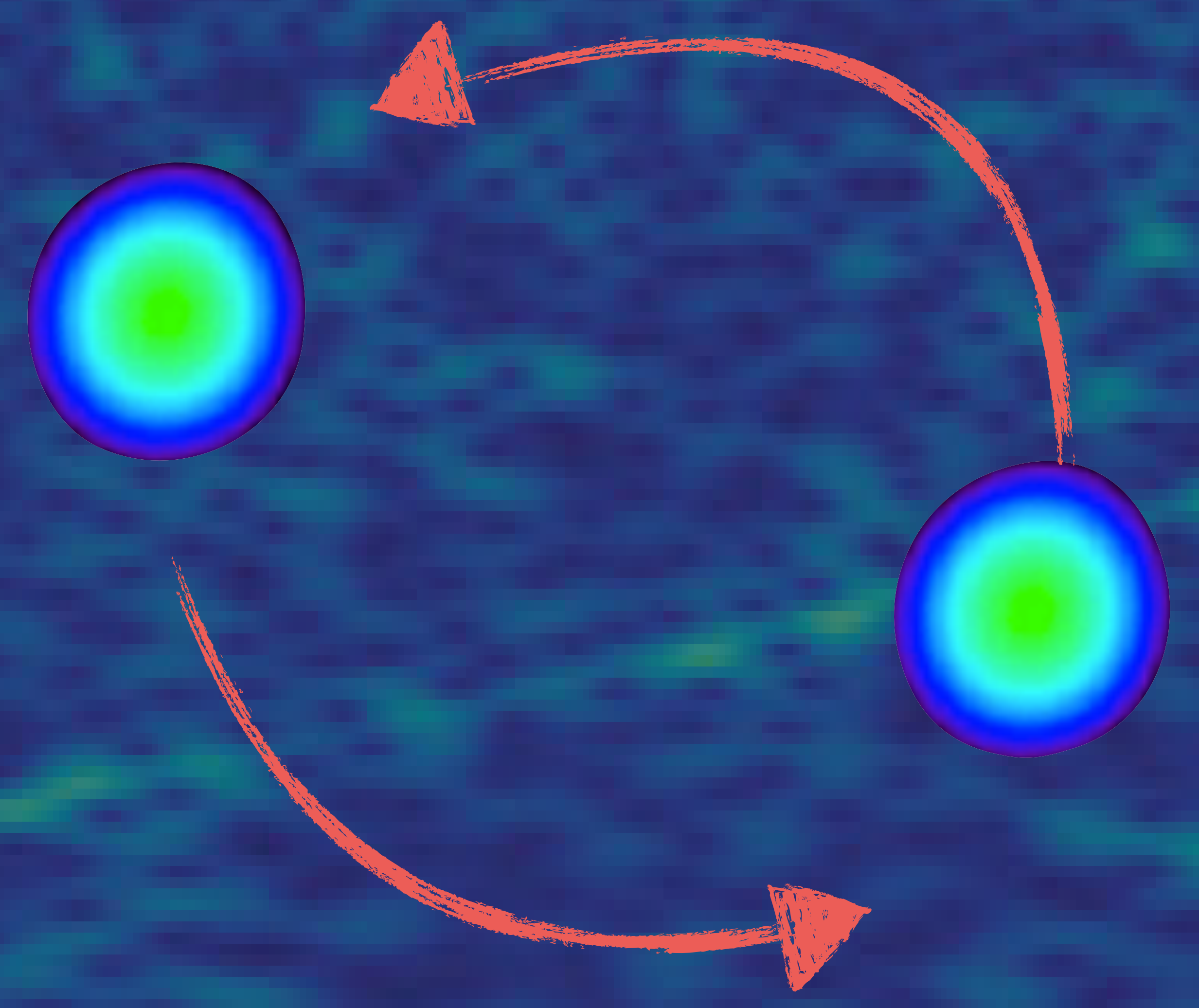
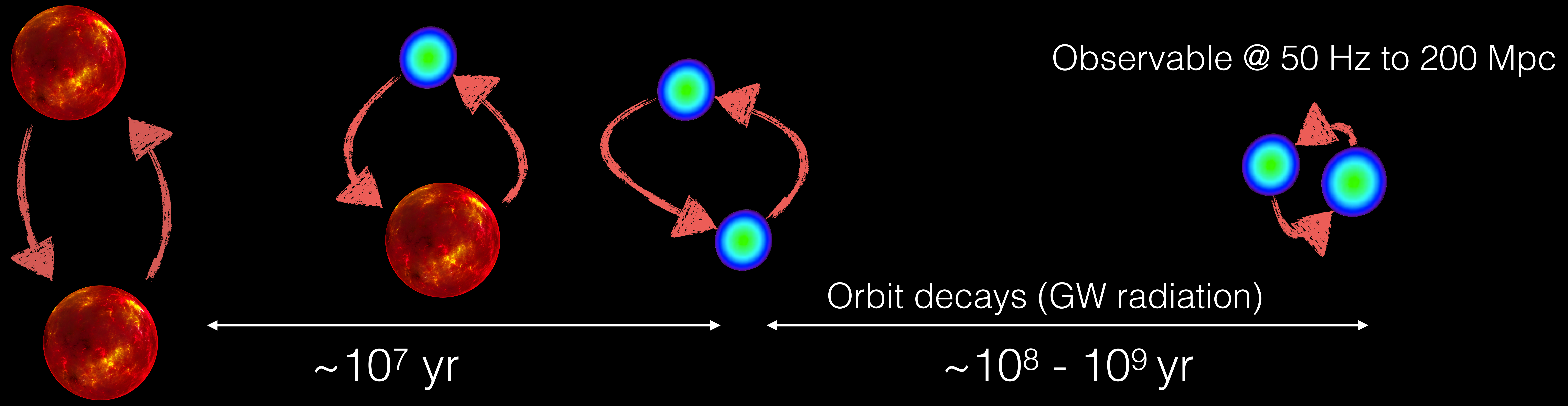
Neutron stars, gravitational waves and nucleosynthesis.

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

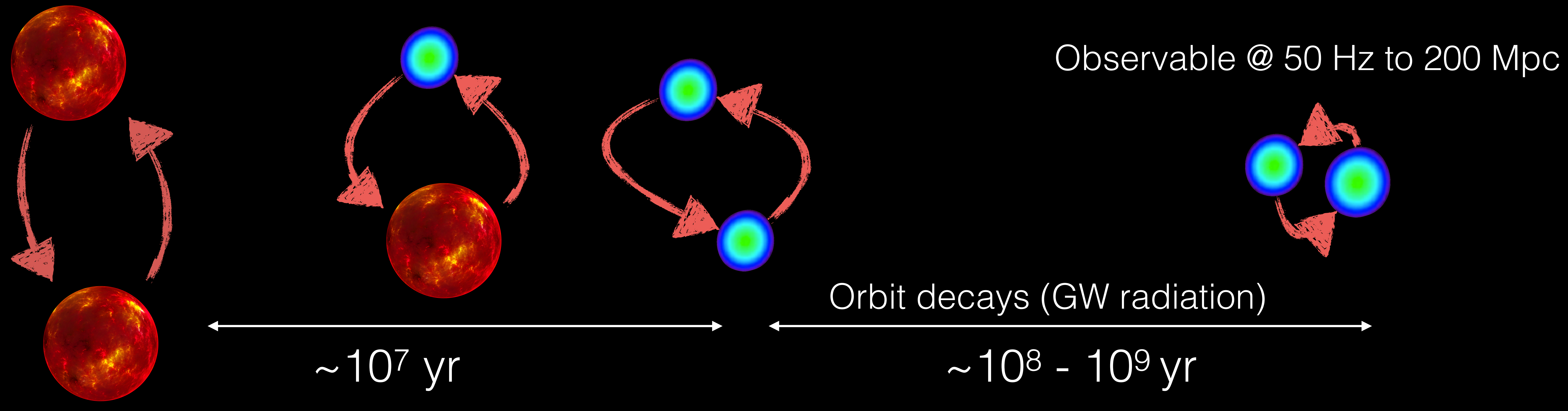


INSTITUTE for
NUCLEAR THEORY

NS Binaries


Observable @ 50 Hz to 200 Mpc
Orbit decays (GW radiation)
~10^7 yr
~10^8 - 10^9 yr

NS Binaries



In the Milky Way

	Orbital Period	Masses (solar)	Time to Merger
B1913+16	0.323 days	1.441 + 1.387	3 x 10^8 yrs
B1534+12	0.421 days	1.333 + 1.347	27 x 10^8 yrs
B2127+11C	0.335 days	1.35 + 1.36	2.2 x 10^8 yrs
J0737-3039	0.102 days	1.34 + 1.25	0.86 x 10^8 yrs
J1756-2251	0.32 days	1.34 + 1.23	17 x 10^8 yrs
J1906+746	0.166 days	1.29 + 1.32	3.1 x 10^8 yrs
J1913+1102	0.201 days	1.65 + 1.24	5 x 10^8 yrs

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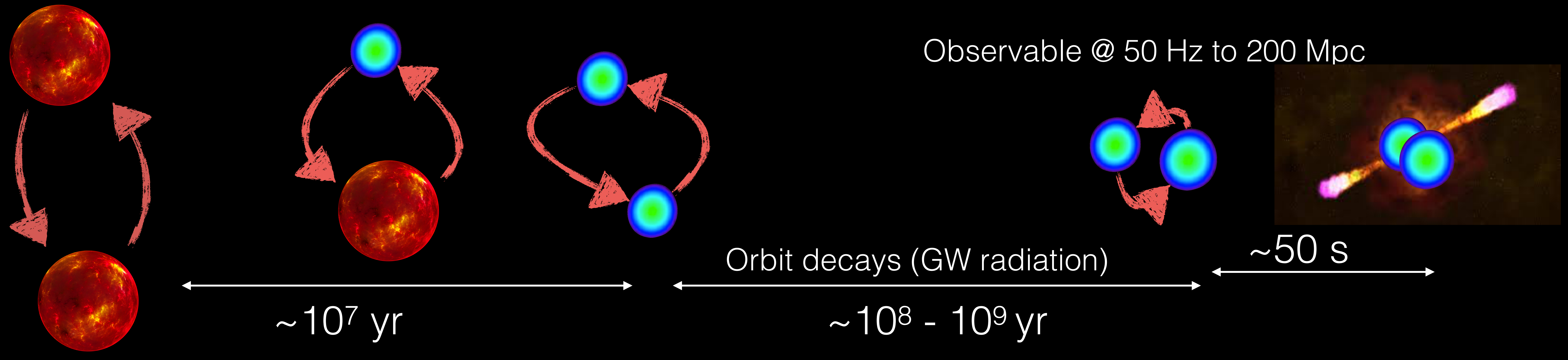

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Short gamma-ray burst rate is ~ 6 /Gpc^3/y

If 2/3 are associated with BNS mergers, the rate in Ad. LIGO at design sensitivity would be about

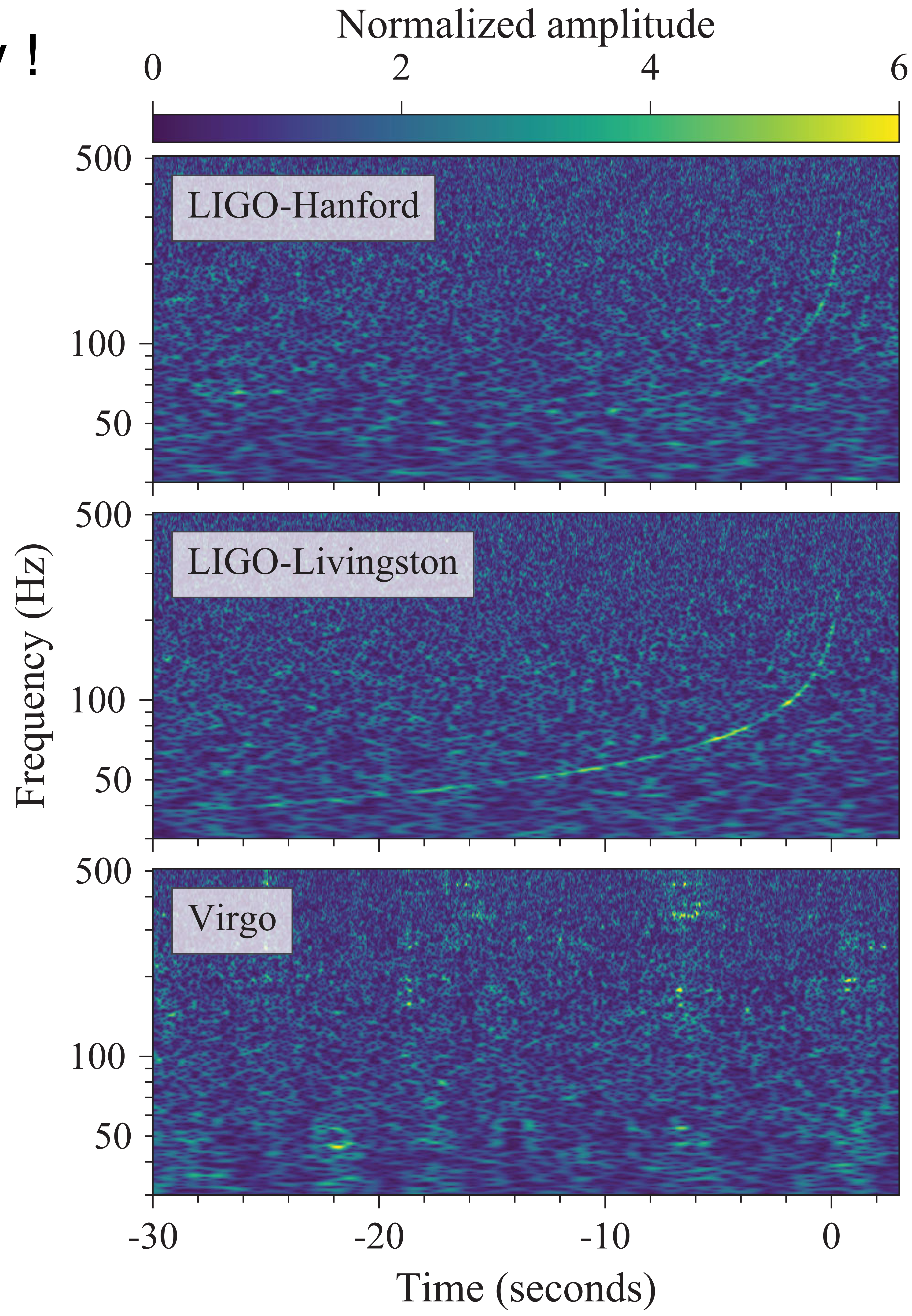
2 per year

Gravitational Waves From Neutron Stars: Finally !

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)



August 17, 2017: Time-domain Multi-messenger astronomy begins

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12:41:06 UTC: Fermi observes the closest SGRB to date !

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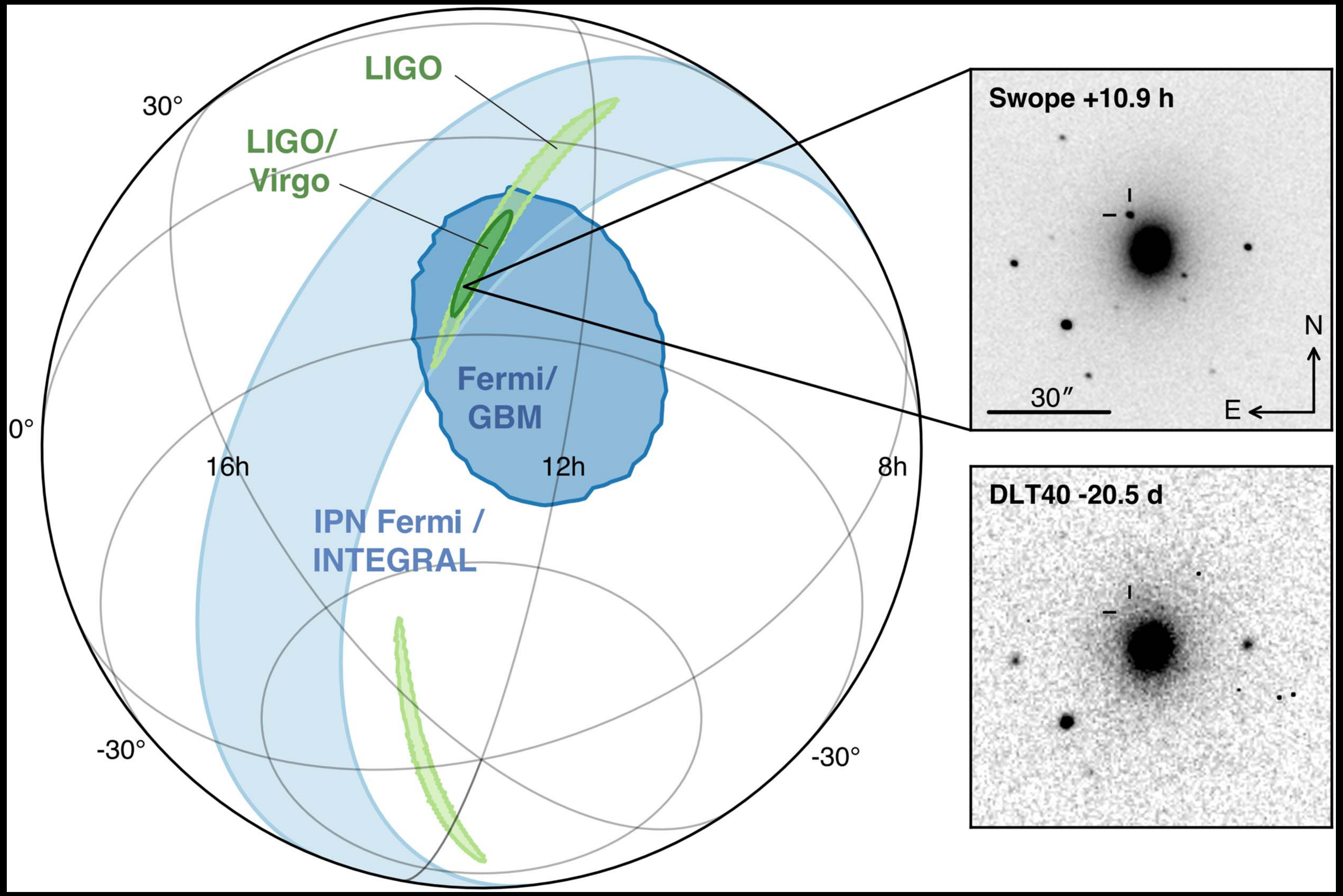

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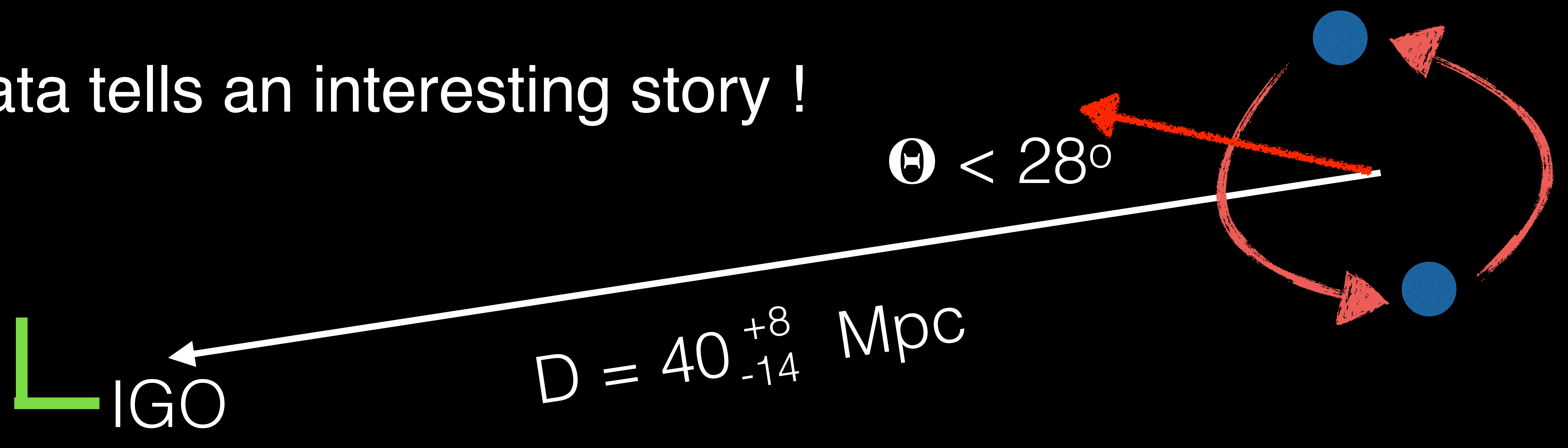
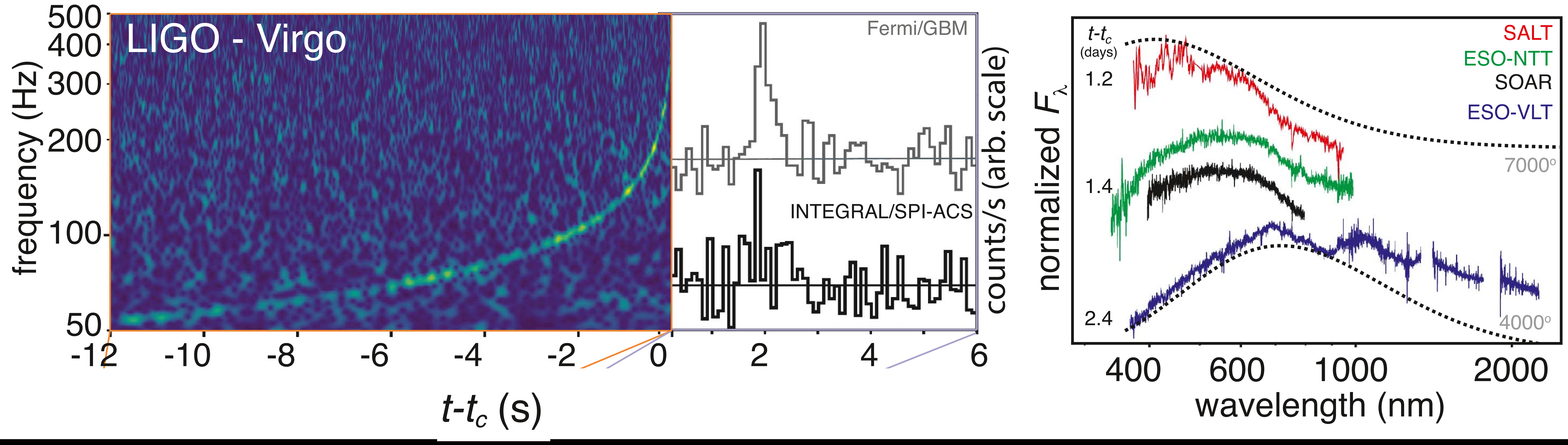
+11 hours: Optical transient detected in a galaxy NGC 4993 at 40 Mpc by the 1M2H team. Carnegie observatories at Los Campanas, Chile.

Taken together the data tells an interesting story !



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

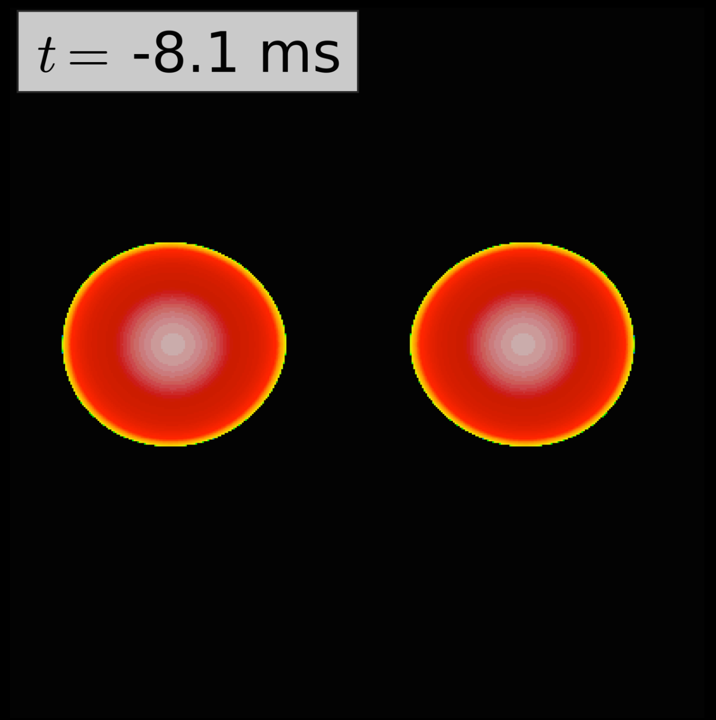
Multi-messenger Observations of a Binary Neutron Star Merger

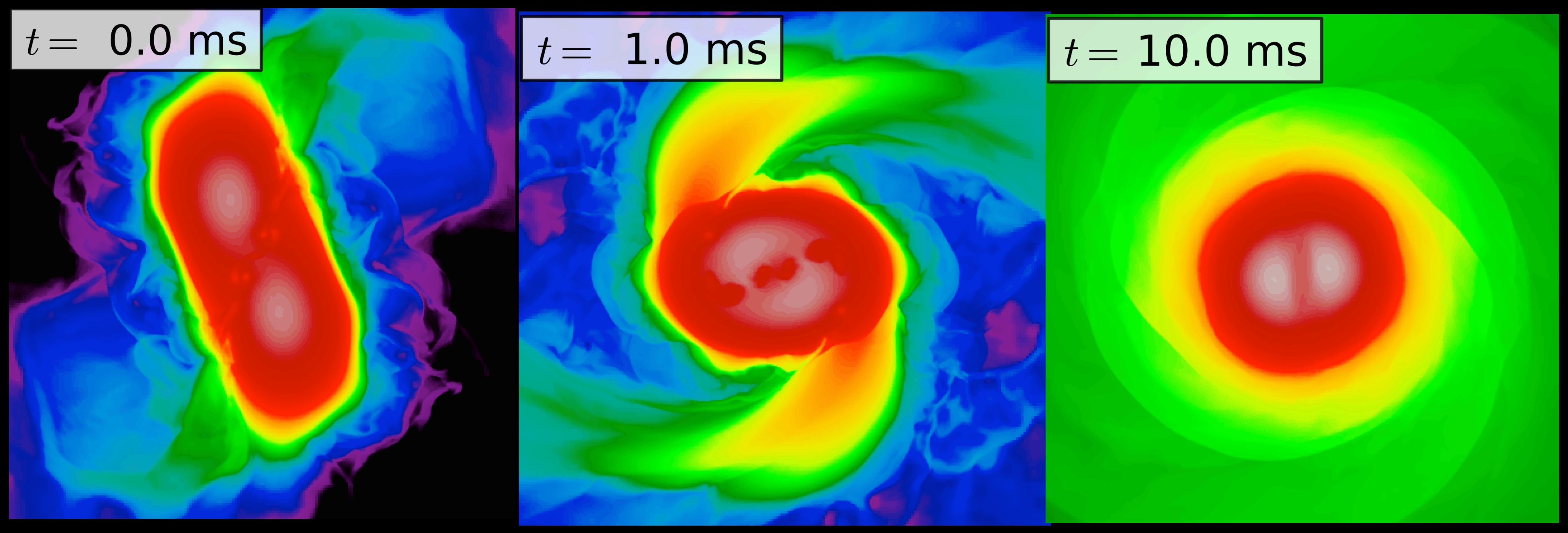


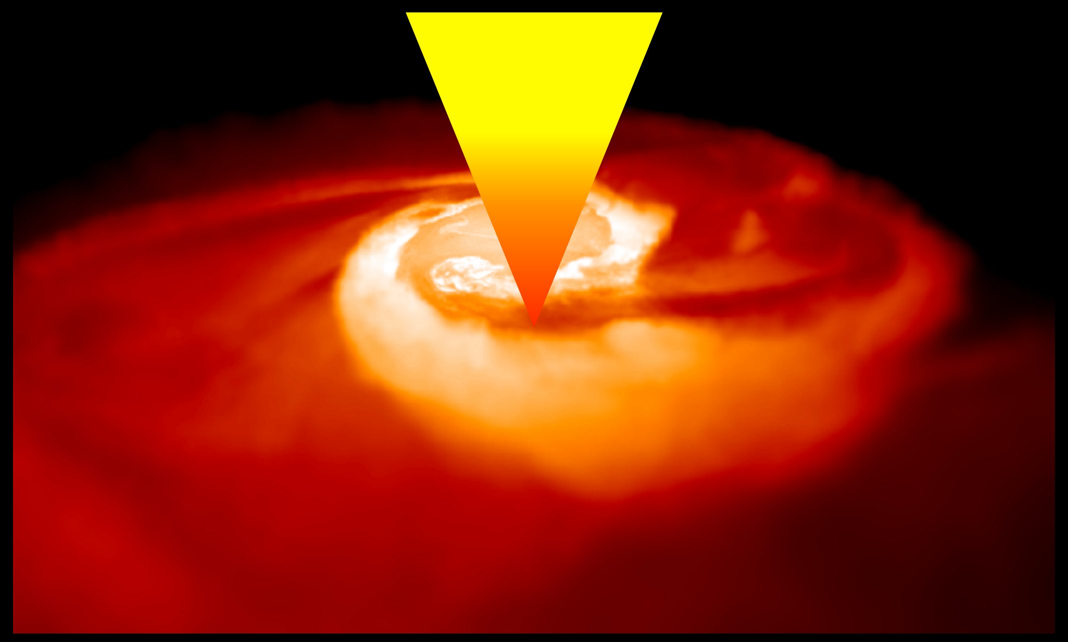
Neutron Star Merger Dynamics

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

Simulations: Rezzola et al (2013)





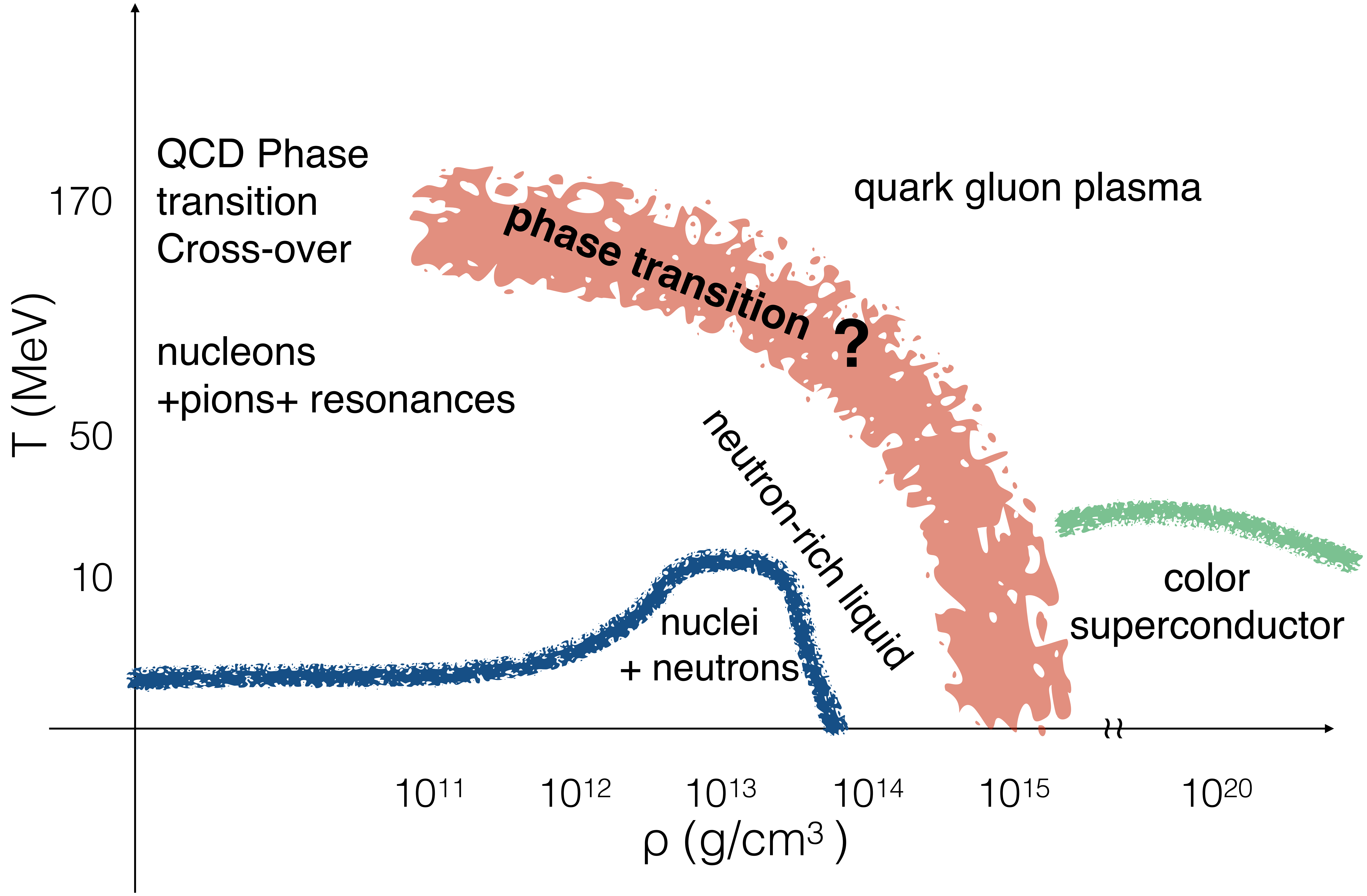


Inspiral:
Gravitational waves,
Tidal Effects

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

Post Merger:
GRB, Afterglows, and
Kilonova

QCD Phase Diagram & Neutron Star Mergers



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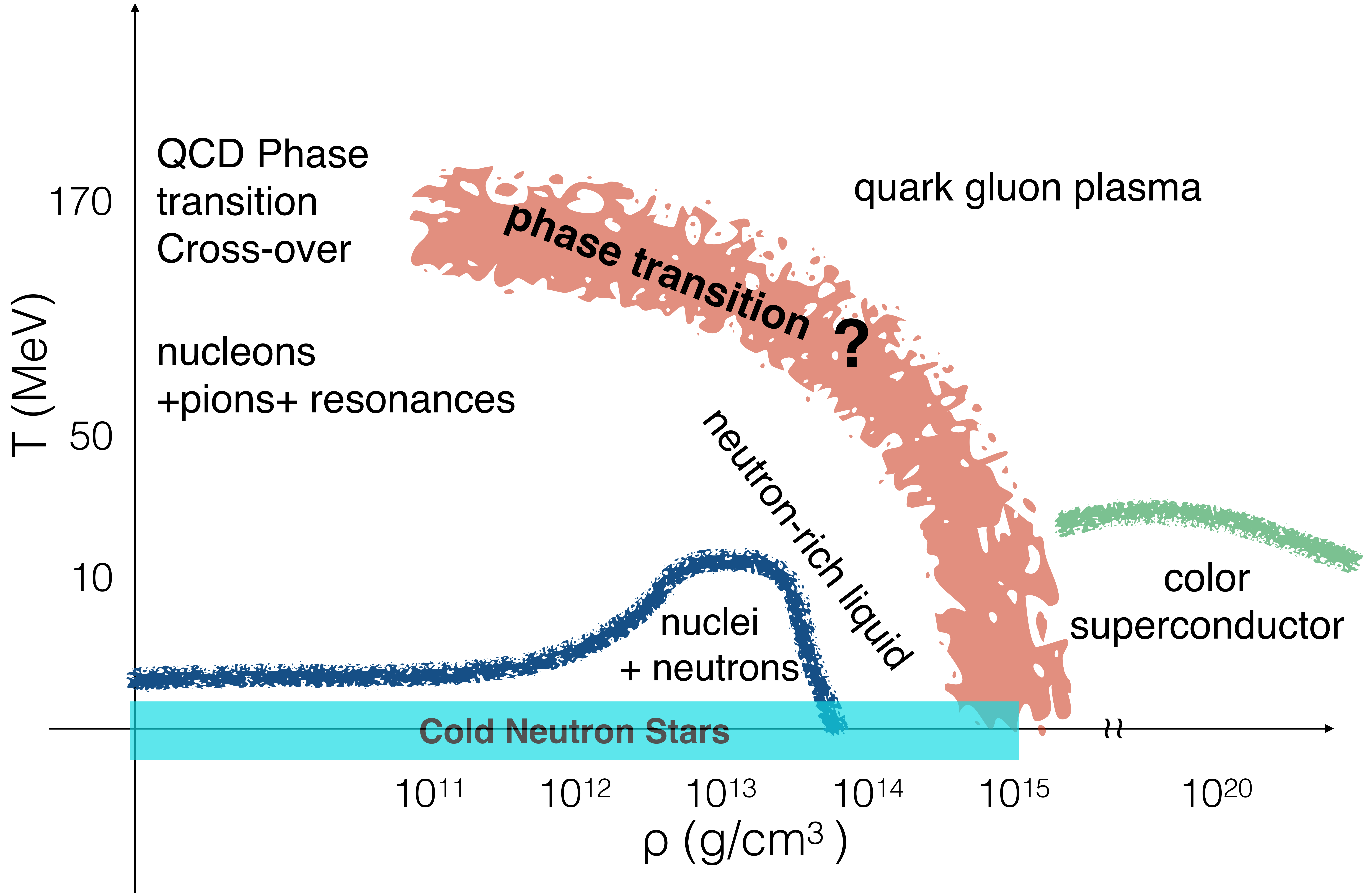

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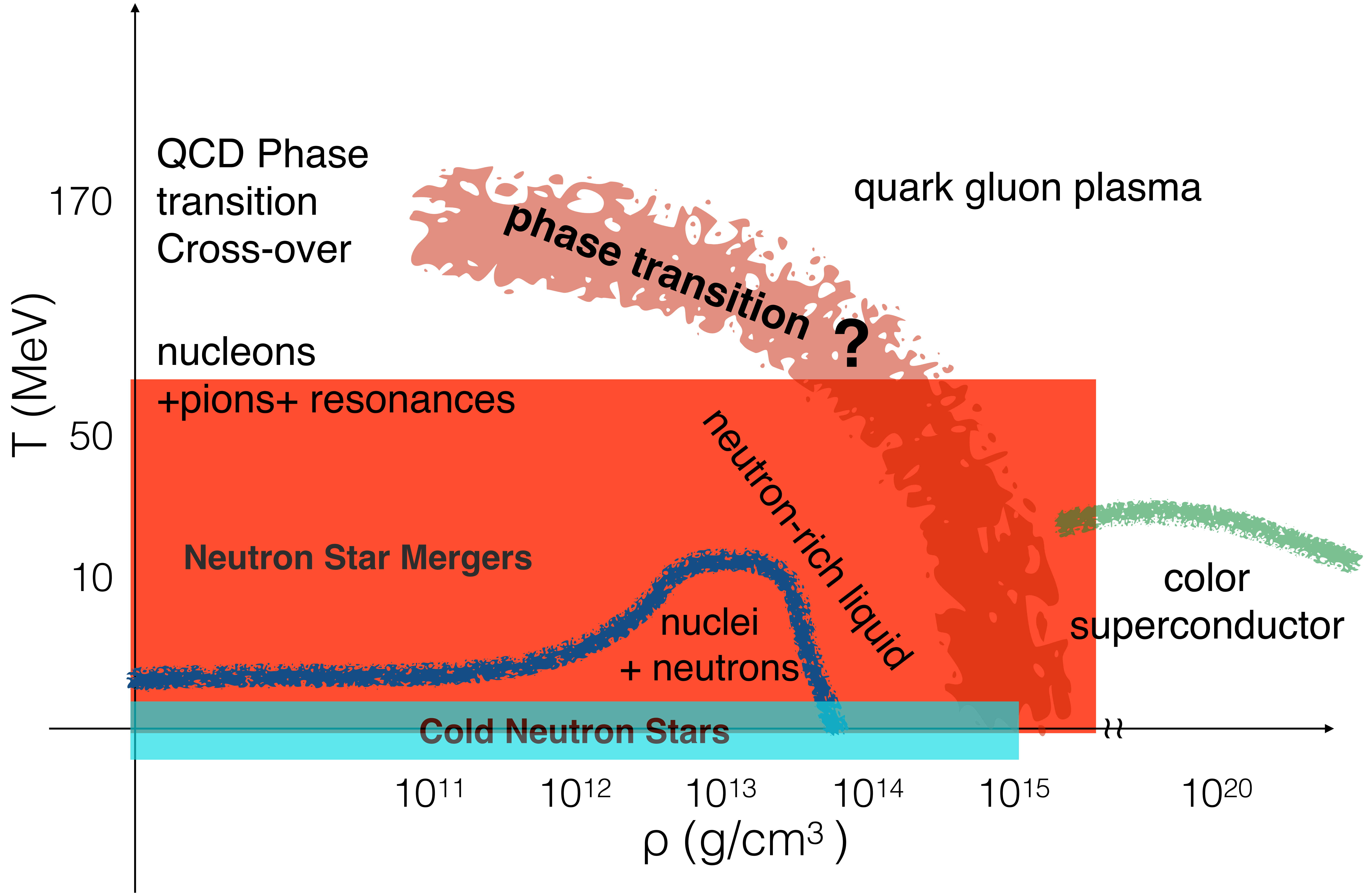

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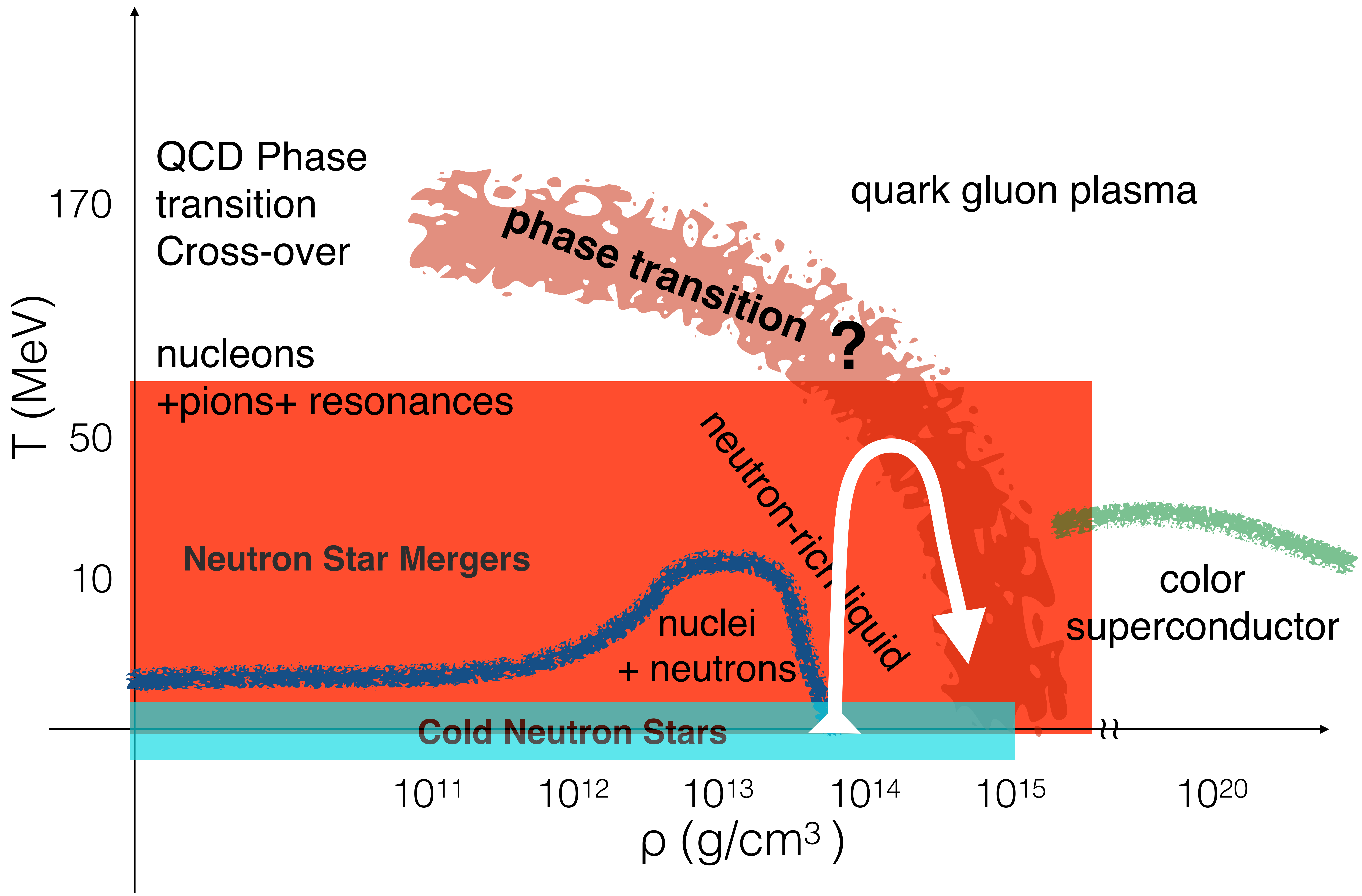
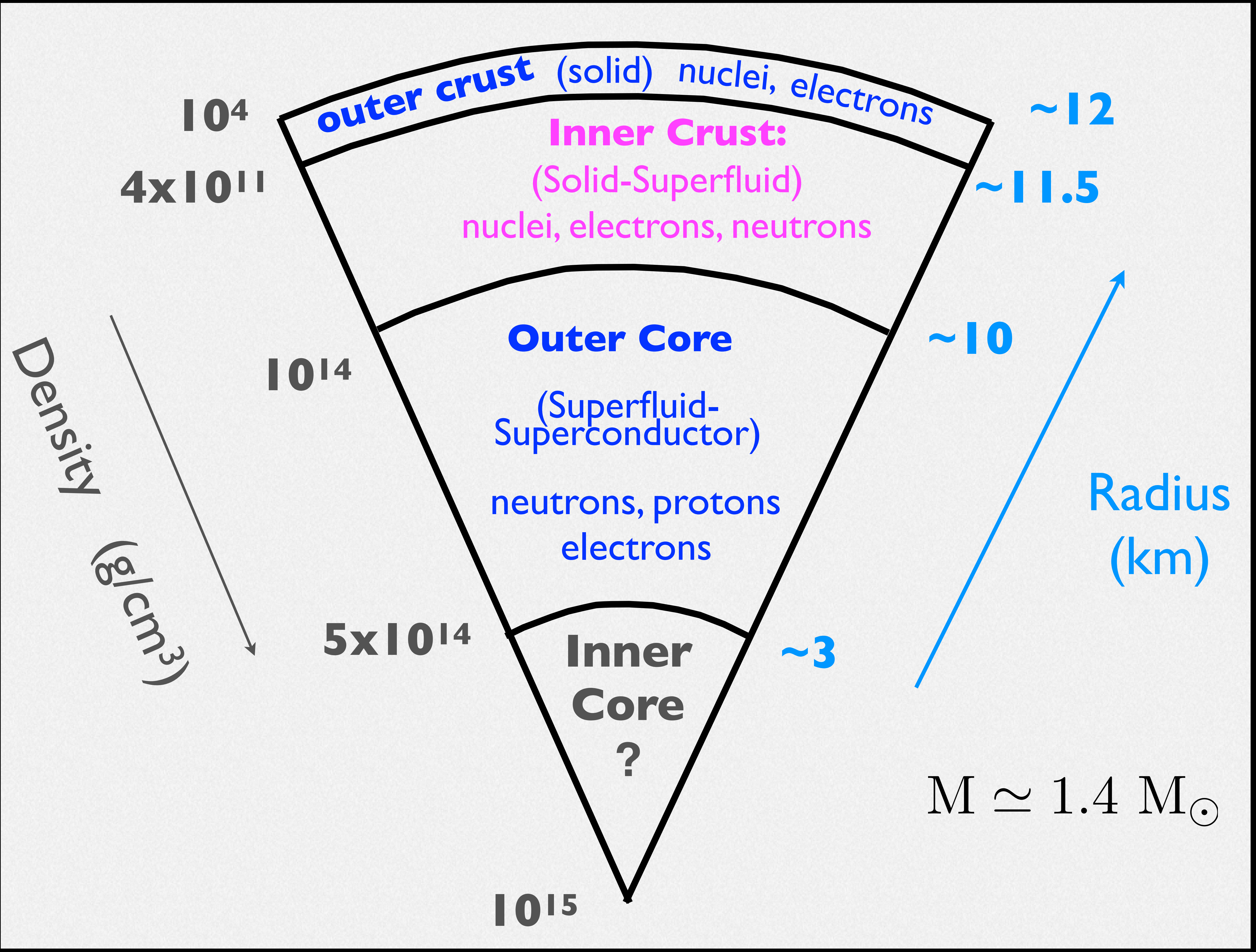
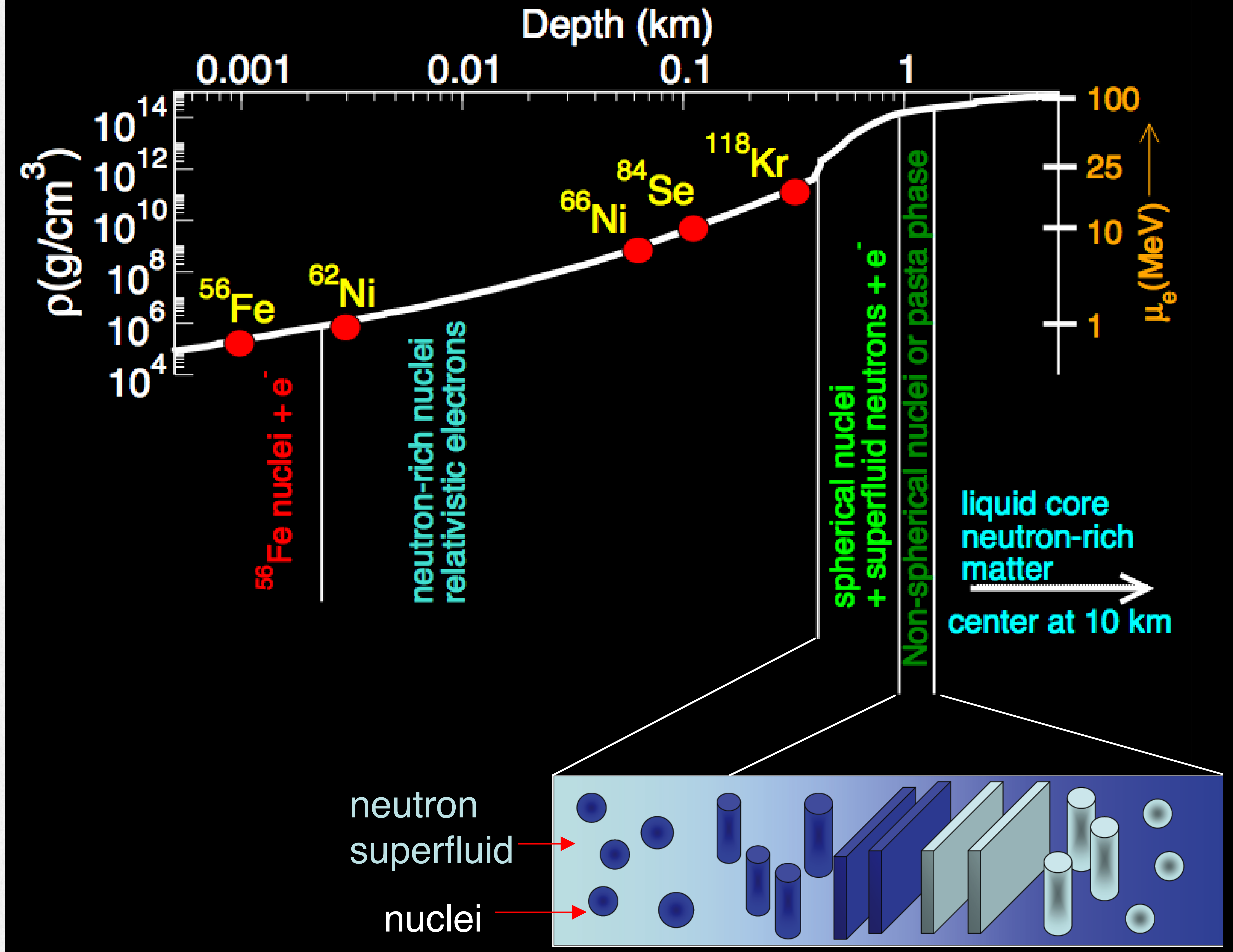


Cold Neutron Stars: A theorist's view

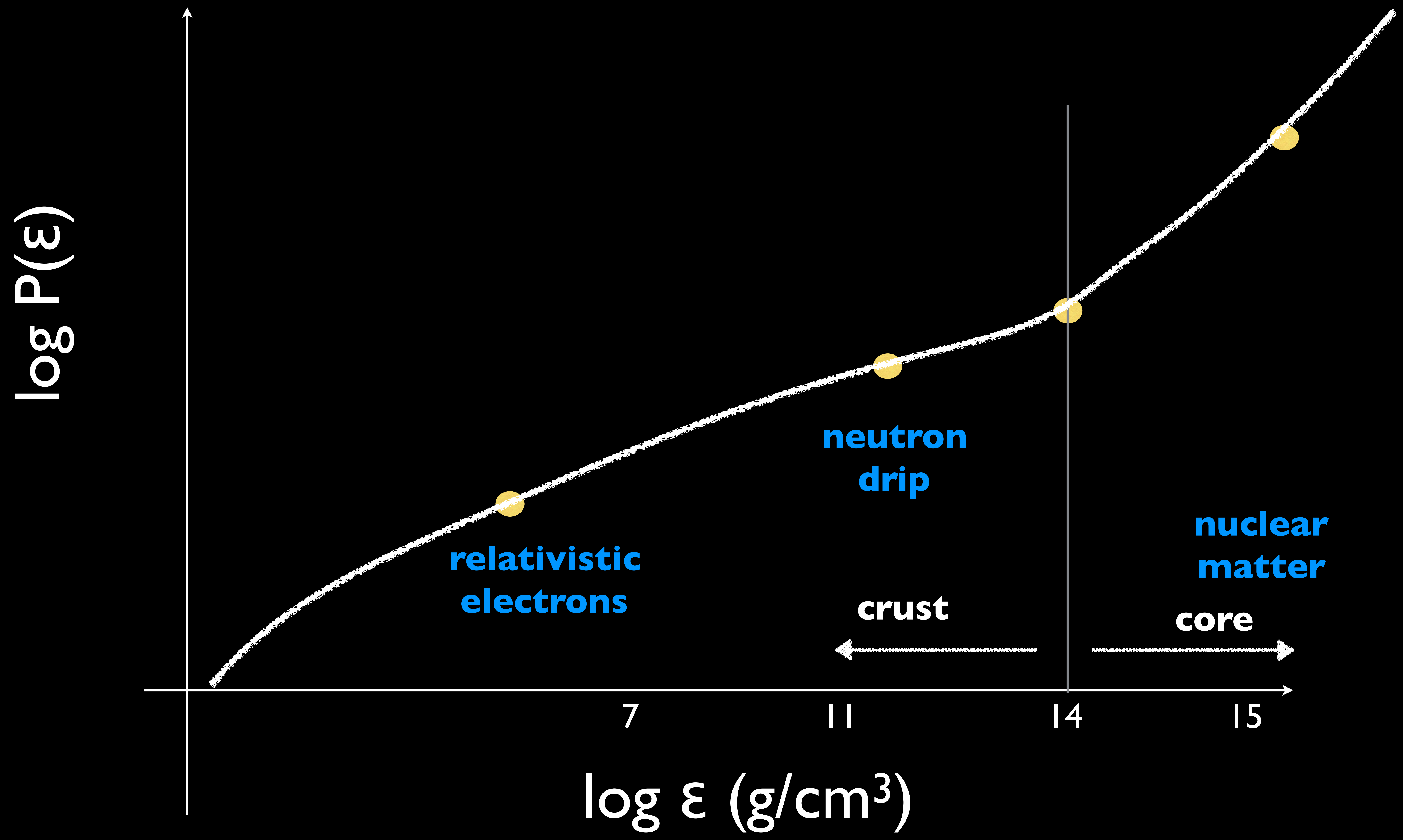




- Nuclear physics describes a large fraction of the neutron star.
- Complex phase structure at low temperature.
- The equation of state is calculable up to a few times 10^{14} g/cm^3.

For a review see: Page & Reddy, Ann. Rev. Nucl. Part. Sci. (2006)

PRESSURE V/S ENERGY DENSITY (EOS)



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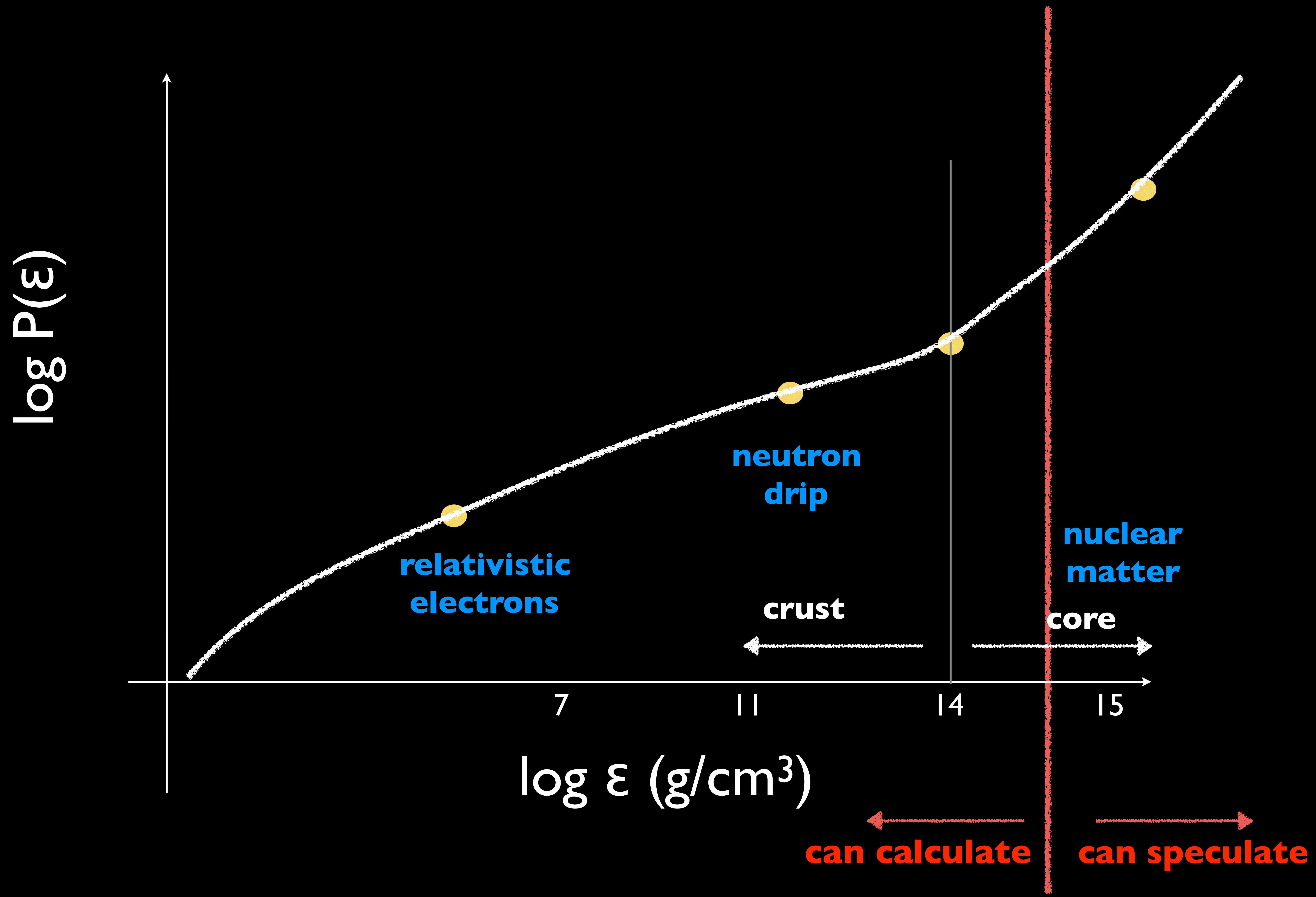

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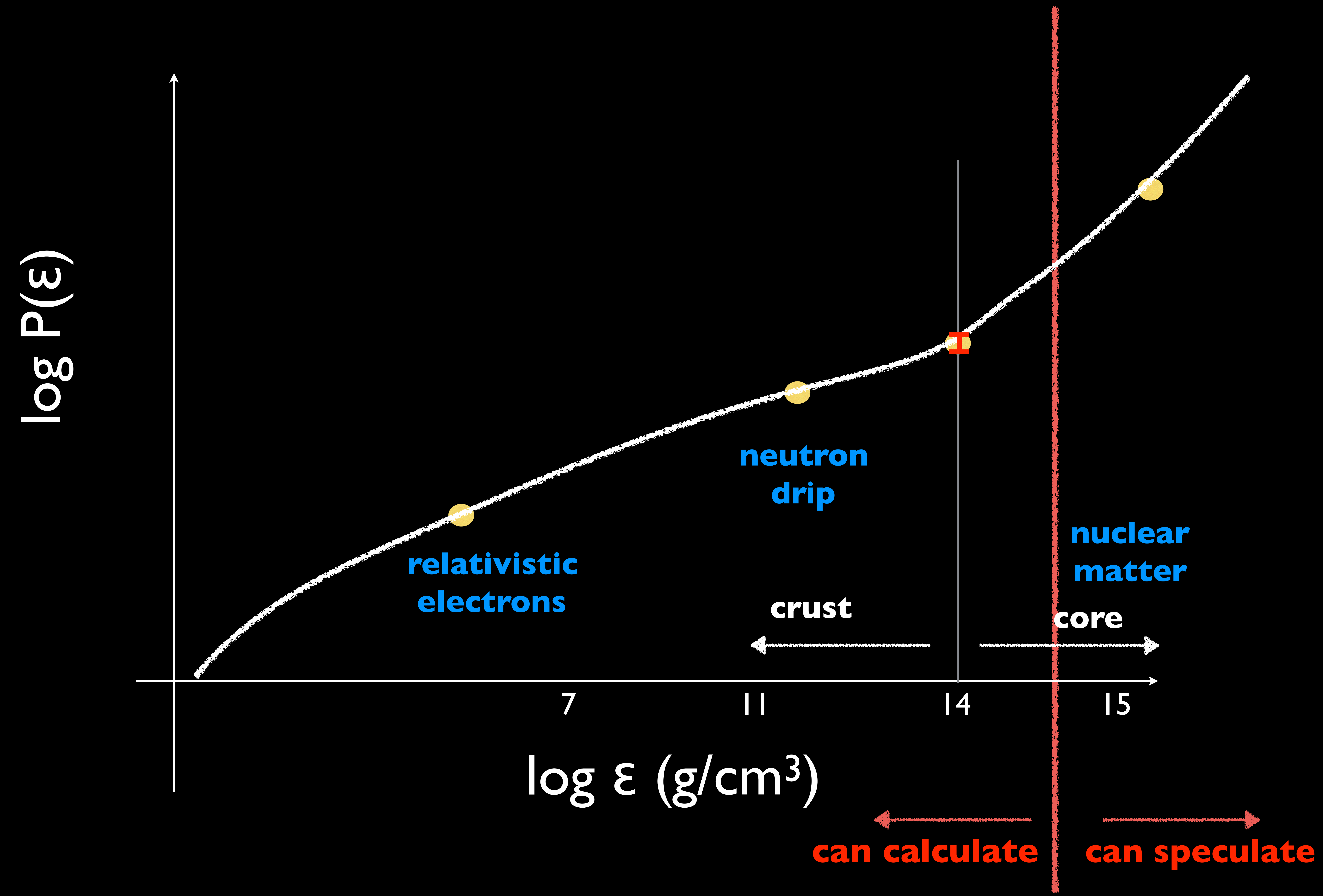

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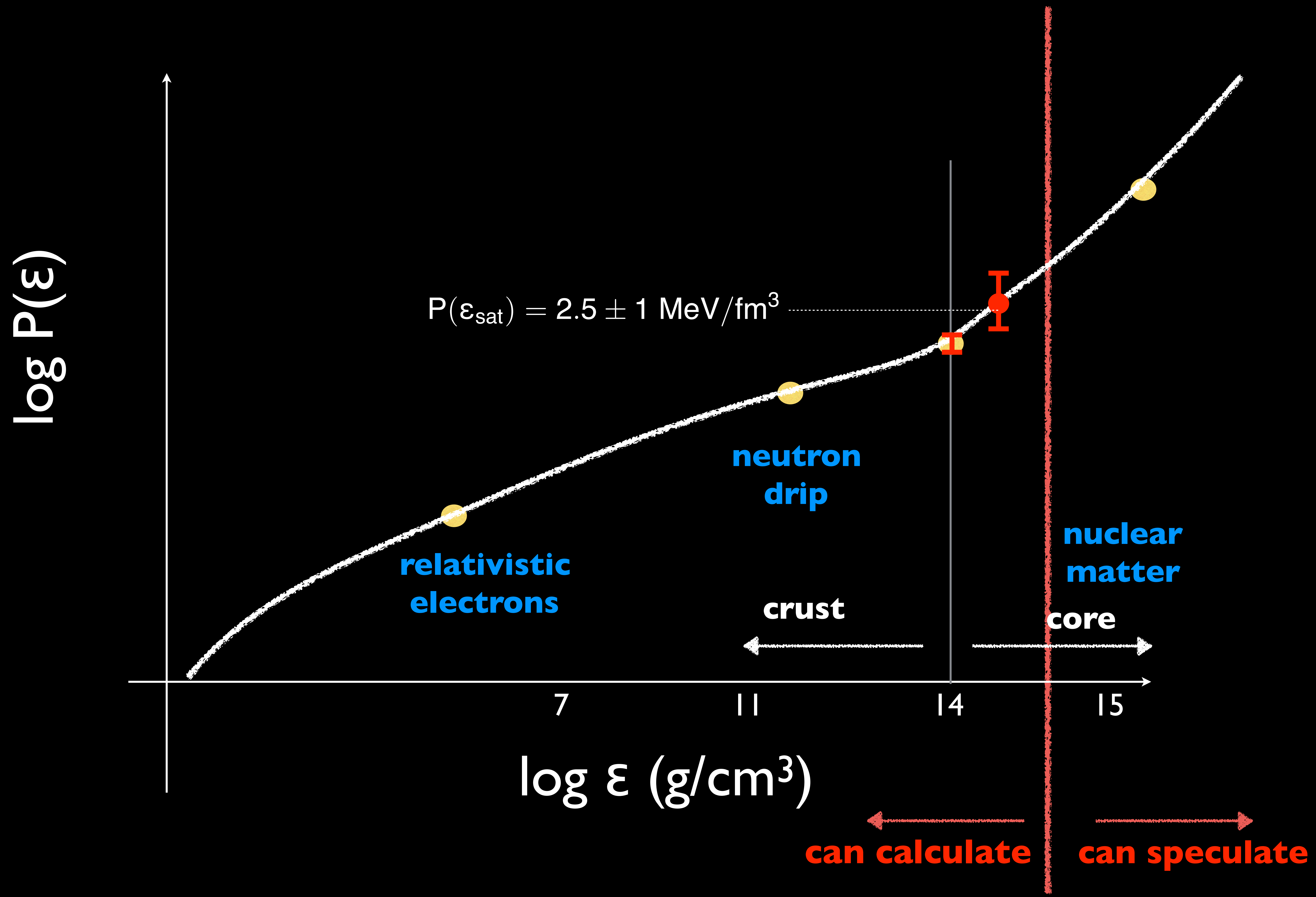

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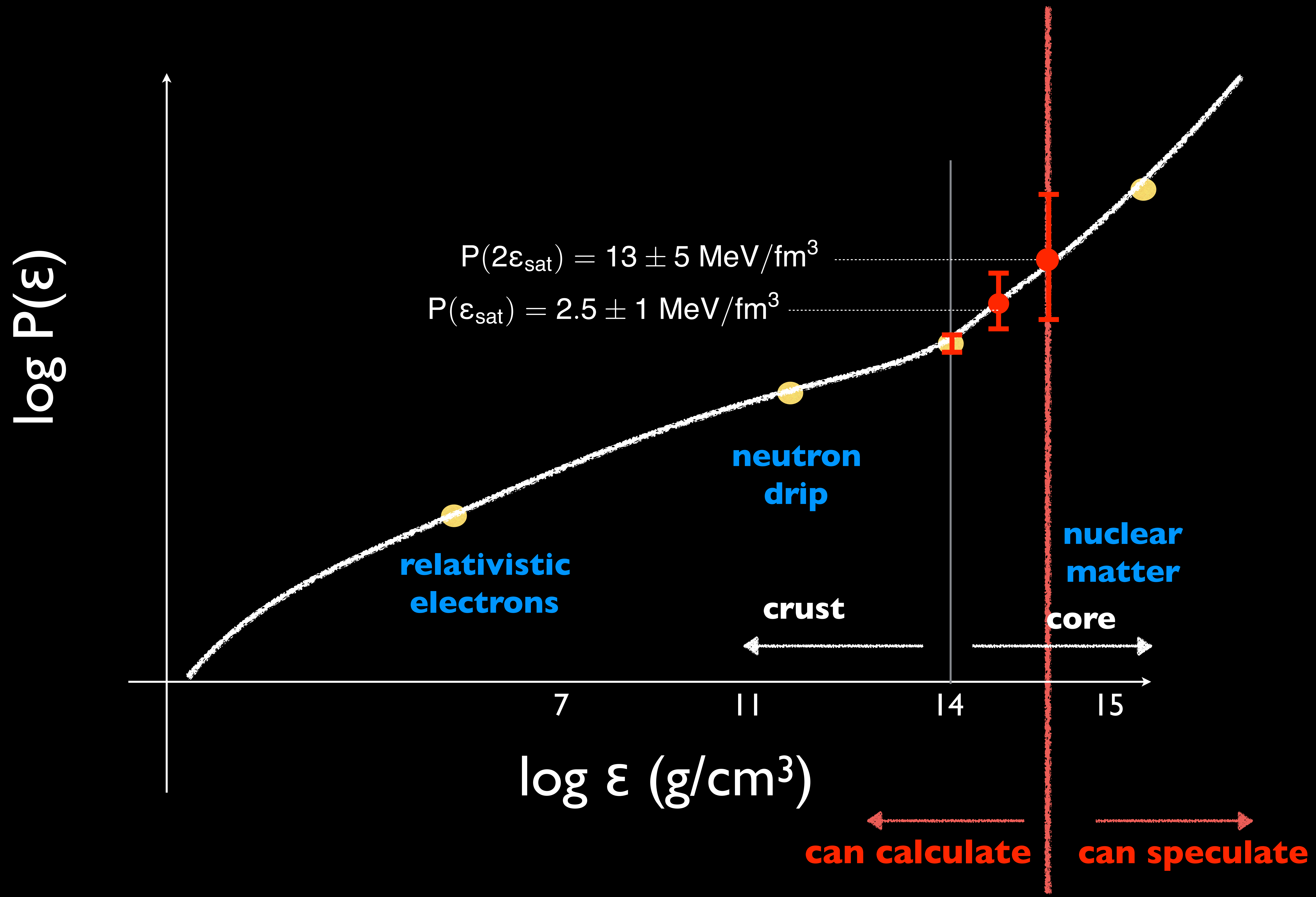

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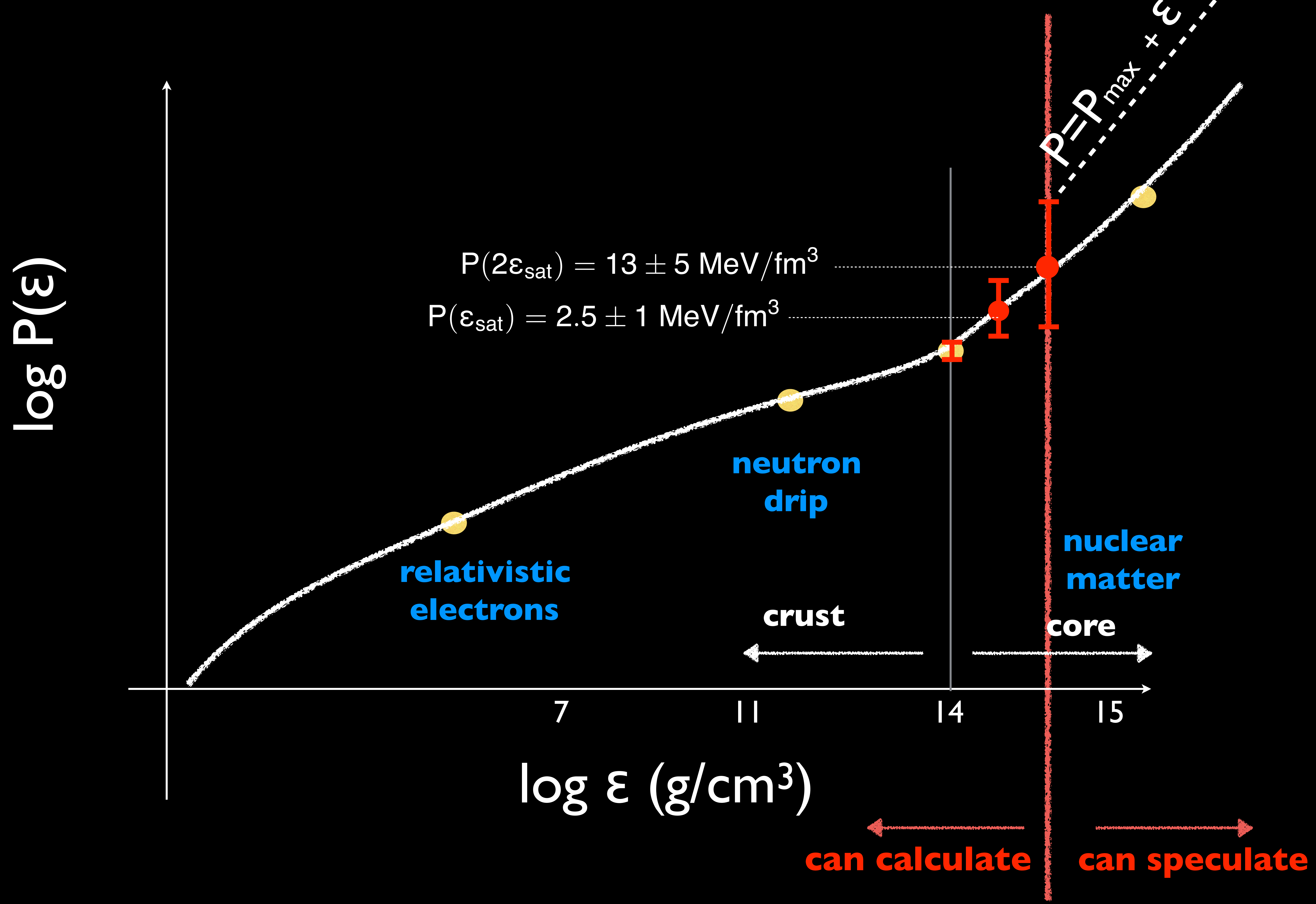

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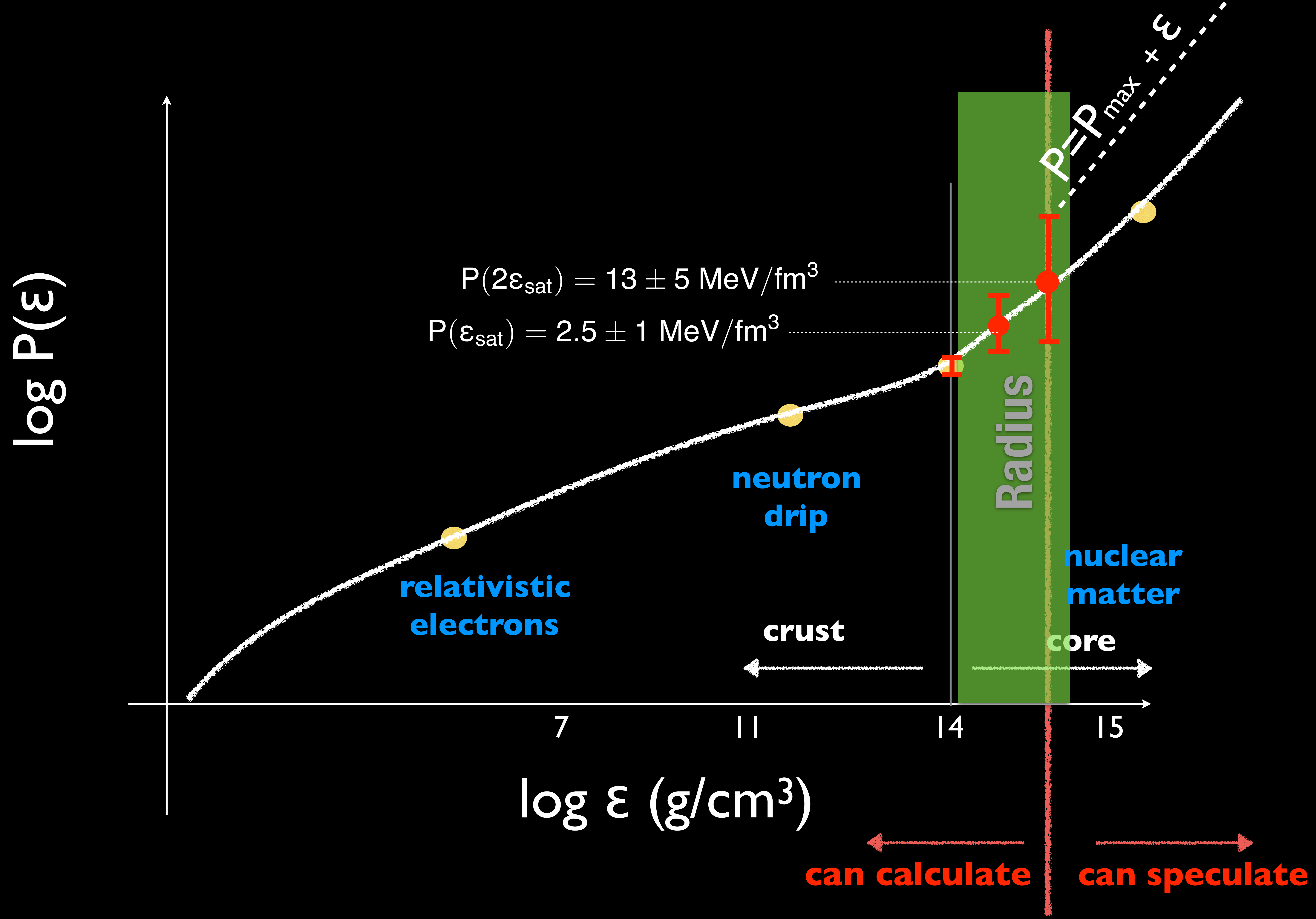

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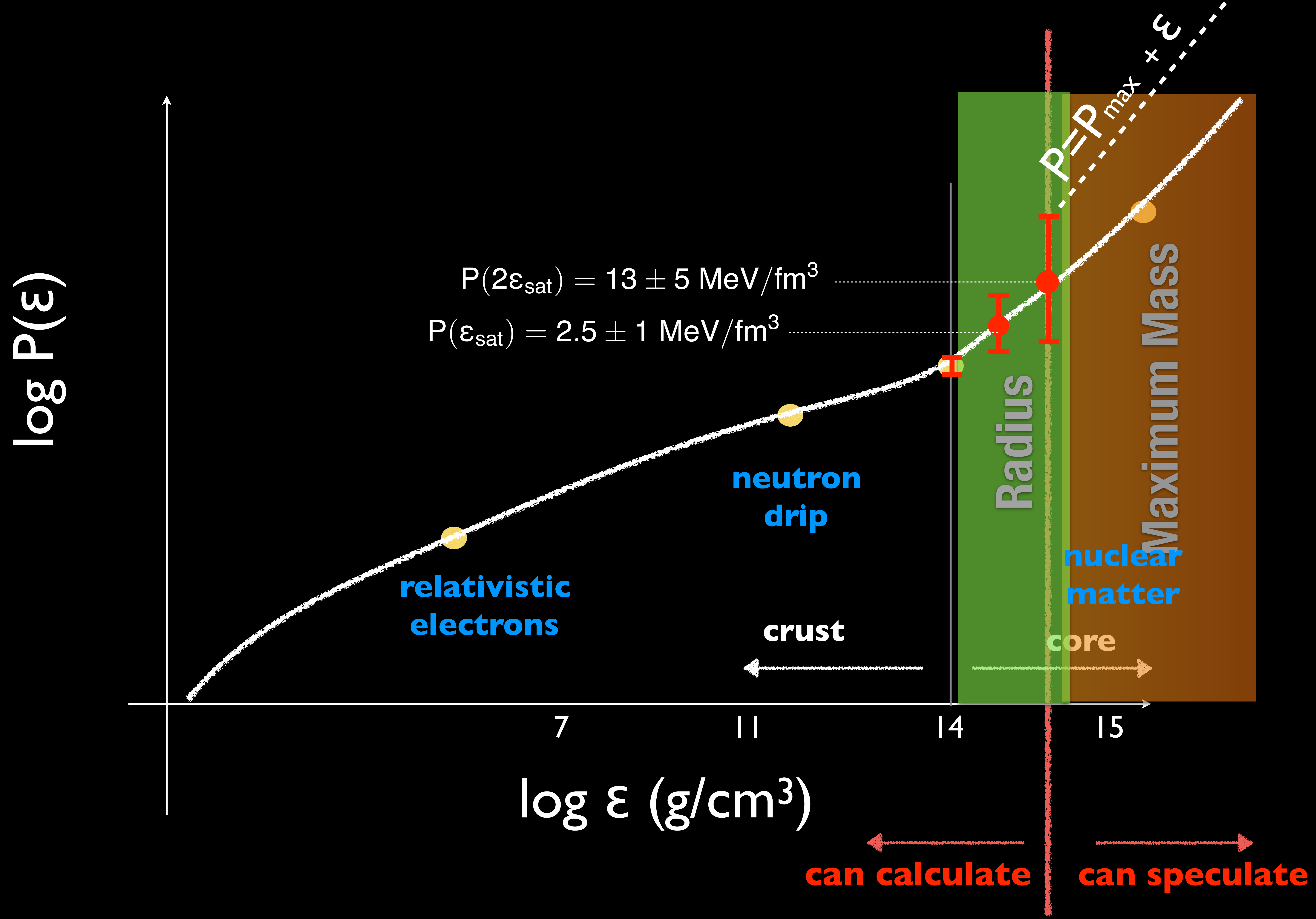

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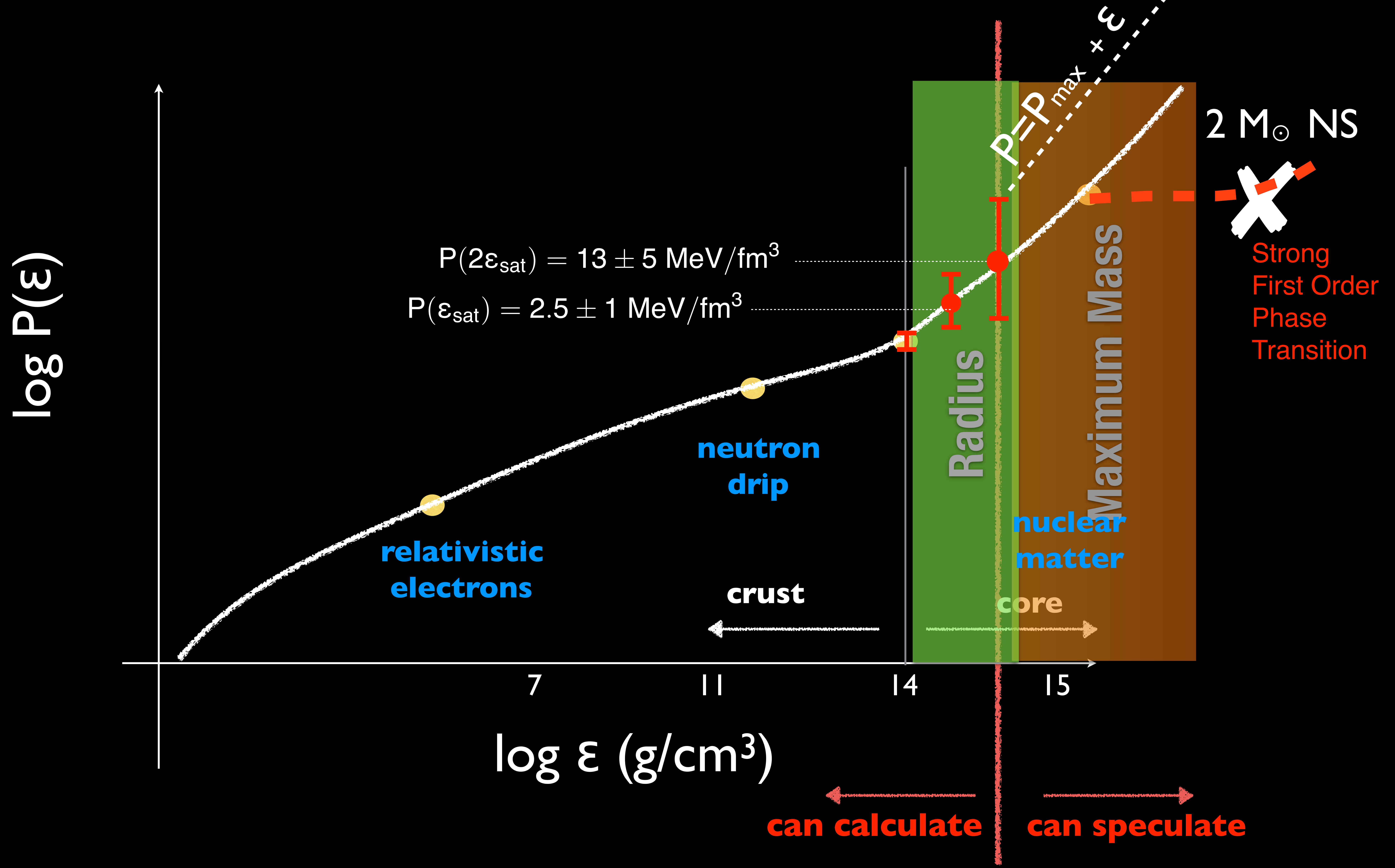

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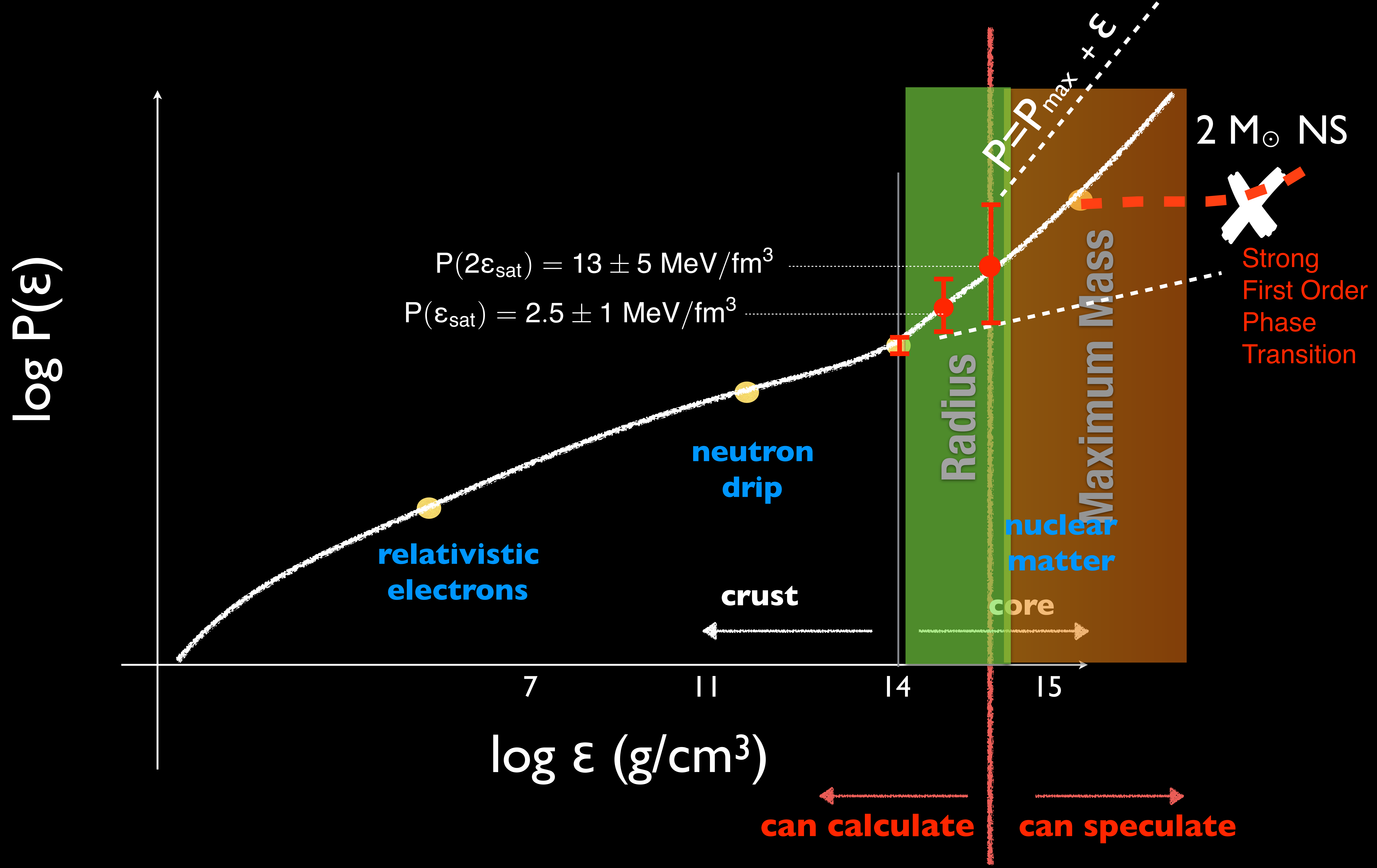
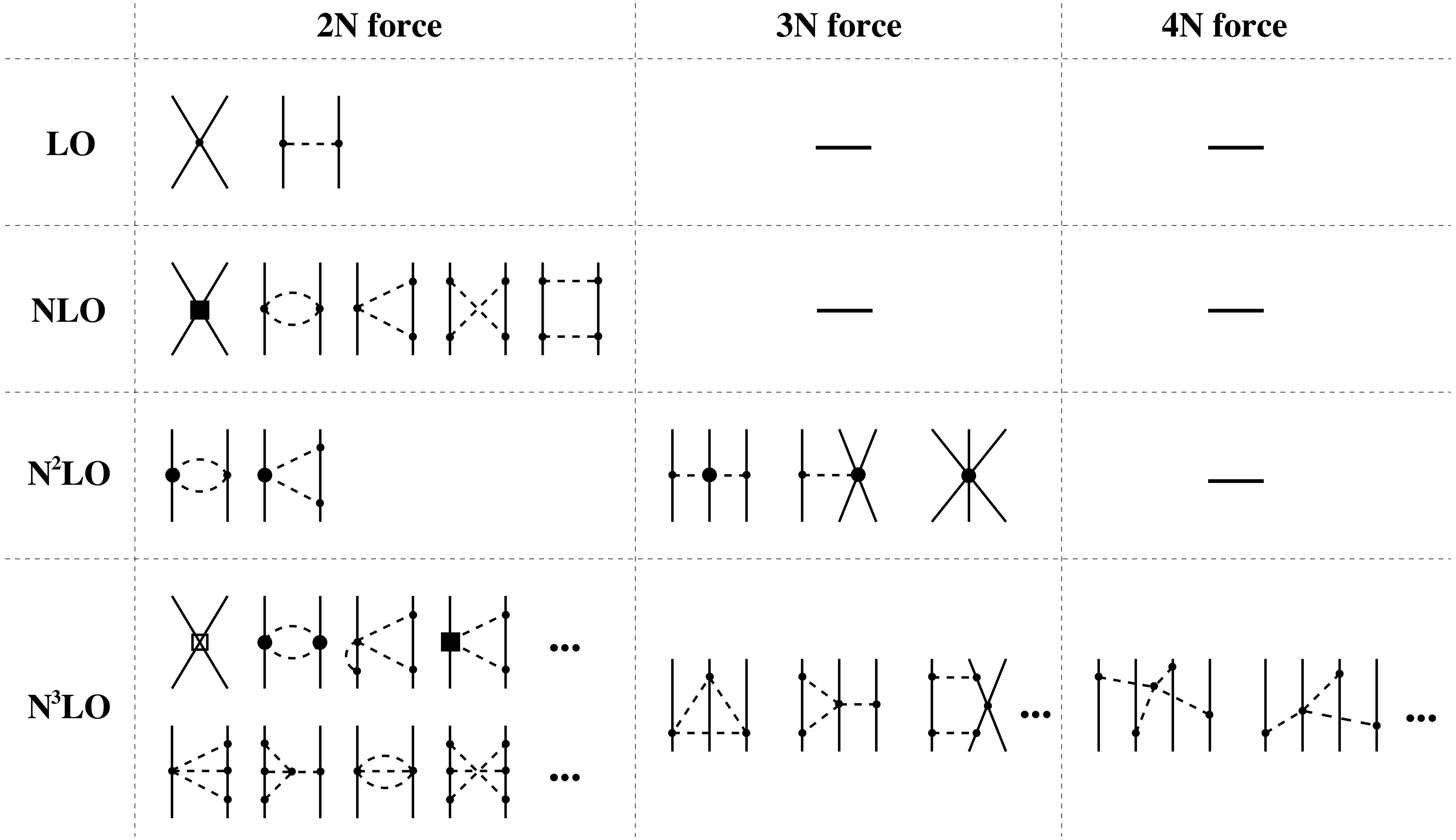
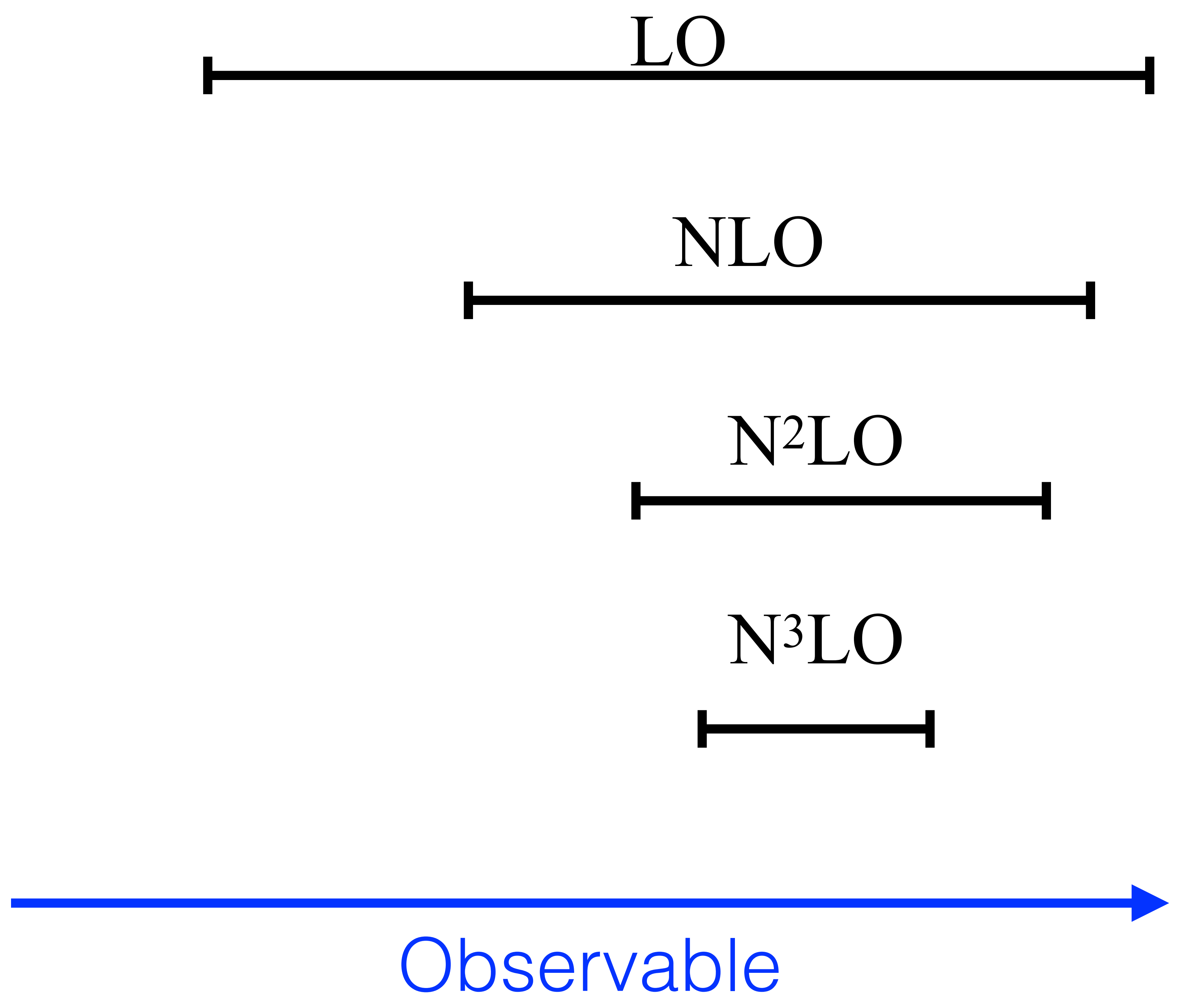


Modern NN & NNN Forces

EFT inspired Hamiltonian 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 ..

Dense matter EOS and NS structure

Modern EOS based on EFT inspired nuclear forces and Quantum Monte Carlo calculations provide useful predictions despite uncertainties at high density. A general high density EOS is constructed sampling the speed of sound constrained by:

- 2 solar mass NS (J0348+0432)
- Causality (speed of sound < c)

Nuclear description viable up to 2.5 x 10^{14} g/cm^3 :

- Radius = 9.5 - 14 kms
- Maximum mass = 2 - 3 solar masses

Nuclear description viable up to 5 x 10^{14} g/cm^3 :

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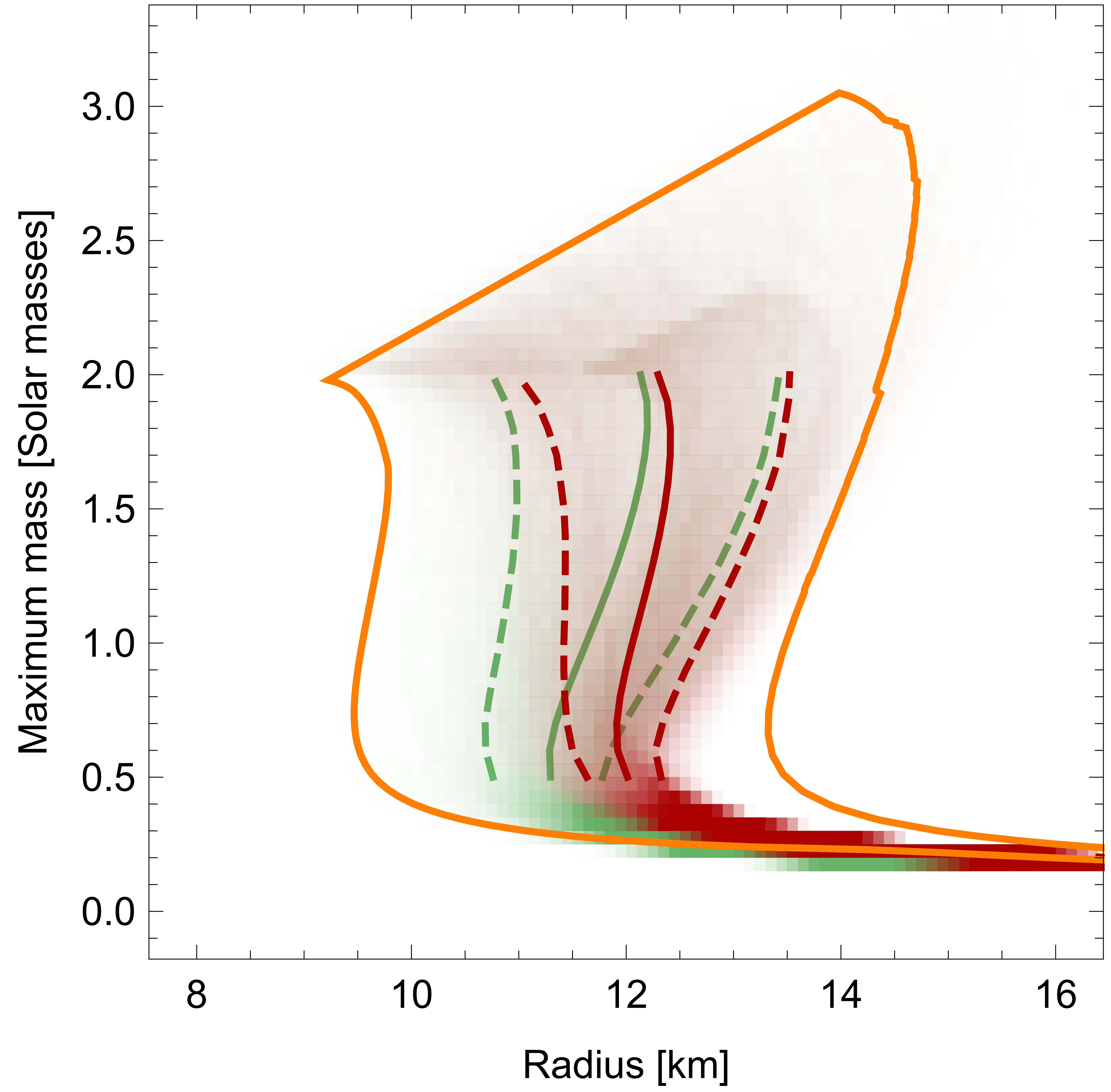

Tews, Gandolfi, Carlson, Reddy (2018), Tews, Margueron, Reddy (2018)
see also Hebeler, Schwenk, Lattimer and Pethick (2010,2013) and Carlson, Gandolfi, Reddy (2012)

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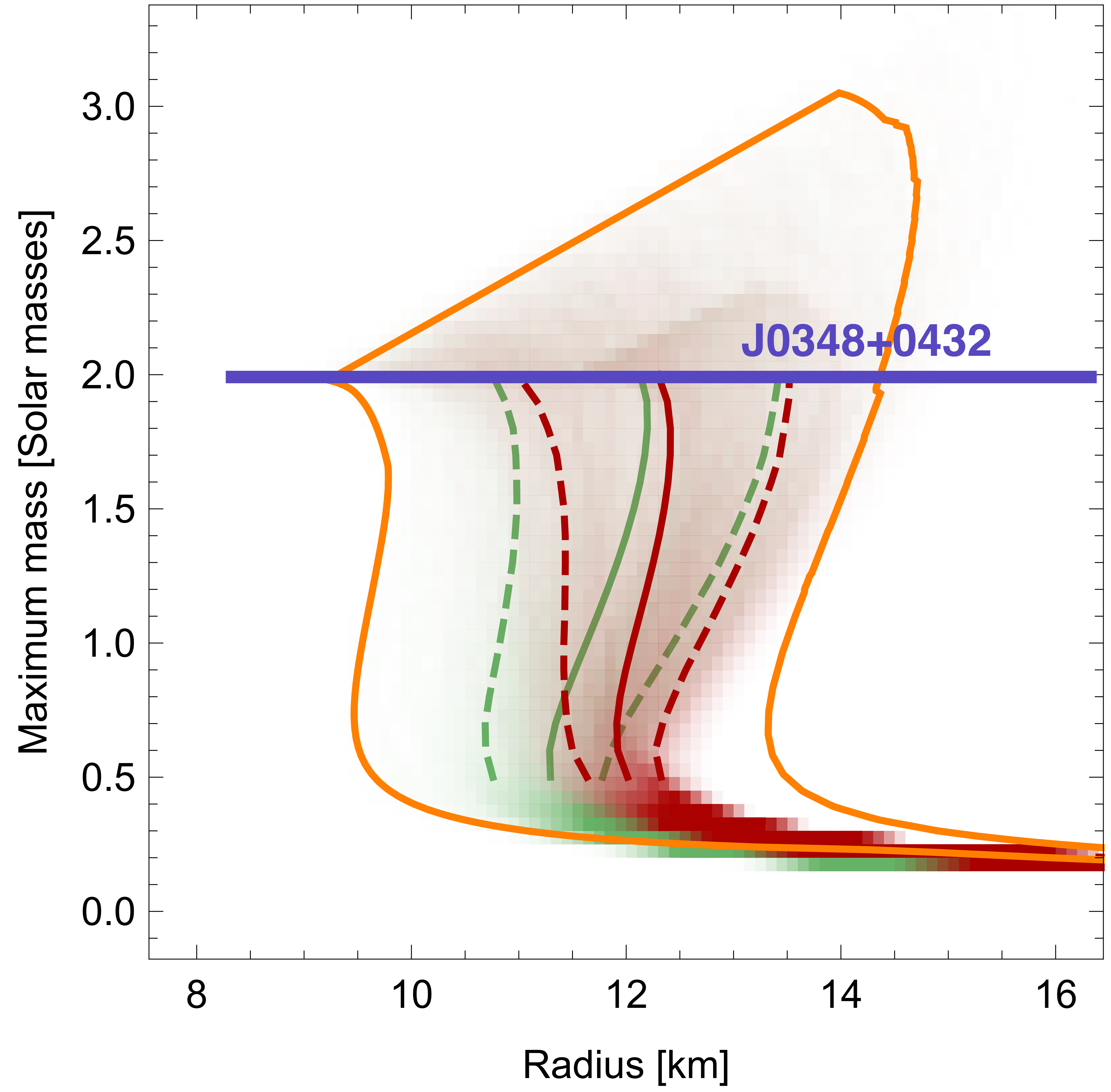

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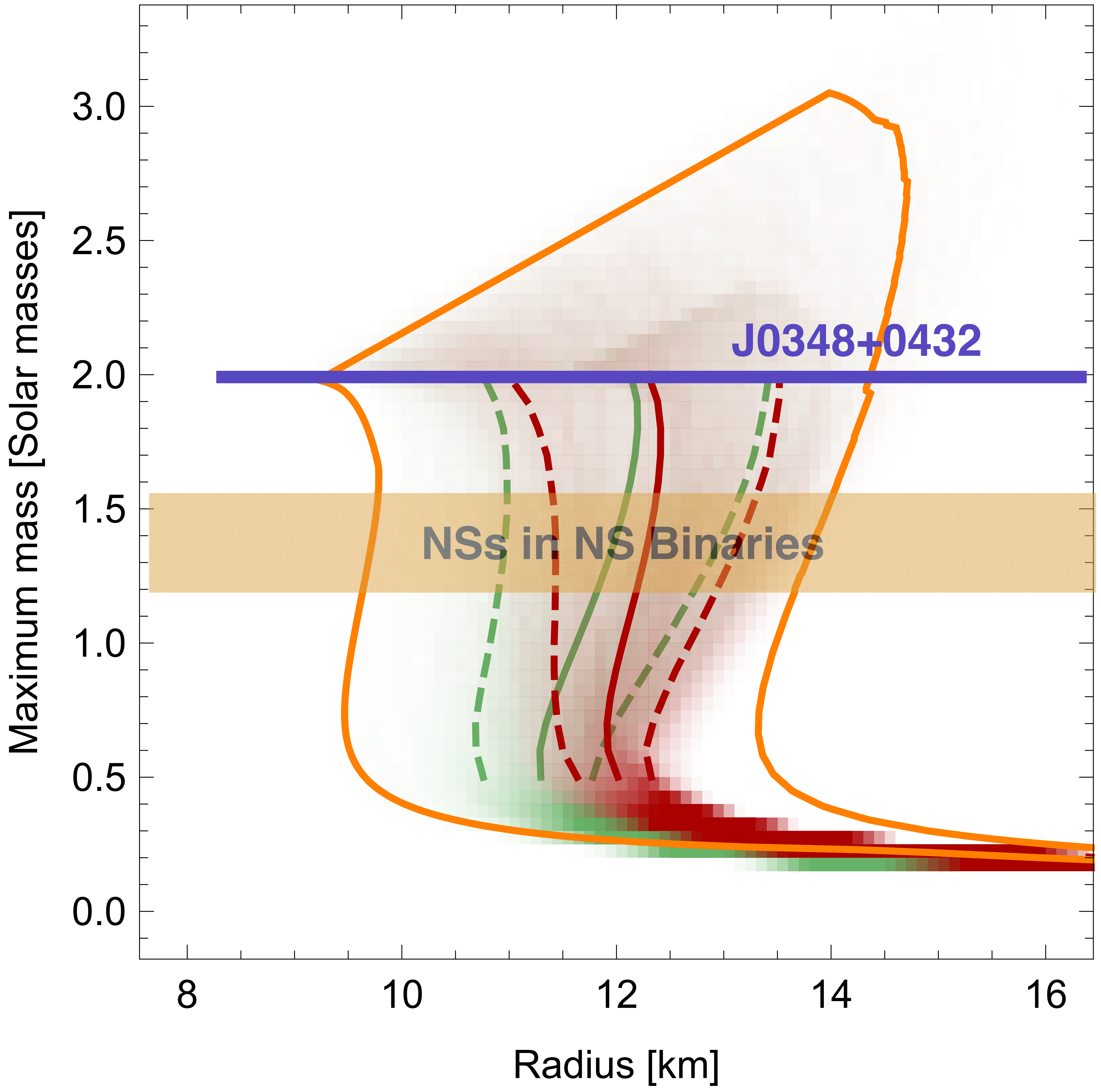

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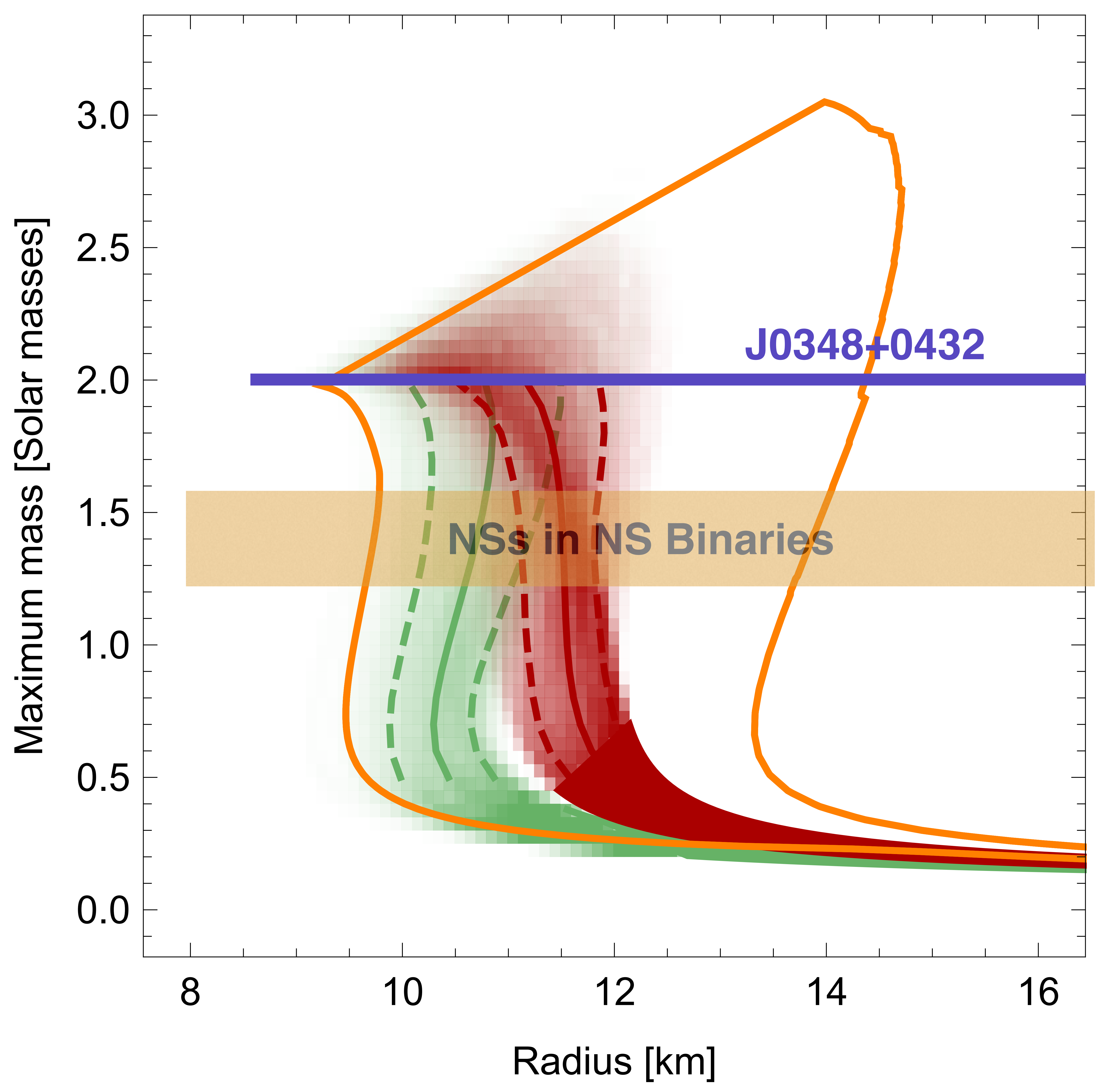

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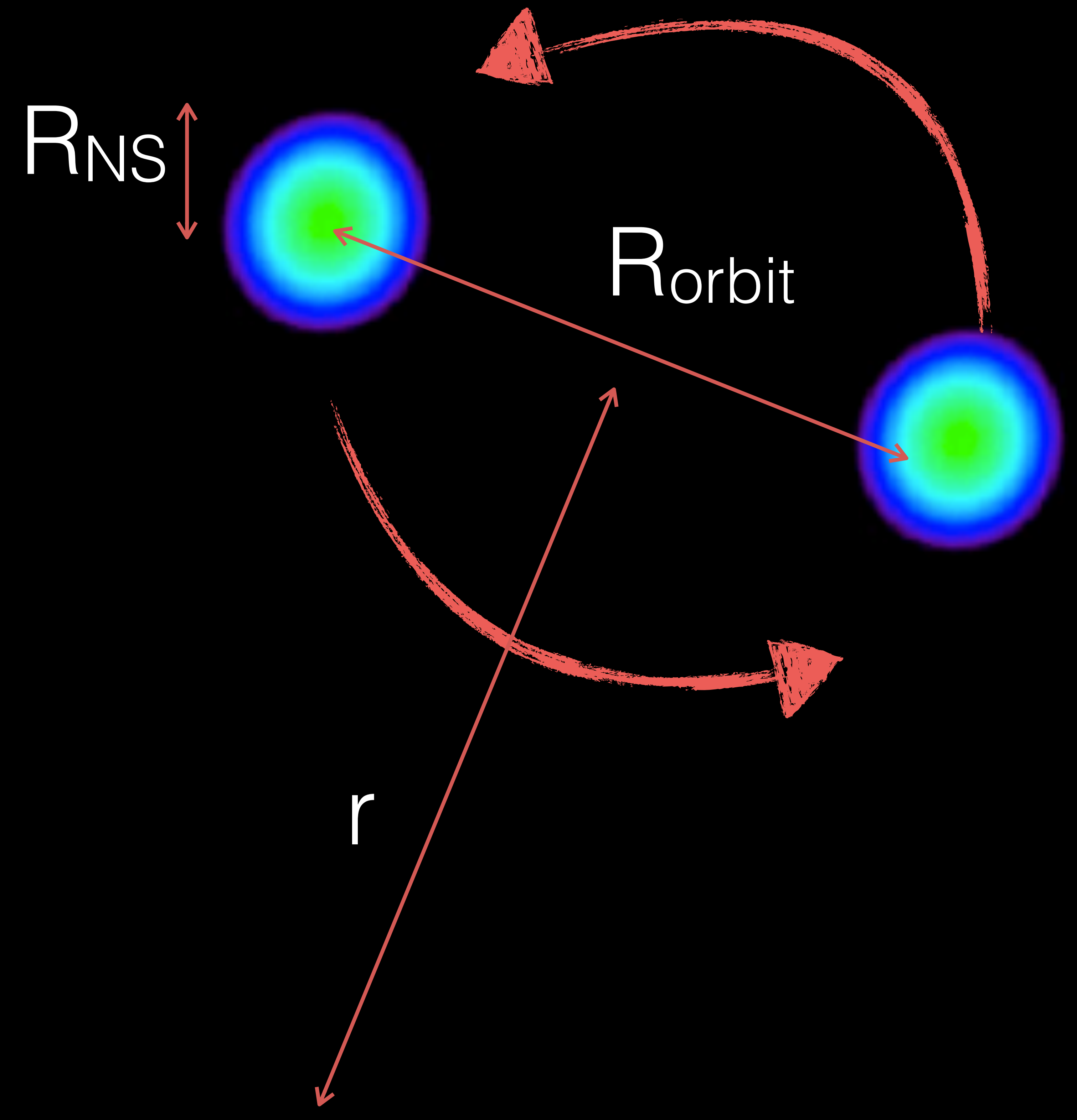
Gravitational waves during inspiral

GWs are produced by fluctuating quadrupoles.



$$g_{\mu\nu}(r,t) = \eta_{\mu\nu} + h_{\mu\nu}(r,t)$$

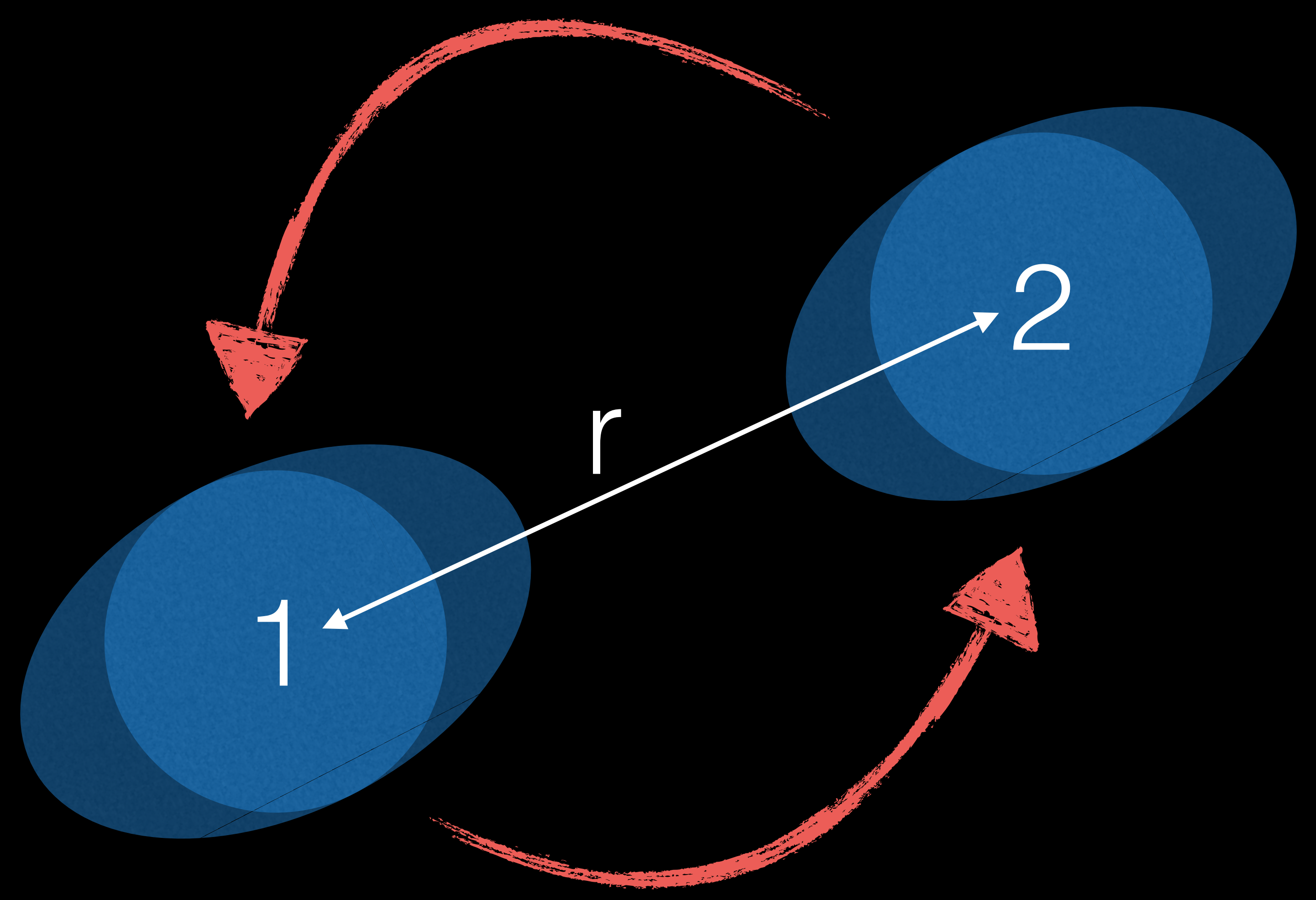
$$h_{\mu\nu}(r,t) = \frac{2G}{r}\ddot{I}_{ij}(t_R) \qquad I_{ij}(t) = \int d^3x\, \rho(t,\vec{x})\, x_i\, x_j$$

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

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

$$h(t) = h\,\cos\left(2\pi\, f(t)\, t\right)$$

Late Inspiral: $R_{orbit} \lesssim 10\ R_{NS}$



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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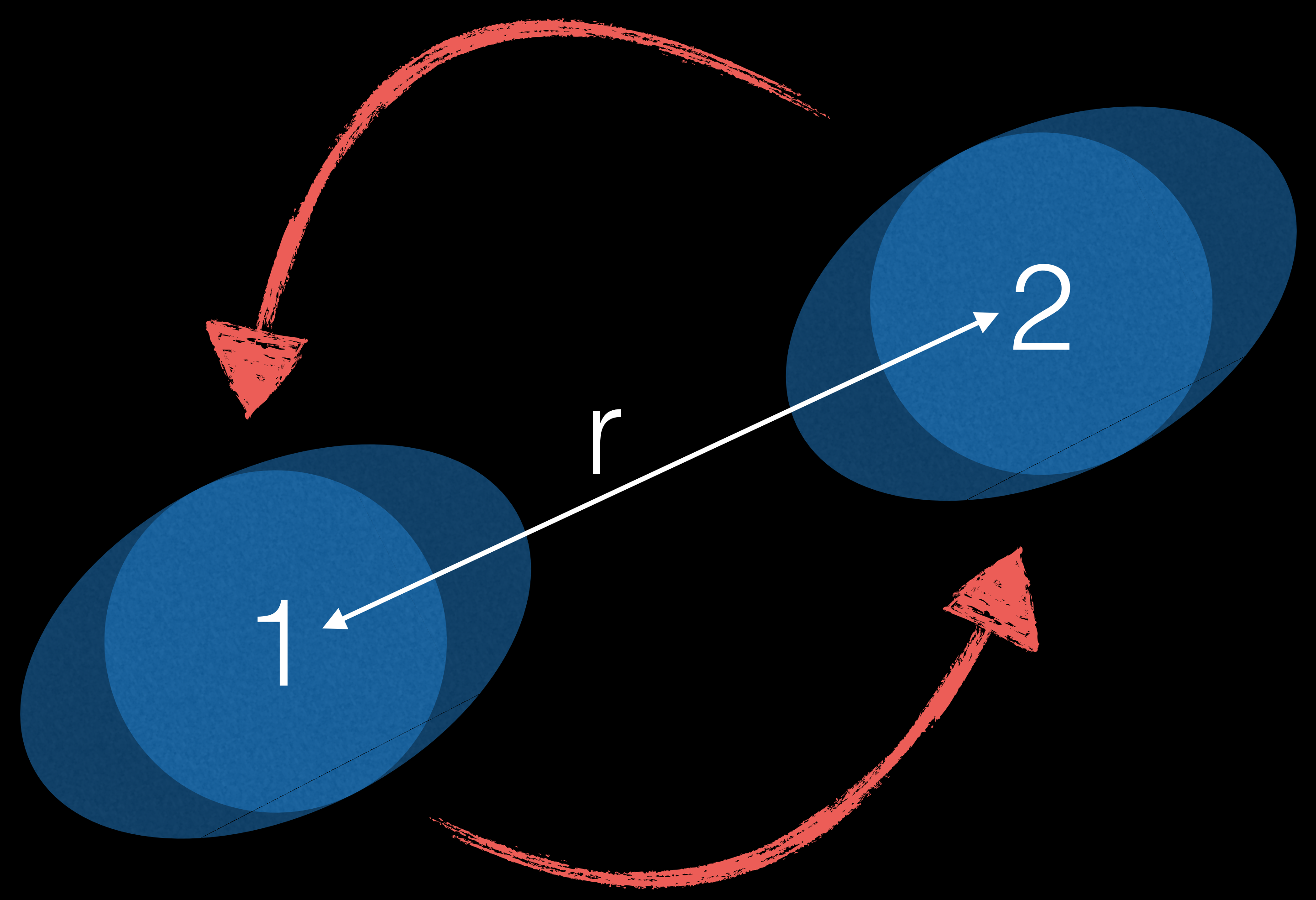

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tidal deformability   external field

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

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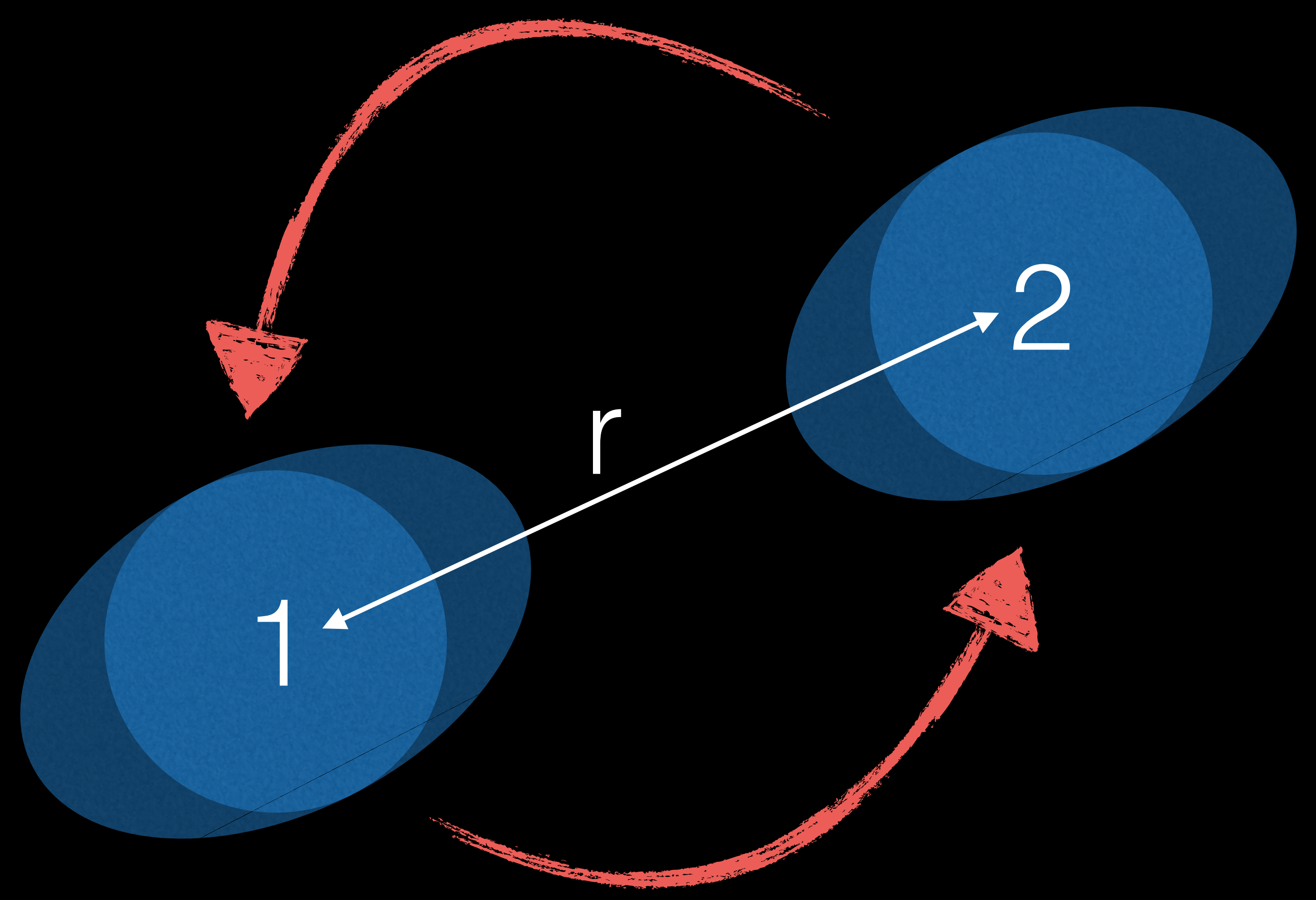

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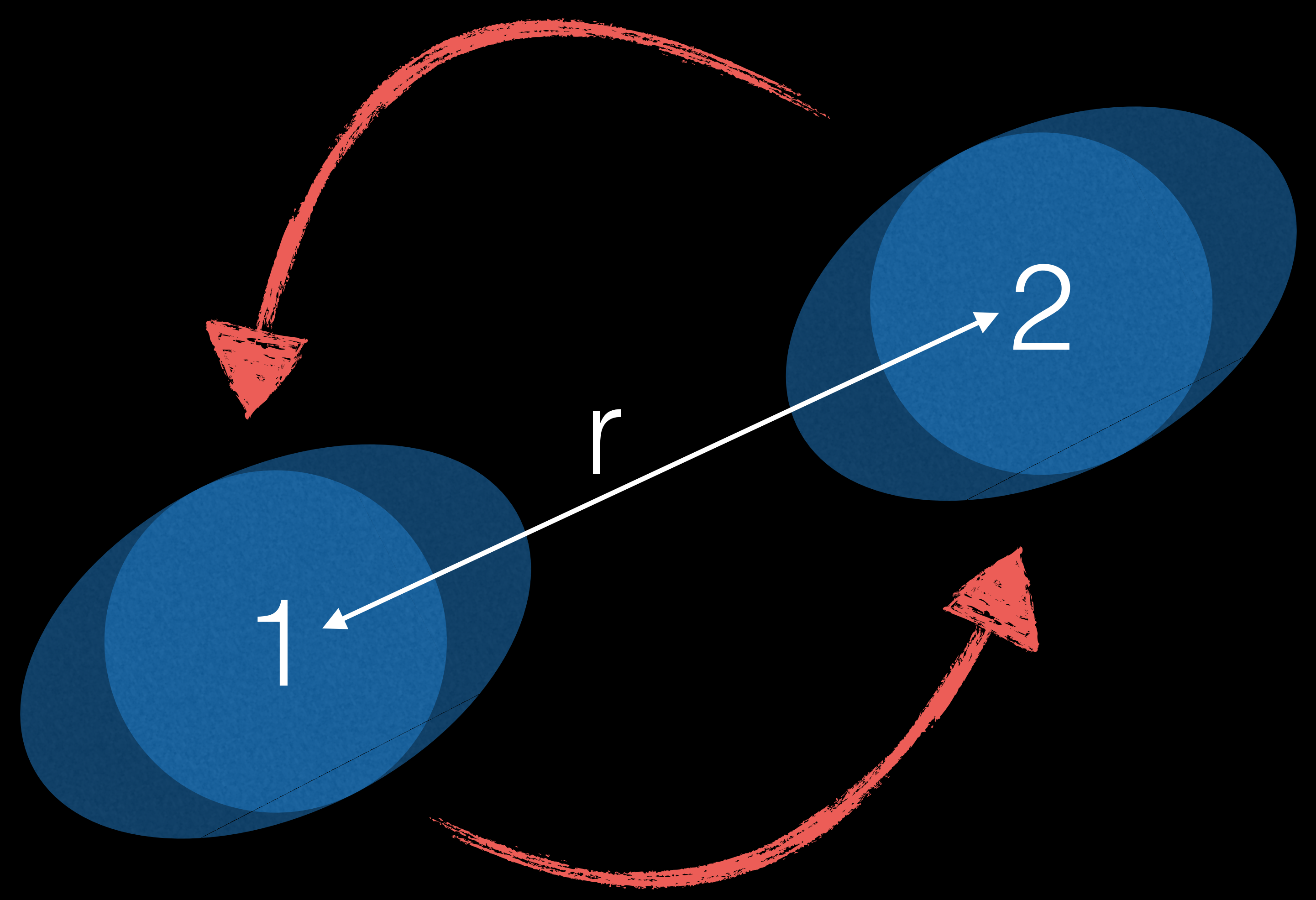

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Dimensionless binary tidal deformability: $\tilde{\Lambda} = \dfrac{16}{13}\left(\left(\dfrac{M_1}{M}\right)^5 \left(1 + \dfrac{M_2}{M_1}\right)\Lambda_1 + 1 \leftrightarrow 2\right)$

Tidal Effects at Late Times

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

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PRL **119,** 161101 (2017) PHYSICAL REVIEW LETTERS week ending 20 OCTOBER 2017

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

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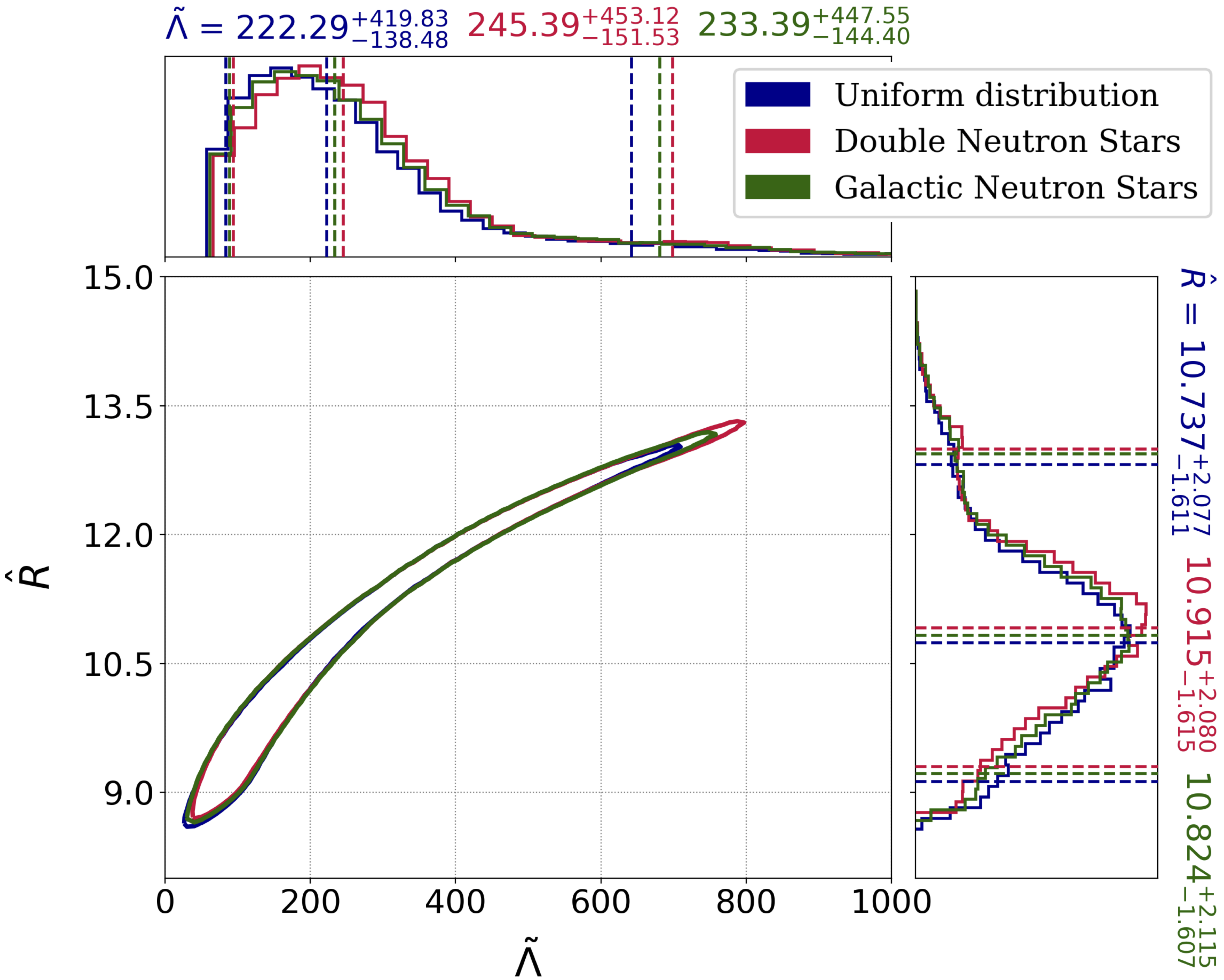
(LIGO Scientific Collaboration and Virgo Collaboration)
(Received 26 September 2017; revised manuscript received 2 October 2017; published 16 October 2017)

Parameters from GW data analysis

Primary mass m_1	$1.36–1.60\ M_\odot$
Secondary mass m_2	$1.17–1.36\ M_\odot$
Chirp mass $\mathcal{M}$	$1.188^{+0.004}_{-0.002} M_\odot$
Mass ratio m_2/m_1	$0.7–1.0$
Total mass m_{tot}	$2.74^{+0.04}_{-0.01} M_\odot$
Radiated energy E_{rad}	$> 0.025 M_\odot c^2$
Luminosity distance D_{L}	40^{+8}_{-14} Mpc
Viewing angle Θ	$\leq 55°$
Using NGC 4993 location	$\leq 28°$
Combined dimensionless tidal deformability $\tilde{\Lambda}$	≤ 800
Dimensionless tidal deformability $\Lambda(1.4 M_\odot)$	≤ 800

Reanalysis with common EOS provides improved constraints

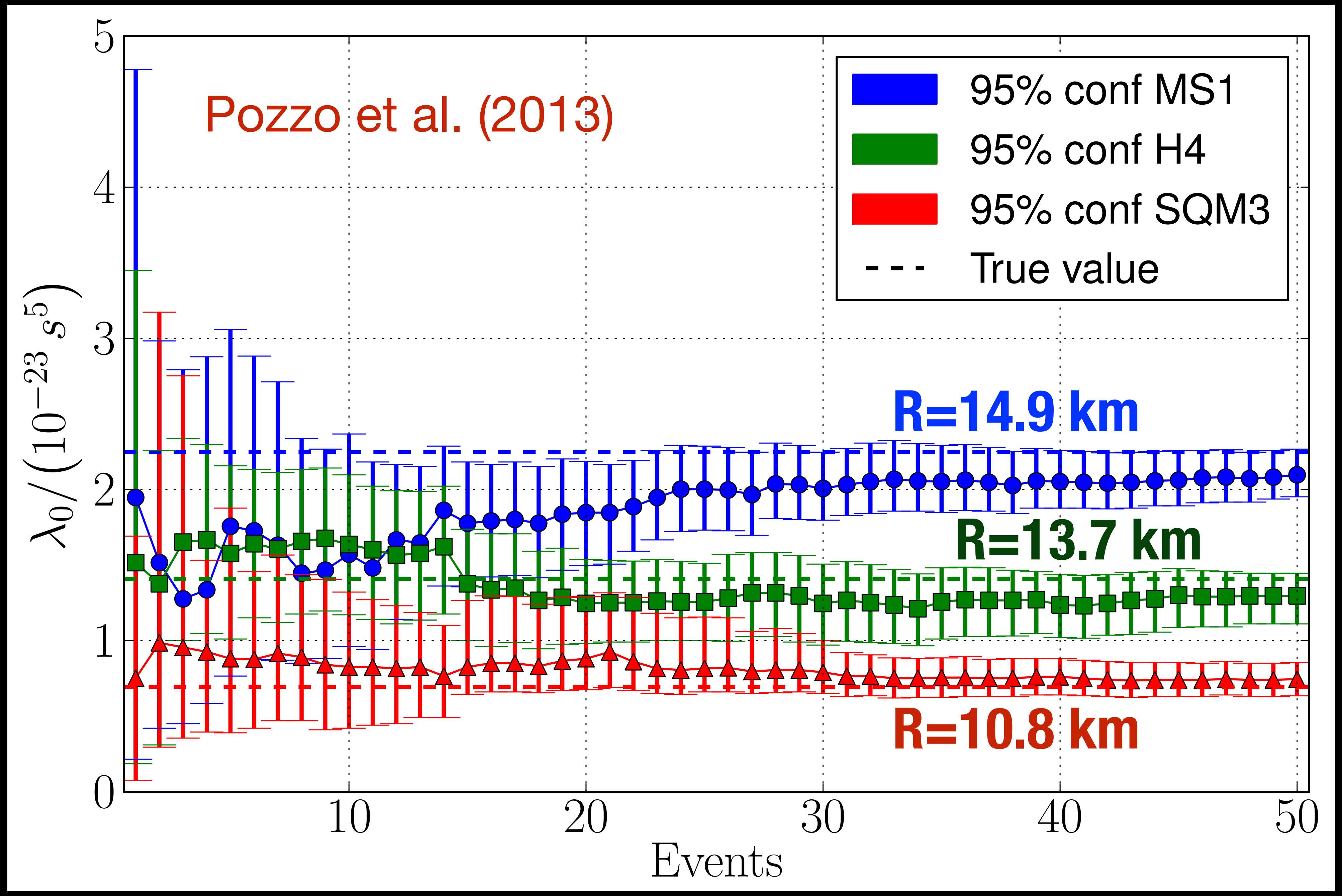


- Tidal deformations are discernible and small suggesting that the NS radius: 9 kms < R < 13 km.
- This range is compatible with current dense matter theories but does not offer new insights.
- With more detections and better high-frequency sensitivity we may be able extract useful constraints for the EOS.

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

Many detections and next generation detectors

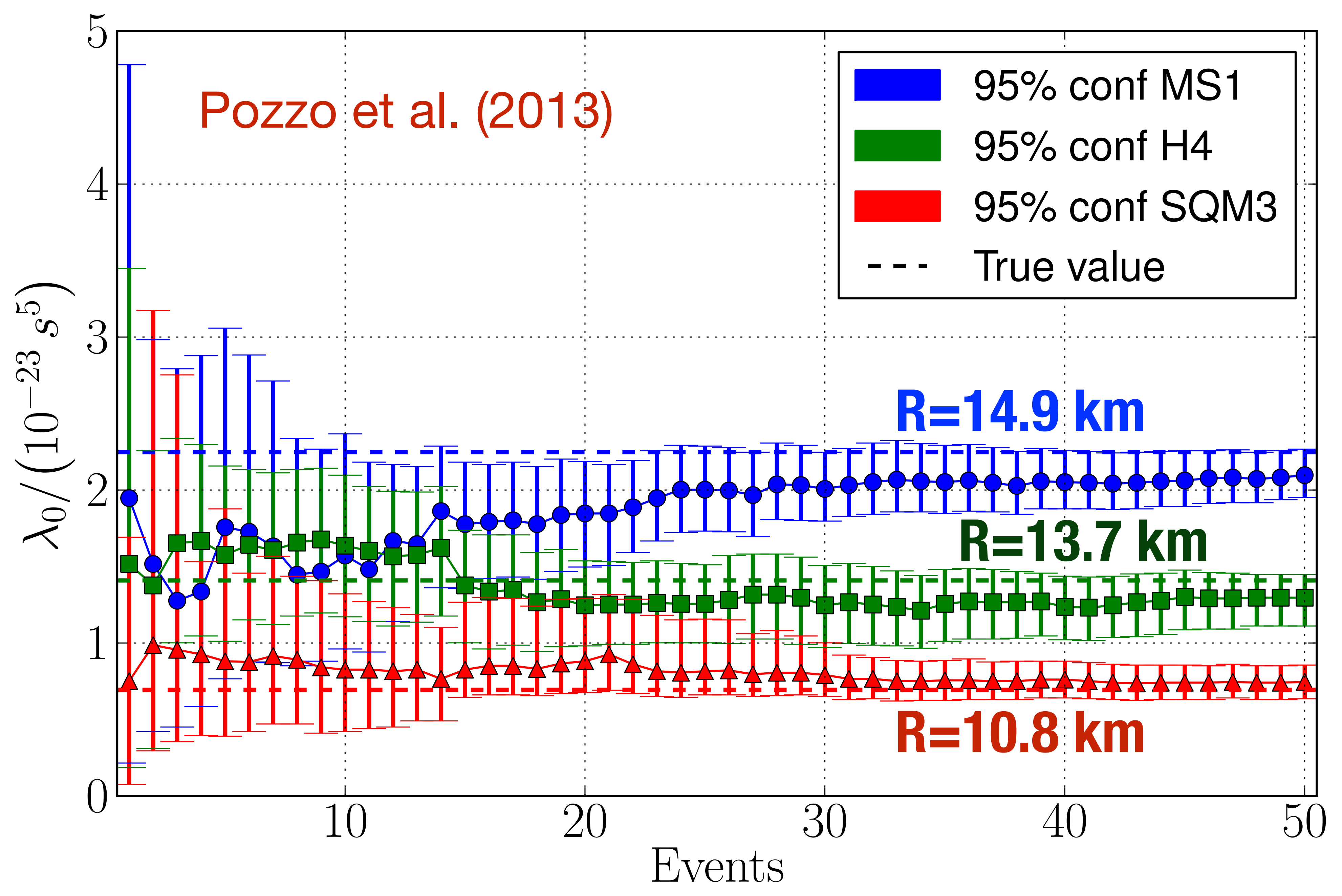
Quadrupole Polarizability



10% measurement of neutron star radius may be possible.

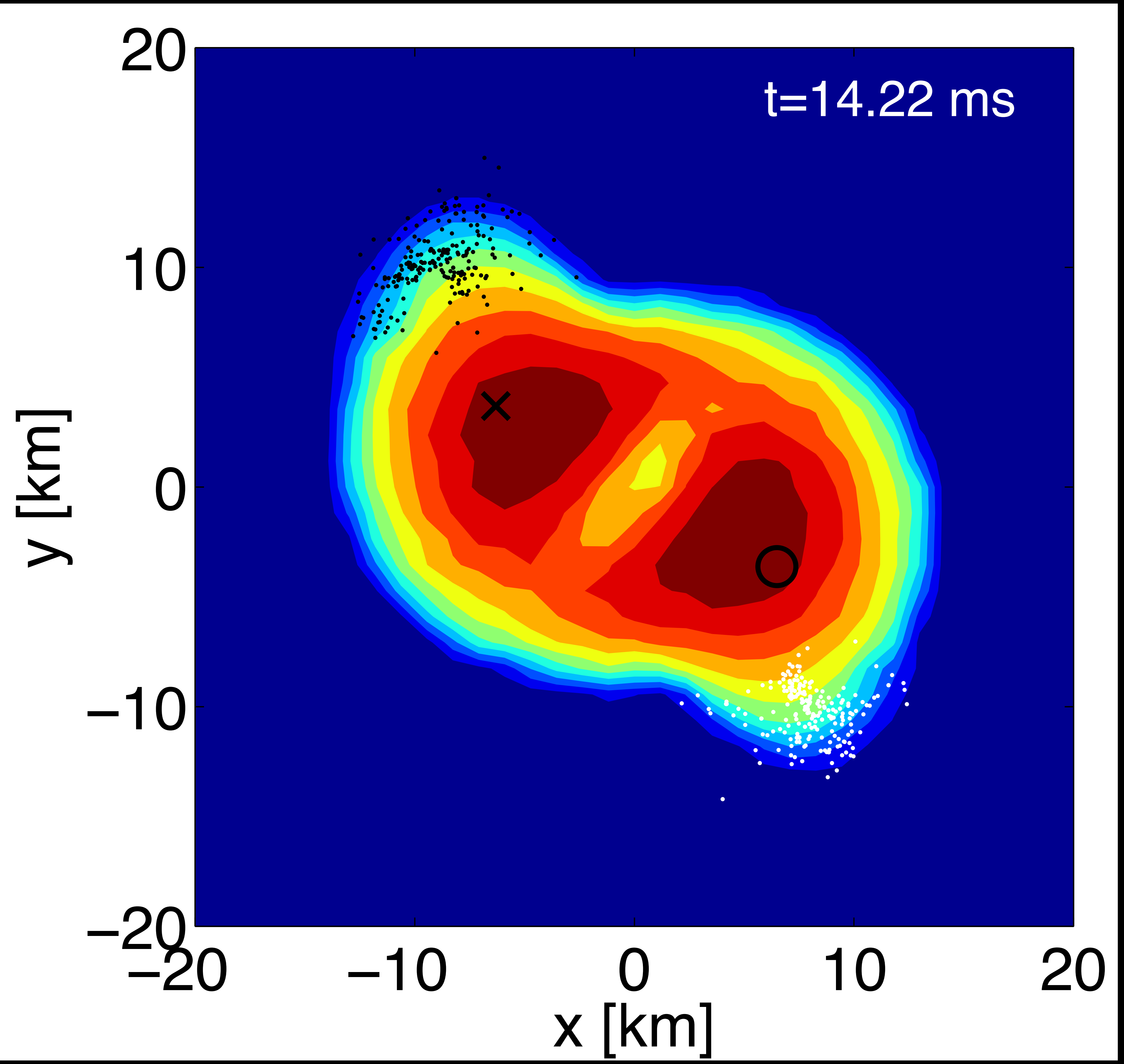
Many detections and next generation detectors

Quadrupole Polarizability

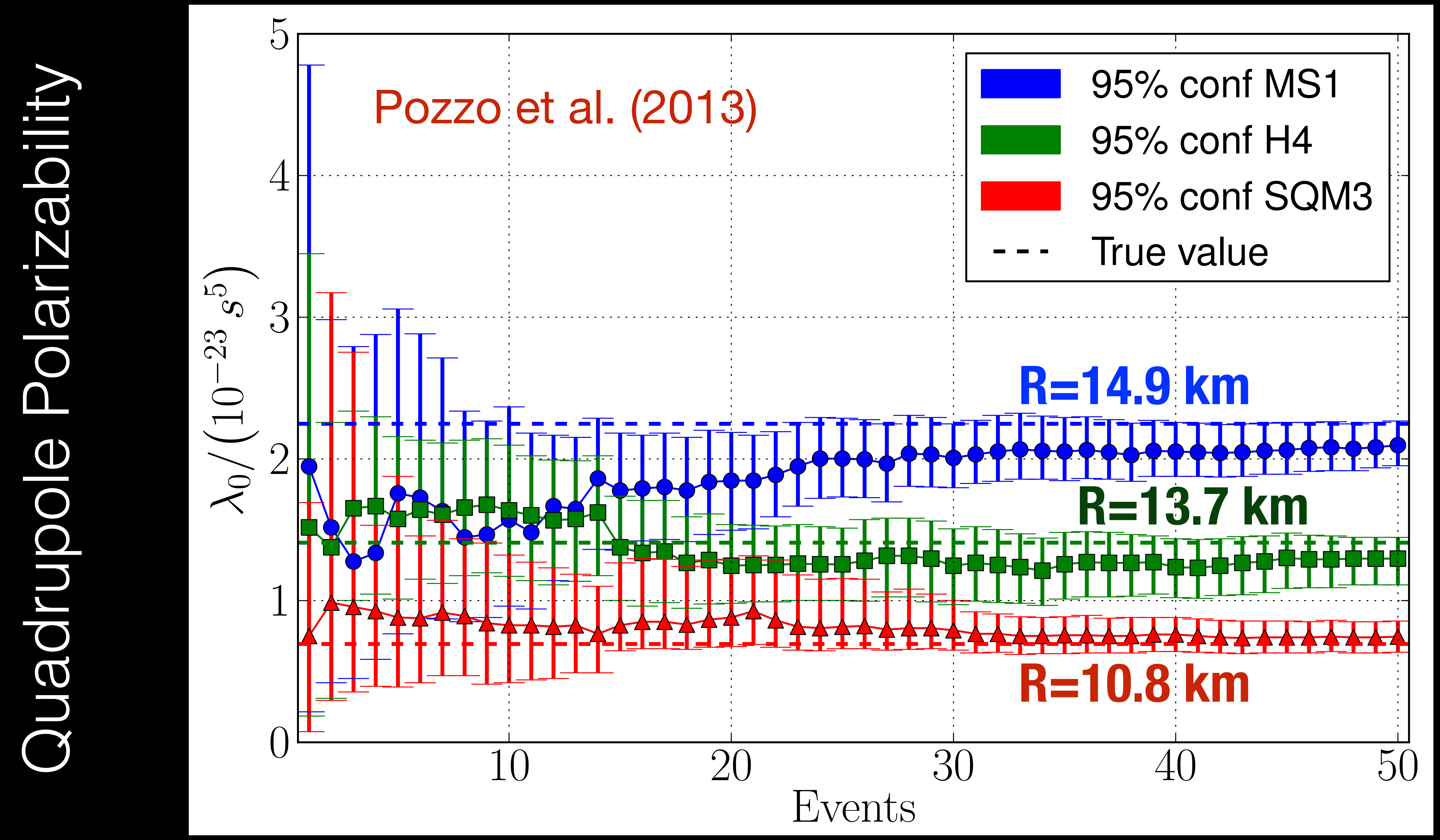


10% measurement of neutron star radius may be possible.

Frequency of quasi-normal modes, post merger are also sensitive to the EOS. Will be accessible with next generation GW detectors.



Many detections and next generation detectors

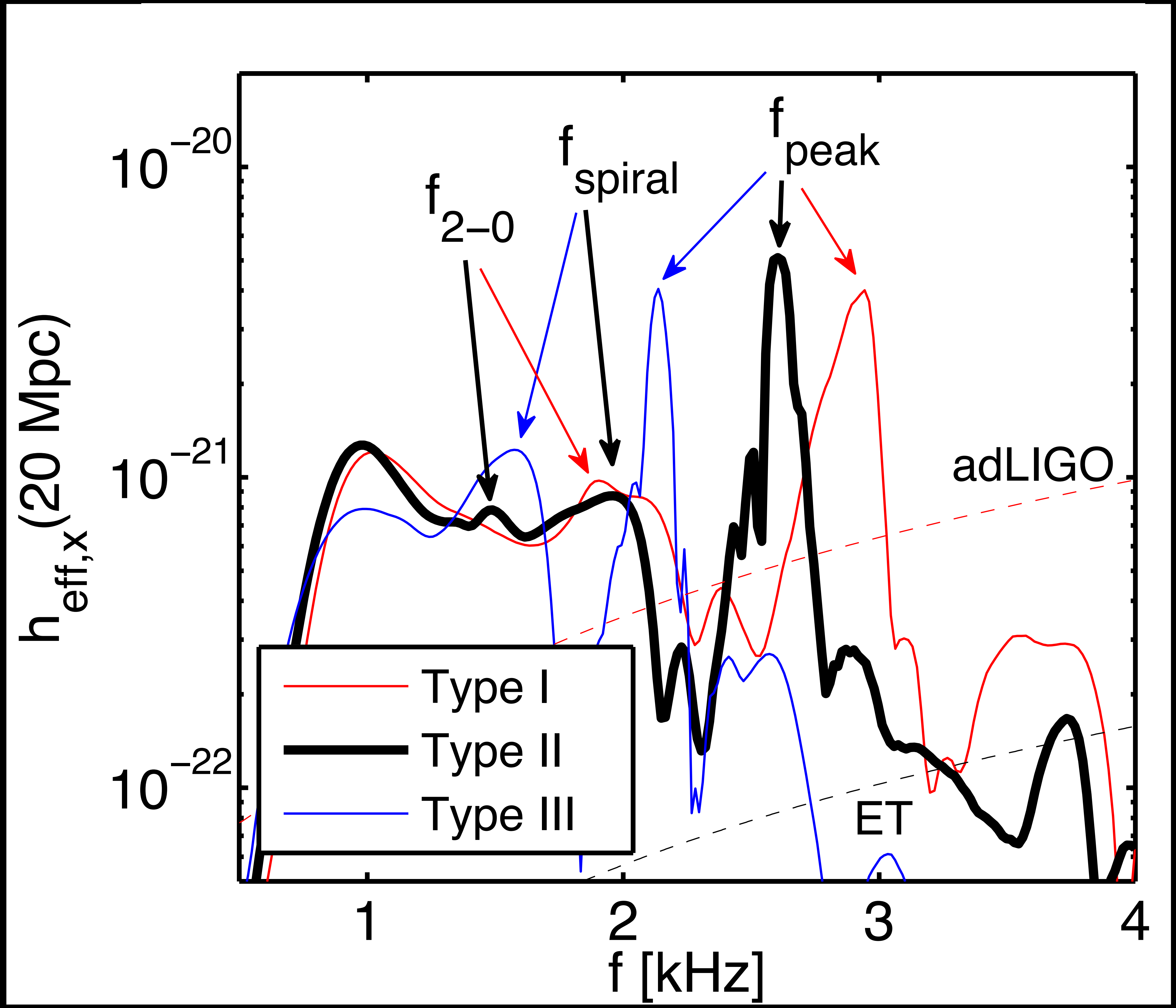


10% measurement of neutron star radius may be possible.

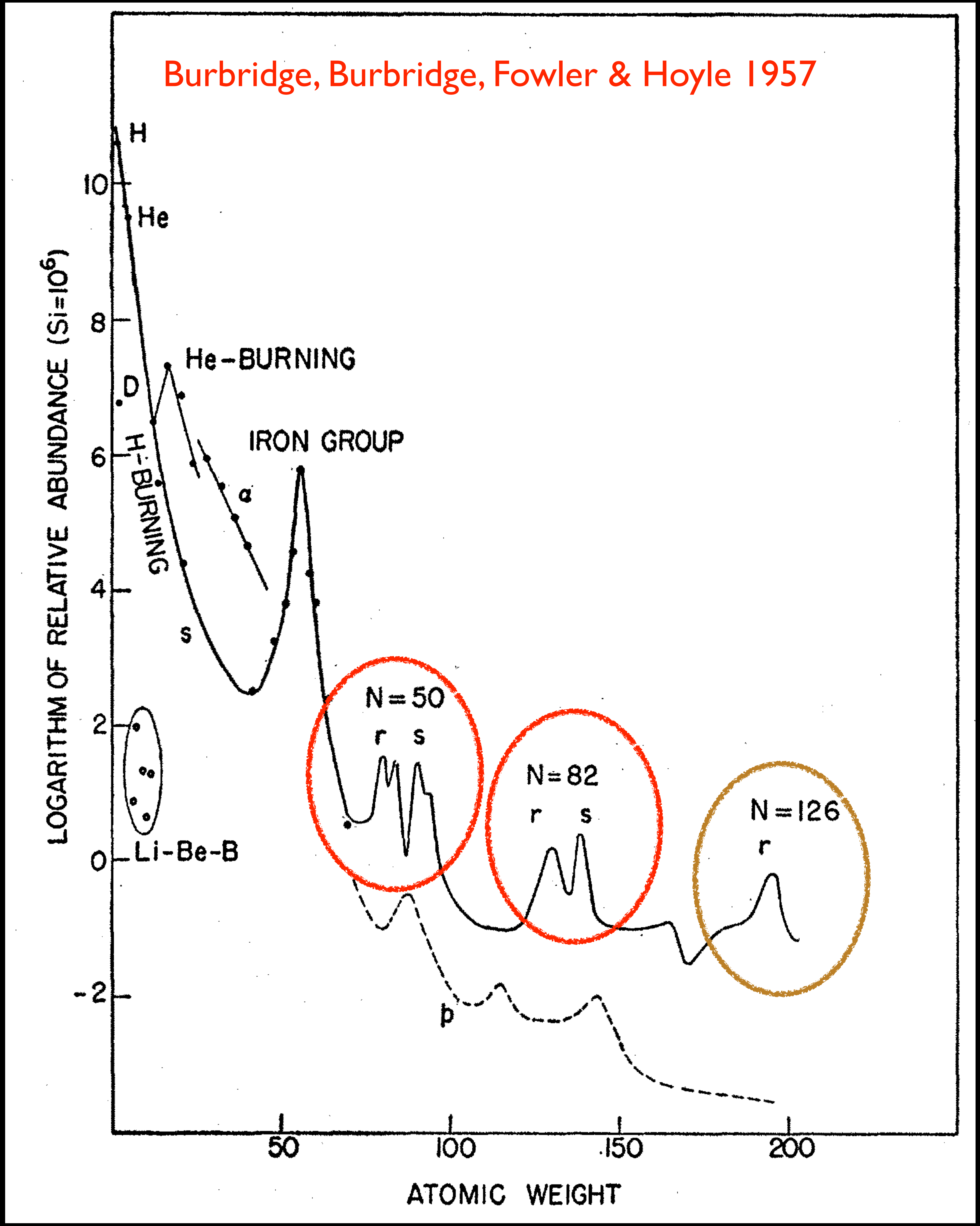
Frequency of quasi-normal modes, post merger are also sensitive to the EOS. Will be accessible with next generation GW detectors.

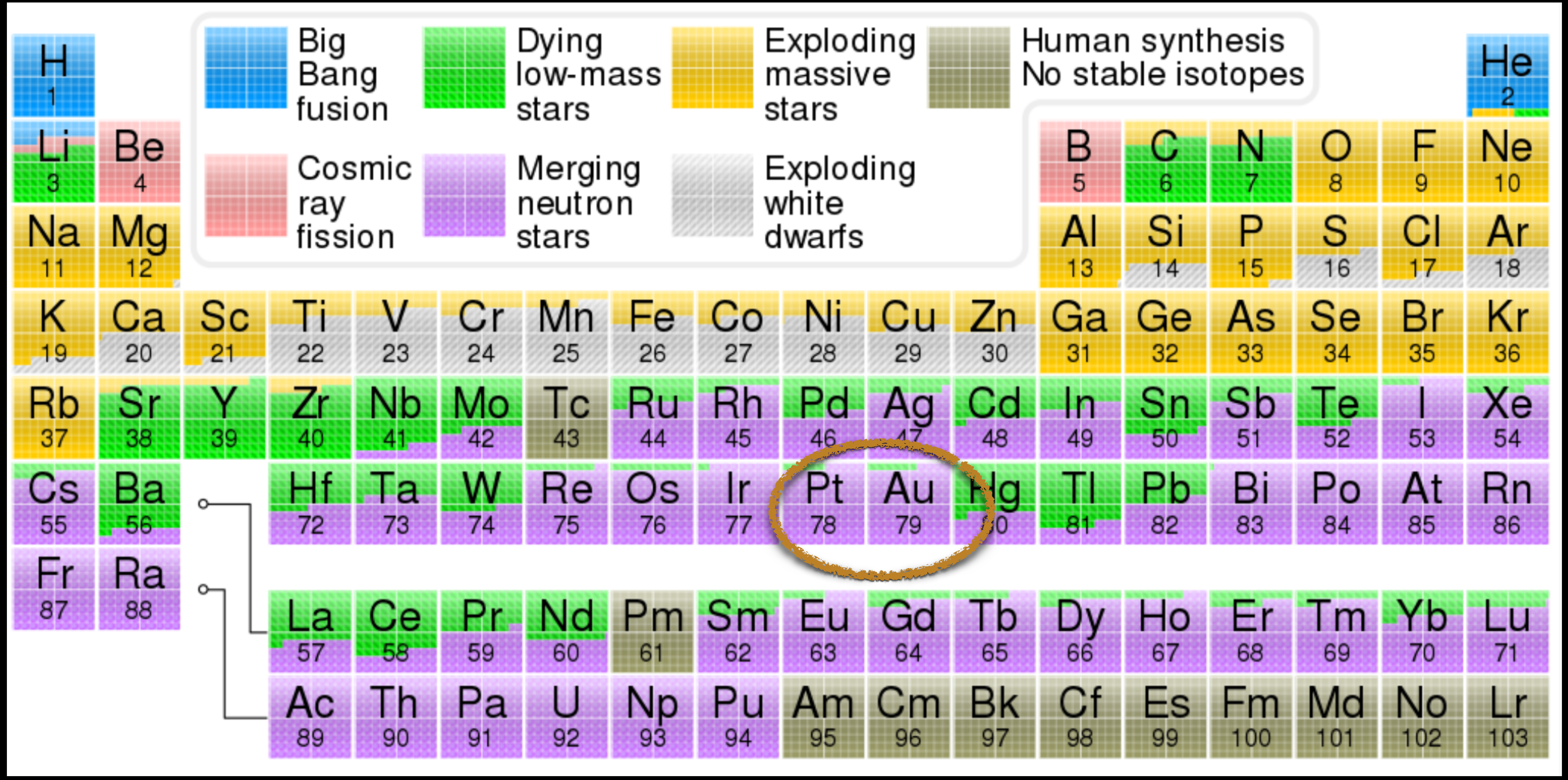
$$
\begin{aligned}
f_{\text{peak}}[\text{kHz}] &= 199(M/R)^2 - 28.1(M/R) + 2.33 \\
f_{\text{spiral}}[\text{kHz}] &= 358(M/R)^2 - 82.1(M/R) + 6.16 \\
f_{2-0}[\text{kHz}] &= 392(M/R)^2 - 88.3(M/R) + 5.95
\end{aligned}
$$

Bauswein & Stergioulas (2015)



Where and how are the heavy-elements made?





https://en.wikipedia.org/wiki/Abundance_of_the_chemical_elements (2018)

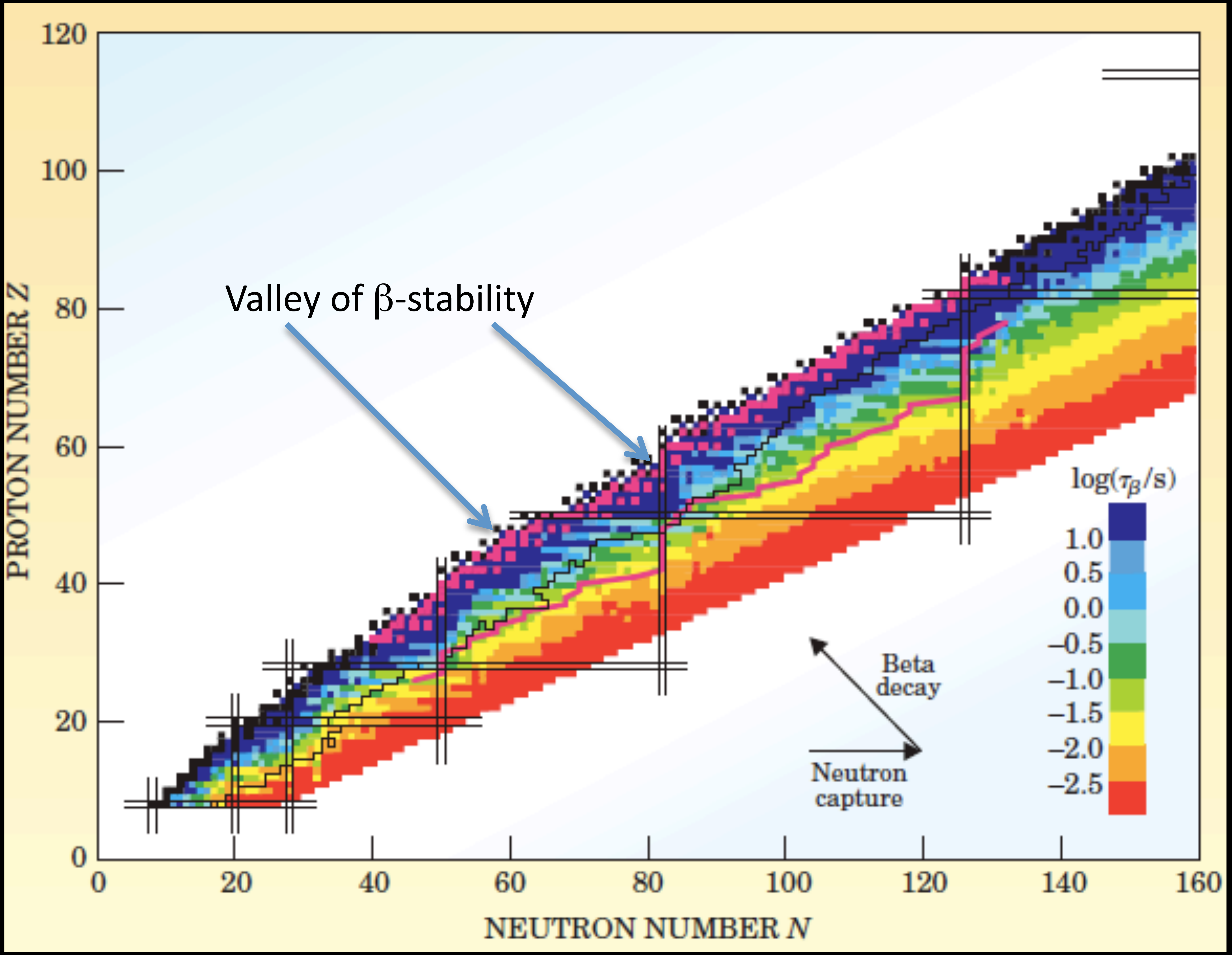
10 years ago most in the community believed core-collapse supernovae was the likely site for the r-process!

Why is it difficult to make the heaviest elements?

If an astrophysical event can eject a hot gas rich in neutrons with a few light nuclei, nuclear reactions will produce gold.

Rapid neutron capture reactions followed by beta-decays in which neutrons turn into protons inside a nucleus successively produce heavier nuclei.

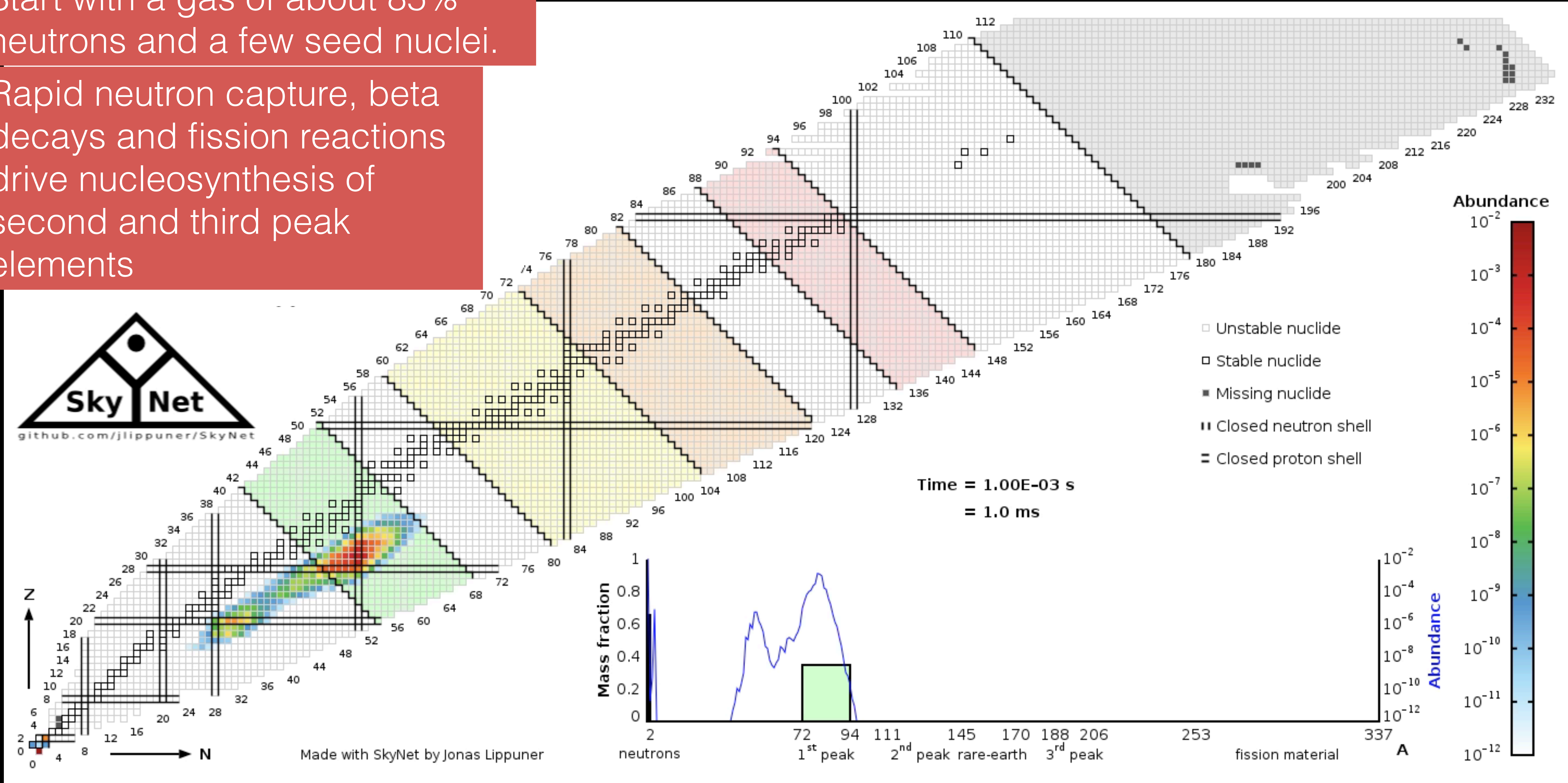
But its hard to find an environment with lot of neutrons per seed nucleus.



Nuclear Reactions in an Expanding Gas

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

Rapid neutron capture, beta decays and fission reactions drive nucleosynthesis of second and third peak elements



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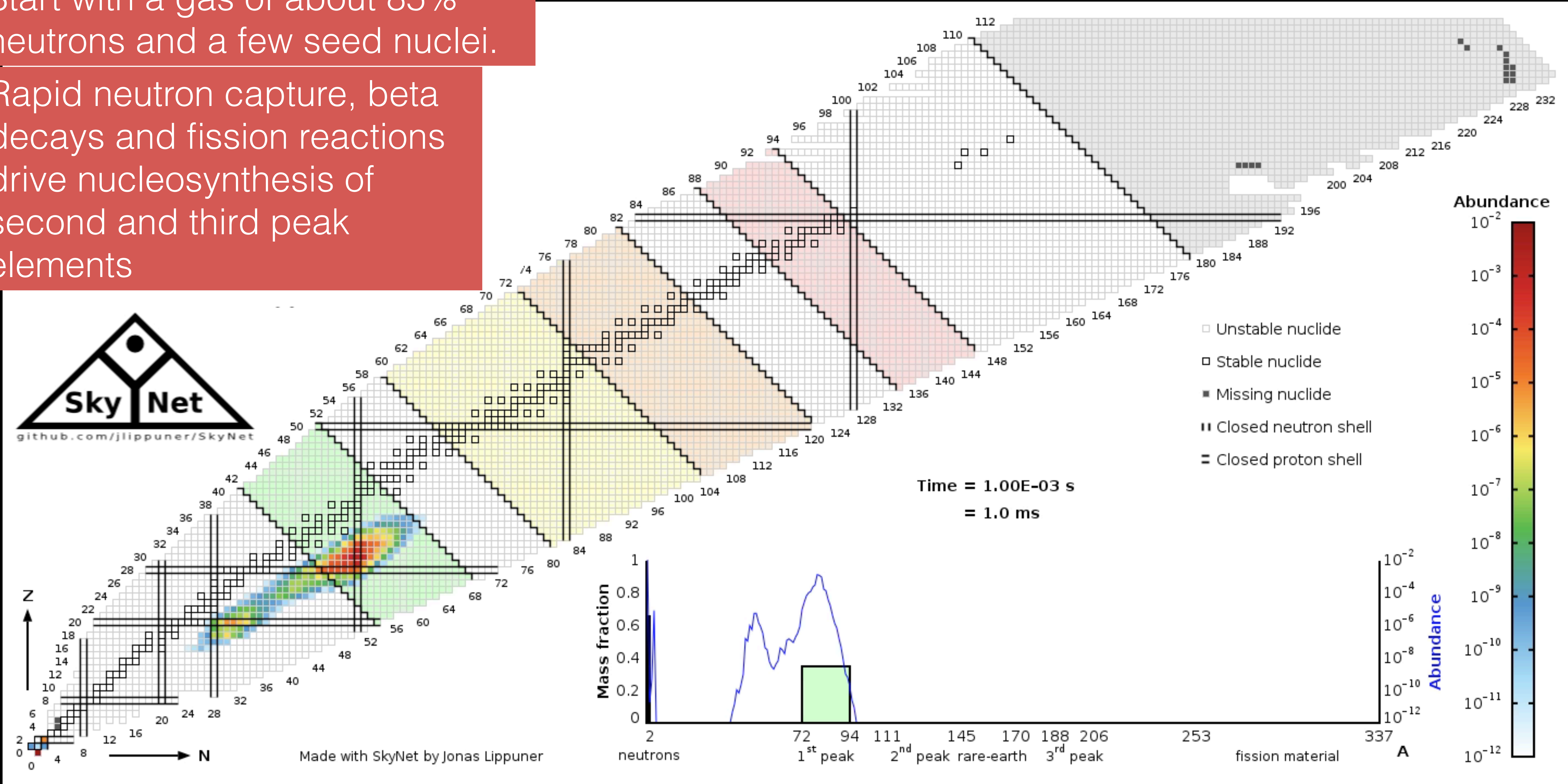

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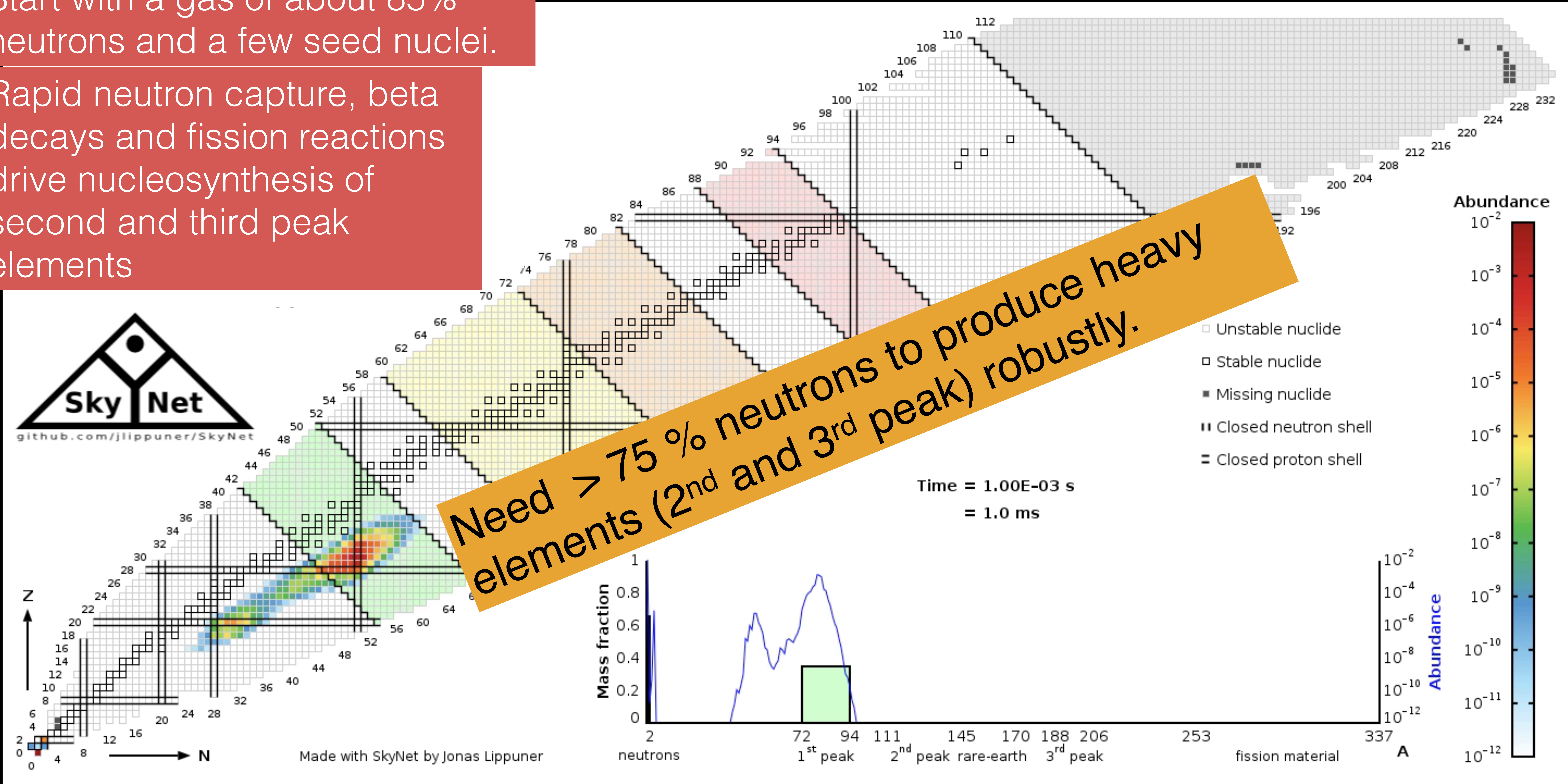


Need > 75 % neutrons to produce heavy elements (2nd and 3rd peak) robustly.

Neutrinos spoil r-process nucleosynthesis in a supernova

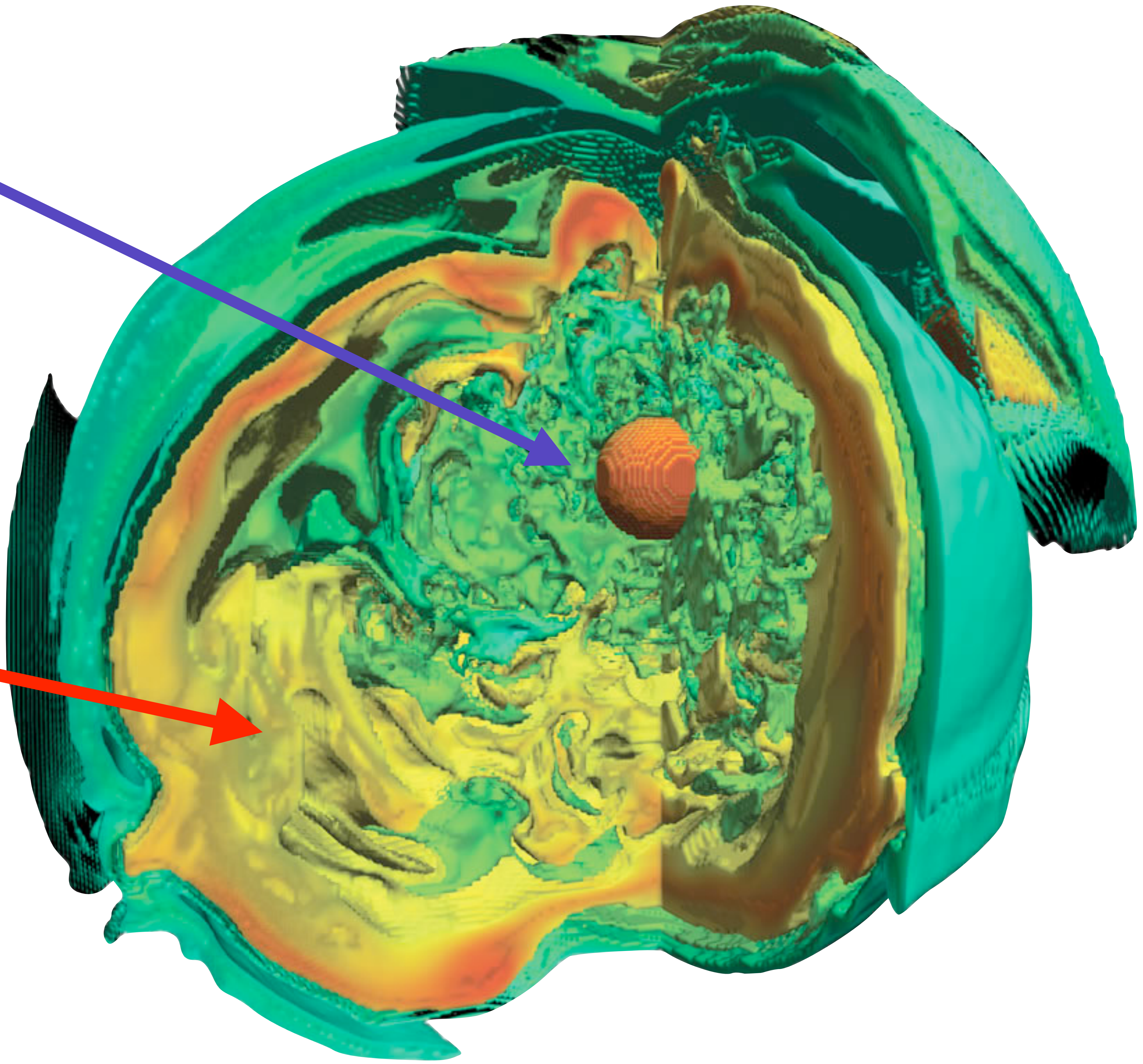
Large neutrino fluxes from the newly born neutron star reduces the neutron excess. Bad for r-process.

$$\begin{cases} \nu_e + n \to e^- + p \\ \bar{\nu}_e + p \to e^+ + n \end{cases}$$

Newly born neutron star emits large flux of all flavors of neutrinos. R =10-20 kms

Recent computer simulations of supernovae indicate that neutrino fluxes from the newly born neutron star reduce the neutron-excess to values well below 75%. Largest values encountered are ~ 55%.

Nucleosynthesis: occurs in a neutrino driven wind
at low-density and high entropy.
R ~ 10^3-10^4 km



Electromagnetic Signatures: Ejecta and Kilonova

- Mergers produce and eject heavy elements.

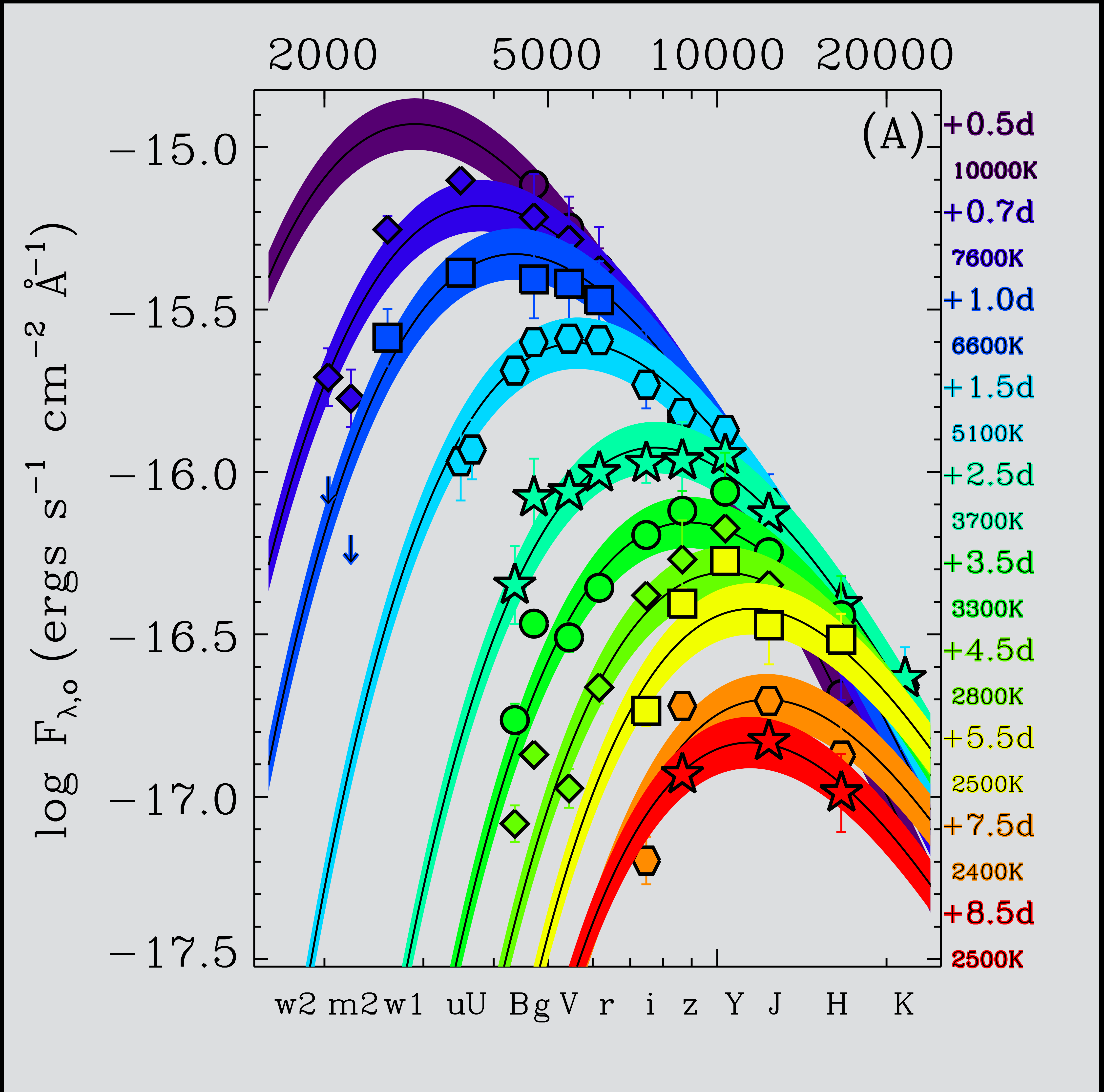
Lattimer & Schramm 1974

- 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

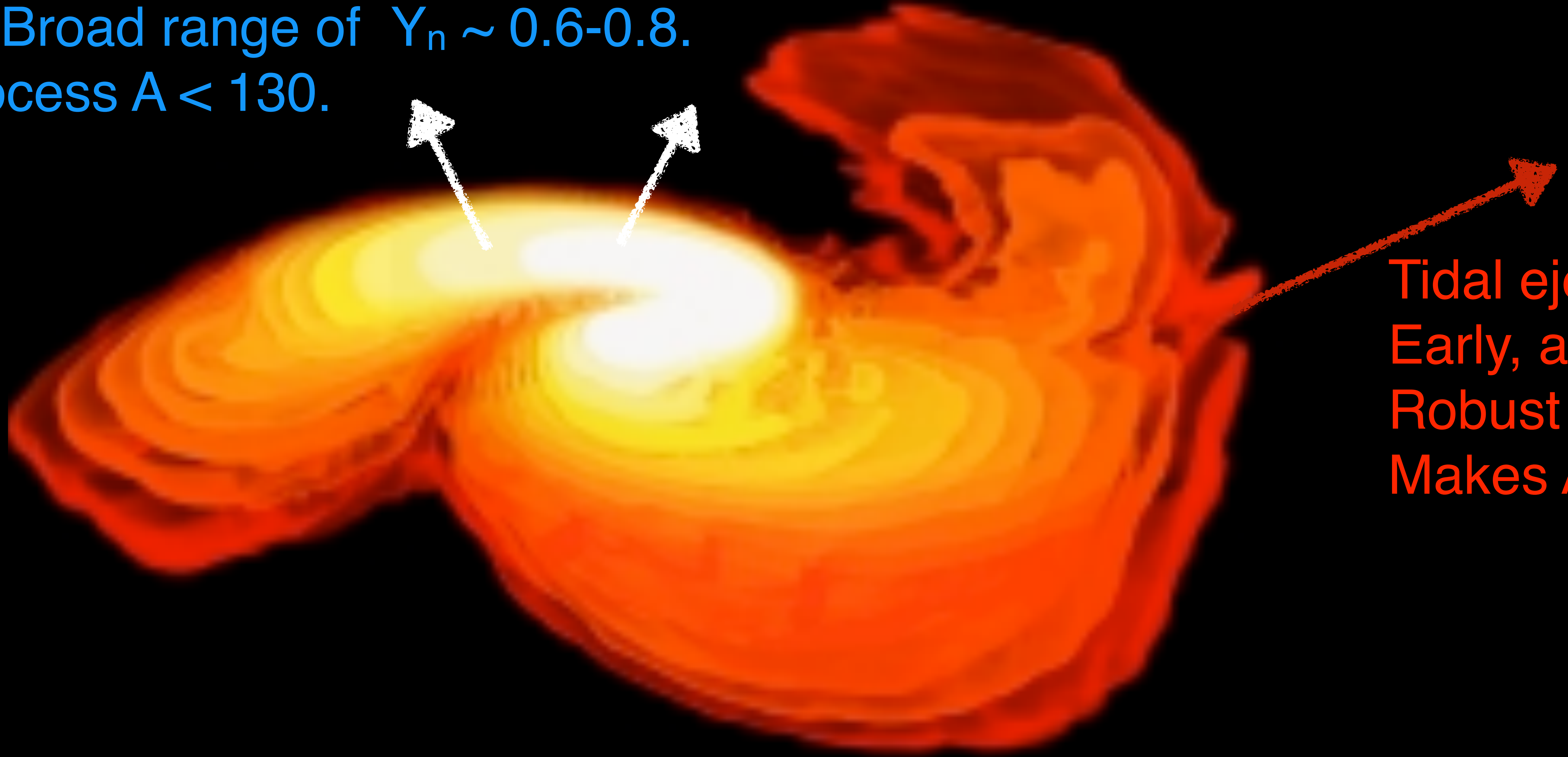
- Magnitude and color of the optical emission is sensitive to the composition of the ejecta.

Kasen 2013



Merger Ejecta & Nucleosynthesis

Shock and neutrino wind driven ejecta:
Processed by weak interaction.
Not as neutron rich. Broad range of $Y_n \sim 0.6\text{-}0.8$.
Makes the light r-process $A < 130$.



Tidal ejecta:
Early, and very neutron-rich. $Y_n > 0.8$
Robust heavy r-process.
Makes A=130 and A=190 peaks.

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

- Neutron star radius
- Lifetime and neutrino emission of the merged hot and rapidly rotating neutron star

Typical mass ejected is about $0.05\ M_\odot$.

Neutron excess in some of the ejecta is moderated by weak interactions

Large neutrino fluxes from the hot hyper-massive neutron star drives matter towards smaller neutron excess.

$$\begin{cases} \nu_e + n \rightarrow e^- + p \\ \bar{\nu}_e + p \rightarrow e^+ + n \end{cases}$$

High temperatures created in dense shocked matter produces positrons. They would also deplete neutrons

$$e^+ + n \rightarrow p + \bar{\nu}_e$$

Neutrino fluxes and spectra are sensitive properties of hot and dense matter and neutrino oscillations.

Lifetime and dynamics of the hyper-massive merged neutron star plays a role.

Heavy nuclei dominate opacity of the ejecta

Metzger et al. 2010 Kasen 2013

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

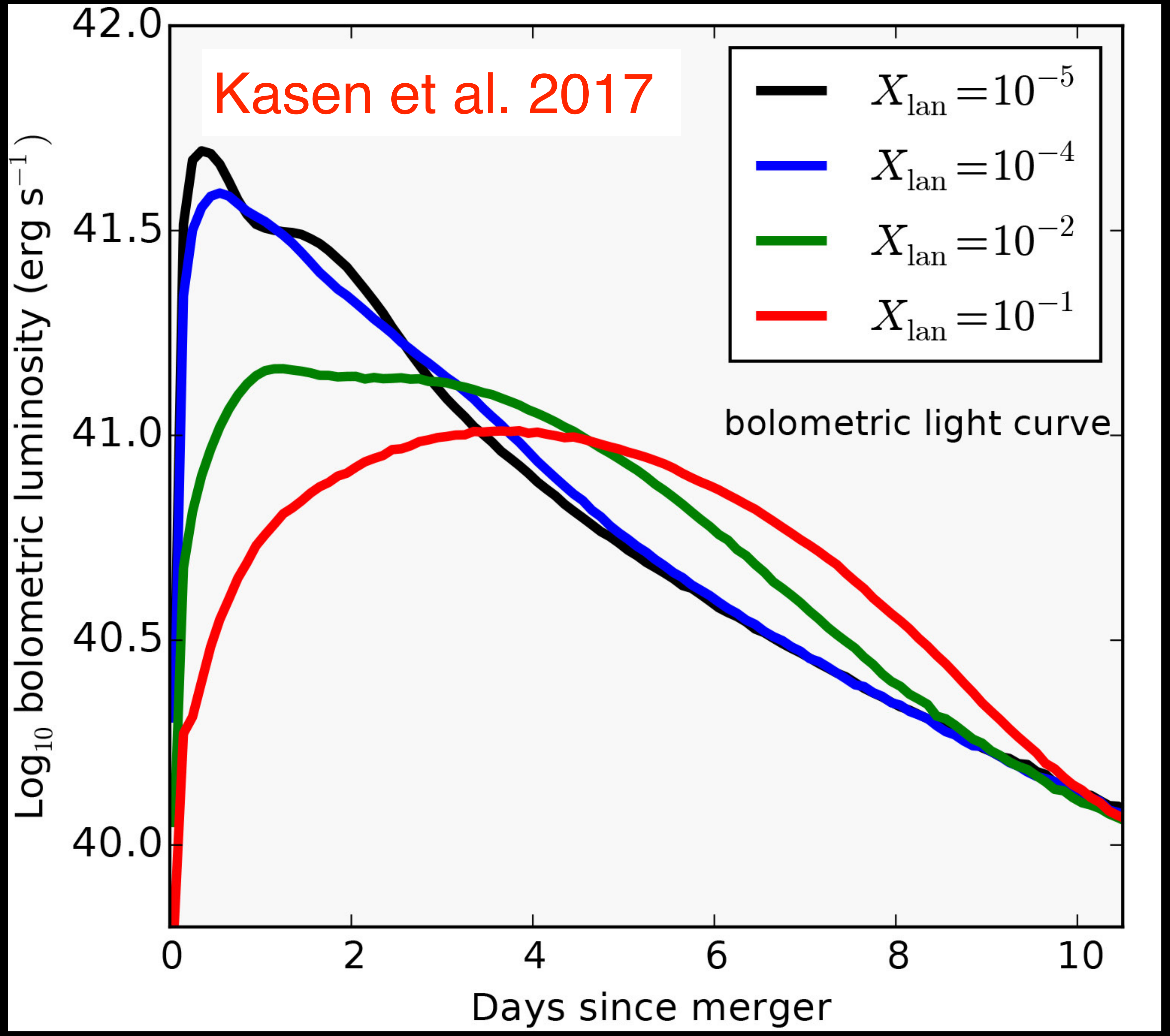
$\kappa_{\text{Fe-like}} \sim 1\ \text{cm}^2/\text{g}$

(d-shell electrons contribute to transitions)

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

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

(f-shell electrons, dense level spacing and order or magnitude more allowed transitions)



To fit observed light curves requires:

~ 0.04 $M_\odot$ of heavy nuclei with A>140

~ 0.025 $M_\odot$ of moderately heavy nuclei with A<140

Tremendous detail in the observed light curves !

Remarkably, models that fit these light curves suggests:

nature Accelerated Article Preview

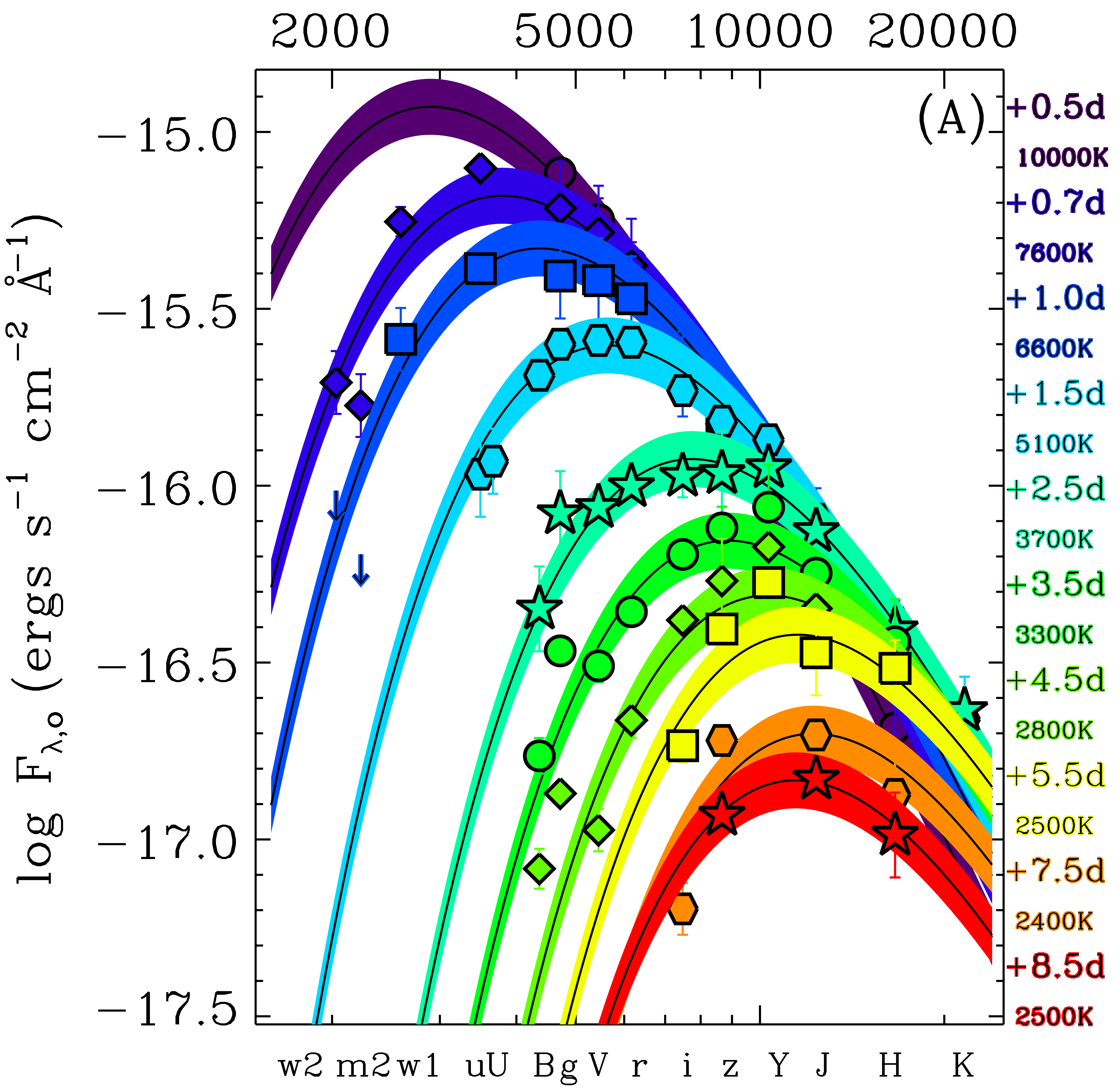
LETTER

doi:10.1038/nature24453

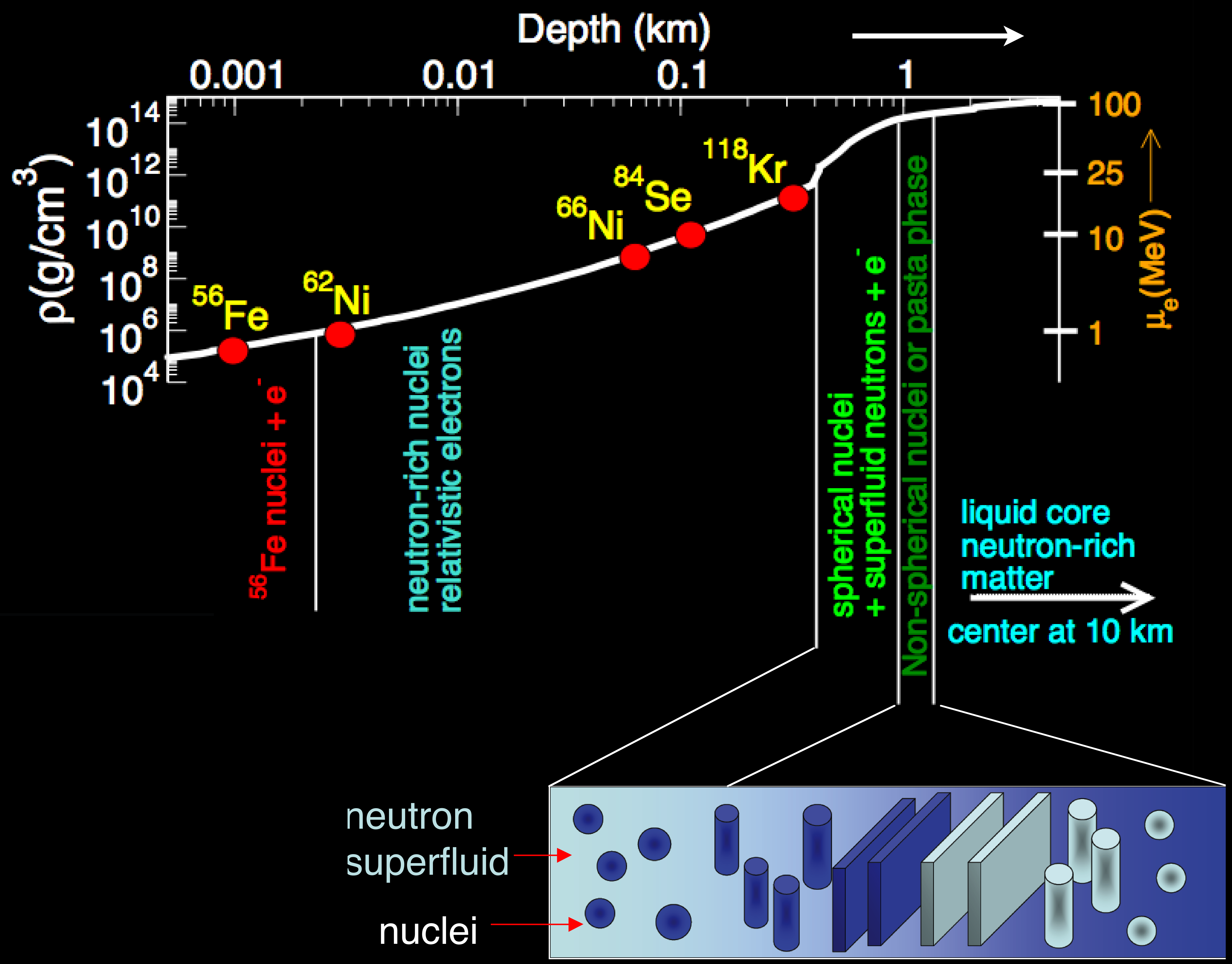
Origin of the heavy elements in binary neutron-star mergers from a gravitational-wave event

Daniel Kasen, Brian Metzger, Jennifer Barnes, Eliot Quataert & Enrico Ramirez-Ruiz

1. Merger ejected ~ 0.06 $M_\odot$ of radioactive nuclei
2. Radioactive ejecta had two components
3. One component with A>130 (heavy r-process)
4. Second component with A<130 (light r-process)
5. Mass of the A>130 component ~ 0.04 $M_\odot$
6. Mass of the A<130 component ~ 0.025 $M_\odot$



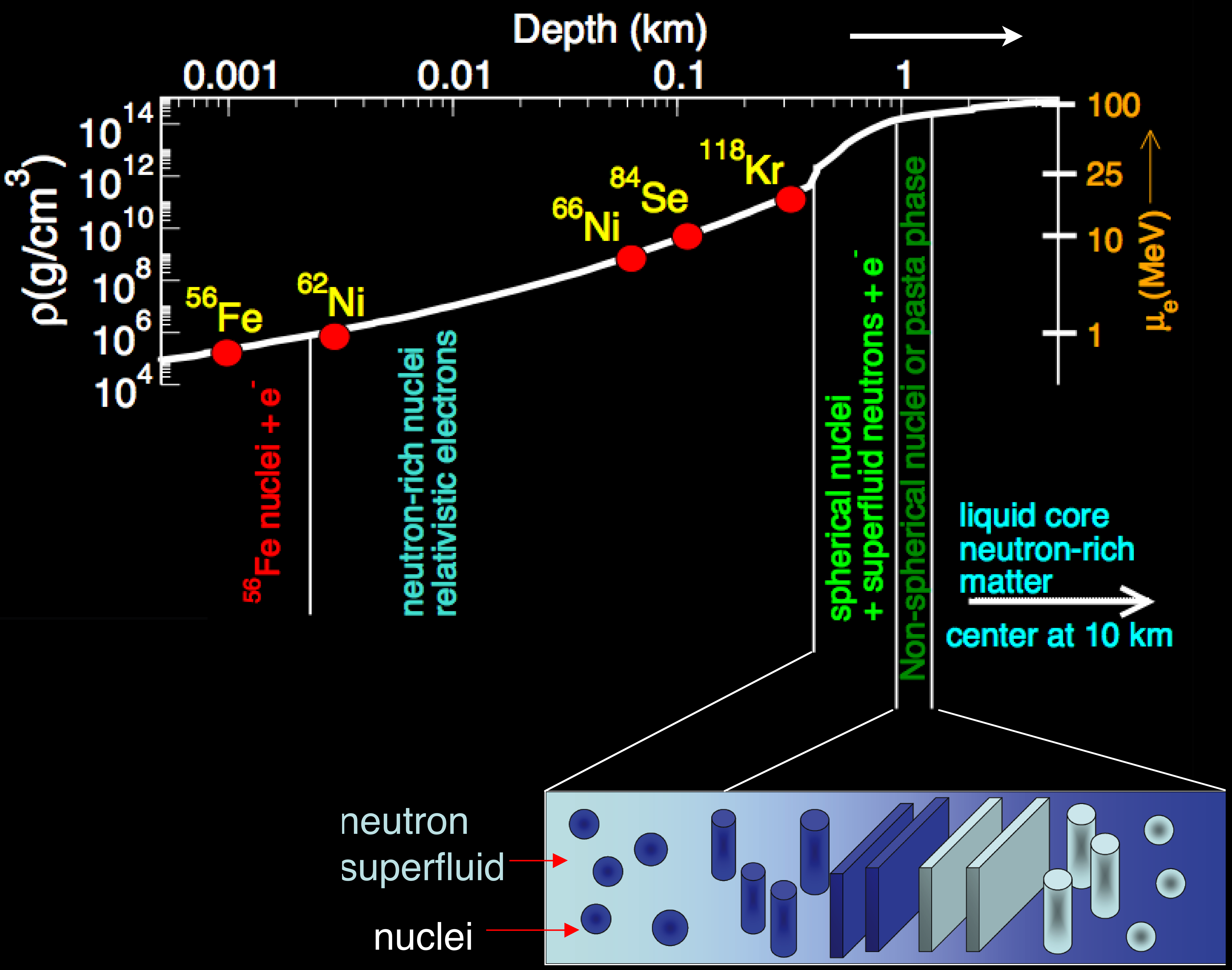
Blast Mining Neutron Stars



Blast Mining Neutron Stars

To extract ~0.03 $M_\odot$ from each neutron star, need to dig down >2 km in depth !

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



Conclusions and Outlook

- NSs merge and emit GWs. The detection rate is likely to be greater than a few per year.
- Constraints on the dense matter EOS will likely improve. With a large sample of observed NSs rare events (outliers) may be the most interesting.
- Connection between EM signals (especially the Kilonova) and GWs will rely on our understanding of dense matter, neutrino physics, nuclear structure and reactions.
- Strong circumstantial evidence for heavy element production in mergers.
- Details worth pursuing with multi-physics merger simulations. Multi-messenger astronomy is here with much to reveal.