Self-interacting dark matter and monochromatic lines

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Dark Side of the Universe 2015

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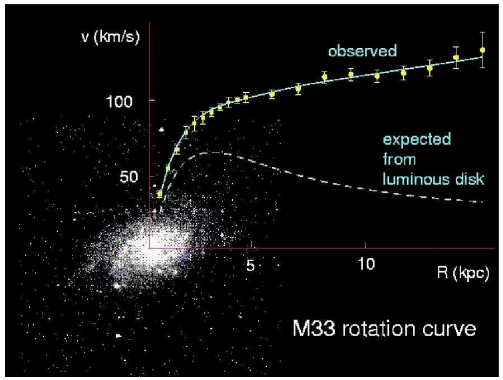
Outline

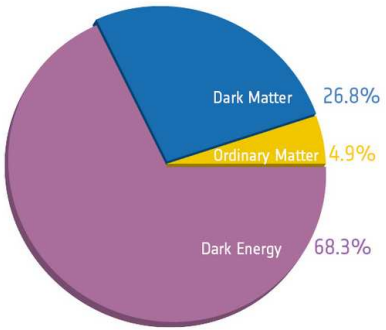
1. Evidences and features of dark matter
2. Self-interacting dark matter and monochromatic lines
   - Offset of the cluster Abell 3827
   - Monochromatic lines from DM annihilations
3. Simple model with psuedo-scalar dark matter
   - Self-interacting cross section
   - Monochromatic lines with constraints
   - Direct detection
4. Summary

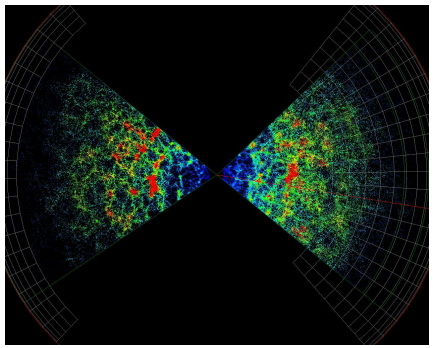
Evidences of dark matter

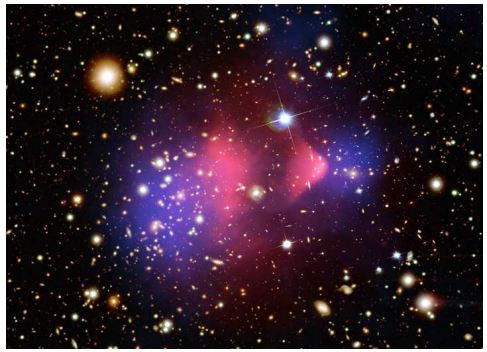
There are many evidences of dark matter.

- Rotation curves of spiral galaxies
- Observation of CMB $(\Omega h^2 = 0.12)$
- Gravitational lensing effect
- Large scale structure of the universe
- Collision of the bullet cluster





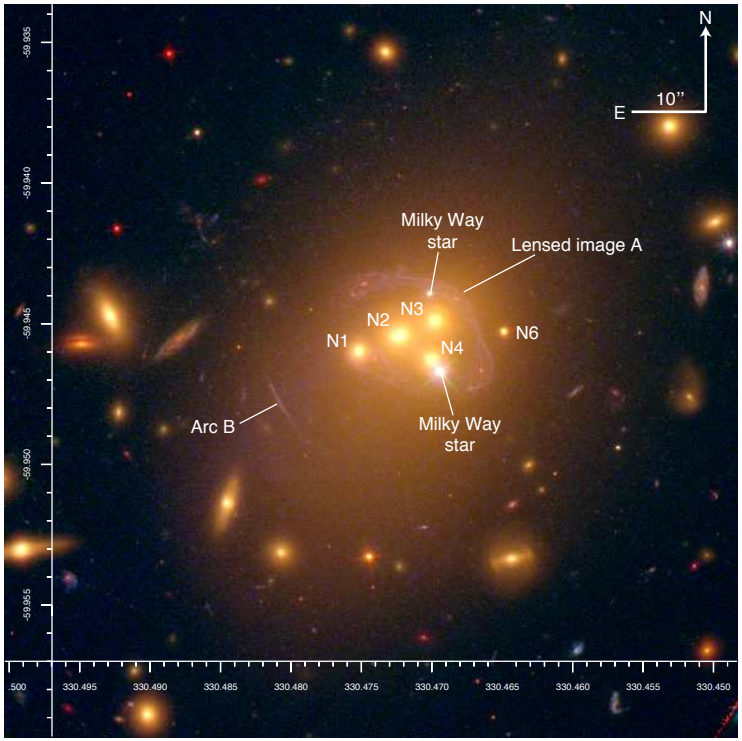


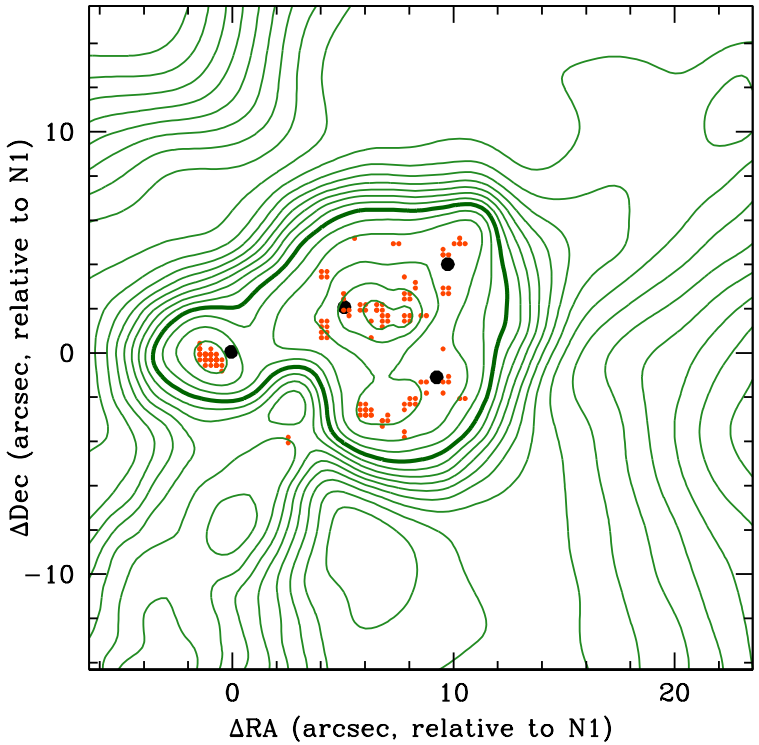


- Existence of dark matter is crucial.
- But its mass and interactions are not known yet.
- The evidences are all indirect through gravitational force.

Cluster Abell3827

- $z = 0.099$ (~ 430 Mpc from the Earth).
- Four galaxies (N1,N2,N3,N4) are localized.
- Offset between center of DM sub-halo and stars is suggested.
- N1 $\Delta = 1.62^{+0.47}_{-0.49}$ kpc offset (3.3 σ significance)
- Consistent between two independent approaches.

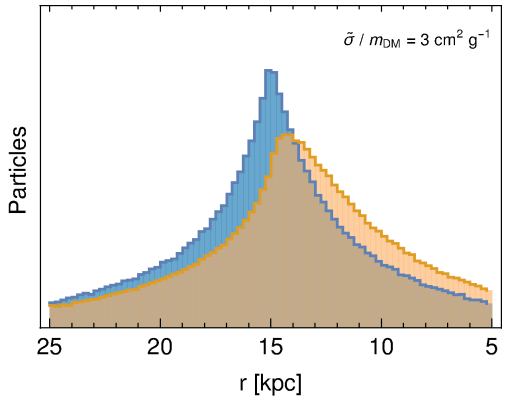




Cluster Abell3827

- Drag force is induced by self-interaction of DM
- 1.62 kpc offset may be interpreted as DM self-interaction

$$\sigma/m \sim 1.7 \times 10^{-4} \left(\frac{10^9 \mathrm{yrs}}{t_{\mathrm{infall}}}\right)^2 \ \mathrm{cm}^2/\mathrm{g}$$
$$\gtrsim 10^{-4} \ \mathrm{cm}^2/\mathrm{g}$$ arXiv:1504.03388
$$\sigma/m \sim 1.5 \ \mathrm{cm}^2/\mathrm{g}$$ arXiv:1504.06576



- Not easy to understand by WIMP with $\mathcal{O}(100)$ GeV.
  $\rightarrow \sigma/m \lesssim 10^{-11} \ \mathrm{cm}^2/\mathrm{g}$
  $\rightarrow$ other scenarios: $\mathbb{Z}_3$ SIMP, Sommerfeld enhancement with light mediator, hidden sector DM etc

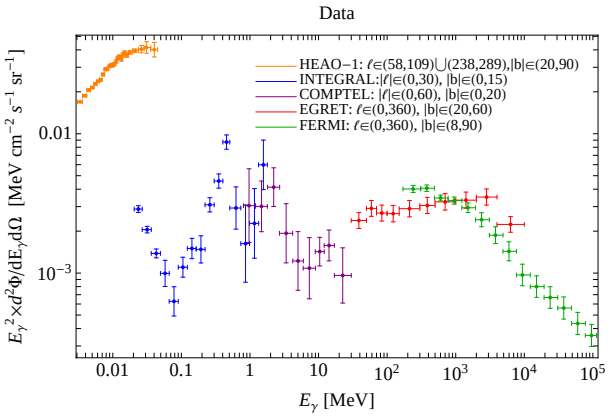
Monochromatic lines

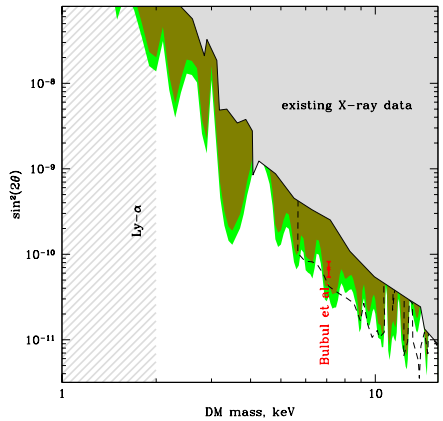
Monochromatic lines can be a smoking-gun signature of DM.

- Flux measured by HEAO-1, INTEGRAL, COMPTEL, EGRET.
- 3.5 keV X-ray excess observed in Perceus cluster and Andromeda galaxy. This may be interpreted by DM decay or annihilation.
- Non-detection from smaller galaxies.

· Milky Way arXiv:1405.7943,
· stacked galaxies arXiv:1408.4115

· dwarf stacked galaxies arXiv:1408.3531
In the case of 7.1 keV decaying DM





We discuss correlation between self-interacting dark matter and monochromatic lines.

The simple model

- add a SM singlet $\Phi = \dfrac{s + ia}{\sqrt{2}}$
- Self-interaction $\frac{\lambda}{4}|\Phi|^4$ is always allowed for a scalar DM.
- CP-odd particle a is massless under the exact global $U(1)$ symmetry. But at some high energy, $U(1) \to \mathbb{Z}_N$ breaking is expected by non-perturbative effect. $\to m_a \ll m_s$

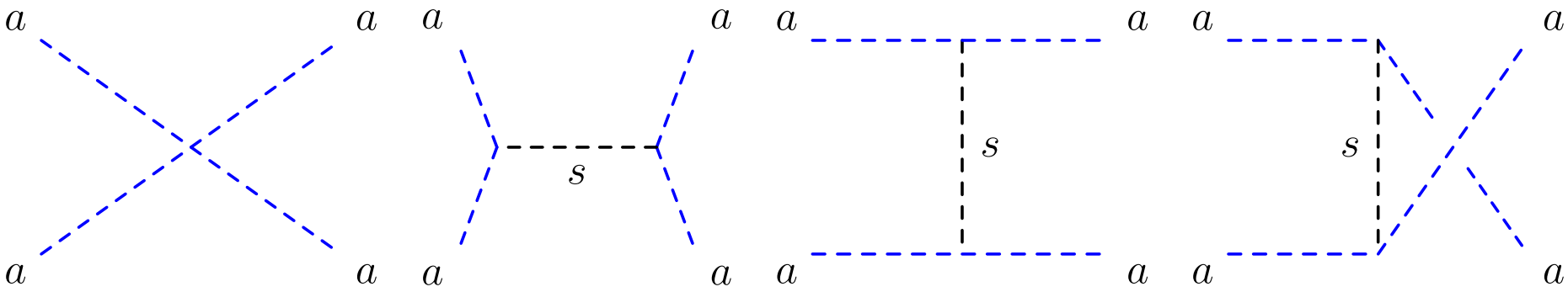
Scalar potential

$$\mathcal{V} = -\mu^2 |\Phi|^2 + \frac{\lambda}{4} |\Phi|^4 + \lambda_{H\Phi} |H|^2 |\Phi|^2$$

After symmetry breaking ($m_s = \sqrt{\lambda}\langle\Phi\rangle$)

$$\to \mathcal{V} = \frac{m_s^2}{2} s^2 + \frac{m_a^2}{2} a^2 + \frac{1}{2}\sqrt{\frac{\lambda}{2}} m_s s \left(s^2 + a^2\right) + \frac{\lambda}{16}\left(s^2 + a^2\right)^2$$

Self-interacting cross section



$$\frac{\sigma_{aa}}{m_a} = \frac{\lambda^2 m_a}{32\pi \left(4m_a^2 - m_s^2\right)^2} \approx \frac{\lambda^2 m_a}{32\pi m_s^4} \quad \text{for} \quad m_a \ll m_s$$

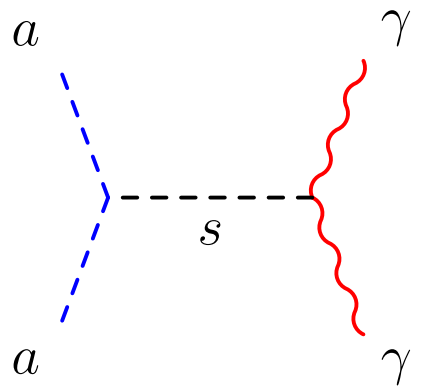
Features

- The cross section σ_{aa} is proportional to m_a^2.
- This is unusual behaviour (cf: $\sigma_{aa} \propto 1/m_a^2$) because of nature of pseudo-Goldstone boson DM.

Annihilation into photons

Effective interaction with photon

$$\mathcal{L}_\gamma = \frac{s}{\Lambda} F_{\mu\nu} F^{\mu\nu}$$



The cross section

$$\to \sigma_{\gamma\gamma} v = \frac{\lambda m_a^2 m_s^2}{\pi \Lambda^2 \left(m_s^2 - 4m_a^2\right)^2} \approx \frac{\lambda m_a^2}{\pi \Lambda^2 m_s^2}$$

- The cross section is proportional to m_a^2.
- The cut-off scale Λ is constrained by observations.

Combine with the self-interacting cross section

$$\sigma v_{\gamma\gamma} = \sqrt{\frac{2}{\pi}} \frac{4 m_a^{3/2}}{\Lambda^2} \sqrt{\frac{\sigma_{aa}}{m_a}}$$

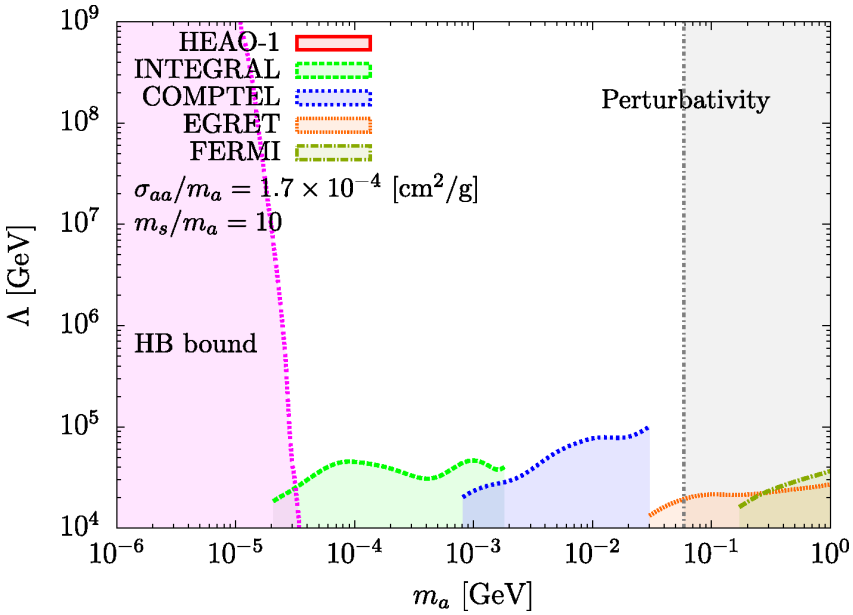
$$\approx 1.3 \times 10^{-33} \left(\frac{100\ \mathrm{TeV}}{\Lambda}\right)^2 \left(\frac{m_a}{3\ \mathrm{keV}}\right)^{3/2} \left(\frac{\sigma_{aa}/m_a}{1\ \mathrm{cm}^2/\mathrm{g}}\right)^{1/2} \ [\mathrm{cm}^3/\mathrm{s}]$$

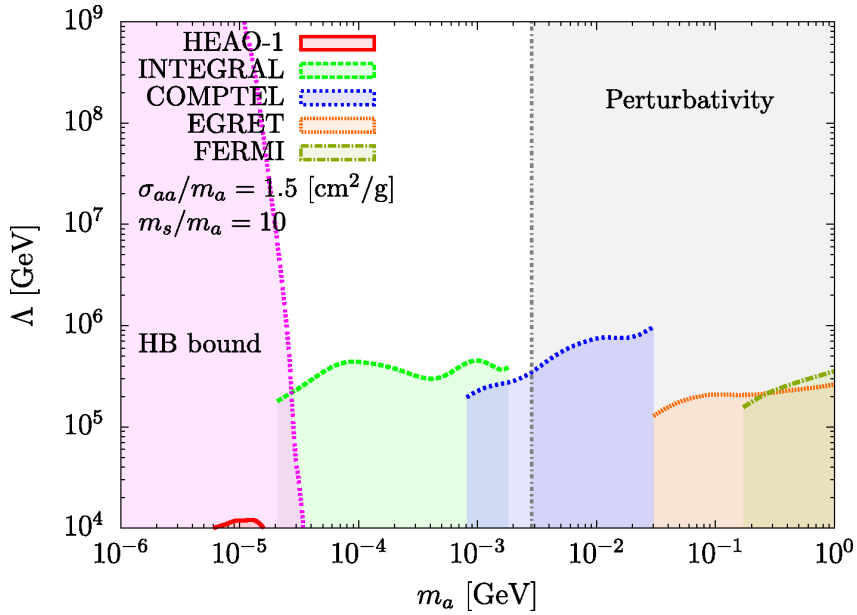
Constraints on Λ

- Horizontal Branch stars
  The mediator particle s can be produced in stars
  helium burning lifetime in stars is shortened $\rightarrow$ give a constraint.
- Mono-photon plus missing energy (ASP and LEP bounds)
  $e^+e^- \rightarrow \gamma \rightarrow s\gamma$

  s decays outside the detector $\Gamma_s = \dfrac{m_s^3}{4\pi\Lambda^2} <$ a few m
- Perturbativity of self-coupling $\lambda \leq 4\pi$
- DM annihilations into photons
  HEAO-1, INTEGRAL, COMPTEL, EGRET, FERMI
  keV $-$ GeV scale of DM mass is constrained.

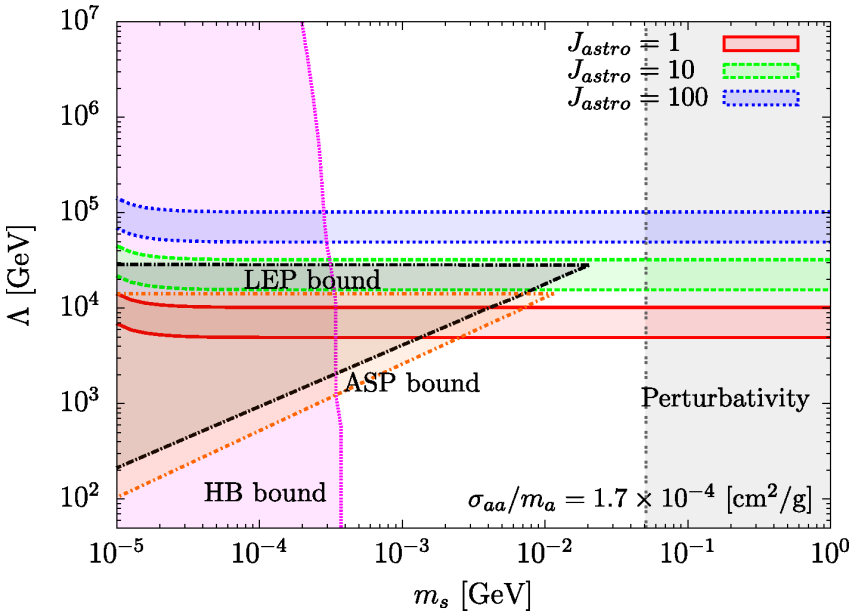
Allowed parameter space

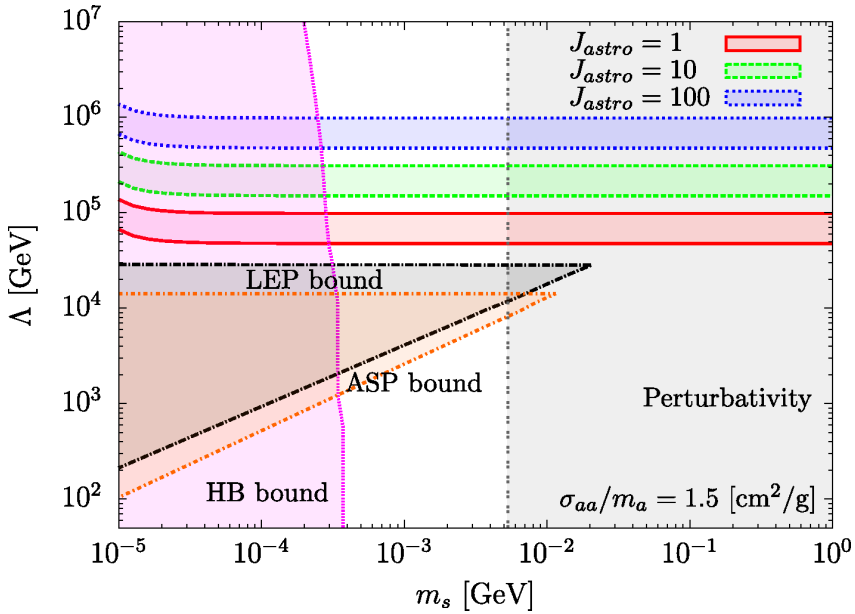




- DM mass is bounded by HB and perturbativity.
  For $\sigma_{aa}/m_a = 1.7 \times 10^{-4}$ cm^2/g, 10 keV $\lesssim m_a \lesssim$ 10 MeV and $\Lambda \gtrsim 10^5$ GeV
  For $\sigma_{aa}/m_a = 1.5$ cm^2/g, 10 keV $\lesssim m_a \lesssim$ 1 MeV and $\Lambda \gtrsim 10^6$ GeV

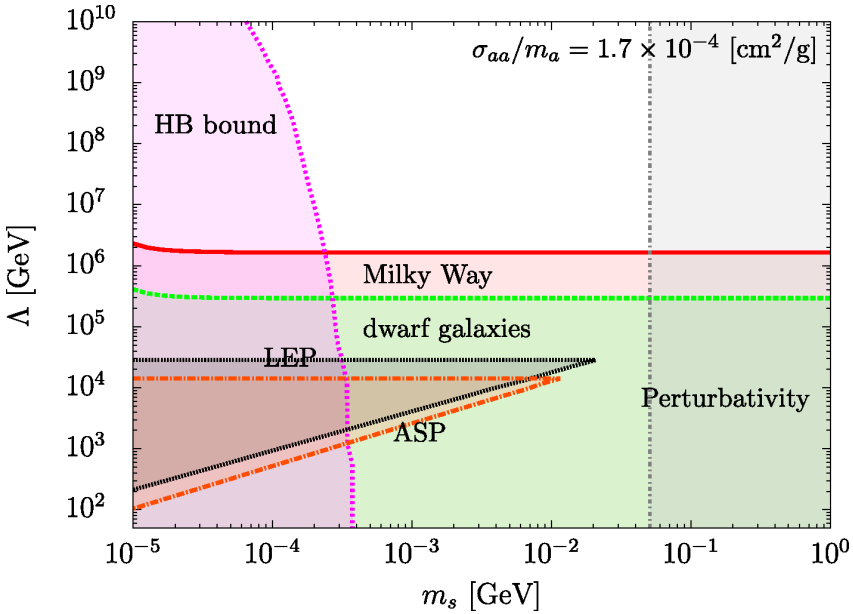
To fit to the 3.5 keV X-ray line

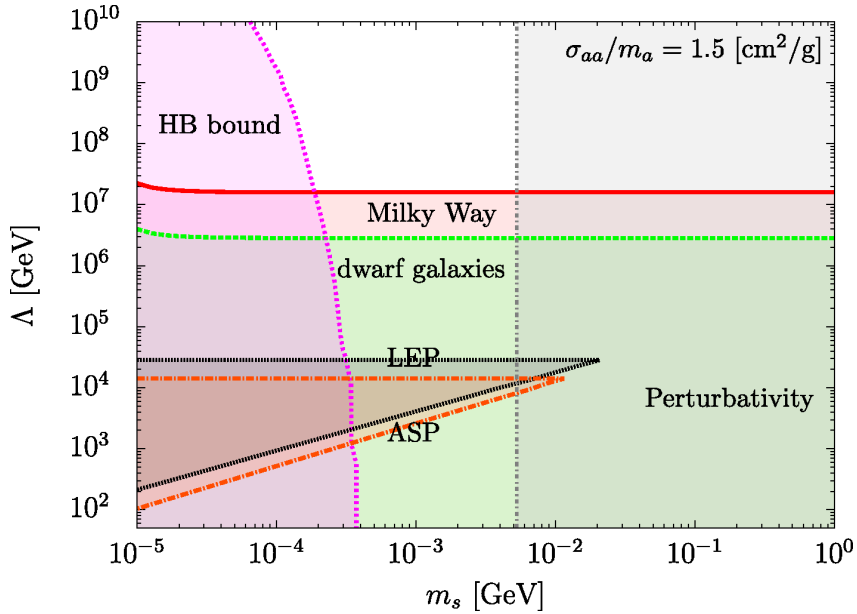




- m_a is fixed to $m_a = 3.5$ keV.
- J_{astro} is astrophysical uncertainty
- $10\ \mathrm{TeV} \lesssim \Lambda \lesssim 1000\ \mathrm{TeV}$ is favoured to fit the excess.

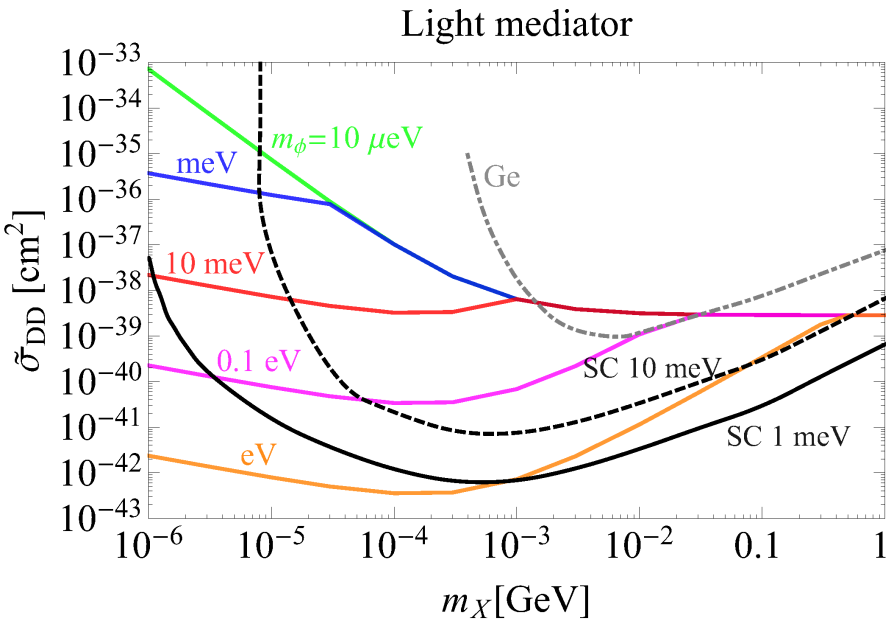
Non-detection of the X-ray excess

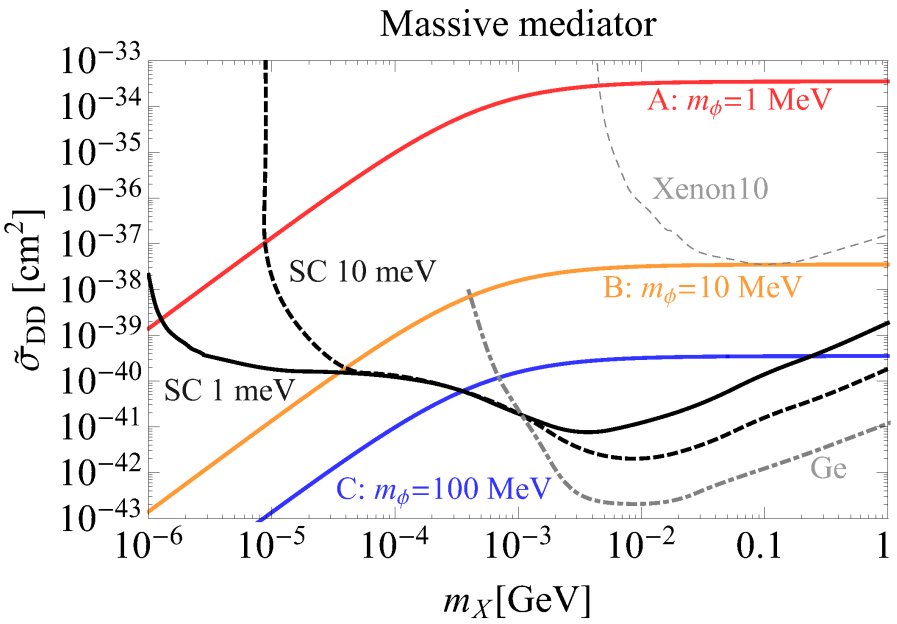




- $\sigma v_{\gamma\gamma} \lesssim 2.5 \times 10^{-36}\ \mathrm{cm}^3/\mathrm{s}$ from stacked dwarf galaxies.
- Interpretation by DM annihilation (decay) is excluded (NFW).
- Other scenarios like an excited DM model can evade.

Direct detection of light DM

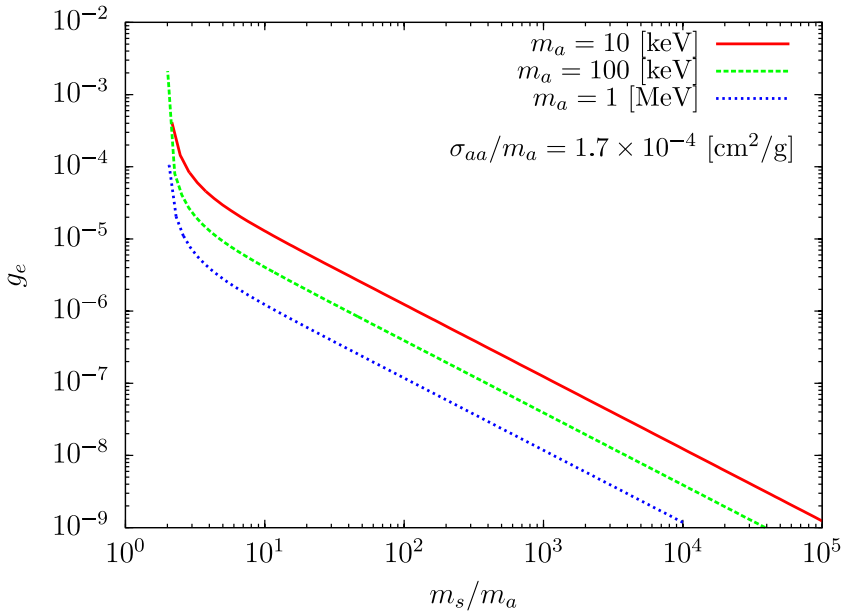


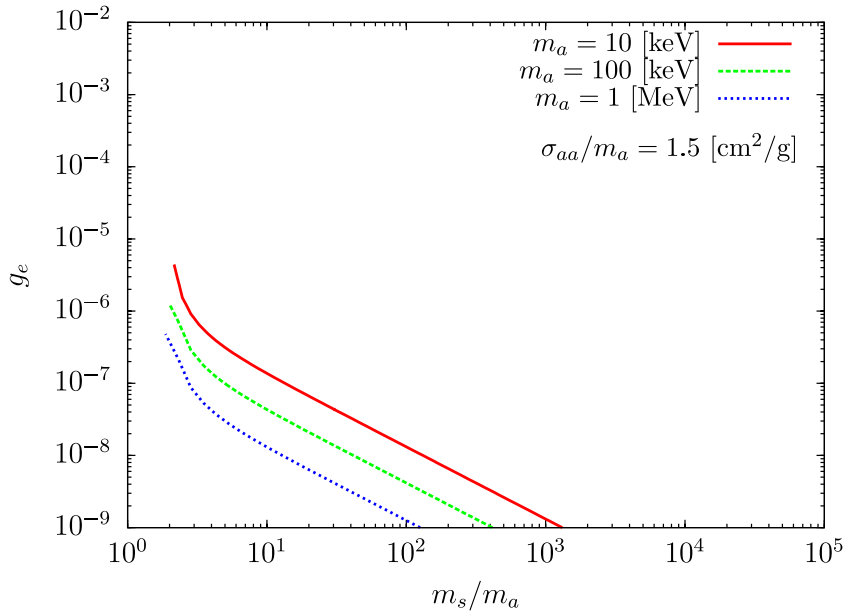


arXiv:1504.07237

- Future experiment with superconductors
- Exploring scattering event with electron
- DM mass target range: 10 keV – 1 GeV
- Expected sensitivity of recoil energy is up to $\mathcal{O}(\mathrm{meV})$

Direct detection of light DM





When the interaction with electron $\mathcal{L} = g_e s\bar{e}e$ is concerned (generated from Higgs mixing)

$$\sigma^e_{\rm DD} = \frac{\lambda^2 g_e^2}{2\pi m_s^4} \frac{m_a^2 m_e^2}{(m_a + m_e)^2} \frac{m_s^2}{4m_a^2}$$

- Coupling up to $g_e \gtrsim 10^{-7}$ can be testable (1kg·year exposure).
- $g_e \lesssim 10^{-7}$ is excluded by perturbativity of λ.

Summary

1. Observation of Abell3827 may imply self-interacting DM.
2. We cosnidered a simple pseudo-scalar DM model.
3. Allowed DM mass scale is keV – MeV in order to have self-interacting cross section being comparable with Abell.
4. This range of DM mass may be searched by future direct detection experiment with superconductors and future gamma-ray experiments like ASTROGAM.