Observational signals of compact dark stars

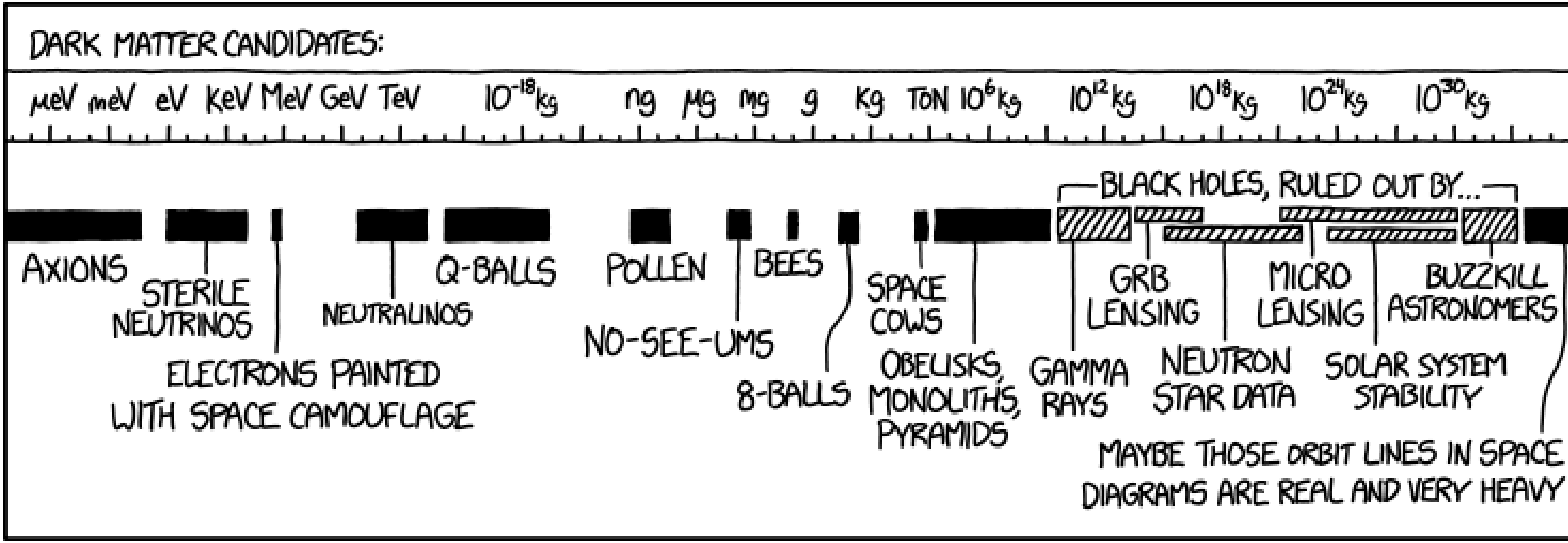
Alejandro Ibarra

In collaboration with Boris Betancourt, Anja Brenner and Chris Kouvaris. arXiv: 2211.05845

DSU, Sydney
December 2022

The dark matter zoo

Explain xkcd



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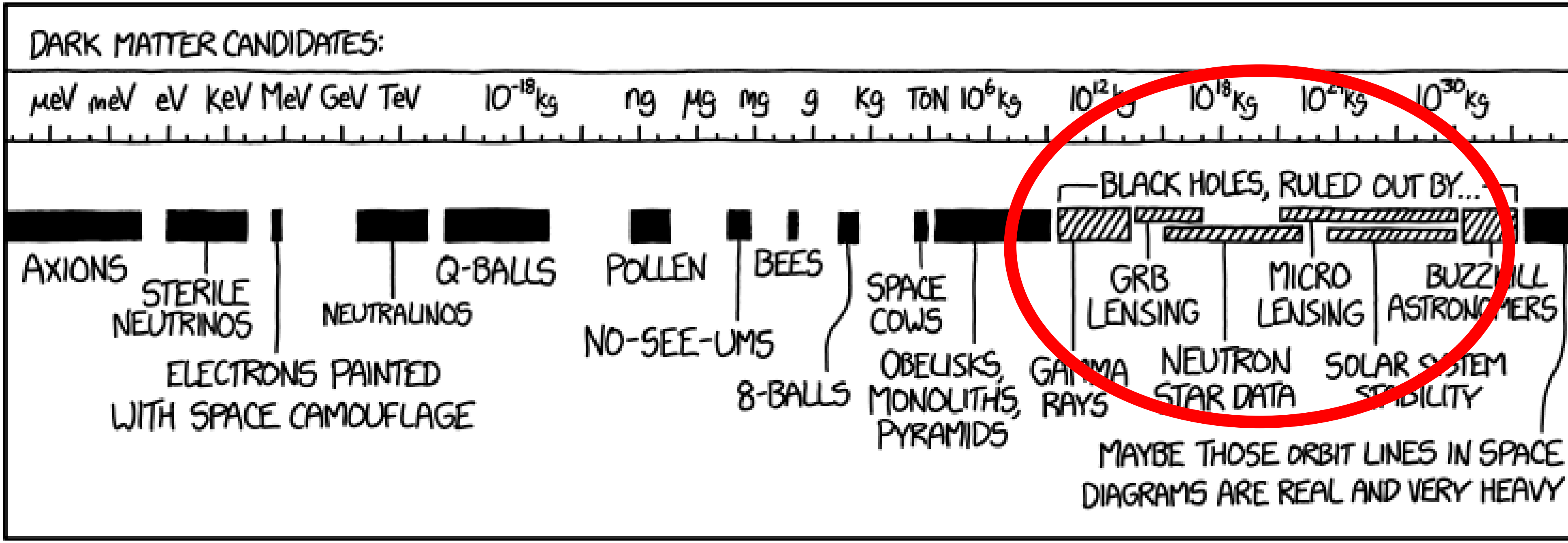

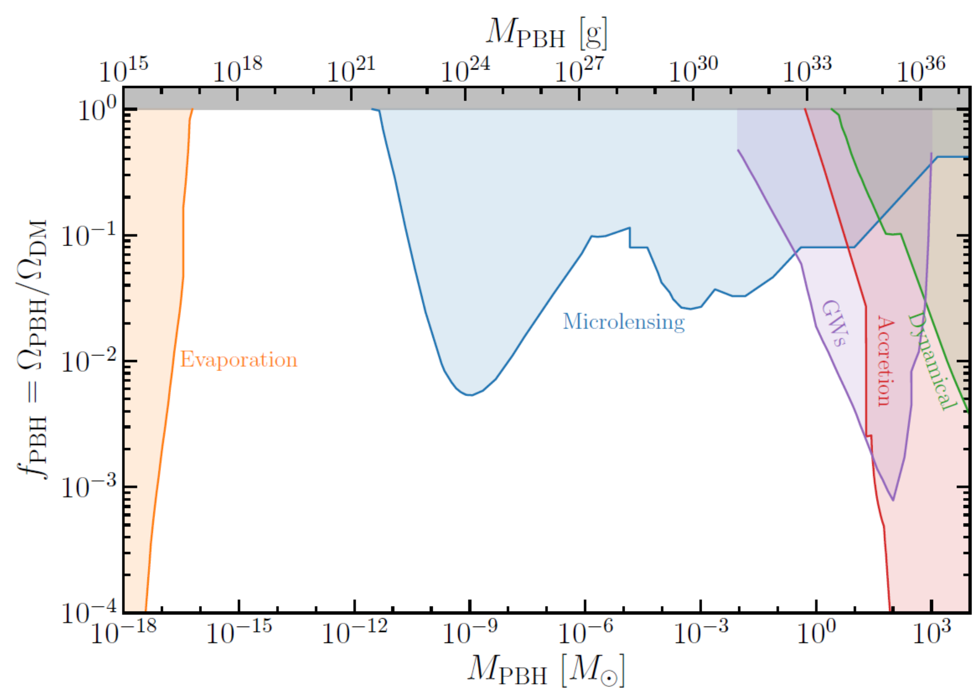

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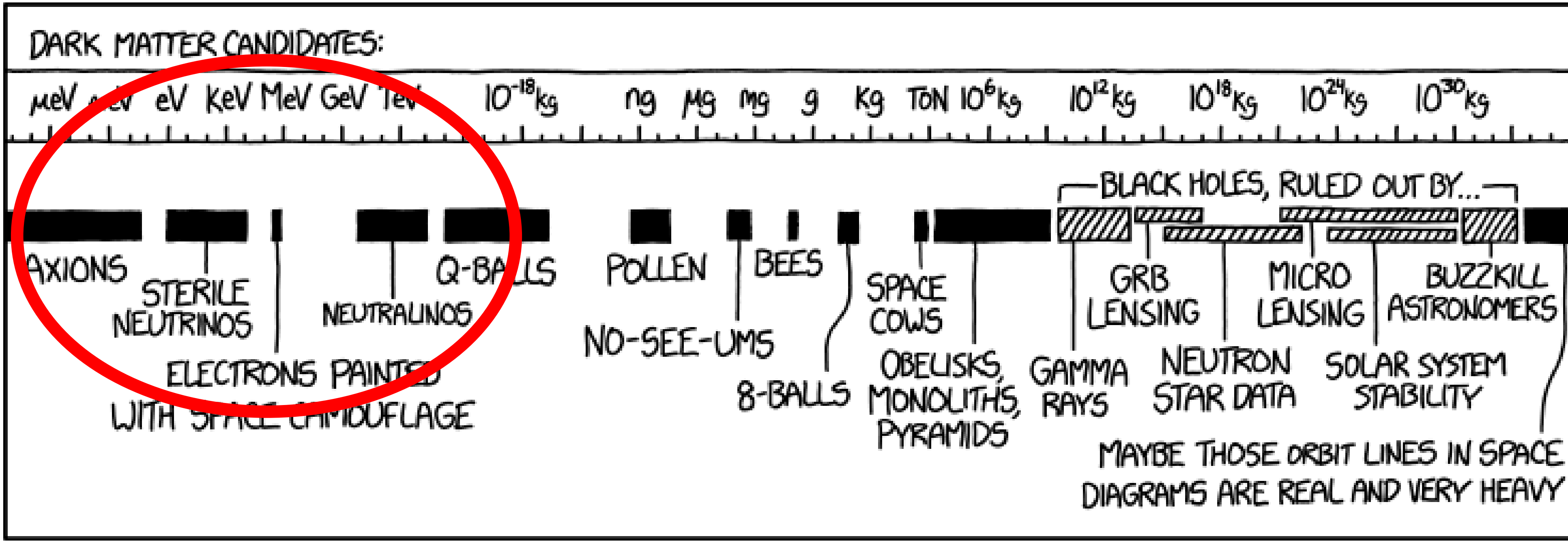

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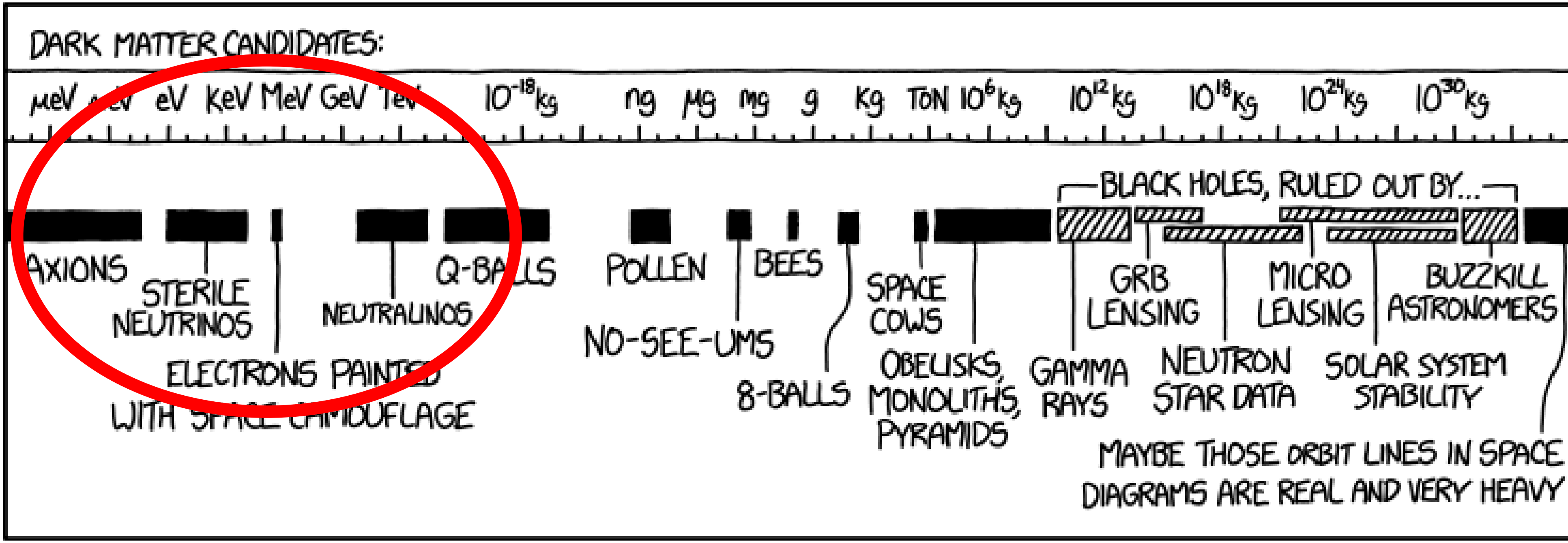

spin

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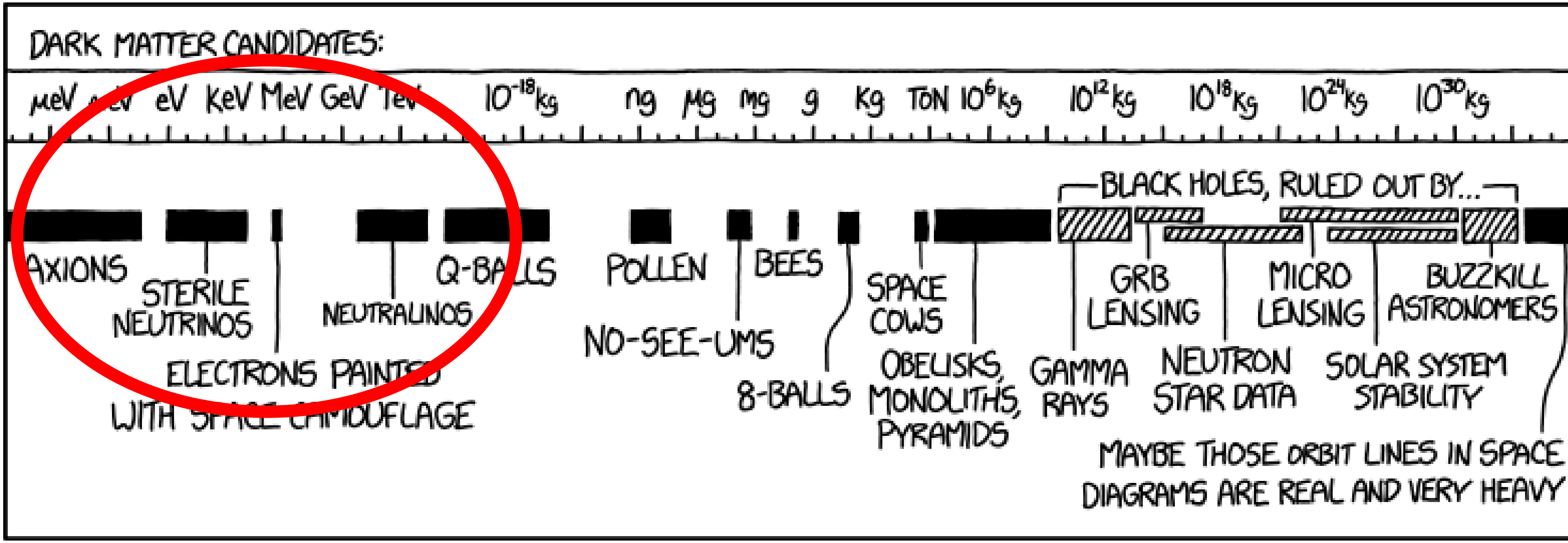

spin

Scattering cross-section to nucleons/electrons

The dark matter zoo

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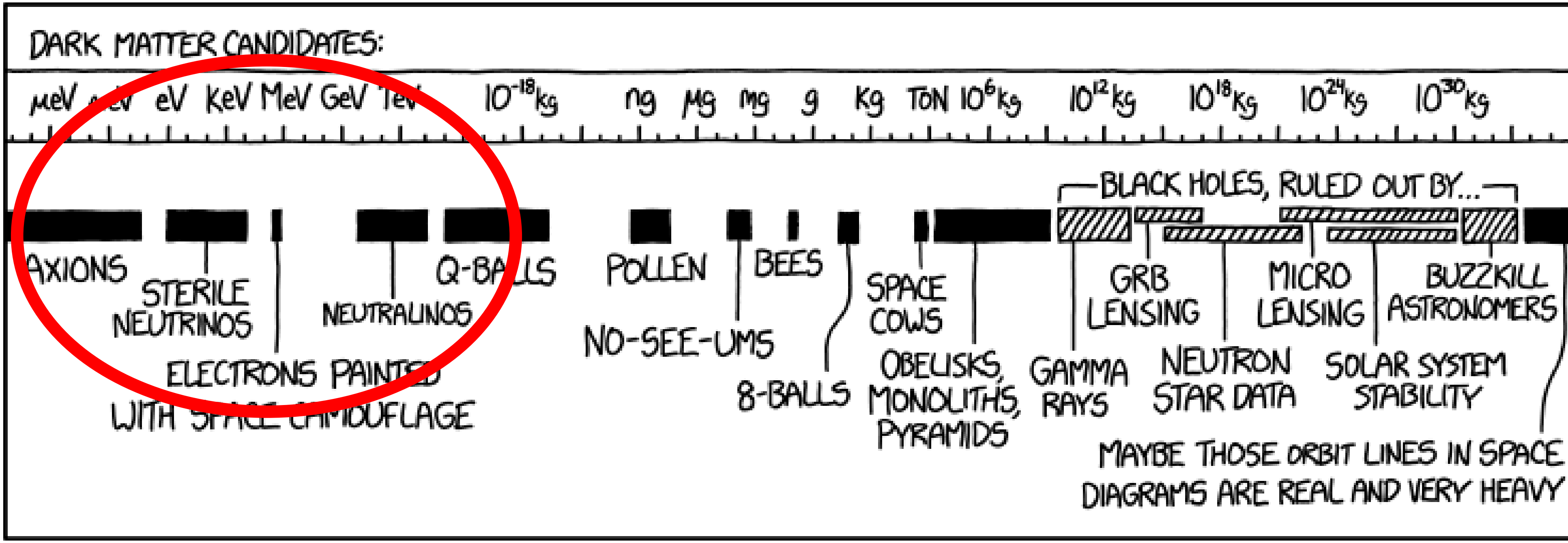

spin

Scattering cross-section to nucleons/electrons

Annihilation cross-section into SM particles

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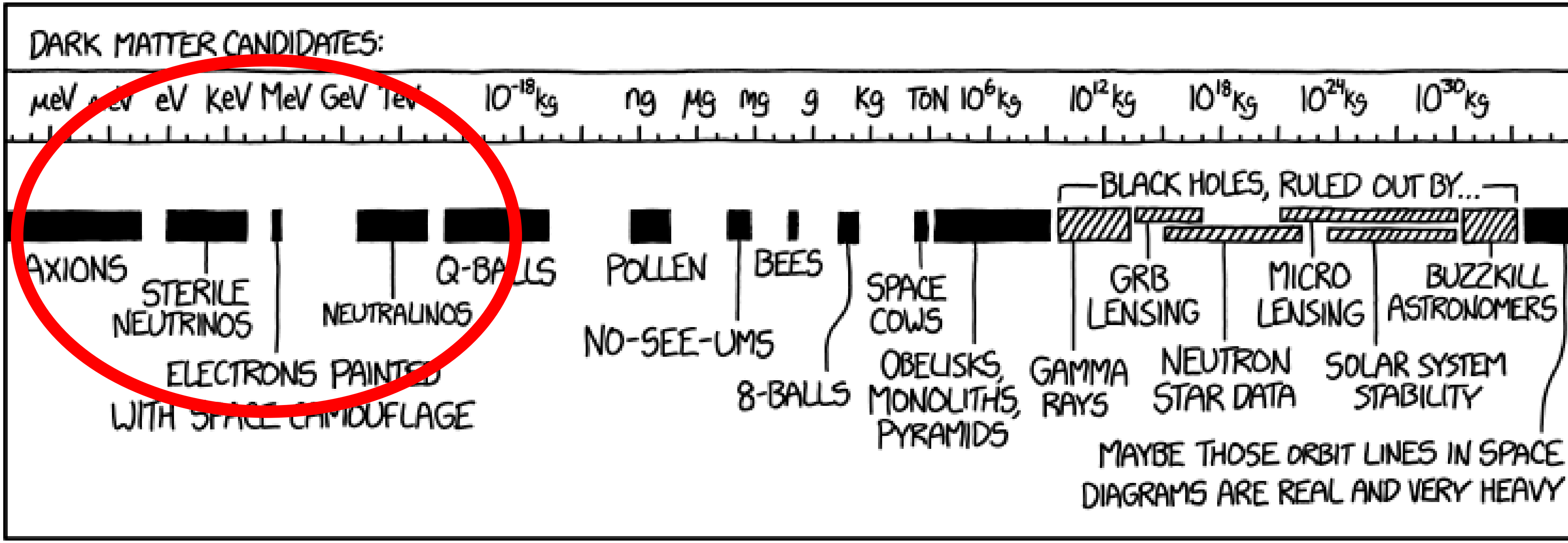
Explain xkcd



- spin
- Scattering cross-section to nucleons/electrons
- Annihilation cross-section into SM particles
- Self-coupling

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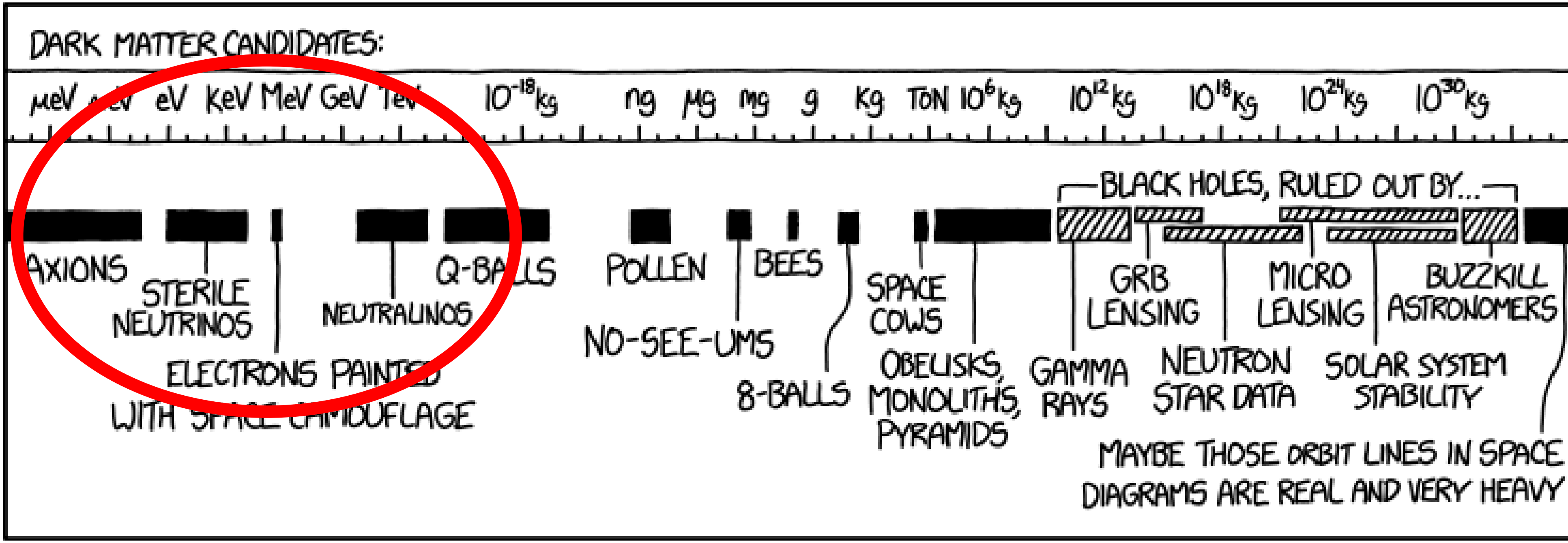

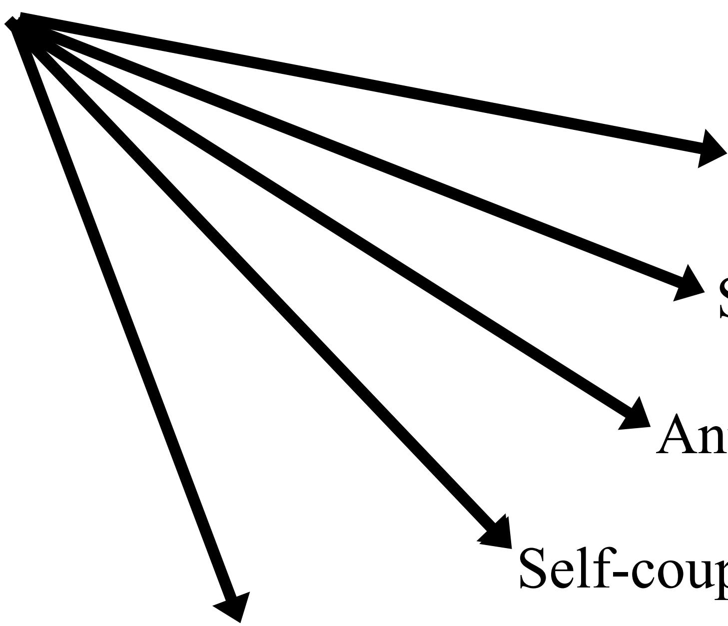

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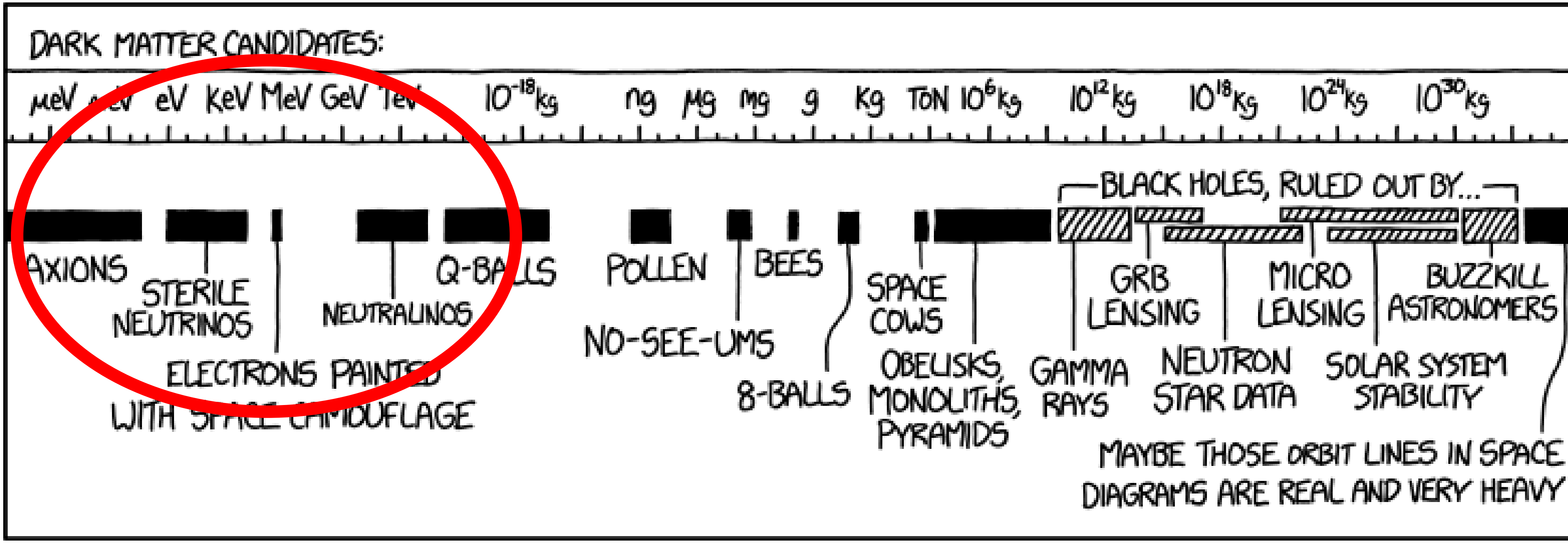

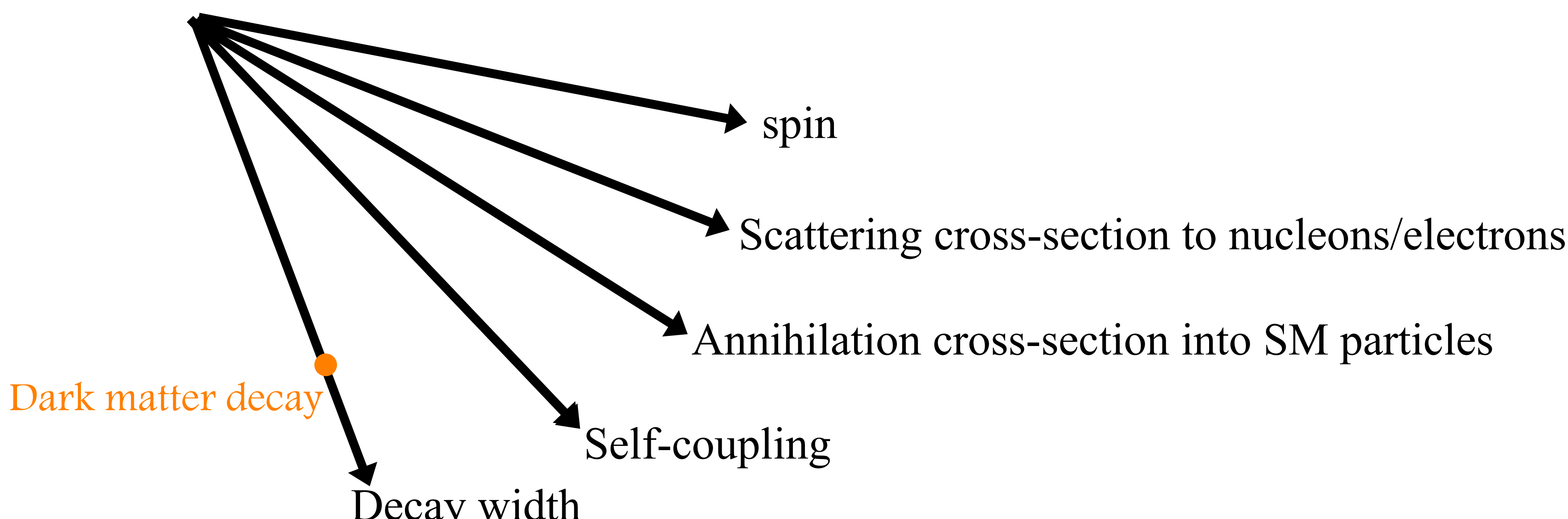

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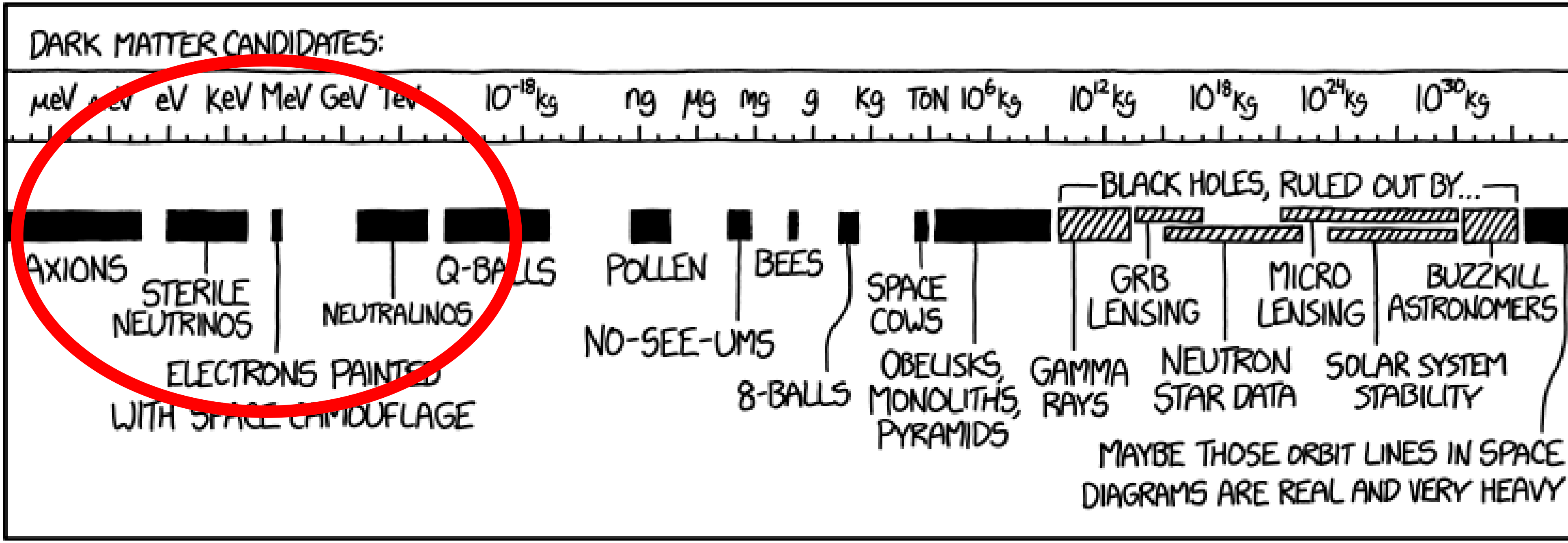

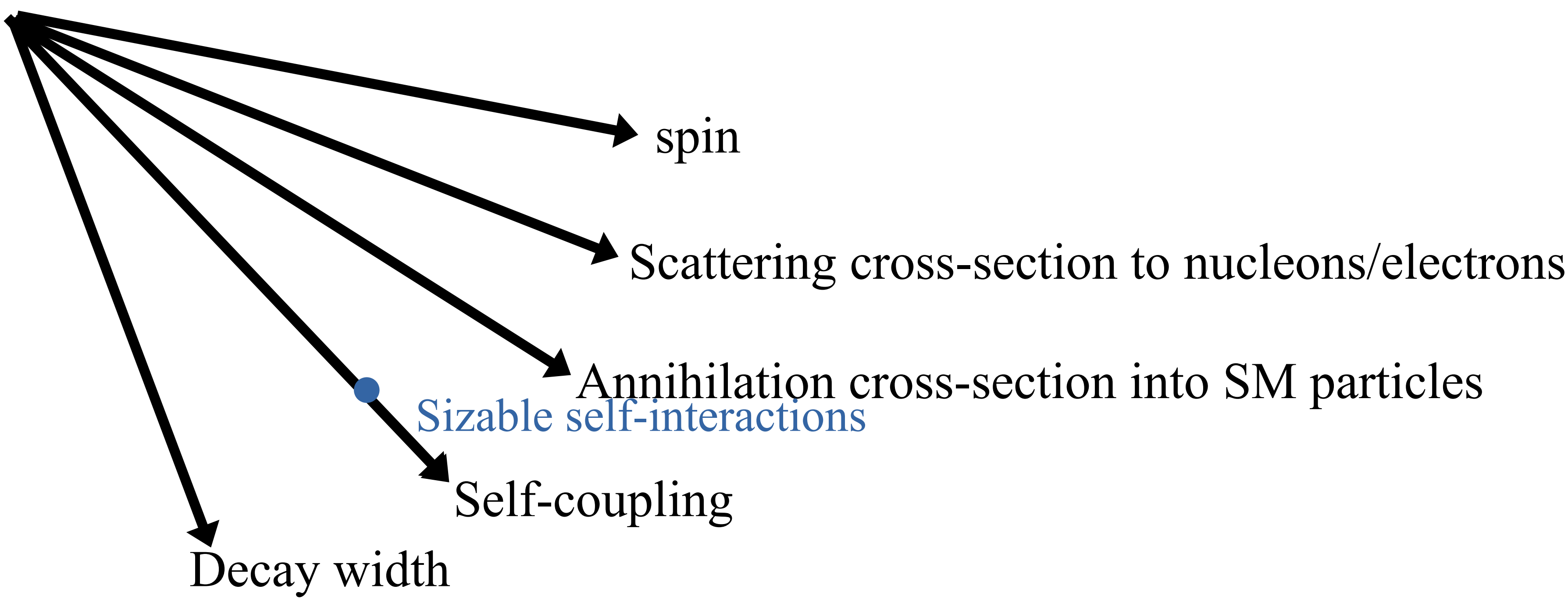

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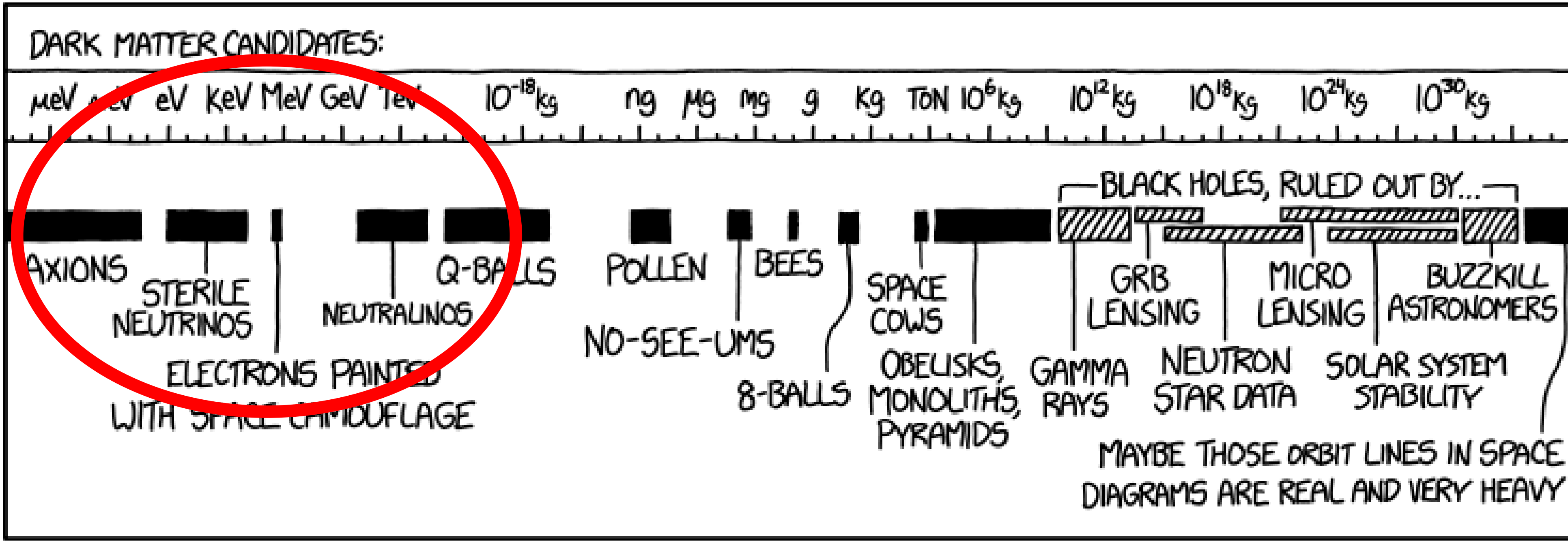

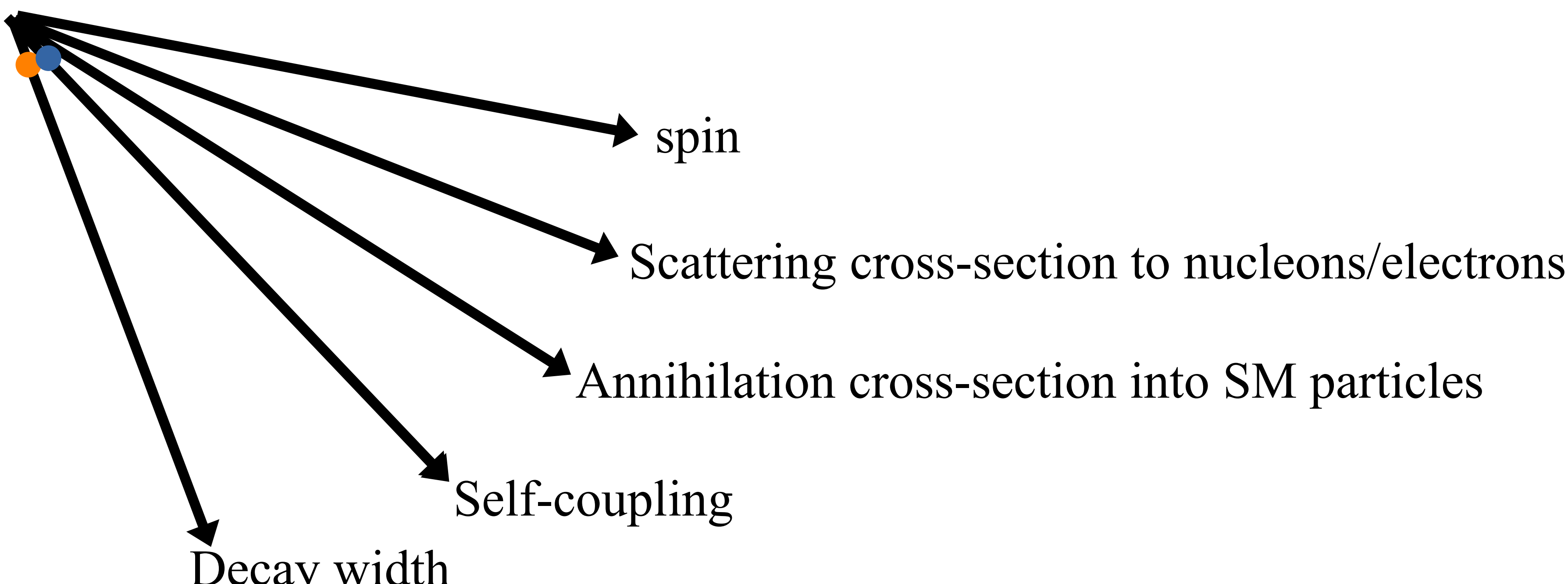

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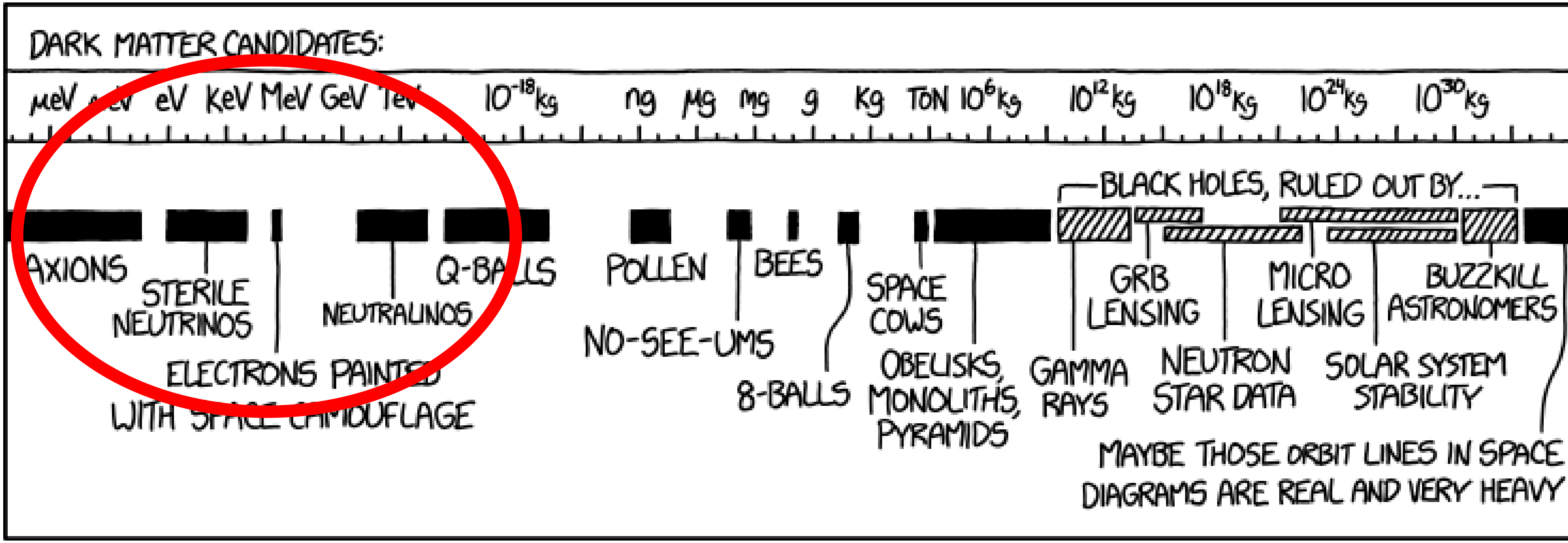

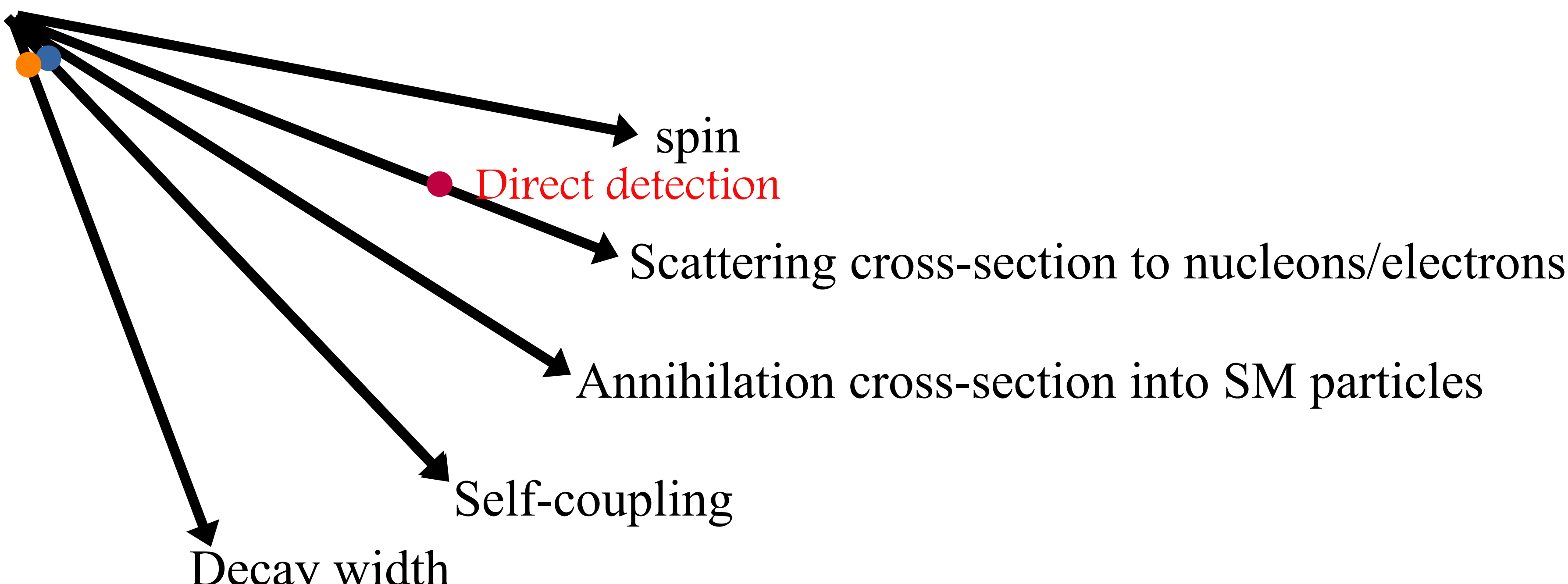

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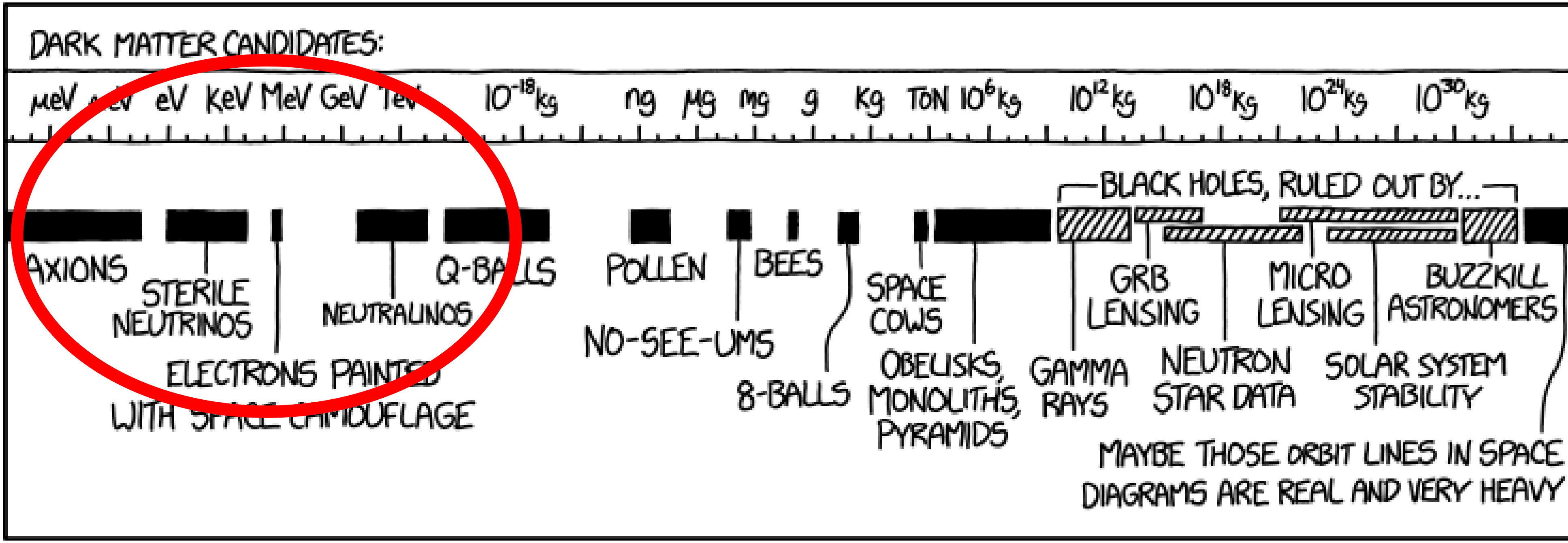

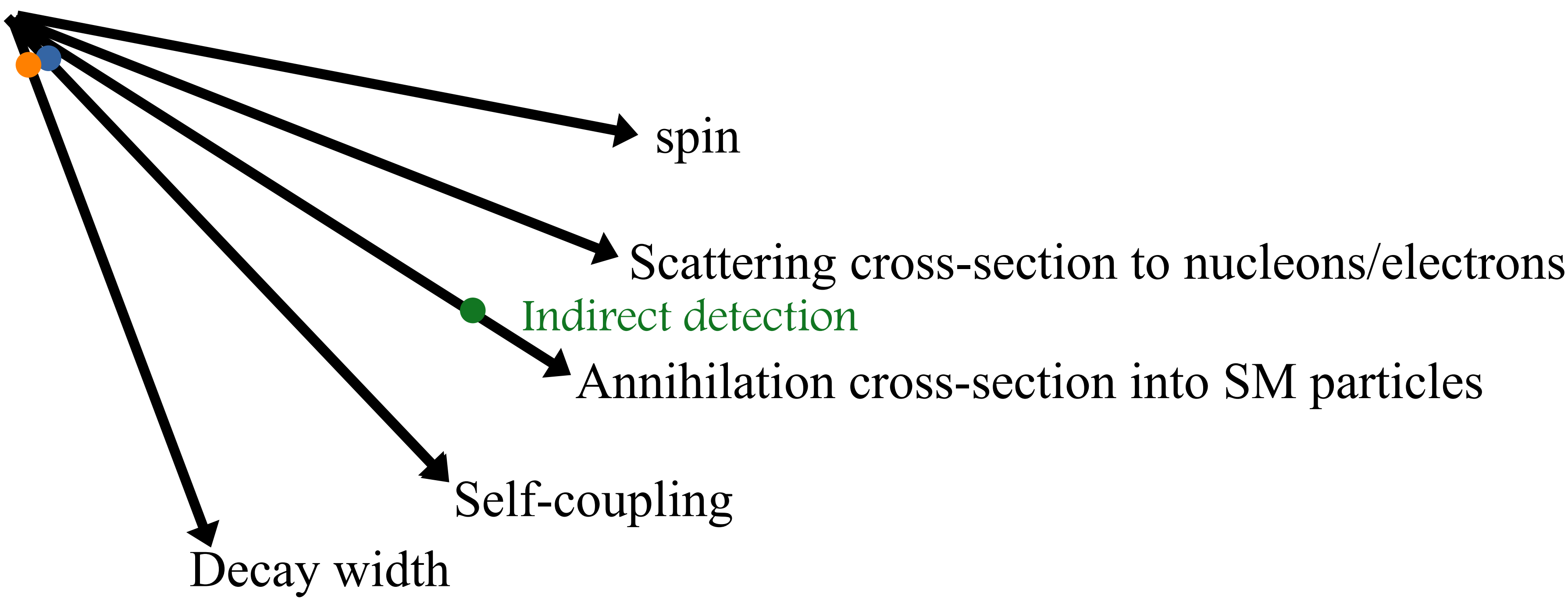

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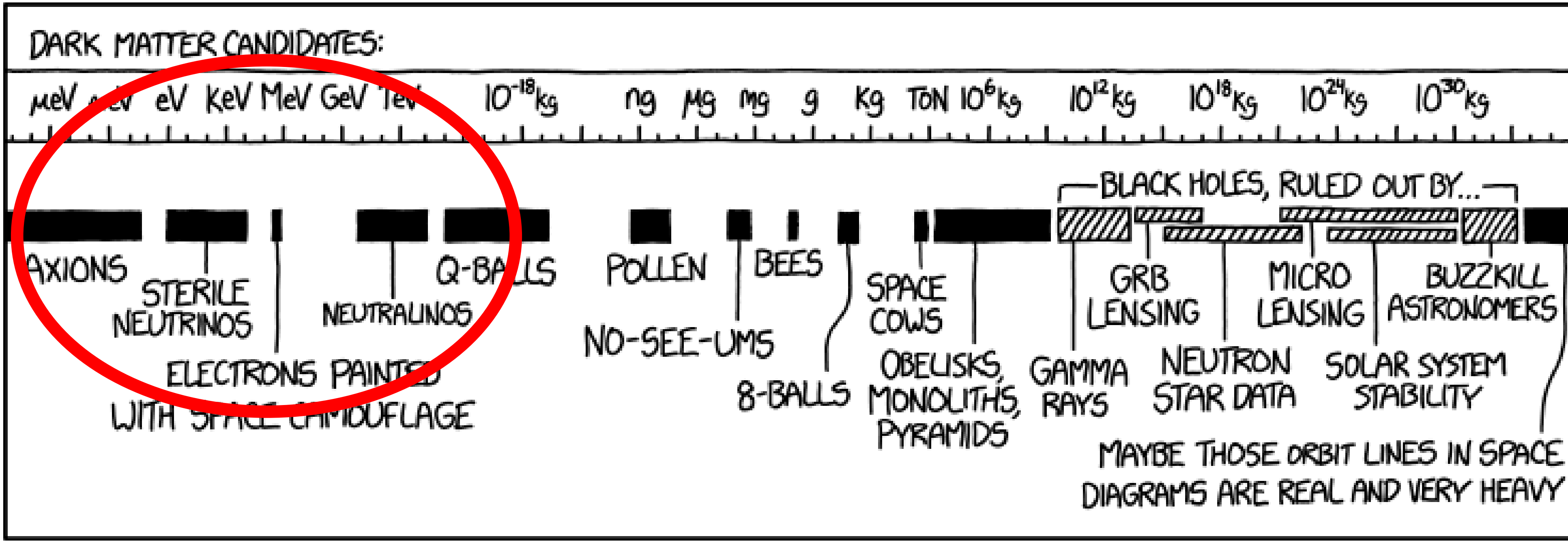

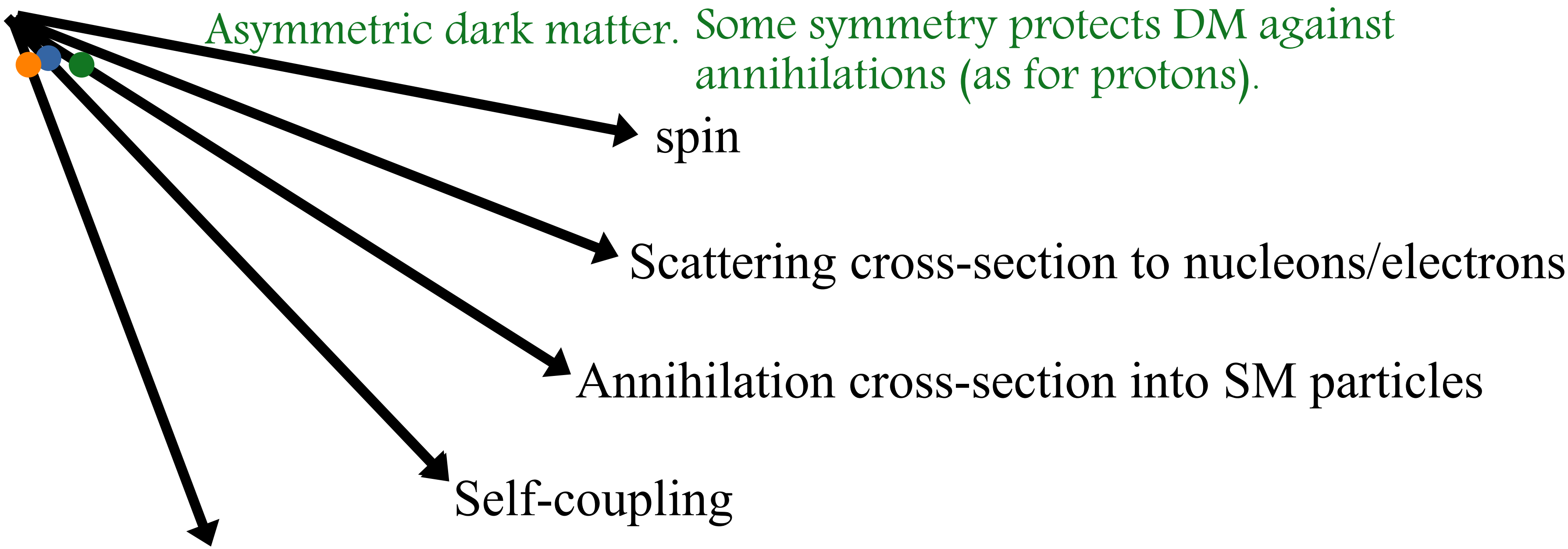

Asymmetric dark matter. Some symmetry protects DM against annihilations (as for protons).

The dark matter zoo

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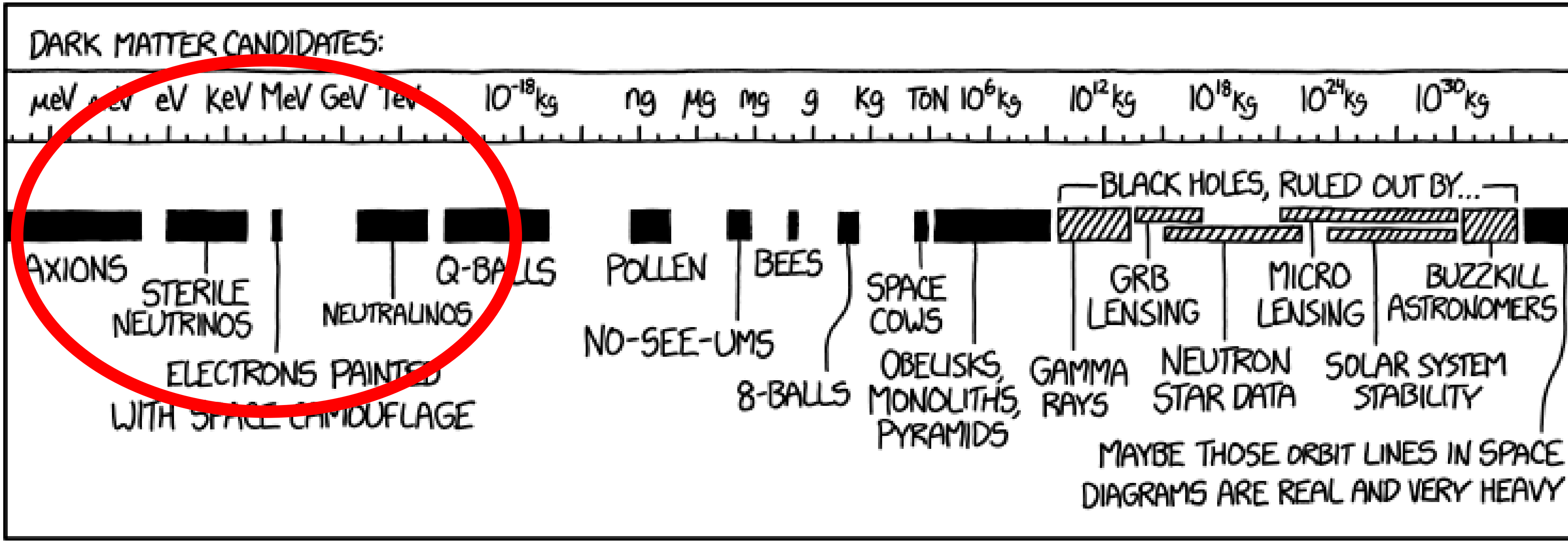

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→ spin

→ Scattering cross-section to nucleons/electrons

→ Annihilation cross-section into SM particles

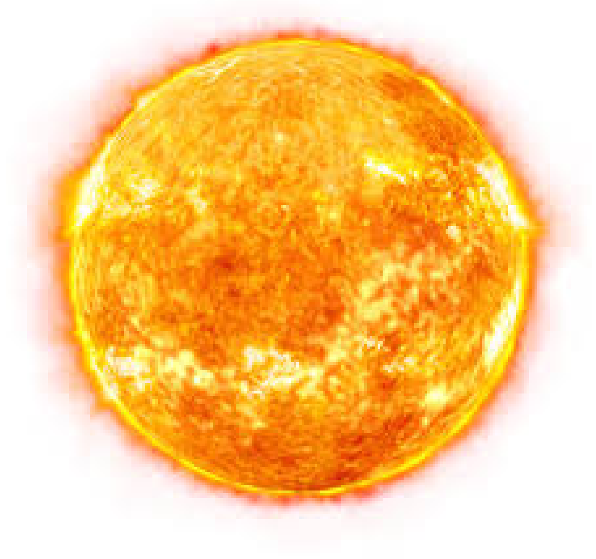
Sizable self-interactions (as for protons)

→ Self-coupling

→ Decay width

The dark matter zoo

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



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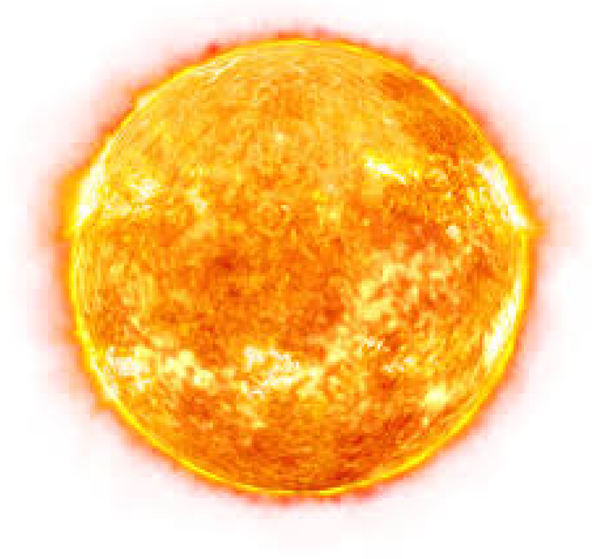

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DM does not annihilate.
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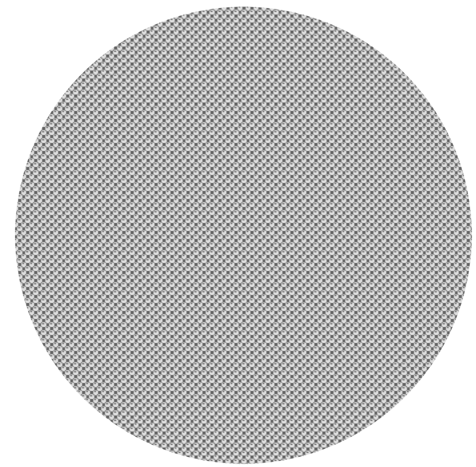
DM form dark stars



The dark matter zoo

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

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

$$R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R = 8\pi G T_{\mu\nu}$$

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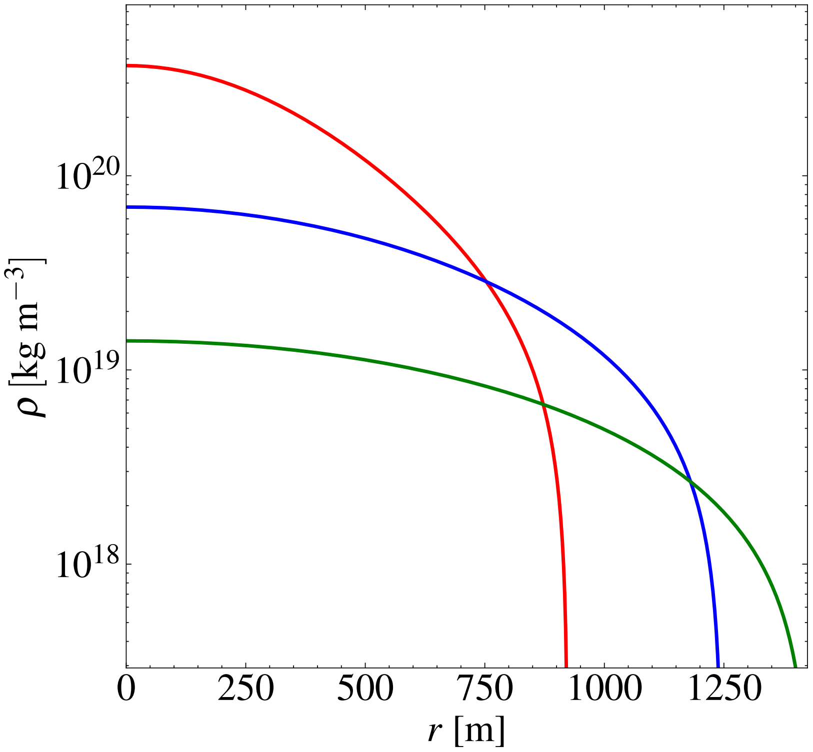

(For m=1 GeV, λ=1)

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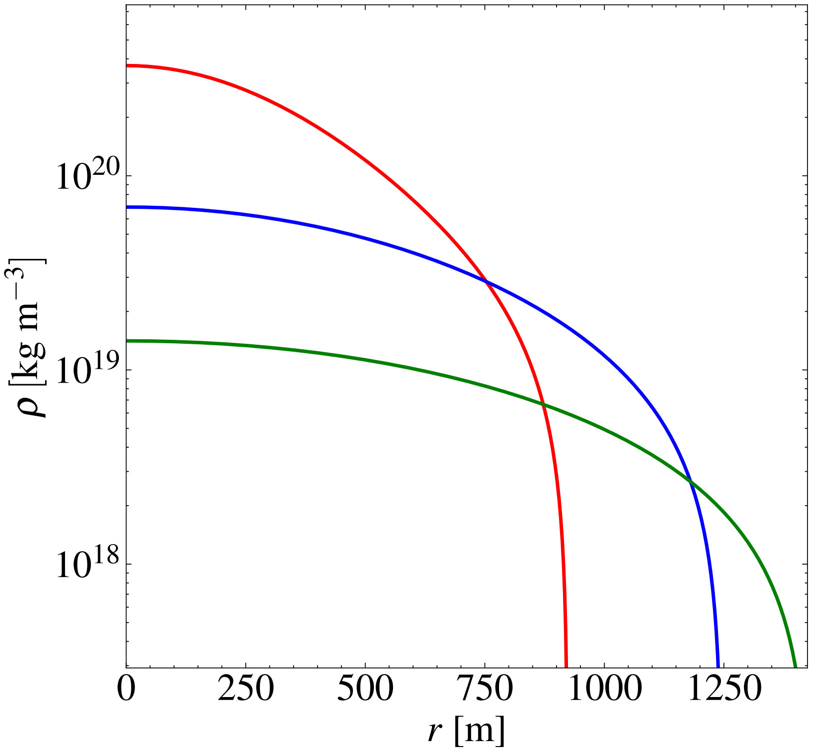

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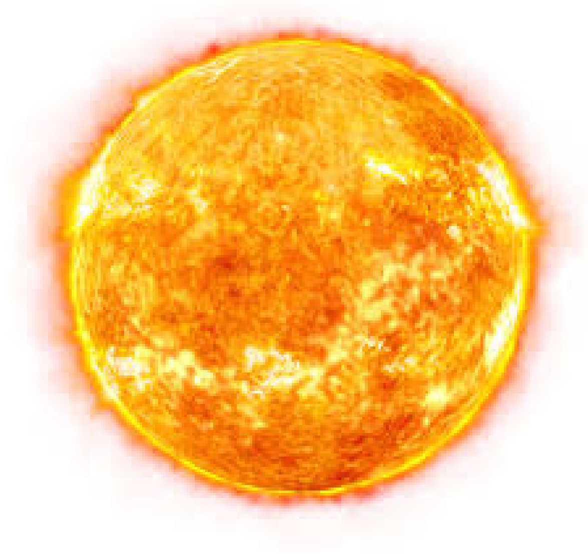
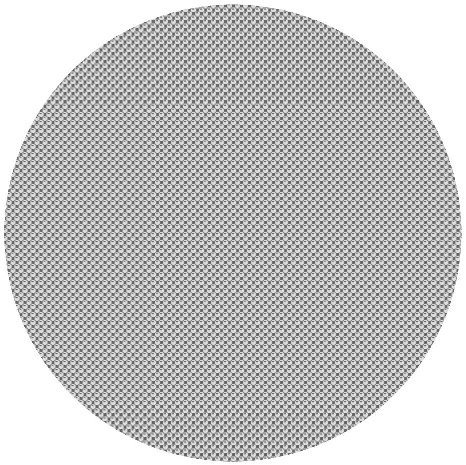
Dark stars are very compact objects

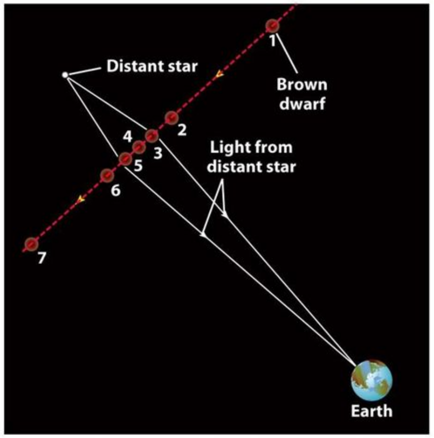
The dark matter zoo

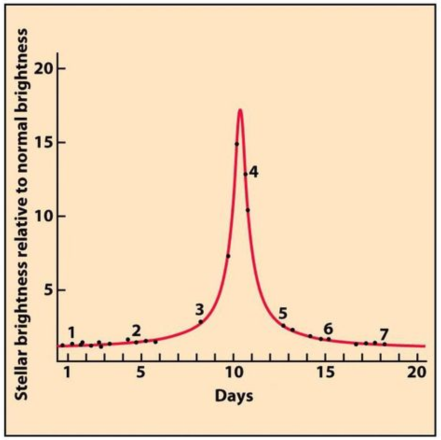
Protons do not annihilate.
Protons have strong self-interactions
Protons form stars

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









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DM does not annihilate.
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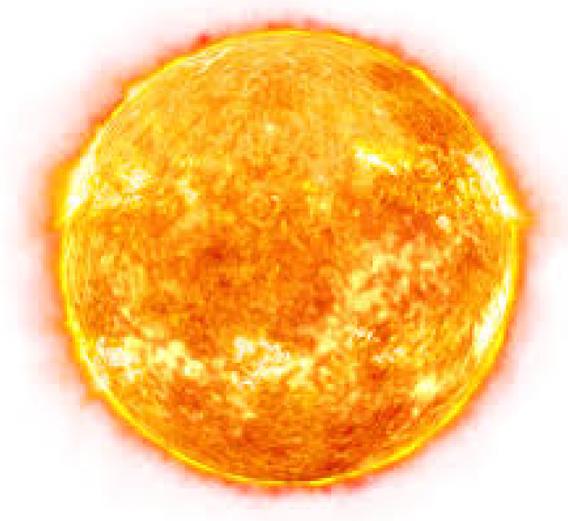
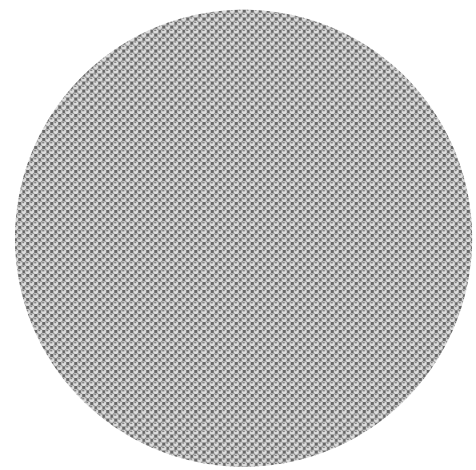
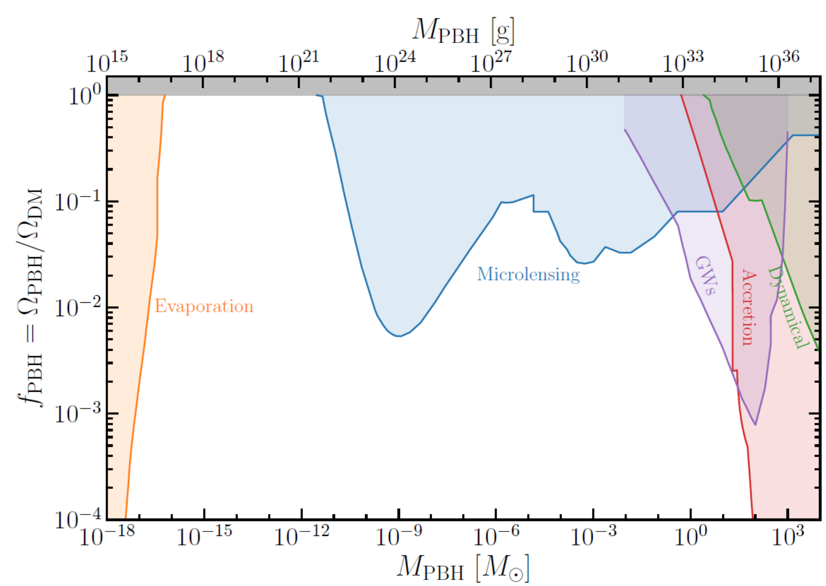
DM form dark stars







Are there other signals from dark stars?

The dark matter zoo

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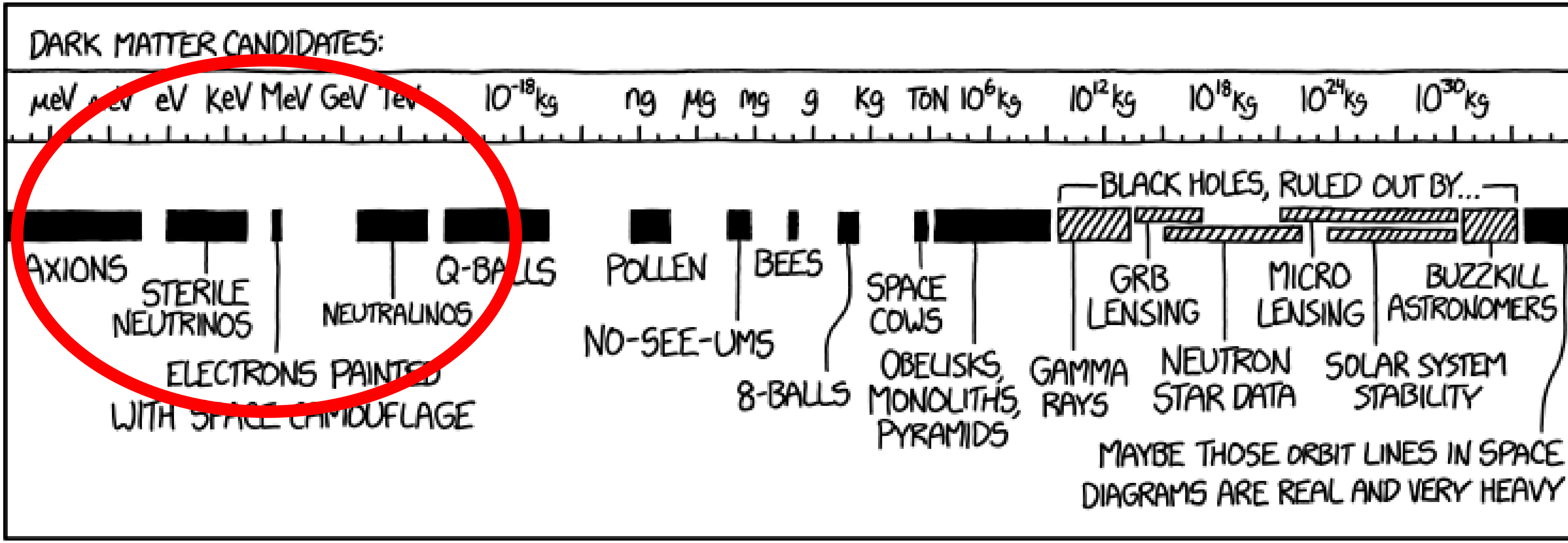

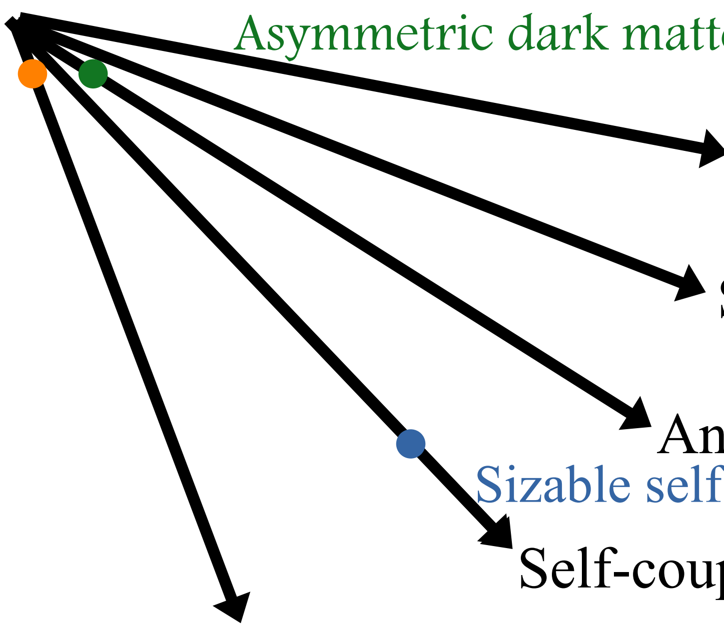

Asymmetric dark matter. Some symmetry protects DM against annihilations (as for protons).

spin

Scattering cross-section to nucleons/electrons

Annihilation cross-section into SM particles

Sizable self-interactions (as for protons)

Self-coupling

Decay width

The dark matter zoo

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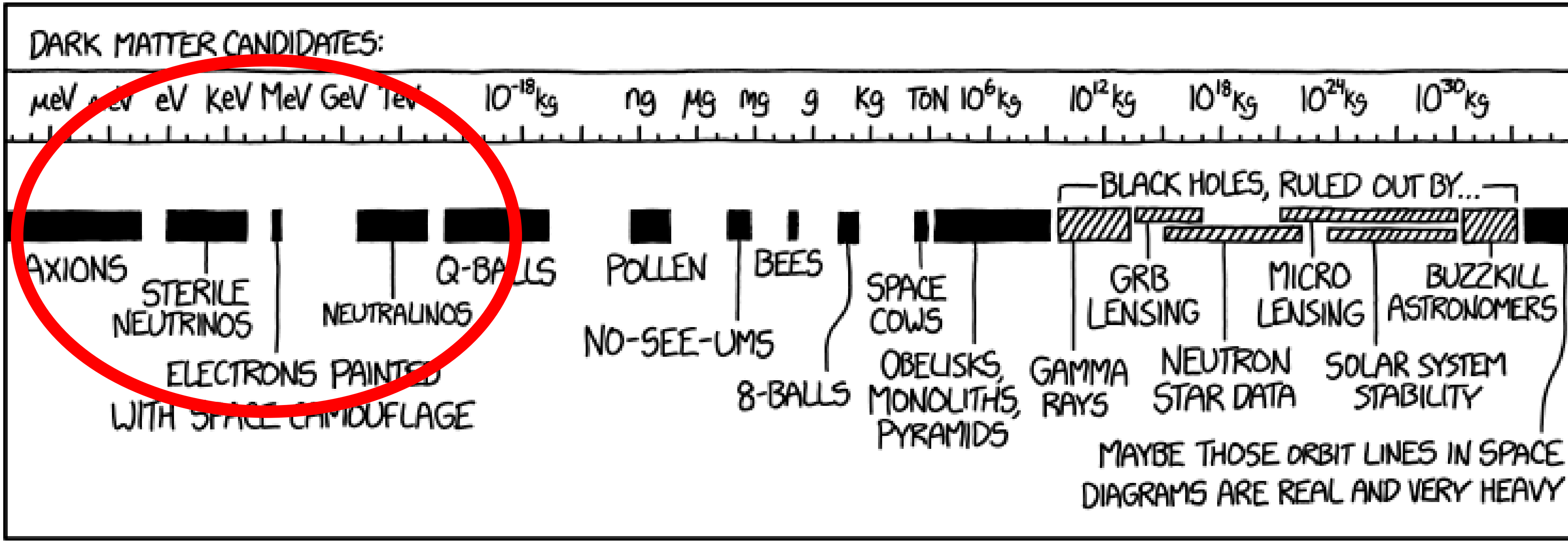

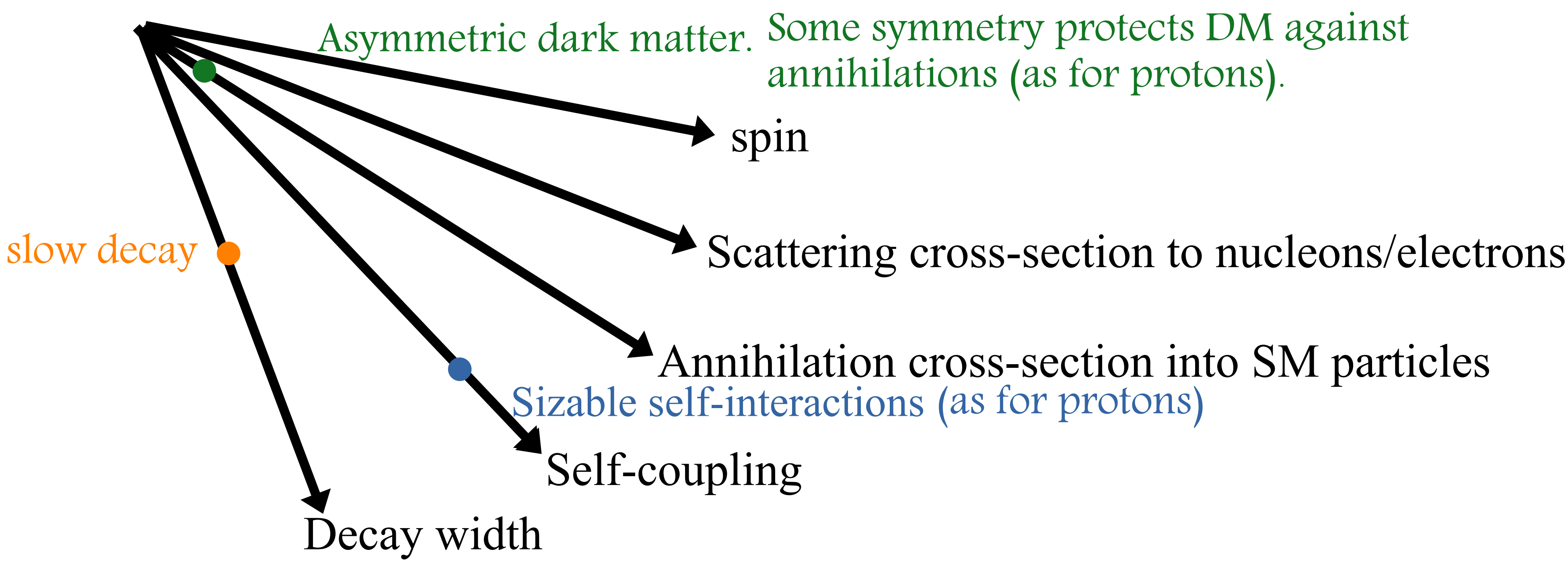

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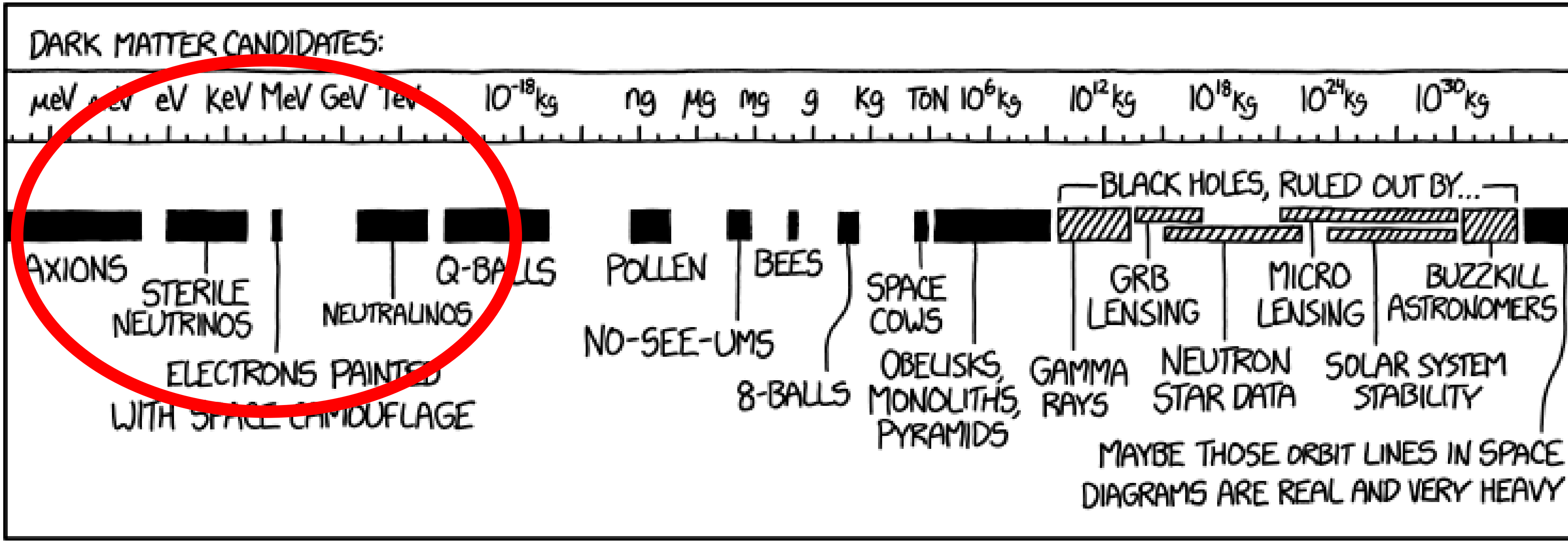

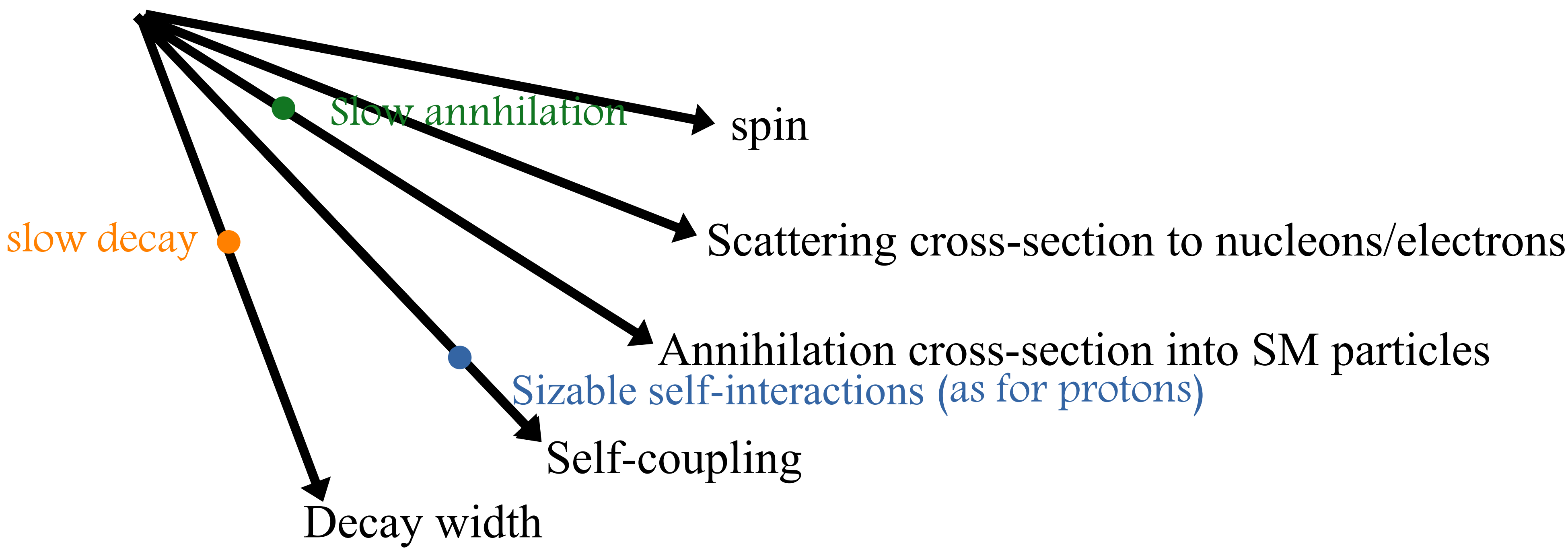

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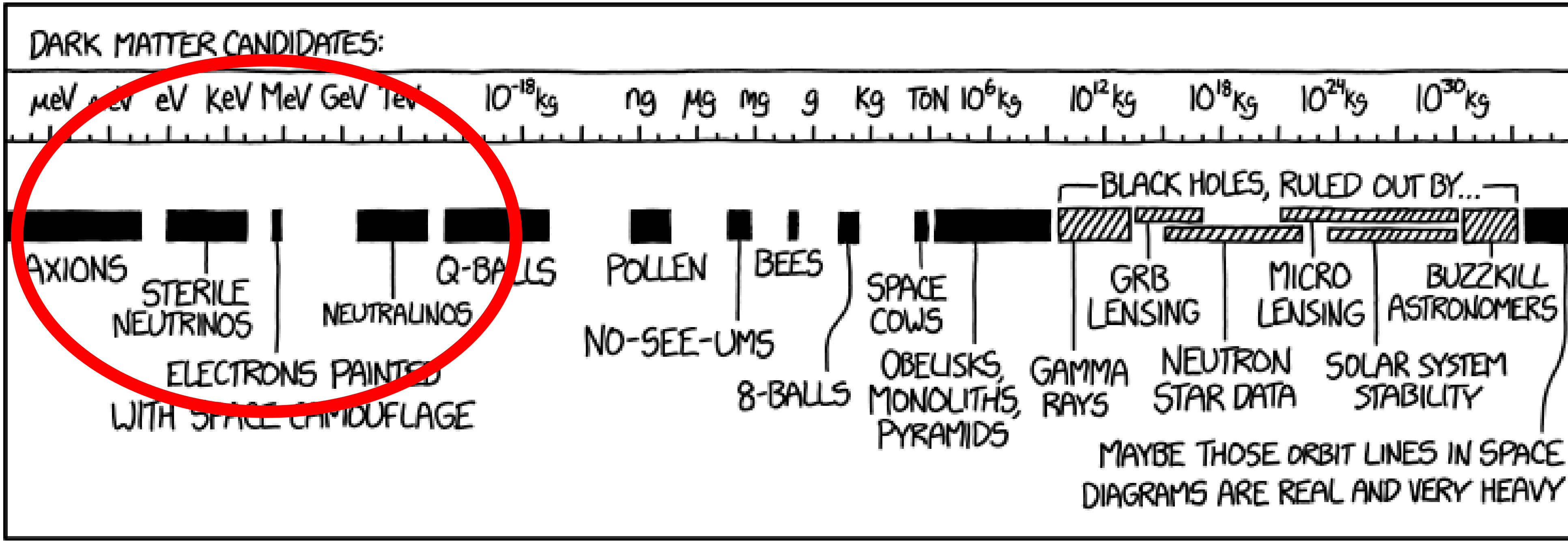

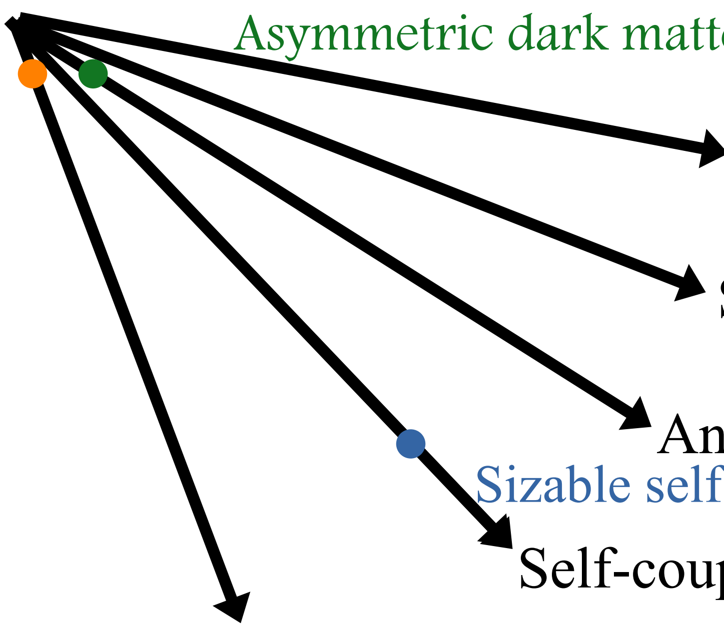

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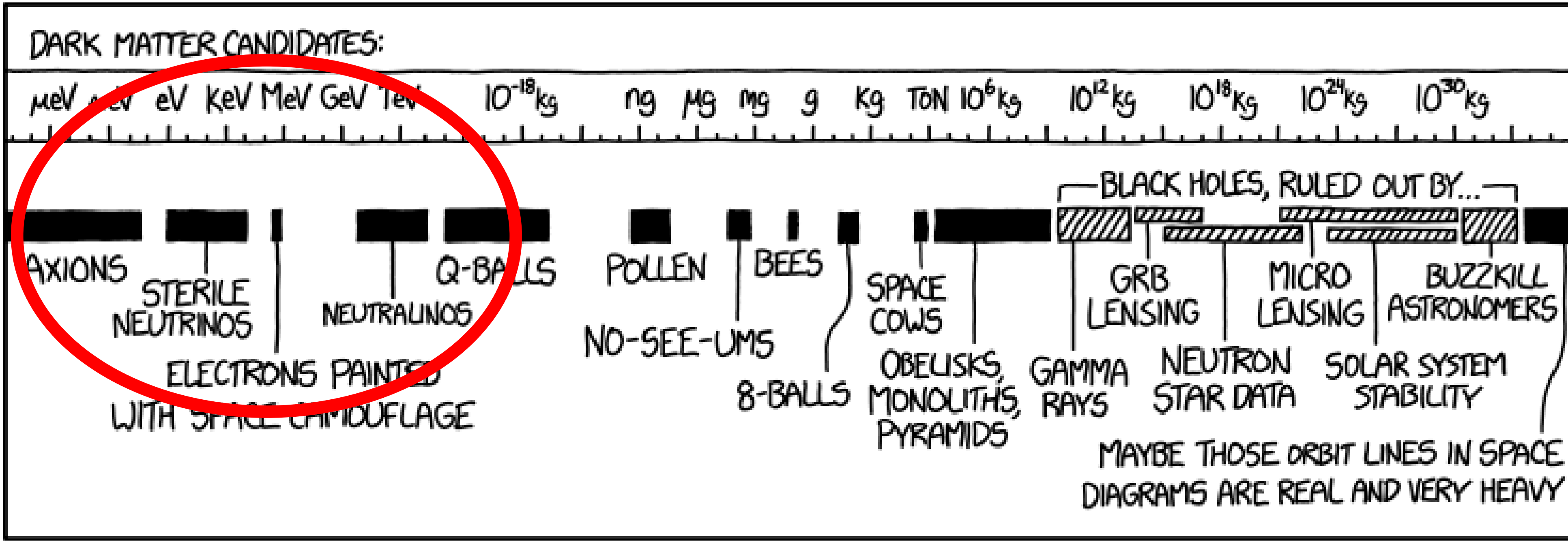


Asymmetric dark matter. Some symmetry protects DM against annihilations (as for protons).

spin

We assume that DM interacts with protons

Scattering cross-section to nucleons/electrons

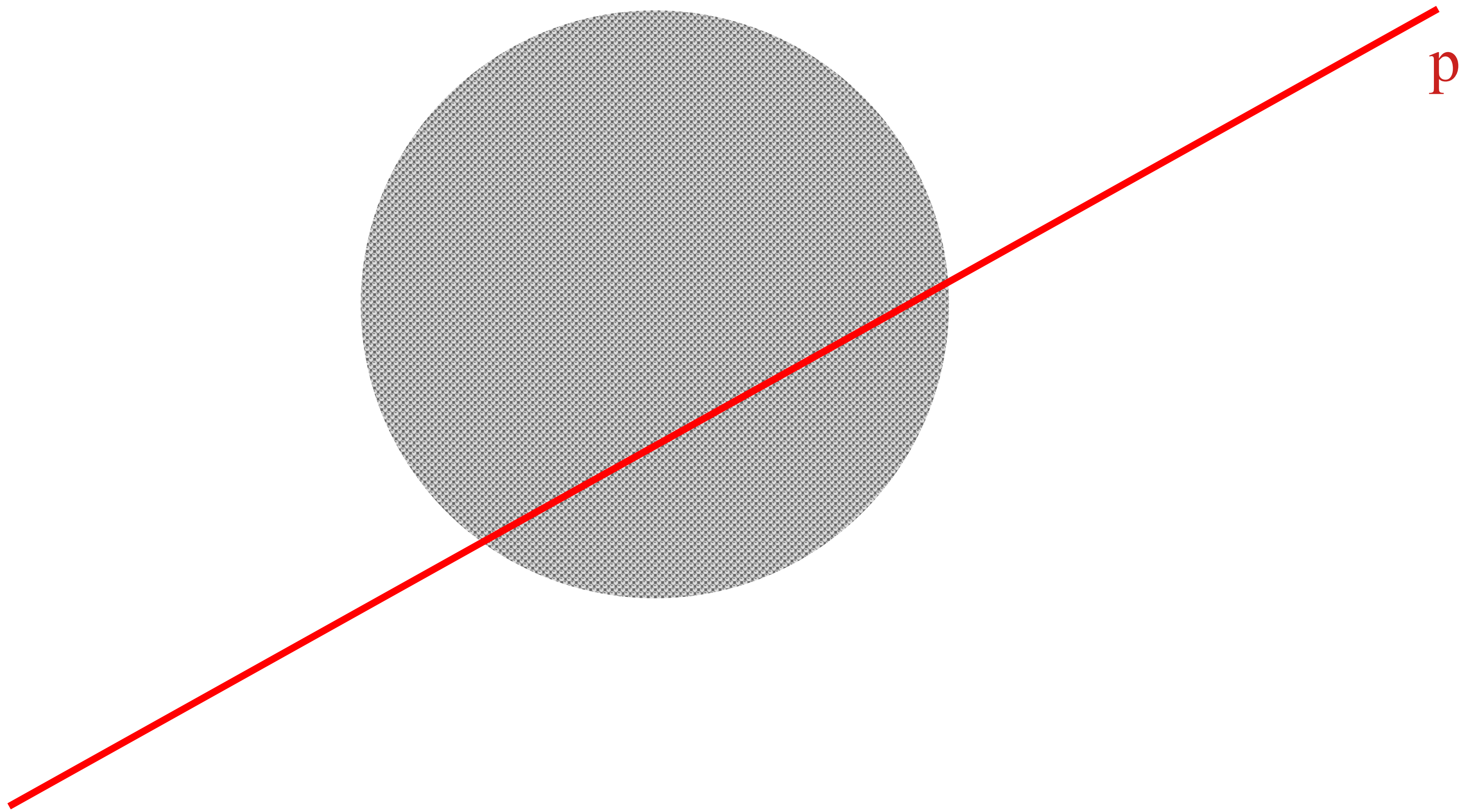
Annihilation cross-section into SM particles

Sizable self-interactions (as for protons)

Self-coupling

Decay width

Proton capture in compact dark stars



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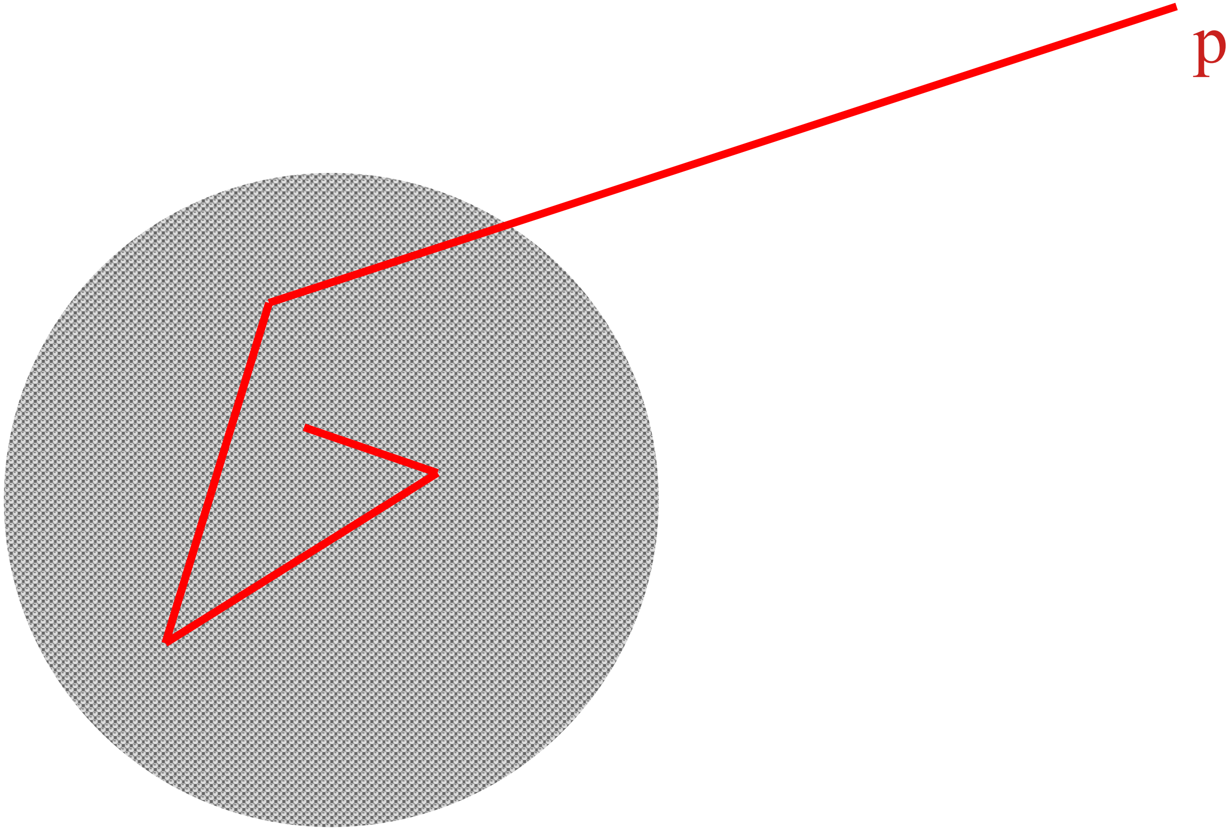

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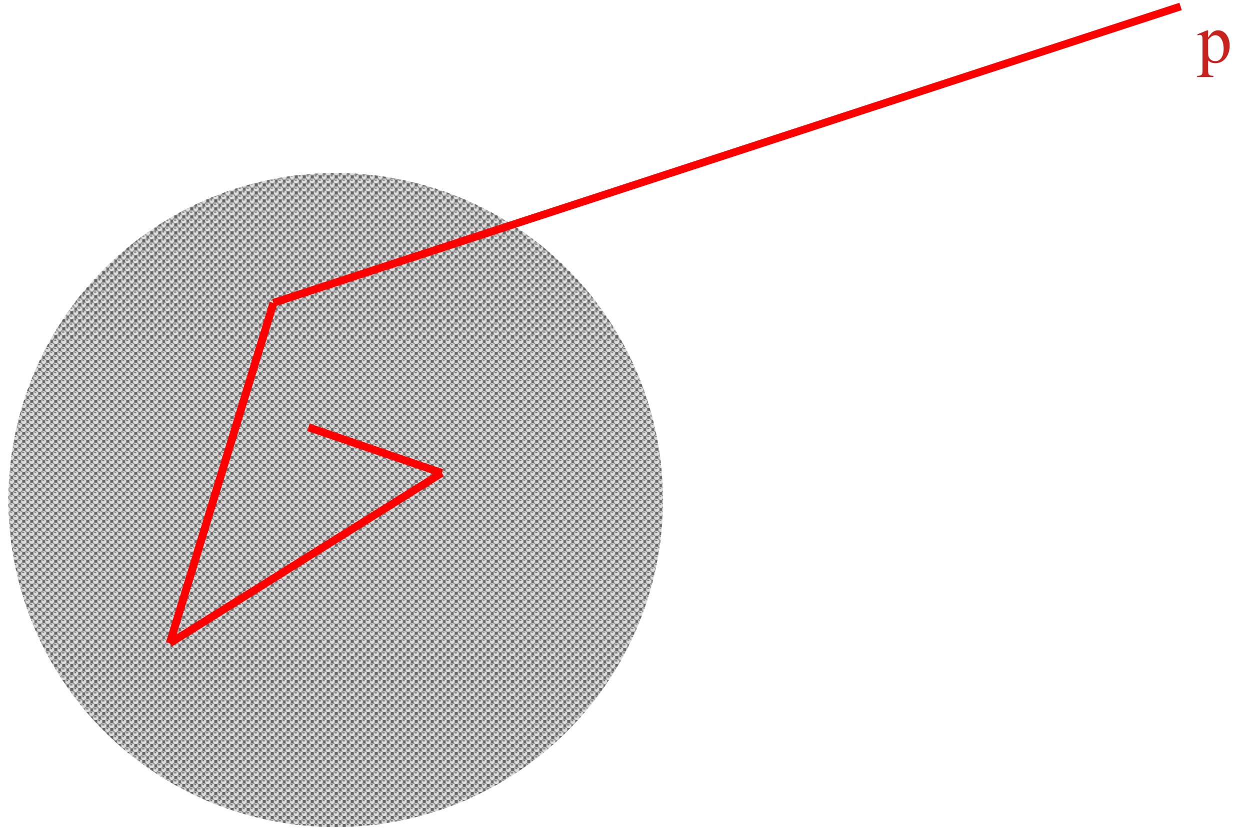

$$C_{v_s} = (1.3 \times 10^{15}\ \mathrm{s}^{-1}) \left(\frac{m}{1\ \mathrm{GeV}}\right)^{-1} \left(\frac{R_{\mathrm{DS}}}{1\ \mathrm{km}}\right)^{3} \left(\frac{\rho_{\mathrm{core}}}{10^{18}\ \mathrm{gr/cm^3}}\right)$$

$$\times \left(\frac{\sigma}{10^{-50}\ \mathrm{cm}^2}\right) \left(\frac{n_p}{10^{-5}\ \mathrm{cm}^{-3}}\right) \left(\frac{v_s}{10^{-3}}\right)^{-1} \mathrm{Erf}\left[\sqrt{\frac{3}{2}}\left(\frac{v_s}{\bar{v}}\right)\right]$$

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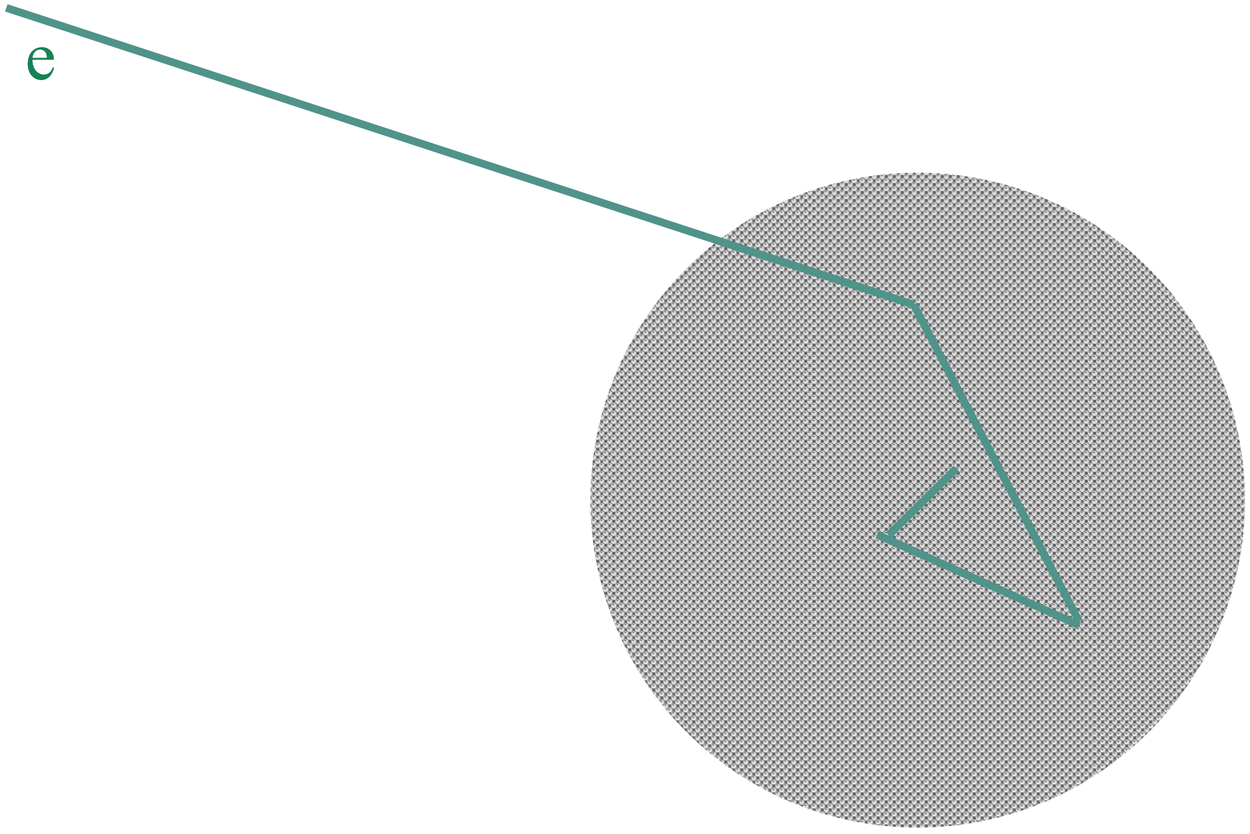

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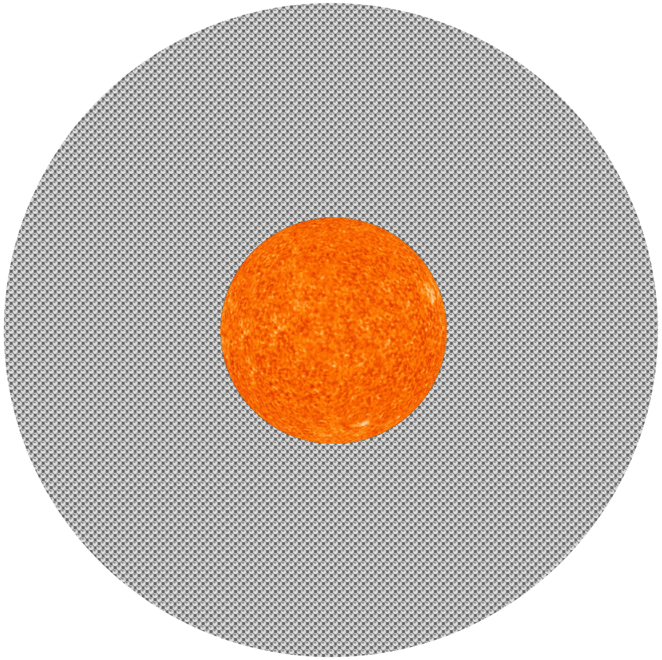

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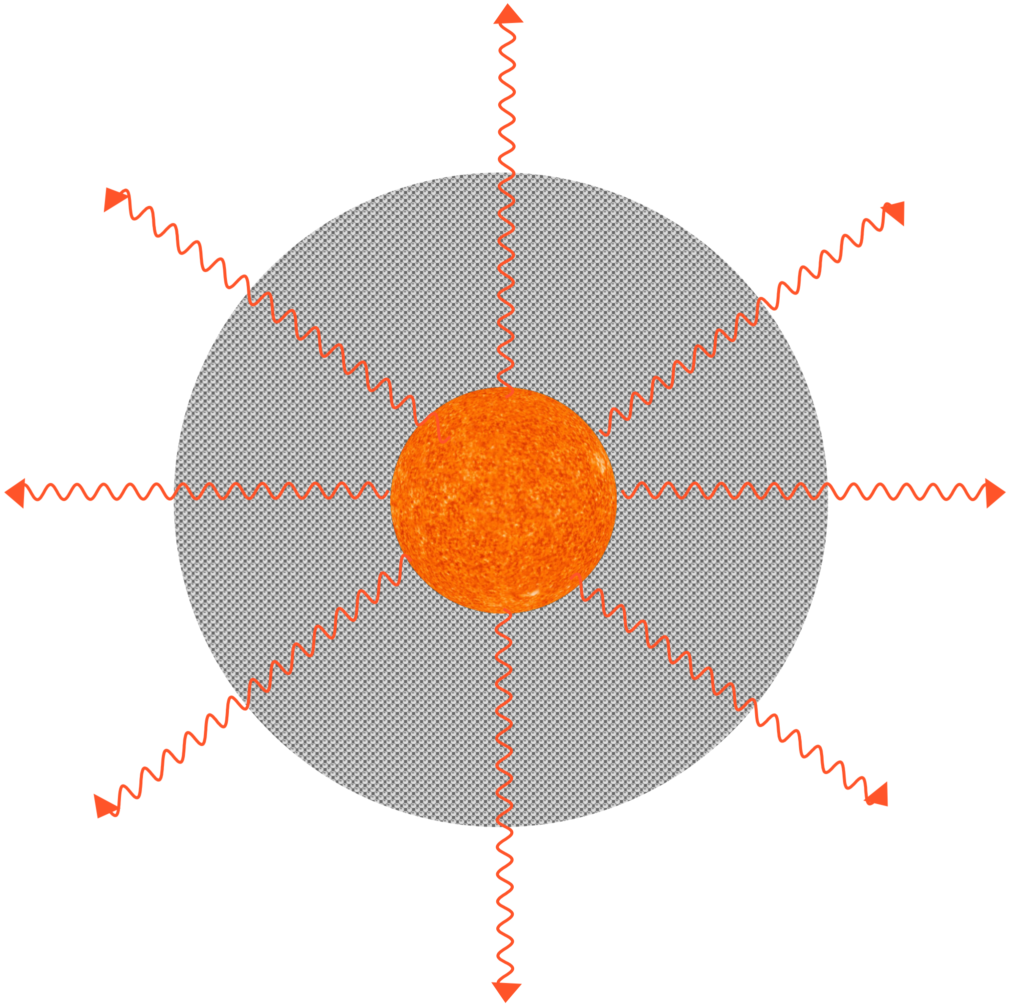

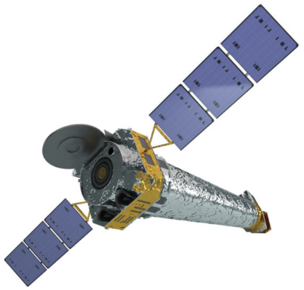

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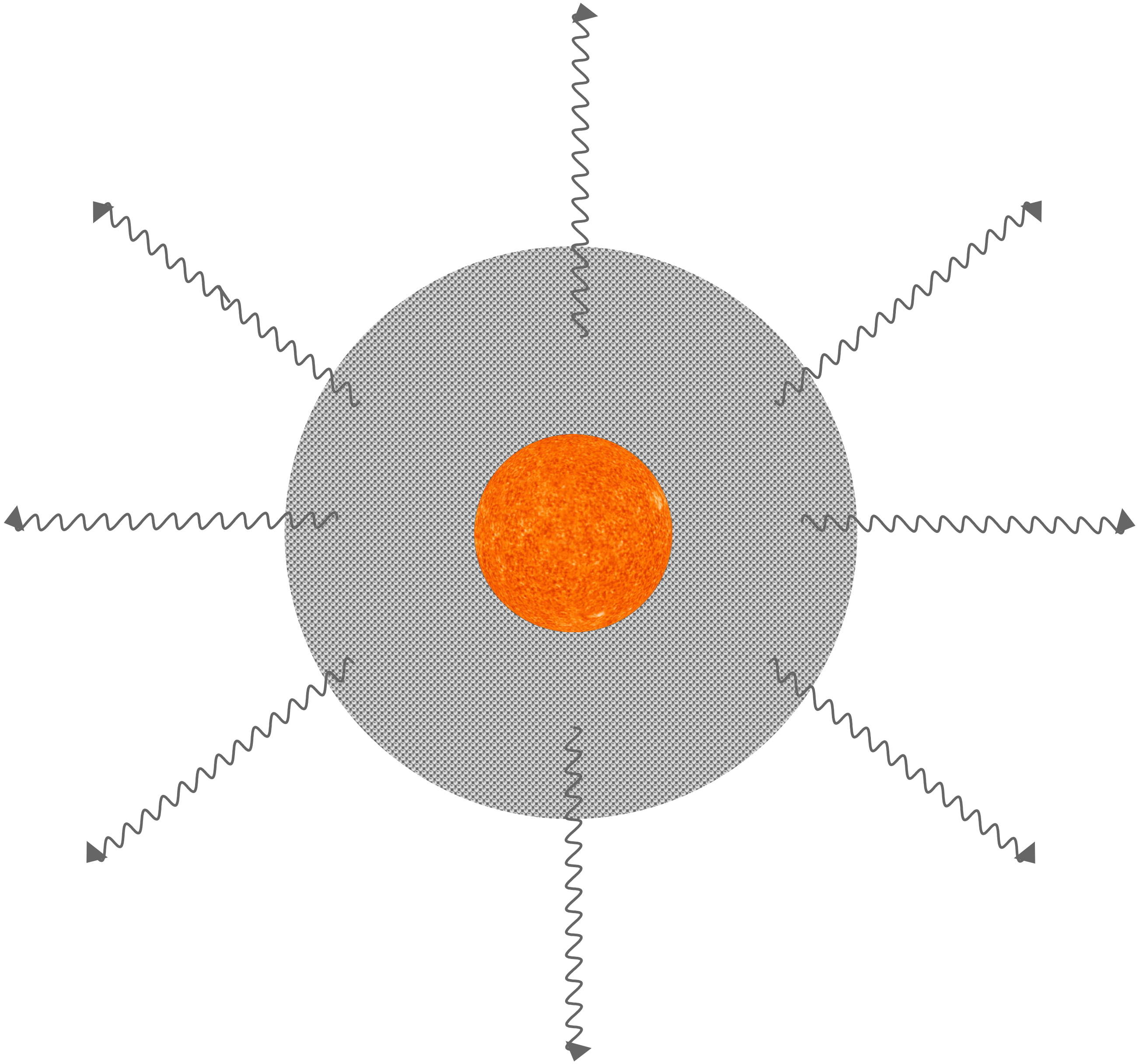

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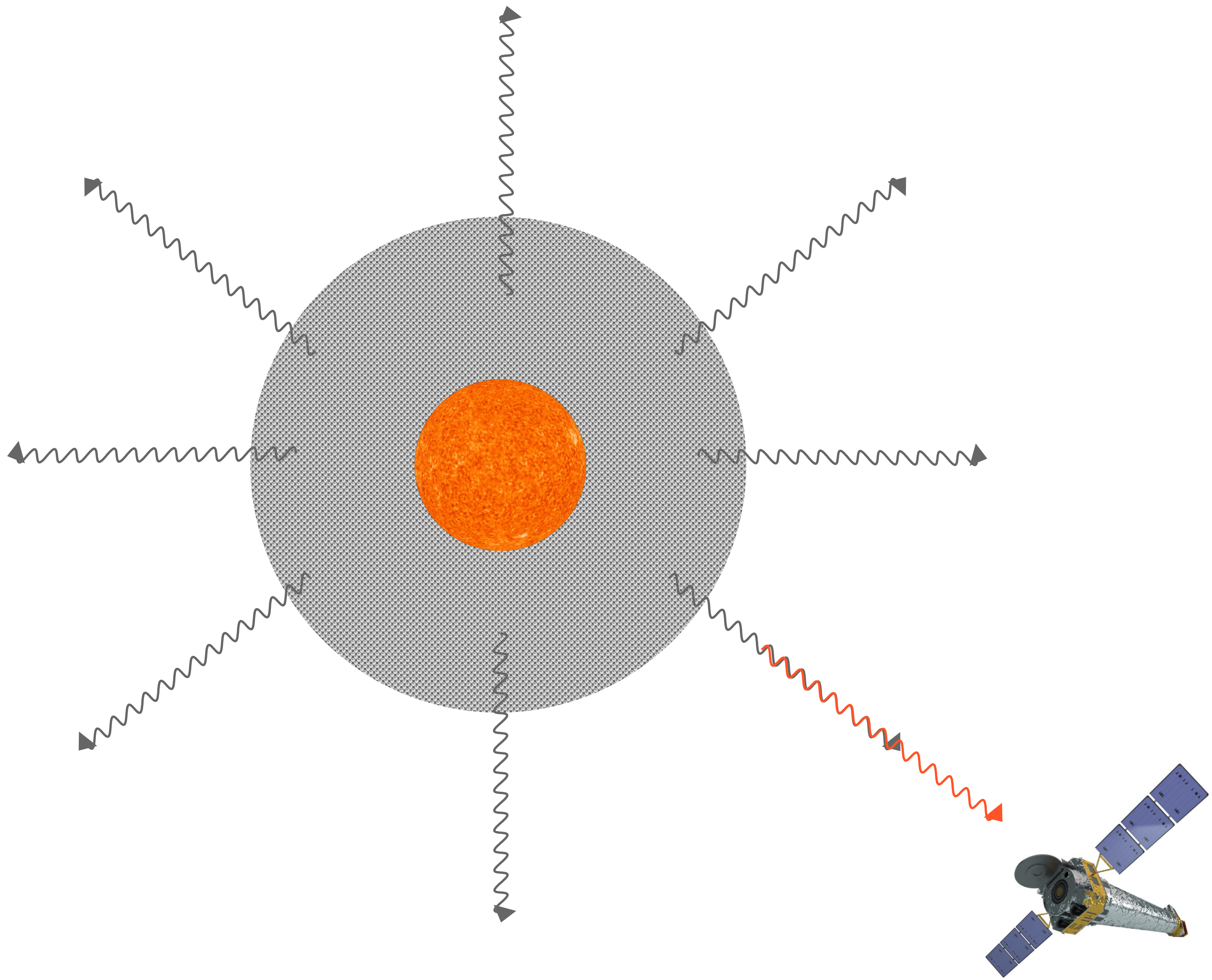

Temperature evolution of the DS

$$\frac{dT}{dt} = -\frac{L_\gamma + L_{\gamma'}}{C_V}$$

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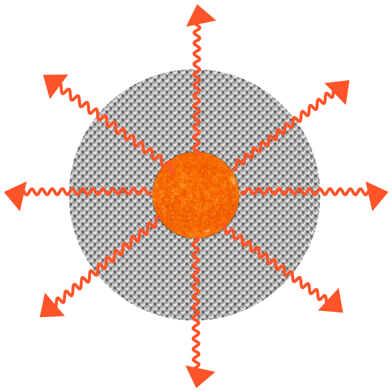
Photon luminosity: $L_\gamma = \left(4\pi r_{\rm th}^2\right) \int_0^\infty I(\nu) d\nu$



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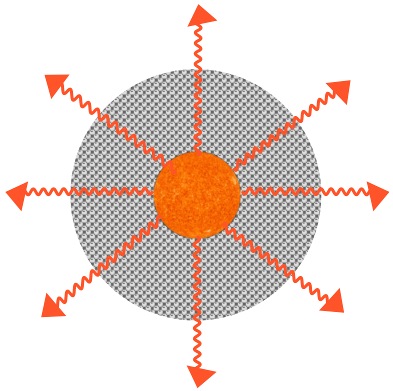

$$r_{\rm th} \sim T^{1/2}$$

$$I(\nu) = \frac{2h}{c^2} \frac{\nu^3}{\mathrm{e}^{\frac{h\nu}{k_B T}} - 1} \left(1 - \mathrm{e}^{-\tau(\nu)}\right)$$

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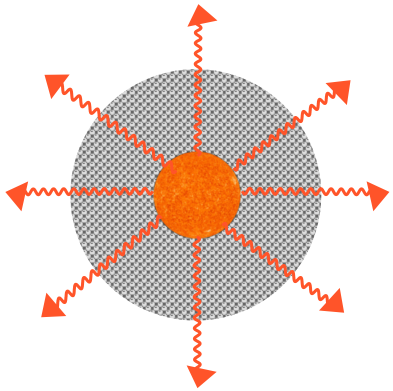

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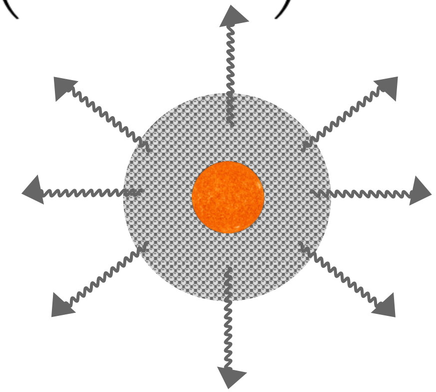

Dark photon luminosity: $L_{\gamma'} = (4\pi R_{\rm DS}^2)\,\sigma_{\rm SB} T^4 e^{-\frac{m_{\gamma'}}{T}}$

Temperature evolution of the DS

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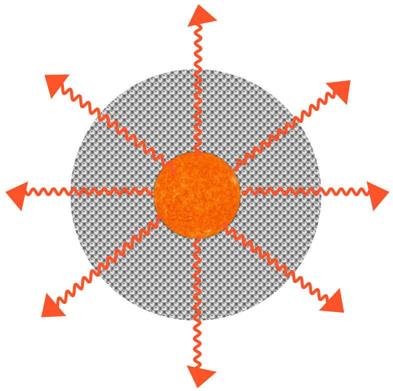
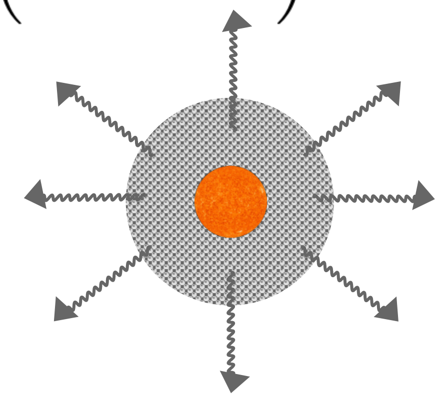


$$r_{\rm th} \sim T^{1/2}$$

$$I(\nu) = \frac{2h}{c^2}\frac{\nu^3}{e^{\frac{h\nu}{k_B T}}-1}\left(1 - e^{-\tau(\nu)}\right)$$

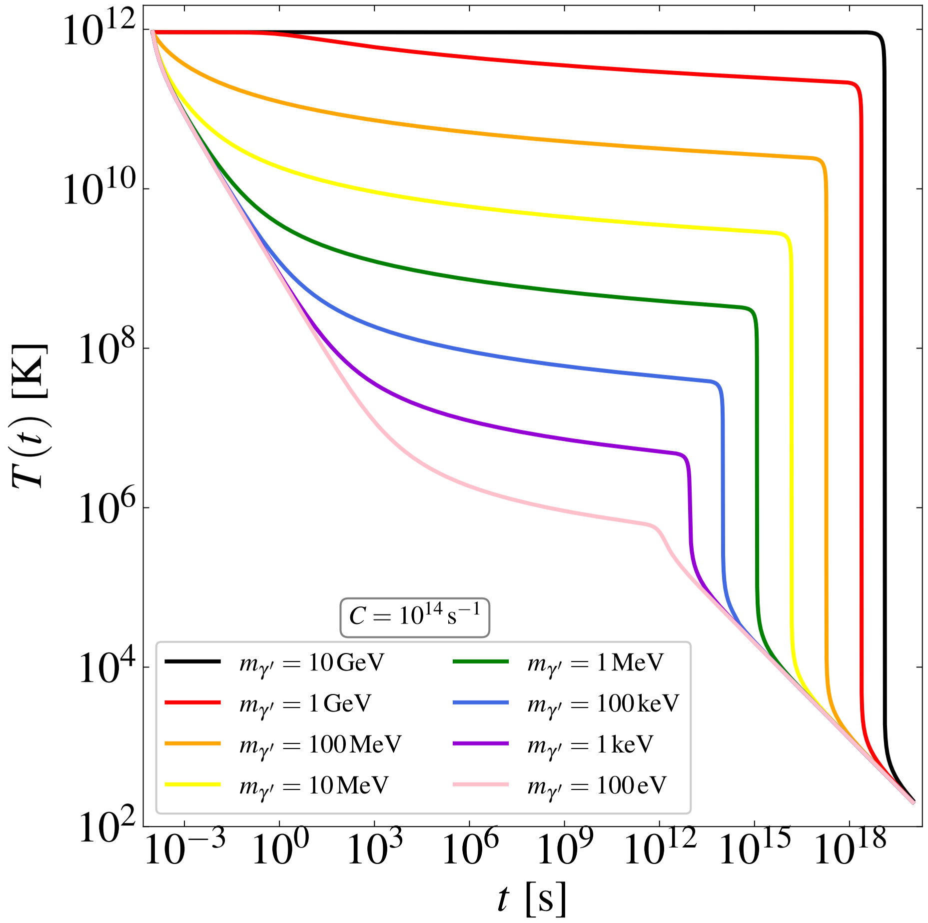
Dark photon luminosity: $L_{\gamma'} = (4\pi R_{\rm DS}^2)\,\sigma_{\rm SB} T^4 e^{-\frac{m_{\gamma'}}{T}}$



Heat capacity: The DM plausibly forms a Bose-Einstein condensate

$$C_{\rm V} \sim T^{3/2}$$

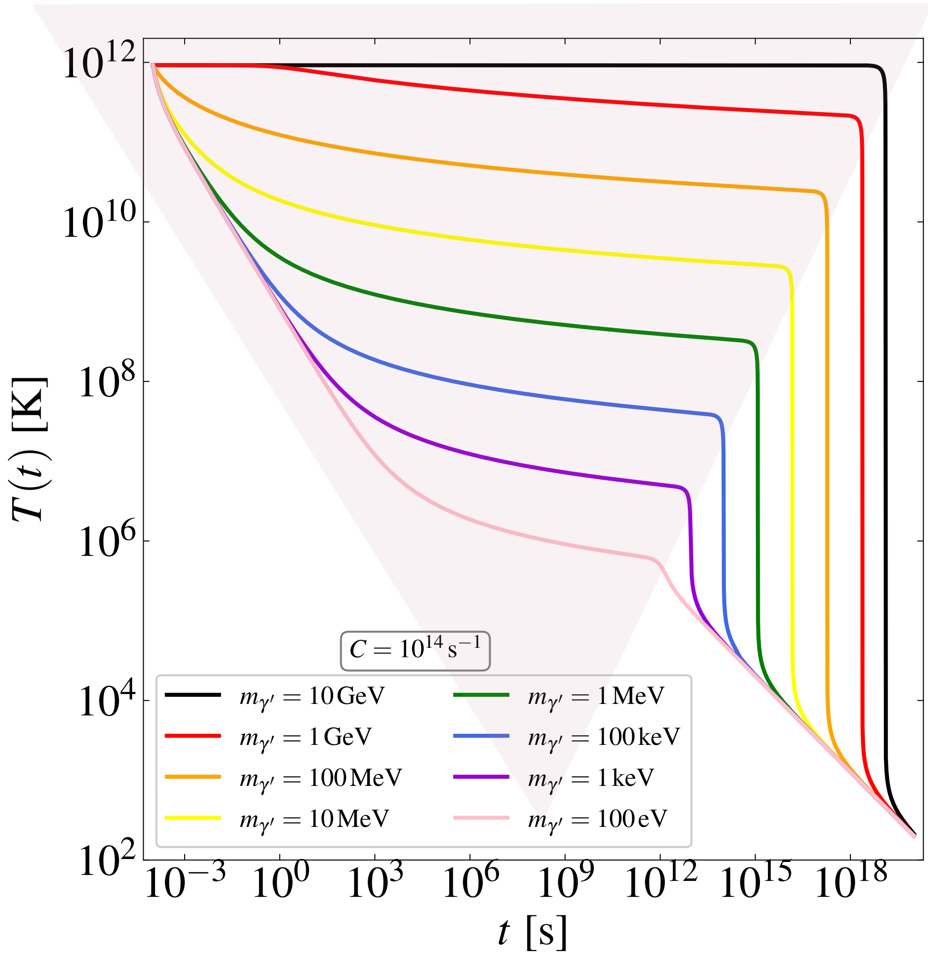
Temperature evolution of the DS



Temperature evolution of the DS

Proton gas optically thin.
Cooling by dark photon emission

$$dT/dt \sim -T^{5/2}\exp(-m_{\gamma'}/T)$$



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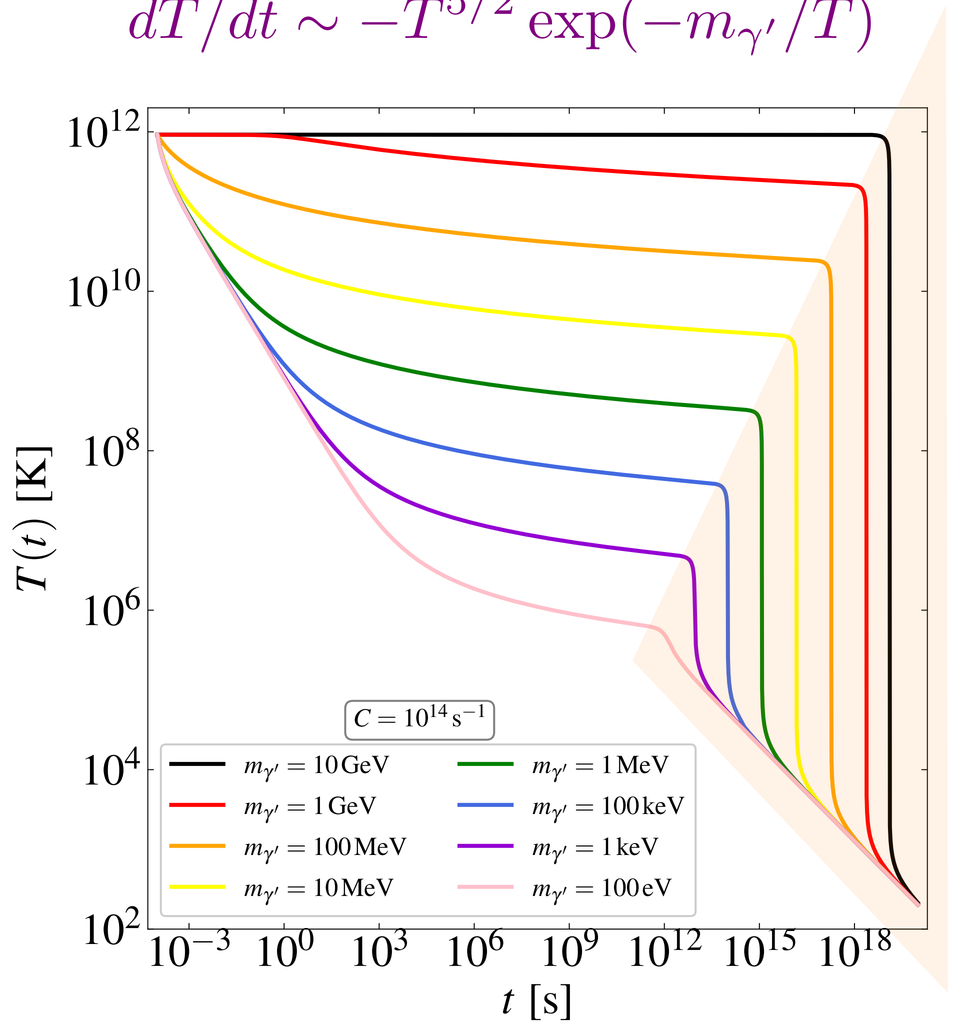

Proton gas optically thick.
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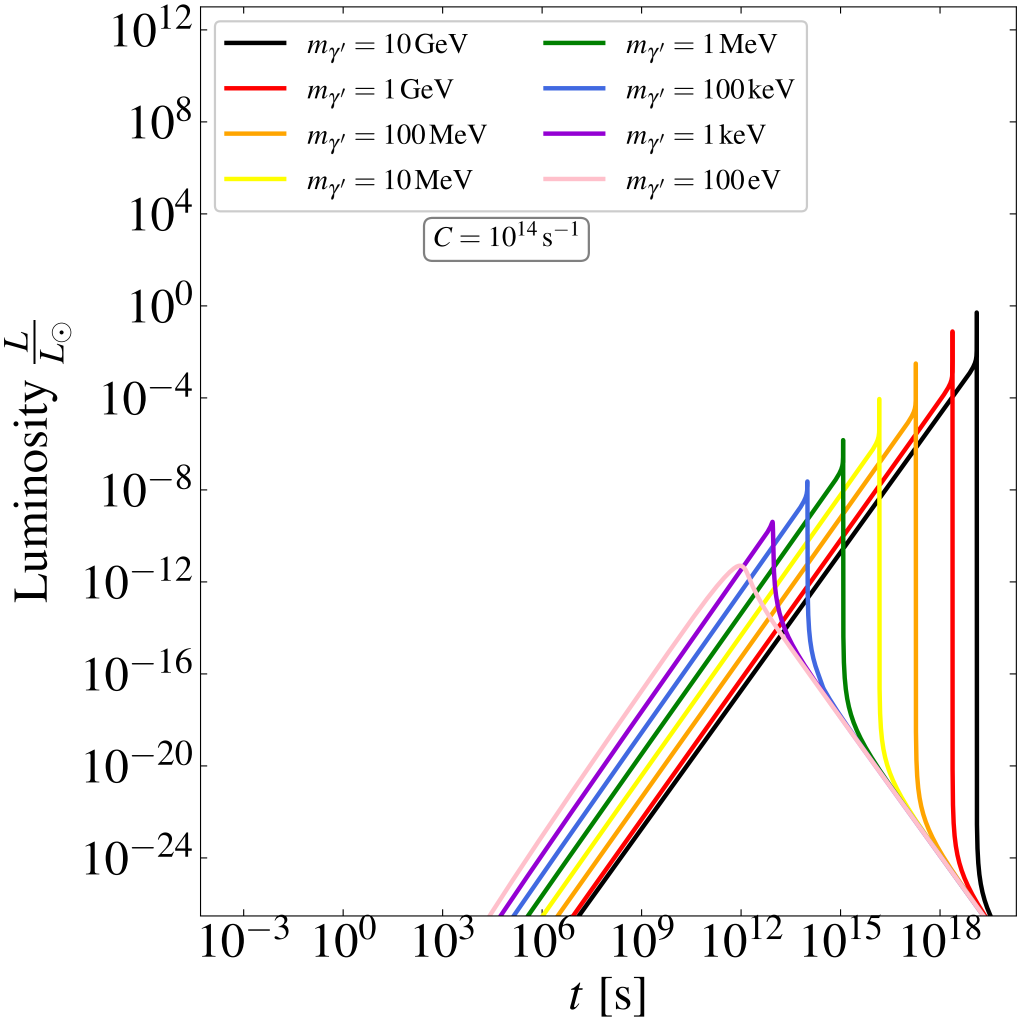
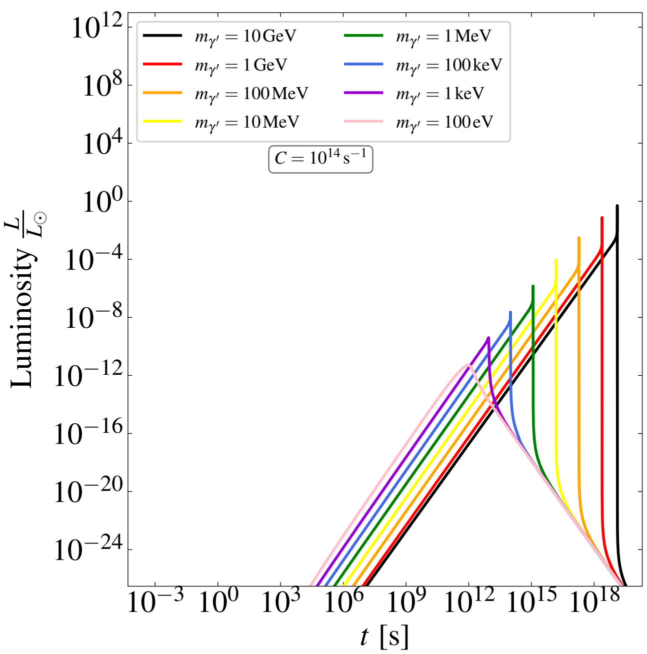
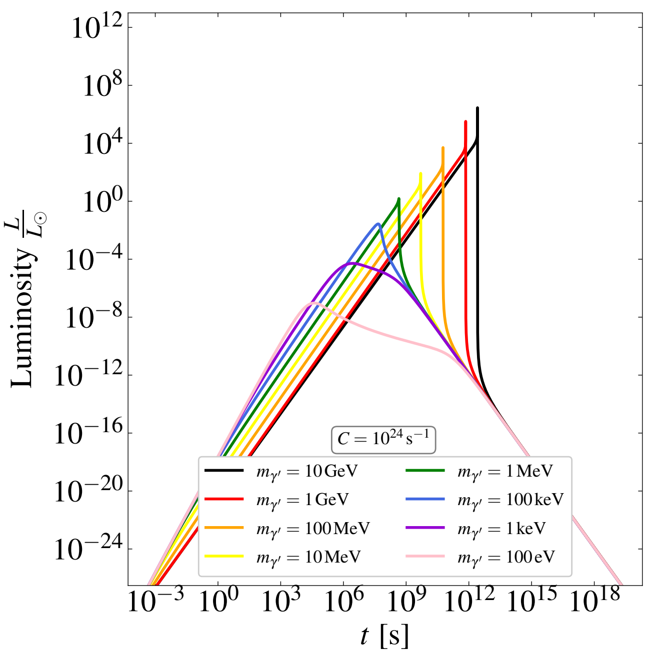
$$dT/dt \sim -T^{7/2}$$

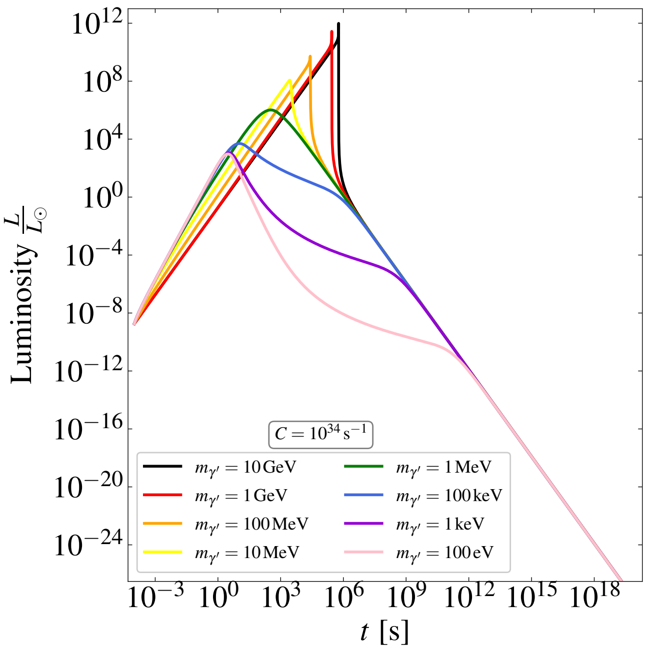
DS luminosity



DS luminosity







Signals from dark stars

Dark stars could still be shining today. They could be detected as a point source in X-rays or γ-rays, with a black body spectrum (or bremsstrahlung), and with no optical counterpart.

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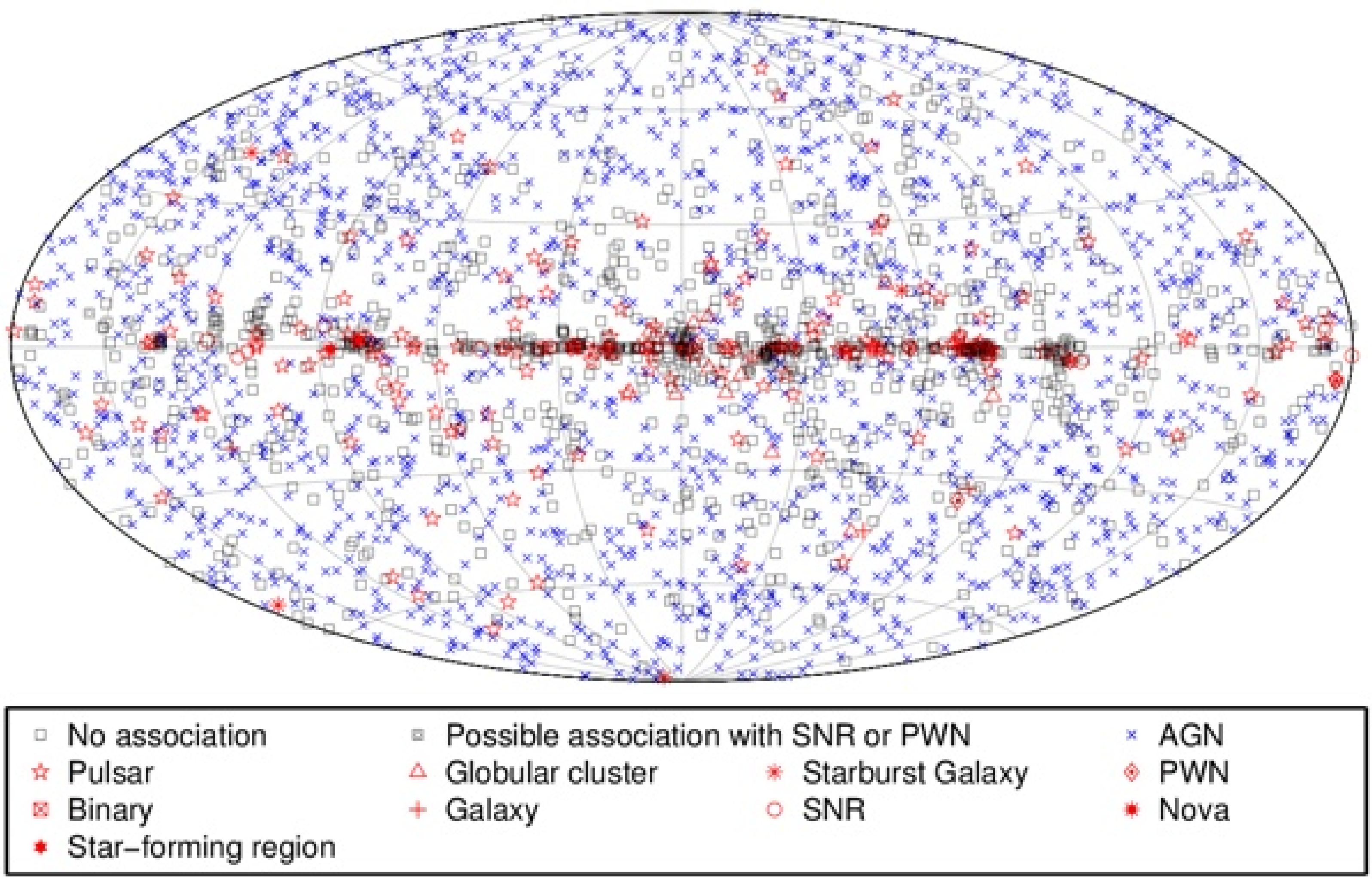

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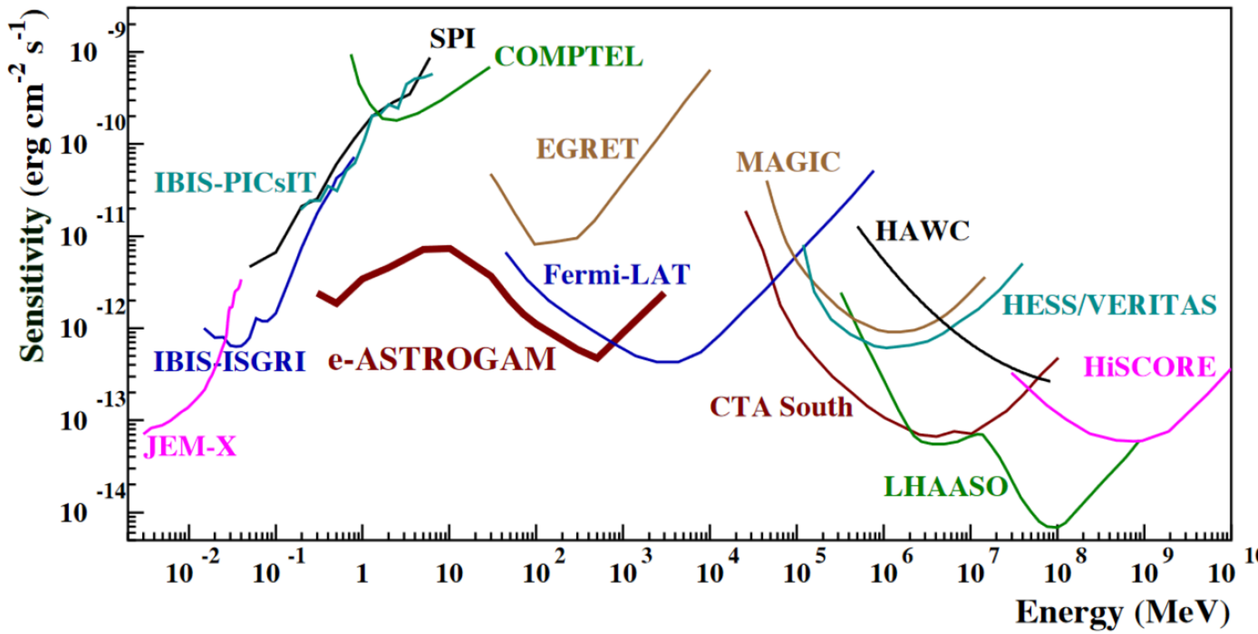

De Angelis et al' 18

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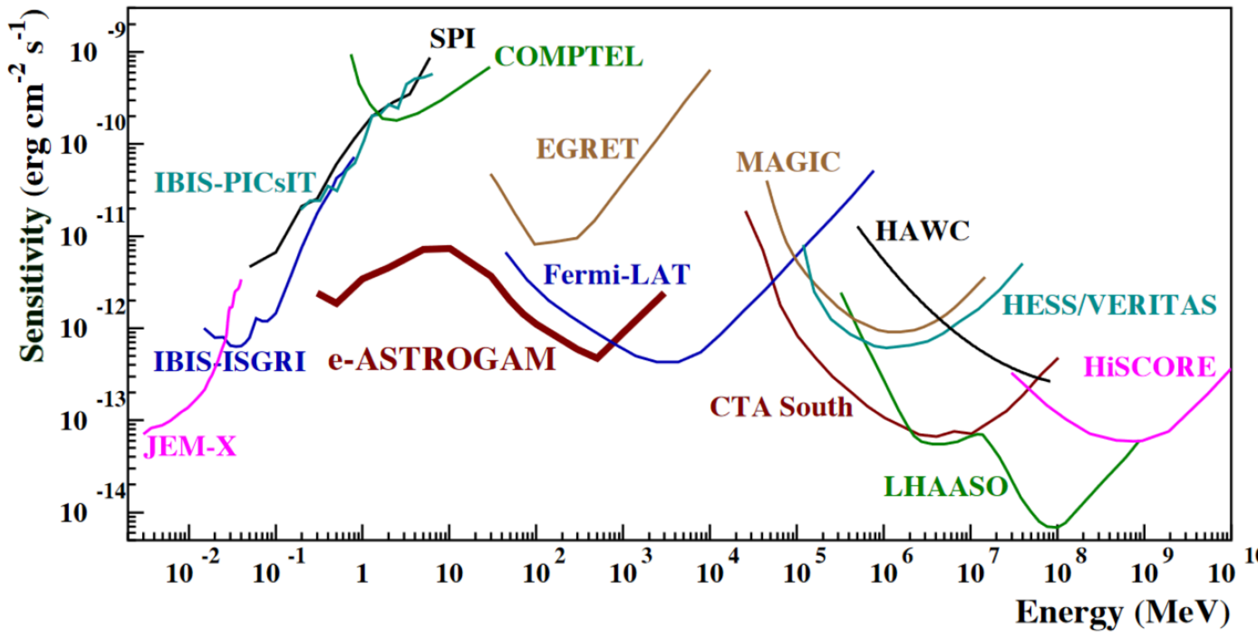

De Angelis et al' 18

For a luminosity L , a dark star within a distance $d < (L/(4\pi S))^{1/2}$ is at the reach of experiments.

$$d < 1.8\,\mathrm{kpc}\left(\frac{L}{L_\odot}\right)^{1/2}\left(\frac{S}{10^{-11}\,\mathrm{erg\,cm^{-2}\,s^{-1}}}\right)^{-1/2}$$

Signals from dark stars

How many dark stars within a distance d ?

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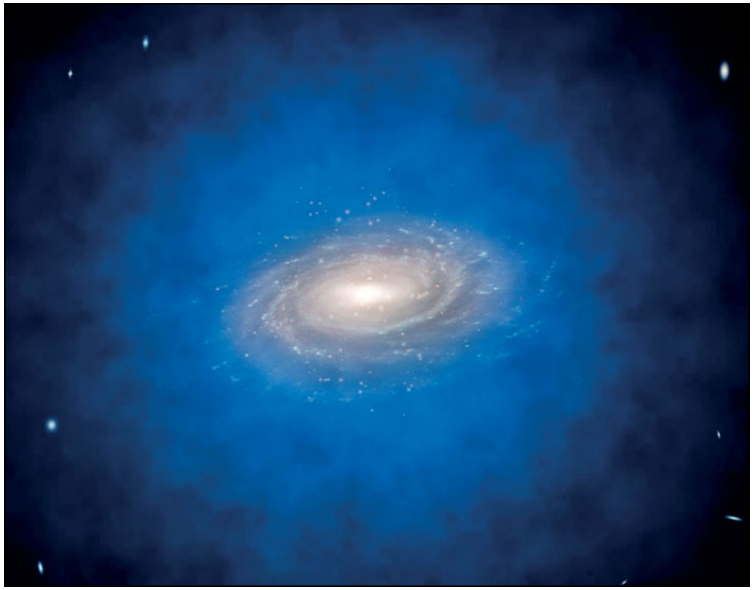
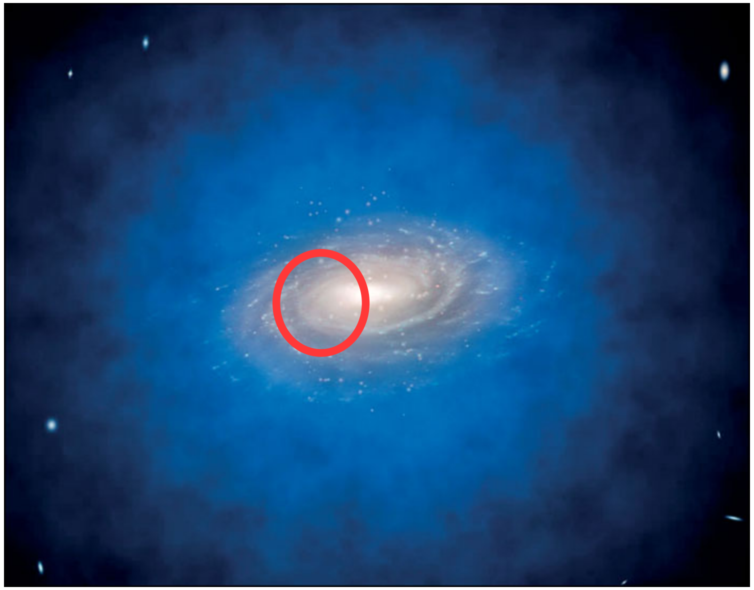
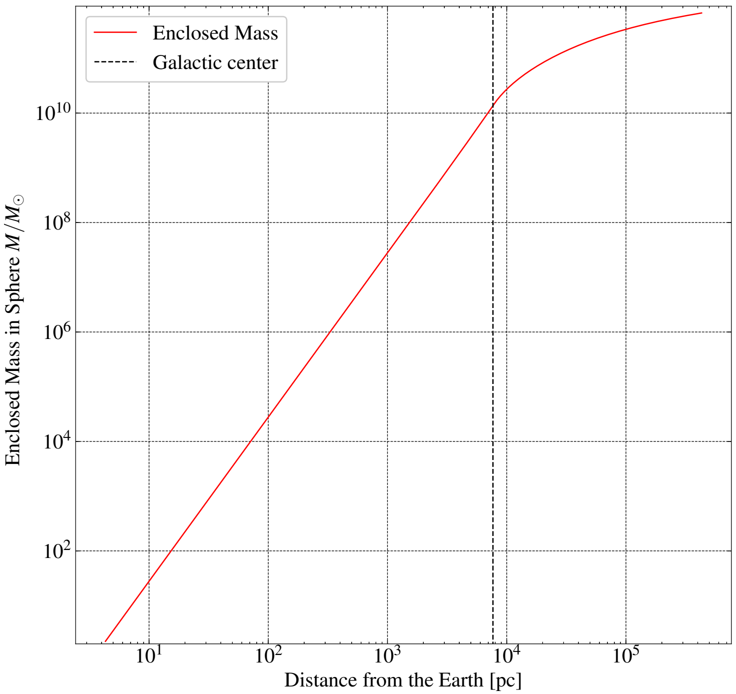


Signals from dark stars

How many dark stars within a distance *d* ?





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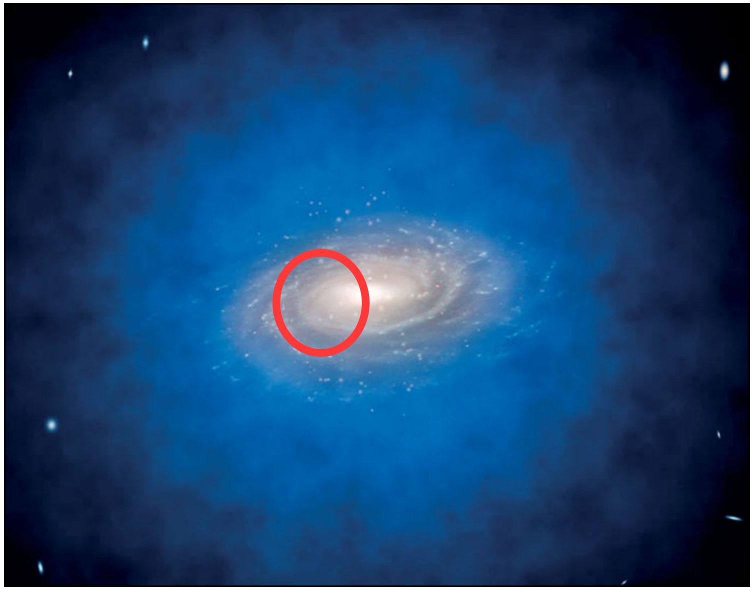
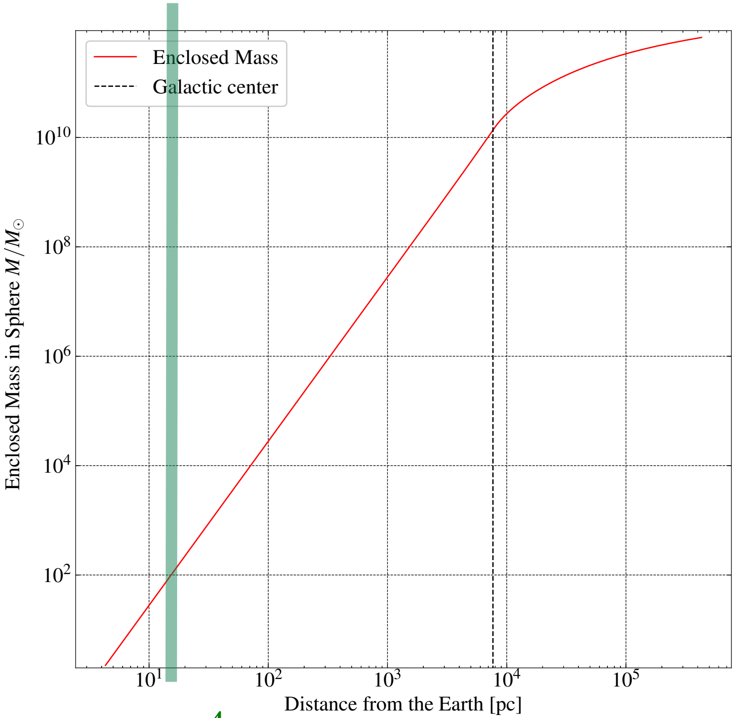
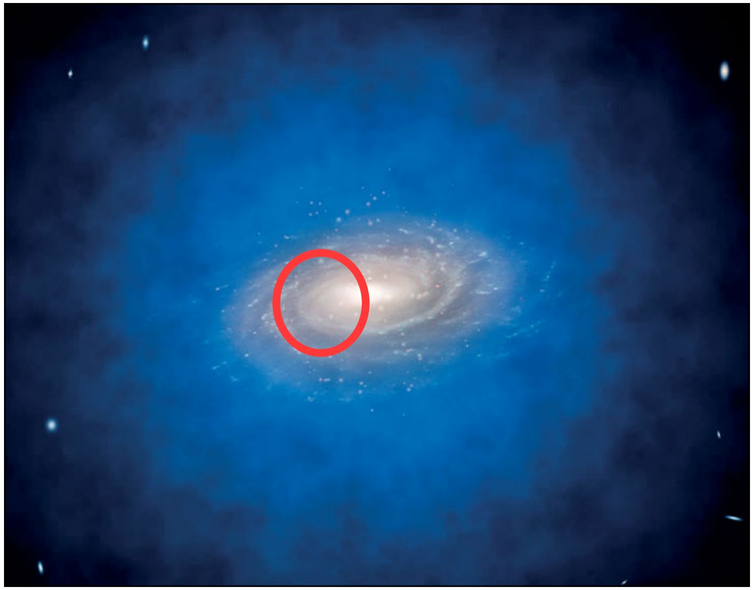


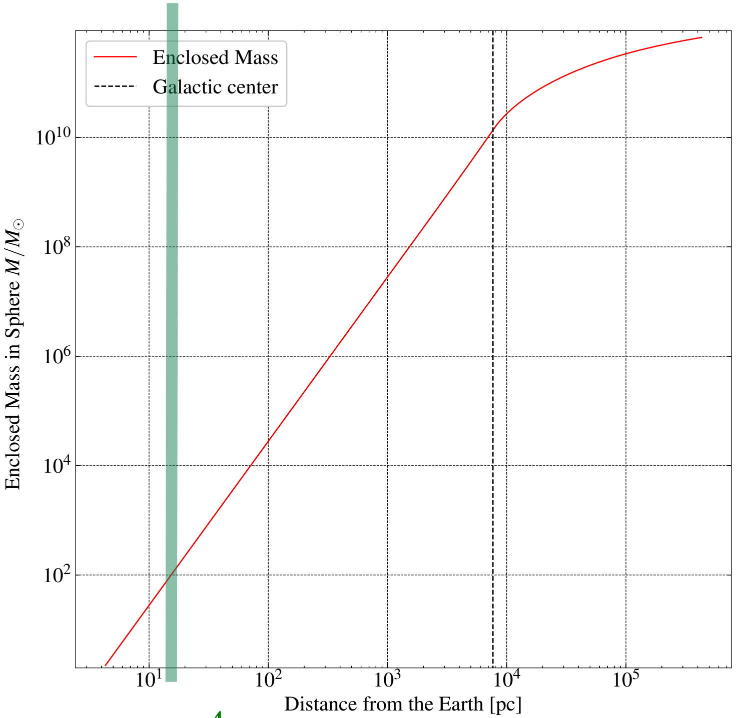


$L = 10^{-4} L_\odot$

Signals from dark stars

How many dark stars within a distance *d* ?





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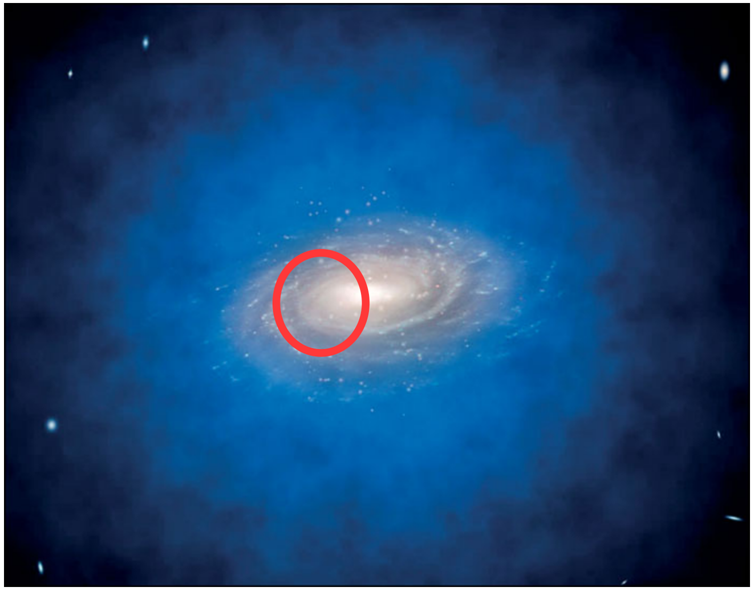
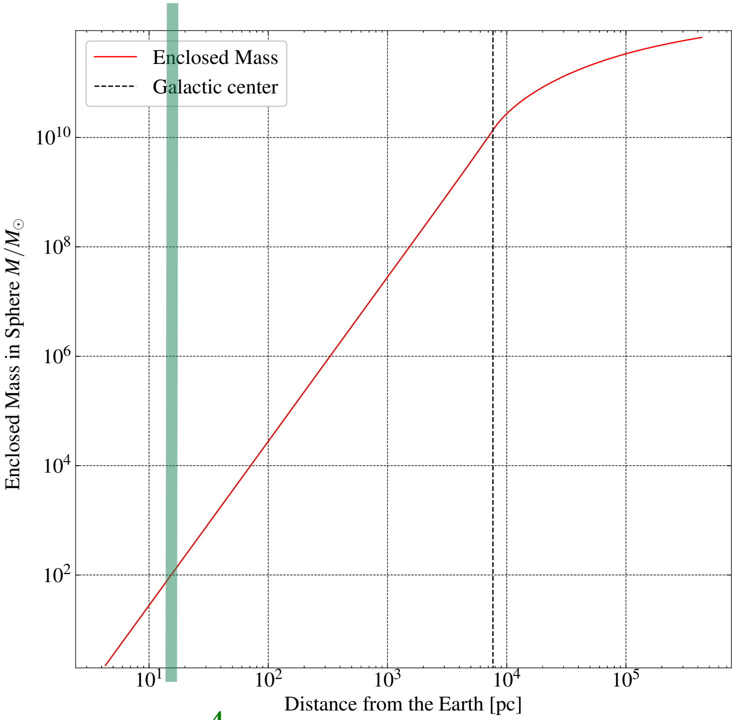
$$N_{\rm DS} = \mathcal{F}_{\rm DS} \frac{M(d)}{M_{\rm DS}}$$

Consider $M_{\rm DS} = M_\odot$, $\mathcal{F}_{\rm DS} = 10^{-2}$

Signals from dark stars

How many dark stars within a distance d ?





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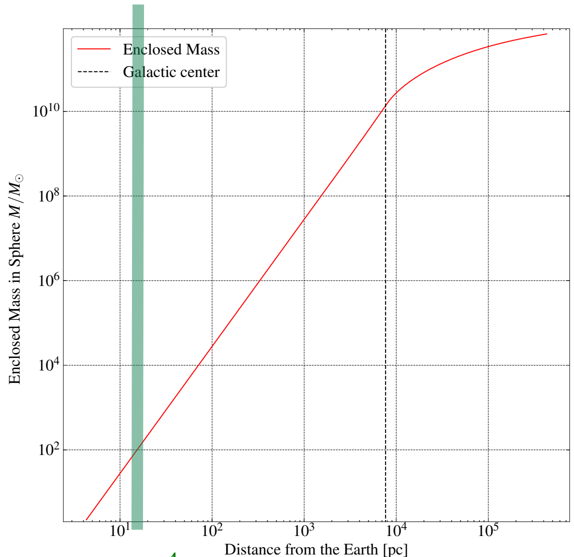
$L = 10^{-4} L_\odot$

$N_{\rm DS} \sim 1$

Signals from dark stars



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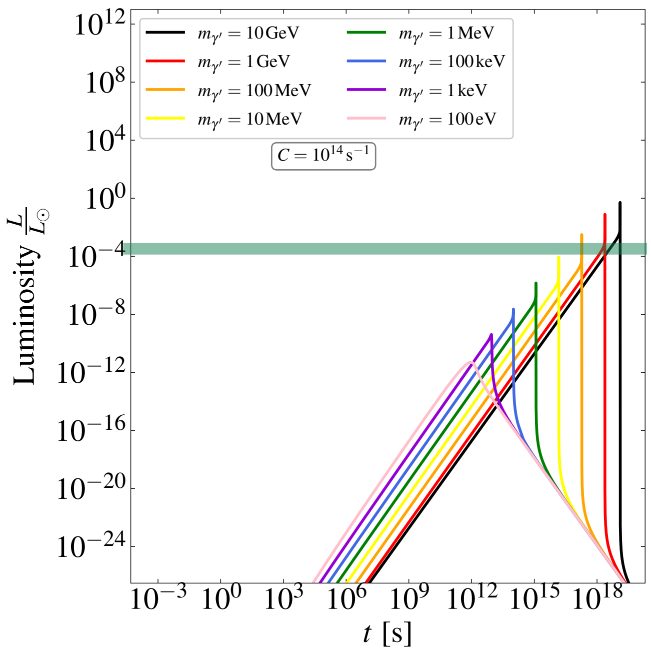
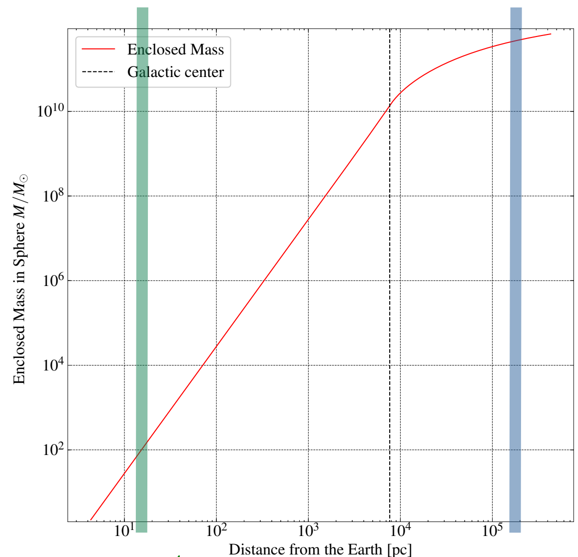


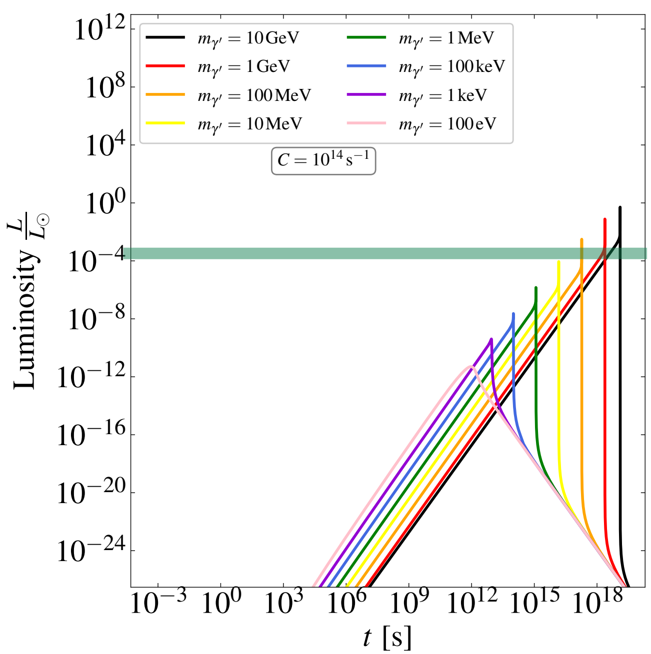
~1 event if *all* DSs formed ~10^{17} s ago

Signals from dark stars



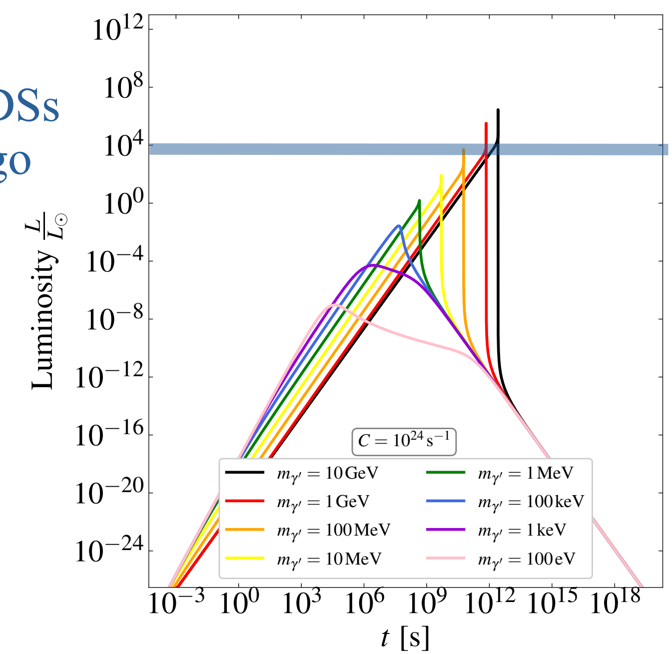
$L = 10^{-4} L_\odot$
$N_{\rm DS} \sim 1$

$L = 10^{4} L_\odot$
$N_{\rm DS} \sim 10^9$



~1 event if *all* DSs formed ~10^{17} s ago

10^9 events if *all* DSs formed ~10^{12} s ago



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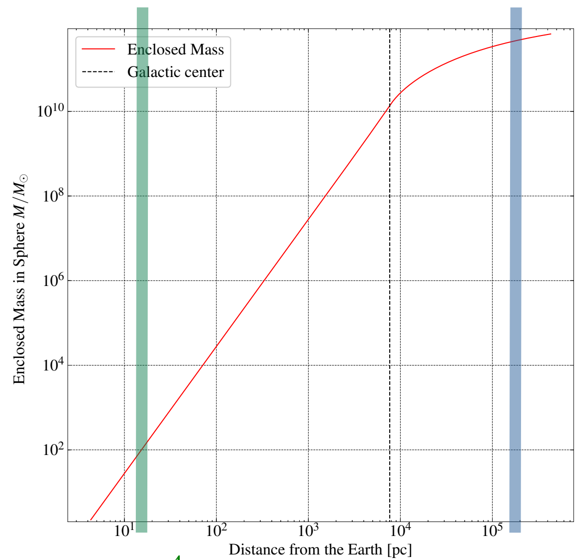

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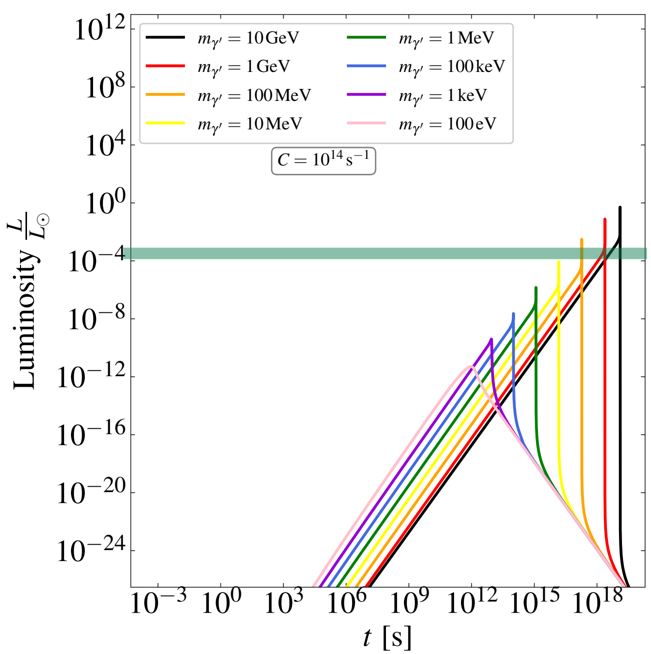

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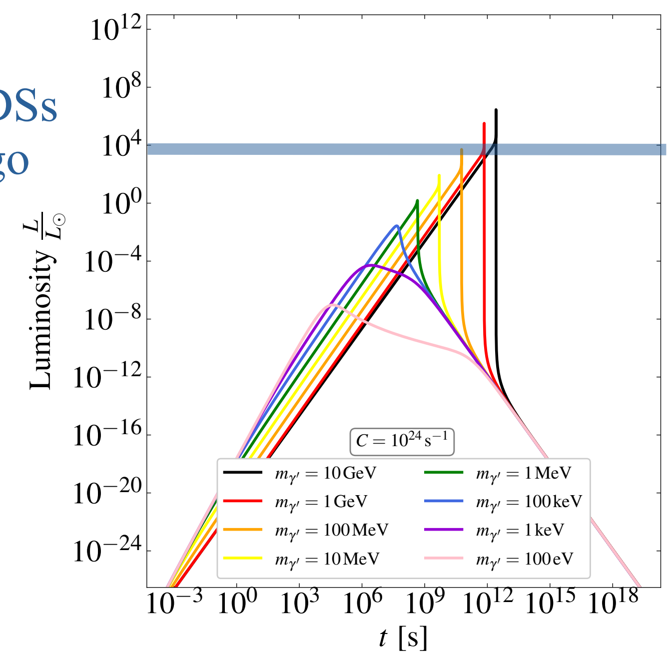
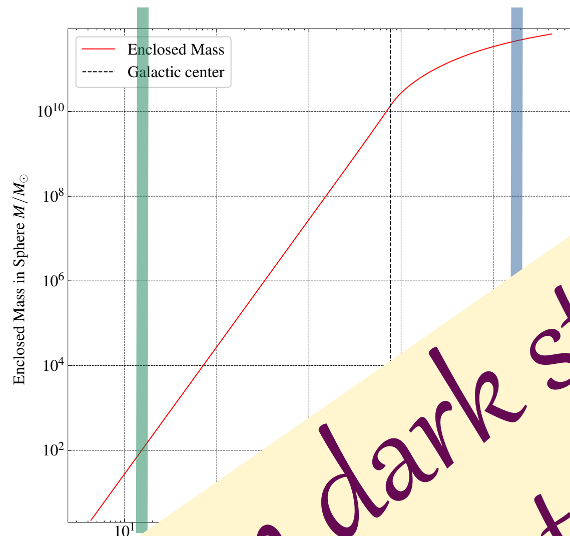


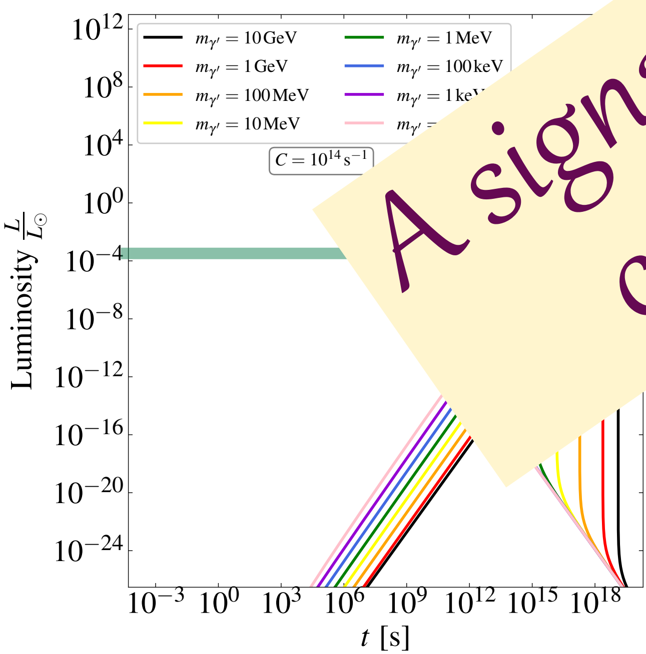
Dark stars could form continuously over time.

Signals from dark stars



$L =$

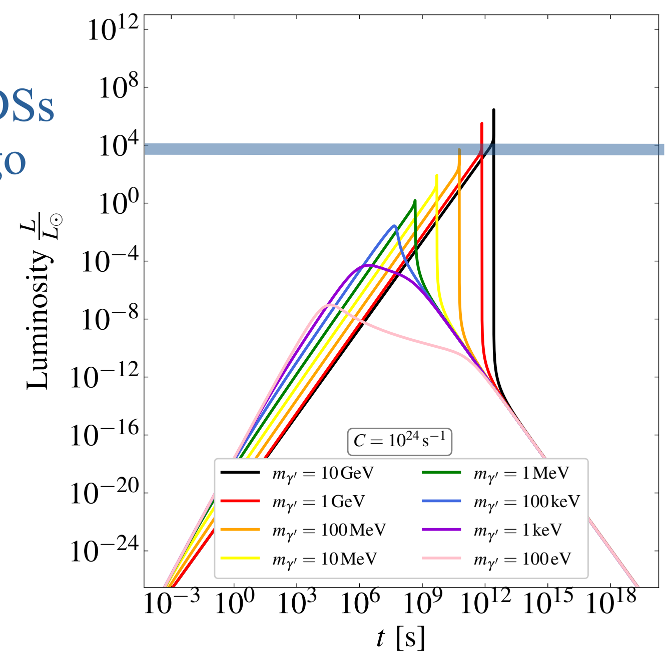
10^9



events if *all* DSs formed ~10^{12} s ago

event if *all* DSs formed ~10^{17} s ago

A signal from dark stars could be detected



Dark stars could form continuously over time.

Conclusions

- If the dark matter particle has strong self-interactions, it could form dark stars, that could be detected in MACHO searches.

- If the dark matter particle interacts with the proton, dark stars could capture protons from the interstellar medium. Electrons are also captured to keep the dark star electrically neutral. (Similar rationale if the dark matter interacts with the electron.)

- The captured electrons and protons form a hot gas that emits radiation with a characteristic spectrum.

- New target for indirect detection of asymmetric dark matter: point sources in X- or γ-rays (from scatterings with protons/electrons, from slow decays or from slow annihilations). These sources would be also detected as MACHOs.