Neutron Stars in the Multi-Messenger Era

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Lecture 1: Basic notions of dense matter. Nuclear interactions and nuclear matter, effective field theory.

Lecture 2: Mass and radius. Linear response, proto-neutron star evolution, supernova neutrino emission and detection.

Lecture 3: Late neutron star cooling: Thermal and transport properties of degenerate matter, cooling of isolated neutron stars, heating and cooling in accreting neutron stars. Observational constraints.

Lecture 4: Neutron stars as laboratories for particle physics:Dark matter candidates (axions and other light weakly interacting particles, WIMPs, compact dark objects). Constraints from observations of neutron star masses, radii and cooling.

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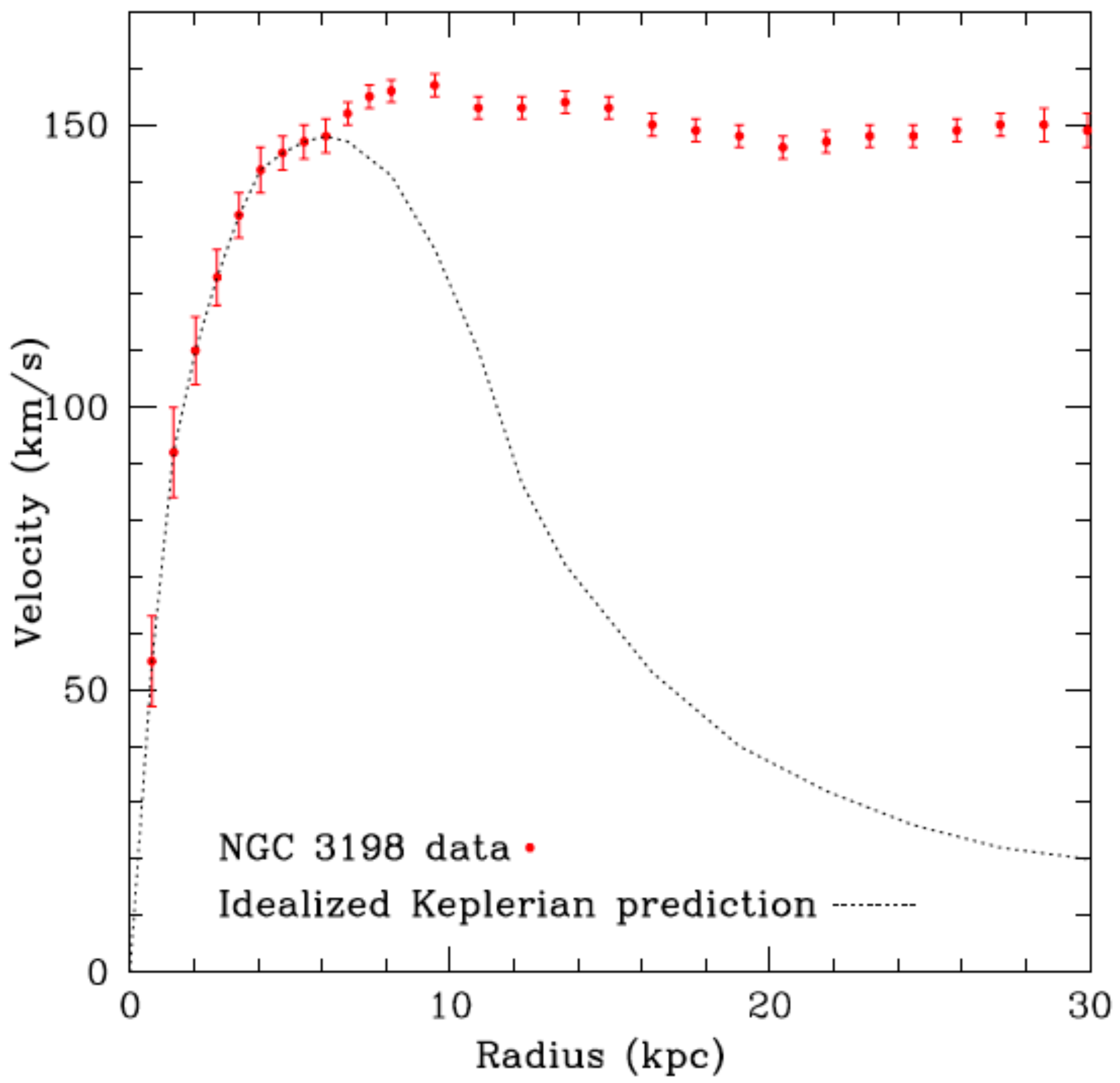
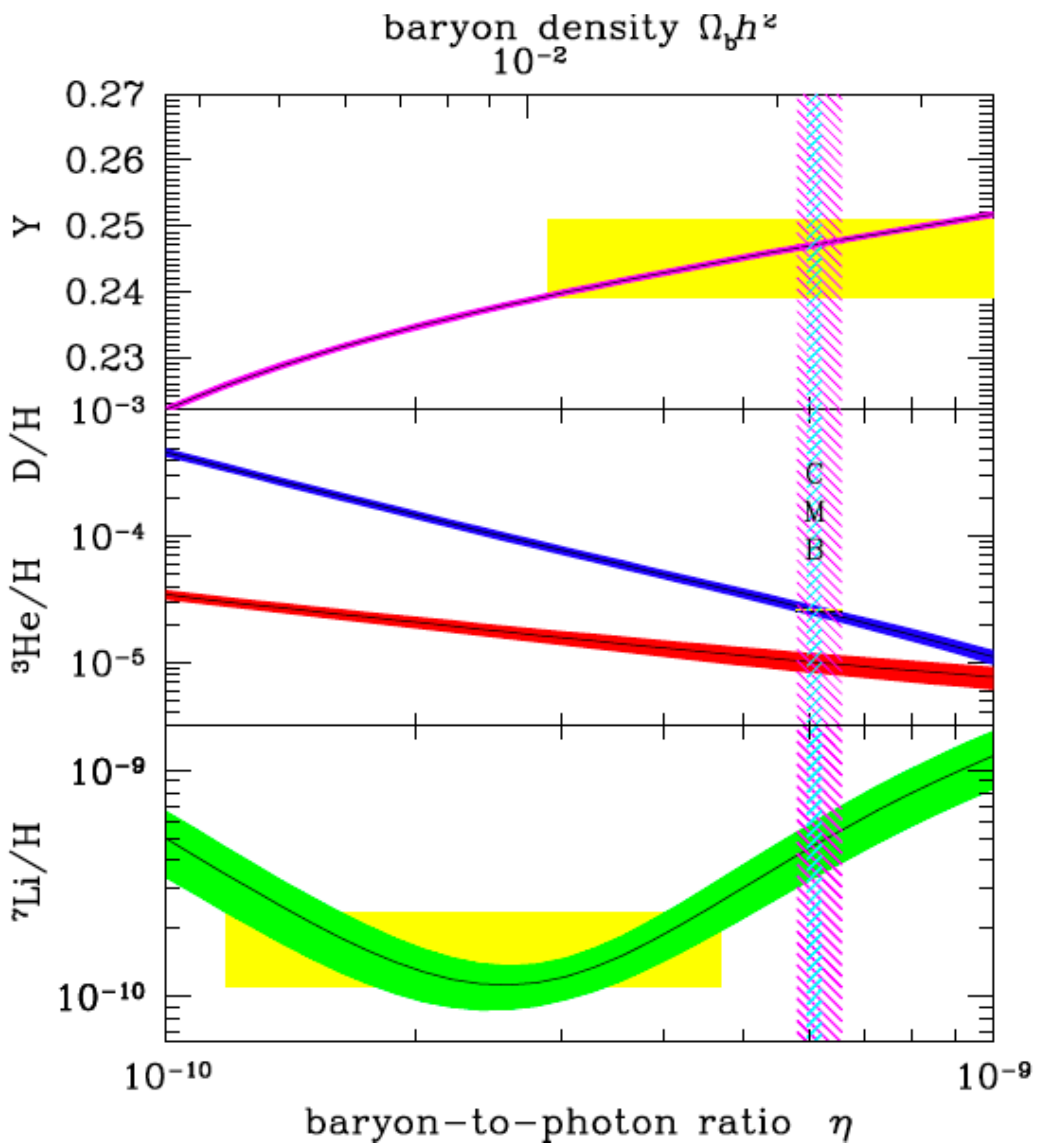
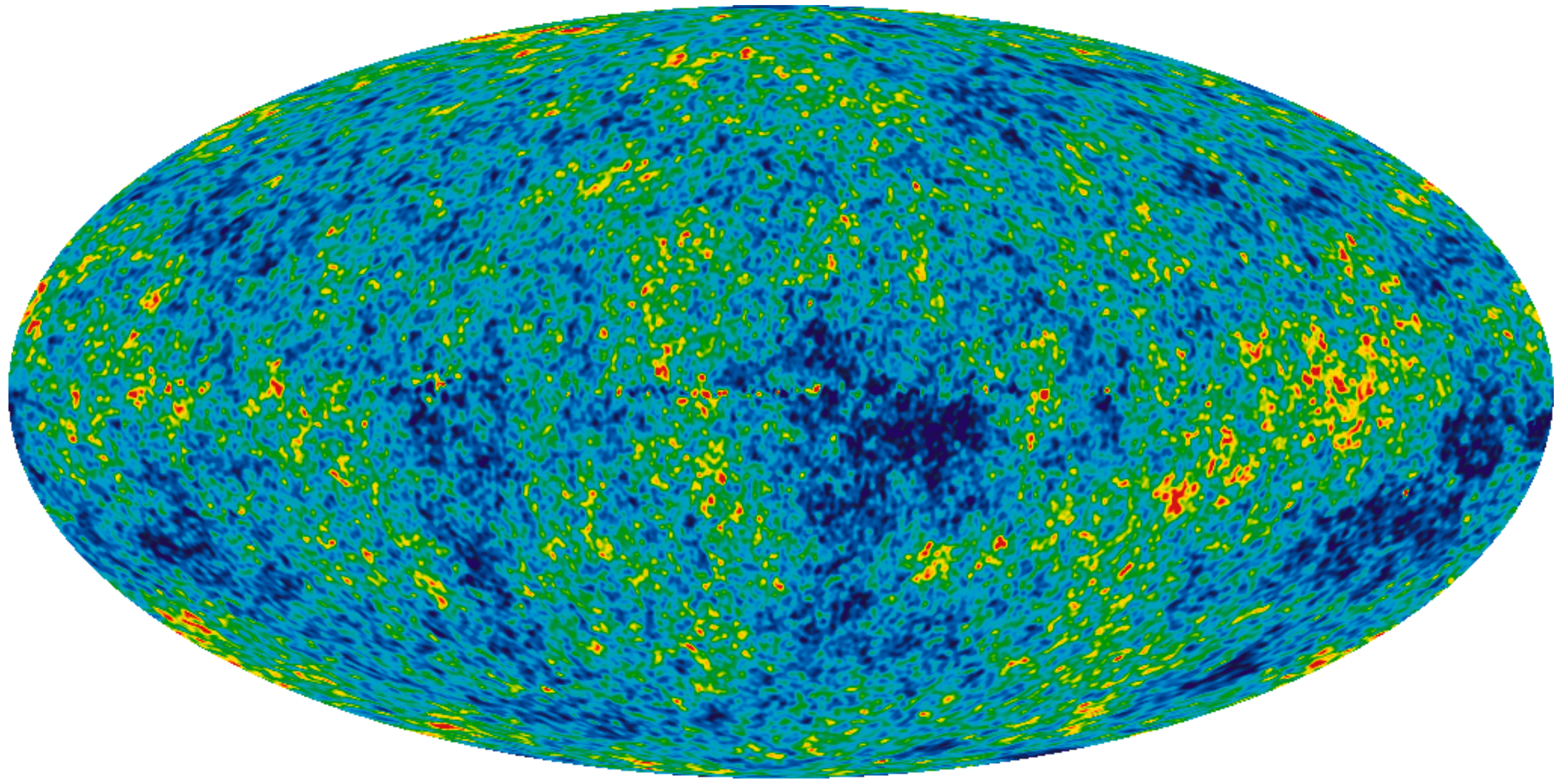
Evidence for Dark Matter

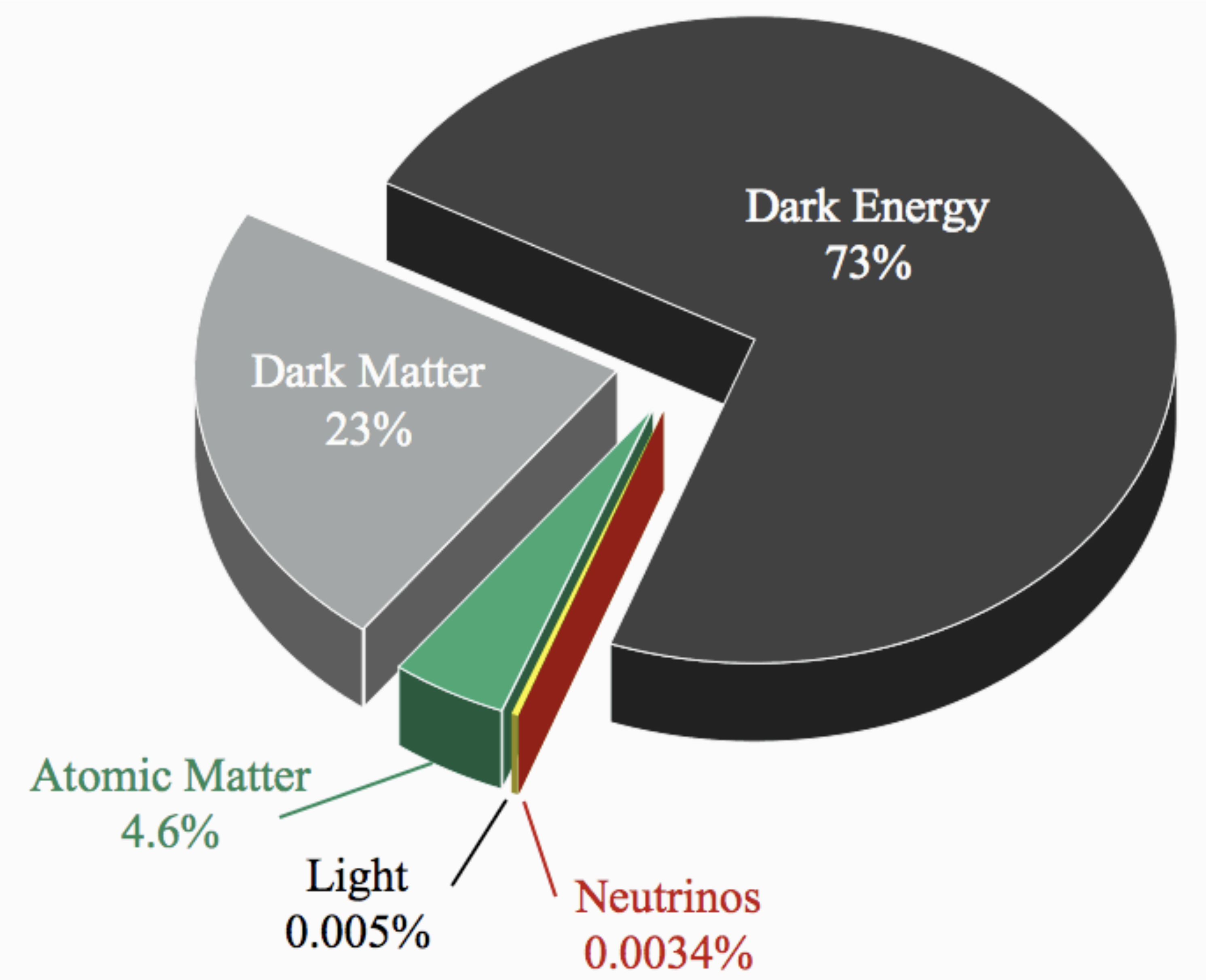






There is very strong evidence from different observations for the existence of dark matter.

Ordinary matter only accounts ~ 20% of the the gravitating matter in the universe!



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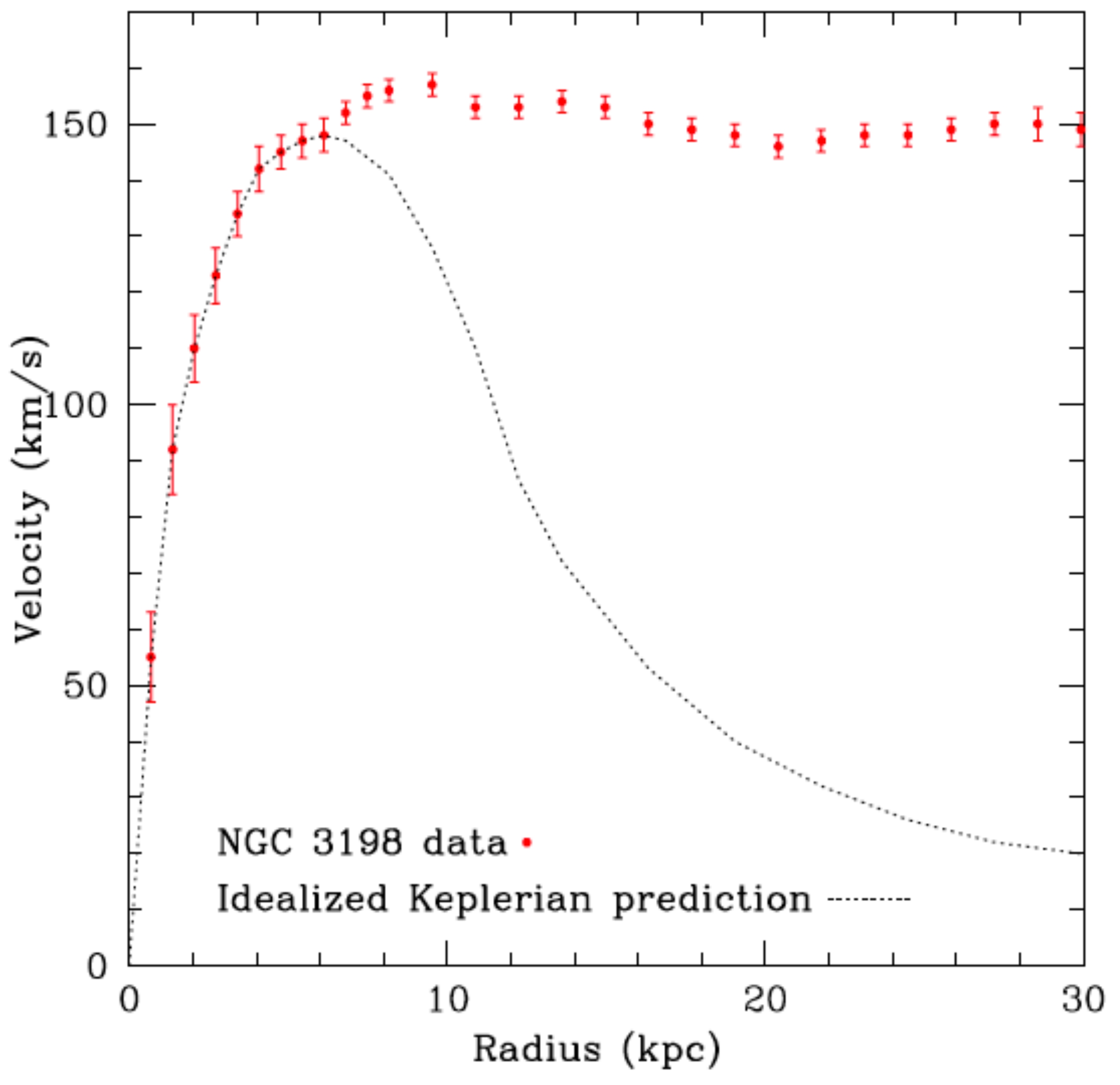

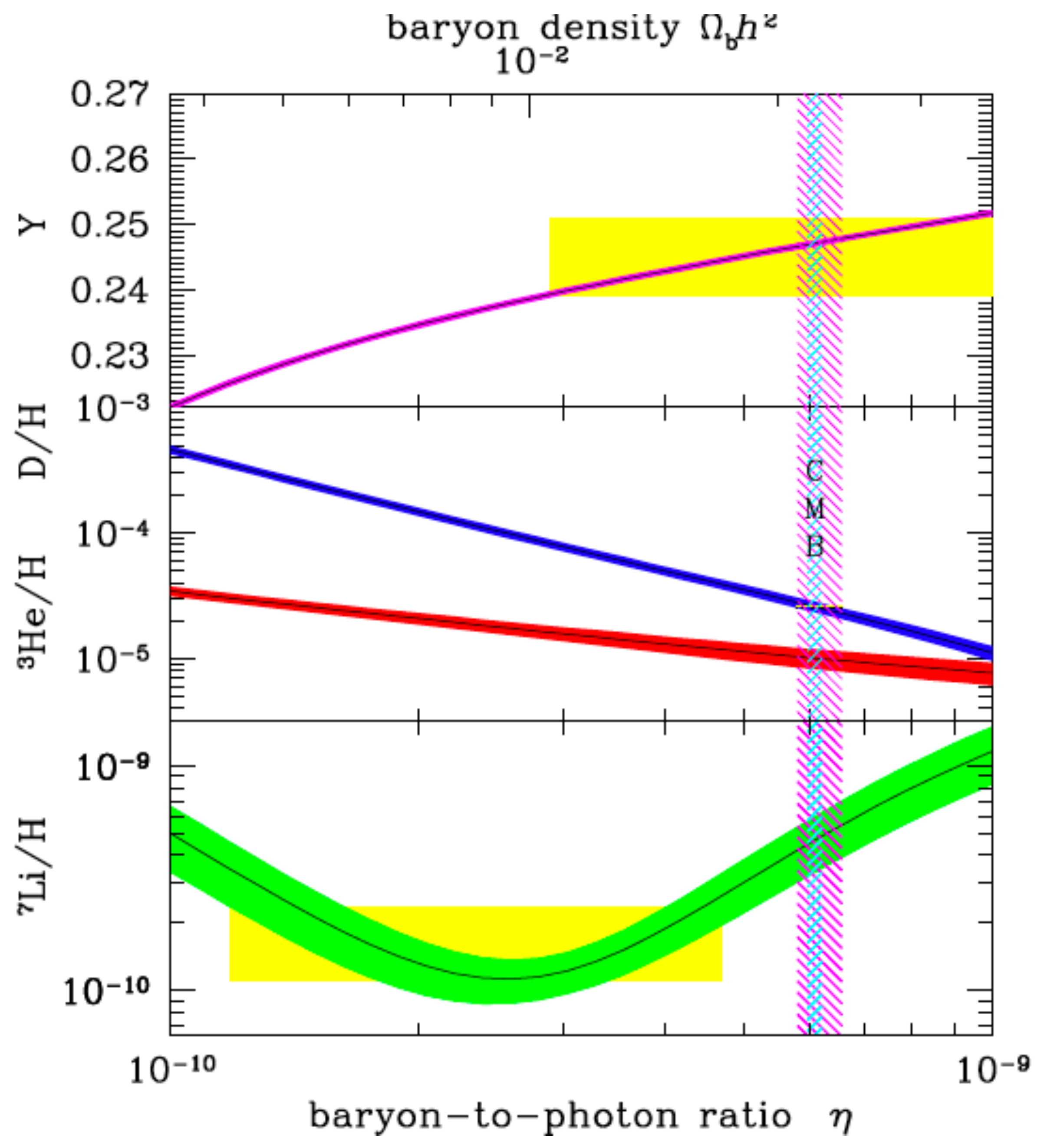

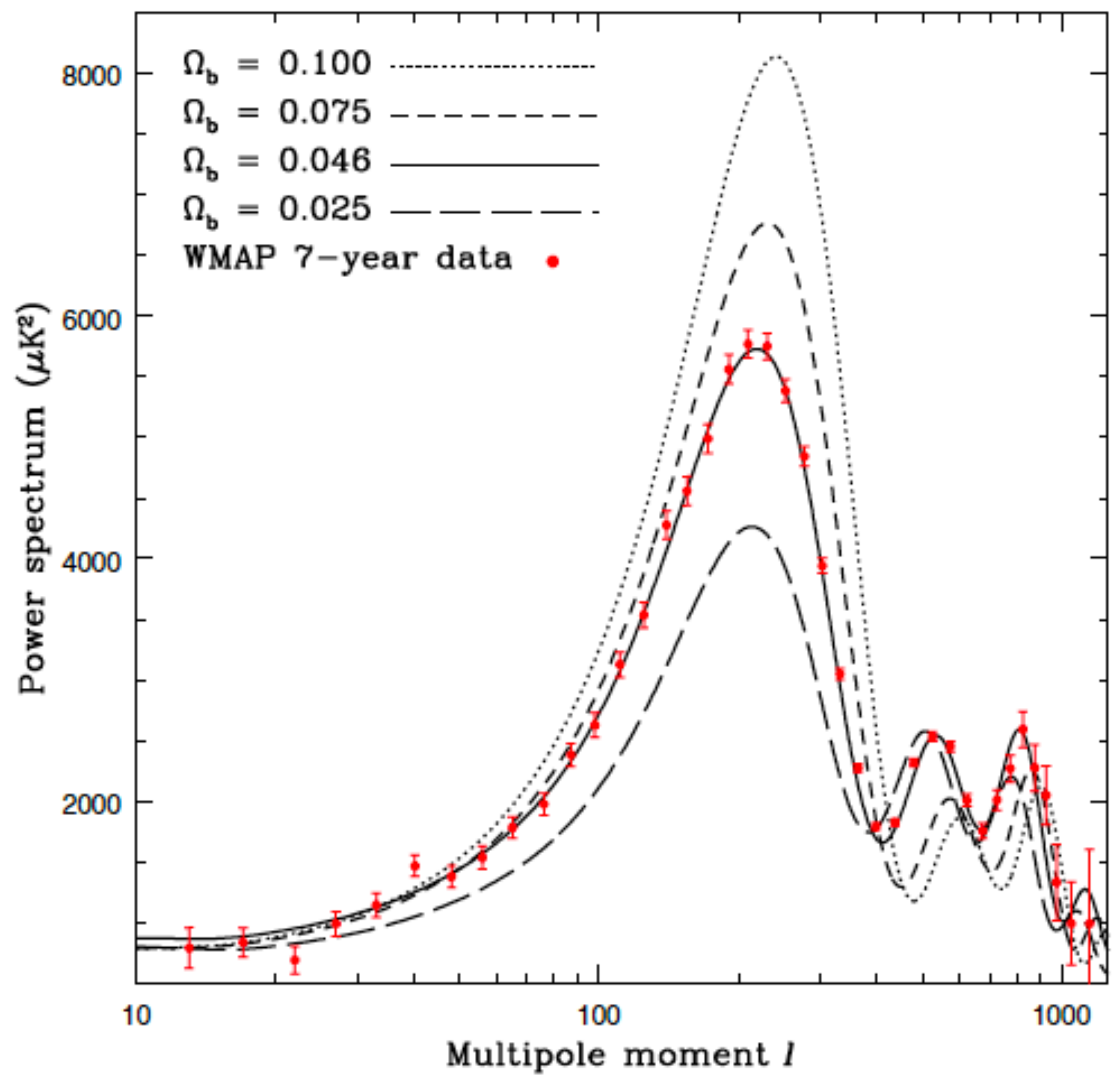

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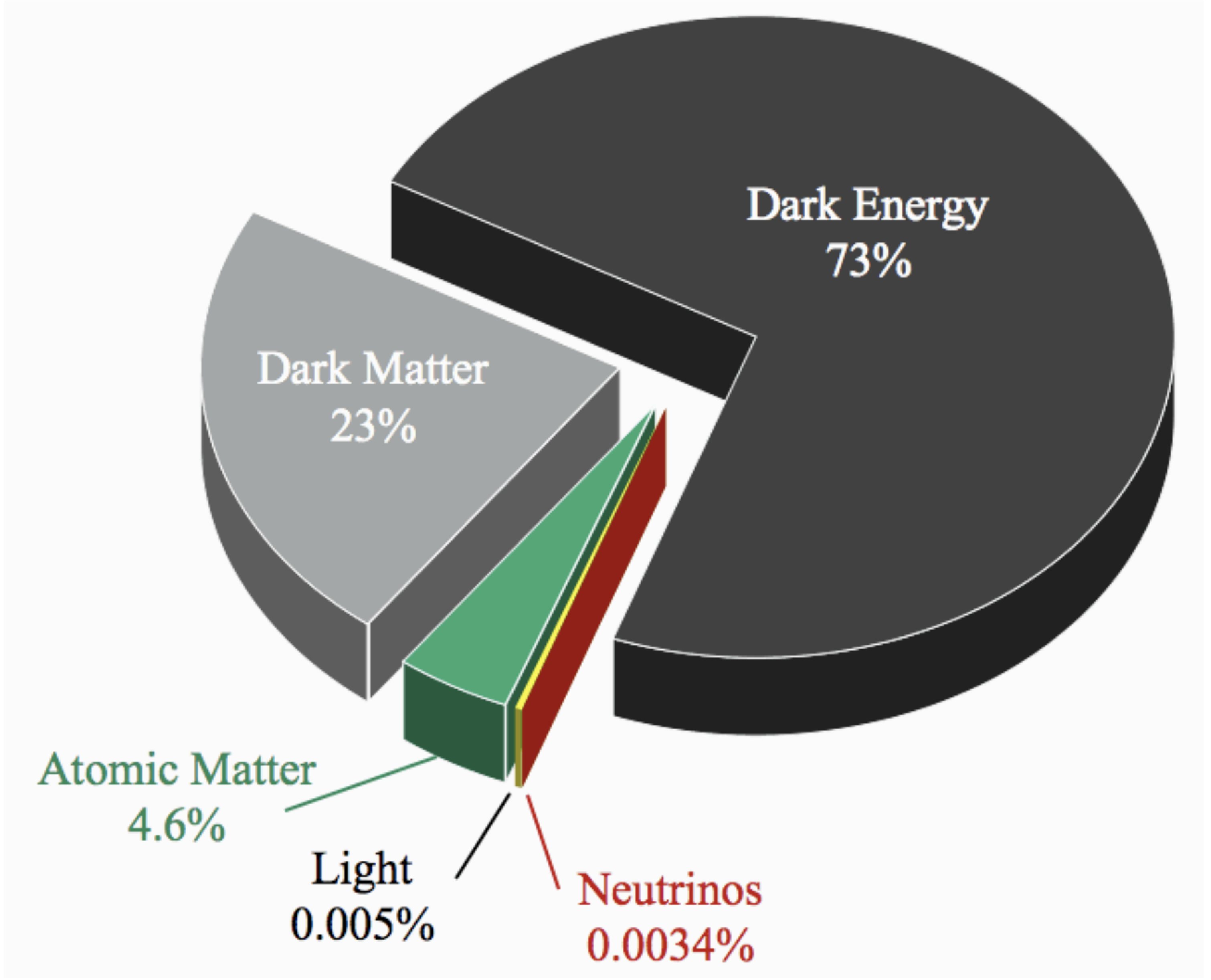
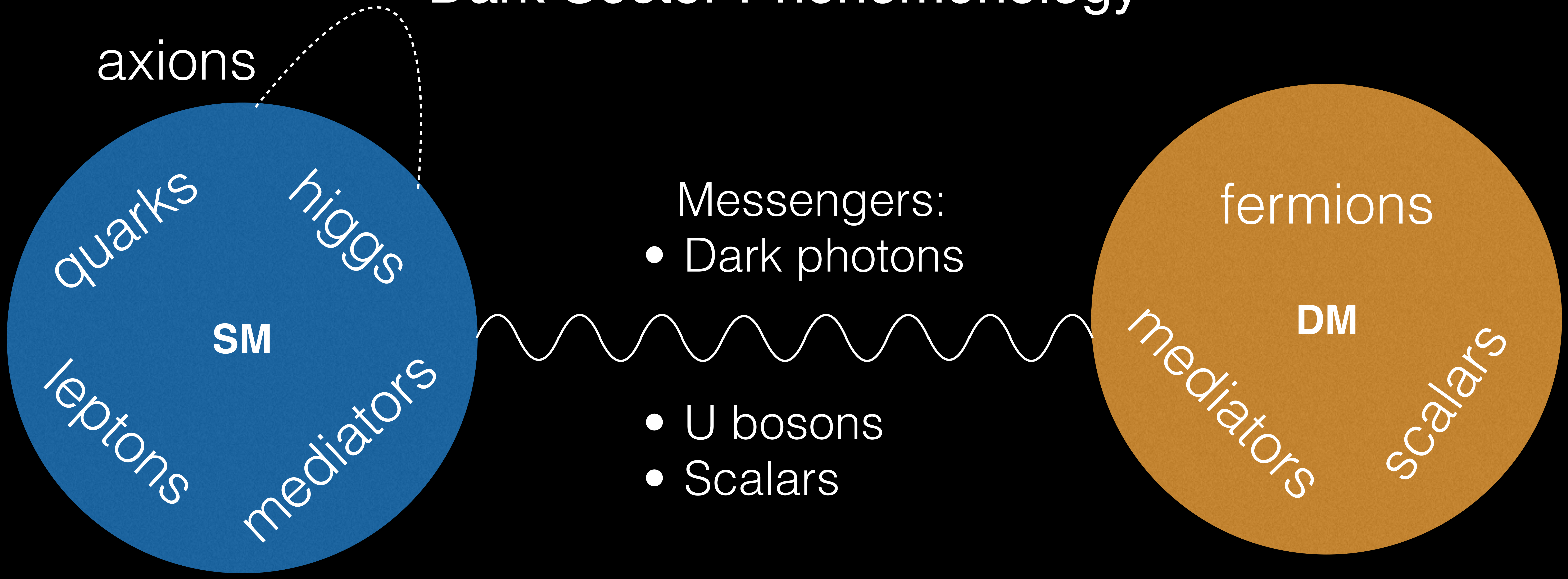
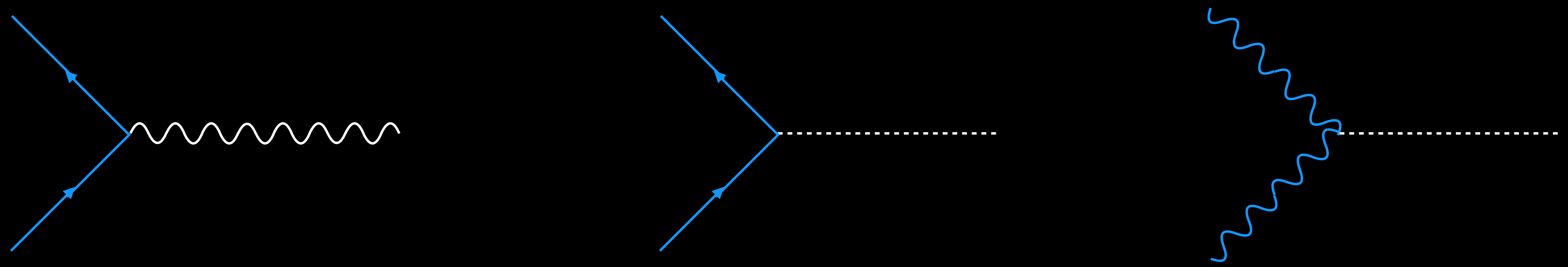


Dark Sector Phenomenology



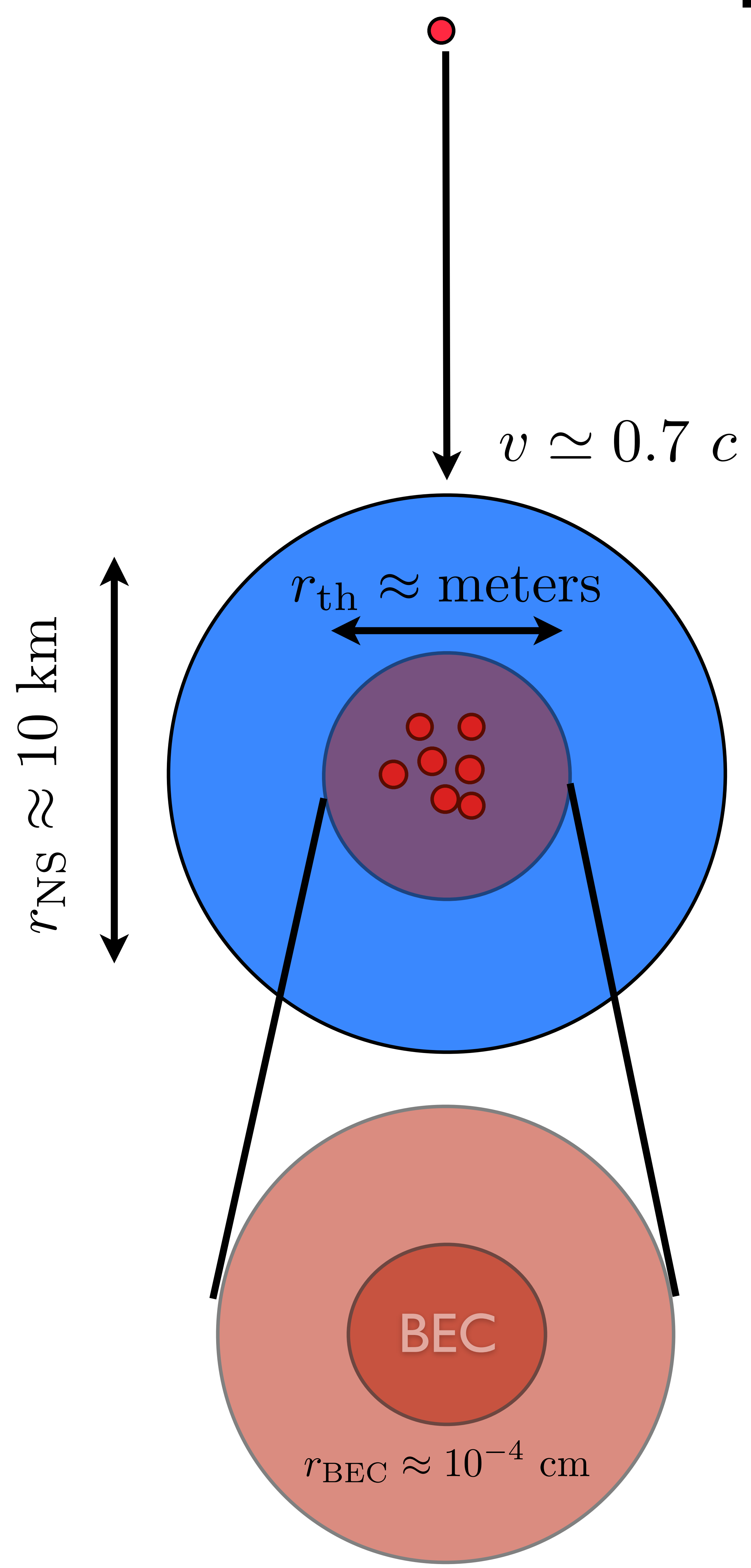
At low energy:



$\mathcal{L}_{A'f} = -\epsilon e q_f \; A'_\mu \; \bar{\psi}_f \gamma^\mu \psi_f$ $\quad \mathcal{L} = \frac{c_f}{2 f_a} \; \partial_\mu a \; \bar{\psi}_f \gamma_\mu \gamma_5 \psi_f$ $\quad \mathcal{L} = g_{a\gamma\gamma} \; a \; \vec{E} \cdot \vec{B}$

How can we use observations of neutron stars to either discover or constrain dark matter?

DM Accretion onto Neutron Stars



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 the BEC triggers collapse.

For a concise recent review see Kouvaris (2013)

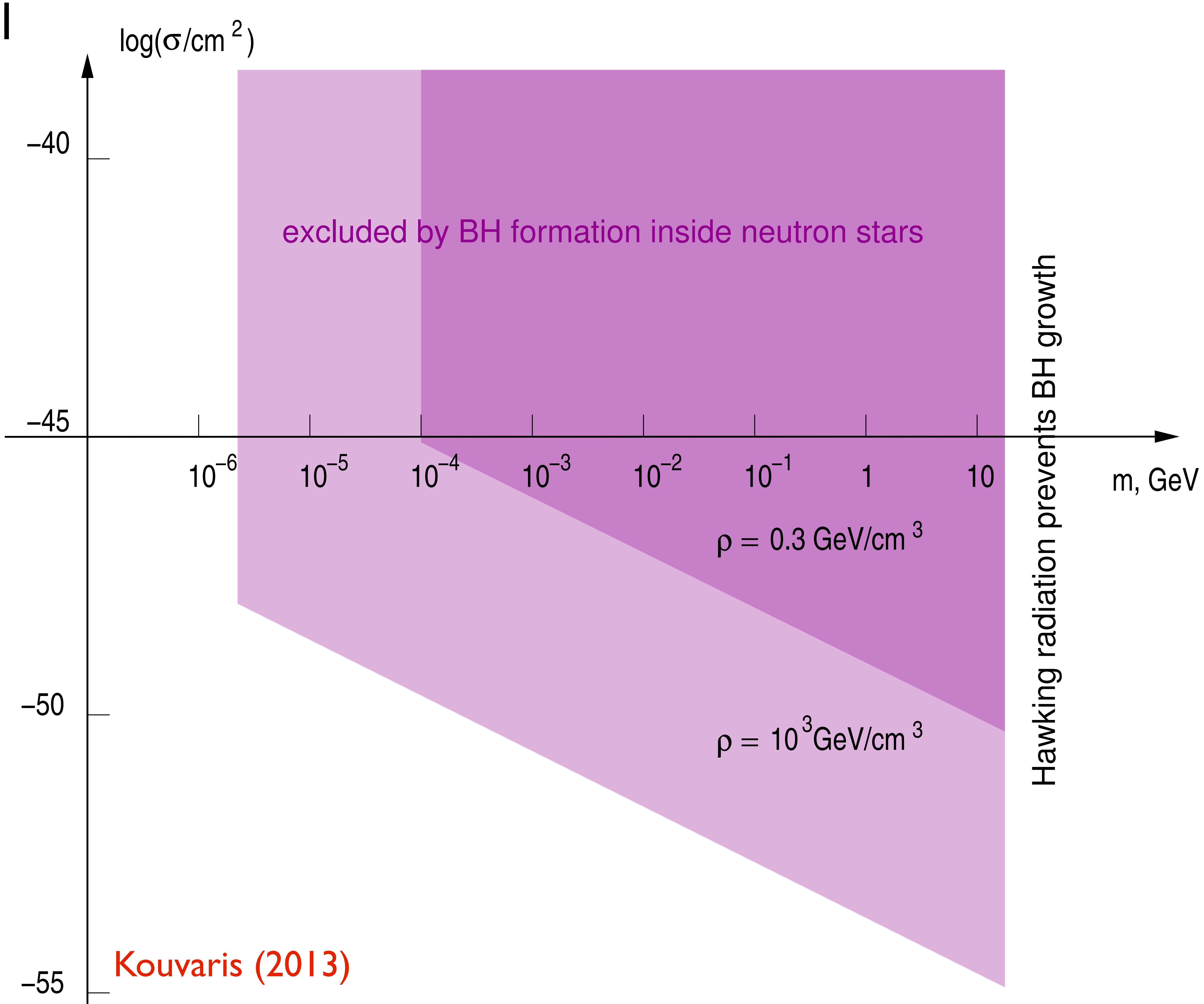
Black-hole Formation

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)



Kouvaris (2013)

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

Constraining Dark Baryons

Particles in the MeV-GeV mass range that couple to baryons or mix with baryons are natural dark matter candidates.

There is speculation that a dark baryon with mass m_χ between 937.76 - 938.78 MeV might explain the neutron life-time discrepancy:

$$n \to \chi + \dots$$

Fornal & Grinstein (2018)

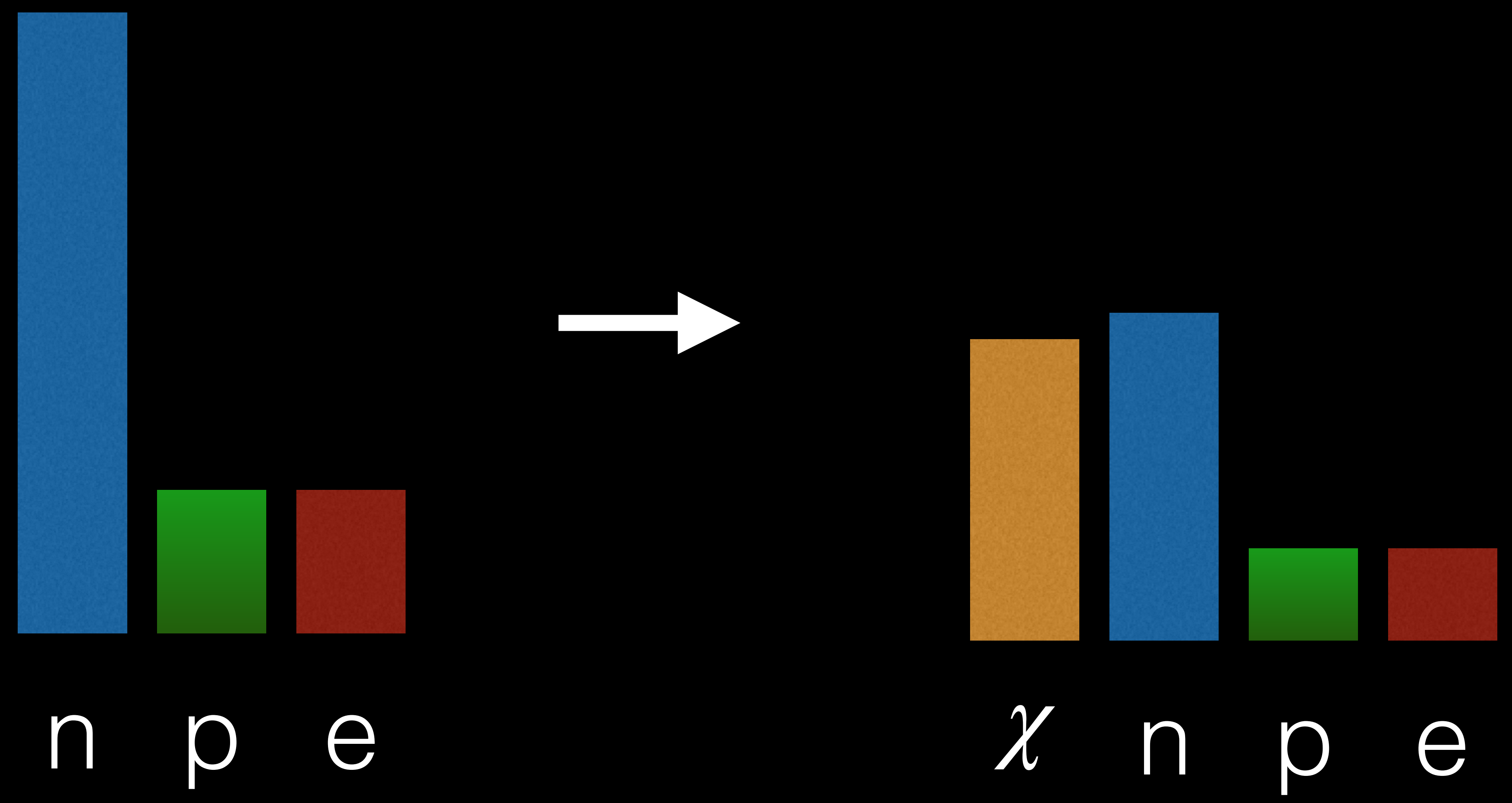
$\tau_n^{\text{bottle}} = 879.6 \pm 0.6 \text{ s}$ —— counts neutrons

$\tau_n^{\text{beam}} = 888.0 \pm 2.0 \text{ s}$ —— counts protons

$$\text{Br}_{n\to\chi} = 1 - \frac{\tau_n^{\text{bottle}}}{\tau_n^{\text{beam}}} = (0.9 \pm 0.2) \times 10^{-2}$$

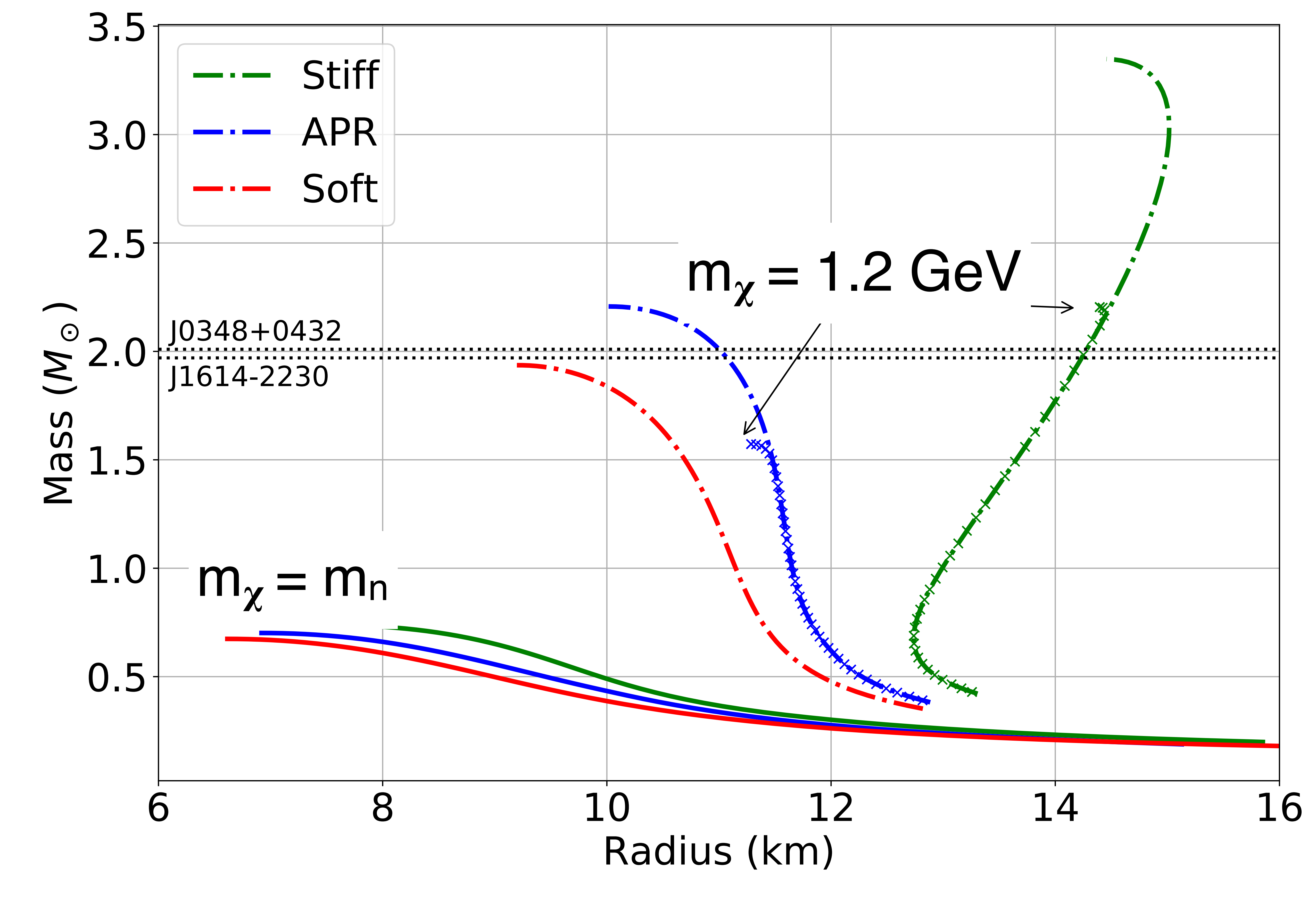
In general, are there hidden baryons which mix with a neutron with a mixing angle $\Theta \geq 10^{-18}$?

Weakly Interacting Dark Baryons Destabilize Neutron Stars



Neutron decay lowers the nucleon density at a given energy density.

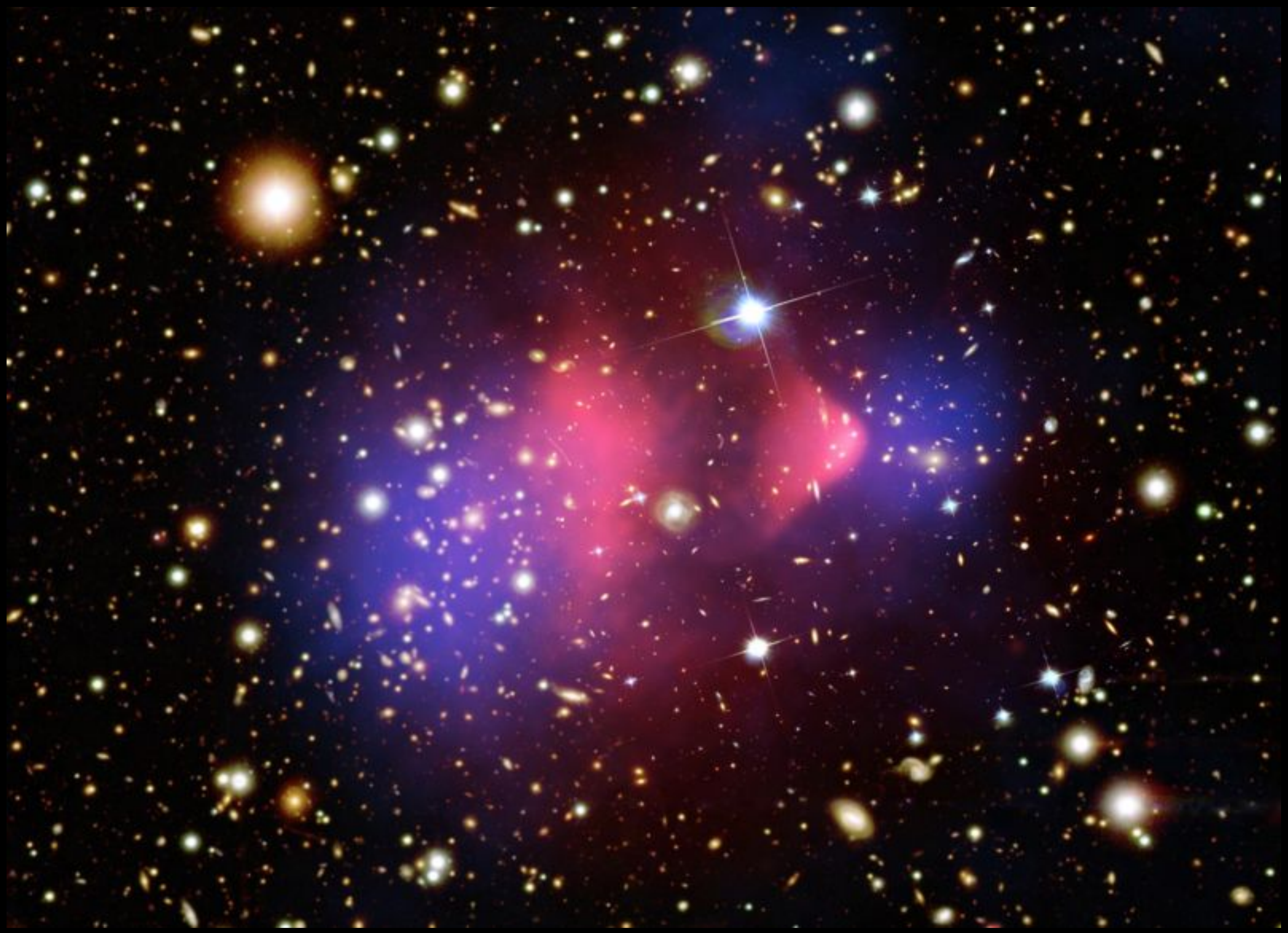
When dark baryons are weakly interacting the equation of state is soft ~ similar to that of a free fermi gas.



This lowers the maximum mass of neutron stars.

Mckeen, Nelson, Reddy, Zhou (2018) Baym, Beck, Geltenbort, Shelton (2018)

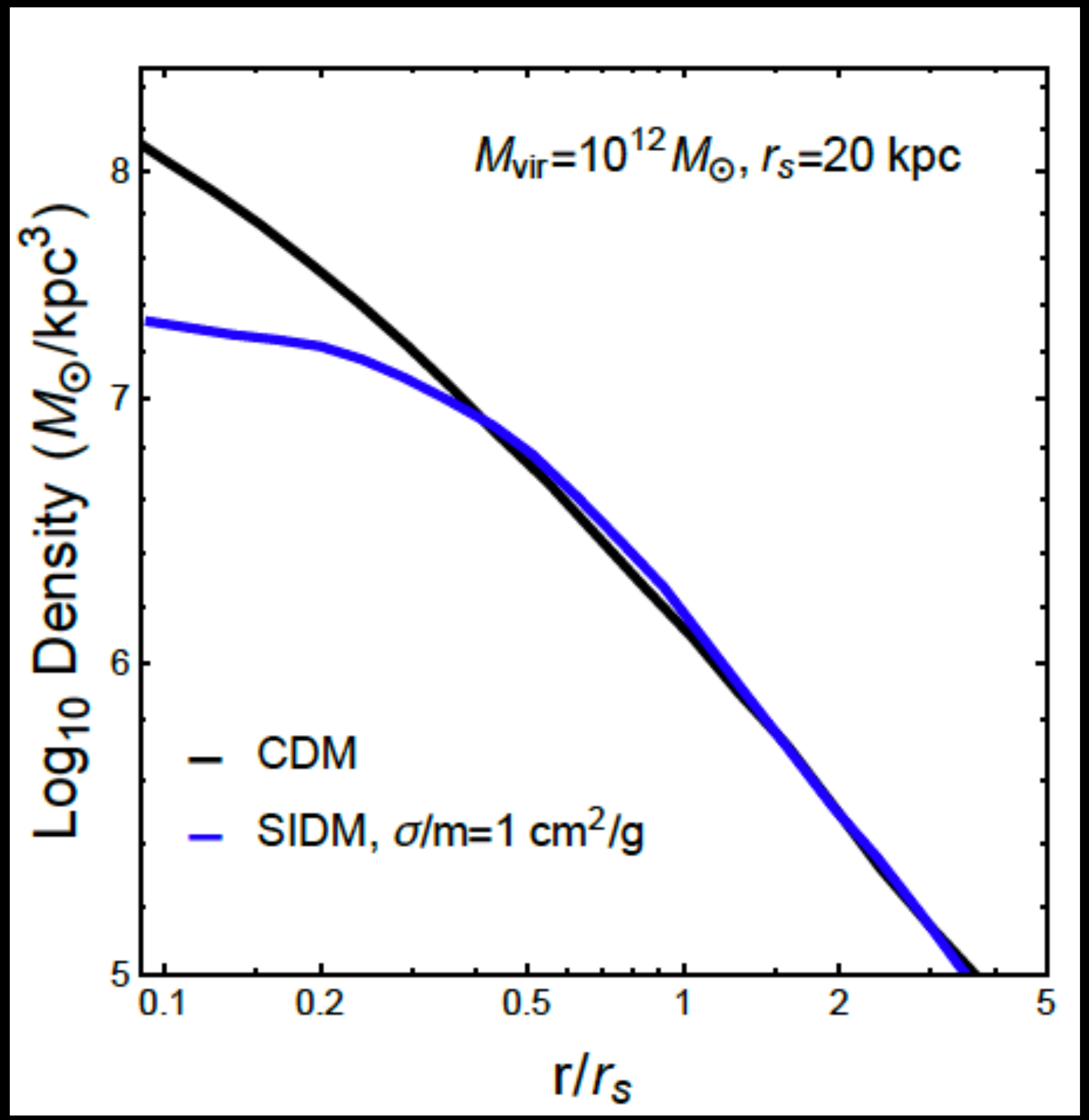
What if dark matter has strong self-interactions?



Bullet Cluster (colliding galaxies)

Limits cross-section in the dark sectors.
Requires:

$$\frac{\sigma}{M} < 1 \ \frac{\text{cm}^2}{\text{g}} \simeq 2 \times 10^{-24} \ \frac{\text{cm}^2}{\text{GeV}}$$



Dark Matter on Small Scales

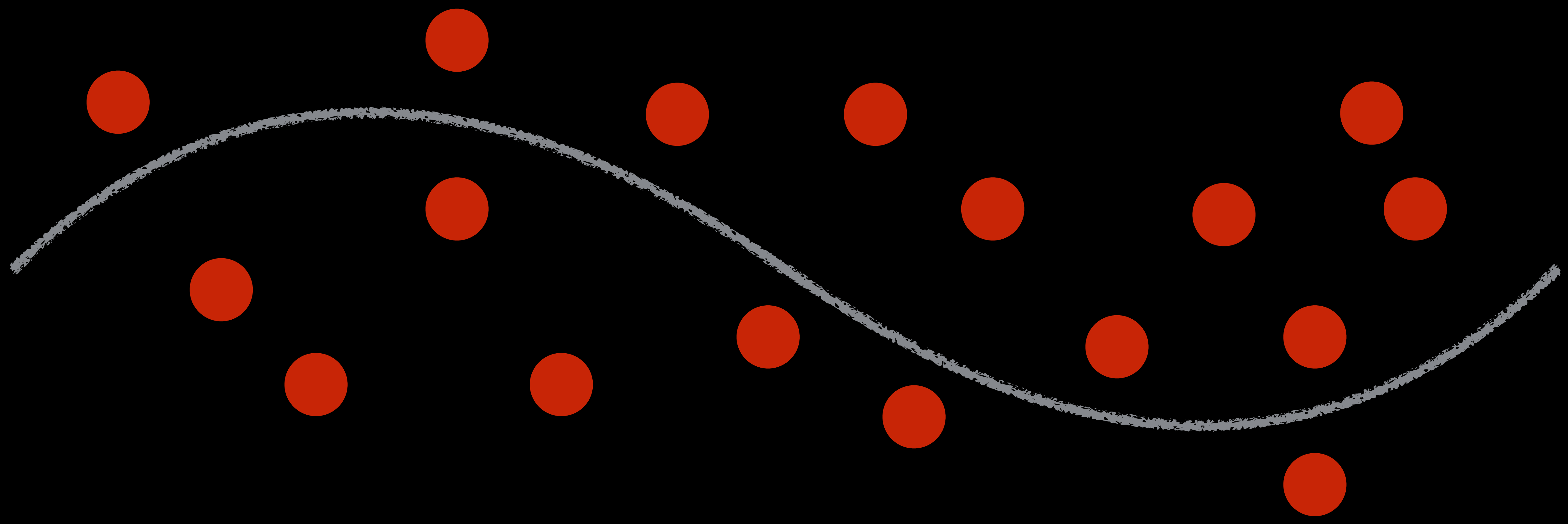
Favors strong interactions in the dark sector.
Requires a velocity dependent cross-section.

$$\frac{\sigma}{M} \simeq 1 \ \frac{\text{cm}^2}{\text{g}} \simeq 2 \times 10^{-24} \ \frac{\text{cm}^2}{\text{GeV}}$$

Tulin & Yu (2017)

Interacting Dark Matter

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



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

Coupling to baryon number can create (dark) charge separation in neutron stars.

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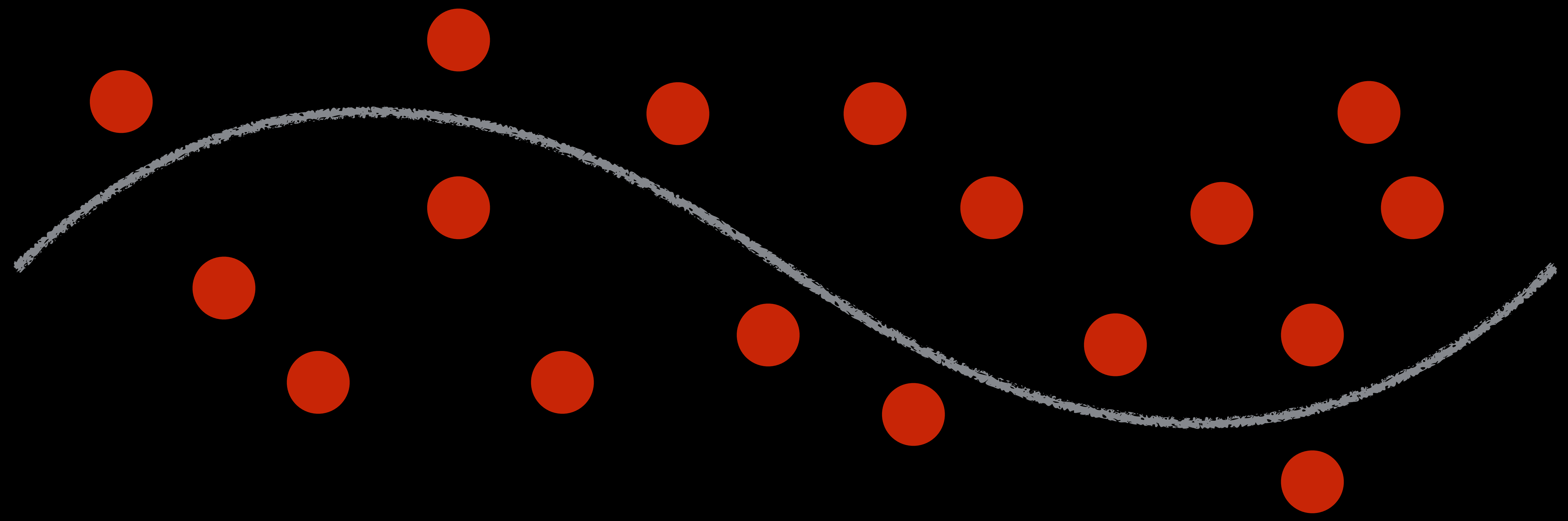

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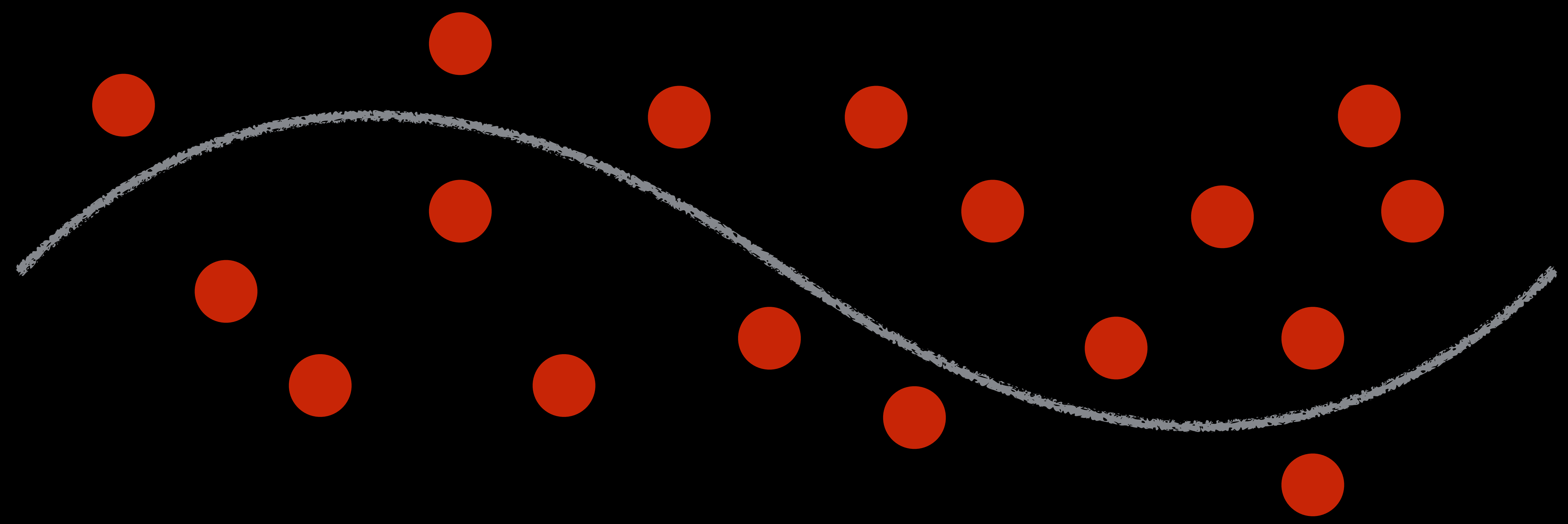

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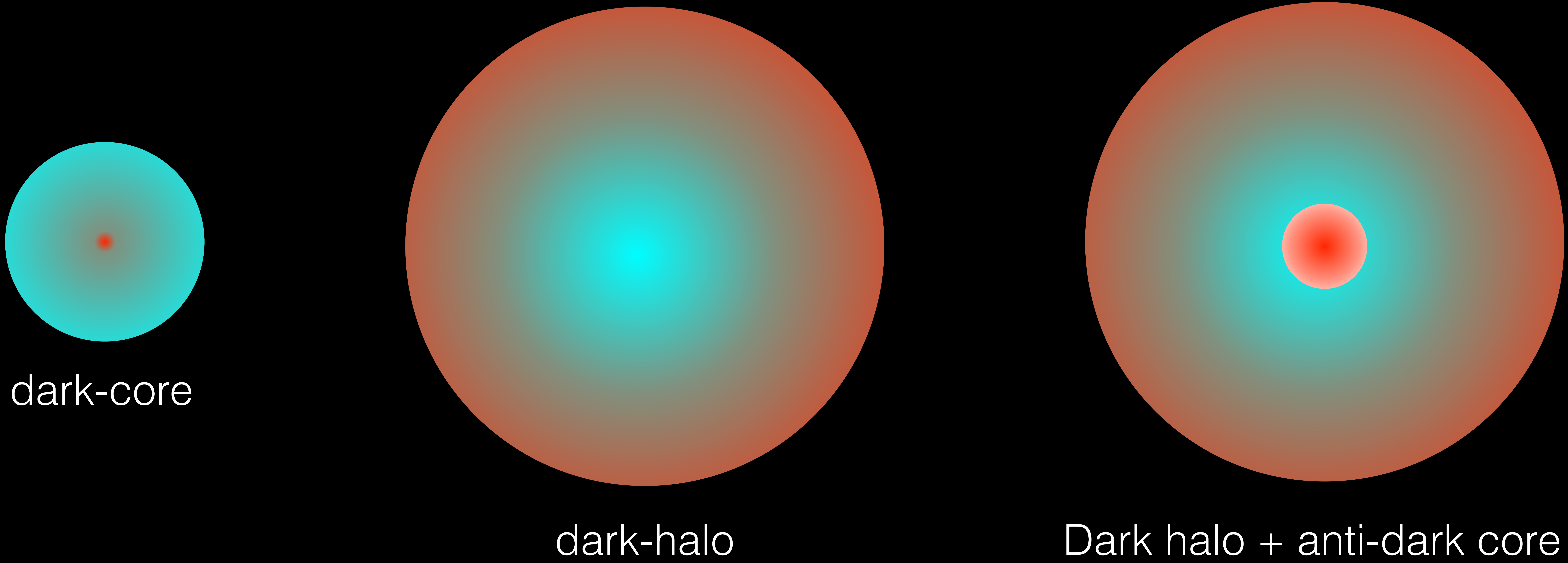
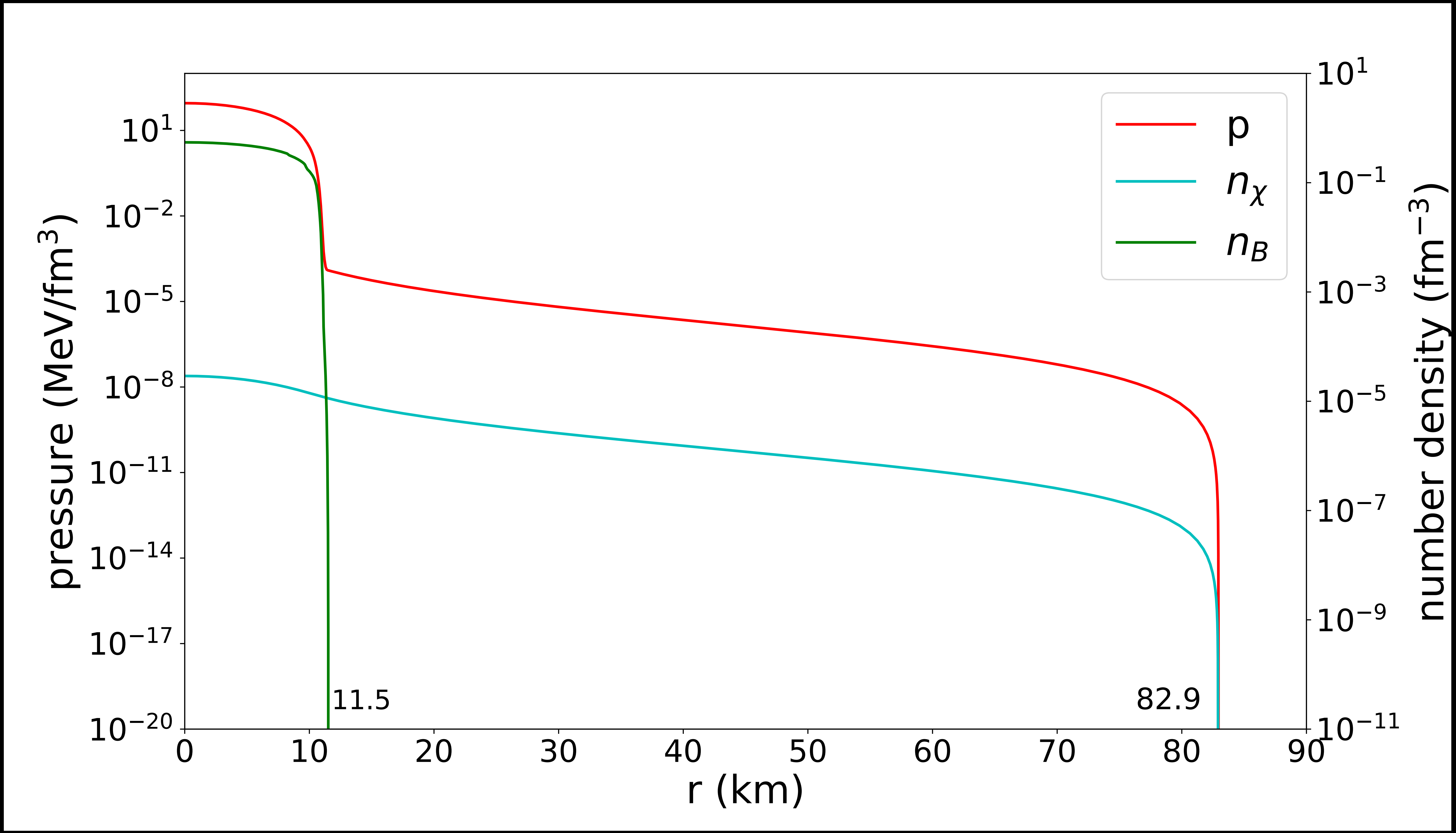
Stable Neutron Stars with Dark Matter



Nelson, Reddy $ Zhou (2018)

Profile of a Neutron Star with a Dark Halo



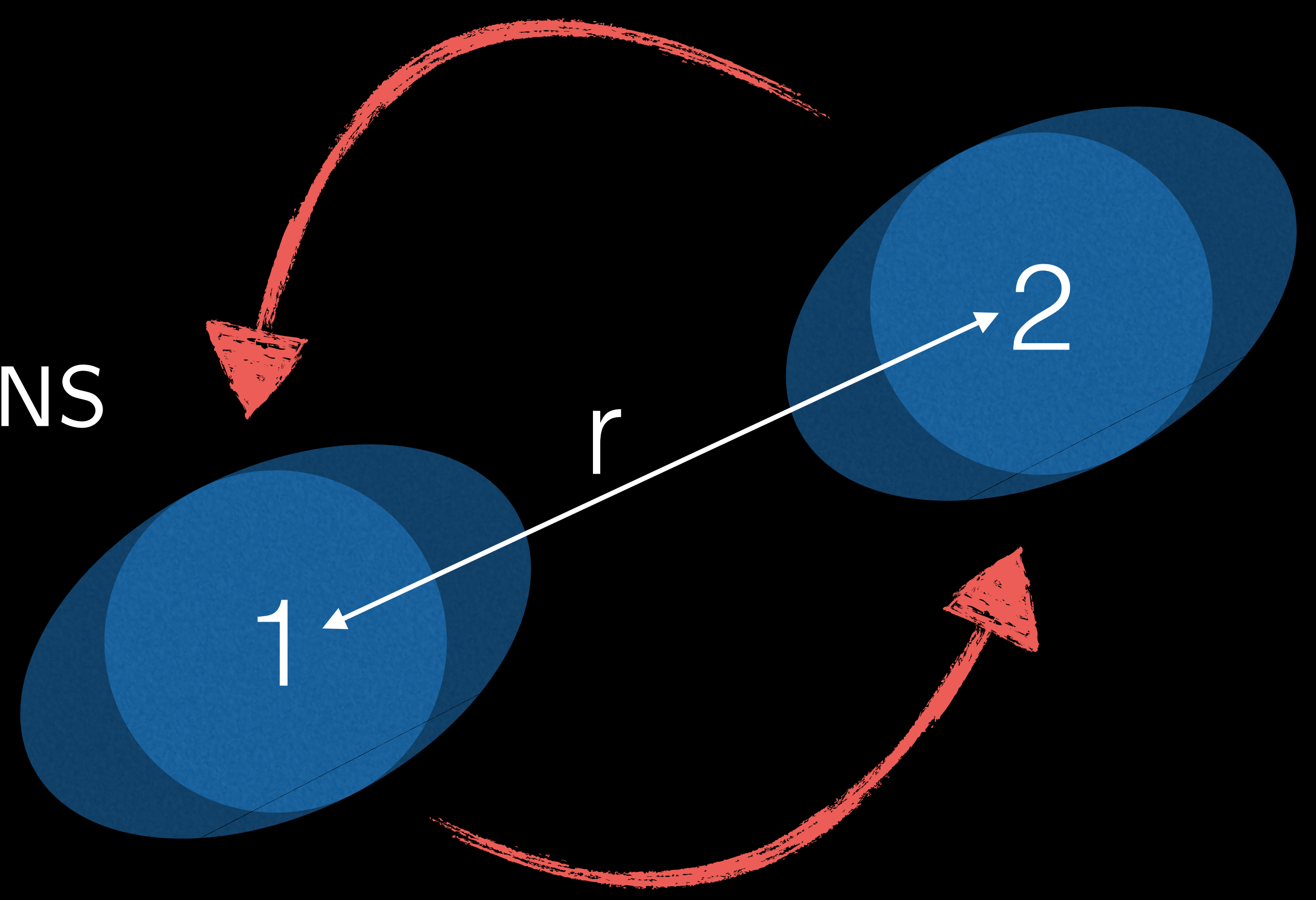
1.4 M_{solar} Neutron star with 10^{-4} M_{solar} of dark matter.

Dark matter: m_χ = 100 MeV

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

Nelson, Reddy, Zhou, ArXiV:1803.03266 (2018)

Tidal Deformation: Measuring the Neutron Star Radius



Tidal forces deform neutron stars.
Induces a quadrupole moment.

$$Q_{xy} = \lambda\ E_{xy} \qquad E_{xy} = -\frac{\partial^2 V_G}{\partial x \partial y}$$

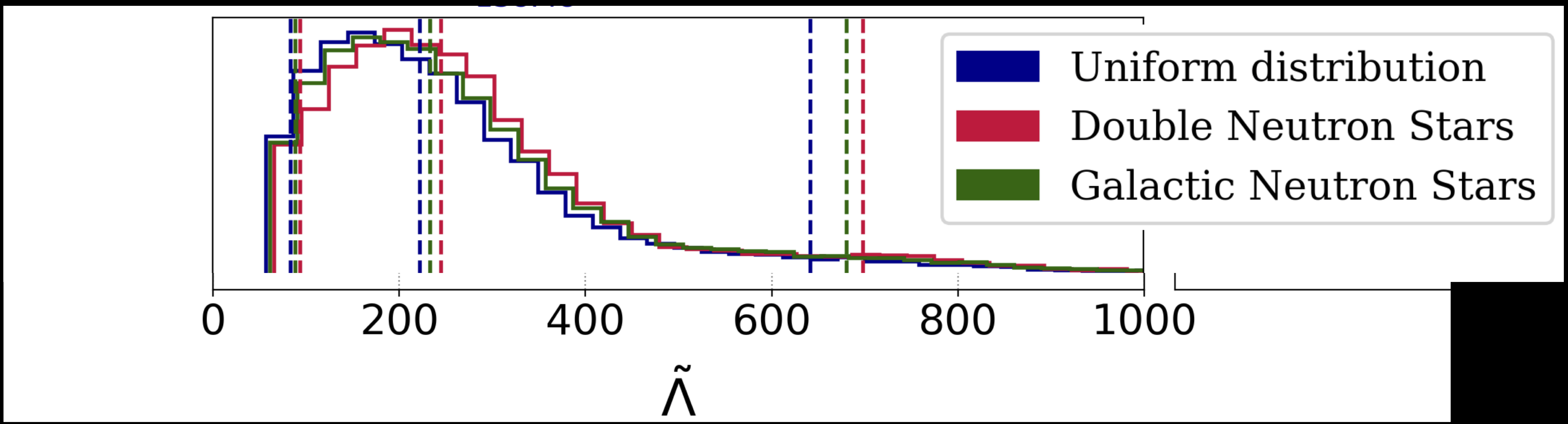
tidal deformability — external field

Tidal interactions change the rotational phase: $\delta\Phi = -\frac{117}{256} v^5 \frac{M}{\mu} \tilde{\Lambda}$

Dimensionless binary tidal deformability: $\tilde{\Lambda} = \frac{16}{13}\left(\left(\frac{M_1}{M}\right)^5\left(1 + \frac{M_2}{M_1}\right)\Lambda_1 + 1 \leftrightarrow 2\right)$

Tidal deformations are large for a large NS: $\Lambda_i = \frac{\lambda_i}{M_i^5} = k_2 \frac{R_i^5}{M_i^5}$

Upper Limit on the Tidal Deformability



GW170817 requires $\tilde{\Lambda} < 800$

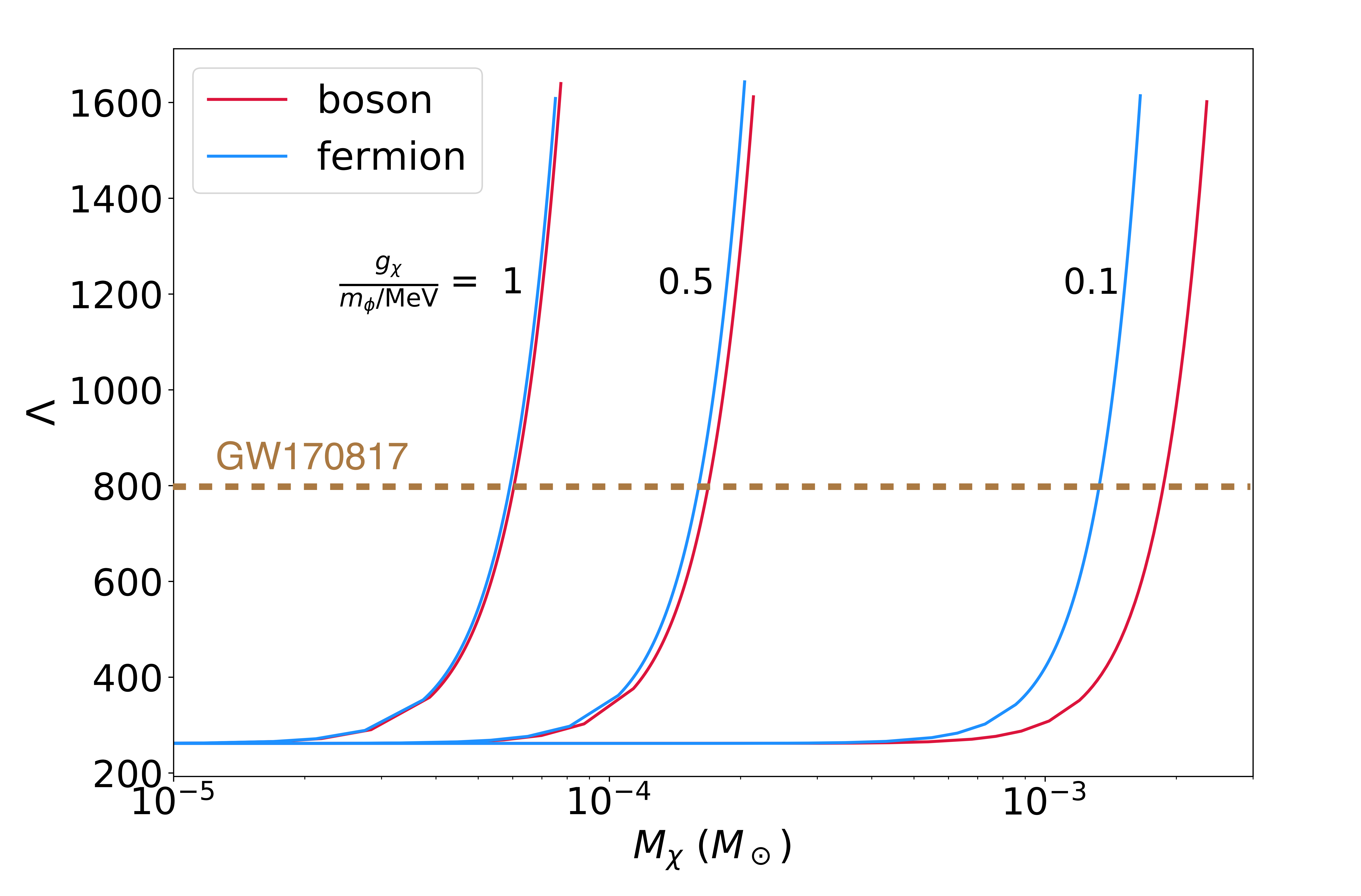
LIGO and Virgo Scientific Collaboration arXiV:1805.11581v1
De et al. PRL (2018)

For light mediators, only trace amounts are needed

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

g_χ/m_Φ = (0.1/MeV) or (10^{-6}/eV)

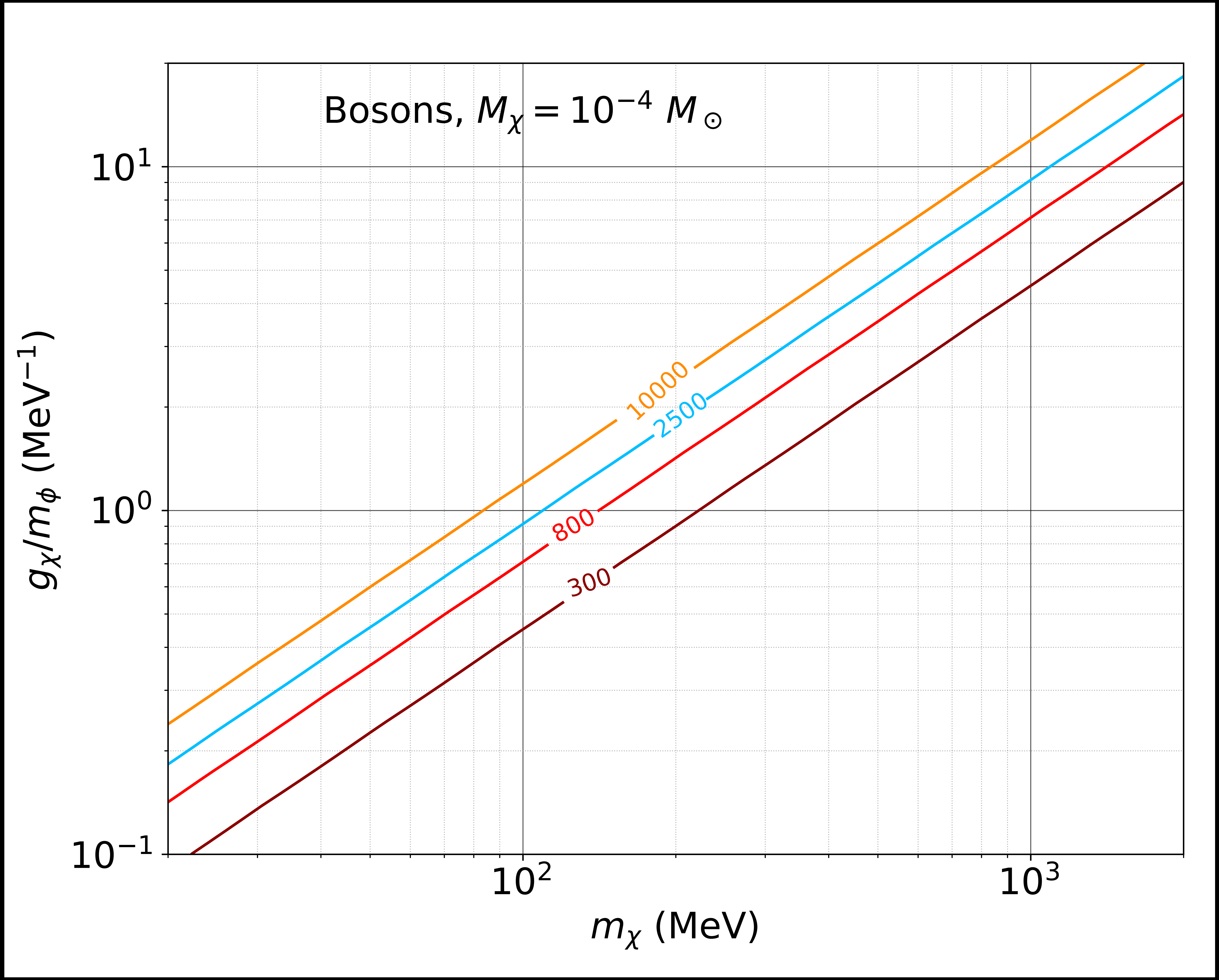
Interactions of “natural” size produce large Λ



Ann Nelson, Sanjay Reddy, Dake Zhou, ArXiV:1803.03266

If NSs contain dark matter:

- GW170817 rules out regions of interacting light dark matter parameter space.
- Light fermions are constrained even when interactions are negligible.
- Note, tidal effects probe interactions in the dark sector even if its interaction with the SM particles is only gravitational.



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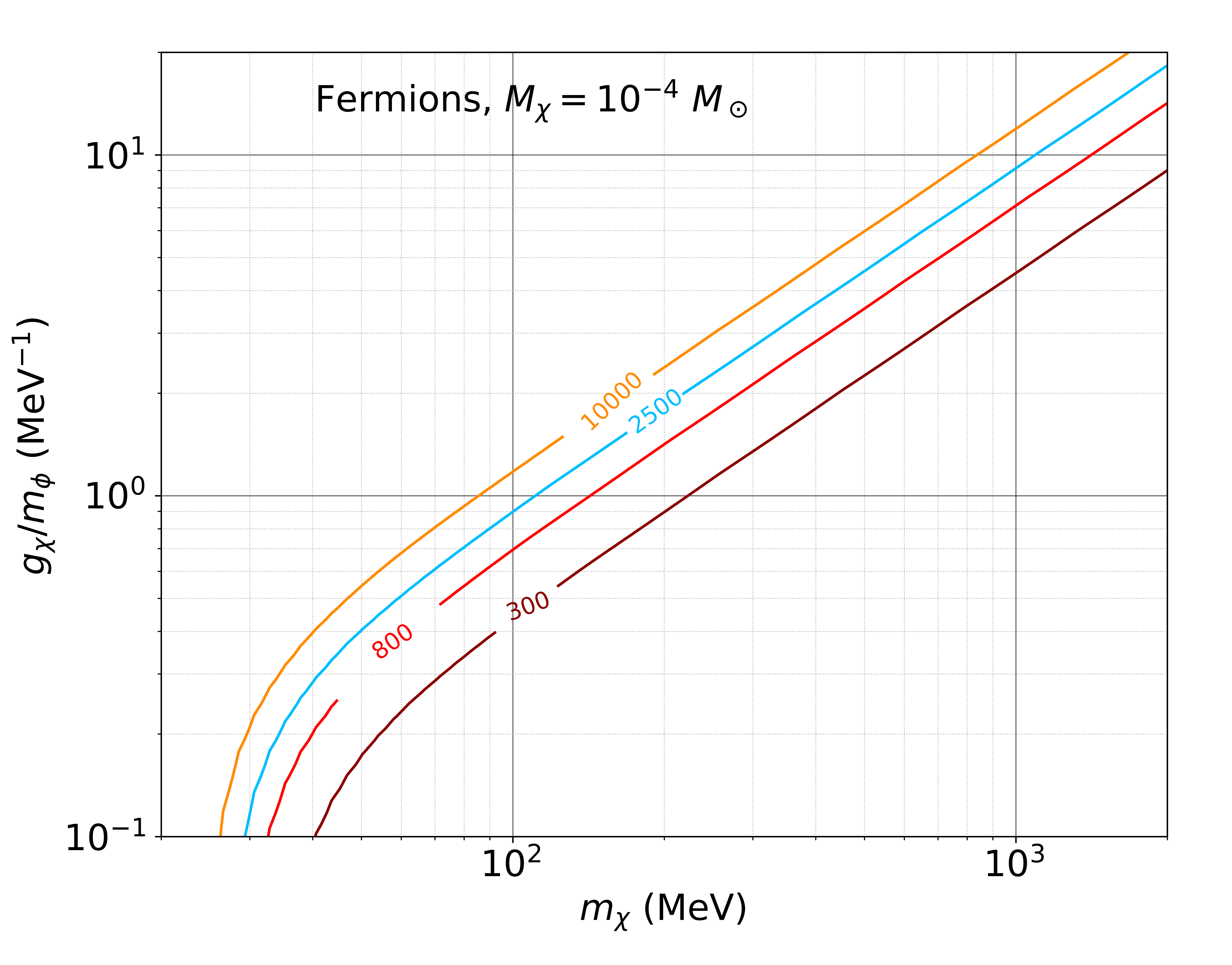

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Could/should neutron stars contain dark matter ?

- Supernova can produce (thermally) $10^{-2}\, M_{solar}$ of < 100 MeV dark matter.
- Coupling to baryons allows for dark charge separation.
- Dark matter could be clumpy. Compact dark objects -CDOs (strongly constrained but not excluded by micro-lensing)
- Dark clumps might seed star formation.

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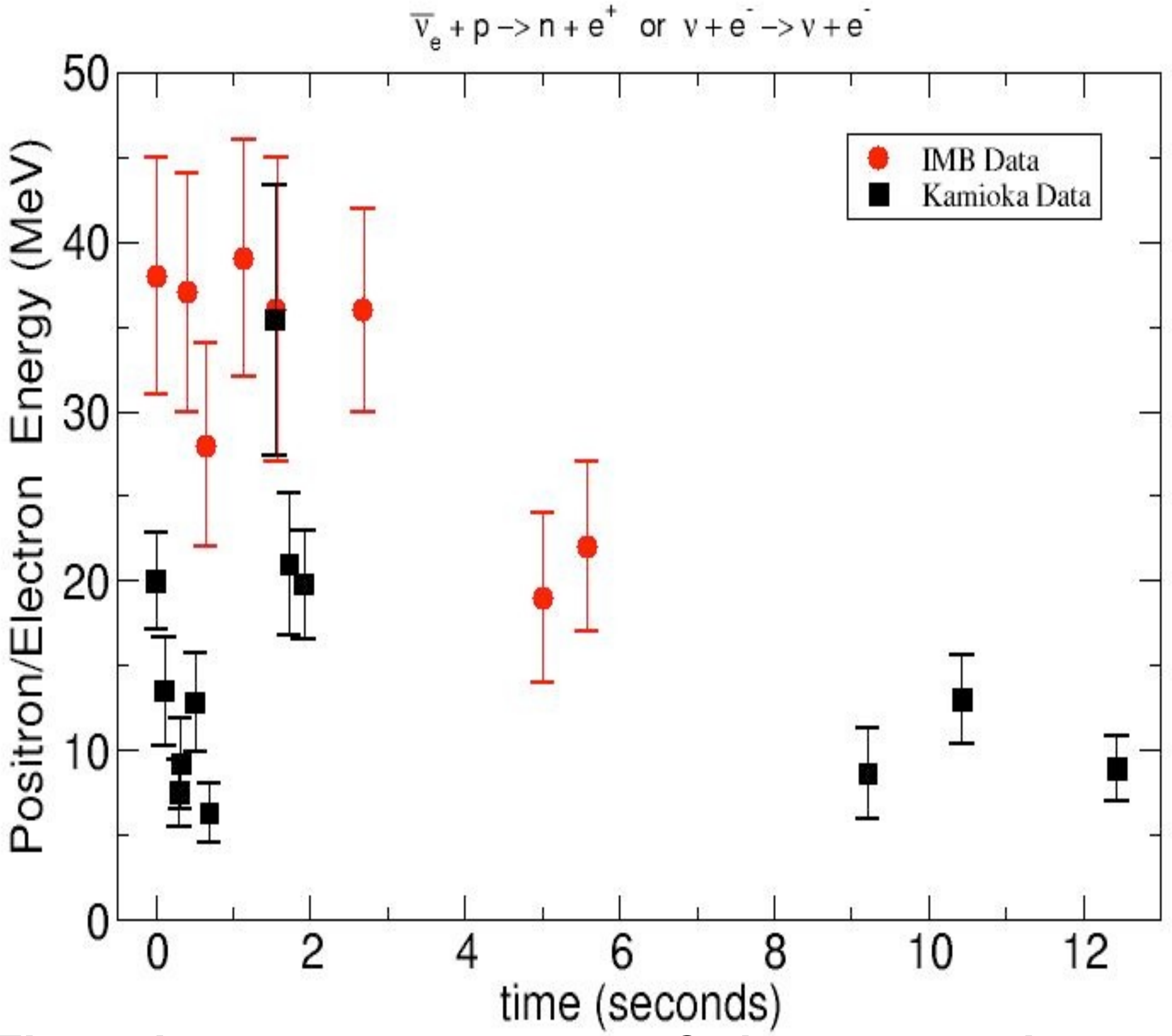
A large variability in the tidal polarizability of the merging neutron stars would be tantalizing evidence !

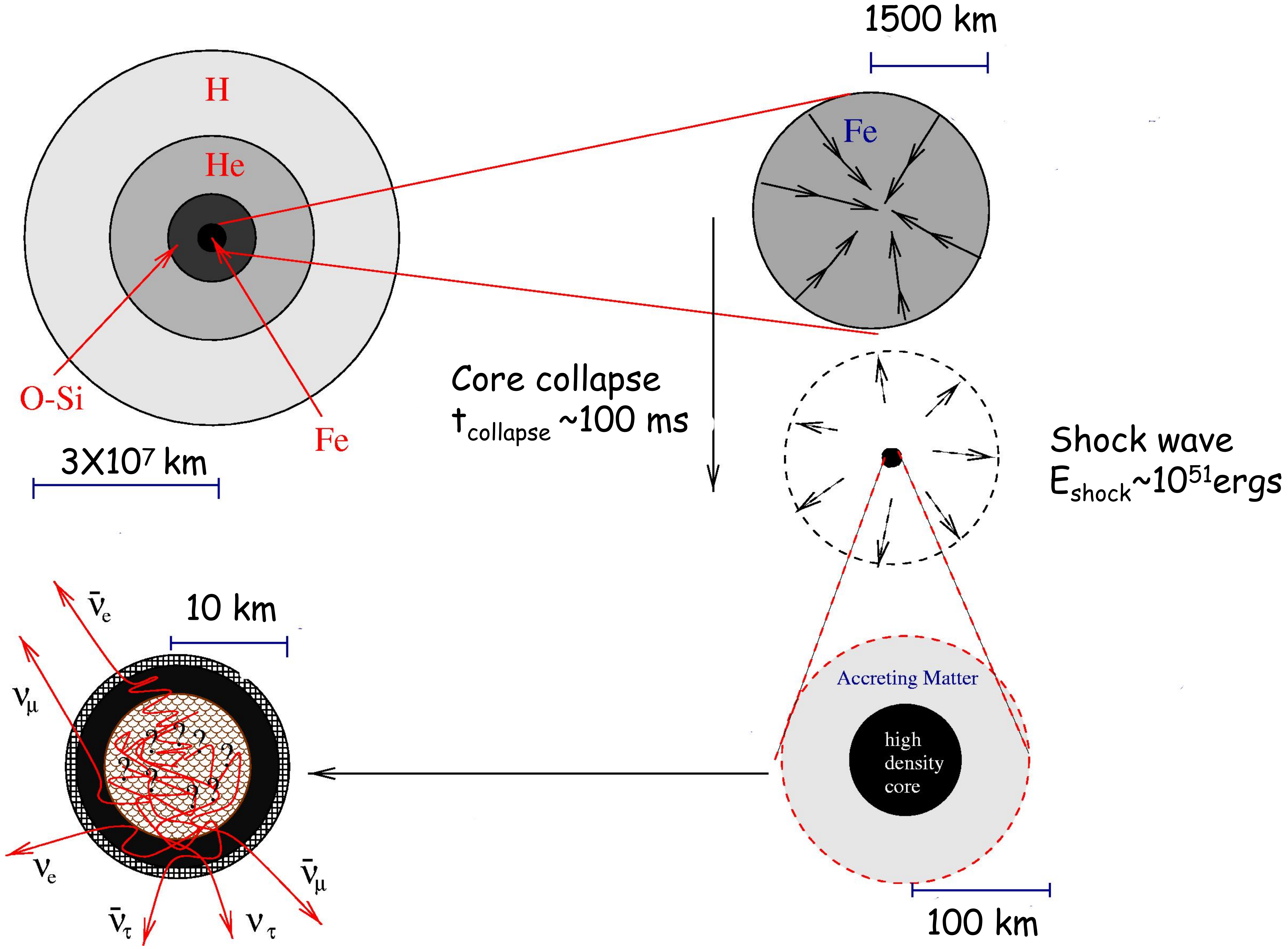
Early Neutron Star Cooling: Supernova Neutrinos

SN 1987a: ~ 20 neutrinos over ~10 s.



- The time structure of the neutrino signal depends on how heat is transported in the neutron star core.

- The spectrum is set by scattering in a hot (T=3-6 MeV) and not so dense (10^{12}-10^{13} g/cm^3) neutrino-sphere. Neutrino oscillations can strongly influence flavor asymmetries.



3 x 10^{53} ergs = 10^{58} × 20 MeV Neutrinos

neutrinos diffuse in the core.

Supernova 1987a bound on energy loss to exotic particles

Early cooling of the newly born neutron star is set by neutrino diffusion and emission and shapes the supernova neutrino signal. Exotic particles that can escape faster would shorten the SN neutrino signal.

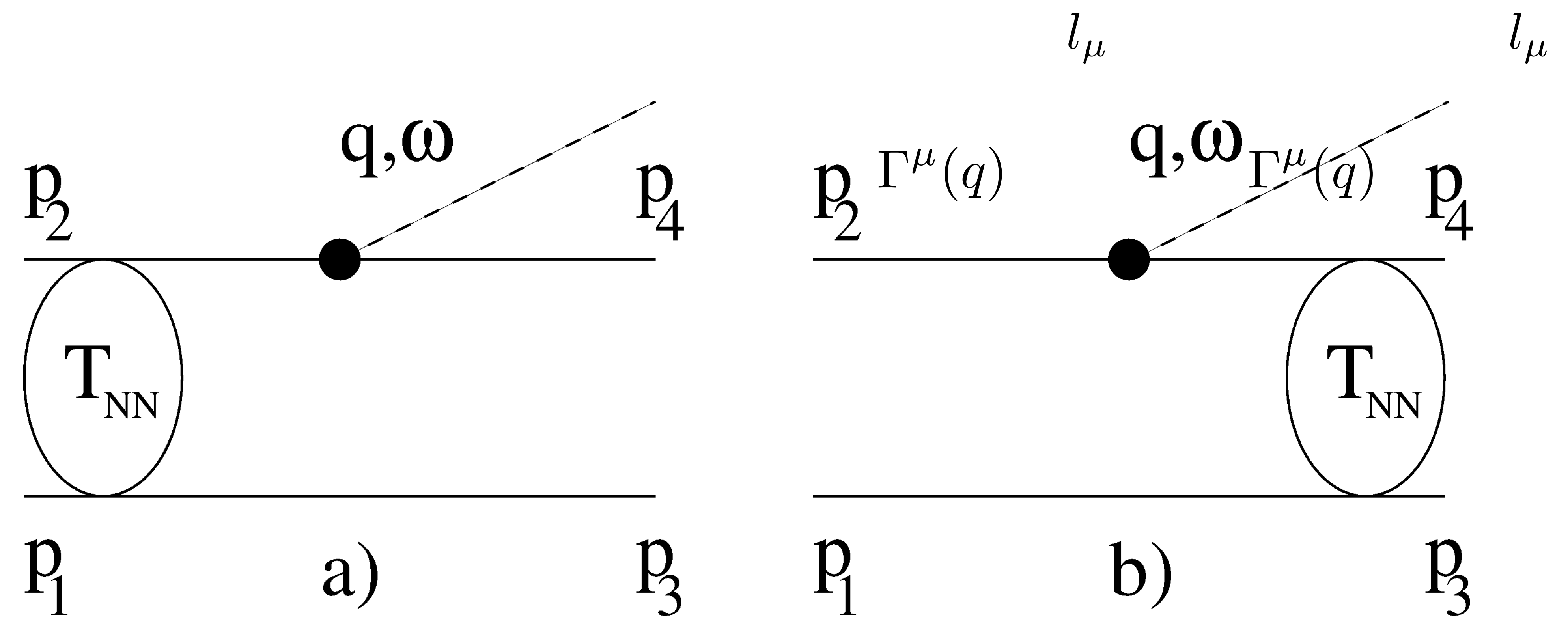
Raffelt's "local" bound: $$\mathcal{E}(\rho = 3 \times 10^{14}\ \mathrm{g/cm^3}, T = 30\ \mathrm{MeV}) < \mathcal{E}_{\mathrm{Raffelt}} = 10^{19}\ \frac{\mathrm{ergs}}{\mathrm{g\ s}}$$

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

The corresponding bound on the luminosity is $$L_{\mathrm{exotic}} < \mathcal{E}_{\mathrm{Raffelt}} \times M_{NS} \simeq 2 \times 10^{52} \frac{M}{M_\odot}\ \frac{\mathrm{ergs}}{\mathrm{s}}$$

Production of Axions & Dark Gauge Bosons in SN

Nucleon-nucleon Bremsstrahlung dominates:



$$\mathcal{A} \approx \frac{l_\mu}{\omega} \; \langle \mathbf{p}_{in} | [T_{NN}, \Gamma^\mu(q)] | \mathbf{p}_{out} >$$

nucleon-nucleon T-matrix

intermediate nucleon - energy denominator

Hanhart, Phillips & Reddy (2001)

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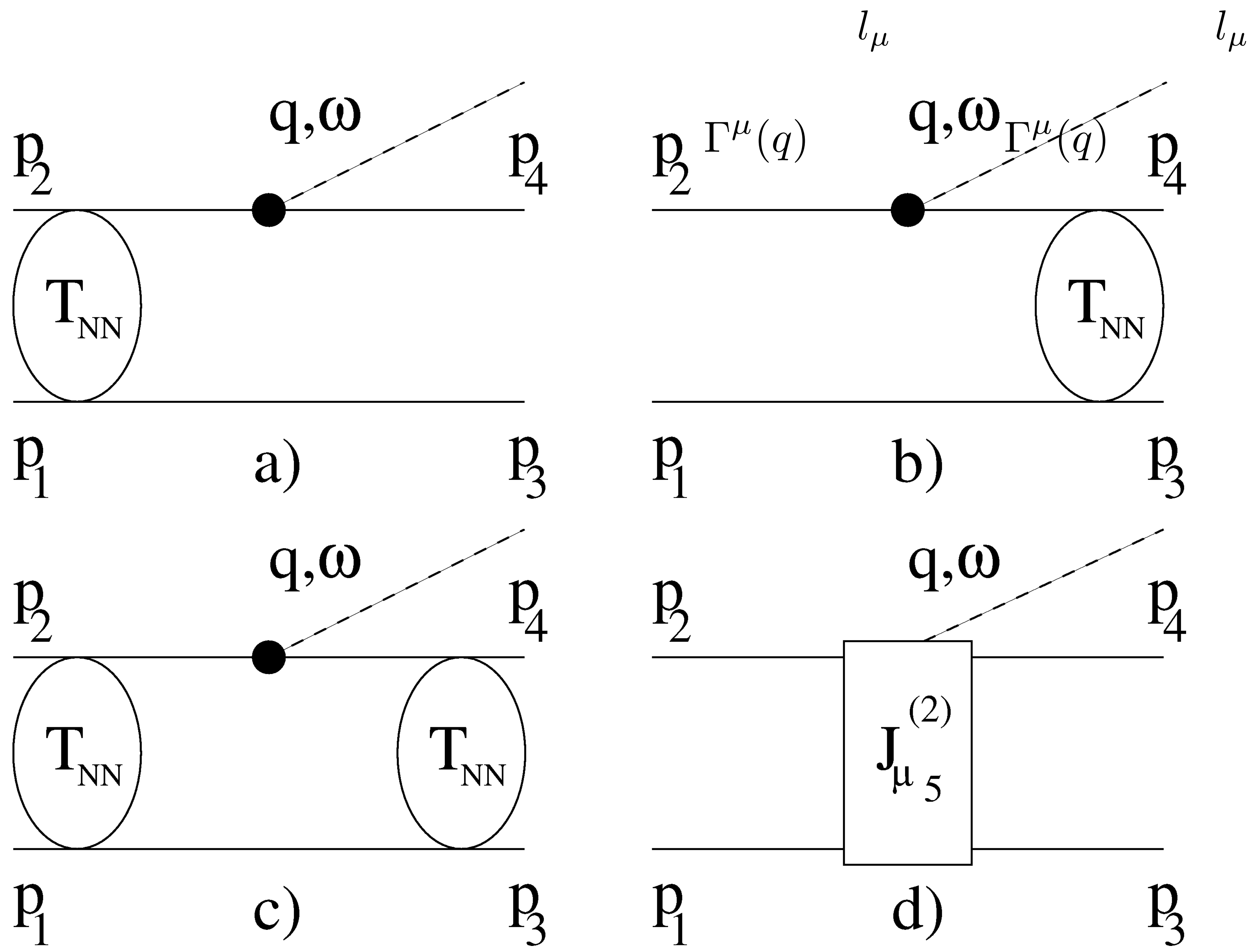

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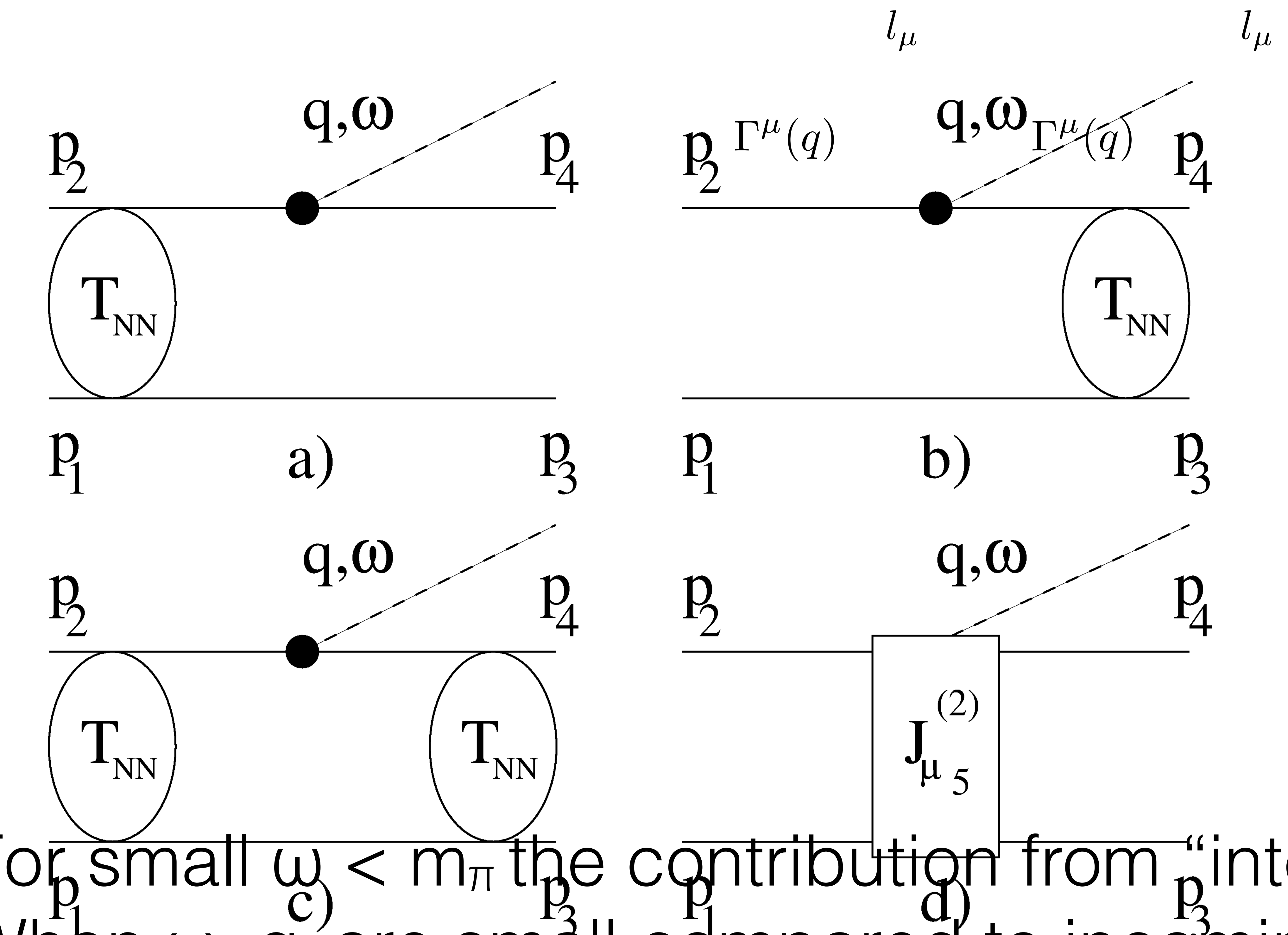

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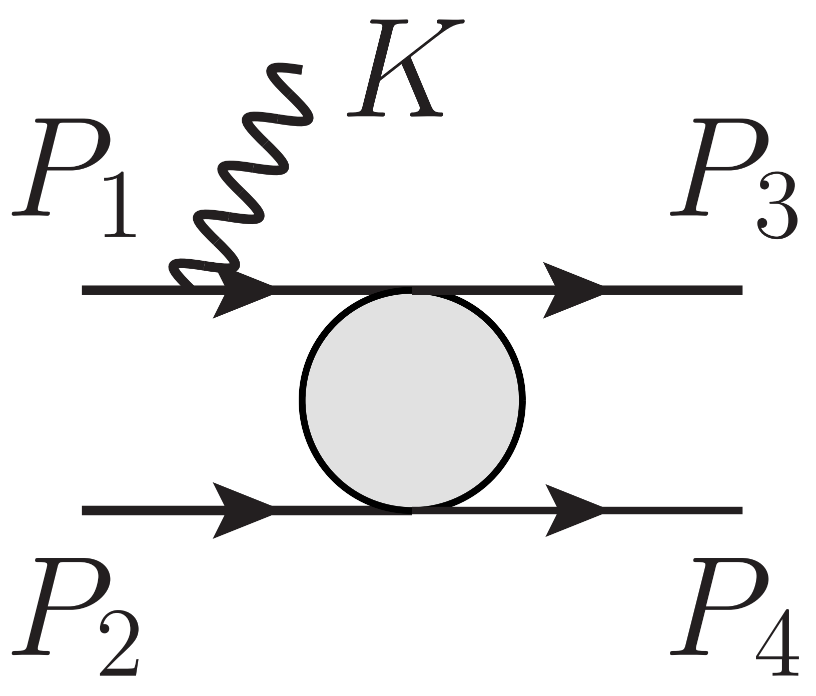
nucleon-nucleon T-matrix

intermediate nucleon - energy denominator

- For small $\omega < m_\pi$ the contribution from “internal” diagrams is small <10%.
- When ω, q are small compared to incoming nucleon energy and momenta T_{NN} can be related to the phase shifts. (Low’s Theorem)

Hanhart, Phillips & Reddy (2001)

Radiating Dark Gauge Bosons



Soft radiation or Low's theorem for Bremsstrahlung

$$d\sigma_{pp\to pp\gamma_i} = -4\pi\alpha_{\rm em}\epsilon_i^2 \; \frac{d^3k}{2\omega}(\epsilon^\mu J_\mu^{(4)})^2 \; d\sigma_{pp\to pp}$$

$$d\sigma_{np\to pp\gamma_Q} = -4\pi\alpha_{\rm em}\epsilon_Q^2 \; \frac{d^3k}{2\omega}(\epsilon^\mu J_\mu^{(2)})^2 \; d\sigma_{np\to np}$$

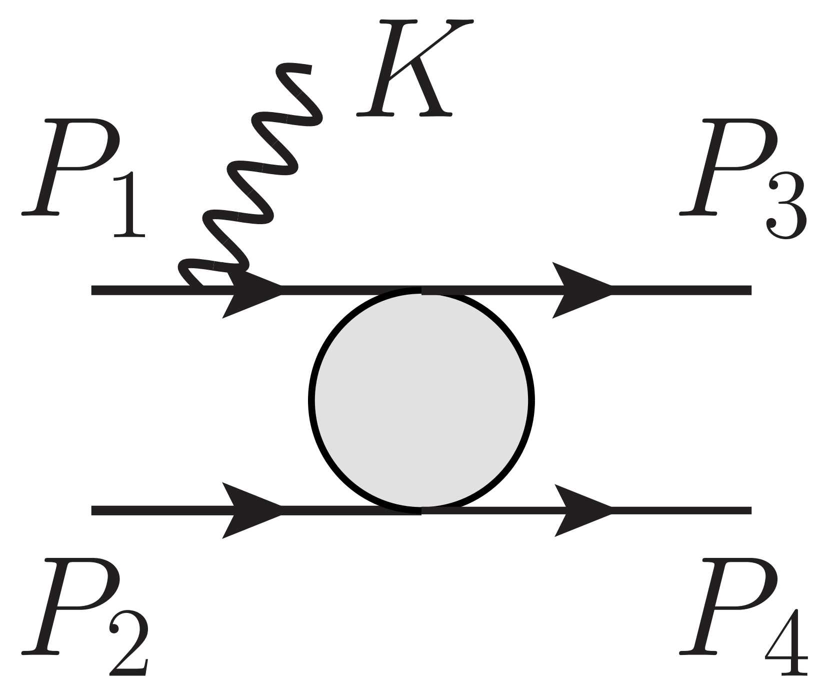
$$d\sigma_{np\to np\gamma_B} = -4\pi\alpha_{\rm em}\epsilon_B^2 \; \frac{d^3k}{2\omega}(\epsilon^\mu J_\mu^{(4)})^2 \; d\sigma_{np\to np}$$

where the dipole and quadrupole currents are

$$J_\mu^{(2)} = \left(\frac{P_1}{P_1\cdot K} - \frac{P_3}{P_3\cdot K}\right)_\mu ,$$

$$J_\mu^{(4)} = \left(\frac{P_1}{P_1\cdot K} + \frac{P_2}{P_2\cdot K} - \frac{P_3}{P_3\cdot K} - \frac{P_4}{P_4\cdot K}\right)_\mu$$

Radiating Dark Gauge Bosons



Soft radiation or Low's theorem for Bremsstrahlung

$$d\sigma_{pp\to pp\gamma_i} = -4\pi\alpha_{\rm em}\epsilon_i^2 \frac{d^3k}{2\omega}(\epsilon^\mu J_\mu^{(4)})^2 \, d\sigma_{pp\to pp}$$

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Rates in the plasma at leading order in the low energy expansion are related to measured nucleon-nucleon cross-sections.

$$\dot\epsilon_{np\to np\gamma_Q} = \frac{\alpha_{\rm em}\epsilon_Q^2}{\pi^{3/2}}\frac{n_n n_p}{(MT)^{3/2}}\int_{m_{\gamma_Q}}^\infty dE_{\rm cm}\, e^{-\frac{E_{\rm cm}}{T}}\, E_{\rm cm}^3\, \mathcal{I}^{(2)}(\frac{m_{\gamma_Q}}{E_{\rm cm}})\, \sigma_{np}^{(2)}(E_{\rm cm})$$

$$\dot\epsilon_{pp\to pp\gamma_Q} = \frac{\alpha_{\rm em}\epsilon_Q^2}{\pi^{3/2}}\frac{n_p n_p}{(MT)^{3/2}}\int_{m_{\gamma_Q}}^\infty dE_{\rm cm}\, e^{-\frac{E_{\rm cm}}{T}}\, \frac{E_{\rm cm}^4}{M}\, \mathcal{I}^{(4)}(\frac{m_{\gamma_Q}}{E_{\rm cm}})\, \sigma_{pp}^{(4)}(E_{\rm cm})$$

$$\dot\epsilon_{ij\to ij\gamma_B} = \frac{\alpha_{\rm em}\epsilon_B^2}{\pi^{3/2}}\frac{n_i n_j}{(MT)^{3/2}}\int_{m_{\gamma_B}}^\infty dE_{\rm cm}\, e^{-\frac{E_{\rm cm}}{T}}\, \frac{E_{\rm cm}^4}{M}\, \mathcal{I}^{(4)}(\frac{m_{\gamma_B}}{E_{\rm cm}})\, \sigma_{ij}^{(4)}(E_{\rm cm})$$

where

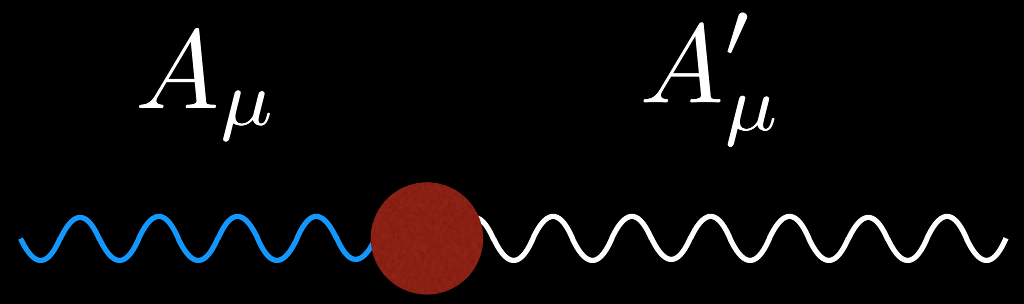
$$\sigma_{ij}^{(2)} = \int d\cos\theta_{\rm cm}\frac{d\sigma_{n_in_j\to n_in_j}}{d\theta_{\rm cm}}(1-\cos\theta_{\rm cm}) ,$$

$$\sigma_{ij}^{(4)} = \int d\cos\theta_{\rm cm}\frac{d\sigma_{n_in_j\to n_in_j}}{d\theta_{\rm cm}}(1-\cos^2\theta_{\rm cm}) .$$

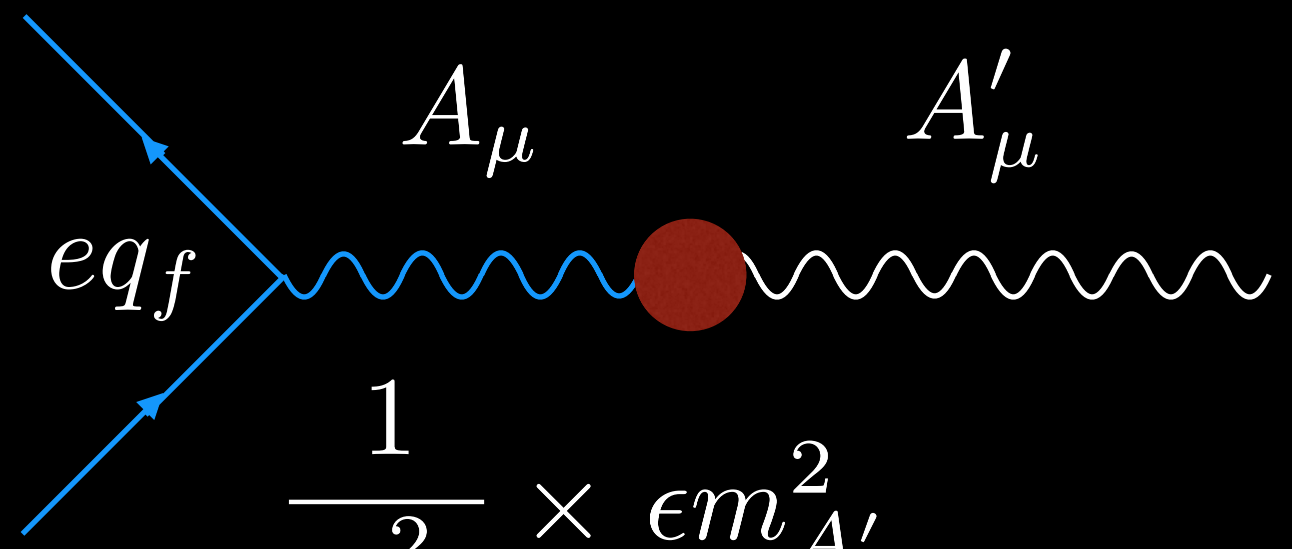
Rrapaj & Reddy (2016)

Plasma Effects for Kinetically Mixed Dark Photons

$$\mathcal{L}_{mix} = -\frac{\epsilon}{2} F'_{\mu\nu}F^{\mu\nu}$$



on-shell: $\mathcal{L}_{mix} = -\epsilon\, m_{A'}^2\, A'_\mu A^\mu$



$$\frac{1}{m_{A'}^2} \times \epsilon m_{A'}^2$$

on-shell: $\mathcal{L}_{A'f} = -\epsilon e q_f\, A'_\mu\, \bar{\psi}_f \gamma^\mu \psi_f$

In a plasma the photon propagator is modified (plasmons):

$$\frac{1}{m_{A'}^2} \to \frac{1}{m_{A'}^2 - \Pi_\gamma}$$

and

$$\mathcal{L}_{A'f} = -\tilde{\epsilon}\, e q_f\, A'_\mu\, \bar{\psi}_f \gamma^\mu \psi_f$$

Effective coupling in the plasma can be greatly modified when dark photon mass ~ plasma frequency.

$$|\tilde{\epsilon}|^2 = \frac{\epsilon^2\, m_{A'}^4}{(m_{A'}^2 - \text{Re}\,\Pi_\gamma)^2 + \text{Im}\,\Pi_\gamma^2}$$

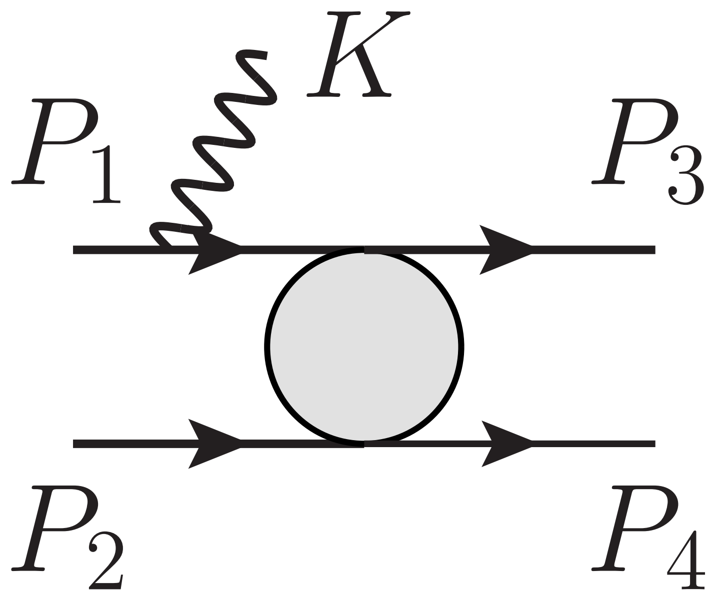
An, Pospelov, Pradler (2013)

Dark Photons

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

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

Nucleon-nucleon Bremsstrahlung dominant production mechanism:



Soft radiation or Low's theorem for photon Bremsstrahlung can be used to estimate these rates in hot and dense matter.

Rrapaj and Reddy (2016)

Effective coupling in the plasma is resonantly enhanced when dark photon mass ~ plasma frequency.

An, Pospelov, Pradler (2013) Chang, Essig, McDermott (2017,2018)

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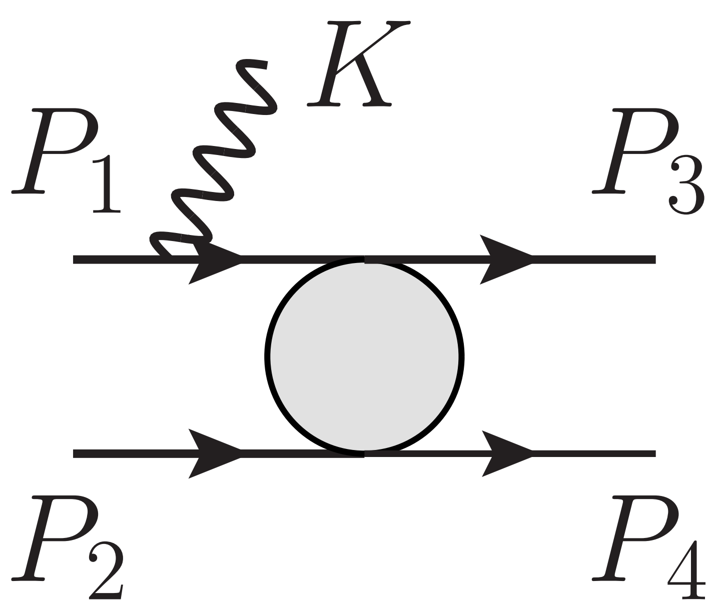

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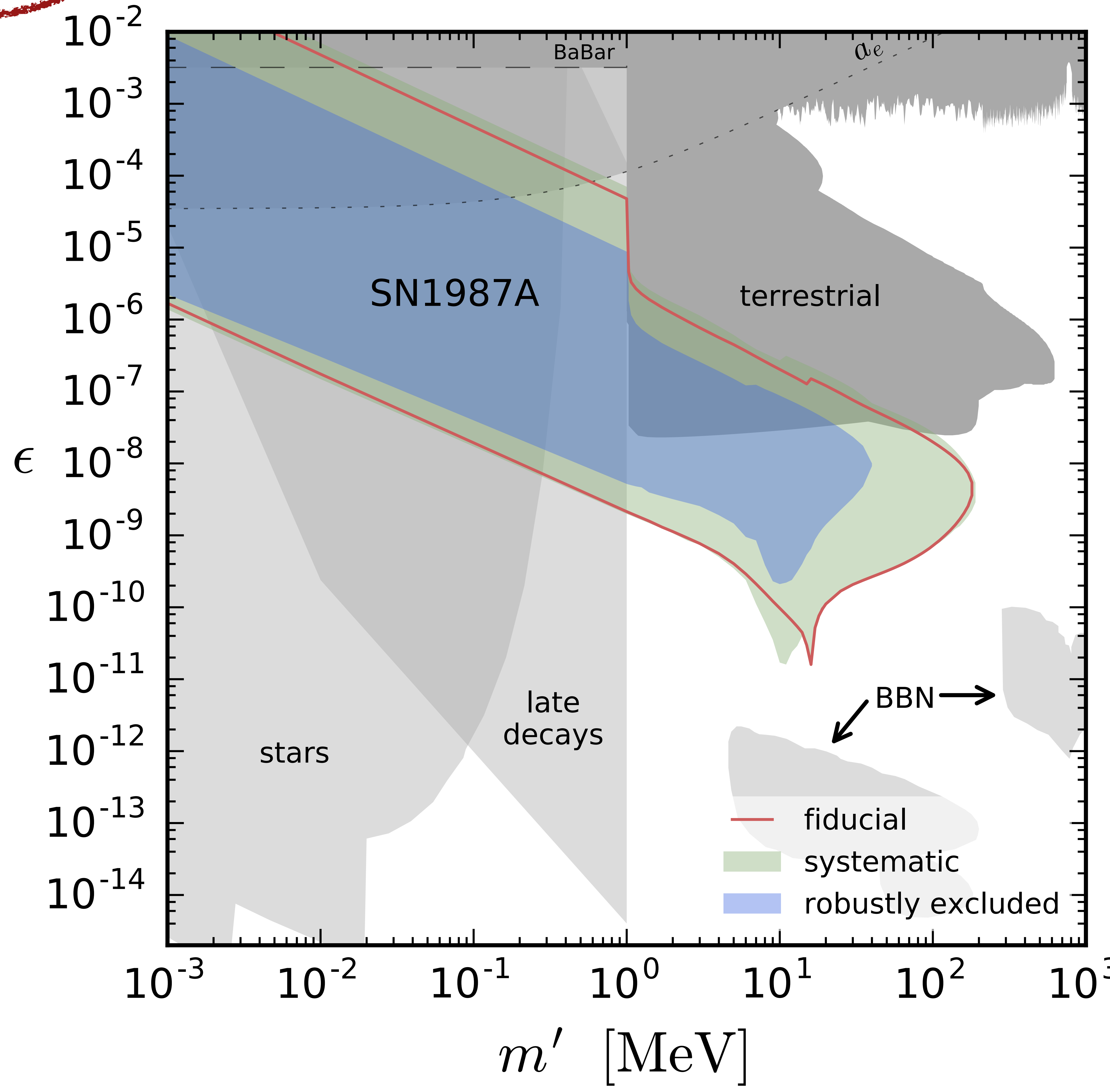


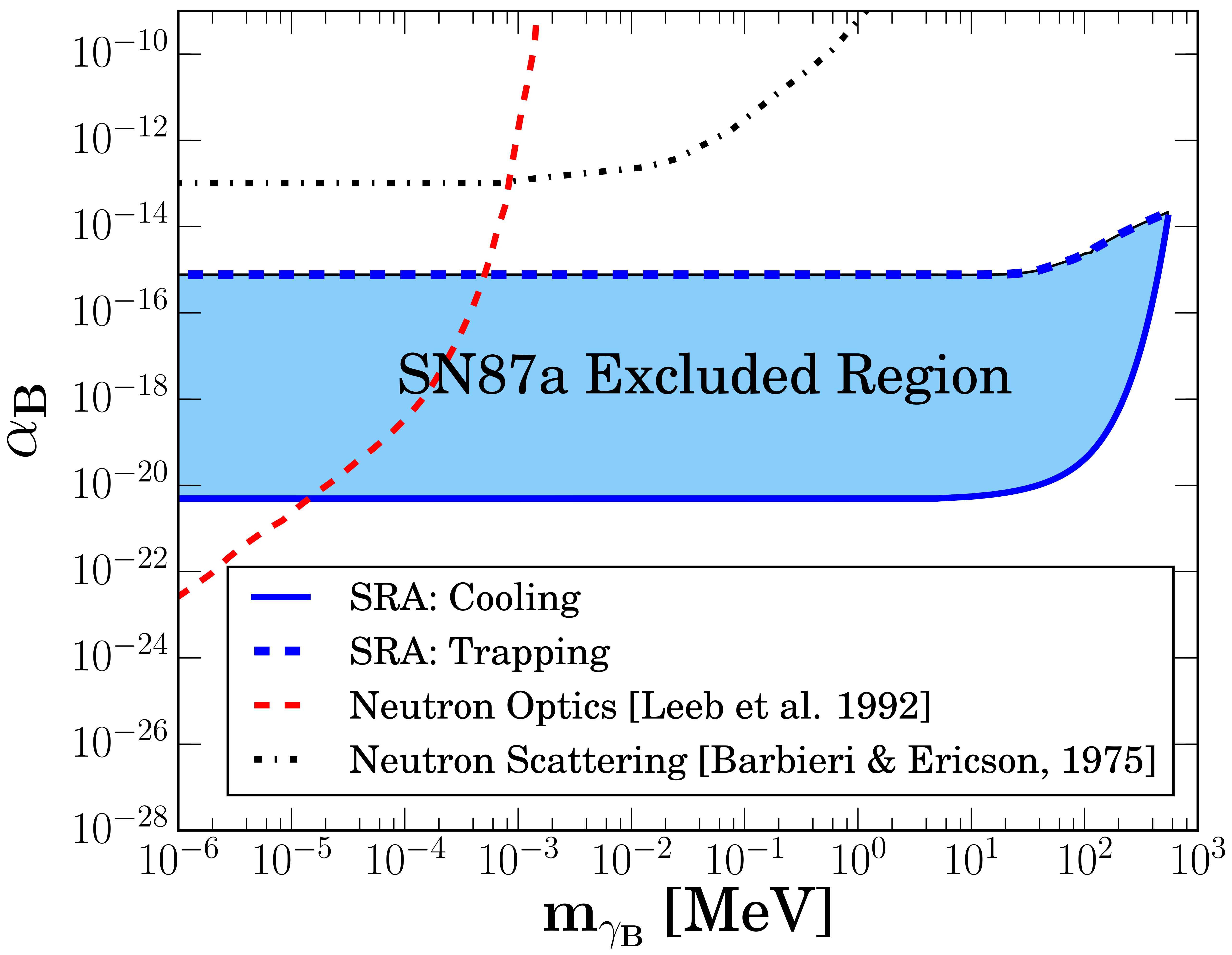
Dark Baryon Number Gauge Boson

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

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

- Nucleon-nucleon bremsstrahlung is the dominant production channel.
- Quadrupolar radiation is modestly suppressed (v^4)

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



Rrapaj and Reddy (2016)

Axions

Introduced to solve the strong CP problem in QCD.

$$\mathscr{L}_{agg} = \frac{g^2}{32\pi^2}\,\frac{a}{f_a}\,G^{\mu\nu}\tilde{G}_{\mu\nu}$$

Axion mass in QCD: $$m_a = \frac{z^{1/2}}{1+z}\,\frac{f_\pi m_\pi}{f_a} = \frac{6.0\,\mathrm{eV}}{f_a/10^6\,\mathrm{GeV}}$$

Couples to photons:

$$L_{a\gamma\gamma} = \frac{g_{a\gamma\gamma}}{4}\,F_{\mu\nu}\tilde{F}^{\mu\nu}a = -g_{a\gamma\gamma}\,\mathbf{E}\cdot\mathbf{B}\,a$$

$$\Gamma_{a\to\gamma\gamma} = \frac{g^2_{a\gamma\gamma}m_a^3}{64\,\pi} = 1.1\times 10^{-24}\,\mathrm{s}^{-1}\left(\frac{m_a}{\mathrm{eV}}\right)^5$$

Couples to fermions (quarks and leptons): $$L_{ajj} = \frac{C_j}{2f_a}\,\bar{\Psi}_j\gamma^\mu\gamma_5\Psi_j\partial_\mu a$$

Axion Production in NSs

For conserved currents $$[T_{nn}, \Gamma_\mu(q)] \propto \frac{q}{M}$$ - radiation needs acceleration

Axions couple to the nucleon spin. Nuclear interactions do not conserve nucleon spin due to strong tensor and spin-orbit interactions.

$$[T_{nn}, \Gamma_\mu(q \to 0)] \neq 0$$

Radiation without acceleration. Driven by spin flips due to tensor interactions.

The axion emissivity (energy radiated/unit volume/unit time) $$\mathcal{E}_a = \frac{C_i^2}{48\pi^2 \; f_a^2} \int d\omega \; \omega^4 \; S_\sigma(\omega)$$

$$f_1 f_2 (1 - f_3)(1 - f_4)$$

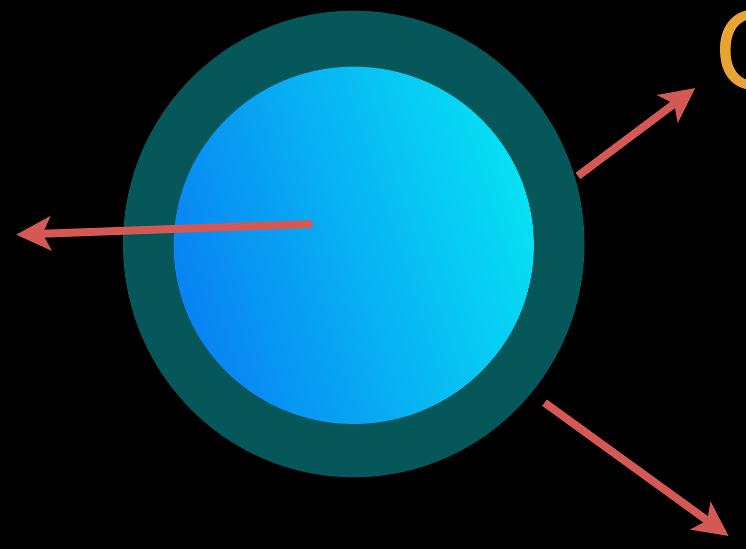
$$S_\sigma(\omega) = \int \left[\prod_{i=1..4} \frac{d^3 p_i}{(2\pi)^3}\right] (2\pi)^4 \delta^3(\mathbf{p_1} + \mathbf{p_2} - \mathbf{p_3} - \mathbf{p_4}) \; \delta(E_1 + E_2 - E_3 - E_4 - \omega) \; \mathcal{F} \; \frac{1}{s} \; \mathcal{H}_{ii}$$

$$\mathcal{H}_{ii} = 16 \; \frac{1}{\omega^2} \sum_{M_s M_s'} \left| \langle 1 M_s', \mathbf{p}' | \left[S_i, \mathbf{T}_{NN} \right] | \mathbf{p}, 1 M_s \rangle \right|^2$$

Hanhart, Phillips & Reddy (2001)

Late Neutron Star Cooling

Isothermal core cools by neutrino emission



Crust cools by conduction

Surface photon emission dominates at late time $t > 10^6$ yrs

Basic neutrino reactions:

- URCA reactions dominate when both proton and neutron $T > T_c$
- Direct URCA requires > 11 % protons.
- In the vicinity of T_c critical fluctuations form and destroy Cooper pairs and enhance neutrino emission.
- For $T \ll T_c$ all neutrino processes are exponentially suppressed.
- When protons are superconducting and neutrons are normal, neutron Bremsstrahlung dominates.

fast: $n \rightarrow e^- + p + \bar{\nu}_e$

medium: $n + n \rightarrow < nn > + \nu + \bar{\nu}$

slow: $n + n \rightarrow n + p + e^- + \bar{\nu}_e$

very slow: $n + n \rightarrow n + n + \nu + \bar{\nu}$

Increasing NS mass (↑)

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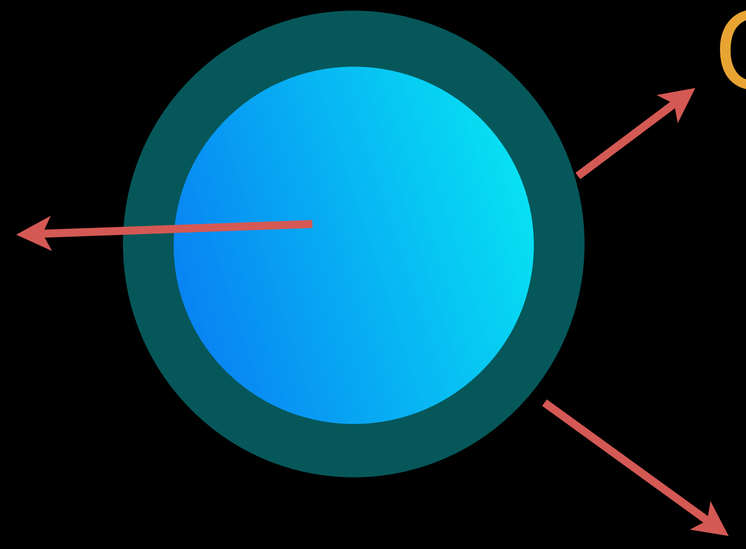

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$n + n \to n + n + \nu + \bar{\nu}$
$n + n \to n + n + a$
$n + p \to n + p + \tilde{\gamma}$

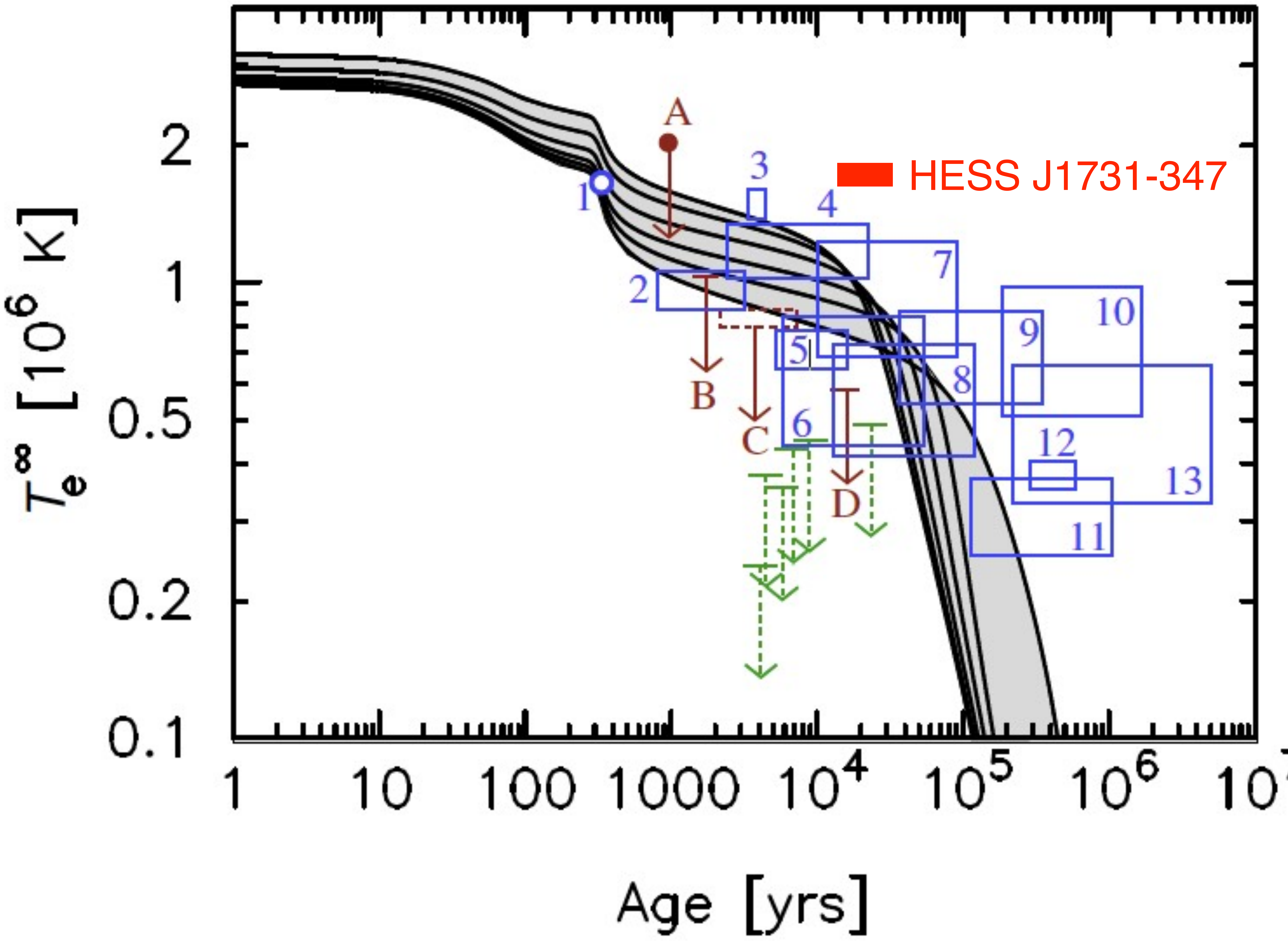
Increasing NS mass

Models can predict the observed variability

By varying the NS mass, surface composition, and critical temperature cooling models provide a fair description of cooling data.

One exception is HESS J1731-34. Too hot. Yakovlev et al (2016, 2017)

HESS requires very slow cooling and **is only compatible with neutron Bremsstrahlung**.



Yakovlev et al (2015) Page et al. (2016)

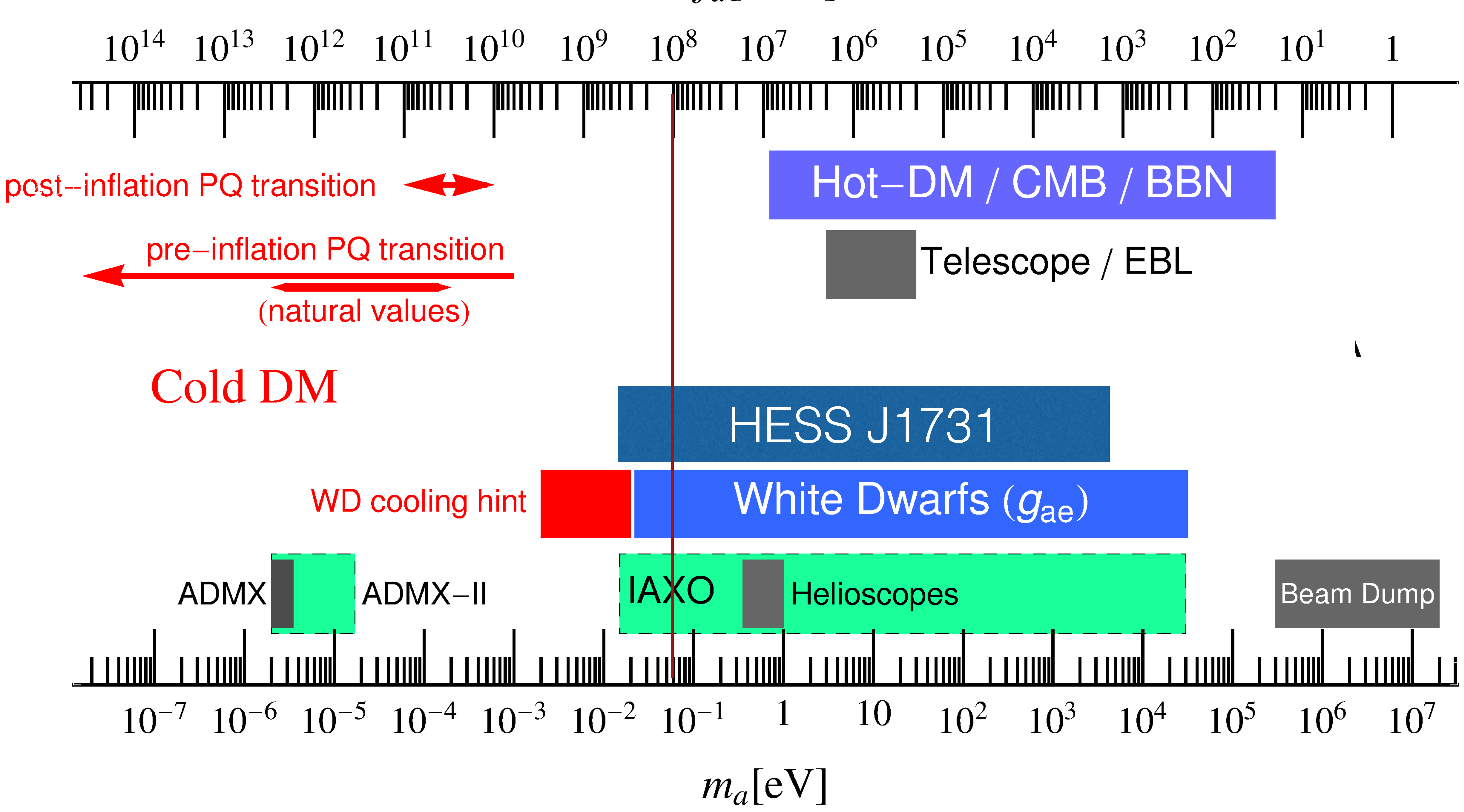
Constraining the QCD Axion

QCD Axions couple to nucleons and can be produced by nucleon-nucleon bremsstrahlung reactions.

SN1987a was used to constrain the coupling $g_{aNN} = C_N \, m_N / f_a$.

Recent work suggests SN1987a requires $f_a > 10^8$ GeV.
(Chang, Essig, McDermott (2018))

PDG (2016) Ringwald, Rosenberg, Rybka



Analysis of HESS J1731 suggests a stronger bound on the DFSZ axion.
Since both neutrinos and axions are produced by the same reaction the analysis is less sensitive to the reaction mechanism.

Beznogov, Page, Rrapaj and Reddy (2018)

HESS J1731 (C_n =0.27):
$f_a > 4 \times 10^8$ GeV [at 99%]
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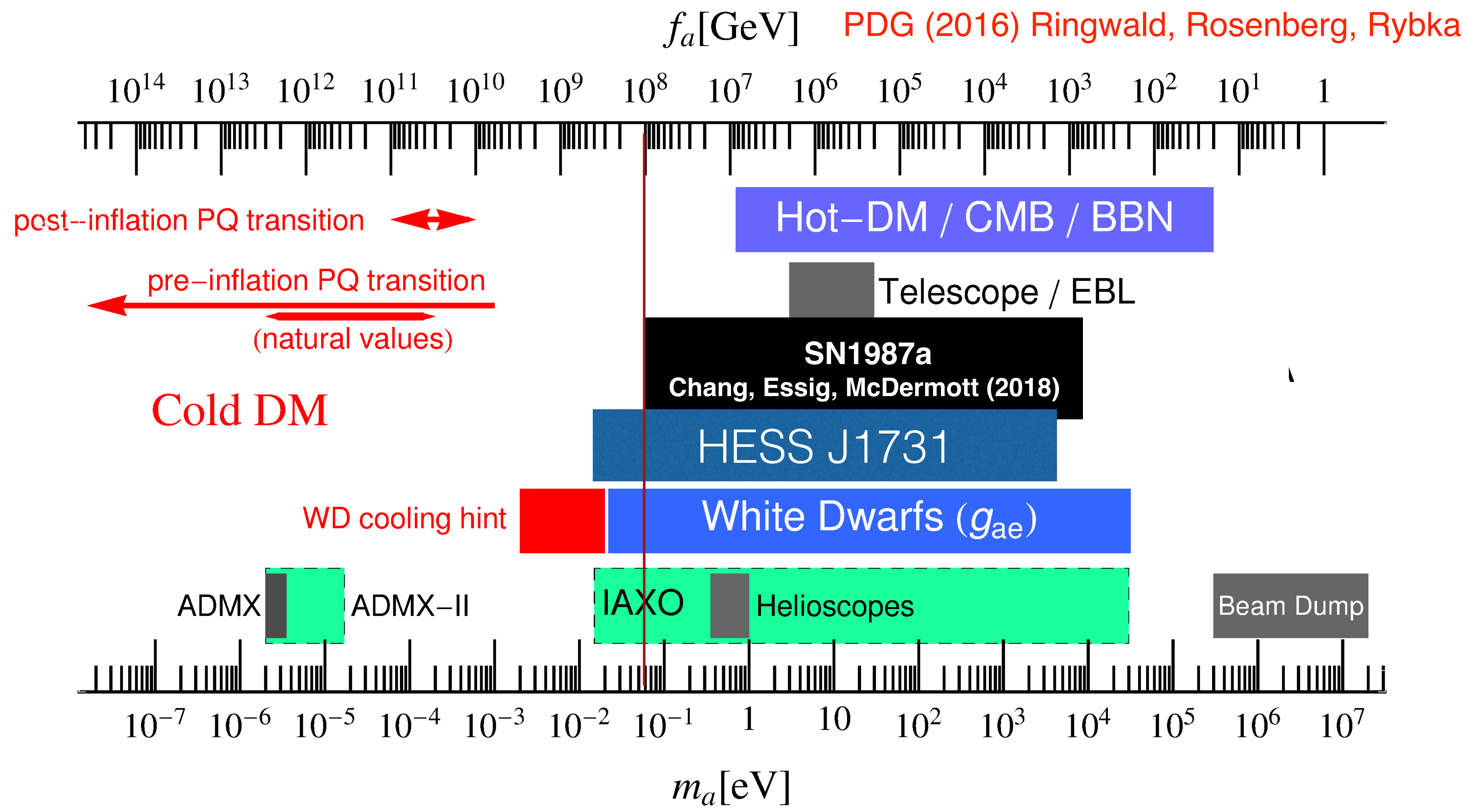

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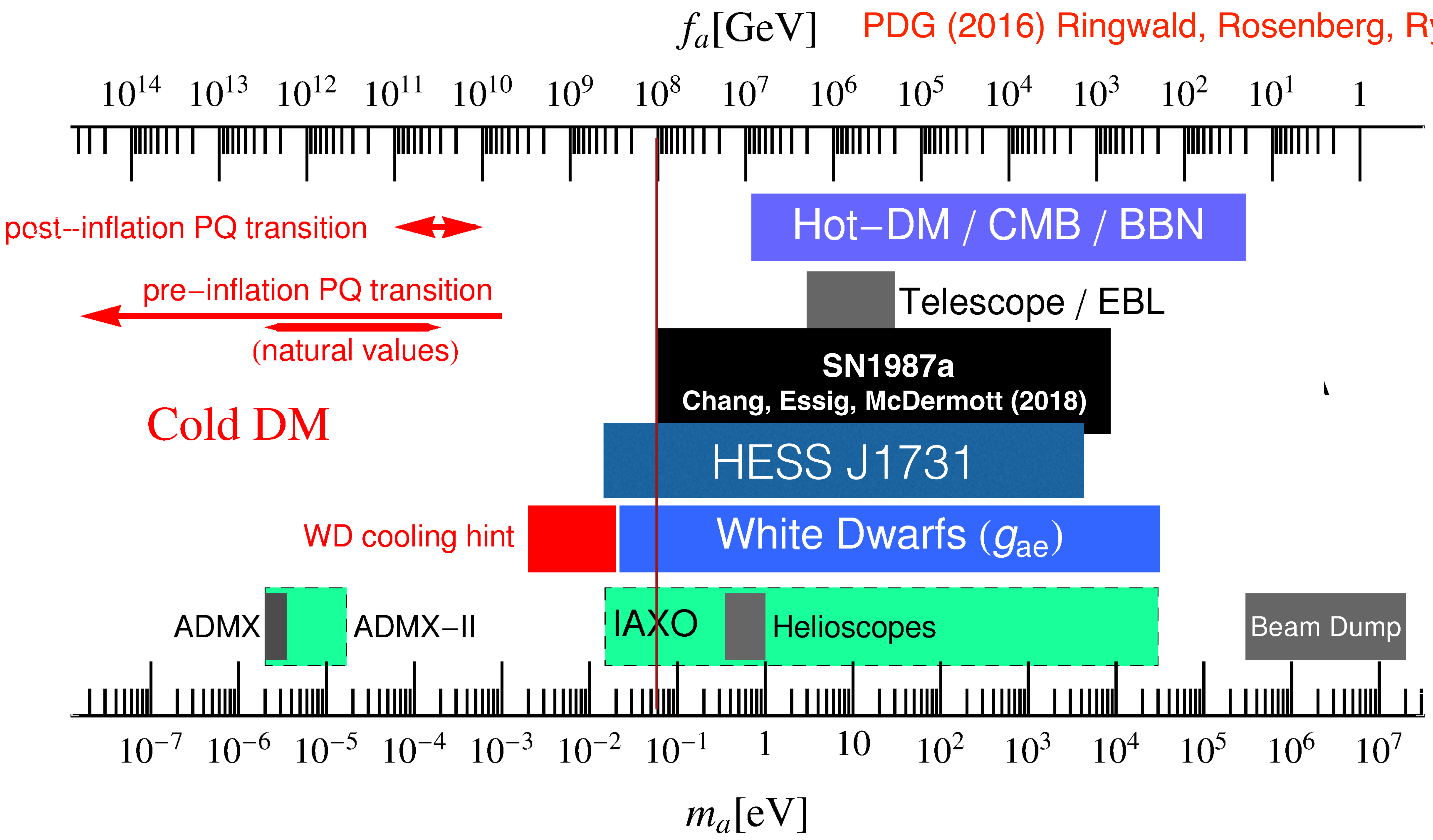

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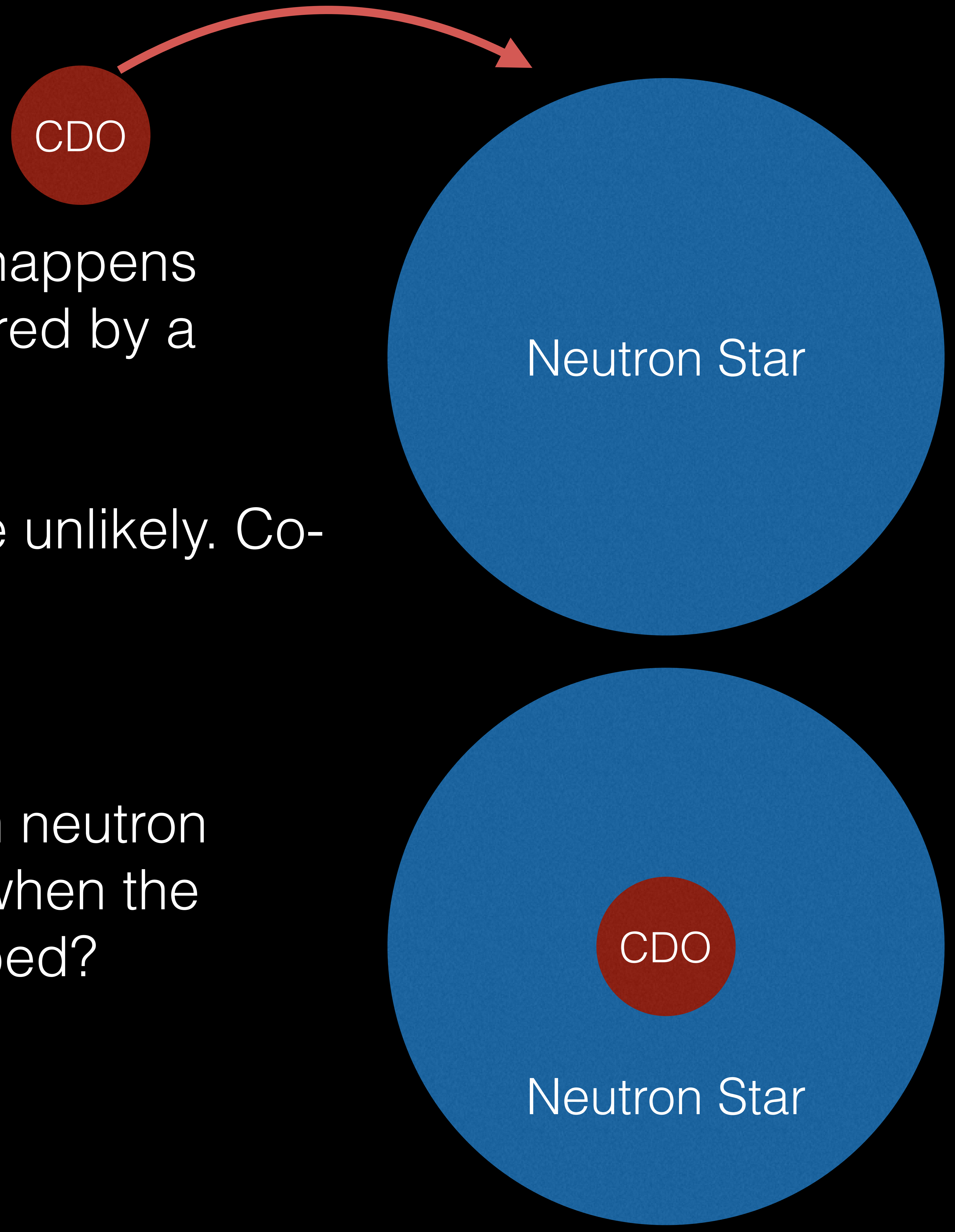
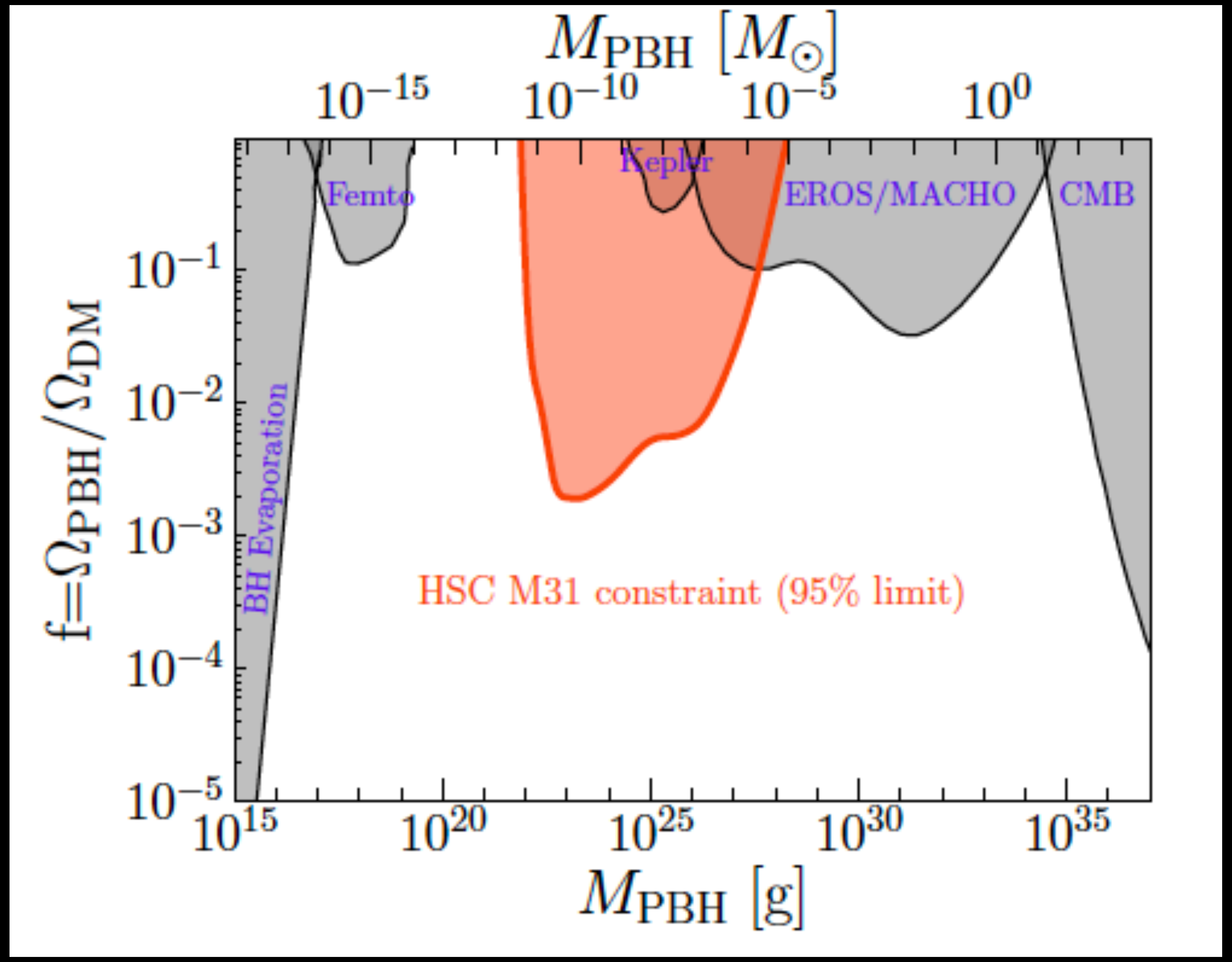
Compact Dark Objects

If CDOs exists, what happens when a CDO is captured by a neutron star?

Random collisions are unlikely. Co-evolution is needed.

If CDOs exist inside in neutron stars what happens when the neutron star is perturbed?





CDOs are constrained by observing micro-lensing of stars in nearby galaxies By CDOs in the Halo.
Constraint assumes all CDOs have the same mass!

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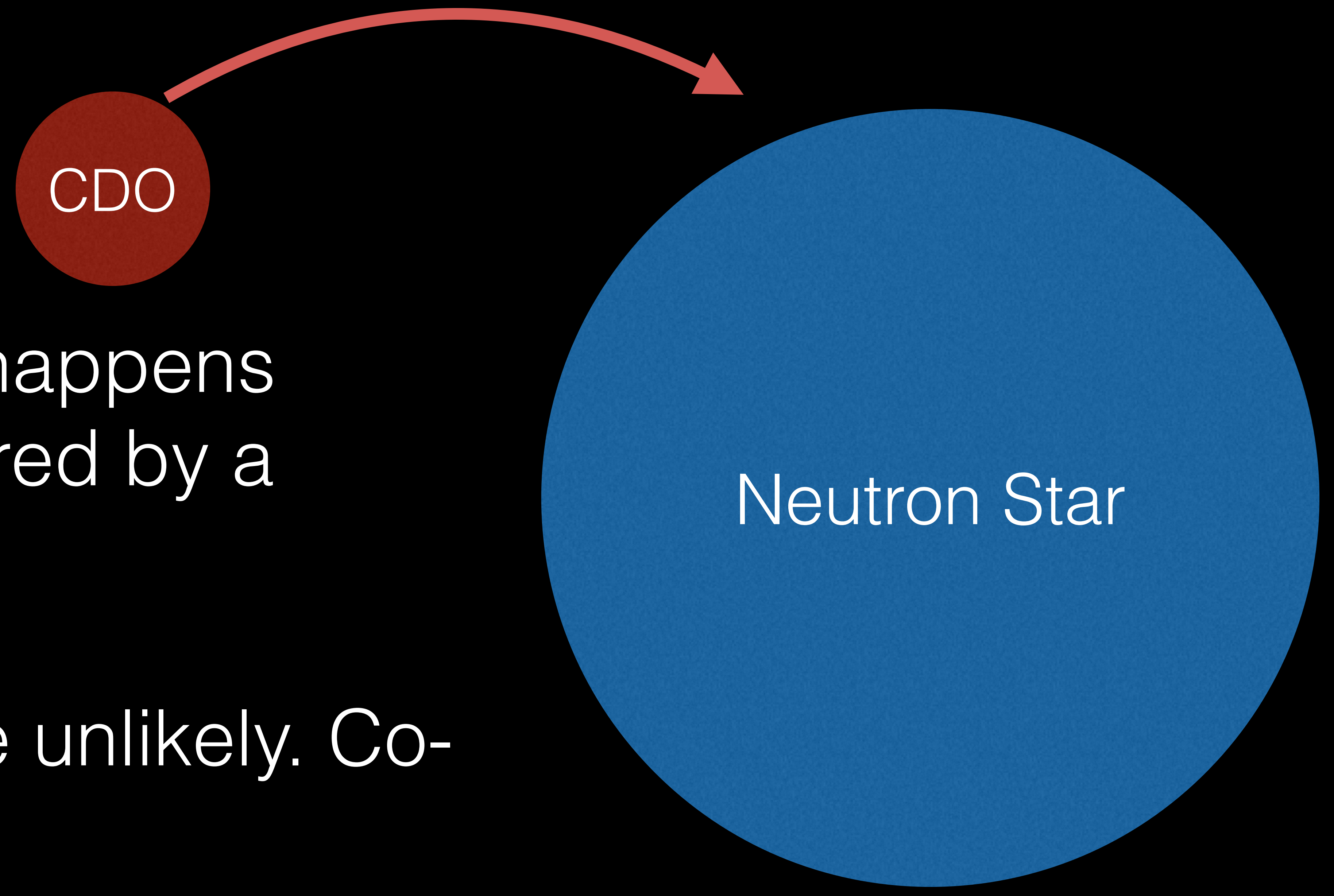

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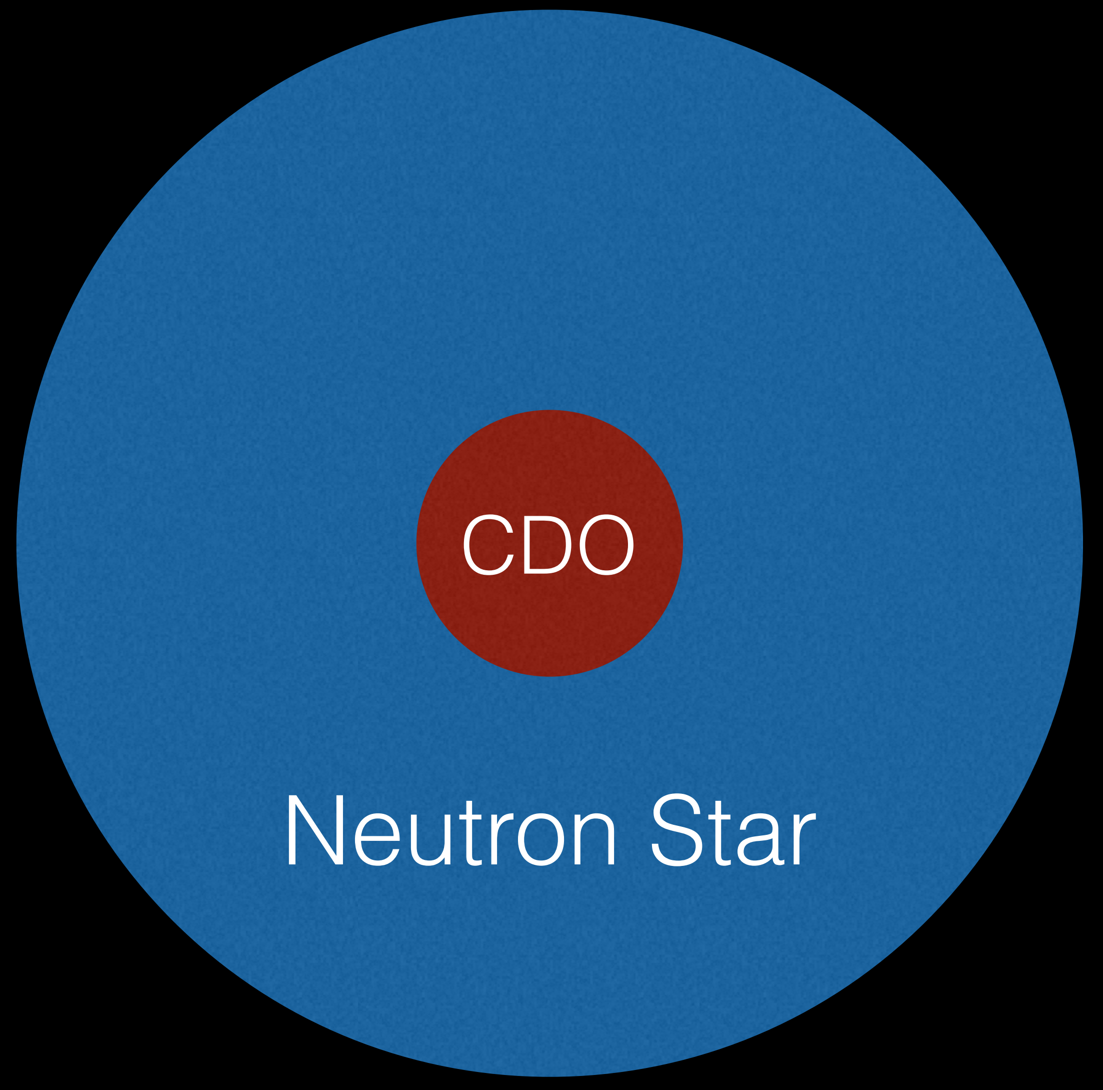

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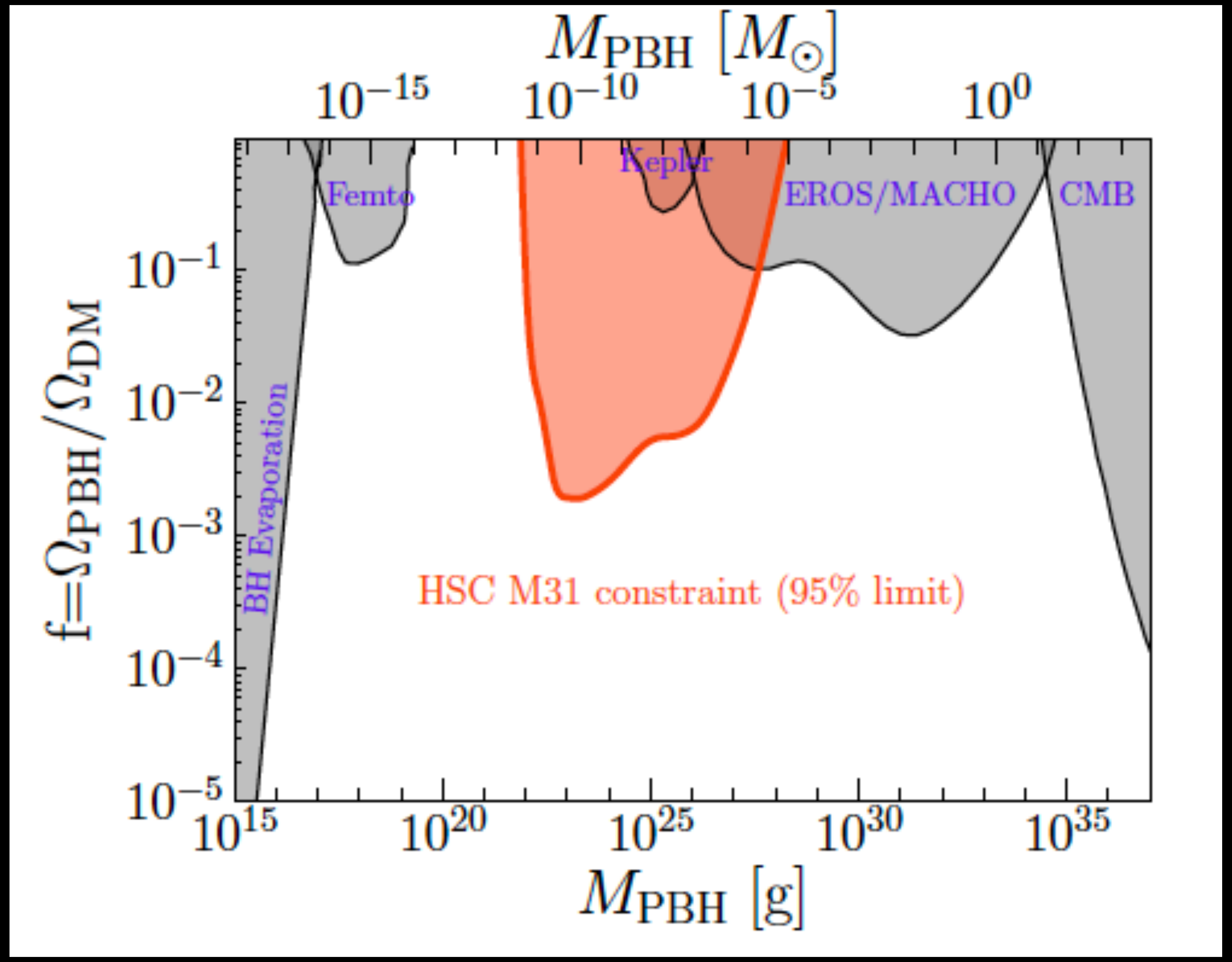

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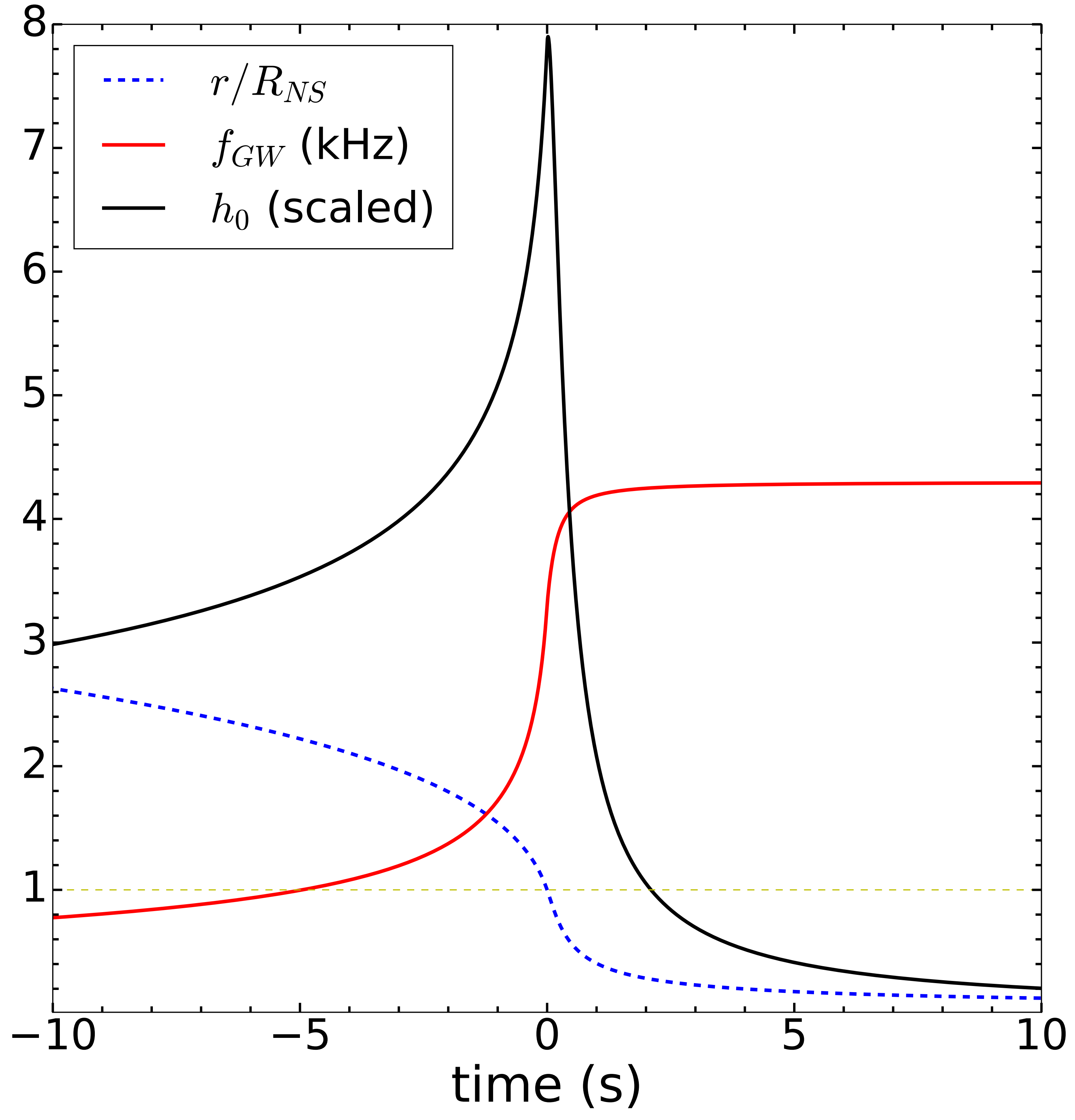
Gravitational Waves From Neutron Star -CDO Systems

If CDOs exist, capture by neutron stars in our galaxy would produce detectable gravitational waves during final inspiral.
Common-envelope phase with frequency of the GW emission set by neutron star core density can last for hours.

$$\nu_c = \sqrt{\frac{G\rho_c}{3\pi}} \simeq 2.7 \left(\frac{\rho_c}{10^{15}\ \mathrm{g/cm^3}}\right)^{1/2} \mathrm{kHz}$$

$$T_{GW} = 10 \left(\frac{10^{-8} M_\odot}{M_{\mathrm{CDO}}}\right) \left(\frac{10\ \mathrm{km}}{r}\right)^2 \left(\frac{5.3\ \mathrm{kHz}}{f_{GW}}\right)^4 \mathrm{hrs}$$



Gravitational wave strain $h_0 \approx \frac{4G}{c^4 d} m_D r^2 \omega^2 \approx 1.4 \times 10^{-25} \left(\frac{m_D\, r^2}{M_\odot\, m^2}\right)\left(\frac{1\, kpc}{d}\right)\left(\frac{f_{GW}}{5.3\,\mathrm{kHz}}\right)^2$

Horowitz and Reddy PRL (2019)

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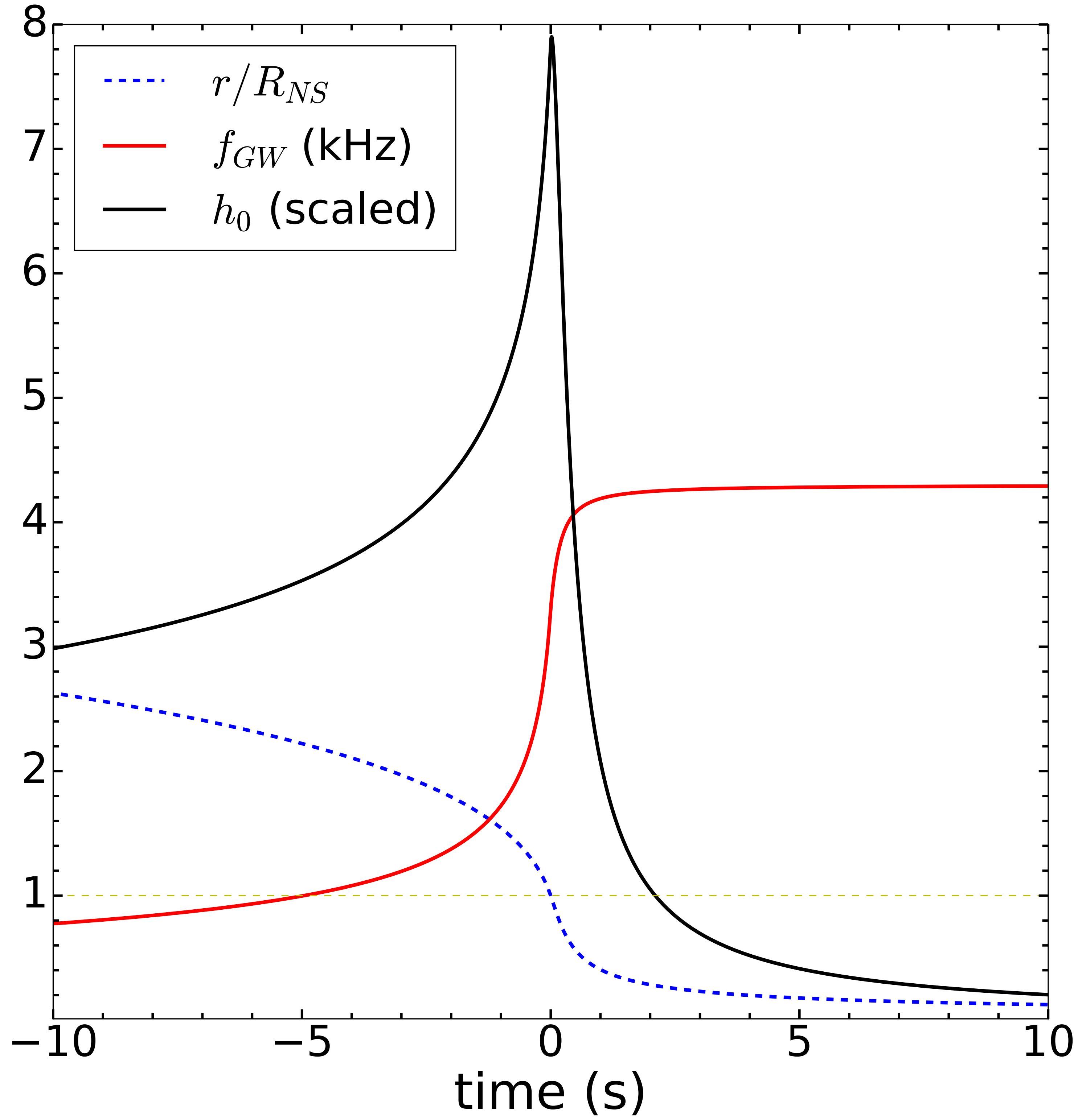

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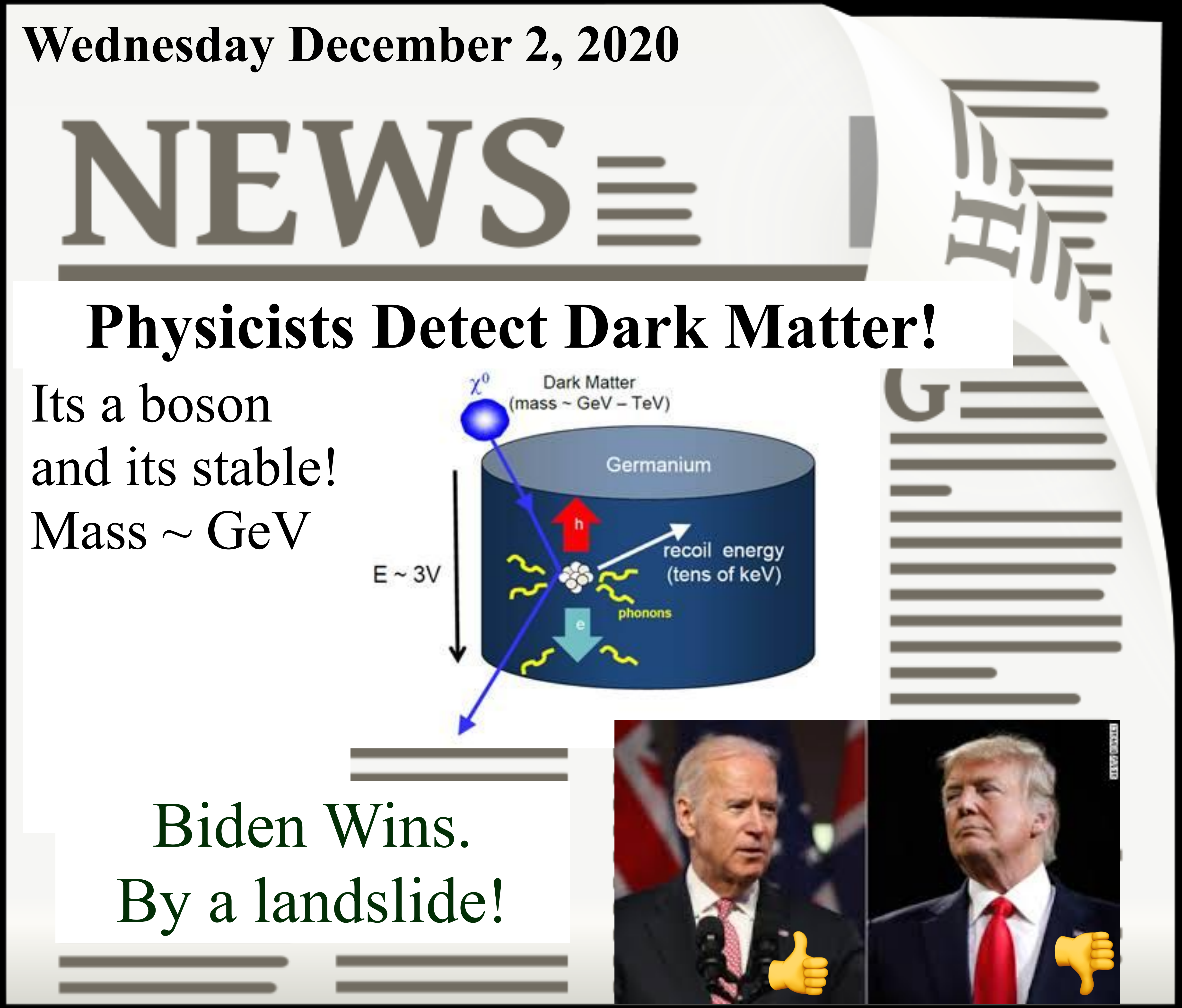
Dark Rattles: Perturbations of a neutron star (for eg. kicks during the supernova) with a CDO inside would produce detectable GWs if energy

$$E \geq 5.4 \times 10^{45}\,\mathrm{ergs}\left(\frac{d}{\mathrm{kpc}}\right)$$

Horowitz and Reddy PRL (2019)

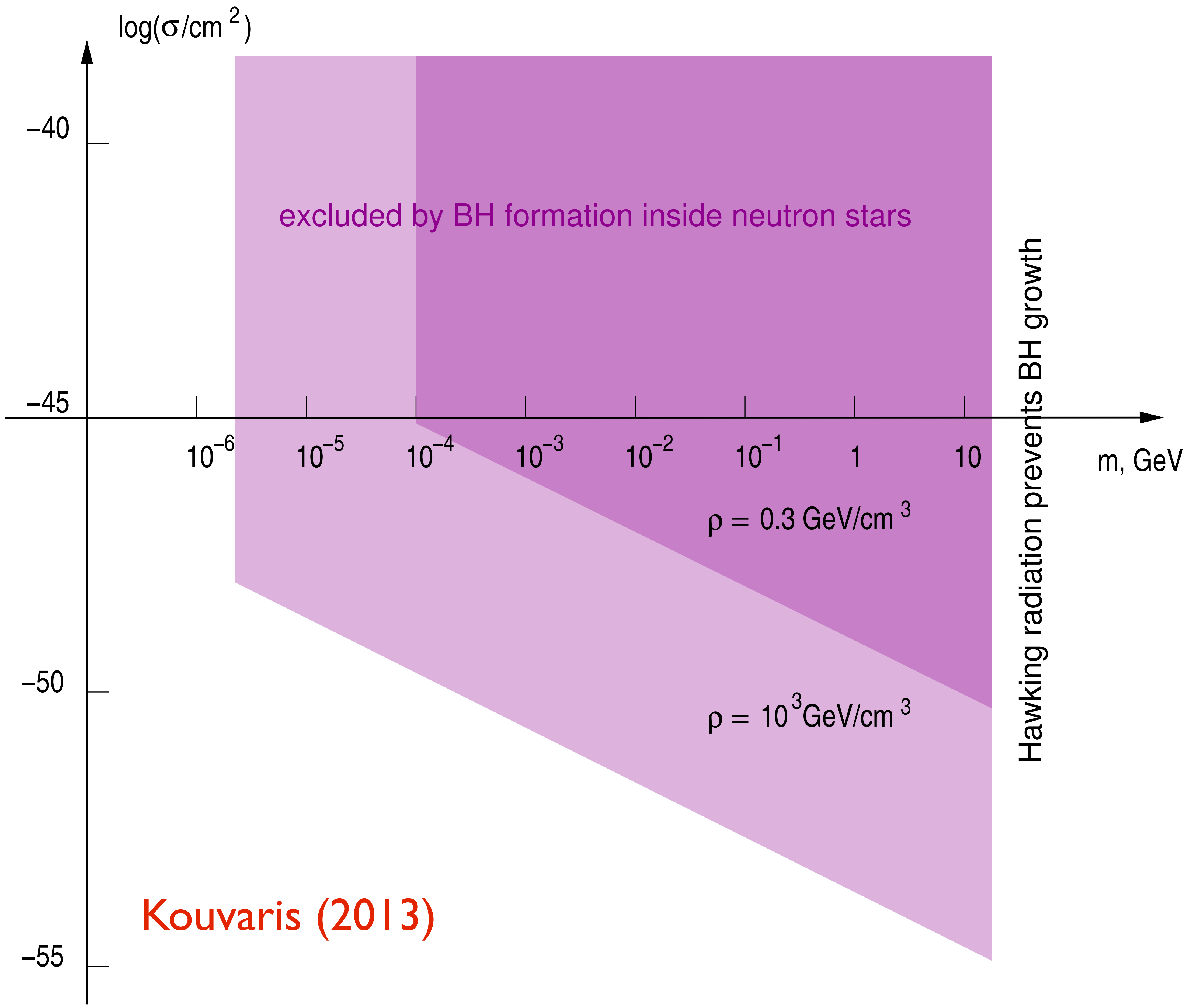
Implications of Dark Matter Detection (for dense matter)

What if our experimentalist colleagues discover dark matter?



Implications of detecting MeV - GeV Dark Matter

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



If asymmetric bosonic dark matter with M < 10 GeV is found in a terrestrial experiment:

Dark matter has (strong) self-interactions.

Or

Matter in the neutron star core is in the CFL phase!

Bertoni, Nelson, Reddy (2015)

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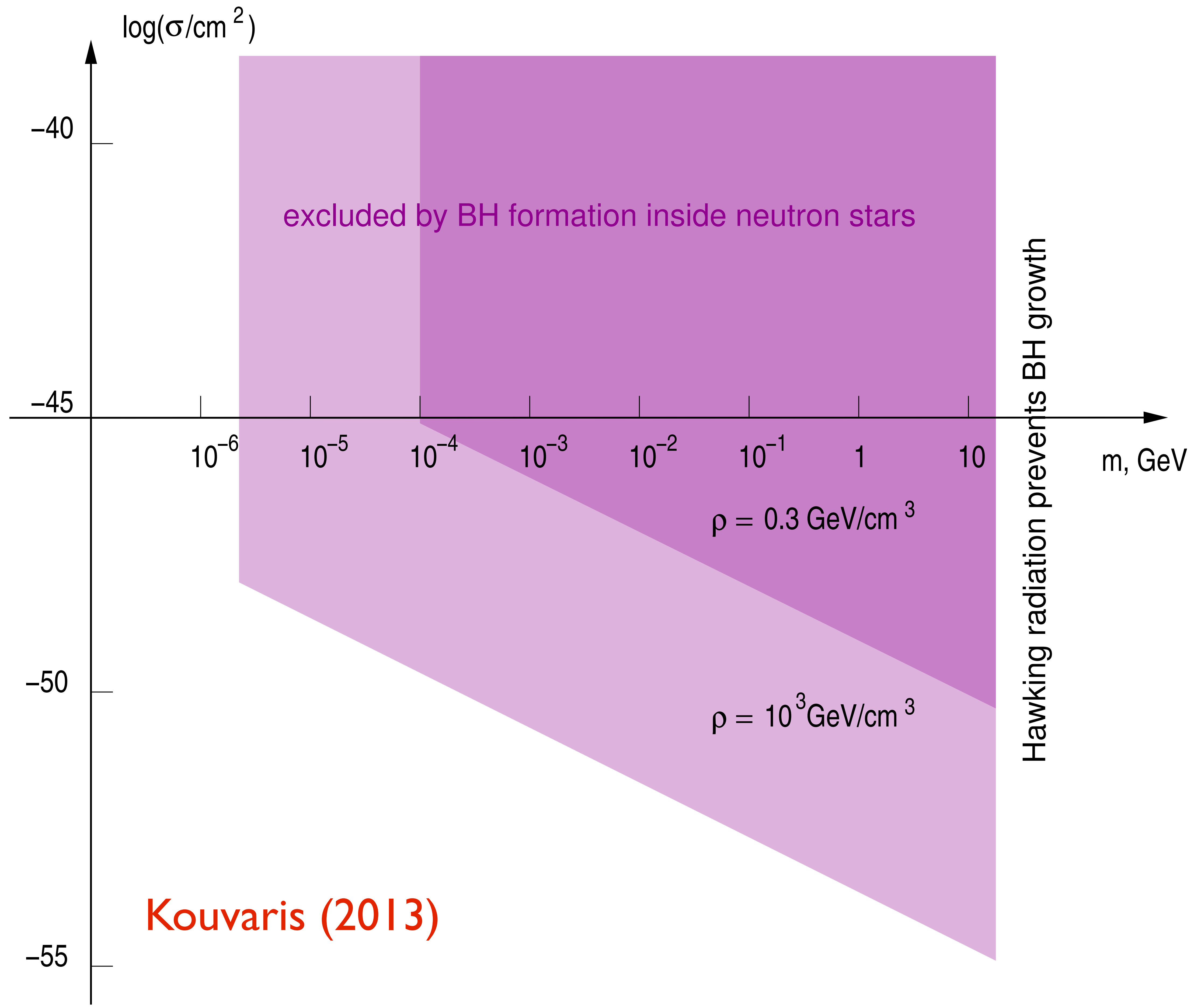

Kouvaris (2013)

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