The Dark Side of the Forces

DIRECT DARK MATTER DETECTION (I)

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DIRECT DARK MATTER DETECTION – OUTLINE

1a. The dark matter landscape

- The big picture
- Dark matter candidates

1b. Weakly Interacting Massive Particles

- Thermal relics: the WIMP paradigm
- Our own (galactic) WIMPs

2. How to catch a WIMP – Tomorrow am

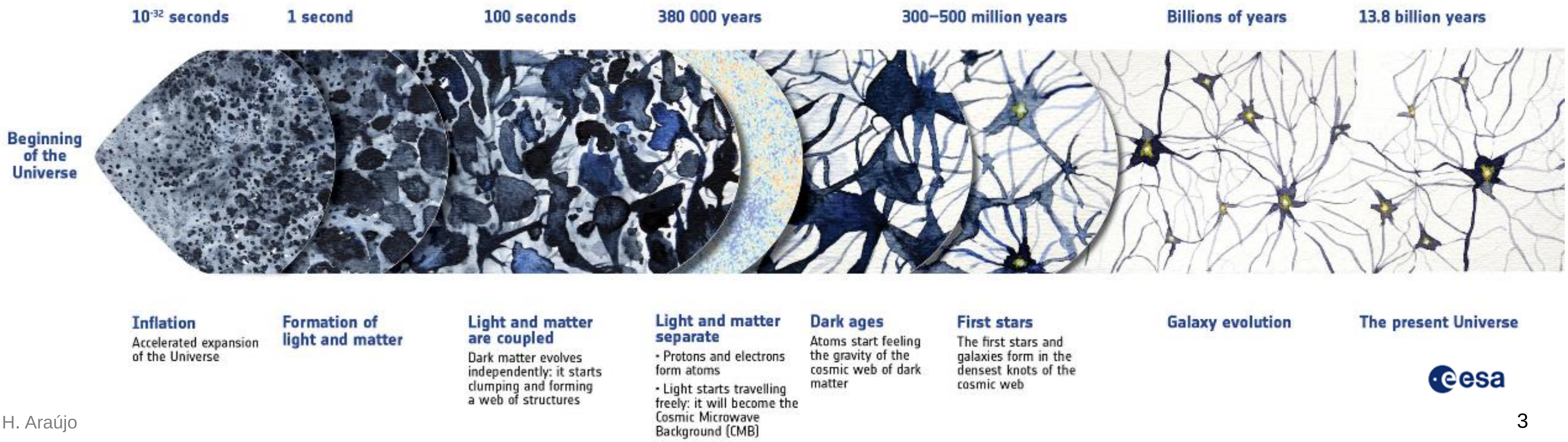
- Direct detection strategies
- The experimental challenge
- Detector technologies

4. Exercises – Tomorrow pm

THE BIG PICTURE

Plenty of (gravitational) evidence for dark matter: at all scales – hence at all times:

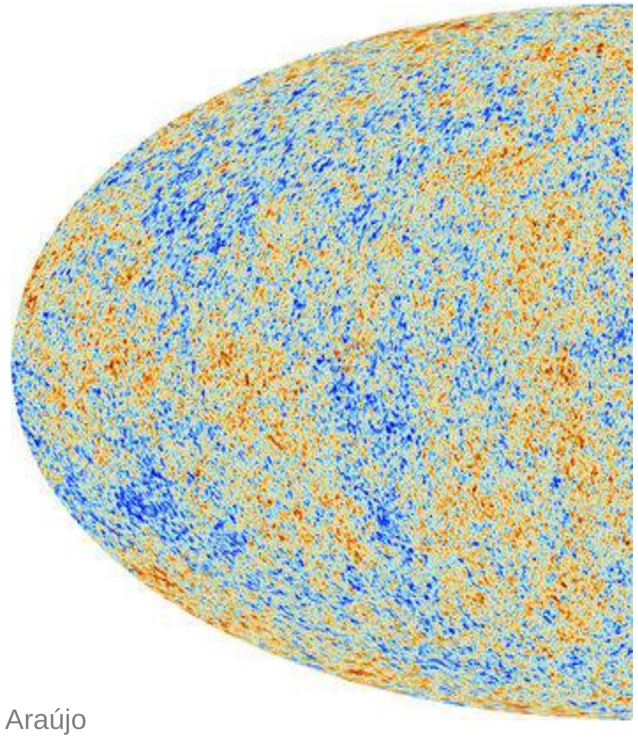
- Fluctuations in the Cosmic Microwave Background
  - Large-scale structure of galaxies and clusters
    - Motion of individual galaxies within clusters
      - How stars move within galaxies

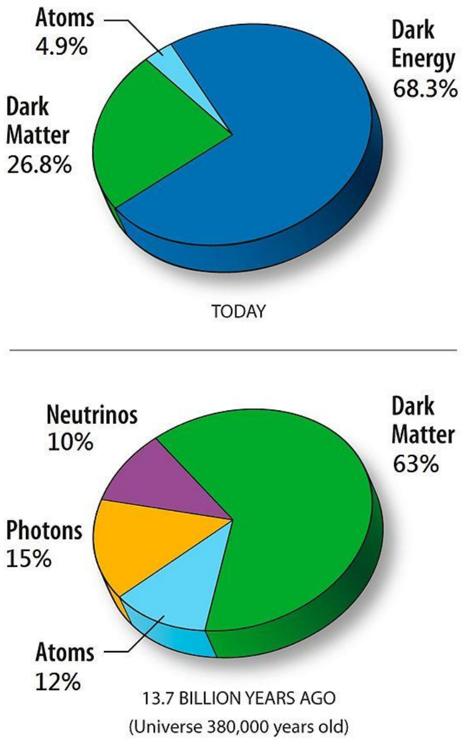


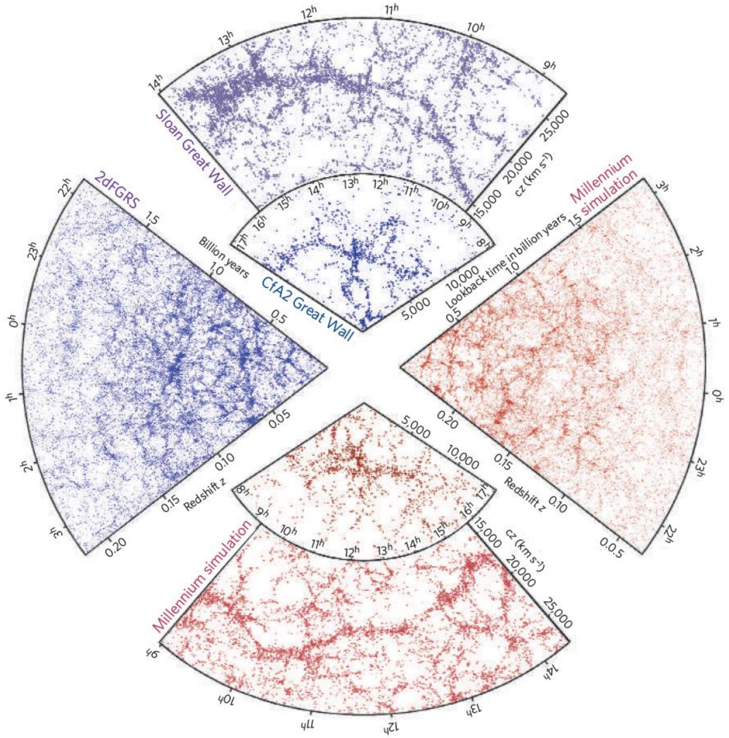
THE BIG PICTURE

The Standard Model of Cosmology (Λ-CDM) is remarkably successful

- Initial conditions photographed at the surface of last scatters (CMB)
  - Left to evolve for 13.7 Gyr under two dark ‘fluids’ – dark energy (Λ) and dark matter (CDM)
    - To produce what we see today – ordinary matter (almost) does not matter…



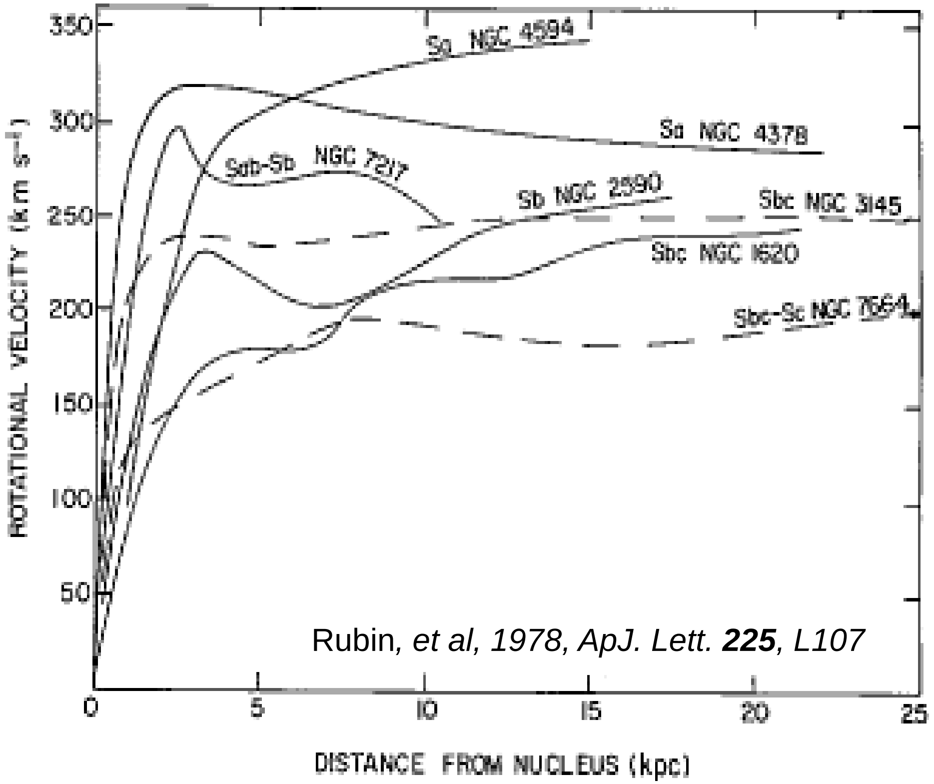




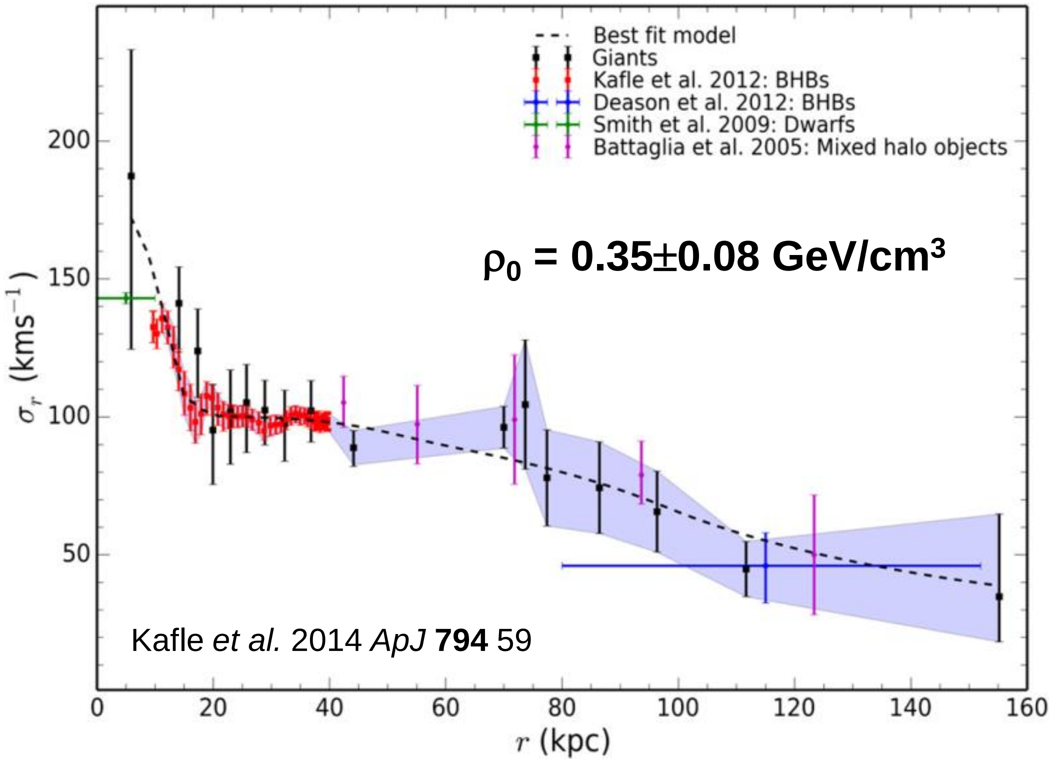
OUR DARK MILKY WAY

- Our Milky Way is not exceptional – it, too, spins too quickly for the luminous matter it contains: we are immersed in a large dark matter halo
- Density near the Sun ~0.35 GeV/cm^3

We shall return to this topic later today

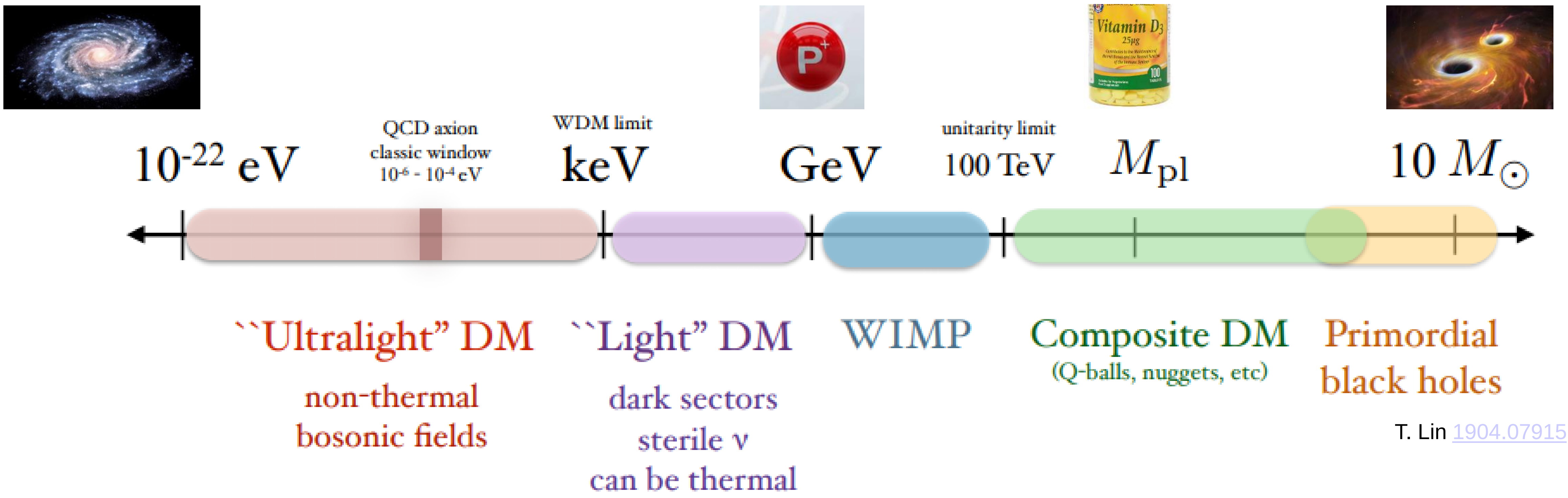


Rubin, *et al, 1978, ApJ. Lett.* ***225****, L107*



Kafle *et al.* 2014 *ApJ* **794** 59

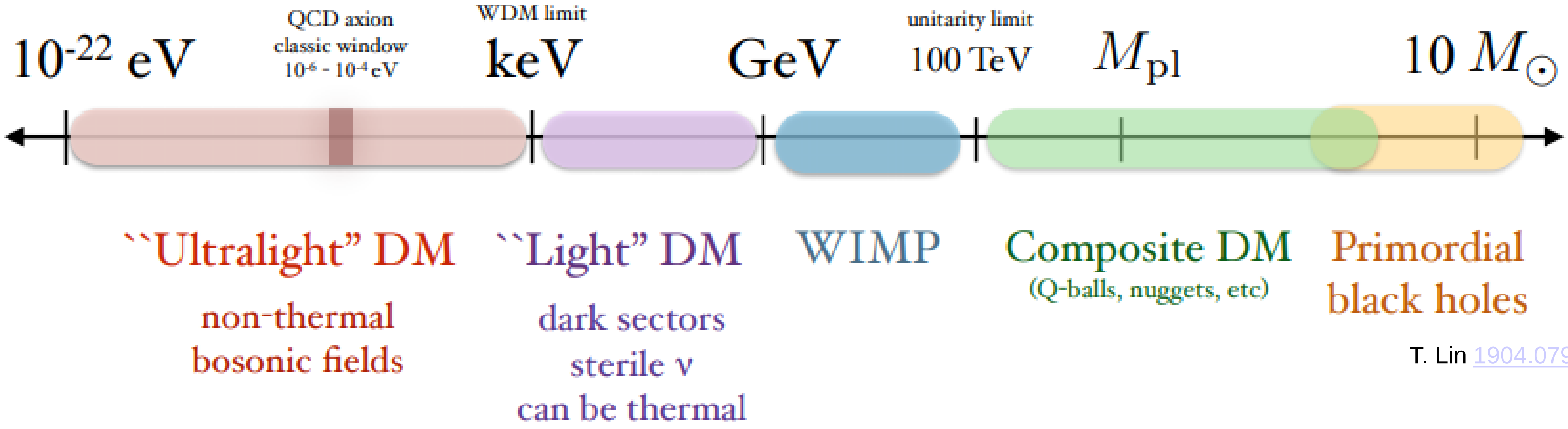
THE DARK MATTER LANDSCAPE



T. Lin 1904.07915

← wave-like (bosons) | particle-like (mostly fermions) →

THE DARK MATTER LANDSCAPE



T. Lin 1904.07915

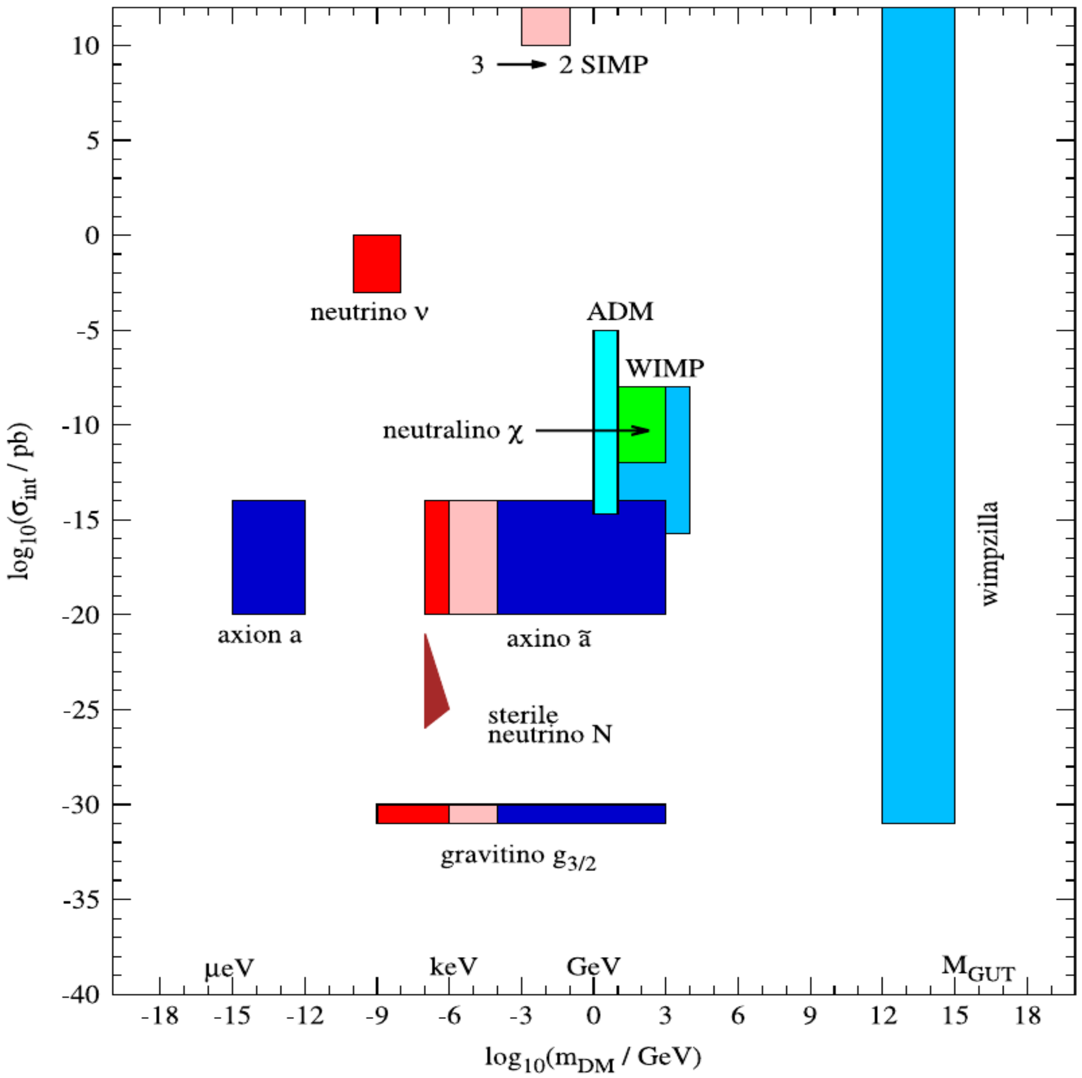
- ULDM: wavelike bosons
- 10^{-22} eV is λ_{dB}~0.4 kpc, (galactic cusp issues…)
- Huge new landscape
- Exciting new experiments
  - E.g. AION
- And good-old QCD axions

- LDM and WIMPs are (mostly) thermally-produced fermions
- WIMPs rely on EW gauge bosons down to Lee-Weinberg limit (~GeV)
  - Direct searches such as LZ
- LDM needs new mediators to avoid overproduction (e.g. dark photon)
  - Beam experiments (e.g. SHIP)
- Some LDM models are non-thermal
  - E.g. sterile neutrinos

- Heavy, (even) more exoteric
- Lumps of dark quark matter
- Dark matter "chemistry"?
- Primordial black holes back in fashion!

THE DARK MATTER LANDSCAPE

H. Baer et al. / Physics Reports 555 (2015) 1–60



Unfortunately,
there are two axes to this story

WAVE-LIKE DARK MATTER

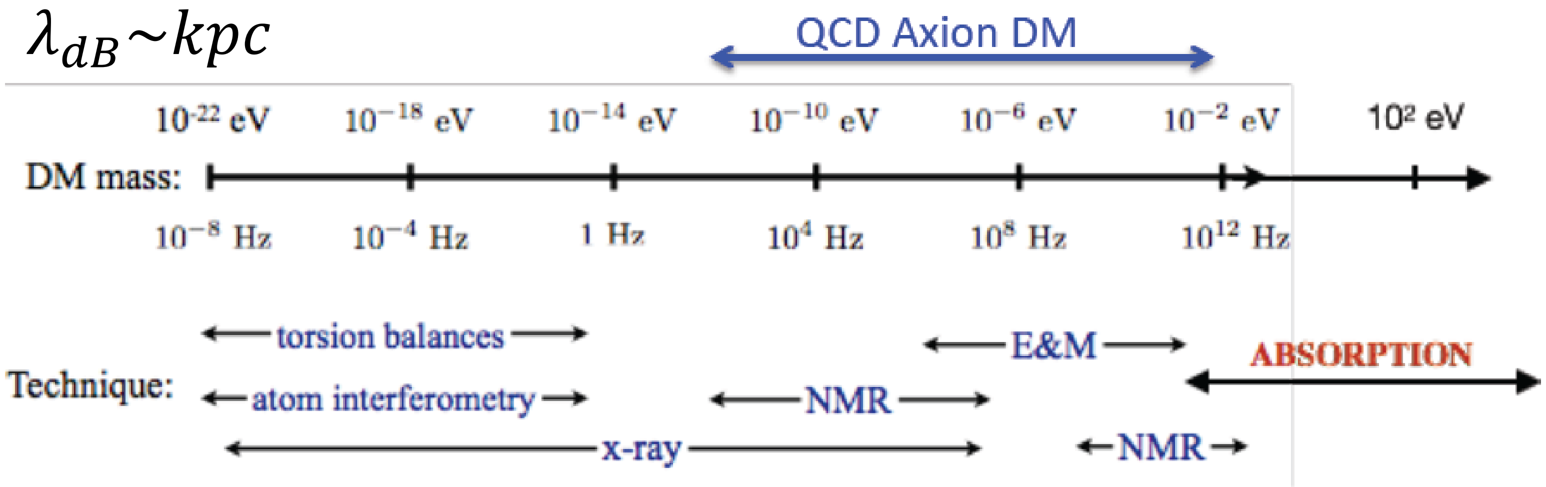
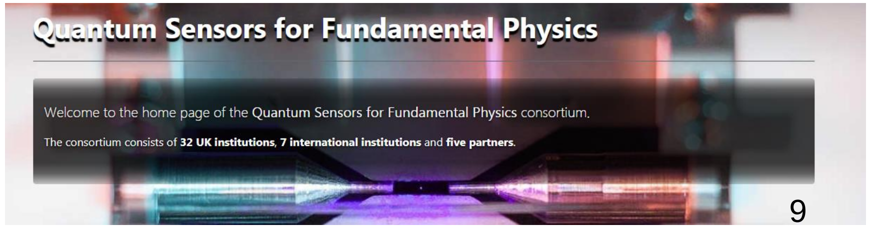


FIG. 2: Schematic illustration of the complementarity of different types of experiments in exploring QCD axion DM and ultralight DM more generally. The horizontal axis illustrates the observationally allowed mass range for ultralight DM, with an arrow highlighting the viable mass range for the QCD axion specifically. Indicative ranges of sensitivity for different techniques are illustrated by dark blue arrows for coherent field, new-force, and X-ray helioscope techniques (see Sec. V), while a red arrow indicates the range of DM masses that can be explored by absorption in direct-detection experiments (see Sec. IV).

US Cosmic Visions: New Ideas in Dark Matter 2017: Community Report (arXiv:1707.04591)



PRIMORDIAL BLACK HOLES? ~~NO~~ MAYBE?

Primordial black hole dark matter and the LIGO/Virgo observations
[Jedamzik 2020]

“The natural prediction of PBH DM formed during the QCD epoch yields a pronounced peak around 1M⊙ with a small mass fraction of PBHs on a shoulder around 30M⊙.

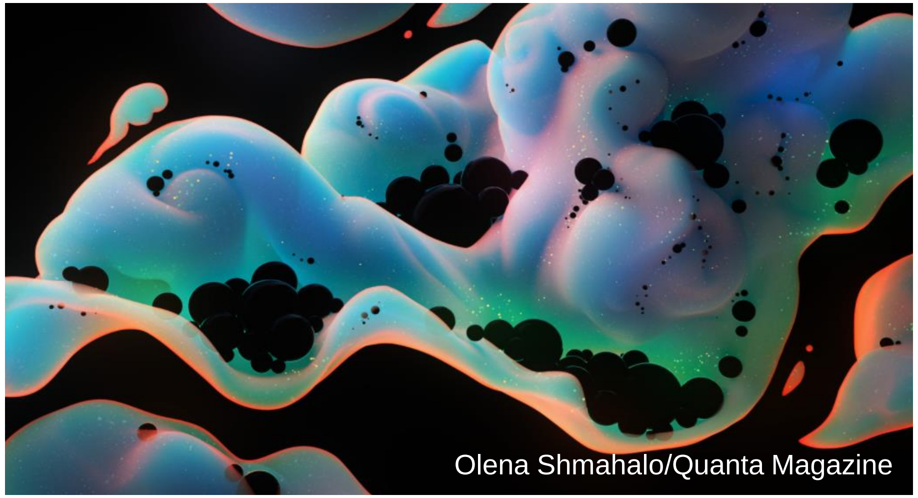
“[We make] a tentative prediction of the merger rate of ~30M⊙ PBH binaries, and find it very close to that determined by LIGO/Virgo.

“We show that current LIGO/Virgo limits on the existence of ~M⊙ binaries do not exclude QCD PBHs to make up all of the cosmic dark matter.

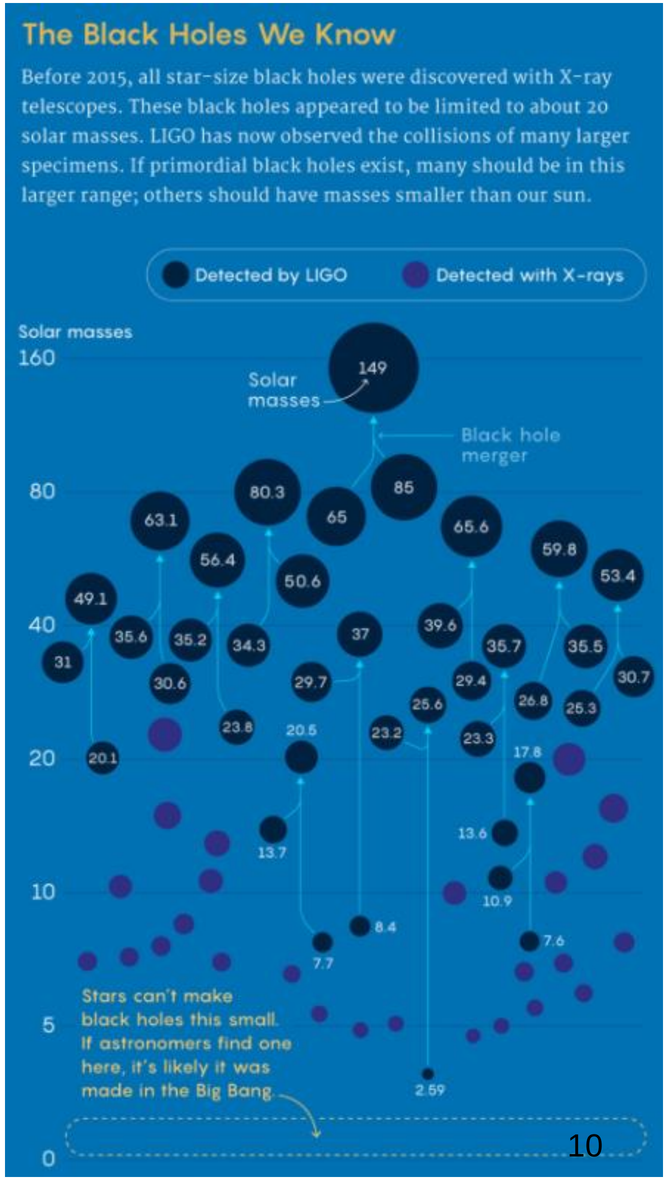
“Microlensing constraints on QCD PBHs should be re-investigated.”

H. Araújo

LIGO/Hanford

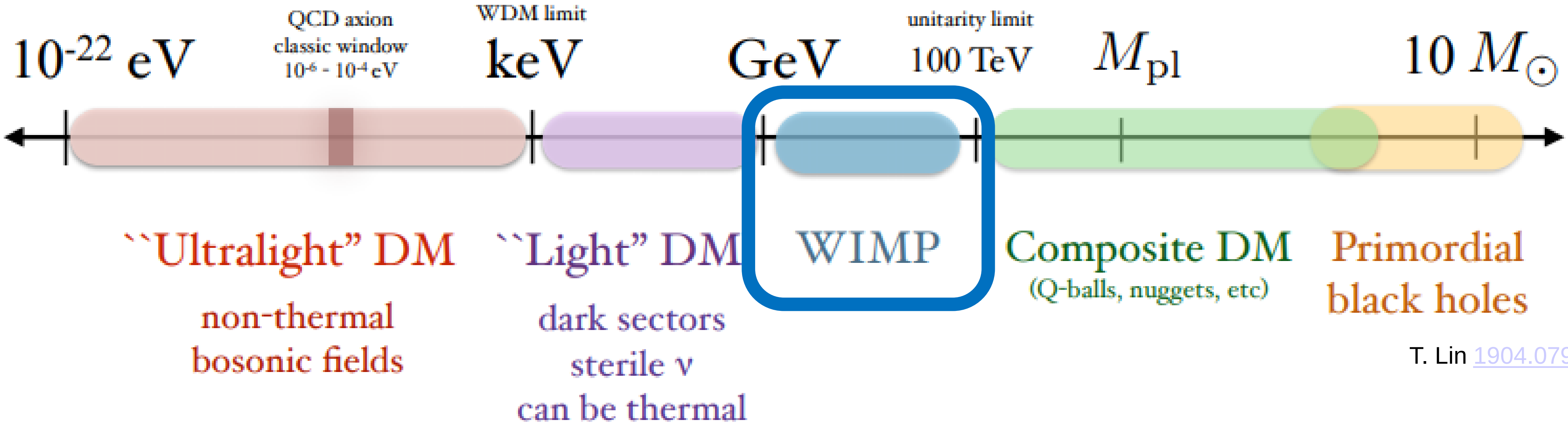


Olena Shmahalo/Quanta Magazine



WEAKLY INTERACTING MASSIVE PARTICLES

WIMPs are stable, neutral, slow, heavy particles produced in the early universe, which feel the gravitational force and – by design – the weak nuclear force



T. Lin 1904.07915

WIMPs can solve the DM problem in all its glory: astrophysical, cosmological, particle physics

WEAKLY INTERACTING MASSIVE PARTICLES

- If dark matter was in ***thermal equilibrium*** in a ***radiation-dominated*** universe:

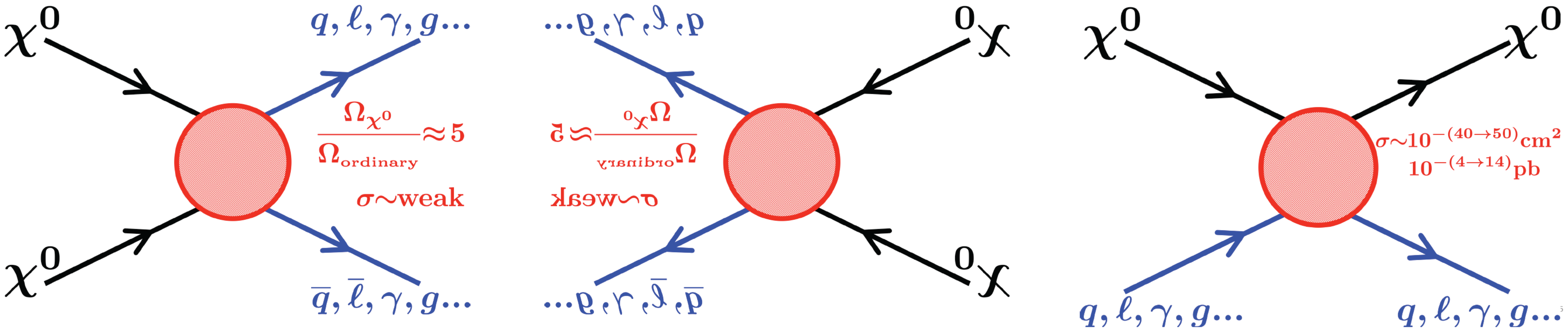
  1) The dark matter particle must be heavier than a few MeV
     (to avoid ruining the successful predictions of BBN)

  2) The dark matter particle must be lighter than ~100 TeV
     (to avoid exceeding the measured dark matter abundance)

- Furthermore, to ***freeze-out*** with the measured abundance, such a particle must annihilate through something comparable to the weak force – *“WIMP Miracle”*

- From this perspective, dark matter candidates with roughly weak-scale masses and interactions – “WIMPs” – are particularly well motivated.

WEAKLY INTERACTING MASSIVE PARTICLES



annihilation
(indirect detection)

production
(collider searches)

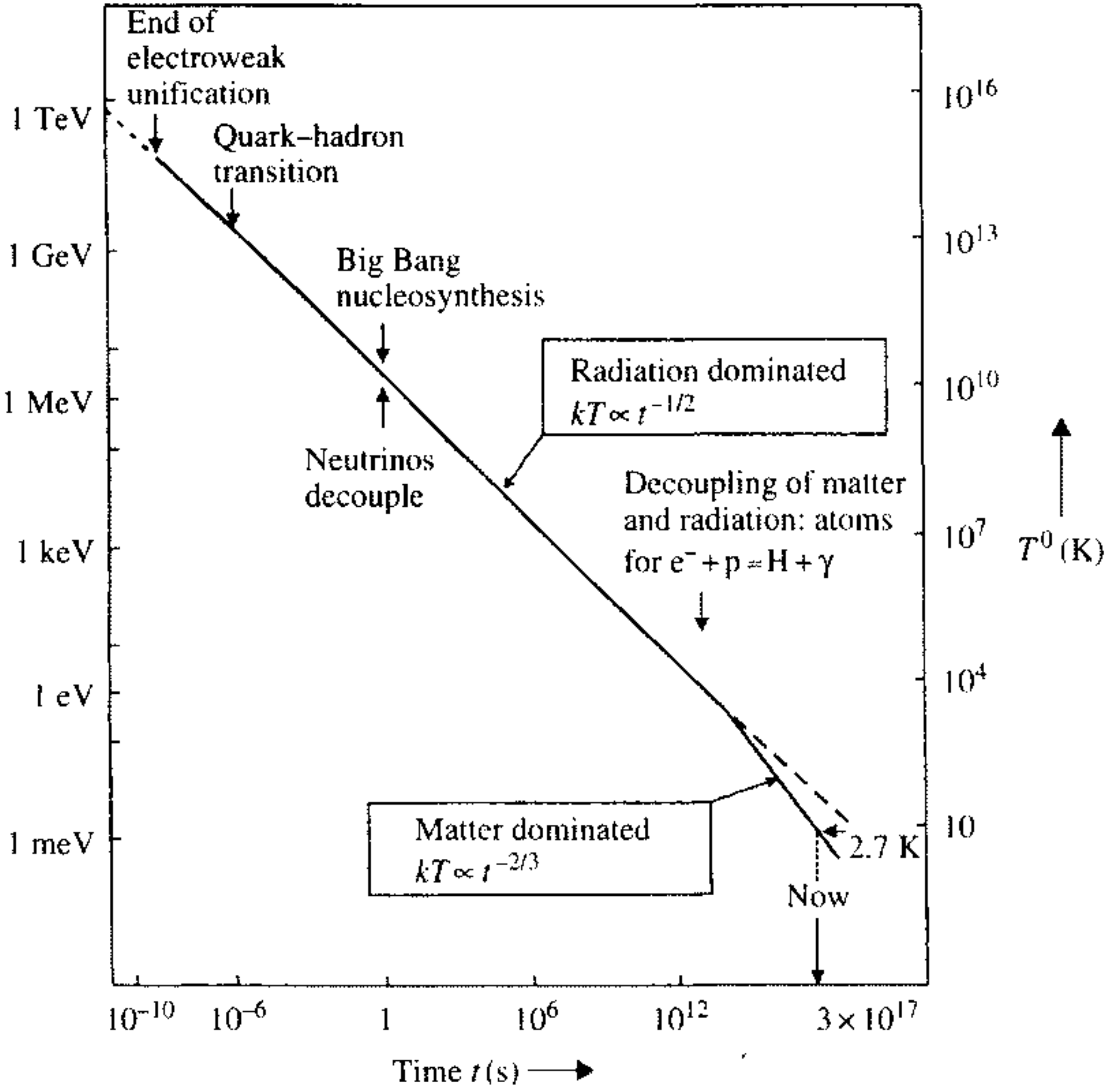
scattering
(direct detection)

thermal equilibrium
in early universe

WEAKLY INTERACTING MASSIVE PARTICLES

- **What do we know about these hypothetical particles?**
  - Cold (non-relativistic at freeze out)
    - Must not wipe out all structure in the early universe (CMB, n-body sims)
  - Non-baryonic
    - No room for more baryons (BBN, CMB baryon damping)
  - Stable
    - Half-life at least comparable to age of the universe
  - No electromagnetic/strong interactions
    - Or we would have “seen” them or “found” them in nuclei
  - ~1 GeV – ~100 TeV mass range
    - Thermal production fails to explain DM abundance beyond this range (more like ~MeV if EW gauge bosons not involved)
- **If WIMPs were produced soon after the Big Bang, how many would be around as a *thermal relic* today?**

AS TIME GOES BY…IT GETS COLDER



THE WIMP PARADIGM (FORMERLY "THE WIMP MIRACLE")

- **Primordial universe: local thermodynamic equilibrium**
  - thermal production rate = annihilation rate
- **Universe expands, a thermal relic is created**
  - Particle annihilation ceases faster than particle production
  - *freeze-out* when annihilation rate falls below expansion rate

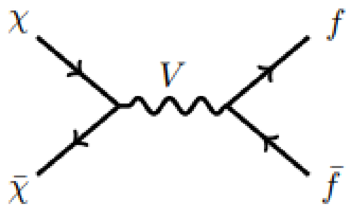
$$n\left\langle \sigma_A v \right\rangle \leq H$$

  - from MB statistics ($T \ll m_\chi$ *at freeze-out*),

$$n(T) = g\left(\frac{m_\chi T}{2\pi}\right)^{3/2} \exp\left(-\frac{m_\chi}{T}\right)$$

  - from cosmology in the radiation epoch,

$$H = 1.66\sqrt{g*}\,\frac{T^2}{m_{Pl}}$$



See e.g. Perkins, *Astroparticle Physics*

n – comoving number density
σ_A – $\chi\bar{\chi}$ annihilation XS
v – relative velocity
H – Hubble parameter at freeze-out
m_χ – WIMP mass
m_{Pl} – Planck mass
T – temperature
g – internal dof of particle
$g*$ – effective relativistic dof

<u>IF</u> (REMEMBER THIS…)

- If we were to assume that
  - The unknown annihilation XS is of the order of a <u>weak XS</u>, then we can write, for a non-relativistic WIMP:

$$\langle \sigma_A v \rangle \sim G_F^2 m_\chi^2$$

$$\langle \sigma_A v \rangle \sim G_F^2 T^2$$

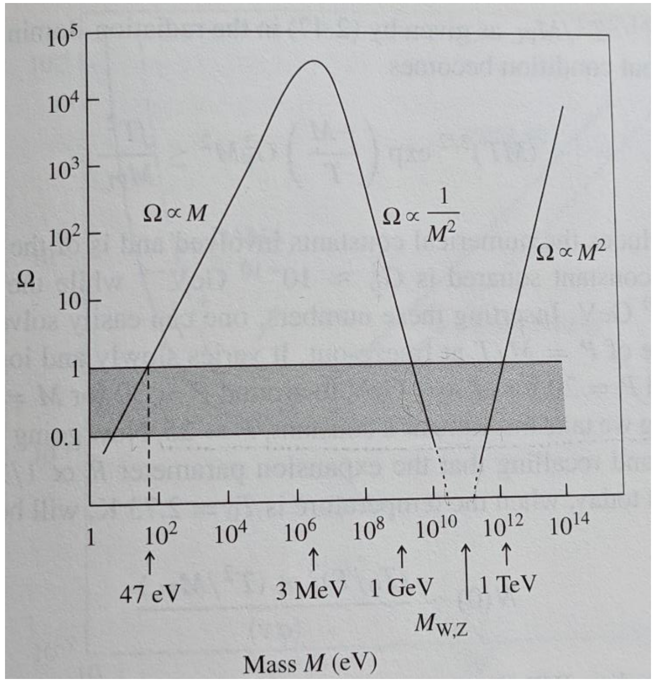
(for relativistic case)

  - The freeze-out condition then becomes:

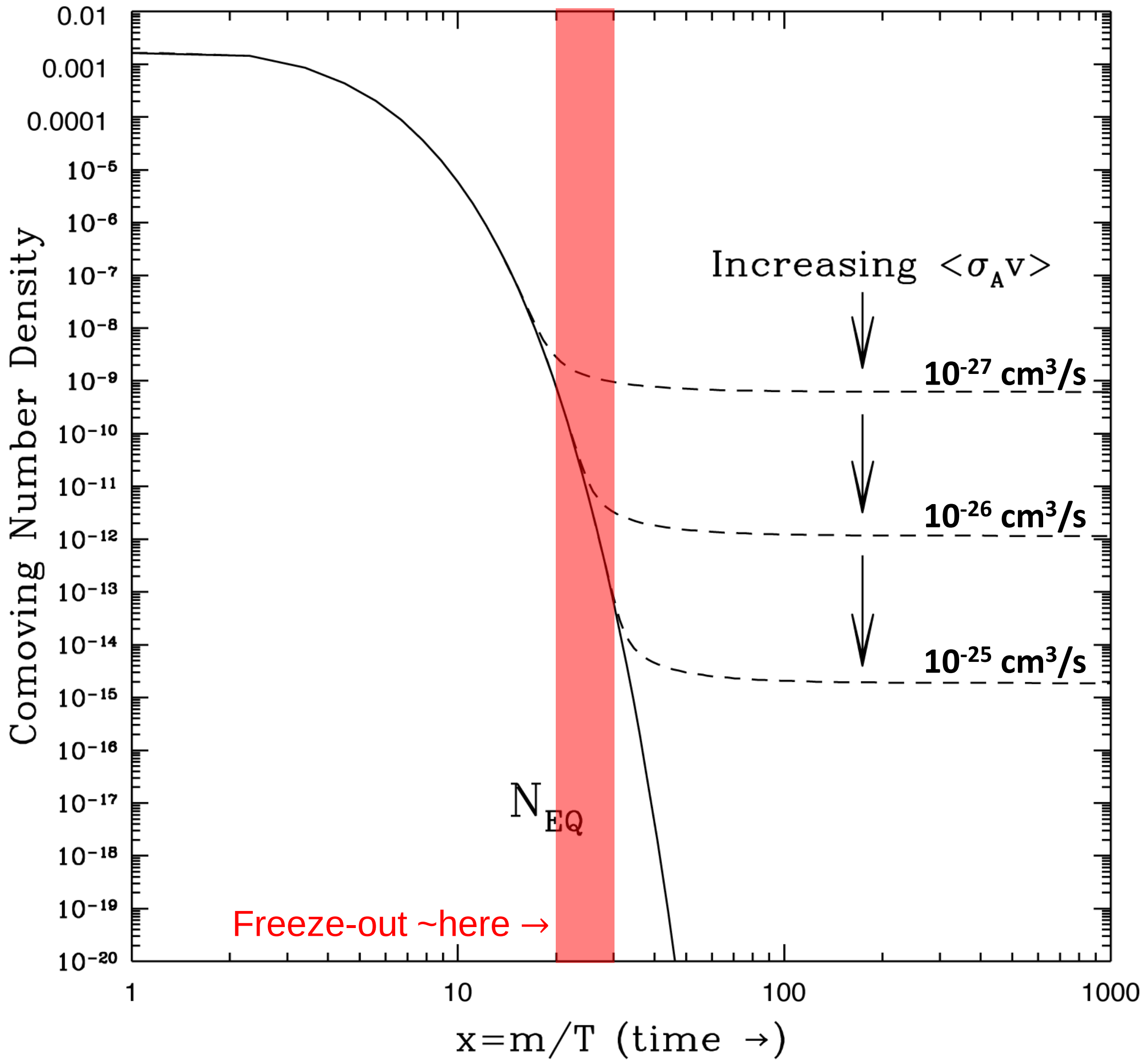
$$(m_\chi T)^{3/2} \exp\left(-\frac{m_\chi}{T}\right) G_F^2 m_\chi^2 = \frac{\sim 100\, T^2}{m_{Pl}}$$

  - Solve numerically for m_χ/T to find when freeze-out occurs
  - Solution: $m_\chi/T \sim 20 - 30$ for $m_\chi = 1 - 100$ GeV

Perkins, *Astroparticle Physics*



WIMP COMOVING NUMBER DENSITY



THEN

- Take m_χ/T = 25 and calculate WIMP number density today (T_0 = 2.73 K), using $n(T) = H(T)/\langle\sigma_A v\rangle$ and noting that the scale-factor $a(t) \propto 1/T$:

$$n(0) = \left(\frac{T_0}{T}\right)^3 \frac{T^2/m_{Pl}}{\langle\sigma_A v\rangle}$$

If the comoving number density n had a certain value at freeze out, what would the density $n(0)$ today?

- Then we obtain the WIMP density parameter:

$$\Omega_\chi = \frac{\rho_\chi}{\rho_c} = \frac{m_\chi n(0)}{\rho_c} \sim \frac{10^{-25}\ \mathrm{cm}^3/s}{\langle\sigma_A v\rangle}$$

What is the density parameter associated with this?

- Finally, confirm that v is small-ish at freeze-out; for $m_\chi/T \sim 25$,

$$\frac{1}{2} m_\chi v^2 = \frac{3}{2} k_B T \ \rightarrow \frac{v}{c} \sim 0.3$$

Good, we promised a cold dark matter candidate

- For a typical weak XS $\langle\sigma_A v\rangle \sim 10^{-26}$ cm^3/s (10-100 pb) WIMPs close the Universe!

$$\Omega_\chi \sim 0.1\text{–}1$$

WHY IS THIS REMARKABLE?

- There is no *a-priori* relationship between the weak interaction (particle physics) and the closure density of the universe (cosmology)

- The energy scales involved are staggeringly different:
  - H ~ 10^{-42} GeV
  - T_0 ~ 10^{-13} GeV
  - m_χ ~ 10^{1-3} GeV
  - m_{Pl} ~ 10^{19} GeV

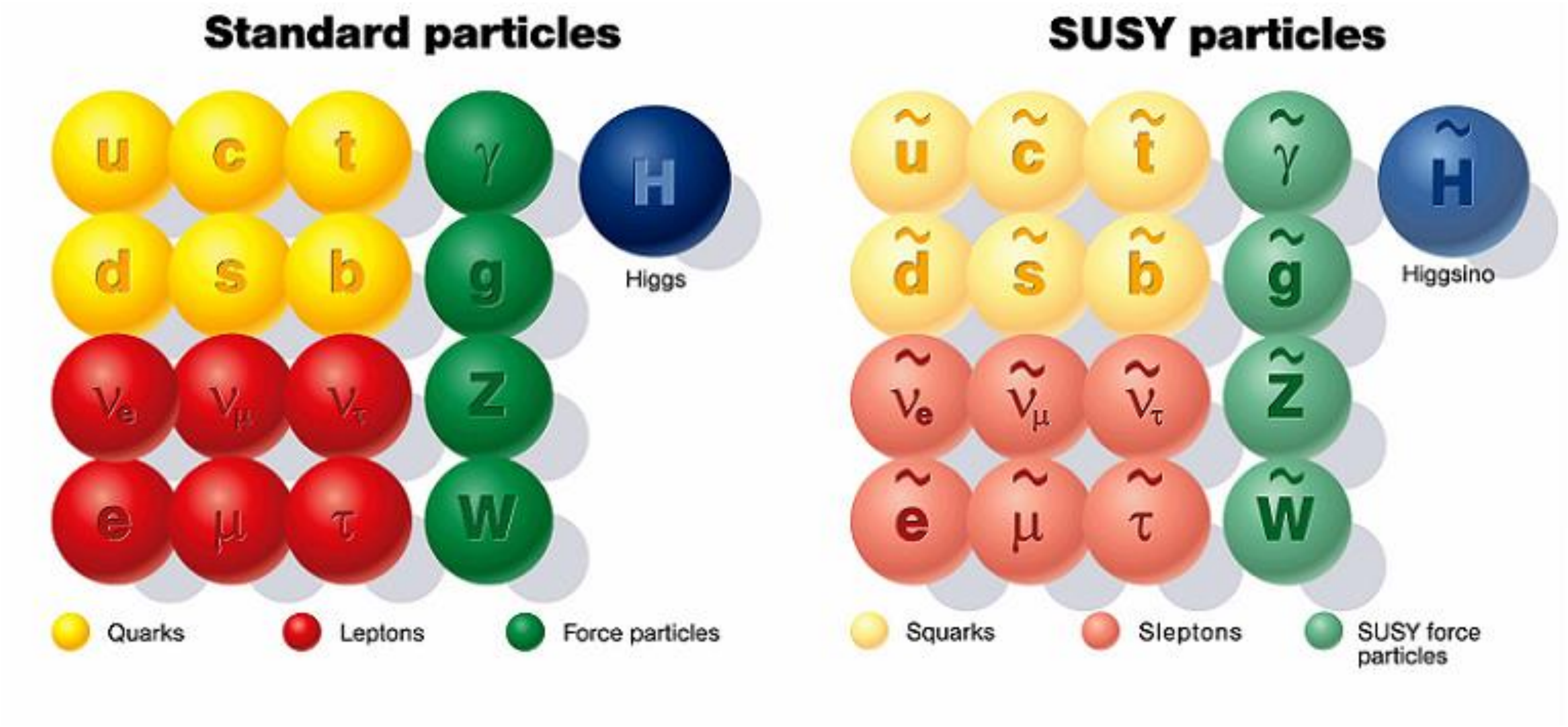
- If there is a new, stable particle
  associated with physics at the electroweak scale,
  then its relic density is sufficient to close the universe;
  i.e. that particle *is* the dark matter

COINCIDENCE?

It could be – but it would be foolish not to look!

SUPERSYMMETRY

- Supersymmetry postulates that for every SM particle there is a corresponding 'sparticle' with spin differing by ½ unit (SM fermions have bosonic SUSY partners and vice-versa)



SUPERSYMMETRY

- SUSY was proposed to solve the hierarchy (naturalness) problem from quadratically-divergent quantum corrections to the Higgs mass

- And to neatly unify the strong and electroweak interactions at ~10^{16} GeV

- SUSY was NOT proposed to solve the dark matter problem...
  But it would, in a rather elegant and natural way

  - Heavier particles decay to the LSP in R-parity conserving processes

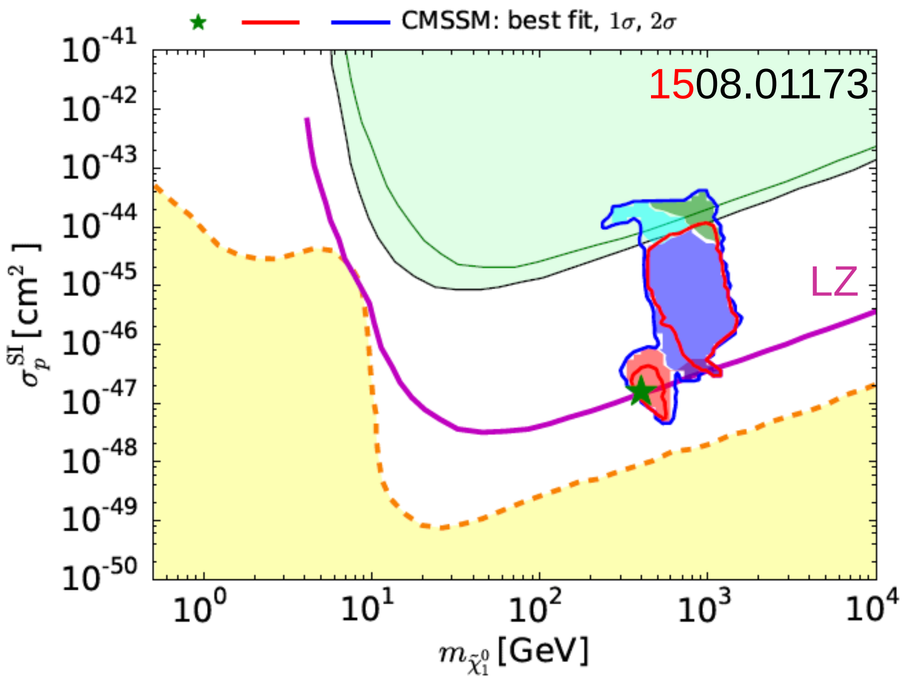
$$R \equiv (-1)^{3(B-L)+2S}$$

  - SUSY predicts a new, stable, elementary particle with M_χ ~ TeV which interacts *weakly* with ordinary matter: the **neutralino** is a great WIMP

  - (But not all WIMPs are neutralinos)

BUT WHERE IS SUSY?

- We have already ruled out the canonical WIMPs, so the “WIMP miracle” may just be a coincidence
- But SUSY is always hiding “around the corner”
- Significant parameter space remains well motivated
- In any case, not all WIMPs emerge from SUSY



LETTERS

Who Ordered Theorists?

The science wars that continue in PHYSICS TODAY seem to be only between theorists of various kinds discussing *gedanken* physics. They don't see the real physics as an experimental science that progresses from one experimental breakthrough to another. Theorists are often irrelevant and sometimes actually hinder progress by sitting on committees and opposing the experiments that lead to new breakthroughs. As we begin this new century, "Who needs theorists?" would be an interesting question to ask. How would physics have progressed in the second half of the 20th century—that is, since I received my PhD in 1950—if theorists had been ignored?

The main breakthroughs in physics since 1950 can be characterized as "who-ordered-that?" effects, named after I. I. Rabi's famous remark about the discovery and existence of the particle we now call the muon. The physics of the 1950s was one experimental discovery of a new who-ordered-that particle after another, with no theoretical prediction beforehand and no theoretical understanding afterward. Finally, by the 1960s, enough who-ordered-that particles had been discovered so that Murray Gell-Mann and Yuval Ne'eman could put them into a kind of Mendeleev table without any under-

and evidence that the partons were quarks, were resisted by the theoretical establishment, as dramatically reported by David Gross at the 1992 SLAC History Conference.

The 1974 November Revolution began with the who-ordered-that discovery of the J/psi by experiments that theorists had insisted were completely useless and a waste of valuable beam time and budget. Of course, as soon as the discovery was confirmed, a chorus of theorists claimed that they had predicted the existence of this hidden charm particle. But none of them had suggested to Burt Richter and Sam Ting to do the experiments that actually found the J/psi. I was one of the theorists who told experimenters how to look for charm in ways that turned out to be useless. My suggestions that charm would most likely be found in electron–positron collisions and that the charm threshold would be seen as an enormous increase in strange particle production were correct, and were recorded in the review by Ben Lee, Mary K. Gaillard, and Jonathan L. Rosner of how to look for charm. But the effect was masked by the next who-ordered-that effect, the discovery of the tau lepton by Martin L. Perl, which cancelled my strange particle excess by a roughly equal number of nonstrange particles. The-

LETTERS (continued from page 15)

sense of them. Now we have the Standard Model. But the Standard Model did not result from great theoretical or philosophical visions. It arose from a succession of who-ordered-that and other pioneering experiments that defied the theorists until there were enough data to enable an after-the-fact analysis that would lead the theorists in the right direction.

I have no patience with social scientists, historians, and philosophers who insist that the "scientific method" is doing experiments to check somebody's theory. The best physics I have known was done by experimenters who ignored theorists completely and used their own intuitions to explore new domains where no one had looked before. No theorists had told them where and how to look.

What guides their explorations? How do they choose where to look? How do they know when to persevere despite continuous failure to find anything new? How do they know when to drop an unproductive line and move on, rather than obstinately pursuing a dead end? These are the questions I should like to see social scientists, historians, and philosophers investigate.

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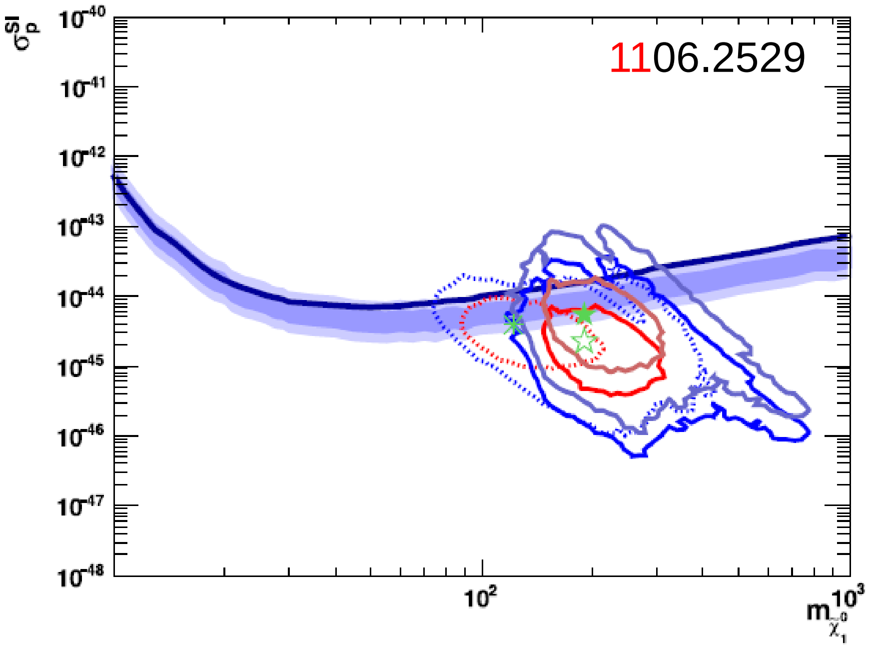
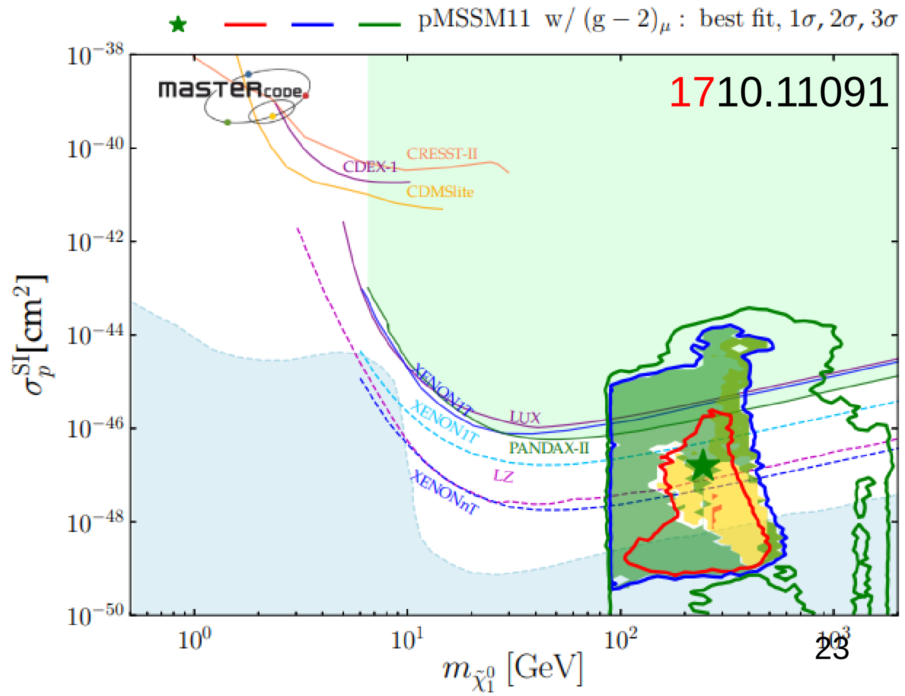
https://physicstoday.scitation.org/doi/pdf/10.1063/1.1292467





RECONCILNIG WIMPS

After D. Hooper

Too soon for despondency: plenty of well-motivated parameter space to explore, and good reasons to stretch the thermal DM paradigm to lower cross sections:

- Co-annihilations between the dark matter and another state
- Annihilations to W, Z and/or Higgs bosons; scattering with nuclei only occurs through highly suppressed loop diagrams
- Interactions which suppress elastic scattering with nuclei by powers of velocity or momentum
- Dark matter that is lighter than a few GeV
- Departures from radiation domination in the early universe
- The dark matter is part of a “hidden sector”

(OUR VERY OWN) GALACTIC DARK MATTER

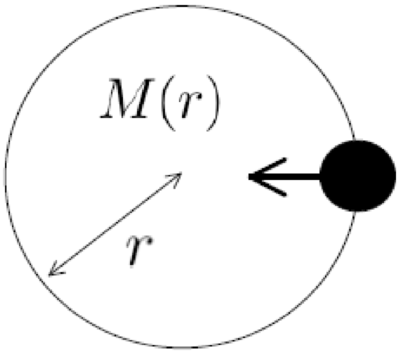
- Approximate as isothermal sphere (no lumps) with Maxwellian velocity distribution
  - But how can we estimate the DM local density ρ_0 and the velocity dispersion?

You are looking at a snapshot of an ‘n-body simulation’ of the Milky Way’s DM halo

(Aquarius Project http://www.mpa-garching.mpg.de/aquarius/)

DYNAMICS: DARK HALO DENSITY PROFILE

- Consider a mass distribution $M(r)$ and apply Newton's laws to an orbiting body with mass m:



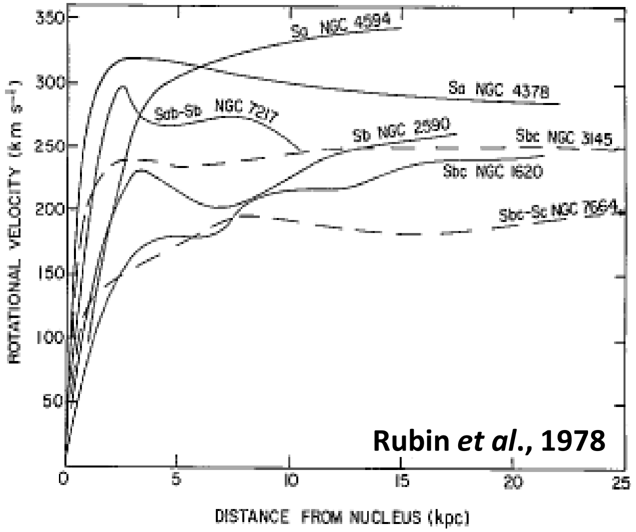
$$G\frac{M(r)m}{r^2} = \frac{mv^2}{r} \quad \rightarrow v^2 = \frac{GM(r)}{r}$$

- If v is constant,

$$M(r) = \frac{v^2 r}{G} \propto r$$

- For a spherical halo $dM(r) = 4\pi r^2 \rho(r) dr$

$$\frac{dM(r)}{dr} = \frac{v^2}{G} = 4\pi r^2 \rho(r)$$

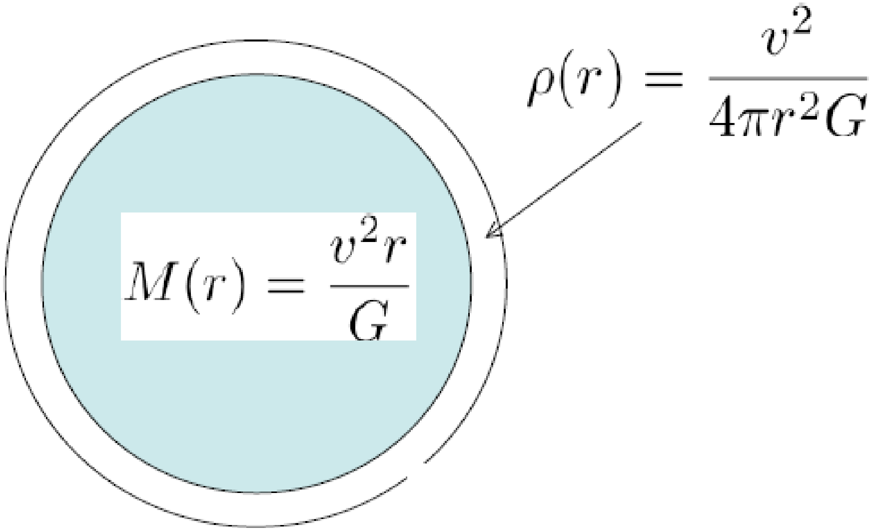


- So, to produce a flat rotation curve we need:

$$\boldsymbol{\rho(r) = \frac{v^2}{4\pi r^2 G} \propto r^{-2}}$$

DYNAMICS: PARTICLE VELOCITY DISTRIBUTION

1. <u>Potential energy</u> contained in halo up to radius R:



$$V = -\int_0^R \frac{GM(r)4\pi r^2 \rho(r)}{r} dr = -\frac{\boldsymbol{v^4 R}}{\boldsymbol{G}}$$

DYNAMICS: PARTICLE VELOCITY DISTRIBUTION

2. Kinetic energy contained in the isothermal halo up to radius R:

$$T = \frac{1}{2}\int_0^R 4\pi r^2 \rho(r)\overline{v_H^2}\,dr$$

$$= \frac{1}{2}\int_0^R 4\pi r^2 \frac{v^2}{4\pi r^2 G}\overline{v_H^2}\,dr$$

$$= \boldsymbol{\frac{v^2\,\overline{v_H^2}\,R}{2G}}$$

- Now, using the Virial Theorem: $V = -2T$

$$\frac{v^4 R}{G} = \frac{v^2\,\overline{v_H^2} R}{G} \rightarrow \boldsymbol{\overline{v_H^2} = v^2}$$

Remarkable result:
rms speed of halo particles
equals *circular speed*
of an orbiting body!

DYNAMICS: LOCAL DARK MATTER DENSITY

- And here on Earth?

$$\rho(r) = \frac{v^2}{4\pi r^2 G}$$

- Take for the velocity the measured orbital velocity of the Sun or other nearby stars around the galactic centre, $v_c \approx 220$ km/s

- Our distance to the galactic centre, $r \approx 8.1$ kpc = 2.5×10^{20} m

- This gives:

$$\rho_0 \sim 0.3 \text{ GeV/cm}^3$$

STANDARD HALO MODEL (SHM)

- **Density profile: cored isothermal halo**

Isothermal sphere with flattened core containing Maxwell-Boltzmann gas:

$$\rho_{\mathrm{Iso}}(r) = \frac{\rho_0}{(1 + r/r_c)^2}$$

Note $\rho \sim r^{-2}$ at large r (flat rotation curve)

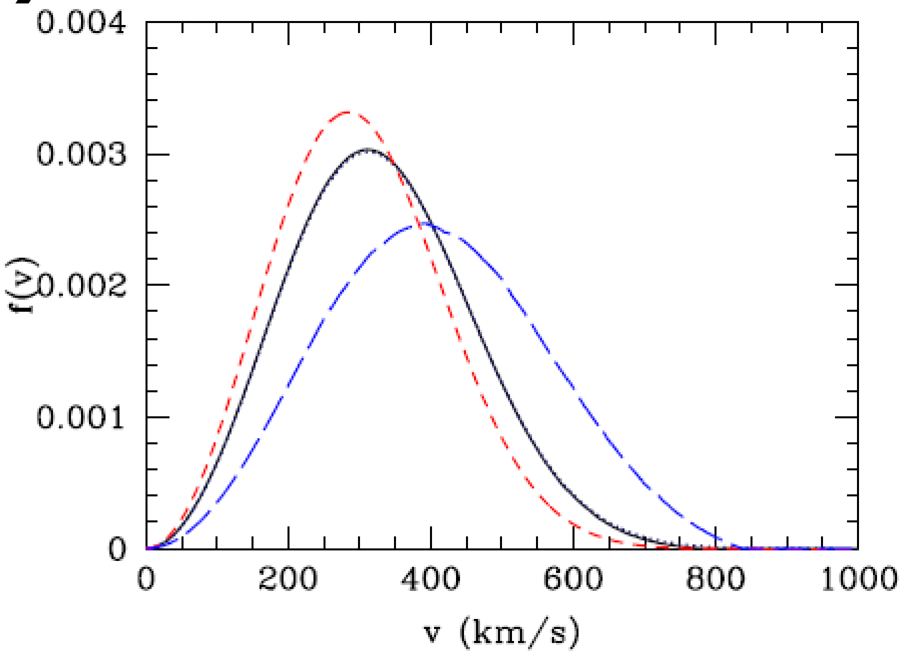
- **Local Density**

ρ_0 = 0.3 GeV/cm^3

- **Velocity distribution**

Maxwellian (Gaussian) velocity distribution, truncated at the galactic escape velocity v_{esc}

For scattering rates need to boost to Earth (detector) frame



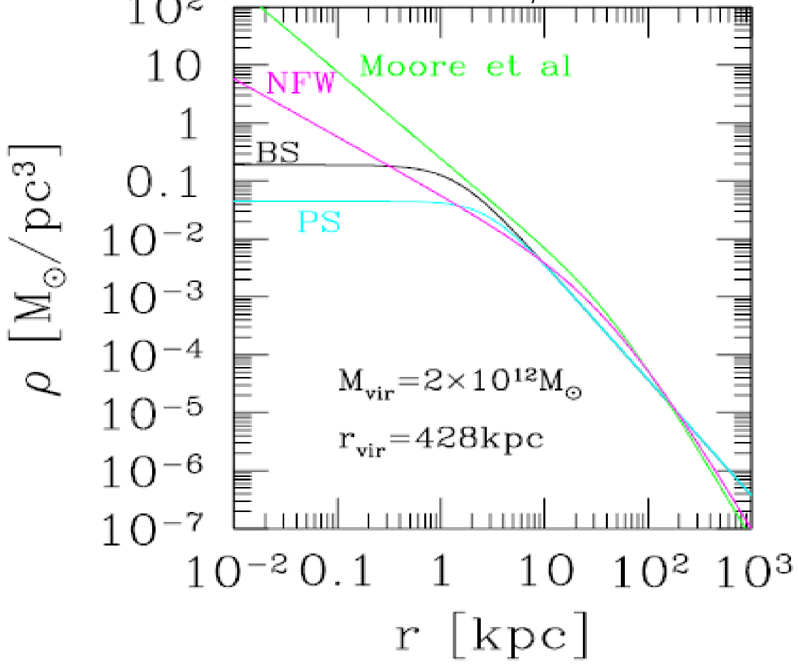
$$f_1(v')\,\mathrm{d}v' = \frac{4v'^2}{\sqrt{\pi}v_0^3}\exp\left(-\frac{v'^2}{v_0^2}\right)\mathrm{d}v'$$

$$v' = v + v_c,\ v_c \sim v_0 \approx 220\,\mathrm{km/s}$$

$$v_{esc} \approx 544\ \mathrm{km/s}$$

MORE REALISTIC HALO MODELS

P. Gondolo, arXiv:0403064



Moore profile

$$\rho_M(r) = \frac{\rho_0}{(r/r_M)^{1.5}[1+r/r_M]^{1.5}},$$

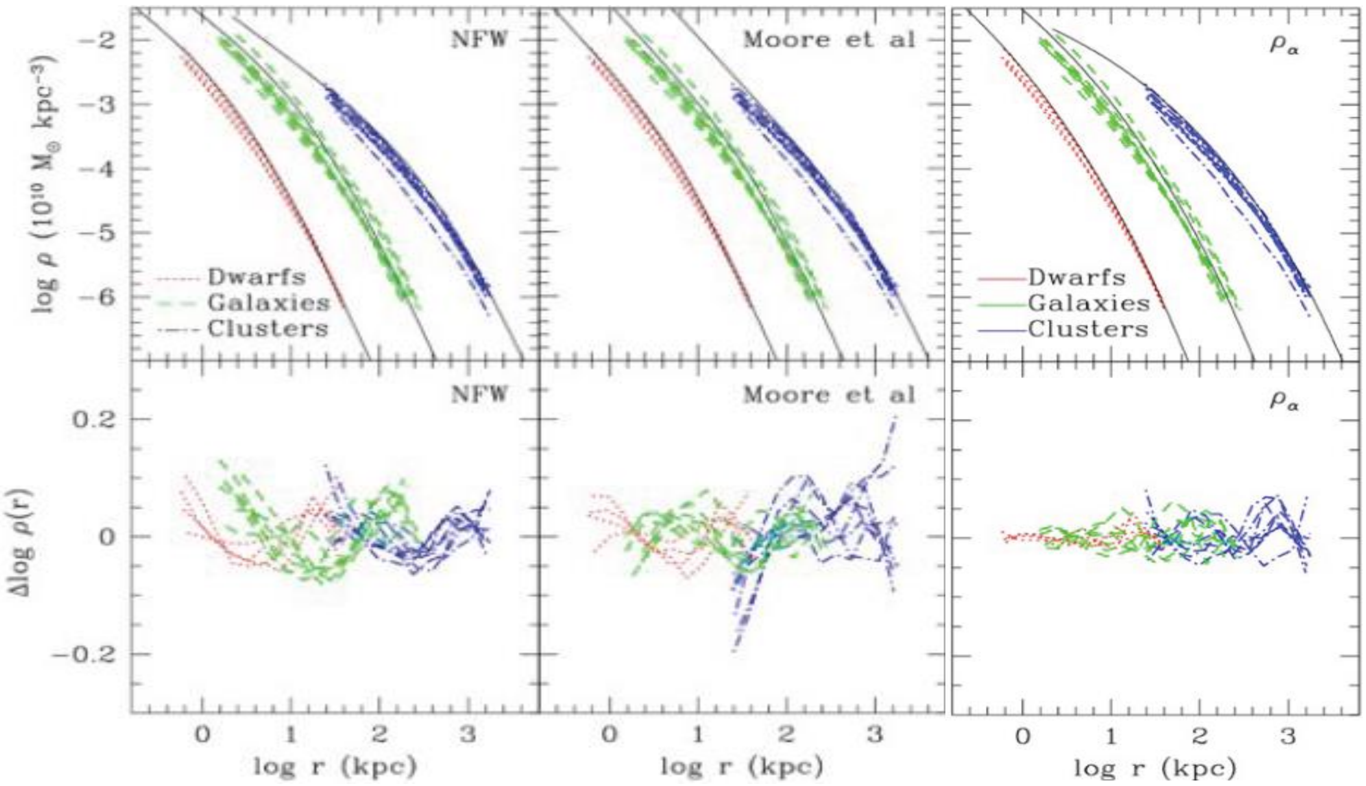
NFW profile

$$\rho_{\rm NFW}(r) = \frac{\rho_0}{(r/r_s)[1+r/r_s]^2},$$

Einasto profile

$$\rho(r) \propto \exp\left(-Ar^{\alpha}\right)$$

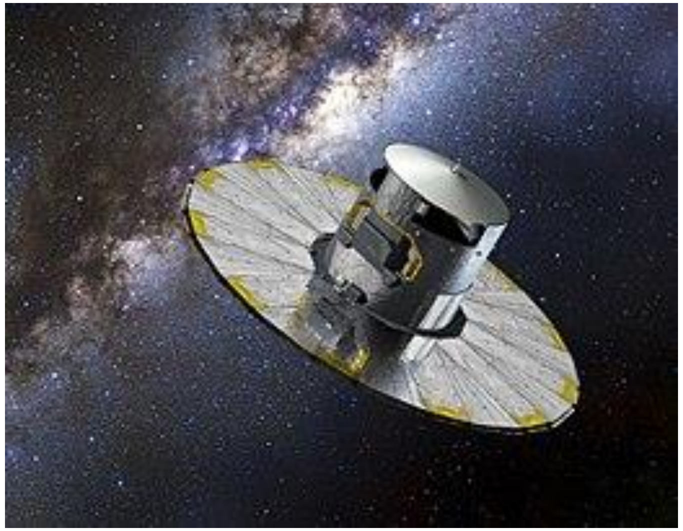
- Realistic halos calculated from n-body simulations (first DM-only, now with baryons too)
- In general these are not far from the Moore and Navarro-Frenk-White profiles; Einasto seems to do a better job



MORE REALISTIC HALO MODELS (THE "SAUSAGE")

- GAIA data transforming understanding of our galaxy: DM halo shape, circular speed and escape velocity better pinned down; better local DM density soon
- Local stellar halo seems to have two component due to an ancient head-on collision with a massive satellite galaxy. As a result, the local halo is bimodal.

https://www.nature.com/articles/d41586-019-00123-y



Credit: A. Fattahi (ICC, Durham, UK) and the Auriga Collaboration

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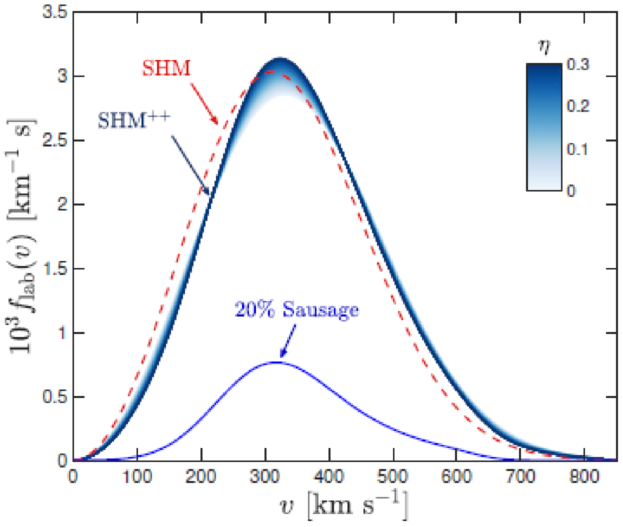
PDG Review 2020

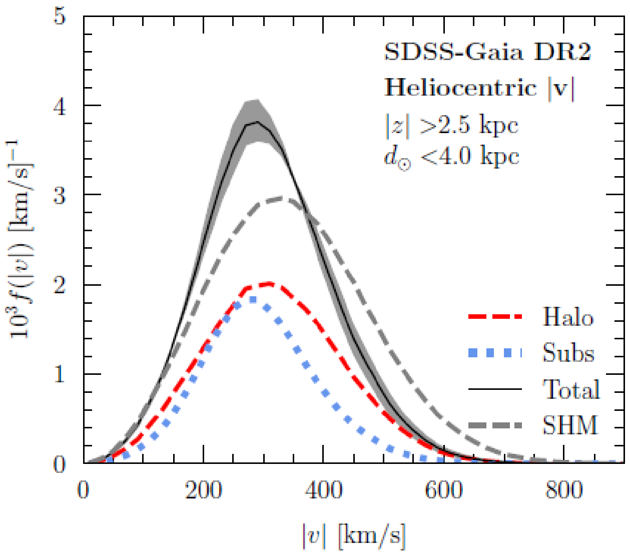
Ultimately the goal is to determine the velocity distribution from observations (for example by studying the motion of stars that share the same kinematics as the DM), and the *Gaia* satellite data offers a unique opportunity to study the various stellar populations. Recently it was revealed that the local stellar halo has two components: a quasi-spherical, weakly rotating structure with metal-poor stars, and a flattened, radially anisotropic structure of metal-rich stars, which arose due to accretion of a large ($10^{11-12}\,M_\odot$) dwarf galaxy around (8-10)$\times 10^9$ y ago [59]. The expectation is that the local DM halo shows a similar bimodal structure, and first velocity distributions of the two components - using the stellar populations as tracers - were inferred in [60]. In Ref. [61], an updated halo model is introduced: it includes the anisotropic structure seen in the *Gaia* data and provides an analytic expression for the velocity distribution. The value of the local DM density is updated to $(0.55 \pm 0.17)\,\mathrm{GeV/cm^3}$, where the 30% error accounts for the systematics. The circular rotation and the escape speeds are updated to $v_c = (233 \pm 3)$ km/s and v_{esc}=528^{+24}_{-25} km/s.

1st June, 2020 8:29am

arXiv:1810.11468



arXiv:1810.12301



TODAY'S CONCLUSIONS

- Gravitational mass is "missing" at all scales/times, including in our own galaxy
  - The case for "dark matter" is incontrovertible, but no direct observation yet
- Several well motivated candidates exist, the most popular are (still) thermal relics with weak interactions: WIMPs solve the DM puzzle in all its dimensions
  - In recent years the community has started to adopt a "no stone unturned" approach, exploring the full range of possibilities from 10^{-22} eV to $M_\odot$ masses
- Newtonian dynamics of spiral galaxies demands a dominant DM component: visible matter alone does not provide strong enough a potential well
  - DM halos are much larger than visible galaxy; 3D structures rather than 2D discs
  - Particle *rms* velocities similar to orbital velocities (Sun), v_0 ~ 220 km/s (~0.001c)
  - Average local density is ~0.3-0.6 GeV/cm^3
  - This is our dark matter: going through you and me right now – can we detect it?