Neutron Stars: New Insights from Theory and Observations

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INSTITUTE for NUCLEAR THEORY

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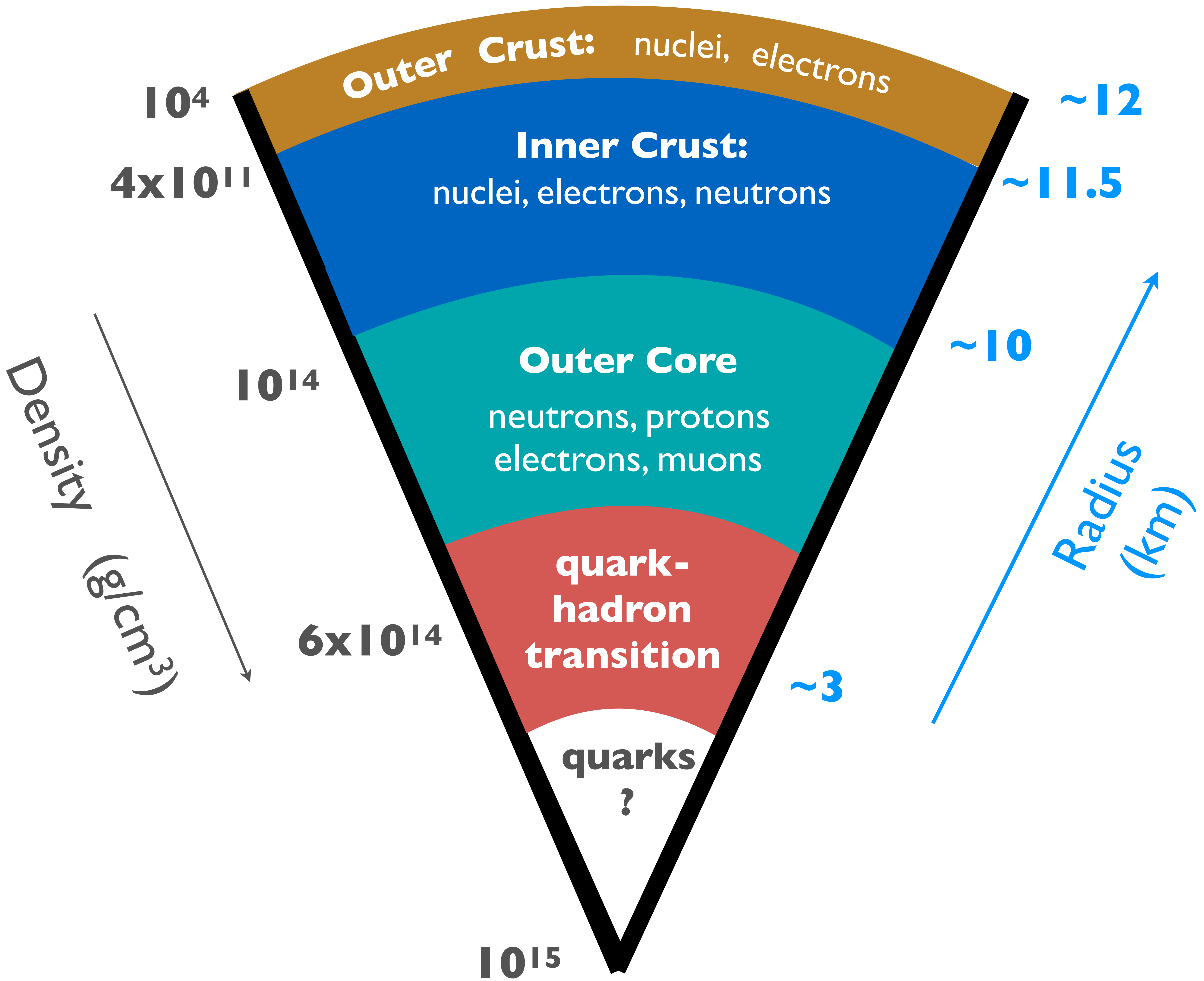
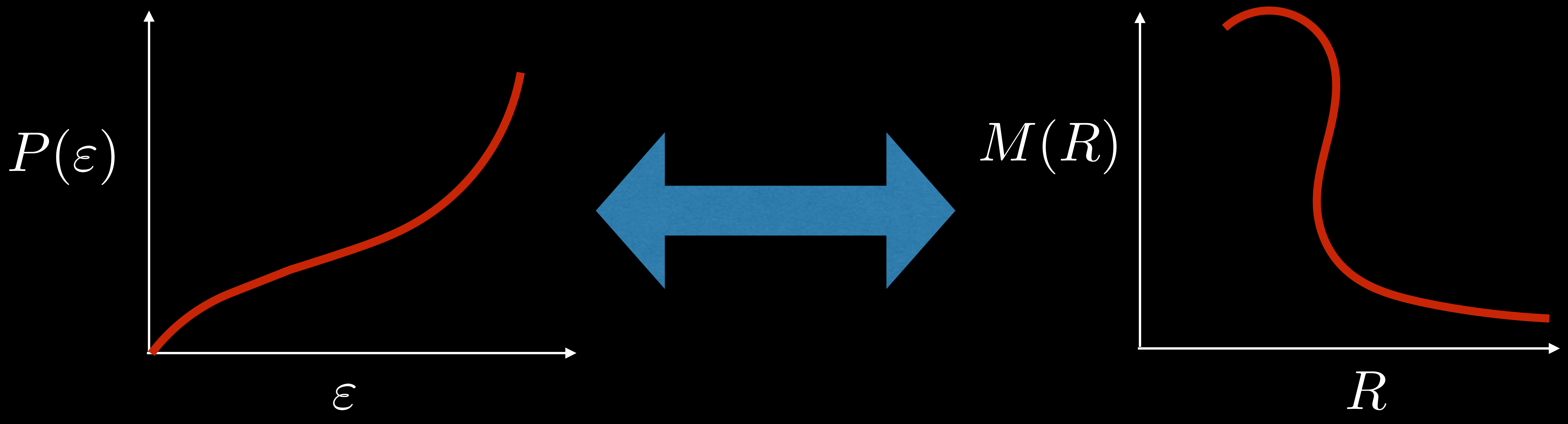
Happy Birthday Wick!

INSTITUTE for
NUCLEAR THEORY

Composition of Dense Matter in Neutron Stars



Equation of State and Neutron Star Structure



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

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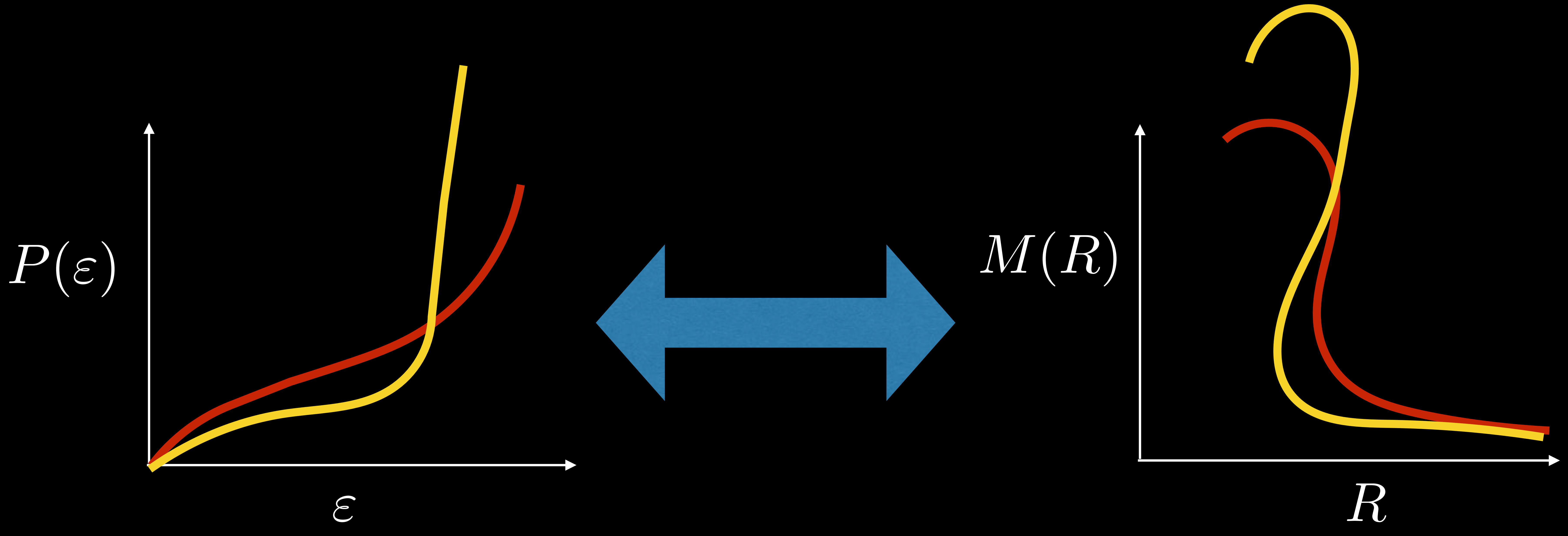

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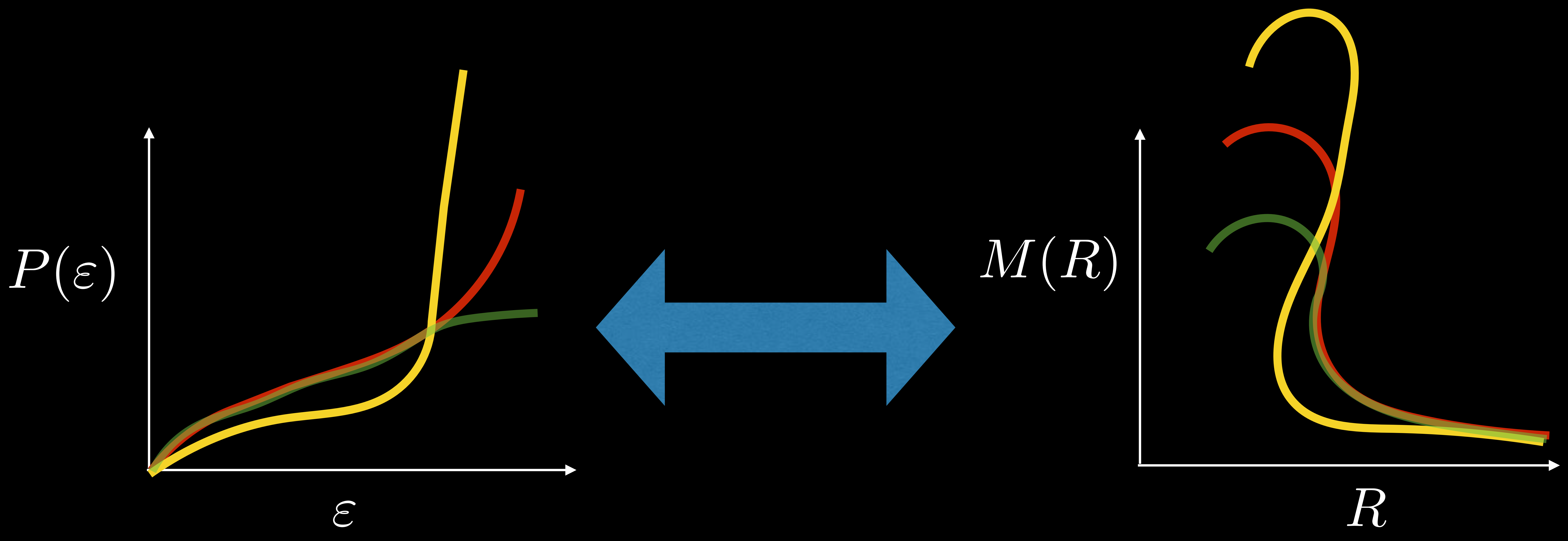

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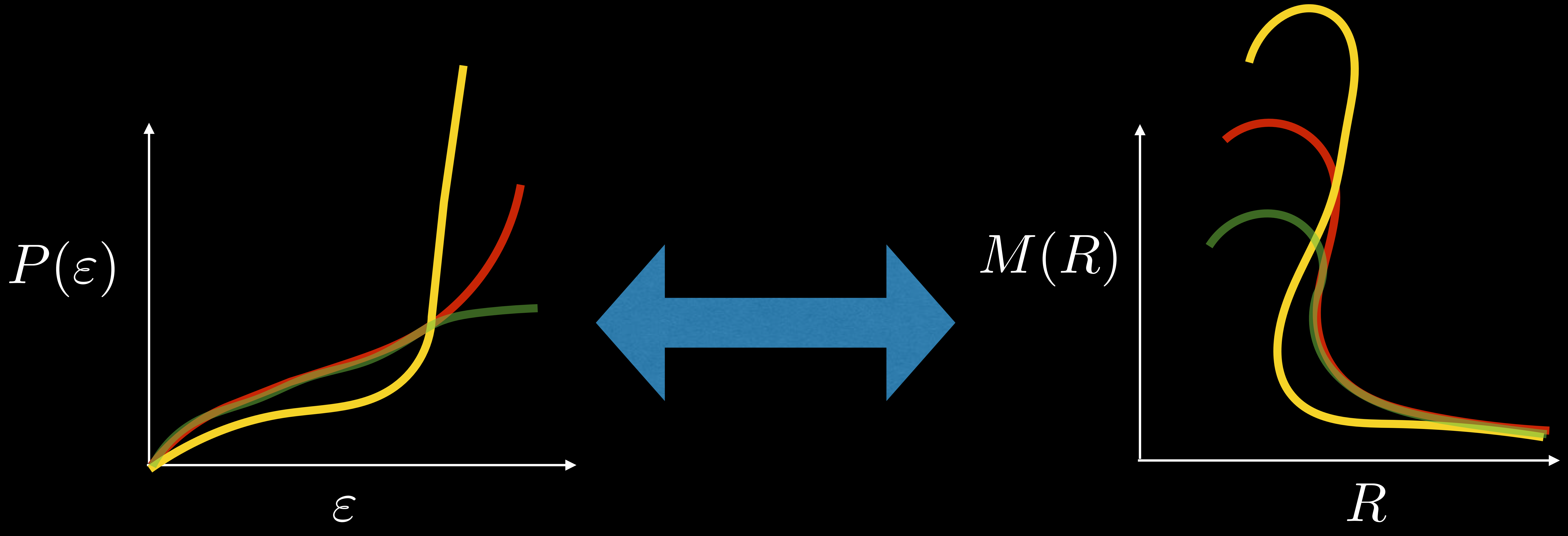
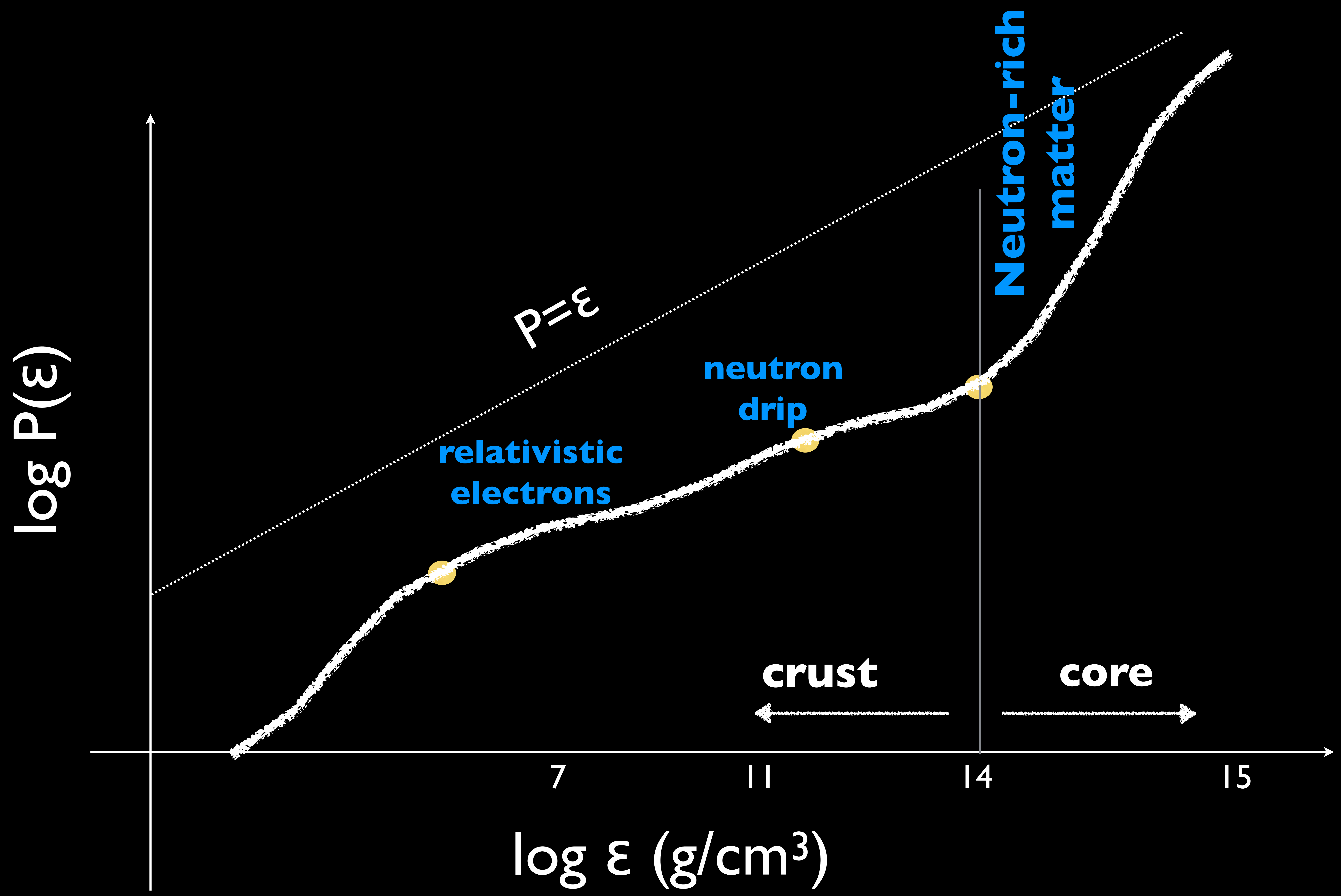


$$P(\varepsilon) + \text{Gen.Rel.} = M(R)$$

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

Pressure v/s Energy Density (EoS)



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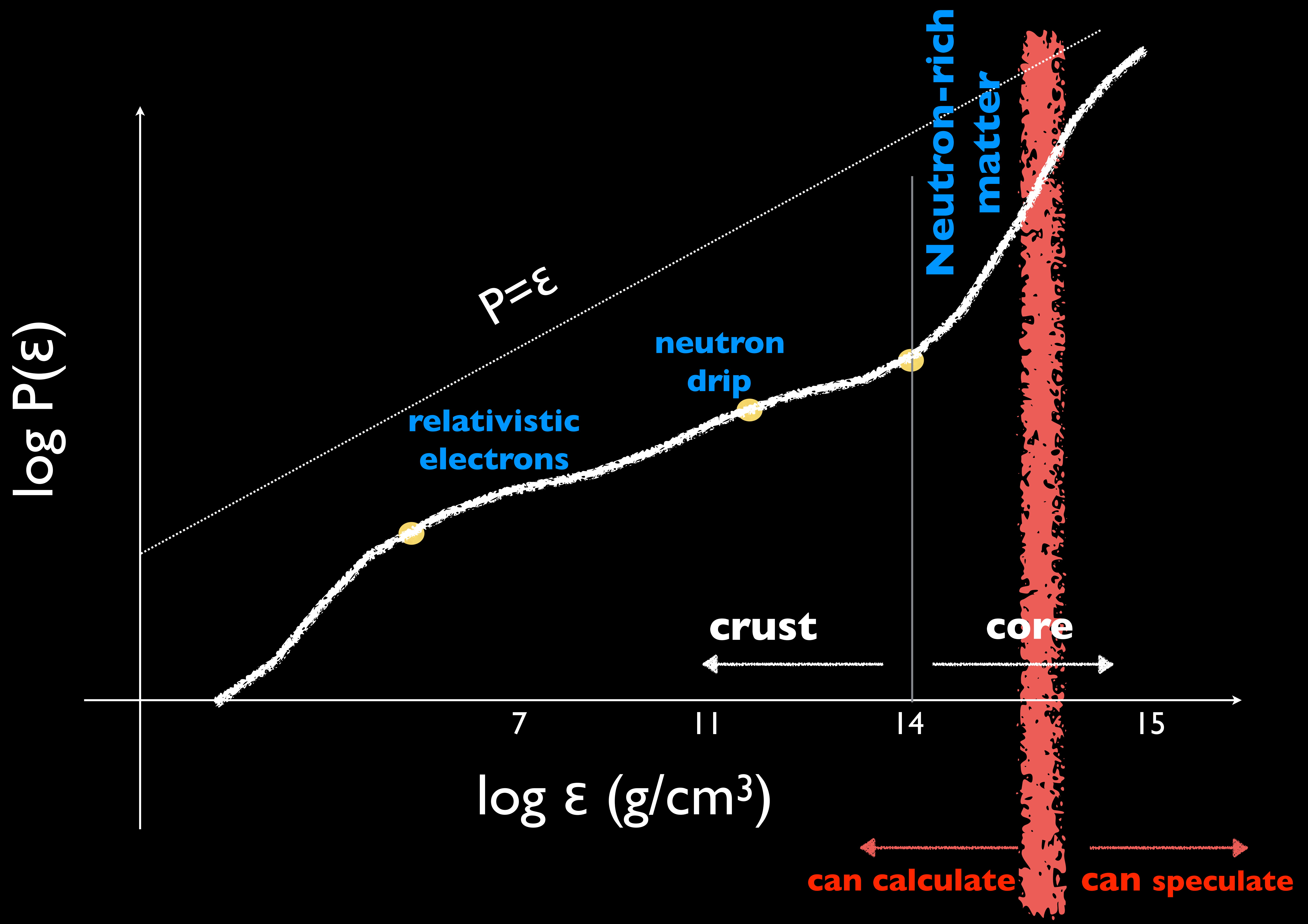

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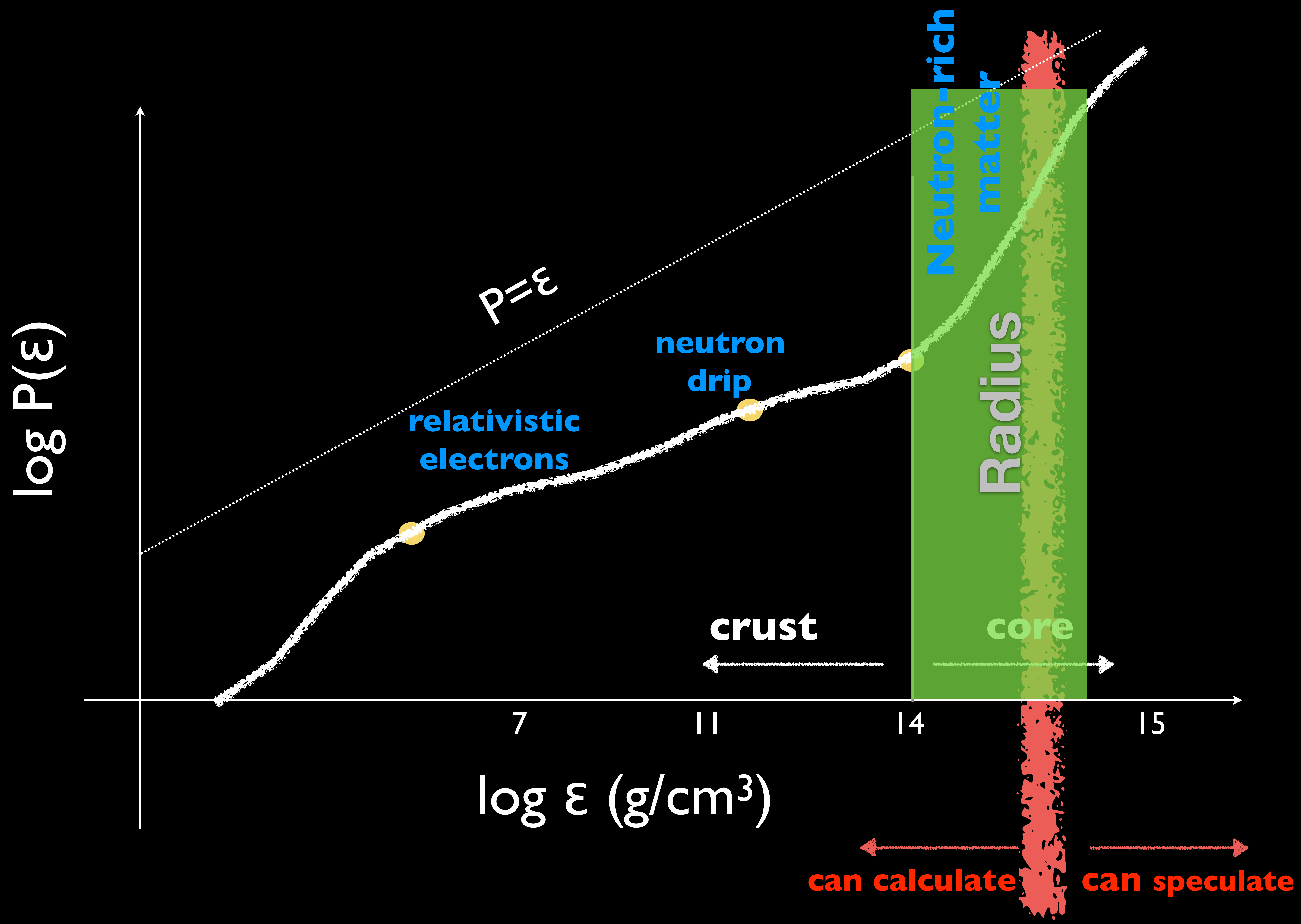

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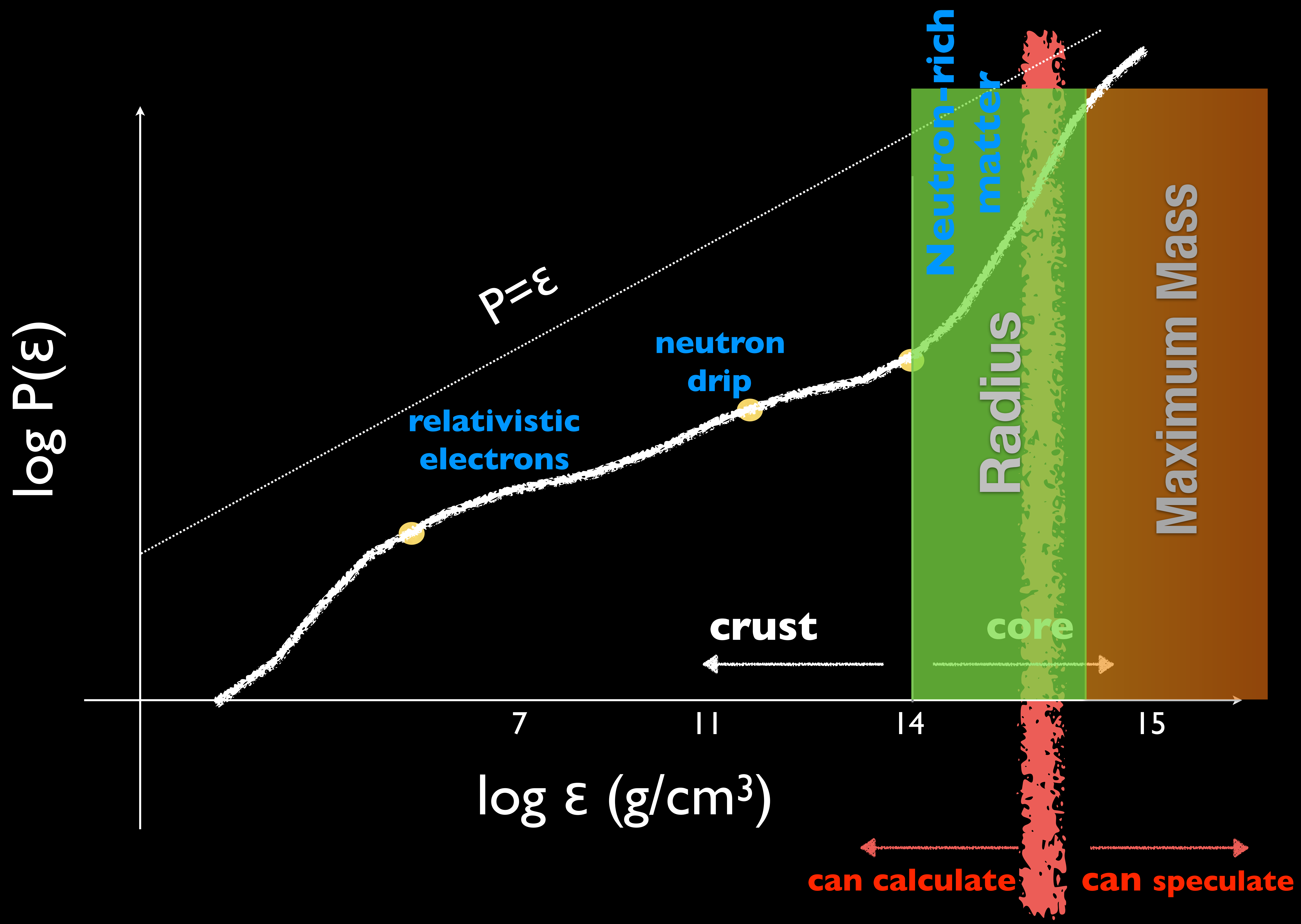
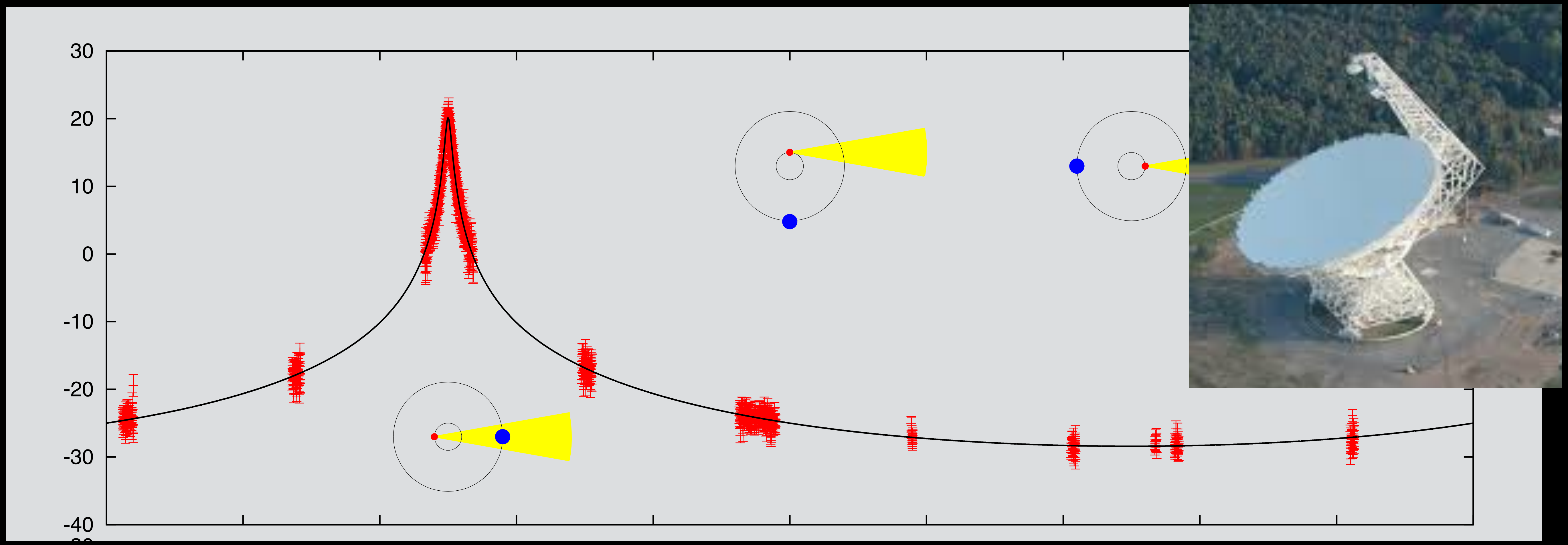


Neutron Star Structure: Observations



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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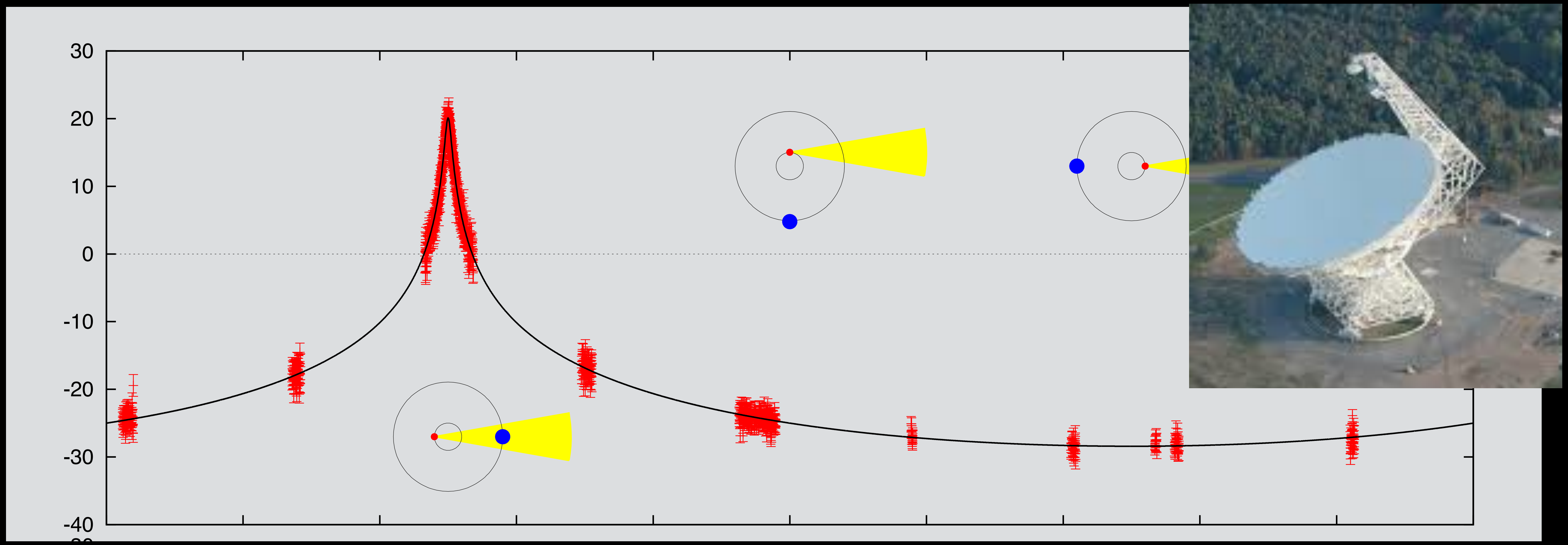

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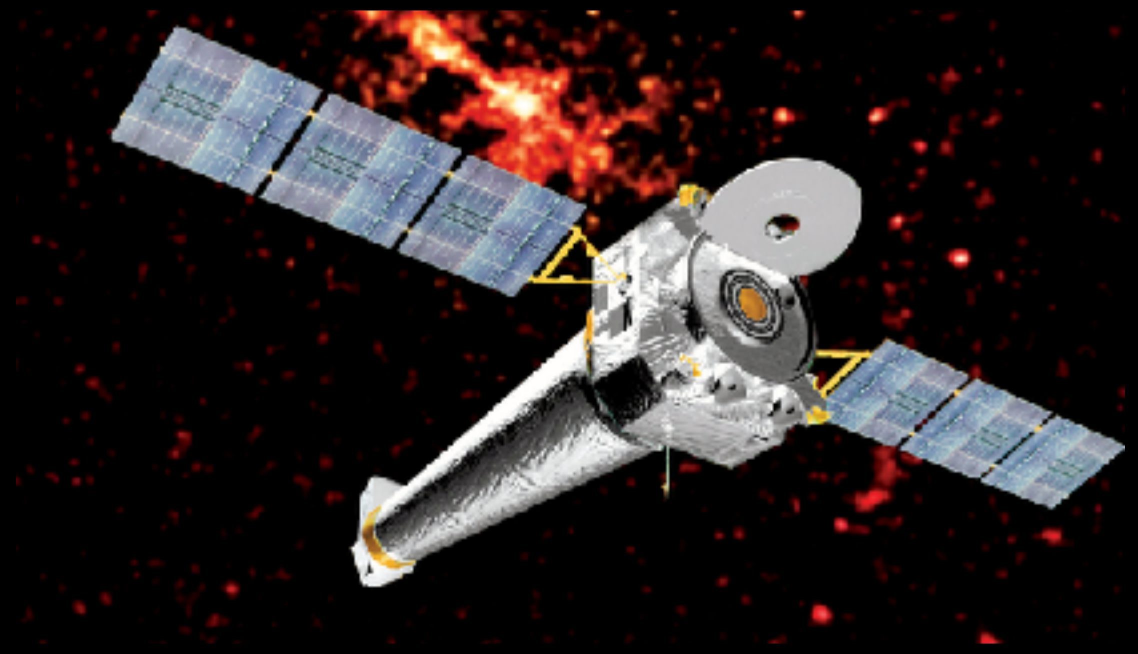
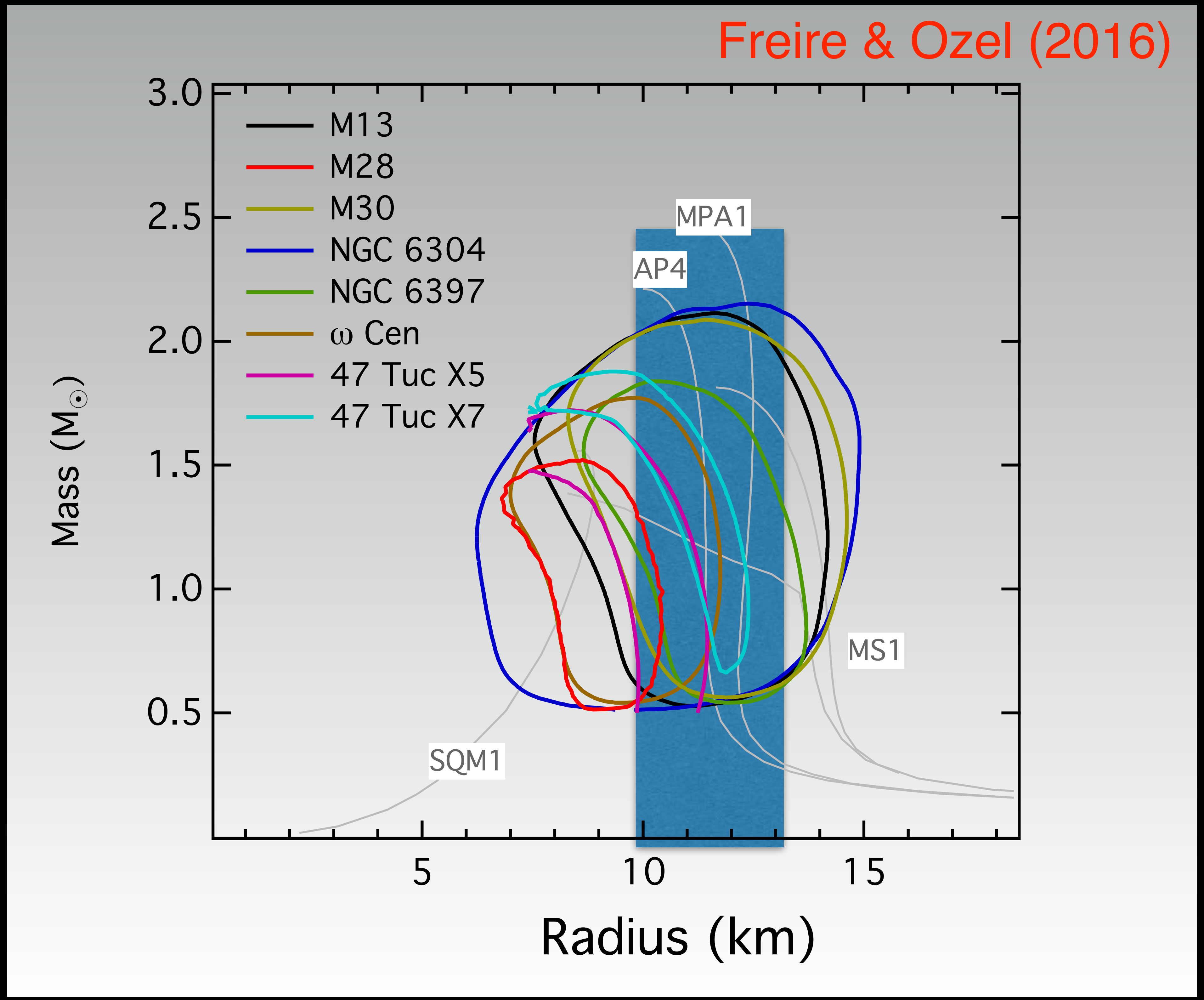




NS radii are difficult to measure:

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

Radii from Hot Spots

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

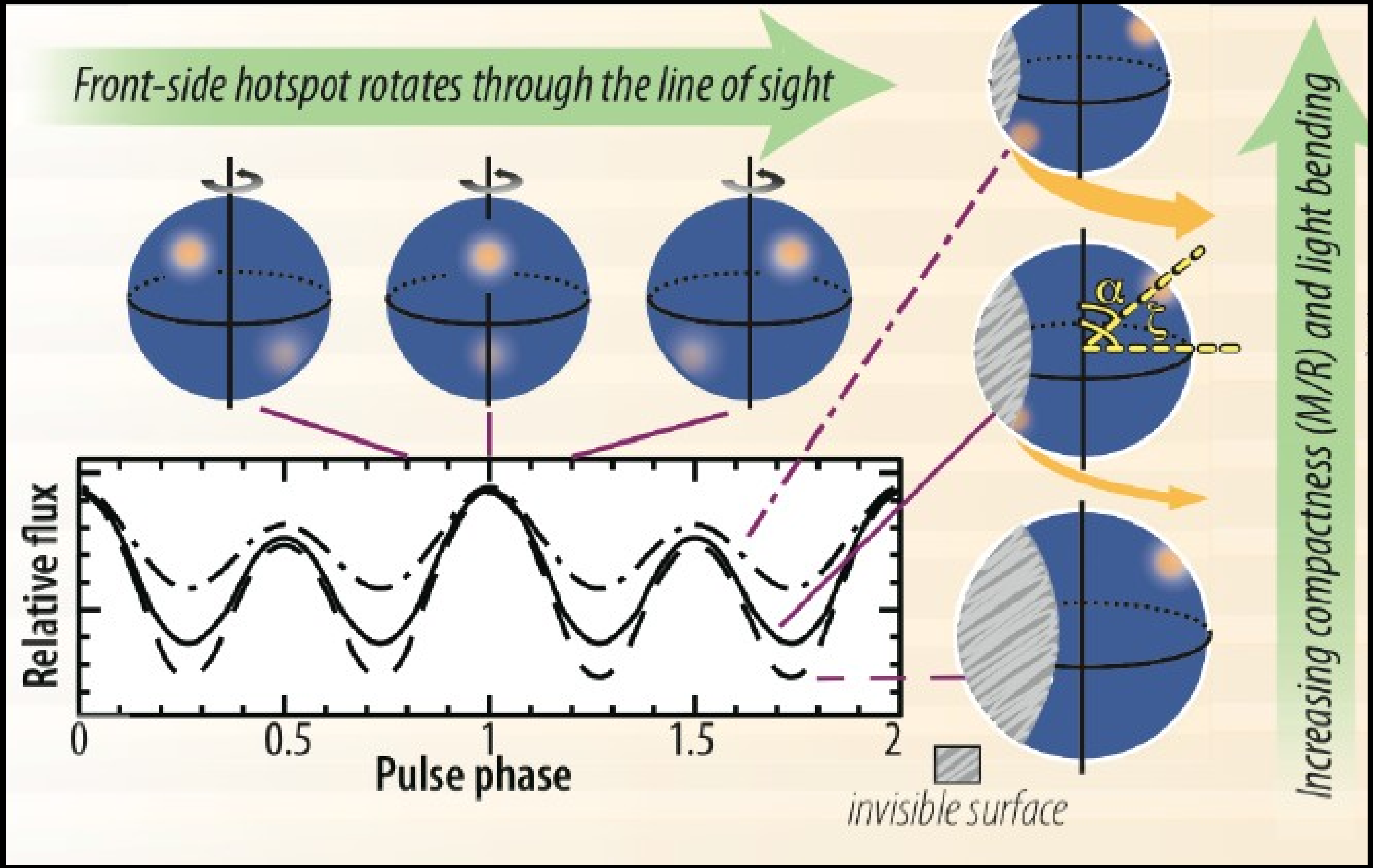
X-ray pulse profiles contain information about the source compactness, mass and radius.

NASA's NICER mission measured the pulse profiles of PSR J0030+0451 and (2 and 3) hot spot models indicate that

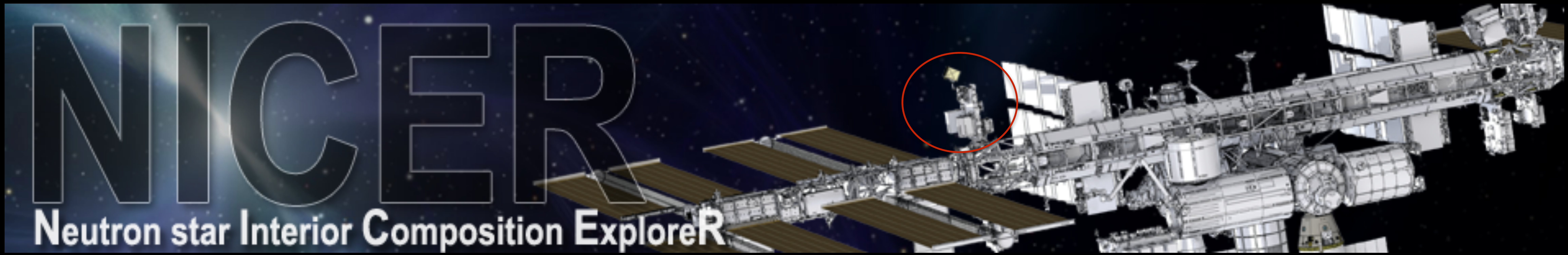
$$M = 1.44^{+0.15}_{-0.14}\ M_\odot \qquad [68\%]$$

$$R = 13.02^{+1.24}_{-1.06}\ \text{km}$$

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



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



GW170817: Gravitational Waves from Neutron Stars!

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

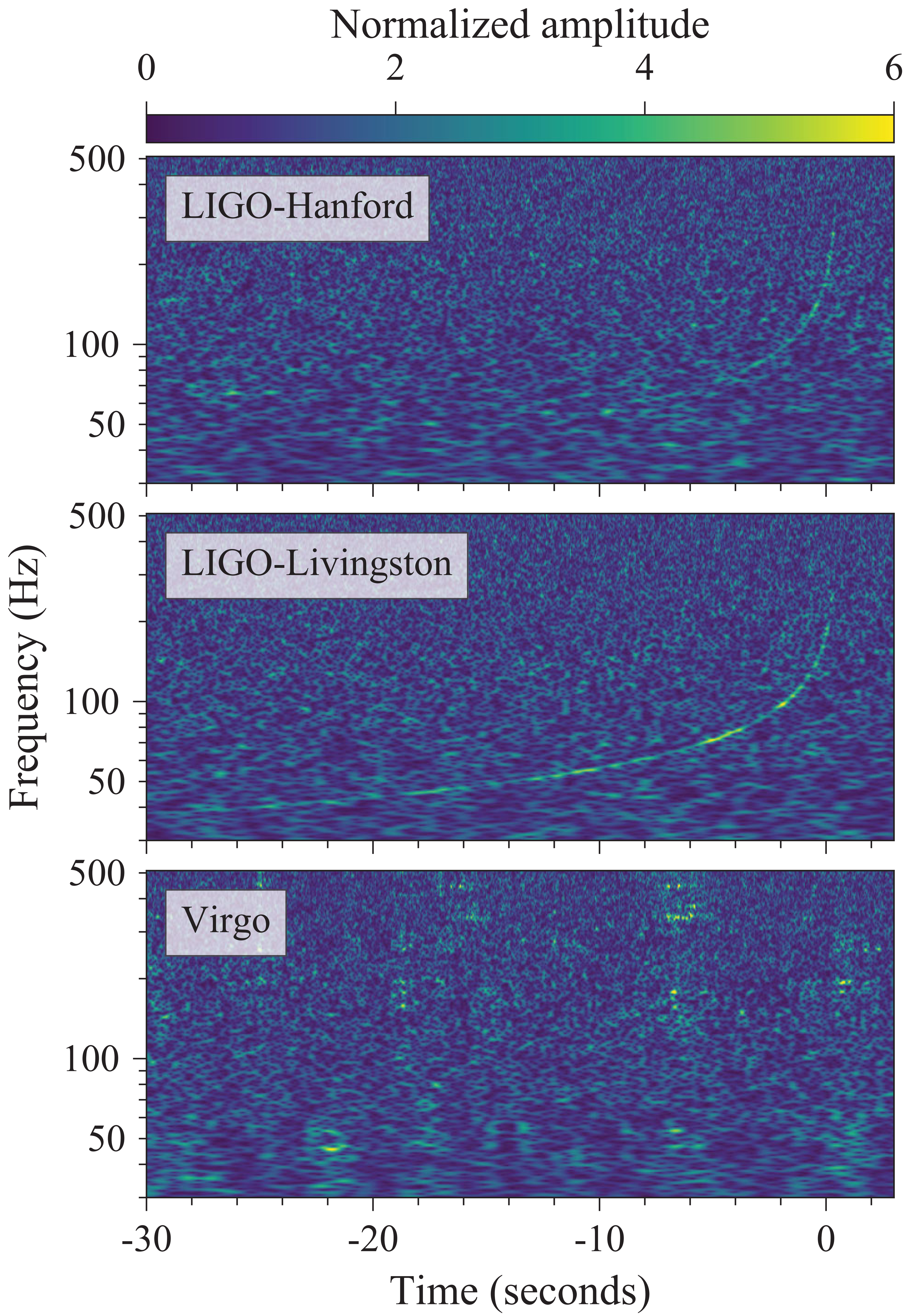
GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral

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

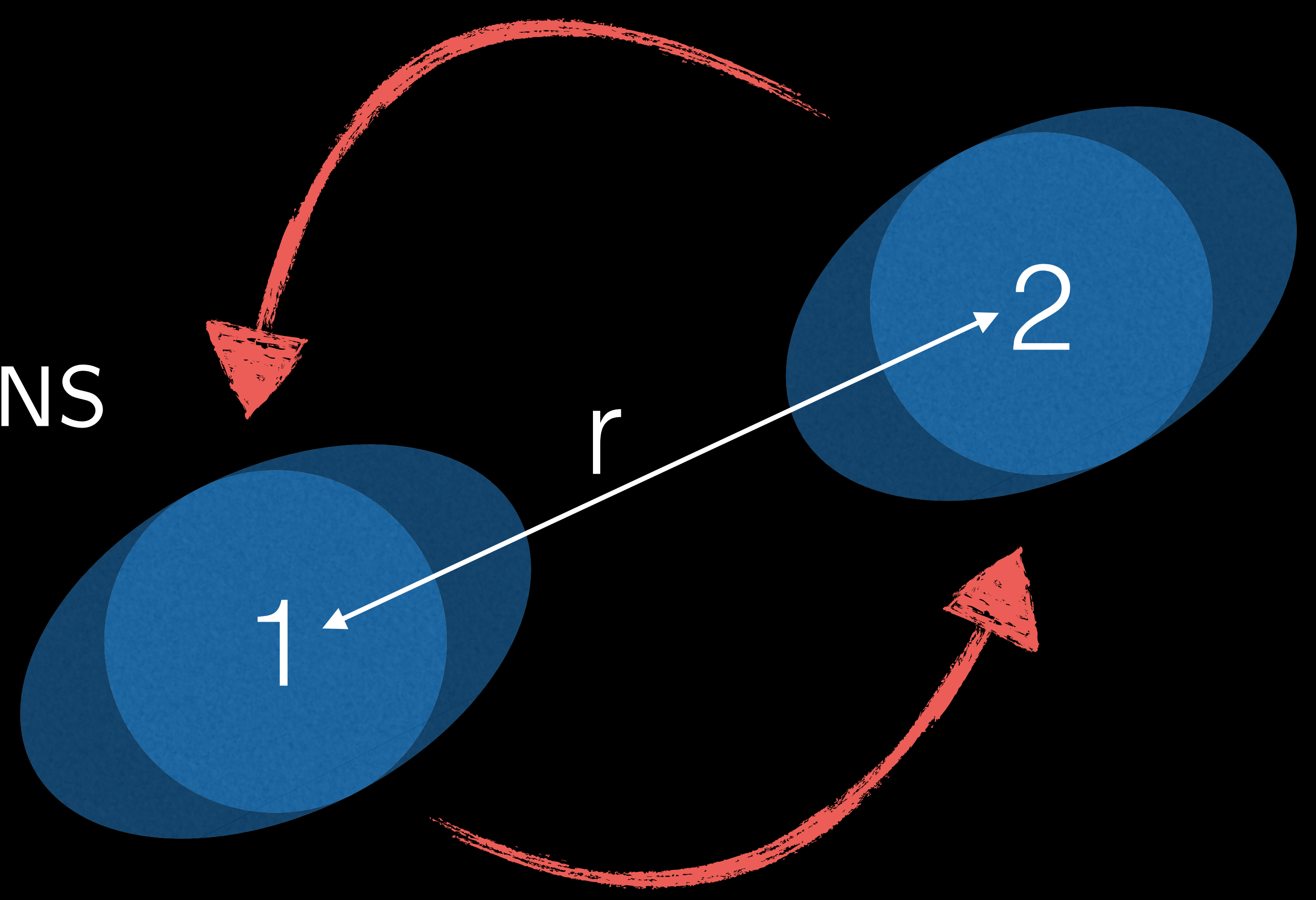
Chirp Mass: $$\mathscr{M} = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_s)^{1/5}} = 1.188^{+0.004}_{-0.002}\ M_\odot$$

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



Tidal Deformation: Measuring the Radius with GWs

$R_{orbit} \lesssim 10\ R_{NS}$



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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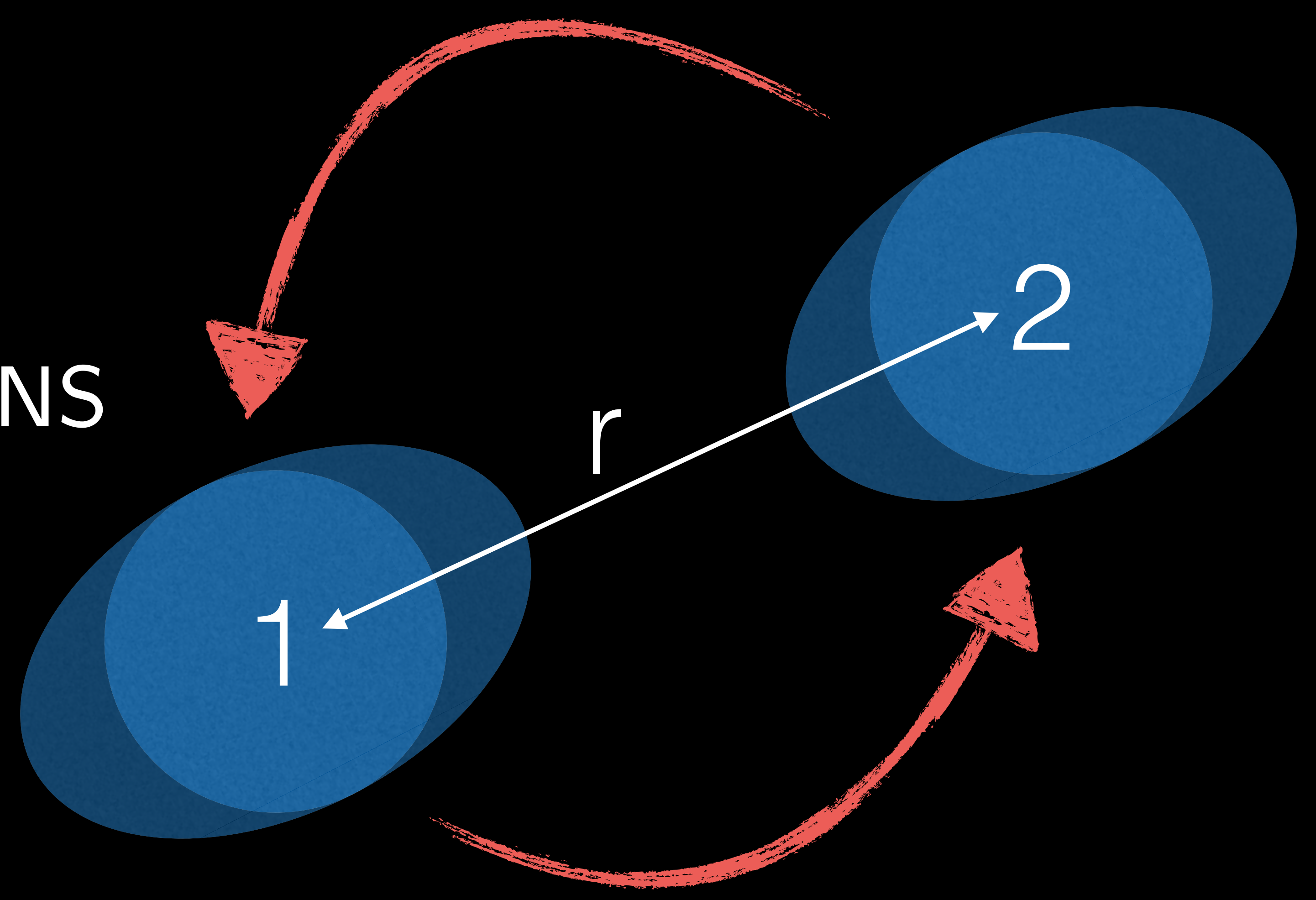

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Tidal interactions change the rotational phase: $\delta\Phi = -\frac{117}{256}\, v^5\, \frac{M}{\mu}\, \tilde{\Lambda}$

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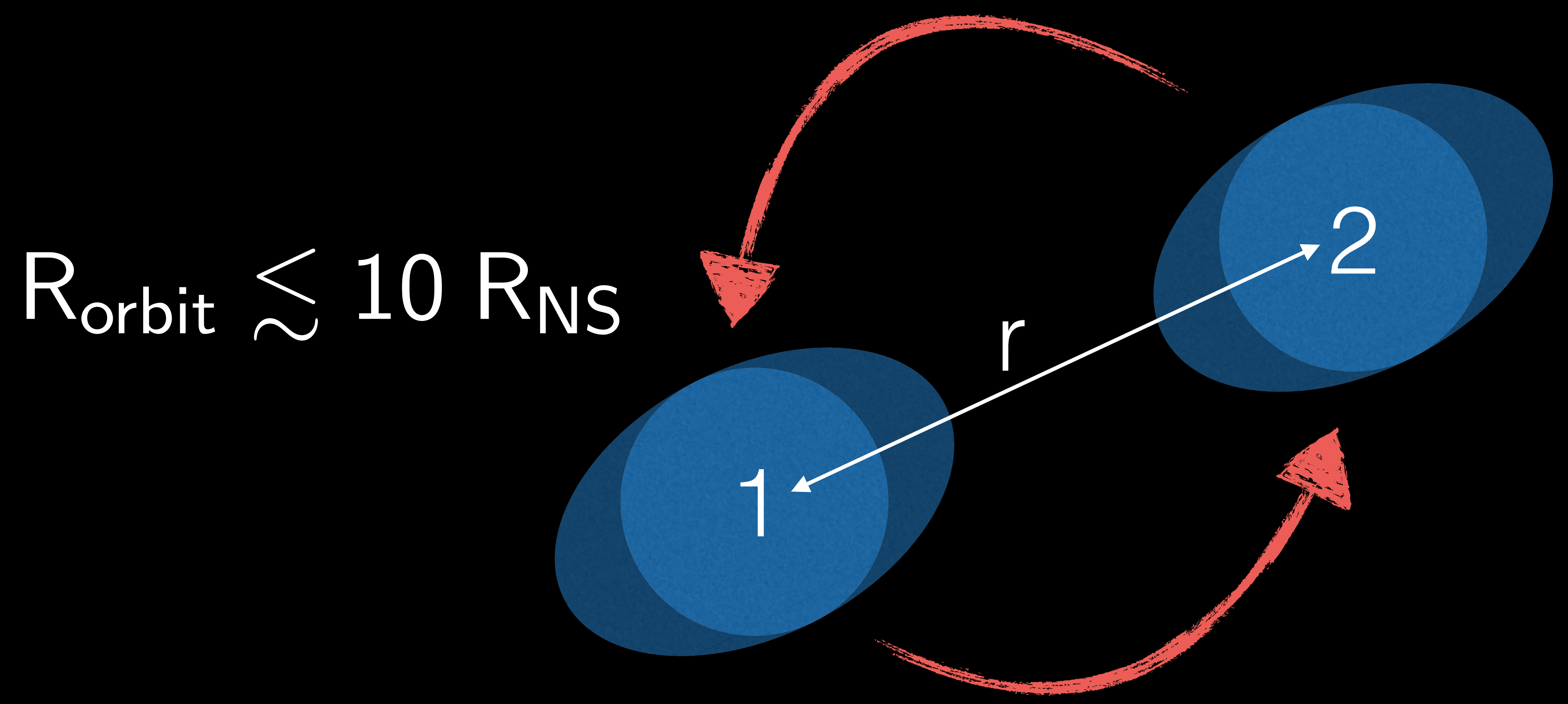

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Dimensionless binary tidal deformability: $\tilde{\Lambda} = \frac{16}{13}\left(\left(\frac{M_1}{M}\right)^5\left(1+\frac{M_2}{M_1}\right)\Lambda_1 + 1 \leftrightarrow 2\right)$

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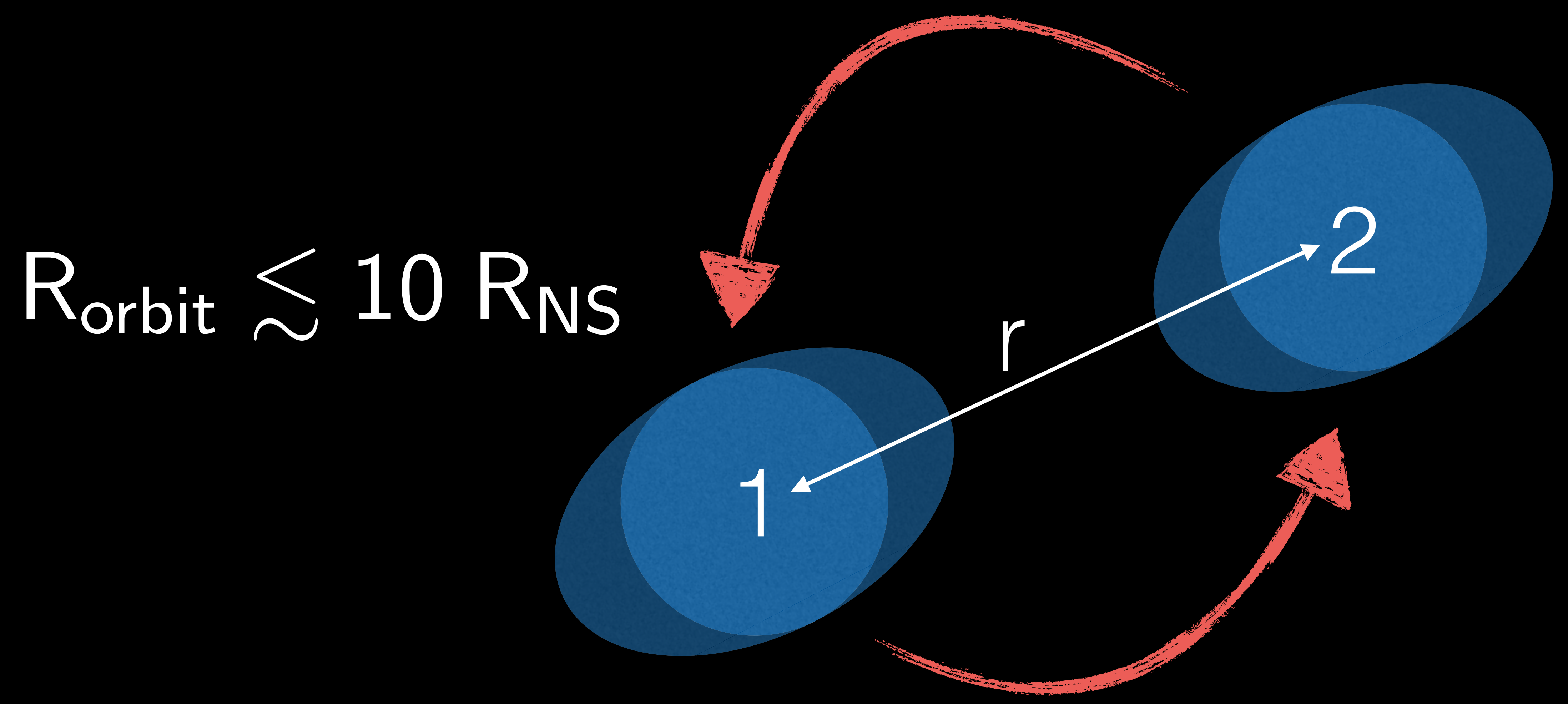

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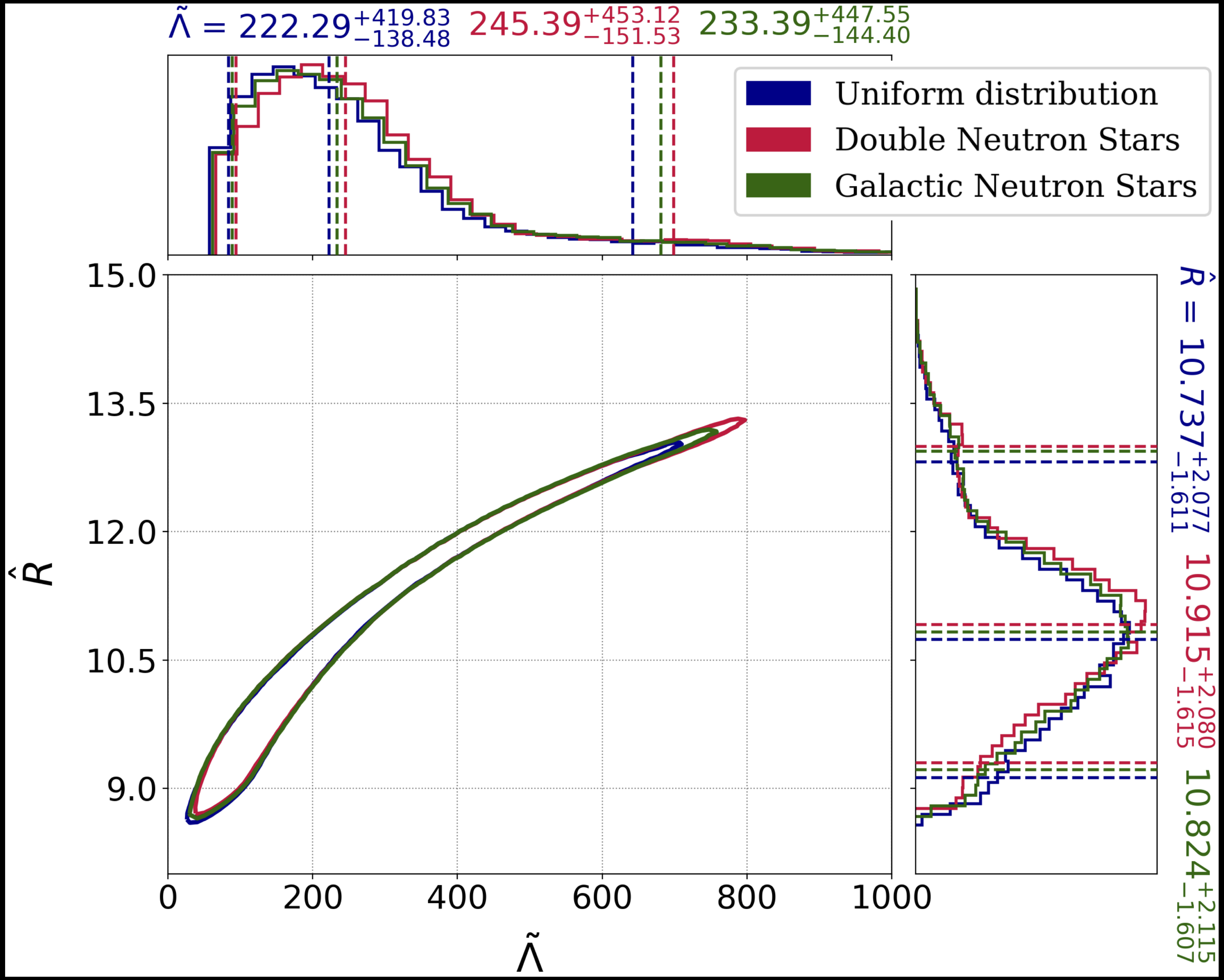
Tidal deformations are large for a large NS: $\Lambda_i = \frac{\lambda_i}{M_i^5} = k_2\frac{R_i^5}{M_i^5}$

Neutron Stars are Small



Tidal deformations (not) observed in GW170817 implies a small NS radius:

R < 13.5 km

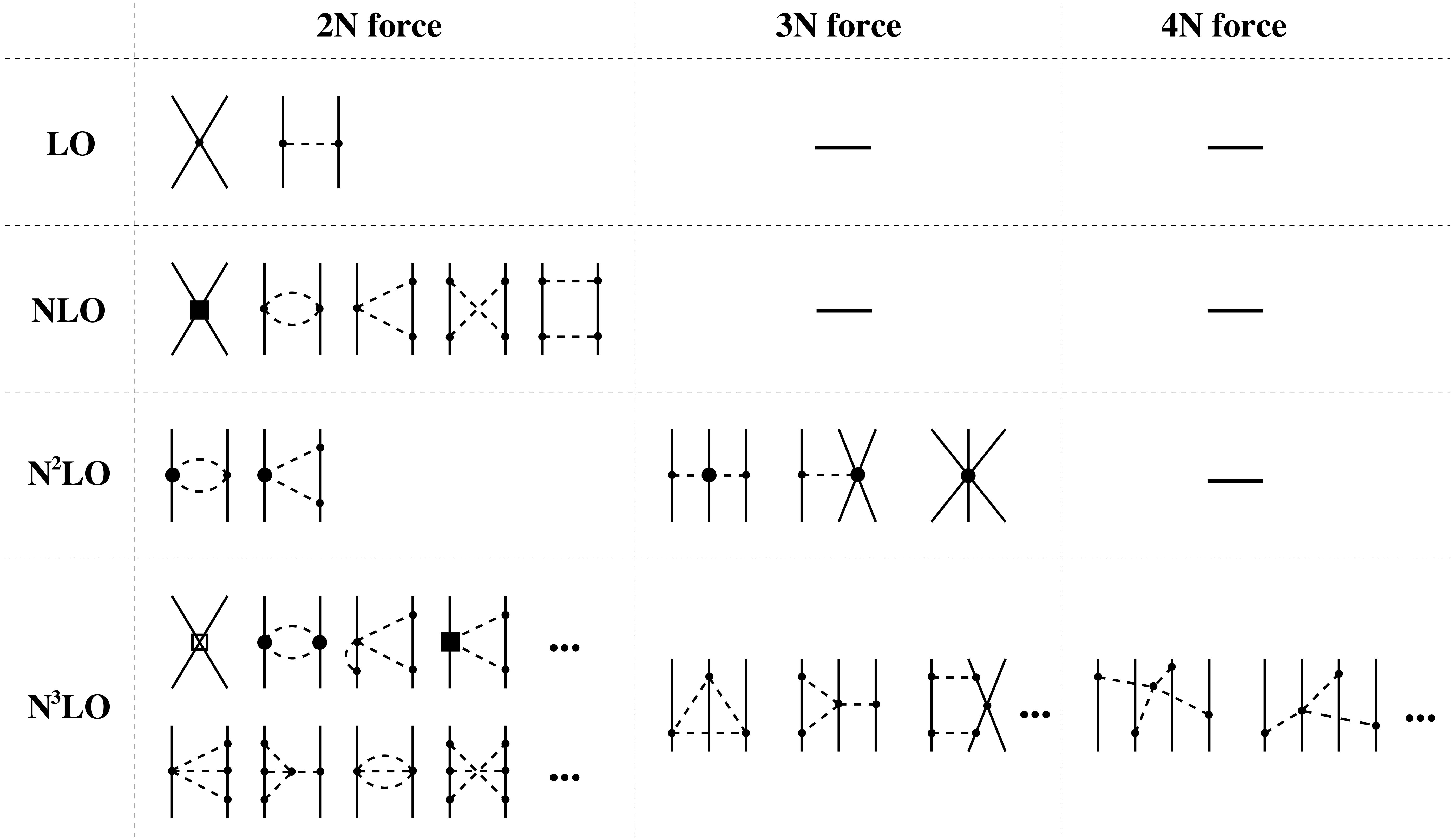
Requiring a maximum mass greater than 2 M_{sun} **implies:**

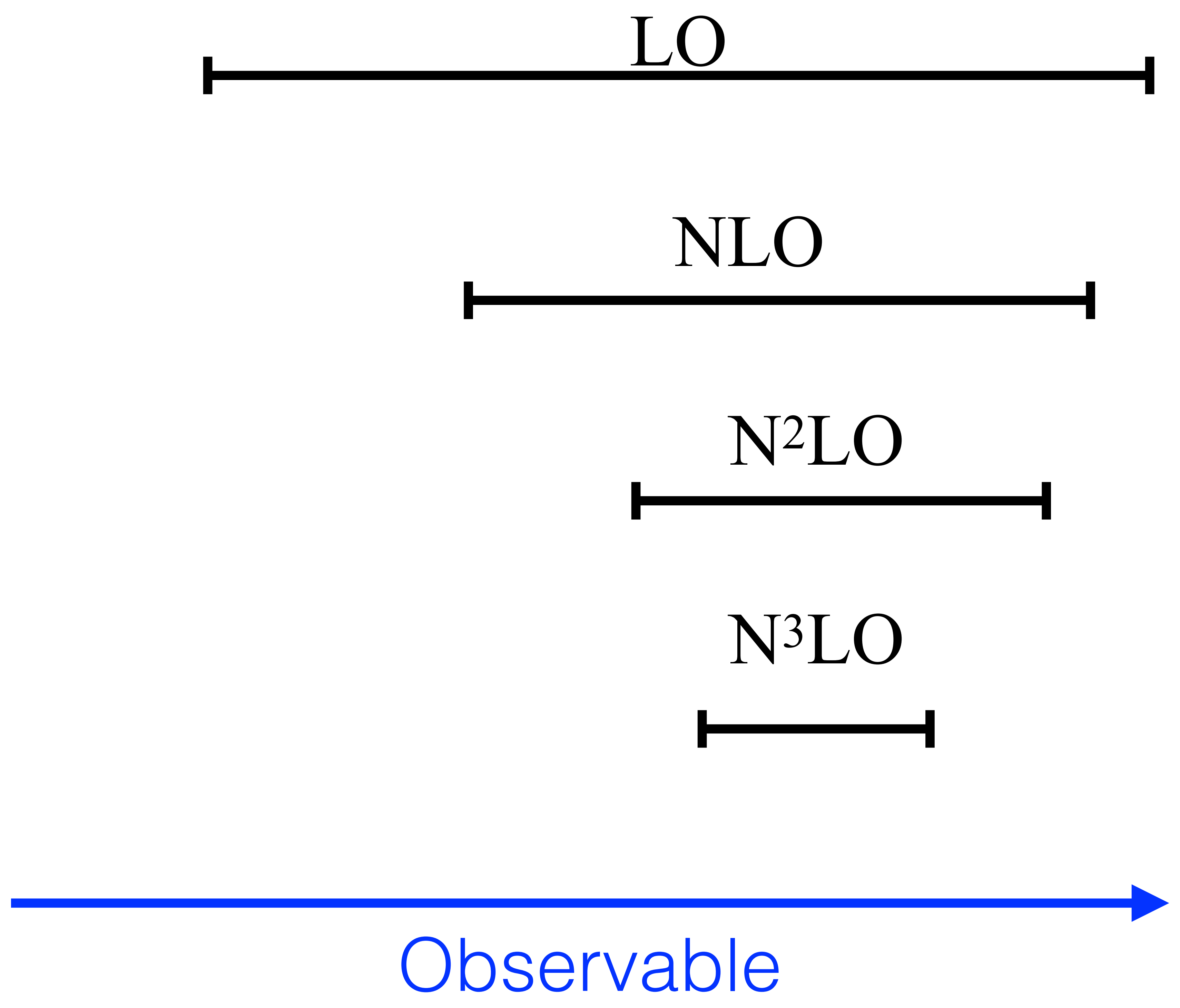
R > 9 km

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

Modern NN & NNN Forces

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





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

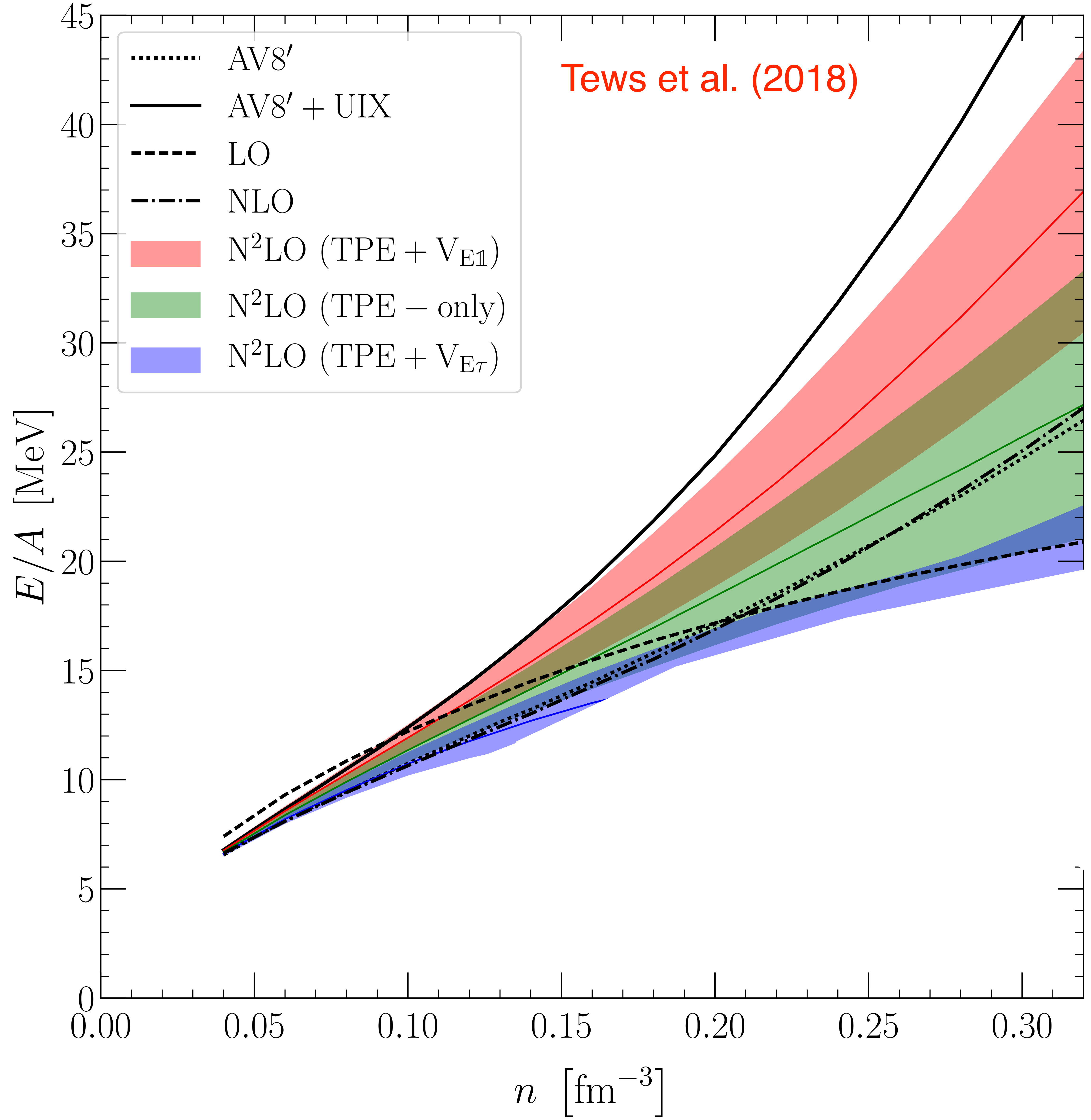
Beane, Bedaque, Epelbaum, Kaplan, Machliedt, Meisner, Phillips, Savage, van Klock, **Weinberg**, Wise ..

Equation of State of Neutron Matter

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

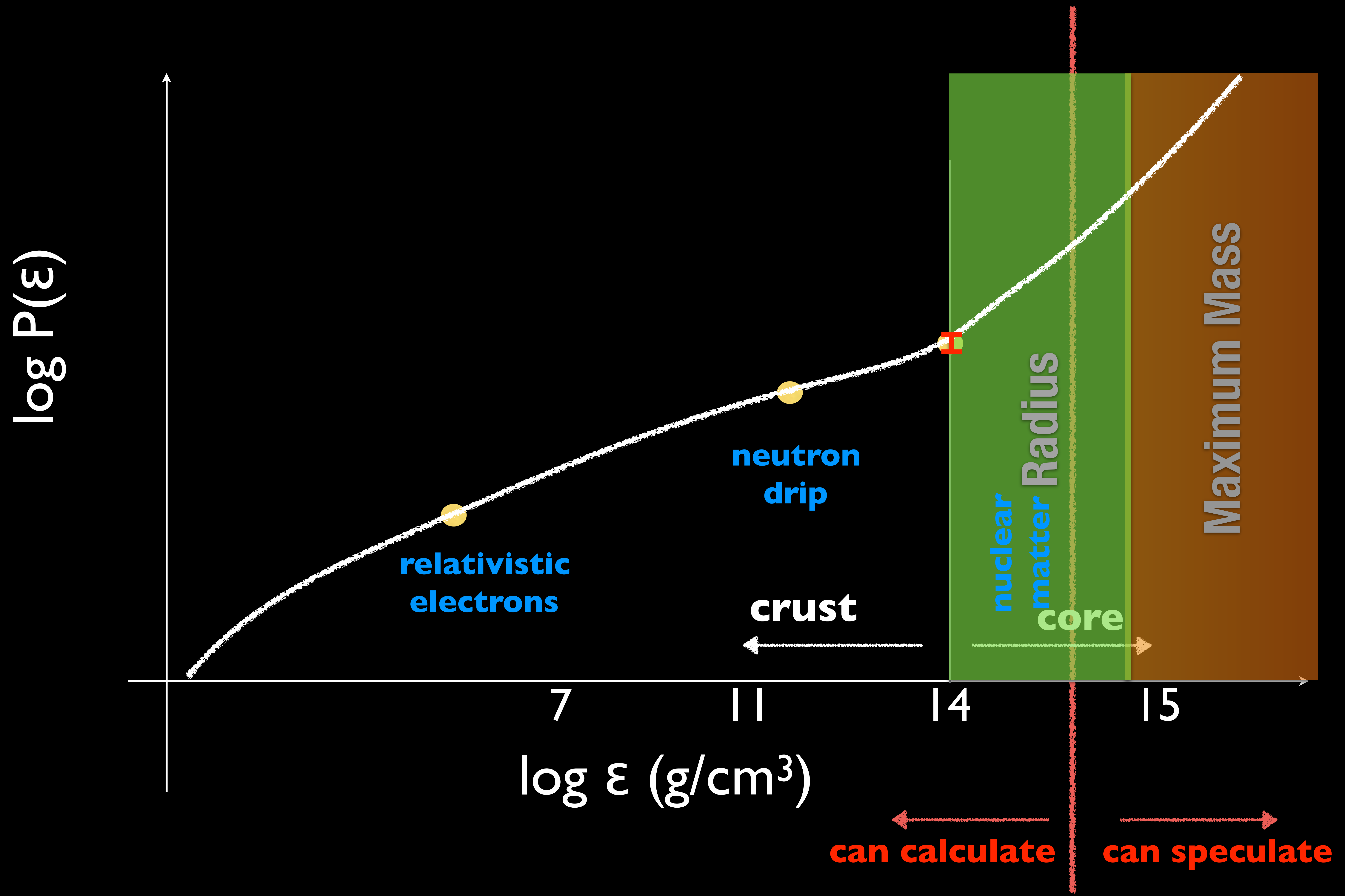
Order-by-order convergence is good at n=0.16 fm^{-3} and reasonable at n=0.32 fm^{-3}.

	n=0.16 fm^{-3}	n=0.32 fm^{-3}
Energy (MeV)	15 ± 3	30 ± 15
Pressure (MeV/fm^{-3})	2.5 ± 1	13 ± 5



Akmal & Pandharipande 1998, Hebeler and Schwenk 2009, Gandolfi, Carlson, Reddy 2010, Tews, Kruger, Hebeler, Schwenk (2013), Holt Kaiser, Weise (2013), Roggero, Mukherjee, Pederiva (2014), Wlazlowski, Holt, Moroz, Bulgac, Roche (2014), Tews et al. (2018)

Constraints on the Equation of State



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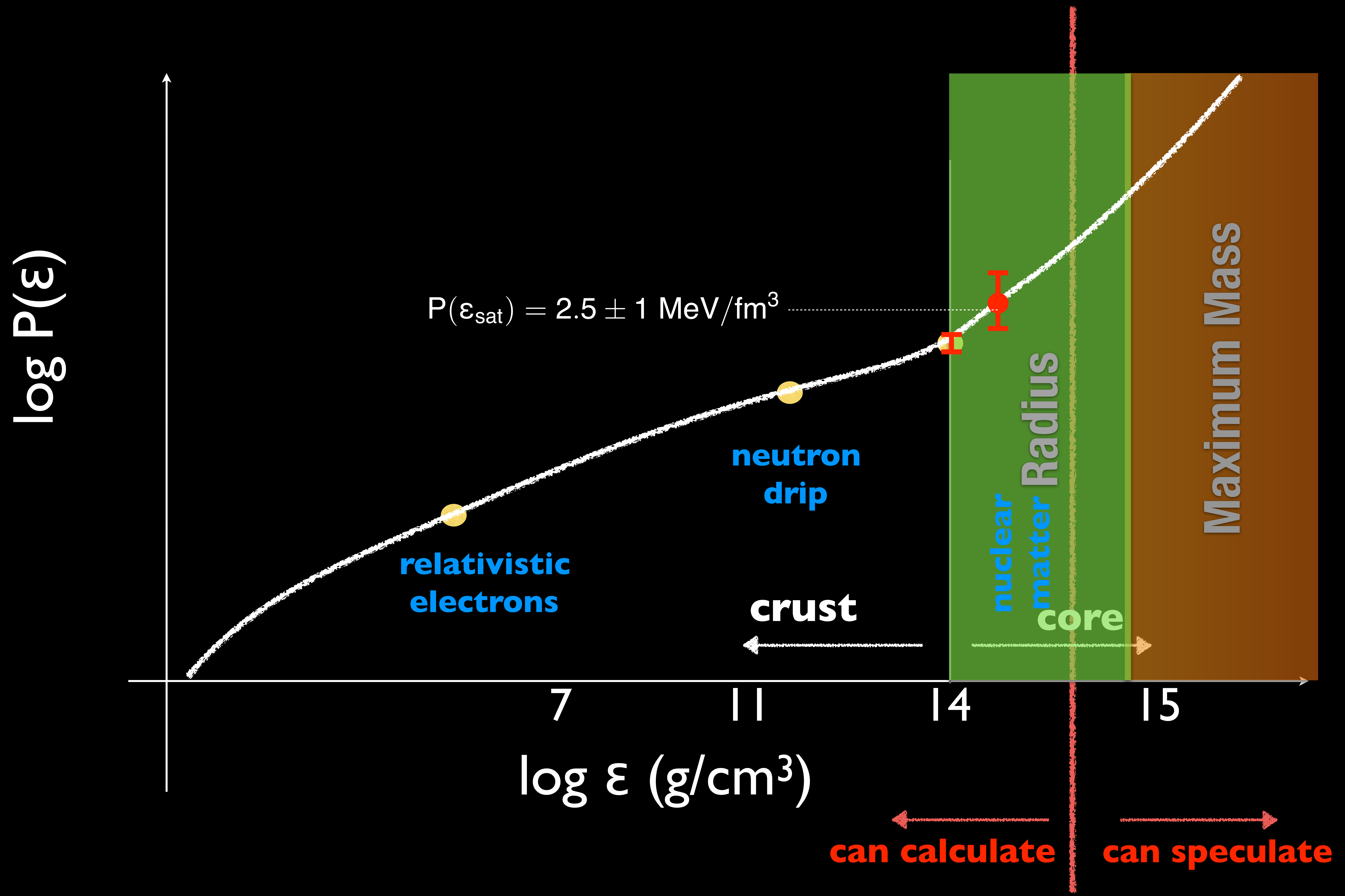

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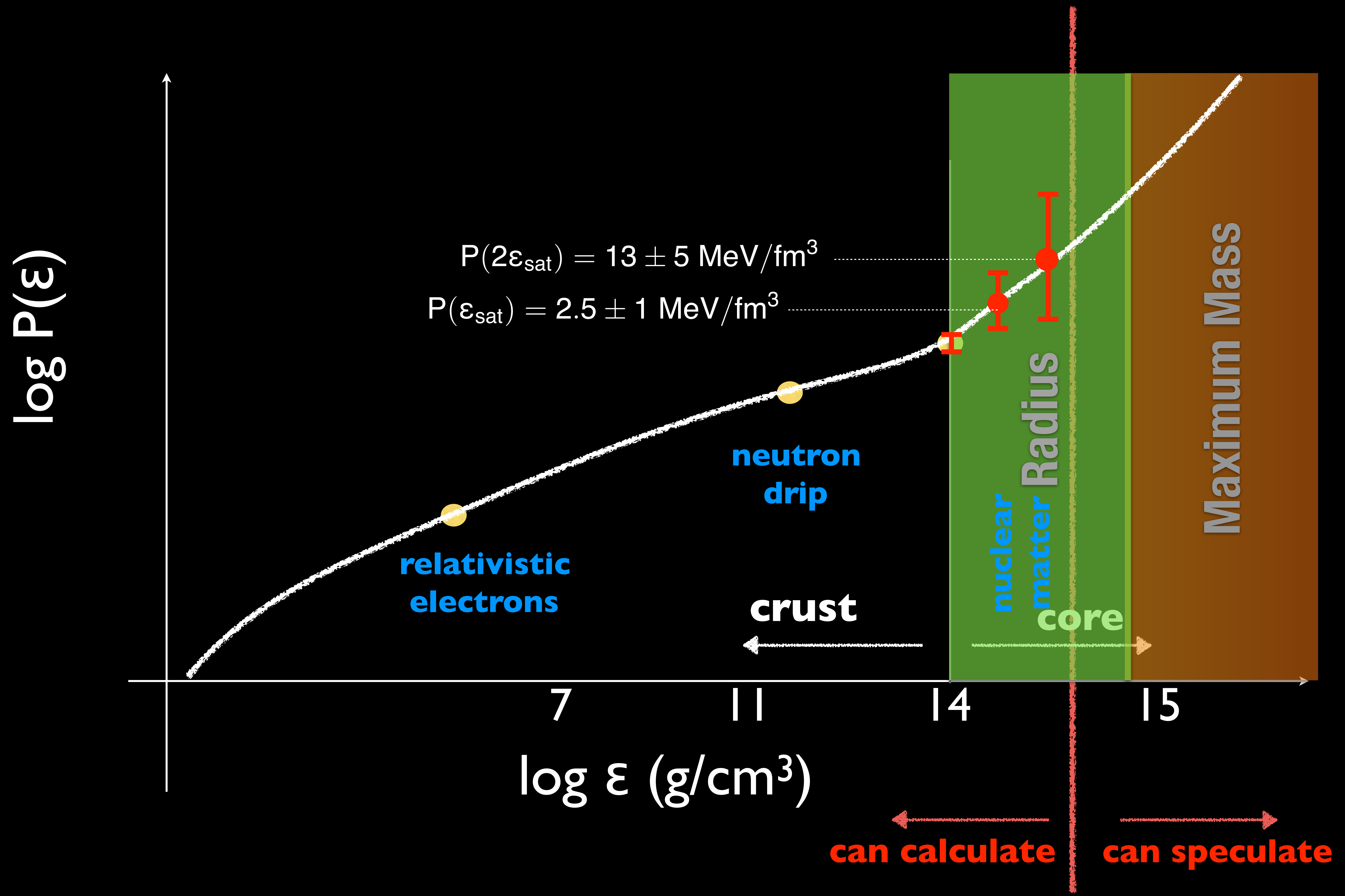

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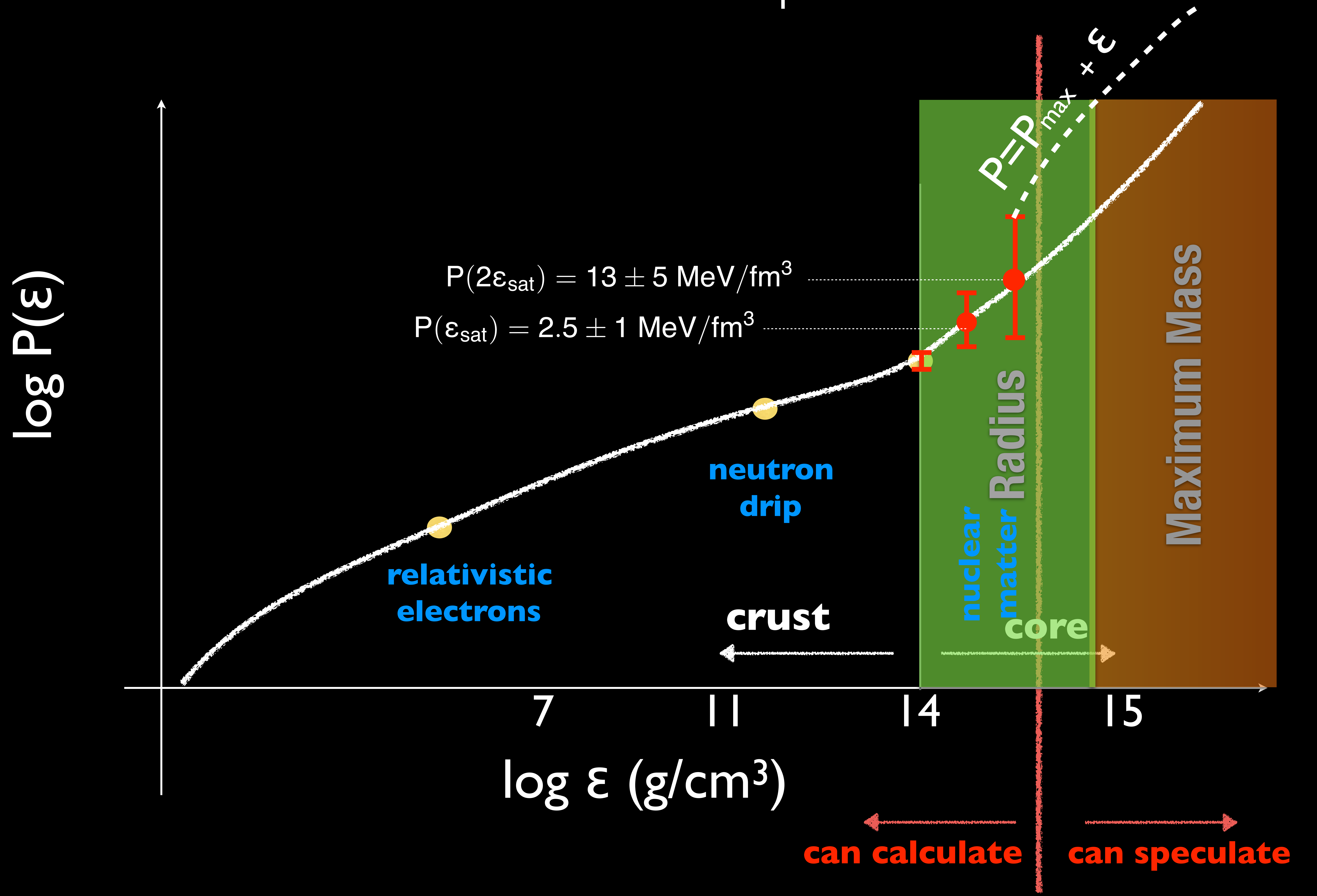

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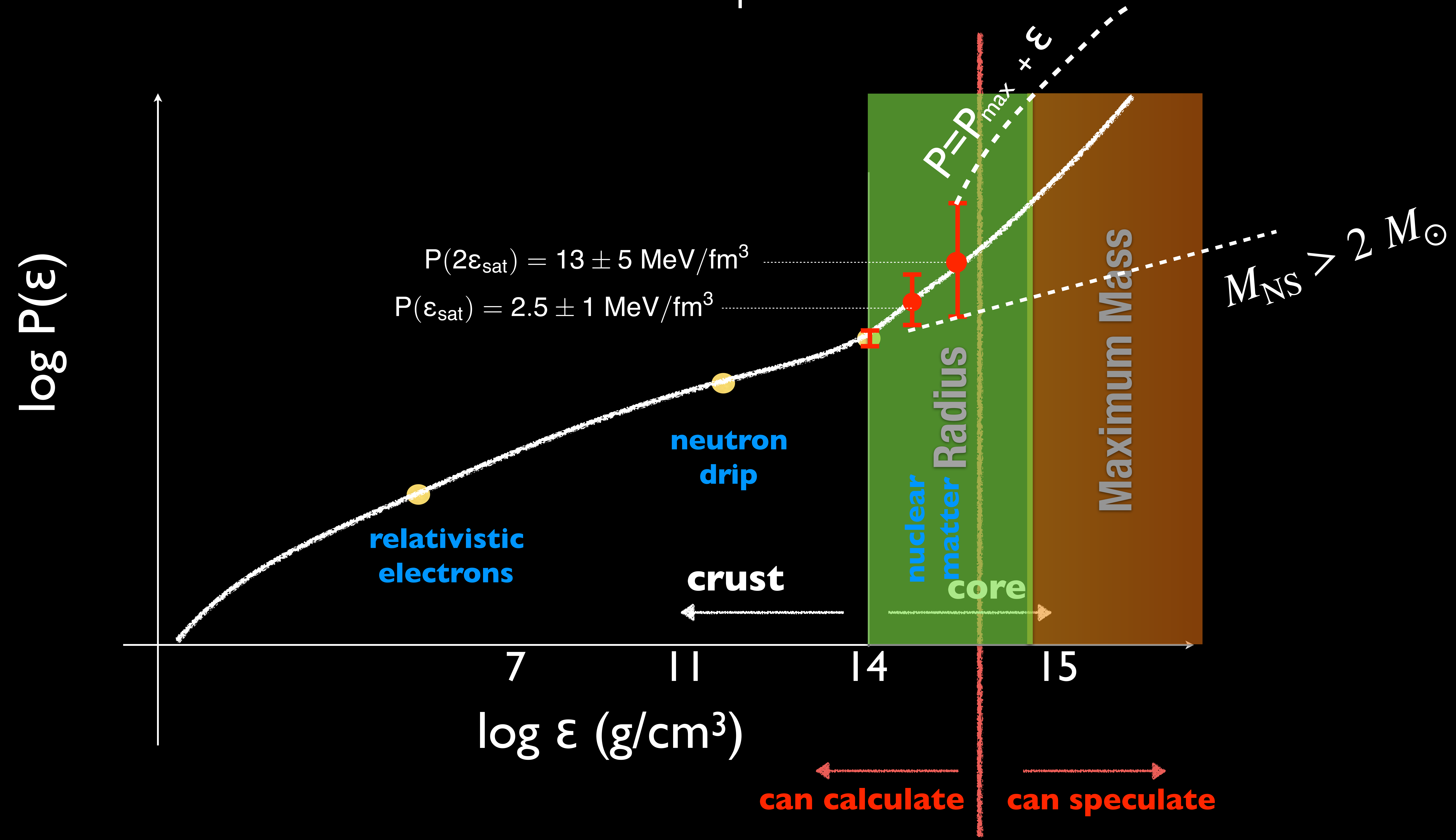
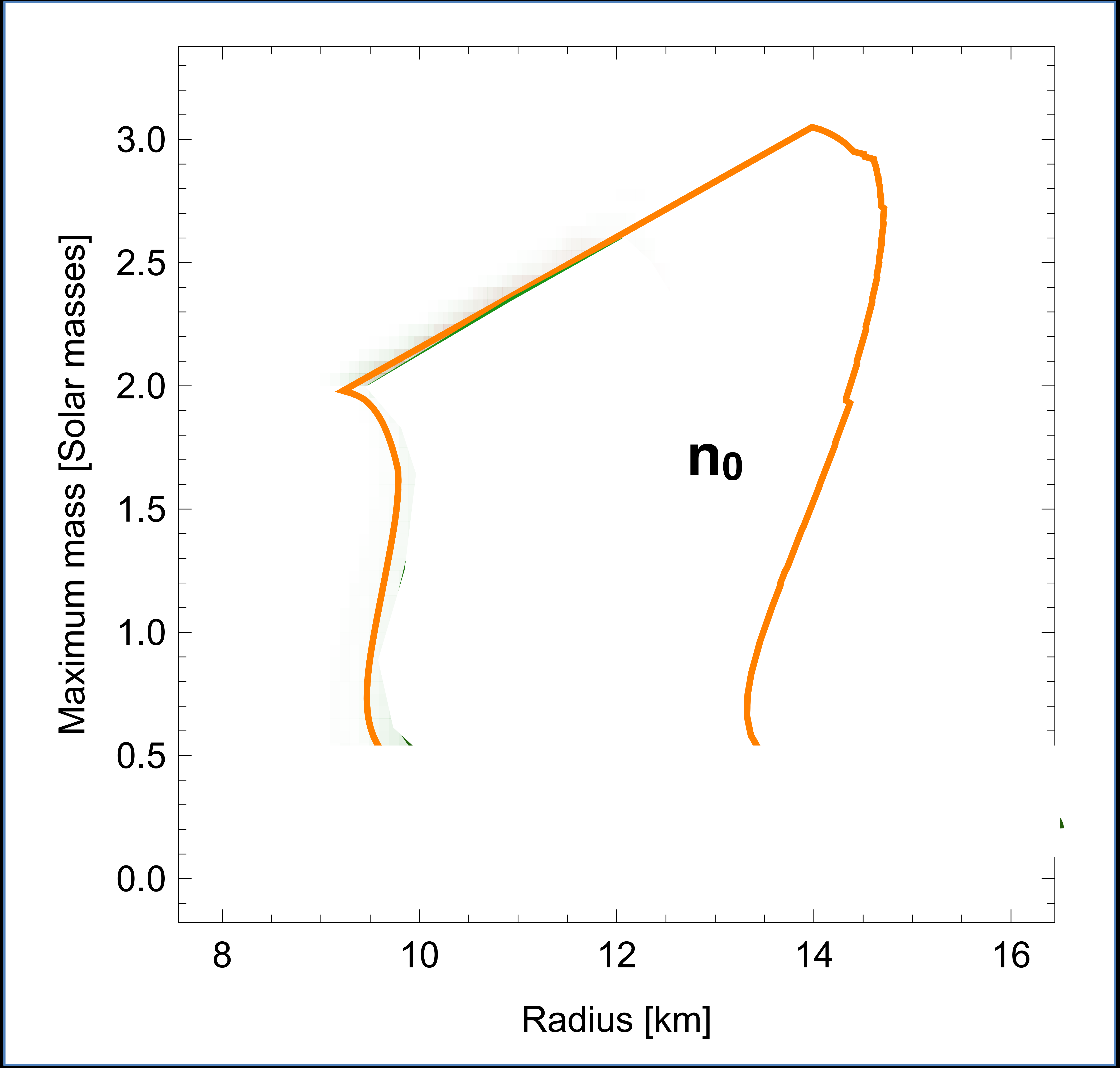


Dense matter EOS and NS structure

Neutron matter calculations and a general parameterization of the sound speed at higher density, constrained by 2 solar mass NS and $c_s < c$, provides robust bounds for NS structure.



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

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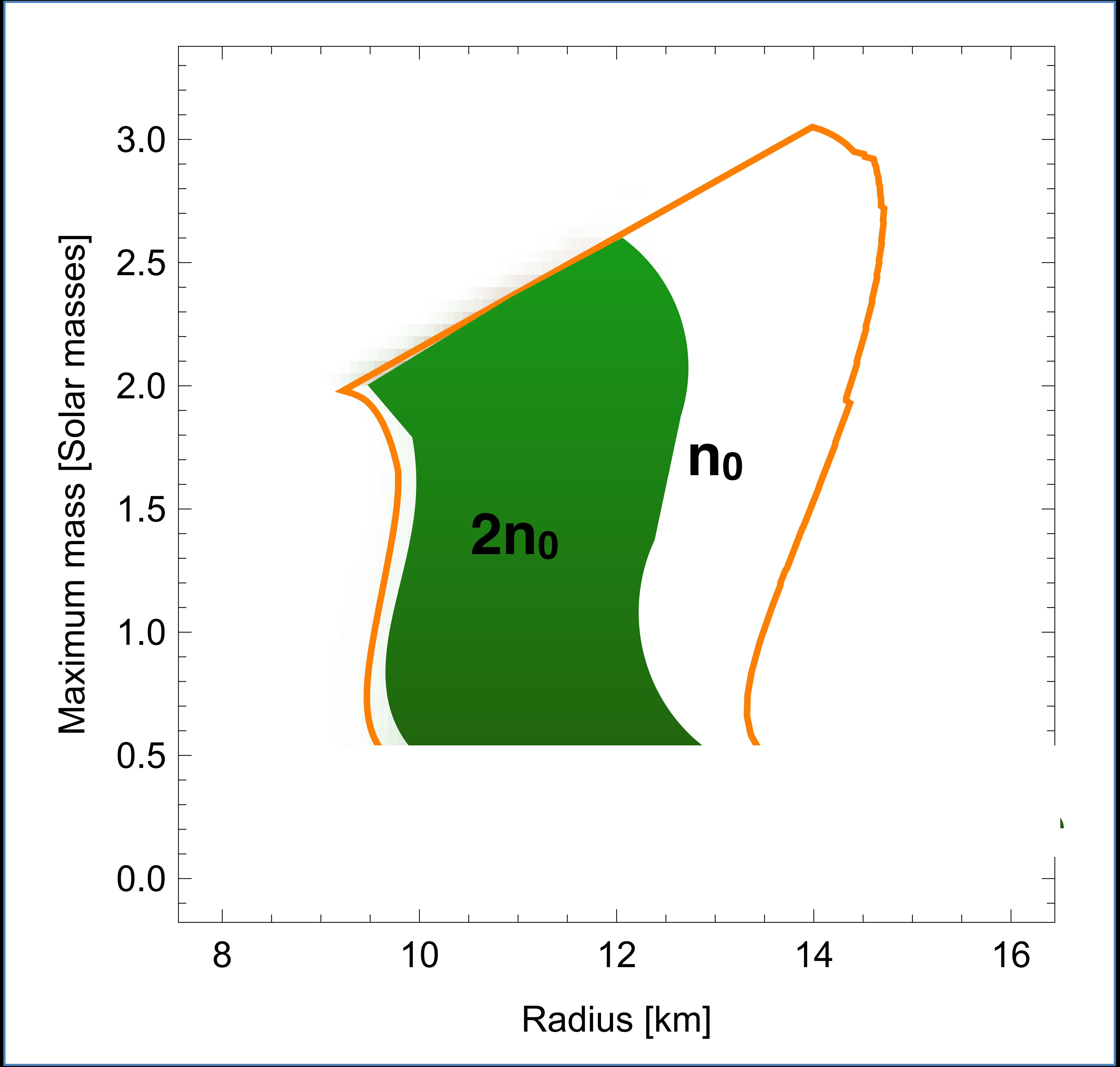

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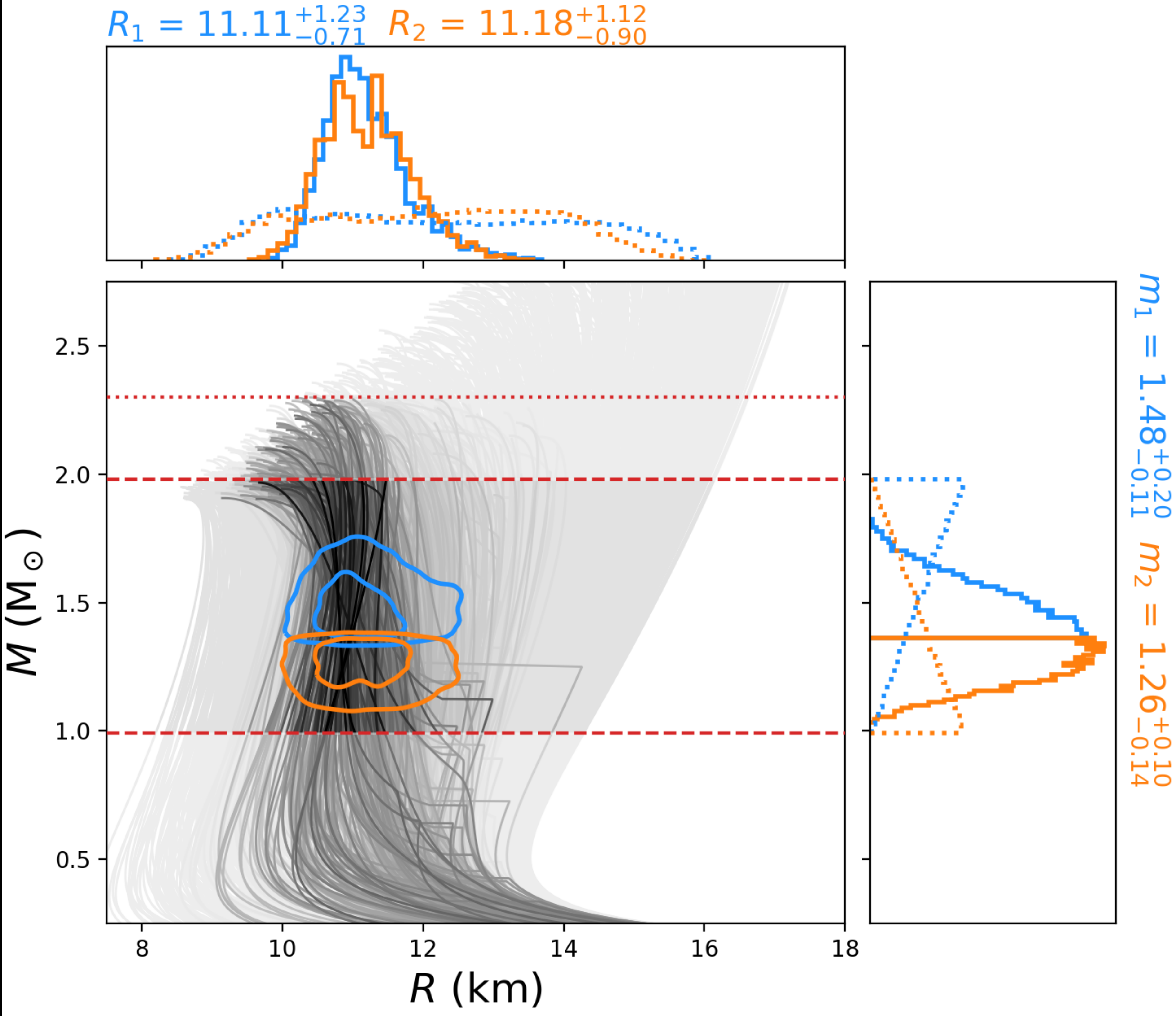
Tighter Constraints: Combining Nuclear Physics and GW170817

GW data analysis that includes nuclear physics input (up to n_0, with errors) to correlate the neutron stars in the binary provides a stringent constraint on the NS radius: Capano et al. (2019)

$$R_{1.4} = 11.2^{+1.2}_{-0.8}\ \text{km}$$

Lower bound is set by EM observations that disfavor the prompt collapse to a black-hole. Bauswein & Stergioulas (2015)



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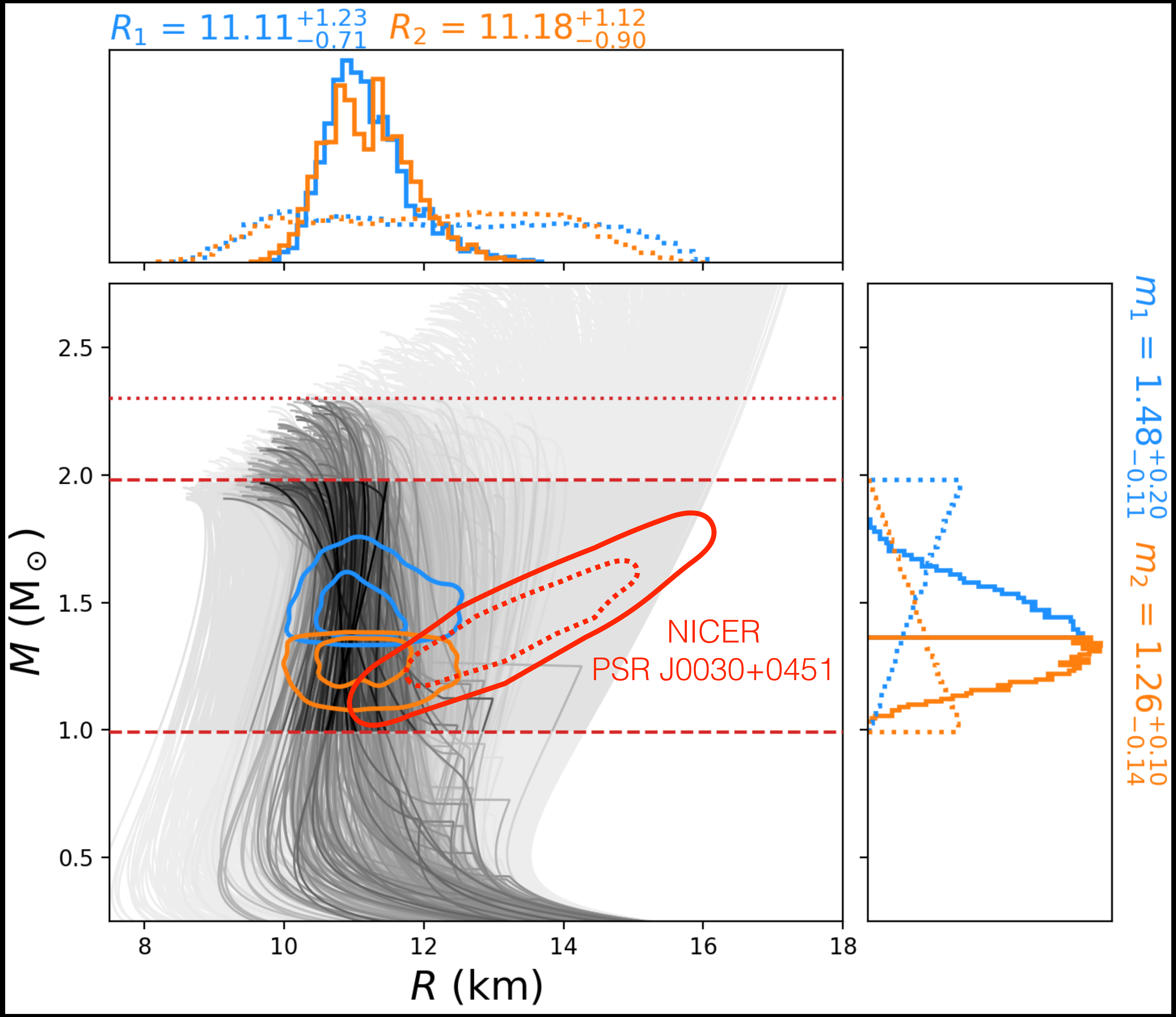

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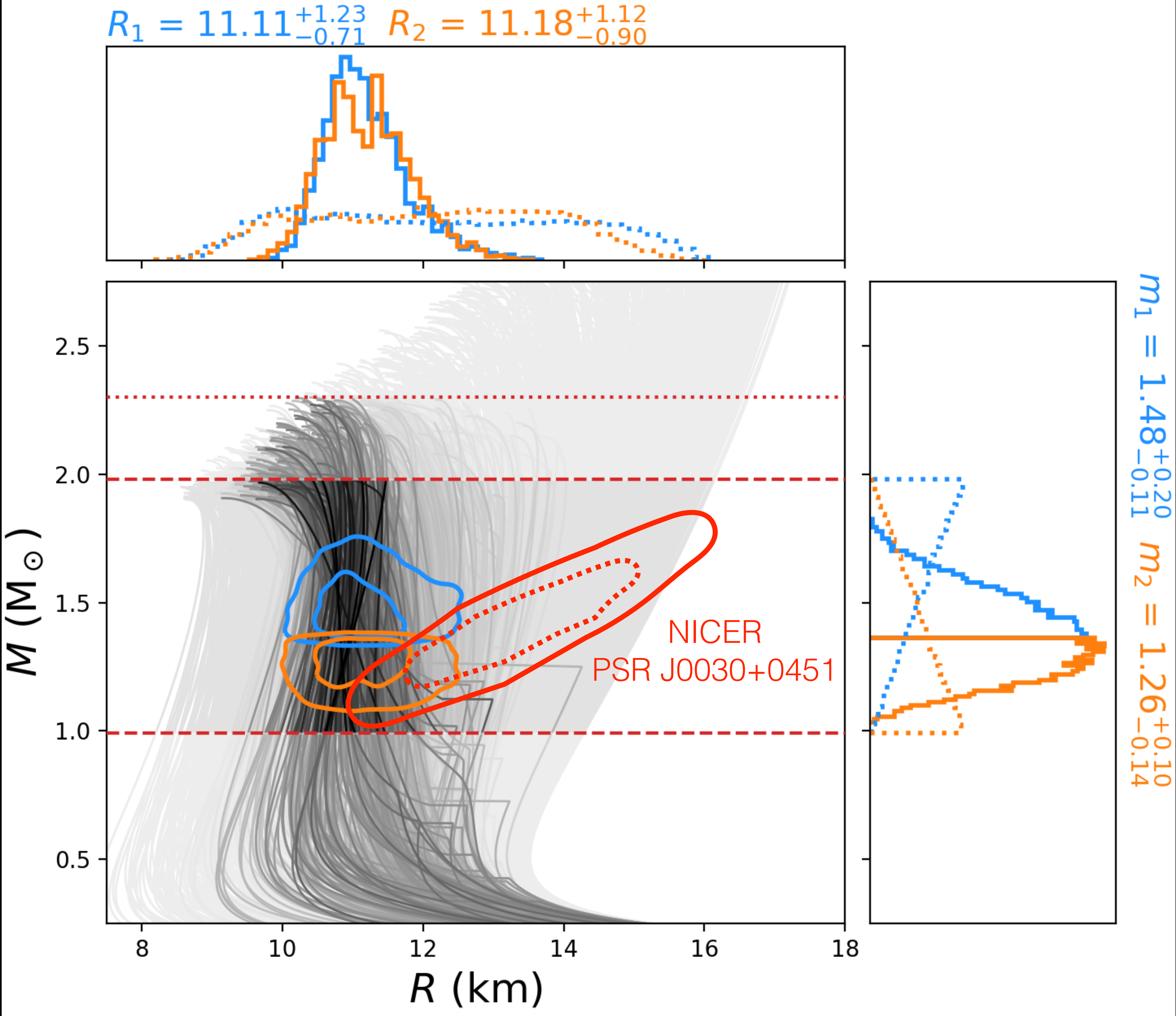
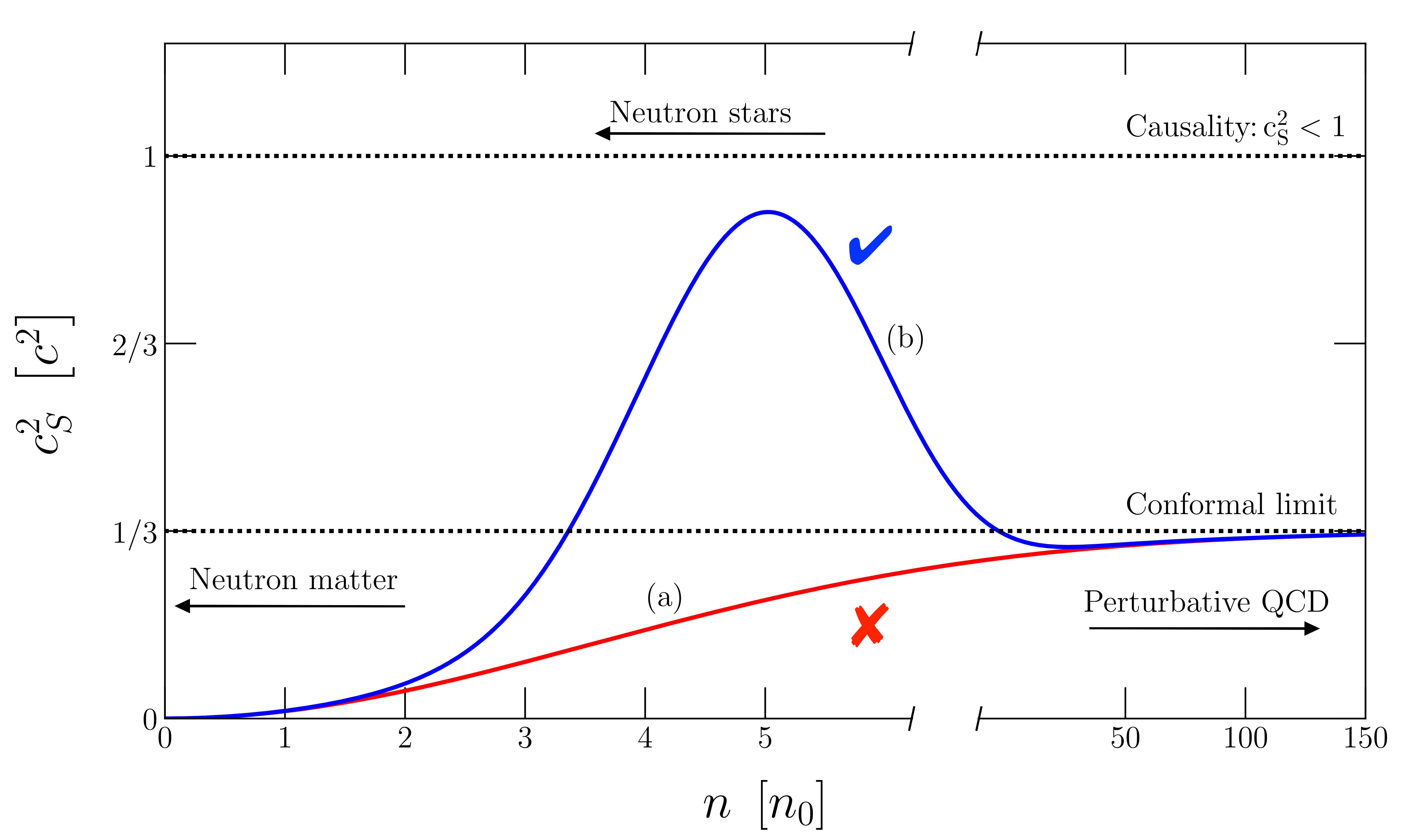
Systematic Errors?



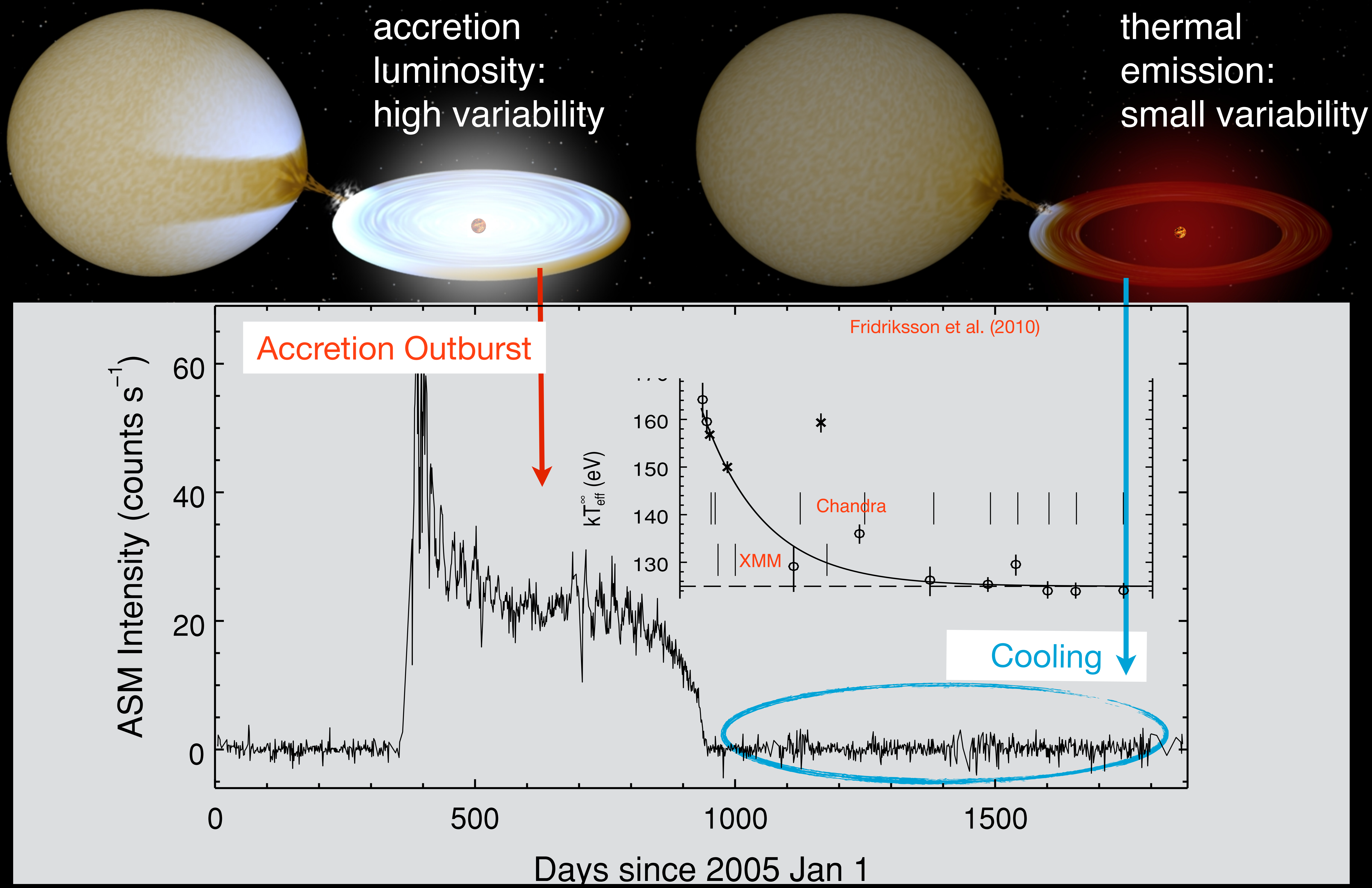
Speed of Sound in Dense Matter

Large observed maximum mass combined with small radius and neutron matter calculations suggests a rapid increase in pressure in the neutron star core. Implies a large and non-monotonic sound speed in dense QCD matter.



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

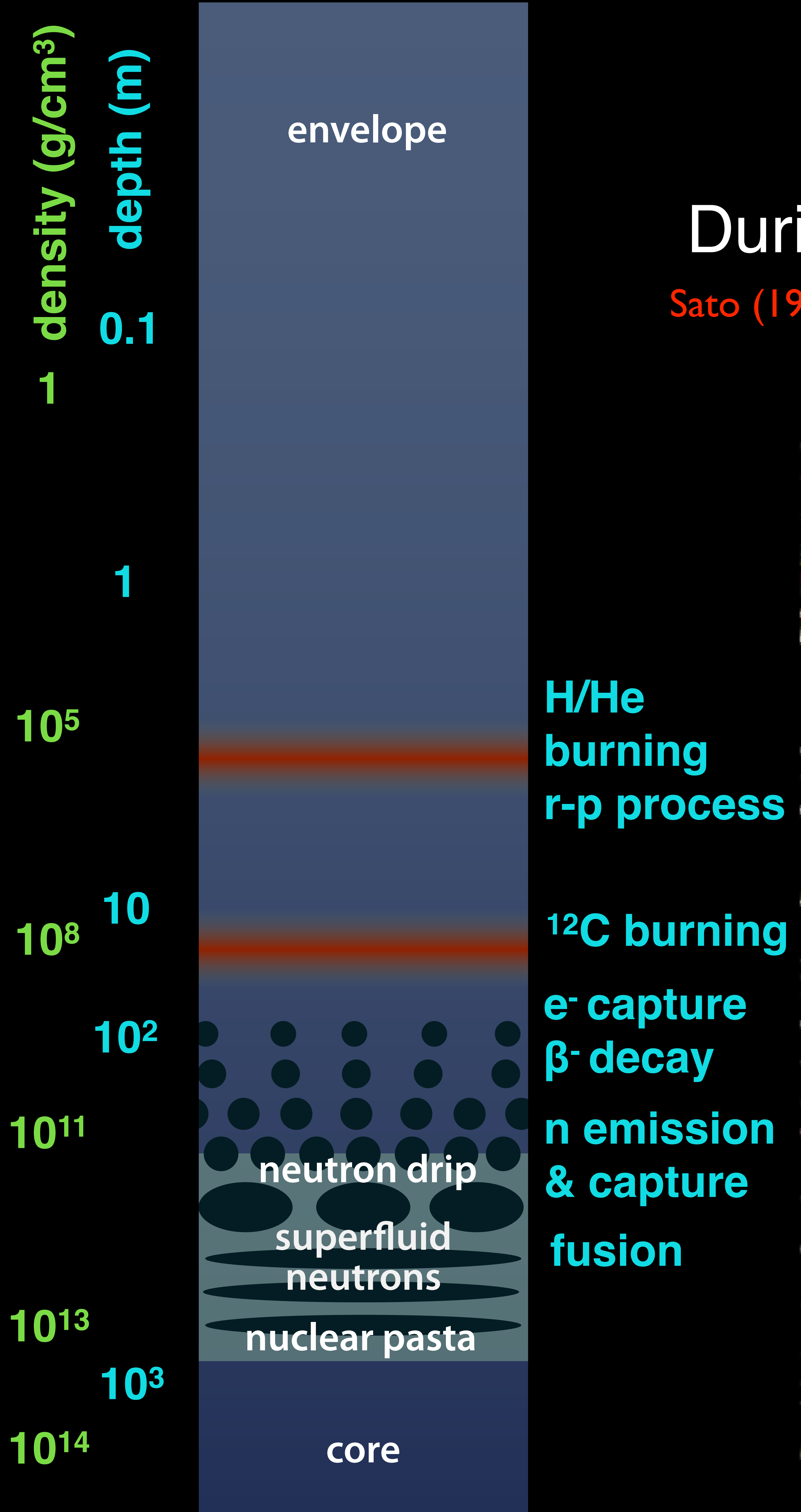
Transiently Accreting Neutron Stars



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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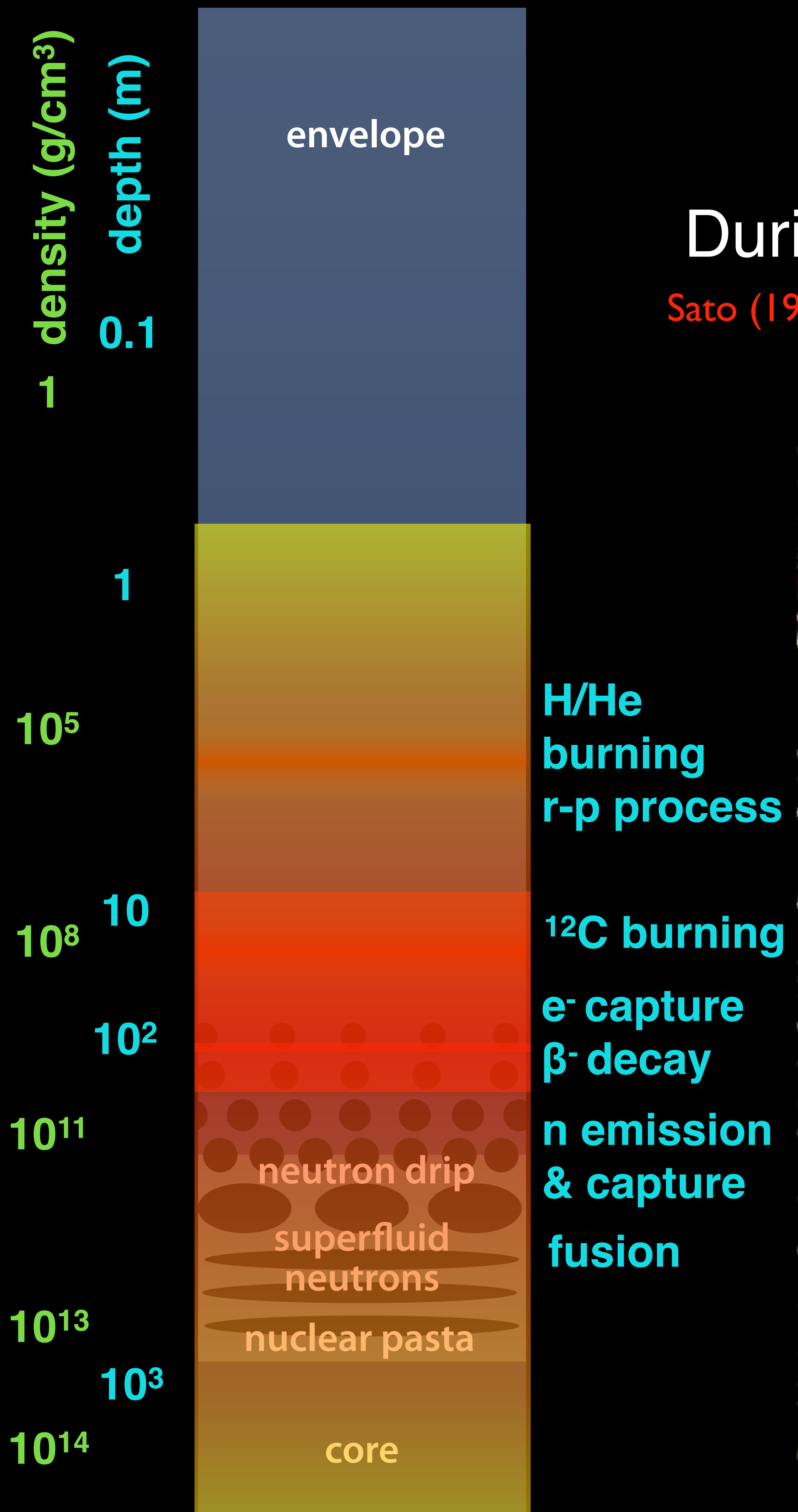


Cooling Post Accretion

- This relaxation was first discovered in 2001 and 6 sources have been studied to date.

- All known Quasi-persistent sources show cooling after accretion

- Cools on a time scale of ~1000 days.

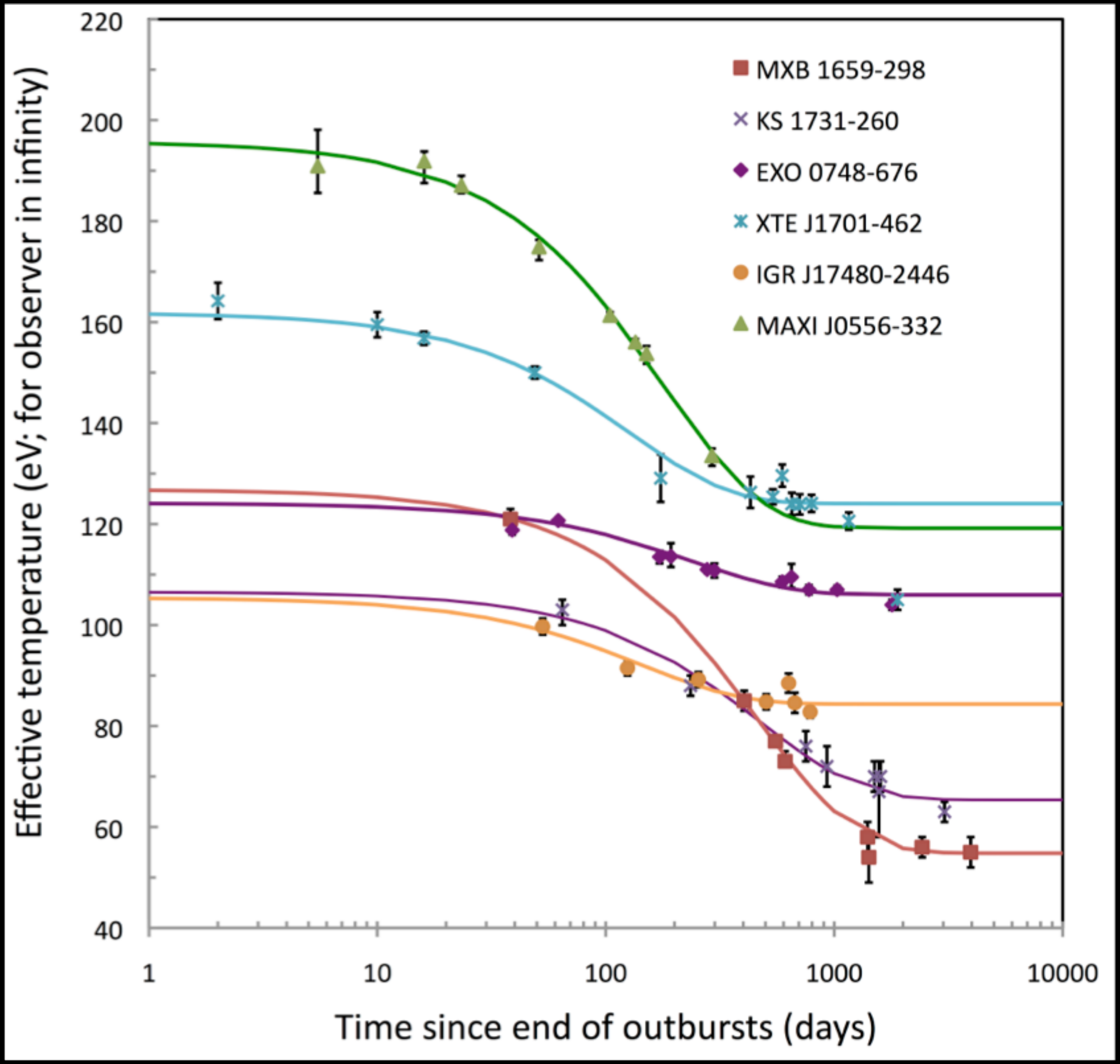
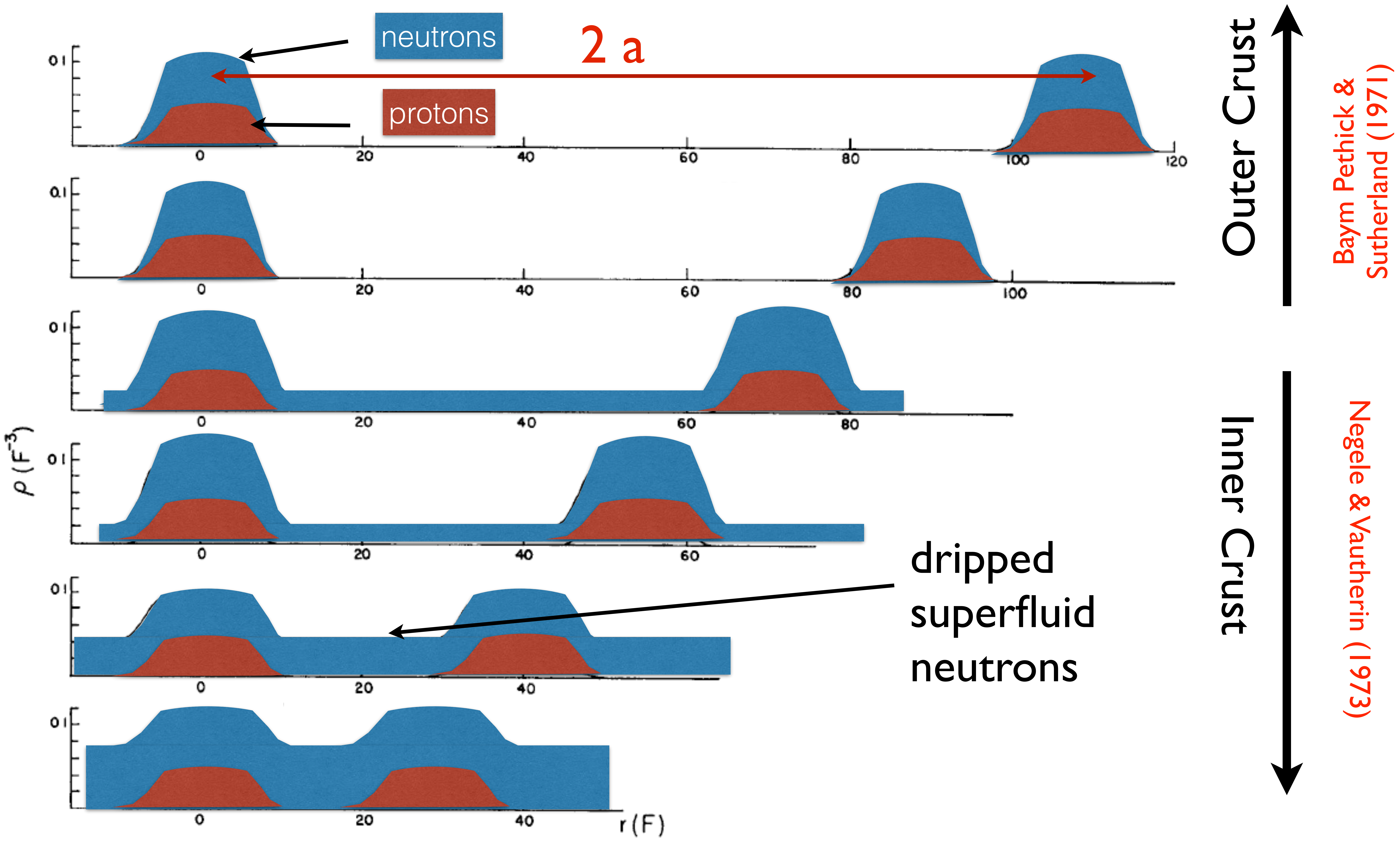


Figure from Rudy Wijnands (2013)

Low Energy Theory for the Neutron Star Crust



Cirigliano, Reddy & Sharma (2011), Page & Reddy (2012), Chamel, Page, & Reddy (2013)

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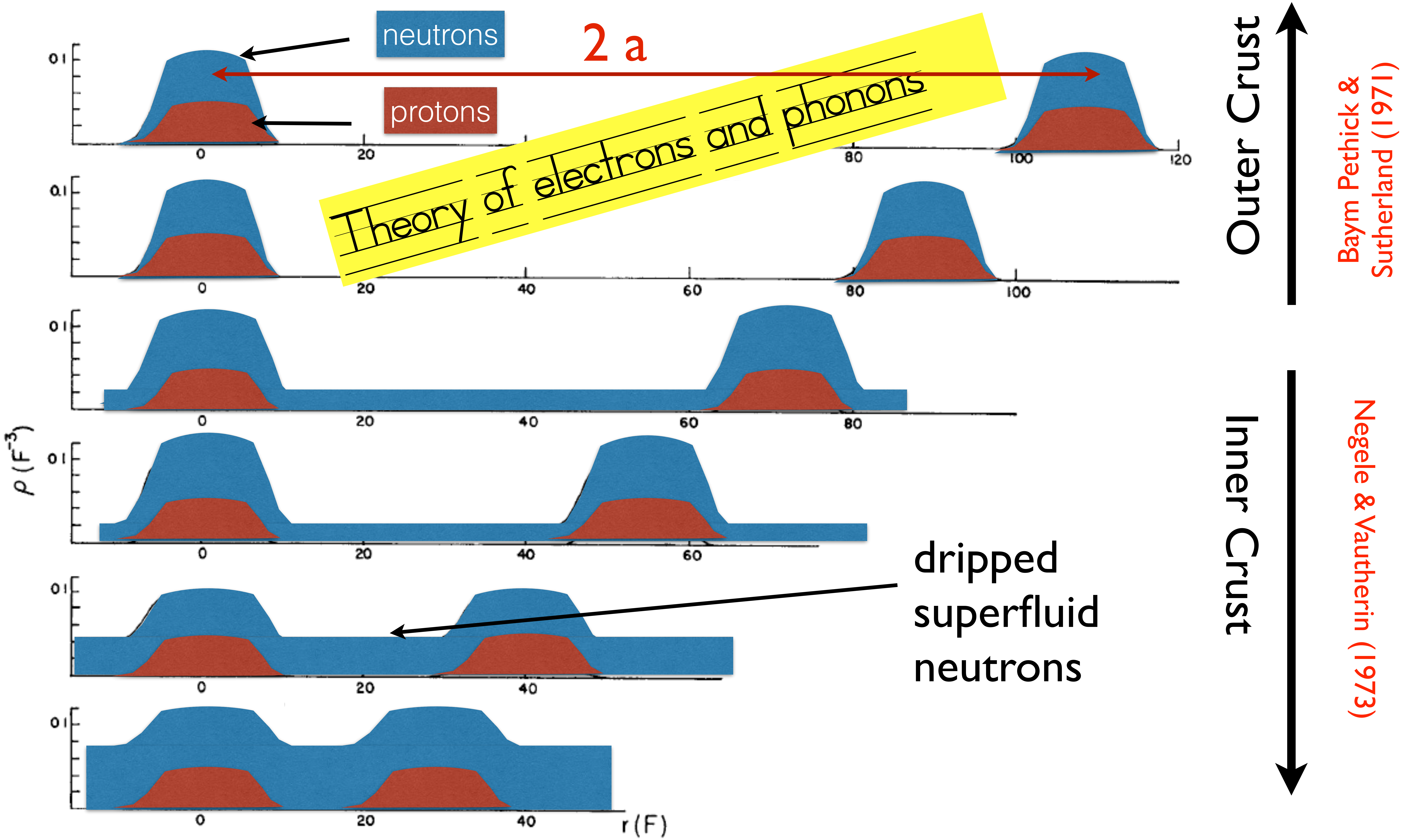

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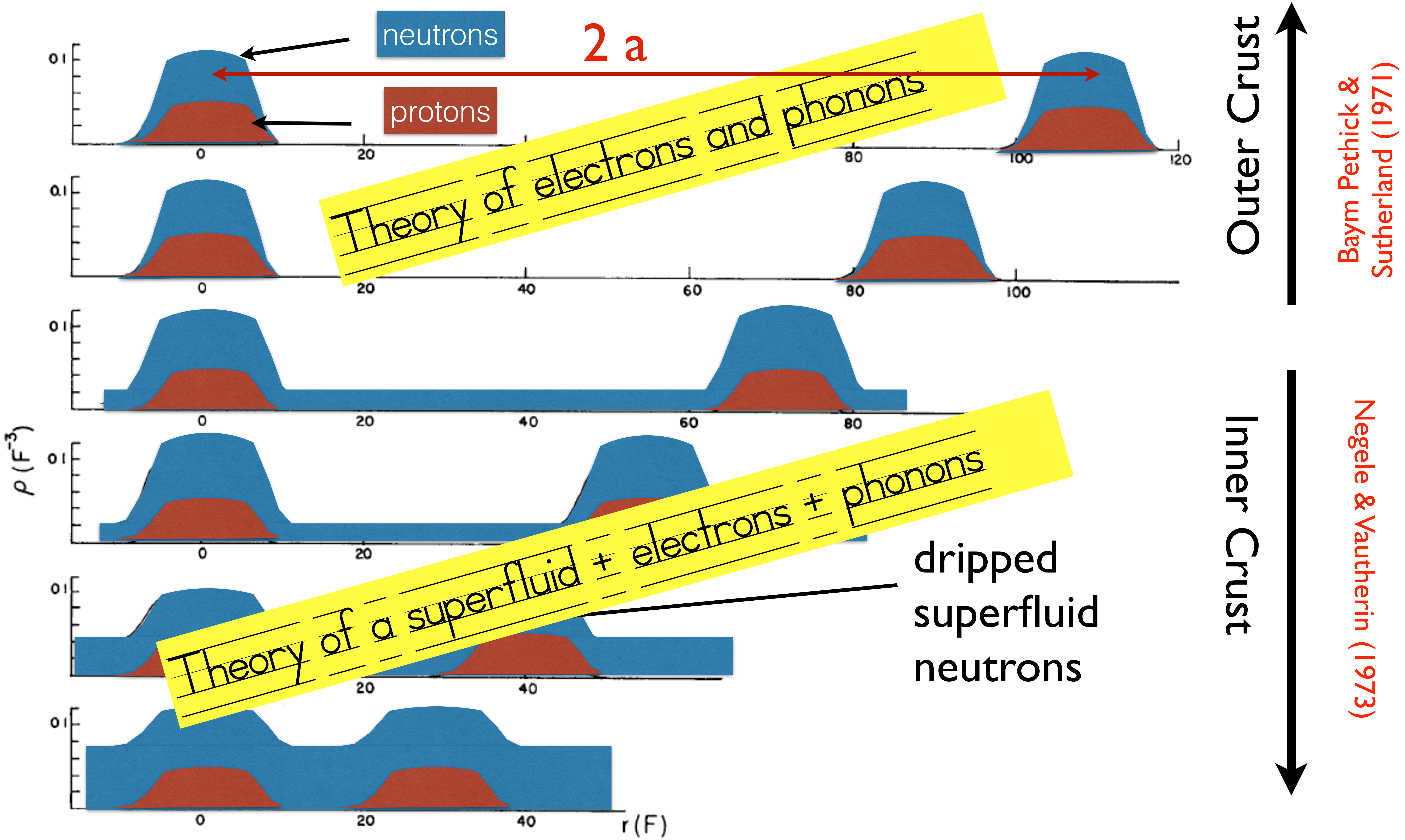

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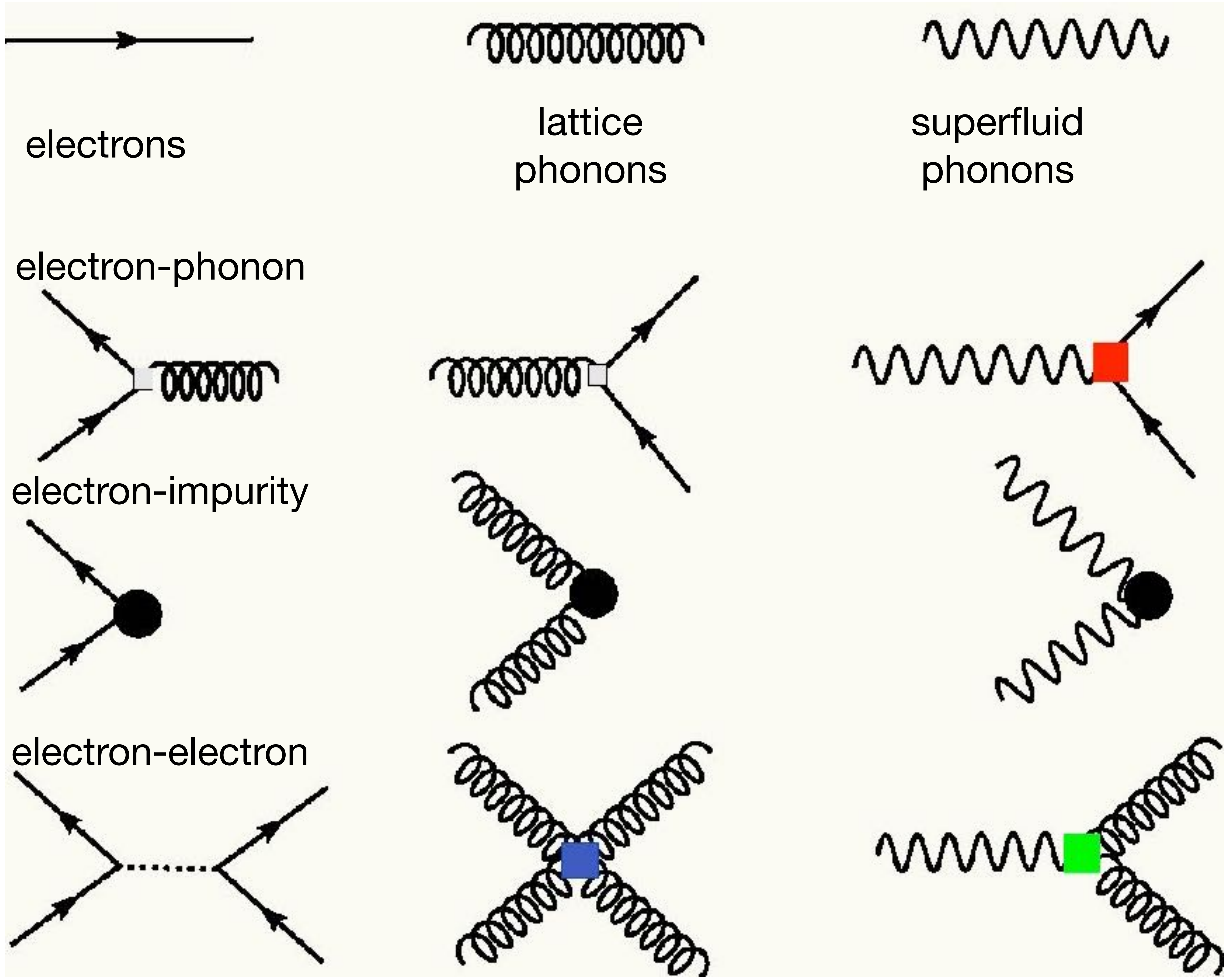
Excitations and Interactions in the Inner Crust

Thermal and transport properties of the solid and superfluid crust can be calculated using effective field theory.

Electrons and phonons are the relevant excitations.

Phonons of the neutron superfluid mix with phonons of the lattice.



In the crystalline-superfluid state electron conduction is high & heat capacity is low.
(Gases and ordinary liquids have low conductivity and high heat capacity.)

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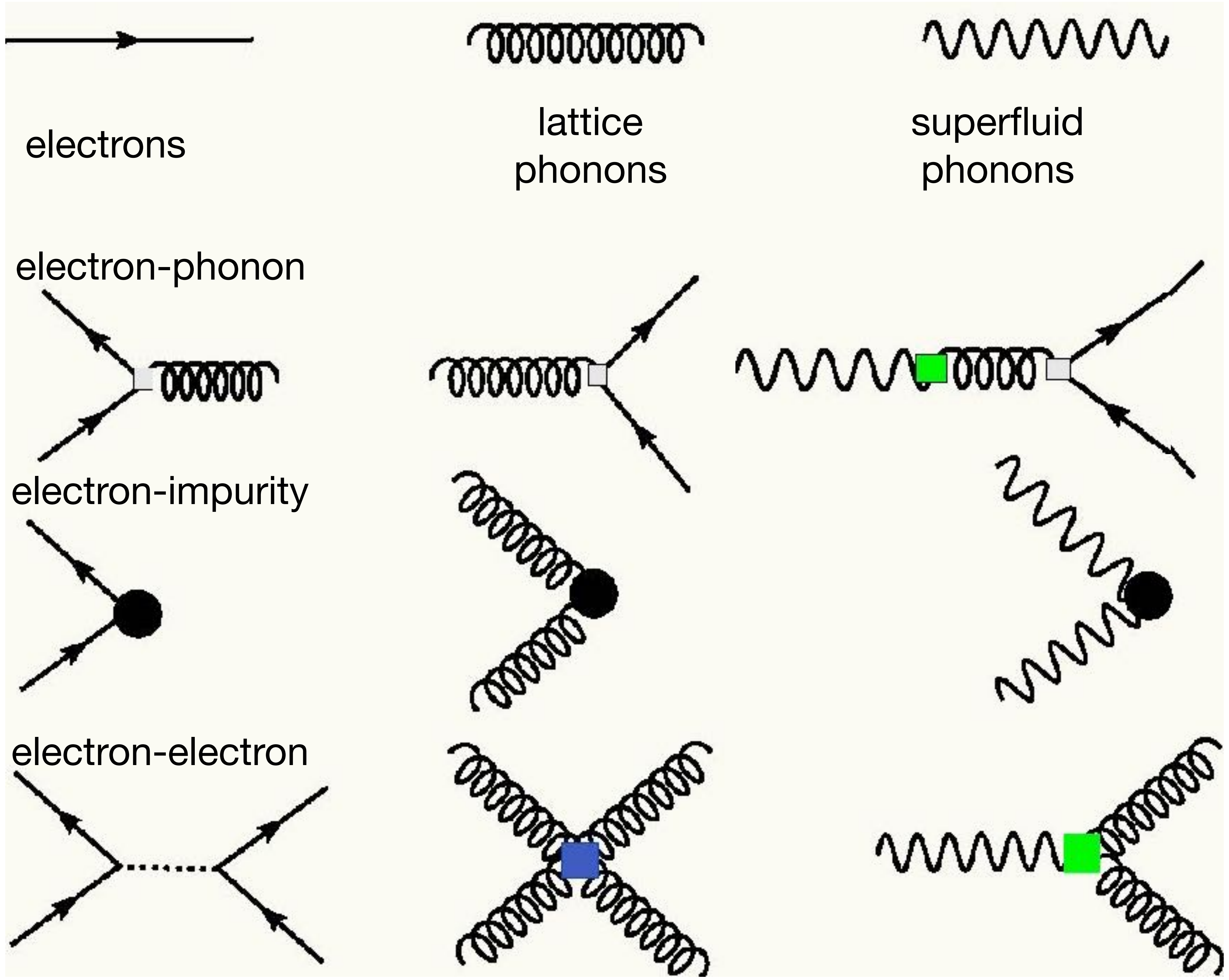

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Connecting to Crust Microphysics

Crustal Specific Heat

Crust Thickness

$$\tau_{\text{cool}} \simeq \frac{C_V}{\kappa} \Delta R^2$$

Thermal Conductivity

- Observed timescales are short.
- Requires small specific heat and large thermal conductivity.

Observations suggest inner curst is solid and superfluid!

Shternin & Yakovlev (2007) Cumming & Brown (2009) Page & Reddy (2011)

Conclusions

Observations of neutron star structure suggests that pressure increases rapidly at supra-nuclear density.

Analysis that combines neutron matter calculations at low density and GW data from GW170817 provides strong constraint [~10%] on the neutron star radius.

Thermal evolution of accreting neutron stars provides evidence for solid and superfluid matter in the inner crust.

Conclusions

Observations of neutron star structure suggests that pressure increases rapidly at supra-nuclear density.

Analysis that combines neutron matter calculations at low density and GW data from GW170817 provides strong constraint [~10%] on the neutron star radius.

Thermal evolution of accreting neutron stars provides evidence for solid and superfluid matter in the inner crust.

GW and EM observations of a few more close-by mergers (with Ad. LIGO at design sensitivity) would be transformative. It would provide a lower bound on the neutron star radius, information about their diversity, and on merger dynamics and nucleosynthesis.