Dark Matter in Neutron Stars

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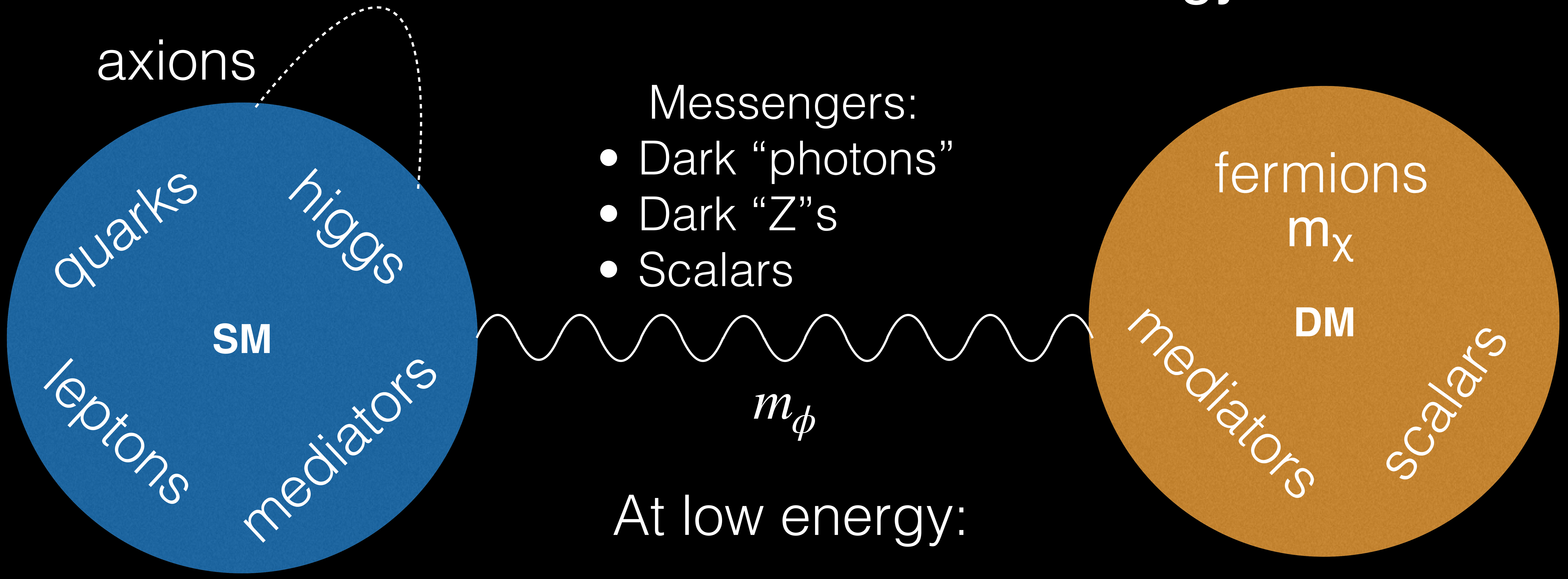
- Dark sectors
- A few things we know about neutron stars.
- Recent constraints from cooling: axions, light dark gauge bosons.
- A new idea: Using gravitational waves to constrain or discover a strongly interacting dark sector.

Dark Sector Phenomenology

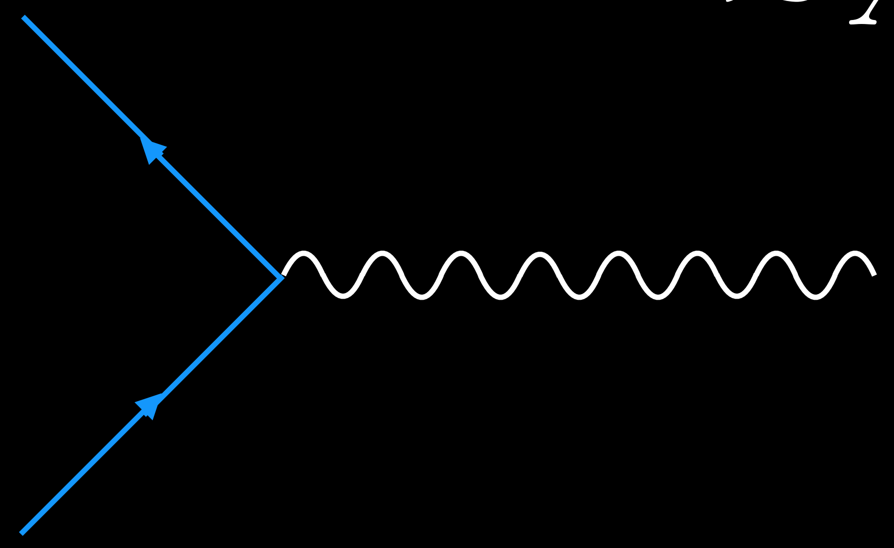


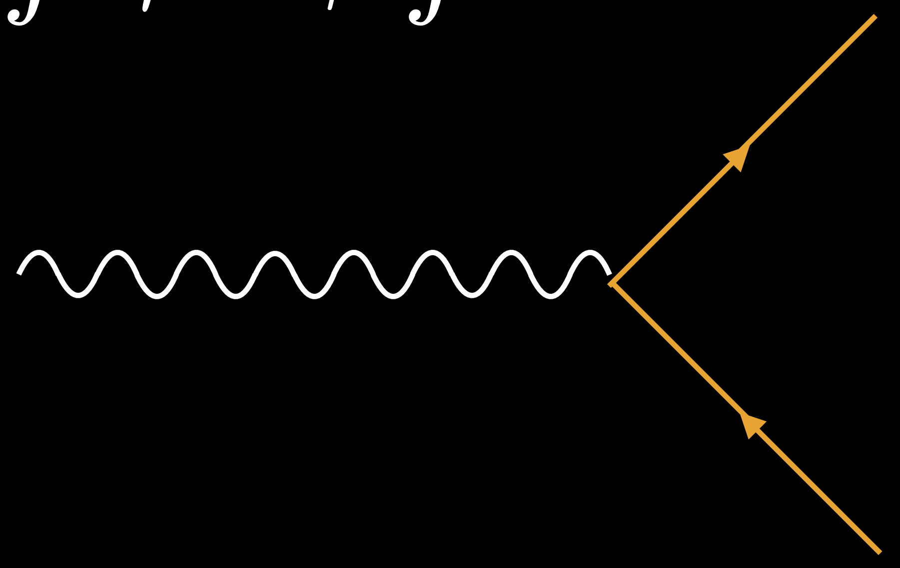
Messengers:

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

At low energy:

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



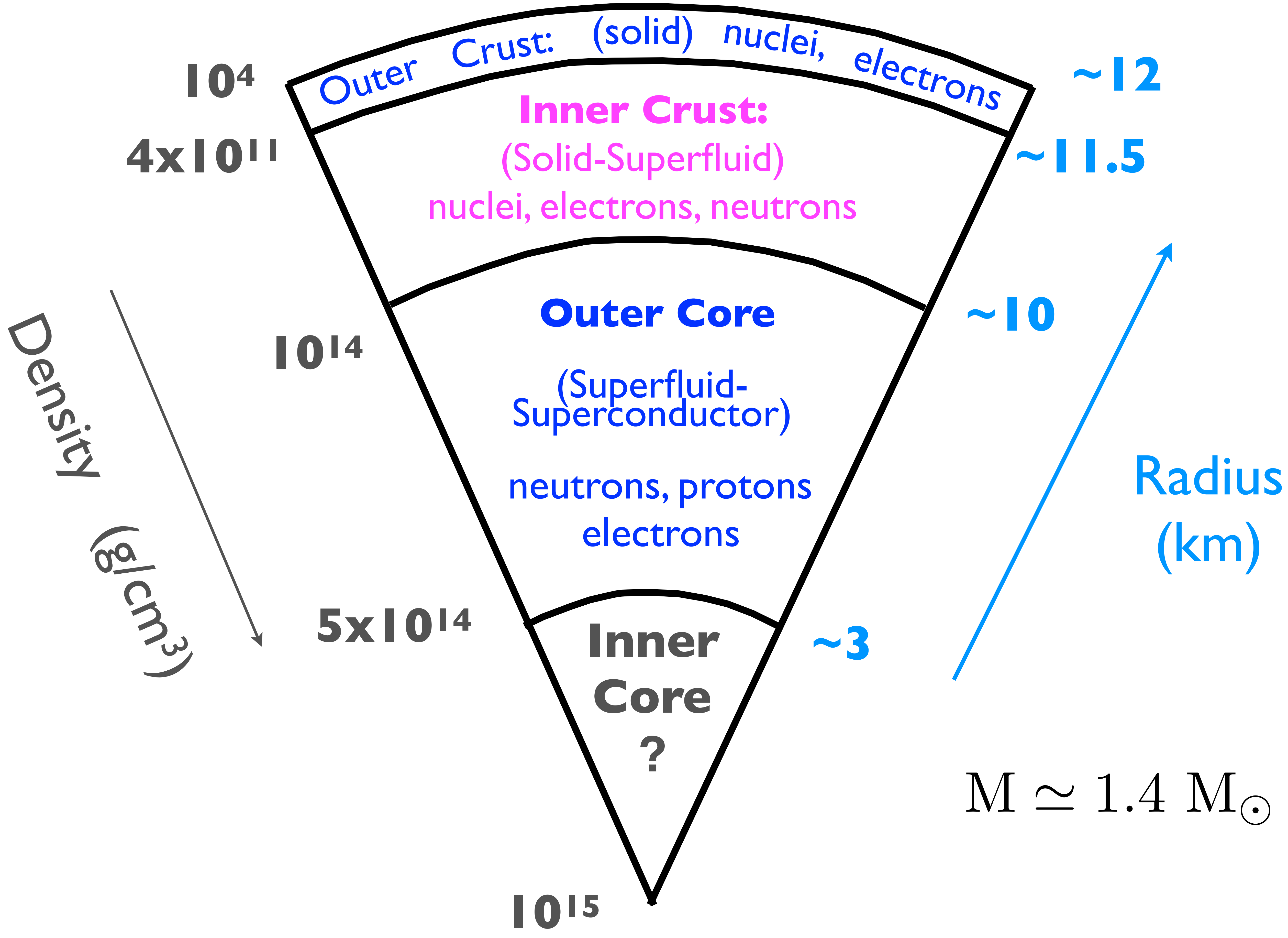


$$V_{\chi B} = \frac{g_\chi g_B}{q^2 + m_\phi^2} = g_\chi g_B \; \frac{e^{-m_\phi r}}{r}$$

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

Neutron Stars 101

- Nuclear physics describes a large fraction of the neutron star.
- Complex phase structure at low temperature.
- The equation of state is fairly well known up to a few times 10^{14} g/cm^3.
- Neutrino cooling processes are also known (up to a factor of a few) but are very sensitive to phase structure at low temperature.



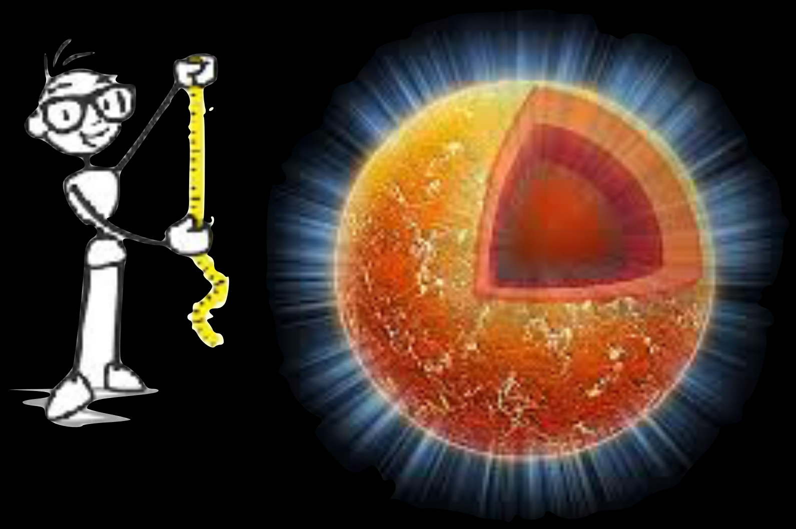
$M \simeq 1.4\ M_\odot$

For a review see: Page & Reddy, Ann. Rev. Nucl. Part. Sci. (2006)

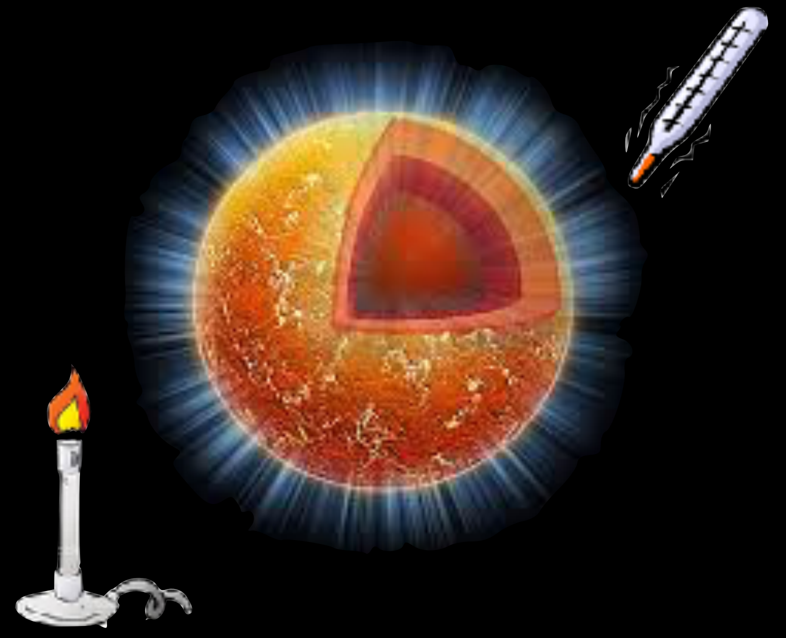
Some Observed Properties of NS

Pulsar timing and relativistic effects in binaries: $M_{NS} : 1.2\ M_\odot - 2.0\ M_\odot$

Maximum mass: $2.0\ M_\odot < M_{Max} < 2.4\ M_\odot(?)$ (GW170817)



Using x-rays and gravitational waves: $9\ \text{km}(?) < R_{NS} < 14\ \text{km}$



Temperature evolution roughly consistent with neutrino cooling.
This applies both to the very early proto-neutron star phase t < 1 min and the late neuton star cooling phase t ~ 10^6 yrs.

Radii and Maximum Masses

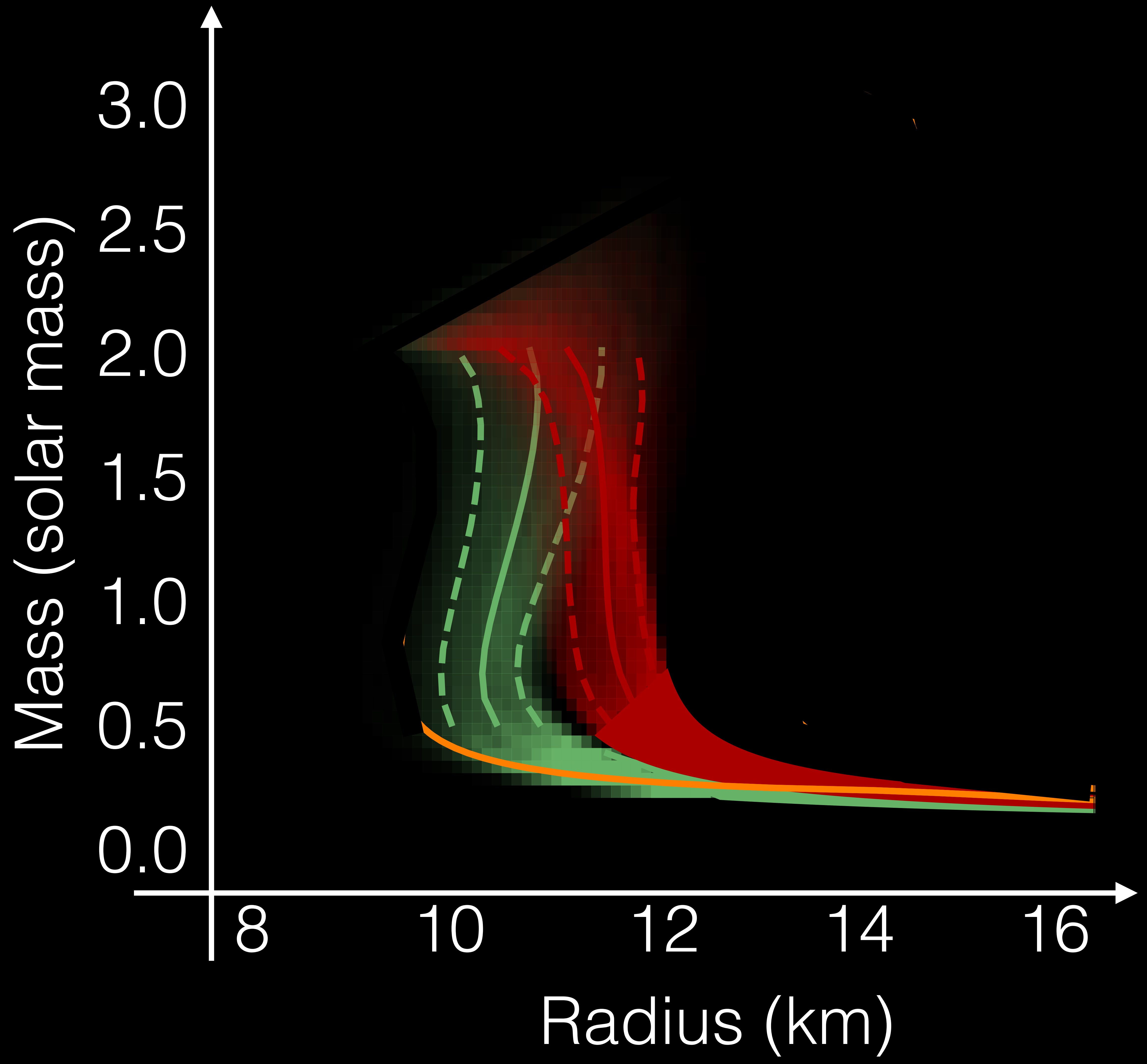
- Modern EOS based on EFT inspired nuclear forces and Quantum Monte Carlo calculations provide useful predictions despite uncertainties at high density.

- Nuclear description viable up to 5 x 10^{14} g/cm^3 :
  - Radius = 10 - 12 kms
  - Maximum mass = 2 - 2.5 solar masses

Tews, Carlson, Gandolfi and Reddy (2018)

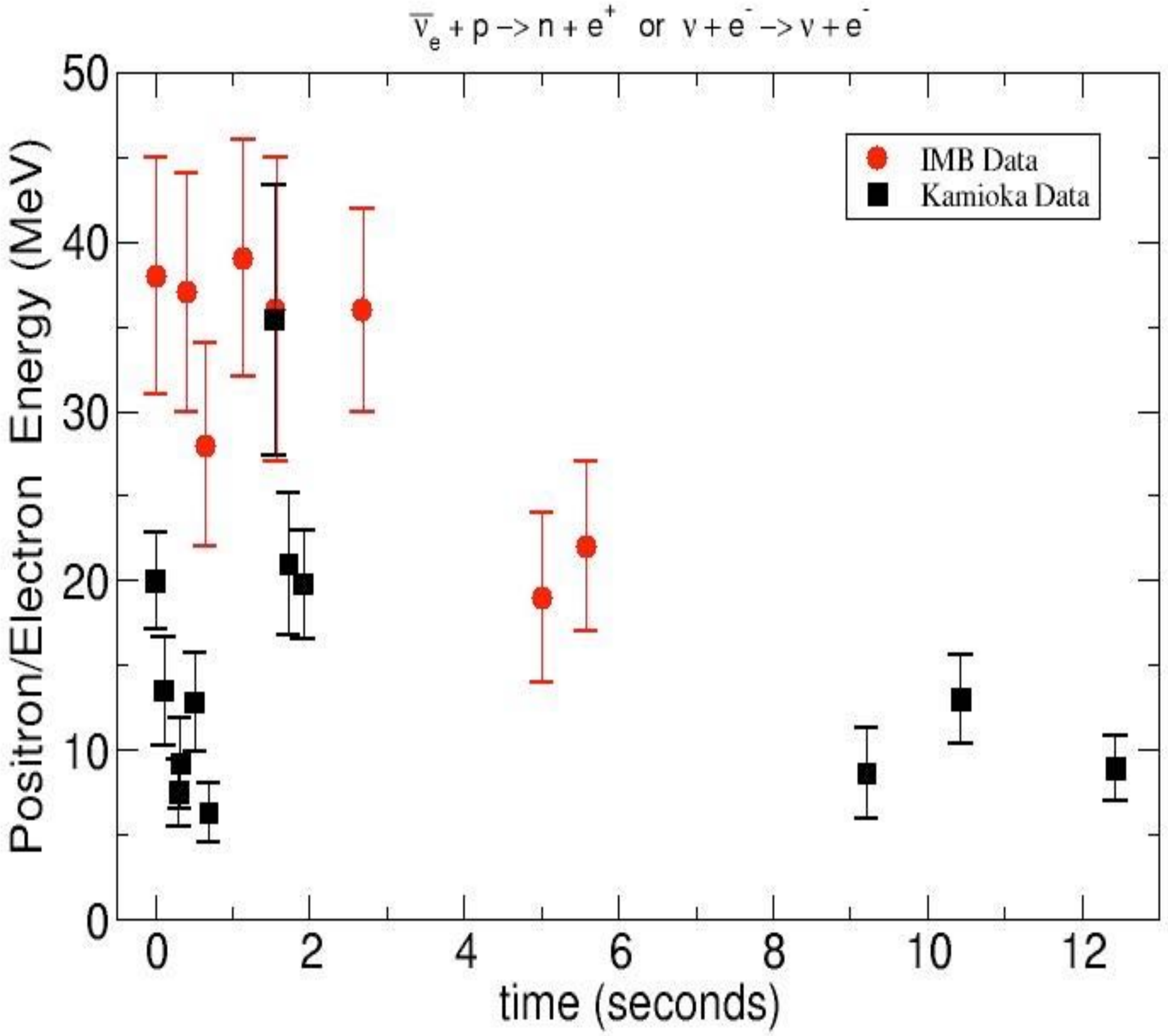
- Nuclear description viable up to 2.5 x 10^{14} g/cm^3 :
  - Radius = 9.5 - 14 kms
  - Maximum mass = 2 - 3 solar masses

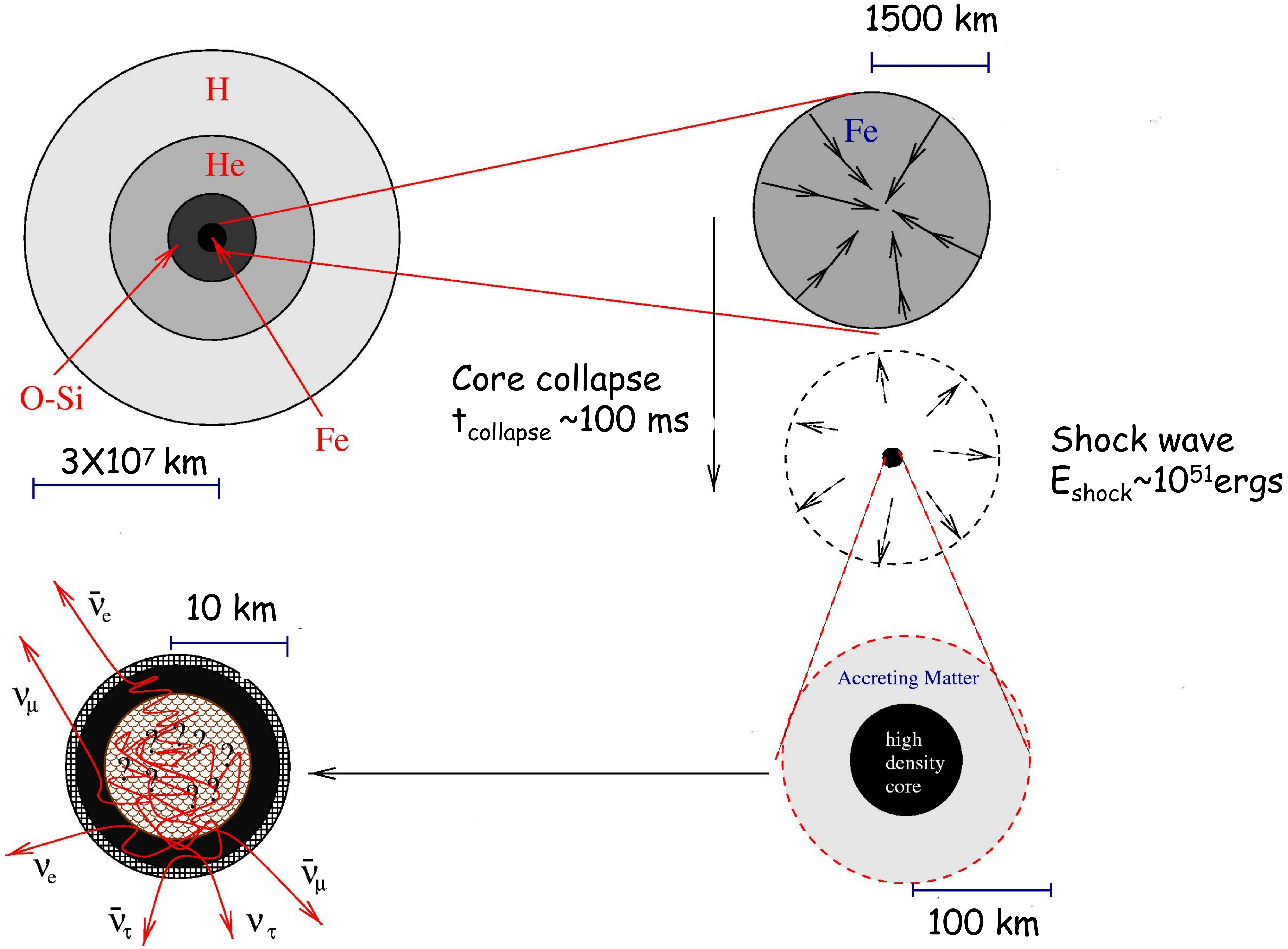
Hebeler, Lattimer, Pethick, Schwenk (2010)



Early Neutron Star Cooling: Supernova Neutrinos

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



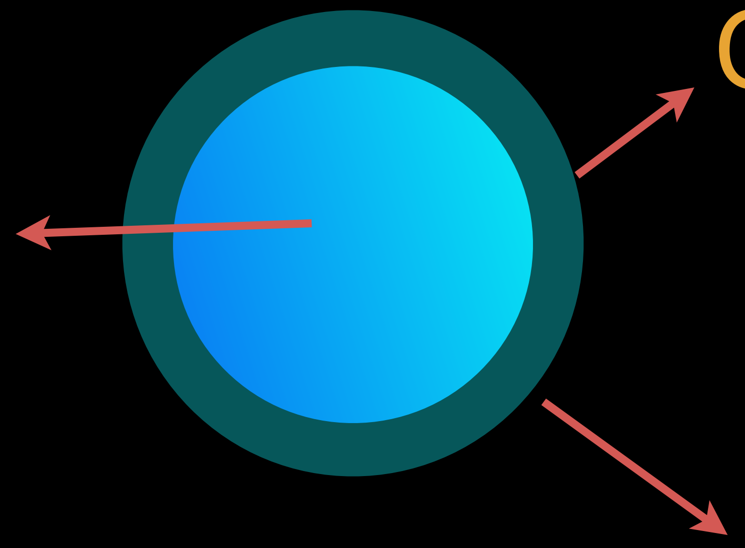


3 x 10^{53} ergs = 10^{58} × 20 MeV Neutrinos

neutrinos diffuse in the core.

- 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.

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

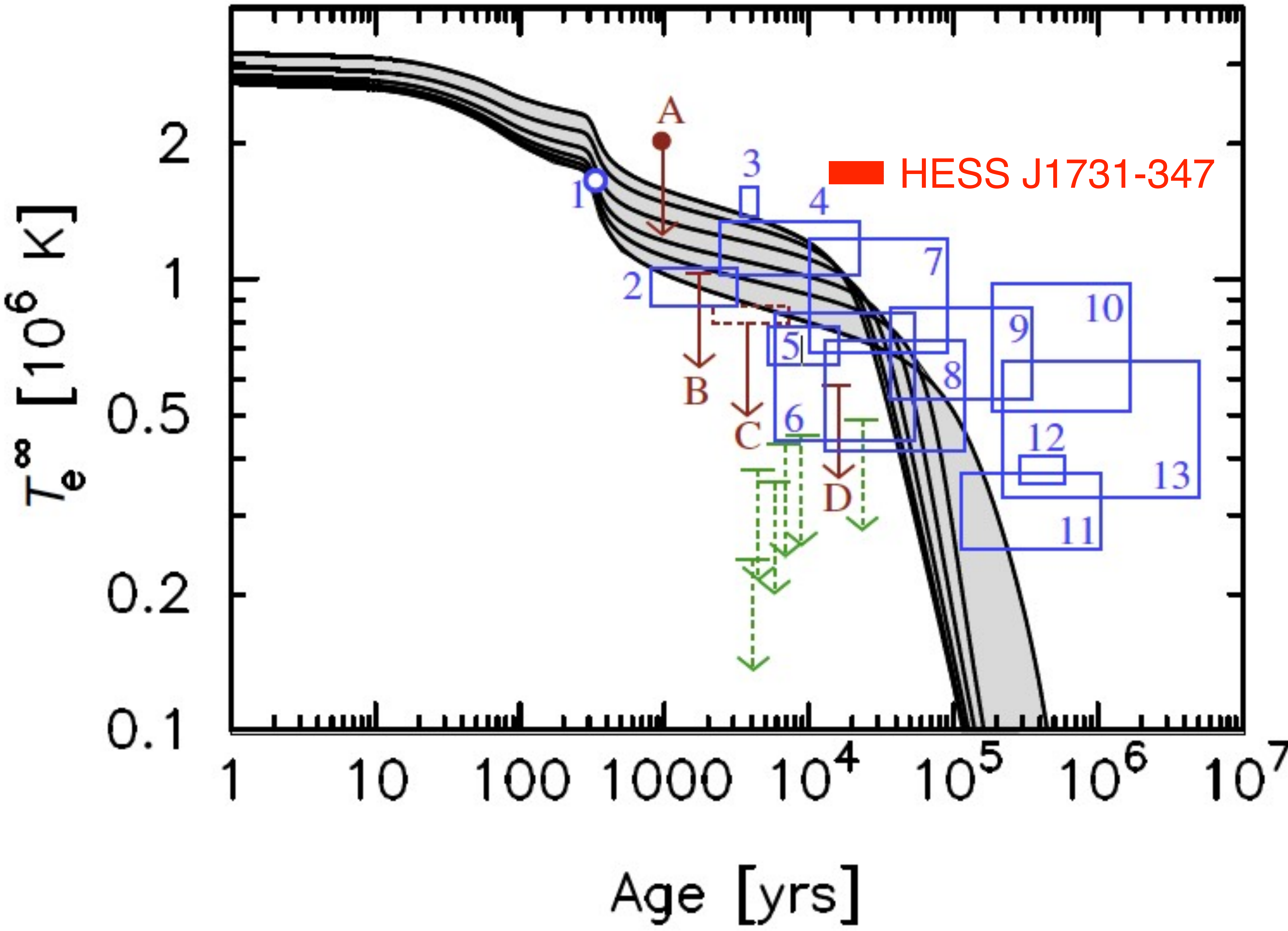
Increasing NS mass

Models are still rudimentary but can accommodate the observed variability

By varying the NS mass and surface composition one can obtain a fit to the data with URCA reactions.

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. Implies a low mass neutron star.



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

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

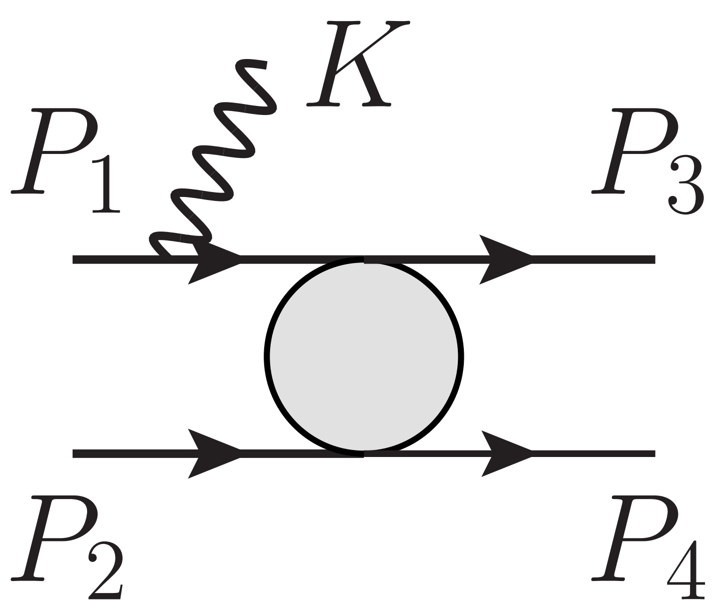
This bound was found empirically by comparing to a suite of proto-neutron star simulations.

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

Dark Photons

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

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



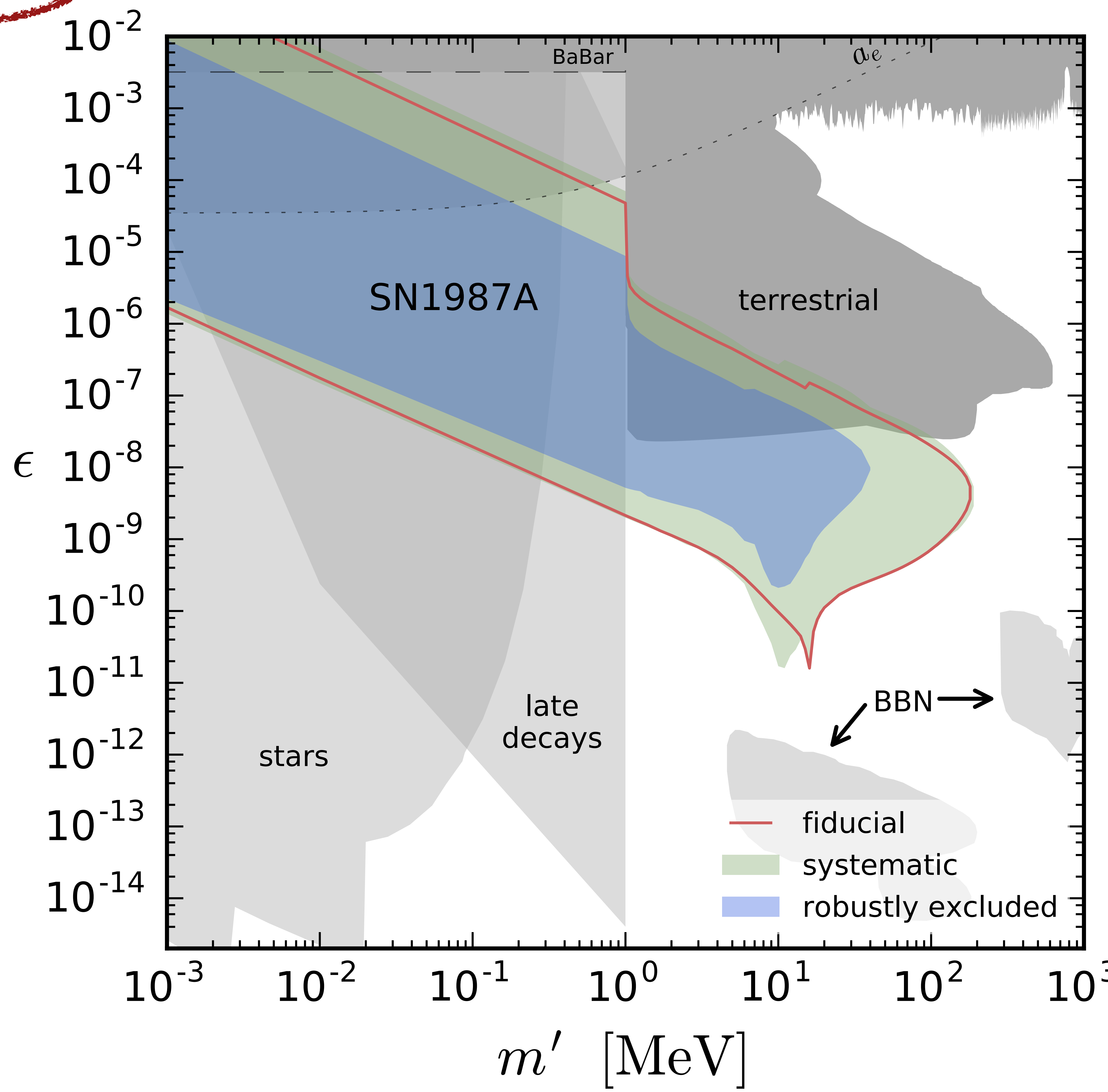
Nucleon-nucleon Bremsstrahlung dominant production mechanism:

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)



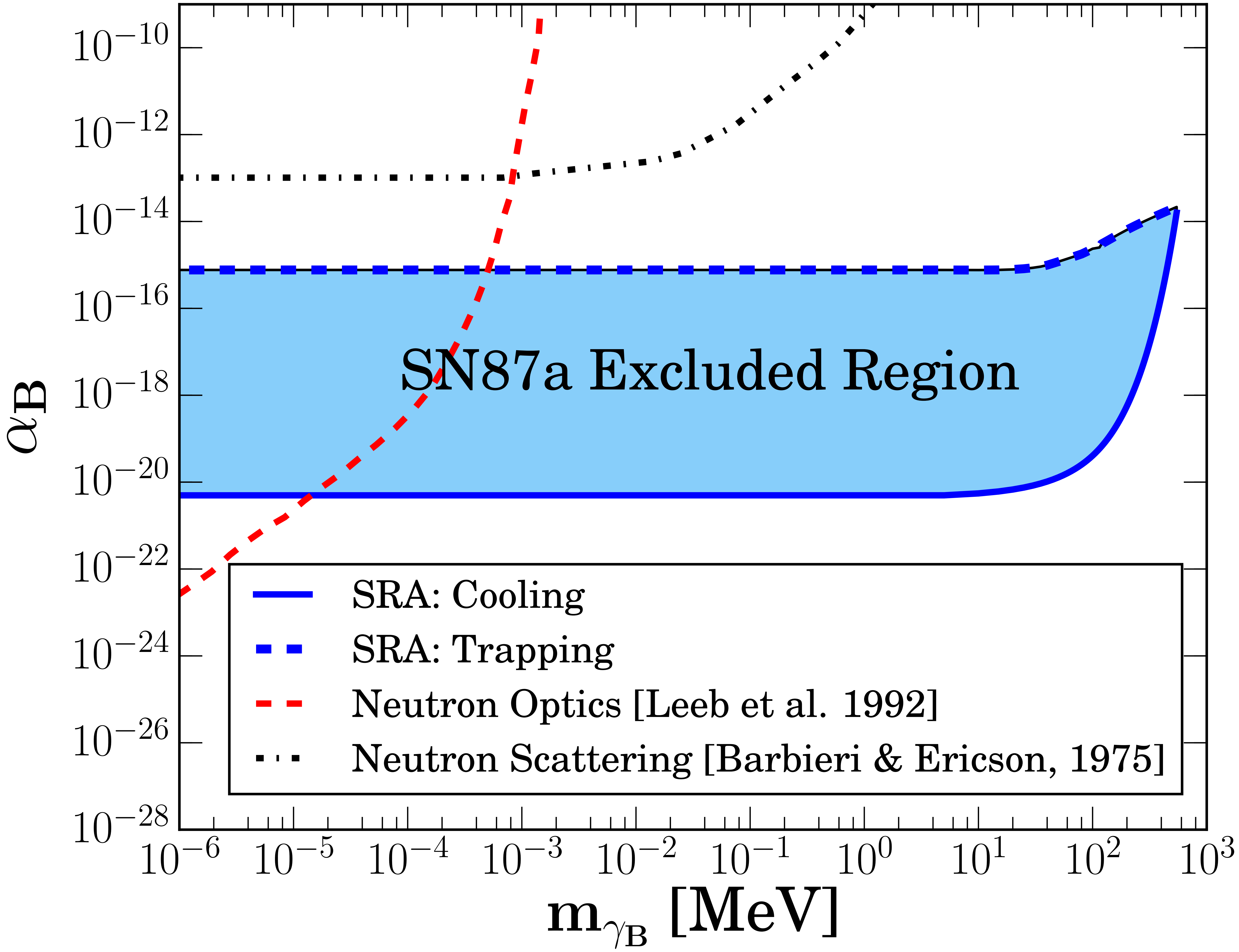
Dark Baryon Number Gauge Boson

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

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

- 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)

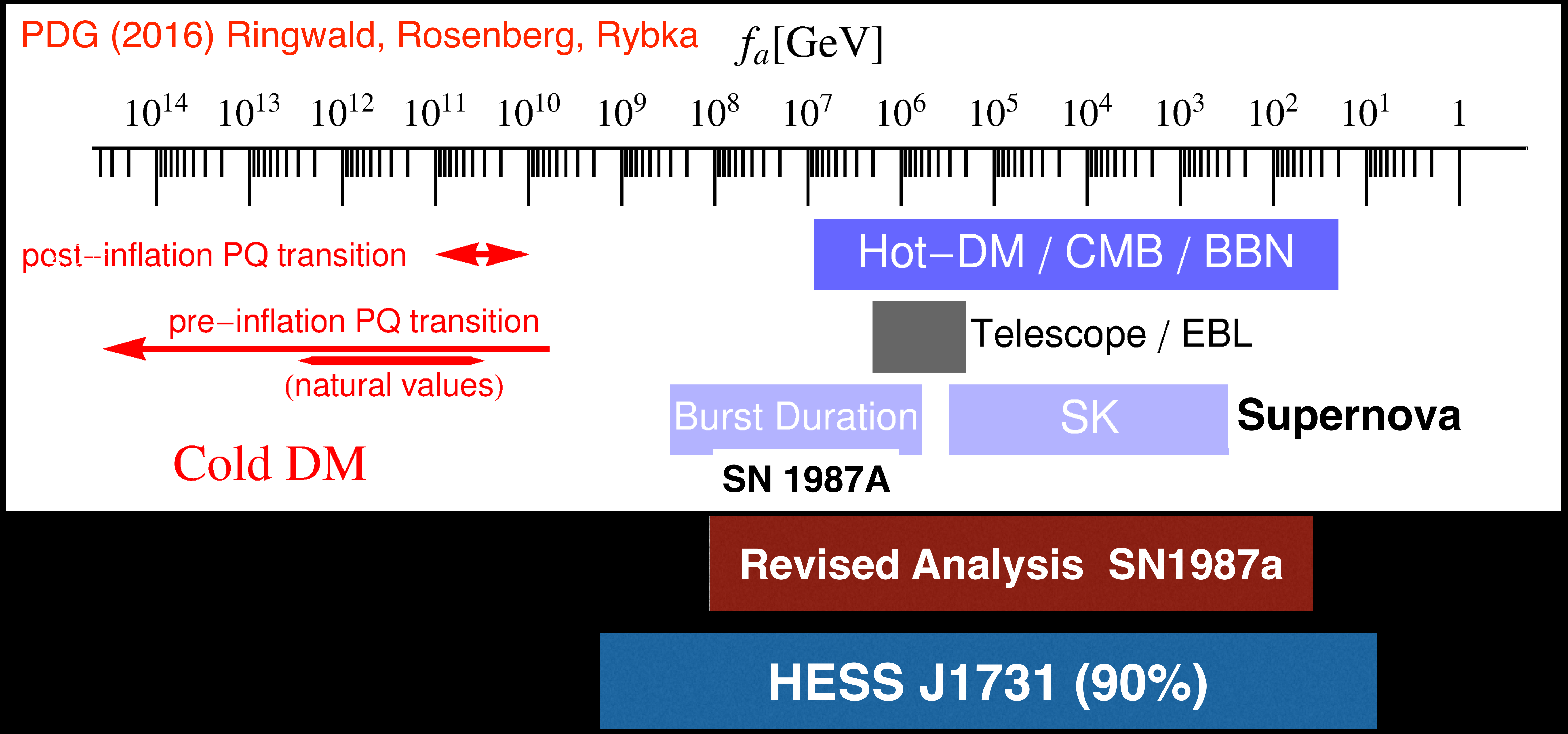
QCD Axions

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

$$n + n \rightarrow n + n + a$$

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))



Analysis of HESS J1731 suggests a slightly 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.

HESS J1731 (C_n =0.27):
$f_a > 4 \times 10^8$ GeV [at 99%]
$f_a > 3 \times 10^9$ GeV [at 90%]

Beznogov, Page, Rrapaj and Reddy (2018)

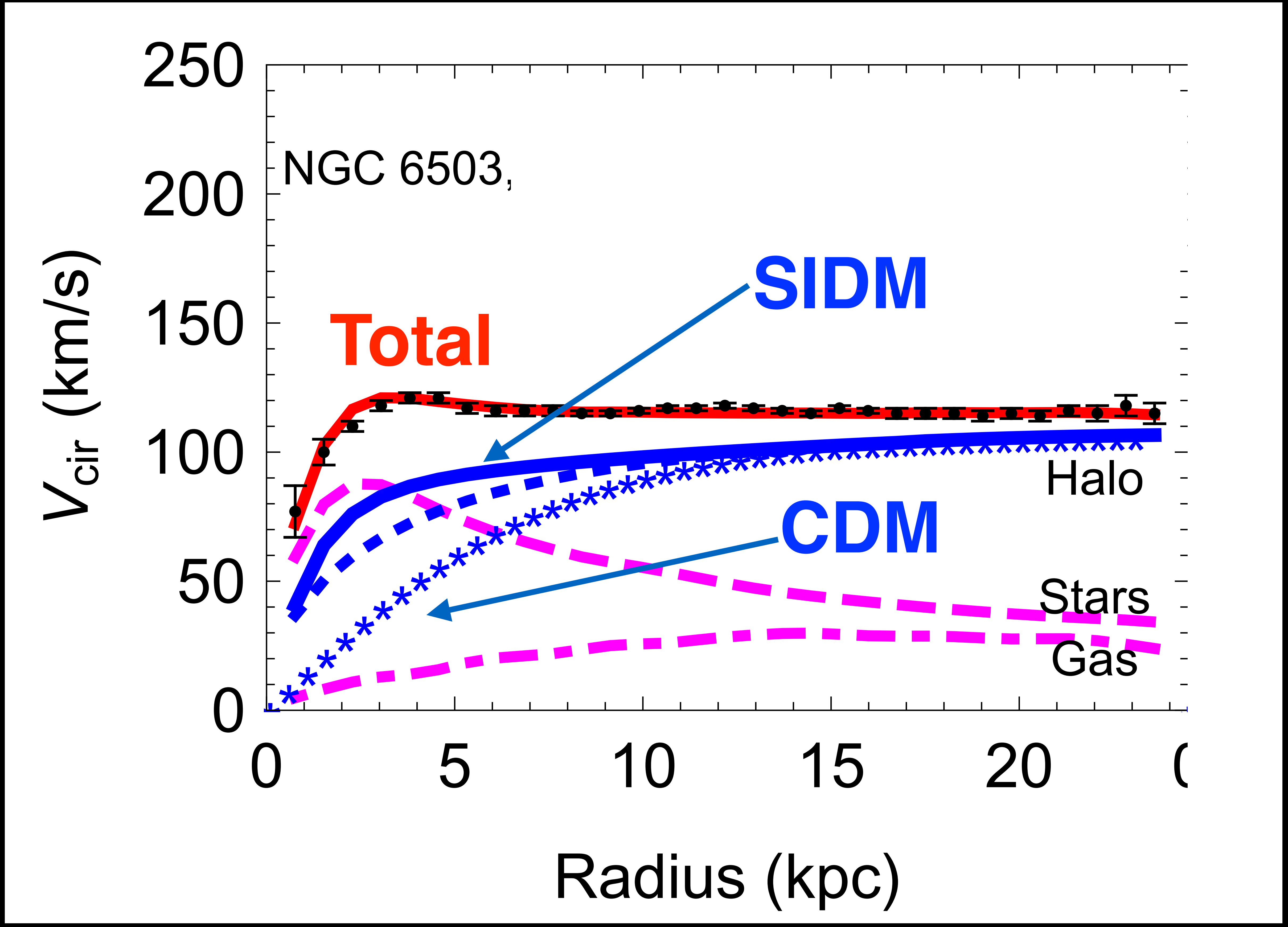
Self-Interacting Dark Matter (SIDM)

Cold (non-interacting) dark matter (CDM) fails to explain fine structure in some galaxy rotation curves.

Strong self-interactions are needed to redistribute dark matter (through collisions and thermalization) to reproduce observations.

The cross-section needed is large

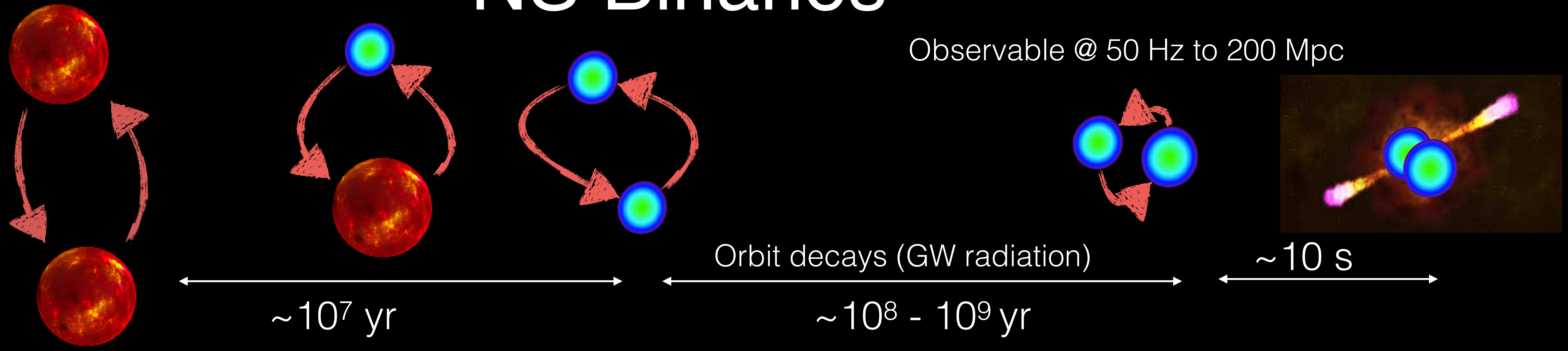
$$\frac{\sigma_{SIDM}}{m_\chi} \simeq \frac{\text{barn}}{\text{GeV}}$$



Kamada, Kaplinghat, Pace, Yu, (2018)

Can we use NSs to constrain these models?

NS Binaries



Observable @ 50 Hz to 200 Mpc

Orbit decays (GW radiation)

~10^7 yr

~10^8 - 10^9 yr

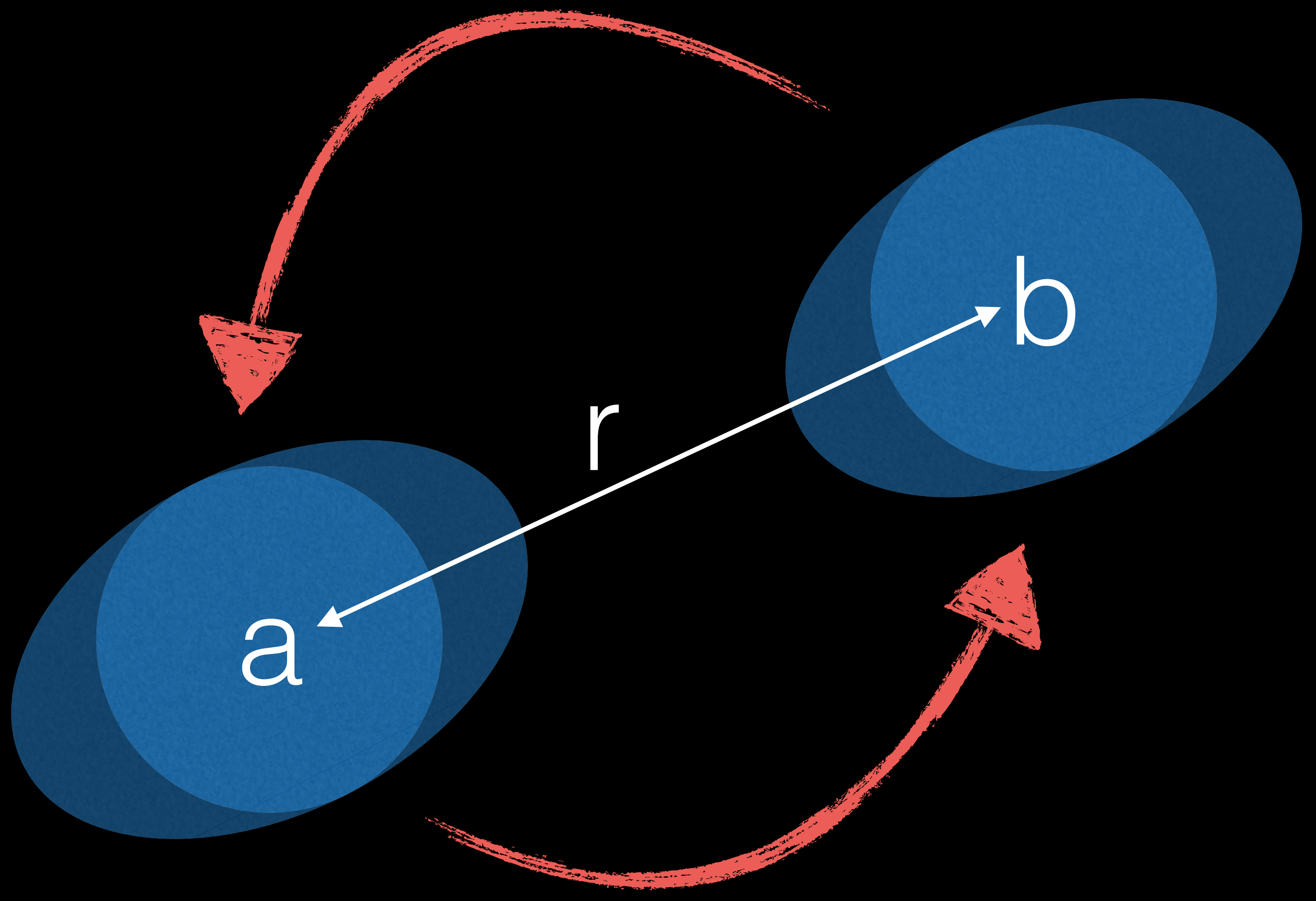
~10 s

In the Milky Way

	Orbital Period	Masses (solar)	Time to Merger
B1913+16	0.323 days	1.441 + 1.387	3 x 10^8 yrs
B1534+12	0.421 days	1.333 + 1.347	27 x 10^8 yrs
B2127+11C	0.335 days	1.35 + 1.36	2.2 x 10^8 yrs
J0737-3039	0.102 days	1.34 + 1.25	0.86 x 10^8 yrs
J1756-2251	0.32 days	1.34 + 1.23	17 x 10^8 yrs
J1906+746	0.166 days	1.29 + 1.32	3.1 x 10^8 yrs
J1913+1102	0.201 days	1.65 + 1.24	5 x 10^8 yrs

Initial expectation for BNS mergers in Ad. LIGO at design sensitivity: 0.4 - 400 / year

Late Inspiral: $R_{orbit} \lesssim 10\ R_{NS}$



Tidal forces deform neutron stars.
Induces a quadrupole moment.

$$Q_{ij} = \lambda\ E_{ij} \qquad E_{ij} = -\frac{\partial^2 V(r)}{\partial x_i \partial x_j}$$

Quadrupole polarizability

External field

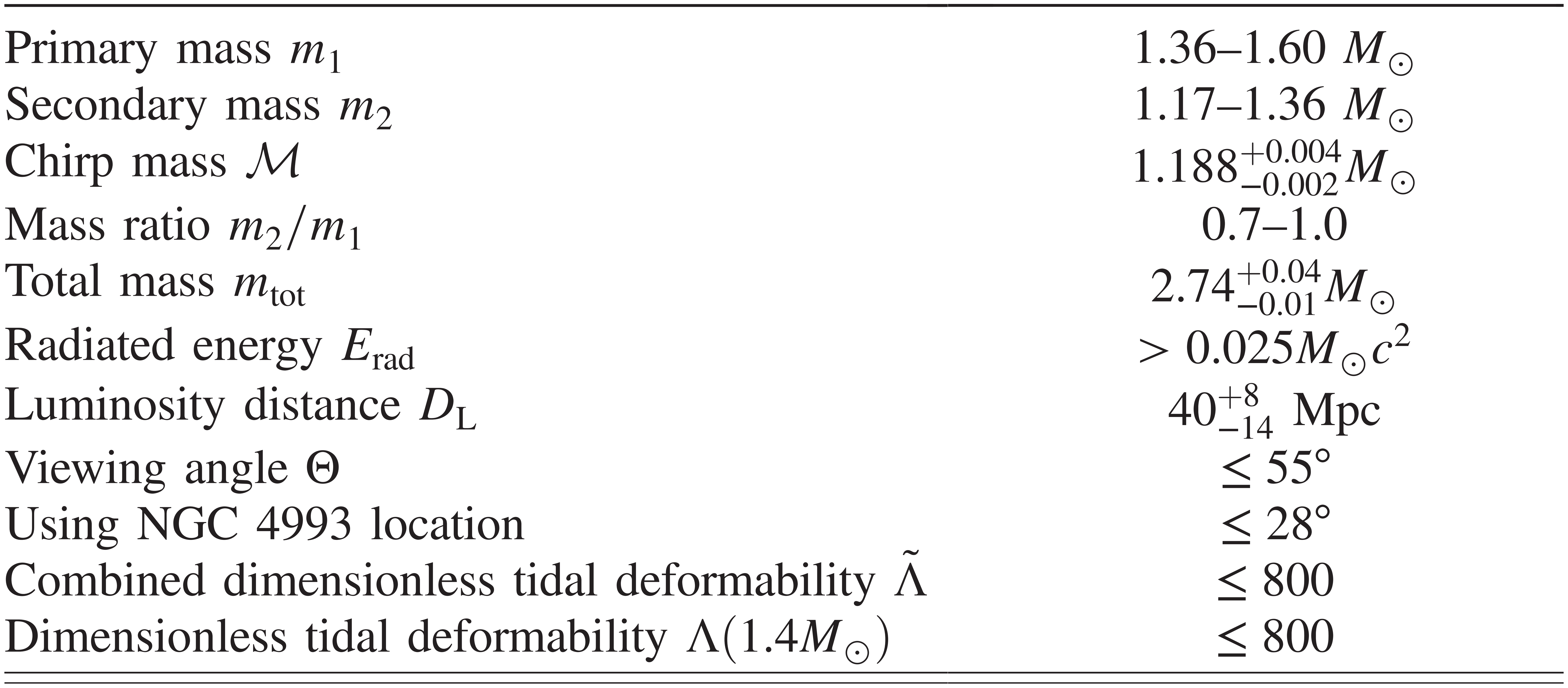
Tidal deformations are large for a large NS: $\lambda = k_2\ R_{NS}^5$

Tidal interactions advance the orbit and change the rotational phase.

Tidal Effects at Late Times

B. Lackey, L. Wade. PRD 91, 043002 (2015)

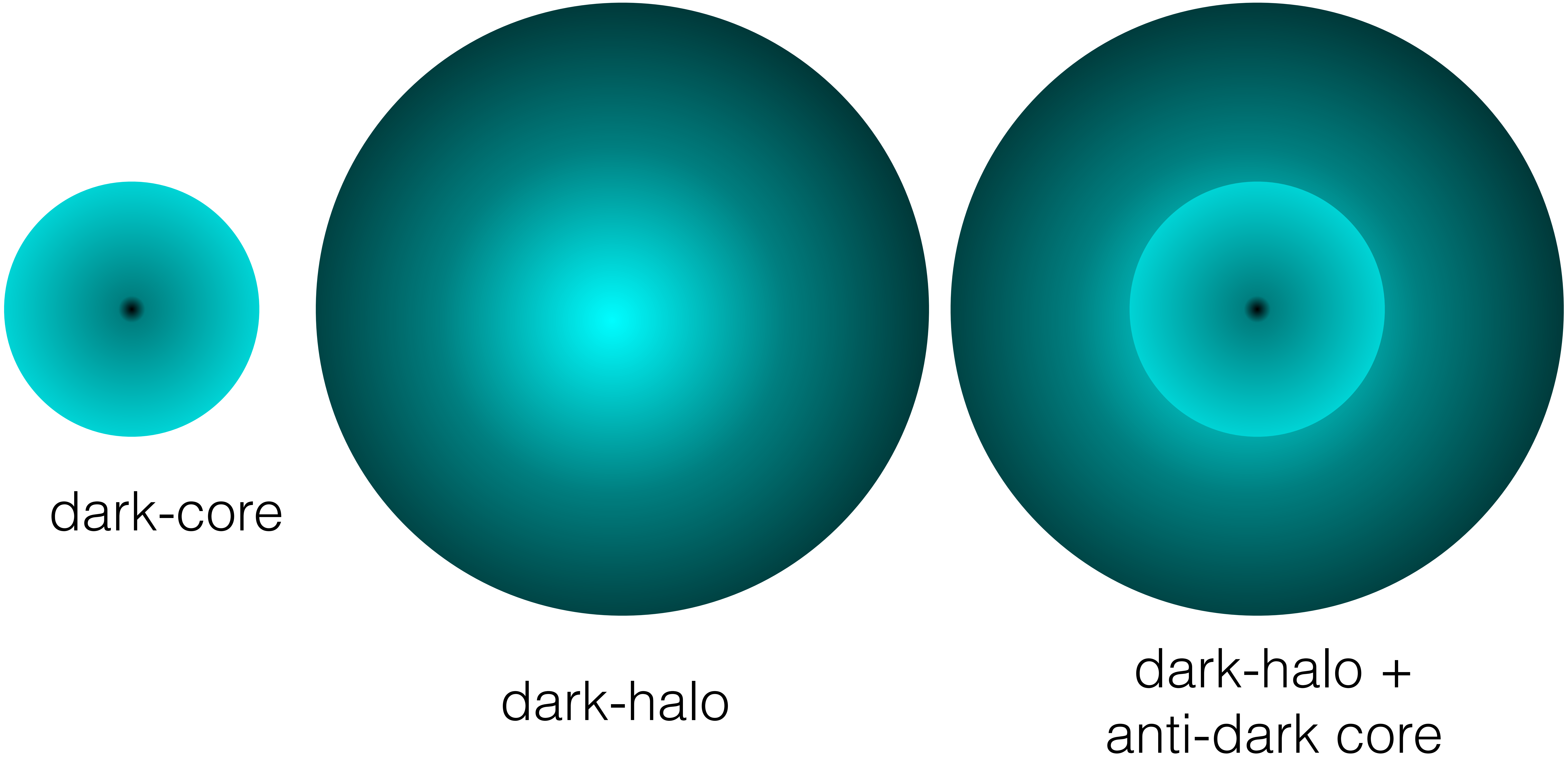
Parameters from GW data analysis



Primary mass m_1	$1.36\text{–}1.60\ M_\odot$
Secondary mass m_2	$1.17\text{–}1.36\ M_\odot$
Chirp mass $\mathcal{M}$	$1.188^{+0.004}_{-0.002} M_\odot$
Mass ratio m_2/m_1	$0.7\text{–}1.0$
Total mass $m_{\rm tot}$	$2.74^{+0.04}_{-0.01} M_\odot$
Radiated energy $E_{\rm rad}$	$> 0.025 M_\odot c^2$
Luminosity distance $D_{\rm L}$	40^{+8}_{-14} Mpc
Viewing angle Θ	$\leq 55°$
Using NGC 4993 location	$\leq 28°$
Combined dimensionless tidal deformability $\tilde{\Lambda}$	≤ 800
Dimensionless tidal deformability $\Lambda(1.4 M_\odot)$	≤ 800

Dark Matter and Neutron Star Structure

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



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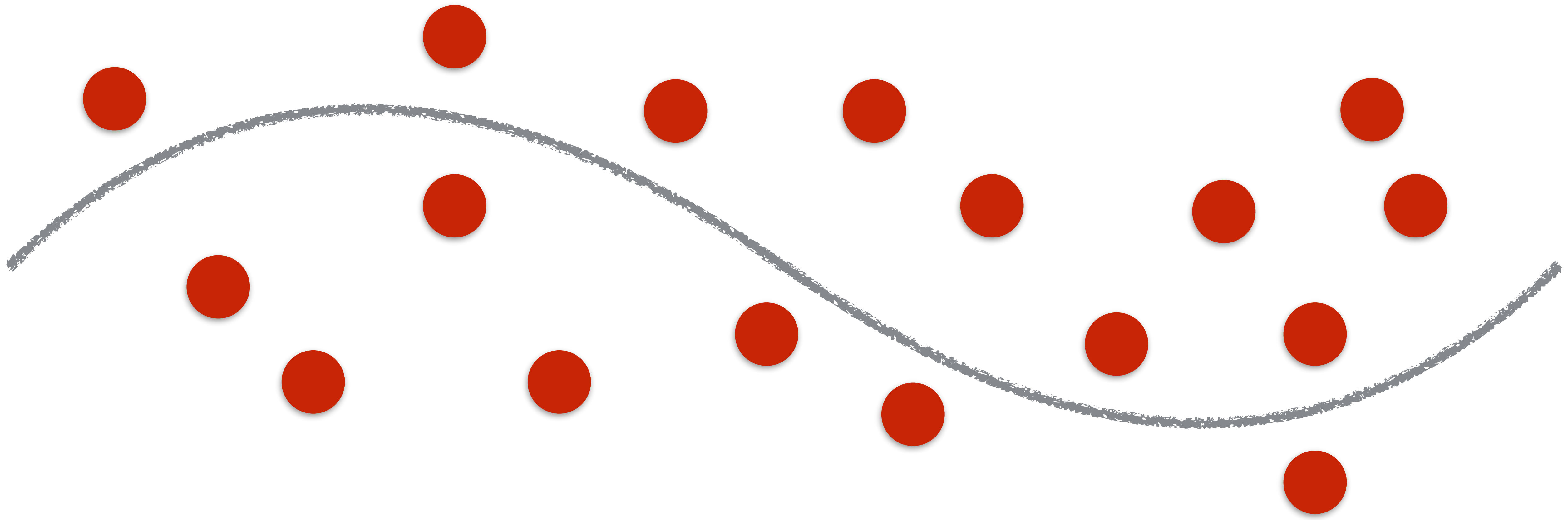
Equation of State of Dark Matter

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

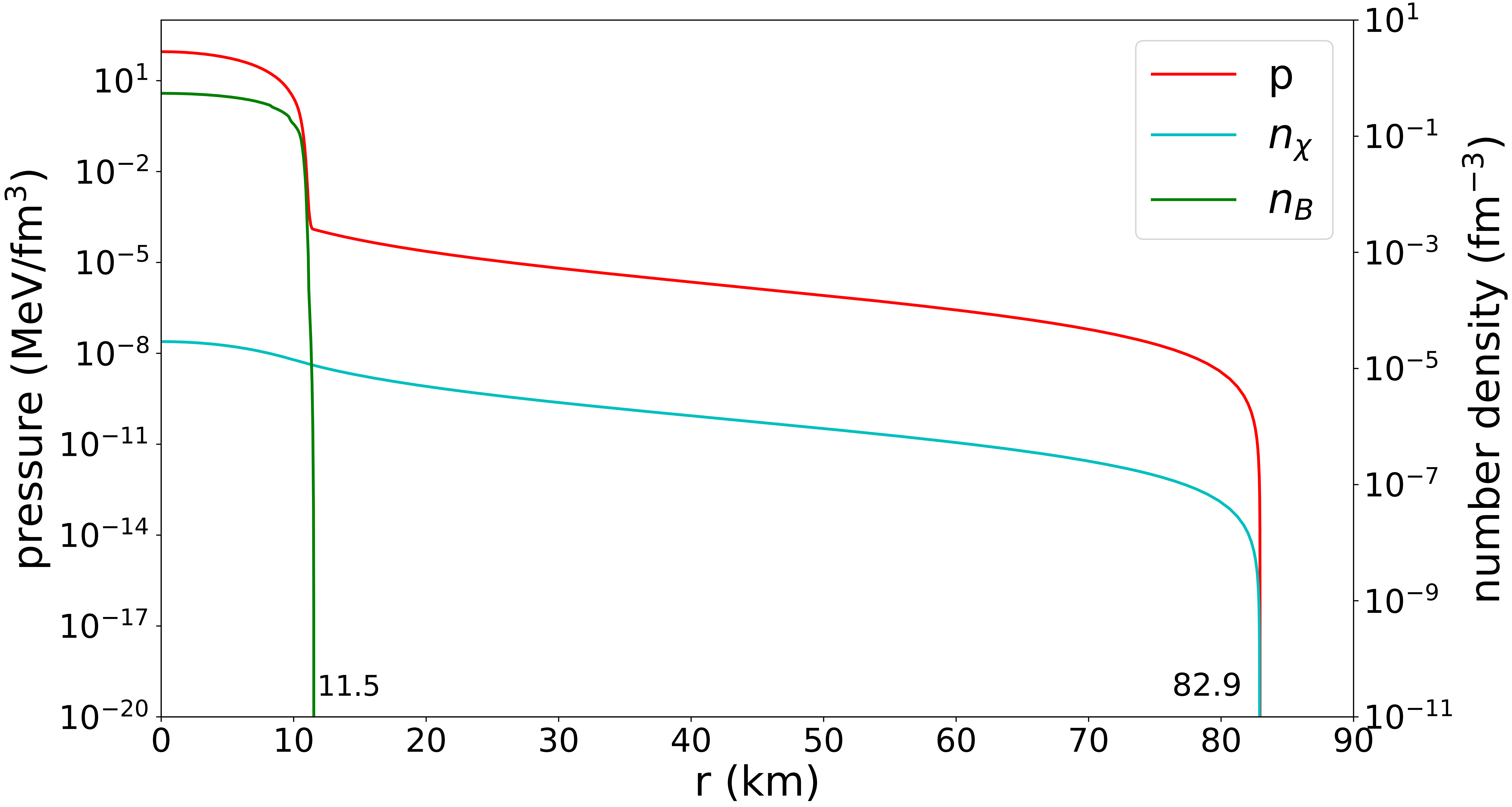
$$+\frac{g_\chi g_B}{m_\phi^2}\, n_B n_\chi$$

$$-\frac{g_\chi g_B}{m_\phi^2}\, n_B n_\chi$$



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

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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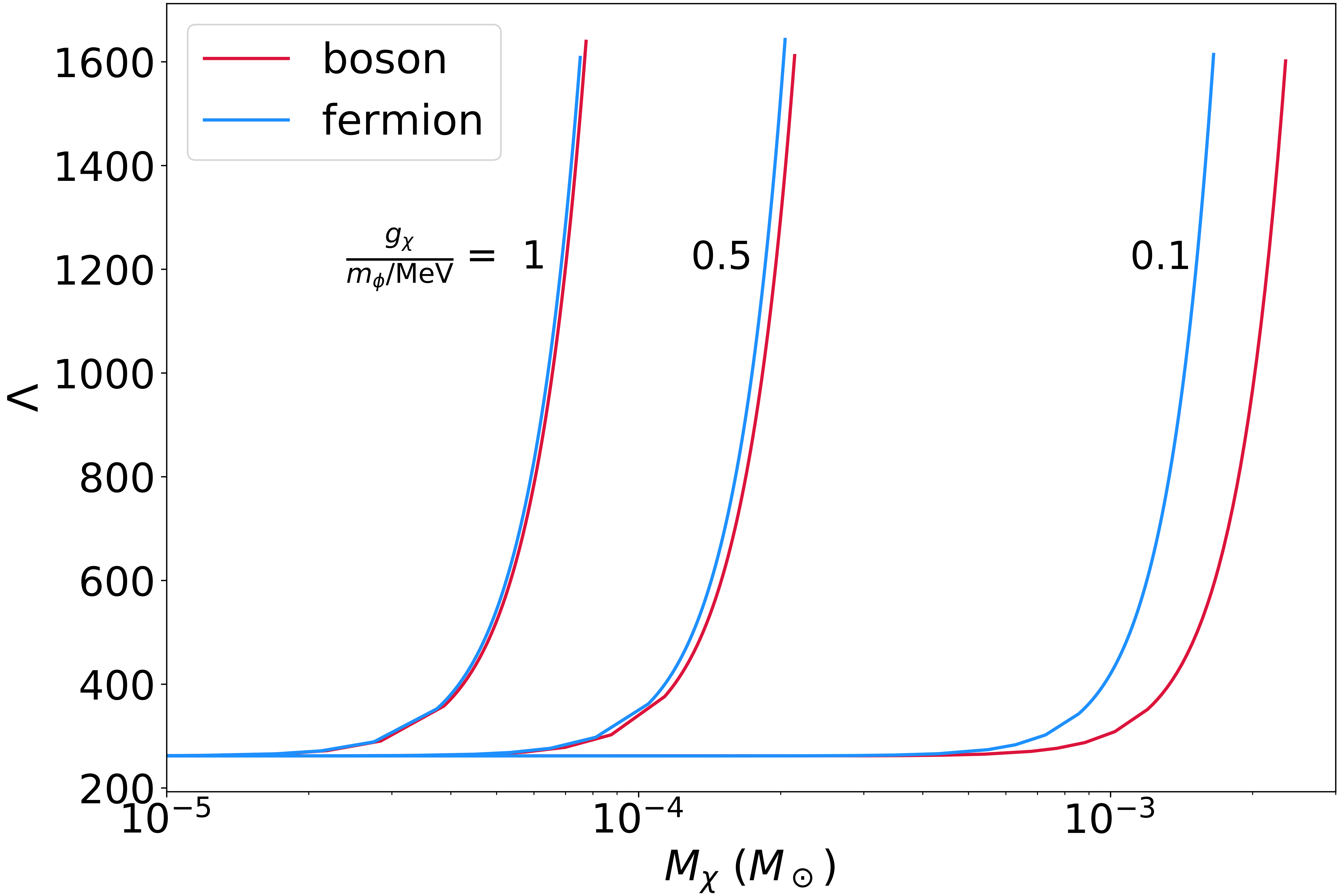
For light mediators, only trace amount of DM is needed

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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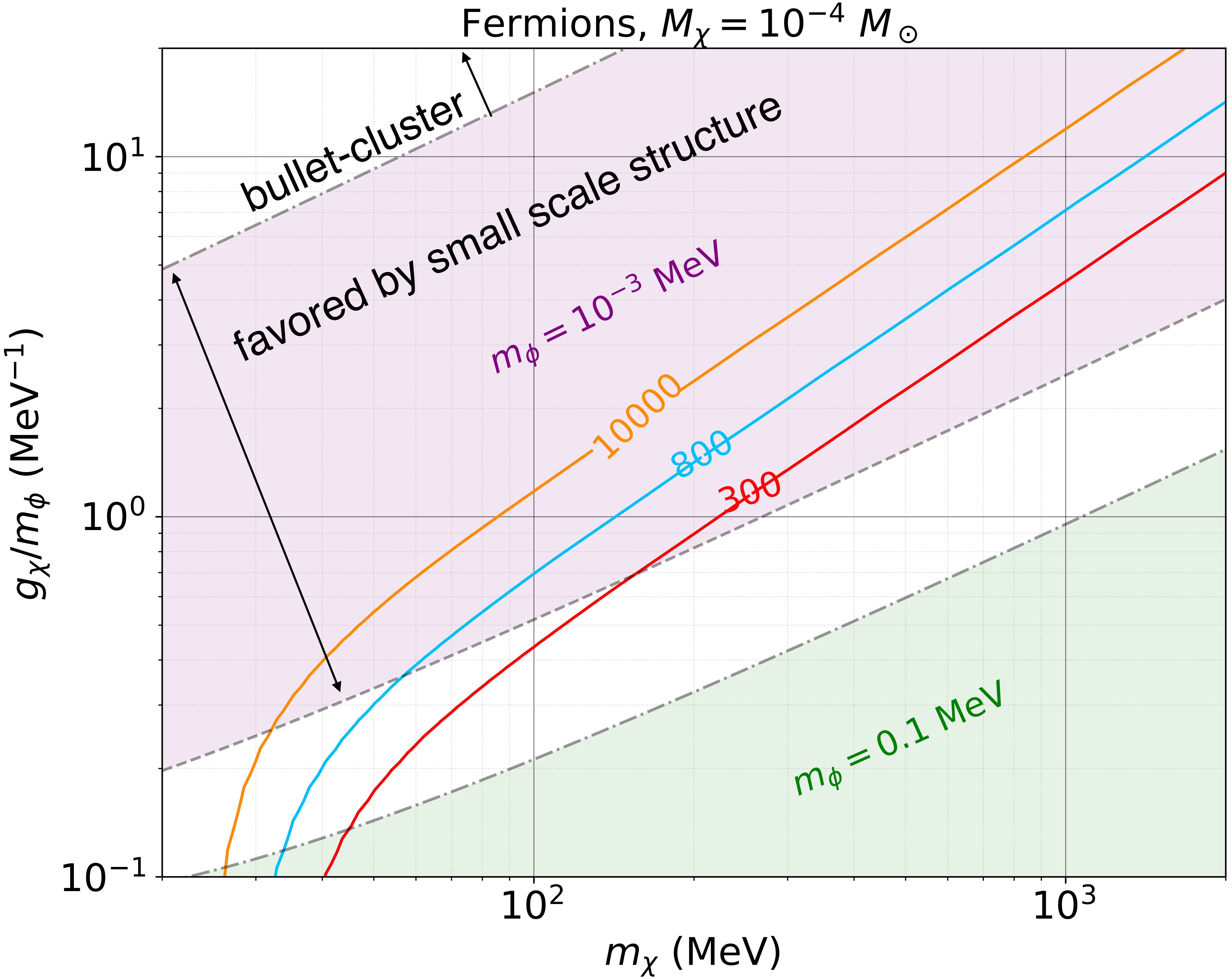
Constraints and Signatures

If all NS contain some dark matter:

- GW170817 rules out regions of the light dark matter parameter space.
- Light fermions are constrained even when interactions are negligible.

If only some NSs contain dark matter:

- NS should show a large variability of their tidal polarizabilities.



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Could/should NS contain dark matter ?

- Supernova can produce $10^{-2}\,M_{solar}$ of < 100 MeV dark matter.
- Coupling to baryons allows for dark charge separation.
- Dark matter could 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 neutron stars. Cooling arguments have provided useful constraints and systematics errors could be better understood.

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.

Trace amounts of interacting asymmetric dark matter in the neutron star can enhance their tidal polarizability (Λ) to discernible values.

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.