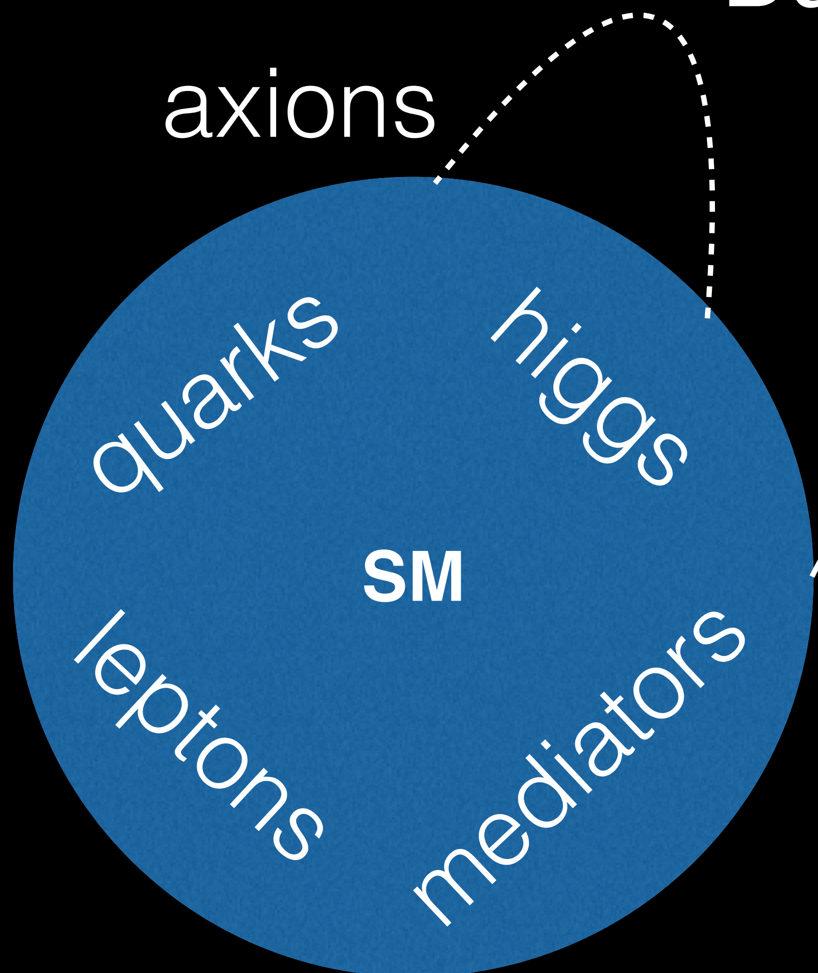
Dark Matter in Neutron Star Mergers

Sanjay Reddy
University of Washington

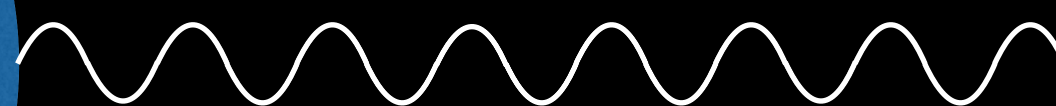
- Sub GeV dark matter
- Some existing constraints
- How to use gravitational waves from BNS mergers to constrain or discover dark sectors.

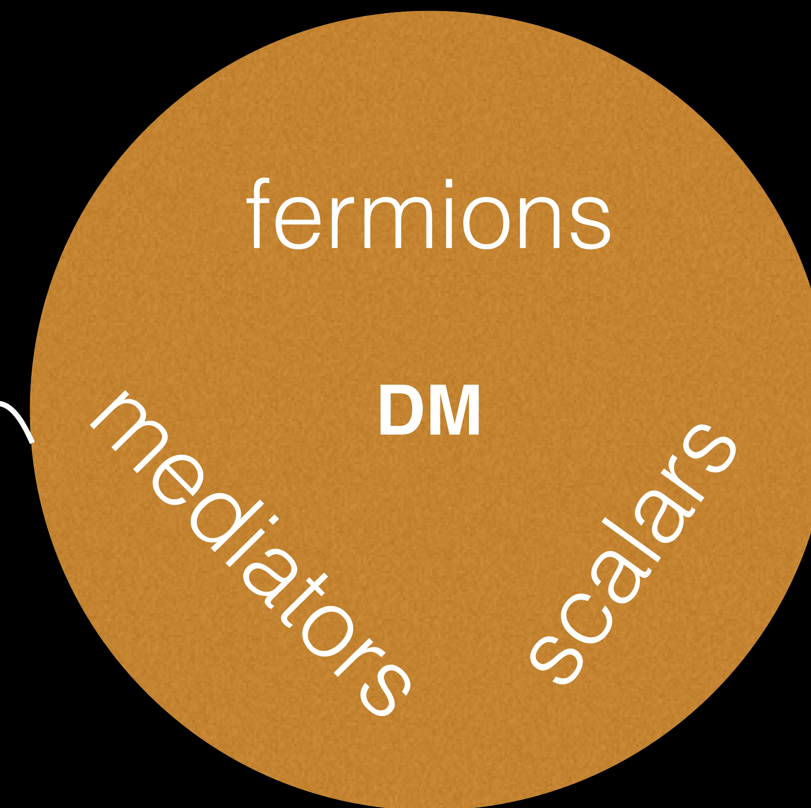
Dark Sector Phenomenology



Messengers:

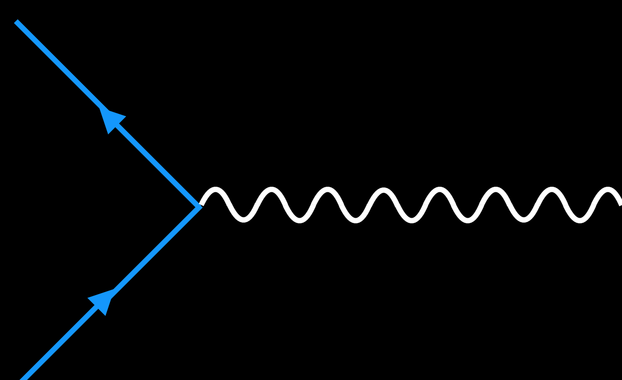
- Dark “photons”
- Dark “Z”s
- Scalars

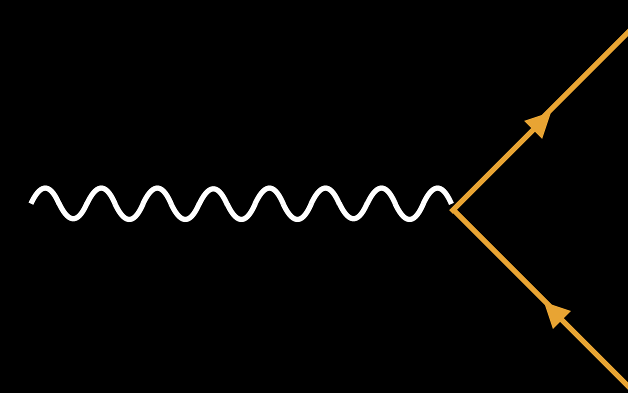




At low energy:

$$\mathcal{L}_{A'f} = g_f \; A'_\mu \; \bar{\psi}_f \gamma^\mu \psi_f$$



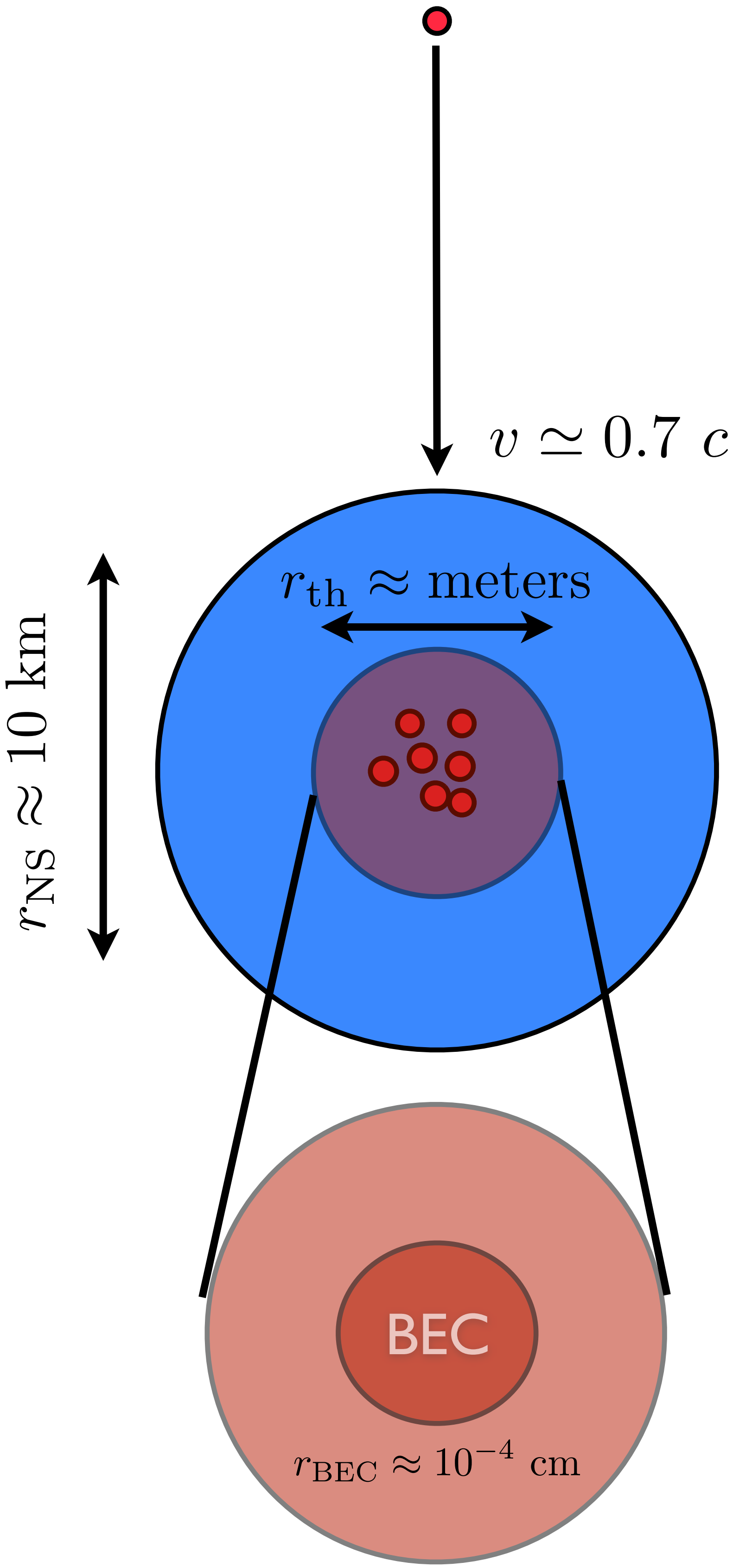


$$V_{\chi B} = \frac{g_\chi g_B}{q^2 + m_\phi^2} = g_\chi g_B \; \frac{e^{-m_\phi r}}{r}$$

$$V_{\chi\chi} = \frac{g_\chi^2}{q^2 + m_\phi^2} = g_\chi^2 \; \frac{e^{-m_\phi r}}{r}$$

DM Accretion onto Neutron Stars

For a concise recent review see Kouvaris (2013)



Mass accretion rate:

$$M_{\rm acc} = 1.3 \times 10^{43} \left(\frac{\rho_{\rm dm}}{0.3 {\rm GeV/cm^3}}\right) \left(\frac{t}{\rm Gyr}\right) f\ {\rm GeV}$$

where $f = {\rm Min}\ [1,\ \frac{\sigma}{10^{-45}\ {\rm cm}^2}]$

Thermalization:

$$\frac{GM(r_{th})m_\chi}{r_{th}} \approx \frac{3}{2}T \Rightarrow r_{th} \approx 2.2\ {\rm m} \left(\frac{T}{10^5\ {\rm K}}\right)^{1/2} \left(\frac{\rm GeV}{m_\chi}\right)^{1/2}$$

Self-Gravitation:

$$M_{\rm sg} > \frac{4}{3}\pi\rho_c r_{\rm th}^3 = 2.2 \times 10^{46}\ {\rm GeV} \left(\frac{m}{\rm GeV}\right)^{-3/2}$$

Bose Einstein Condensation:

$$M_{\rm BEC} > 8 \times 10^{27} \left(\frac{\rm GeV}{m}\right)^{1.5}\ {\rm GeV}$$

Formation of BEC triggers collapse.

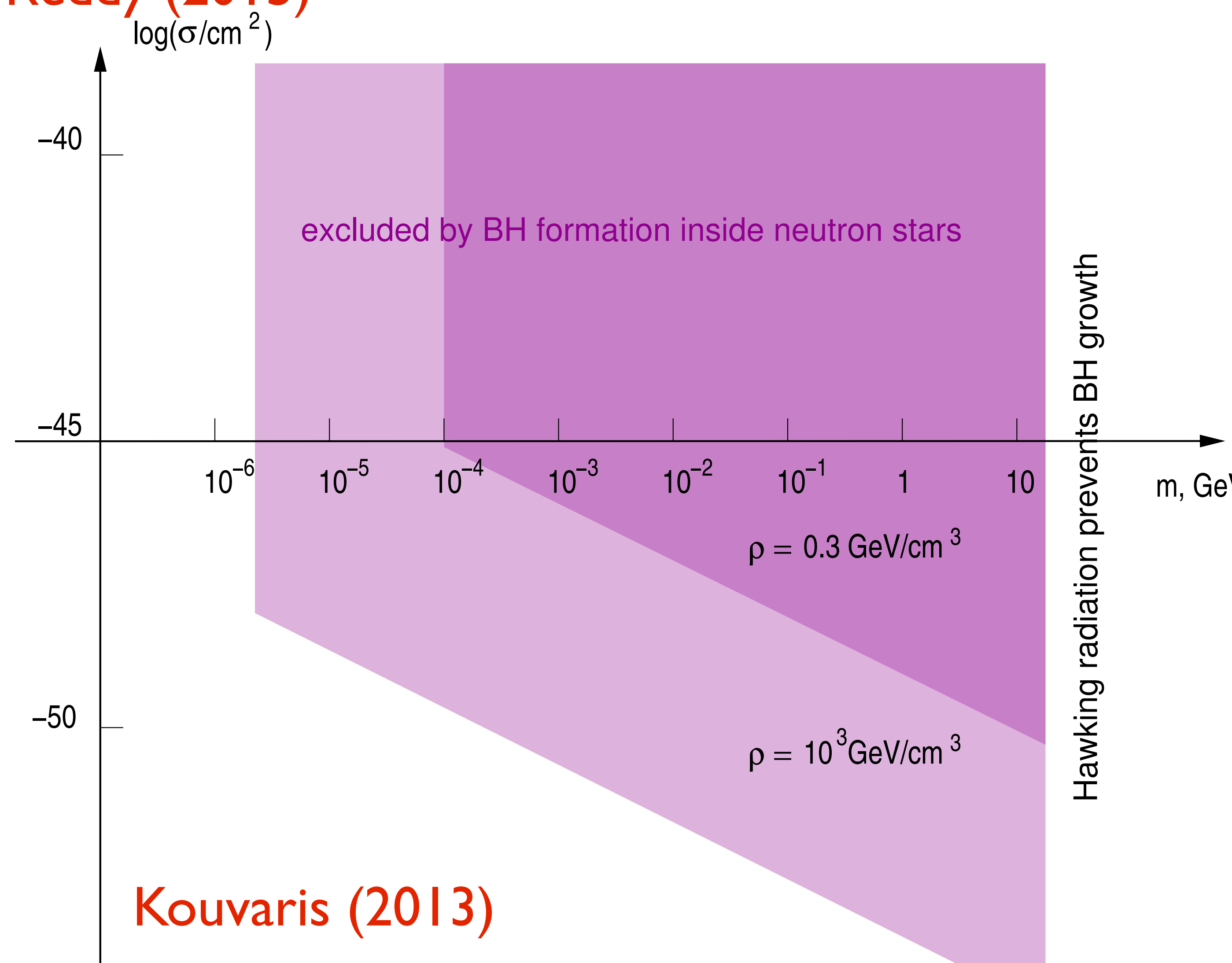
Black-hole Formation

Idea: Asymmetric bosonic dark matter can induce the collapse of the NS to a black hole. Goldman & Nussinov (1989)

This idea has been explored in more detail by:

- Kouvaris and Tinyakov (2011)
- McDermott, Yu and Zurek (2012)
- Kouvaris (2012) & (2013)
- Guver, Erkoca, Reno, Sarcevic (2012)
- Fan, Yang, Chang (2012)
- Bell, Melatos and Petraki (2013)
- Jamison (2013)
- Bertoni, Nelson, Reddy (2015)

Existence of old neutron stars with estimated ages ~ 10^{10} years provide strong constraints on asymmetric DM.



Kouvaris (2013)

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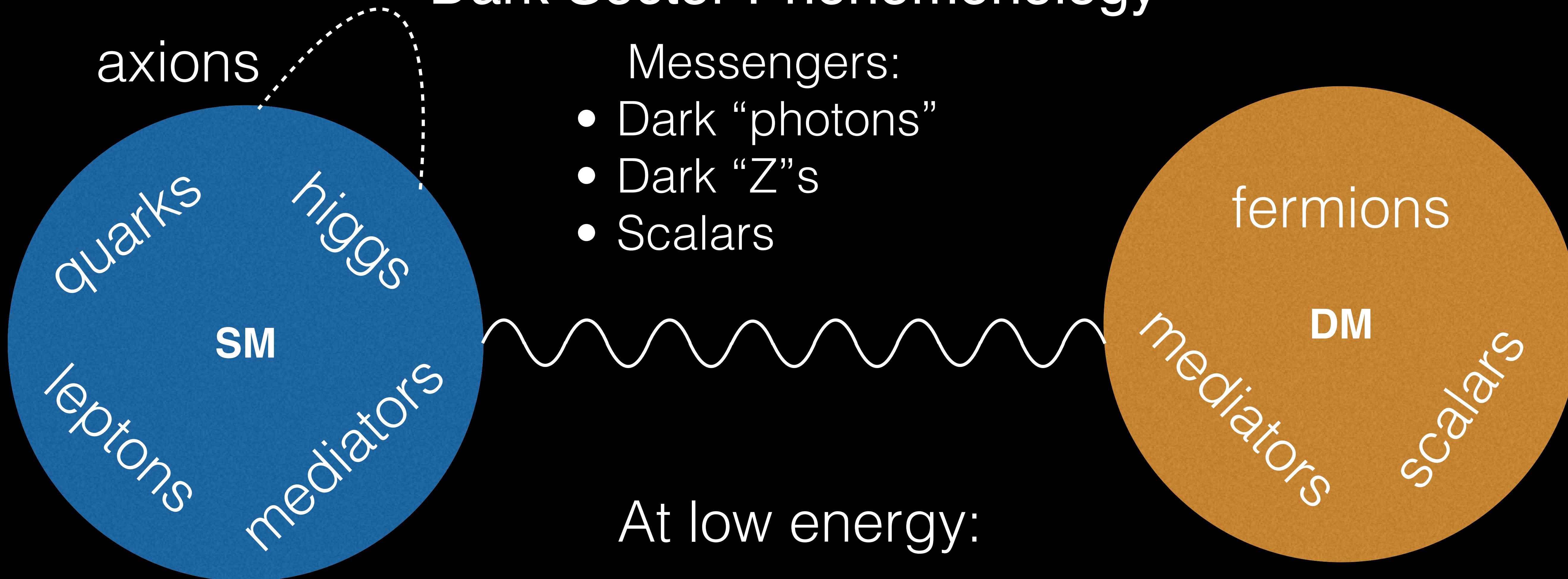

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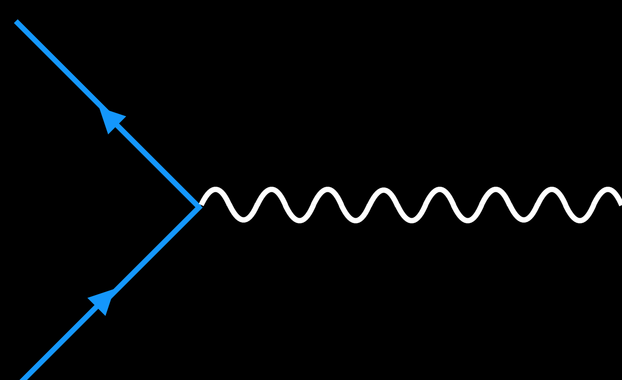

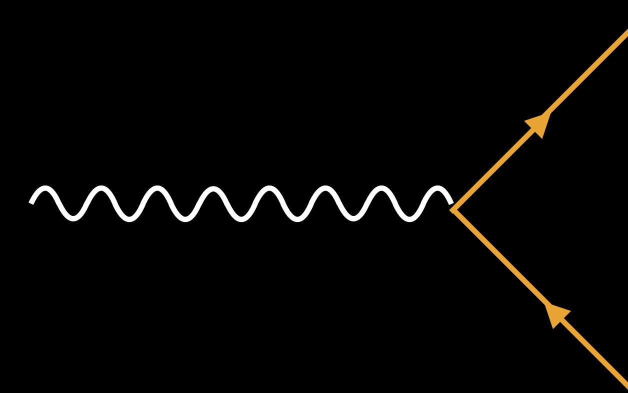

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Dark Photons

$$\mathcal{L} \supset g_Q A'_\mu J_\mu^{\mathrm{EM}} + g_B B_\mu J_\mu^{\mathrm{B}} - \frac{1}{2} m_{\gamma_Q}^2 A'_\mu A'^\mu - \frac{1}{2} m_{\gamma_B}^2 B_\mu B^\mu$$

$$g_Q = \sqrt{4\pi\alpha}\ \epsilon$$

Chang, Essig, McDermott (2017)

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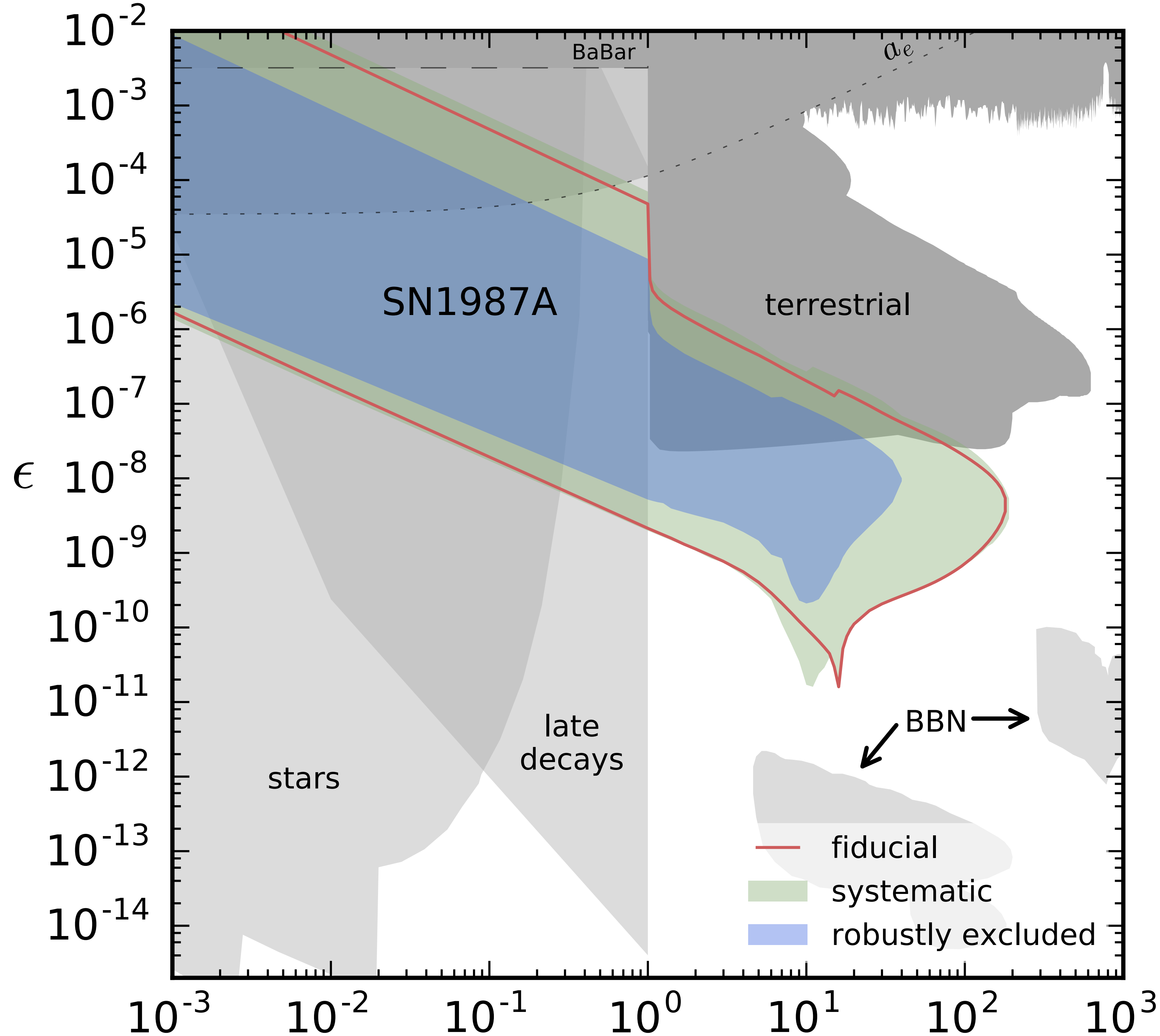


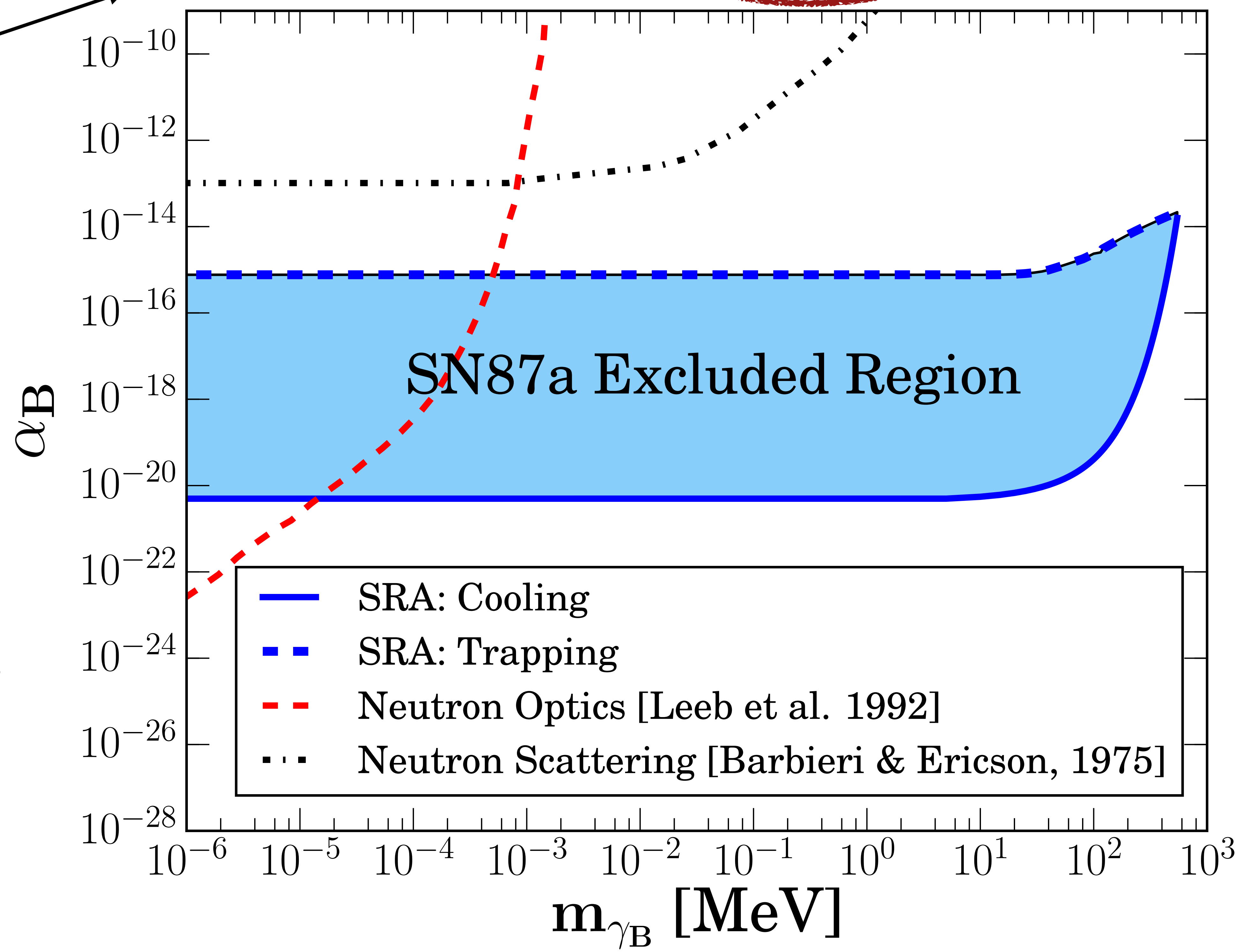
Chang, Essig, McDermott (2017)

Dark Baryon Number Gauge Boson

$$\mathcal{L} \supset g_Q A'_\mu J^{\text{EM}}_\mu + g_B B_\mu J^{\text{B}}_\mu - \frac{1}{2} m^2_{\gamma_Q} A'_\mu A'^\mu - \frac{1}{2} m^2_{\gamma_B} B_\mu B^\mu$$

$$\alpha_B = \frac{g_B^2}{4\pi}$$

- Neutrino burst from SN87a provides stringent constraints.
- Constraints from RG and HB stars are relatively weaker.



Rrapaj and Reddy (2016)

SN87a bound on energy loss to exotic particles

Raffelt's "local" bound:

$$\mathcal{E}(\rho = 3 \times 10^{14}\ \mathrm{g/cm}^3, T = 30\ \mathrm{MeV}) < \mathcal{E}_{\mathrm{Raffelt}} = 10^{19}\ \frac{\mathrm{ergs}}{\mathrm{g\ s}}$$

This bound was found empirically by comparing to a suite of proto-neutron star simulations.

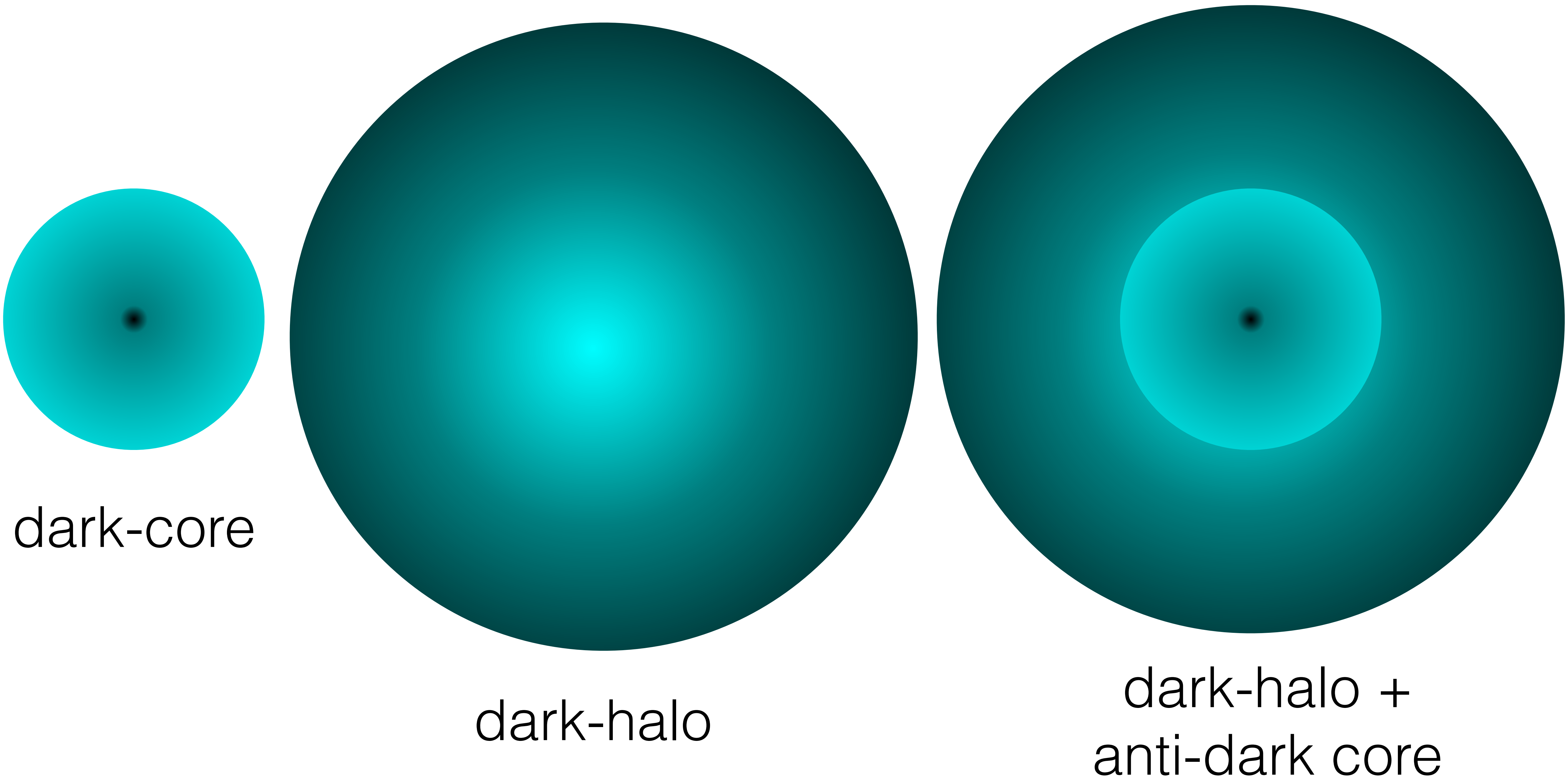
The corresponding bound on the luminosity is

$$L_{\mathrm{exotic}} < \mathcal{E}_{\mathrm{Raffelt}} \times M_{NS} \simeq 2 \times 10^{52} \frac{M}{M_{\odot}}\ \frac{\mathrm{ergs}}{\mathrm{s}}$$

Requires $g_B < 10^{-10}$ for $m_\phi < 100\ \mathrm{MeV}$

Dark Matter and Neutron Star Structure

Trace amounts of dark matter can influence the structure of neutron stars.



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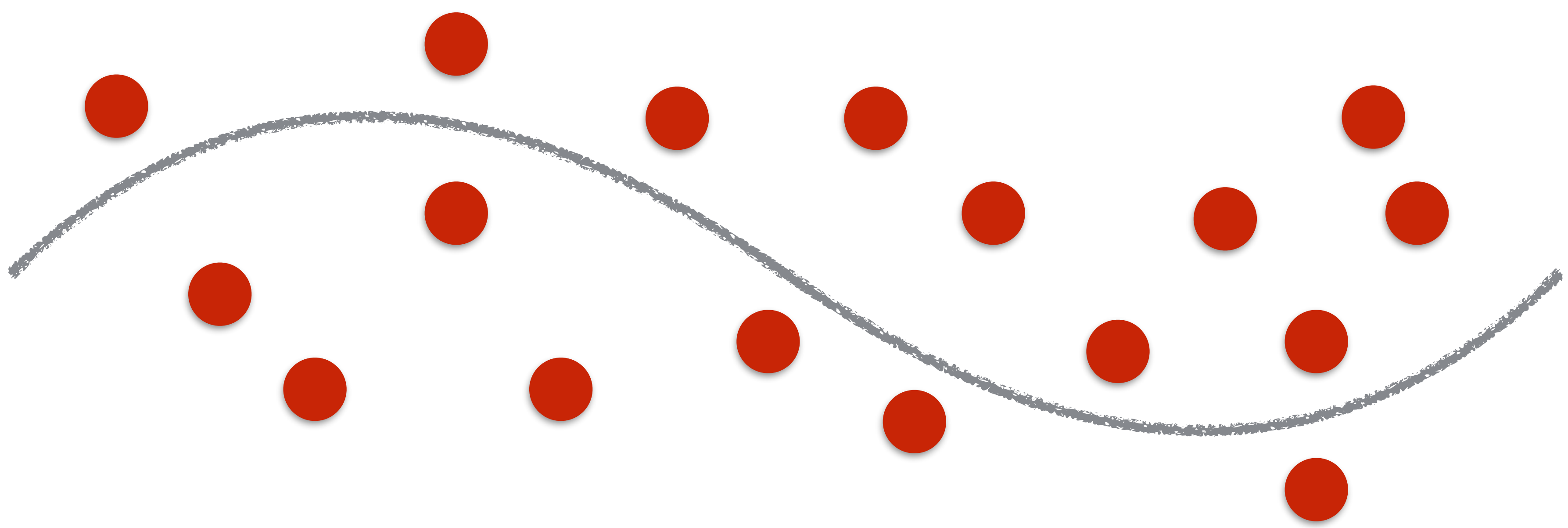
Equation of State of Dark Matter

Energy density: $$\epsilon_\chi = \epsilon_{\rm kin} + m_\chi n_\chi + \frac{g_\chi^2}{2m_\phi^2}\; n_\chi^2$$



Large coherent enhancement of interactions when Compton wavelength of mediator is larger than the inter-particle separation.

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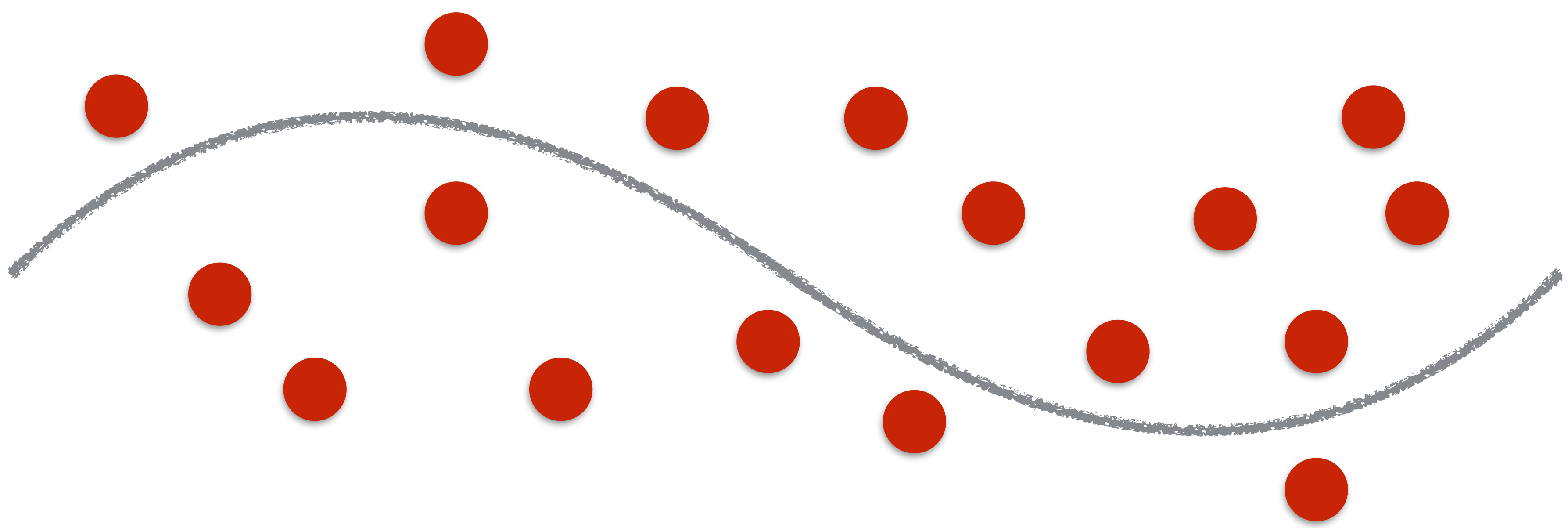

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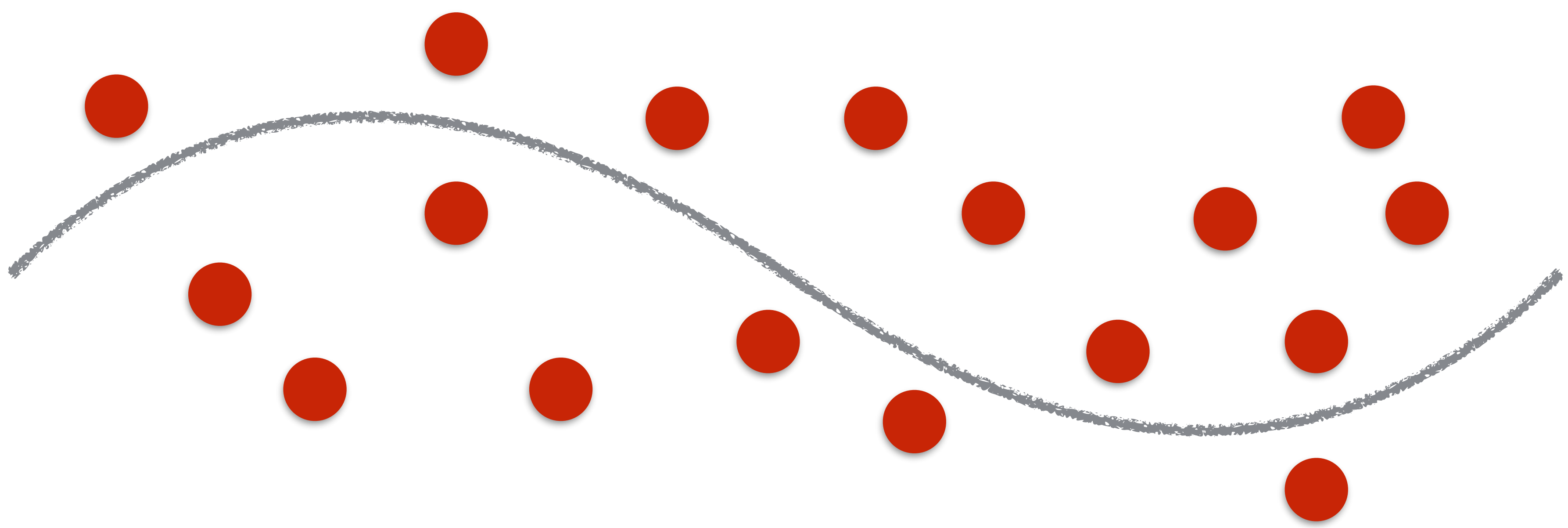

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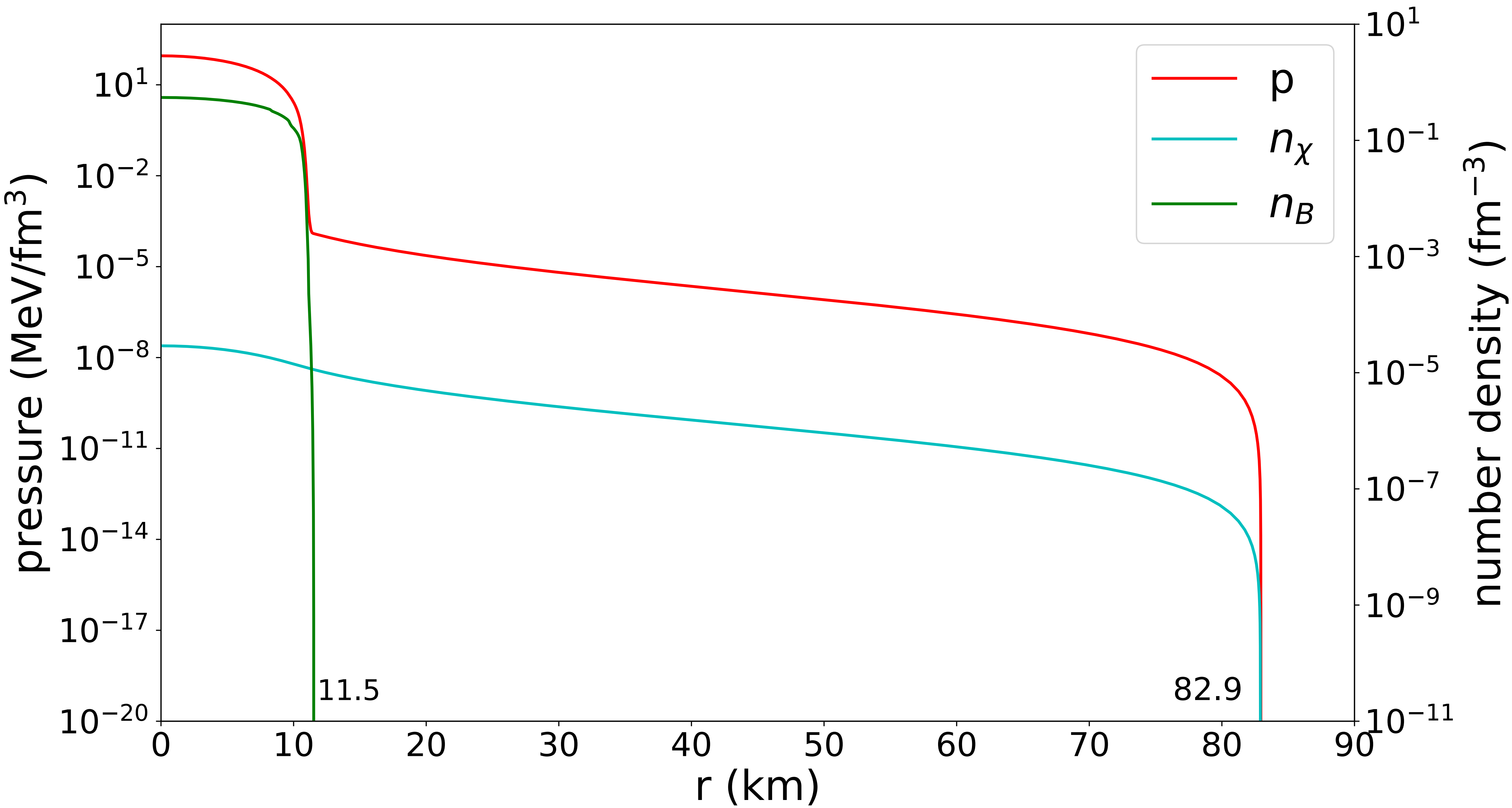
Profile of a Dark Neutron Star



1.4 M_{solar} Neutron star with 10^{-4} M_{solar} of dark matter.

Dark matter: m_χ = 100 MeV

Interactions: g_χ/m_Φ = (0.5/MeV) or (0.5x10^{-6}/eV)

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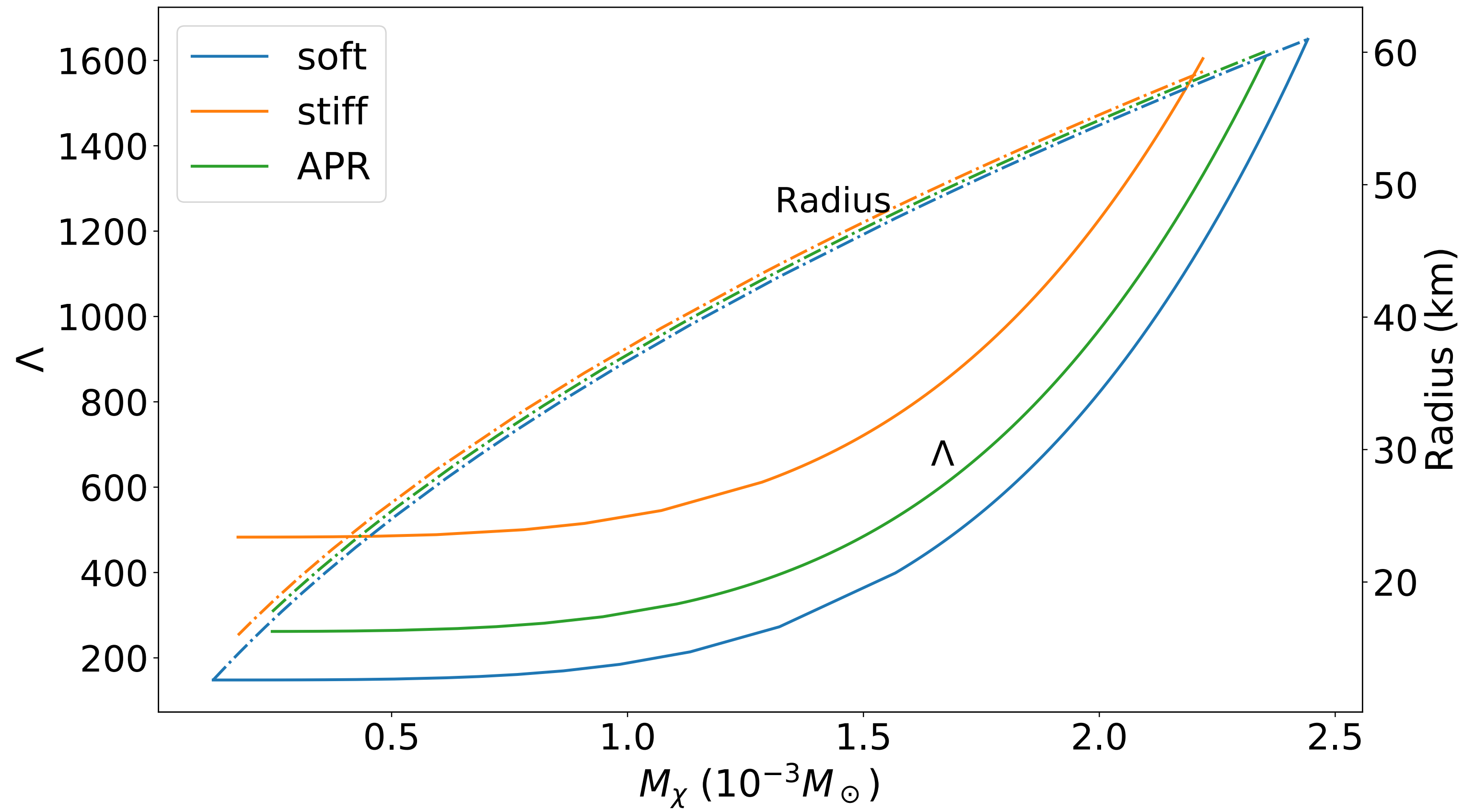
For light mediators, only trace amounts are needed

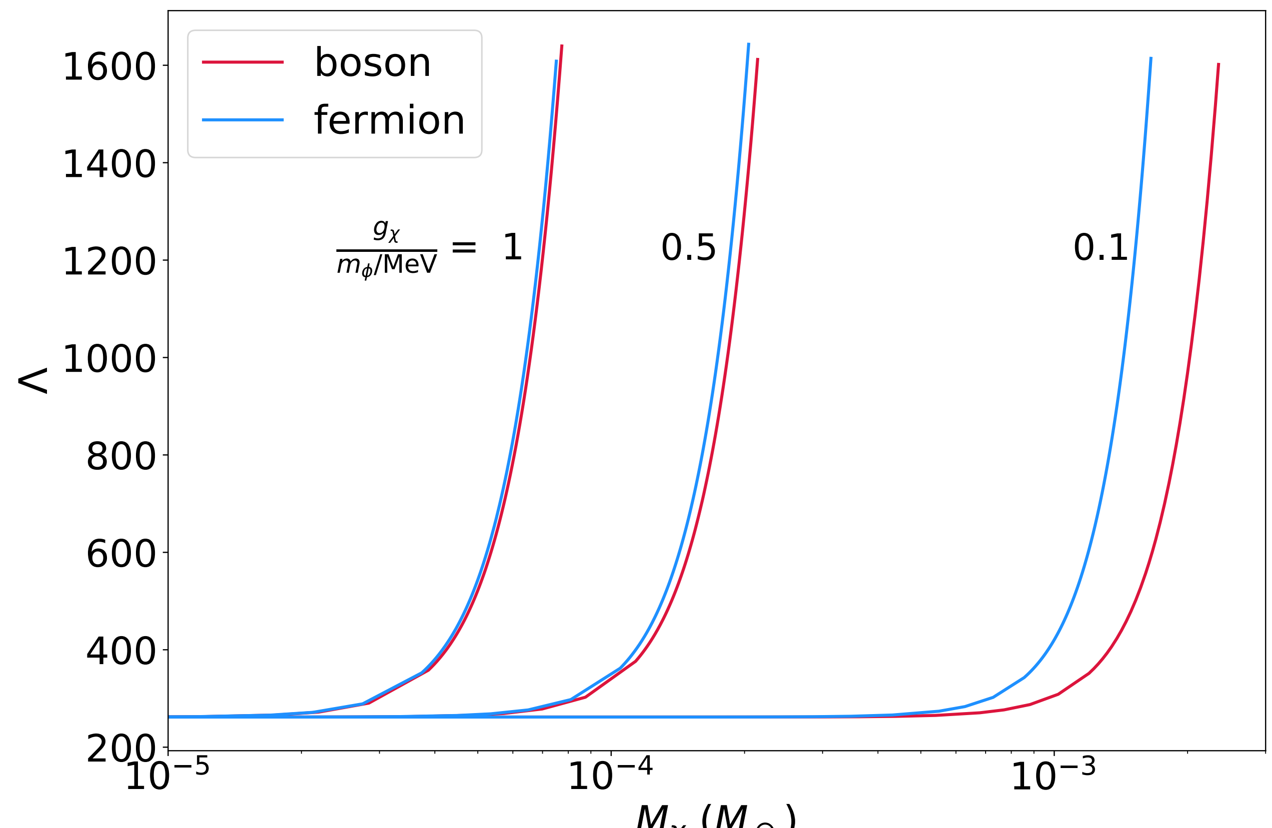
10^{-4}-10^{-2} M_{solar} is adequate to enhance $\Lambda > 800$!

m_χ = 100 MeV

g_χ/m_Φ = (0.1/MeV) or (10^{-6}/eV)



Interactions of “natural” size produce large Λ



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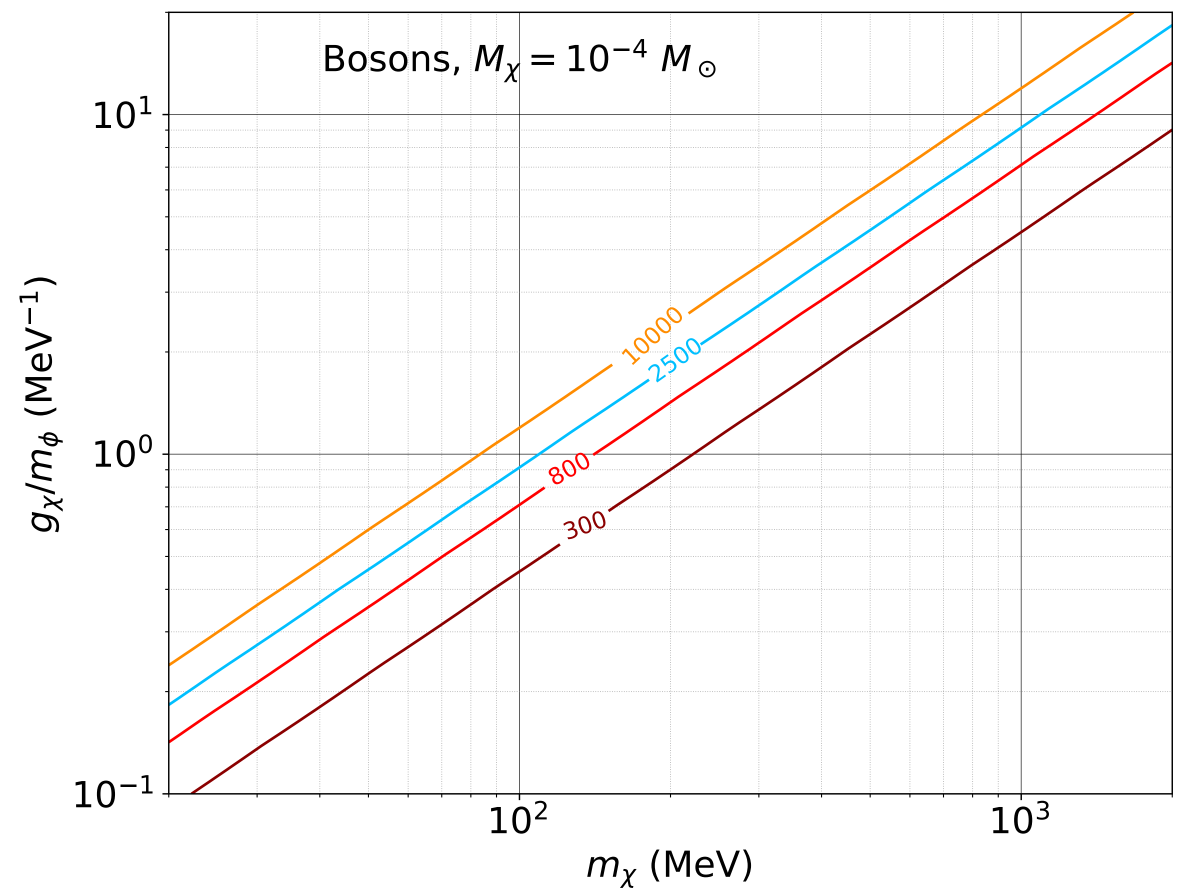
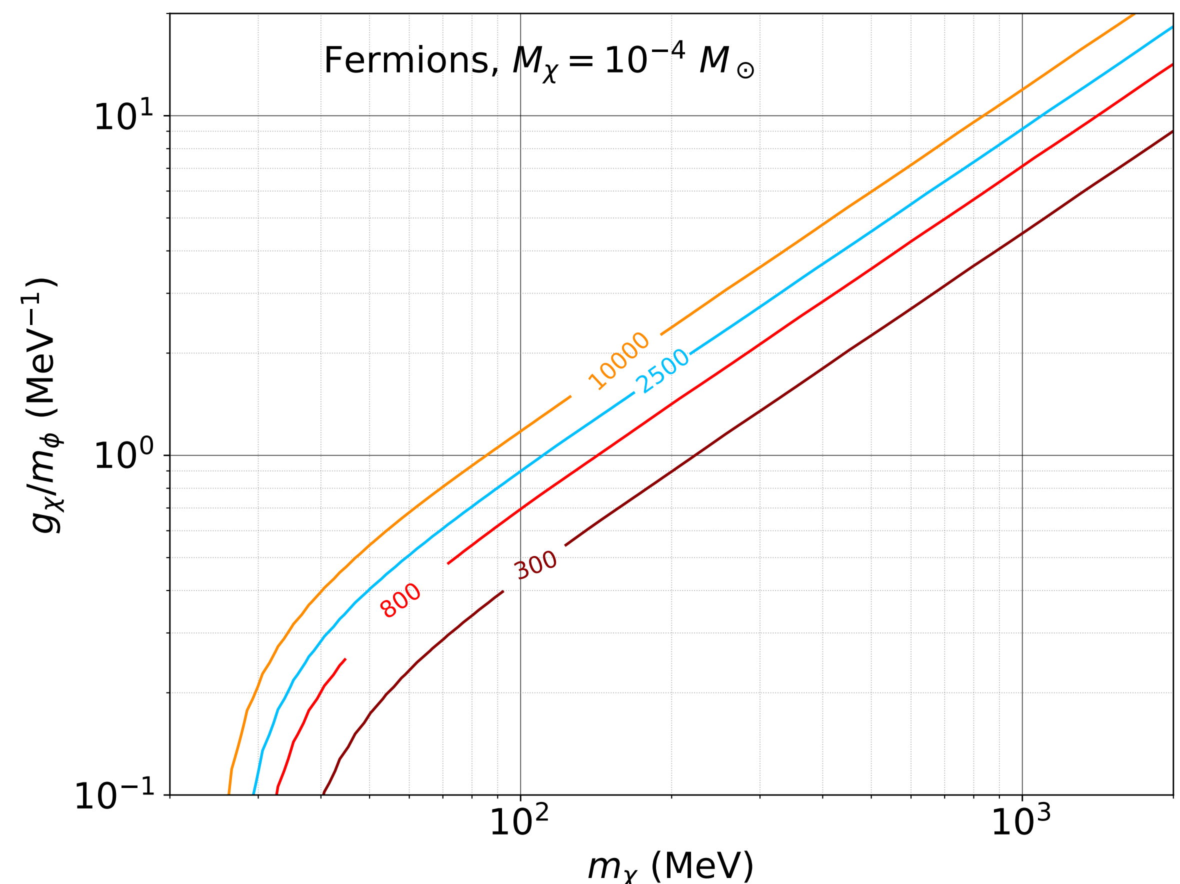
GW170817 rules out extensive regions of the dark matter model space if NS contain dark matter.





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Could/should NS contain dark matter ?

- Supernova can easily produce $10^{-4}\ M_{solar}$ of < 100 MeV dark matter.
- Coupling to baryons allows for dark charge separation.
- Dark matter might be clumpy.
- Dark clumps might seed star formation.
- Might be the best place to find them ?

Conclusions

MeV-GeV dark matter can play a role in mergers. Trace amounts of interacting dark matter in the neutron star can enhance their tidal polarizability (Λ) to discernible values.

Neutron stars can accrete, inherit, or create their own dark matter. Dark matter production during supernova and mergers can be significant even for very weak coupling.

If Ad. LIGO suggests either large Λ or a large variability in Λ, it may reveal the particle nature of dark matter - gravitationally !

If not, it provides useful constraints on generic dark matter models with light mediators.