Looking for the dark side of the Universe

F. Neves (LIP Coimbra)

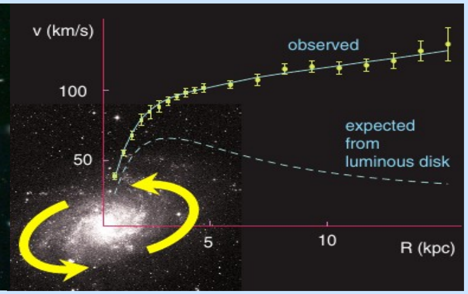
Café com Física, DFUC, 3 Oct 2018

Outline

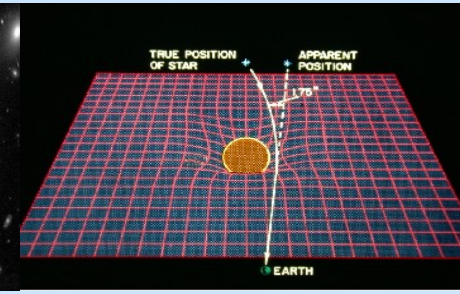
- Why Dark Matter: the experimental evidences;
- What is Dark Matter and its properties;
- How Can we detect Dark Matter;
- Direct detection: Axions and WIMPs;
- Gravitational waves;
- Recent progress & future directions.

Dark Matter evidences overview

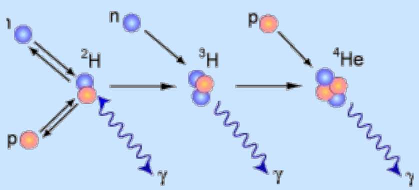
Motion of stars, gas and galaxies
(1st reference in 1933 by Fritz Zwicky)

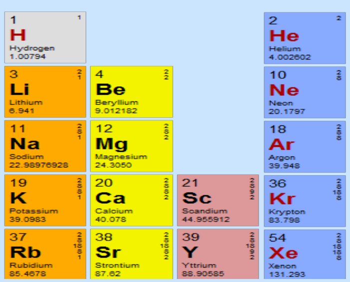


Gravitational Lensing

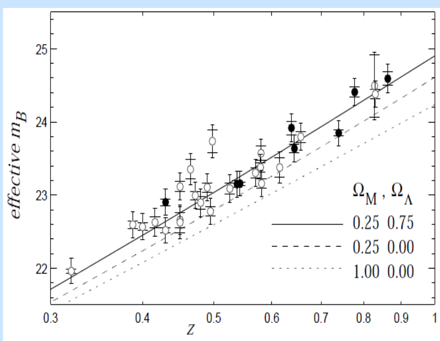


Nucleosynthesis





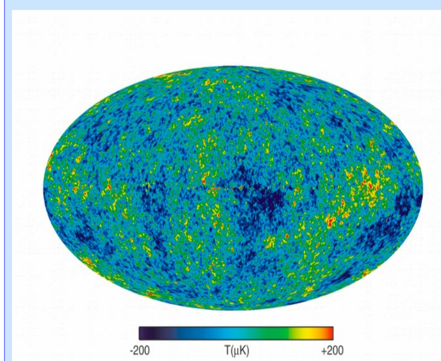
Supernovae



Ω_Λ = 0.702 ± 0.02

Ω_m = 0.298 ± 0.0022

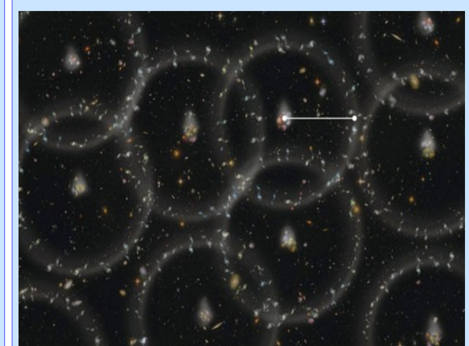
Cosmic microwave background



Ω_m = 0.3111 ± 0.0056

Ω_b = 0.0224 ± 0.0002

Baryonic acoustic oscillations

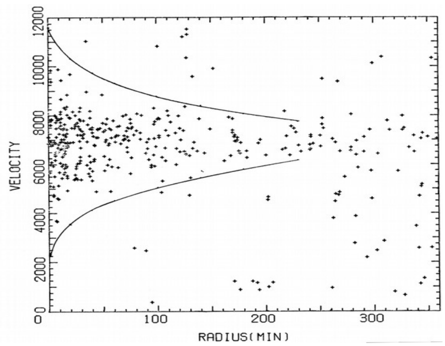


Ω_m = 0.296 ± 0.029

Ω_Λ = 0.699 ± 0.100

First Dark Matter evidences: Motion of stars, gas and galaxies

Velocity of galaxies:



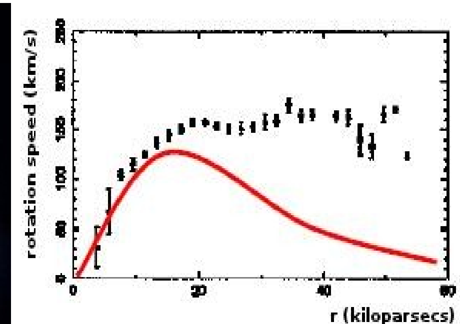
- Fritz Zwicky, 1933;
- Measurement of the velocity of galaxies in the *Coma* cluster;
- Using the Virial theorem:

$$\langle KE\rangle = -\frac{1}{2}\langle PE\rangle$$

$$\frac{1}{2}Mv^2 \qquad\qquad G\frac{Mm}{R}$$

- Concluded: $\mathbf{M_{visible}}$ $\mathbf{\sim 0.005 M_{cluster}}$

Galaxy rotation curves:



- Vera Rubin, 1970;
- If most of the matter was in the bulk of the galaxy (ie. luminous mass):

$$\frac{mv_r^2}{r} = G\frac{mM}{r^2} \rightarrow v_r \sim \frac{1}{\sqrt{r}}$$

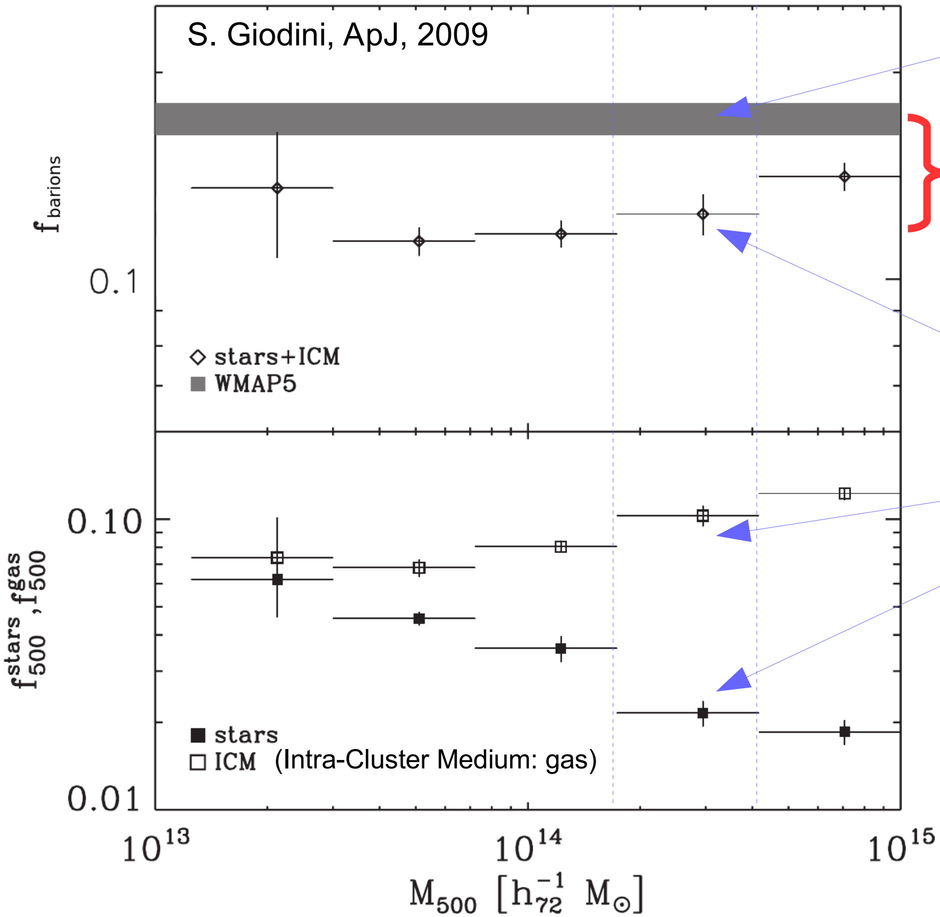
- But we observe v_r~const, which implies:

$$\frac{M(r)}{r} \sim const$$

- With a fraction of $\mathbf{M_{visible}}$ $\mathbf{\sim 0.3 M_{galaxy.}}$

Dynamic of galaxy clusters

- Systematic survey of 118 galaxy clusters with $0.1 \leq z \leq 1$ ($M_{500} \sim 10^{13} - 10^{15}\ M_\odot$)



WMAP (5 years) result (2009)

Only ~5% discrepancy in missing baryons when compared to CMB results (i.e. all Universe).

Sum of gas and stars (all baryons)

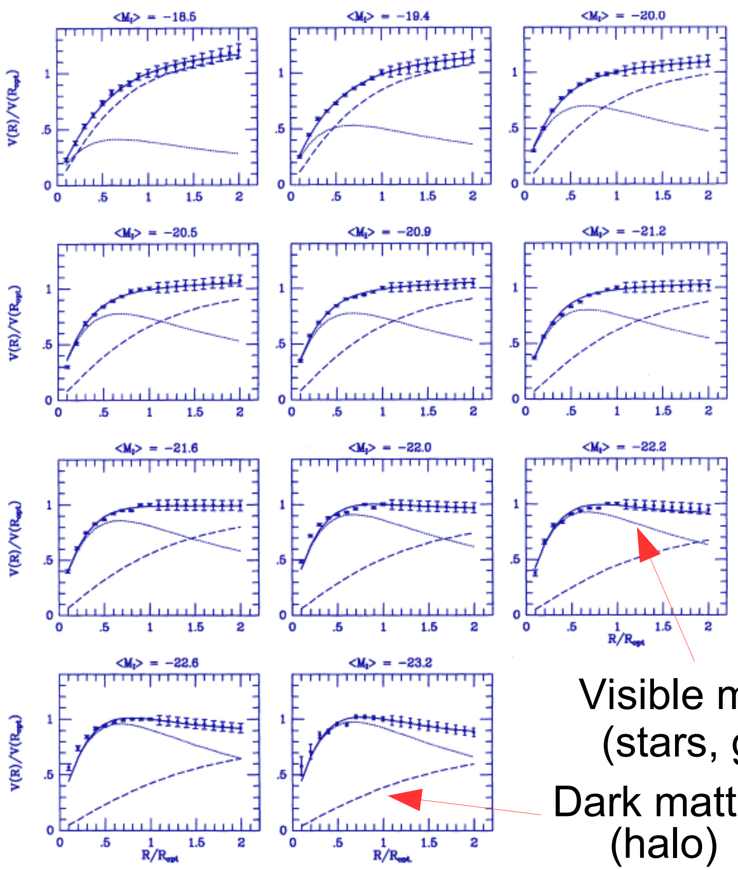
10% of mass in gas

2% of mass in stars

- **~83% of mass in non-baryonic Dark Matter!**

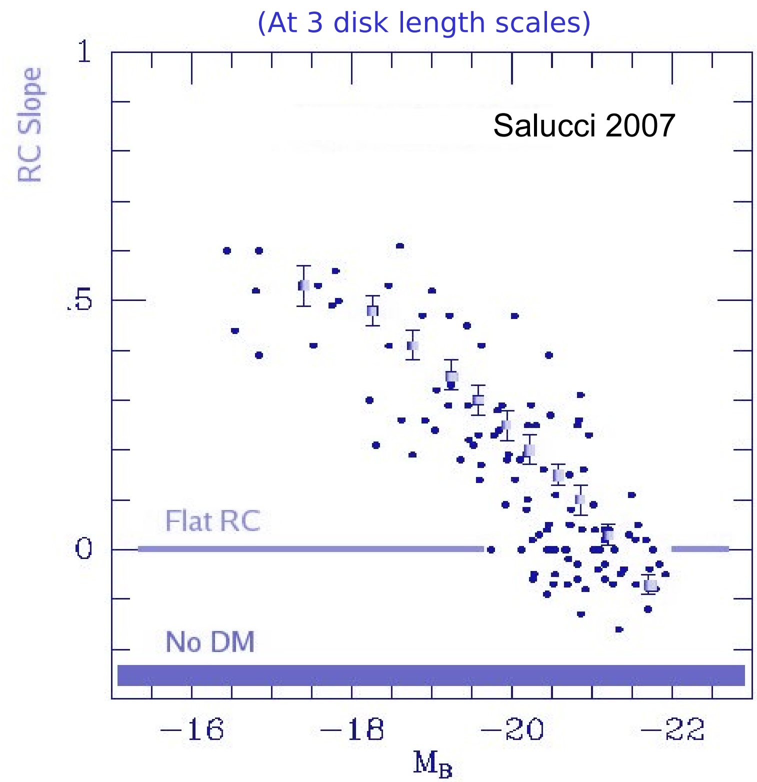
Dynamic of galaxies: rotation curves (RC)

3200 spiral galaxies
(magnitude from -22 to -16)



Visible matter
(stars, gas)

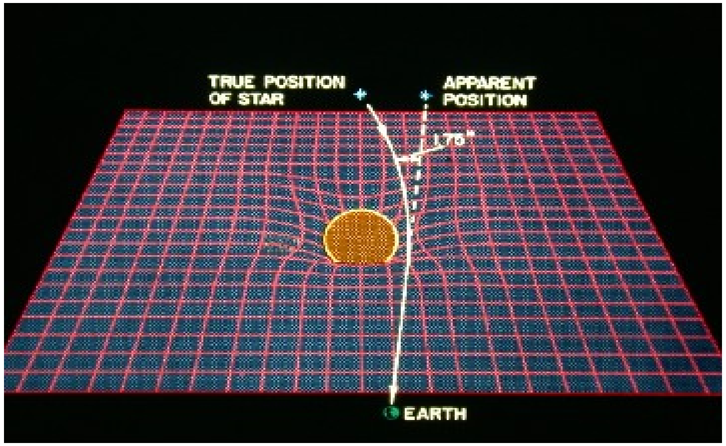
Dark matter
(halo)

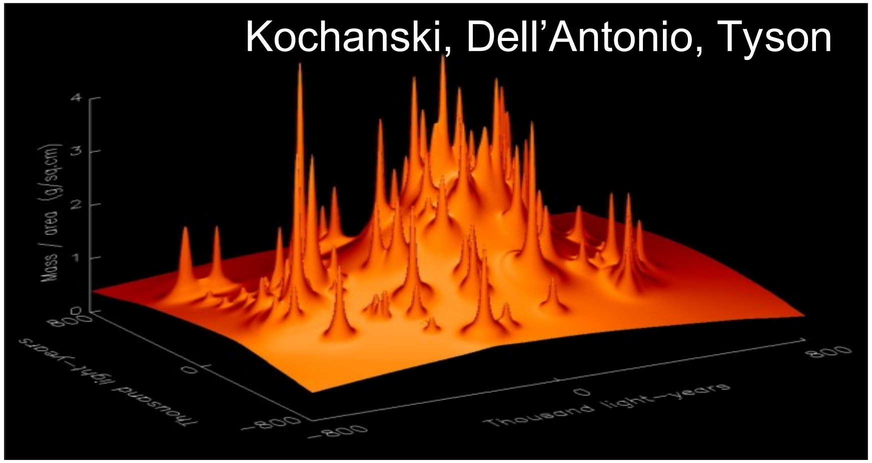


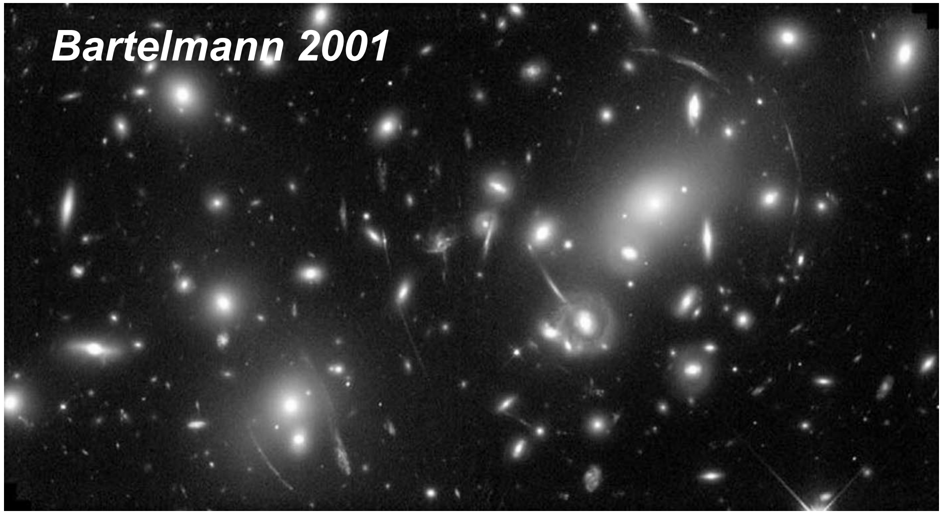
- **Dark Matter content can be >90% in some galaxies!**
- Surveys extended to other types of galaxies (e.g. elliptic).

Gravitational Lensing

- **Strong lensing**: large light deflection and multiple images of background objects;
- **Weak lensing**: small distortion (~1%) on the images of background objects (statistical measurements allows reconstruction of foreground lens).
- **Micro-lensing**: there is no distortion in shape but the amount of light received from a background object changes in time.

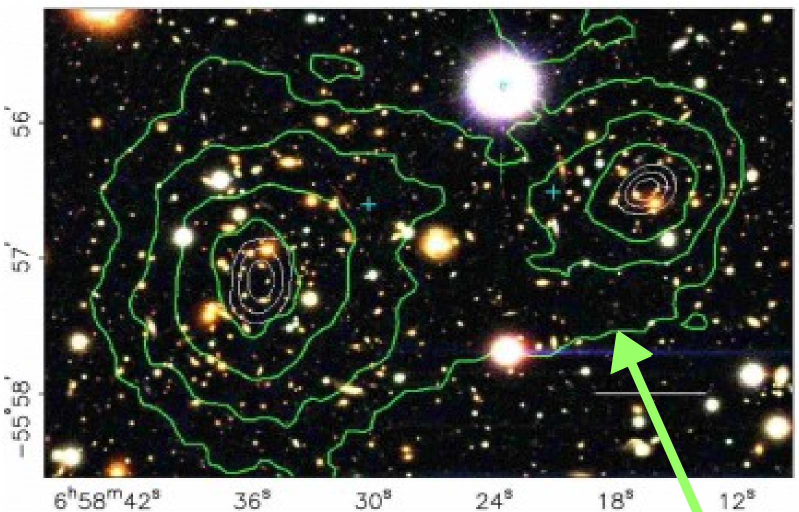




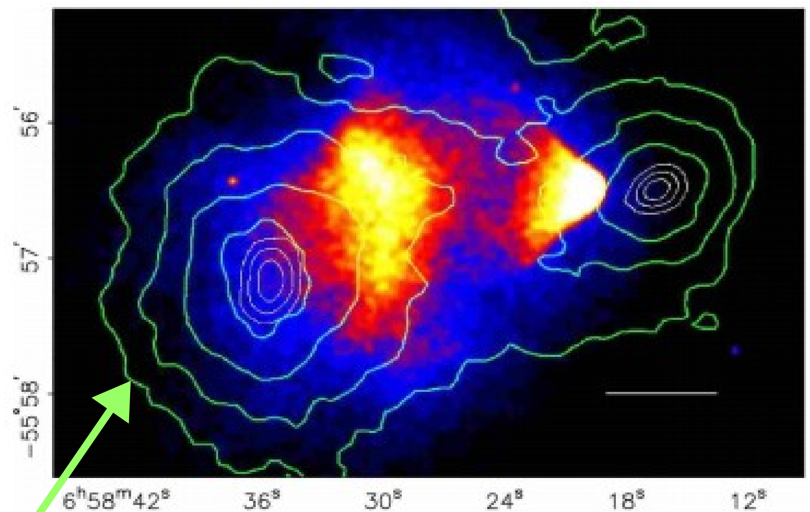


The Bullet Cluster:
A “*smoking gun*” evidence...

Optical image (Magellan telescope)



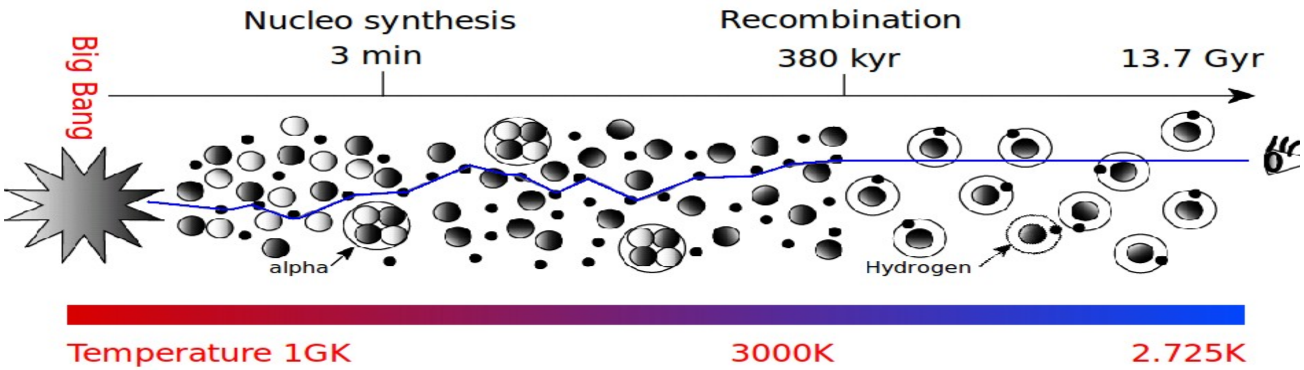
X-Ray image (Chandra telescope)

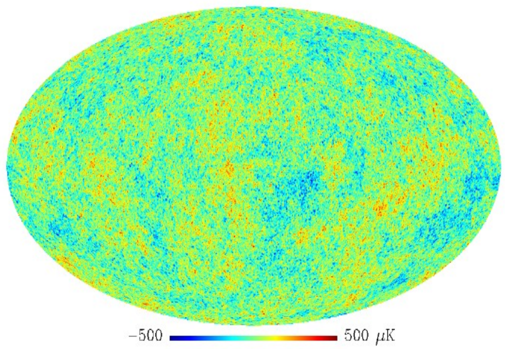


(Superimposed) Contours of spatial distribution of mass
from gravitational (weak) lensing

- The gravitational lensing is strongest in two separated regions (wells) near the visible galaxies (stars);
- The two gravitational wells are displaced from the gas (X-Ray) which accounts for most of the baryonic mass of the two colliding galaxy clusters;

Cosmic **M**icrowave **B**ackground





- When the universe cooled enough to form hydrogen (~1000K) , the density of free electrons dropped and the the **photon-matter interactions stopped** (the photons energy was smaller than the energy required to ionize hydrogen);
- The **anisotropies** (1:10^5) in the CMB are explained as **density fluctuations in the photon-baryon plasma** (tightly coupled by photon scattering and electromagnetic interactions) due to acoustic oscillations in the plasma;
- **The CMB is a snapshot of the Universe at the "moment of the last scattering",** red shifted down to microwave by the expansion of the universe.

Cosmic **M**icrowave **B**ackground

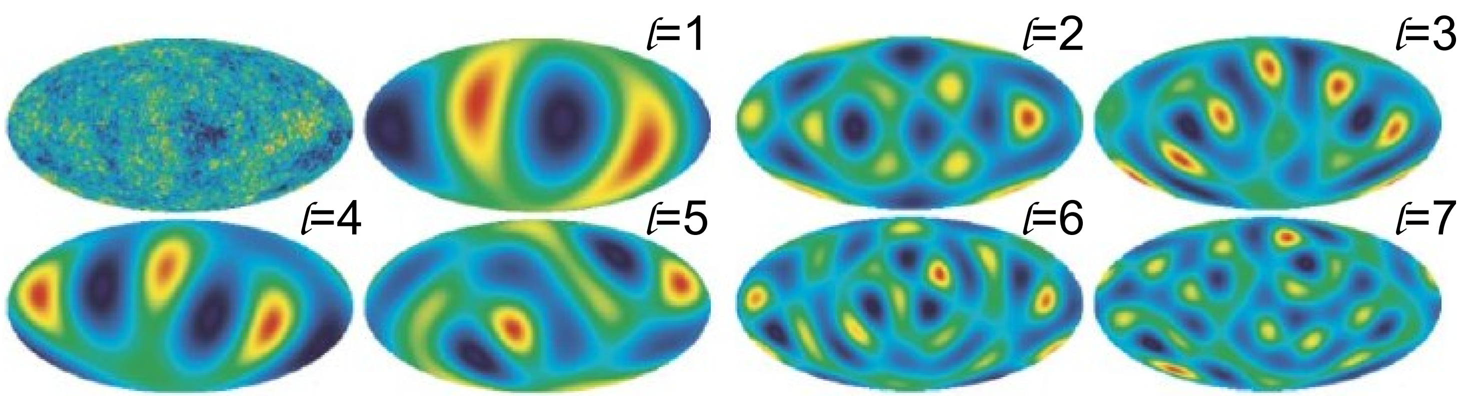
- An expansion in spherical harmonics (Y) is used to separate the **multipole moments** ℓ (i.e angular scales) characterizing the angular separation and intensity of the thermal fluctuations/anisotropies independently of the direction;
- Mean temperature ($\ell=0$) and Doppler shift due to the movement of the sun (ℓ=1) subtracted to reveal much smaller anisotropies (<mk);

$$T(\theta,\phi) = \langle T_{CMB} \rangle + \mathrm{A}_{\mathrm{doppler}} \cos\theta + \sum_{l=2}^{\inf} \sum_{m=-l}^{l} a_{lm} Y_{lm}(\theta,\phi)$$

Mean temperature ($\ell=0$)
(2.722 ± 0.027 K)

Doppler shift (ℓ=1)
(3.555 ± 0.008 K)

correlation amplitude

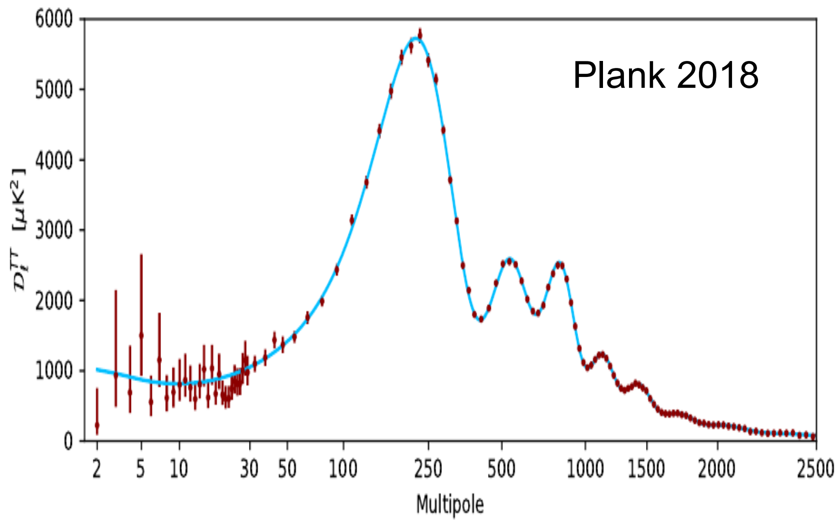


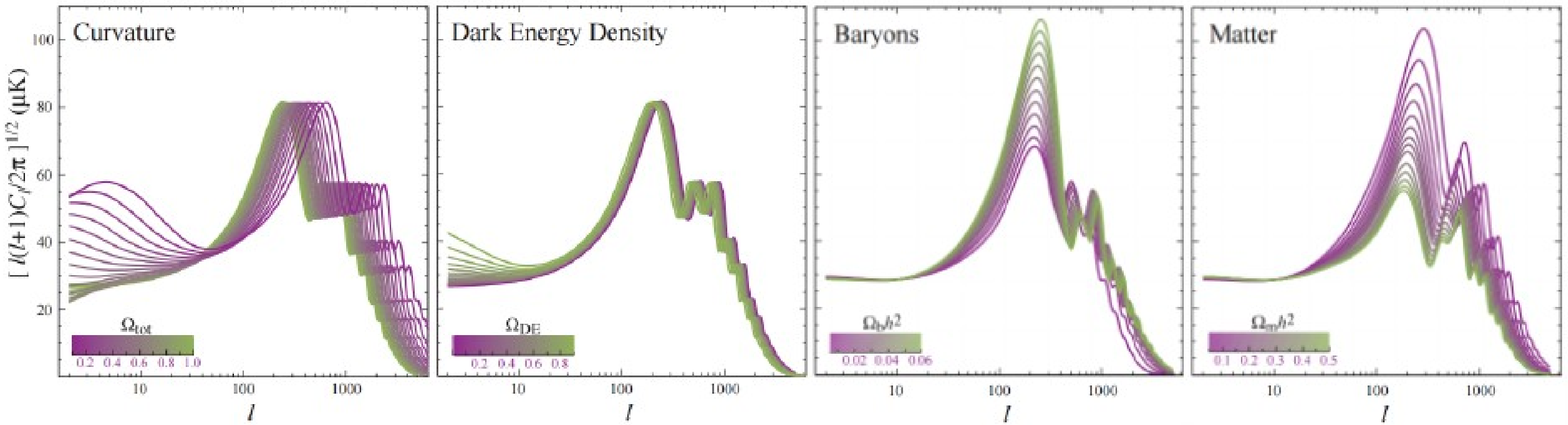
Cosmic **M**icrowave **B**ackground

- Fit the multipole ($\ell \geq 2$) power spectrum to the density parameters of **Λ-CDM model**:

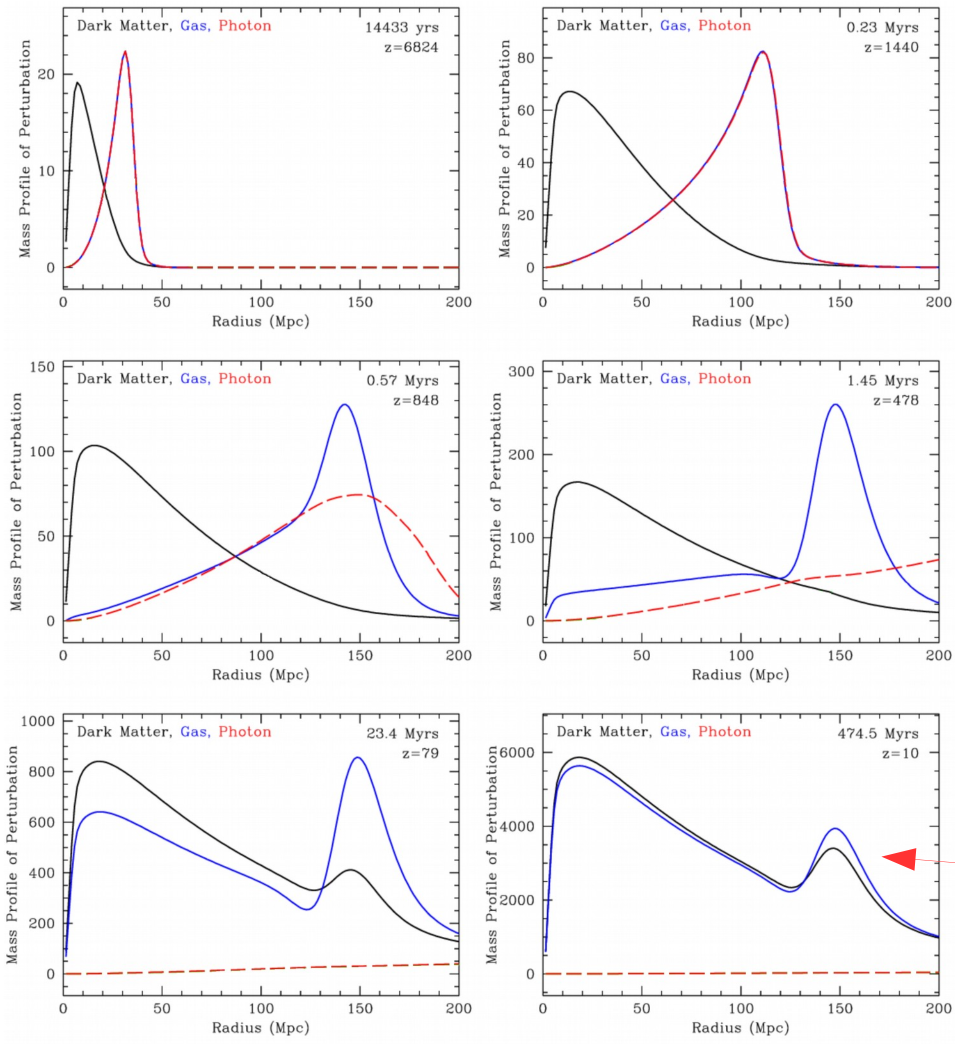
Parameter	Symbol	Value
Hubble constant $[km\ \ s^{-1}\ \ Mpc^{-1}]$	H_0	67.36 ± 0.54
Baryon energy density	$\Omega_b h^2$	0.02237 ± 0.00015
Cold Dark Matter energy density	$\Omega_{DM} h^2$	0.11933 ± 0.00091
Total matter energy density	Ω_m	0.3111 ± 0.0056
Dark energy density	Ω_Λ	0.6889 ± 0.0056
Curvature	Ω_κ	0.0007 ± 0.0019
Sum of neutrino masses $[eV]$	$\sum m_\nu$	<0.12 (95%)
Age of the Universe [Gy]		13.787 ± 0.020

(combine data from Plank TT,TE,EE+lowE+lensing+BAO)





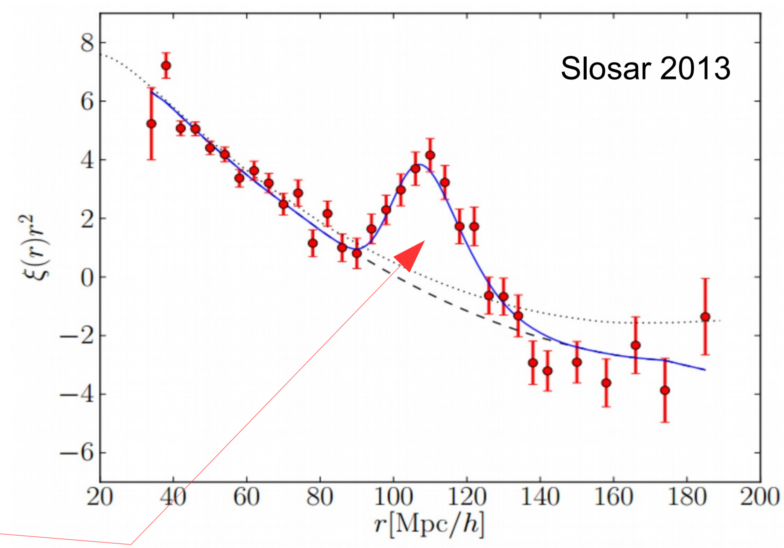
Baryon Acoustic Oscilations



- Confirms the growth of structures by gravitational instability from the baryon-photon decoupling to the present and agrees with CMB results:

$\Omega_m = 0.296 \pm 0.029$

$\Omega_\Lambda = 0.699 \pm 0.100$ (Shadab, 2016)



<u>Acoustic peak</u>: larger number of massive structures found at a distance equal to the scale of the sound horizon.

Supernovae type Ia

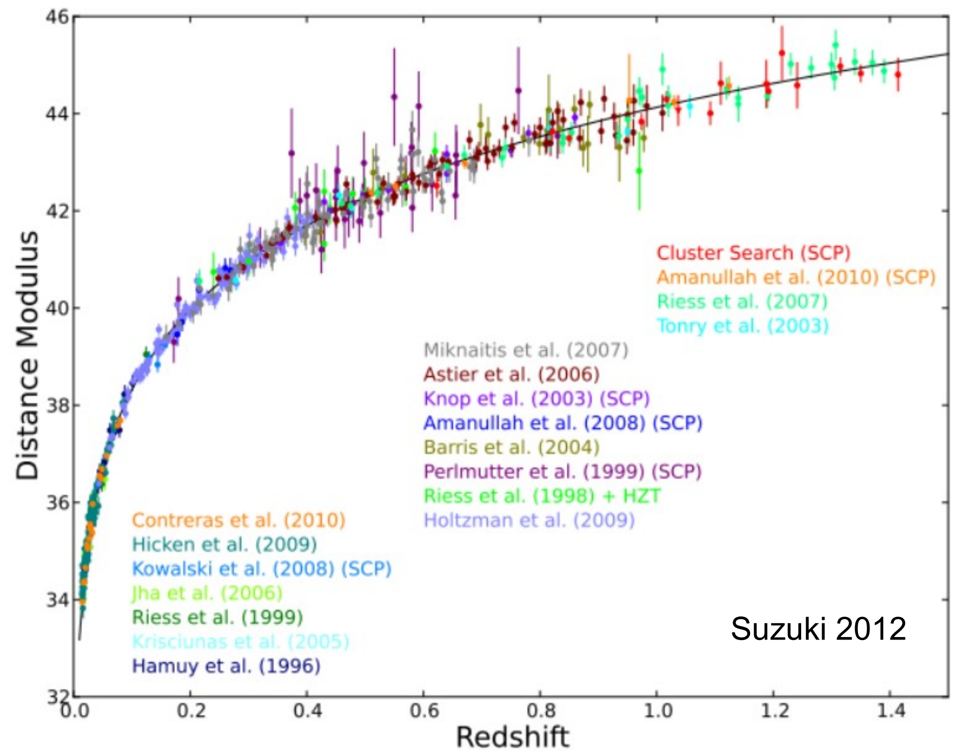
Standard candles: have the same intrinsic luminosity (same nuclear chain reaction occurring at the same stellar mass), allowing to calculate:

- **Distance** (D): relation between the intrinsic luminosity to its apparent luminosity;
- **recessional velocity** (v): redshift;
- Hubble's Law: $\mathbf{v = H_0 D}$;

$\mathbf{H_0}$ is a function of the Universe's expansion acceleration, which is characterised by the density parameters: $\mathbf{\Omega_\Lambda}$, $\mathbf{\Omega_m}$:

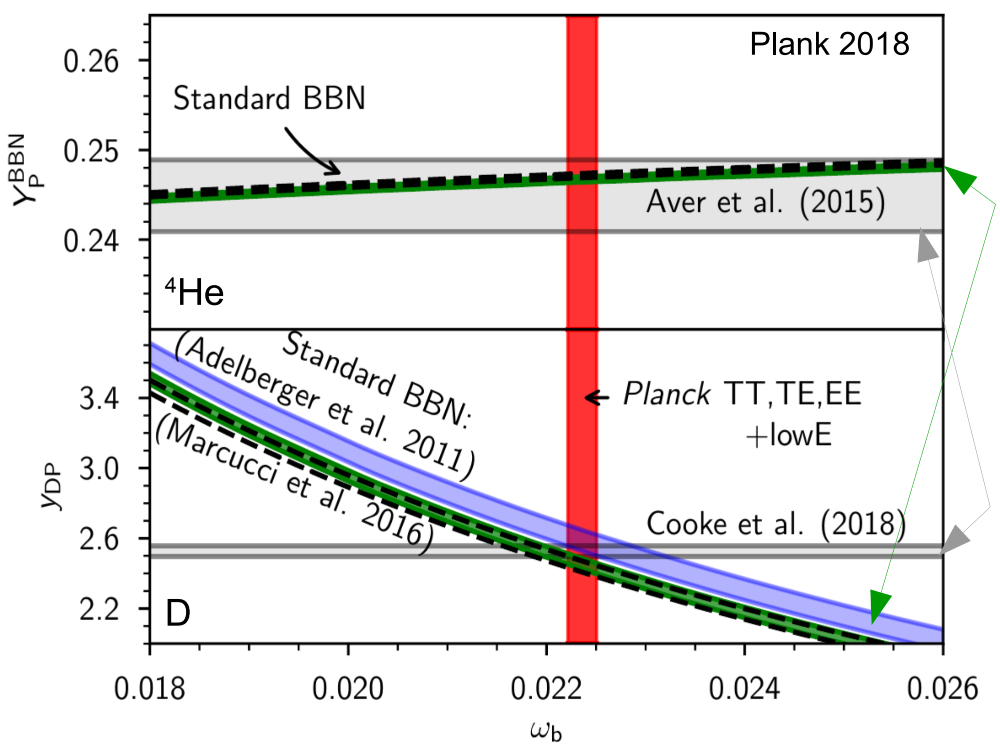
Combined data from various Ia supernovae surveys (Scolnic 2018):

- $\mathbf{\Omega_\Lambda = 0.702 \pm 0.02}$;
- $\mathbf{\Omega_m = 0.298 \pm 0.022}$



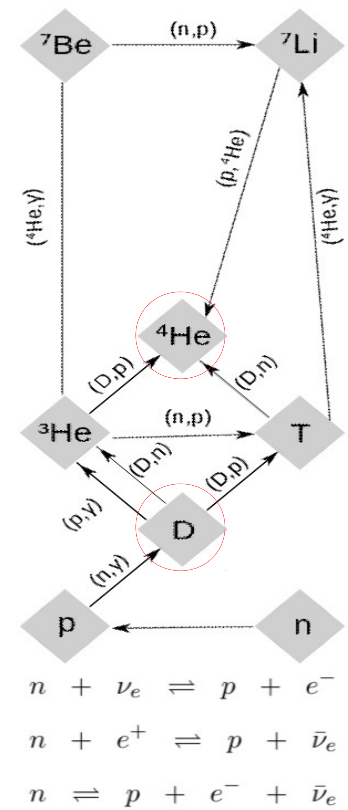
BigBang Nucleosynthesis

The **BBN** predicts light element abundances as a function of parameters also relevant to the CMB: baryon-to-photon density ratio ($\mathbf{n_b / n_\gamma}$), the radiation density ($\mathbf{\Omega_\Lambda}$) and the chemical potential of the electron neutrinos (n $\leftrightarrow$ p reactions);



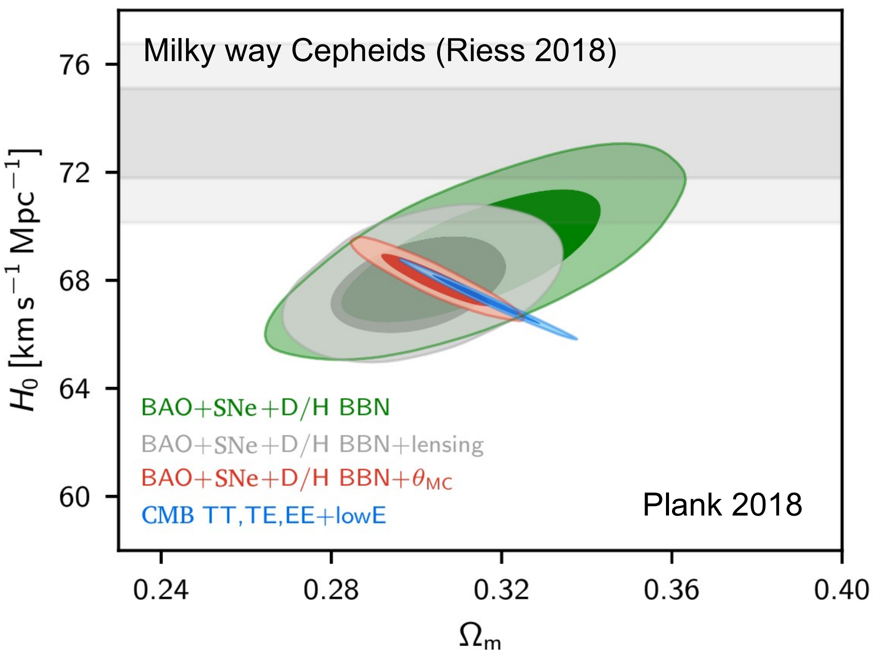
1σ uncertainties on nuclear reaction rates and neutron lifetime

1σ observational constrains on primordial elem. abundances



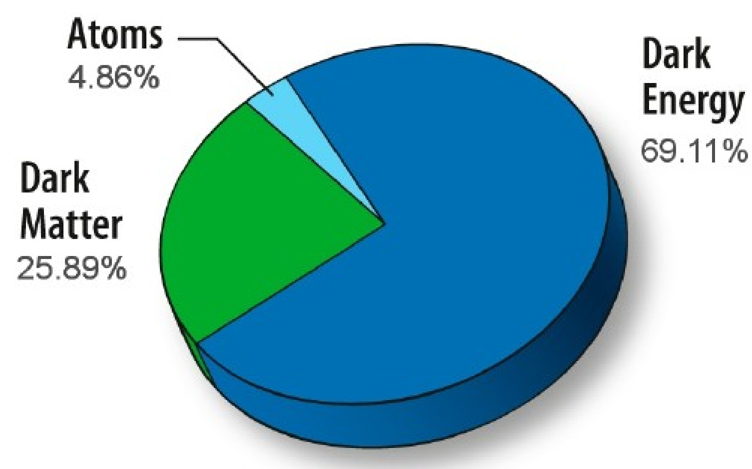
Combining the evidences

constraints on H_0 and Ω_m in ΛCDM from CMB, BAO, SNe and BBN



TT - temperature power spectrum;
EE - polarization power spectrum;
TE - cross temperature-polarization power spectrum;
LowE – uses the EE likelihood

- Extraordinary agreement in precision cosmology;
- Present Universe mostly made out of dark energy, dark matter, and small contribution from baryonic matter;
- **We only understand ≈5% of the constituents of our universe!**

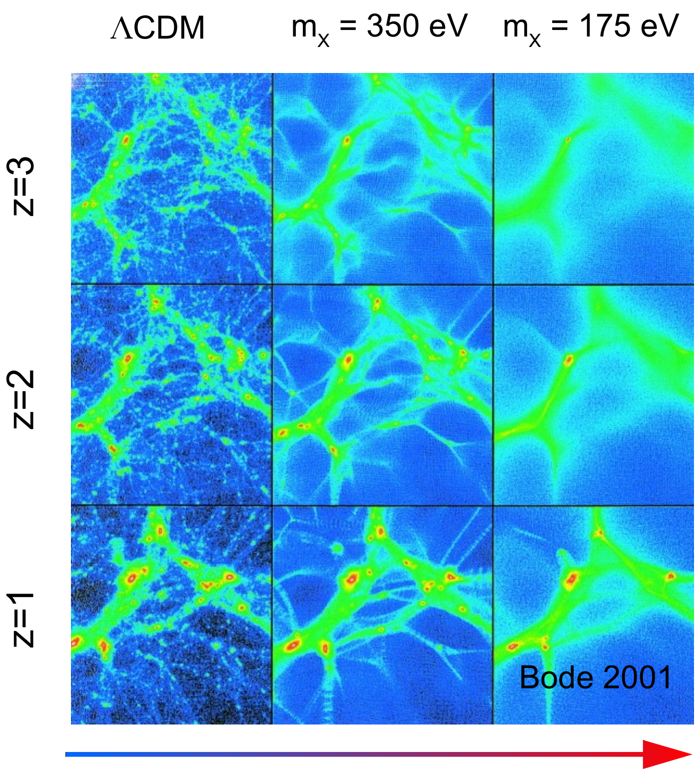


What is Dark Matter?

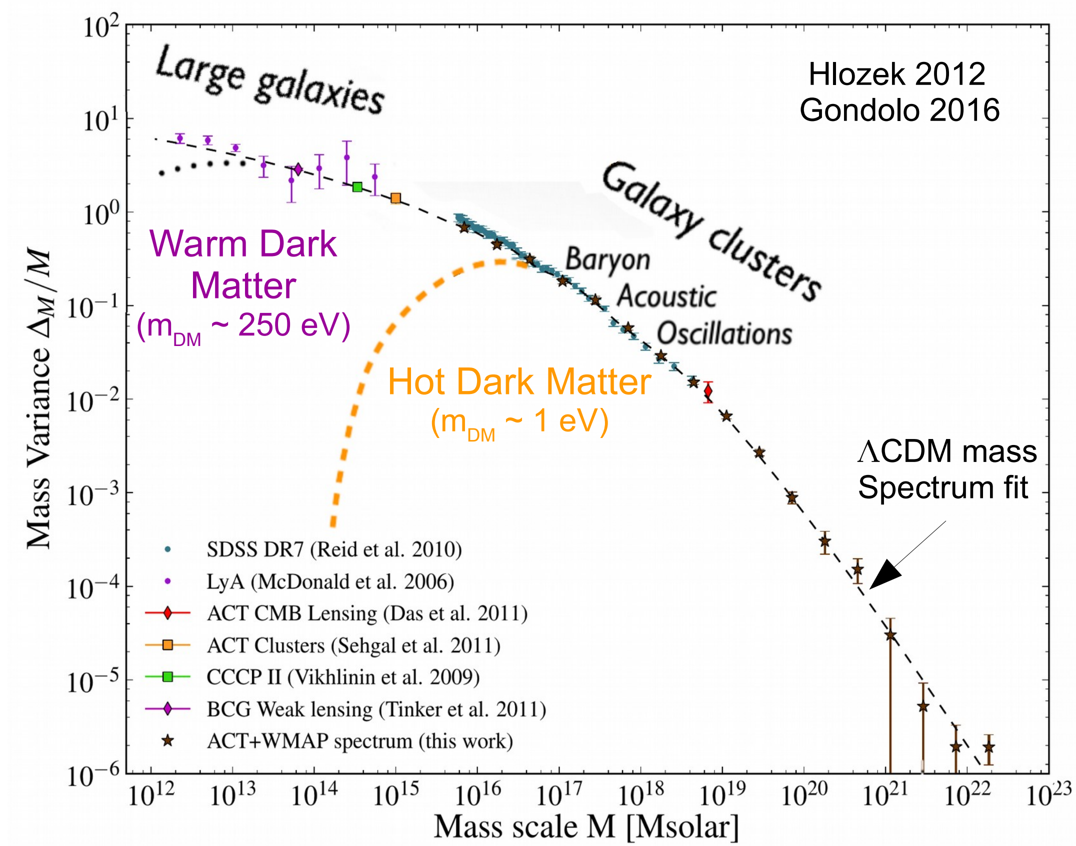
- Invisible baryonic mass (*~3%*) - **MACHOS** (*MAssive Compact Halo Objects*):
  - Brown stars, black Holes, planets;
  - CMB, BAO, BBN … ~80% of matter is non-baryonic!
- **MOND** (*MOdified Newtonian Dynamics*):
  - Can explain (some) galaxy rotation curves;
  - Does not explain gravitational lensing, CMB, BAO or BBN...
- **Hot Dark Matter** (*~2%*) – neutrinos:
  - Too light to explain the Dark Matter density;
  - Disfavoured in scenarios of large scale structure formation;
- **Cold Dark Matter** (*~80%*):
  - Axions (and ALPs): also a candidate to solve the strong CP violation;
  - **WIMPs** (*Weakly Interacting Massive Particles*): generic designation given to particles having a set of properties defined to solve the DM problem;
    - **neutralino** (MSSM): linear combination of the supersymmetric partners of the photon (*photinos*), Z^0 (*zinos*) and the Higgs bosons (*higgzinos*); etc.
- (even) more exotic: holeums, sterile neutrino, gravitinos...

What is Dark Matter?

- The observed mass distribution is matched by the ΛCDM (from large galaxies to the Hubble horizon) when compared with scenarios using lighter dark matter;



suppression of satellite galaxies for lighter DM



What is Dark Matter?

- No known particle can be non-baryonic **cold** Dark Matter!

Gondolo 2016

Light;
Couples to the plasma;
Disappears too quickly;
Its hot dark matter;

Non-thermal relics: Axions, …
- Not in equilibrium with the plasma;
- Produced from topological defects …
- Semi-relativistic at kinetic decoupling;
- Smallest structures are erased;
- Sensitive to initial conditions.

Thermal Relics: WIMPs (neutralinos, …), ...
- Produced in collisions of plasma particles;
- Thermal equilibrium with the plasma;
- Non-relativistic kinetic energies when decoupling;
- Small structures form first then merge;
- … insensitive to initial conditions.

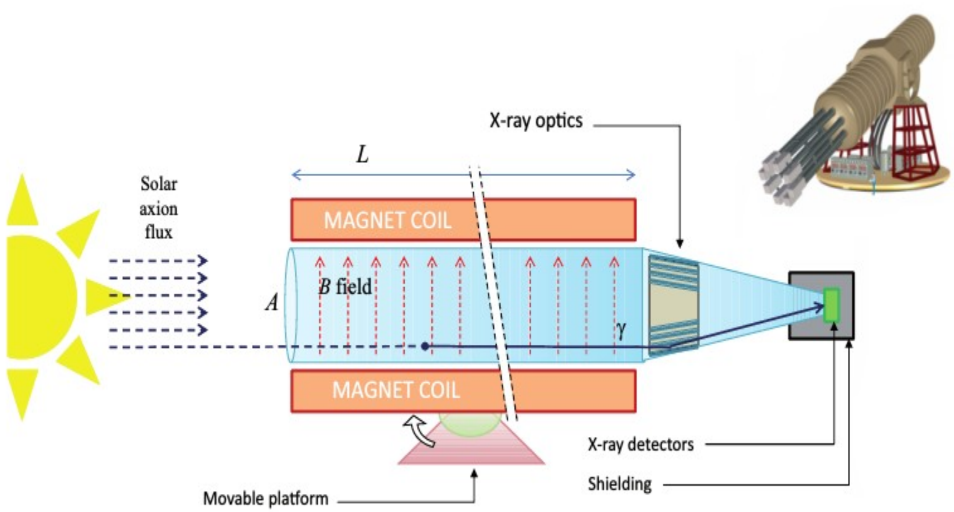
(Many) other candidates...

Detecting Dark Matter: Axions

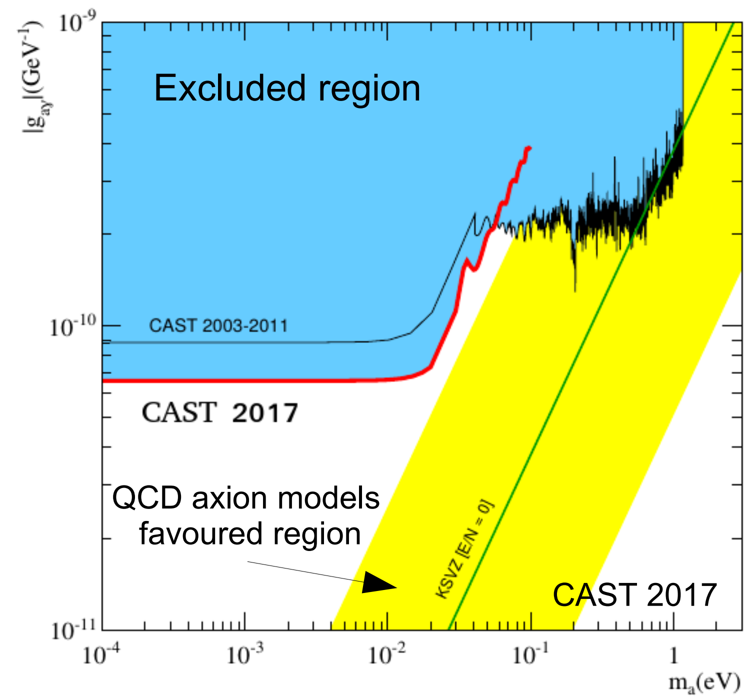
- $M_{axion} \sim 10^{-4}$ - 1 eVc^{-2}
- **Direct detection**: Axions couple ($g_{a\gamma\gamma}$) to magnetic fields (**B**)

Probability of an axion convert to a photon over a length **L** with moment transfer ***q***

$$P_{a\gamma} \propto (BLg_{a\gamma\gamma})^2 \frac{(1-cosqL)}{(qL)^2}$$



Axion helioscopes (CAST, IAXO)



Detecting Dark Matter: Axions

- **Direct detection**: probing smaller coupling constants ($\mathbf{g_{a\gamma\gamma}}$) using a magnetic field (**B**) applied across a resonance cavity.
- $M_{axion} \sim 10^{-10}$ - 10^{-6} eVc^{-2}

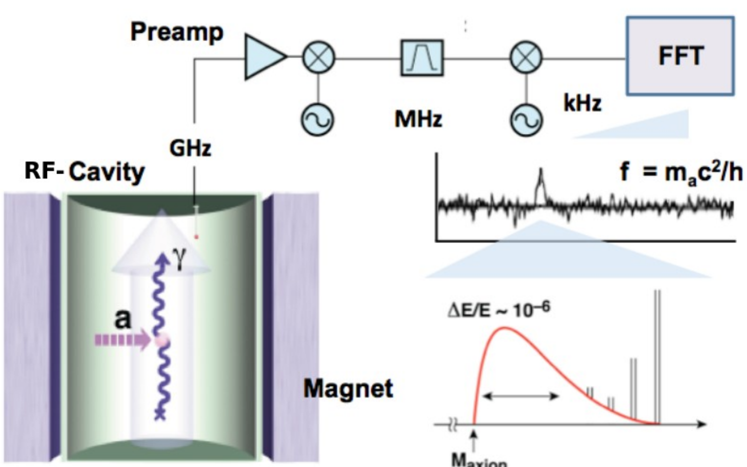
Axions mass (m_a) and local density (ρ_a)

Volume (V), form (C) and quality (Q_L) factors of the RF-cavity

Signal power (antenna)

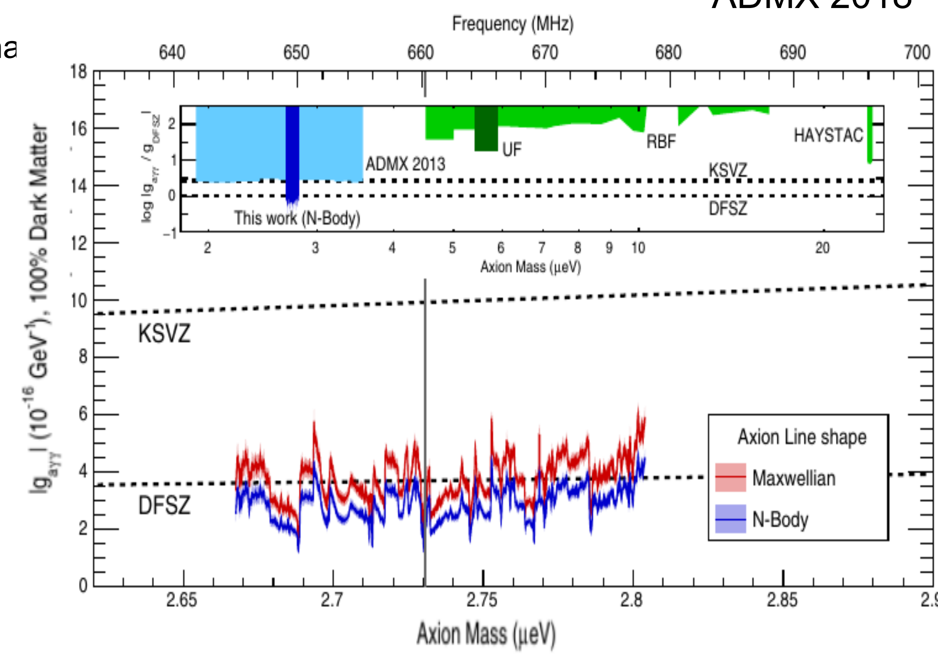
$$P_{\rm SIG} = \eta g^2_{a\gamma\gamma}\left(\frac{\rho_a}{m_a}\right)B^2VCQ_L$$

Fraction of the power coupled out by the antenna



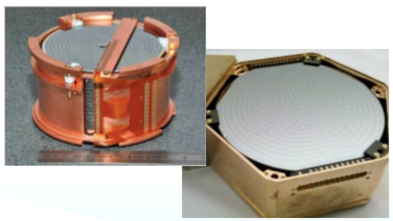
Graham 2016

ADMX 2018



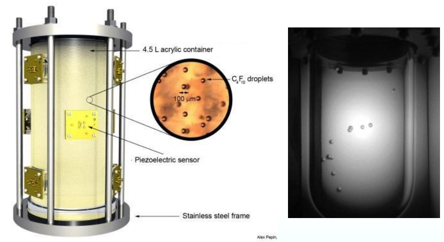
Detecting Dark Matter: WIMPs

Crystals



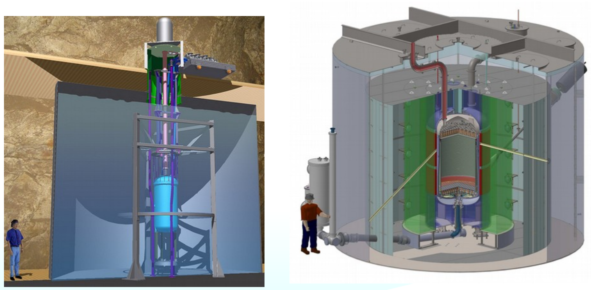
DAMA, SuperCDMS, CRESST, SABRE, EDELWEISS...

Superheated liquids



COUPP, PICASO, SIMPLE...

Liquid Noble Gases

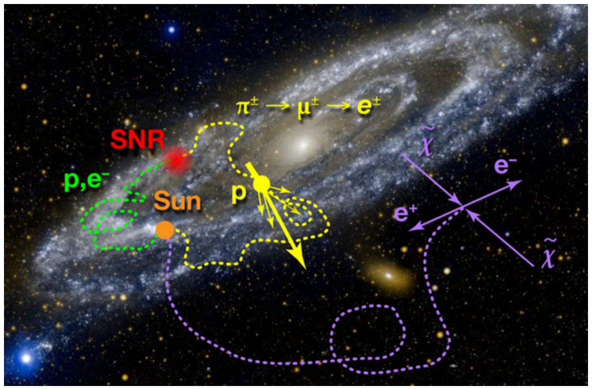


...

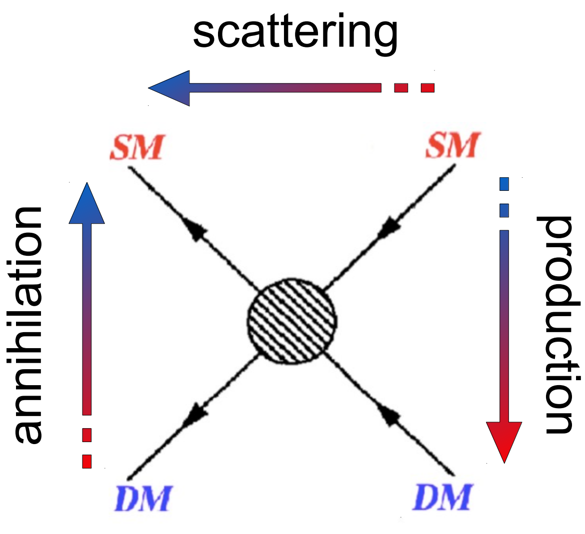
LUX/LZ, XENON, ArDM, PandaX, Darkside, ...

Direct detection

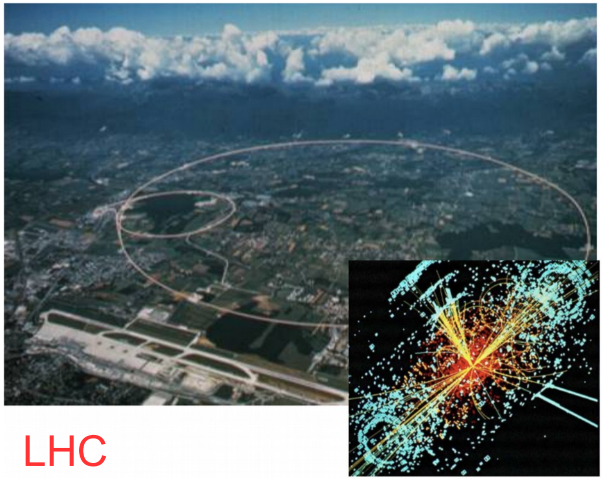
Indirect detection



FERMI, PAMELA, AMS, HESS, IceCube, ...



Colliders

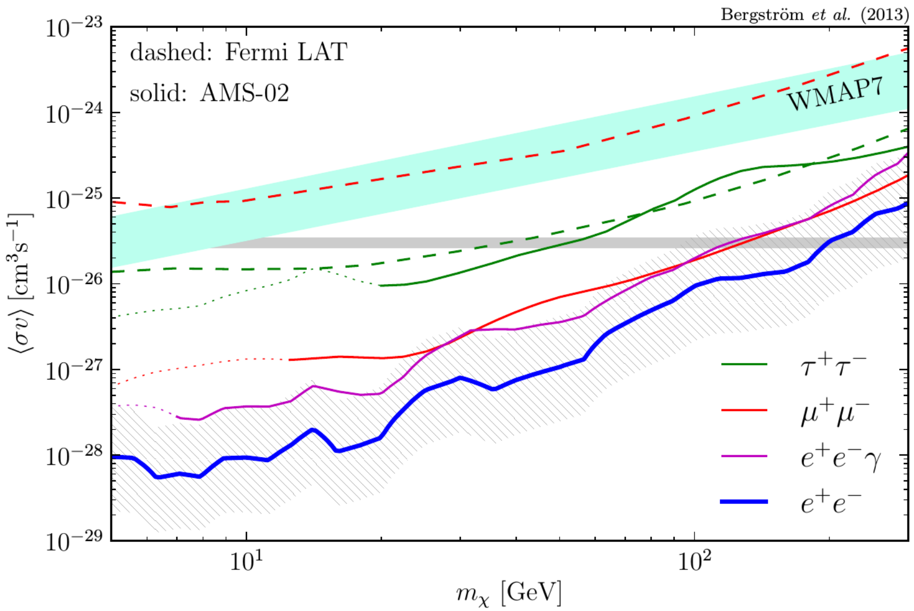


LHC

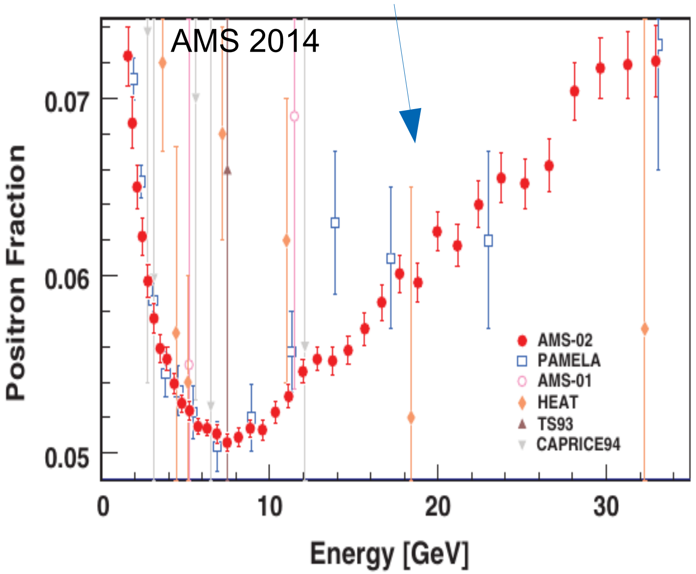
Indirect detection of WIMPs

Observation of the SM products of Dark Matter annihilation:

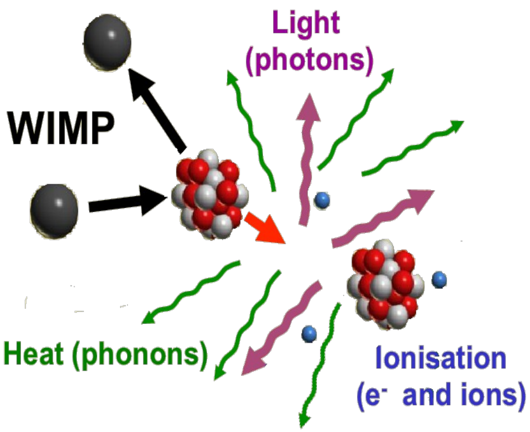
- Look at locations where WIMPs accumulate: centre of galaxies and galaxy clusters;
- WIMPs annihilation products are **cosmic rays** and **gamma rays:**
  - PAMELA, AMS, HESS, VERITAS, Fermi-LAT, HAWK, CTA
- Look at WIMPs sinking into Earth/Sun: high energy **neutrinos:**
  - IceCube, ANTARES
- Astronomical uncertainties are significant...



WIMPs annihilation?

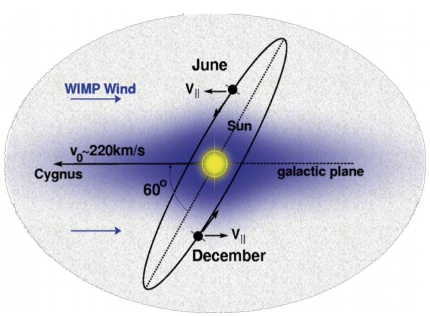


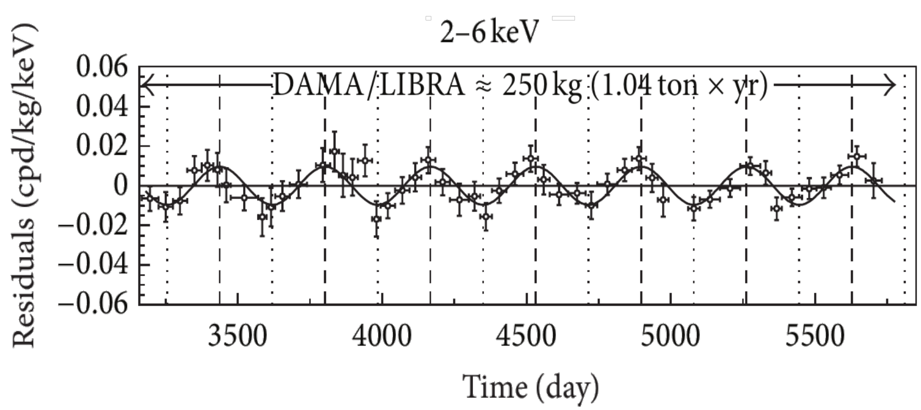
Direct detection of WIMPs



- M_{WIMP} in the *~10 GeV – 1 TeV* range;
- WIMP do not interact via strong/electromagnetic forces;
- **Direct detection**: WIMP-nucleus scattering:
  - Spin Independent (SI): $\sigma_{SI} \sim A^2$ (dominant for A>30);
  - Spin Dependent (SD): $\sigma_{SD} \sim J(J+1)$;

For each target both the **recoil energy** spectrum and the **interaction rate** (and its time modulation - DAMA) depend on the local **WIMP density** and **velocity distribution model.**

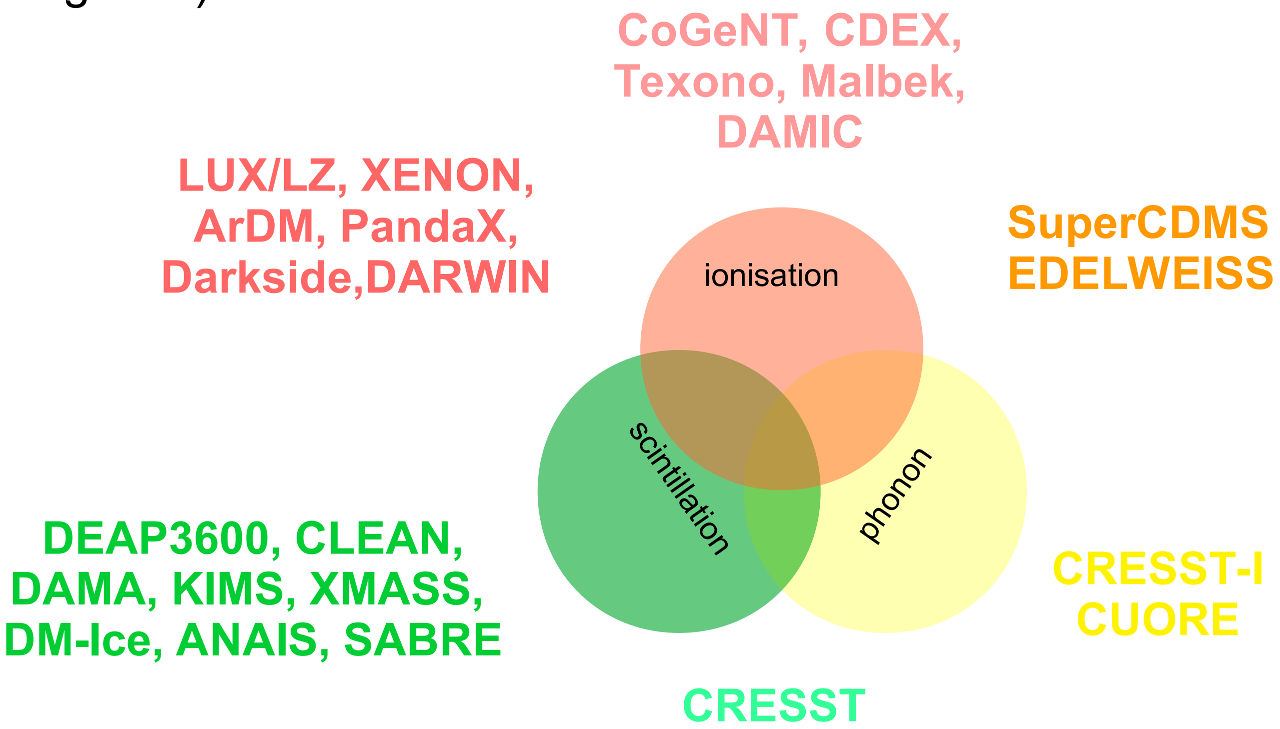




DAMA: annual modulation with CL > 9σ!!
BUT...

WIMPs detection techniques

- The use of **different target materials** (A,J) and different **detection techniques** (e.g. different backgrounds, efficiencies, selections cuts) will allow to interpret *undoubtedly* a positive signal as WIMPs (see DAMA & annual modulation signal...)

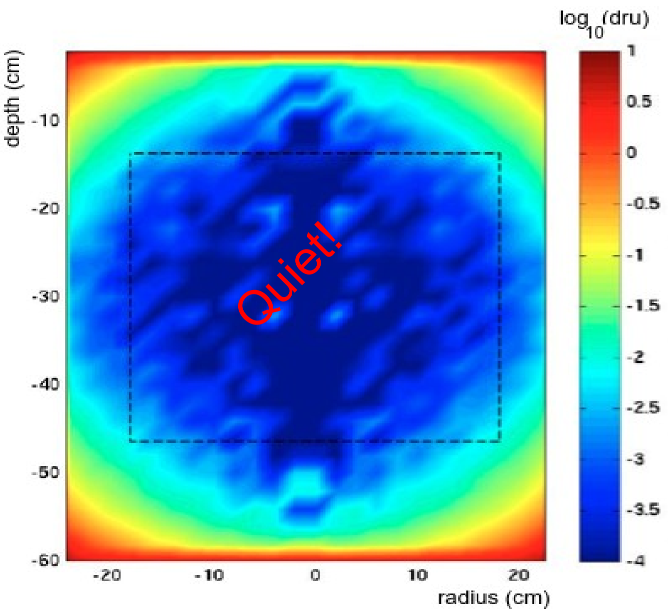


Tracking:
DRIFT, DMTPC, MIMAC, NEWAGE

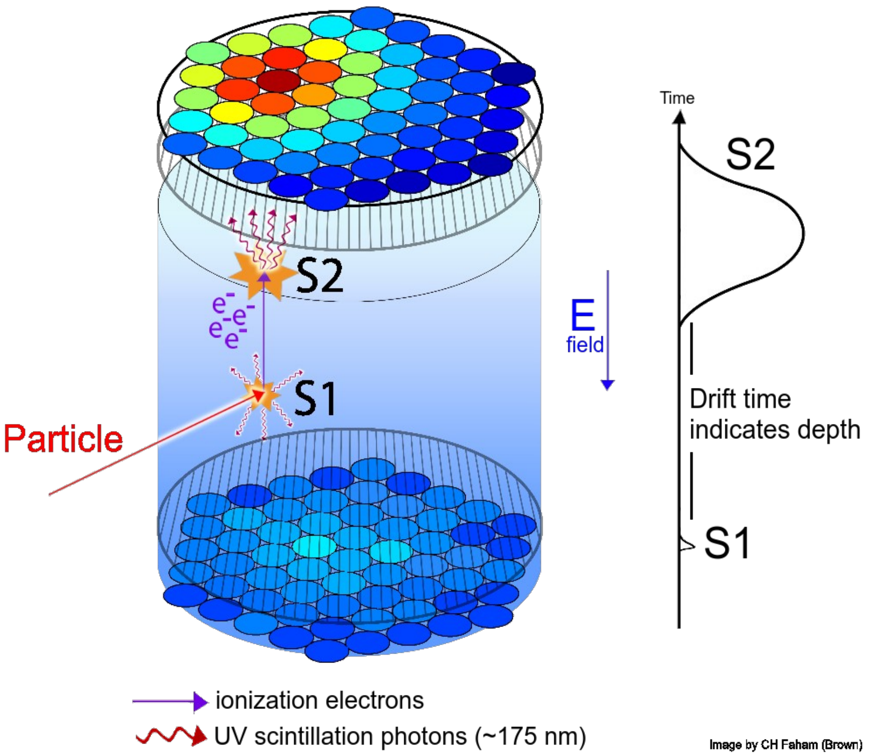
Superheated liquids:
COUPP, PICO
PICASSO, SIMPLE

Choosing a target/technique e.g.: Why using liquid xenon?

- **High density** ($\approx 3\ g/cm^3$): manageable detector volumes ($R_{WIMP} \sim 10^{-5}$-10^{-2} *event/kg/day*);
- **High atomic number** (*A~131*): good for *spin-independent* interactions; plus *spin-dependent* sensitivity (~1/2 odd isotopes in natural xenon);
- Allows **easy/affordable scalability** to ton-level detectors (LZ, XENON-nT);
- Allows **self- passive shielding** by selection of an inner fiducial volume while **active-vetoing** interactions on the outer volume;
- Natural xenon has **no long-lived radioactive isotopes**; plus Kr contamination can be easily reduced to ppt level;
- **Low energy threshold** (*~1 keVee*) with photosensors immersed in the liquid for efficient light collection;
- **Nuclear recoil vs e^-/γ-ray discrimination** by simultaneous detection of *prompt scintillation* and *charge* drift away of the interaction site by an electric field;

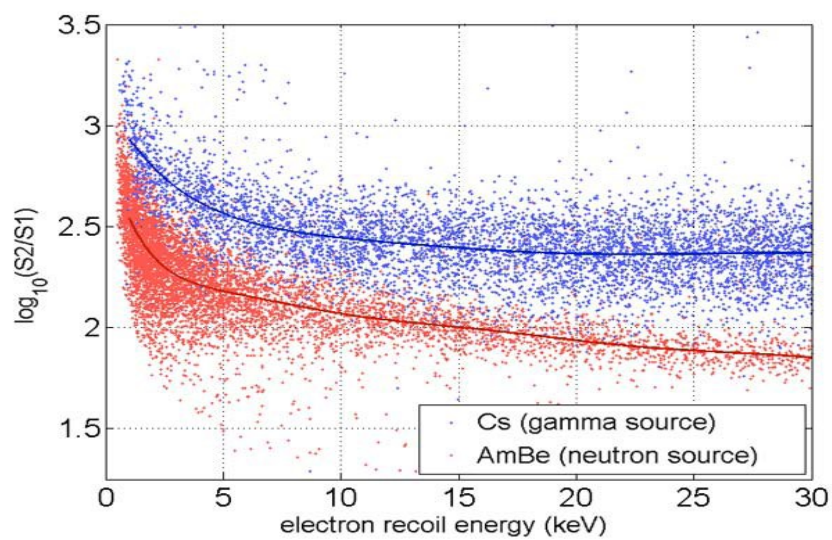


Xenon TPC working principle

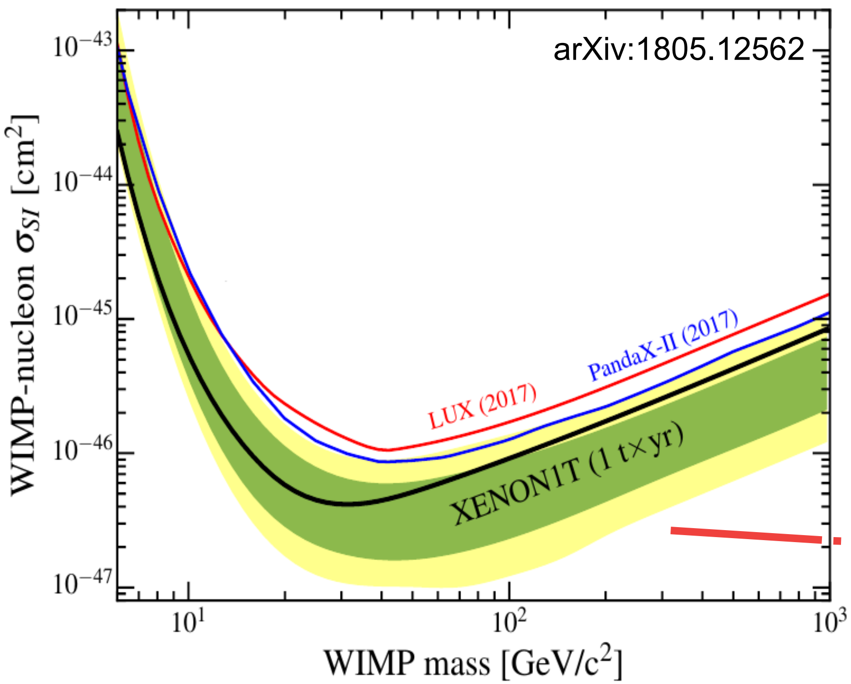


- **(x,y) position reconstruction**: from the S2 light pattern;
- **Depth of interaction (z)**: e^- drift time in the liquid (time difference between S2 and S1);

- **Prompt scintillation (S1)**: energy scale (keVee);
- **Proportional scintillation (S2)**: measurement of the e^- charge extracted from the liquid to the gas.
- **S2/S1** depends on the ionising particle (nuclear/electron recoil): **99.5% ER/NR rejection expected** (50% NR acceptance)**.**

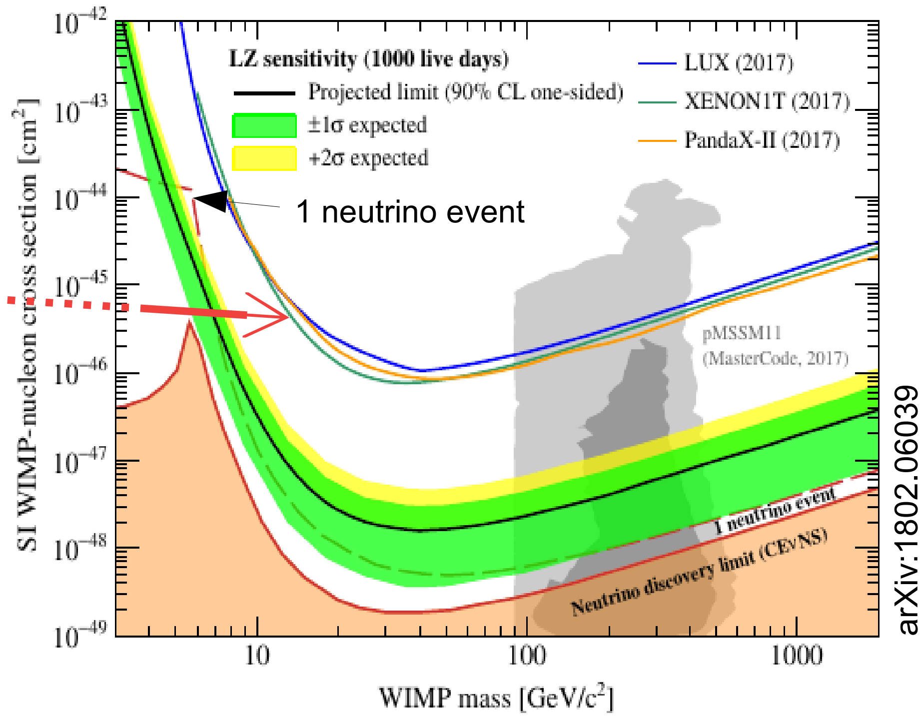


Latest WIMPs SI-search results…
And the next generation detector (LZ)



LZ (LUX-ZEPLIN):

- 5.6 T fiducial (10 T total);
- 6 keVnr analysis threshold;
- 1000 live days;
- **1.6 x 10^{-48} cm^2** at **40 GeV**

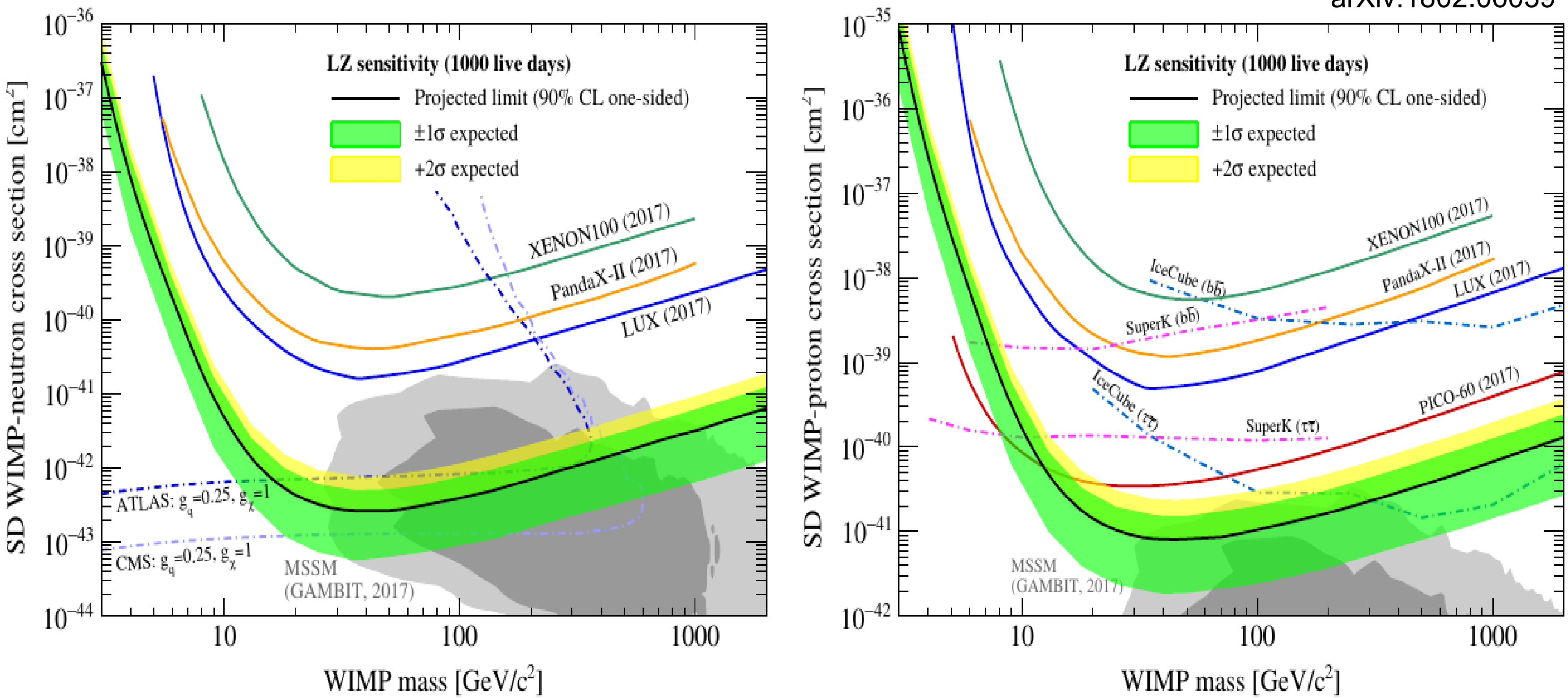


- **XENON-1T** now excludes significant portions of the 1-sigma regions for WIMPs favoured SUSY models.

Latest WIMPs SD-search results…
And the next generation detector (LZ)

WIMP-nucleon Spin-Dependent (SD) exclusion limit (PLR analysis) of **σ_n = 2.7 x 10^{-43} cm^2** and **σ_p = 8.1 x 10^{-42} cm^2 at 40 GeV c^{-2}** for a run of **1000 days and 5.6 tonne** fiducial mass.

arXiv:1802.06039

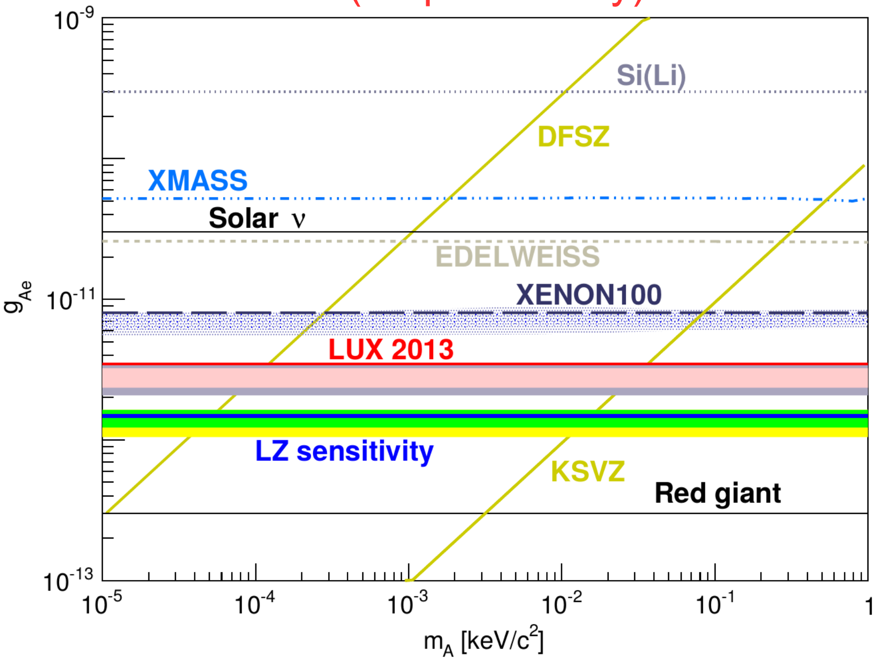


LZ sensitivity to Axions and ALPs

For **1000 live-days, 5.6 ton** fiducial mass
(LZ Baseline assumptions)

Axions

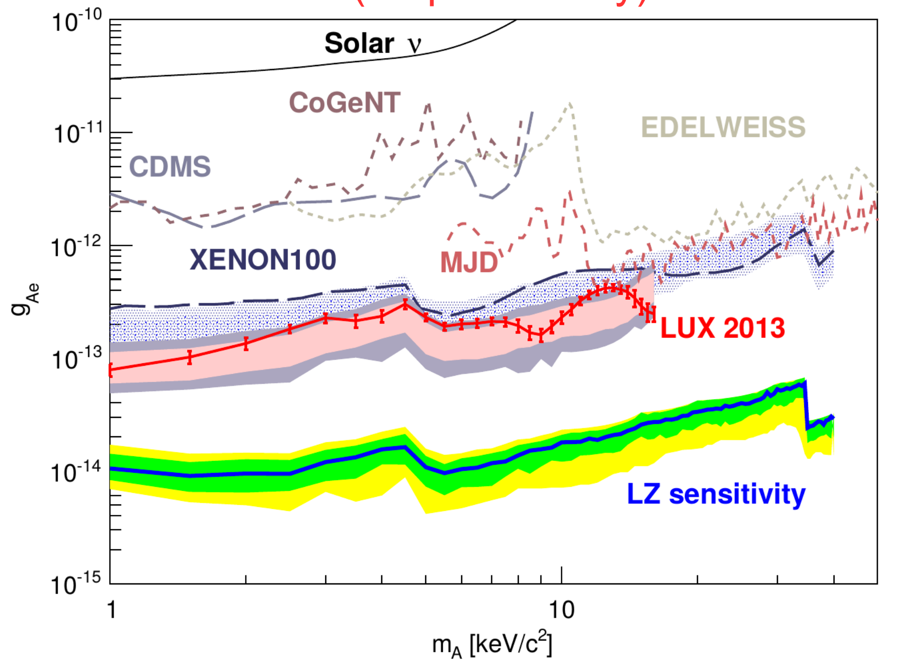
(LZ preliminary)



Excludes $\mathbf{g_{Ae} > 1.5 \times 10^{-12}}$ (90% CL)

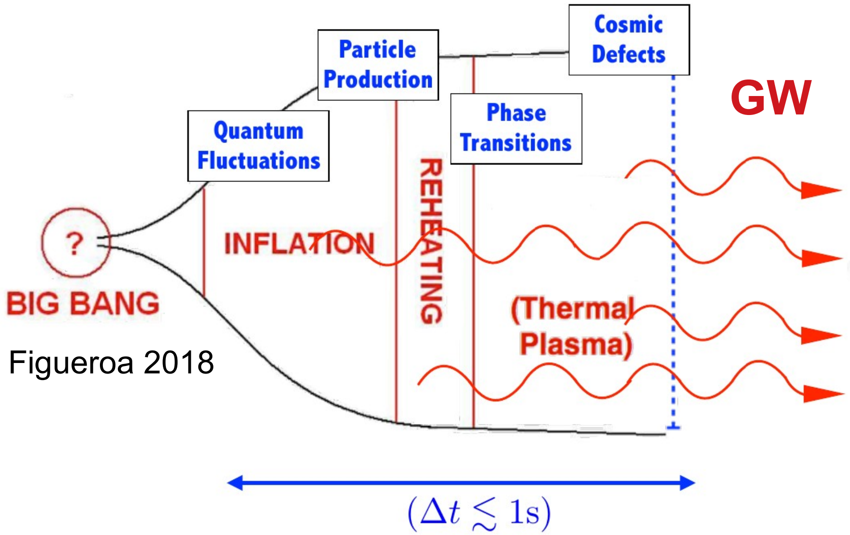
ALPs

(LZ preliminary)

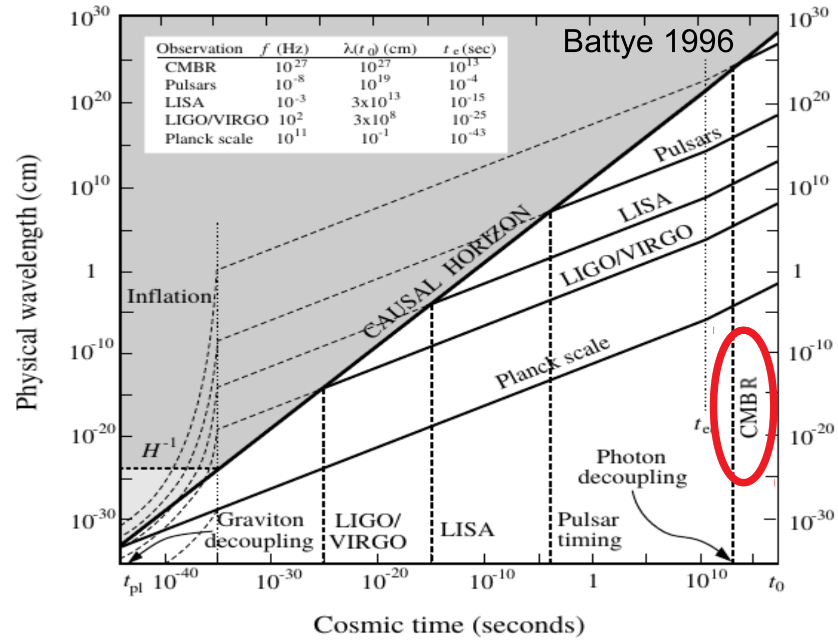


Excludes $\mathbf{g_{Ae} \gtrsim 1 \times 10^{-14}}$ (90% CL)
across the mass range 1-40 keV.c^{-2}

Gravitational Waves (GW)



Times (after Big-Bang) probed by different GW experiments



GW produced from inflation, reheating, phase transitions and cosmic defects;

- … **direct detection** probably only viable from inflation, but:

GW generate **B-mode polarization** in the CMB (while density fluctuations generated only E-modes):

- Results from BICEP2/Keck+Planck (2015) are **consistent with B-modes from dust component alone**… after removal of dust component, results indicate the **Existence of B-modes** (**7.0σ** significance) – **but ...**

Conclusions

- **There is overwhelming astrophysical evidence for non- baryonic cold dark matter;**

- **The nature of cold dark matter is still unknown, and many candidates/solutions have been proposed;**

- **There is some controversial detection of dark matter signals;**

- **Most of the experimental effort is currently focused on the detection of WIMPs, AXIONs and ALP particles;**

- **(recent detection of) gravitational waves supply a new tool to probe the 1st fractions of a second following the Big-Bang (e.g did inflation happened?);**

- **… a lot of precision data is available from various sources to test against different models and dark matter candidates!**