Current Status of Dark Matter

Alejandro Ibarra

ICHEPAP 2023,
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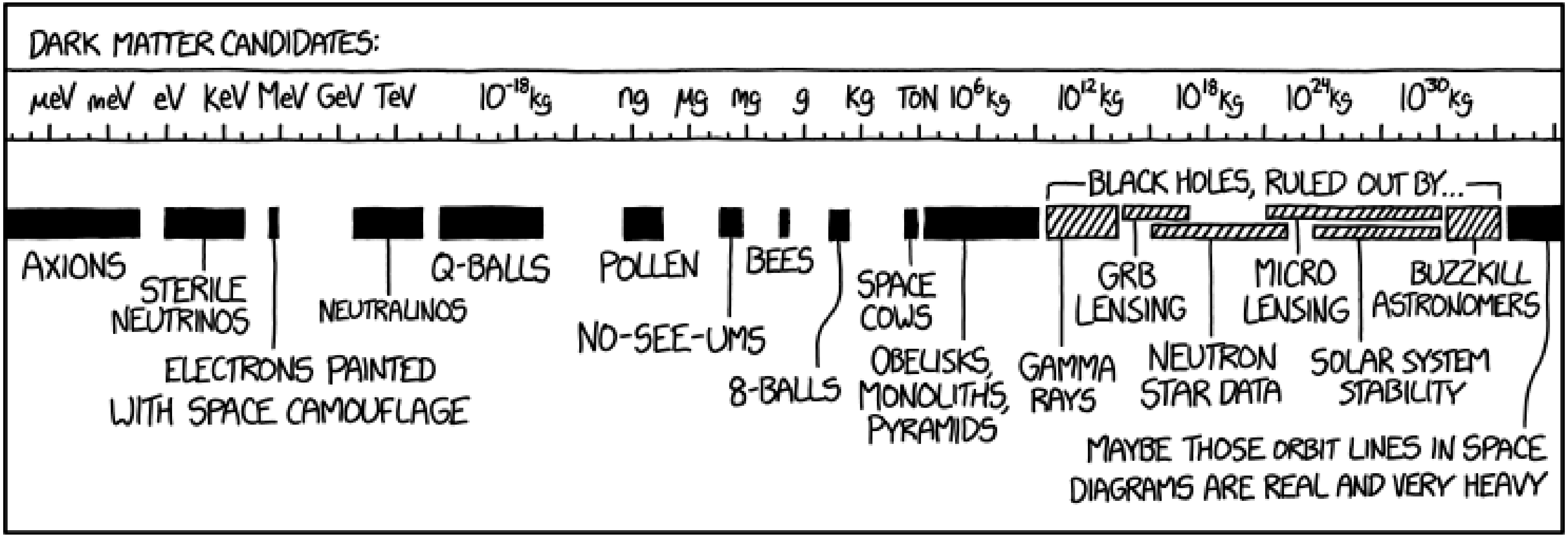
December 2023

The dark matter zoo

Explain xkcd



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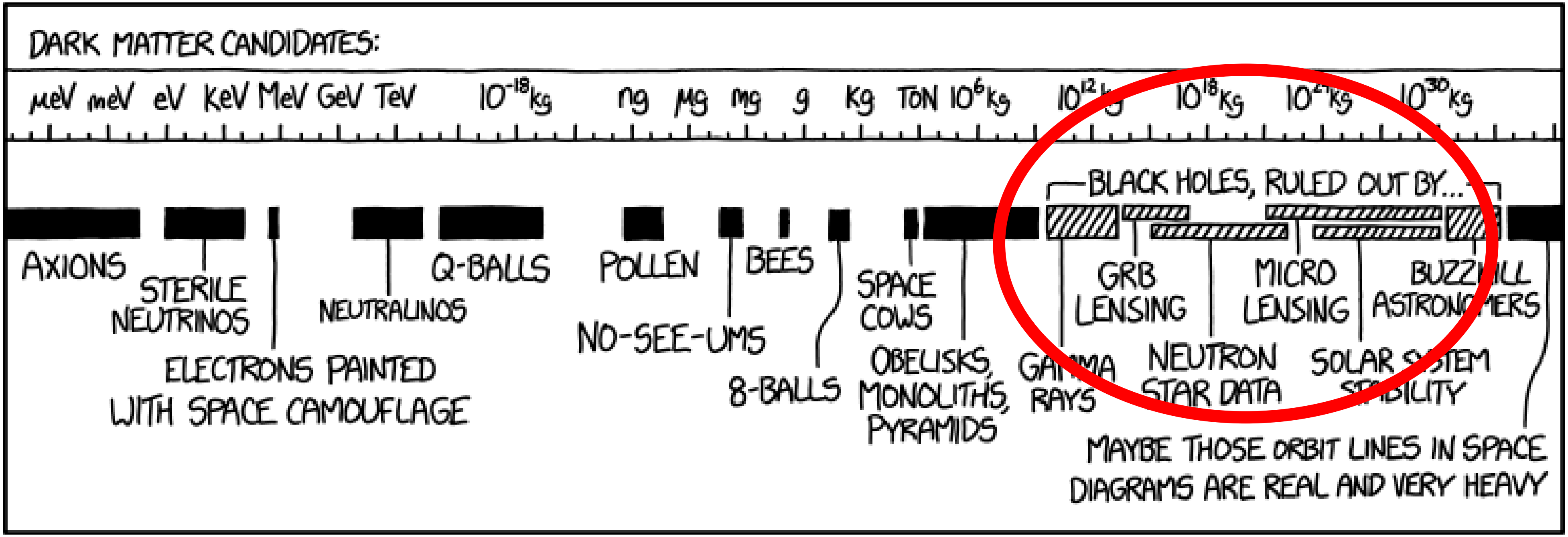

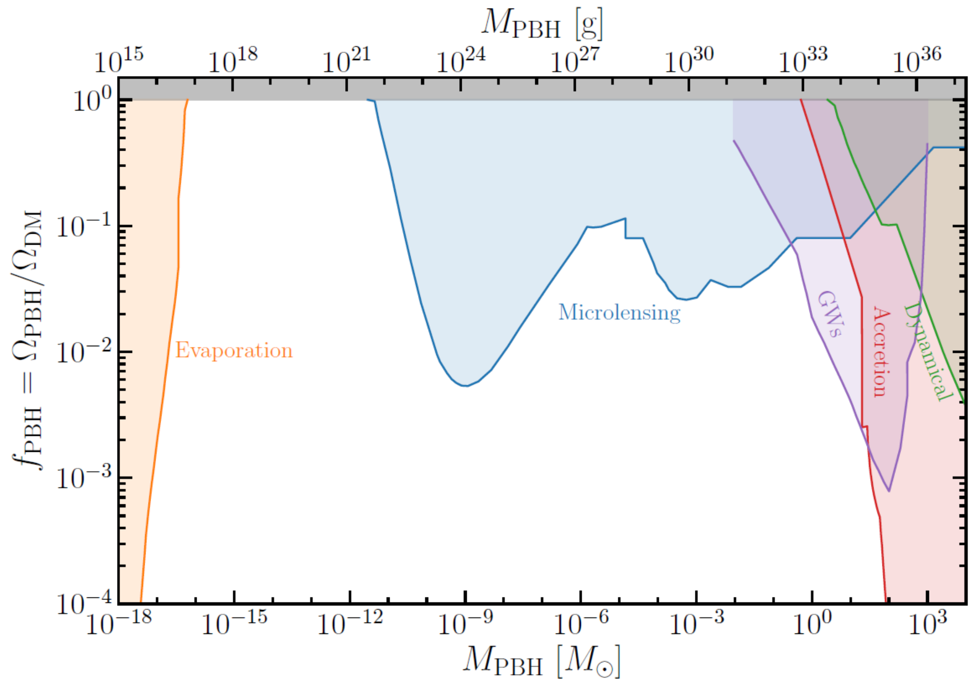

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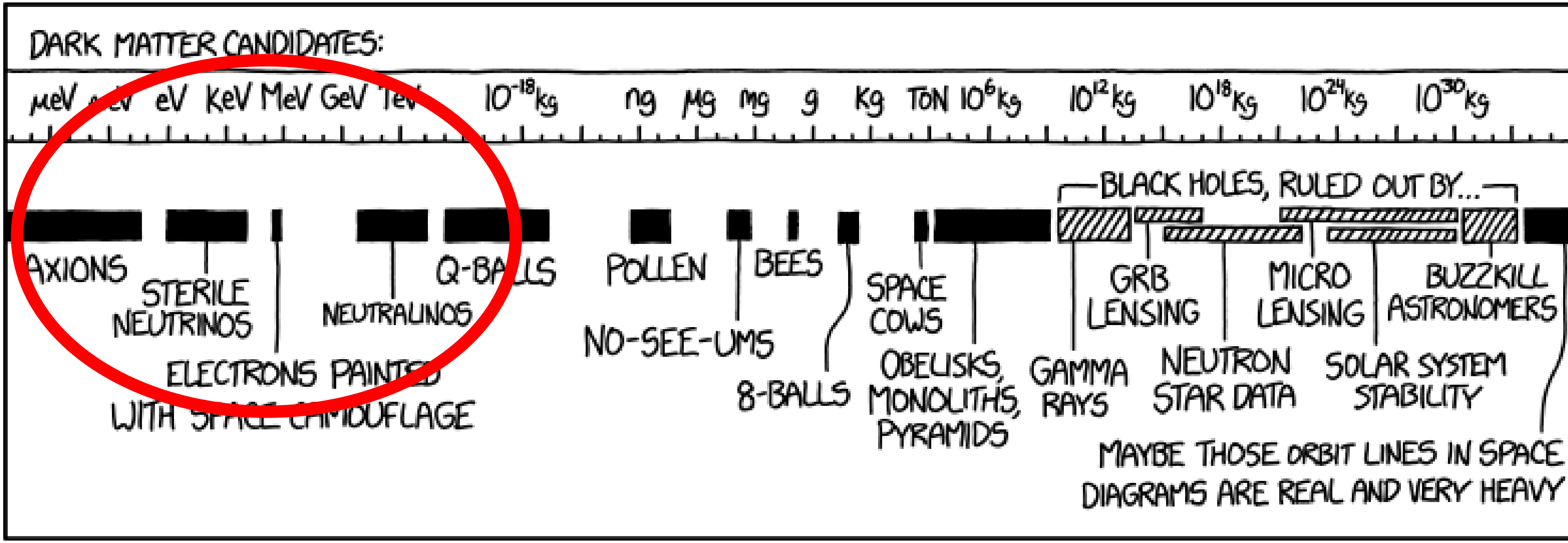

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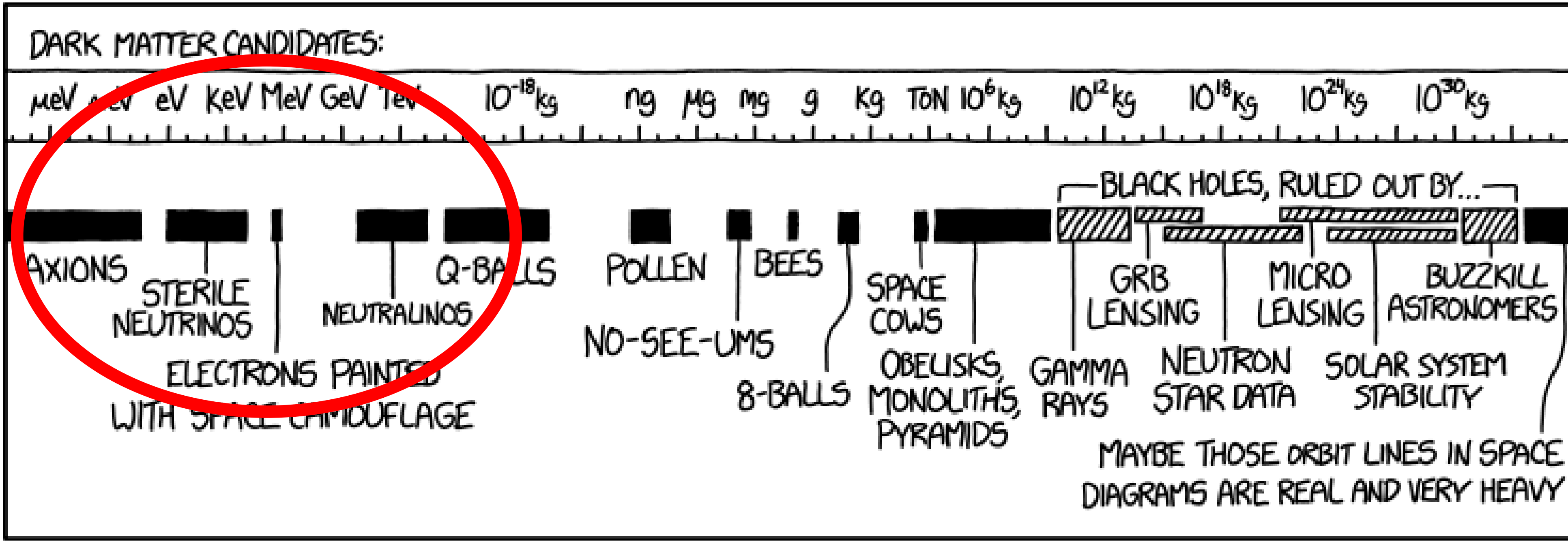

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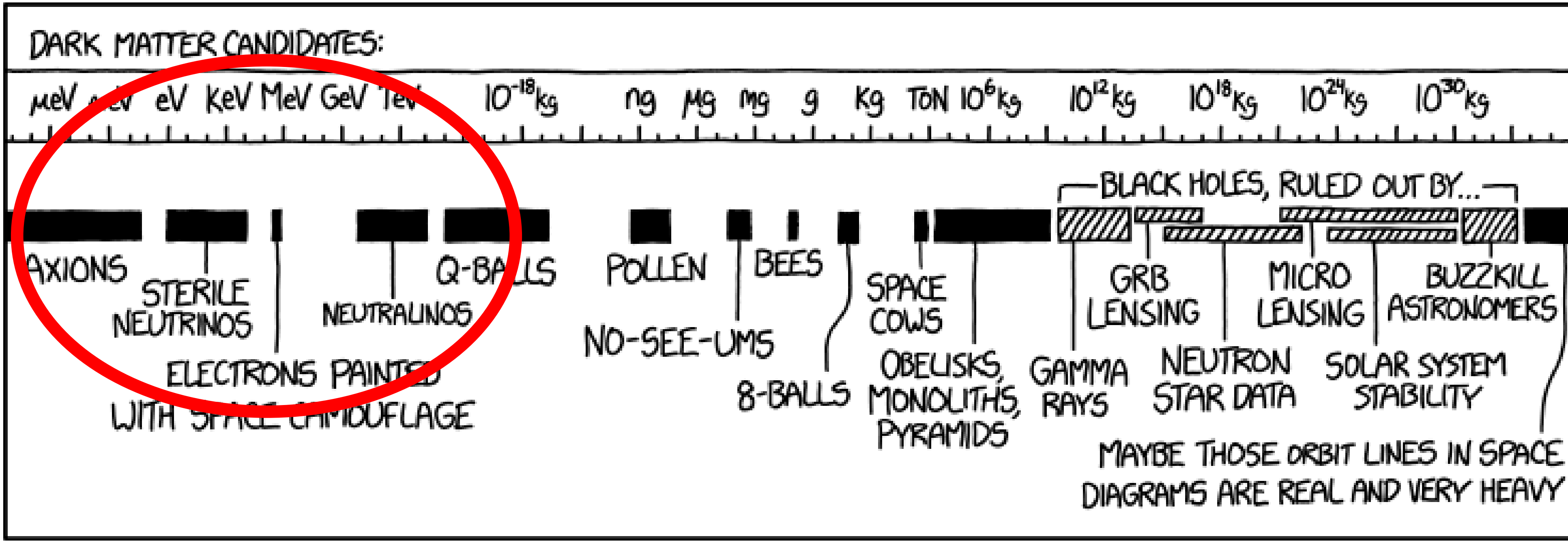

spin

Scattering cross-section off SM particles

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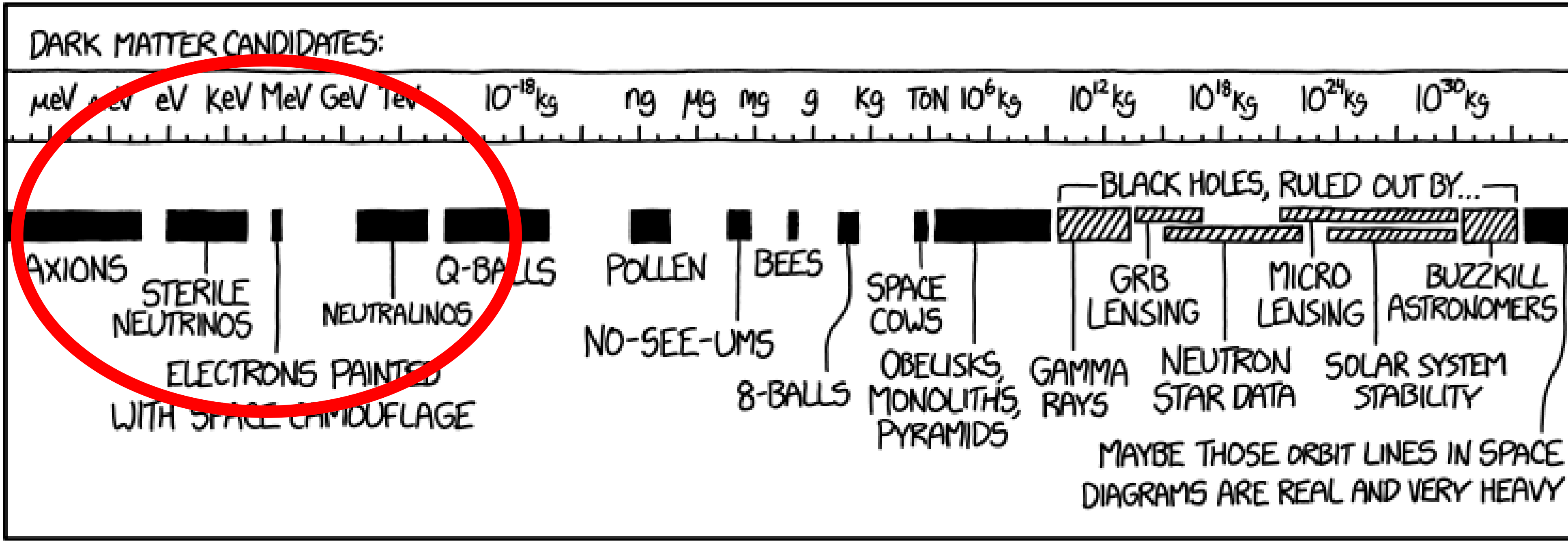

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Annihilation cross-section into SM particles

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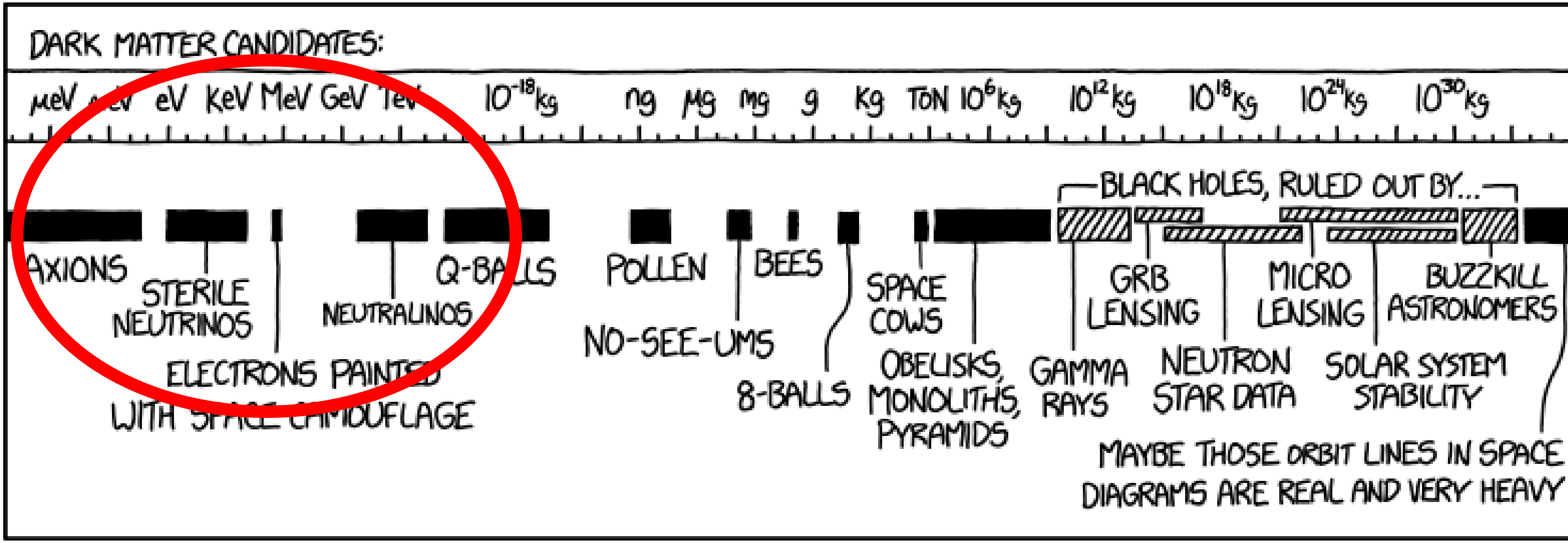

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Self-coupling

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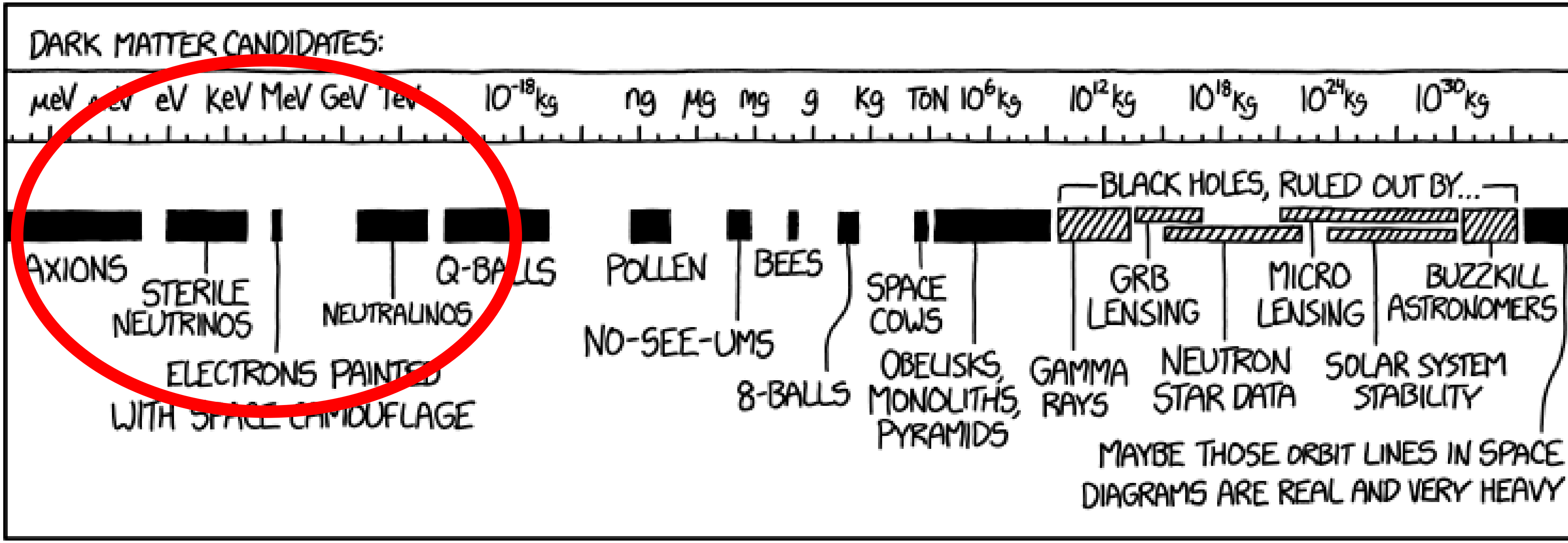

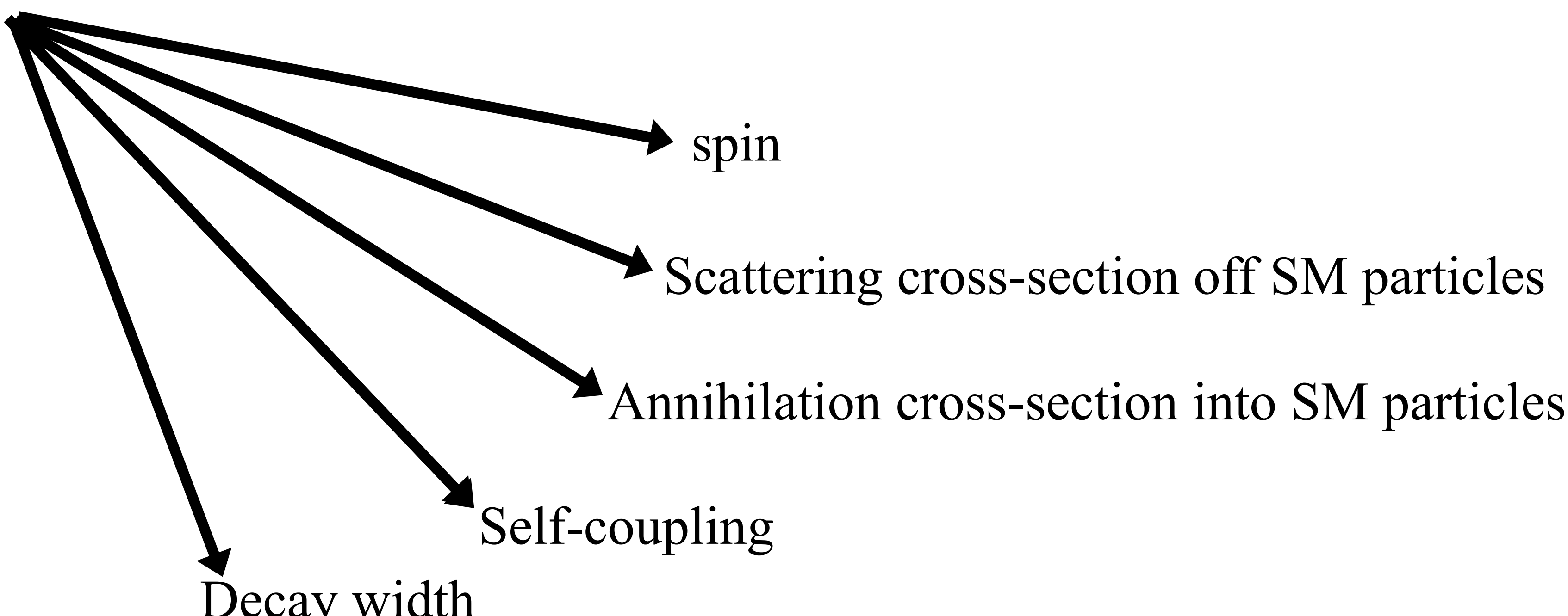

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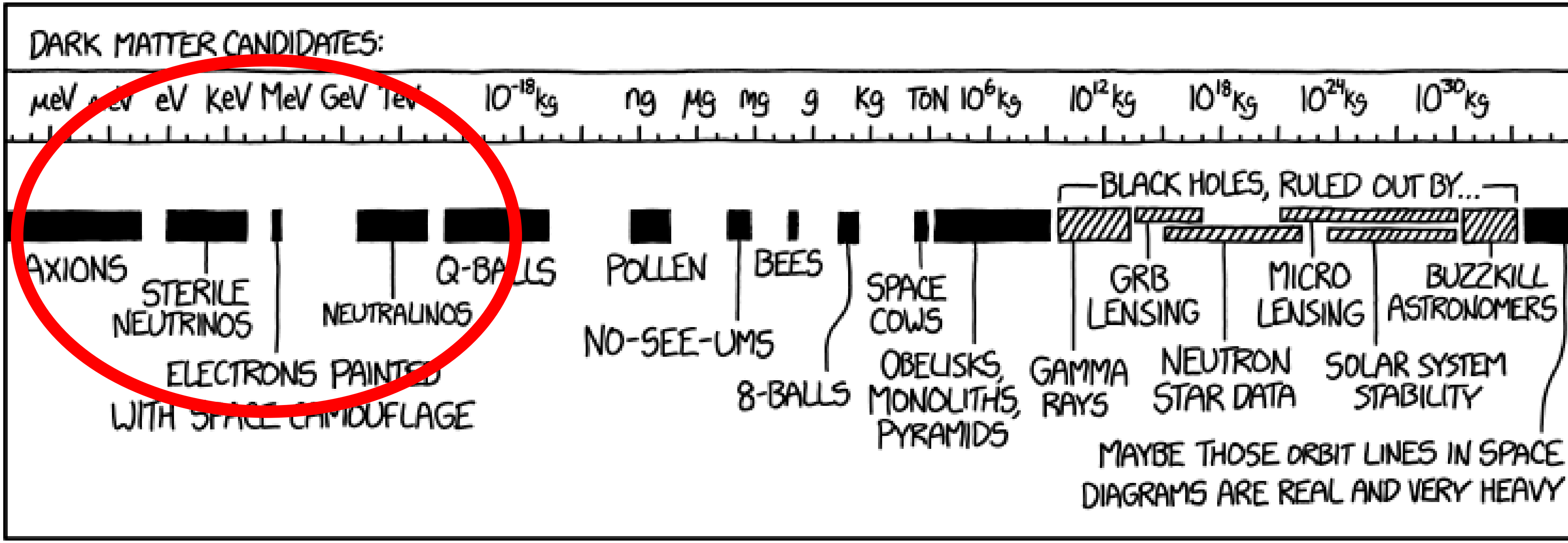

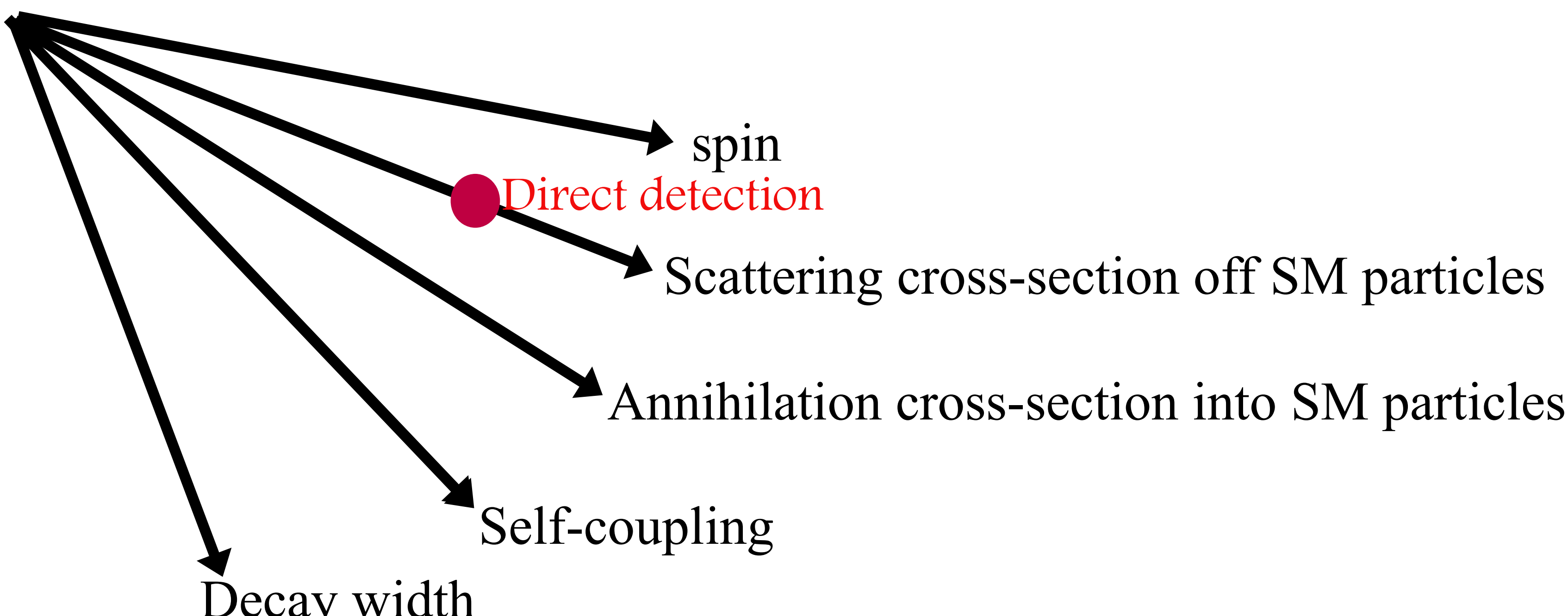

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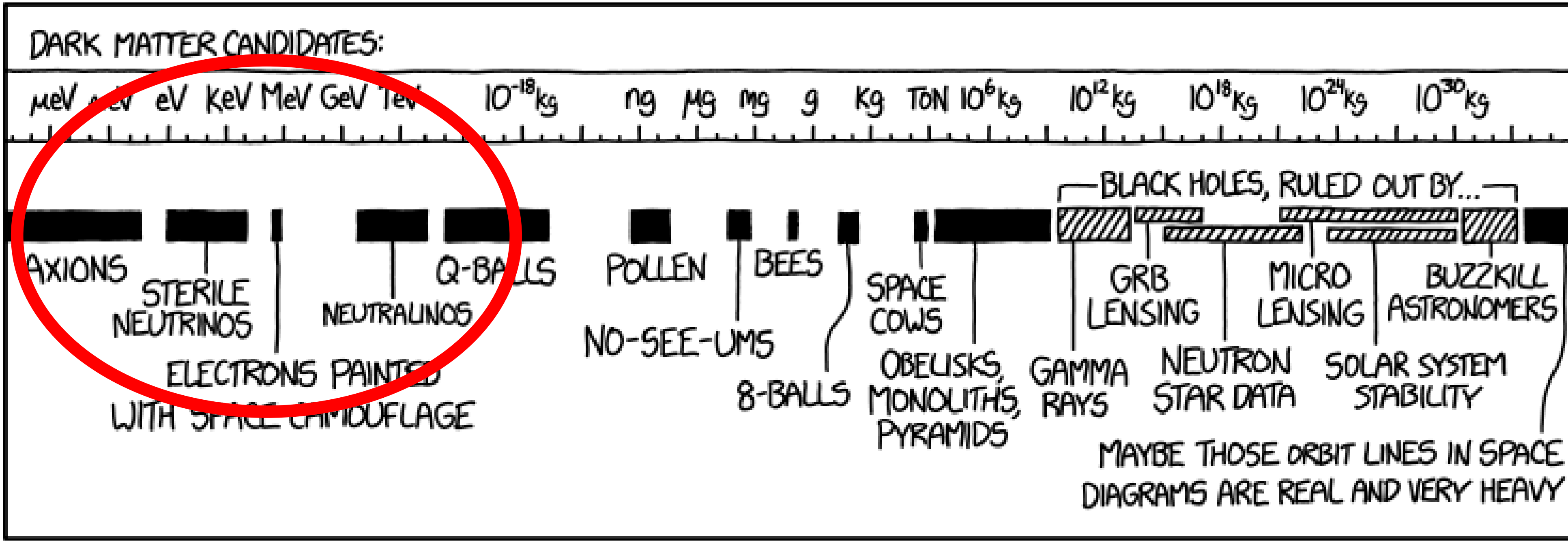

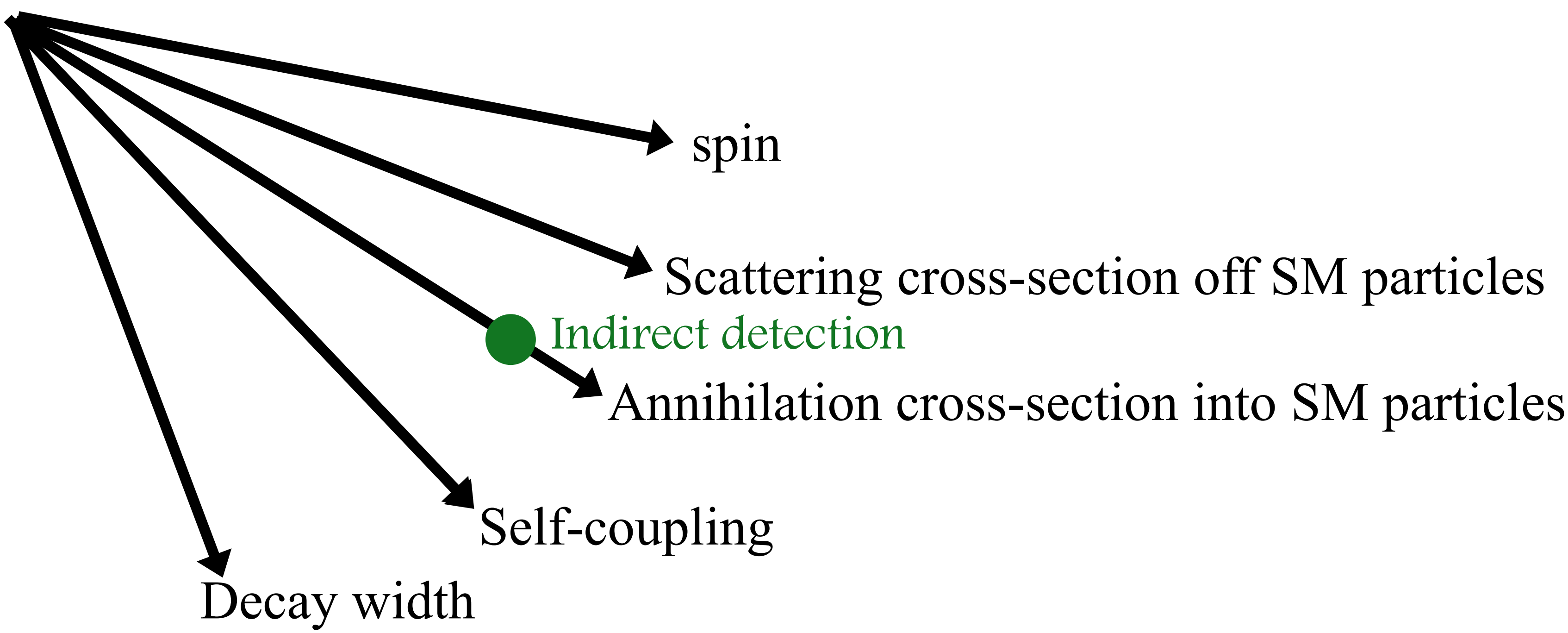

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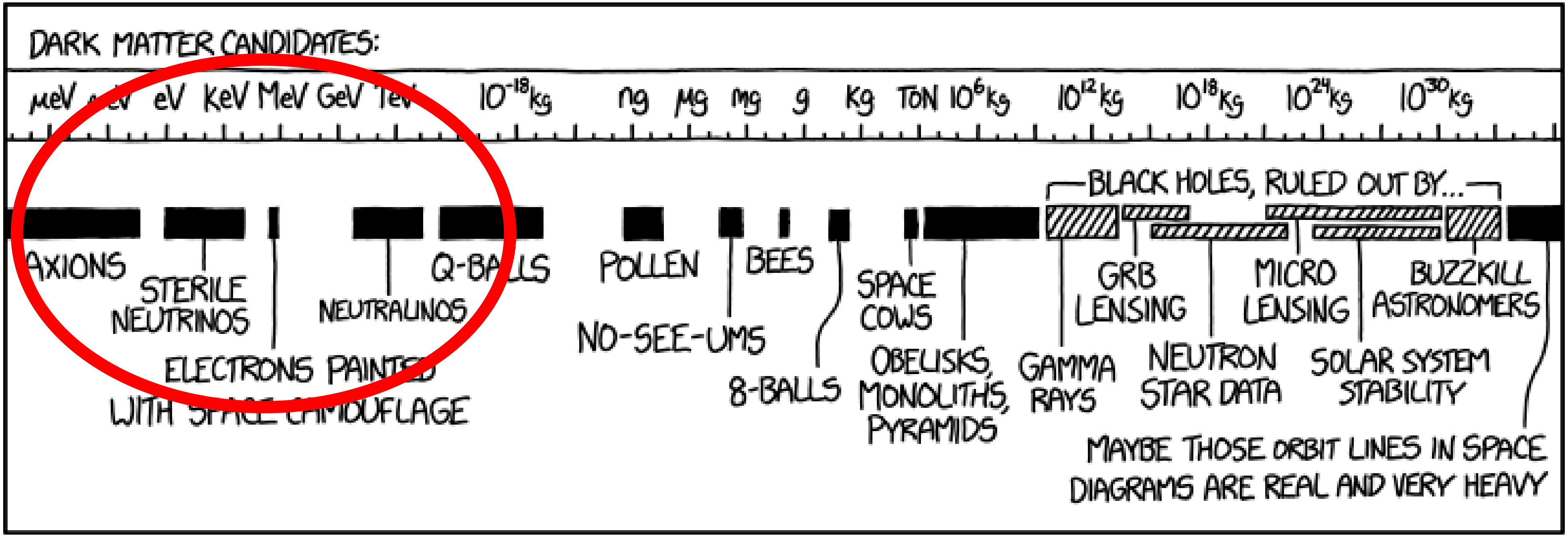

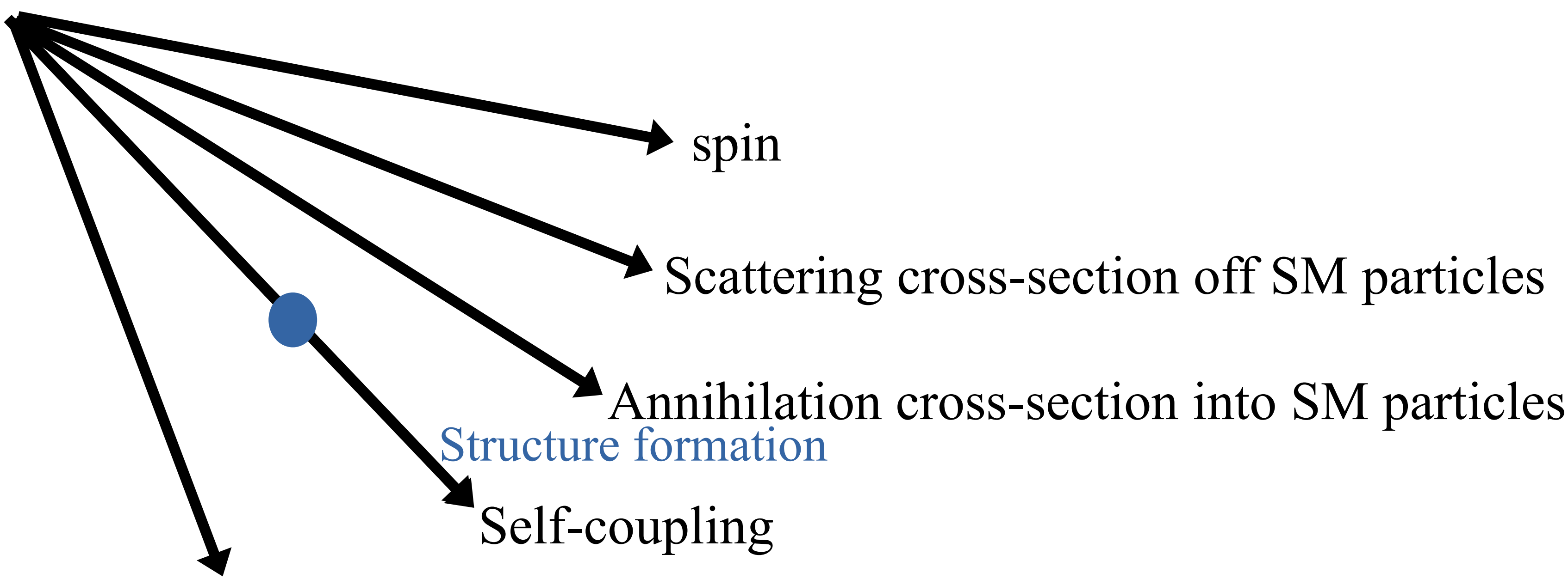

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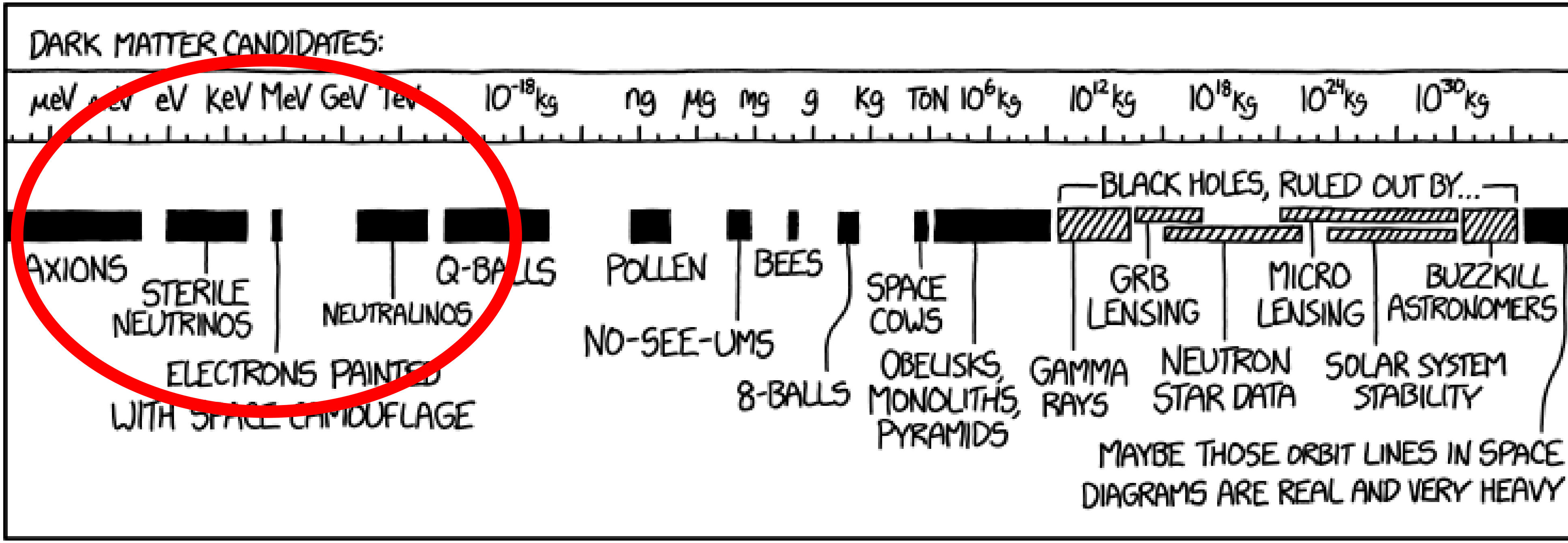
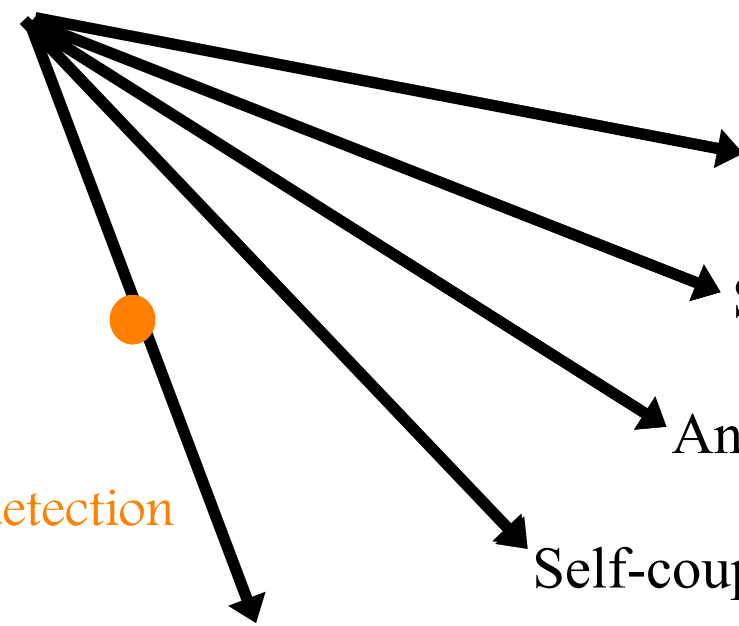




spin

Scattering cross-section off SM particles

Annihilation cross-section into SM particles

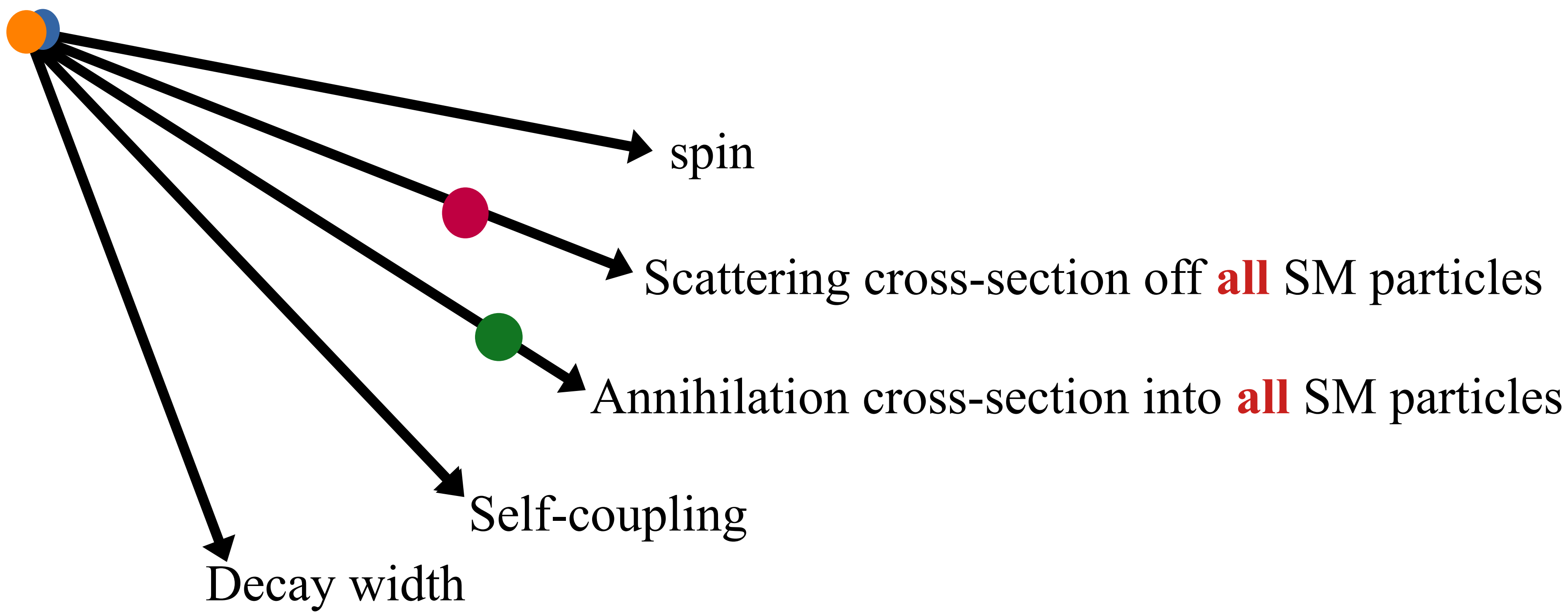
Self-coupling

Indirect detection

Decay width

The dark matter zoo

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



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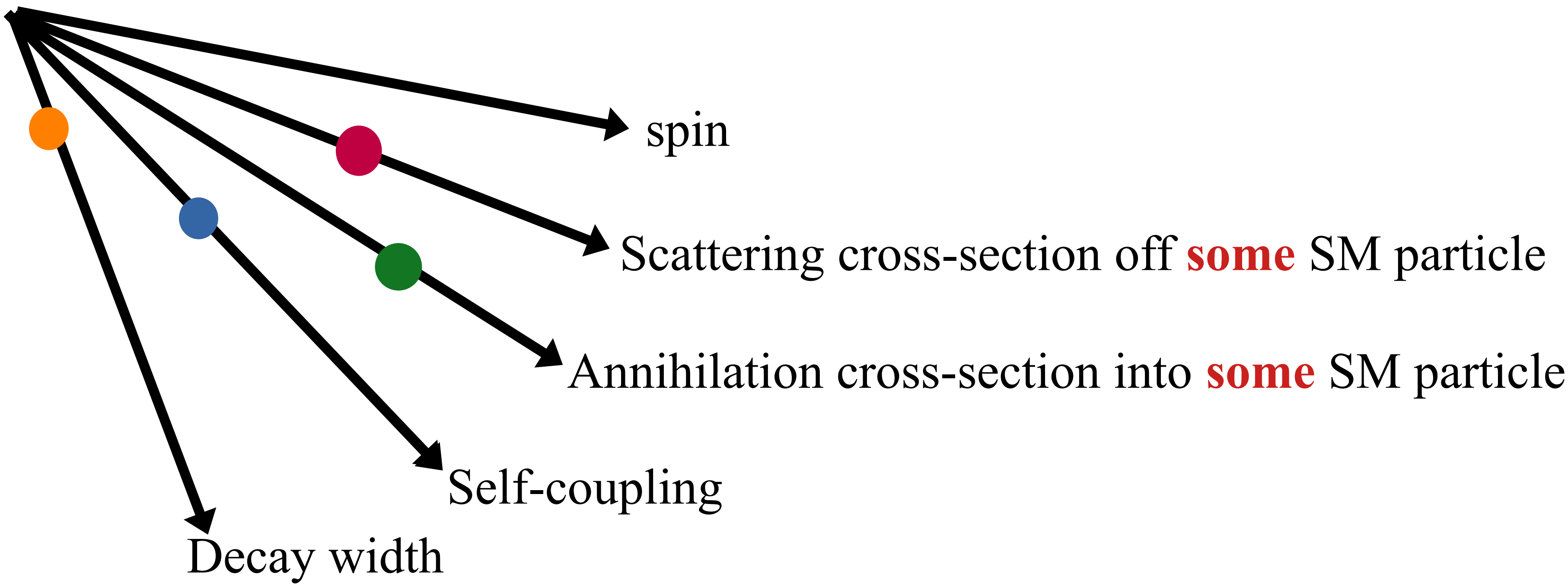

Modern approach:

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

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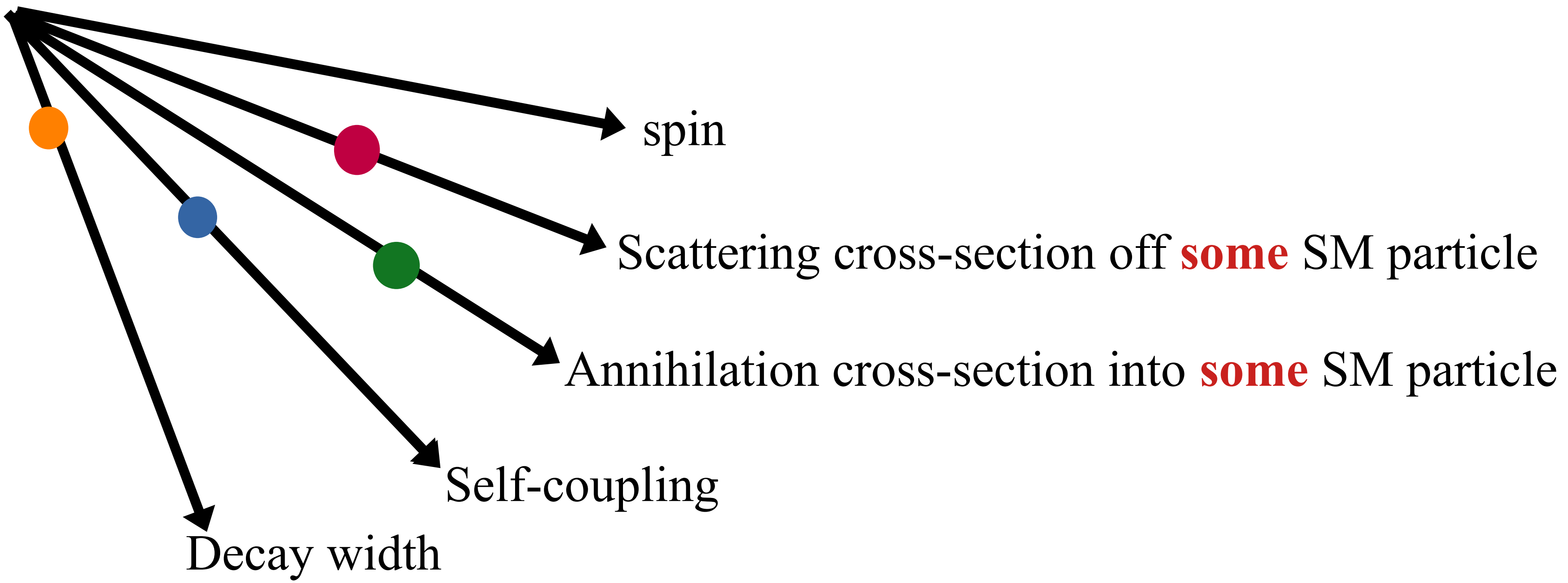
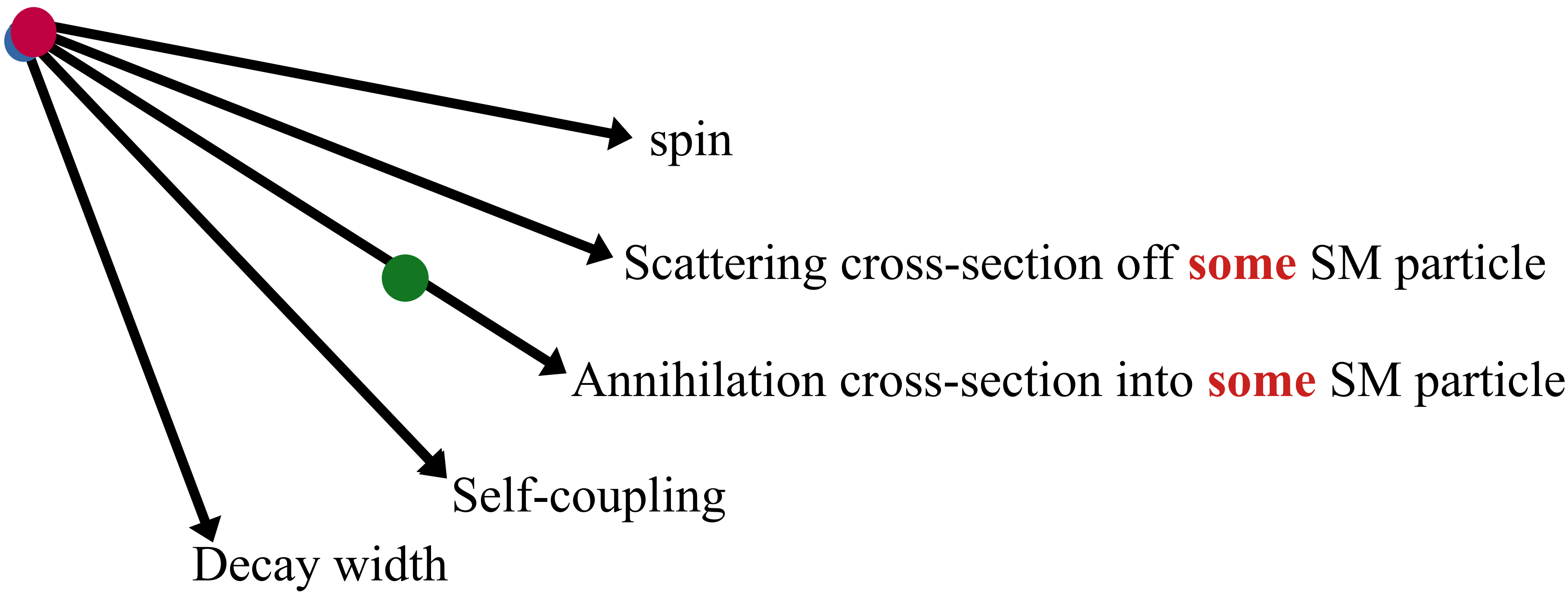


Modern approach:

- 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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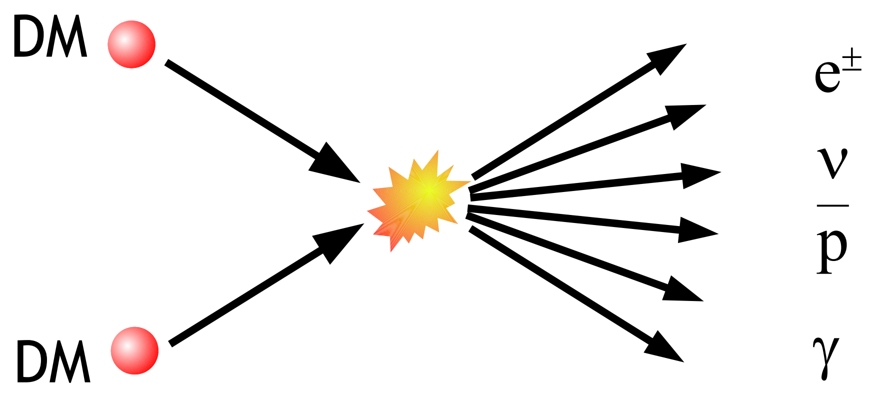

Number of particles of the type "i" produced at the position r per unit time and unit volume:

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

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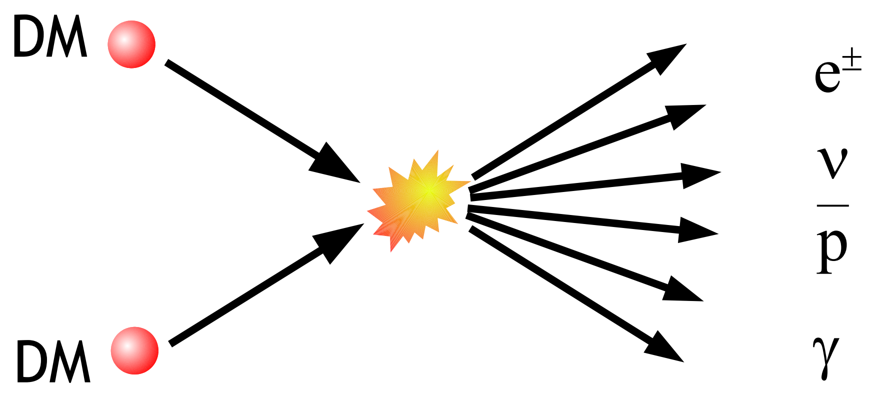
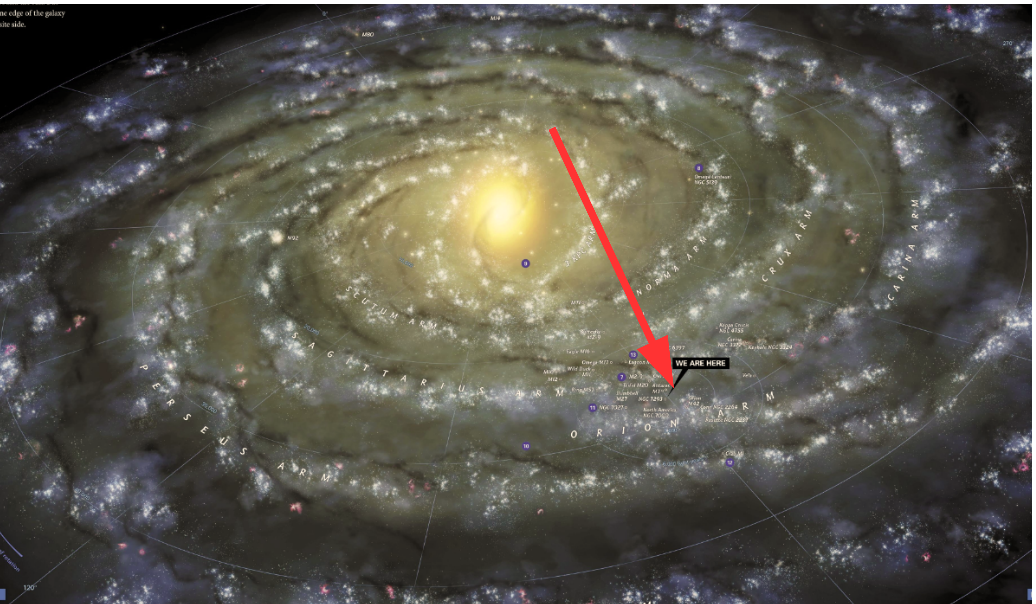
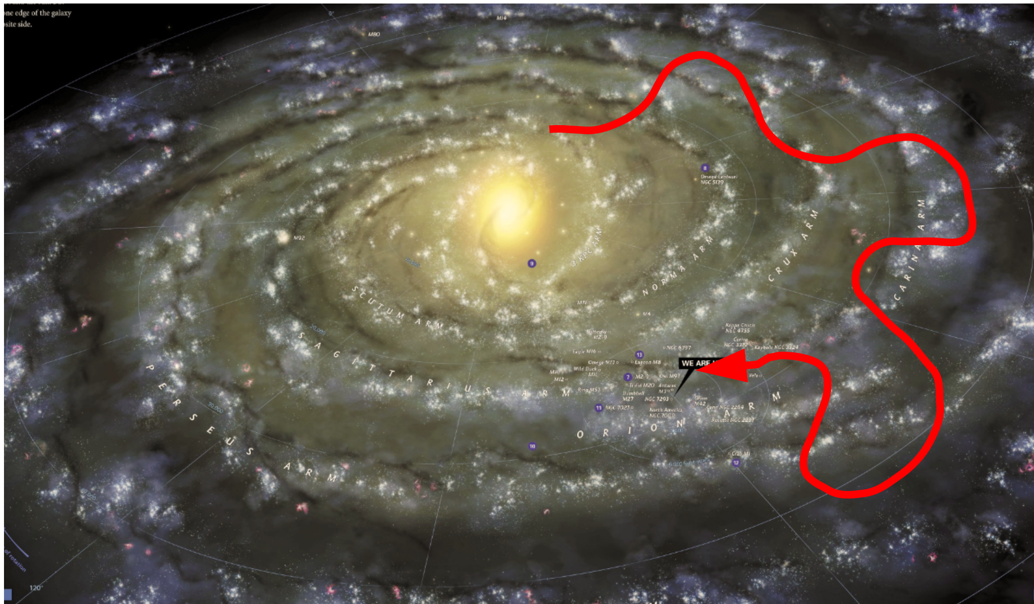


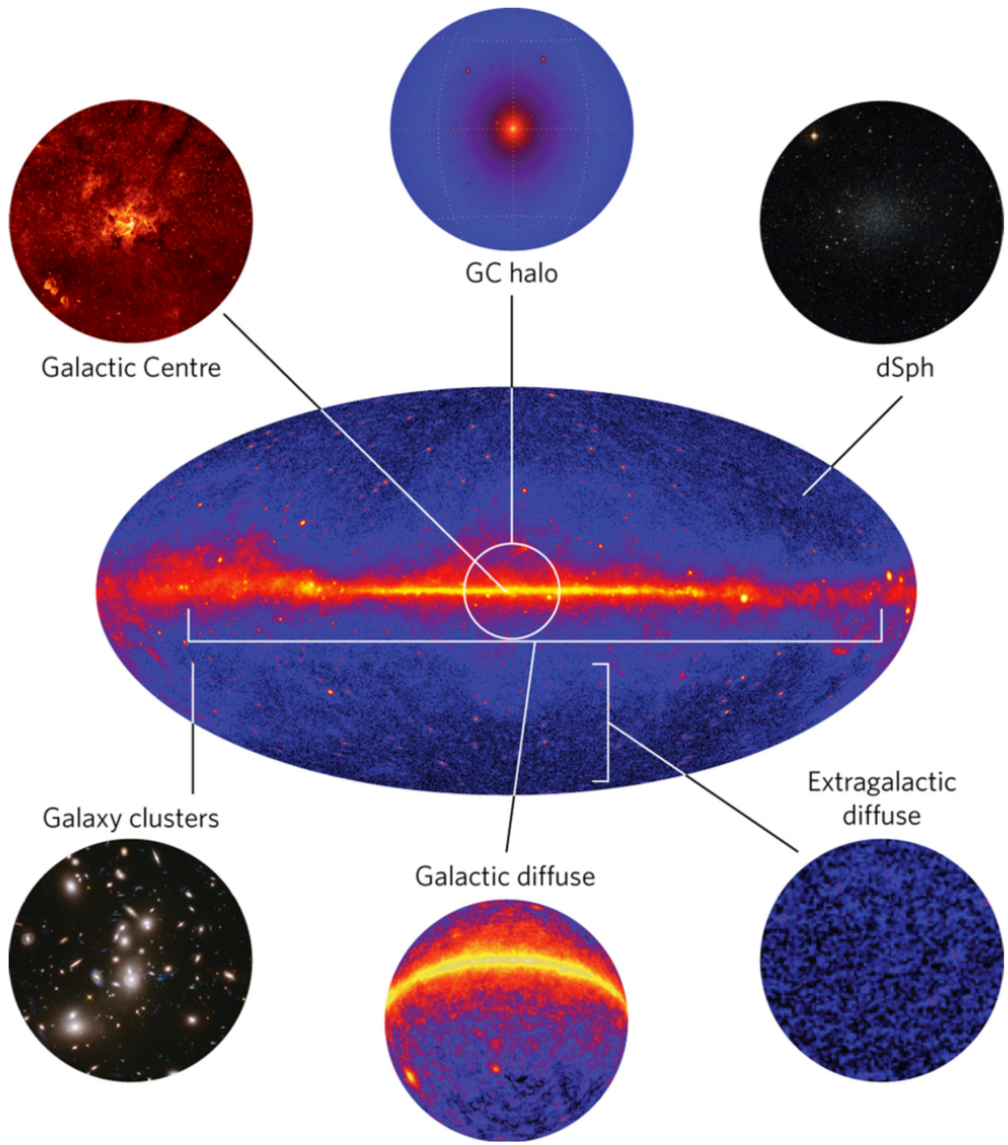
Neutral particles propagate in straight lines practically without losing energy. Charged particles, on the other hand, propagate in a complicated way through the tangled magnetic field of our Galaxy.





Gamma-rays from dark matter annihilation

Possible targets for detection of gamma-rays from annihilation



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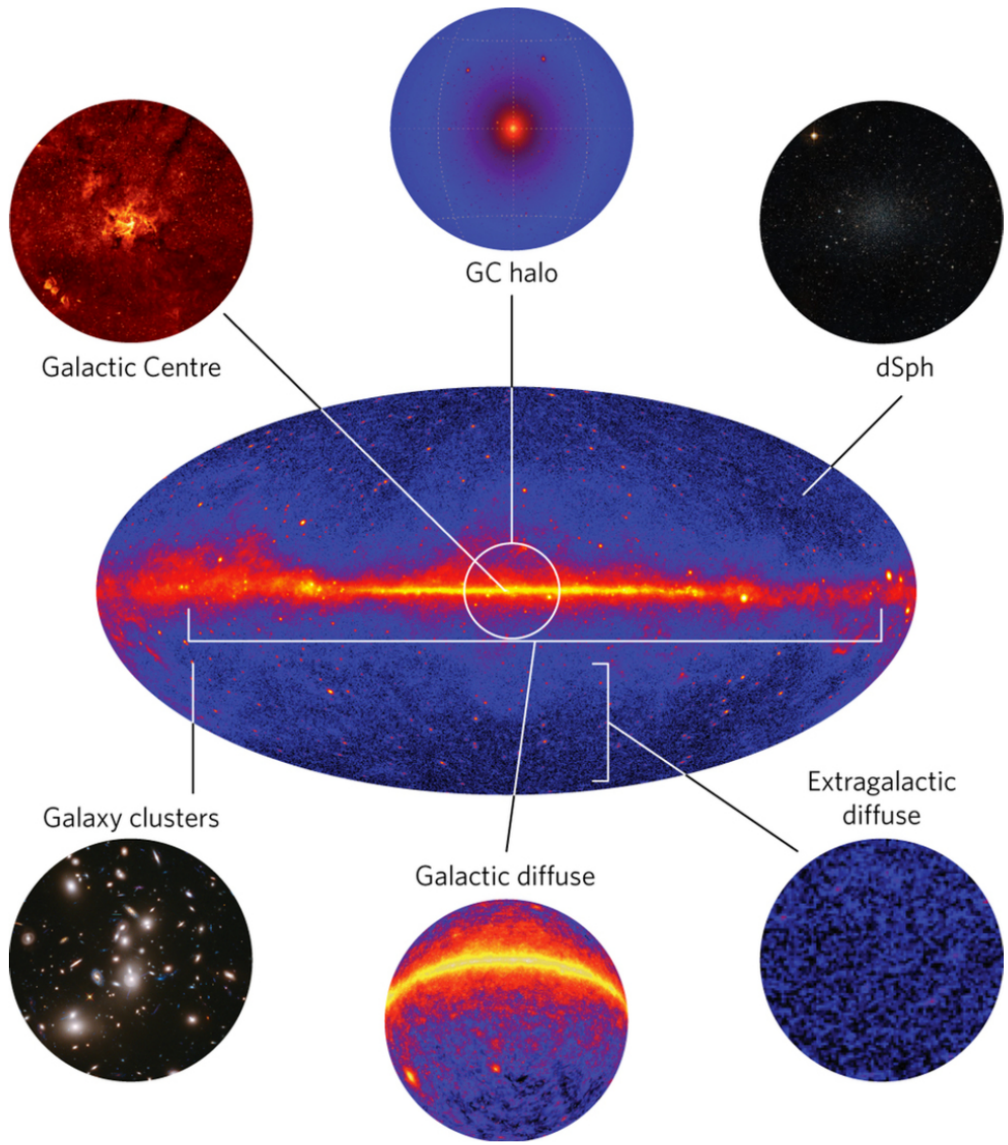

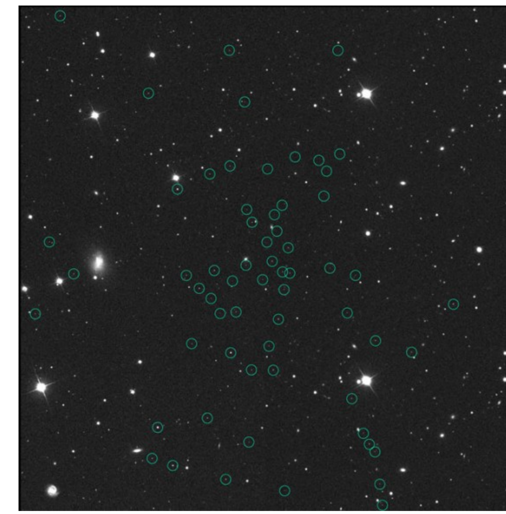

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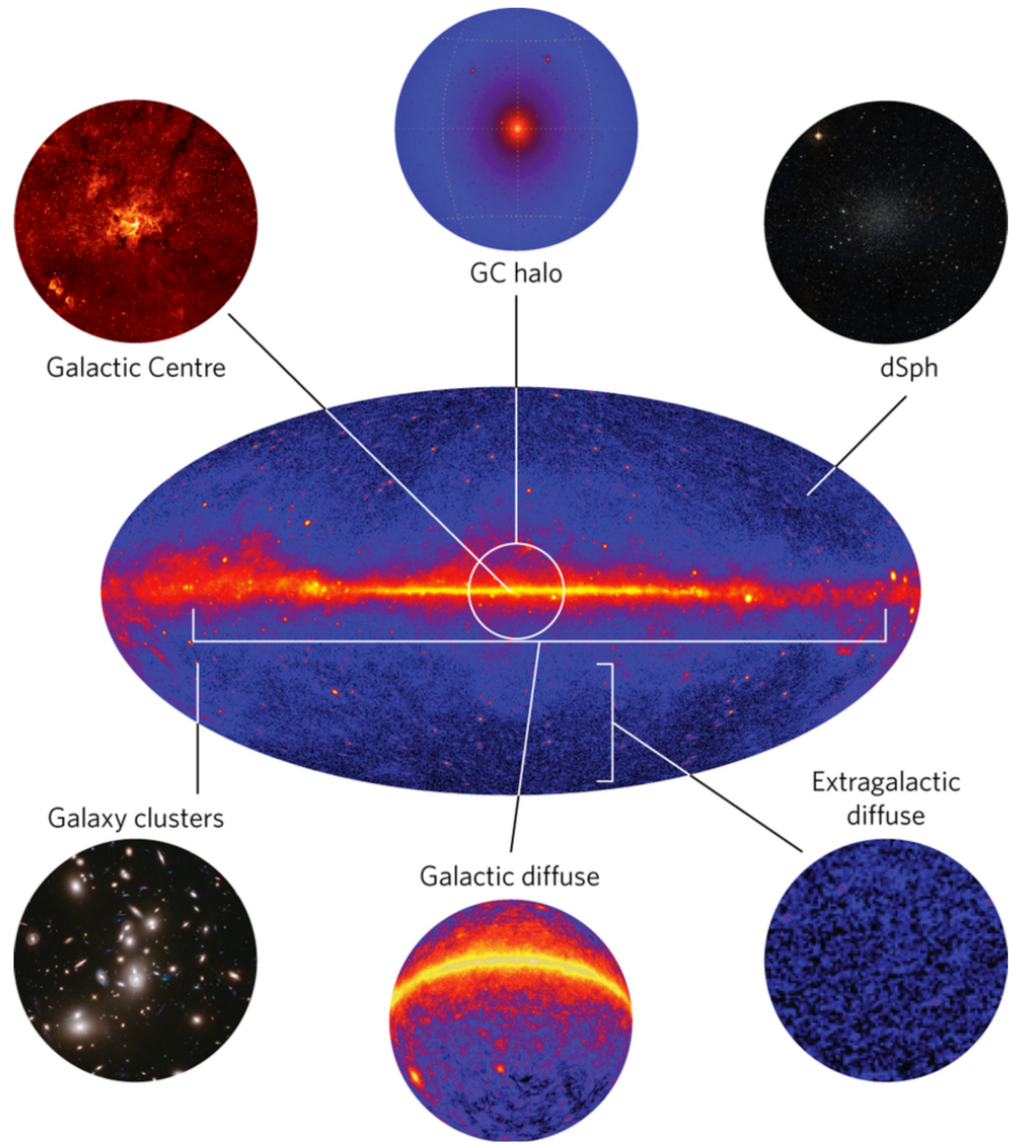

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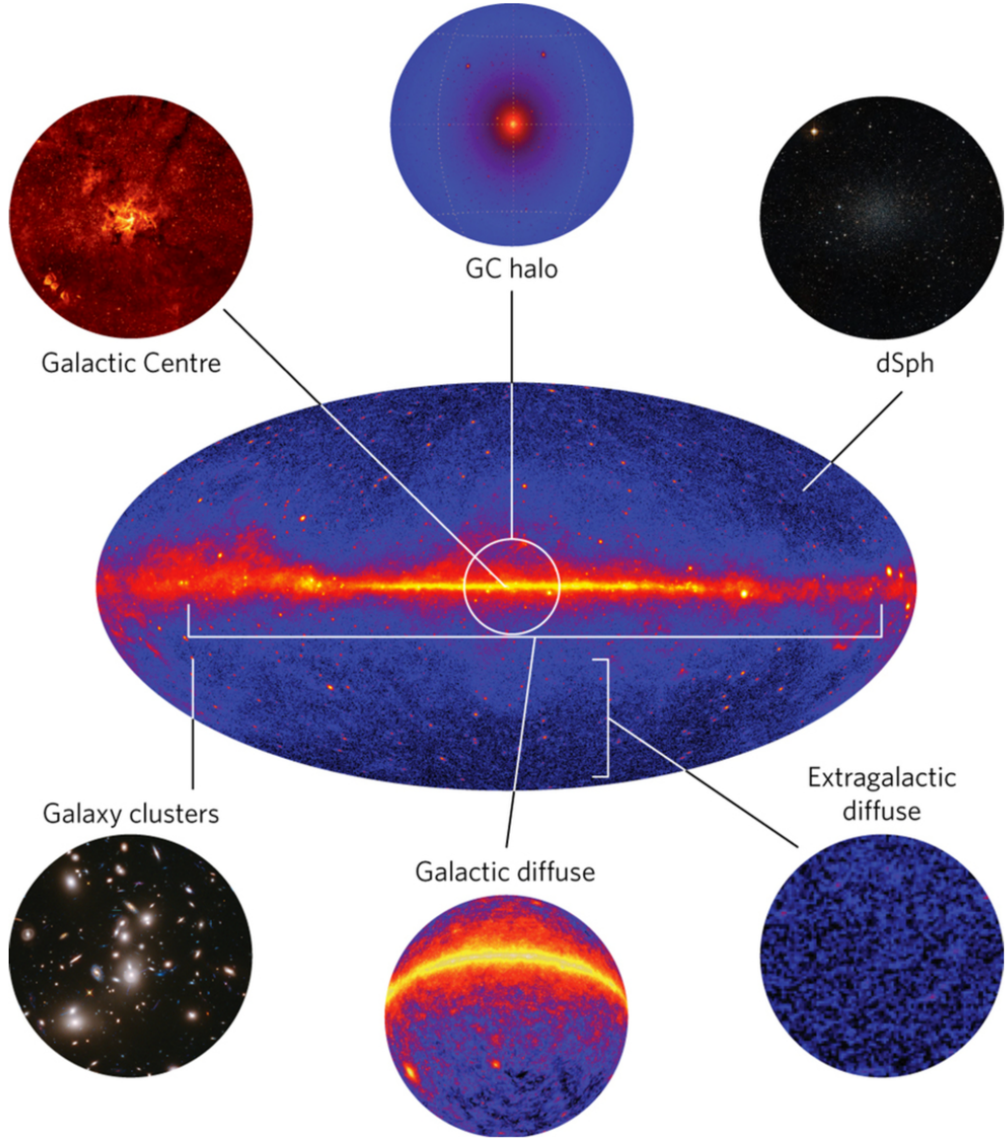

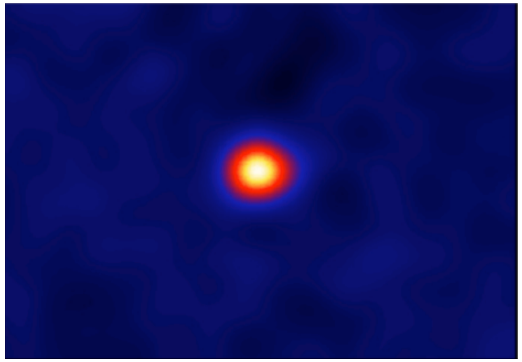

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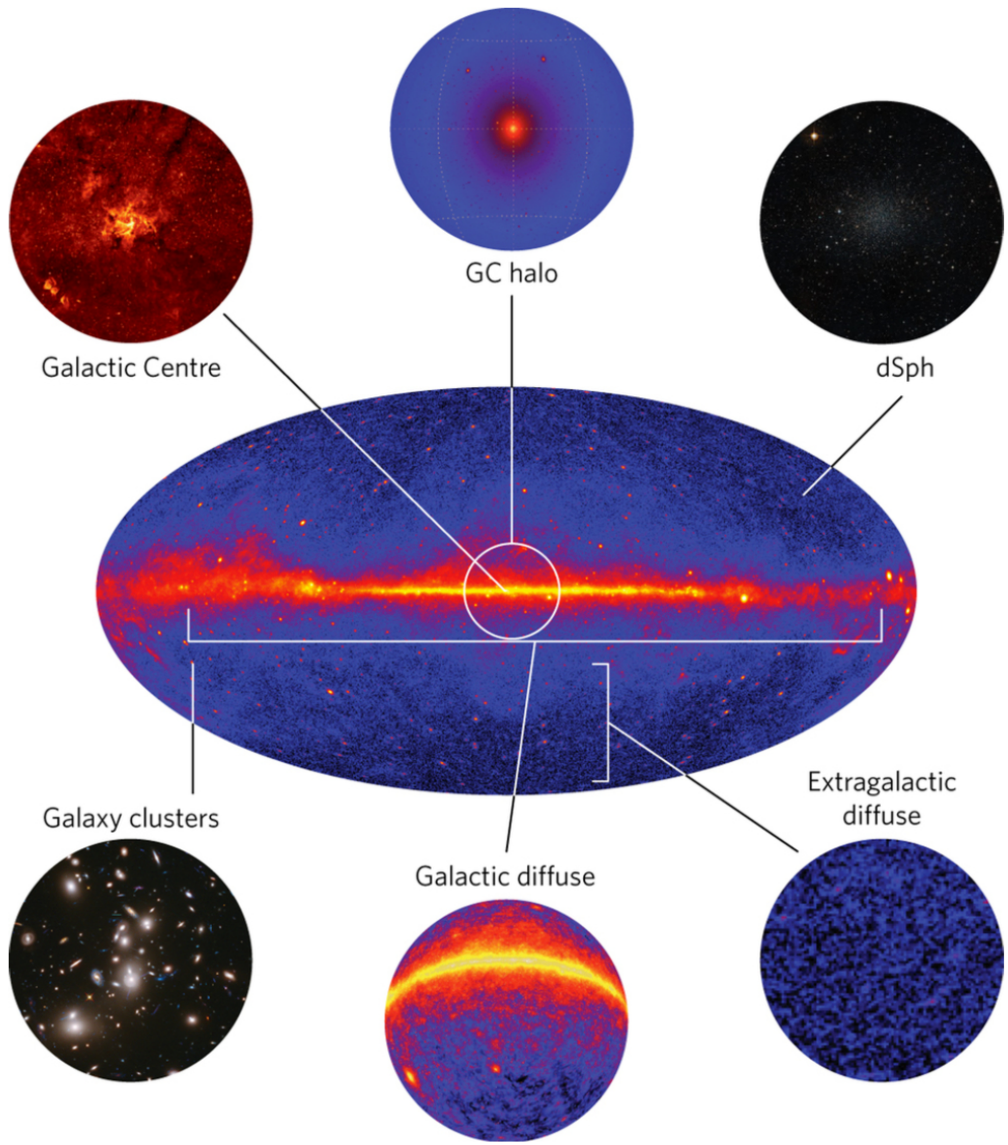

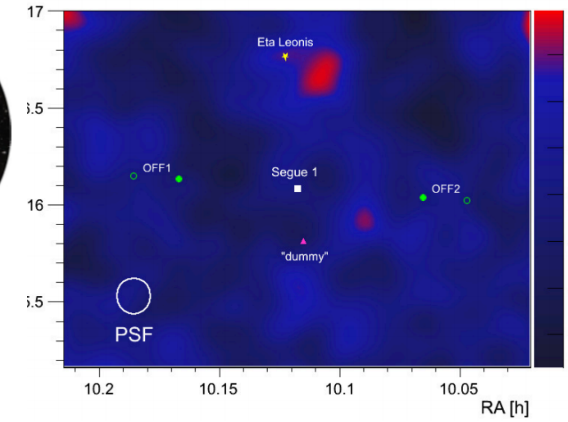

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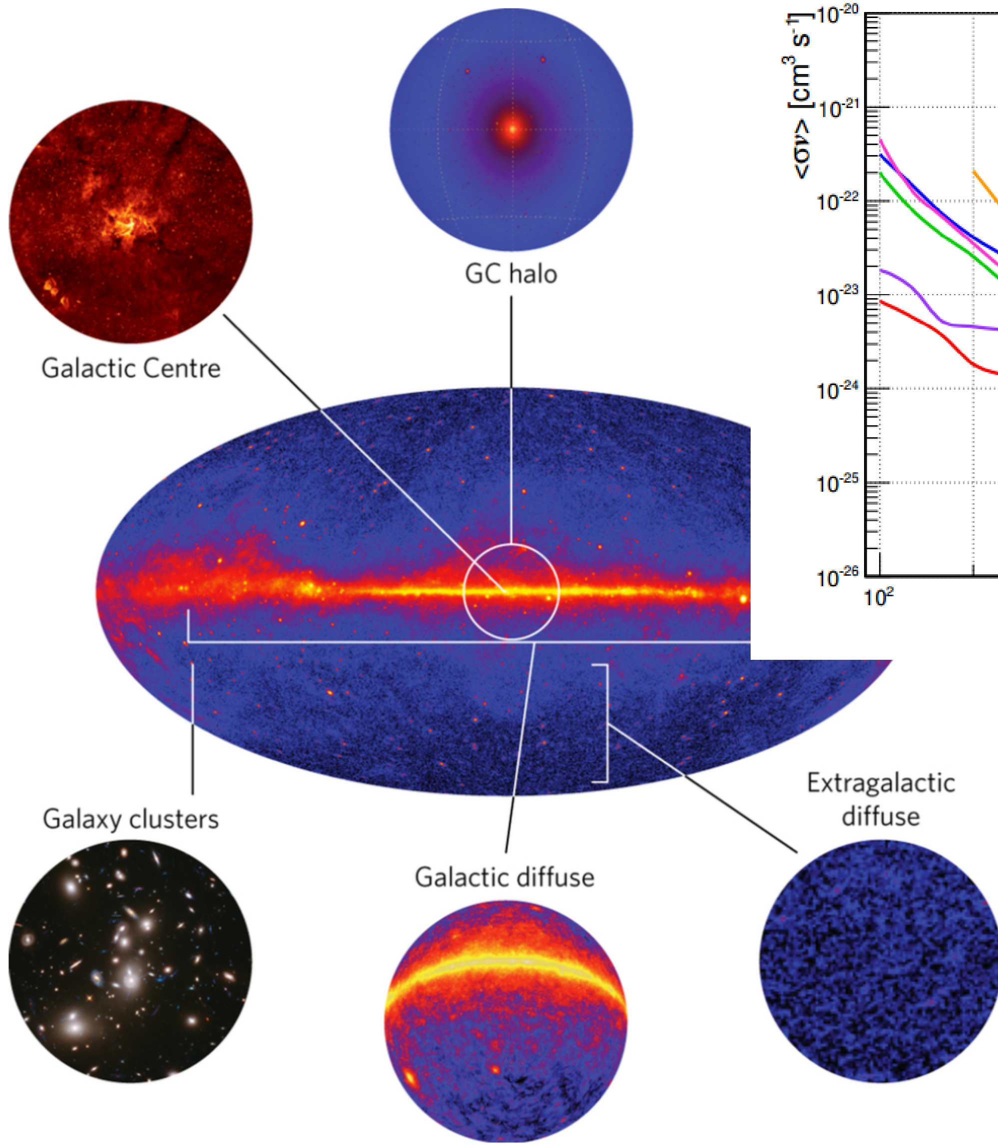

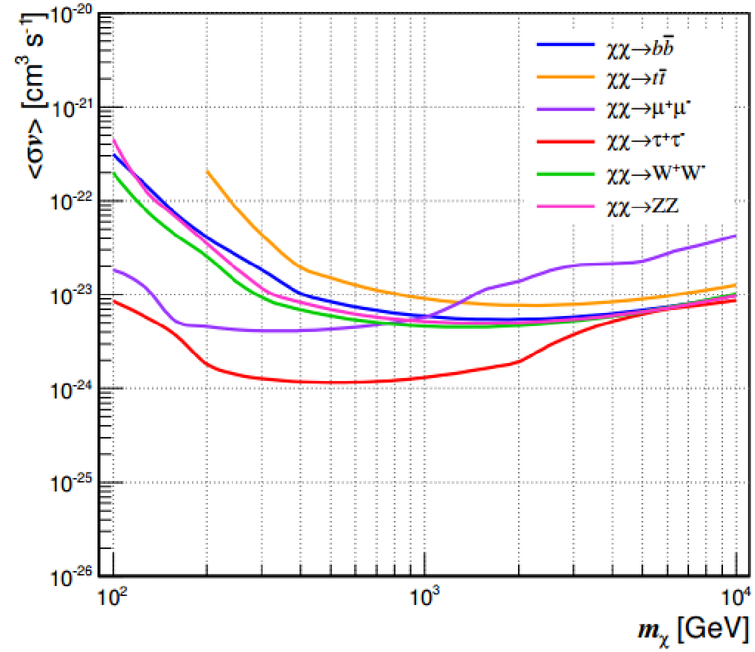

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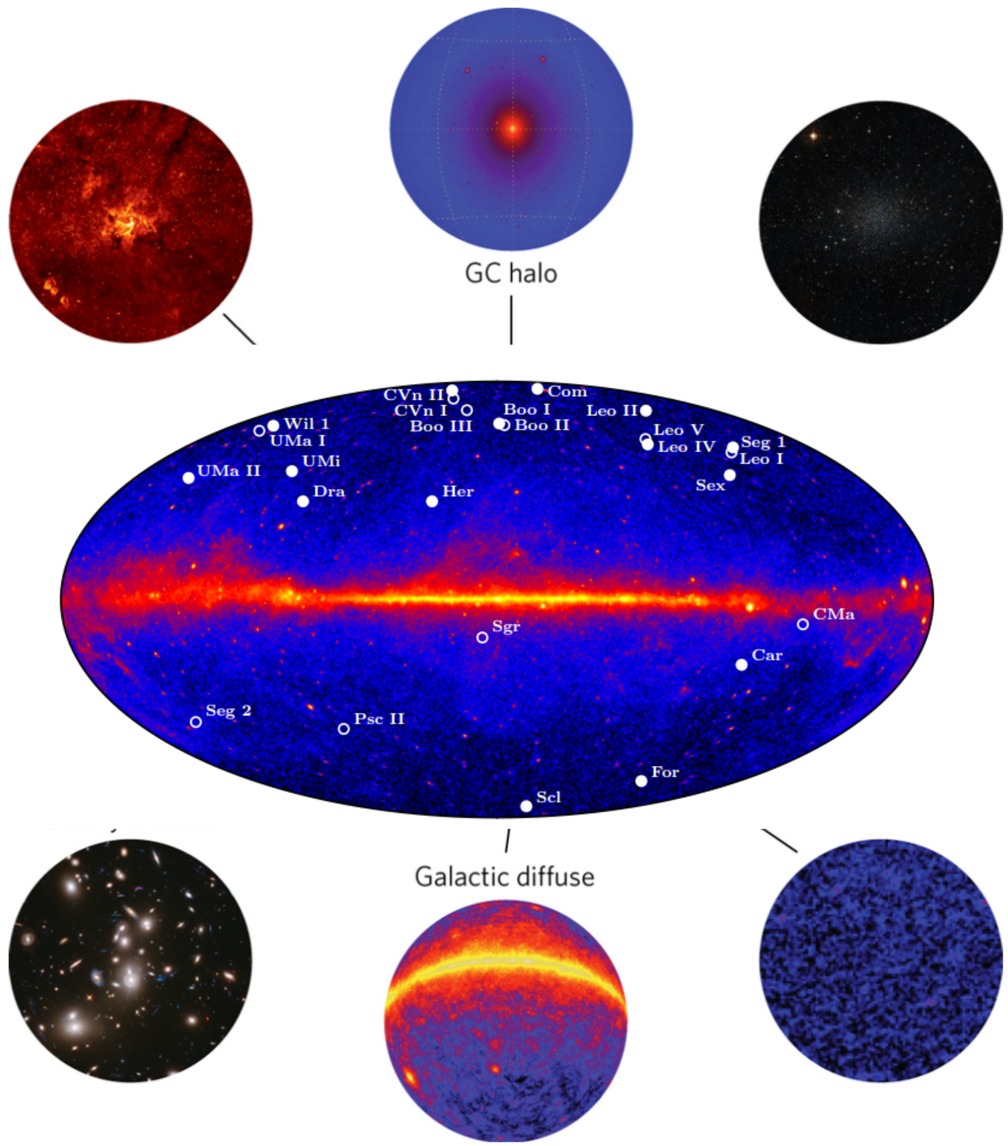

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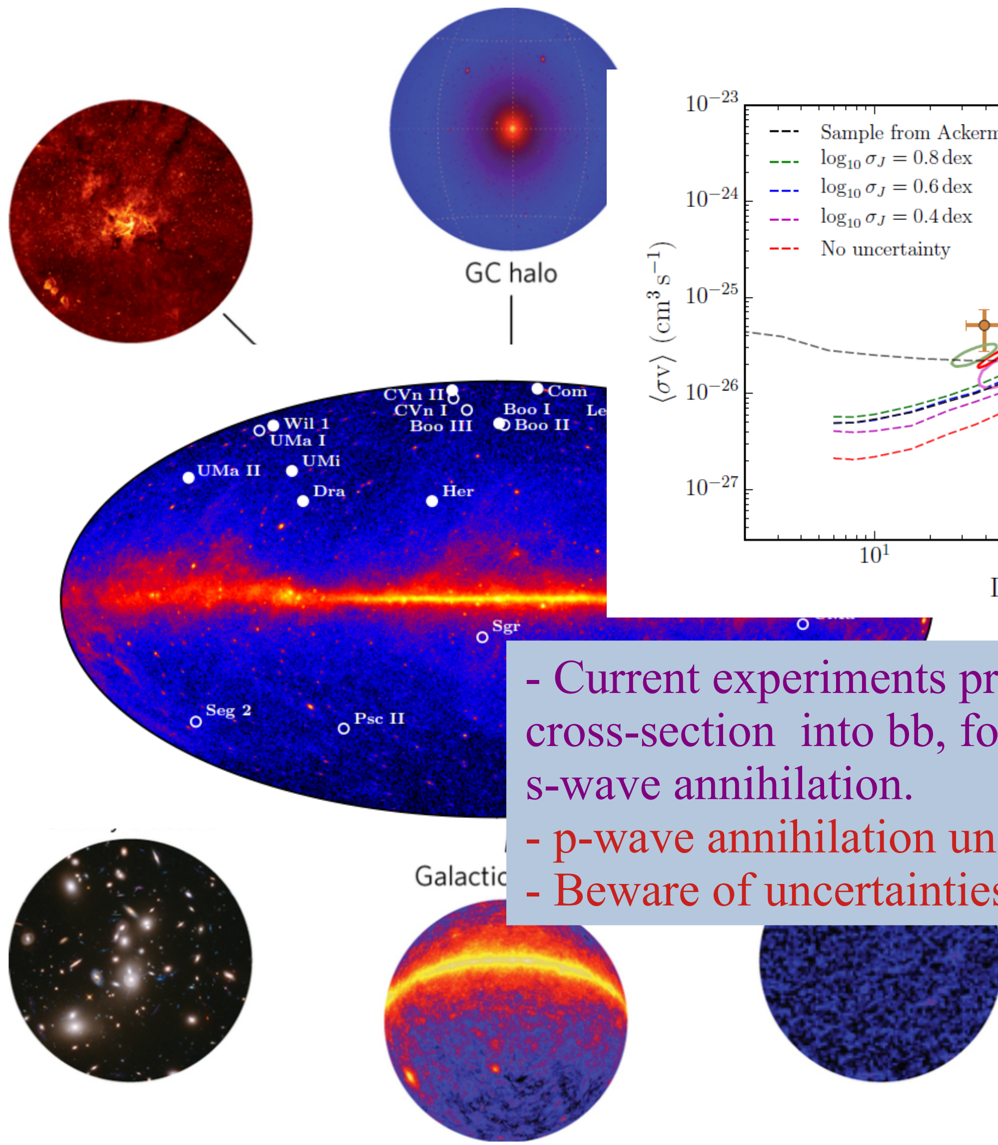

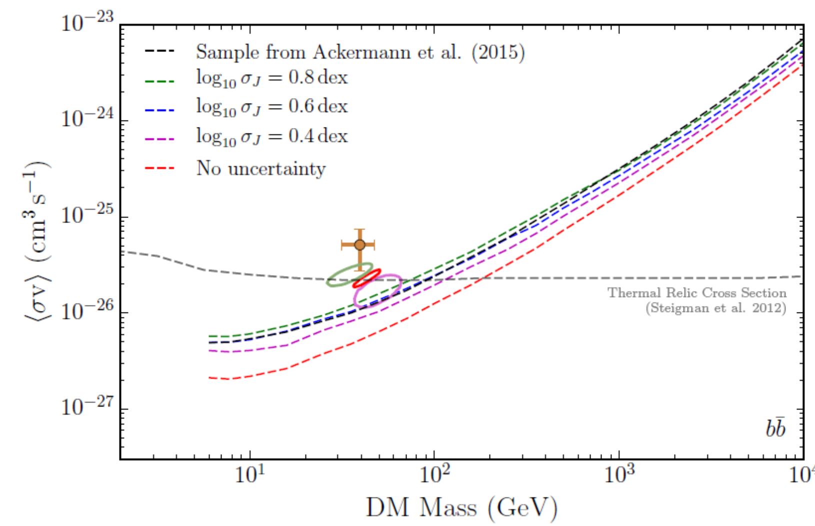

- Current experiments probe the thermal annihilation cross-section into bb, for m<100 GeV, assuming s-wave annihilation.
- p-wave annihilation unconstrained.
- Beware of uncertainties in the J-factors.

Gamma-rays from dark matter annihilation

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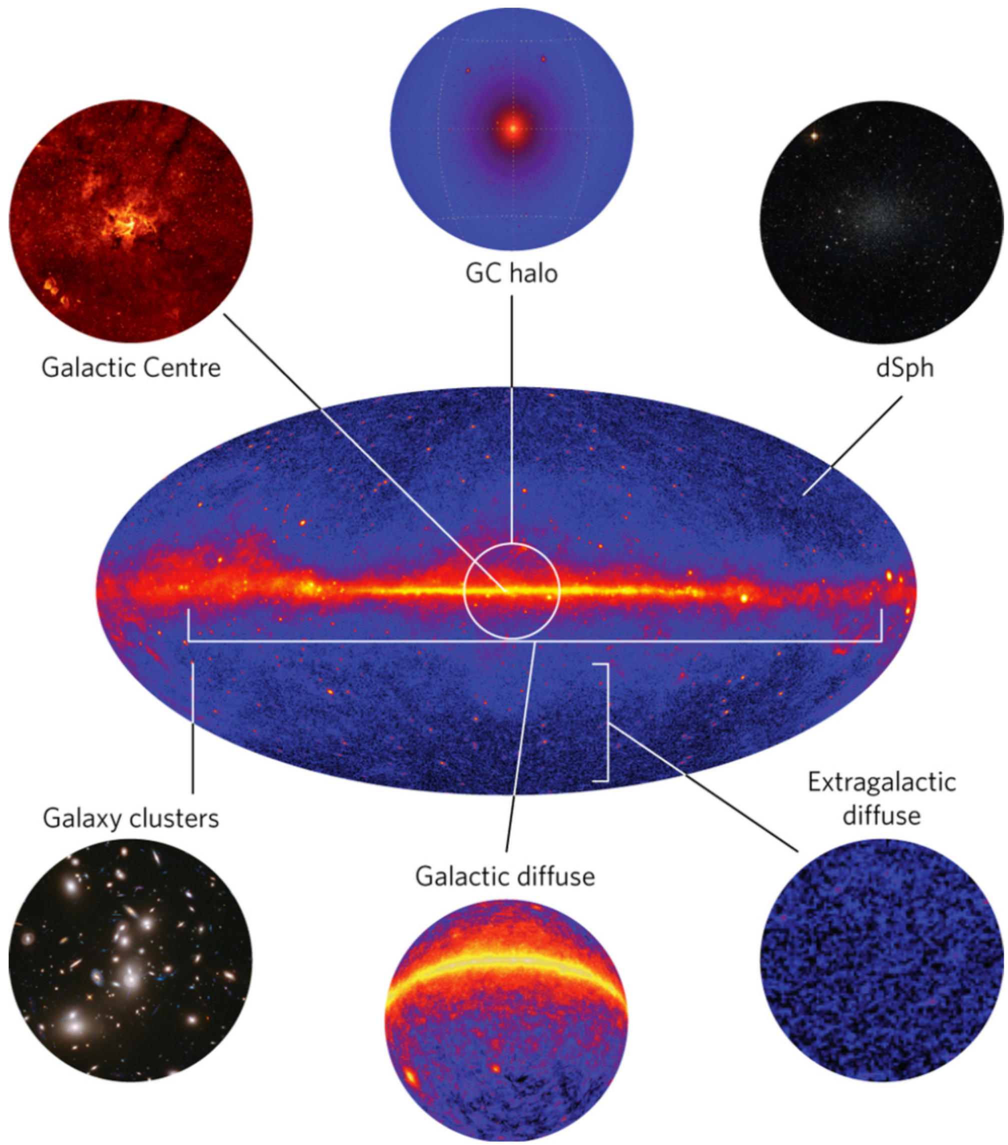

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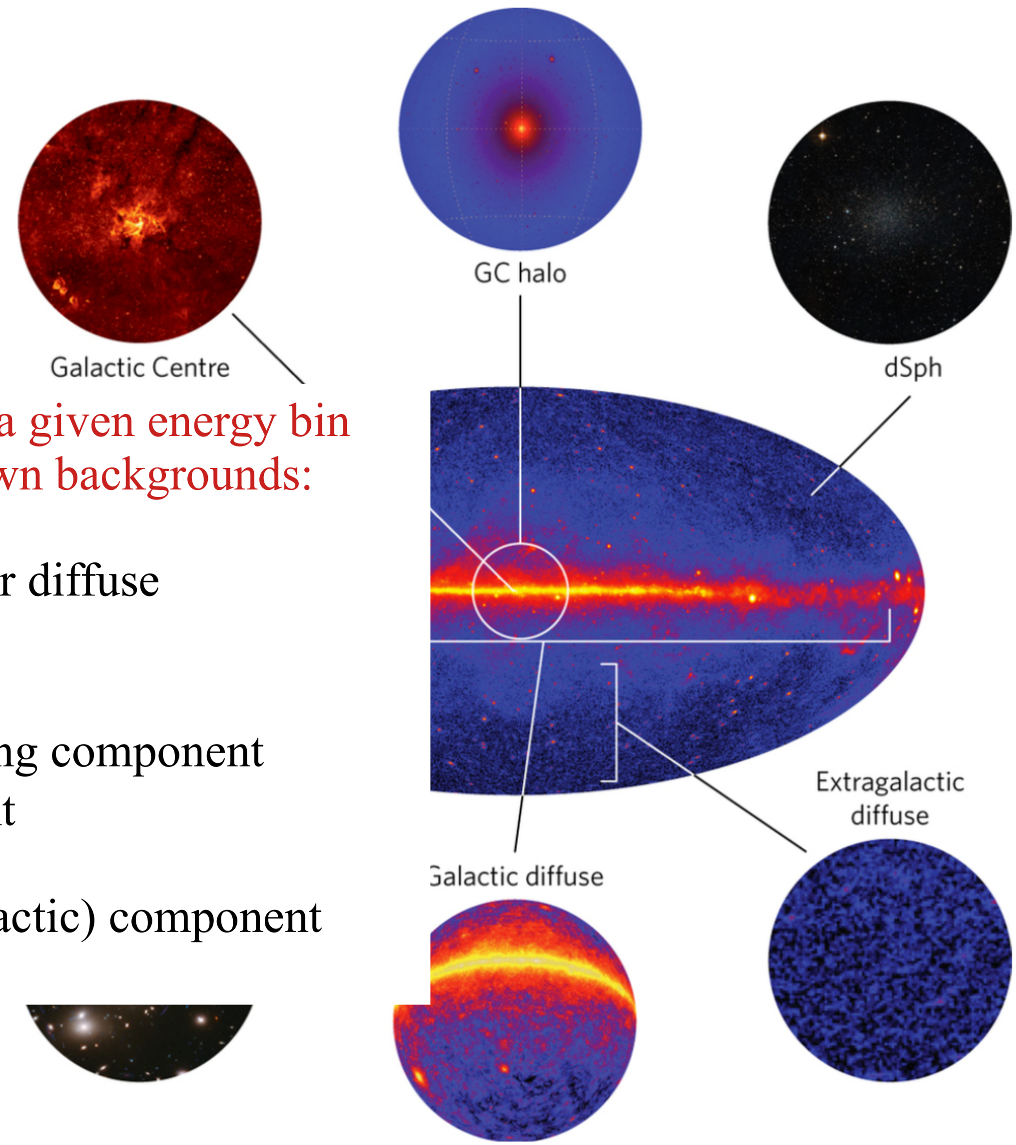

Take the sky map in a given energy bin and subtract the known backgrounds:

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

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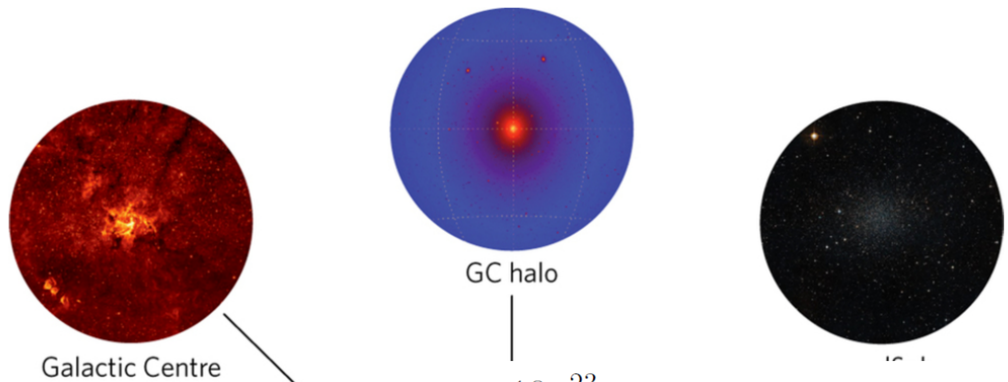

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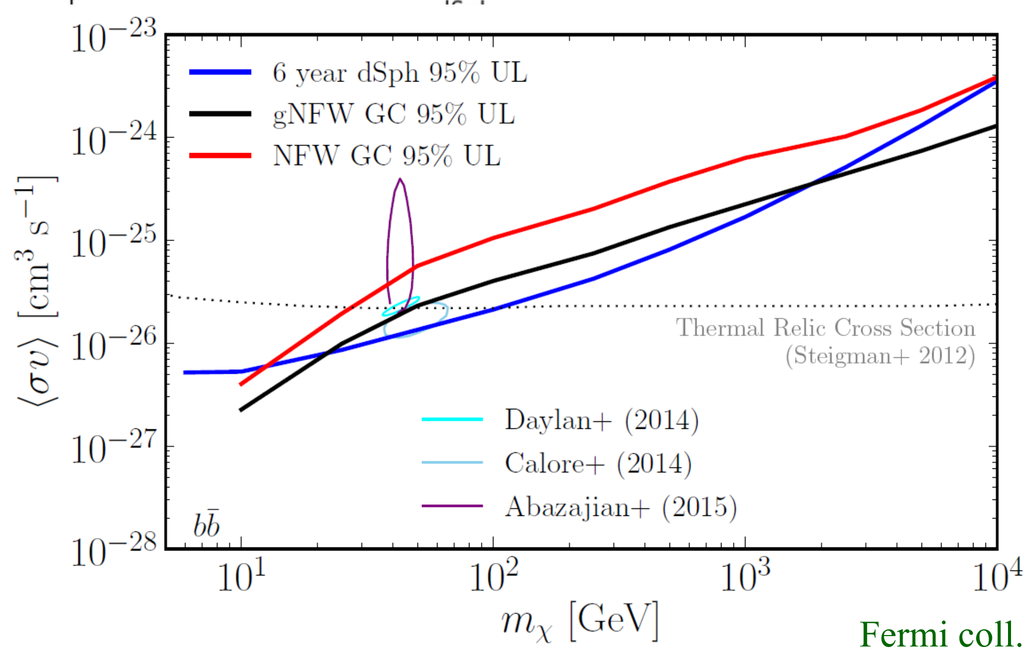
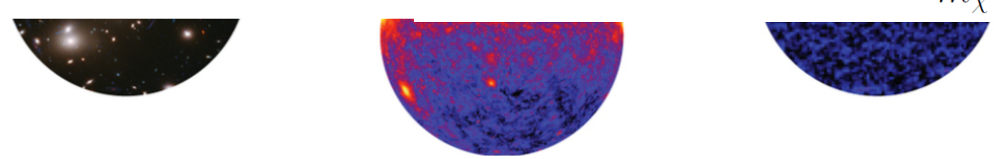


Fermi coll. '17



Antimatter from dark matter annihilation

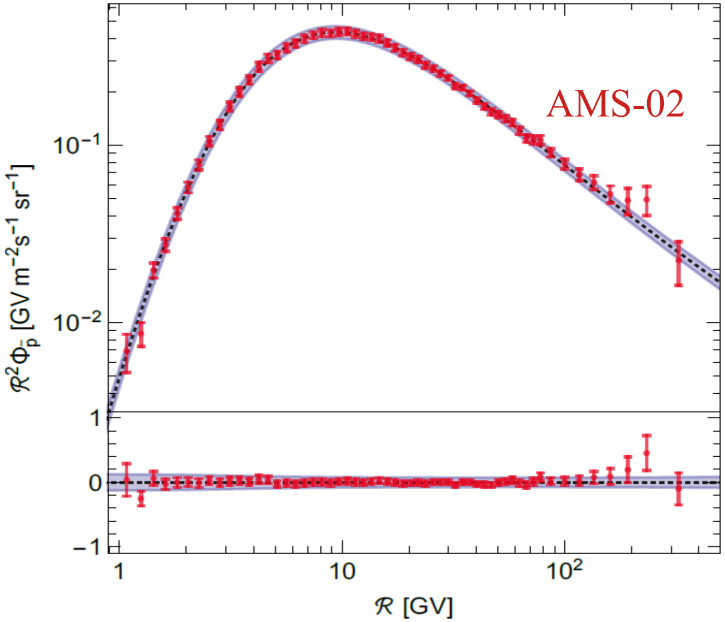
Antimatter particles propagate through the tangled magnetic field of the galaxy in a complicated way, losing energy on their way.

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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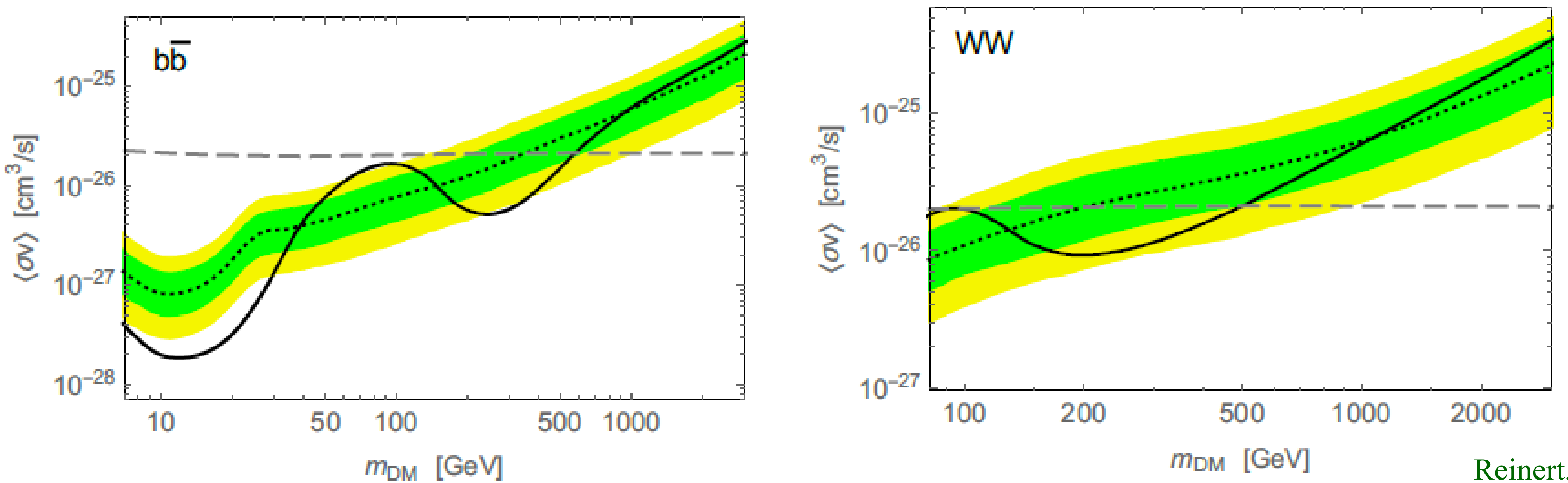

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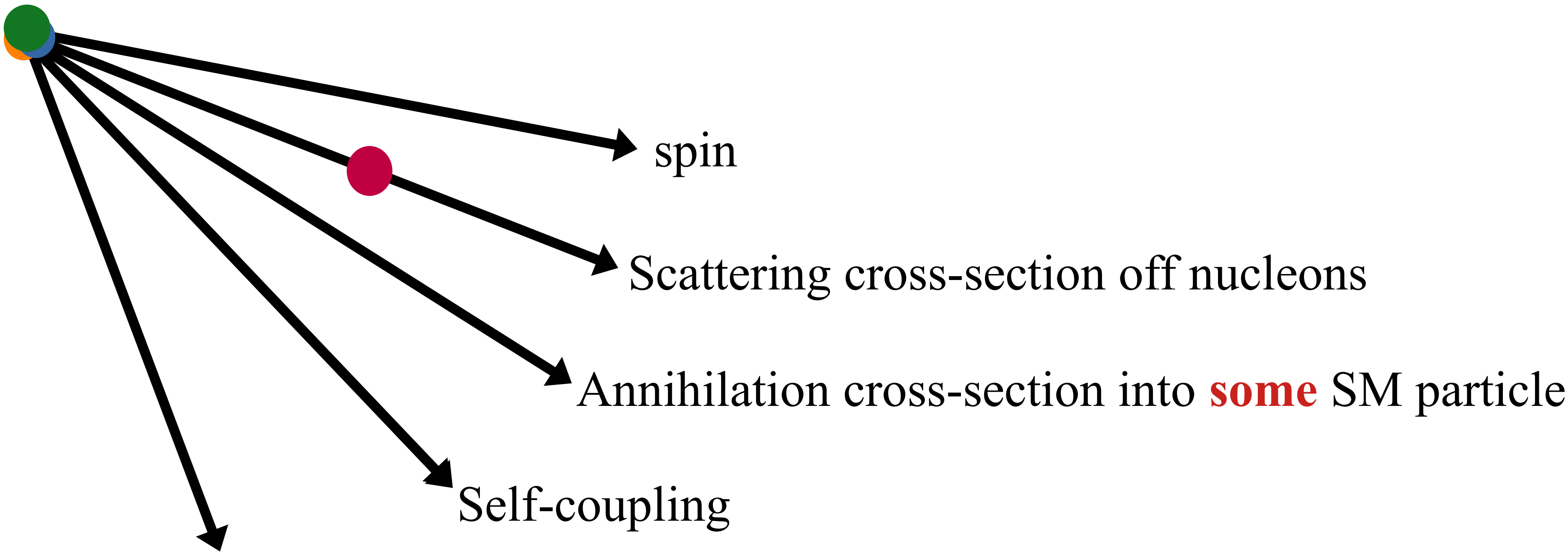
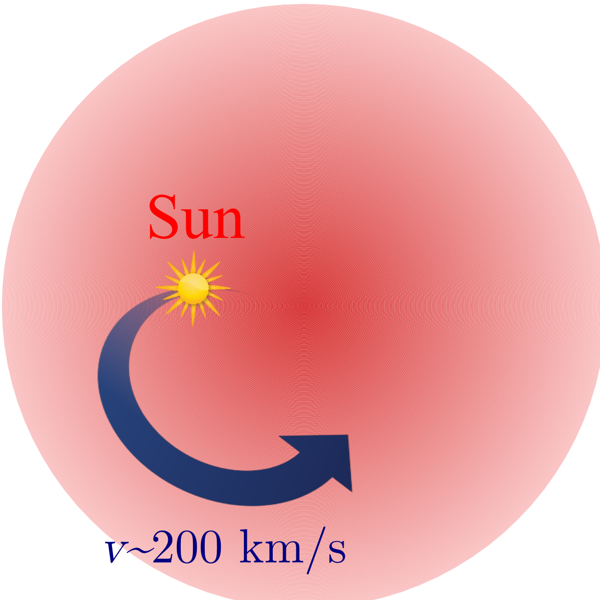
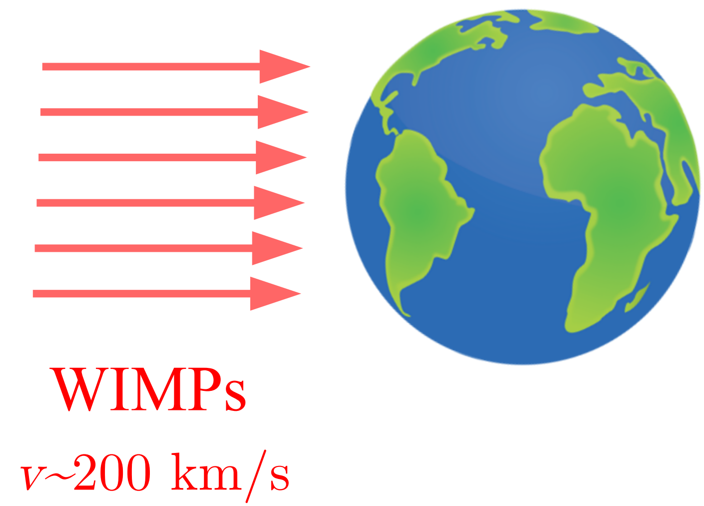
Probing the scattering with nucleons



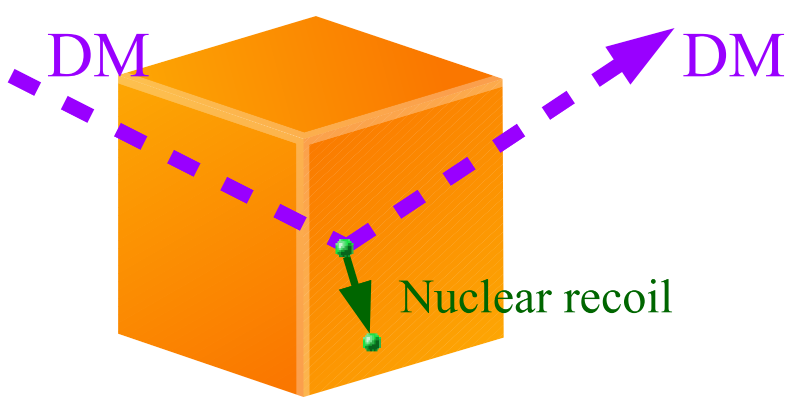
Probing the scattering with nucleons

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



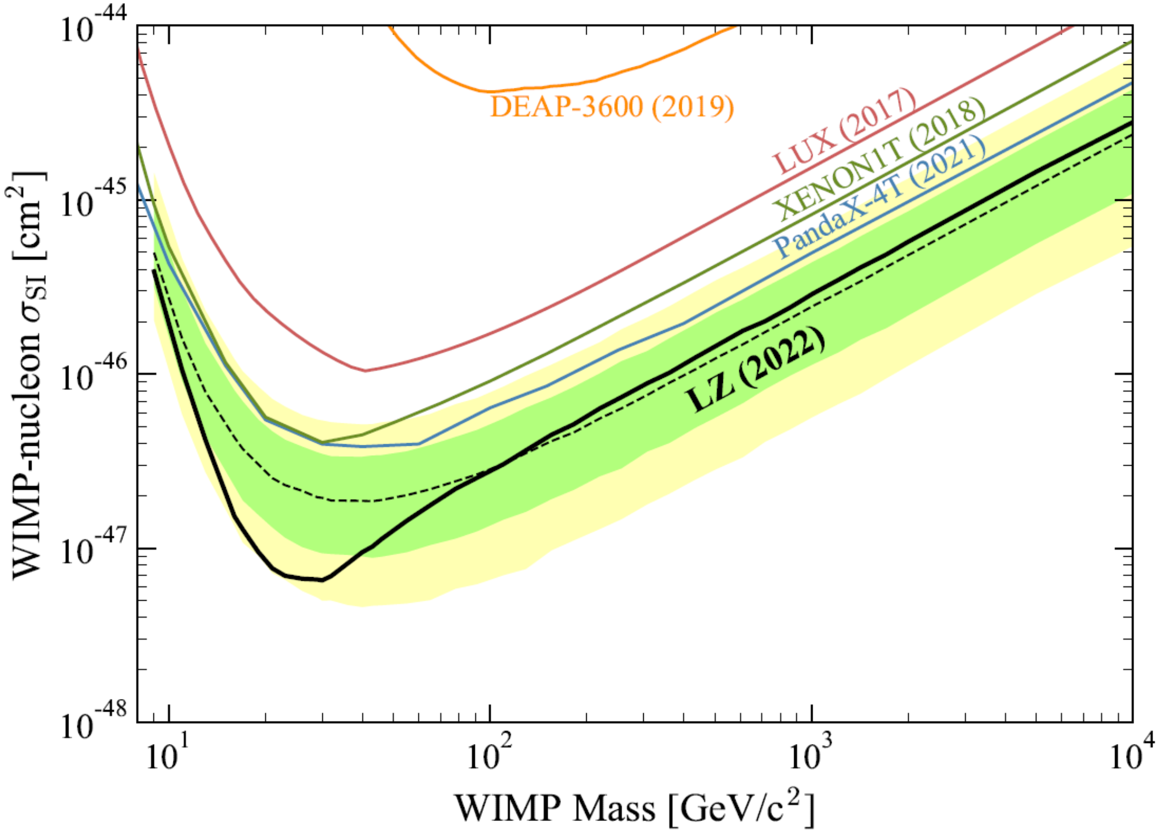


Once in a while a dark matter particle will interact with a nucleus. The nucleus then recoils, producing vibrations, ionizations or scintillation light in the detector.



No significant excess detected so far

Probing the scattering with nucleons



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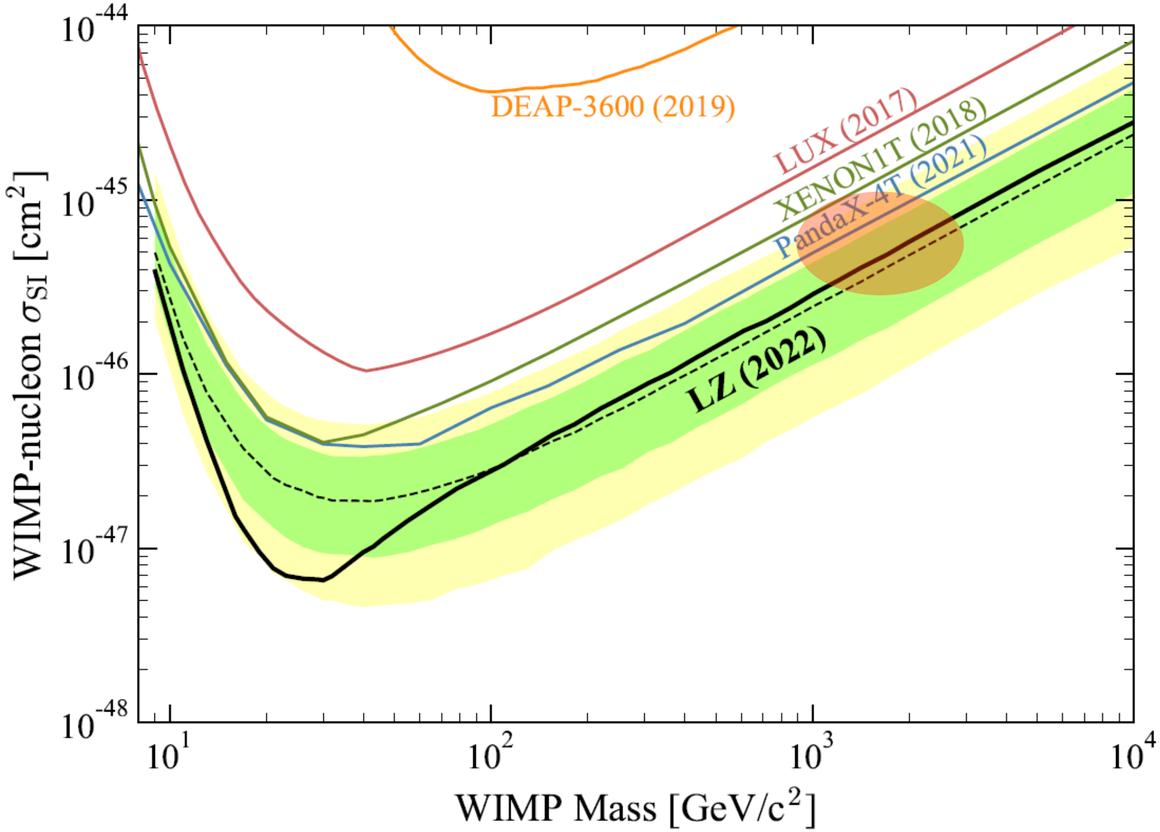

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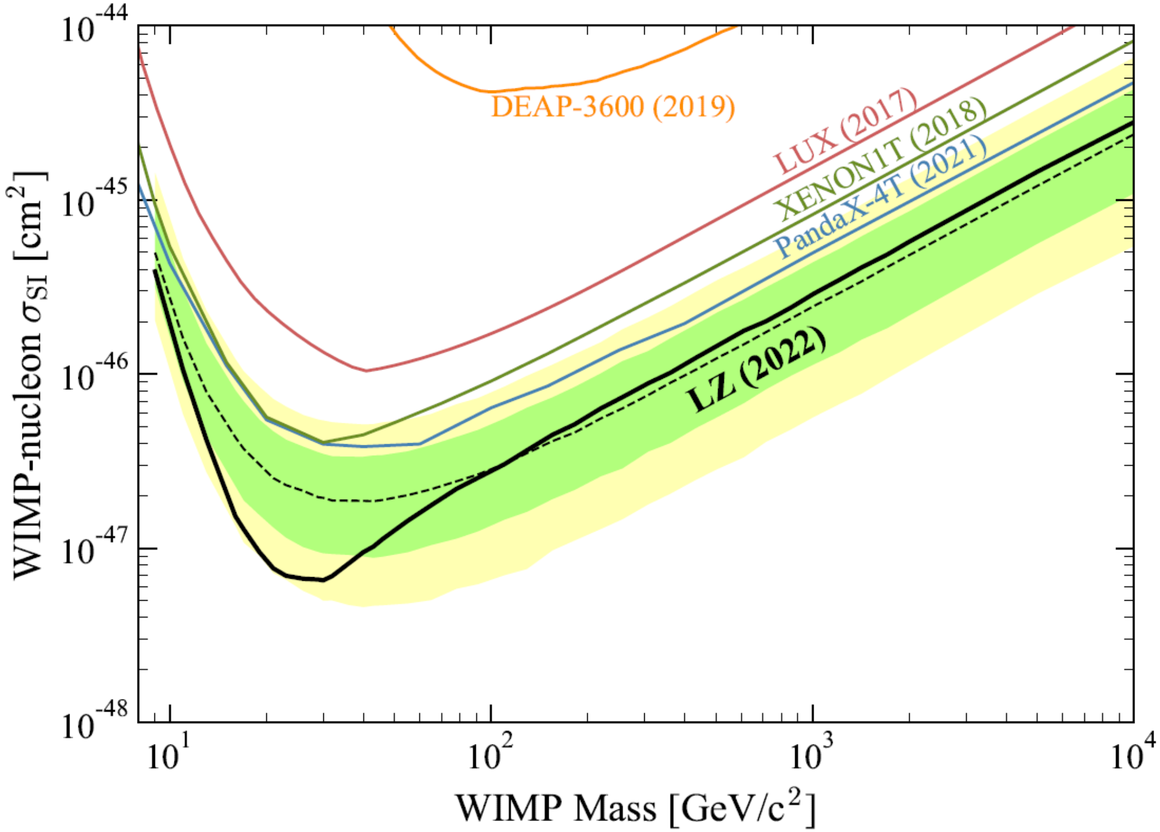

Smallprint:

- 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.

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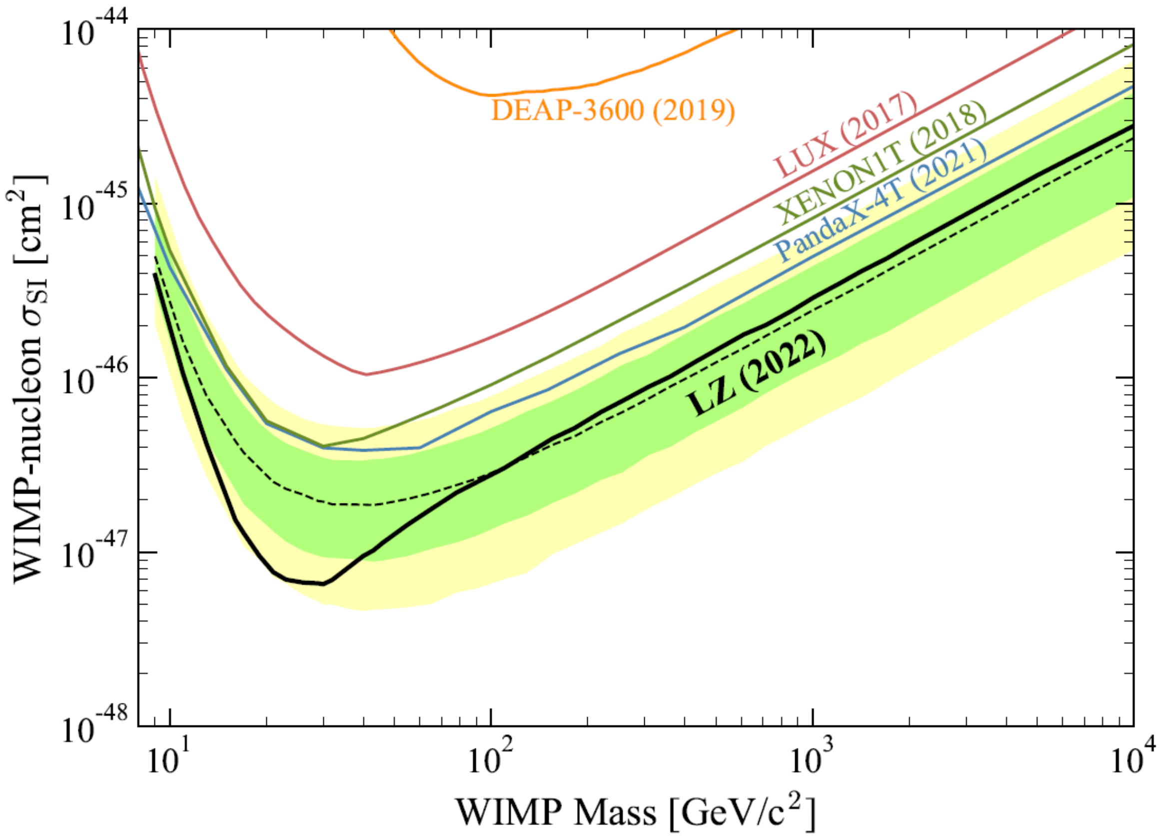

Differential recoil rate

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

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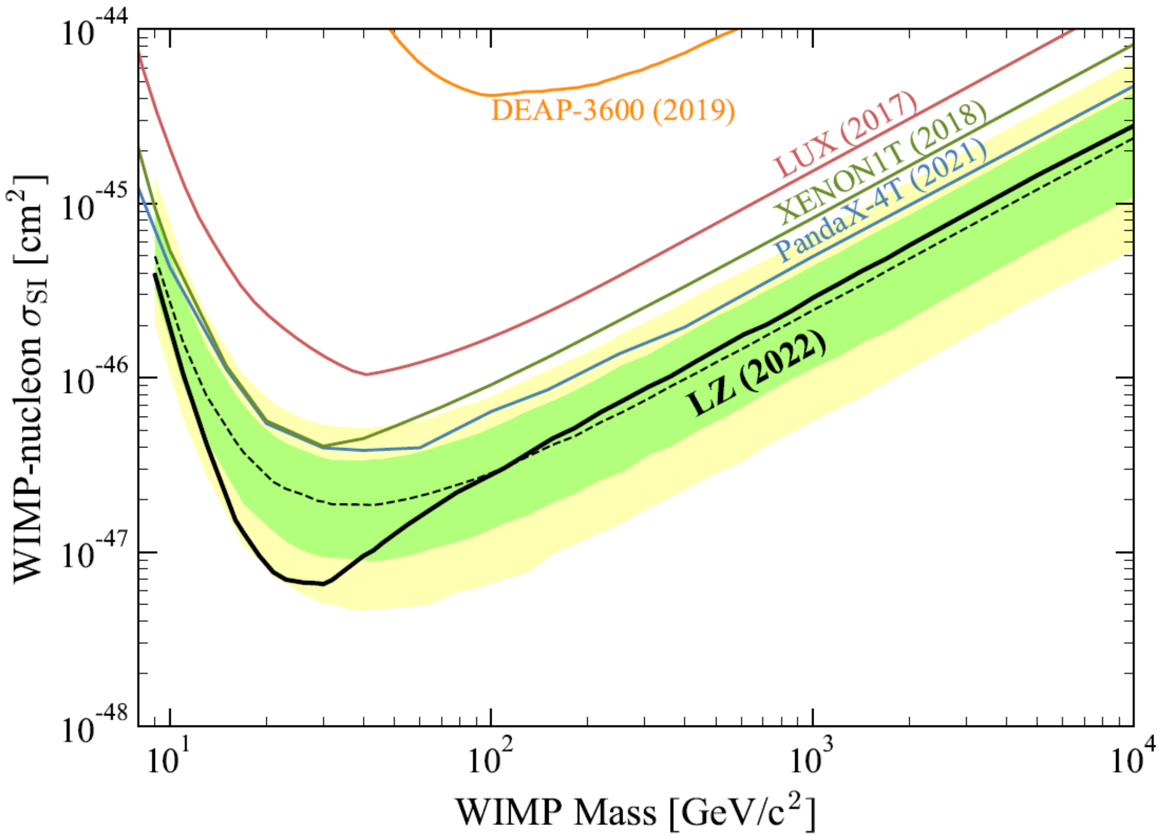

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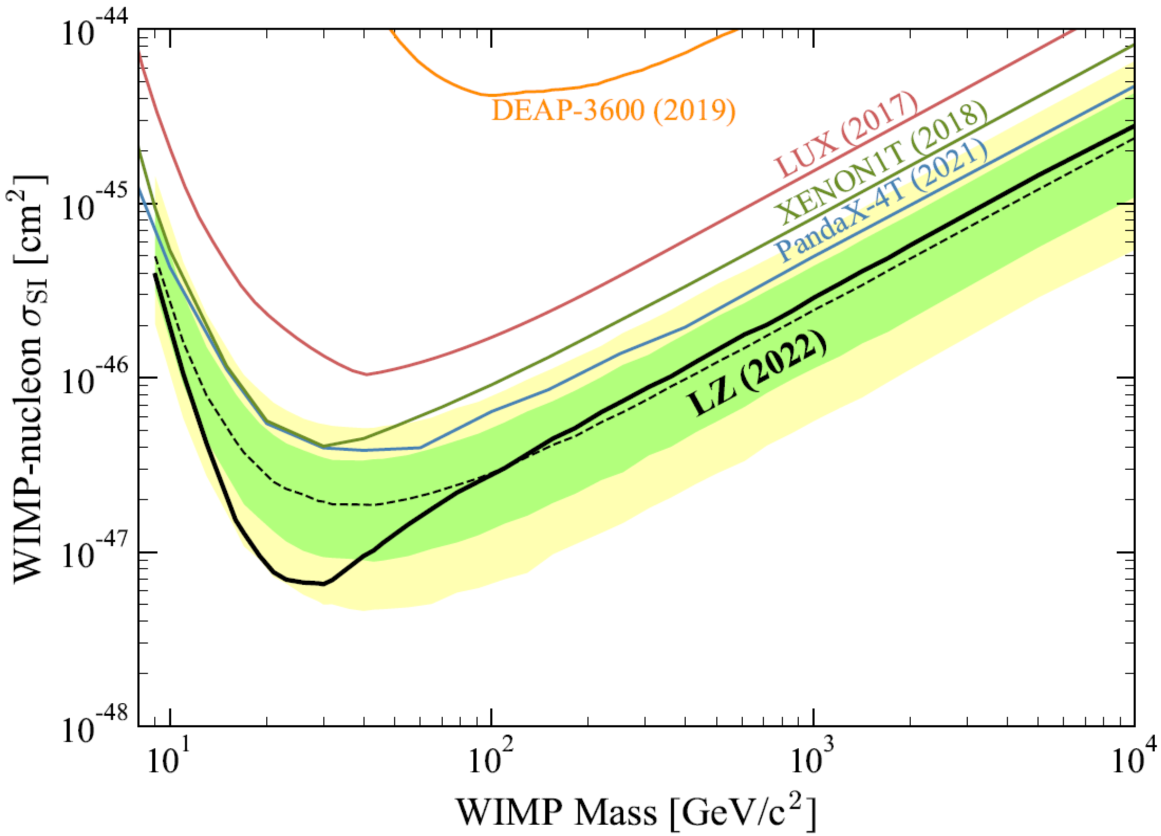

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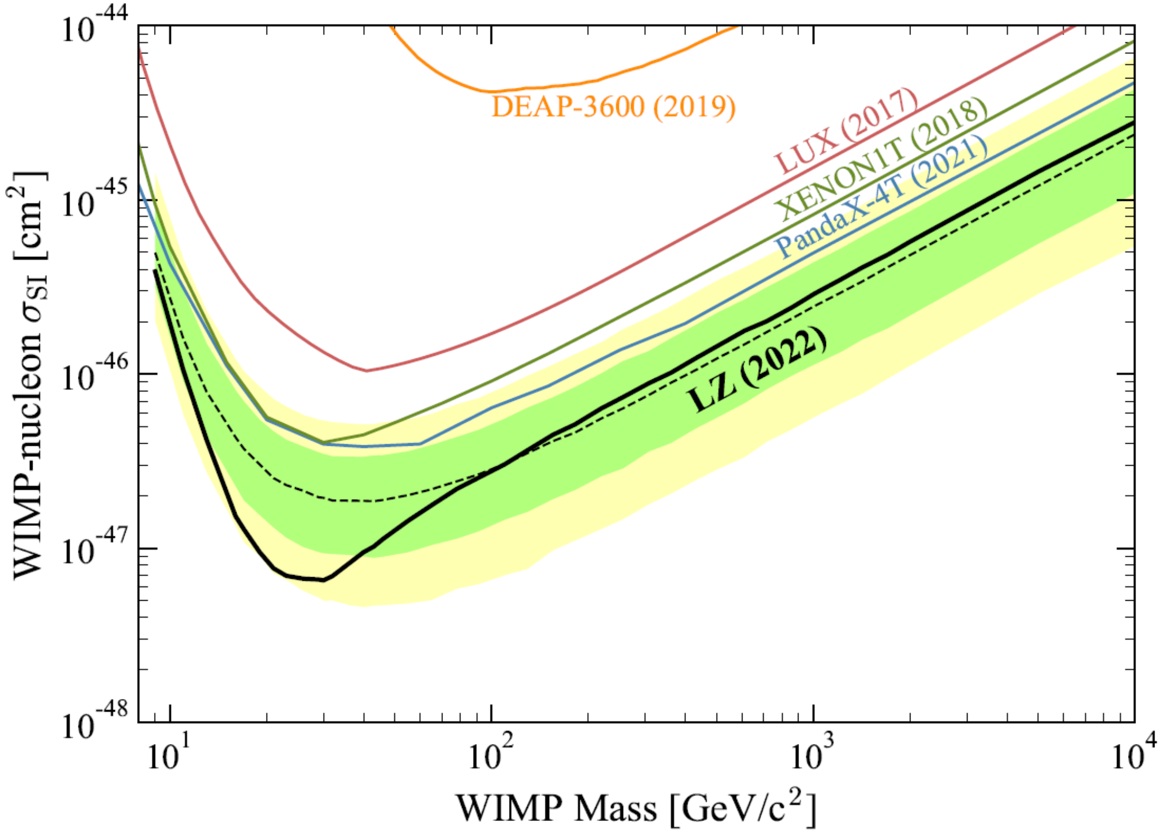

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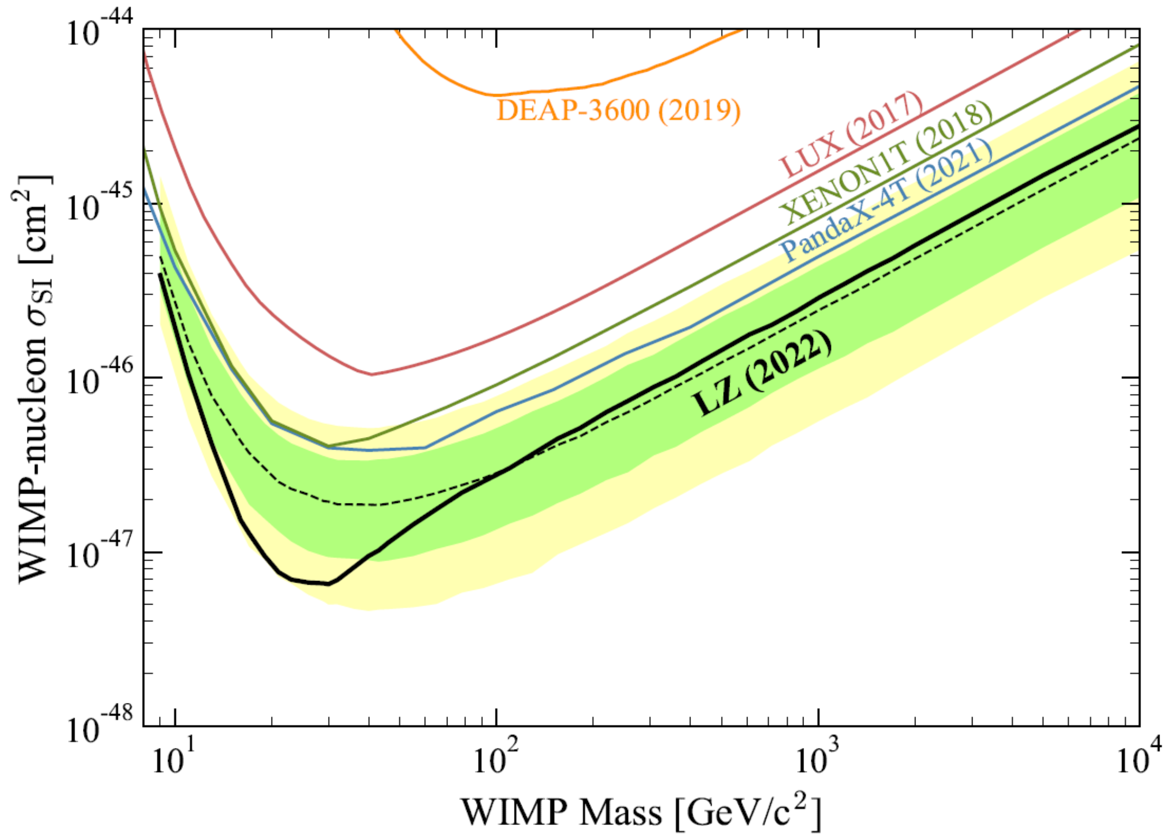

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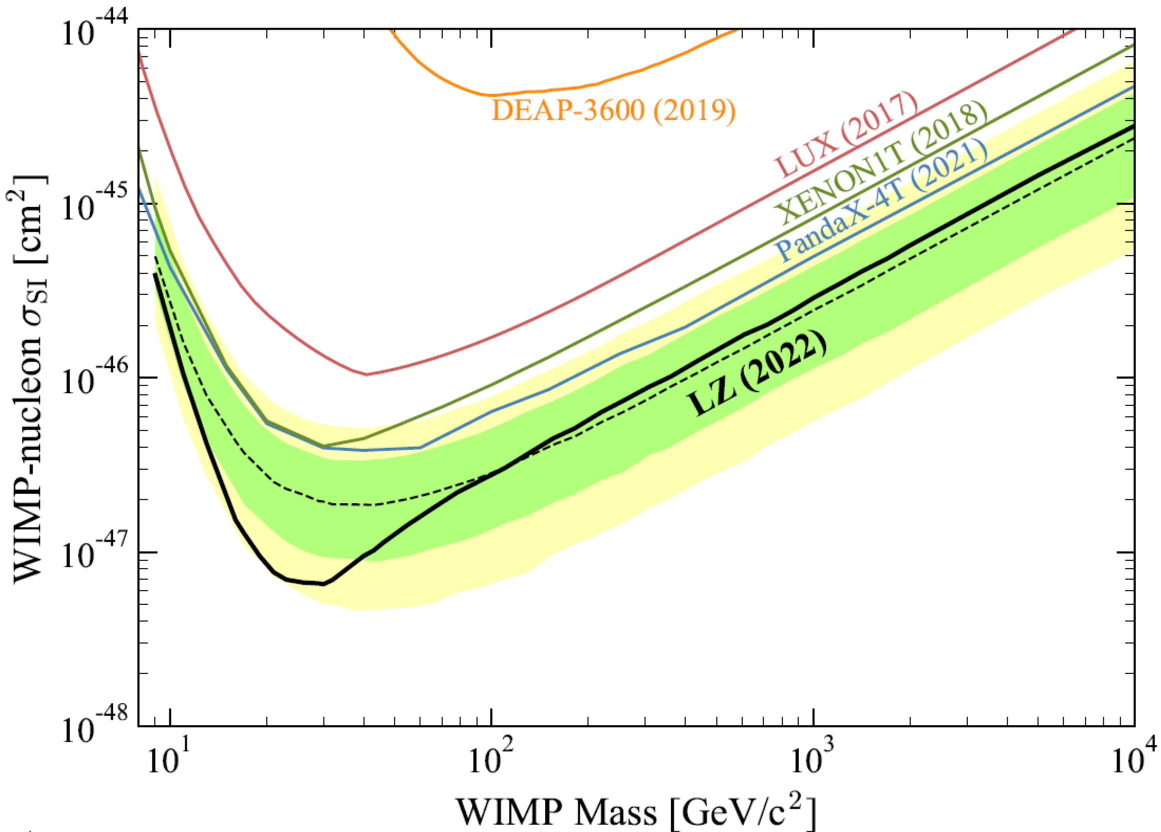
$$\frac{dR}{dE_R} = \frac{\rho_{\rm loc}}{m_A m_{\rm DM}} \int_{v \geq v_{\rm min}(E_R)} {\rm d}^3v \, v f(\vec{v} + \vec{v}_{\rm obs}(t)) \frac{{\rm d}\sigma}{{\rm d}E_R}$$

? ? ? ?

Probing the scattering with nucleons



Smallprint:

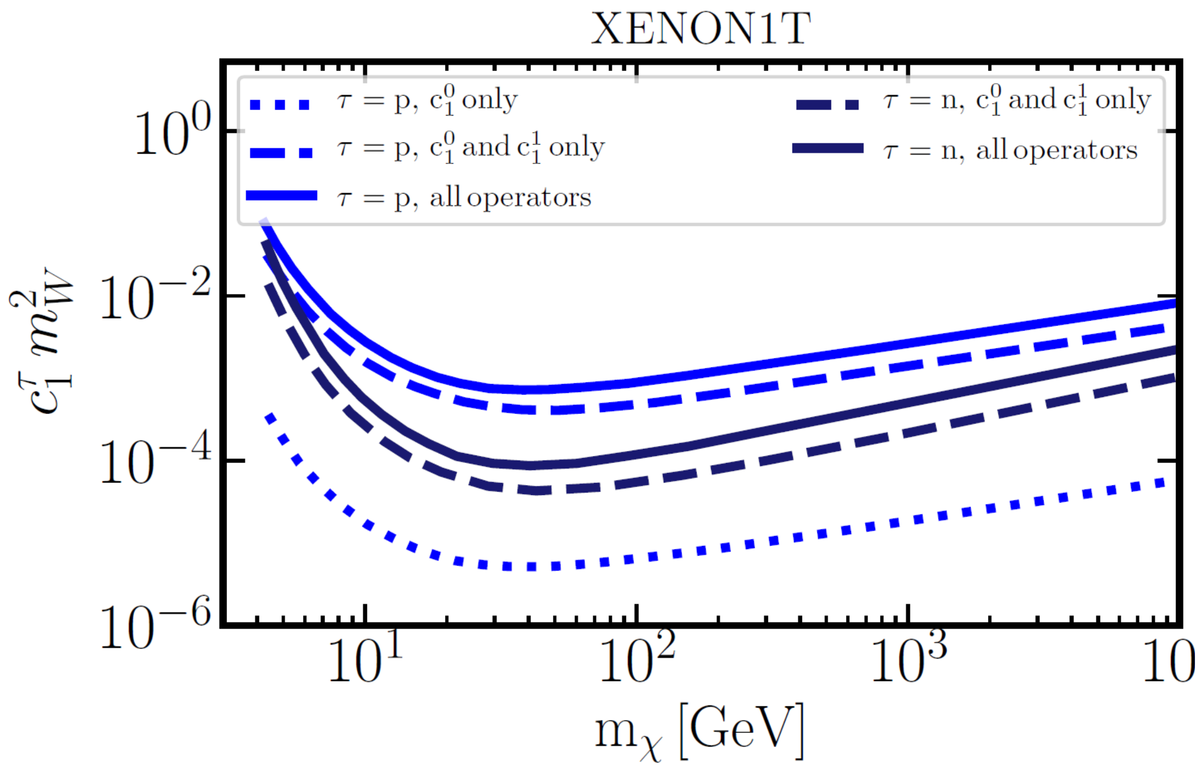
- DM interacts only through the spin-independent interaction
- DM couples with equal strength to protons and neutrons (isoscalar)
- Local DM density ρ=0.3 GeV/cm3.
- DM velocity distribution given by a Maxwell-Boltzmann, truncated at the escape velocity.

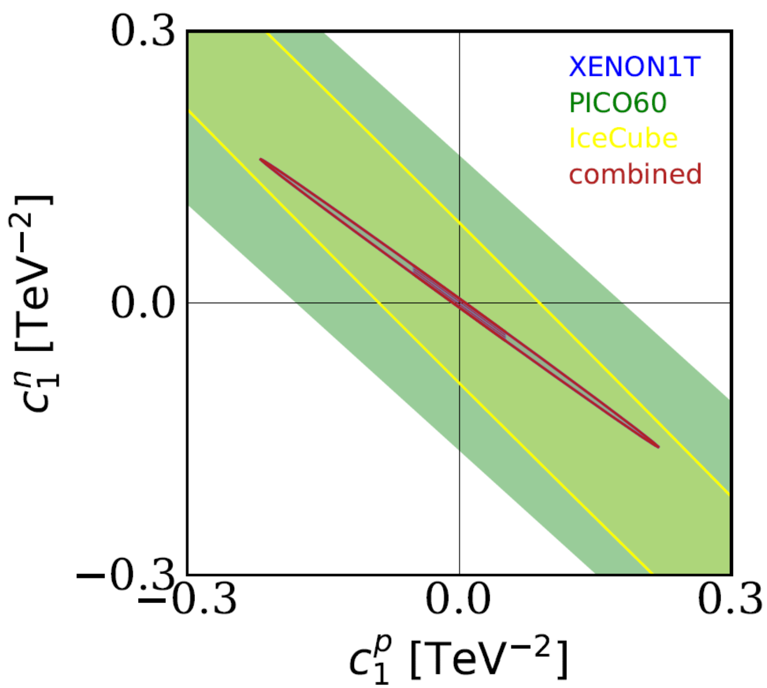
Probing the scattering with nucleons

Consider the Hamiltonian of the SI interaction:

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

The two interactions can interfere.





Brenner et al '22

Probing the scattering with nucleons

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

Probing the scattering with nucleons

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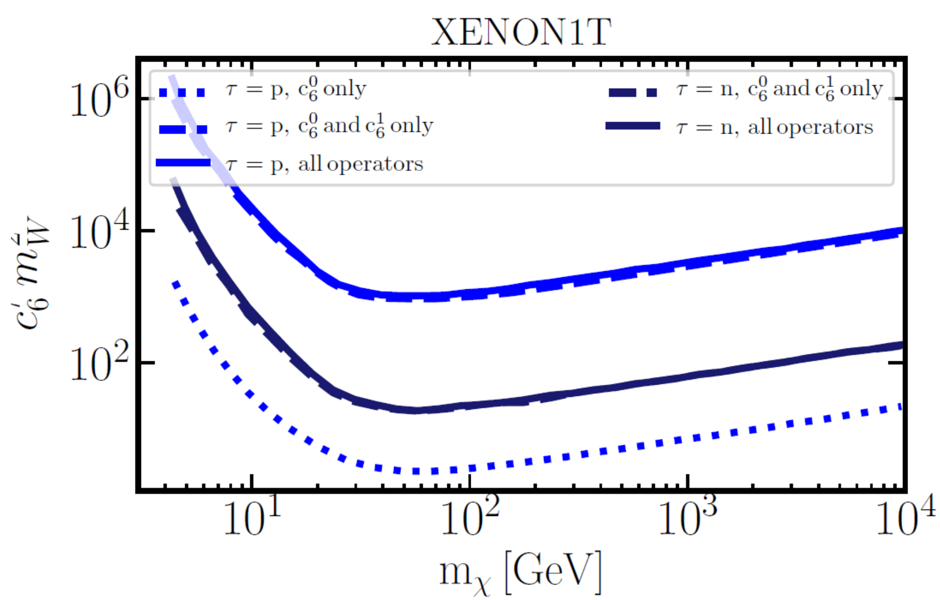
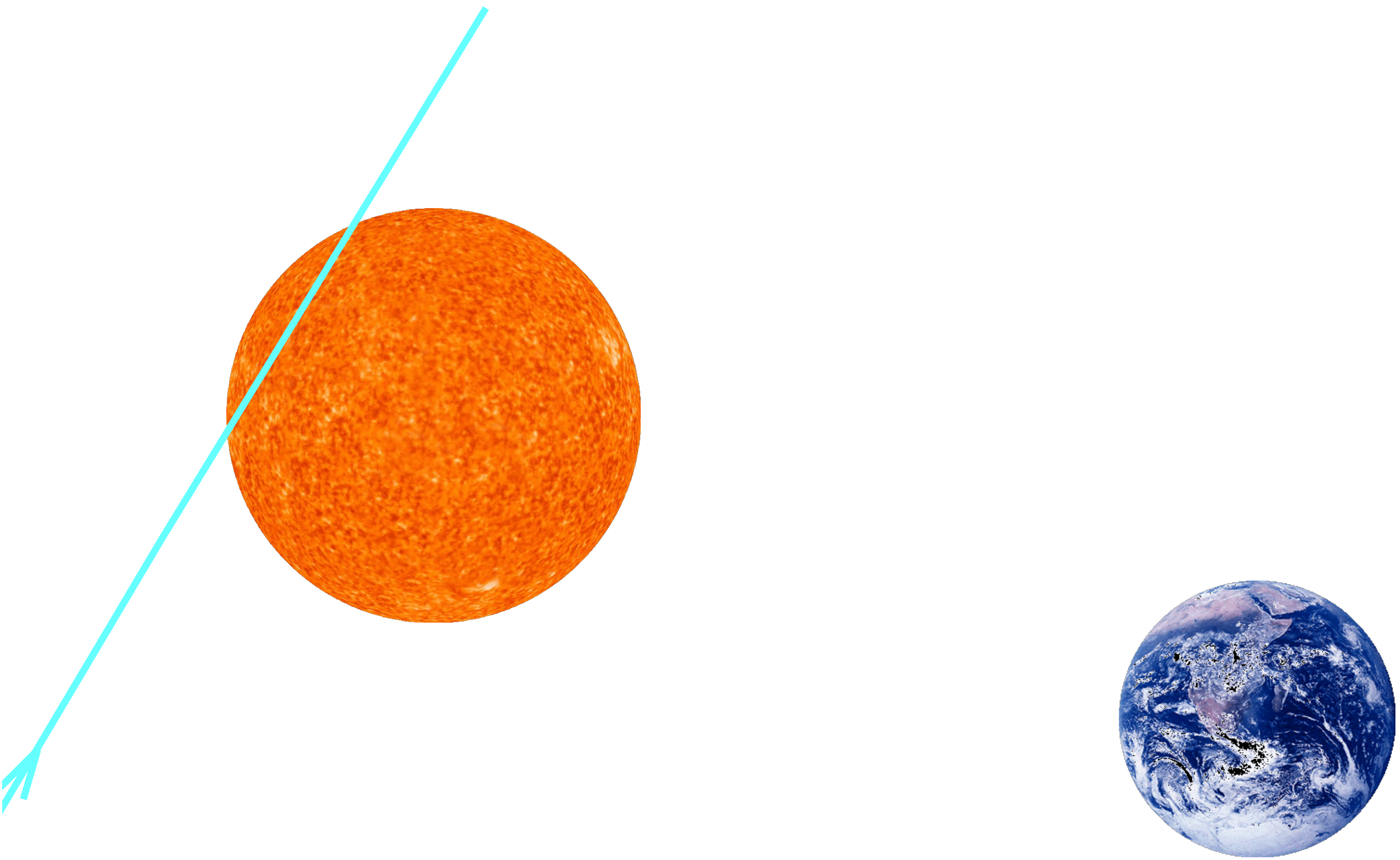


Using the Sun to probe scattering with nucleons



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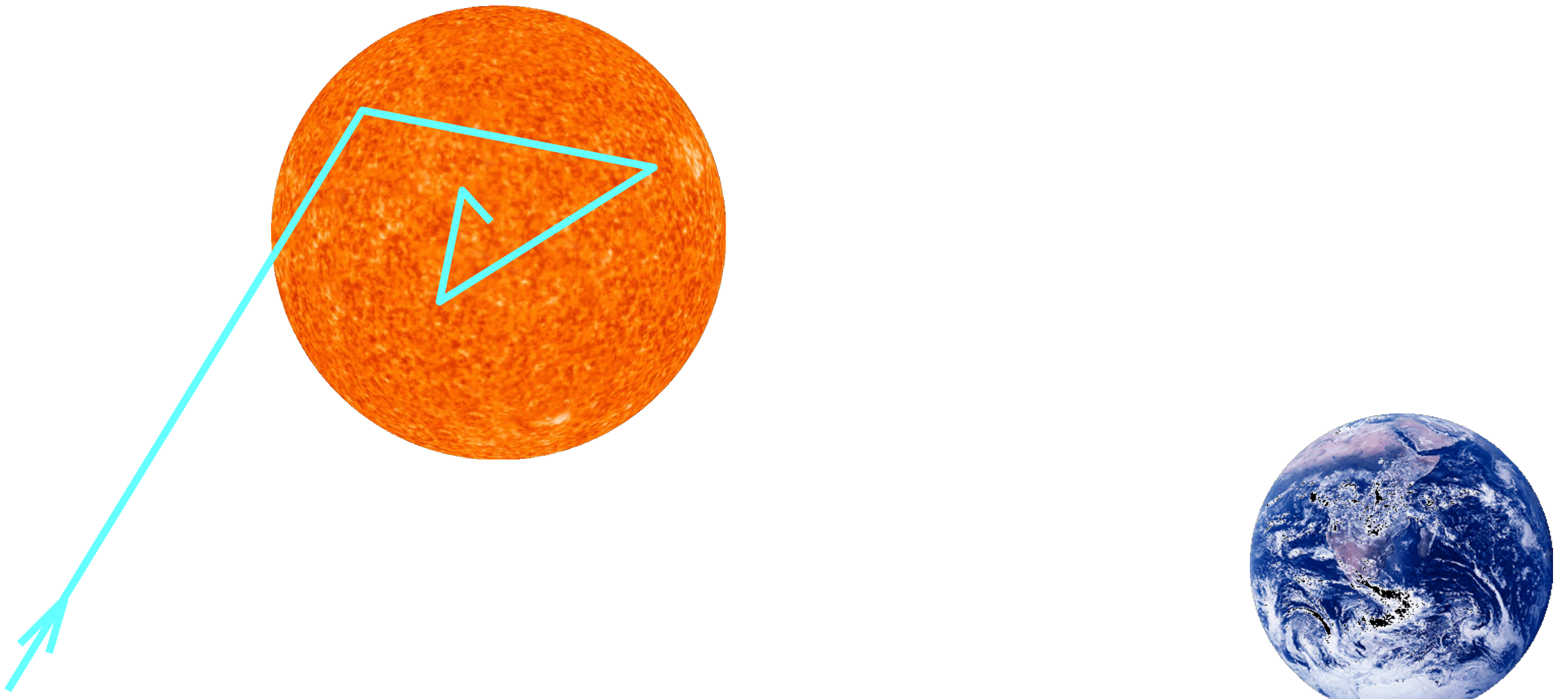

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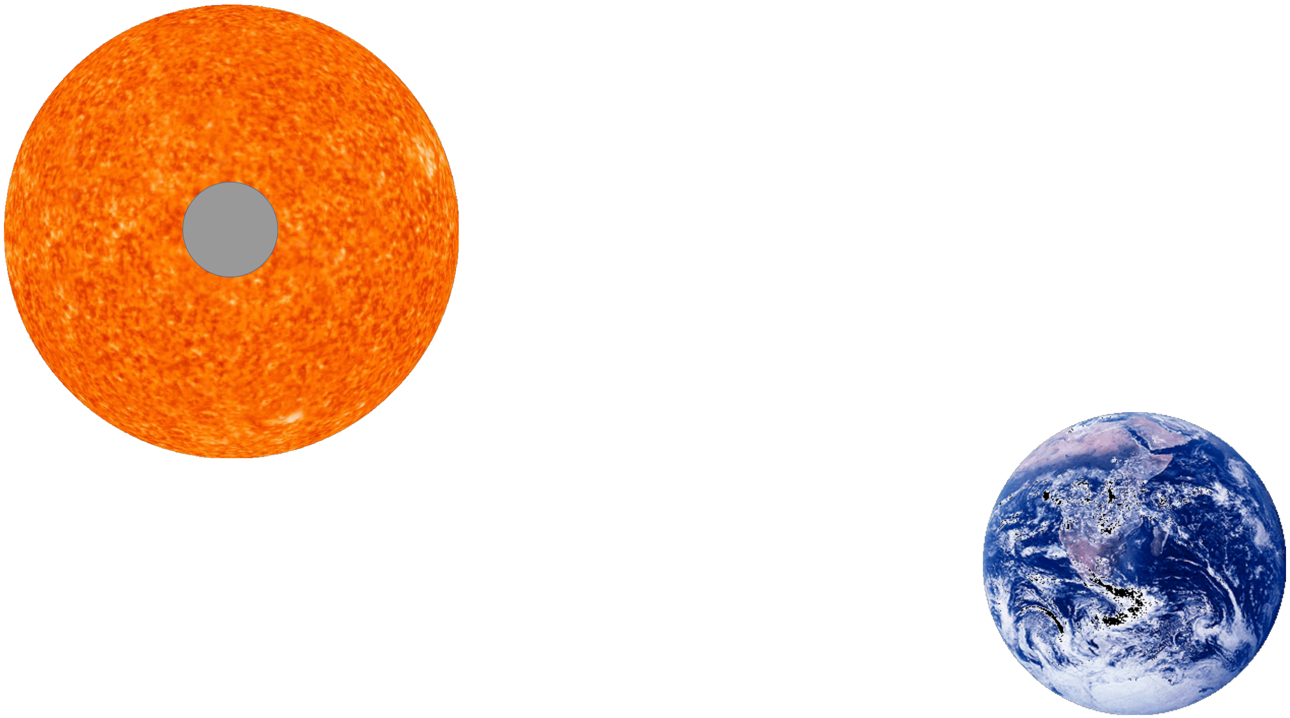
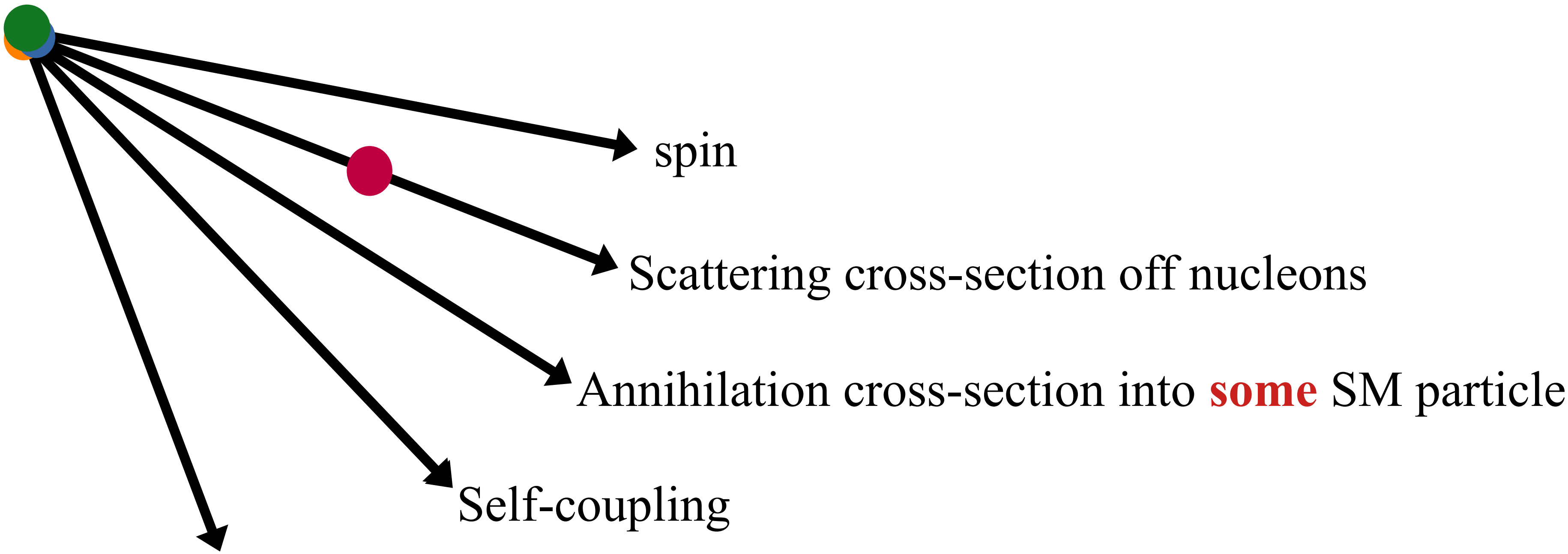
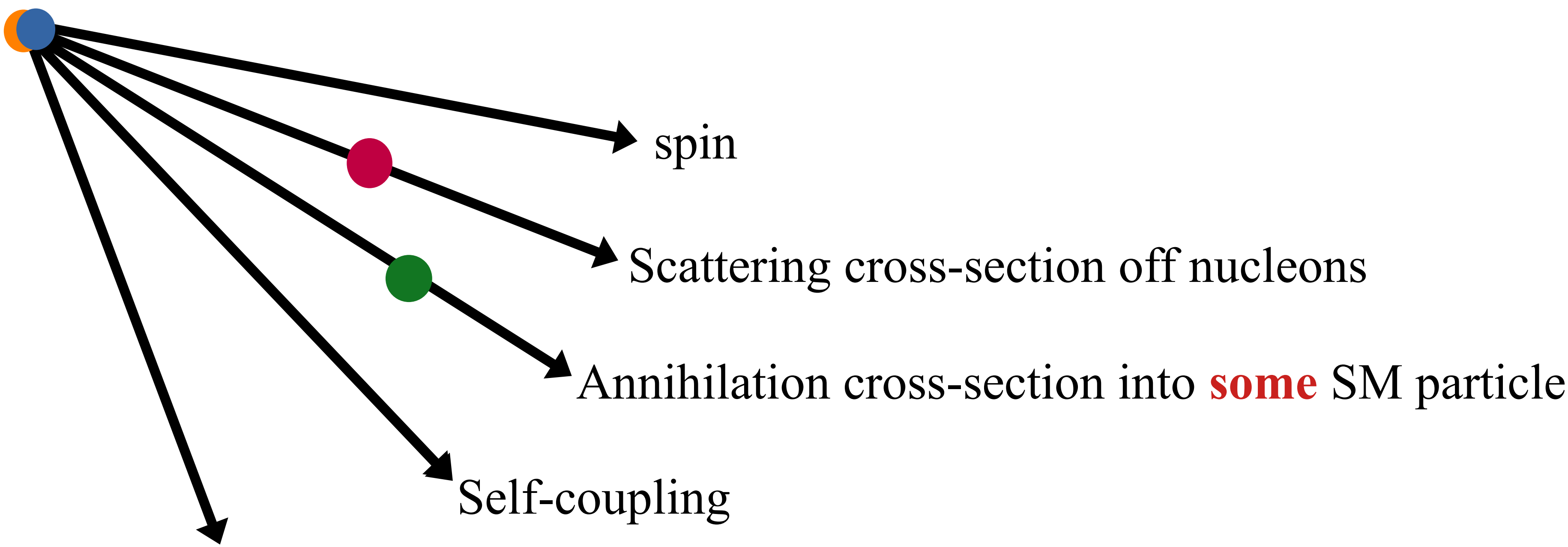



spin
Scattering cross-section off nucleons
Annihilation cross-section into **some** SM particle
Self-coupling



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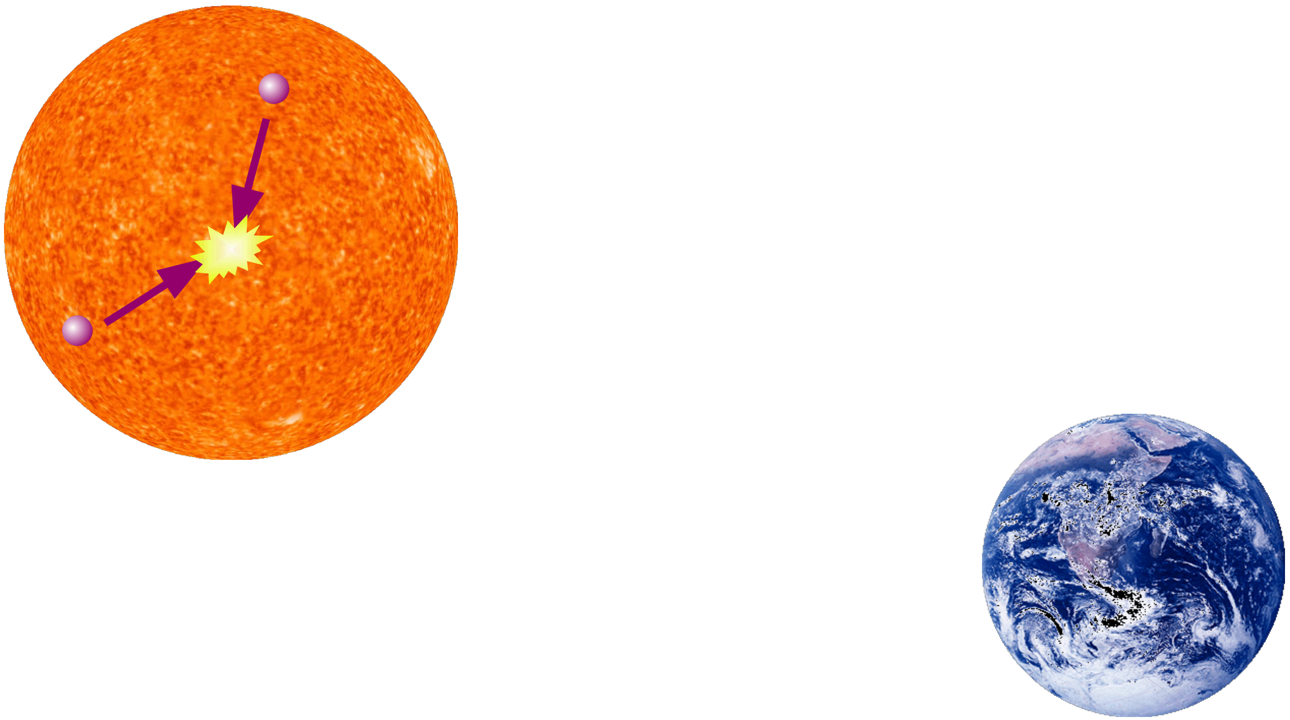

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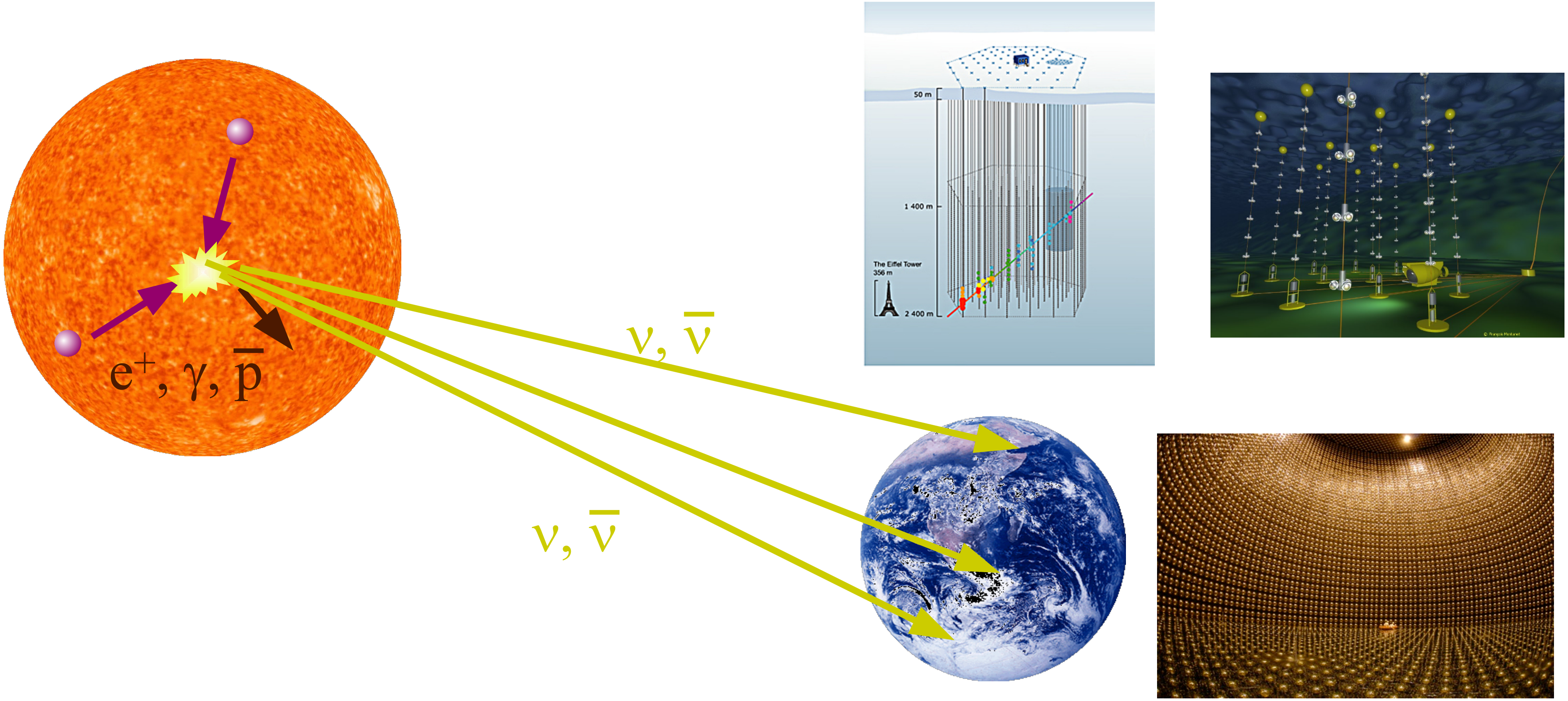
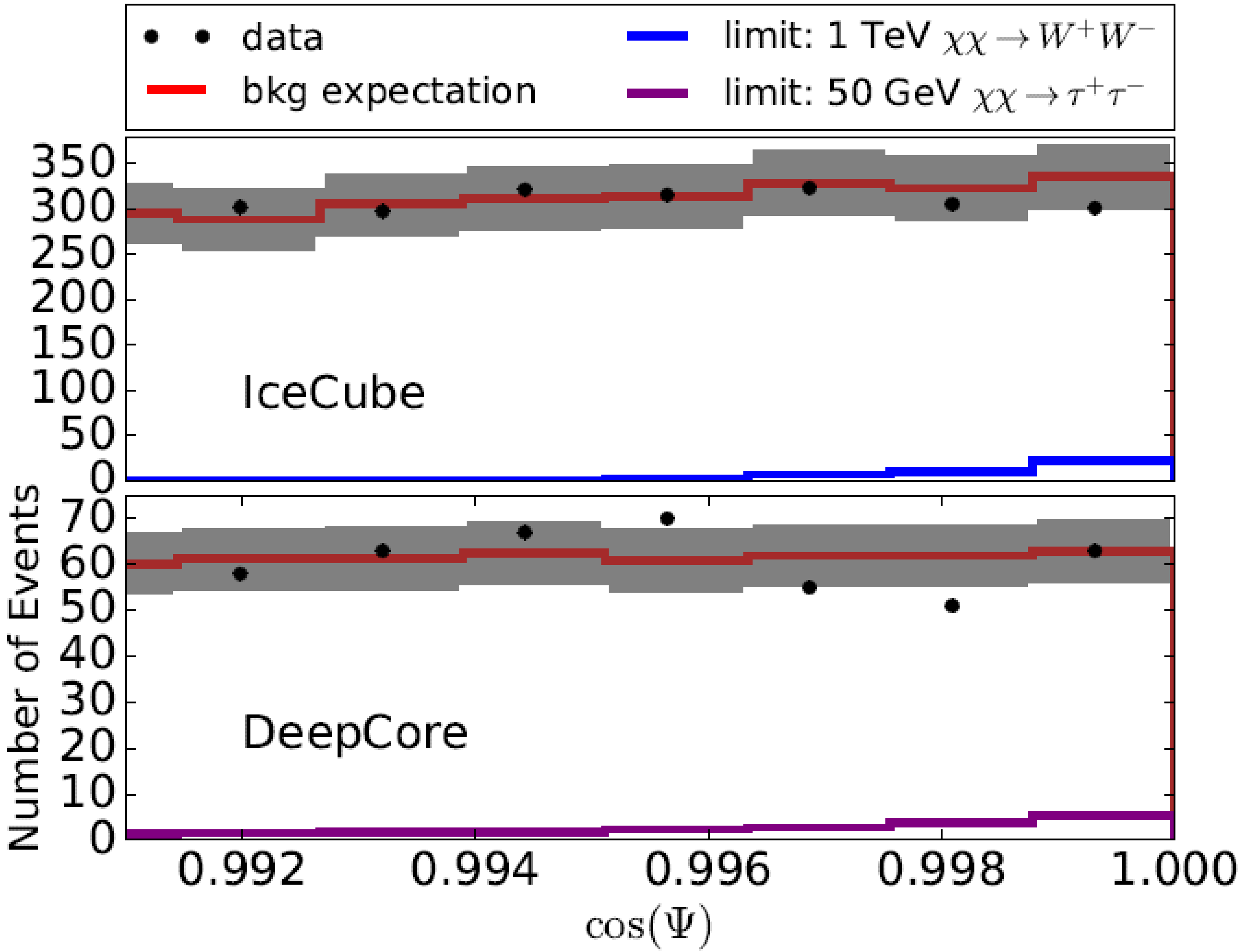


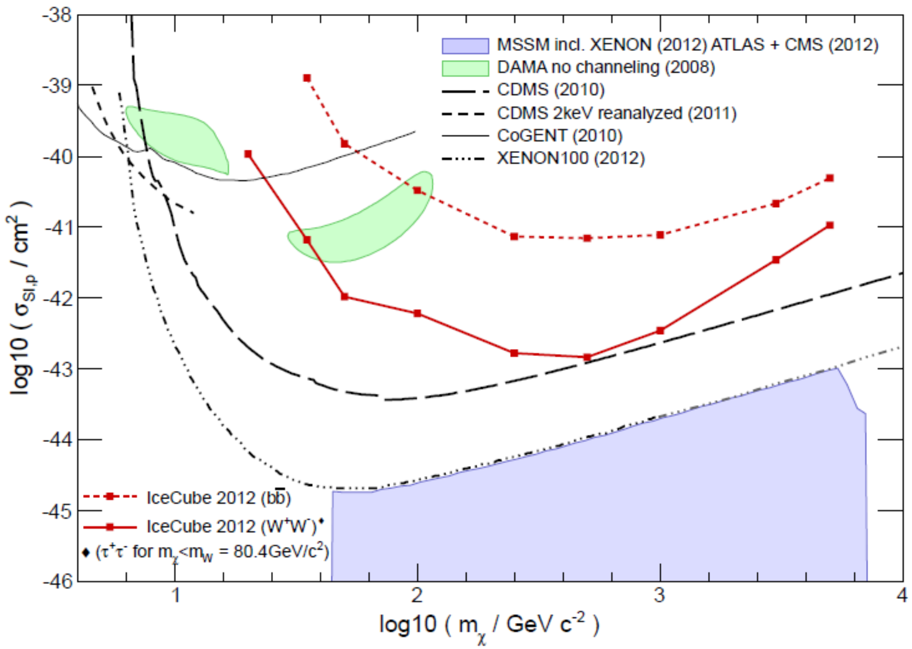
Using the Sun to probe scattering with nucleons

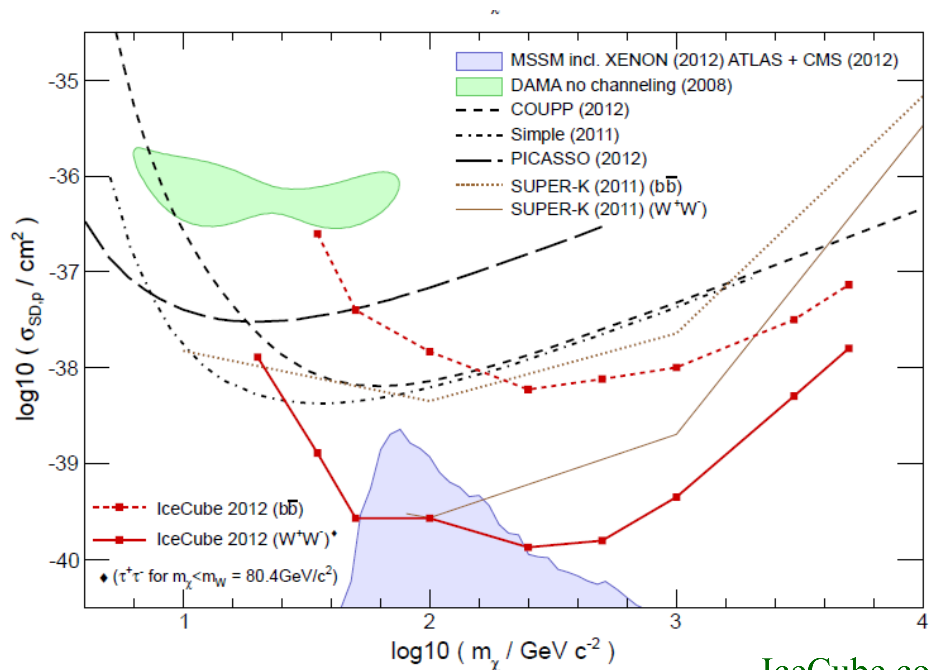
Observations consistent with the background-only hypothesis



IceCube collaboration
arXiv:1612.05949

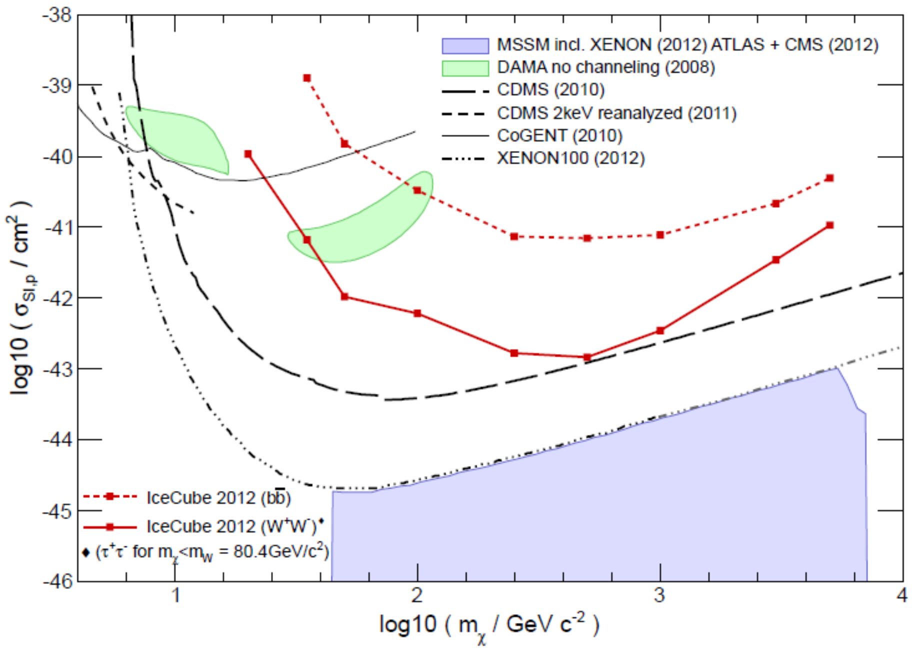
Using the Sun to probe scattering with nucleons

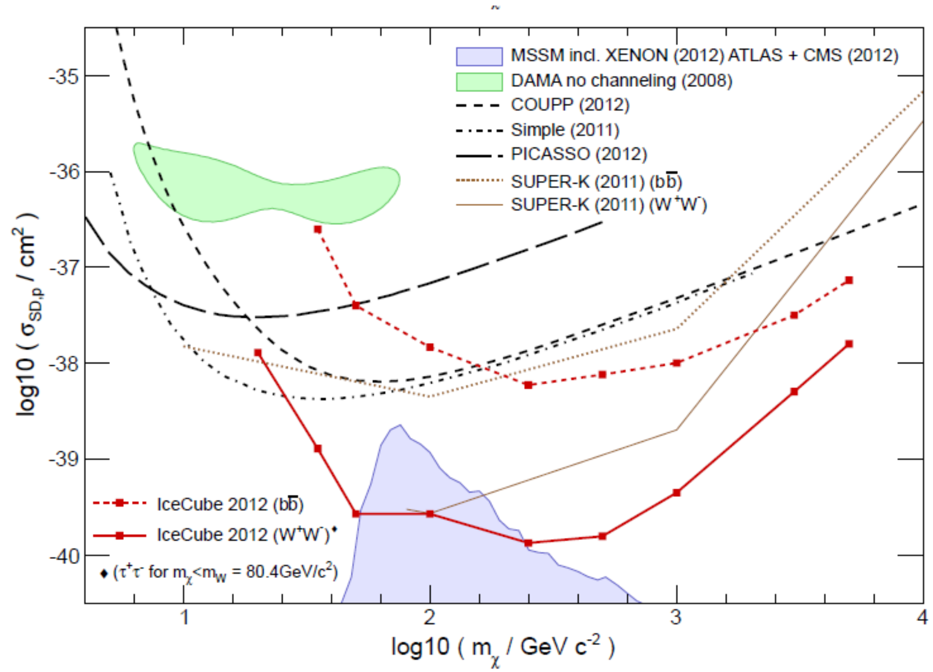


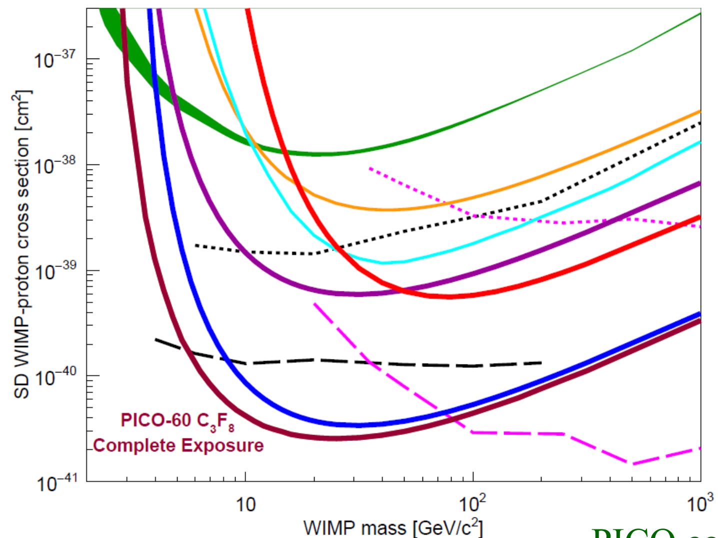


IceCube coll’12

Using the Sun to probe scattering with nucleons



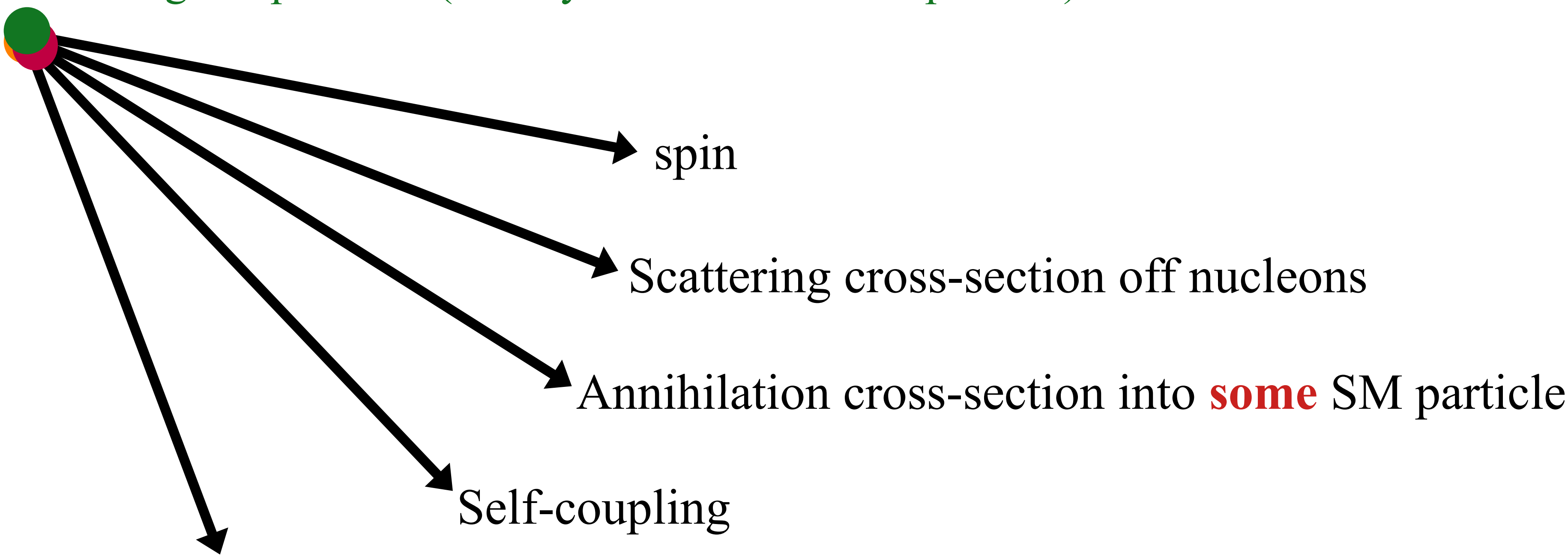




PICO coll'19

Probing alternative scenarios: ADM

"Asymmetric dark matter": a symmetry protects DM against annihilations into lighter particles (as baryon number for the protons)



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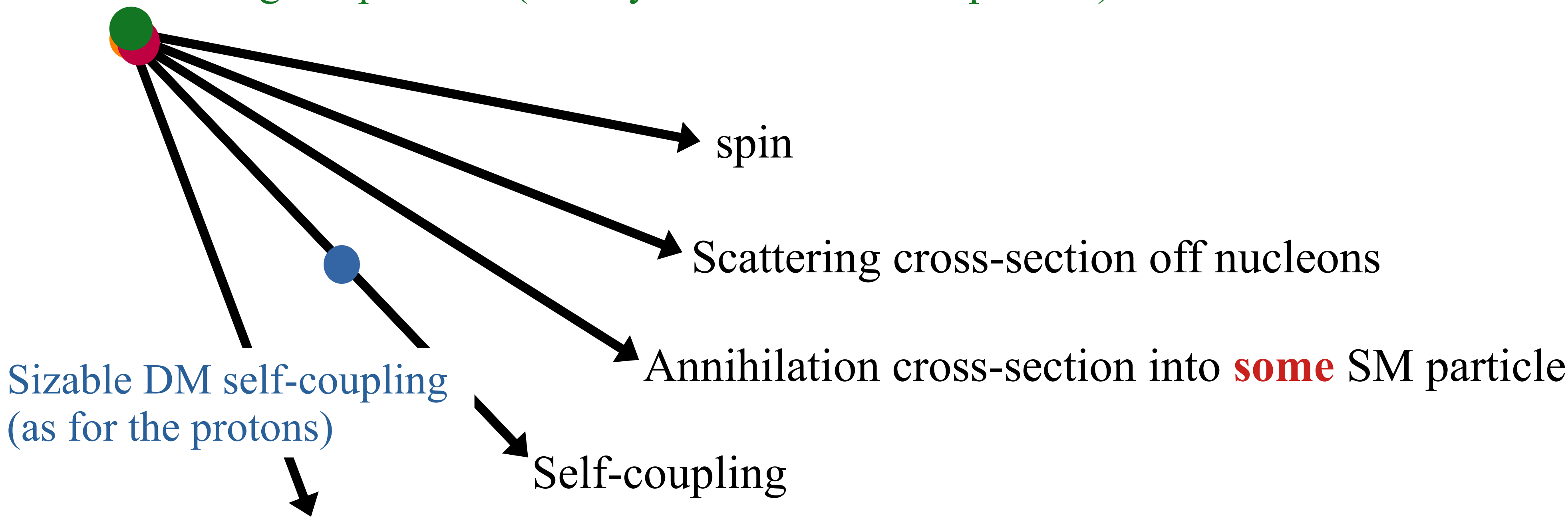

Probing alternative scenarios: ADM

Protons do not annihilate.
Protons have strong self-interactions
Protons form stars

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Protons do not annihilate.
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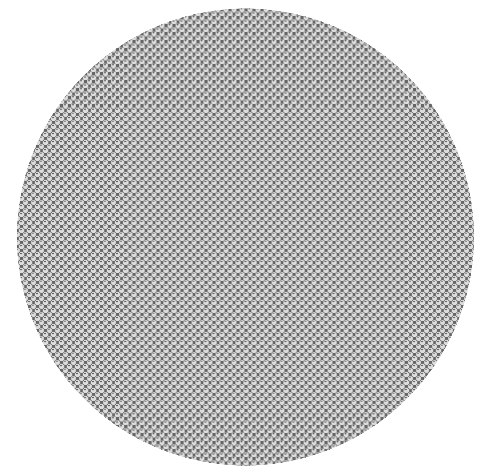
DM does not annihilate.
DM has strong self-interactions
DM form dark stars



Probing alternative scenarios: ADM

Density profile of dark stars calculable from the Klein-Gordon equation in curved spacetime (for bosonic DM) and the Einstein equations:

Colpi et al'86

$$g^{\mu\nu}\nabla_\mu\nabla_\nu\phi - m^2\phi - \lambda|\phi|^2\phi = 0$$

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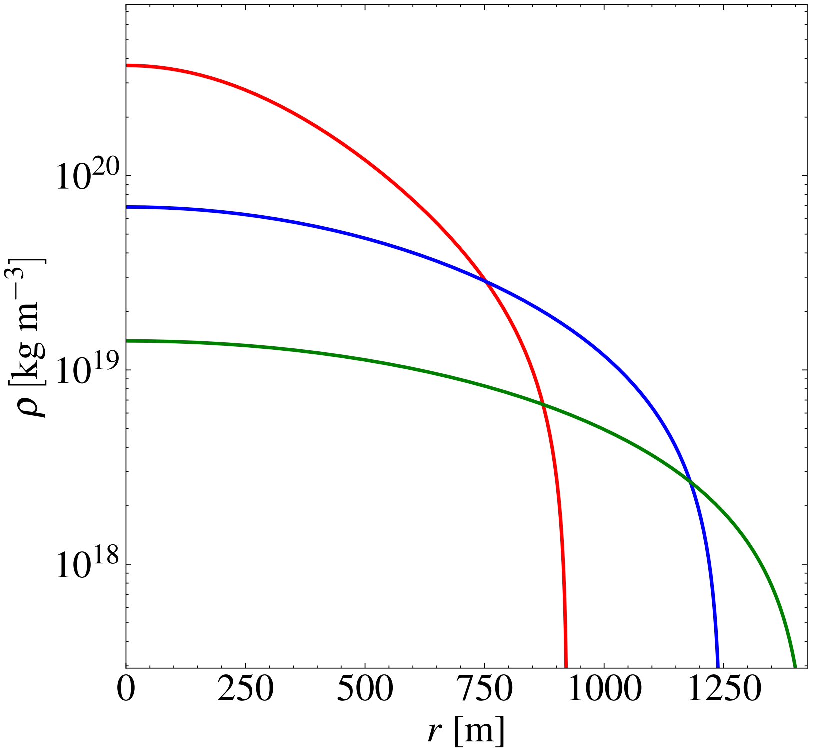


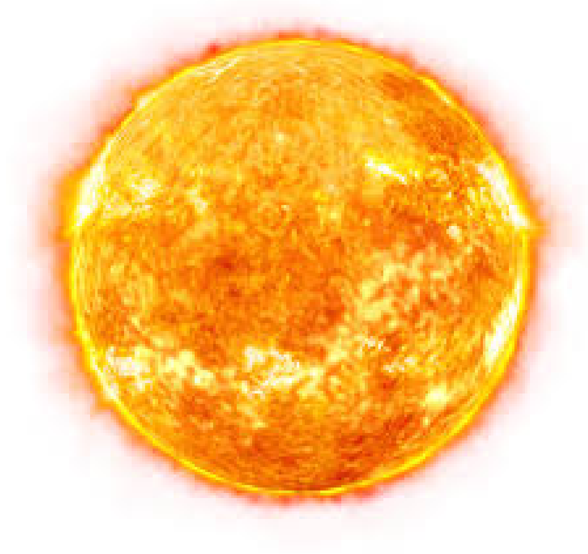
(For m=1 GeV, λ=1)

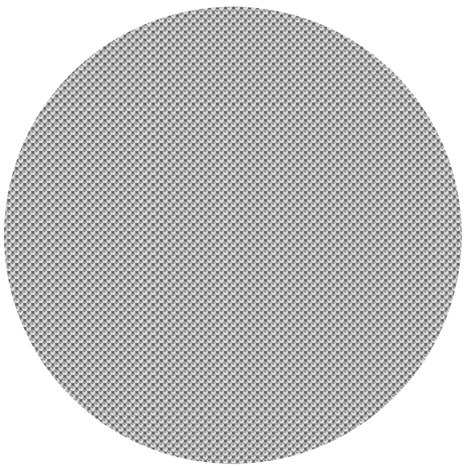
Dark stars are very compact objects

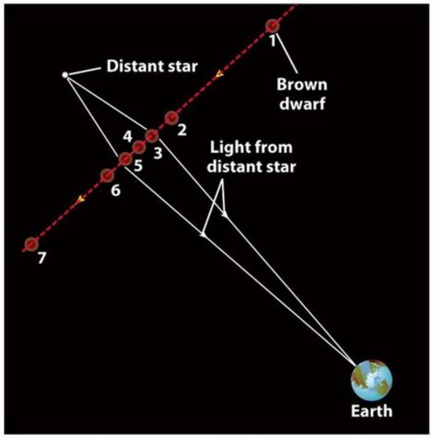
Probing alternative scenarios: ADM

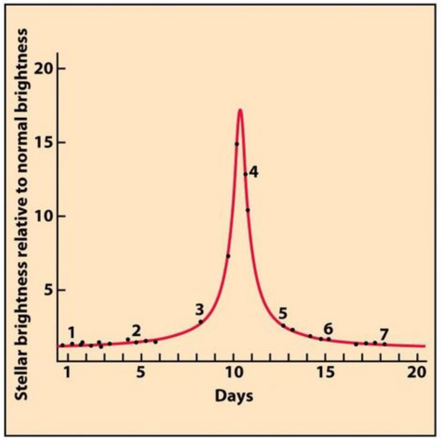
Protons do not annihilate.
Protons have strong self-interactions
Protons form stars

DM does not annihilate.
DM has strong self-interactions
DM form dark stars

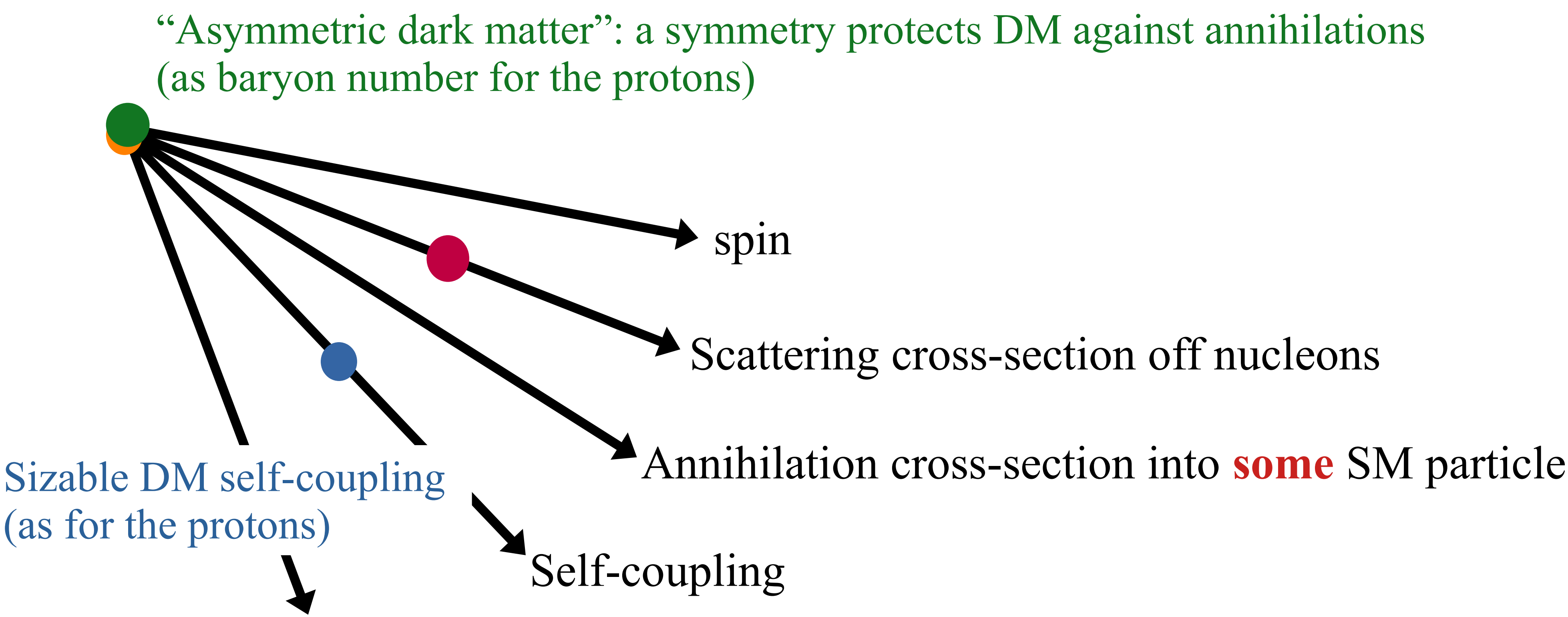








Using DSs to probe scattering with nucleons



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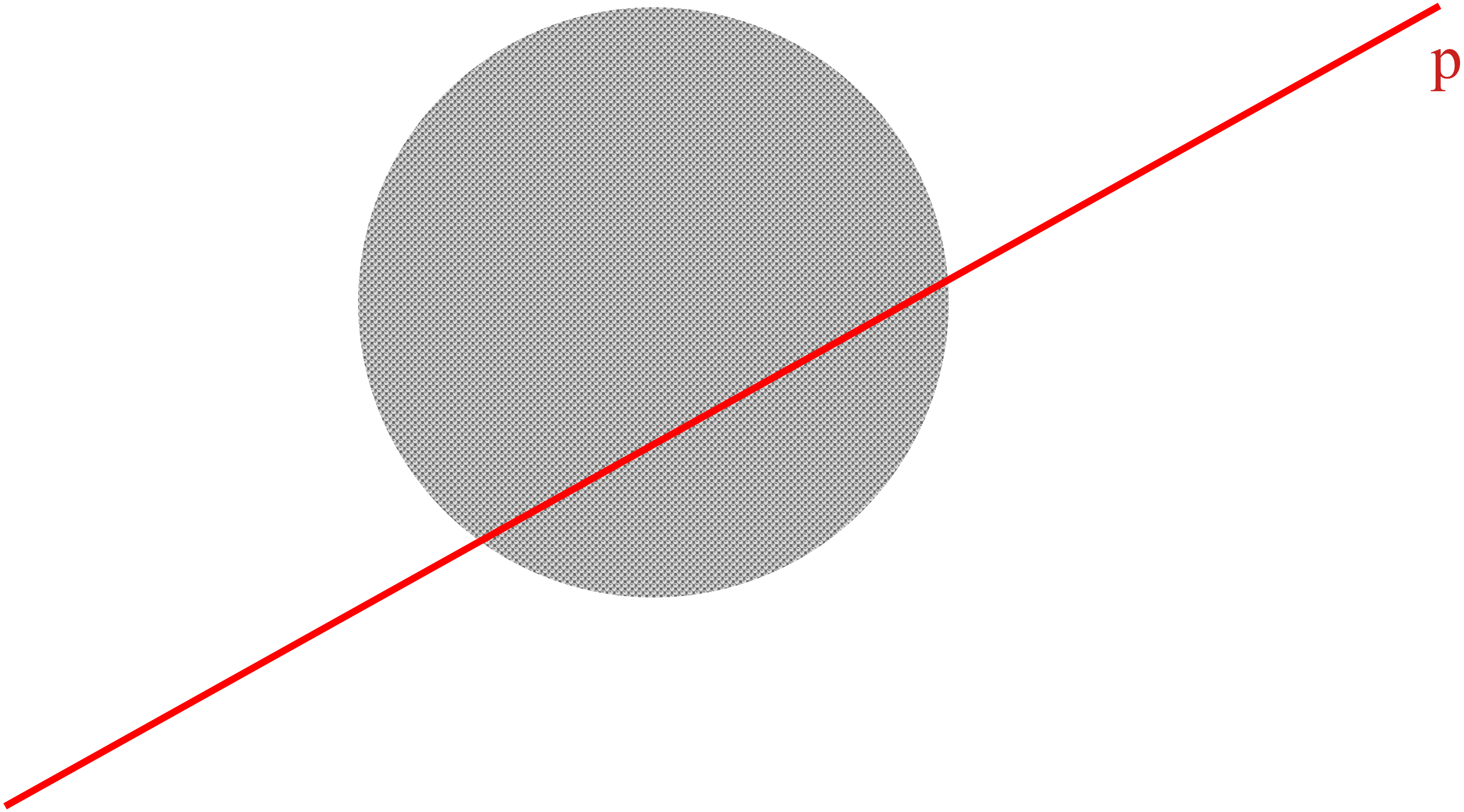

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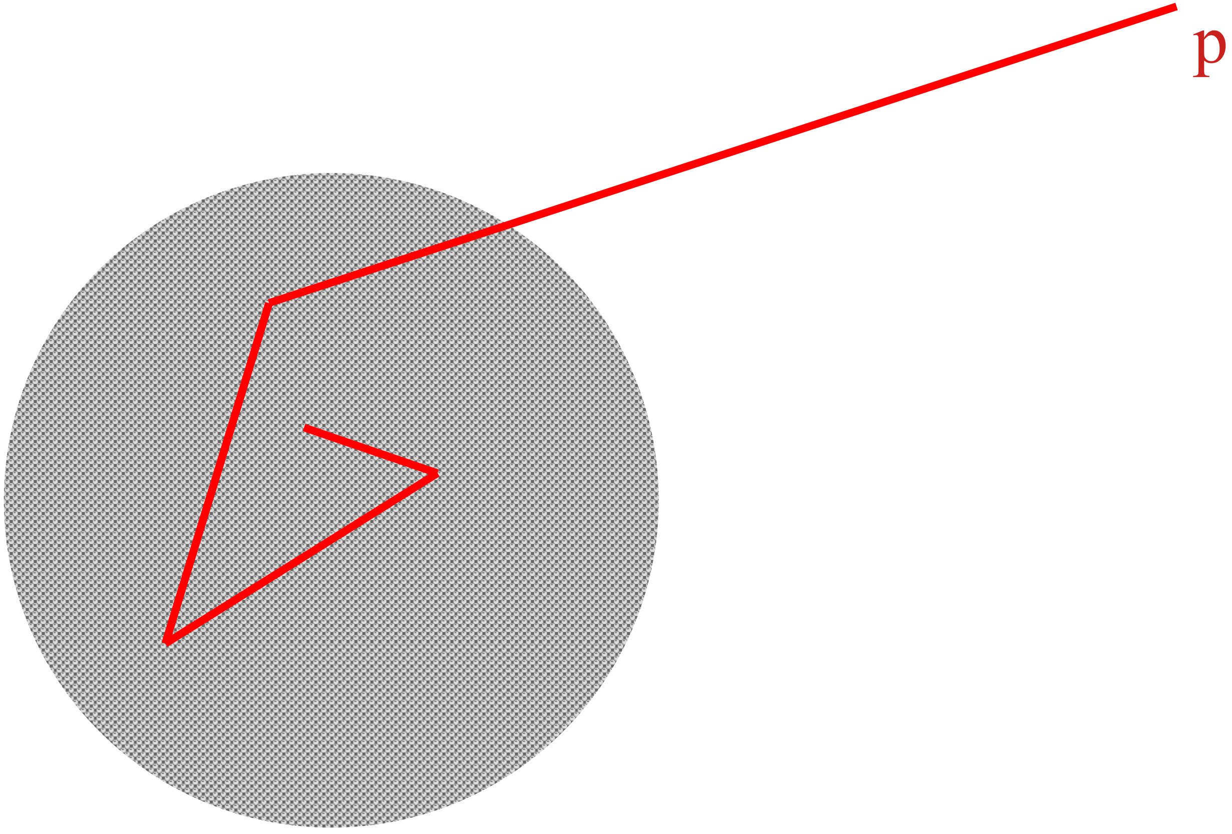

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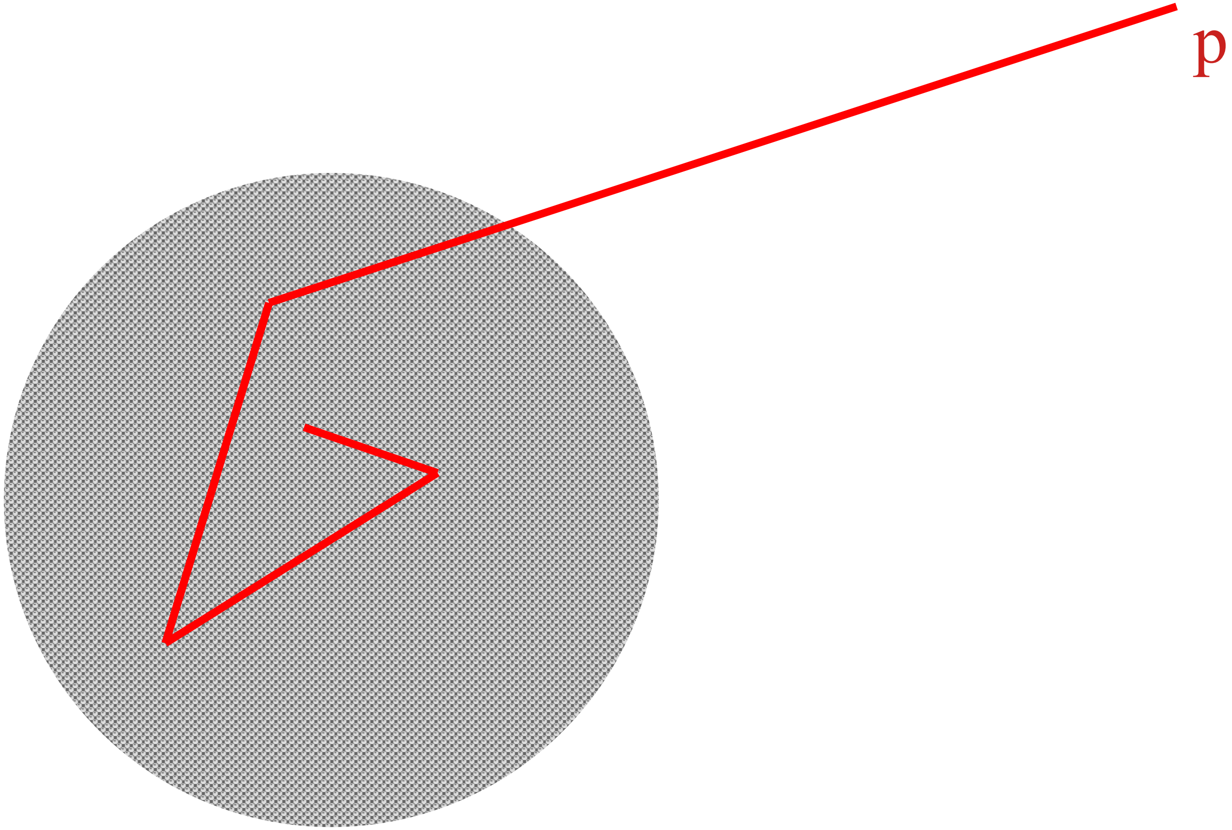
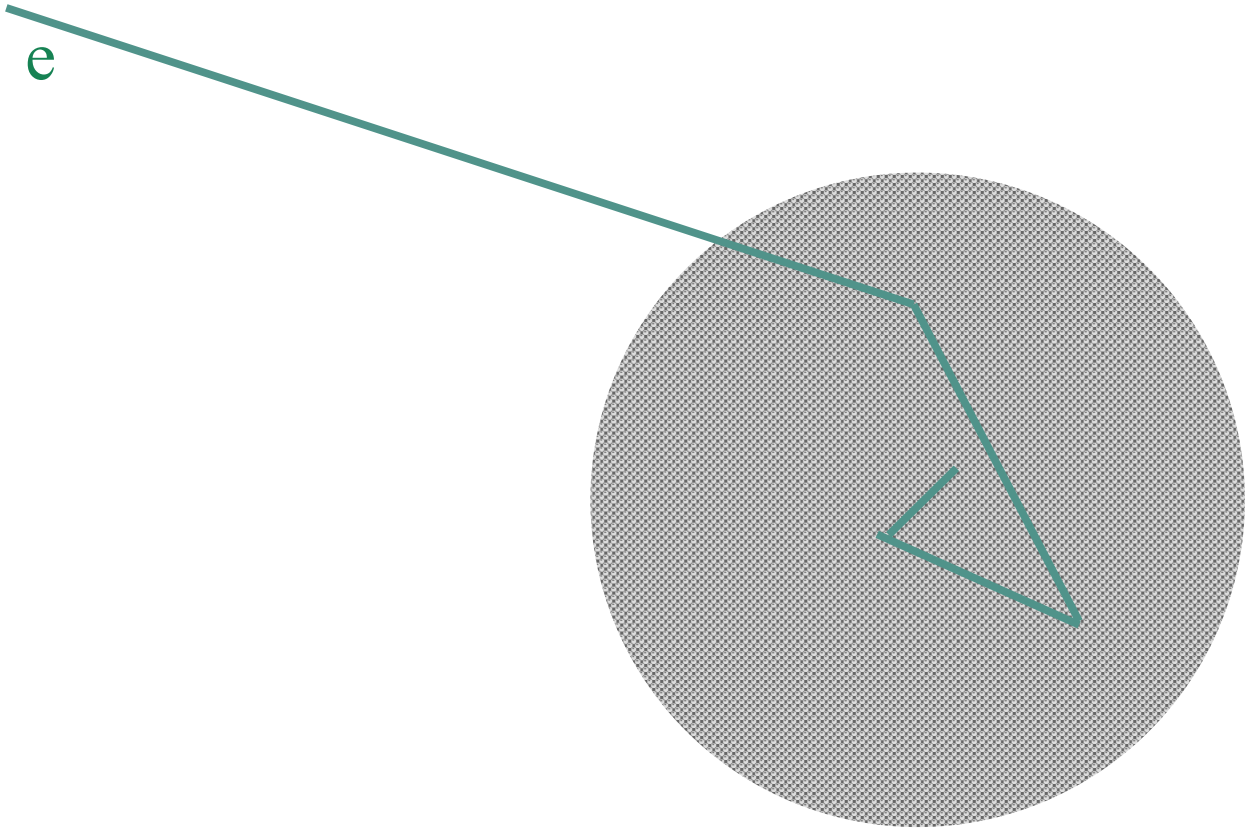


$$C \sim (10^{18}\ \mathrm{s}^{-1}) \left[\left(\frac{\sigma}{10^{-45}\ \mathrm{cm}^2} \right) \left(\frac{n_p}{10^{-5}\ \mathrm{cm}^{-3}} \right) \right] \left(\frac{R_{\mathrm{DS}}}{1\ \mathrm{km}} \right)^3 \left(\frac{M}{M_\odot} \right)^{-\frac{3}{2}}$$

Using DSs to probe scattering with nucleons



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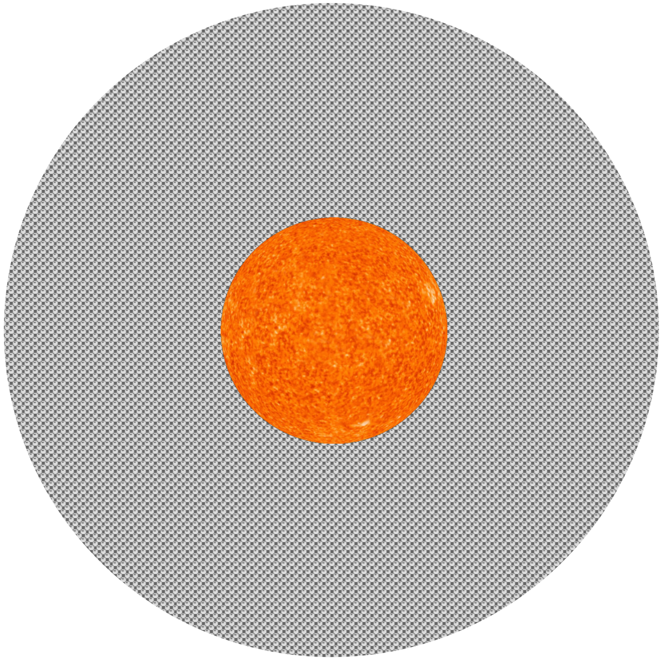

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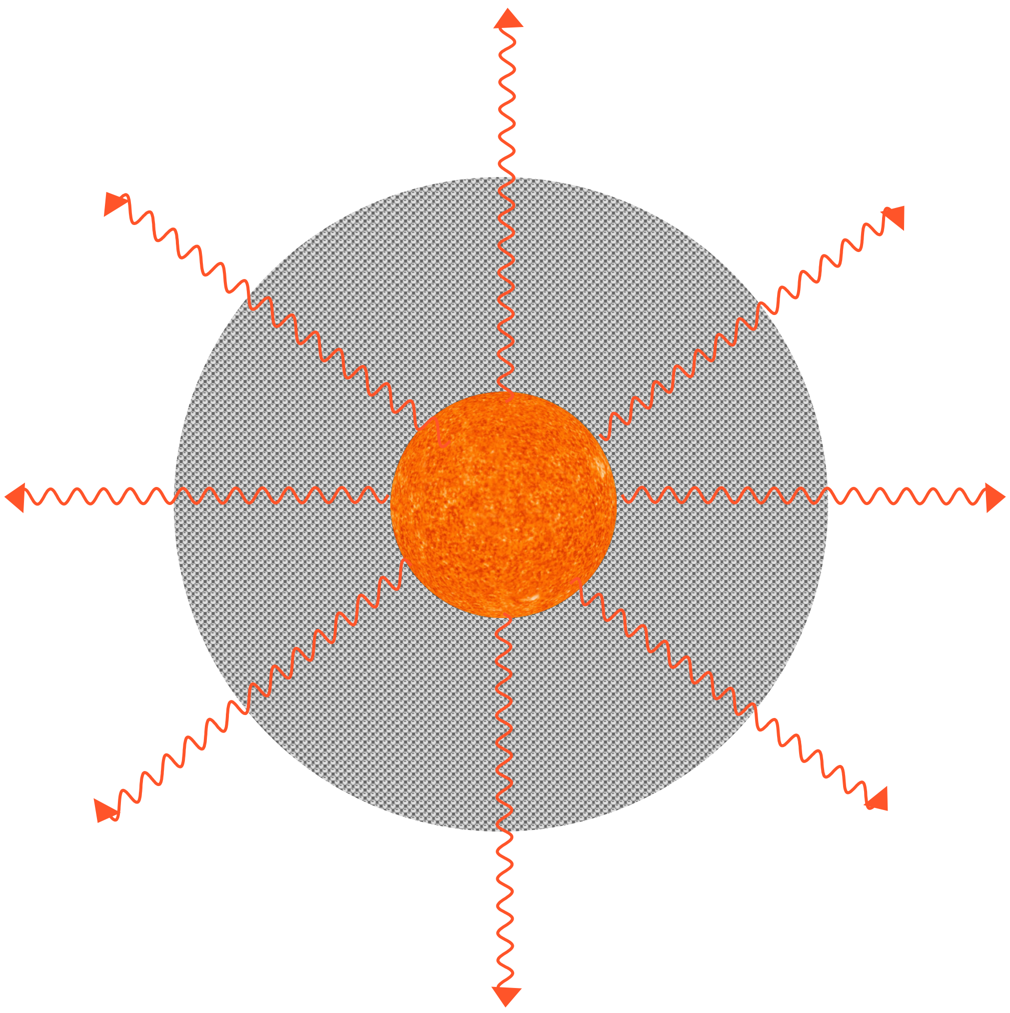

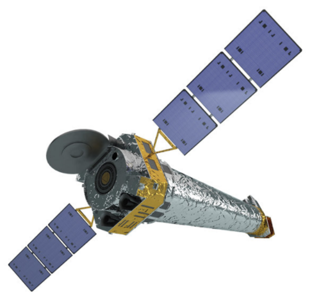

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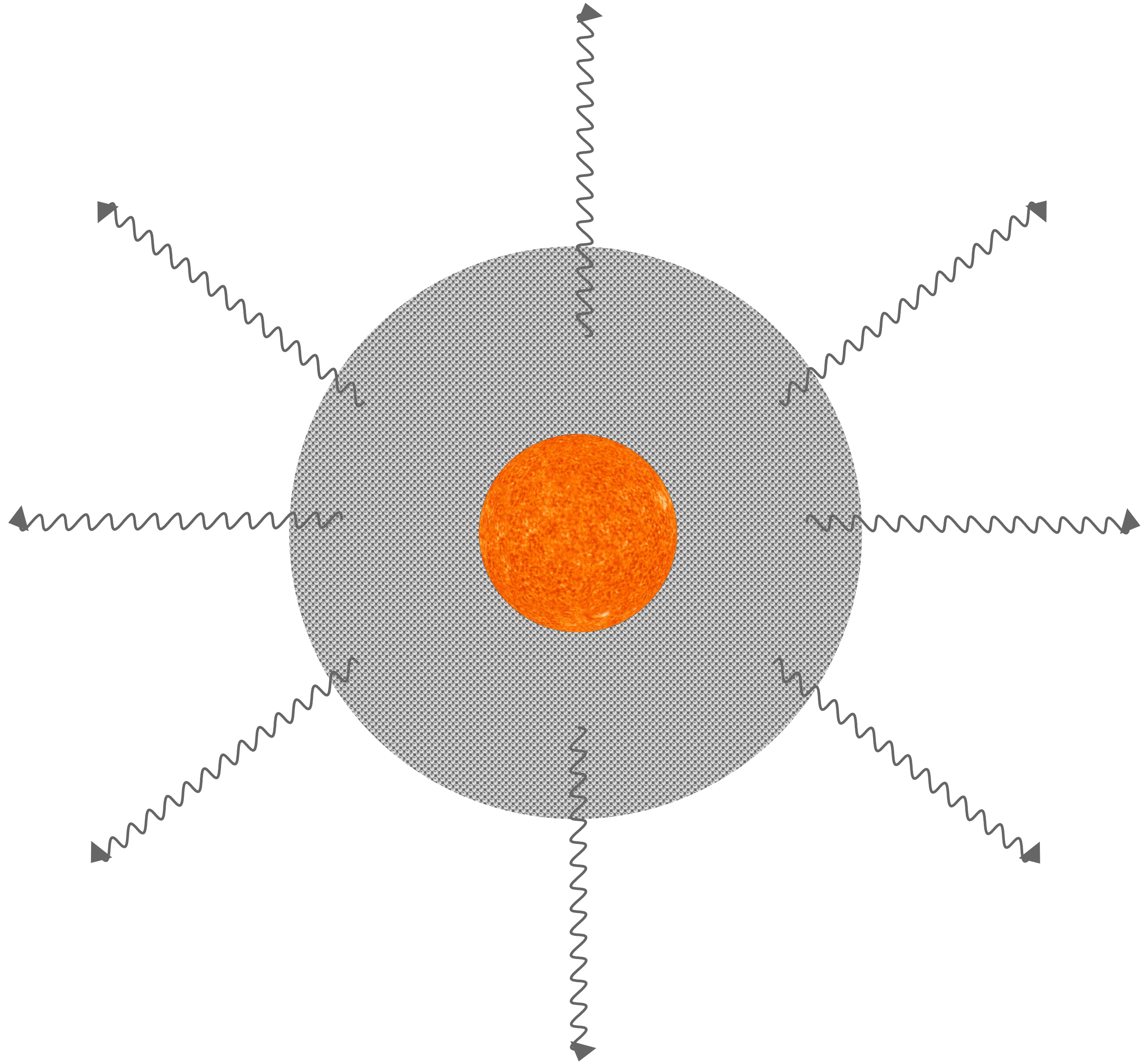

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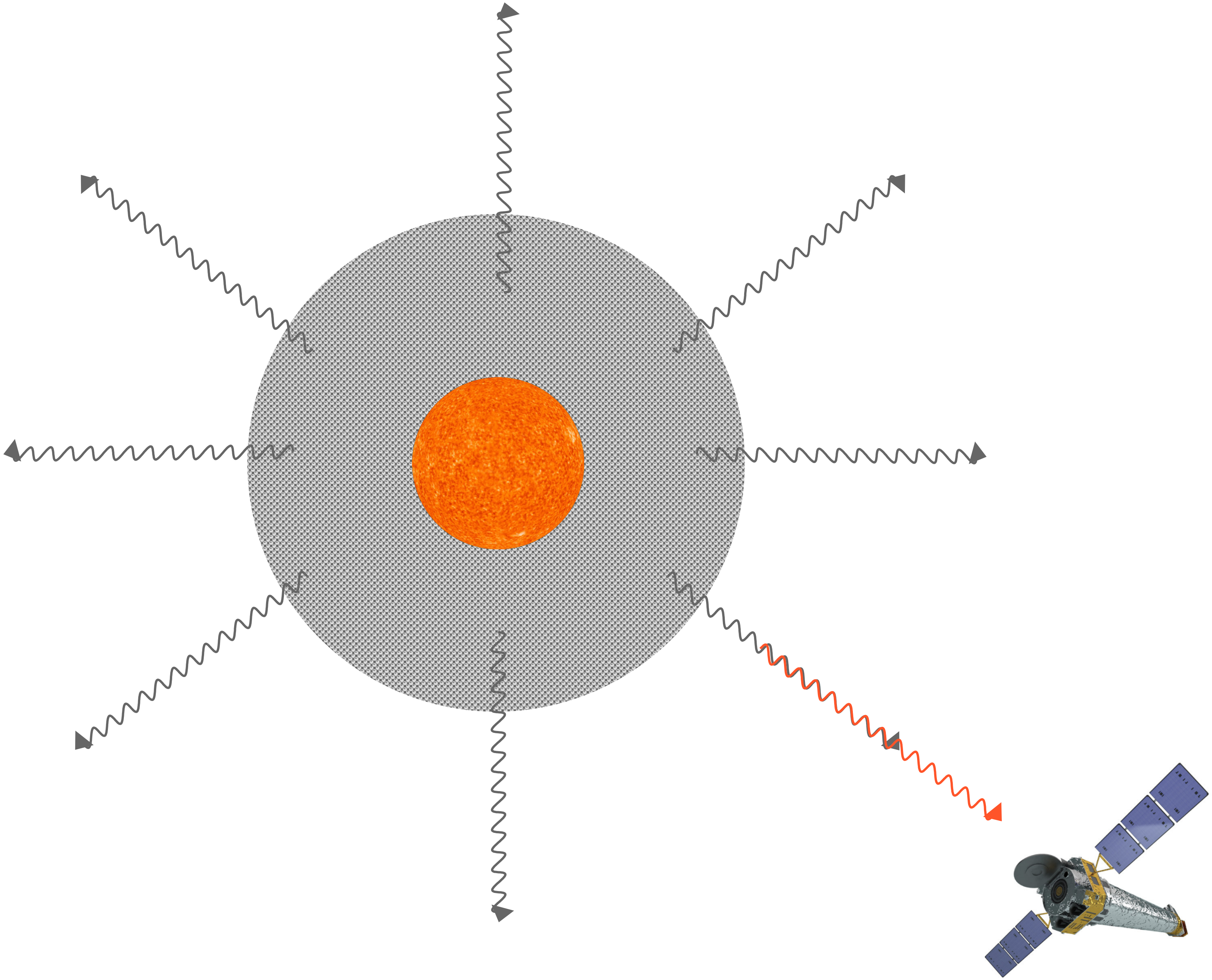
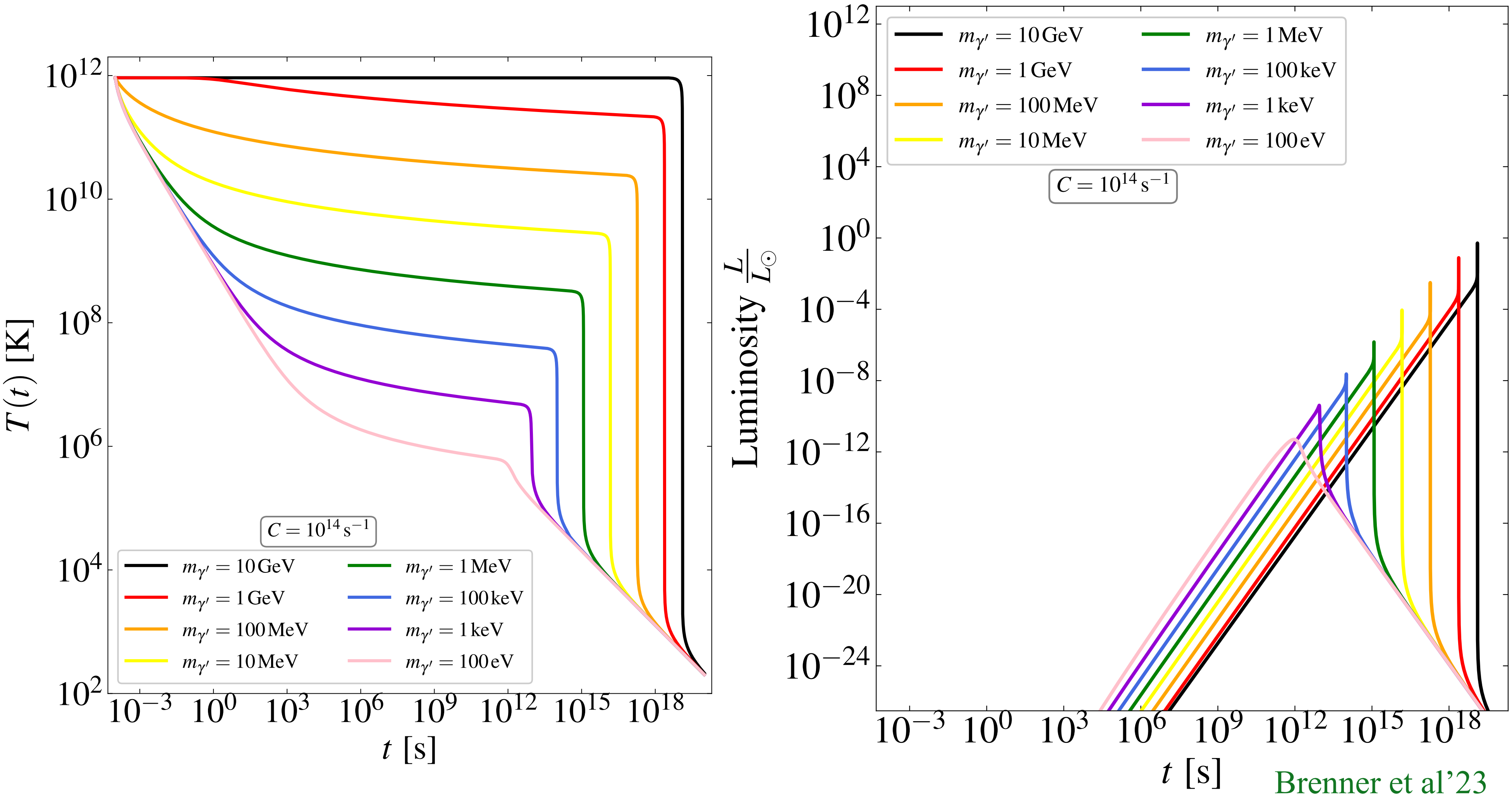


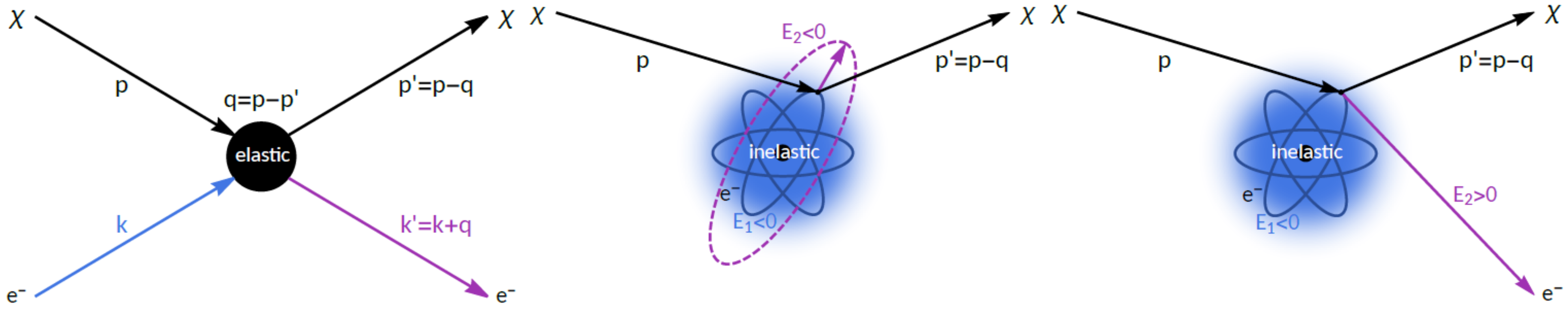
Using DSs to probe scattering with nucleons



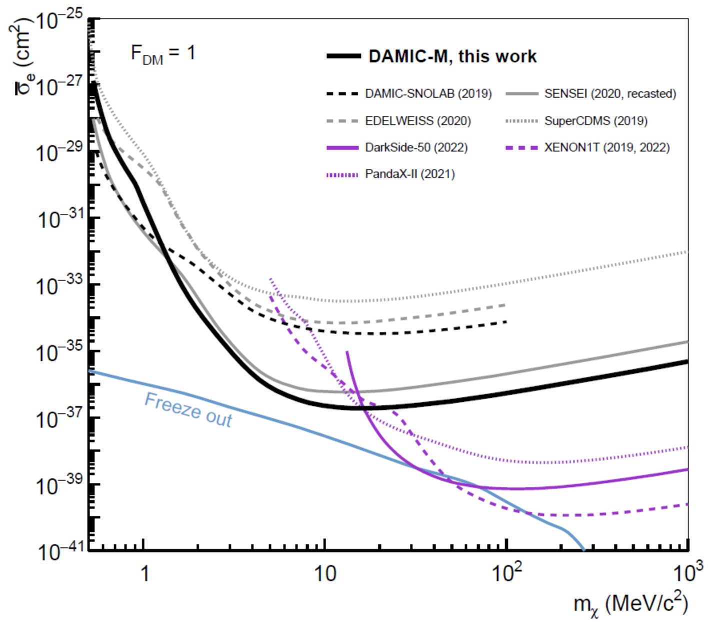
The "dark star" could be very luminous in gamma-rays

If L=10^{-4} L_{sol}, current instruments could detect up to 100 sources, if 1% of the dark matter is in the form of dark stars.

Probing the scattering with electrons



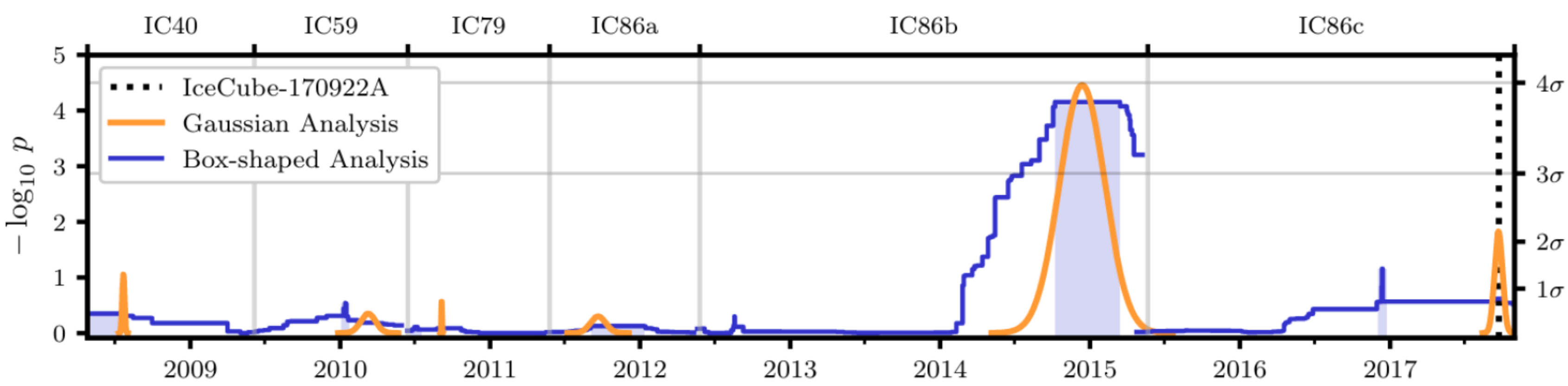
From Catena et al'20



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..

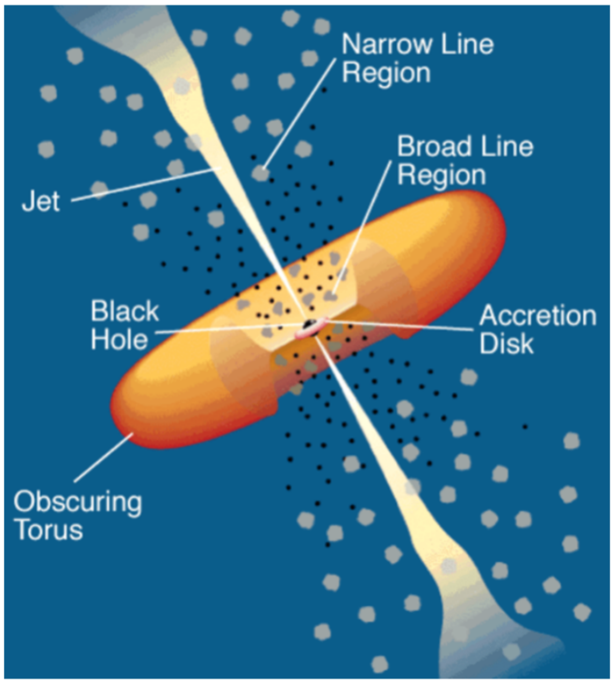
Archival data found 13±5 events coincident with TXS 0506+056.

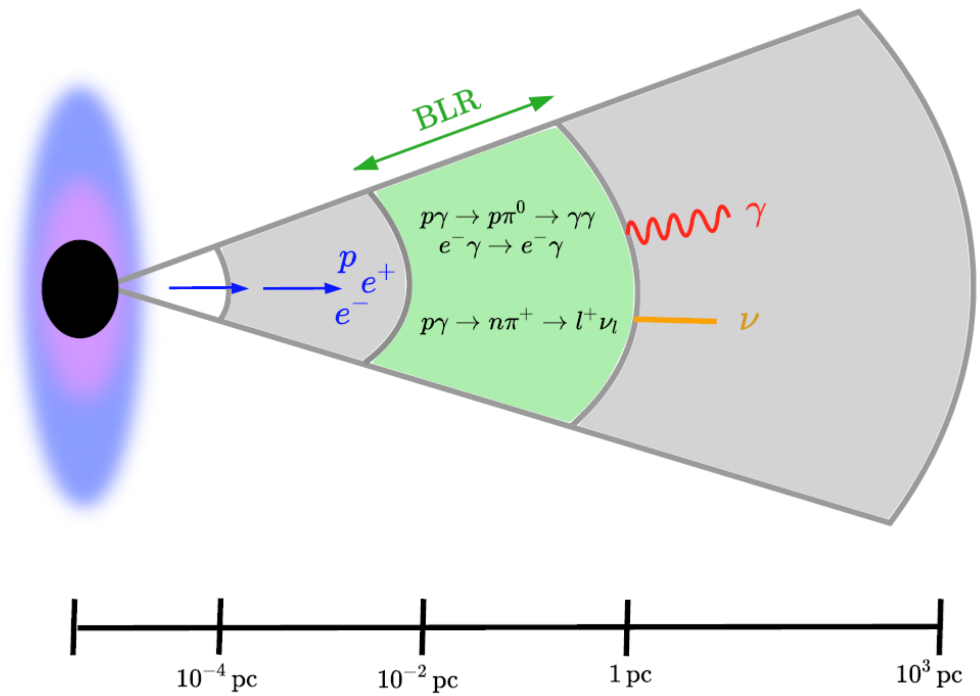


First known source of high energy astrophysical neutrinos

Probing the scattering with neutrinos

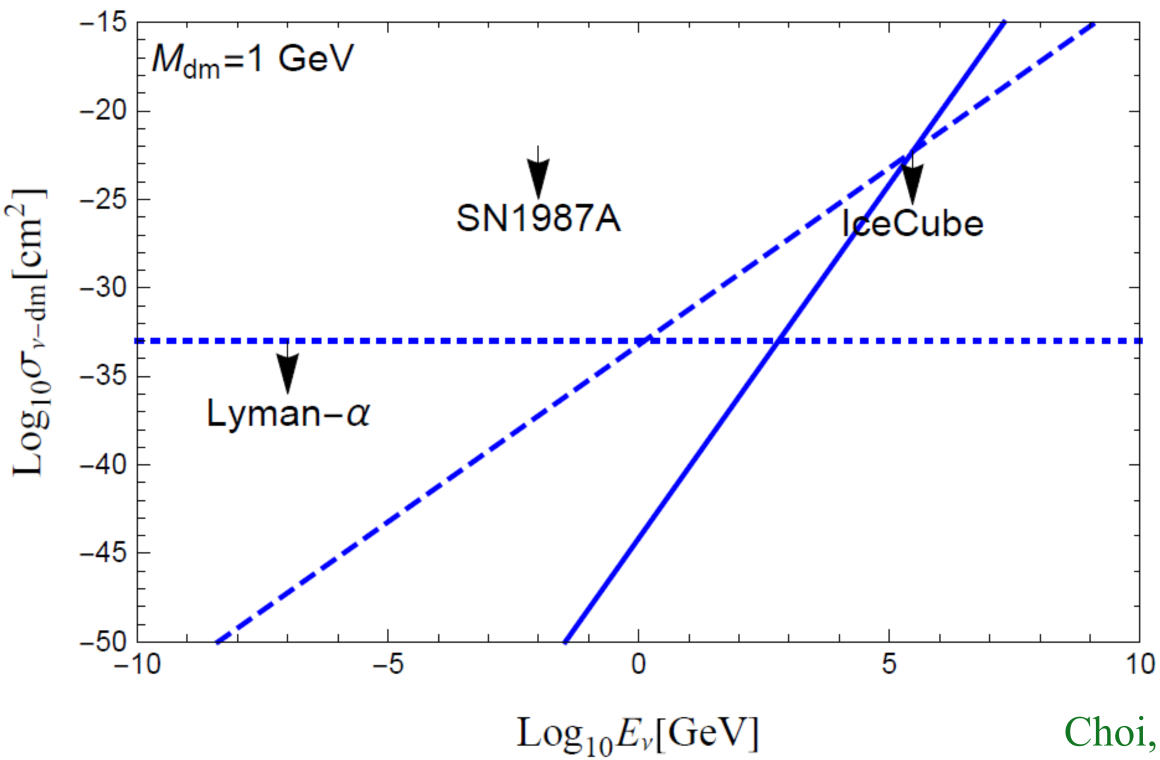
The neutrino and photon fluxes can be qualitatively well reproduced in leptohadronic models.





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

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

$$\gamma_{\rm sp} = \frac{9-2\gamma}{4-\gamma}$$

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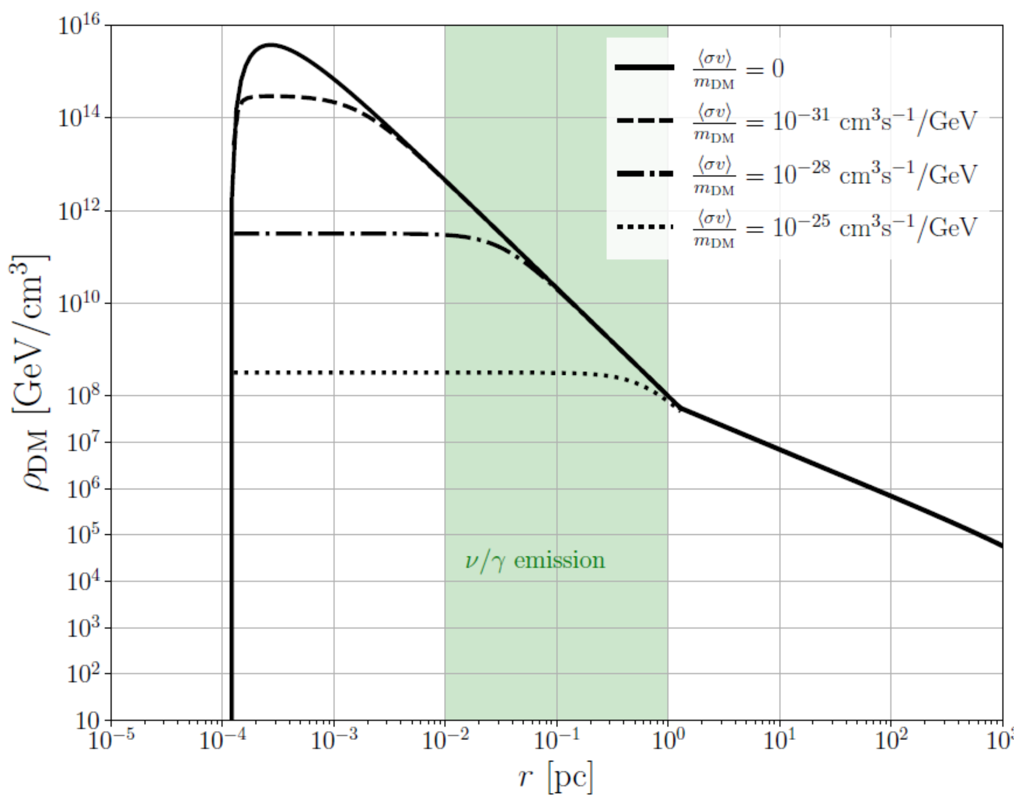

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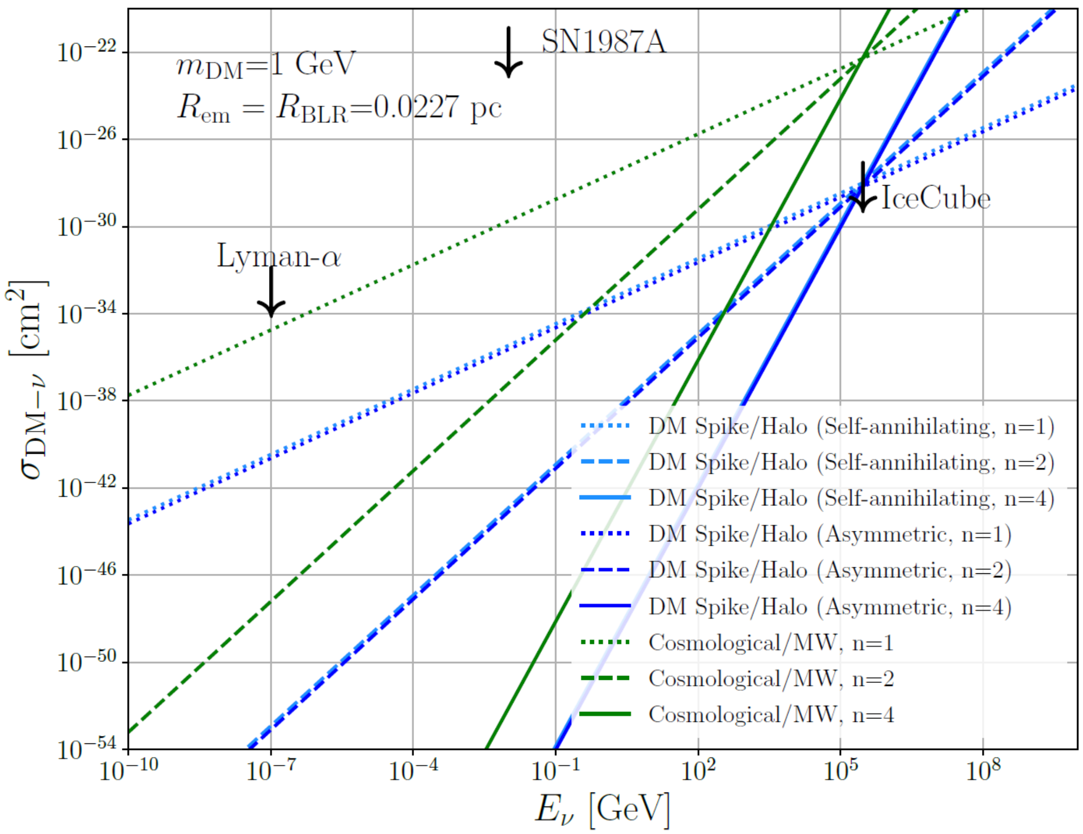
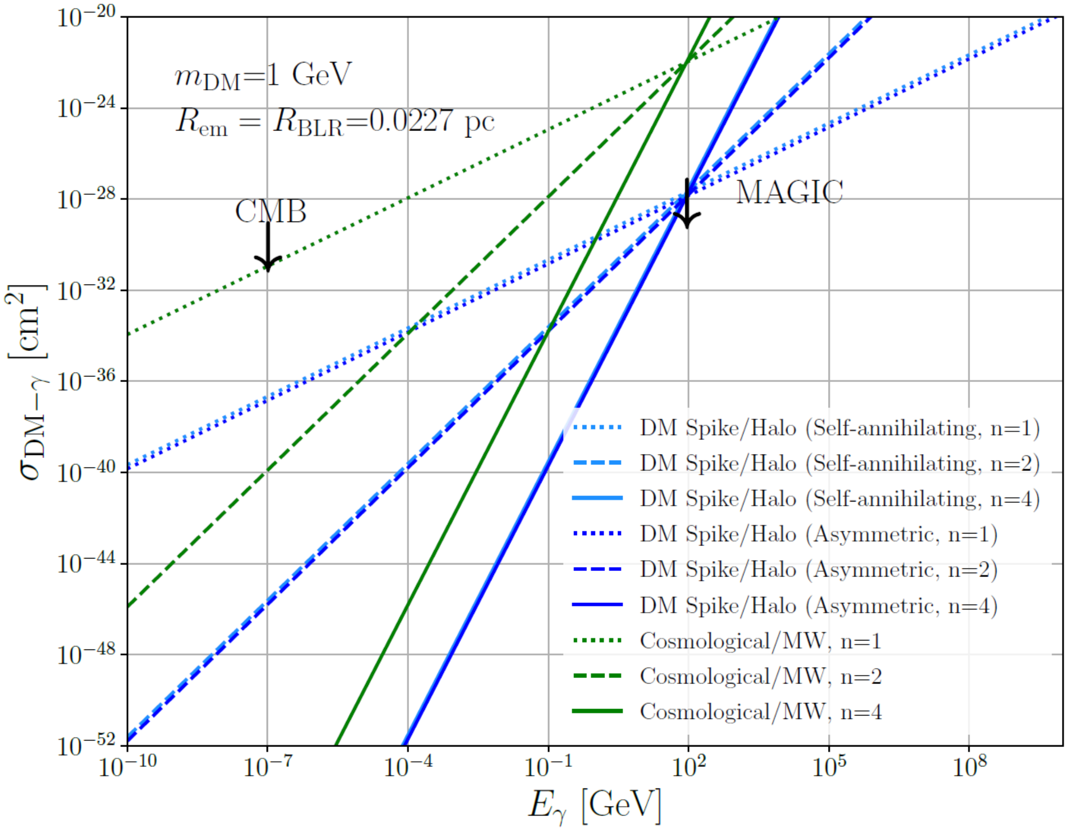


Probing the scattering with photons



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 (compact dark stars, active galactic nuclei, etc.) open new opportunities to detect non-gravitational signals of dark matter.