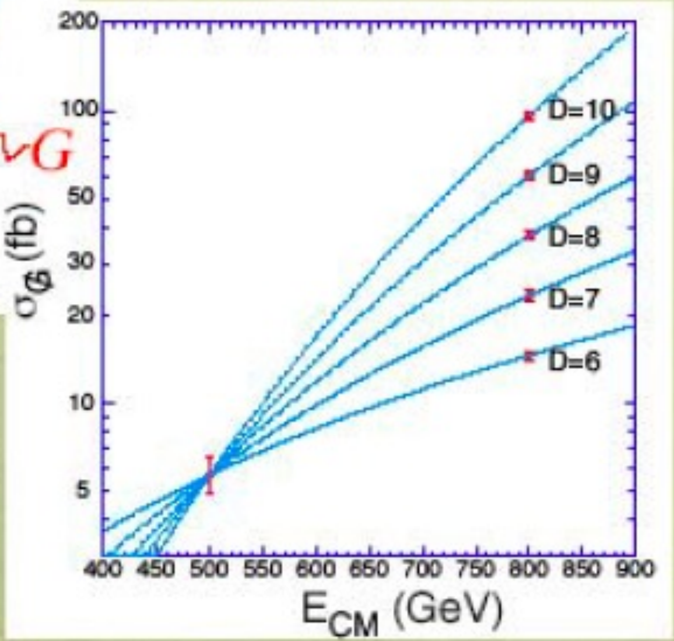
→ **VISIBILITY AT LHC**: there exist "excited" states of the ordinary particles (**Kaluza-Klein states**) and some of them are accessible at LHC (the lightest KK state may be a stable particle and it can constitute the DM)

Hidden Dimensions

- *Hidden dimensions*
- *Can emit graviton into the bulk*
- *Events with apparent energy imbalance*

How many extra dimensions are there?





ROADS TO GO BEYOND THE STANDARD MODEL (II)

- 2) NO NEED TO "PROTECT" THE HIGGS MASS AT THE ELW. SCALE: THE HIGGS IS A COMPOSITE OBJECT (for instance, a fermion condensate) WHOSE COMPOSITENESS SCALE IS THE ELW. SCALE (cfr. the pion mass case)

$\longrightarrow$ VISIBILITY AT LHC: THERE EXIST NEW (STRONG) INTERACTIONS AT THE ELW. SCALE WHICH PRODUCE THE HIGGS CONDENSATE (new resonances,, new bound states, a new rescaled QCD at 1 TeV)

ROADS TO GO BEYOND THE STANDARD MODEL (III)

- **3) THE MASS OF THE ELEMENTARY HIGGS BOSON IS "PROTECTED" AT THE ELW. SCALE BECAUSE OF THE PRESENCE AT THAT ENERGY OF A NEW SYMMETRY, THE SUPERSYMMETRY (SUSY)**

  → **VISIBILITY AT LHC**: WE'LL SEE (SOME OF) THE **SUSY PARTICLES AND THEIR INTERACTIONS**. THE LIGHTEST SUSY PARTCILE (**LSP**) IS LIKELY TO BE STABLE AND PROVIDE THE **DM**. **AT THE SAME TIME, WE COULD DISCOVER SUSY AND THE SOURCE OF 90% OF THE ENTIRE MATTER PRESENT IN THE UNIVERSE.**

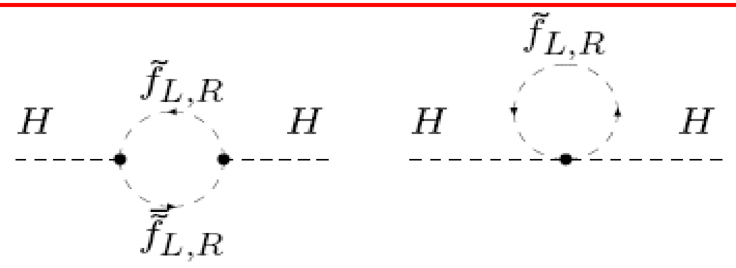
THE SUSY PATH

$$Q\,|\,boson> = |\,fermion> \qquad Q\,|\,fermion> = |\,boson>$$

$$[b,b]=0, \quad \{f,f\}=0 \;\Rightarrow \qquad \{Q^i_\alpha, \bar{Q}^j_{\dot\beta}\} = 2\delta^{ij}(\sigma^\mu)_{\alpha\dot\beta}P_\mu$$

Effectively: SM particles have SUSY partners (e.g. $f_{L,R} \to \tilde{f}_{L,R}$)

SUSY: additional contributions from scalar fields:



$$\Sigma_H^{\tilde{f}} \sim N_{\tilde{f}}\,\lambda_{\tilde{f}}^2 \int d^4k \left(\frac{1}{k^2 - m_{\tilde{f}_L}^2} + \frac{1}{k^2 - m_{\tilde{f}_R}^2}\right) + \text{ terms without quadratic div.}$$

for $\Lambda \to \infty$: $\quad \Sigma_H^{\tilde{f}} \sim N_{\tilde{f}}\,\lambda_{\tilde{f}}^2\,\Lambda^2$

$\Rightarrow$ quadratic divergences cancel for

$$N_{\tilde{f}_L} = N_{\tilde{f}_R} \;=\; N_f$$
$$\lambda^2_{\tilde{f}} \;=\; \lambda^2_f$$

complete correction vanishes if furthermore

$$m_{\tilde{f}} = m_f$$

Soft SUSY breaking: $m^2_{\tilde{f}} = m^2_f + \Delta^2, \quad \lambda^2_{\tilde{f}} = \lambda^2_f$

$$\Rightarrow \Sigma_H^{f+\tilde{f}} \sim N_f \, \lambda^2_f \, \Delta^2 + \ldots$$

$\Rightarrow$ correction stays acceptably small if mass splitting is of weak scale

$\Rightarrow$ realized if mass scale of SUSY partners

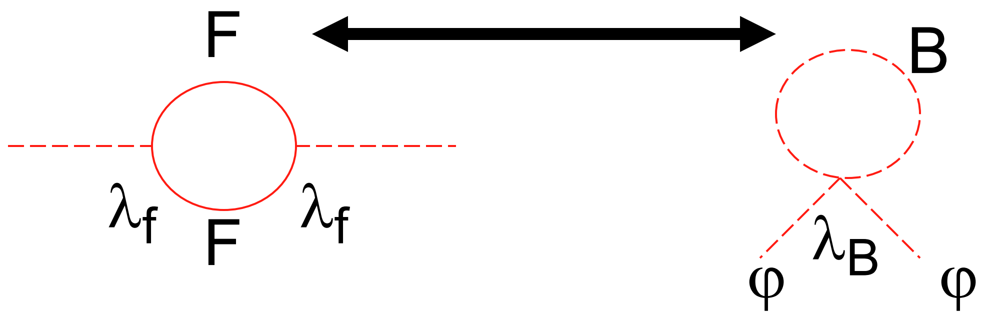
$$M_{\mathrm{SUSY}} \lesssim 1\,\mathrm{TeV}$$

$\boxed{\Rightarrow \text{SUSY at TeV scale provides attractive solution of hierarchy problem}}$

HIERARCHY PROBLEM: THE SUSY WAY

SUSY HAS TO BE BROKEN AT A SCALE CLOSE
TO 1TeV $\longrightarrow$ LOW ENERGY SUSY

$m_\varphi^2 \propto \Lambda^2$ $\longrightarrow$ Scale of susy breaking



$$\delta m^2_\varphi \sim \frac{(\lambda_B - \lambda^2_f)}{16\,\pi^2}\,\Lambda^2$$

$\longrightarrow$ $[m^2_B - m^2_F]^{1/2} \sim 1/\sqrt{G_F}$

$\begin{pmatrix} B \\ F \end{pmatrix}$ In SUSY multiplet

SPLITTING IN MASS BETWEEN B and F of O (ELW. SCALE)

Simplest (N=1) SUSY Multiplets

Bosons and Fermions come in pairs

$$(\varphi, \psi) \qquad (\lambda, A_\mu) \qquad (\tilde{g}, g)$$

Spin 0 Spin 1/2 Spin 1/2 Spin 1 Spin 3/2 Spin 2

scalar chiral fermion majorana fermion vector gravitino graviton

D. KAZAKOV

Particle Content of the MSSM

Superfield	*Bosons*	*Fermions*	$SU_c(3)$	$SU_L(2)$	$U_Y(1)$
Gauge					
G^a	*gluon* g^a	*gluino* $\tilde{g}^a$	8	1	0
V^k	*Weak* $W^k(W^\pm, Z)$	*wino, zino* $\tilde{w}^k(\tilde{w}^\pm, \tilde{z})$	1	3	0
V'	*Hypercharge* $B(\gamma)$	*bino* $\tilde{b}(\tilde{\gamma})$	1	1	0
Matter					
L_i	sleptons $\tilde{L}_i = (\tilde{\nu}, \tilde{e})_L$	leptons $L_i = (\nu, e)_L$	1	2	-1
E_i	sleptons $\tilde{E}_i = \tilde{e}_R$	leptons $E_i = e_R$	1	1	2
Q_i	squarks $\tilde{Q}_i = (\tilde{u}, \tilde{d})_L$	quarks $Q_i = (u, d)_L$	3	2	$1/3$
U_i	squarks $\tilde{U}_i = \tilde{u}_R$	quarks $U_i = u_R^c$	3^*	1	$-4/3$
D_i	squarks $\tilde{D}_i = \tilde{d}_R$	quarks $D_i = d_R^c$	3^*	1	$2/3$
Higgs					
H_1	Higgses H_1	higgsinos $\tilde{H}_1$	1	2	-1
H_2	Higgses H_2	higgsinos $\tilde{H}_2$	1	2	1

THE FATE OF B AND L IN THE SM AND MSSM

- **IN THE SM B AND L ARE "AUTOMATIC" SYMMETRIES**: NO B or L VIOLATING OPERATOR OF DIM.≤4 INVARIANT UNDER THE GAUGE SIMMETRY SU(3) X SU(2) X U(1) IS ALLOWED (B AND L ARE CONSERVED AT ANY ORDER IN PERTURBATION THEORY, BUT ARE VIOLATED AT THE QUANTUM LEVEL (ONLY B – L IS EXACTLY PRESERVED)
- **IN THE MSSM**, THANKS TO THE EXTENDED PARTICLE SPECTRUM WITH NEW SUSY PARTNERS CARRYING B AND L, **IT IS POSSIBLE TO WRITE (RENORMALIZABLE) OPERATORS WHICH VIOLATE EITHER B OR L**
- $\longrightarrow$ IF BOTH B AND L VIOLATING OPERATORS ARE PRESENT, GIVEN THAT SUSY PARTNER MASSES ARE OF O(TEV), THERE IS NO WAY TO PREVENT A **TOO FAST PROTON DECAY** UNLESS THE YUKAWA COUPLINGS ARE INCREDIBLY SMALL!

ADDITIONAL DISCRETE SYMMETRY IN THE MSSM TO SLOW DOWN P - DECAY

- SIMPLEST (and nicest) SOLUTION: ADD A SYMMETRY WHICH **FORBIDS ALL B AND L VIOLATING OPERATORS**

  → **R PARITY**

- SINCE B AND L 4-DIM. OPERATORS INVOLVE 2 ORDINARY FERMIONS AND A SUSY SCALAR PARTICLE, THE SIMPLEST WAY TO ELIMINATE ALL OF THEM:

R = +1 FOR ORDINARY PARTICLES

R = - 1 FOR SUSY PARTNERS

IMPLICATIONS OF IMPOSING R PARITY:

i) The superpartners are created or destroyed in pairs;

ii) **THE LIGHTEST SUPERPARTNER IS ABSOLUTELY STABLE**

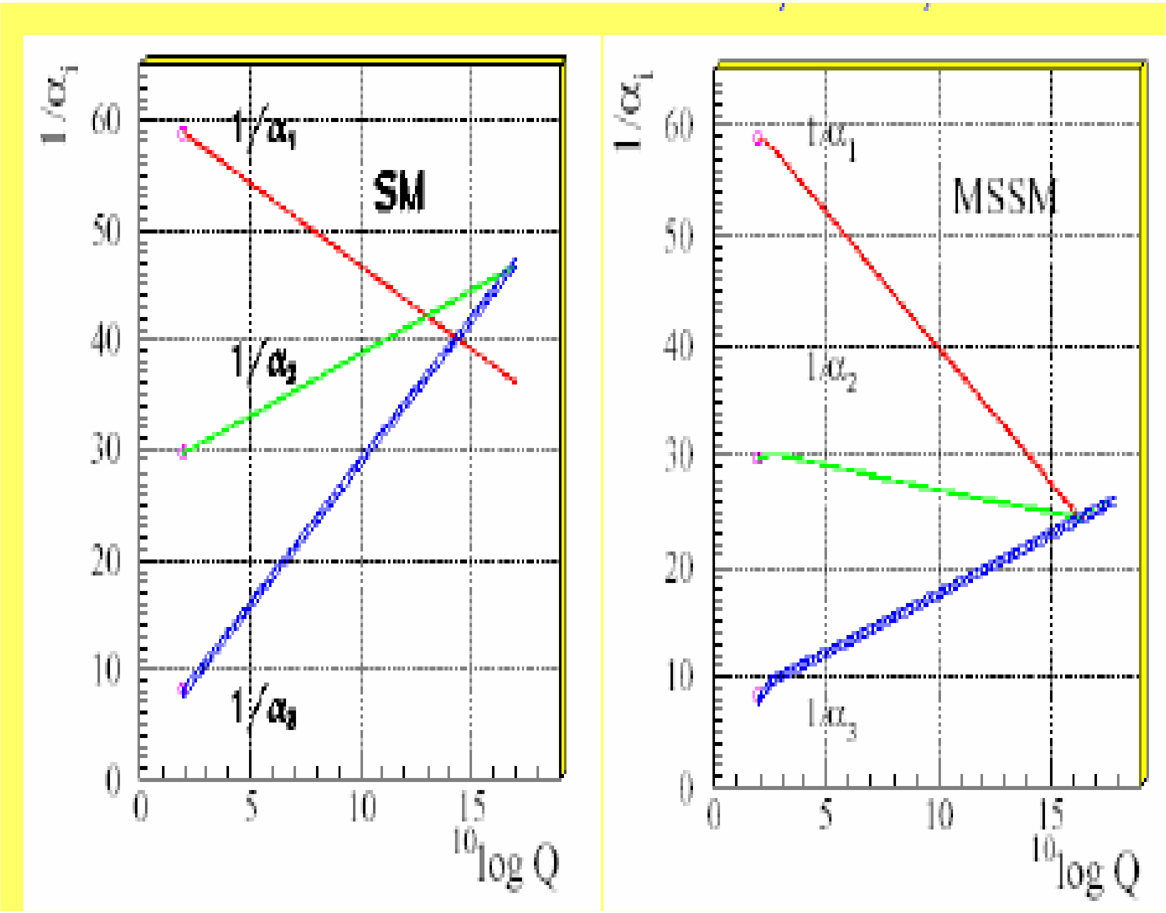
BROKEN R PARITY

- PROTON DECAY REQUIRES THE VIOLATION OF BOTH B AND L

$\longrightarrow$ NOT NECESSARY TO HAVE R PARITY TO KILL B AND L VIOLATING OPERATORS

$\longrightarrow$ ENOUGH TO IMPOSE AN **ADDITIONAL DISCRETE SYMMETRY TO FORBID EITHER B OR L VIOLATING OPERATORS**; RESTRICTIONS ON THE YUKAWA COUPLINGS OF THE SURVIVING B OR L VIOLATING OPERATORS

LOW-ENERGY SUSY AND UNIFICATION



Input

$\alpha^{-1}(M_Z) = 128.978 \pm 0.027$

$\sin^2 \theta_{\overline{MS}} = 0.23146 \pm 0.00017$

$\alpha_s(M_Z) = 0.1184 \pm 0.0031$

Output

$M_{SUSY} = 10^{3.4 \pm 0.9 \pm 0.4}$ GeV

$M_{GUT} = 10^{15.8 \pm 0.3 \pm 0.1}$ GeV

$\alpha_{GUT}^{-1} = 26.3 \pm 1.9 \pm 1.0$

SUSY & DM : a successful marriage

- Supersymmetrizing the SM does not lead necessarily to a stable SUSY particle to be a DM candidate.
- However, the mere SUSY version of the SM is known to lead to a too fast p-decay. Hence, necessarily, the SUSY version of the SM has to be **supplemented with some additional (ad hoc?) symmetry to prevent the p-decay catastrophe.**
- Certainly the simplest and maybe also the most attractive solution is **to impose the discrete R-parity** symmetry
- MSSM + R PARITY $\longrightarrow$ LIGHTEST SUSY PARTICLE (LSP) IS STABLE .
- The LSP can constitute an interesting DM candidate in several interesting realizations of the MSSM (i.e., with different SUSY breaking mechanisms including gravity, gaugino, gauge, anomaly mediations, and in various regions of the parameter space).

WHO IS THE LSP?

- **SUPERGRAVITY** (transmission of the SUSY breaking from the hidden to the obsevable sector occurring via gravitational interactions): best candidate to play the role of LSP:

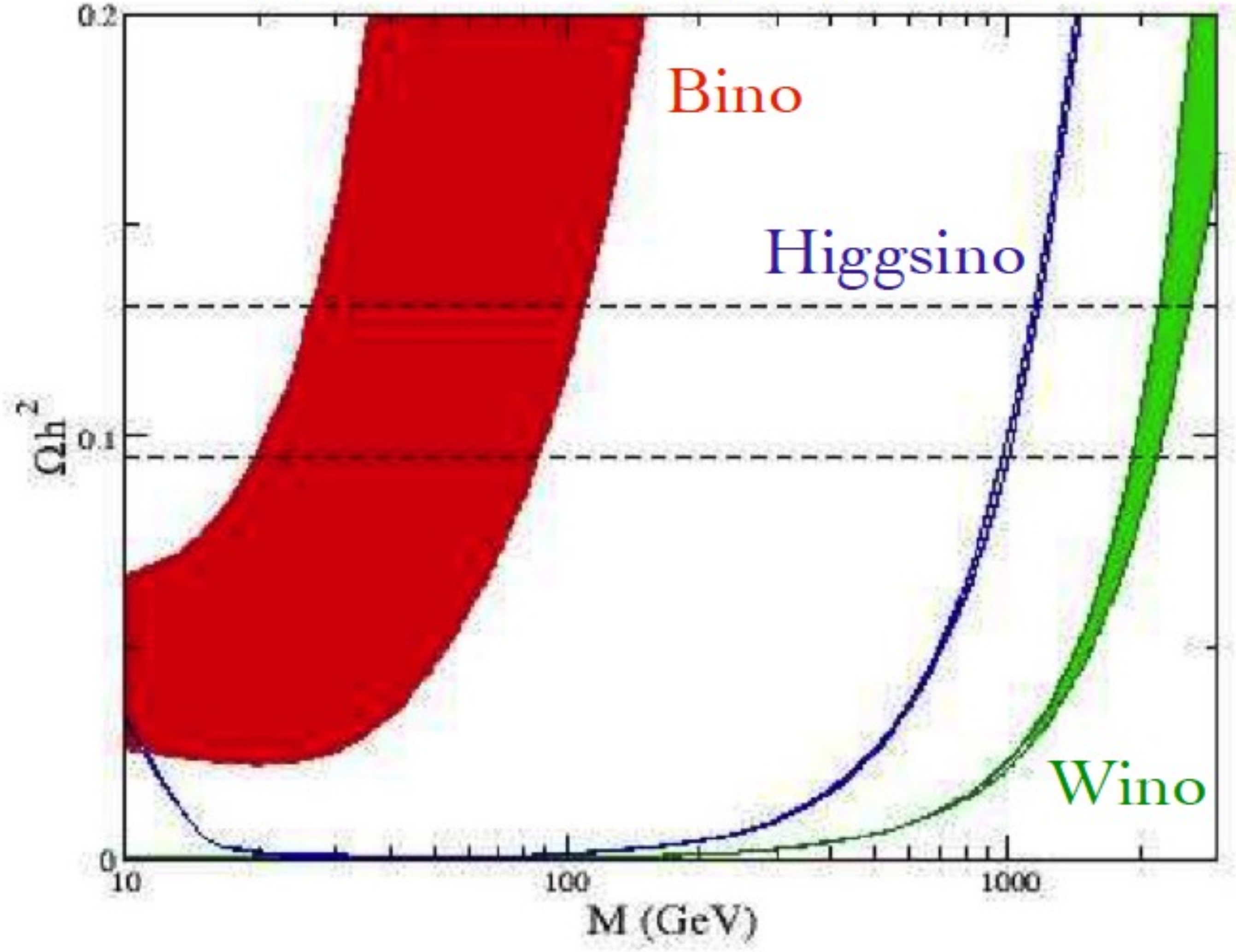
  NEUTRALINO (i.e., the lightest of the four eigenstates of the 4x4 neutralino mass matrix)

In **CMSSM**: the LSP neutralino is almost entirely a BINO

Well-tempered neutralino

Relic density strongly dependent on neutralino nature !!!

[Arkani-Hamed, Delgado & Giudice 0601041]



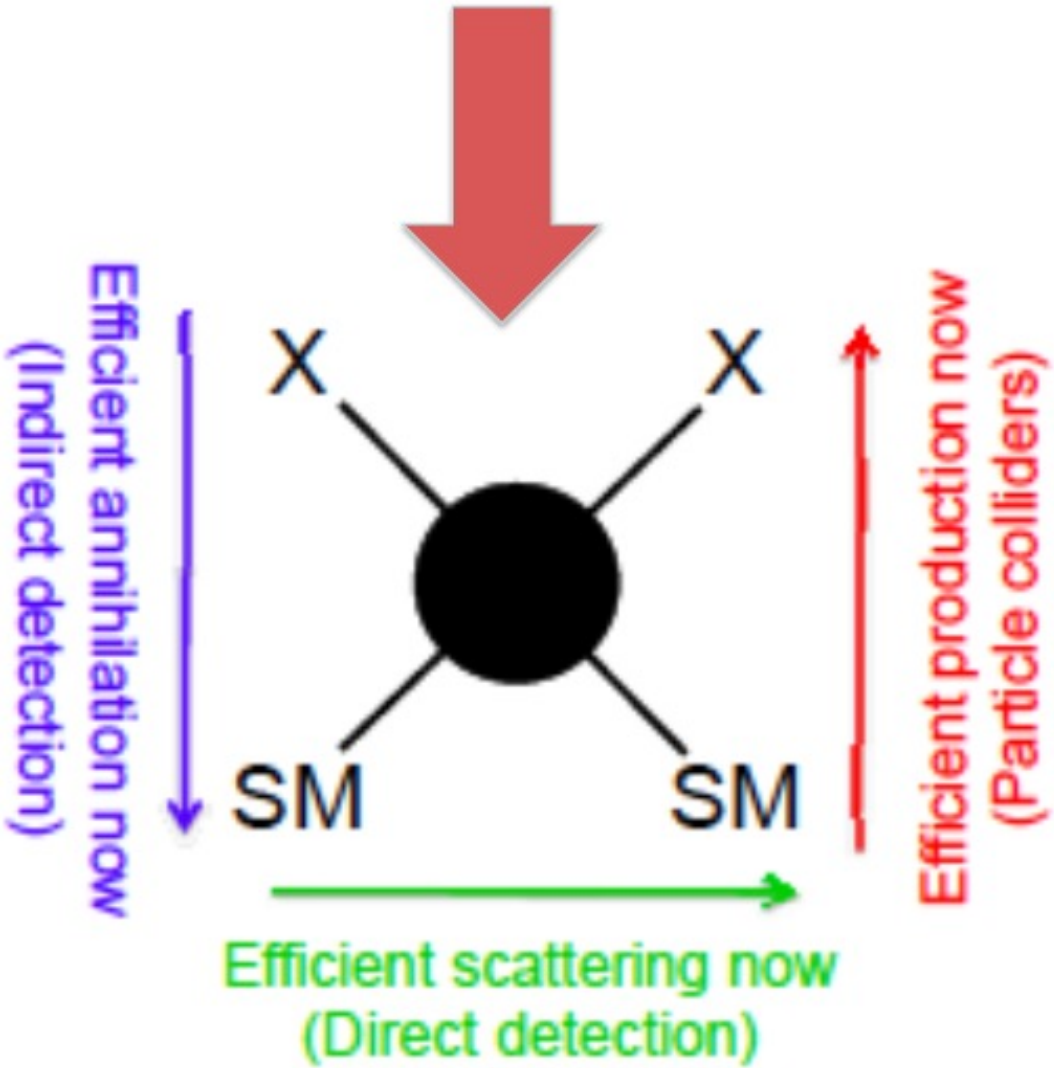
CONNECTION DM – ELW. SCALE

THE WIMP MIRACLE :STABLE ELW. SCALE WIMPs

	SUSY	EXTRA DIM.	LITTLE HIGGS.
1) ENLARGEMENT OF THE SM	(x^μ, θ)	(x^μ, j^i)	SM part + new part
	Anticomm. Coord.	New bosonic Coord.	to cancel Λ^2 at 1-Loop
2) SELECTION RULE	*R-PARITY LSP*	*KK-PARITY LKP*	*T-PARITY LTP*
→ DISCRETE SYMM.	Neutralino spin 1/2	spin1	spin0
→ STABLE NEW PART.			
3) FIND REGION (S) PARAM. SPACE WHERE THE "L" NEW PART. IS NEUTRAL + $\Omega_L h^2$ OK	m_{LSP} ~100 - 200 GeV	m_{LKP} ~600 - 800 GeV	m_{LTP} ~400 - 800 GeV

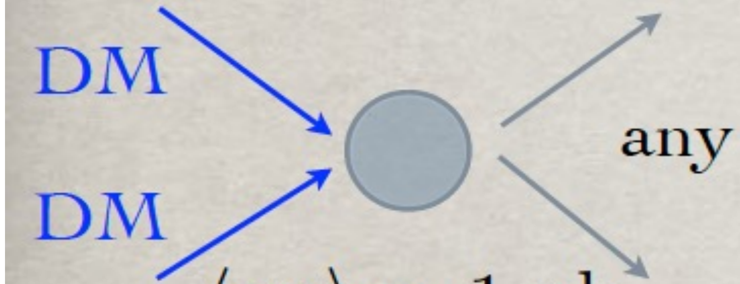
R-parity is an ADDITIONAL discrete symmetry imposed to prevent SUSY particles with masses at the electroweak scale to mediate a too fast proton decay!

DM COMPLEMENTARITY: efficient annihilation in the early Universe implies today



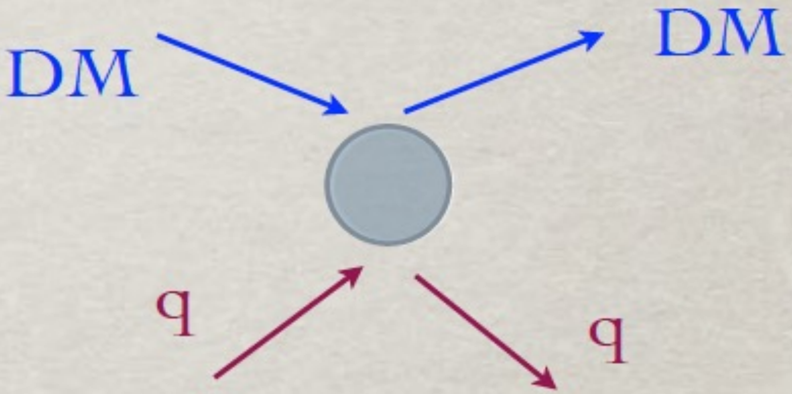
THE WIMP CONNECTION

Early Universe: $\Omega_{CDM} h^2$

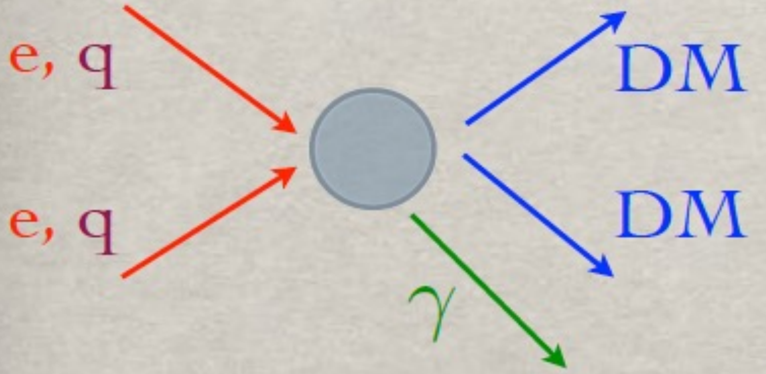


$\langle \sigma v \rangle \sim 1$ pb

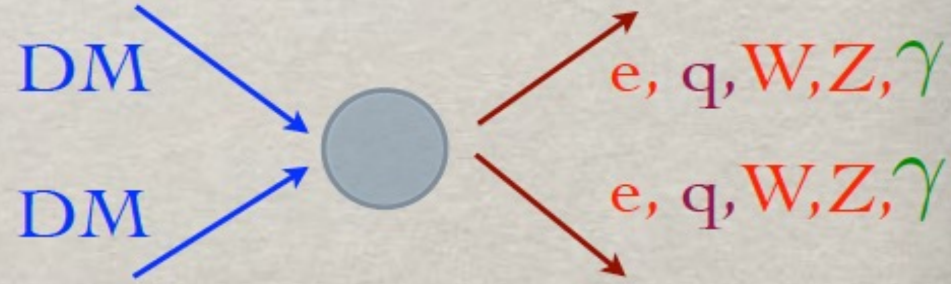
Direct Detection:



Colliders: LHC/ILC



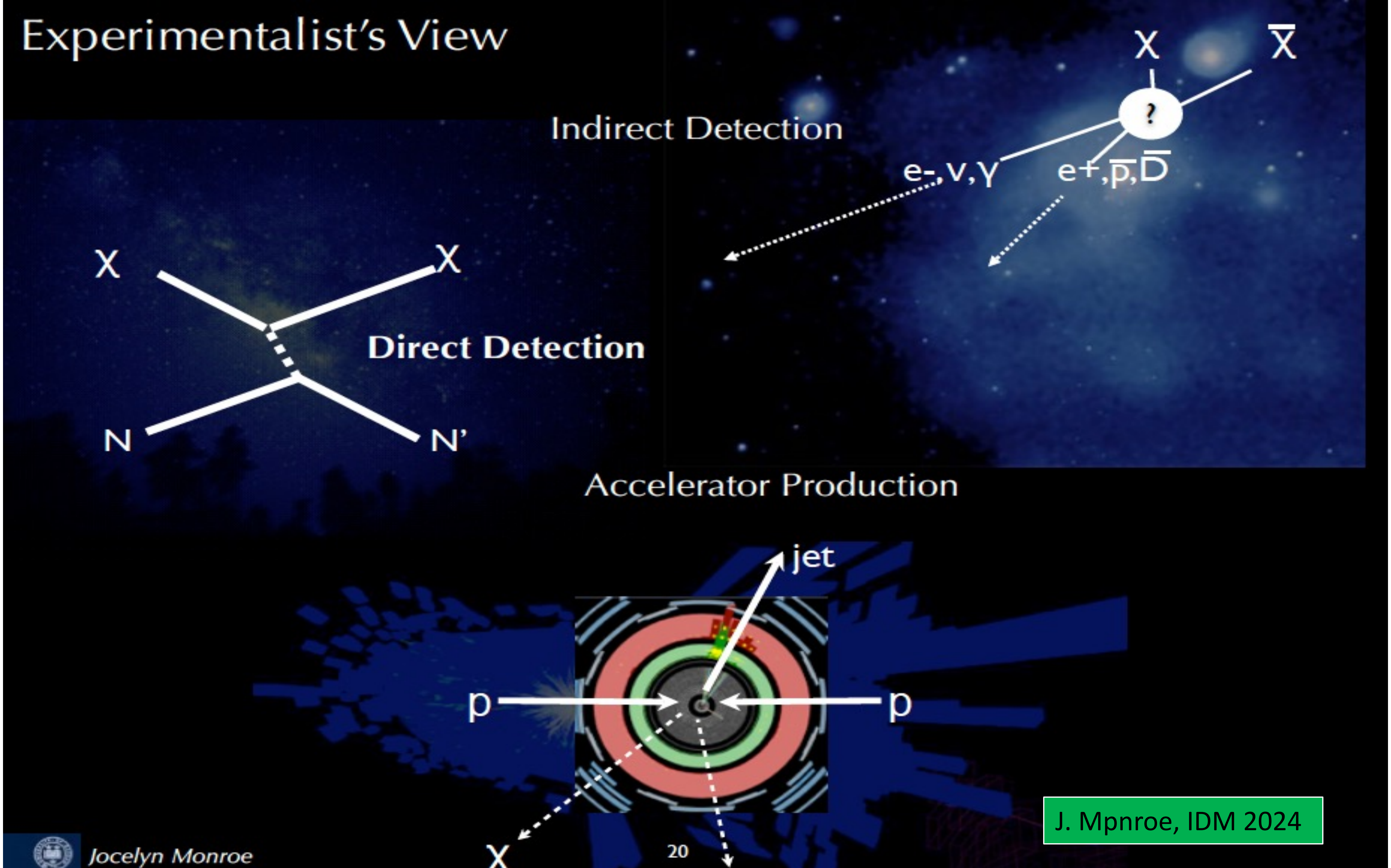
Indirect Detection:



3 different ways to check this hypothesis !!!

L. Covi, Erice 2024

Experimentalist's View



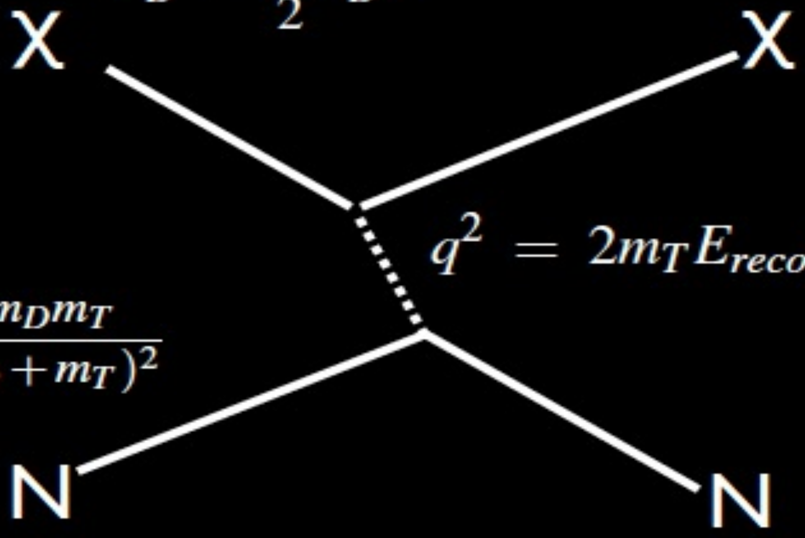
J. Mpnroe, IDM 2024

Direct Detection Strategies

scattering kinematics: $v/c \sim 8E\text{-}4!$

recoil angle strongly correlated
with incoming WIMP direction

$$E_D = \frac{1}{2} m_D v^2$$



$$q^2 = 2 m_T E_{recoil}$$

$$r = \frac{4 m_D m_T}{(m_D + m_T)^2}$$

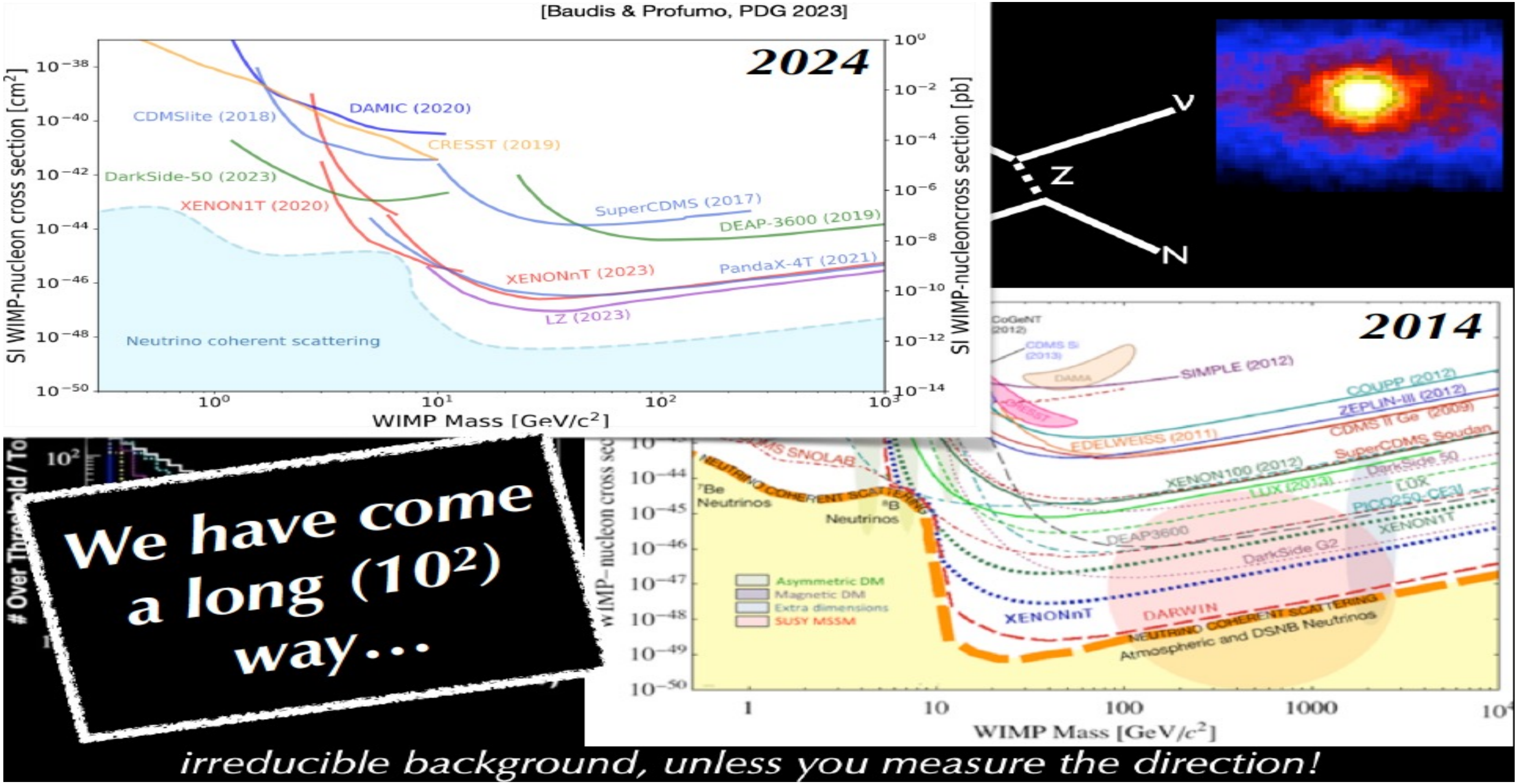
$$E_{recoil} = E_D r \frac{(1 - \cos\theta)}{2}$$

<u>Spin Independent:</u>
χ scatters coherently off of
the entire nucleus A: $\sigma \sim A^2$
D. Z. Freedman, PRD 9, 1389 (1974)

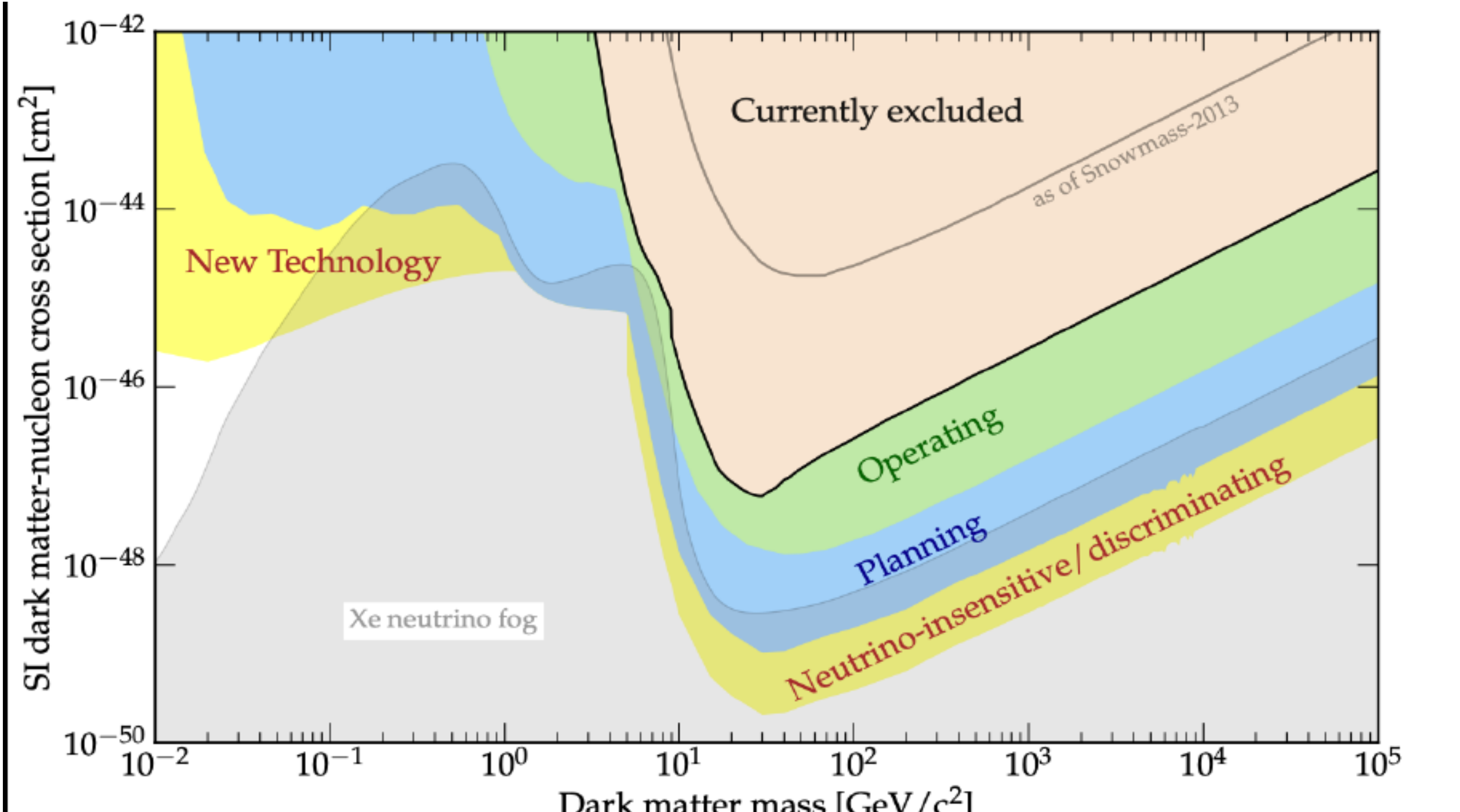
<u>Spin Dependent:</u>
mainly unpaired nucleons contribute
to scattering amplitude: $\sigma \sim J(J+1)$

J. Mpnroe, IDM 2024

(Desperately?) seeking WIMPS



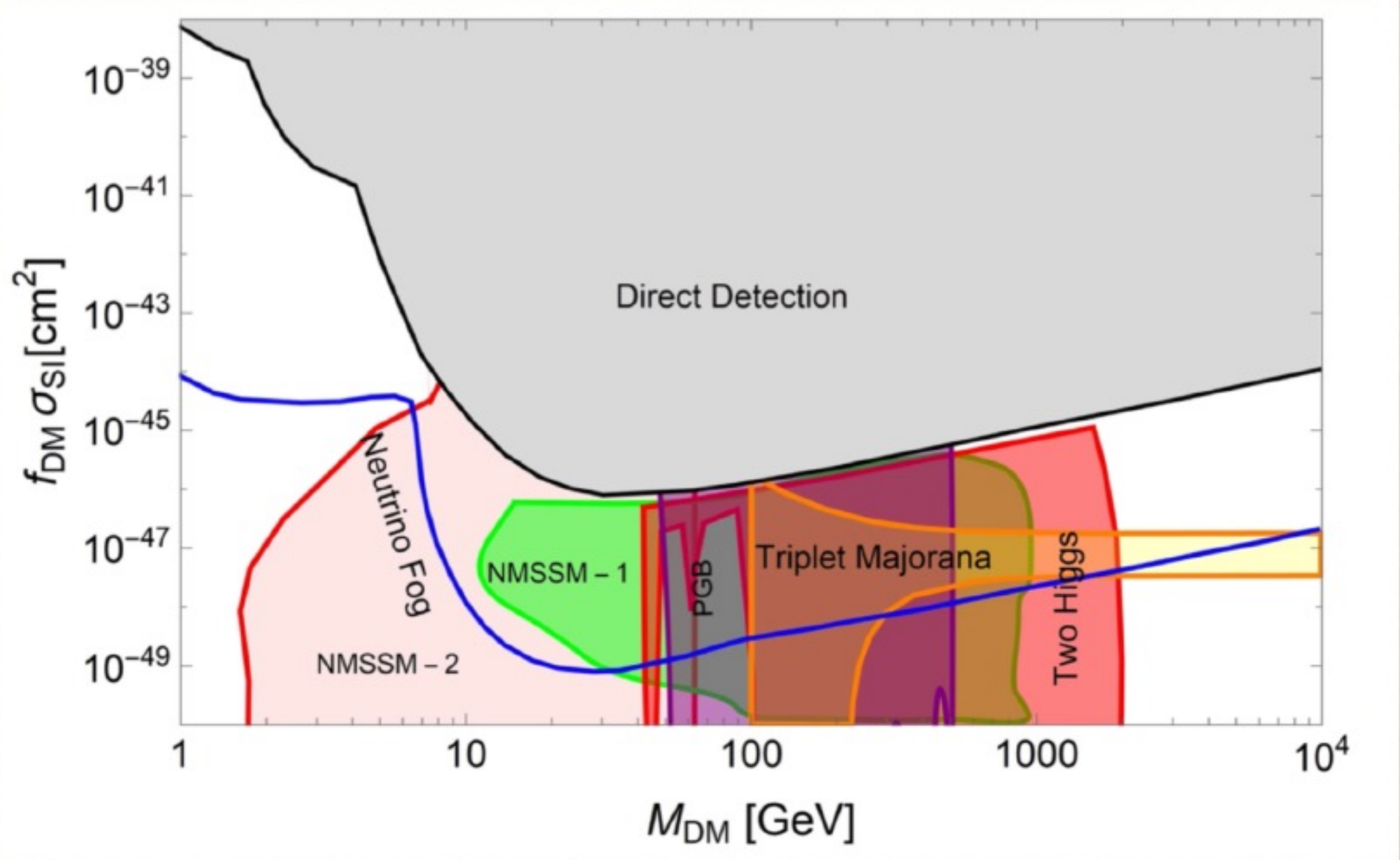
J. Monroe, IDM 2024



Currently excluded
as of Snowmass-2013
New Technology
Operating
Planning
Neutrino-insensitive/discriminating
Xe neutrino fog
SI dark matter-nucleon cross section [cm^2]
Dark matter mass [GeV/c^2]
10^{-42}
10^{-44}
10^{-46}
10^{-48}
10^{-50}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
10^{5}

WIMP Models...
...not yet excluded !

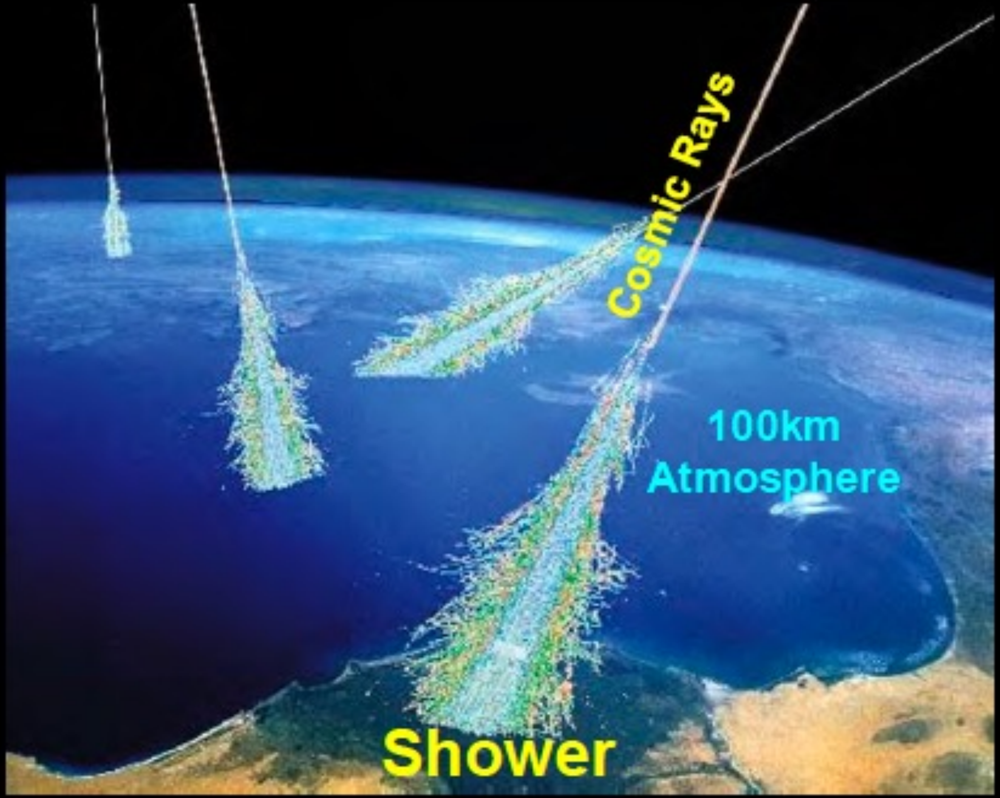
[Snowmass 2021 Cosmic Frontier ArXiv:2203.08084]



AMS on the Space Station

Provides precision, long-duration measurements of charged cosmic rays to study the Origin of the Cosmos, the physics of Dark Matter and of Antimatter

Charged cosmic rays have mass.
They are absorbed by the
100 km of Earth's atmosphere (10m of water).
The properties ($\pm Z$, P) of charged cosmic rays
cannot be studied accurately on the ground.

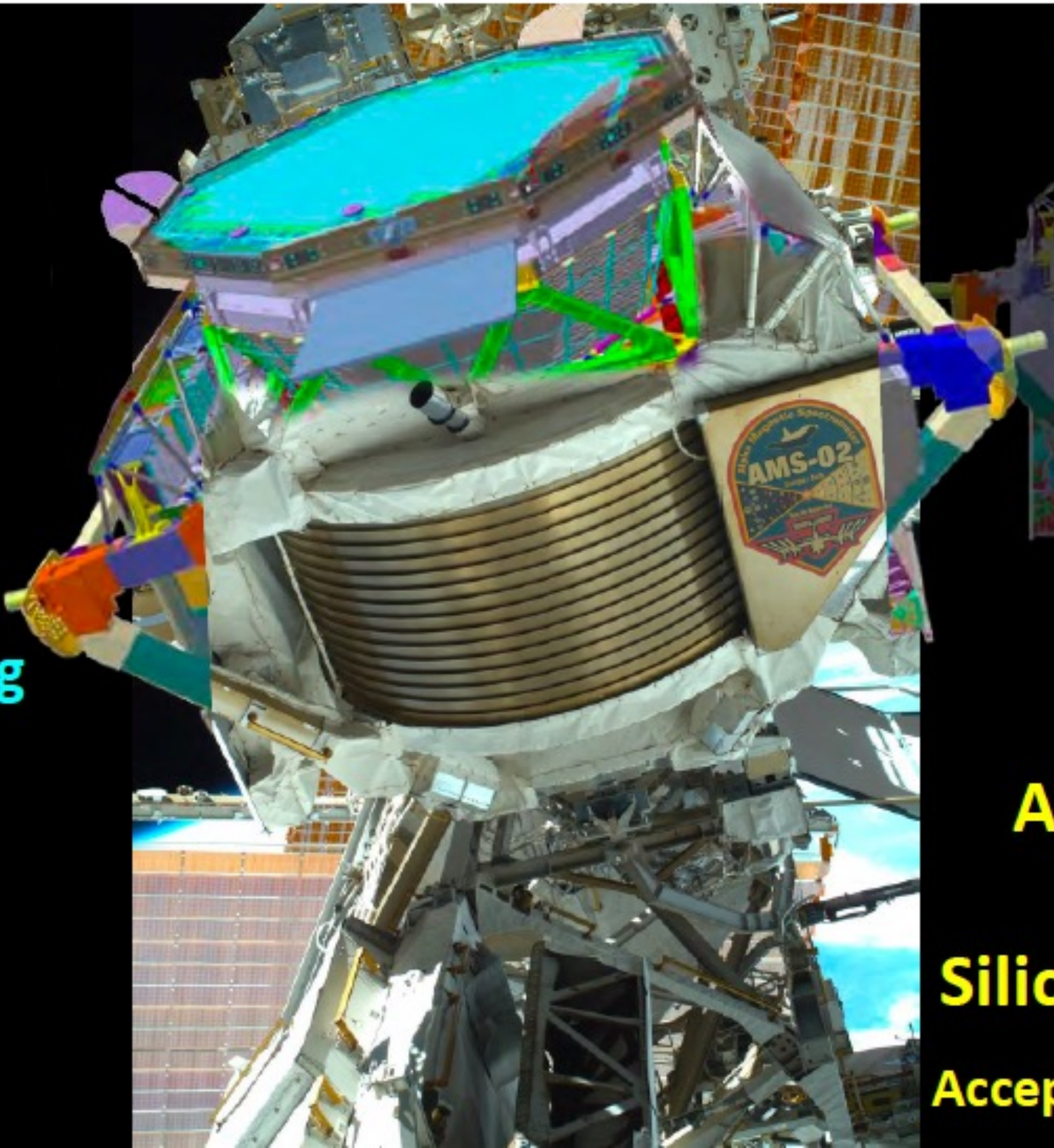


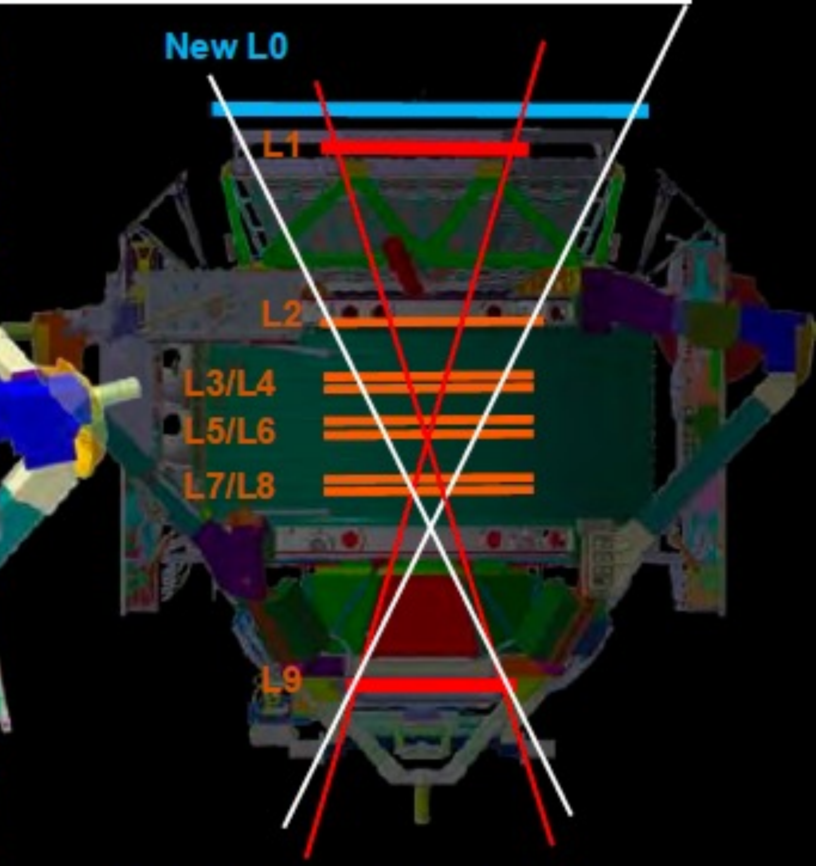
To measure cosmic ray charge and momentum
requires a magnetic spectrometer
in space

The AMS-02 Upgrade (AMS-02.2)

AMS 2011-2026

Continuous data-taking





AMS 2026-2030+

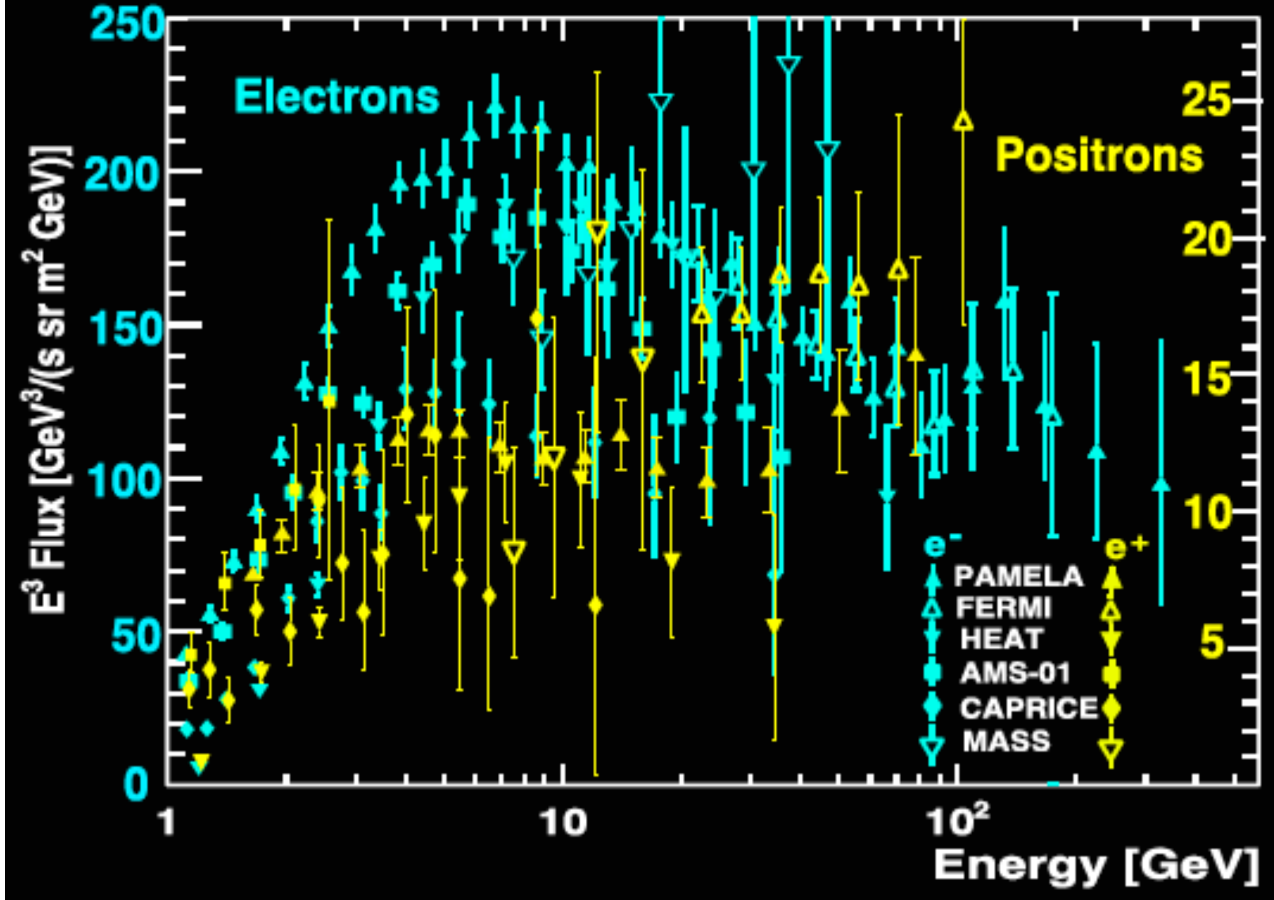
New 4+4m^2

Silicon Tracker Planes

Acceptance increased to 300%

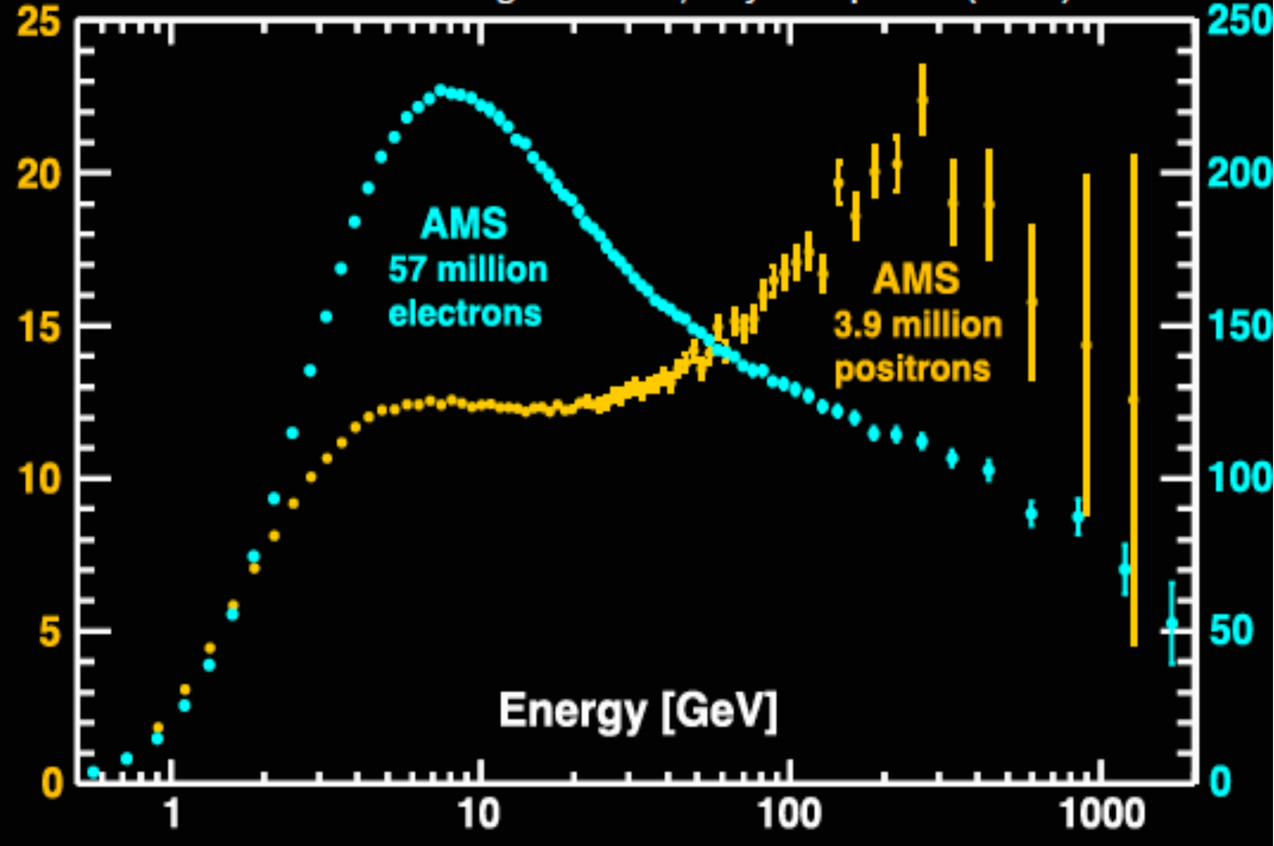
AMS Electron and Positron Fluxes

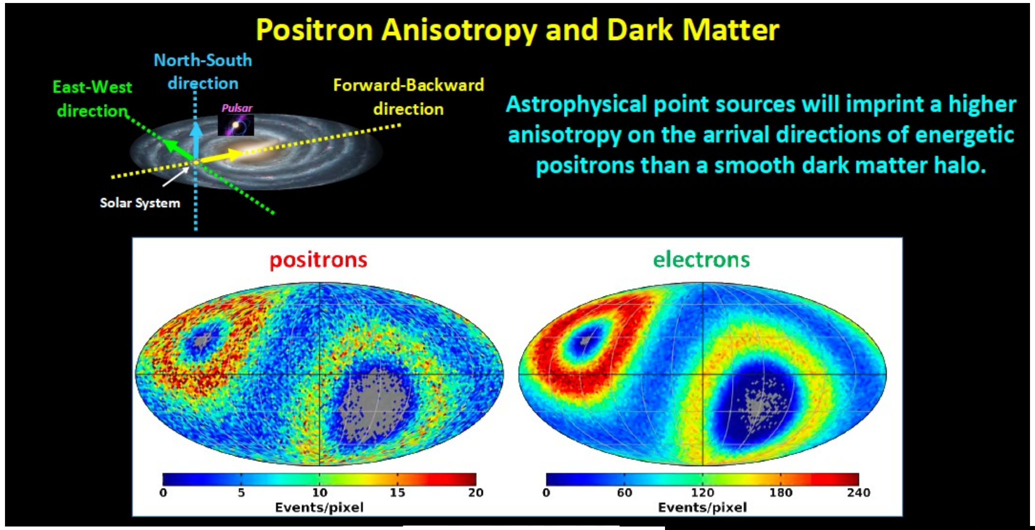
Measurements before AMS



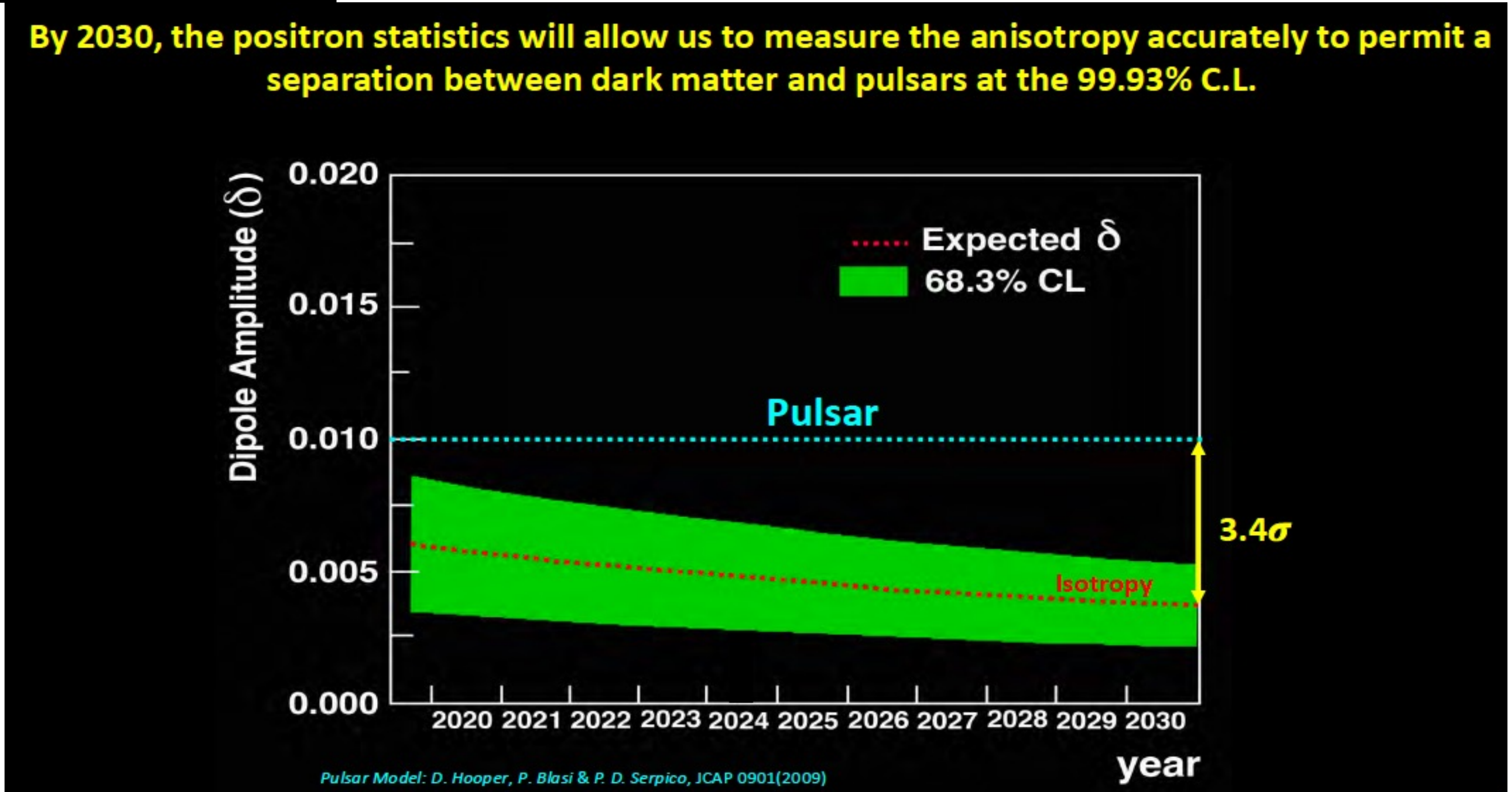
AMS measurements

M. Aguilar *et al.*, Phys. Rep. **894** (2021) 1-116.

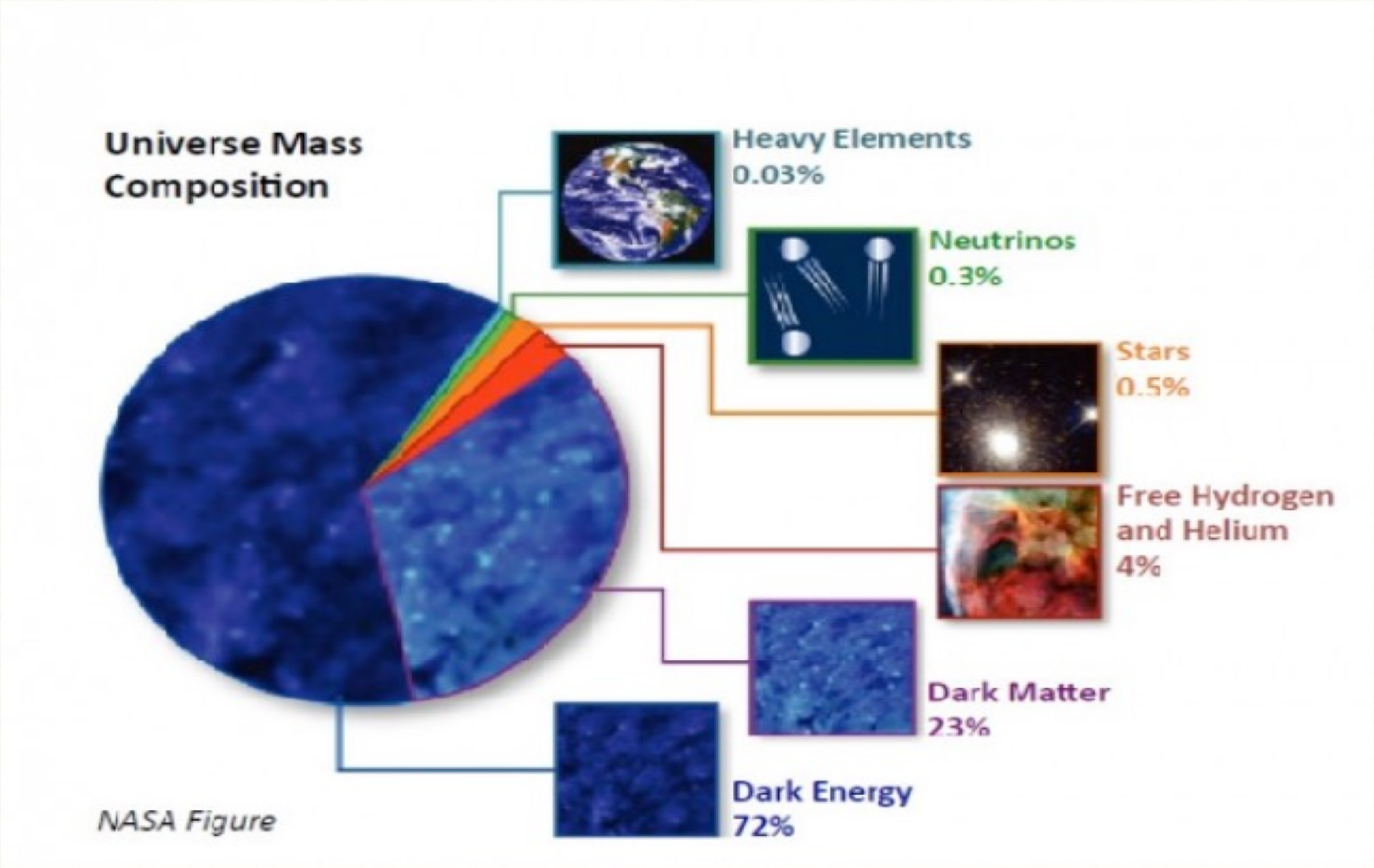




How to discriminate whether positrons come from a **pulsar** or from **DM**



Universe composition



Why $\Omega_{DM}h^2 \sim 5\,\Omega_B h^2$?

Asymmetric Dark Matter

[Griest & Seckel '87, Kaplan, Luty & Zurek 90, ...]

Assume instead that there is an asymmetry stored in DM as in baryons: DM asymmetry generated in the same way as the baryon asymmetry..
It may also be generated together with the baryon asymmetry and then it is natural to expect the SAME asymmetry in both sectors.

$$\Psi \to B + X$$

$$n_{DM} \sim n_b \to \Omega_{DM} \sim 5\,\Omega_b$$

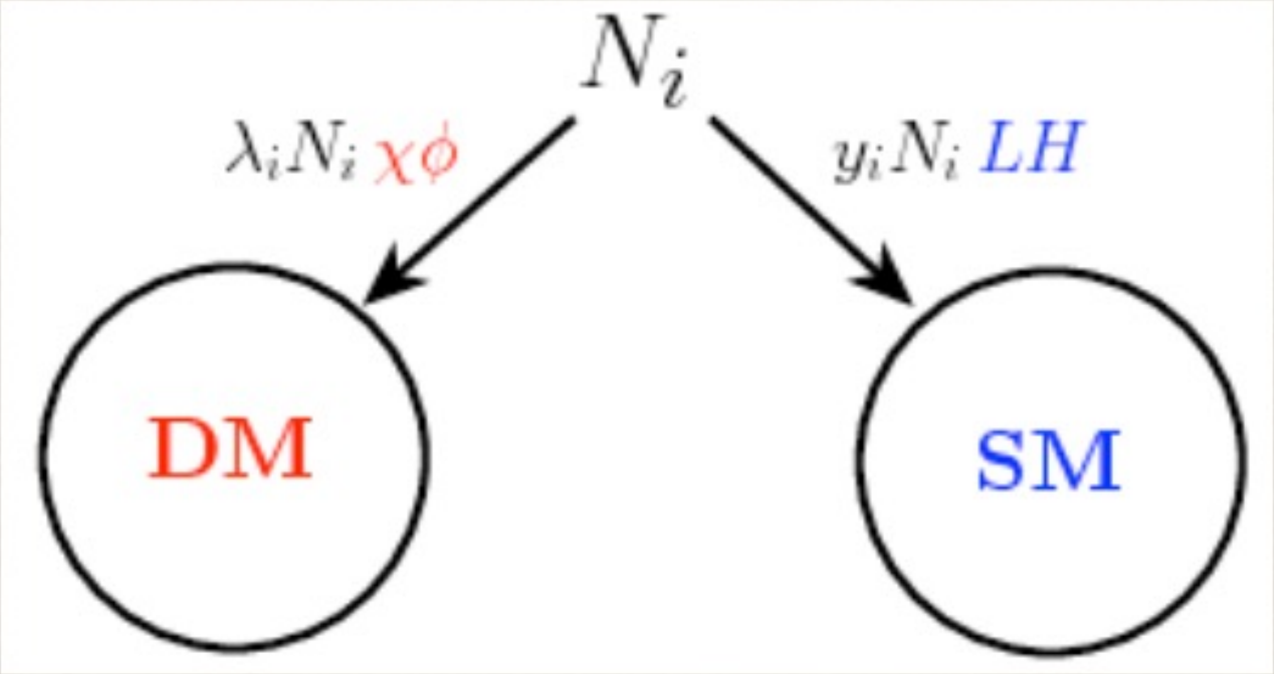
$$\text{for } m_{DM} \sim 5\,m_p = 5\,\text{GeV}$$

The puzzle of similar densities can be given by similar masses !

ASYMMETRIC DARK MATTER

[Griest & Seckel '87, Kaplan, Luty &Zurek 90, ...
Falkowski, Ruderman & Volansky 2011]

Simple mechanism to generate such case:
out-of-equilibrium decay of a particle producing both B-L and DM, e.g. even decay of a RH neutrino



For the last ~30 years we have been focusing on the WIMP scenario

WIMP ⟷ Weak Scale Physics (~100 GeV)

Our experimental effort is strongly focused on the WIMP!

New production mechanisms and mediation schemes often imply a hidden dark sector. Possibly with complex dynamics.

Such hidden sectors often include low scale particles, below the GeV scale.

Very different from the WIMP paradigm!!

Or **very light axions**, or axion-like particles (**ALPs**) or **very heavy**, macroscopic objects DM, for instance **primordial Black Holes**

Dark Sectors

What is meant by a dark sector ?
A Hidden sector, with Dark matter, that talks to us through a Portal

Standard Model → Portal → Dark Sector

Portal can be the Higgs boson itself or New Messenger/s

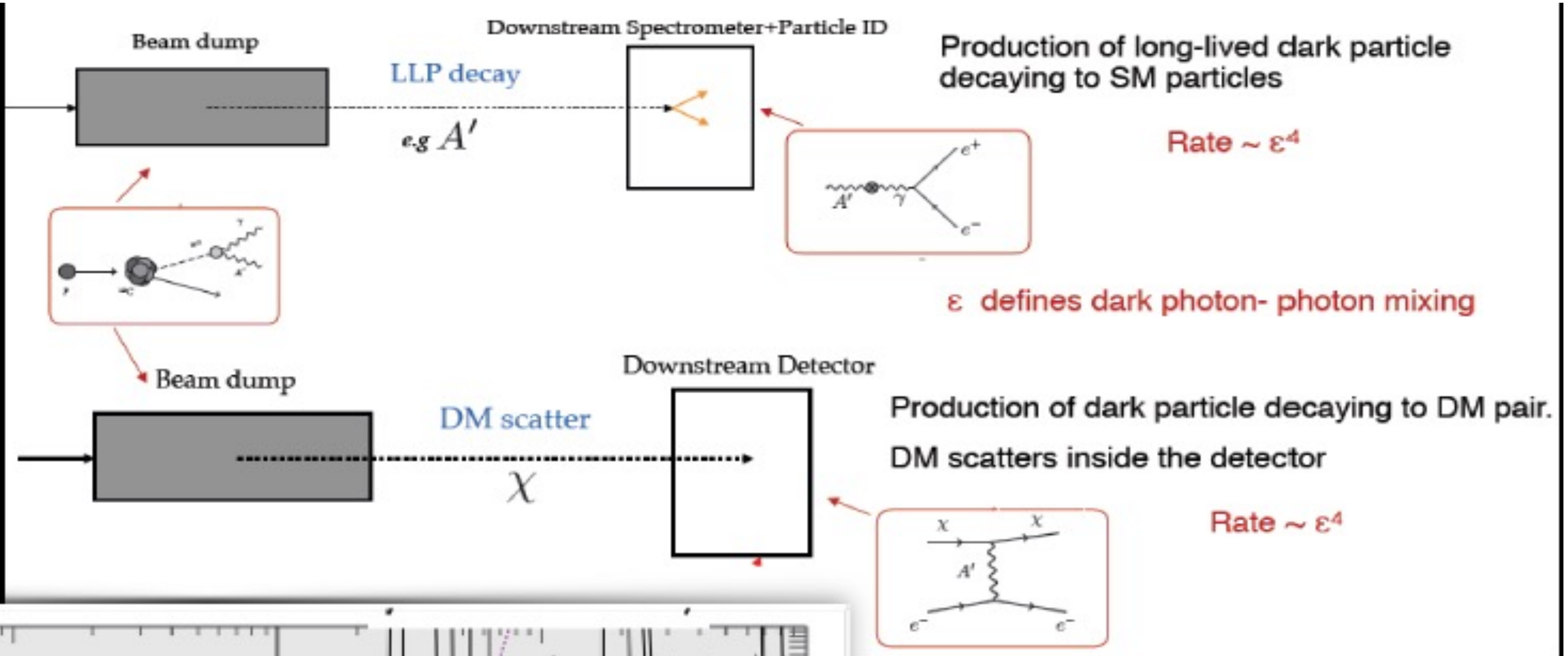
Dark sector has dynamics which is not fixed by Standard Model dynamics
→ New Forces and New Symmetries
→ Multiple new states in the dark sector, including Dark Matter candidates

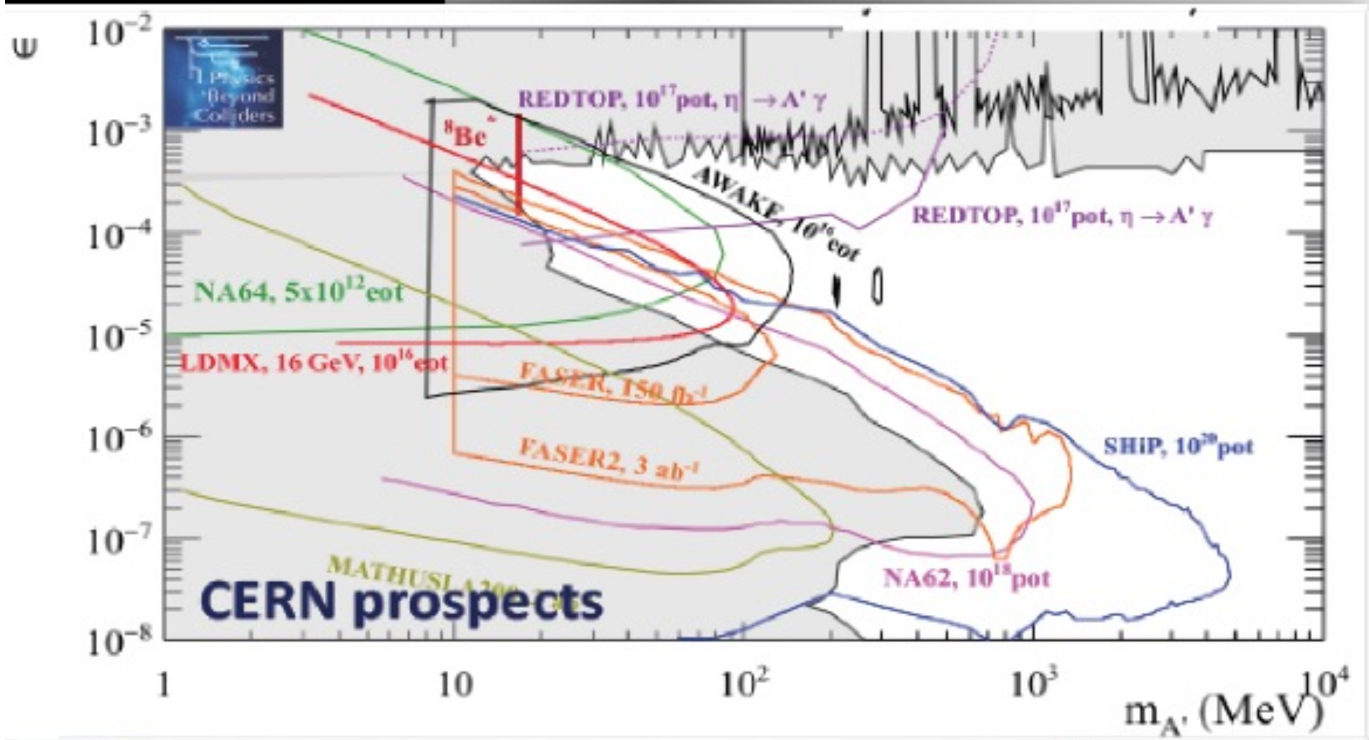
Interesting, distinctive phenomenology
Long-Lived Particles
Feebly interacting particles (FIP's)

Summary talk by Asai and Catena of the DM WG at the EU Strategy Granada Symposium

Fixed-Target Strategies

Renaissance of the fixed-target!

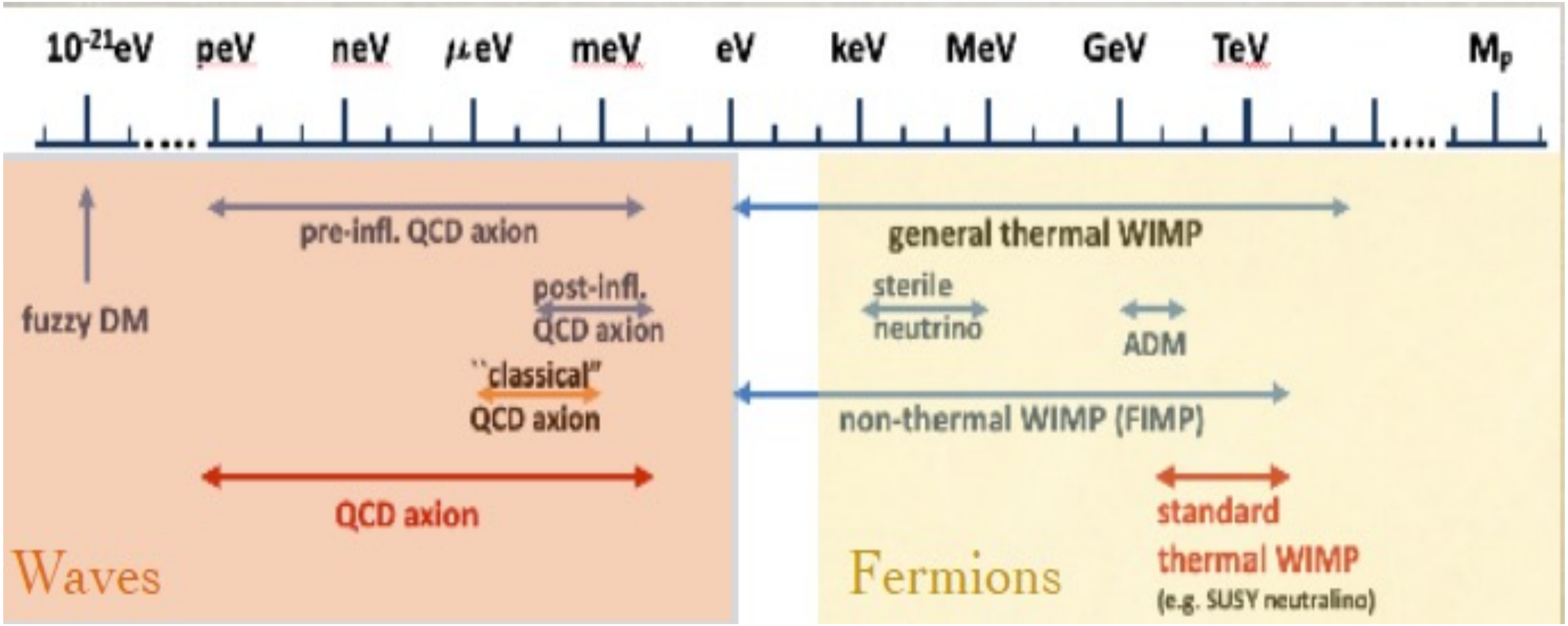




Many new experiments planned or proposed for hidden sector searches.

Major synergistic topic of Dark Sectors work at CERN.

Ellis et al., ESPPU Physics Briefing Book, CERN-ESU-004 (2019)



10^{-21}eV
peV
neV
μeV
meV
eV
keV
MeV
GeV
TeV
M_p
fuzzy DM
pre-infl. QCD axion
post-infl.
QCD axion
``classical''
QCD axion
QCD axion
Waves
general thermal WIMP
sterile
neutrino
ADM
non-thermal WIMP (FIMP)
standard
thermal WIMP
(e.g. SUSY neutralino)
Fermions

Strong CP & the Axion

The QCD vacuum has a non trivial structure, as a superposition of different topological configurations, giving rise to strong CP problem from the term:

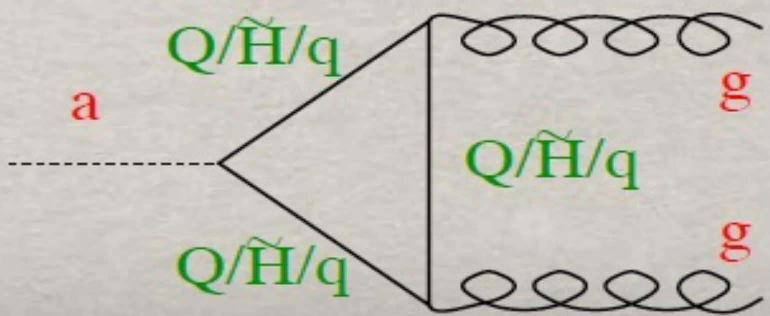
$$\mathcal{L} = \theta \, \frac{\alpha_s}{8\pi} F^b_{\mu\nu} \tilde{F}^{\mu\nu}_b$$

['t Hooft 76]

But from the bounds on neutron el. dipole moment $\theta < 10^{-9}$

Peccei-Quinn solution: add a chiral global U(1) and break it spontaneously at f_a, leaving the axion, a pseudo-Goldstone boson, interacting as

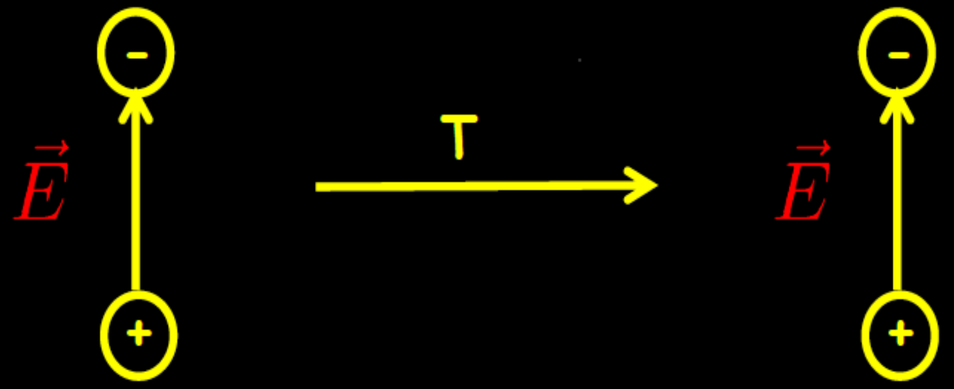
$$\mathcal{L}_{PQ} = \frac{\alpha_s}{8\pi f_a} a F^b_{\mu\nu} \tilde{F}^{\mu\nu}_b$$



$$S = \int d^4x \left[-\frac{1}{4} G^{\mu\nu} G_{\mu\nu} - \frac{\theta}{4} G^{\mu\nu} \tilde{G}_{\mu\nu} + i\bar{\psi} D_\mu \gamma^\mu \psi -\right.$$

$$\text{"} \sim \theta \vec{E} \cdot \vec{B} \text{"}$$

- The θ-term violates time reversal (T=CP)!



T=CP

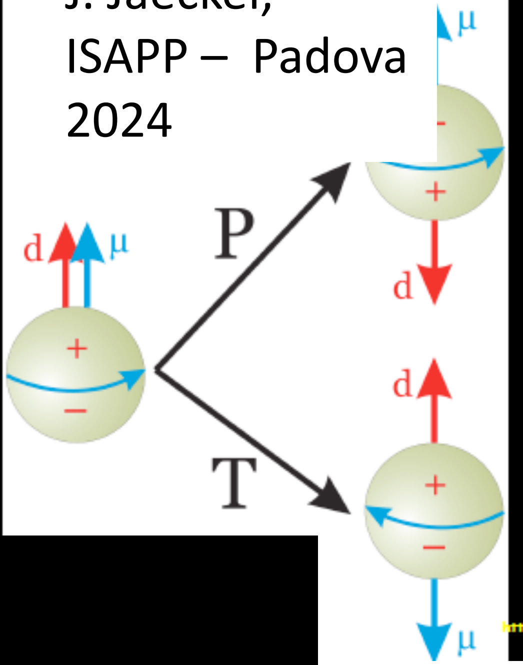
$$\vec{E} \longrightarrow \vec{E}$$

$$\vec{B} \longrightarrow -\vec{B}$$

$$\vec{E} \cdot \vec{B} \longrightarrow -\vec{E} \cdot \vec{B}$$

Electric dipole moment of the neutron!

J. Jaeckel, ISAPP – Padova 2024



- Detailed calculation gives

$$|\vec{d}| \sim 1 - 10 \times 10^{-16} e\, cm\, \theta$$

$$\Rightarrow |\theta| \lesssim 10^{-10}$$

?

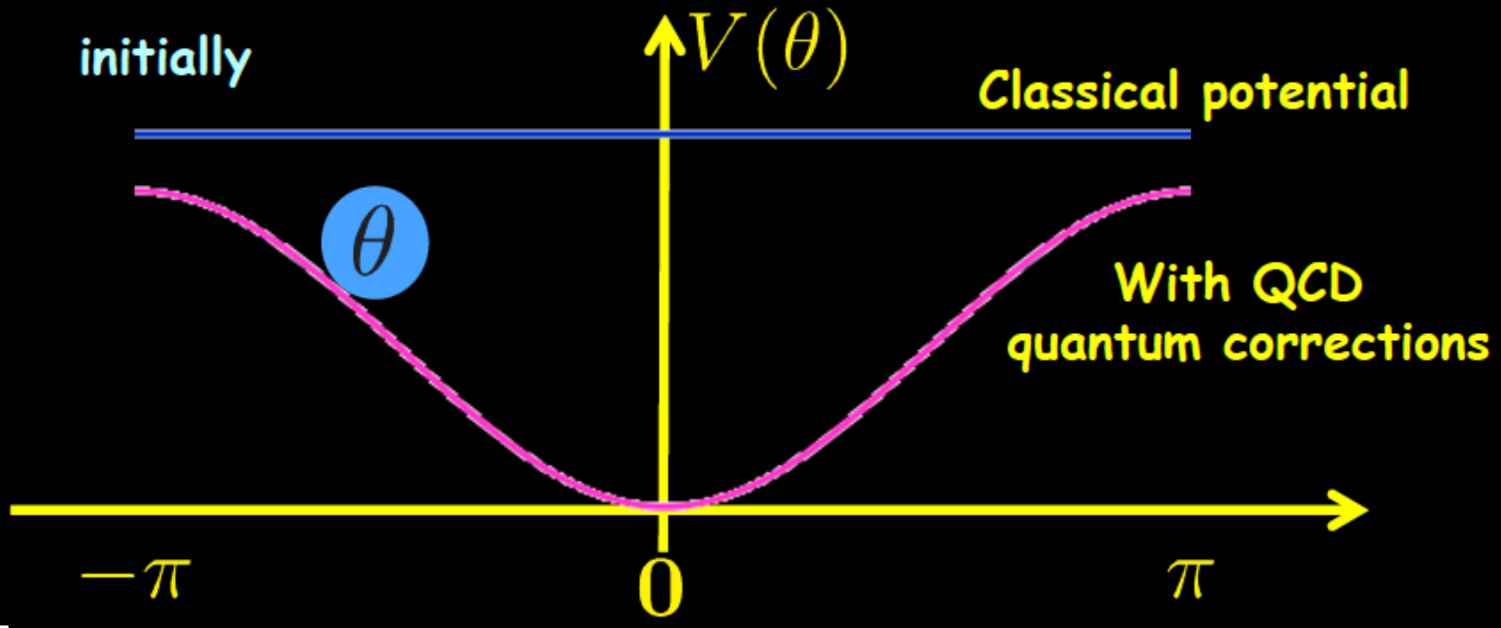
⇒ **Extremely unnatural!**

J. Jaeckel, ISAPP – Padova 2024

The axion solution to the strong CP problem

J. Jaeckel,
ISAPP – Padova 2024

- Make θ dynamical → it can change its value



- Canonically normalize $\theta = a/f_a$

→ $V[a/f_a = \theta = 0] \leq V[\theta] \quad \forall\theta$

→ $\theta = a/f_a$ will evolve to $a = \theta = 0$

→ CP is conserved

a is Goldstone boson of a U(1) symmetry → Axion!

J. Jaeckel,
ISAPP – Padova 2024

Peccei-Quinn Symmetry

- Toy model:

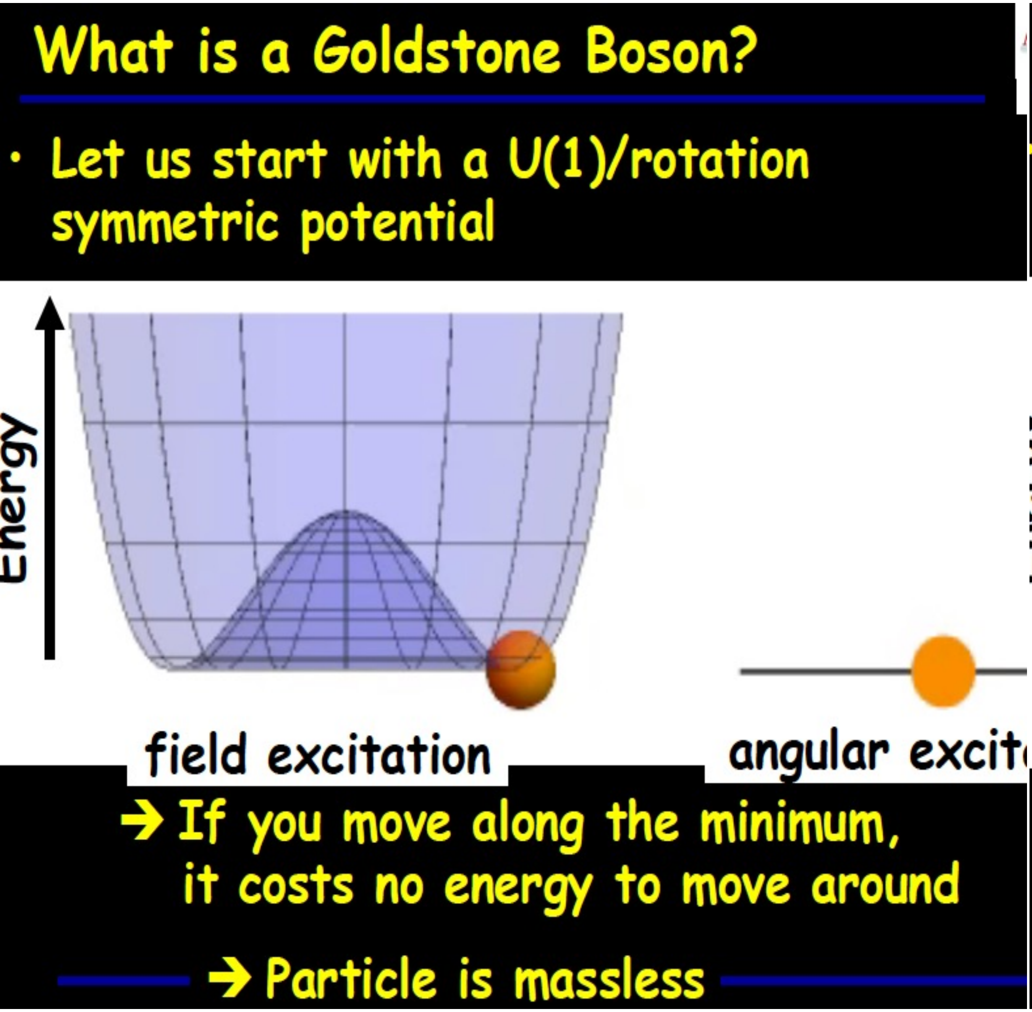
$$\mathcal{L} = -\frac{1}{4}F^2 + i\bar{\psi}D_\mu\gamma^\mu\psi - |\partial_\mu\phi|^2 - \mu^2|\phi|^2 - \lambda|\phi|^4$$
$$+\bar{\psi}\left(Y\phi\frac{1+\gamma_5}{2} + Y^\star\phi^\star\frac{1-\gamma_5}{2}\right)\psi$$

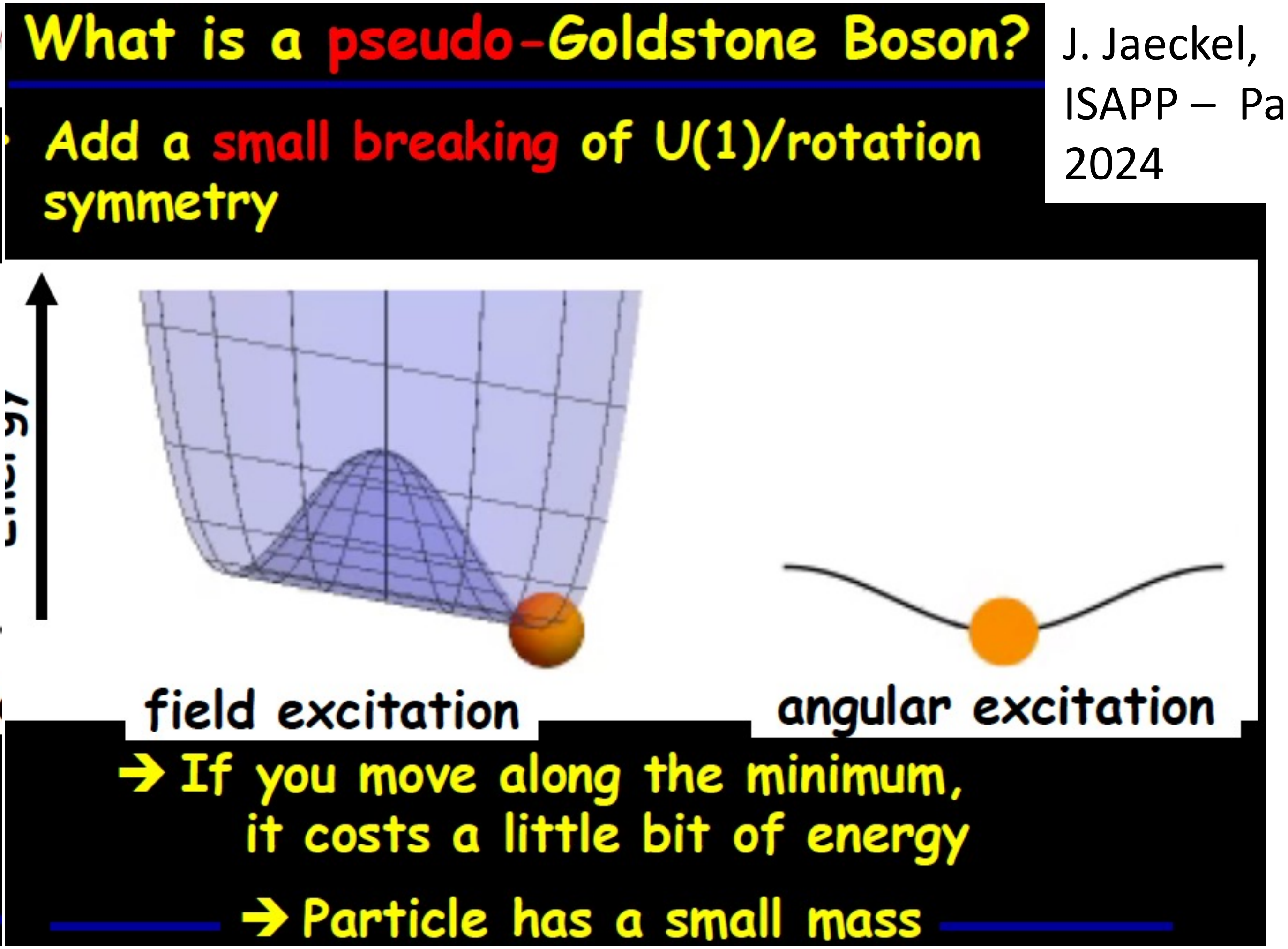
- U(1): $\phi \rightarrow \exp(i\beta)\phi$

$$\psi \rightarrow \exp\left(-i\frac{\beta}{2}\gamma_5\right)\psi$$

- If $\mu^2<0$ we have SSB

→ Phase is Goldstone → Use it as Axion





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Breaking of the ***exact U(1) PQ symmetry*** → axion is the resulting masslessGoldstone boson

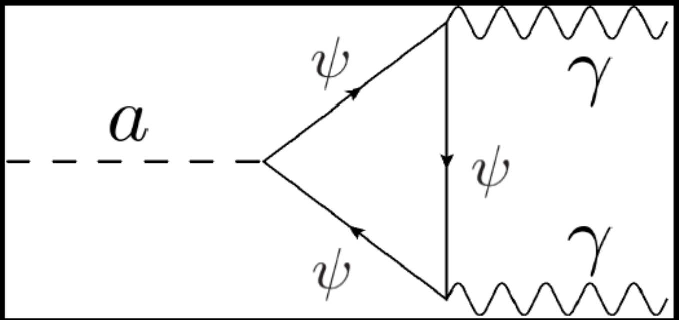
Wilczek, Weinberg → due to quantum effects, the PQ symmetry is ANOMALOUS, hence it is **NOT** an exact symmetry even before the SSB the axion is a massive ***PSEUDO-Goldone boson***

Mass and **couplings** of the axion as a function of the **PQ symmetry breaking scale** f_a

$$m_a \simeq 6\ \mathrm{eV}\ \frac{10^6\ \mathrm{GeV}}{f_a}$$

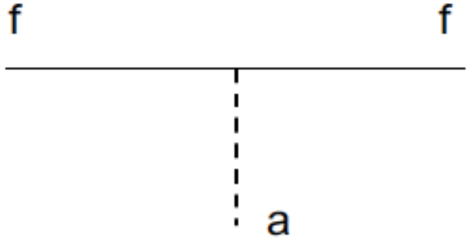
The Coupling to FF (GG analog)

- A diagram

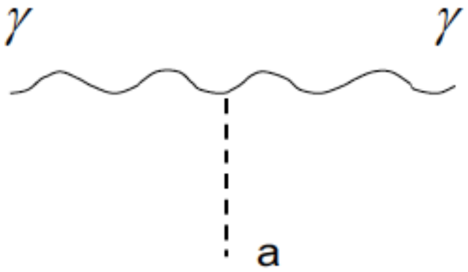


- And a dimensional argument:

$$g \sim \frac{1}{\mathrm{mass}} \sim \frac{1}{f_a}$$



$$\mathcal{L}_{a\bar{f}f} = i g_f \frac{a}{f_a} \bar{f}\gamma_5 f$$



$$\mathcal{L}_{a\gamma\gamma} = g_\gamma \frac{a}{f_a} \vec{E}\cdot\vec{B}$$

g_γ = 0.97 in KSVZ model
0.36 in DFSZ model

Axions as Dark Matter

Their energy density by misalignment is

$$\Omega_a h^2 = 0.5 \left(\frac{f_a}{10^{12}\mathrm{GeV}} \right)^{7/6} \theta_i^2 \quad \to P(\theta_i)$$

Axions can contribute to star/SN cooling and so

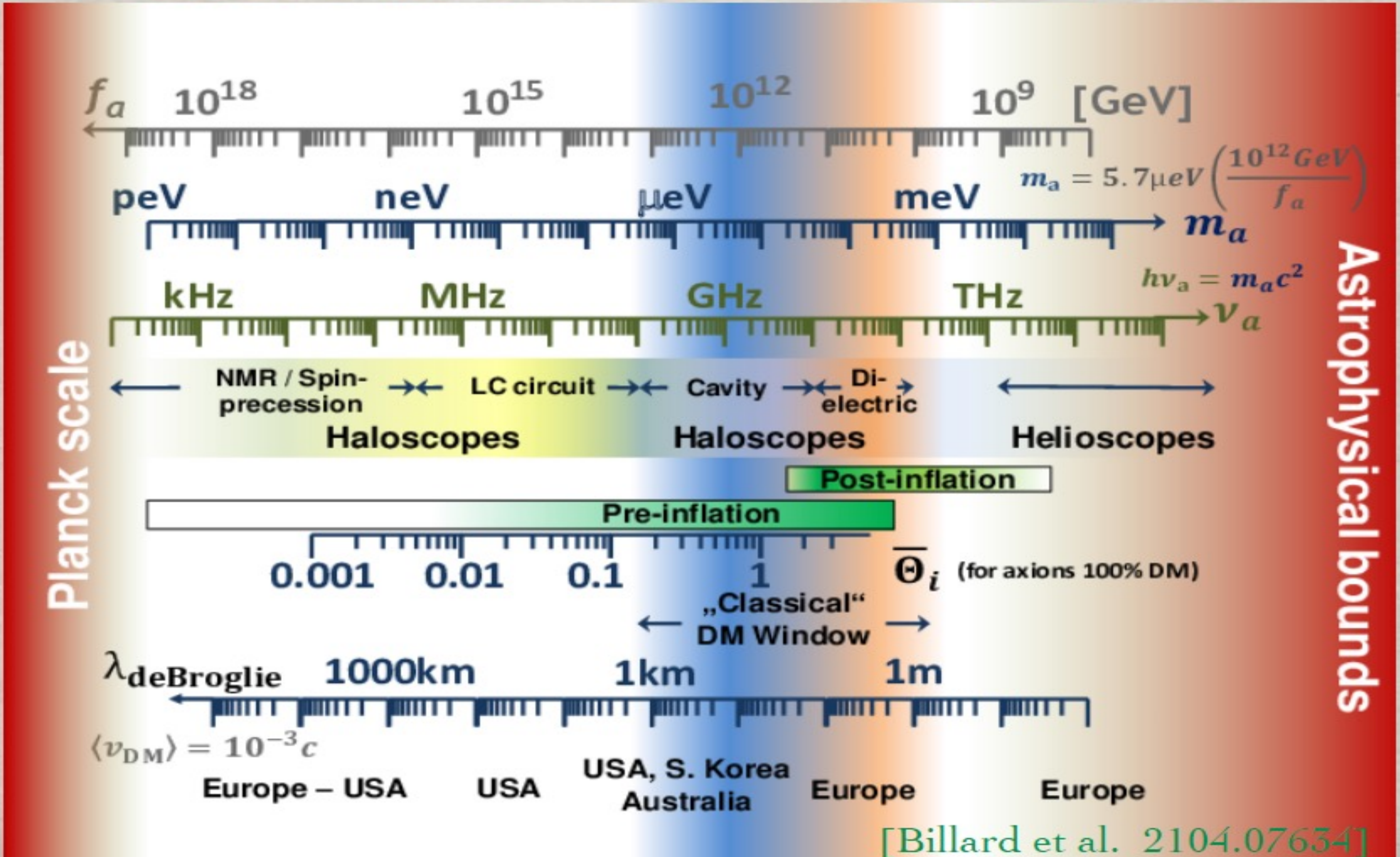
$$0.5 \times 10^{10}\mathrm{GeV} \leq f_a \leq 10^{12}\mathrm{GeV}$$

[Raffelt 98]

Therefore the mass for axion DM is very small:

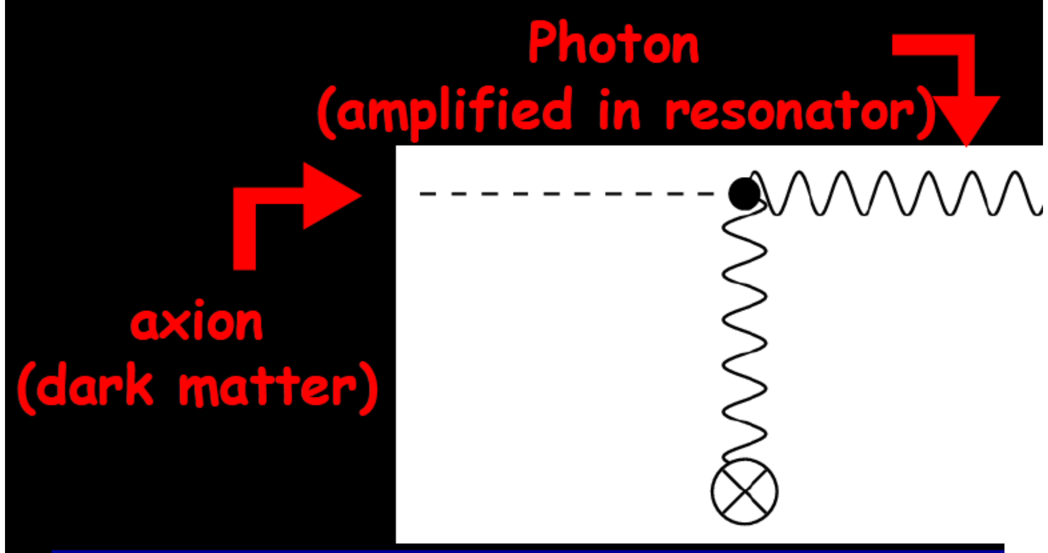
$$m_a = \Lambda_{QCD}^2 / f_a \sim 6 \times 10^{-5}\mathrm{eV} \left(\frac{f_a}{10^{11}\mathrm{GeV}} \right)^{-1}$$

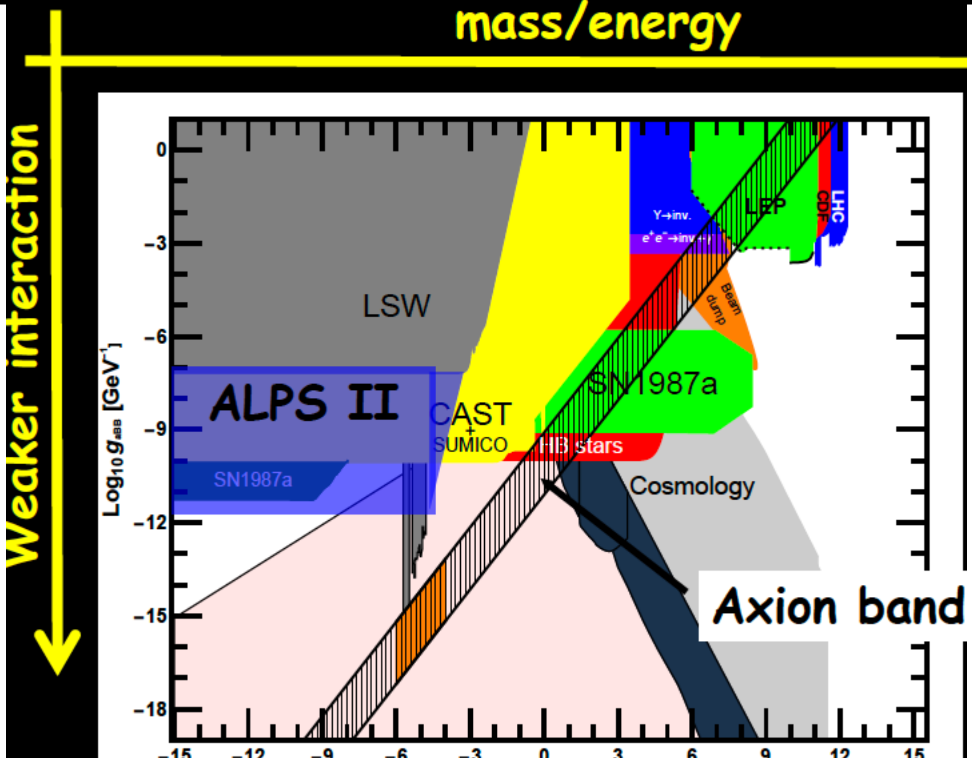
Axion's constraints



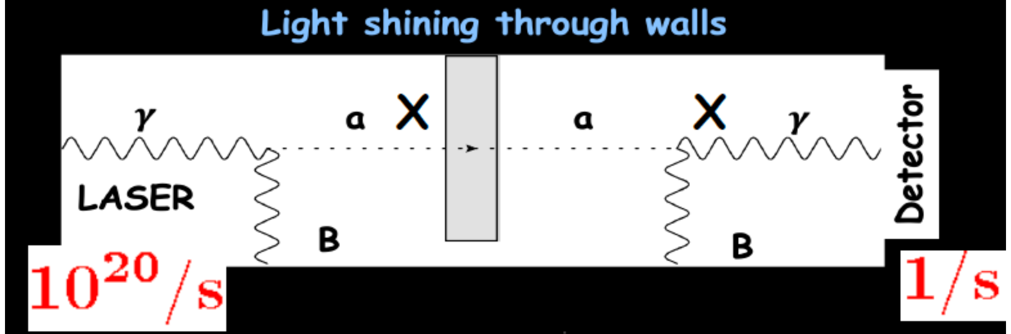
[Billard et al. 2104.07634]

- Photon Regeneration

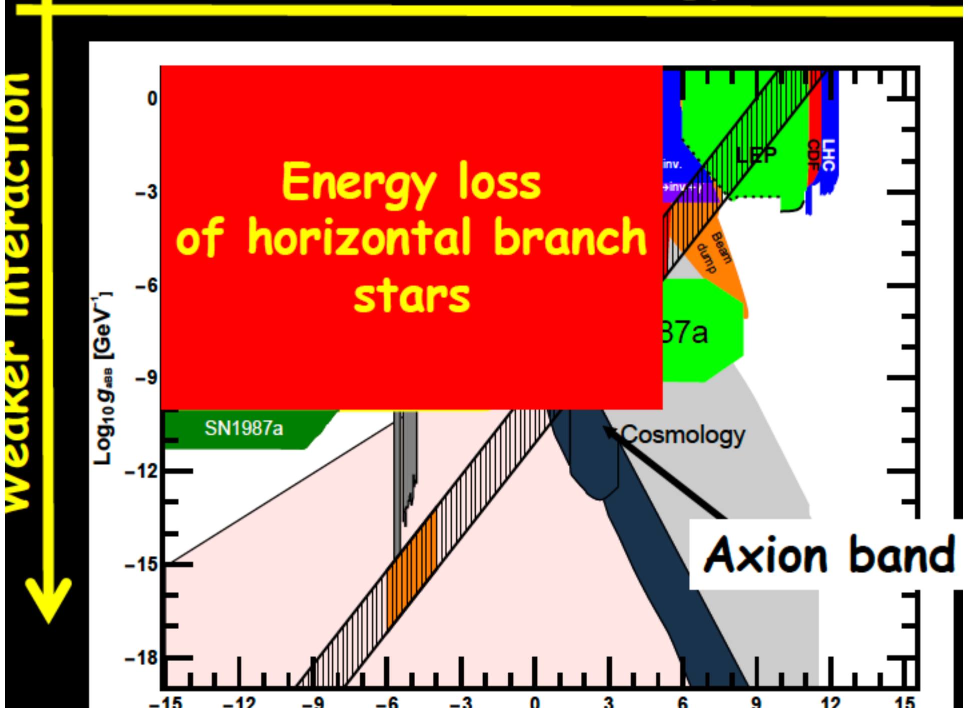




Light shining through walls



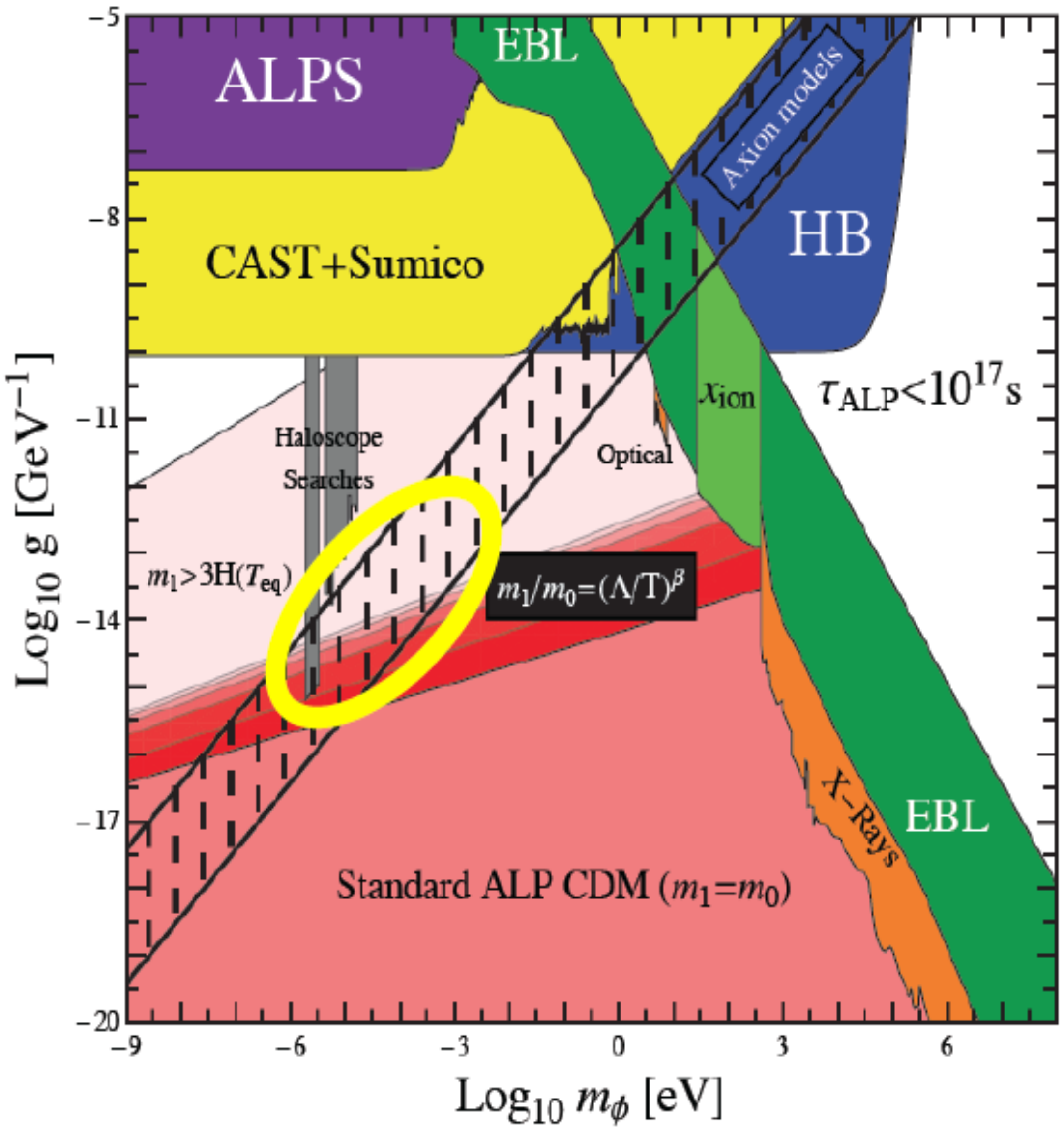
- Test $P_{\gamma\to X\to\gamma} \lesssim 10^{-20}$
- Enormous precision!
- Study extremely weak couplings!



Axion(-like particle) Dark Matter

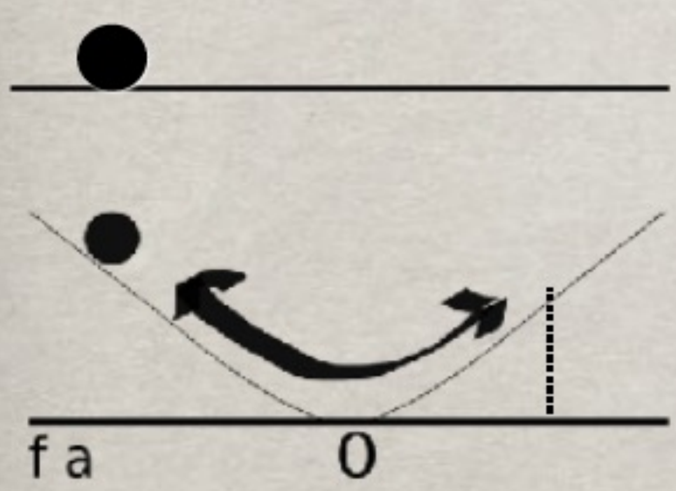
~10^7 GeV

~10^{12} GeV



Axions as Dark Matter

The axion is also a very natural DM candidate,
but in this case in the form of a condensate,
e.g. generated by the misalignment mechanism:



Before the QCD phase transition the potential for the axion is flat

After the QCD phase transition a potential is generated

$$V(a) = \Lambda_{QCD}^4 \left(1 - \cos\left(\theta + \frac{a}{f_a}\right)\right)$$

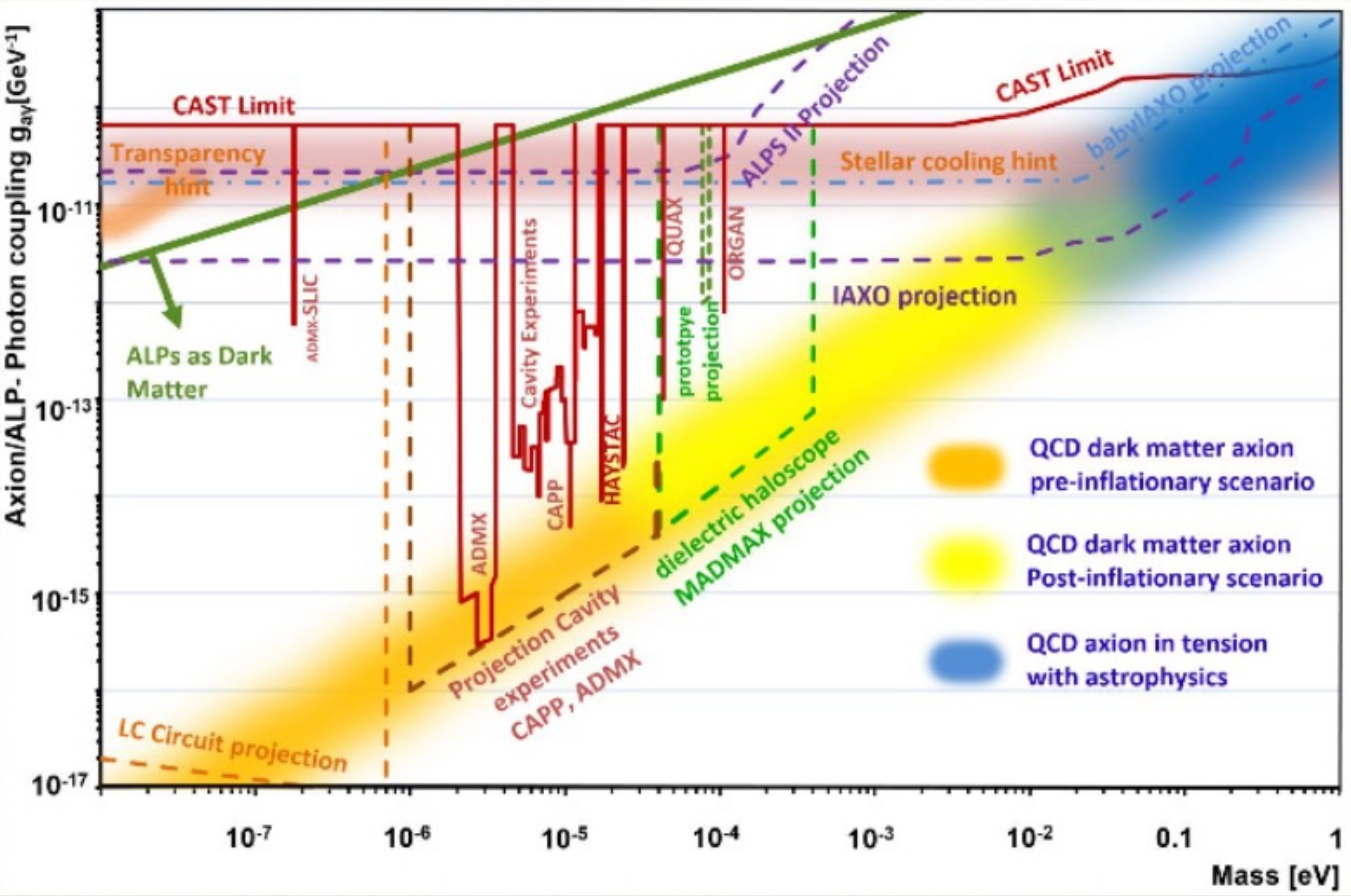
by instanton's effects and the axion starts to oscillate coherently around the minimum:

$$\Omega_a h^2 = 0.5 \left(\frac{f_a}{10^{12}\mathrm{GeV}}\right)^{7/6} \theta_i^2$$

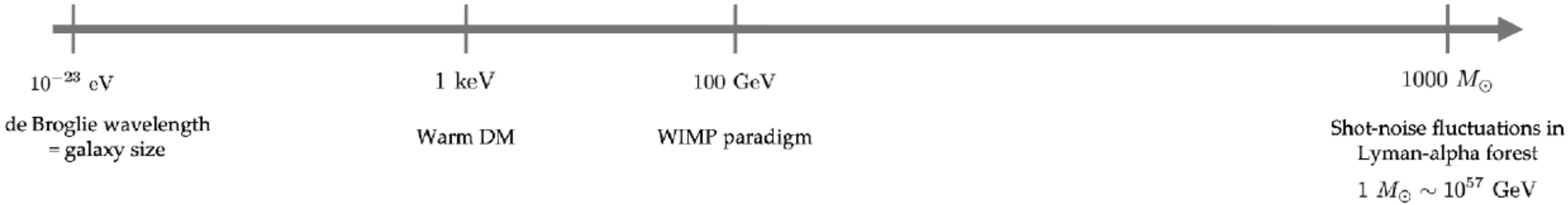
zero momentum particles >> CDM !

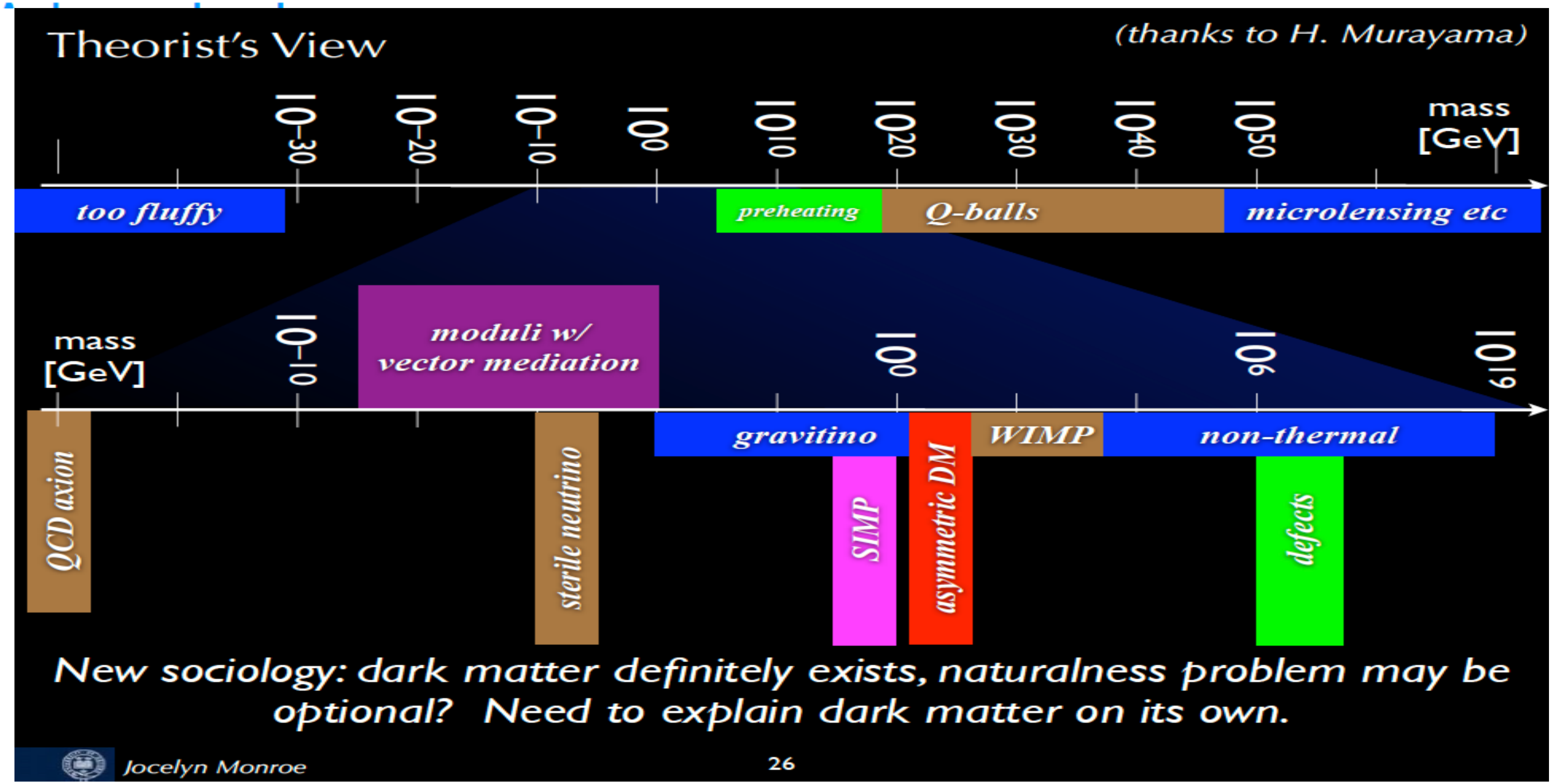
AXION DM SEARCHES

The right abundance can be obtained if the Peccei-Quinn scale is of the order of 10^{11-12} GeV and the mass in the μeV.



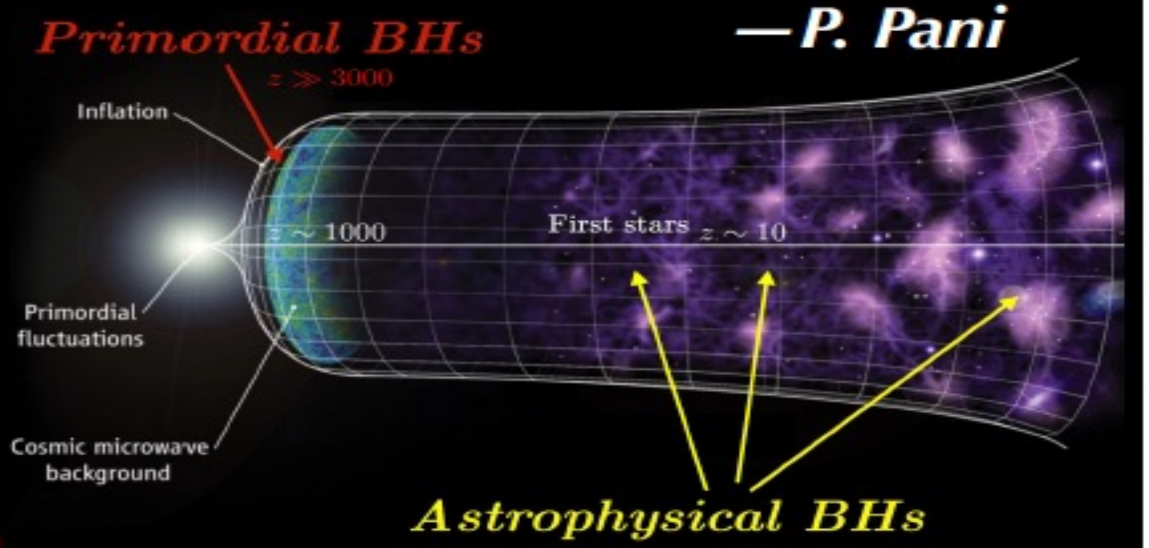
The Range of Possibilities is Stunning!

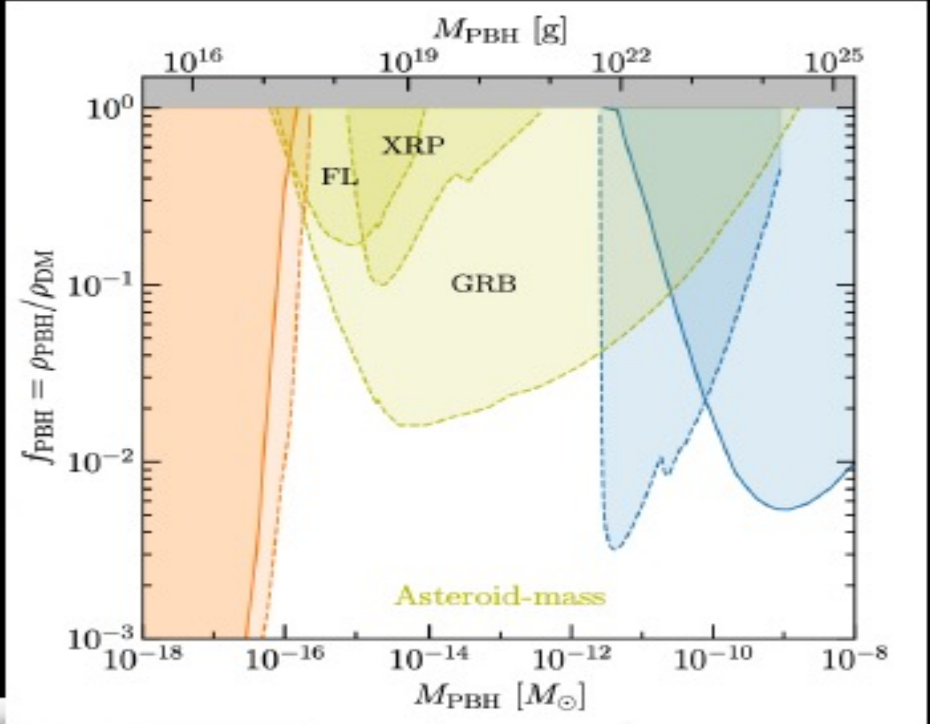




Very, Very Heavy Dark Matter

—P. Pani





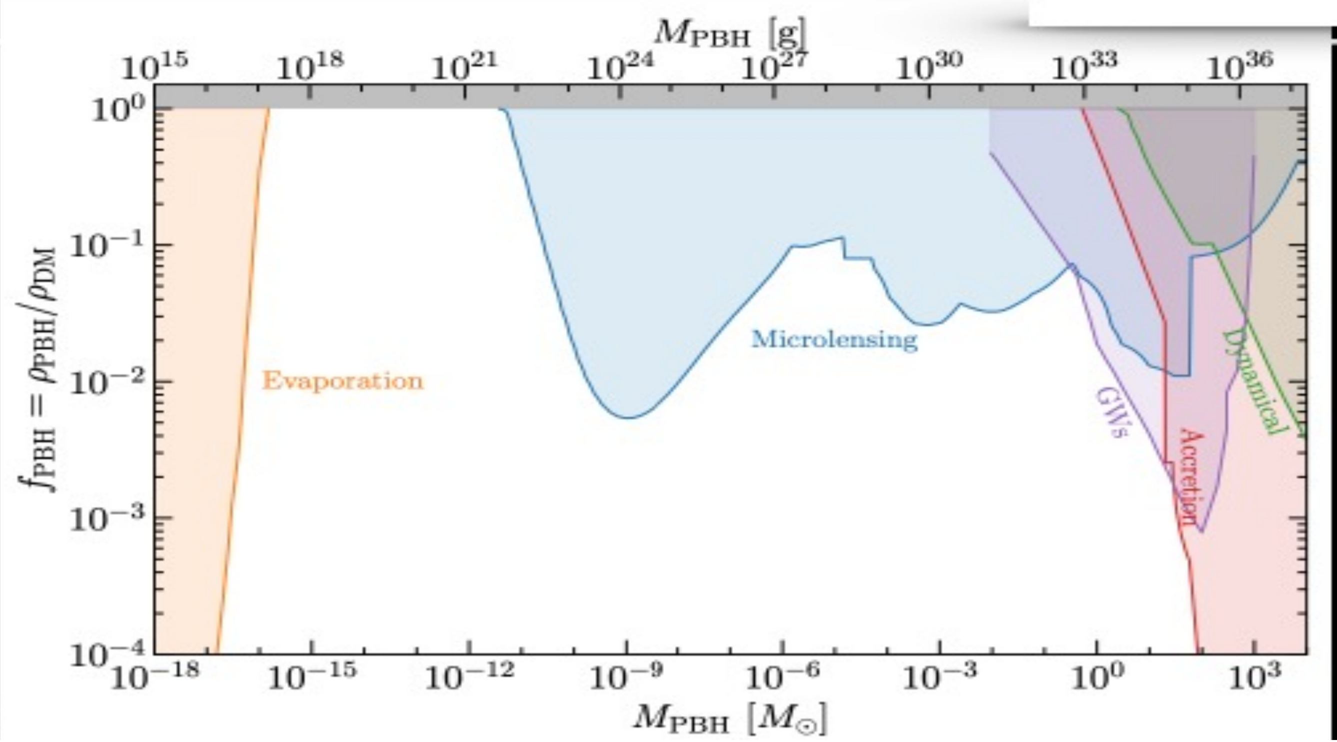
mass [GeV]

non-thermal

defects

10^{19}

Green et al, 2402.15211



What the SM does not account for...

neutrino masses
dark matter
baryogenesis
inflation

→ OBSERVATIONAL REASONS

3rd final take-home message

$M_{HIGGS} / M_{PLANCK} \sim 10^{-16}$

$E_{VACUUM}(DE) / M_{HIGGS} \sim 10^{-14}$

$\Theta_{\text{CPV in STRONG INTERAC.}} < 10^{-9}$

→ THEOR. REASONS

+ lack of UNIFICATION of the ELW. and strong interactions

+lack of a physical "explanation" of the (largely different) masses and mixings of the fermions

THE MISTERY OF THE 5 NUMBERS THAT THE SM IS UNABLE TO EXPLAIN

- *Stars and galaxies are only ~0.5%*
- *Neutrinos are ~0.1–1.5%* **NEUTRINO MASS**
- *Rest of ordinary matter (electrons, protons & neutrons) are 4.4%*
- *Dark Matter* 27 % **WHAT IS DM MADE OF?**
- *Dark Energy* 68 % **ENERGY OF THE QUANTUM VACUUM?**
- *Anti-Matter 0%* **WHAT PRODUCED THE COSMIC MATTER-ANTIMATTER ASYMMETRY**
- *Higgs Bose-Einstein condensate ~10^{62}%??* **COSMOLOGICAL CONSTANT PROBLEM (QUANTUM VACUUM ENERGY?)**