La physique fondamentale par le biais des messagers astrophysiques

Ecole de Gif 2024 - Astronomie Multimessagers

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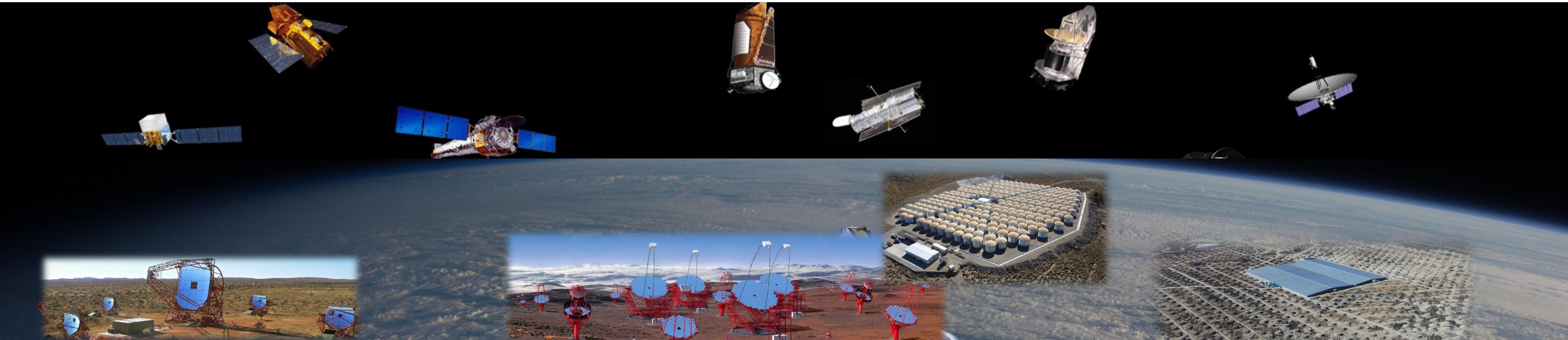
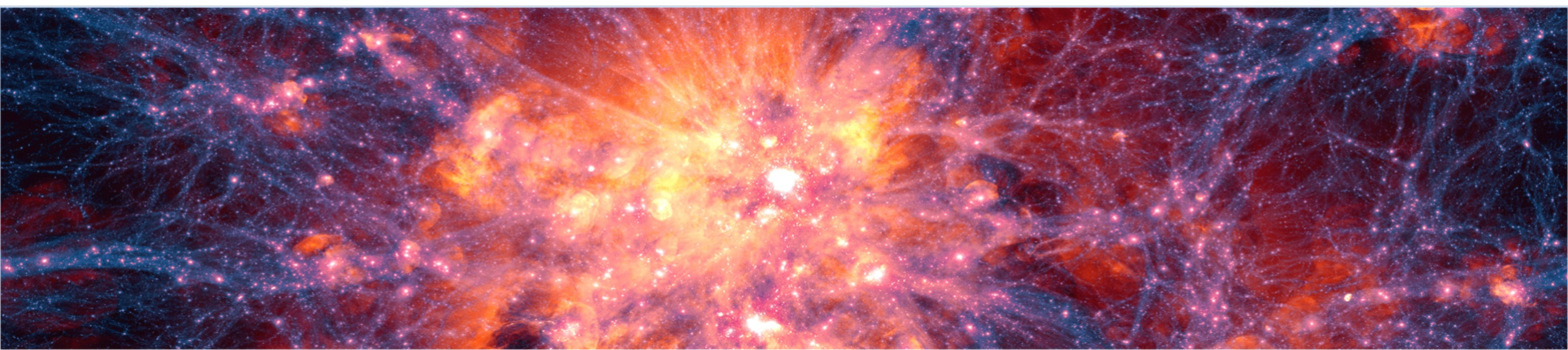


Some caveats

- I was asked to talk about fundamental physics in the context of multi-messenger astronomy
  - Not an easy task
  - It will be far from exhaustive
  - It will (obviously) be a biased and partial personal view
- I'll mostly focused on neutral messengers, i.e., gamma rays and neutrinos
- Estimates are given throughout the lectures, they can be performed as back-envelope computation
- A big thank to all people that provided materials

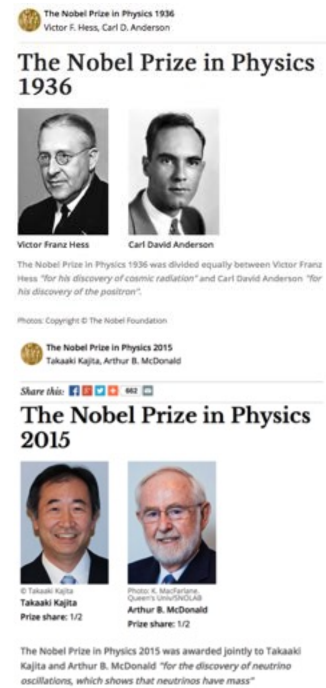
Some readings

- The Early Universe, E. Kolb, M. Turner, Westview Press
- Galactic Dynamics, J. Binney, S. Tremaine, Princeton Univ. Pr ess
- High energy astrophysics, M. Longair, Cambridge Univ. Press
- Very High Energy Cosmic Gamma Radiation, F. Aharonian, World Scientific
- Astroparticle Physics: Theory and Phenomenology, G. Sigl, Atlantis Press Paris



Why looking for fundamental physics in "cosmic" rays ?

- Existence of cosmic rays by V. Hess after a high-altitude balloon flight (1912)
- Particle zoo: discovery of muon (1937), pion (1947), Kaon (1947), Λ the first strange baryon (1951)



- It already happened in the past to find surprise in astro data that led to major discoveries
  - e.g., neutrino oscillations : systematically detected less ν's than predicted from the Sun, angular/energy dependence of atmospheric neutrino fluxes: ν *oscillations* $\rightarrow m_\nu \neq 0$
- Physics BSM is strongly motivated
  - Anomalies in astroparticle observables do exist and BSM physics may be the answer
  - You expect astrophysical signatures of BSM physics. If you don't find them you set constraints in the relevant parameter space

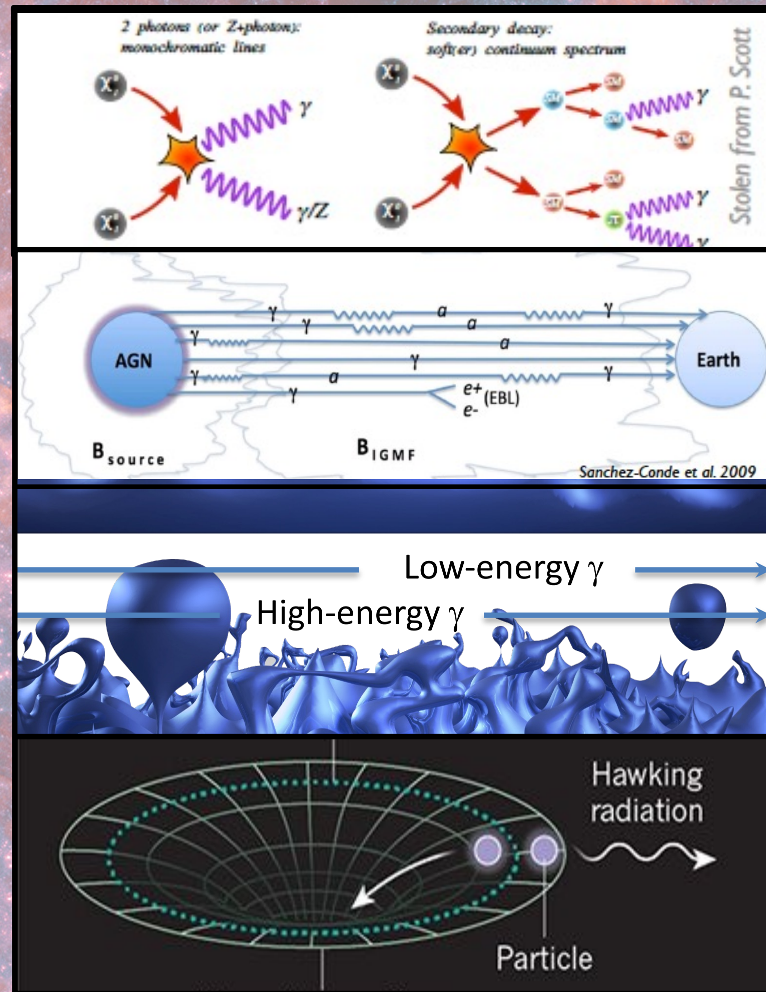
Why looking for fundamental physics in 'cosmic' rays ?

- Quite reasonable if we consider the unusual scales of density, temperature, size, time, energy… when compared with what is achievable in Earth laboratories!
  - orders of magnitude away from familiar ranges: conceivable that some physics extrapolations may fail, highlighting new phenomena/regimes

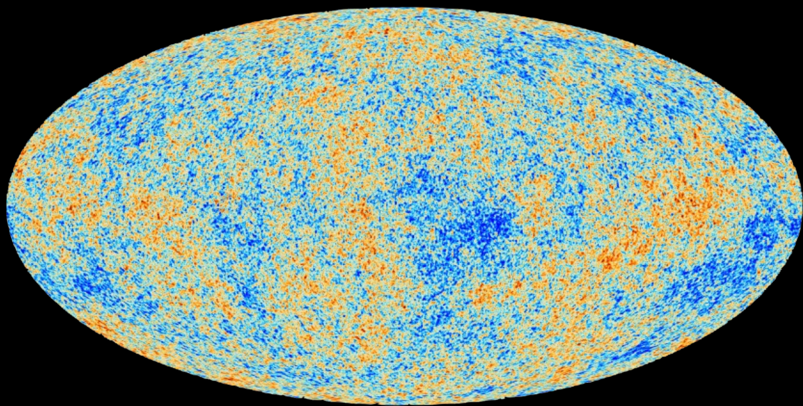
- **A challenging task:**
  - We do not control the environment (« initial state »)
  - This requires significant effort in parallel to understand astrophysics, in order to derive « robust » signatures

Outline of the lectures

- **Preamble**
  - Standard model cosmology, dark matter evidences
  - Mass bounds on dark matter
  - Neutral messengers
- **WIMP-like Dark Matter**
  - WIMP paradigm, annihilation/decay, spectral features
  - Dark matter distribution, J-factors
  - Galactic Centre and dwarf galaxies
- **Axion and Axion-like particles**
  - Photon-ALP mixing, EBL, spectral irregularities
- **Lorentz-invariance violation**
  - Time-of-flight measurement
  - Modified pair cross section
- **Primordial black holes**
  - Evaporation and burst searches, PBH dark matter

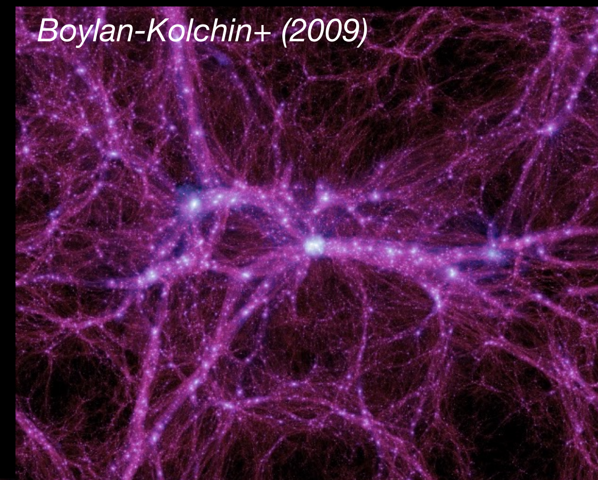


Standard model cosmology and Dark Matter



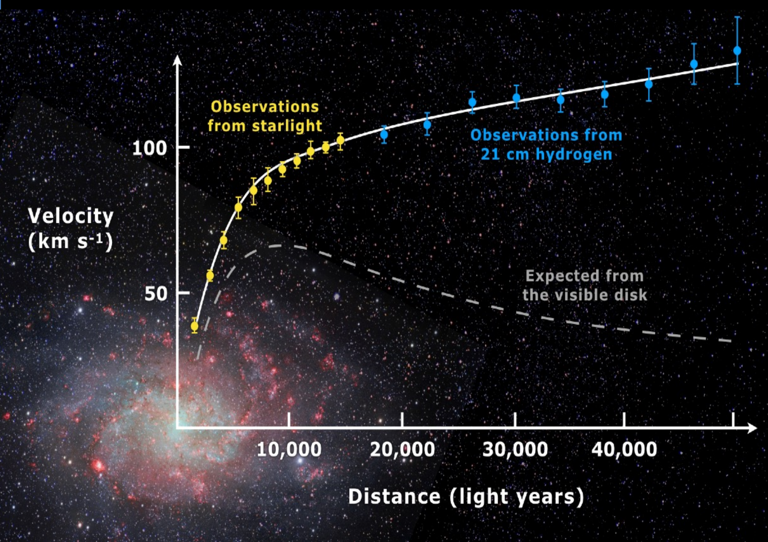
- **68% dark energy**
- **5% baryons**
- **27% dark matter (cold, collisionless)**

In the standard model of cosmology

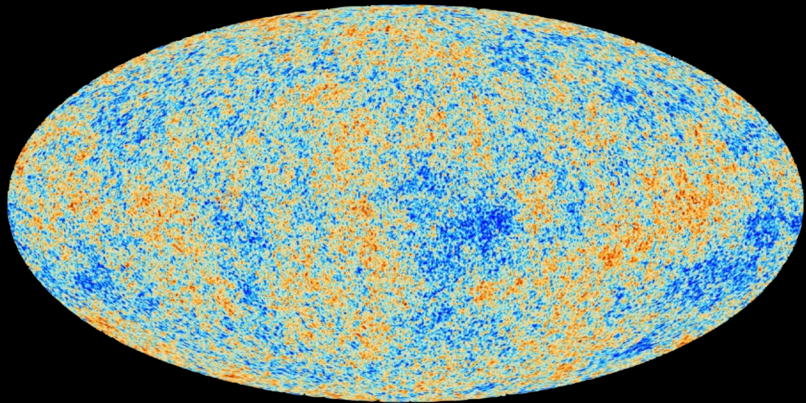


Dark matter density perturbations grow and become nonlinear
→ study structure formation with N-body simulations

Dark matter forms self-gravitating halos that host galaxies



Dark Matter : what we know



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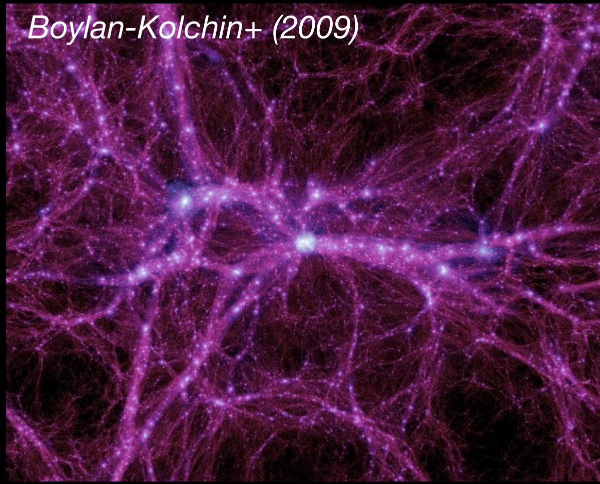

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80% of the matter in the universe

- neutral particle
- cold or not too warm
- very feebly interacting
- stable or very long lived
- possibly a relic from the early universe

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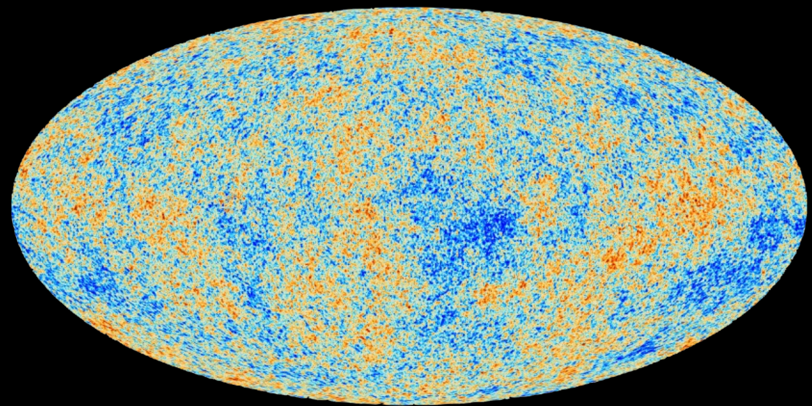

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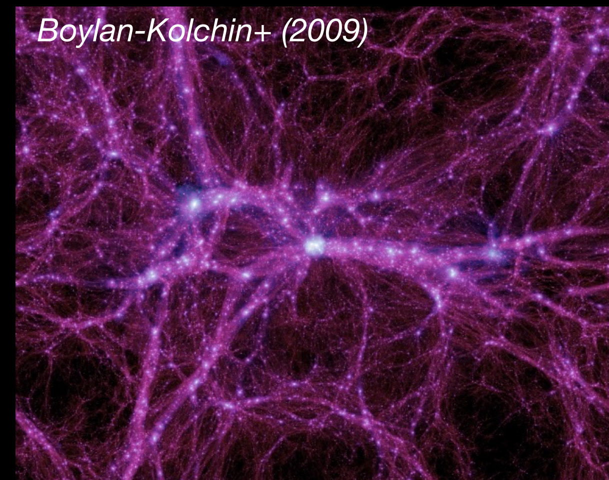

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→ study structure formation with N-body simulations

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~80% of the matter in the universe

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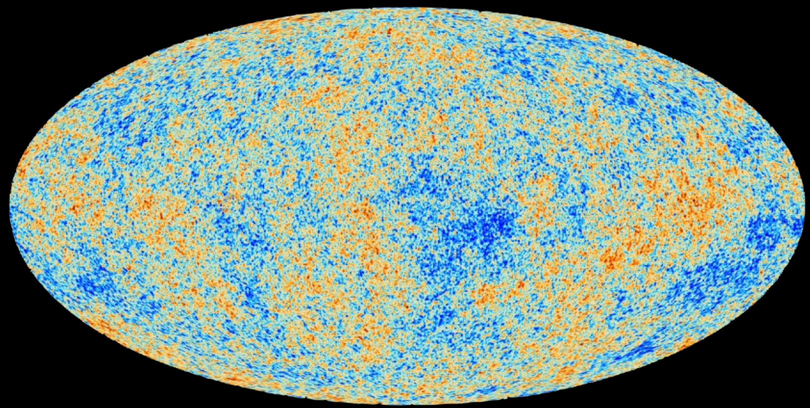
No good particle dark matter candidates within the Standard Model

Dark Matter : what we don't know



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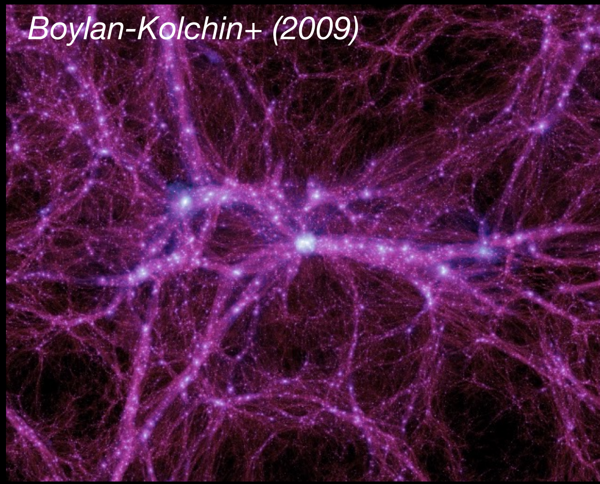


Dark matter density perturbations grow and become nonlinear
→ study structure formation with N-body simulations

Dark matter forms self-gravitating halos that host galaxies

Still a list of open questions :

- **Is there cosmic evidence to go beyond the cold and collisionless paradigm ?**
- **Production in the early universe and connection to late universe observables?**
- **Is DM wave-like or particle-like? Is it at all a particle (e.g. primordial black holes) ?**
- **Does dark matter have important self-interactions?**
- **Whether it's absolutely stable, or decays slowly over time…**

Classical discovery of dark matter

In a number of astrophysical bound systems (galaxies, clusters, …) one finds a mismatch between the mass inferred by gravitational probes and the mass inferred by electromagnetic observables, with the former much larger than the latter. The excess of the former with respect to the latter is dubbed Dark Matter.

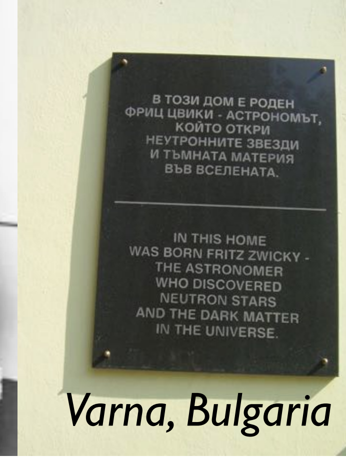
1) No implication that DM is an exotic form of matter. It might still be ordinary matter which does not shine (e.g., dim stars, planets, cold/dark and/or rarefied gas, …)

2) DM notion implicitly assumes that the theory of gravity used (Einstein GR, most often in its Newtonian limit) is correct

3) The fact that it is called matter (as opposed, e.g., to radiation) has to do with the fact that its effects are inferred in bound systems, so that DM clusters and forms structures

Taken from P. Serpico

The Coma cluster



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*

- **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 :

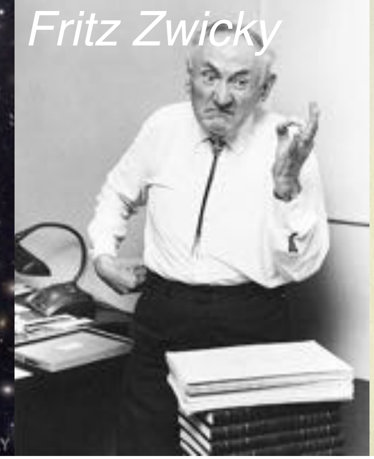
$$2T = M\langle v^2\rangle$$

- **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~ 4×10^{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 $\langle v^2_r\rangle = (1000\ km/s)^2$

The Coma cluster



- **We know today that alarge fraction of the mass of the galaxy clusters is made of hot gas:** the mass of the gas in Coma is ~ 2 x10^{14} $M_\odot$, which represents ~10% of the total mass. More than 85% of the mass is made of dark matter.

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.

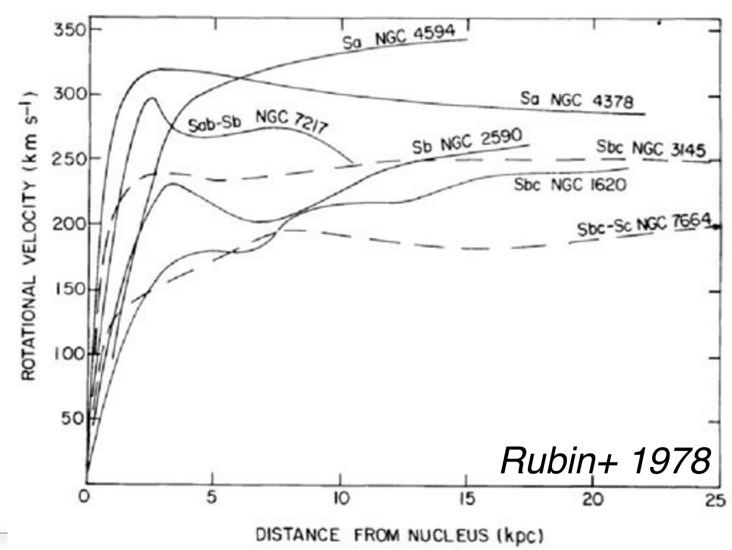
- **Circular velocity of starts determined by enclosed mass**

$$v_c^2(<R) = R\frac{d\phi_{\rm tot}}{dR} = \frac{GM(<R)}{R} \qquad M(<R) \equiv 4\pi\int_0^R r^2\rho(r)dr$$

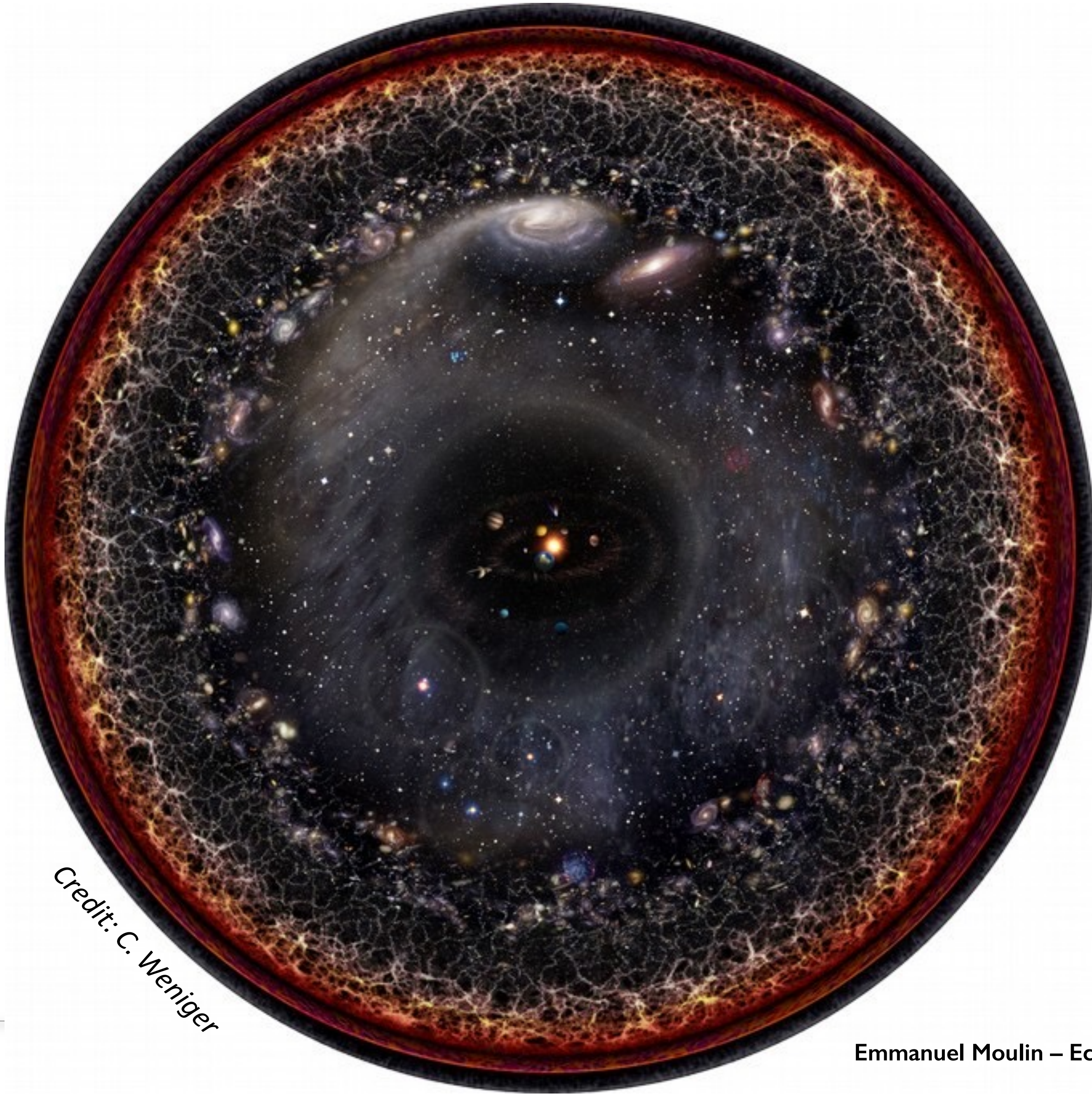
- **Centrally concentrated mass implies while observed v_c^2 ~ constant → M(<R) ∝ R**

$$v_c^2 \propto \frac{1}{R}$$

$$\rightarrow \quad \rho(r) \propto \frac{1}{r^2}$$

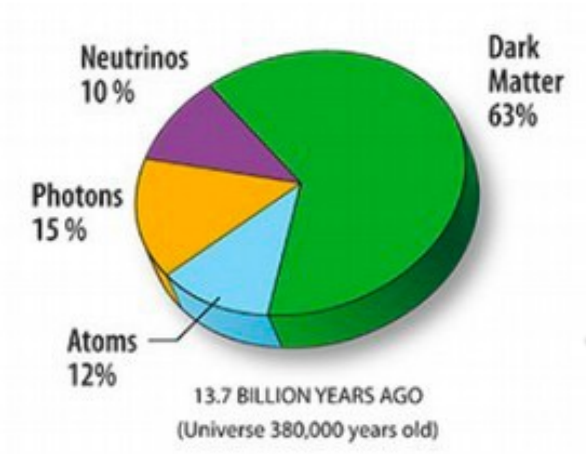


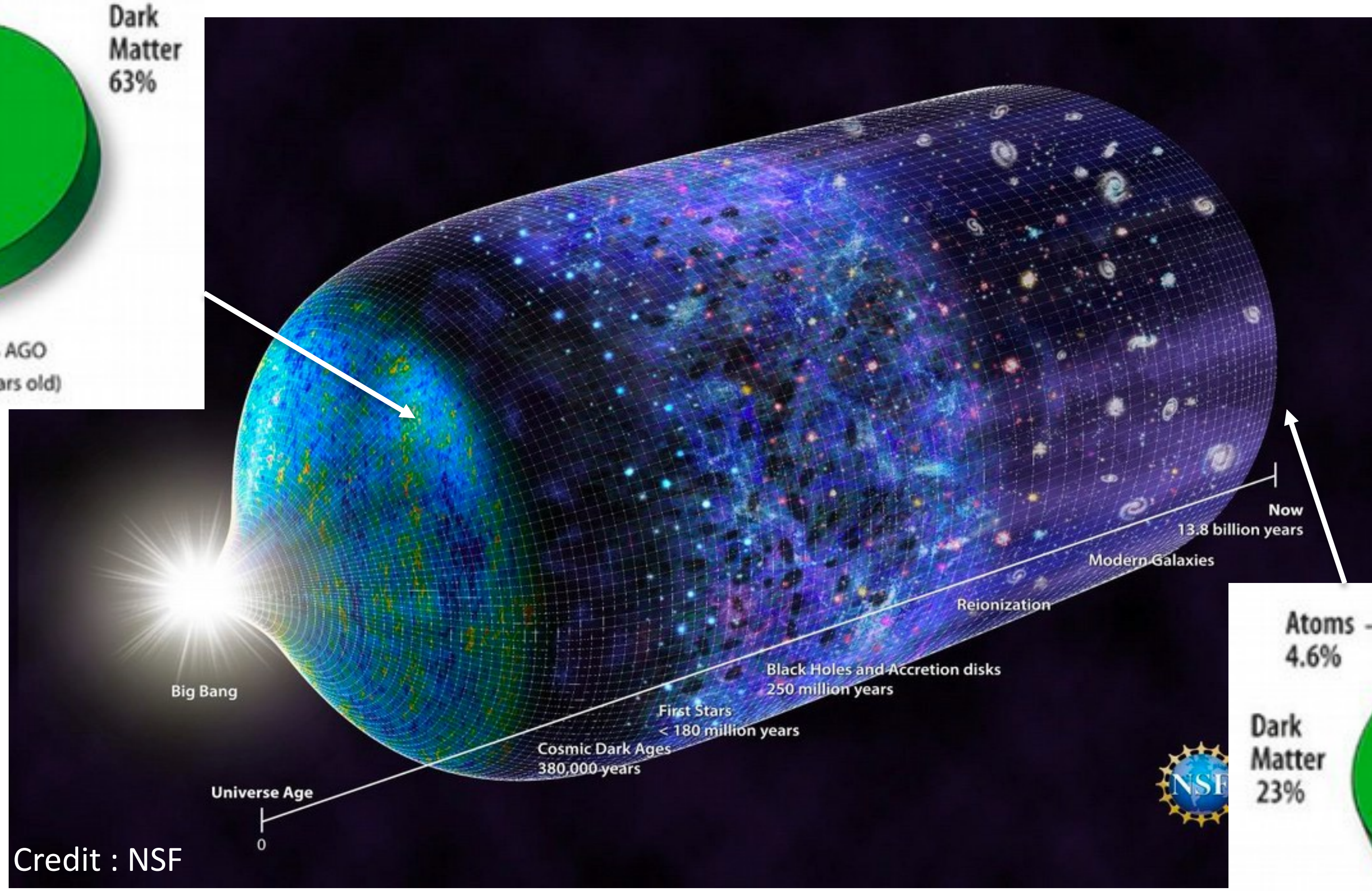
Modern evidences of dark matter

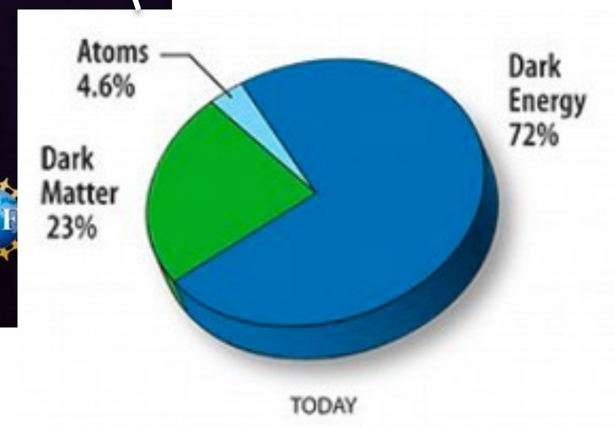


- Solar neigbourhood Milky Way rotation
- Satellite galaxies
- Nearby galaxies
- Galaxy groups/clusters
- Large scale structure
- Cosmic microwave background
- Baryonic Acoutic Oscillations
- Primoridal nucleosynthesis

Dark matter dominates the universe



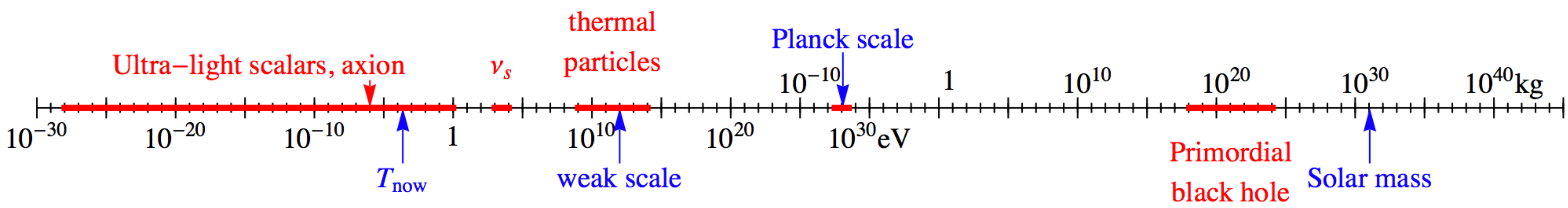




DM was dominant force in Universe from ~40kyrs to ~5Gyrs. Without DM, Universe would look very different.

But what is it ?

The landscape of Dark Matter

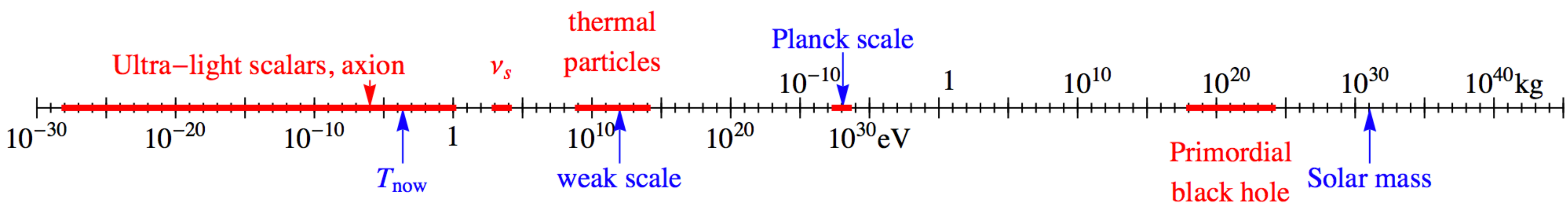


- Enormous spectrum of possible candidates beyond the Standard Model, over a huge range of mass scales

- 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

The landscape of Dark Matter



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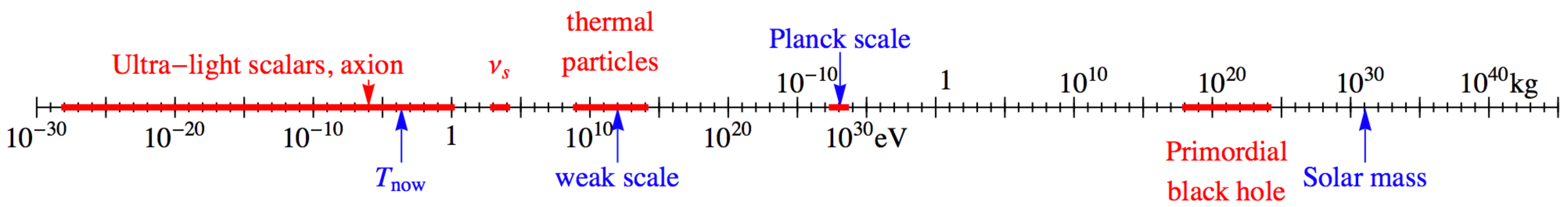
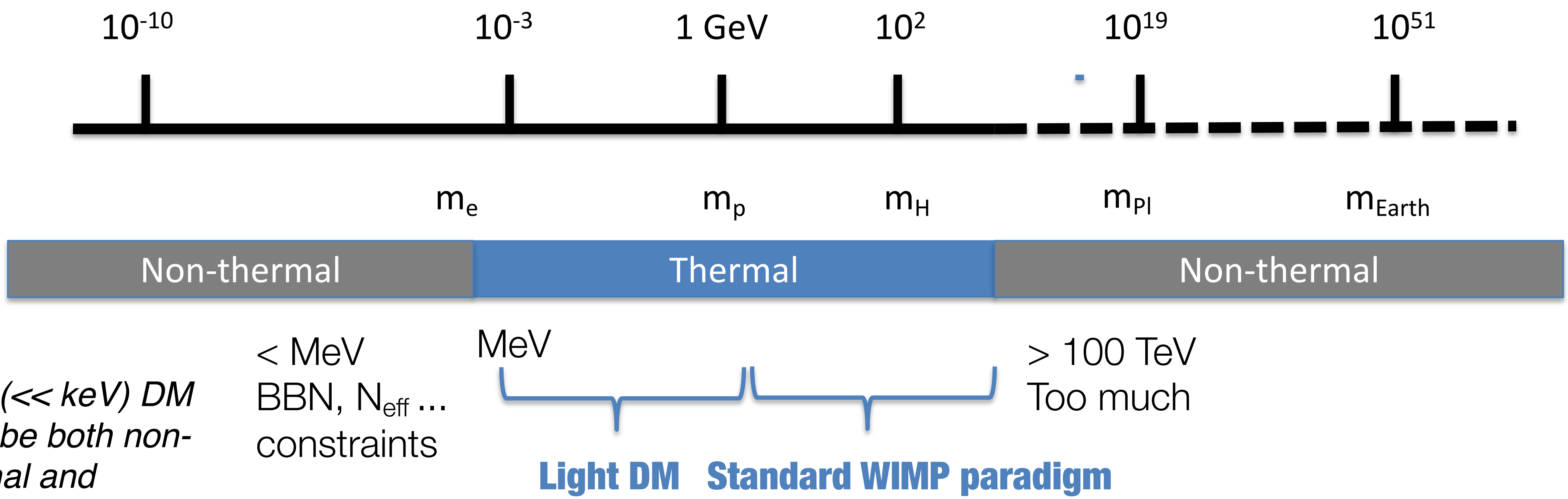


- **Enormous spectrum of possible candidates beyond the Standard Model, over a huge range of mass scales**

- **The classfication of dark matter candidates is largely based on the particle physics features of the underlying models**

- **An alternative approach is to shift focus toward exploring wide ranges of the possible phenomena in an effort to understand how well existing experimental searches cover the space of possibilities, and eventually how new experimental opportunities provide sensitivity to regions of theory-space that are not captured by the current programs**

DM as a thermal relic from the Early Universe

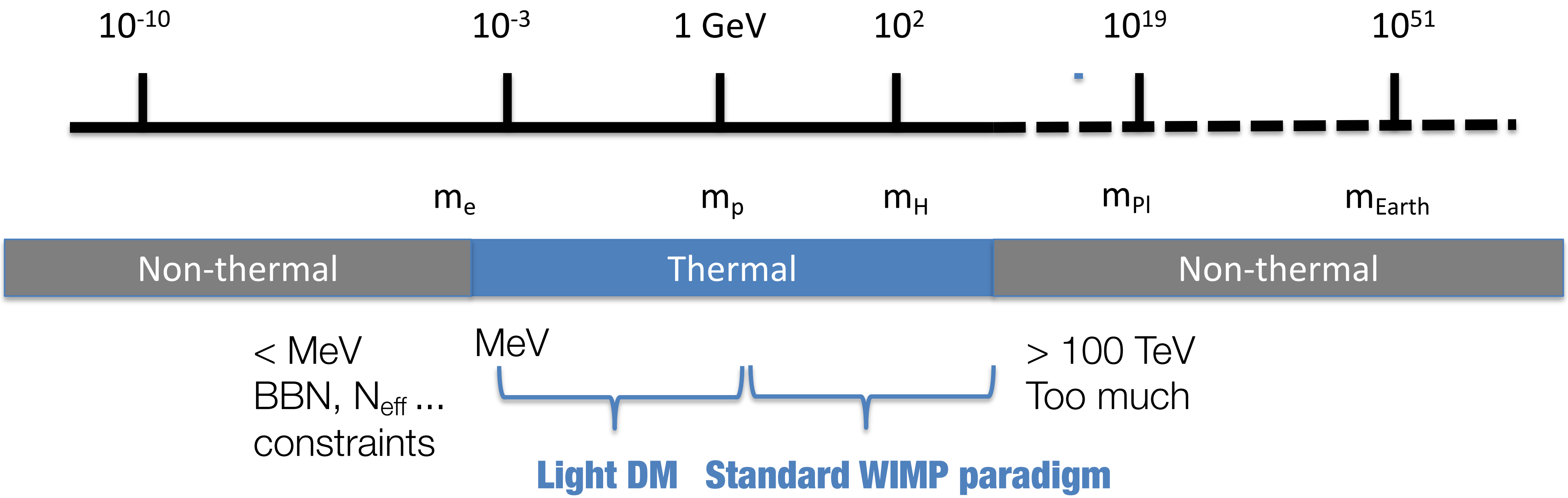


Light (<< keV) DM must be both non-thermal and bosonic - classic example is the axion

There is a long-standing connection between dark matter and the TeV scale:

- New physics at the O(TeV) scale could potentially help resolve the hierarchy problem
- Interactions of TeV-scale DM through weak-scale mediators can naturally generate the observed abundance of dark matter

DM as a thermal relic from the Early Universe



- The weak interaction mass scale and ordinary gauge couplings give right relic DM density

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

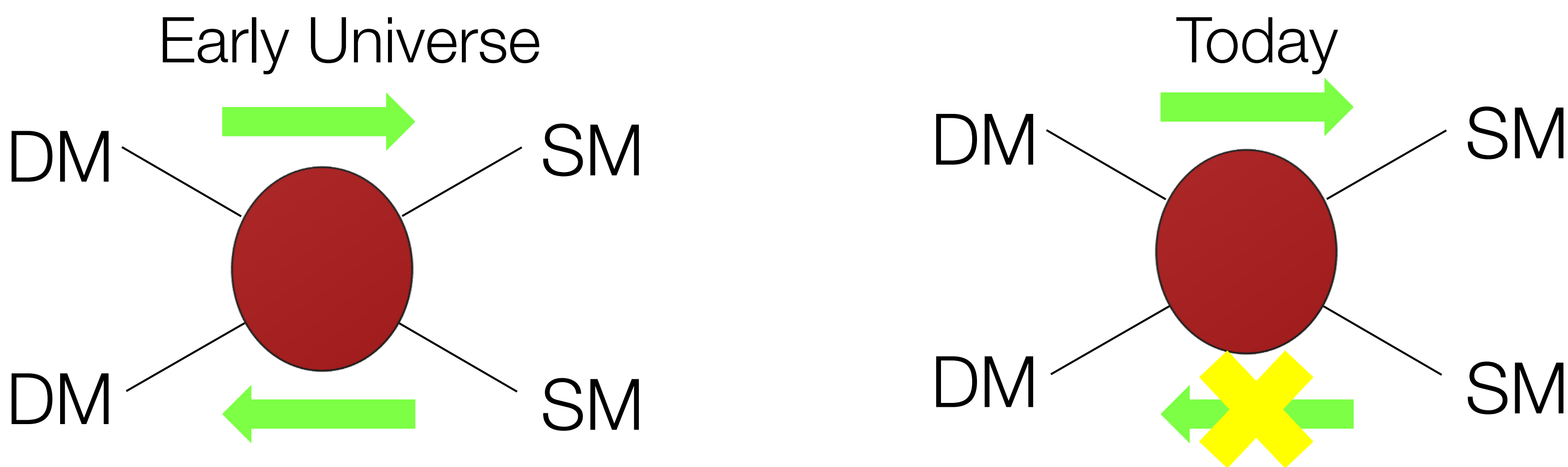
- GeV-TeV mass scale makes them **Cold Dark Matter**

→ **Provides benchmark for indirect detection: thermally-produced WIMPs**

Annihilation benchmark : thermal density

- **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)**

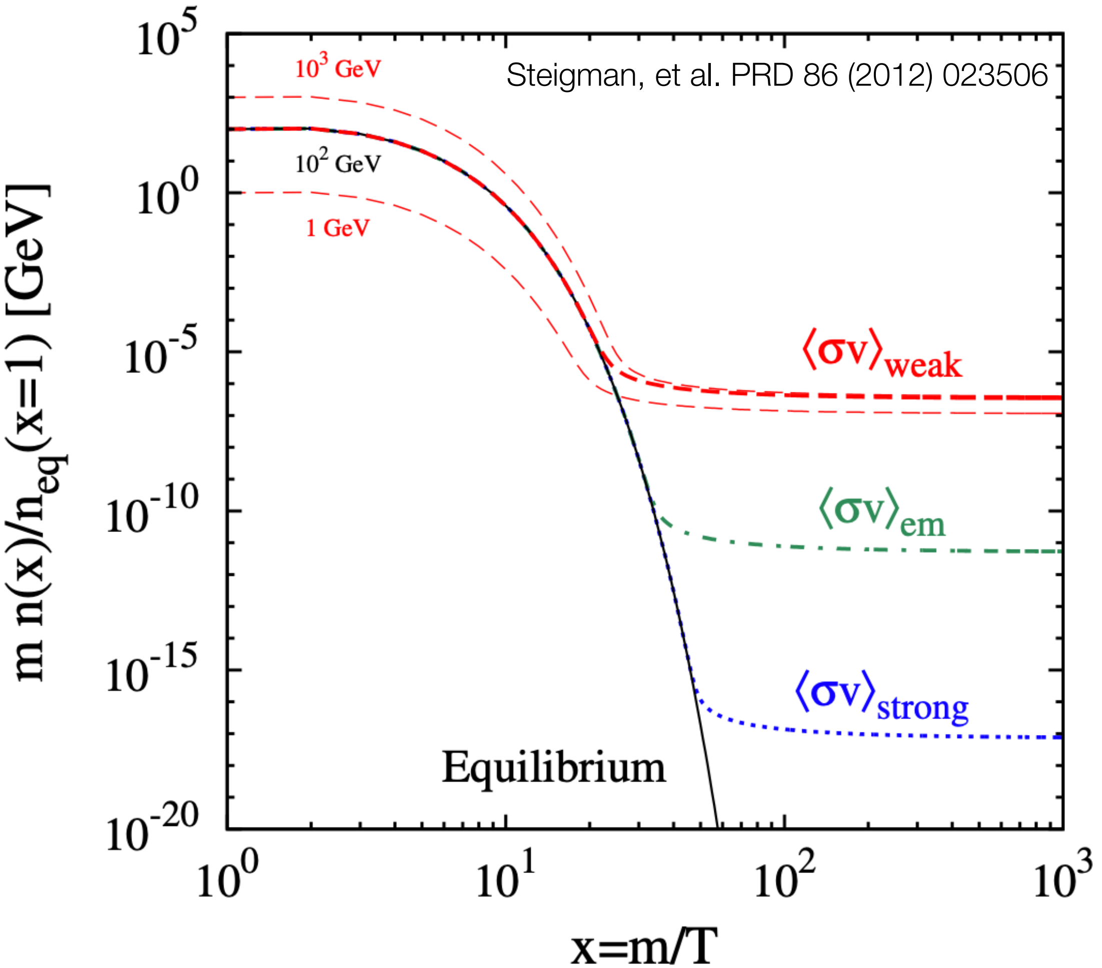


- **At some point in the early universe, annihilation stops because of the expansion rate, the DM density is then frozen**

Annihilation benchmark: thermal density

- **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 ».**

A bit more details on thermal density

- A full treatment involves the Boltzmann equation for particles in comoving volume

$$\frac{dn}{dt} = -3\,Hn - \langle \sigma v \rangle (n^2 - n_{\rm eq}^2)$$

- H : Hubble parameter,
- <σv> thermally-averaged annihilation cross-section of DM particles times relative velocity,
- neq is the equilibrium number density of DM particles

- When the universe cooled down, SM SM → DM DM is no more possible, exponential depletion of DM around T ~ m_{DM}

- Simple estimate : freeze-out occurs when timescales for expansion and annihilation rates are similar:

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

- After freezeout, DM number density n scales as $a^{-3} \sim (1+z)^{-3} \sim T^3$:

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

A bit more details on thermal density (II)

- With $$H^2 \sim \frac{\rho}{M_{Pl}^2}$$ taken at the freezeout temperature T_f

and assuming that freezeout occurs during radiation dominated area ($\rho \propto T^4$), the number density today is:

$$n(T_0) \sim \frac{T_f^2}{\langle \sigma v \rangle M_{Pl}} \left(\frac{T_0}{T_f} \right)^3$$

- Freezeout usually triggered by exponential depletion of DM around $T_f \sim m_{DM}$, the mass density is given by:

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

A bit more details on thermal density (III)

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

- The relic density $\Omega = \rho/\rho_c$ is inversely proportional to the annihilation cross section at T_f.

- The freeze-out temperature occurs around $T_f \sim m_{DM}$
  $\longrightarrow$ DM mass dependence largely cancels out

- Ignoring logarithmic dependence, on can find: $m_{DM}/T_f \sim 10 – 30$. In this simple estimate, the DM particle freezes out of equilibrium at a temperature well below its mass, making it a cold thermal relic.

See Jugmann, Kamionkowski, Giest, Phys.Rept. 267 (1996) 195-373

A bit more details on thermal density: caveats

- If the relic is very light or feebly coupled, this may not be the case.

- For a particle species that freezes out when relativistic, the late-time density corresponds to the early density diluted by the cosmic expansion
- It should then be comparable to the number density of photons so that:

  $\rho_\nu = m_\nu n_\nu \sim m_\nu n_\gamma \sim m_\nu 2\text{x}10^9 n_B \sim m_\nu 2\text{x}10^9 \rho_B/1\text{GeV}$.

  Knowing the DM and baryon densities today are of the same oder,

  $m_\nu \sim \text{eV}$

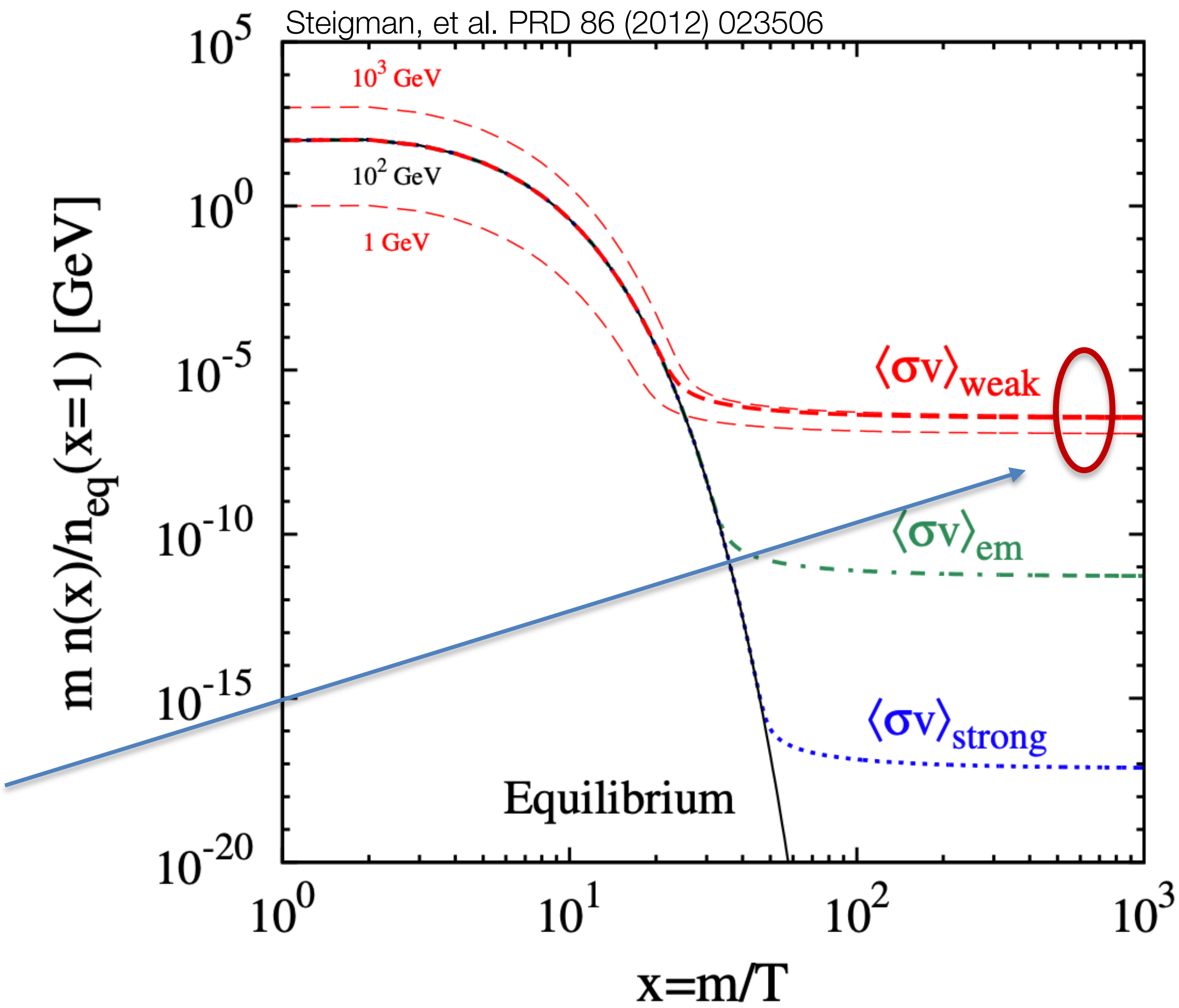
- This mass scale implies that the DM would be relativistic during the epoch relevant to structure formation, and would thus behave as « hot DM »: a scenario where hot DM constitutes all the DM would lead to dramatic changes to structure formation.

Annihilation benchmark: thermal density

- Present density inversely proportional to the strength of the interaction

- Almost independent of particle mass

Works in the ~10 MeV - 100 TeV mass range



Annihilating dark matter : thermal WIMPs

Weakly Interacting Massive Particles (WIMPs)

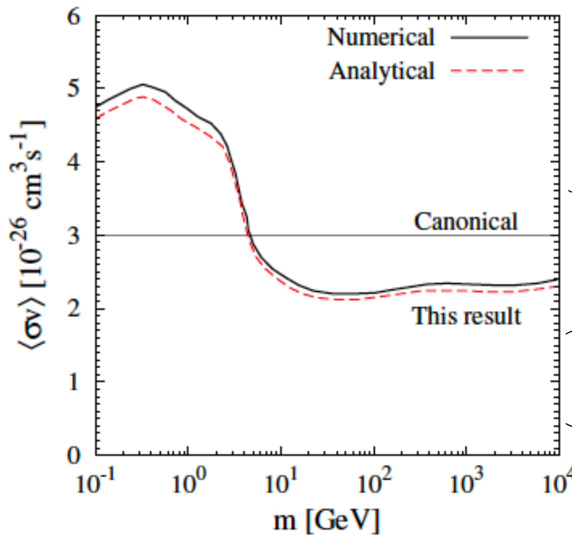
– The weak interaction mass scale and ordinary gauge couplings give right relic DM density

$$\Omega_{\rm DM}h^2 = \frac{3\times10^{-27}\ {\rm cm^3 s^{-1}}}{\langle\sigma v\rangle}$$

$$\langle\sigma v\rangle_{\rm W} \sim \frac{\alpha^2}{m^2_{\rm WIMP}} \sim 10^{-26}{\rm cm^3 s^{-1}}$$

for weak cross section of about 1 pb and relative velocity v ~ v_f ~ 0.3c

A careful calculation gives 2 x 10^{-26} cm^3s^{-1}, almost independent of the mass



G. Steigman, et al. PRD86, 23506 (2012)

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 uncertainty principle
  - With the Planck constant and considering a non-relativistic particle
  - then derive a lower bound on its mass

Draco dwarf spheroidal galaxy

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

  - Not a 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: 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, on 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, e.g., 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

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

- Using r_{GC} = 10 pc, M_{GC} = 10^5 pc, the BH mass should be lower than ~10^4 M_{sun} to avoid the disruption of the globular cluster over a Gyr

Astrophysical messengers

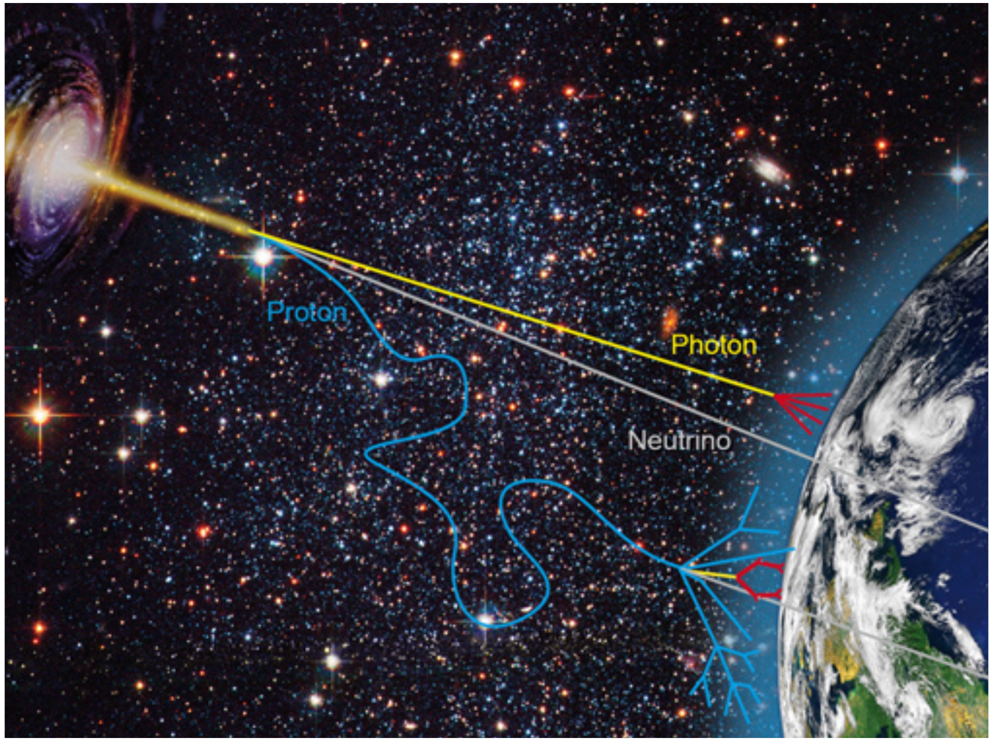
Neutral messengers – γ and ν

- Point to their sources : directional information
  → mapping of acceleration /propagation/production sites

- Can reveal the abundance and distribution of DM
  - need to account for absorption at extragalactic scale for gamma rays

  → 2D (occasionally 3D) information on source distribution - very valuable for separating signal from background

- Characteristic DM spectral features may be present in the spectrum



Identification of DM is possible

→ **the gamma-ray/neutrino distribution in the sky can tell us the DM density distribution**

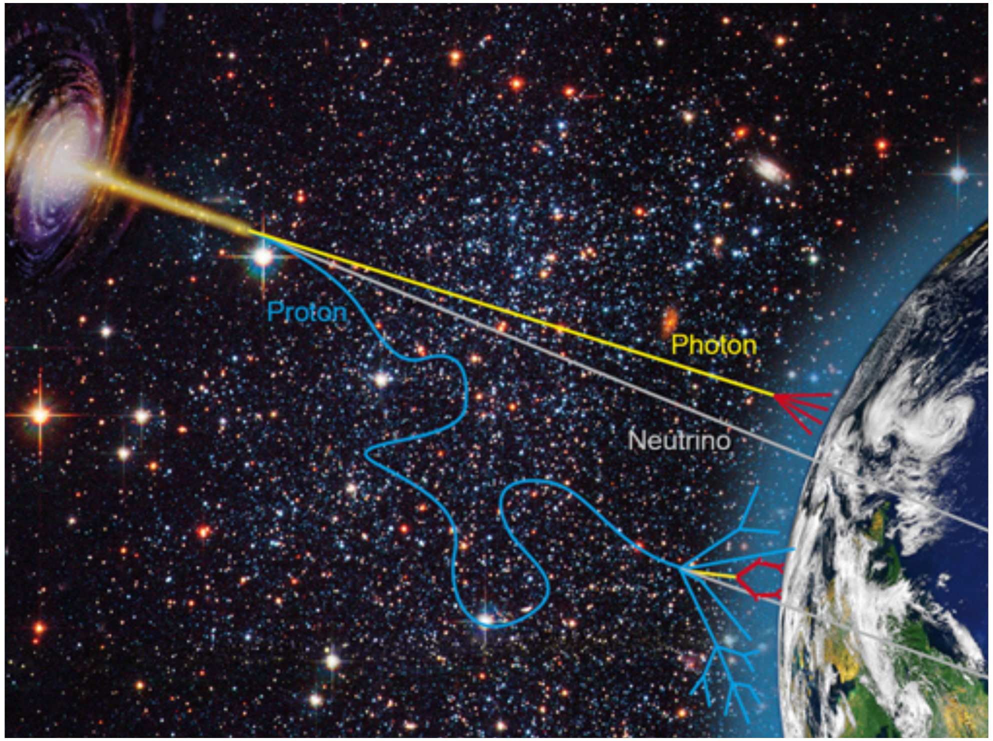
→ **the gamma-ray/neutrino spectrum can tells us the reaction process and DM mass**

Astrophysical messengers

Neutral messengers – γ and ν

Charged messengers – p, e$^{\pm}$, …

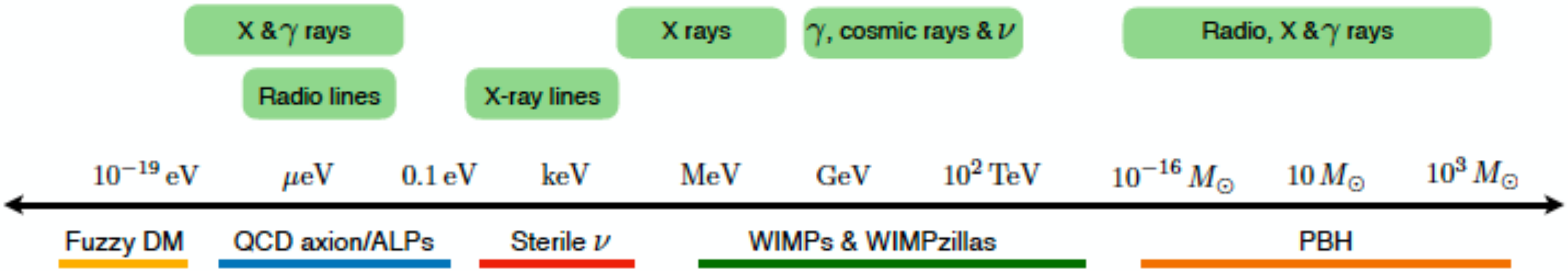
- Charged particles are affected by Galactic magnetic fields - trajectories do not point back toward sources
- CRs can lose energy rapidly, so even on sub-Galactic scales, their spectrum changes with distance from the source
- Makes signal/background separation more difficult, unless expected background is small



High energy anti-matter particles are rare enough that an excess can shine noticeably above backgrounds

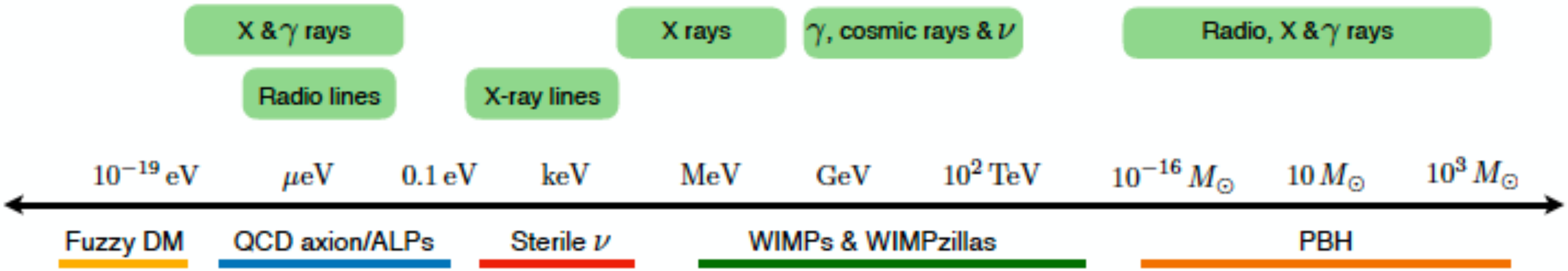
Astrophysical messengers

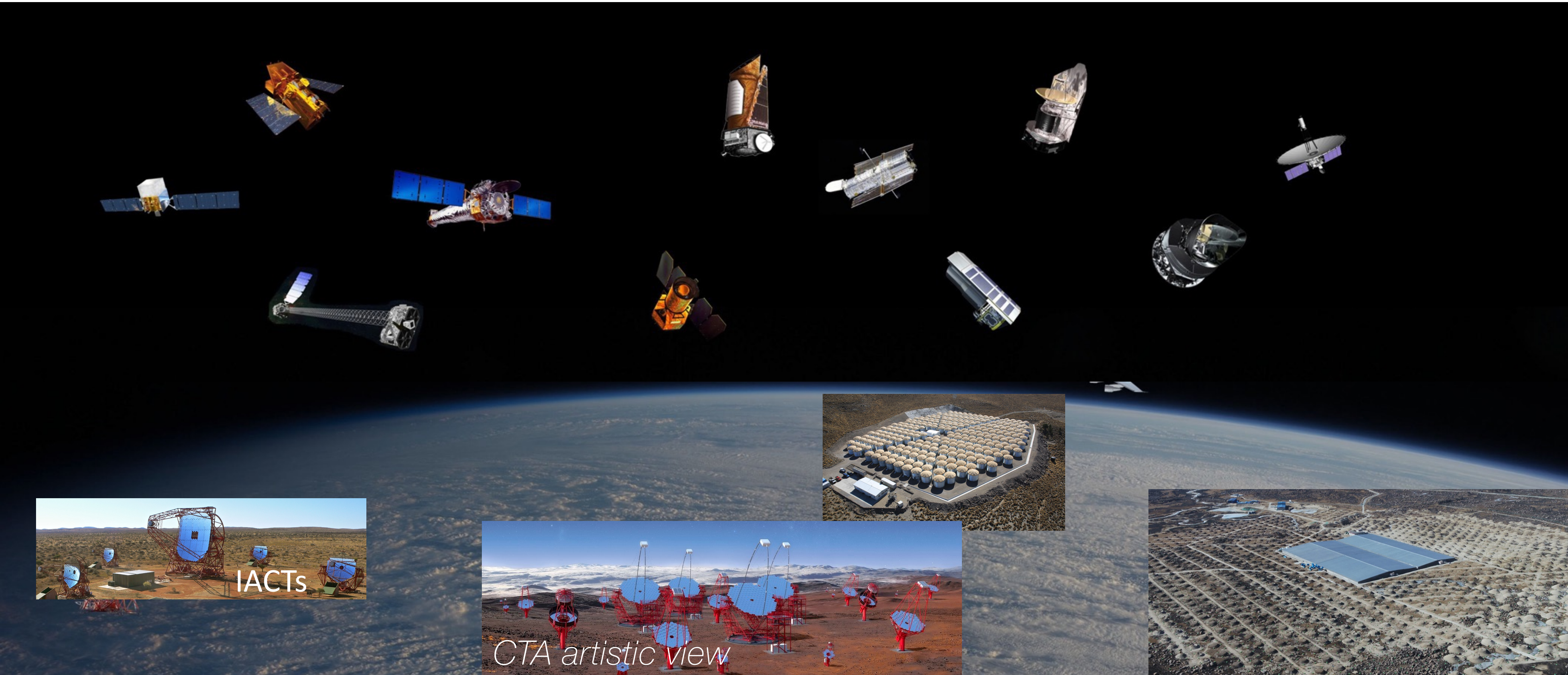
EuCAPT White Paper, arXiv:2110.10074



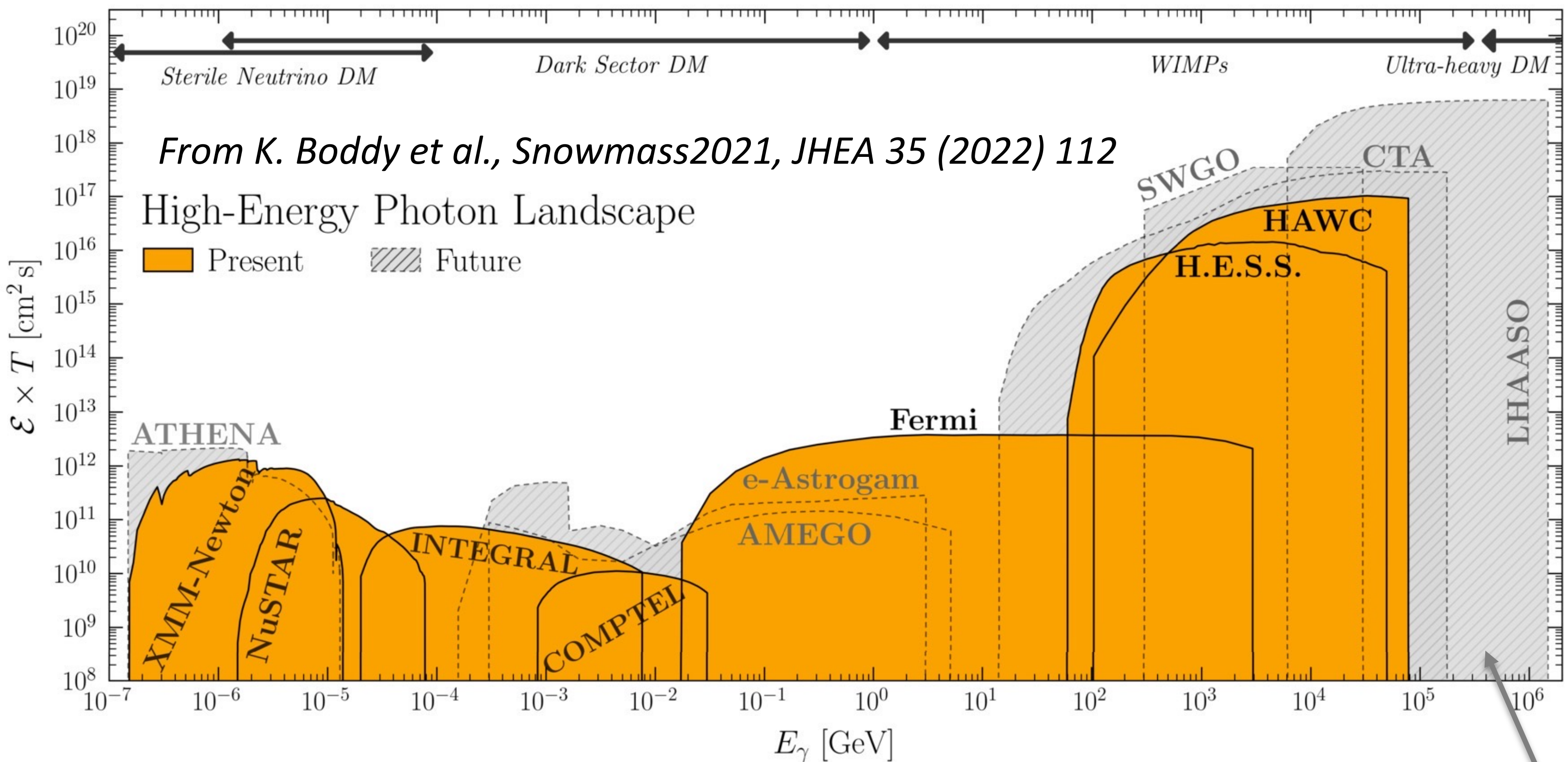
Astrophysical messengers and experiments

EuCAPT White Paper, arXiv:2110.10074





Exposure of γ-ray instruments for annihilating/decaying DM



$\mathcal{E}$: Effective area
T : Observation time

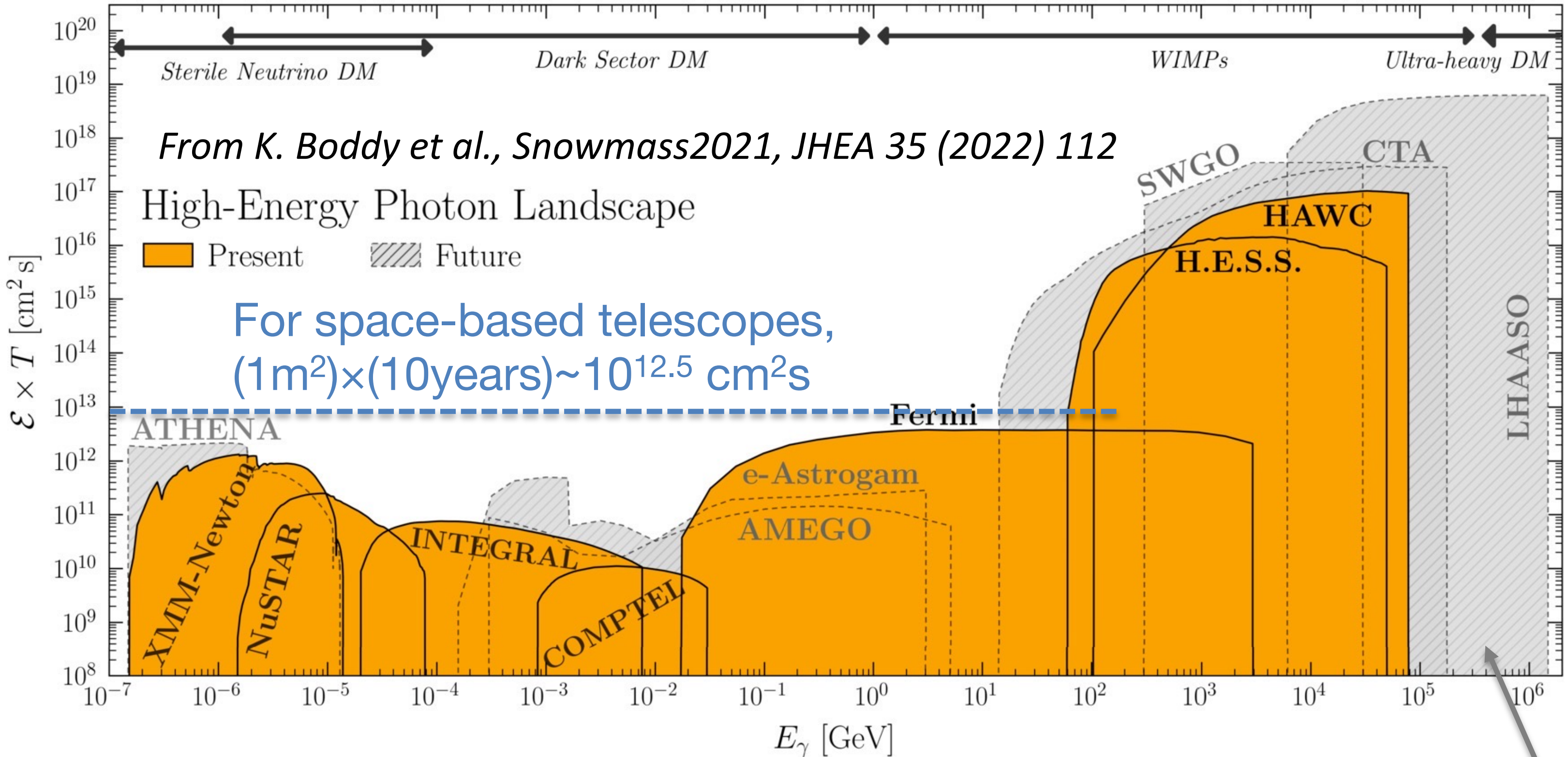
Nb of detected photons :
$\propto \Phi \times \mathcal{E} \times T$

Disclaimer:
- one of the many ways to compare instruments
- for some DM searches, FoV or energy resolution can be critical as well

- High Energies: dramatic improvement within ten years
- At keV–GeV energies, the expected observational progress is more modest at the level of exposure

- PeV photons detected by LHASSO
- Also instruments searching for even higher energies, e.g., AUGER

Exposure of γ-ray instruments for annihilating/decaying DM



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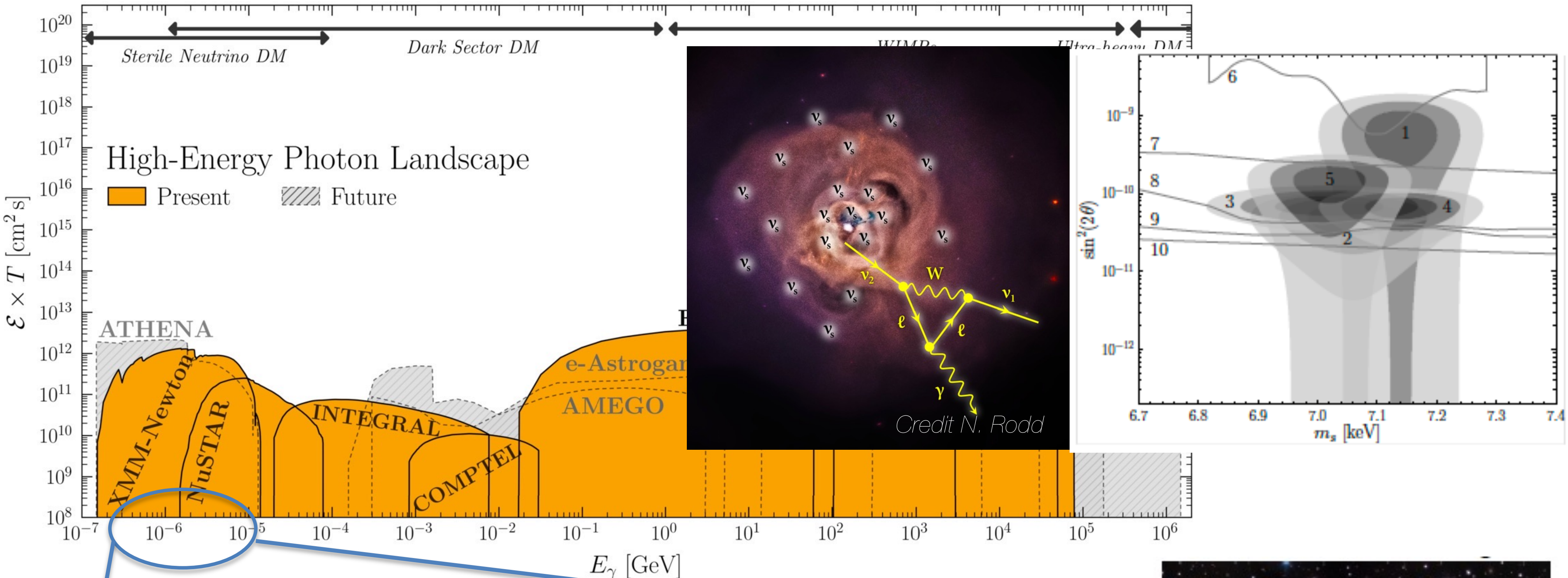
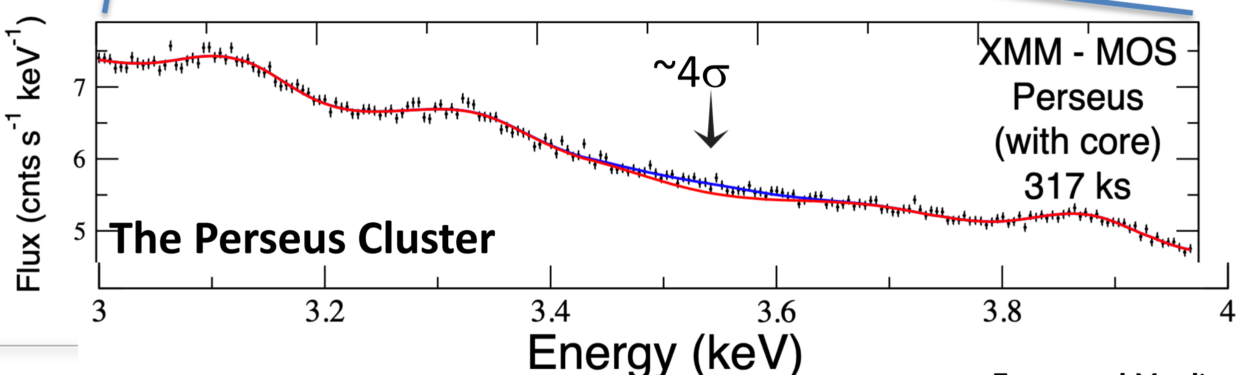
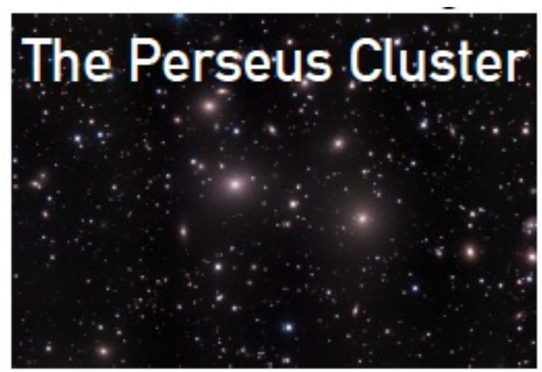
Sterile neutrino and the 3.5 keV line

Important existing datasets with XMM, INTEGRAL







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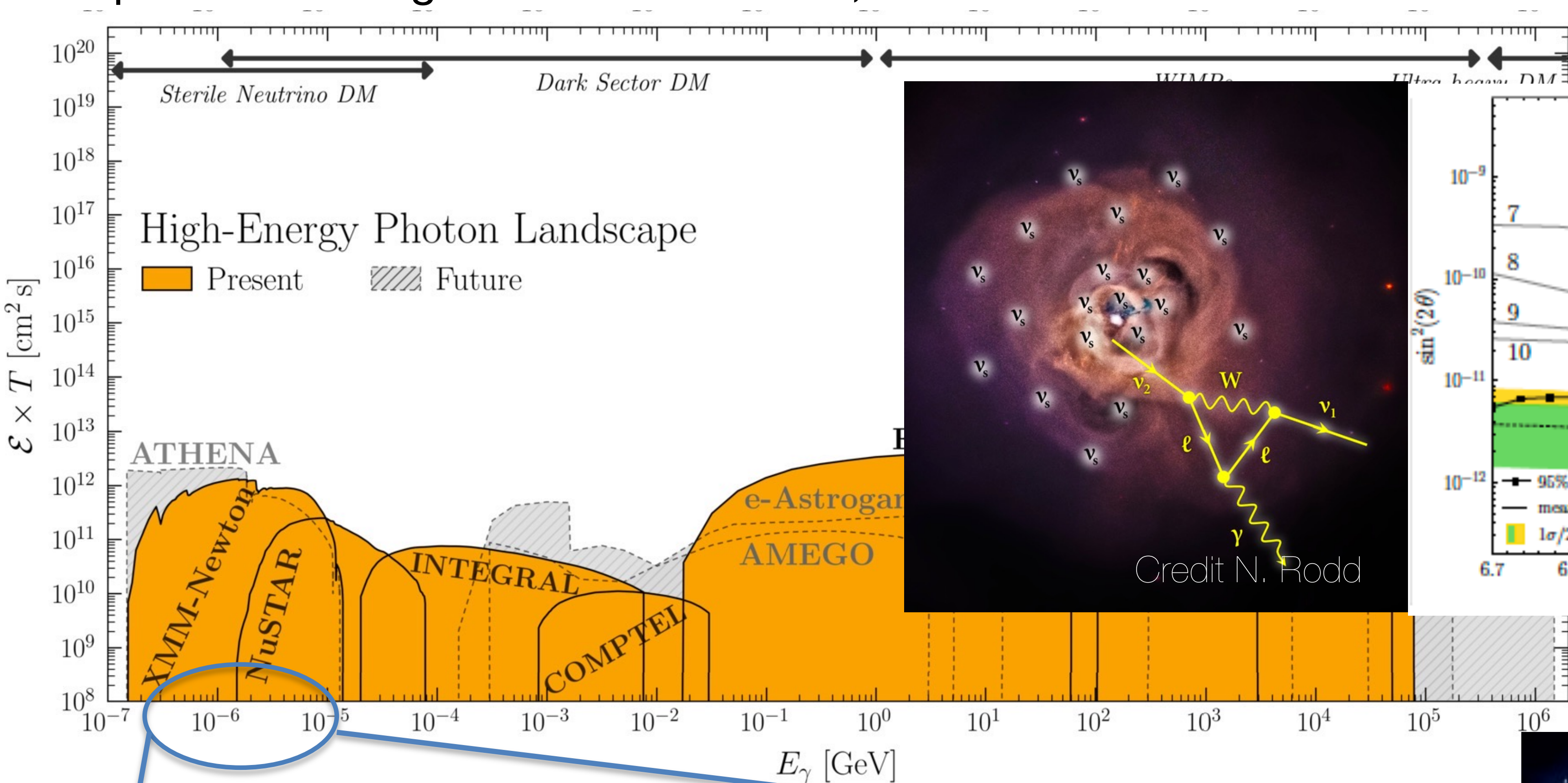

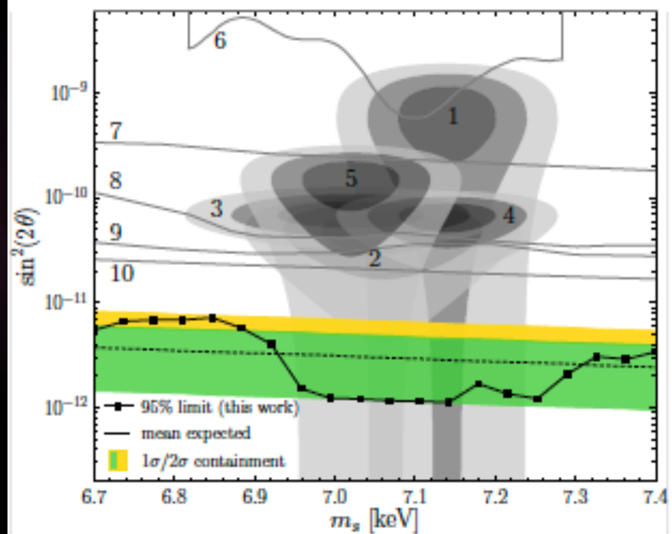

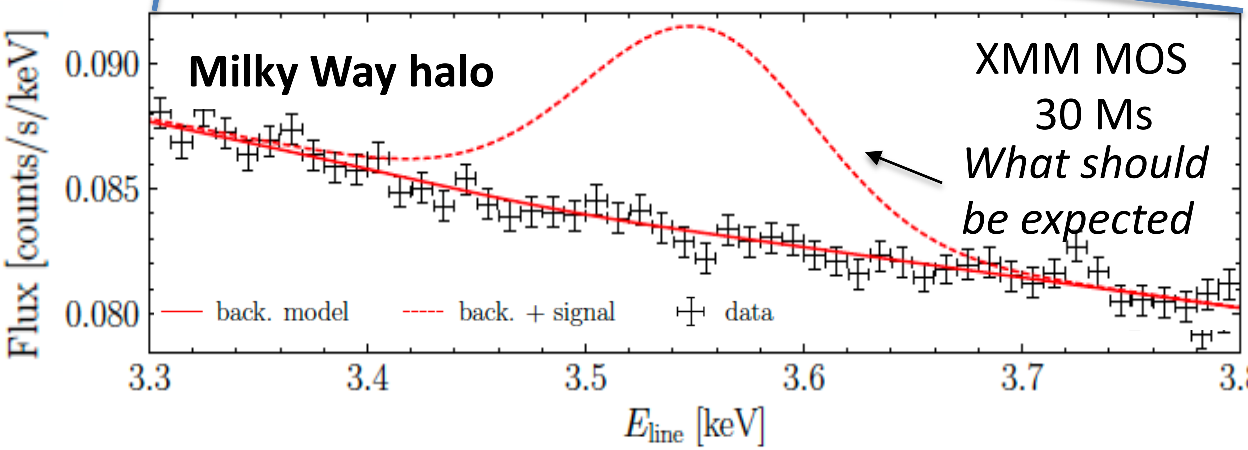

Sterile neutrino and the 3.5 keV line

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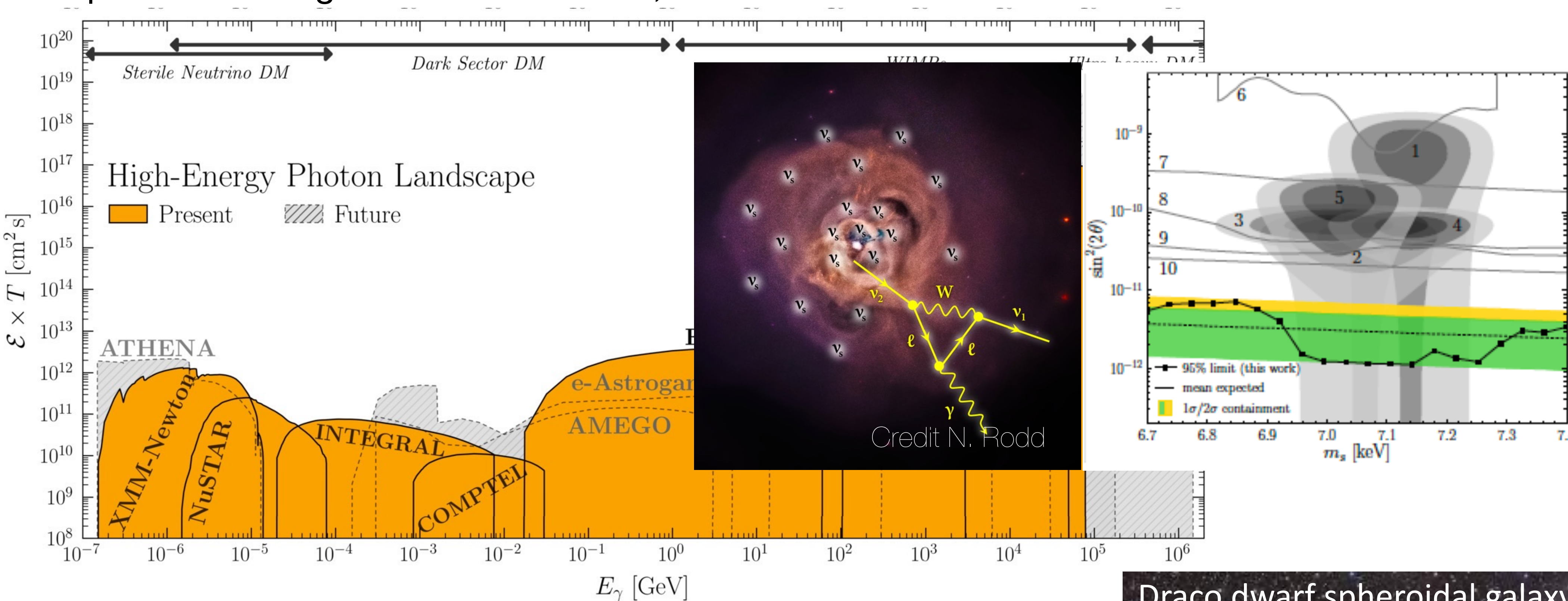
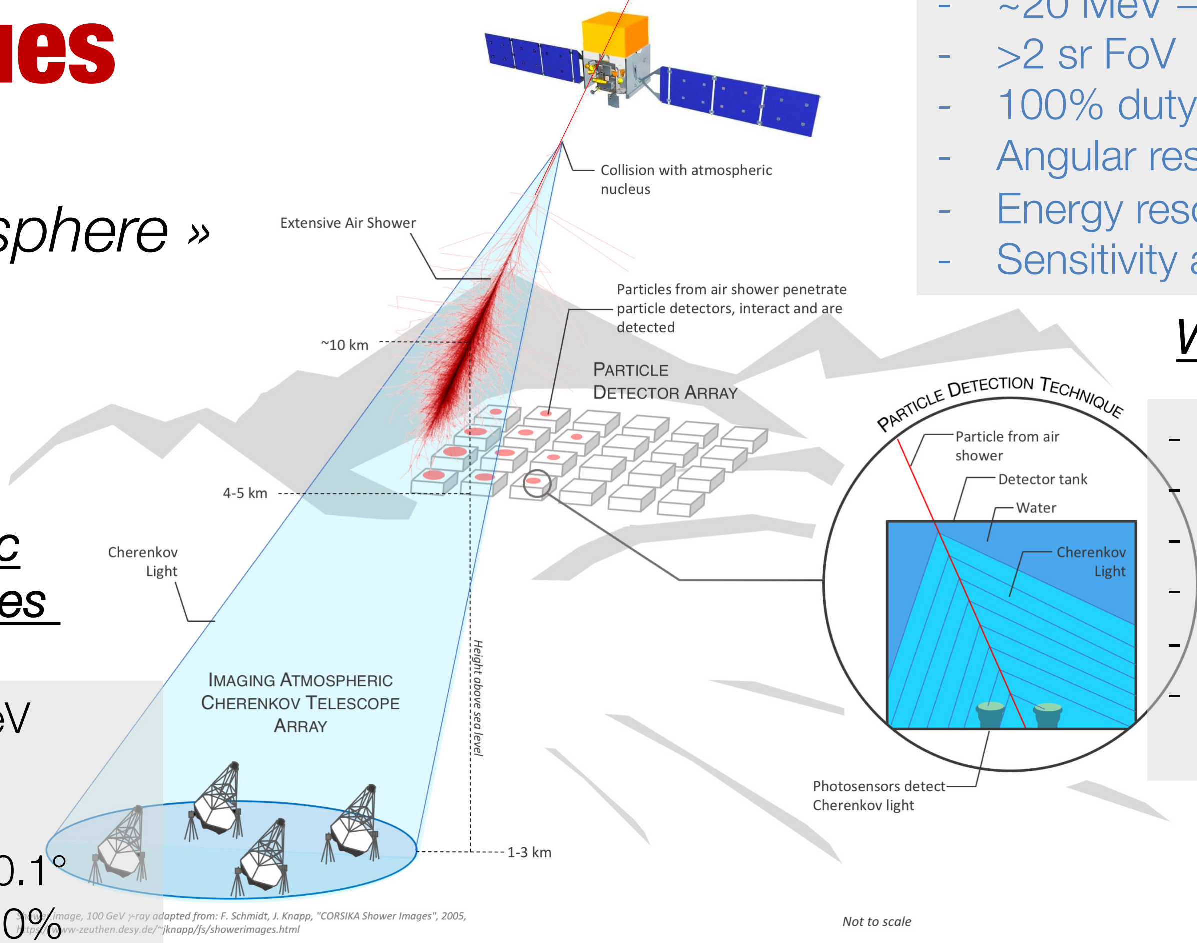


- 1.6 Msec XMM-Newton observations of the dwarf spheroidal galaxy Draco exluded also a 3.5 keV DM line
- Line seen in galaxy clusters plausibly from background mismodeling

Gamma-ray observational techniques

« Blocked by the atmosphere »



Satellites

- ~20 MeV → 300 GeV
- >2 sr FoV
- 100% duty cycle
- Angular resolution 0.15-3.5°
- Energy resolution ~10%
- Sensitivity a few % Crab flux

Water Cherenkov Detectors

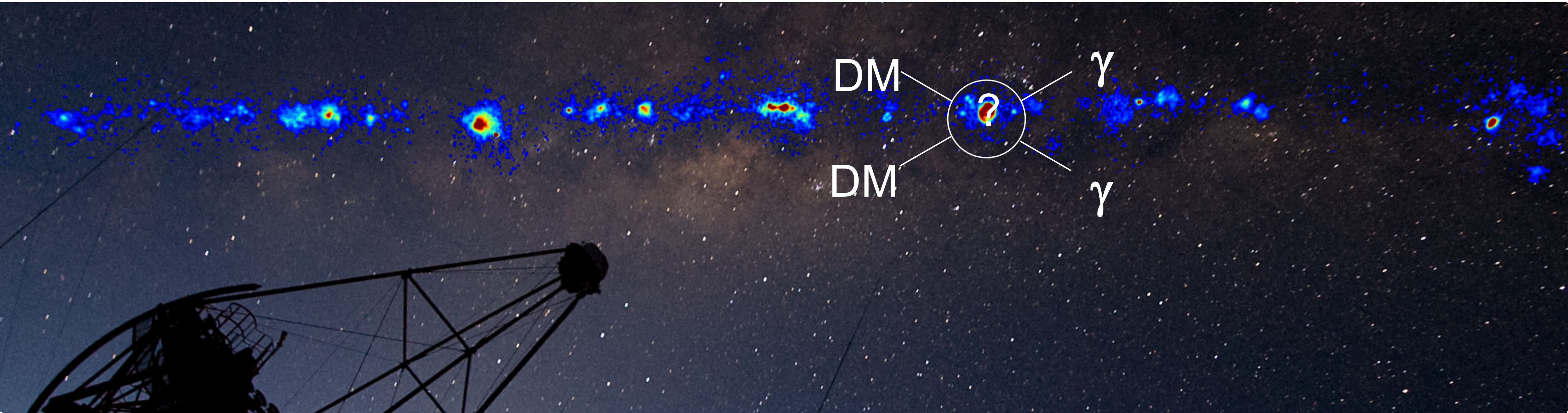
- ~100 GeV → 1 PeV
- 90% duty cycle
- ~sr FoV
- angular resolution 0.2 - 0.8°
- energy resolution ~50%
- sensitivity 5-10% Crab flux

Imaging Atmospheric Cherenkov Telescopes

- ~30 GeV → ~100 TeV
- Small FoV : ~ 5°
- Duty-cycle: 10-15%
- Angular resolution <0.1°
- Energy resolution ~10%
- sensitivity 1% Crab flux

- **IACT can provide detailed morphologies of limited region of the sky**
- **Satellites/WCD are very powerful to scan large regions**

WIMP : Annihilation and Decay



Particle dark matter emission

$$\mathrm{DM}\ (\mathrm{DM}) \rightarrow \ \mathrm{SM}\ \mathrm{SM}$$

- N = 1 : decay, N=2 : annihilation
- Annhilation/Decay at almost rest : $E_{CM} \simeq$ signal energy

Particle dark matter emission

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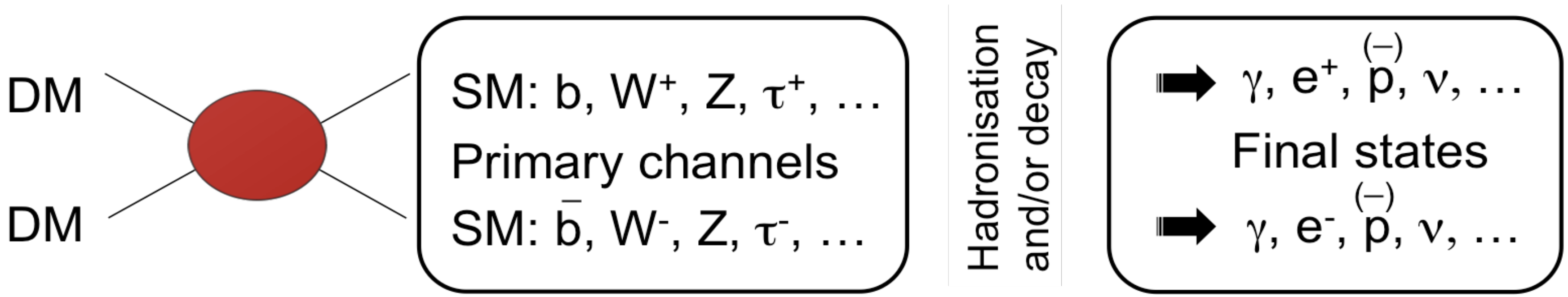
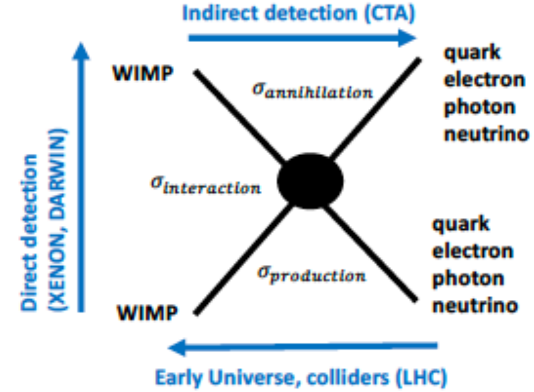
- Self-conjugated dark matter annihilation



How to look for WIMPs ?



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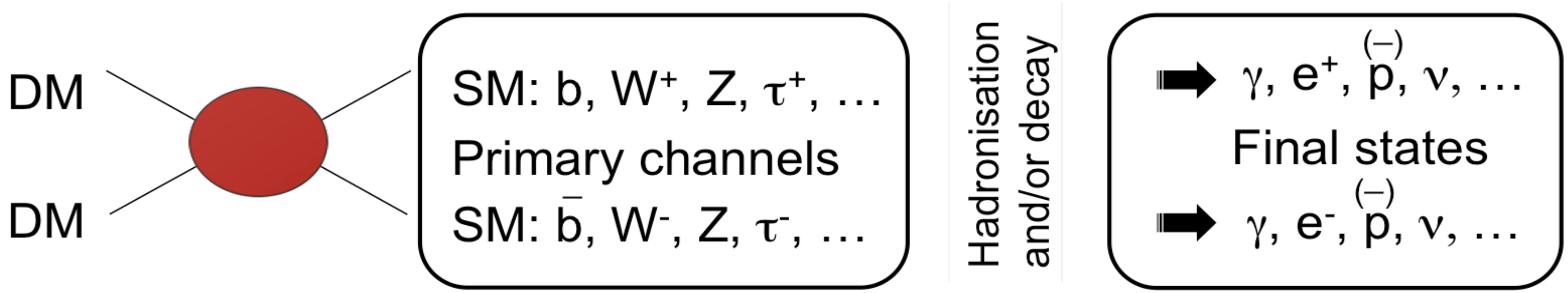

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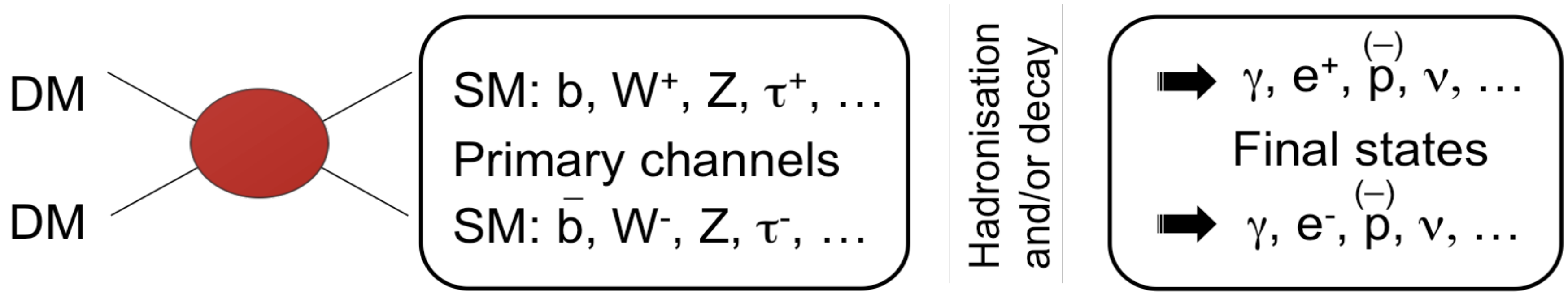
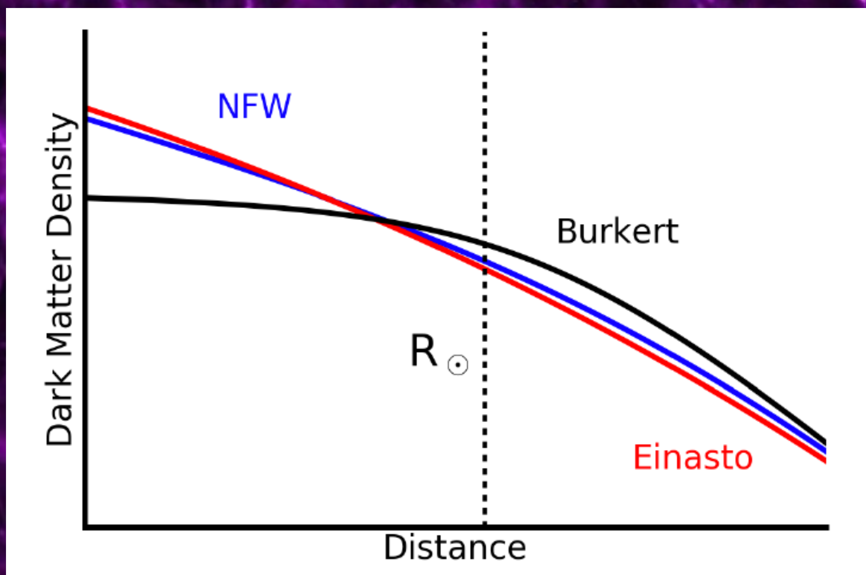
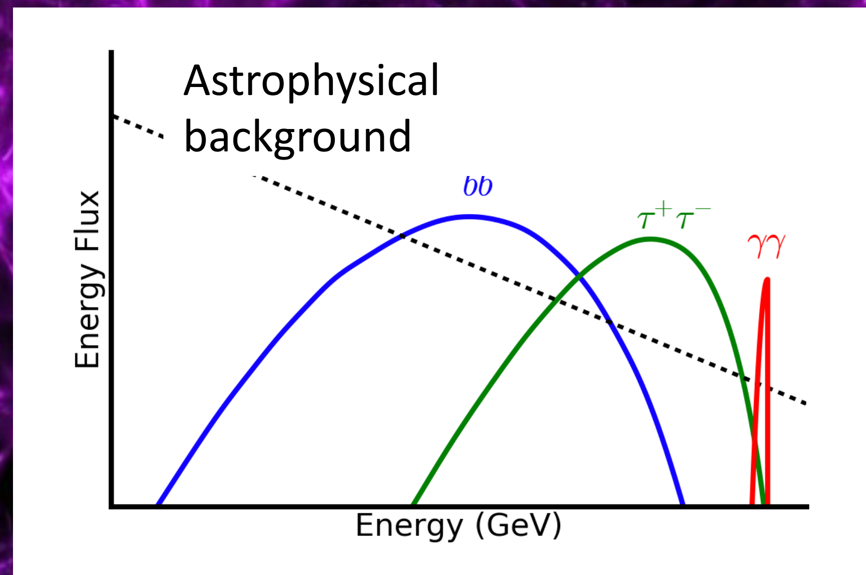






For self-conjugated DM annihilation:

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

Gamma rays / neutrinos

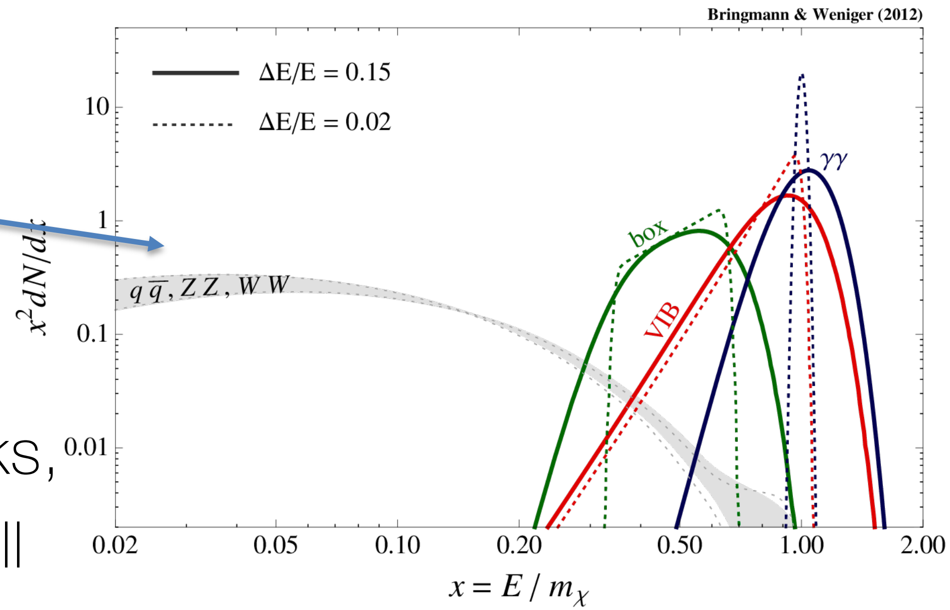
- **Do not suffer from propagation effects : they point back to the source**
  - Can reveal the abundance and distribution of DM
    - need to account for absorption at extragalactic scale for gamma rays
  - We can obtain 2D (occasionally 3D) information on source distribution - very valuable for separating signal from background
  - Strength of signal from a given source determined by dark matter content - parameterized by "Jfactor
- **Characteristic spectral features may be present in the spectrum at these energies**
  - Good discrimination against background

Identification of DM is possible:

- the gamma-ray/neutrino distribution in the sky can tell us the DM density distribution
- the gamma-ray/neutrino spectrum can tells us the reaction process and DM mass

Spectral features from DM annihilation

Continuum
(Hadronic channel)



- If DM self-annihilates to leptons gauge bosons, or any combinations of quarks, copious neutral and charged pions will be produced in the subsequent decays of those
- Neutral pions decay to a photon pair ($\pi_0 \rightarrow \gamma\gamma$) with a 99% branching ratio, so a broad spectrum of photons is produced up to the DM mass*, along with electrons and positrons from the charged pion decays.
- Spectrum that typically peaks at an energy around $m_\chi/10$ (in units of E2dN/dE).

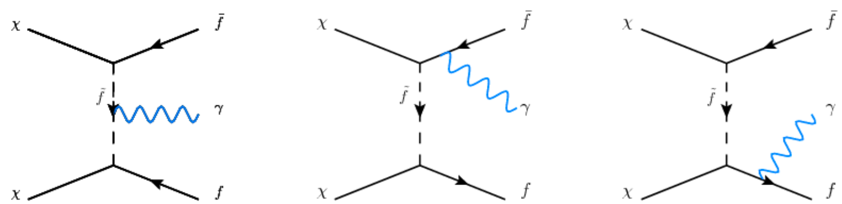
* the annihilation process takes place almost at rest

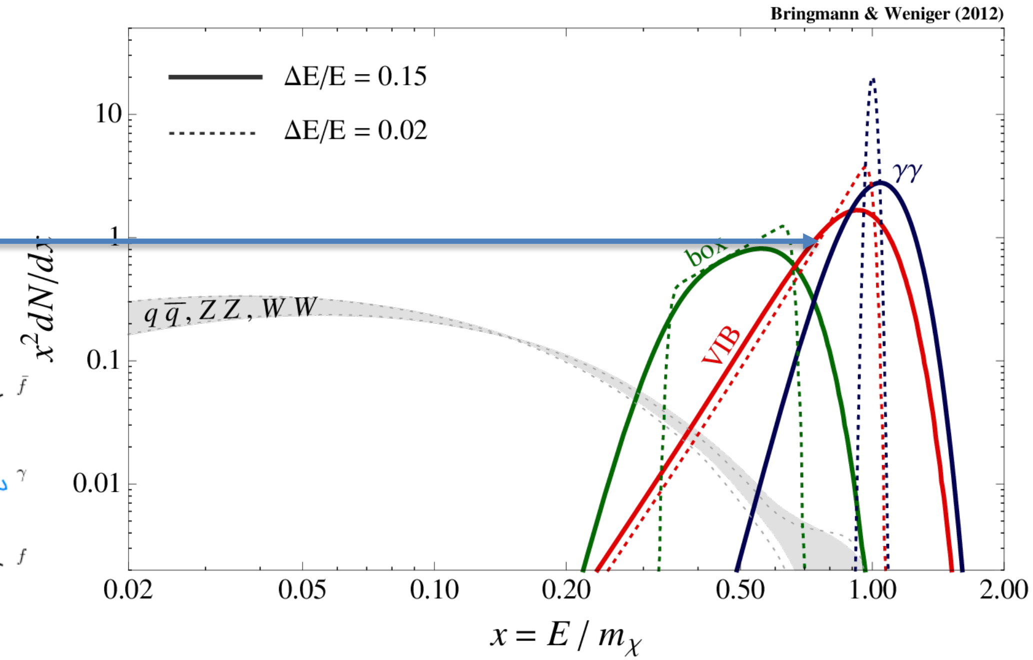
Spectral features from DM annihilation

Continuum

Leptonic channel

$$\chi\chi \rightarrow \bar{f}f\gamma$$



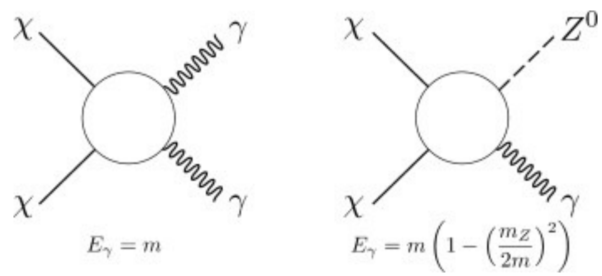


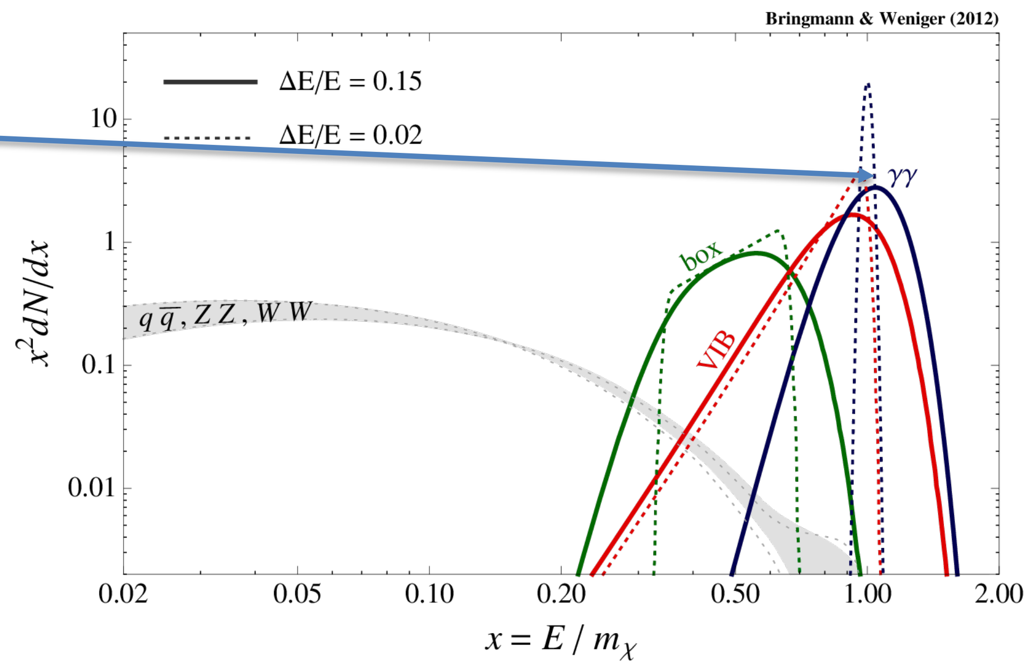
- Photons are produced directly only as part of 3-body final states, by final state radiation or internal bremsstrahlung
- The rate for photon production is suppressed, and the photon spectrum is typically quite hard, peaked toward the DM mass
- Note that similar hard photon spectra can be produced if the DM decays into a mediator that subsequently decays to photons.

Spectral features from DM annihilation

Line

$$\chi\chi \rightarrow \gamma\gamma, \gamma Z^0$$





- the DM annihilates directly to (or in the neutrino case), or a monoenergetic photon plus another particle. Such channels allow bump-like searches, and greatly reduce the possible astrophysical backgrounds;
- a clear detection of a gamma-ray spectral line would be very diffcult to explain with conventional astrophysics

Spectral features: a few remarks

- DM is known to carry no electric charge, and thus cannot couple directly to photons, so the line signal must be suppressed by $(1/a)^2$ compared to the continuum

- The IB/FSR induced signal is suppressed by (1/a) compared to the continuum

- For neutrinos the qualitative picture is similar to photons for the hadronic and line cases :
  - the direct coupling to neutrinos need not be loop-suppressed
  - the leptonic case can be different: annihilation to muons will produce an unsuppressed neutrino spectrum

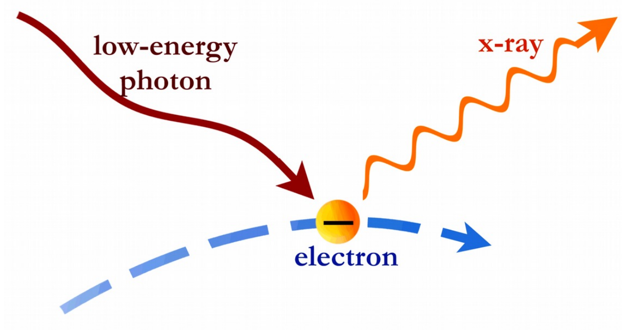
Spectral features: a few remarks

- **Charged particles from DM annihilation can also give rise to secondary photons, due to upscattering of ambient photons from starlight or the cosmic microwave background, and synchrotron radiation from high-energy charged particles propagating in a magnetic field.**

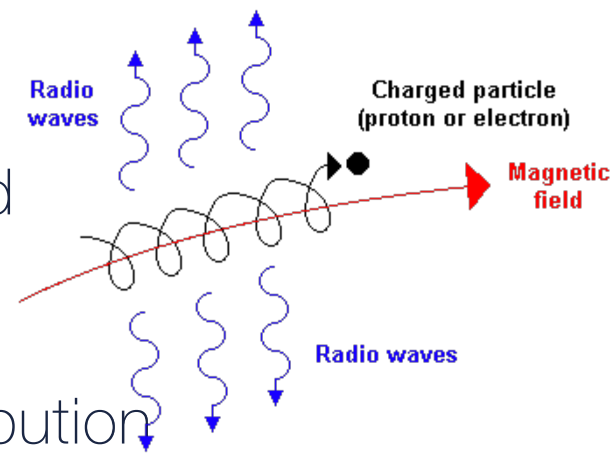
Secondary photons

Various mechanisms can generate photon signals from high energetic charged particles, in particular electrons and positrons.

- Inverse Compton: emission up-scattering of the interstellar radiation field (starlight, dust emission, CMB) up to > GeV energies



- Synchrotron emission: radio emission of electrons propagating the Galactic magnetic field



- For leptonic channels, this is an important contribution to the signal; however, it depends on modeling the propagation of the charged particles.

Gamma-ray flux from DM annihilation

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

Particle physics:
- Cross sections
- Differential photon yield
- DM particle mass

Astrophysics: J-factor
- DM distribution in the target

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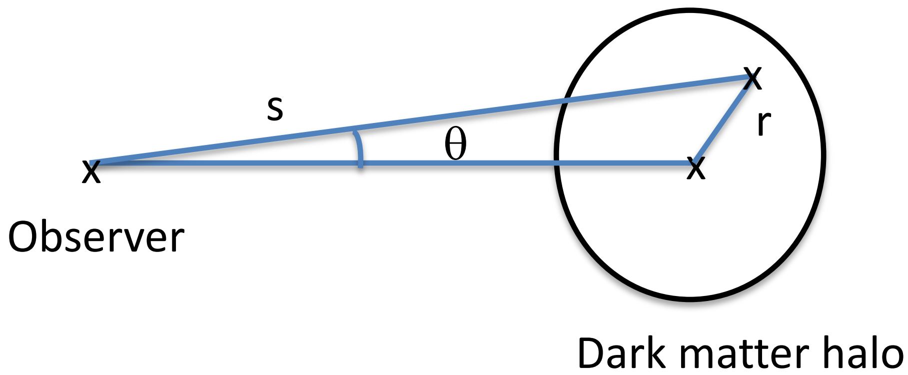
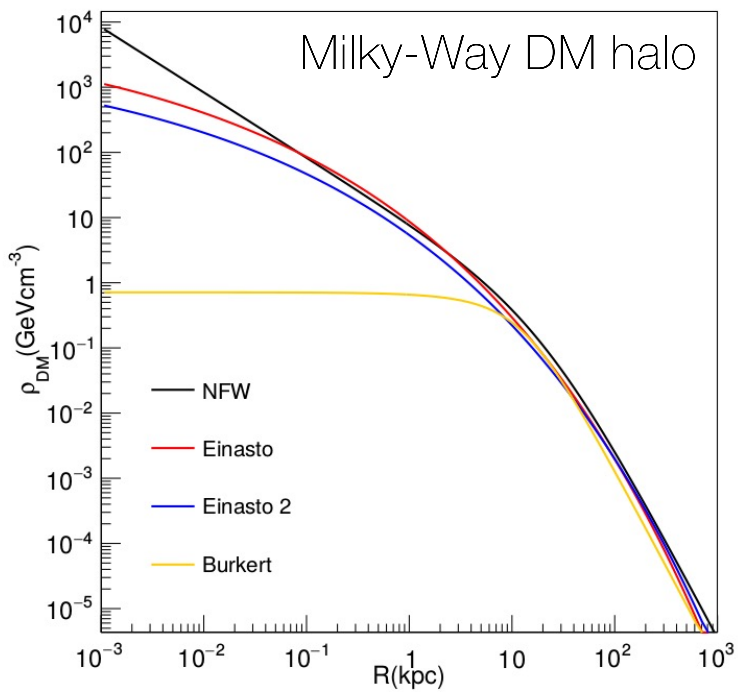
$$J(\Delta\Omega) = \int_{\Delta\Omega}\int_{\rm los} \rho^2(r(s,\theta))\mathrm{d}s\mathrm{d}\Omega.$$

Astrophysics: J-factor

depends on the DM desnsity distribution ρ in the object





Uncertainties related to baryon feedback, tidal stripping, clustering, …

Flux from DM annihilation

- Consider a volume dV with a density ρ_{DM}, at a distance R from the observer, the rate of annihilation/volume/time is:

$$\frac{dN}{dV\,dt} = \frac{n_{DM}^2}{2}\langle\sigma v\rangle = \frac{\rho_{DM}^2}{2m_{DM}^2}\langle\sigma v\rangle$$

- If the spectrum produced per annihilation is dN/dE, then the spectrum per annihilation/volume/time is:

$$\frac{dN}{dV\,dtdE} = \frac{\rho_{DM}^2}{2m_{DM}^2}\langle\sigma v\rangle\frac{dN}{dE}$$

- The spectrum per unit of time observed in a detector area of dA is :

$$\frac{dN_{obs}}{dtdE} = \frac{\rho_{DM}^2}{2m_{DM}^2}\langle\sigma v\rangle\frac{dN}{dE}dV\frac{dA}{4\pi R^2}$$

Flux from DM annihilation (II)

- Integrating over the volume dV in spherical polar coordinates (dV = $R^2 dR d\Omega$), the observed spectrum per unit of time observed per detector area dA is :

$$\frac{dN_{obs}}{dtdEdA} = \frac{1}{8\pi m_{DM}^2}\langle\sigma v\rangle \frac{dN}{dE} \int \rho_{DM}^2 dR d\Omega$$

Particle physics:
- Cross sections
- Differential photon yield
- DM particle mass

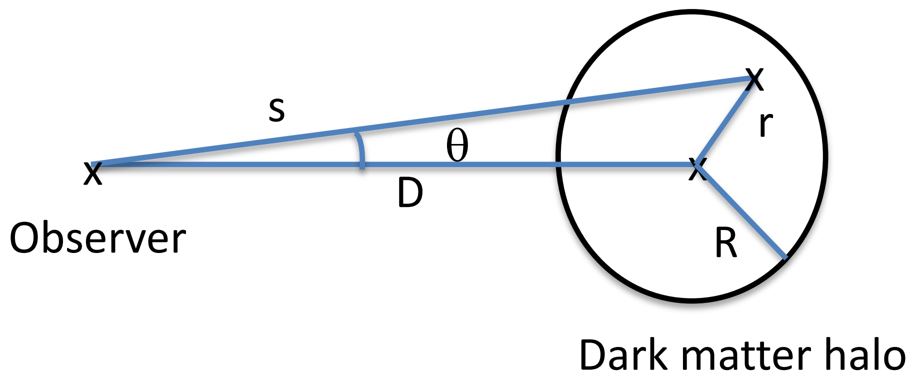
Astrophysics: J-factor
- DM distribution in the target

- For decaying DM, similar arguments give:

$$\frac{dN_{obs}}{dtdEdA} = \frac{1}{4\pi m_{DM}} \frac{1}{\tau} \frac{dN}{dE} \int \rho_{DM} dR d\Omega$$

J-factors

- The J-factor encodes all of the relevant astrophysical information.
- Consider the simple example of DM particles annihilating in a spherical dwarf galaxy of radius R, uniform density ρ_X, and located at a distance D:



- For D >> R, on can show that the J-factor is given by:

$$J(\Delta\Omega) = \int_{\Delta\Omega} \int_{LOS} \rho^2(r(s,\theta))ds d\Omega \simeq \frac{4\pi R^3 \rho_X^2}{3D^2}$$

A quick estimate with a J-factor

- Typical J-factors:
  - dwarf satellite galaxies of Milky Way: $10^{17\text{-}20}$ GeV^2/cm^5
  - Galactic center region (within 1 degree): 10^{22} GeV^2/cm^5

This assumes a Navarro Frenk and White profile for the DM distribution:

$$\rho_{NFW} = \frac{\rho_s}{r/r_s(1+(r/r_s)^2)}$$

- A thermal relic cross section, a 1 TeV DM, ~1 photon produced per annihilation in energy bin of interest
- A ground-based detector (with detection efficiency ~ 1, excellent background rejection) with an effective detection area of 10^5 m^2 would receive about 1 photon per minute. Note however that the background rate is much higher.

J-factors at cosmological distances (I)

- If photons come to us over cosmological distances, the redshifting needs to be taken into account.
- The source spectrum has to be evaluated at $E_z = E_0(1+z)$.
- Write integral in terms of redshift z rather than distance.

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- Write integral in terms of redshift z rather than distance.

For a simple example, let us consider the isotropic signal from annihilation of DM in the intergalactic medium, with density equal to the overall cosmological DM density.

$\longrightarrow$ we must integrate over photons (or neutrinos) originating from all possible redshifts

J-factors at cosmological distances (II)

- We are interested in the photon density and spectrum in a present-day volume dV_0, arising from annihilation at all earlier times:

$$\frac{dN}{dE_0 dV_0} = \int dz \frac{dt}{dz} \frac{dN(z)}{dE} \langle \sigma v \rangle \frac{\rho^2(z)}{2 m_{DM}^2} \frac{dV_z}{dV_0}$$

  - dV_z is the physical volume at redshift z
  - scale factor a ∝ (1+z), so $dV_z/dV_0 = 1/(1+z)^3$
  - dln(1+z)/dt = - dln a/dt = -H(z), so dt/dz = -1/(H(z)(1+z))

$$\frac{dN}{dE_0 dV_0} = \int dz \frac{1}{H(z)(1+z)^3} \frac{dN(z)}{dE_z} \langle \sigma v \rangle \frac{\rho^2(z)}{2 m_{DM}^2}$$

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- Integrating over the volume in spherical polar coordinates ($dV = R^2 dR d\Omega$), the observed spectrum observed in a detector area of dA is

$$\frac{dN_{obs}}{dE_0 dA} = \int dz \frac{1}{H(z)(1+z)^3} \frac{dN(z)}{dE_z} \langle \sigma v \rangle \frac{\rho^2(z)}{2m_{DM}^2} \frac{dR d\Omega}{4\pi}$$

J-factors at cosmological distances (III)

- For particles travelling at the speed of light dR = c dt, and integrating over the volume:

$$\frac{dN_{obs}}{dE_0 dAdt} = \int d\Omega \frac{c}{4\pi} \int dz \frac{1}{H(z)(1+z)^3} \left.\frac{dN}{dE_z}\right|_{E_z=E_0(1+z)} \langle\sigma v\rangle \frac{\rho^2(z,\theta,\phi)}{2m_{DM}^2}$$

- To include absorption, insert a factor of the form $e^{-\tau(E,z)}$ inside the integral, where the function $\tau(E,z)$ describes the optical depth for a photon emitted at redshift z and with (measured at z = 0) energy E_0.

Astrophysical J-factor

$$J(\Delta\Omega) = \int_{\Delta\Omega} \int_{\mathrm{los}} \rho^2(r(s,\theta))\mathrm{d}s\mathrm{d}\Omega.$$

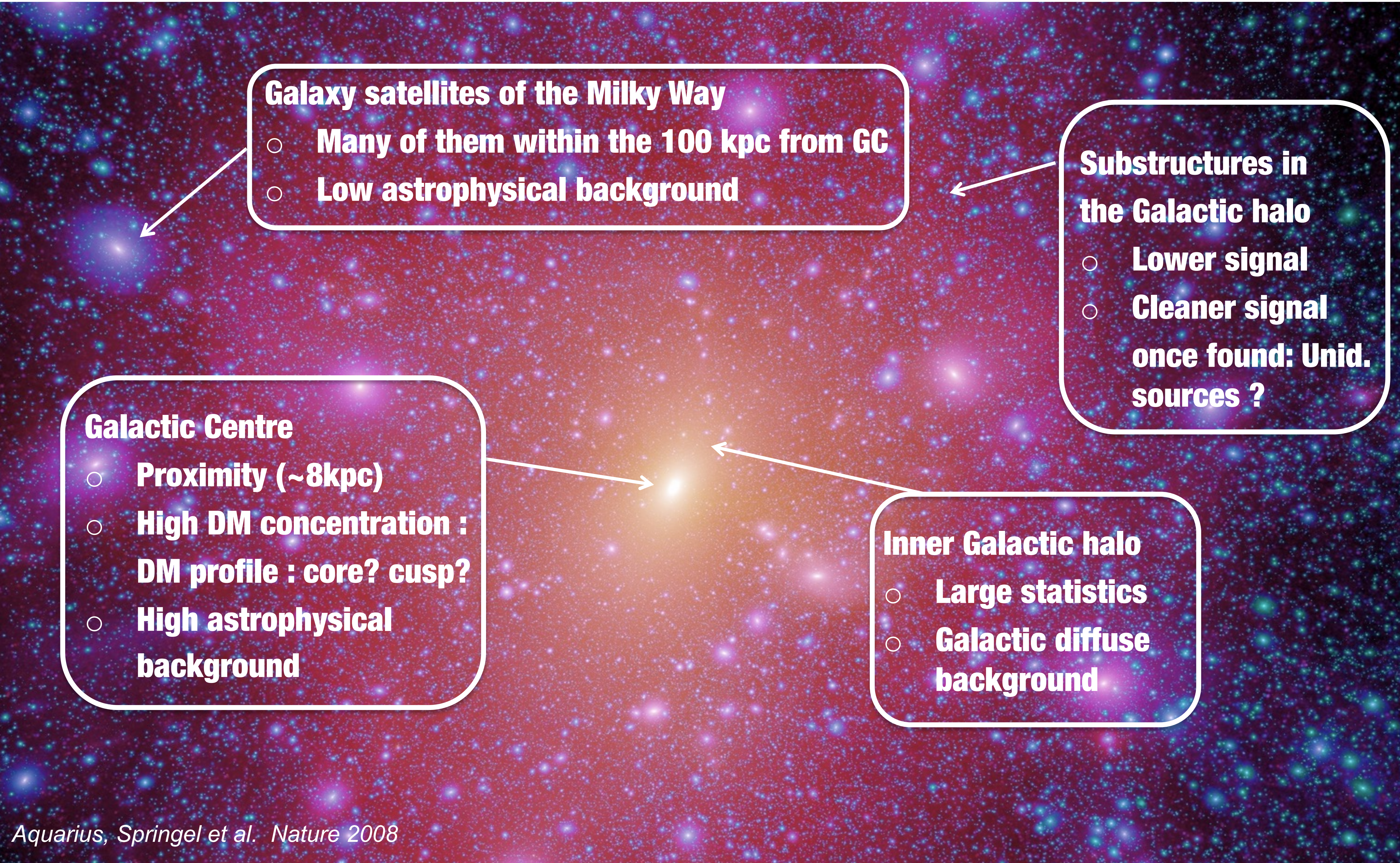
Annihilation depends quadratically on DM density, i.e., depends on poorly known **clumpiness** of DM

$$\langle \rho^2 \rangle \geq \langle \rho \rangle^2$$

- **Determination from**
  - N-boby simulations (non-linear regime)
  - mass modelling

- **Where to look?**

Targets at galactic scales

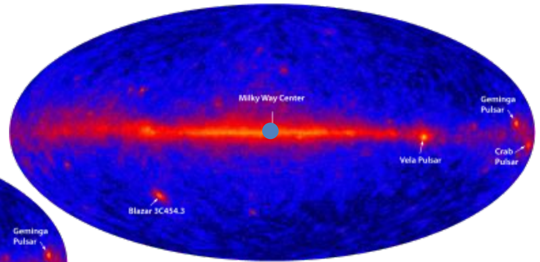


Aquarius, Springel et al. Nature 2008

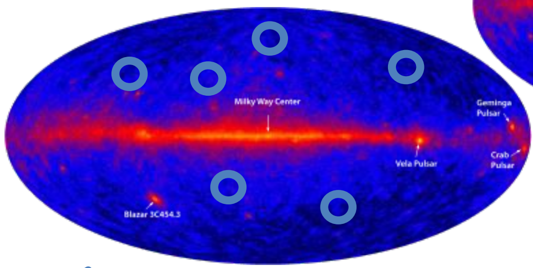
Observational targets and challenges

Likelihood of Strong signal

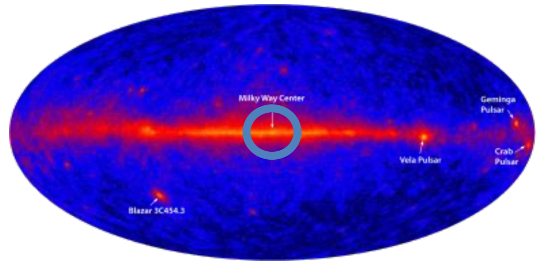
Galactic Centre



Galaxy clusters



Galactic Center halo

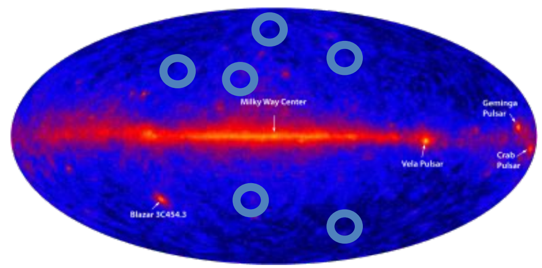


Large

Uncertainties

Robust Constraints

Dwarf Galaxies

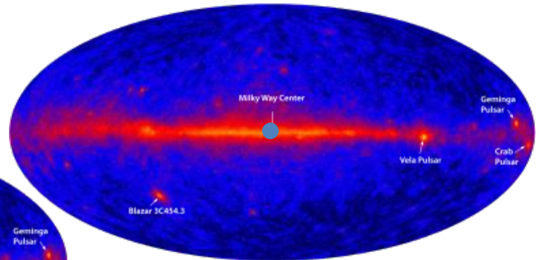


Maximize the quantity of DM signal (close distance and large DM density) wrt background (astrophysical sources)

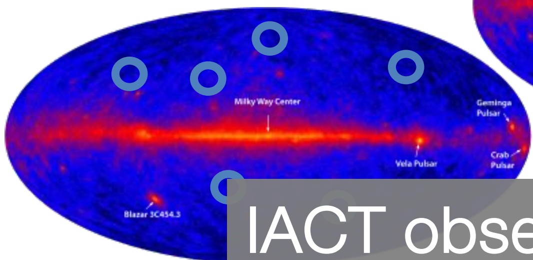
Targets and challenges

Likelihood of Strong signal

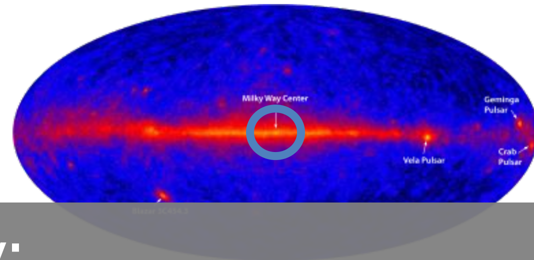
Galactic Centre



Galaxy clusters



Galactic Center halo



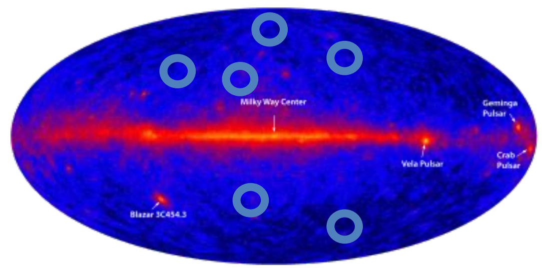
IACT observational strategy:

- Deep observations of the Galactic Center region
- Observations of the most promising dwarf galaxies

Large Uncertainties

Robust Constraints

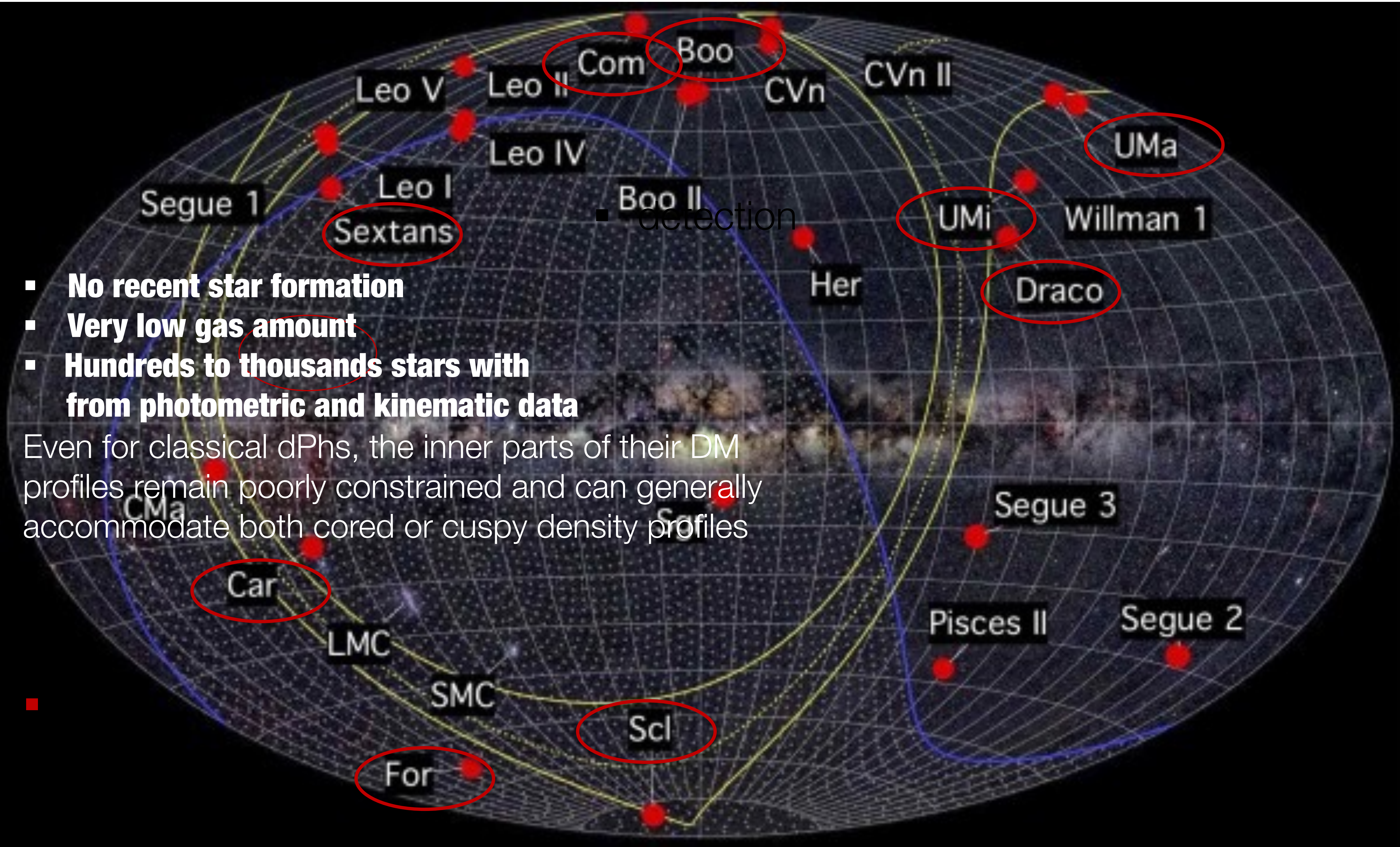
Dwarf Galaxies



Maximize the quantity of DM signal (close distance and large DM density) wrt background (astrophysical sources)

See the CTA Dark matter programme EM et al., in Science with the Cherenkov Telescope Array, World Scientific, 2019

Classical dwarf spheroidal galaxies

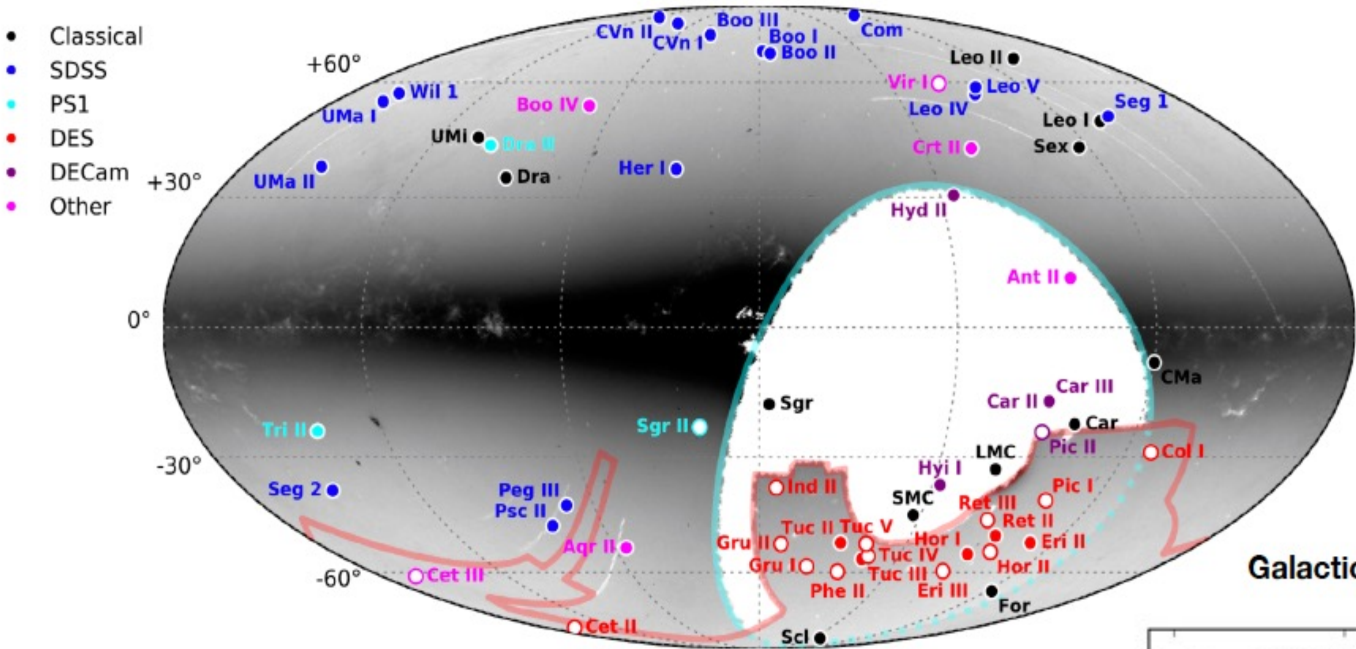


- detection

- No recent star formation
- Very low gas amount
- Hundreds to thousands stars with from photometric and kinematic data

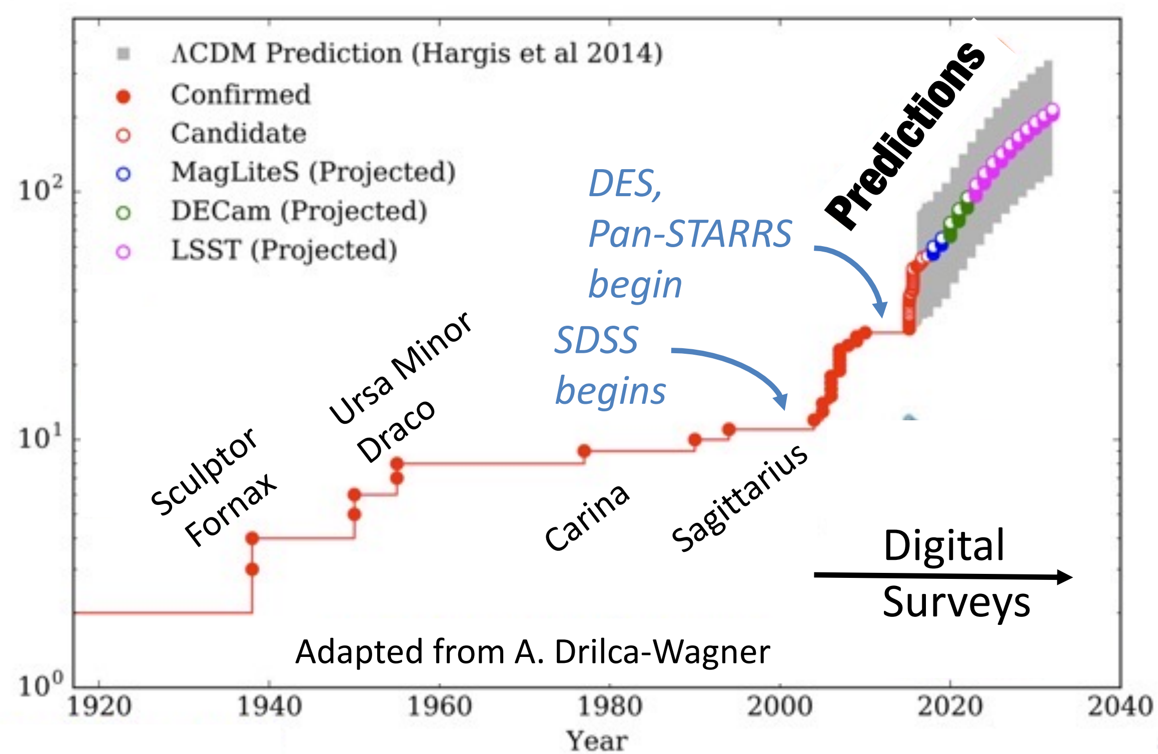
Even for classical dPhs, the inner parts of their DM profiles remain poorly constrained and can generally accommodate both cored or cuspy density profiles

A growing number of known targets



- **Census of Milky Way satellites including all dwarf galaxies spectroscopically confirmed as well as suspected ones**

- More to be discovered in the future thanks to improvements in telescope technologies and performances, e.g., the ''Vera C. Rubin'' Observatory



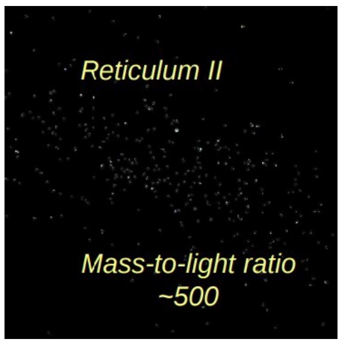
Dark Matter profiles in dSphs

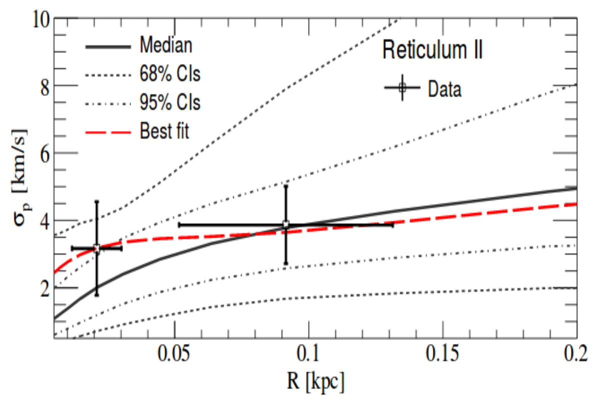
- **Modelling of the DM distribution**
  - Pressure-supported systems
  - Stars of kinematic tracers of the gravitational potential

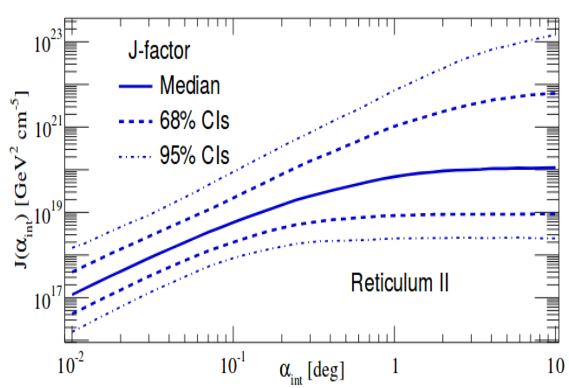
Jeans equation assuming equilibrium, non-rotating (and spherical) system

- Even for classical dPhs, the inner parts of their DM profiles remain poorly constrained and can generally accommodate both cored or cuspy density profiles

- The example for the ultra-faint dwarf spheroidal galaxy Reticulum II:



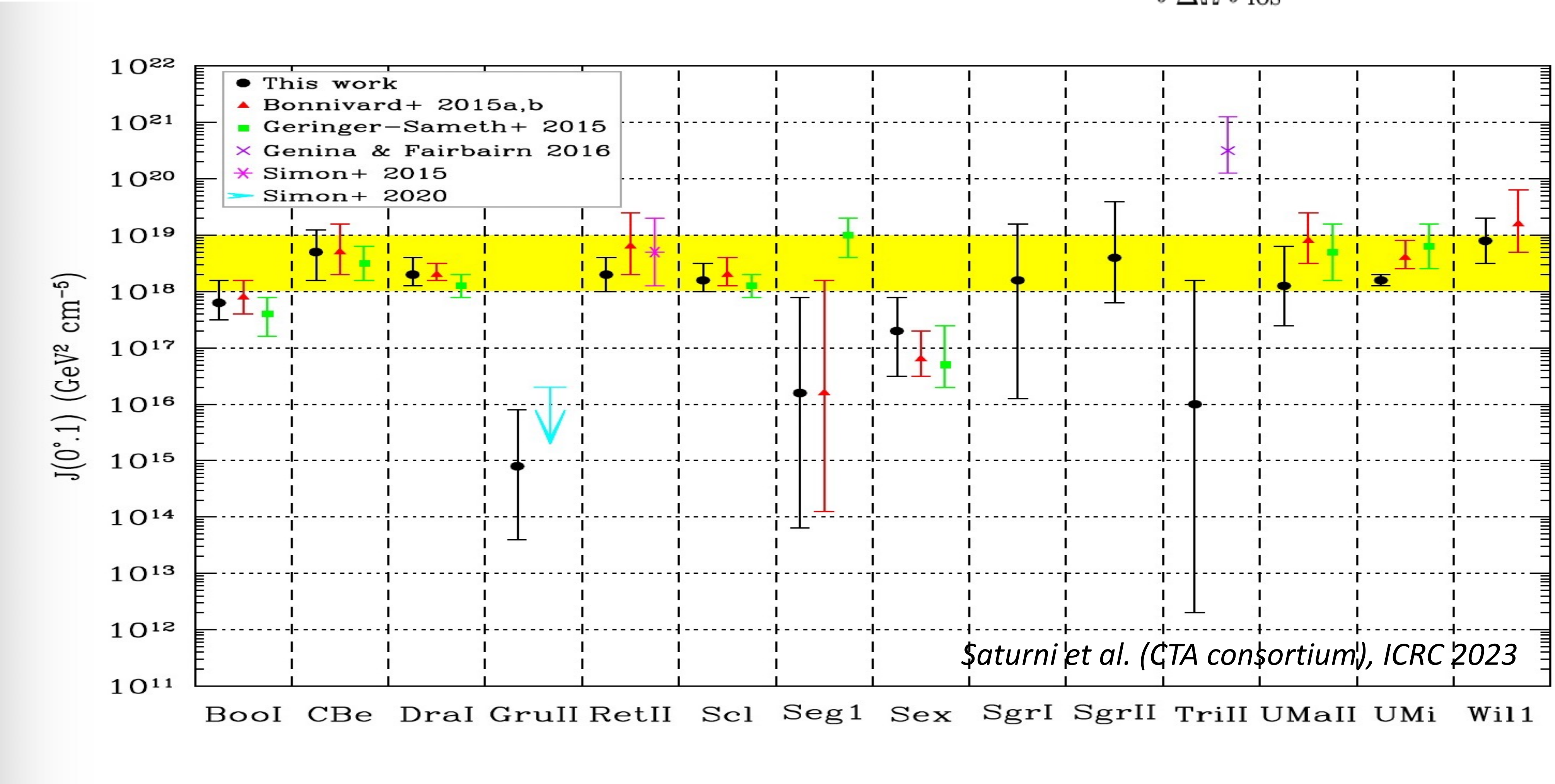




<u>Disclaimer</u> : Impact of triaxiality on halos, stellar membership probability, binary stars, tidal disruption, …

Comparison of J-factors

$$J(\Delta\Omega) = \int_{\Delta\Omega}\int_{\rm los} \rho^2(r(s,\theta))\,{\rm d}s\,{\rm d}\Omega.$$

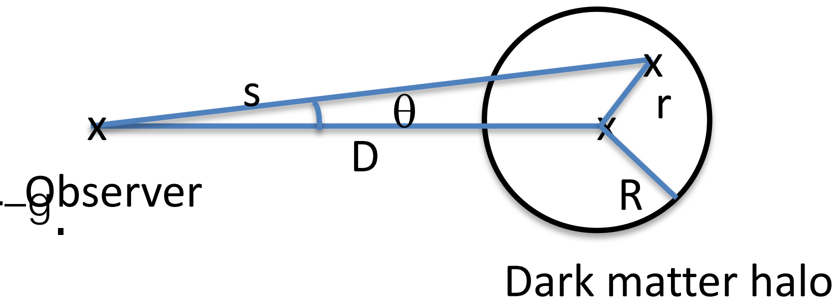


Saturni et al. (CTA consortium), ICRC 2023

- **Expected spread due to assumptions and/or choices on kinematic datasets, light and DM profiles, velocity anisotropy, stellar membership probability, triaxiality of the halo, …**

J-factor estimates for dSphs

- Small-angle approximation q<<1(D<<R)



- Let's consider the density to follow $\rho(r) = \rho_0 r^{-g}$.
  - with $r = \sqrt{s^2 + D^2 - 2Ds\cos\theta}$ and $x = s/D$

the J-factor writes $J(\theta) = \frac{\rho_0^2}{D^{2\gamma-1}} \int_0^{\infty} \frac{dx}{(1 + x^2 - 2\,x\,\cos\theta)^{\gamma}}$

  - For $1/2 < \gamma < 3/2$, one can show that :

$$J(\Delta\Omega) \simeq 2\pi^2 \frac{\rho_0^2}{D^{2\gamma-1}} \frac{\Gamma(\gamma - 1/2)}{\Gamma(\gamma)\Gamma(1/2)} \frac{\theta^{3-2\gamma}}{3 - 2\gamma}$$

J-factor estimates for dSphs

- J-factors in dSphs are usullay derived via the Jeans modeling which describes dSphs as an uncompressible system at equilibrium (Binney&Tremaine 2008)
- Assuming spherical symmetry, the Jeans equation writes

$$\frac{1}{\nu(r)}\frac{d}{dr}\left(\nu(r)\sigma_r(r)\right) + 2\frac{\beta(r)\sigma_r(r)}{r} = -\frac{GM(r)}{r^2}$$

$\nu(r)$, $\sigma_r(r)$, and $\beta(r) = 1 - \sigma_t(r)/\sigma_r(r)$ describe the 3-dimensional density, radial velocity dispersion, and orbital anisotropy, respectively, of the stellar component.

- Adopting the Plummer profile for stellar density $\nu(r) \propto \left(1 + (r/r_h)^2\right)^{-5/2}$, with r_h is the half-light radius, isotropic velocity dispersion ($\beta = 0$) and a constant velocity dispersion s

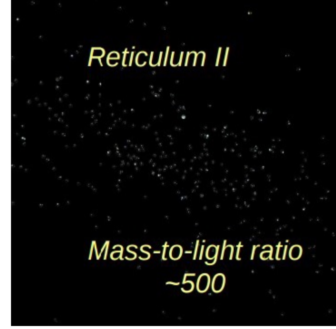
$$M(r) = 5\frac{\sigma^2 r_h}{G}\left(\frac{r}{r_h}\right)^3\left(\frac{1}{1 + r^2/r_h^2}\right)$$

and

$$M(r_\mathrm{h}) = \frac{5}{2}\frac{\sigma_\mathrm{los}^2 r_\mathrm{h}}{G}$$

with $\sigma = \sigma_{los}$

J-factor estimates for dSphs



- For the DM density $\rho = \rho_0 r^{-\gamma}$, one gets $M(r) = M(r_h)(r/r_h)^{3-\gamma}$, therefore, the DM density expresses as

$$\rho(r) = \frac{5}{8\pi} \frac{\sigma_{\rm los}^2 (3-\gamma)}{G r_{\rm h}^{2-\gamma}} r^{-\gamma}$$

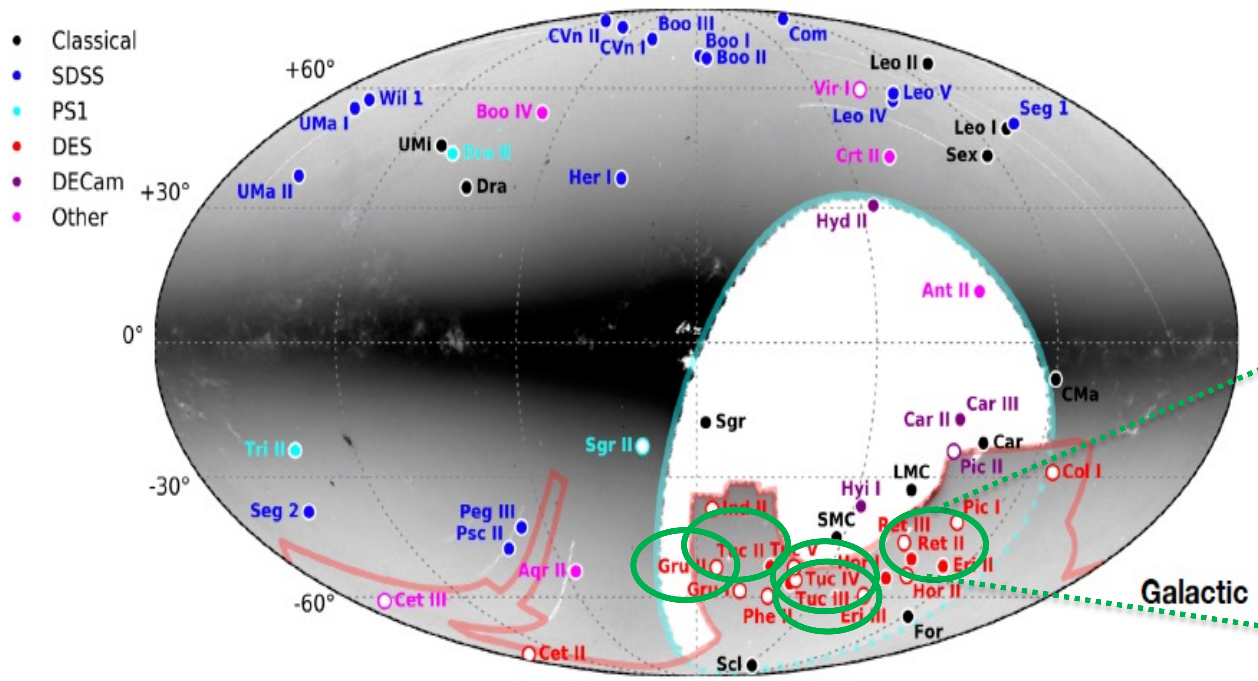
- Using the result derived in the small angle approximation, one gets:

$$J(\Delta\Omega) \simeq \frac{25}{64} \frac{\sigma_{\rm los}^4}{G^2} \frac{1}{D^2 R_{\rm h}} \left(\frac{D\theta}{R_{\rm h}}\right)^{3-2\gamma} \frac{(3-\gamma)^2}{3-2\gamma} \frac{2\Gamma(\gamma - 1/2)}{\Gamma(\gamma)\Gamma(1/2)}$$

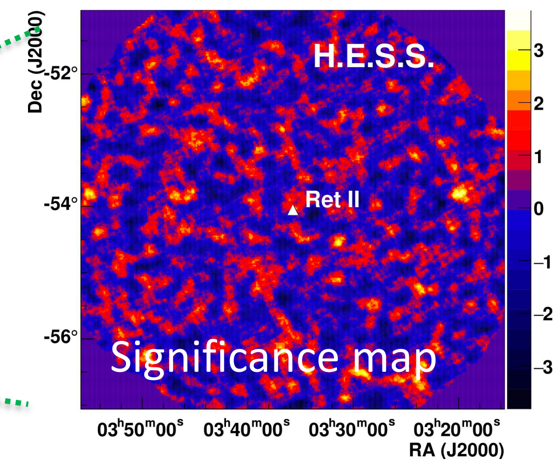
- For Reticulum II ultra-faint dSph with D = 32 kpc, R_h = 15 pc and an averaged velocity dispersion σ_{los} = 5 km s^{-1}, an integration angle of 0.5°, and γ = 1, one can show that :

$$\log_{10}(J/\mathrm{GeV^2 cm^{-5}})(< 0.5^\circ) = 18.7$$

Ultra-faint dSph obervations with H.E.S.S.

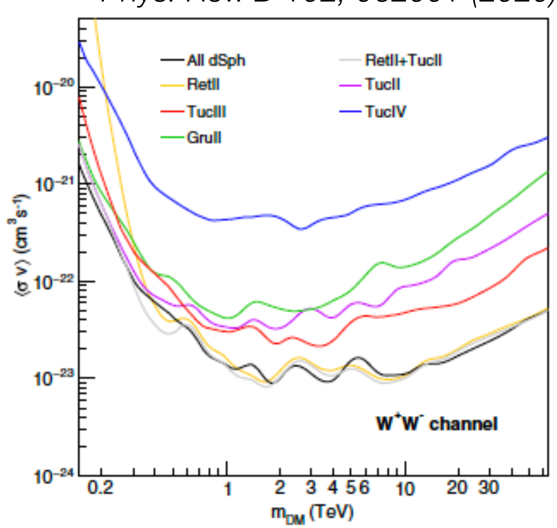


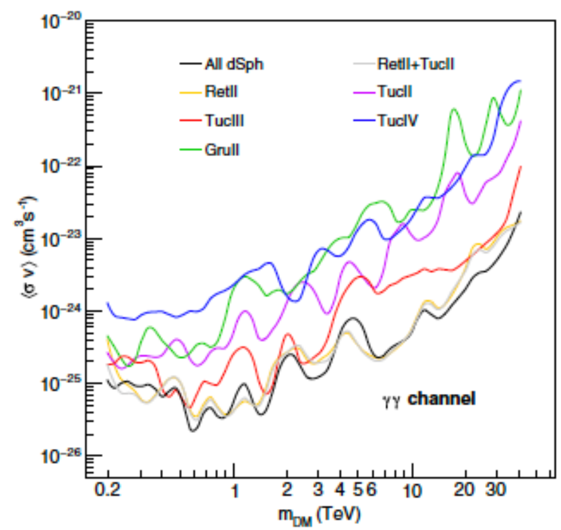
Dark Energy Survey (DES) dwarf galaxy satellites selected and observed by H.E.S.S. (~80 hours)



- Combined limits from H.E.S.S. observations of Ret II, Tuc II, Tuc III, Tuc IV, and Grus II
- No significant signal, neither in incividual nor combined datasets → upper limits

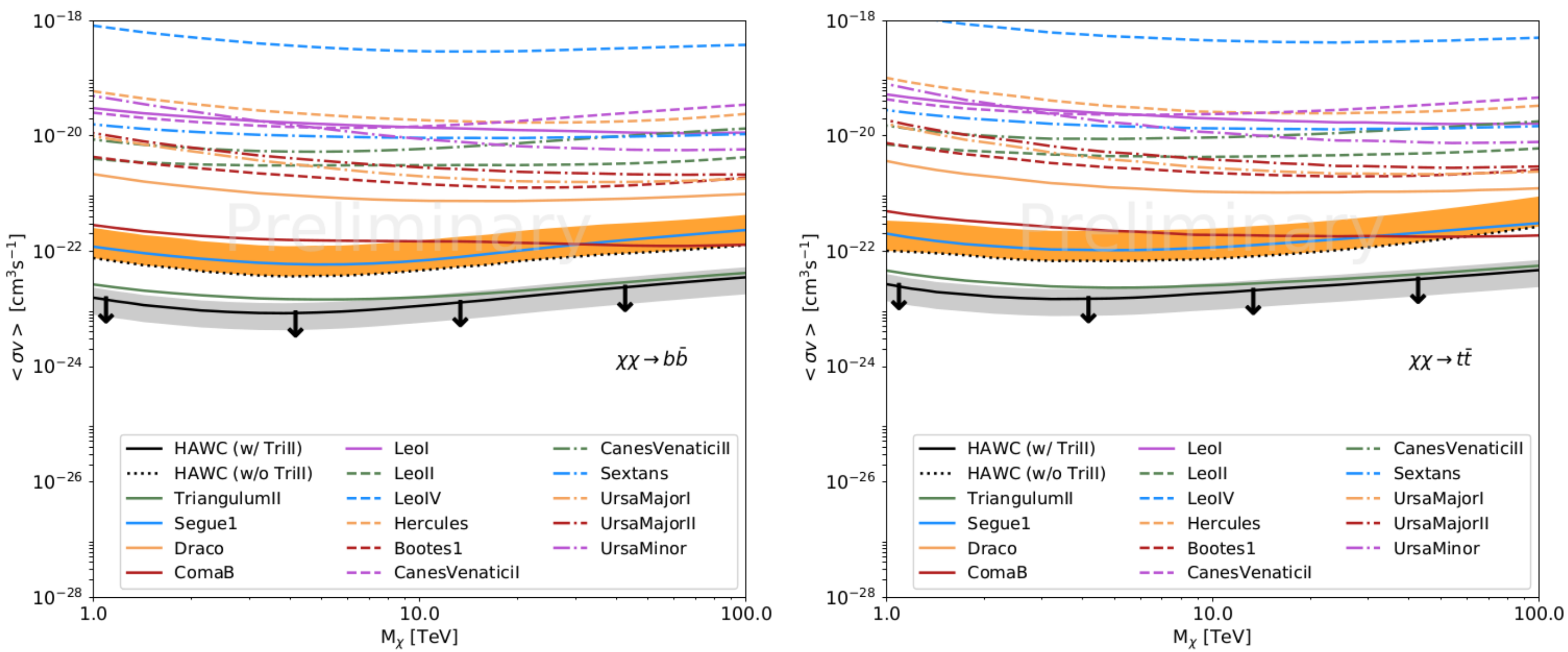
H.E.S.S. Collaboration (Rinchuiso, EM, Armand, Poireau), Phys. Rev. D 102, 062001 (2020)





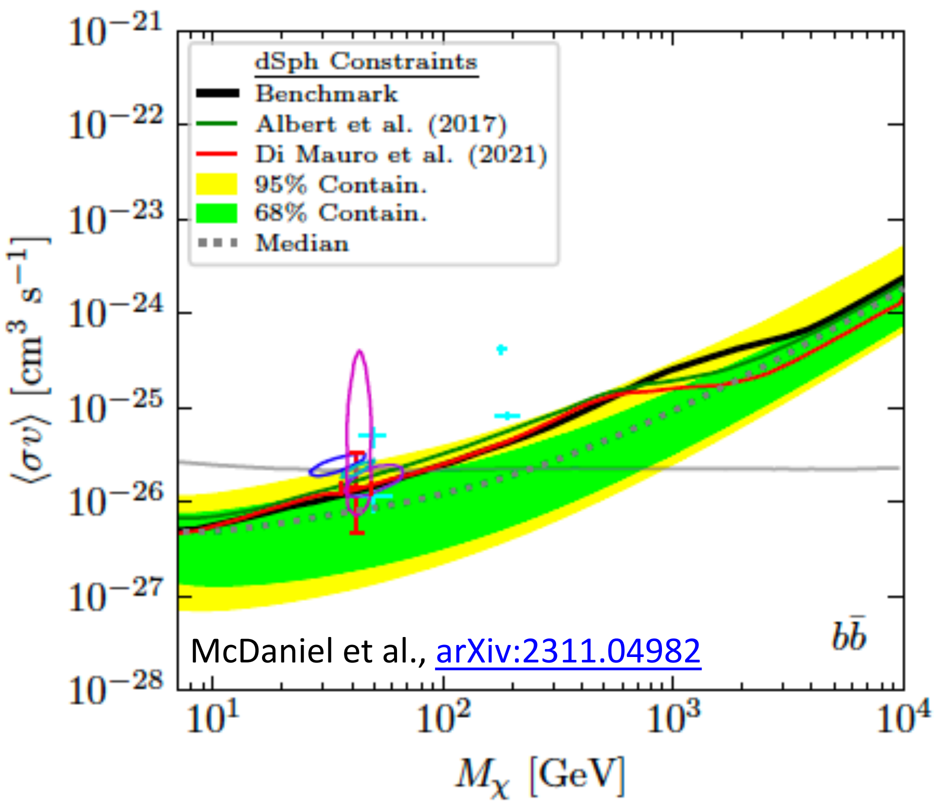
HAWC searches towards dSphs

- Combination of 15 dSph in a joint likelihood analysis, 507 days of observations
- DM mass range 1-100 TeV
- The dataset includes galaxies with large uncertainty on the J-factor
- Systematic uncertainties on observed flux are included in the bands



Constraints from dwarf galaxies

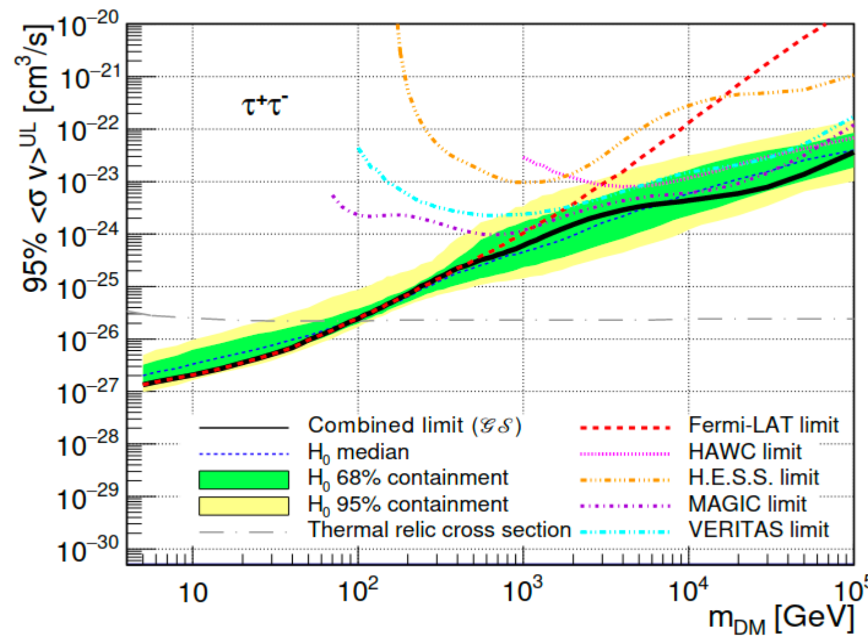
- **Fermi-LAT contraints 14-year dataset**



- Thermal-relic annihilation cross section probed for masses up to 100 GeV

- **Joint effort to combine observations**

- This analysis framework allows us to perform multi-instrument and multi-target analysis
- Common elements :
  - Agreed model parameters
  - Sharable likelihood table formats
  - Joint likelihood test statistic

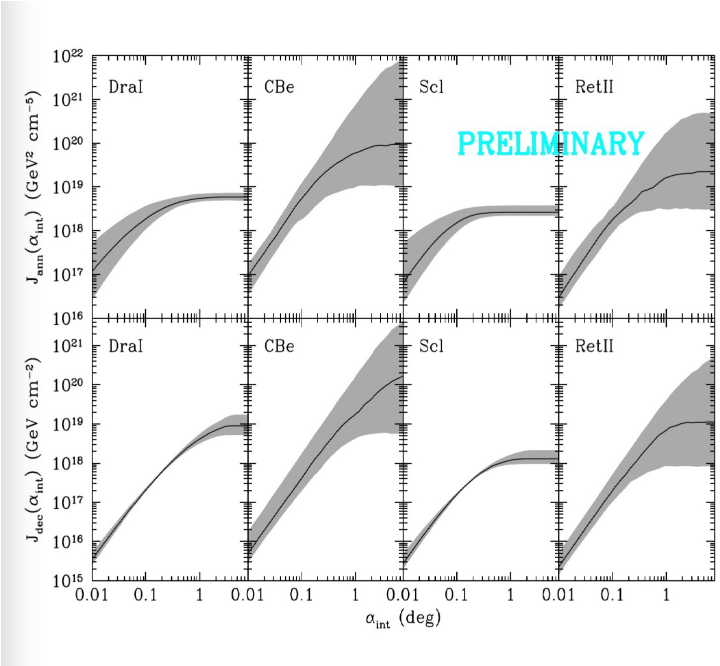


Kerszberg et al. ICRC 2023

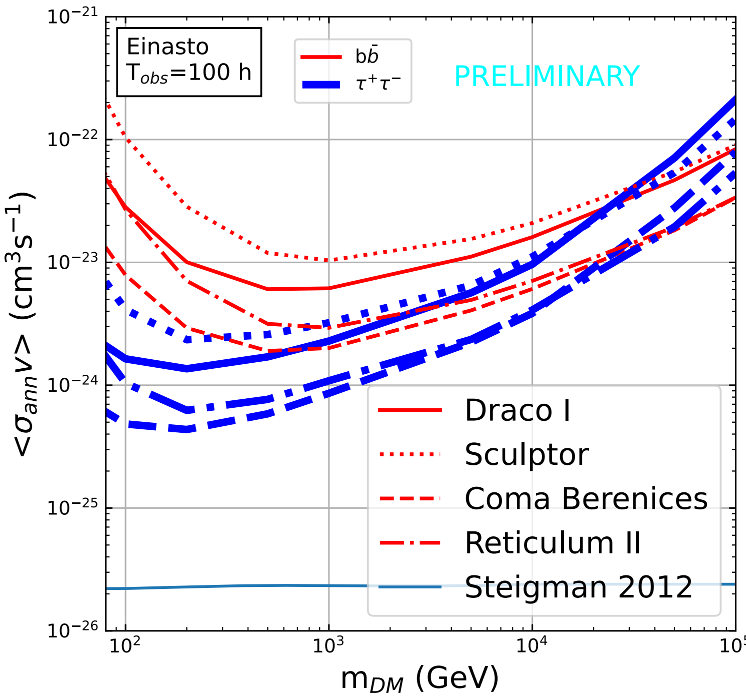
Prospects with CTA

- **Selection of optimal targets**:
    1. distance (d < 100 pc);
    2. culmination zenith angle (ZA < 40°);
    3. availability of good spectro-photometric data
- **Surviving sample:**

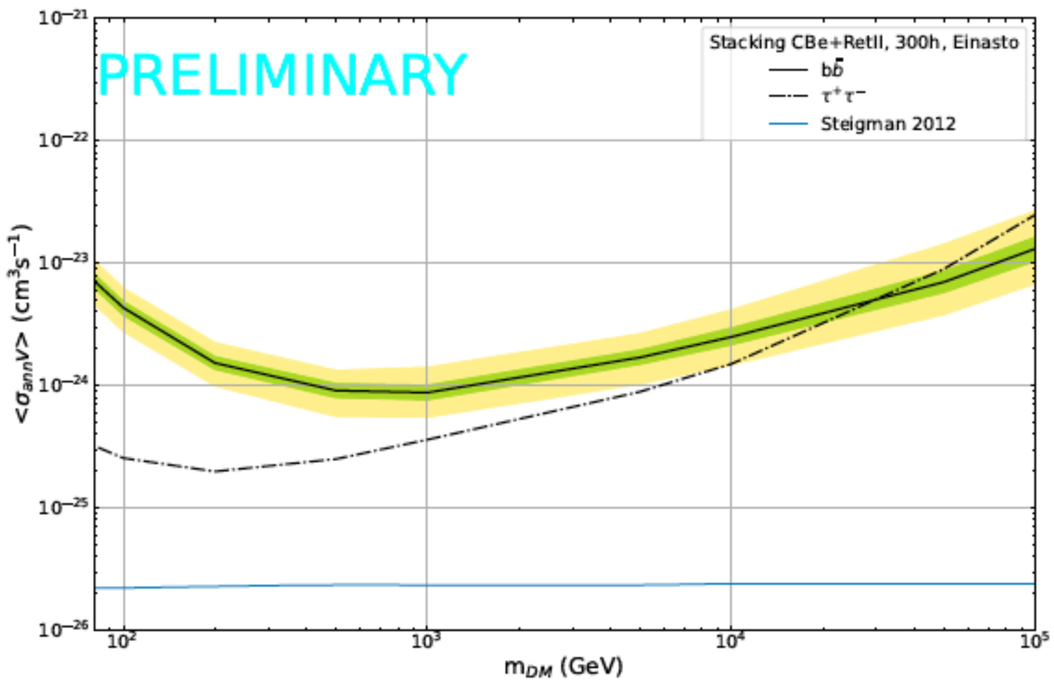
- 8 Northern dSphs: 2 classical + 6 ultra-faint
- 6 Southern dSphs : 3 classical + 3 ultra-faint



100-h observations for each dSph assumed



Saturni et al. (CTA consortium), ICRC2023



Dark matter substructures in Galactic halos

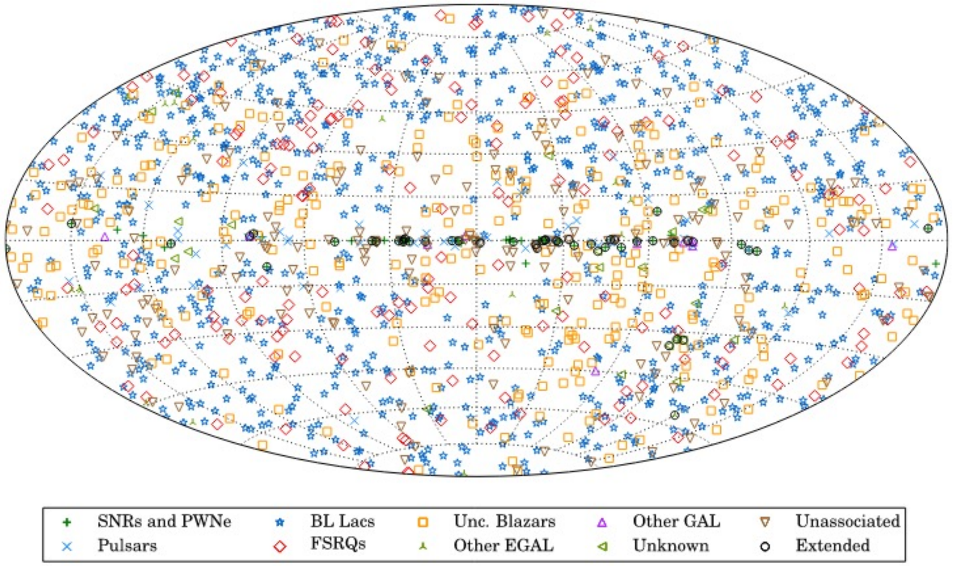
- **Dark Matter Subhalos**

1. **Assuming subhalos composed by WIMPs**
   → could shine in gamma-rays

2. **Fermi-LAT revealed a population of sources that lack association at other wavelenghts;**
   → these sources are classified as Unassociated
   → careful selection can tell us what the promosing DM subhalo candidates

- Lower signal than the GC region
- No other wavelengths counterpart
- No astrophyiscal background

Location : selection through the catalog of (Hard) Fermi-LAT sources ?



Ajello et al., Astrophys. J. Suppl. 2017, 232, 18

200 unassociated over
1556 sources in the Fermi-LAT catalogue

Dark matter substructures in the MW halo

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   ⟶ could shine in gamma-rays

2. **Fermi-LAT revealed a population of sources that lack association at other wavelenghts;**
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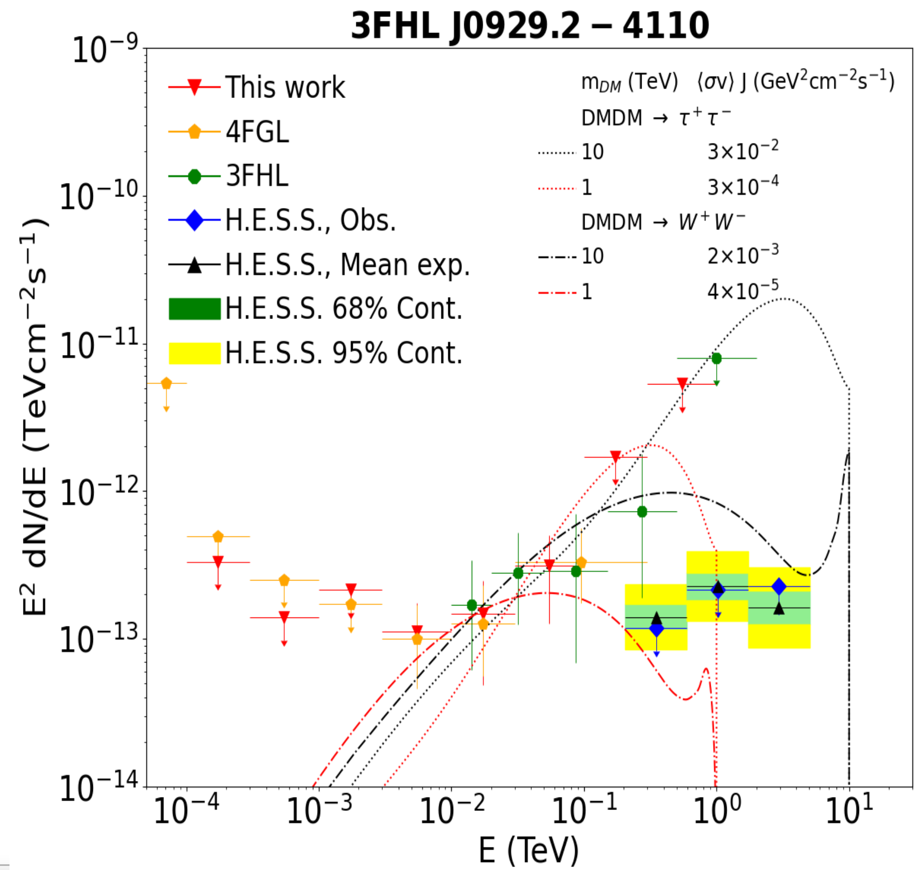
   ⟶ careful selection can tell us what the promosing DM subhalo candidates

- **Selection of the unassociated sources in the Third catalog of Hard Fermi-LAT sources (3FHL) to obtain the most promising UFOs for H.E.S.S. observations**



H.E.S.S. Coll. (Montanari, Malyshev, EM) Astrophys.J., 918, 17 (2021)

Dark matter substructures in Galactic halos ?

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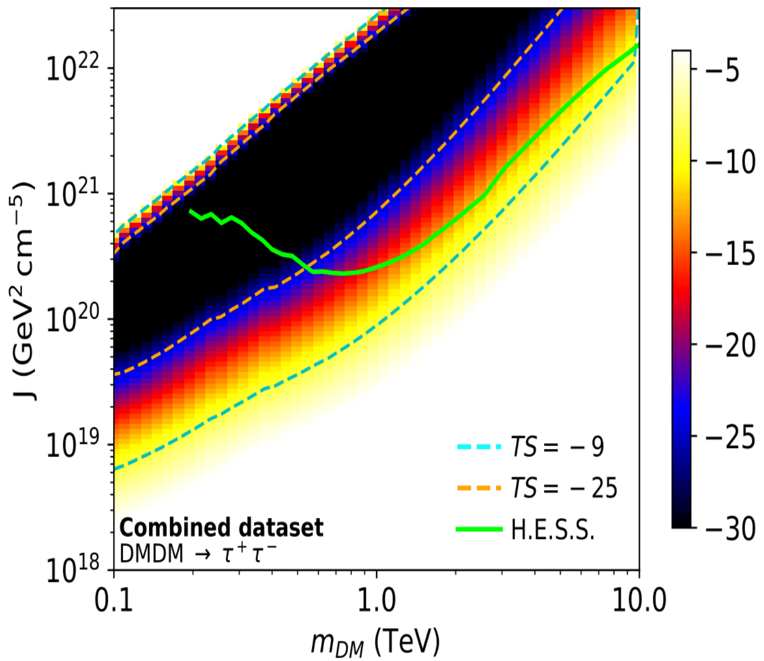
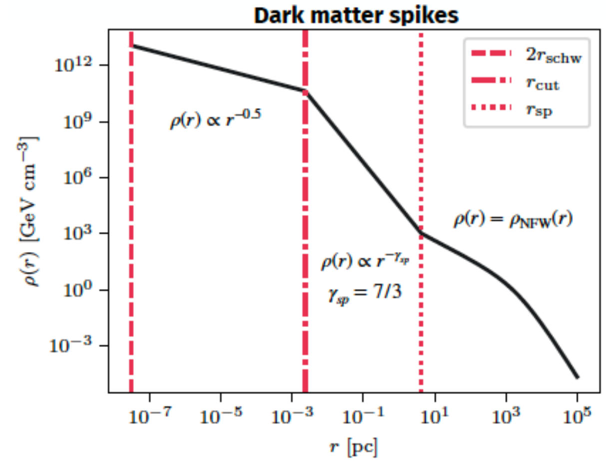


H.E.S.S. Coll. (Montanari, Malyshev, EM) Astrophys.J., 918, 17 (2021)

Assuming thermally-produced WIMPs: → UFOs very unlikely DM subhalos

Intermediate-mass black holes in the Milky Way halo

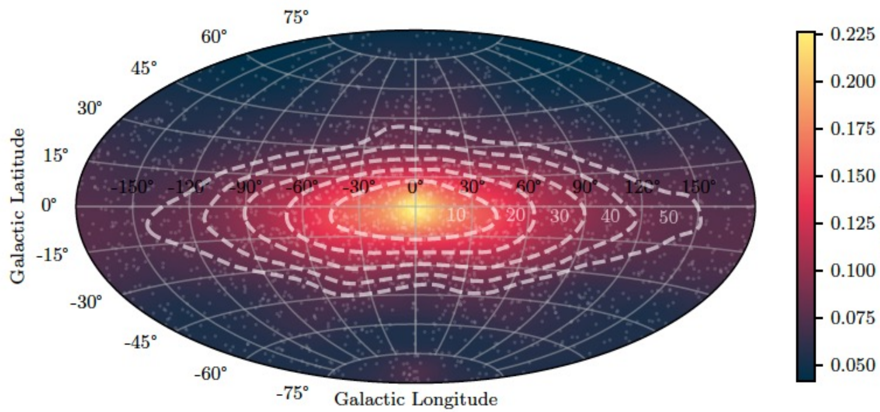
- IMBHs (10^2 - 10^6 $M_\odot$) are expected to be surrounded by high dark matter densities, so-called dark matter spikes (Gondolo&Silk 1991)
  → significant enhancement of the gamma-ray signal
  Zhao&Silk (2005), Bertone, Zentner, Silk (2005)
  → strong constraints from early H.E.S.S. searches in the Galactic plane survey H.E.S.S. coll. (EM,Bertone), PRD 78, 072008 (2008)



- IMBH would manifest as unidentified bright pointlike sources

- From the denstity profile, one can show that the gamma-ray flux expresses as

$$\Phi(E,D) = \frac{1}{2}\frac{\langle\sigma v\rangle}{m_\chi^2}\frac{1}{D^2}\frac{dN}{dE}\int_{2r_{schw}}^{r_{sp}} \rho^2(r) r^2 dr$$
$$\approx \frac{dN}{dE}\frac{\langle\sigma v\rangle}{m_\chi^2 D^2}\rho(r_{sp})^2 r_{sp}^3 \frac{2\gamma_{sp}-1}{8\gamma_{sp}-12}\left(\frac{r_{cut}}{r_{sp}}\right)^{3-2\gamma_{sp}}$$



Aschersleben, Bertone, Horns, EM, Pelleiter, Vecchi JCAP 09 (2024) 005

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  $\longrightarrow$ significant enhancement of the gamma-ray signal
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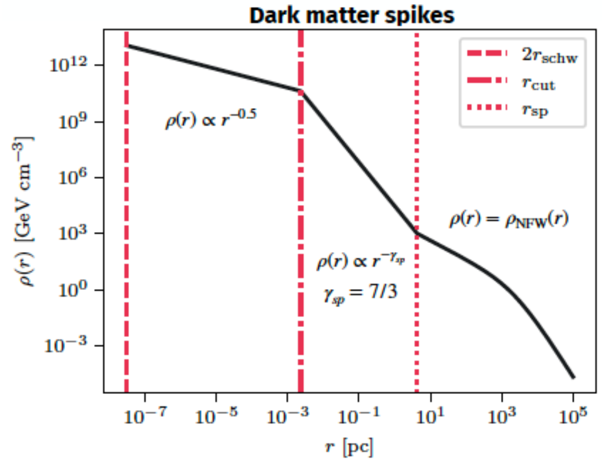
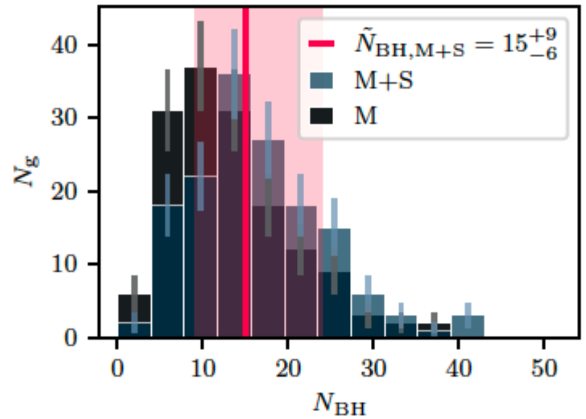


- IMBH would manifest as unidentified bright pointlike sources

- Advancements in cosmological simulations(e.g. EAGLE) provide today a more comprehensive and refined understanding of IMBHs populating MW-like galaxies

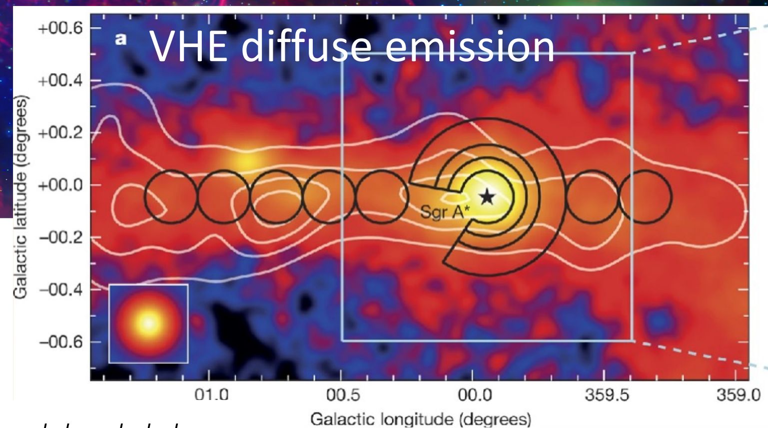
- IACT observations of the Inner Galaxy Survey, the Galactic Plane, Extragalactic Survey
  - $N_{BH,HESS} = 0.6^{+0.4}_{-0.3}$ within the fields of view
  - $N_{BH,CTA} = 1.1^{+0.8}_{-0.6}$ in the Galactic plane survey

MW-like galaxy



Aschersleben, Bertone, Horns, EM, Pelleiter, Vecchi JCAP 09 (2024) 005

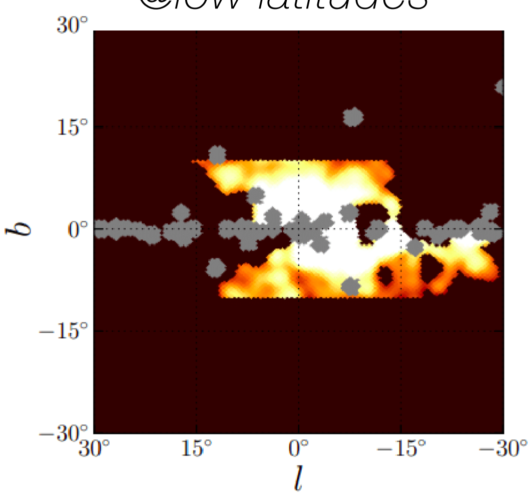
The Galactic Center



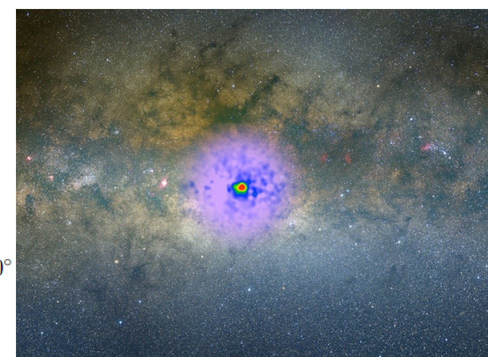
- A complex region at VHE: base of Fermi Bubbles, an hypothetical population of millisecond pulsars, … with extended structures beyond single fov and/or source confusion

- Expected to be the brightest sources of DM annihilations

Fermi bubbles.
@low latitudes

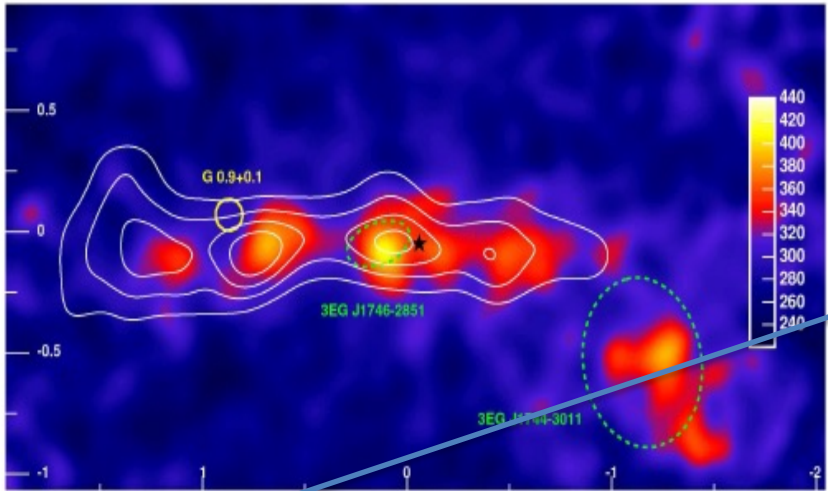


The Galactic Centre Excess seen by Fermi-LAT

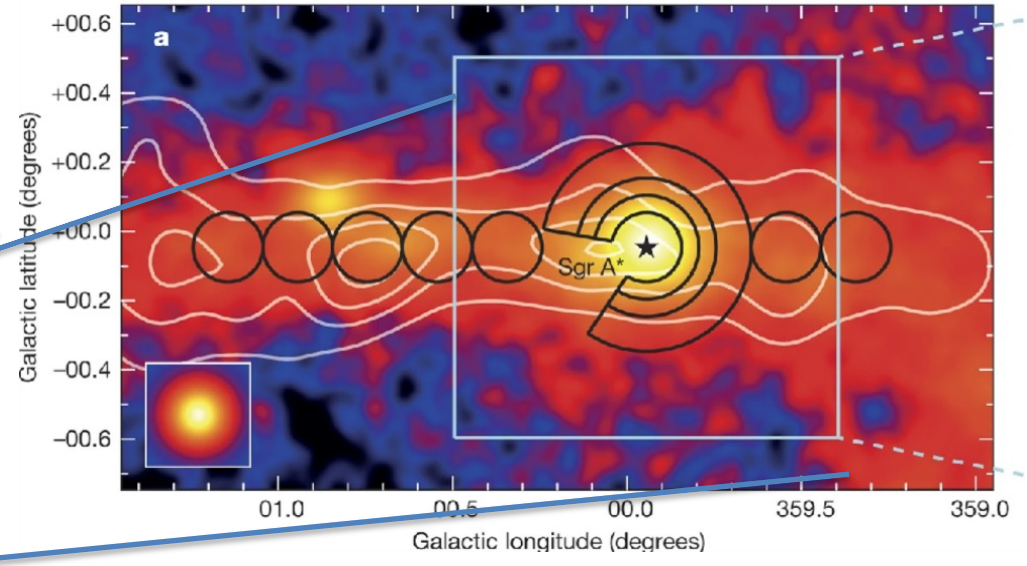


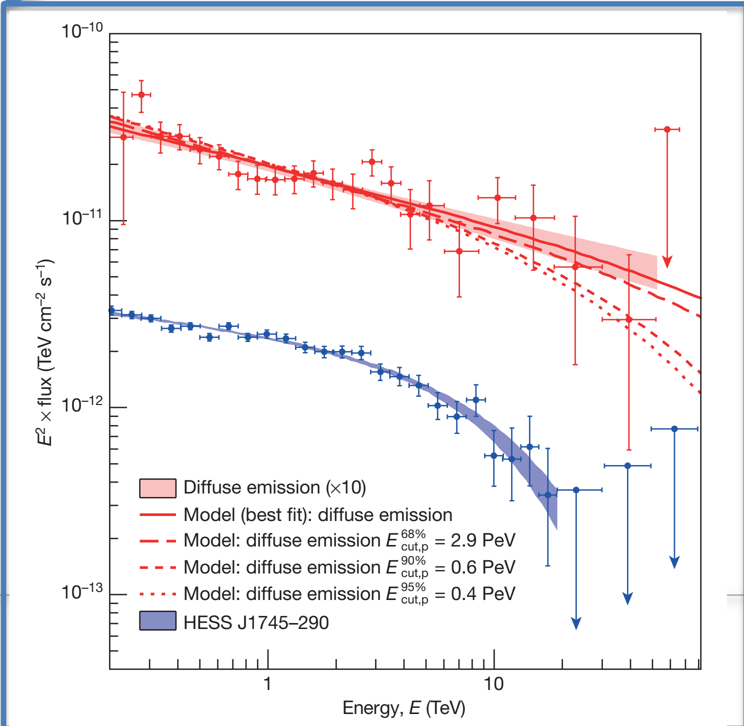
VHE gamma rays in the Galactic Centre

2006



2016…



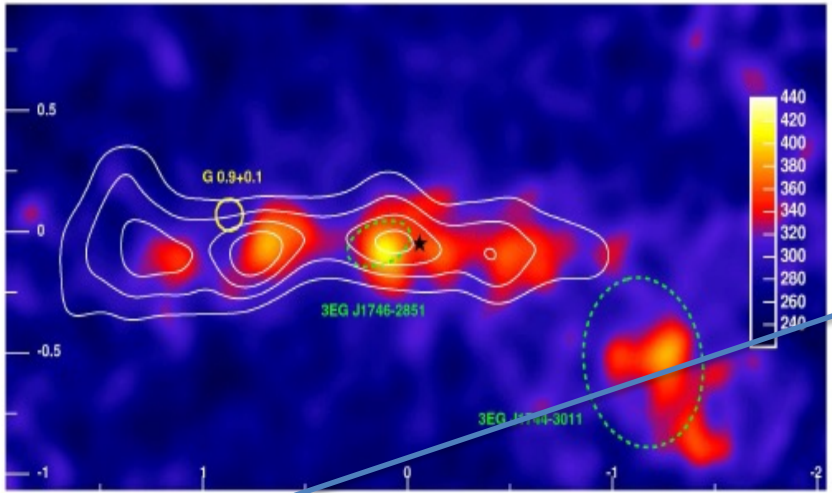


- Diffuse emission in the Galactic Centre
  - Gamma-ray spectrum measured up to 50 TeV: power law with index 2.3 with no energy cut-off
  - → parent proton spectrum should extend at least to PeV energies

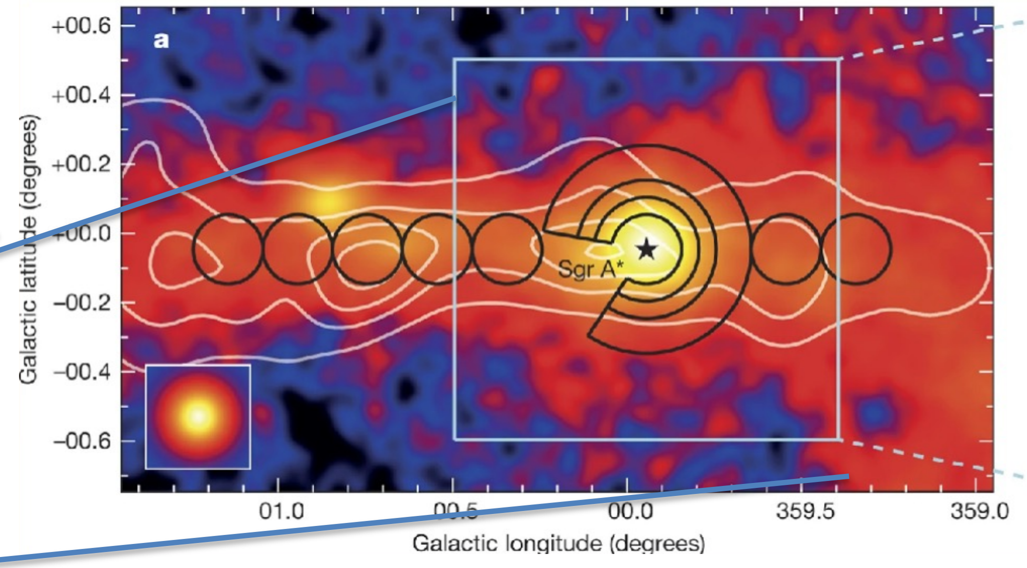
- **First Galactic Pevatron detected**
  H.E.S.S Coll (Aharonian, Gabici, EM, Viana), Nature 476, 531 (2016)

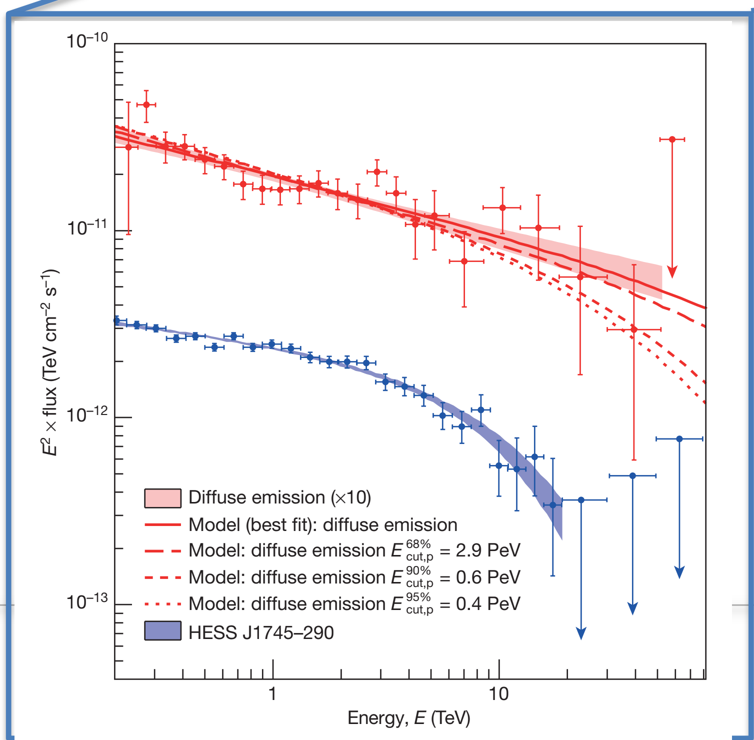
VHE gamma rays in the Galactic Centre

2006



2016…



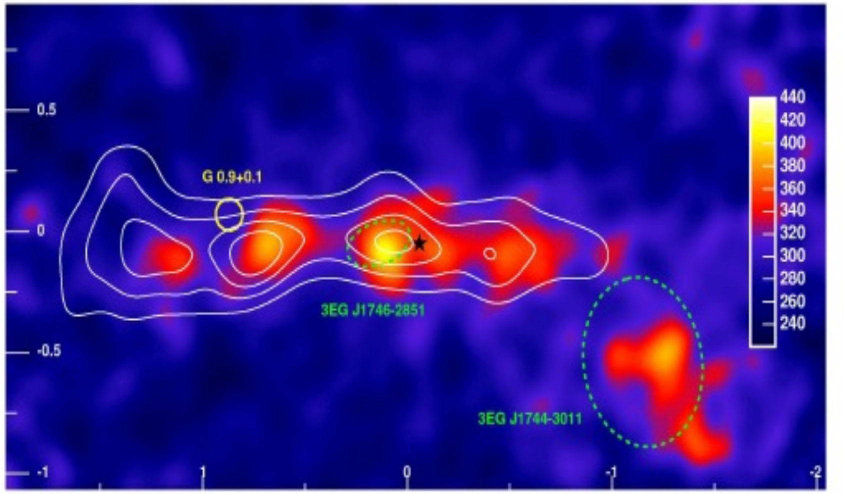


- Diffuse emission in the Galactic Centre
  - Gamma-ray spectrum measured up to 50 TeV: power law with index 2.3 with no energy cut-off

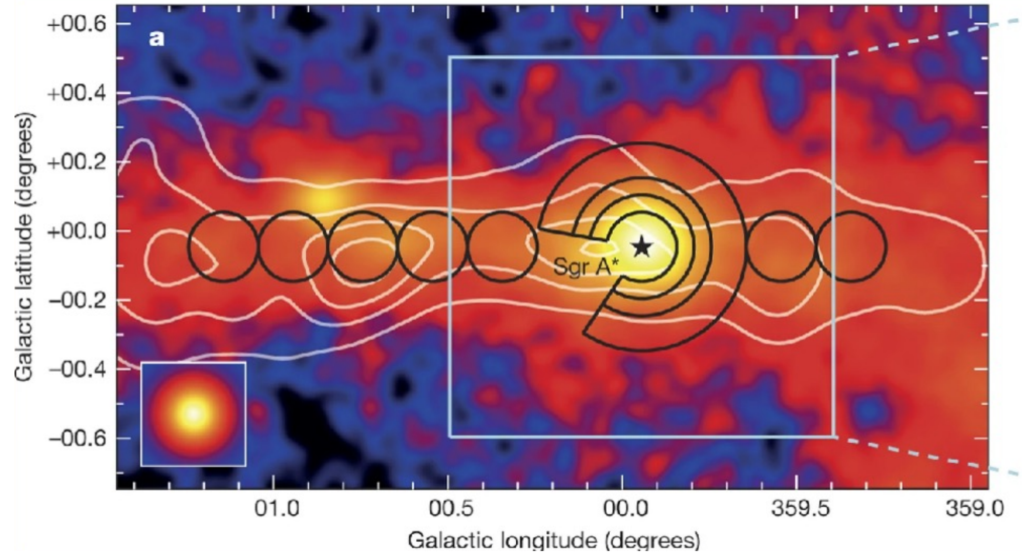
- **Alternative scenarios:**
  - *Connecting the new H.E.S.S. diffuse emission at the Galactic Center with the Fermi GeV excess: A combination of millisecond pulsars and heavy dark matter?* Lacroix, Silk, EM, Boehm, PRD 94 (2016) 12, 123008
  - *Pevatron at the Galactic Center: Multi-Wavelength Signatures from Millisecond Pulsars*, Guepin, Rinchiuso, Kotera, EM, Silk, JCAP 07 (2018) 042

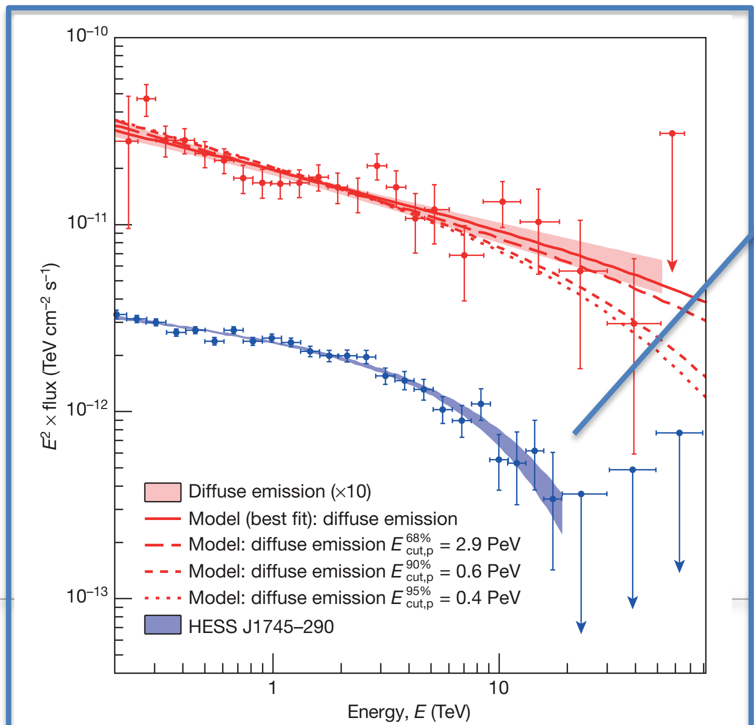
VHE gamma rays in the Galactic Centre

2006



2016…





The VHE GC source HESS 1745-290:

- **strong energy suppression at several TeV**

- Can be well described by (super-)exponential cut-off power-law parametrization
- No time variability so far
- Nature of the sources ? acceleration high energy protons in the vicinity of Sgr A*; a pulsar wind nebula G359.95-0.04 a spike of annihilating DM particles

Nature of the central source HESS J1745-290 ?

- How to go further with VHE gamma-rays

→ Morphology in the energy cut-off region

  - gamma-ray spectrum for the proton-induced emission: $\Phi_{\rm EPL}(E) = A_s E^{-\Gamma_s} e^{-E/E_c}$
  - DM-induced spectrum template: $\Phi_{\rm SEPL}(E) = A_s E^{-\Gamma_s} e^{-(E/E_c)^\beta}$

Nature of the central source HESS J1745-290 ?

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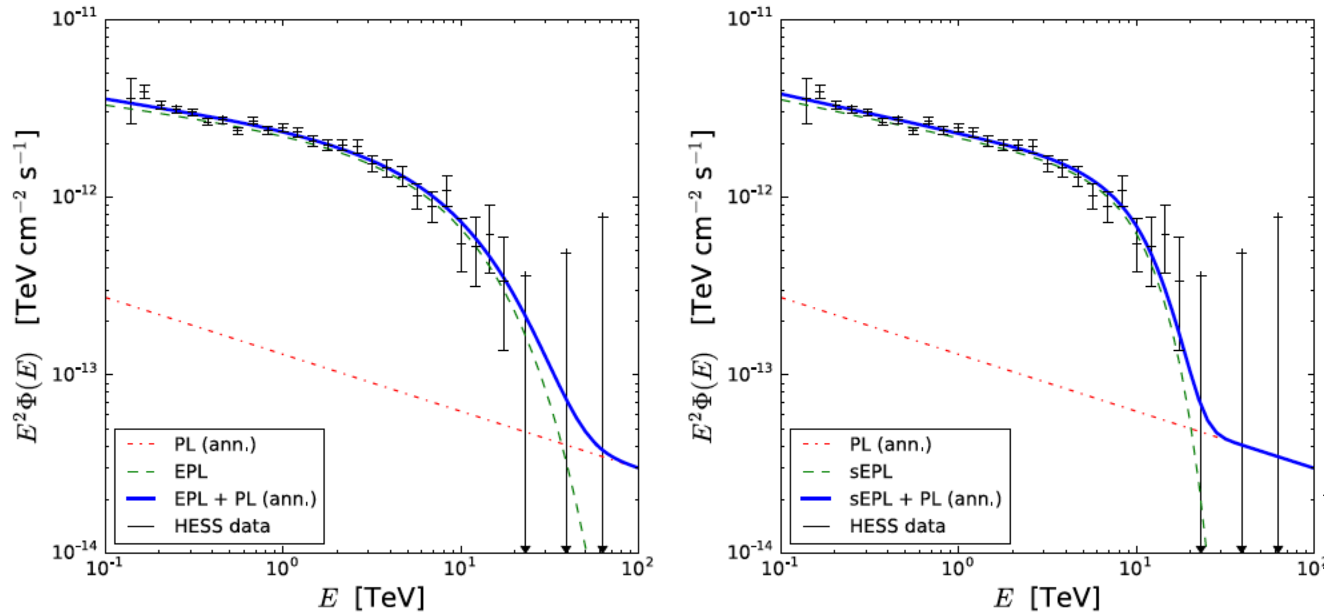
- Data well described by both EPL and a SEPL spectral templates
  - Present statistics is not sufficient to significantly discrimintate among the two templates



Belikov, EM, Silk, PRD94, 103005 (2016)

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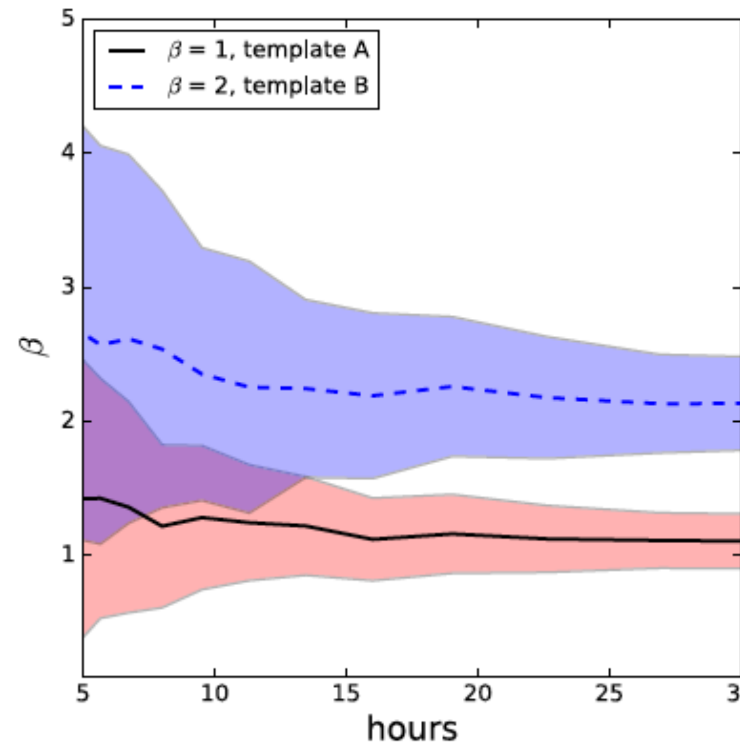


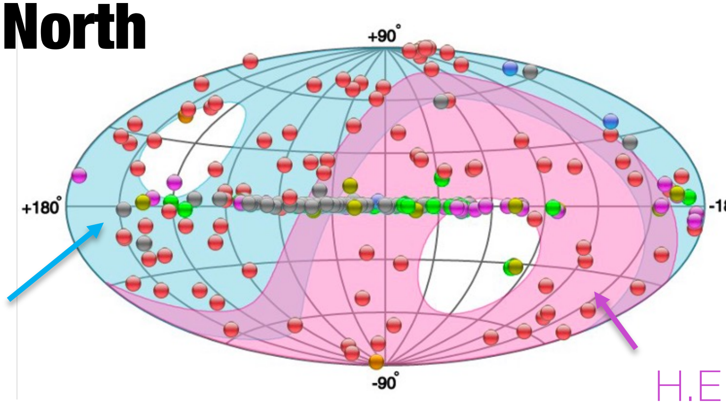
Belikov, EM, Silk, PRD 94, 103005 (2016)

CTA should be able to reliably distinguish SEPL from EPL models in about several ten hours of observation time

Galactic Centre observations by IACTs

- **Visibility from North and South Hemisphere**

MAGIC, VERITAS, HAWC, LHASSO

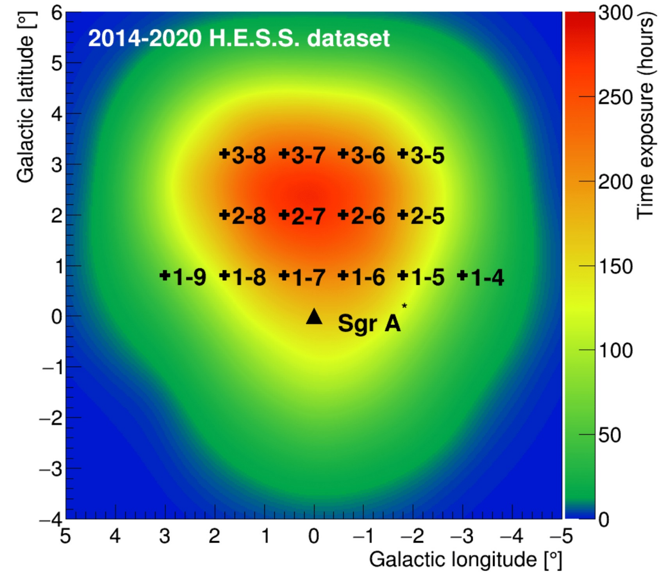


H.E.S.S

- **O(100) hour datasets are being taken**

Searches currently still statistically dominated
→ continued benefit from more observations
e.g., *Montanari, EM, Rodd, PRD107, 043038 (2023)*

Deep survey of the inner Galaxy going on with H.E.S.S.
- Negative latitude scan started



H.E.S.S. coll. (Montanari, Malyshev, EM), Phys. Rev. Lett. 129, 111101 (2022)

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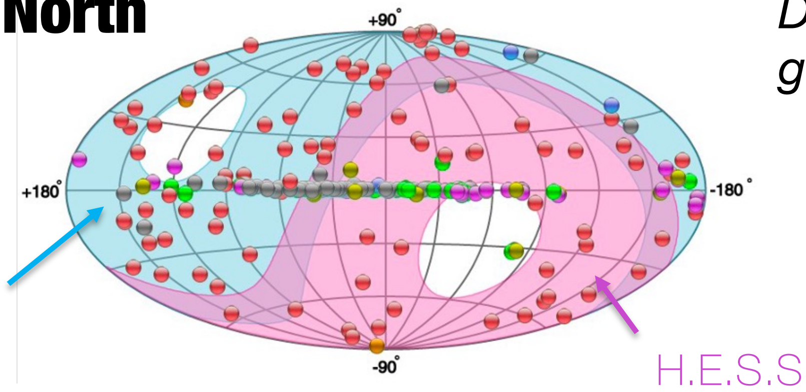

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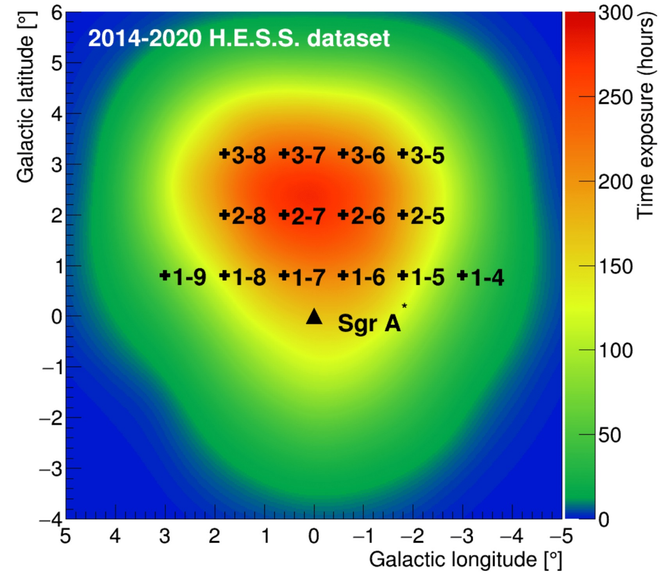

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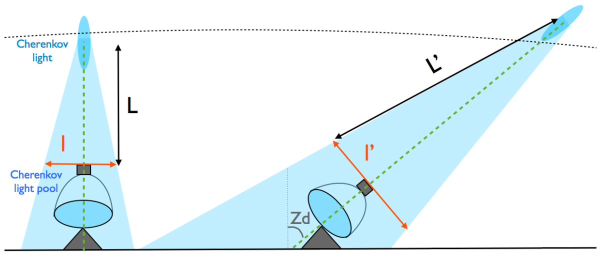
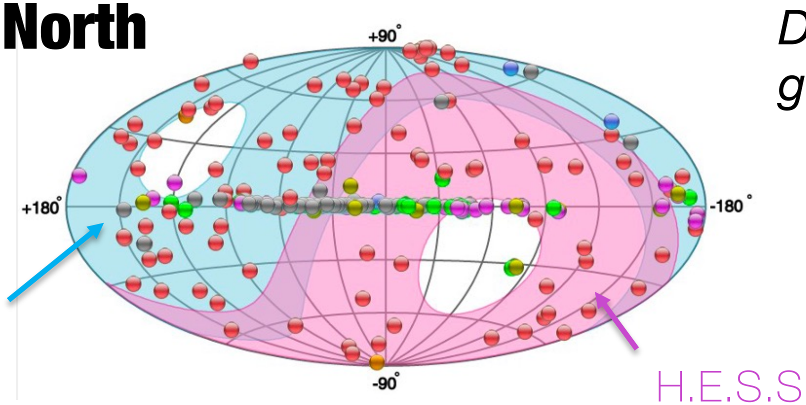


Credit. S. Abe

- a raise in the energy threshold
- effective area at higher energies increased up to an order of magnitude compared to low zenith angles
- higher systematic uncertainties

Galactic Centre observations by IACTs

- **Visibility from North and South Hemisphere**



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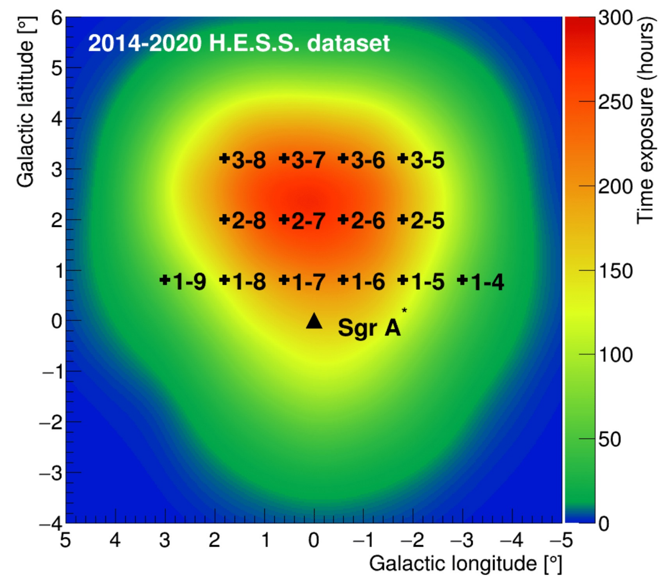

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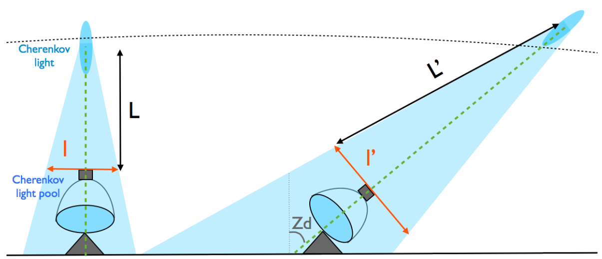
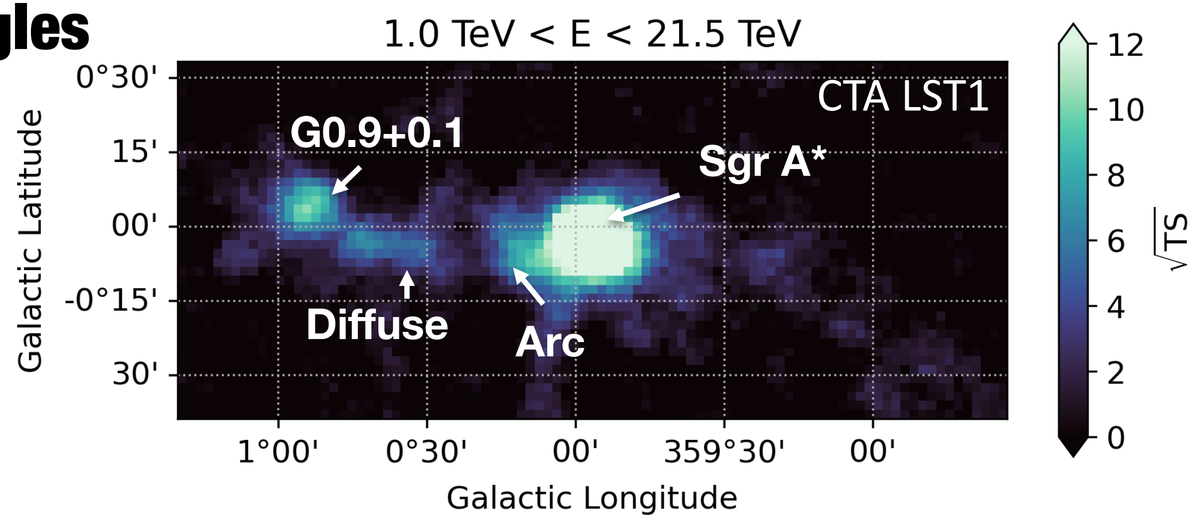


Credit. S. Abe



Galactic Centre observations by IACTs

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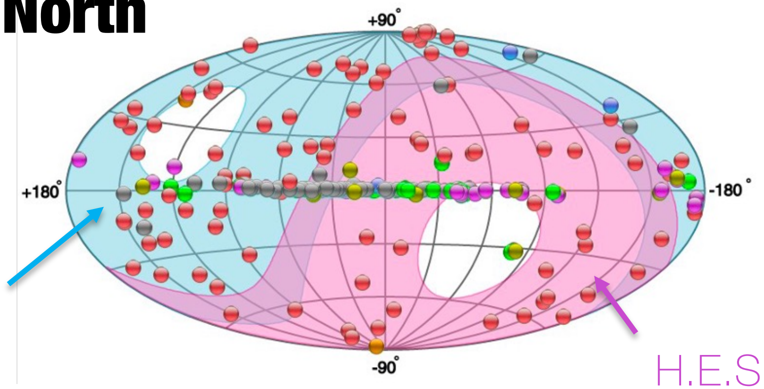

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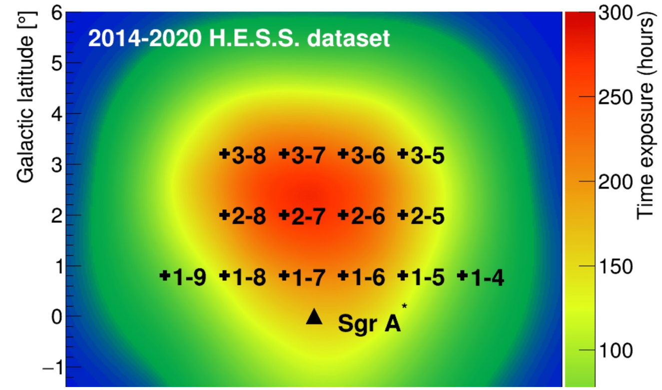

H.E.S.S. coll. (Montanari, N. Phys. Rev. Lett. 129, 111

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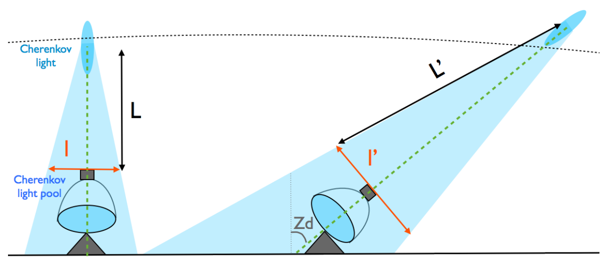
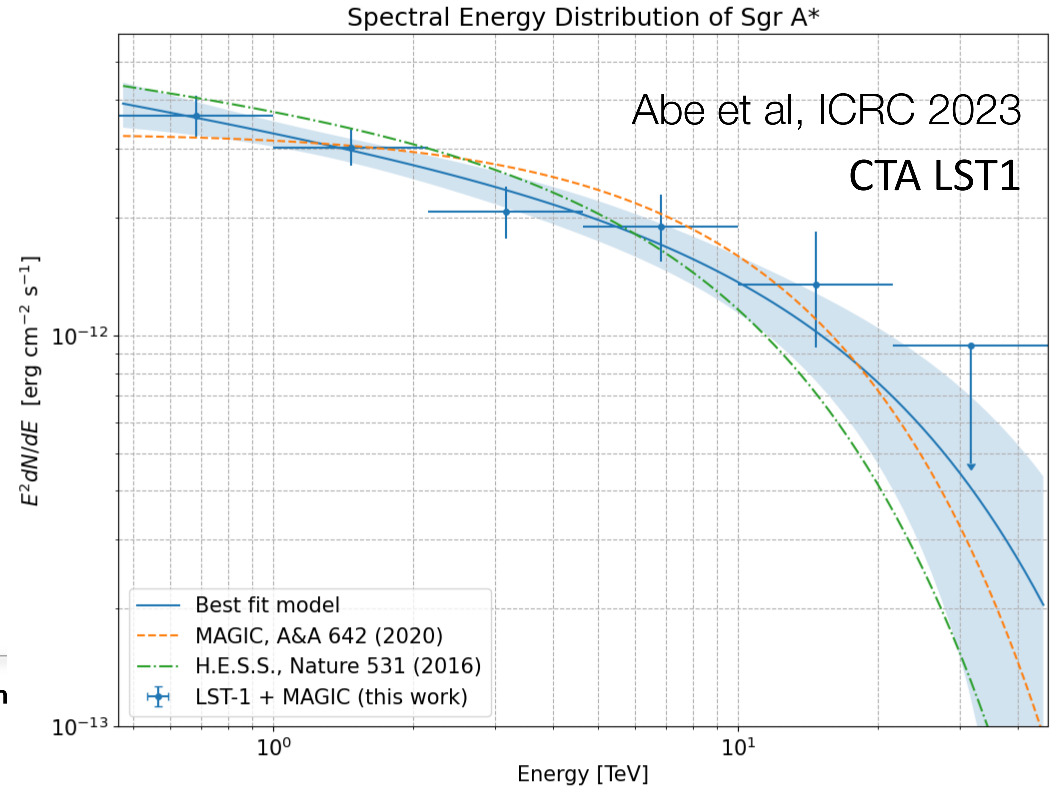
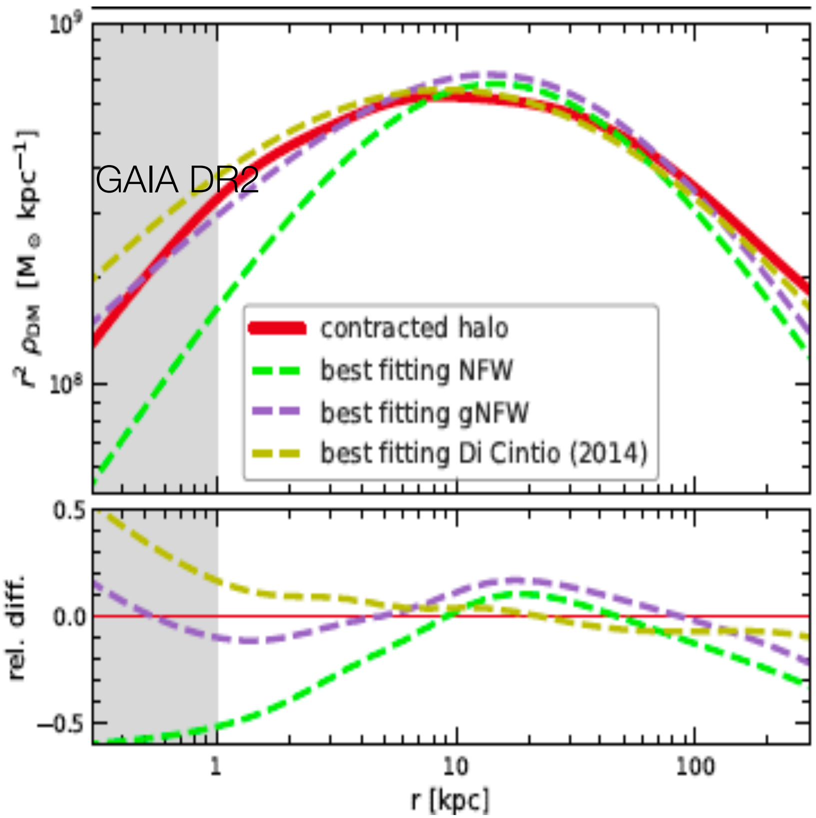




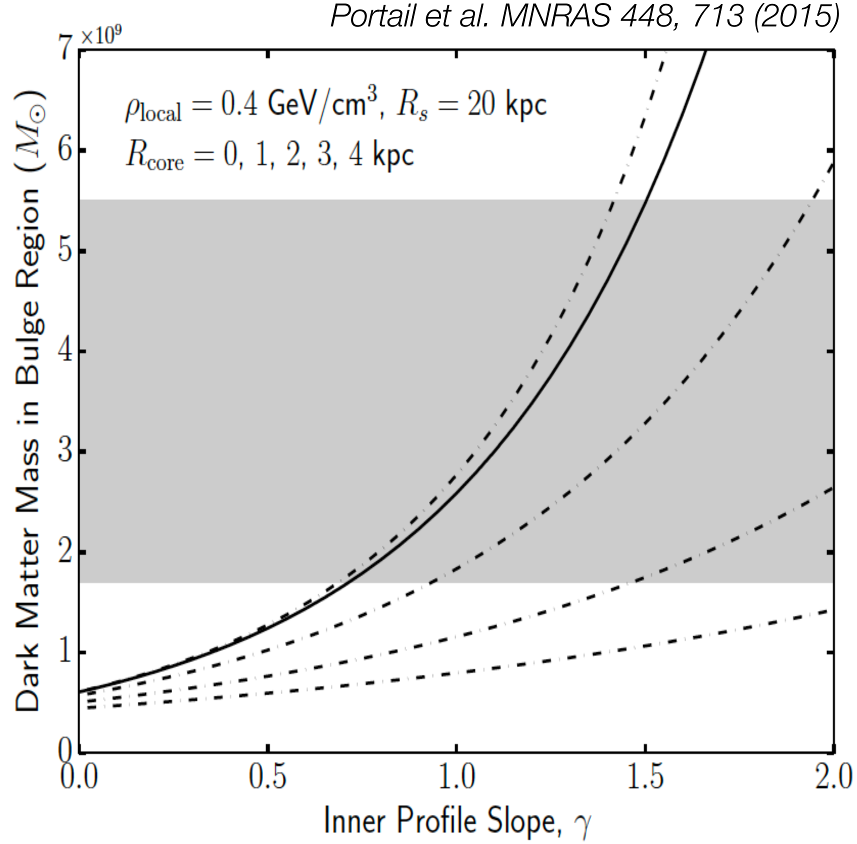
Dark matter distribution in the inner Milky Way

- **Mass modelling using kinematic tracers (stars, gas, …)**
  - careful modeling of the baryonic component and associated systematic uncertainties

Cautun et al. MNRAS 494, 4291 (2020)



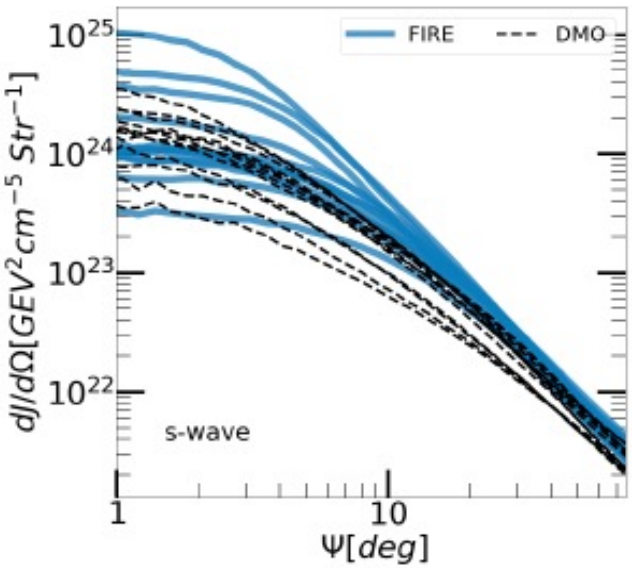
Portail et al. MNRAS 448, 713 (2015)



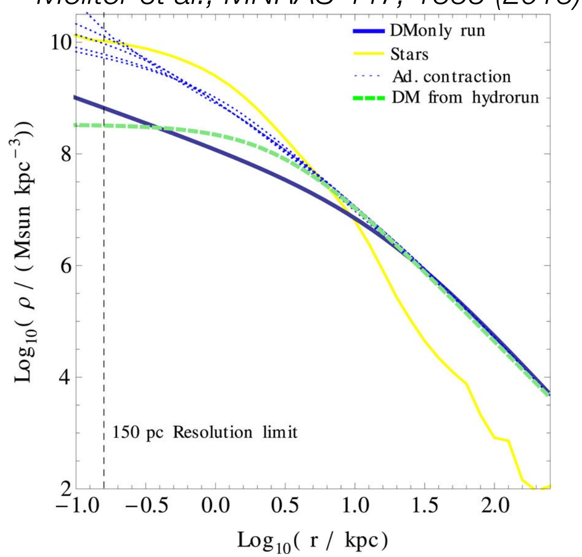
Dark matter distribution in the inner Milky Way

- **Hydrodynamical N-body simulations:**
  - Physics of baryons plays a crucial role at small scales
  - Baryonic feedback on the DM halo → large uncertainties
  - the resolution limit of simulations becomes also relevant

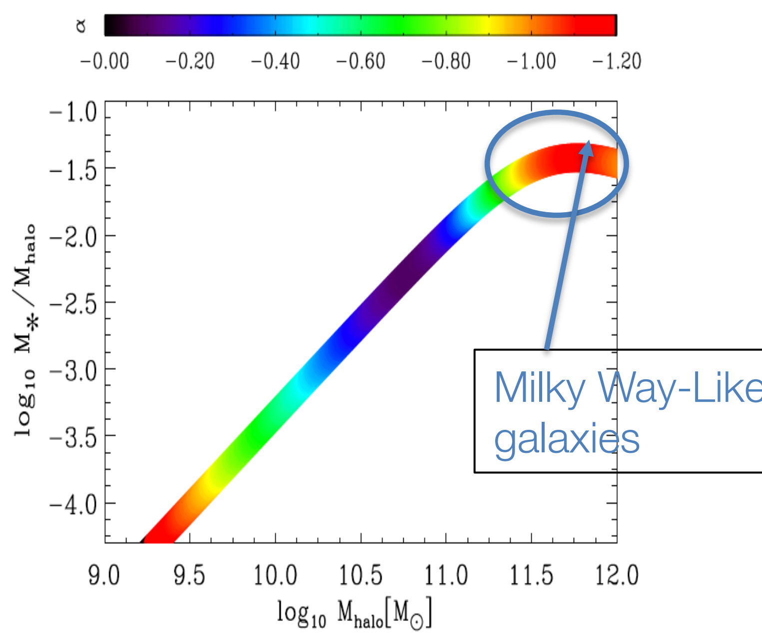
McKeown et al. MNRAS 513, 55 (2022)



Molitor et al., MNRAS 447, 1353 (2015)



Di Cintio et al., MNRAS 437, 415 (2014)

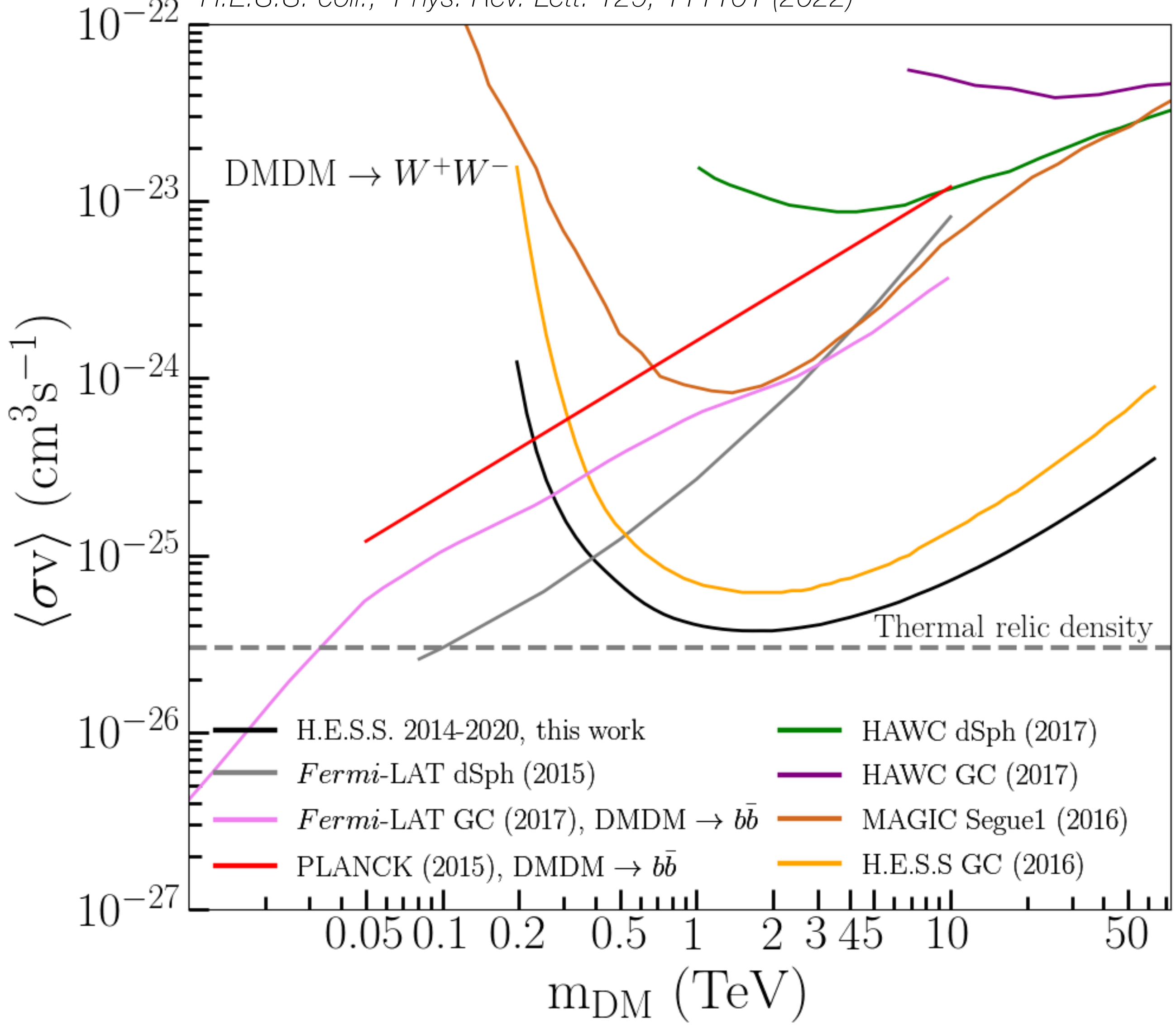


- DM distribution not firmly predicted from simulations nor constrained by observations

WIMP status from GeV-TeV observations

- Strong constraints from VHE gamma rays probing thermal relic TeV DM
- **Some of the simplest thermal WIMP scenarios, e.g., pure higgsinos and winos produce the measured DM abundance not yet detected**

H.E.S.S. coll., Phys. Rev. Lett. 129, 111101 (2022)

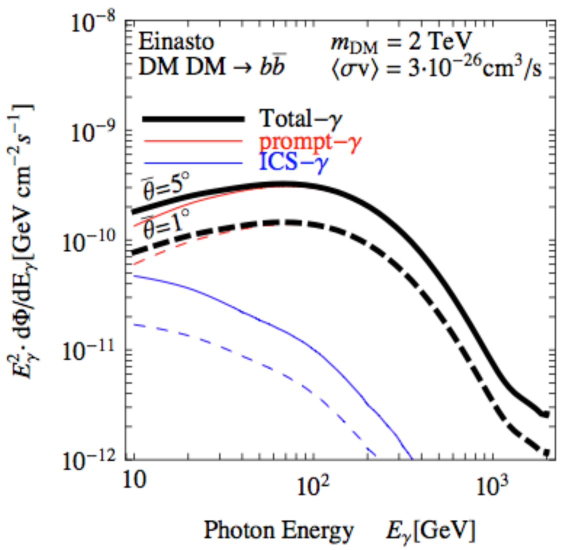


Gamma-ray fluxes from DM annihaliation with secondary emissions

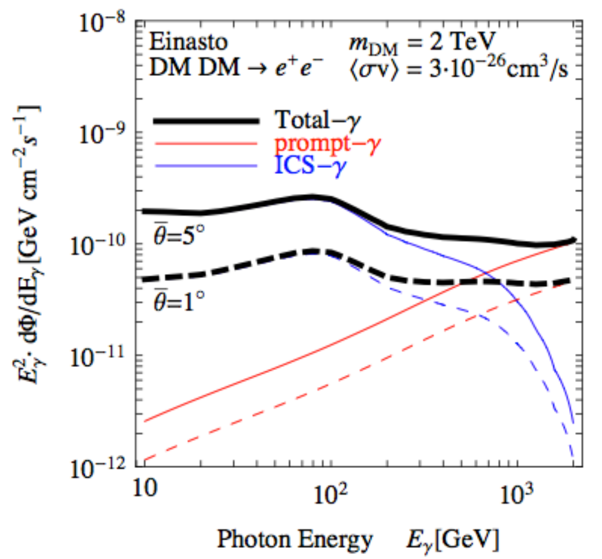
$$\frac{d\Phi_{tot}}{dE} = \frac{d\Phi_{p}}{dE} + \frac{d\Phi_{ICS}}{dE}$$

Inverse Compton scattering of e± on ambient radiation CMB, infrared, optical

- Strong ISRF in the GC region
- Additional gamma rays in the final states
  - depends strongly on the annihillation channel



Hadronic channels : No significant contribution From ICS



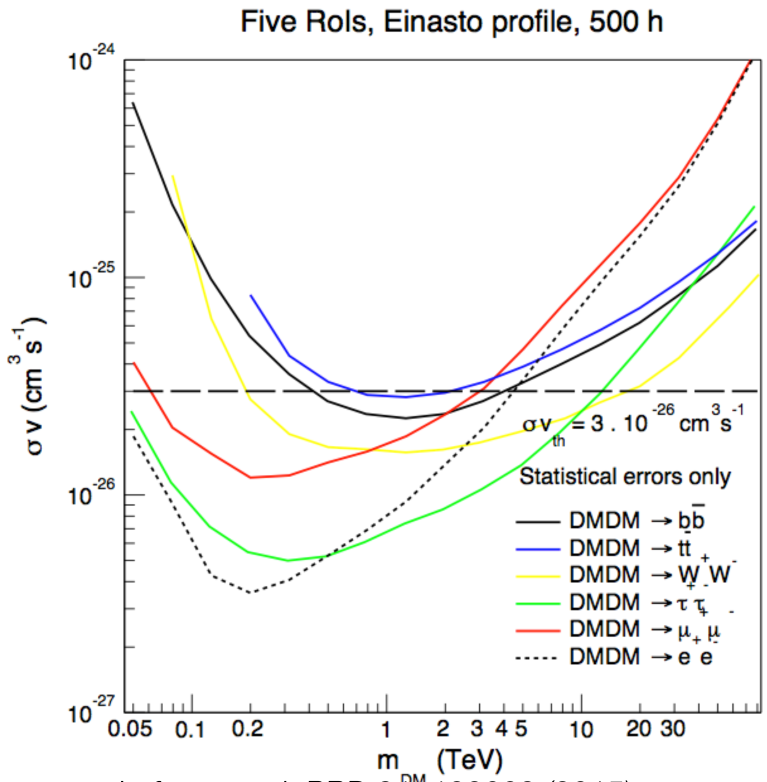
Leptonic channels : Important contribution from ICS processes, from 10 GeV to several hundred of GeV, well above CTA energy

Gamma-ray fluxes from DM annihaliation with secondary emissions

$$\frac{d\Phi_{tot}}{dE} = \frac{d\Phi_{p}}{dE} + \frac{d\Phi_{ICS}}{dE}$$ ← Inverse Compton scattering of $e^{\pm}$ on ambient radiation CMB, infrared, optical

- Strong ISRF in the GC region
- Additional gamma rays in the final states
  - depends strongly on the annihillation channel
- Strong constraints for the leptonic channel from the ICS contribution

CTA Sensitivity in the inner 5deg of the GC



Lefranc et al. PRD 91, 122003 (2015)

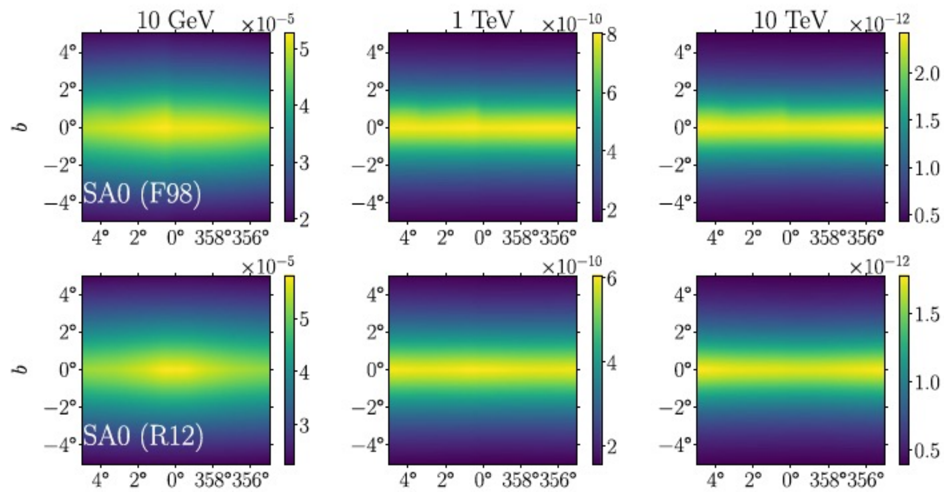
Gamma-ray backgrounds in the GC region

- **Guaranteed gamma-ray emission** from astrophysical sources and cosmic-ray interactions with gas (brem.,, pp interaction) and ambient photons (ICS)

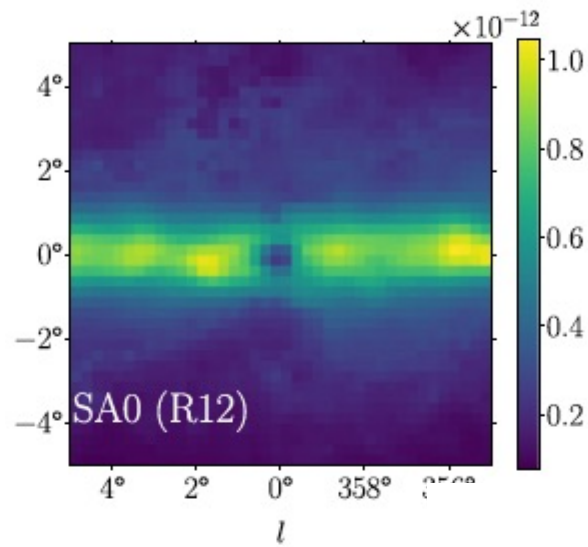
- **Modelling uncertainty** from source populations, cosmic-ray propagation, and target distributions (gas, radiation fields)

- **Careful assessment iwith S/B and systematic uncertainty modelling**

Inverse Compton flux maps predicted by GALPROP v57 [in units of TeV–1 cm–2 s–1 sr–1.

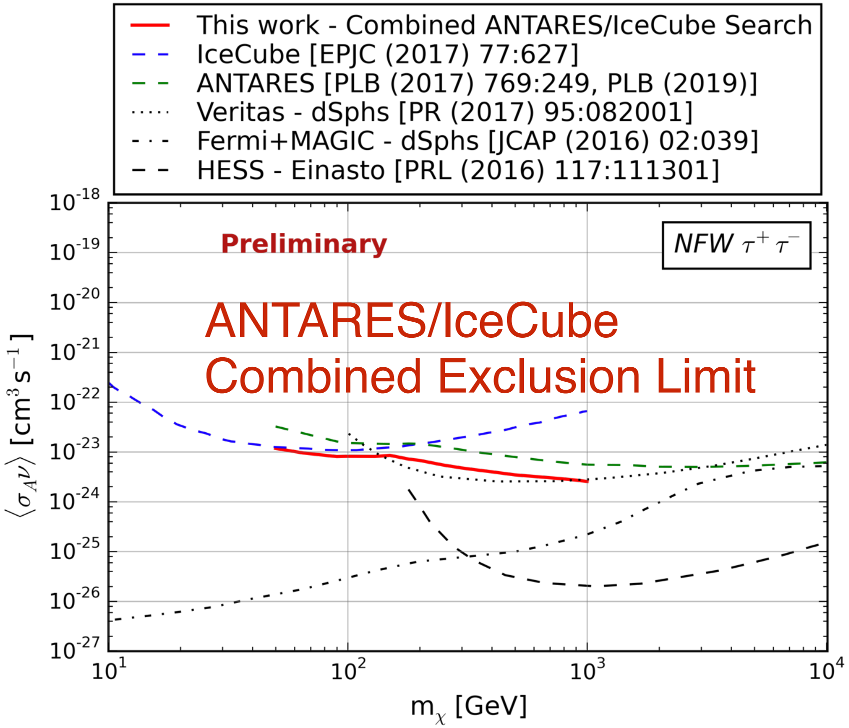


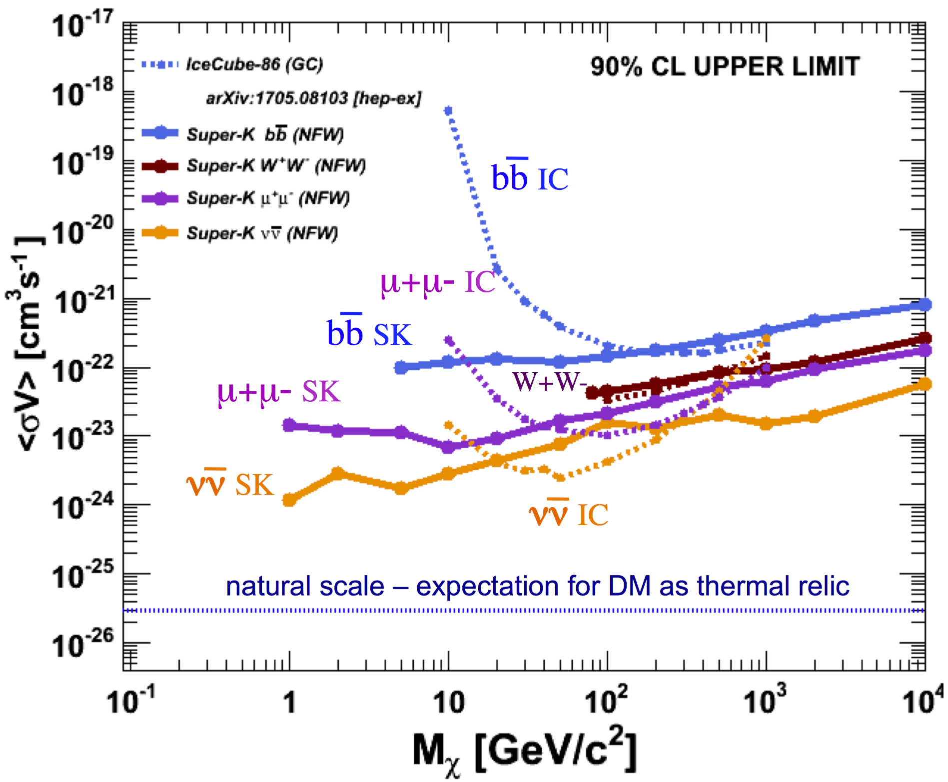
Montanari, Macias, EM, Phys. Rev. D 108, 083027 (2023)



Hadronic flux maps at an energy of 10 TeV computed with GALPROP v57 in units of TeV–1 cm–2 s–1 sr–1

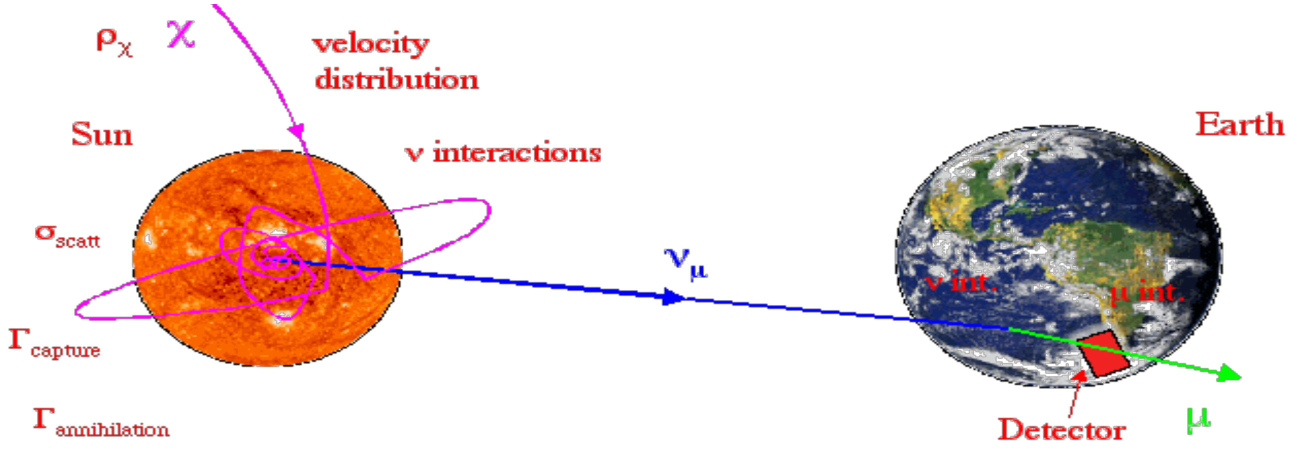
Neutrinos: Galactic Center / Galactic Halo





- Combined analysis enhances sensitivity in overlap region and helps to make analyses more comparable
- Very competitive result from Super-K for dark matter masses below a 100GeV

Neutrinos from DM capture in the Sun

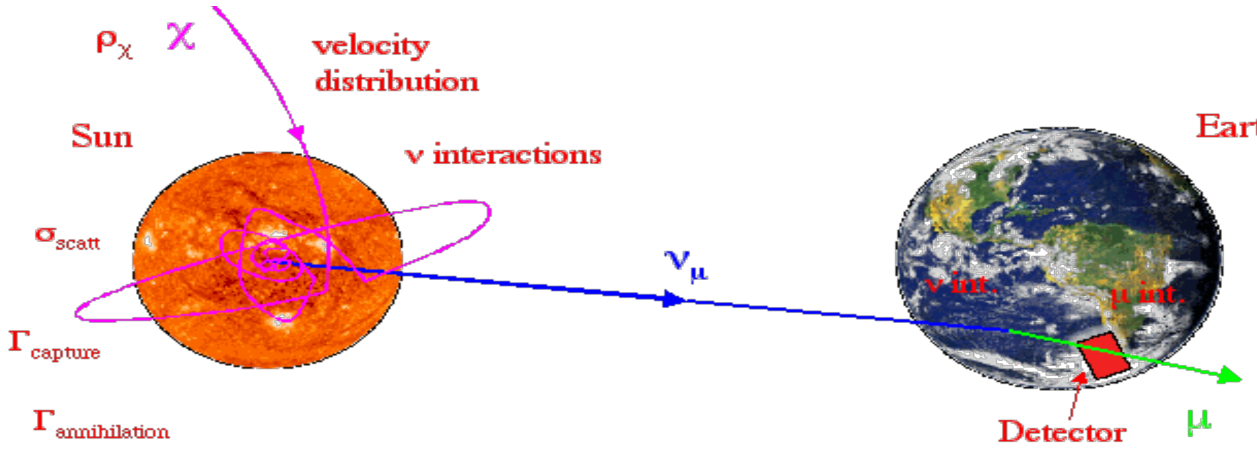


- WIMPs occasionally scatter on atomic nuclei inside the Sun. If their velocity drops below the escape velocity, they are trapped in an orbit around the Sun, lose more energy and finally accumulate at the Sun's center.

- Can apply to capture in the Earth

- Neutrino telescopes can probe the spin-independent / spin dependent cross section on the proton

Neutrinos from DM capture in the Sun

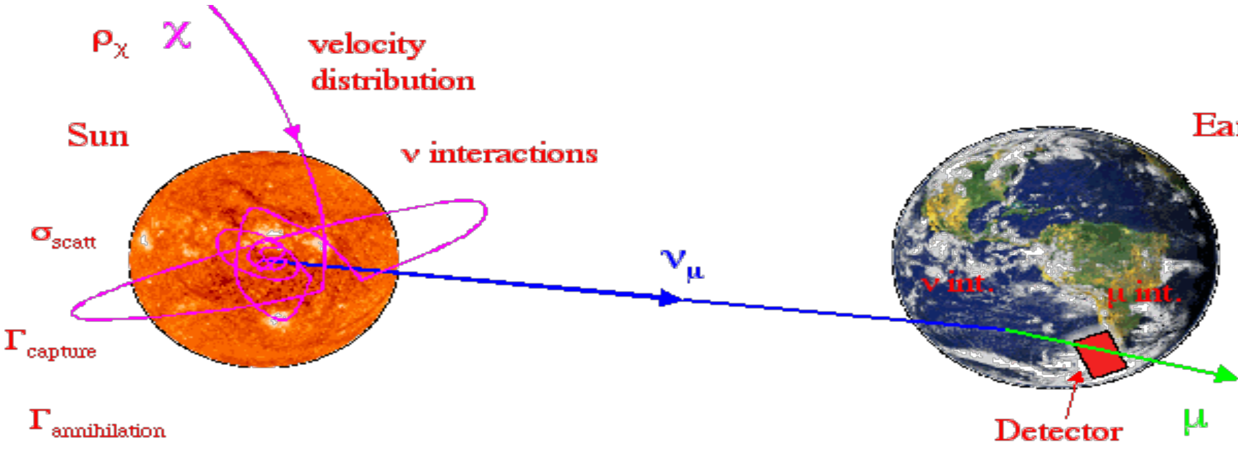


- A quick estimate: assuming that f_X is the flux of dark matter particles in the Solar System, M is the mass of the Sun, and s_{Xp} is the dark matter-proton elastic scattering cross section, the Solar capture rate C is:

$$C = \Phi\left(\frac{M_\odot}{m_p}\right)\sigma_{Xp}$$

- With the local DM density ρ_X~0.3 GeV/cm3, <v_X>~300 km/s: $\phi_X \sim 10^2$ cm^{-2}s^{-1} (100 GeV/m_X)

Neutrinos from DM capture in the Sun



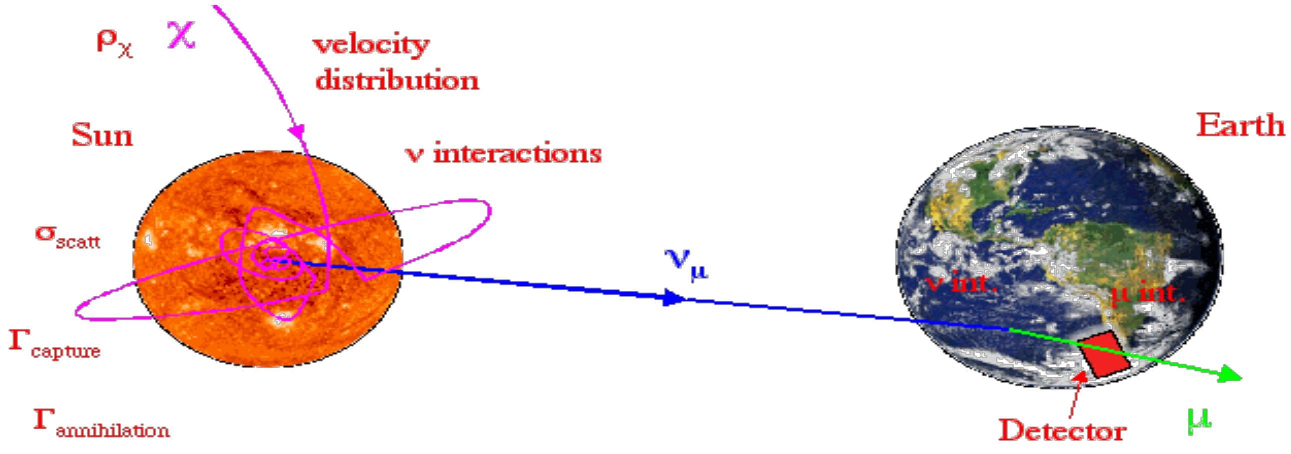
- The number of dark matter particles present in the Sun as a function of time N(t) (neglecting DM escape) is :

$$\dot{N}(t) = C_\odot - C_A N^2(t)$$

- In equilibrium, the annihilation rate G_A is fully determined by the capture rate :

$$\Gamma_A = \frac{1}{2} C_A N^2(t) = \frac{C_\odot}{2}$$

Neutrinos from DM capture in the Sun



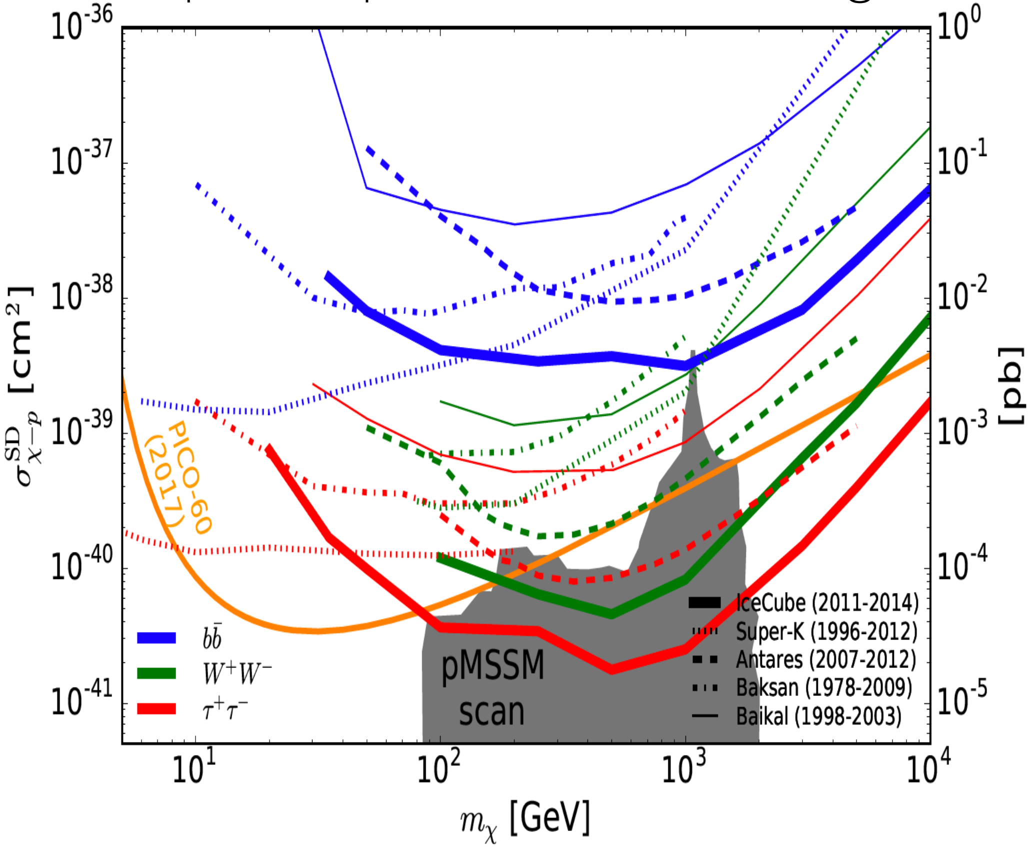
- Putting numbers together :

$$\Gamma_A \sim 10^{16} s^{-1} \left(\frac{1TeV}{m_X}\right)\left(\frac{\sigma_{Xp}}{10^{-42} cm^2}\right)$$

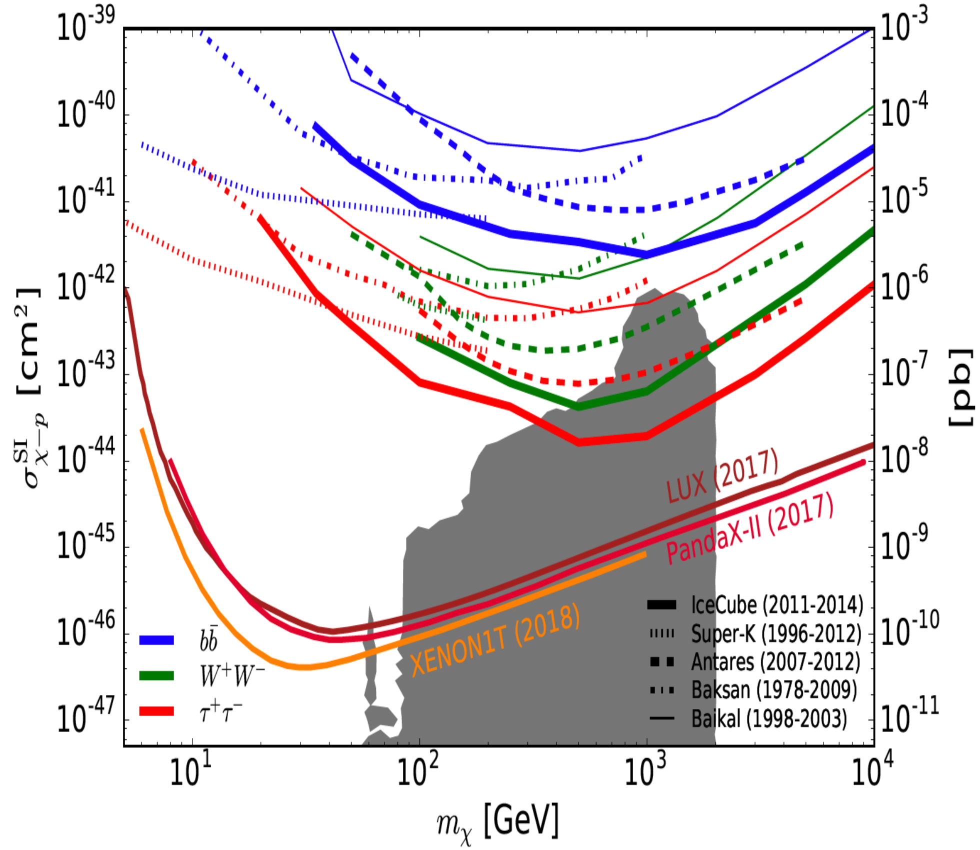
- Constraints from neutrino telescopes towards the Sun are not on the dark matter's annihilation cross section, but on its elastic scattering cross section with nuclei.

Neutrinos from DM capture in the Sun

Spin-dependent scattering

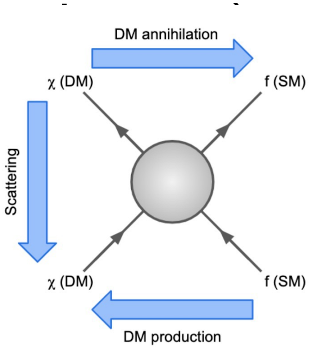


Spin-independent scattering



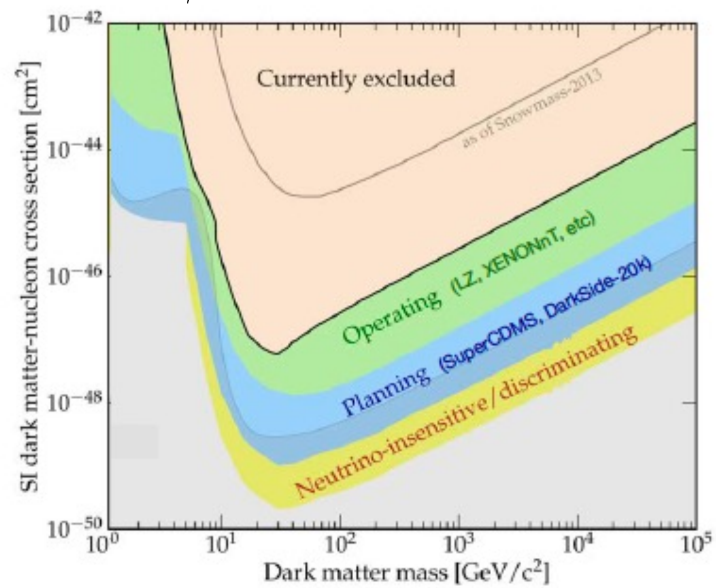
WIMP status

1 GeV – 100 TeV, electroweak couplings with SM



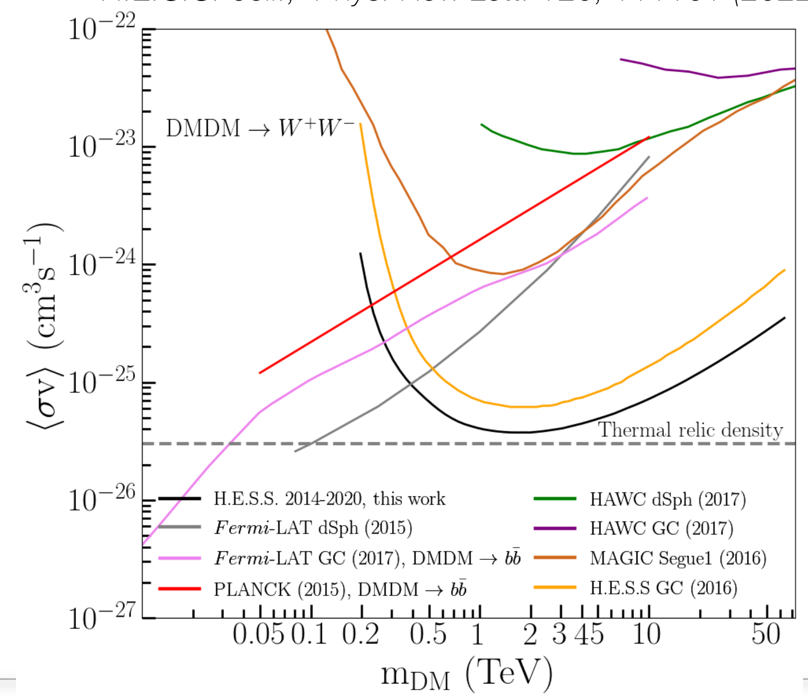
- **No detection (yet) of new weak-scale physics at the LHC**
- **No detection (yet) of WIMPs in direct dark matter searches**

2021 Snowmass Community Study
Chapter 5: Cosmic Frontier



- Strong constraints from direct searches probing cross sections as small as 10^{-47} cm^2 @ 30 GeV
- Strong constraints from VHE gamma rays probing thermal relic TeV DM

H.E.S.S. coll., Phys. Rev. Lett. 129, 111101 (2022)



- **Some of the simplest thermal WIMP scenarios, e.g., pure higgsinos and winos produce the measured DM abundance not yet detected**