Des particules au cosmos
À la recherche de la matière noire

XIIIe Rencontres d'été de l'infiniment grand à l'infiniment petit

30 Juin 2026

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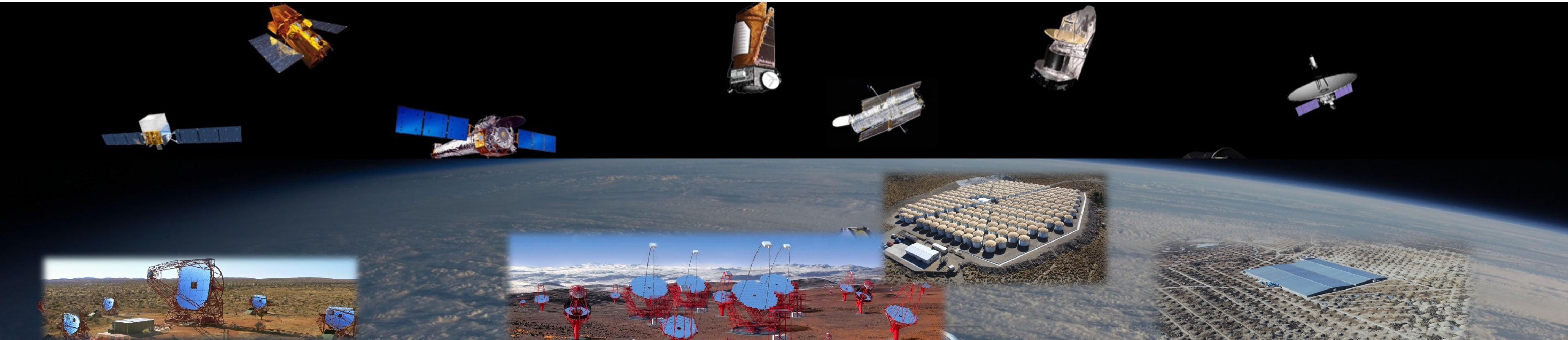

OUTLINE

1. Dark Matter : a required component
1.1 Observations of galaxy and galaxy cluster dynamics
1.2 At large scales : cosmological probes

2. What do we know about dark matter ?
2.1 Bounds on dark matter mass
2.2 Theoretical models of dark matter candidates

3. Testing the WIMP model
3.1 Direct detection : the XENONnT experiment
3.2 Indirect detection : observations with H.E.S.S. and CTAO

4. An alternative model : the axion
4.1 Astrophysical searches with gamma rays

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2. Wha… dark matter…

2.1 Bou…

2.2 Theore…

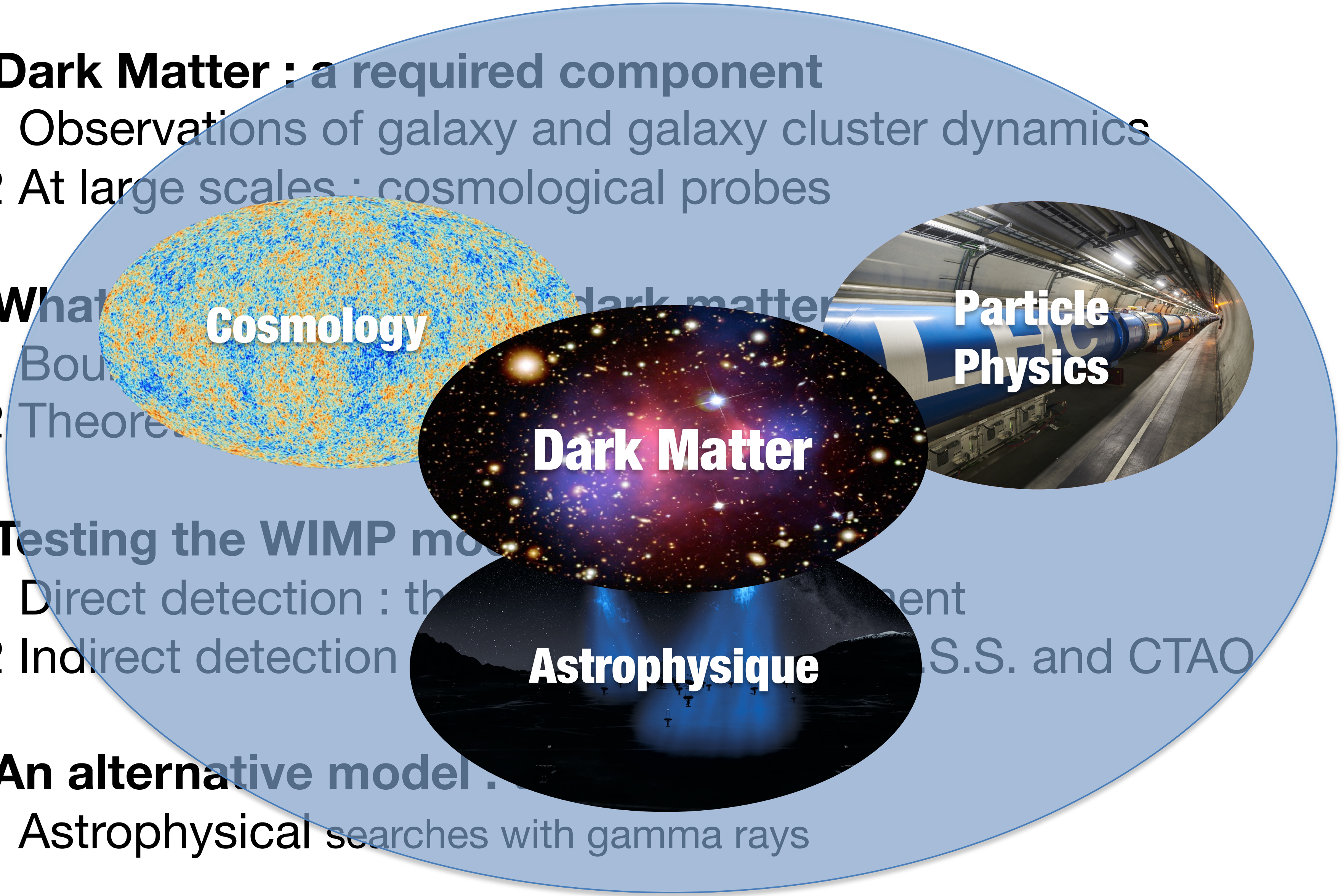
3. Testing the WIMP mo…

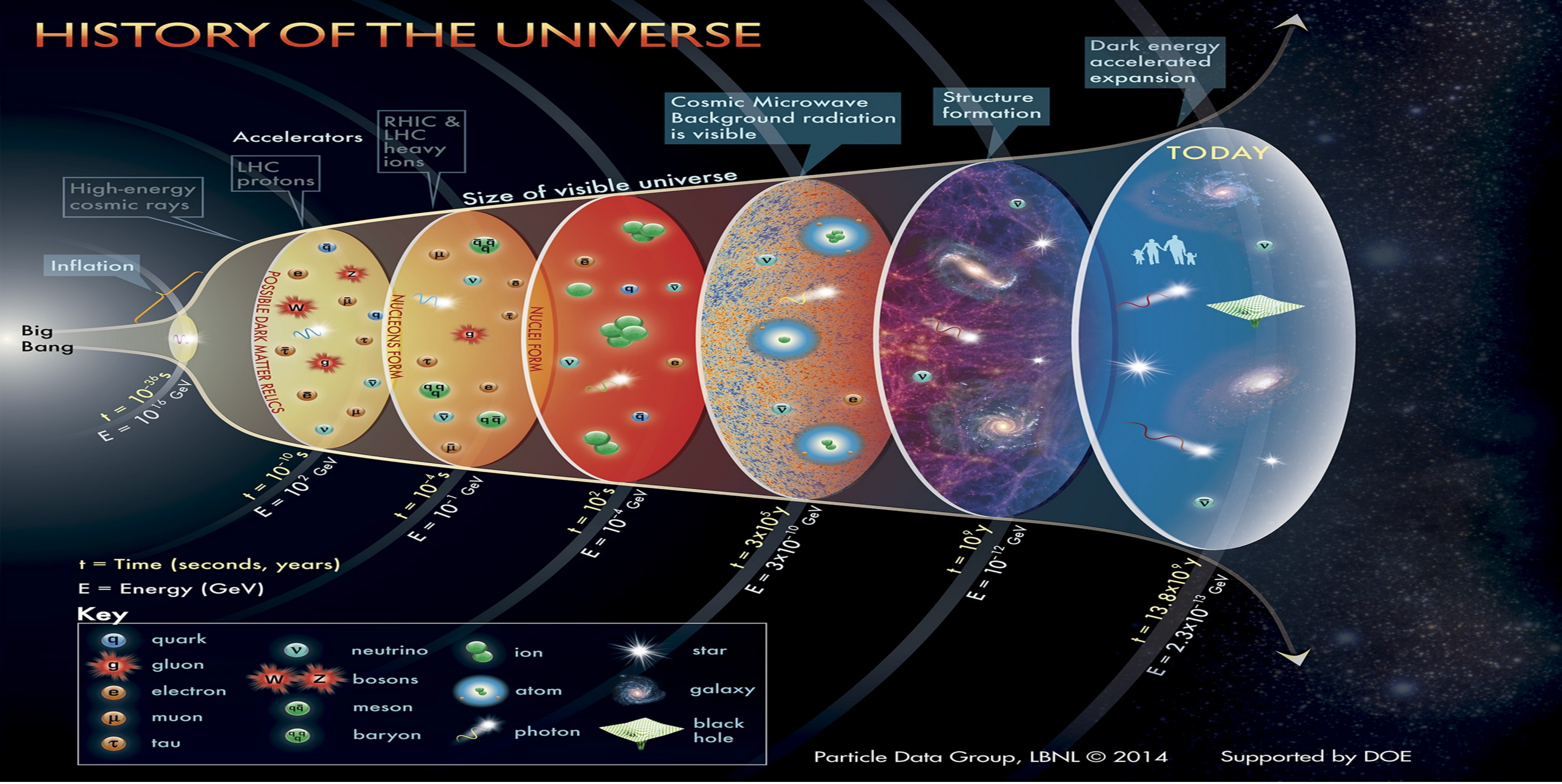
3.1 Direct detection : th… …ent

3.2 Indirect detection … …S.S. and CTAO

4. An alternative model : …

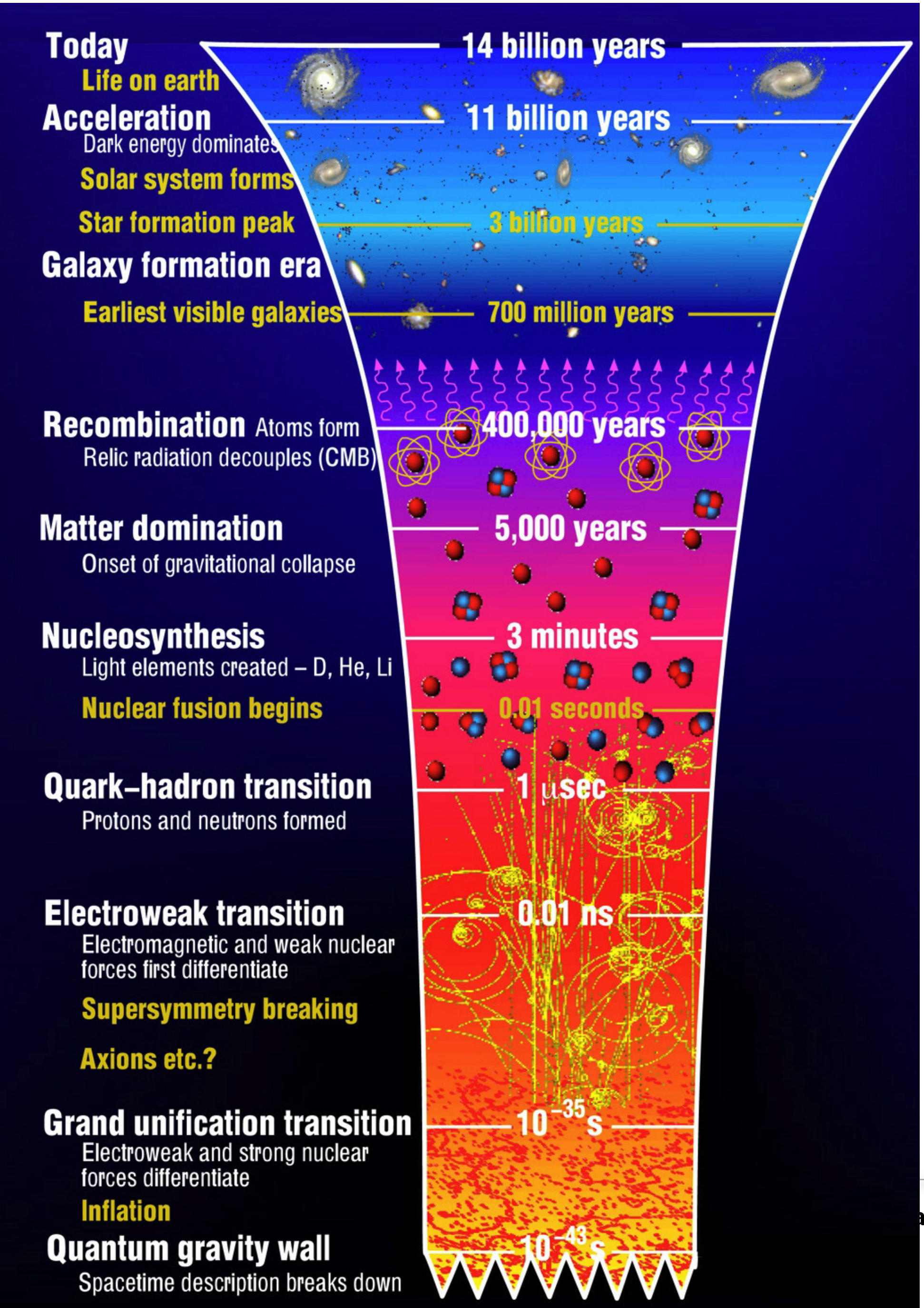
4.1 Astrophysical searches with gamma rays





Time →		min		10^5 yr	10^9 yr	10^{10} yr	
← Redshift		10^6	3000	1100.	10	1	0
← Temperature	TeV	keV		eV			2.7 K

History of the Universe



Dark energy dominates

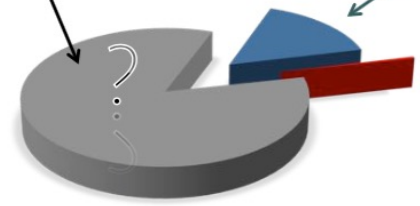
Matter dominates :
Structure formation

Radiation dominates
the primordial plasma

Unknown physics
new particles…

About 84% of the matter content in the Universe is unknown…

How do we know ?



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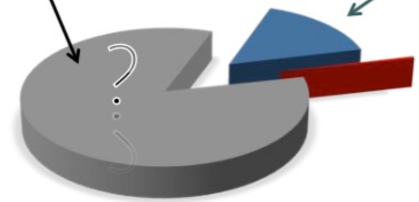

1) Dynamics of gravitationnally bounded objects : galaxies and galaxy clusters

2) Dynamics of the universe with Friedman equations + distance measurements in the universe

3) Large-scale structure formation
   - Baryonic acoustic oscillations (BAO)
   - Fluctuation of the matter density at large scale : CMB
   - Large scale galaxy distribution (LSS)

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The Coma cluster

- **Virial theorem:**

$$2\langle T\rangle + \langle U_{tot}\rangle = 0$$

$$T = N\frac{m}{2}\langle v^2\rangle$$

where m is the typical Galaxy mass.
With M = N m a proxy of the cluster mass :

$$2T = M\langle v^2\rangle$$

Die Rotverschiebung von extragalaktischen Nebeln", Helvetica Physica Acta (1933) 6, 110–127. "On the Masses of Nebulae and of Clusters of Nebulae*", ApJ (1937) 86, 217*
**Nebula=Early XXth century name for what we call now galaxy*

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- **Estimate of the gravitational potential energy of a self-gravitating homogeneous sphere of radius R**

$$\langle U_{tot}\rangle \simeq -\frac{3}{5}\frac{G_N M^2}{R}$$

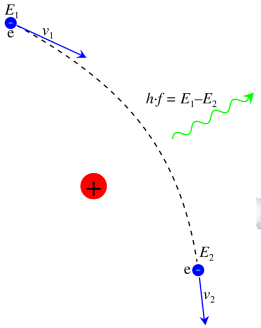
- **Assuming equipartition of the kinetic energy $\langle v^2\rangle = 3\langle v_r^2\rangle$ and applying the virial theorem, one obtains that the total mass is~ $4\times10^{14}\,M_\odot$**
  → about **400 times larger than the observed mass in galaxies**
  with R ≃ 3 Mpc and measurements of the radial velocities of the galaxies $\langle v^2_r\rangle = (1000\text{ km/s})^2$

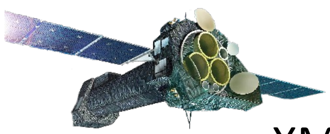
The Coma cluster

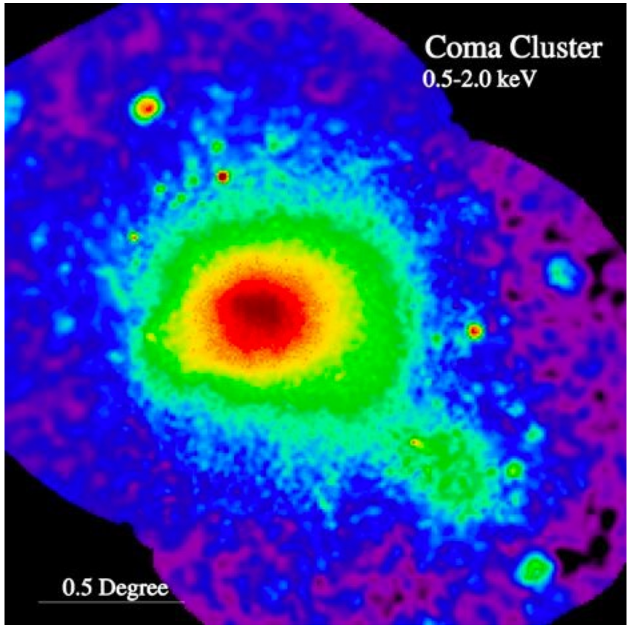
- **We know today that a large fraction of the mass of the galaxy clusters is made of hot gas**

  - gas is ionized and produces X-ray photons from electron Bremsstrahlung
  - from the measured X-ray flux and mean energy, angular size and distance, one can derive the mass in protons
  - using hydrostatic equilibrium, one can estimate that

$$M_{\rm tot} \simeq \frac{6\,kT\,R}{G\,m_p}$$




XMM-Newton



- X-ray size is about 1° at a distance of ~100 Mpc

→ **the mass of the gas in Coma is ~ 10^{14} $M_\odot$**

The Coma cluster

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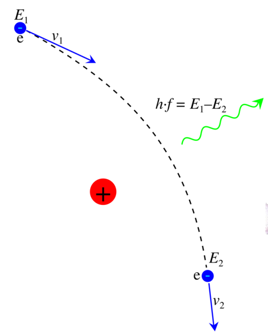
  - gas is ionized and produces X-ray photons from electron Bremsstrahlung
  - from the measured X-ray flux and mean energy, angular size and distance, one can derive the mass in protons

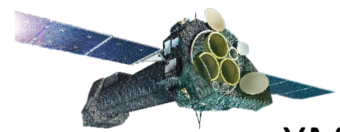
  → the mass of the gas in Coma is ~ 2 x10^{14} $M_\odot$

<u>Mass content:</u>
Stars : 3x10^{13} $M_\odot$ 2%
Gas: 10^{14} $M_\odot$ 11%

→ More than 85% of the mass is made of dark matter.

Similar results for Virgo cluster (Sinclair Smith 1937)





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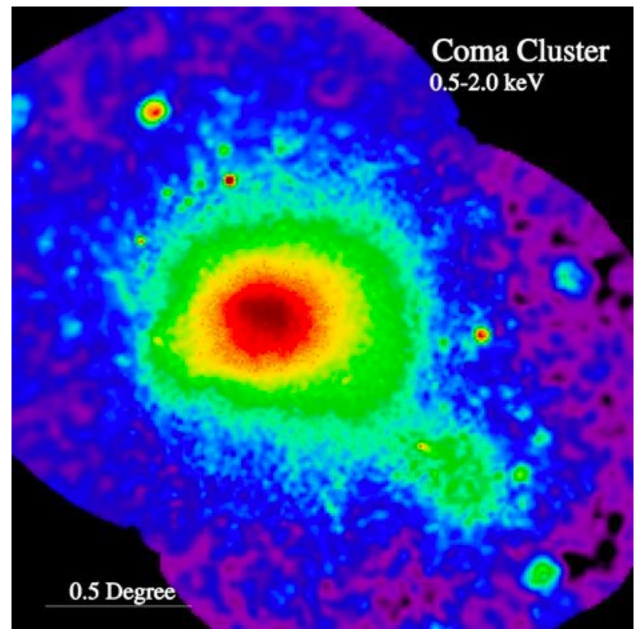
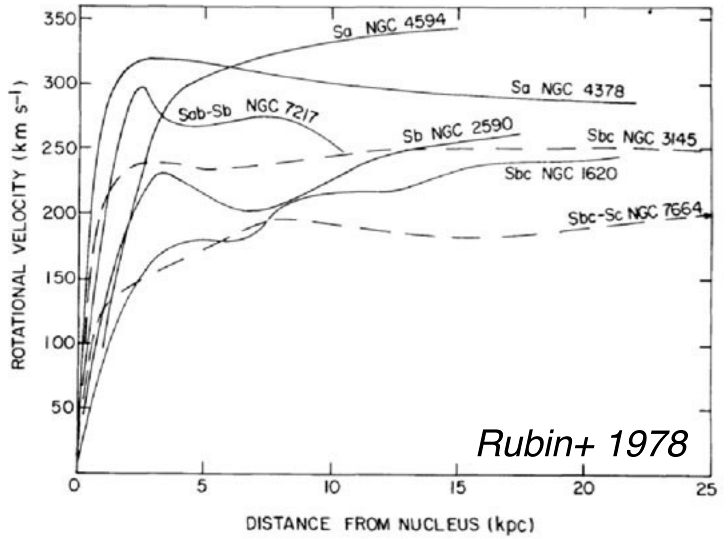


Galactic rotation curve

Rubin and Kent Ford also confirmed this hypothesized missing component (Rubin&Ford1970): the velocity of the stars in the Andromeda galaxy (M31) does not follow Kepler's law 1/√r behavior.



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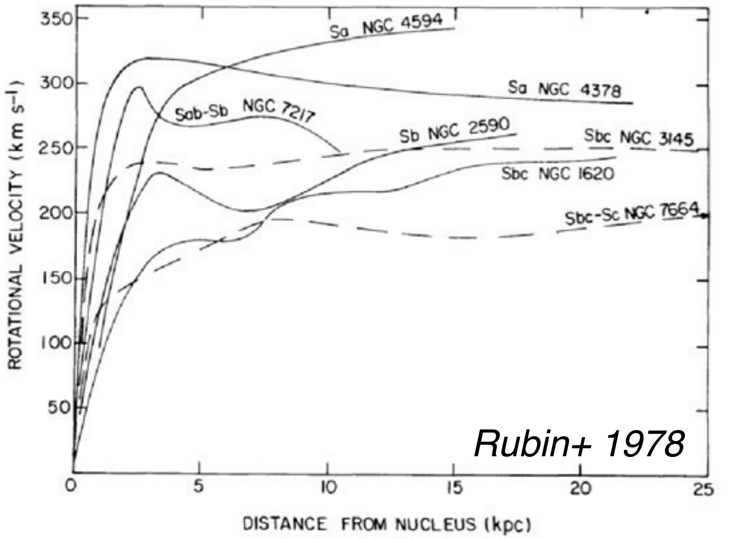
- **Centrally concentrated mass implies**

while observed v_c^2 ~ constant
→ M(<R) ∝ R → $\rho(r) \propto \frac{1}{r^2}$



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- **Circular velocity of stars determined by enclosed mass**

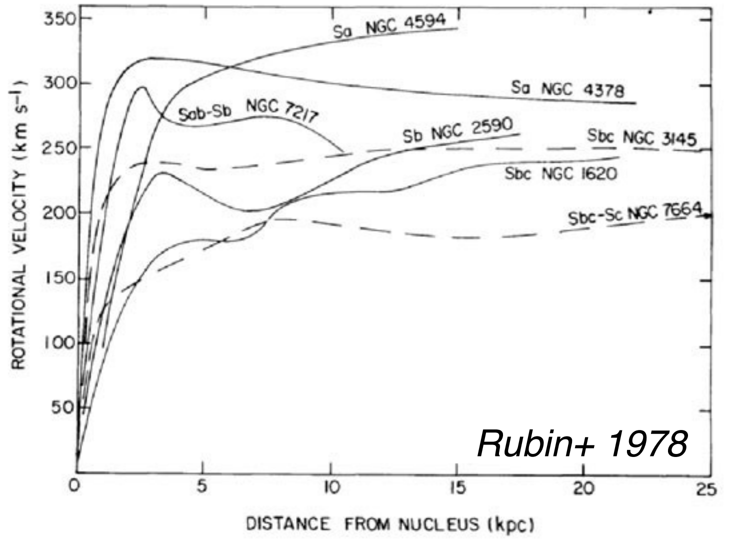
$$v_c^2(<R) = R\frac{d\phi_{\rm tot}}{dR} = \frac{GM(<R)}{R}$$

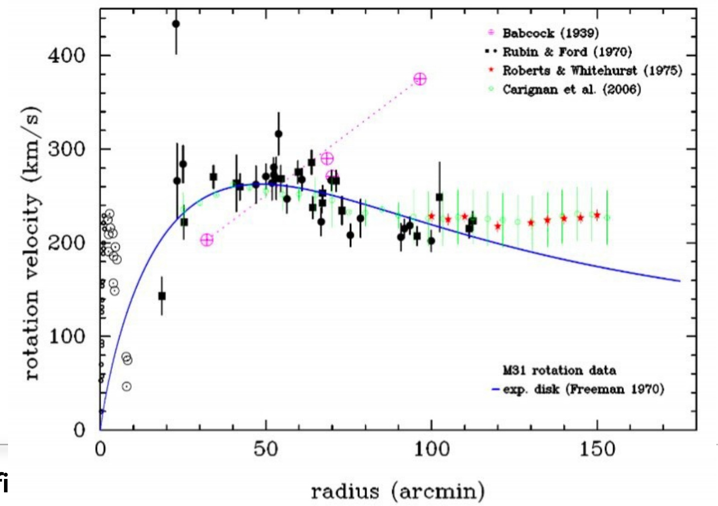
with $$M(<R) \equiv 4\pi\int_0^R r^2\rho(r)dr$$

- **Centrally concentrated mass implies** $$v_c^2 \propto \frac{1}{R}$$

while observed v_c^2 ~ constant
→ M(<R) ∝ R → $$\rho(r) \propto \frac{1}{r^2}$$

Radio observations of the 21cm hyperfine transition of neutral hydrogen (HI) probe larger distance and enable the existence of flat rotation curves robustly.





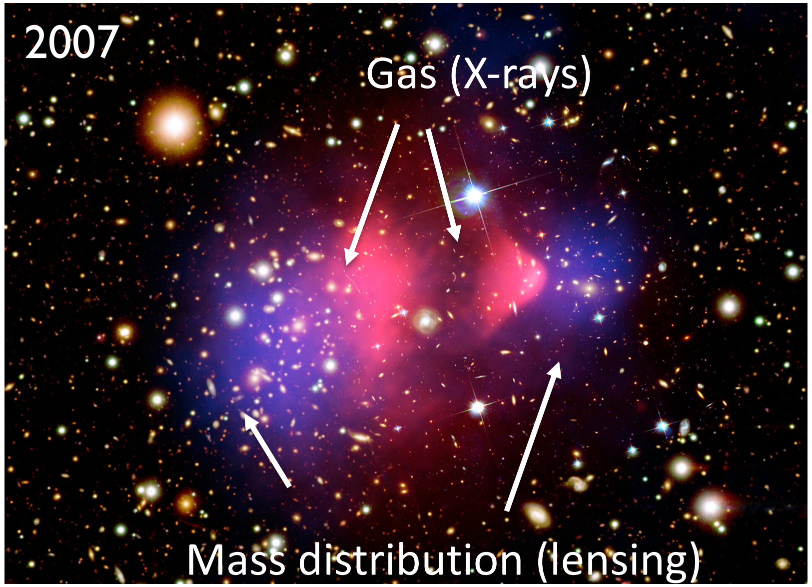
The Bullet Cluster

- **Colliding galaxy clusters**

→ the different behaviour of gas (colliding) and galaxies / dark matter (collisionless) can be directly observed

- gaz clouds interact and separate from the potential wheel
- gaz is not reponsible for the potential

→ « Proof of dark matter »



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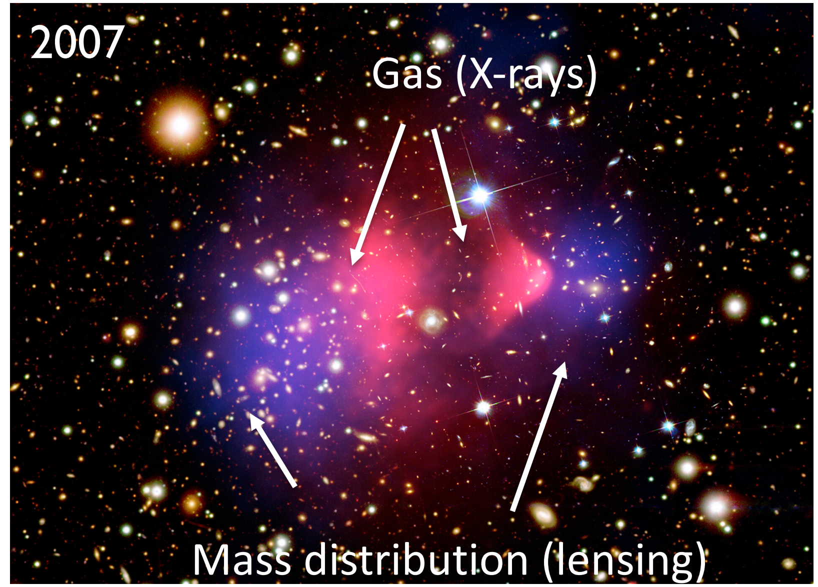

- With σ = section efficace de collision DM-DM
  - probability of interaction is $p \sim n\,\sigma\,L$ with $n = 3M/(4\pi L^3 m)$
  - $p < 1 \rightarrow \sigma/m \gtrsim 2\ \mathrm{cm^2/g}$ for $L = 1$ Mpc and $M = 5\times10^{14}\ M_\odot$

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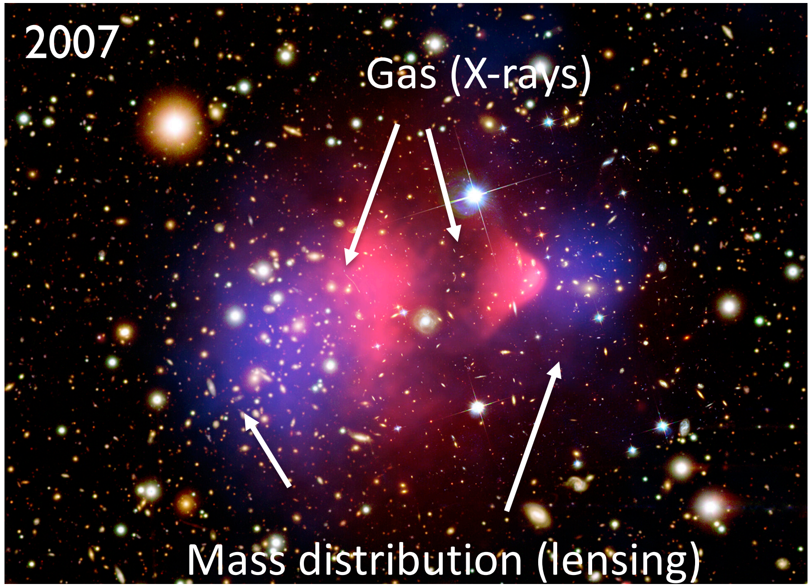

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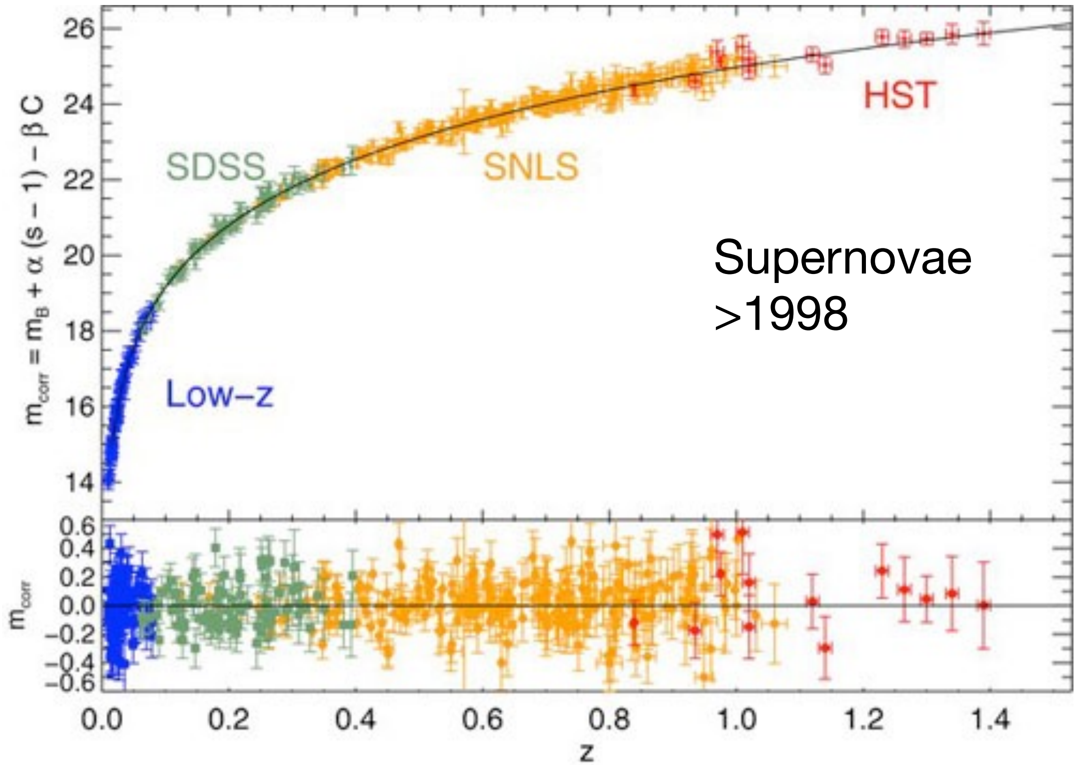
- Dark matter is collisionless : an example of the microphysics properties of dark matter
  - For GeV mass DM, s < 1 barn (strong interaction…)

Cosmological probes

Distance measurement



Supernovae together with CMB, BAO measurements

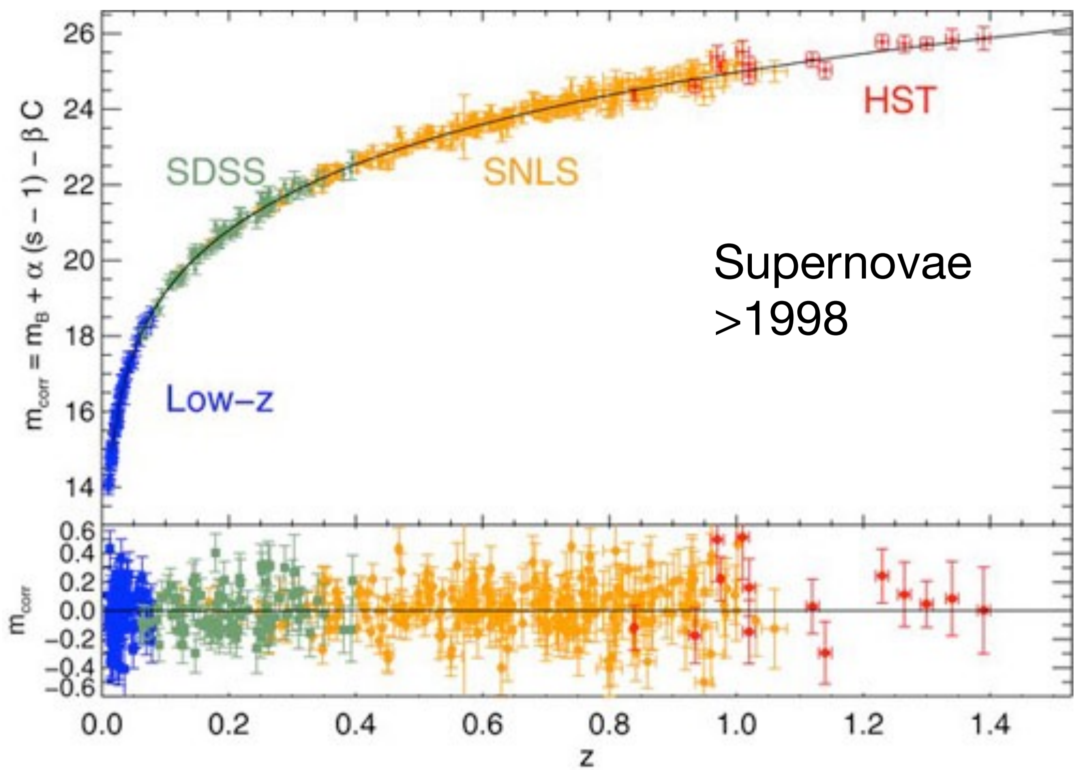
- Universe is flat
- $\Omega_M = 0.3, \Omega_\Lambda = 0.7$

Λ: dark energy

M: total matter, non-relativistic

Cosmological probes

Distance measurement



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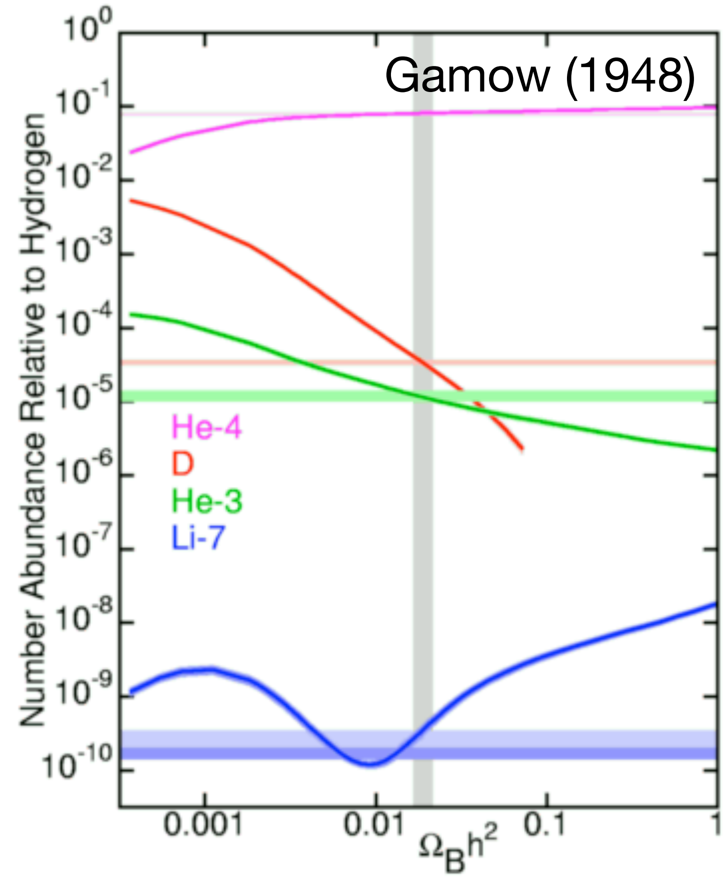
Primordial nucleosynthesis



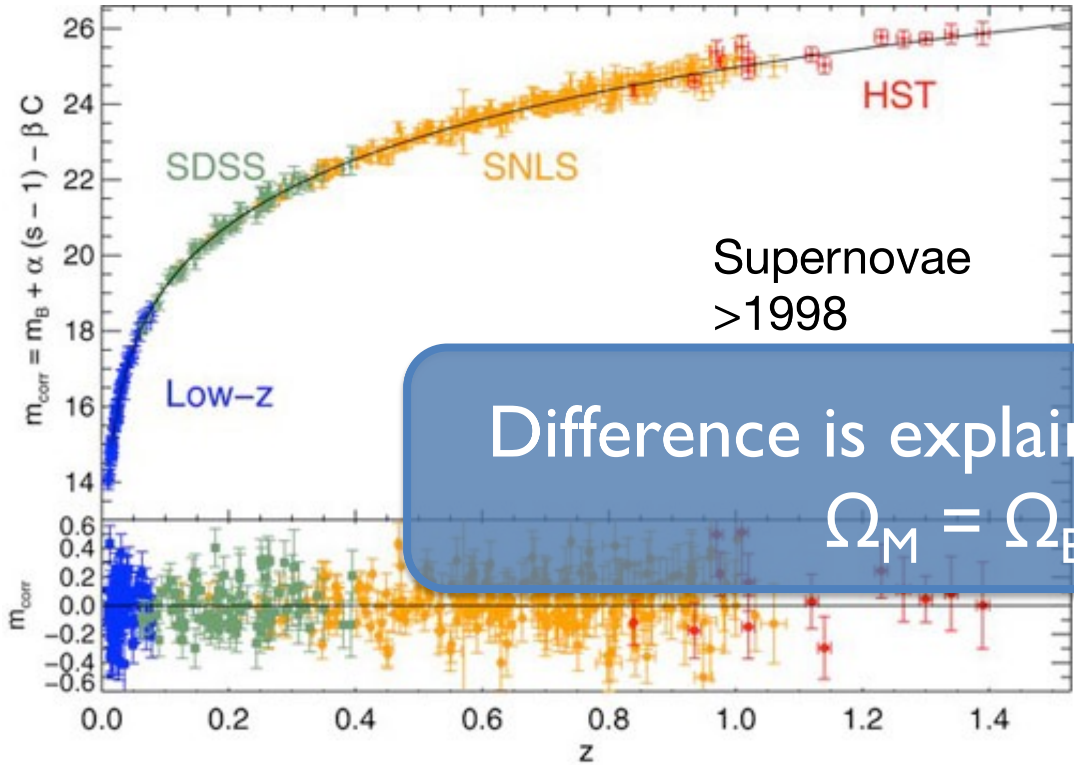
B: baryons = « ordinary matter »

Predictions dependent of Ω_B

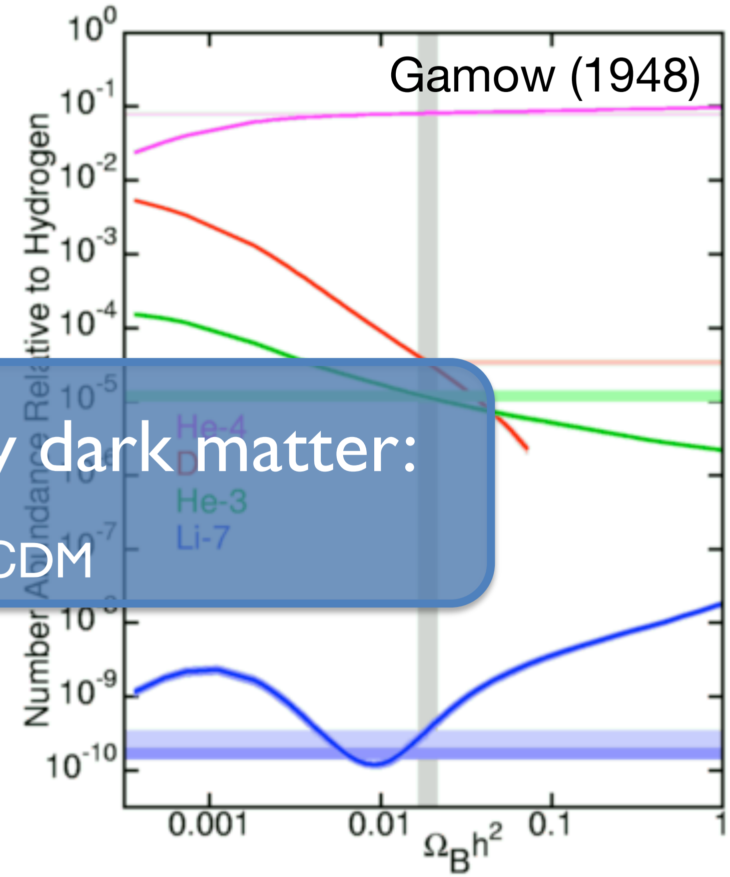
Observations : $\Omega_B = 0.04$

Cosmological probes

Distance measurement



Primordial nucleosynthesis



Difference is explained by dark matter:

$\Omega_M = \Omega_B + \Omega_{CDM}$

Supernovae together with CMB, BAO measurements

- Universe is flat
- $\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$

Λ: dark energy

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B: baryons = ordinary matter"

Predictions dependent of Ω_B

Observations : $\Omega_B = 0.04$

OUTLINE

What is the mass of Dark Matter ?

- **DM must be gravitationally bounded on scales**
- Observation of a dwarf spheroidal galaxy
  - Smallest bounded objects dominated by DM
  - Velocity of about 10-50 km/s

Draco dwarf spheroidal galaxy

A lower bound on Dark Matter mass

- **DM must be gravitationally bounded on scales. at least as large as the size of a dwarf spheroidal galaxy**
  - make use of the Heisenberg uncertainty principle : λ_{dB} should not be greater than the size of the galaxy
    - with the Planck constant and considering a non-relativistic particle, derive a lower bound on its mass

$$m \gtrsim 10^{-22}\mathrm{eV}\left(\frac{1\,\mathrm{kpc}}{r_{\mathrm{dSph}}}\right)\left(\frac{20\,\mathrm{km/s}}{v_{\mathrm{dSph}}}\right)$$

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$$m \gtrsim 10^{-22}\mathrm{eV}\left(\frac{1\,\mathrm{kpc}}{r_{\mathrm{dSph}}}\right)\left(\frac{20\,\mathrm{km/s}}{v_{\mathrm{dSph}}}\right)$$

  - Not a a very stringent bound…
  - However, quantum effects can drastically change such a lower bound:
    - e.g. if DM is a fermion, because in this case its phase space density is bounded by the so-called Pauli blocking effect

Mass bound of Fermionic Dark Matter

- DM is a fermion (spin 1/2): no more than one fermion per quantum state
  $\rightarrow$ set limit on how light the fermion can be, a.k.a. the Tremaine-Gunn bound

Mass bound of Fermionic Dark Matter

- DM is a fermion (spin 1/2): no more than one fermion per quantum state
  → set limit on how light the fermion can be, a.k.a. the Tremaine-Gunn bound
- For non-interacting and non-relativistic fermions of mass m_f : $$E_f = \frac{\hbar}{2m_f}\left(3\pi^2 n_f\right)^{3/2}$$
- Assuming a sphere of constant density of mass M and radius R, one can get the Fermi velocity $v_f(M, R, m_f)$
- Requesting that the Fermi velocity is less than the escape velocity $v_{esc} = (2GM/R)^{1/2}$, one obtains for DM-dominated system like dwarf galaxies:

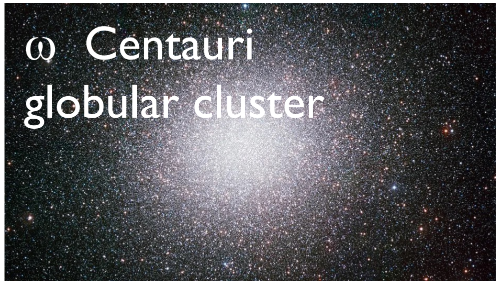
$$m^4 \gtrsim (100\,\mathrm{eV})^4 \left(\frac{5\times 10^8\,\mathrm{M}_\odot}{M_{\mathrm{dSph}}}\right)^{1/2} \left(\frac{2.5\,\mathrm{kpc}}{r_{\mathrm{dSph}}}\right)^{3/2}$$

Draco dwarf spheroidal galaxy

- The difference of 23 orders of magnitude with previous lower bound esimate tells us how important quantum effects might be in the description of DM

An upper bound on Dark Matter mass

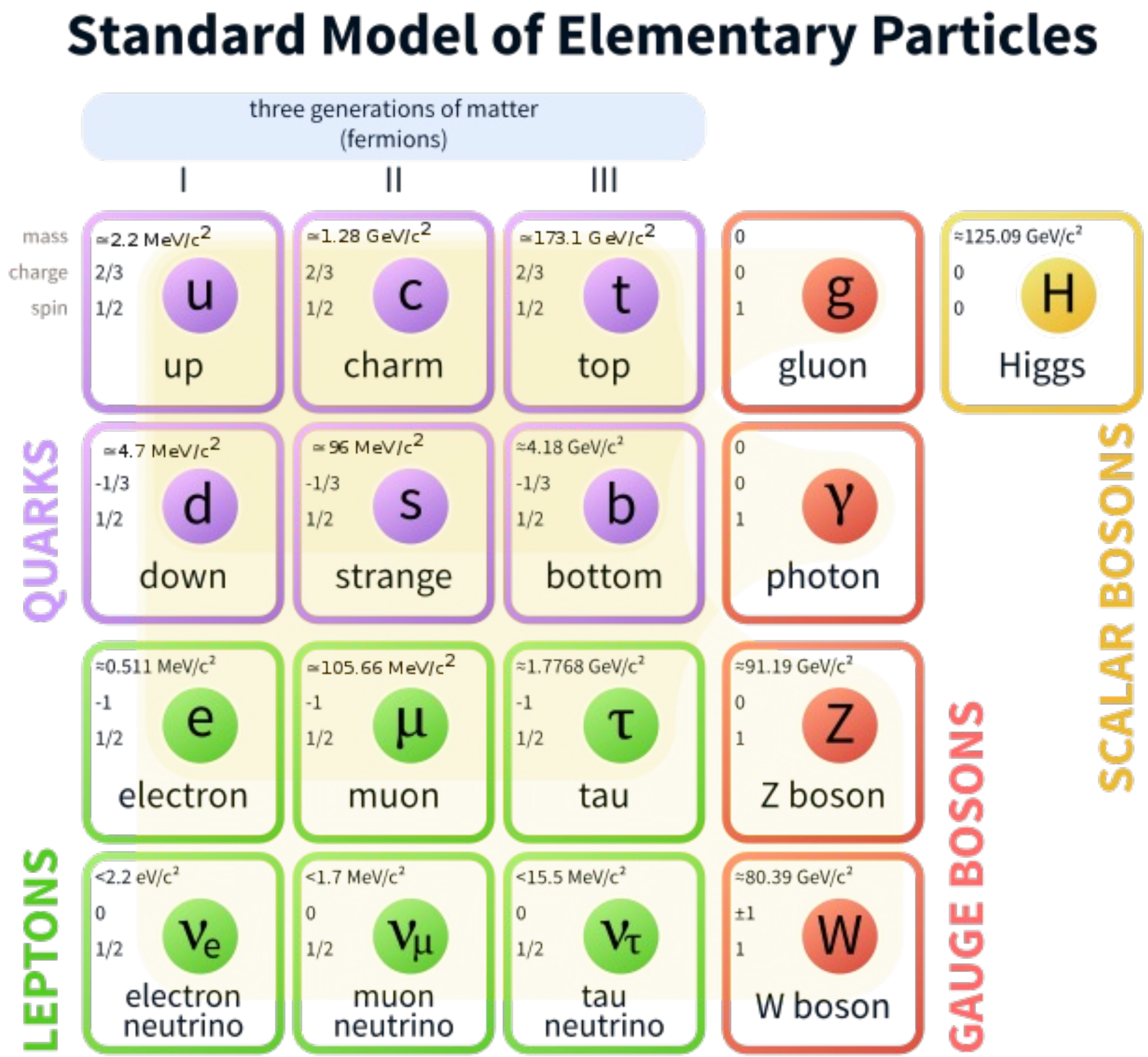
- **Macroscopic Dark Matter can tidally disrupt structures**
  - Encounters between black holes and stellar systems can affect dynamics of their stars, such as changes in their velocities, and eventually unbound the system



- Passing BH composing the DM halo will increase velocity dispersion in the cluster, and thus their total energy (see Carr&Sakallariedou 1999)
- For globular clusters:
  - modelled as a Plummer sphere
  - using typical GC parameters
  - and given that GC survived for the ~age of the Milkly Way

$$M_{BH} \lesssim 10^4 \left(\frac{M_{\rm GC}}{10^5\,{\rm M}_\odot}\right)\left(\frac{r_{\rm GC}}{10\,{\rm pc}}\right)\left(\frac{t_{\rm L}}{10\,{\rm Gyr}}\right) M_\odot$$

Standard Model particles and Dark matter



Dark matter

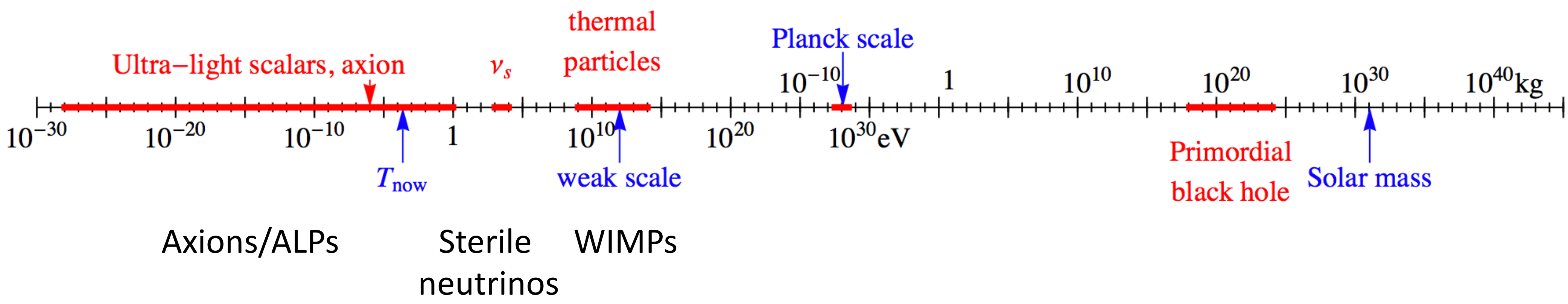
- neutral particle (no electric and strong charges)
- very feebly interacting
- stable or very long lived
- possibly a relic from the early universe

Neutrinos : too light

- relativistic in the early universe

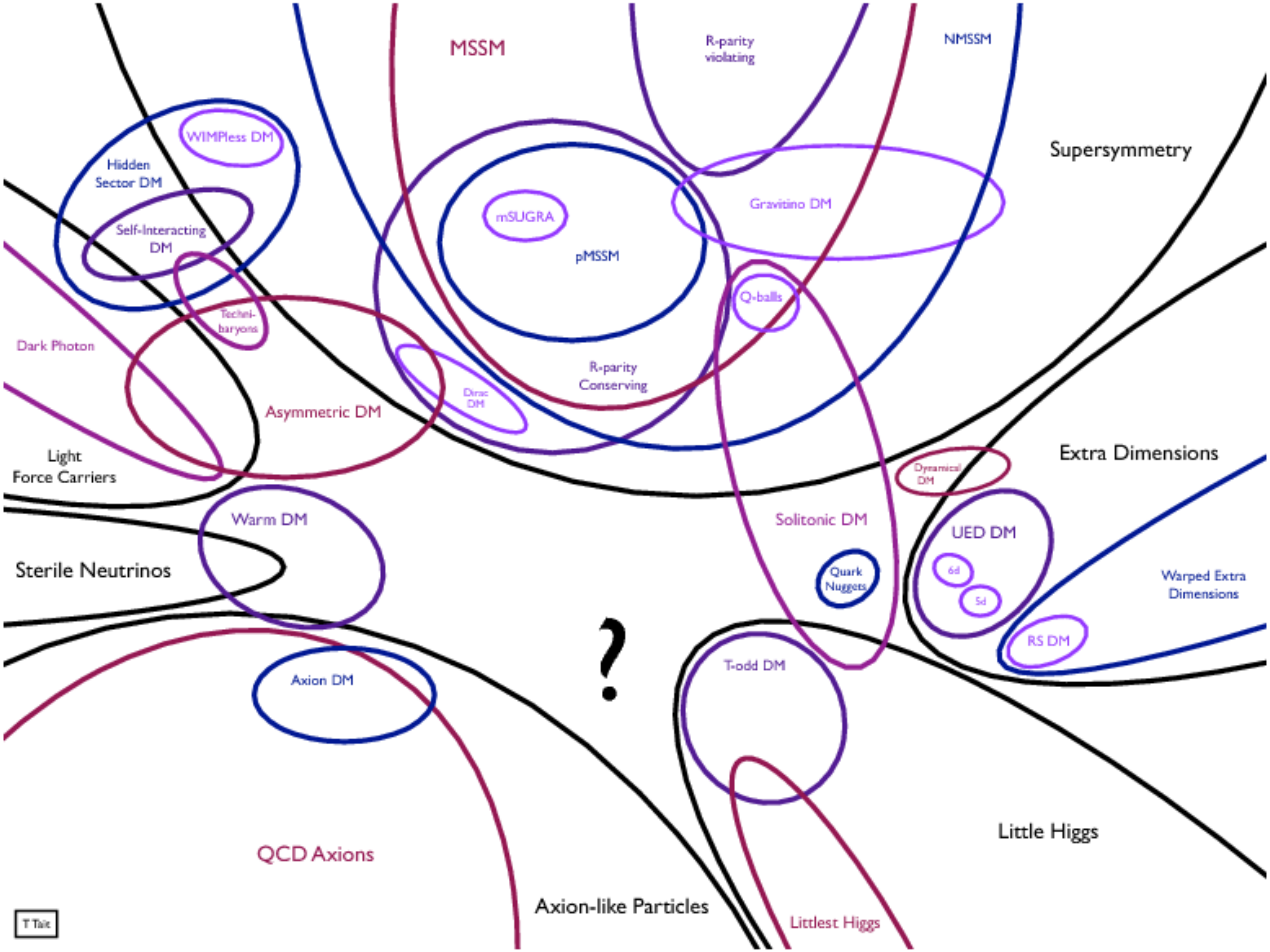
As of 2026, the microphysics nature od dark matter (mass, interaction and couplings) is unknown

The landscape of Dark Matter



- Enormous spectrum of possible candidates beyond the Standard Model, over a huge range of mass scales
- Cosmic experiments seek to detect and measure dark matter in its natural habitat: the halo of our Galaxy, the halos of distant galaxies, and the large-scale structure of the Universe
- Cosmic observables can establish that a given discovery is, in fact, associated with the dark matter in the Universe

Popular Dark Matter models in 2015 …



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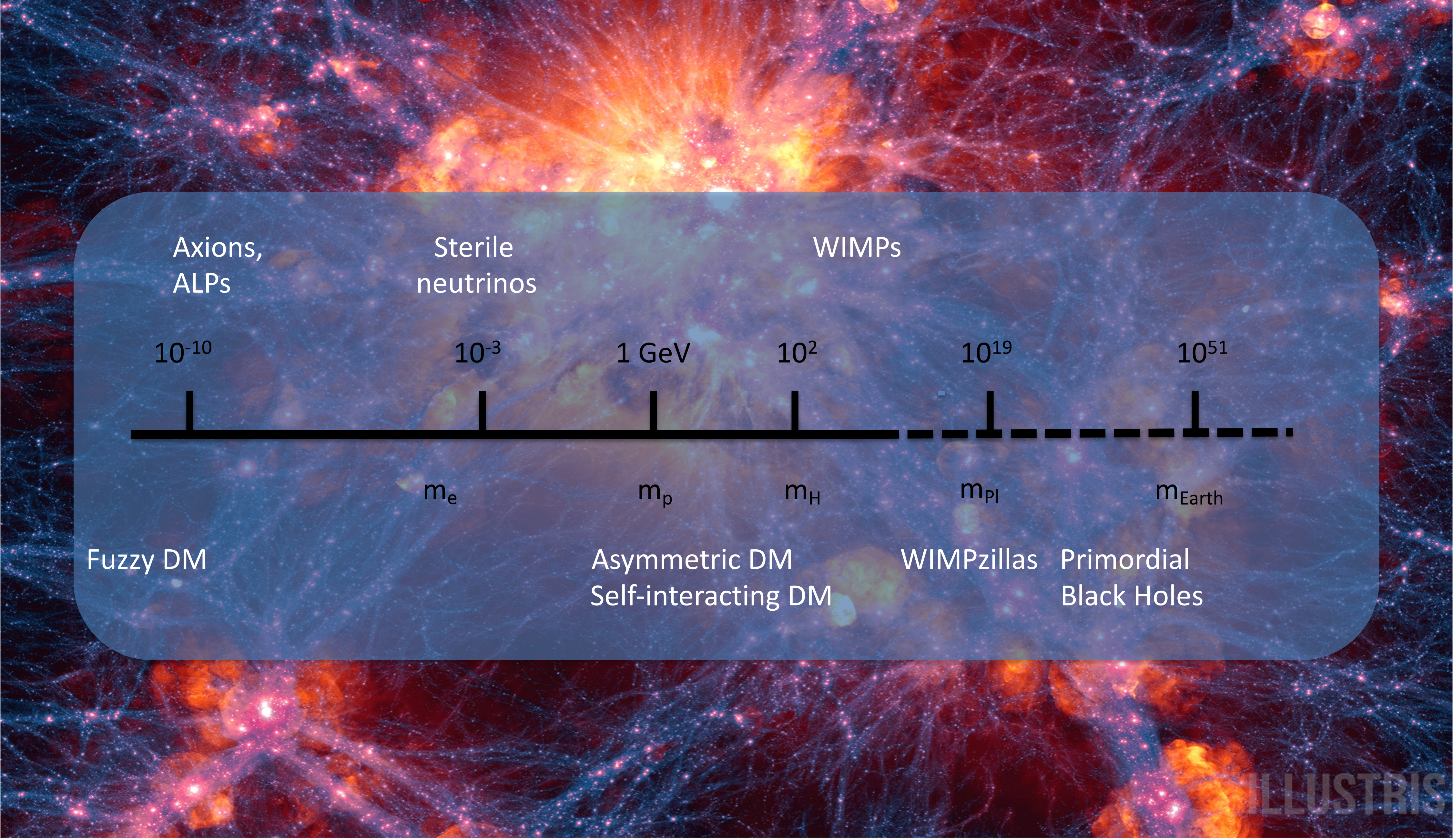
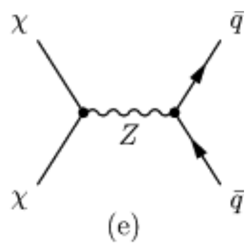
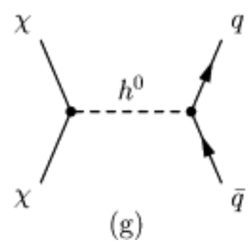


The WIMP model

- **Weakly Interacting Massive Particle : well-motivated scenario**
  - **Devised in the 80s, started to be probed in the 2000s**

- Assume new physics at the electroweak interaction scale
  - solve he. Hierarcy problem
  - e.g., supersymmtry oid extra dimensionss
  - New stabe particle χ : Mass ~ »electroweak scale" ~ 10 GeV - 1 TeV (W, Z, Higgs ~ 100 GeV)
  - Interaction with Standard Model particles with weak couplings, e.g., :





Examples of annihilation diagram

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  - New stabe particle χ : Mass ~ »electroweak scale" ~ 10 GeV - 1 TeV (W, Z, Higgs ~ 100 GeV)
  - Interaction with Standard Model particles with weak couplings
- The weak interaction mass scale and ordinary gauge couplings give right relic DM density

$$\Omega_{\rm DM} h^2 = \frac{3 \times 10^{-27}\ {\rm cm^3 s^{-1}}}{\langle \sigma v \rangle} \qquad \langle \sigma v \rangle_{\rm W} \sim \frac{\alpha^2}{m^2_{\rm WIMP}} \sim 3 \times 10^{-26} {\rm cm^3 s^{-1}}$$

  - Annihilation cross section scale provides the mesured DM density : « WIMP miracle »

The WIMP model in more details

- You may have already heard about the 'WIMP miracle', more generally called "thermal relic" scenario

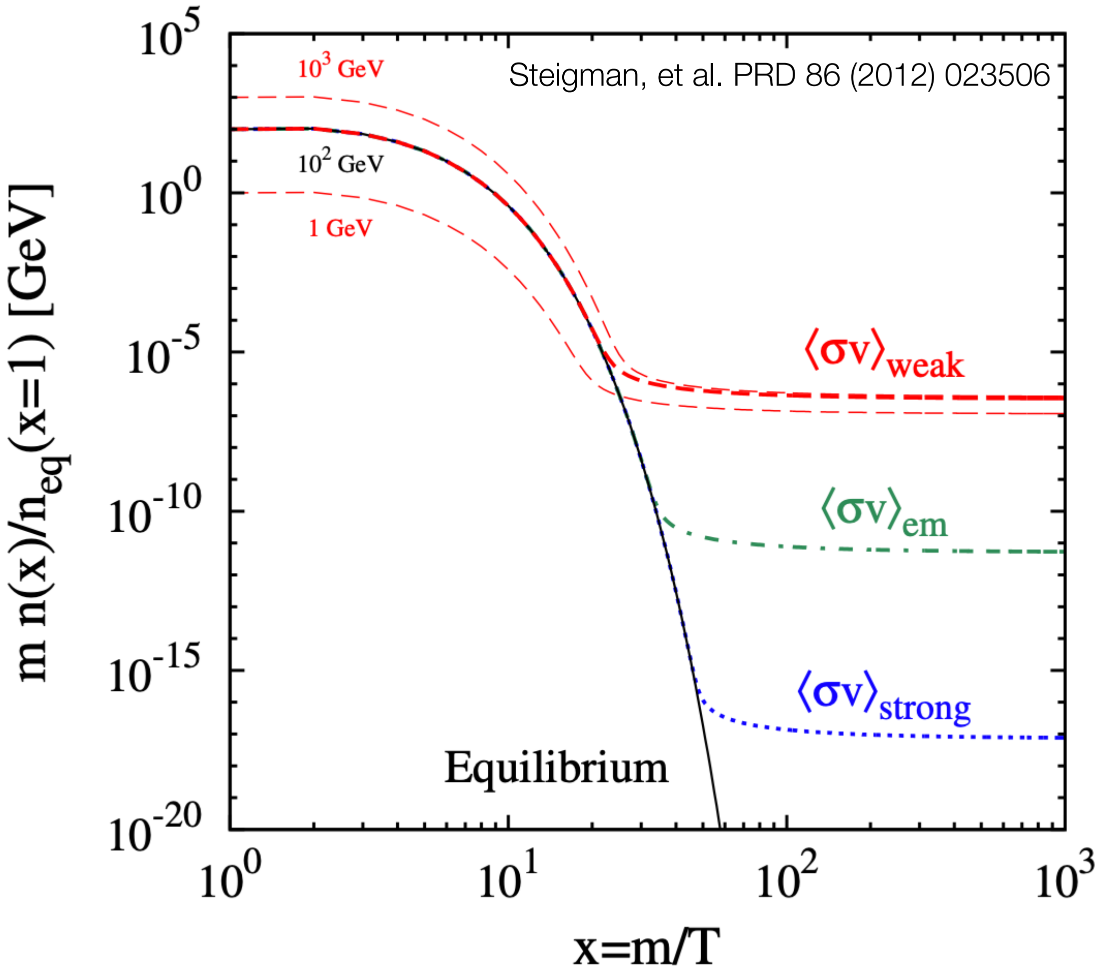
- DM is in thermal equilibrium early on, then is depleted via annihilation (DM does not need to be weak-scale at this point)

- At some point in the early universe, annihilation stops because of the expansion rate, the DM density is then frozen

The WIMP model in more details

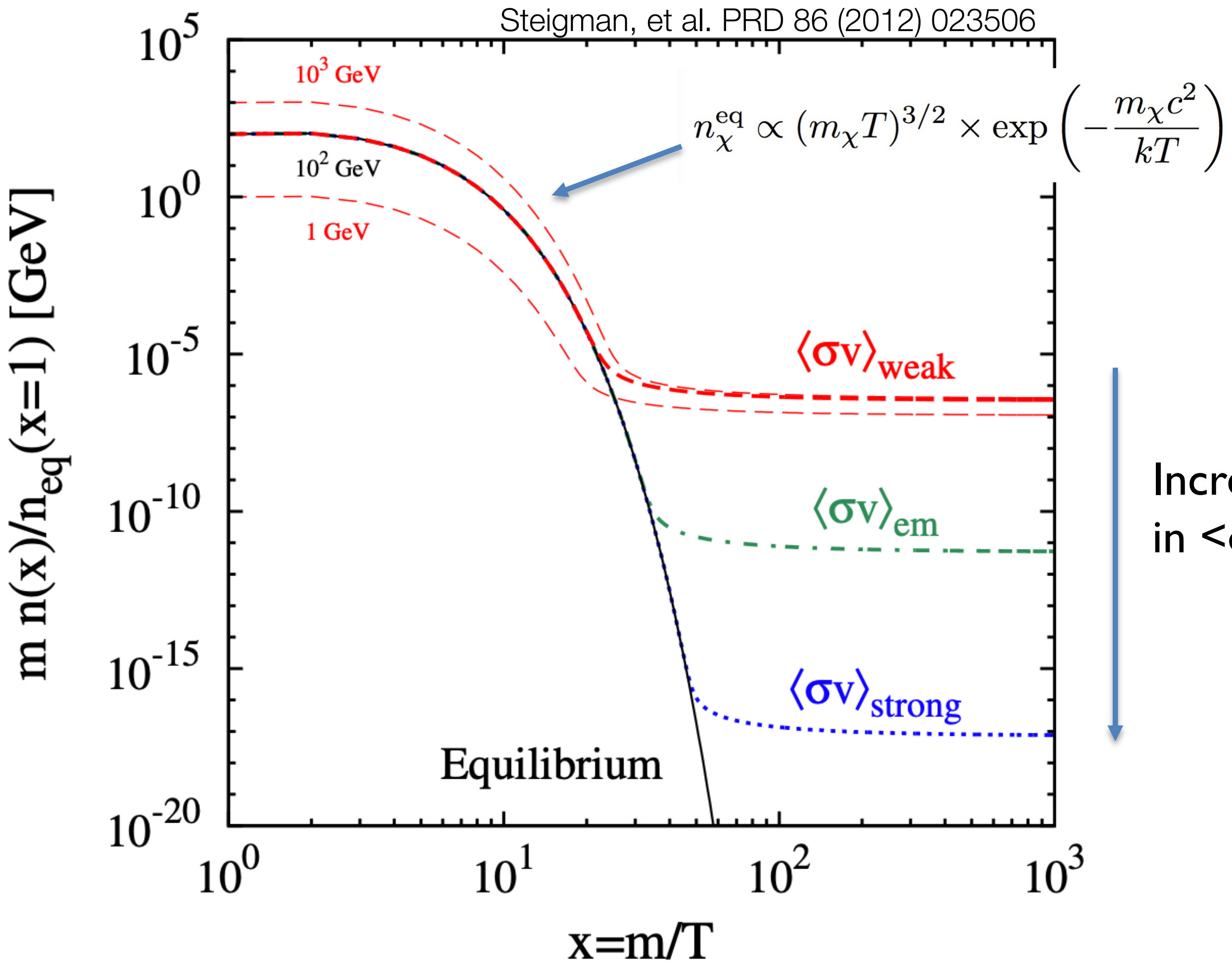
- Early on, temperature is high enough and DM particles could interact with SM particles and vice-versa

- As Universe cooled down and expanded, their density decreased, they interacted less frequently



- At some point, the Hubble expansion time becomes comparable to the time needed for a given DM particle to annihilate; we refer to this point as « freezeout ».

The WIMP model in more details



Increase in <σv>

- Freeze-out occurs when timescales for expansion and annihilation rates are similar:

$$H(T_f) \sim n_{eq}(T_f)\langle\sigma v\rangle$$

$$n(T_0) = n_{eq}(T_f)\left(\frac{T_0}{T_f}\right)^3$$

H α T^2 (radiation dominated era)

$$\rho(T_0) = n(T_0)m_{DM} \sim \frac{T_0^3}{\langle\sigma v\rangle M_{Pl}}\left(\frac{m_{DM}}{T_f}\right)$$

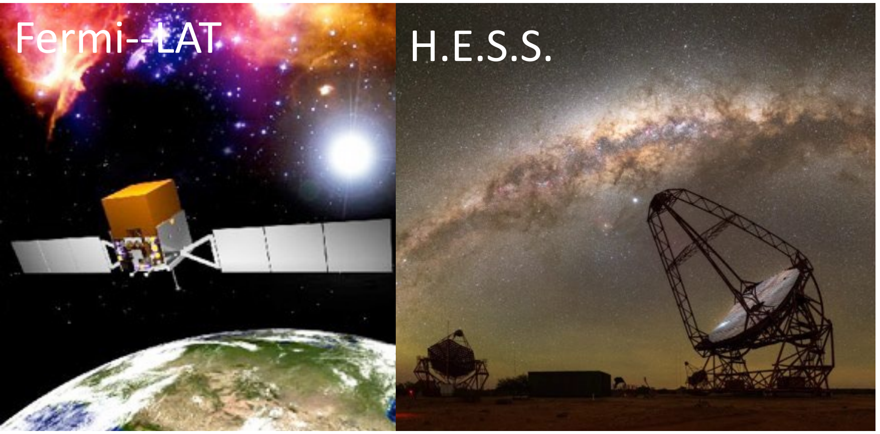
$$\Omega_\chi = \rho_\chi(T_0)/\rho_c$$

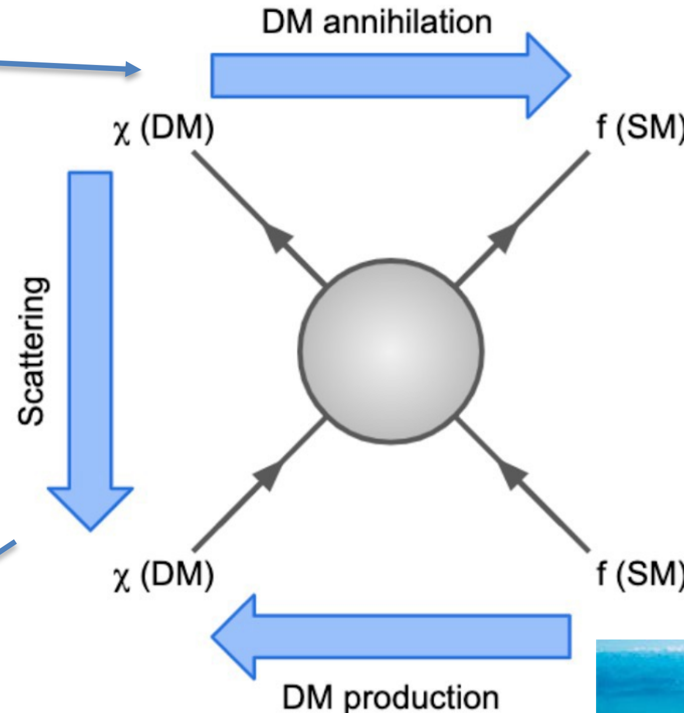
$$\Omega_\chi h^2 = \frac{3\times 10^{-27}\ \mathrm{cm^3/s}}{\langle\sigma v\rangle}$$

OUTLINE

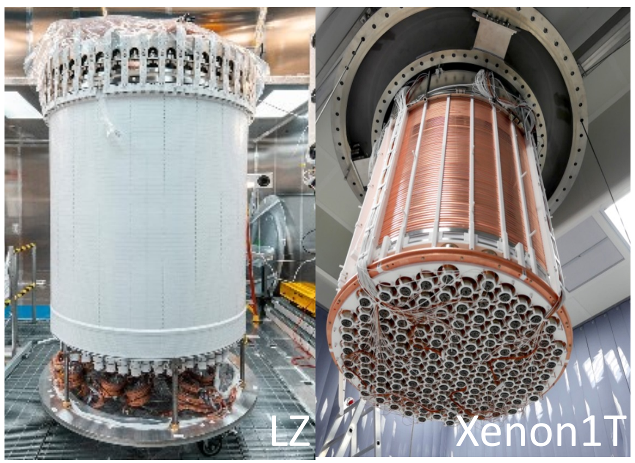
Testing the WIMP model

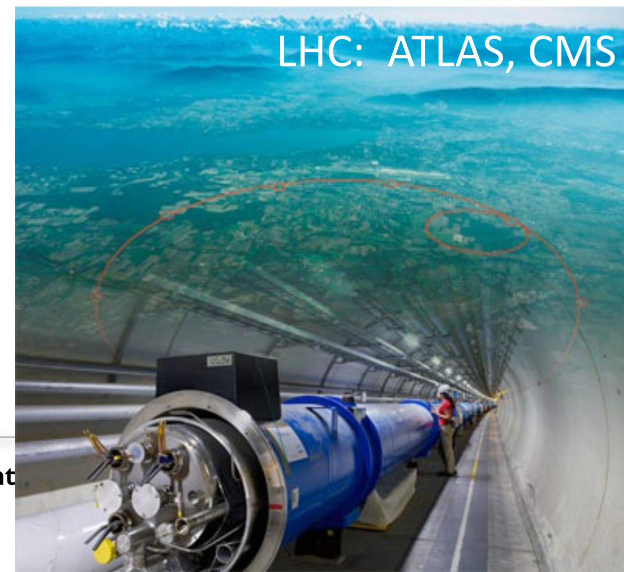
- **Detection techniques : direct, indirect detection, and production**





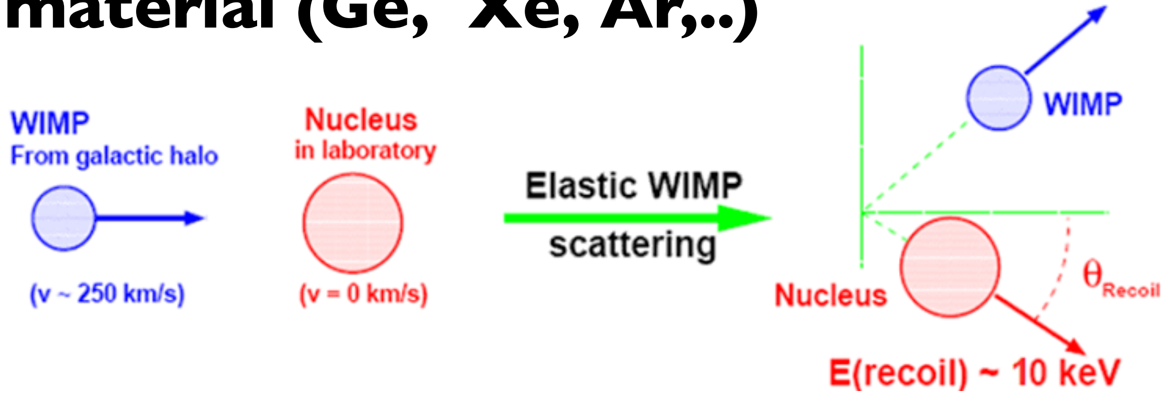
Current experiments reached the required sensitivity to probe the WIMP model

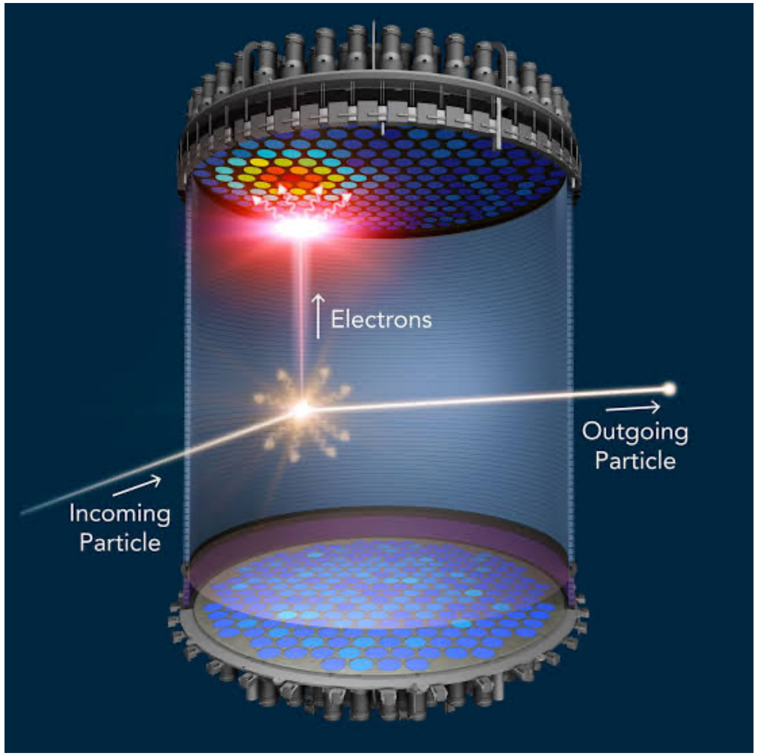




WIMP direct detection

- **WIMP elastic scattering off nucleus composing the target material (Ge, Xe, Ar,..)**

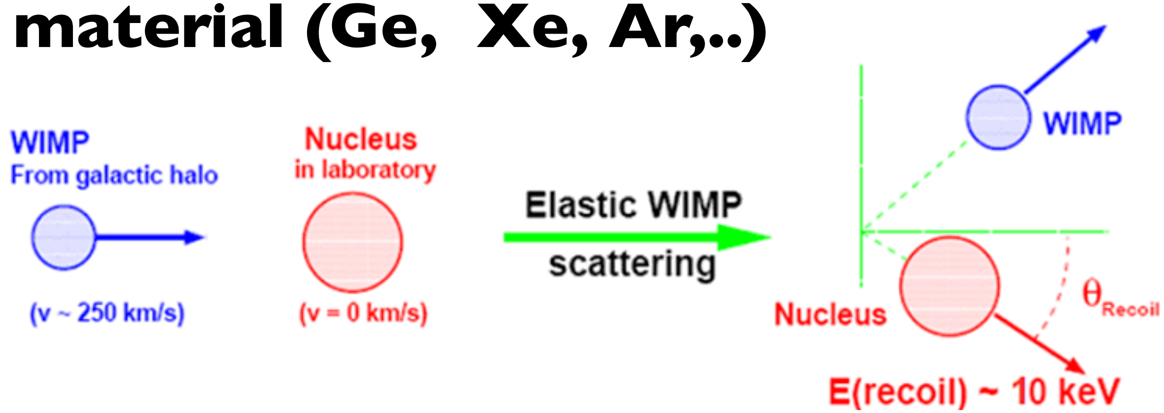




- Recoil energy : $E_r = \left(\frac{m_\chi}{2} v^2\right) \times \frac{4 m_N m_\chi}{(m_N + m_\chi)^2} \times \cos^2 \vartheta_r$
- Event rate : $R = \sigma_{\chi-N} \times \left(\frac{\rho_0}{m_\chi}\right) \times \langle v \rangle \times \frac{1}{m_N}$
  - ρ_0 : local DM density
  - About 1 interaction / ton / day for A = 100 et $\sigma \sim 3 \times 10^{-32}$ cm^2
- Require specific detectors:
  - Low energy threshold: ~keV
  - Low radioactive background

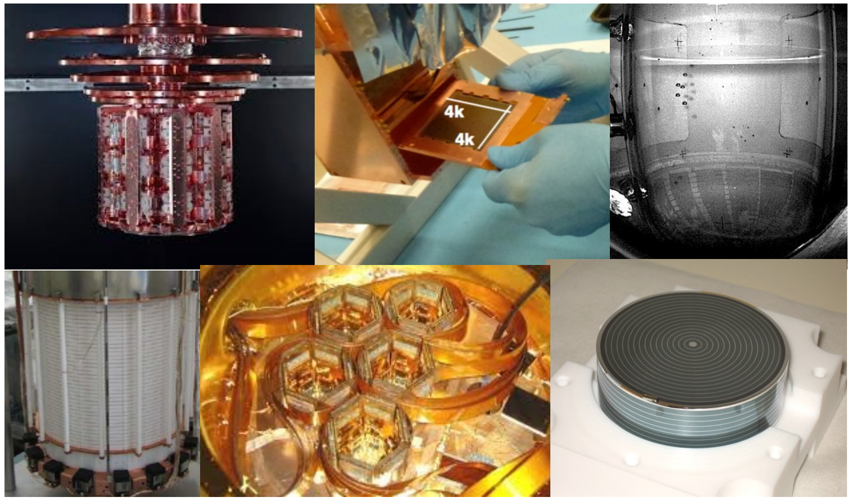
WIMP direct detection

- **WIMP elastic scattering off nucleus composing the gtarget material (Ge, Xe, Ar,..)**



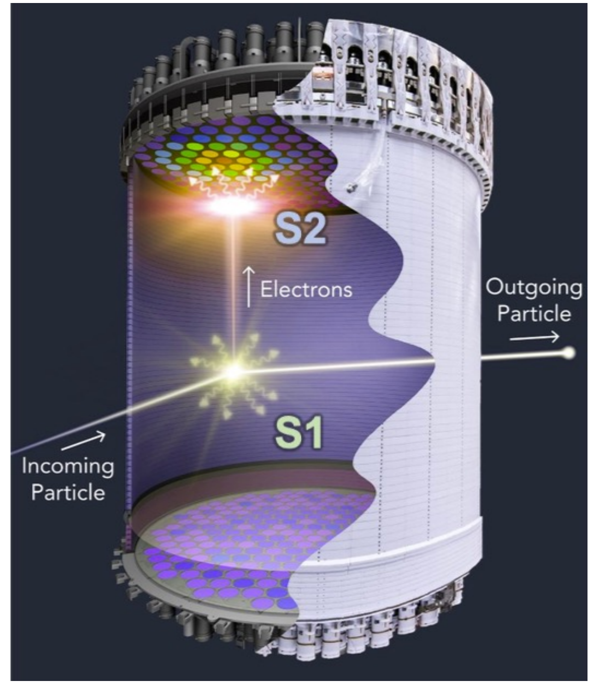
- Underground infrastructures : tunnels, mines, …
  - e.g., Modane (Frejus) and Gran Sasso labs

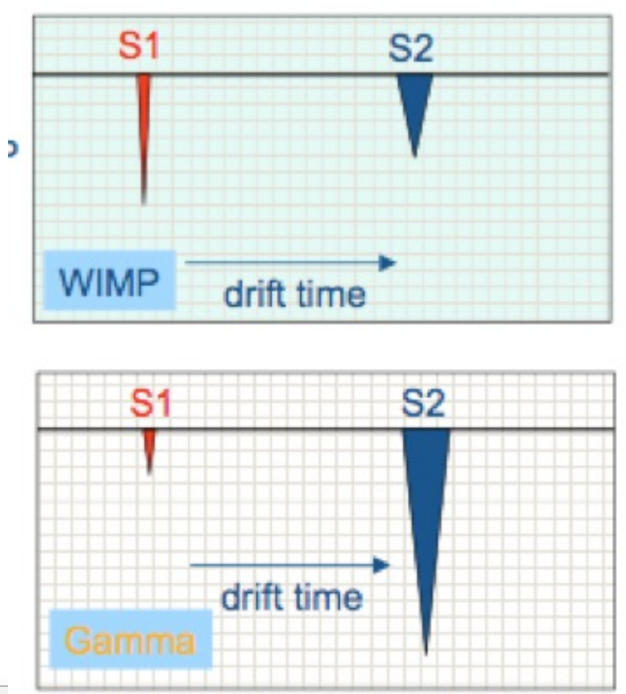
  to attenuate the flux of cosmic rays
- Dedicated detectors to measure energy deposit of the nuclear recoils
- Many technologies tested using heat, ionization, scintillation, tracks measurements



Double-phase Xenon detector

- **Liquid Xenon at 165 K in Gran Sasso laboratory**
- **PMTs as ultra sensitive détector**
  - « S1 » : direct light: scintillation
  - « S2 » : light emitted by electrons when entering the gaseous phase: ionisation





$(S2/S1)_{wimp} << (S2/S1)_{gamma}$

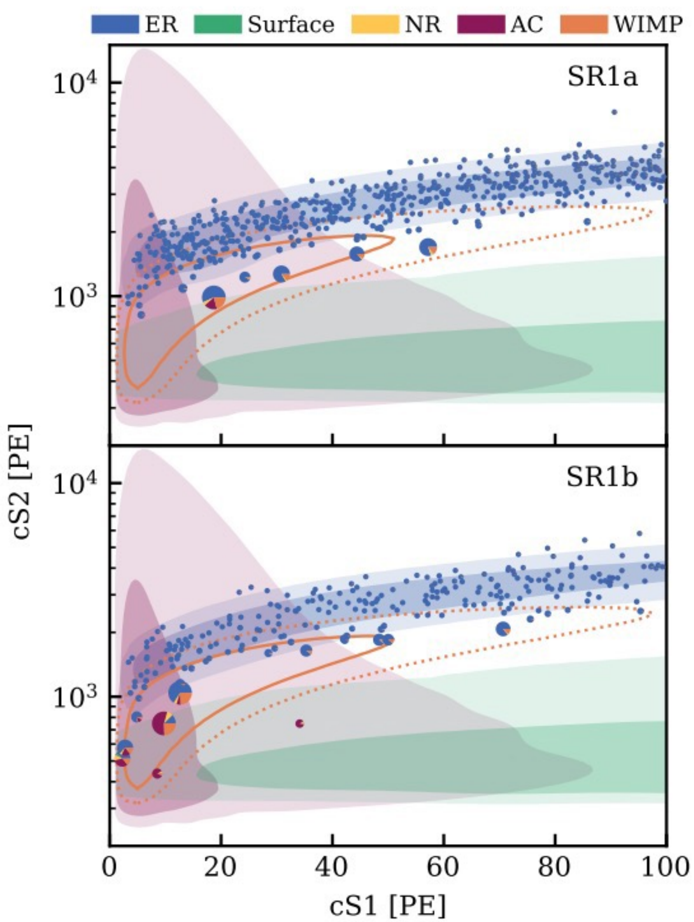
- .. 2000s and R&D 2007
- Technical proof (XENON10) 2008-2012 expérience à petite échelle
- XENON100 2014-2018 expérience
- XENON1t 2020
- upgrade XENONnT
- 2023 first results XENONnT

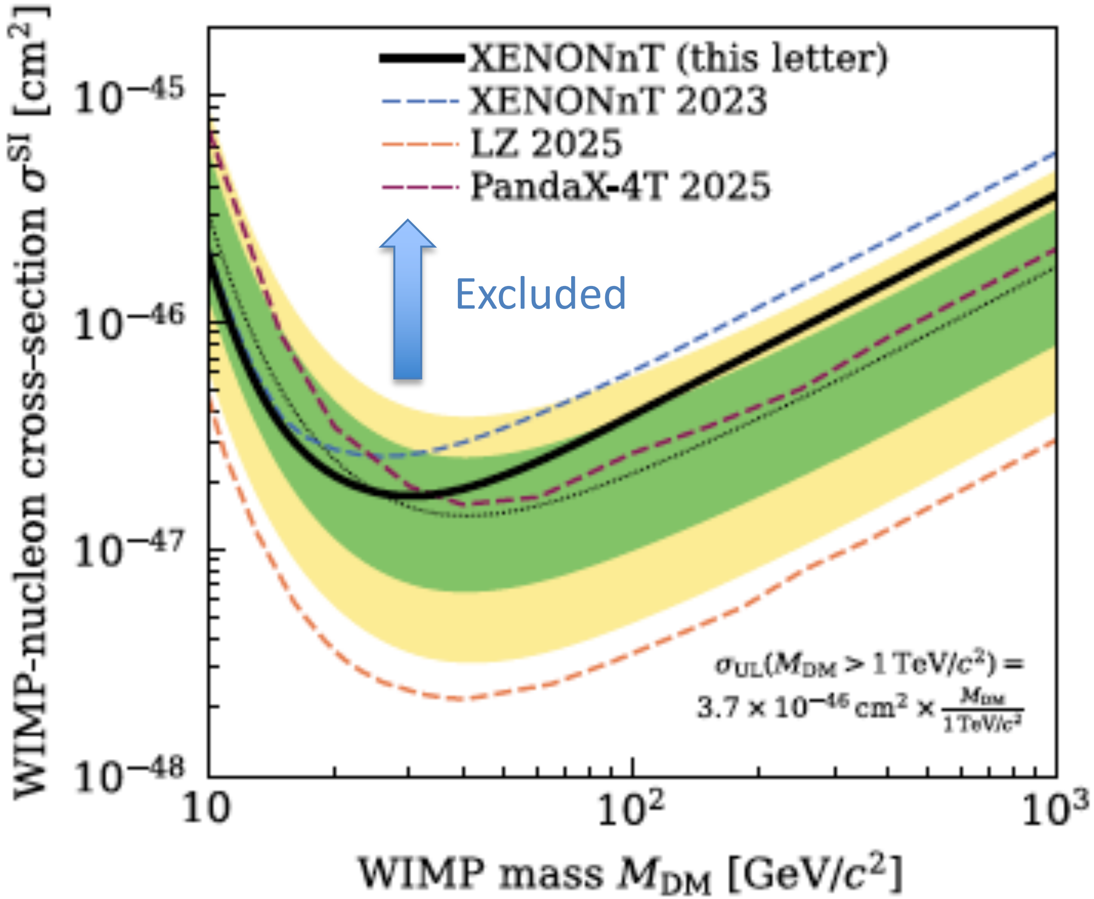
XENONnT results in 2025

XENONnT: 5.9 tonnes of Xe (active volume), 494 PMTs

Exposure of 3.1 tonne-years

No significant signal above background

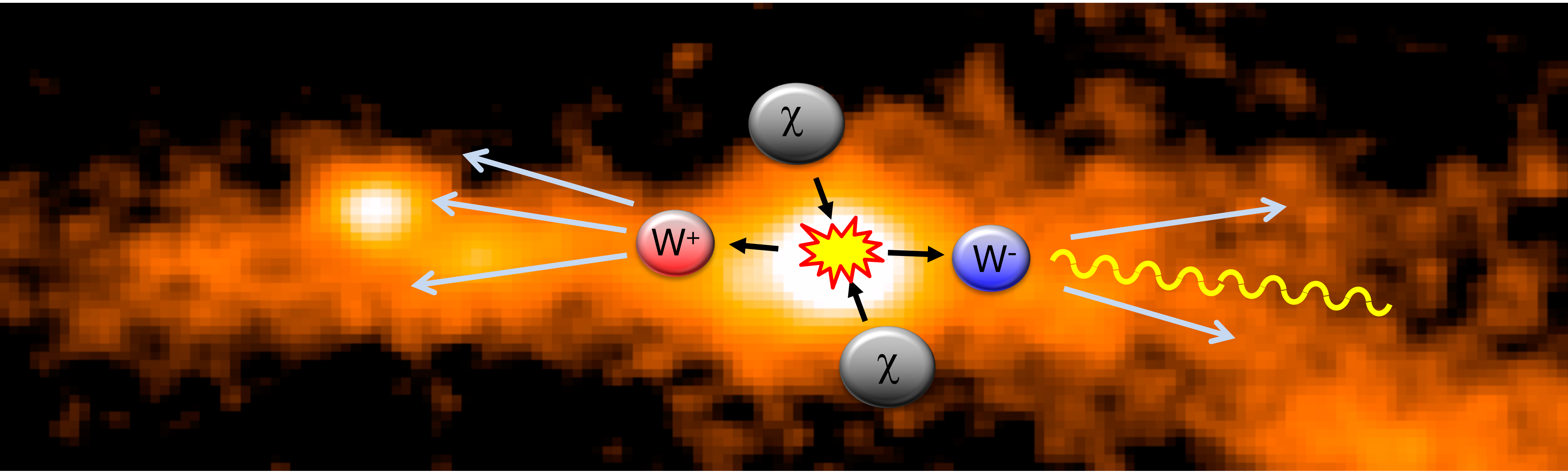


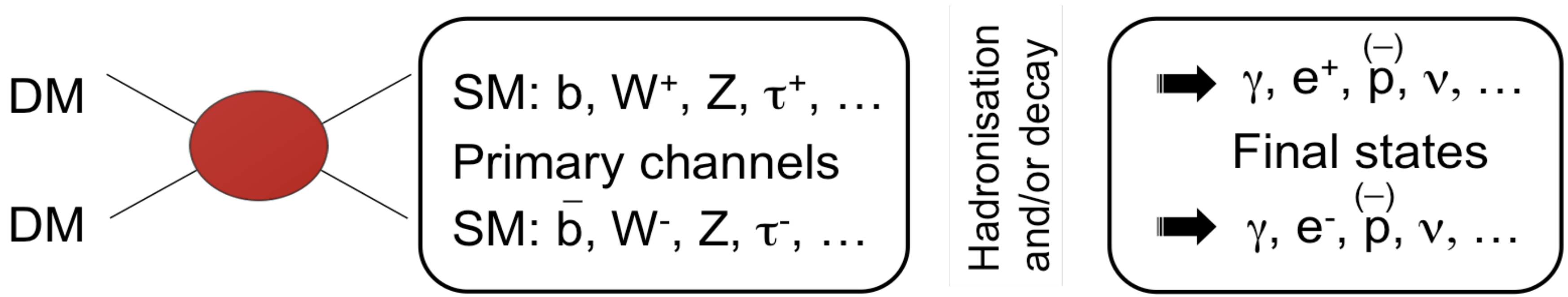


Sensitivities reach the neutrino floor:

- events from solar neutrino coherent elastic scattering being observed

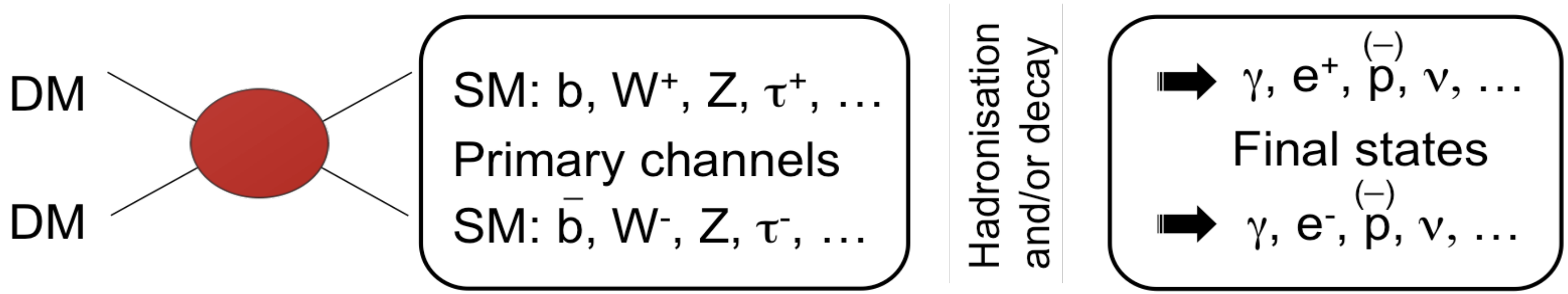
WIMP indirect detection

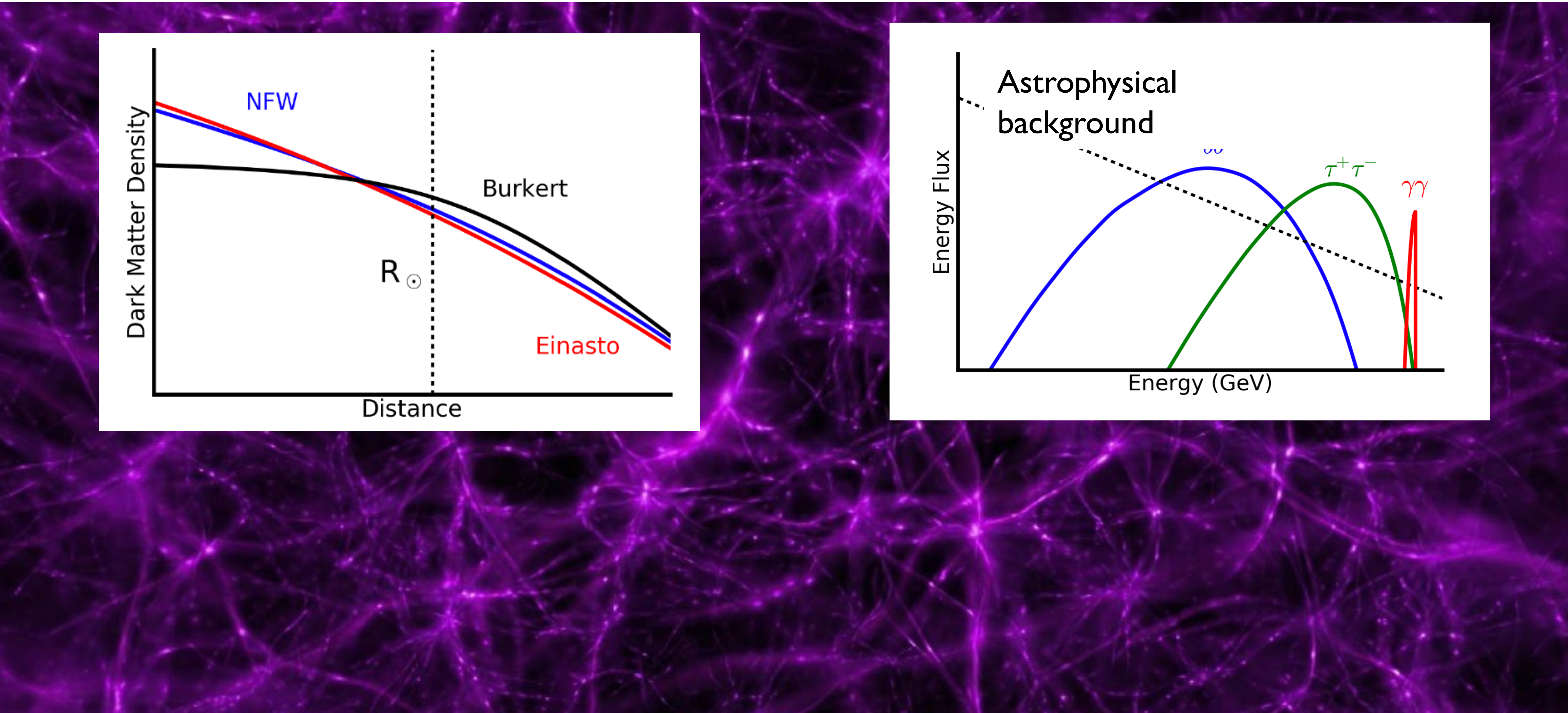




- Annhilation at almost rest : $E_{CM} \simeq$ signal energy
- Self-conjugated dark matter annihilation

WIMP indirect detection





WIMP indirect detection

- **Predicted flux from DM self-annihilation**

Annihilation cross section

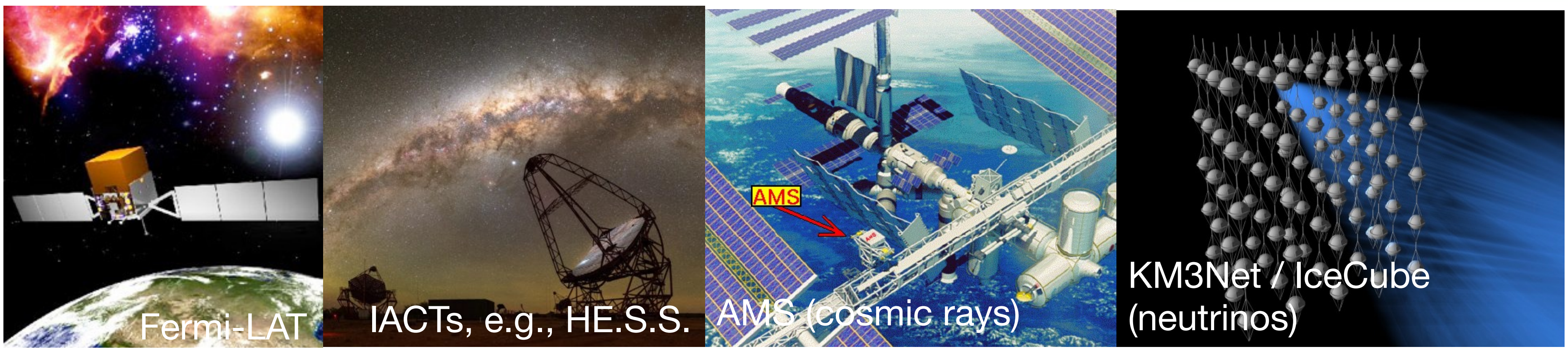
$$\frac{d\Phi(\Delta\Omega, E_i)}{dE} = \frac{1}{4\pi}\frac{\langle\sigma v\rangle}{2m_{DM}^2}\frac{dN_i}{dE} \times \int_{\Delta\Omega} d\Omega \int_{l.o.s} \rho^2(r[s])ds$$

Particle physics

Observed
Field of view

Astrophysics

$$J = \int d\Omega \int dl \rho^2 \sim \frac{M^2}{D^2 R^3}$$

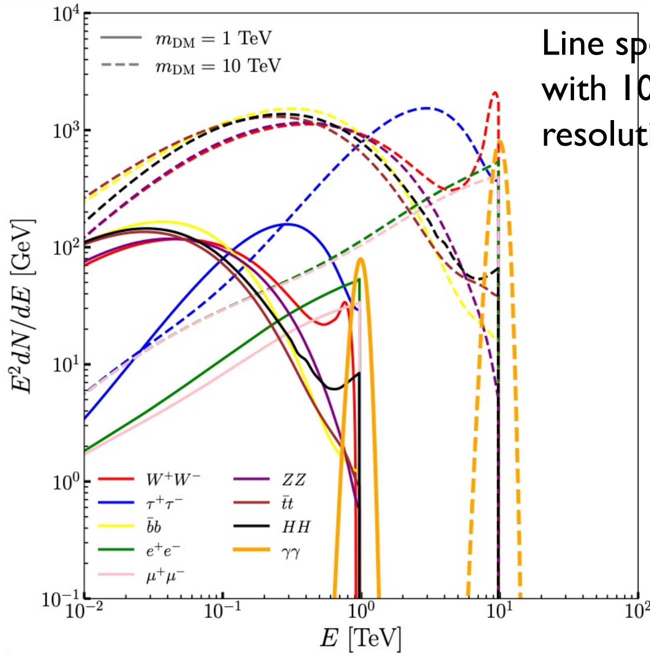


Search for γ-ray line from DM annihilations

- Gamma-ray line signal from χχ→γγ or χχ→γZ is a very "clean" possible annihilation channel

- No astrophysical lines expected

→ Best prospect for a "smoking gun" indirect signal for DM

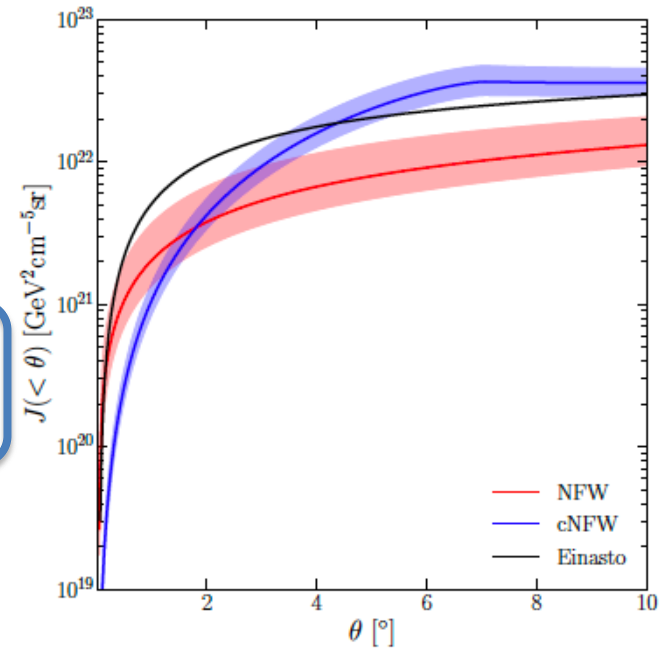


Line spectrum with 10% energy resolution

Search for γ-ray line in the Galactic Centre

- Considering the DM distribution according to a standard Einasto profile with a local DM density of 0.39 GeV/cm^3, the gamma-ray flux in the inner 1 degree around the GC can be estimated as :

$$\Phi_\gamma(>0.1\,\mathrm{TeV}) \simeq 4\times10^{-14}\,\mathrm{cm^{-2}s^{-1}}\left(\frac{\langle\sigma v\rangle}{2\times10^{-26}\,\mathrm{cm^3s^{-1}}}\right)\left(\frac{\int_{0.1\,\mathrm{TeV}}\frac{dN}{dE}dE}{0.1}\right)\left(\frac{m_{\mathrm{DM}}}{1\,\mathrm{TeV}}\right)^{-2}$$



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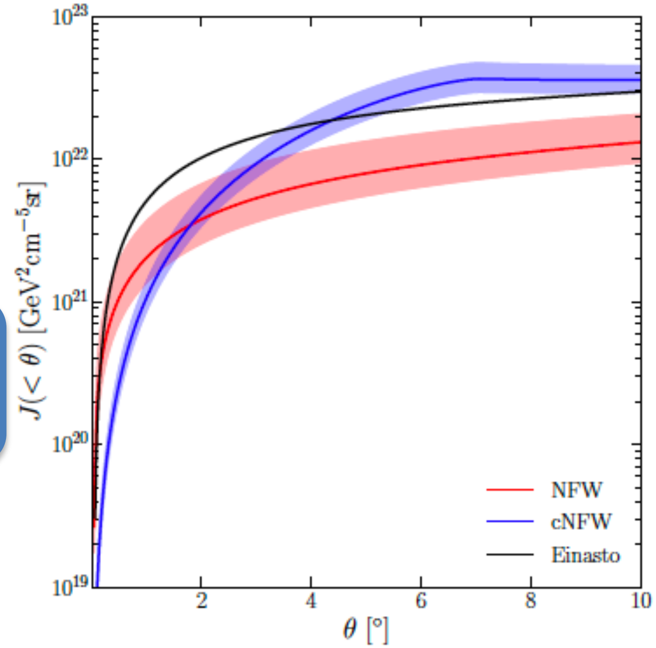


- Gamma-ray line signal from $\chi\chi\rightarrow\gamma\gamma$ channel :
  $dN/dE = 2\,\delta(E - m_{DM})$

- Assuming a residual background (assumed to be isotropic)
  $d\Phi_{\mathrm{Res.Bkg.}}/dE \simeq 10^{-8}\mathrm{TeV^{-1}cm^{-2}s^{-1}sr^{-1}}(E/1\,\mathrm{TeV})^{-2.3}$
  one can estimate the value of $\langle\sigma v\rangle_{\gamma\gamma}$ for a detection at $n\sigma$ confidence level: the number of gamma rays from DM annihilation exceeds the statistical background

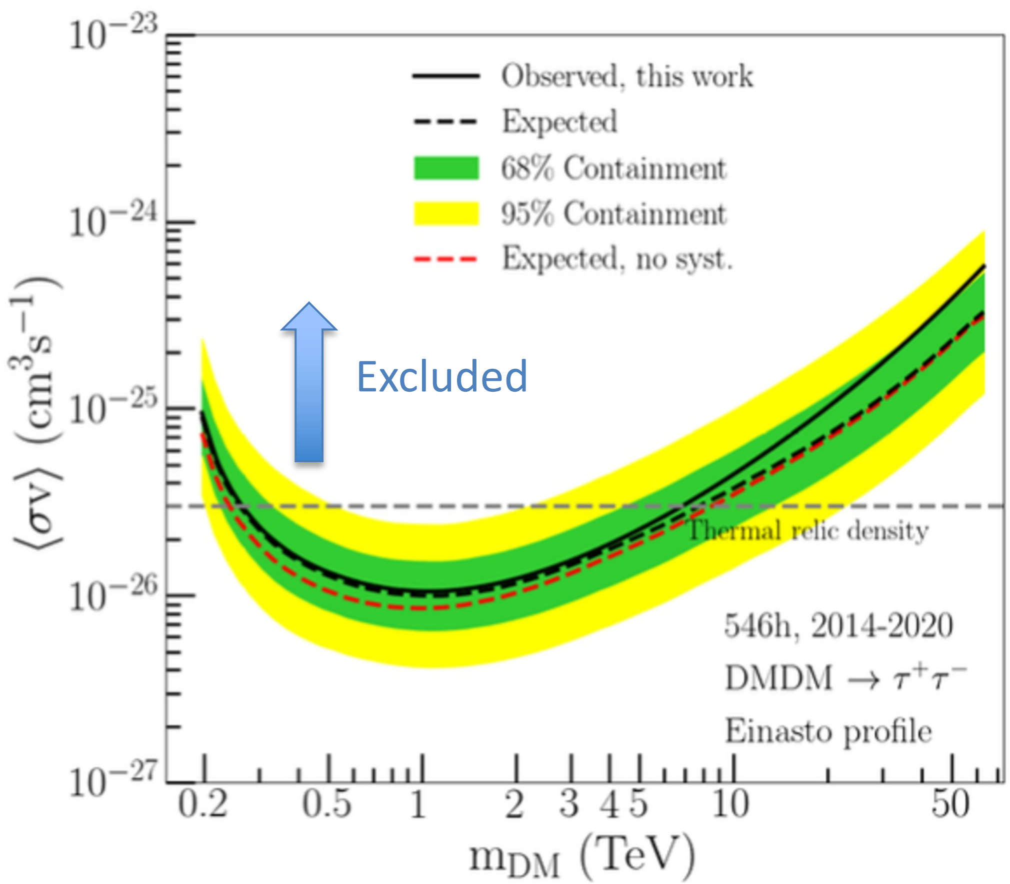
$$N_\gamma^{\mathrm{DM}}/\sqrt{N_{\mathrm{Res.Bkg.}}} \geq n$$

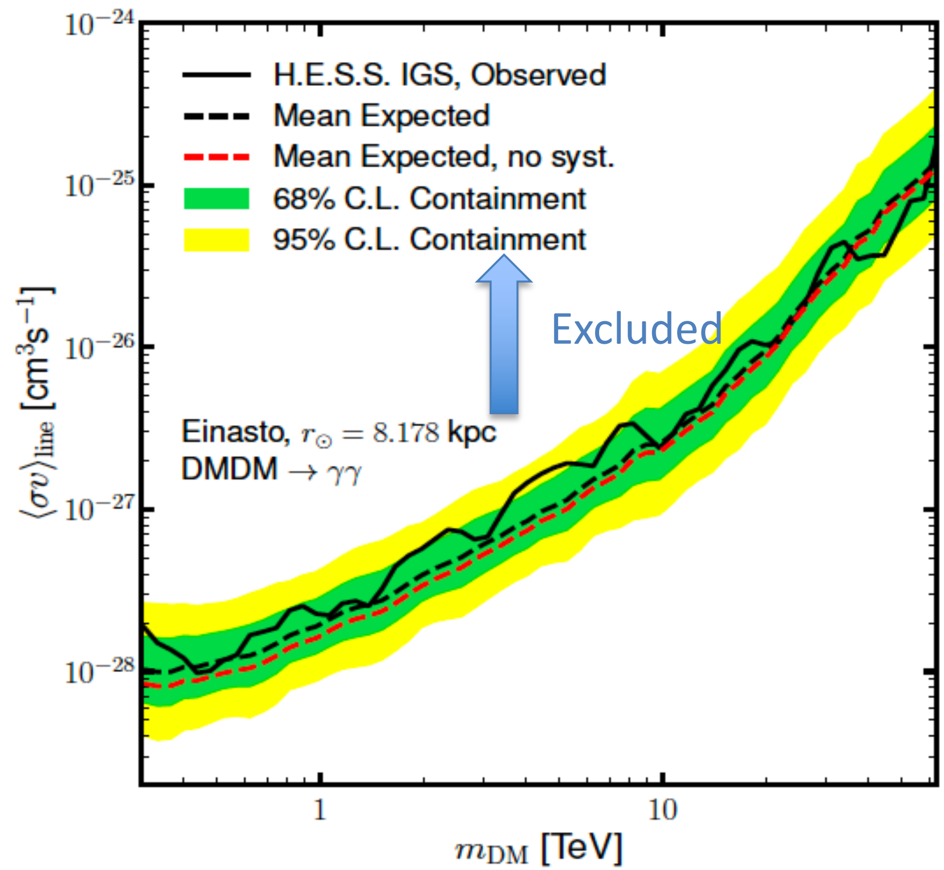
- For an observation time of 100 hours with a constant acceptance of 10^5 m^2 above 100 GeV, one can show that:

$$\langle\sigma v\rangle_{\gamma\gamma} \gtrsim 2n\times10^{-27}\,\mathrm{cm^3s^{-1}}\times\left(m_{\mathrm{DM}}/1\mathrm{TeV}\right)^2$$

Constraints from H.E.S.S. observations of the Galactic Center (2022, 2025)

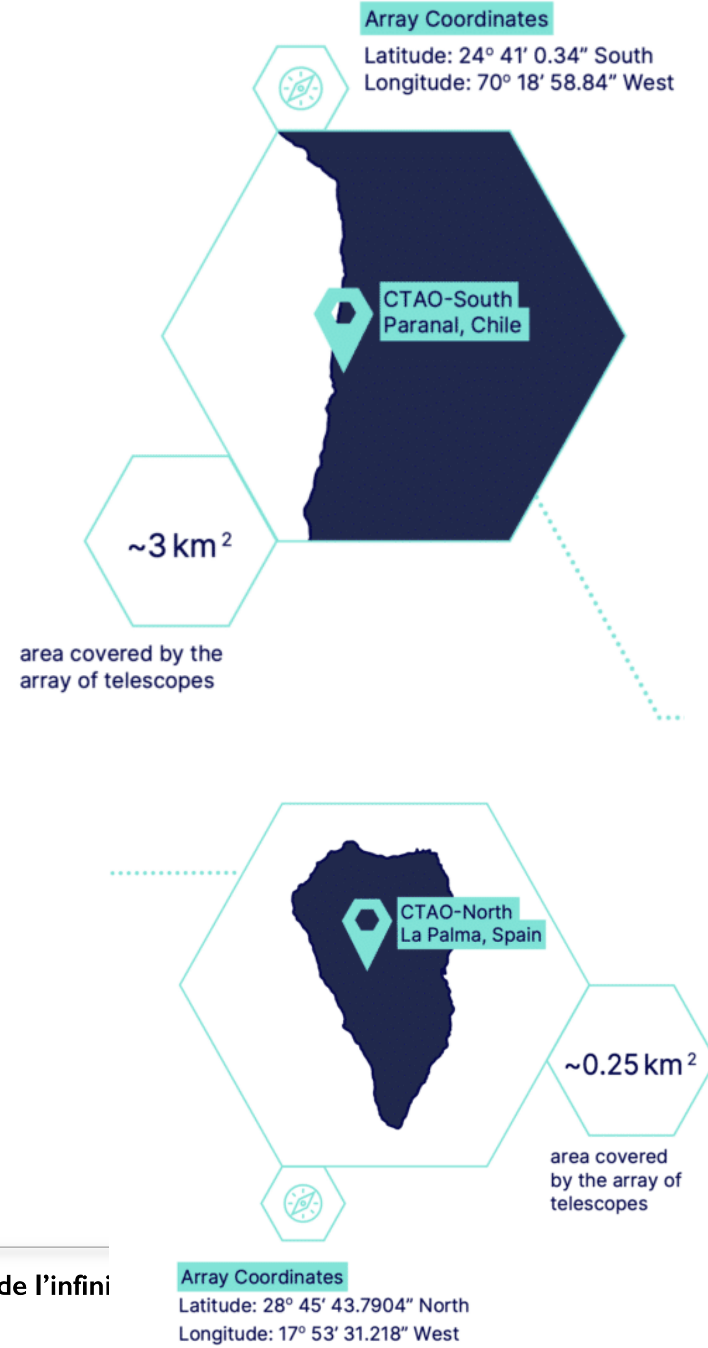
- Deep observatios of the GC region, 546 hours
- No significant signal above baground
  → set upper limit on the annihialtion cross section





Forecat sensitivity in VHE gamma rays

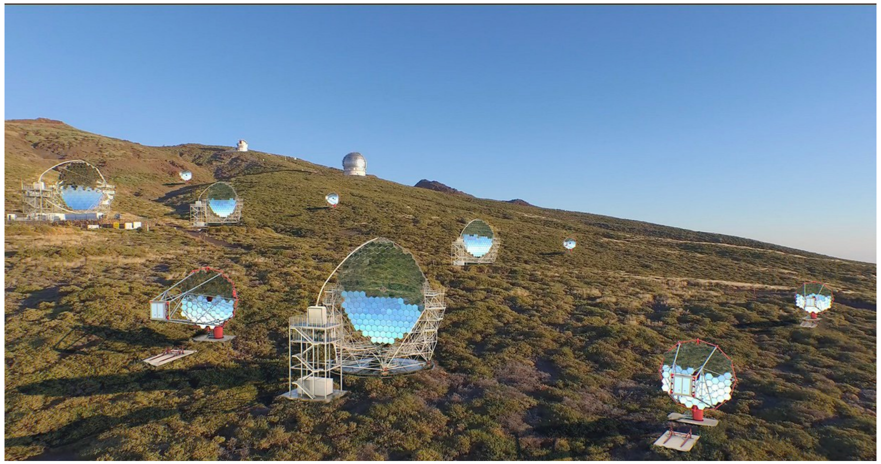
Next-generation array of Imaging Atmospheric Cherenkov Telescopes: *the Cherenkov Telescope Array Observatory*

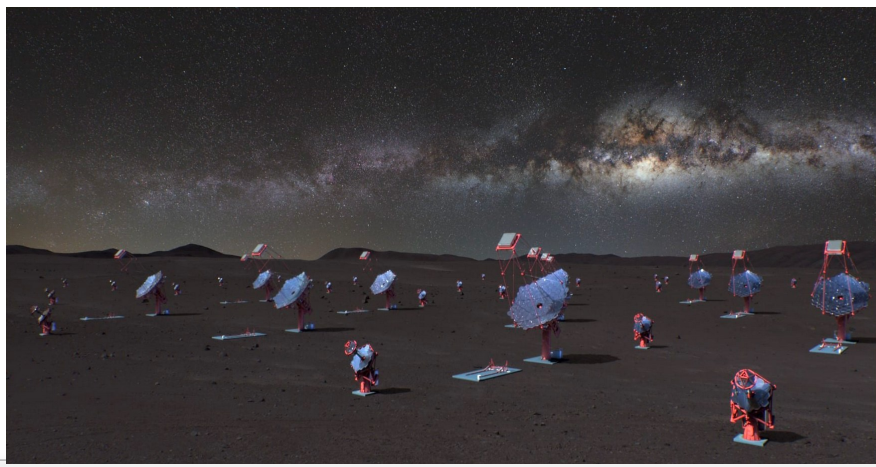


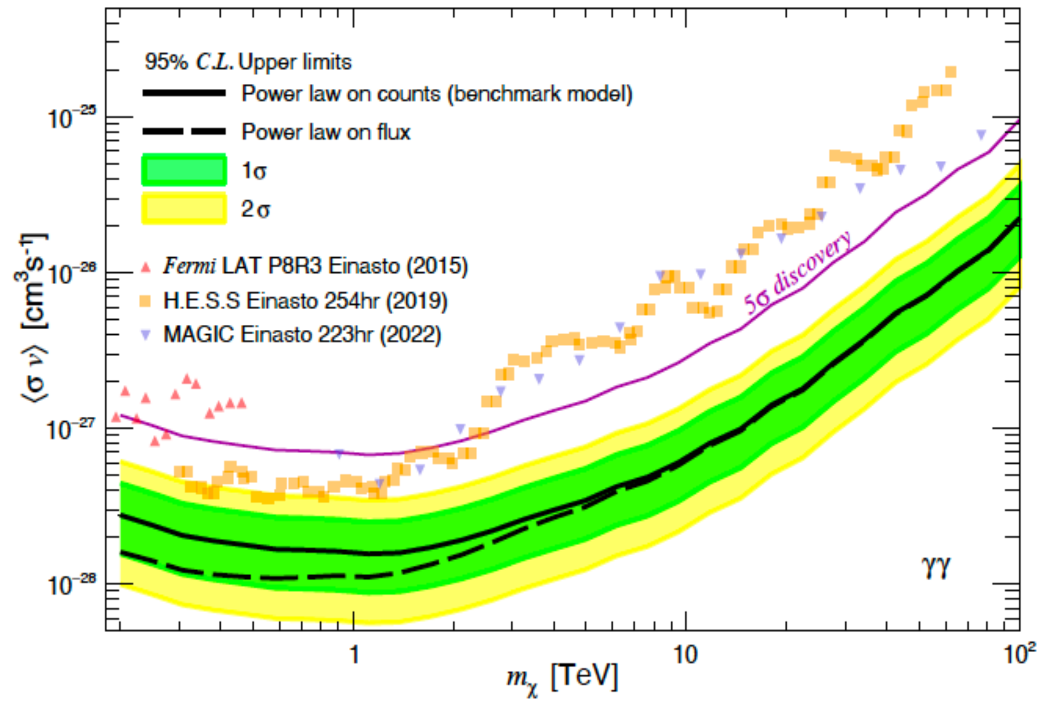
Forecat sensitivity in VHE gamma rays

Next-generation IACTs : the Cherenkov Telescope Array Observatory

- CTAO North – La Palma, Canary Island : 4 LSTs and 9 MSTs
- CTAO South – Atacama desert, Chile : 14 MSTs and 37 SSTs







Prospects with GC observations (500 h)

- A factor of 2-to-10 improvement compared to H.E.S.S./MAGIC

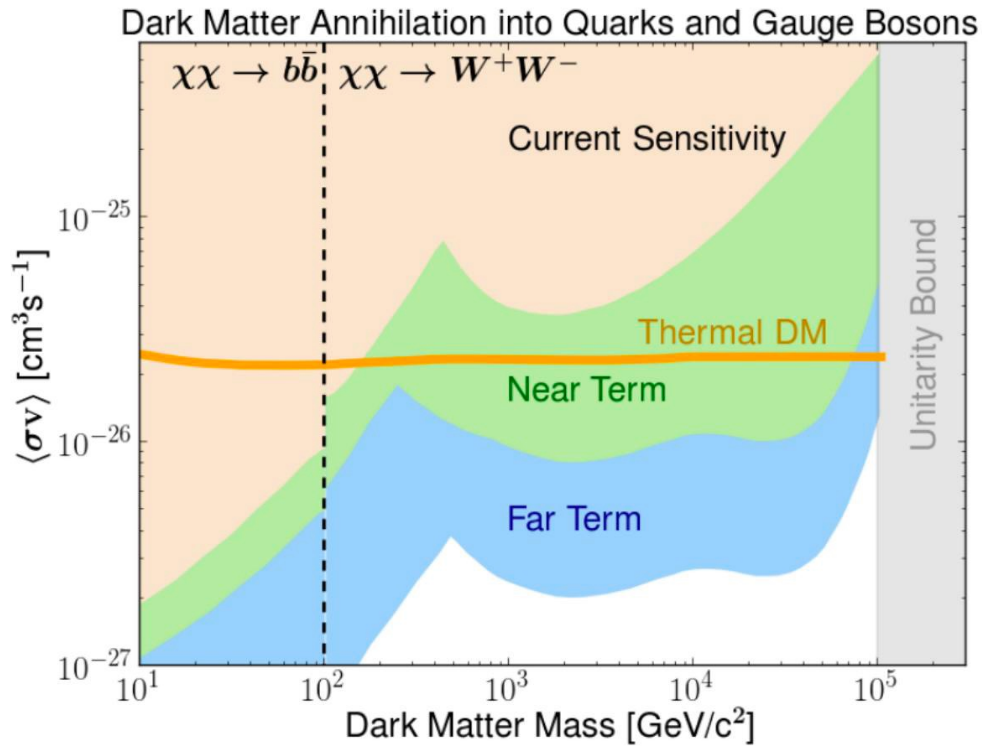
WIMP status

- Worldwide experimental effort:
  - searches deployed with various tecnhiques over the last two decades
  - relevant sensitivity is reached to probe some plausible WIMP models

- No confirmed detection so far, some anomalies that did not convince the community

- The WIMP model is being probed
  - however the parameter space is large …

- New directions being investigated



OUTLINE

1. Dark Matter : a required component
1.1 Observations of galaxy and galaxy cluster dynamics
1.2 At large scales : cosmological probes

2. What do we know about dark matter ?
2.1 Bounds on dark matter mass
2.2 Theoretical models of dark matter candidates

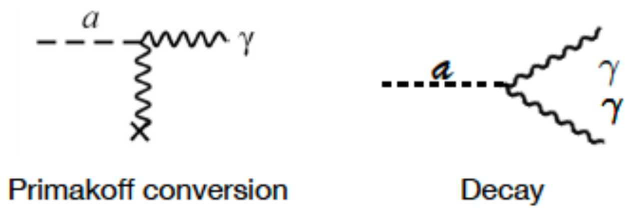
3. Testing the WIMP model
3.1 Direct detection : the XENONnT experiment
3.2 Indirect detection : observations with H.E.S.S. and CTAO

4. An alternative model : the axion
4.1 Astrophysical searches with gamma rays

Axions and Axion-Like Particles

- Strong CP problem : no violation of the CP-symmetry observed in strong interaction

- Axion is by-product of a solution to this :
  - Light pseudo-scalar particle
  - Viable cold dark matter candidate
  - Induced coupling with photons : g_{agg}



- Axion-like particles:
  - As opposed to axions, mass and coupling constant are unrelated
  - can to explain the current amount of DM with :

$$g_{a\gamma\gamma} < 10^{-12}\left[\frac{m_a}{1\ \text{neV}}\right]^{1/2}\text{GeV}^{-1}$$

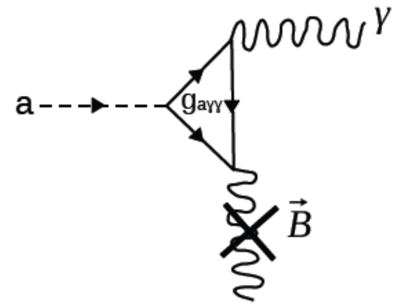
[e.g. Arias et al. 2012]

from misalignment mechanism

→ Very Weakly Interacting Slim Particles - WISPs

ALP searches with VHE gamma rays

- In the presence of an external magnetic field
  → possibility to have ALP-Photon oscillations
- The conversion probability $P_{a\gamma\gamma}$ is dependent on the magnetic field intensity and orientation as well as the scale of the magnetized region



ALP searches with VHE gamma rays

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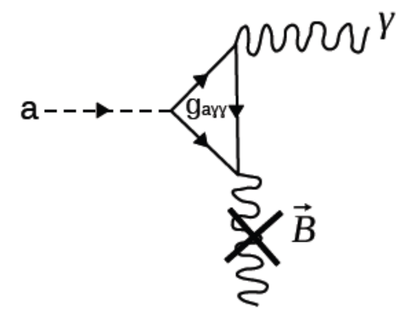
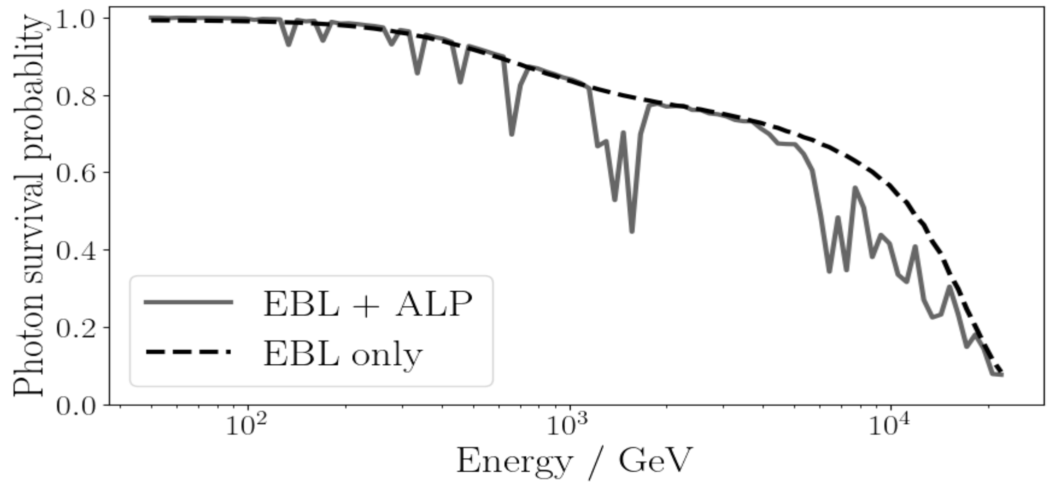
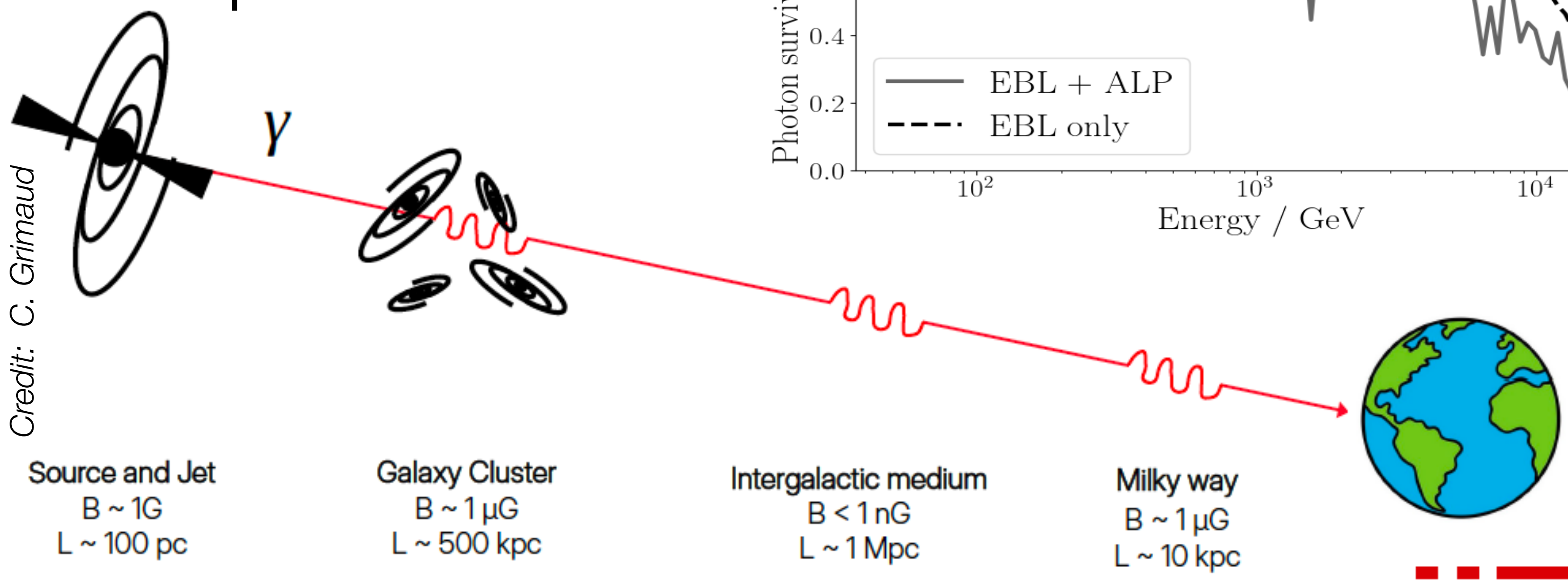
- The conversion probability Paγγ is dependent on the magnetic field intensity and orientation as well as the scale of the magnetized region



- Wiggles: energy-dependent deviations from smooth GeV-TeV spectrum

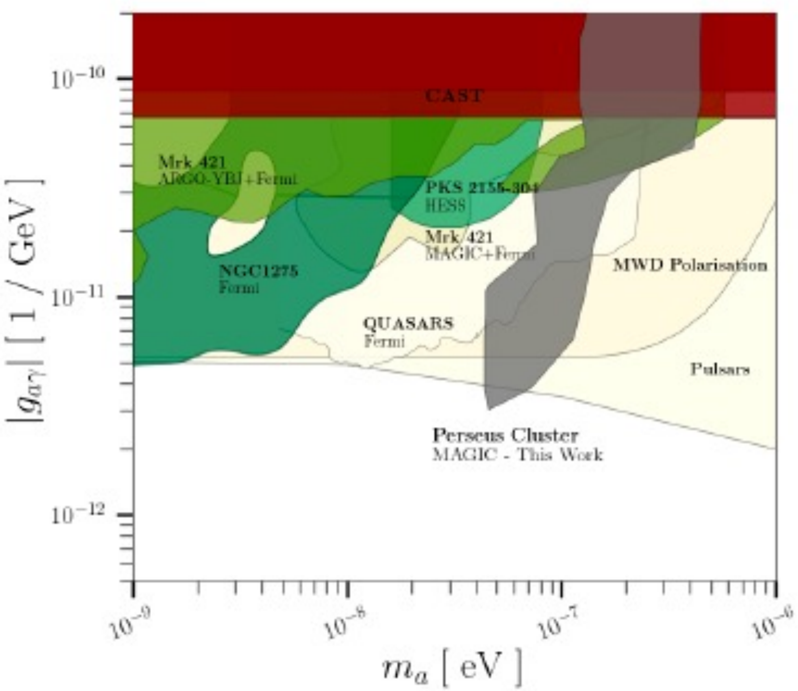




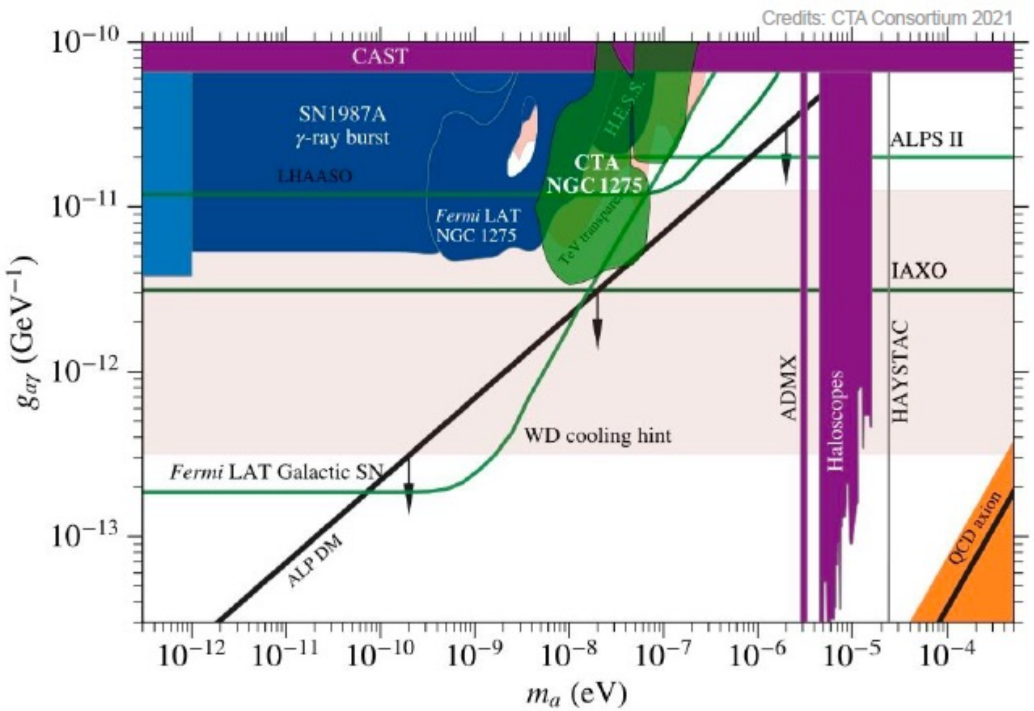
ALP searches with VHE gamma rays

- Astrophysical magnetic fields - Milky-way, Cluster of galaxies, Intergalactic Magnetic Field : not coherent
- The conversion probability $P_{a\gamma\gamma}$ is dependent on the magnetic field intensity and orientation as well as the scale of the magnetized region → average over all possible realizations of B

S. Abe et al., MAGIC Coll. Phys.Dark Univ. 44 (2024) 101425



Prospects for CTA: Perseus cluster

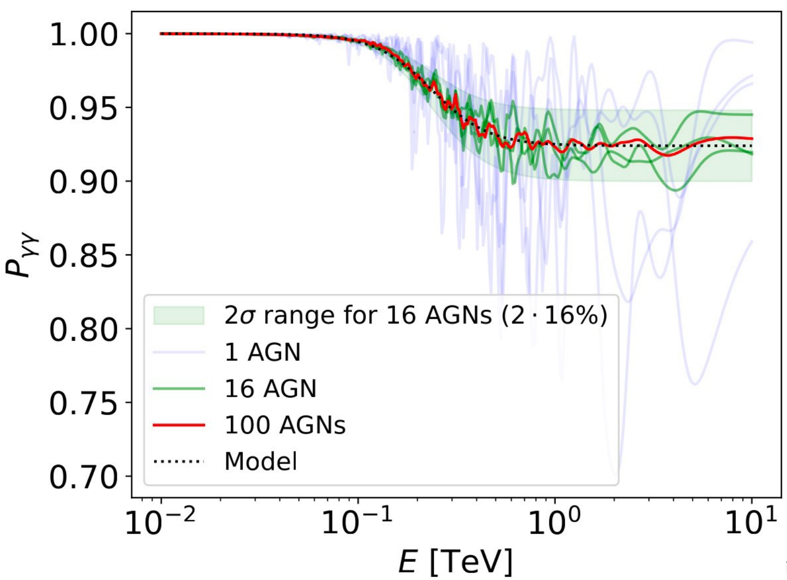


Probing ALP with AGN-GalaxyCluster pairs

Caveat: for GC, no reliable measurement of the small-scale properties of the field (orientation, domain length) → need to marginalize over a large number of small-scale configuration of the magnetic field

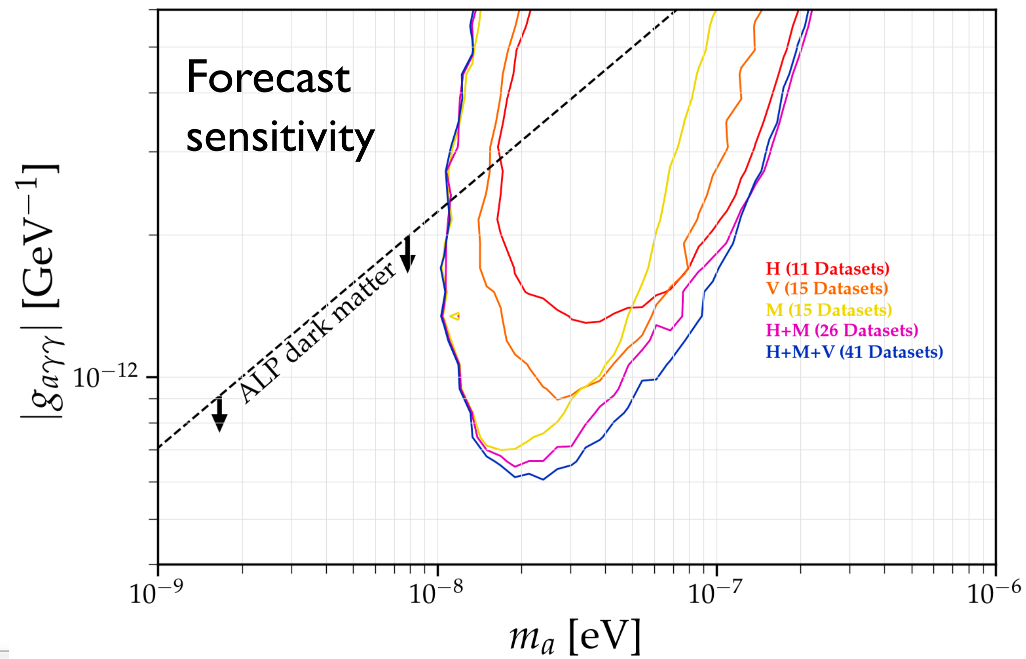
- Stacking analysis of multiple AGN-GC pairs
→ gives a smooth predictable spectral imprint

$(m_a, g_{a\gamma\gamma}) = (20\ \text{neV}, 7\times10^{-13}\ \text{GeV}^{-1})\ B_0 = 3\ \text{muG}$



AGN-GC selection

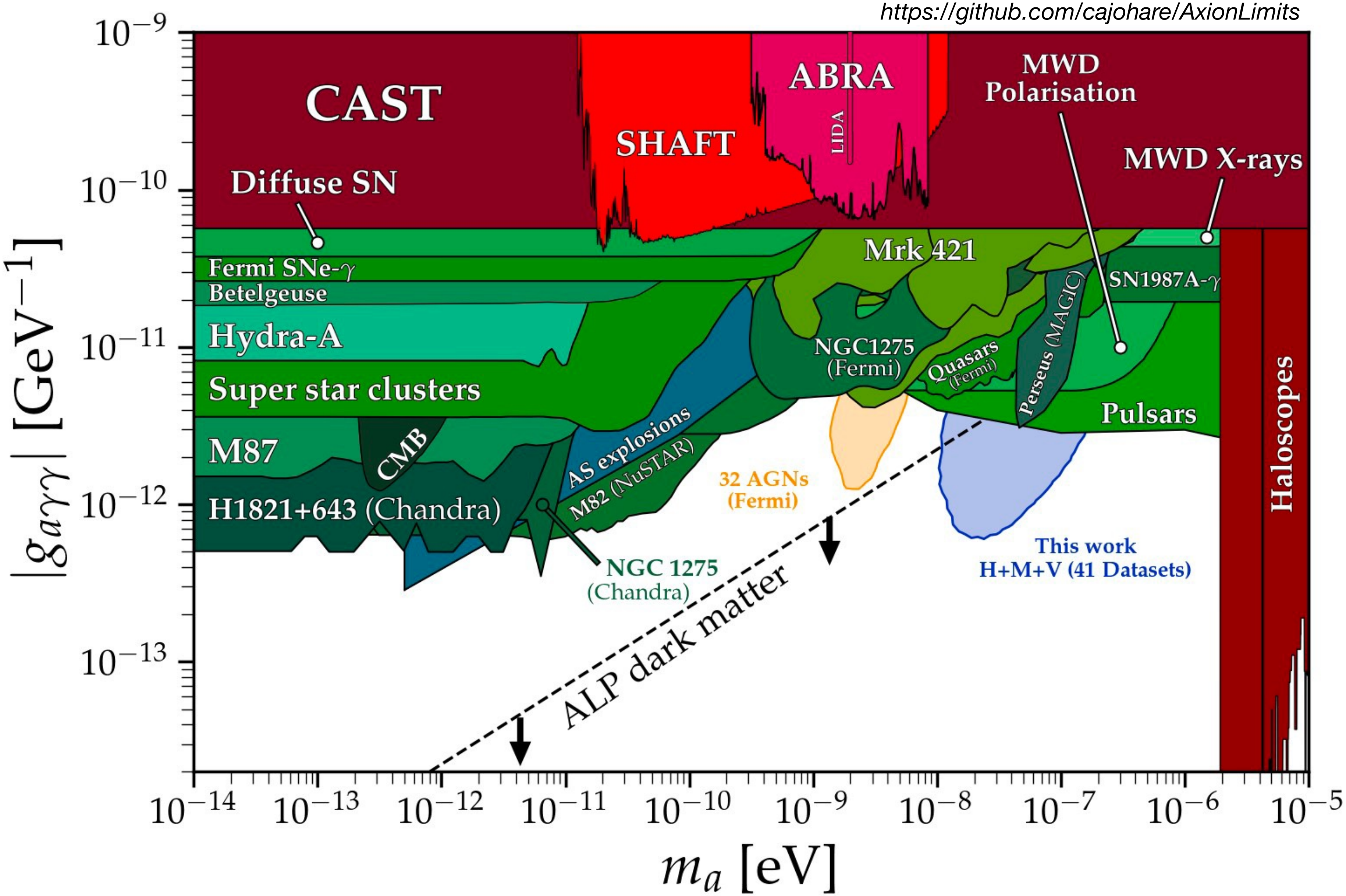
>10 GeV gamma-ray bright AGNs with SZ catalog (GC)
→ 16 AGN-GC pairs selected
→ 41 datasets from H.E.S.S., MAGIC and VERITAS



Grimaud, EM, Malyshev et al. accepted JCAP (2026)

High-energy astrophysics limits

https://github.com/cajohare/AxionLimits



Merci de votre attention

- **Outstanding observations in cosmology over the past two decades**
  → We know a lot about the history of our Universe
  → All points towards the existence of dark matter

- **The fundamental nature of "dark matter", as a physical object, is a complete mystery**
  - Many hypotheses, many models ...
  - Tremendous worldwide experimental effort with various searched techniques
  - Several detection claims

  ... But none of these hints is confirmed so far. The mystery remains.

- Researchers "best guess model" in 2000s : WIMPs (new electroweak physics)
  - Extensive searches: accelerators (LHC), direct, indirect searches

  → Scenario was not confirmed
- Search for axions: « second best guess » from particle physics since the 80s
  - Experimental effort being deployed, sensitivity being increased via multiple techniques

- What should we do now ? Some of current alternative research paths:
  - Test the primordial black hole hypothesis (also very constrained)
  - Search for modified gravity