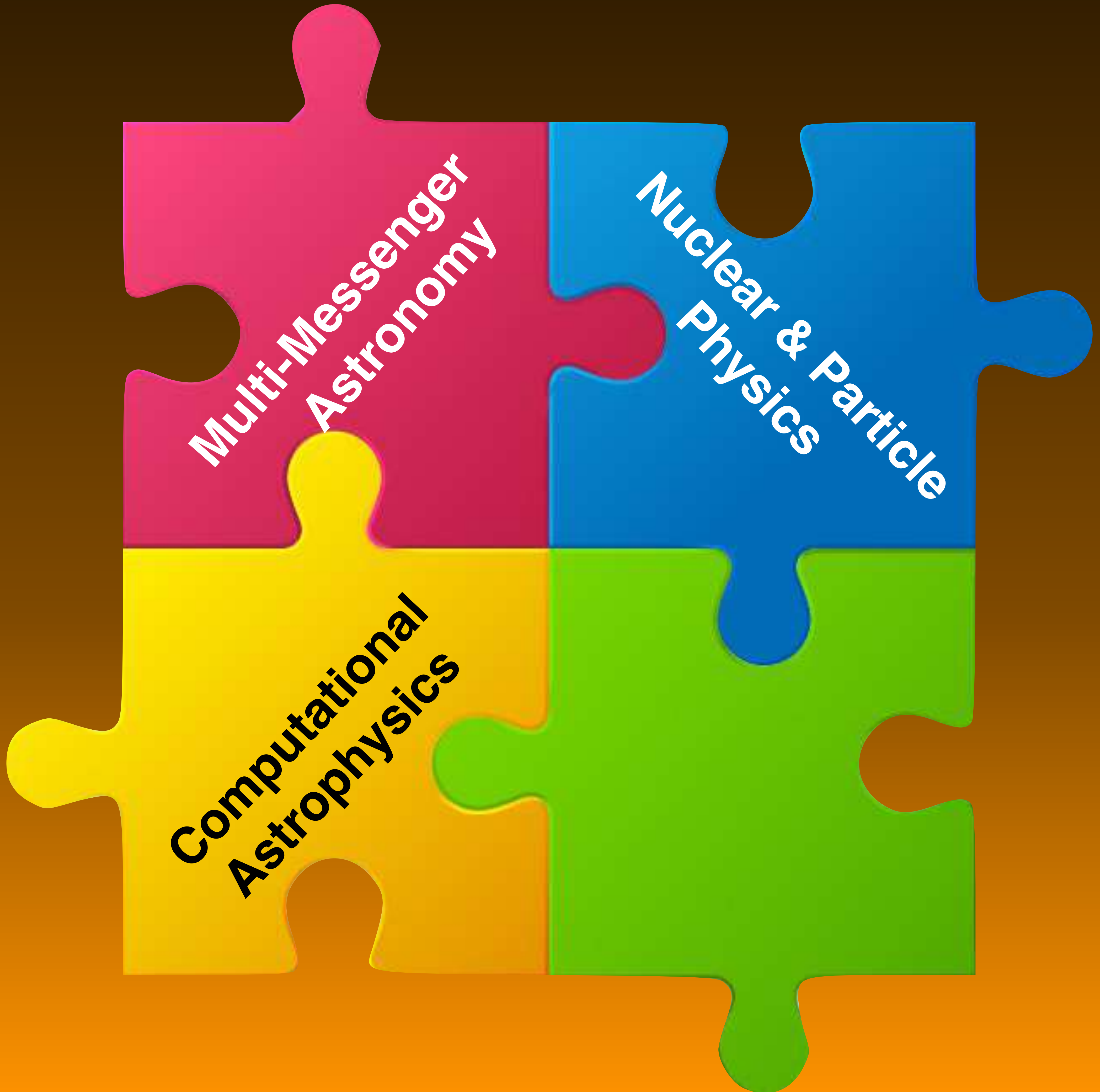
Dense Matter in Neutron Stars and its Role in Multi-Messenger Astrophysics

Sanjay Reddy
Institute for Nuclear Theory,
University of Washington, Seattle



Multi-Messenger Astronomy

Nuclear & Particle Physics

Computational Astrophysics

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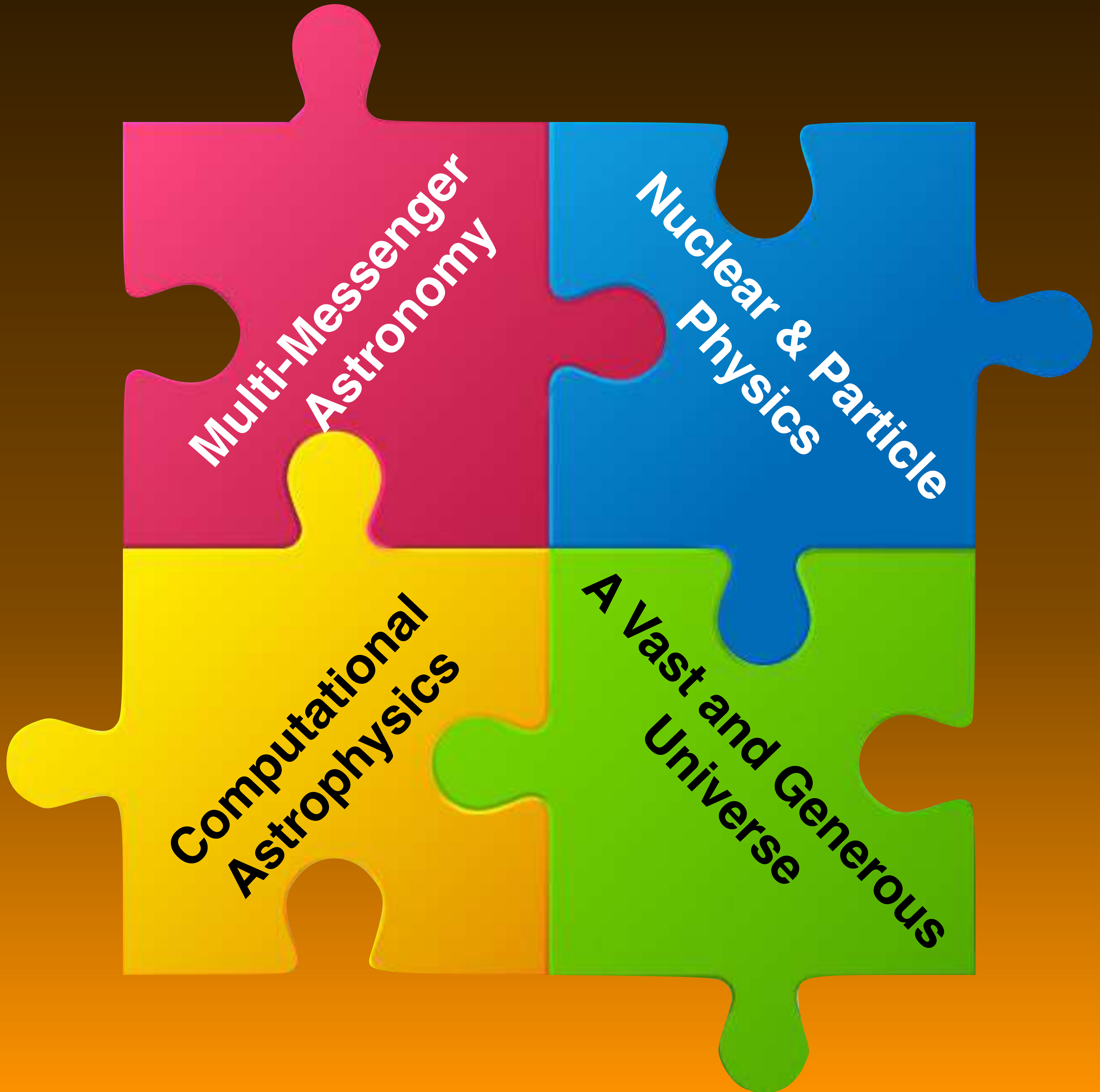

Multi-Messenger Astronomy

Nuclear & Particle Physics

Computational Astrophysics

A Vast and Generous Universe

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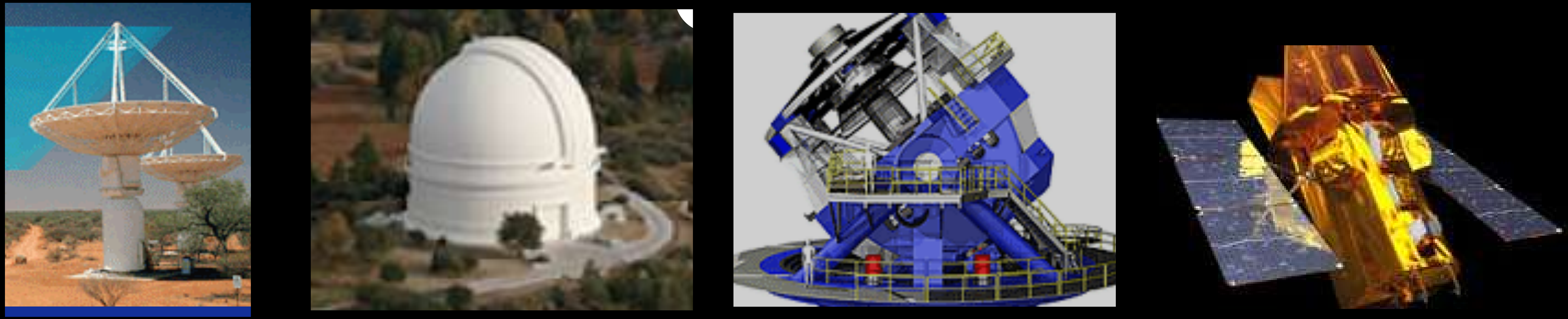
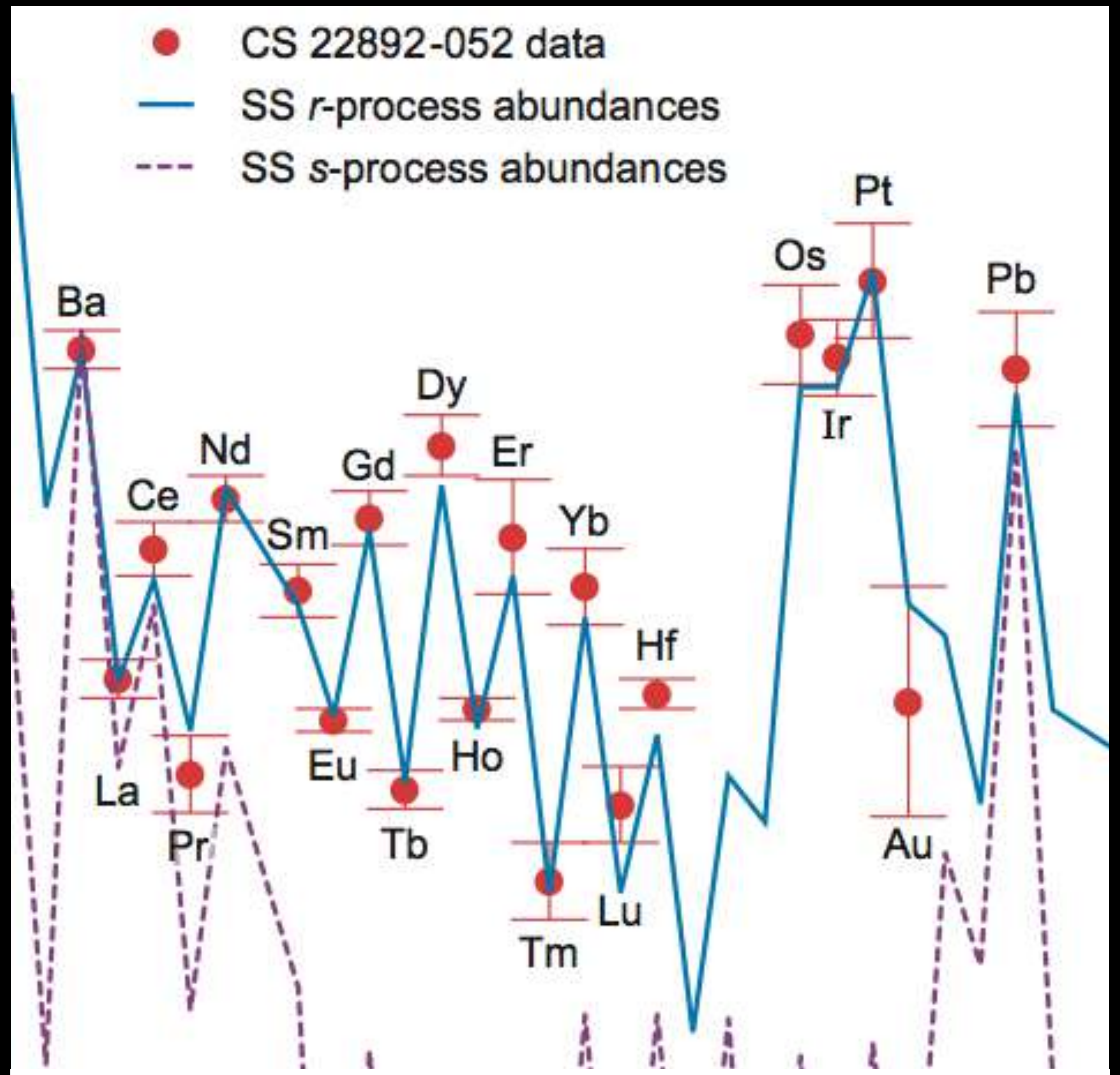
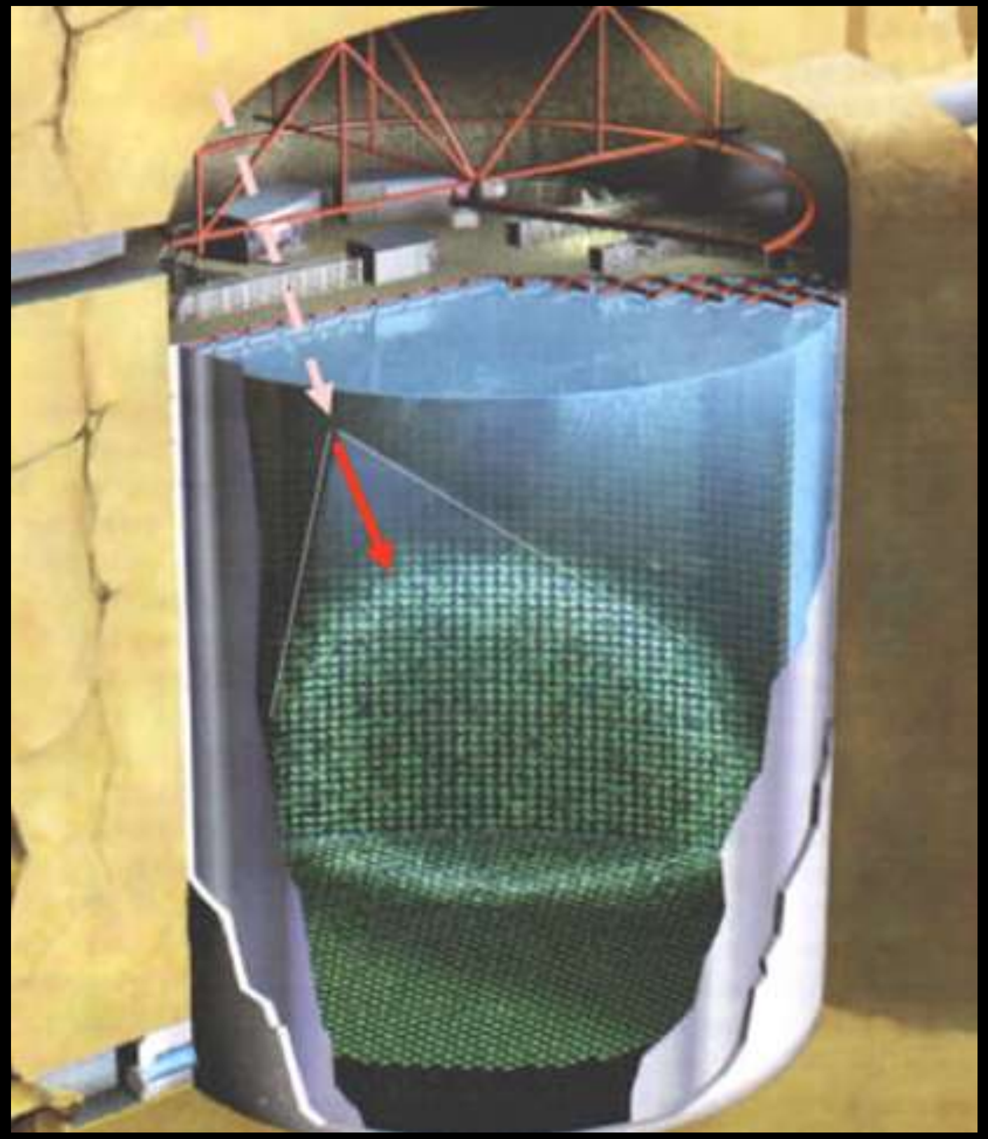
Best of Times: The Multi-Messenger Era



Photons



Abundances

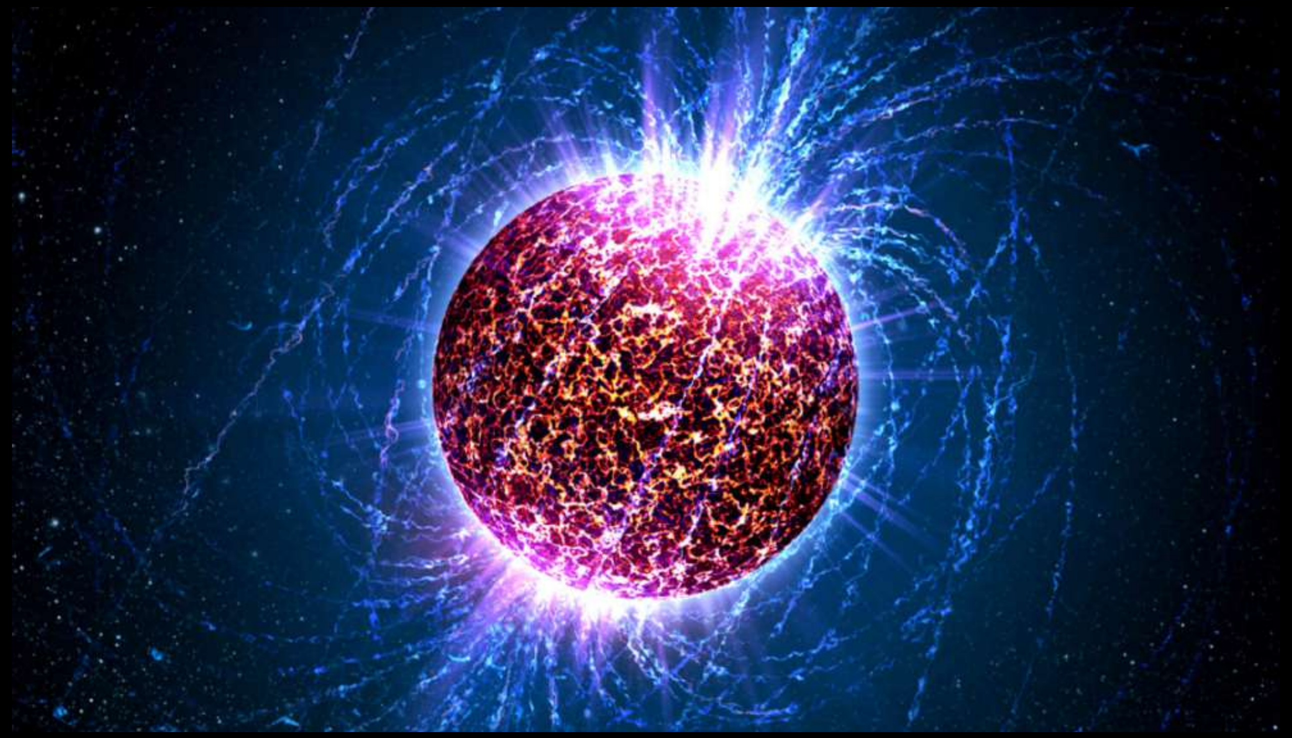


Neutrinos

Gravitational Waves

Big Questions

What powers the most extreme phenomena in the universe?



What are the states of matter encountered inside neutron stars?

Where and how are the heavy elements such as gold, platinum and uranium made?

What is dark matter?

Outline:

- Introduction to neutron stars

- Neutron star structure

- Neutron star dynamics
    - Accreting neutron stars
    - Neutron star mergers

- The dark side of neutron stars

- Conclusions and outlook

Neutron Stars: A Brief History

"With all reserve we advance the view that a super-nova represents the transition of an ordinary star into a neutron star, consisting mainly of neutrons. Such a star may possess a very small radius and an extremely high density."

Zwicky & Baade (1934)
Extraordinary Vision!

Neutron Stars: A Brief History

Using a radio “telescope”

- 1000 posts and 120 miles of cable over 5 acres !

Jocelyn Bell discovers very regular periodic pulses of extraterrestrial origin.

Period << 1 s!

Jocelyn Bell & Anthony Hewish (1967)

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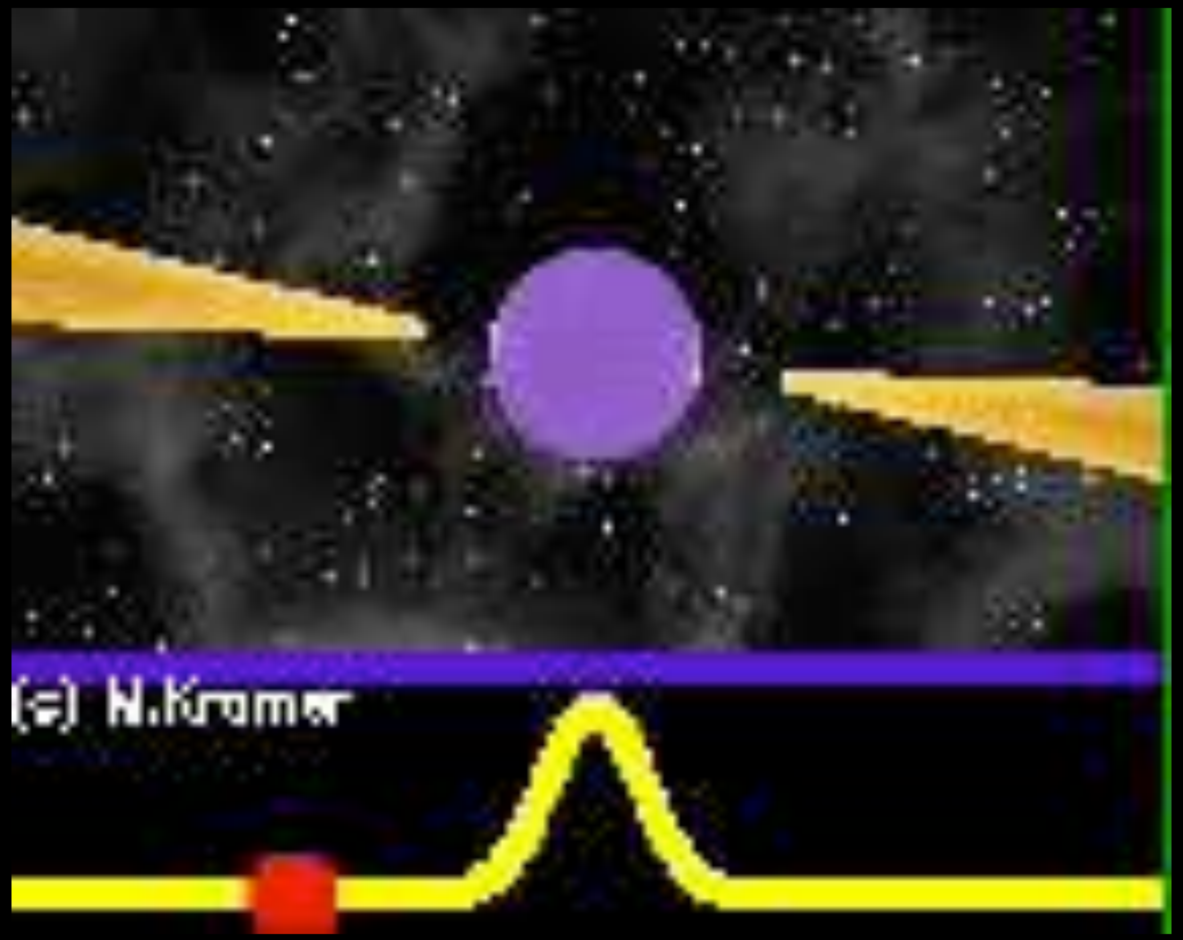

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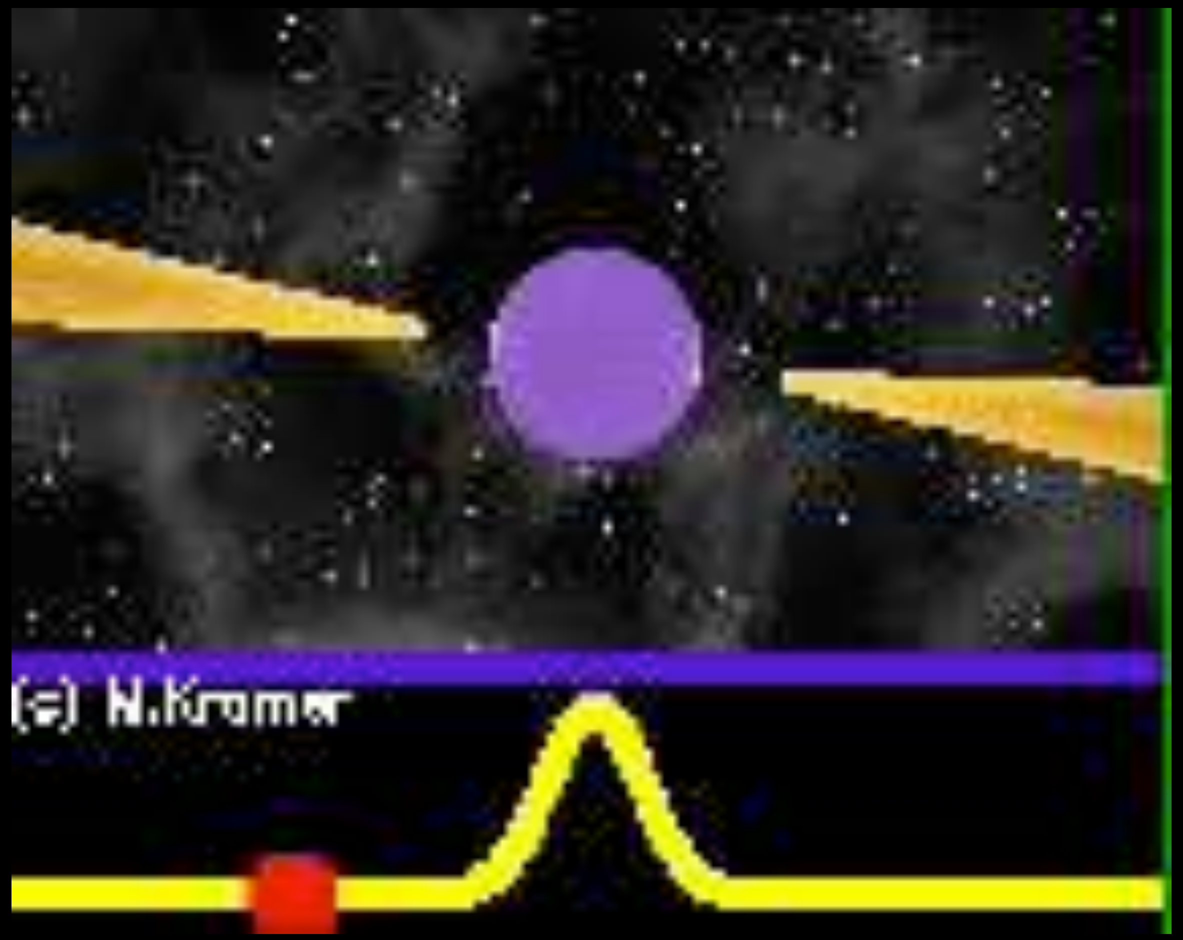
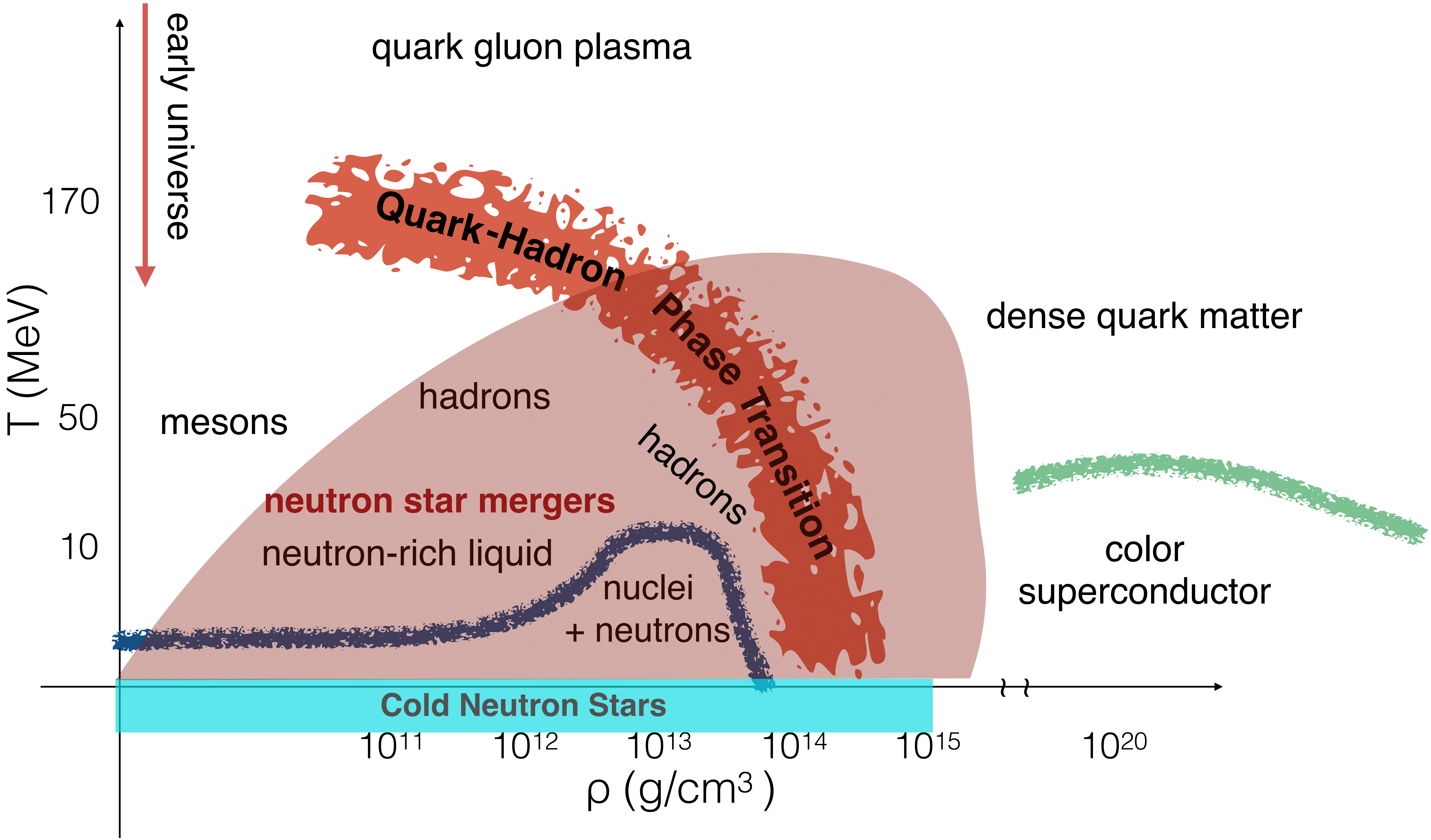


Jocelyn Bell & Anthony Hewish (1967)

Pulsars are discovered and identified as neutron stars!

Neutrons Stars & the QCD Phase Diagram



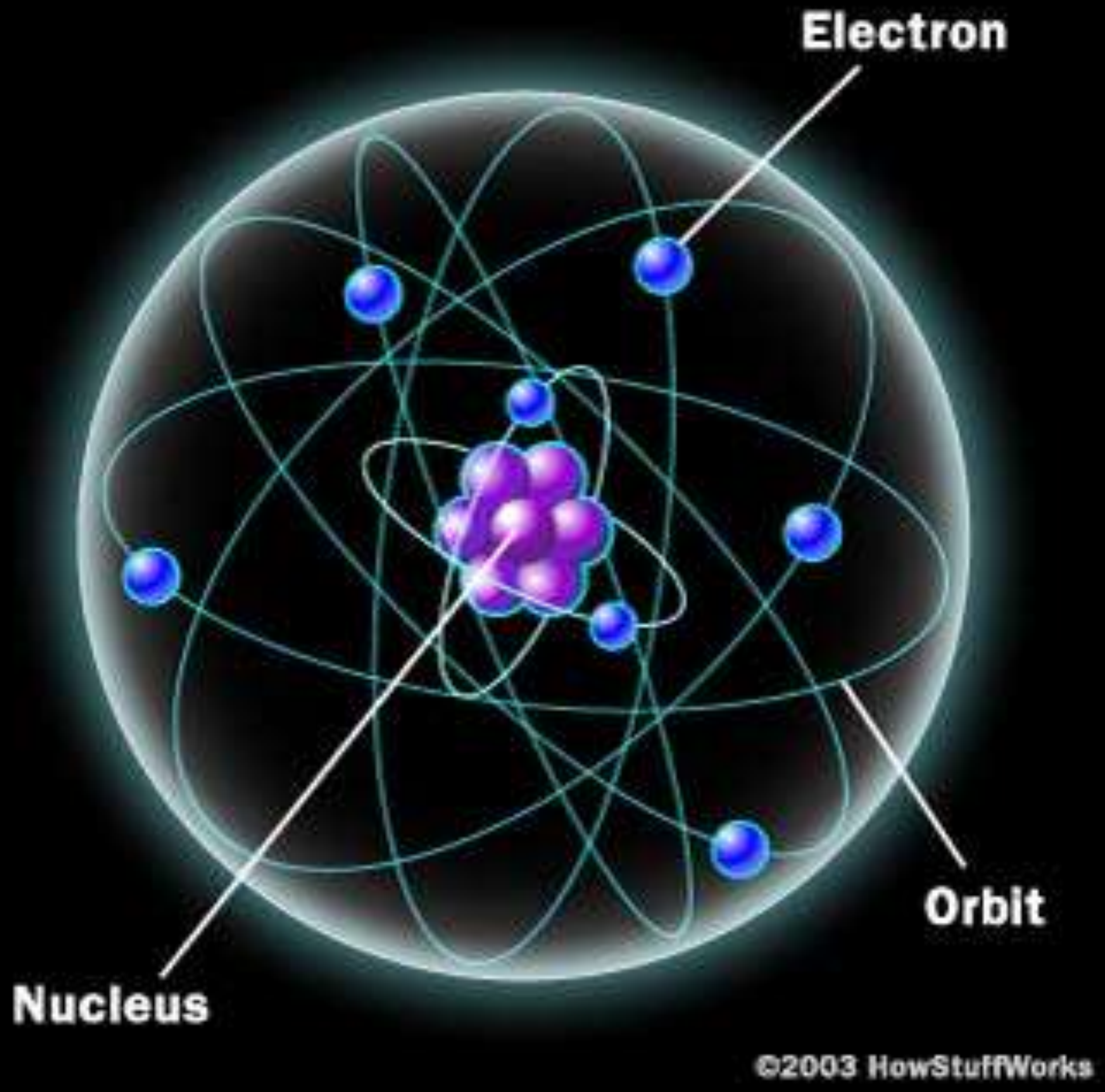
Dense Matter

Density of iron at atmospheric pressure

$$\rho \simeq 8\ \mathrm{g/cm^3}$$

Density of an Fe atom: $\rho \simeq 8\ \mathrm{g/cm^3}$

Density of an Fe nucleus: $\rho \simeq 2.5 \times 10^{14} \mathrm{g/cm^3}$



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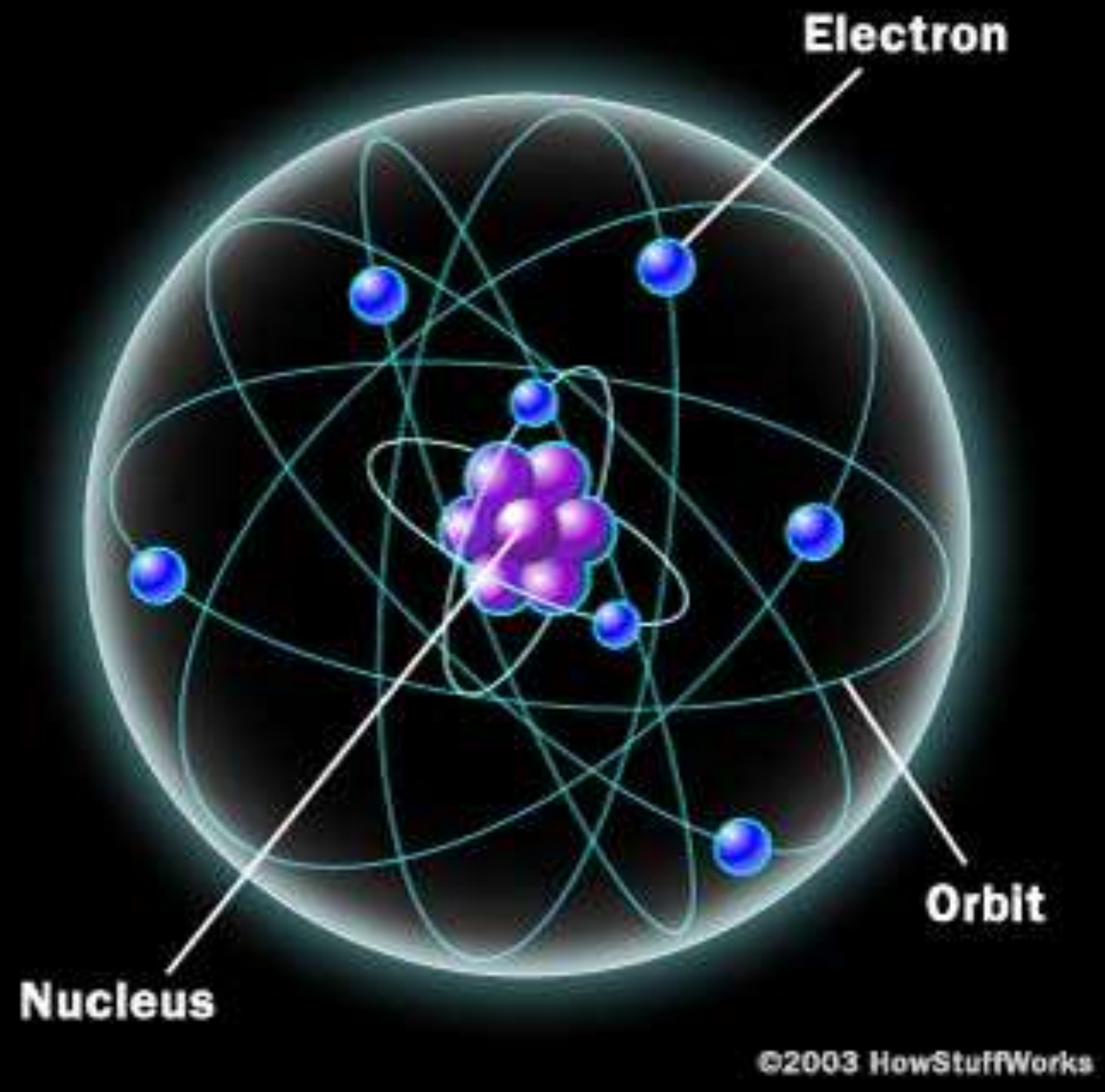
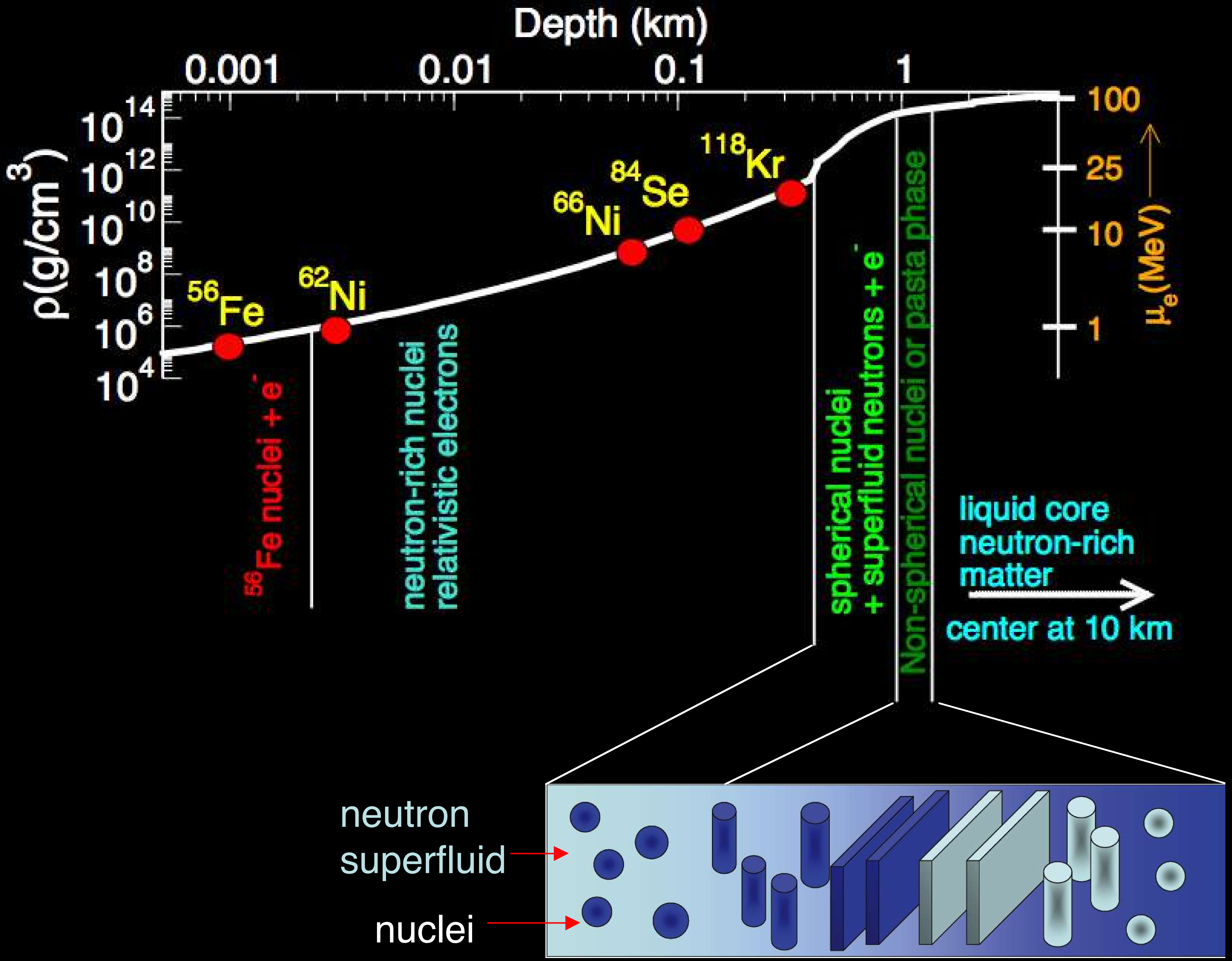


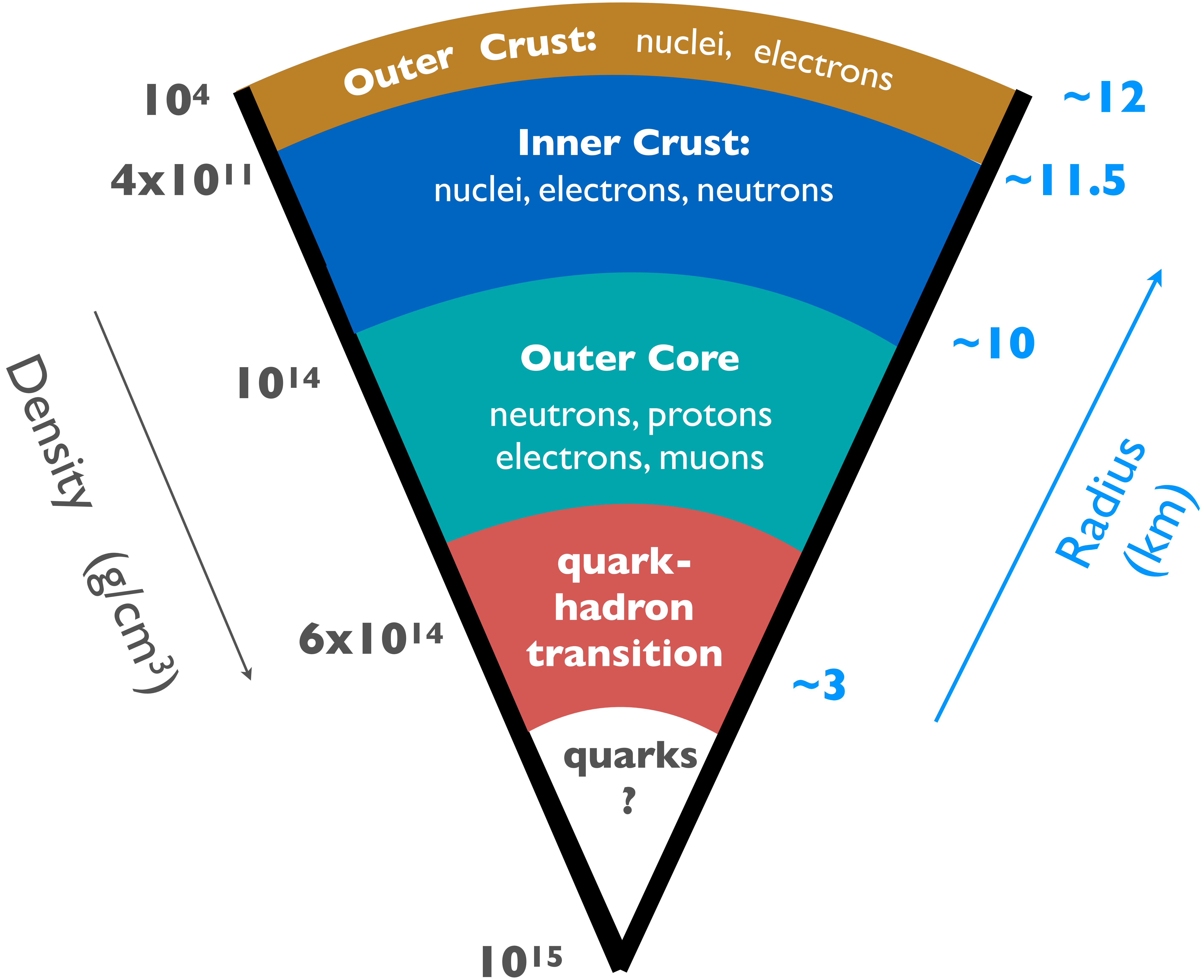
Compressing matter begins with the compression of electrons.

Compressing Matter:
A tale of frustration and liberation

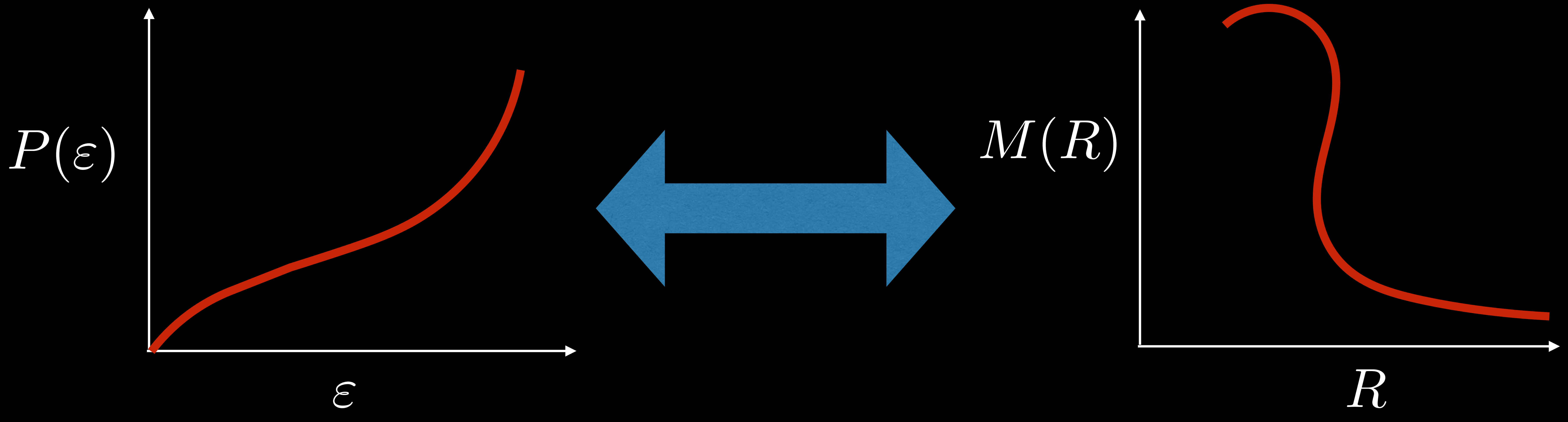
Density	Fermi Energy (Frustration)	Phenomena (Liberation)
10^3 - 10^6 g/cm^3	Electron Fermi Energy $\mu_e = 10$ keV– MeV	Ionization
10^6 - 10^{11} g/cm^3	Electron Fermi Energy $\mu_e = 1-25$ MeV	Neutron-rich Nuclei $e+p \rightarrow n+\nu_e$
10^{11} - 10^{14} g/cm^3	Neutron Fermi Energy $\mu_n = 1-30$ MeV	Neutron-drip superfluidity
10^{14} - 10^{15} g/cm^3	Neutron Fermi Energy $\mu_n = 30-1000$ MeV	Nuclear matter Quarks ?


Depth (km)
0.001
0.01
0.1
1
$\rho(g/cm^3)$
10^{14}
10^{12}
10^{10}
10^{8}
10^{6}
10^{4}
^{56}Fe
^{62}Ni
^{66}Ni
^{84}Se
^{118}Kr
100
25
10
1
μ_e(MeV)
^{56}Fe nuclei + e^-
neutron-rich nuclei
relativistic electrons
spherical nuclei
+ superfluid neutrons + e^-
Non-spherical nuclei or pasta phase
liquid core
neutron-rich
matter
center at 10 km
neutron
superfluid
nuclei

Composition of Dense Matter in Neutron Stars

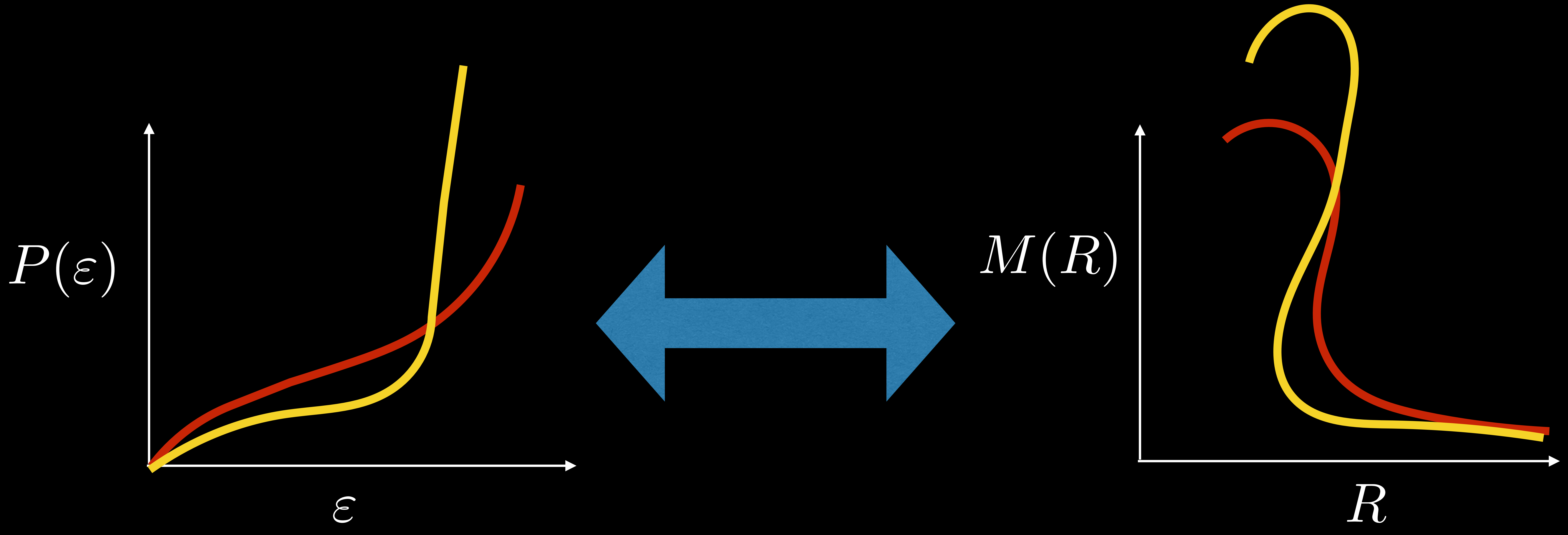


Equation of State and Neutron Star Structure



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

Equation of State and Neutron Star Structure



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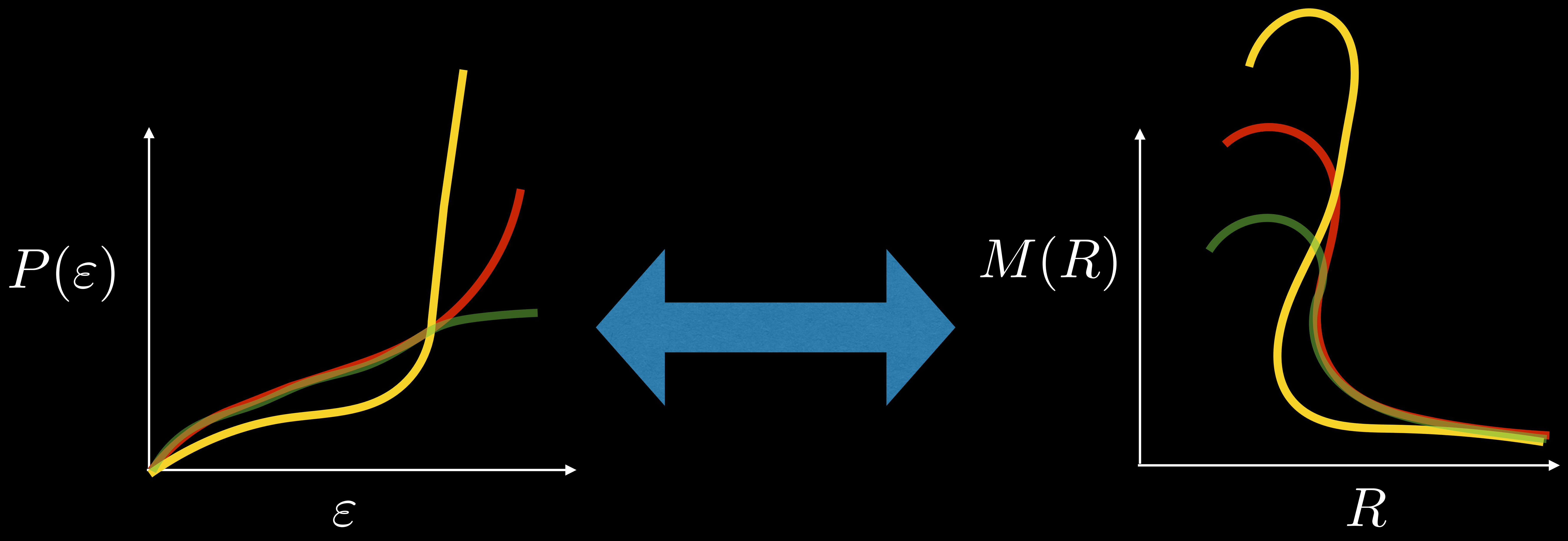

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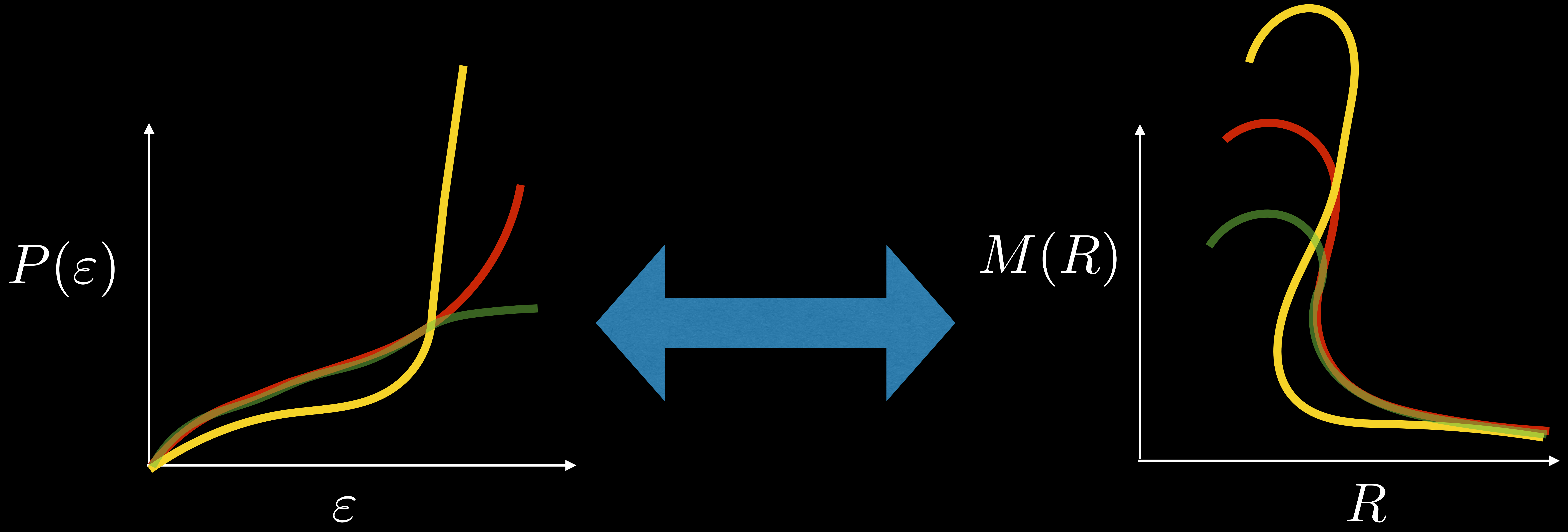
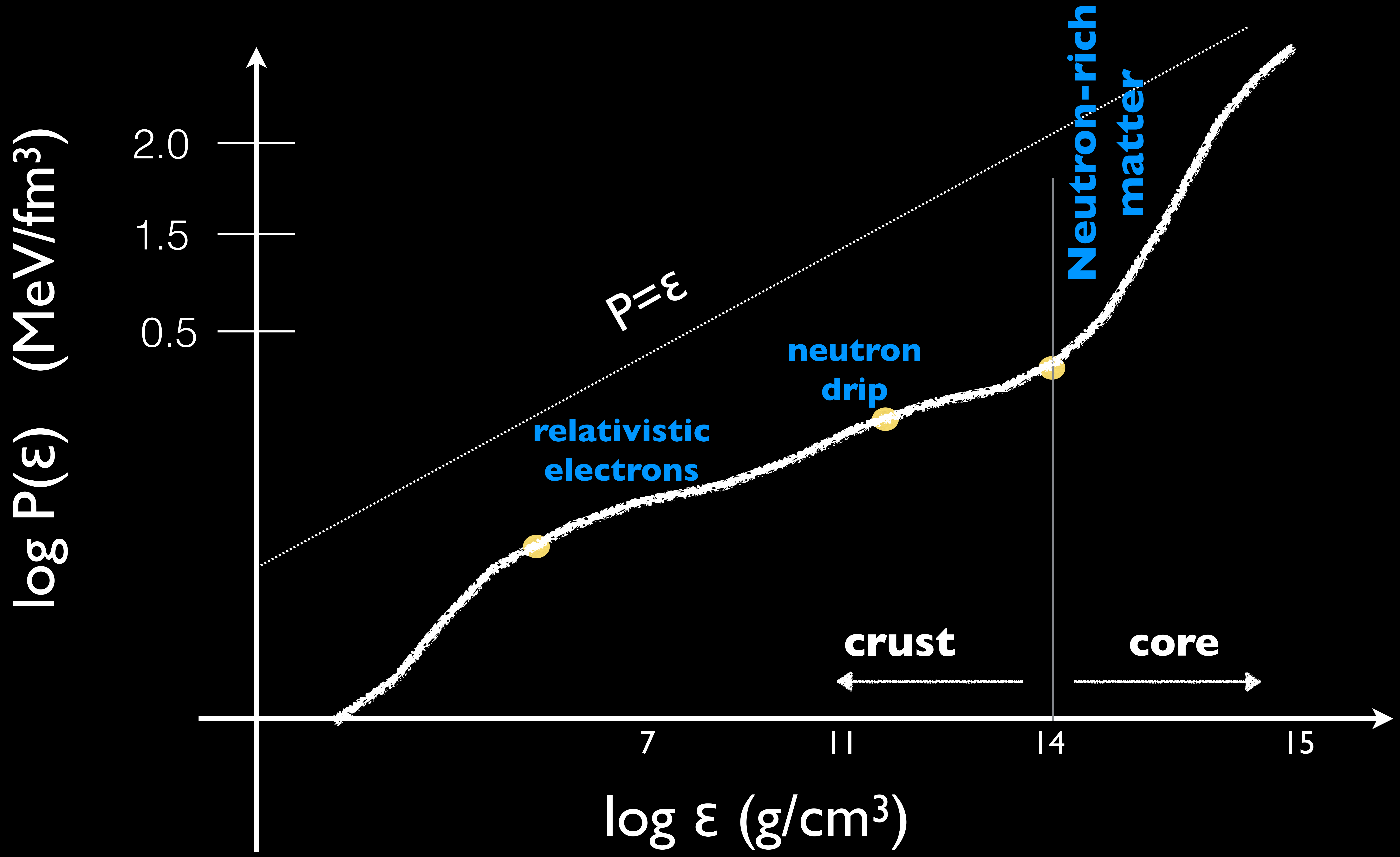


$$P(\varepsilon) + \text{Gen.Rel.} = M(R)$$

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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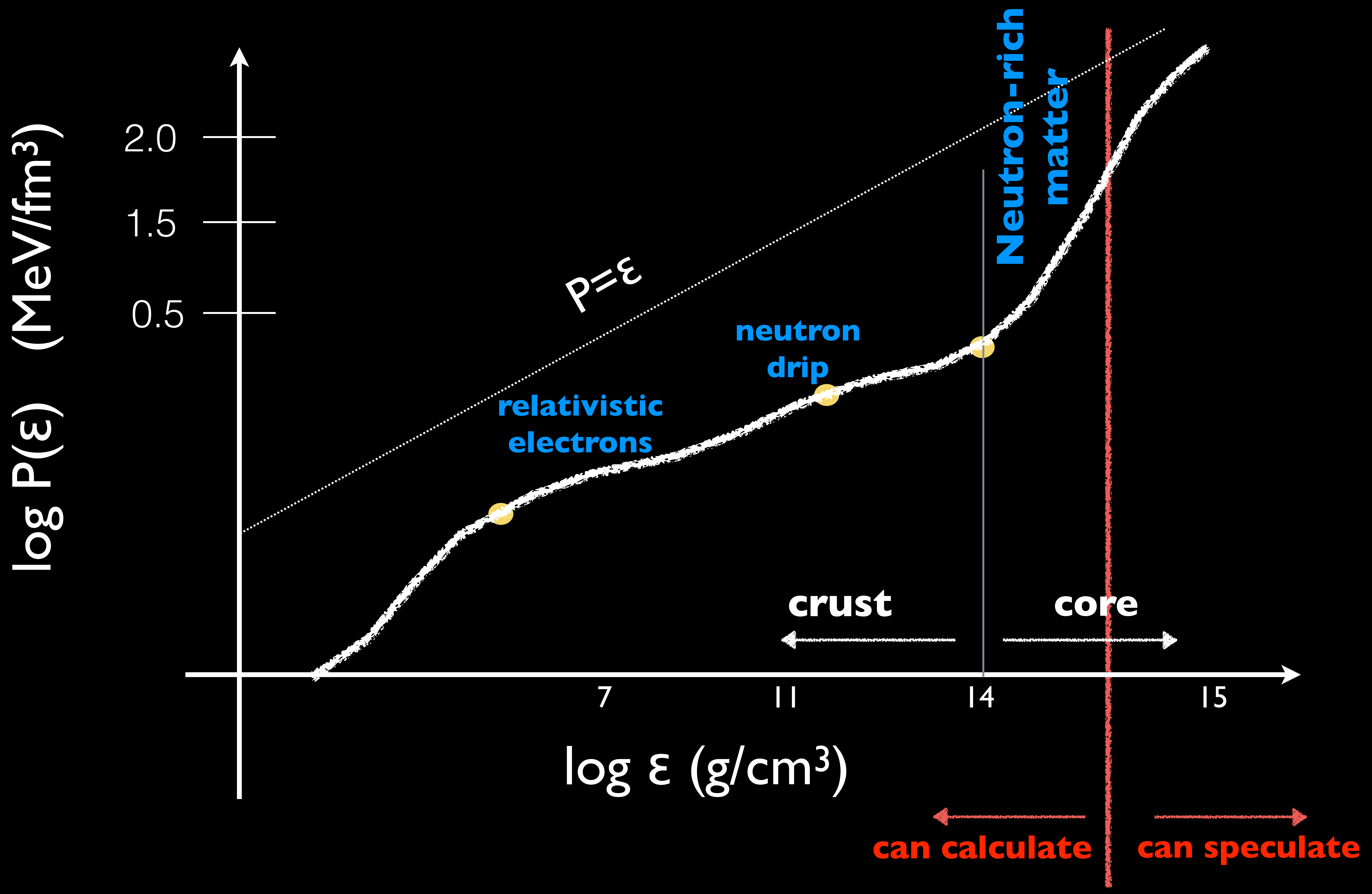

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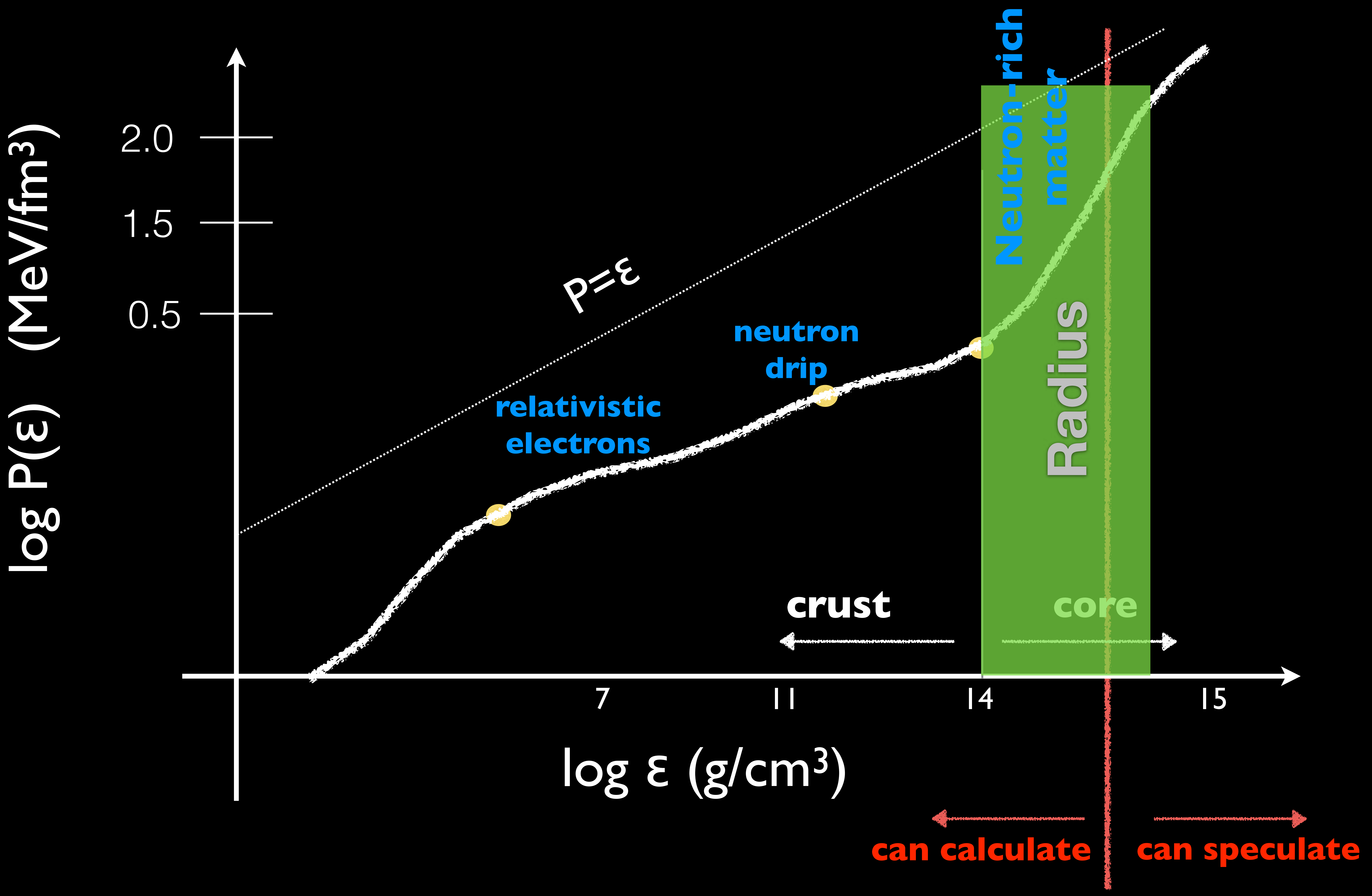

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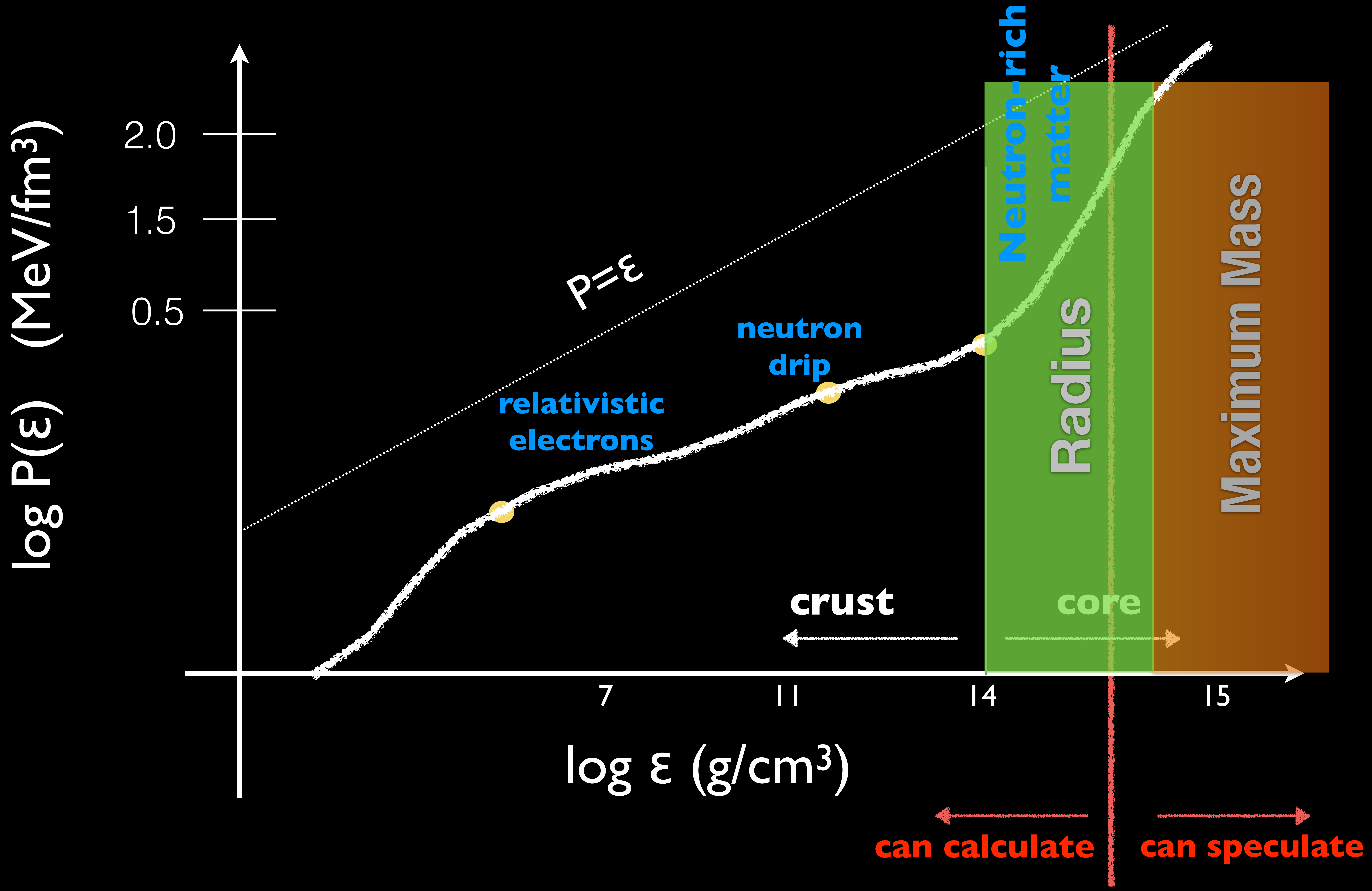
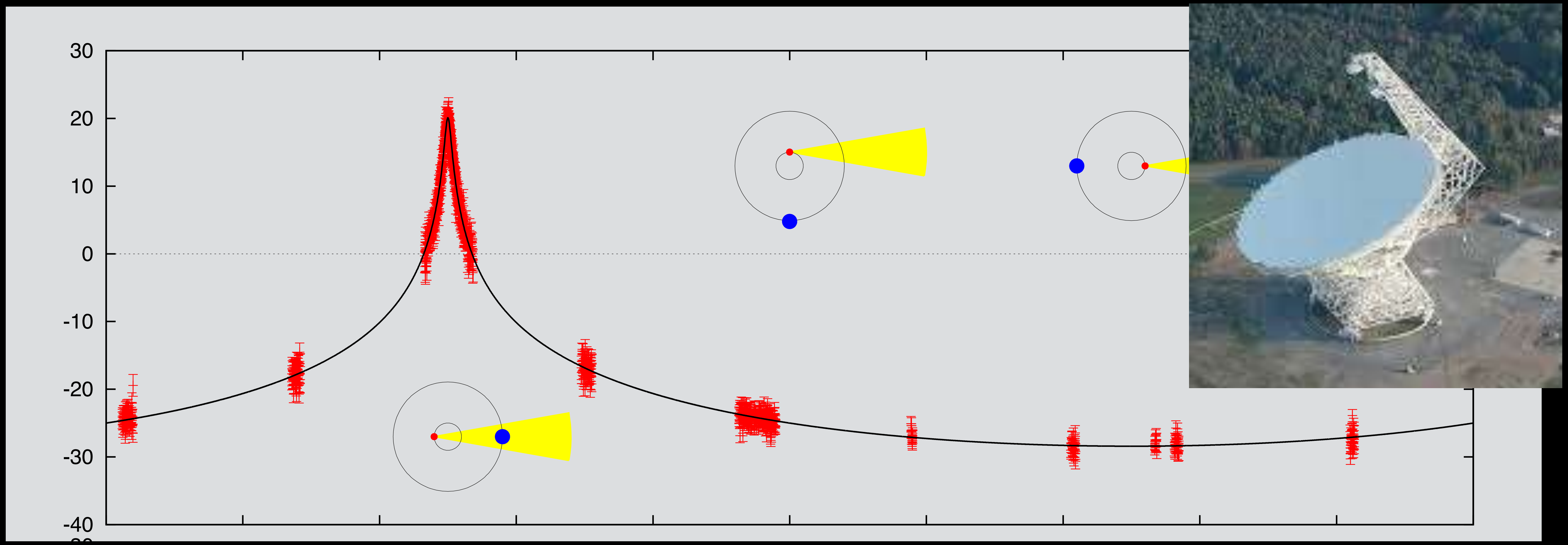


Neutron Star Structure: Observations



2 $M_\odot$ neutron stars exist.

PSR J1614-2230: M=1.93(2)

Demorest et al. (2010)

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

Anthoniadis et al. (2013)

MSP J0740+6620: M=2.17(10) $M_\odot$

Cromartie et al. (2019)

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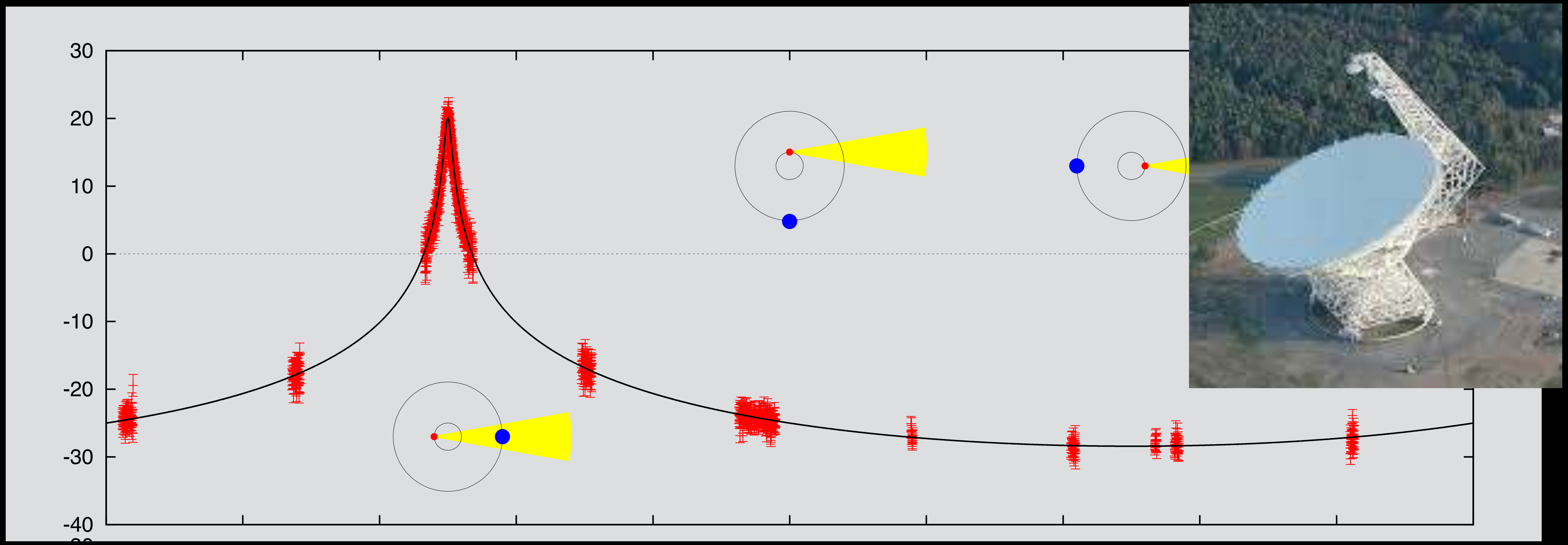

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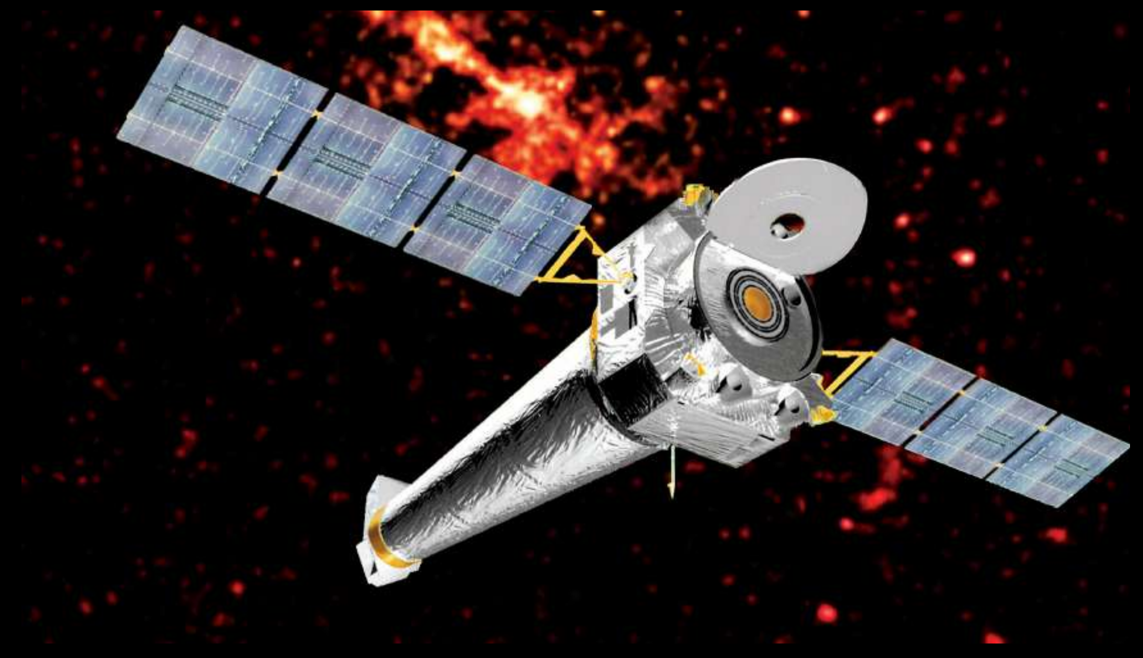
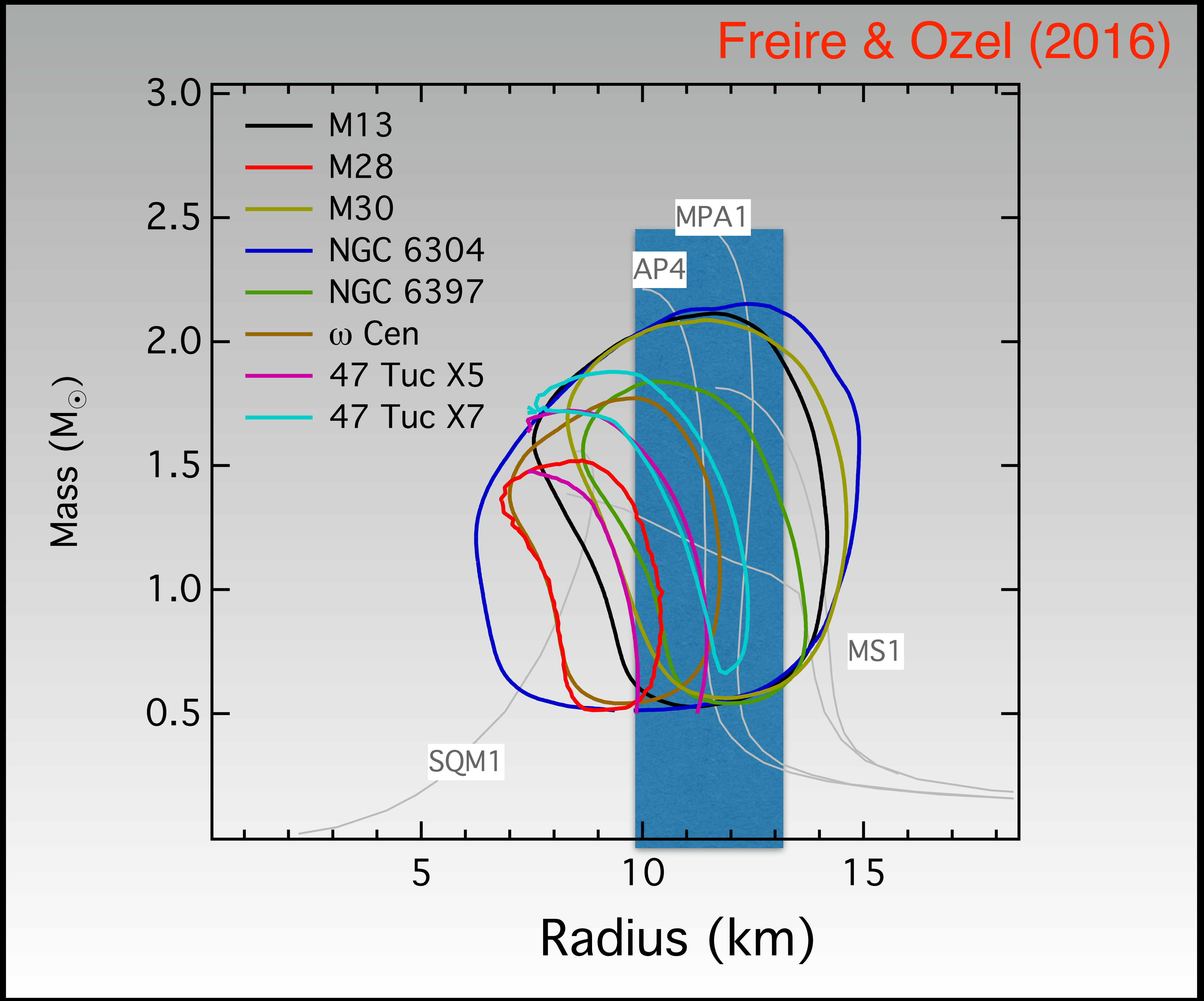


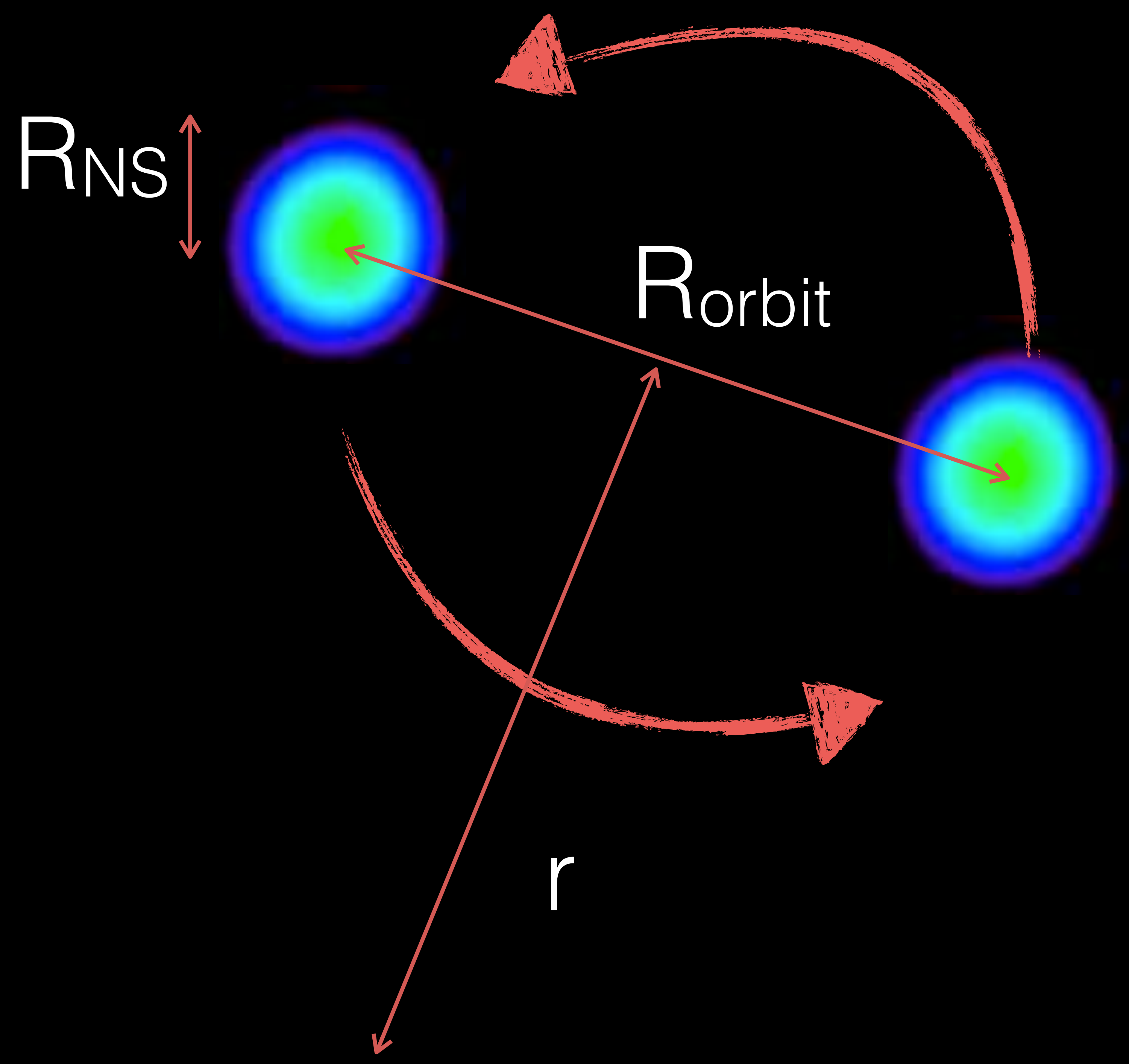
NS radii are difficult to measure:

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



Freire & Ozel (2016)

Binary Inspiral and Gravitational Waves



GWs are produced by fluctuating quadrupoles.

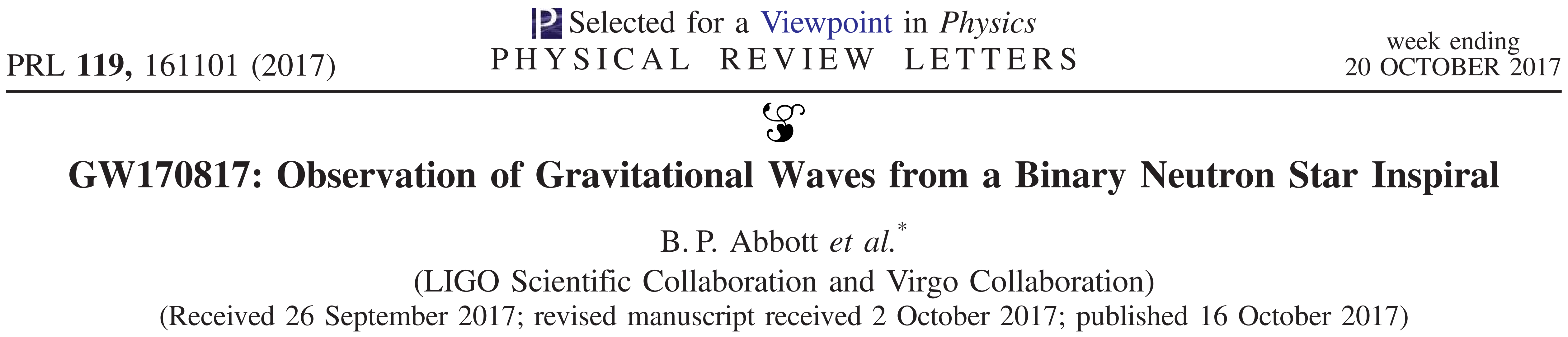
$$h_{\mu\nu}(r,t) = \frac{2G}{r}\,\ddot{I}_{ij}(t_R)$$

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

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

- Advanced LIGO can detect the last 100 or so orbits of a neutron star merger.

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)

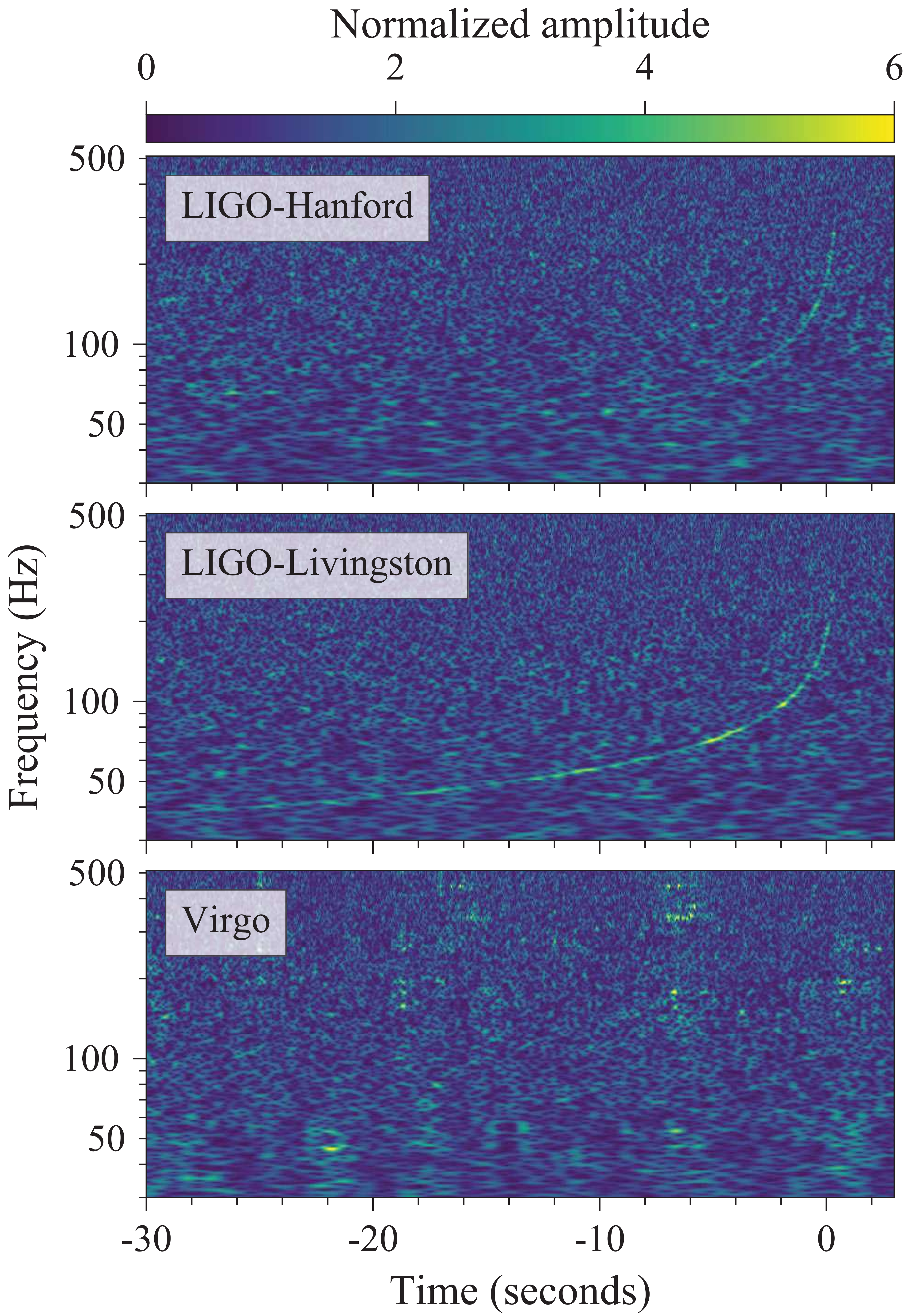
Component masses:

$$m_1 = 1.47 \pm 0.13\ M_\odot$$

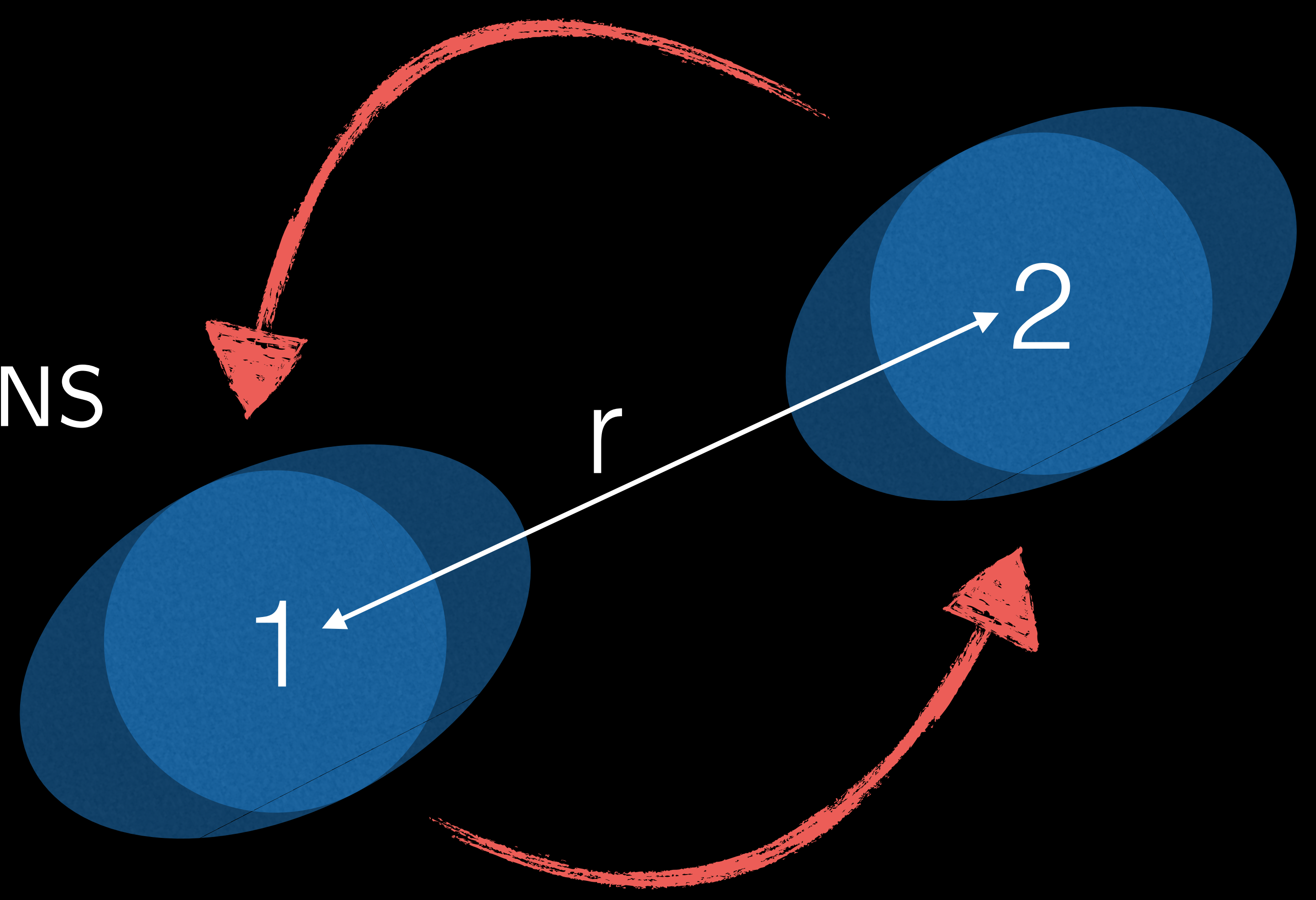
$$m_2 = 1.17 \pm 0.09\ M_\odot$$

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



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

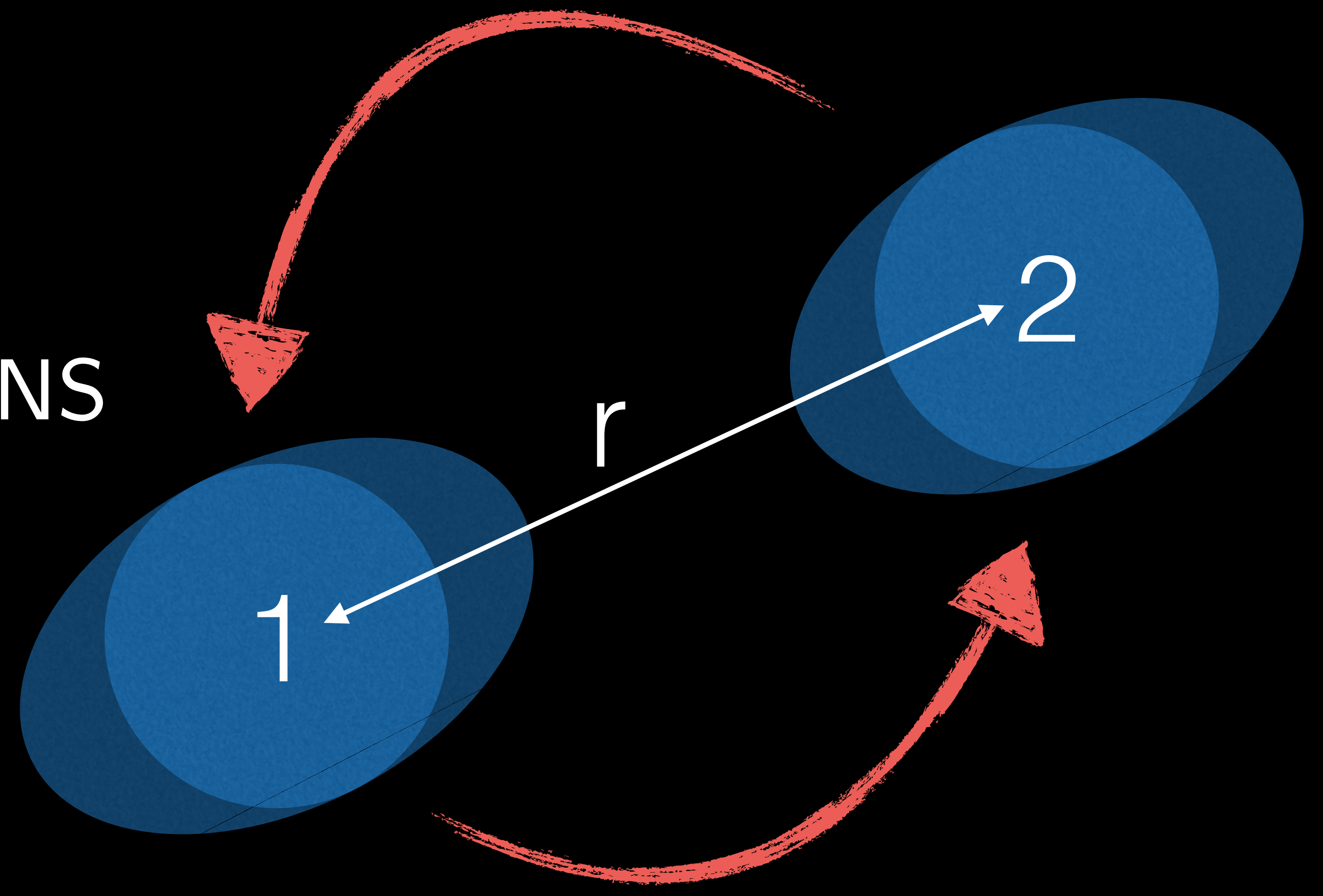
Tidal forces deform neutron stars.
Induces a quadrupole moment.

$$Q_{xy} = \lambda\ E_{xy} \qquad E_{xy} = -\frac{\partial^2 V_G}{\partial x \partial y}$$

tidal deformability

external field

Tidal Deformation: Measuring the Radius with GWs



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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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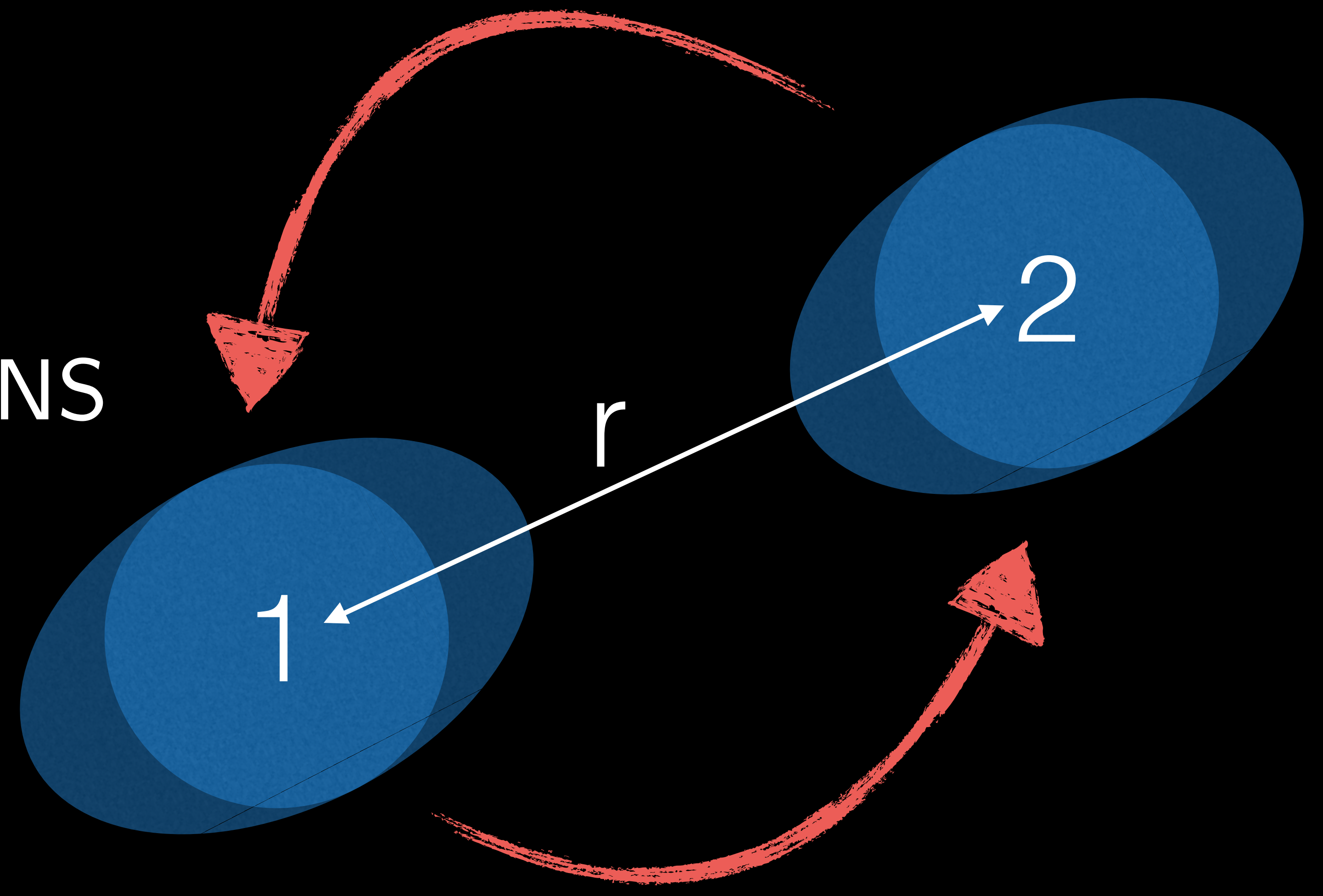

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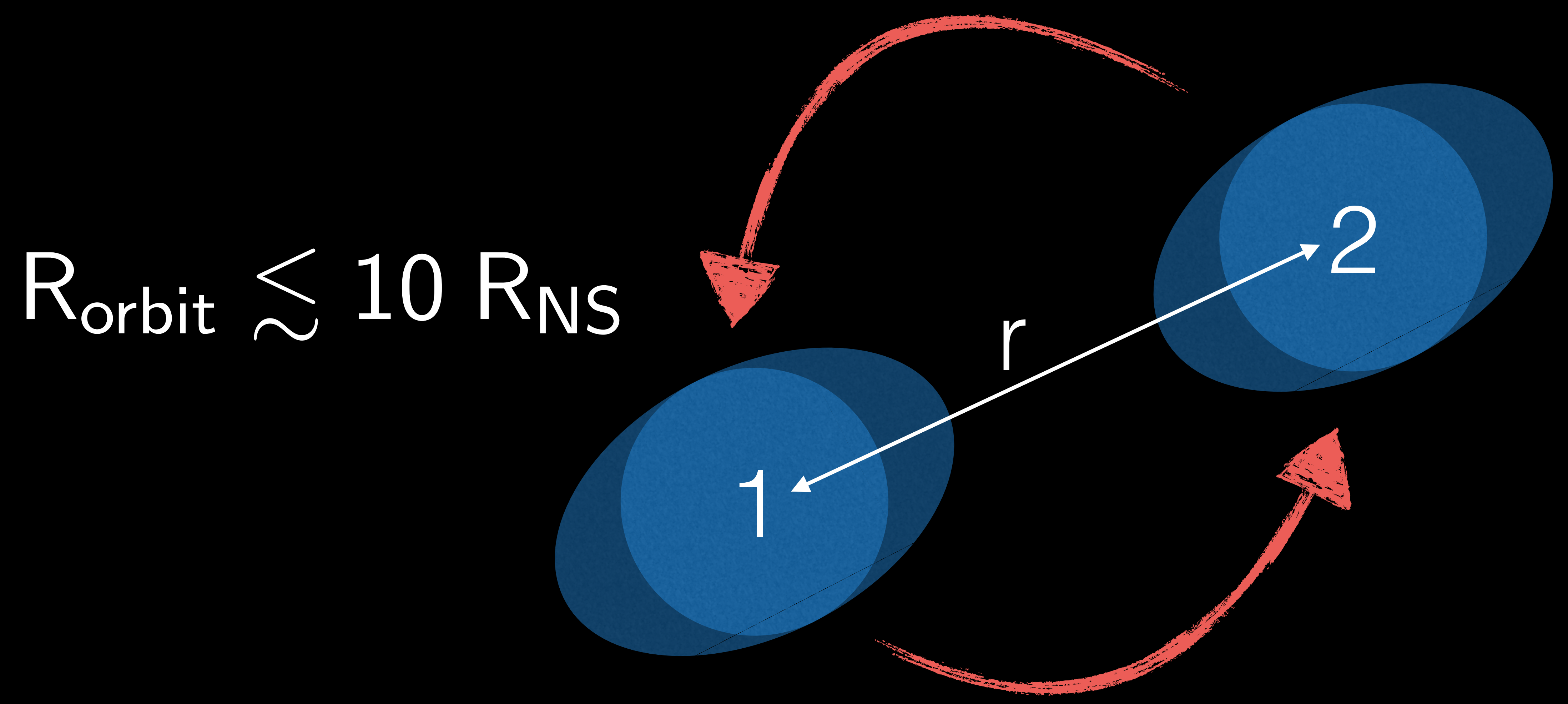
Dimensionless binary tidal deformability: $\tilde{\Lambda} = \frac{16}{13}\left(\left(\frac{M_1}{M}\right)^5 \left(1 + \frac{M_2}{M_1}\right) \Lambda_1 + 1 \leftrightarrow 2\right)$

Tidal Deformation: Measuring the Radius with GWs



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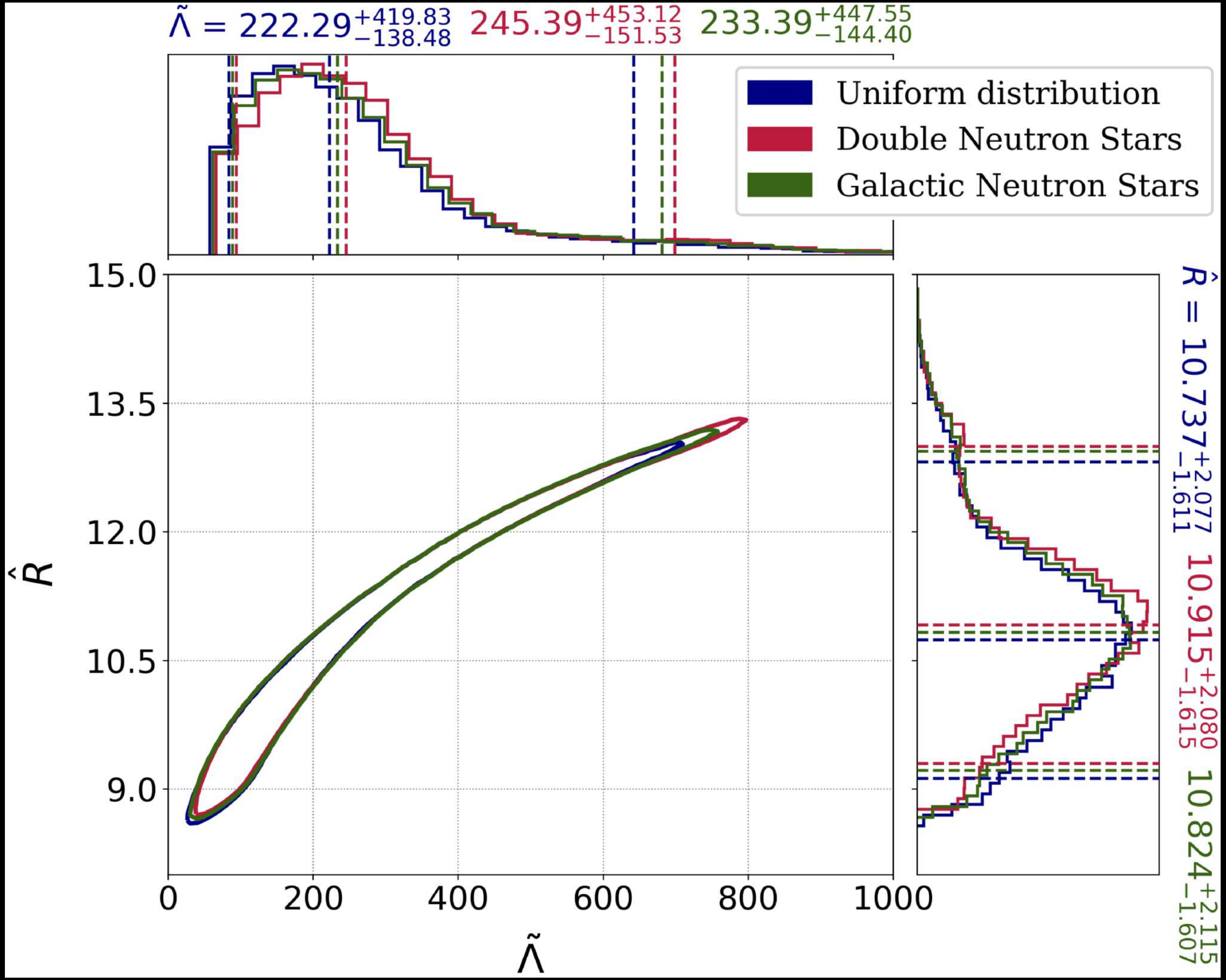
Tidal deformations are large for a large NS: $\Lambda_i = \frac{\lambda_i}{M_i^5} = k_2 \frac{R_i^5}{M_i^5}$

Neutron Stars are Small



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

R < 13 km

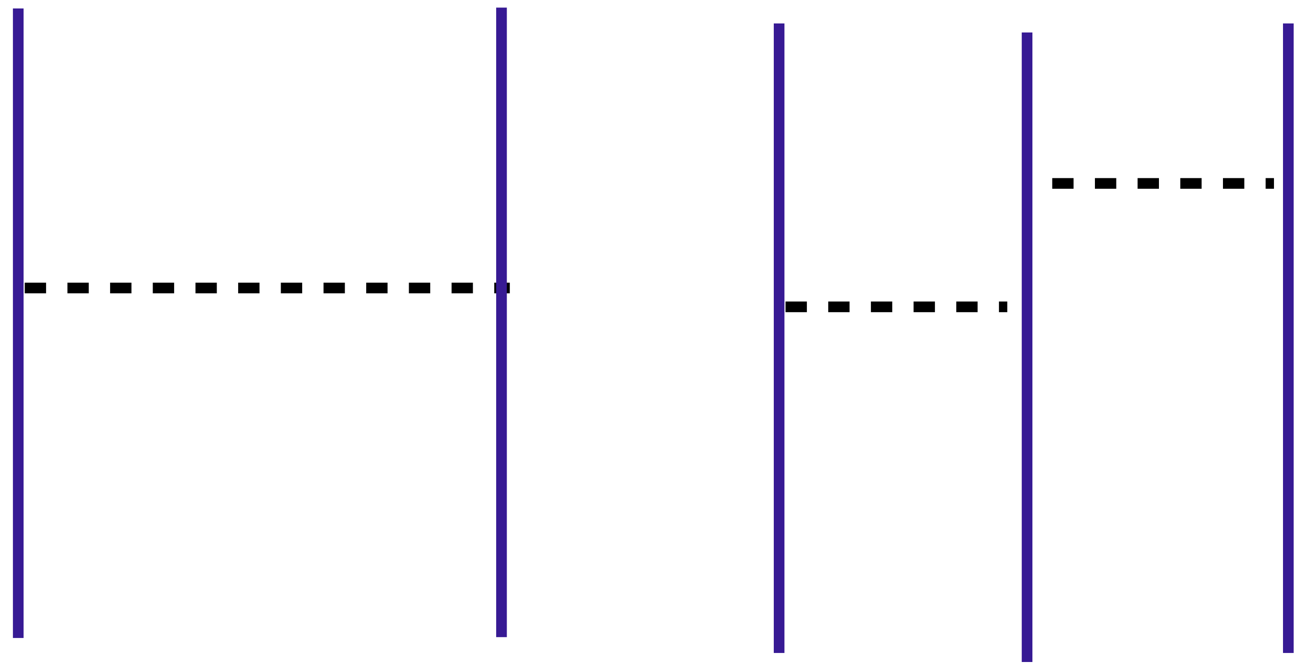
Requiring a maximum mass greater than 2 M_{sun} **implies:**

R > 9 km

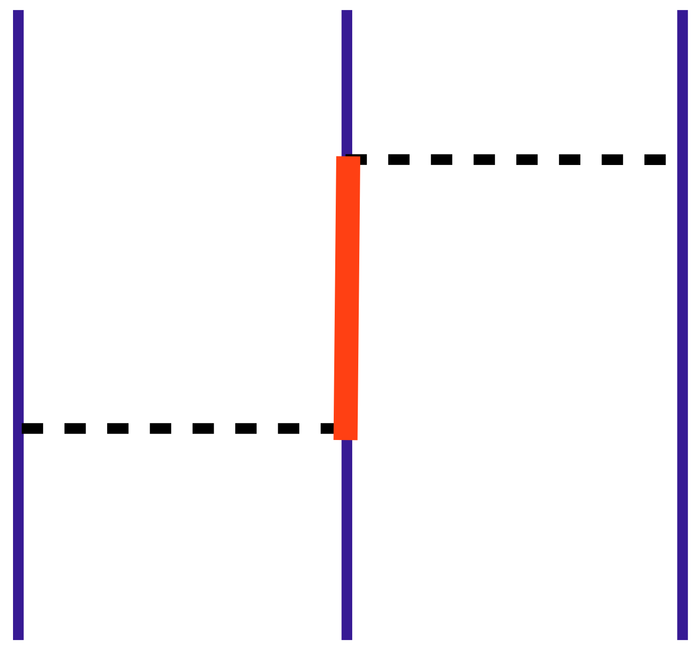
De et al. PRL (2018)
See also LIGO and Virgo Scientific Collaboration arXiV:1805.11581v1

Nuclear Interactions and Many Body Theory

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



two-body nucleon-nucleon potential is well constrained by scattering data.



three-neutron potential is not well constrained by data. Modern effective field theory (EFT) of nuclear interactions provides guidance.

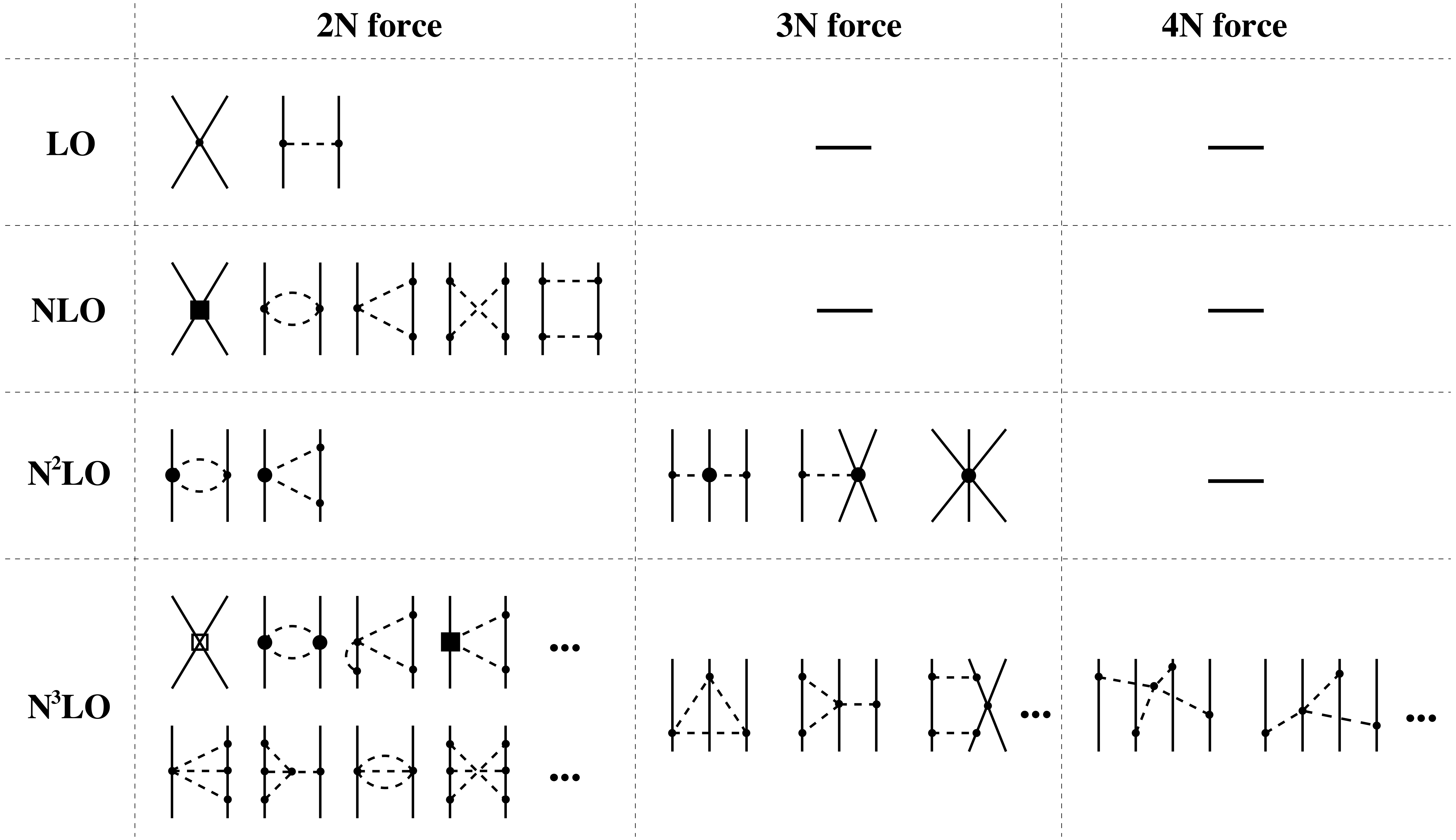
Quantum Many-Body Theory:

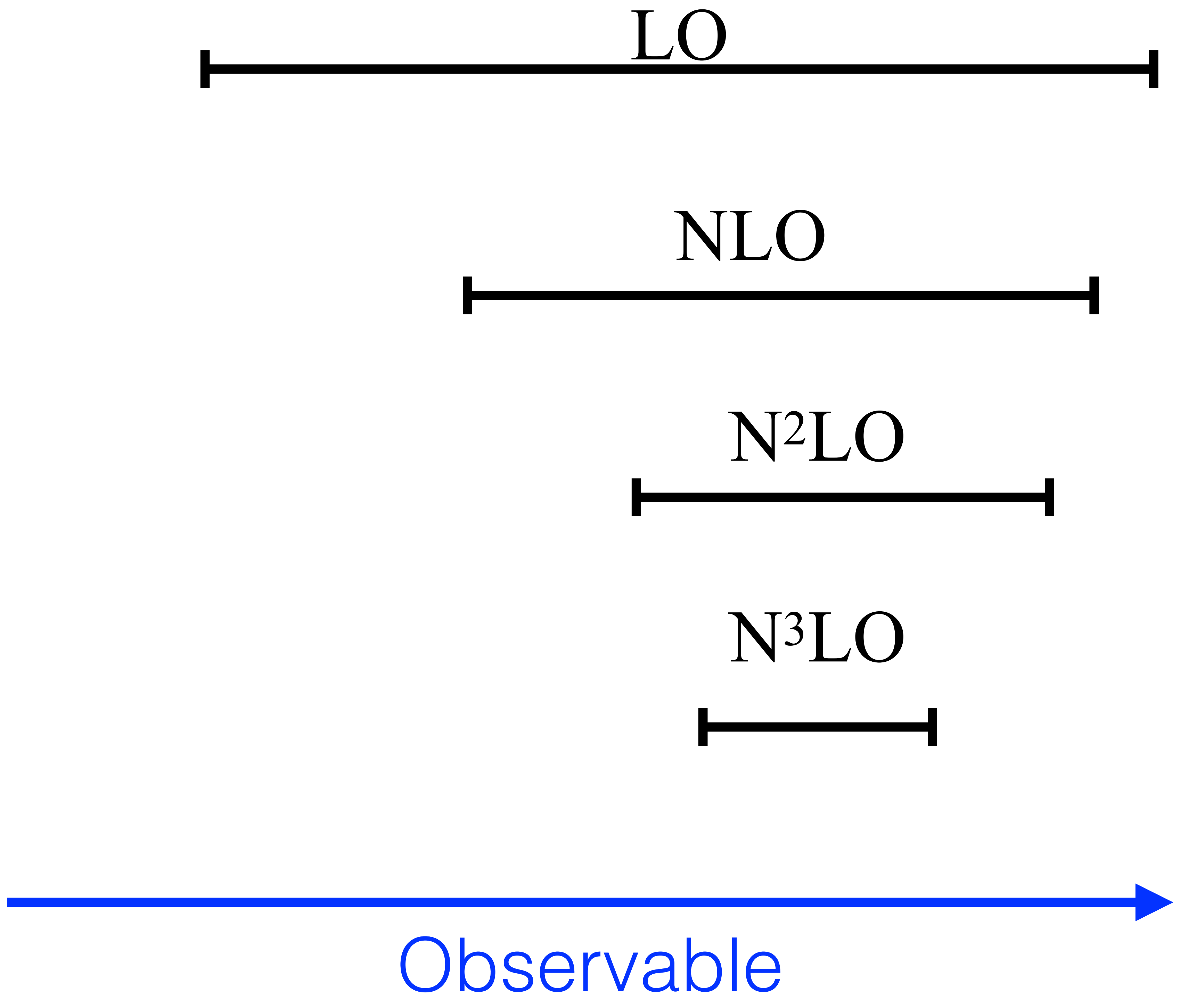
Quantum Monte Carlo
Many-Body Perturbation Theory
Coupled Cluster

$$\epsilon(n_n, n_p), P(n_n, n_p)$$

Modern NN & NNN Forces

EFT inspired 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 ..

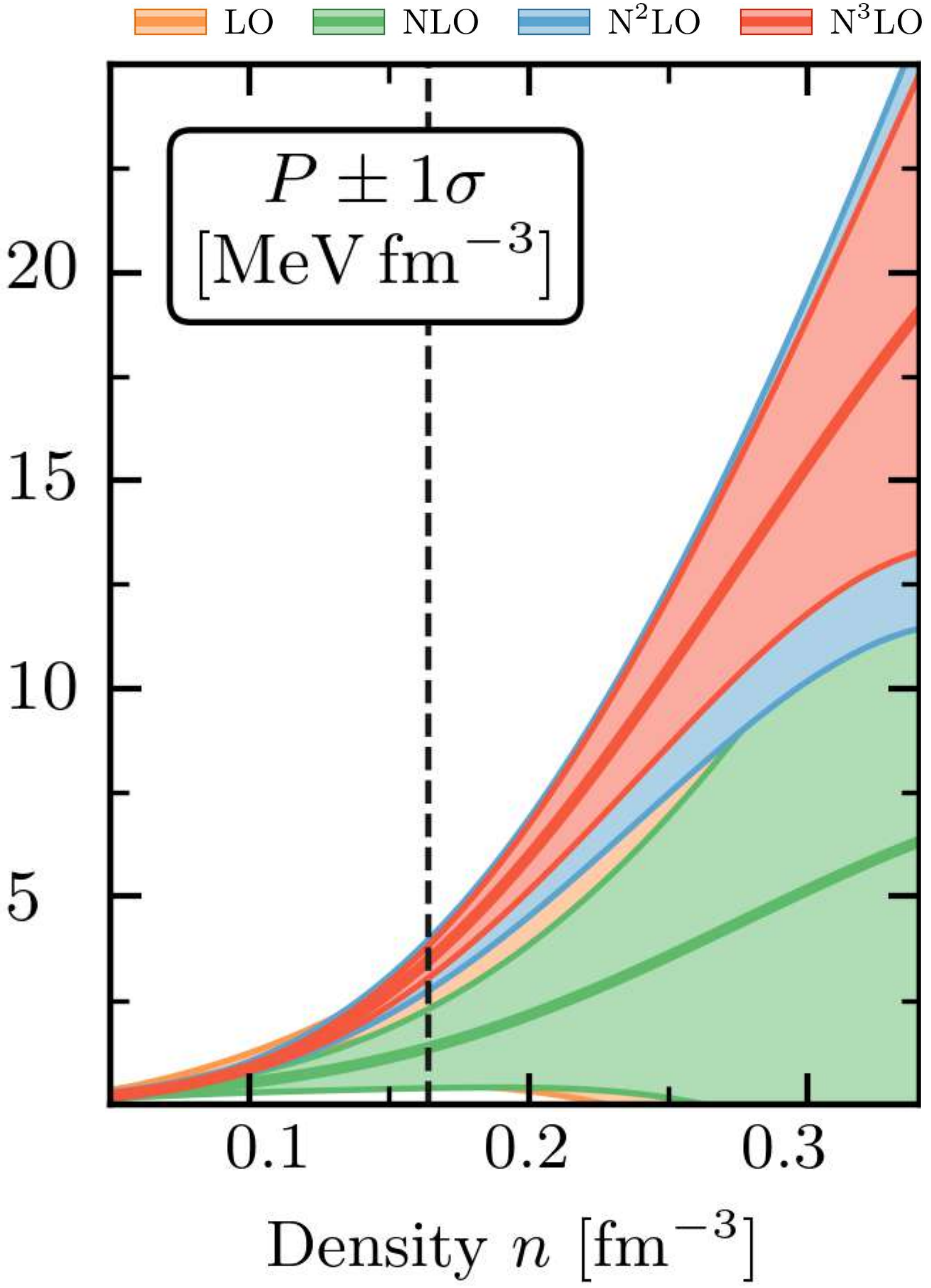
Equation of State of Neutron Matter

Quantum many-body calculations of neutron matter using EFT potentials appear to converge up to twice nuclear saturation density.

There remain some open questions about how to regulate the theory and best practicers to estimate errors.

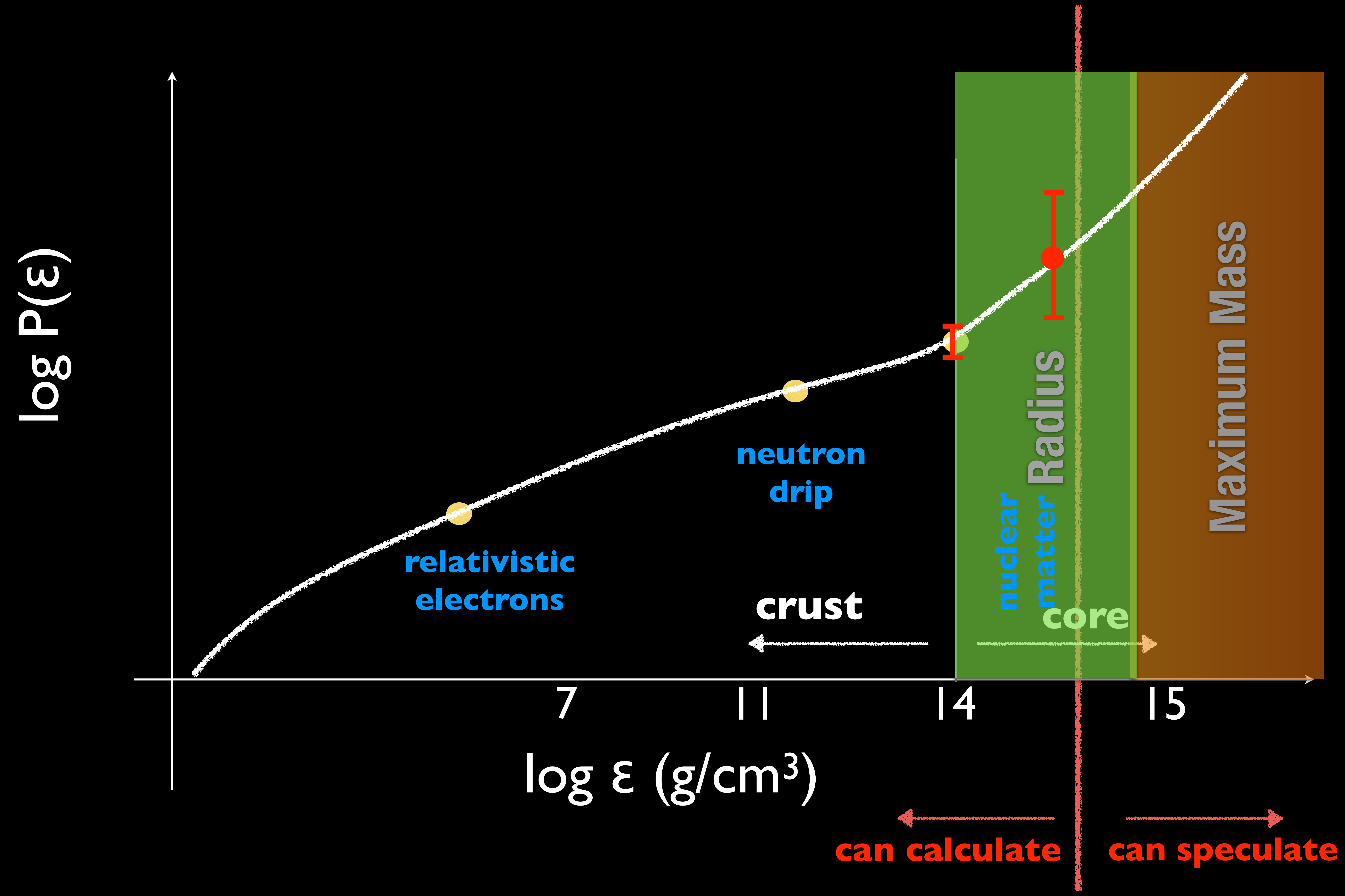
	Tews et al. (QMC, N^2LO)	Drischler et al. (MBPT)
$P(n_{sat})$	2.1 ± 0.7 MeV/fm^3	3.4 ± 0.7 MeV/fm^3
$P(2n_{sat})$	13 ± 7 MeV/fm^3	17 ± 4.5 MeV/fm^3

Hebeler and Schwenk 2009, Gandolfi, Carlson, Reddy 2010, 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, Furnstahl, Melendez, Phillips, (2020),



Drischler, Furnstahl, Melendez, Phillips (2020)

Constraints on the Equation of State



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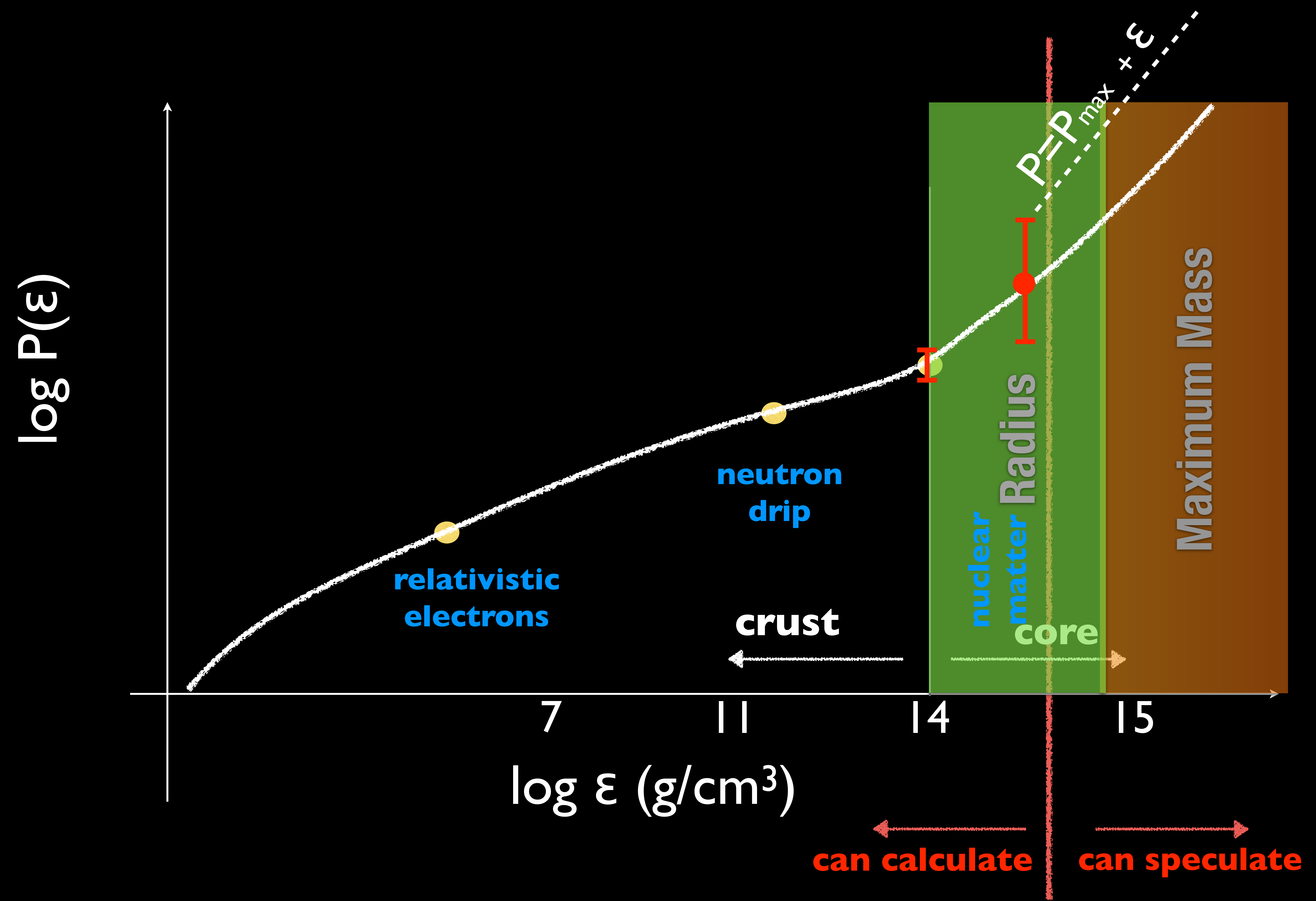

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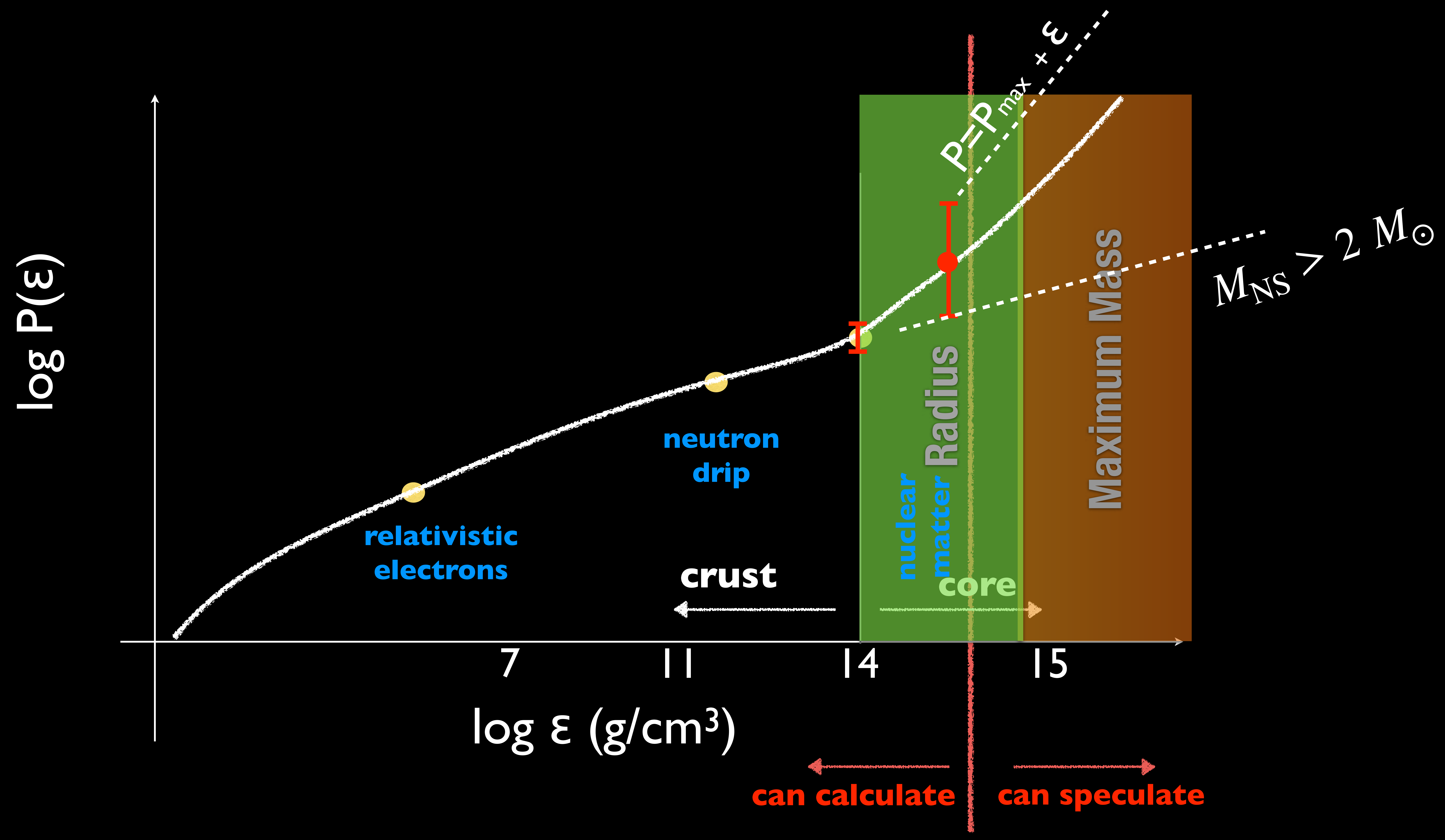
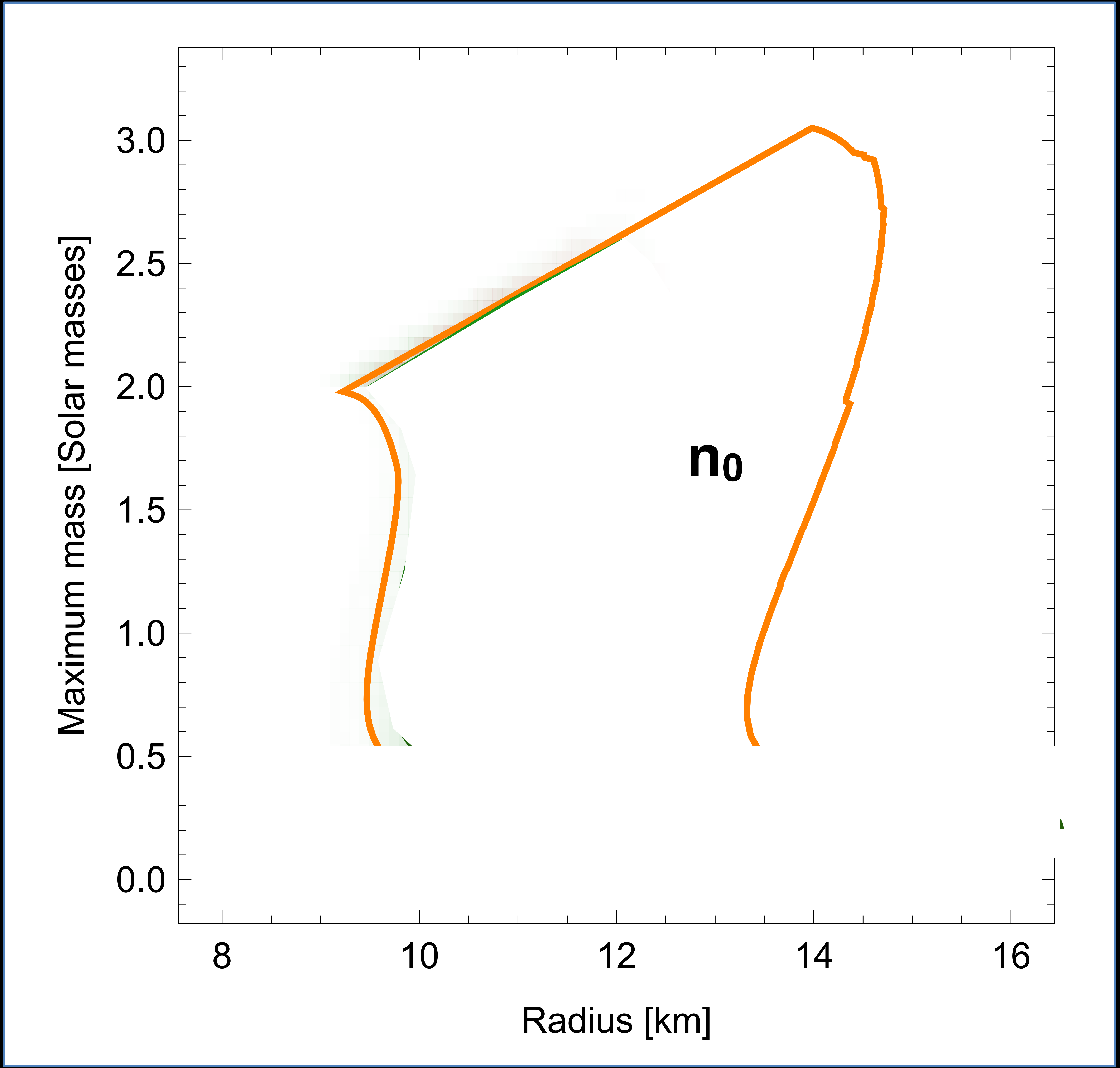


Dense matter EOS and NS structure

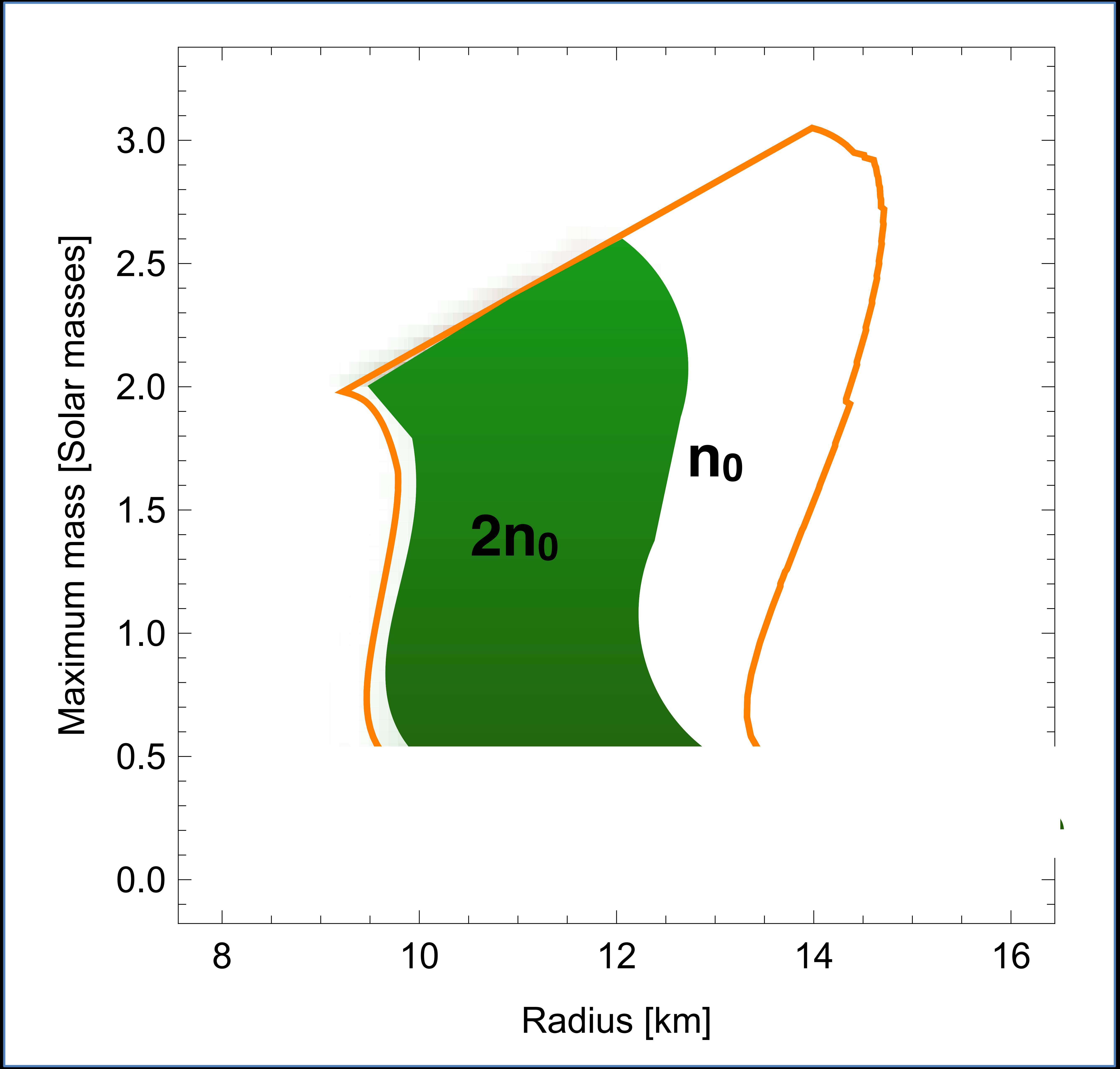
Neutron matter calculations and a general parameterization of the sound speed at higher density, constrained by 2 solar mass NS and $c_s < c$, constrain NS structure.



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

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 $c_s < c$, constrain NS structure.



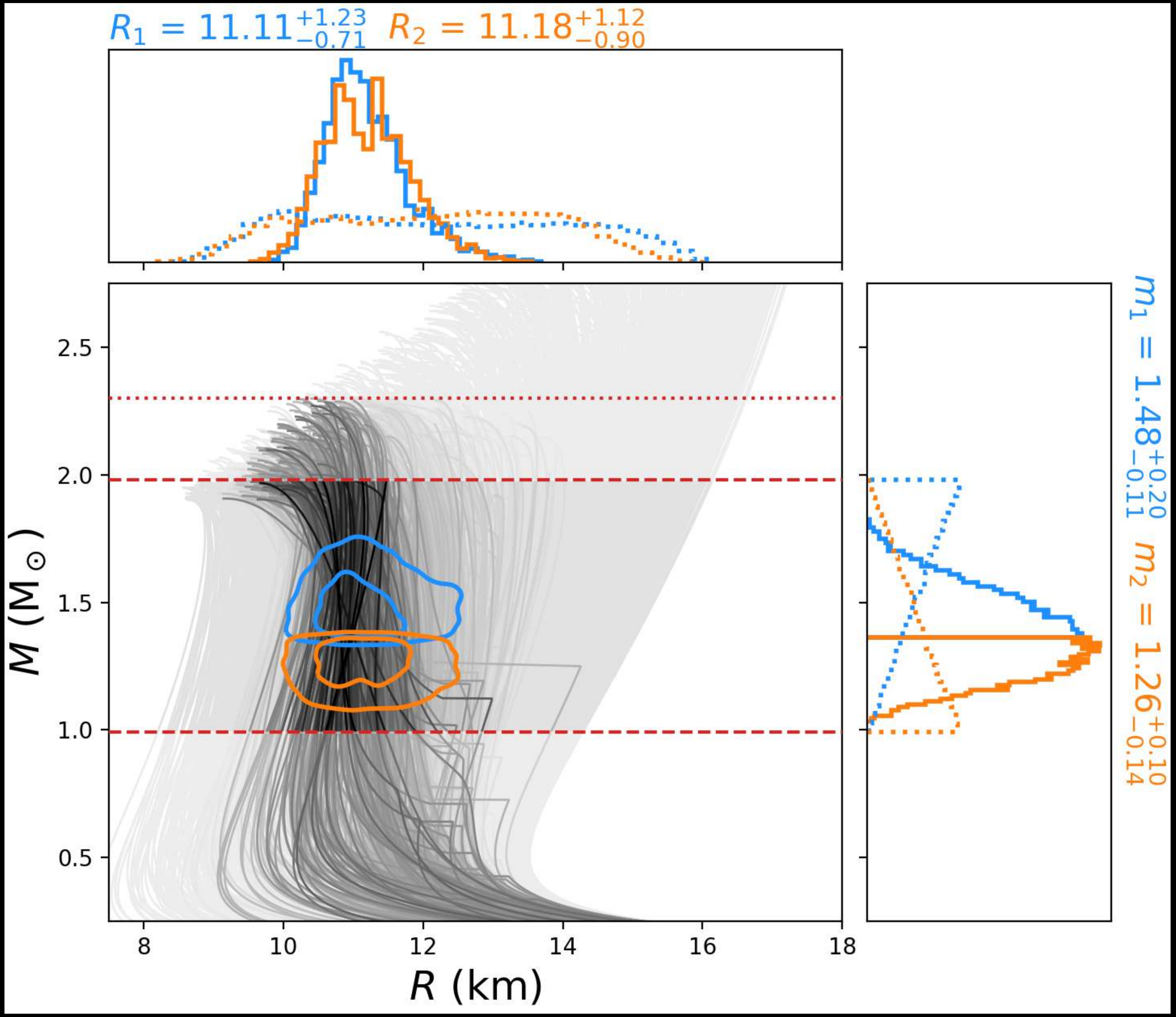
Tews, Gandolfi, Carlson, Reddy (2018), Tews, Margueron, Reddy (2018)
Hebeler, Schwenk, Lattimer and Pethick (2010,2013) and Carlson, Gandolfi, Reddy (2012)

Tighter Constraints: Combining Nuclear Physics and GW170817

Nuclear physics input correlates the neutron stars in the binary and provides an informed prior for GW data analysis. Helps extract stringent constraints on the NS radius:

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

Lower bound is set by EM observations that disfavor the prompt collapse to a black-hole.



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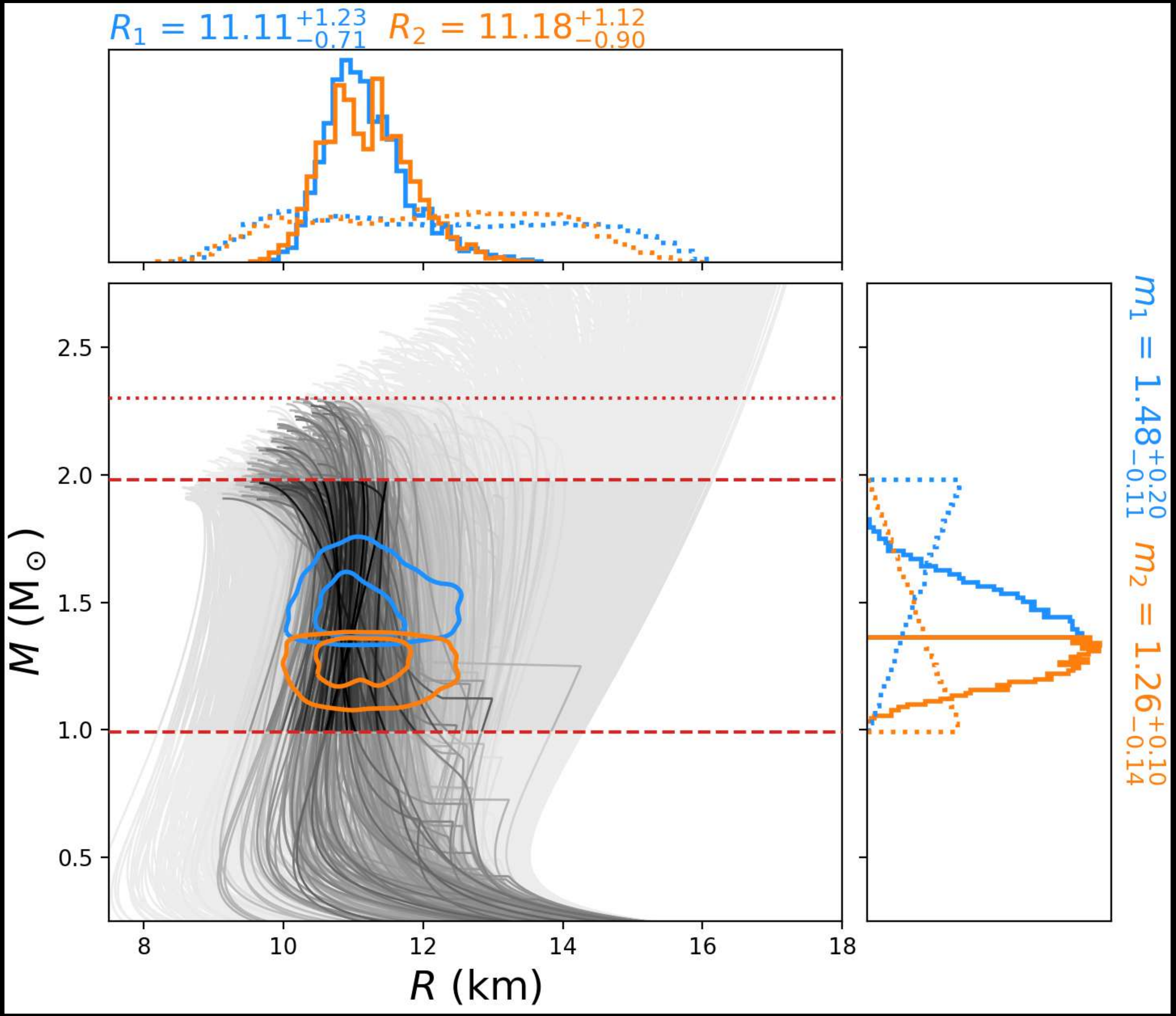

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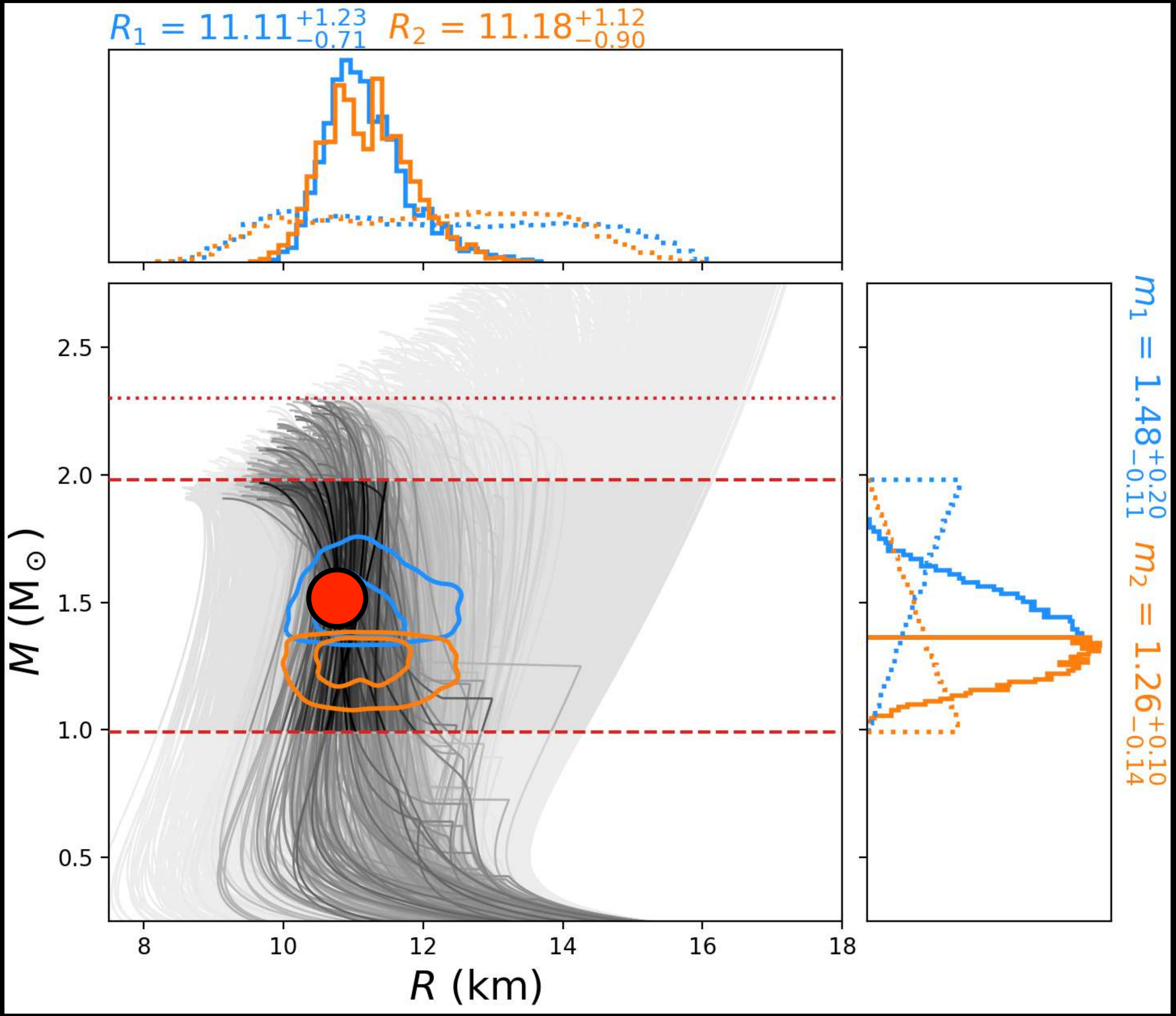

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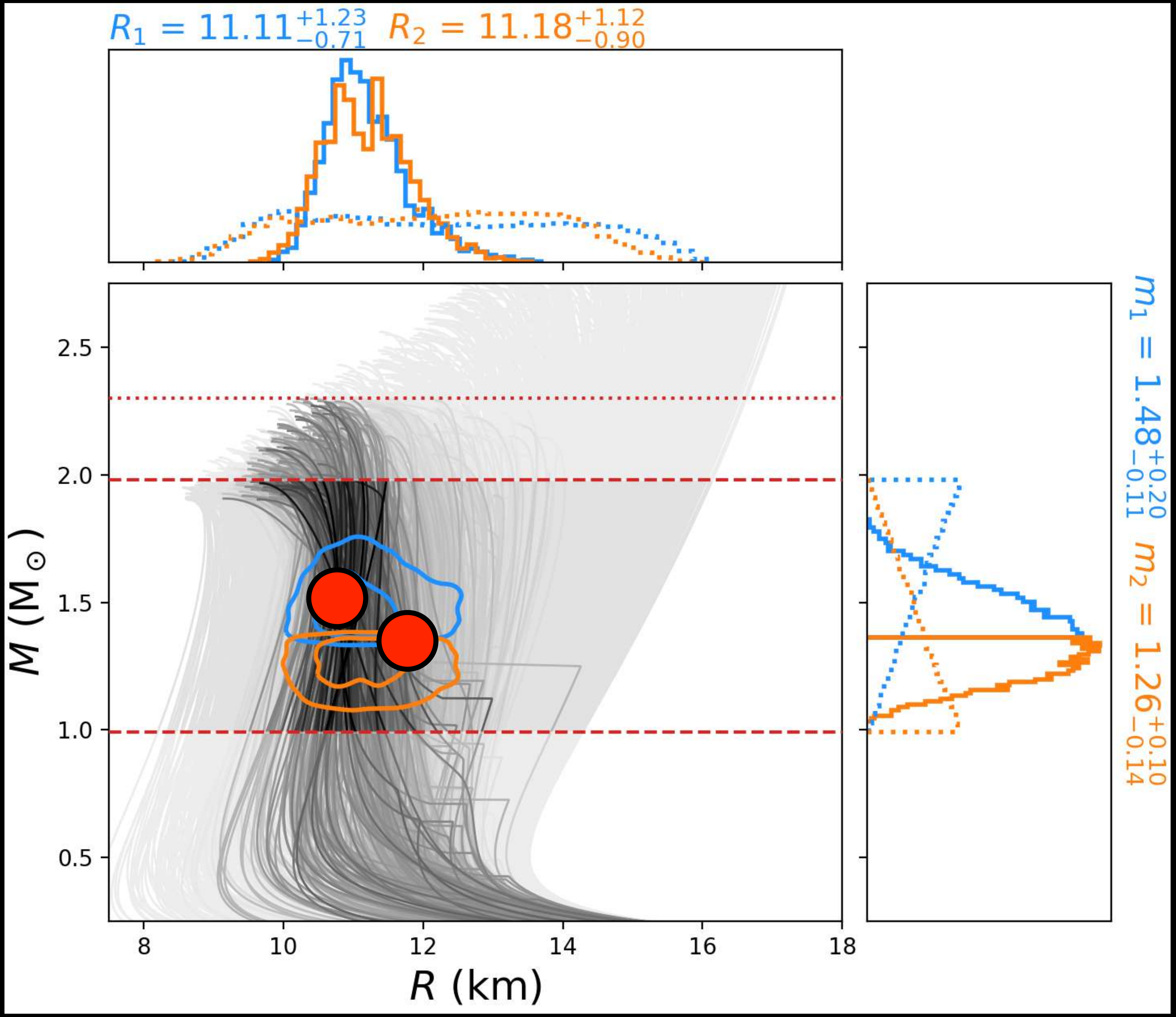

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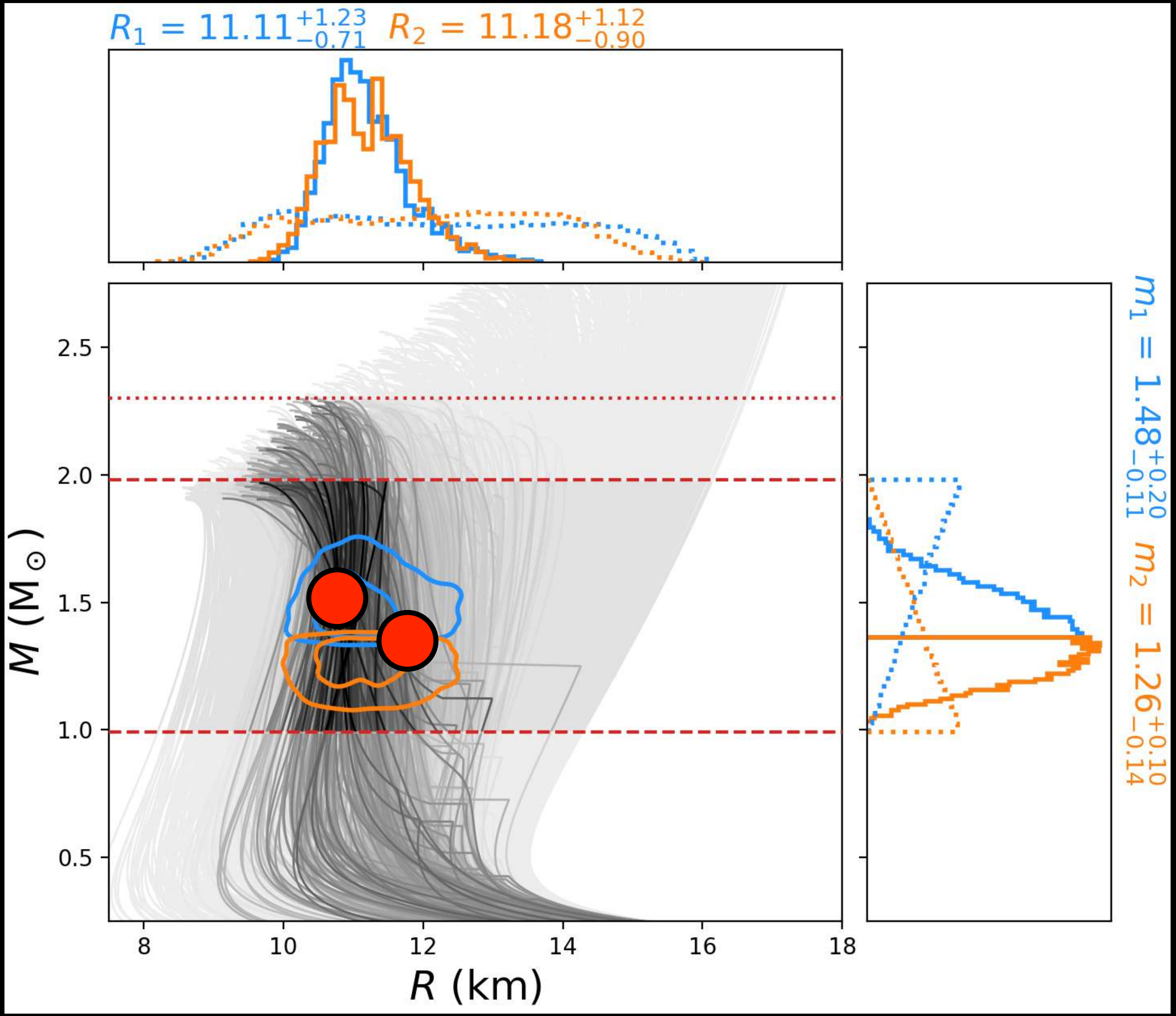
With tighter constraints we could discover phase transitions in the core.



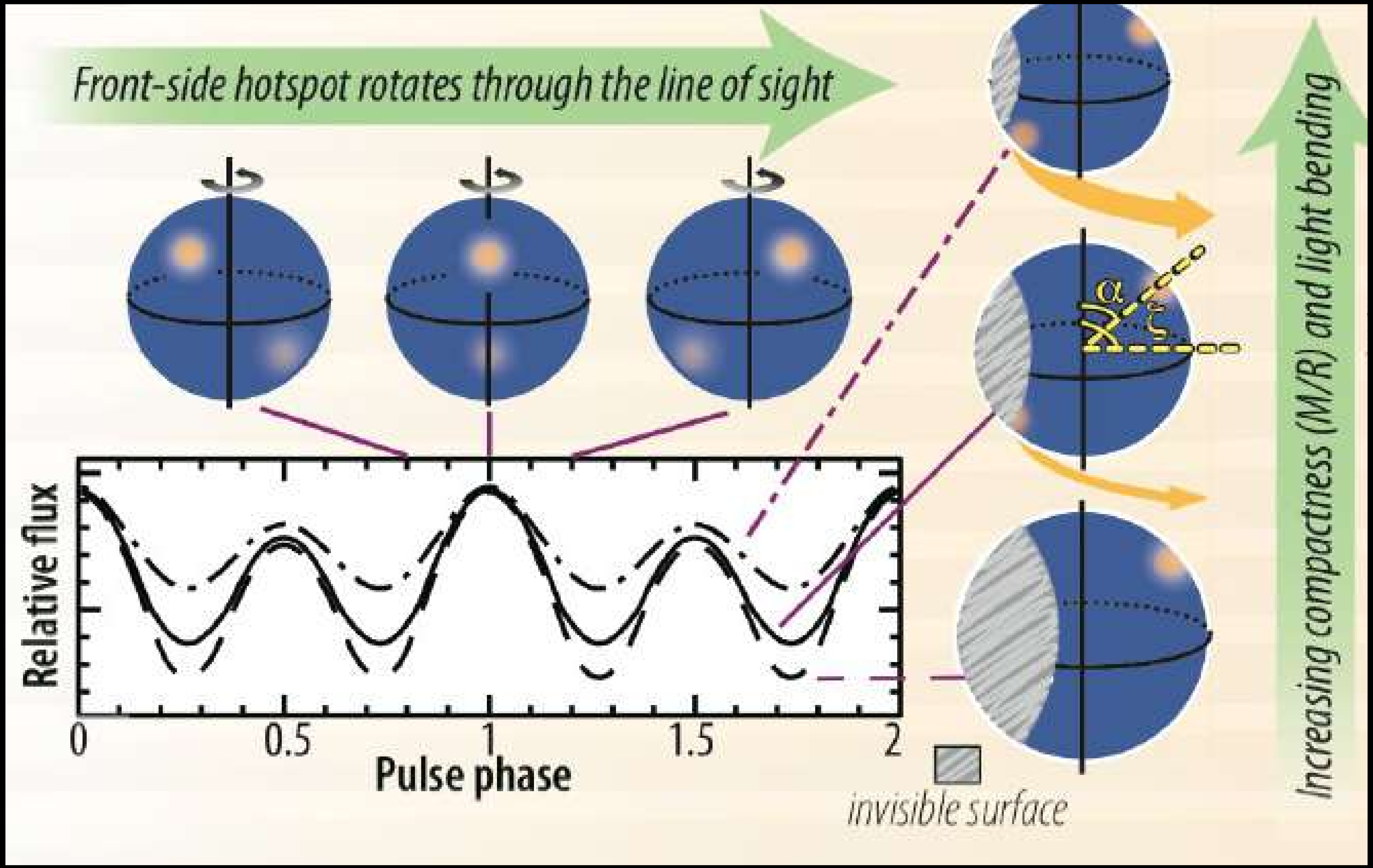
NICER: Radii from Hot Spots

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

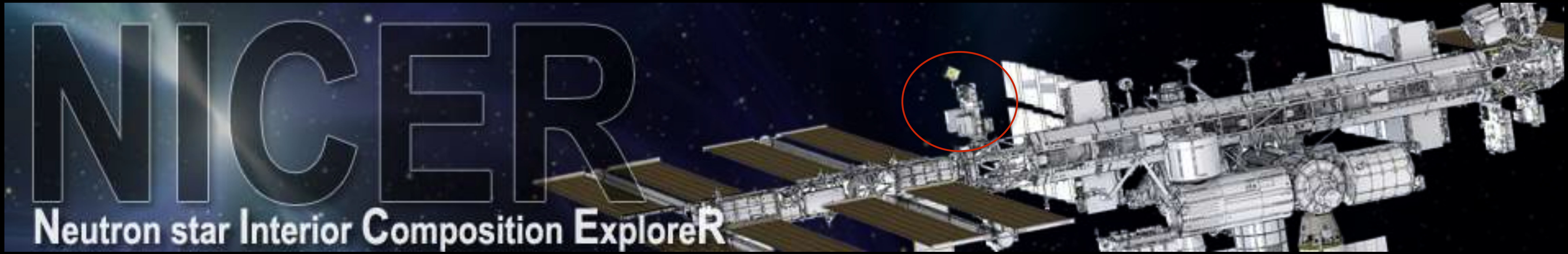
X-ray pulse profiles contain information about the source compactness.

NASA’s NICER mission has acquired data from a couple of neutron stars. Data analyzed from one source is compatible with GW170817 but favors larger radii with larger errors.

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



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



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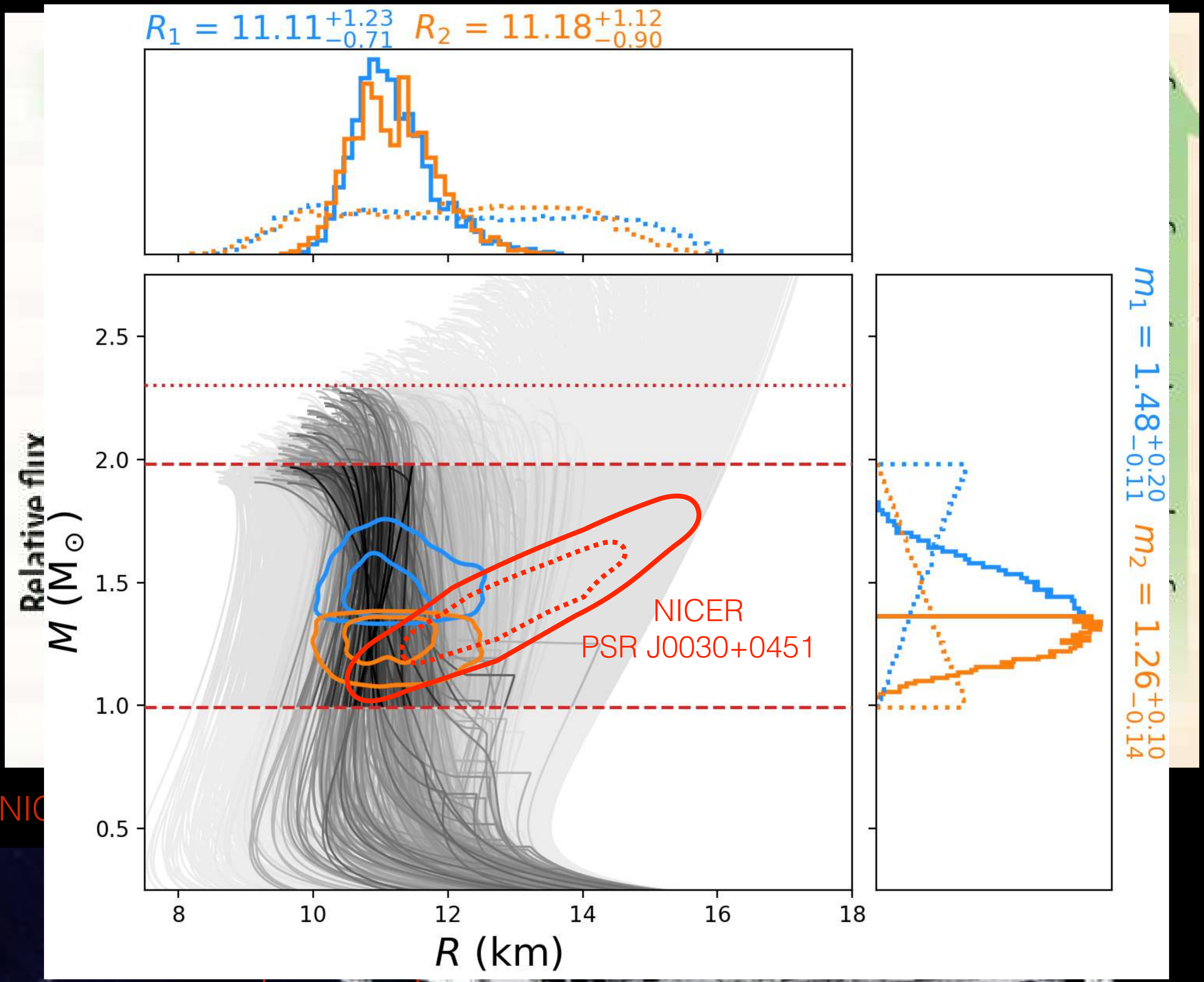
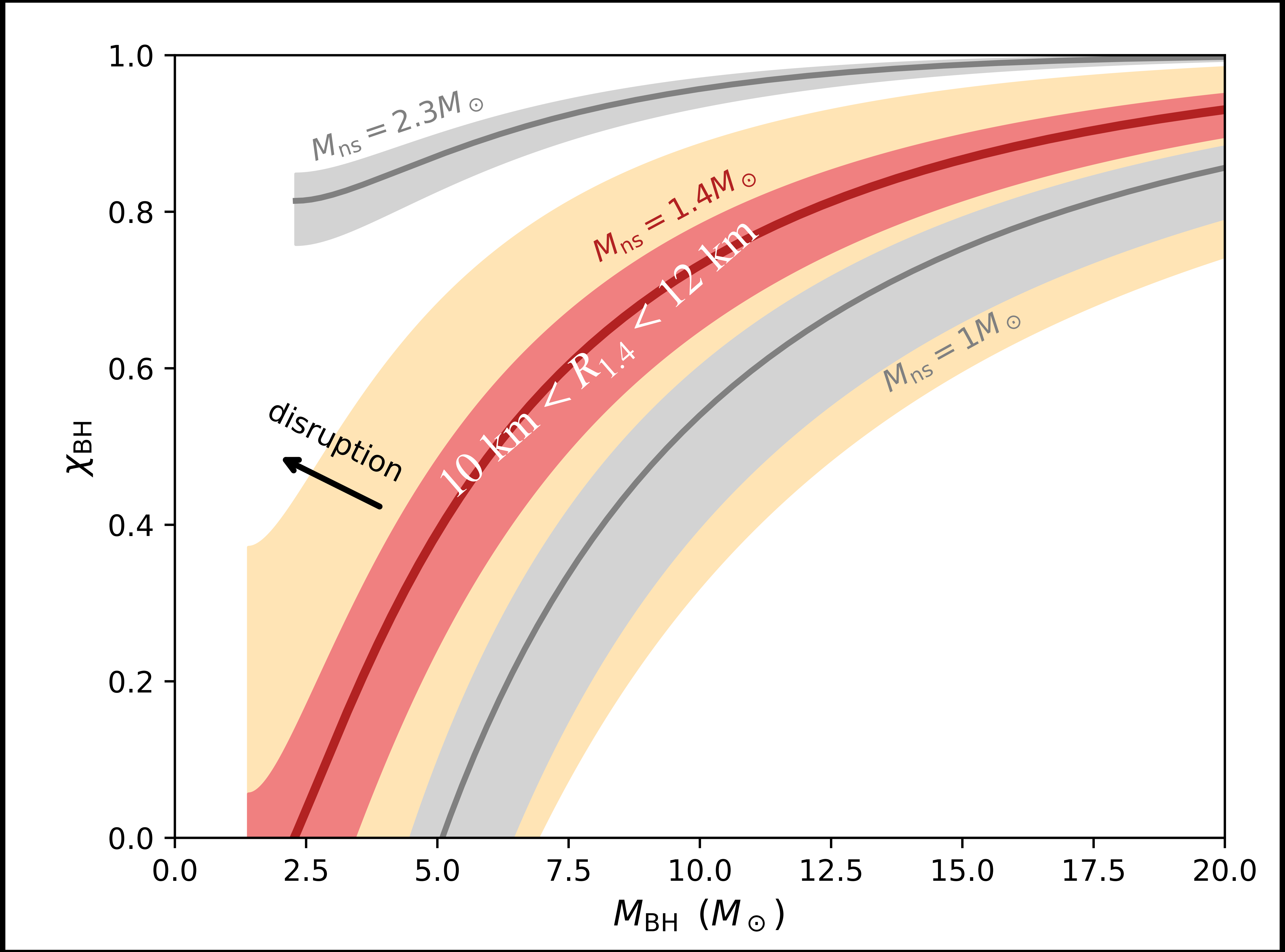


A Small Radius (R< 12 kms) has Many Astrophysical Implications:

- It impacts the interpretation of x-ray emission from neutron stars.
- It affects the size of the neutron crust and associated observables.
- Impacts the neutron star maximum mass and dynamics of neutron star mergers.
- Influences the amount of material ejected during mergers and nucleosynthesis.
- Determines if mergers involving neutron stars and black-holes can produce EM signals.



Disruption of a NS in NS-BH collisions

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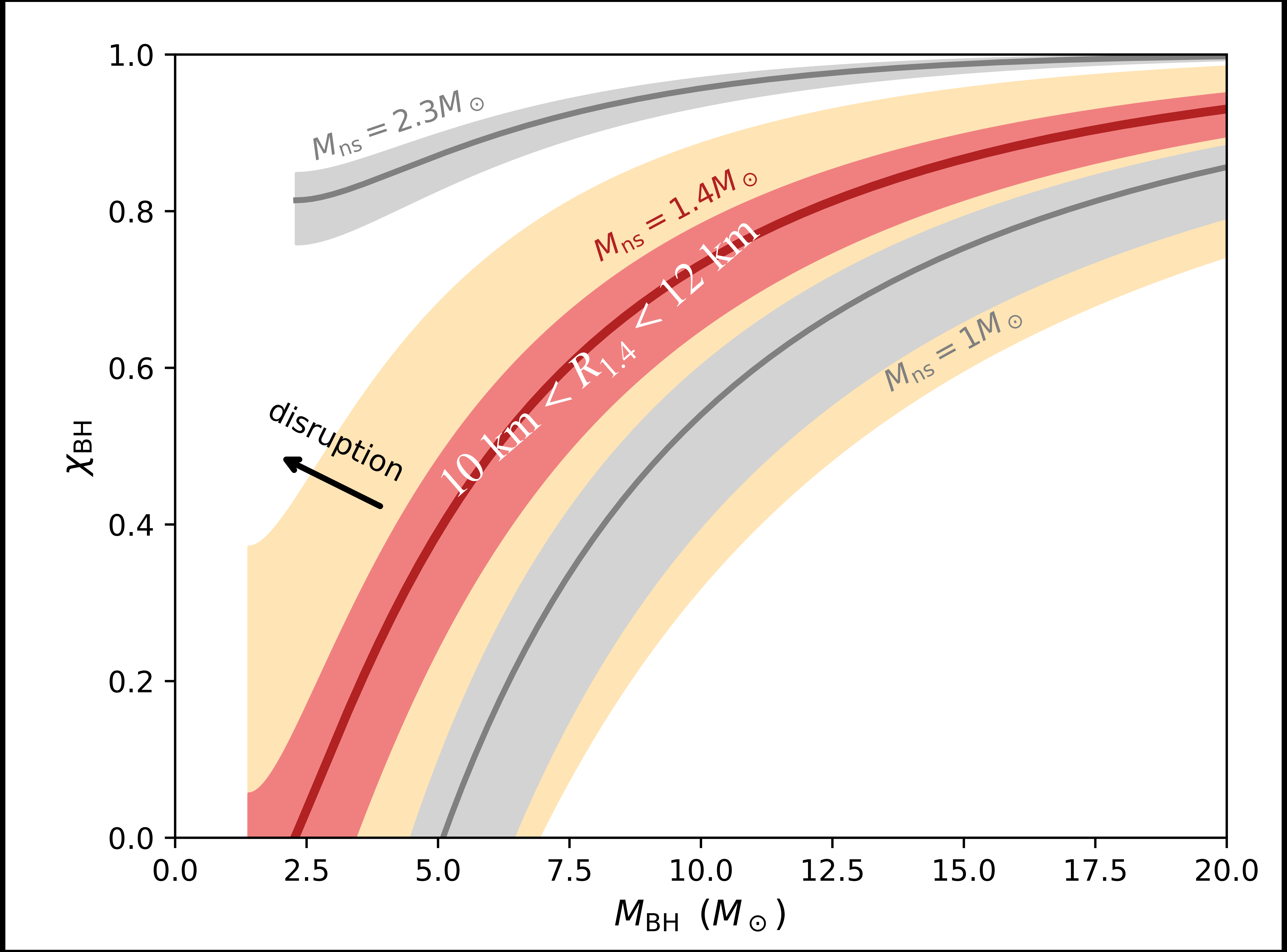


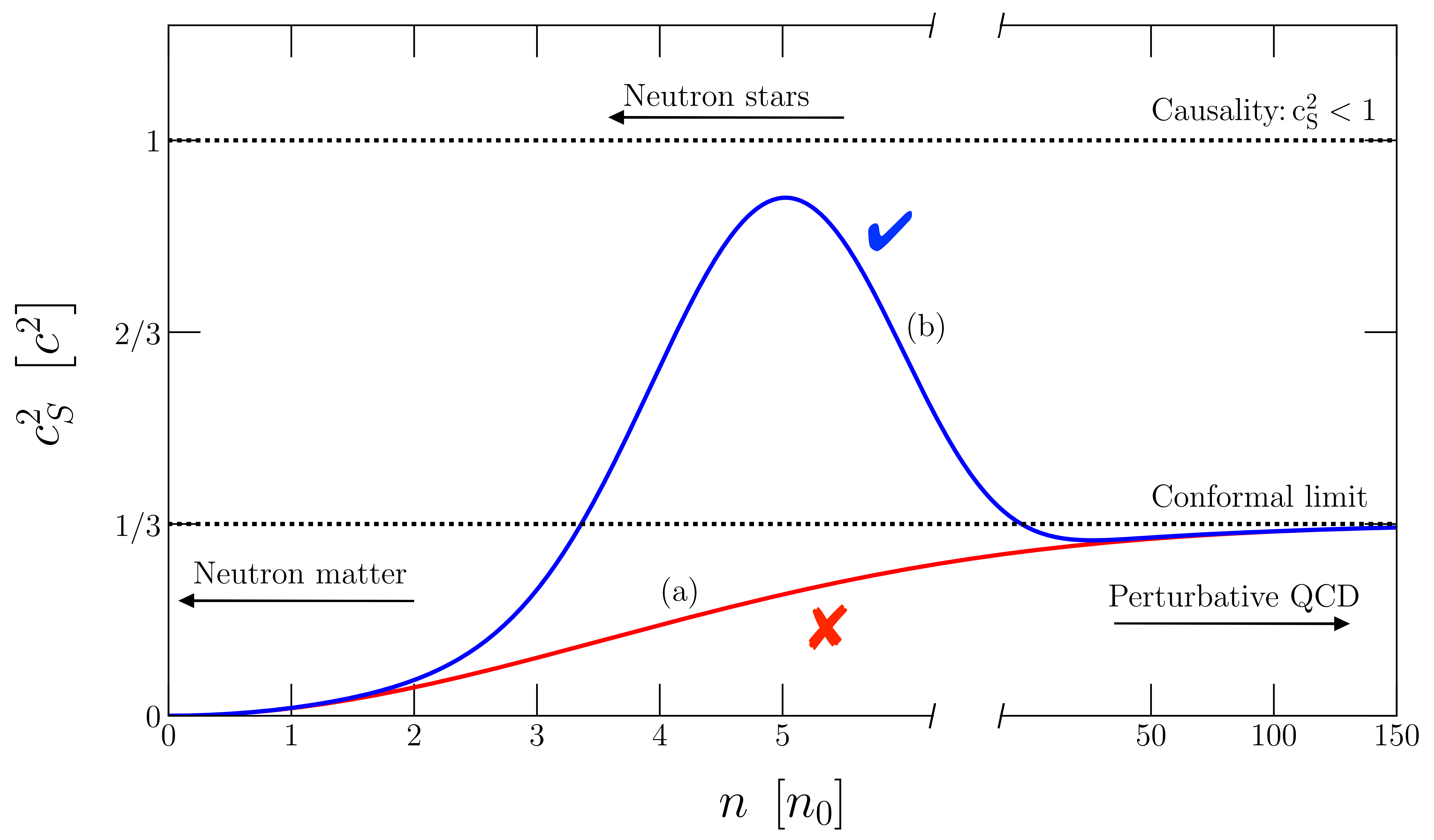
Disruption of a NS in NS-BH collisions

Capano et al. (2019)

Speed of Sound in Dense Matter

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

Large 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.



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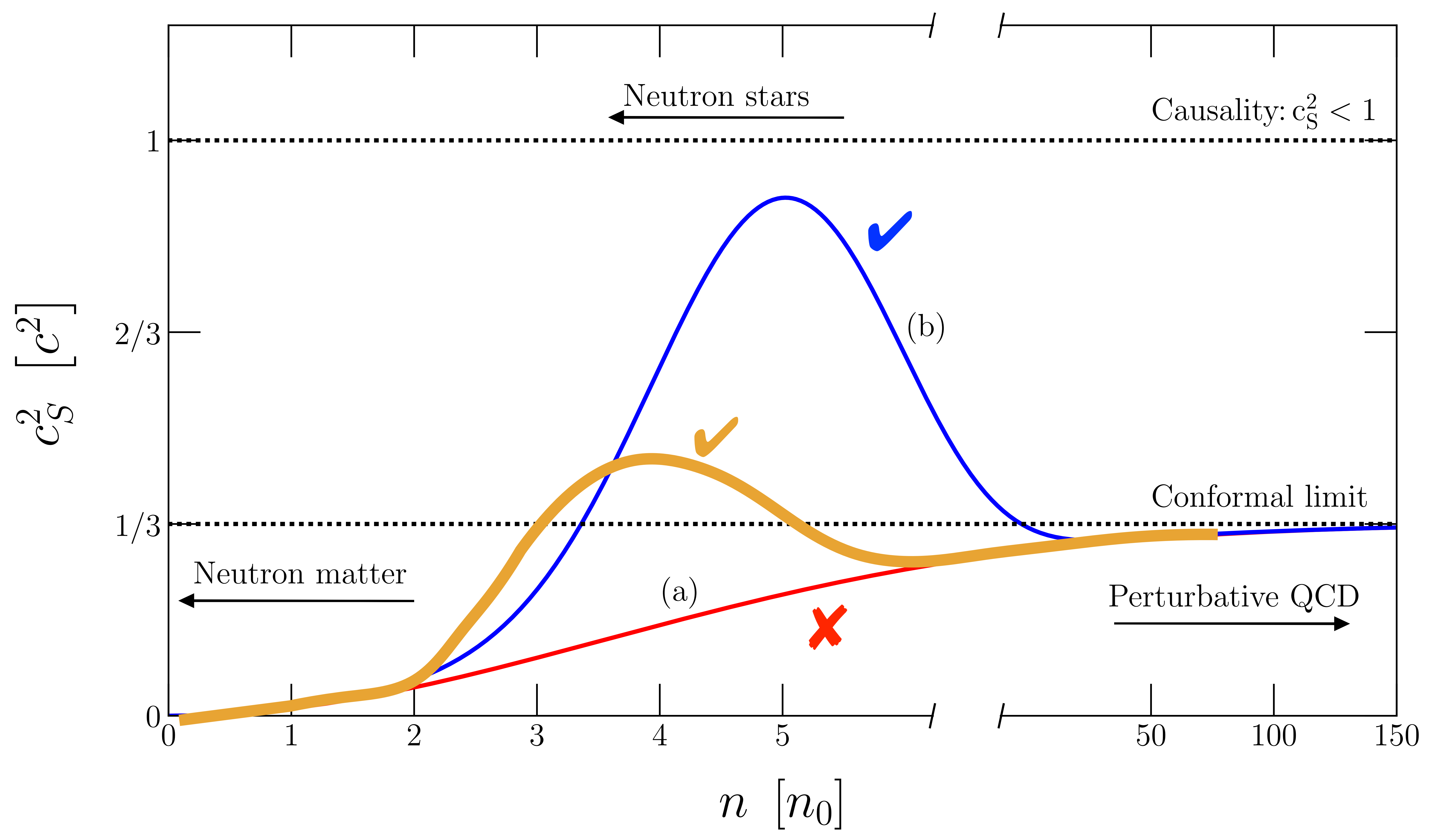

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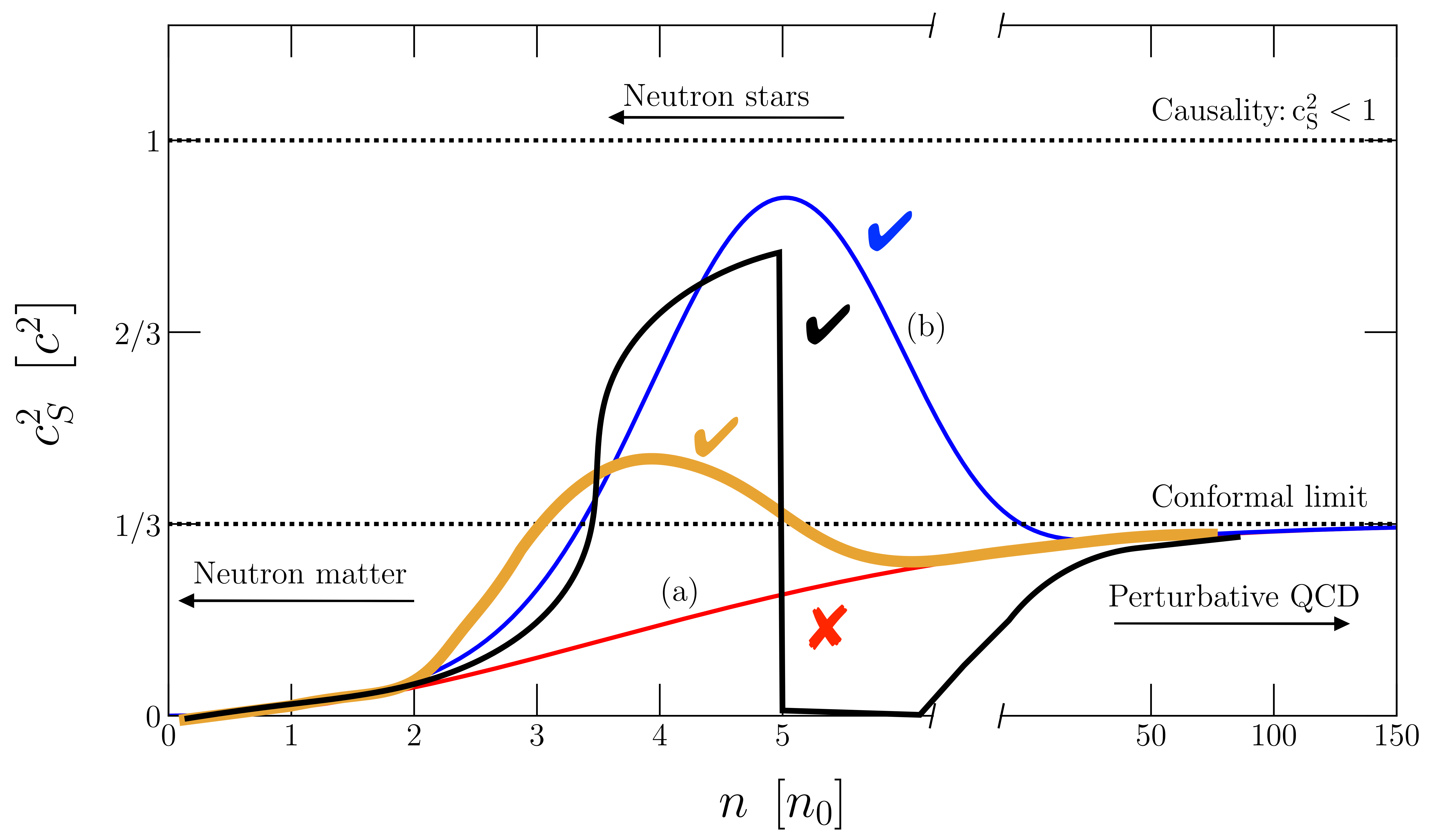

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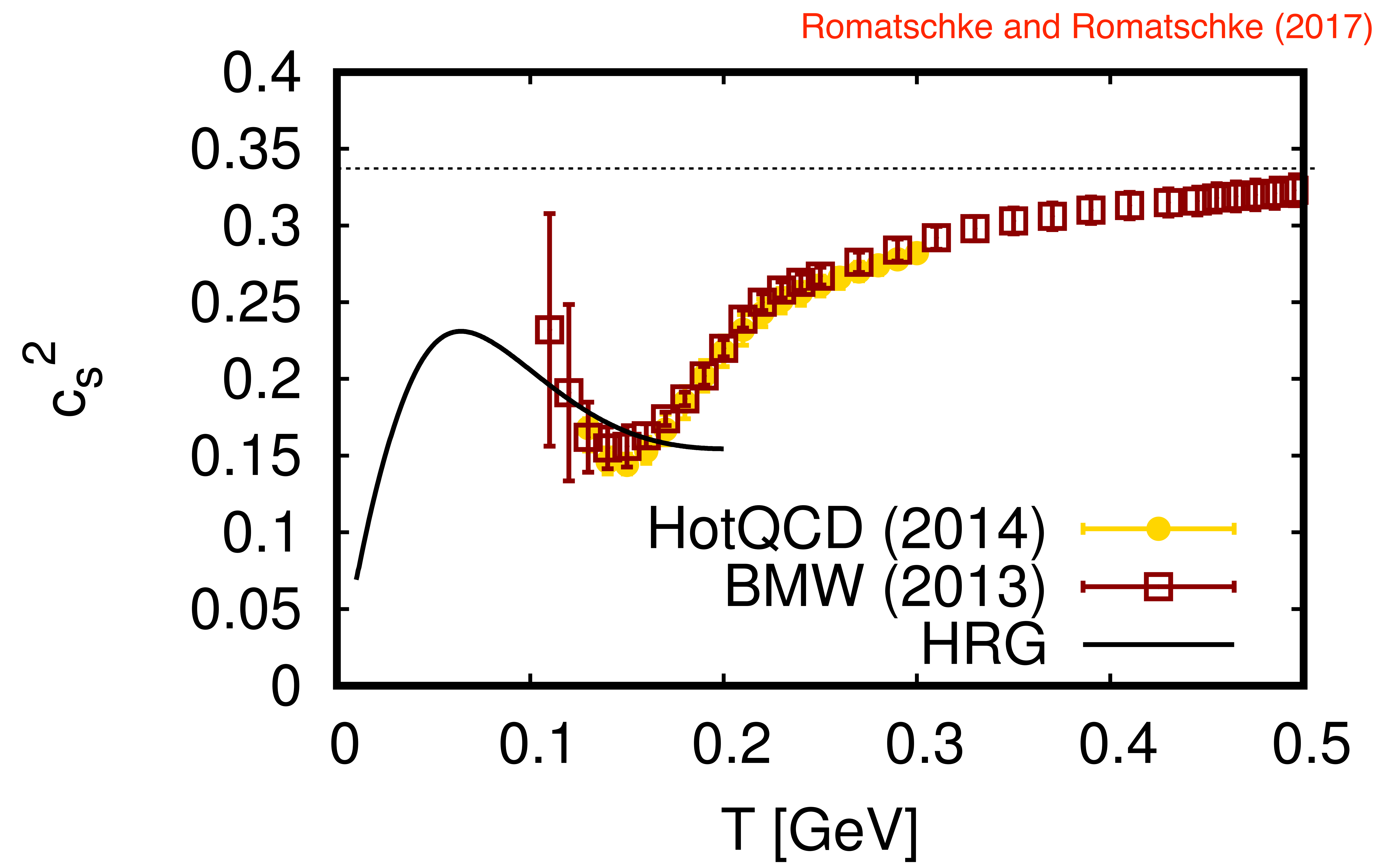
Speed of Sound in QCD at Finite Temperature

The speed of sound at zero baryon density and finite temperature can be determined using Lattice QCD calculations of the EOS (and experimental extractions from hydrodynamic flow observed in heavy-ion collisions).

Also shows non-monotonic behavior but remains small.

$$c_S^2 < \frac{1}{3}$$


Romatschke and Romatschke (2017)

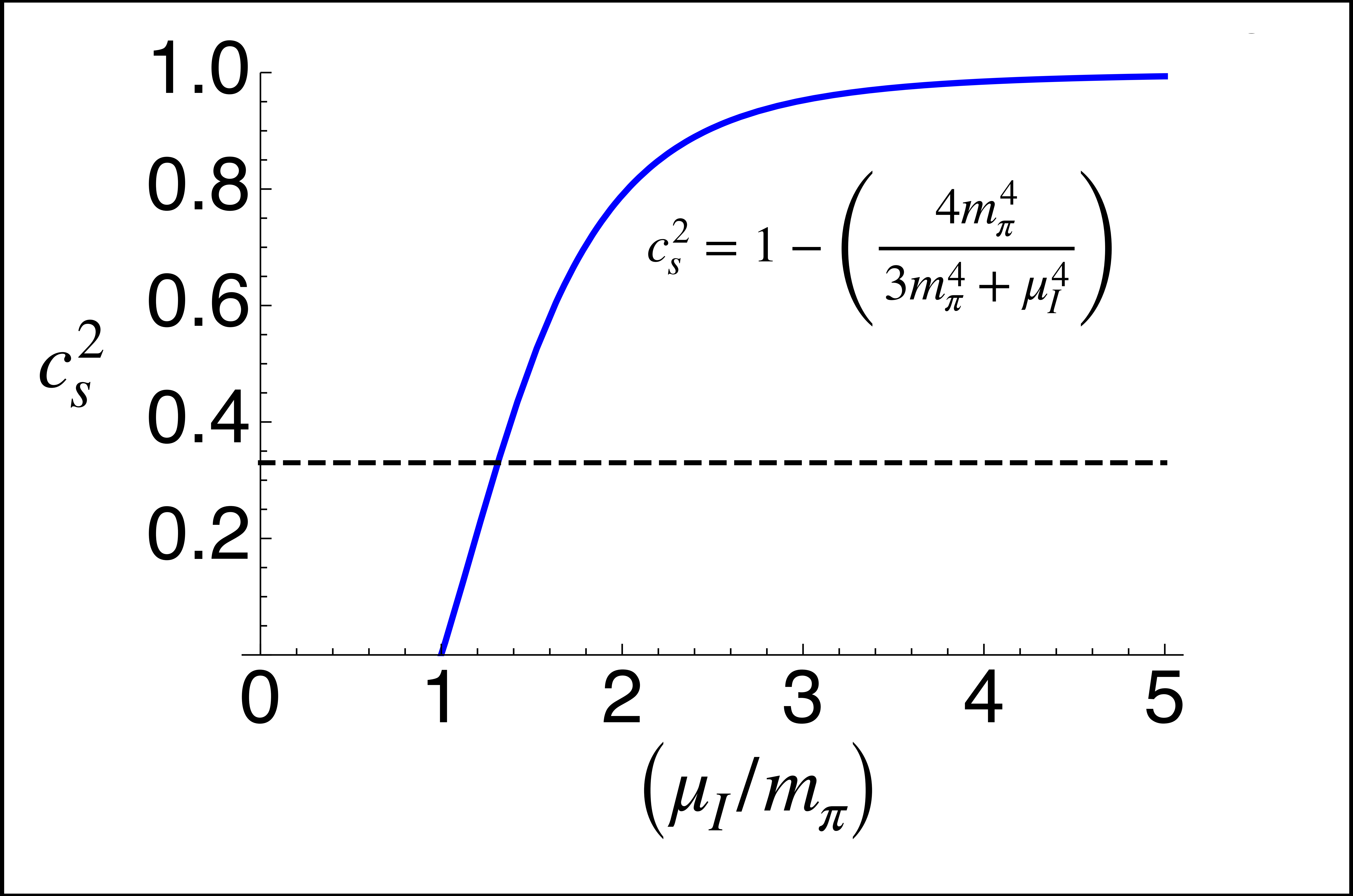
Borsanyi, Fodor, Hoelbling, Katz, Krieg, and Szabo., (2014)
Borsanyi, Endrodi, Fodor, Jakovac, Katz, Krieg, Ratti, and Szabo (2010).
Bazavov et al. (2014)

Speed of Sound in QCD at Finite Isospin Density

Controlled calculations of QCD matter with a finite isospin chemical potential predict a large speed of sound at relatively low isospin density.

$$c_S^2 \simeq 1$$

Both Chiral Perturbation Theory and Lattice QCD have been used to describe the pion condensed ground state and are in remarkable agreement.



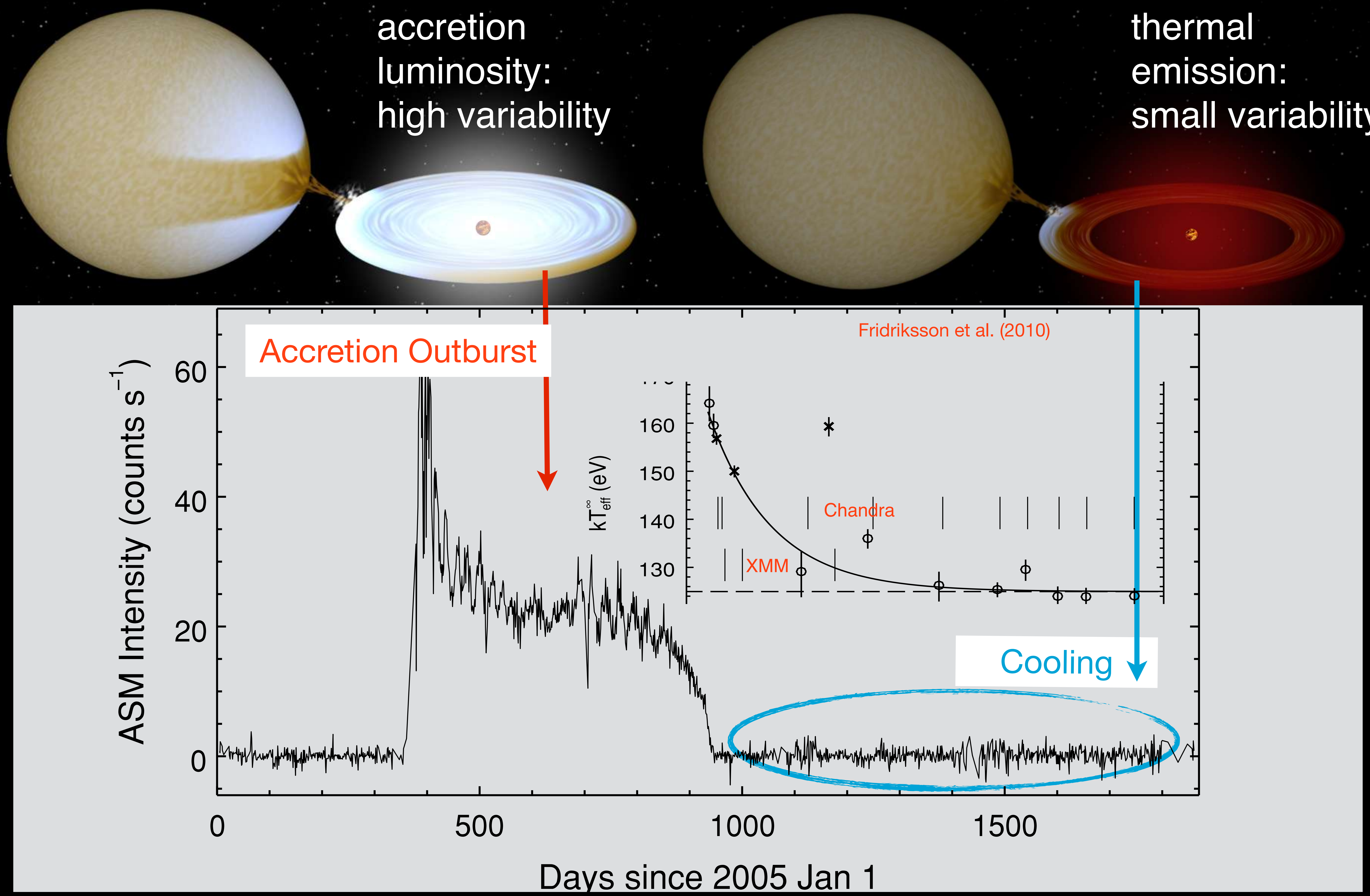
Son and Stephanov (2001)
Detmold, Savage, Torok, Beane, Luu, Orginos, Parreno (NPLQCD) (2008)

Neutron Star Dynamics

Accreting Neutron Stars: Nature’s Low Temperature Laboratory

Neutron Star Mergers: Hottest and Densest Matter in the Universe

Transiently Accreting Neutron Stars



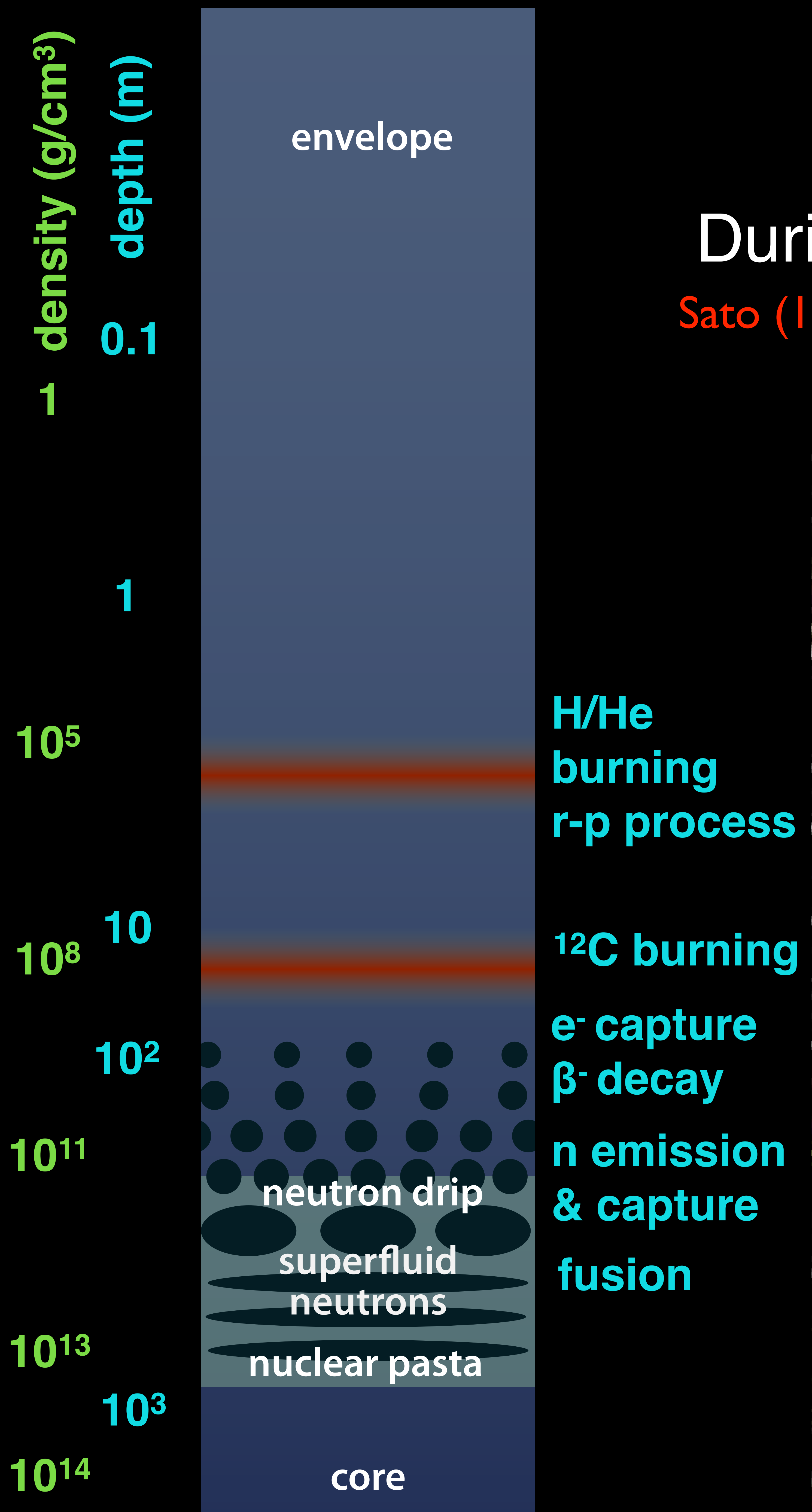
accretion
luminosity:
high variability

thermal
emission:
small variability

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).



density (g/cm^3)

depth (m)

0.1

1

1

10^5

10

10^8

10^2

10^{11}

10^{13}

10^3

10^{14}

envelope

neutron drip

superfluid neutrons

nuclear pasta

core

H/He burning r-p process

^{12}C burning

e$^-$ capture
β$^-$ decay

n emission & capture

fusion

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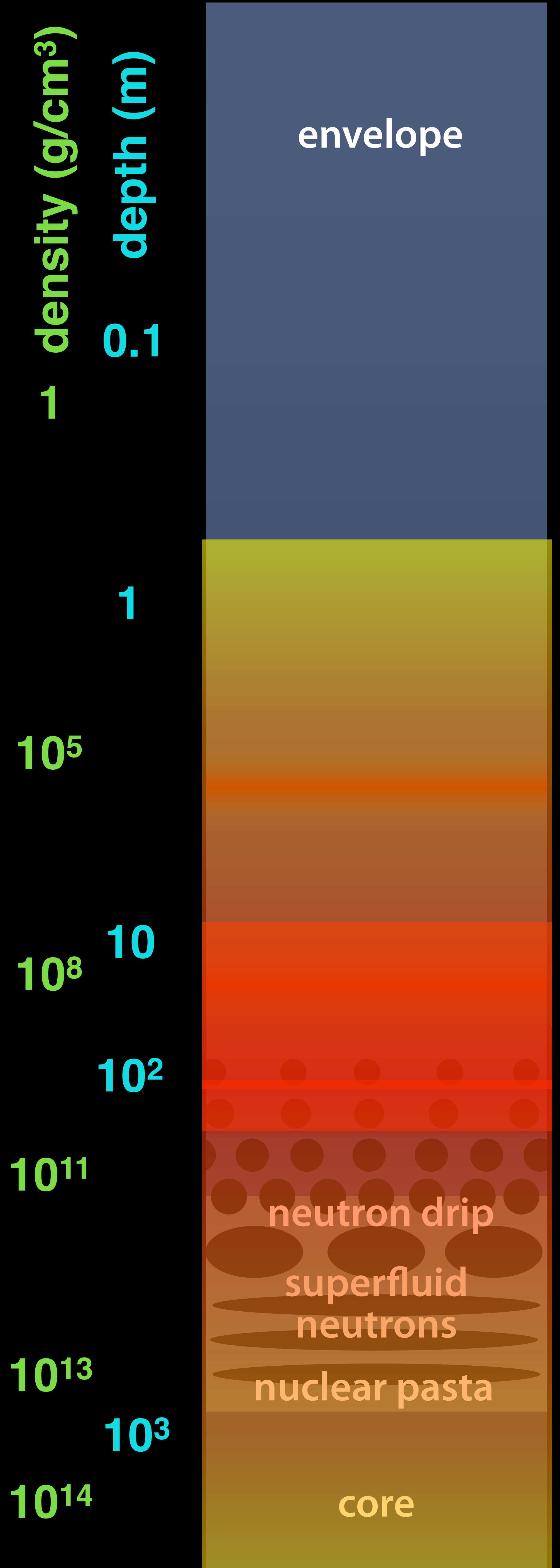


H/He burning r-p process

^{12}C burning

e$^-$ capture

β$^-$ decay

n emission & capture

fusion

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 is set by heat transport in the inner crust.

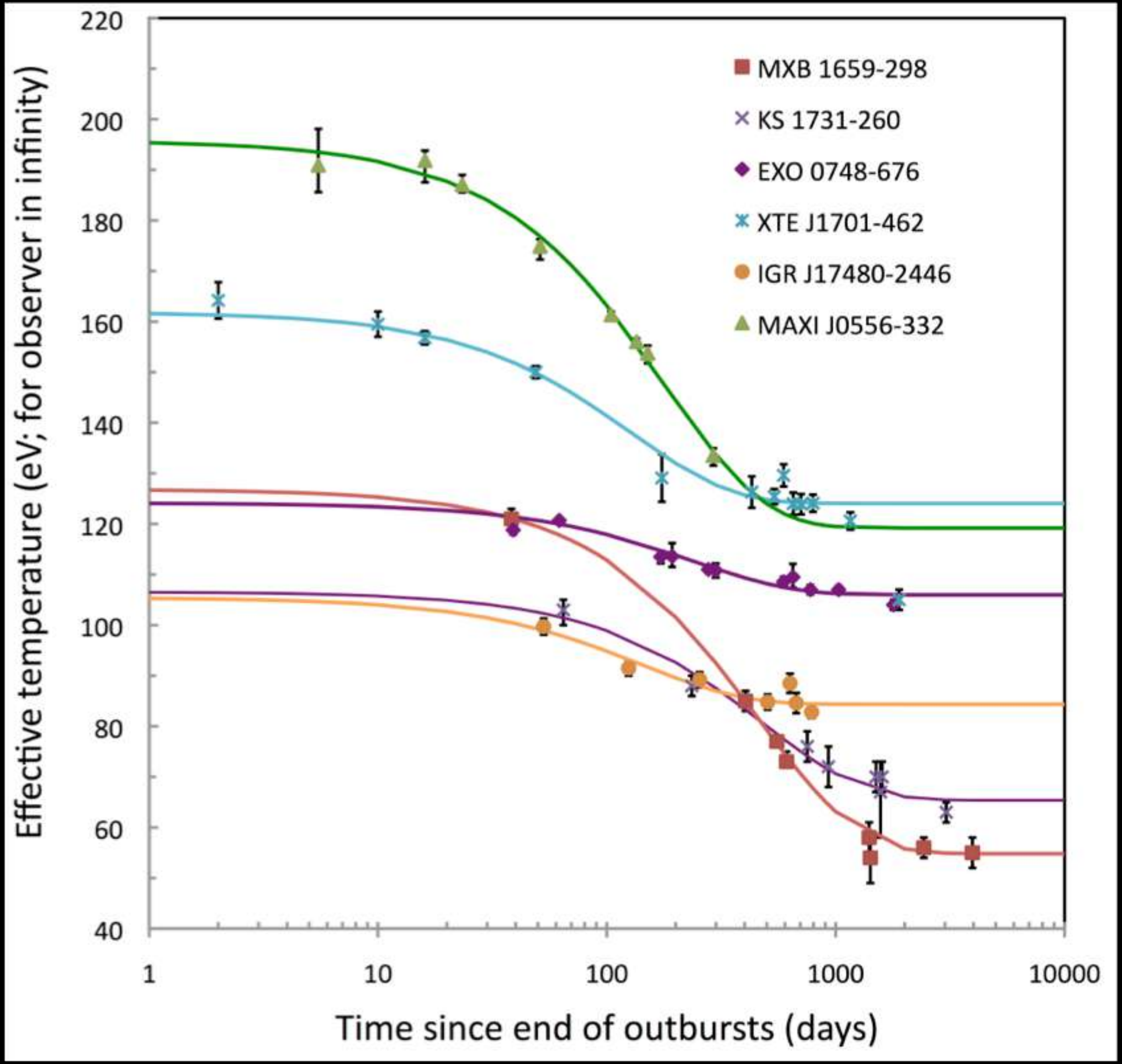


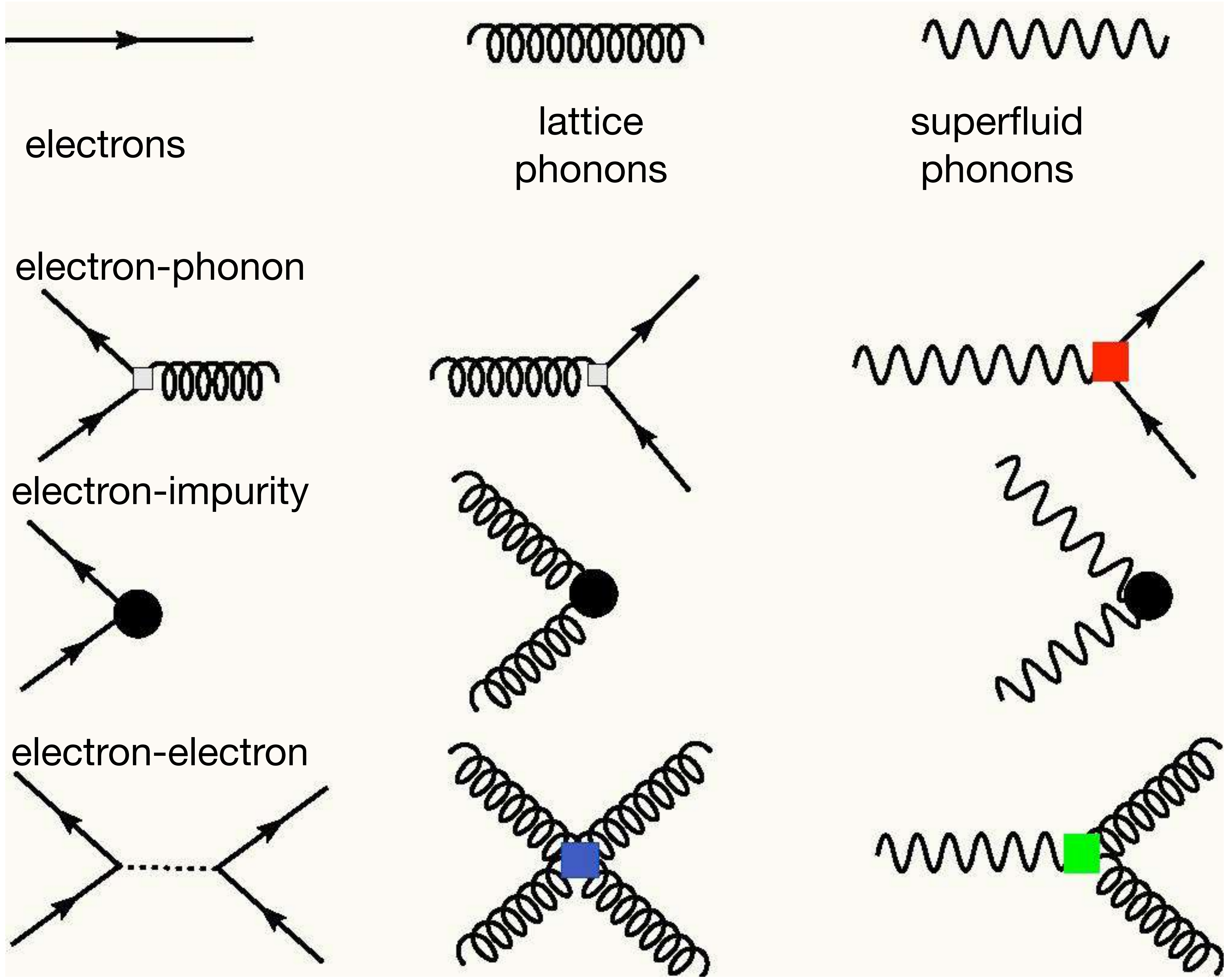
Figure from Rudy Wijnands (2013)

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.)

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

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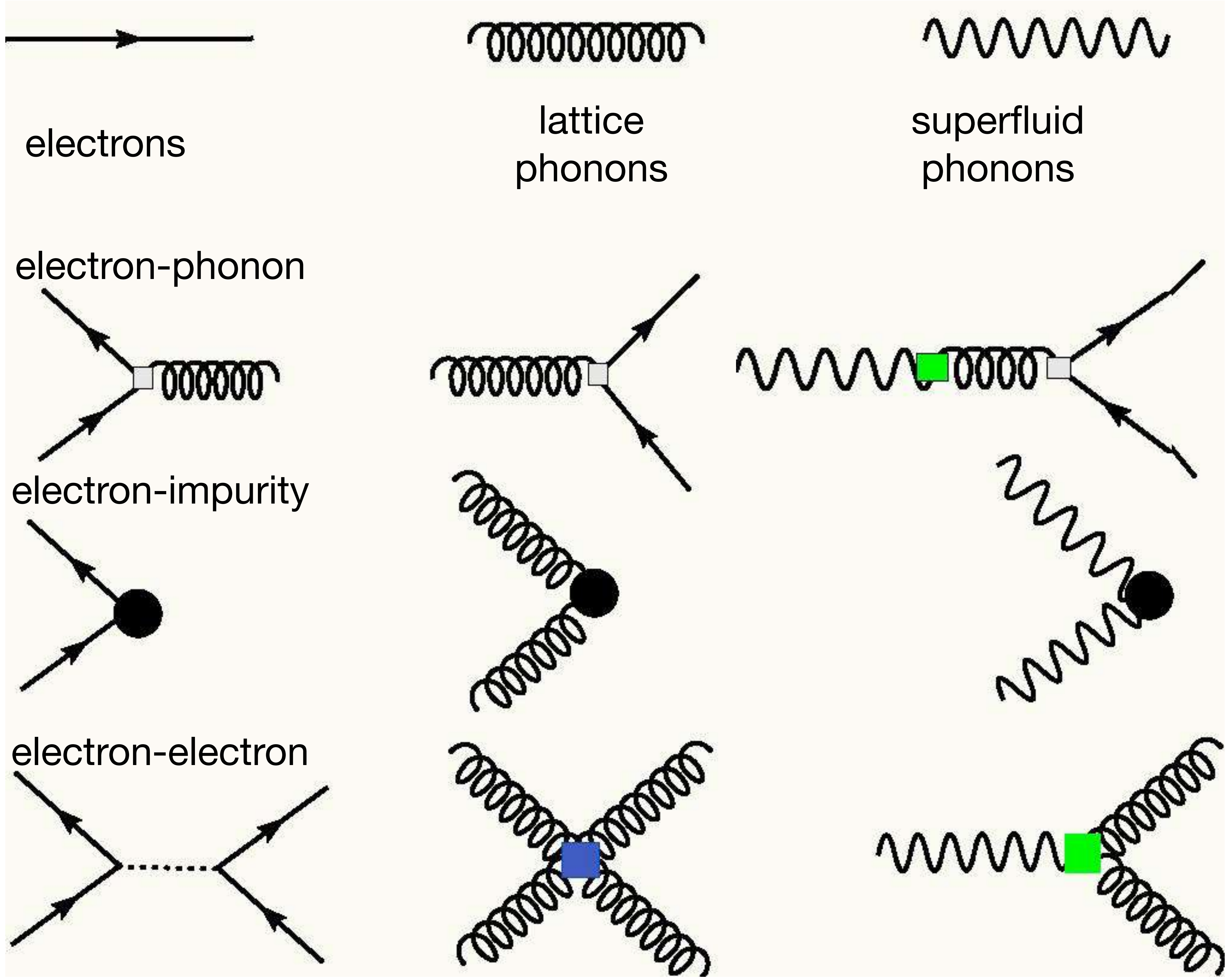

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Connecting to Crust Microphysics

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)

Neutron Star Mergers: The Ultimate Collision

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

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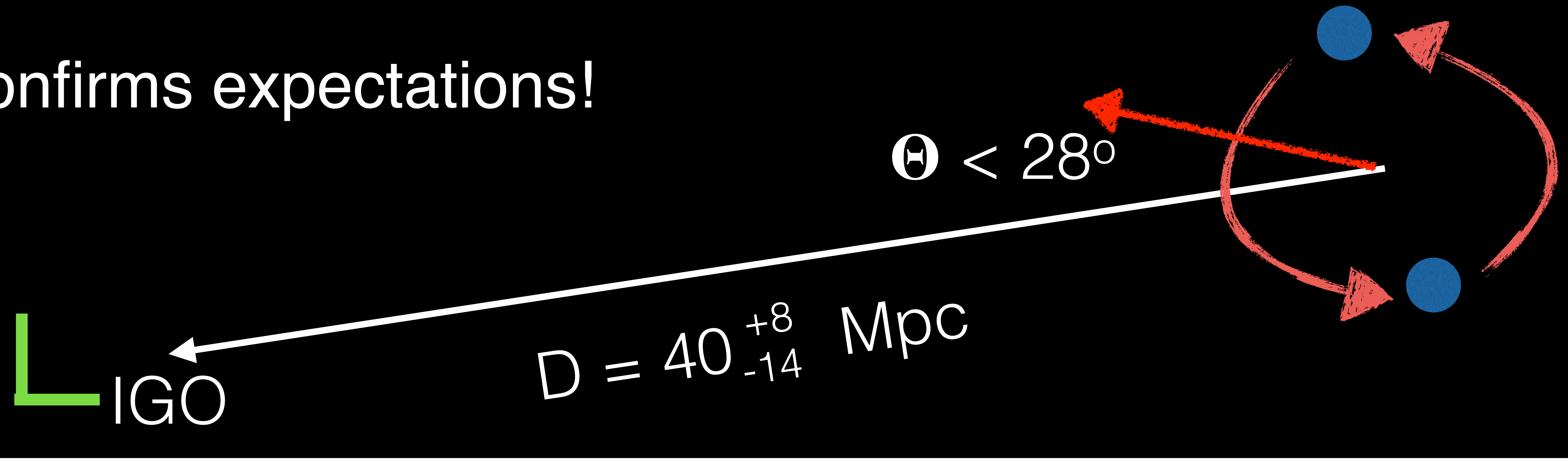
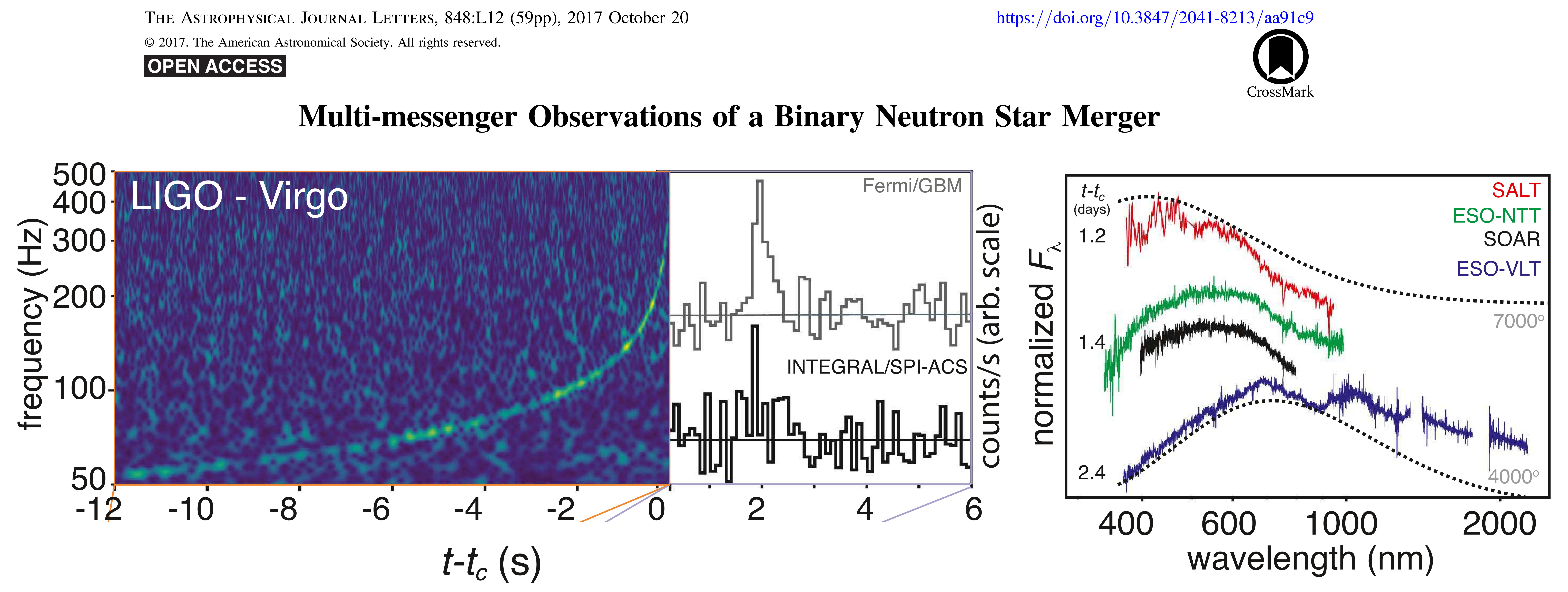
GW170817 confirms expectations!



$\Theta < 28^{\circ}$

LIGO

$D = 40^{+8}_{-14}$ Mpc



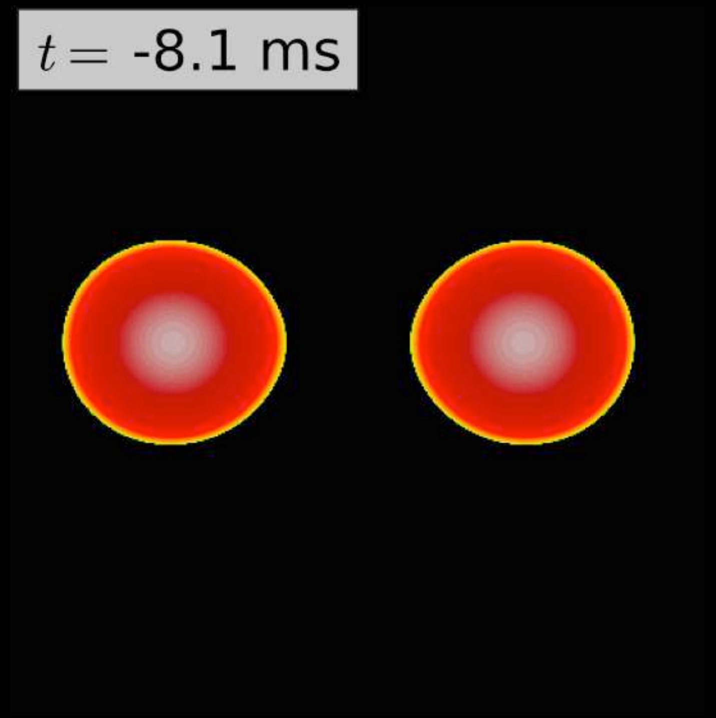
The Astrophysical Journal Letters, 848:L12 (59pp), 2017 October 20
https://doi.org/10.3847/2041-8213/aa91c9

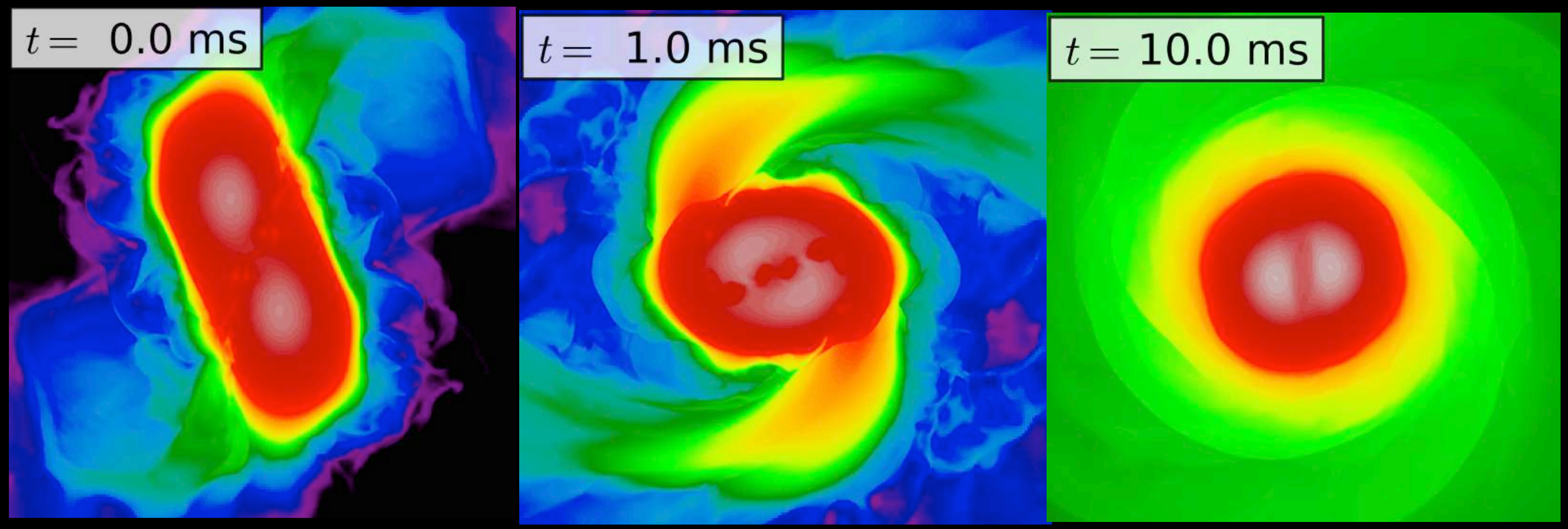
Multi-messenger Observations of a Binary Neutron Star Merger

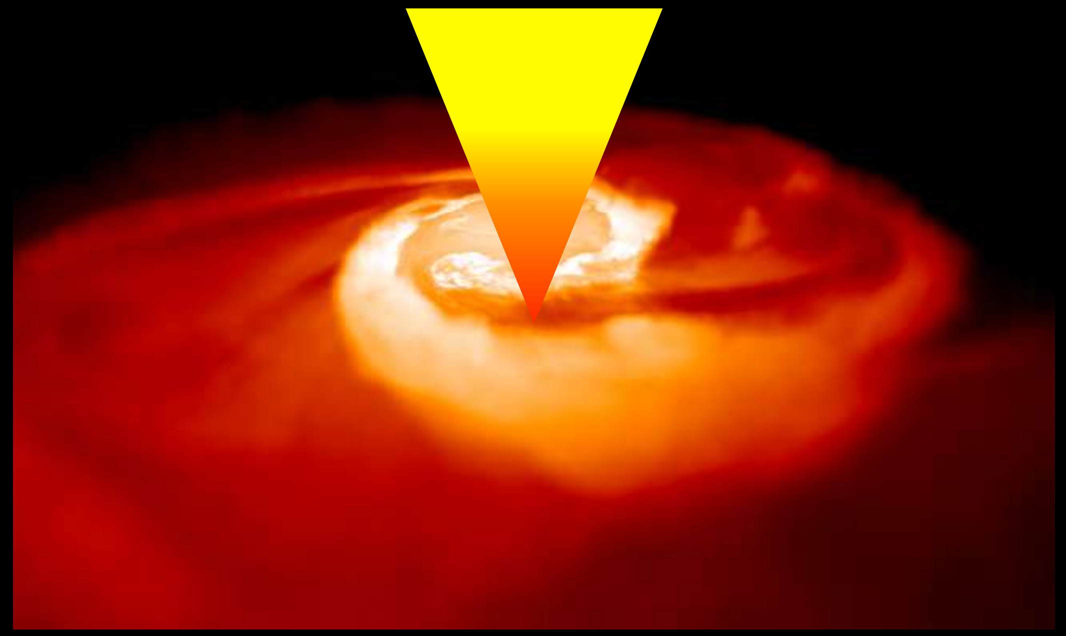
Neutron Star Merger Dynamics

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

Simulations: Rezzola et al (2013)







Inspiral:
Gravitational waves,
Tidal Effects

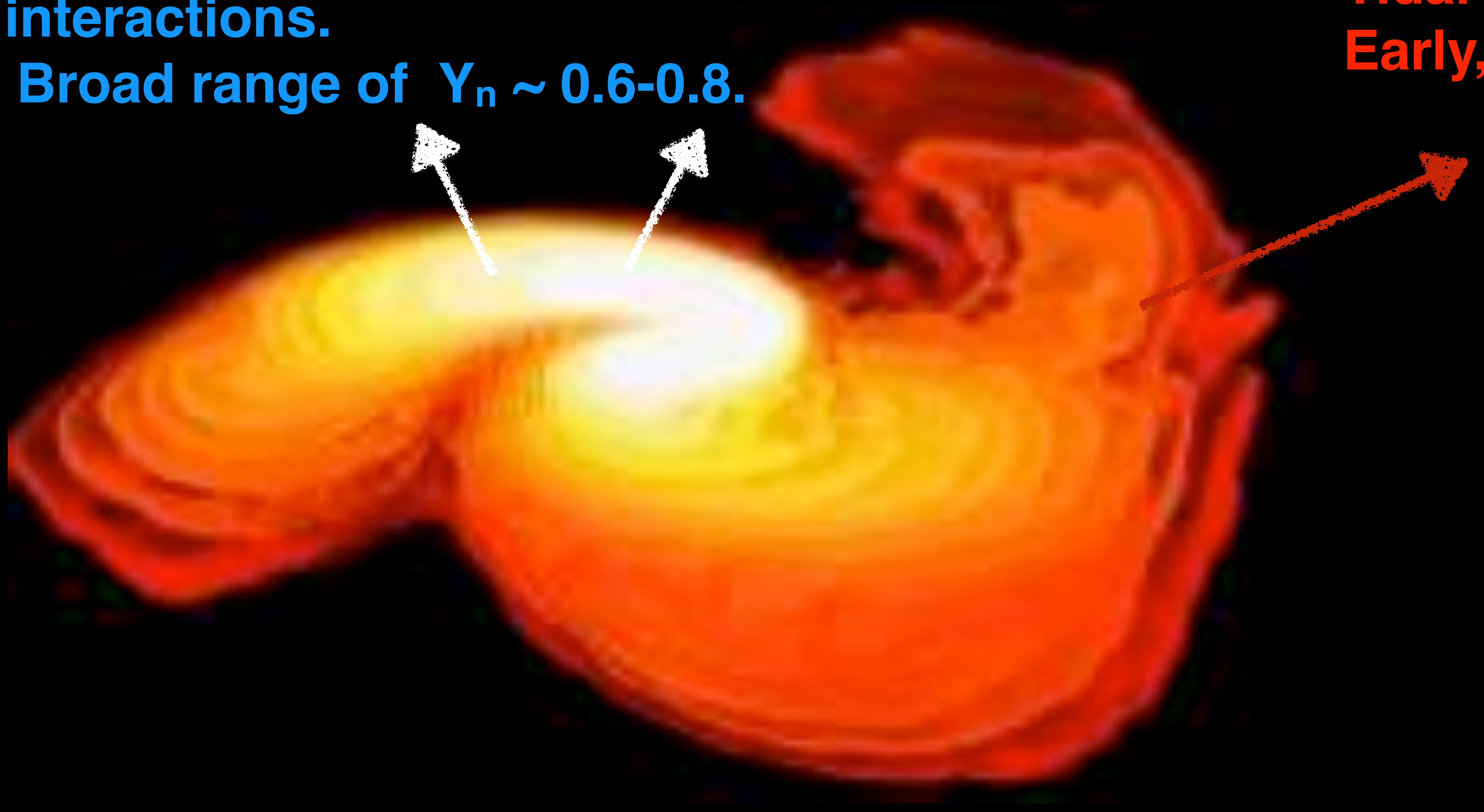
Merger:
Disruption, NS oscillations, ejecta
and r-process nucleosynthesis

Post Merger:
GRB, Afterglows, and
Kilonova

- Evolution is complex. Relies on multi-physics large-scale numerical relativity simulations.

- Observables sensitive to equation of state and response of matter at extreme density.

Merger Ejecta & Nucleosynthesis



Shock and neutrino wind driven ejecta:
Processed by weak interactions.
Not as neutron rich. Broad range of $Y_n \sim 0.6\text{-}0.8$.

Tidal ejecta:
Early, and very neutron-rich. $Y_n > 0.8$

Simulations find that the amount and composition of the material ejected depends:

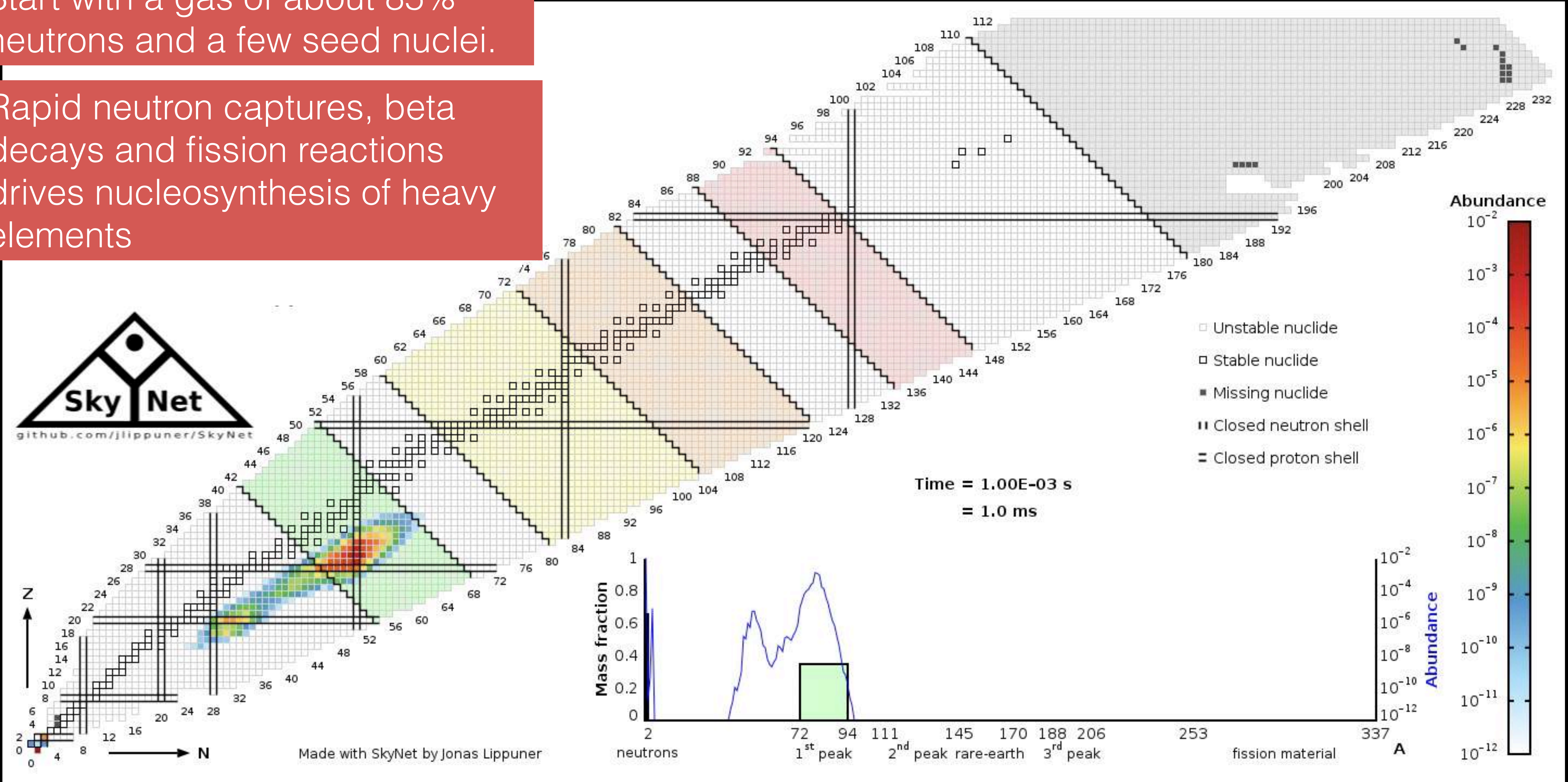
- Lifetime and neutrino emission of the hyper massive, hot and rapidly rotating neutron star
- Neutron star radius

Both these properties are largely set by properties of matter at extreme density and temperature.

Nuclear Reactions in an Expanding Gas

Start with a gas of about 85% neutrons and a few seed nuclei.

Rapid neutron captures, beta decays and fission reactions drives nucleosynthesis of heavy elements



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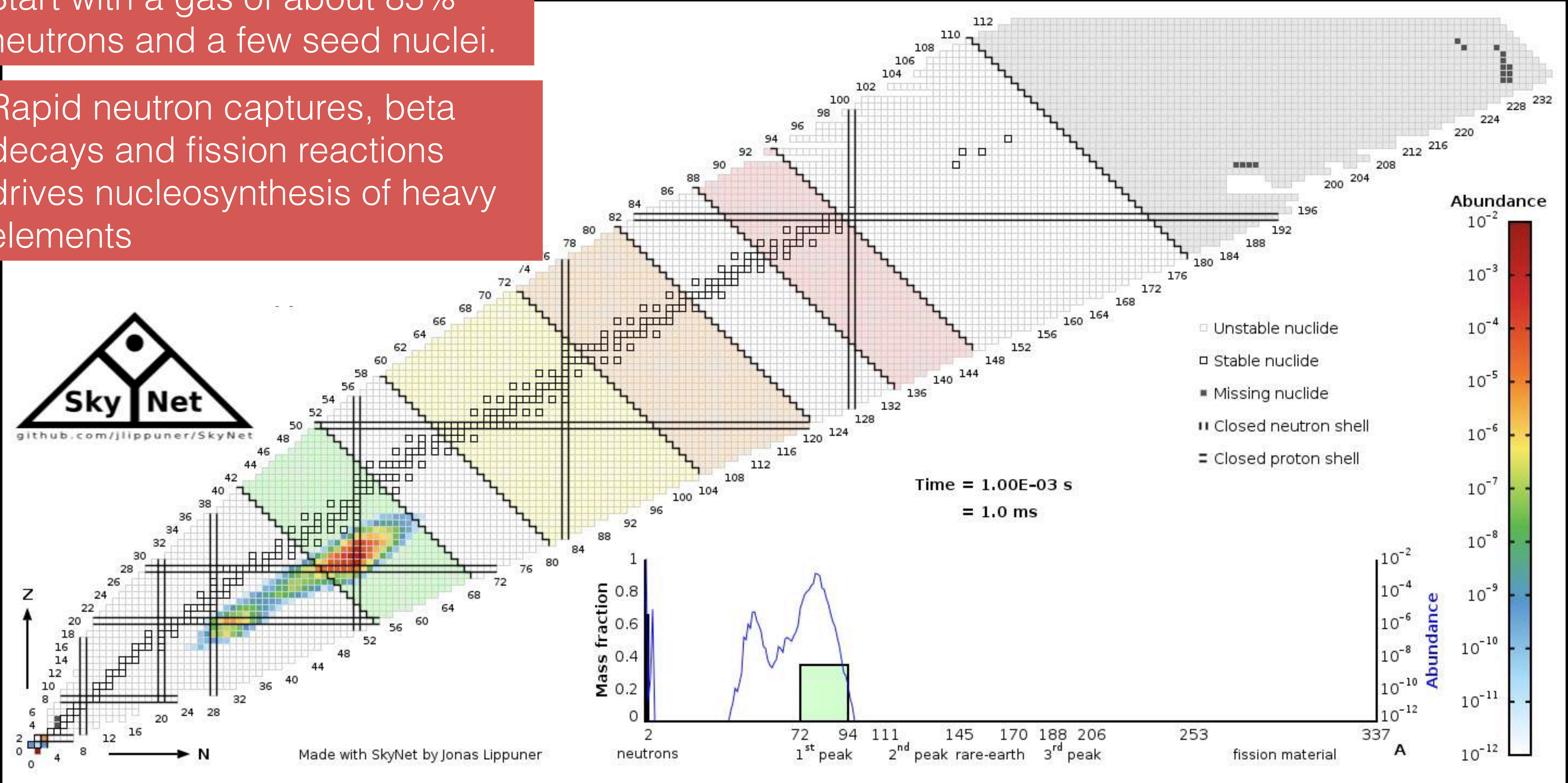

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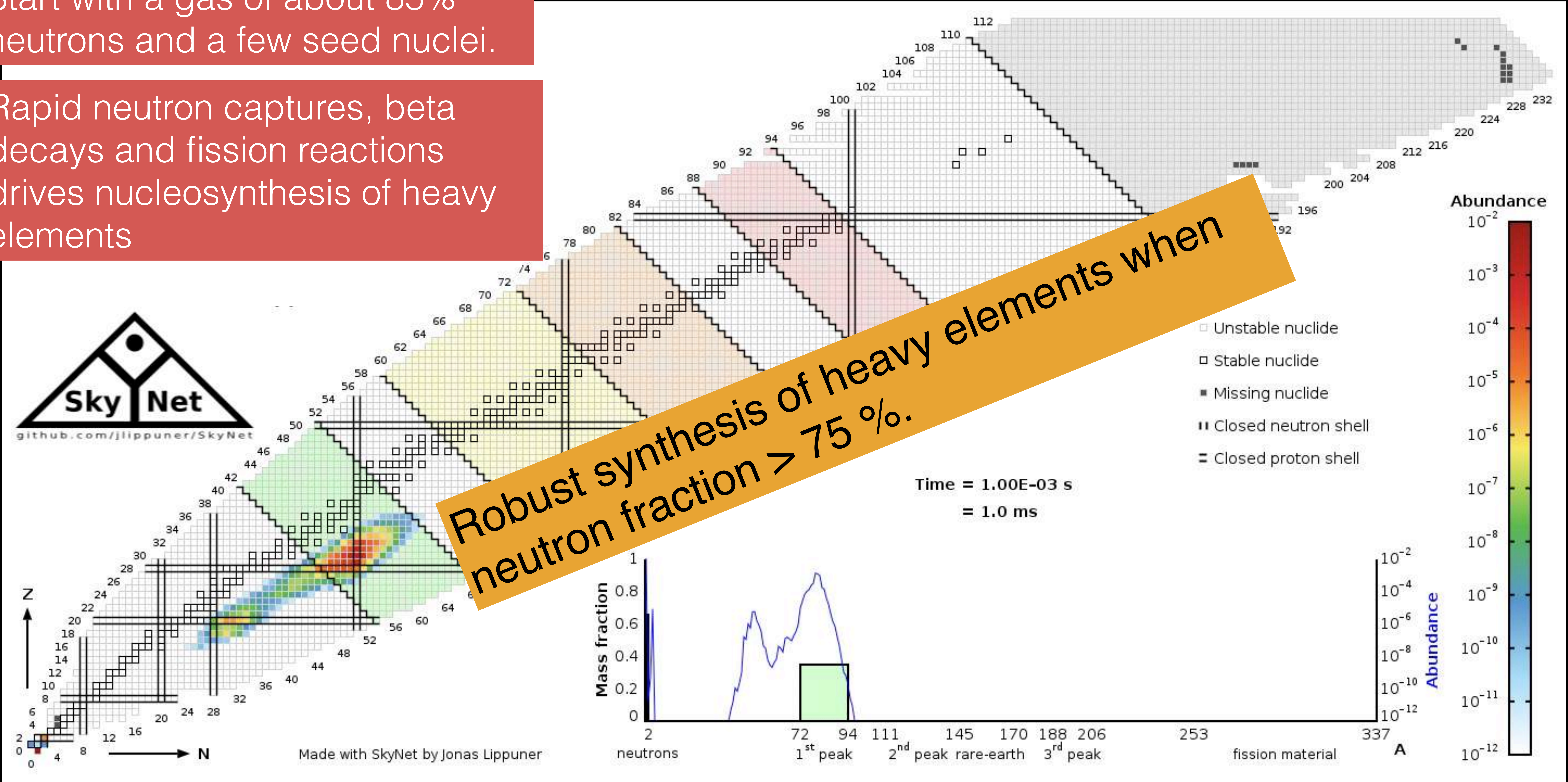

Robust synthesis of heavy elements when neutron fraction > 75 %.

Electromagnetic Signatures: Ejecta and Kilonova

- Radioactive heavy elements power an EM signal.

Eichler, Livio, Piran, Schramm 1989, Li & Paczynski 1998,
Metzger et al. 2010, Roberts et al. 2011, Goriely et al. 2011

- Magnitude and color of the optical emission is sensitive to the composition of the ejecta.

Kasen 2013

- Observed light curves from GW17081 provide indirect evidence for heavy-elements in the ejecta.

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Kilonova is Sensitive to the Composition of Heavy Elements in the Ejecta

Metzger et al. 2010 Kasen 2013

- Iron group elements made when ejecta has $Y_n < 0.75$ have an opacity

$$\kappa_{\text{Fe-like}} \sim 1\ \text{cm}^2/\text{g}$$

- Heavy r-process elements (with lanthanides) made when ejecta has $Y_n > 0.8$ have an opacity

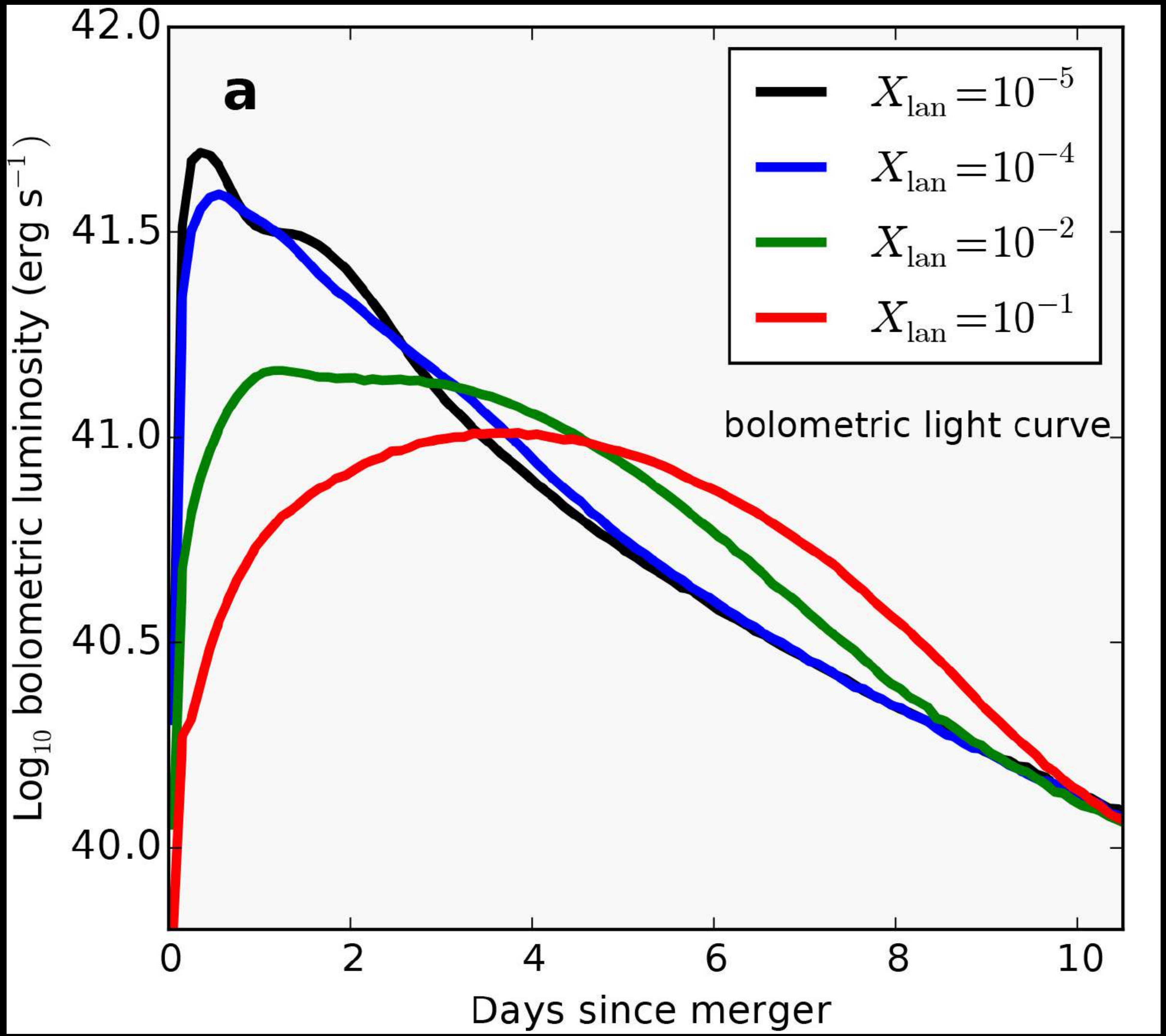
$$\kappa_{\text{Lanthanides}} \sim 10\ \text{cm}^2/\text{g}$$

To fit observed light curves requires:

~ 0.04 $M_\odot$ (?) of nuclei with A>140

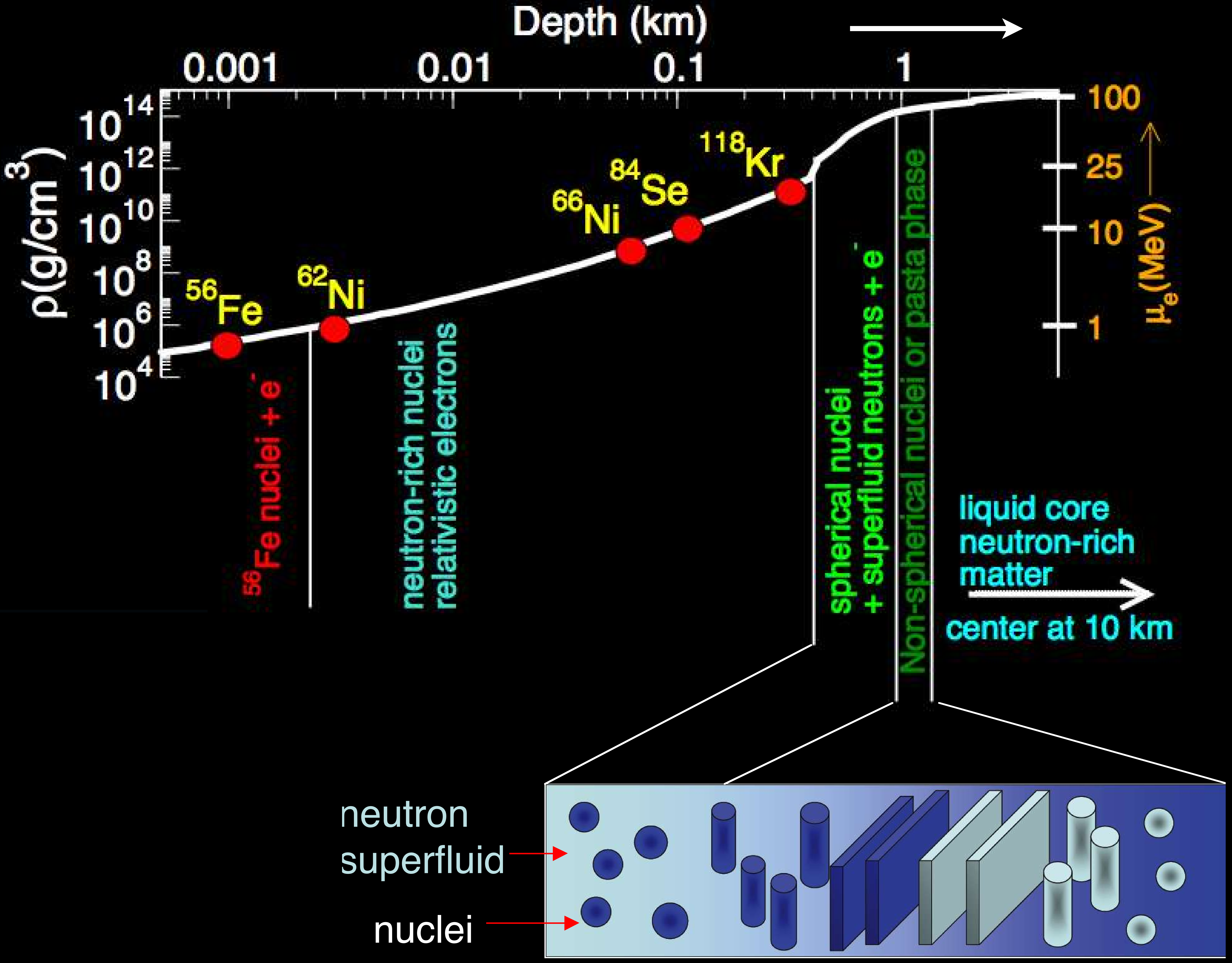
~ 0.025 $M_\odot$ (?) of nuclei with A<140

Kasen et al. 2017



Blast Mining Neutron Stars

To extract a few percent of a their mass from each neutron star, need to blast out outer 2 kms!



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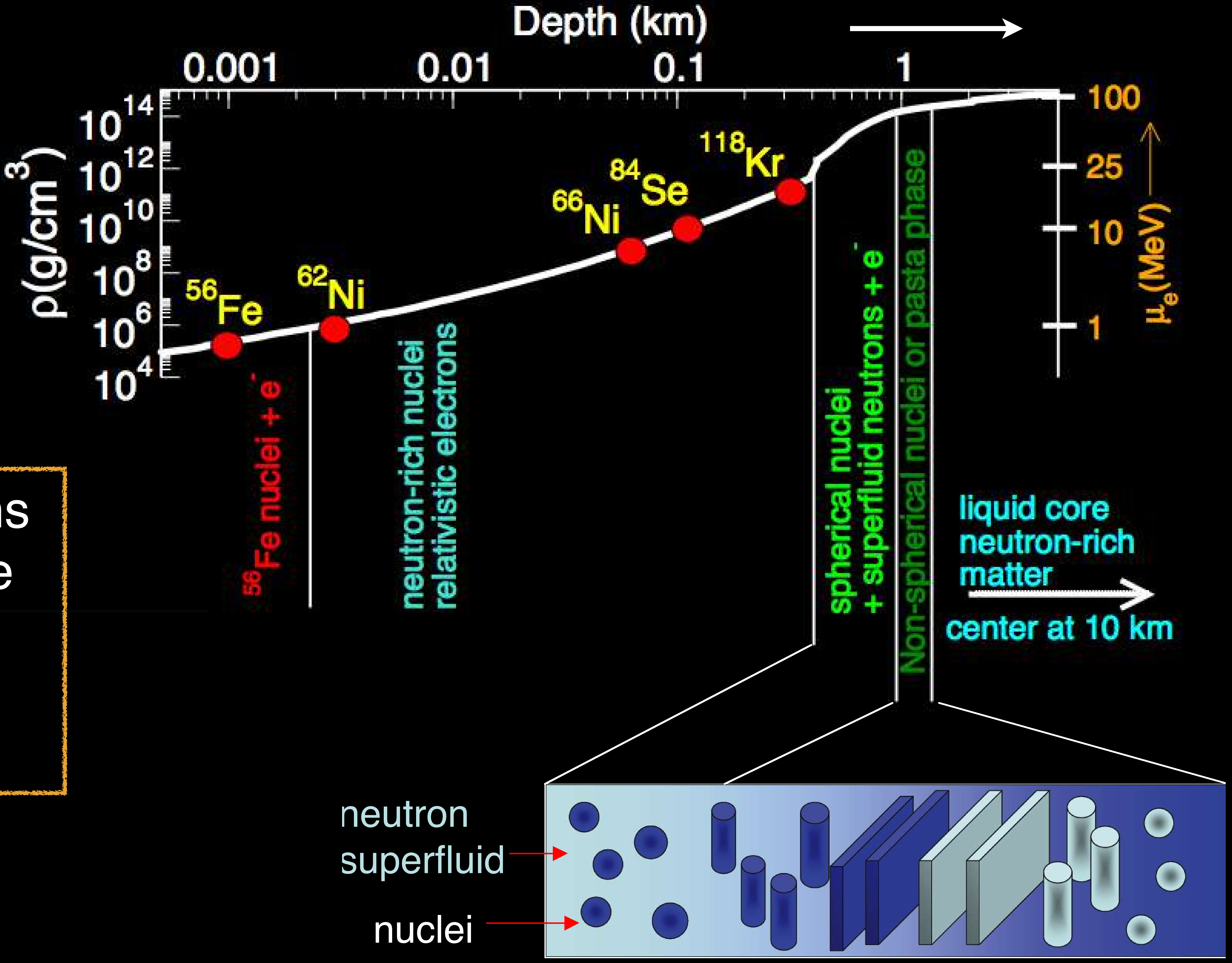
79 protons and 118 neutrons in a gold nucleus were once neutrons, swimming in a superfluid ocean inside a neutron star !

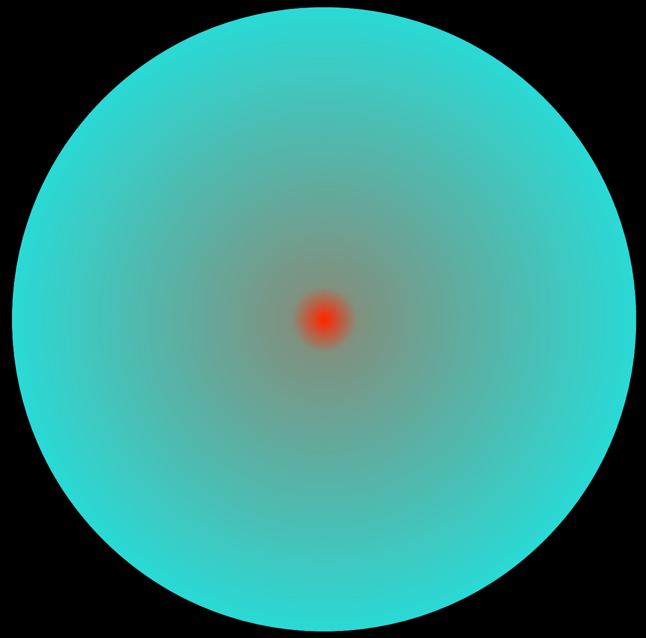


Hunting for Dark Matter

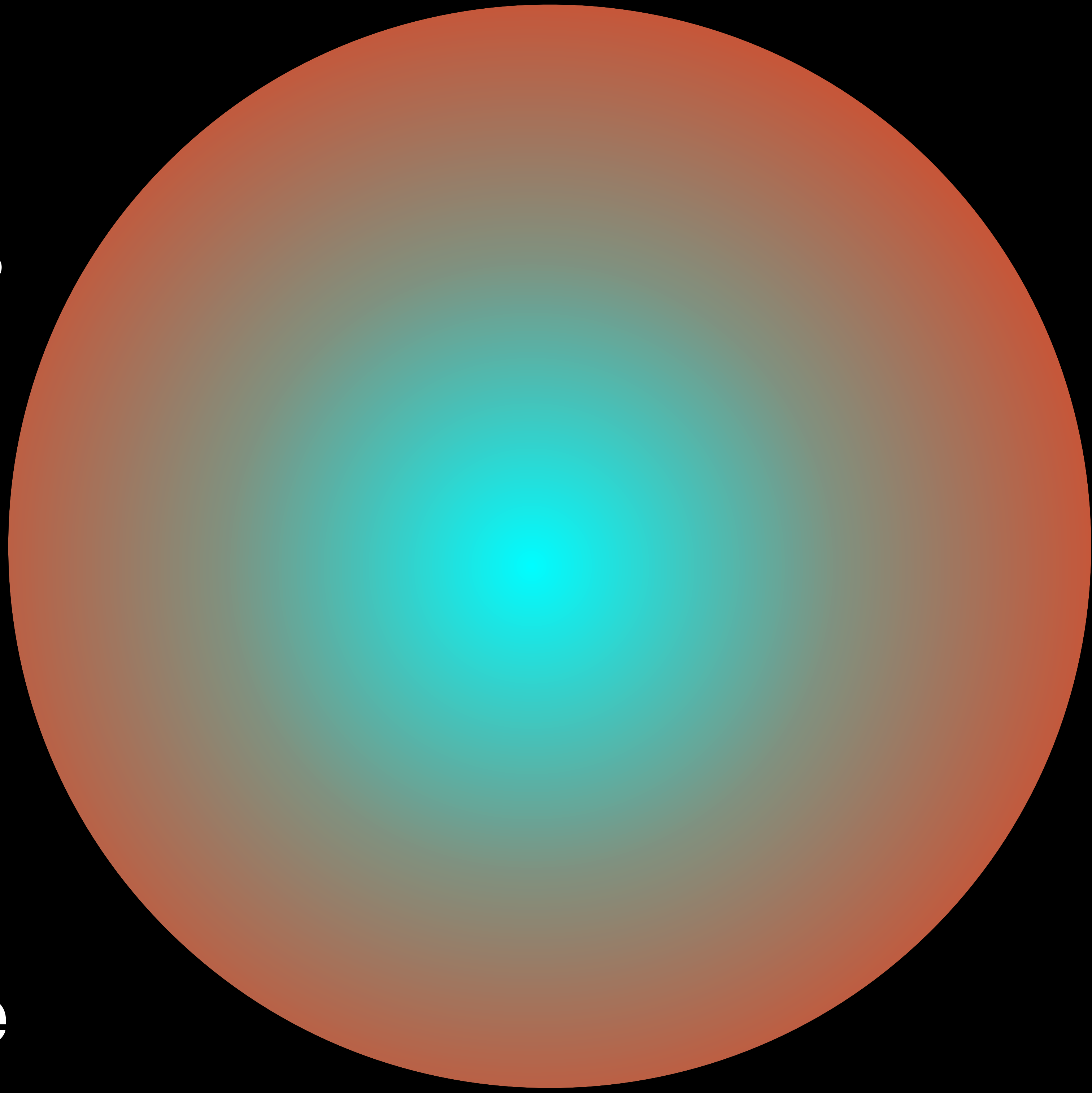
Using Neutron Stars and Gravitational Waves

Neutron stars are great places to look for dark matter:

- Can accrete and trap dark matter.
- Can thermally produce dark matter with mass < 1 GeV.

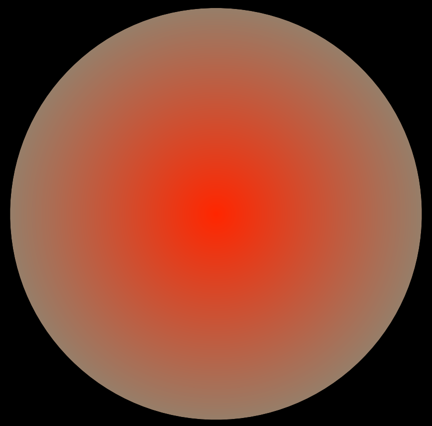


NS + dark-core



NS + dark-halo

Self-interacting dark matter could form hybrid neutron stars and compact dark objects.



Compact Dark Objects

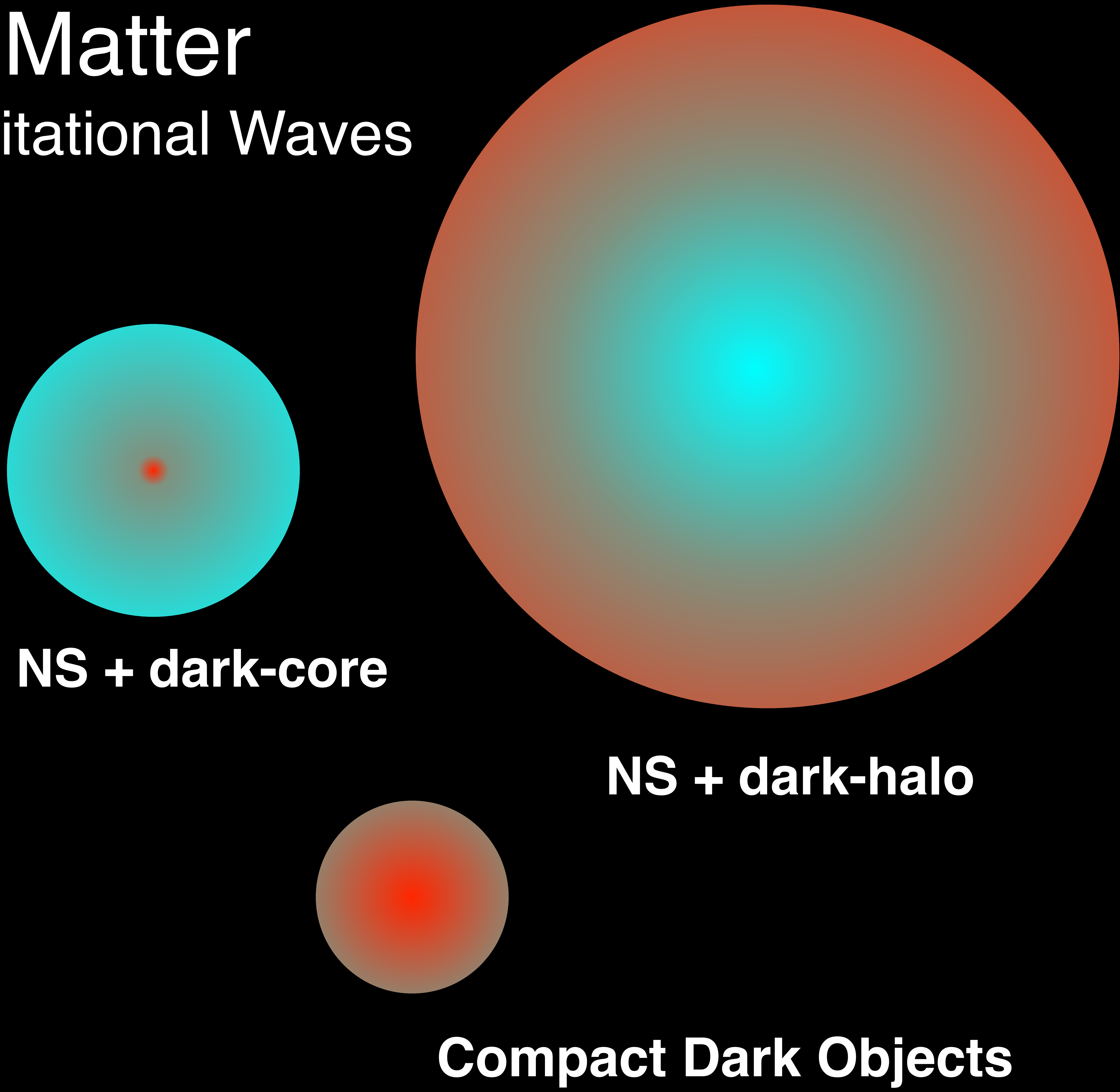
Nelson, Reddy & Zhou (2018)   Horowitz & Reddy (2018)

Hunting for Dark Matter

Using Neutron Stars and Gravitational Waves

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



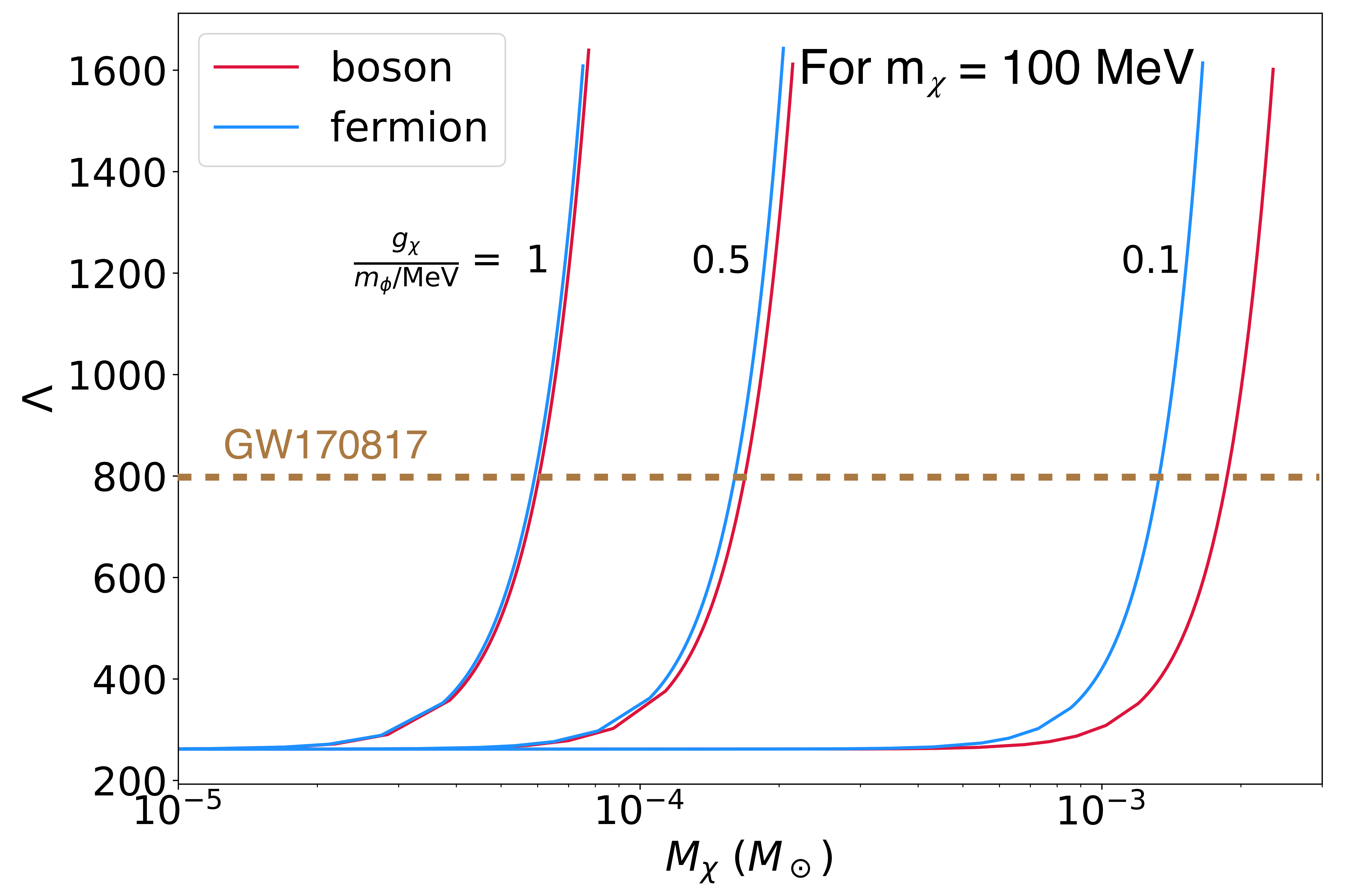
Nelson, Reddy $ Zhou (2018)   Horowitz & Reddy (2018)

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 provides adequate repulsion.

g_χ/m_Φ = (0.1/MeV) or (10^{-6}/eV)



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

The future is bright and loud

Current generation GW detectors at design sensitivity are expected to detect neutron star mergers at a rate of few 10s per year. A small fraction will be close!

Next generation GW detectors, expected to be 10 times more sensitive, have expected event rates > 10,000/ year!

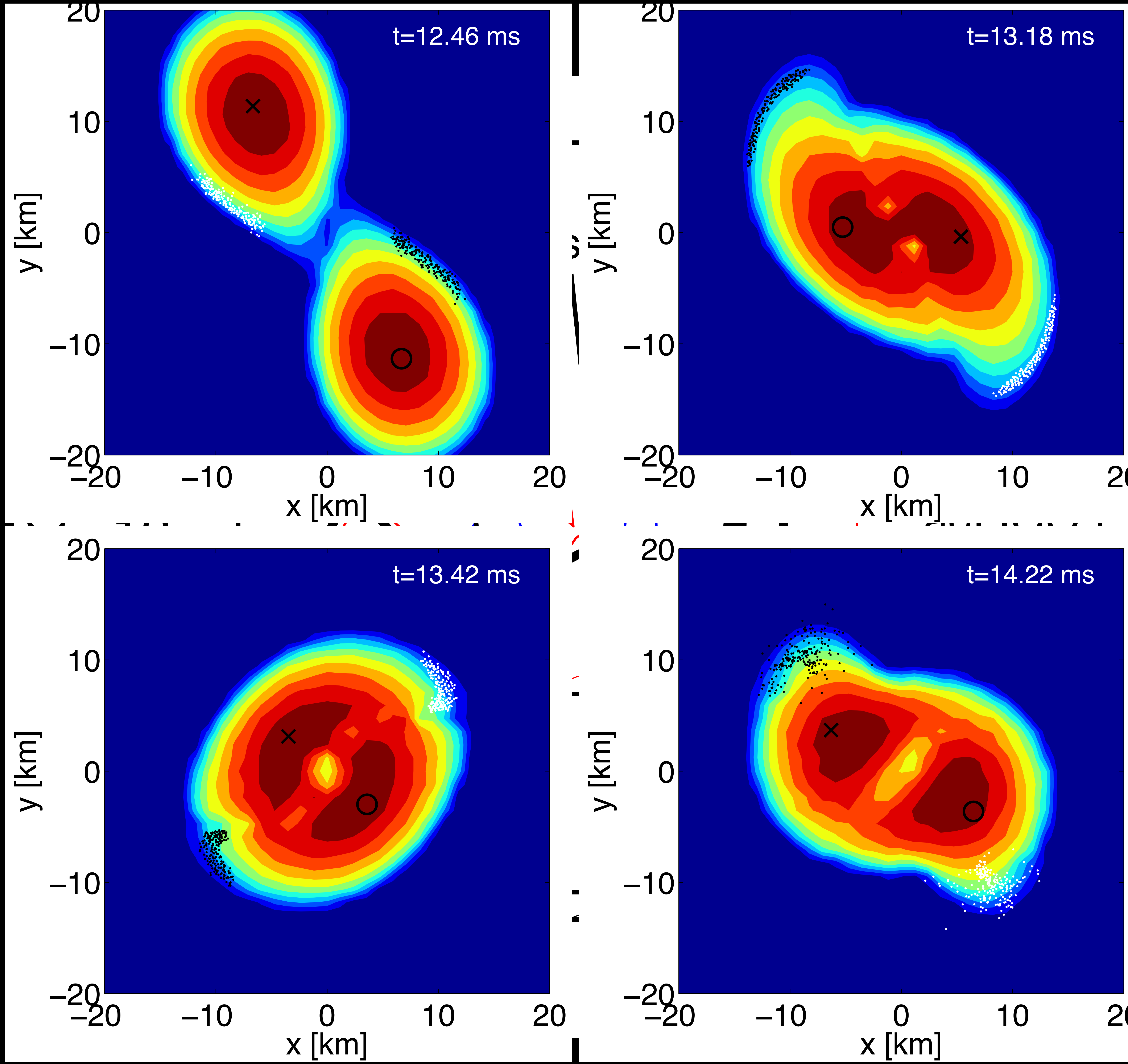
EM observations of accreting neutron stars, x-ray gamma-ray bursts and kilo-nova light curves will improve with new instruments and campaigns.

Next (3rd) Generation GW detectors

Next generation GW detectors, Cosmic Explorer (US) and Einstein Telescope (Europe) will be 10 times more sensitive:

- Measure NS masses and radii at the few percent level!
- Detect post-merger dynamics.

Spectrum of quasi-normal modes excited during the merger its set by the equation of state of nature’s hottest and densest matter.



Bauswein & Stergioulas (2015)

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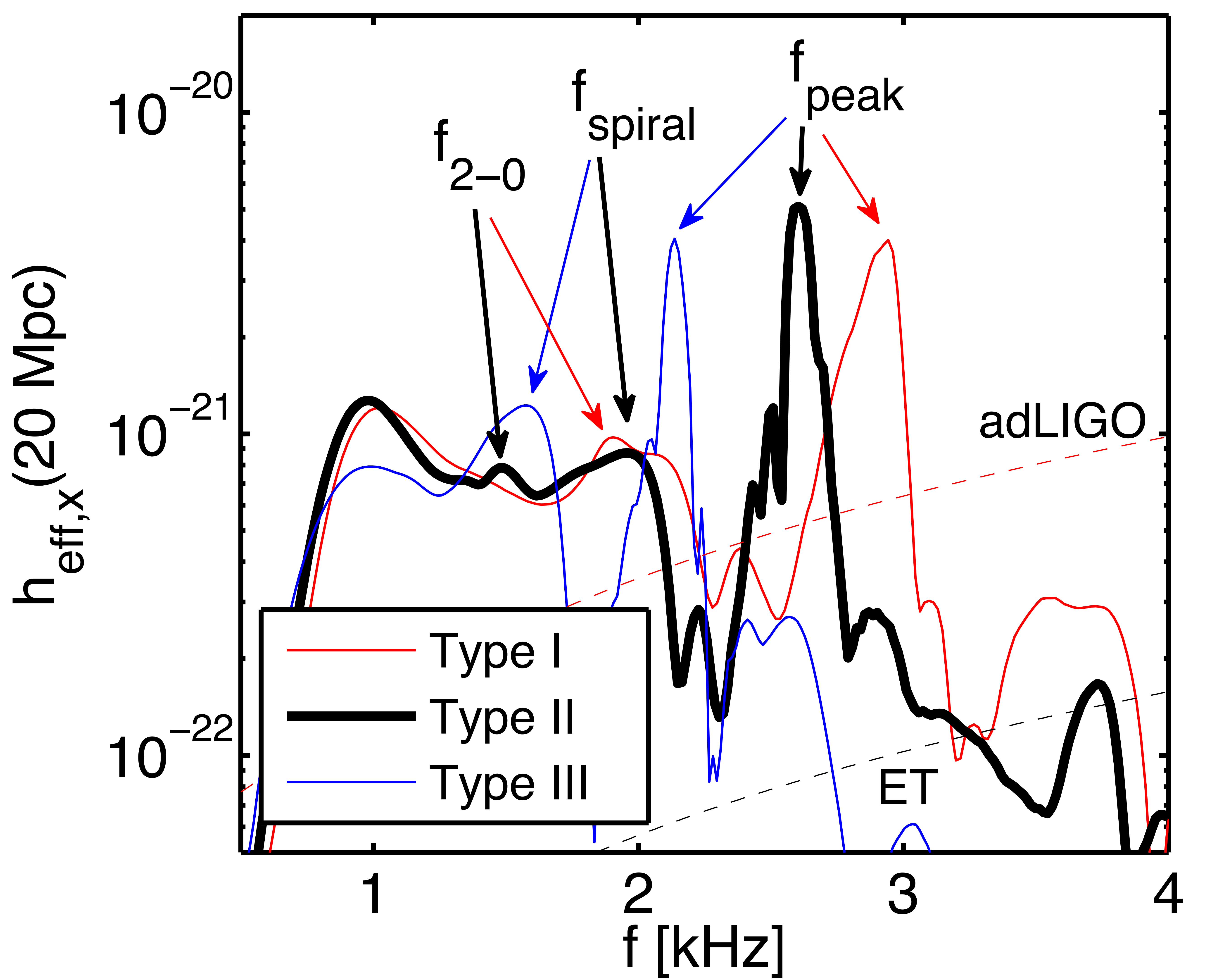

Bauswein & Stergioulas (2015)

Conclusions

- NSs are poised a play a central role in the multi-messenger era.
- Disparate recent observations have provided detailed information about neutron star interiors.
- The first observation of a neutron star merger event exceeded our expectations. Provided evidence for heavy element synthesis and useful limits on the radii of neutron stars.
- Interpreting multi-messenger observations of merges will rely on a coordinated efforts that combines computational astrophysics and nuclear and particle physics. Has great potential for discovery.

Tidal Effects at Late Times

400Hz up to merger

B. Lackey, L. Wade. PRD 91, 043002 (2015)