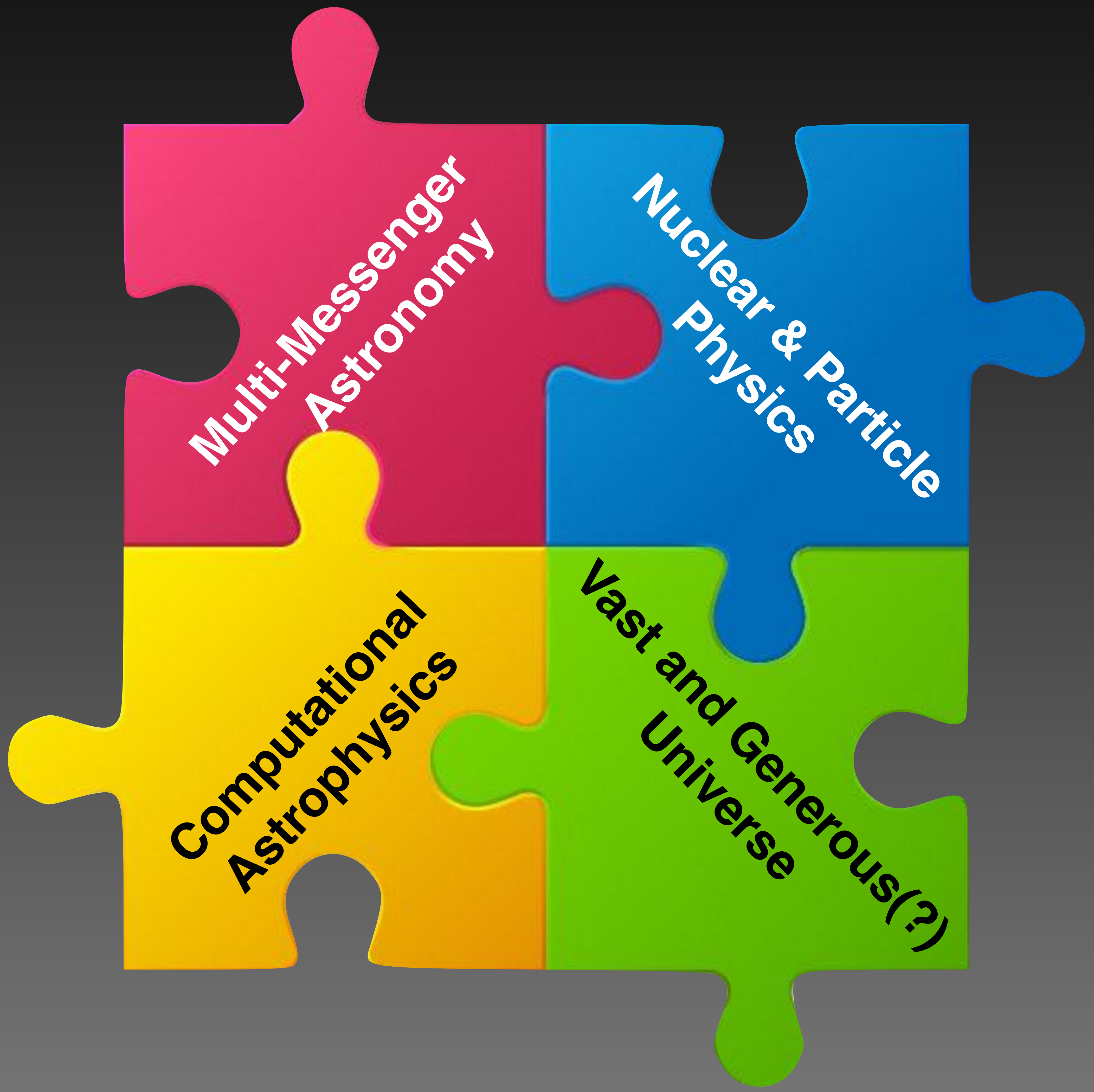
Neutron Stars as Nuclear and Particle Physics Laboratories

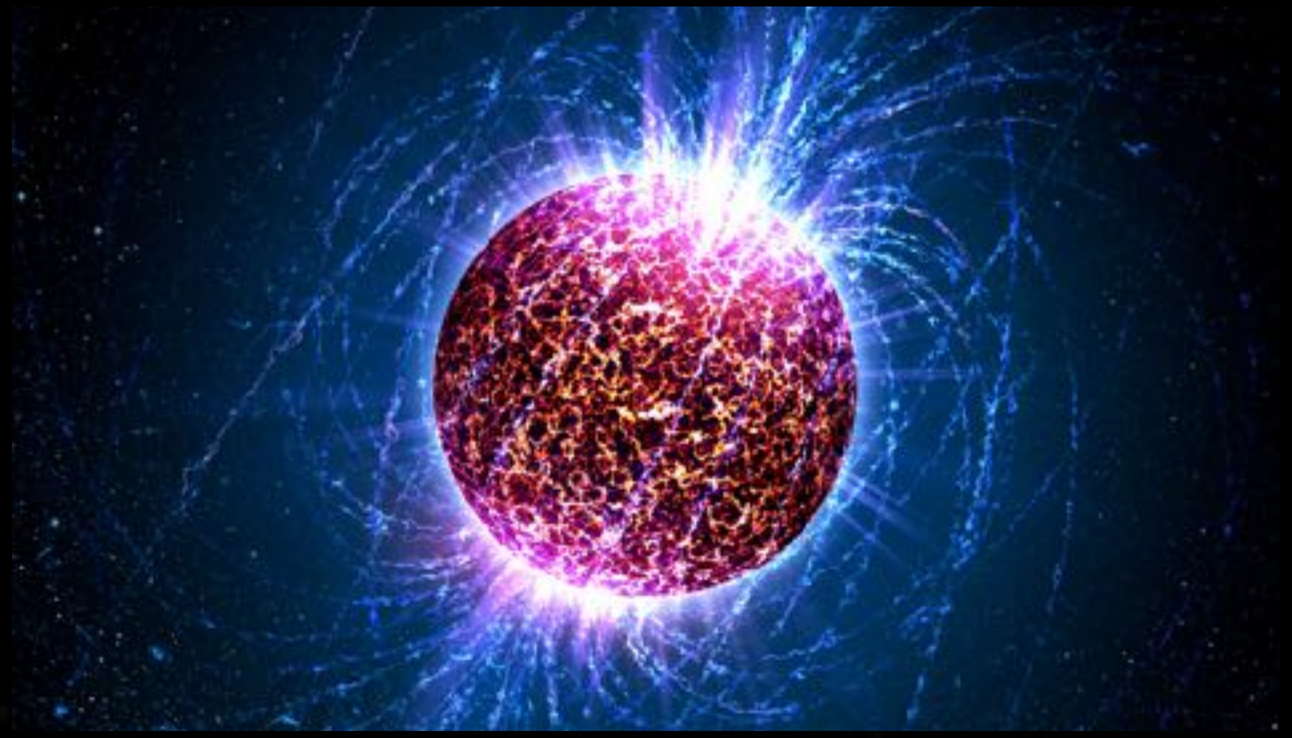
Sanjay Reddy, University of Washington, Seattle

- Introduction & motivation
- Mass, radius, ChiEFT & sound speed
- The dark side of neutron stars
- Open issues in ChiEFT & new 3NFs



INSTITUTE for
NUCLEAR THEORY

Neutron Stars and Big Questions



Nature of matter at extreme density?

Origin of cosmic explosions?

Synthesis of heavy elements?

Nature of dark matter?

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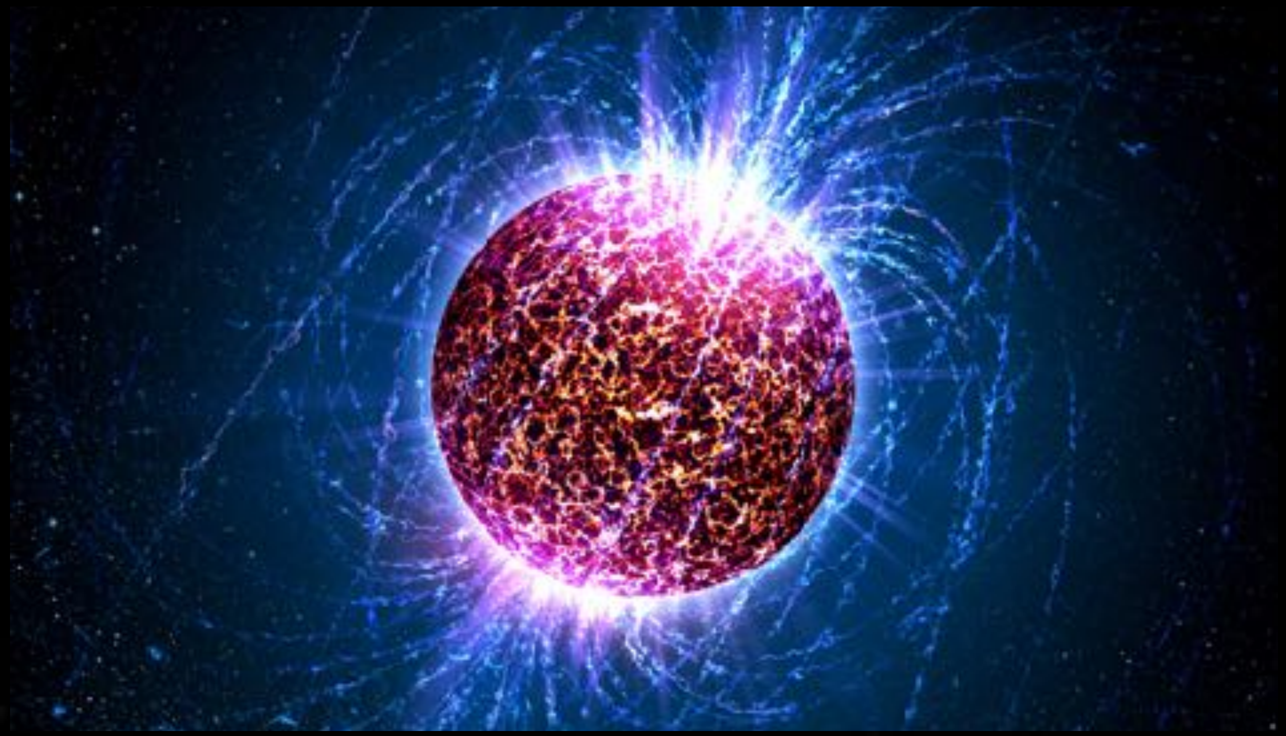

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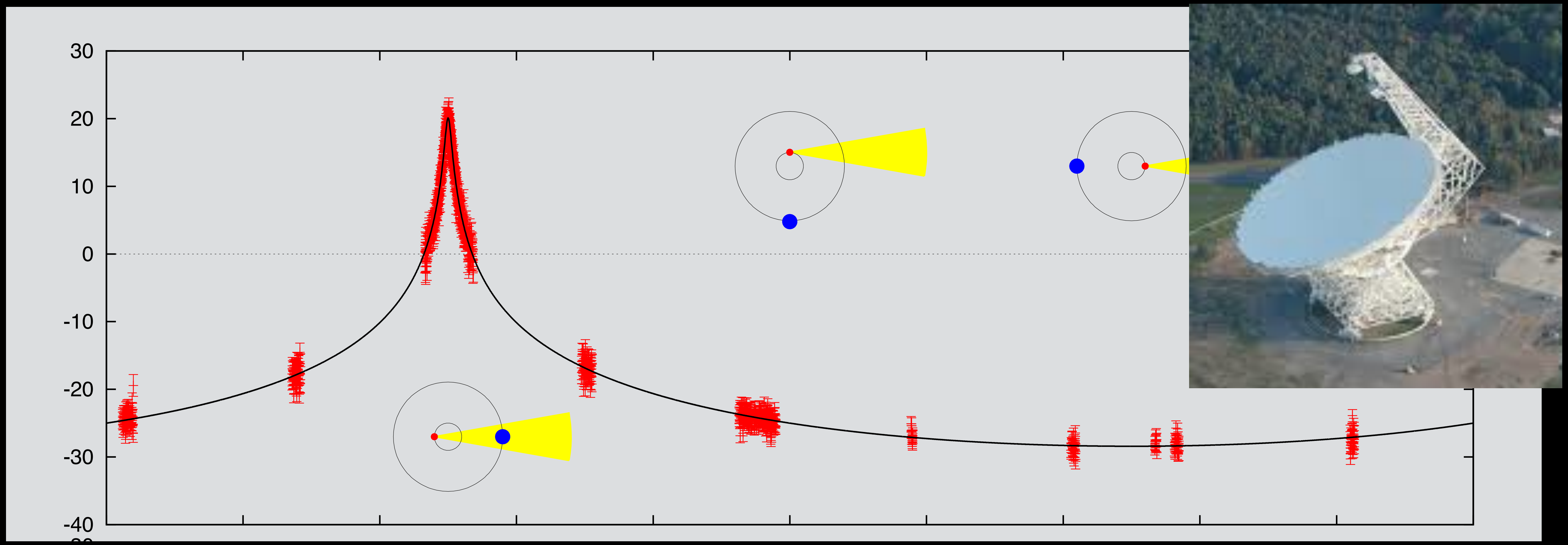
Measuring and interpreting neutron star properties has far reaching implications.

(Relevant to probe its interior)

	EM (Radio, Optical, X-Ray, Gamma Ray)	Neutrinos	Gravitational Waves
Mass	👍		
Radius	🤞		🤞
Tidal Deformability			👍
Spin (t)	👍	👍	🤞
Temperature (t)	🤞	👍	
Seismology	🤞	🤞	👍
Binding Energy		🤞	

Neutron Star Structure: Observations



2 $M_\odot$ neutron stars exist.

PSR J1614-2230: M=1.93(2)

Demorest et al. (2010)

PSR J0348+0432: M=2.01(4) $M_\odot$

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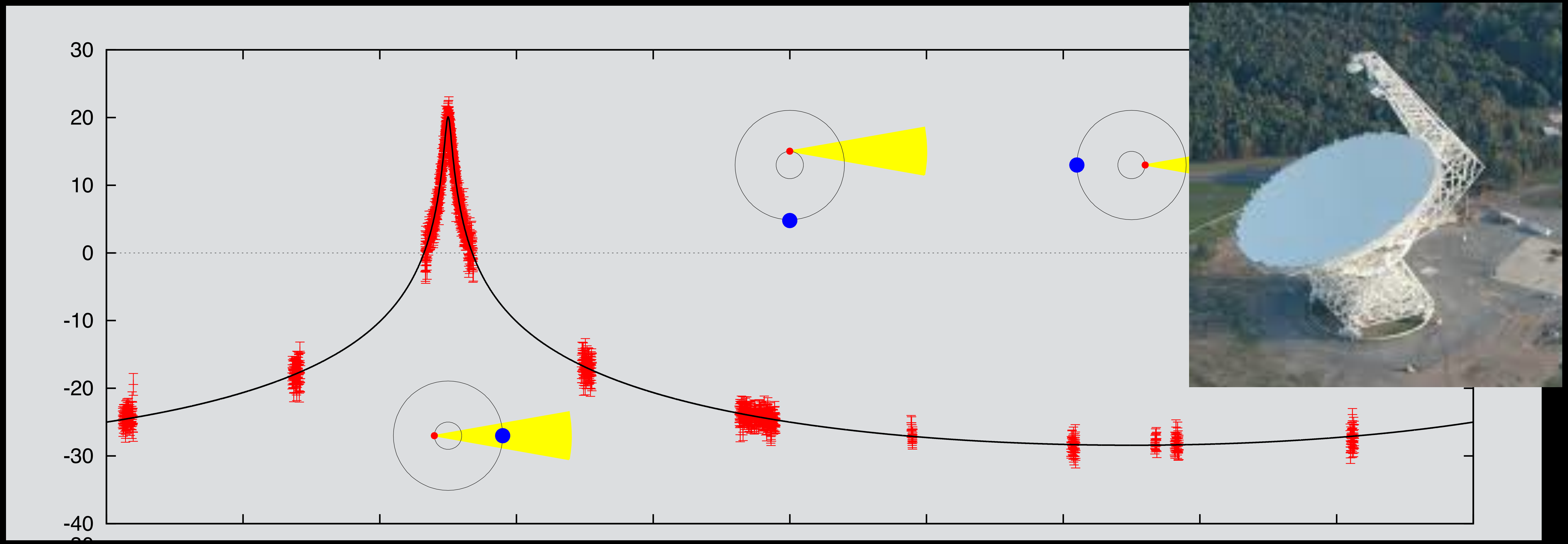

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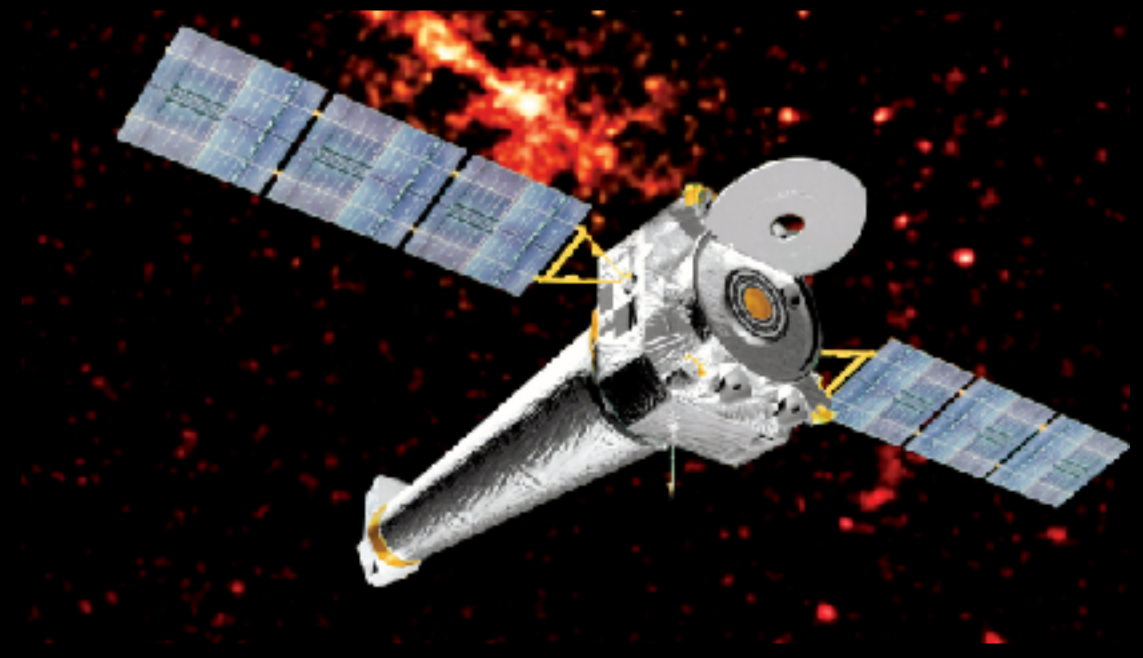
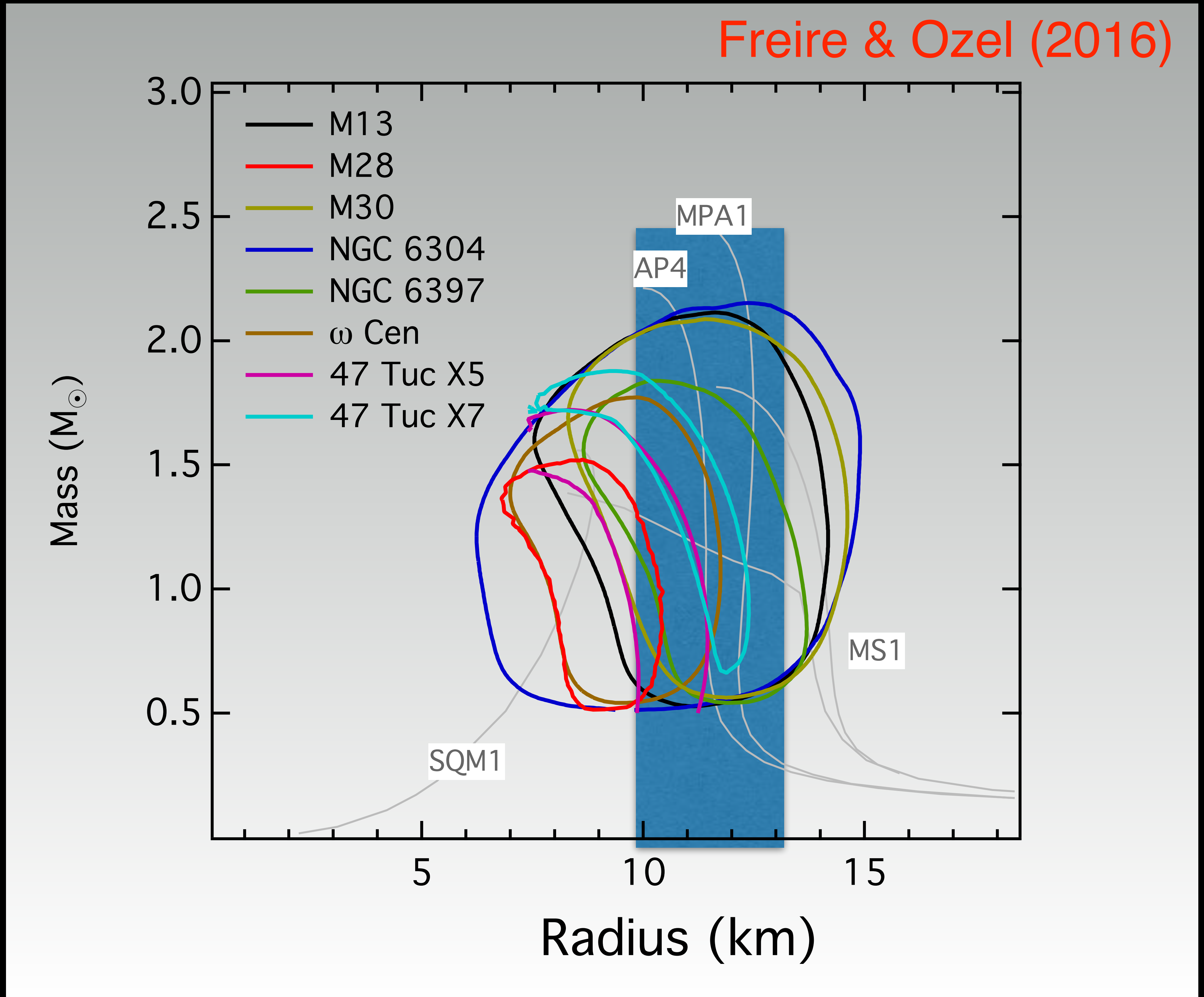




NS radii are difficult to measure:

Poorly understood systematic errors, preclude the determination of NS radius using x-ray observations of surface thermal emission.

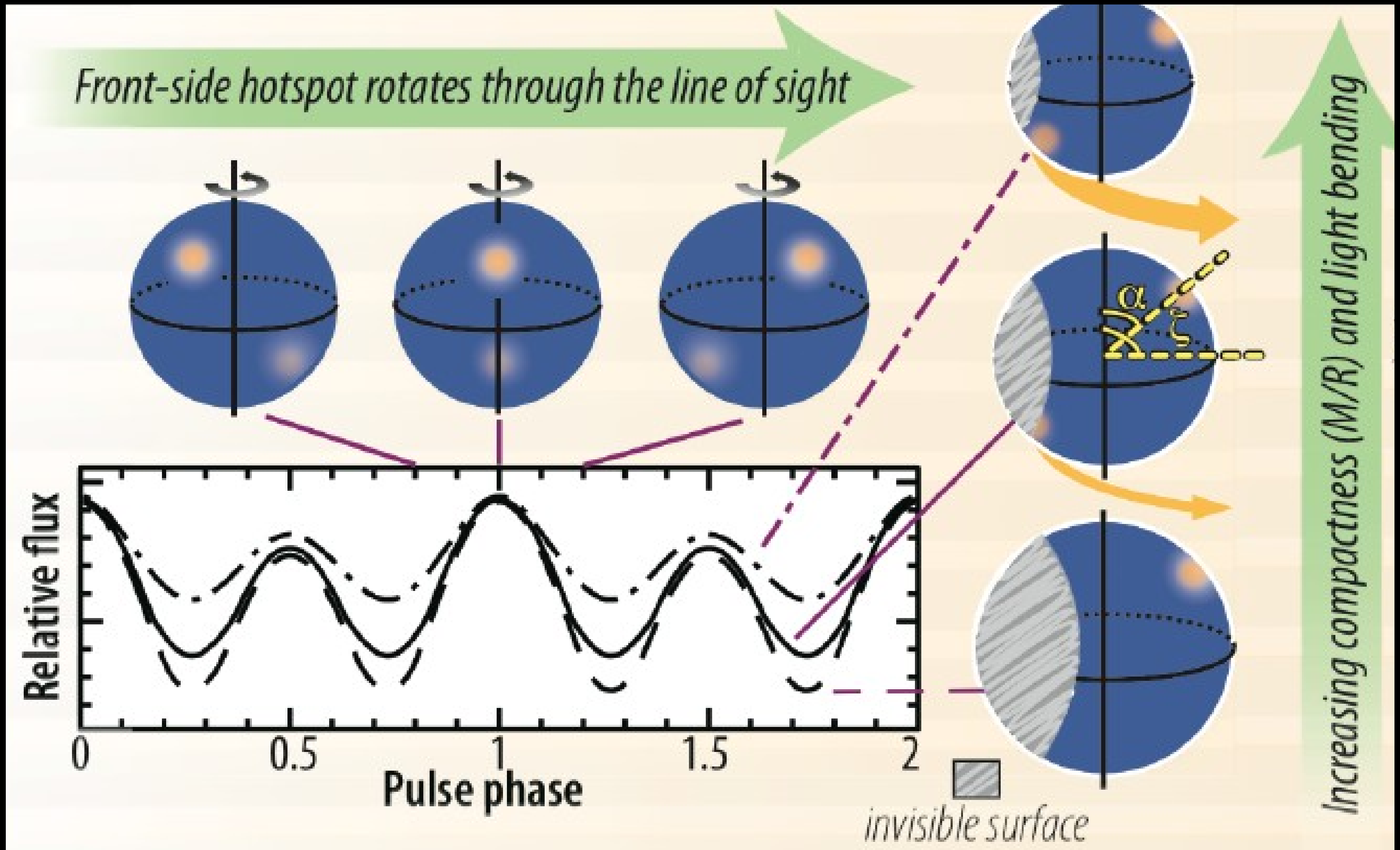
NICER: Radii from Hot Spots

Emission from rotating neutron stars with hot spots is sensitive to space-time geometry.

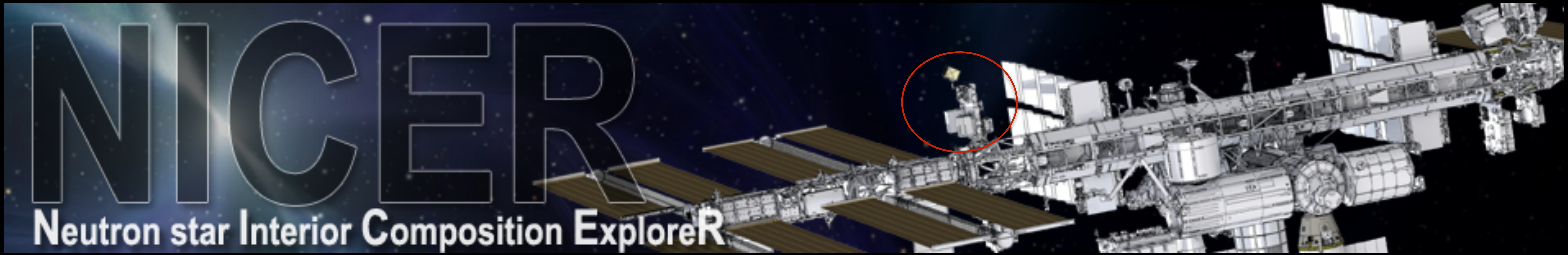
X-ray pulse profiles contain information about the source compactness.

NASA's NICER mission has acquired data from a couple of neutron stars. Modeling of hot spots and their x-ray emission favors radii in the 12-14 km range.

Riley et al. (2019,2021), Miller et al. (2019,2021)



NICER Science Overview Arzoumanian, et. al. (2014)



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PSR J0030:

$$M = 1.44 \pm 0.15 \; M_\odot$$

$$R_e = 12.0 - 14.3 \text{ km}$$

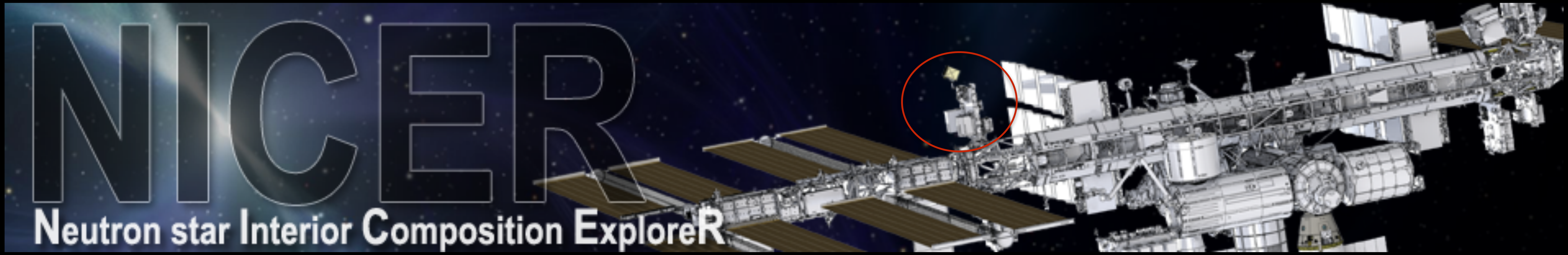
Miller et al. (2019), Riley et al. (2019)

PSR J0740:

$$M = 2.08 \pm 0.07 \; M_\odot$$

$$R_e = 12.2 - 16.3 \text{ km}$$ Miller et al. (2021)

$$R_e = 12.4^{+1.3}_{-1.0} \text{ km}$$ Riley et al. (2021)



GW170817: Gravitational Waves from Neutron Stars

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

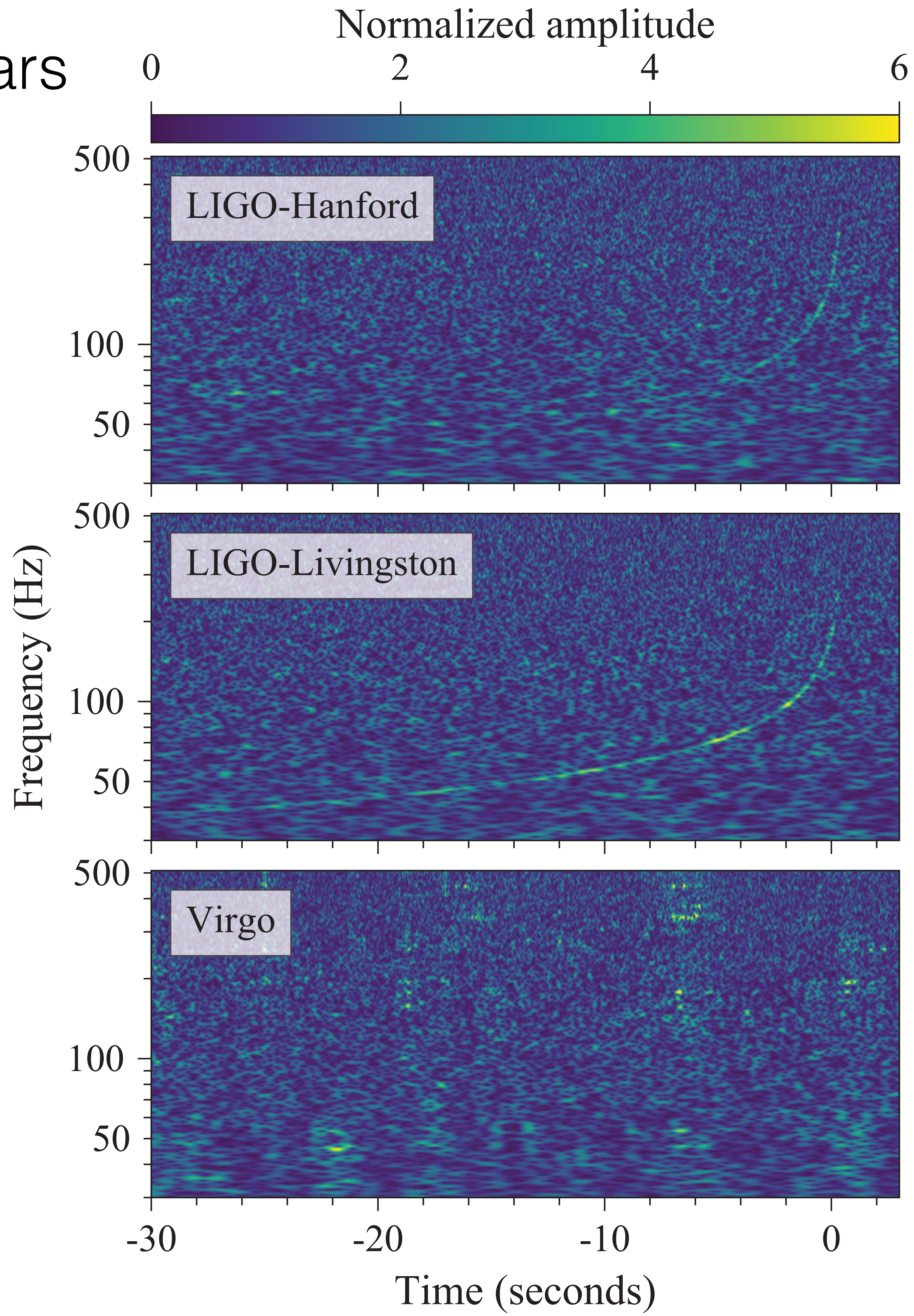
GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral

B. P. Abbott *et al.*[*]
(LIGO Scientific Collaboration and Virgo Collaboration)
(Received 26 September 2017; revised manuscript received 2 October 2017; published 16 October 2017)

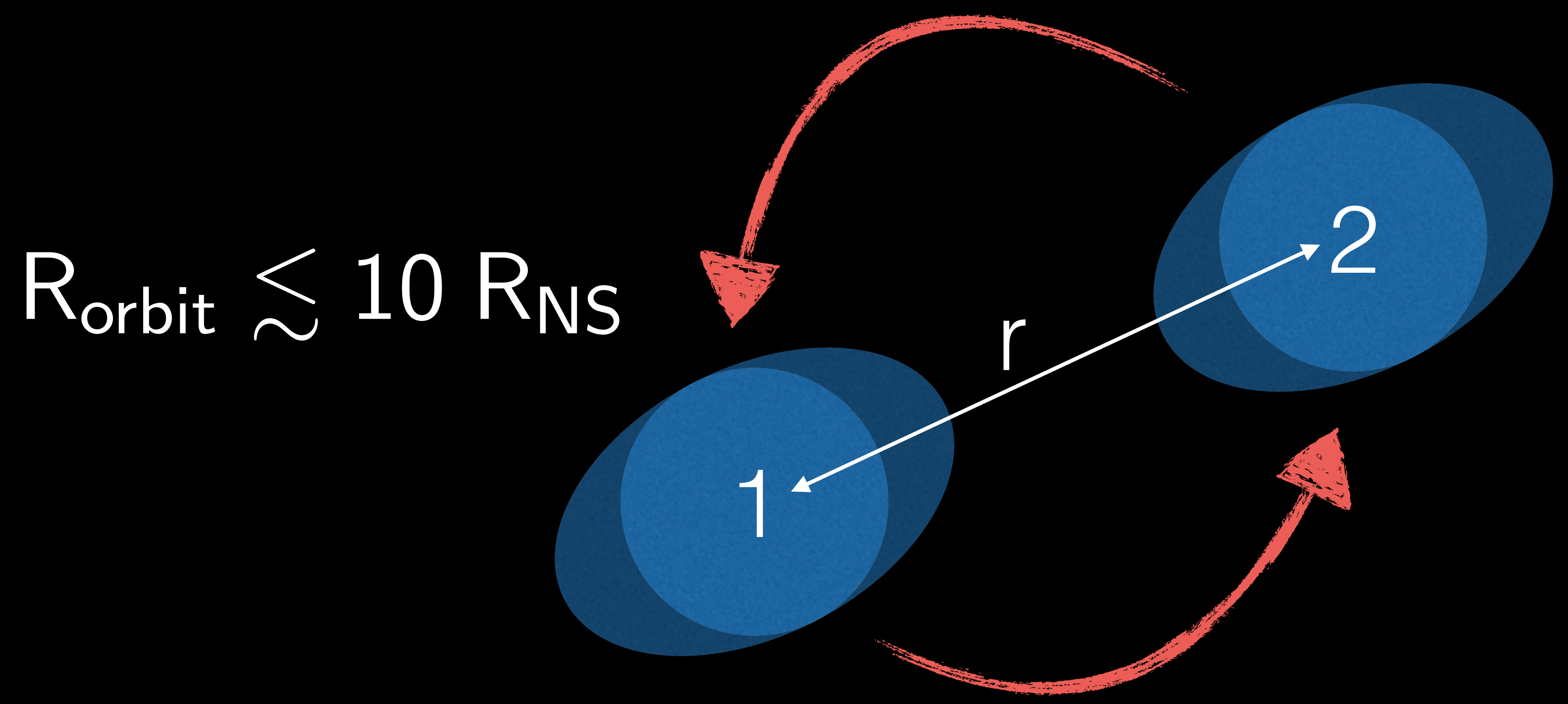
Component masses:
$$m_1 = 1.47 \pm 0.13\ M_\odot$$
$$m_2 = 1.17 \pm 0.09\ M_\odot$$

Chirp Mass: $$\mathscr{M} = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_s)^{1/5}} = 1.188^{+0.004}_{-0.002}\ M_\odot$$

Total Mass: $$M = m_1 + m_2 = 2.74^{+0.04}_{-0.01}\ M_\odot$$



Tidal Deformation: Measuring the Radius with GWs



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

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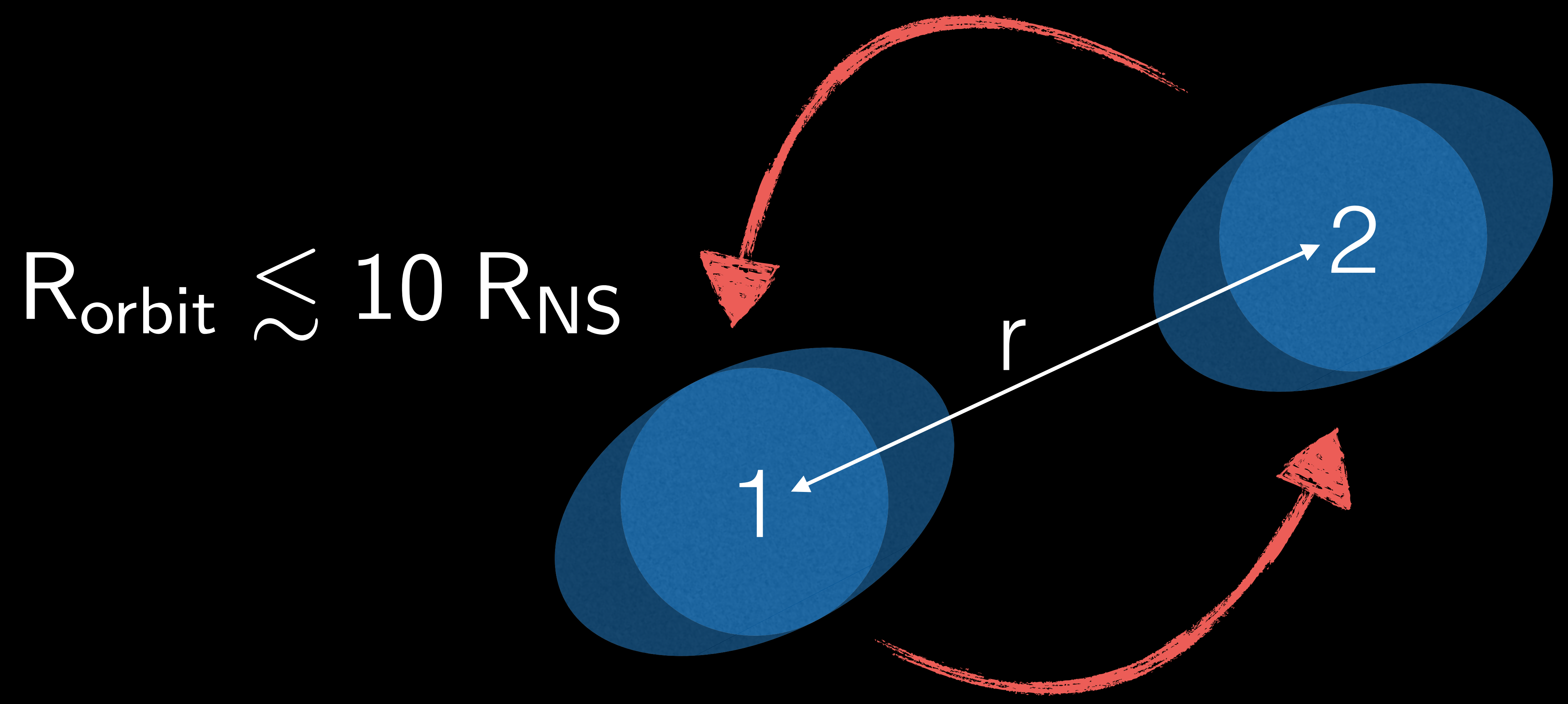

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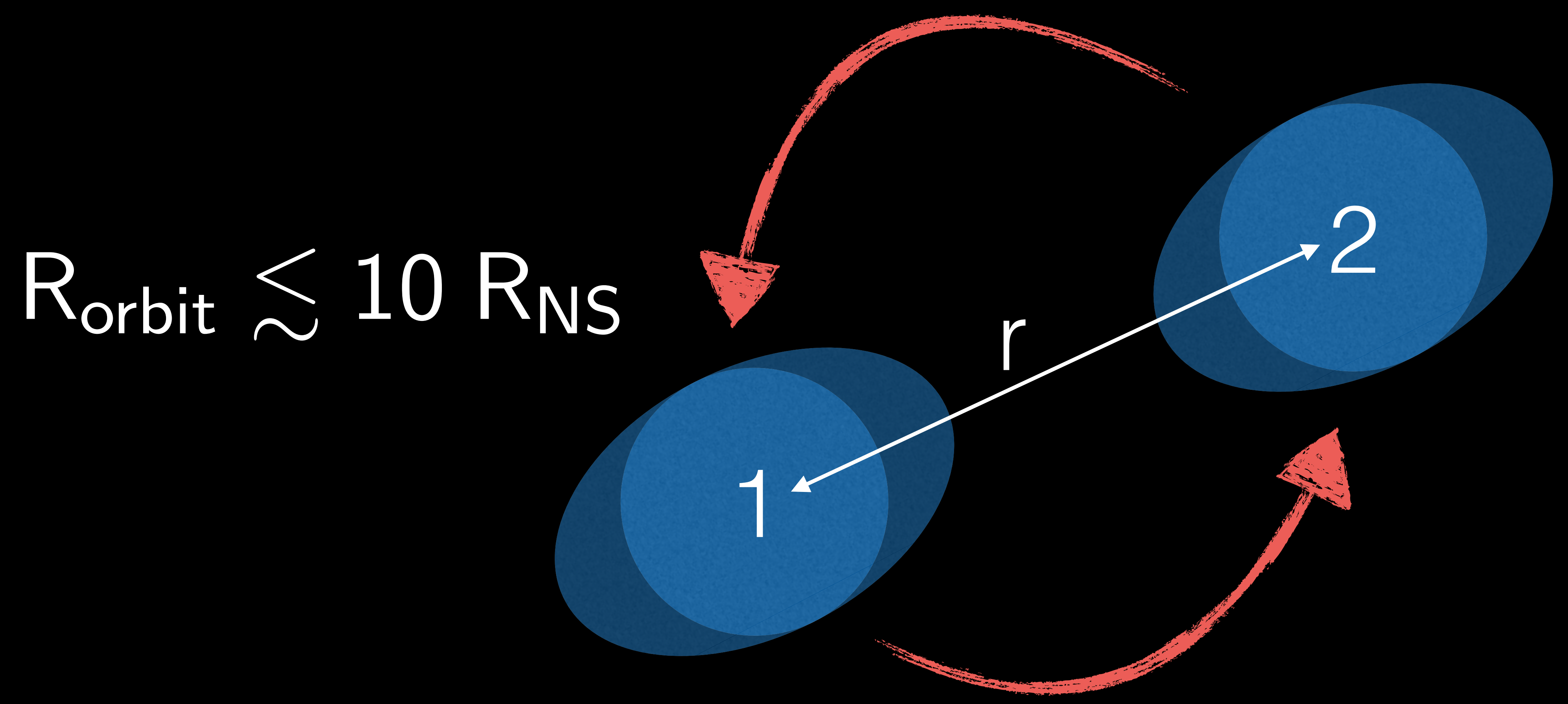

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Dimensionless binary tidal deformability: $\tilde{\Lambda} = \frac{16}{13}\left(\left(\frac{M_1}{M}\right)^5\left(1+\frac{M_2}{M_1}\right)\Lambda_1 + 1 \leftrightarrow 2\right)$

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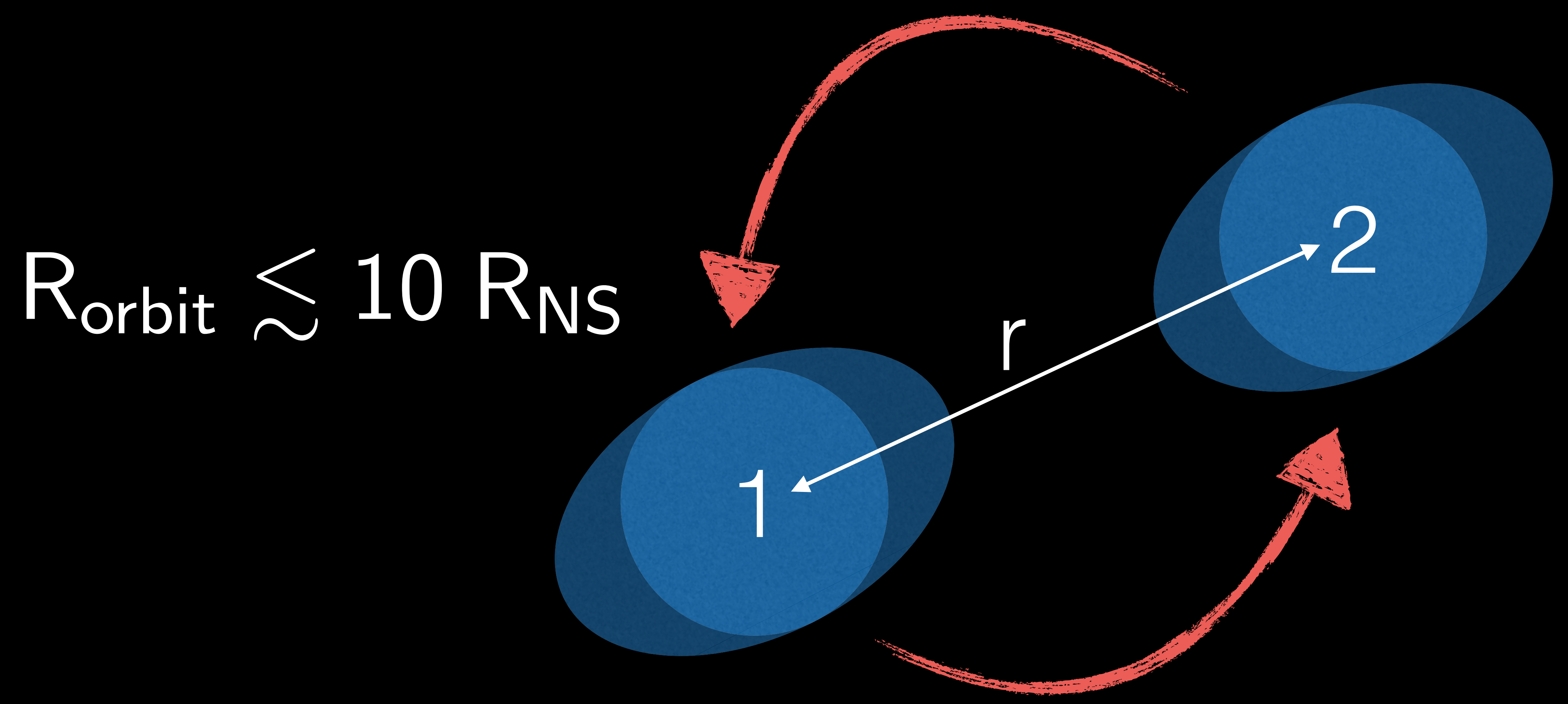

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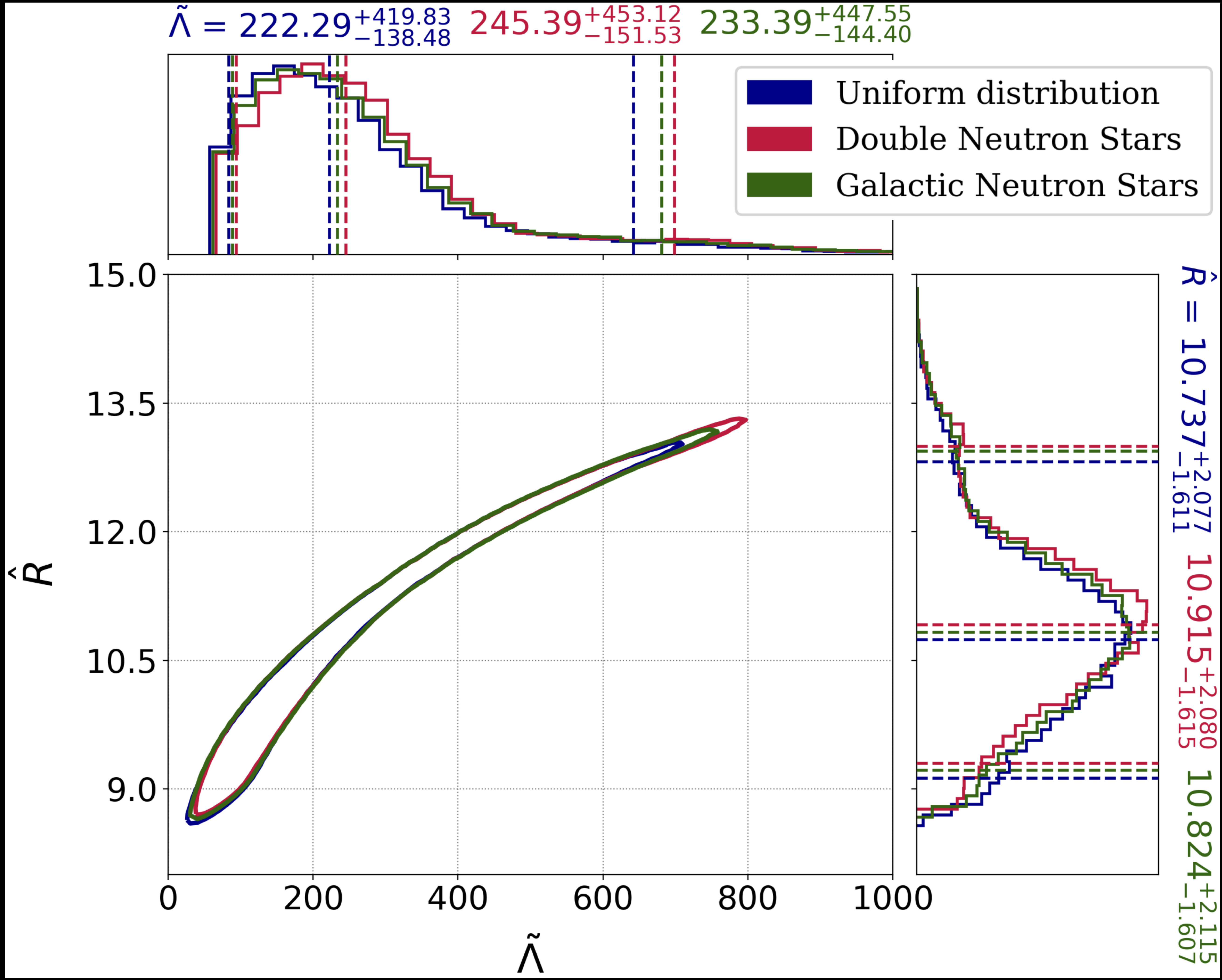
Tidal deformations are large for a large NS: $\Lambda_i = \frac{\lambda_i}{M_i^5} = k_2 \frac{R_i^5}{M_i^5}$

Radius constraints from GW170817

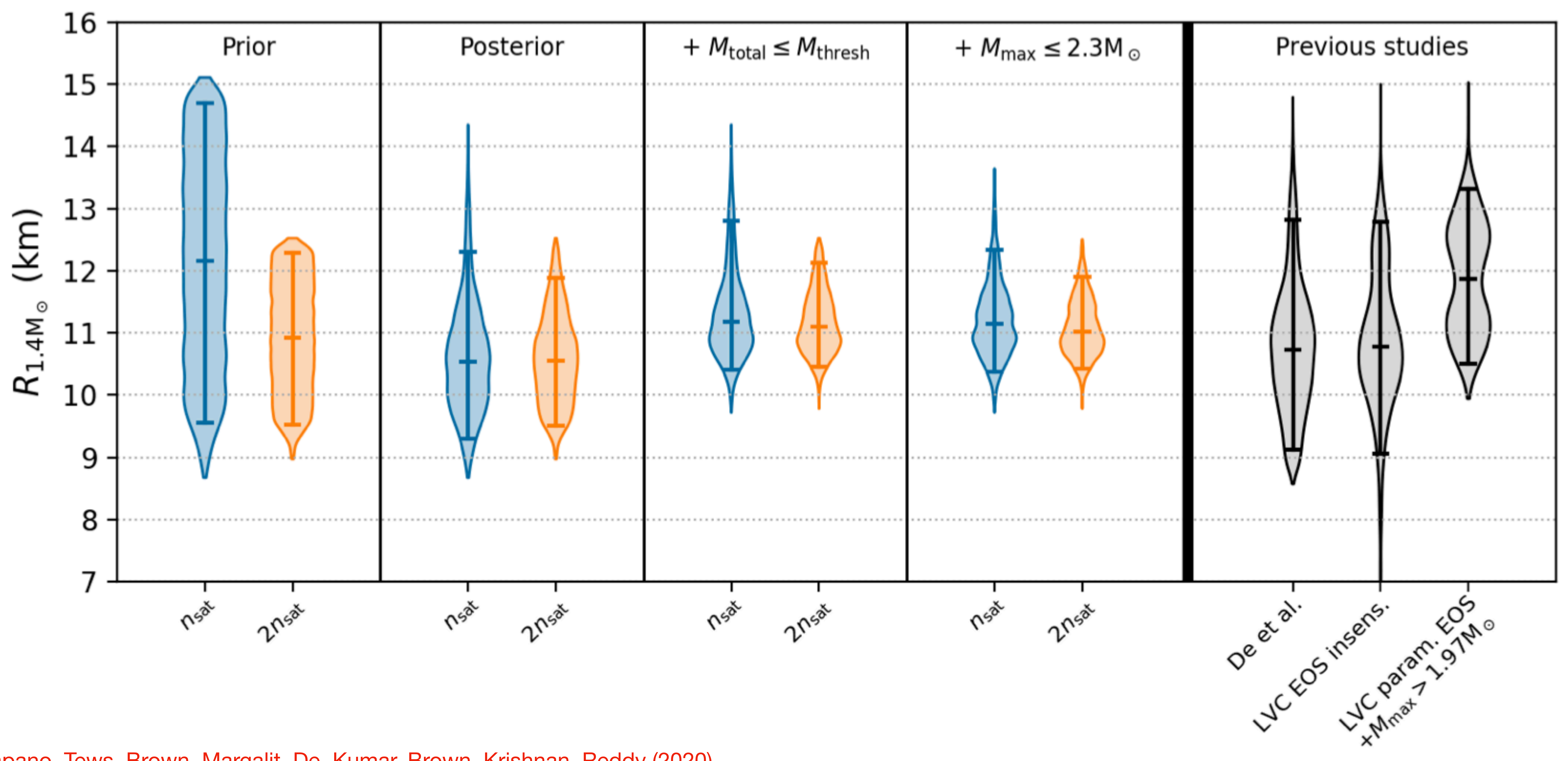


Tidal deformations (not) observed in GW170817 implies a small NS radius: R < 13 km

One can combine additional information from nuclear physics and electromagnetic observations to improve the constraint.

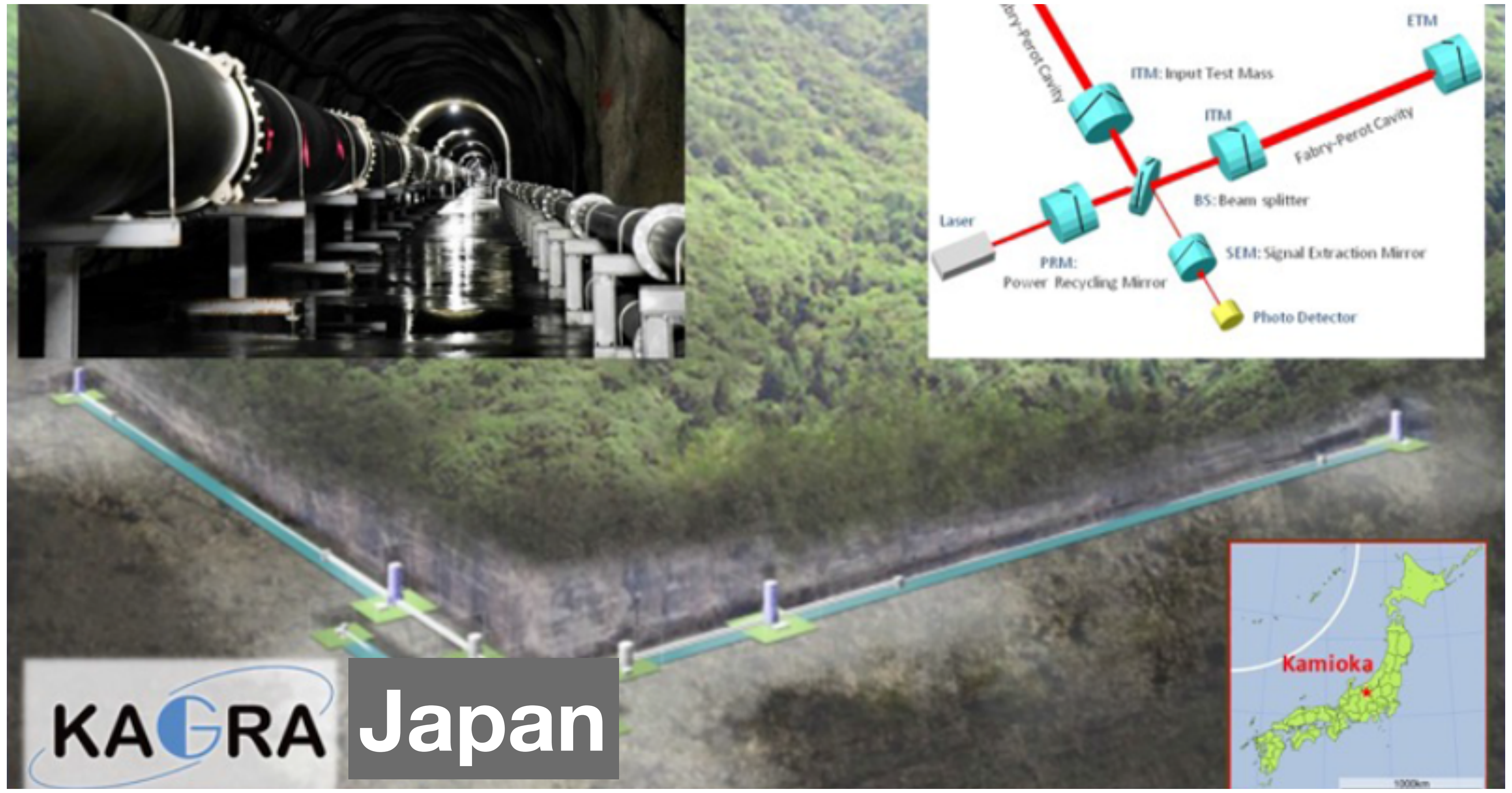
De et al. PRL (2018)
See also LIGO and Virgo Scientific Collaboration arXiV:1805.11581v1

Radius constraints from GW170817

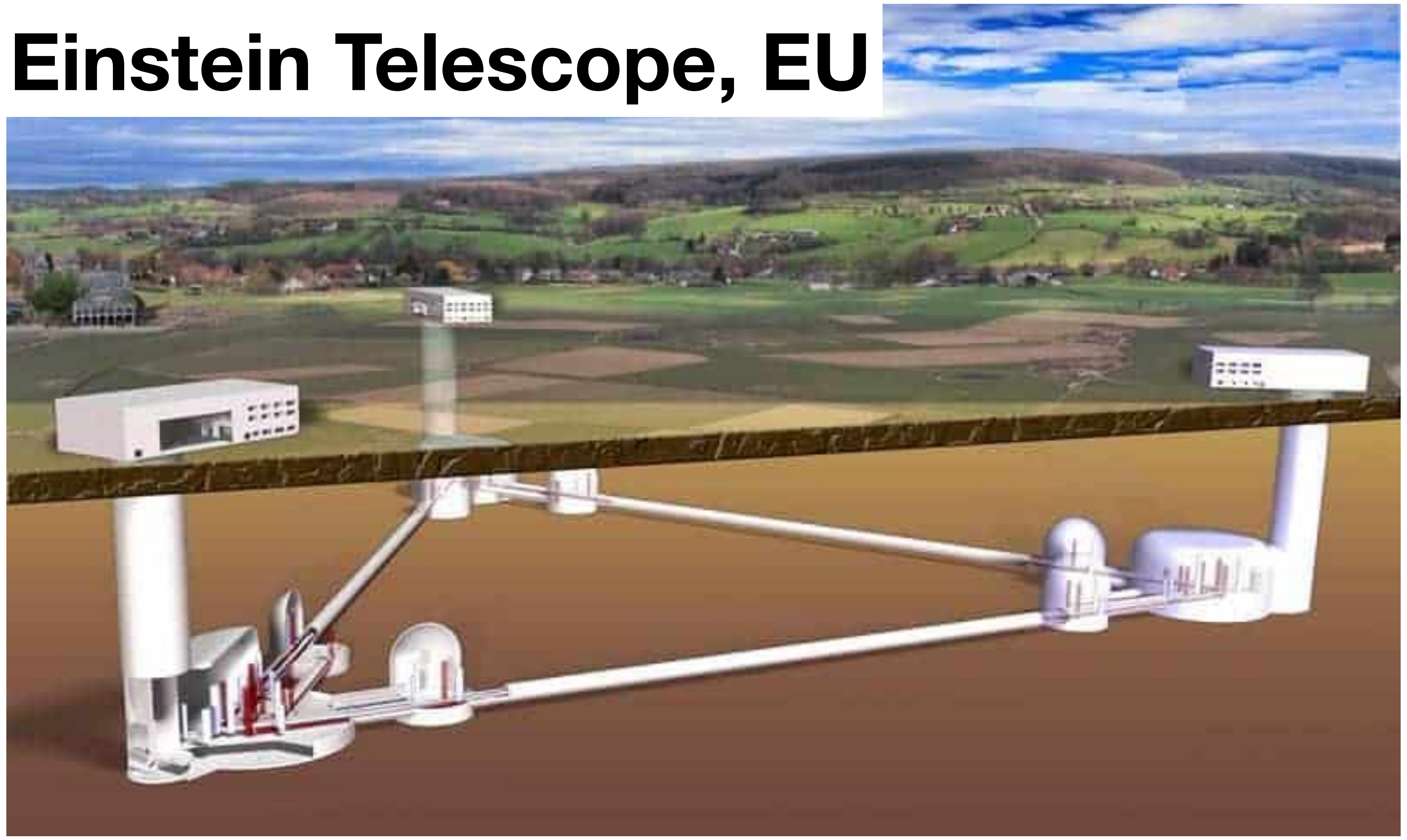


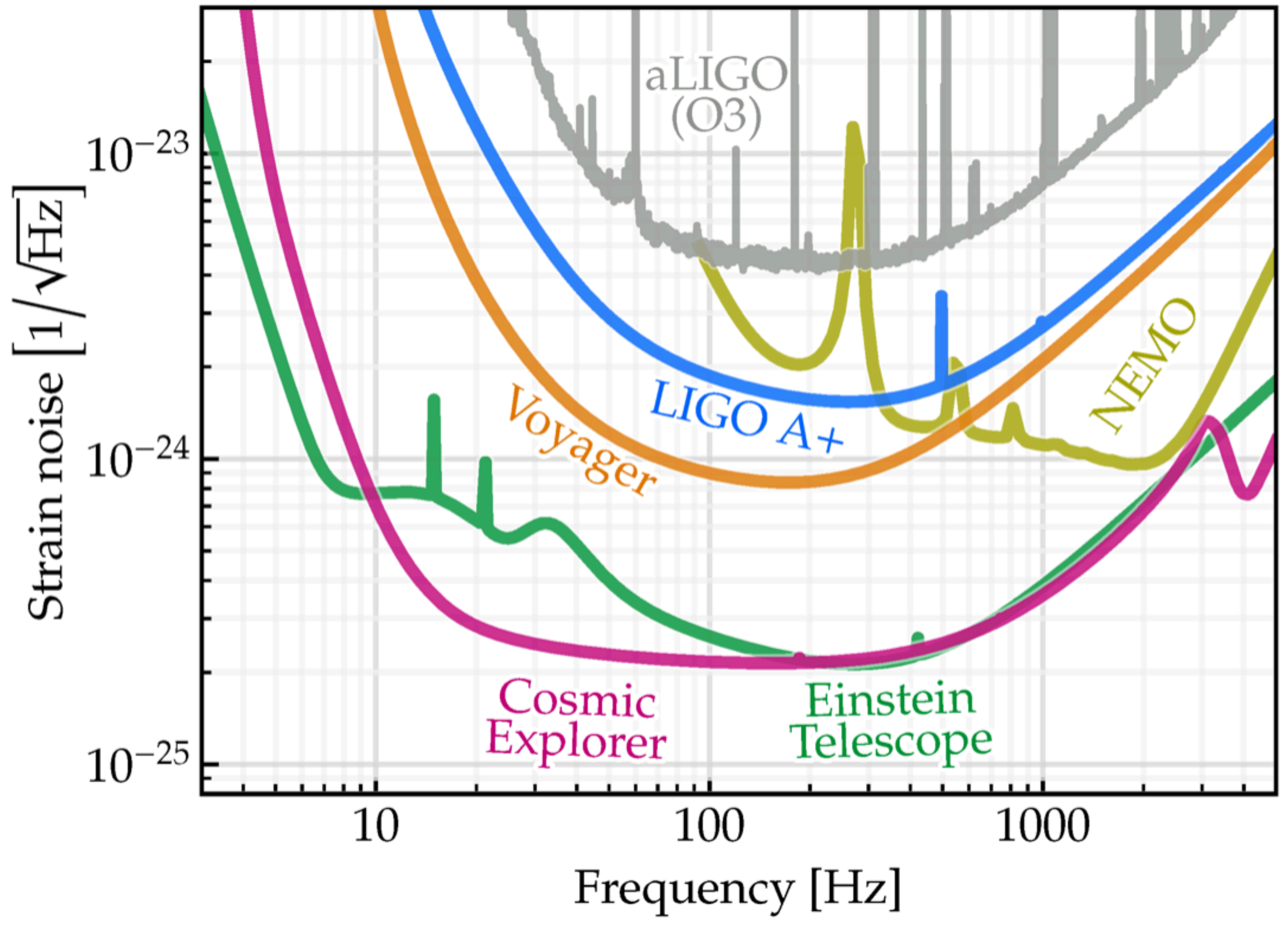
Capano, Tews, Brown, Margalit, De, Kumar, Brown, Krishnan, Reddy (2020)


LIGO India


ETM
ITM: Input Test Mass
ITM
Fabry-Perot Cavity
Laser
BS: Beam splitter
PRM:
Power Recycling Mirror
SEM: Signal Extraction Mirror
Photo Detector
Kamioka
KAGRA
Japan


Cosmic Explorer, USA

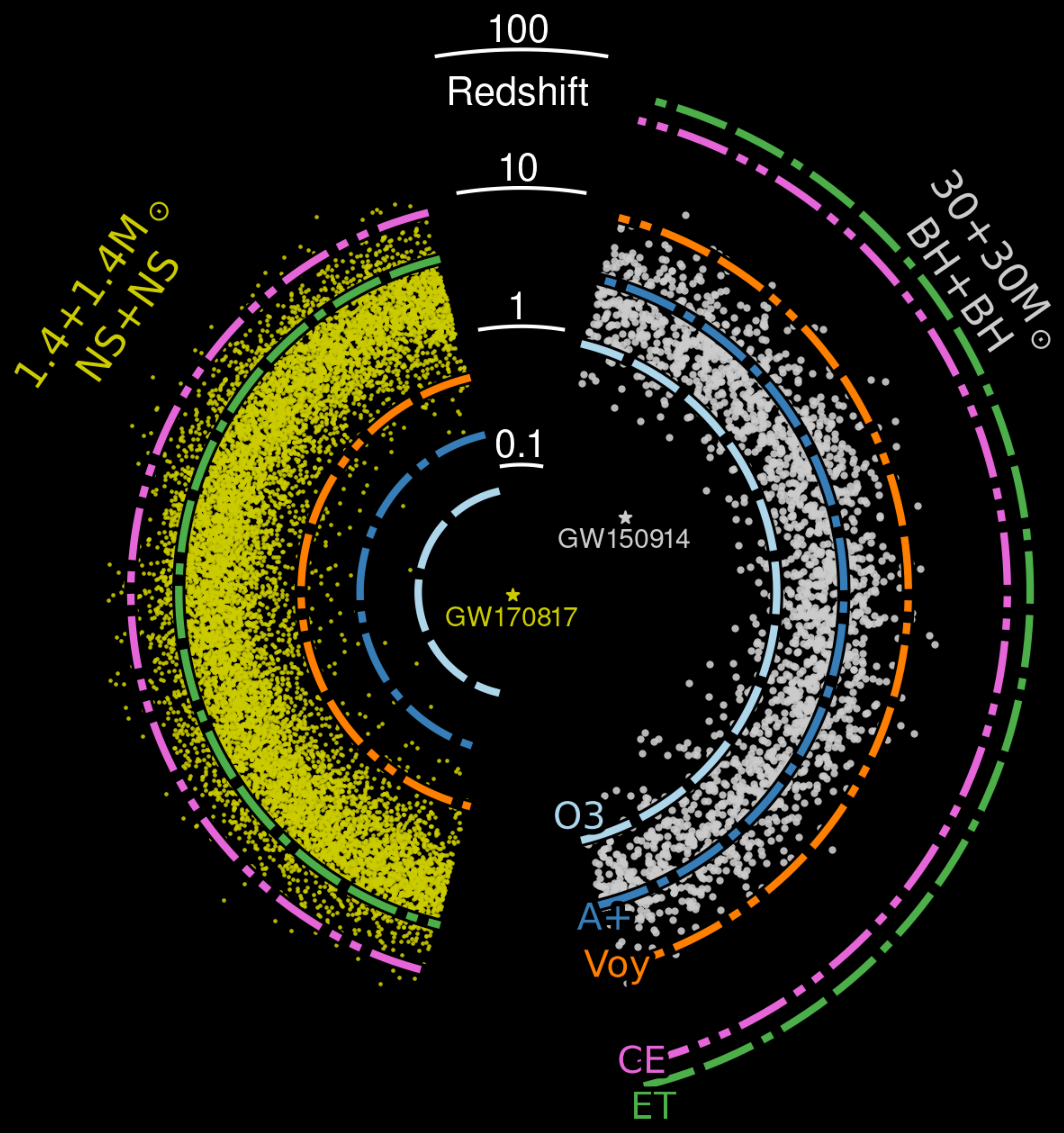

Einstein Telescope, EU



aLIGO (O3)
LIGO A+
Voyager
NEMO
Cosmic Explorer
Einstein Telescope
10^{-23}
10^{-24}
10^{-25}
Strain noise $[1/\sqrt{\mathrm{Hz}}]$
10
100
1000
Frequency [Hz]

Golden Age for Compact Object Astrophysics

- We anticipate a wealth of new data relating to compact object mergers during the next 10-20 years.
- GW astronomy is poised to detect all mergers with staggering event rates!



Next-generation GW detectors will detect > 20,000 BNS/year

About 100 events/year will be provide precise (error < 10%) measurements of NS masses and radii.

Animation Credit: NASA's Goddard Space Flight Center/CI Lab

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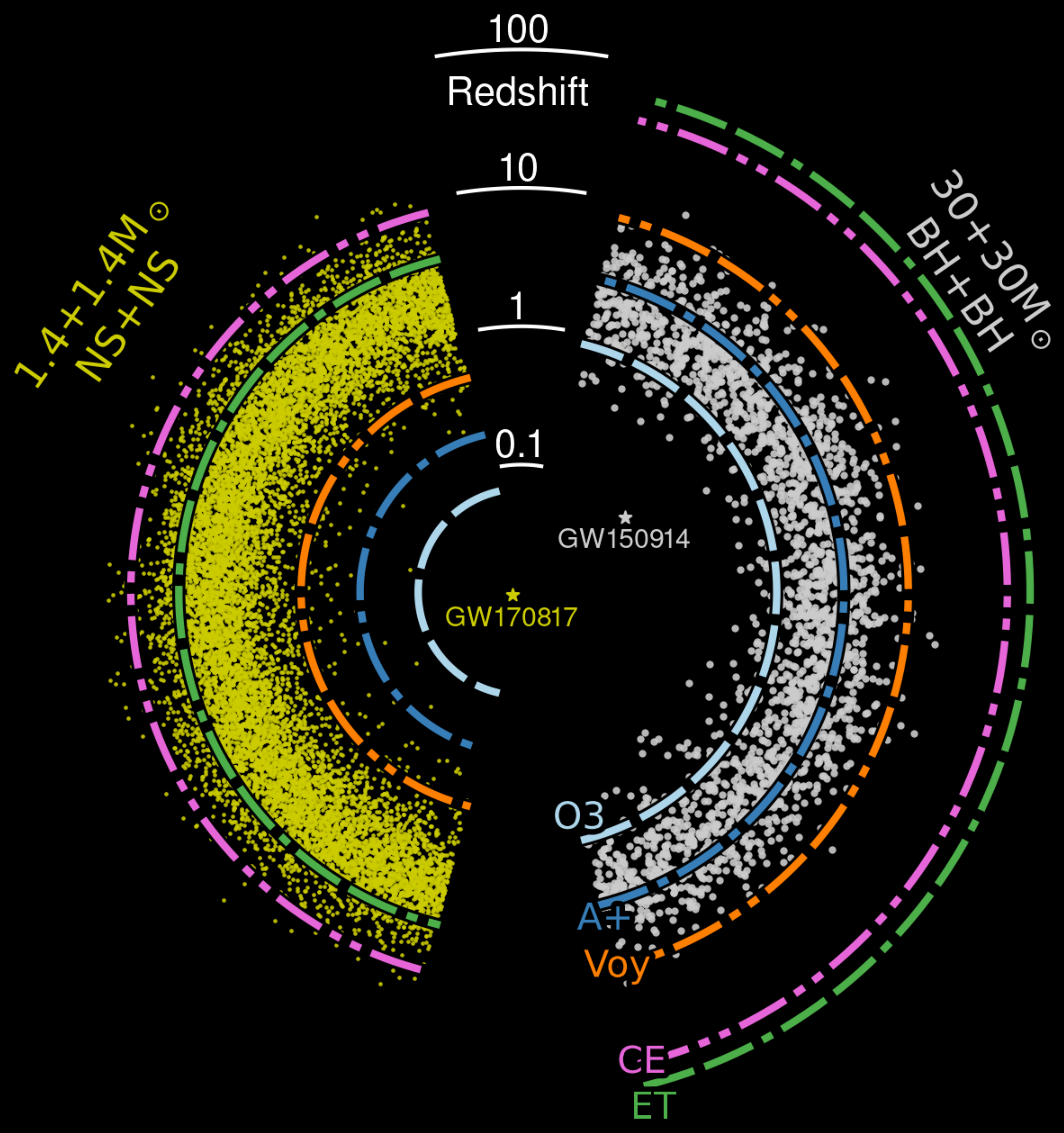

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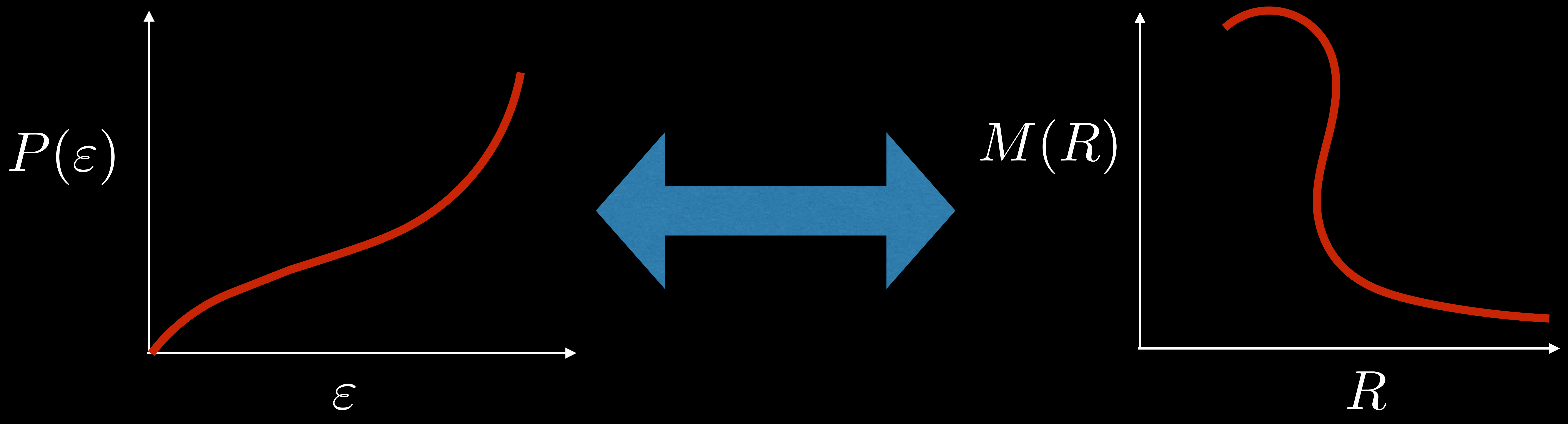

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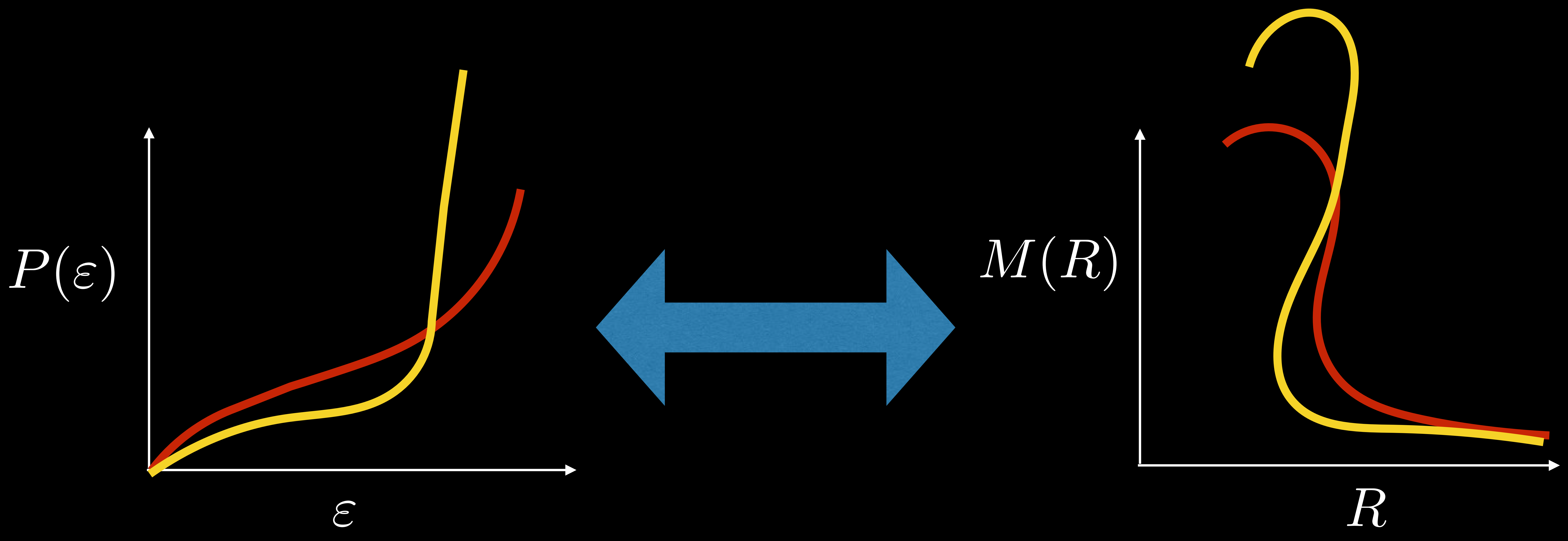

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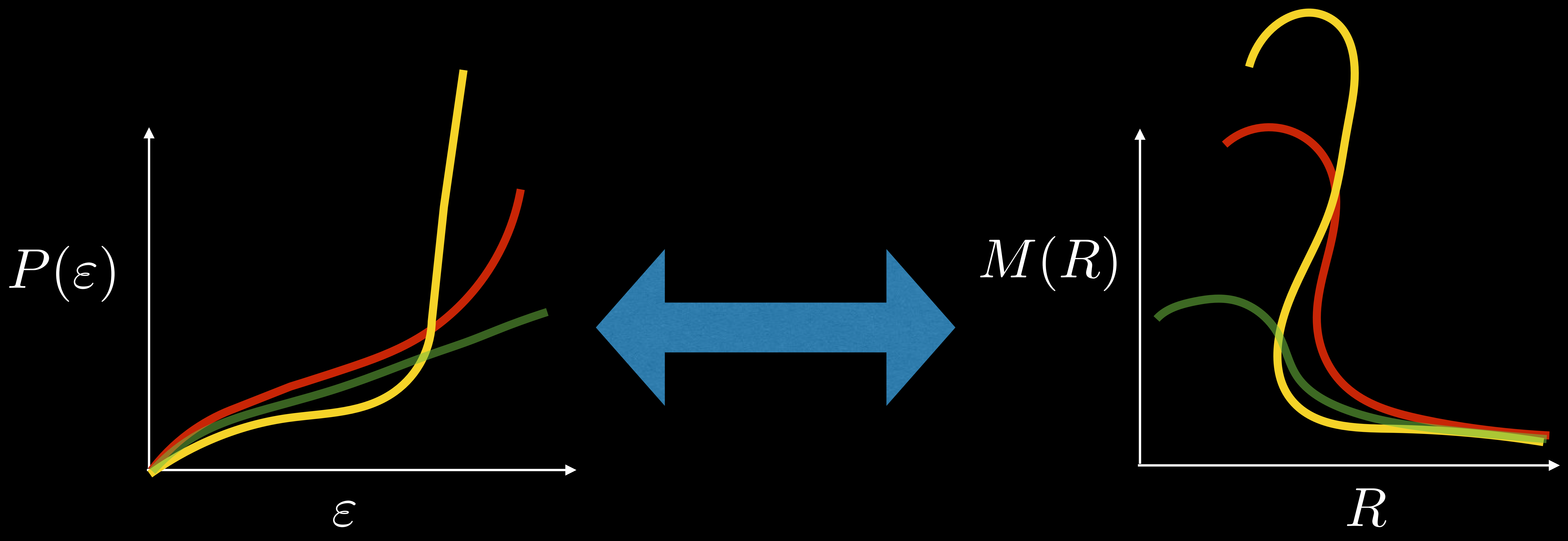

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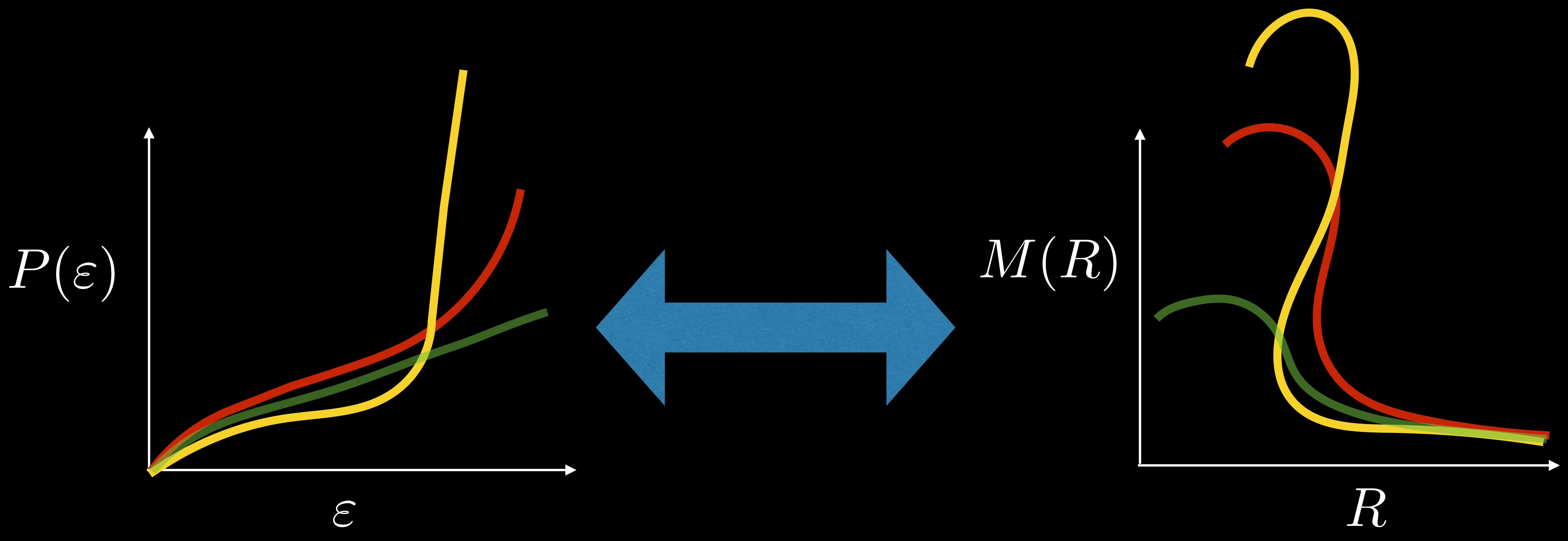
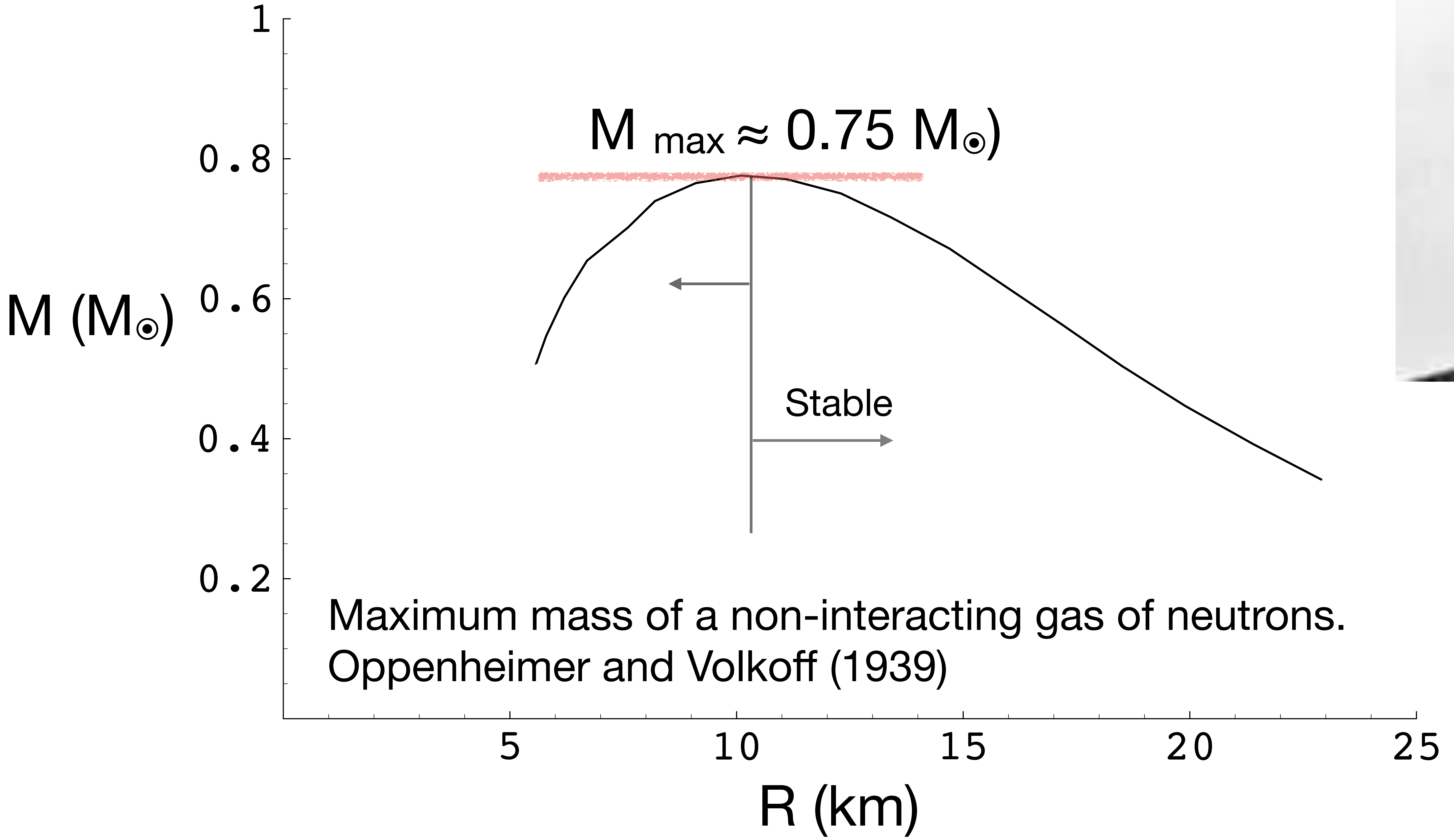


$$P(\varepsilon) + \text{Gen.Rel.} = M(R)$$

A small radius and large maximum mass implies a rapid transition from low pressure to high pressure with density.

Interactions Matter



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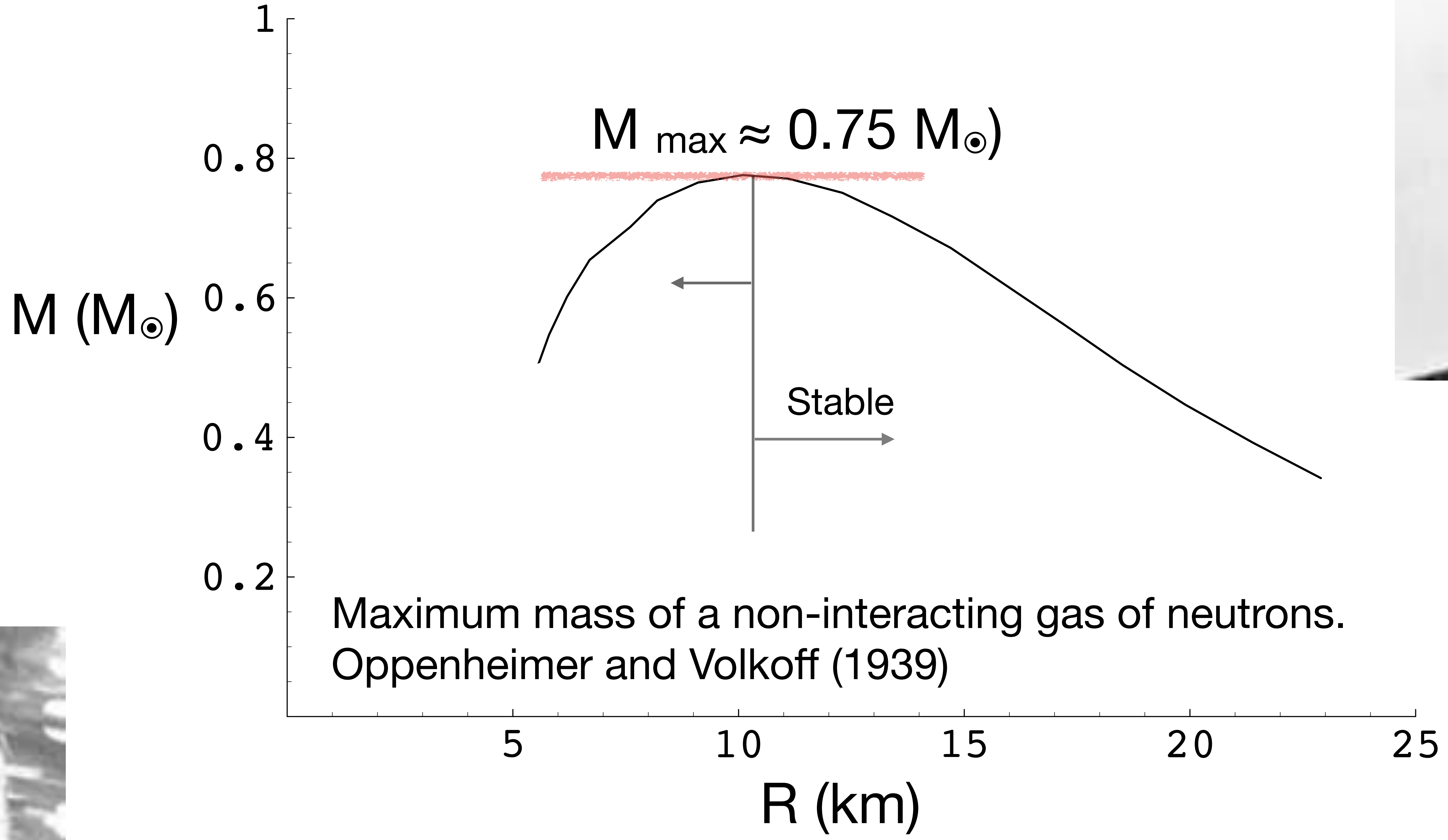

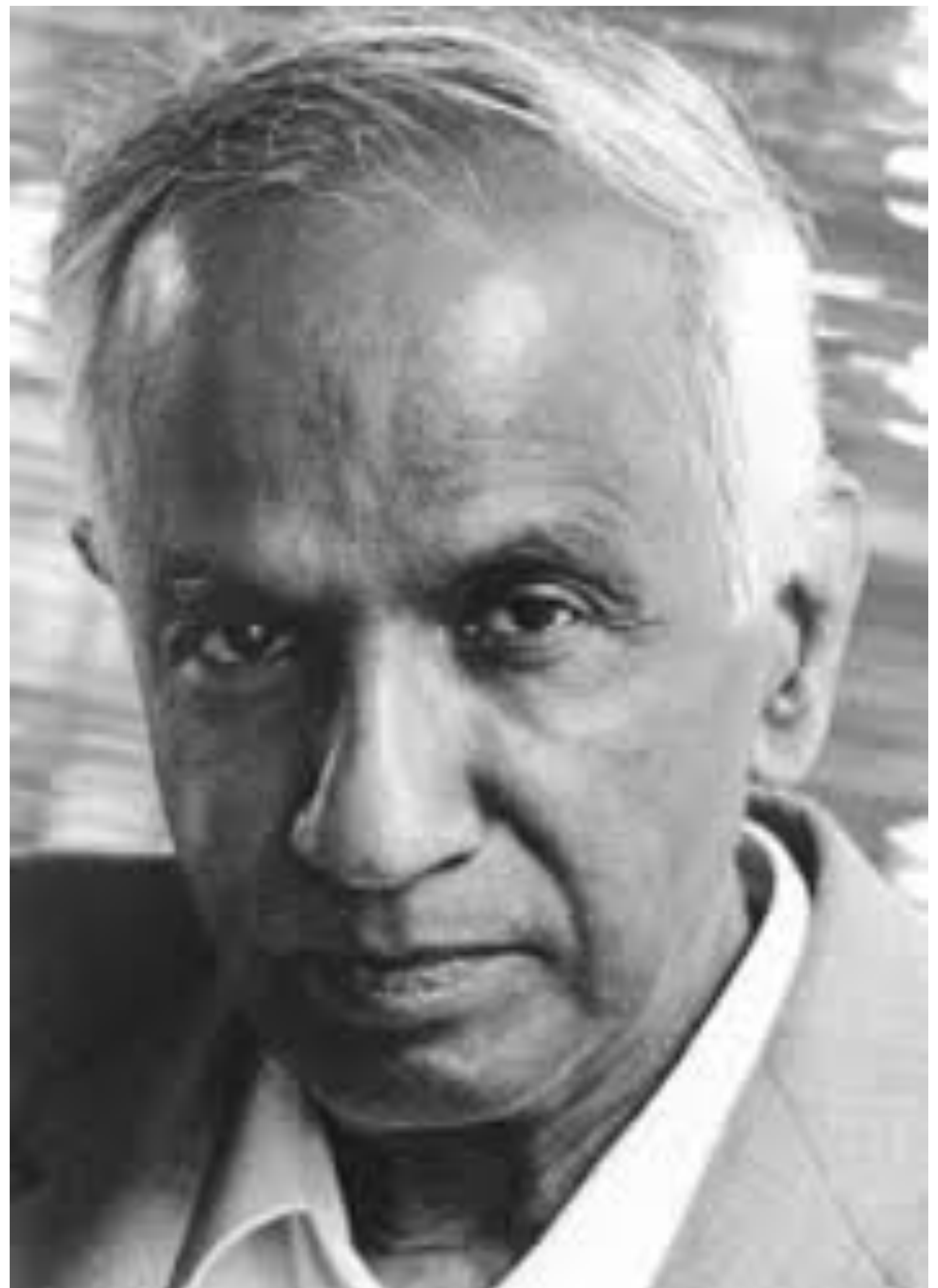

Chandrashekar had already shown that electron degeneracy pressure would support an iron core ~ 1.4 $M_\odot$ in massive stars.

If Oppenheimer's calculation of the maximum mass was correct neutron stars would not exist ! Neither would supernova !

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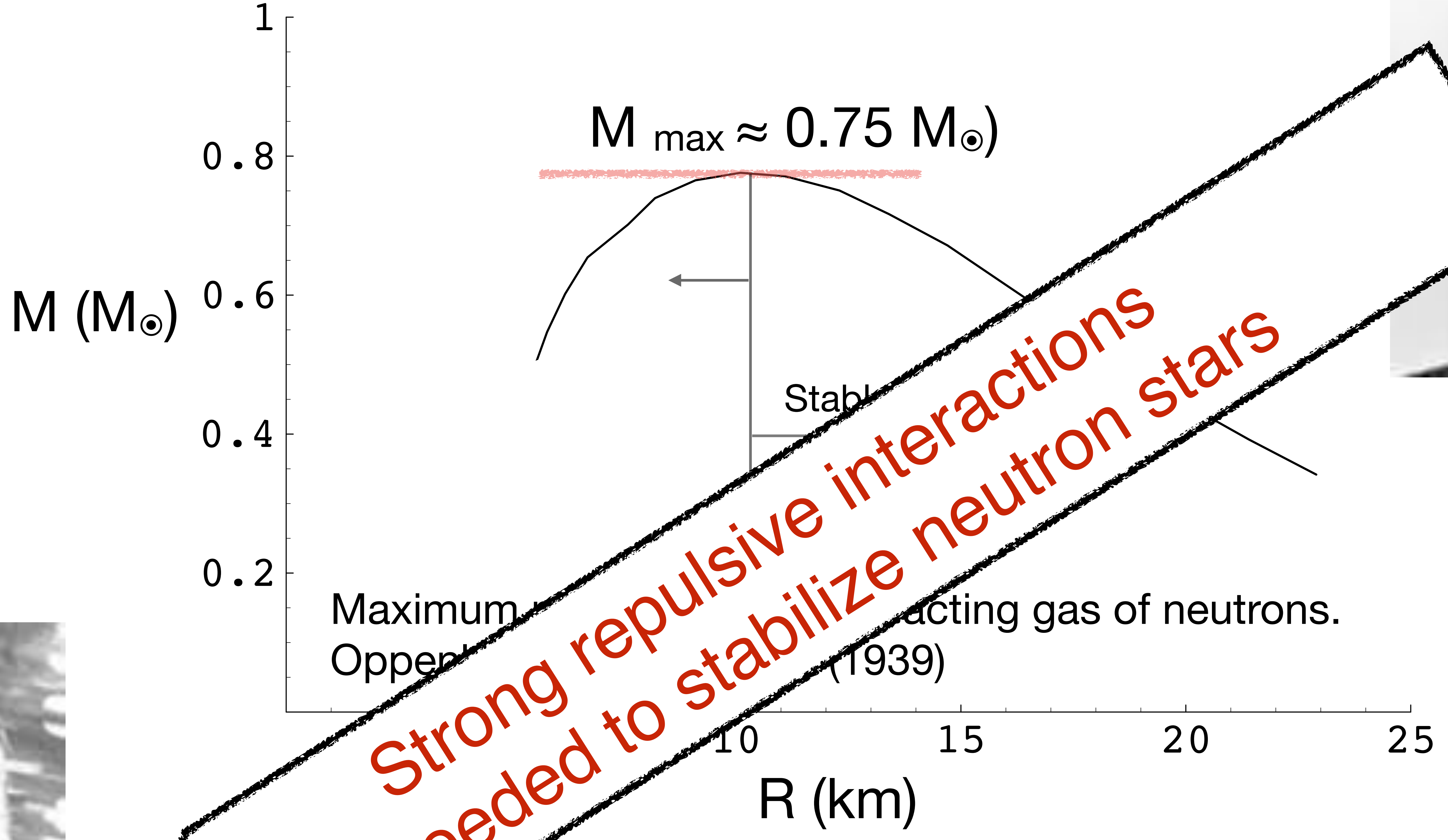

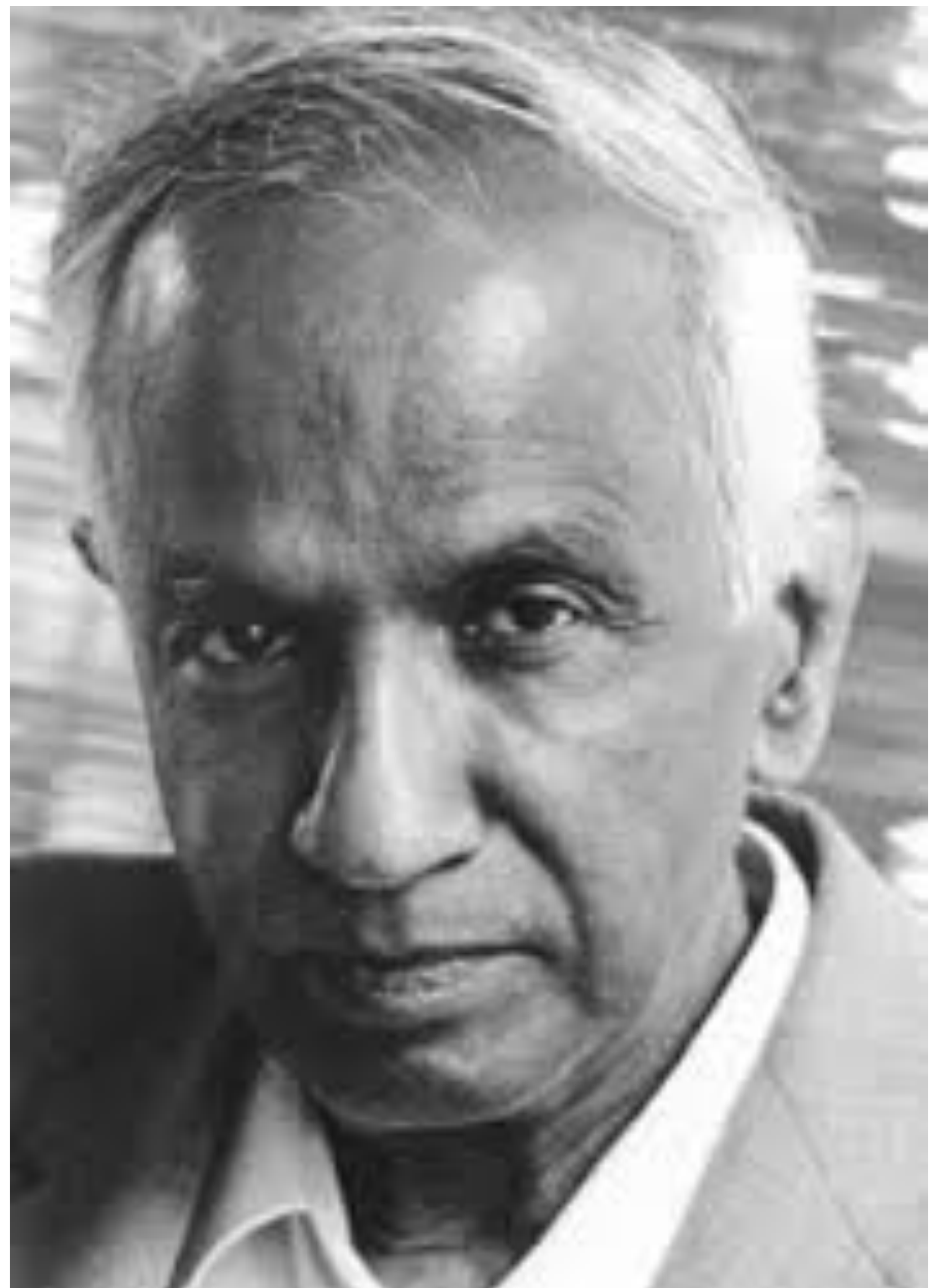

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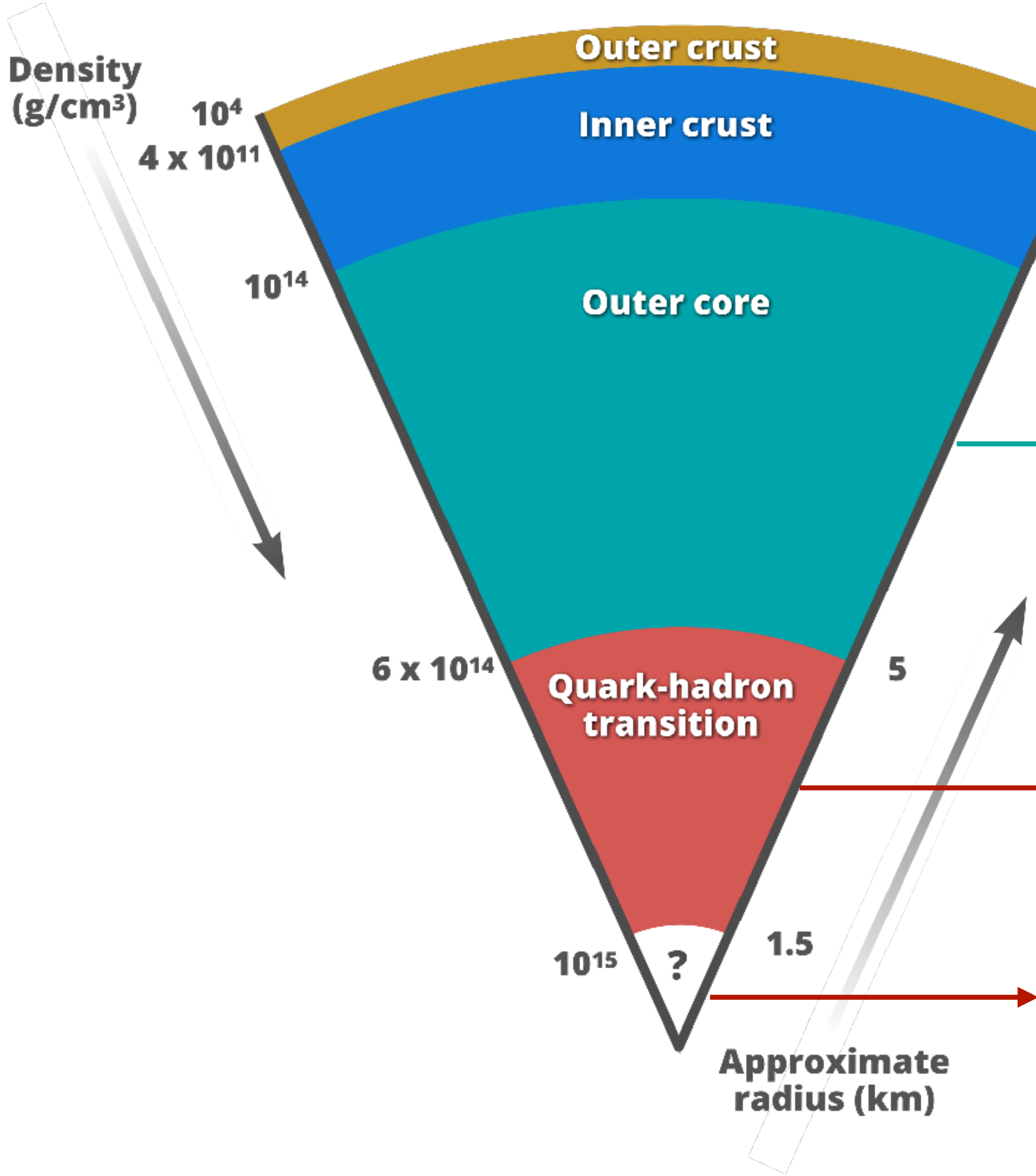
Inside Neutron Stars



Nuclei and relativistic electrons.

Neutron-rich nuclei, relativistic electrons, superfluid neutrons

Neutrons (~ 90%), protons, relativistic electrons, muons. Description in terms of baryons remains useful. Superfluid neutrons & superconducting protons.

Complex strongly interacting relativistic matter. Description not simple in terms of either baryons or quarks. Quarkyonic Matter?

Ordered quark matter? color superconductor?

General Constraints on the Equation of State

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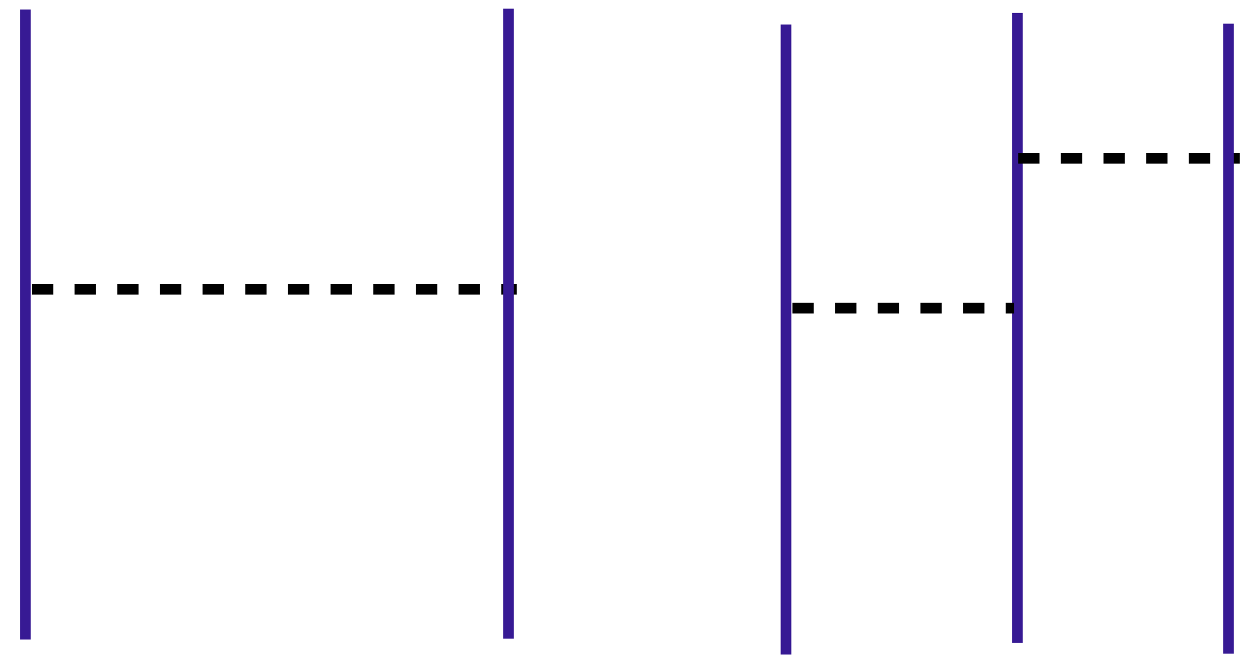
Nuclear Interactions and Many Body Theory

$$H_{\text{nuclear}} = \frac{\nabla^2}{2M} + V_{\text{NN}} + V_{\text{NNN}} + \cdots$$



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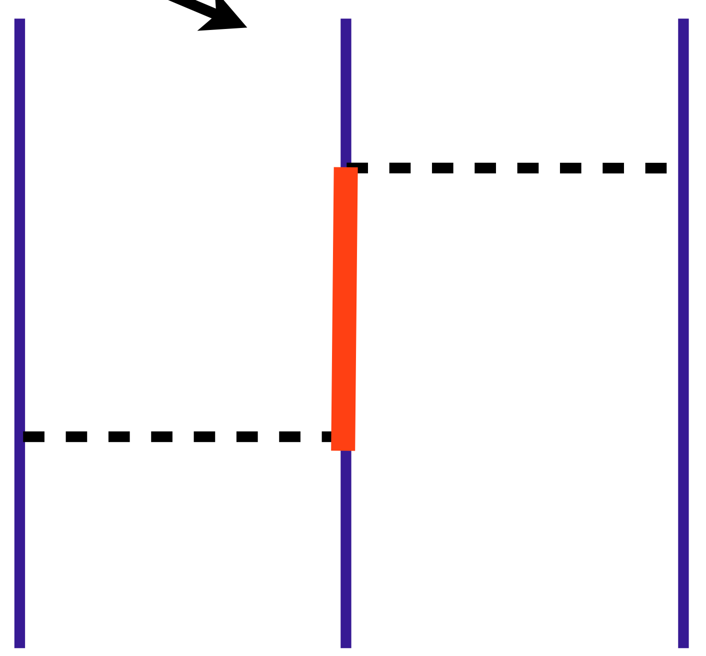

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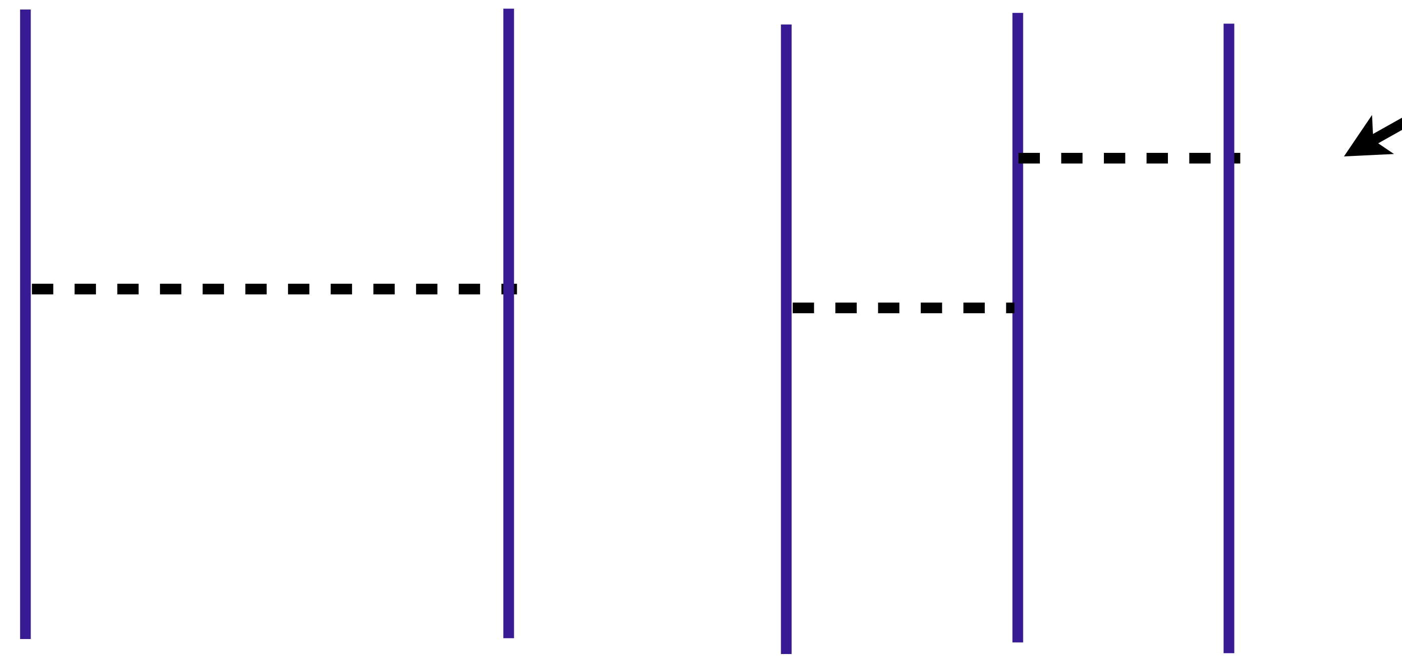

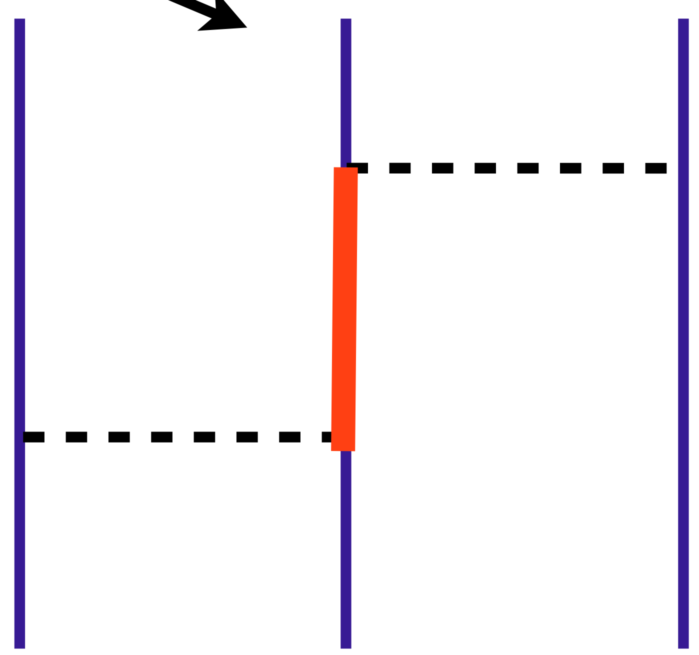

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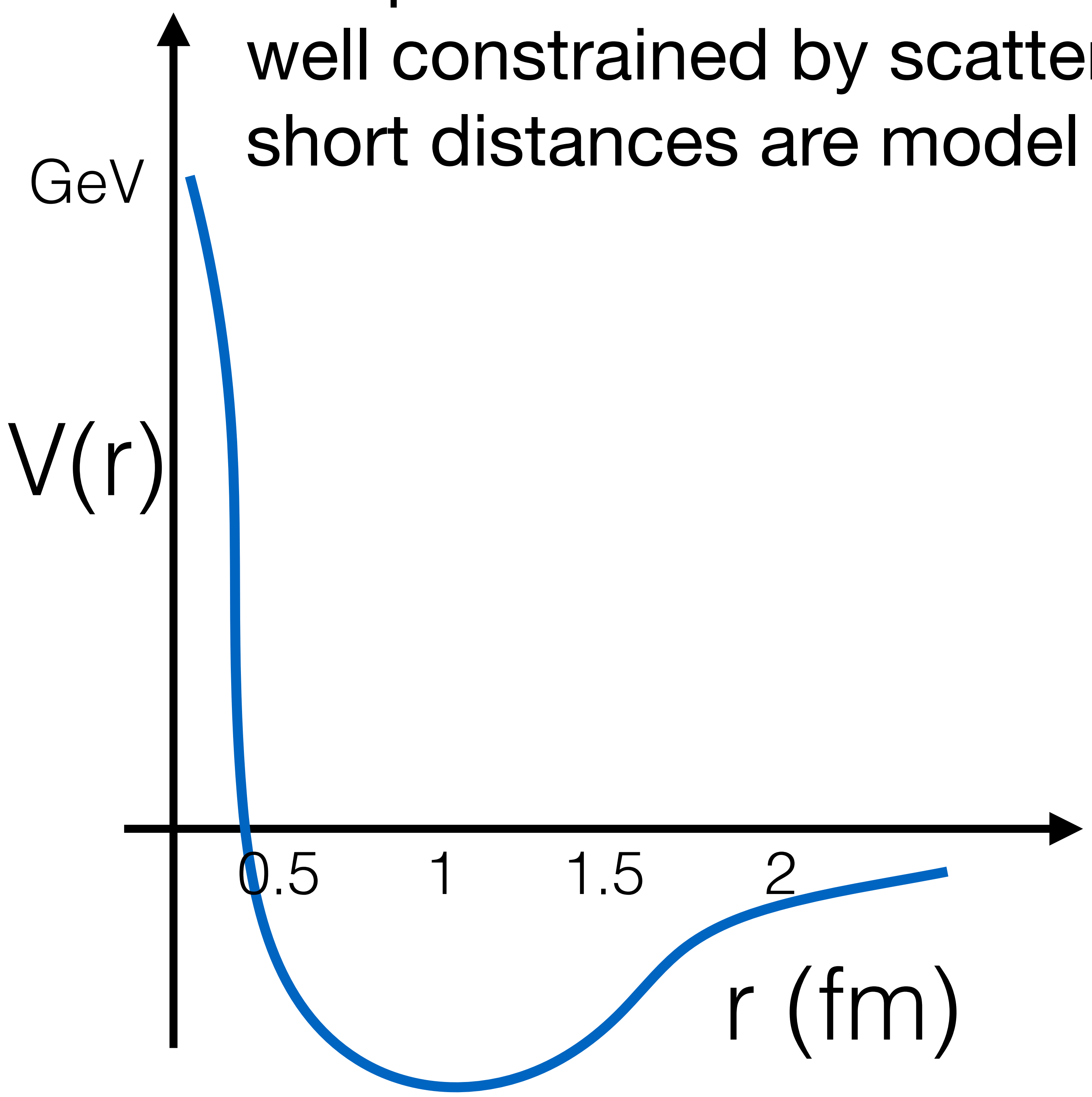

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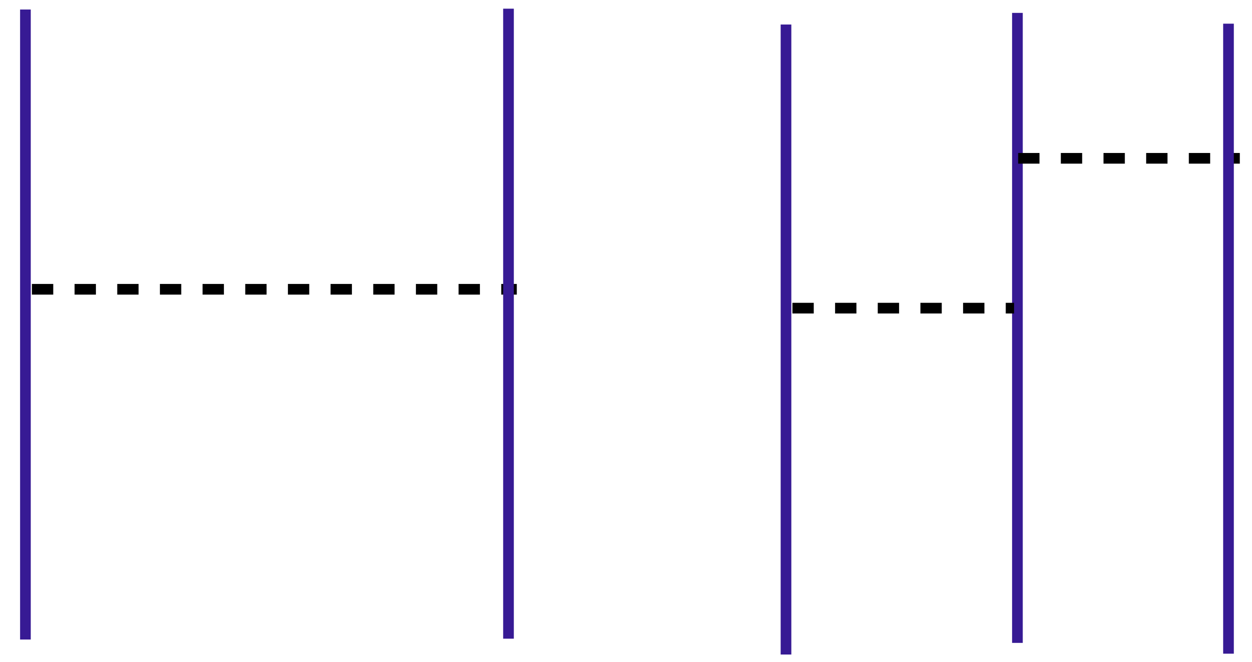

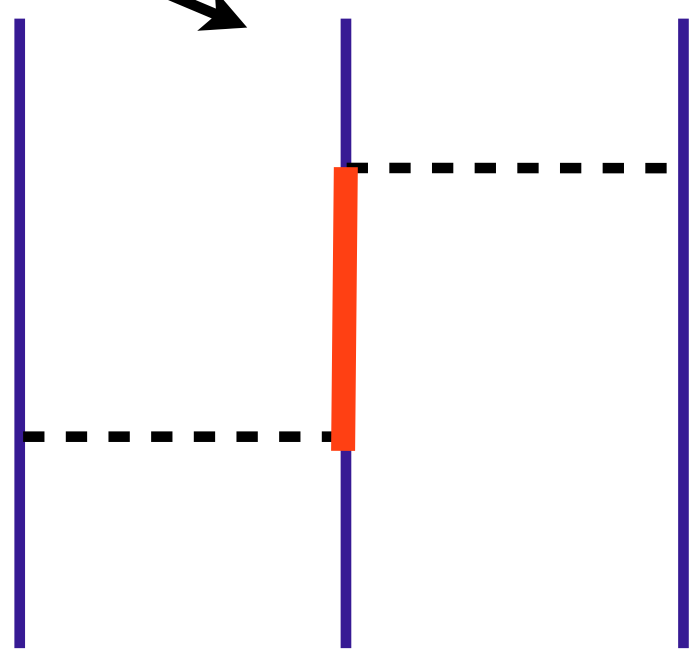

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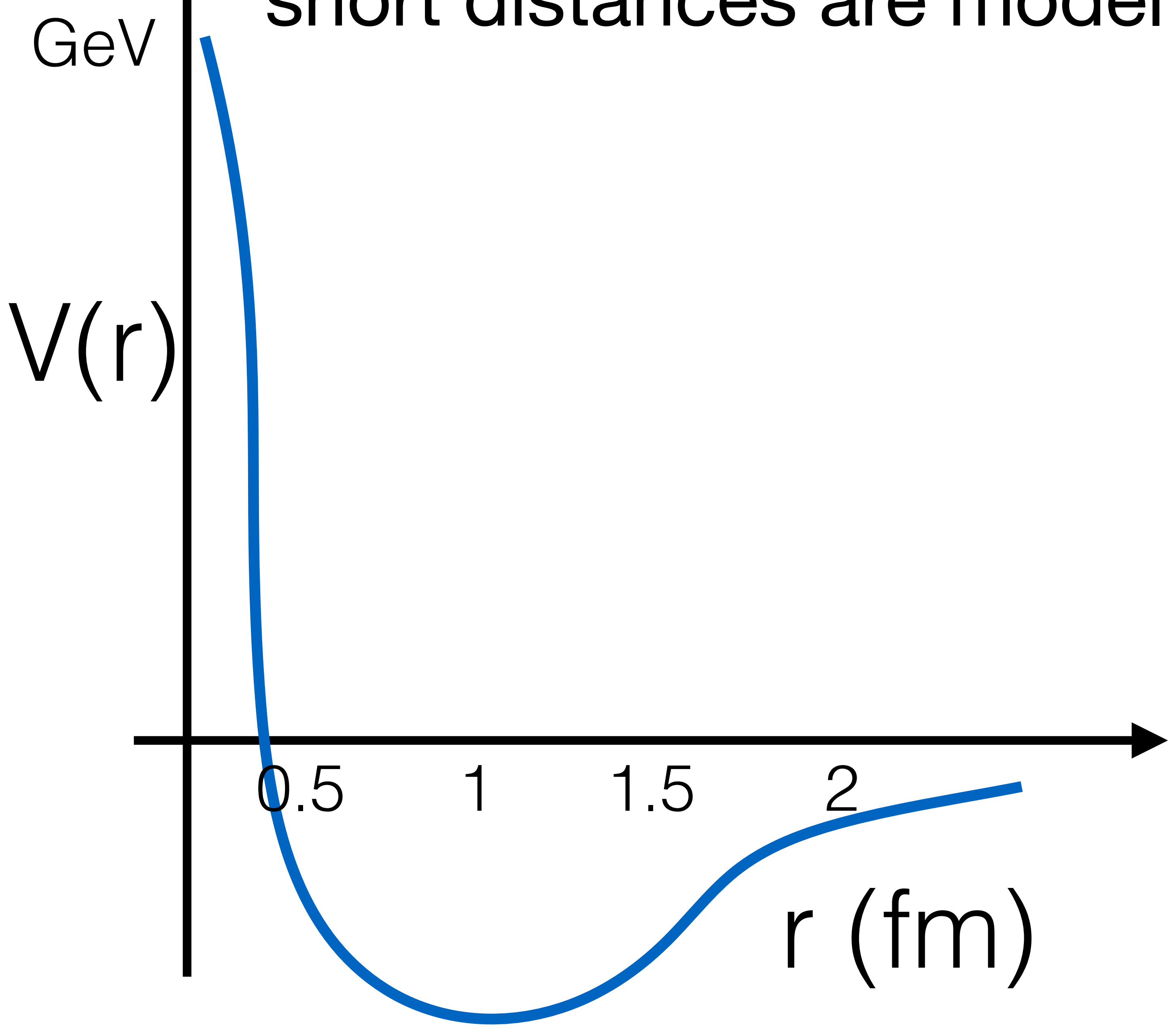
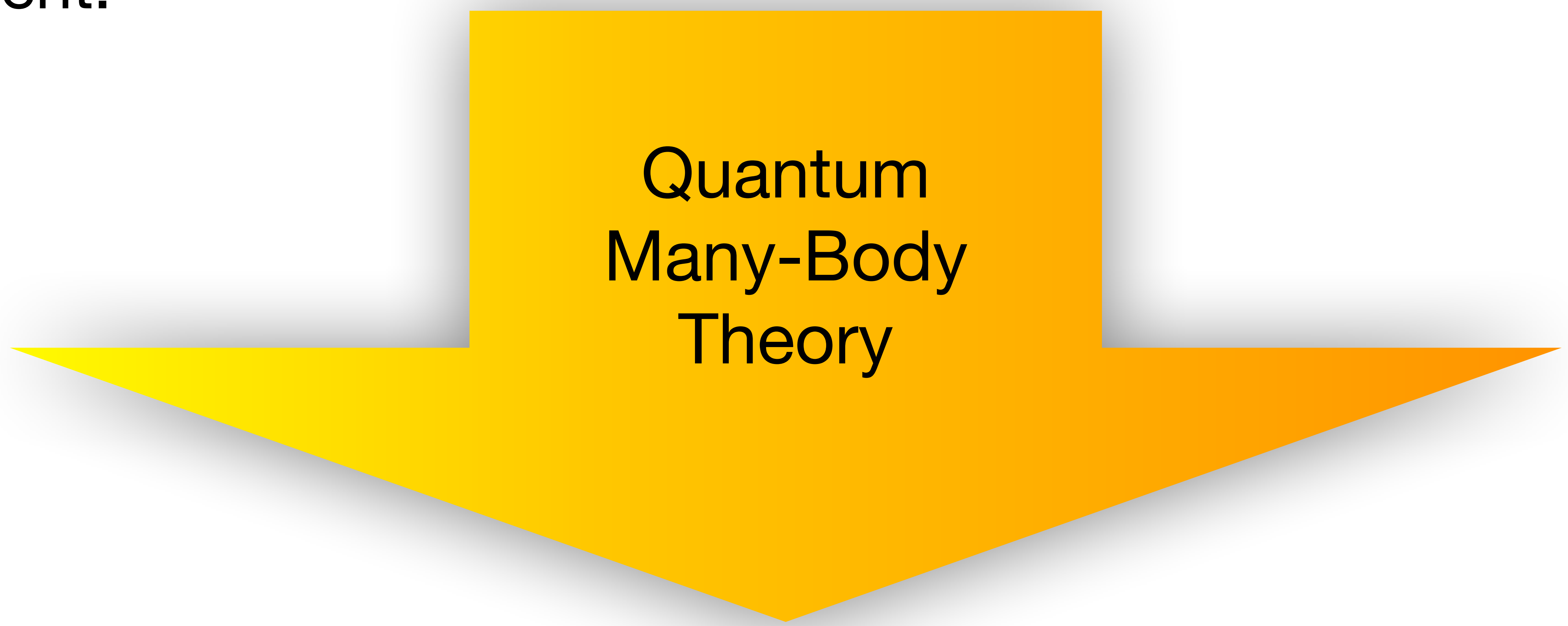
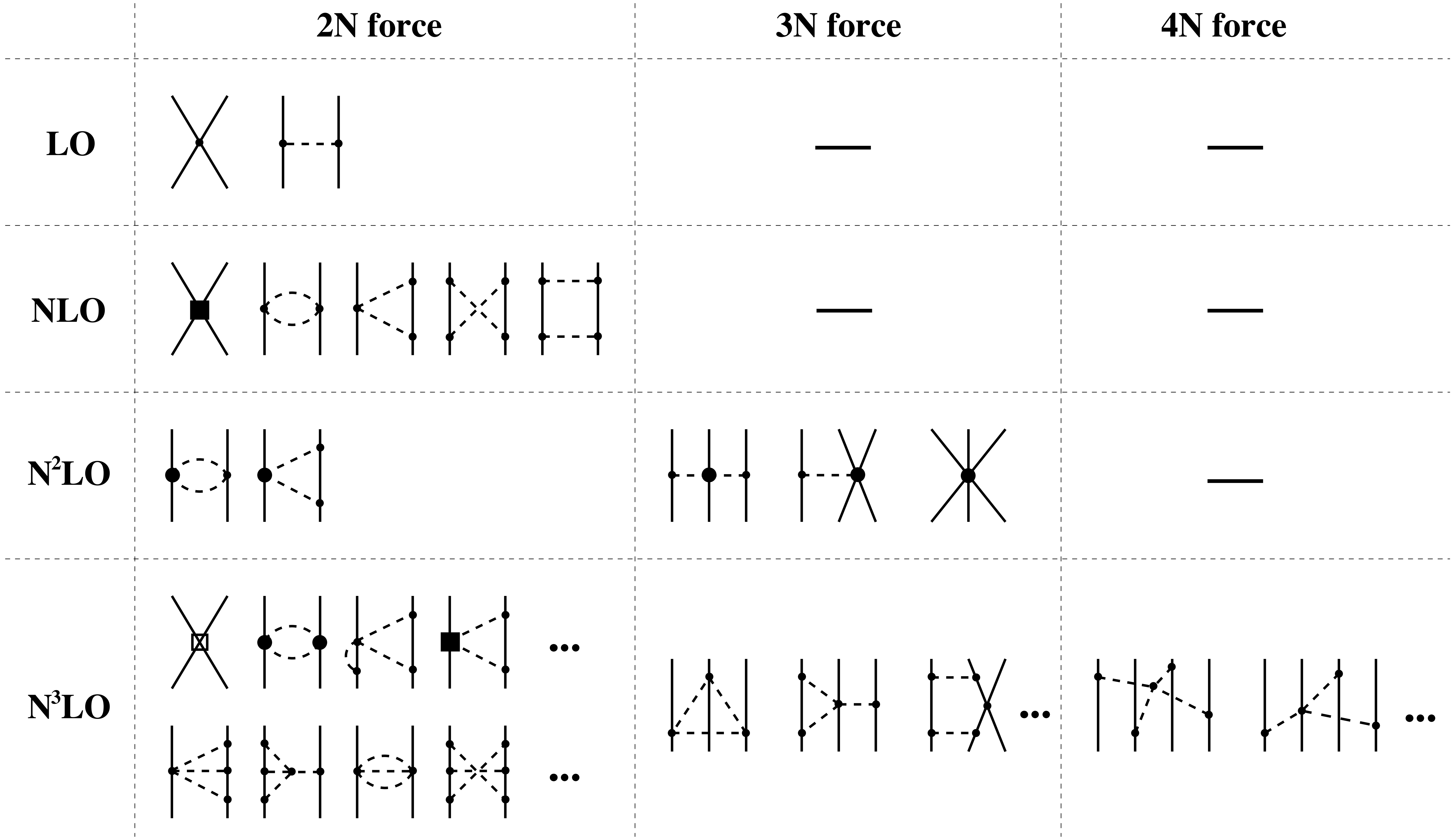


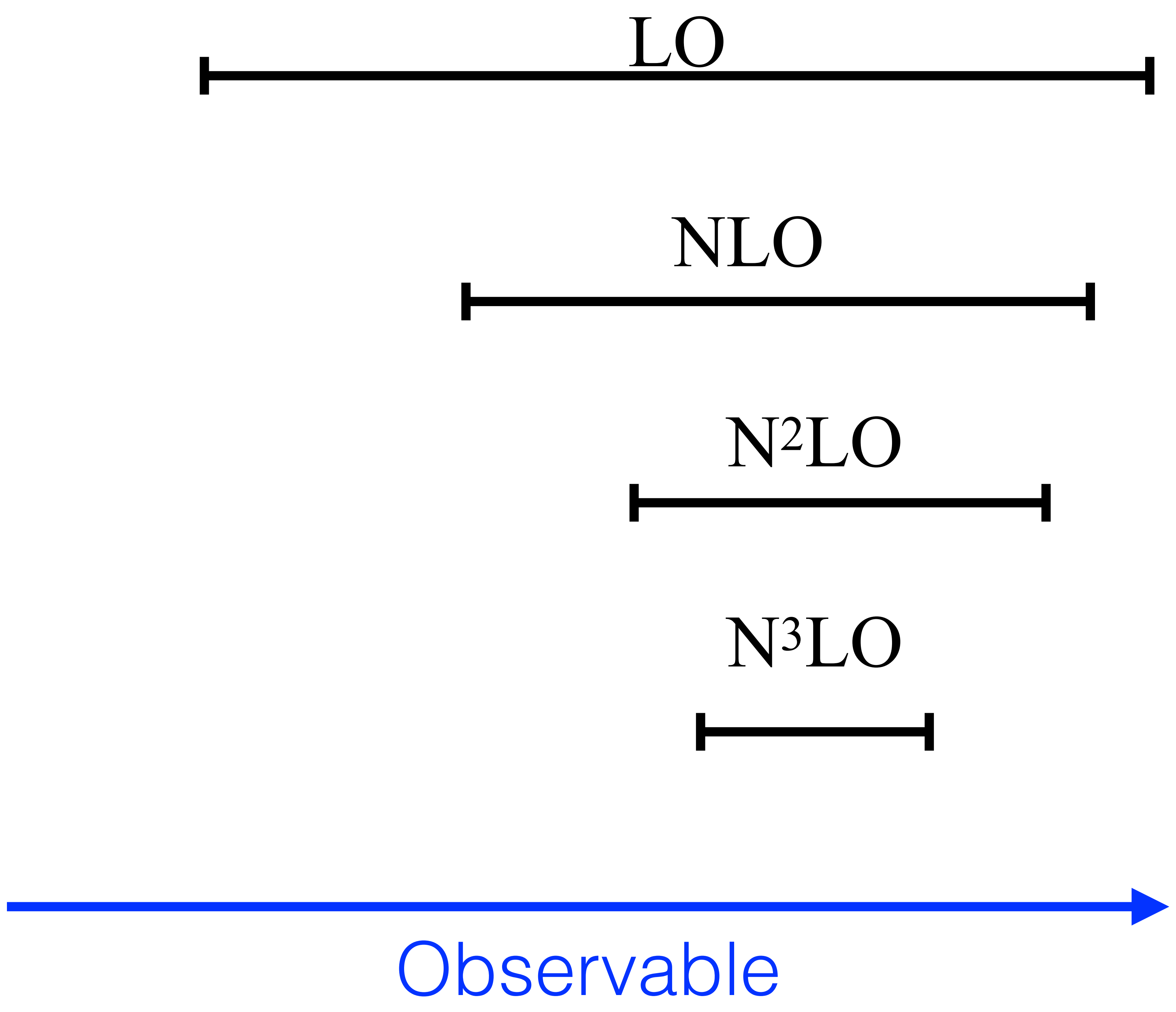


$E(\rho_n, \rho_p)$ & Equation of State

Nuclear Forces from Effective Field Theory (EFT)

EFT Hamiltonians organizes operators in powers of the momentum: $\dfrac{Q}{\Lambda_B}$





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 ..

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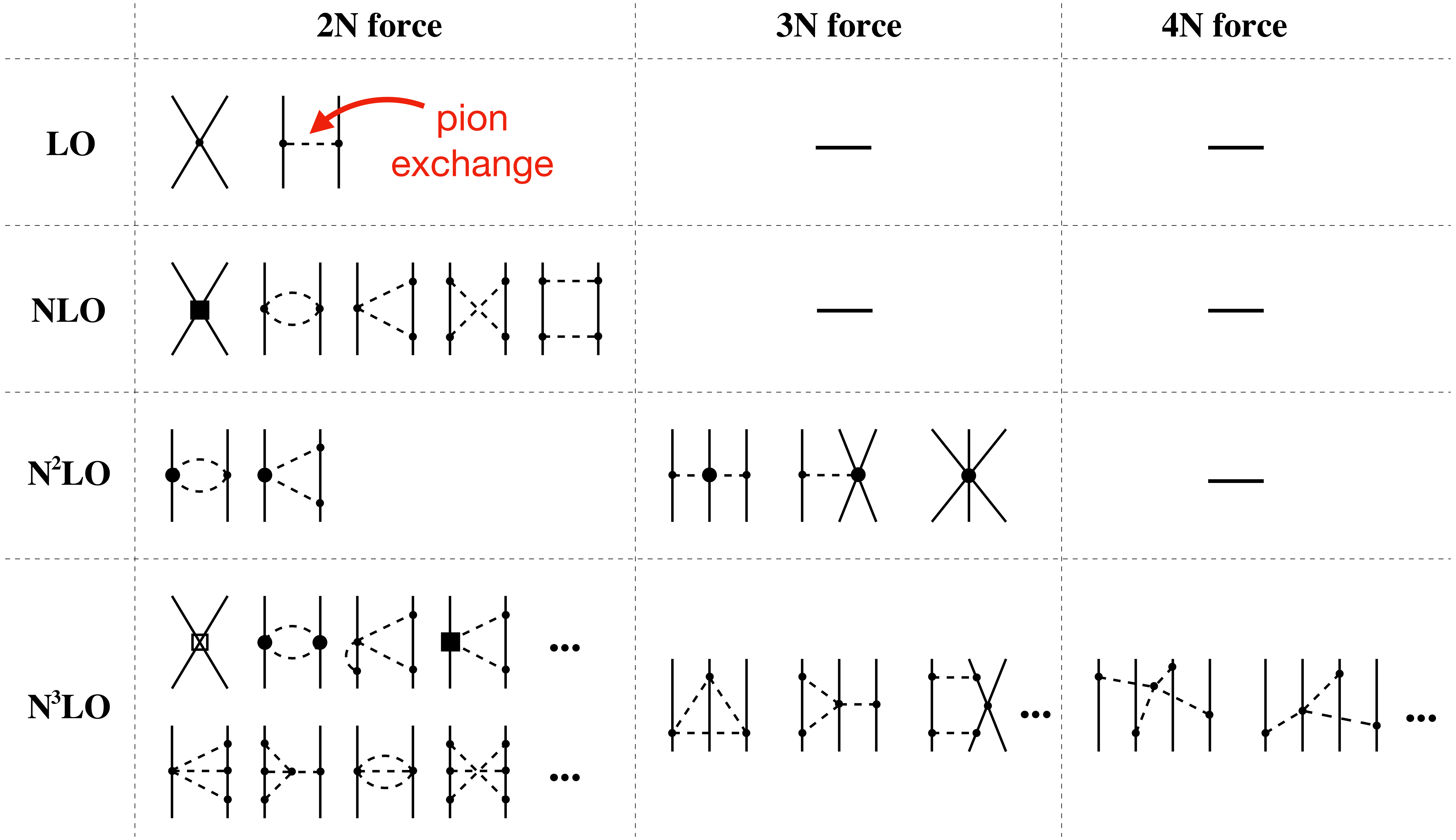

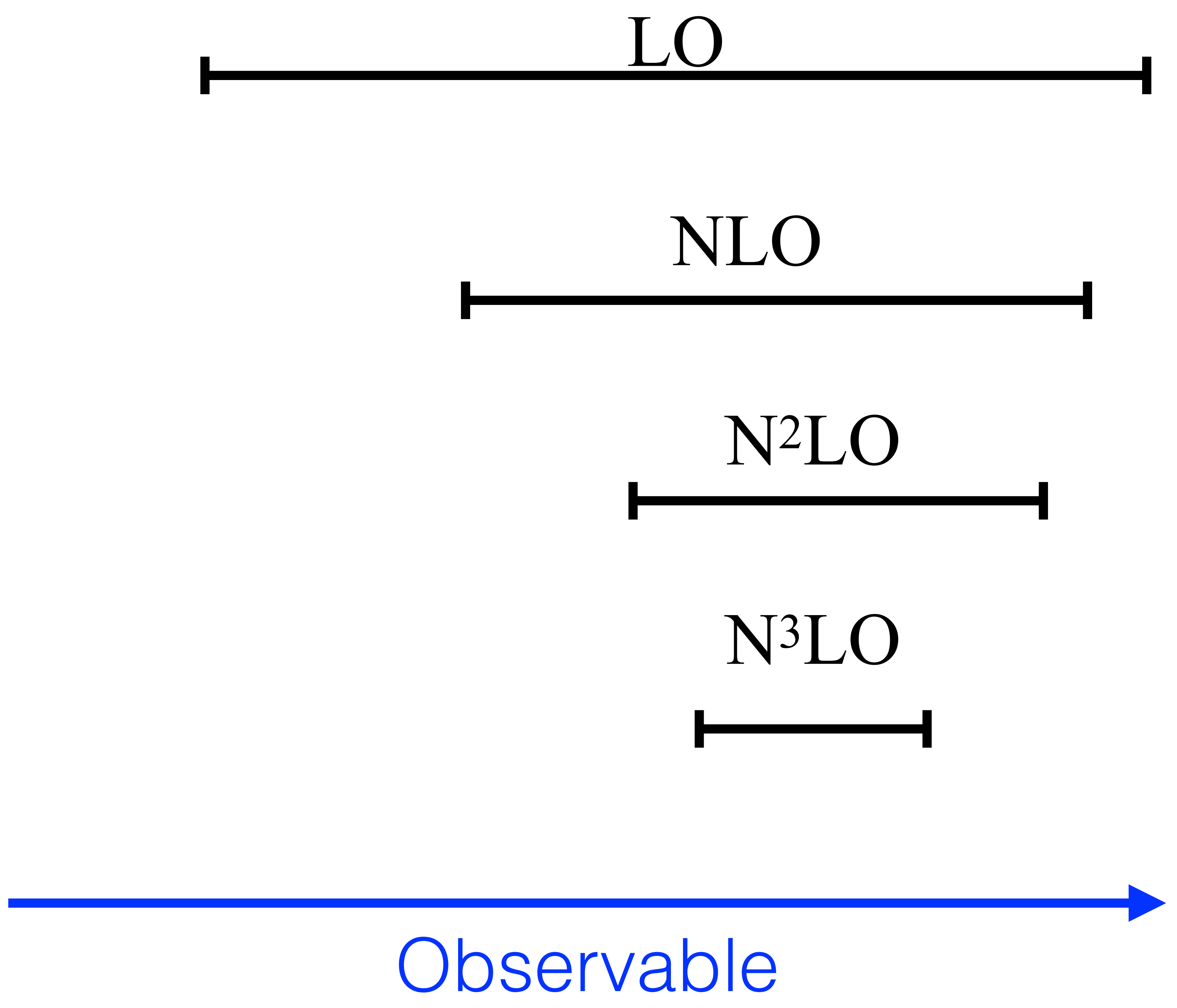

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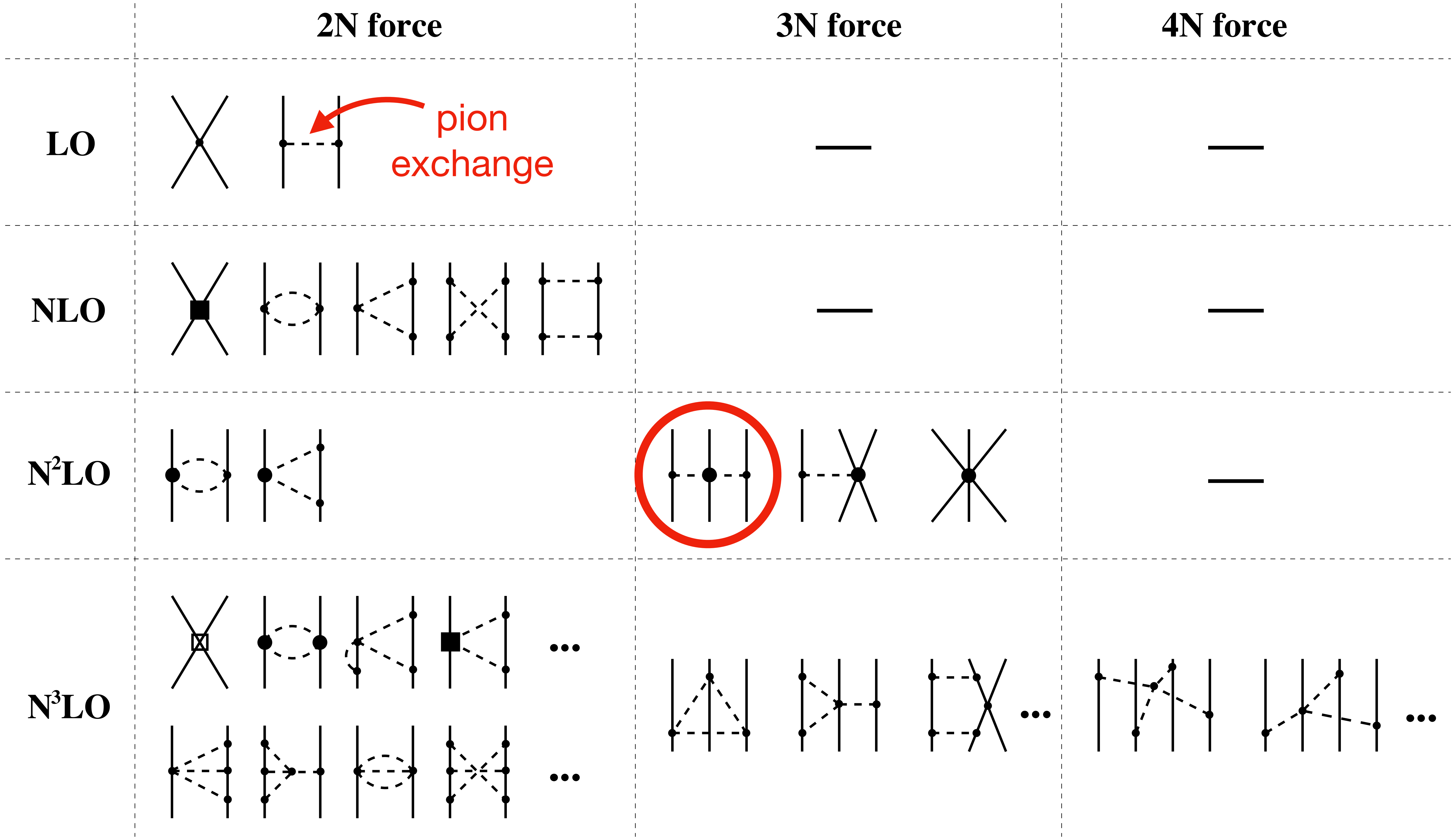
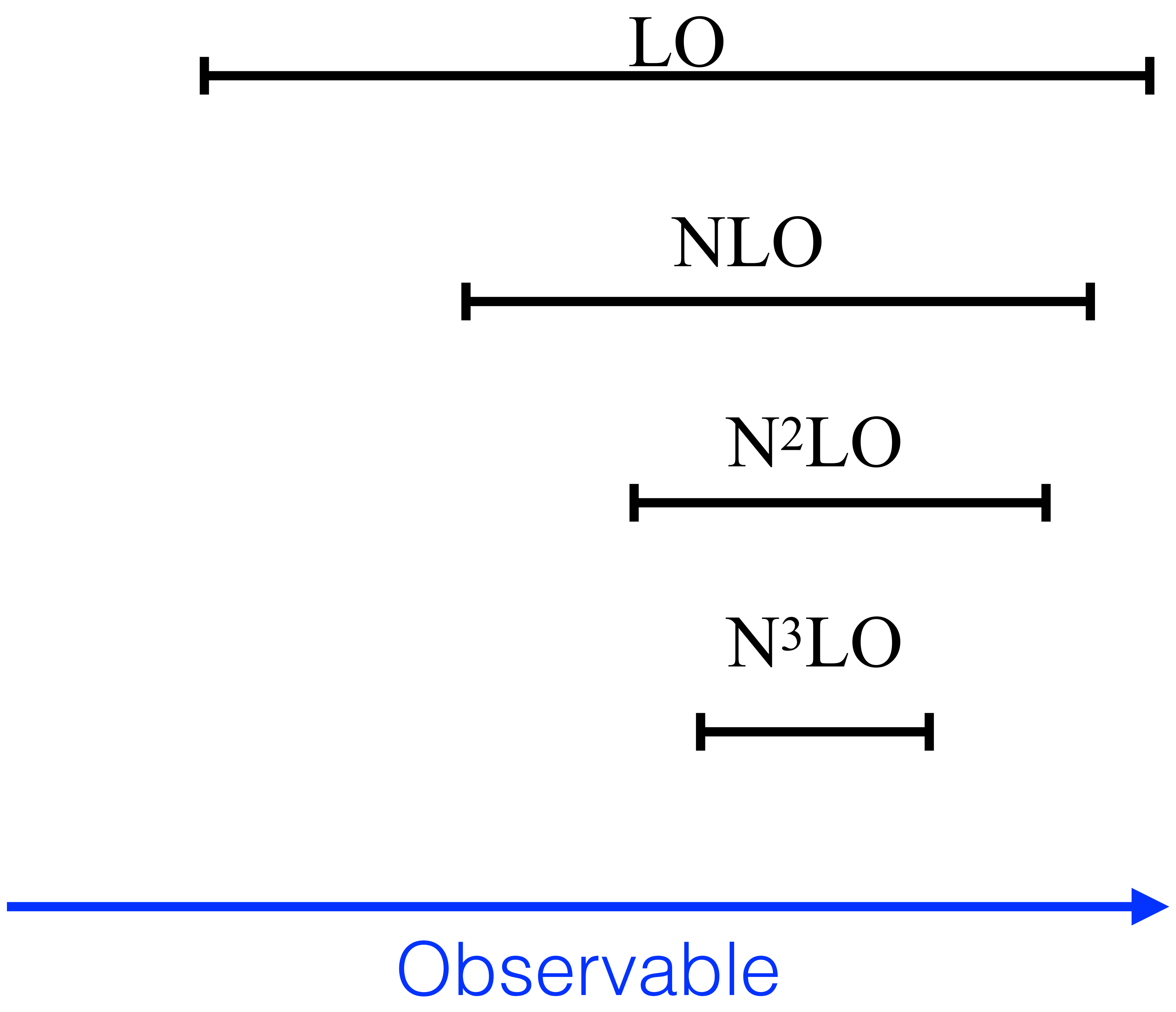




Allows for error estimation*. Provides guidance for the structure of three and many-body forces.

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

Chiral-EFT: The Good, the Bad, and the Power-Counting Ugly

Incorporates symmetries and provides an expansion of operators to estimate errors.

The connection to QCD, particularly to the quark masses, remains difficult to quantify.

The cut-off needed to regulate loop-integrals can only be varied over a small range. Not RG invariant.

Equation of State of Dense Nuclear Matter

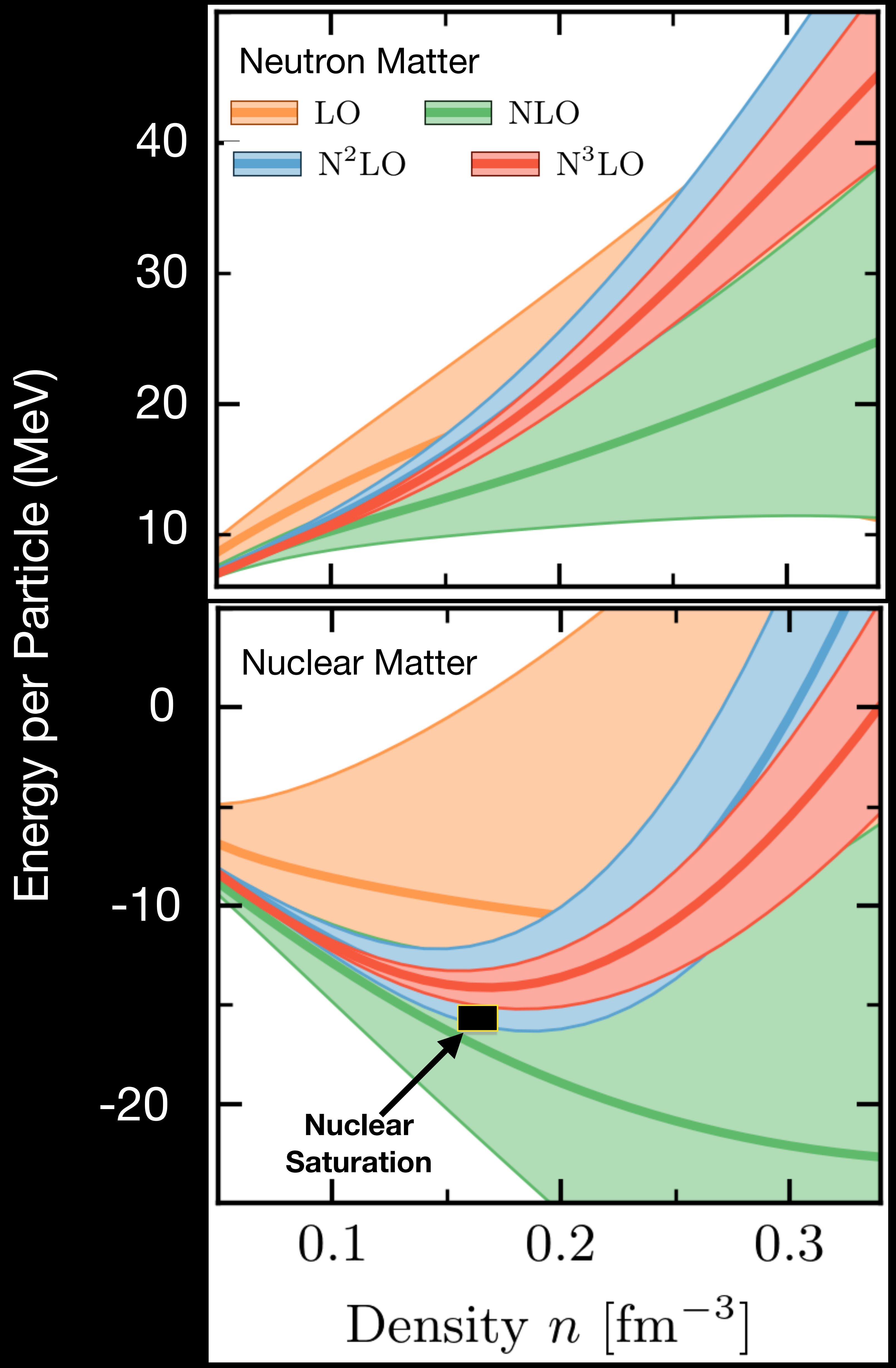
Quantum many-body calculations of neutron matter and nuclear matter using EFT potentials show convergence up to about twice nuclear saturation density.

Hebeler and Schwenk (2009), Gandolfi, Carlson, Reddy (2010), Gezerlis et al. (2013), Tews, Kruger, Hebeler, Schwenk (2013), Holt Kaiser, Weise (2013), Hagen et al. (2013), Roggero, Mukherjee, Pederiva (2014), Wlazlowski, Holt, Moroz, Bulgac, Roche (2014), Tews et al. (2018), Drischler et al., (2020).

Three-nucleon forces at N²LO play a key role. They provide the repulsion needed for saturation the pressure needed to hold up neutron stars.

Drischler et al. used Bayesian methods to systematically estimate the EFT truncation errors in neutron and nuclear matter.

Drischler, Furnstahl, Melendez, Phillips, (2020).



Drischler et al., (2020).

Equation of State of Neutron Star Matter

In neutron stars, matter is in equilibrium with respect to weak interactions and contains a small fraction (about 5-10%) of protons, electrons and muons:

Many-body perturbation theory and Bayesian estimates of the EFT truncation errors predict:

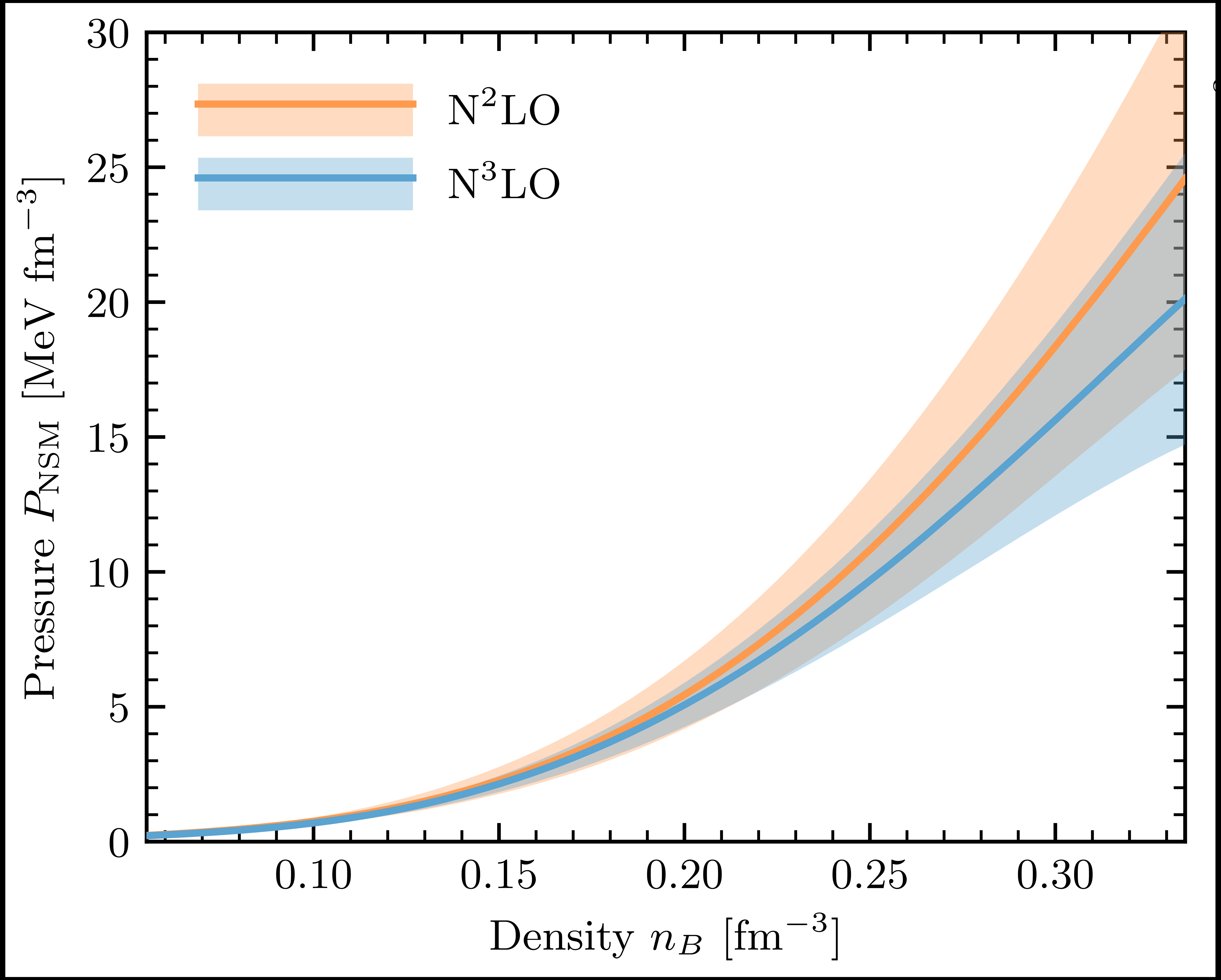
$$P_{\mathrm{NSM}}(n_B = 0.16\ \mathrm{fm}^{-3}) = 3.0 \pm 0.4\ \mathrm{MeV/fm}^3$$

$$P_{\mathrm{NSM}}(n_B = 0.34\ \mathrm{fm}^{-3}) = 20.0 \pm 5\ \mathrm{MeV/fm}^3$$

Christian Drischler

Sophia Han

Tianqi Zhao



Drischler, Han, Lattimer, Prakash, Reddy, Zhao (2020)

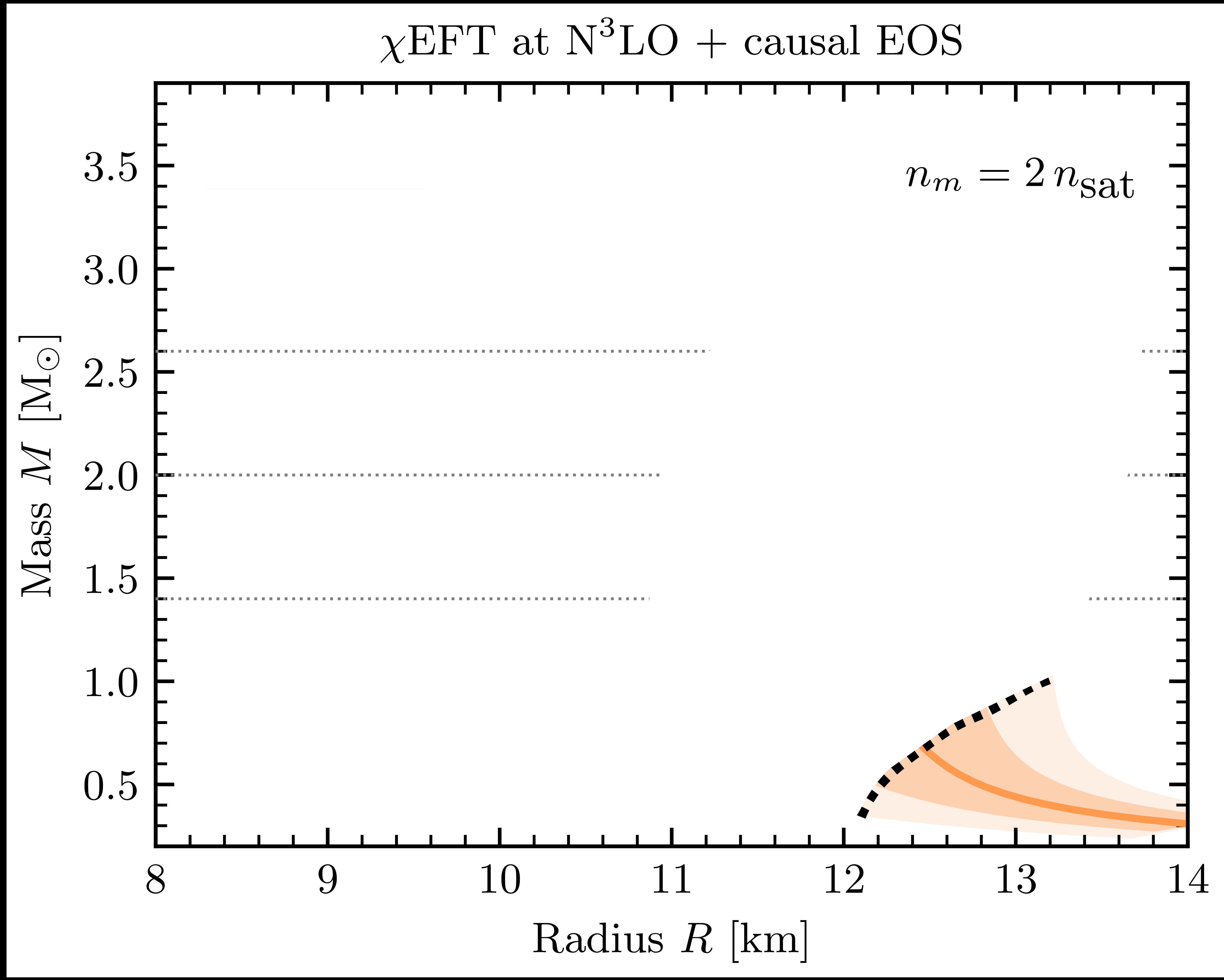
Bounds on Neutron Star Radii

EFT predictions for the EOS can be combined with extremal high-density EOS (with $c_s^2 = 1$) to derive robust bounds on the radius of a NS of any mass.

The lower limit on the NS maximum mass obtained from observations strengthen these bounds:

- $M_{\max} > 2.0\ M_{\odot}$, 9.2 km < $R_{1.4}$ < 13.2 km
- $M_{\max} > 2.6\ M_{\odot}$, 11.2 km < $R_{1.4}$ < 13.2 km

If $R_{1.4}$ is small (<11.5 km) or large (>12.5 km), it would imply a very large speed of sound in the cores of massive neutron stars.



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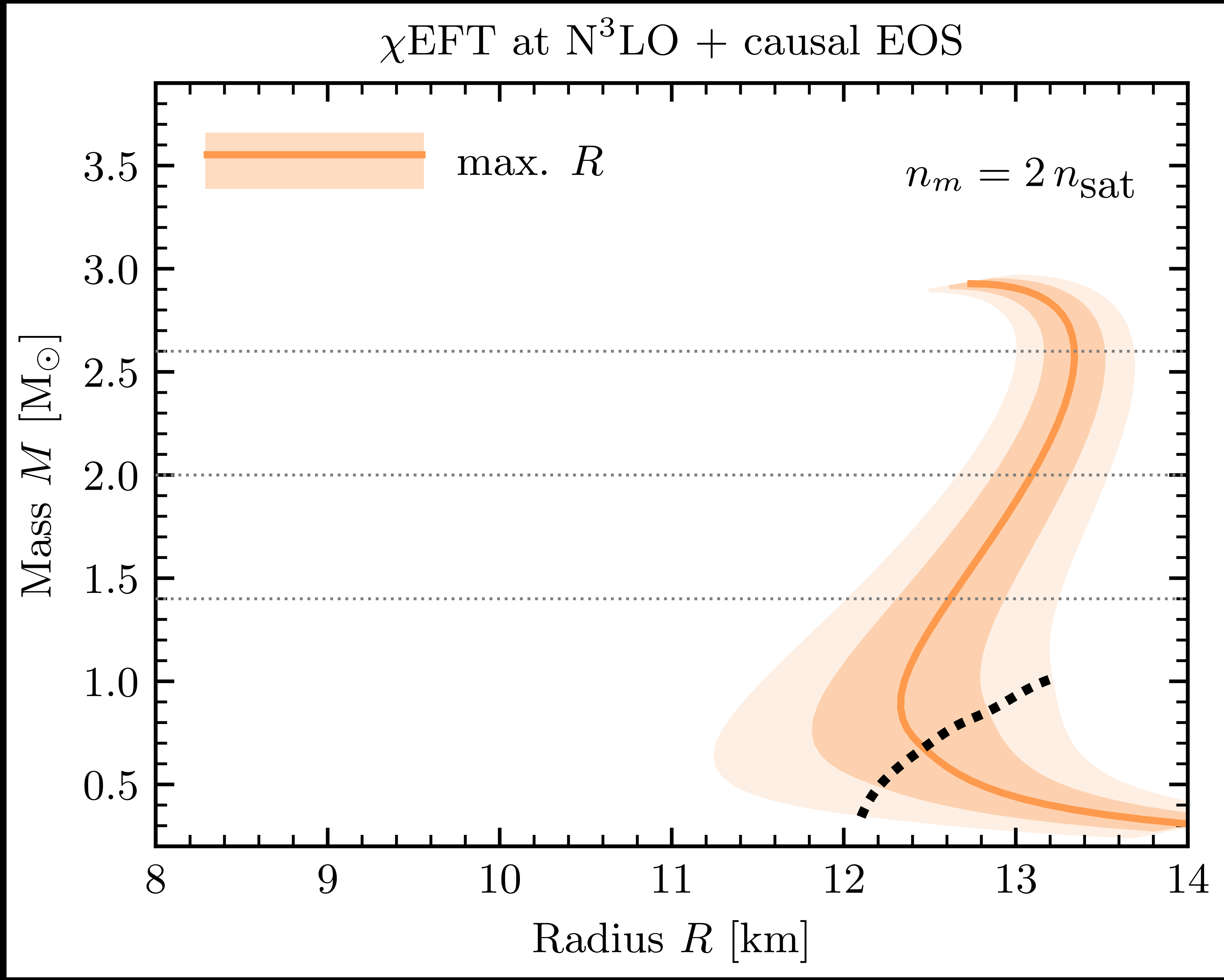

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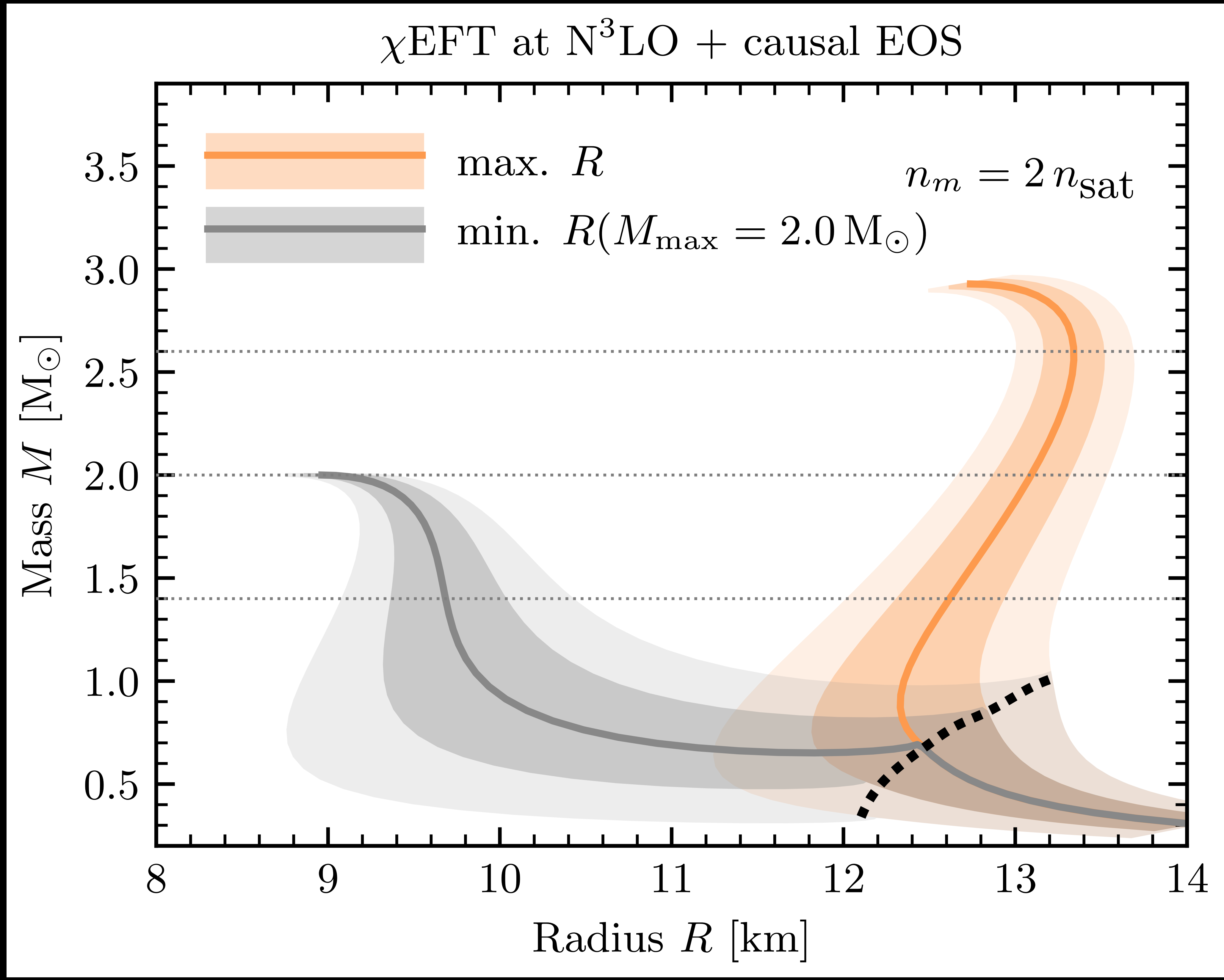

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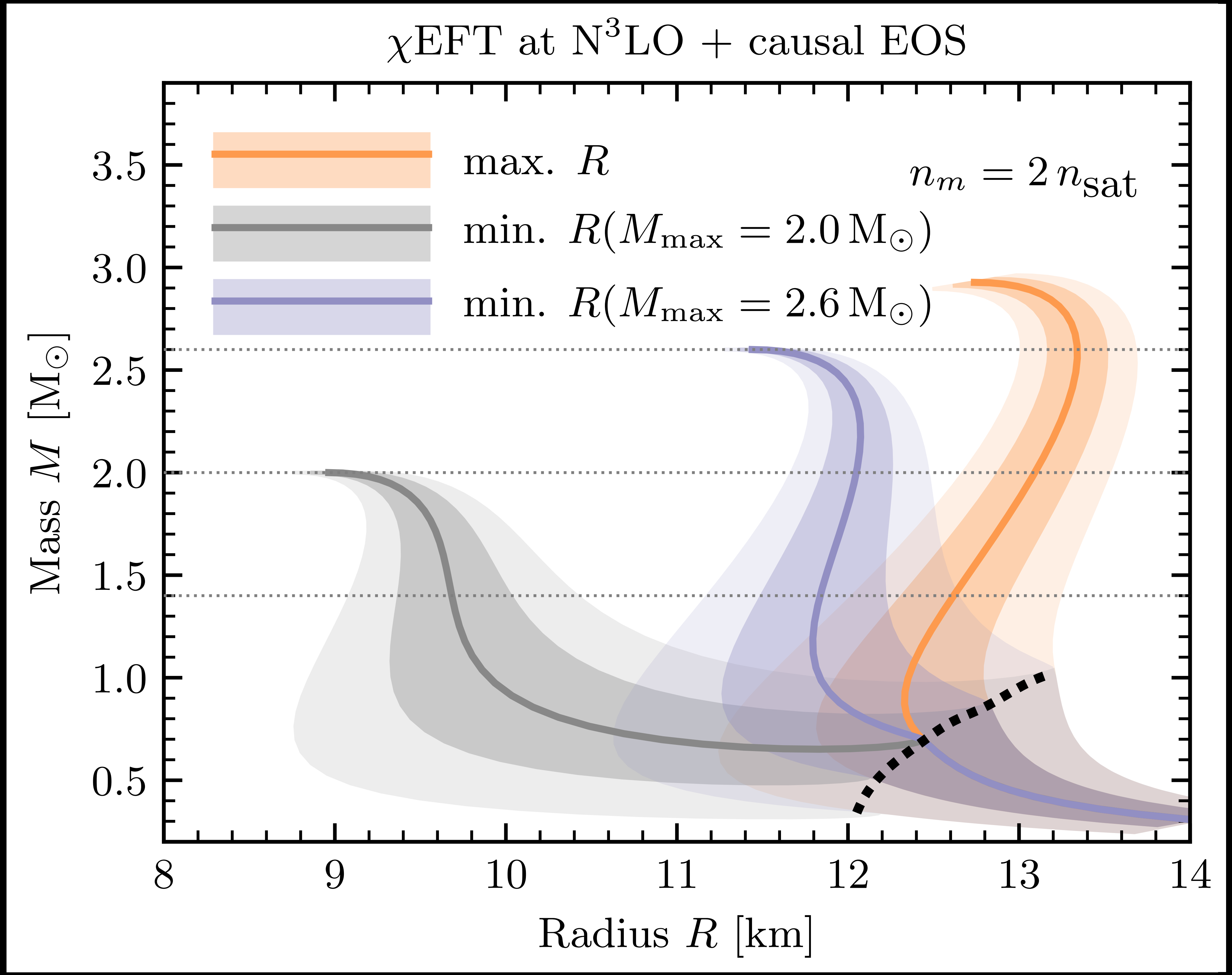
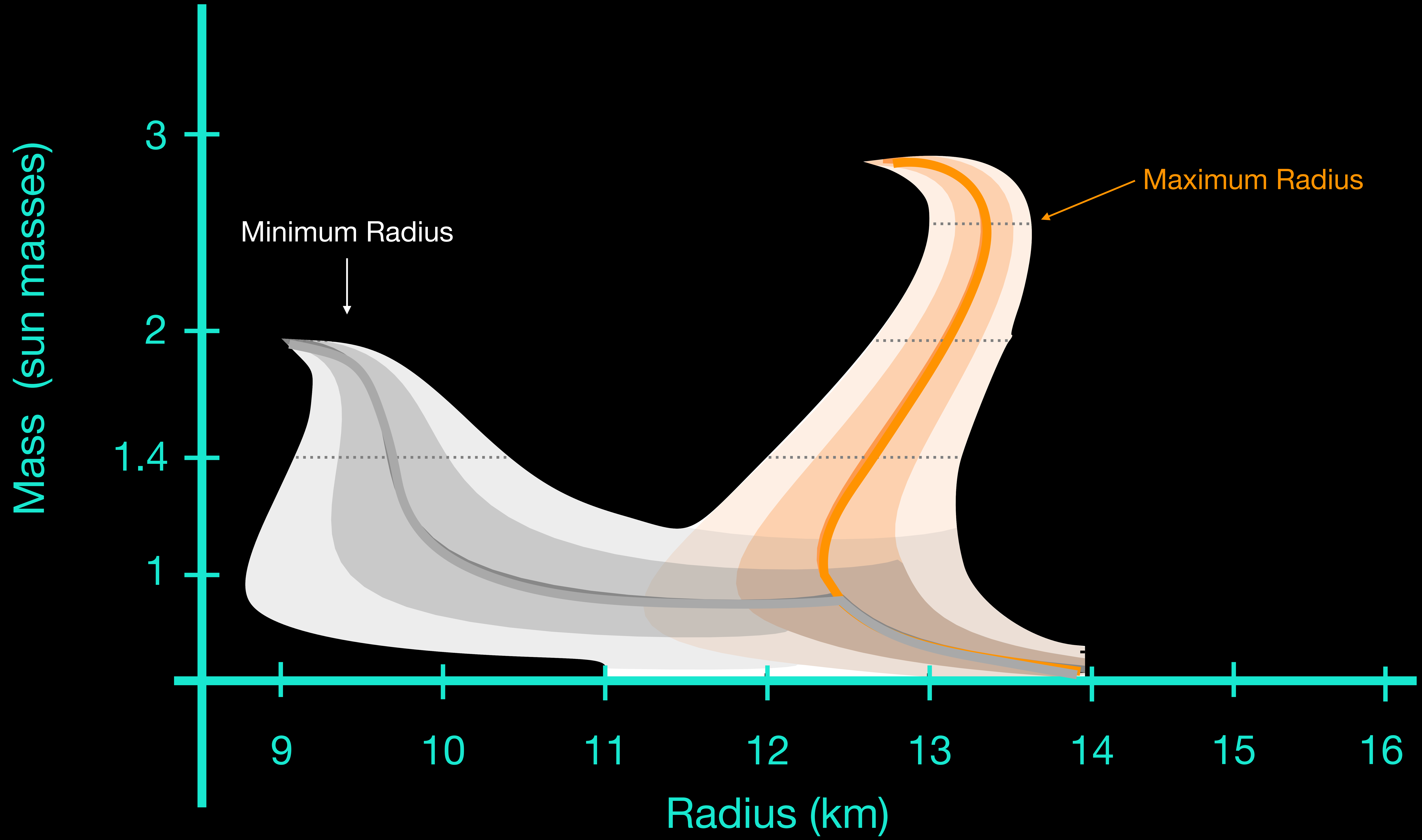


Drischler, Han, Lattimer, Prakash, Reddy, Zhao (2020)

Observational Constraints



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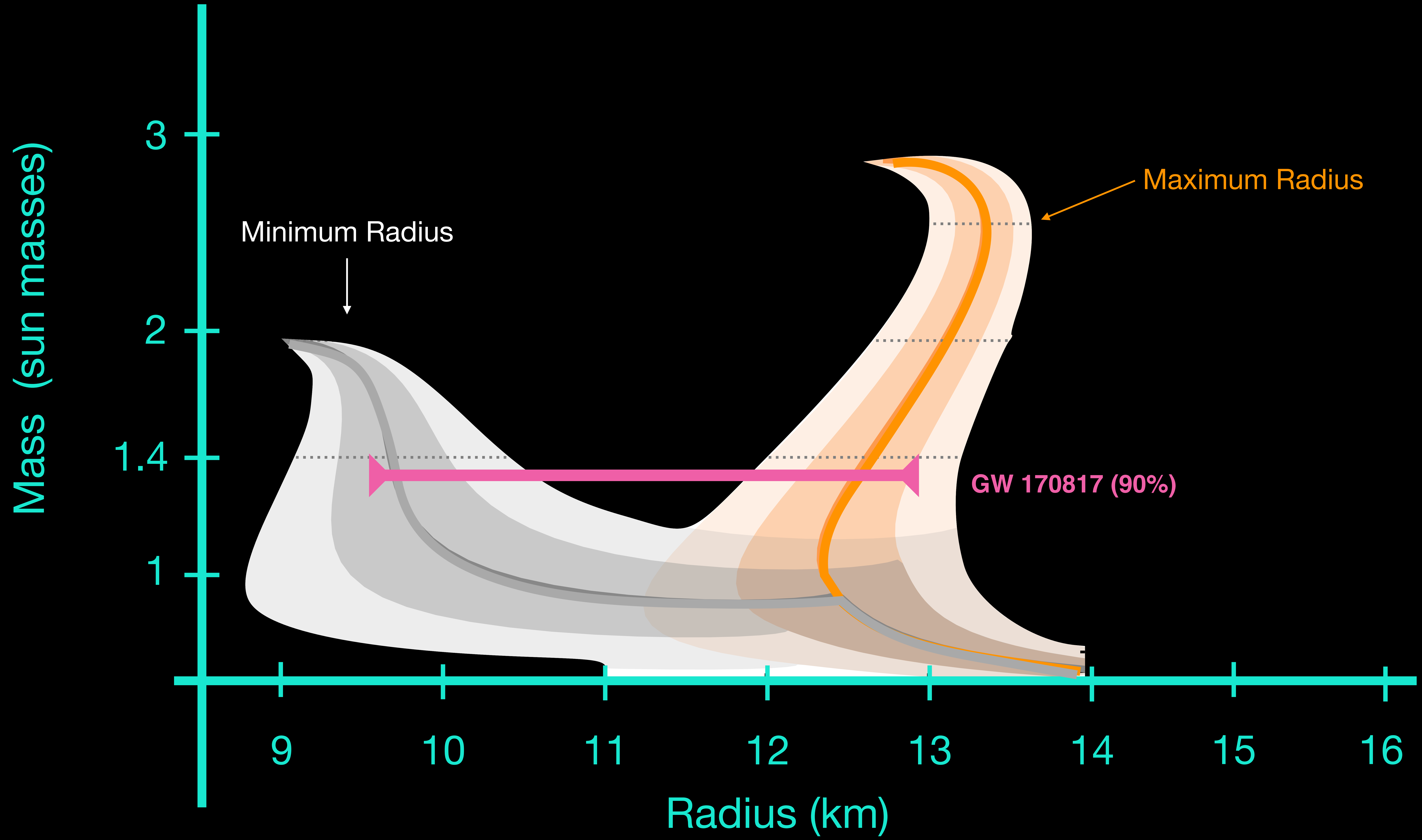

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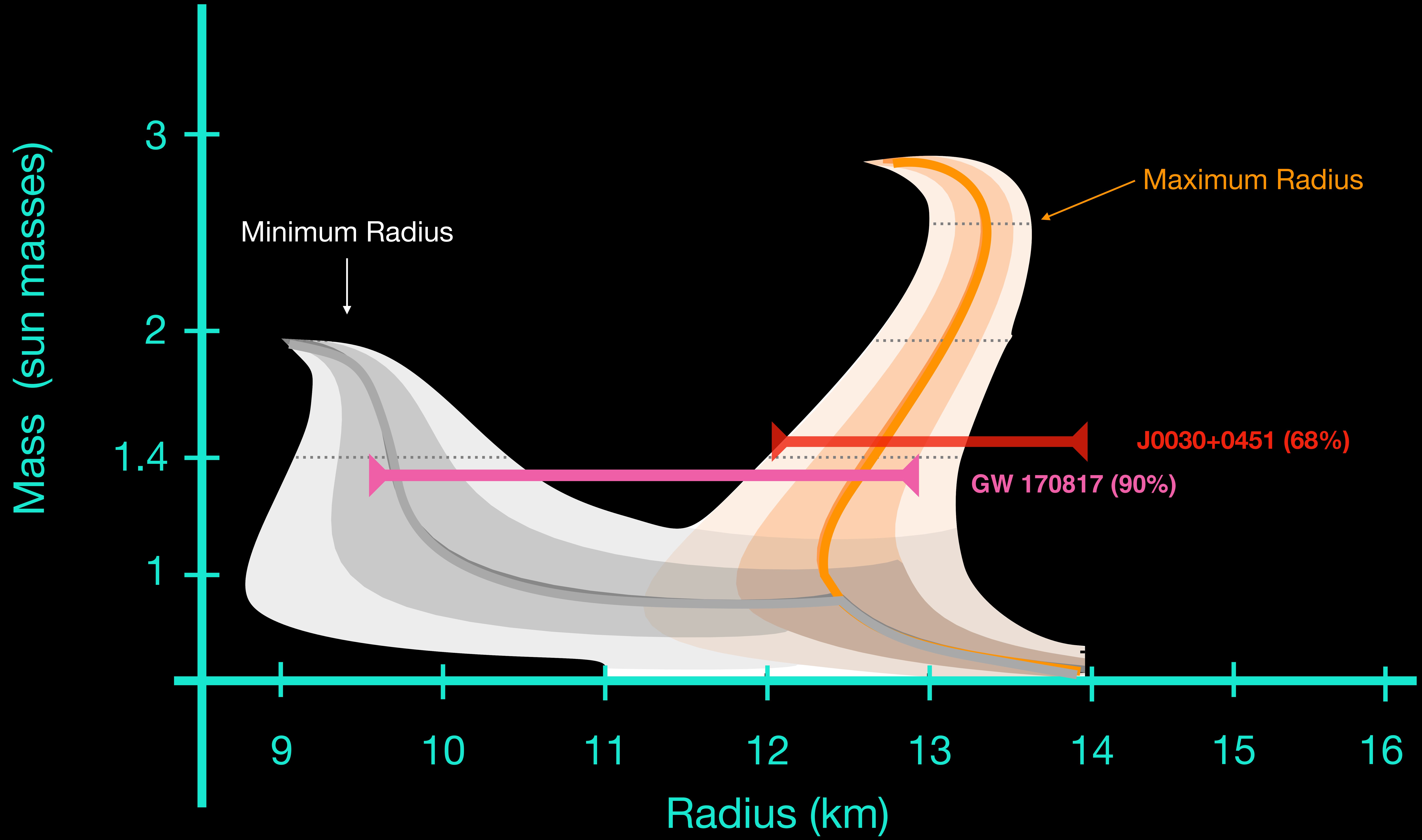

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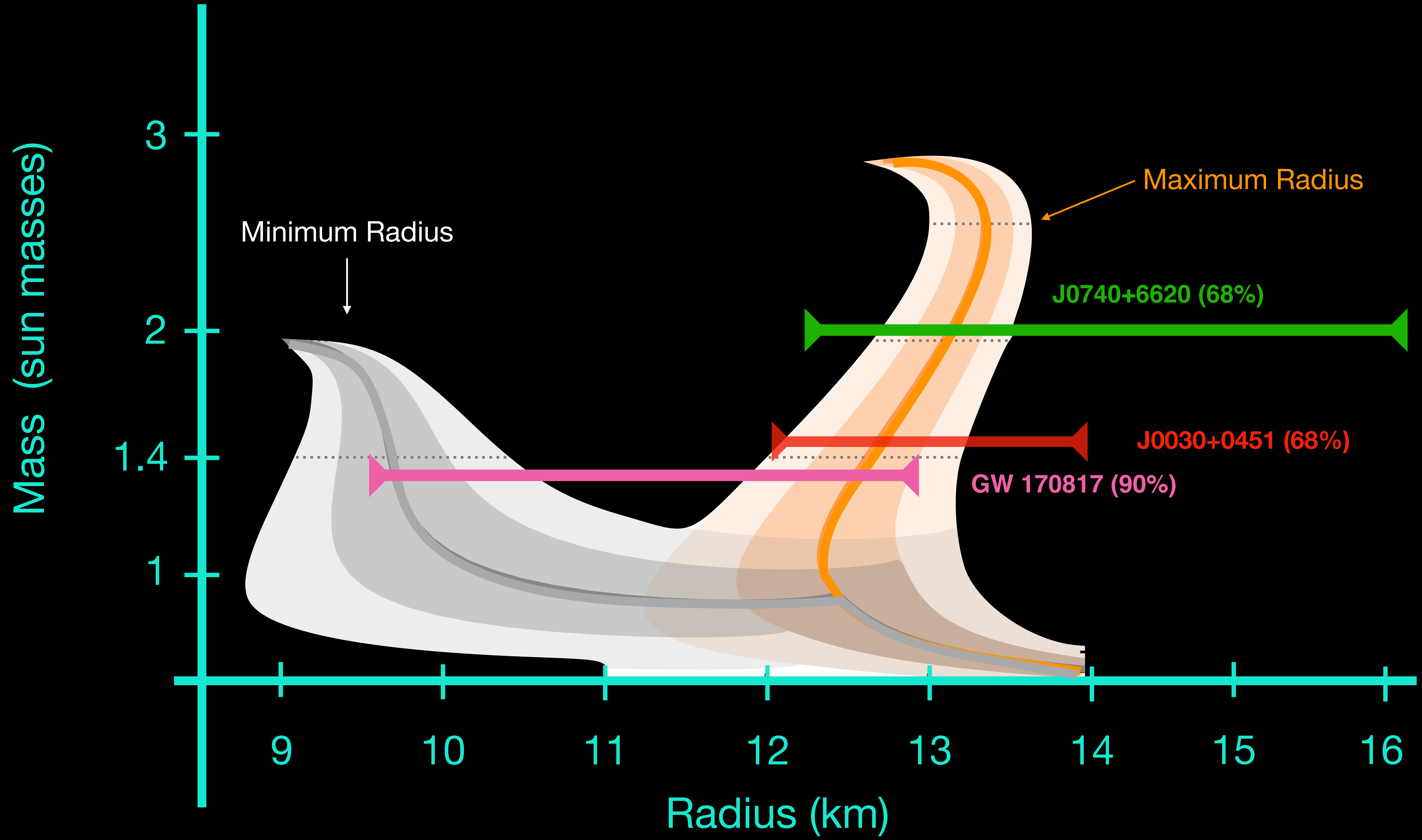

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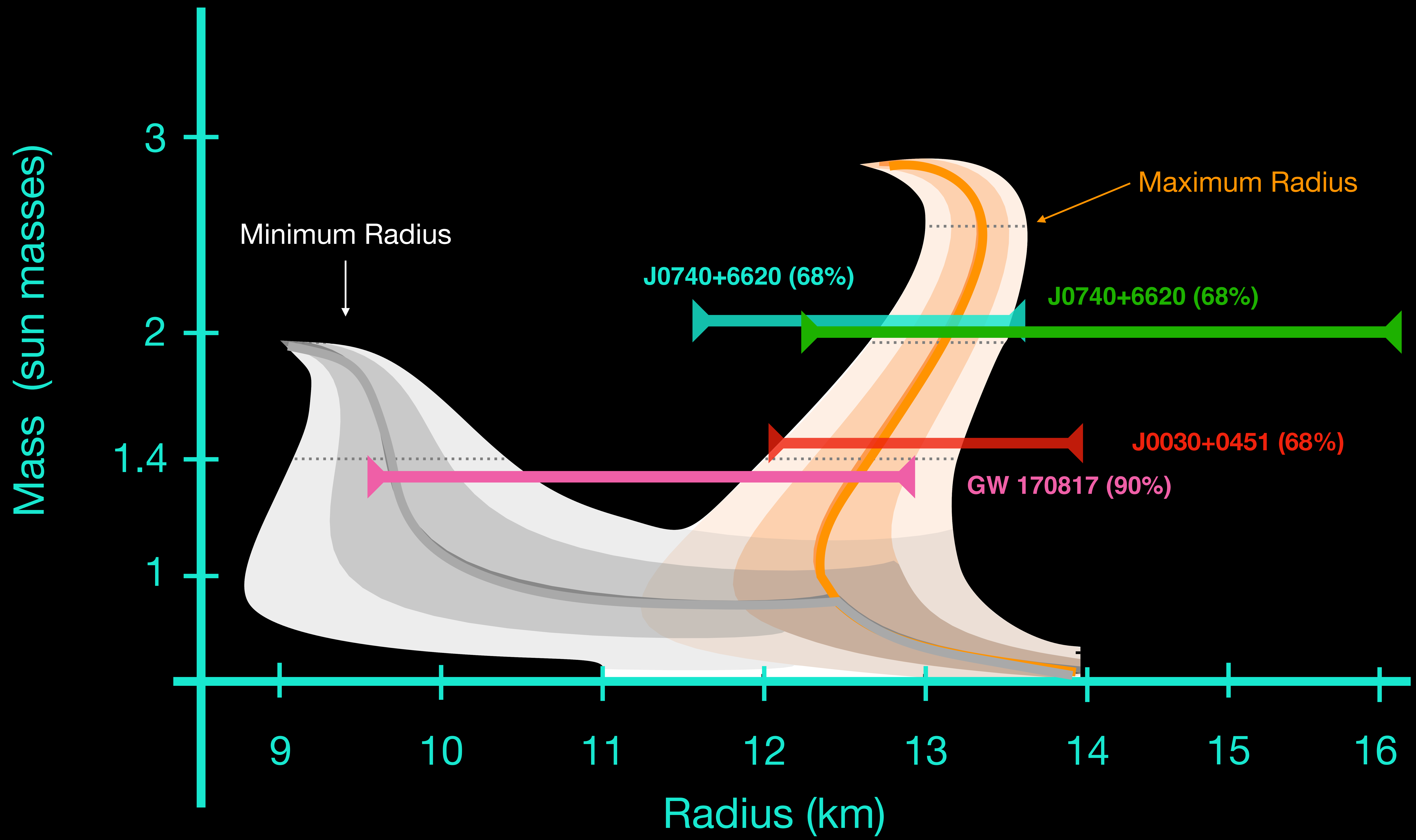

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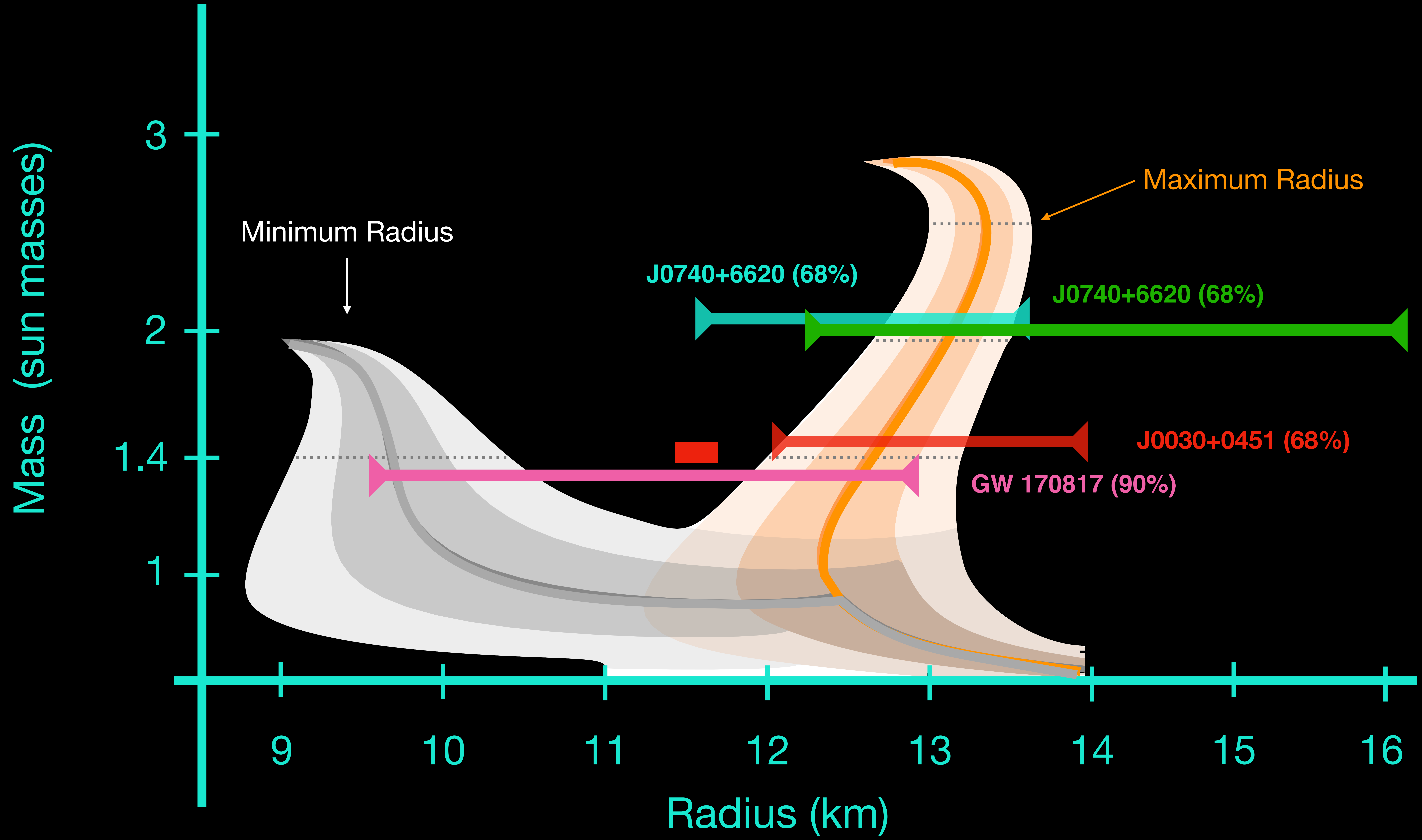

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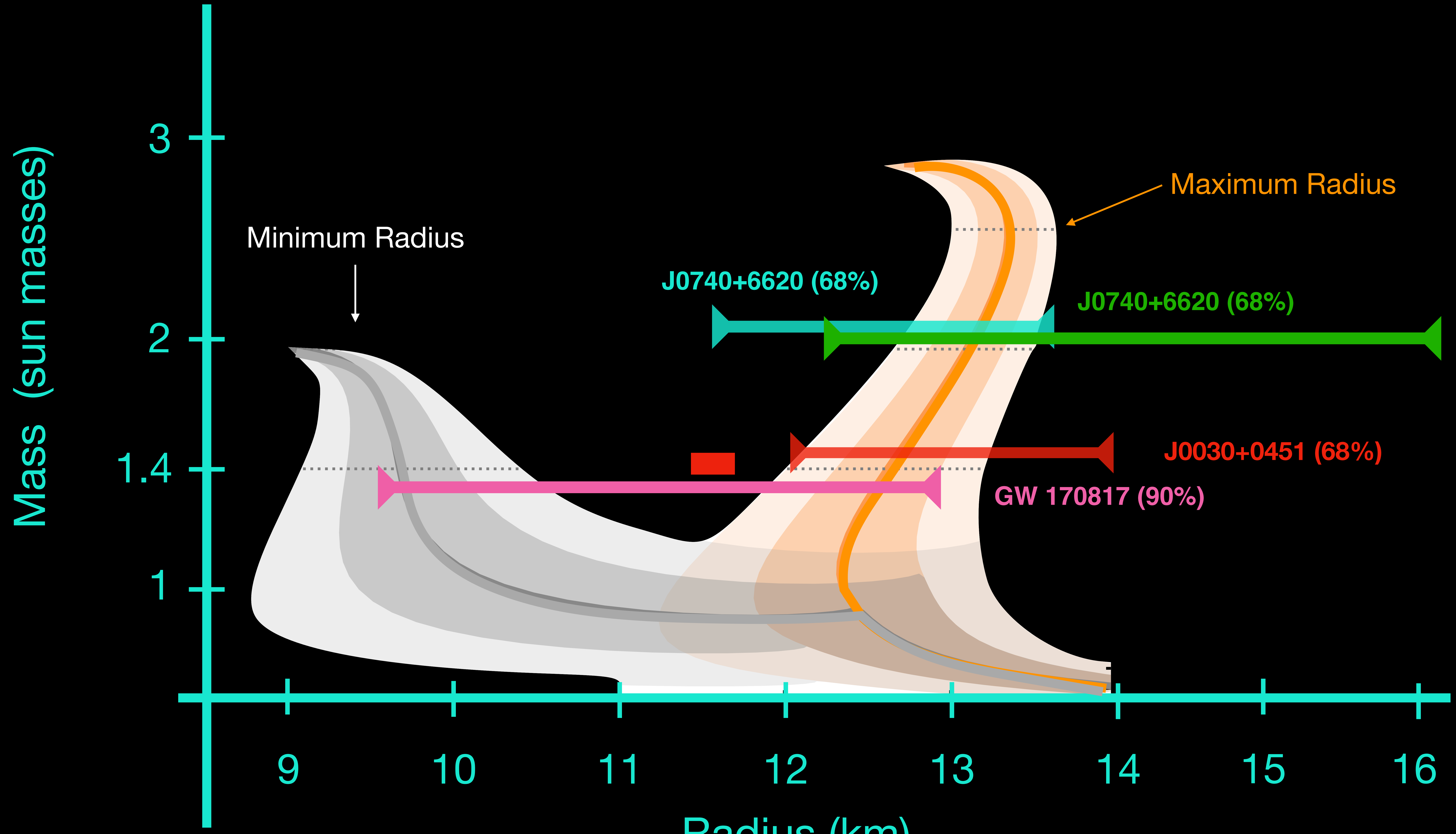

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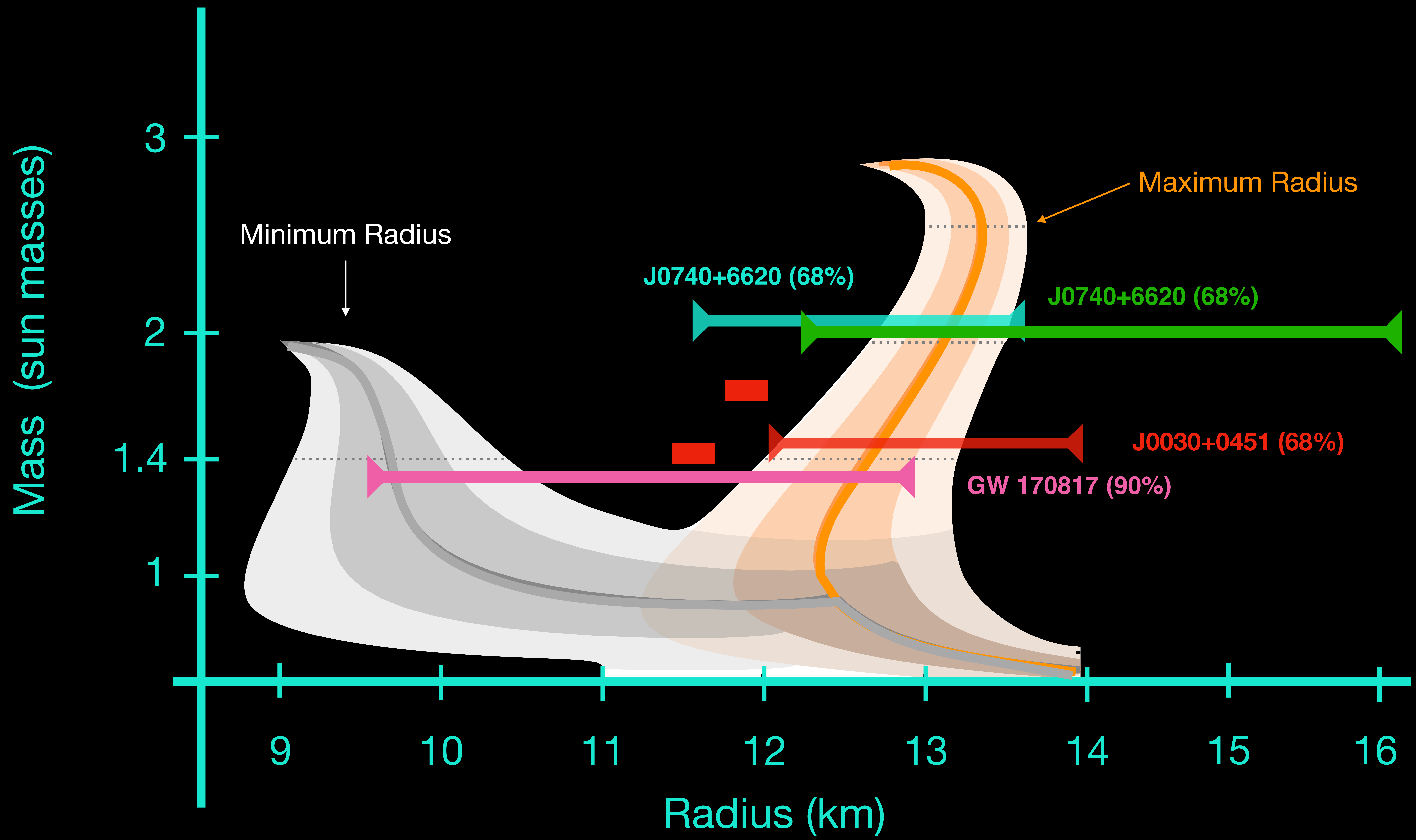

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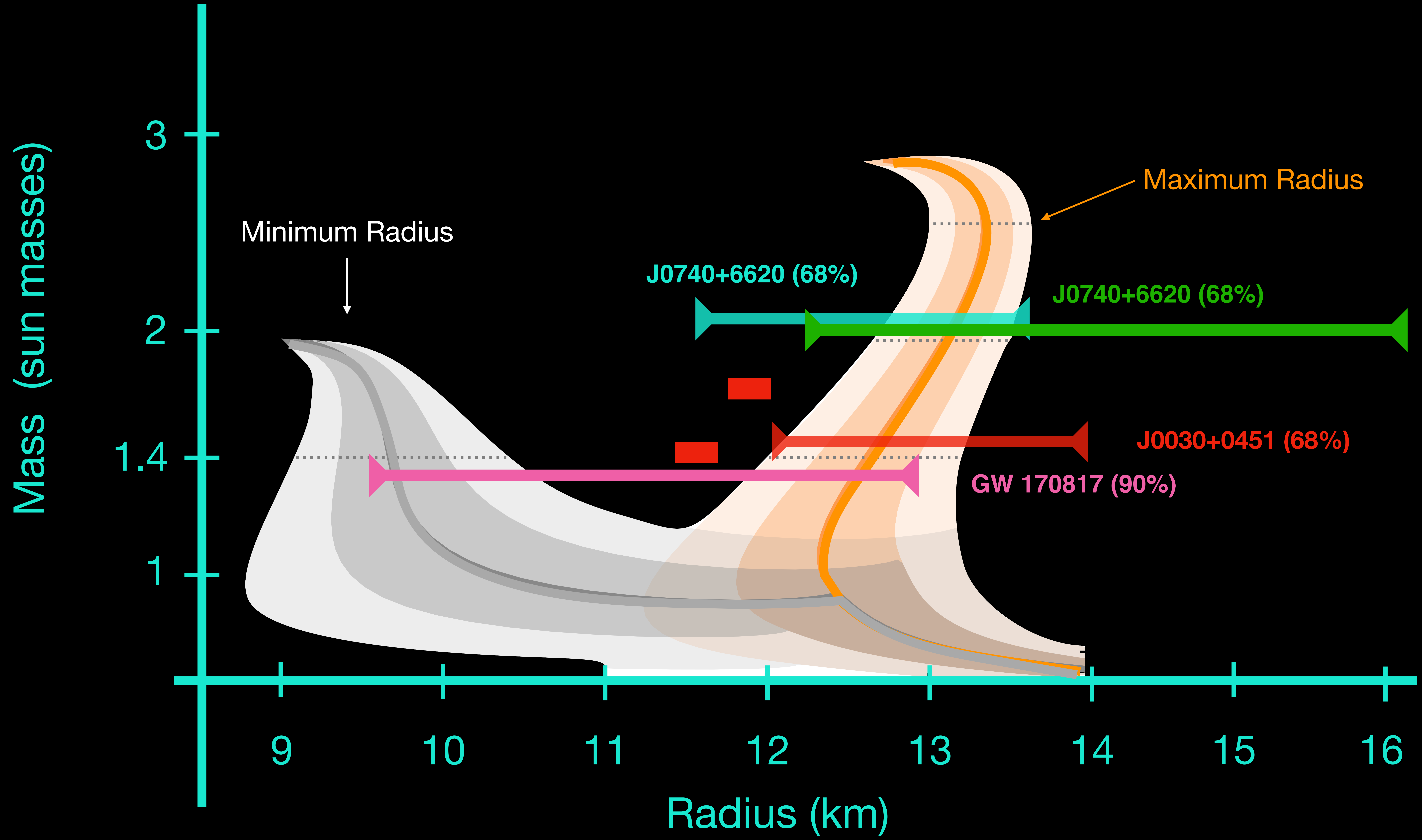


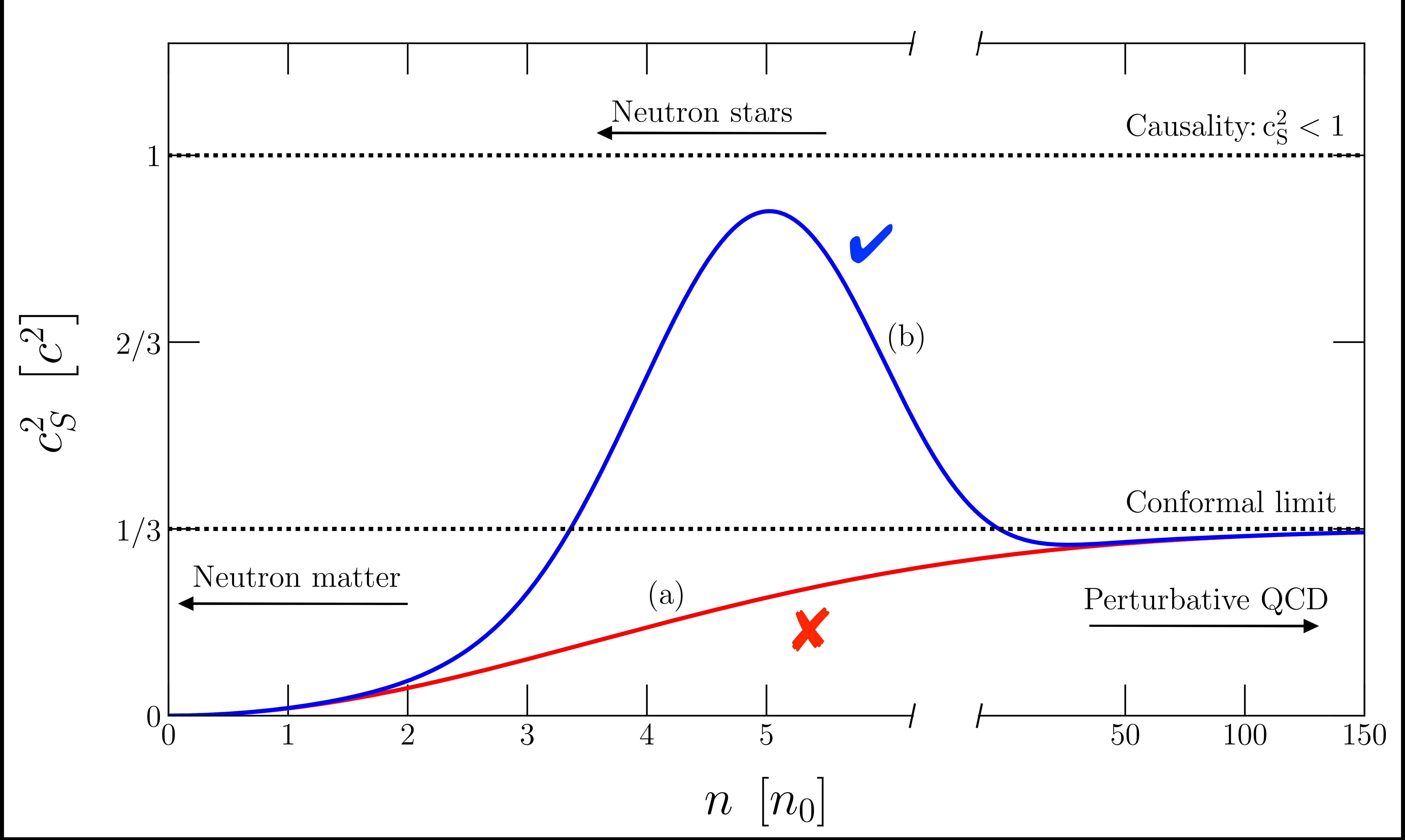
Speed of Sound in Dense Matter

$$c_s^2 = \frac{\partial P}{\partial \epsilon}$$

Large maximum mass and observed radii, combined with neutron matter calculations suggests a rapid increase in pressure in the neutron star core.

This implies a large and non-monotonic sound speed in dense QCD matter.

Suggests the existence of a strongly interacting phase of relativistic matter.



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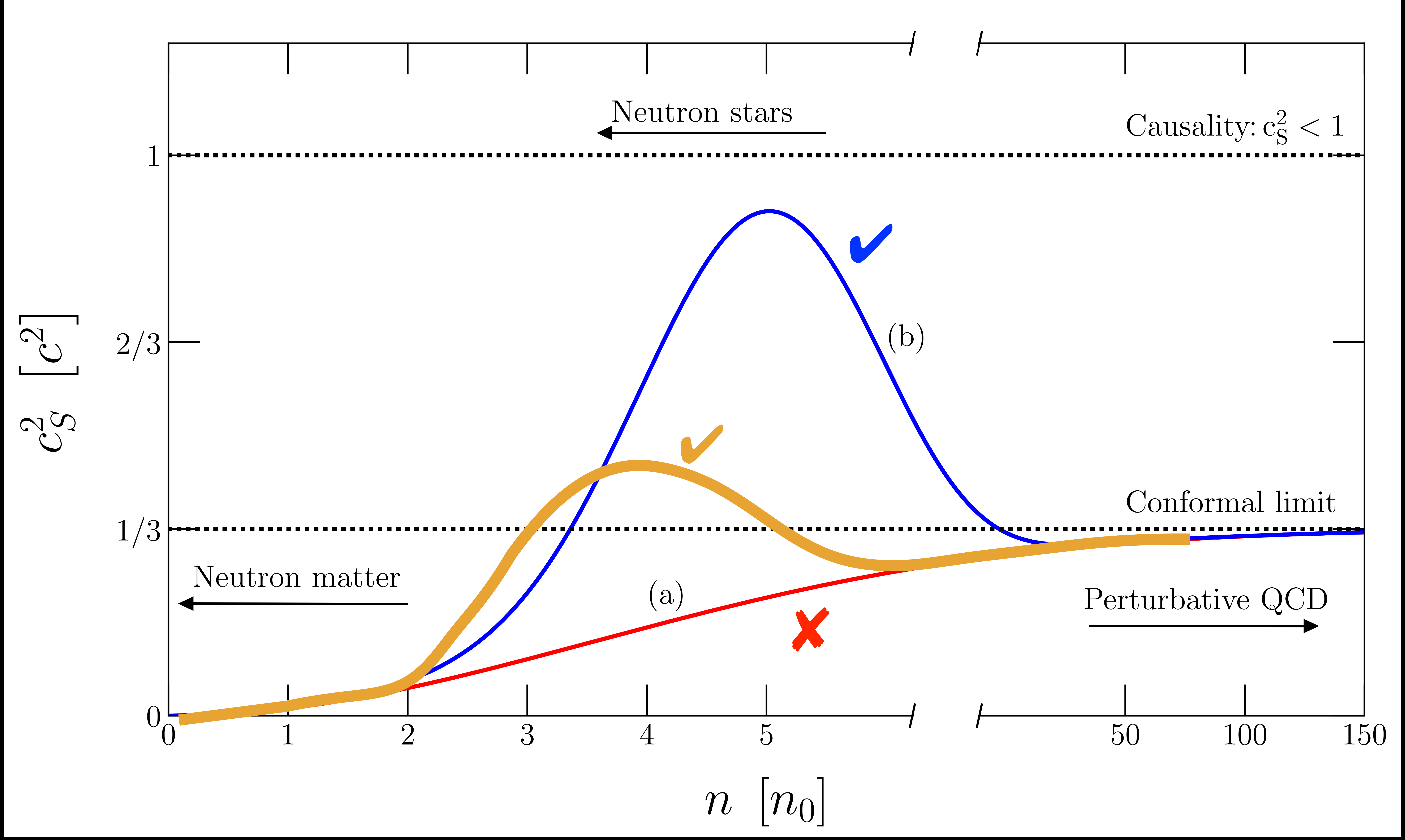

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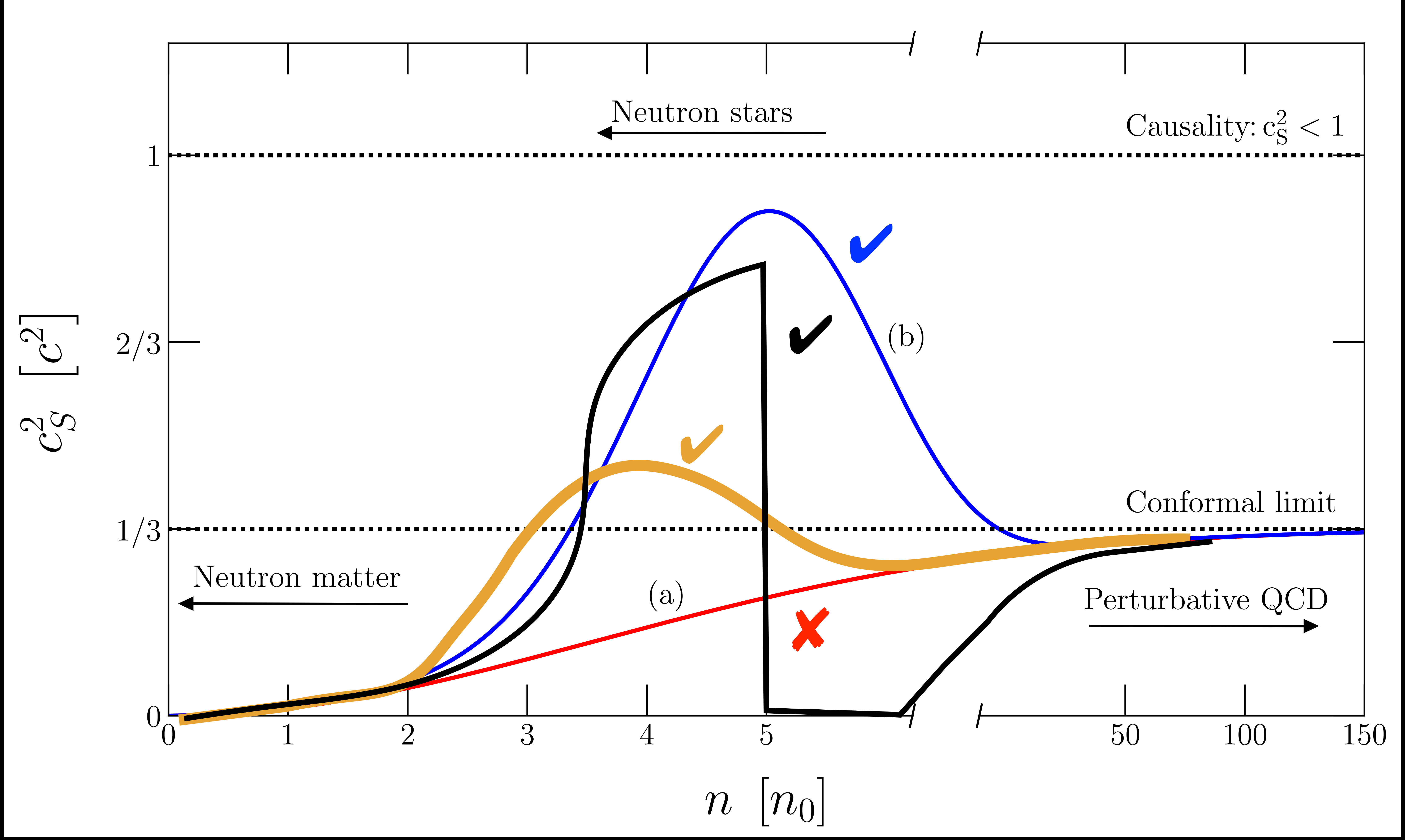

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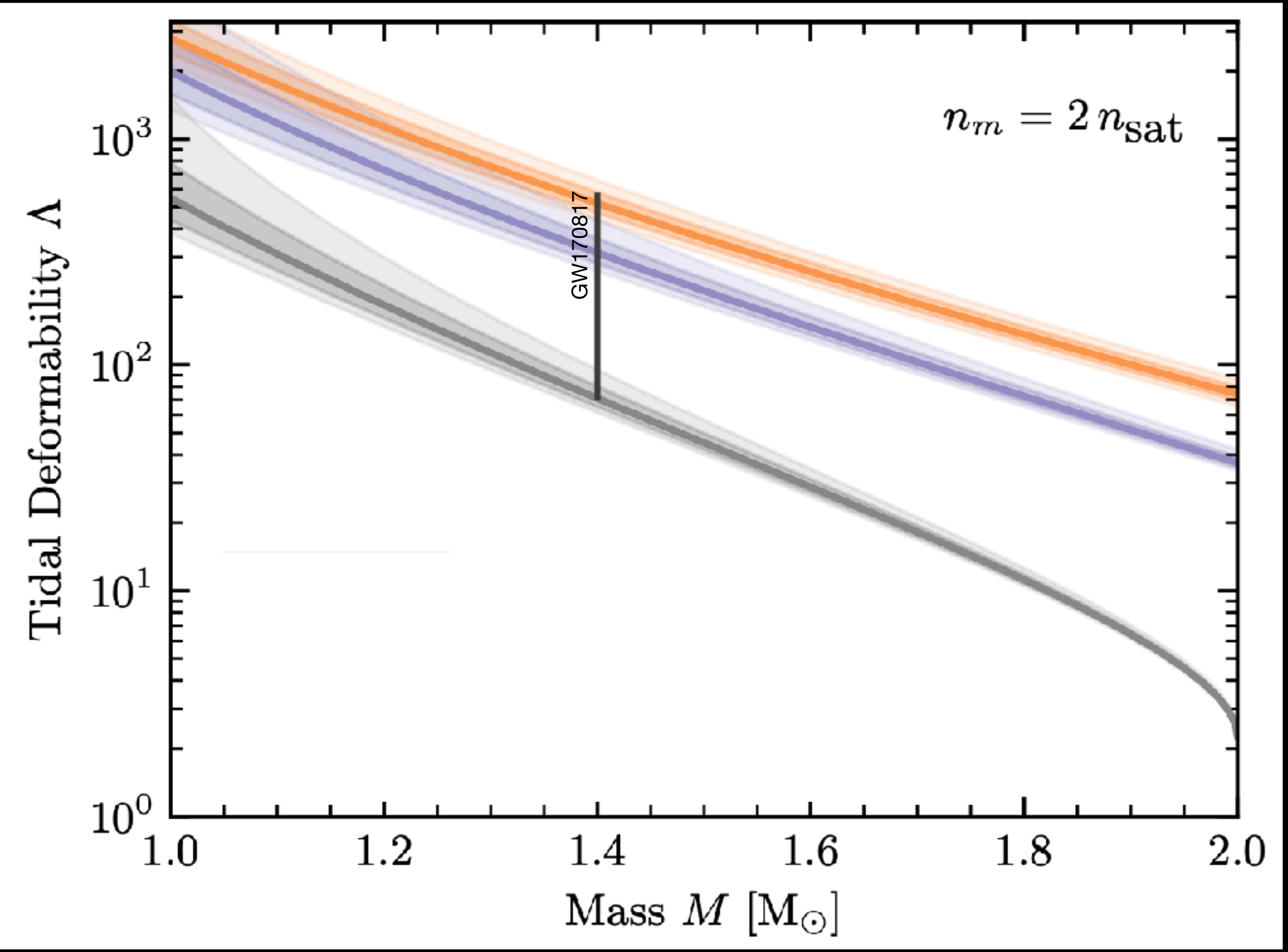
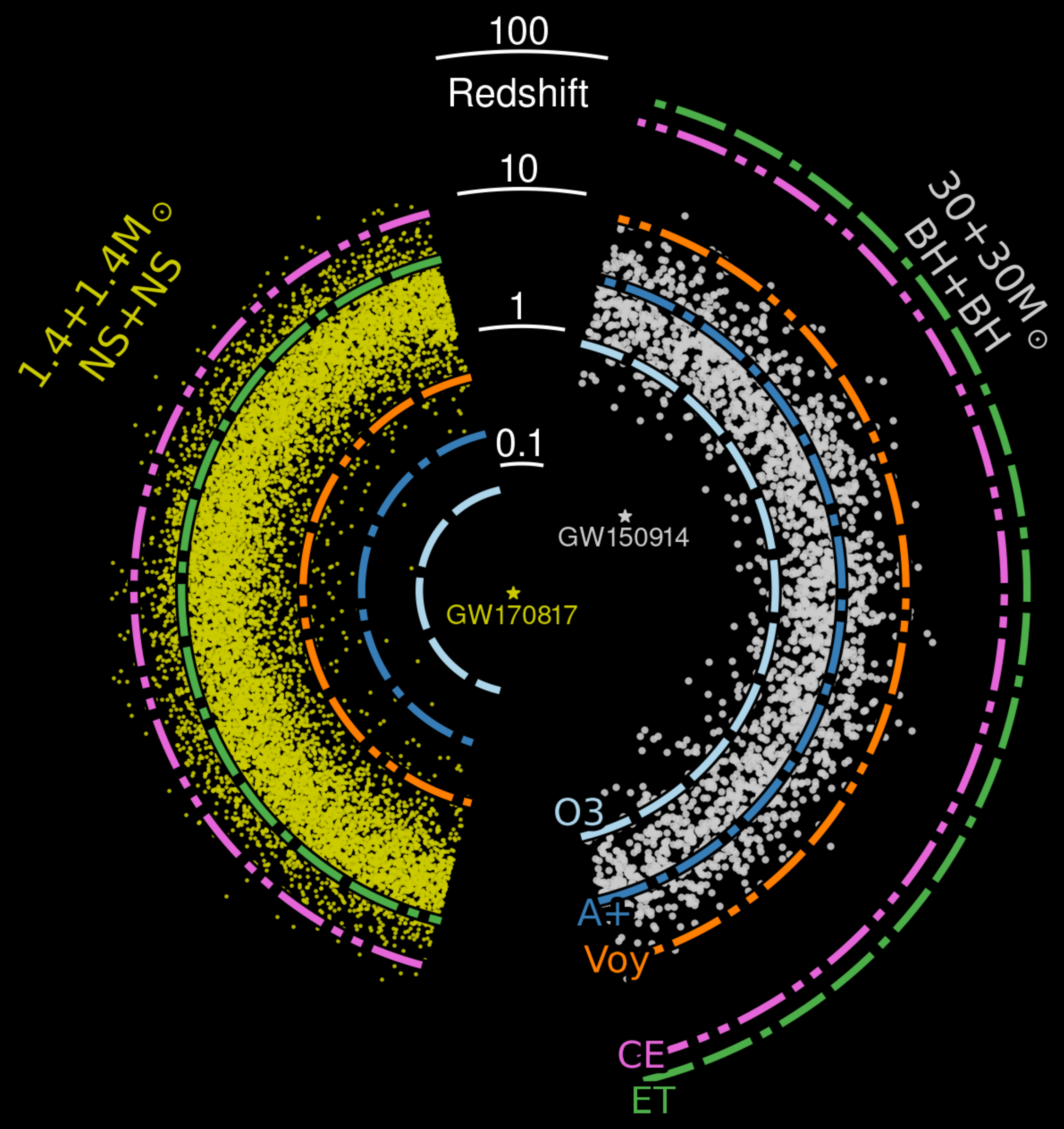
Tidal Deformability & Compact Object Populations



Drischler, Han, Lattimer, Prakash, Reddy, Zhao (2020)

Large sample size: 100,000 BNS/year.



~100 measurements of the masses and tidal deformability per year is within reach of next-generation GW detectors.

A Horizon Study for Cosmic Explorer: Science, Observatories, and Community
https://arxiv.org/abs/2109.09882

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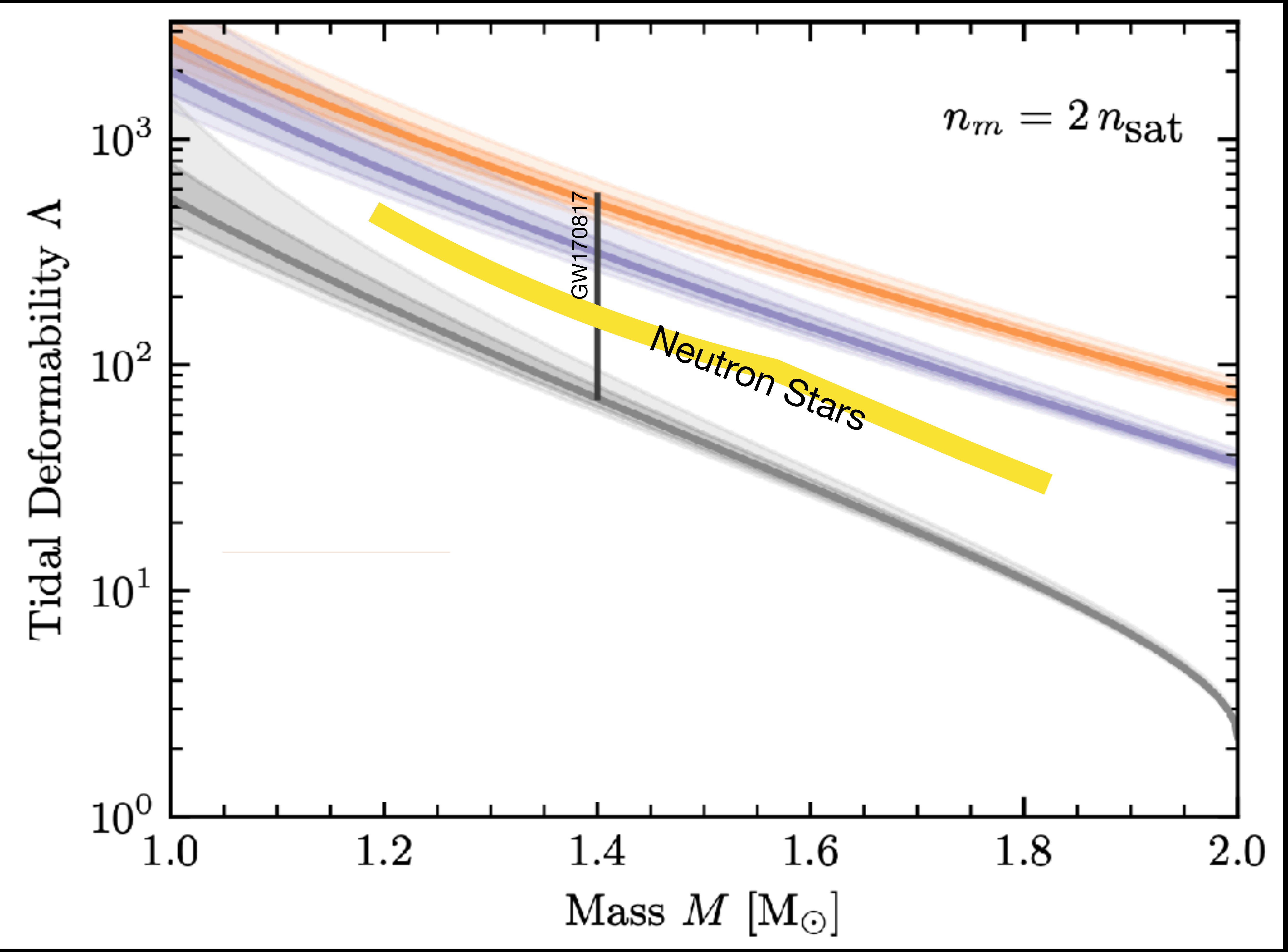

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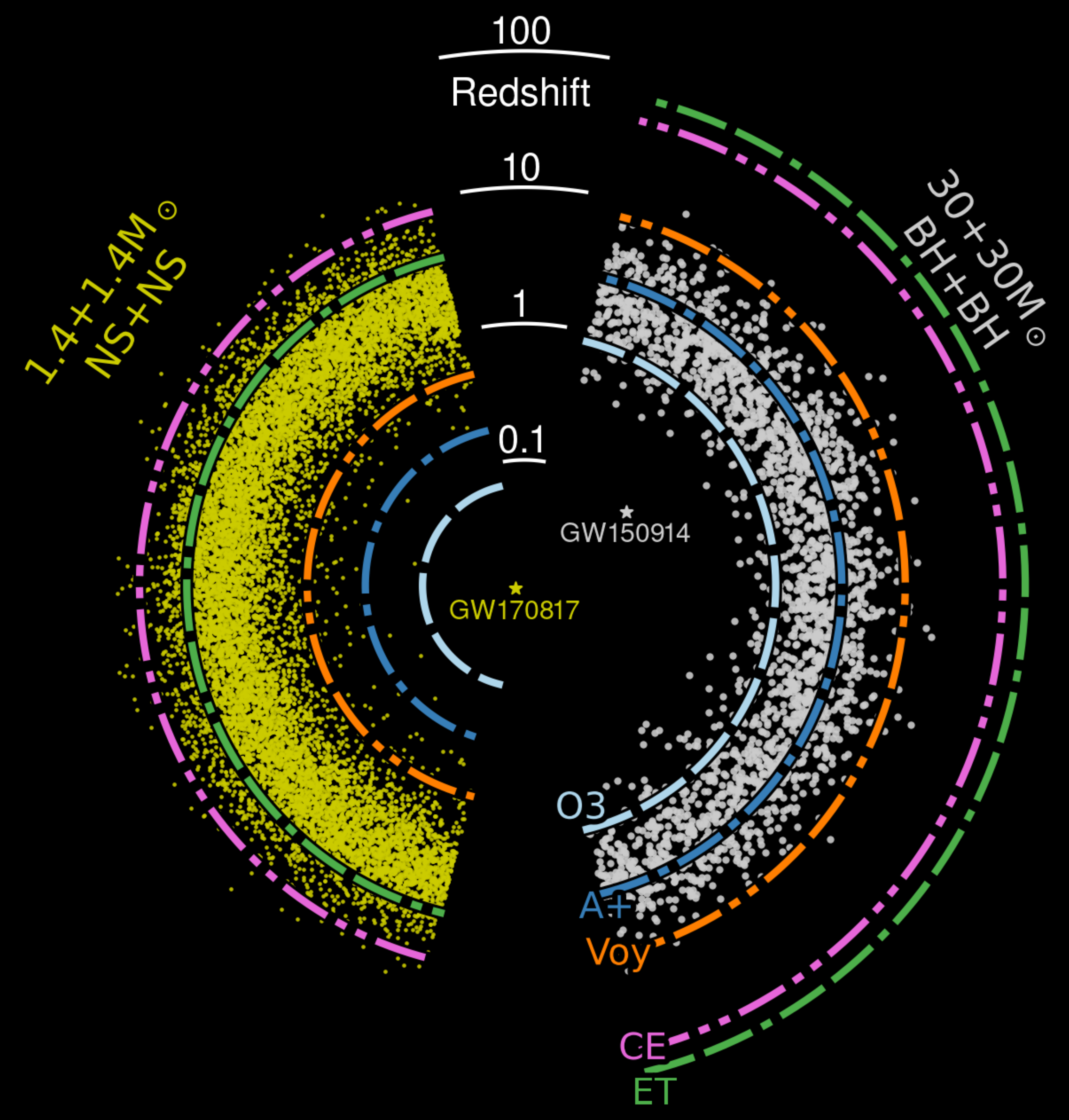

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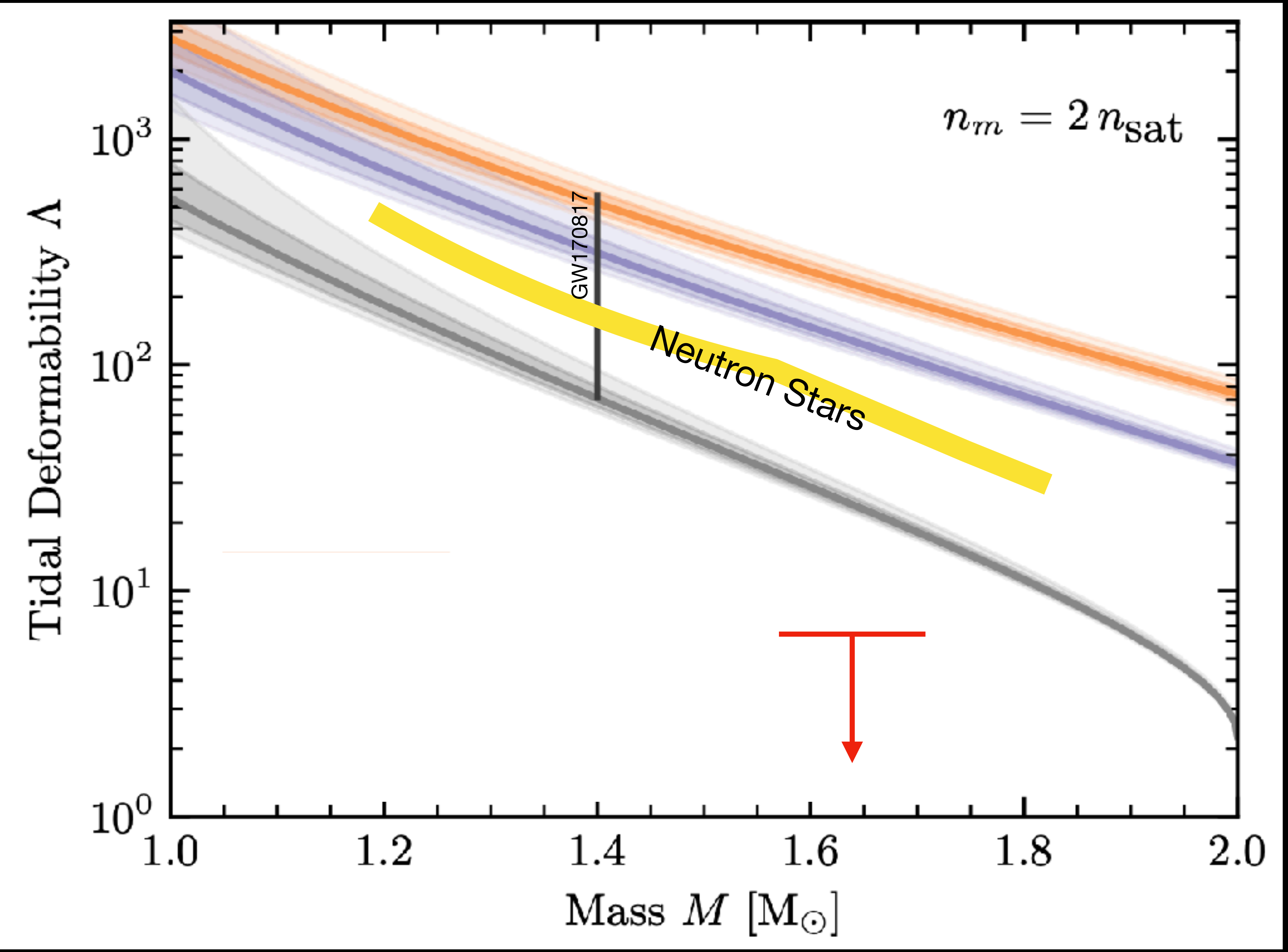

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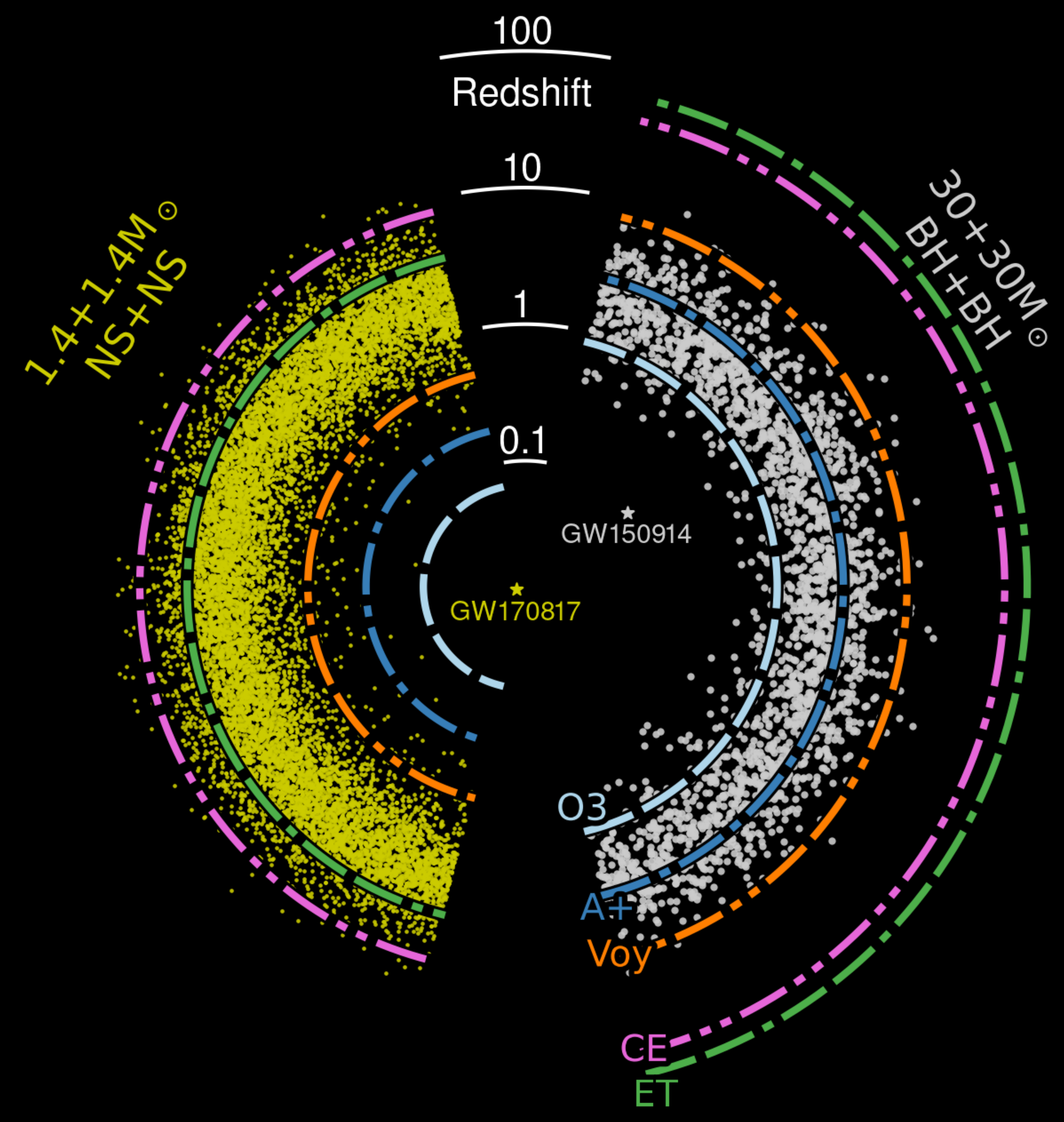

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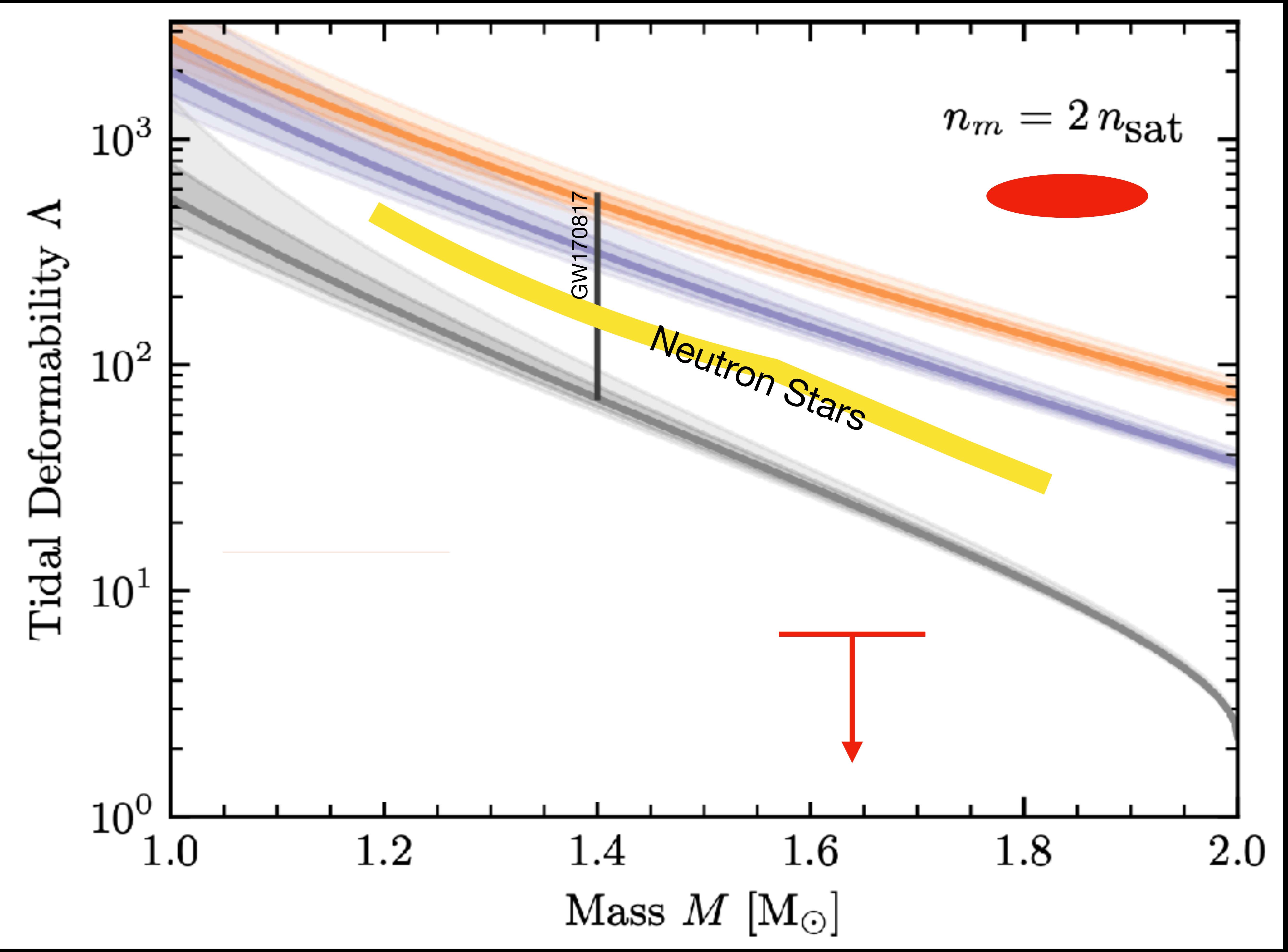

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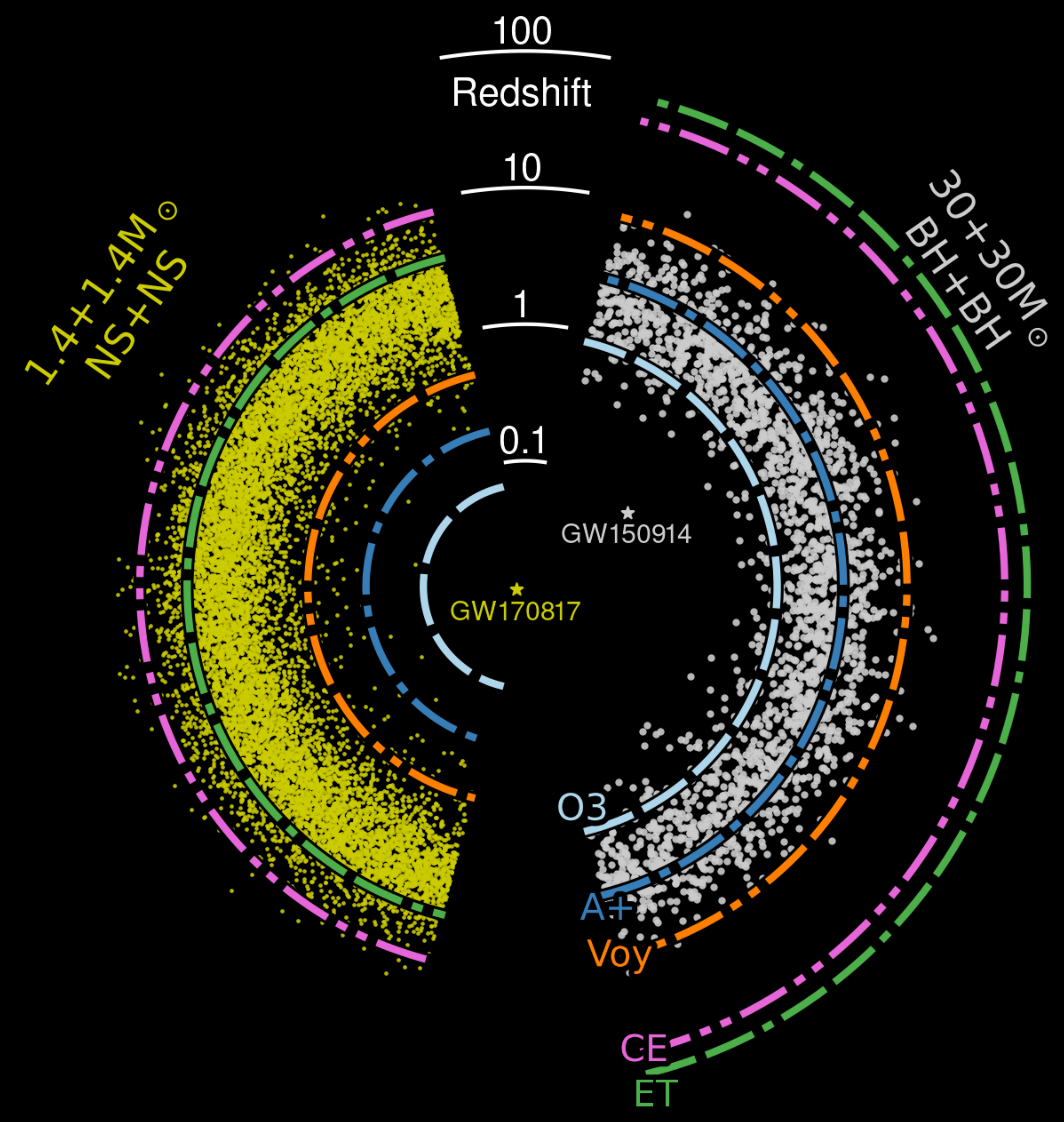

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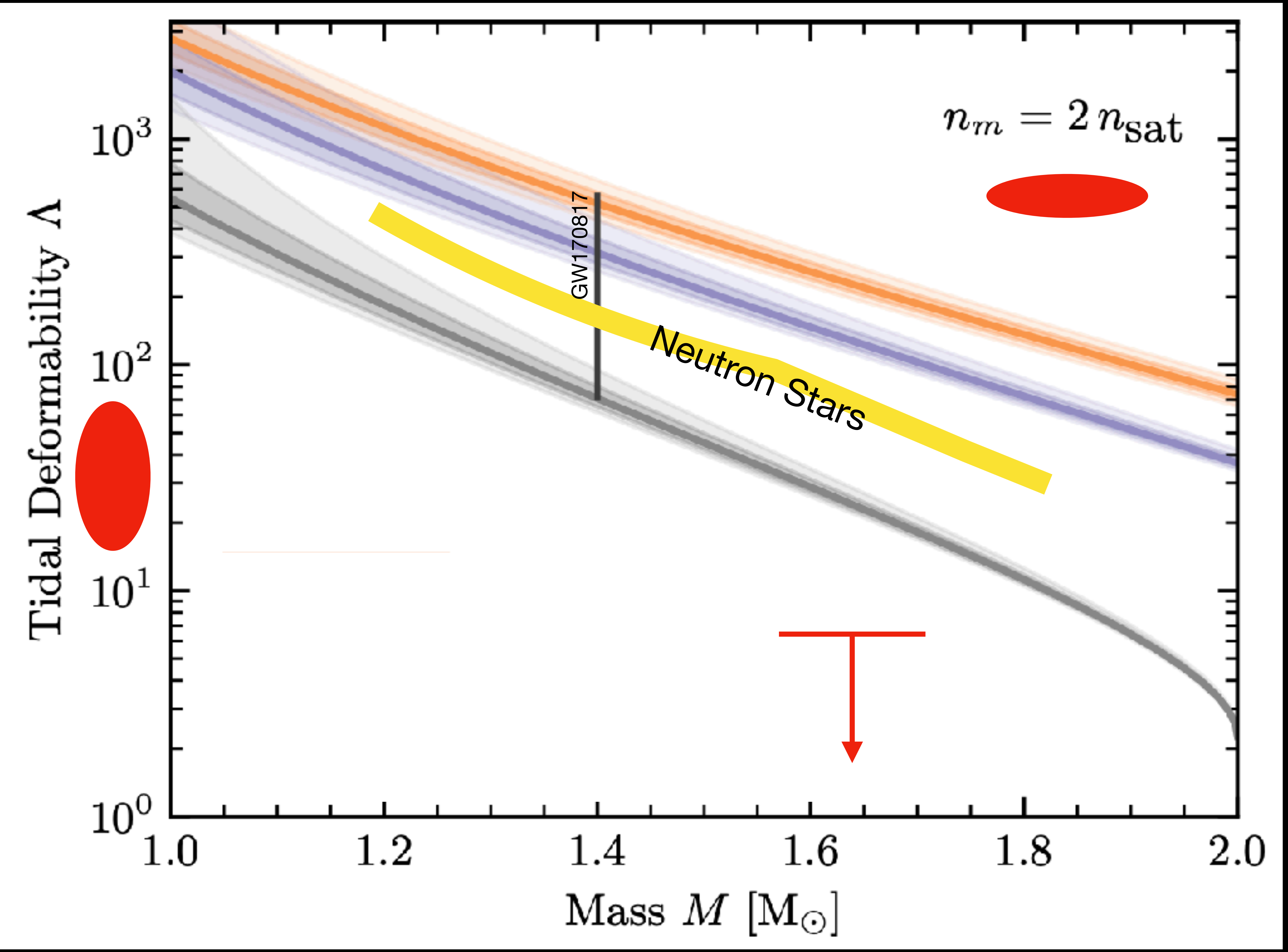

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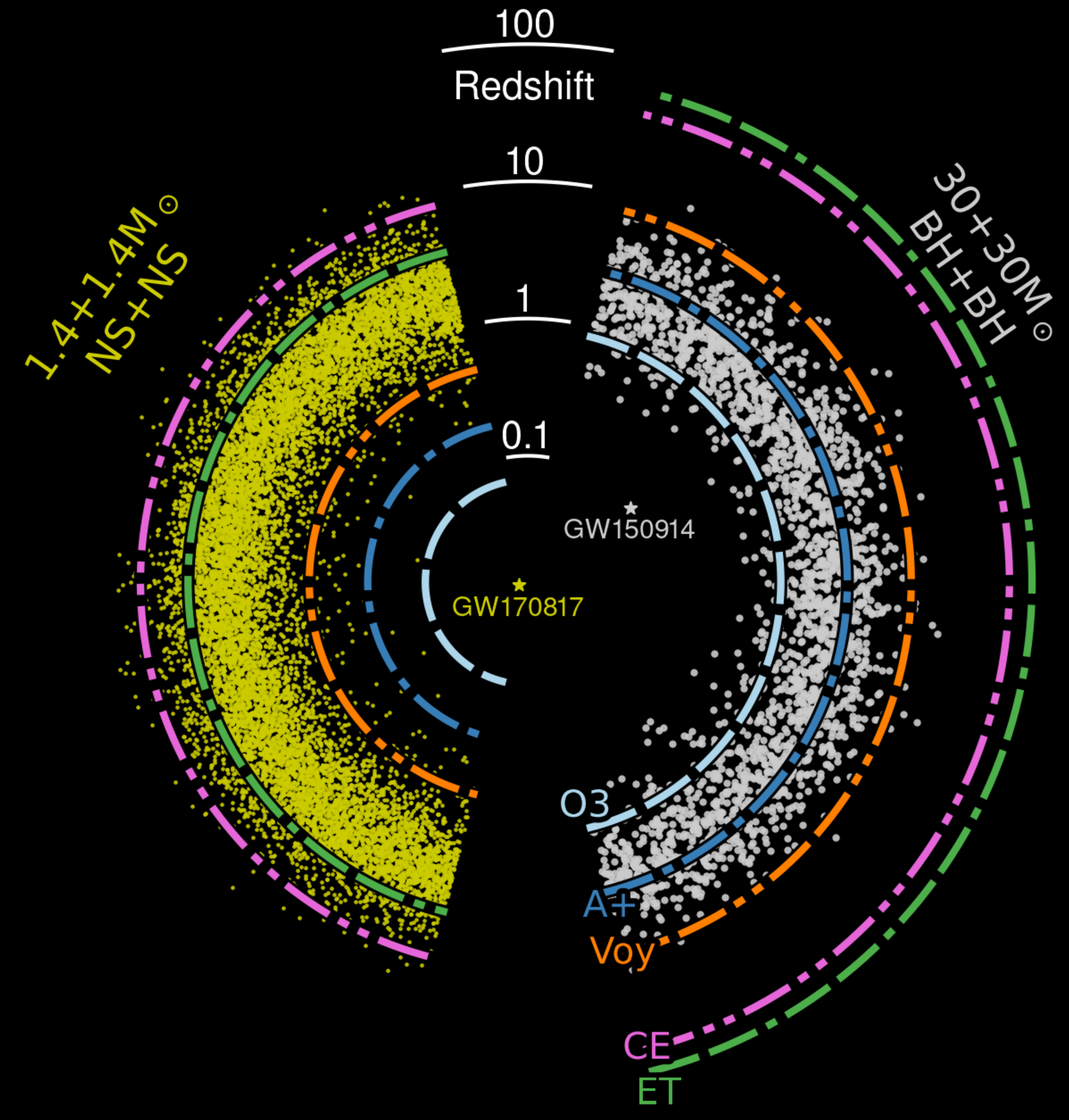

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The Dark Side of Neuton stars

Neutron stars are great places to look for dark matter

- They accrete and trap dark matter.

$$M_\chi < 10^{-14} M_\odot \left(\frac{\rho_\chi}{1 \text{ GeV/cm}^3} \right) \frac{t}{\text{Gyr}}$$

- Produce dark matter due to its high density.

$$M_\chi \lesssim M_\odot \text{ for } m_\chi < 2 \text{ GeV}$$

- Produce dark matter due to high temperatures at birth or during mergers.

$$M_\chi \lesssim 10^{-1}\, M_\odot \text{ for } m_\chi < 100 \text{ MeV}$$

Black-Holes in the Neutron Star Mass-Range

Idea: Accretion of asymmetric bosonic dark matter can induce the collapse of an NS to a BH.

Goldman & Nussinov (1989)

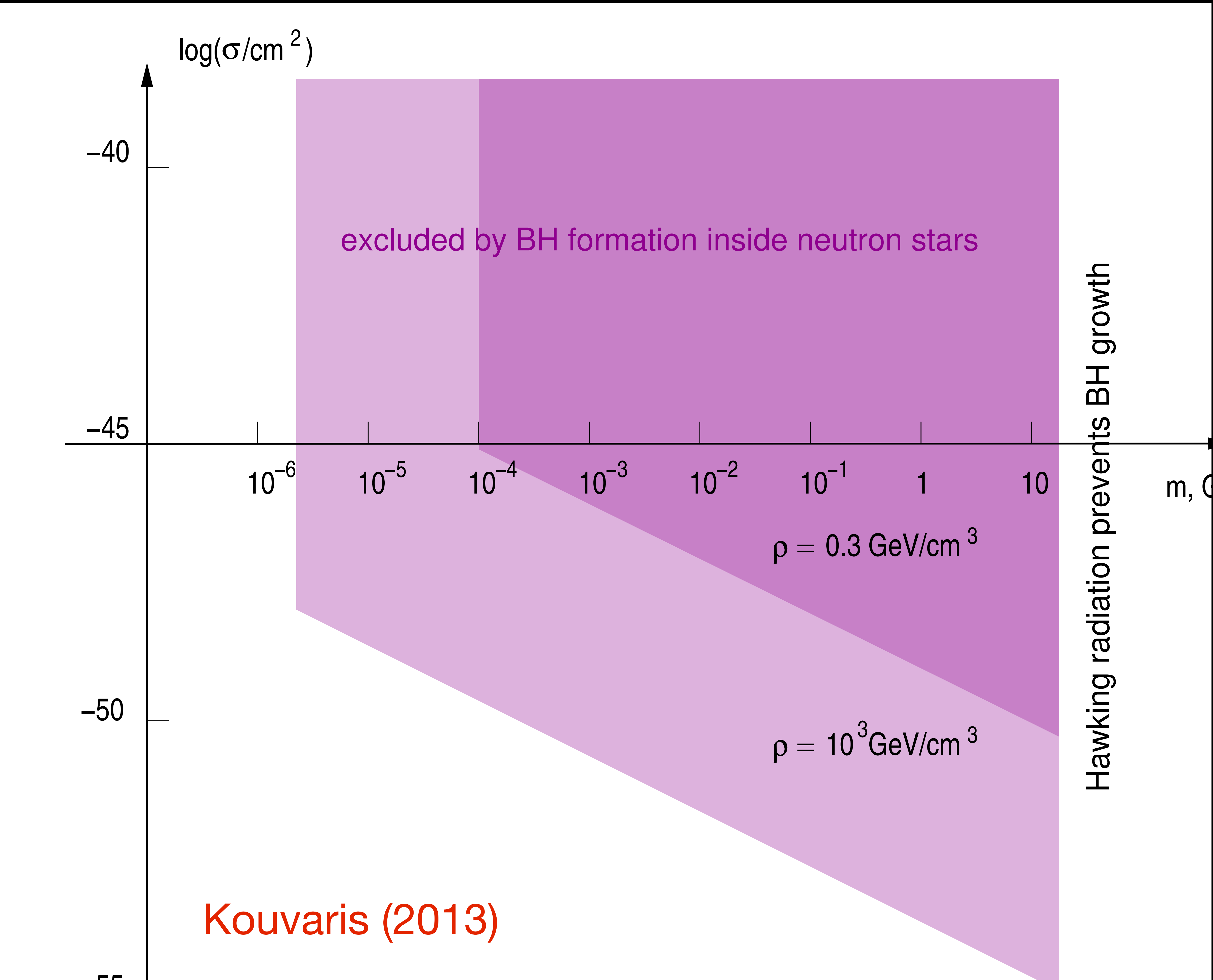
$$M_\chi \approx 10^{-14} M_\odot \ \mathrm{Min}\left[\frac{\sigma}{2\times 10^{-45}\mathrm{cm}^2}, 1\right] \left(\frac{\rho_\chi}{1\ \mathrm{GeV/cm}^3}\right) \frac{t}{\mathrm{Gyr}}$$

The maximum mass of weakly Interacting bosons is negligible:

$$M_{\mathrm{Bosons}} \approx 10^{-18}\ M_\odot \left(\frac{\mathrm{GeV}}{m_\chi}\right)$$

The existence of old neutron stars in the Milkyway with estimated age ~ Gyr provides strong constraints on asymmetric DM.

For a concise reviews see Kouvaris (2013) and Zurek (2013)

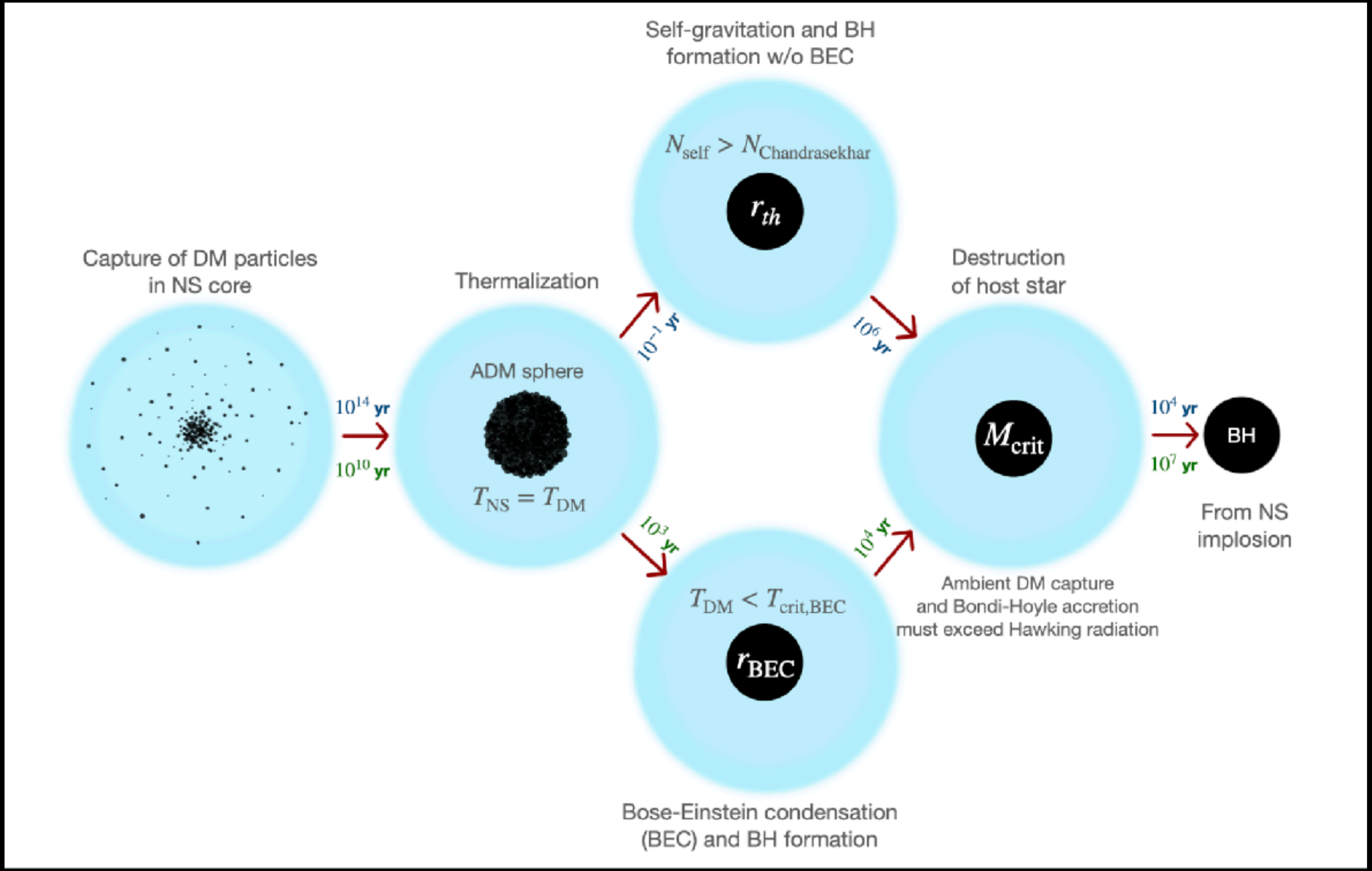


Time Scale for Converting NSs into BHs

For dark matter in the 1-10^6 GeV mass range, black hole formation is complex and involves several timescales.

Capture time is typically the limiting step. But, thermalization can be slow in exotic superfluid phases and depends on processes in the inner core!

C. Kouvaris and P. Tinyakov (2011)
S. D. McDermott, H.-B. Yu, and K. M. Zurek, (2012)
B. Bertoni, A. E. Nelson, and S. Reddy (2013)
+ many more, more refined recent analyses.



Divya Singh, Gupta, Berti, Reddy, Sathyaprakash (2024)

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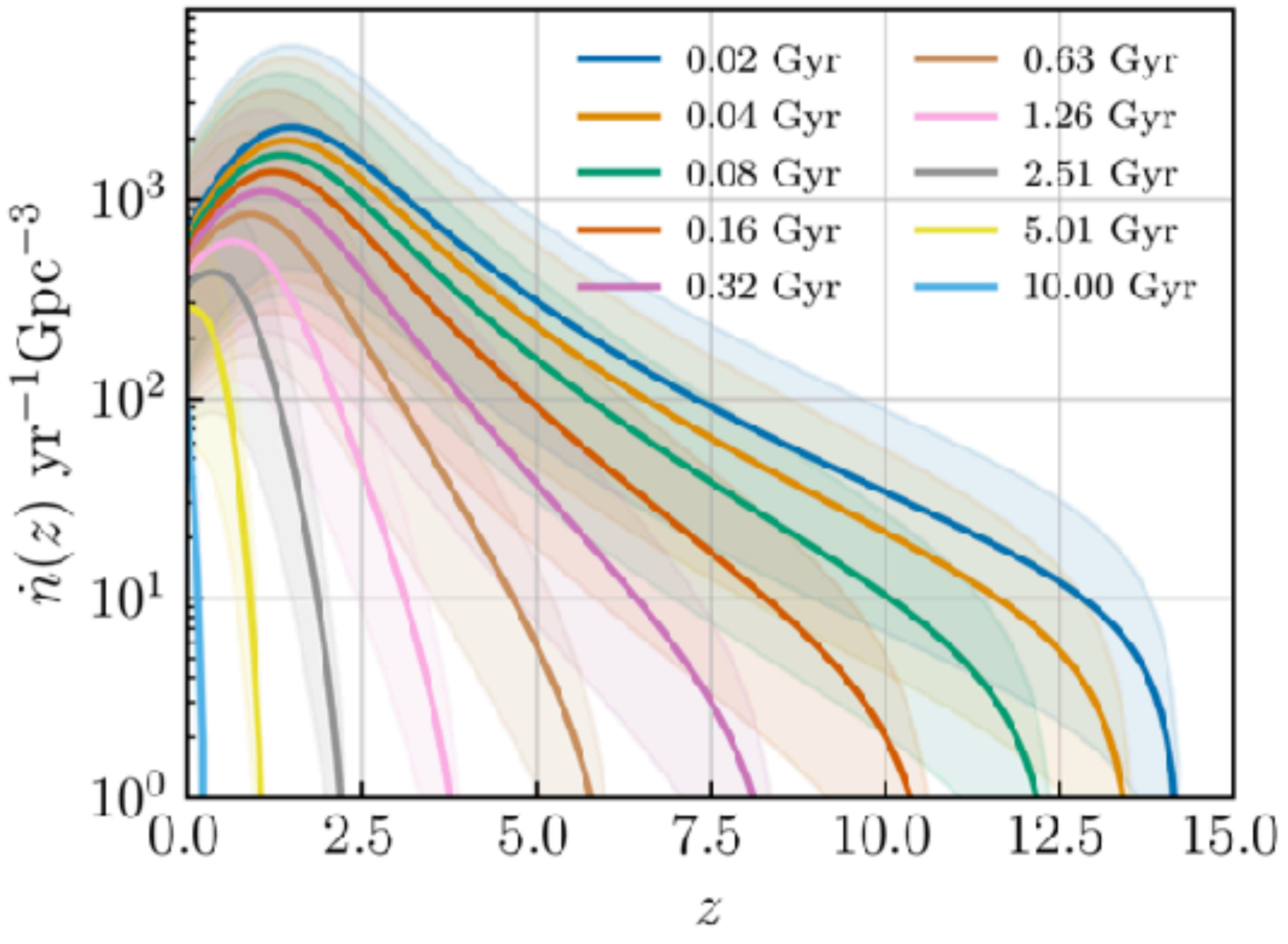
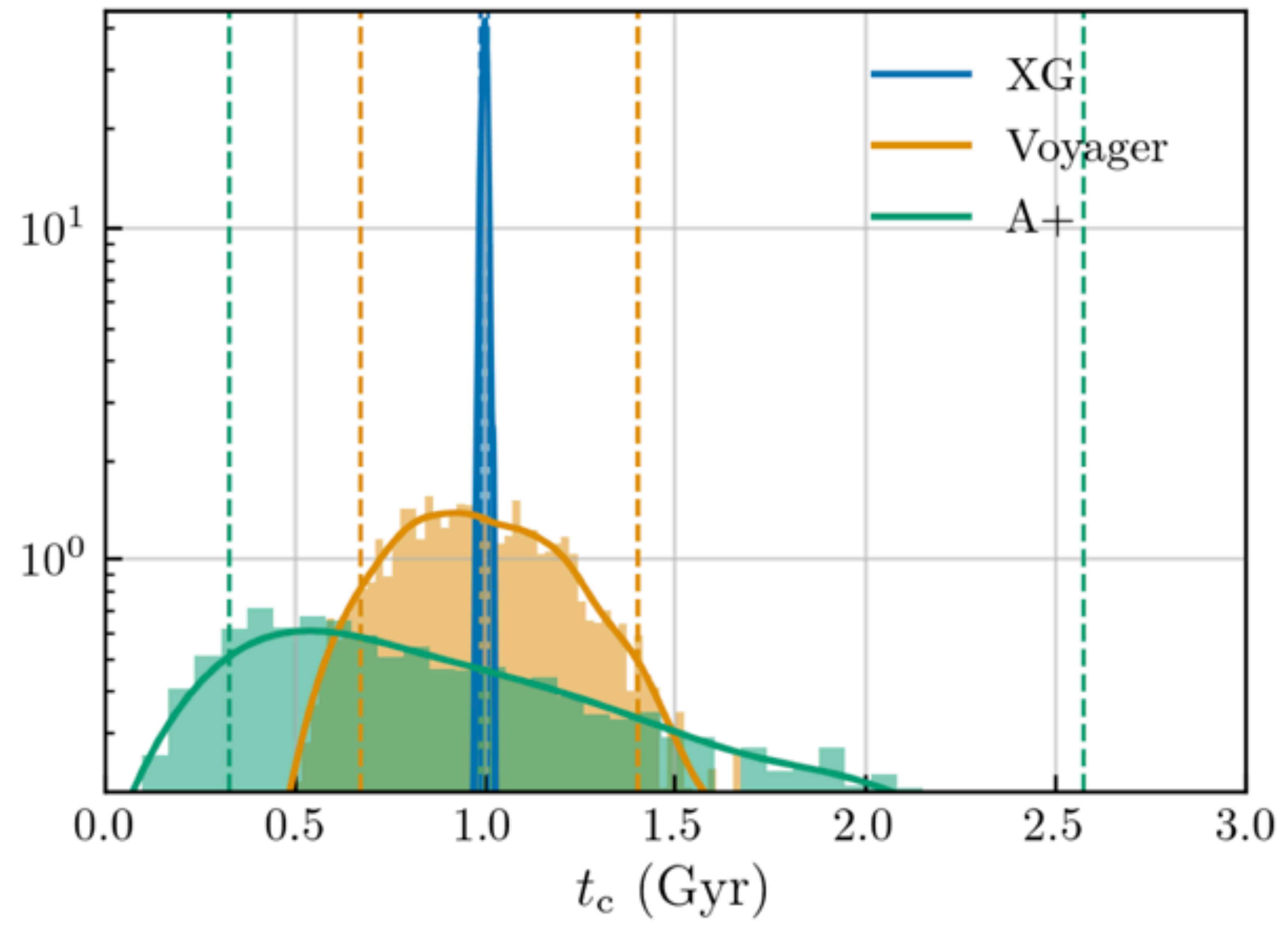


The number of merging black holes formed from NS implosion grows rapidly when the collape time is less than a Gyr.

A measurement of the tidal deformability will allow us to distinguish BBH from BNS to infer the collape time in next generation detectors.



Divya Singh, Gupta, Berti, Reddy, Sathyaprakash (2024)

Constraining Dark Baryons

Dark sectors could contain particles in the MeV-GeV mass range that mix with baryons.

There was speculation that a dark baryon with mass m_χ between 937.76 - 938.78 MeV might explain the discrepancy between neutron lifetime measurements. Fornal & Grinstein (2018)

$$n \to \chi + \ldots$$

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

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

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

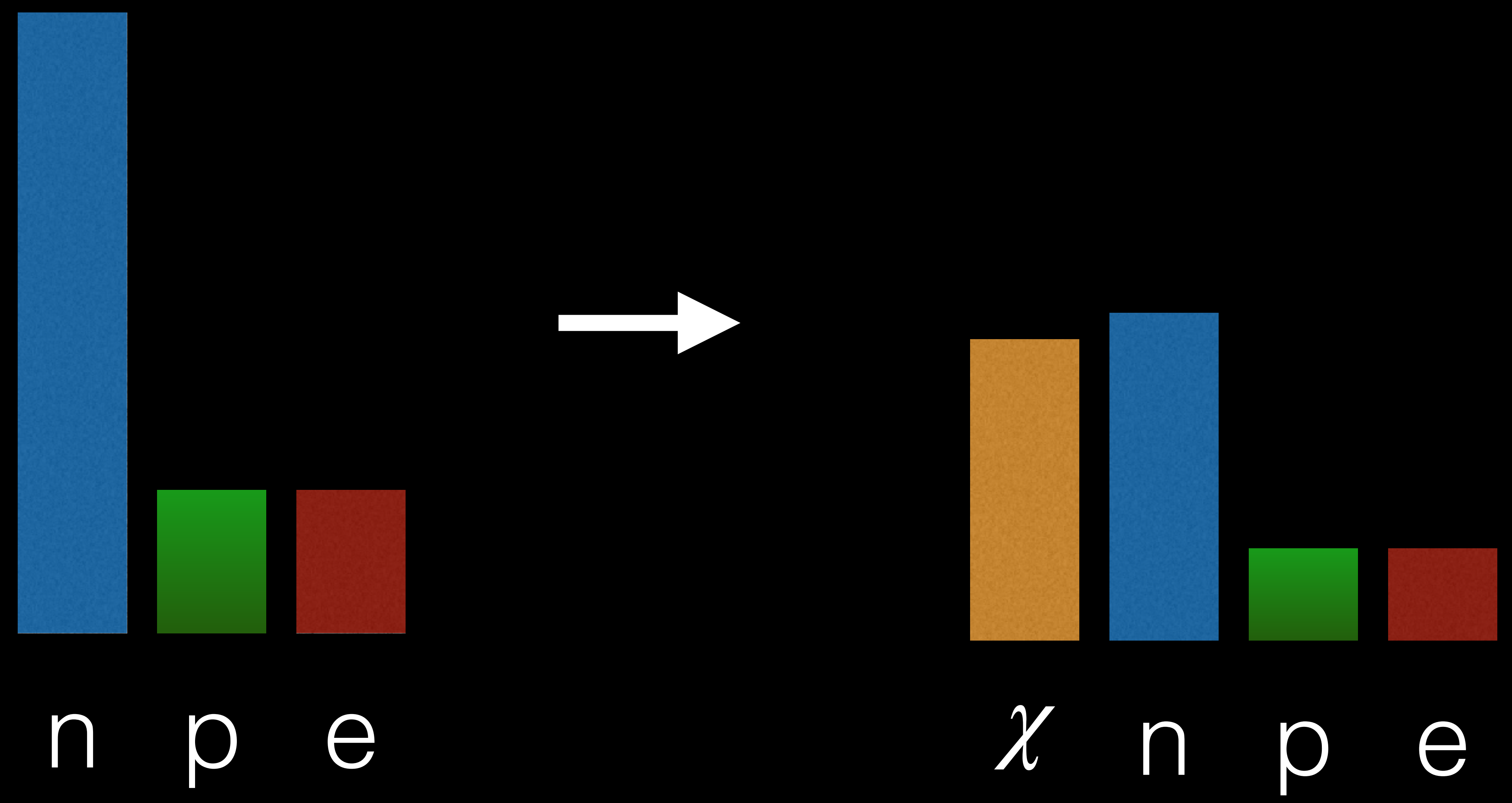
A model for hidden baryons that mix with the neutron:

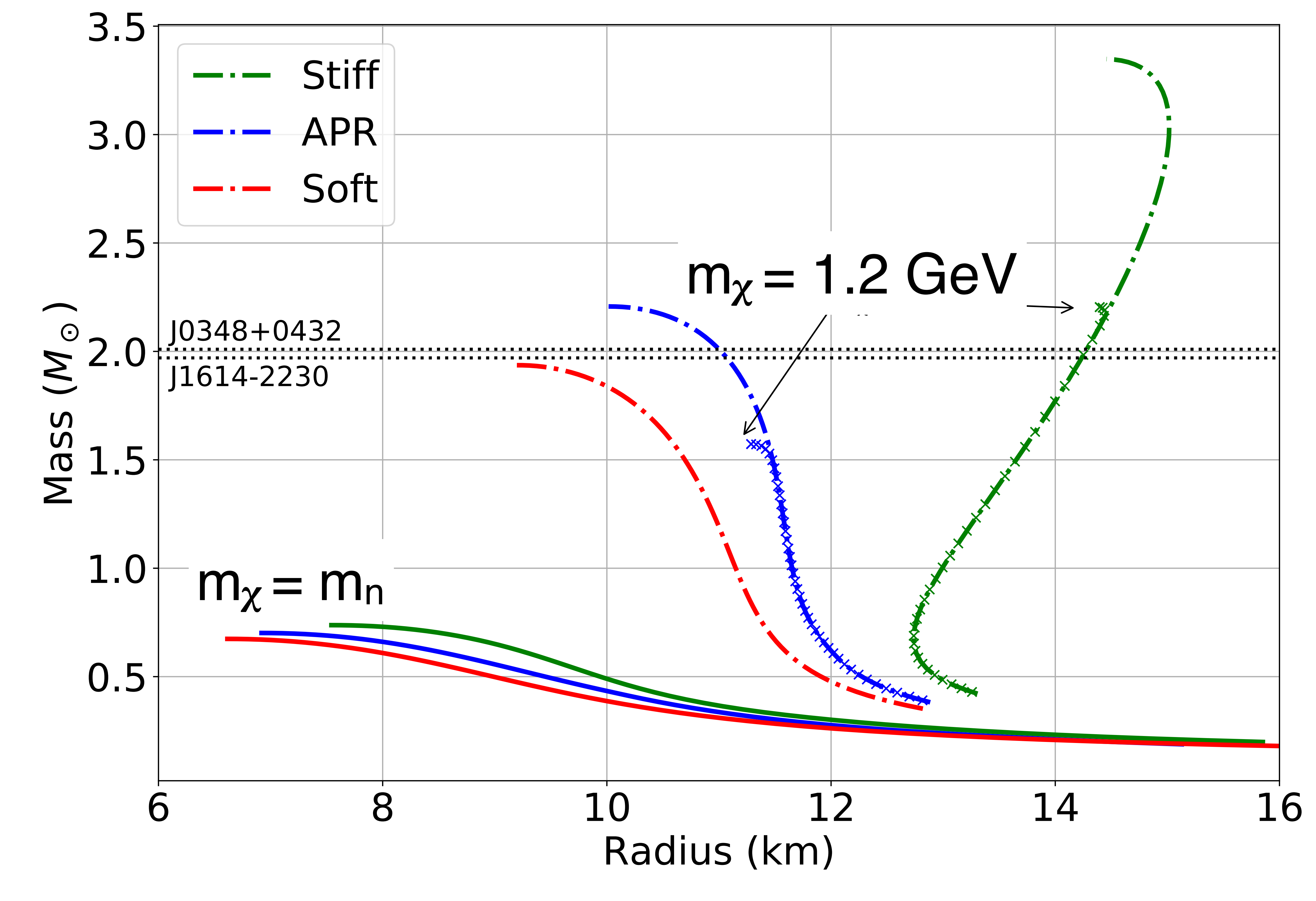
$$\mathcal{L}_{\text{eff}} = \bar{n}\,(i\partial\!\!\!/ - m_n)\,n + \bar{\chi}\,(i\partial\!\!\!/ - m_\chi)\,\chi - \delta\,(\bar{\chi}n + \bar{n}\chi)$$

Mixing angle: $\theta = \dfrac{\delta}{\Delta M}$ ⮕ An explanation of the anomaly requires $\theta \simeq 10^{-9}$

Neutron stars can probe much smaller mixing angles: $\theta \simeq 10^{-18}$

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)

Motta, Guichon and Thomas (2018)

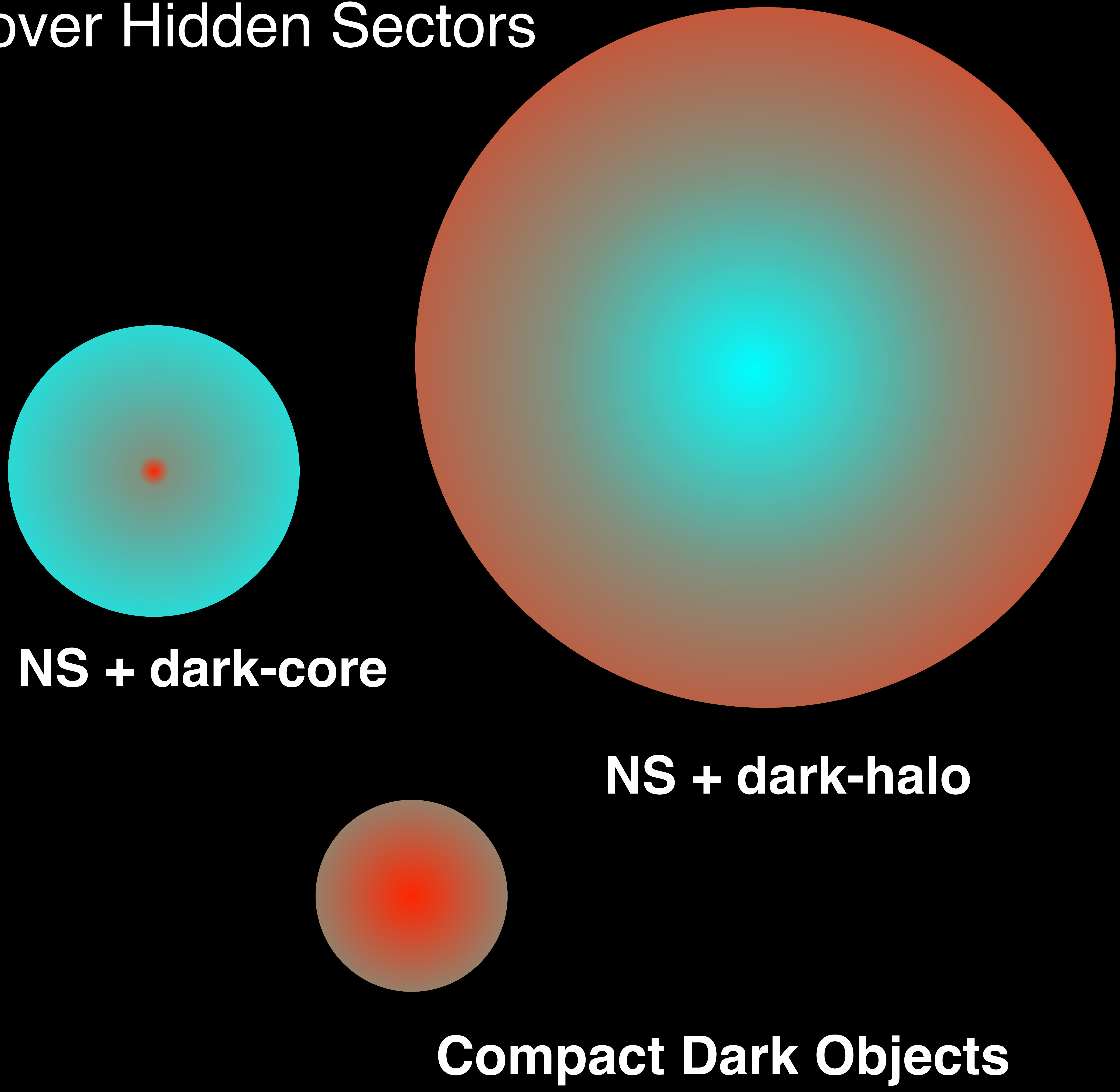
Self-interacting Dark Matter

Using Gravitational Waves to Discover Hidden Sectors

Self-interacting dark matter can be stable and bound to neutron stars - a new class of compact dark objects.

Gravitational wave observations of binary compact objects whose masses and tidal deformability's differ from those expected from neutron stars and stellar black holes would provide conclusive evidence for a strongly self-interacting dark sector:

Mass $< 0.1\ M_{solar}$
Tidal Deformability > 600



Nelson, Reddy, & Zhou (2018)   Horowitz & Reddy (2018)

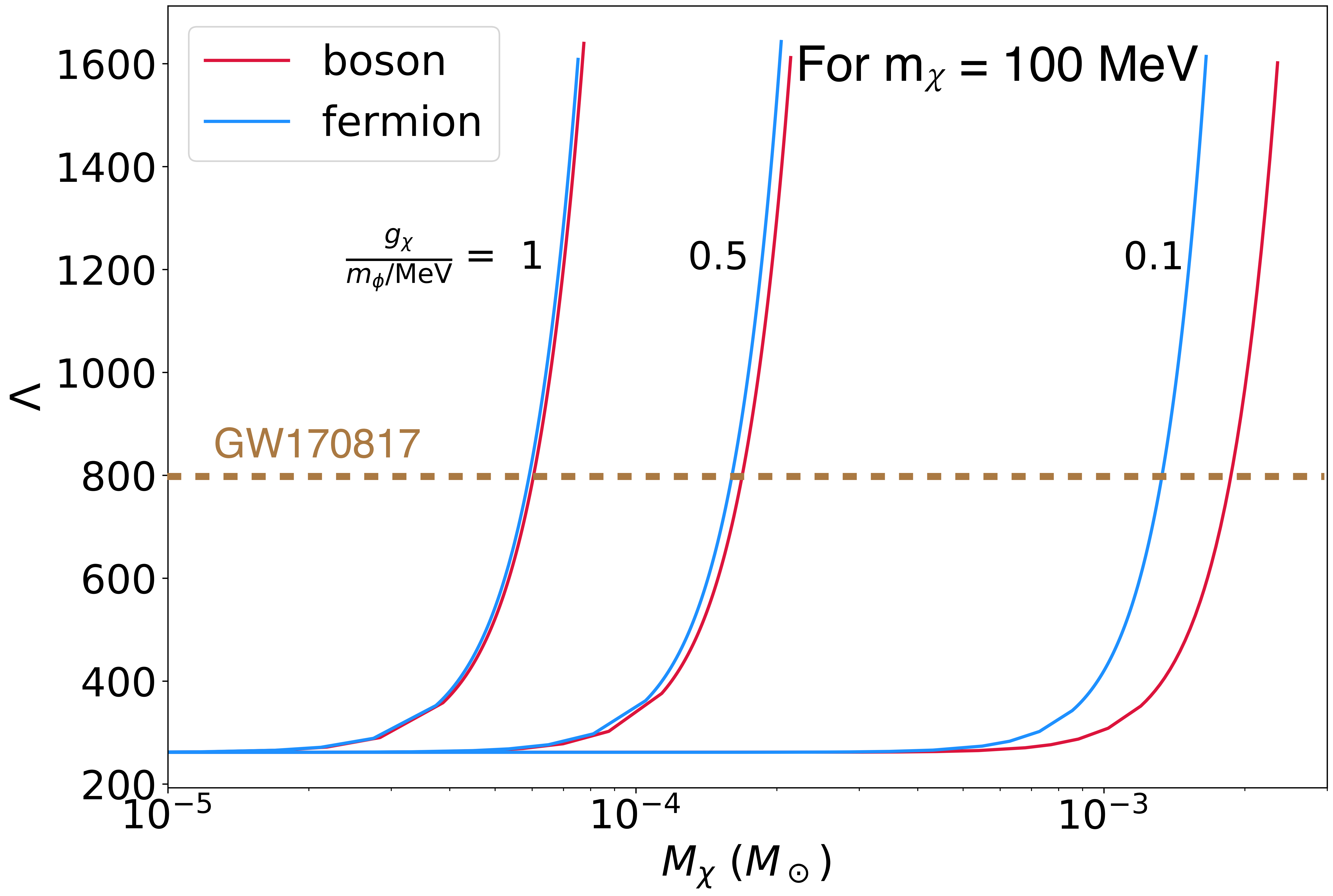
Dark Halos Alter Tidal Interactions

Trace amount of light dark matter ~ 10^{-4}-10^{-2} M_{solar} is adequate to enhance the tidal deformability $\Lambda > 800$!

Self-Interactions of "natural-size" can provide adequate repulsion.

g_χ/m_Φ = (0.1/MeV) or (10^{-6}/eV)

Nelson, Reddy, Zhou (2019)



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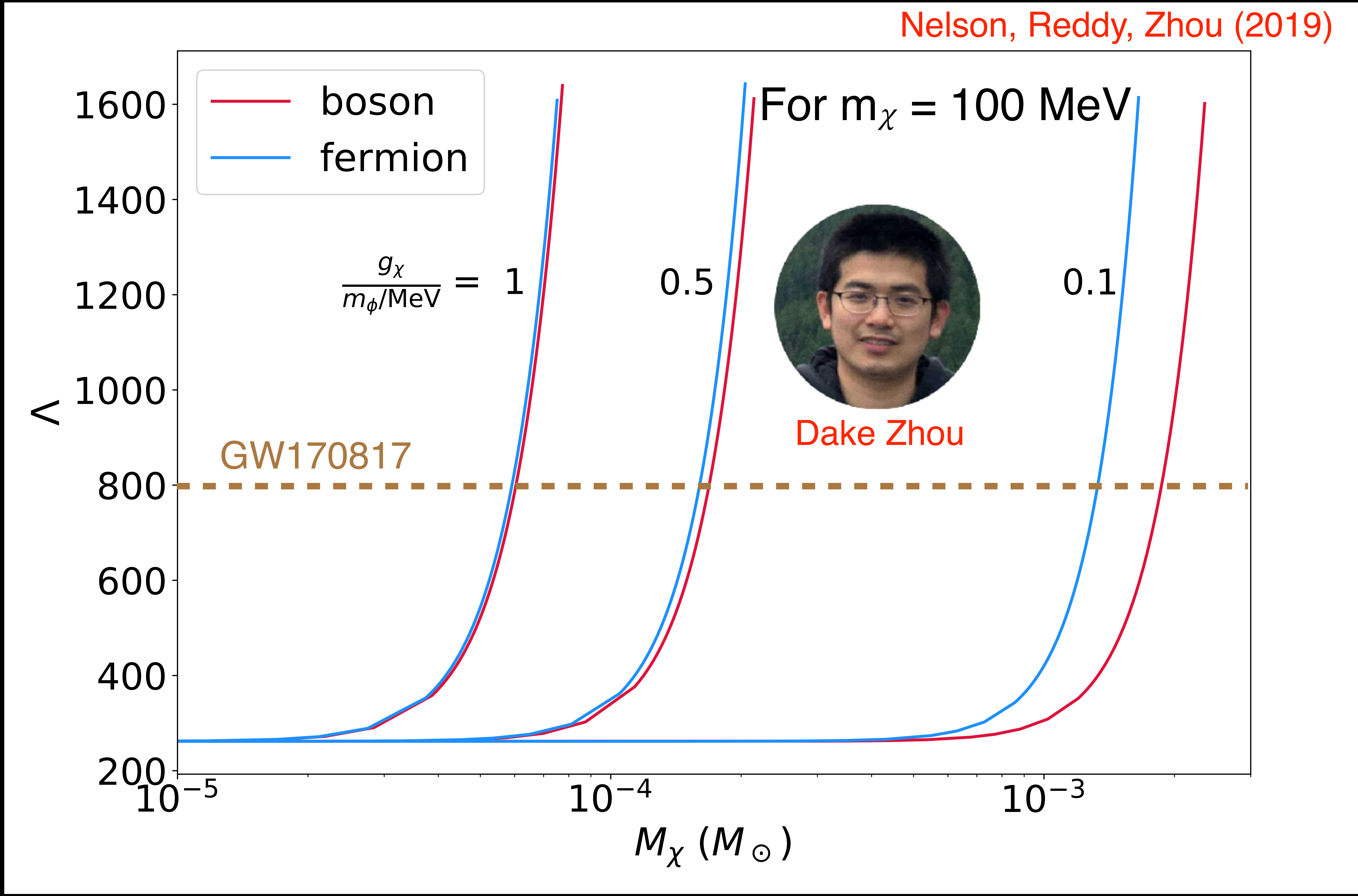

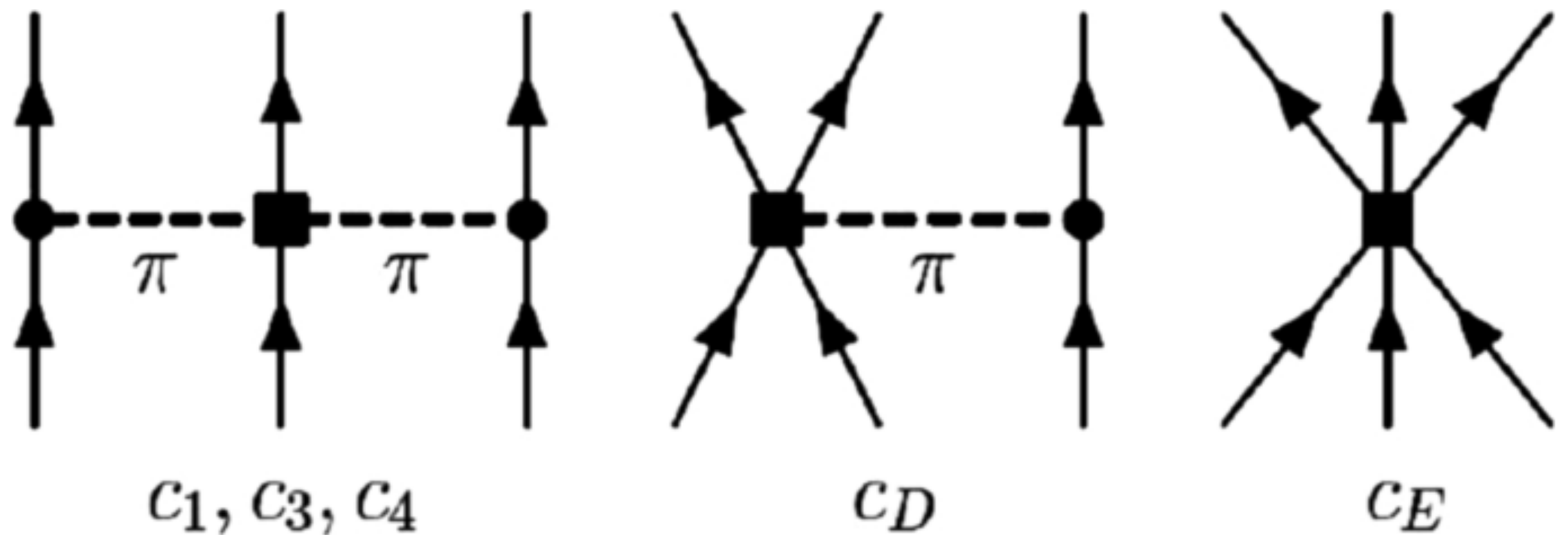

C. Drischler, R. J. Furnstahl, J. A. Meleldez, D. R. Phillips (2021)

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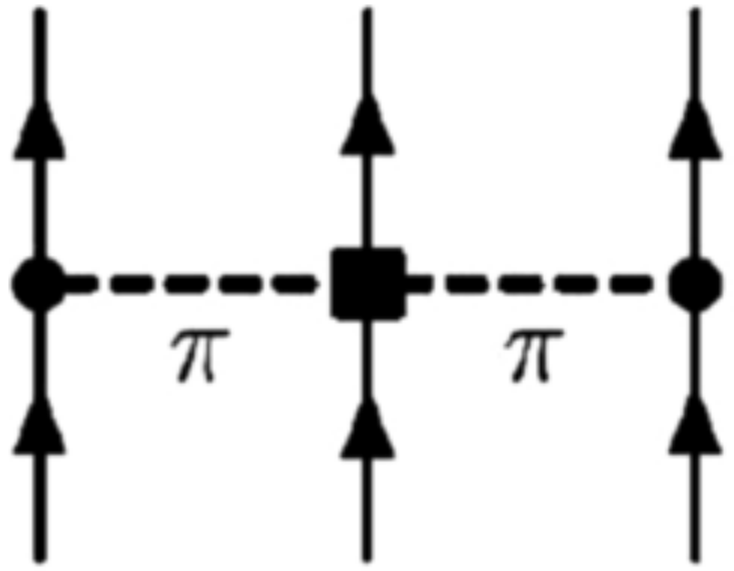

c_1, c_3, c_4

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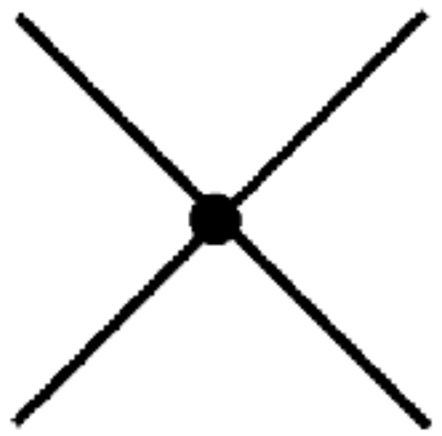
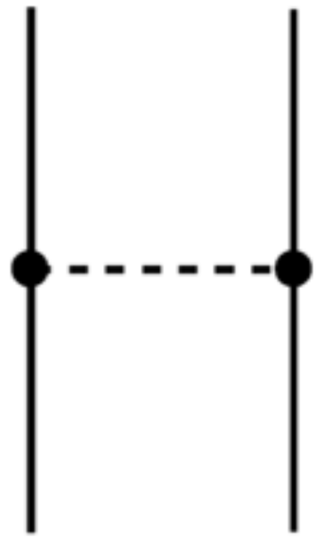
I. Tews,R. Somasundaram,D. Lonardoni,H. Göttling, R. Seutin, J. Carlson S. Gandolfi,K. Hebeler, A. Schwenk (2024)

Renormalization of the NN interaction in ChiEFT





$$V_{\rm LO}(q) = \qquad C_0 + D_2\ m_\pi^2 \qquad + \qquad \frac{g_A^2}{4f_\pi^2}\ \frac{\sigma_1 \cdot \mathbf{q}\ \sigma_{\mathbf{2}} \cdot \mathbf{q}}{\mathbf{q}^2 + m_\pi^2}\ \tau_1 \cdot \tau_2$$

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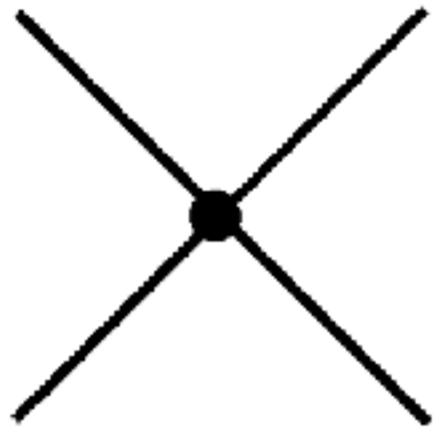

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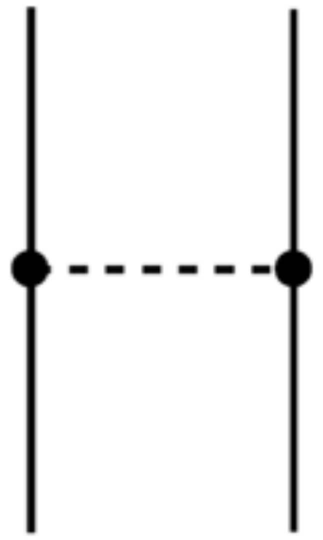
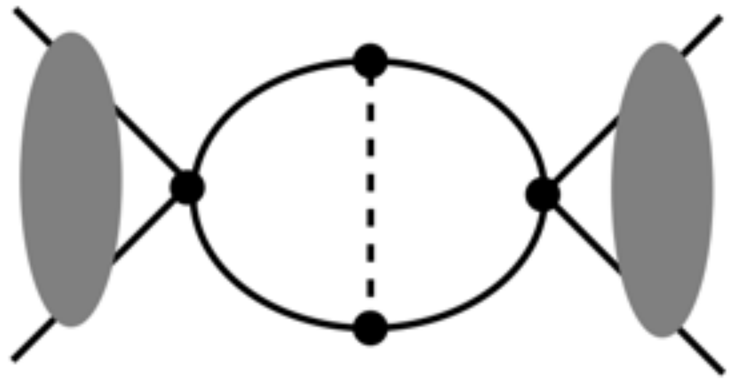


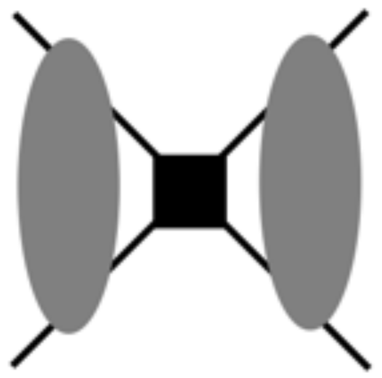
$$V_{\mathrm{LO}}(q) = C_0 + D_2\, m_\pi^2 + \frac{g_A^2}{4f_\pi^2}\,\frac{\sigma_1\cdot\mathbf{q}\;\sigma_2\cdot\mathbf{q}}{\mathbf{q}^2+m_\pi^2}\,\tau_1\cdot\tau_2$$

Renormalization requires D_2 :

Kaplan, Savage, Wise (1998)

To obtain a scattering amplitude that is independent of regularization or cut-off Λ requires:





$$\Lambda\frac{d}{d\Lambda}\left(\frac{D_2}{C_0^2}\right)_{\mathrm{KSW}} = \frac{g_A^2 m_N^2}{64\pi^2 f_\pi^2} \quad\Longrightarrow\quad \frac{|D_2|}{C_0^2} \approx \frac{g_A^2 m_N^2}{64\pi^2 f_\pi^2} \simeq \frac{1}{4}$$

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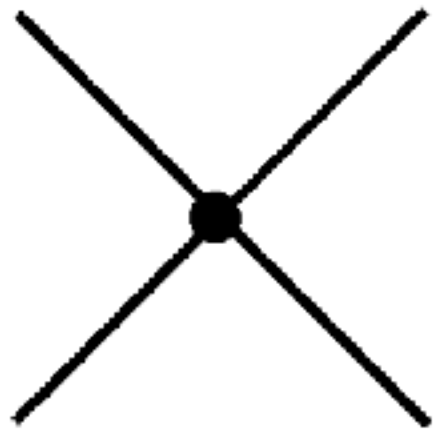

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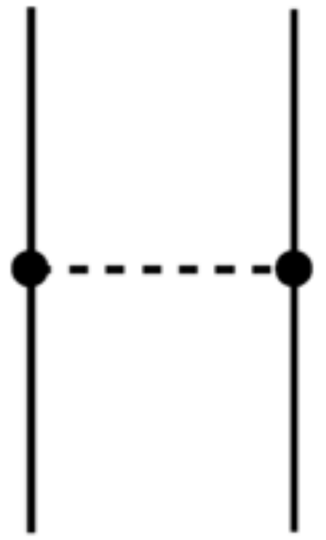

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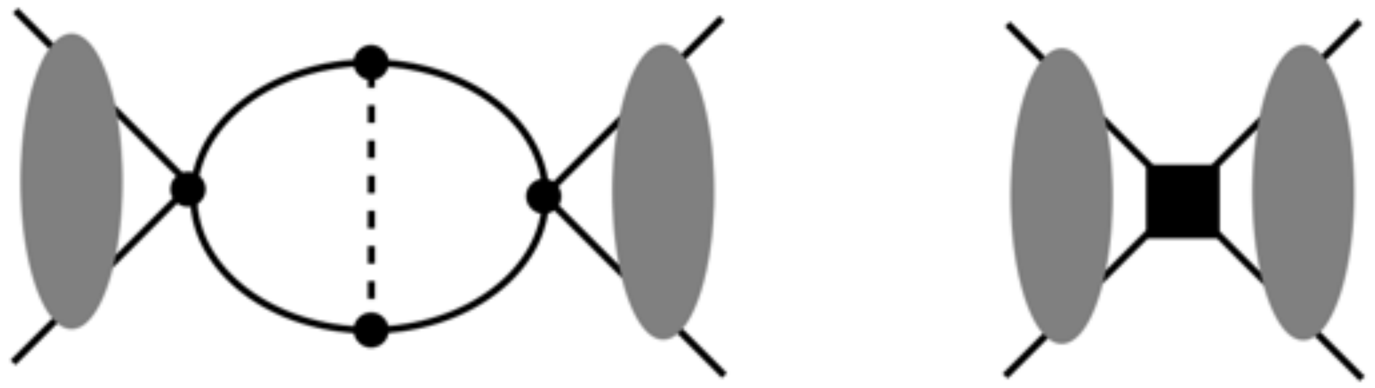

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Analysis of 2-nucleon scattering in Lattice QCD for different values m_π could, in principle, determine D_2 but systematics are too large at this time.

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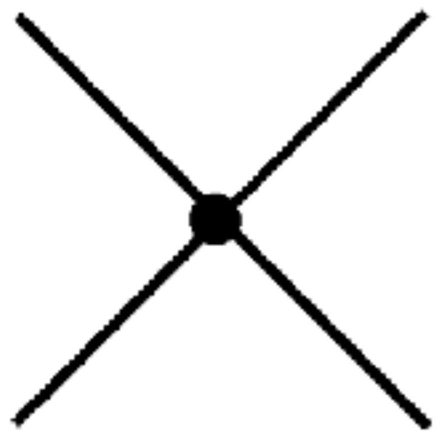
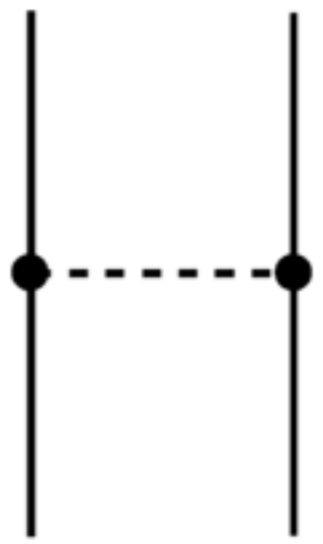
 $+$ 

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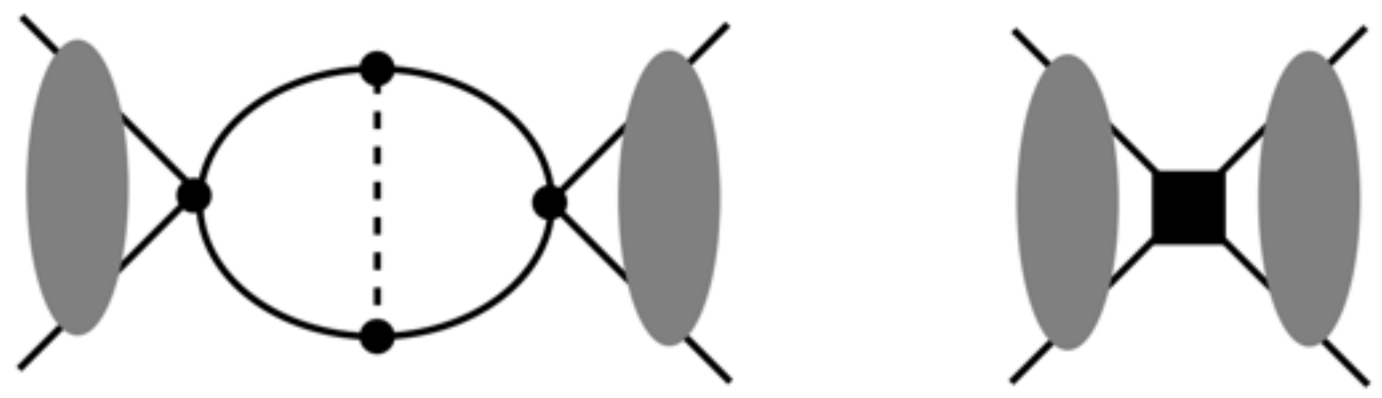

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Analysis of 2-nucleon scattering in Lattice QCD for different values m_π could, in principle, determine D_2 but systematics are too large at this time.

Beane, Bedaque, Detmold, Savage (NPLQCD), Walker-Loud (Cal-Lat), Aoki, Hatsuda, Ishii (HAL QCD Collaboration), ….

D_2 and Coupling to Pions

Chiral symmetry requires that pion mass terms only appear in a specified form:

$$m_\pi^2 \Rightarrow m_\pi^2 \left(1 + \frac{\pi_a \pi_b}{2f_\pi^2}\, \delta_{ab} + \cdots \right)$$

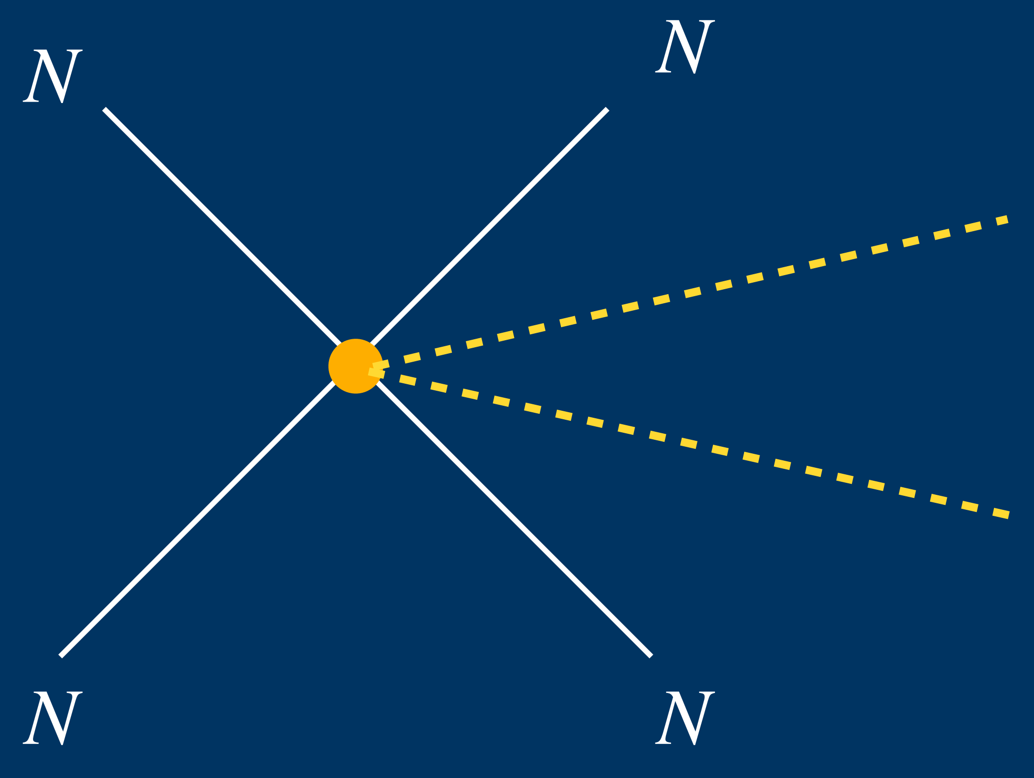
This induces a coupling of pions to two-nucleons:

$D_2\ m_\pi^2$

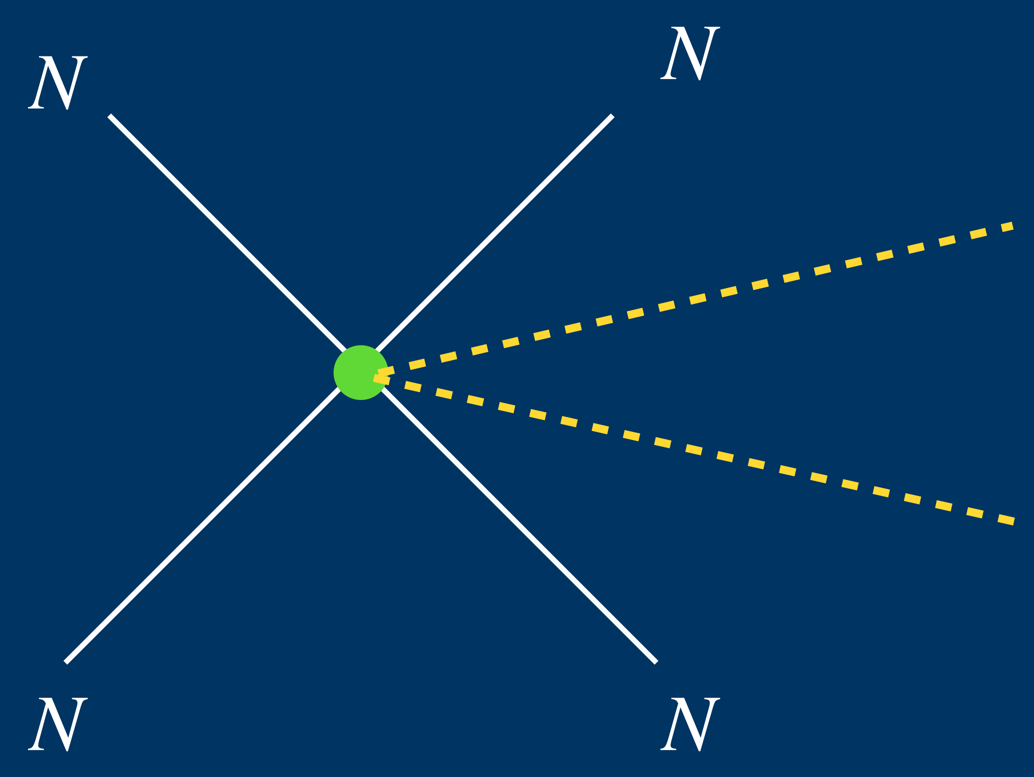
$D_2\ \dfrac{m_\pi^2}{2f_\pi^2}$

Two more enhanced pion-two-nucleon couplings: E_2 and F_2

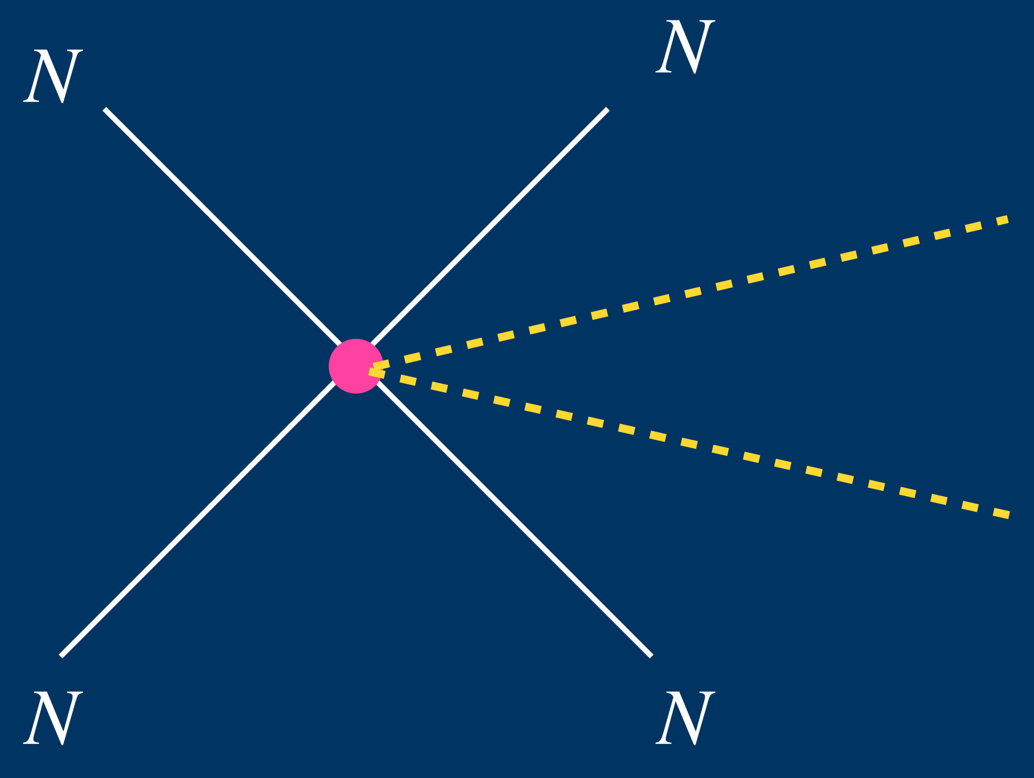
B. Borasoy and H. W. Griesshammer (2001), (2003)



$D_2 \, m_\pi^2$



$E_2 \, \omega^2$



$F_2 \, q^2$

$D_2, E_2, \& \ F_2$ are enhanced for the same reason and are apriori expected to be of similar size.

Typical size of these LECs: $D_2 \approx E_2 \approx F_2 \approx \dfrac{1}{5 f_\pi^4}$

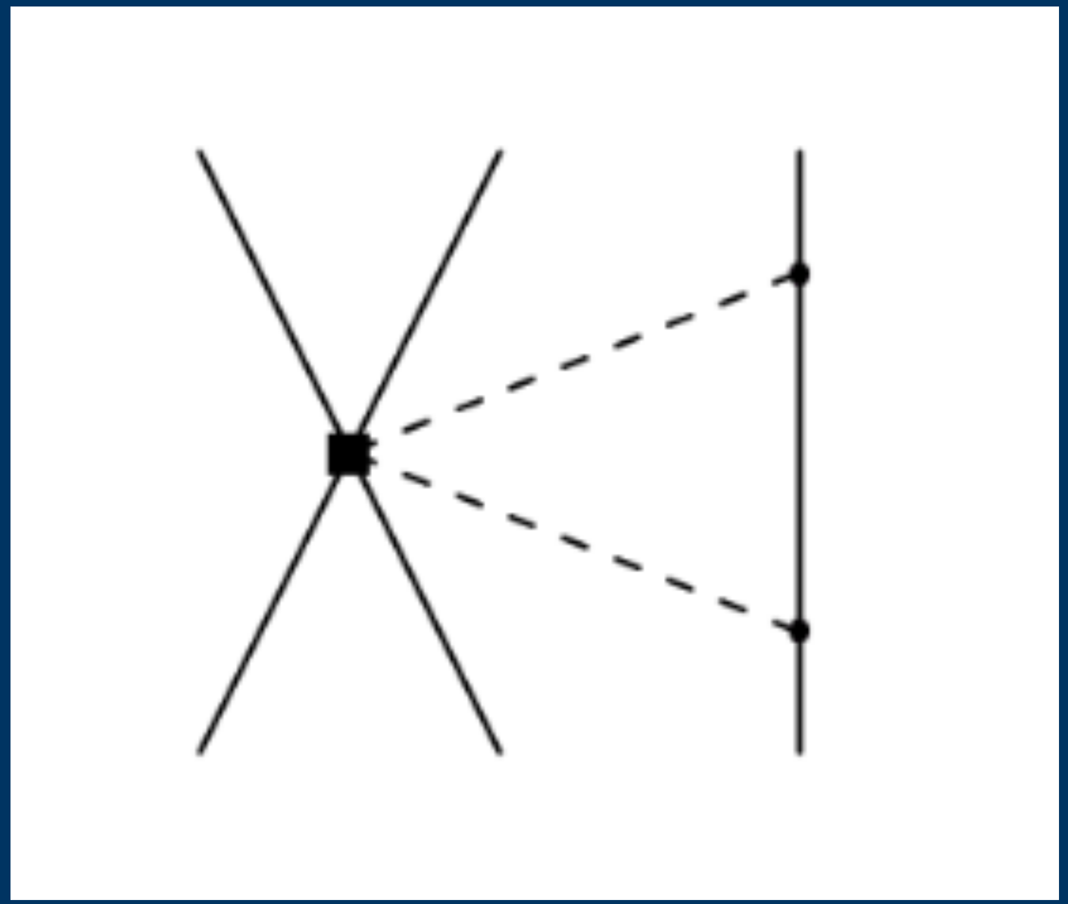
Note, in Naive Dimensional Analysis: $D_2 \approx E_2 \approx F_2 \approx \dfrac{1}{\Lambda^4}$

A New Class of Three Nucleon Forces

Vincenzo Cirigliano, Maria Dawid, Wouter Dekens and Sanjay Reddy (2024)

3NF due to pion coupling to two nucleons are large because:

- D_2 & F_2 are enhanced by the large n-n scattering length.
- Enhanced loop contribution due to small nucleon kinetic energy.



$$V^{i'j'k'}_{ijk}(\vec{q}_1,\vec{q}_2,\vec{q}_3) = -\frac{9g_A^2 D_2 m_\pi^3}{128\pi f_\pi^4}\kappa^{i'j'}_{ij}\delta_{kk'}\,\mathcal{I}\left(\frac{\vec{q}_3^{\,2}}{4m_\pi^2}\right)$$ where $$\mathcal{I}(b) = \frac{2}{3}\left(1+\left(\frac{1}{2\sqrt{b}}+\sqrt{b}\right)\cot^{-1}(1/\sqrt{b})\right)$$

$$V^{i'j'k'}_{ijk}(\vec{q}_1,\vec{q}_2,\vec{q}_3) = -\frac{15F_2 g_A^2 m_\pi^3}{16\pi f_\pi^4}\delta_{kk'}\left(\bar{f}_2^S\delta_{ii'}\delta_{jj'}+\bar{f}_2^T\vec{\sigma}_{i'i}\cdot\vec{\sigma}_{j'j}\right)\mathcal{J}\left(\frac{\vec{q}_3^{\,2}}{4m_\pi^2}\right)$$ where $$\mathcal{J}(b) = \frac{3}{5}\left((1+2b)\mathcal{I}(b)+\frac{2}{3}\right)$$

Maria Dawid

Wouter Dekens

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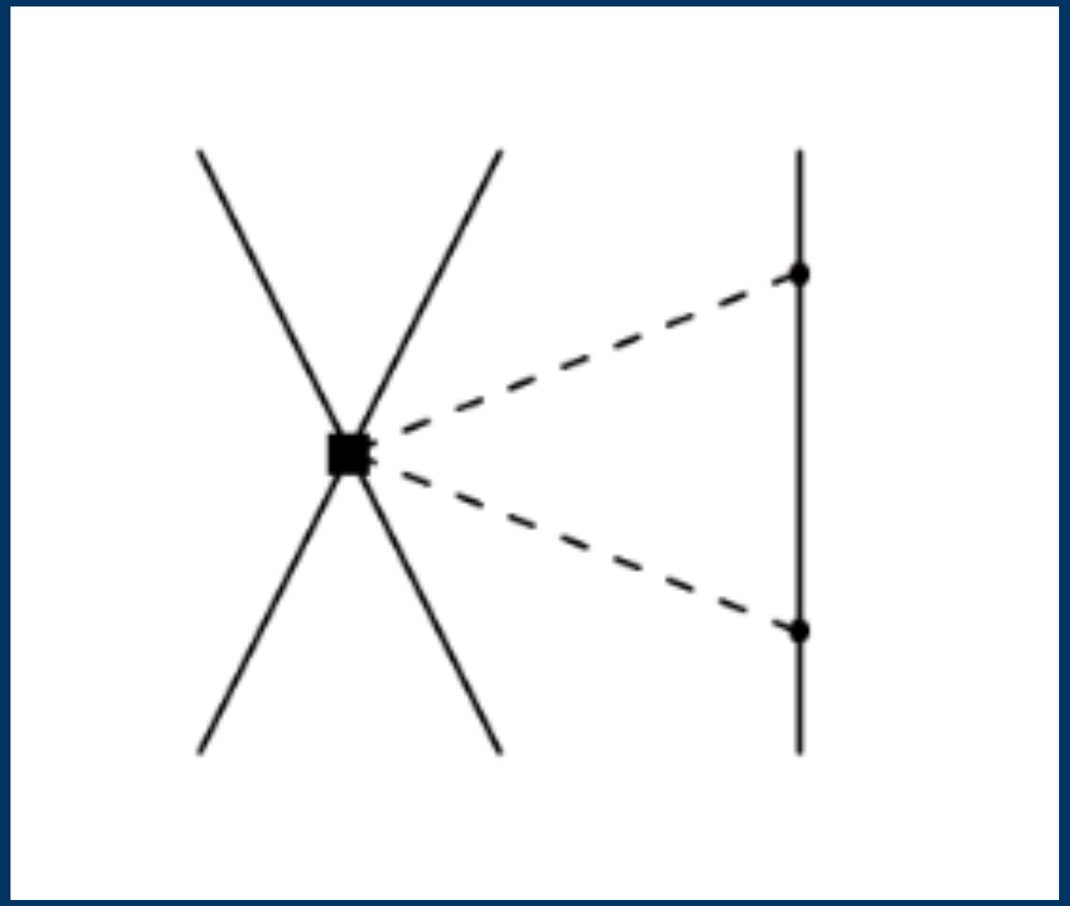

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where

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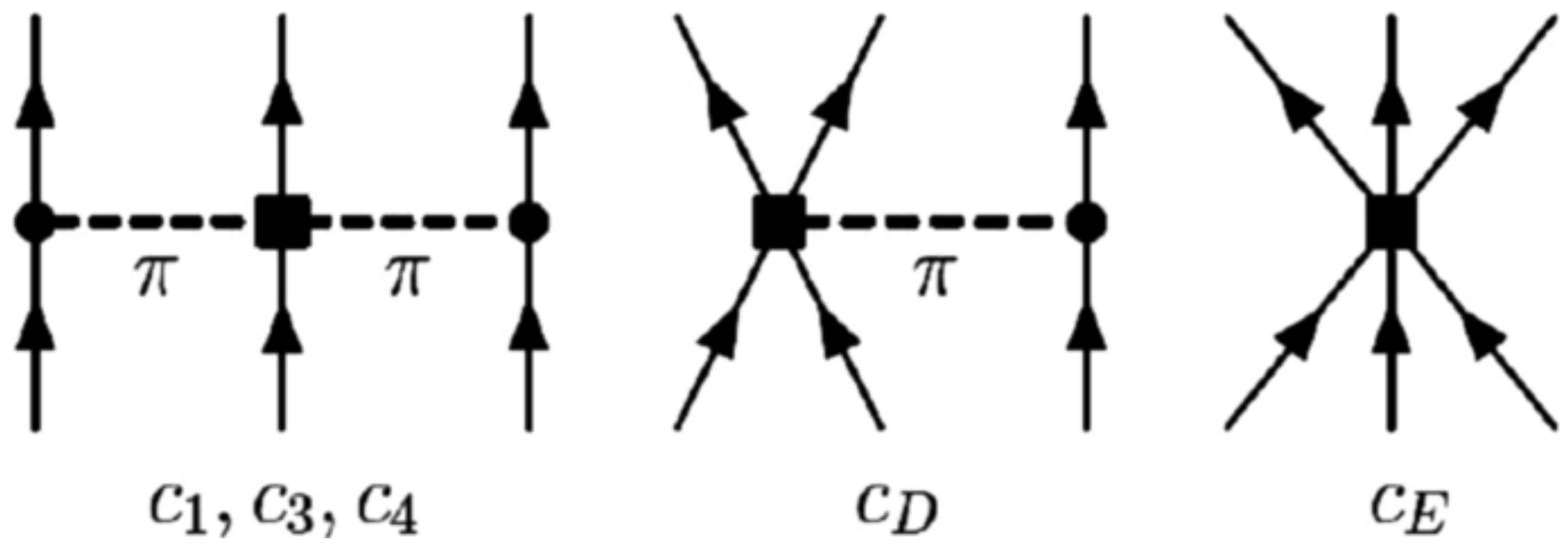
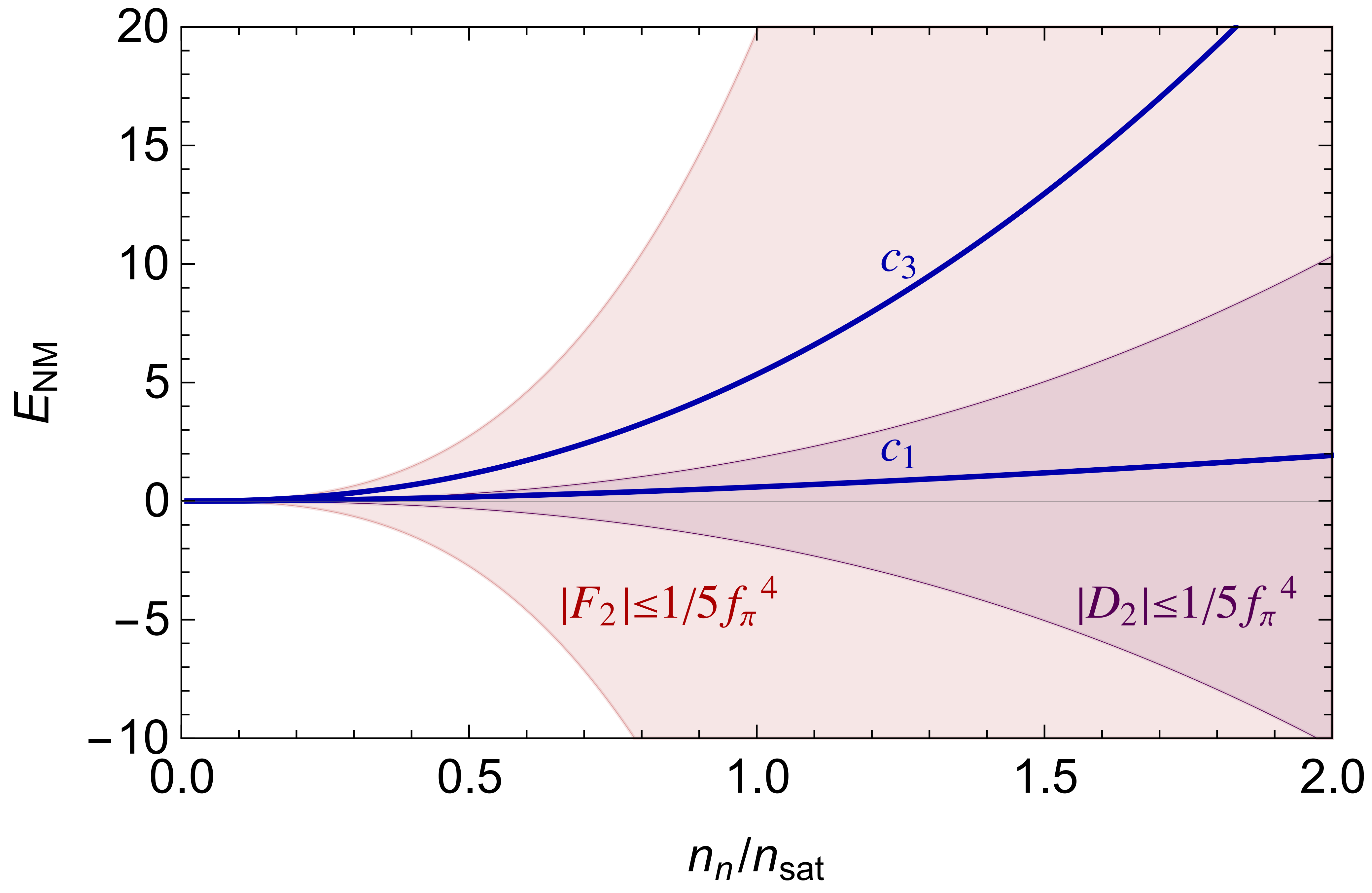
D_2 and F_2 Contributions to the Energy are Large

In neutron and nuclear matter, the leading 3NF plays a critical role.





The new 3NF can be large enough to compete with the NNLO forces currently employed in Chiral EFT.

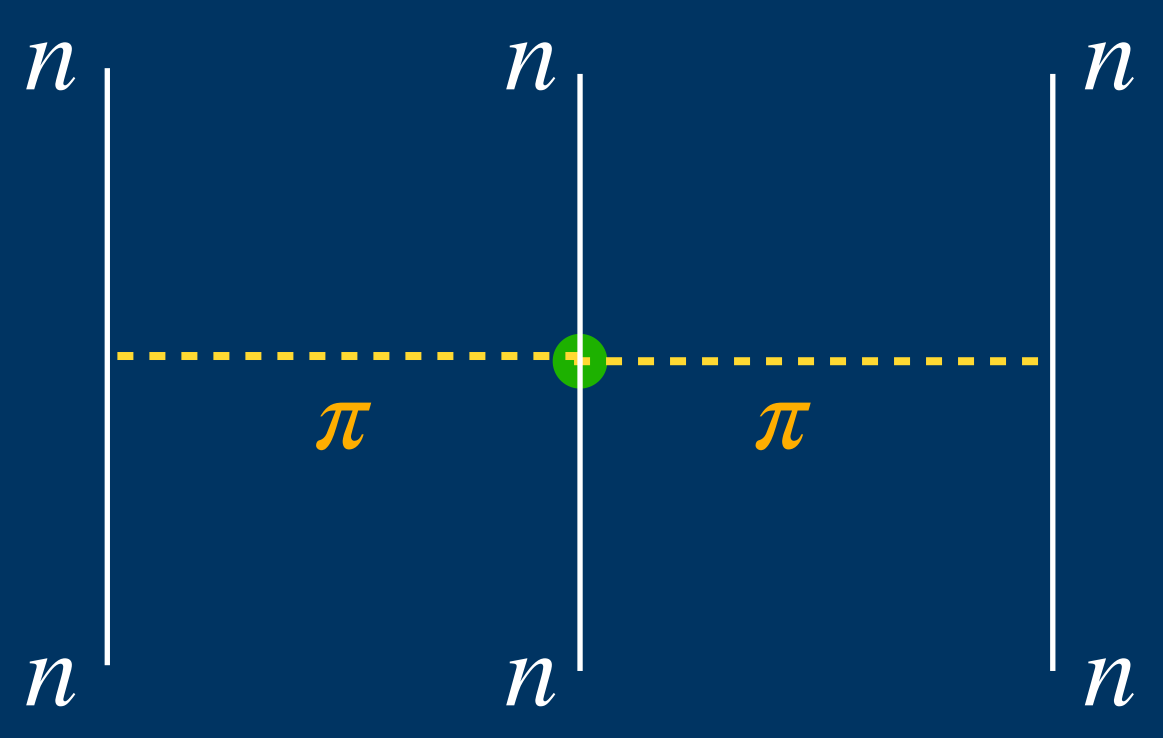
The uncertainty is large because D_2 & F_2 are not yet known.

Nuclear structure and pion-nucleus scattering data can independently constrain D_2 & F_2.

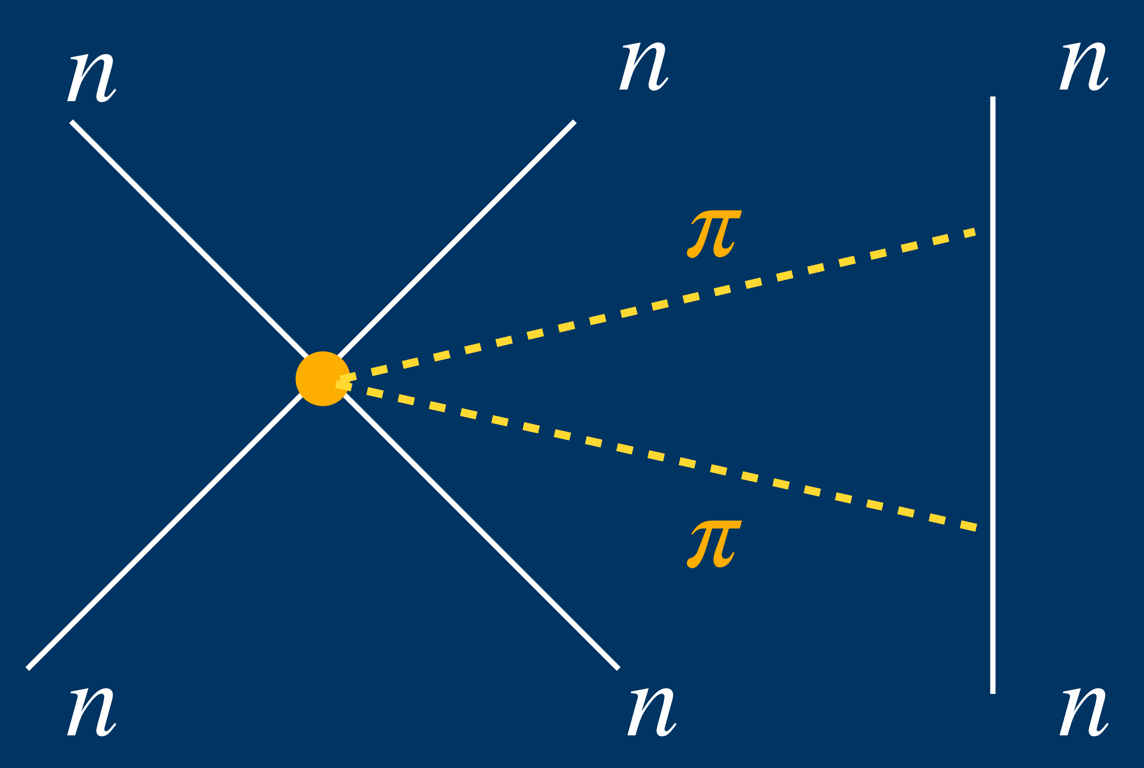
Independent determinations would test the convergence of EFT and estimates of truncation errors.

V. Cirigliano, M. Dawid, W. Dekens, S. Reddy (2024)

Neutron Matter: Underestimating Errors?



c_1 & c_3



D_2 & F_2

Chiral EFT at N^2L0 predicts

$$P(n_{\text{sat}}) = 3.1 \pm 0.5 \ \text{MeV/fm}^3$$

C. Drischler, R. J. Furnstahl, J. A. Meleldez, D. R. Phillips (2021)

$$P(n_{\text{sat}}) = 2.2 \pm 0.4 \ (\text{MeV/fm}^3)$$

I. Tews,R. Somasundaram,D. Lonardoni,H. Göttling, R. Seutin, J. Carlson S. Gandolfi,K. Hebeler, A. Schwenk (2024)

Current Paradigm:

Leading 3NF is determined by pion-nucleon scattering data. Independent of multi-nucleon information . Errors are small becasue there are no 3NF short-distance contributions.

Our calculation:

Pion coupling to two-nucleons can play a role. Information about two-nucleon dynamics influences 3NF to ensure proper renormalization. Error estimates will likely need revision.

We estimate the contribution to the pressure from our new 3NFs to be:

$$\delta P_{3\text{NF}} = \left[0.7\left(\frac{D_2}{D_2^{\text{ref}}}\right) + 8.8\left(\frac{F_2}{F_2^{\text{ref}}}\right)\right] \frac{\text{MeV}}{\text{fm}^3}$$

where $$|D_2^{\text{ref}}| = |F_2^{\text{ref}}| = \frac{1}{5f_\pi^4}$$

V. Cirigliano, M. Dawid, W. Dekens, S. Reddy (2024)

Simple Error Estimates with Empirical Constraints

Energy of neutron matter at $E_{\rm NM}(n_B = n_{\rm sat}) = -16 \pm 0.4 + S_0 \;\; \mathrm{MeV}$

where the symmetry energy

$$S_0 = 32 \pm 2 \;\mathrm{MeV}$$

We correlate D_2 and F_2 assuming that these new 3NFs contribute δS_0 to the symmetry energy. This allows us to estimate the error in the pressure of neutron matter.

Binding energy and radii of light and medum mass nuclei can constrain D_2 and F_2. Several groups are currently working on it.