Neutron Star Matter: EOS & Phase Structure

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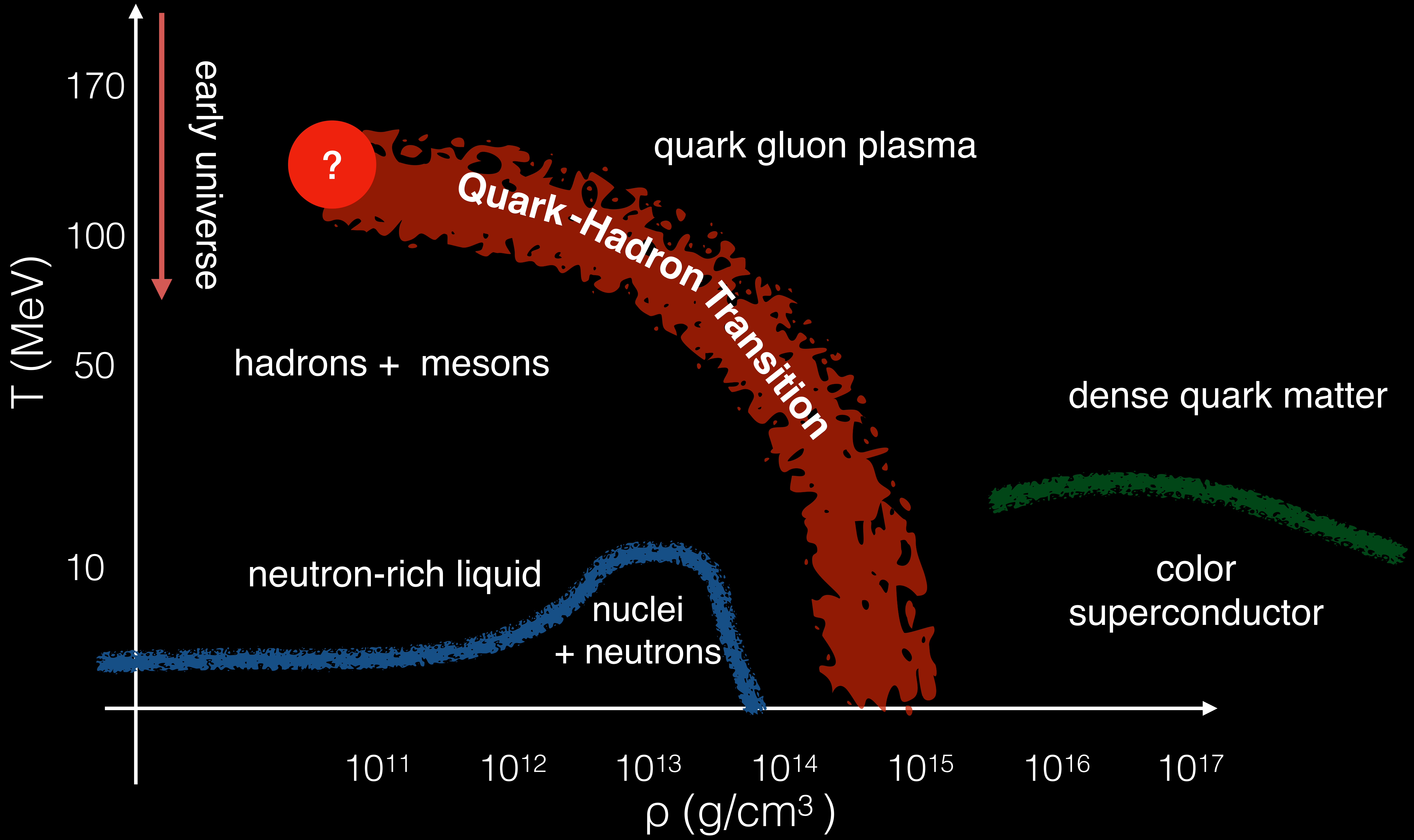
U.S. DEPARTMENT OF ENERGY Office of Science

N3AS Network for Neutrinos, Nuclear Astrophysics, and Symmetries PHYSICS FRONTIER CENTER

NSF

CPOD 2024 - 15th Workshop on Critical Point and Onset of Deconfinement

QCD under extreme conditions



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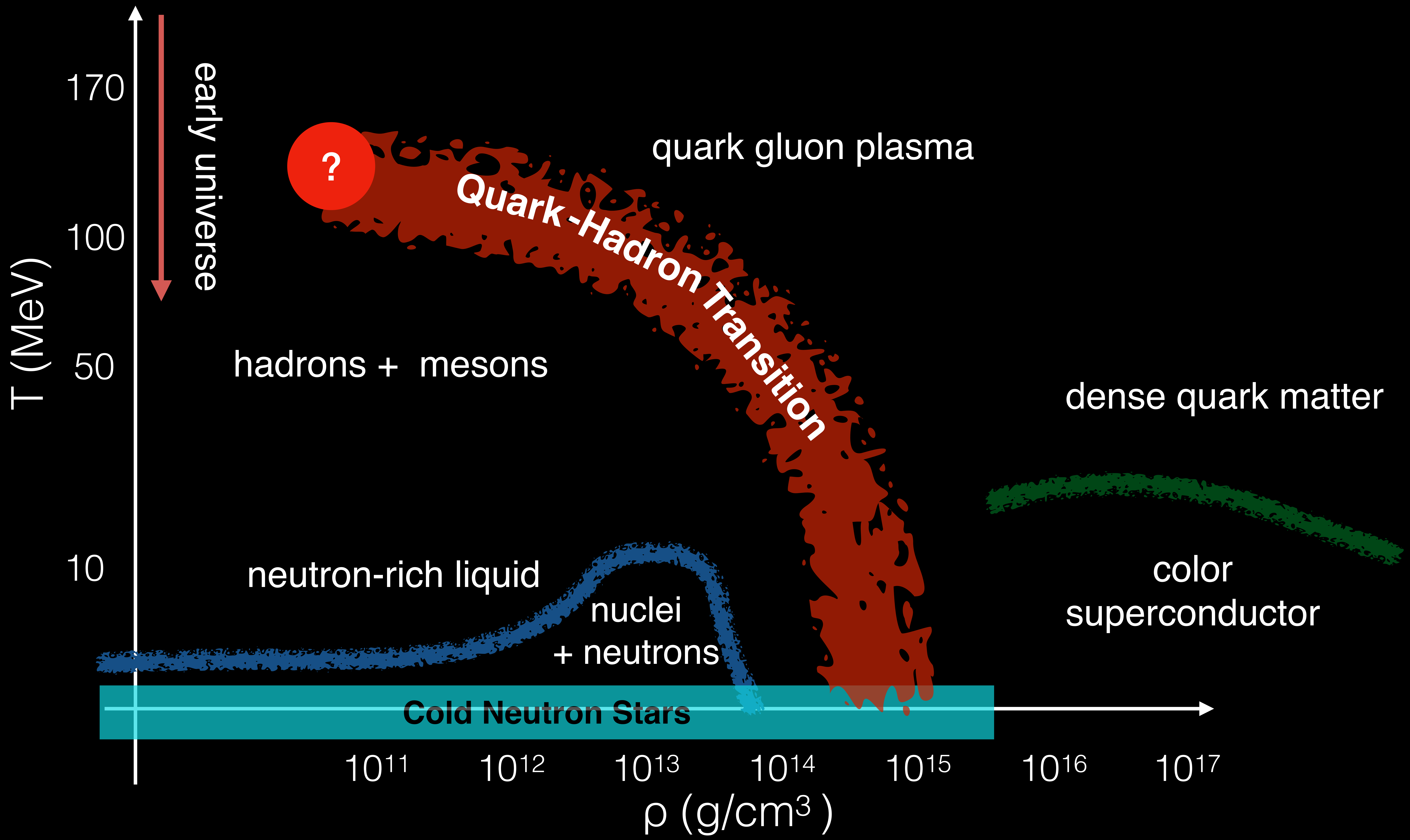

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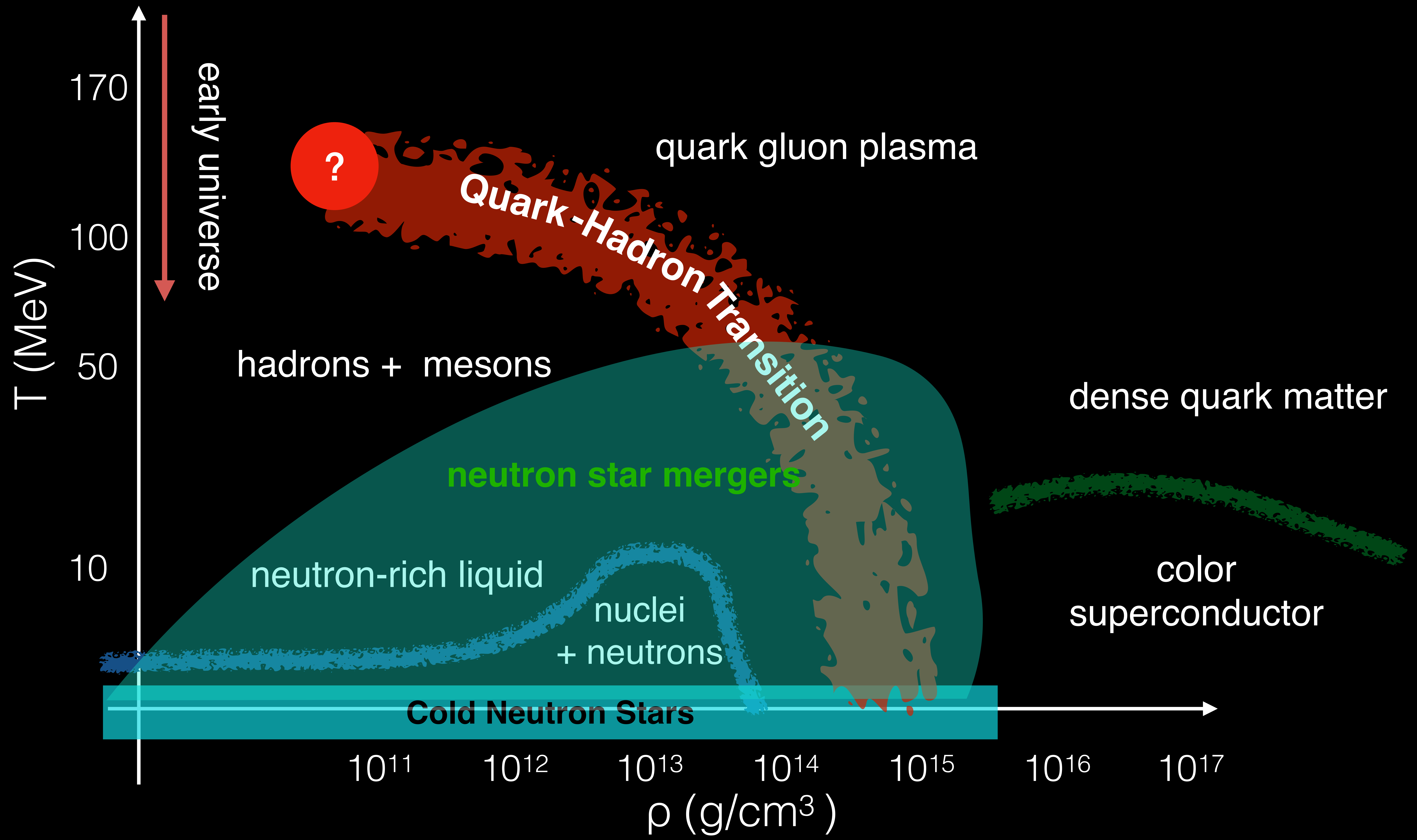


Low Temperature Phases of Matter

Coulomb Solid +
Relativistic Electrons:

Coulomb Solid +
Relativistic Electrons +
Superfluid Neutrons

Thermal and Transport
Properties?
Vortex Dynamics?
Entrainment?
Disorder?
Topology?

Nuclear Pasta:
Non-Spherical
Nuclei + Electrons
+ Superfluid
Neutrons

Thermal and
Transport
Properties?
Superfluid and
Vortex Dynamics?
Entrainment?
Disorder?
Topology?

Neutron-rich
Matter:

Proton
Fraction?
Superfluid?
Superconductor
?

Strongly coupled relativistic
matter:

Composition?
Chiral Symmetry?
Deconfinement?
Quarkyonic?
Superfluidity?
Superconductivity?

Color Flavor
Locked Quark
Matter?
Transparent
insulator.

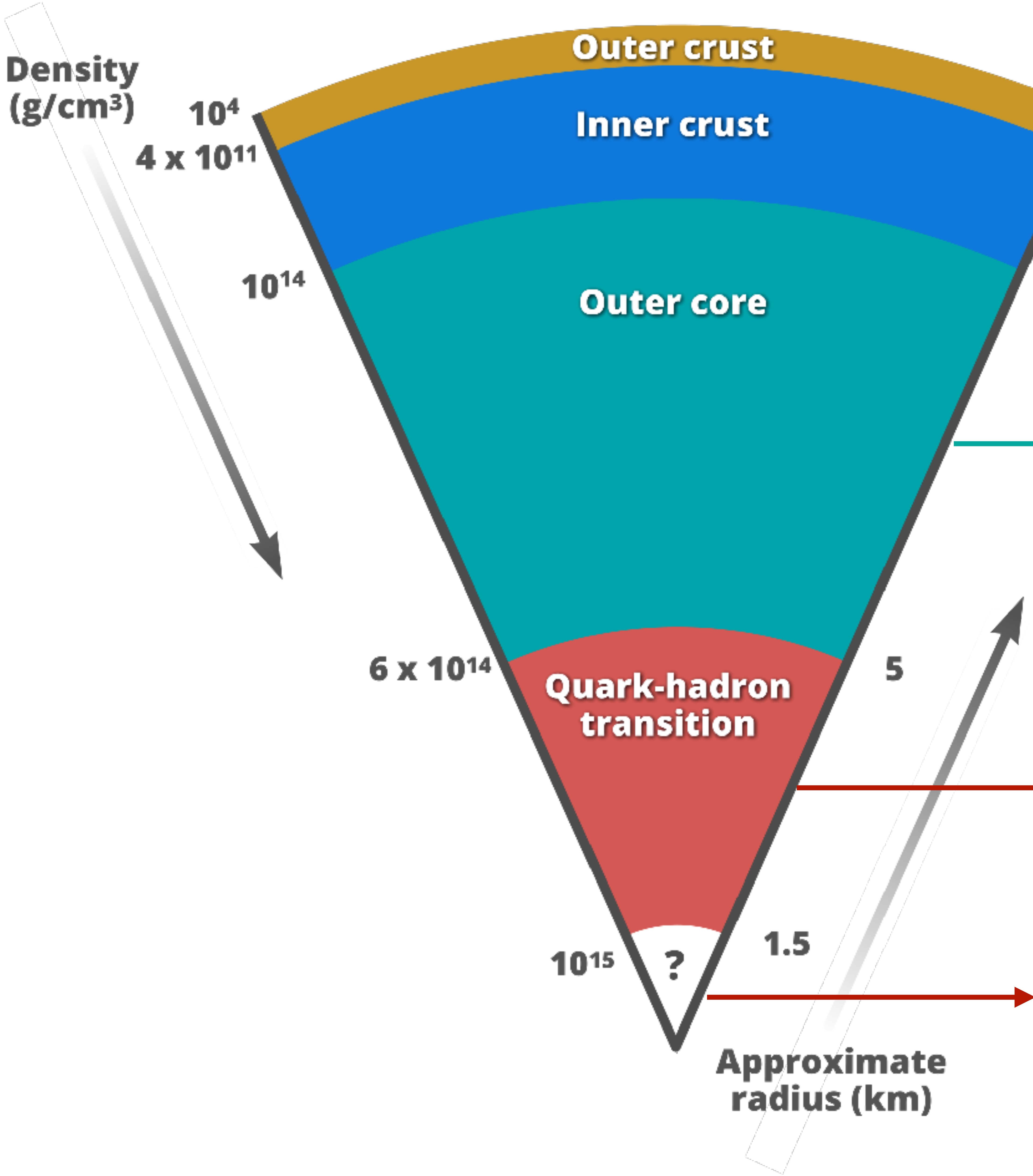
ρ (g/cm³)

10^{10} 10^{11} 10^{12} 10^{13} 10^{14} n_{sat} 10^{15} 10^{16} 10^{17}

$c_s^2/c^2 \ll 1$ $c_s^2/c^2 < 1/3$ $c_s^2/c^2 \simeq 1$ $c_s^2/c^2 \simeq 1/3$

939 $\approx \mu_B$(MeV) 1000 2000 3000

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?

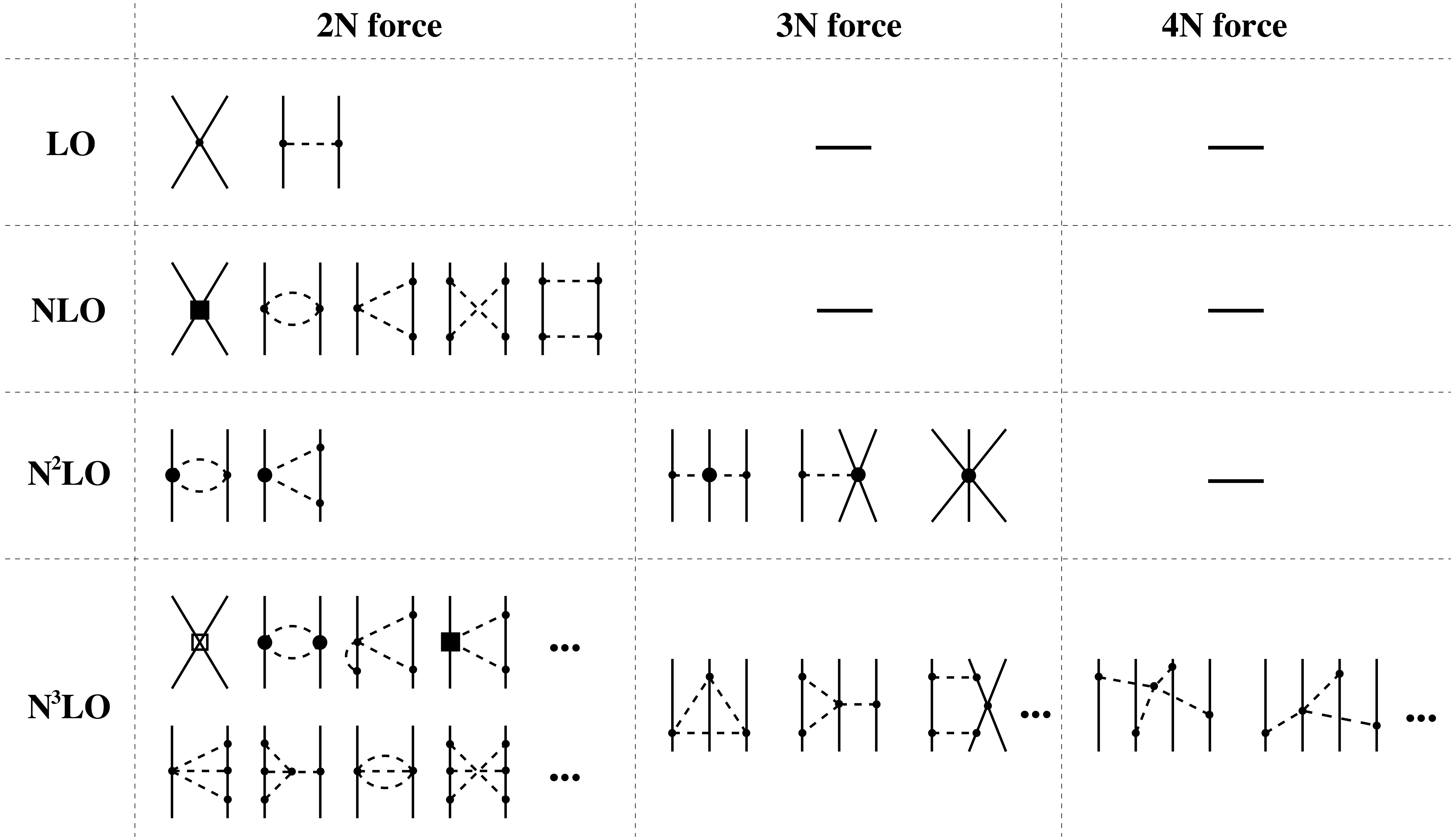
General Constraints on the Equation of State

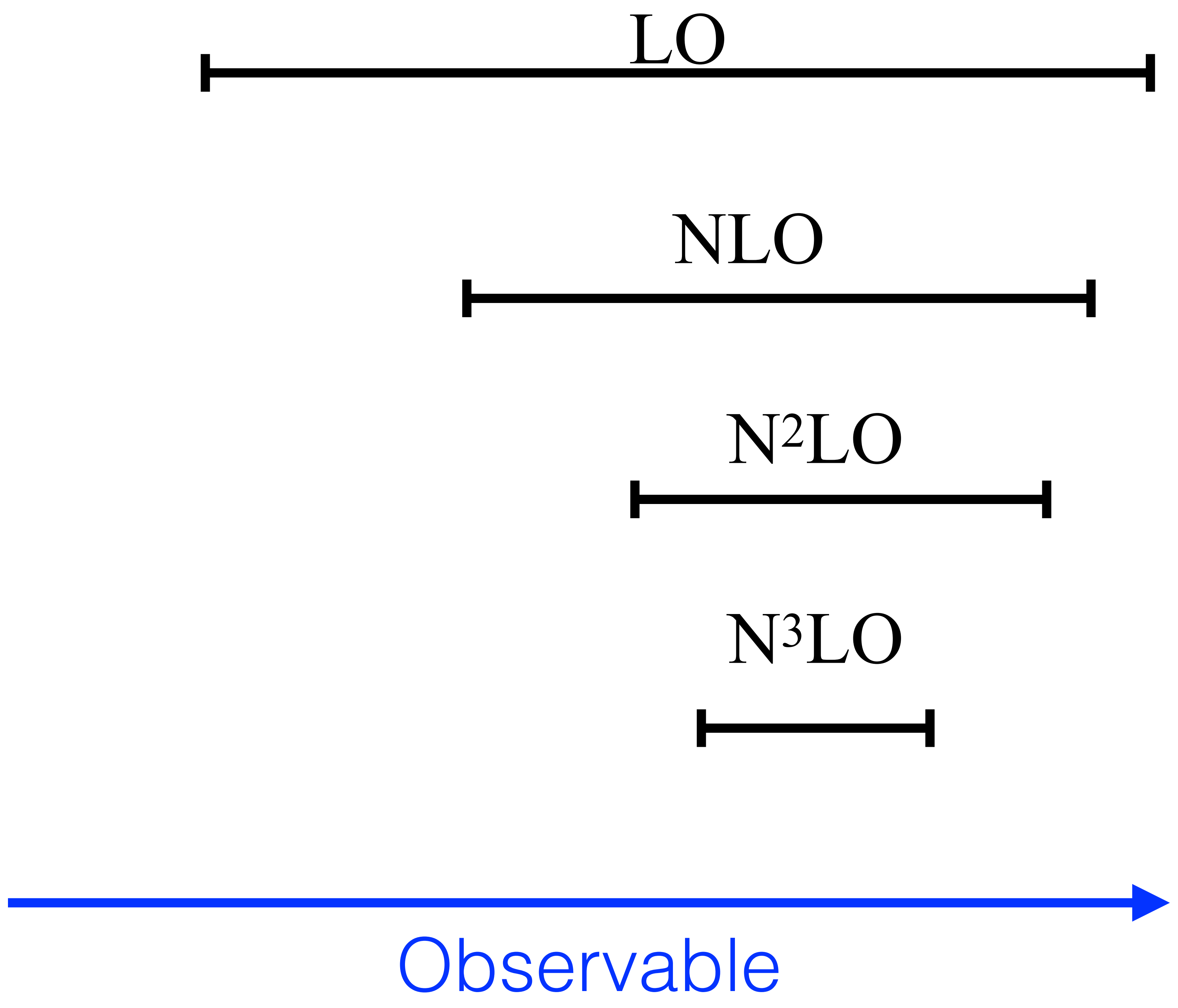
General Constraints on the Equation of State

General Constraints on the 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 ..

Equation of State of Dense Nuclear Matter

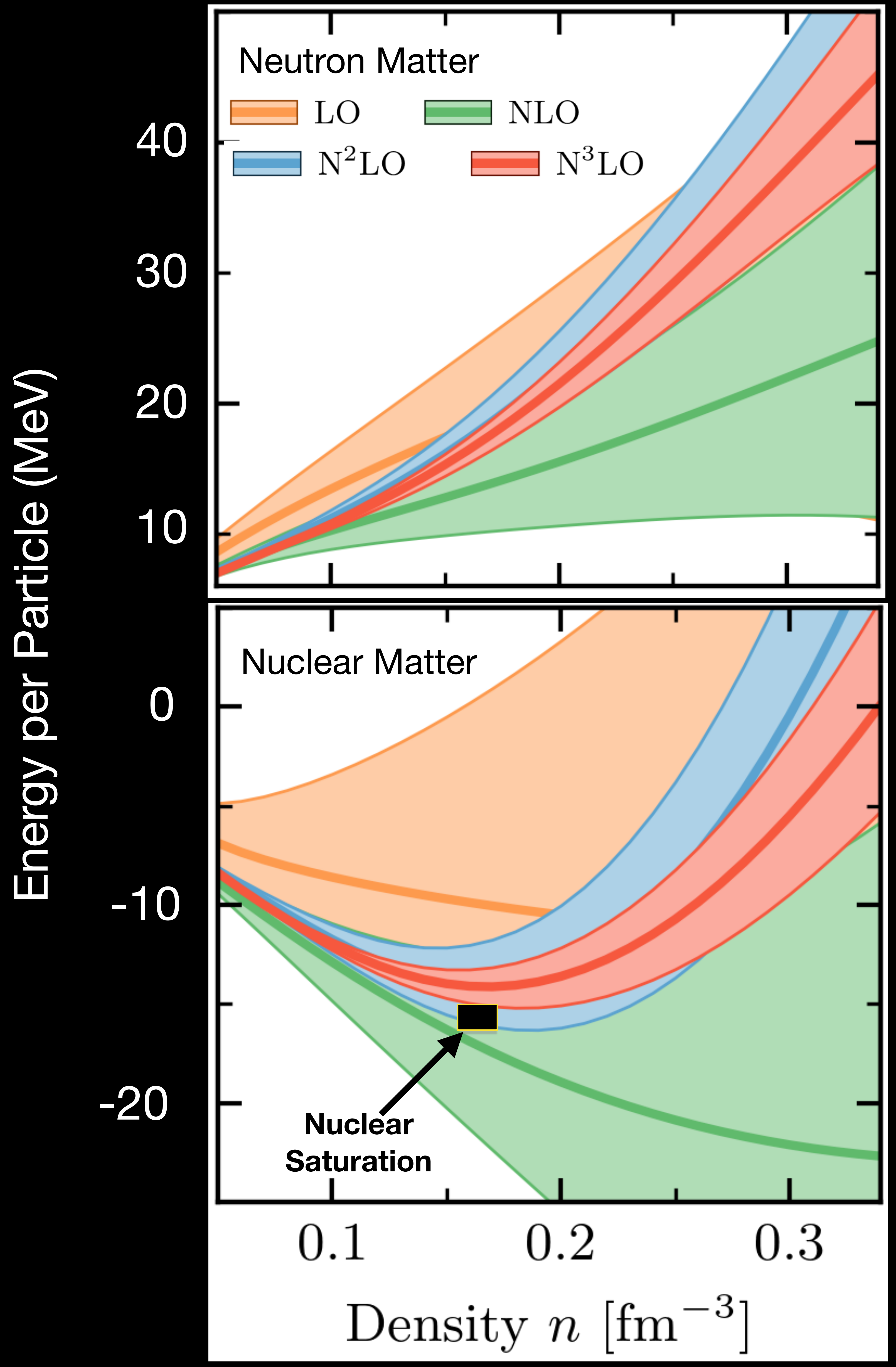
Quantum many-body calculations of neutron matter and nuclear matter using EFT potentials show convergence up to about twice nuclear saturation density.

Many-body perturbation theory and Quantum Monte Carlo methods have both been employed to calculate the energy on dense neutron matter.

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).

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:

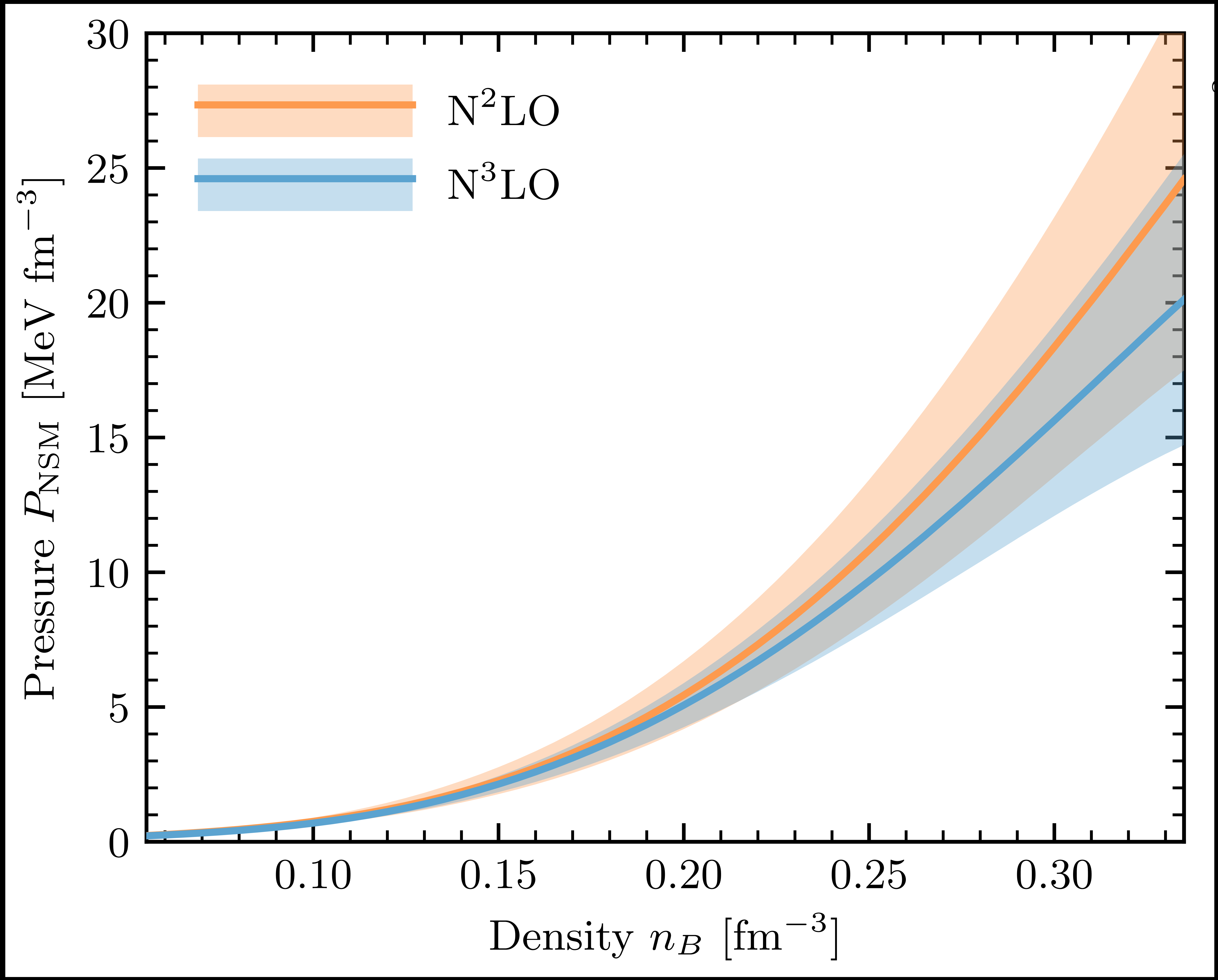
$$P_{\mathrm{NSM}}(n_B = 0.16\ \mathrm{fm}^{-3}) = 3.0 \pm 0.2\ \mathrm{MeV/fm}^3$$

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

Christian Drischler

Sophia Han

Tianqi Zhao



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

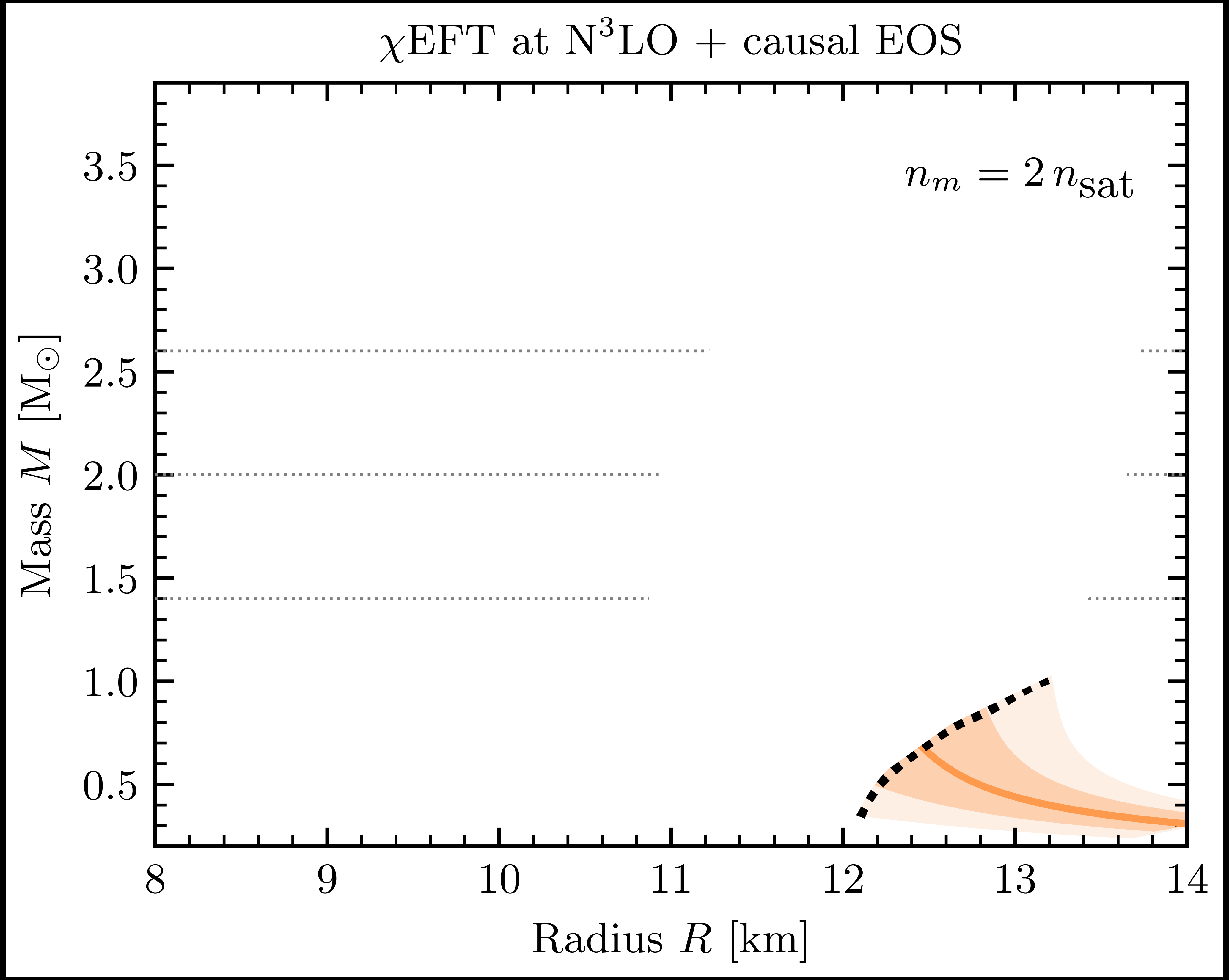
Bounds on Neutron Star Radii

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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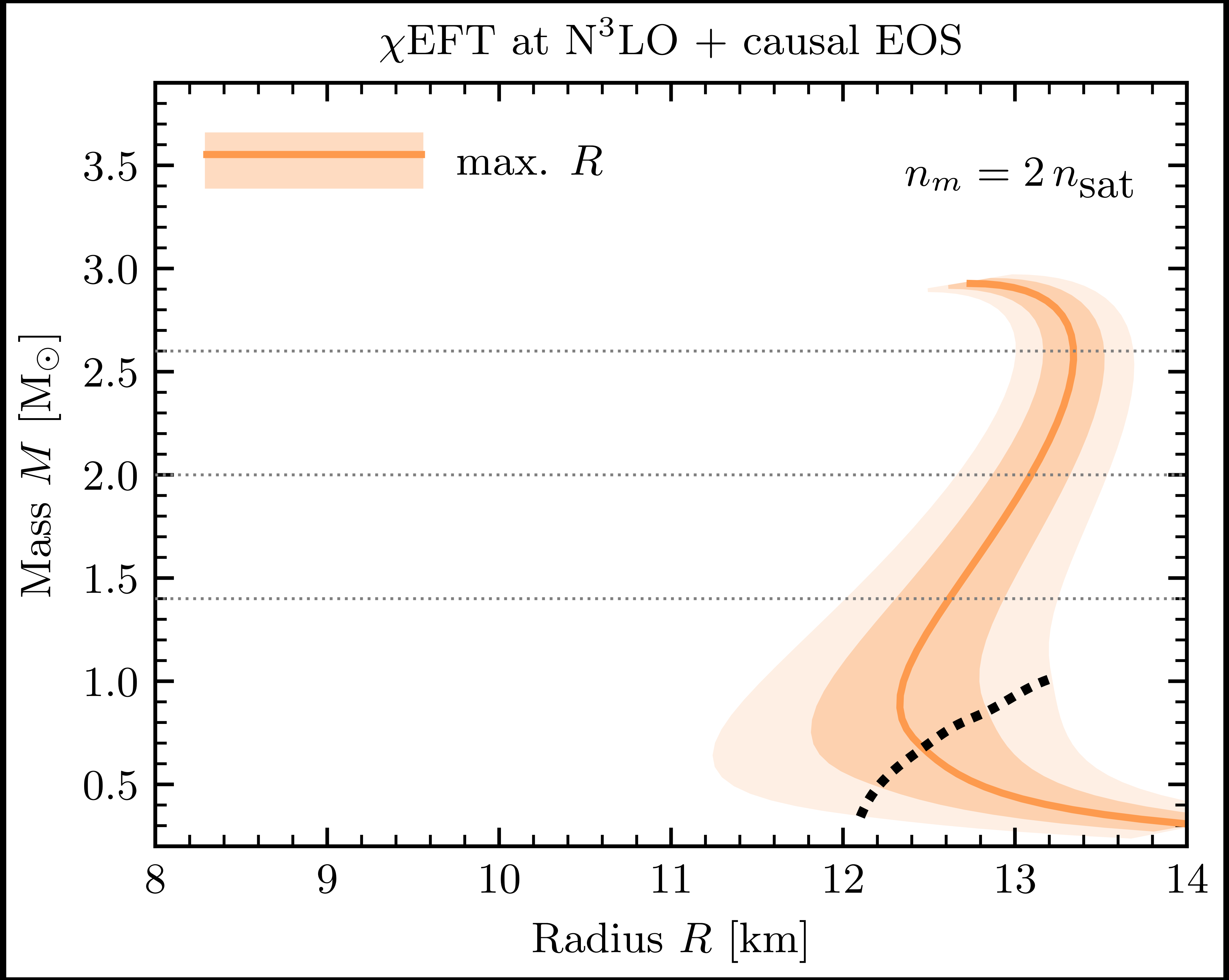

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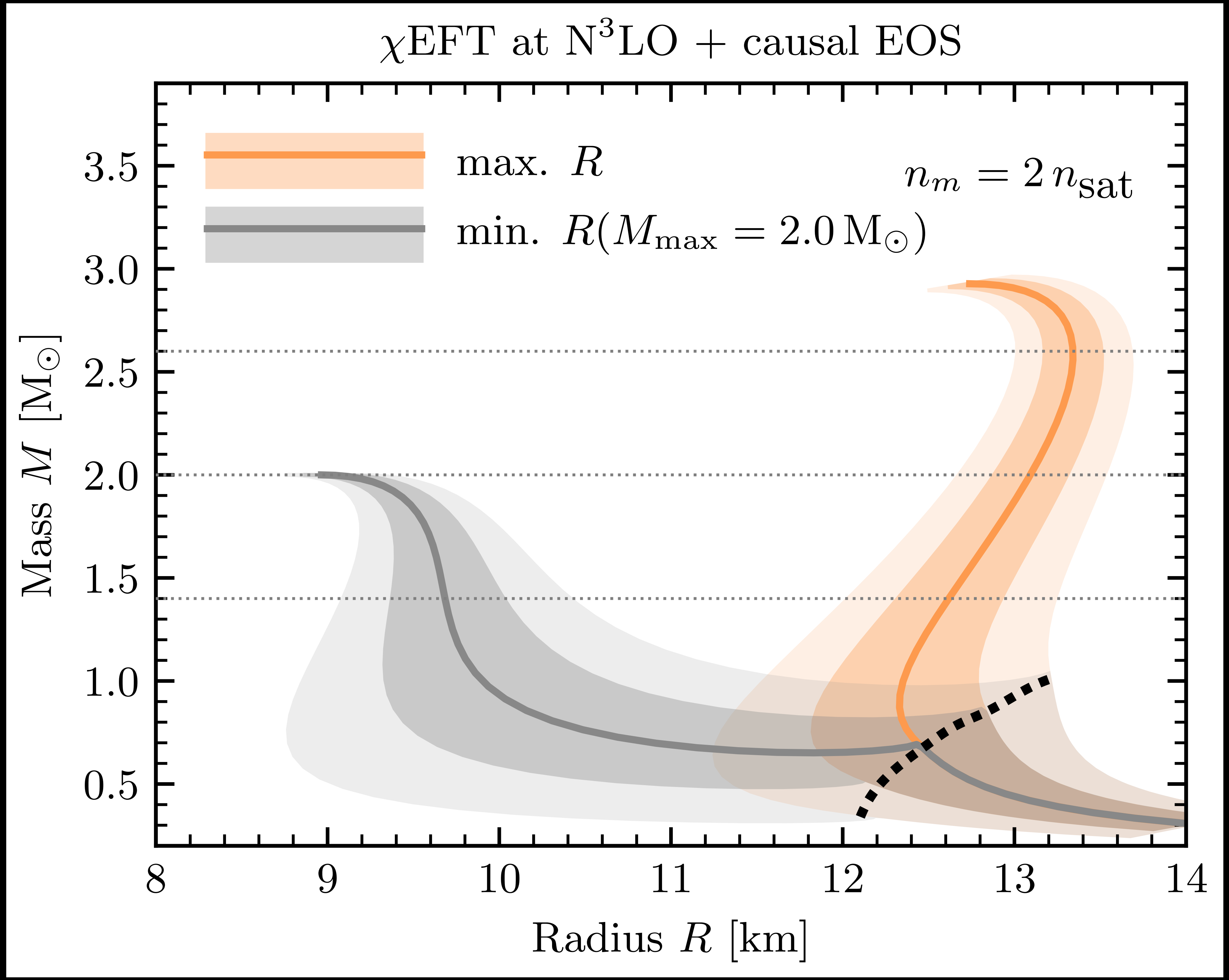

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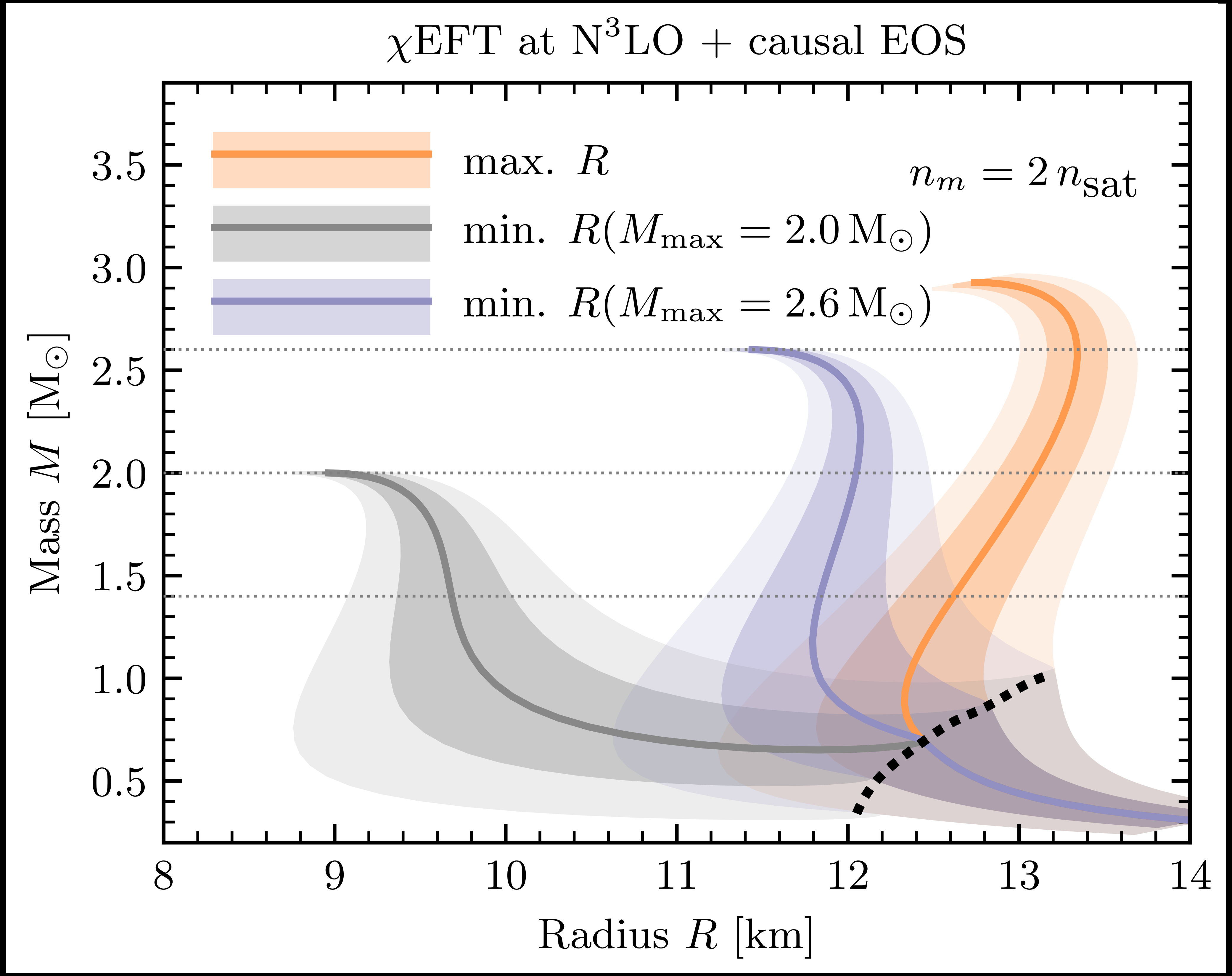

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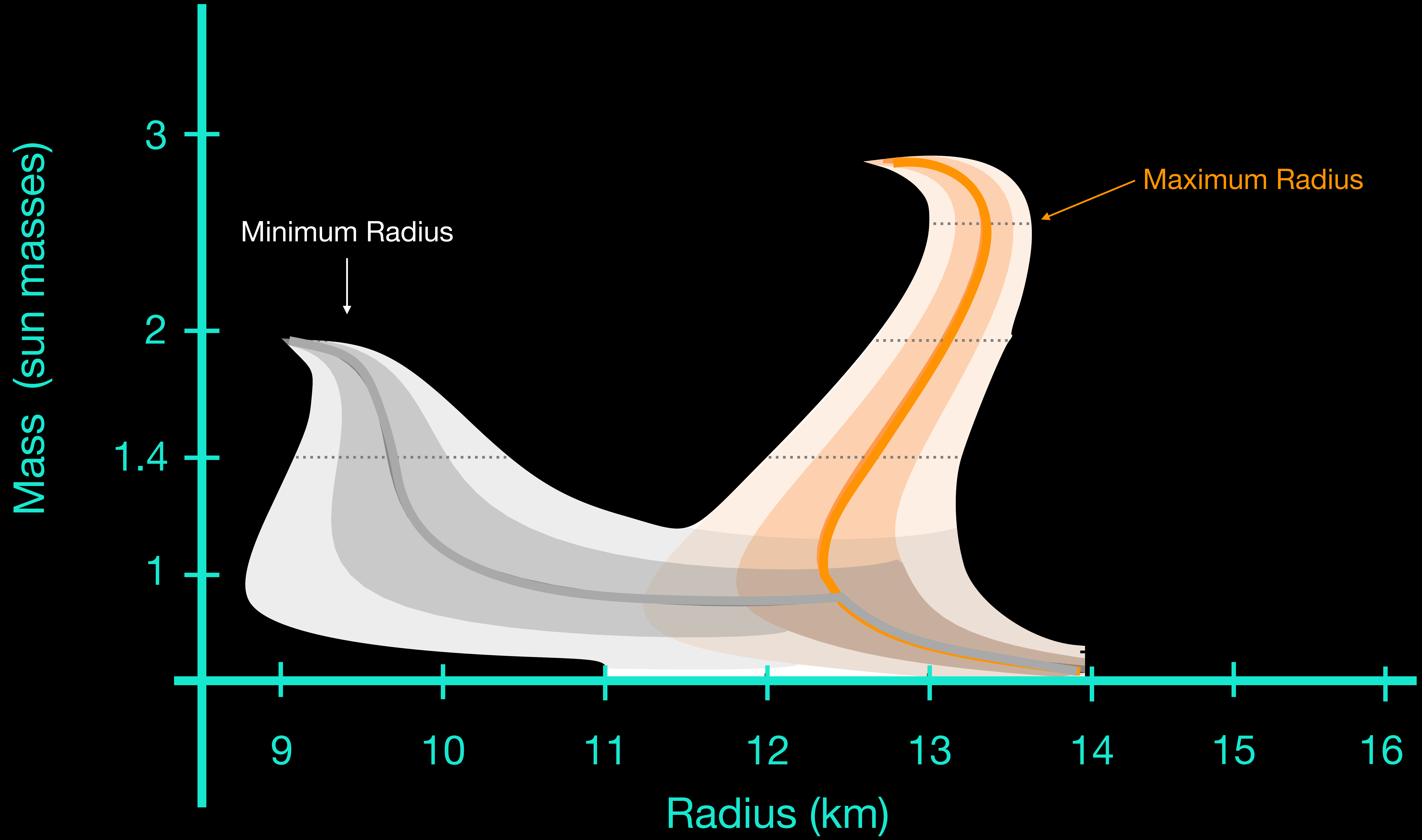
Theoretical and Observational Constraints



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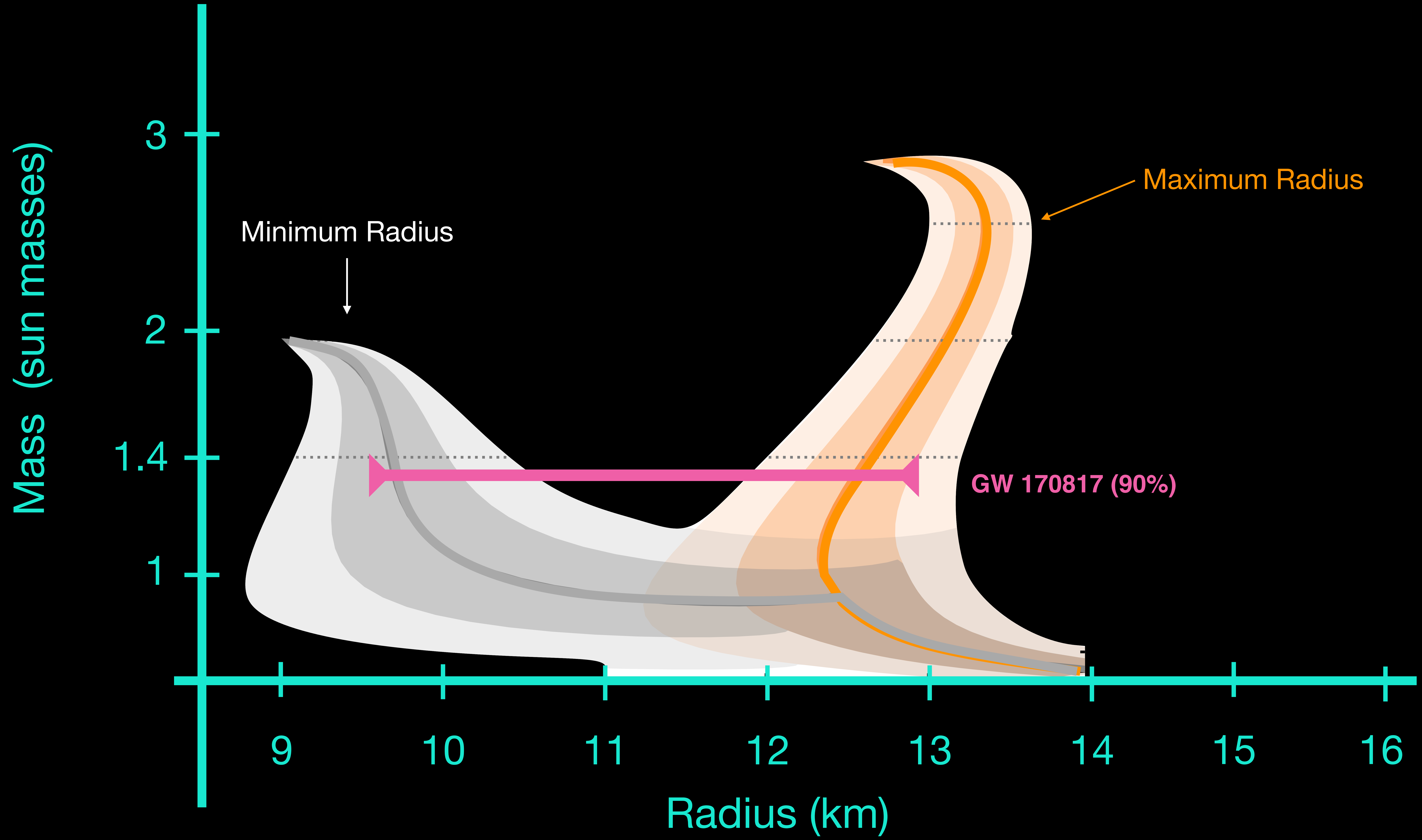

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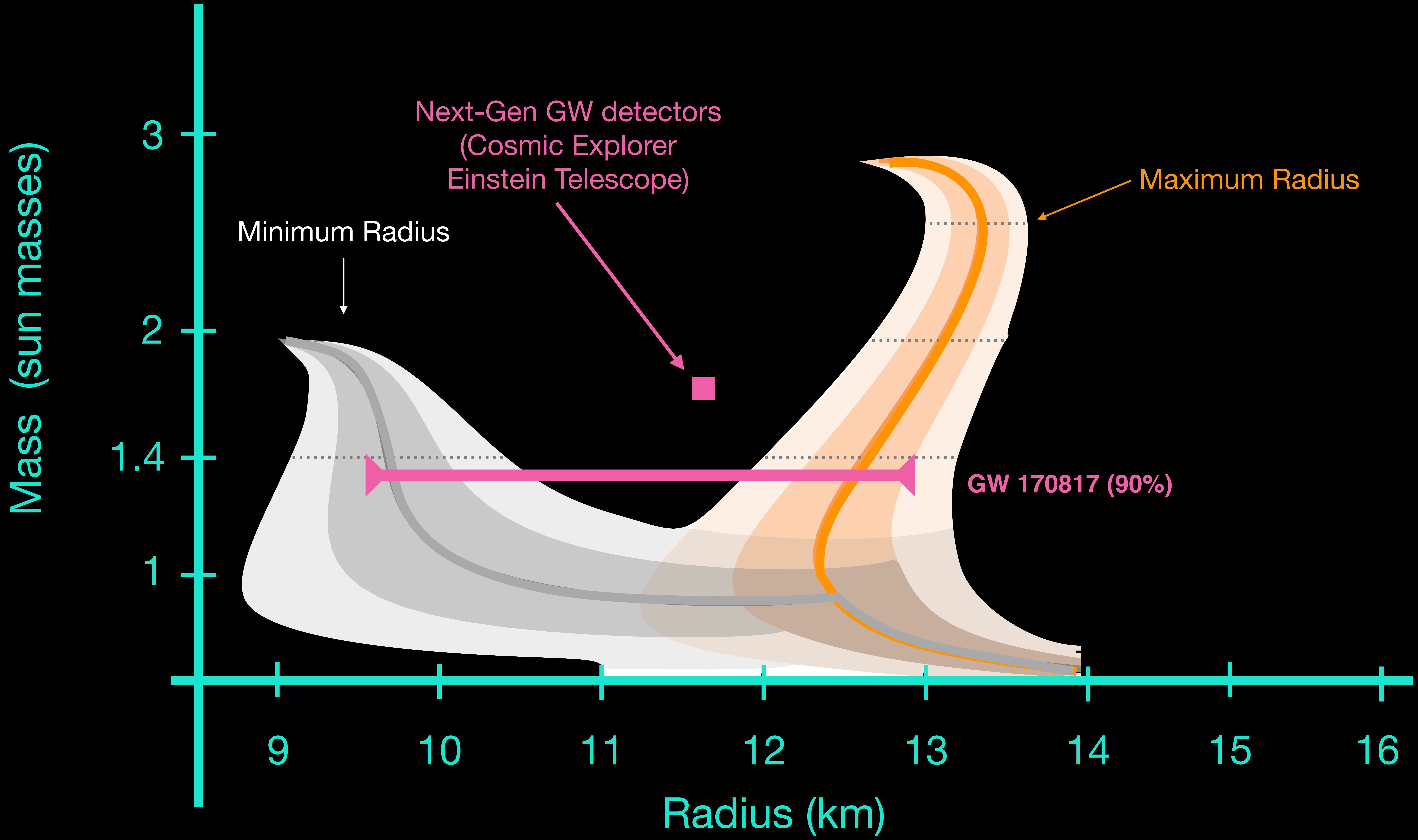

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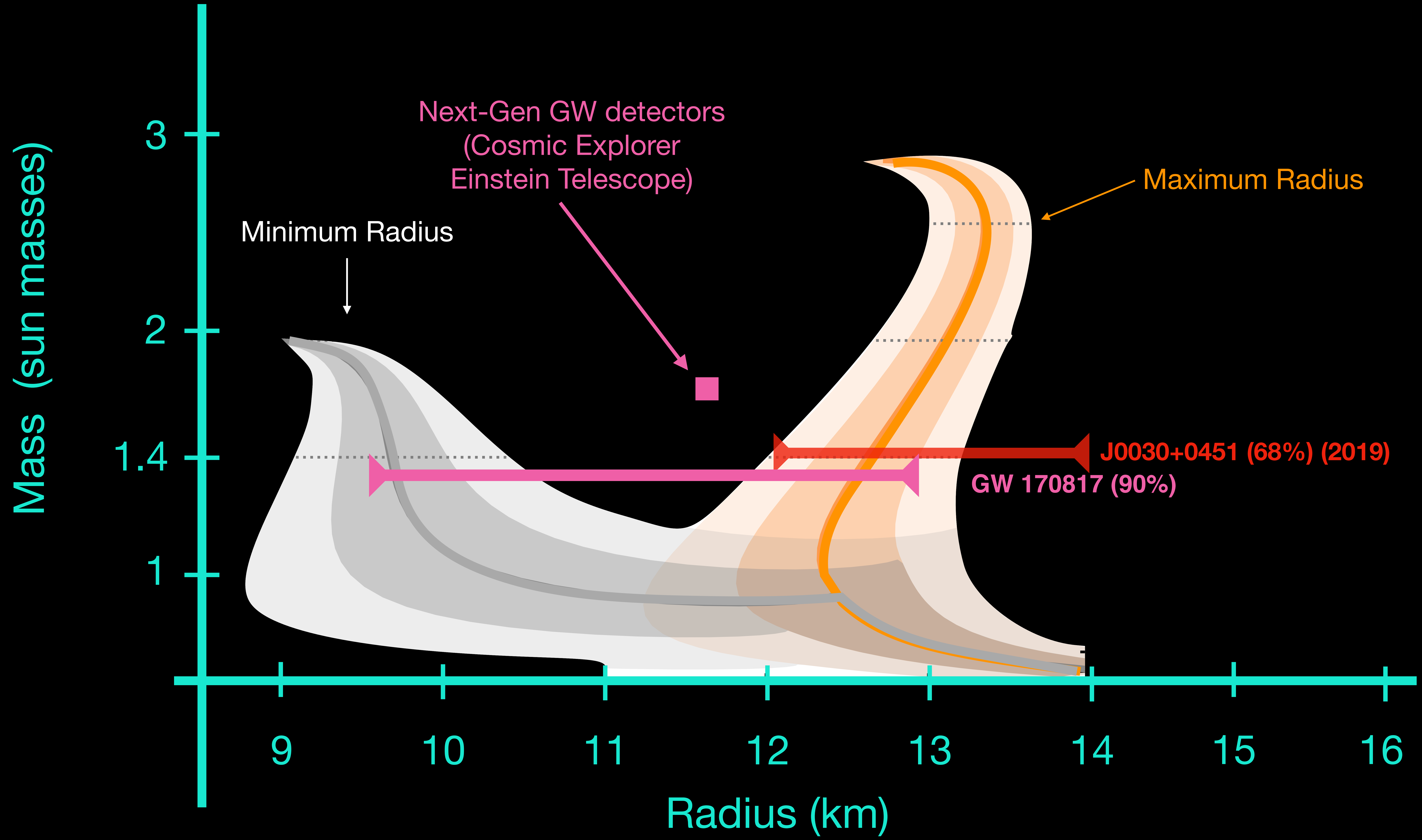

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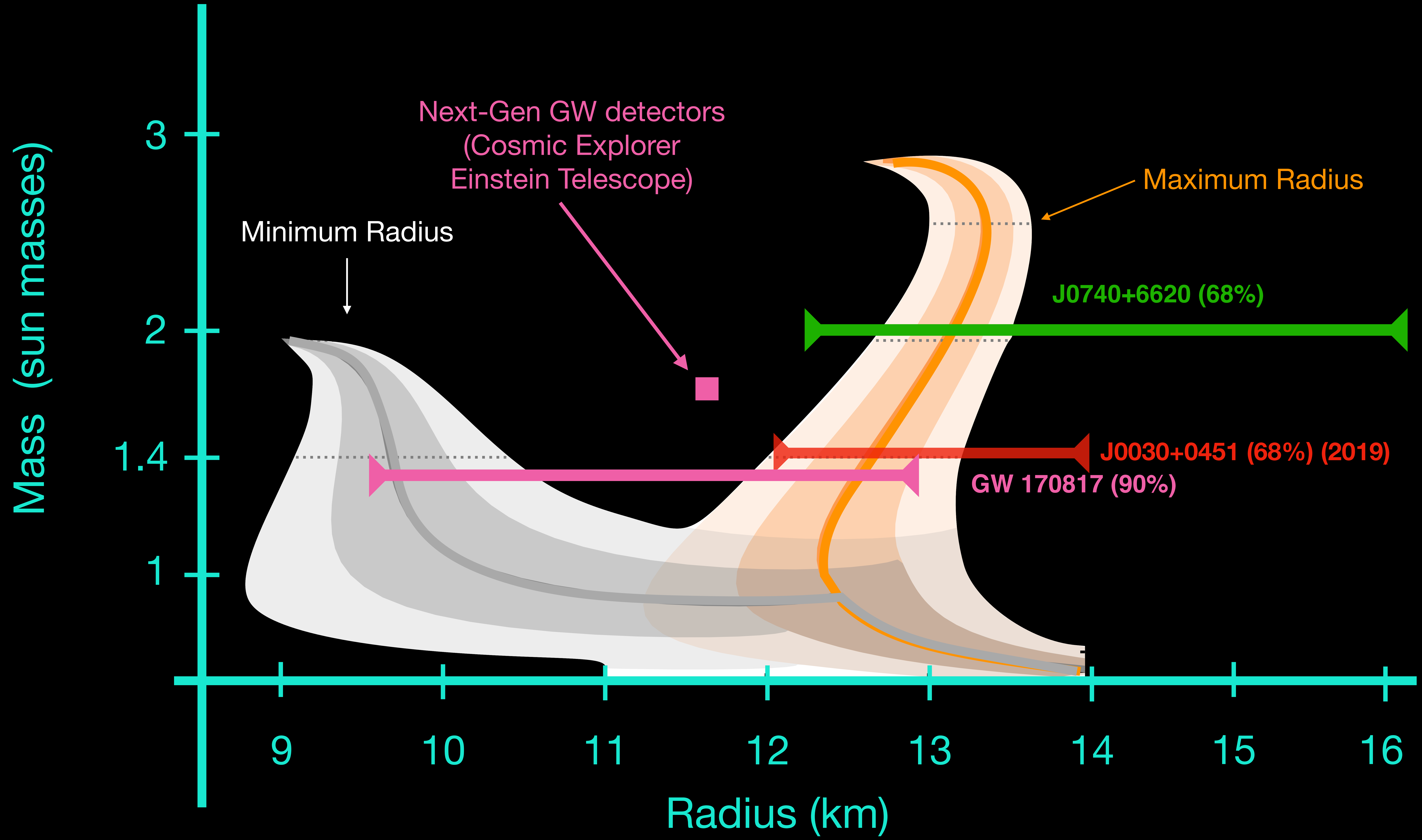

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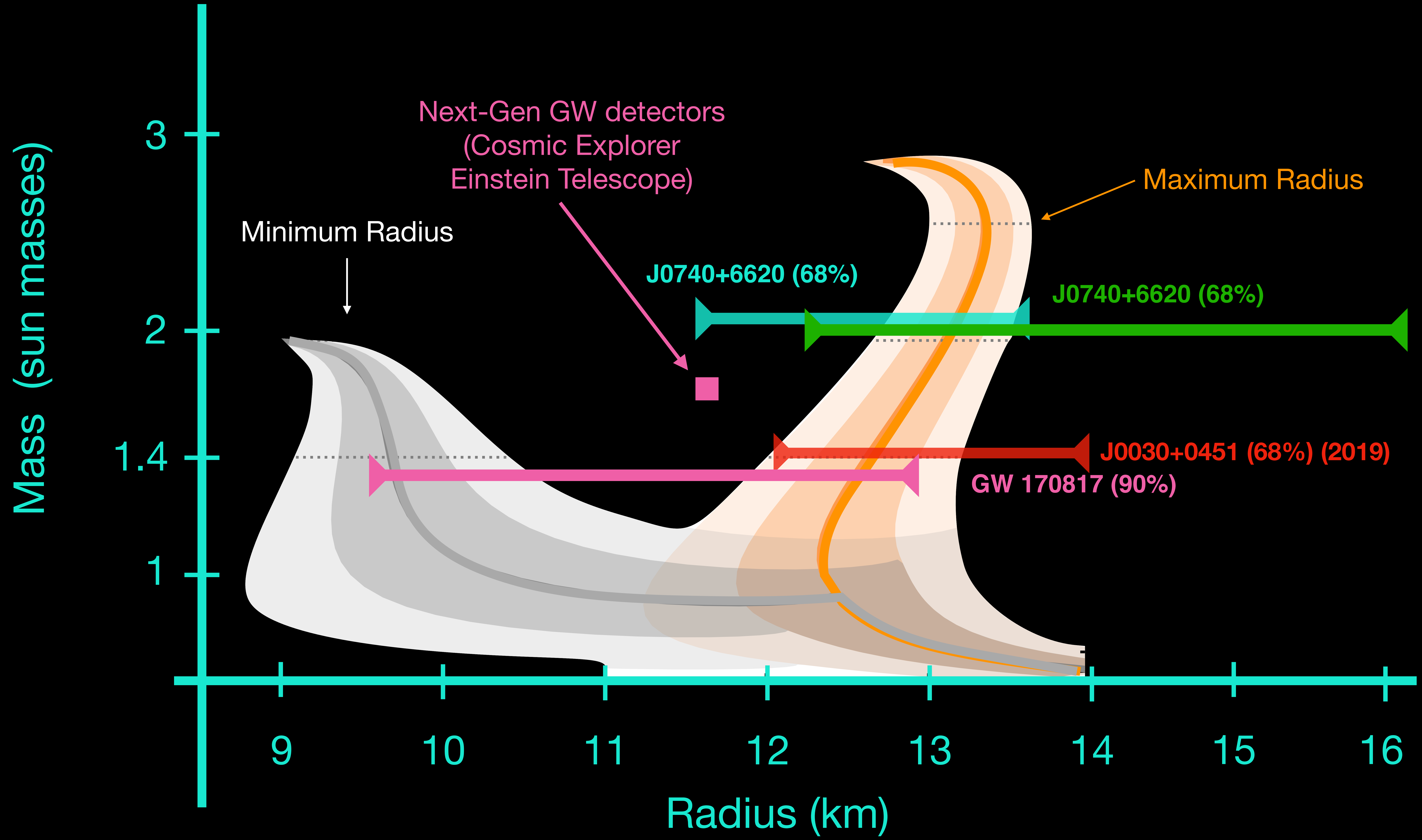

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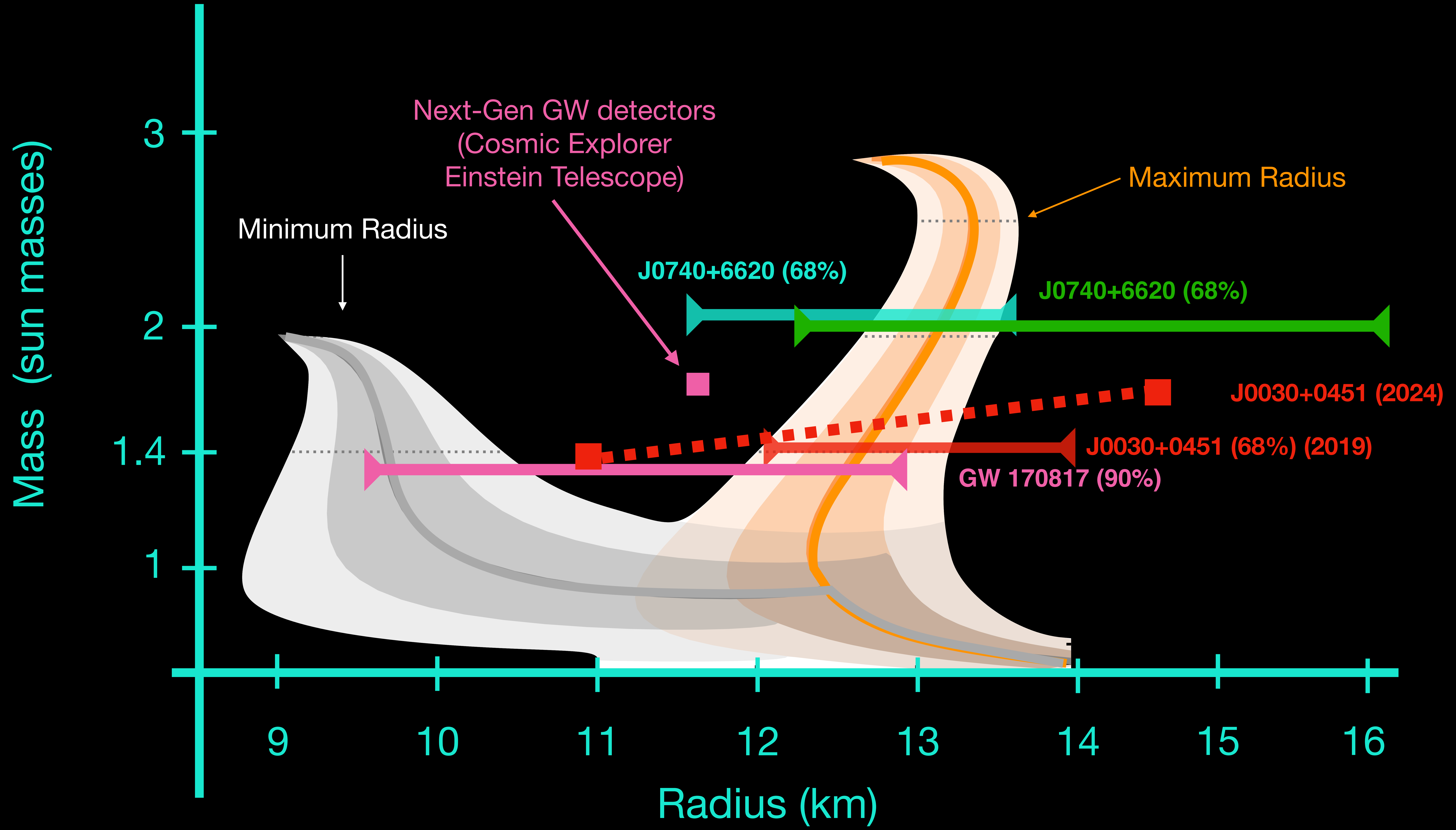

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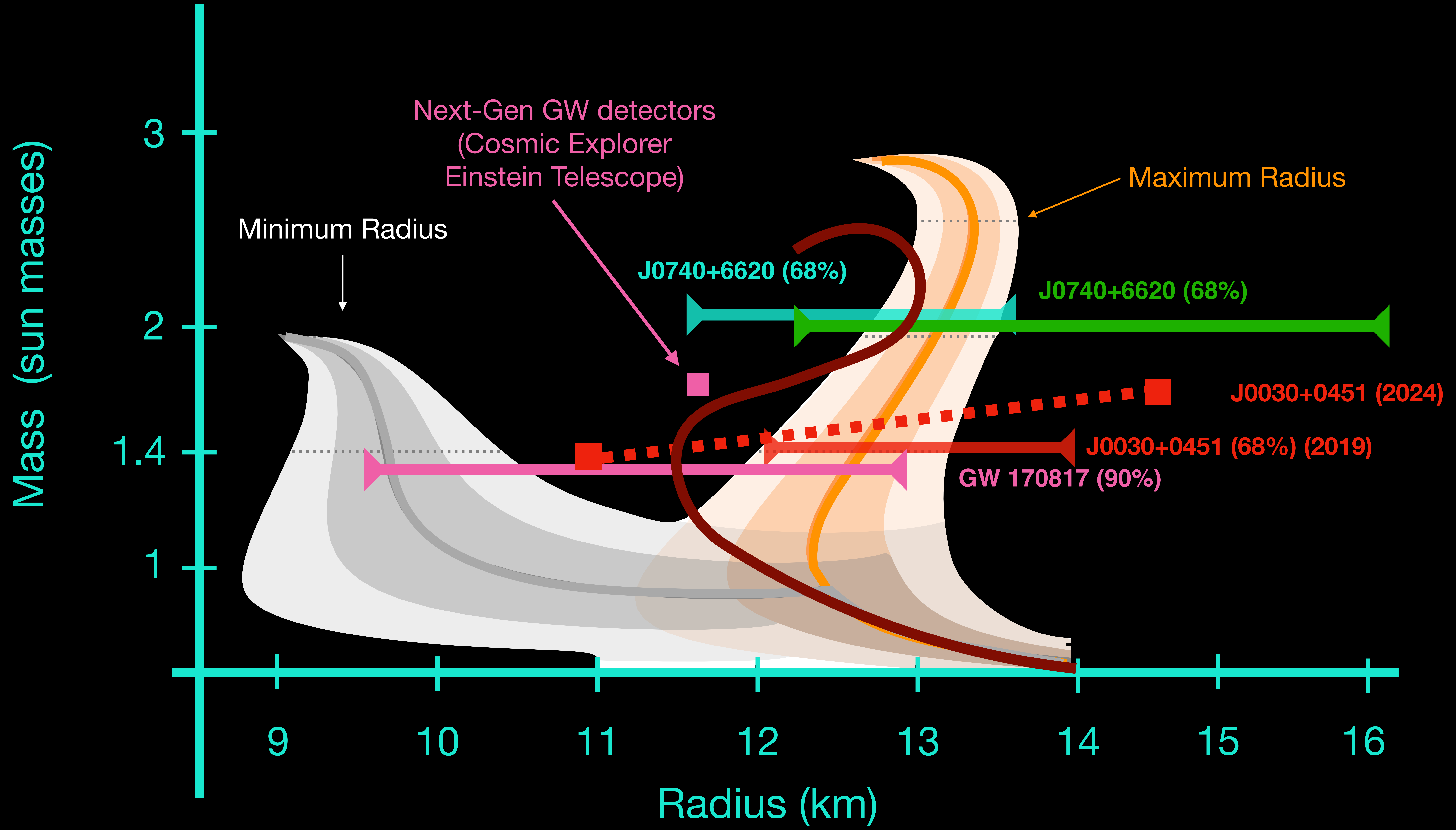


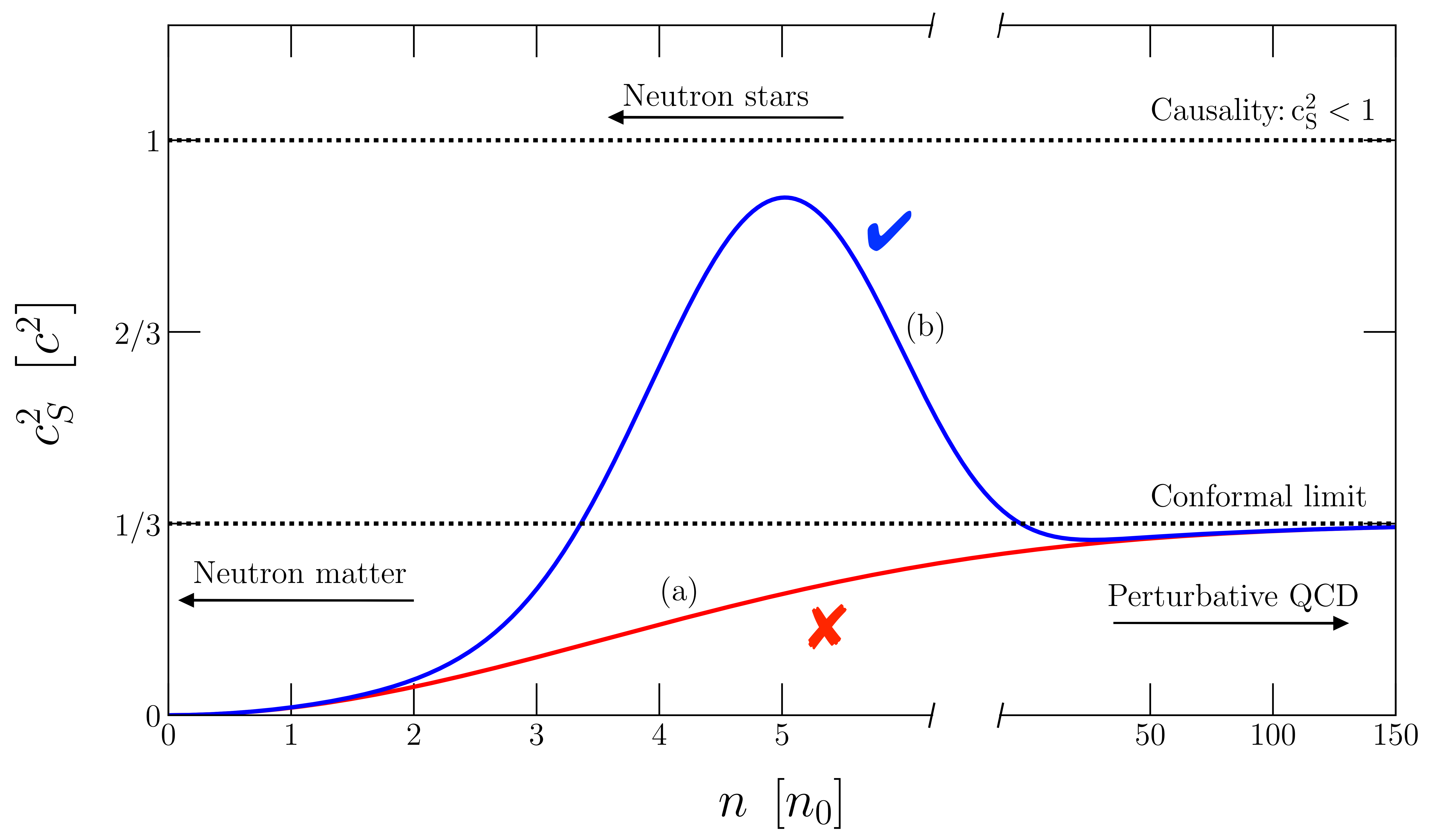
Speed of Sound in Dense Matter

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

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.



Tews, Carlson, Gandolfi and Reddy (2018)
Steiner & Bedaque (2016)

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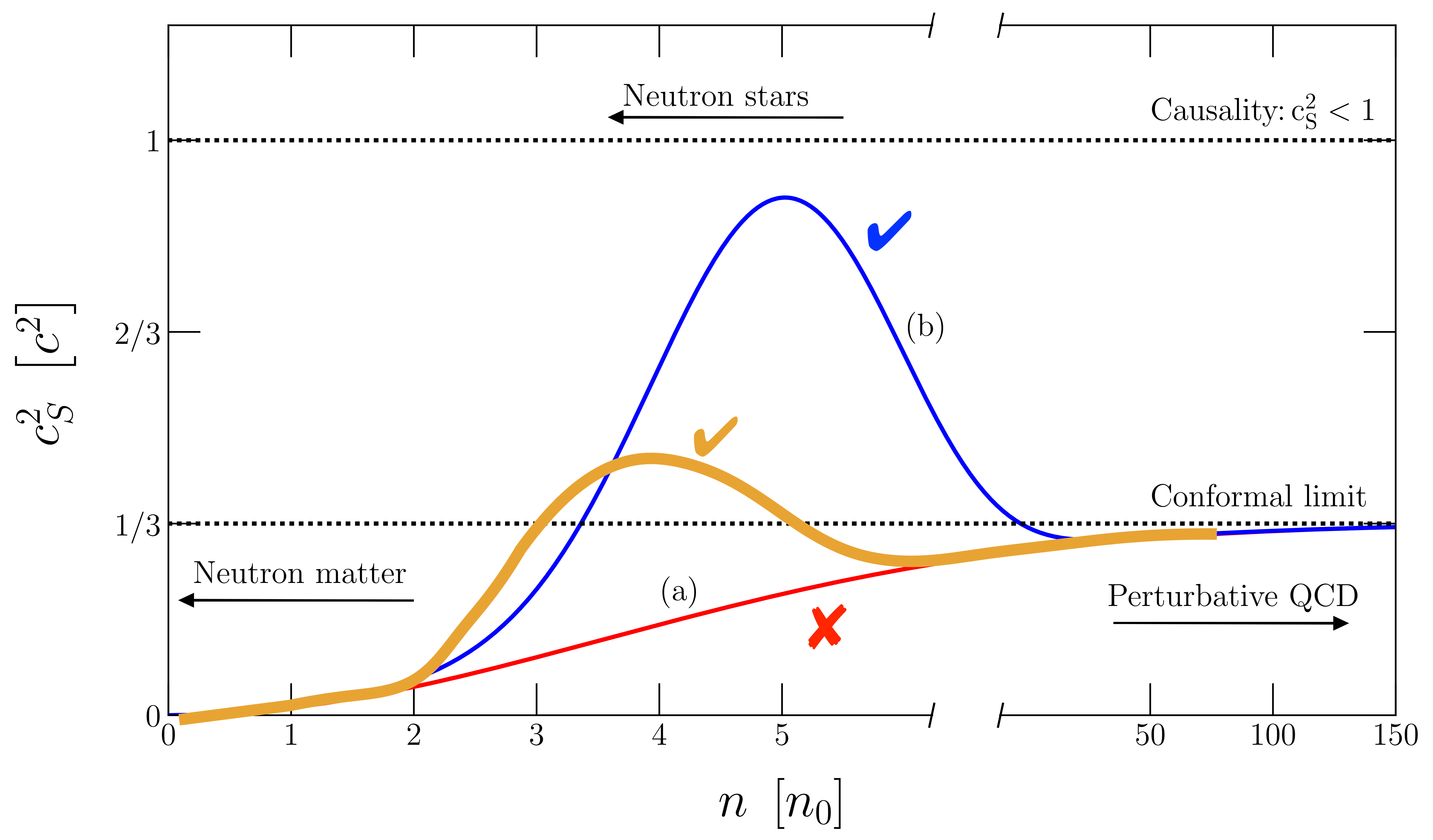

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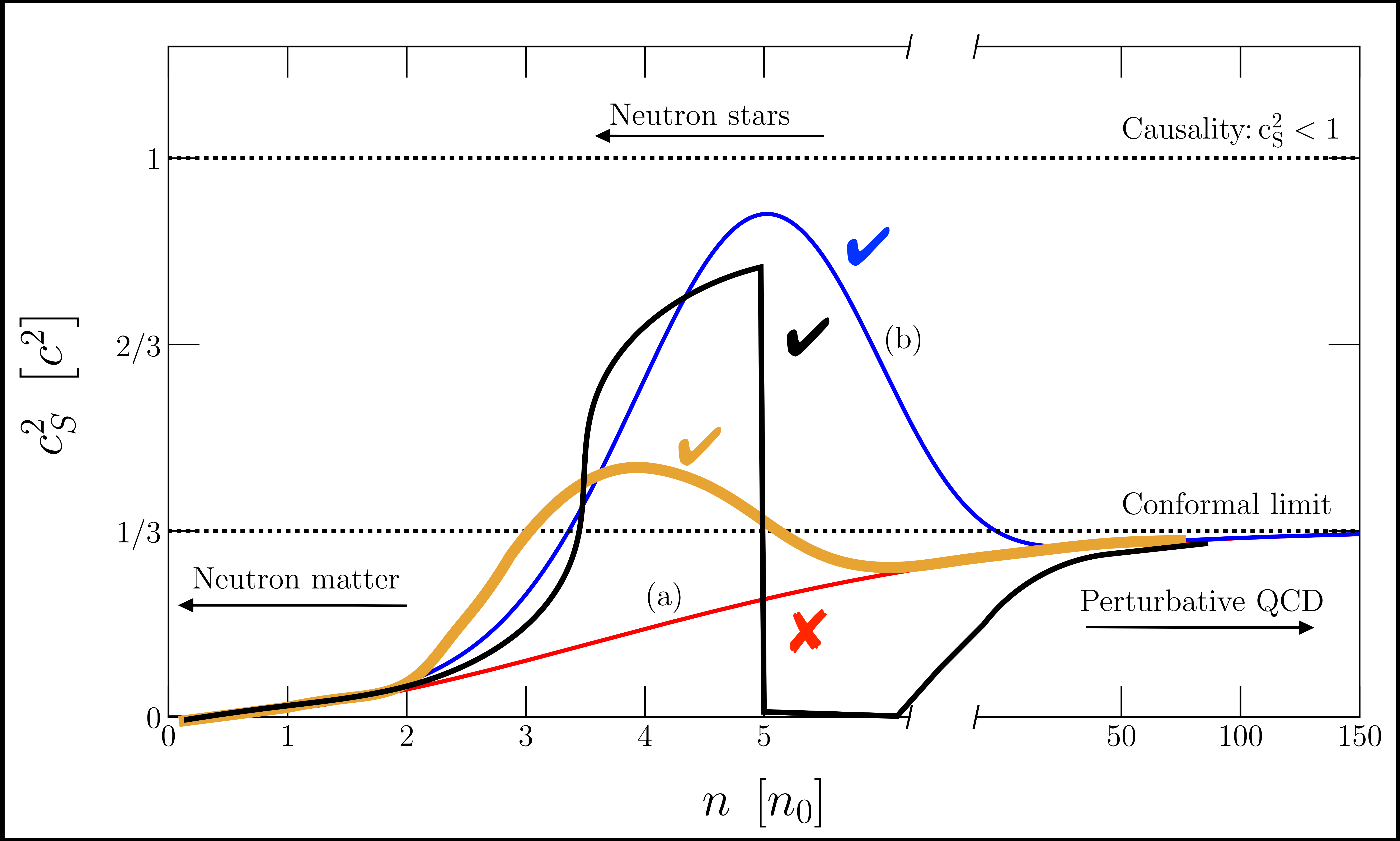

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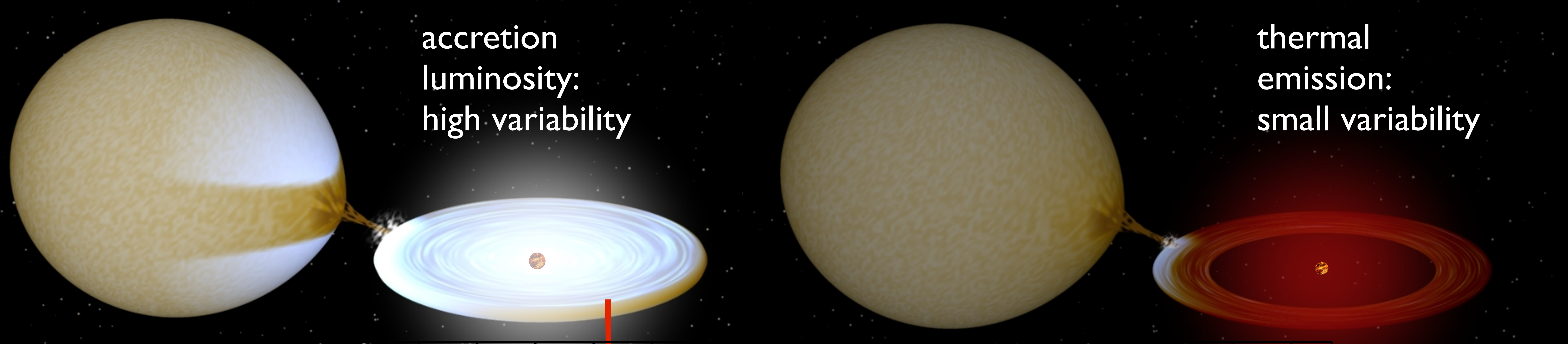
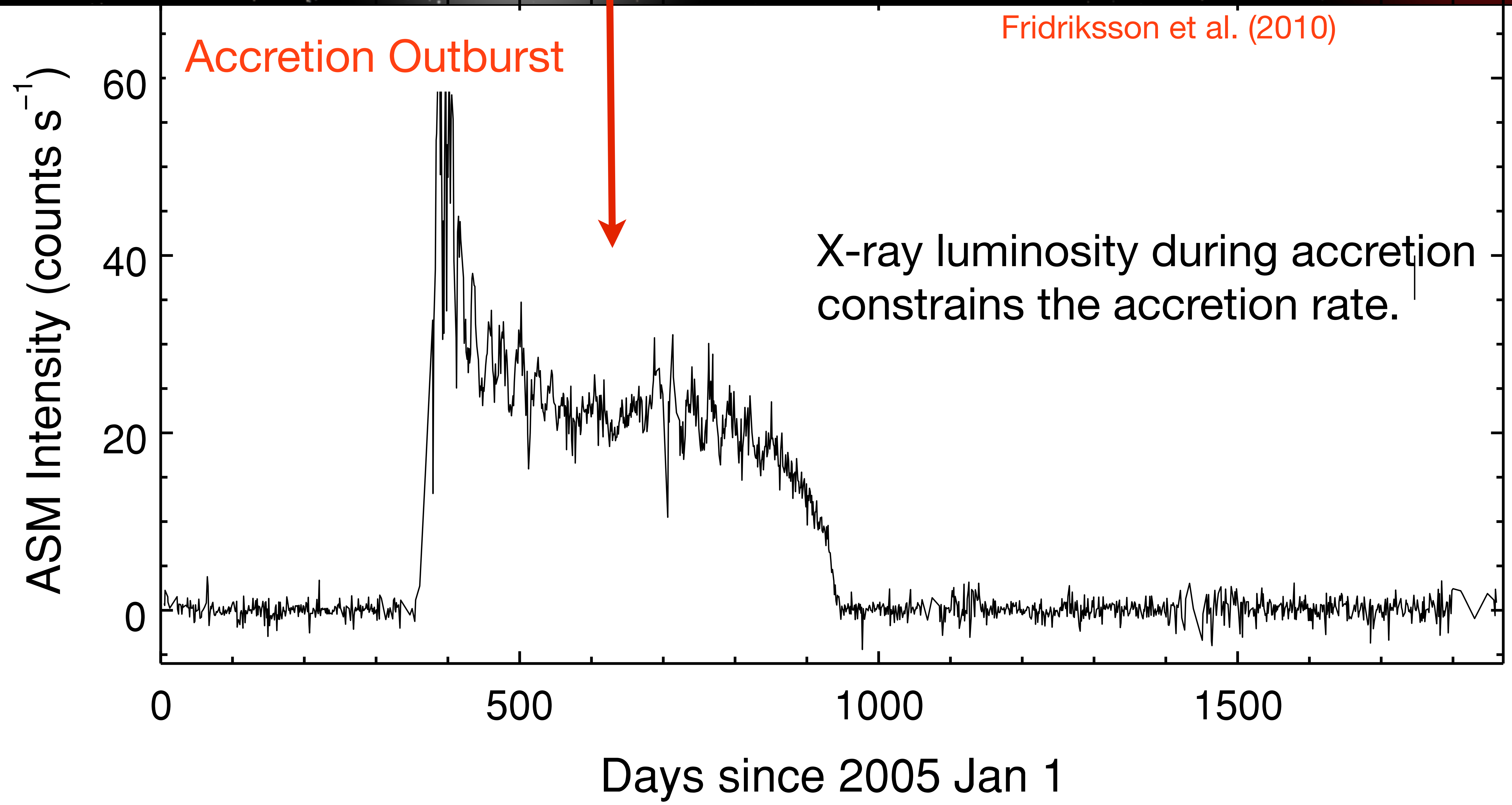
Is the NS core a fermi liquid or superconductor or superfluid ?

- The equation of state is insensitive to pairing at the Fermi surface.
- Need access to low-temperature properties such as response and specific heat to distinguish between phases.
- Neutrino cooling rates and heat capacity are exponentially supressed due to pairing at low temperature $\propto \exp(-\Delta/T)$
- Observations of accreting neutron stars can constrain the fraction of the baryons or quarks that can form Cooper pairs.

Transiently Accreting Neutron Stars





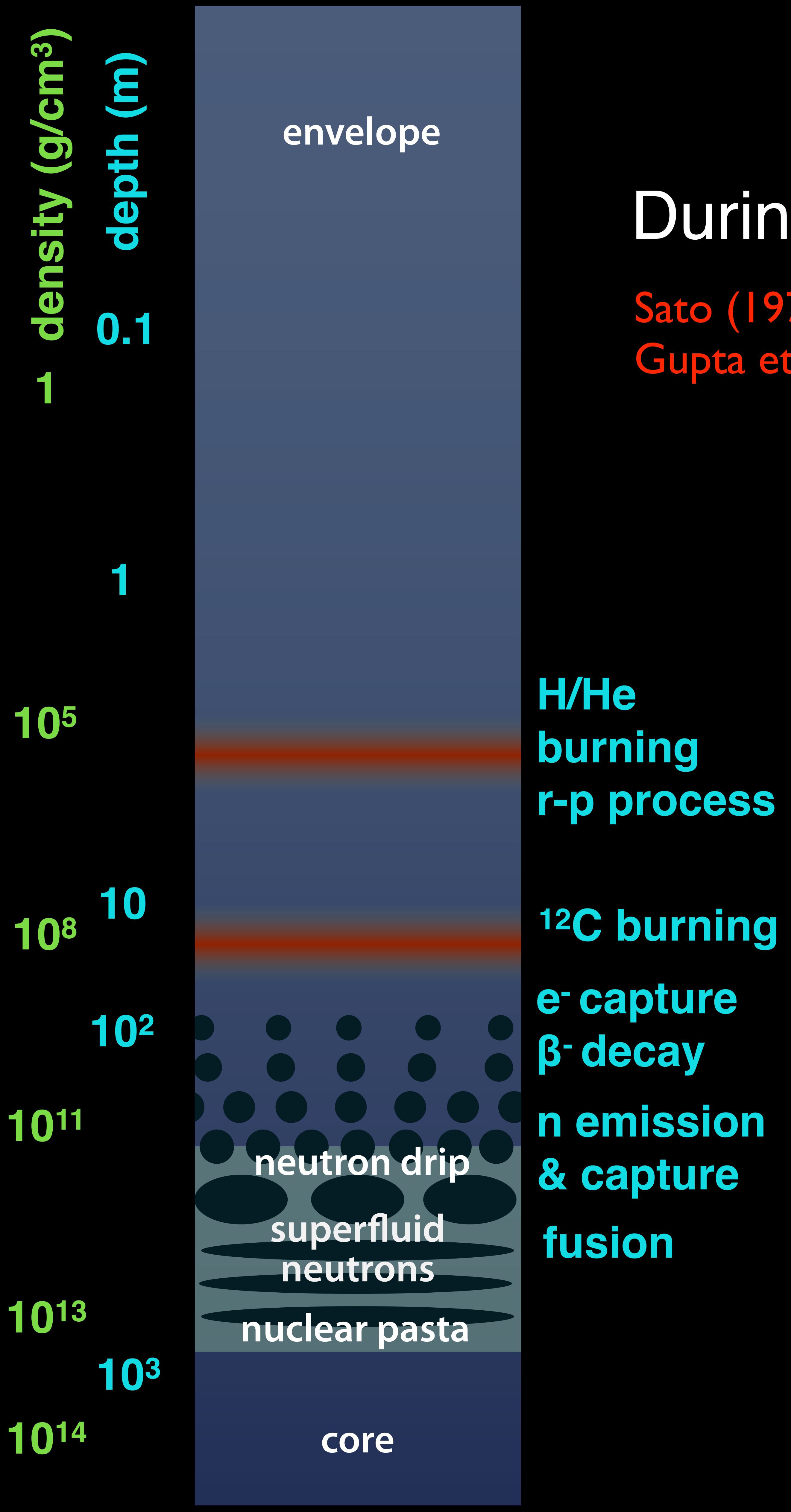
Fridriksson et al. (2010)

X-ray luminosity during accretion constrains the accretion rate.

Deep Crustal Heating

During accretion nuclear reactions release: ~ 2-4 MeV / nucleon

Sato (1974), Haensel & Zdunik (1990), Brown, Bildsten Rutledge (1998)
Gupta et al (2007,2011).



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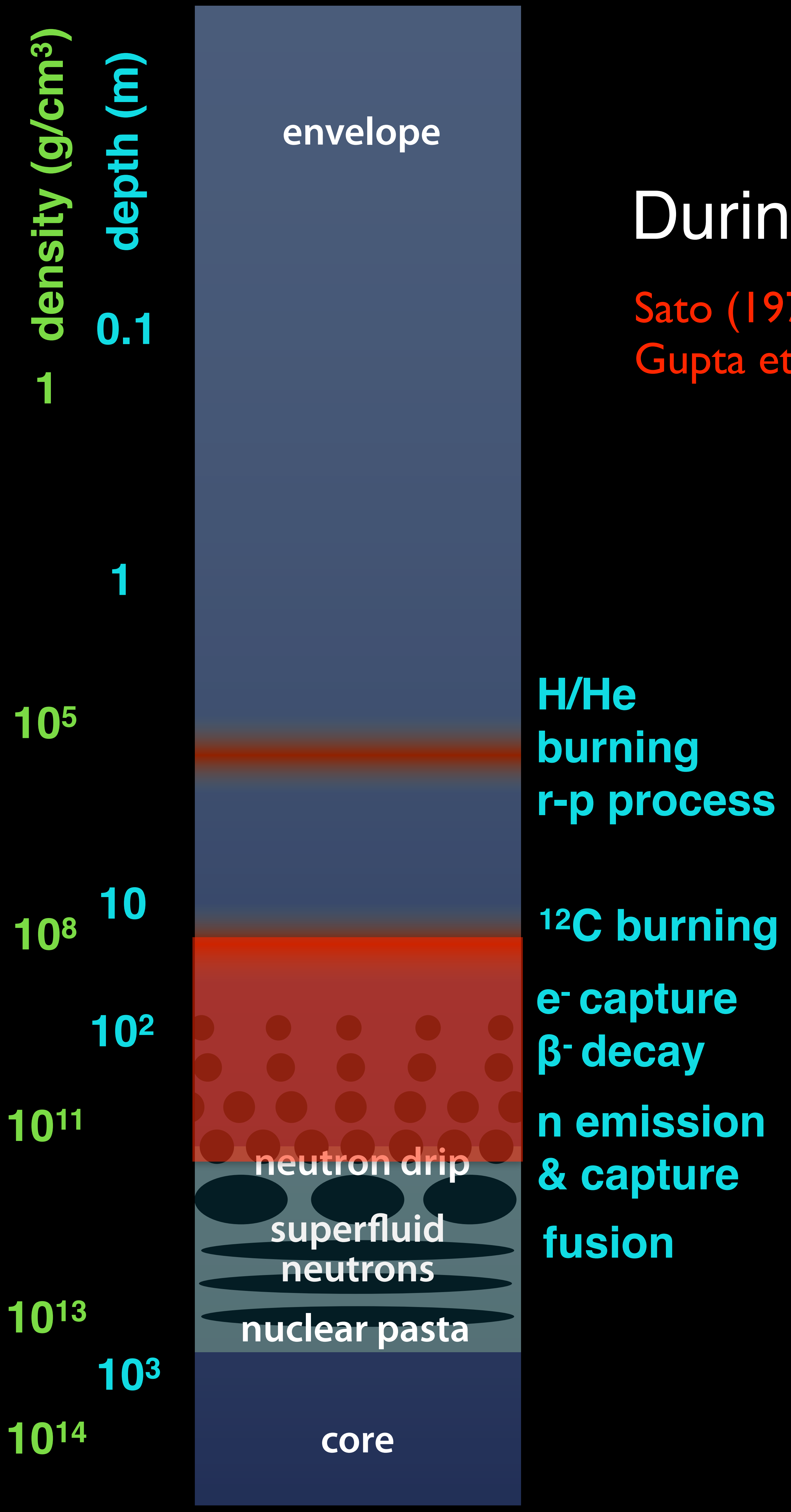

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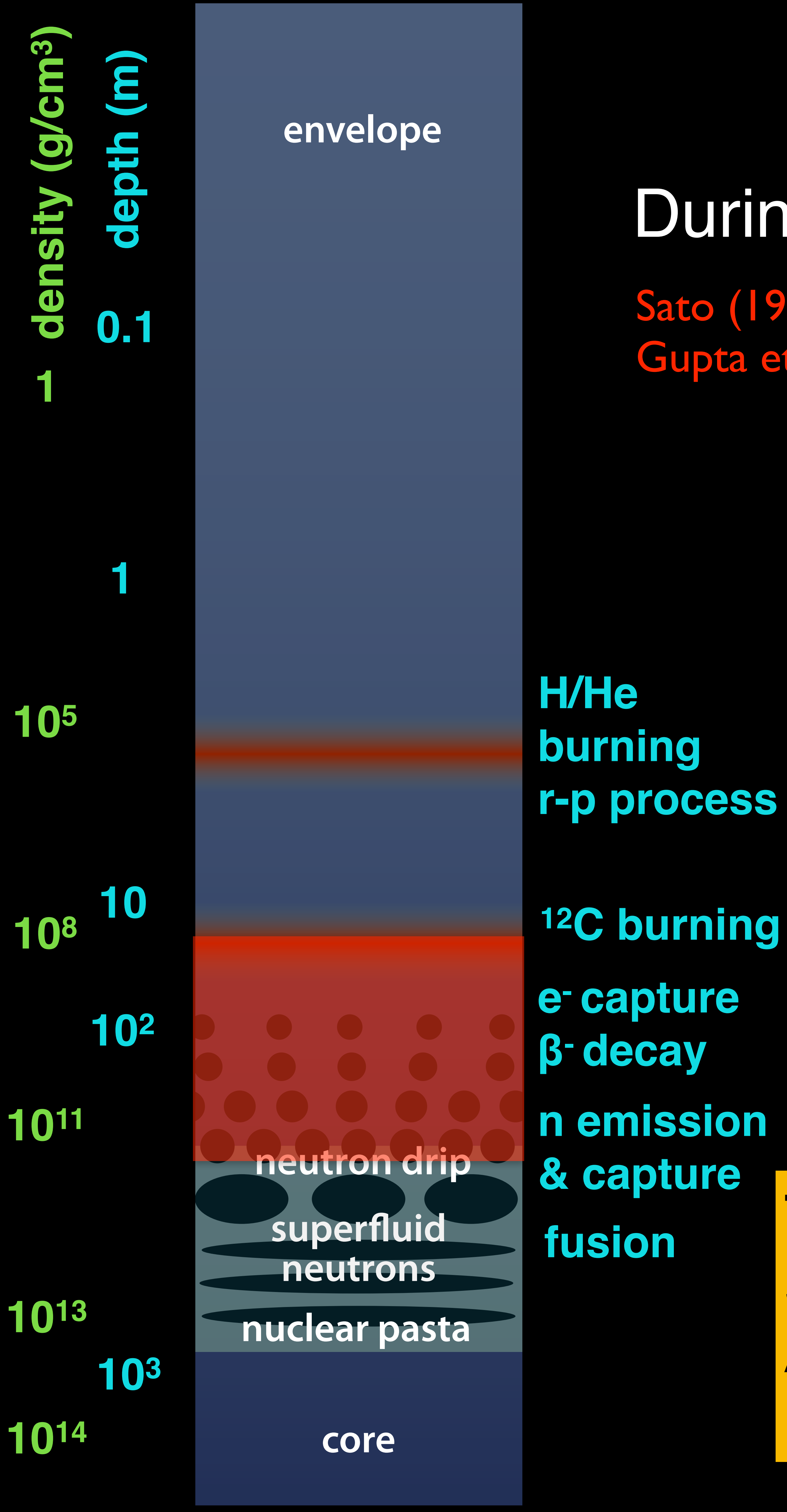

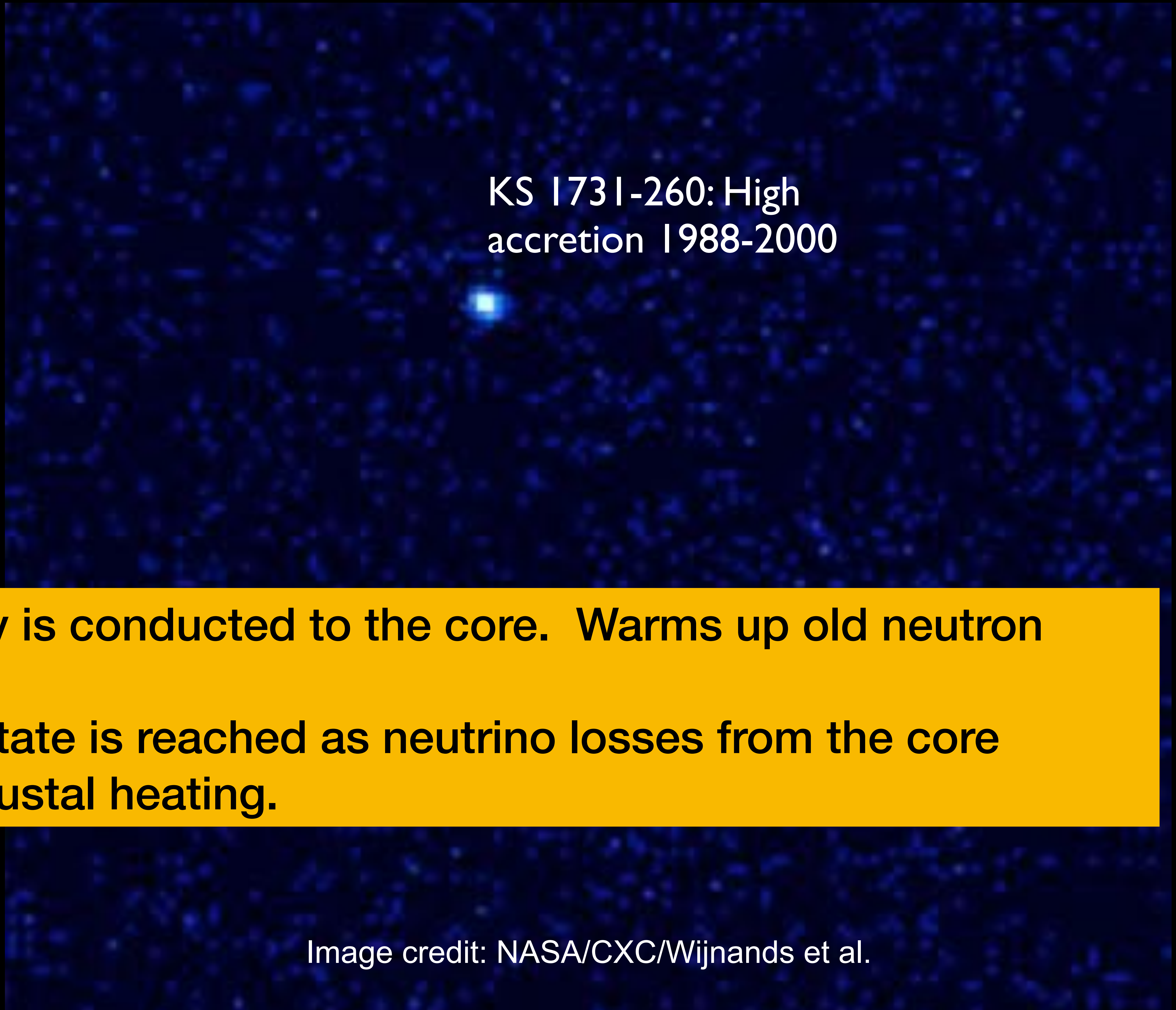

The energy is conducted to the core. Warms up old neutron stars.
A steady state is reached as neutrino losses from the core balance crustal heating.

Image credit: NASA/CXC/Wijnands et al.

Measuring the Heat Capacity of the Core

Heat the star, allow it to relax, and observe the change in temperature:

$$C_{NS}\ dT = dQ$$

Cumming et al. (2016)

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Measuring the Heat Capacity of the Core

Heat the star, allow it to relax, and observe the change in temperature:

$$C_{NS}\ dT = dQ$$

When $C_{NS} = \alpha\, T$: $\quad \frac{\alpha}{2}\left(T_f^2 - T_i^2\right) = \Delta Q$

Lower limit: $\quad C_{NS}(T_f) > 2\frac{\Delta Q}{T_f}$

$$\Delta Q = \dot{H} \times t_H - L_\nu \times (t_H + t_{obs})$$

heating rate

duration of heating

neutrino cooling rate

time of observation (after heating ceases)

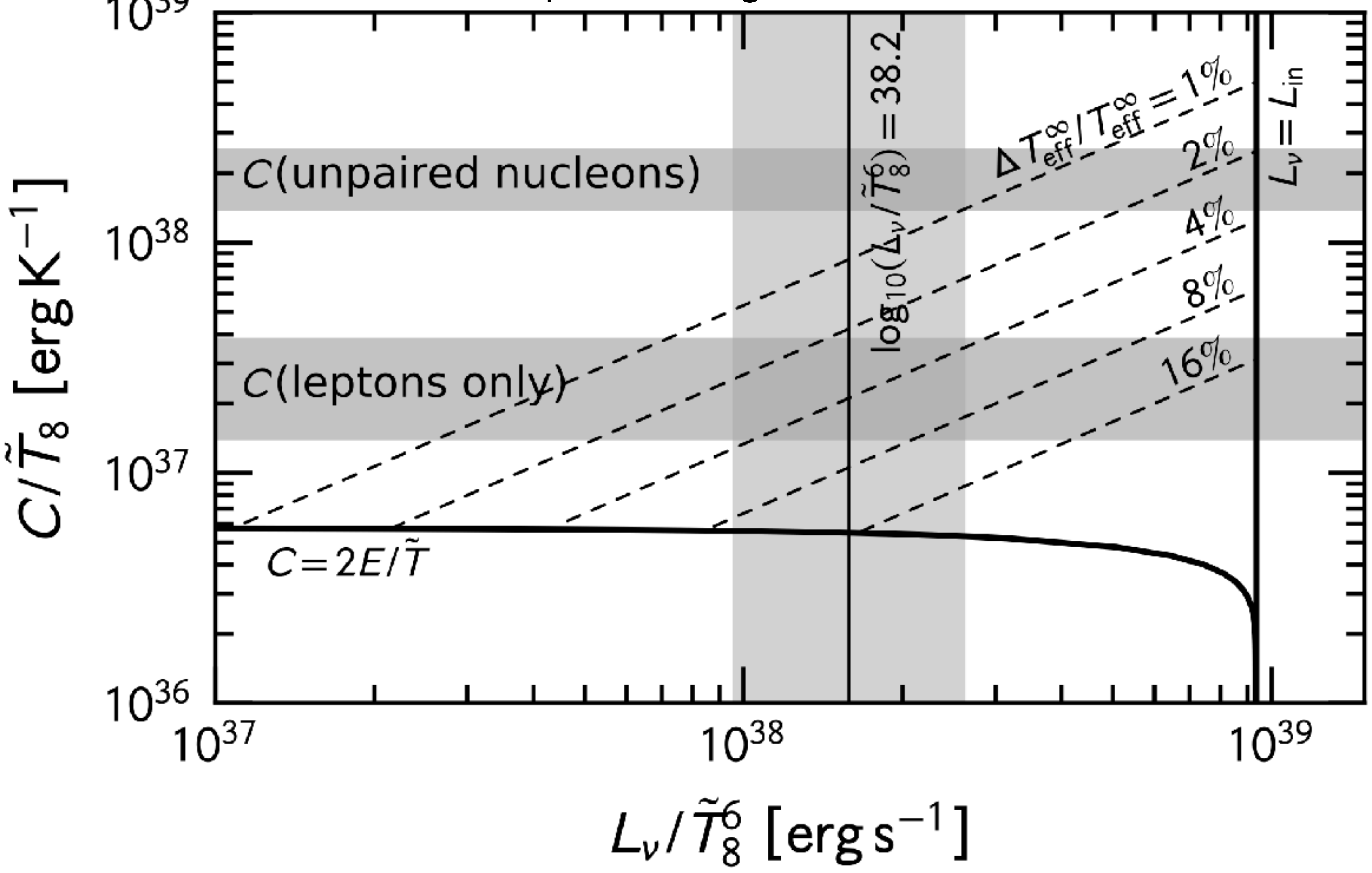
Cumming et al. (2016)

Constraining the Neutrino Emissivity and Heat Capacity

In systems with repeated accretion outbursts, we can infer the neutrino luminosity by estimating the net crustal heat deposition.

If cooling is observed between accretion events, it would constrain the specific heat. A 10% change in the core temperature on a 10 year time scale, would require that most fermions are gapped- either superfluid or superconducting.

Rapid Cooling of MXB 1659-29



Brown at al. (2018)

Pairing in the core (typical density $n_B \simeq 4\ n_{sat}$)

- High sound speed requires strong repulsive interactions.
- In neutron matter, these interactions are modeled by the exchange of vector mesons

Questions:

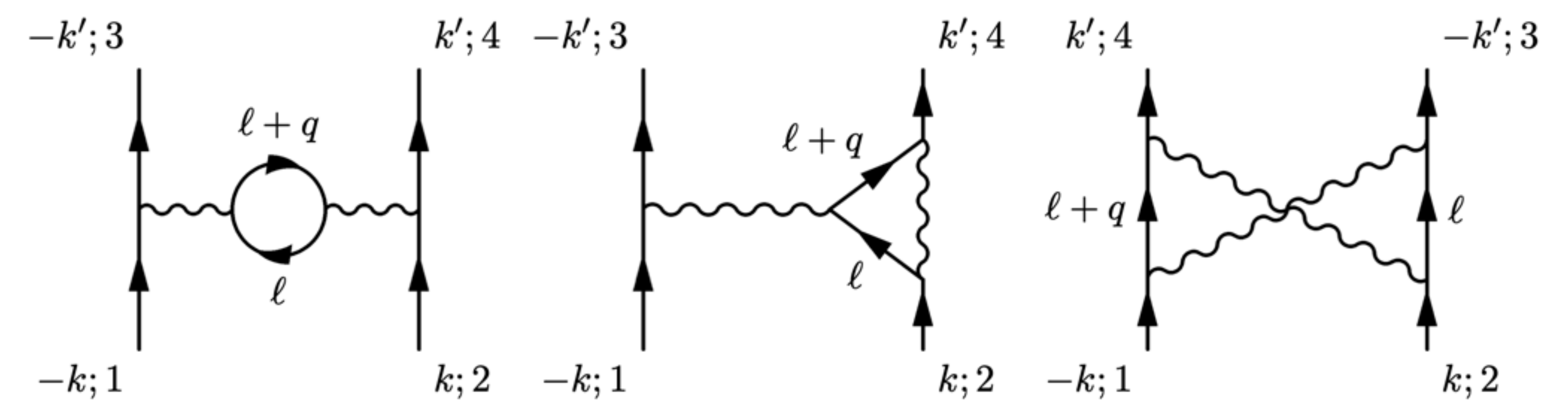
1. Can fermions pair if their interactions are mediated by massive vector bosons?
2. Can the pairing gap be related to the sound speed?

Answers:

1. Yes. ${}^3P_2$ pairing is likely.

2. In some scenarios.

Pairing through the Kohn-Luttinger Mechanism:



Induced Pairing in Neutron Matter

An old subject, first studies by Fay and Lazer in 1968!

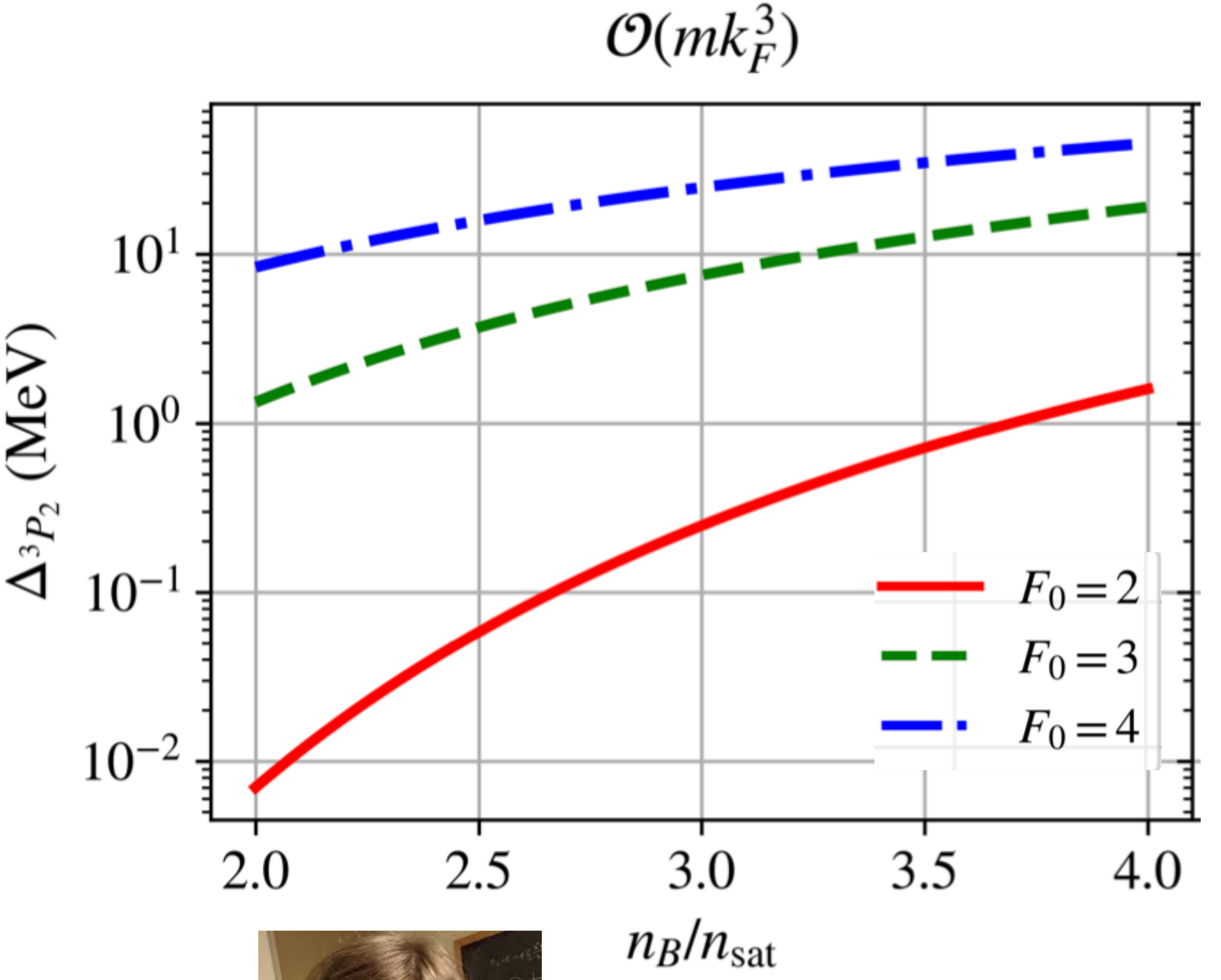
see review by Gezerlis, Pethick and Schwenk arXiv:1406.6109 (2014)

Large short-range repulsion due heavy vector meson exchange naturally leads to pairing in the $^3P_2$ channel.

Interesting interplay between central and spin-orbit forces.

The strength of the vector repulsion is related to the sound speed.

$$c_s^2 = \frac{k_F^2}{3mm^*}\,(1+F_0)$$



Kumamoto & Reddy (2024)

Summary & Conclusions

- Mass and radius measurements can and will provide strong constraints on the sound speed in the neutron star core.
- X-ray observations can provide valuable guidance but GW's are needed to obtains stringent constraints.
- We will need to observe and interpret thermal phenomena in accreting (and magnetized) neutron stars to constrain low temperature properties.
- There appears to some diversity in the cooling of neutron stars. A few old accreting neutron stars appear to be cooling rapidly.
- Long term monitoring of these systems can constrain the specific heat of the core.
- Screening of repulsive vector interactions provides a mechanism to pair fermions in the $^3P_2$ channel.