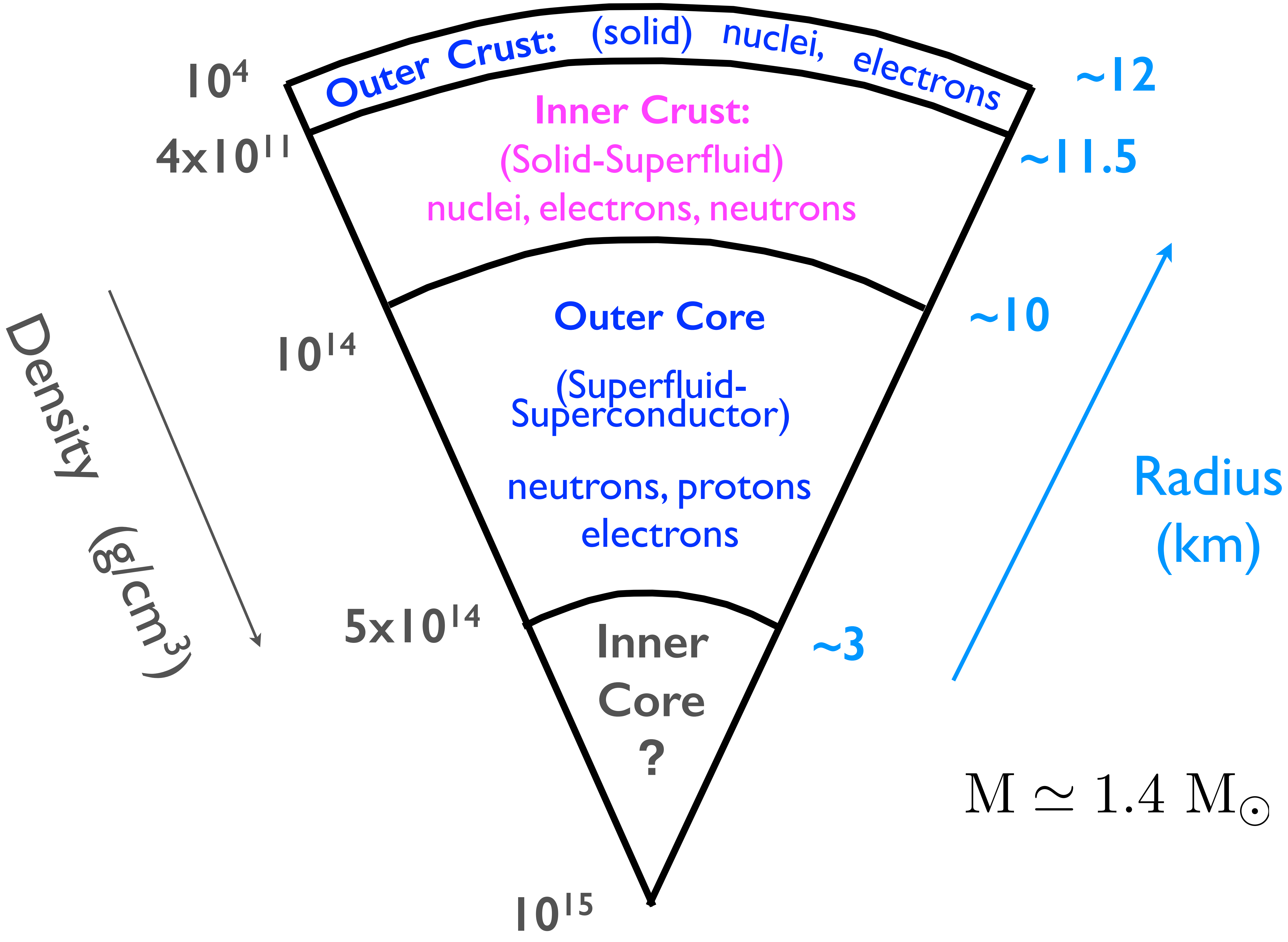
# Neutron Stars as Laboratories for Particle Physics

Sanjay Reddy
Institute for Nuclear Theory, University of Washington

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

# 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.

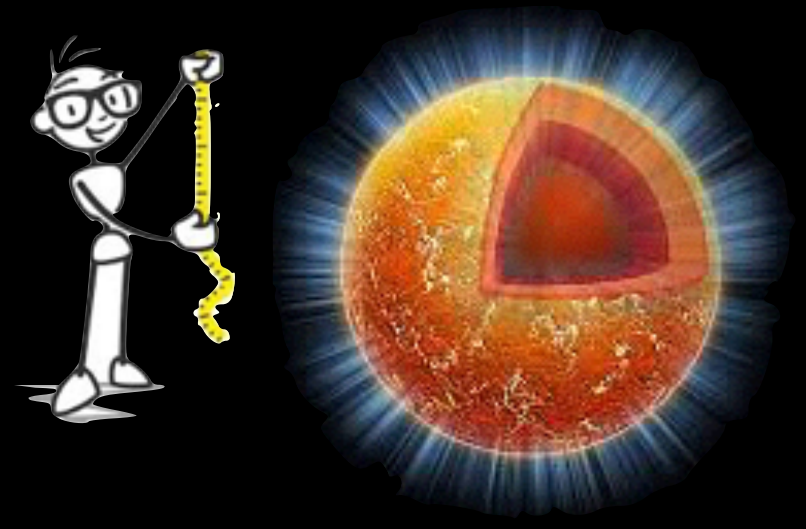



For a review see: Page & Reddy, Ann. Rev. Nucl. Part. Sci. (2006)

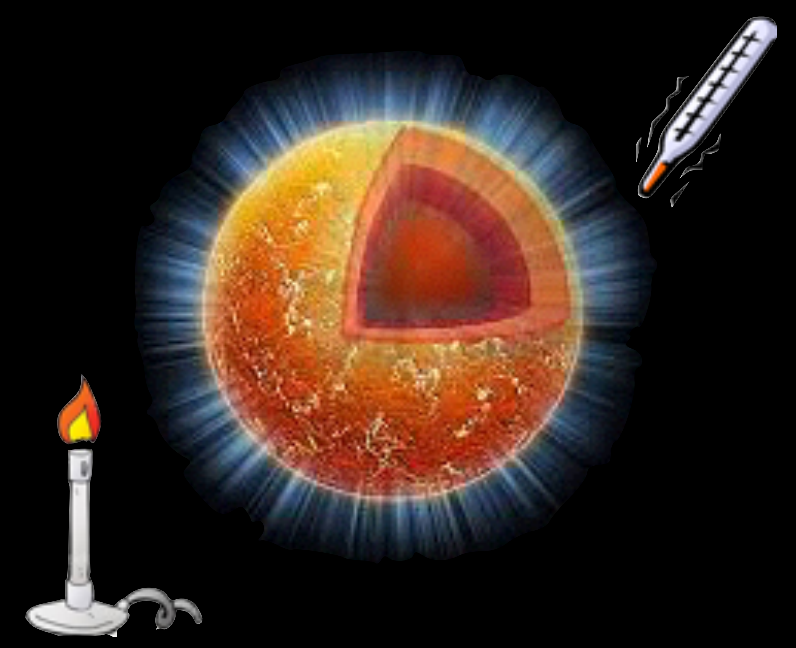
# Some Observed Properties of NS

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)

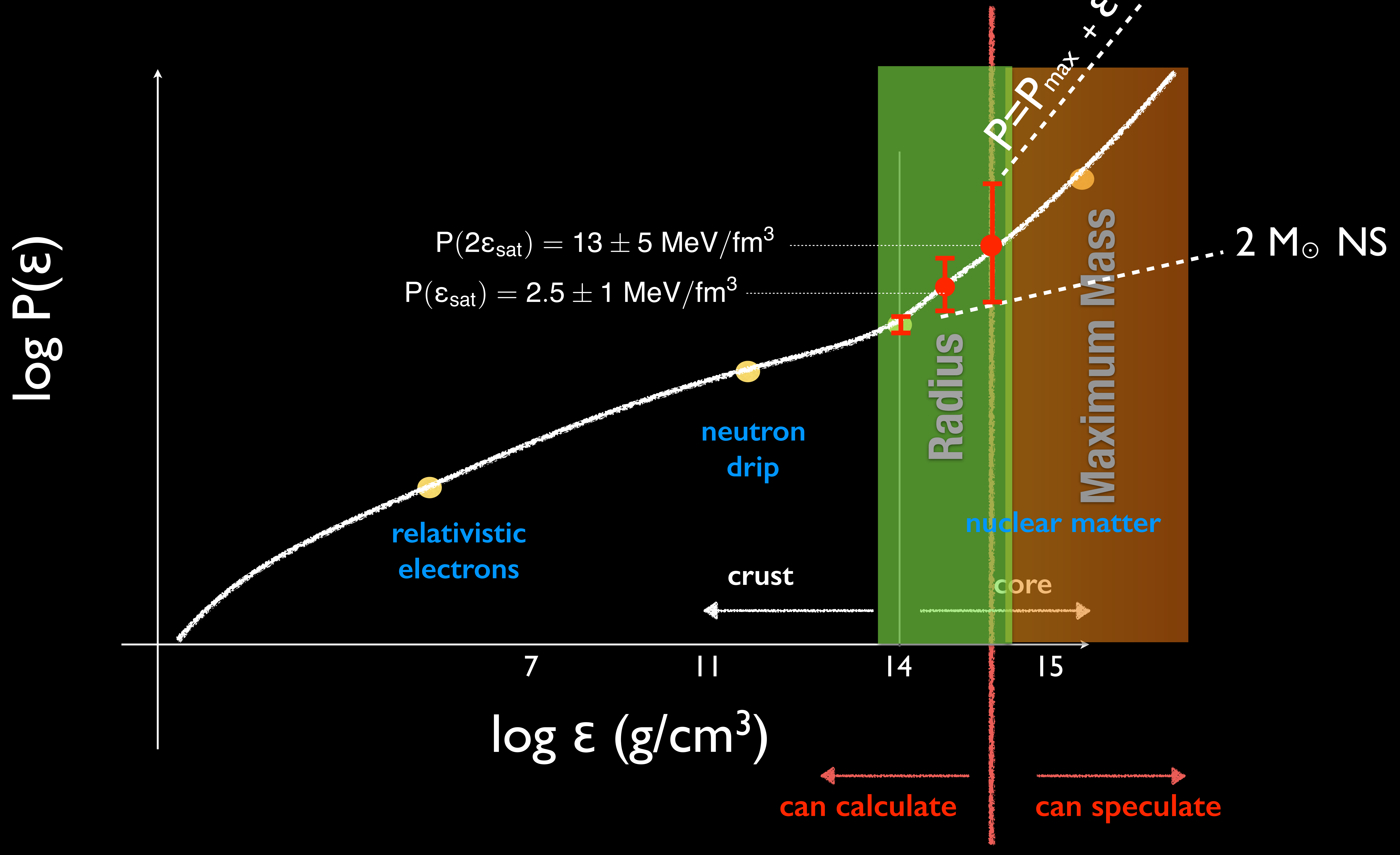


Using x-rays and gravitational waves: $9\text{ km}(?) < R_{NS} < 14\text{ km}$



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 $t \sim 10^6$ yrs.

# PRESSURE V/S ENERGY DENSITY (EOS)

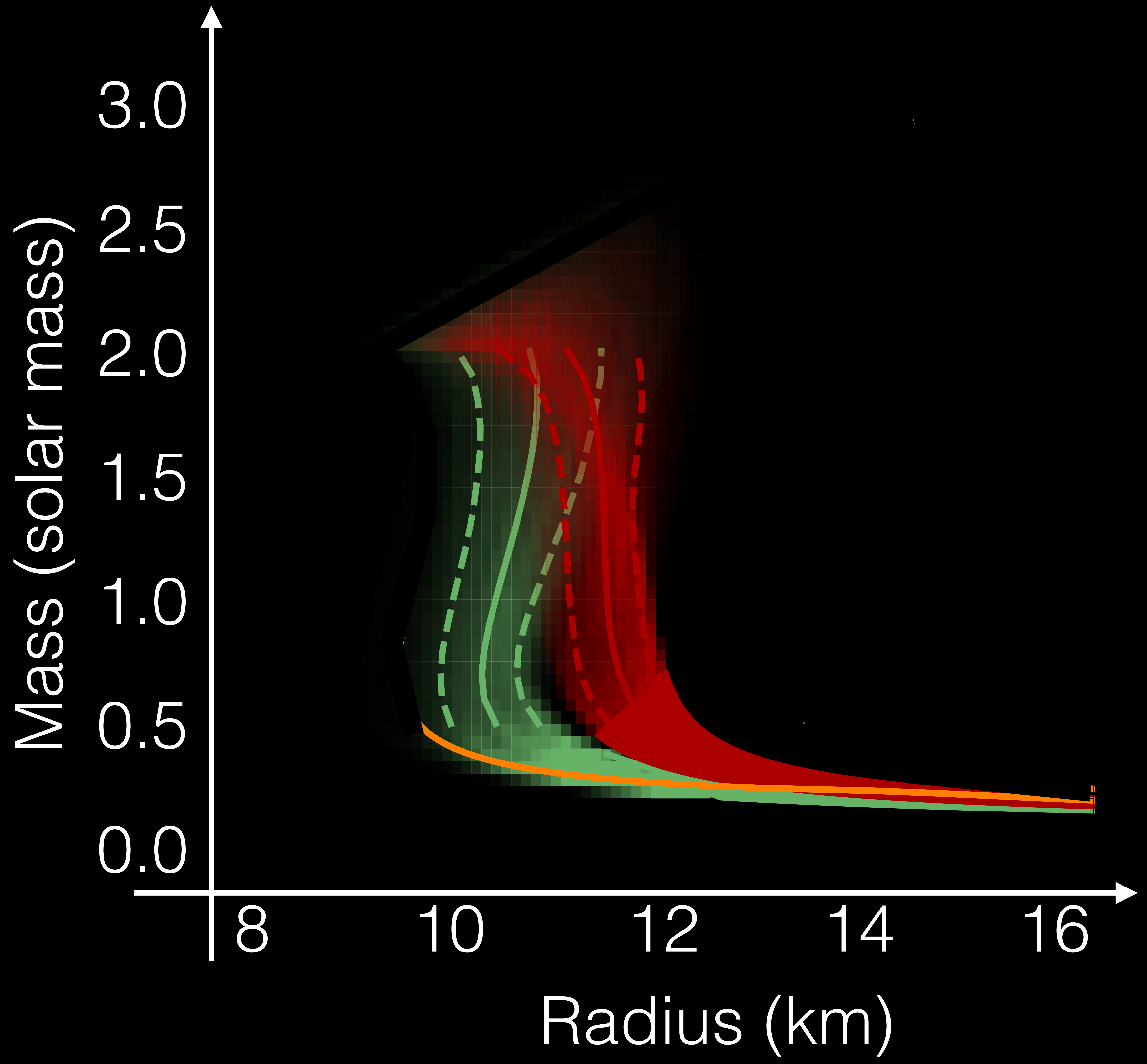


# Radii and Maximum Masses

- 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

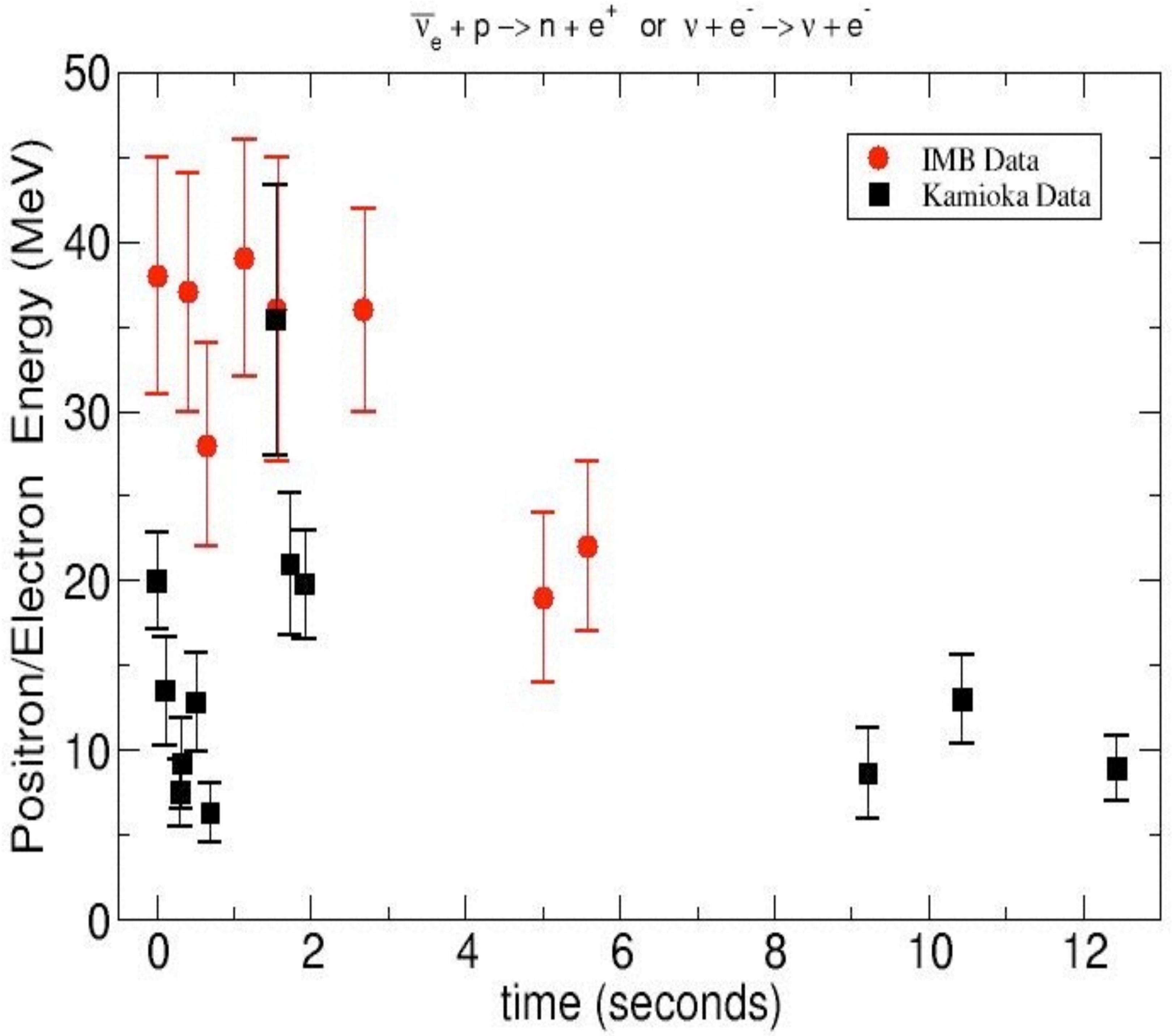
- Nuclear description viable up to 2.5 x $10^{14}$ g/cm$^3$ :
  - Radius = 9.5 - 14 kms
  - Maximum mass = 2 - 3 solar masses




Tews, Carlson, Gandolfi and Reddy (2018)

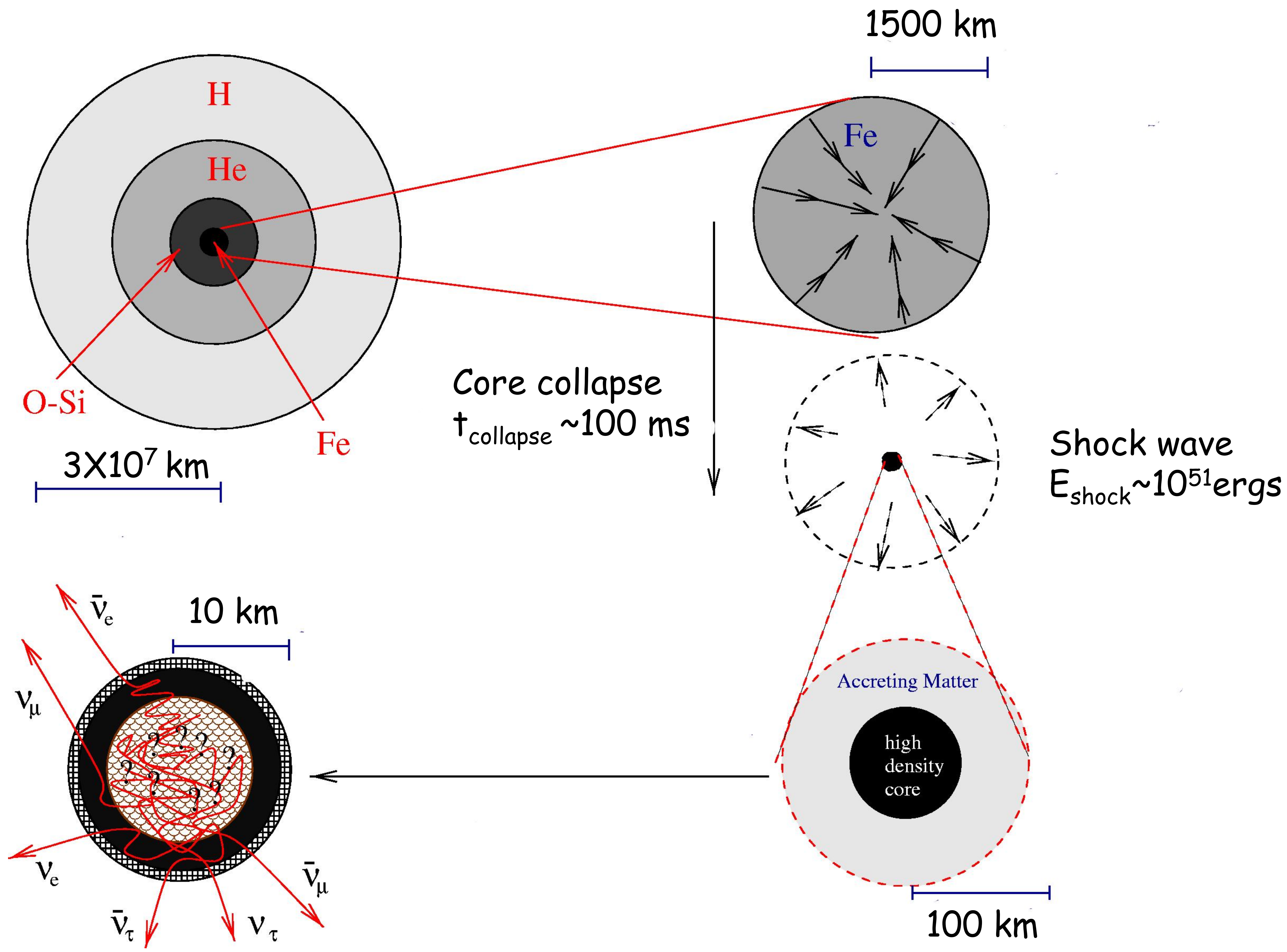
# Early Neutron Star Cooling: Supernova Neutrinos

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.

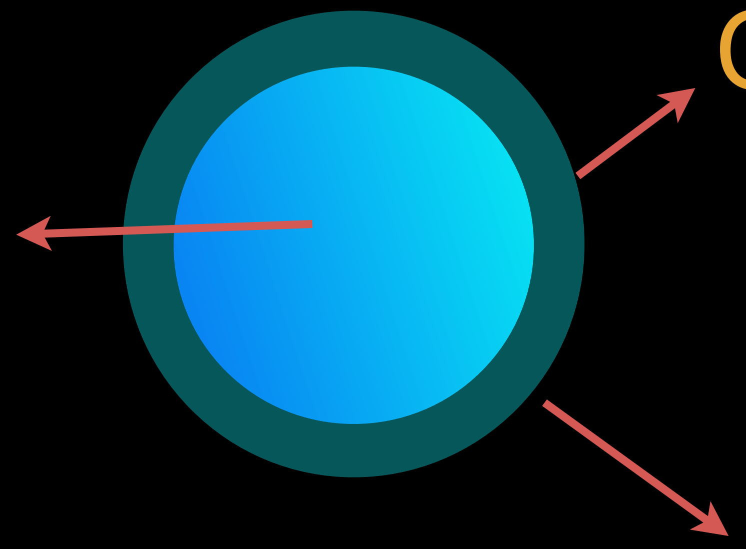



**3 x $10^{53}$ ergs = $10^{58}$ × 20 MeV Neutrinos**

**neutrinos diffuse in the core.**

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

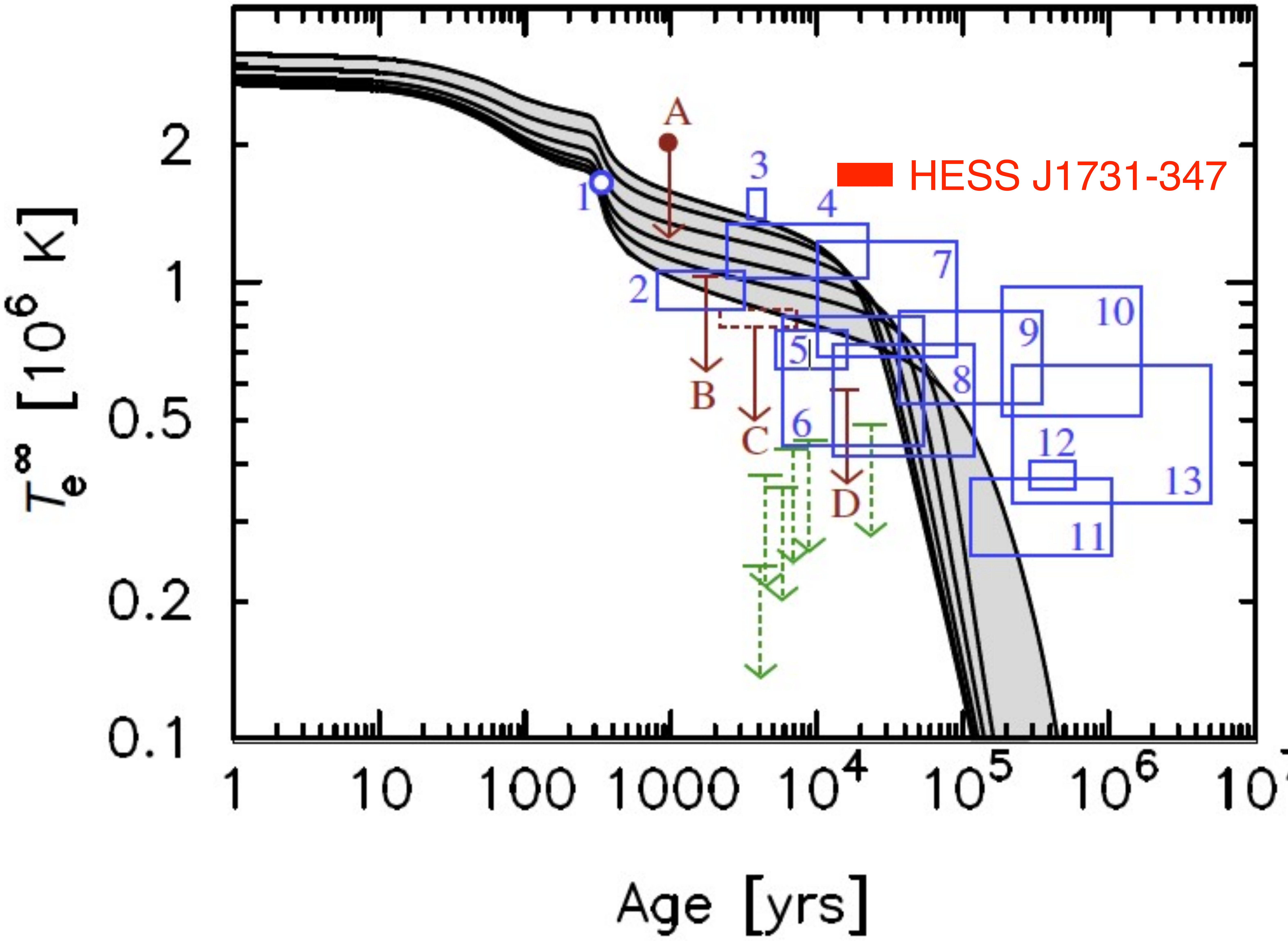
Increasing NS mass

# Models can predict the observed variability

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

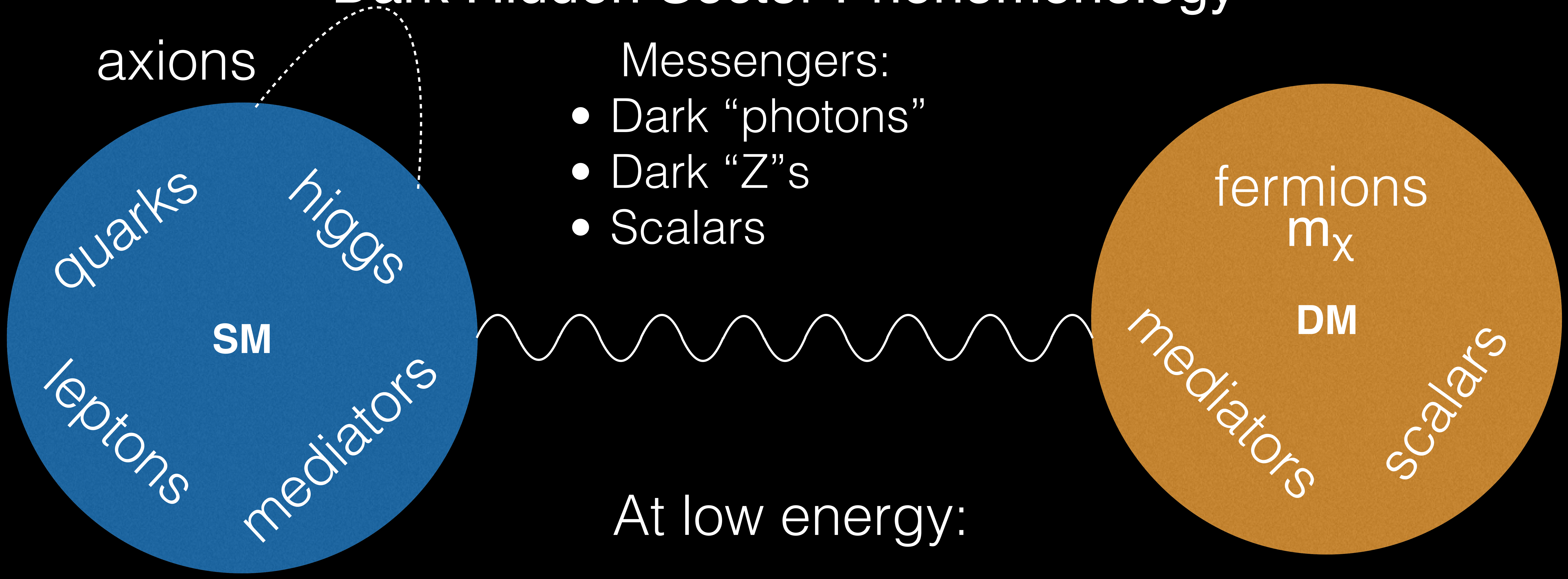
One exception is HESS J1731-34. Too hot. Yakovlev et al (2016, 2017)

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




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

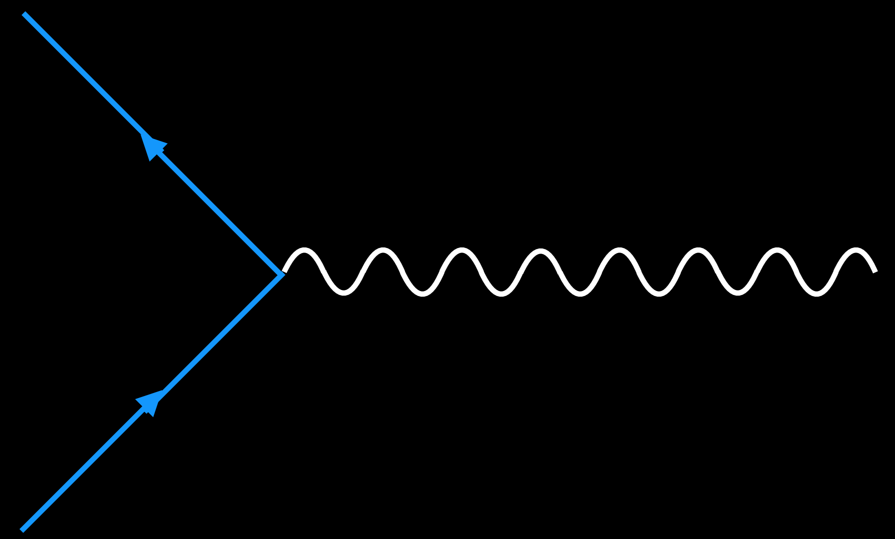
# Dark Hidden Sector Phenomenology

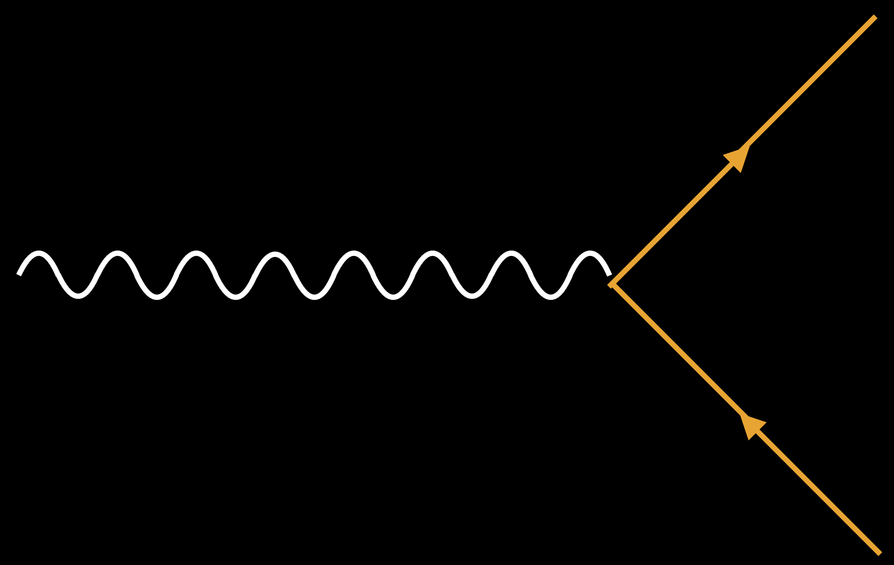



Messengers:
- Dark "photons"
- Dark "Z"s
- Scalars

At low energy:

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





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

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

# 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.

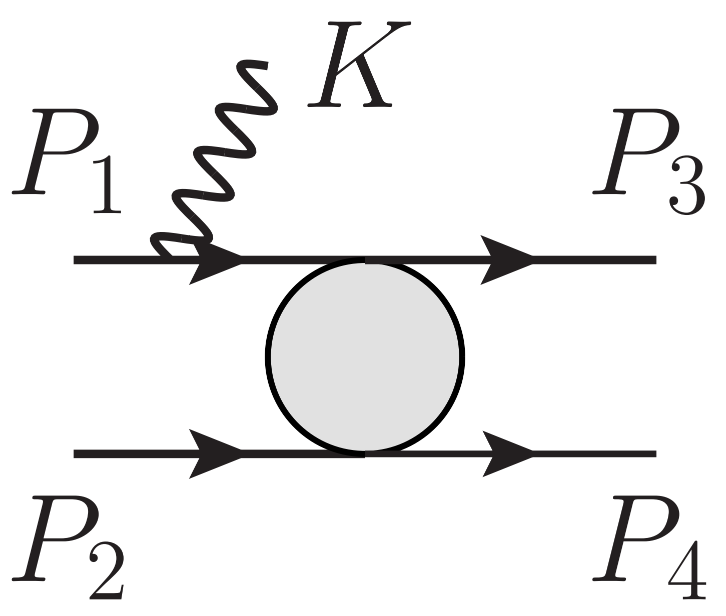
The corresponding bound on the luminosity is $$L_{\mathrm{exotic}} < \mathcal{E}_{\mathrm{Raffelt}} \times M_{NS} \simeq 2\times 10^{52}\frac{M}{M_\odot}\ \frac{\mathrm{ergs}}{\mathrm{s}}$$

# Dark Photons

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

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

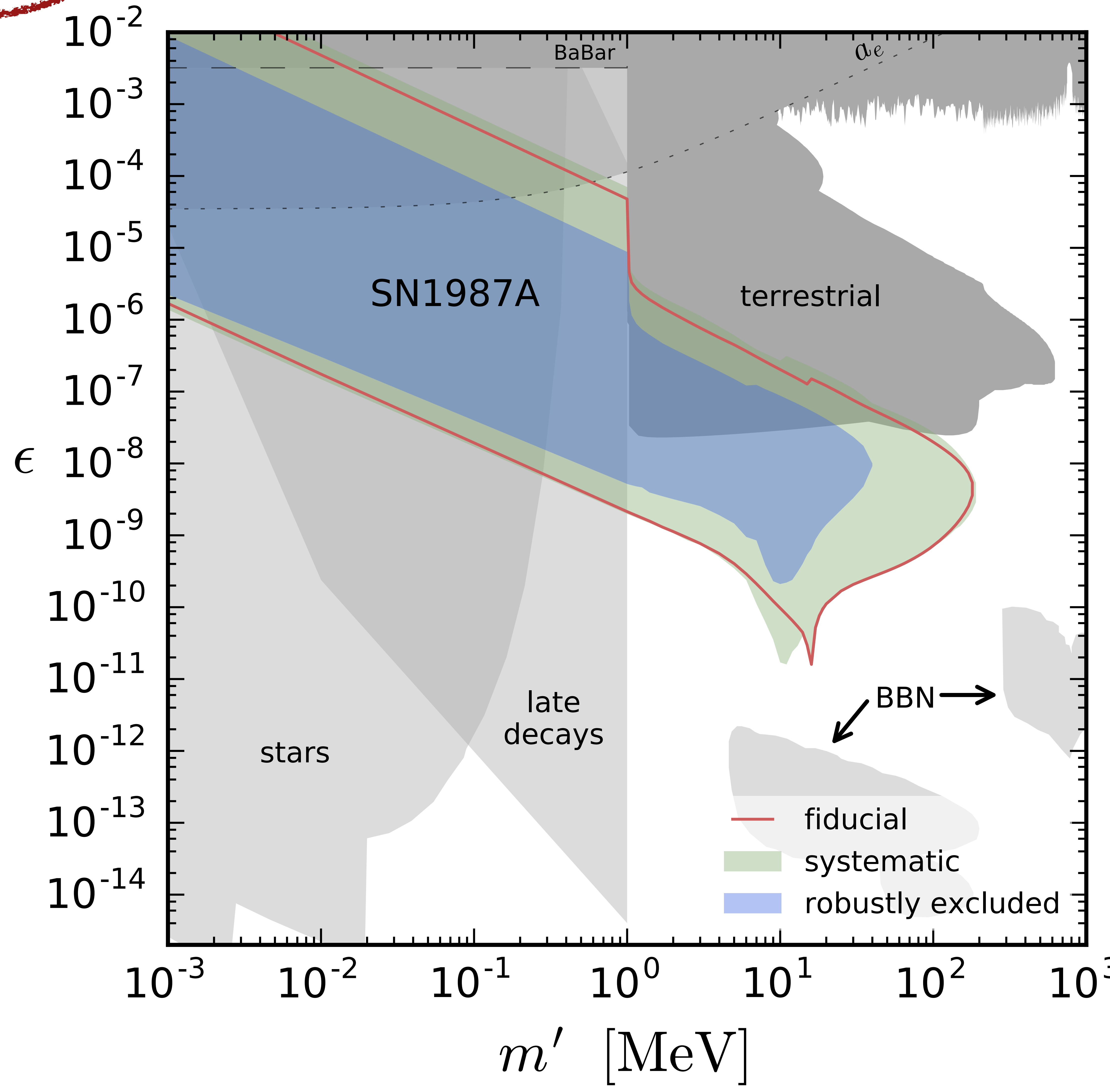
Nucleon-nucleon Bremsstrahlung dominant production mechanism:




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)



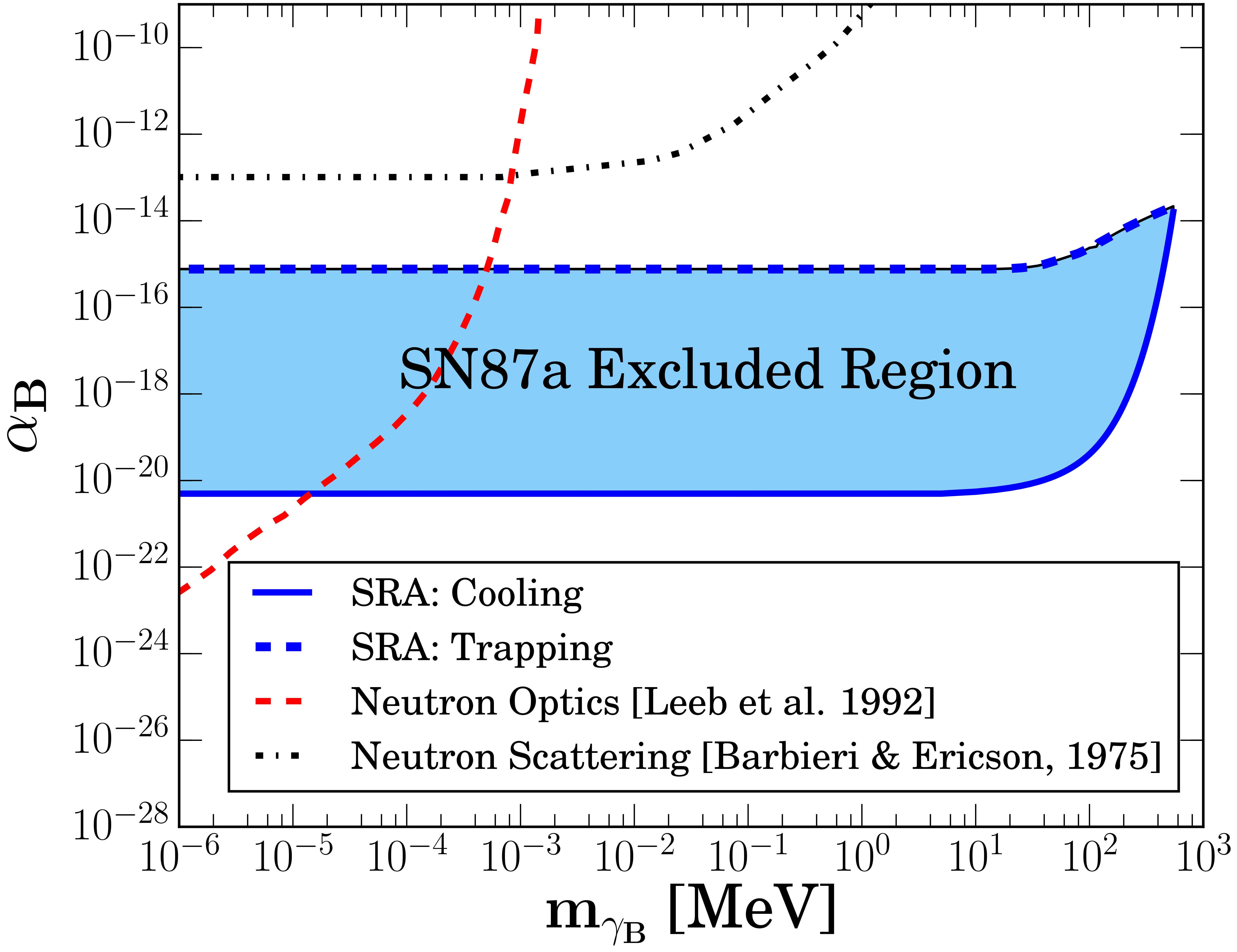
# Dark Baryon Number Gauge Boson

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

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

- 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)

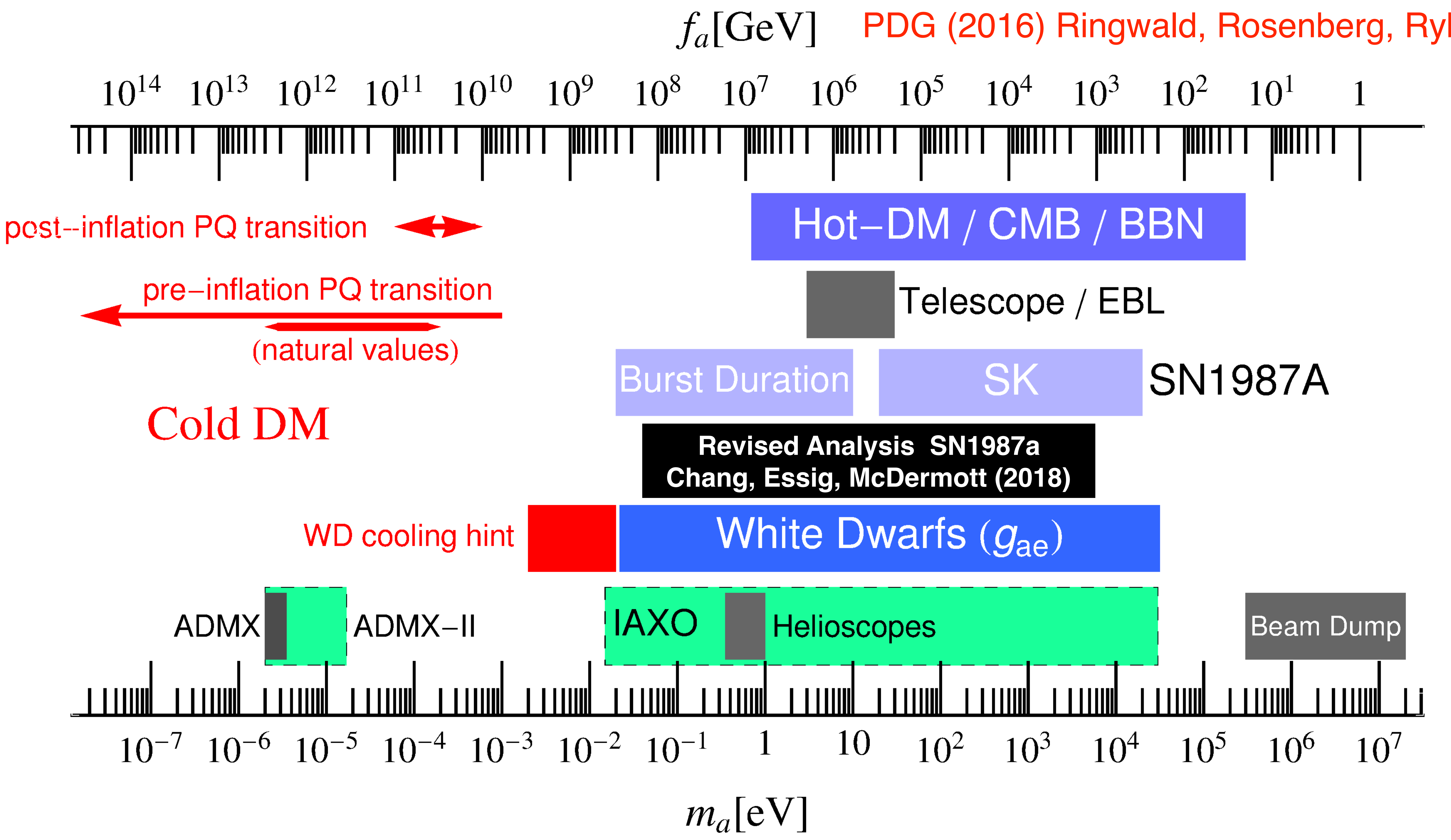
# QCD Axions

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 (in prep. ) 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.

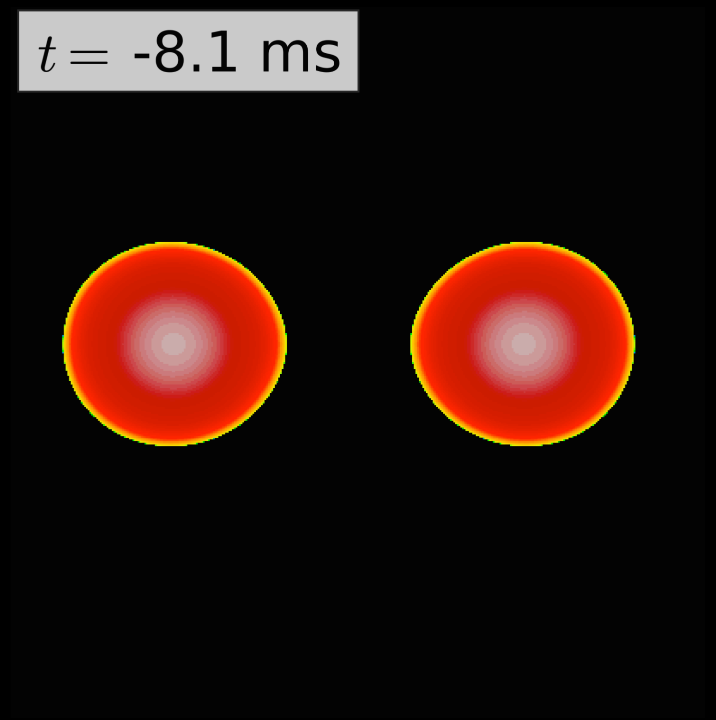
HESS J1731 ($C_n$ =0.27):
$f_a > 4 \times 10^8$ GeV [at 99%]
$f_a > 3 \times 10^9$ GeV [at 90%]

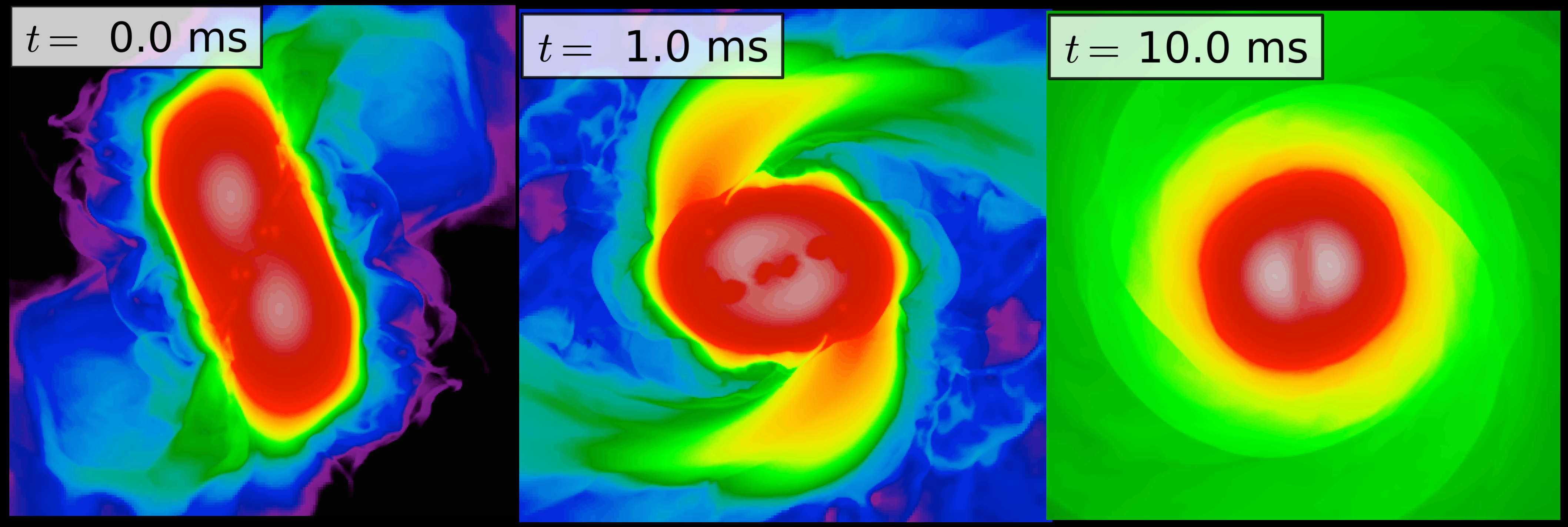
Beznogov, Page, Rrapaj and Reddy (2018) in prep.

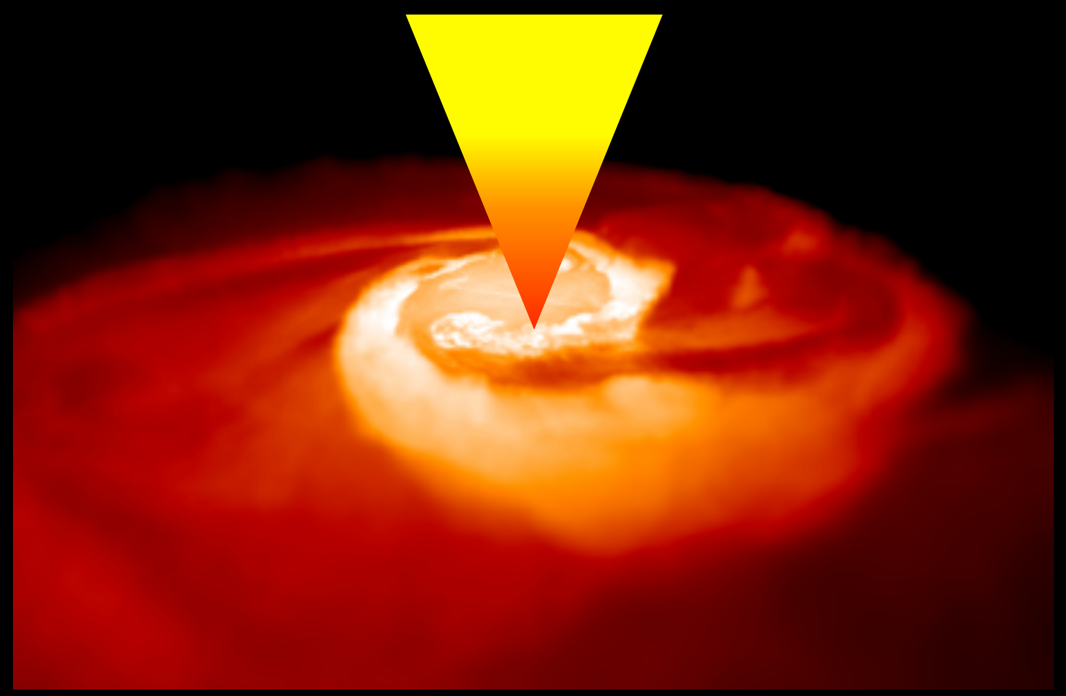
# Neutron Star Mergers

(General) Relativistic (Very) Heavy-Ion Collisions at ~ 100 MeV/nucleon

Simulations: Rezzola et al (2013)



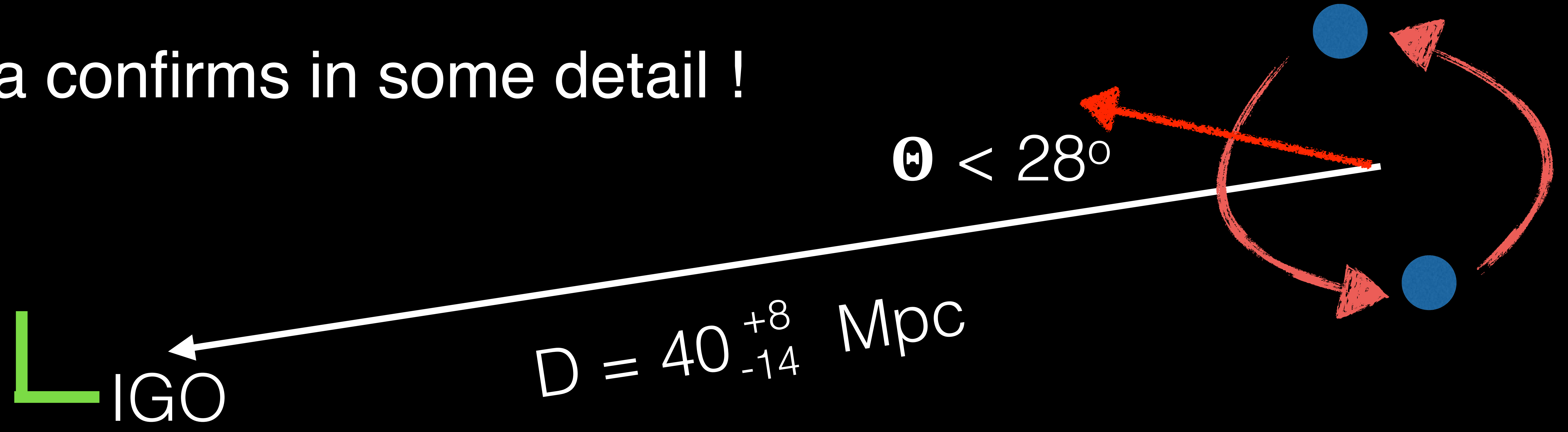



Inspiral:
Gravitational waves,
Tidal Effects

Merger:
Disruption, NS oscillations, ejecta
and r-process nucleosynthesis

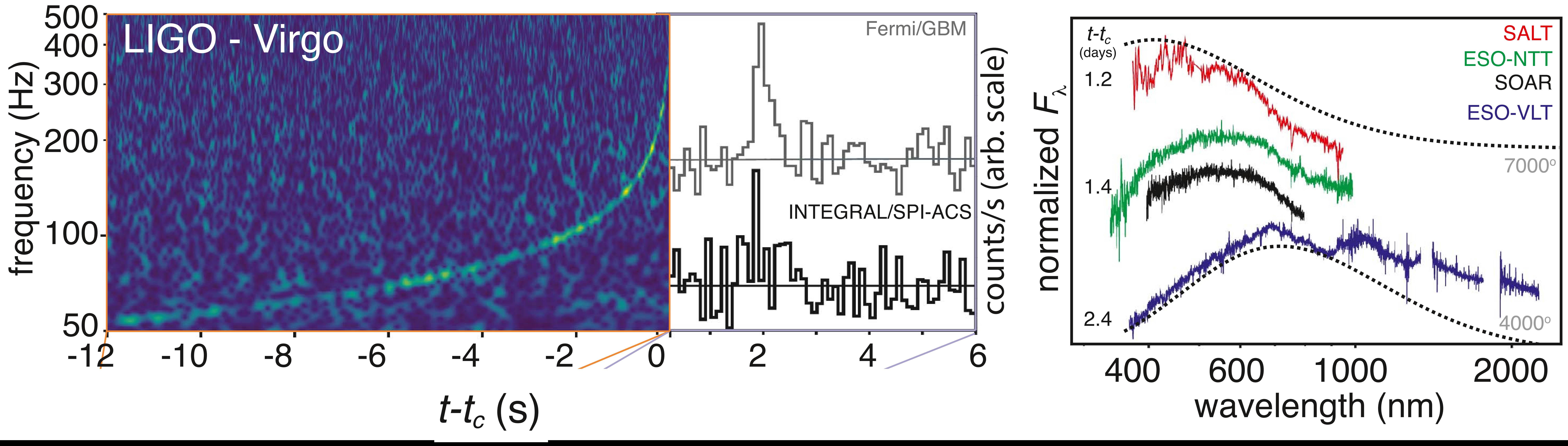
Post Merger:
GRBs, Afterglows, and
Kilonova

# GW170817 data confirms in some detail !



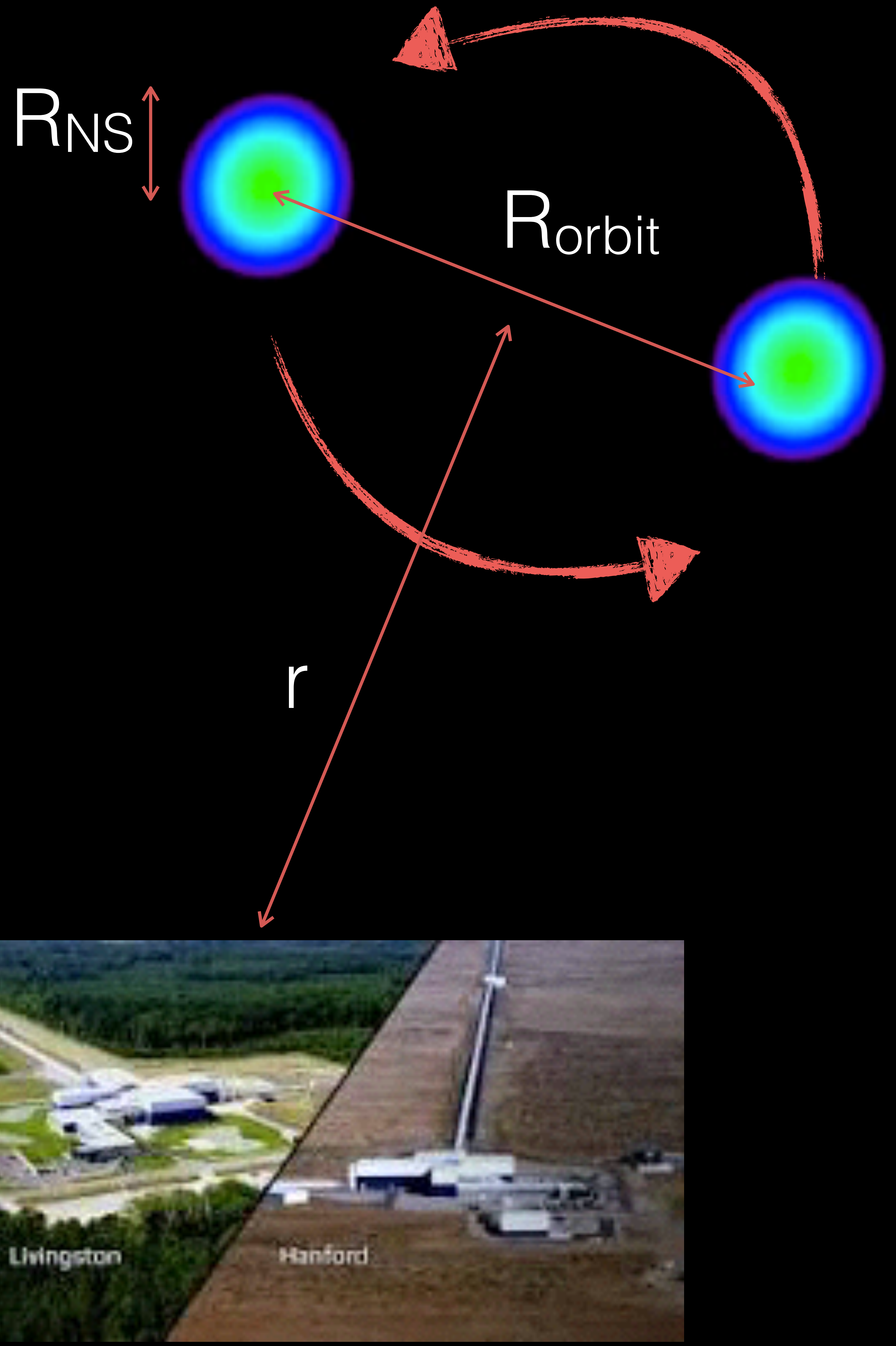

The Astrophysical Journal Letters, 848:L12 (59pp), 2017 October 20 https://doi.org/10.3847/2041-8213/aa91c9


## Multi-messenger Observations of a Binary Neutron Star Merger



# Gravitational waves during inspiral

GWs are produced by fluctuating quadrupoles.




$$g_{\mu\nu}(r,t) = \eta_{\mu\nu} + h_{\mu\nu}(r,t)$$

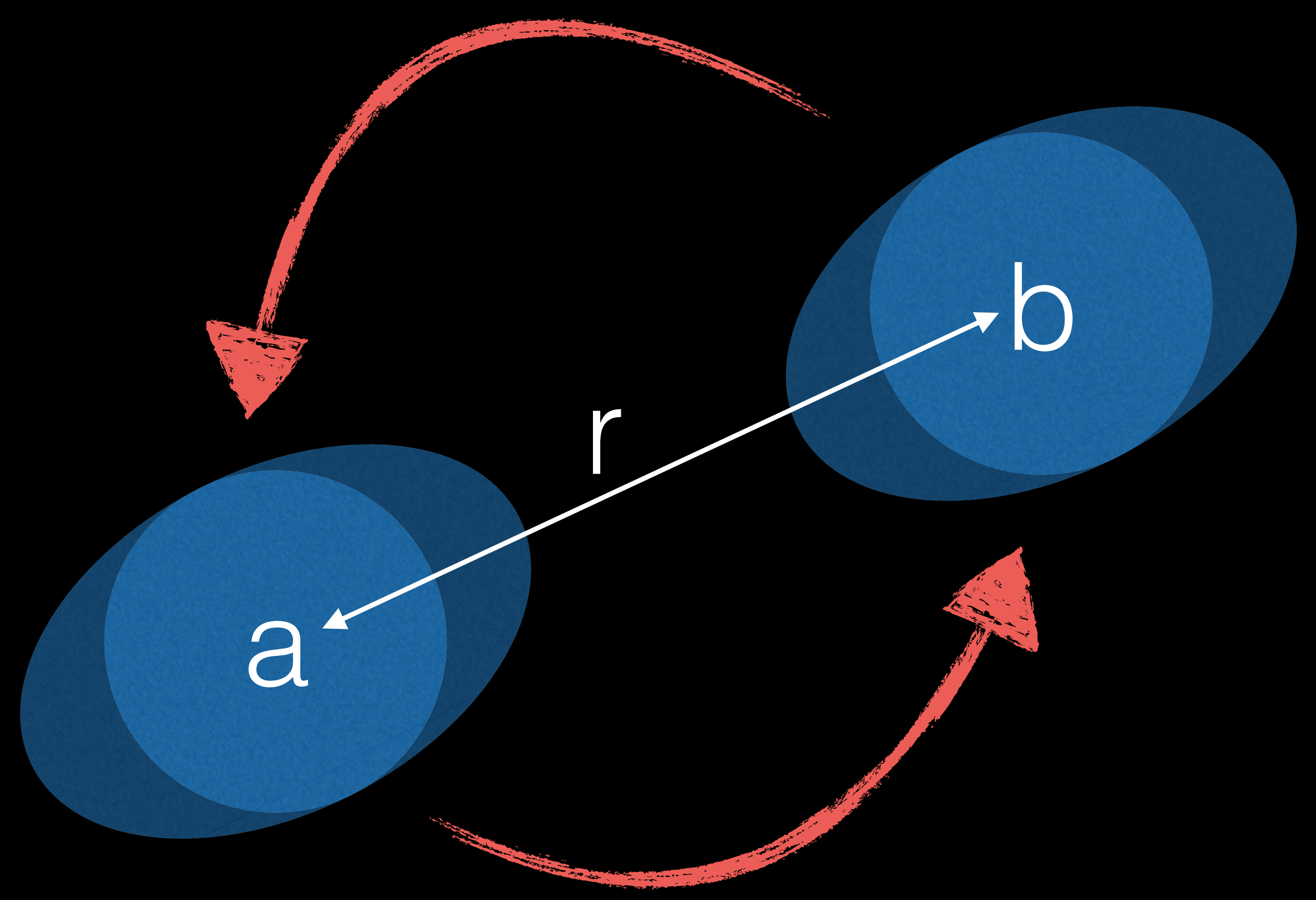
$$h_{\mu\nu}(r,t) = \frac{2G}{r}\,\ddot{I}_{ij}(t_R) \qquad I_{ij}(t) = \int d^3x\,\rho(t,\vec{x})\,x_i\,x_j$$

For $R_{orbit} >> R_{NS}$: $\ddot{I}_{ij}(t) \approx M\,R^2_{orbit}\,f^2 \approx M^{5/3}\,f^{2/3}$

$$h \approx 10^{-23}\left(\frac{M_{NS}}{M_\odot}\right)^{5/3}\left(\frac{f}{200\text{ Hz}}\right)^{2/3}\left(\frac{100\text{ Mpc}}{r}\right)$$

$$h(t) = h\,\cos(2\pi\,f(t)\,t)$$

# 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)

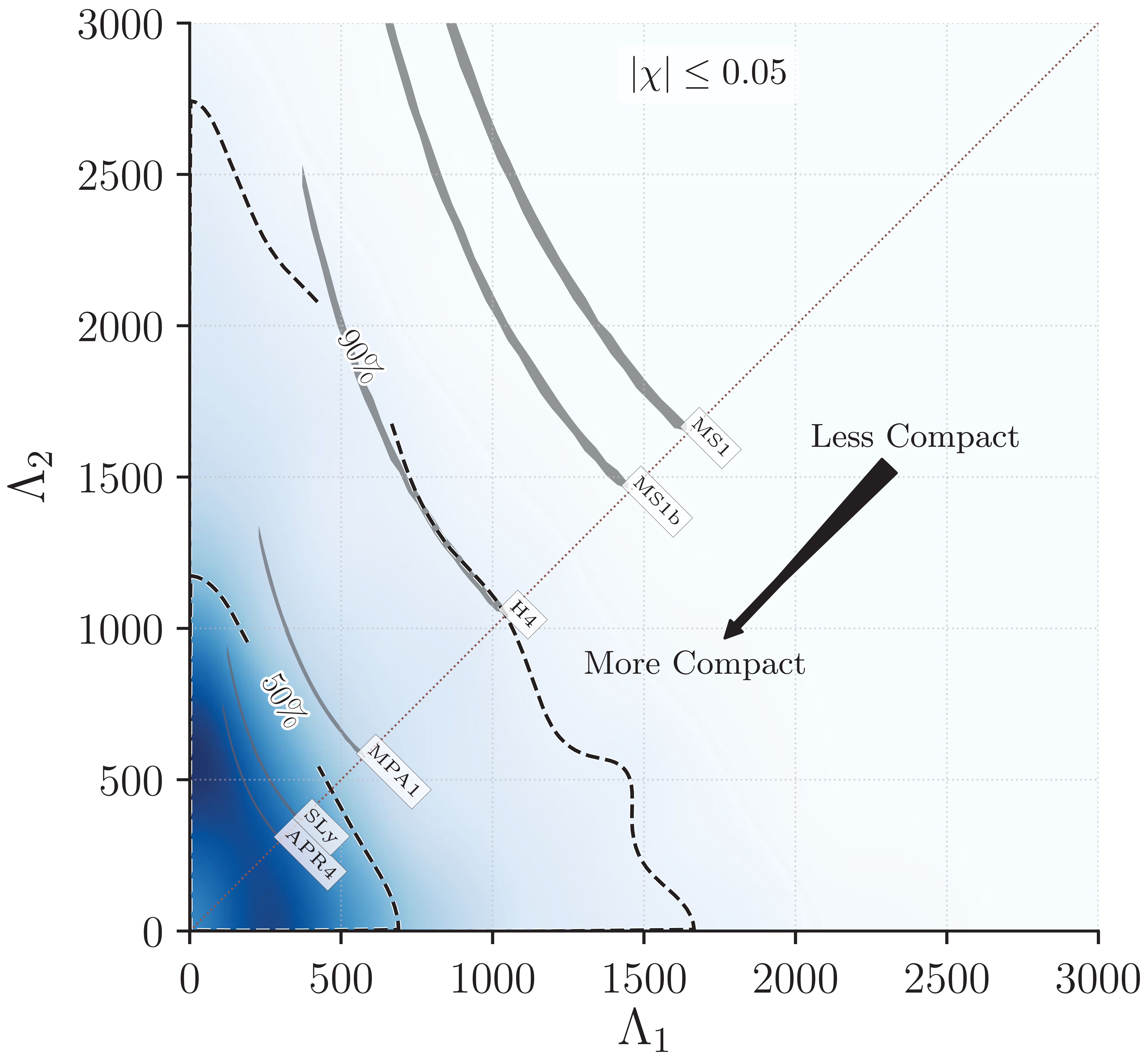
# Parameters from GW data analysis

| | |
|---|---|
| Primary mass $m_1$ | 1.36–1.60 $M_\odot$ |
| Secondary mass $m_2$ | 1.17–1.36 $M_\odot$ |
| Chirp mass $\mathcal{M}$ | $1.188^{+0.004}_{-0.002} M_\odot$ |
| Mass ratio $m_2/m_1$ | 0.7–1.0 |
| 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 $\Theta$ | $\leq 55°$ |
| Using NGC 4993 location | $\leq 28°$ |
| Combined dimensionless tidal deformability $\tilde{\Lambda}$ | $\leq 800$ |
| Dimensionless tidal deformability $\Lambda(1.4 M_\odot)$ | $\leq 800$ |

PRL 119, 161101 (2017) Selected for a Viewpoint in Physics PHYSICAL REVIEW LETTERS week ending 20 OCTOBER 2017

# GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral

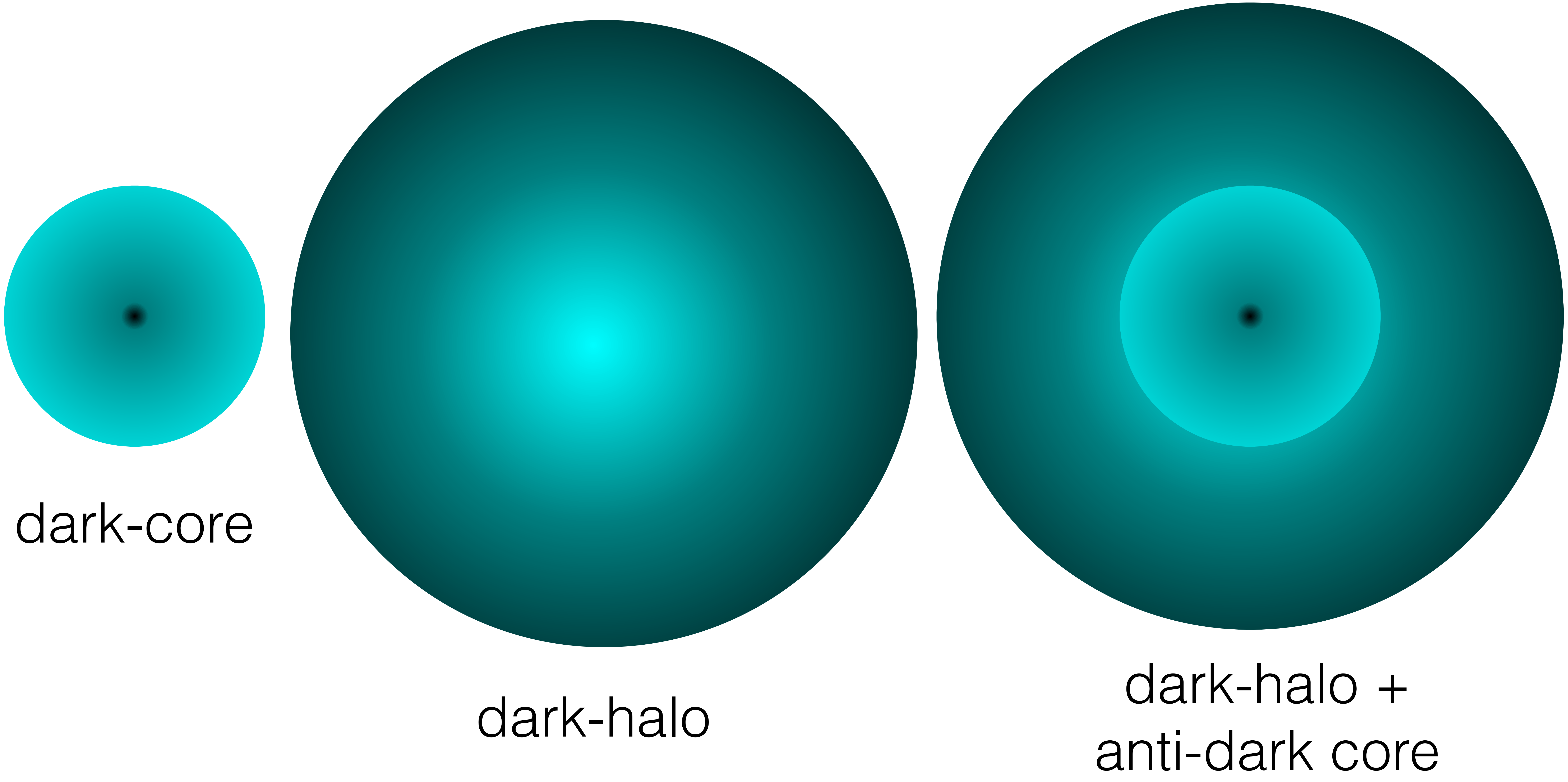
B. P. Abbott et al.*
(LIGO Scientific Collaboration and Virgo Collaboration)




- Tidal deformations were small suggesting that R < 14 km. Compatible with current dense matter theories.
- Data favors a finite tidal polarizability but cannot distinguish between radii in the range 9-13 kms.

# Dark Matter and Neutron Star Structure

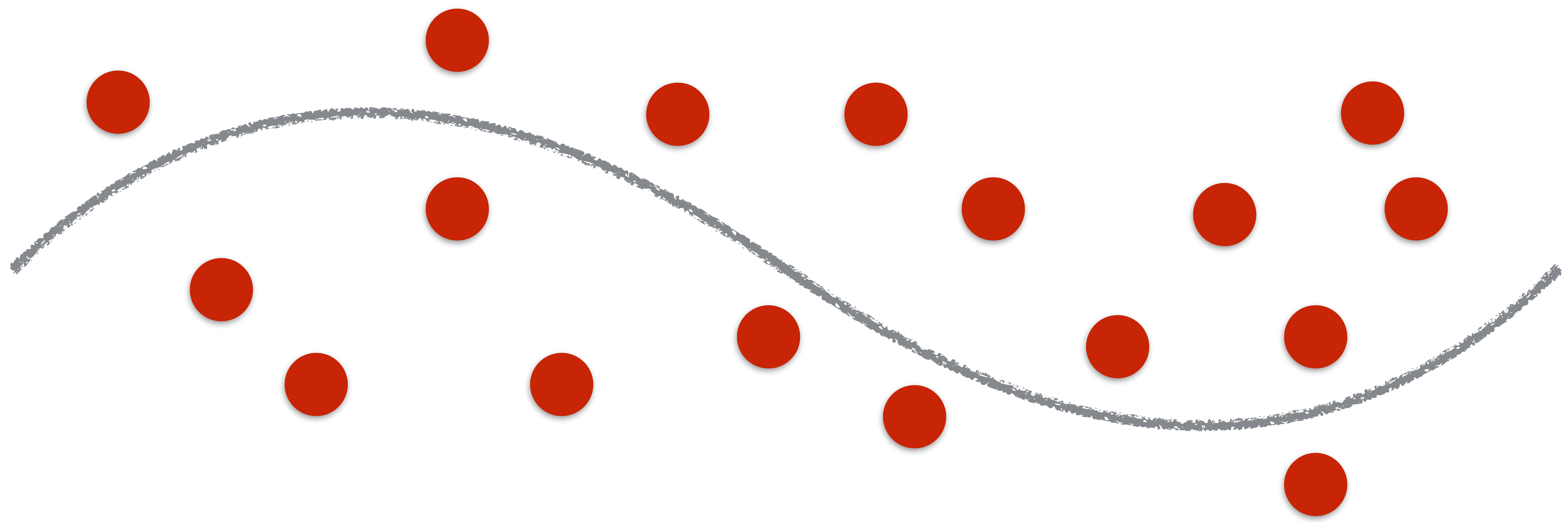
Trace amounts of dark matter can influence the structure of neutron stars.




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

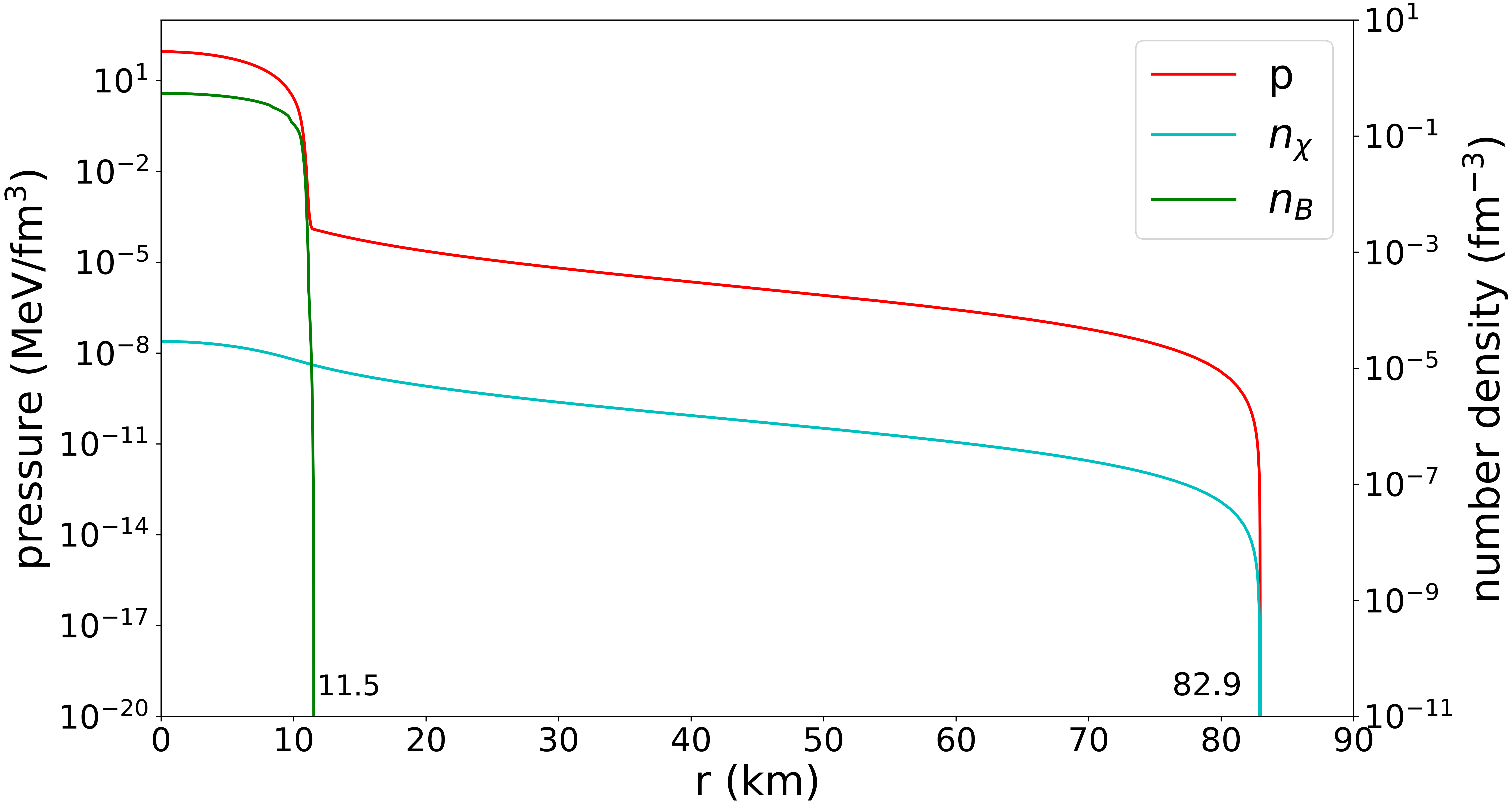
# Equation of State of Dark Matter

Energy density: $$\epsilon_\chi = \epsilon_{\text{kin}} + m_\chi n_\chi + \frac{g_\chi^2}{2m_\phi^2}\ n_\chi^2 \quad \begin{matrix} +\frac{g_\chi g_B}{m_\phi^2}\ n_B n_\chi \\ -\frac{g_\chi g_B}{m_\phi^2}\ n_B n_\chi \end{matrix}$$



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: $m_\chi$ = 100 MeV

Interactions: $g_\chi/m_\Phi$ = (0.5/MeV) or (0.5x$10^{-6}$/eV)

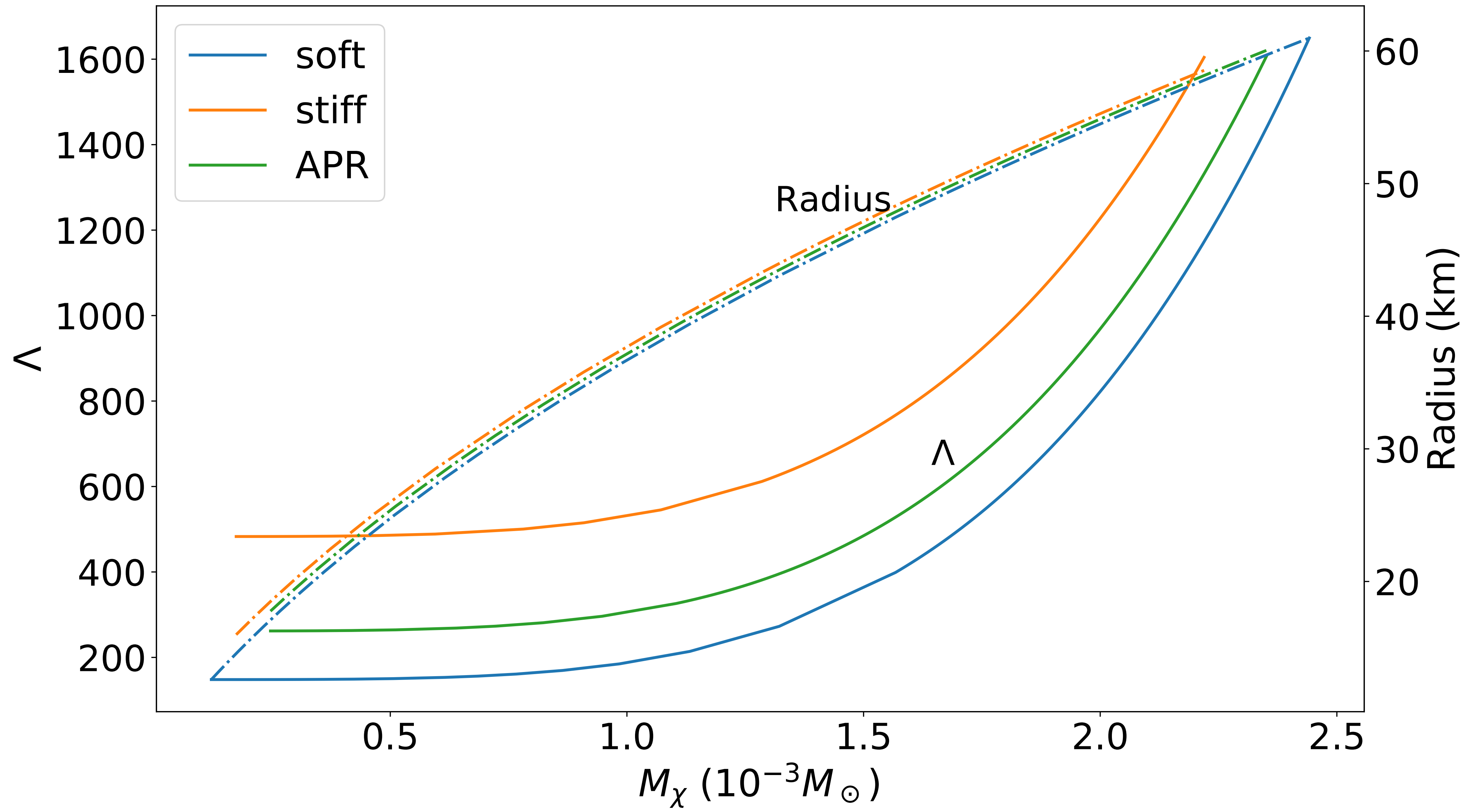
Ann Nelson, Sanjay Reddy, Dake Zhou, ArXiV:1803.03266

# For light mediators, only trace amounts are needed

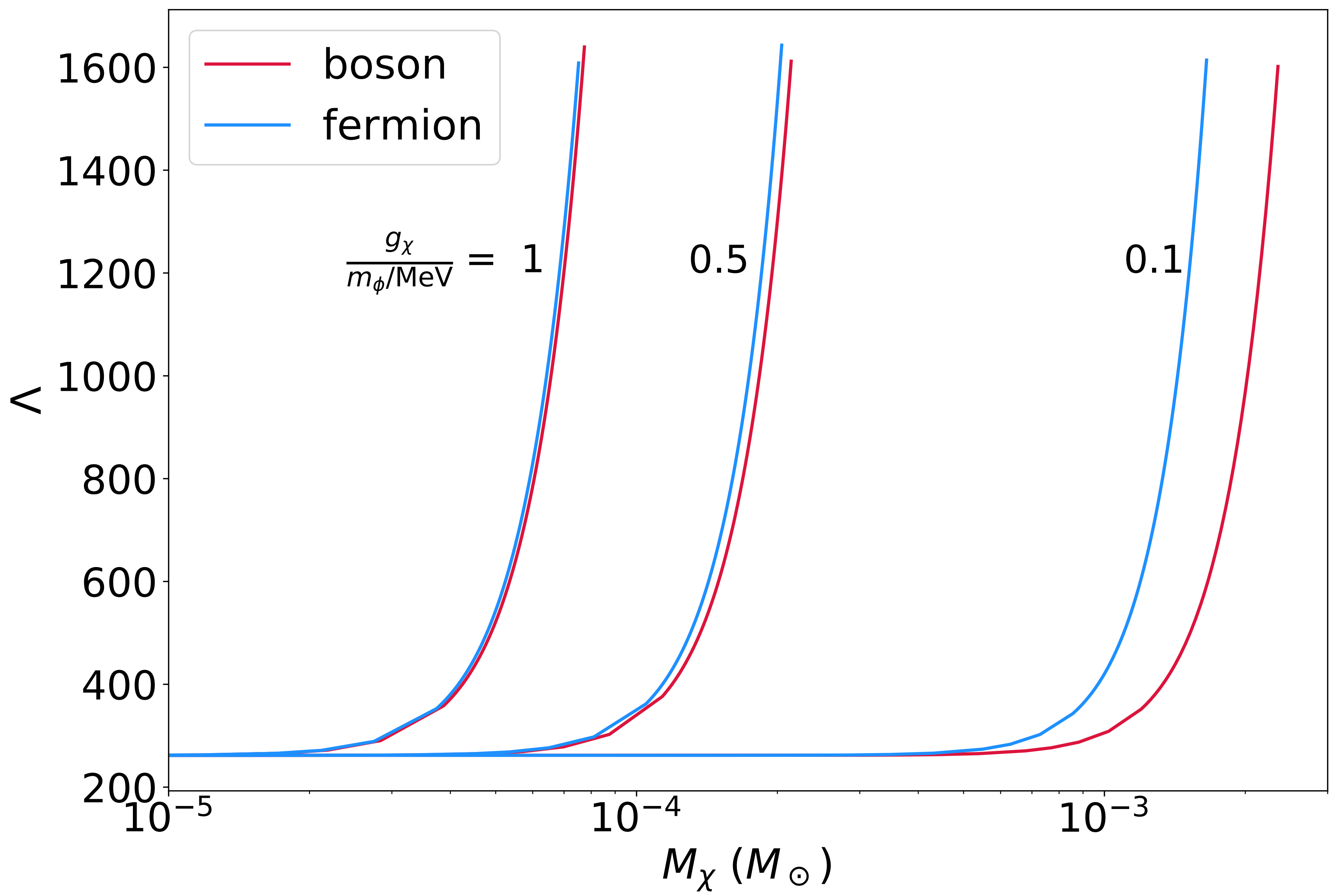
$10^{-4}$-$10^{-2}$ $M_{solar}$ is adequate to enhance $\Lambda > 800$ !

$m_\chi$ = 100 MeV

$g_\chi/m_\Phi$ = (0.1/MeV) or ($10^{-6}$/eV)




Interactions of "natural" size produce large Λ

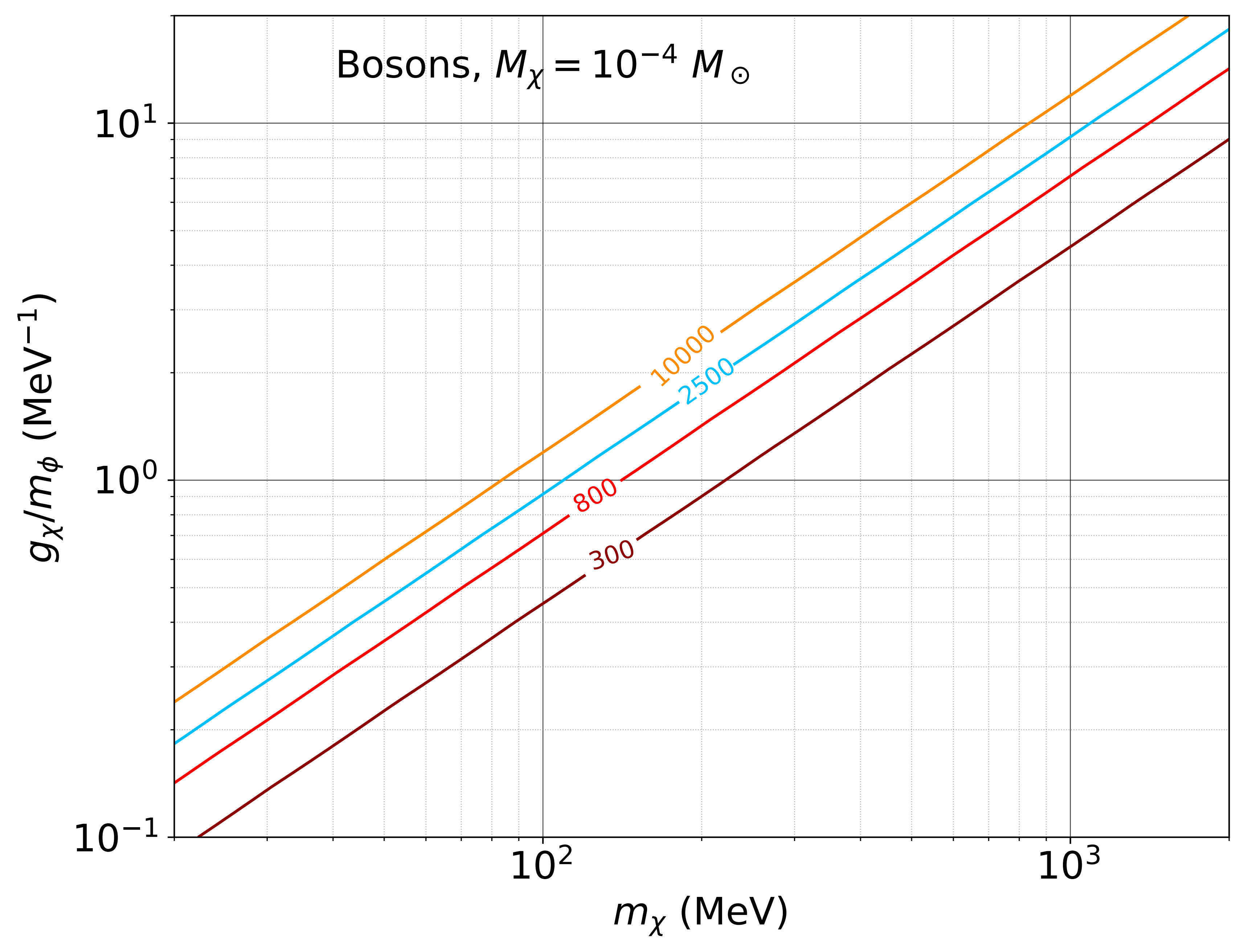


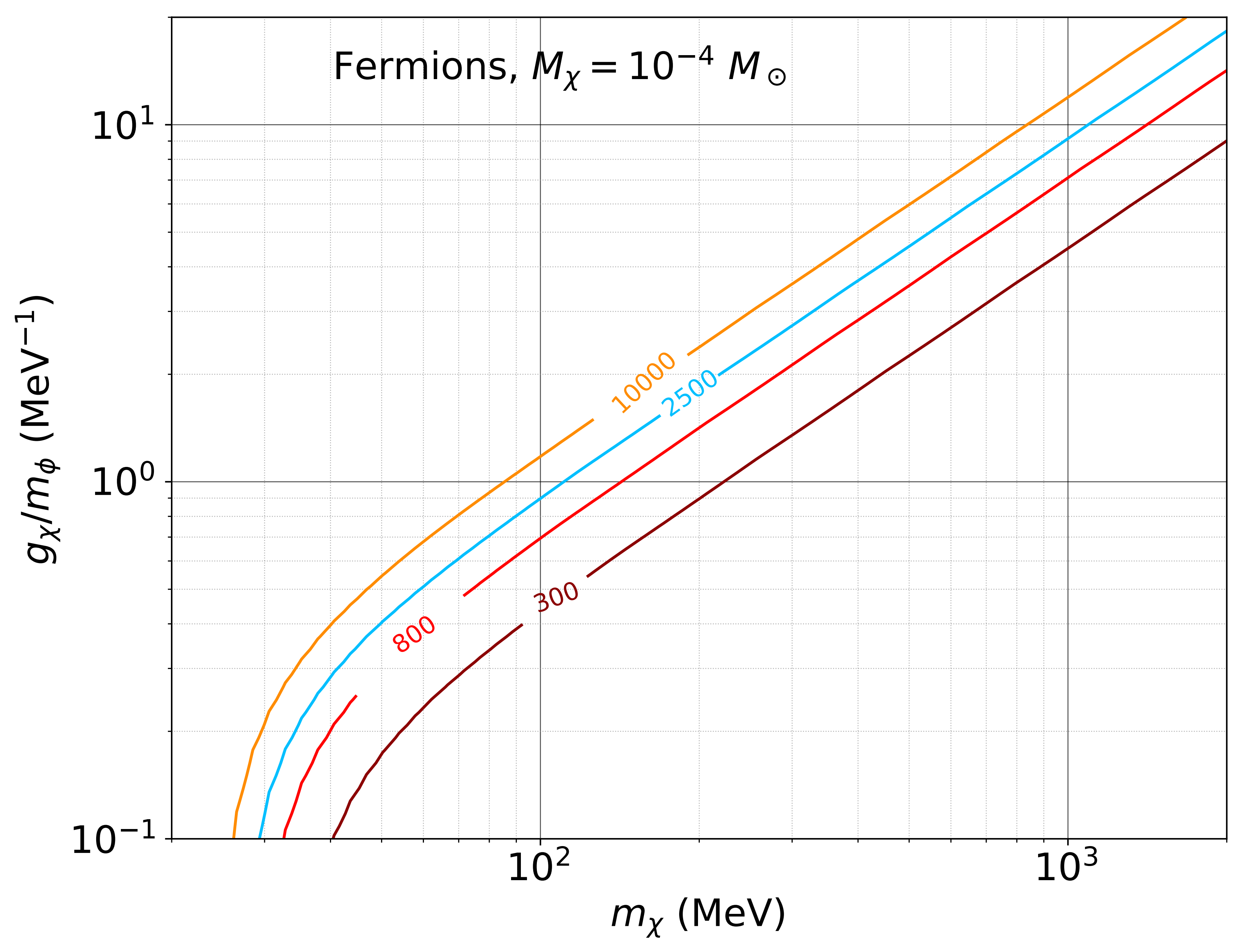

Ann Nelson, Sanjay Reddy, Dake Zhou, ArXiV:1803.03266

# If NS contain some dark matter:

GW170817 rules out regions of the light dark matter model parameter space.

Light fermions are constrained even when interactions are negligible.




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

# 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.

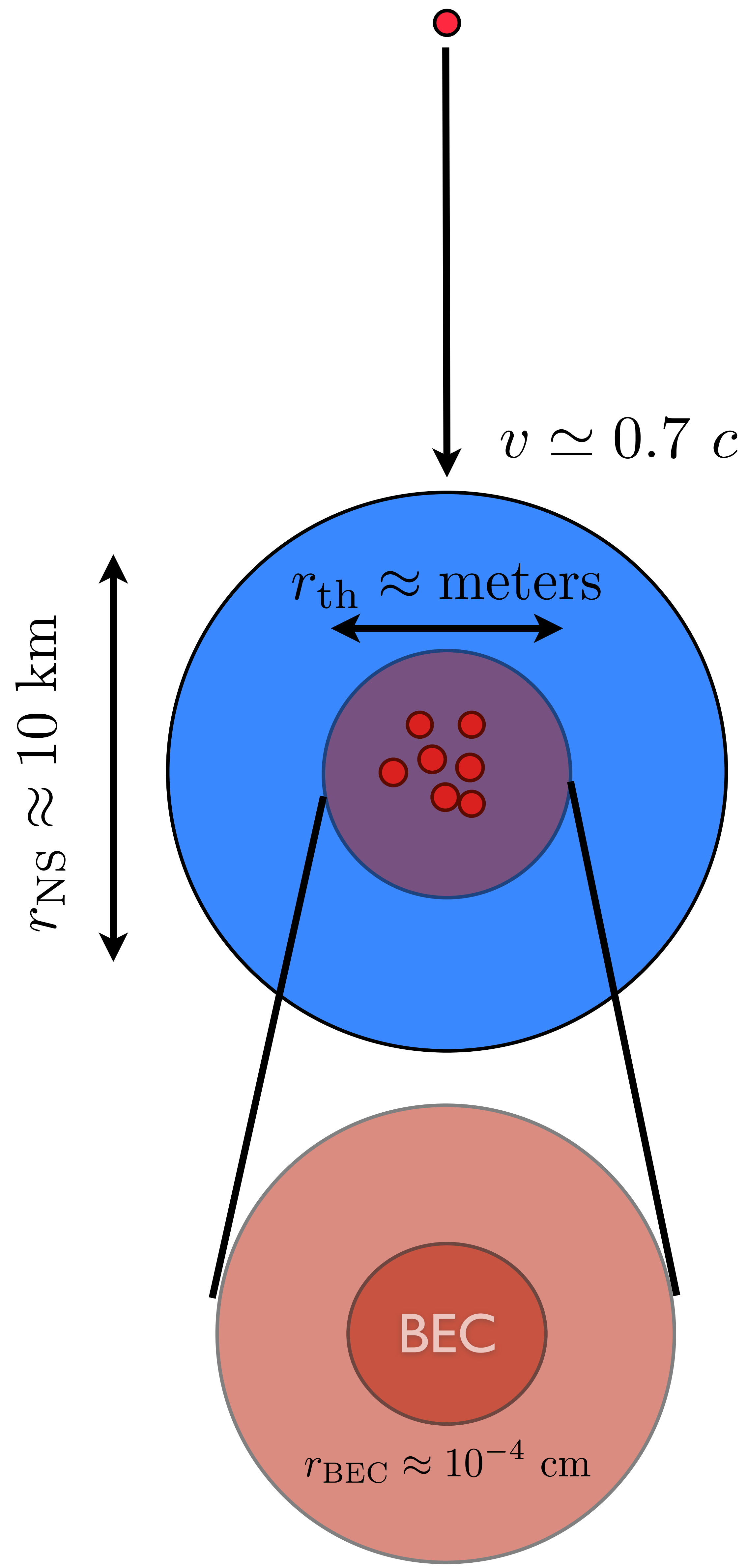
Neutron stars can accrete, inherit, or create their own dark matter. Dark matter production during supernova and mergers can be significant even for very weak coupling.

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

If Ad. LIGO suggests either large $\Lambda$ or a large variability in $\Lambda$, it may reveal the particle nature of dark matter - gravitationally ! If not, it provides useful constraints on generic dark matter models with light mediators.

# 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.

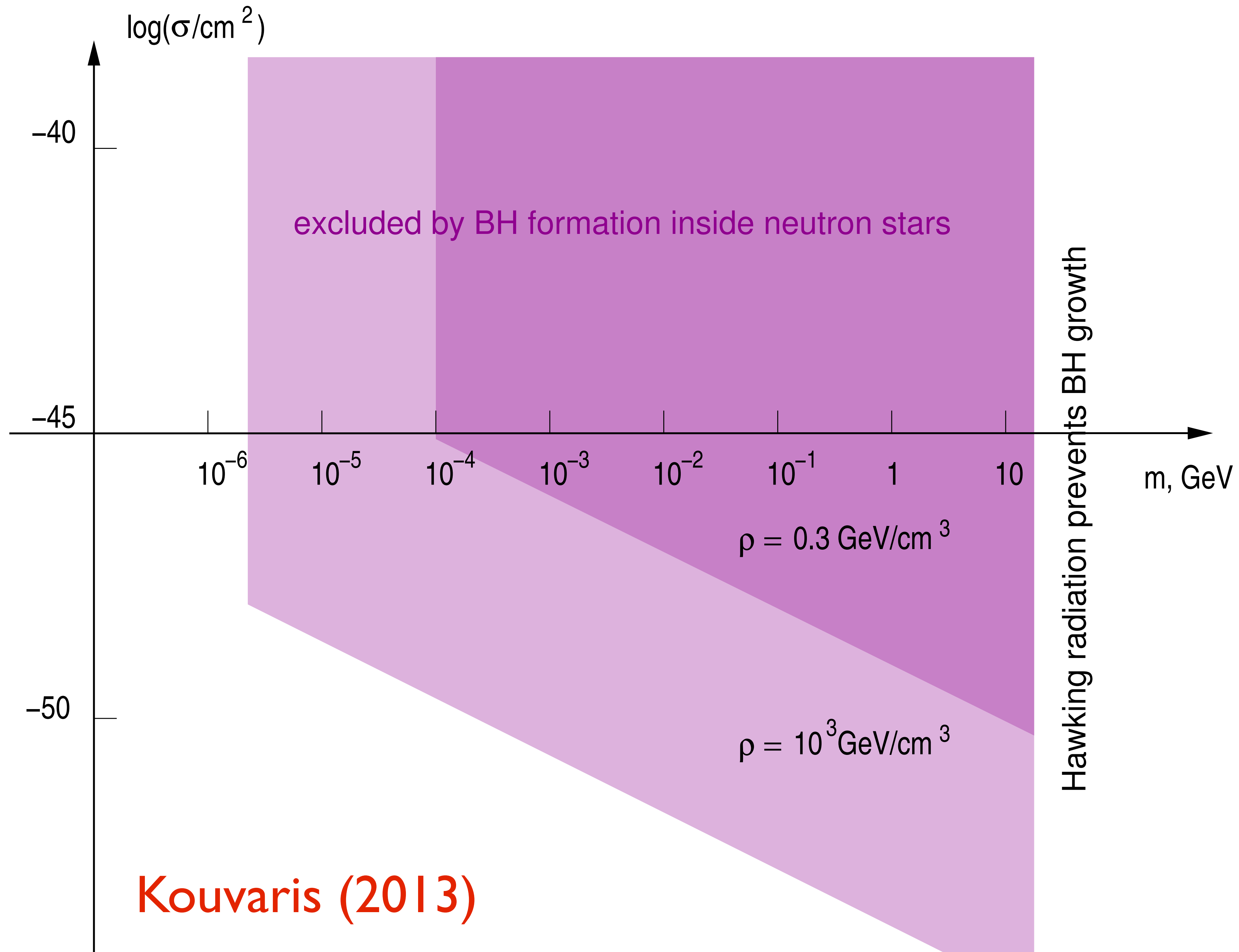
# Black-hole Formation

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:

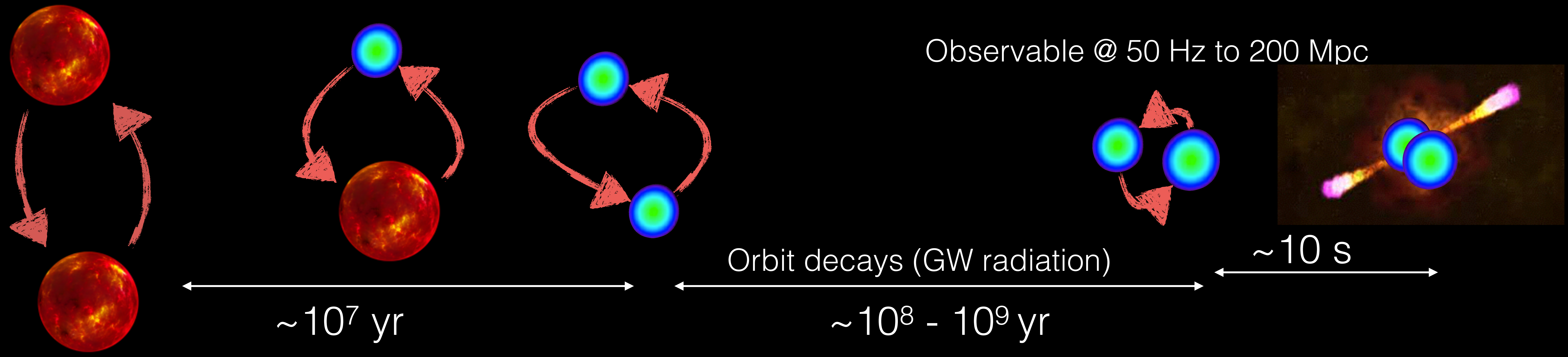
- Kouvaris and Tinyakov (2011)
- McDermott, Yu and Zurek (2012)
- Kouvaris (2012) & (2013)
- Guver, Erkoca, Reno, Sarcevic (2012)
- Fan, Yang, Chang (2012)
- Bell, Melatos and Petraki (2013)
- Jamison (2013)
- Bertoni, Nelson, Reddy (2015)

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




Kouvaris (2013)

# NS Binaries




## In the Milky Way

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

SGRB rate is $\sim$ 6 /Gpc$^3$/y

If 2/3 of SGRBs are associated with BNS mergers, the rate in Ad. LIGO at design sensitivity would be about

2 per year

after accounting for beaming.

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