Istituzioni di Astrofisica e Cosmologia:

UNIVERSE’S COMPONENTS

For a review: https://arxiv.org/pdf/2104.11488
https://pdg.lbl.gov/2023/reviews/rpp2022-rev-dark-matter.pdf

A.A. 2024/2025 | Matteo Costanzi - University of Trieste / INAF

RADIATION AND NEUTRINO

Cosmic Microwave Background radiation:

- Black body spectrum with $T_\gamma = 2.73$ K today

$$\rho_\gamma = \frac{aT_\gamma^4}{c^2} \simeq 4.7 \cdot 10^{-34} g/cm^3 \qquad \Rightarrow \qquad \Omega_\gamma \simeq 2.5 \cdot 10^{-5} h^{-2}$$

Cosmic Neutrino Background:

- $\rho_\nu \sim N_\nu \cdot 10^{-34}$ g/cm^3
- Minimum mass from oscillation experiment 0.06 eV
- Maximum total mass from cosmological probes ~0.6 eV

$$\Omega_\nu h^2 = \frac{\sum m_\nu}{93.14\text{eV}} \rightarrow 0.001 < \Omega_\nu < 0.02$$

ORDINARY MATTER

Luminous matter (starts):

- **Luminous density: $\rho_L \sim 2 \cdot 10^8\, h\, L_\odot\, \mathrm{Mpc}^{-3}$**
- **Assuming a matter-luminosity ration <M/L> ~ 1 $M_\odot / L_\odot$:**

$$\Omega_{\rm lum} h \simeq 0.002 - 0.006$$

ORDINARY MATTER

Big Bang Nucleosynthesis:

- Light elements – ^3He, ^4He, D, ^7Li – produced in the early Universe (t<3min)
- Baryon density (p, n, helium, ecc):

$$\Omega_b h^2 = 0.0224 \pm 0.0001$$

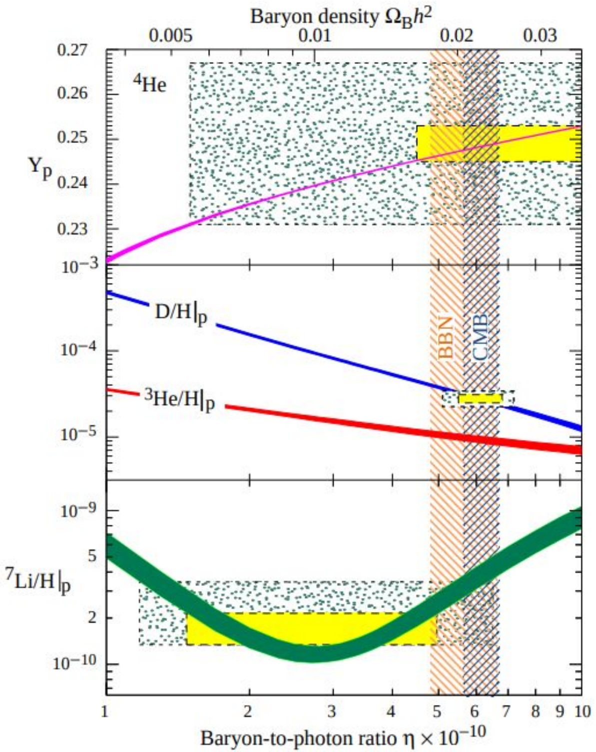
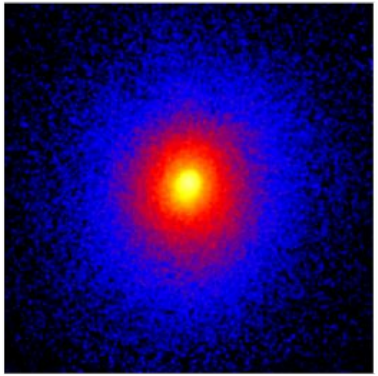


Figure 1.1: The abundances of ^{4}He, D, ^{3}He and ^{7}Li as predicted by the standard model of big-bang nucleosynthesis. Boxes indicate the observed light element abundances (smaller boxes: 2σ statistical errors; larger boxes: $\pm 2\sigma$ statistical and systematic errors). The narrow vertical band indicates the CMB measure of the cosmic baryon density. See full-color version on color pages at end of book.

ORDINARY MATTER

Baryon Catastrophe:

- **Cluster of galaxies:**
    - **Intra Cluster Medium ≃ $6h^{-3/2}$ % of the total mass**
    - **Stars and galaxies ≃ 2% of the total mass**
- **Assuming that the baryon fraction in a cluster is representative of the cosmological baryon fraction, (assuming that a part of the baryon in a cluster might be are dark)**



$$\Omega_b/\Omega_M \geq 0.06\, h^{-3/2} + 0.02 \;\rightarrow\; \Omega_M \leq \frac{0.02\, h^{-2}}{0.06\, h^{-3/2} + 0.02} \leq 0.33$$

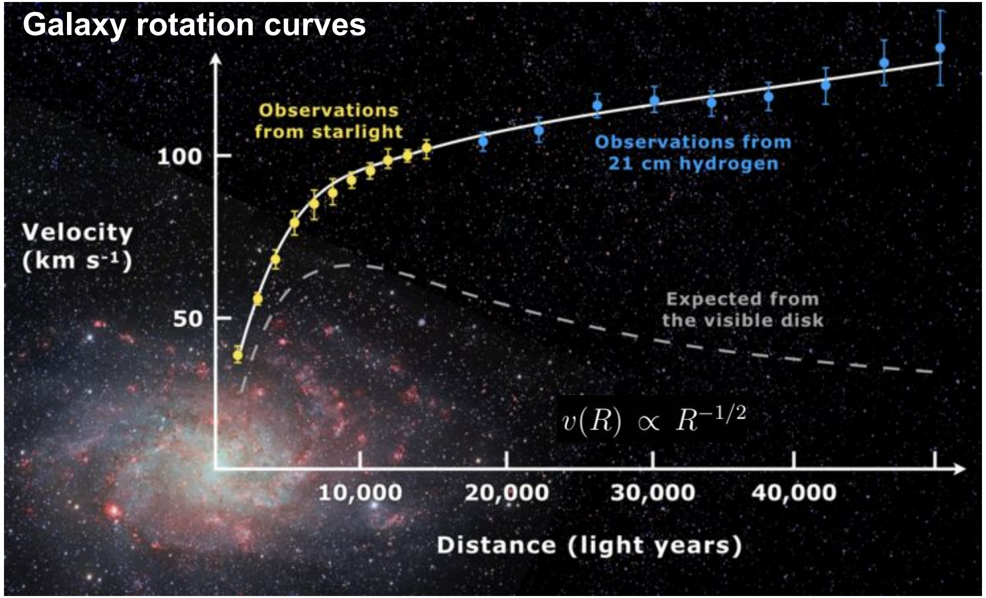
There's more matter than we see.. Ordinary matter makes only ~15% of total matter

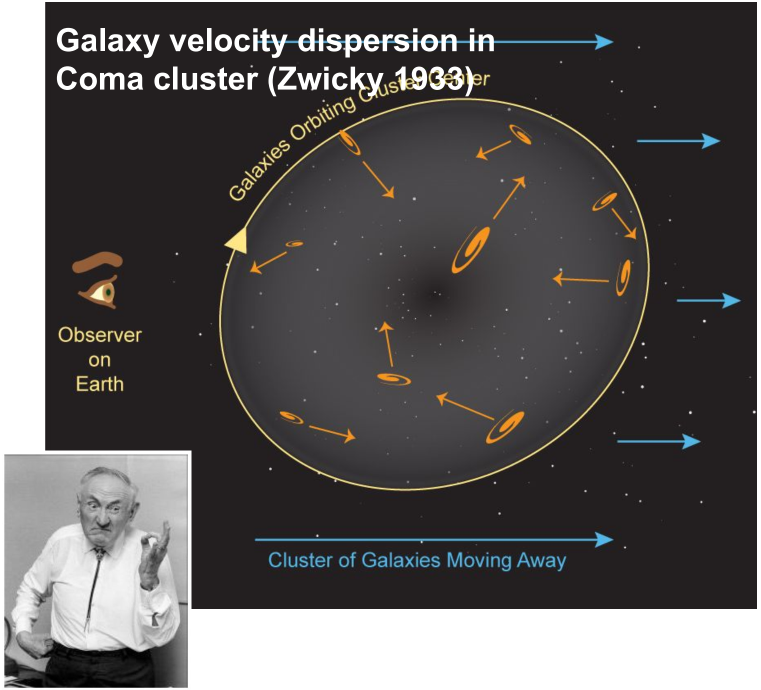
photons:	$\Omega_{\gamma,0} = 5.35\times10^{-5}$
neutrinos*:	$\Omega_{\nu,0} = 3.65\times10^{-5}$
total radiation:	$\Omega_{r,0} = 9.0\times10^{-5}$
baryonic matter:	$\Omega_{bary,0} = 0.048$
(cold) dark matter:	$\Omega_{dm,0} = 0.262$
total matter:	$\Omega_{m,0} = 0.31$
cosmological constant:	$\Omega_{\Lambda,0} = 1 - \Omega_{m,0} - \Omega_{r,0} \approx 0.69$

*assumes massless neutrinos

OBSERVATIONAL EVIDENCES

Dynamics of galaxies and galaxy clusters:



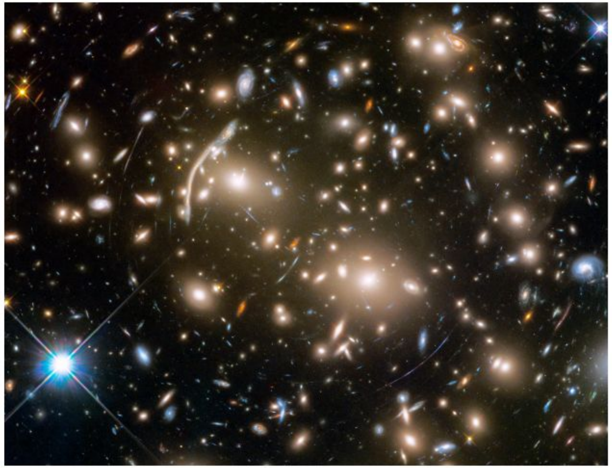


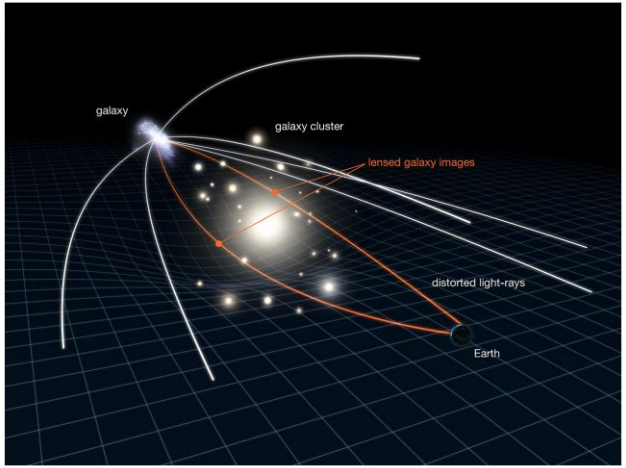
$$\langle M/L \rangle \sim 30\, h\, M_\odot / L_\odot$$

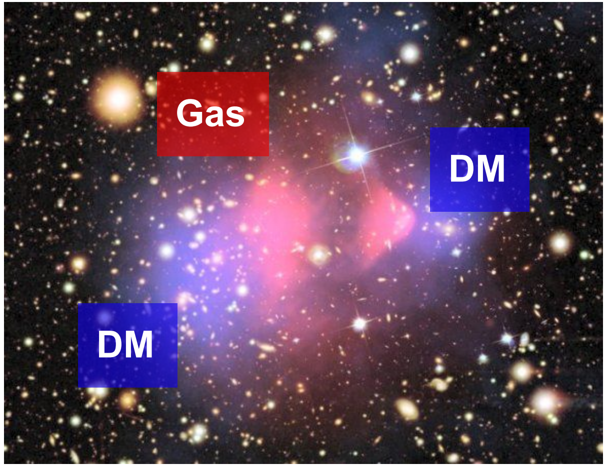
$$\langle M/L \rangle \sim 100 - 400\, h\; M_\odot / L_\odot$$

OBSERVATIONAL EVIDENCES

Cluster mass from lensing:

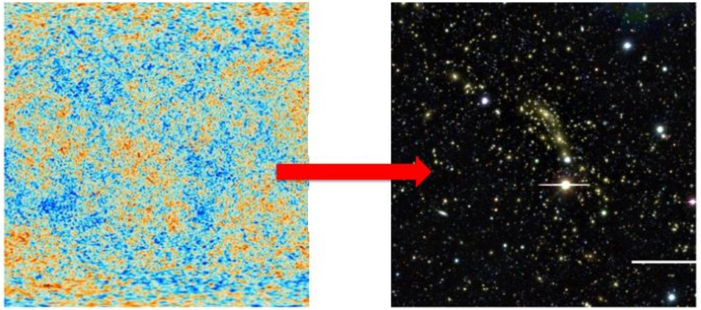






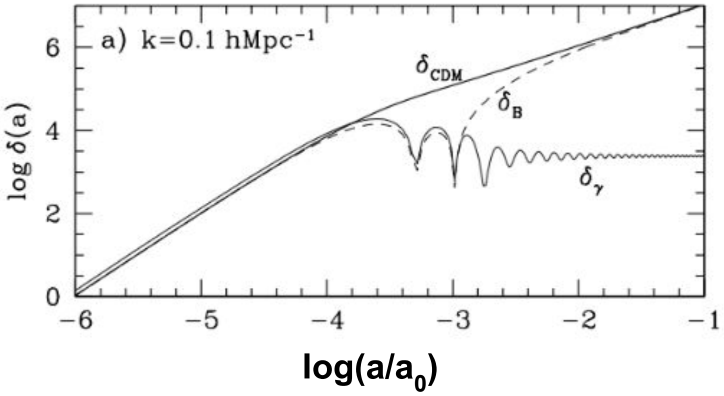
OBSERVATIONAL EVIDENCES

Growth of structures between CMB LSS and us



Structure at 380,000 years – 10^{-5} of CMB

Structure at 13.8 billion years – density contrasts > 10^{3}



At recombination:

$$\delta\rho_b/\rho_b|_{\rm rec} \approx 10^{-5}$$

Today w/o DM:

$$\delta\rho_b/\rho_b|_{\rm today} \approx \frac{\delta\rho_b/\rho_b|_{\rm rec}}{a_{\rm rec}} \approx 10^{-2}$$

Today observed:

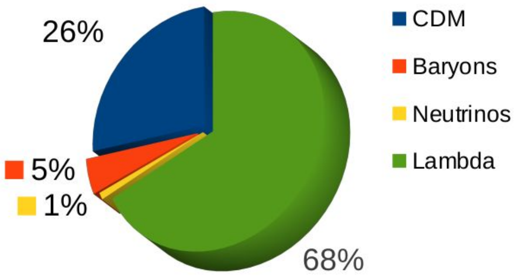
$$\delta\rho_b/\rho_b|_{\rm obs} \gg 1$$

THE ΛCDM MODEL

Cold Dark Matter properties:

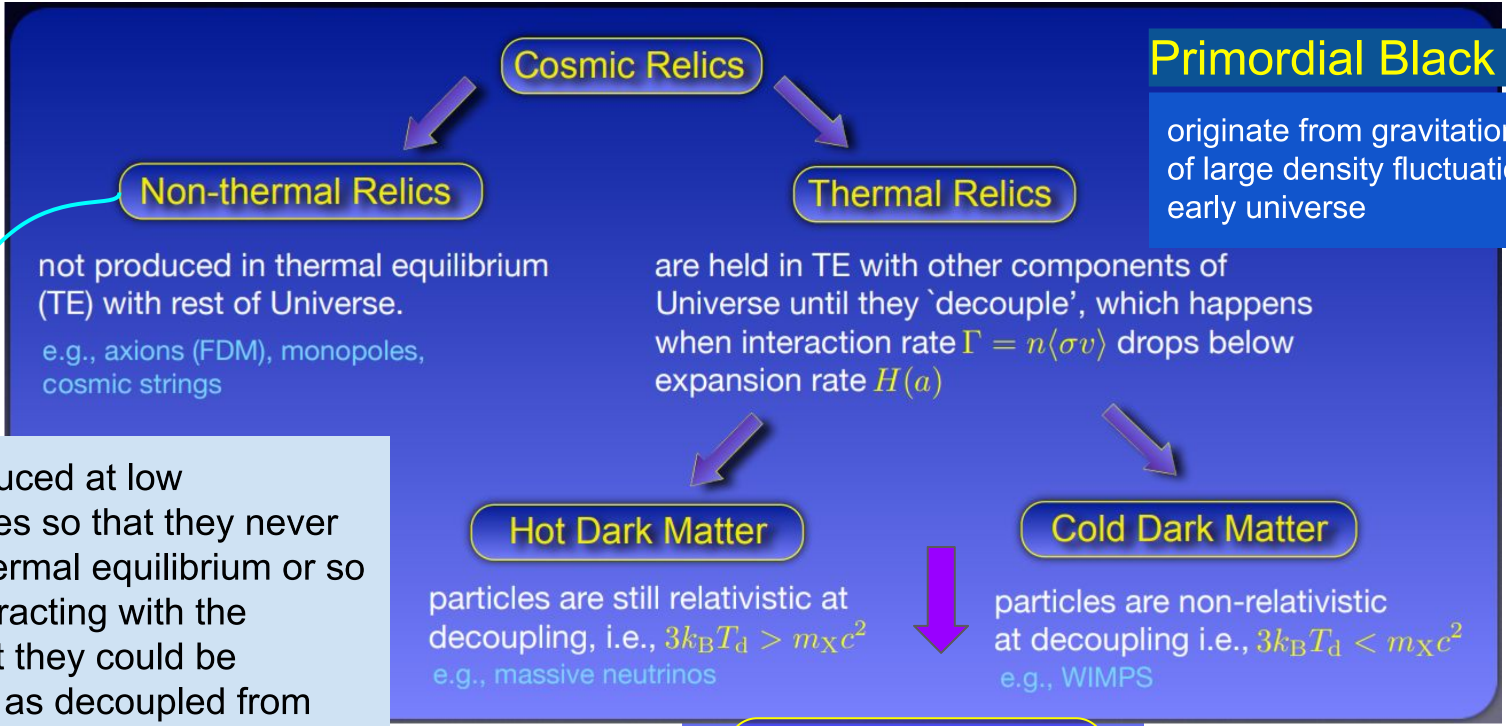
- **Electrically neutral**
- **Uncolored (neutral color charge)**
- **Weakly interacting (collisionless/pressureless)**
- **Stable (originate in the early universe)**
- **Negligible velocity from the standpoint of structure formation (cold)**

The ΛCDM universe



Standard Model fails at providing a dark matter candidate, so it is necessary to consider scenarios beyond the Standard Model

THERMAL AND NON-THERMAL RELICS



Primordial Black Holes

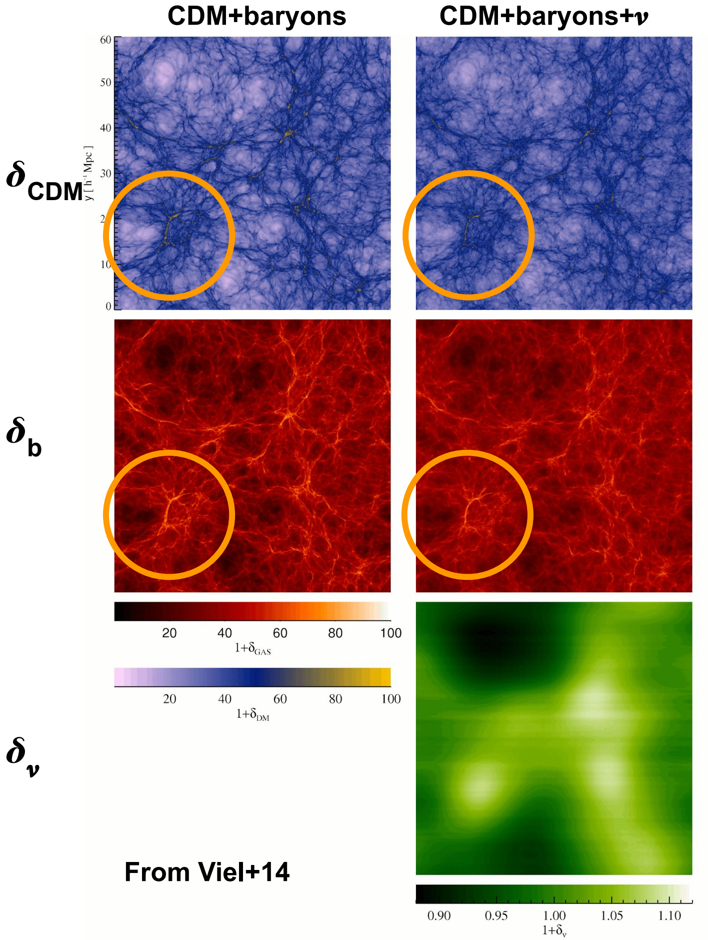
originate from gravitational collapse of large density fluctuations in the early universe

Either produced at low temperatures so that they never reached thermal equilibrium or so weakly interacting with the plasma that they could be considered as decoupled from the primordial plasma

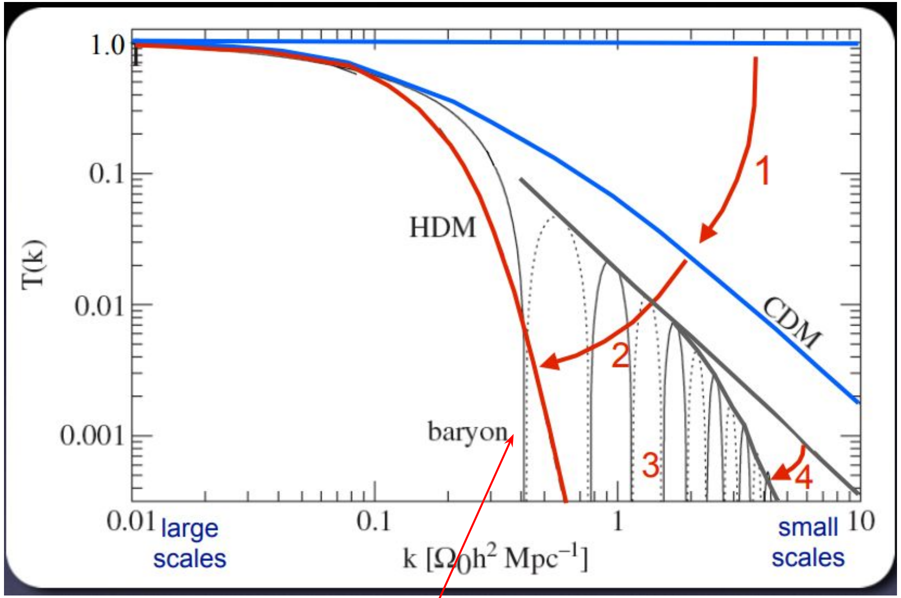
Warm Dark Matter

E.g. keV sterile neutrino

MASSIVE NEUTRINOS



From Viel+14



The thermal velocity of DM particles determines the free streaming length below which structure formation is suppressed (free-streaming damping)

$$k_{\rm FS} \sim 15.6 \frac{h}{\rm Mpc} \left(\frac{m_{\rm WDM}}{1{\rm keV}}\right)^{4/3} \left(\frac{0.12}{\Omega_{DM} h^2}\right)^{1/3}$$

DARK MATTER DETECTION

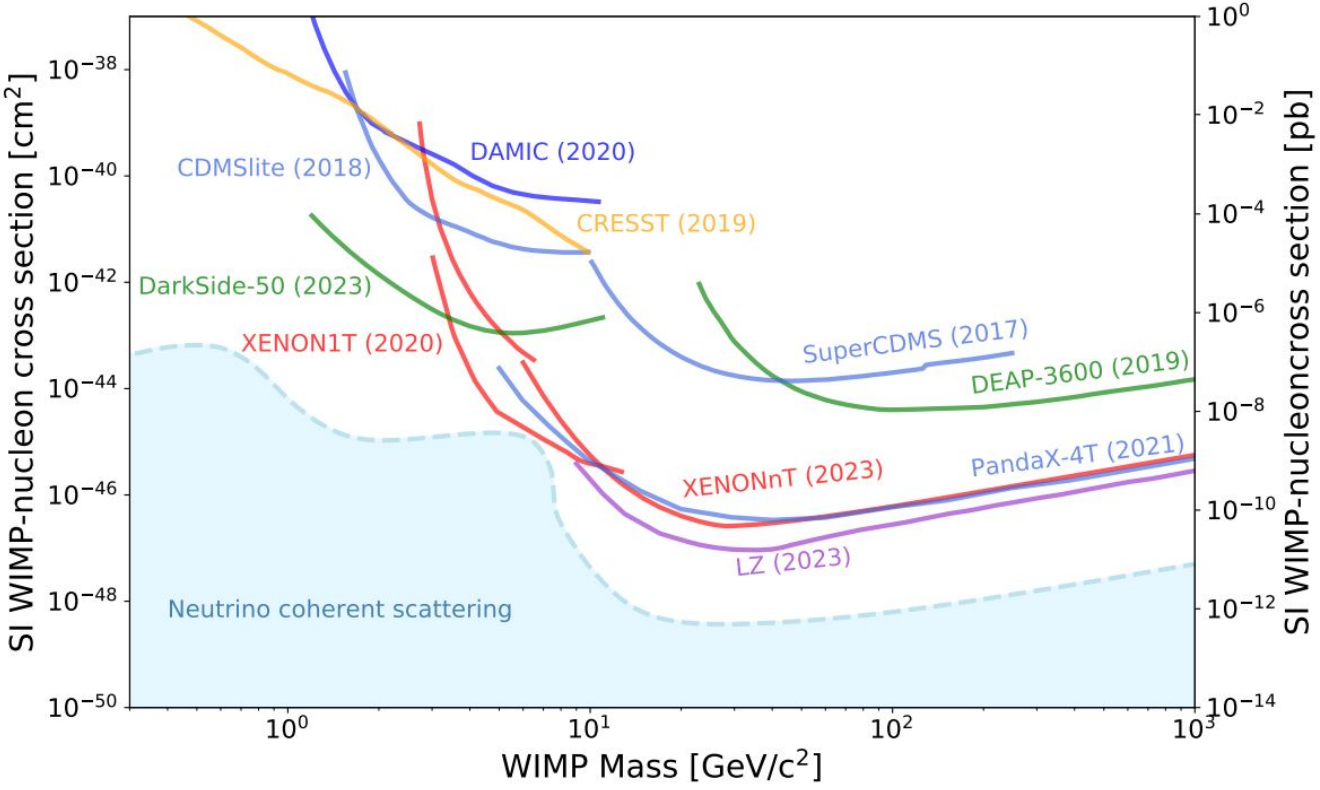
Direct detection:

Dark matter interacts with standard matter via scattering with the nucleons (or electrons) of the atoms present in the experiments. The idea is to measure the recoil energy of nuclei in order to detect their interactions with matter, and to estimate the dark matter mass and the scattering cross section with nucleons, σ_N

Indirect detection:

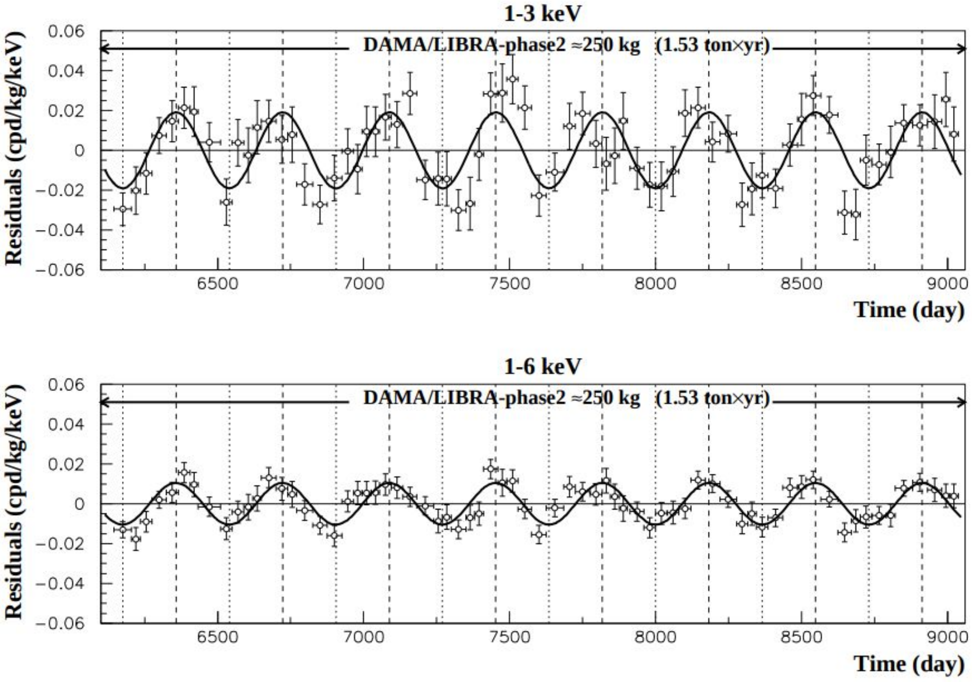
Indirect DM detection refers to the search for the annihilation or decay debris from DM particles, resulting in detectable species, including especially gamma rays, neutrinos, and antimatter particles

Direct detection constraints:



Direct detection:

DAMA/LIBRA (~250 kg of ultra-radiopure NaI(Tl) crystal scintillator): detection of annually modulated event rate with a statistical significance of 12.9 σ C.L.



Interpretation of the signal: The origin of the DM annual modulation signature and of its peculiar features is due to the Earth motion with respect to the DM particles constituting the Galactic Dark Halo. In fact, as a consequence of the Earth's revolution around the Sun, which is moving in the Galaxy with respect to the Local Standard of Rest towards the star Vega near the constellation of Hercules, the Earth should be crossed by a larger flux of DM particles around ≃ 2 June and by a smaller one around ≃ 2 December. In the former case the Earth orbital velocity is summed to that of the solar system with respect to the Galaxy, while in the latter the two velocities are subtracted

Indirect detection constraints: