Observational signals of compact dark stars

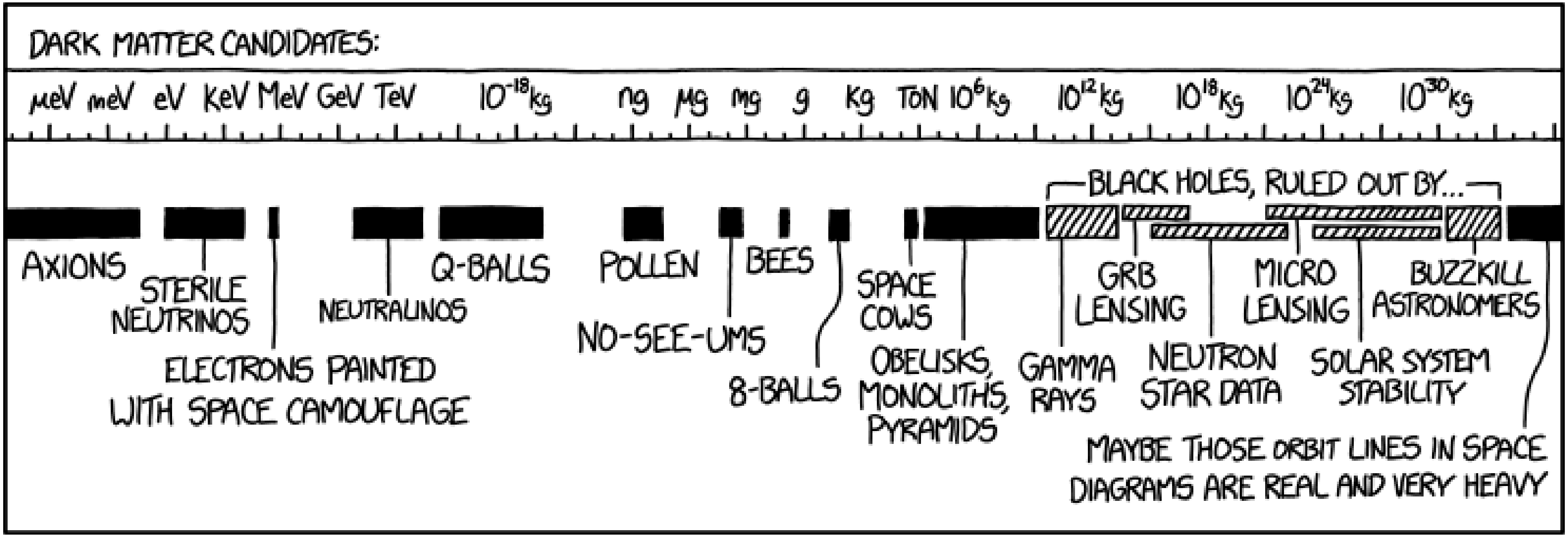
Alejandro Ibarra

In collaboration with Boris Betancourt, Anja Brenner and Chris Kouvaris. To appear

MOCa
Bogota
June 1st, 2022

The dark matter zoo

Explain xkcd



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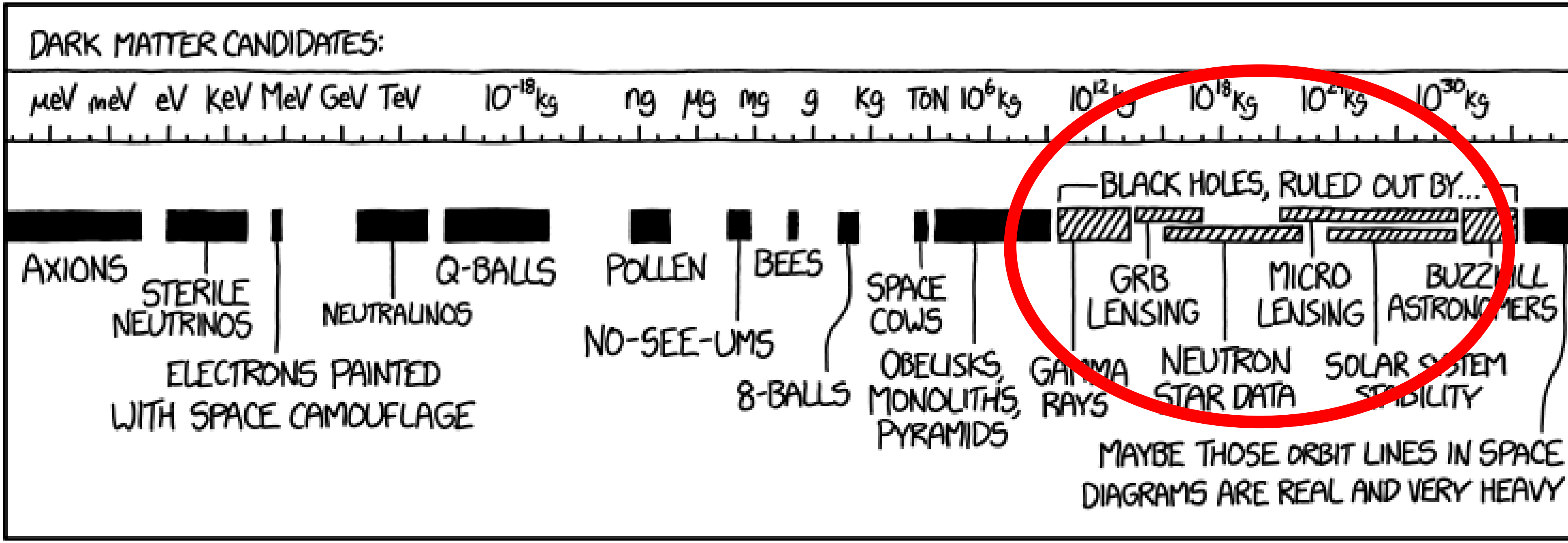

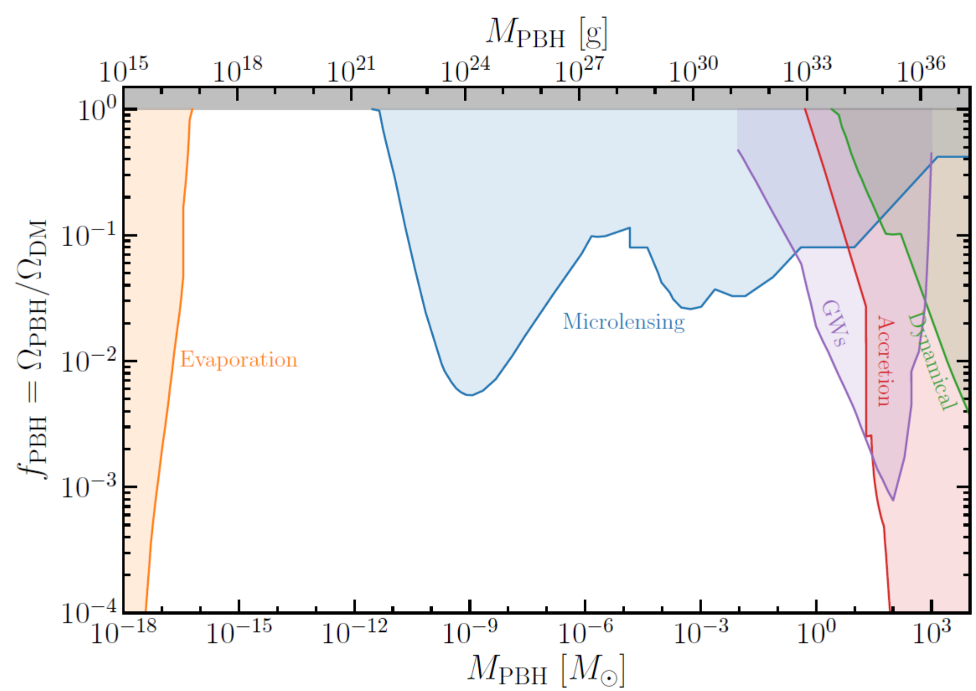

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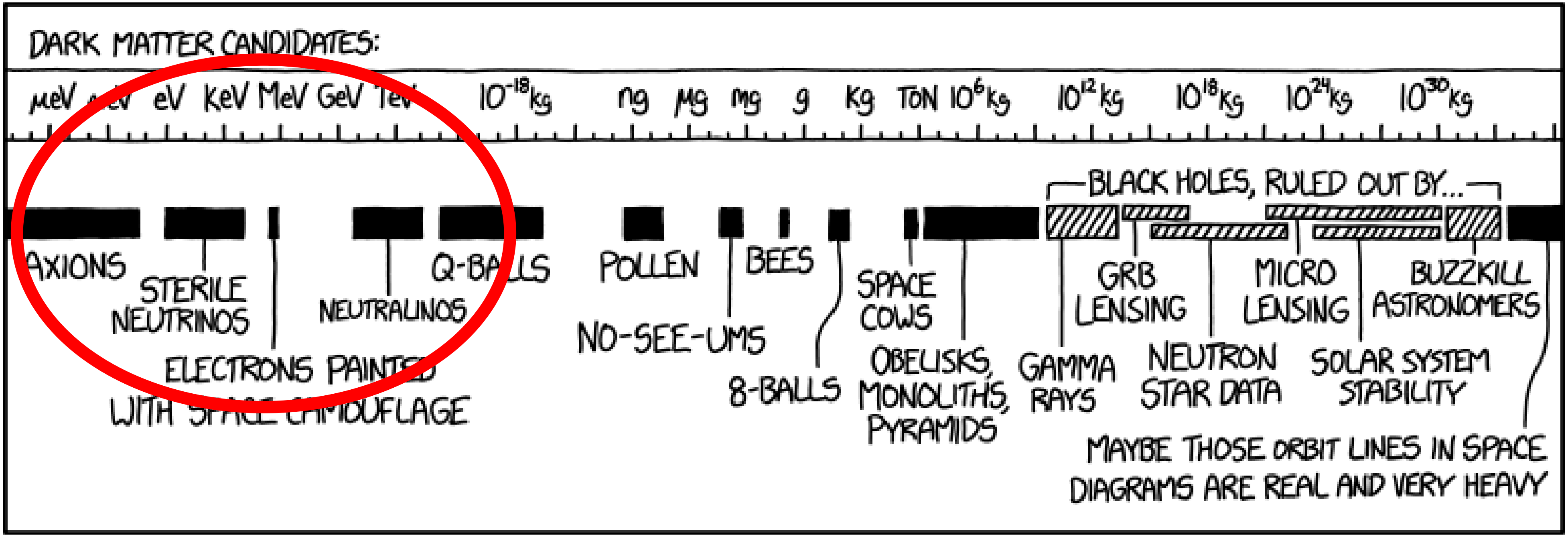

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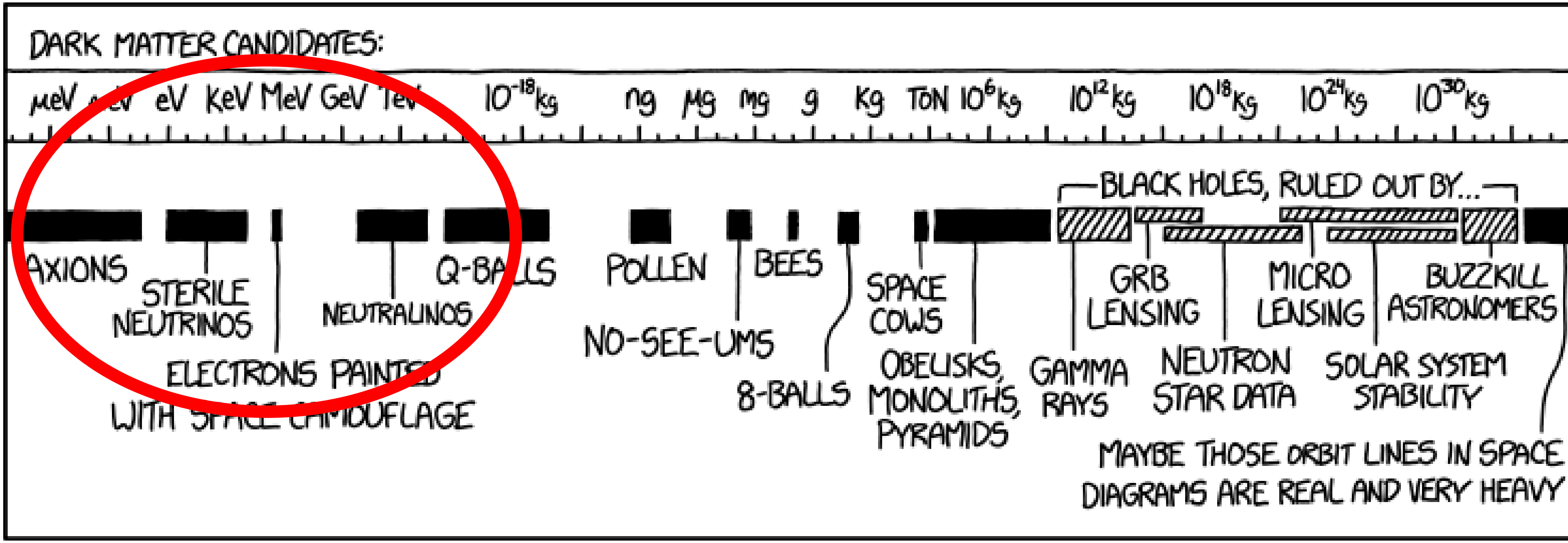

spin

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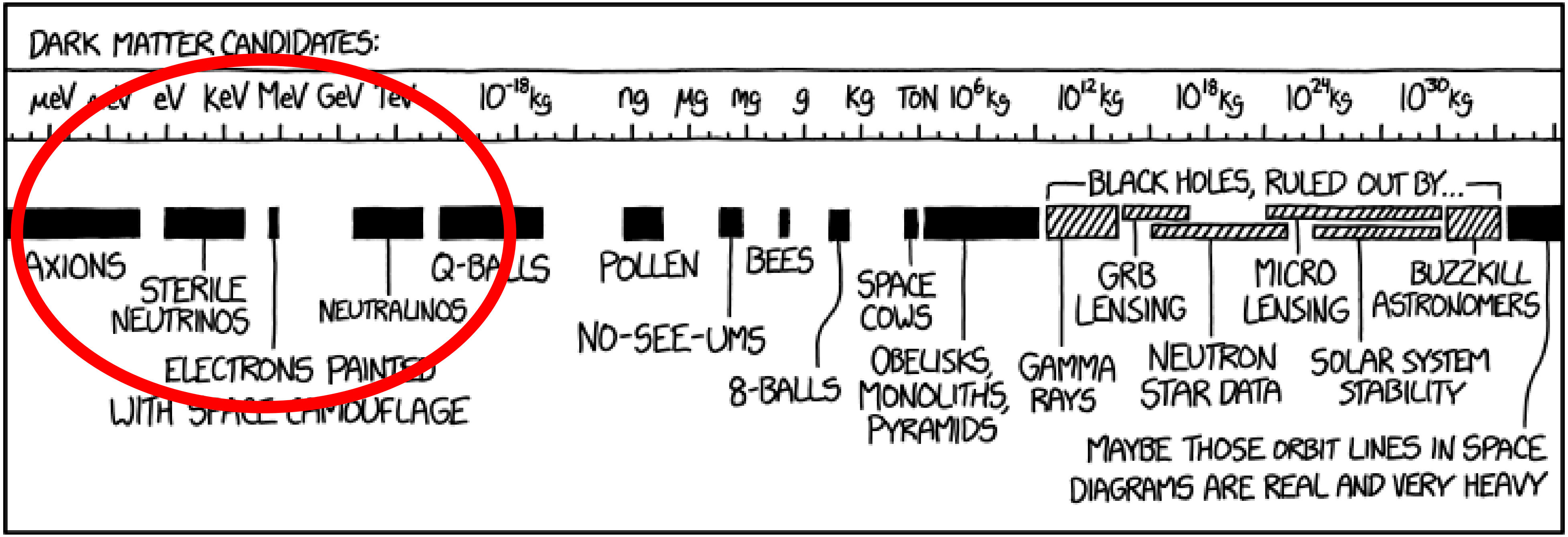

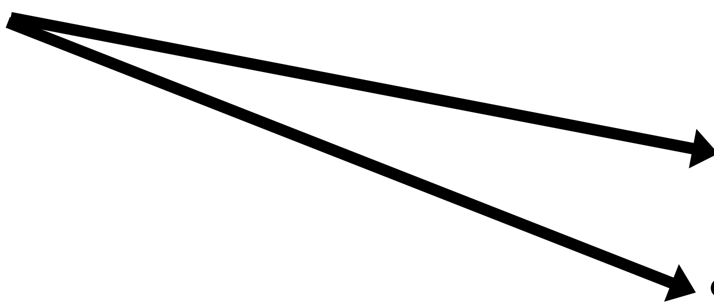

spin

Scattering cross-section to nucleons/electrons

The dark matter zoo

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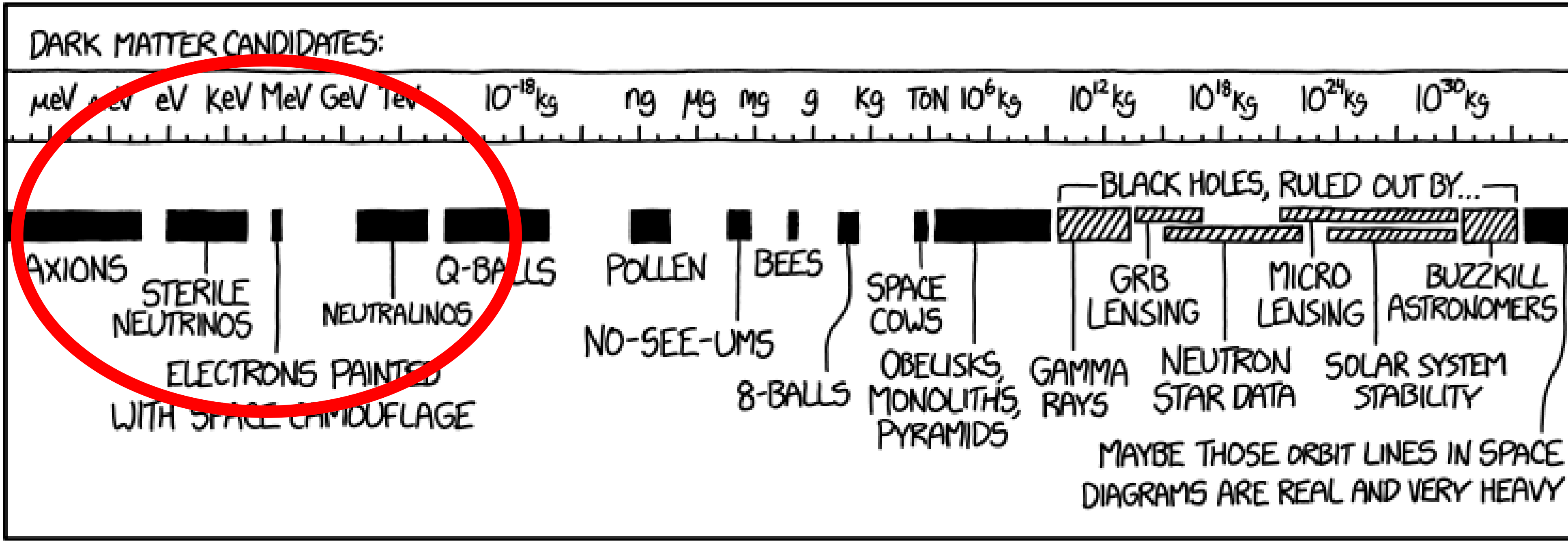

spin

Scattering cross-section to nucleons/electrons

Annihilation cross-section into SM particles

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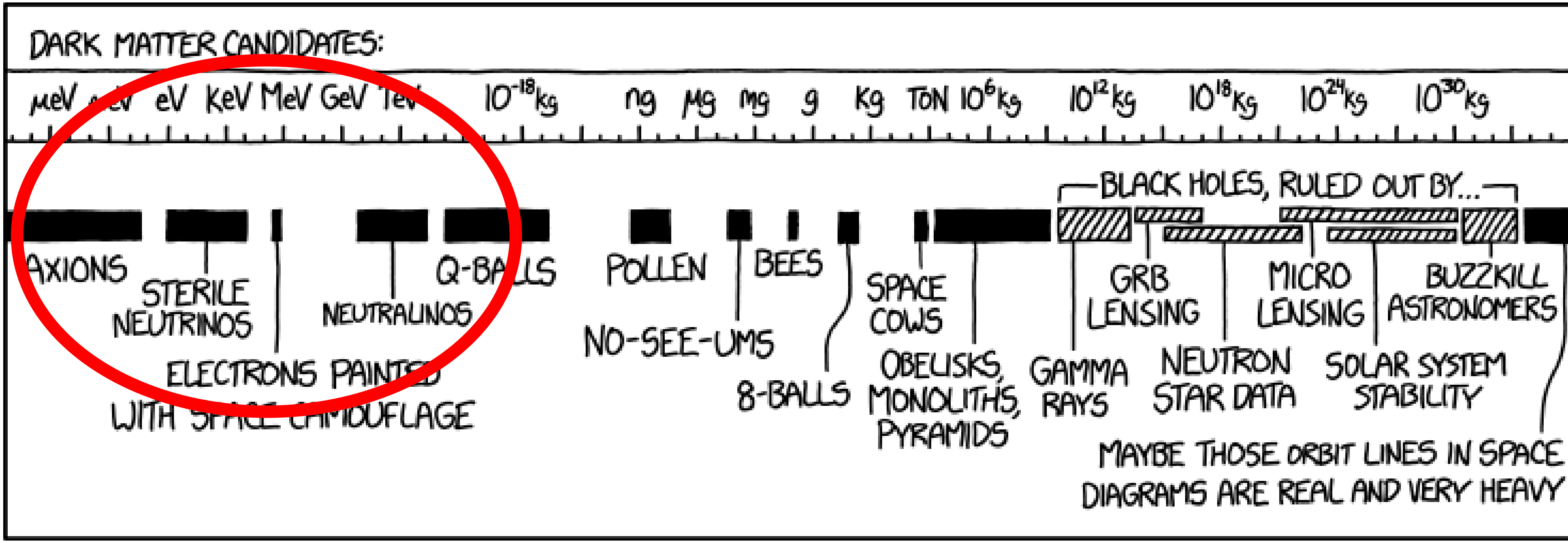

- spin
- Scattering cross-section to nucleons/electrons
- Annihilation cross-section into SM particles
- Self-coupling

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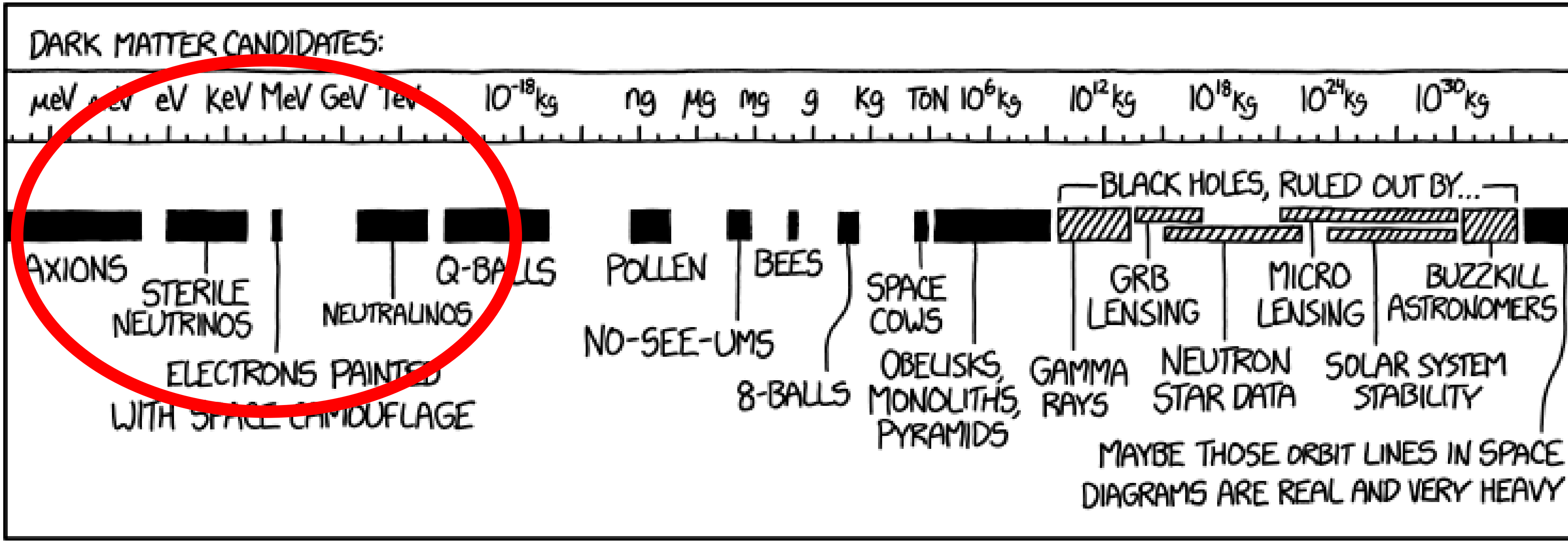

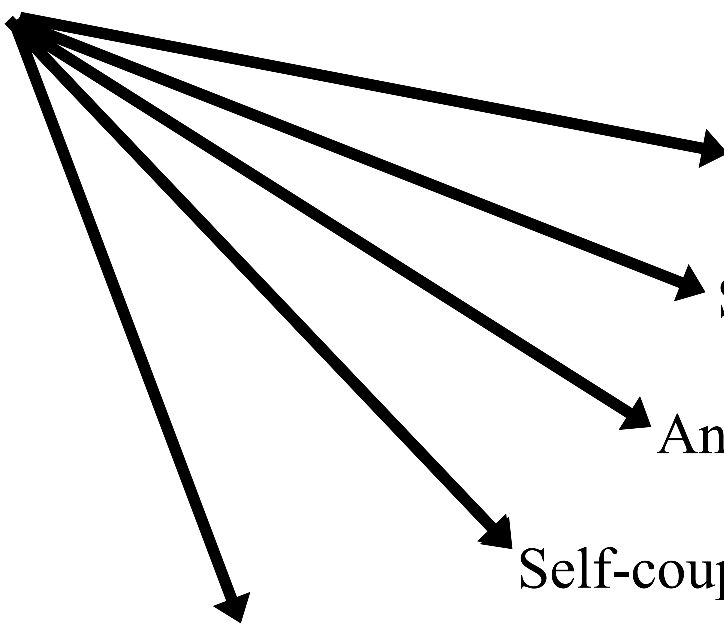

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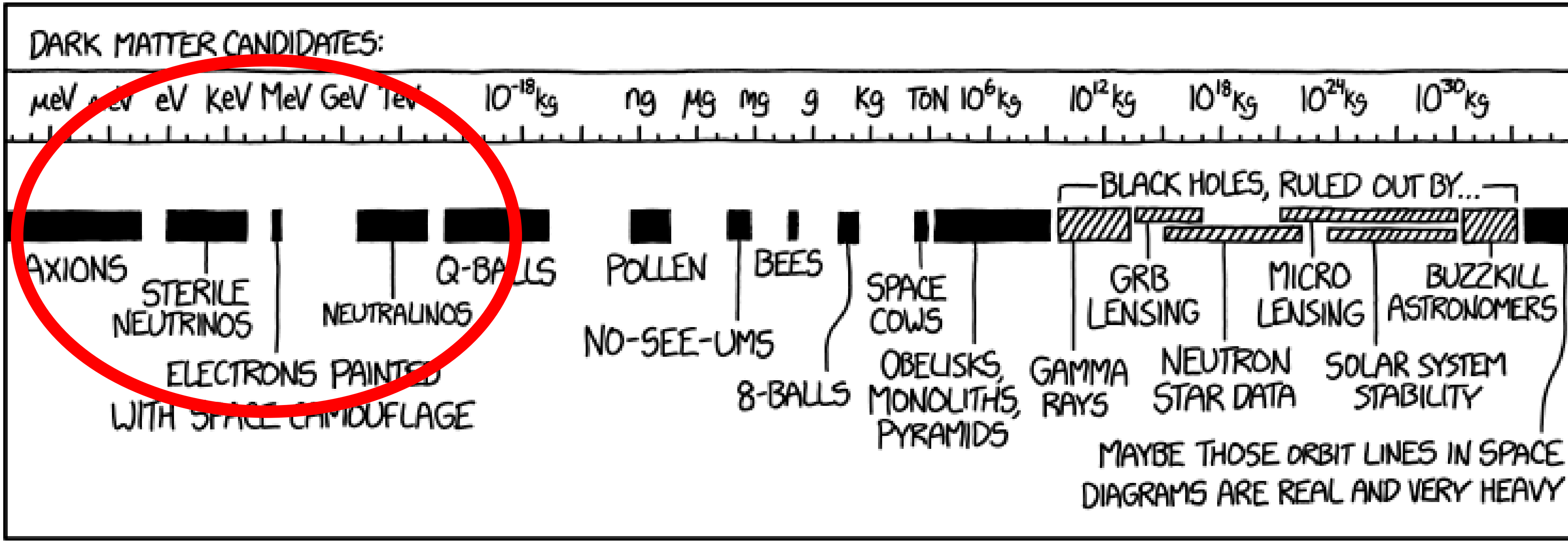

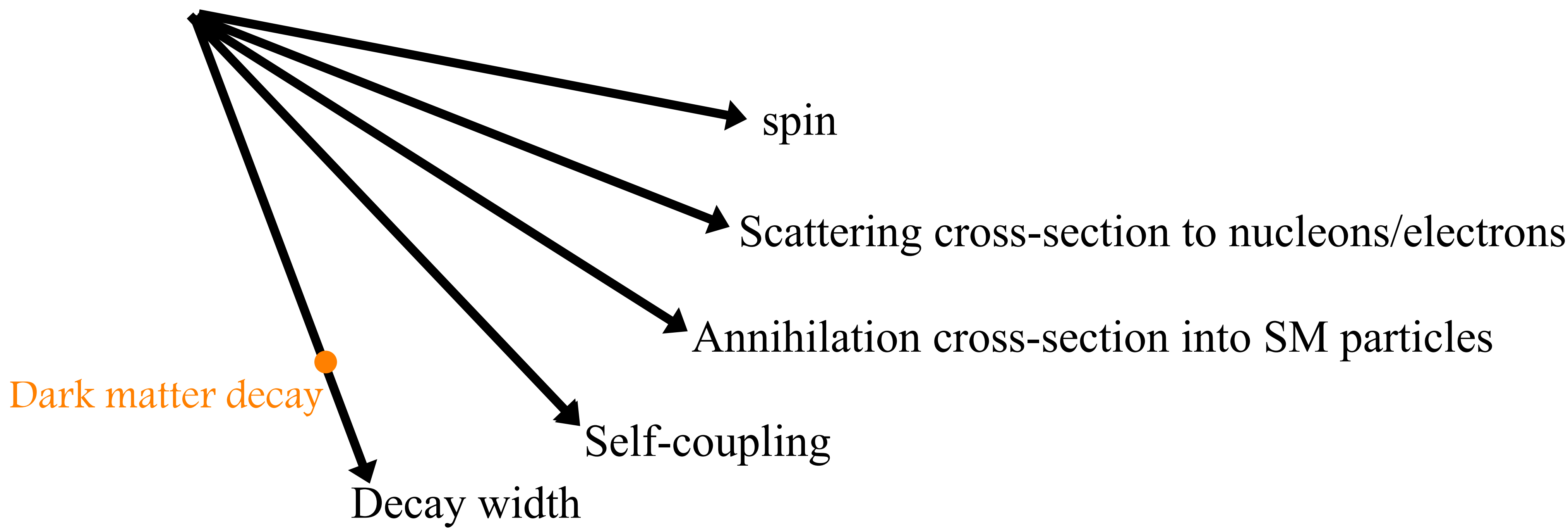

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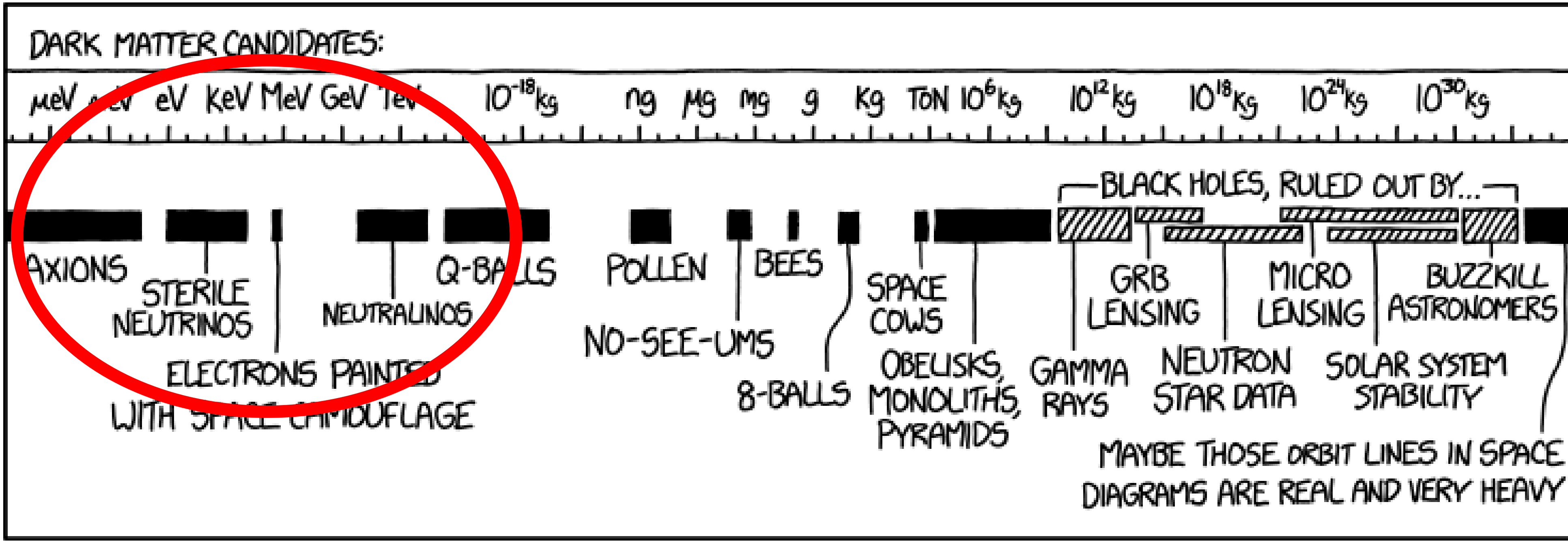

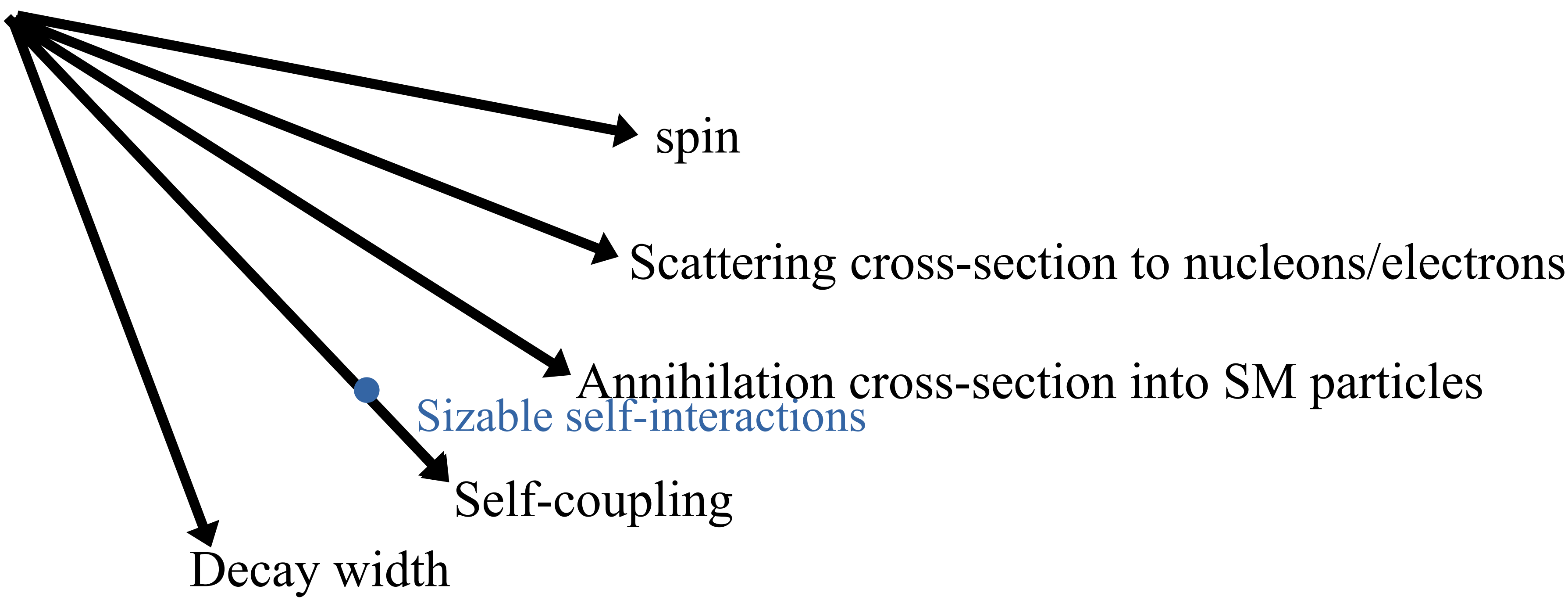

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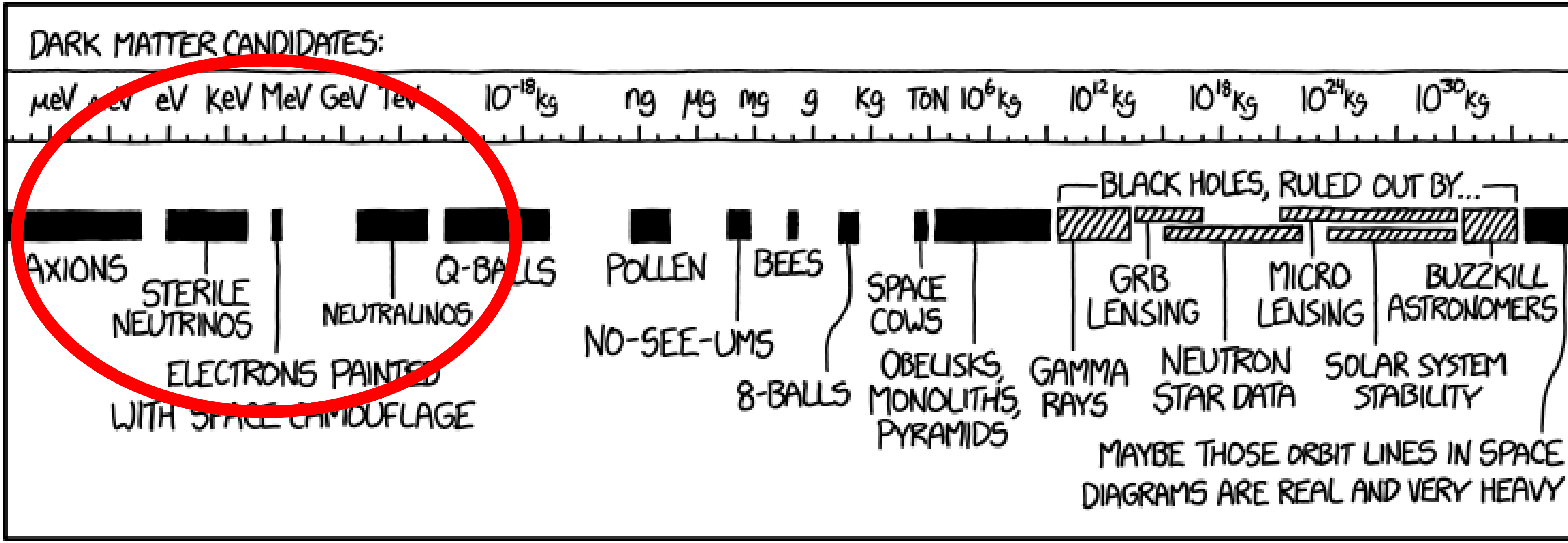

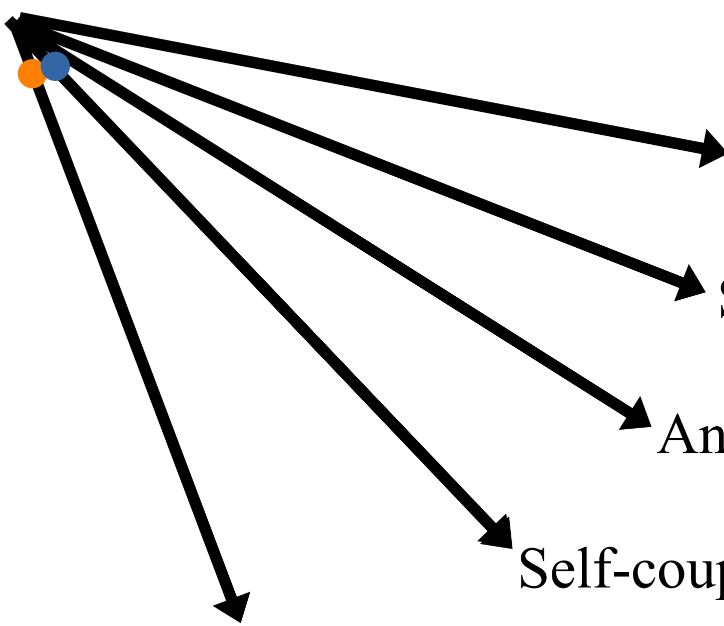

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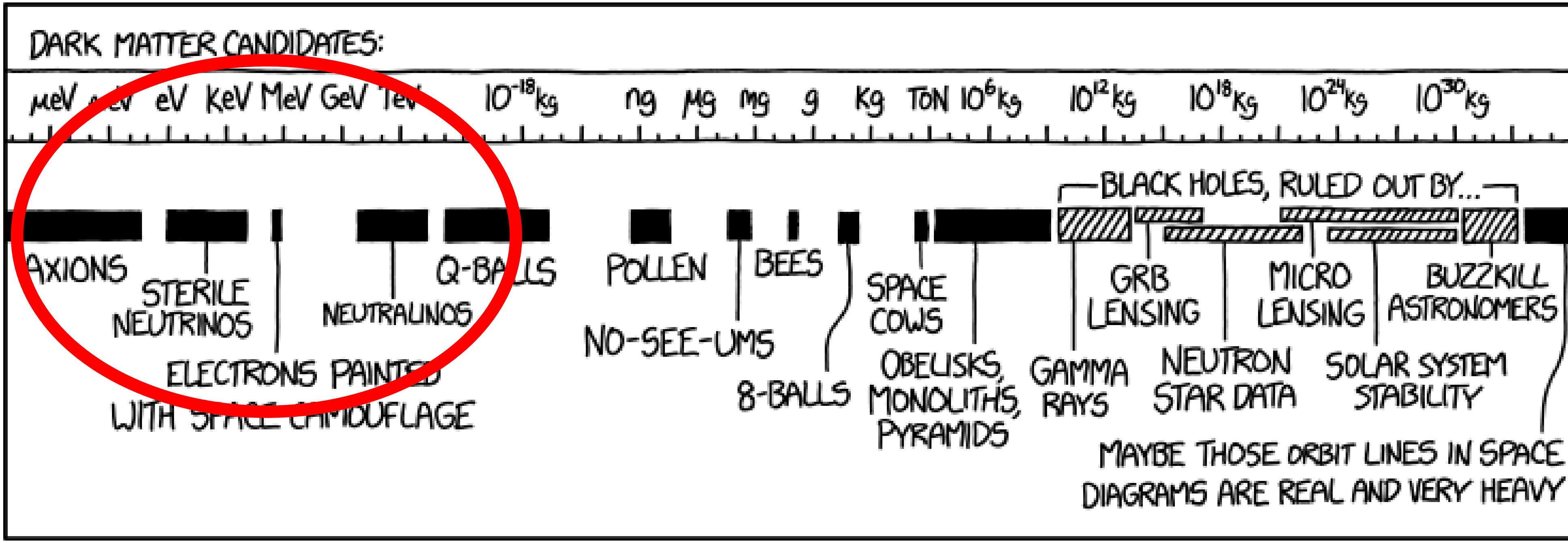

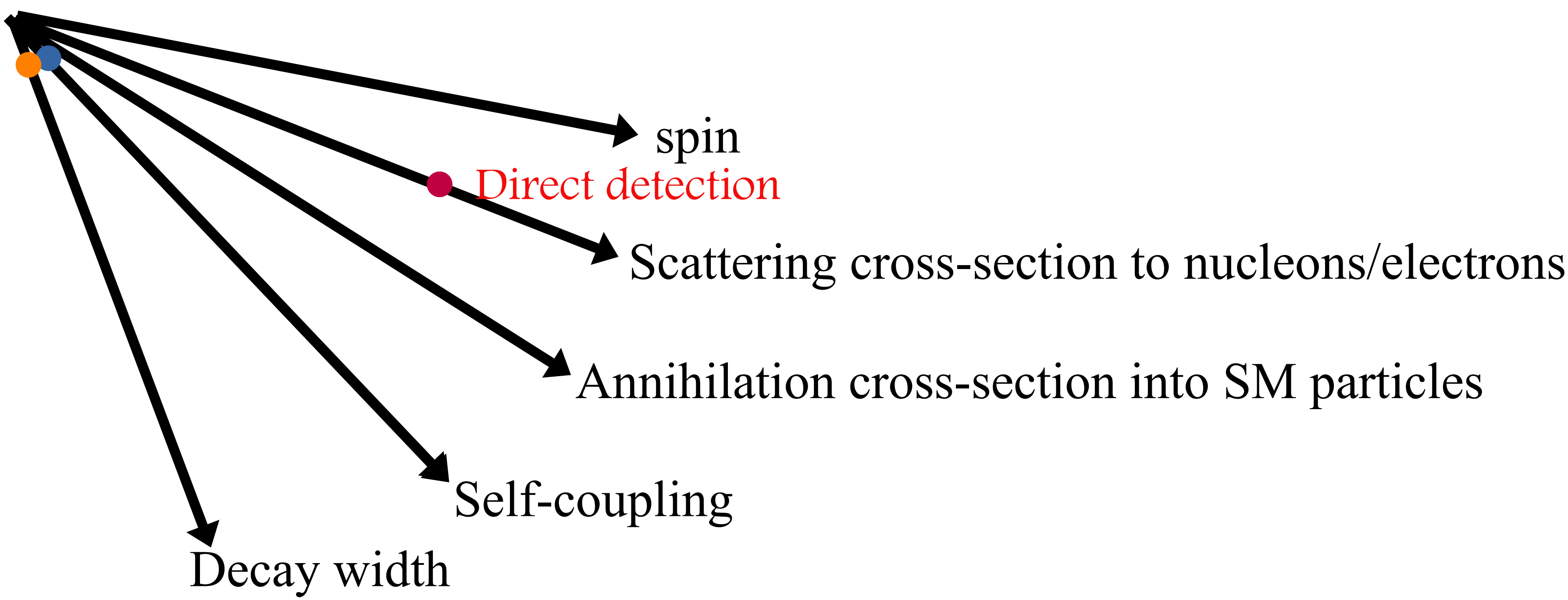

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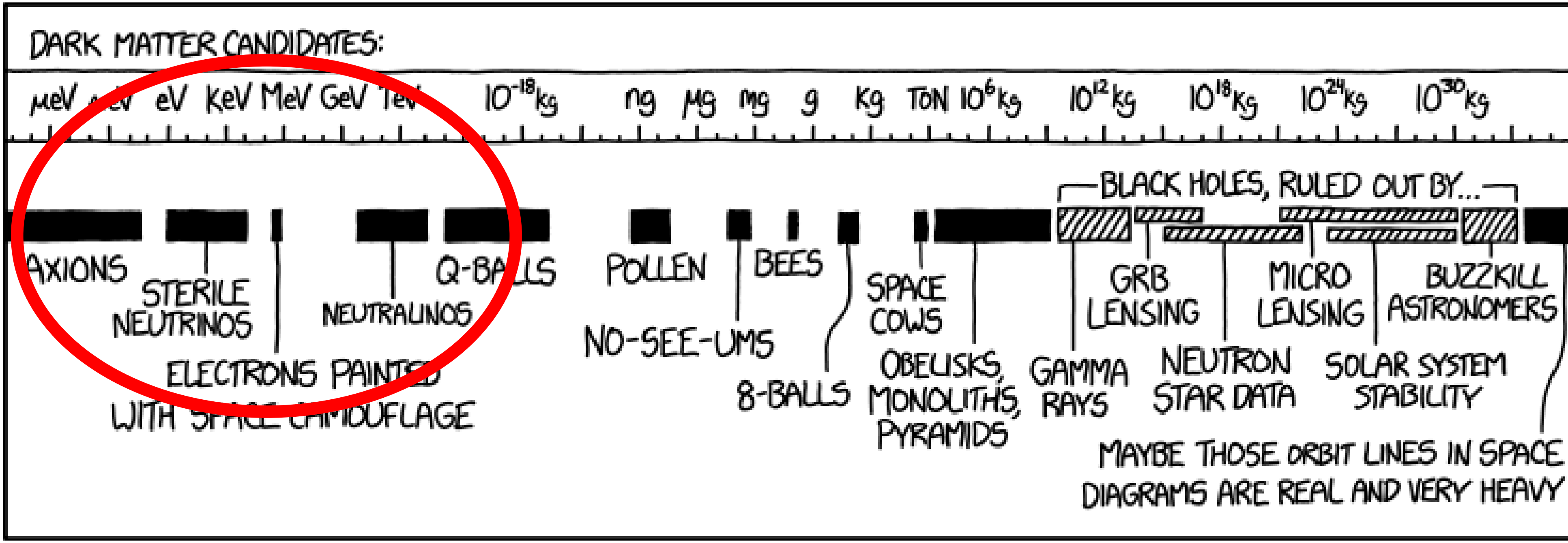

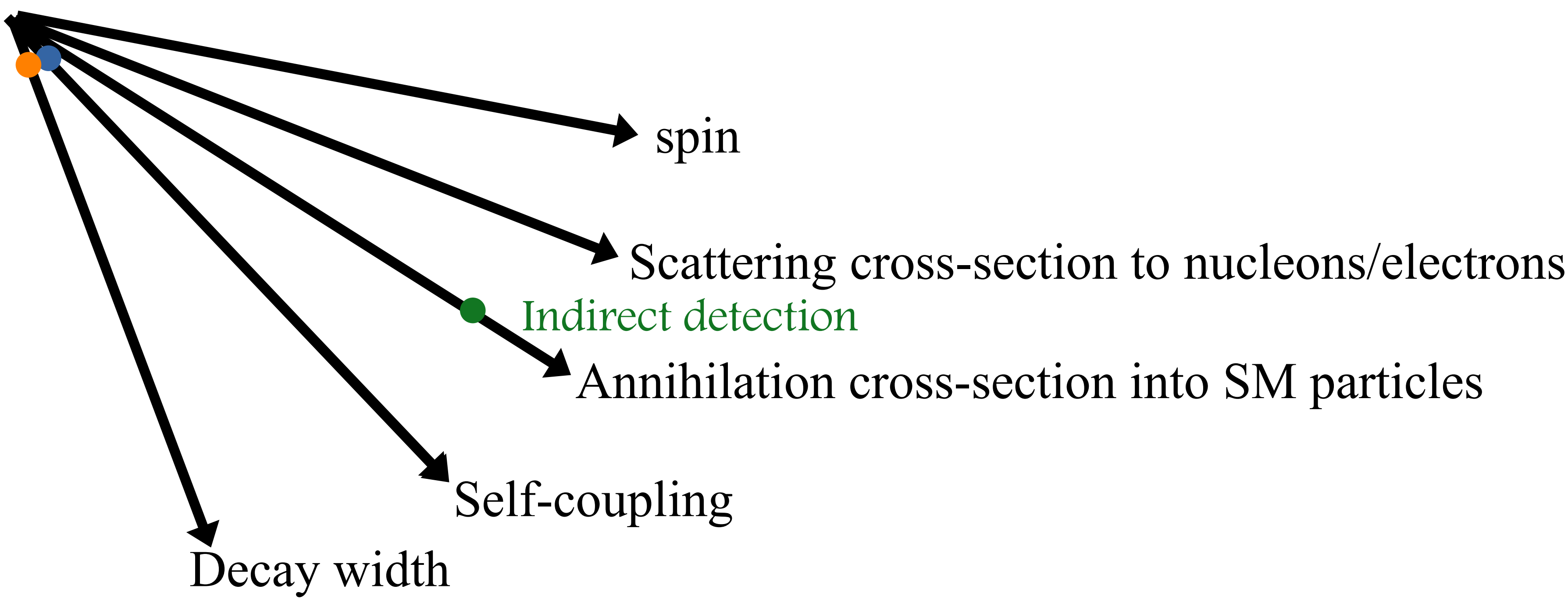

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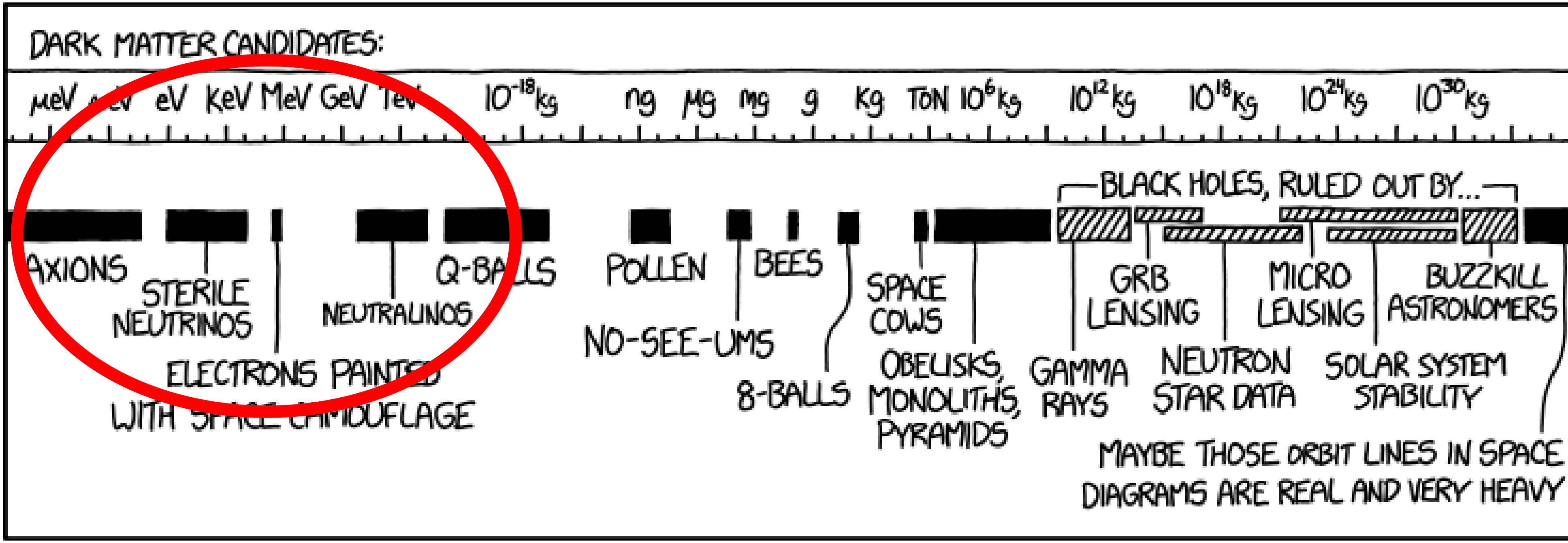
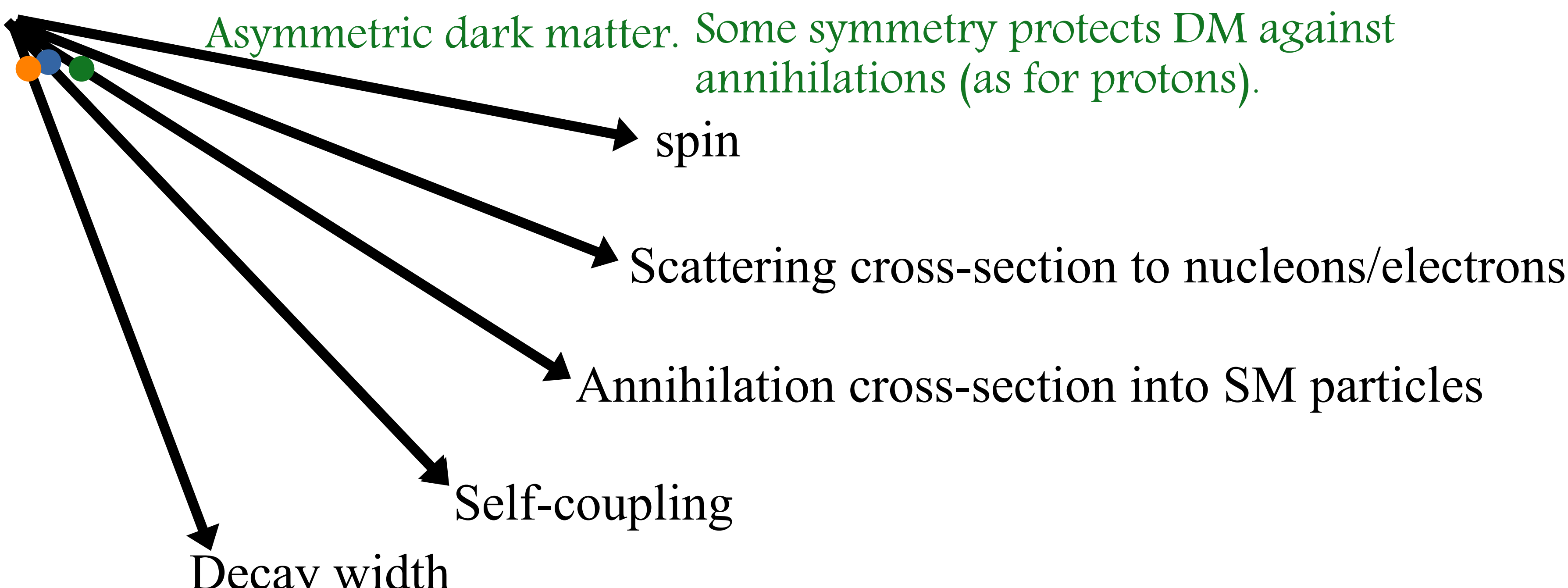


Asymmetric dark matter. Some symmetry protects DM against annihilations (as for protons).



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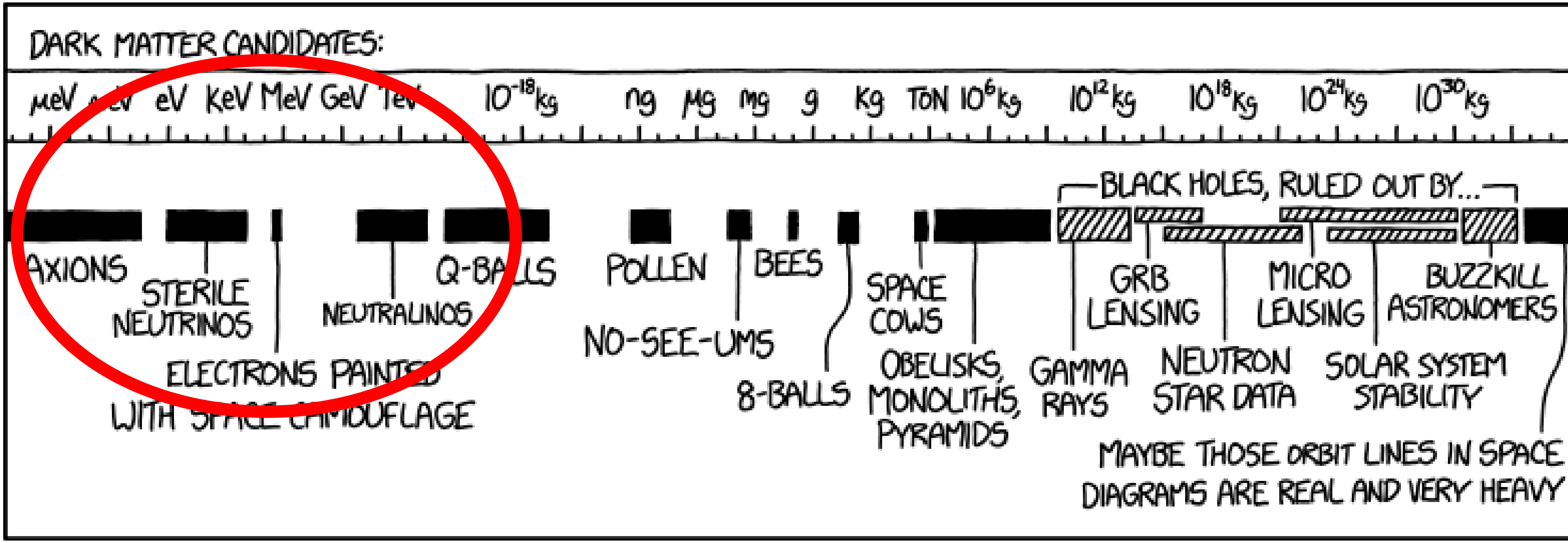

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Annihilation cross-section into SM particles

Sizable self-interactions (as for protons)

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Decay width

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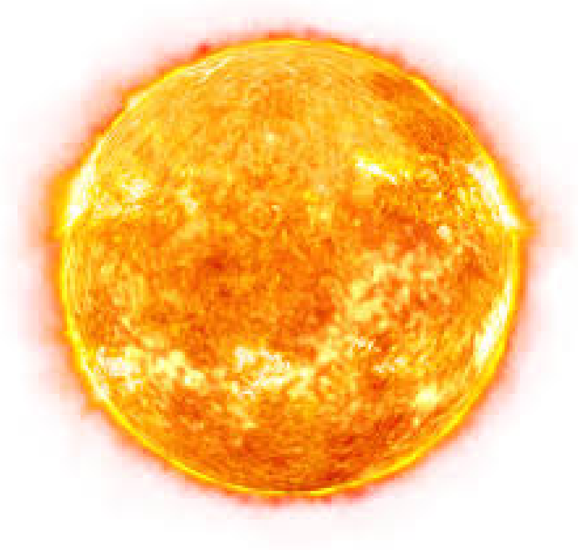
Protons do not annihilate.
Protons have strong self-interactions
Protons form stars



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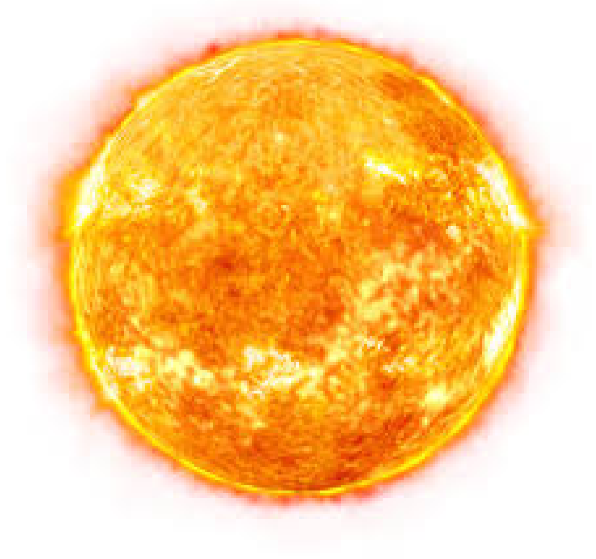

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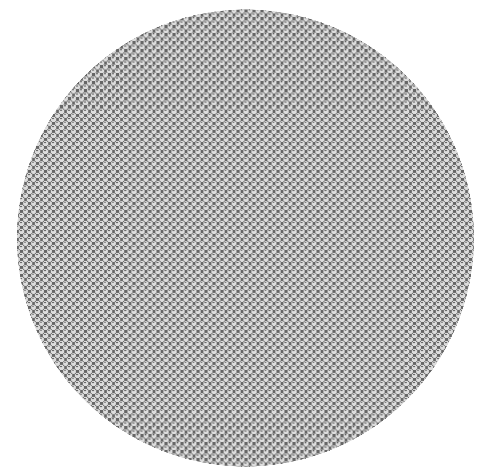

The dark matter zoo

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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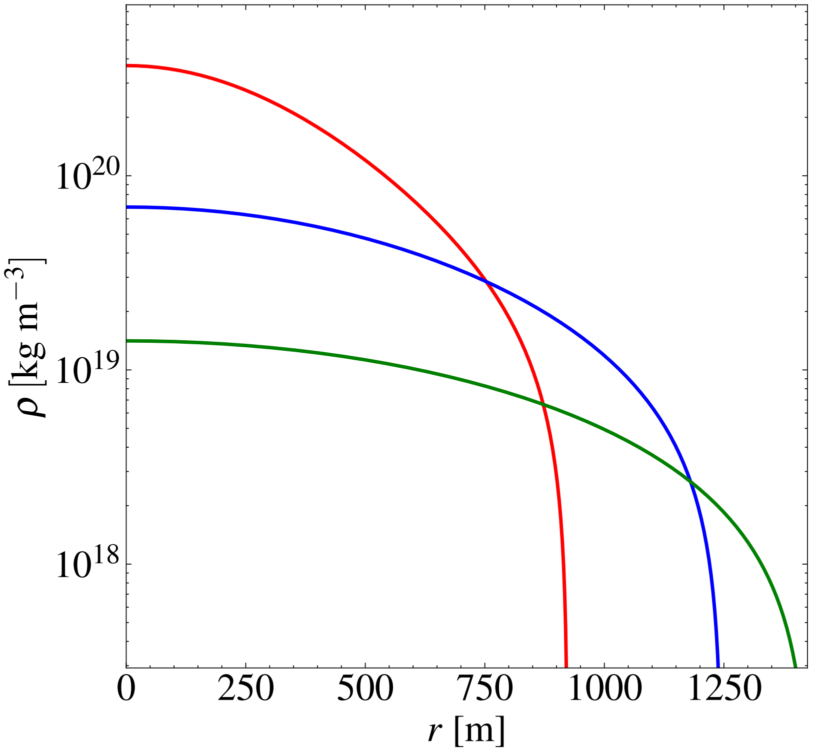

(For m=1 GeV, λ=1)

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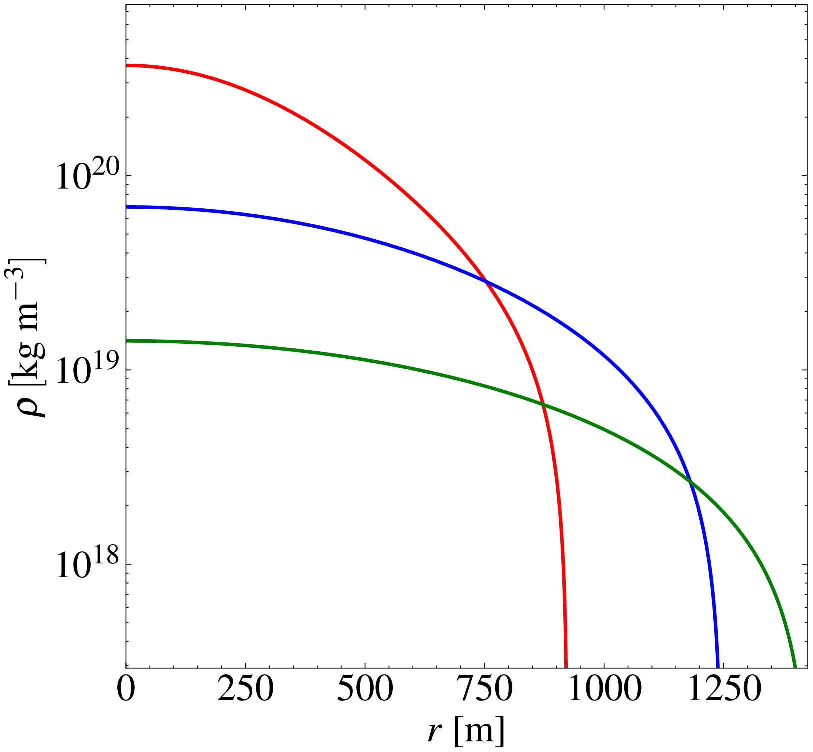

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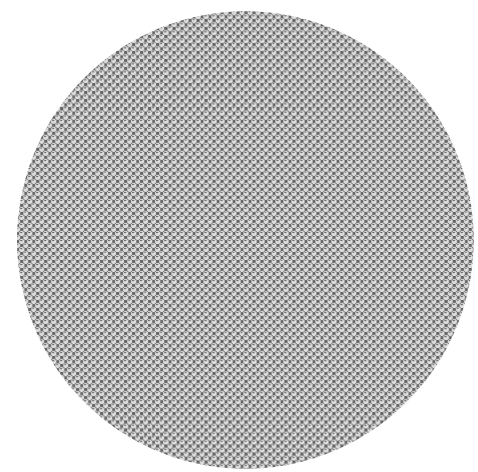
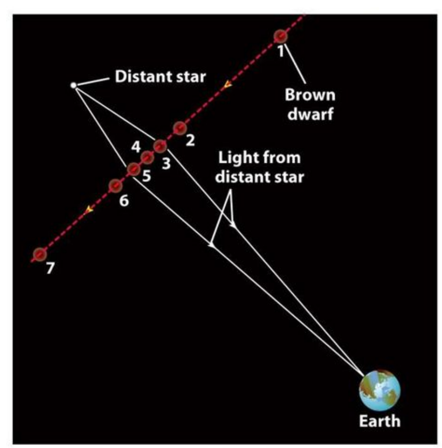
Dark stars are very compact objects

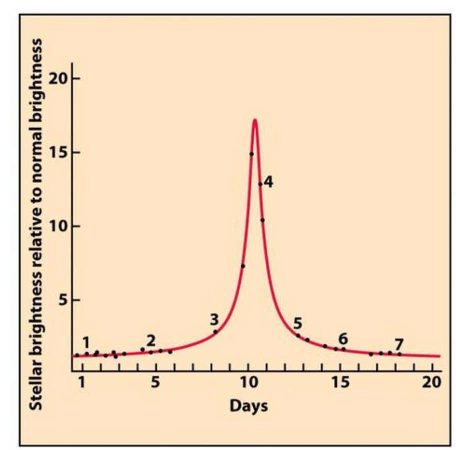
The dark matter zoo

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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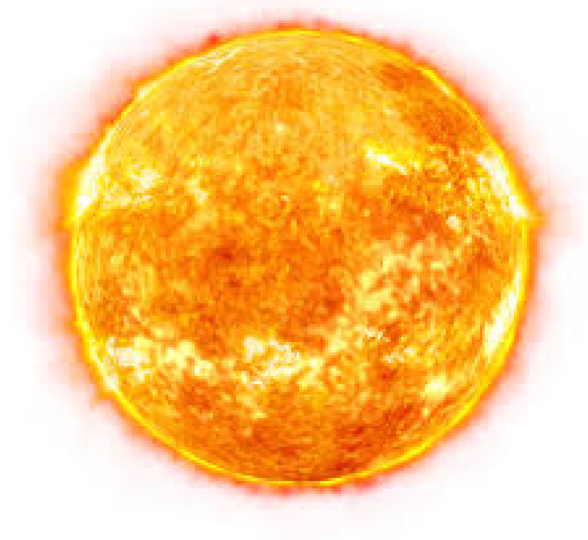

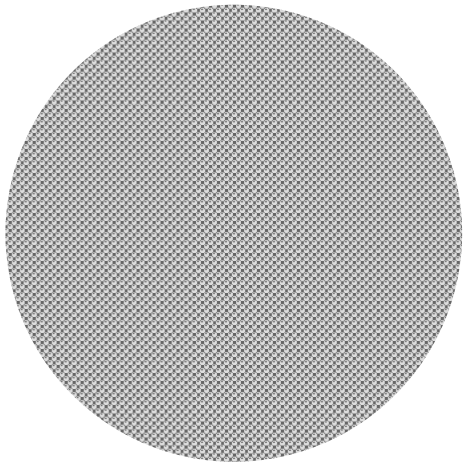

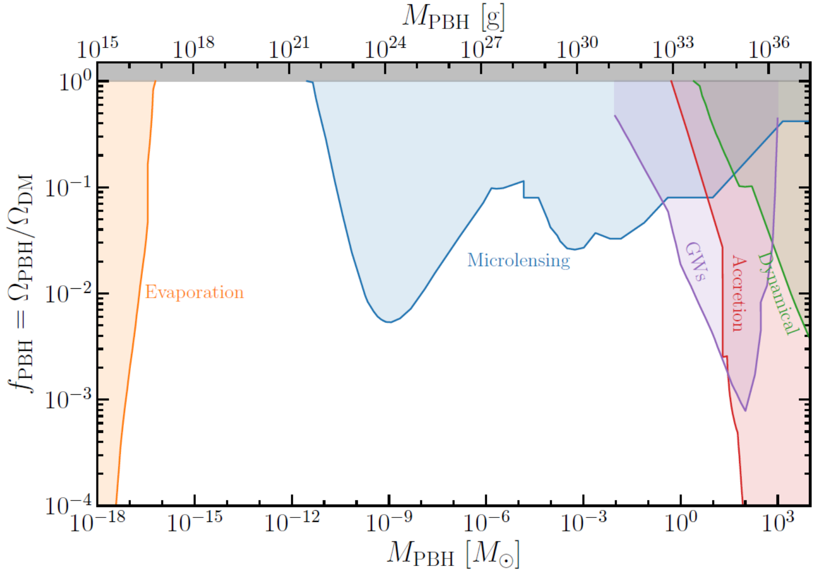

Are there other signals from dark stars?

The dark matter zoo

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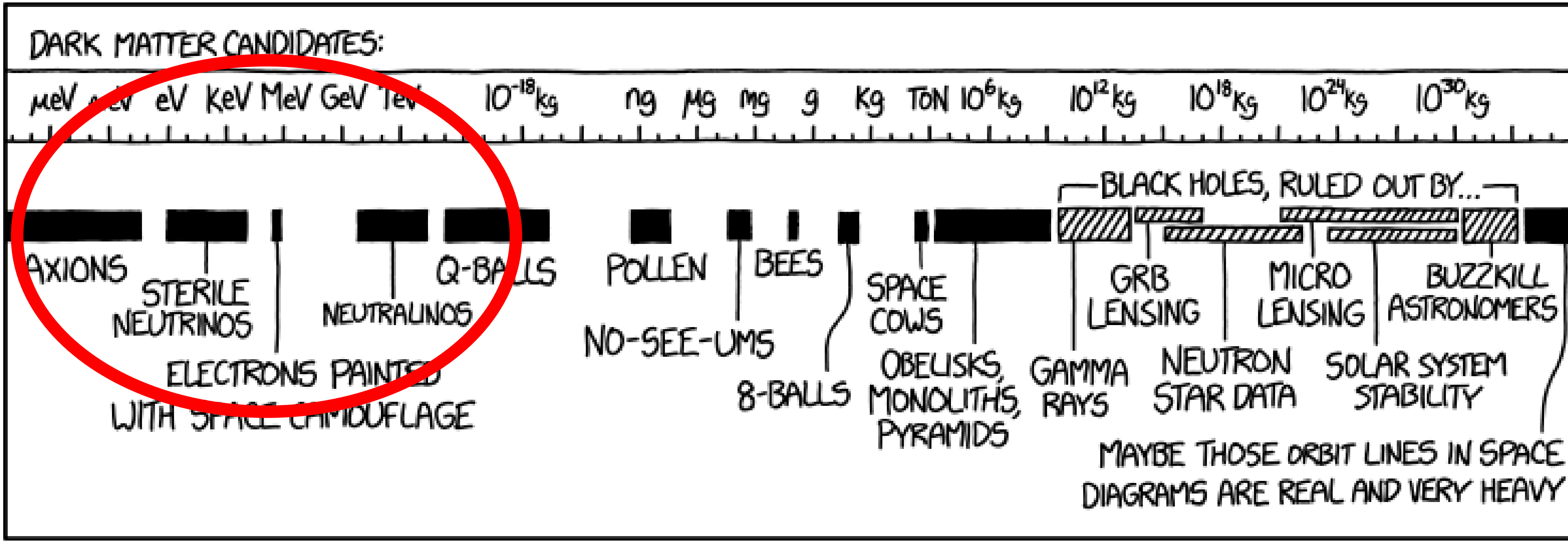

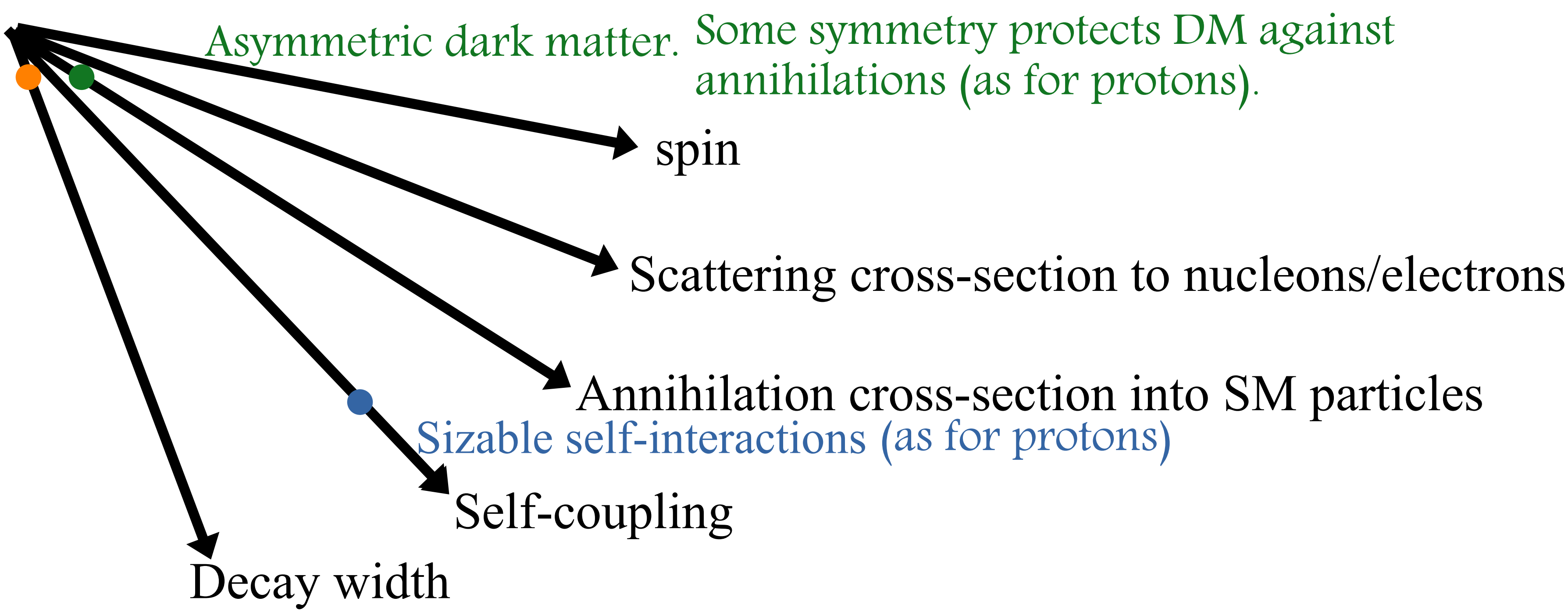

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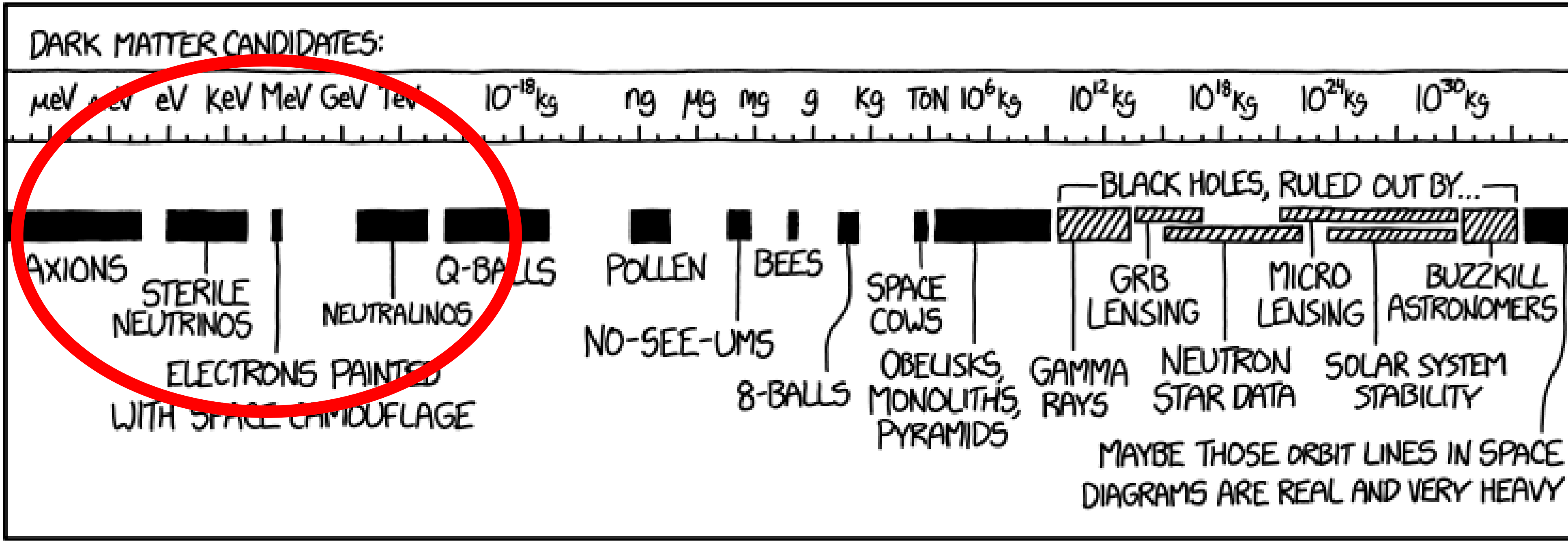

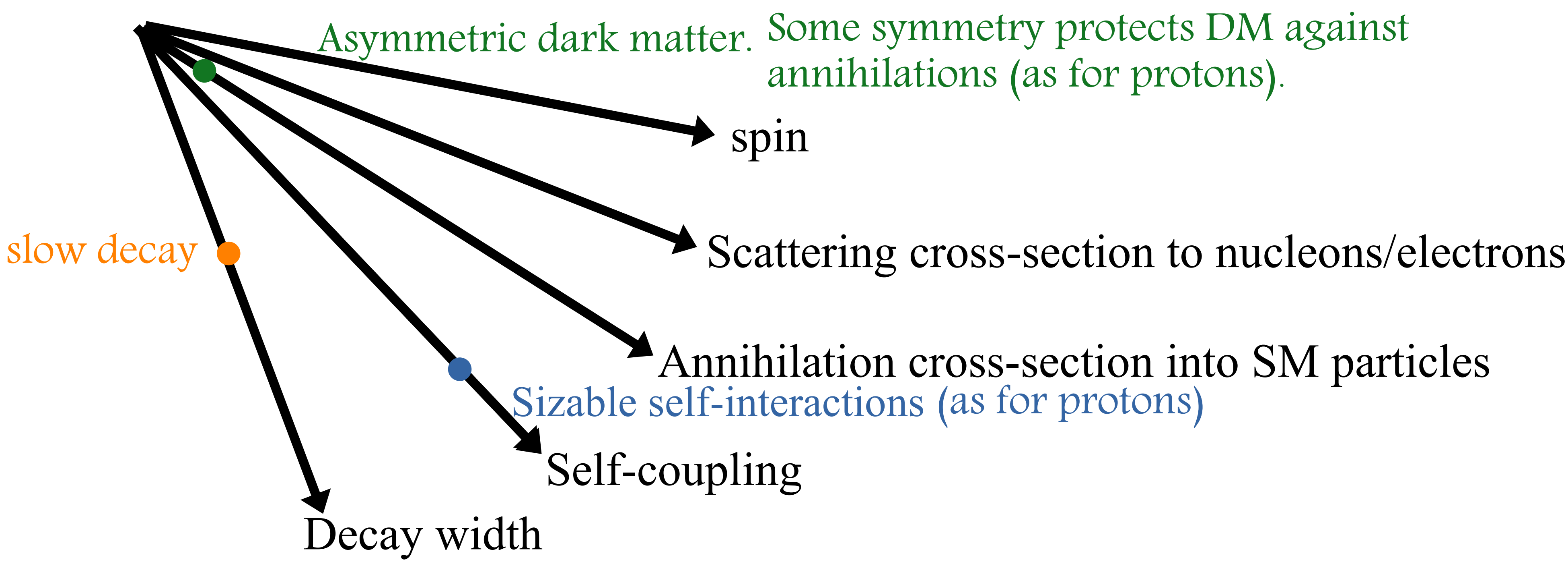

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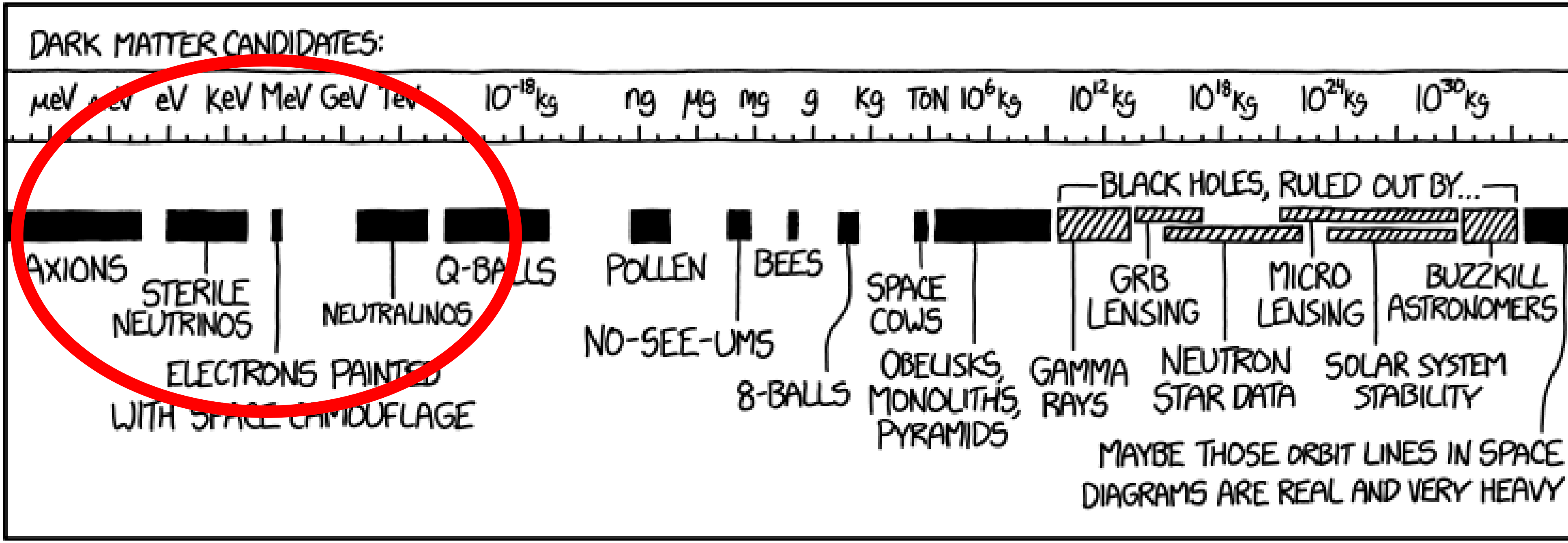

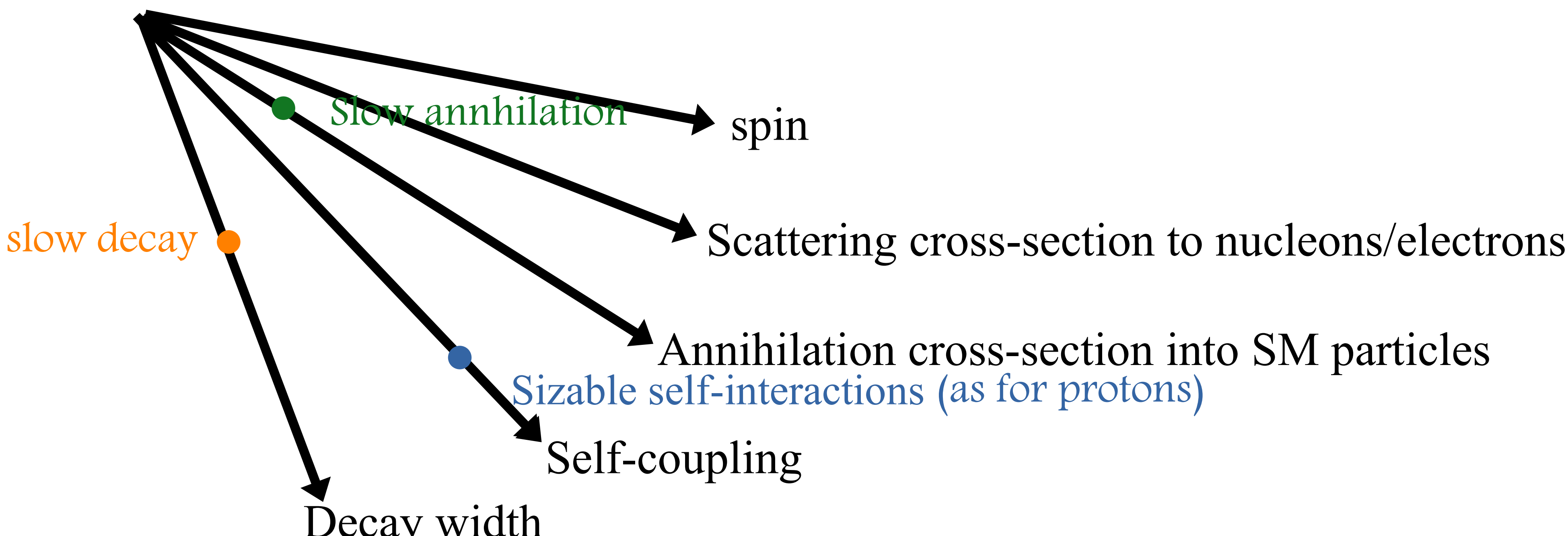

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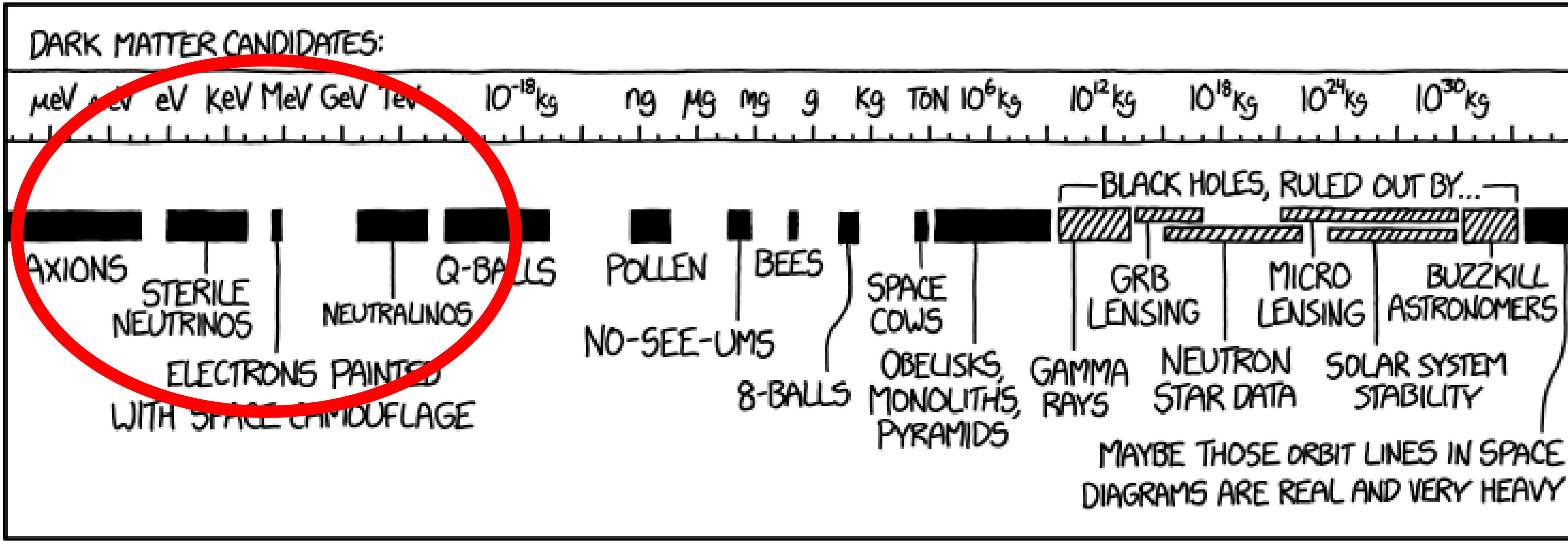

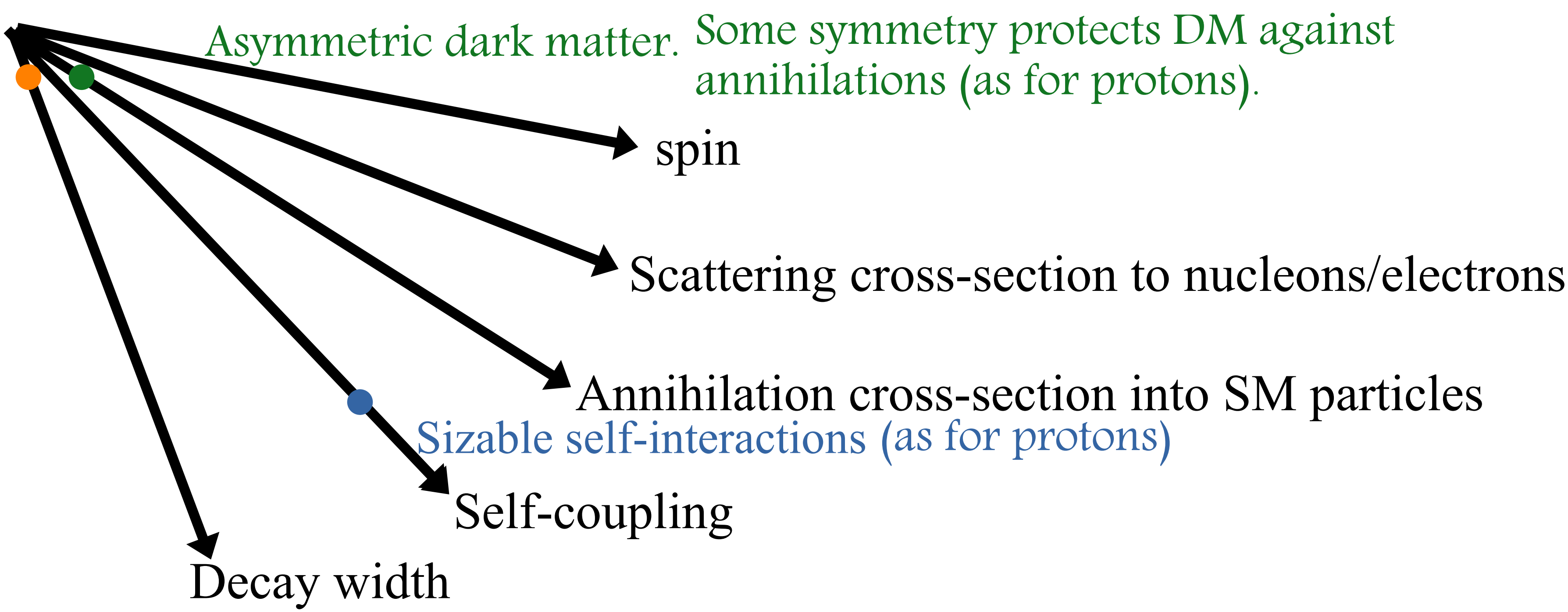

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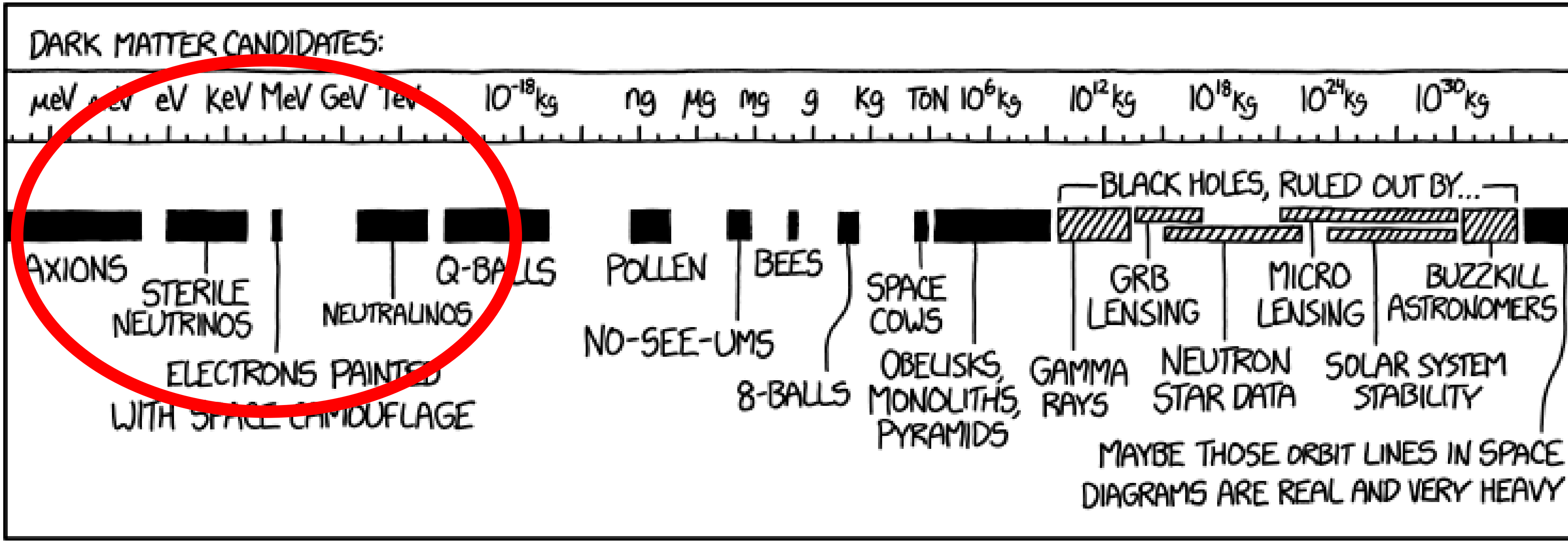
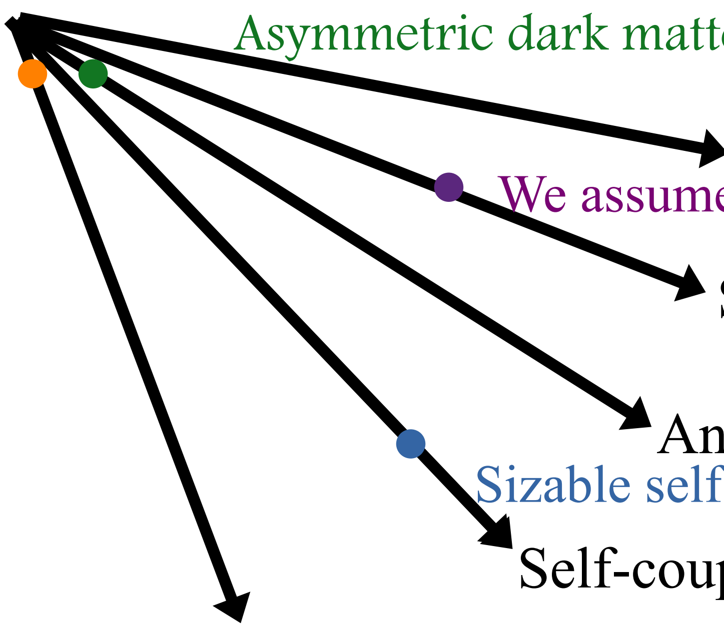




Asymmetric dark matter. Some symmetry protects DM against annihilations (as for protons).

spin

We assume that DM interacts with protons

Scattering cross-section to nucleons/electrons

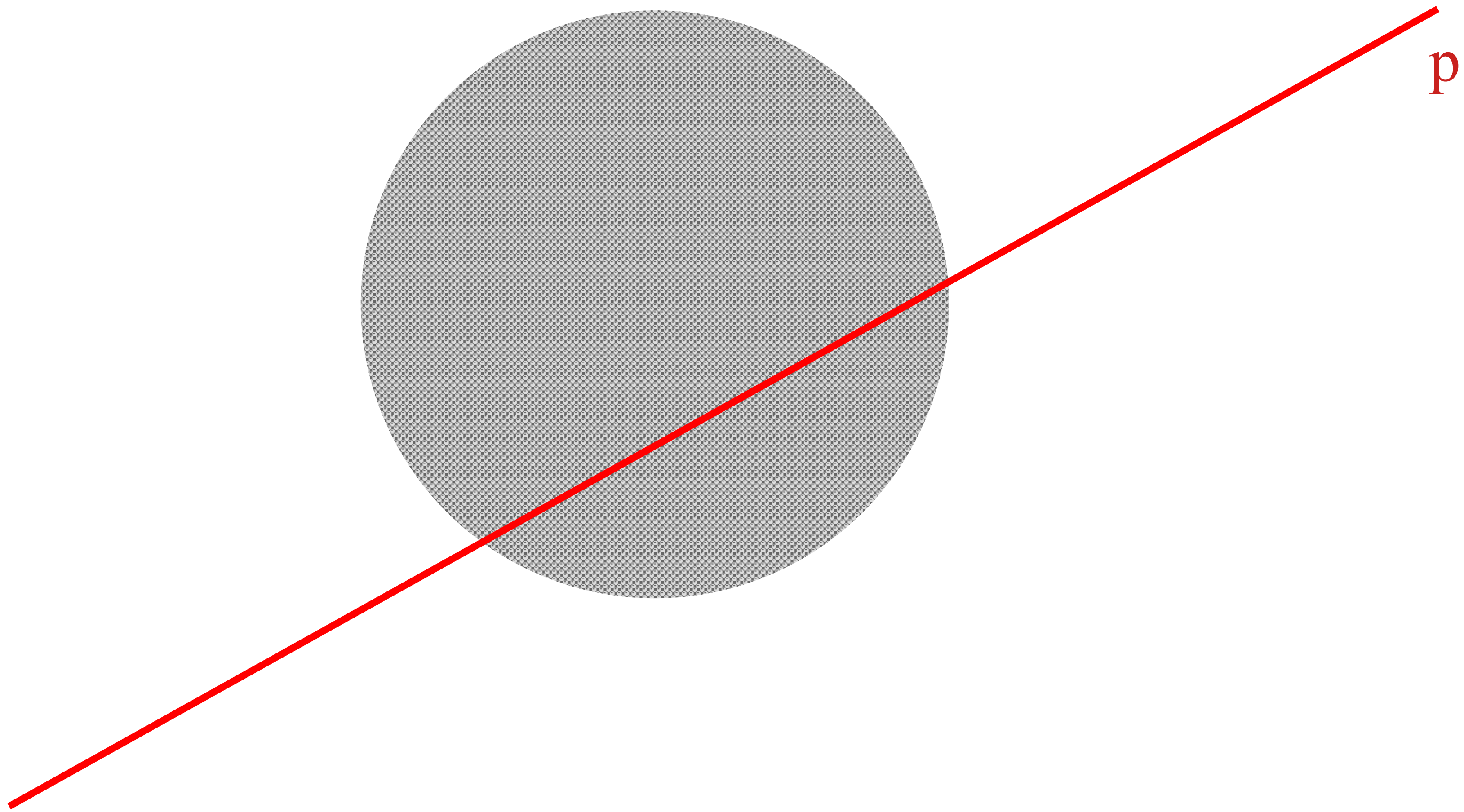
Annihilation cross-section into SM particles

Sizable self-interactions (as for protons)

Self-coupling

Decay width

Proton capture in compact dark stars



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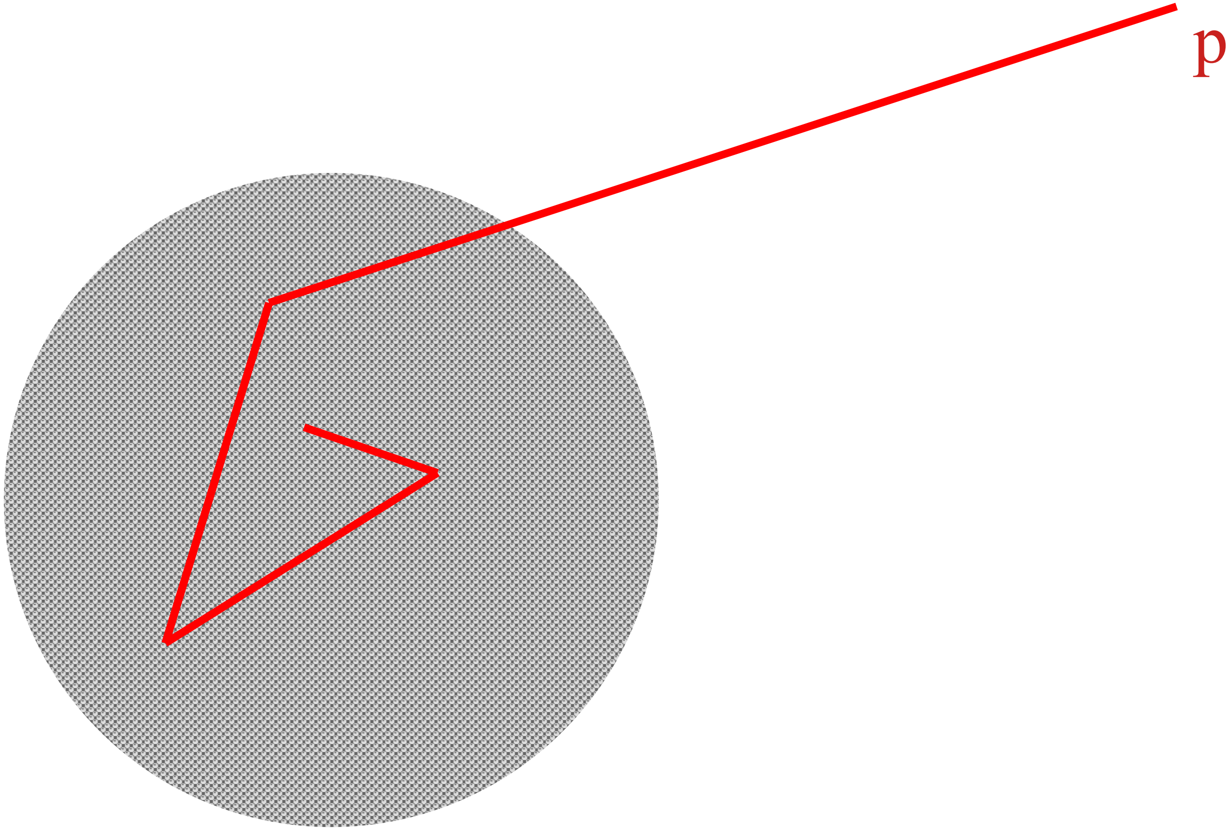

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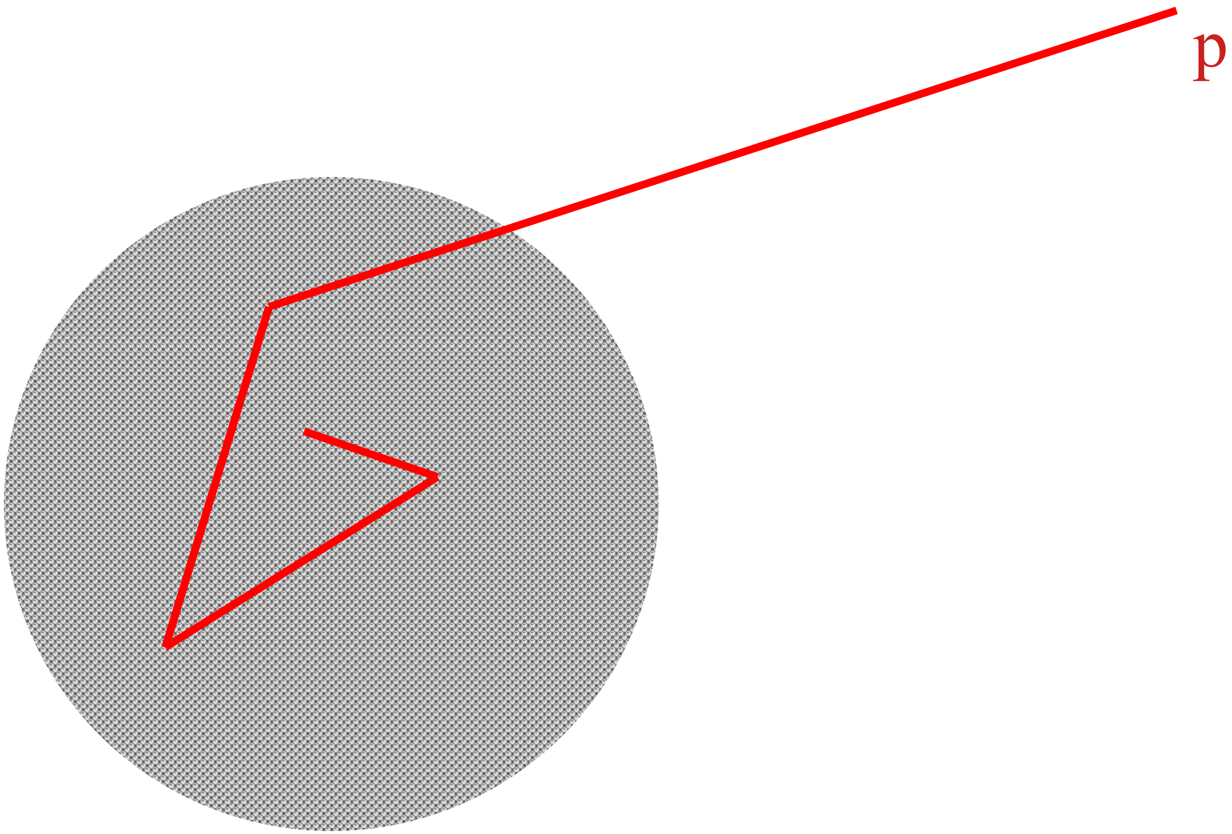
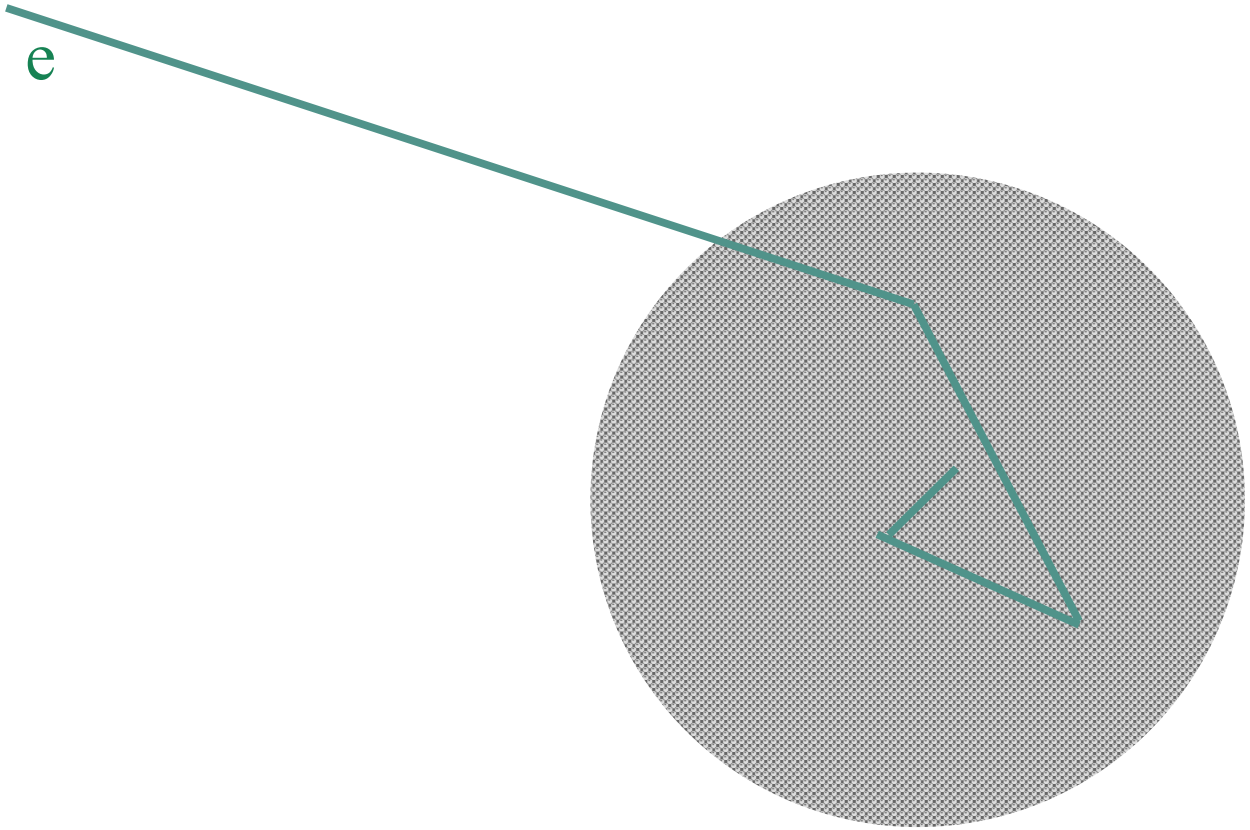


$$C \sim (10^{18}\ \mathrm{s}^{-1}) \left[\left(\frac{\sigma}{10^{-45}\ \mathrm{cm}^2} \right) \left(\frac{n_p}{10^{-5}\ \mathrm{cm}^{-3}} \right) \right] \left(\frac{R_{\mathrm{DS}}}{1\ \mathrm{km}} \right)^3 \left(\frac{M}{M_\odot} \right)^{-\frac{3}{2}}$$

Proton capture in compact dark stars



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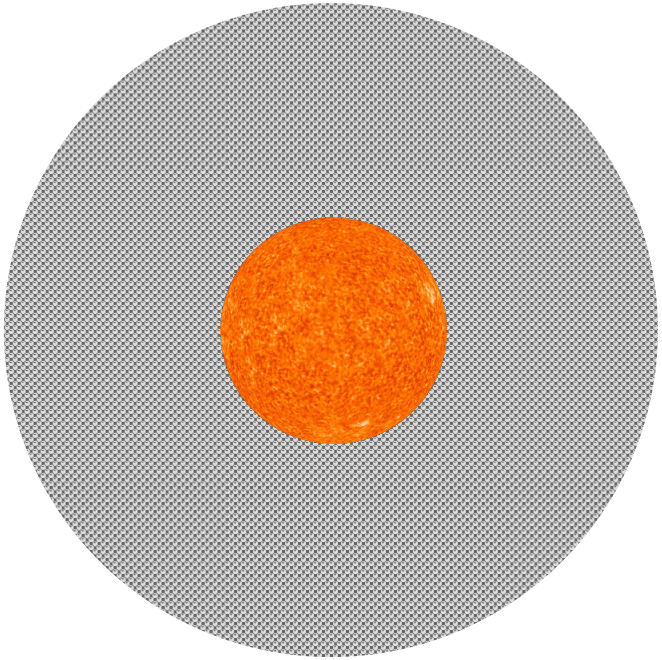

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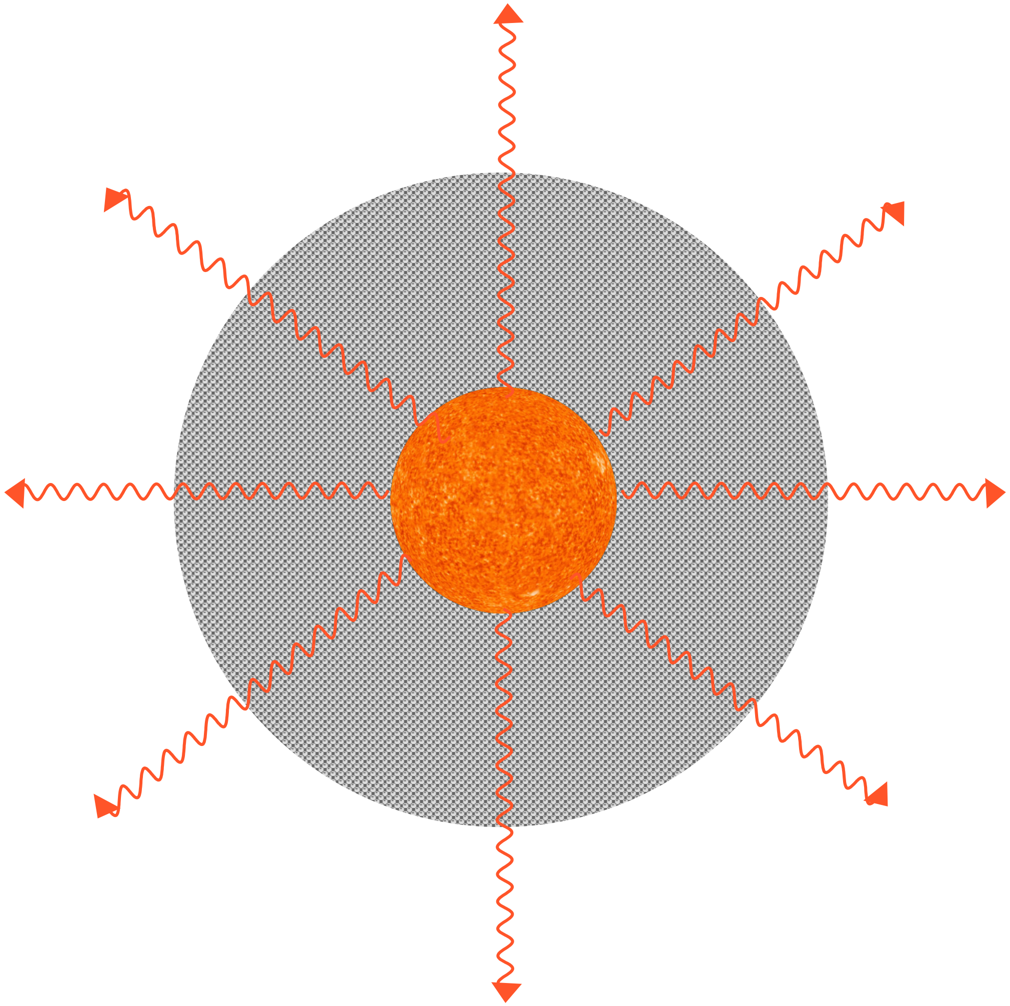

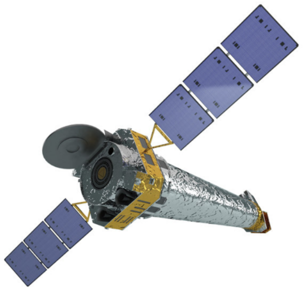

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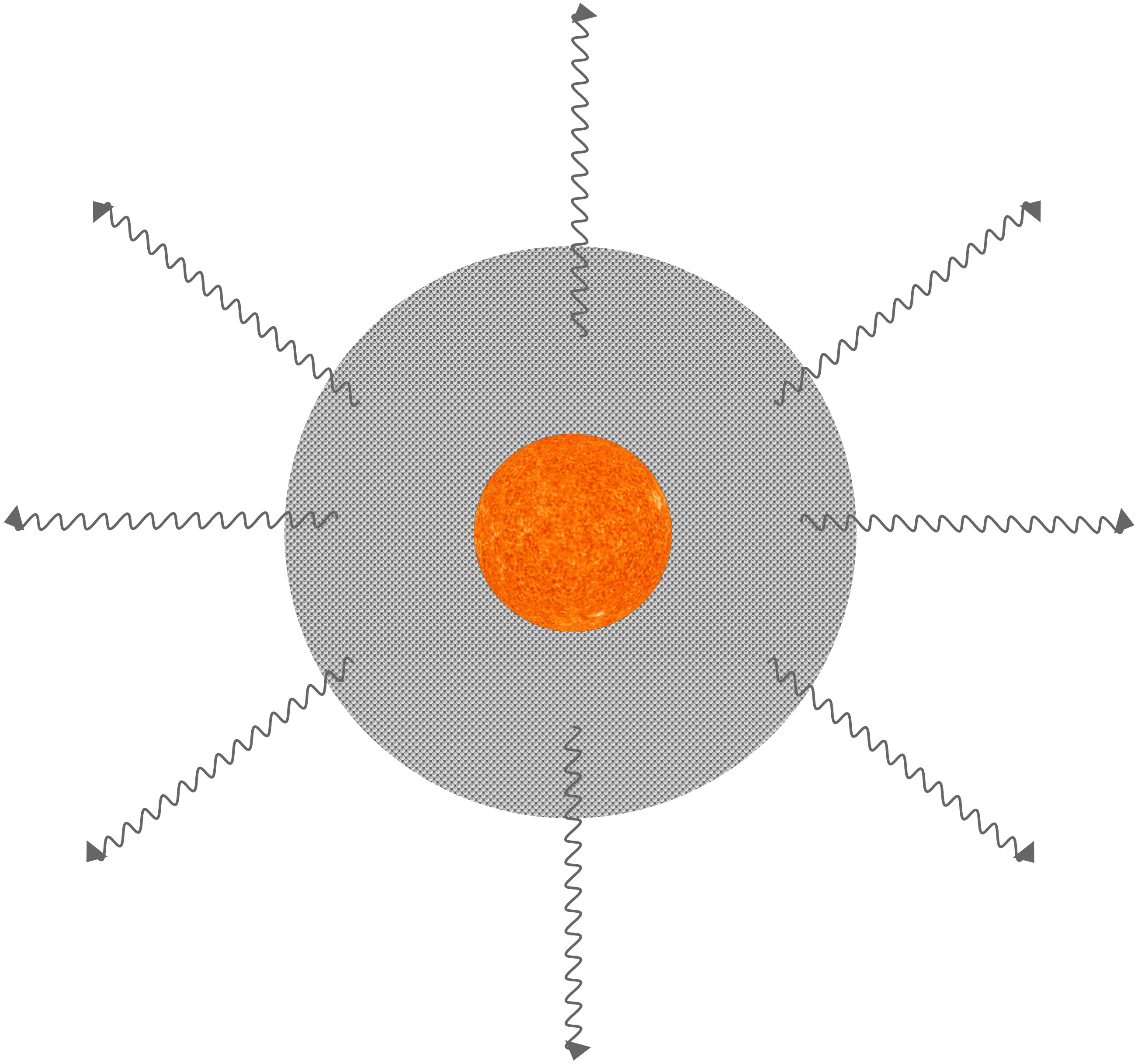

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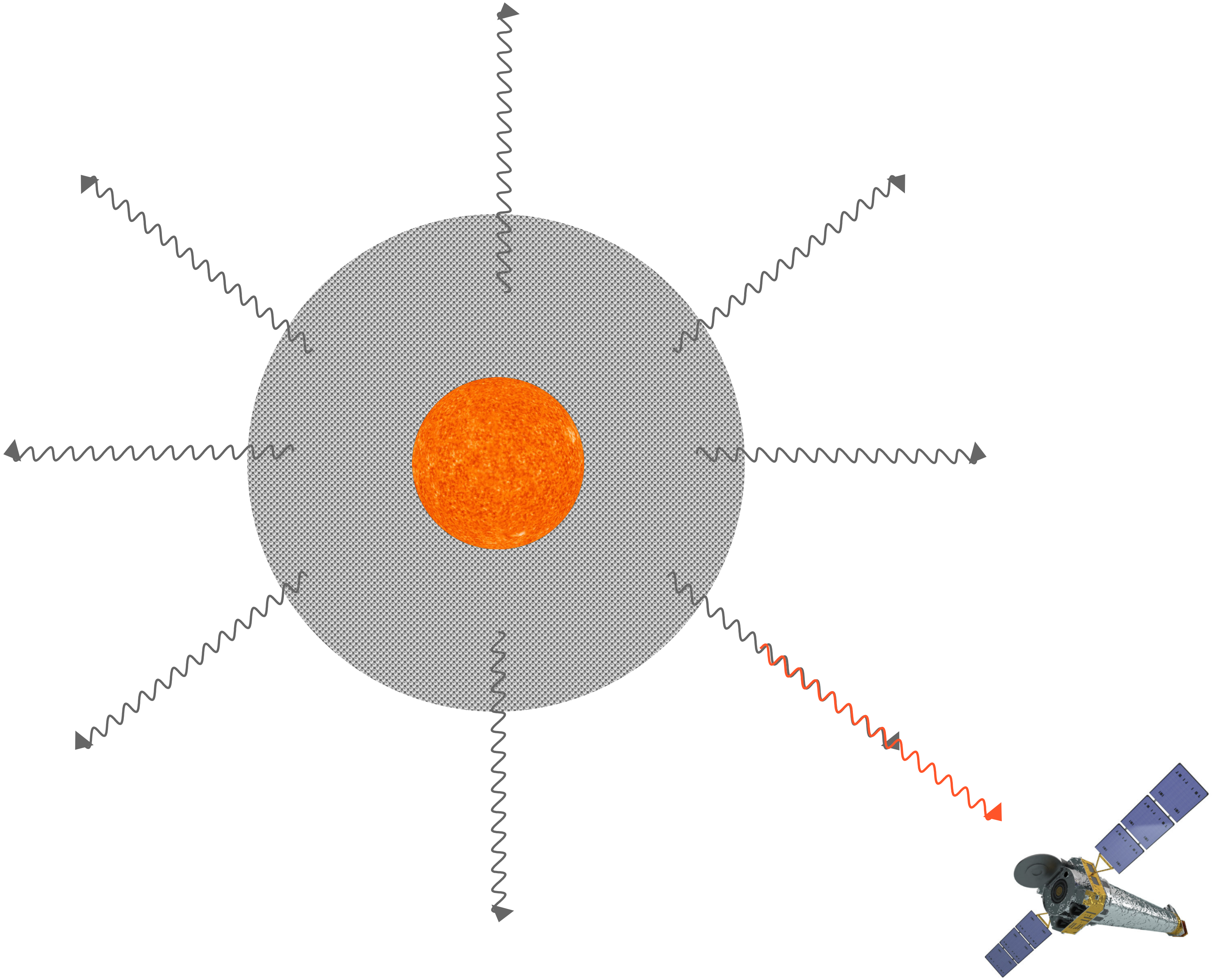

Temperature evolution of the DS

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

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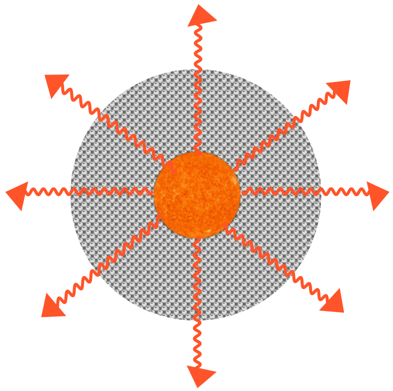
Photon luminosity: $L_\gamma = \left(4\pi r_{\rm th}^2\right) \int_0^\infty I(\nu) d\nu$



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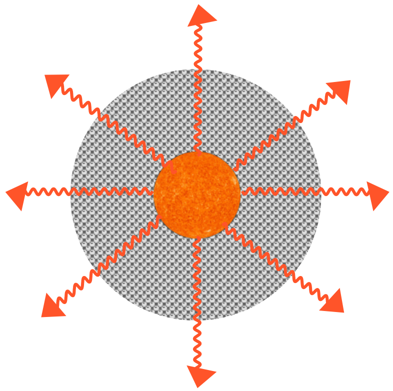

Photon luminosity: $L_\gamma = (4\pi r_{\rm th}^2)\int_0^\infty I(\nu)d\nu$

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

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

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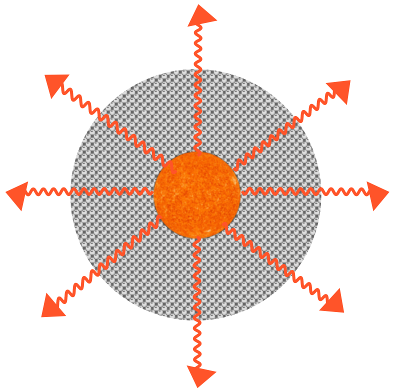
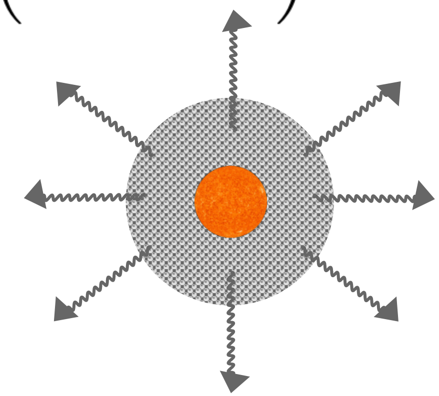


Dark photon luminosity: $L_{\gamma'} = (4\pi R_{\rm DS}^2)\,\sigma_{\rm SB}T^4{\rm e}^{-\frac{m_{\gamma'}}{T}}$



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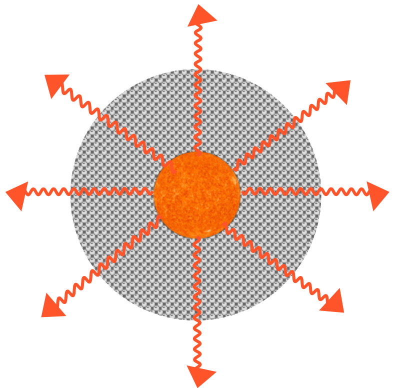

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$$r_{\rm th} \sim T^{1/2}$$

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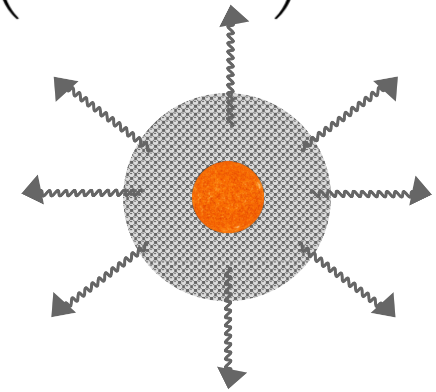
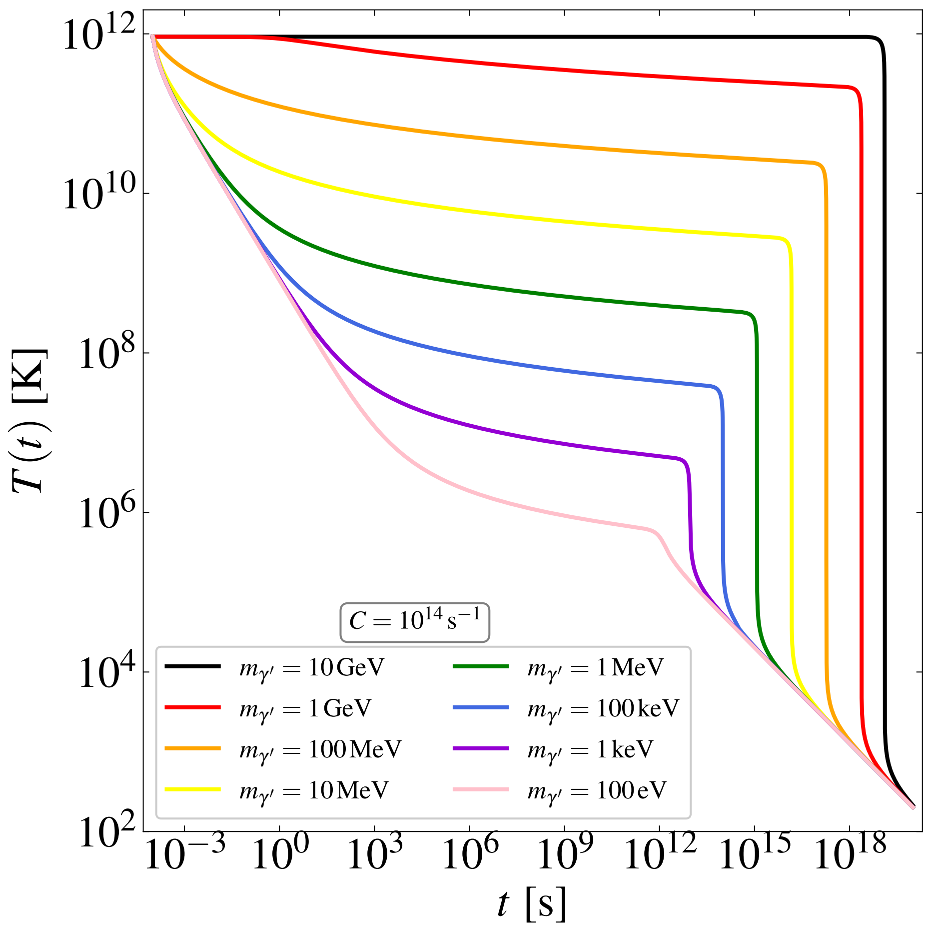


Dark photon luminosity: $L_{\gamma'} = \left(4\pi R_{\rm DS}^2\right)\sigma_{\rm SB}T^4{\rm e}^{-\frac{m_{\gamma'}}{T}}$

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

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

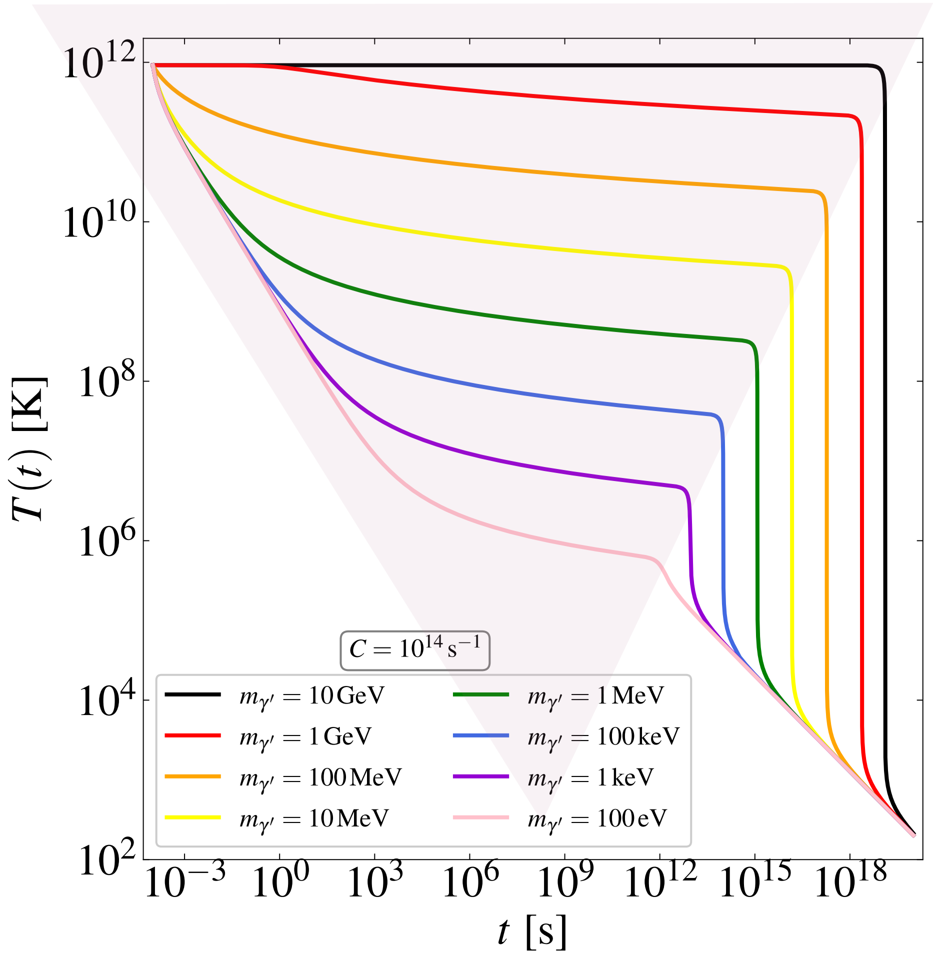
Temperature evolution of the DS



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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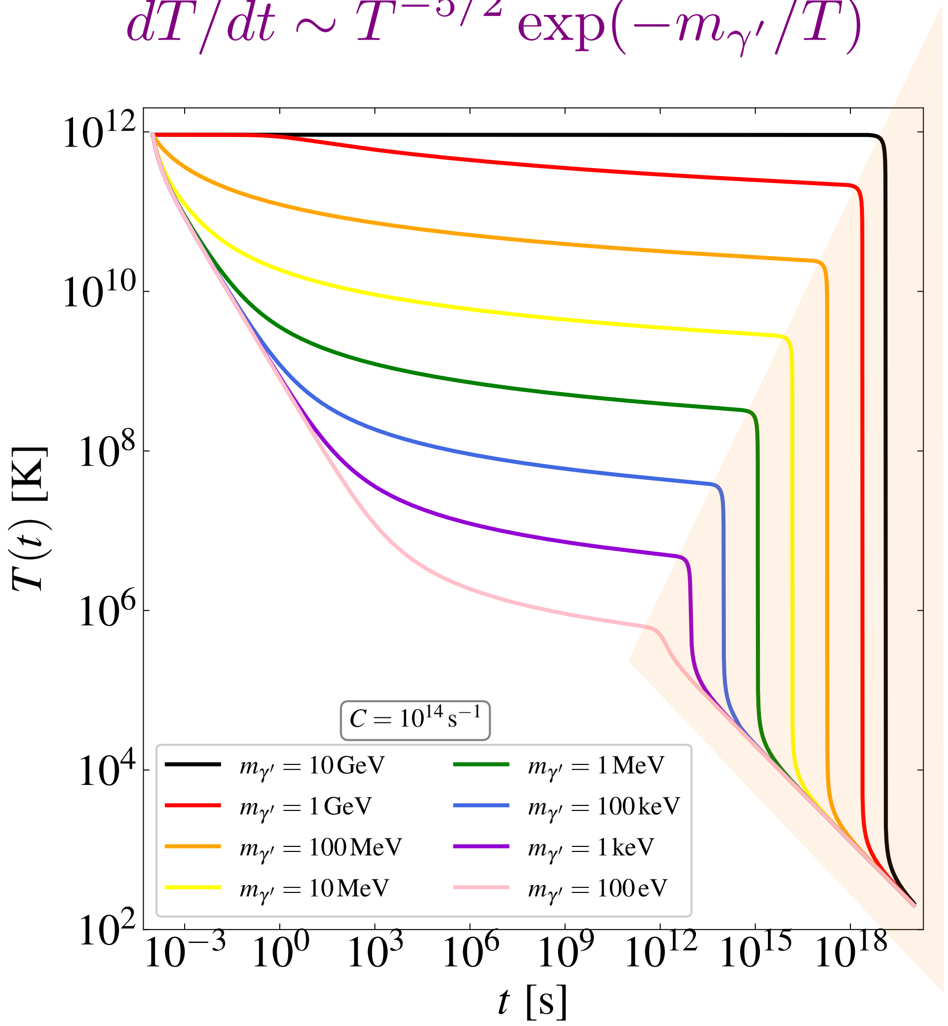
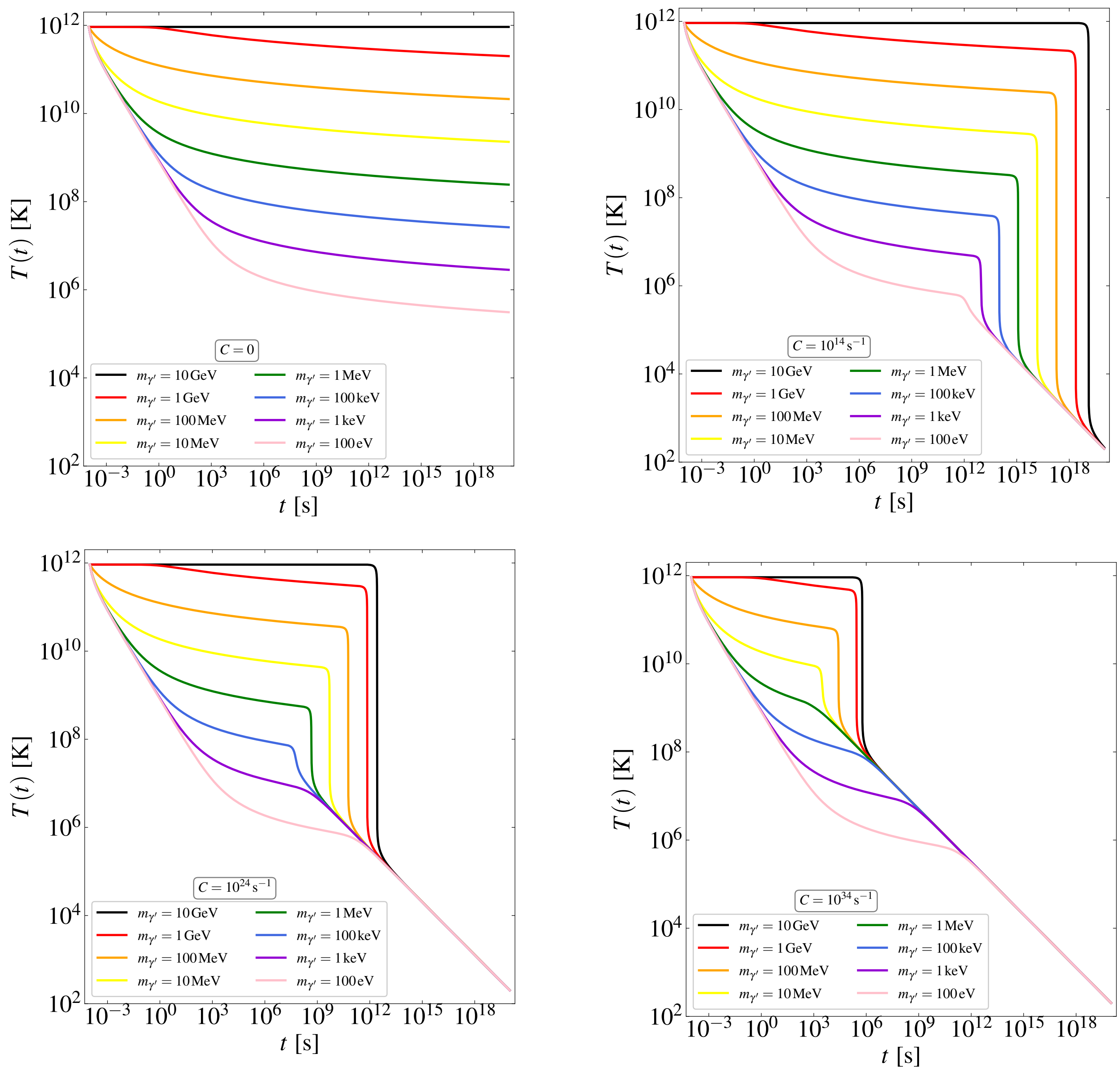


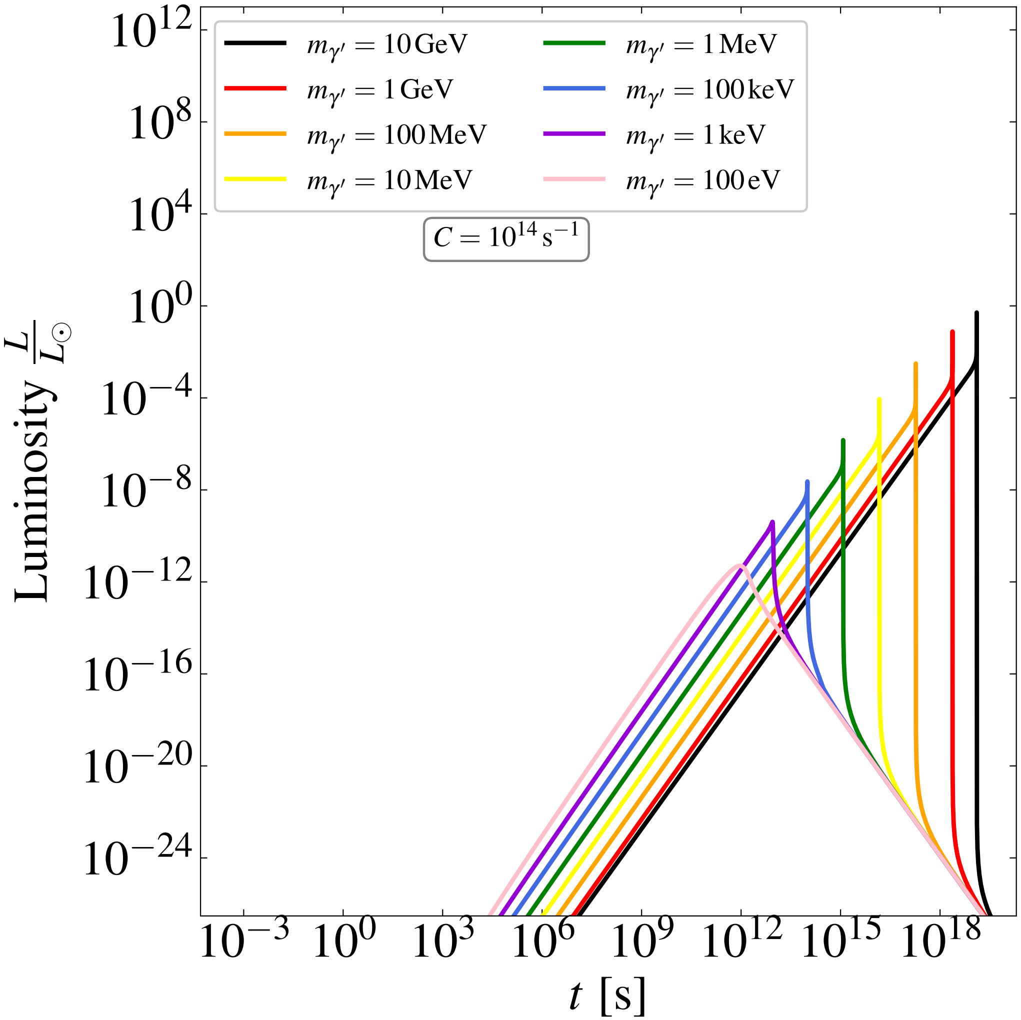
Proton gas optically thick.
Cooling by photon emission

$$dT/dt \sim T^{-7/2}$$

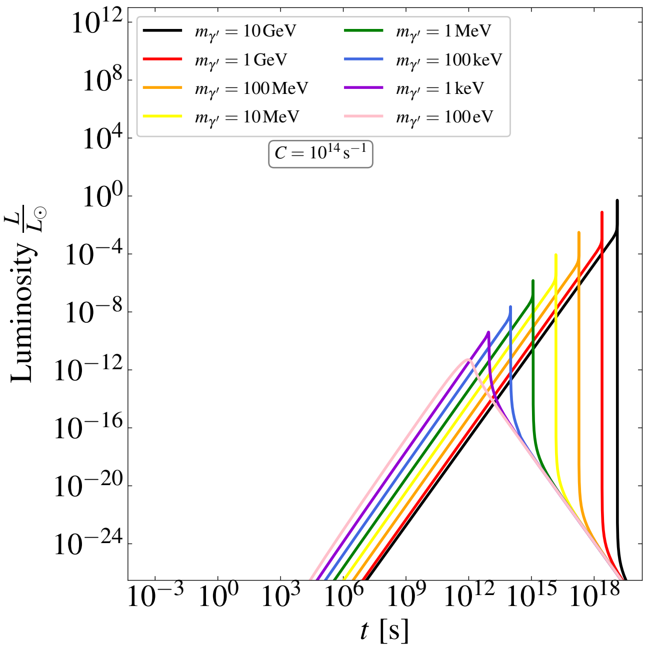
Temperature evolution of the DS

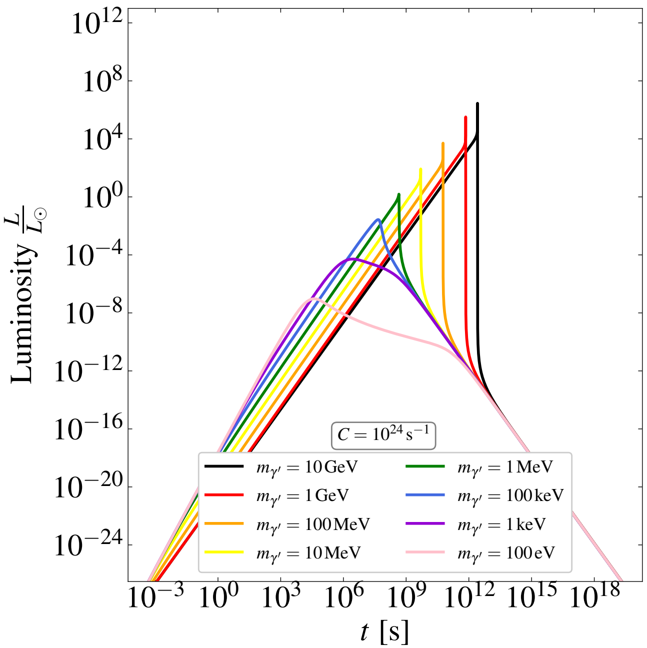


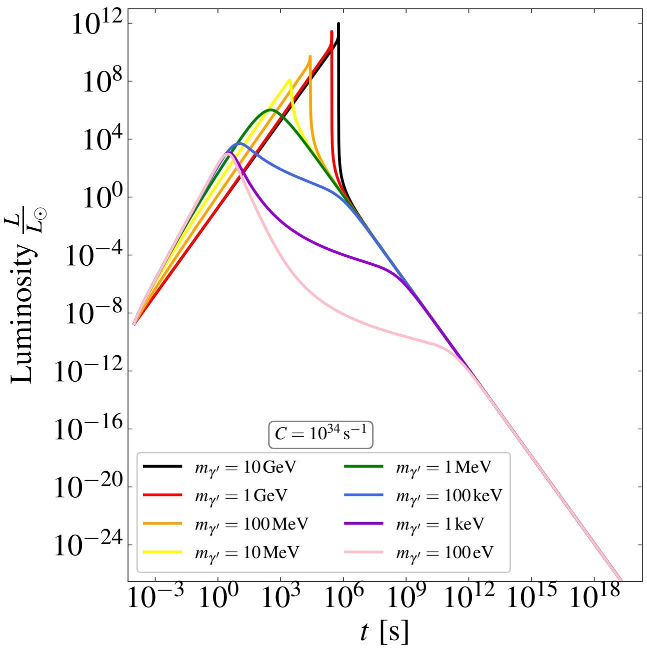
DS luminosity



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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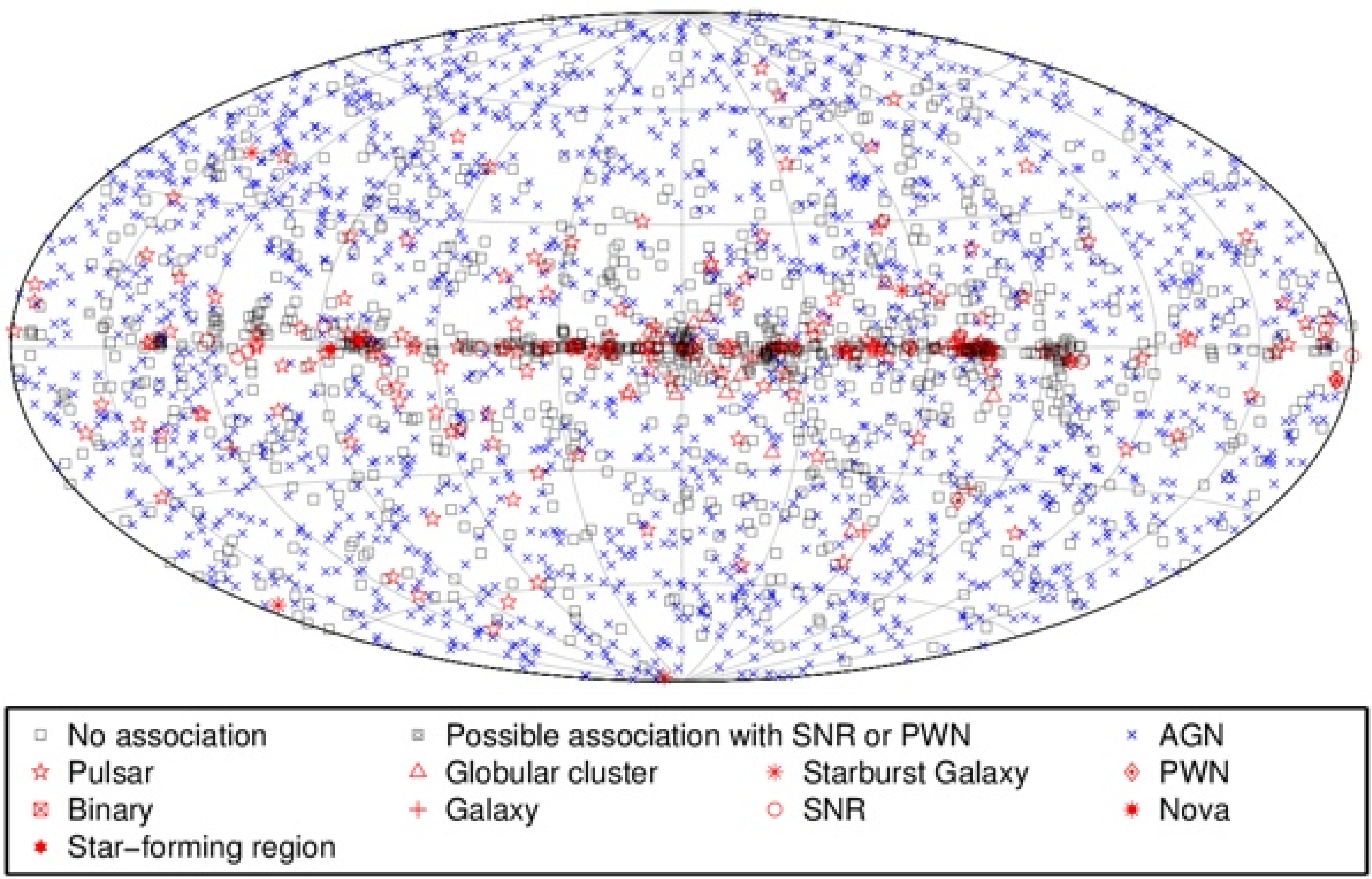

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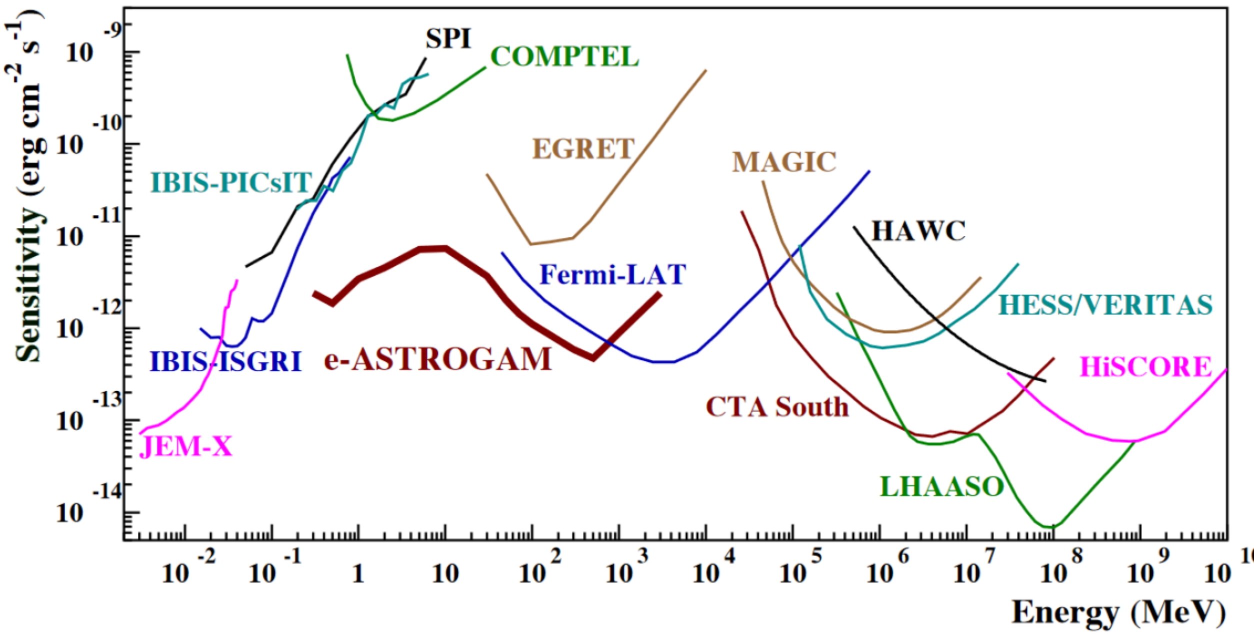

De Angelis et al' 18

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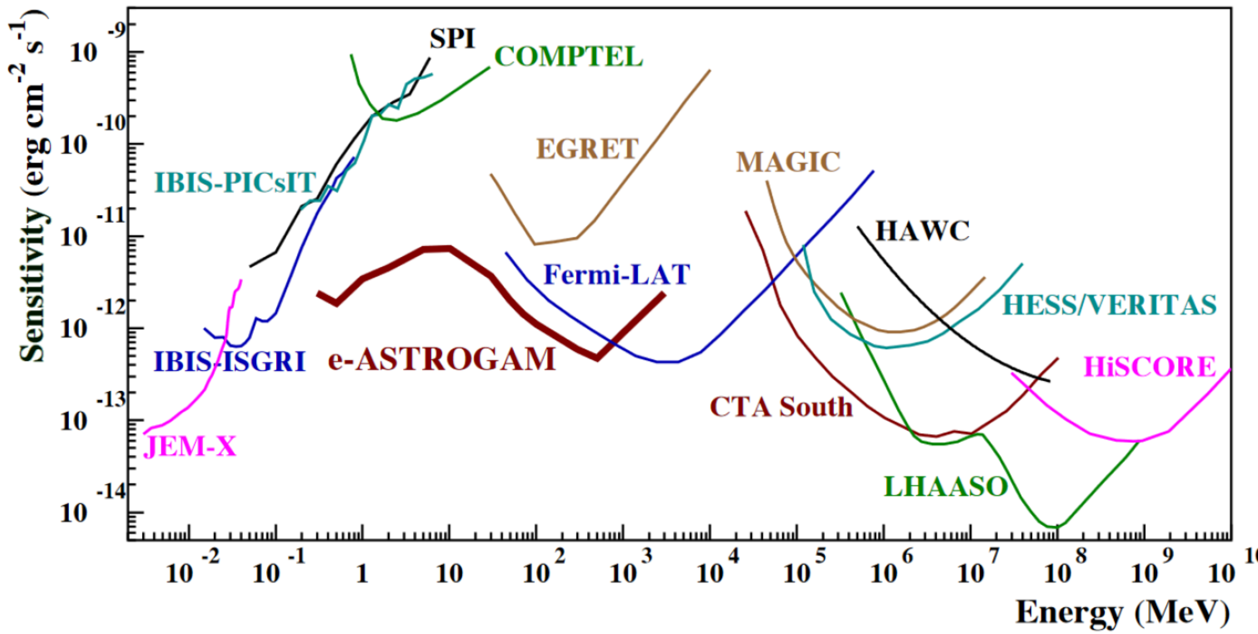

De Angelis et al' 18

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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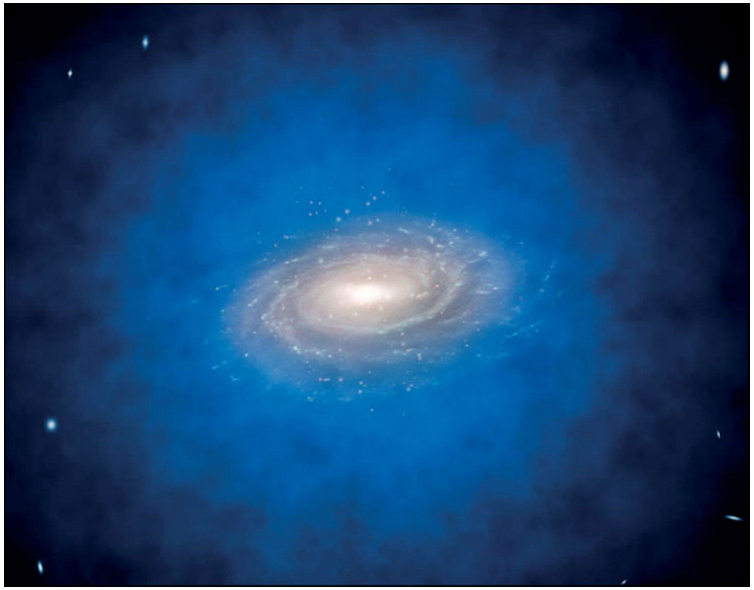

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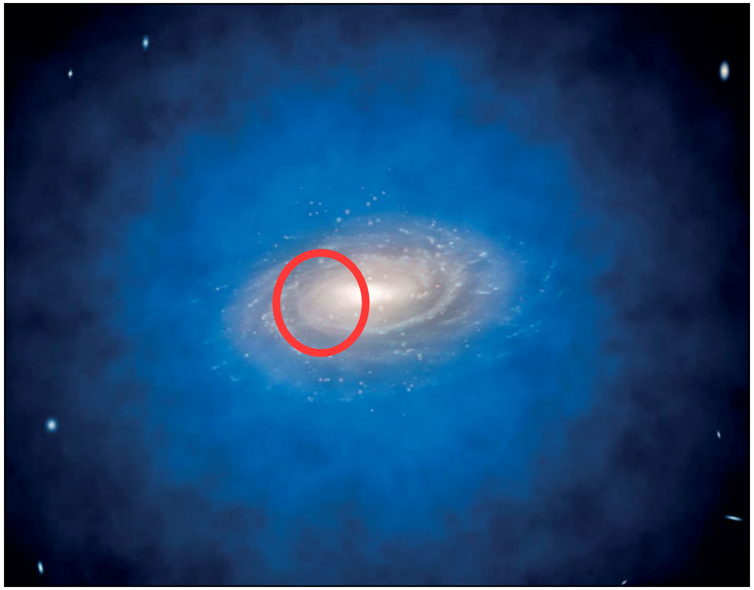
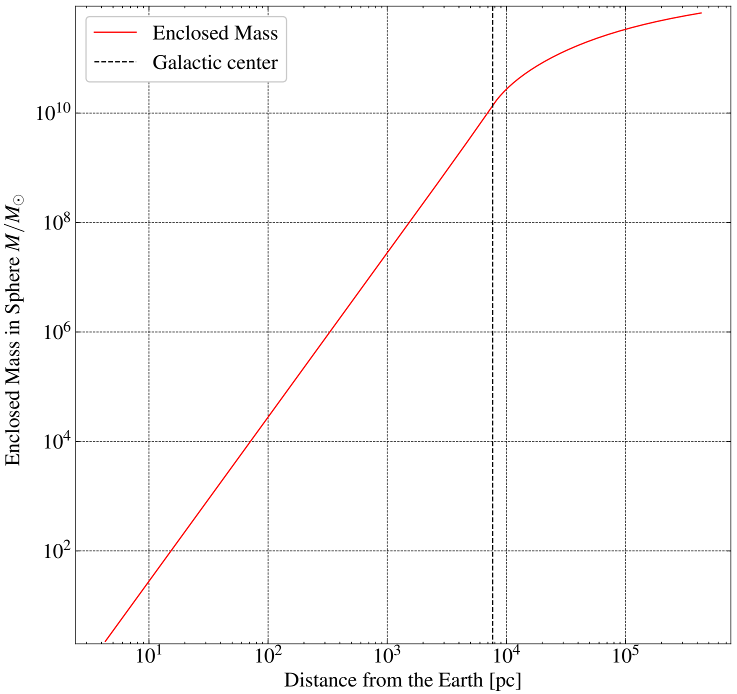
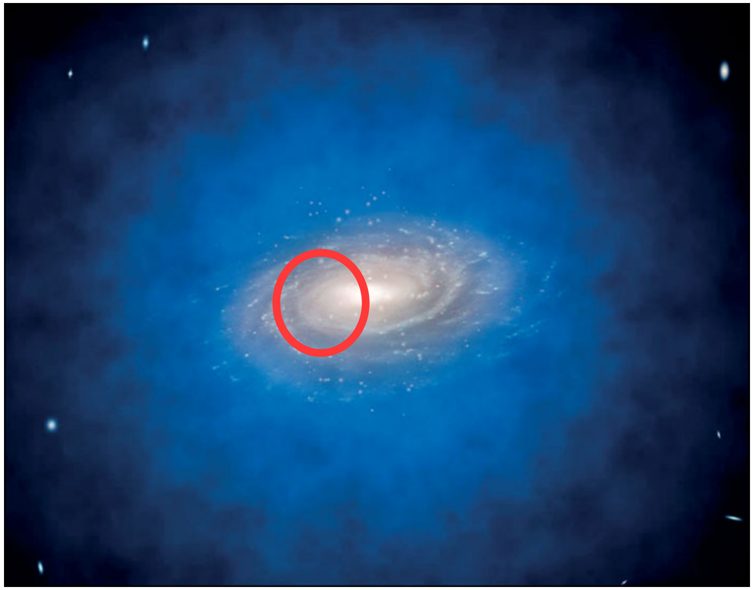
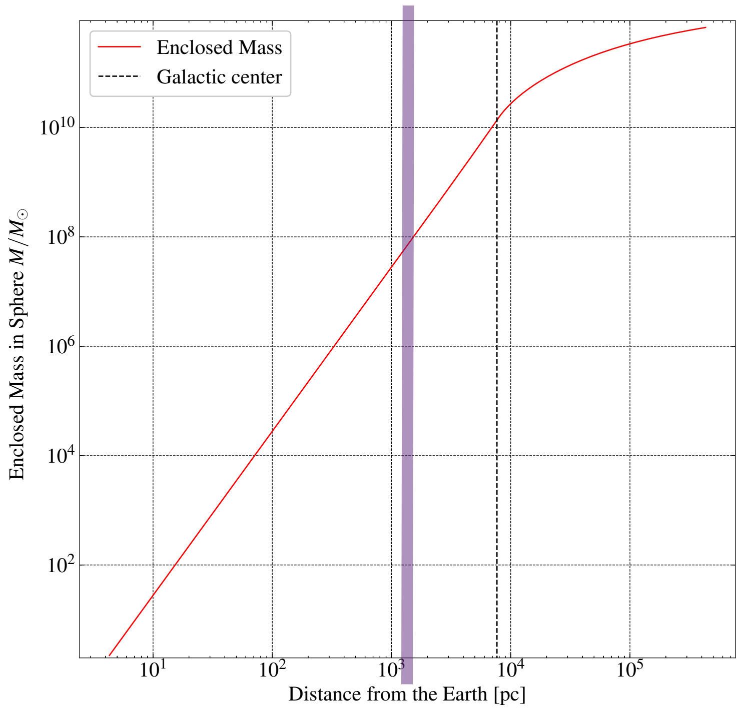




Signals from dark stars

How many dark stars within a distance *d* ?

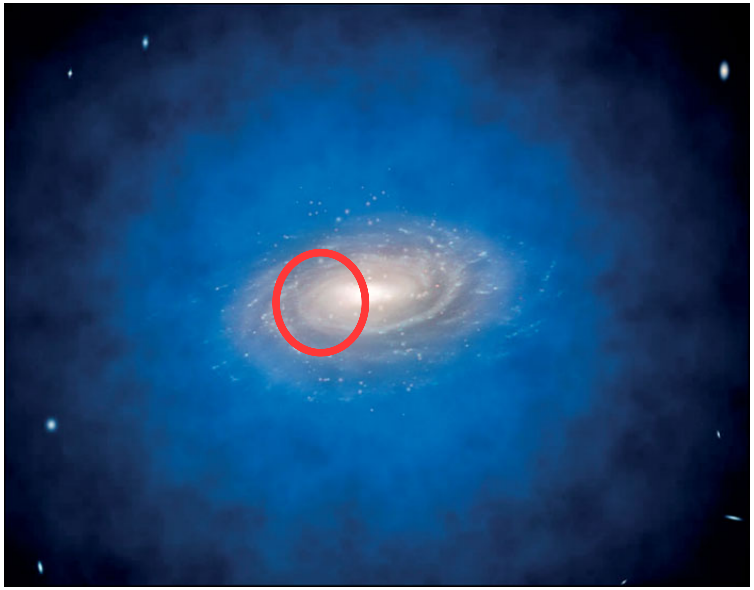


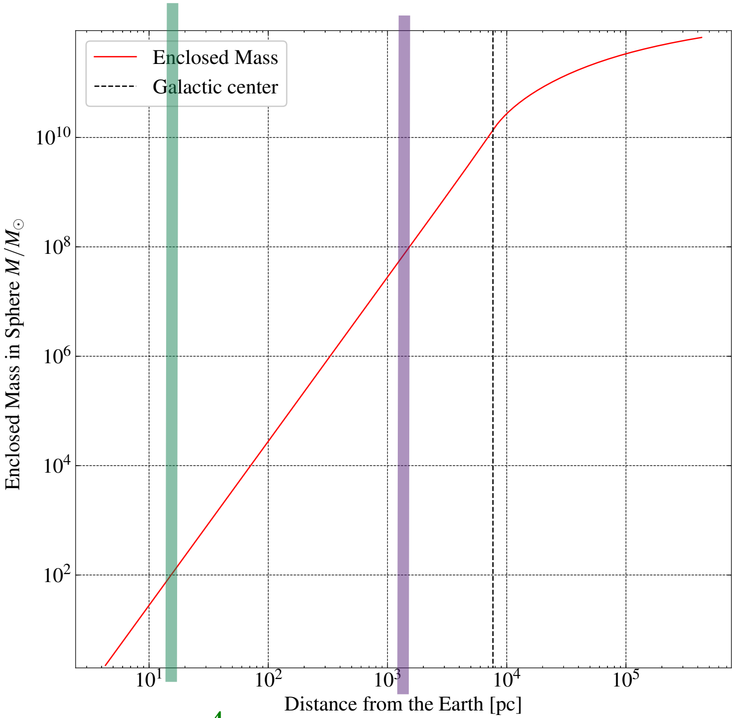


$L = L_\odot$

Signals from dark stars

How many dark stars within a distance d ?

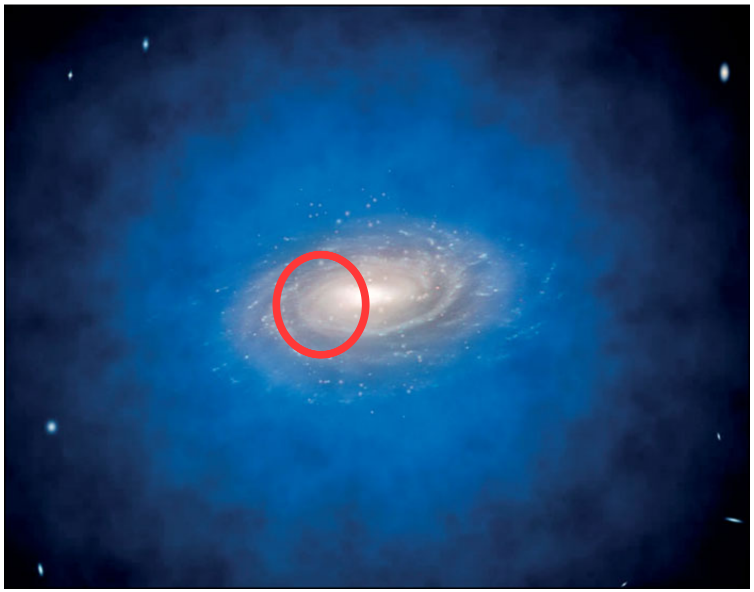


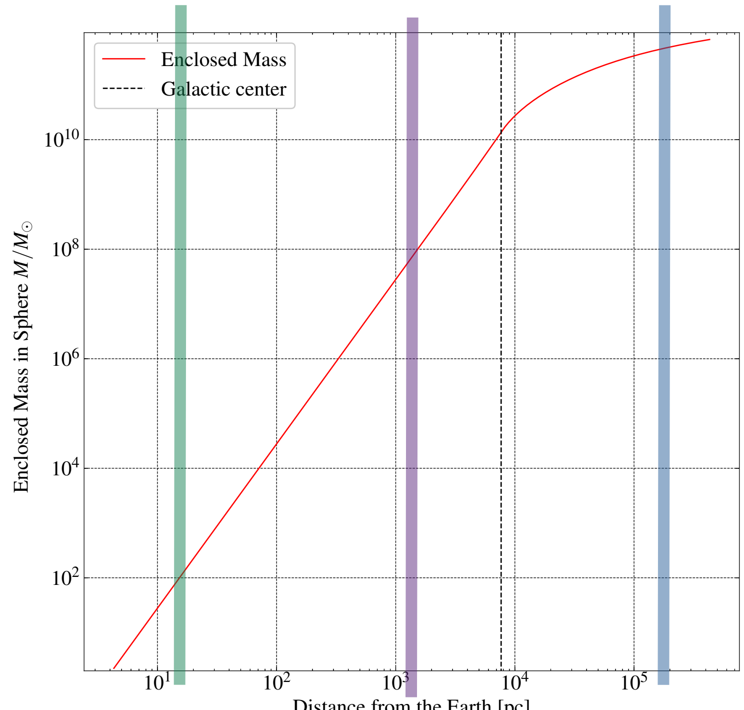


$L = 10^{-4} L_\odot$ $\quad L = L_\odot$

Signals from dark stars

How many dark stars within a distance d ?





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

Signals from dark stars

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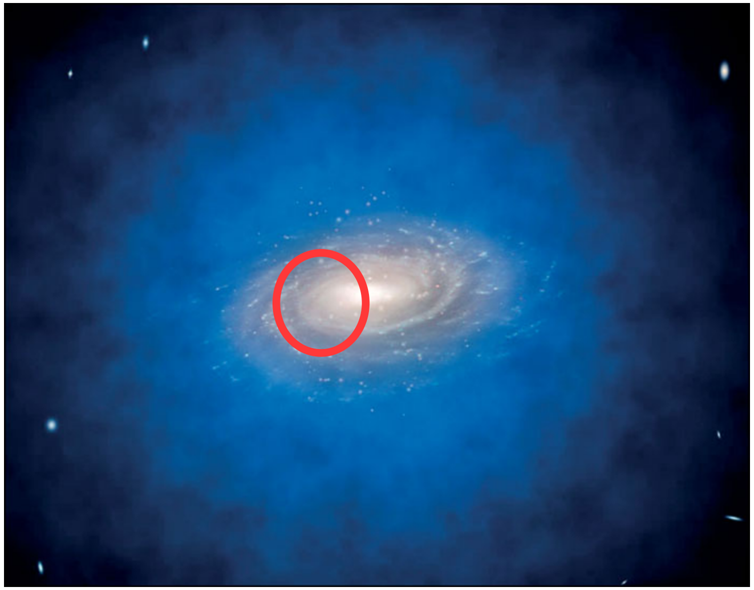
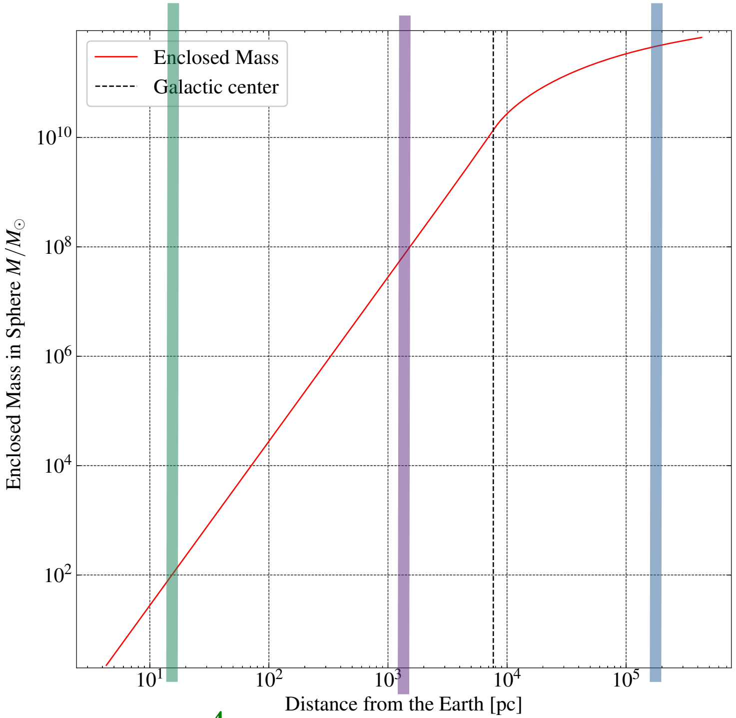




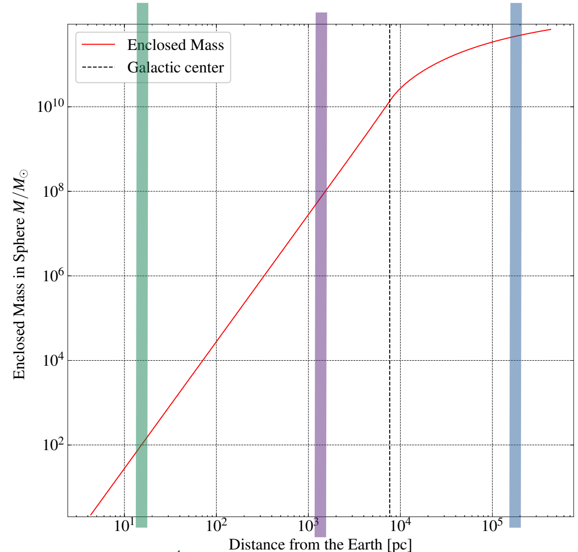
$L = 10^{-4} L_\odot$ $\quad L = L_\odot$ $\quad L = 10^{4} L_\odot$

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

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

$N_{\rm DS} \sim 100$ $\quad N_{\rm DS} \sim 10^{6}$ $\quad N_{\rm DS} \sim 10^{9}$

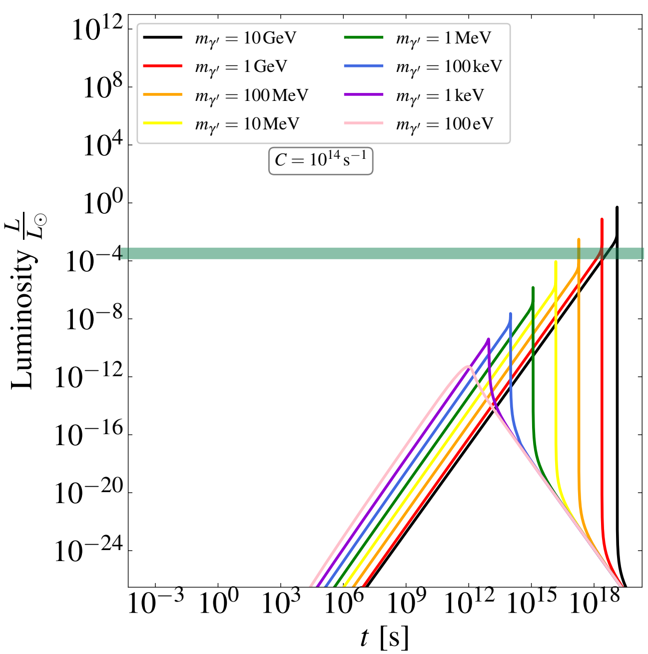
Signals from dark stars



$L = 10^{-4} L_\odot$ $\quad N_{\rm DS} \sim 100$

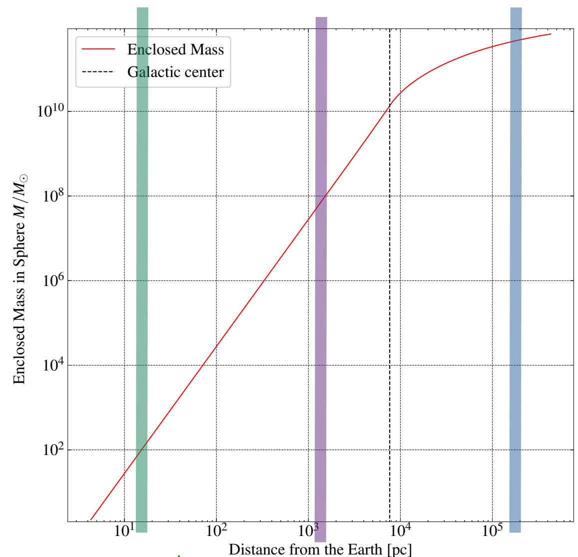
$L = L_\odot$ $\quad N_{\rm DS} \sim 10^6$

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



100 events if *all* DSs formed ~10^{18} s ago

Signals from dark stars



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

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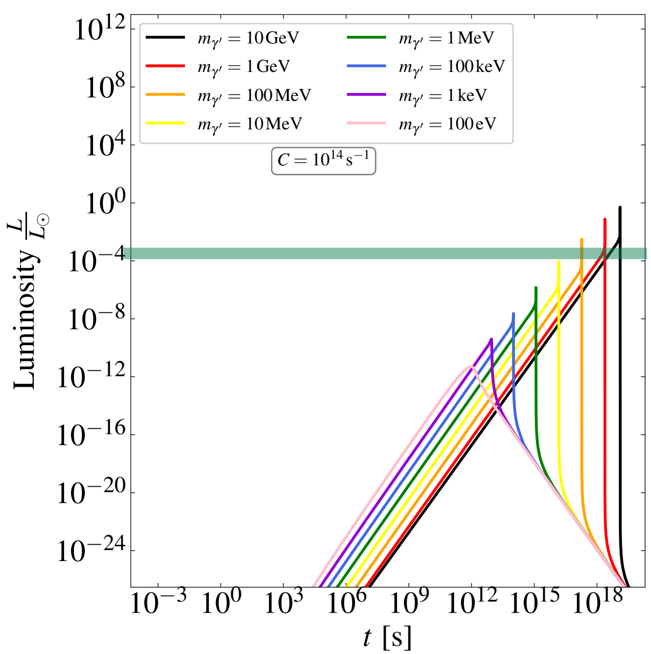
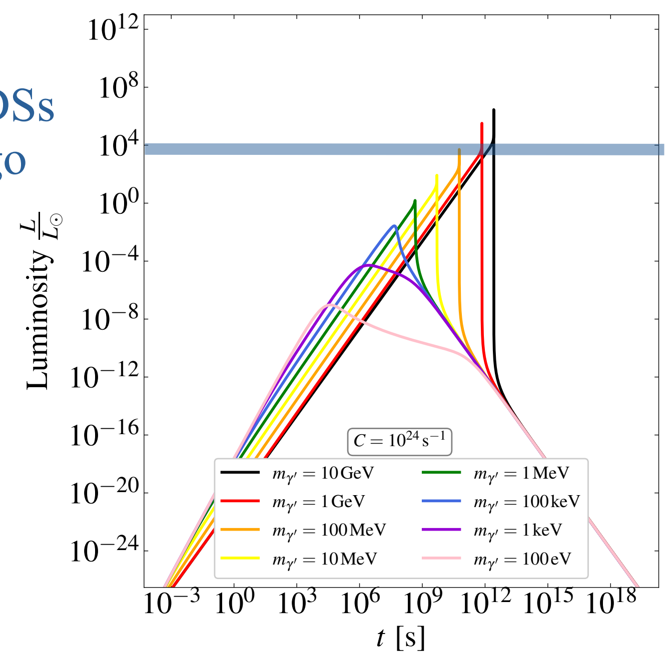
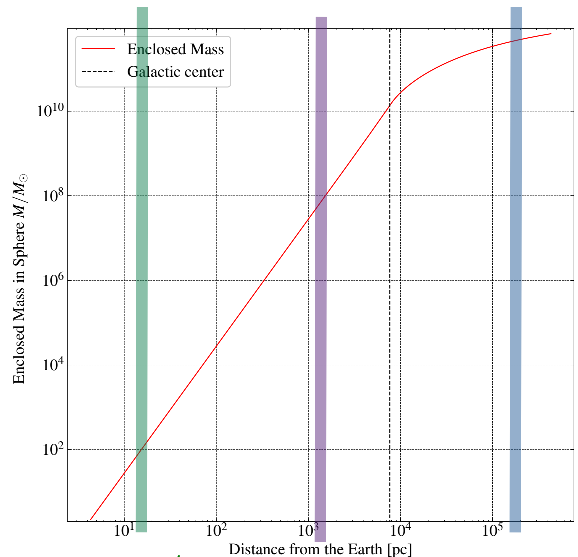


10^9 events if *all* DSs formed $\sim 10^{12}$ s ago

100 events if *all* DSs formed $\sim 10^{18}$ s ago



Signals from dark stars



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

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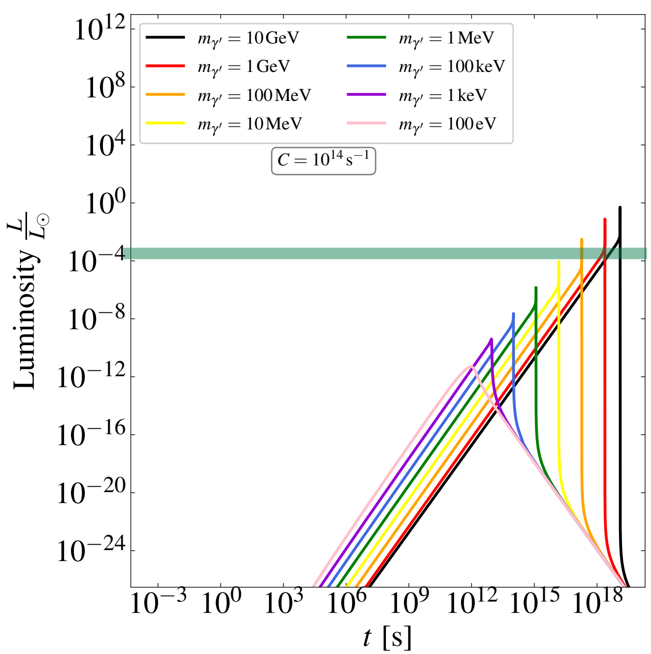

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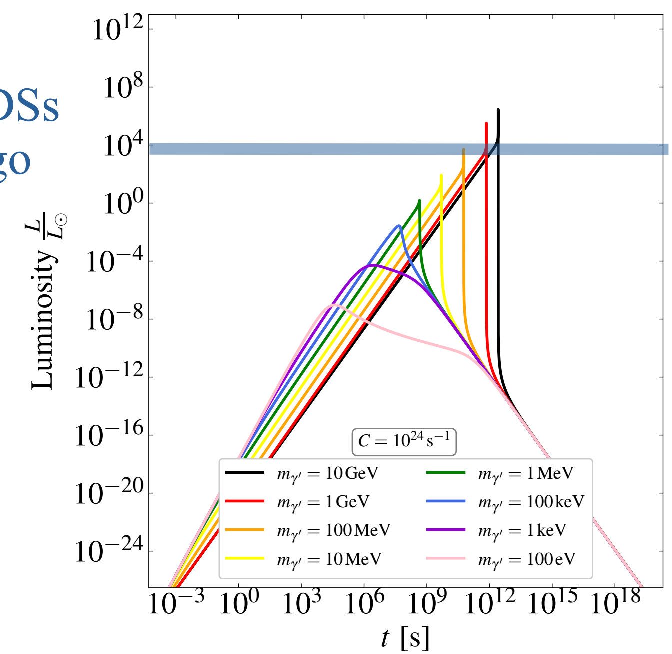
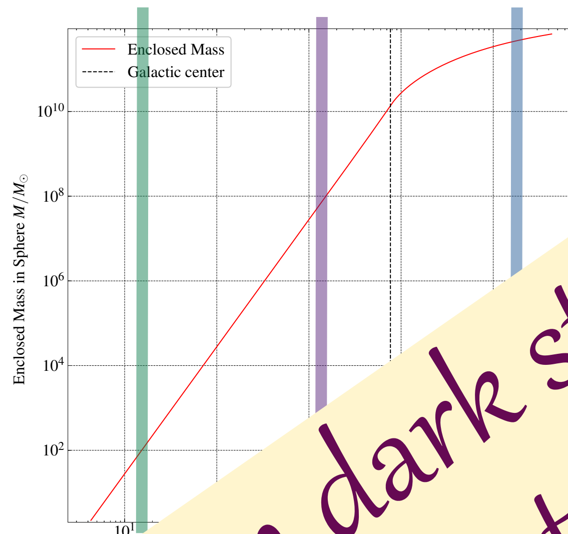


Dark stars could form continuously over time.

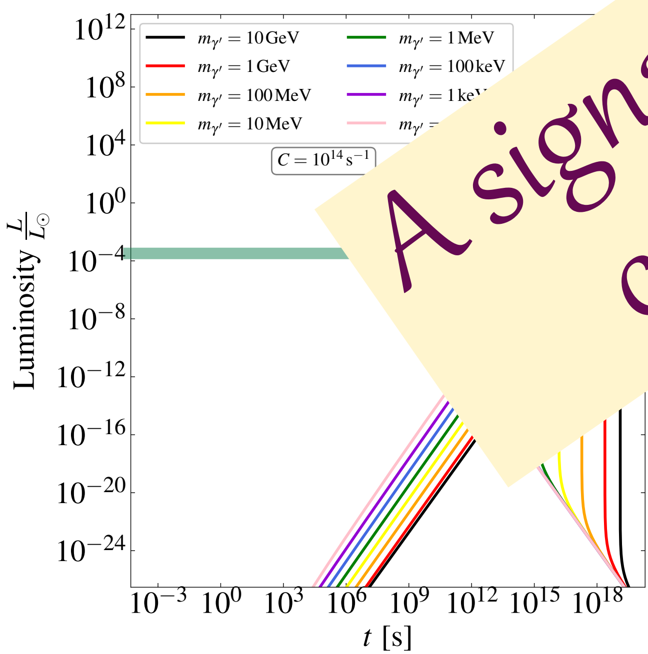
Signals from dark stars



A signal from dark stars could be detected

$L =$

10^9



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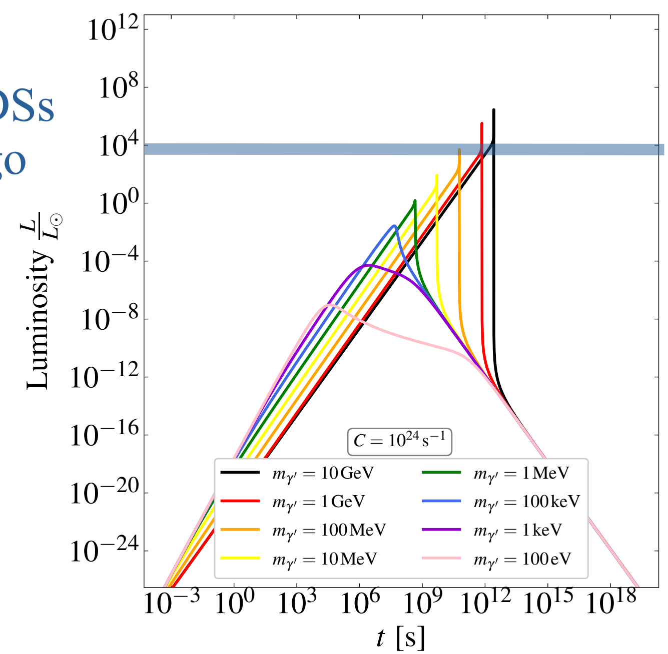
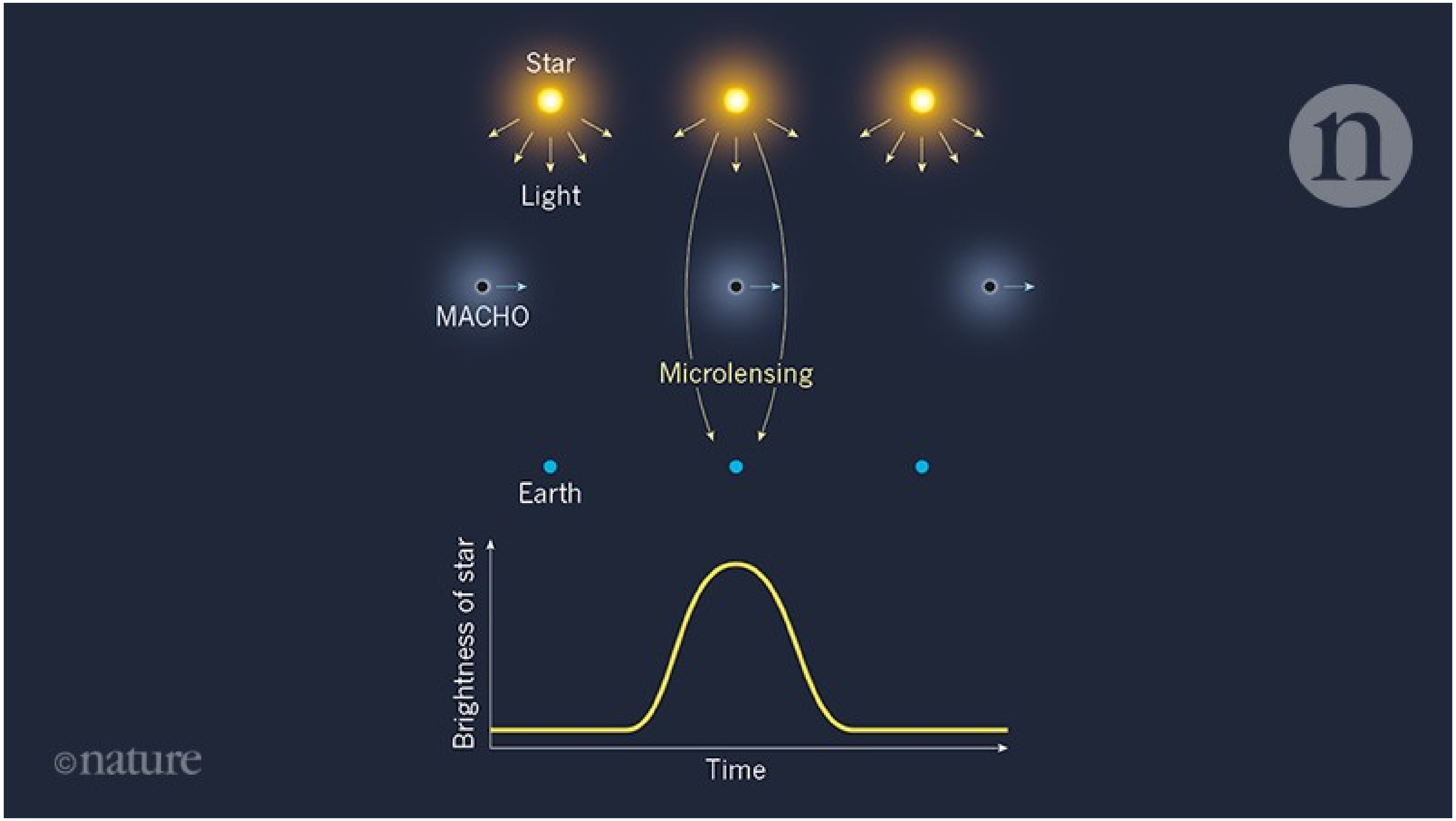


Dark stars could form continuously over time.

Signals from dark stars

Smoking gun: MACHO event, shining in X-rays or γ-rays.



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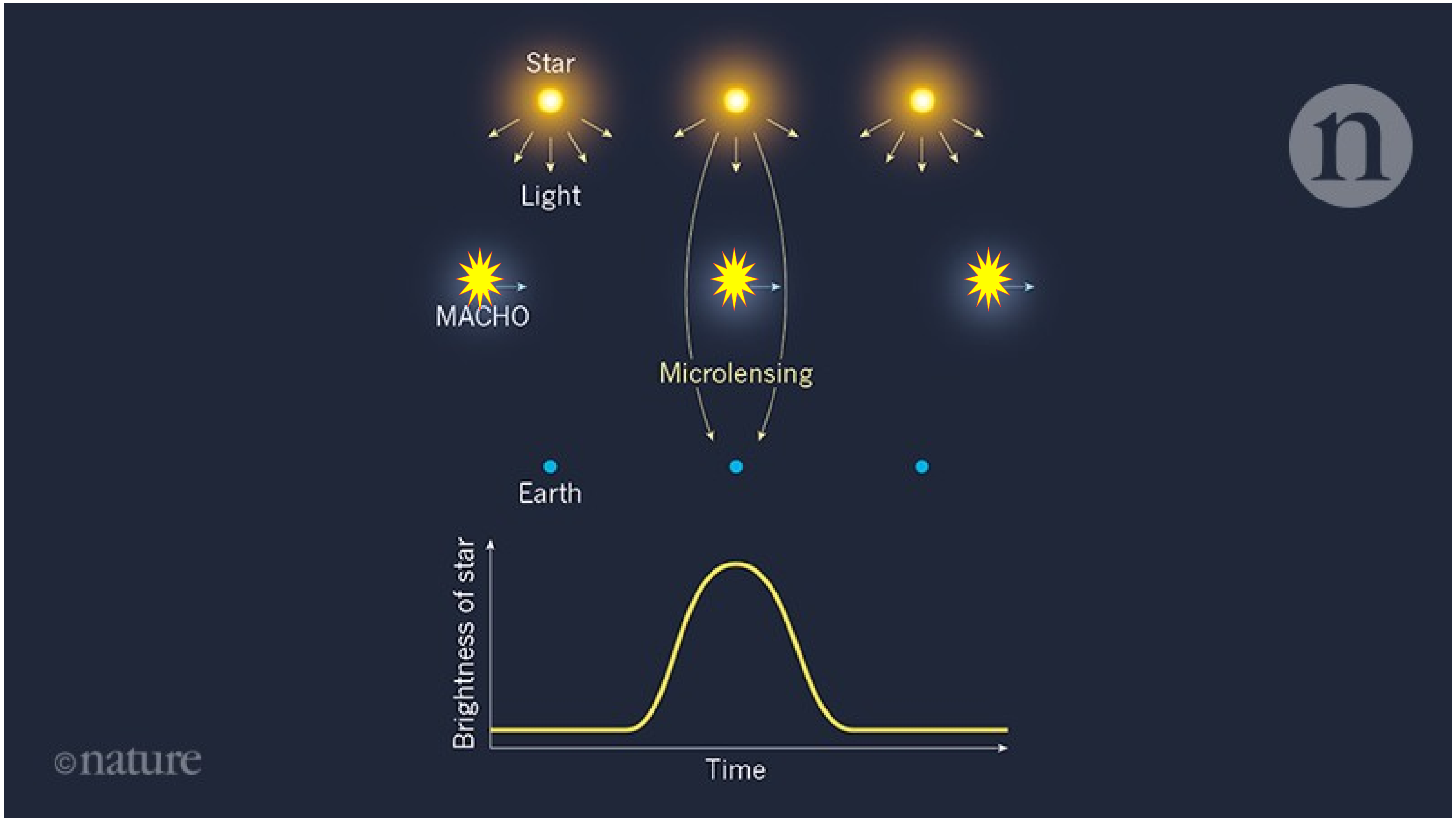

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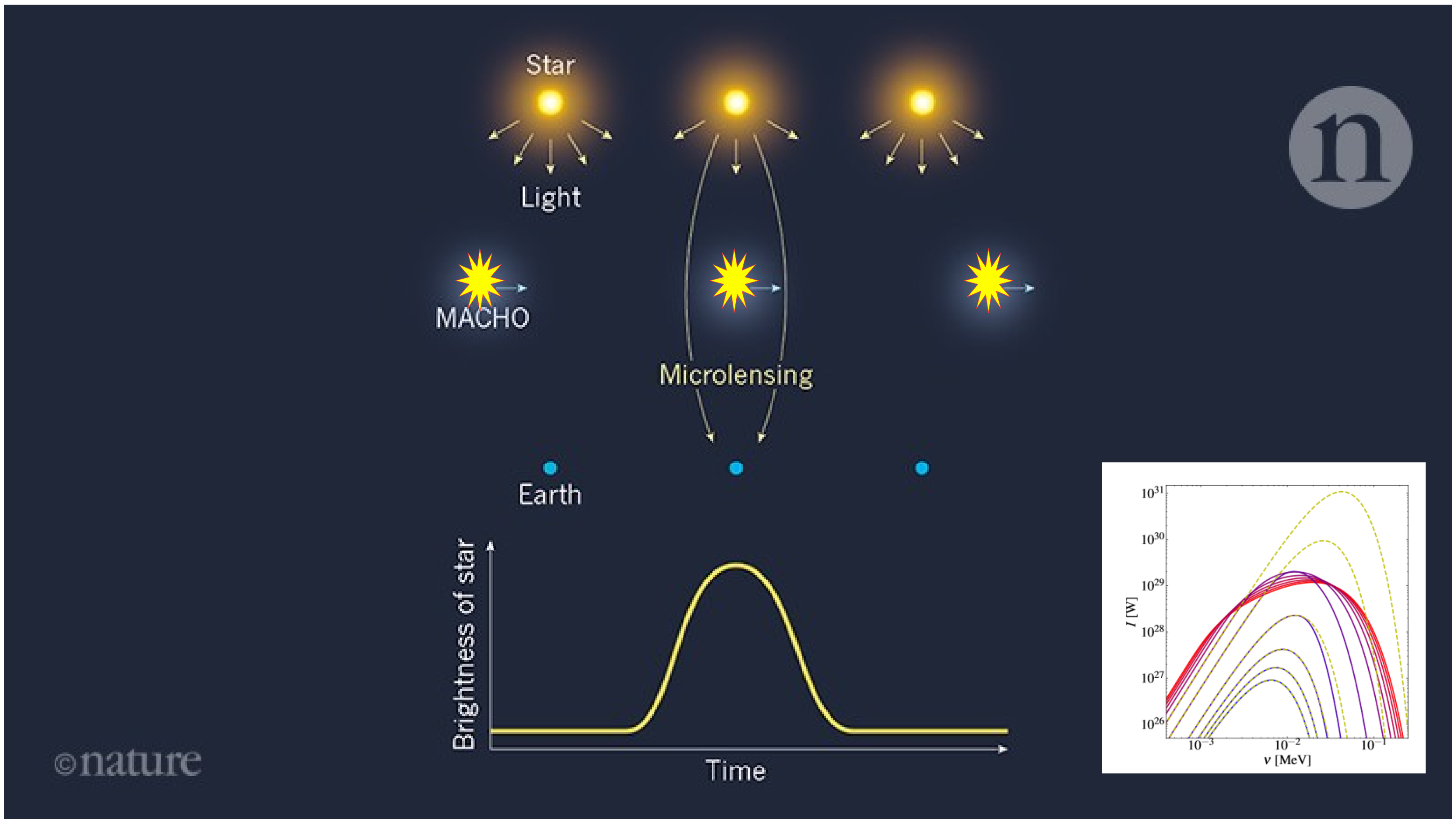

Conclusions

- 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.

- Point sources in X- or γ-rays could be detected at Earth. These sources would be also detected as MACHOs. Smoking gun for dark matter that interacts with itself and with protons/electrons.

- The radiation (and dark radiation) emitted by the dark star could have other astronomical or cosmological consequences (e.g. in reionization). In progress.