Equation of State & Neutrino Interactions in Mergers

Sanjay Reddy
Institute for Nuclear Theory, University of Washington

Part I: Some Recent Results

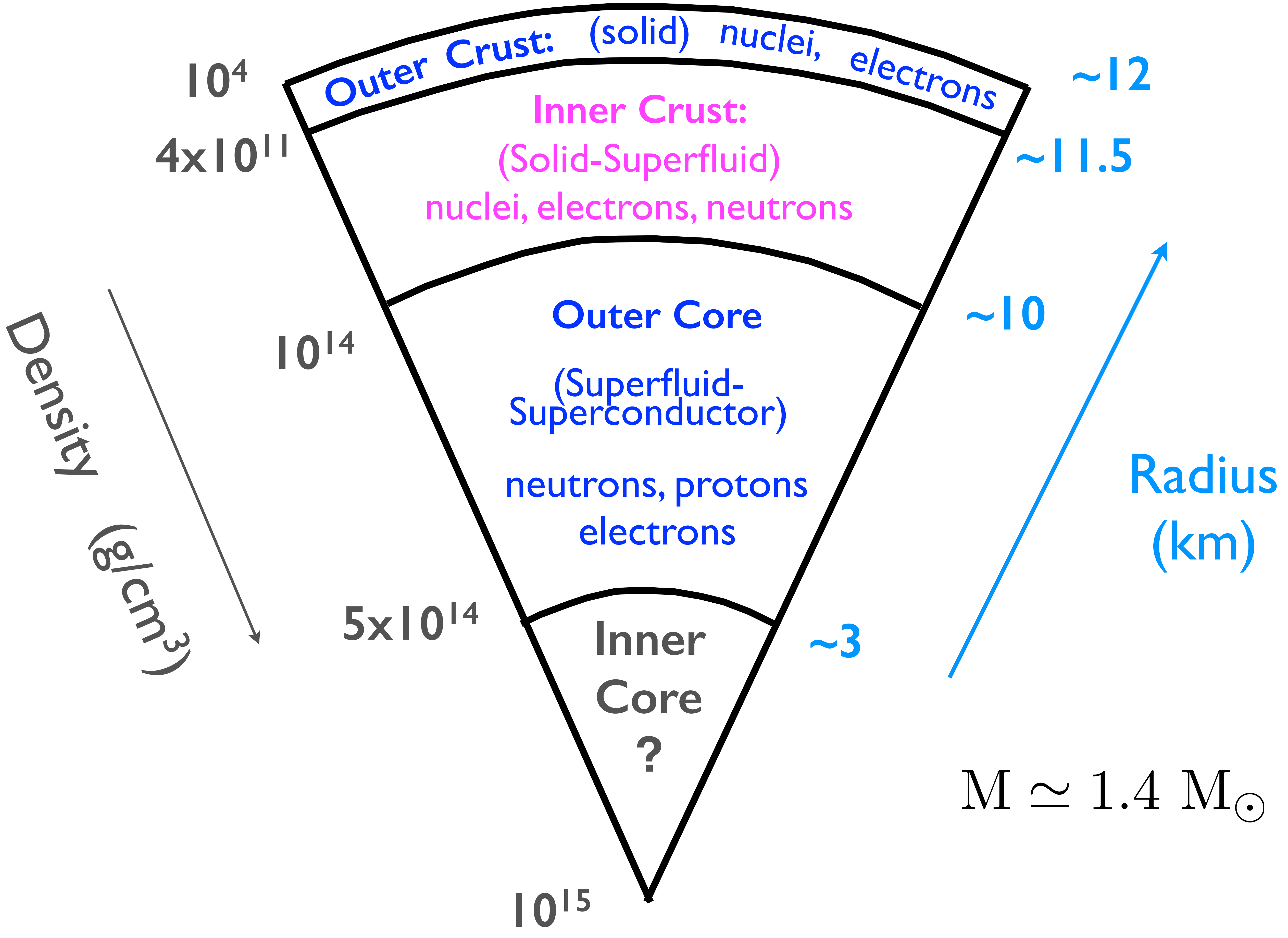
- Tidal deformability of neutron stars and cold dense matter.
- Constraining interacting dark matter with GW170817.
- Neutrino interactions at sub-nuclear density.

Part II: Discussion (Tetyana)

- EOS of hot dense matter and heavy-ion experiments.
- Specific heat, temperature and neutrino spectrum.
- Neutrino shear viscosity and bulk-viscosity.

Neutron Stars: A theorist's view

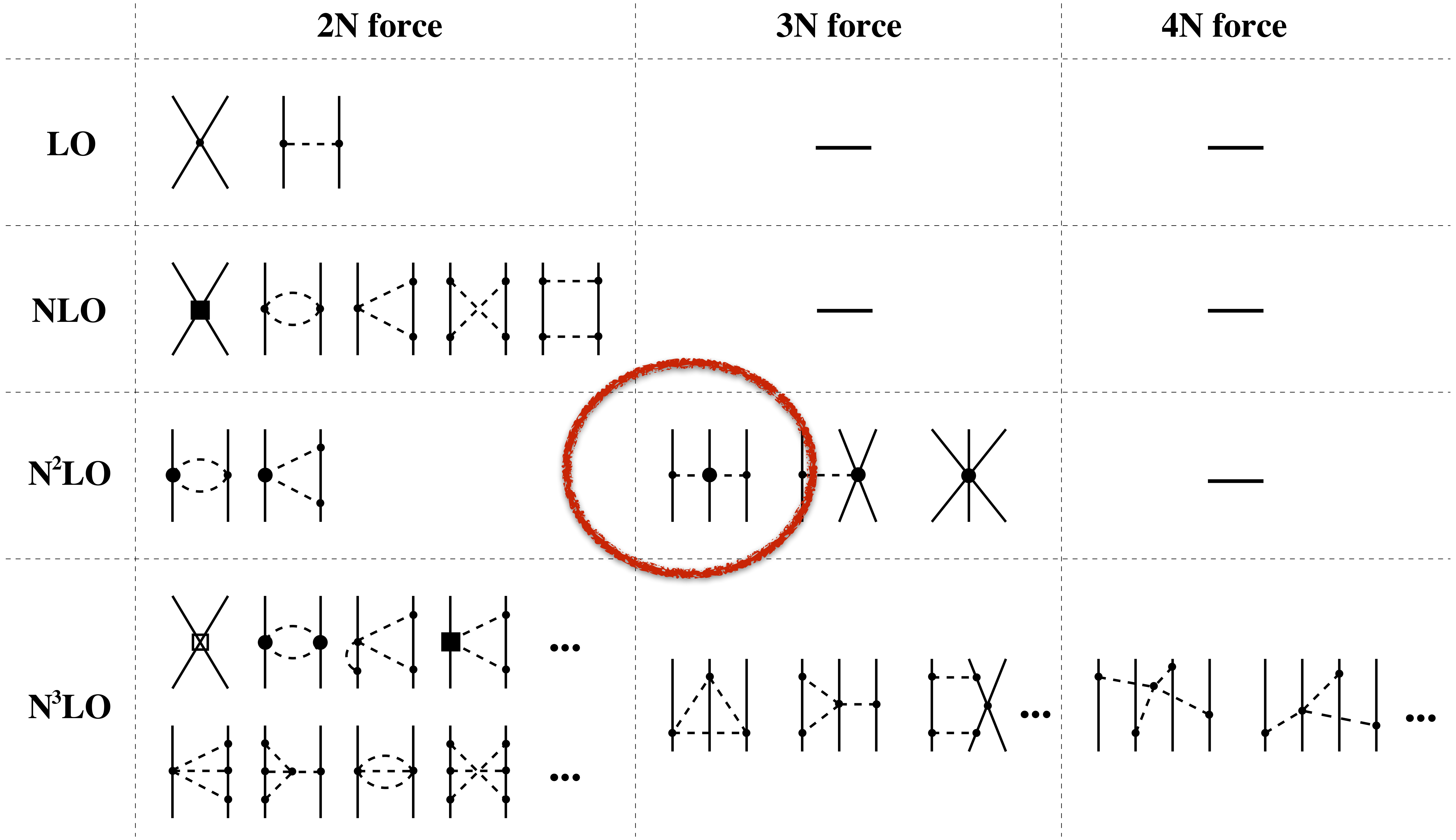
- Nuclear physics describes a large fraction of the neutron star.
- Radius is largely determined by the properties of the outer core and maximum mass by the inner core.
- The equation of state up to a few times 10^{14} g/cm^3 can be calculated.

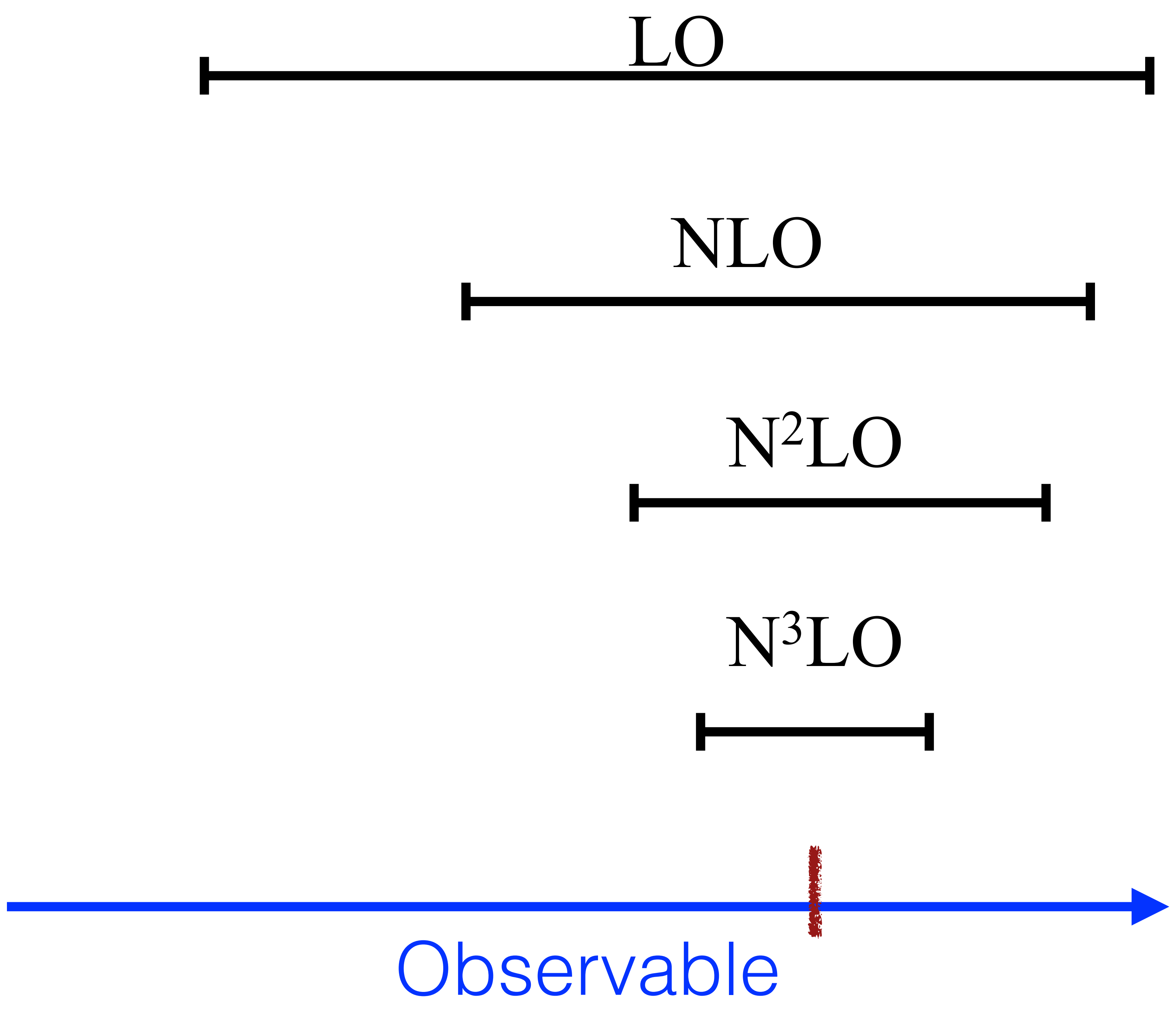


$M \simeq 1.4\ M_\odot$

Effective Field Theory: Chiral NN & NNN Forces

Organizes the nuclear Hamiltonian in powers of the momentum: $\dfrac{p}{\Lambda_B}$

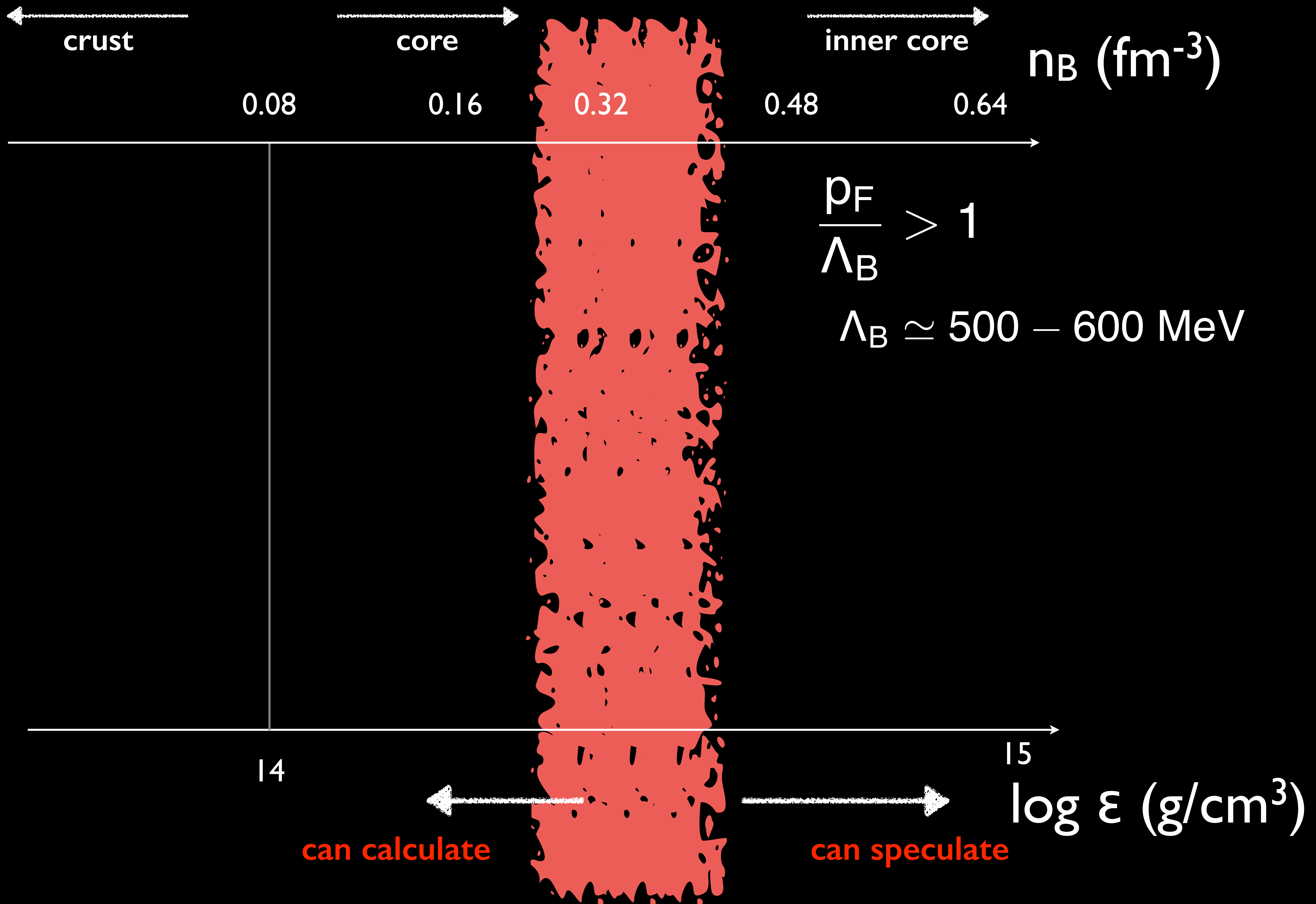




Allows for error estimation. Provides guidance for the structure of three and many-body forces.

Beane, Bedaque, Epelbaum, Kaplan, Machliedt, Meisner, Phillips, Savage, van Klock, **Weinberg**, Wise ..

The limits of nuclear theory



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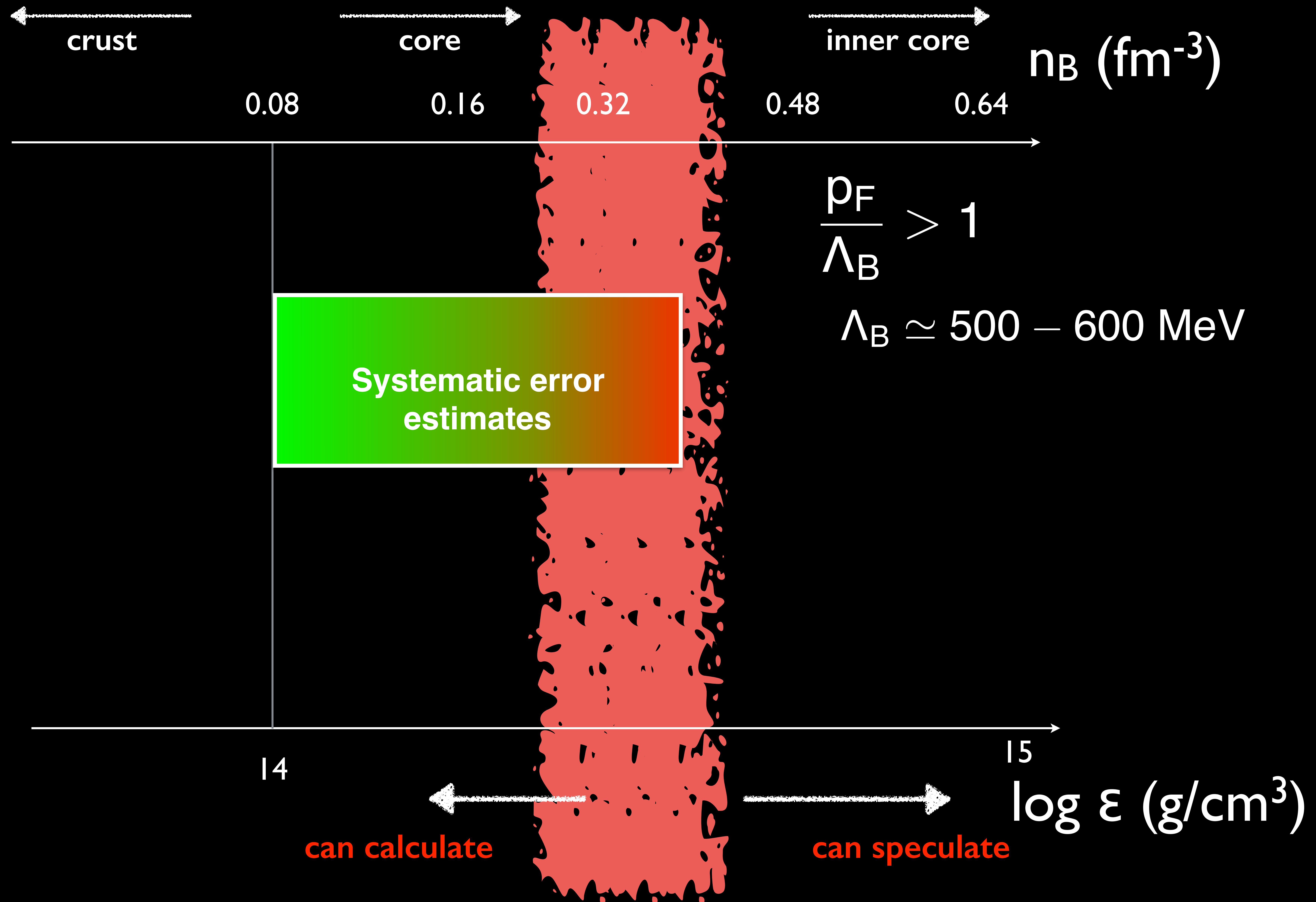
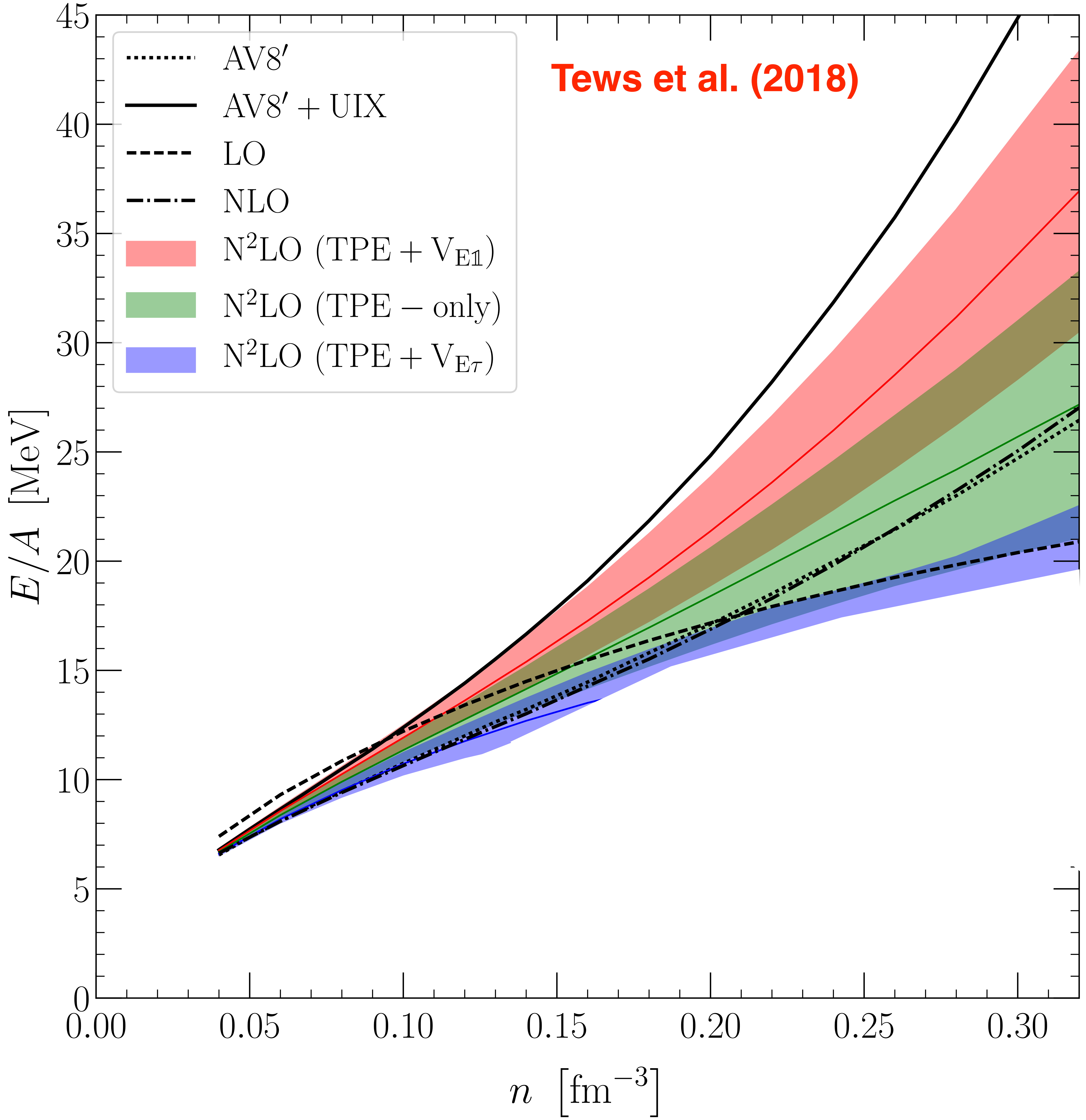


Equation of State of Neutron Matter

Reliable calculations of neutron matter are now possible using QMC and EFT inspired Hamiltonians.

Order-by-order convergence is good at $n=0.16\ \mathrm{fm}^{-3}$ and reasonable at $n=0.32\ \mathrm{fm}^{-3}$.

	$n=0.16\ \mathrm{fm}^{-3}$	$n=0.32\ \mathrm{fm}^{-3}$
Energy (MeV)	15 ± 3	30 ± 15
Pressure ($\mathrm{MeV/fm}^{-3}$)	2.2 ± 1.5	10 ± 8



Hebeler and Schwenk 2009, Tews, Kruger, Hebeler, Schwenk (2013), Holt Kaiser, Weise (2013), Roggero, Mukherjee, Pederiva (2014), Wlazlowski, Holt, Moroz, Bulgac, Roche (2014), Tews et al. (2018)

Does the EFT remain useful at twice saturation density?

		free	pheno.	LO	NLO	N^2LO (TPE-only)
P	n_0	3.7	3.3	$1.3 \pm 0.7\,(1.1)$	$1.6 \pm 0.4\,(0.8)$	$1.8 \pm 0.2\,(0.5)$
(MeV/fm^3)	$2n_0$	11.9	25.8	$3.1 \pm 3.7\,(6.1)$	$9.8 \pm 4.4\,(5.6)$	$7.8 \pm 2.8\,(4.7)$

uncertainty $\Delta X^{\mathrm{N^2LO}}$ at order N^{2}LO is given by

$$\Delta X^{\mathrm{N^2LO}} = \max\left(Q^4 \left|X^{\mathrm{LO}} - X^{\mathrm{free}}\right|, Q^2 \left|X^{\mathrm{NLO}} - X^{\mathrm{LO}}\right|, Q \left|X^{\mathrm{N^2LO}} - X^{\mathrm{NLO}}\right|\right)$$

$$Q = \frac{\alpha\, p_F}{\Lambda_B} \qquad \alpha = 0.75\text{-}1 \qquad \Lambda_B = 500 \text{ MeV}$$

$$p_F(n_0) = 331 \text{ MeV}$$
$$p_F(2n_0) = 417 \text{ MeV}$$

Does the EFT remain useful at twice saturation density?

		free	pheno.	LO	NLO	$\mathrm{N}^2\mathrm{LO}$ (TPE-only)	$\mathrm{N}^2\mathrm{LO}$ $(+\,V_{E,\mathbb{1}})$	$\mathrm{N}^2\mathrm{LO}$ $(+V_{E,\tau})$
P	n_0	3.7	3.3	$1.3 \pm 0.7\,(1.1)$	$1.6 \pm 0.4\,(0.8)$	$1.8 \pm 0.2\,(0.5)$	$2.4 \pm 0.4\,(0.6)$	$1.1 \pm 0.3\,(0.5)$
(MeV/fm^3)	$2n_0$	11.9	25.8	$3.1 \pm 3.7\,(6.1)$	$9.8 \pm 4.4\,(5.6)$	$7.8 \pm 2.8\,(4.7)$	$15.1 \pm 3.4\,(4.7)$	$-2.6 \pm 8.1\,(10.4)$

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E/A	n_0	35.1	19.1	$15.5 \pm 5.2\,(8.6)$	$14.3 \pm 2.7\,(5.7)$	$15.6 \pm 1.4\,(3.8)$	$17.3 \pm 1.5\,(3.8)$	$13.5 \pm 1.4\,(3.8)$
	$2n_0$	55.7	49.9	$20.9 \pm 14.6\,(24.3)$	$27.0 \pm 9.4\,(20.3)$	$27.2 \pm 6.1\,(16.9)$	$36.9 \pm 6.4\,(16.9)$	$14.3 \pm 8.2\,(16.9)$
P	n_0	3.7	3.3	$1.3 \pm 0.7\,(1.1)$	$1.6 \pm 0.4\,(0.8)$	$1.8 \pm 0.2\,(0.5)$	$2.4 \pm 0.4\,(0.6)$	$1.1 \pm 0.3\,(0.5)$
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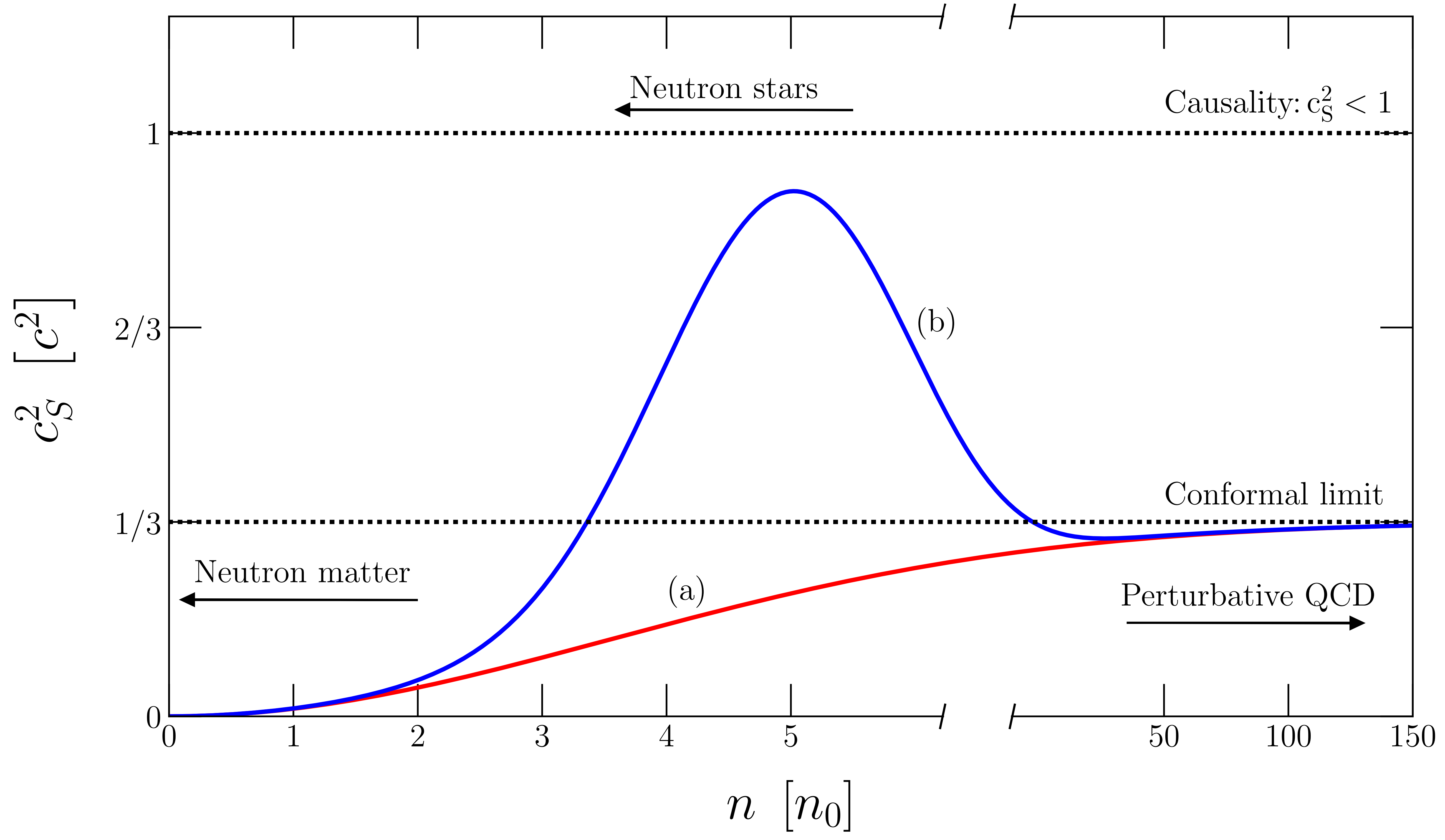
Parametrizing the high density EOS: Speed of sound

Parameterizing the high density EOS with arbitrary density dependence of the speed of sound (chosen to be between 0-1) is:

1. Convenient
2. Physical
3. Avoids artificial discontinuities associated with matching polytropes.
4. Allows to make easier connections to heavy-ion experiments (which probe hydrodynamic evolution).

Small NS radii (R< 13 km) together with a maximum mass > 2 M_{solar} and neutron matter and pQCD constraints suggest that the speed of sound is not a monotonically increasing function of density! (Bedaque & Steiner (2017))



Tews, Carlson, Gandolfi & Reddy (2018)

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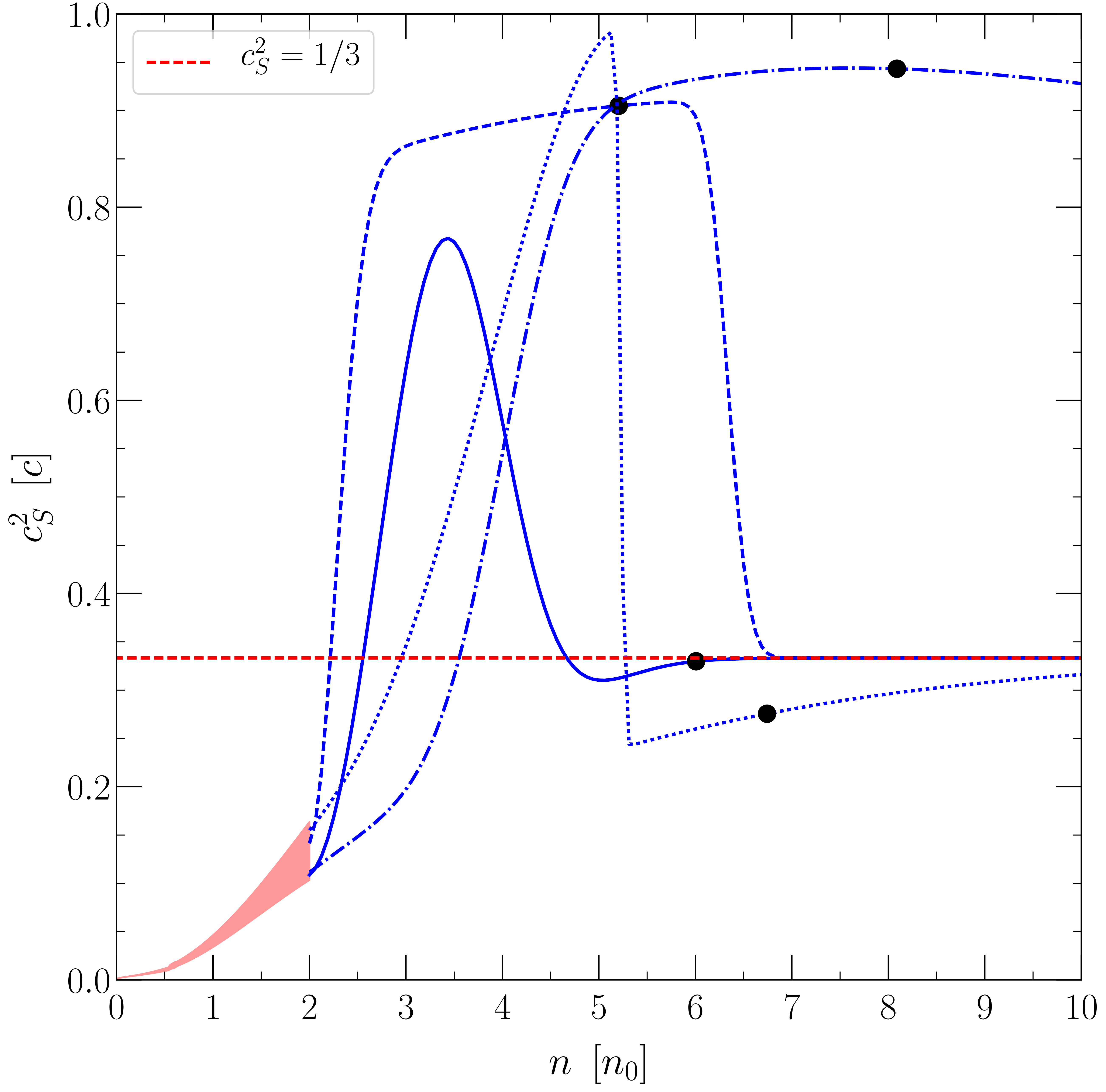


Tews, Carlson, Gandolfi & Reddy (2018)

Dense matter EOS and NS structure

Neutron matter calculations and a sound speed at higher density constrained only by 2 solar mass NS and causality provide useful constraints on NS properties. We call this the speed of sound model (CSM). It encompasses all possibilities consistent with EFT calculations of neutron matter.

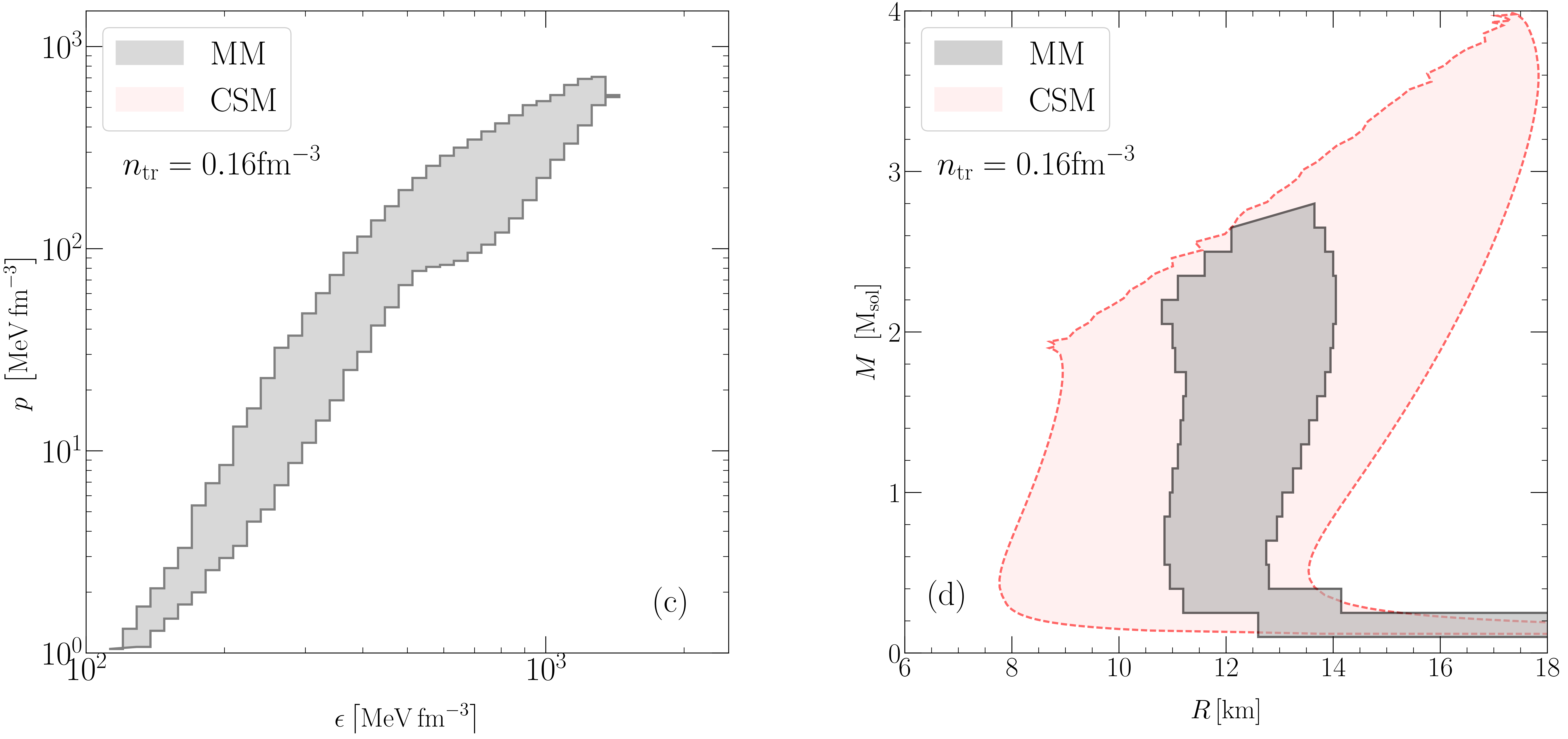
EFT error estimates (albeit large) at twice saturation density provides useful constraints:

$R_{1.4} = 9.5 - 12.5$ km

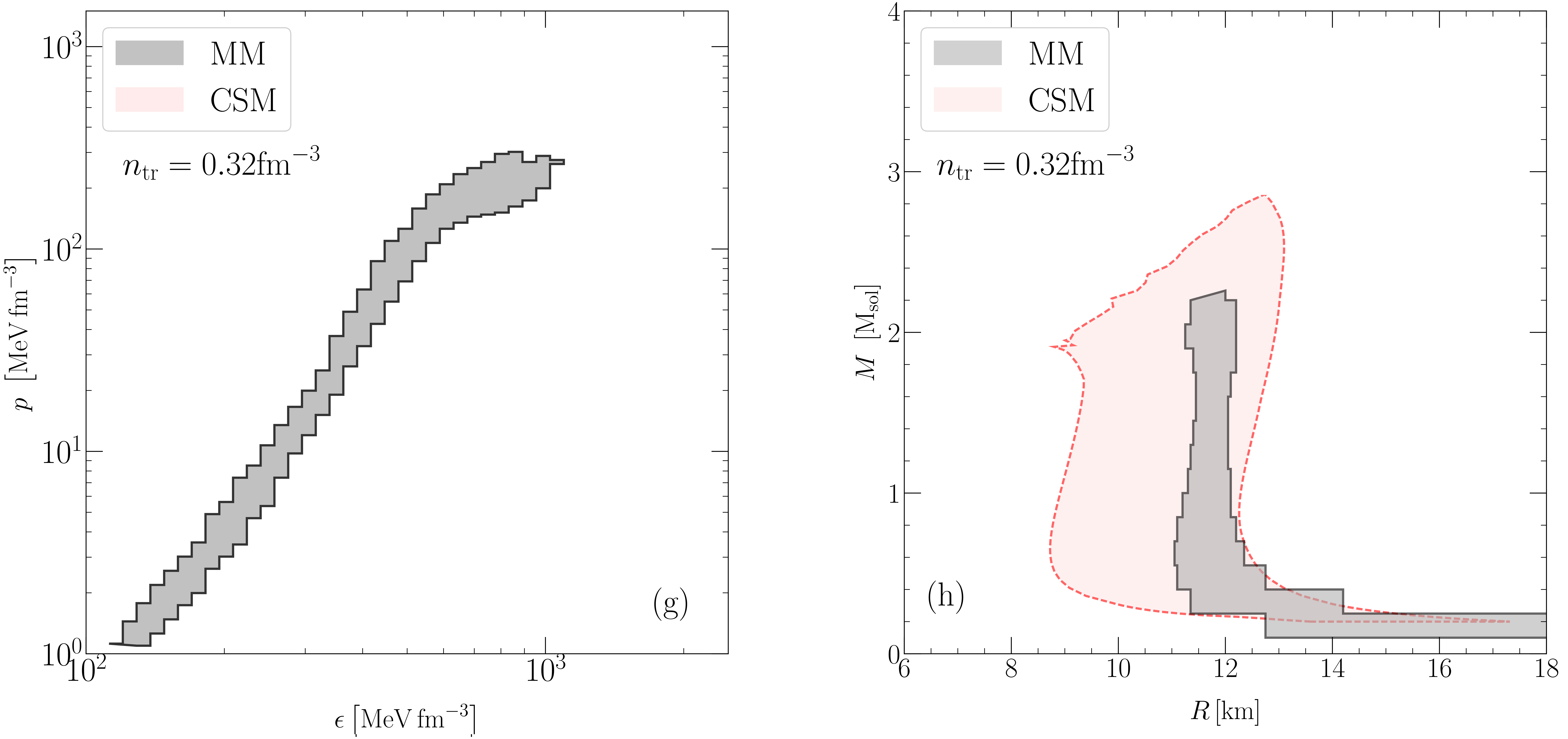
$M_{max} = 2.0 - 2.8\ M_{solar}$

Assumptions about a “smooth” EOS from two to four times saturation density provides more stringent constraints on the mass-radius curves. We call this the minimal model (MM). Smoothness is defined by a fourth order Taylor expansion about saturation density.

Tews, Gandolfi, Carlson, Reddy (2018), Tews, Margueron, Reddy (2018)
see also Hebeler, Schwenk, Lattimer and Pethick (2010,2013) and Carlson, Gandolfi, Reddy (2012)



MM
CSM
$n_{\rm tr} = 0.16{\rm fm}^{-3}$
(c)
p [MeV fm^{-3}]
ϵ [MeV fm^{-3}]
10^0
10^1
10^2
10^3
MM
CSM
$n_{\rm tr} = 0.16{\rm fm}^{-3}$
(d)
M [M$_{\rm sol}$]
R [km]
0
1
2
3
4
6
8
10
12
14
16
18

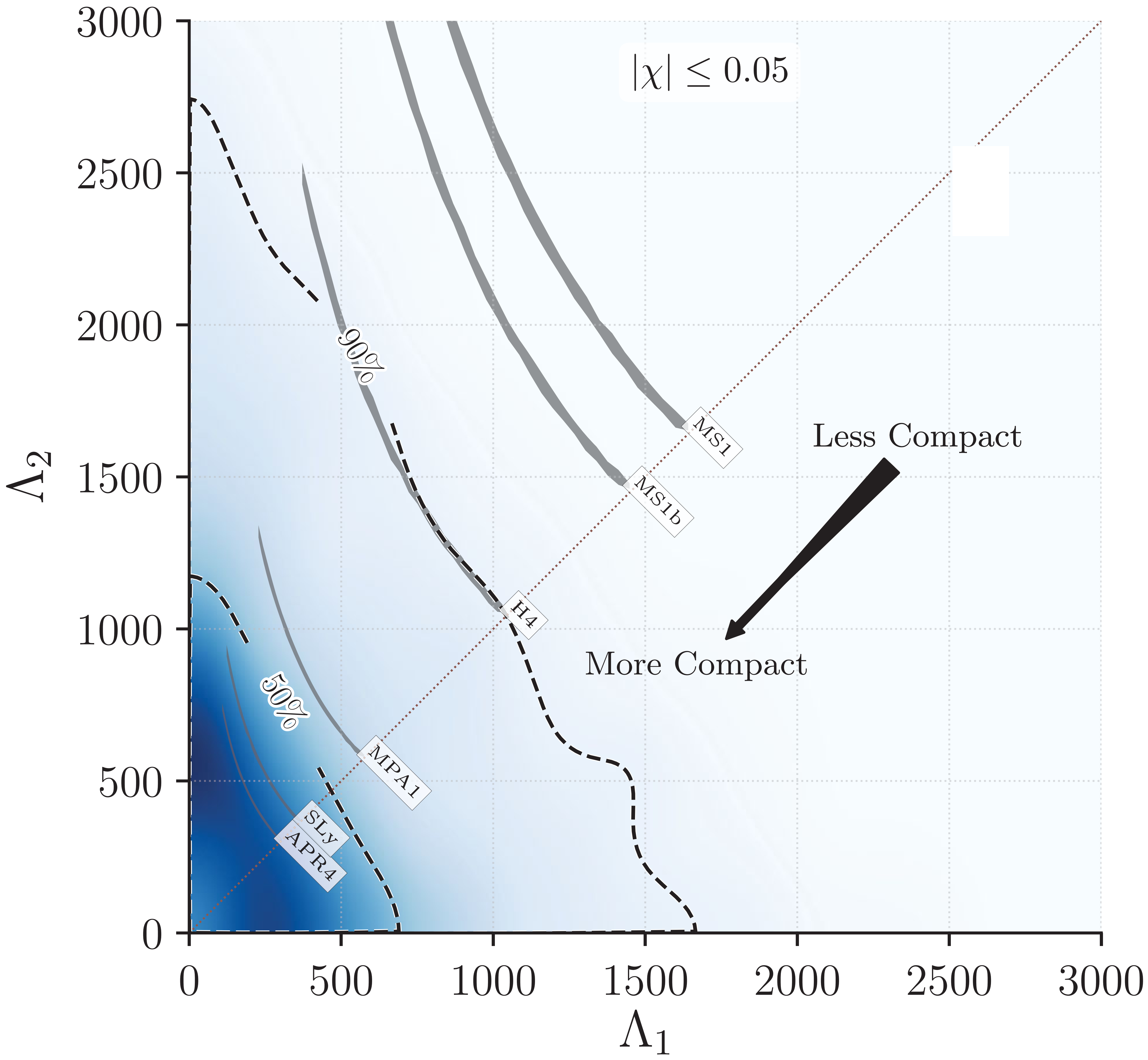


MM
CSM
$n_{\mathrm{tr}} = 0.32\mathrm{fm}^{-3}$
$p\ [\mathrm{MeV\ fm}^{-3}]$
$\epsilon\ [\mathrm{MeV\ fm}^{-3}]$
10^0
10^1
10^2
10^3
(g)
MM
CSM
$n_{\mathrm{tr}} = 0.32\mathrm{fm}^{-3}$
$M\ [\mathrm{M_{sol}}]$
$R\ [\mathrm{km}]$
0
1
2
3
4
6
8
10
12
14
16
18
(h)

Selected for a Viewpoint in *Physics*
PRL **119,** 161101 (2017) 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 < 13.5 km. Compatible with current dense matter theories.

- Data favors a finite tidal polarizability.

- GW170817 excludes EOS that are incompatible with ab initio calculations of neutron matter up to twice nuclear density.

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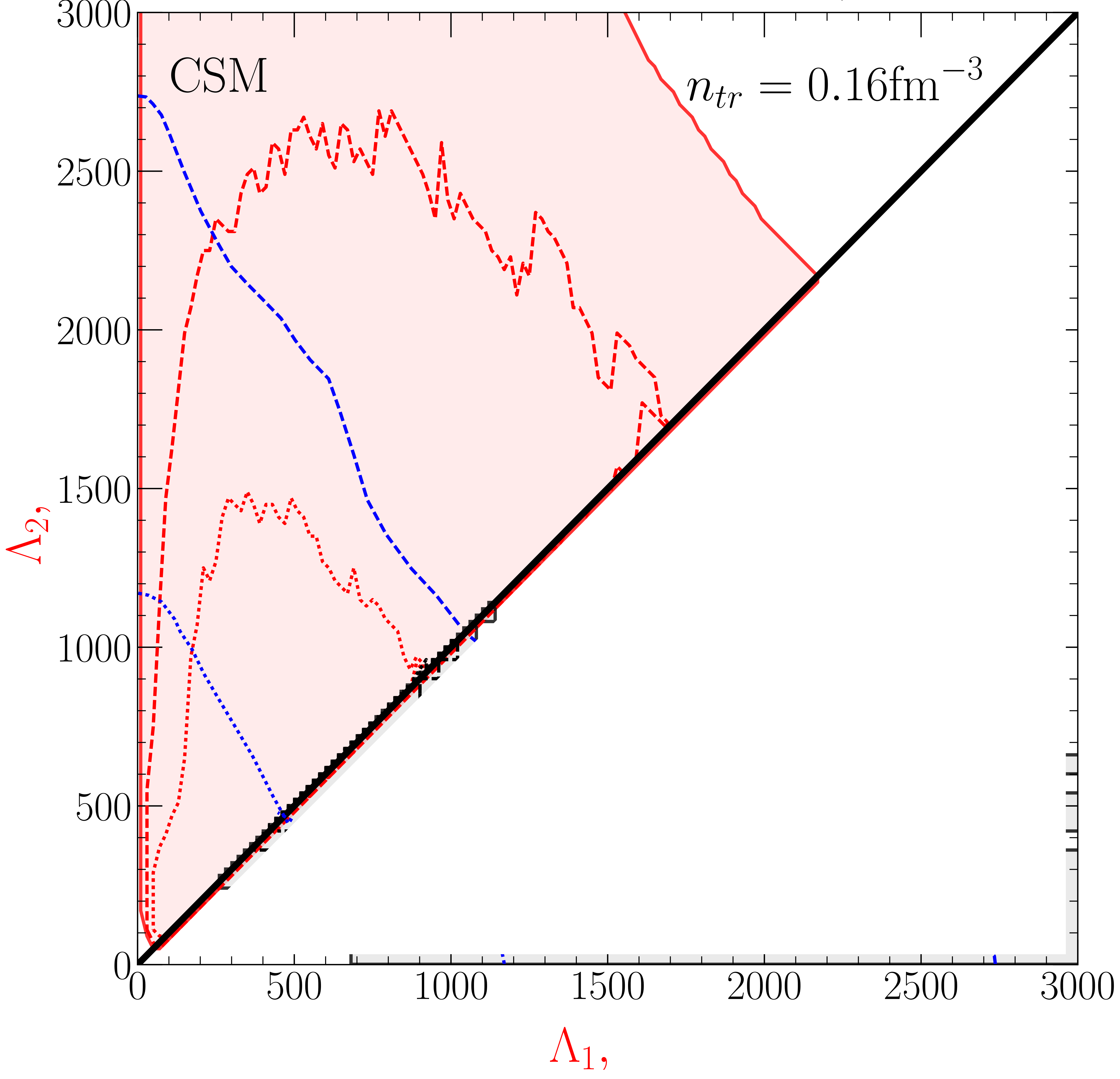

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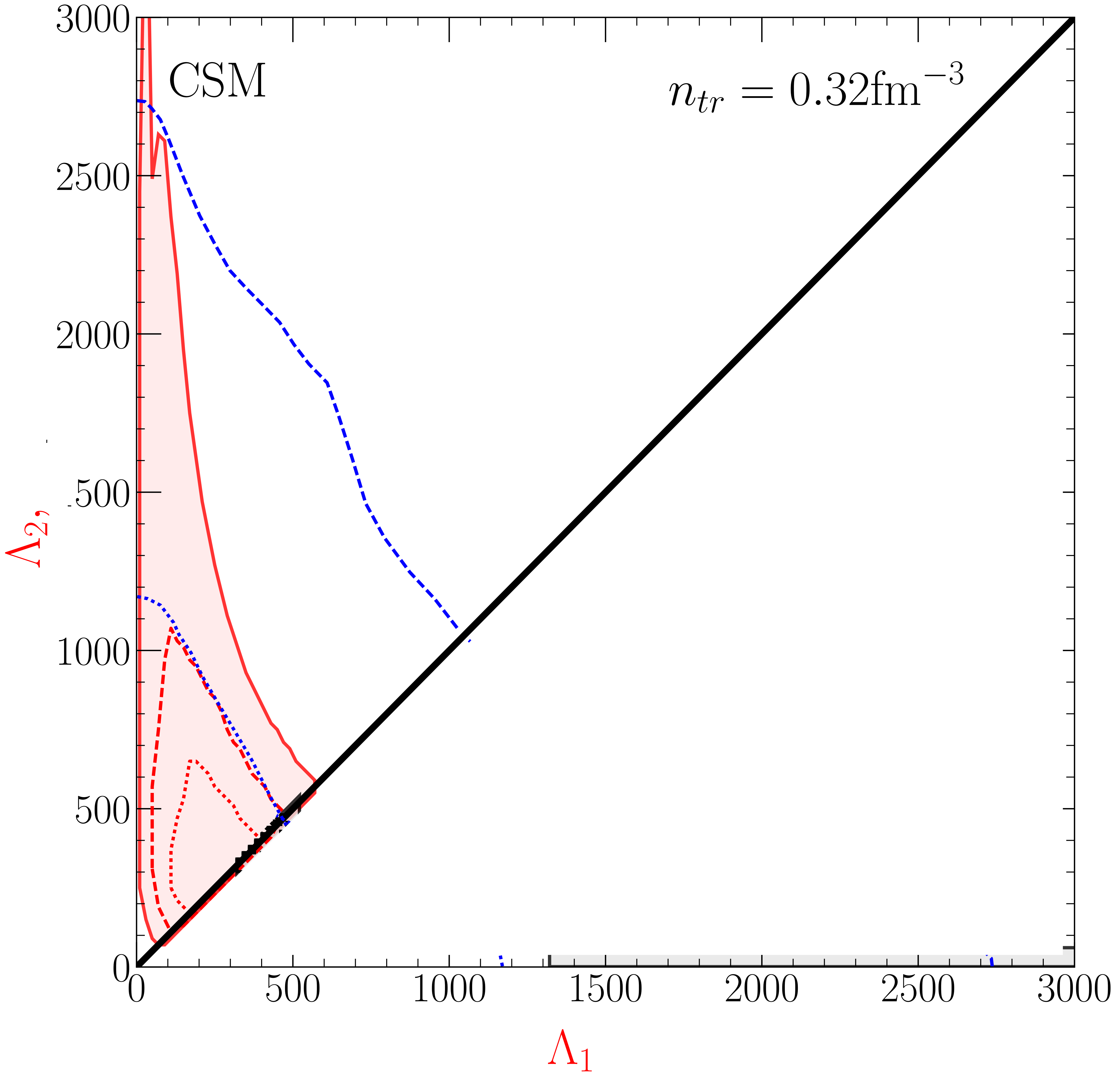

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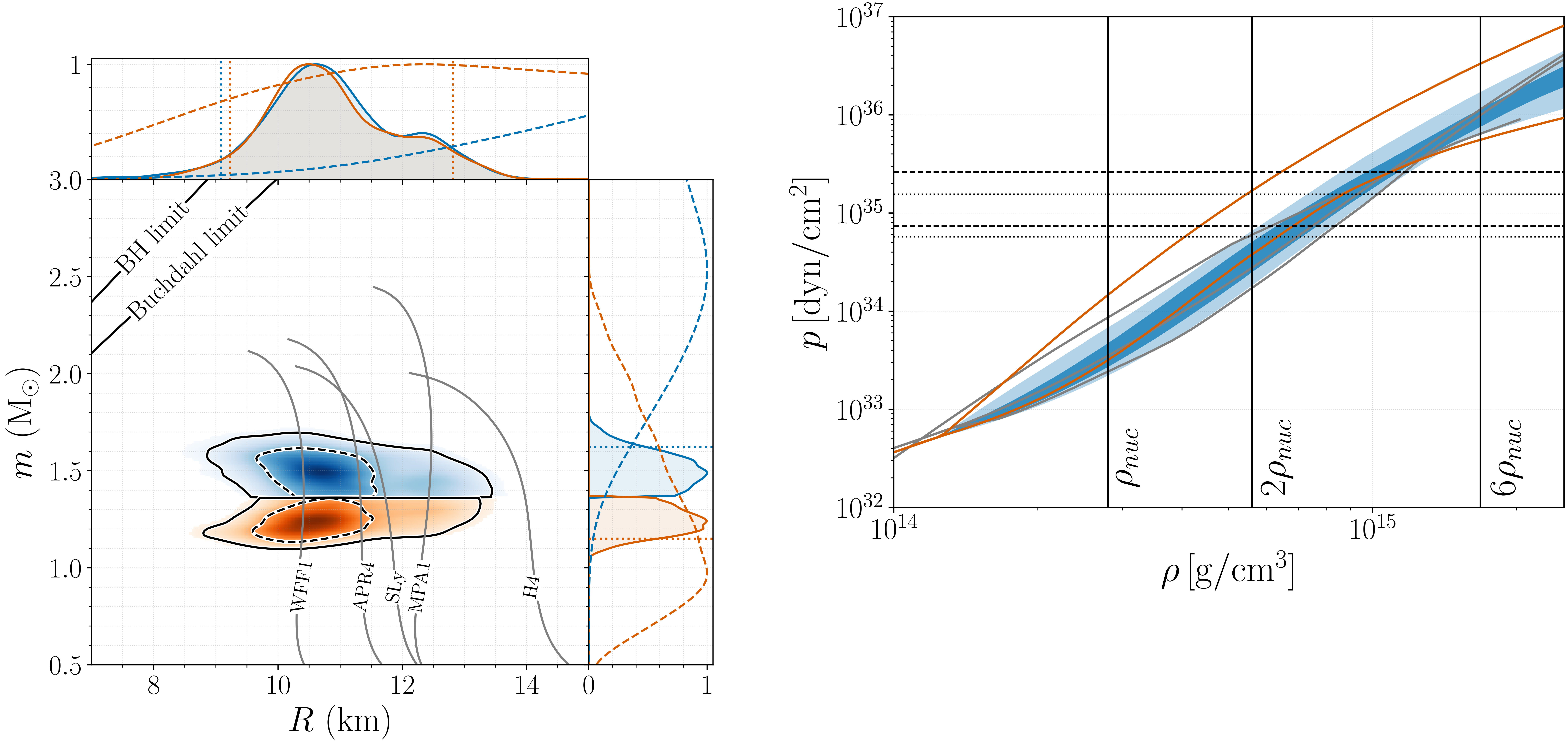
The LIGO Scientific Collaboration and The Virgo Collaboration

(compiled 30 May 2018)



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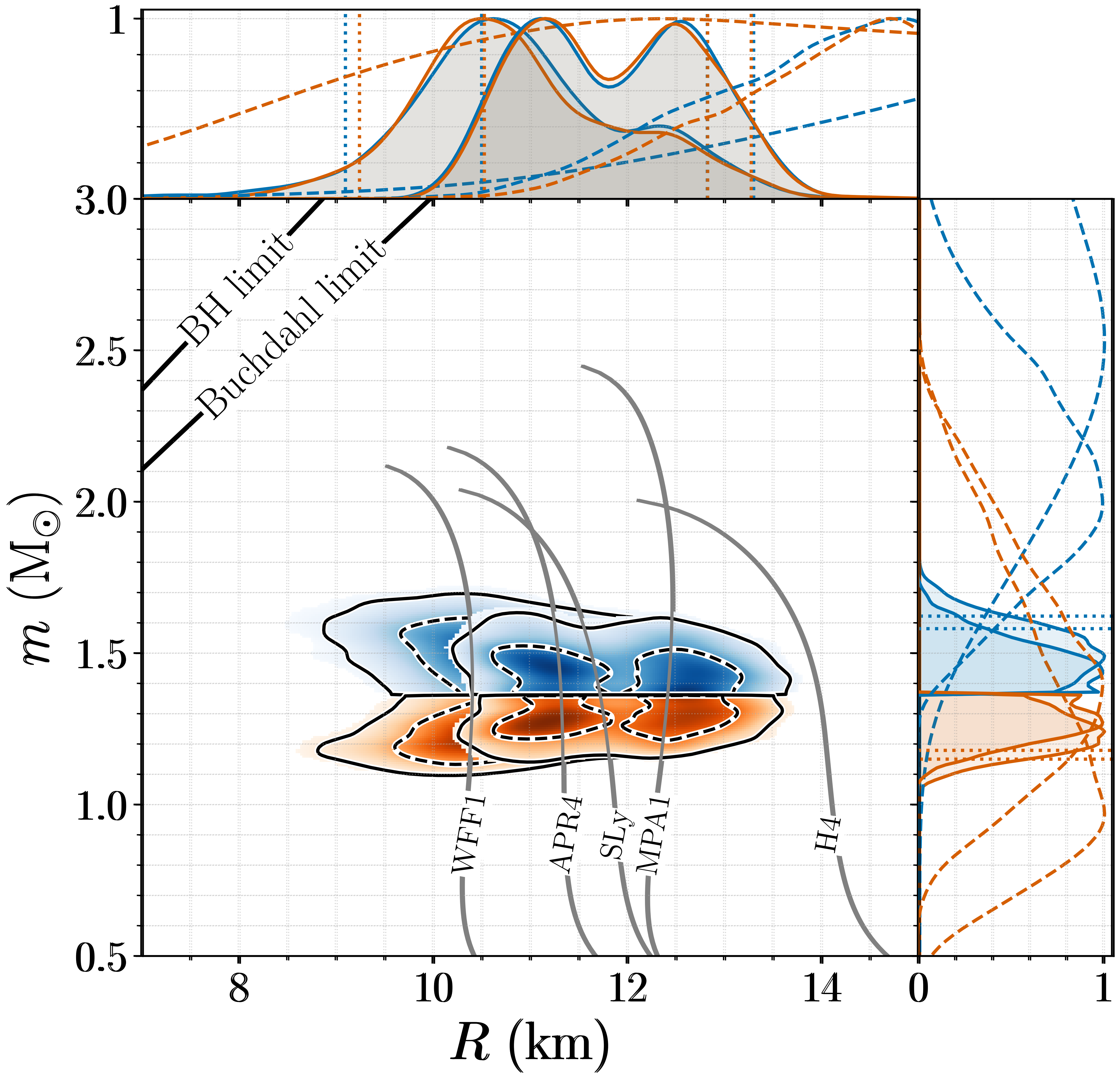

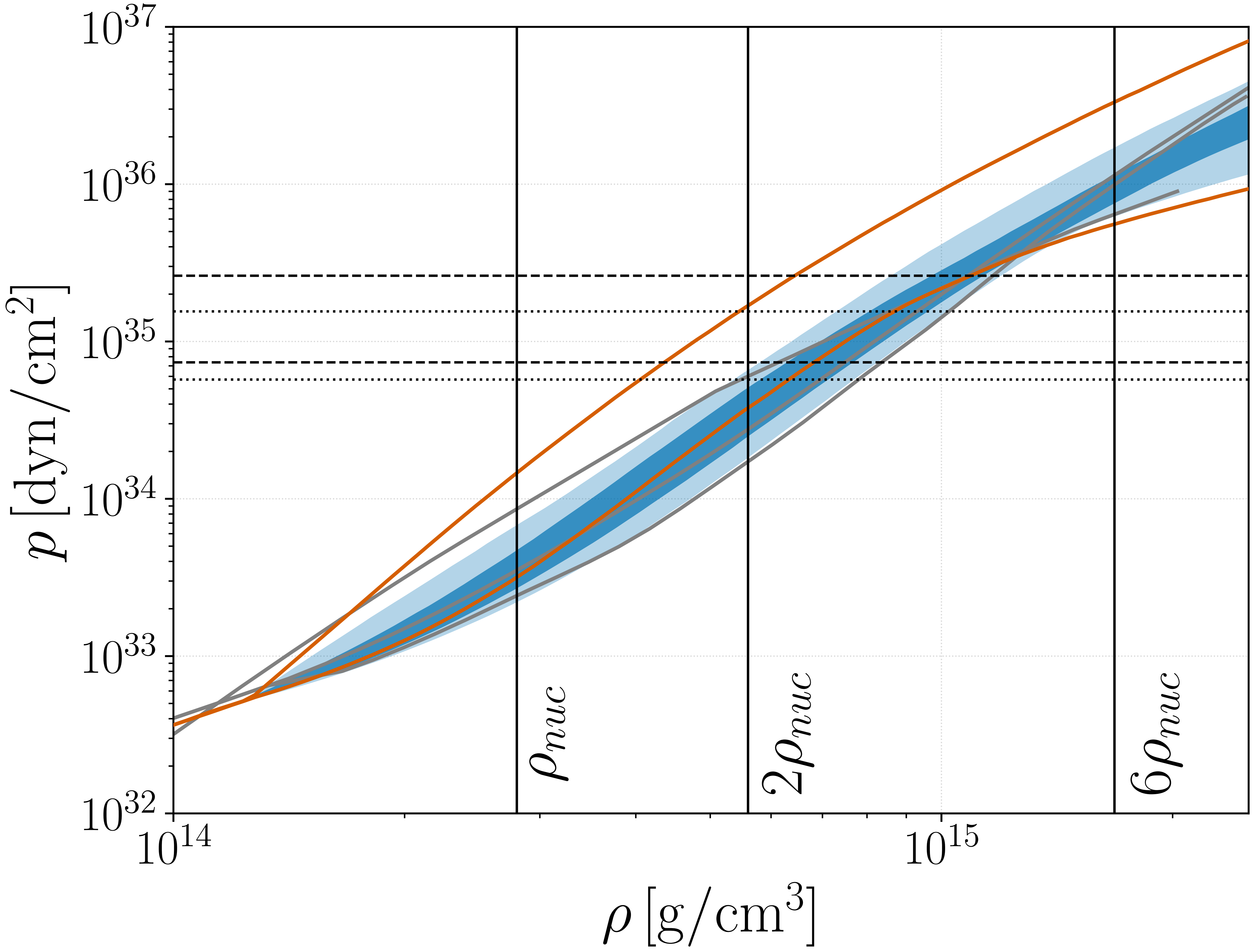

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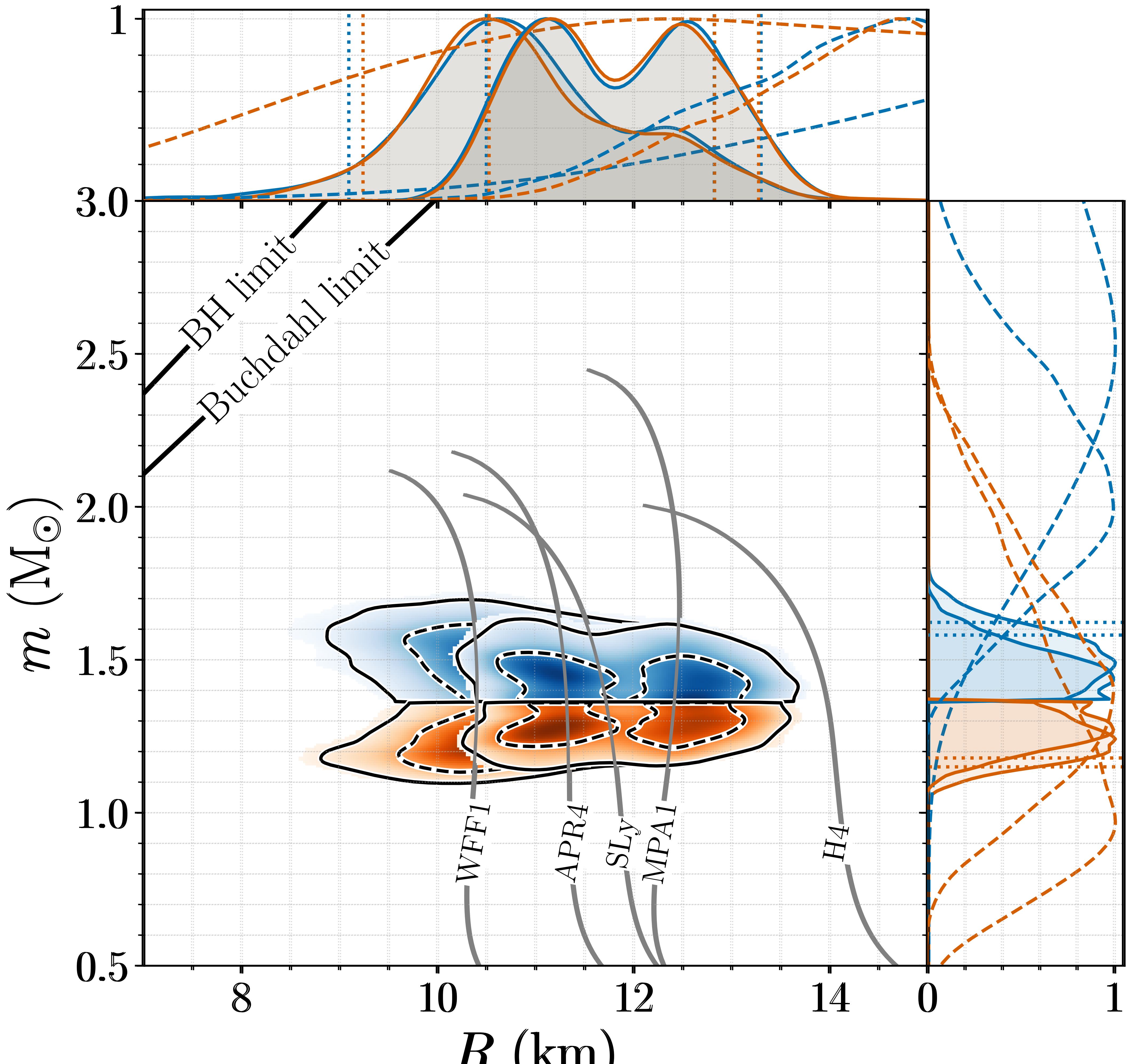

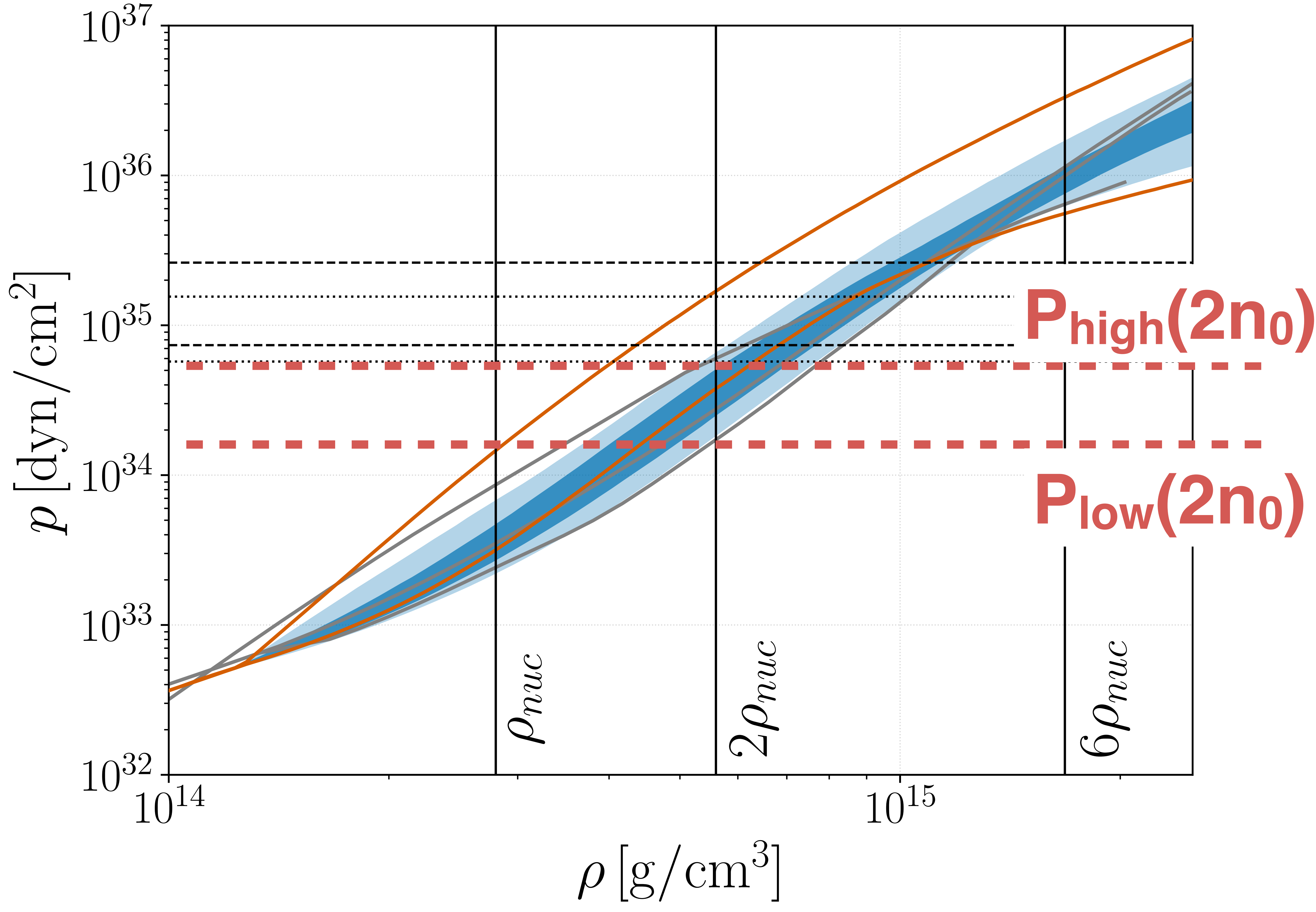

$P_{low}(2n_0)$ = 11 MeV/fm^3

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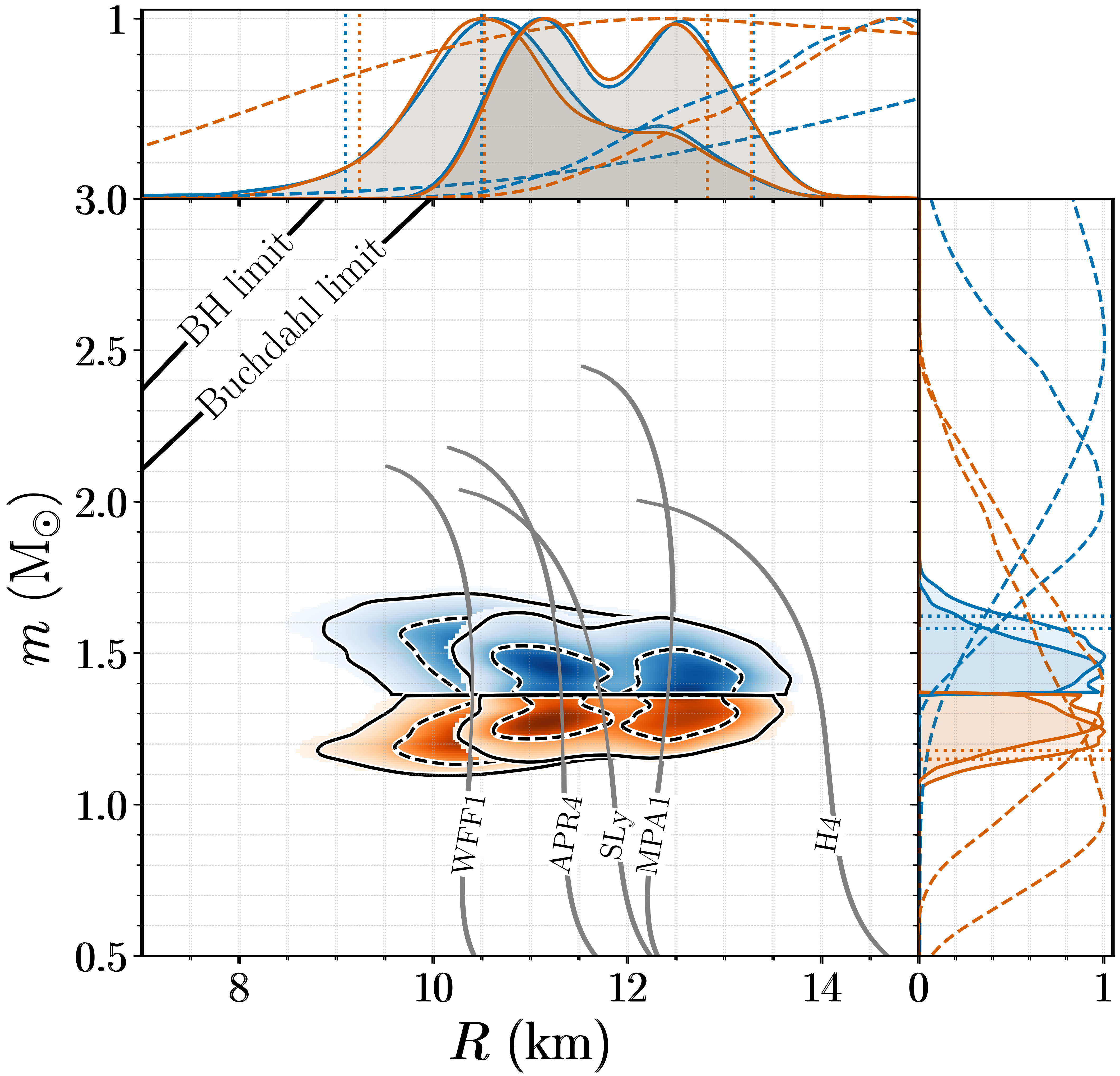

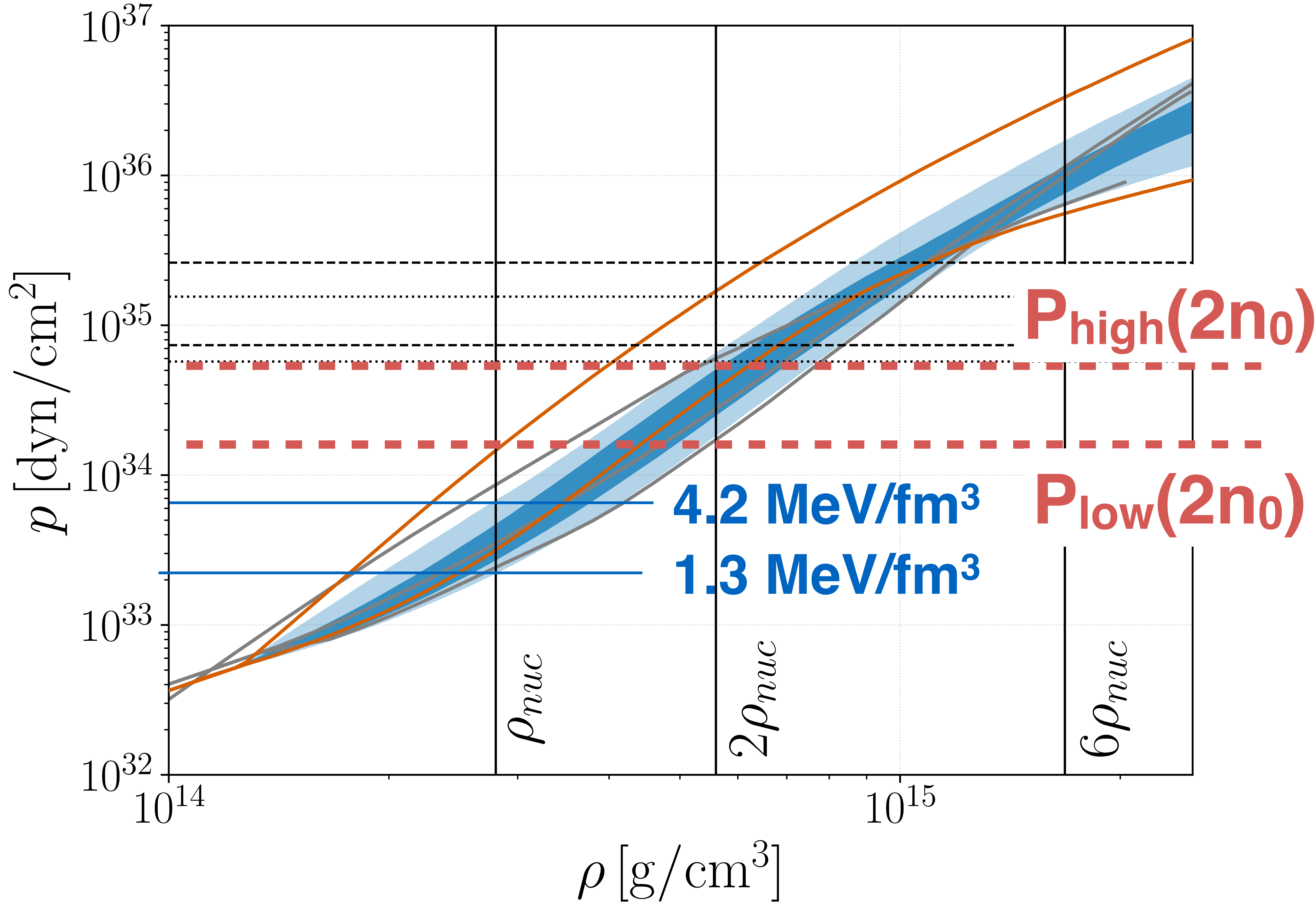

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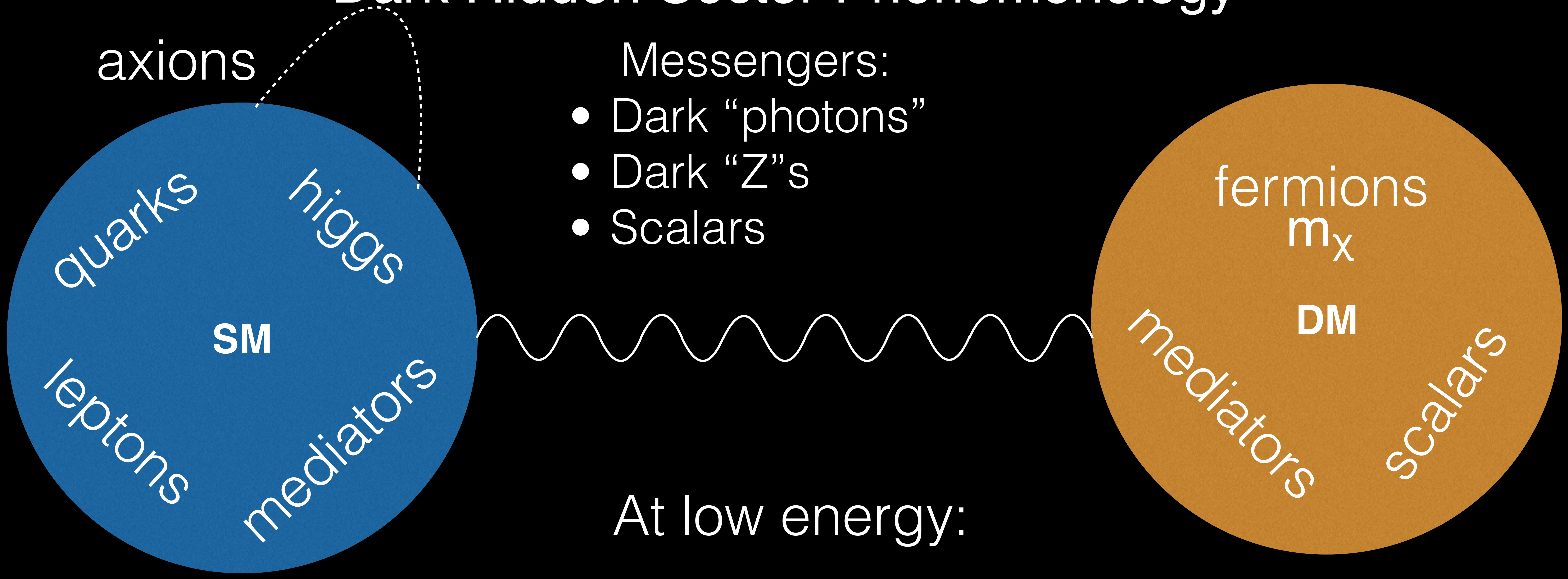
Part II: The dark side of neutron stars

Dark Hidden Sector Phenomenology

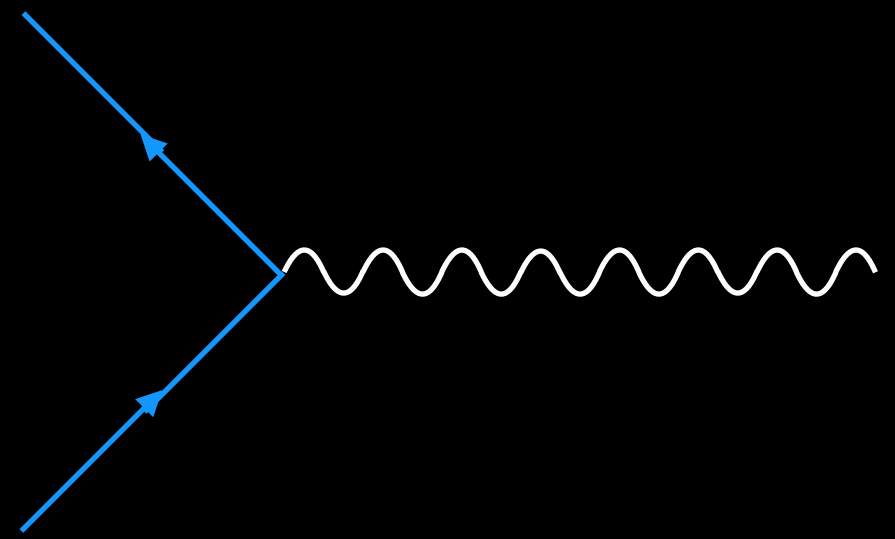


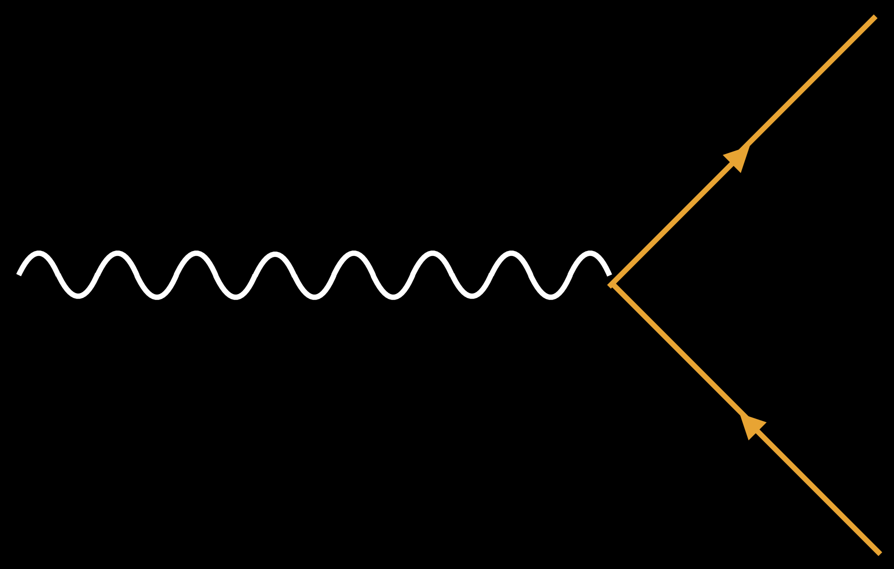
Messengers:

- Dark "photons"
- Dark "Z"s
- Scalars

At low energy:

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



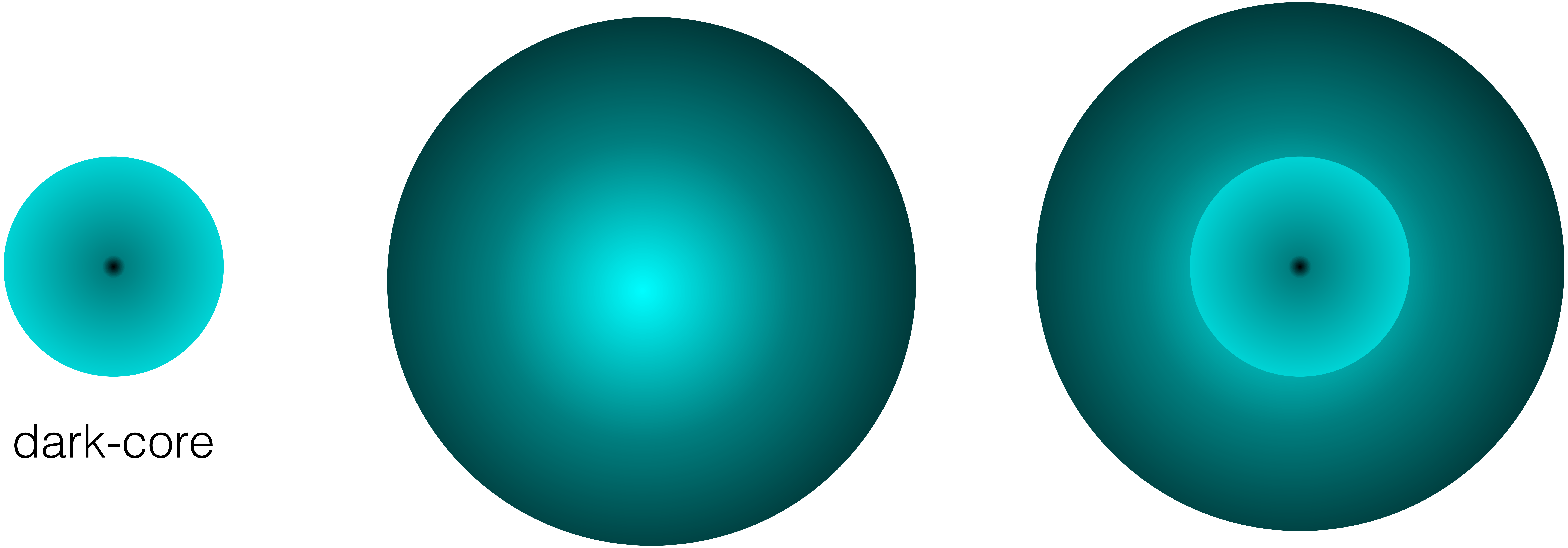


$$V_{\chi B} = \frac{g_\chi g_B}{q^2 + m_\phi^2} = g_\chi g_B \; \frac{e^{-m_\phi r}}{r}$$

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

Stable Dark Matter and Neutron Star Structure

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



dark-core

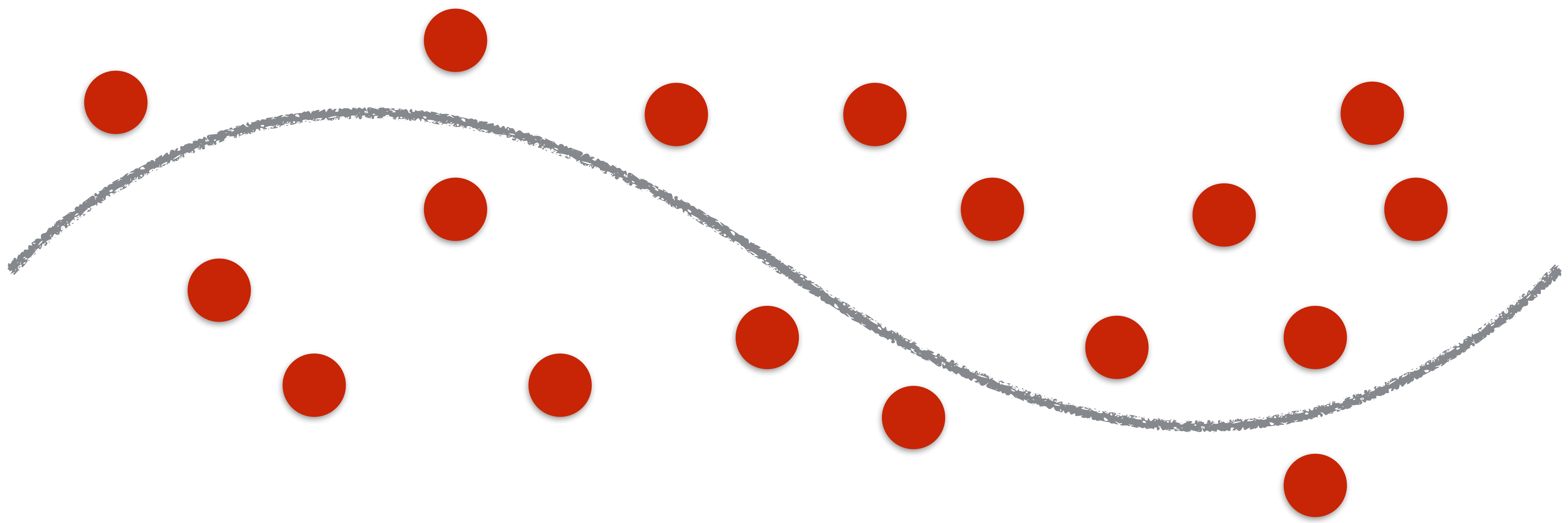
dark-halo

dark-halo +
anti-dark core

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

Strongly Interacting Dark Matter ?

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

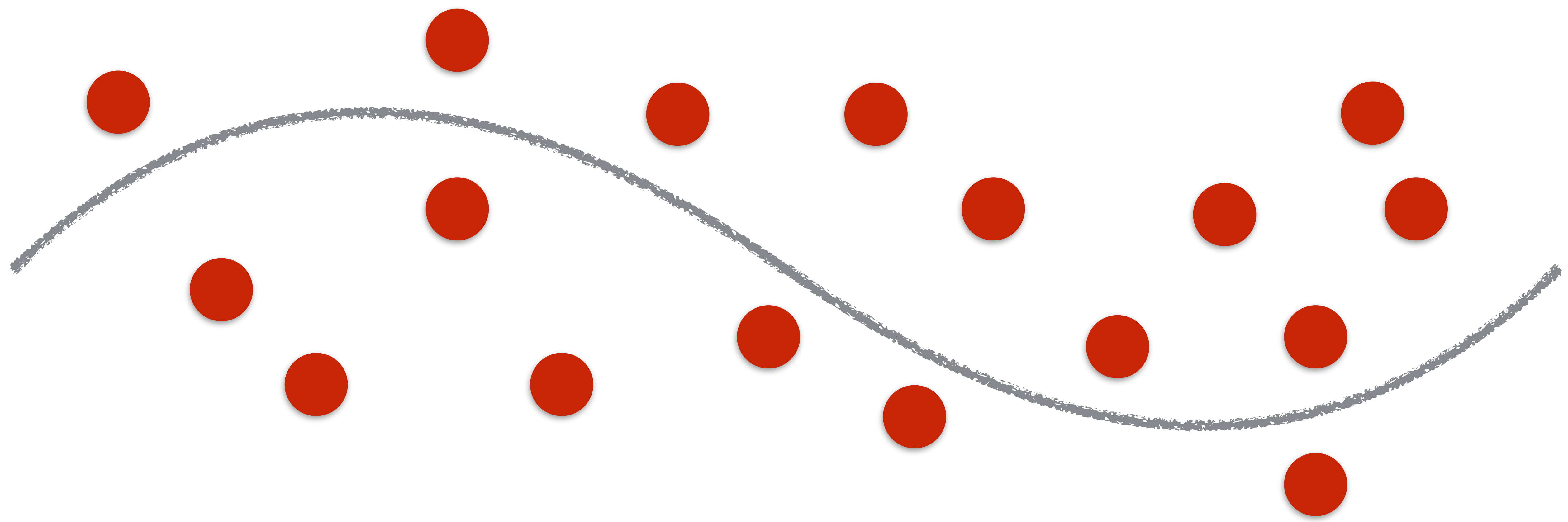


Large enhancement of interactions when Compton wavelength of mediator is larger than the inter-particle distance.
Coupling to baryon number can create (dark) charge separation in neutron stars.

Strongly Interacting Dark Matter ?

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

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



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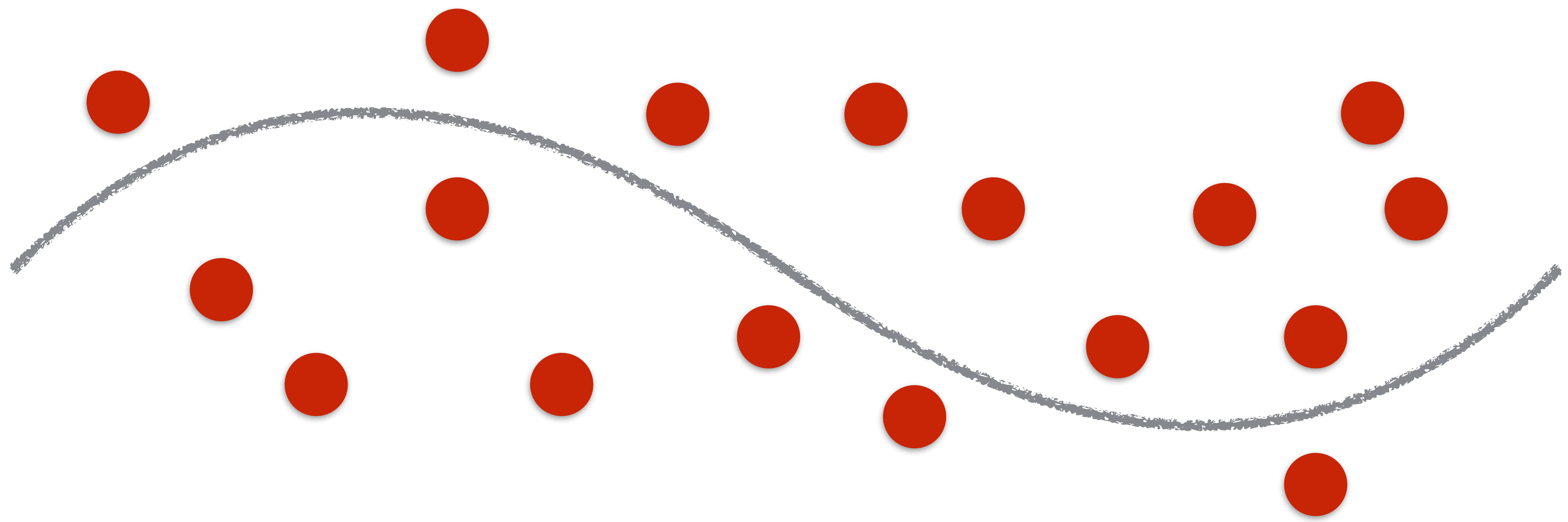

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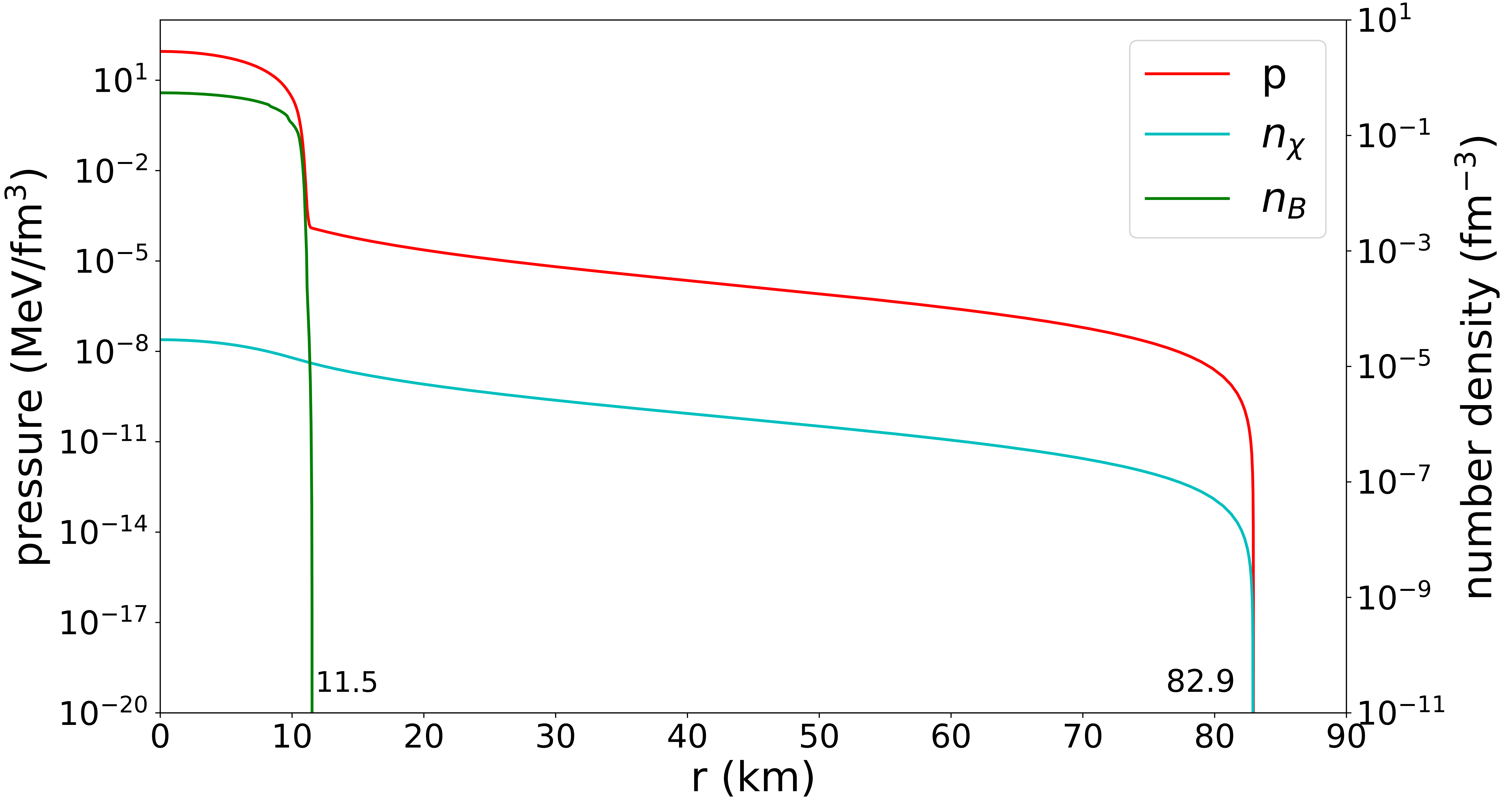
Profile of a Dark Neutron Star



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)

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

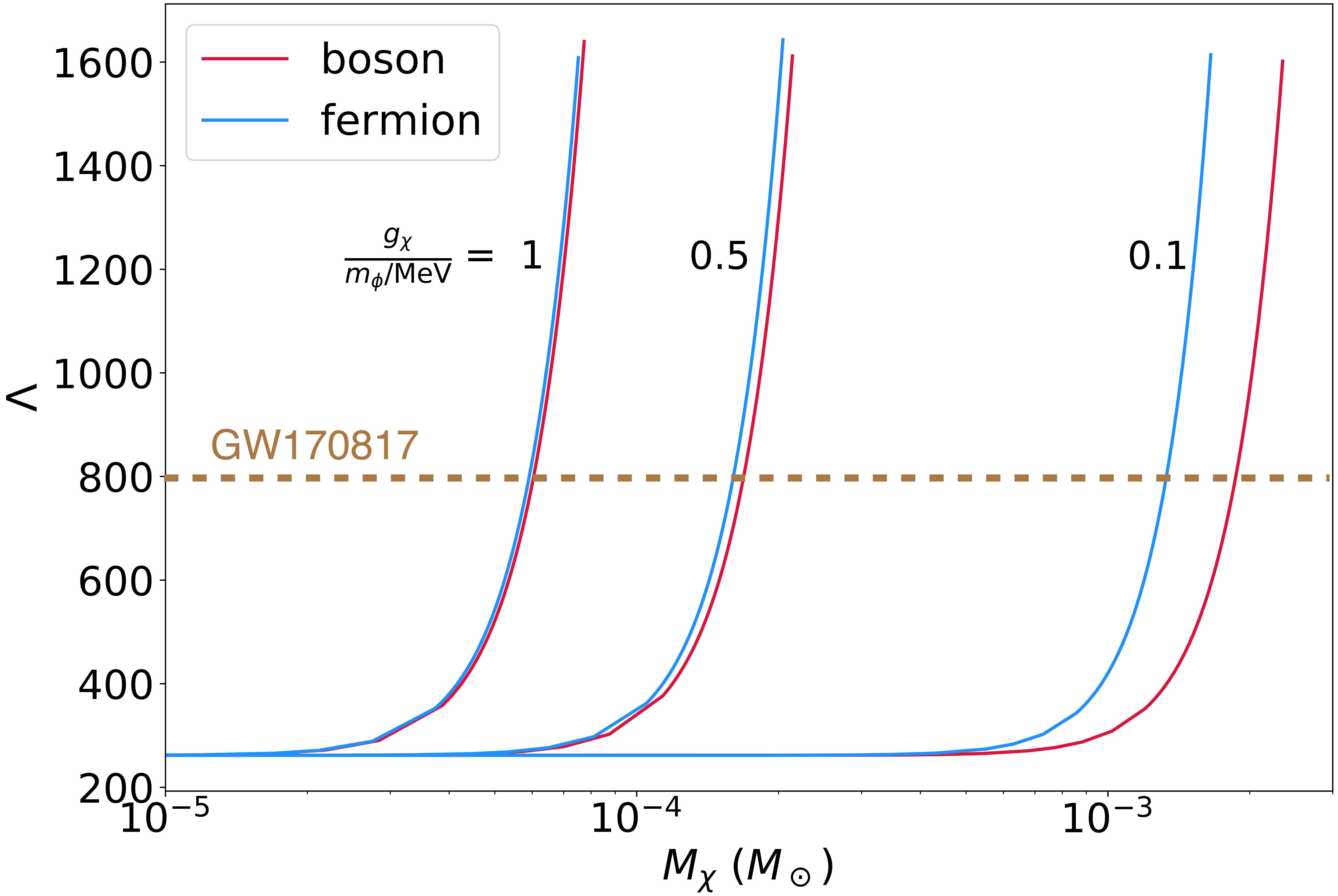
For light mediators, only trace amounts are needed

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

For m_χ = 100 MeV

g_χ/m_Φ = (0.1/MeV) or (10^{-6}/eV)

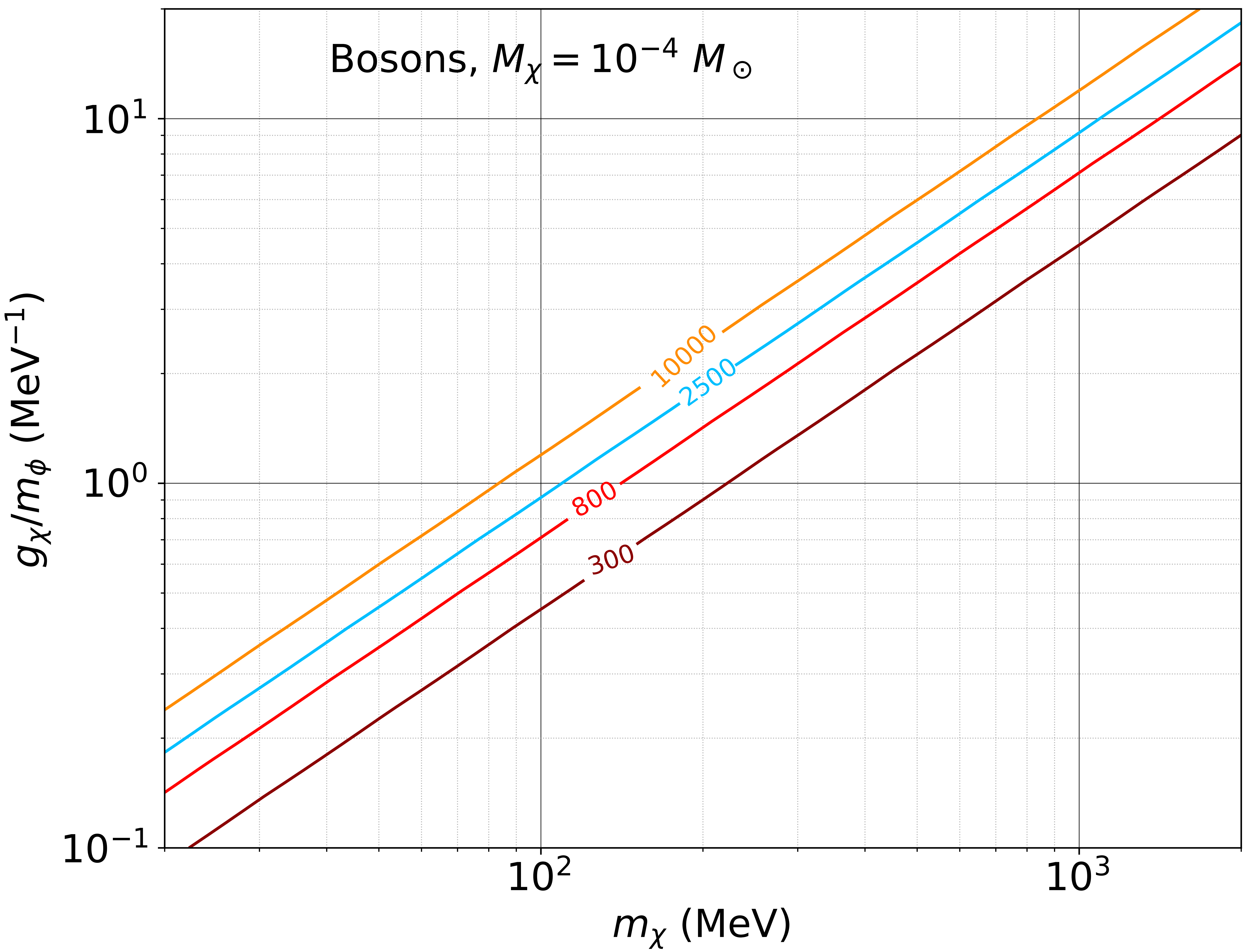
Interactions of "natural" size produce large Λ



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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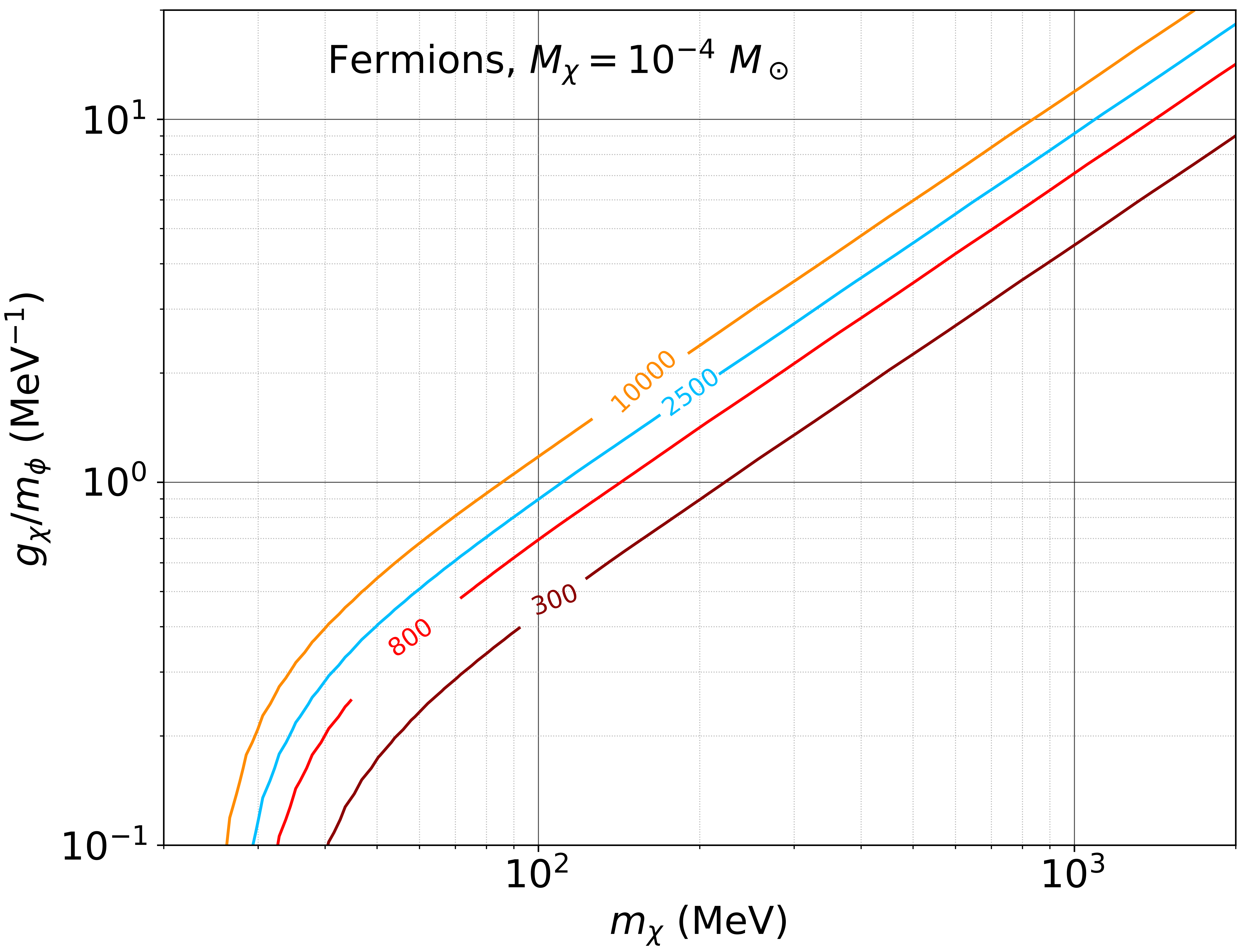

Ann Nelson, Sanjay Reddy, Dake Zhou, ArXiV:1803.03266

Could/should neutron stars contain dark matter ?

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- Coupling to baryons allows for dark charge separation.
- Dark matter could be clumpy.
- 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 !

Neutrino Interactions in Dense Matter

Low energy Lagrangian: $\mathcal{L} = \frac{G_F}{\sqrt{2}} \, l_\mu \; j^\mu$ $\qquad l_1 + N_2 \to l_3 + N_4$

Absorption:	$l_\mu^{cc} = \bar{l}\gamma_\mu(1-\gamma_5)\nu_l$	$j_{cc}^\mu = \bar{\Psi}_p \left(\gamma^\mu(g_V - g_A\gamma_5) + F_2 \frac{i\sigma^{\mu\alpha}q_\alpha}{2M}\right) \Psi_n$
Scattering:	$l_\mu^{nc} = \bar{\nu}\gamma_\mu(1-\gamma_5)\nu$	$j_{nc}^\mu = \bar{\Psi}_i \; (\gamma^\mu(C_V^i - C_A^i\gamma_5) + F_2^i \frac{i\sigma^{\mu\alpha}q_\alpha}{2M}) \; \Psi_i$

Rate: $$\frac{d\Gamma(E_1)}{dE_3 d\mu_{13}} = \frac{G_F^2}{32\pi^2} \frac{p_3}{E_1} (1 - f_3(E_3)) L_{\mu\nu} \; \mathcal{S}^{\mu\nu}(q_0, q)$$

Dynamic structure function: $$\mathcal{S}^{\mu\nu}(q_0,q) = \frac{-2 \; \mathrm{Im} \; \mathbf{\Pi}^{\mu\nu}(q_0,q)}{1 - \exp\left(-(q_0 + \Delta\mu)/T\right)}$$

Current-current correlations functions: $$\mathbf{\Pi}^{\mu\nu}(q_0,q) = -i \int dt \; d^3x \; \theta(t) \; e^{i(q_0 t - \vec{q}\cdot\vec{x})} \langle \; |[j_\mu \; (\vec{x},t), j_\nu(\vec{0},0)]| \; \rangle$$

difficult to calculate in general due to the non-perturbative nature of strong interactions.

Sawyer (1970s), Iwamoto & Pethick (1980s),
Burrows & Sawyer, Horowitz & Wehrberger, Raffelt et al., Reddy et al. (1990s),
Benhar, Carlson, Gandolfi, Horowitz, Lavato, Pethick, Reddy, Roberts, Schwenk, Shen, and others (2000s)

Neutrino-nucleon scattering

Nucleon currents simplify in the non-relativistic limit:

$$j^{\mu}_{nc} = \underset{\substack{\uparrow \\ \text{density}}}{\Psi^{\dagger}\Psi}\ \delta^{\mu}_{0} + \underset{\substack{\uparrow \\ \text{spin-density}}}{\Psi^{\dagger}\sigma_k\Psi}\ \delta^{\mu}_{k} + \mathcal{O}[\frac{p}{M}]$$

$$\frac{d\Gamma(E_1)}{d\Omega dE_3} = \frac{G_F^2}{4\pi^2}\ E_3^2\ \left[C_V^2(1+\cos\theta_{13})S_\rho(\omega,q) + C_A^2(3-\cos\theta_{13})S_\sigma(\omega,q)\right]$$

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dynamic response functions

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Integrate over the final neutrino energy:

$$\frac{d\Gamma(E_1)}{dq} = \frac{G_F^2}{\pi}\ q\ \left(C_V^2 I_{\rho}(q) + C_A^2 I_{\sigma}(q)\right)$$

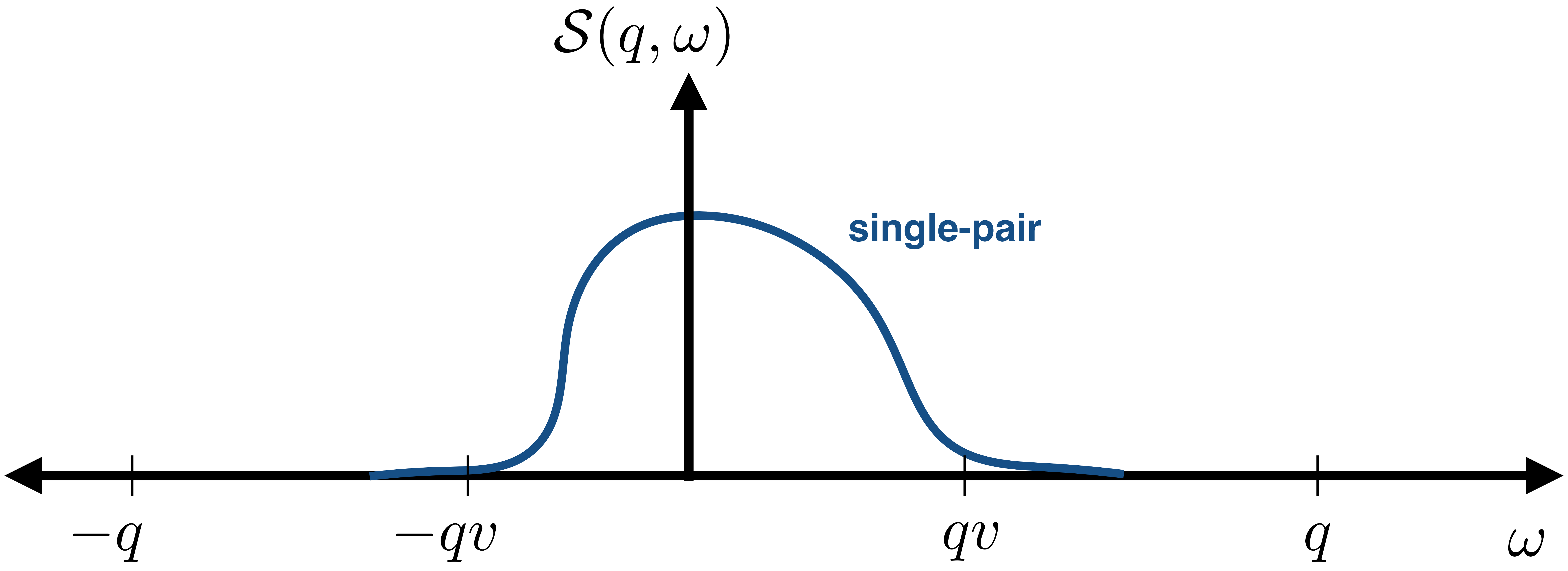
The "static" response functions are :

$$I_{\rho}(q) = \tilde{S}_{\rho}(q)\ \left(1 - \frac{q^2}{4E_1^2} - \frac{\langle\omega_{\rho}(q)\rangle}{E_1} + \frac{\langle\omega_{\rho}^2(q)\rangle}{4E_1^2}\right)$$

$$I_{\sigma}(q) = \tilde{S}_{\sigma}(q)\ \left(1 + \frac{q^2}{4E_1^2} - \frac{\langle\omega_{\sigma}(q)\rangle}{E_1} - \frac{\langle\omega_{\sigma}^2(q)\rangle}{4E_1^2}\right)$$

$$\tilde{S}_{\alpha}(q) = \int_{-q}^{\omega_{max}} d\omega\ S_{\alpha}(\omega,q) \qquad \langle\omega_{\alpha}^n\rangle = \frac{\int_{-q}^{\omega_{max}} d\omega\ \omega^n\ S_{\alpha}(\omega,q)}{\tilde{S}_{\alpha}(q)}$$

General Structure of the Dynamic Response



In hot and dense nuclear matter single-pair, multi-particle and collective modes all contri
energy response.

- At small ω response is governed by hydrodynamic.
- Single-pair response dominates for $|\omega\tau_{coll}| > 1$ and $|\omega| < qv$.
- Multi-particle response dominates for $|\omega| > qv$.
- Collective modes arise due to repulsive interactions.

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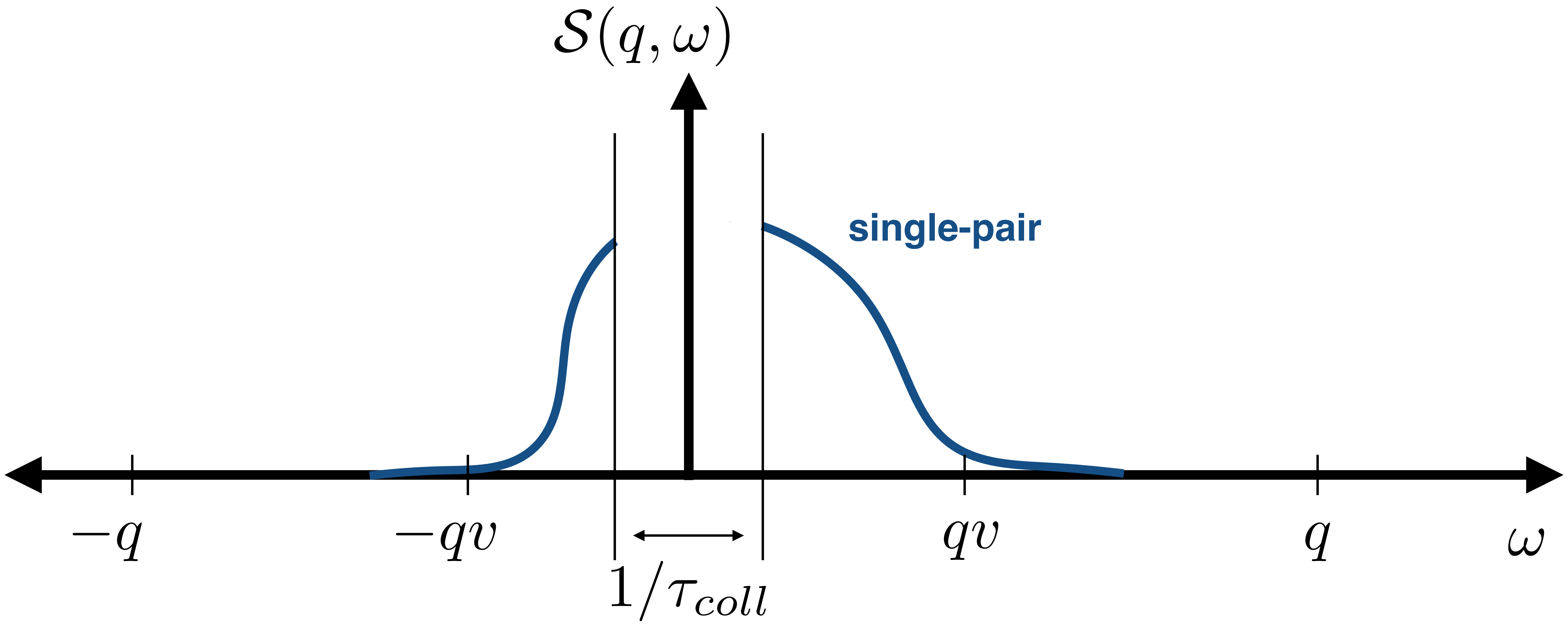

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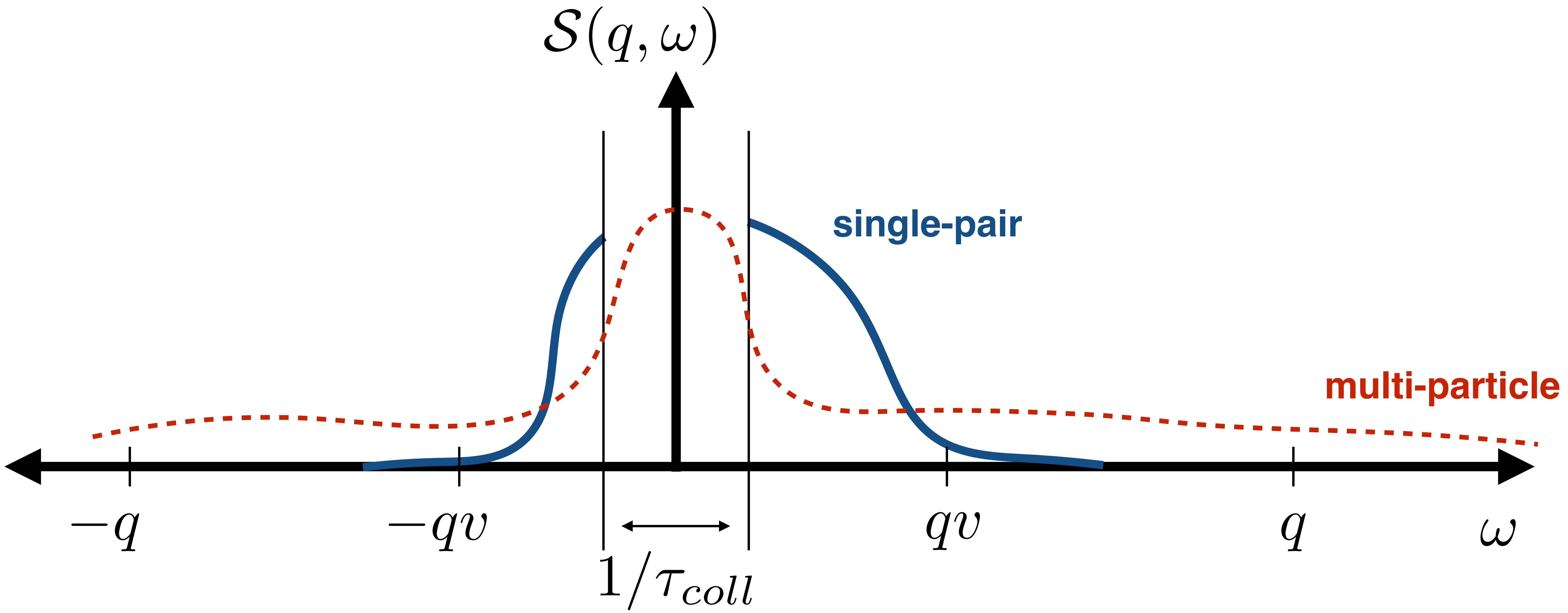

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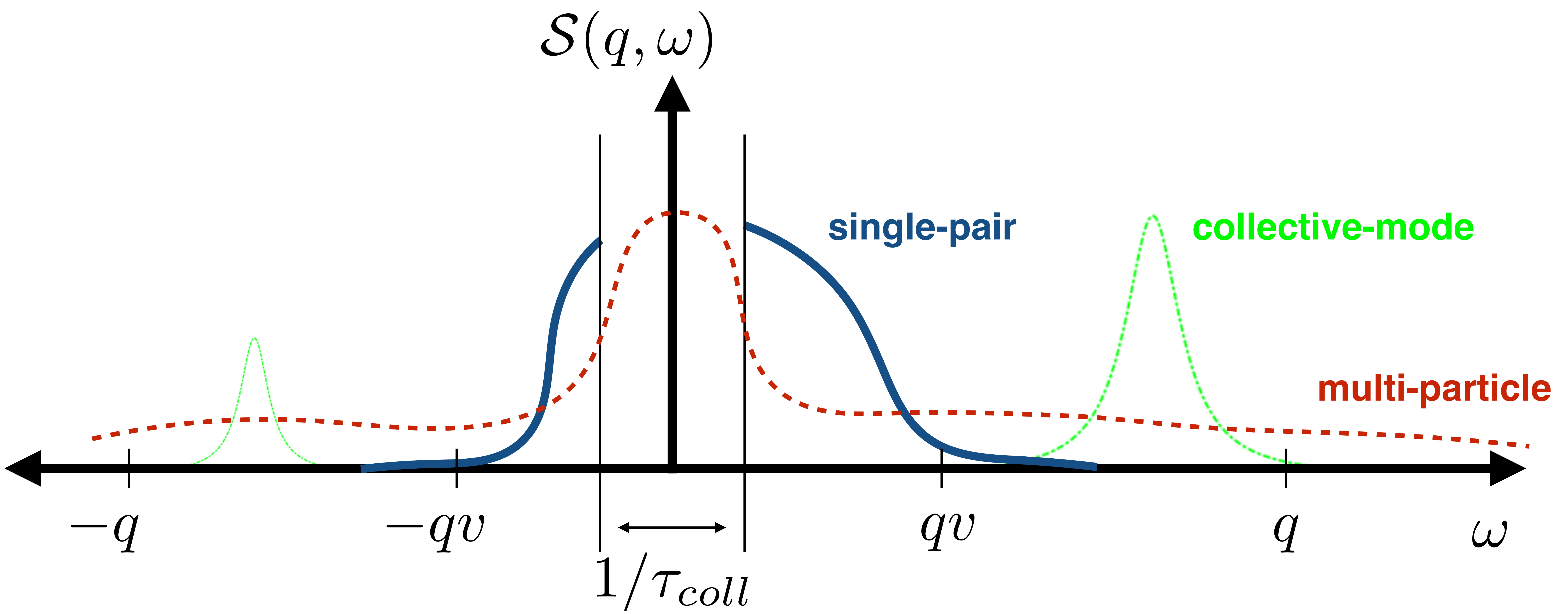

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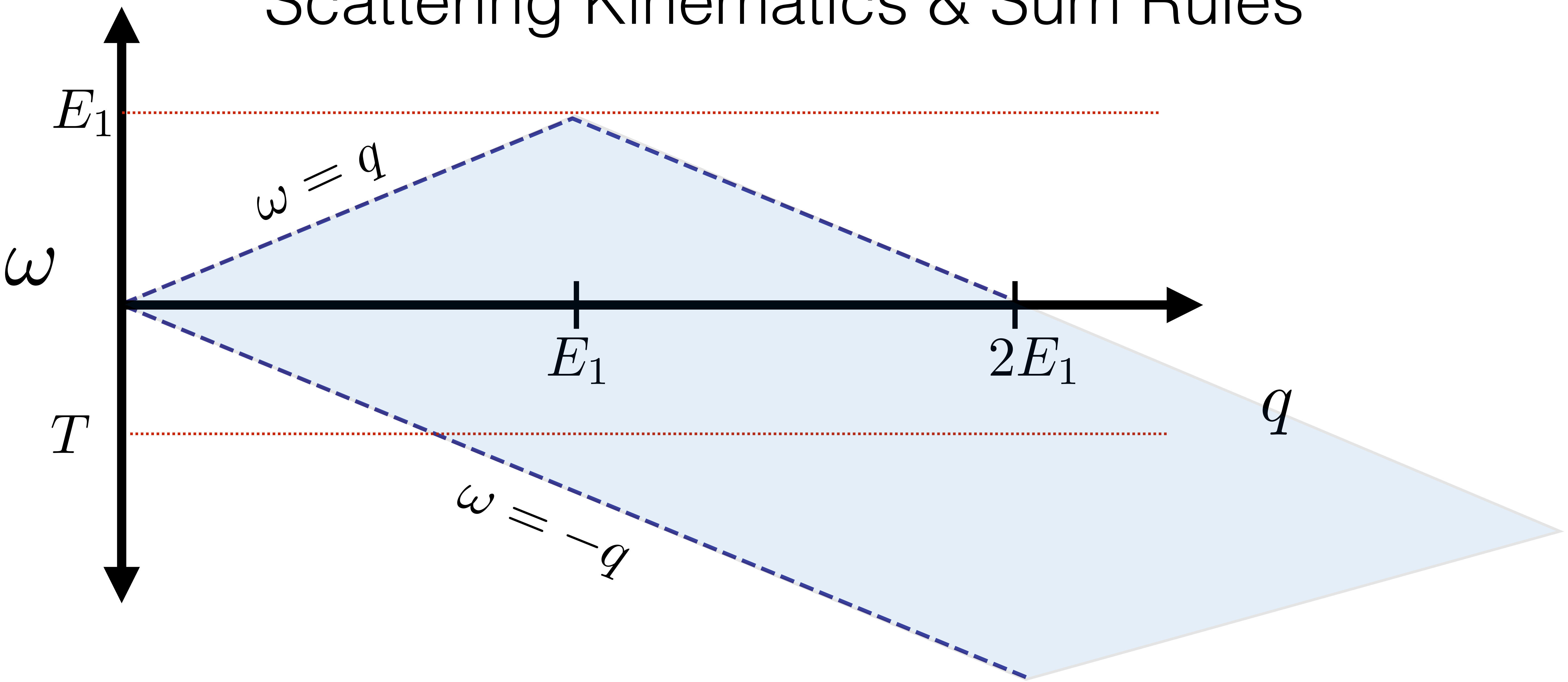
Scattering Kinematics & Sum Rules



Neutrinos only probe the space-like region with $|\omega| < q$

In general $\tilde{S}_\alpha(q) = \int_{-q}^{\omega_{max}} d\omega \; S_\alpha(\omega, q) \; < \quad S_\alpha(q) = \int_{-\infty}^{\infty} d\omega \; S_\alpha(\omega, q)$

In practice for conserved currents at long-wavelengths:

$$\tilde{S}_\rho(q \to 0) = S_\rho(q \to 0)$$
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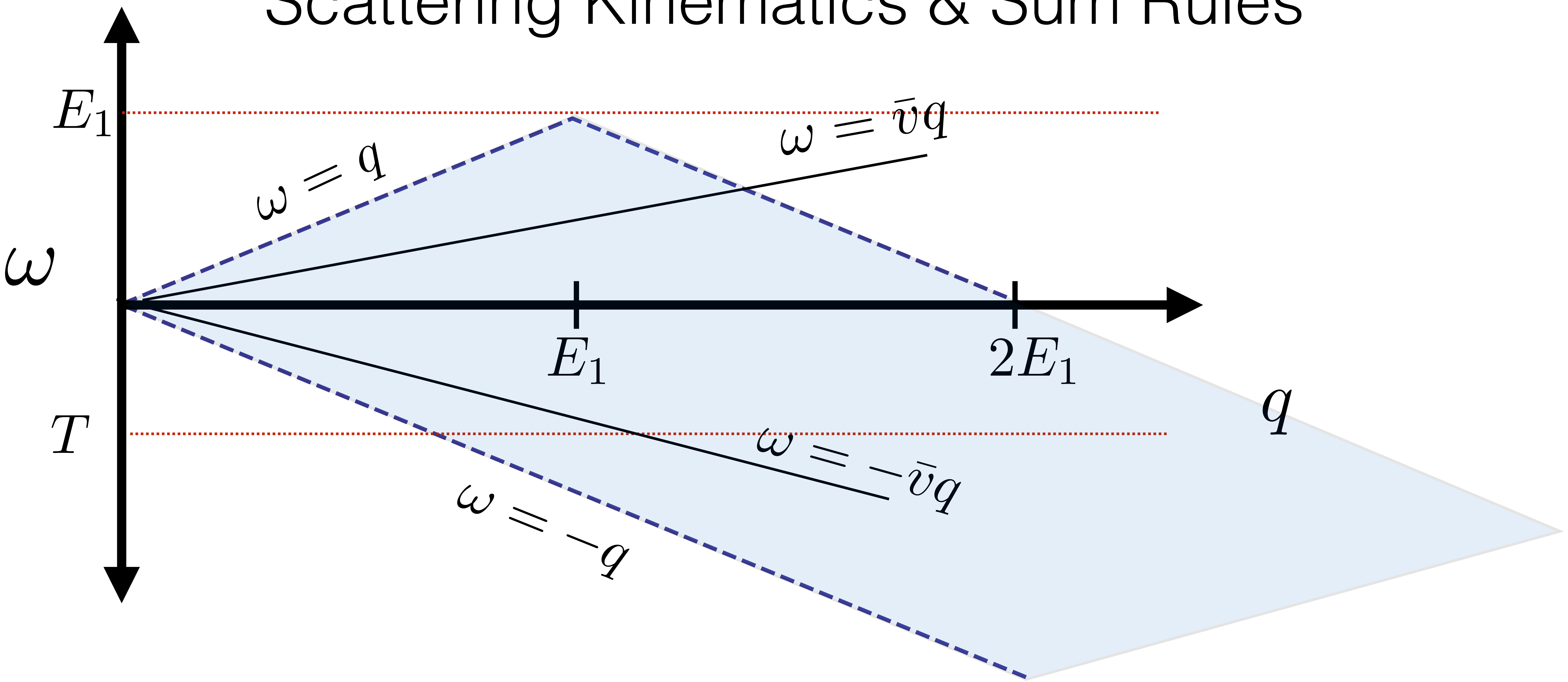
At high temperature $S_\rho(q \to 0) = T \left(\frac{\partial n}{\partial \mu}\right)_T$

Scattering Kinematics & Sum Rules



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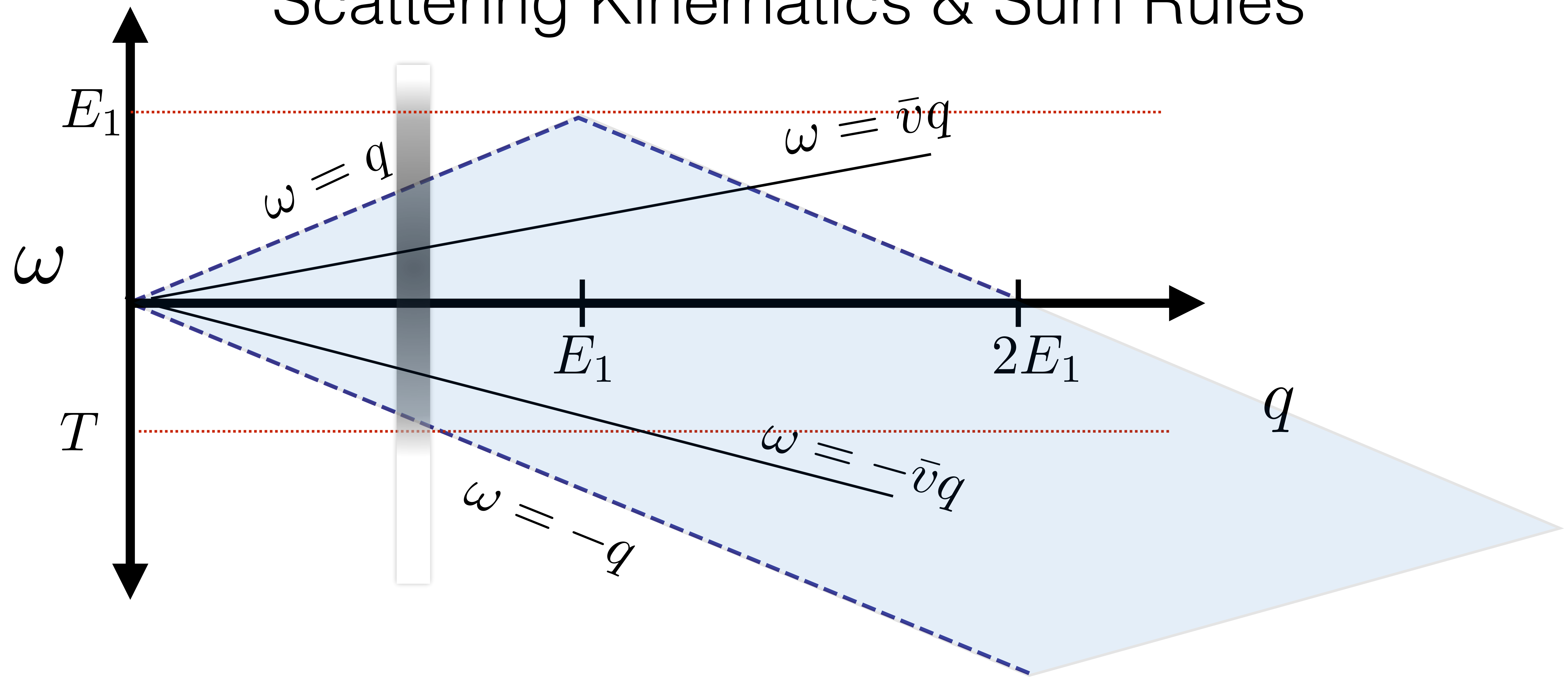

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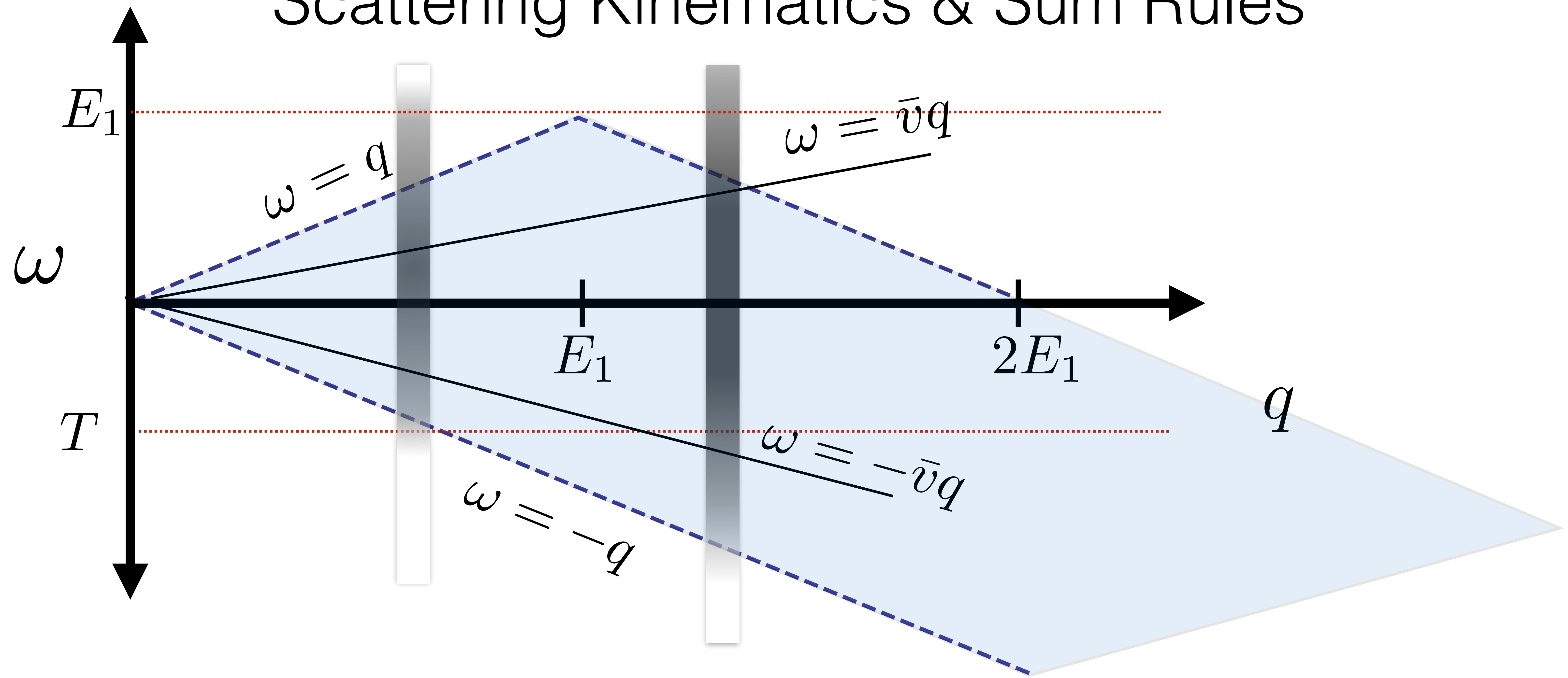

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Long-wavelength Response using the Virial EoS

Assumes that scattering is nearly elastic to include all many-body correlations through the structure factors.

$$\tilde{S}_\rho(q) = \int_{-q}^{\omega_{max}} d\omega \; S_\rho(\omega, q) \simeq S_\rho(q) \qquad \tilde{S}_\rho(q \to 0) = S_\rho(q \to 0)$$

Calculate the static structure factors using the compressibility or thermodynamic sum rule

$$S_\rho(q \to 0) = T \left(\frac{\partial n}{\partial \mu}\right)_T$$

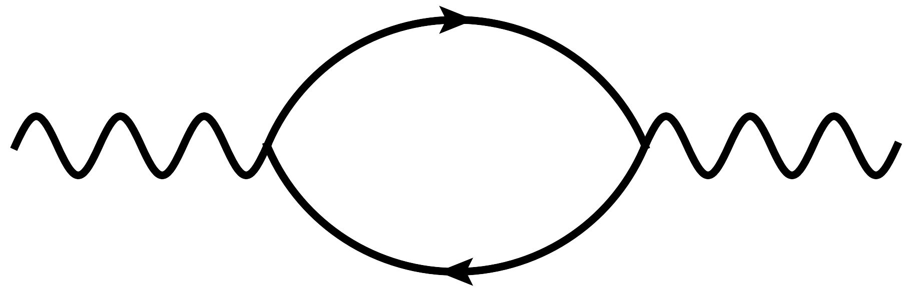
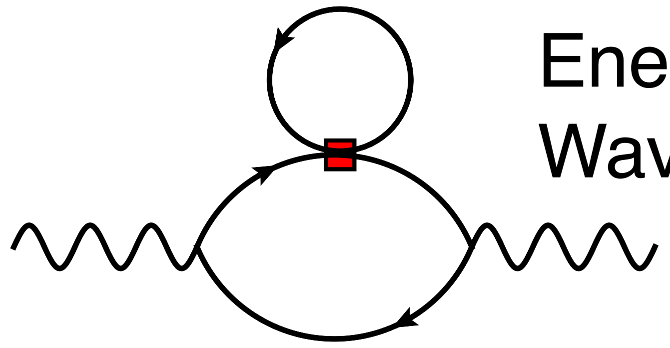
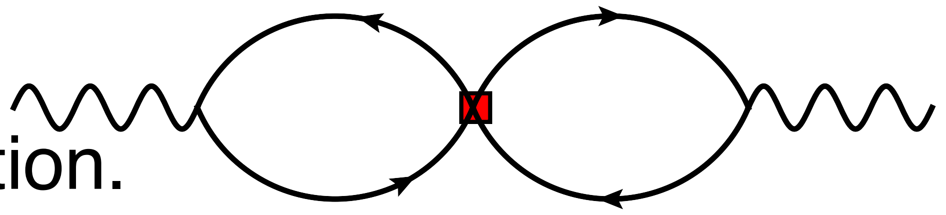
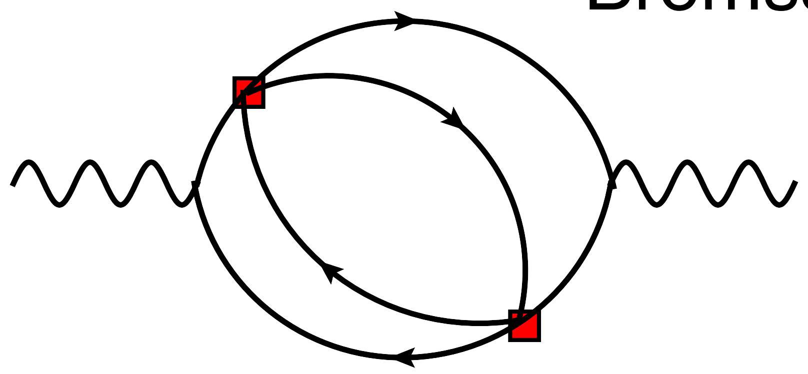
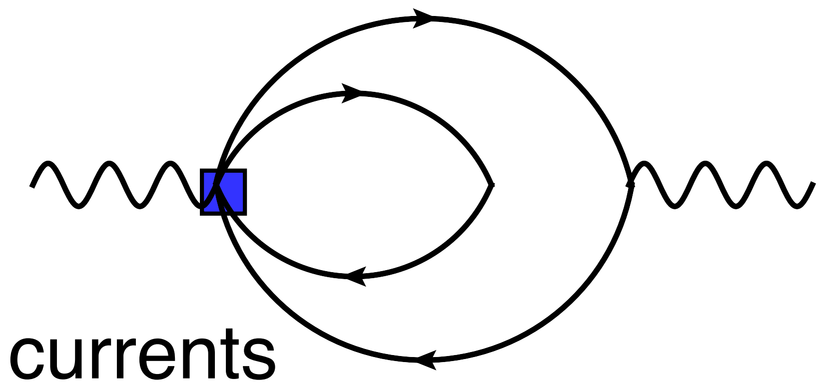
Sawyer (1975, 1979)
Horowitz and Schwenk (2005), Horowitz et al. (2017)

This is an excellent approximation for the density response relevant to neutral current reactions in the neutrino sphere.

The spin response and charged current reactions require some dynamical input.

Pseudo-potential for Hot & Dilute Nuclear Matter

The dynamic structure factor calculable using standard diagrammatic "perturbation" theory - with a twist.
Interactions represented by a pseudo-potential: $\mathcal{V}_{ps} \propto \dfrac{\delta(p_{rel})}{p_{rel}\ M}$

	Leading order diagram neglects interactions.	$\mathcal{O}[z]$
 Energy and density shifts. Wave-function renormalization. Screening. Vertex renormalization. 	Includes interactions at leading order. Consistent with the viral expansion.	$\mathcal{O}[z^2\ \mathcal{V}_{ps}]$
 Bremsstrahlung processes 2-body or meson-exchange currents 	Includes 2p-2h excitations and 2-body currents. These corrections are beyond the leading order viral expansion.	$\mathcal{O}[z^2\ \mathcal{V}_{ps}^2]$

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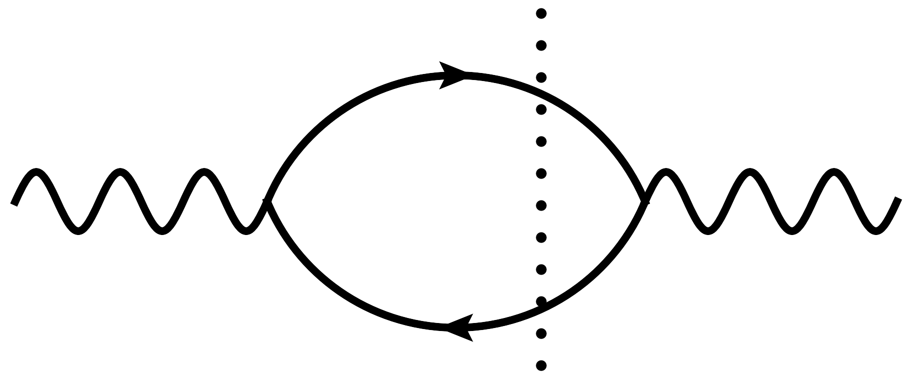
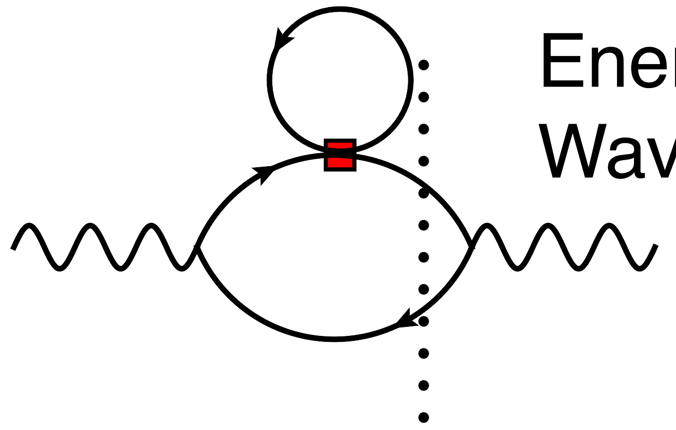
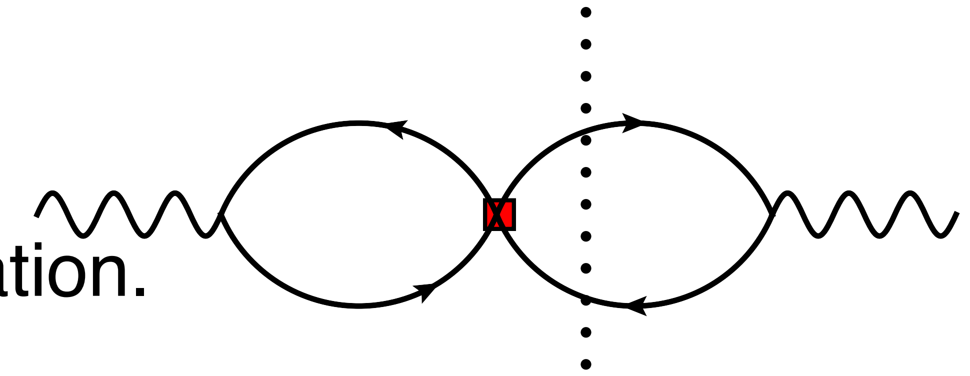
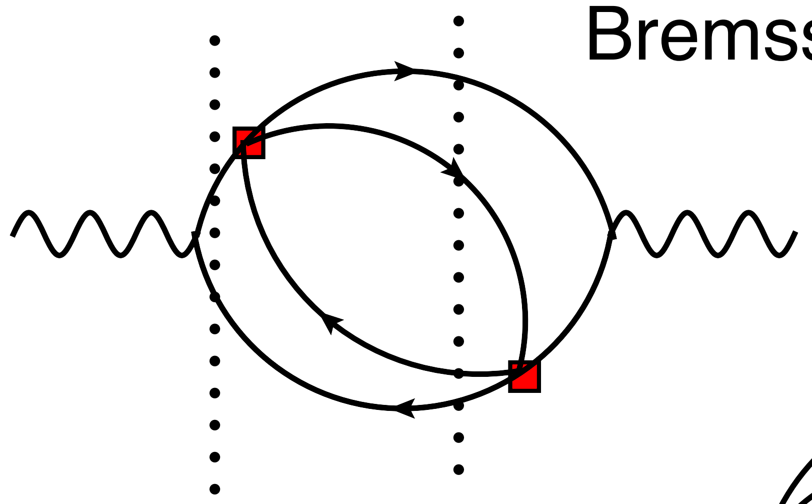
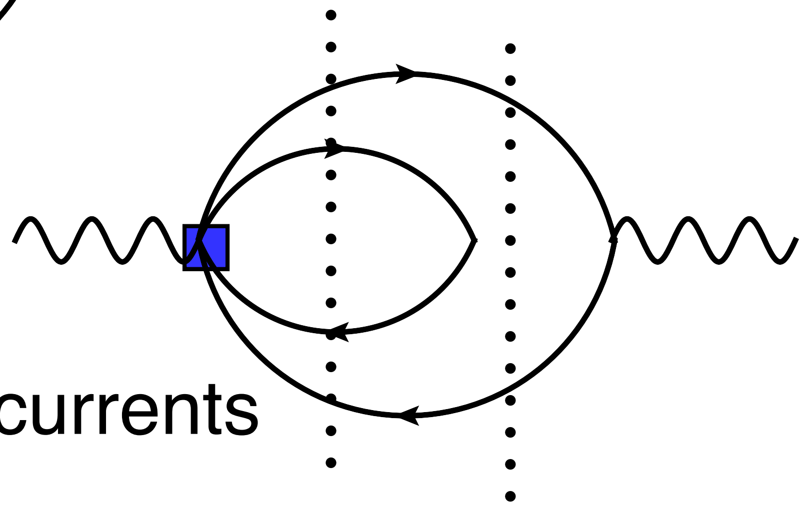
	Leading order diagram neglects interactions.	$\mathcal{O}[z]$
 Energy and density shifts. Wave-function renormalization.  Screening. Vertex renormalization.	Includes interactions at leading order. Consistent with the viral expansion.	$\mathcal{O}[z^2\ \mathcal{V}_{ps}]$
 Bremsstrahlung processes  2-body or meson-exchange currents	Includes 2p-2h excitations and 2-body currents. These corrections are beyond the leading order viral expansion.	$\mathcal{O}[z^2\ \mathcal{V}_{ps}^2]$

Response functions in hot and (not so) dense neutron matter.

Dynamical Structure Function

Static Structure Function

Bedaque, Reddy, Sen, Warrington (2018)

Conclusions

Theory and experimental efforts to pin down the EOS between 1-2 n_0 is important for neutron star structure and an area in which we can anticipate progress in the near term.

A factor of 2 reduction in the error associated with the measured tidal polarizability is needed to provide specific input for dense matter physics. High values would be intriguing.

Neutron stars can accrete, inherit, or create their own dark matter. Trace amounts of interacting asymmetric dark matter in the neutron star can enhance their tidal polarizability (Λ) to discernible values.

Neutrino interactions in the decoupling region can be calculated rather well. Several open questions remain at higher density and temperature — should be revenant for calculations of the neutrino shear viscosity and weak interaction induced bulk viscosity.