Theoretical Overview of Dark Matter Physics

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NPB 2024
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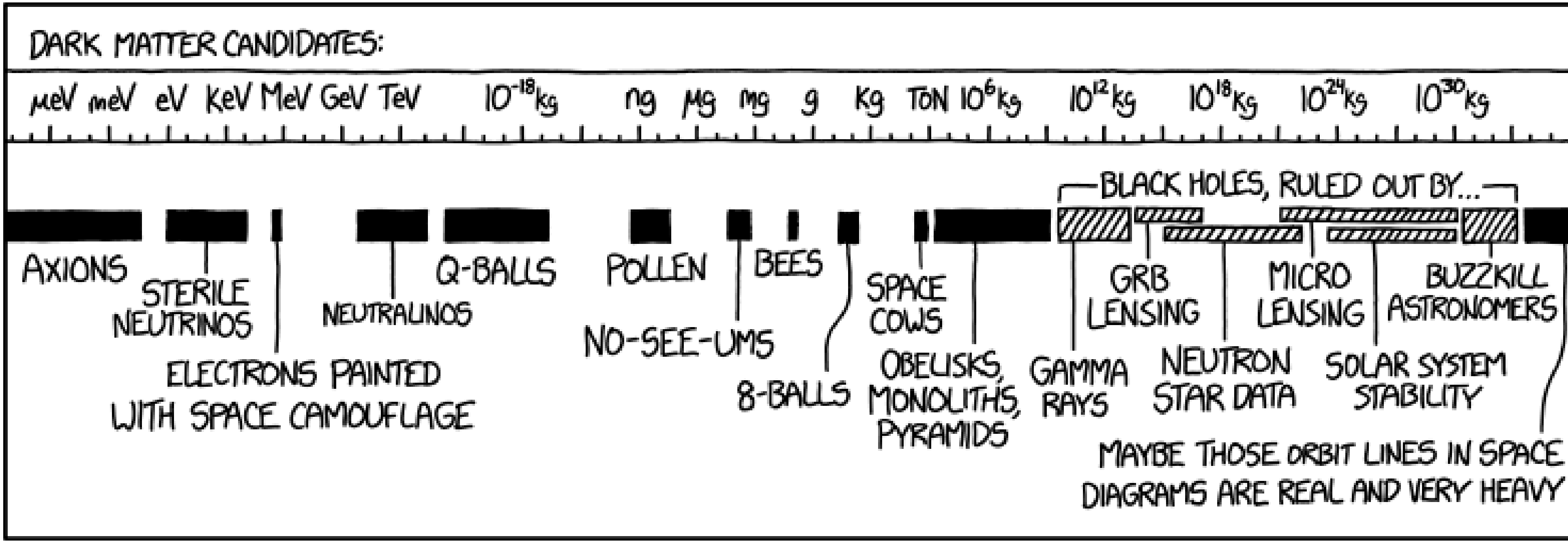
February 2024

The dark matter zoo

Explain xkcd



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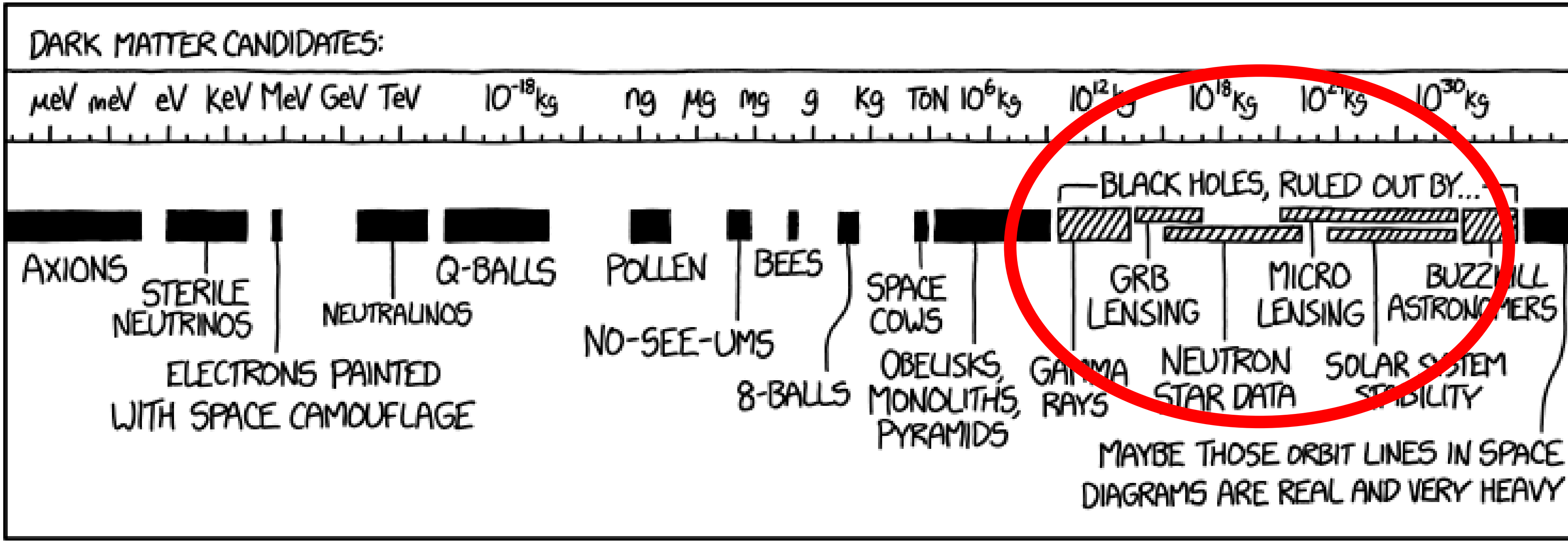

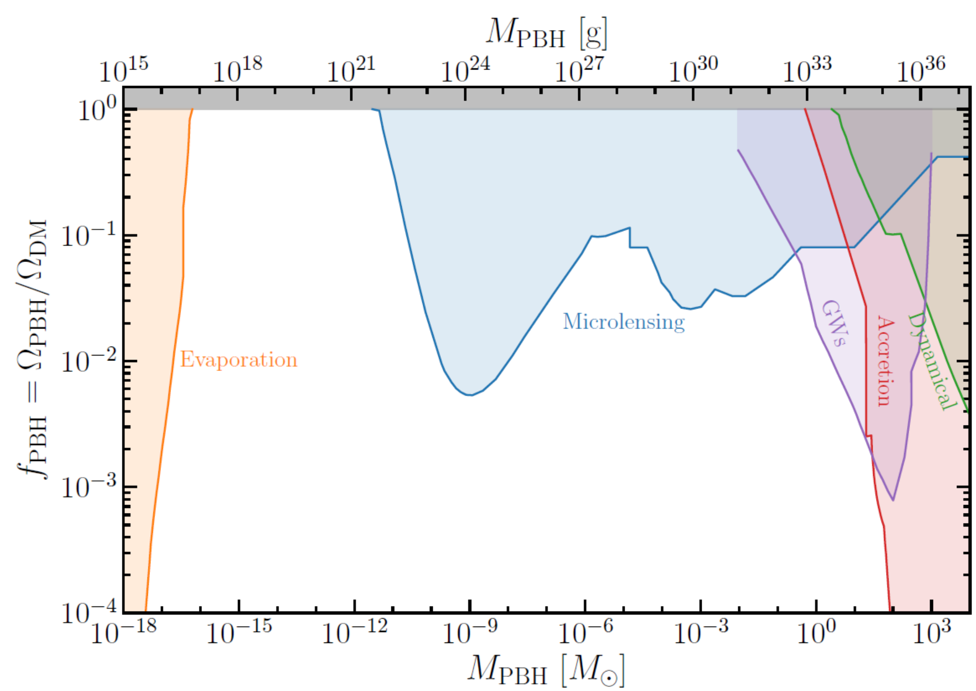

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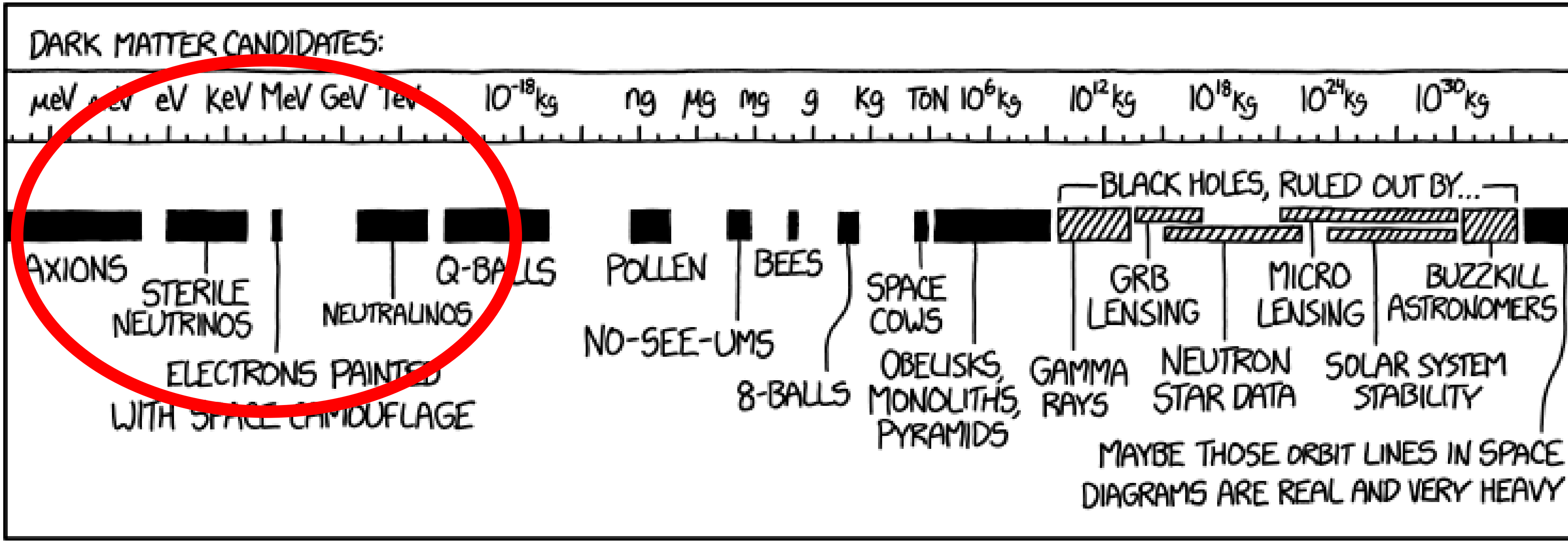

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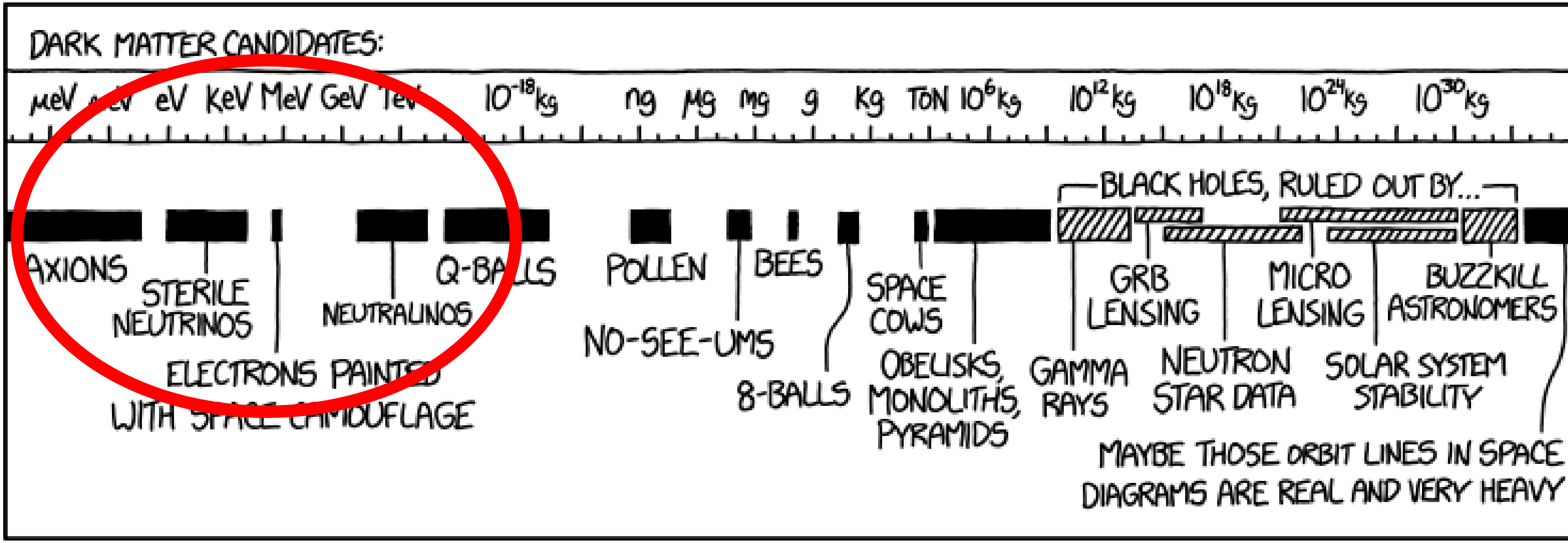

spin

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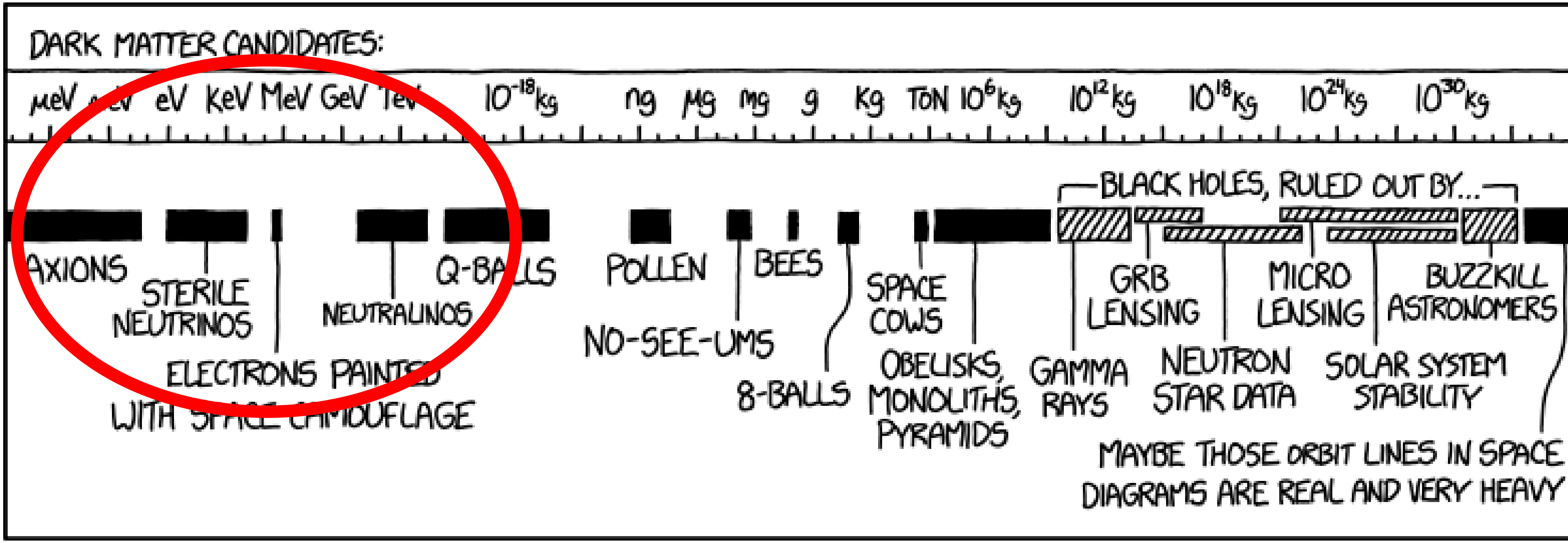

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Scattering cross-section off SM particles

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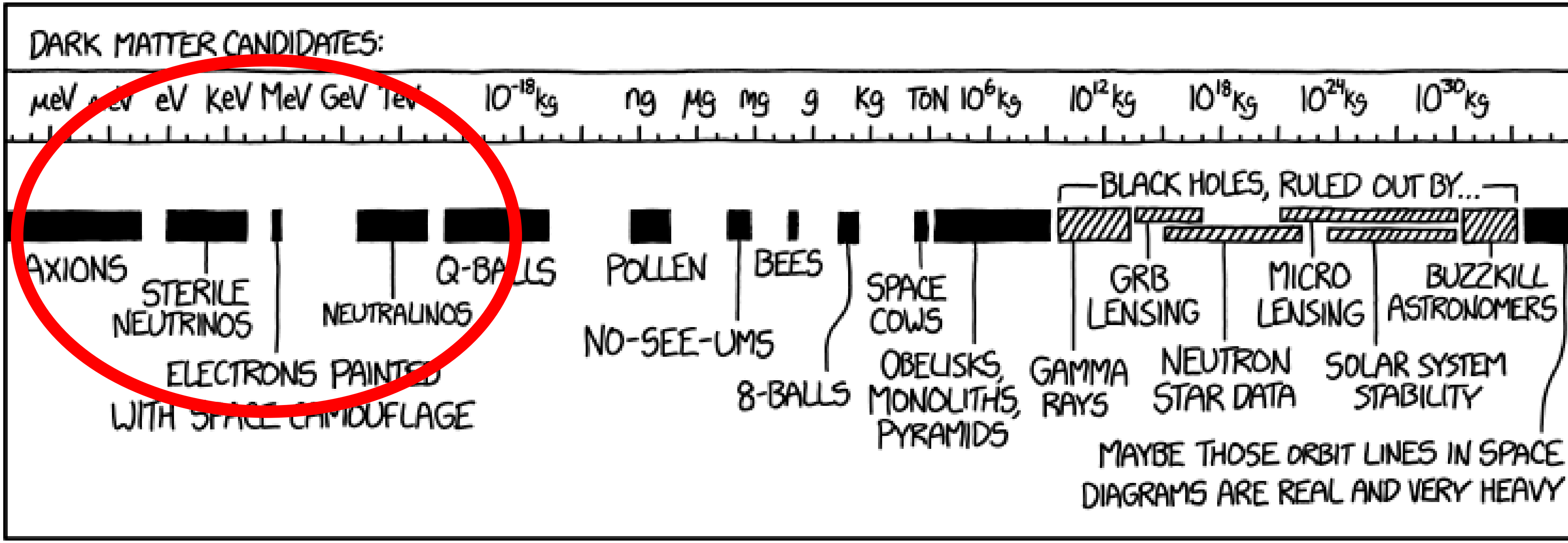

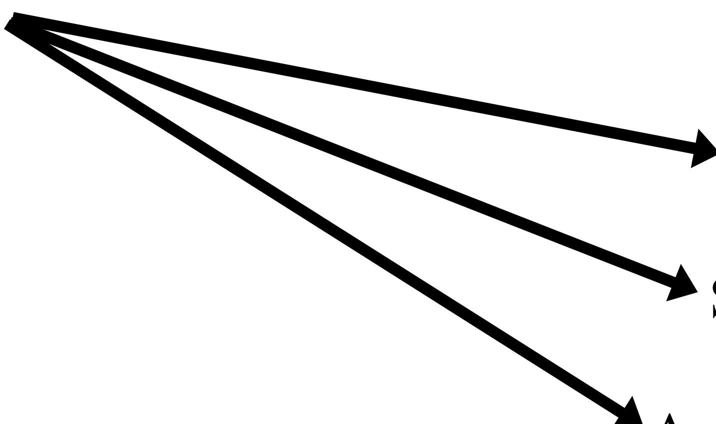

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Scattering cross-section off SM particles

Annihilation cross-section into SM particles

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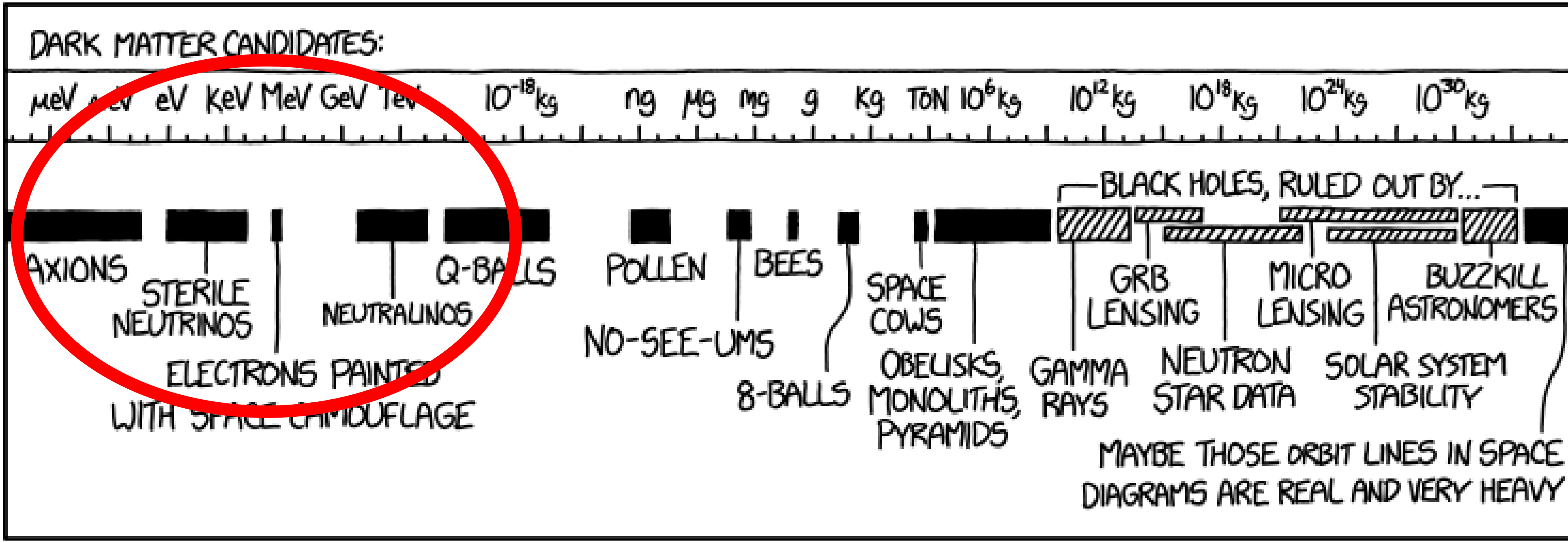

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Annihilation cross-section into SM particles

Self-coupling

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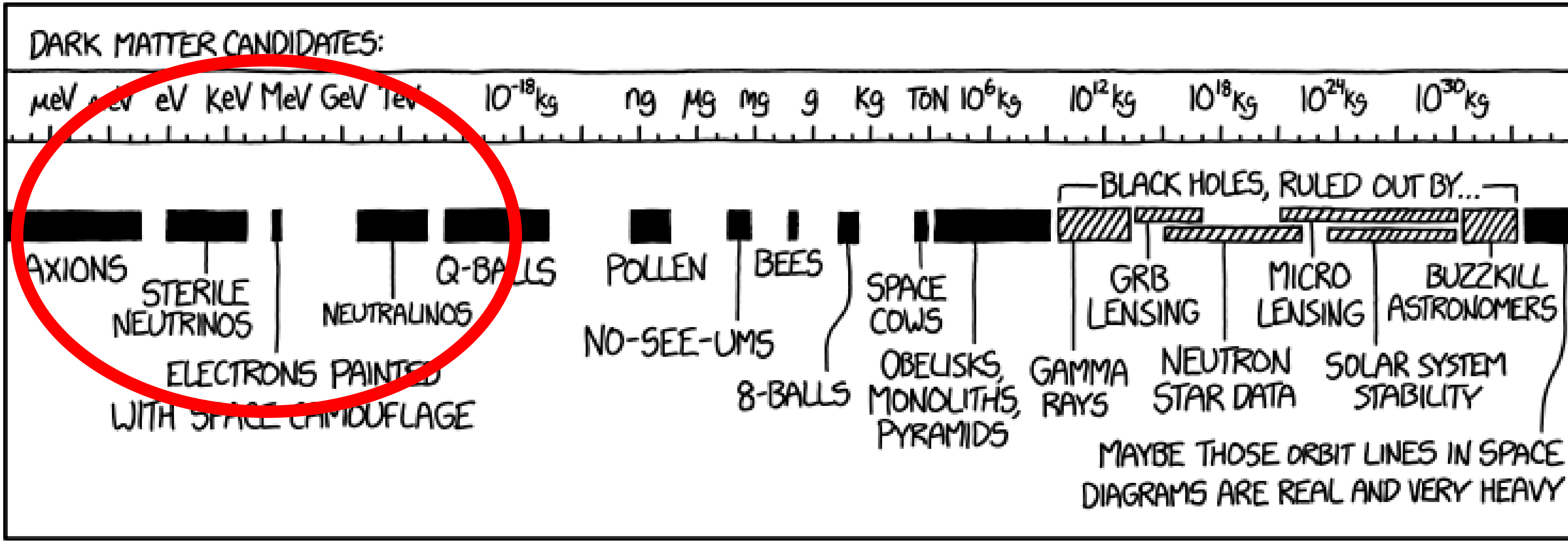

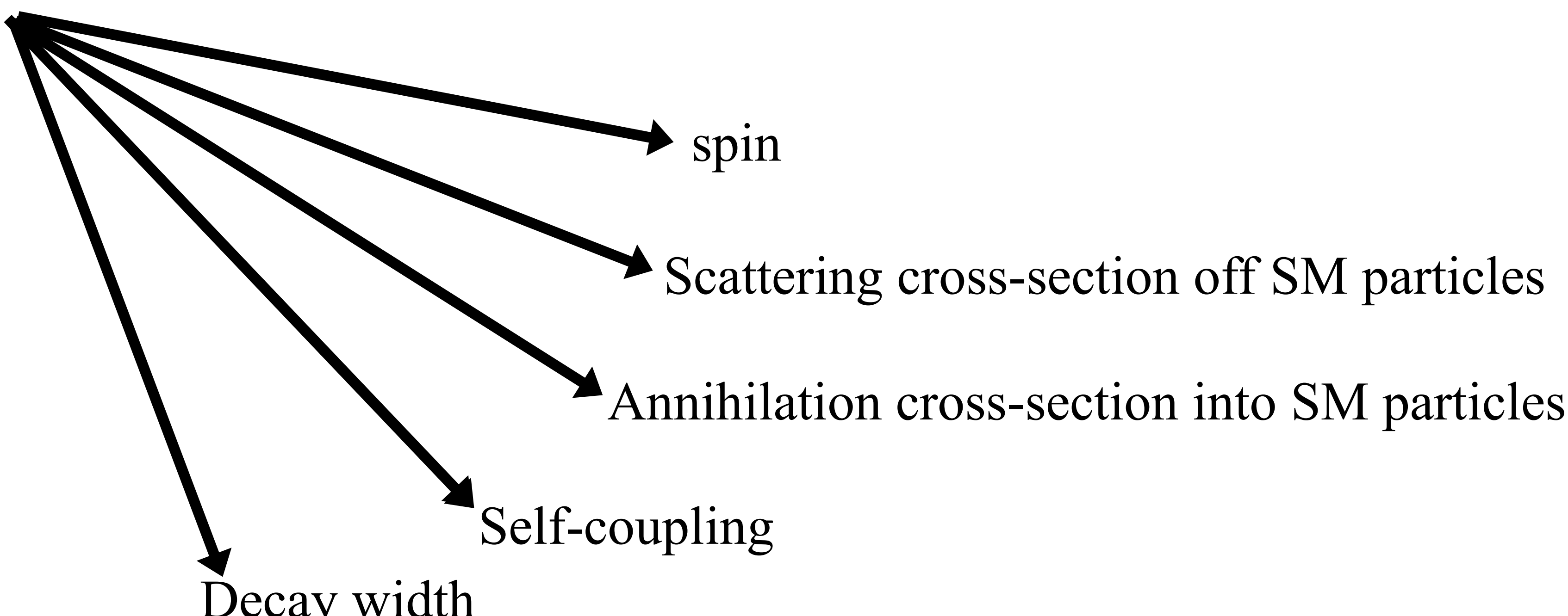

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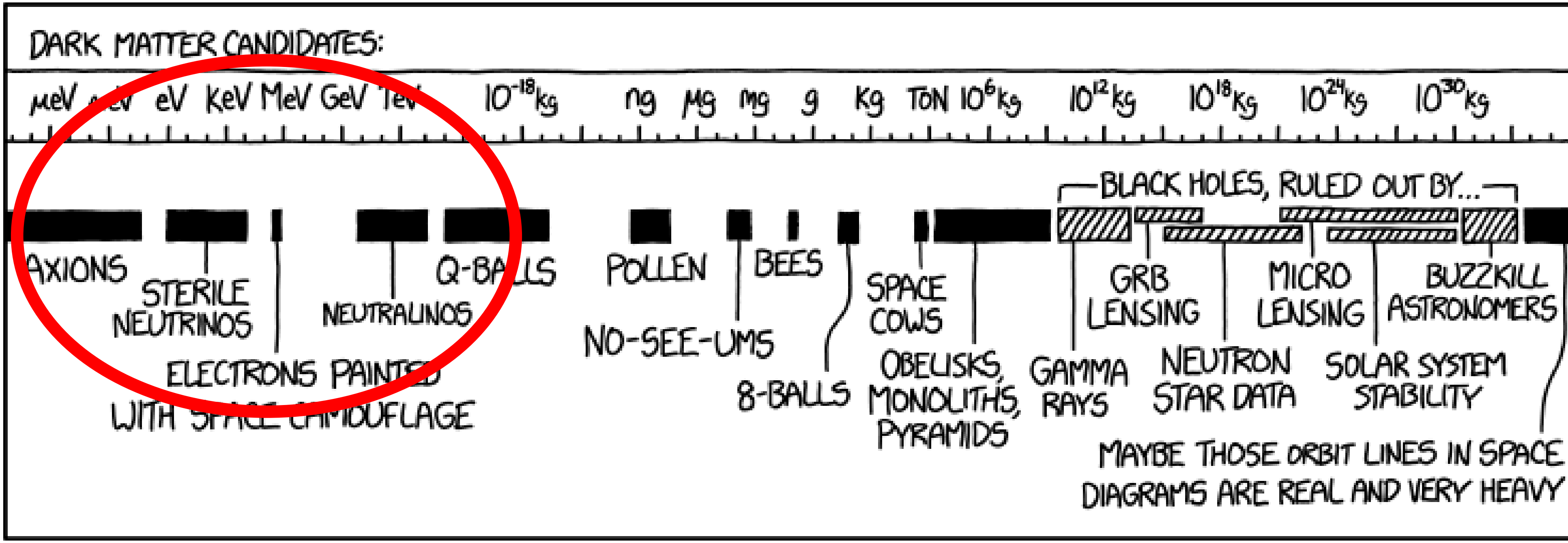

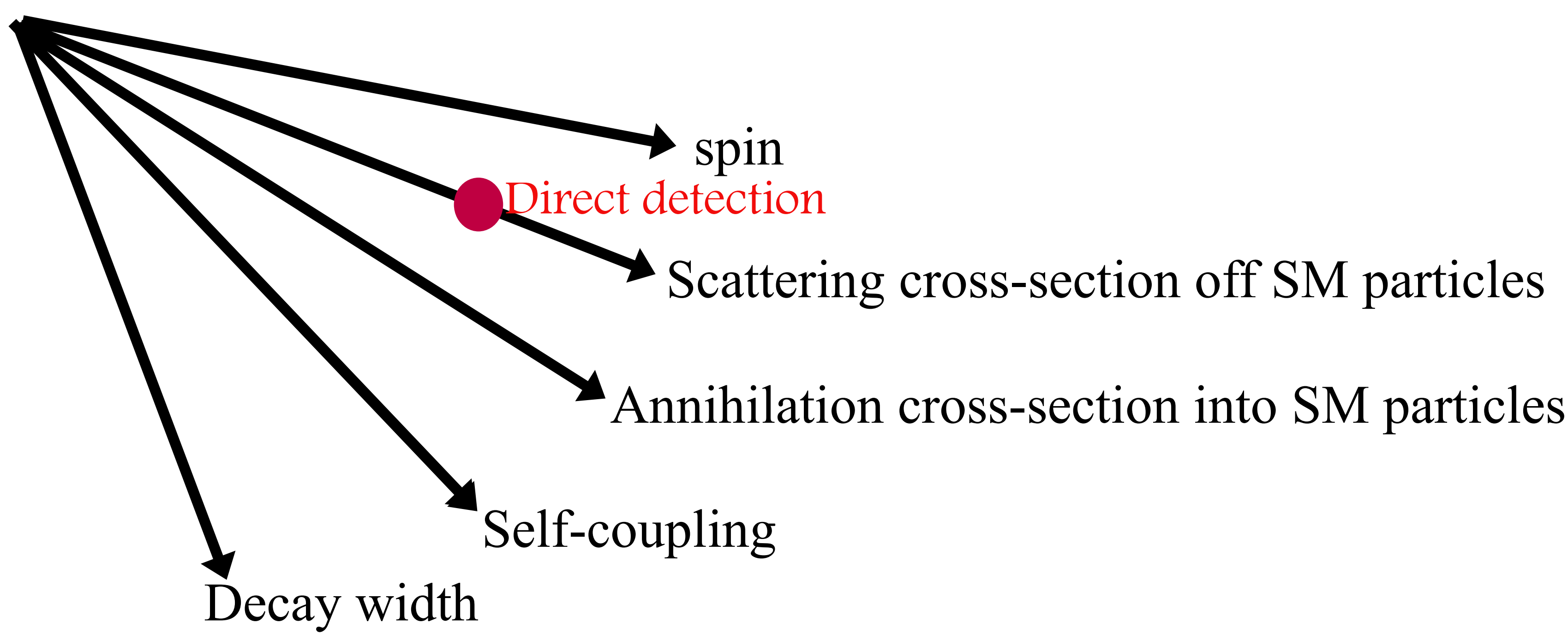

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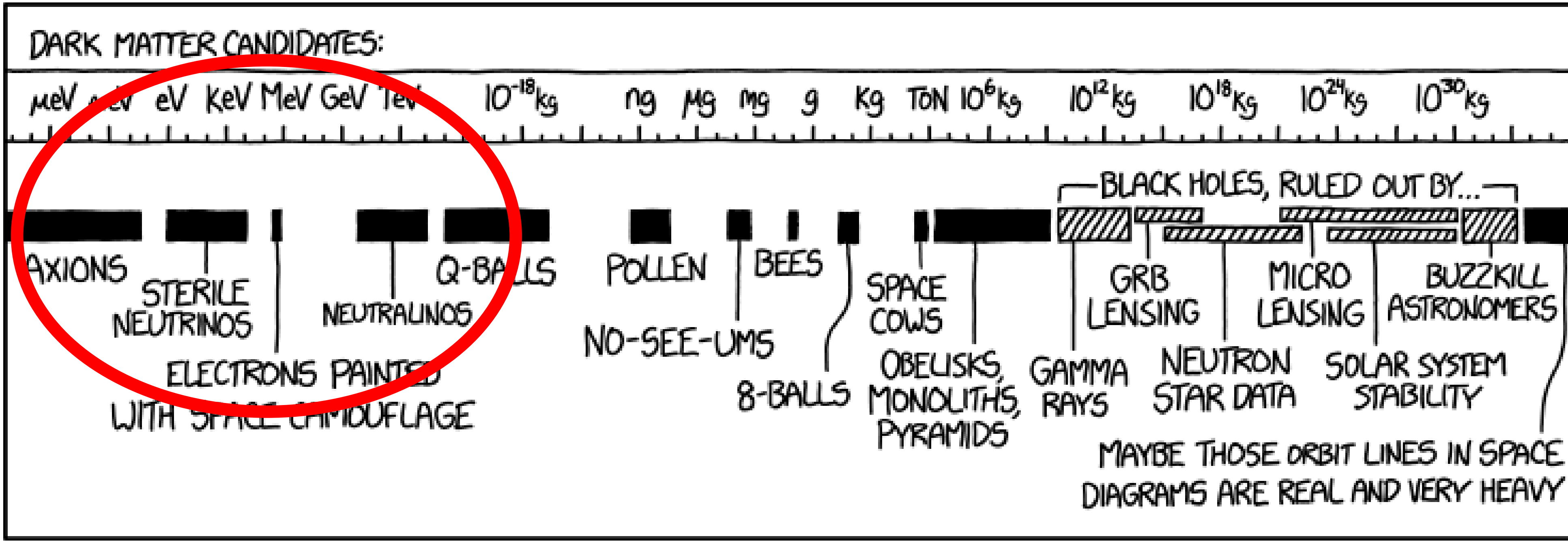

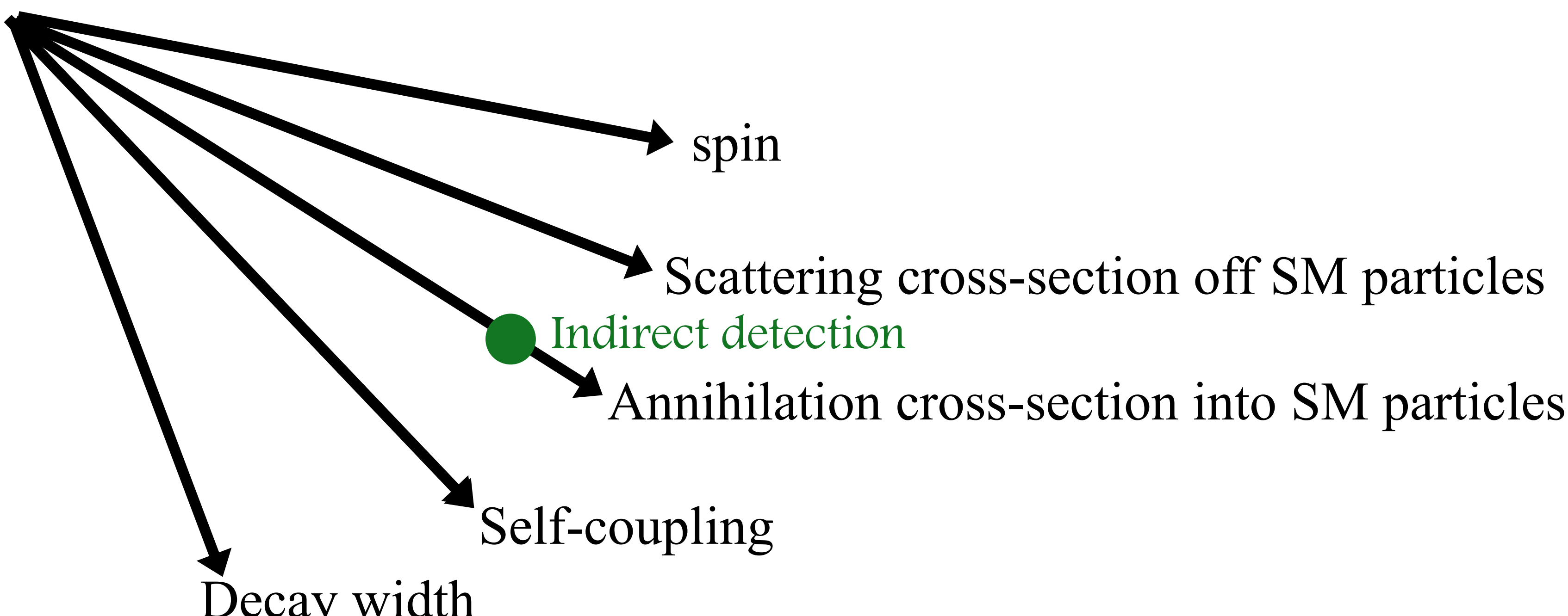

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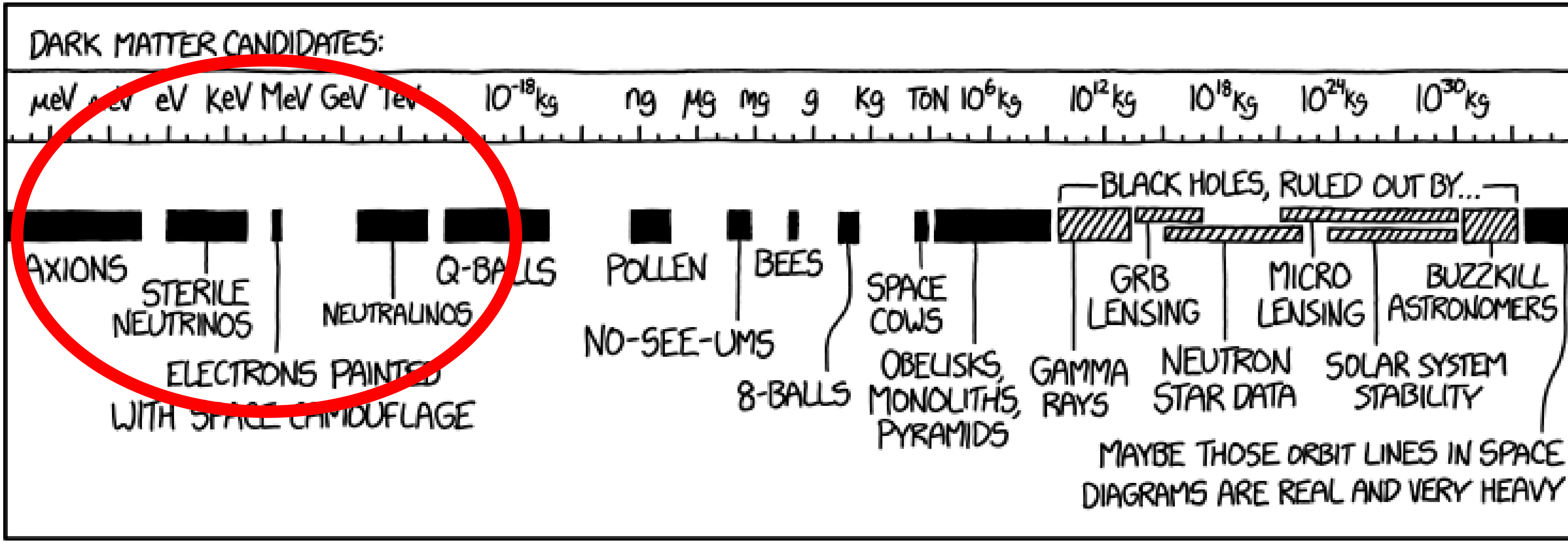

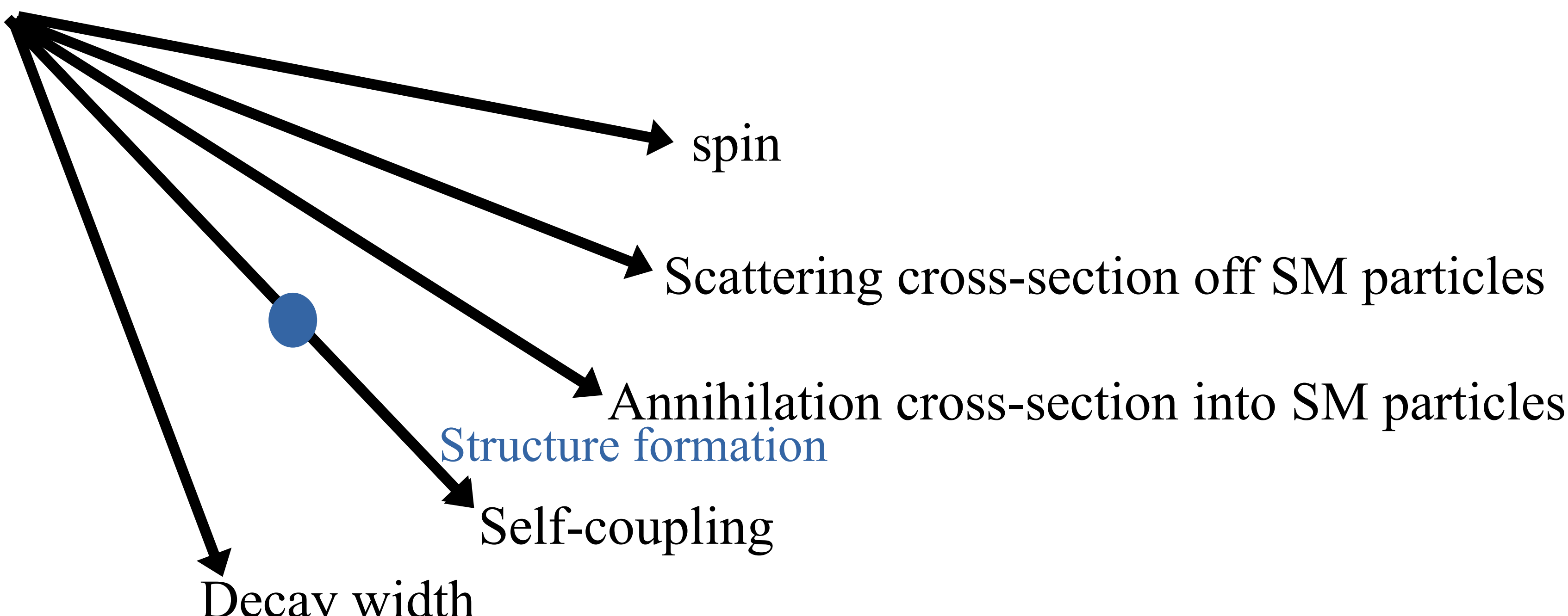

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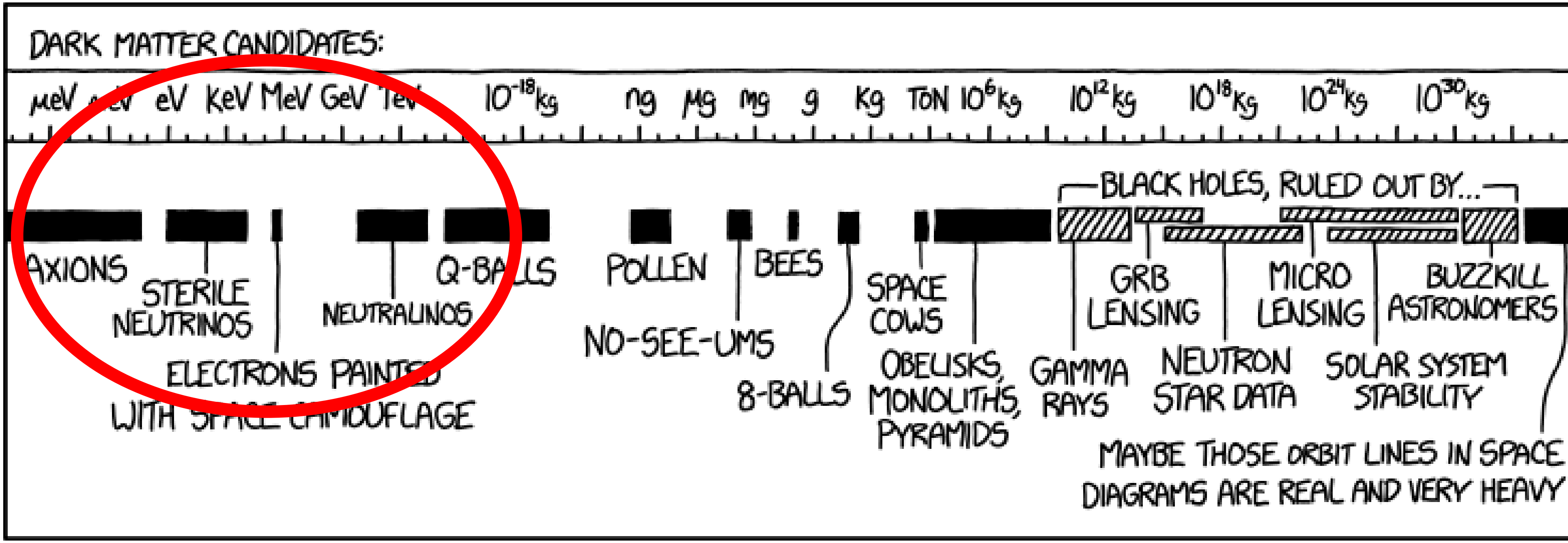
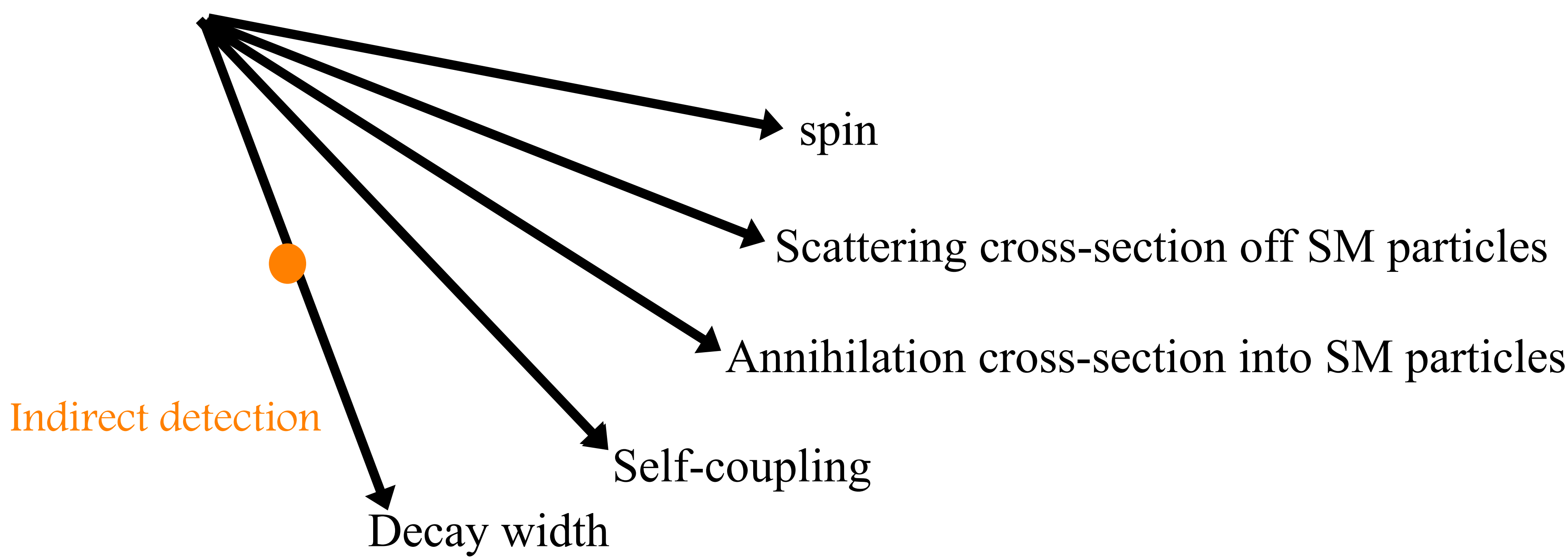
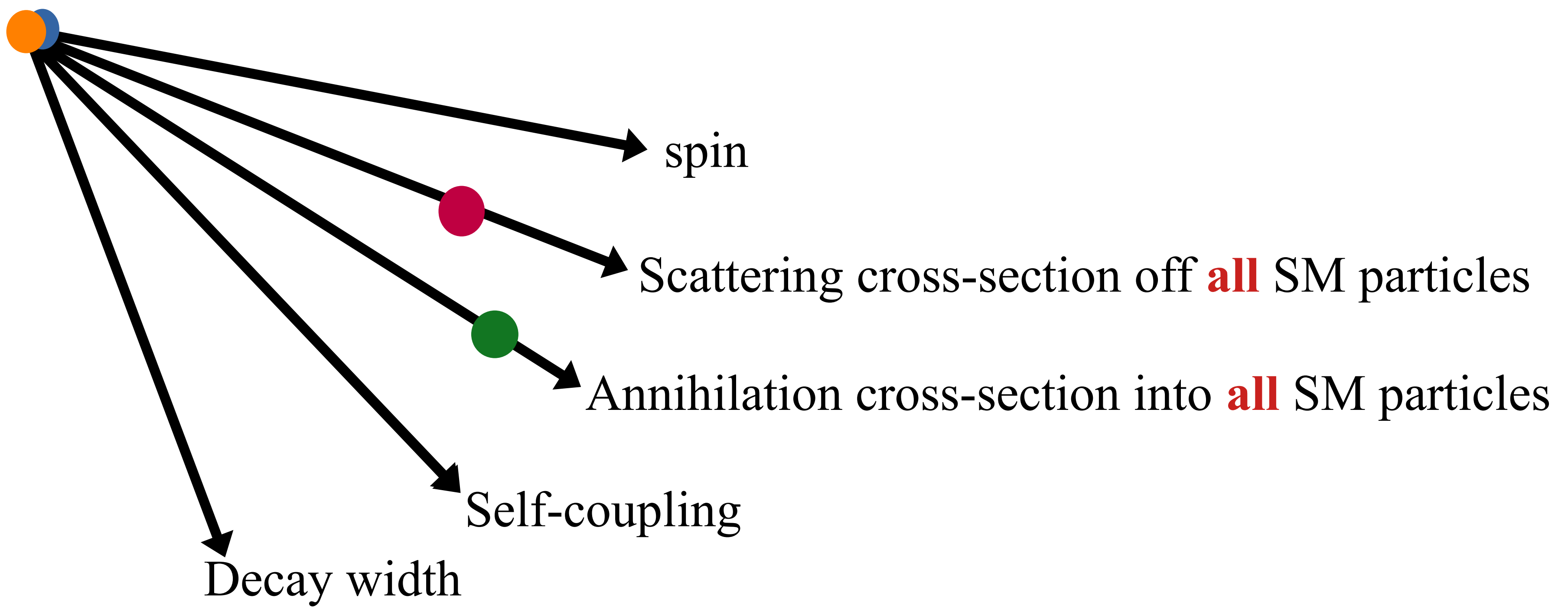




The dark matter zoo

Traditional dark matter searches optimized to detect the lightest neutralino of the Minimal Supersymmetric Standard Model.



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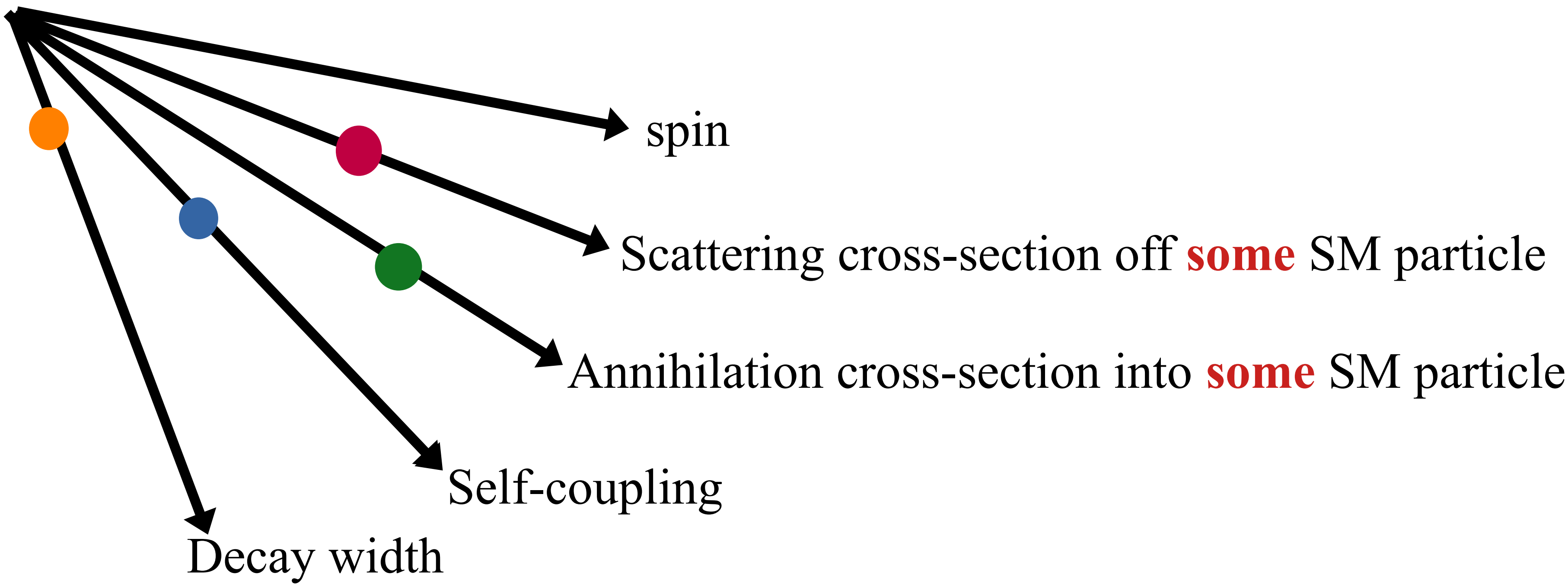

Modern approach:

- Be agnostic about the model.
- Identify distinct DM signals that allow to explore as much parameter space as possible.

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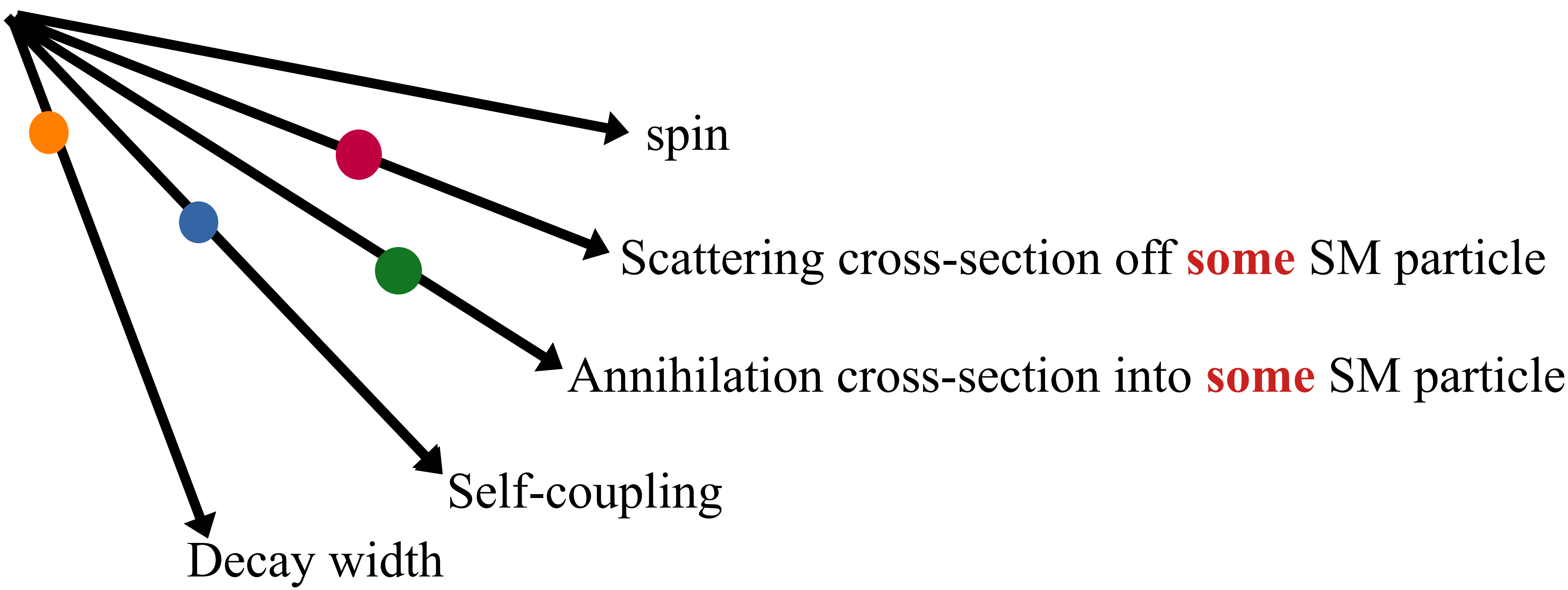

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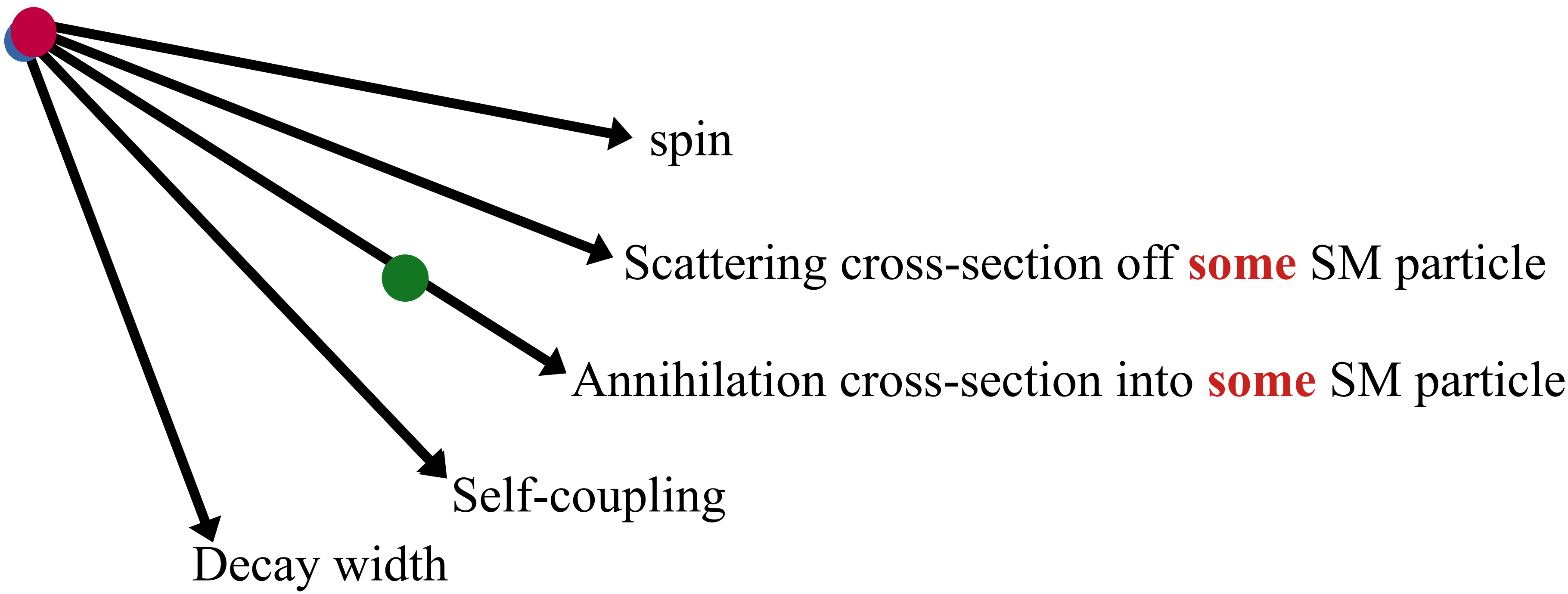
- Be agnostic about the model.
- Identify distinct DM signals that allow to explore as much parameter space as possible.

No stone must be left unturned!

Probing the annihilation cross-section



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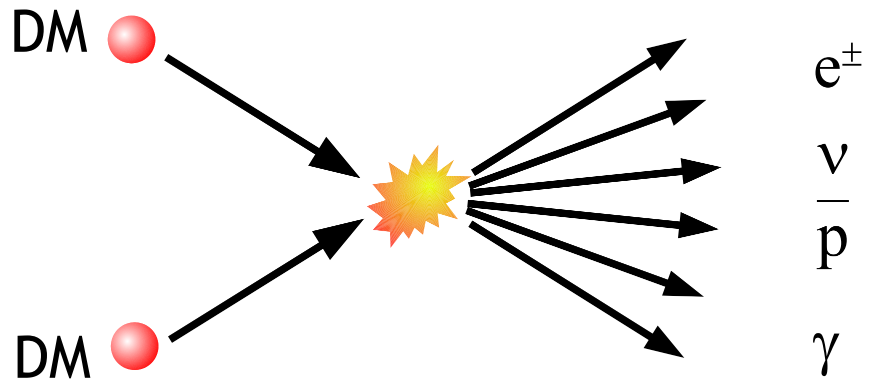

Number of particles of the type "i" produced at the position r per unit time and unit volume:

$$Q(T,\vec{r}) = \frac{1}{2}\frac{\rho_\chi^2(\vec{r})}{m_\chi^2}\sum_i (\sigma v)_i \frac{dN^i}{dT}$$

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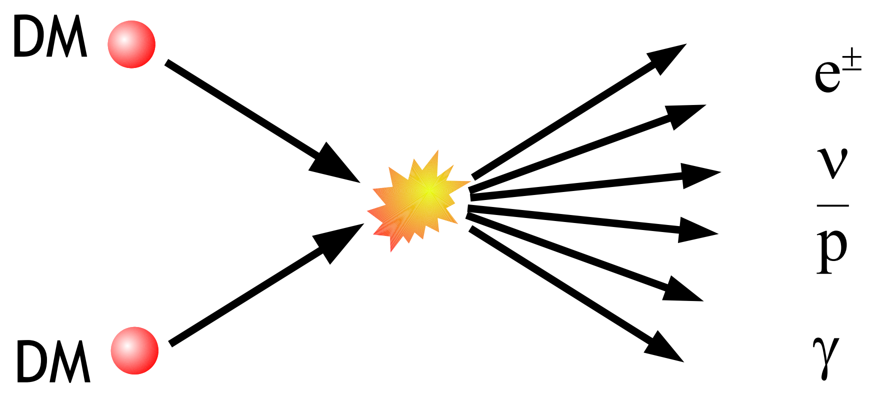
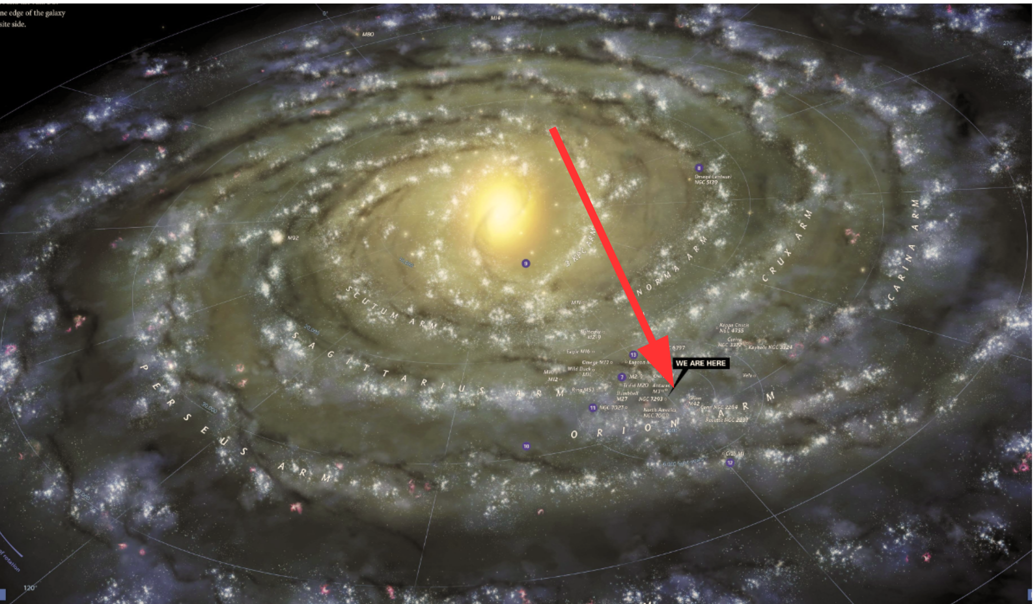
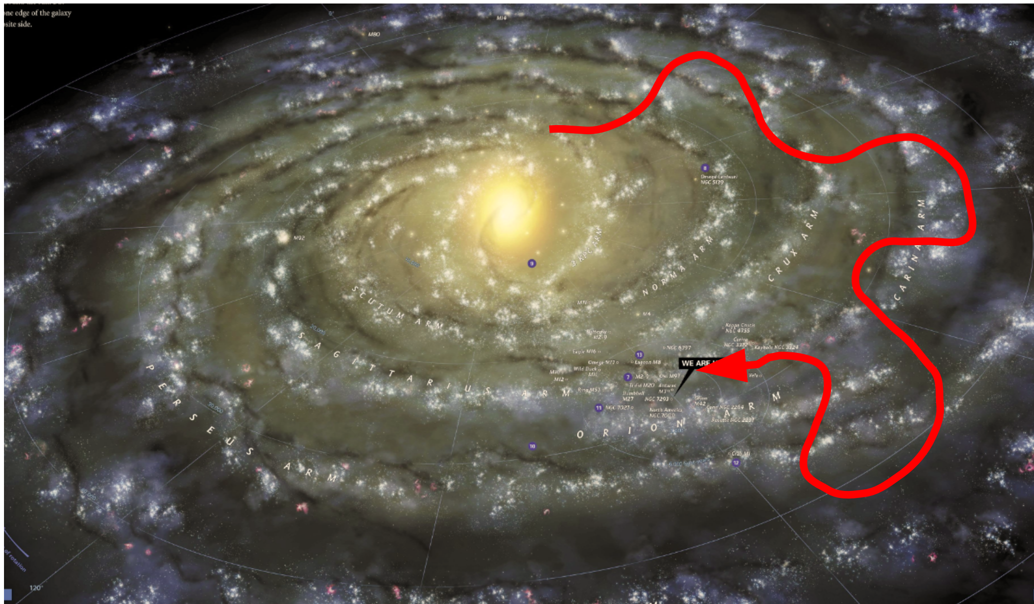


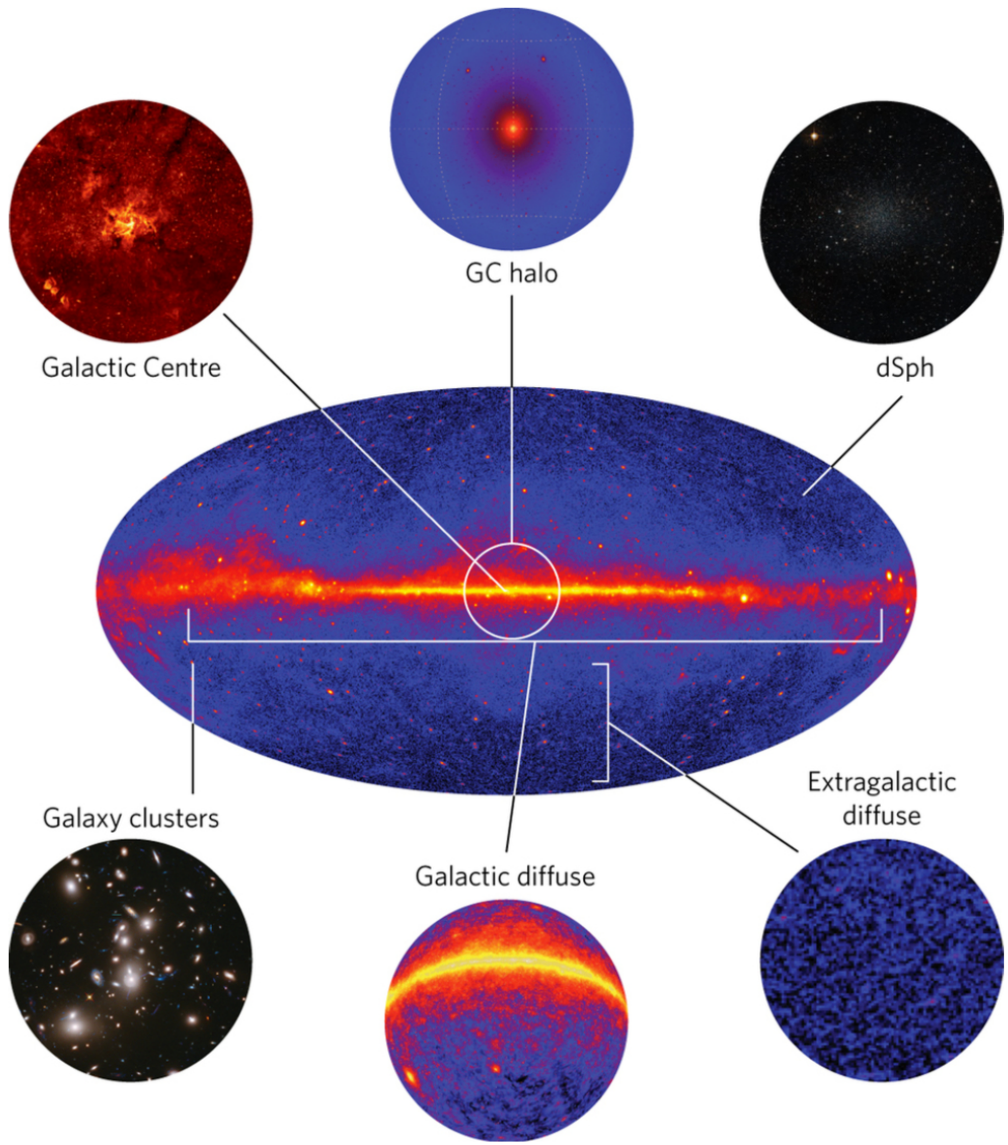
Neutral particles propagate in straight lines practically without losing energy. Charged particles, on the other hand, propagate in a complicated way through the tangled magnetic field of our Galaxy.





Gamma-rays from dark matter annihilation

Possible targets for detection of gamma-rays from annihilation



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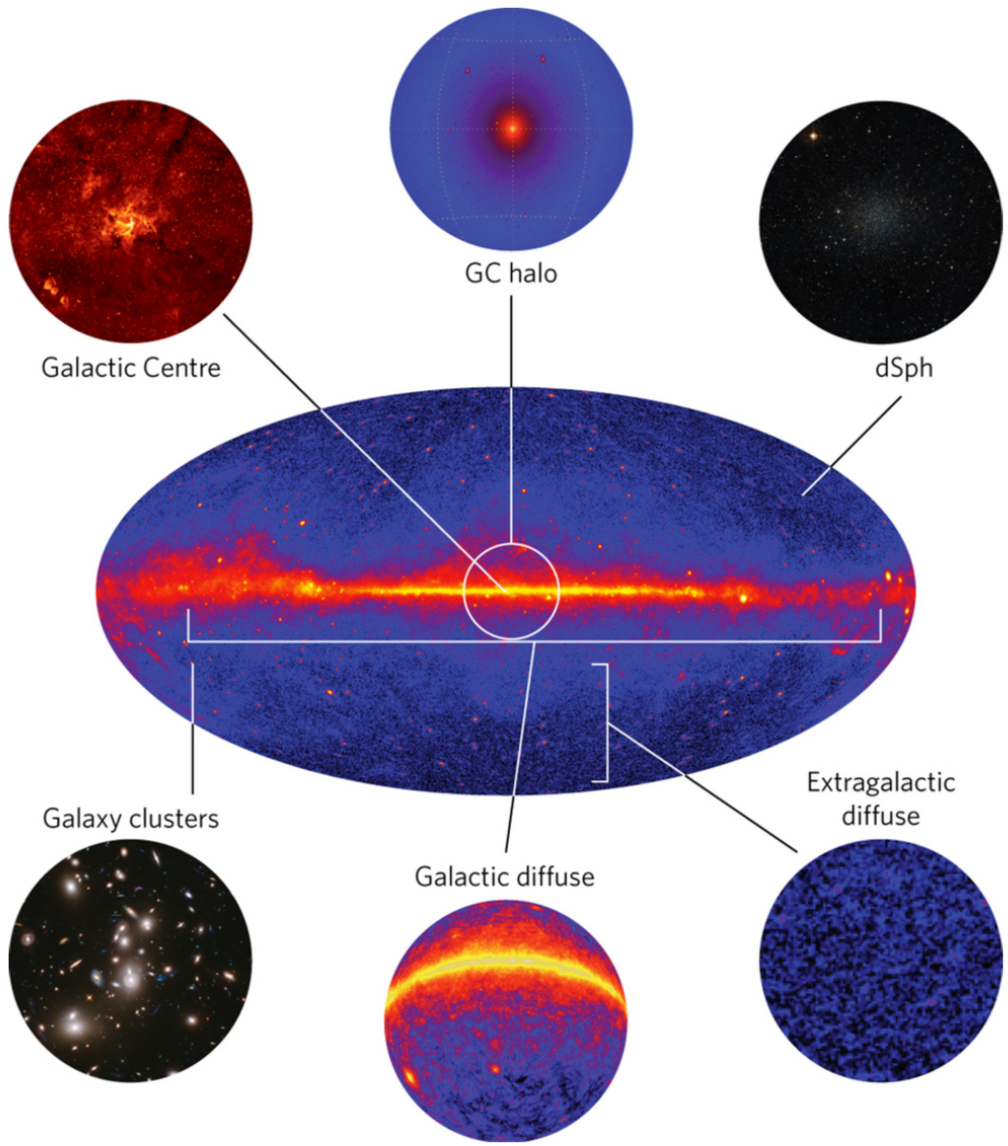

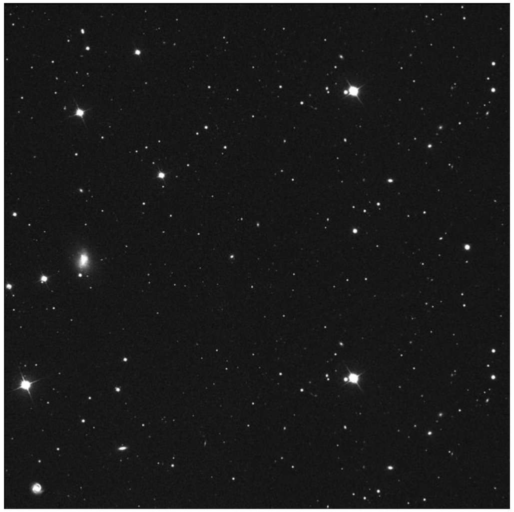

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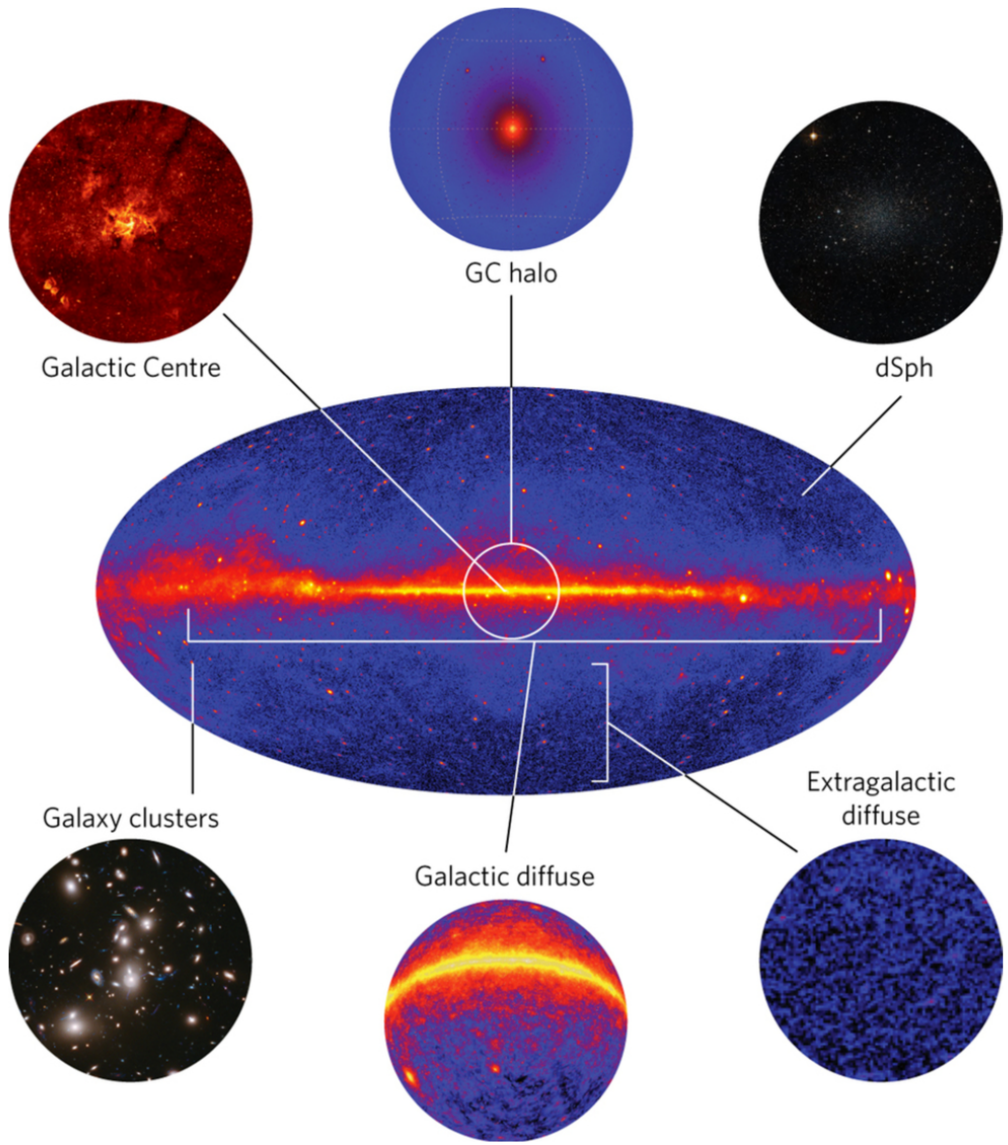

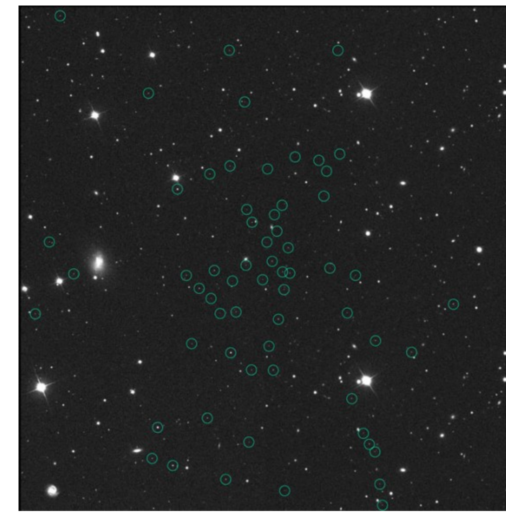

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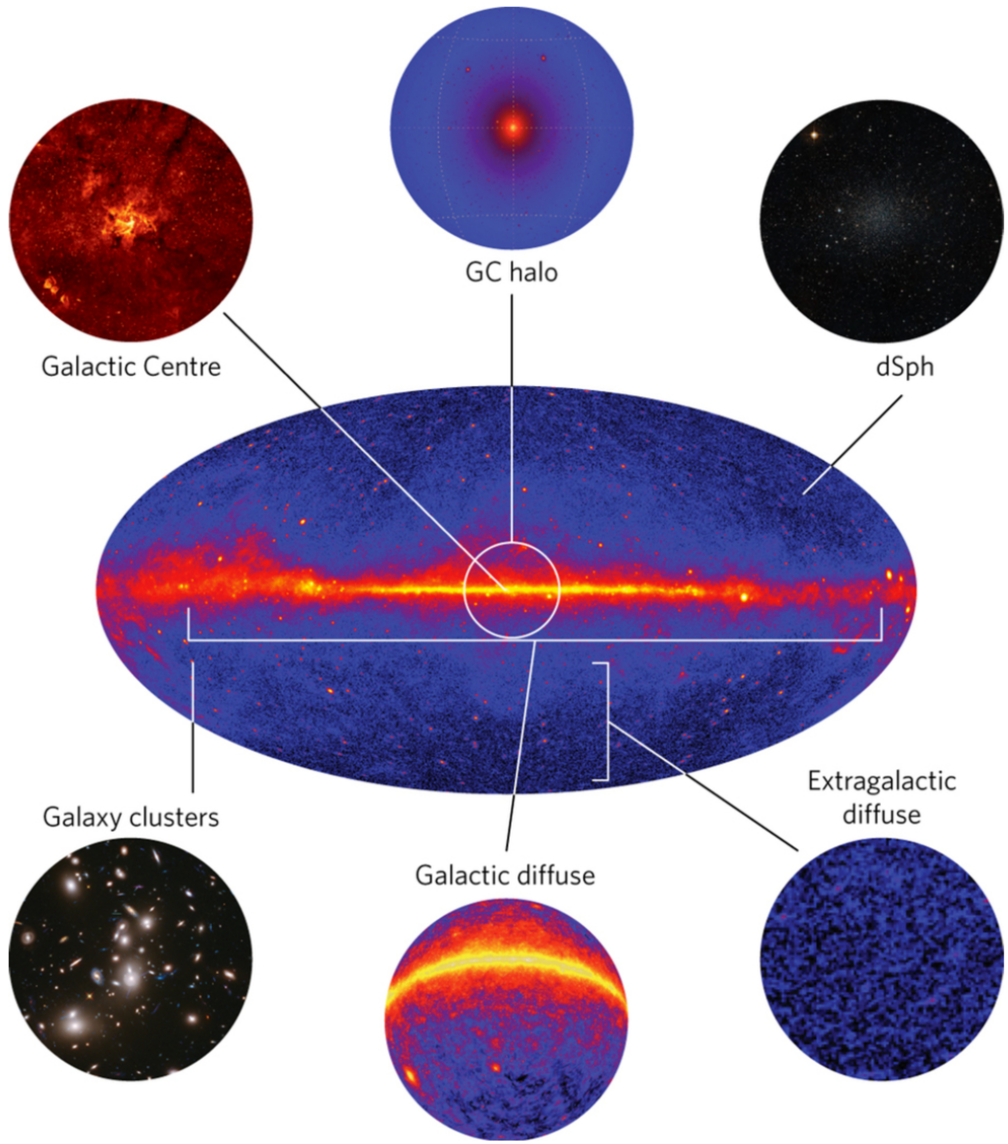

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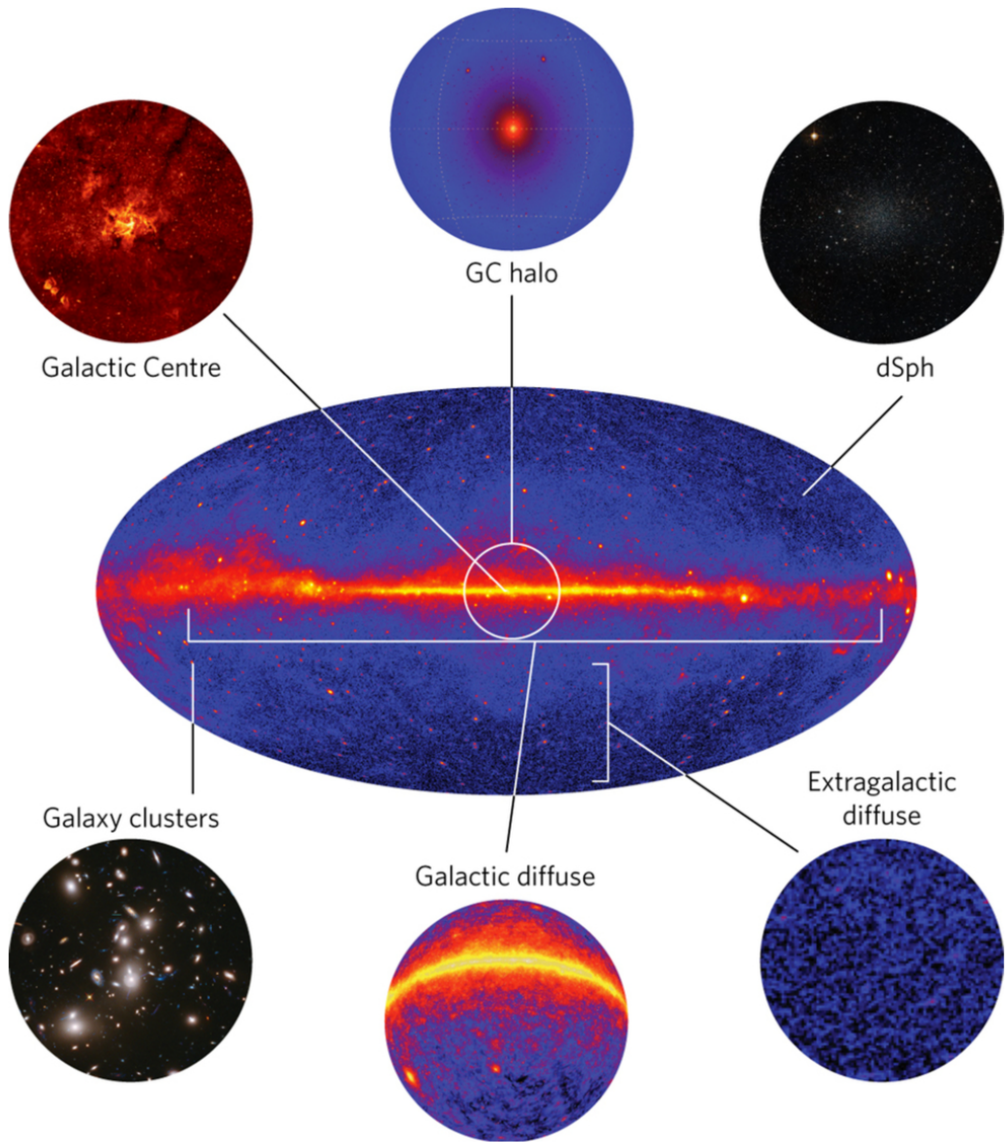

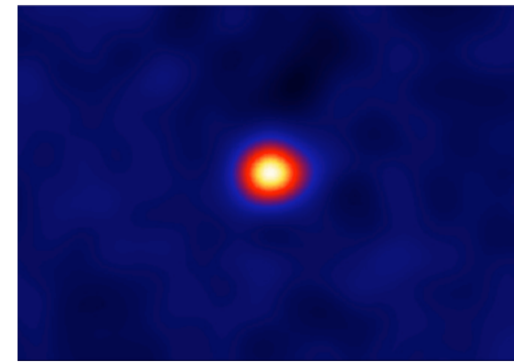

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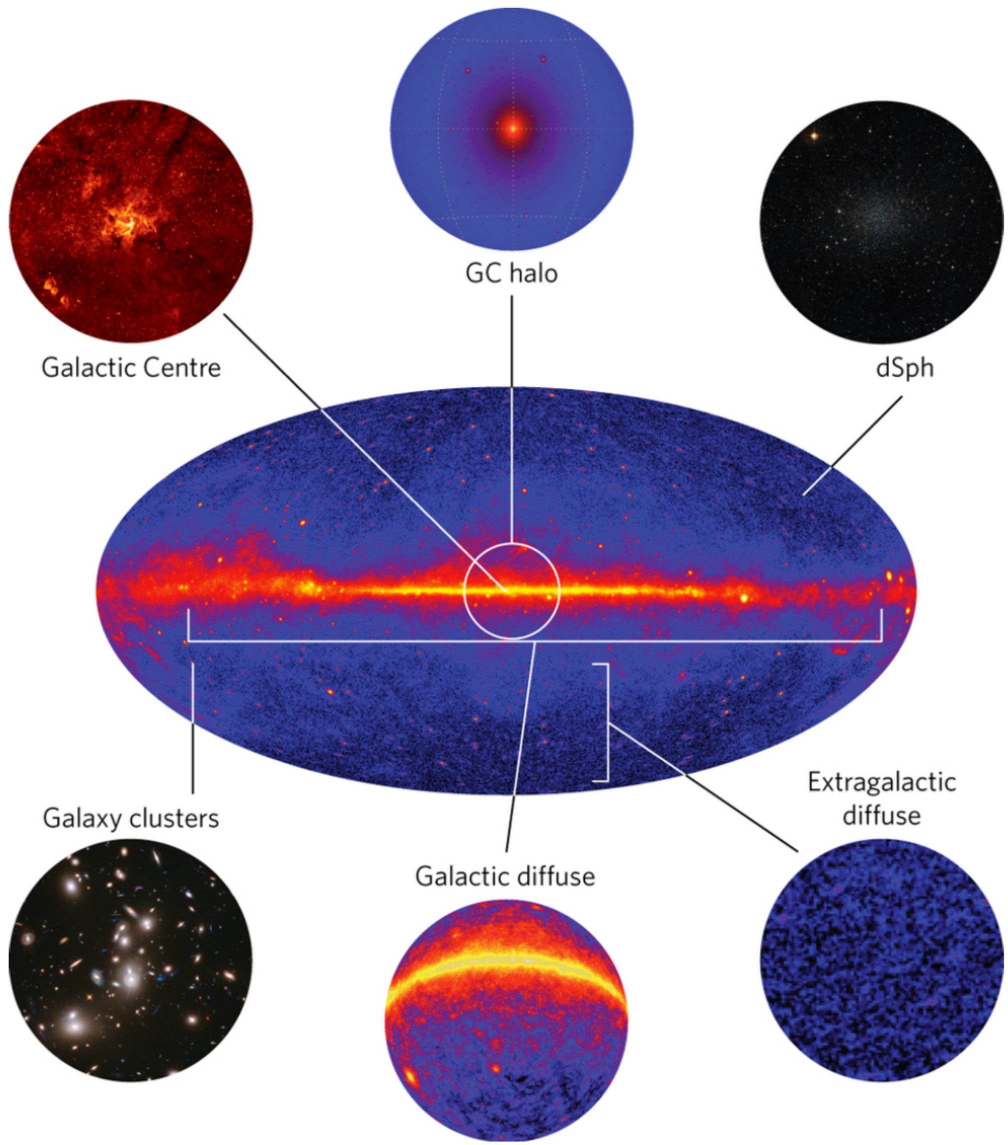

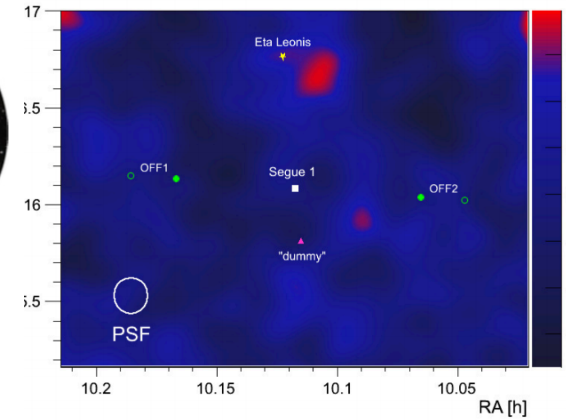

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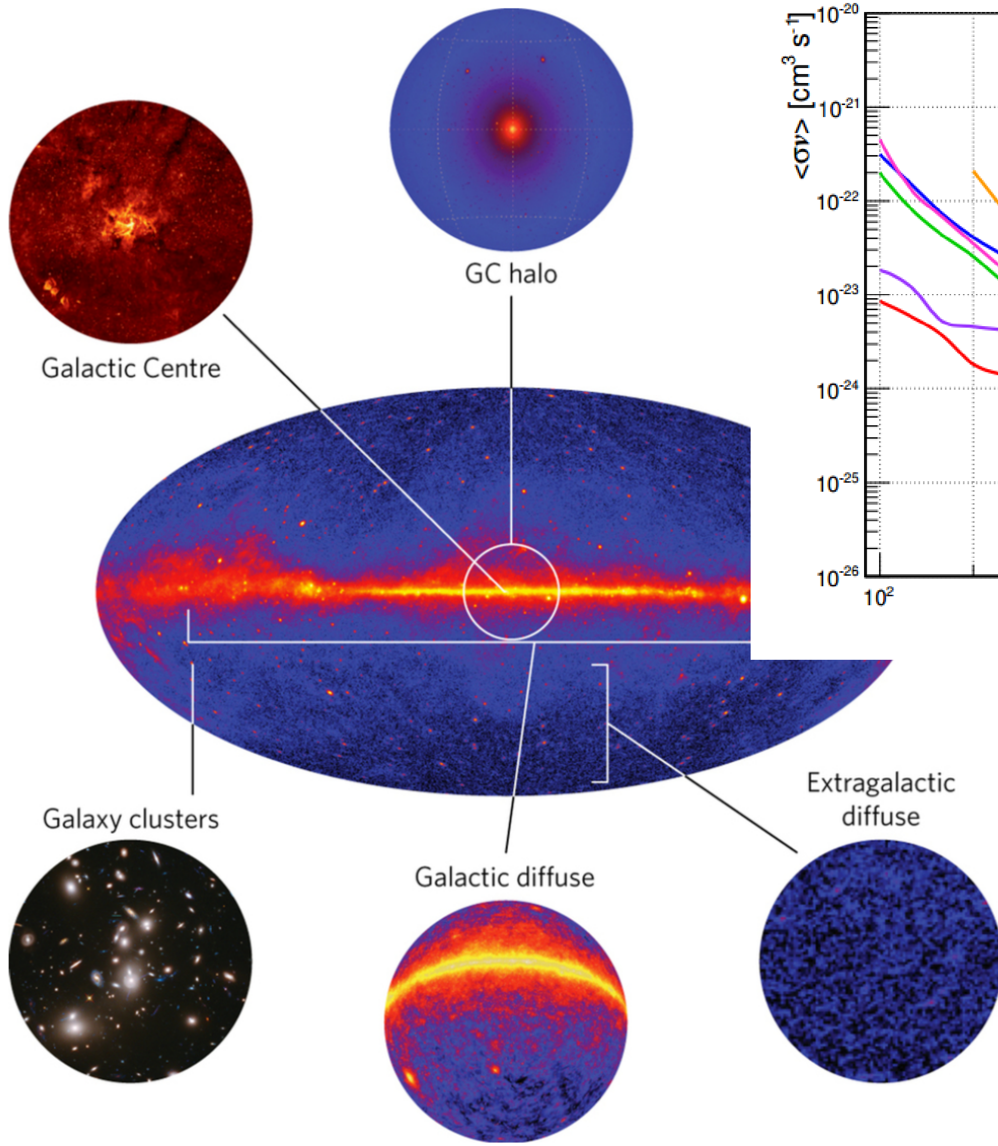

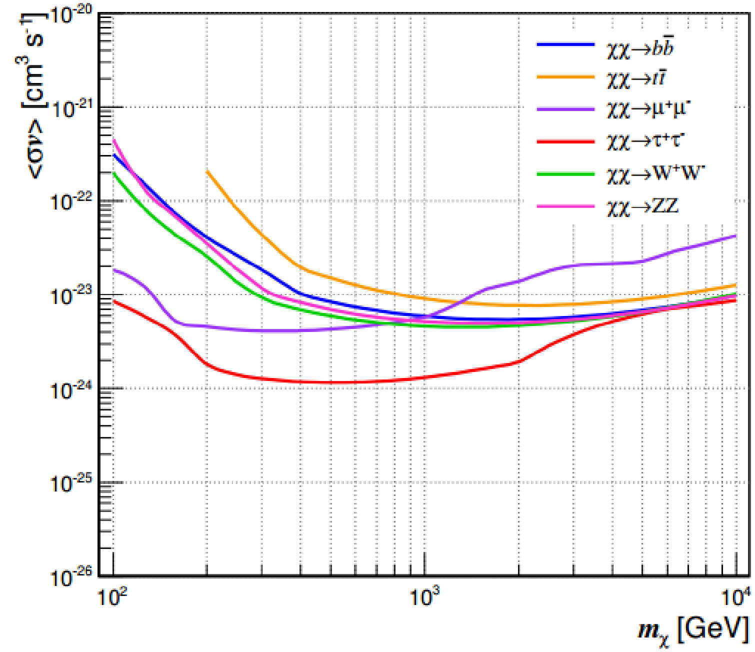

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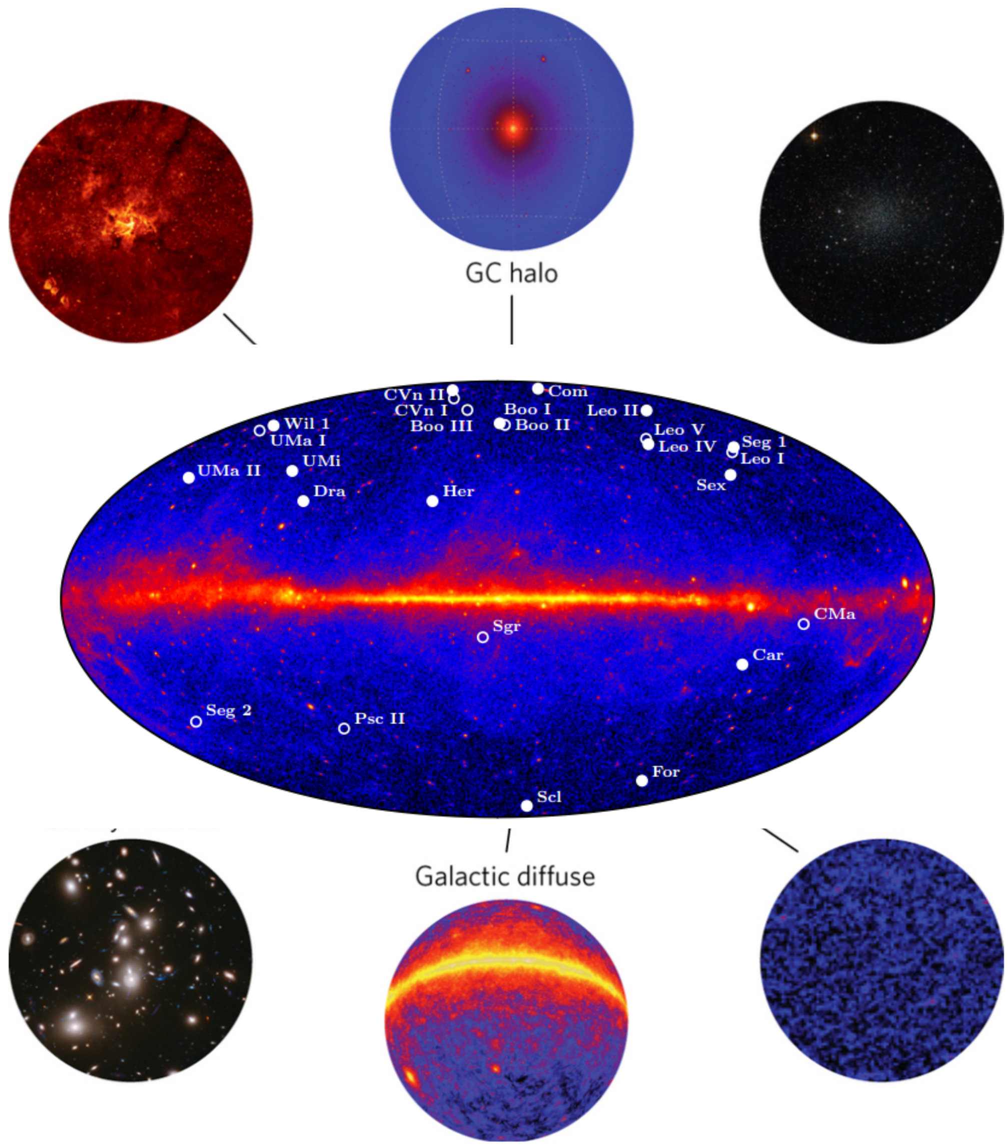

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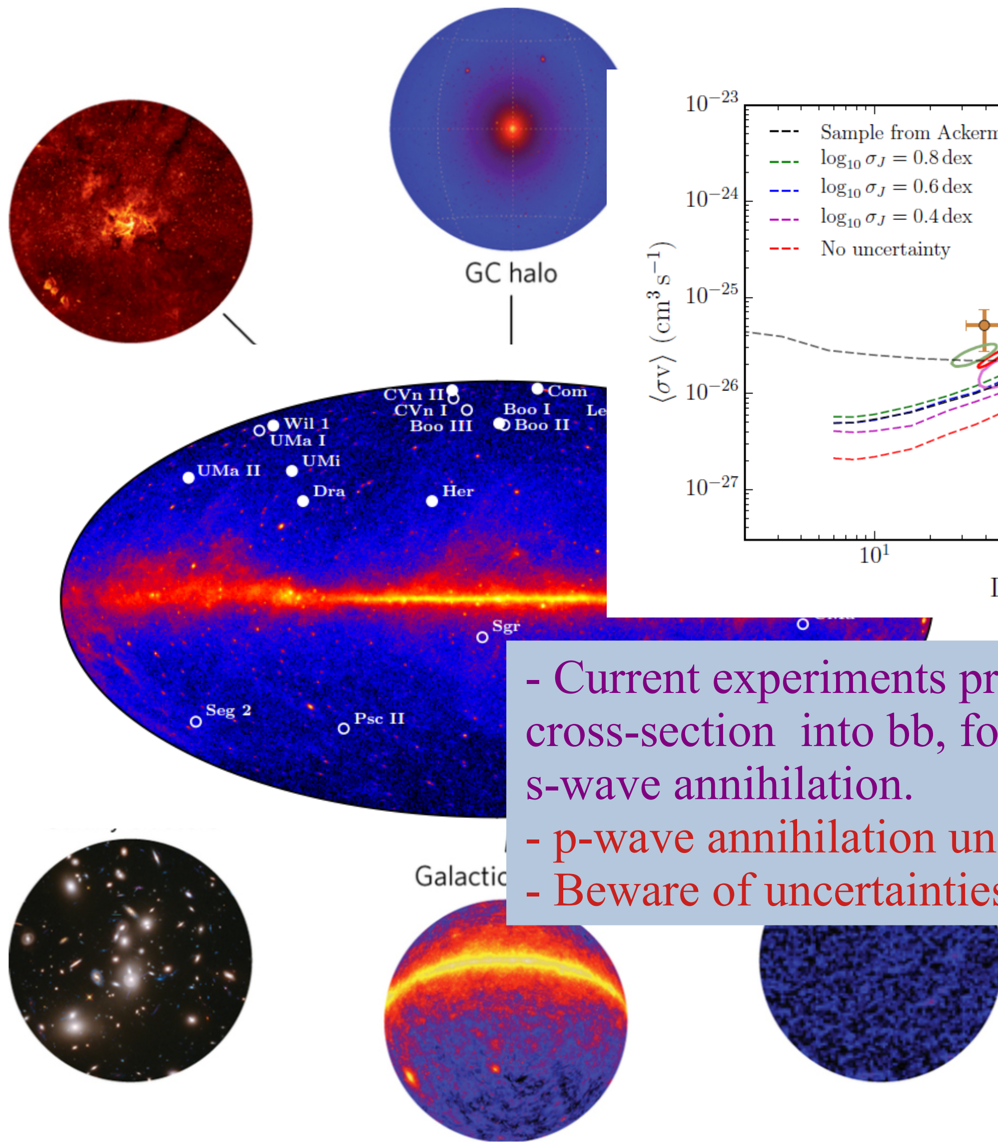

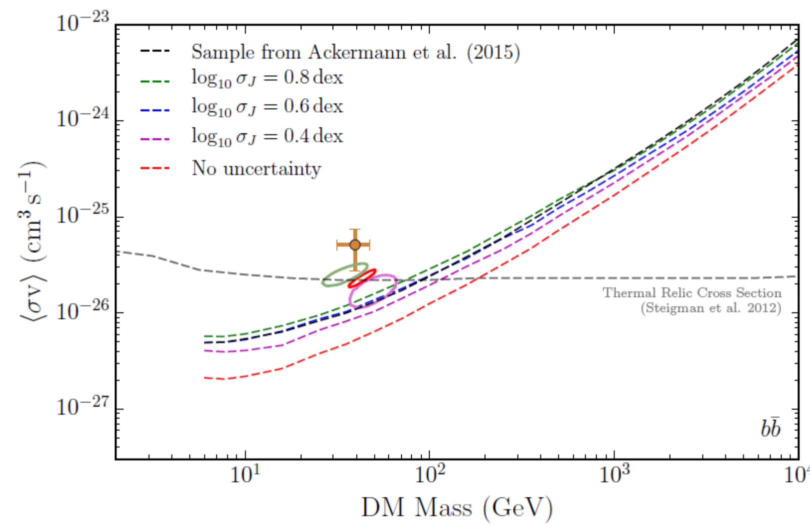

- Current experiments probe the thermal annihilation cross-section into bb, for m<100 GeV, assuming s-wave annihilation.
- p-wave annihilation unconstrained.
- Beware of uncertainties in the J-factors.

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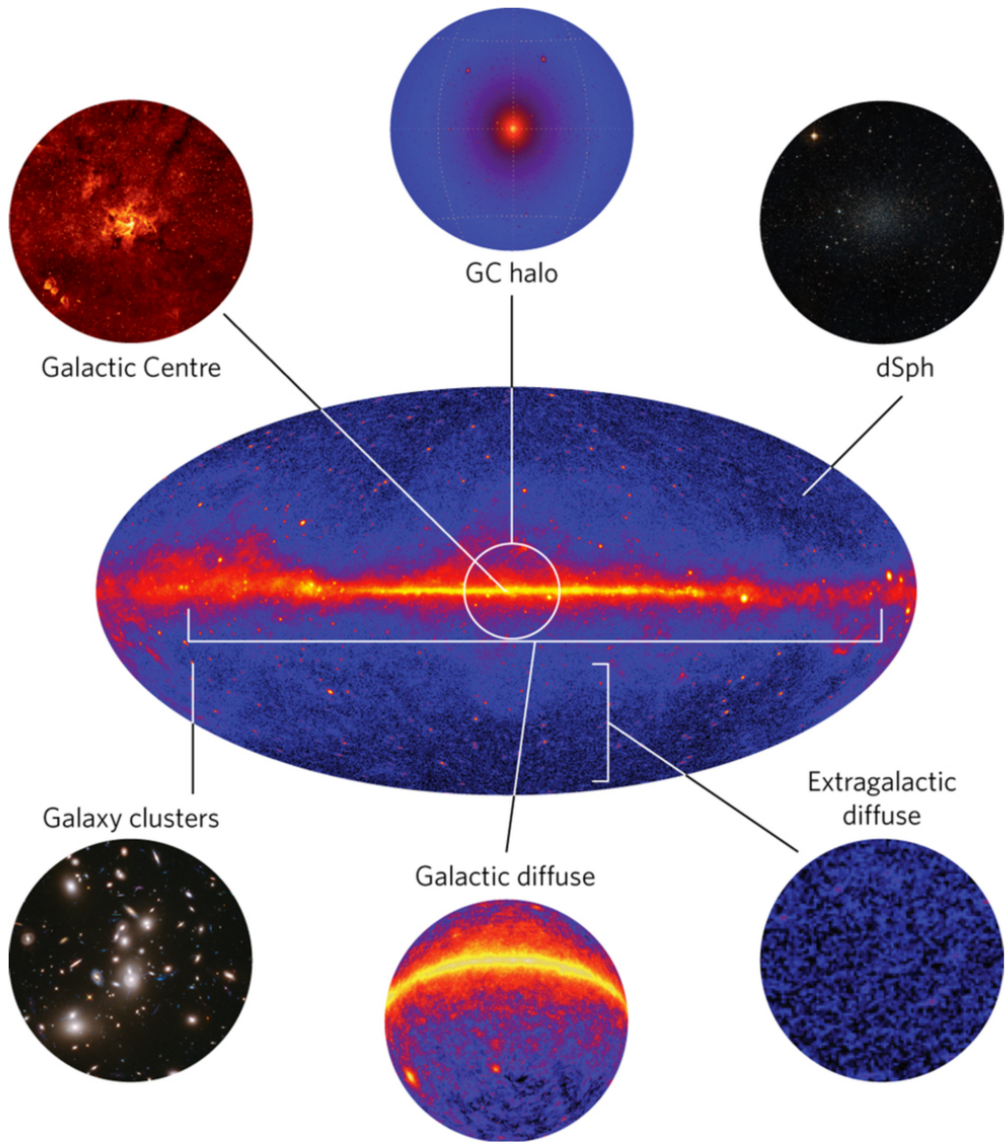

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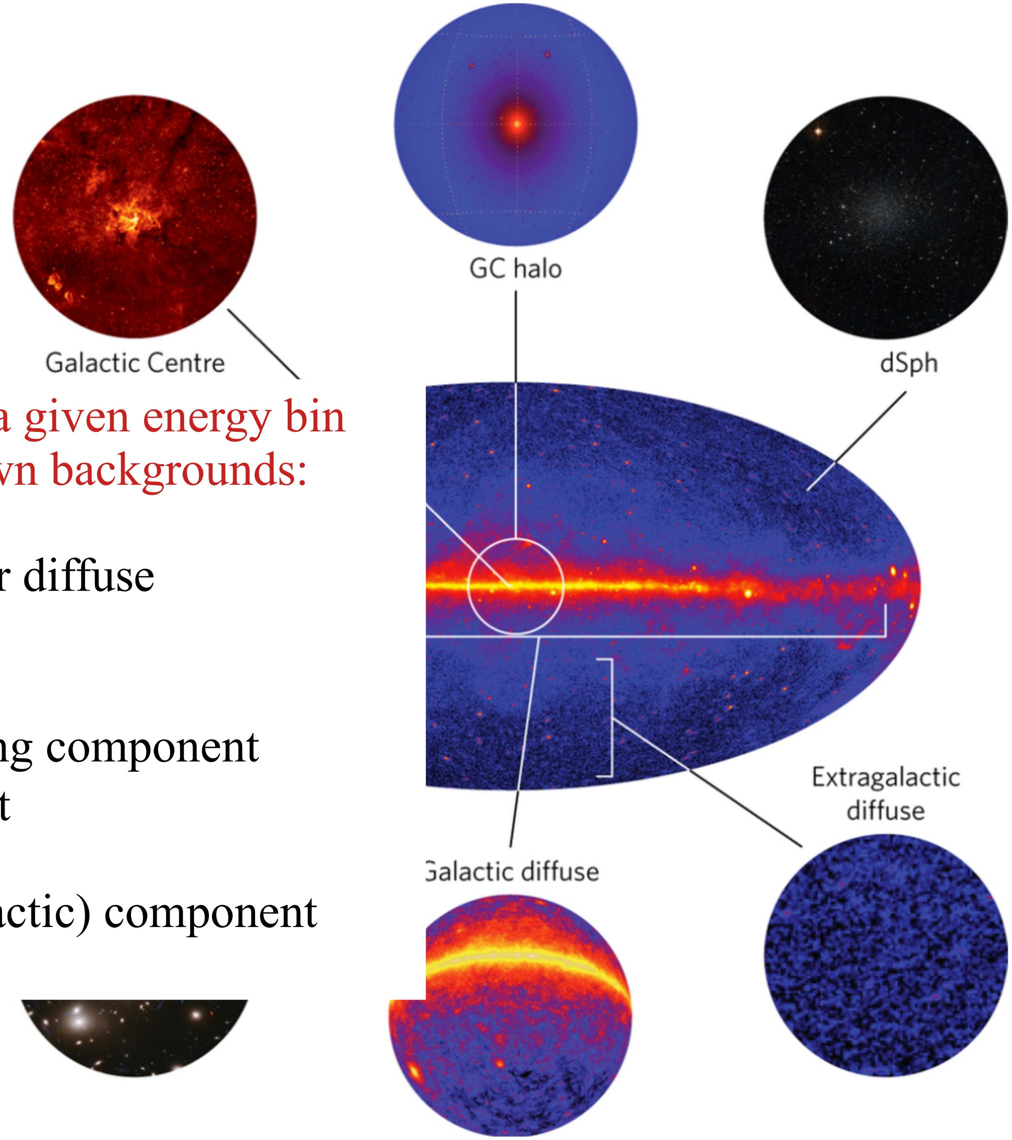

Take the sky map in a given energy bin and subtract the known backgrounds:

- Sources
- Spatial template for diffuse galactic emission
  - π_0 component
  - Bremmstrahlung component
  - ICS component
- Fermi bubbles
- Isotropic (extragalactic) component

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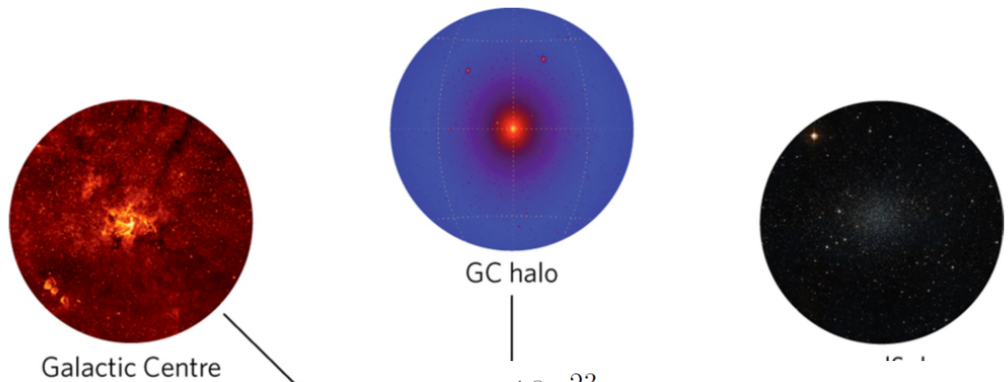

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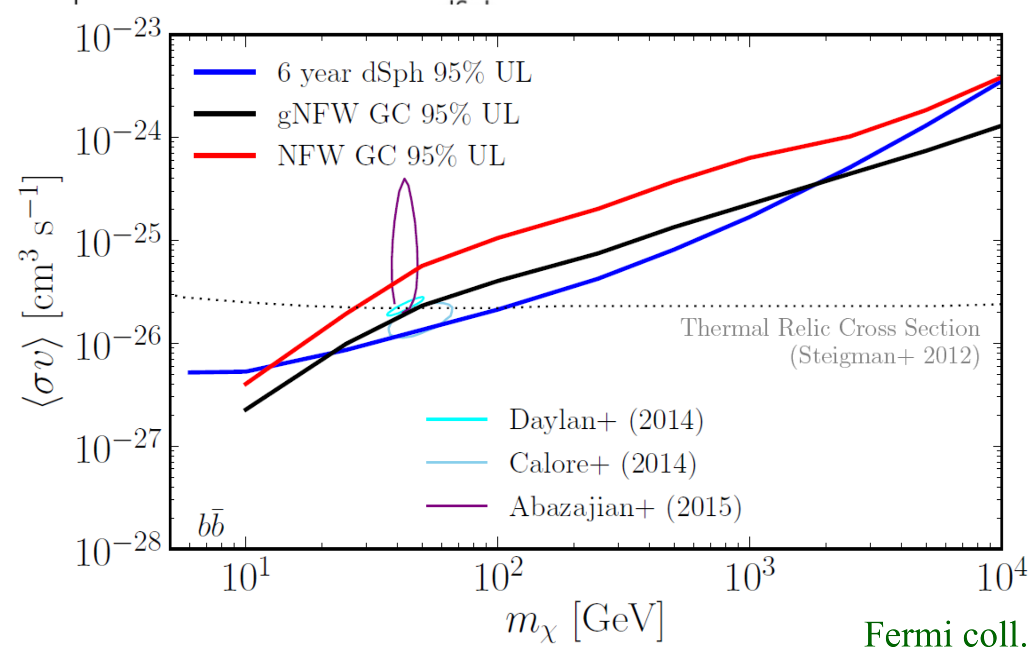
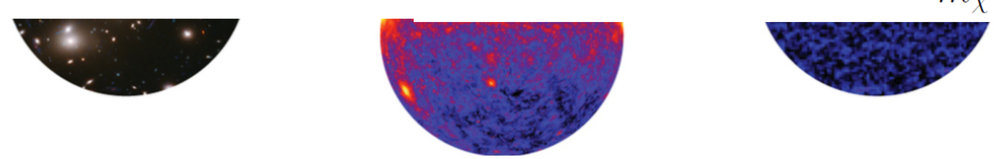


Fermi coll. '17



Antimatter from dark matter annihilation

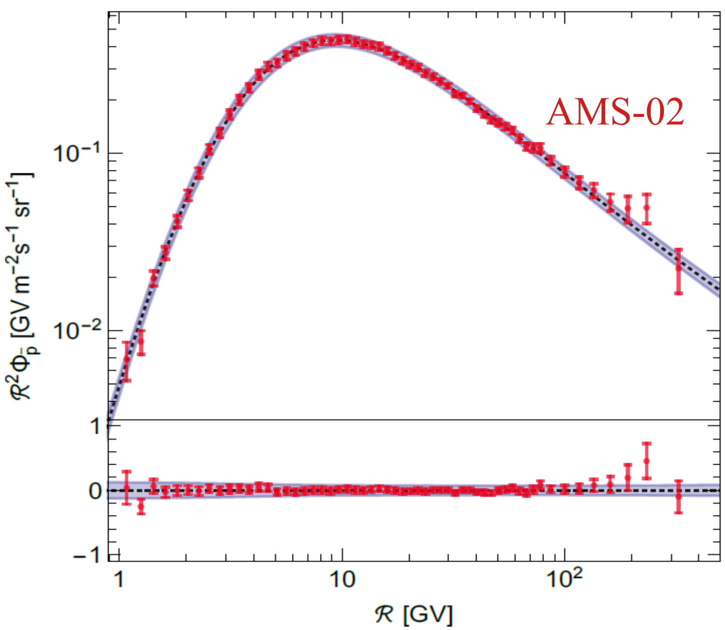
Antimatter particles propagate through the tangled magnetic field of the galaxy in a complicated way, losing energy on their way.

Model the propagation with a diffusion equation:

$$0 = \frac{\partial f}{\partial t} = \nabla \cdot [K(T,\vec{r})\nabla f] + \frac{\partial}{\partial T}[b(T,\vec{r})f] - \nabla \cdot [\vec{V}_c(\vec{r})f] - 2h\delta(z)\Gamma_{\rm ann} f + Q(T,\vec{r}) \,.$$

Assumptions on the quantities entering are necessary.

Still, very good agreement between the expected antiproton flux from collisions of cosmic rays on the nuclei of the interstellar medium, and the antiproton data.



Reinert, Winkler.
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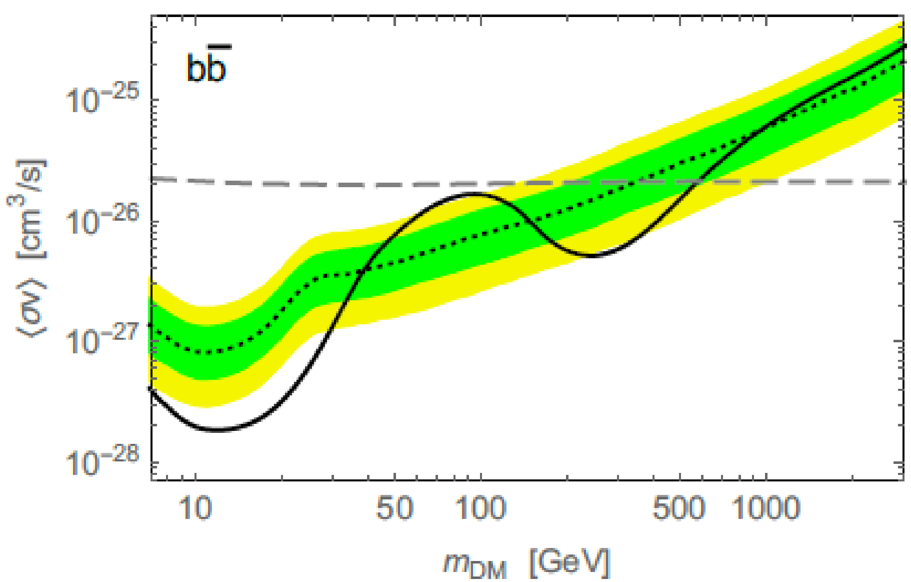

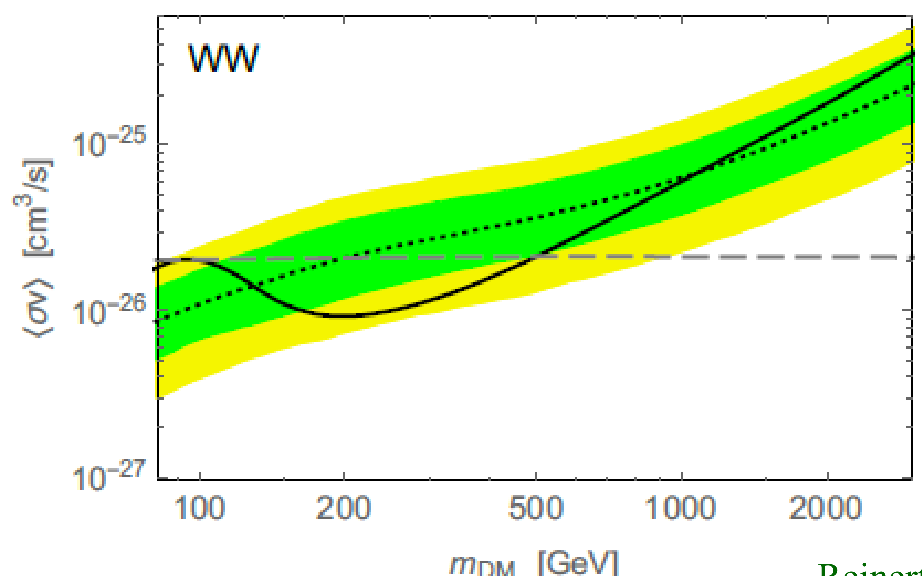

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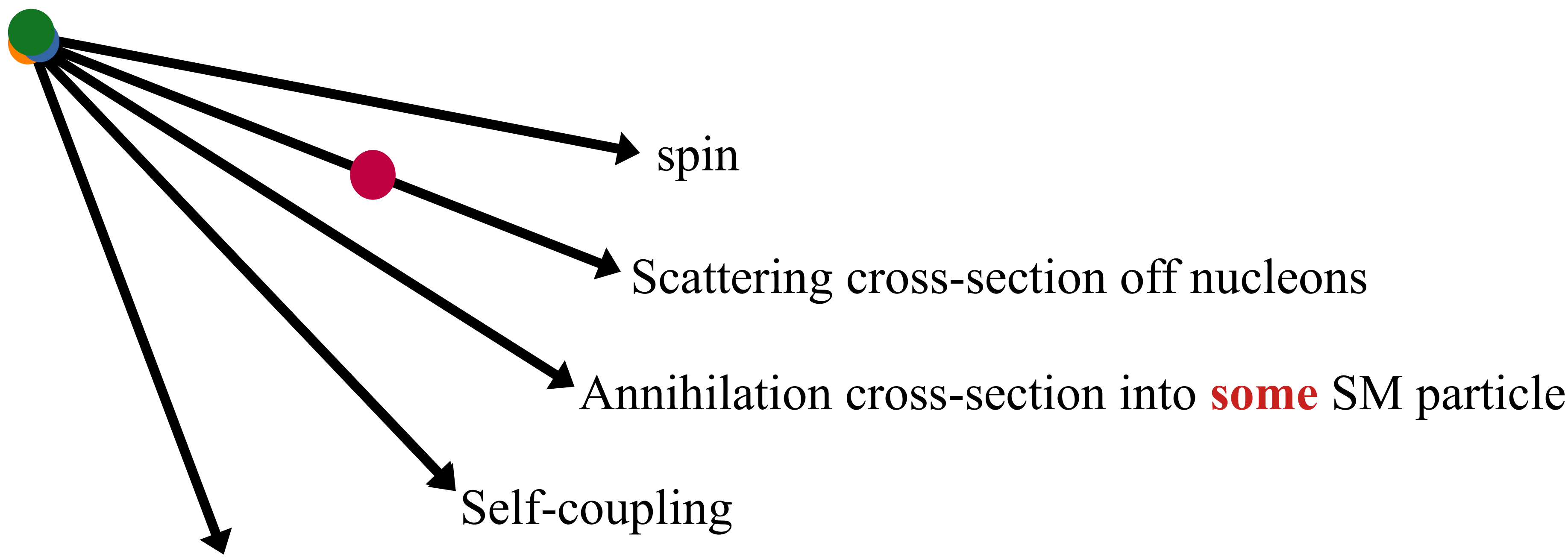
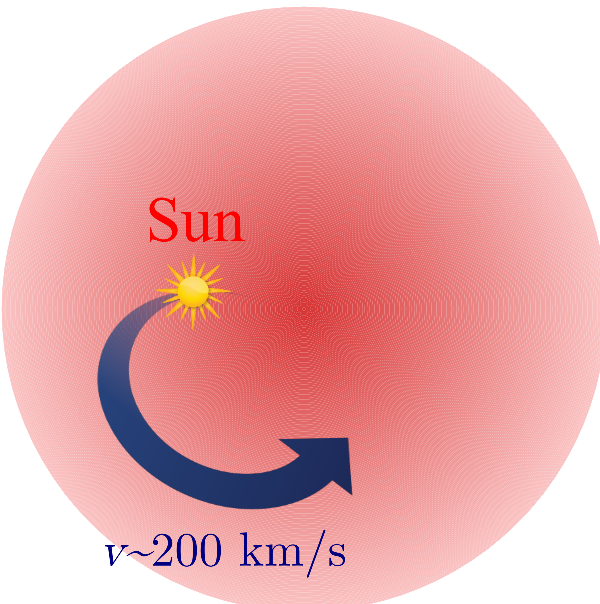
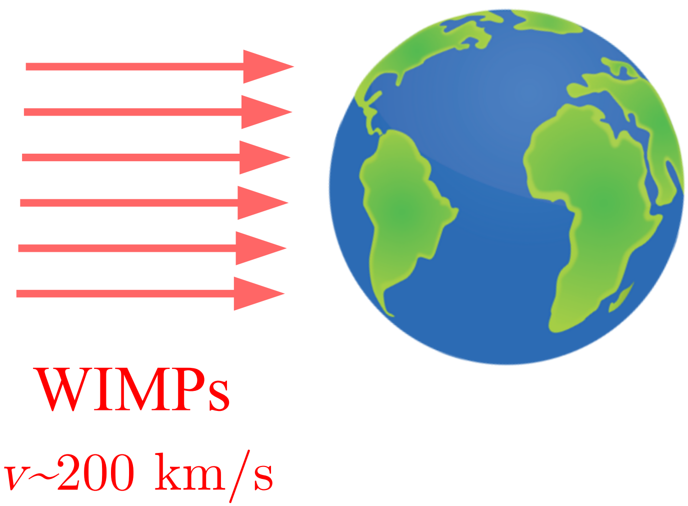
Probing the scattering with nucleons



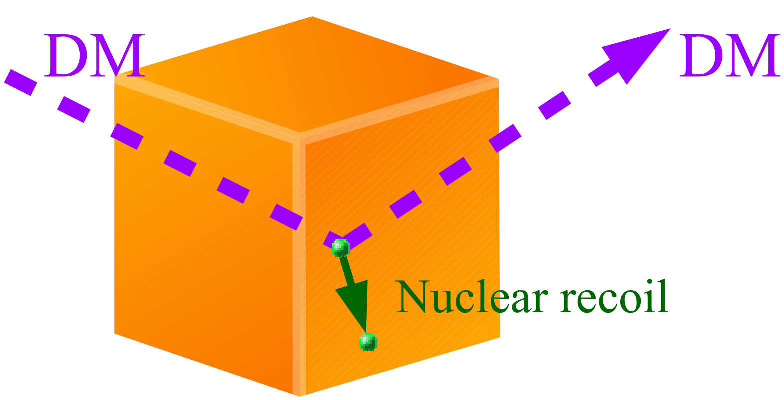
Probing the scattering with nucleons

The Sun (and the Earth) might be moving through a “gas” of dark matter particles.





Once in a while a dark matter particle will interact with a nucleus. The nucleus then recoils, producing vibrations, ionizations or scintillation light in the detector.



No significant excess detected so far

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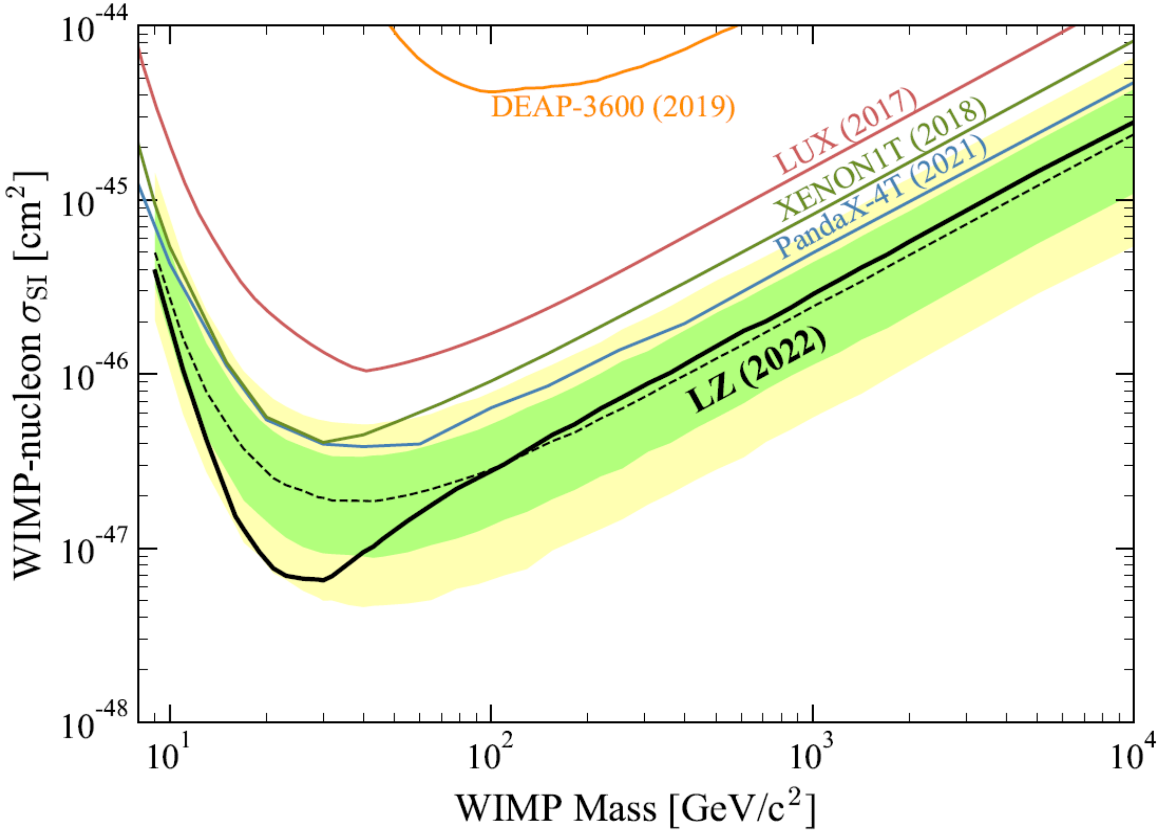

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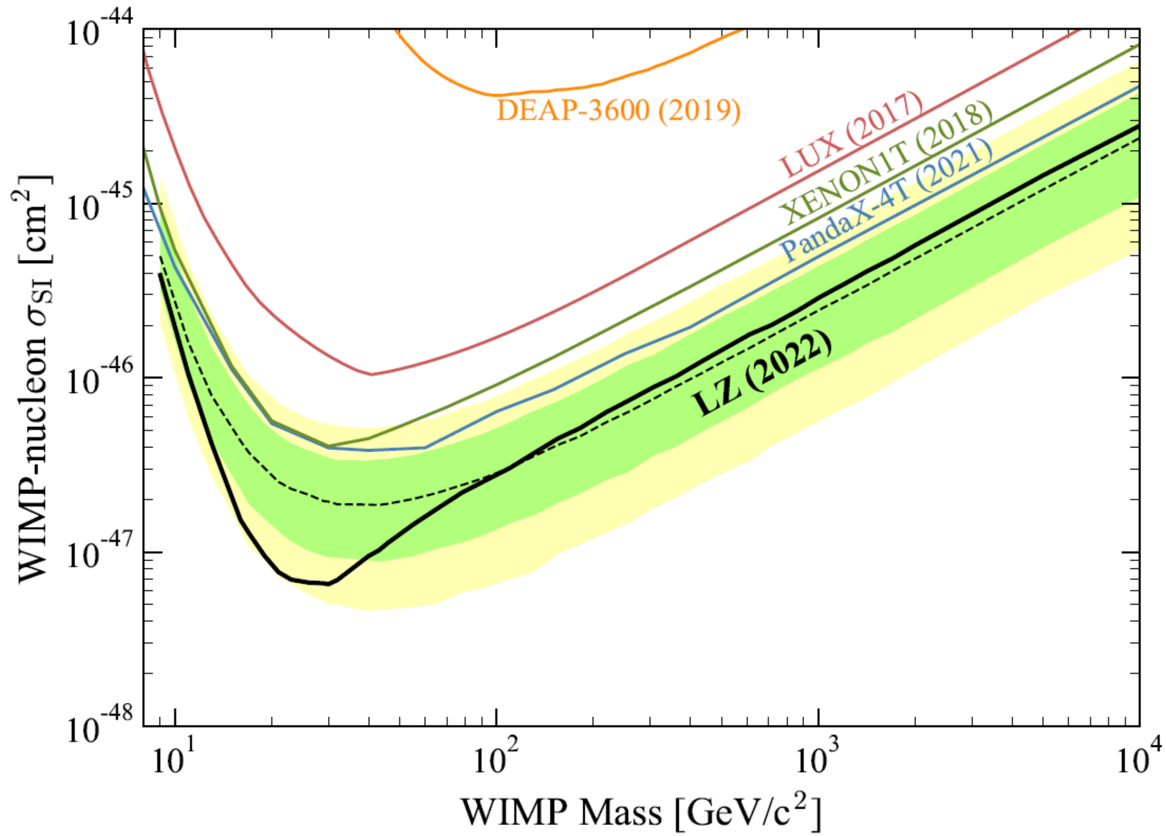

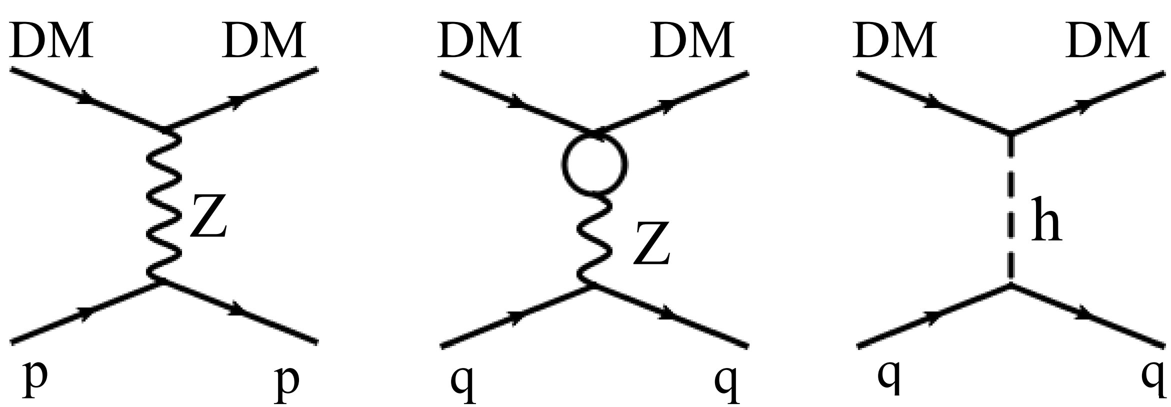

$\sigma \sim 10^{-40}\,\mathrm{cm}^2$ $\sigma \sim 10^{-45}\,\mathrm{cm}^2$ $\sigma \lesssim 10^{-45}\,\mathrm{cm}^2$

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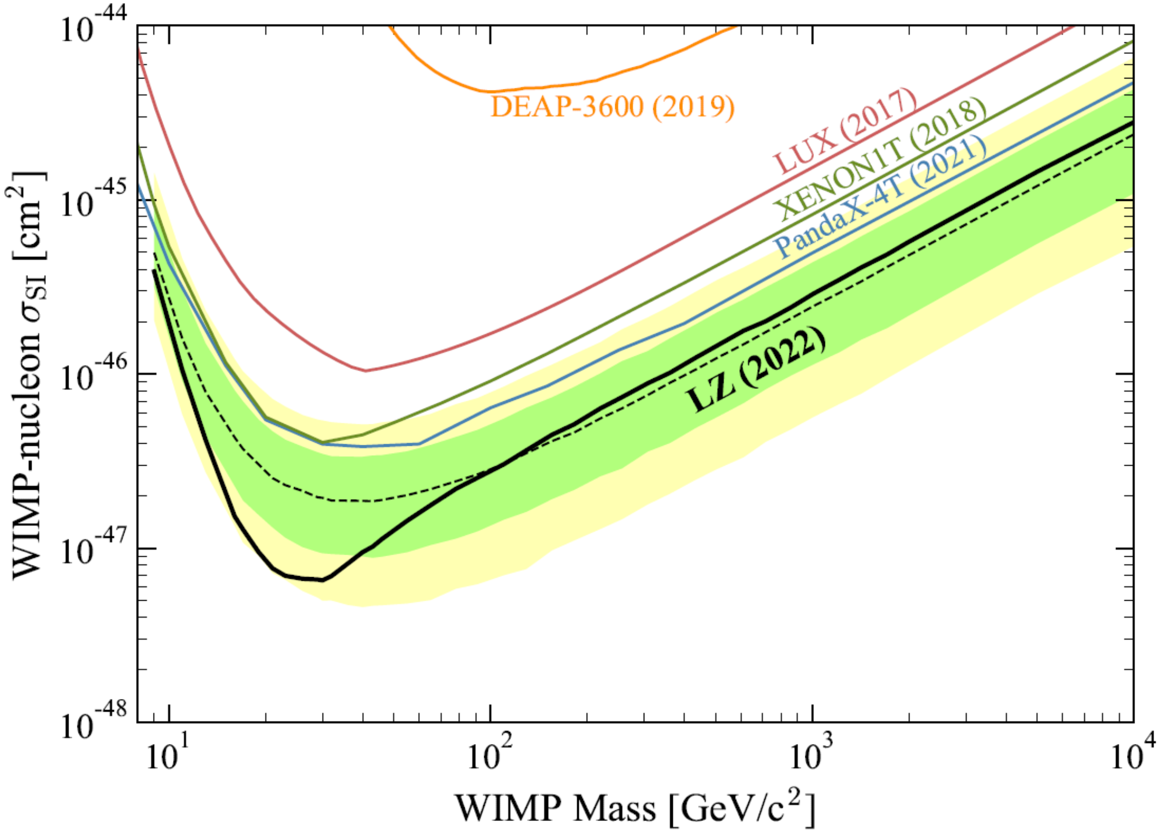
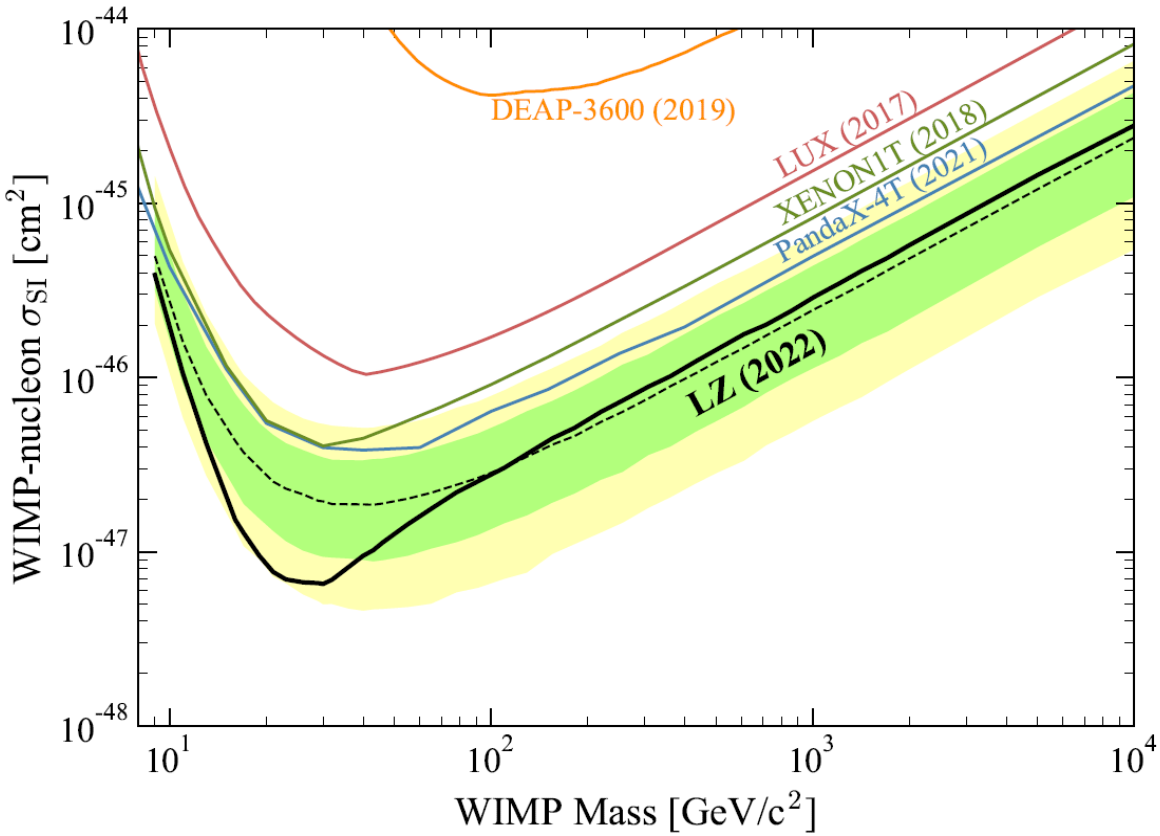


Smallprint:

- DM interacts only through the spin-independent interaction
- DM couples with equal strength to protons and neutrons (isoscalar)
- Local DM density ρ=0.3 GeV/cm3.
- DM velocity distribution given by a Maxwell-Boltzmann, truncated at the escape velocity.

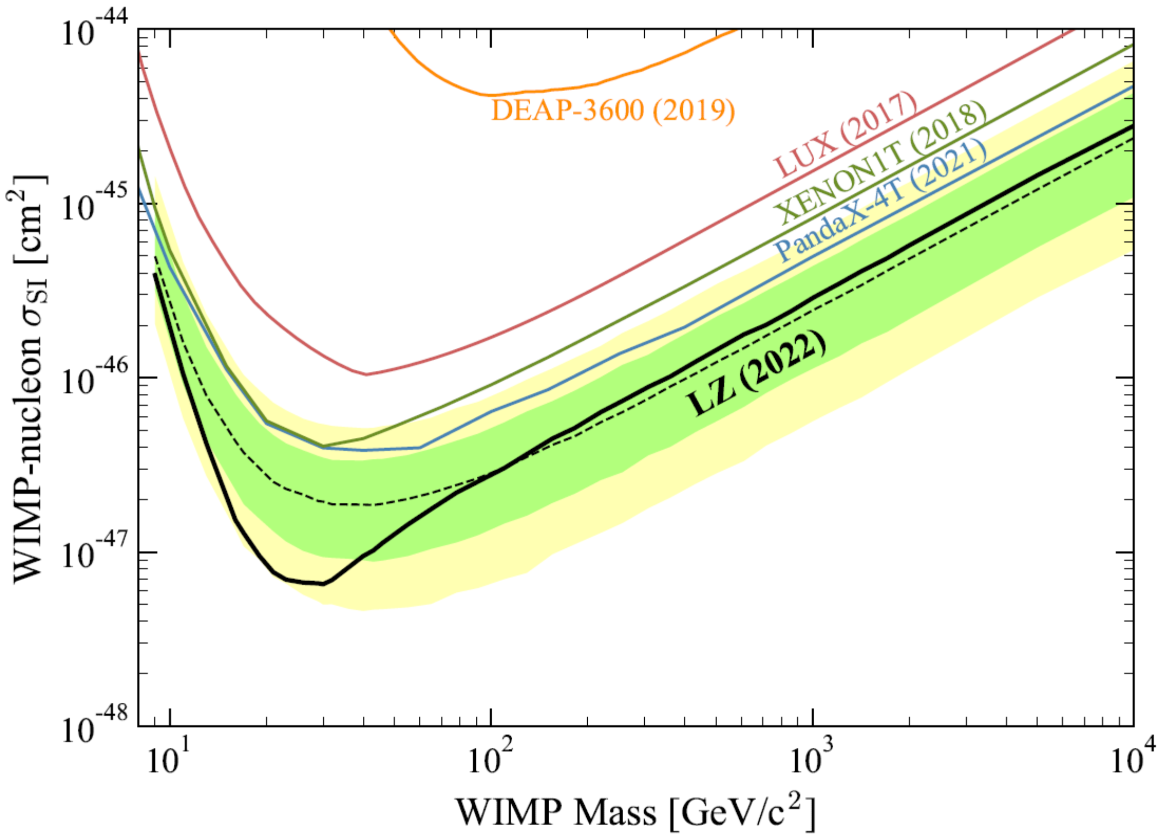
Probing the scattering with nucleons



Differential recoil rate

$$\frac{dR}{dE_R} = \frac{\rho_{\rm loc}}{m_A m_{\rm DM}} \int_{v \geq v_{\rm min}(E_R)} {\rm d}^3 v \, v f(\vec{v} + \vec{v}_{\rm obs}(t)) \, \frac{{\rm d}\sigma}{{\rm d}E_R}$$

Probing the scattering with nucleons



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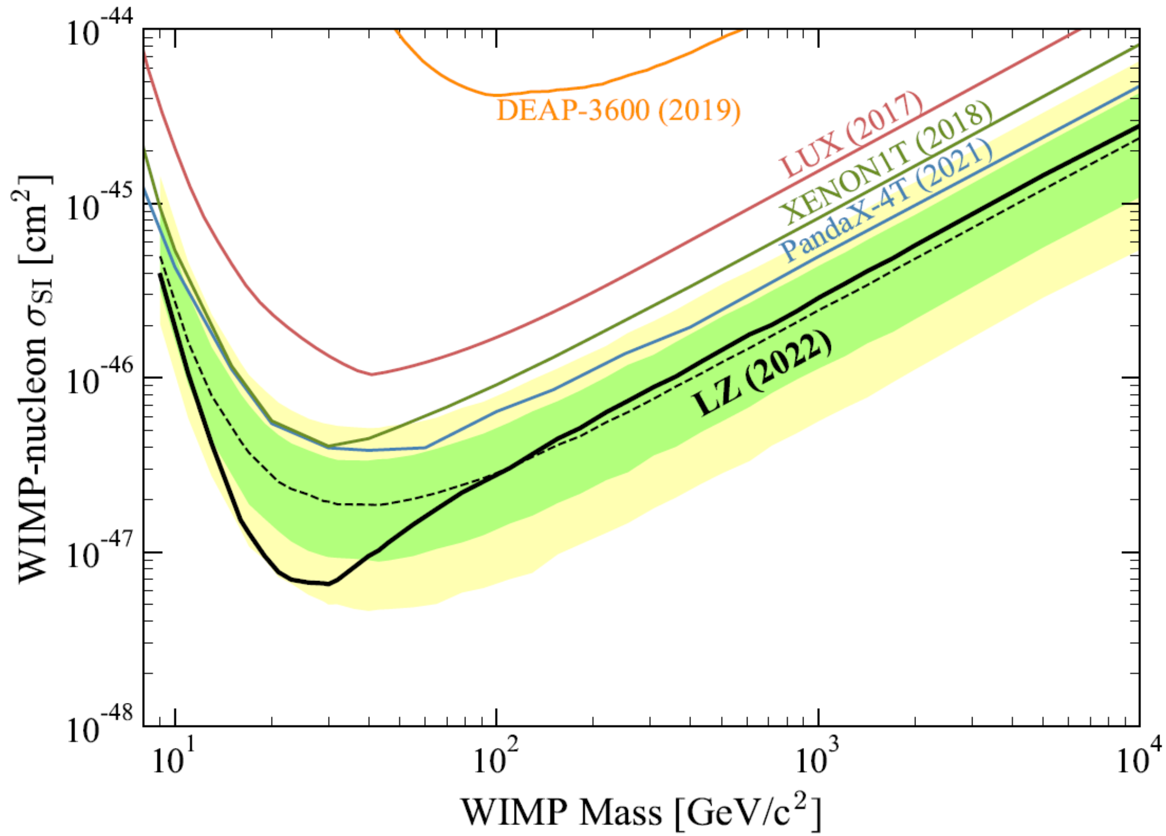
?

Probing the scattering with nucleons



Differential recoil rate

$$\frac{dR}{dE_R} = \frac{\rho_{\text{loc}}}{m_A m_{\text{DM}}} \int_{v \geq v_{\min}(E_R)} \mathrm{d}^3 v \, v f(\vec{v} + \vec{v}_{\text{obs}}(t)) \frac{\mathrm{d}\sigma}{\mathrm{d}E_R}$$

? ?

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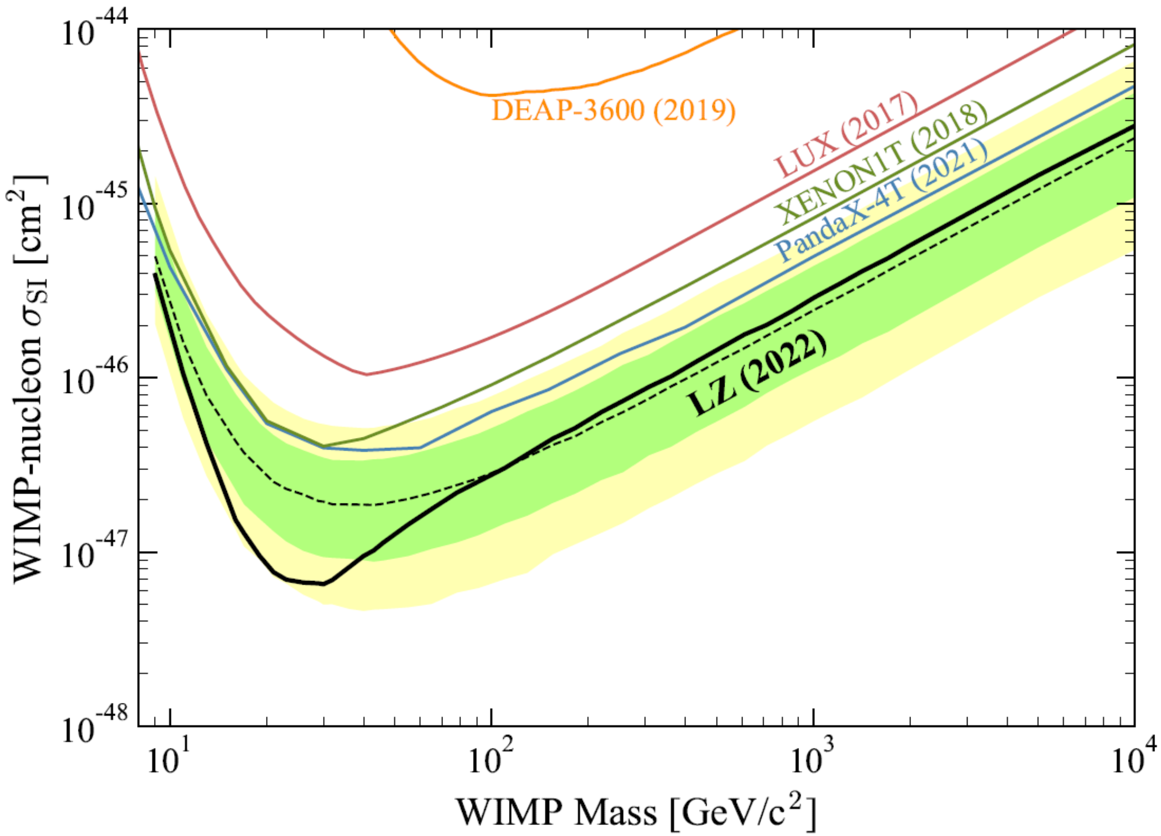

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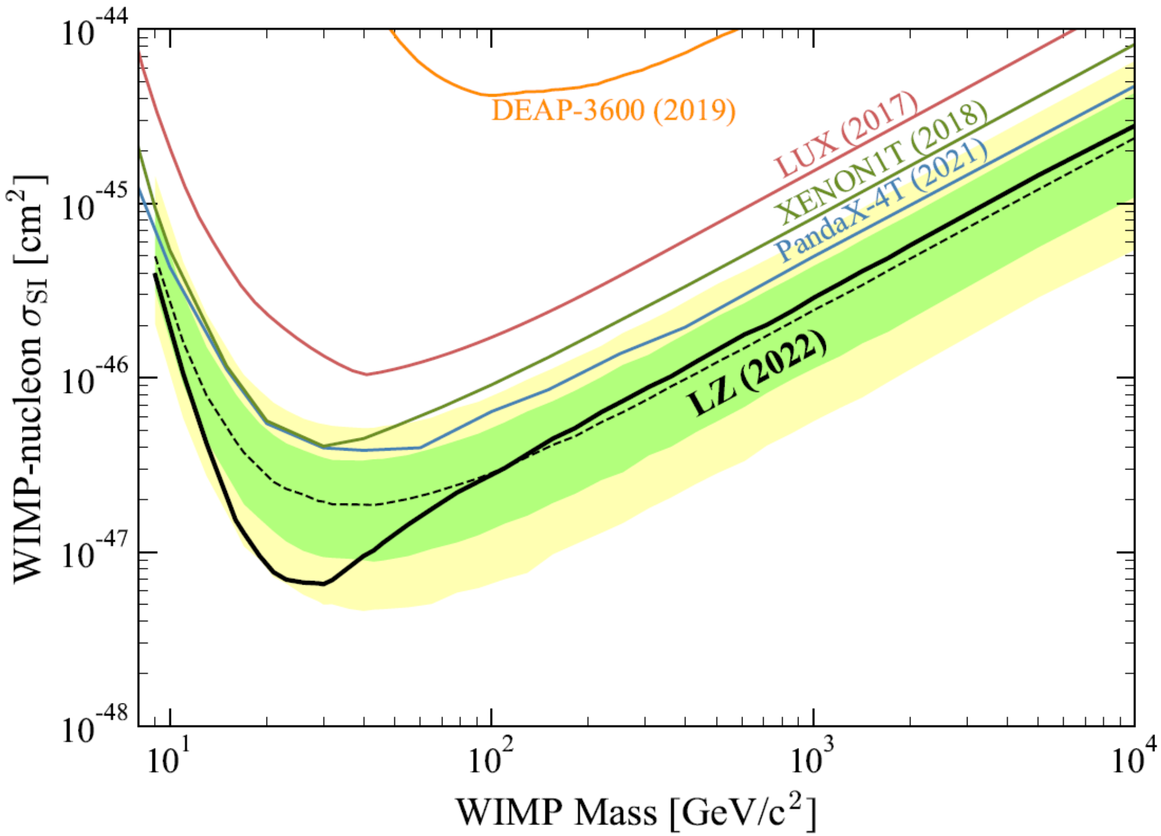

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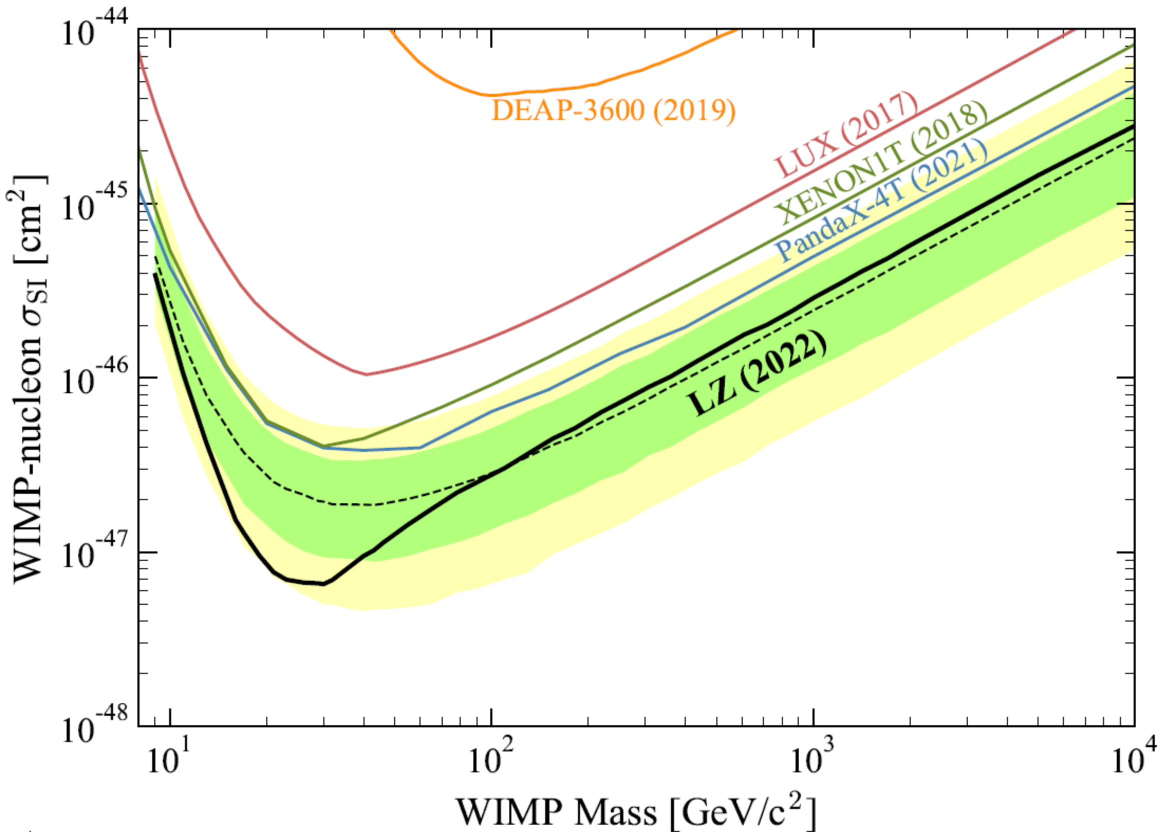


Smallprint:

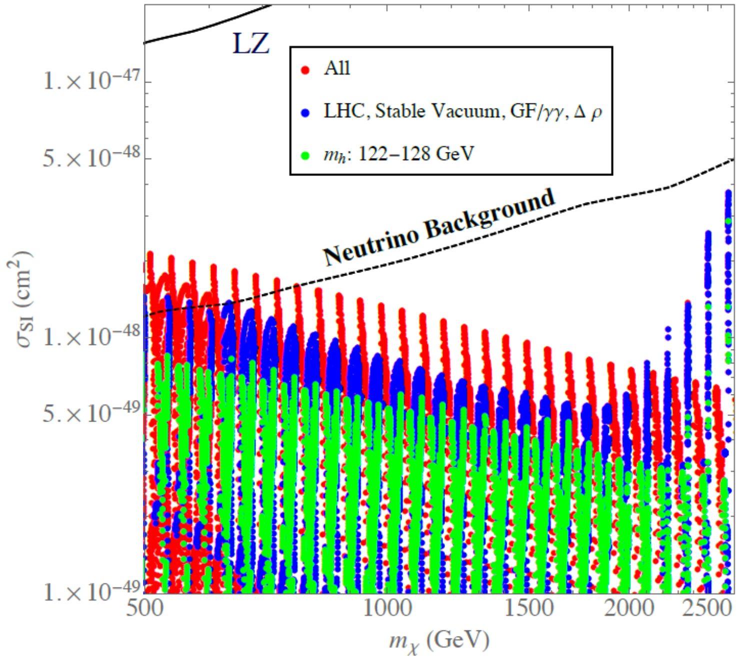
- DM interacts only through the spin-independent interaction
- DM couples with equal strength to protons and neutrons (isoscalar)
- Local DM density ρ=0.3 GeV/cm3.
- DM velocity distribution given by a Maxwell-Boltzmann, truncated at the escape velocity.

Probing the scattering with nucleons

Strictly, current limits are stringent for dark matter candidates that couple at tree level to the valence quarks through the spin-independent interaction (as the supersymmetric bino).

Many well motivated possibilities still weakly constrained by direct detection experiments:

- DM coupling to heavy quarks/leptons



Pierce et al '17

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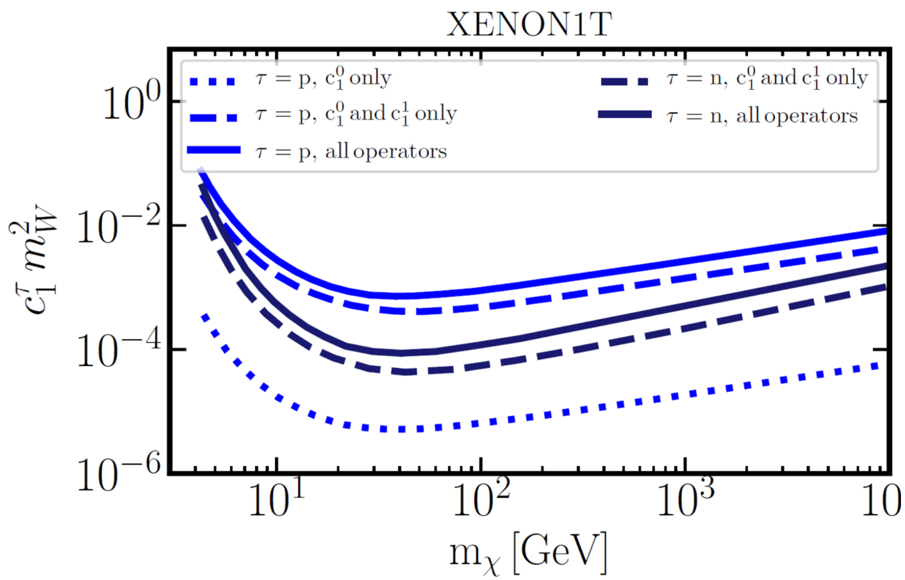
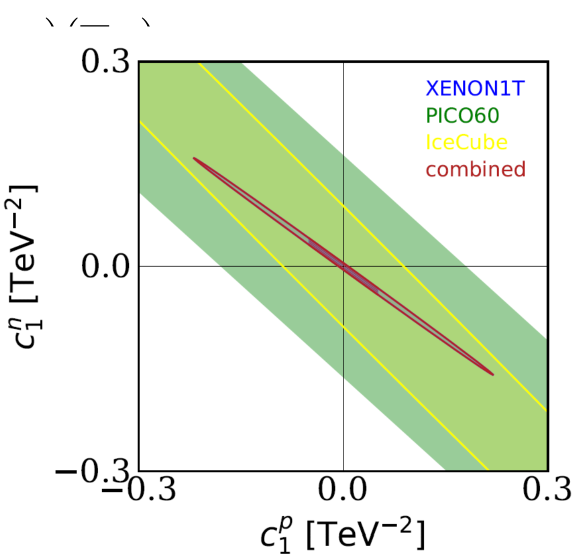
- Interference between isoscalar and isovector interactions

$$\mathcal{H} = c_p(\overline{\chi}p)(\overline{p}\chi) + c_n(\overline{\chi}n)(\overline{n}\chi)$$





Brenner et al ‘22

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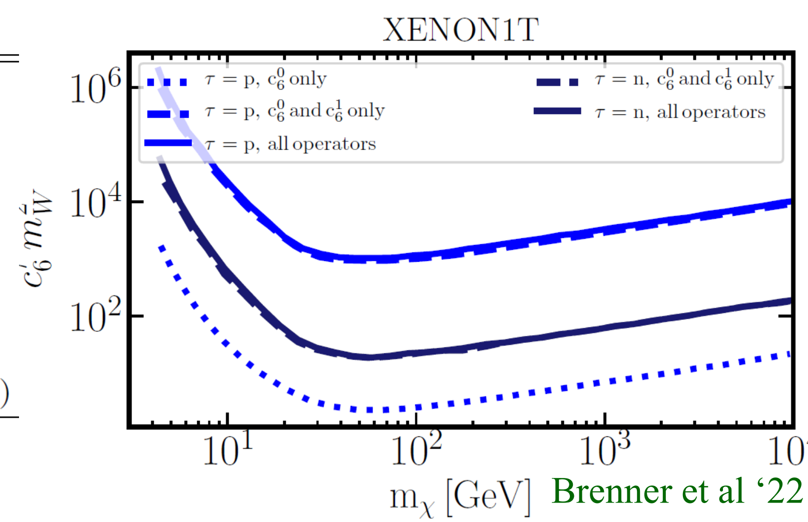
- DM-nucleon interactions different to SI

$\mathcal{O}_1 = 1_\chi 1_N$	$\mathcal{O}_9 = i\vec{S}_\chi \cdot (\vec{S}_N \times \frac{\vec{q}}{m_N})$
$\mathcal{O}_3 = i\vec{S}_N \cdot (\frac{\vec{q}}{m_N} \times \vec{v}^\perp)$	$\mathcal{O}_{10} = i\vec{S}_N \cdot \frac{\vec{q}}{m_N}$
$\mathcal{O}_4 = \vec{S}_\chi \cdot \vec{S}_N$	$\mathcal{O}_{11} = i\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}$
$\mathcal{O}_5 = i\vec{S}_\chi \cdot (\frac{\vec{q}}{m_N} \times \vec{v}^\perp)$	$\mathcal{O}_{12} = \vec{S}_\chi \cdot (\vec{S}_N \times \vec{v}^\perp)$
$\mathcal{O}_6 = (\vec{S}_\chi \cdot \frac{\vec{q}}{m_N})(\vec{S}_N \cdot \frac{\vec{q}}{m_N})$	$\mathcal{O}_{13} = i(\vec{S}_\chi \cdot \vec{v}^\perp)(\vec{S}_N \cdot \frac{\vec{q}}{m_N})$
$\mathcal{O}_7 = \vec{S}_N \cdot \vec{v}^\perp$	$\mathcal{O}_{14} = i(\vec{S}_\chi \cdot \frac{\vec{q}}{m_N})(\vec{S}_N \cdot \vec{v}^\perp)$
$\mathcal{O}_8 = \vec{S}_\chi \cdot \vec{v}^\perp$	$\mathcal{O}_{15} = -(\vec{S}_\chi \cdot \frac{\vec{q}}{m_N})((\vec{S}_N \times \vec{v}^\perp) \cdot \frac{\vec{q}}{m_N})$

Fitzpatrick et al. '12



Brenner et al '22

Probing the scattering with nucleons

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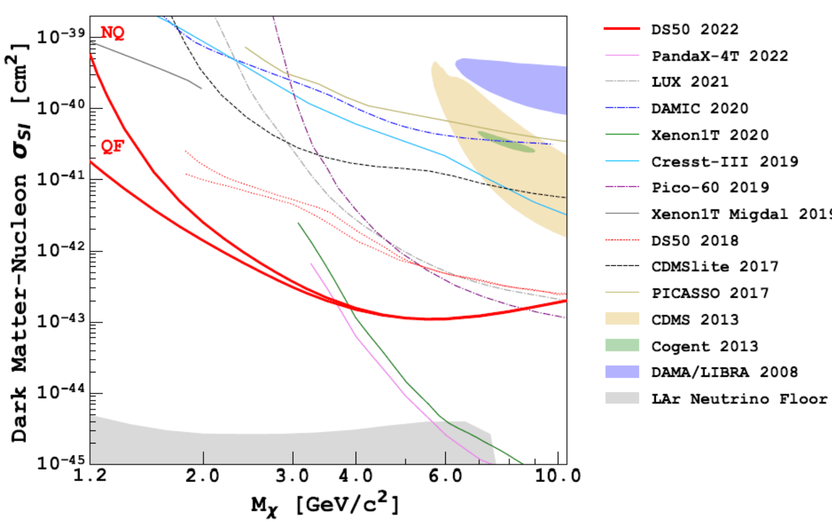
- DM-nucleon interactions different to SI
- Light dark matter



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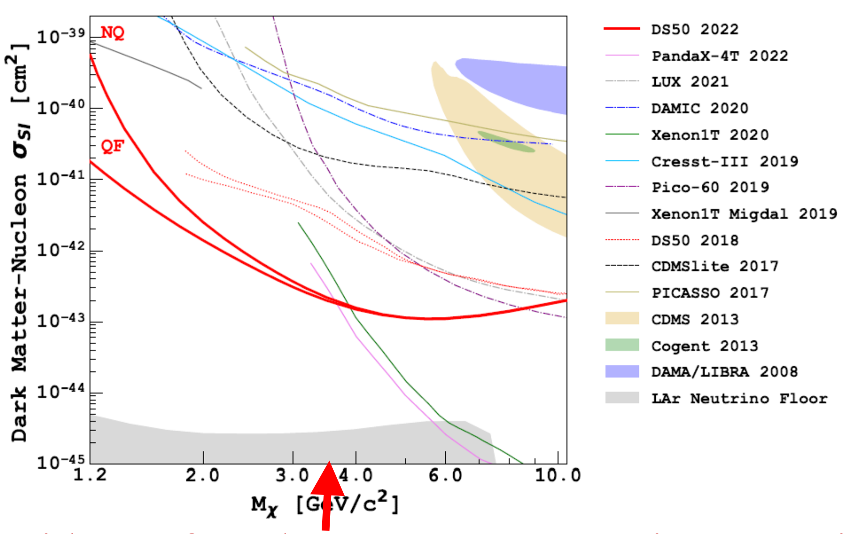
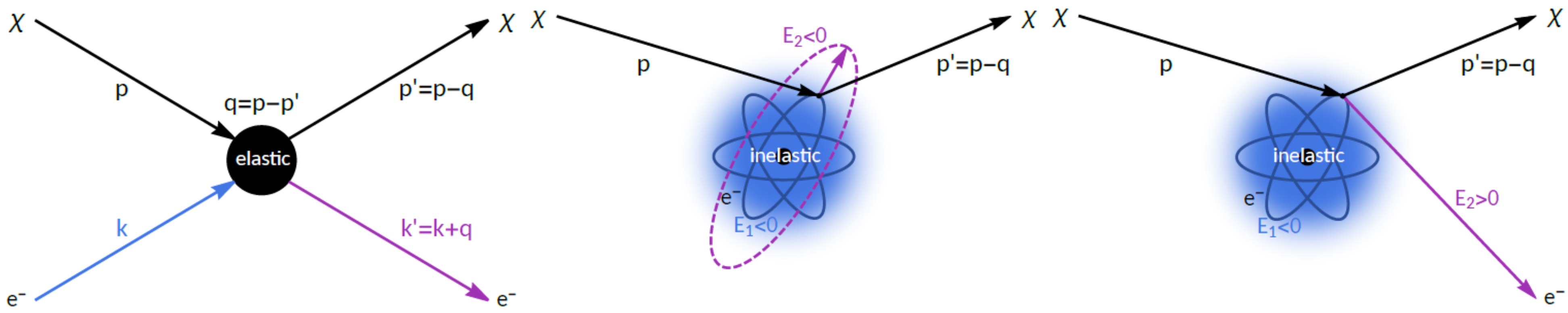
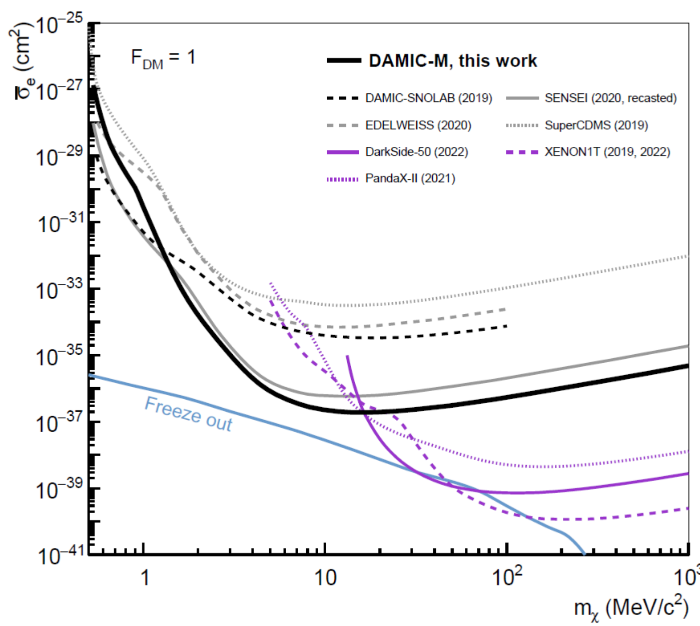


There is no evidence for a baryon asymmetry in our Universe.
m_{DM}~3.4 GeV is predicted by a mechanism that does not require the Sakharov conditions to explain observations. Ciscar, AI, Vandecasteeele '23

Probing the scattering with electrons



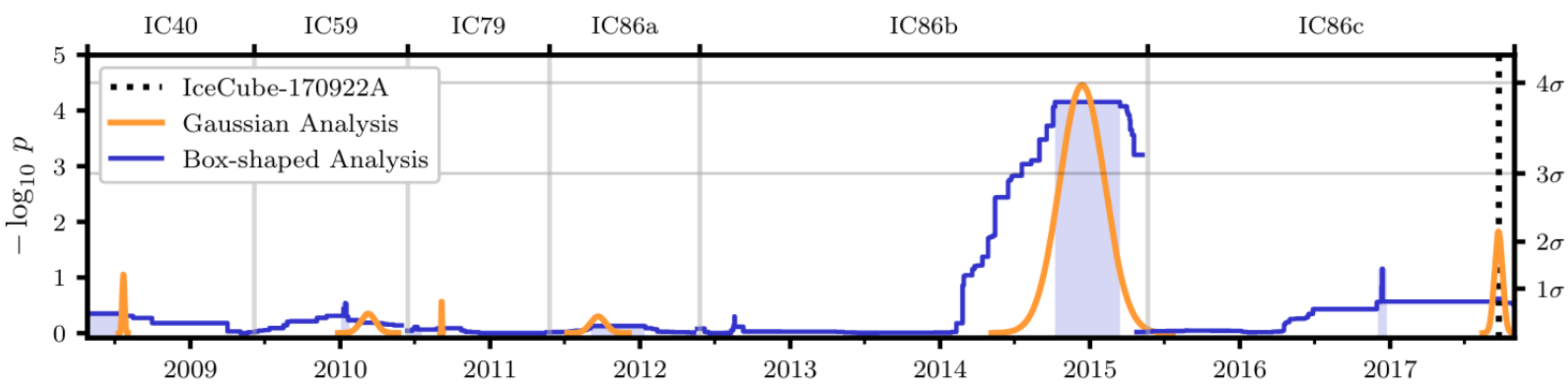
From Catena et al'20



Probing the scattering with neutrinos

The neutrino event IceCube-170922A was coincident in direction and time with a gamma-ray flare from the blazar TXS 0506+056, located 1.75 Gpc away from the Earth.

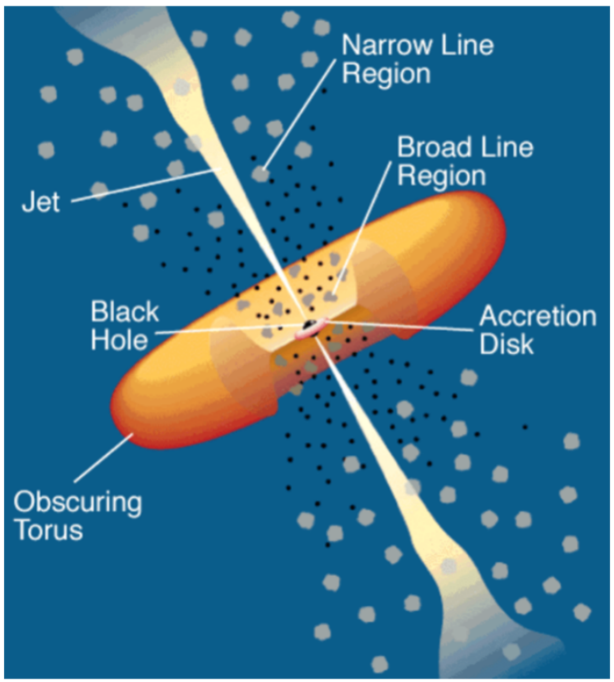
Archival data found 13±5 events coincident with TXS 0506+056.

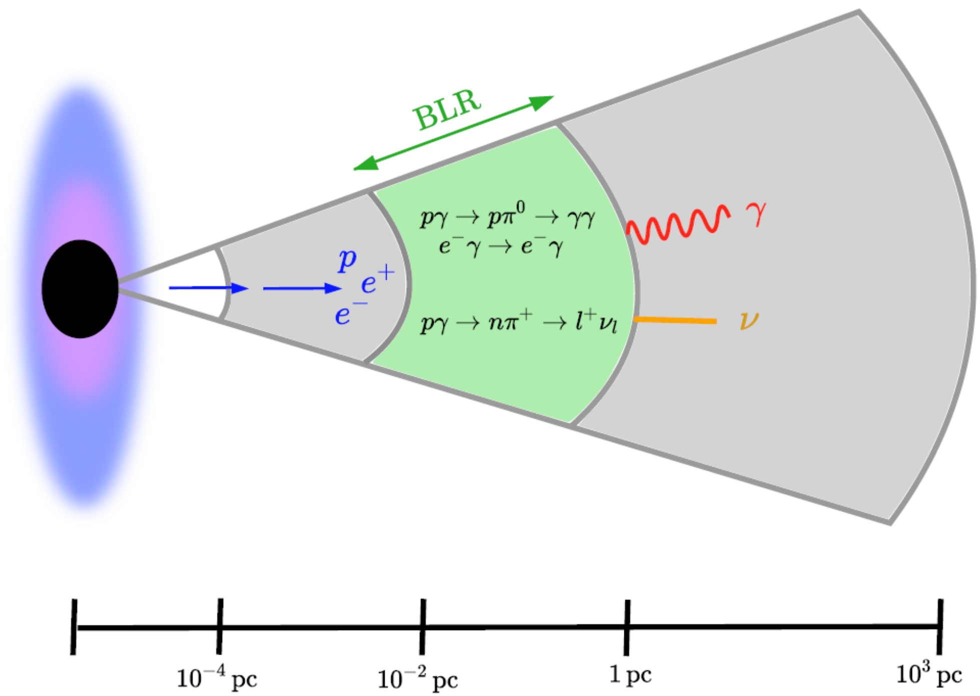


First known source of high energy astrophysical neutrinos

Probing the scattering with neutrinos

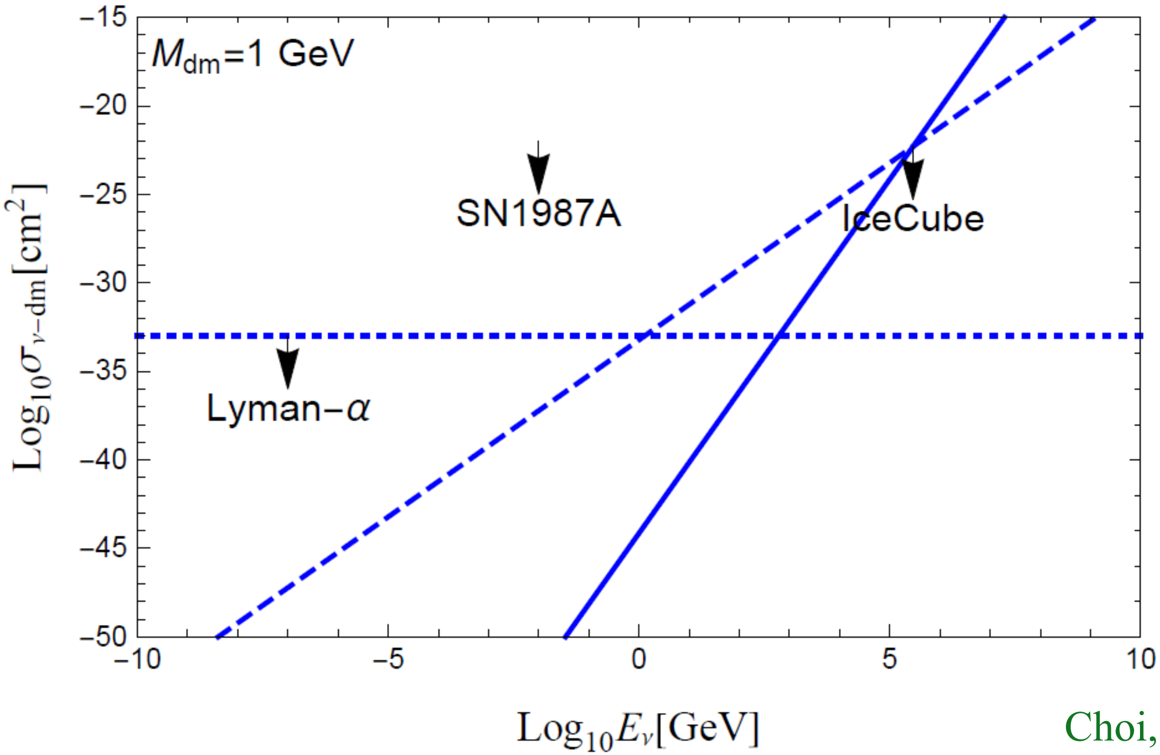
The neutrino and photon fluxes can be qualitatively well reproduced in leptohadronic models.





Neutrinos propagate through the intergalactic medium and through the Milky Way before reaching us. If the dark matter neutrino cross-section is large, the neutrino flux would be attenuated.

Probing the scattering with neutrinos



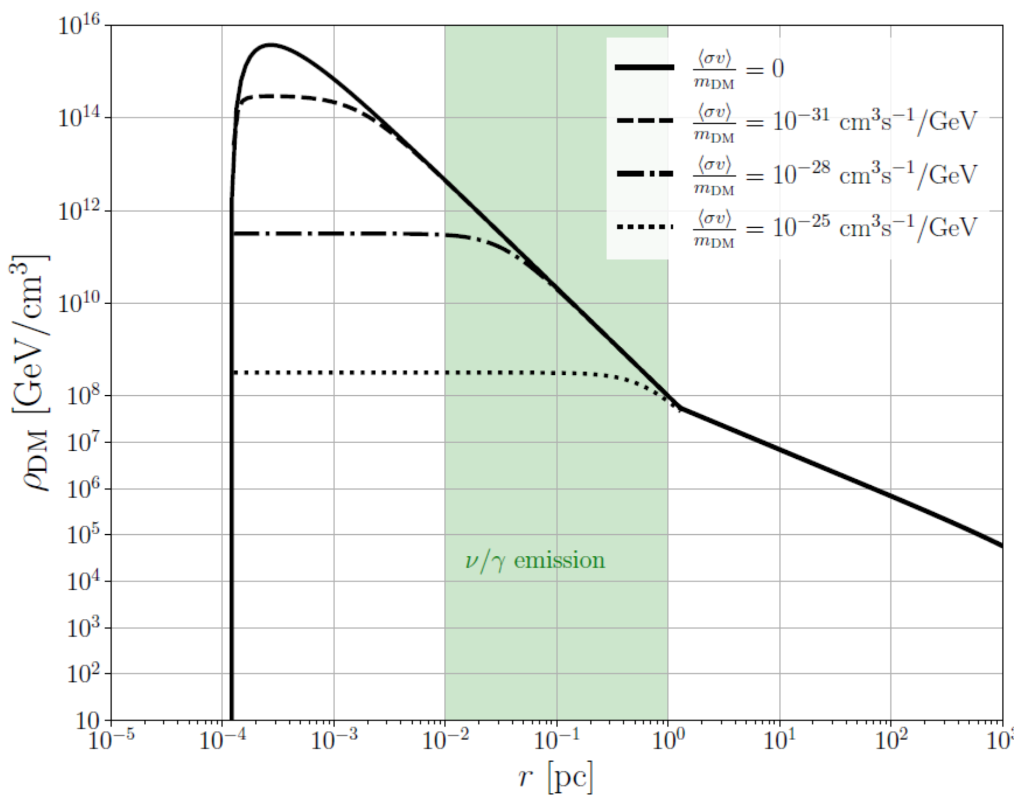
Choi, Kim, Rott'19
Kelly, Machado '19

Probing the scattering with neutrinos

In the center of the blazar it is located a supermassive black hole, with mass ~ 3×10^8 M_{sun}.

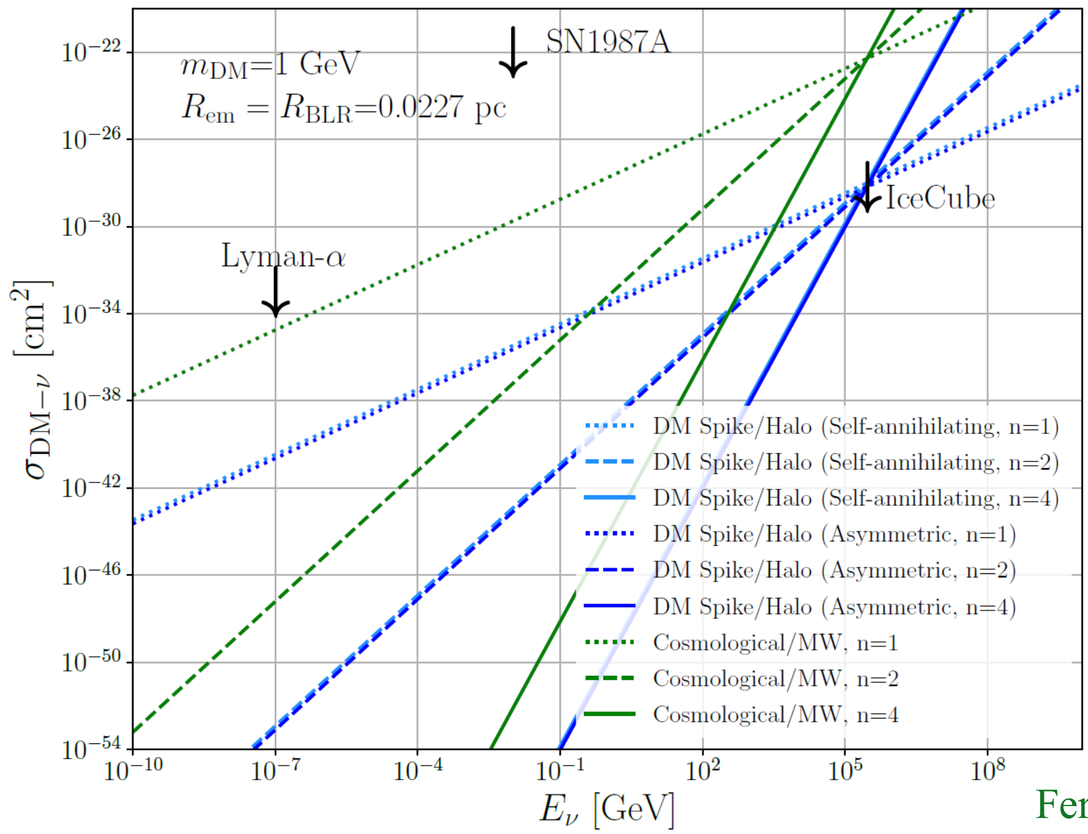
The adiabatic growth of the black hole produces a "spike" in the dark matter distribution Gondolo, Silk'99, Peebles '72, Quinlan, Hernquist, Sigurdsson '95

$$\rho(r) = \rho_0 \left(\frac{r_0}{r}\right) \longrightarrow \rho_{\rm sp} \sim \rho_R \left(\frac{R_{\rm sp}}{r}\right)^{7/3}$$



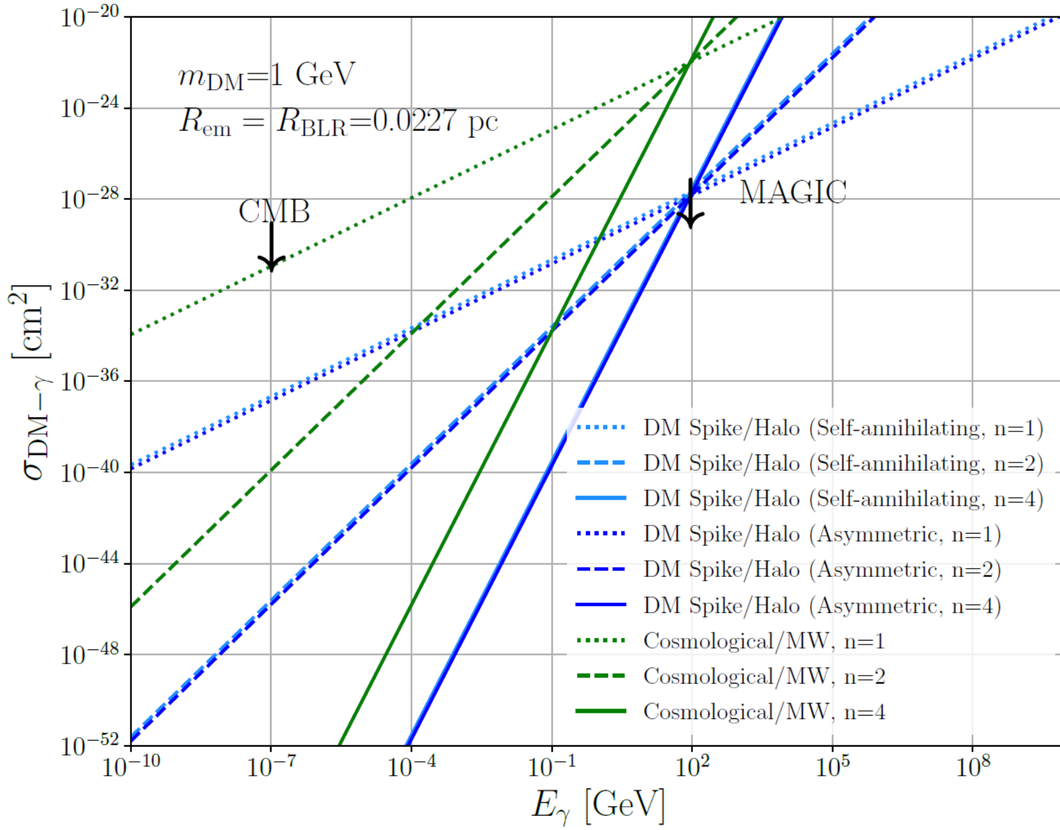
Ferrer, Herrera, AI'22

Probing the scattering with neutrinos



Ferrer, Herrera, AI'22

Probing the scattering with photons



Ferrer, Herrera, AI'22

Conclusions

- After 40+ years of search, there is still no concluding evidence that dark matter is made of elementary particles.
- “Traditional” searches put some tension on some WIMP scenarios. Many other scenarios still poorly constrained by data.
- Better experiments are needed, but also new ideas for dark matter detection.
- Astronomical objects (e.g. active galactic nuclei) and cosmological observations open new opportunities to detect non-gravitational signals of dark matter.