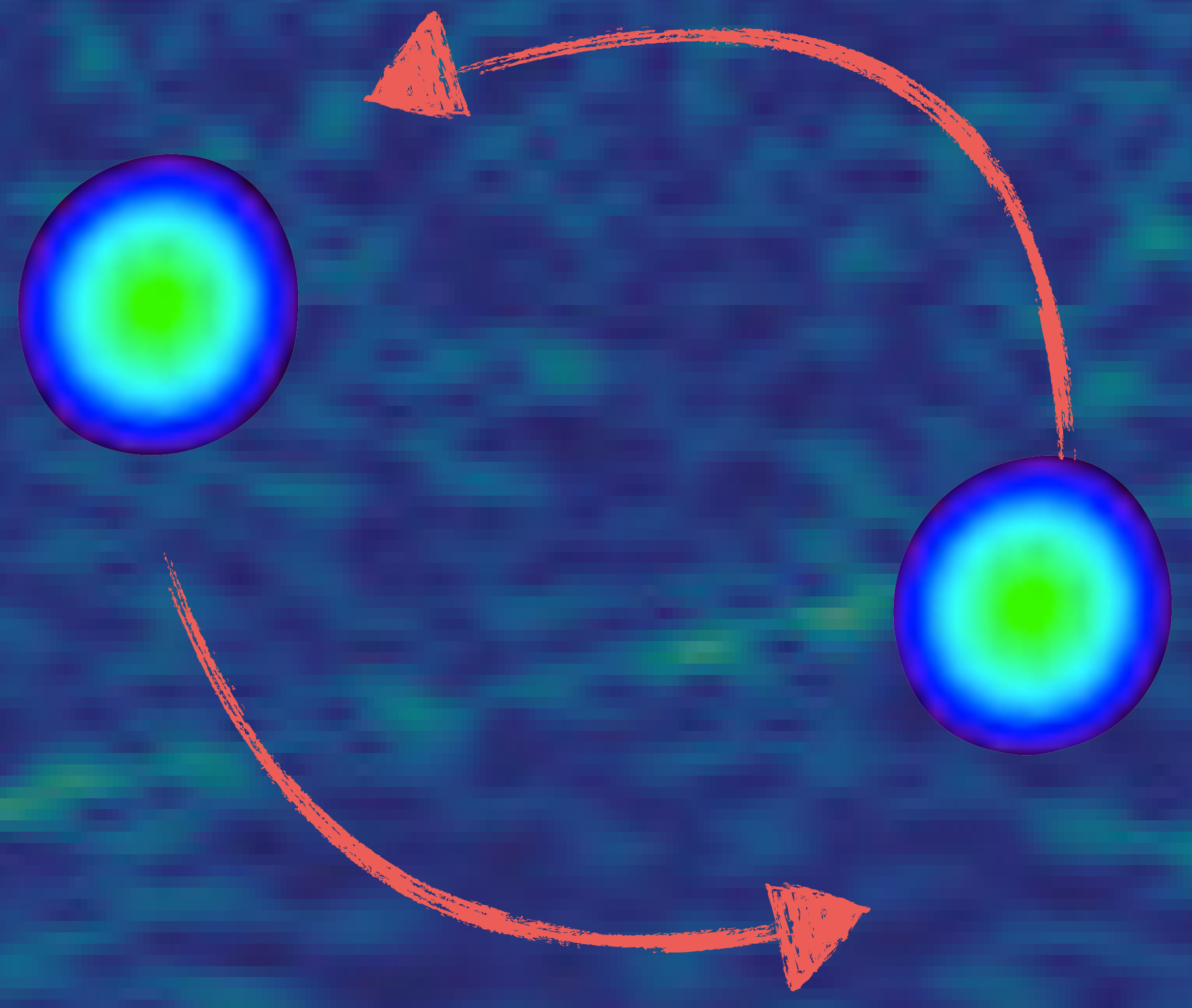
The ultimate collision: Neutron stars rattle, shine, and sparkle.

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



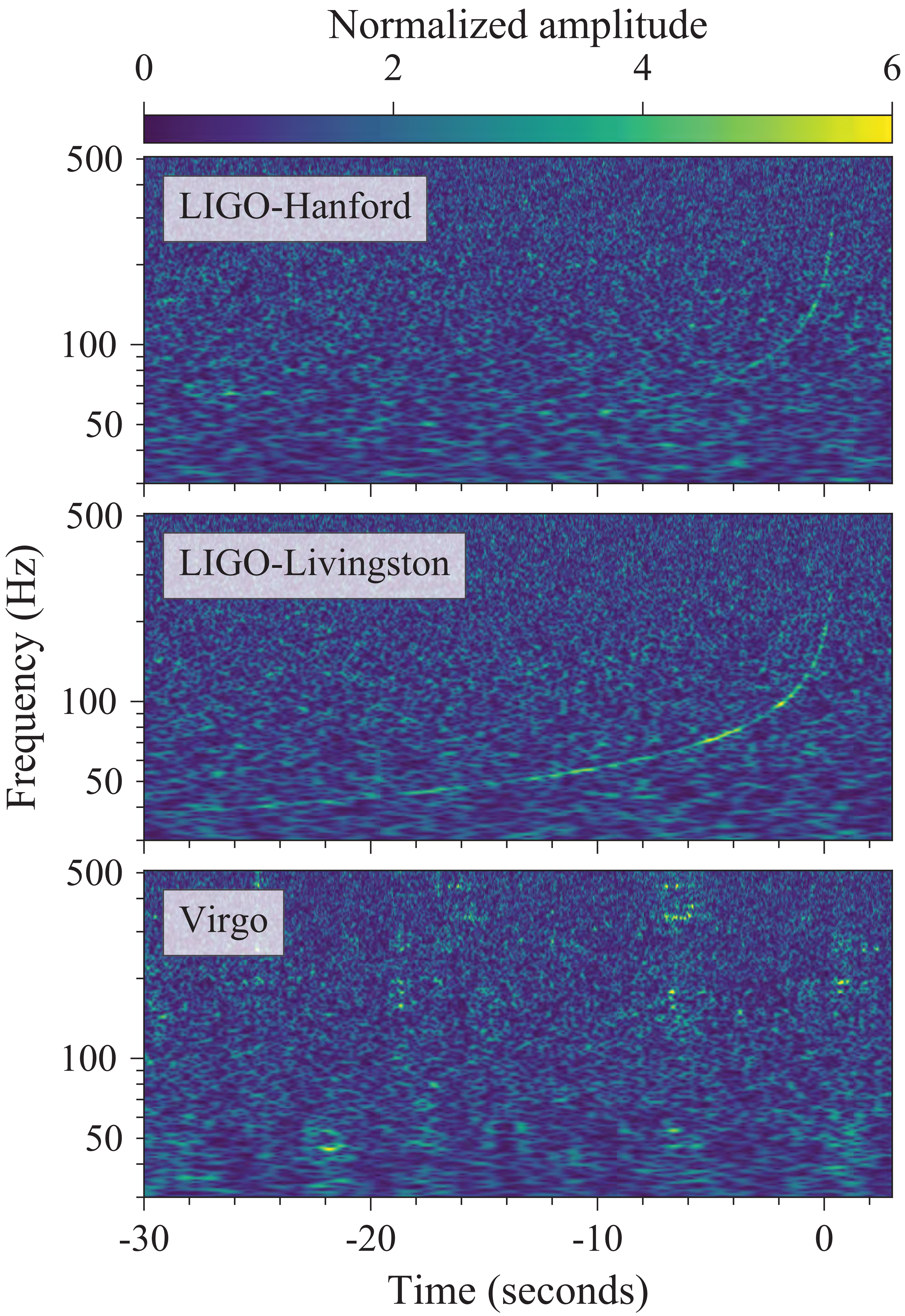
INSTITUTE for
NUCLEAR THEORY

Gravitational Waves

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

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

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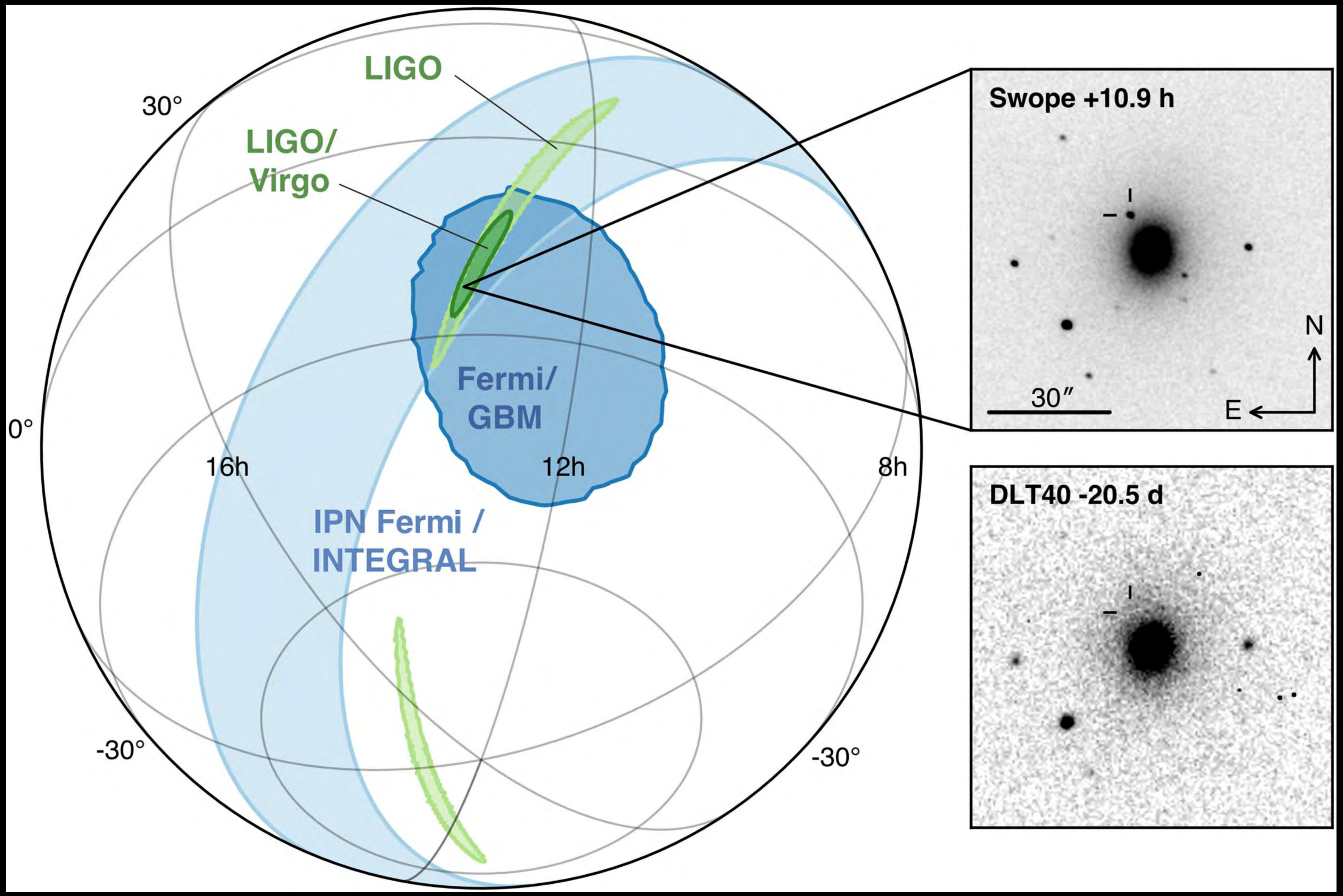

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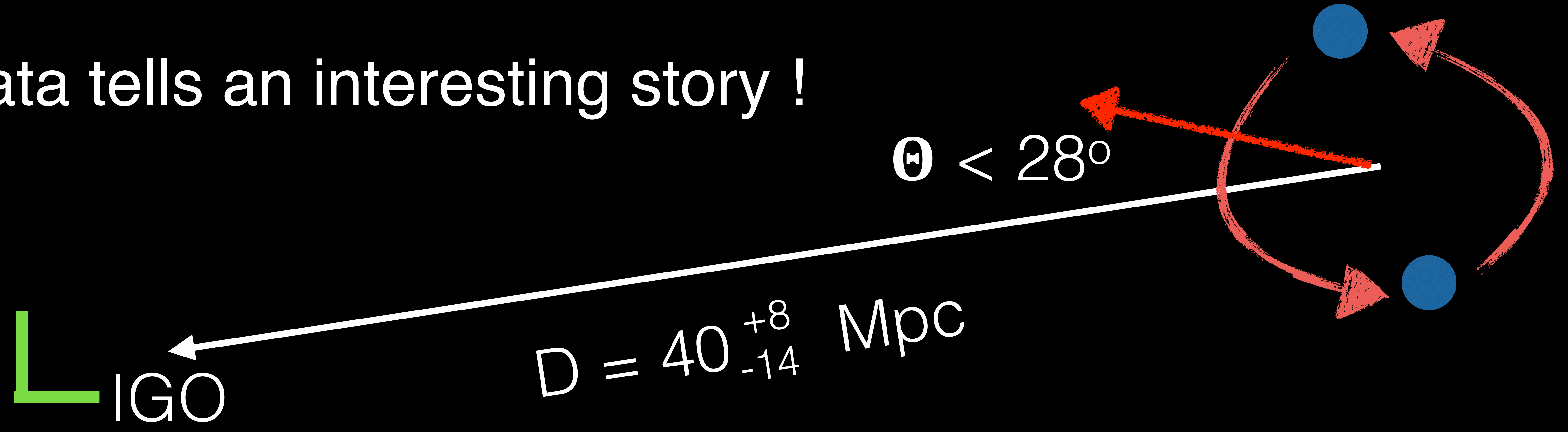
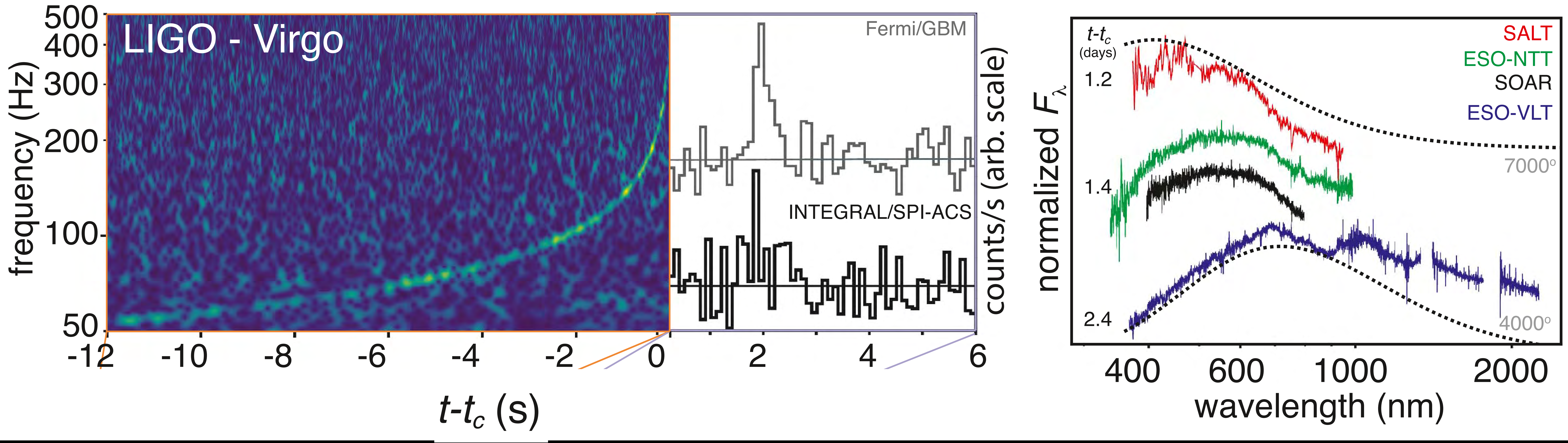
+27 minutes: Alert notice (GCN) sent by Ad. LIGO
+11 hours: Optical transient detected in a galaxy NGC 4993 at 40 Mpc by the 1M2H team.
Carnegie observatories at Los Campanas, Chile.

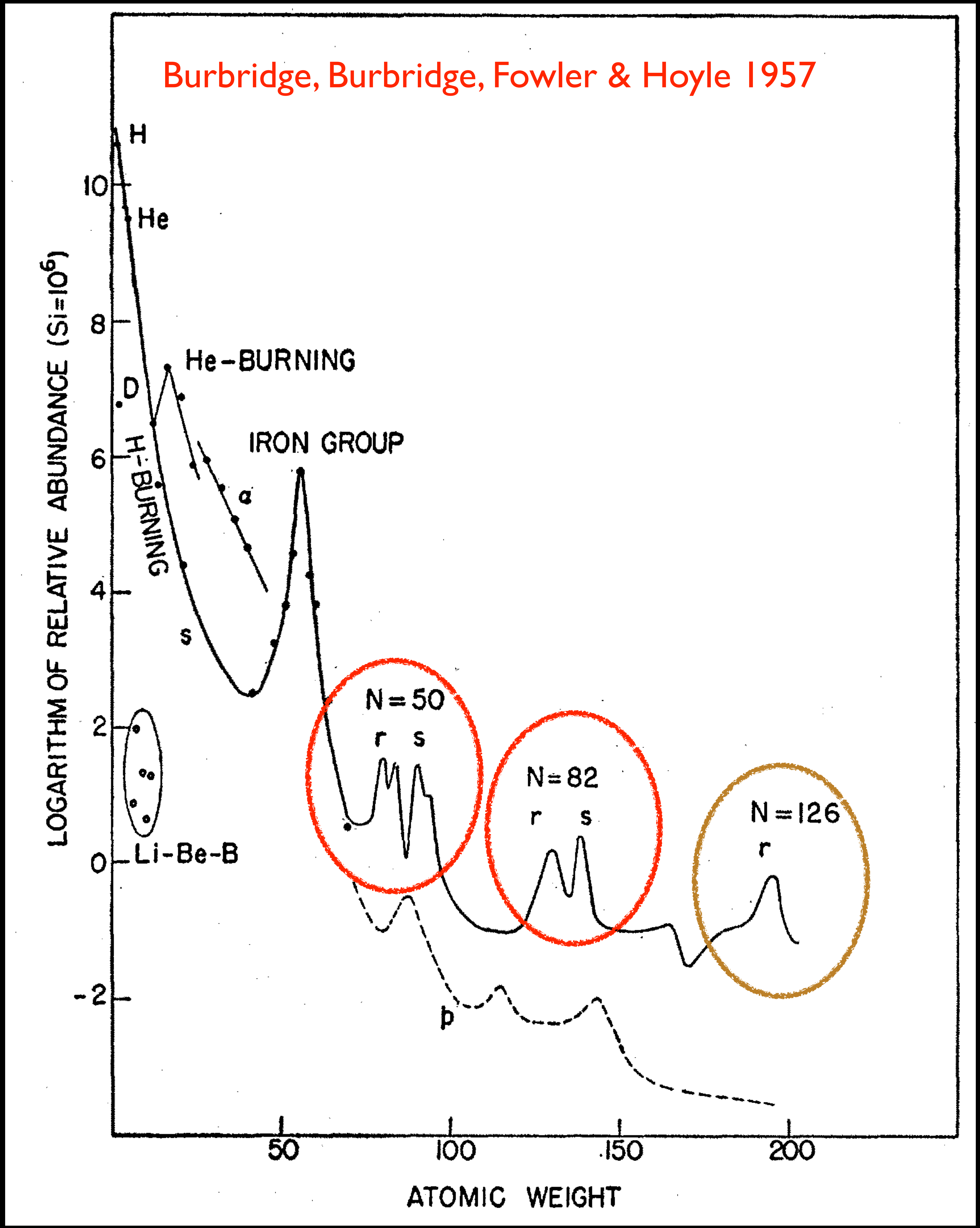
Taken together the data tells an interesting story !



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

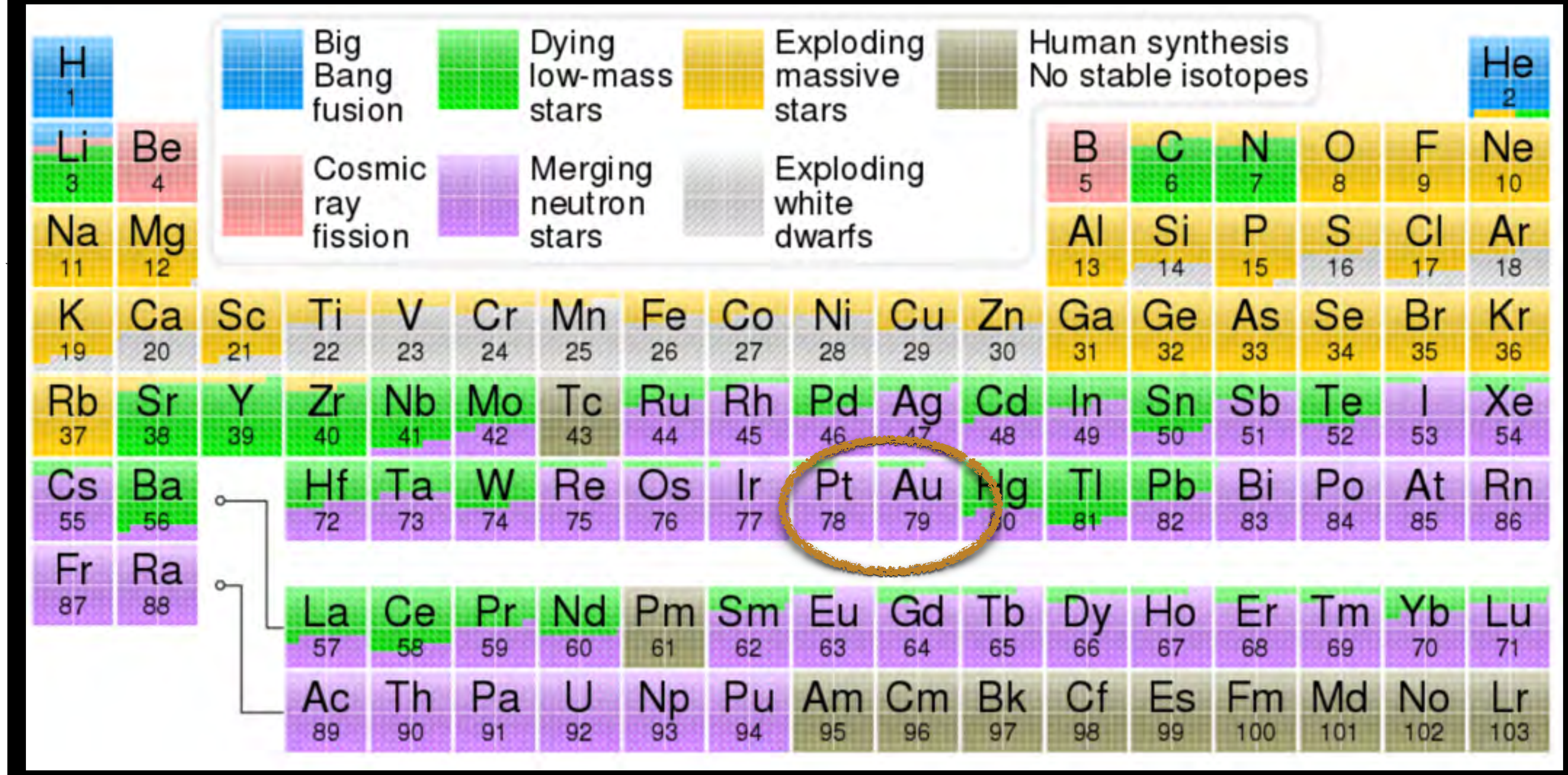




Where and how are the heavy-elements made?

It now seems likely that gold, platinum, plutonium and uranium can only be synthesized by colliding neutron stars !

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



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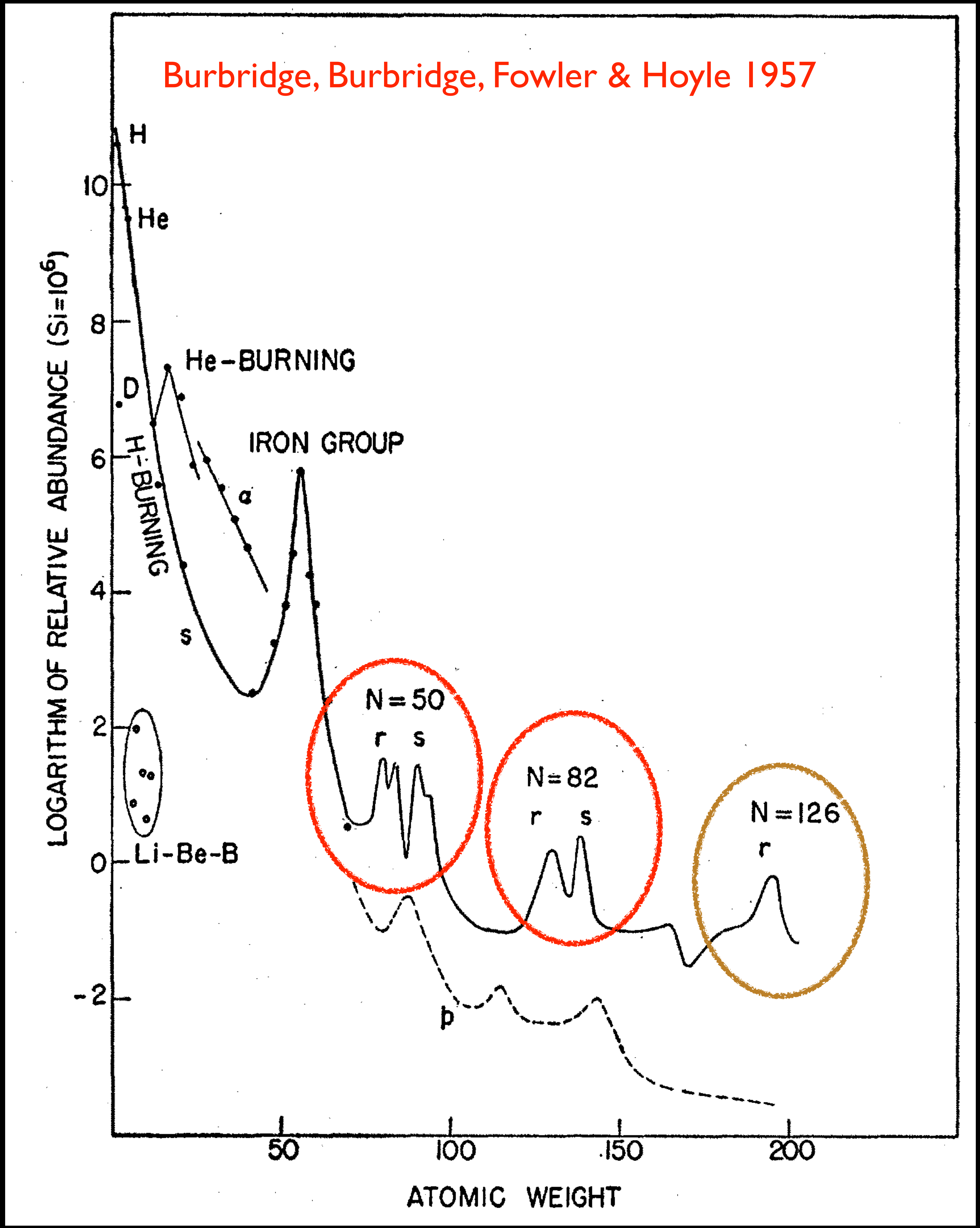

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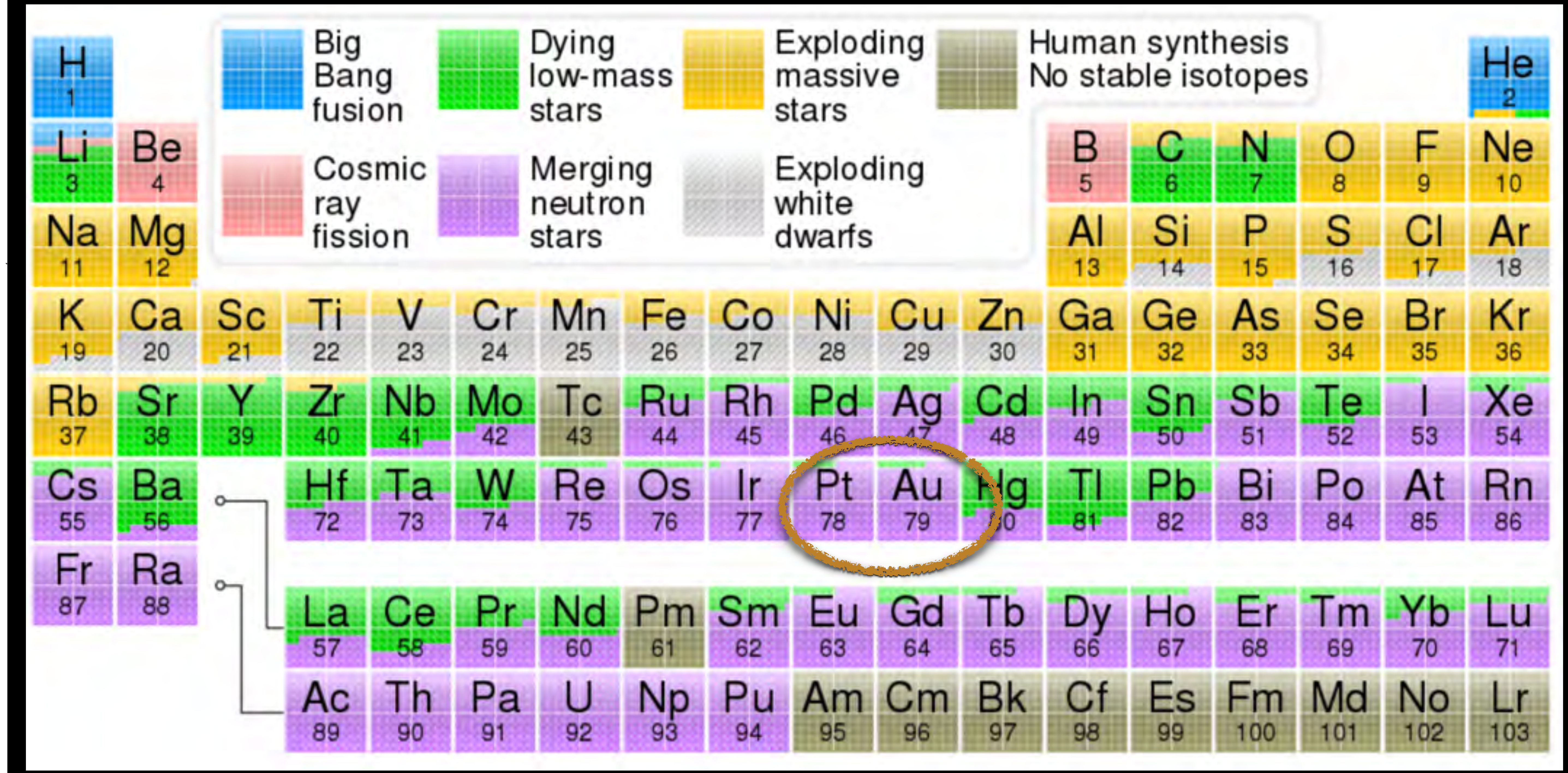

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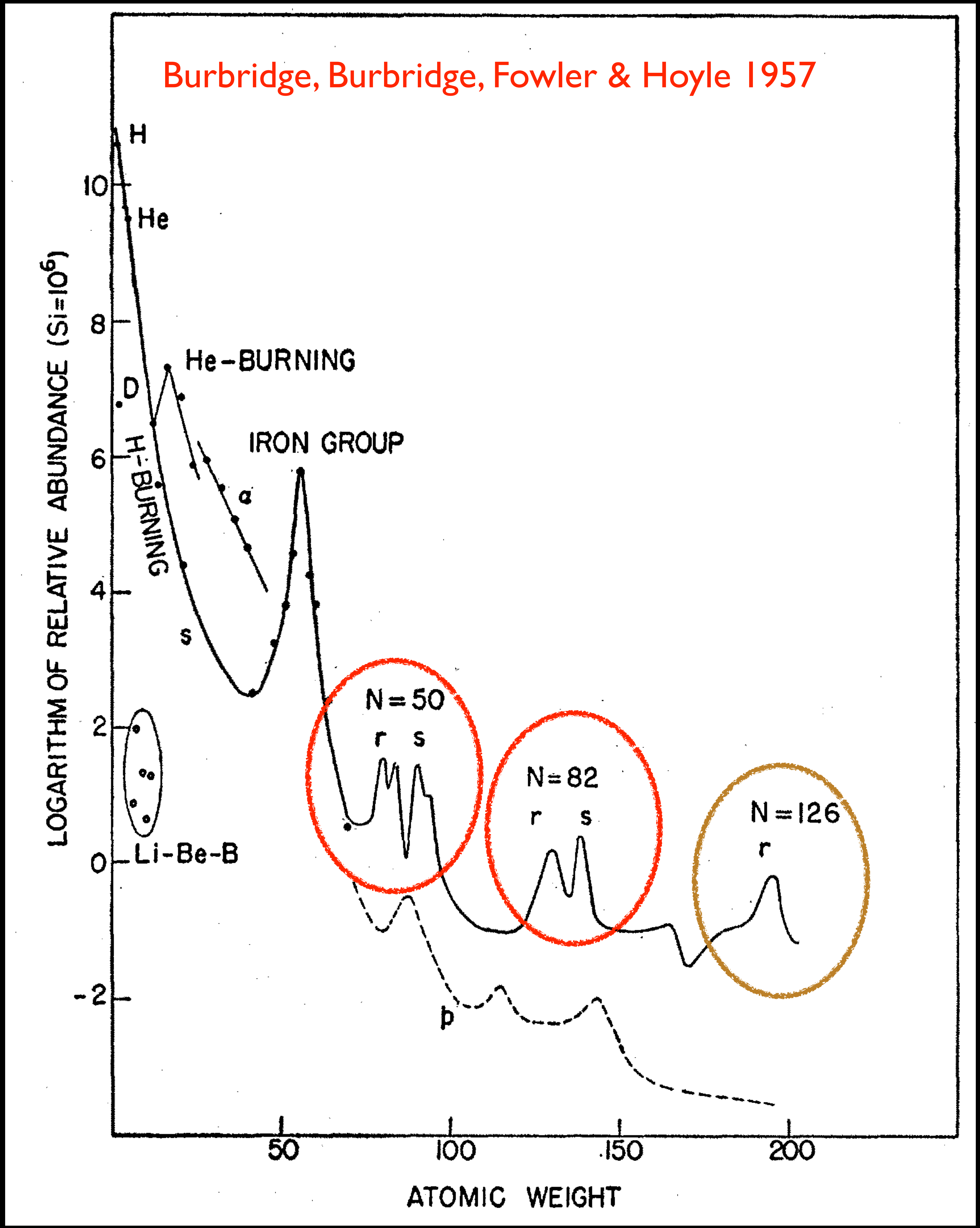

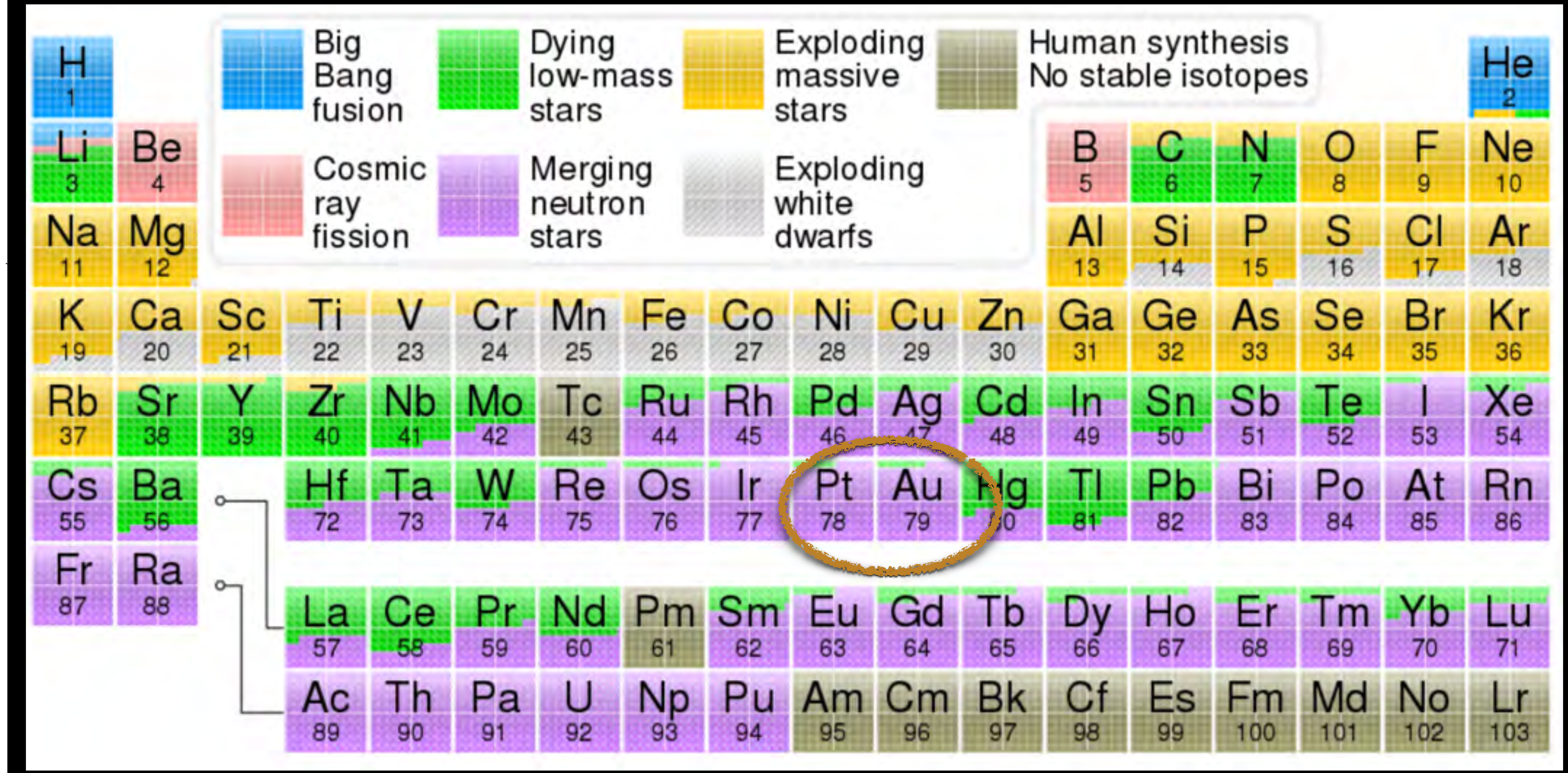

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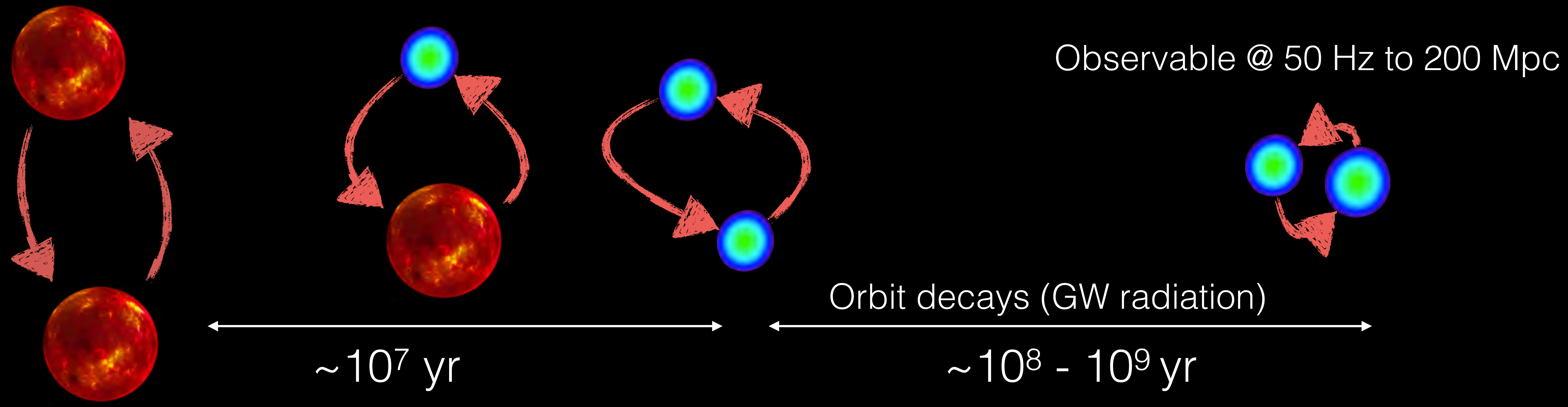
NS Binaries



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
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J1906+746	0.166 days	1.29 + 1.32	3.1 x 10^8 yrs
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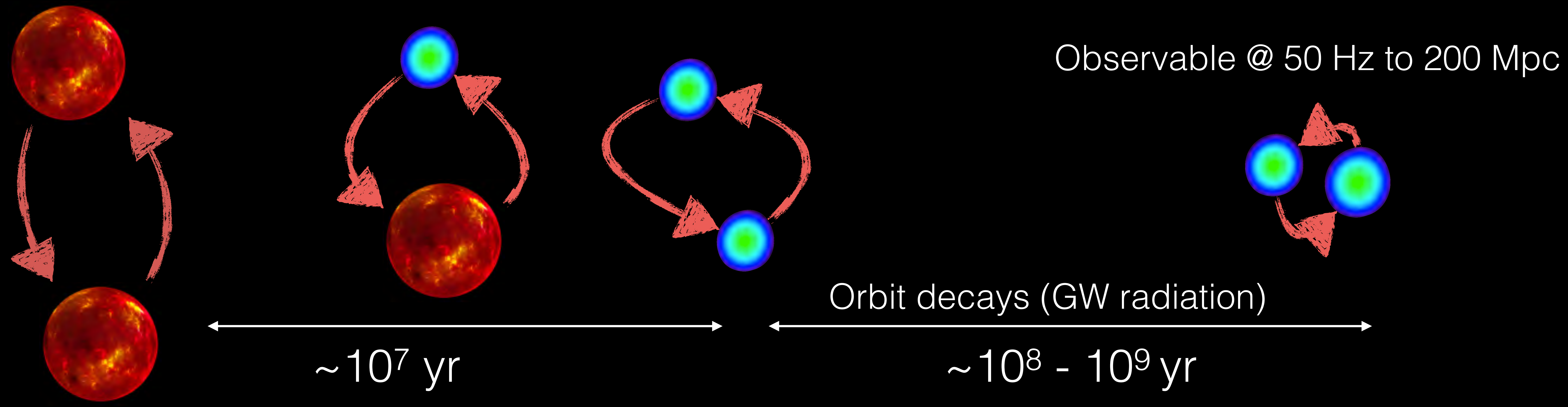

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Initial expectation for BNS mergers in Ad. LIGO at design sensitivity: 0.4 - 400 / year

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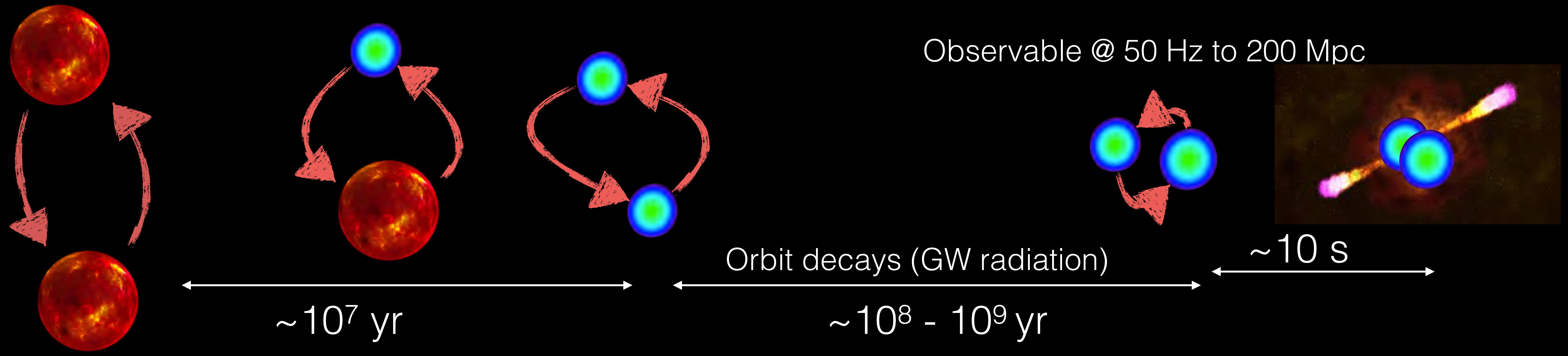

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SGRB rate is ~ 6 /Gpc^3/y

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

2 per year

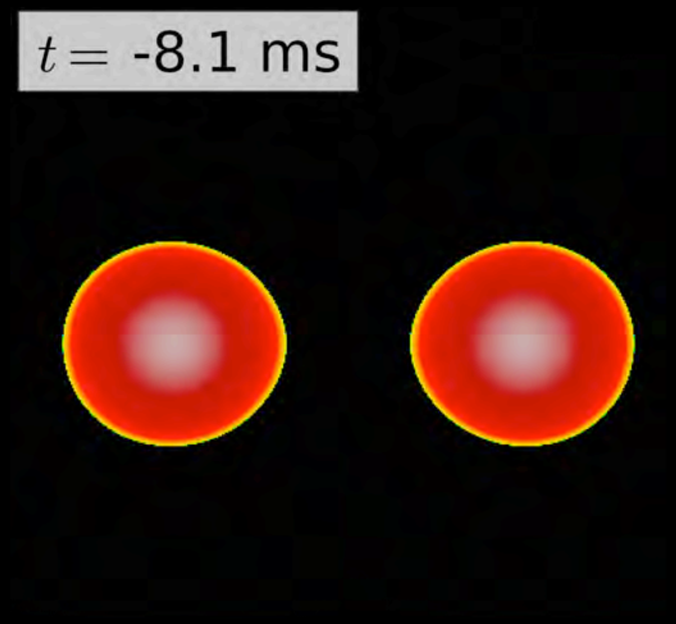
after accounting for beaming.

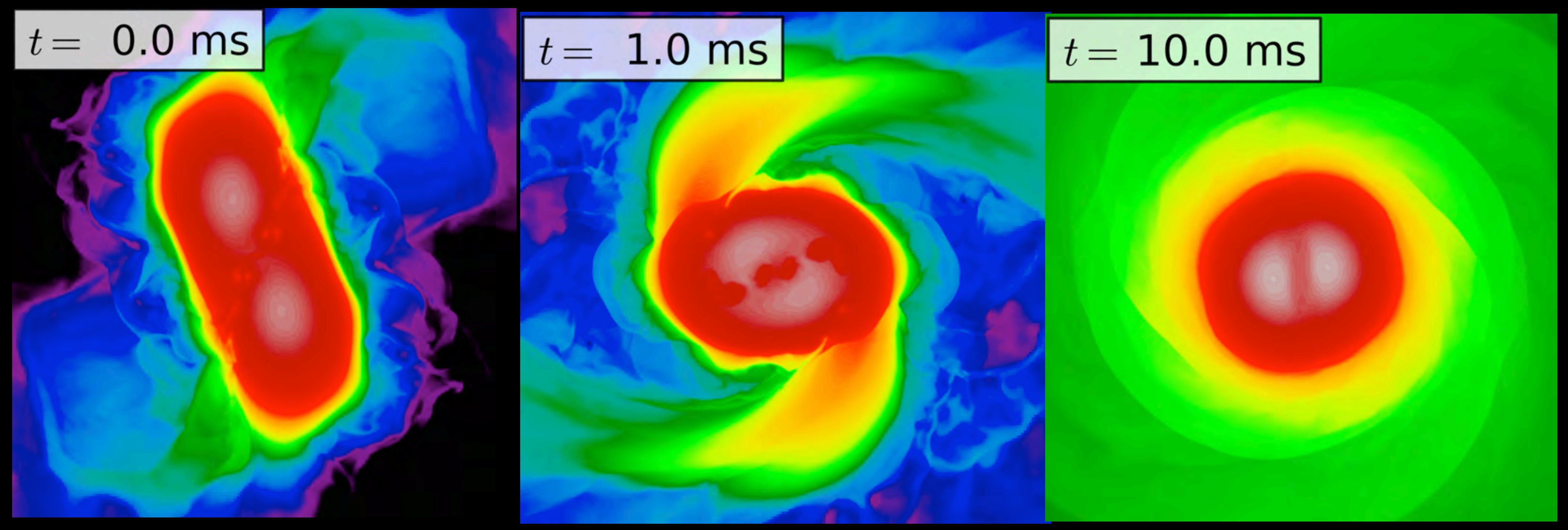
Initial expectation for BNS mergers in Ad. LIGO at design sensitivity: 0.4 - 400 / year

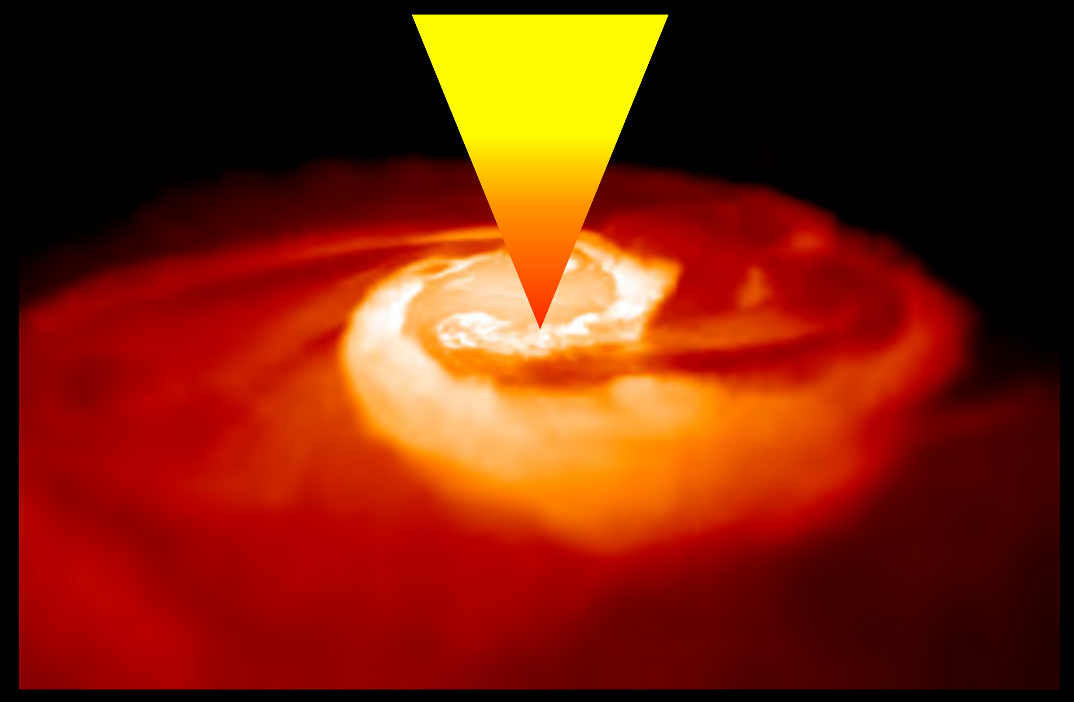
Neutron Star Merger Dynamics

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

Simulations: Rezzola et al (2013)







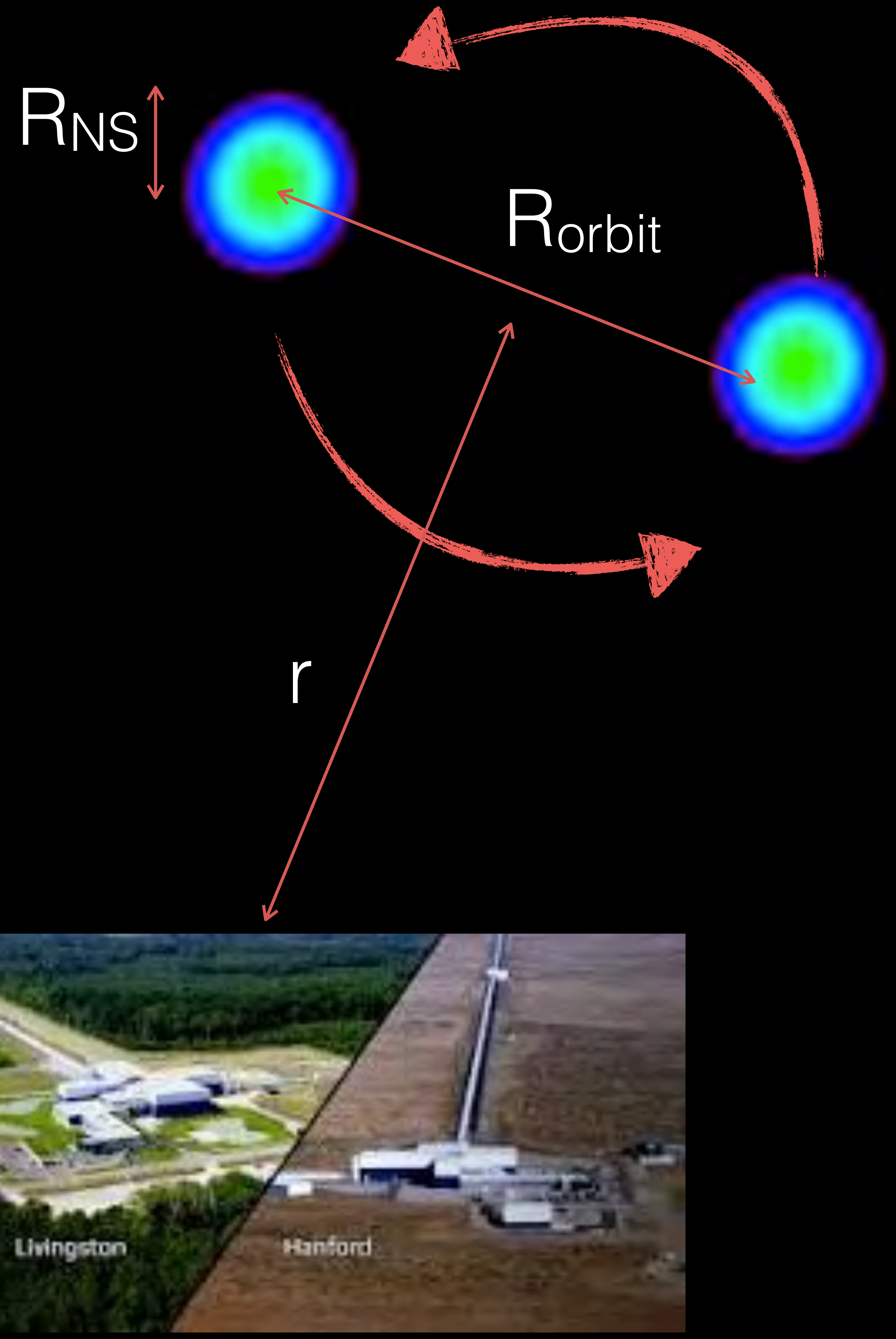
Inspiral:
Gravitational waves,
Tidal Effects

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

Post Merger:
GRBs, Afterglows, and
Kilonova

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

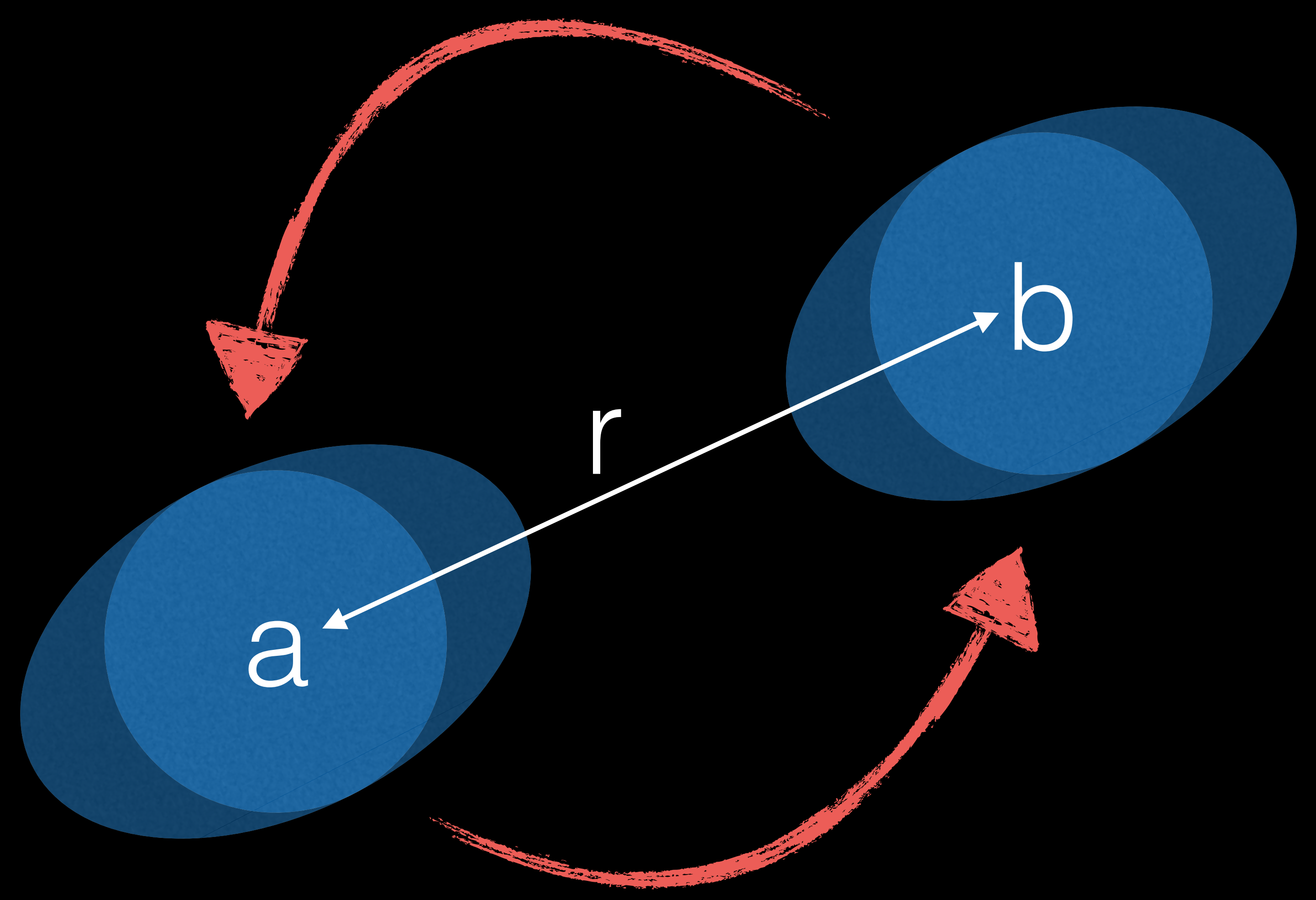
$$h \approx 10^{-23} \left(\frac{M_{NS}}{M_\odot}\right)^{5/3} \left(\frac{f}{200\text{ Hz}}\right)^{2/3} \left(\frac{100\text{ Mpc}}{r}\right)$$

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

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 $m_{\rm tot}$	$2.74^{+0.04}_{-0.01} M_\odot$
Radiated energy $E_{\rm rad}$	$> 0.025 M_\odot c^2$
Luminosity distance $D_{\rm L}$	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

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



Tidal forces deform neutron stars.
Induces a quadrupole moment.

$$Q_{ij} = \lambda\, E_{ij} \qquad E_{ij} = -\frac{\partial^2 V(r)}{\partial x_i \partial x_j}$$

Quadrupole polarizability

External field

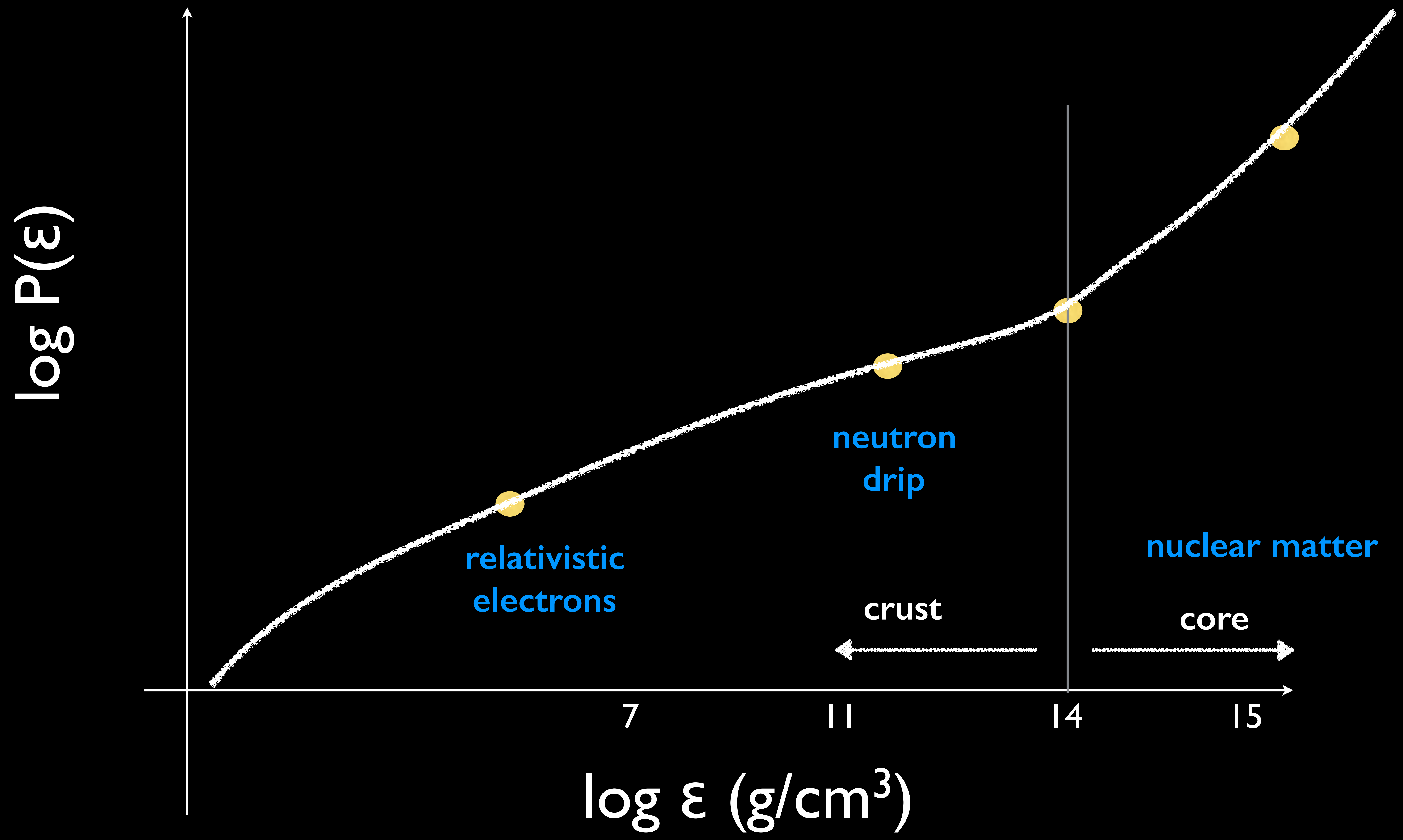
Tidal deformations are large for large NS: $\lambda = k_2\, R_{NS}^5$

Tidal interactions advance the orbit and changes the rotational phase.

Tidal Effects at Late Times

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

PRESSURE V/S ENERGY DENSITY (EOS)



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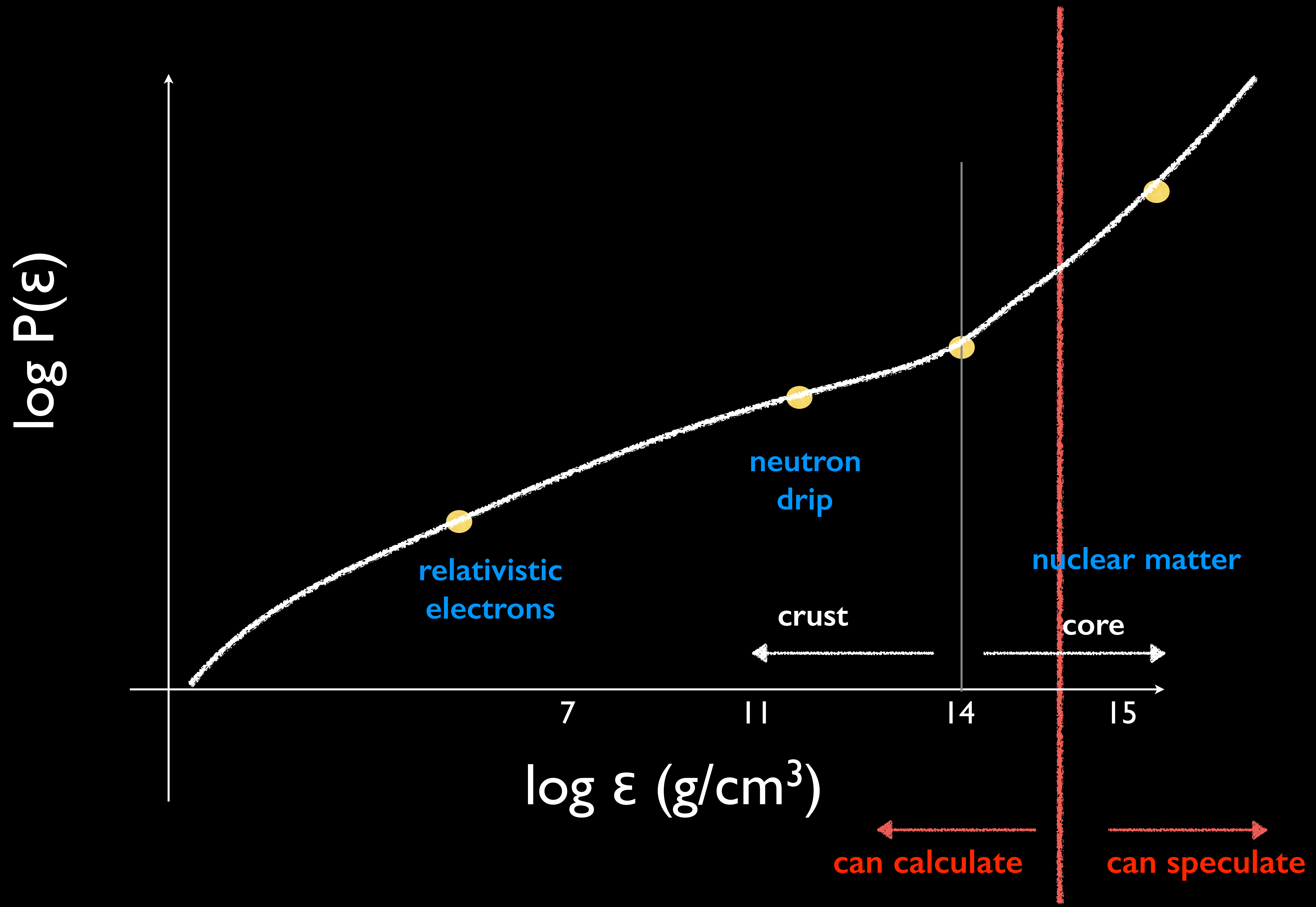

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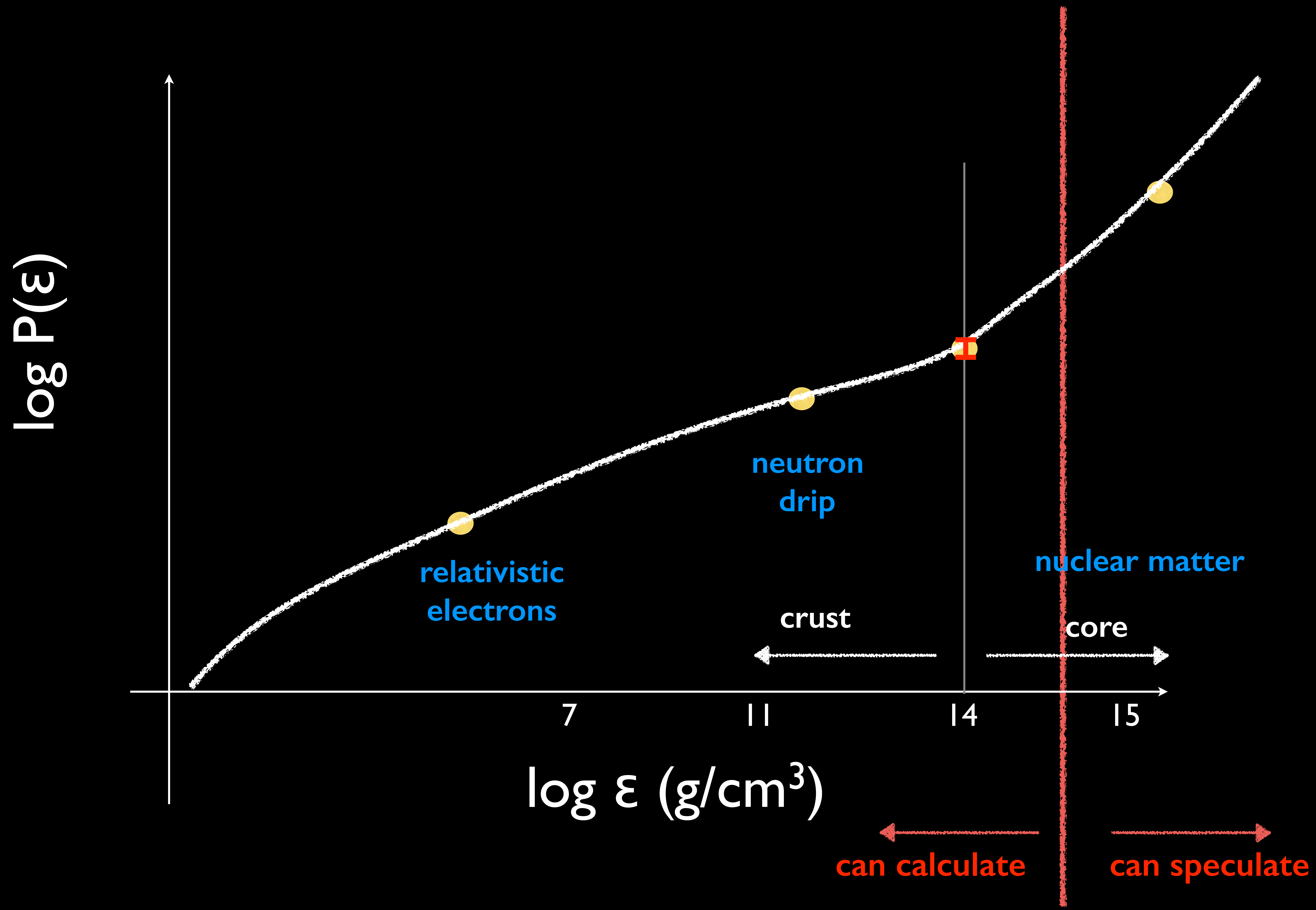

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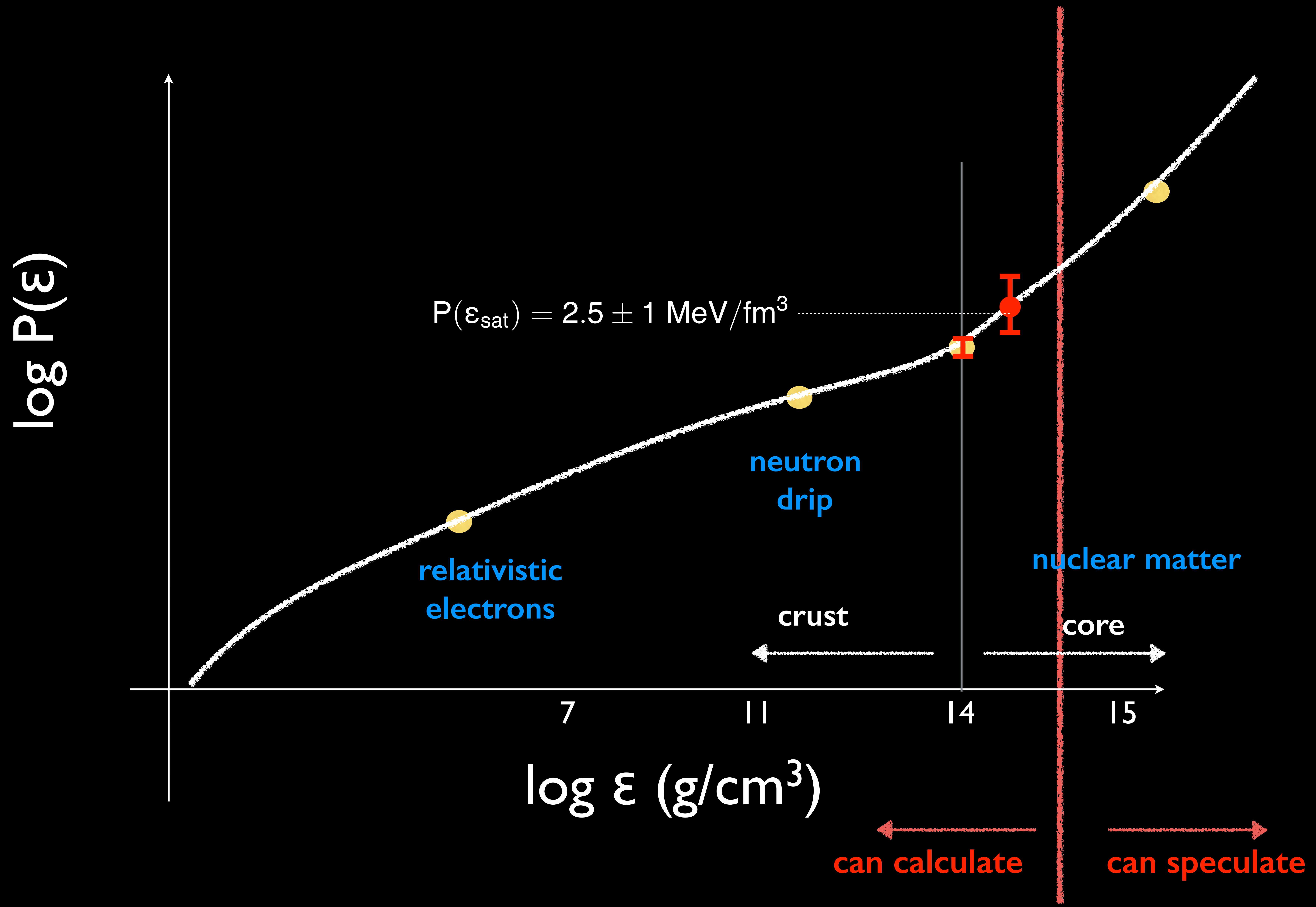

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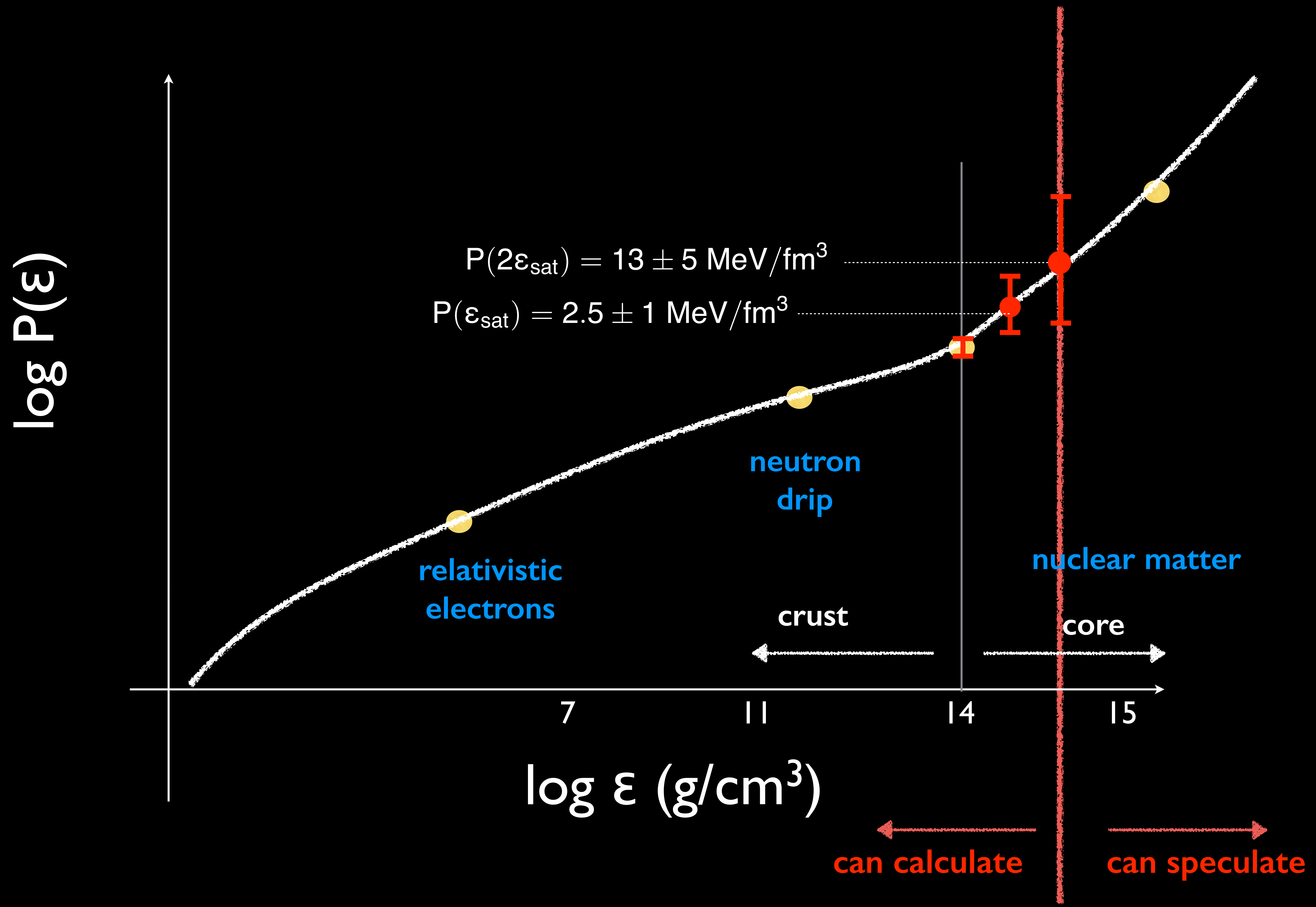

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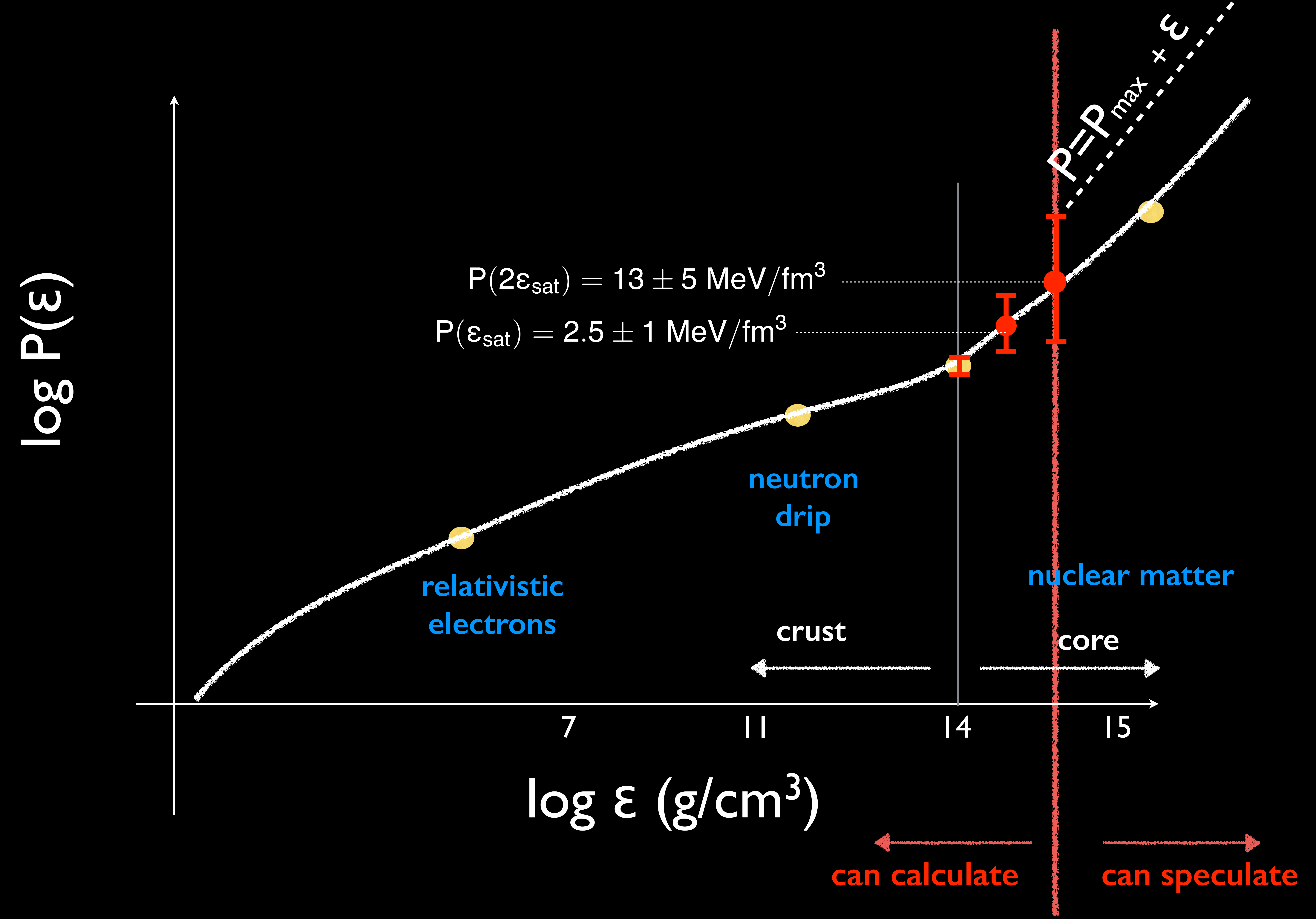

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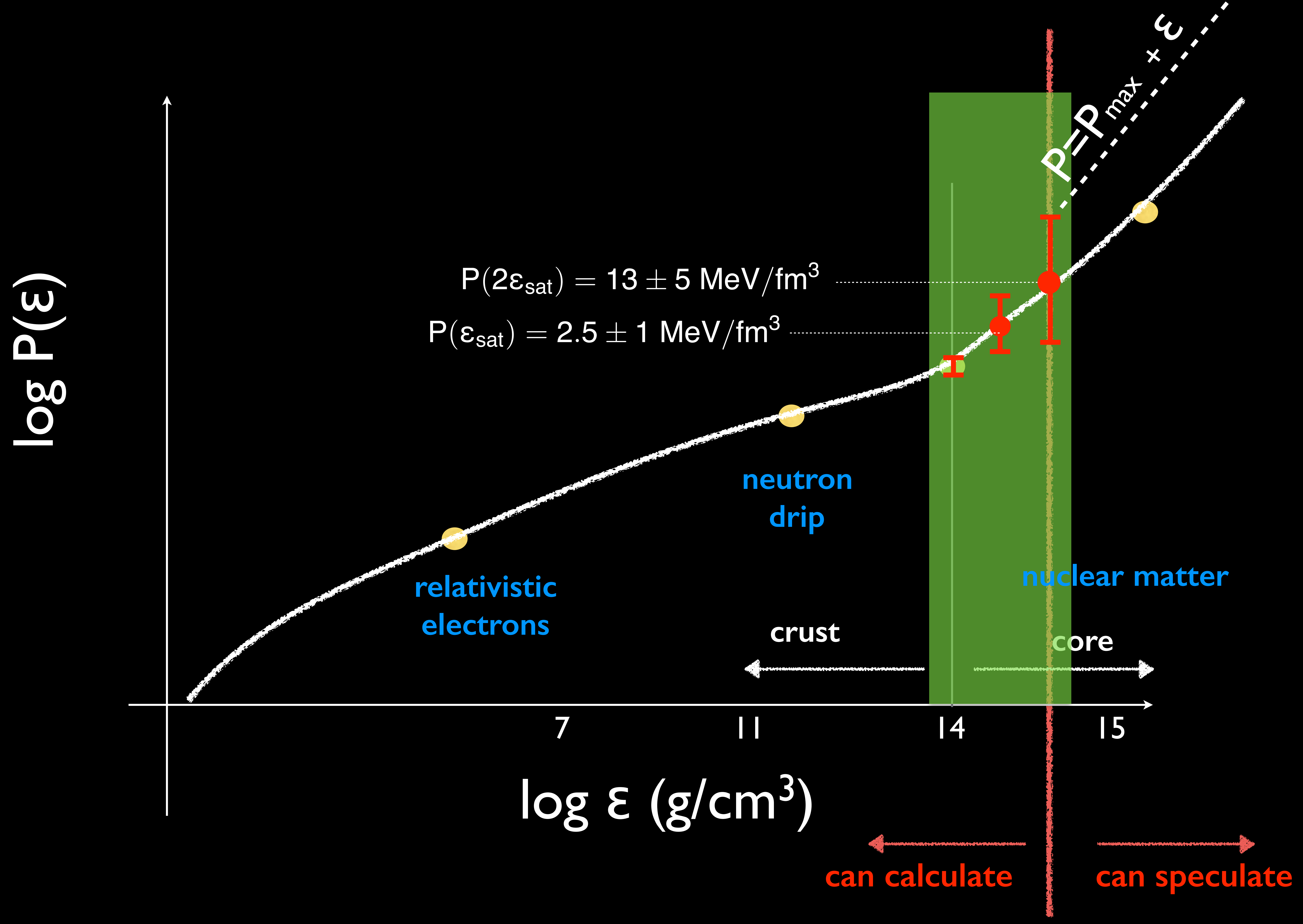

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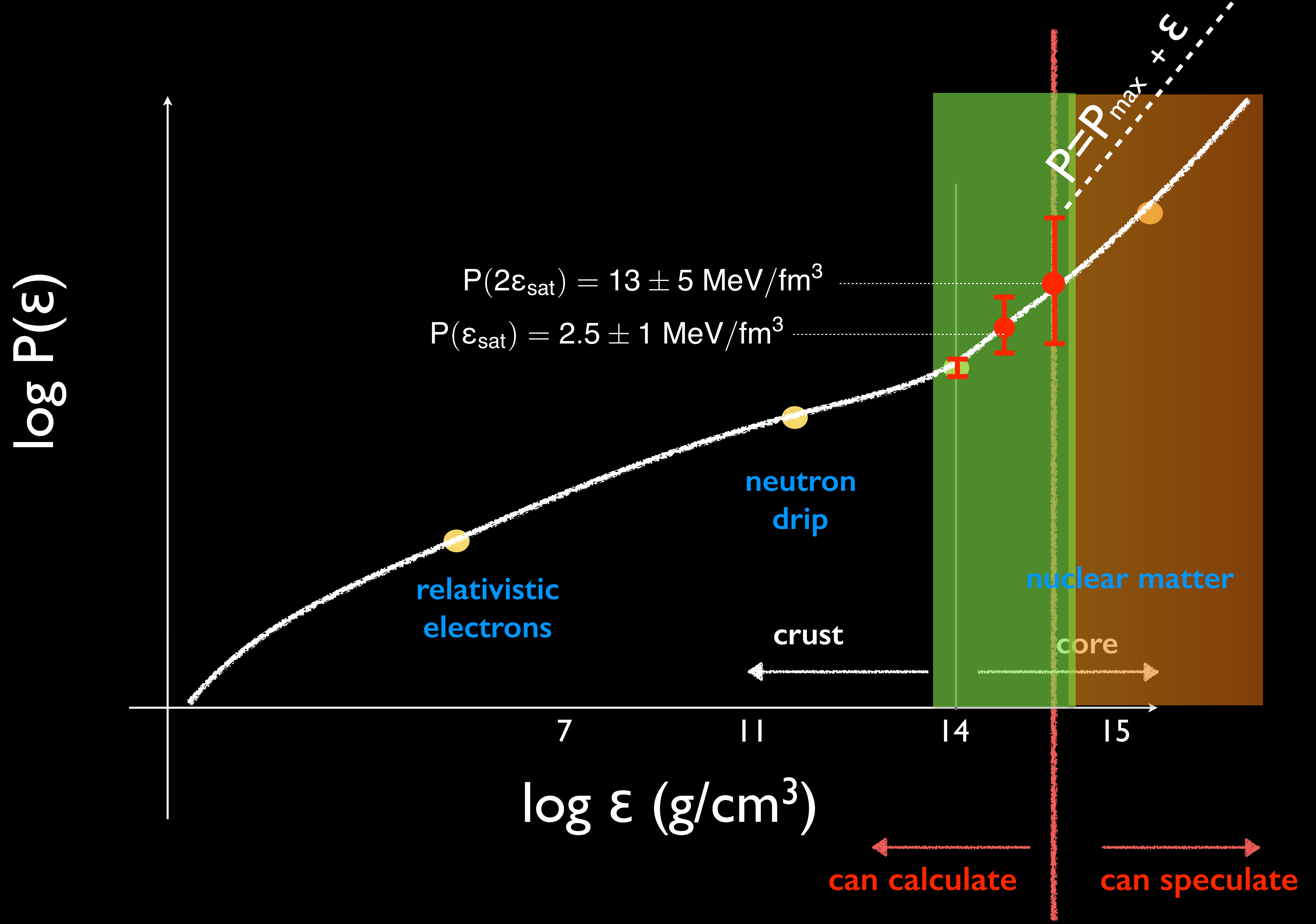

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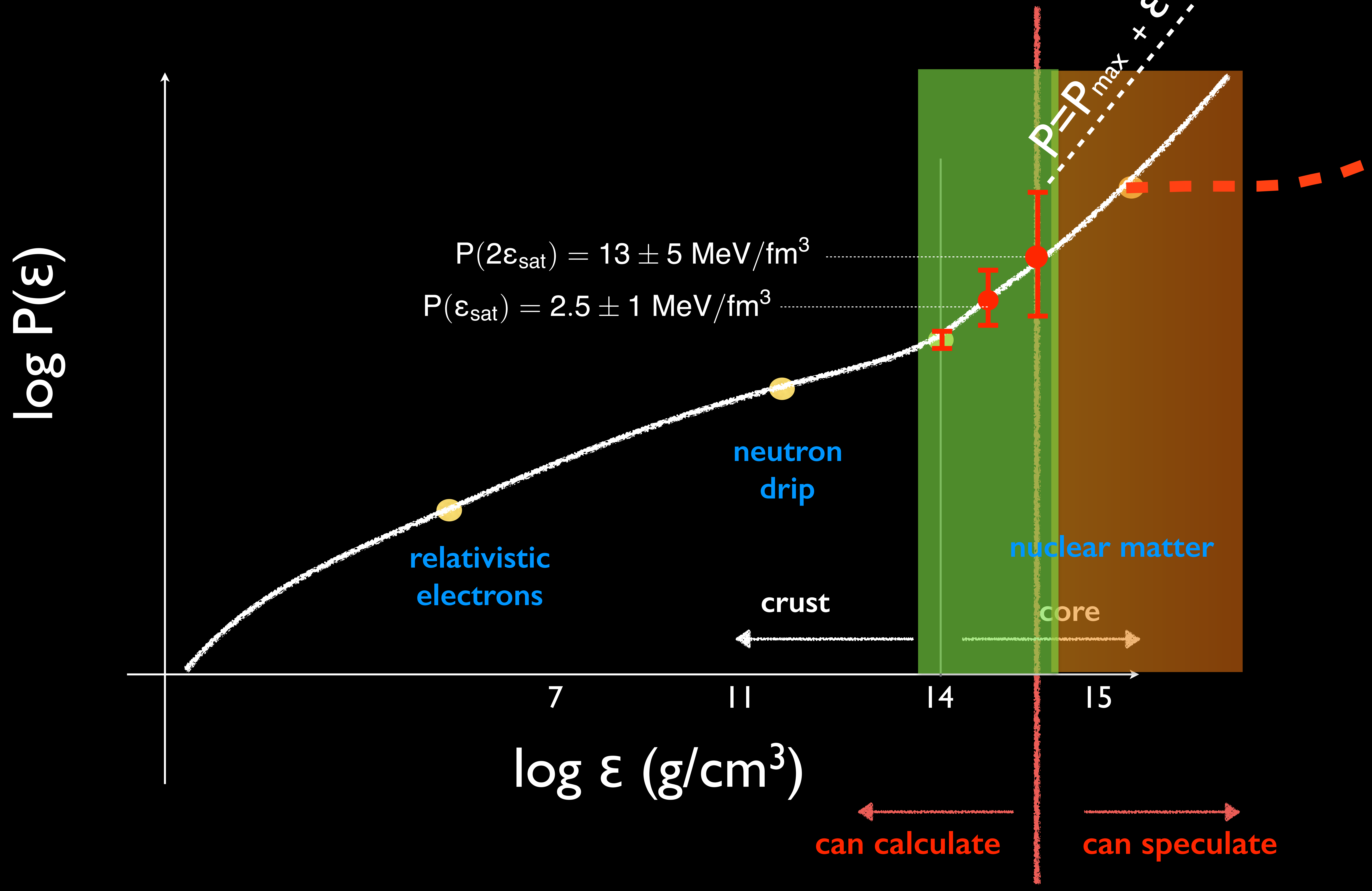

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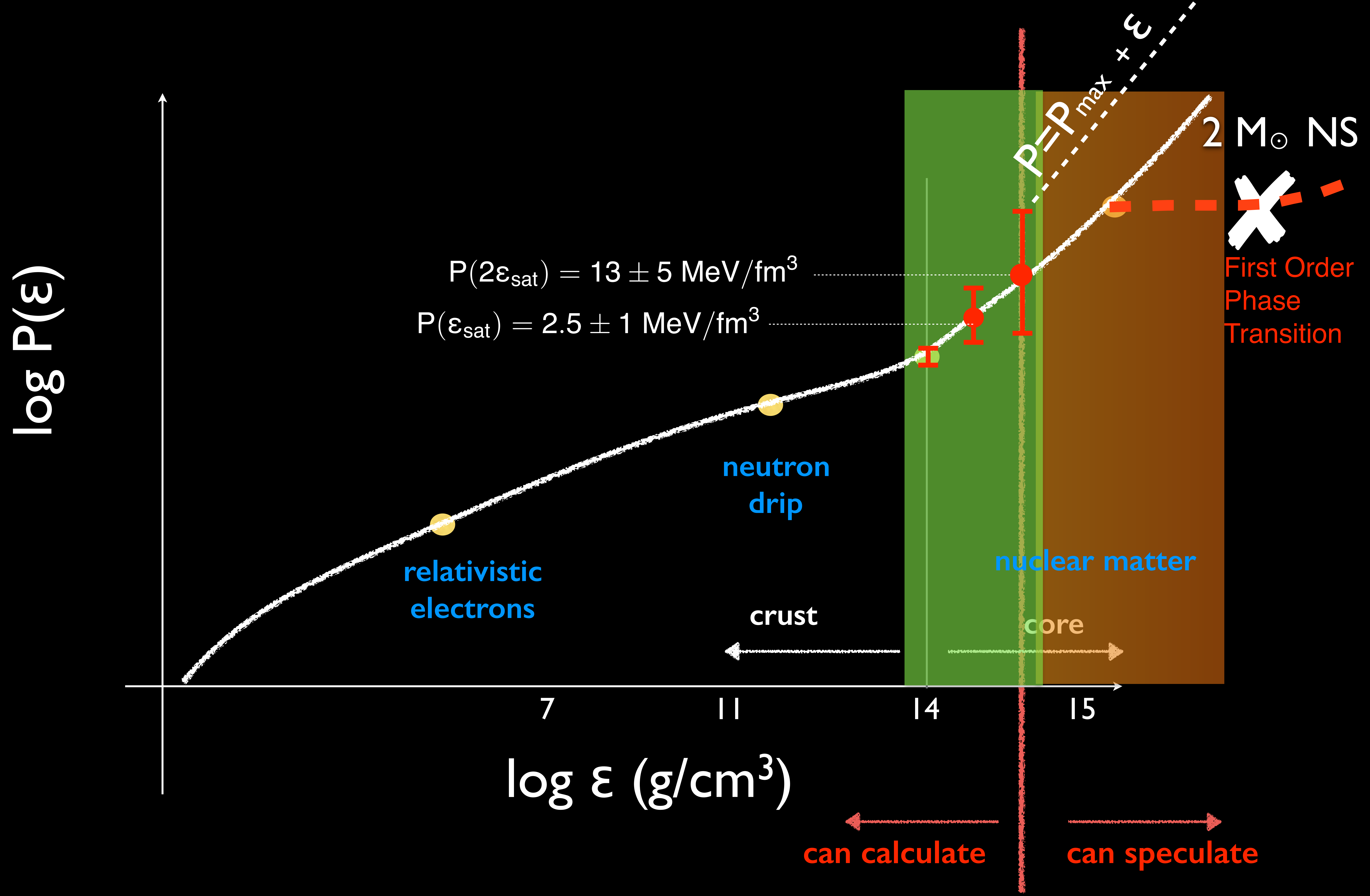

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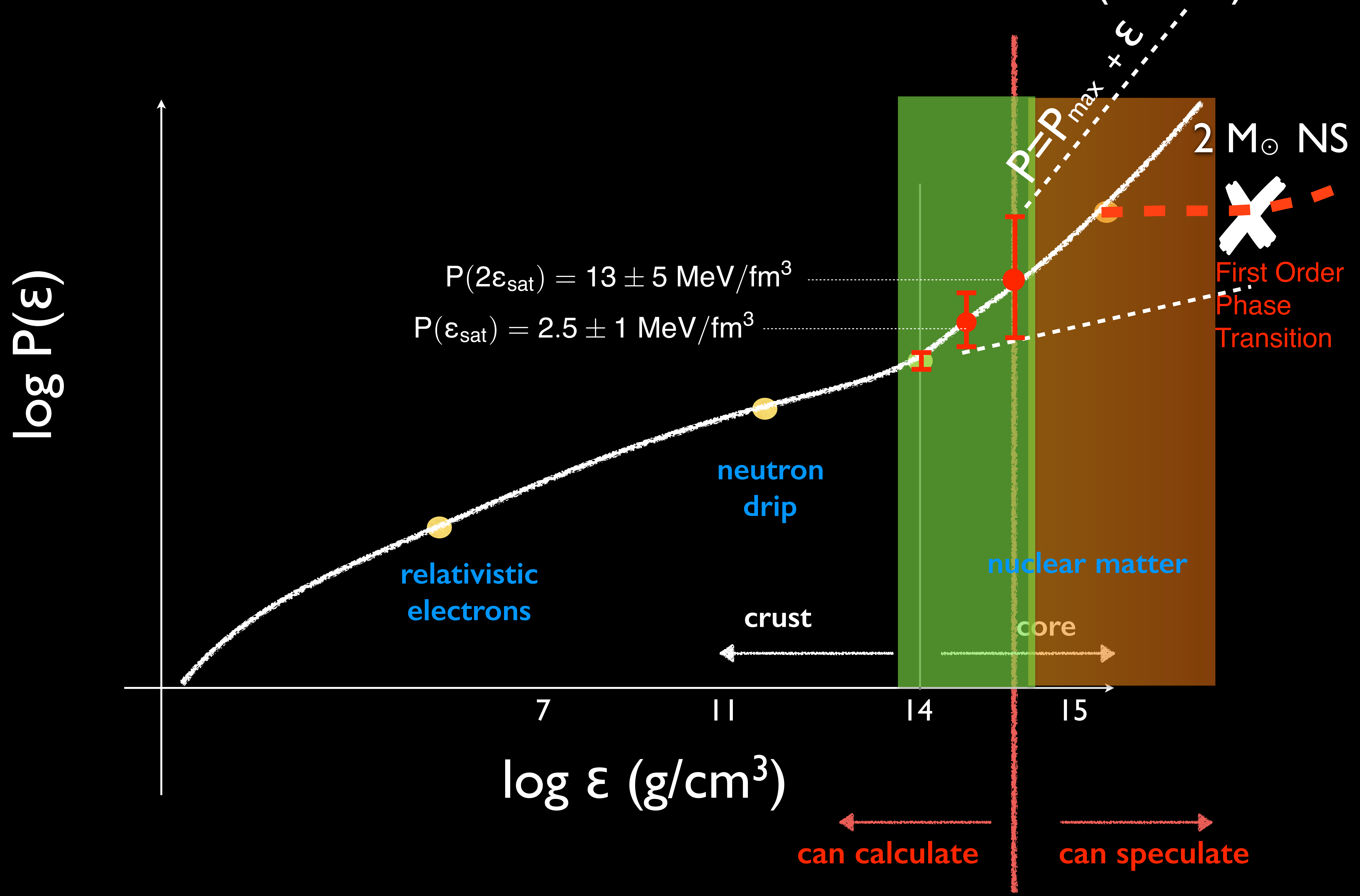
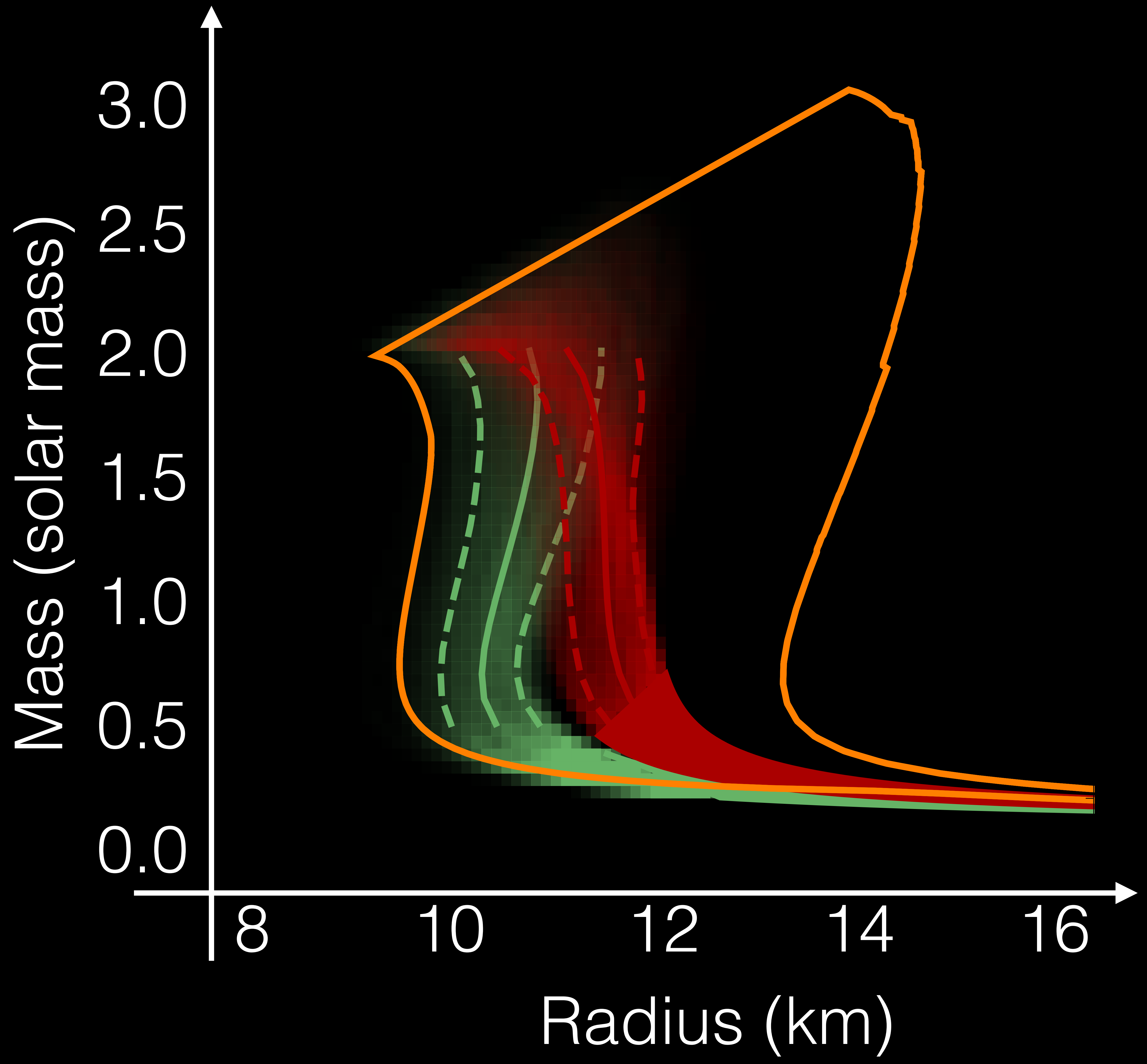


Radii and Maximum Masses

- Modern EOS based on EFT inspired nuclear forces and Quantum Monte Carlo calculations provide useful predictions despite uncertainties at high density.

- Nuclear description viable up to 5 x 10^{14} g/cm^3 :
  - Radius = 10 - 12 kms
  - Maximum mass = 2 - 2.5 solar masses

- Nuclear description viable up to 2.5 x 10^{14} g/cm^3 :
  - Radius = 9.5 - 14 kms
  - Maximum mass = 2 - 3 solar masses



Tews, Carlson, Gandolfi and Reddy (2018)

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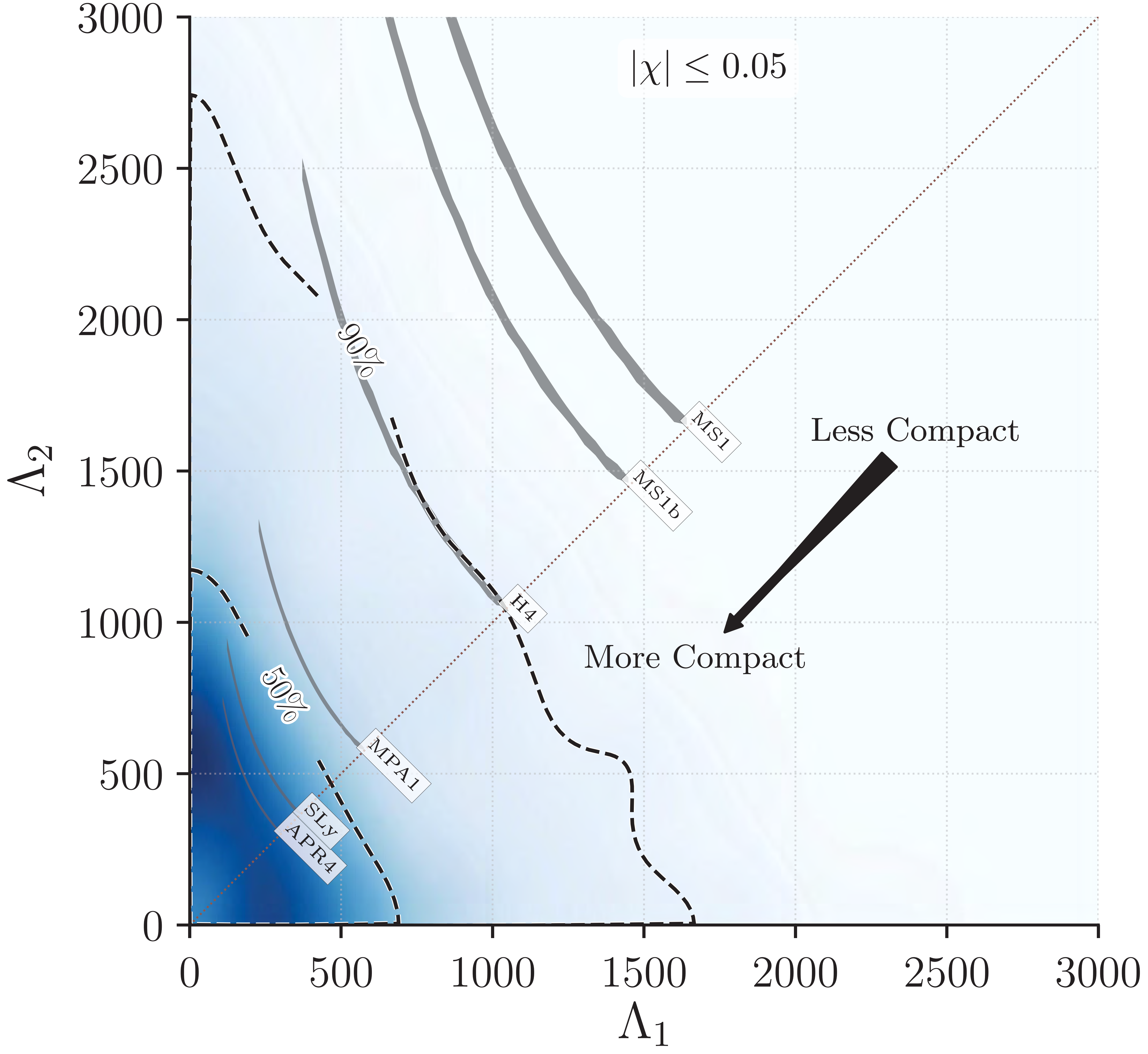
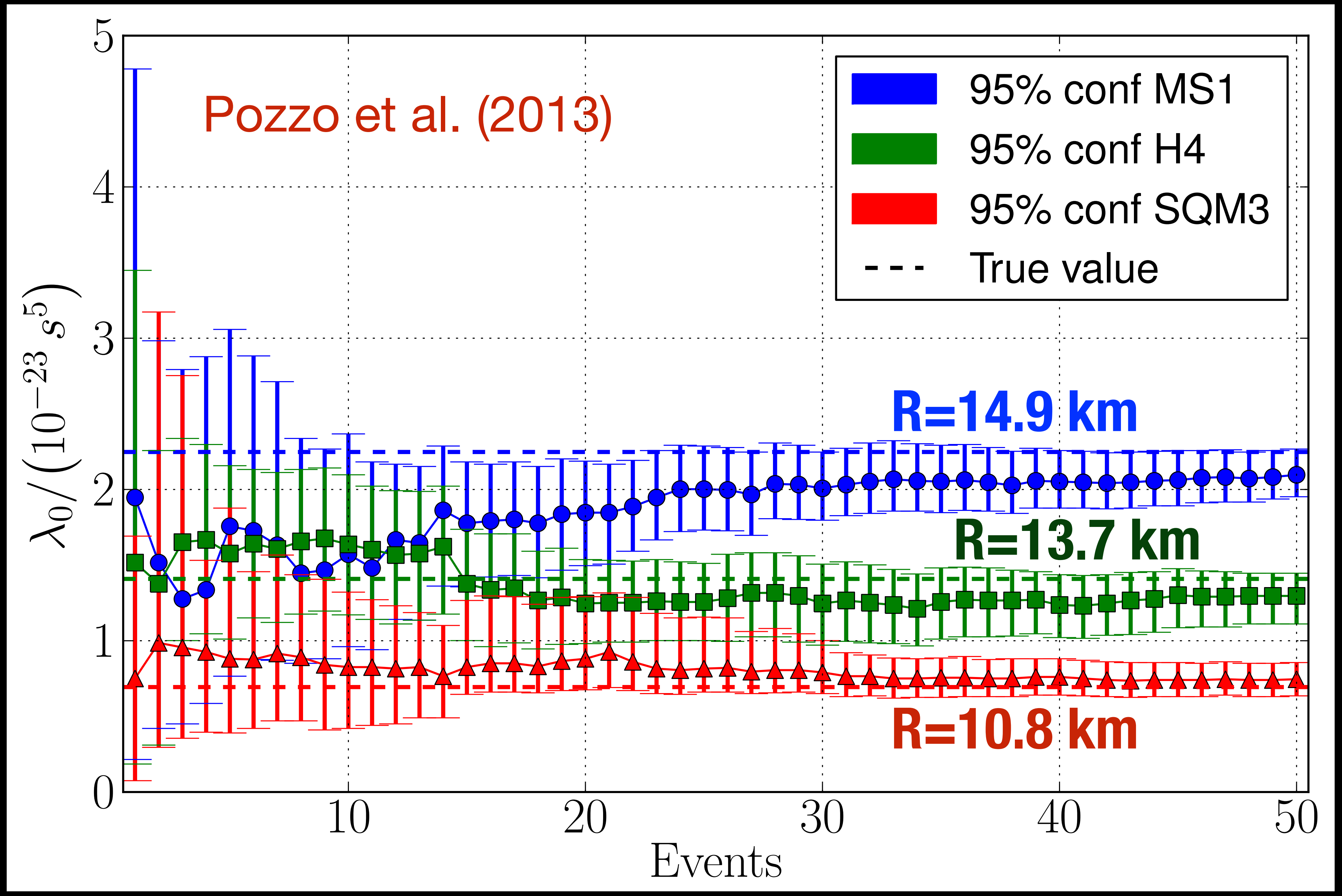


- R > 14 km are disfavored.
- Data favor a finite polarizability but cannot distinguish between radii in the range 9-13 kms.

Many detections and next generation detectors

Quadrupole Polarizability



10% measurement of neutron star radius may be possible.

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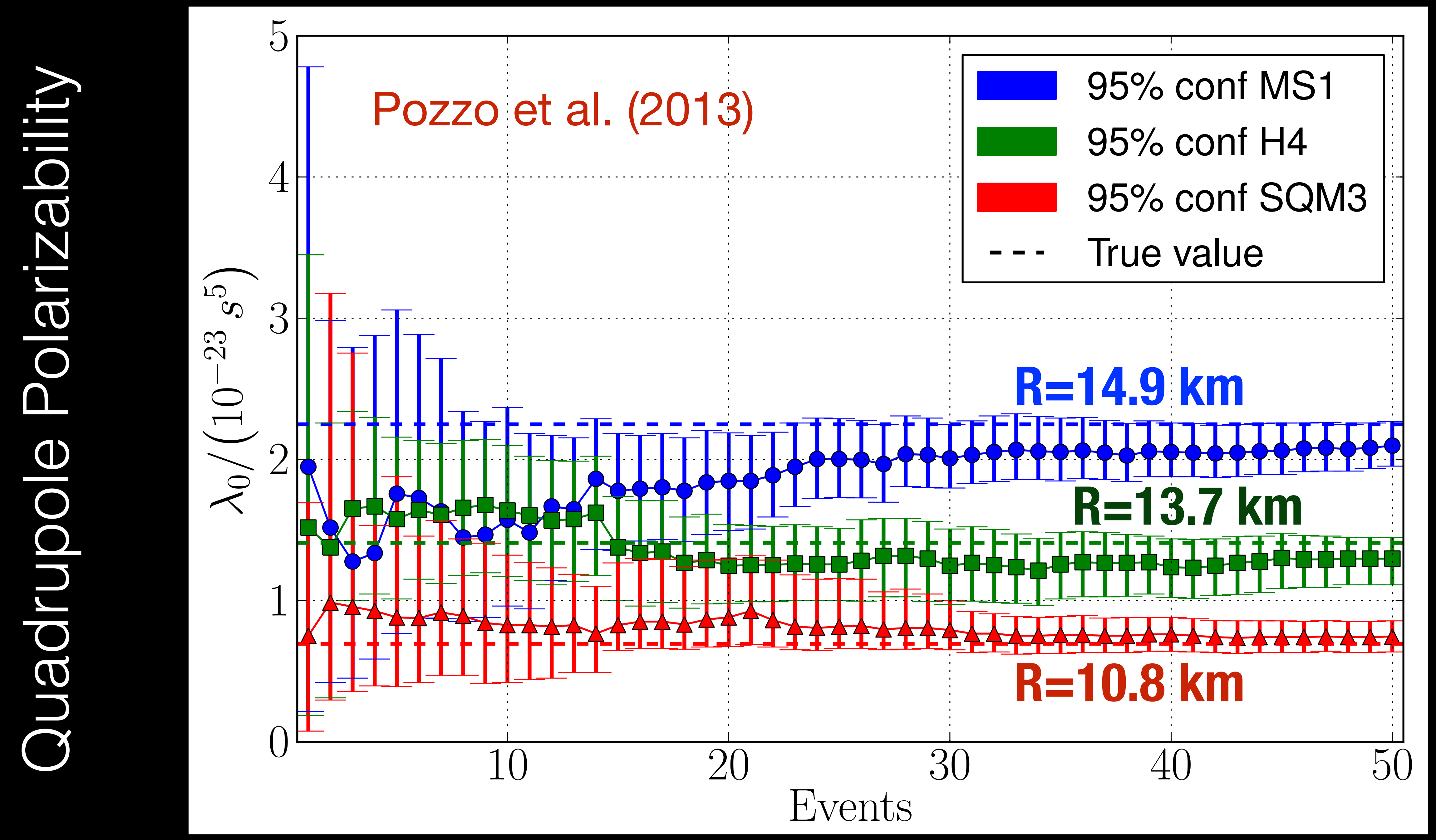

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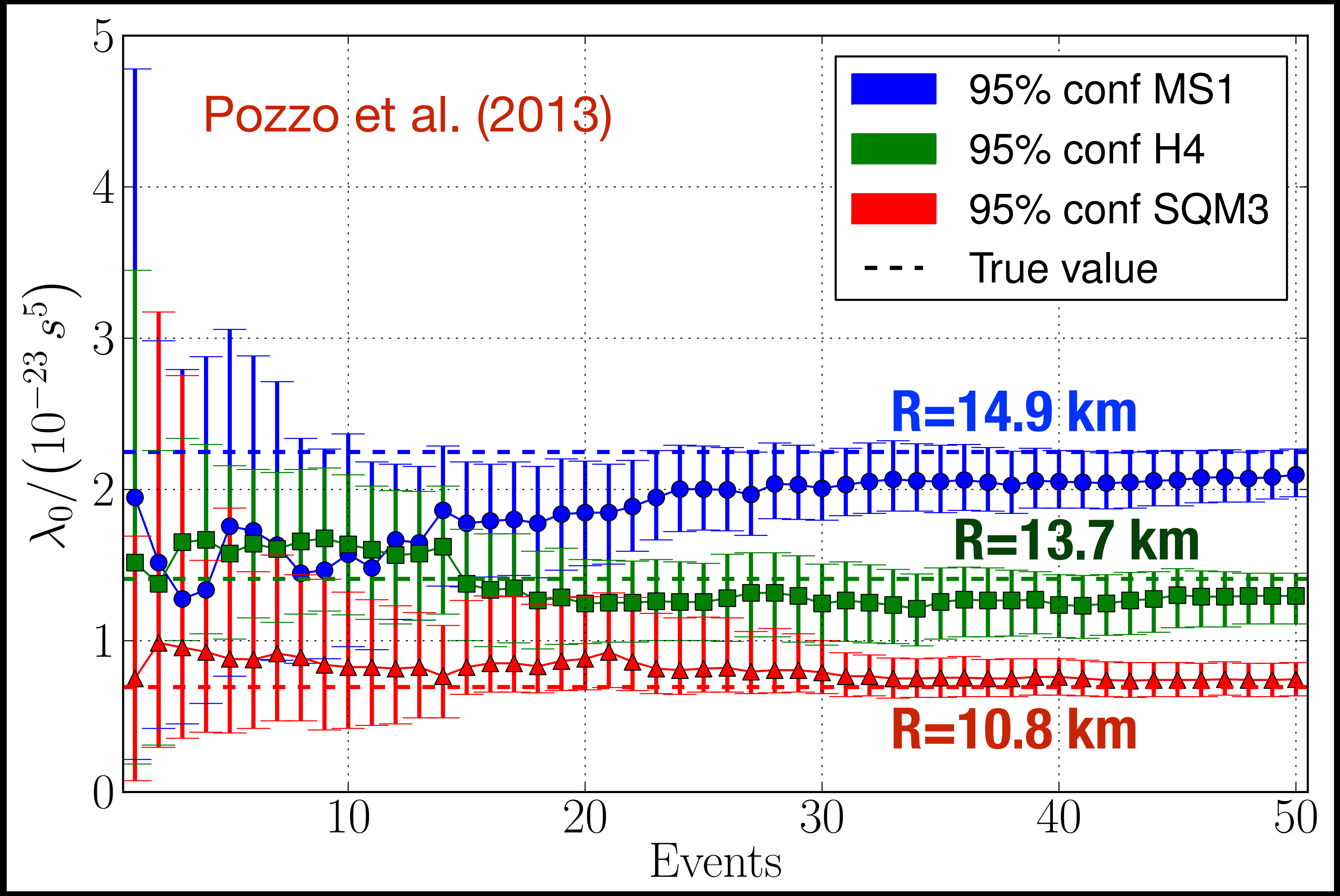

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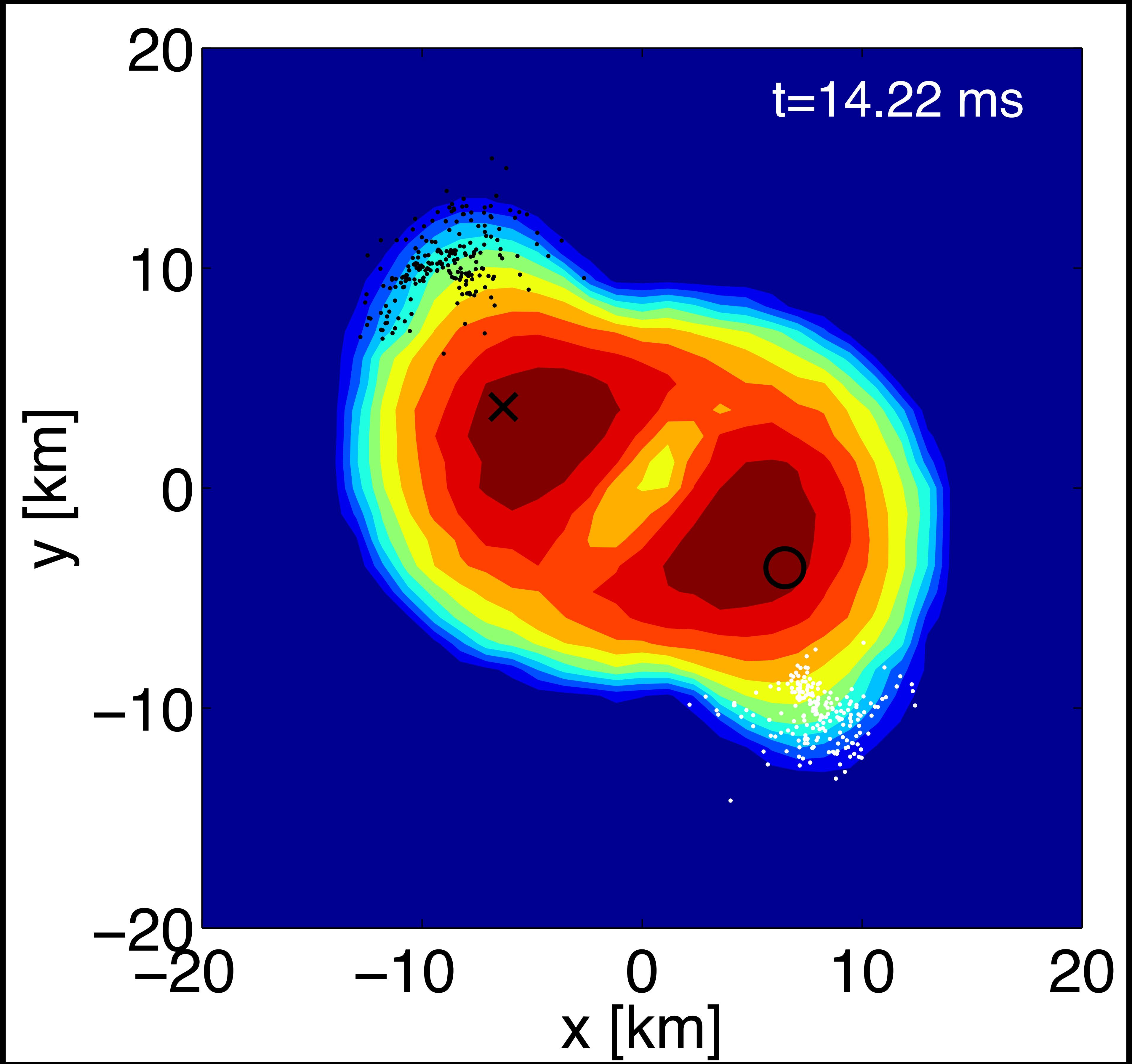

Frequency of quasi-normal modes, post merger are also sensitive to the EOS. Will be accessible with next generation GW detectors.

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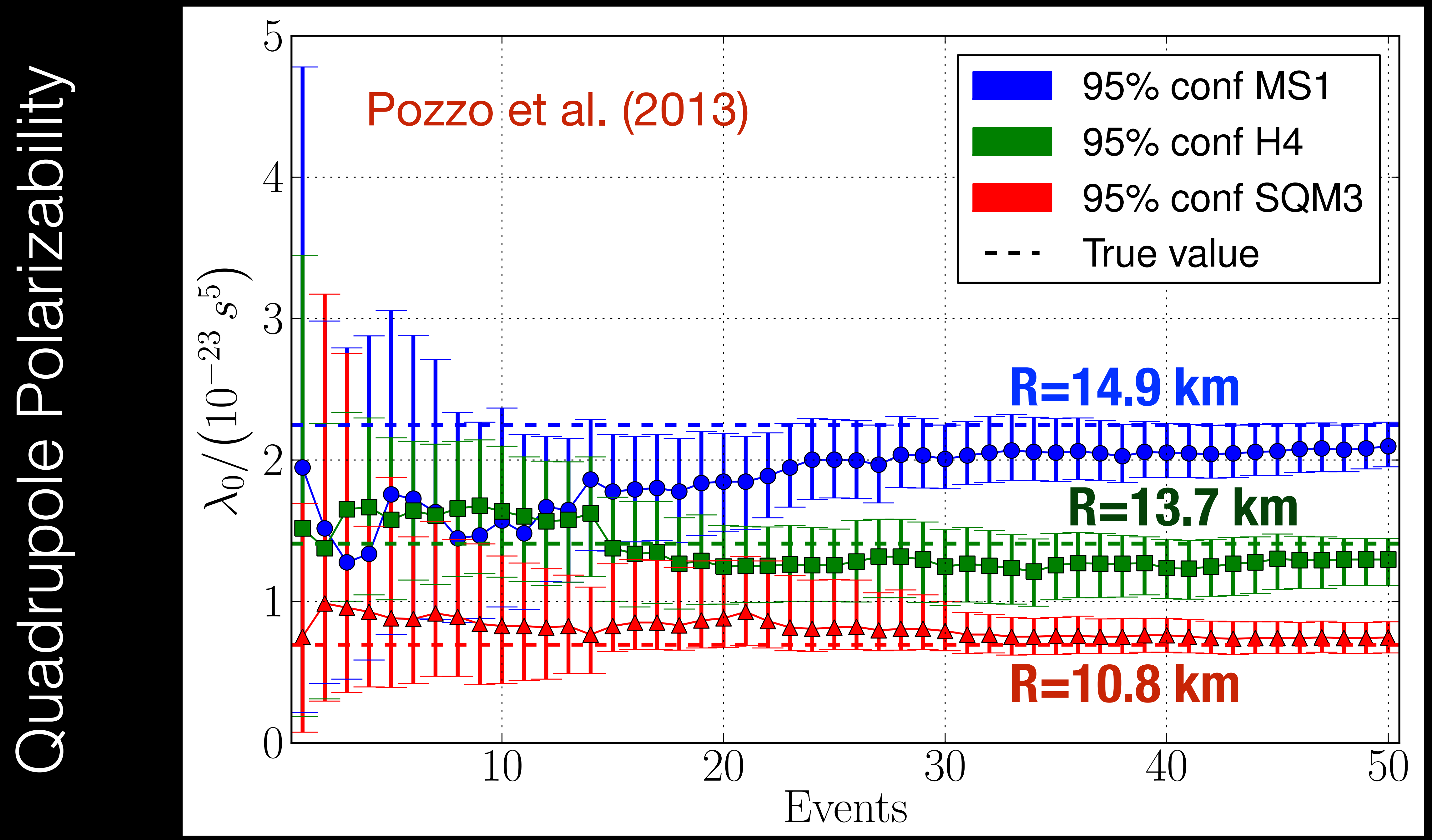

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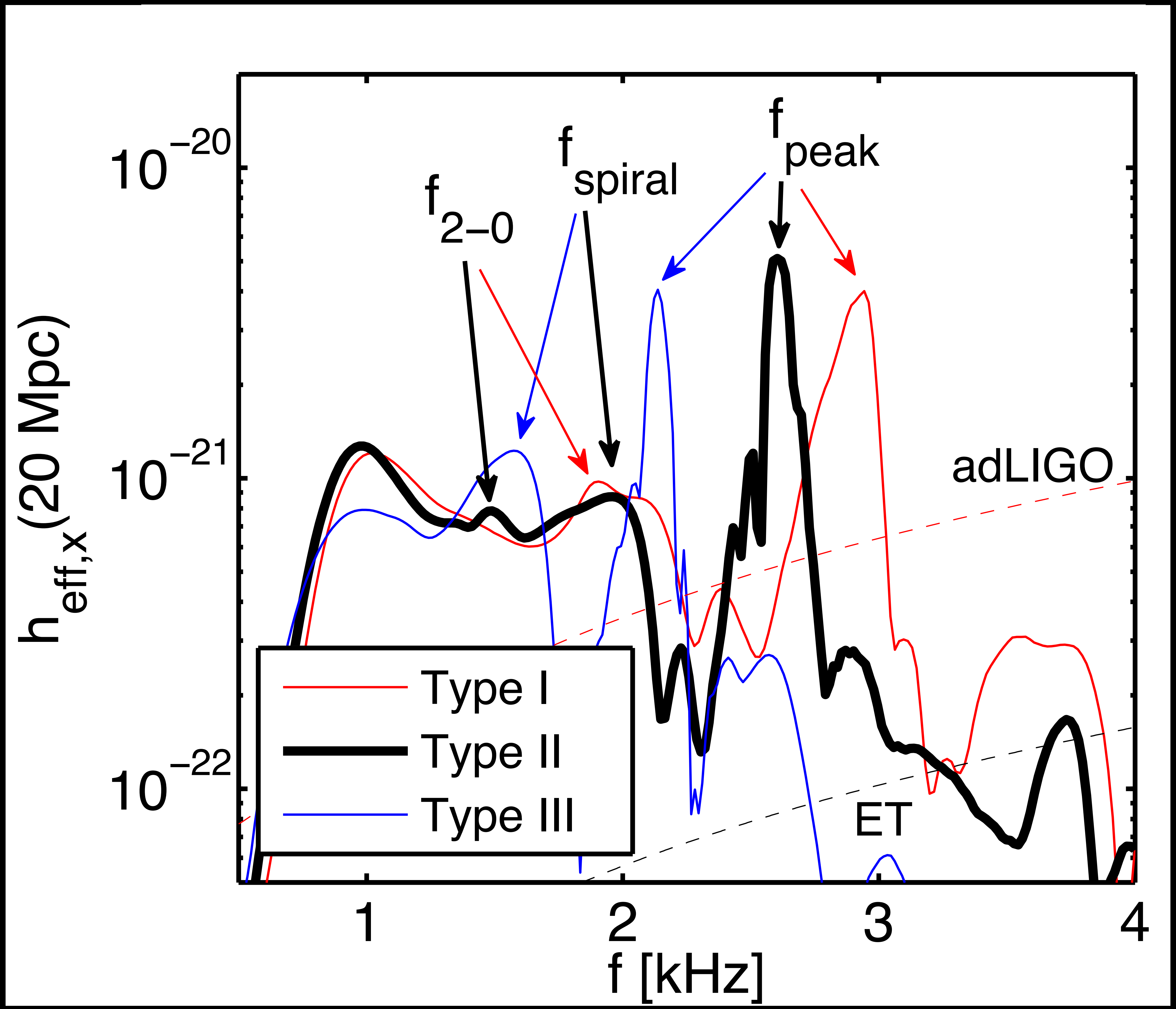

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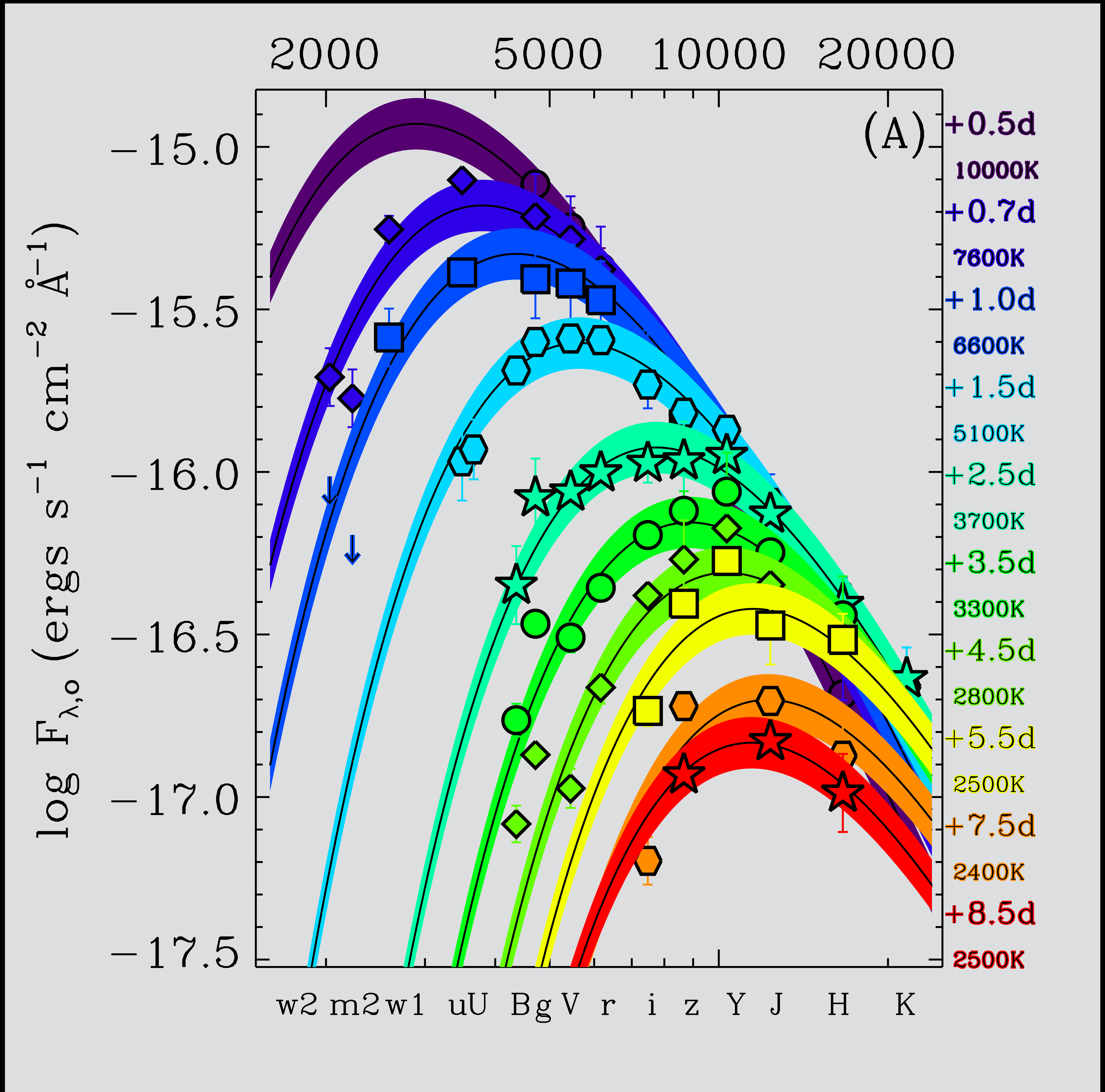
$$f_{\rm peak}[{\rm kHz}] = 199(M/R)^2 - 28.1(M/R) + 2.33$$
$$f_{\rm spiral}[{\rm kHz}] = 358(M/R)^2 - 82.1(M/R) + 6.16$$
$$f_{2-0}[{\rm kHz}] = 392(M/R)^2 - 88.3(M/R) + 5.95$$

Bauswein & Stergioulas (2015)

Electromagnetic Signatures: Ejecta and Kilonova

- Mergers produce and heavy elements.
  Lattimer & Schramm 1974
- Radioactive heavy elements synthesized and ejected 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



Tremendous detail in the observed light curves !

Remarkably, models that fit these light curves suggests:

nature Accelerated Article Preview

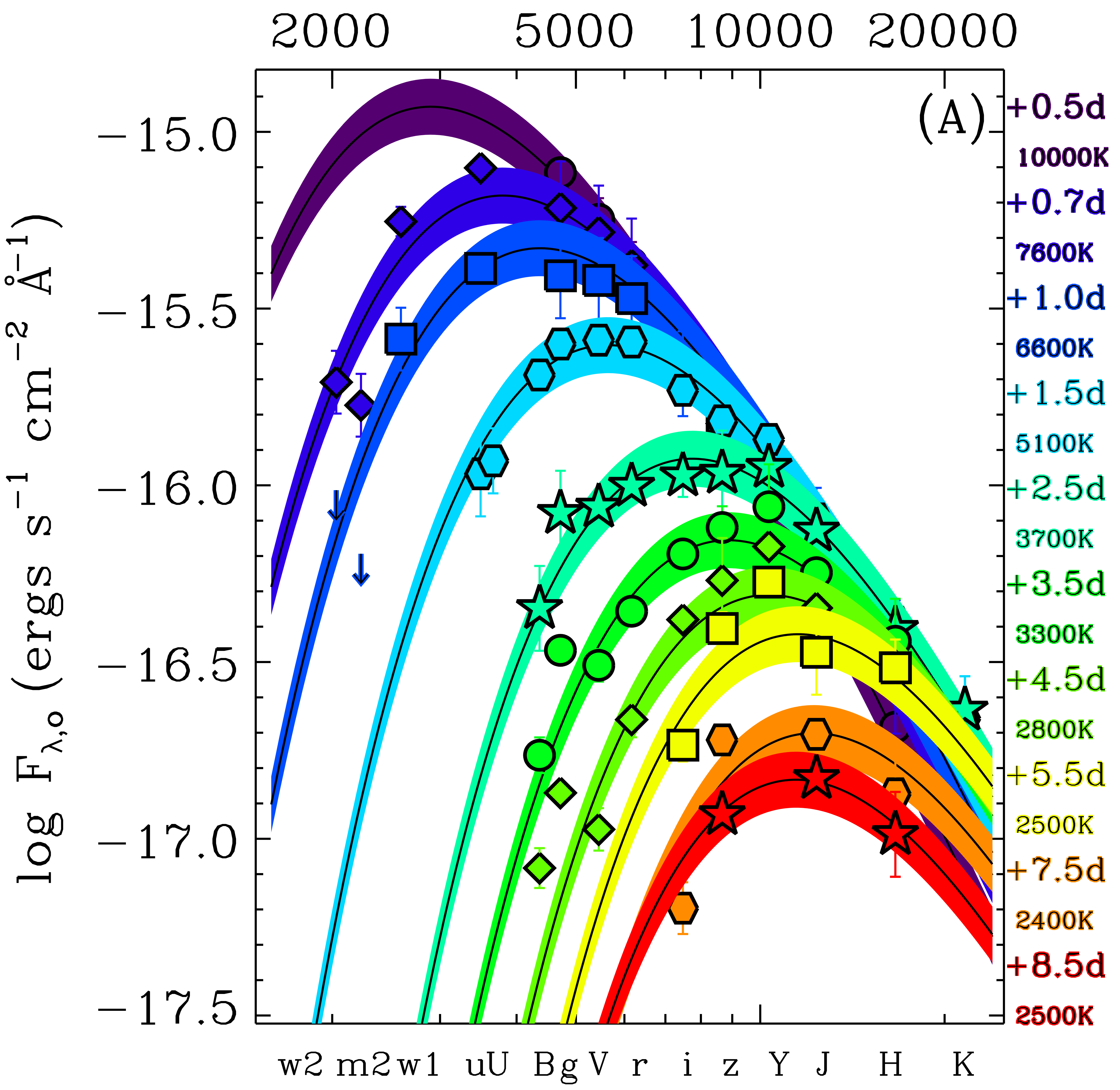
LETTER

doi:10.1038/nature24453

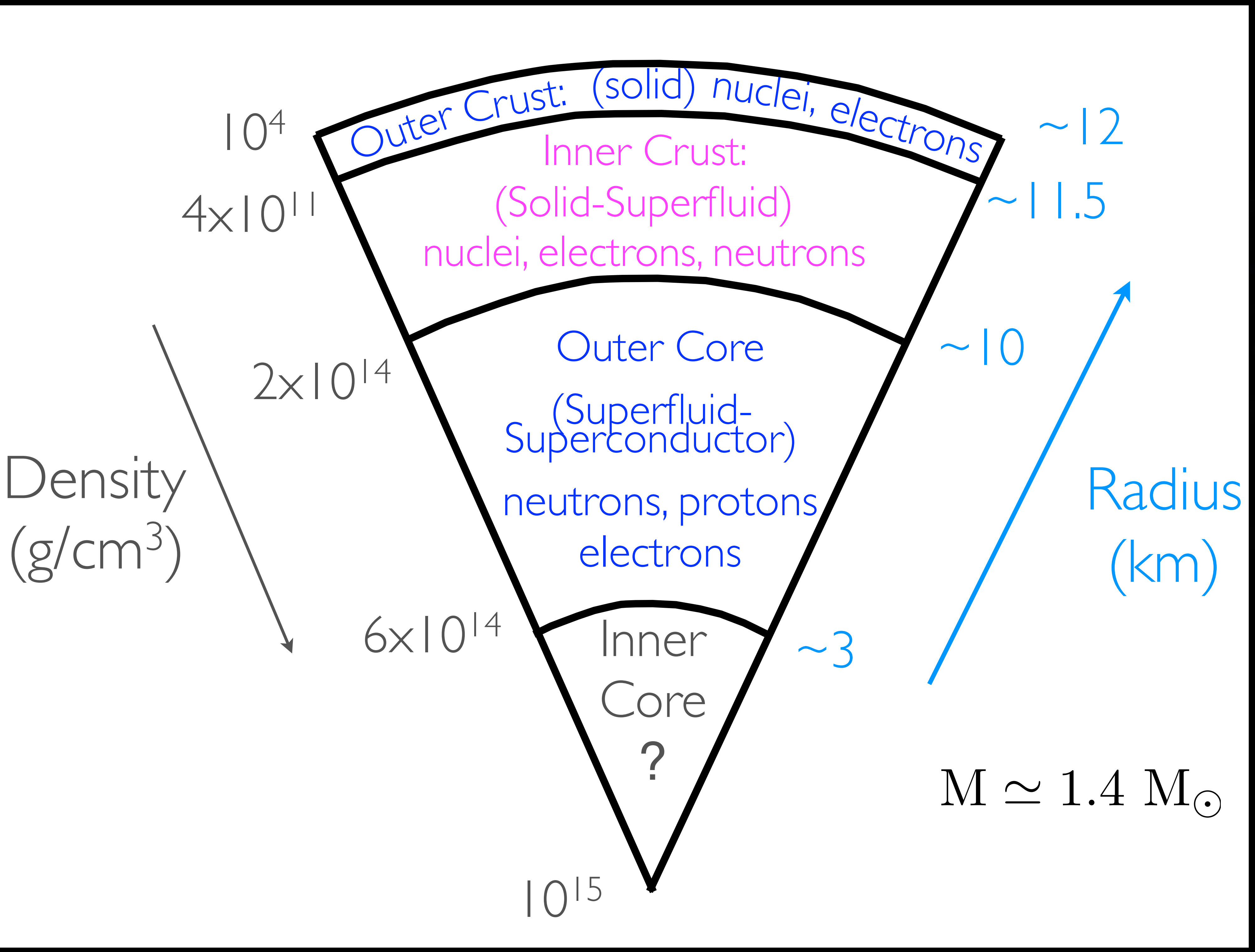
Origin of the heavy elements in binary neutron-star mergers from a gravitational-wave event

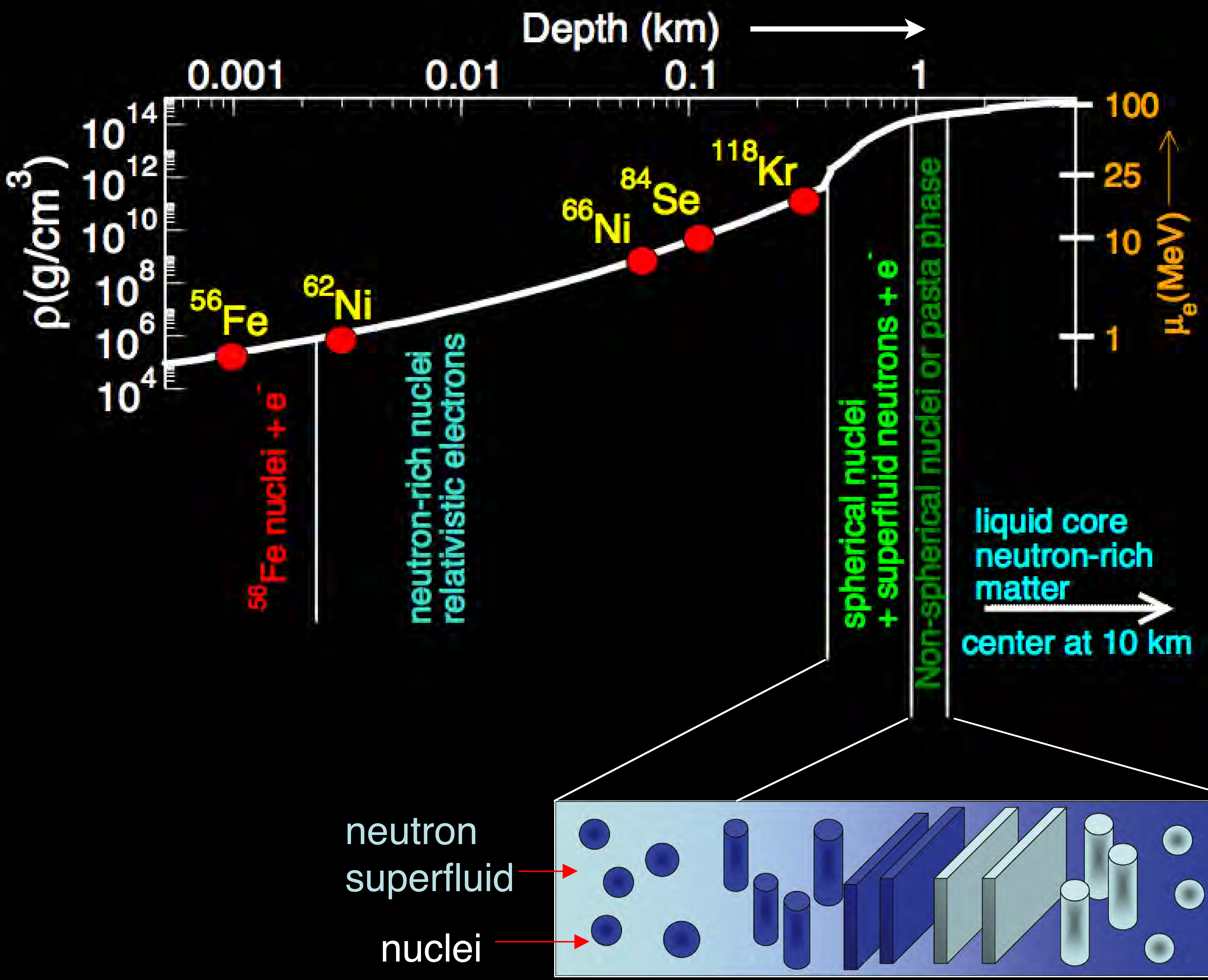
Daniel Kasen, Brian Metzger, Jennifer Barnes, Eliot Quataert & Enrico Ramirez-Ruiz

1. Merger ejected ~ 0.06 $M_\odot$ of radioactive nuclei
2. Radioactive ejecta had two components
3. One component with A>140 (heavy r-process)
4. Second component with A<140 (light r-process)
5. Mass of the A>140 component ~ 0.04 $M_\odot$
6. Mass of the A<140 component ~ 0.025 $M_\odot$

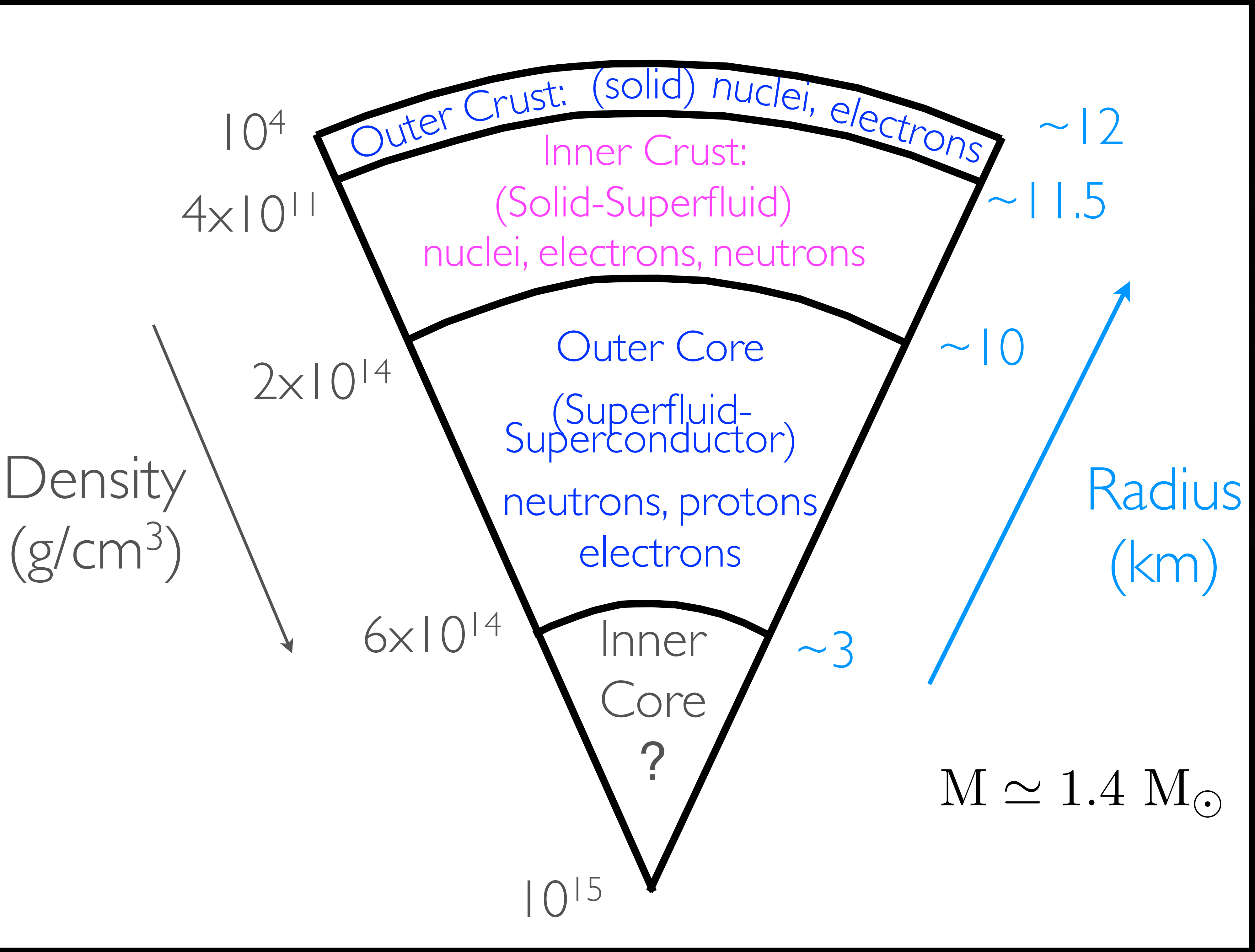


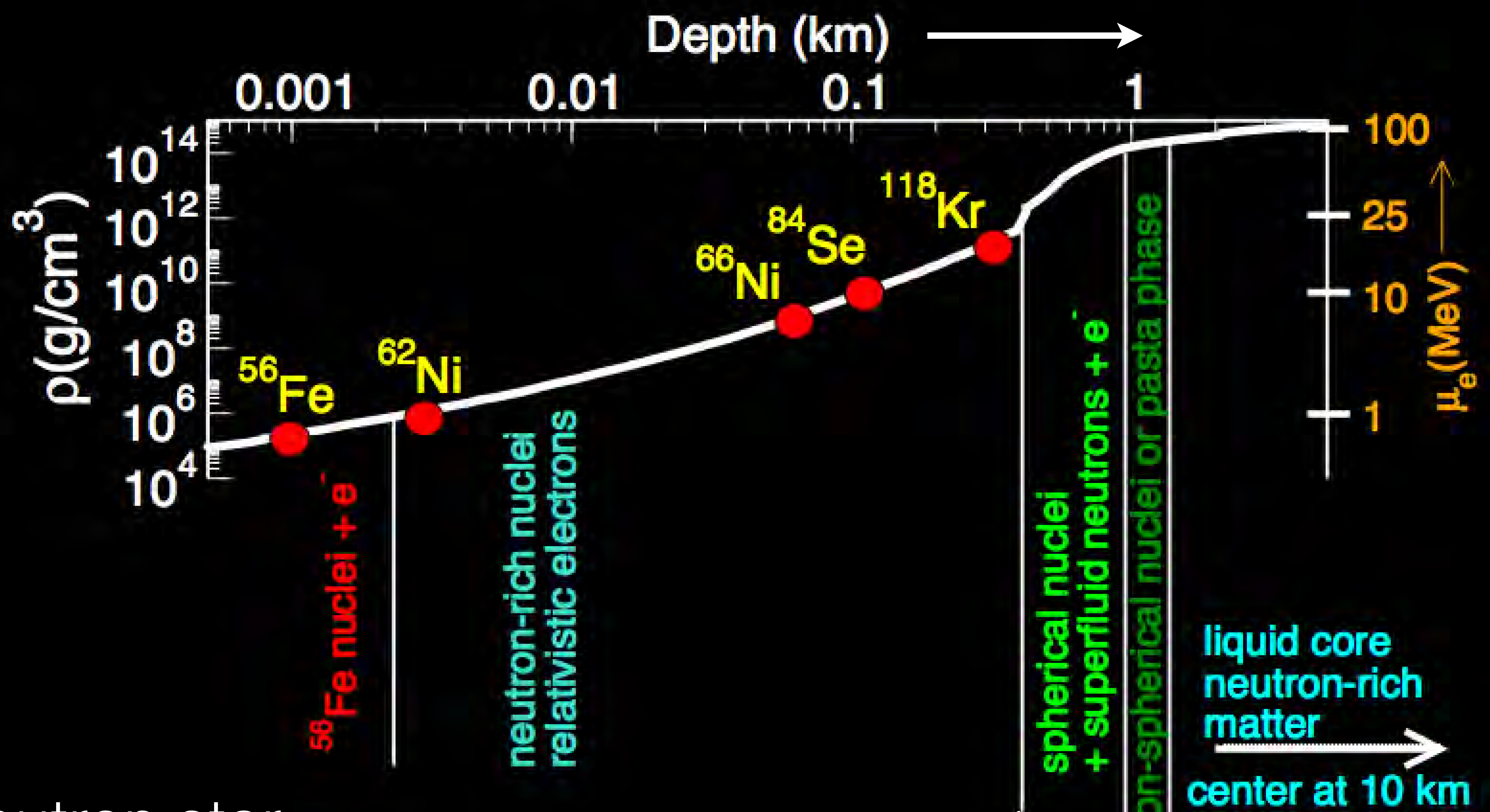
Blast Mining Neutron Stars

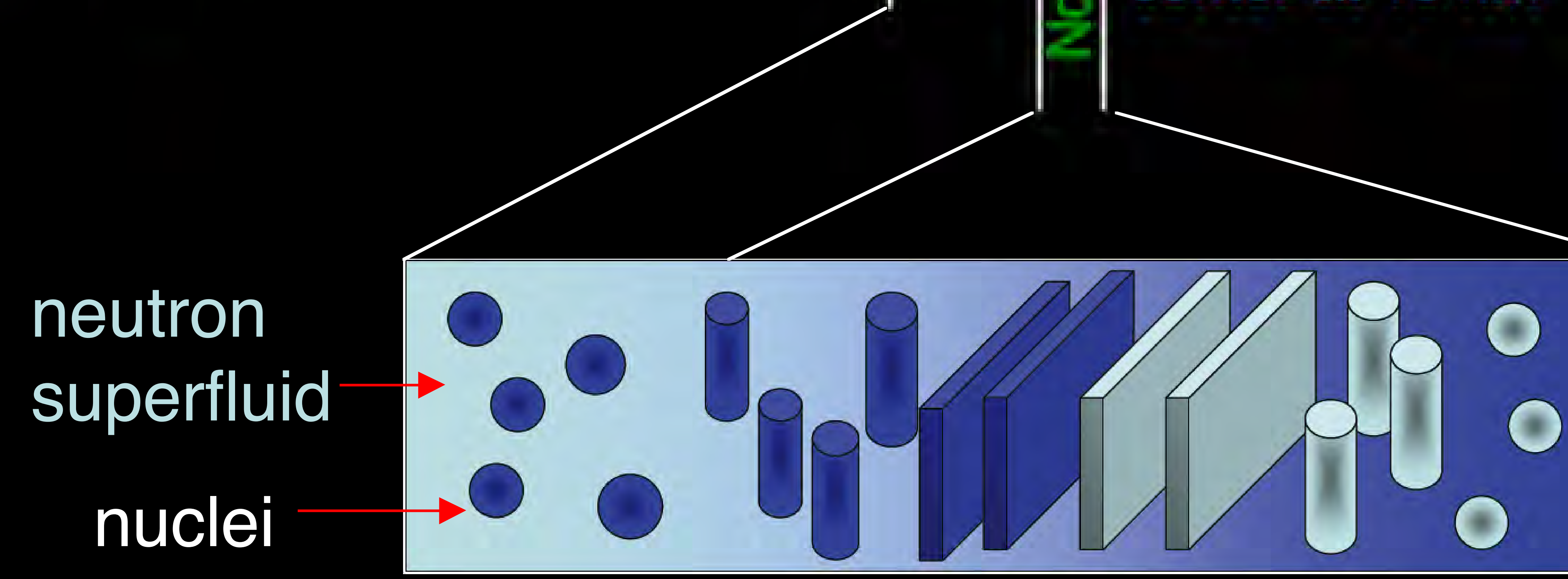




Blast Mining Neutron Stars







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

Ejection during the merger decompresses dense neutron-rich matter. $Y_p=Y_e$ ~ 0.05-0.1

Nucleosynthesis

As dense neutron rich matter rapidly decompresses, some iron-peak nuclei form on a strong interaction timescale (instantly).

These seed nuclei capture the extra neutrons until they reach the neutron-drip line. A sequence of (slower) beta-decays and neutron captures synthesize heavier elements.

The reaction pathways are complex and depend on nuclear structure and reactions on nuclei far from stability. [motivated large experimental [FRIB] and theoretical effort in low-energy nuclear physics]

The qualitative features of the final abundances are most sensitive to the initial neutron excess.

Neutron excess is moderated by weak interactions

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

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

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

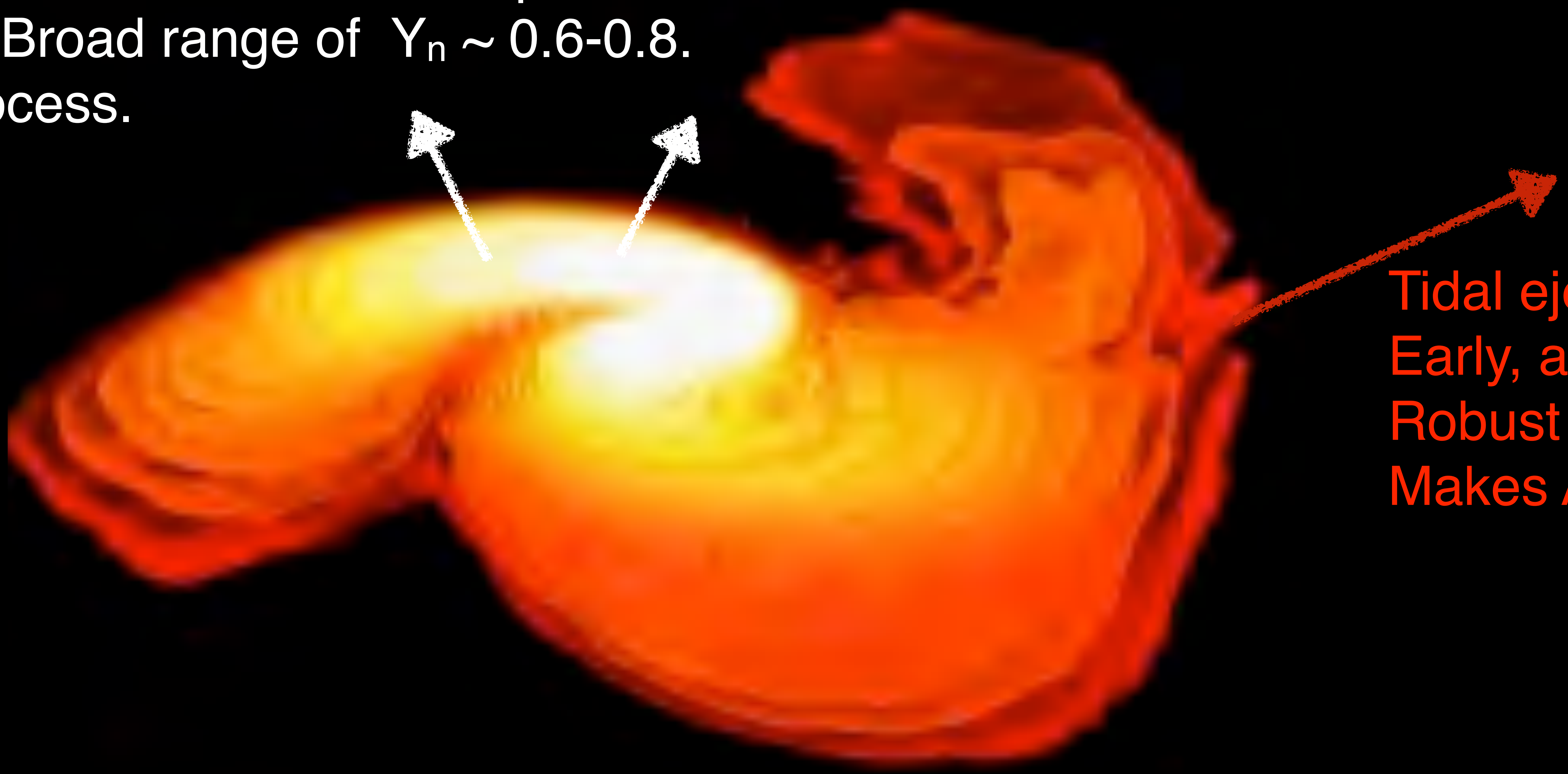
High temperatures created in dense shocked matter produces positrons. They would also deplete neutrons

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

Roberts and Reddy (2012, 2016)

Merger Ejecta

Shock and neutrino wind driven ejecta:
Processed by neutrinos, much like in a supernova.
Not as neutron rich. Broad range of $Y_n \sim 0.6\text{-}0.8$.
Makes the light r-process.



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
- Magnetic fields generated during the merger.

Typical mass ejected is between 0.01-0.05 $M_\odot$.

Heavy nuclei dominate opacity

Kasen 2013   Metzger et al. 2010

Atomic structure matters. Detailed opacities have now been done included in transport calculations.

- Iron group elements part made when $Y_e > 0.25$ have an opacity

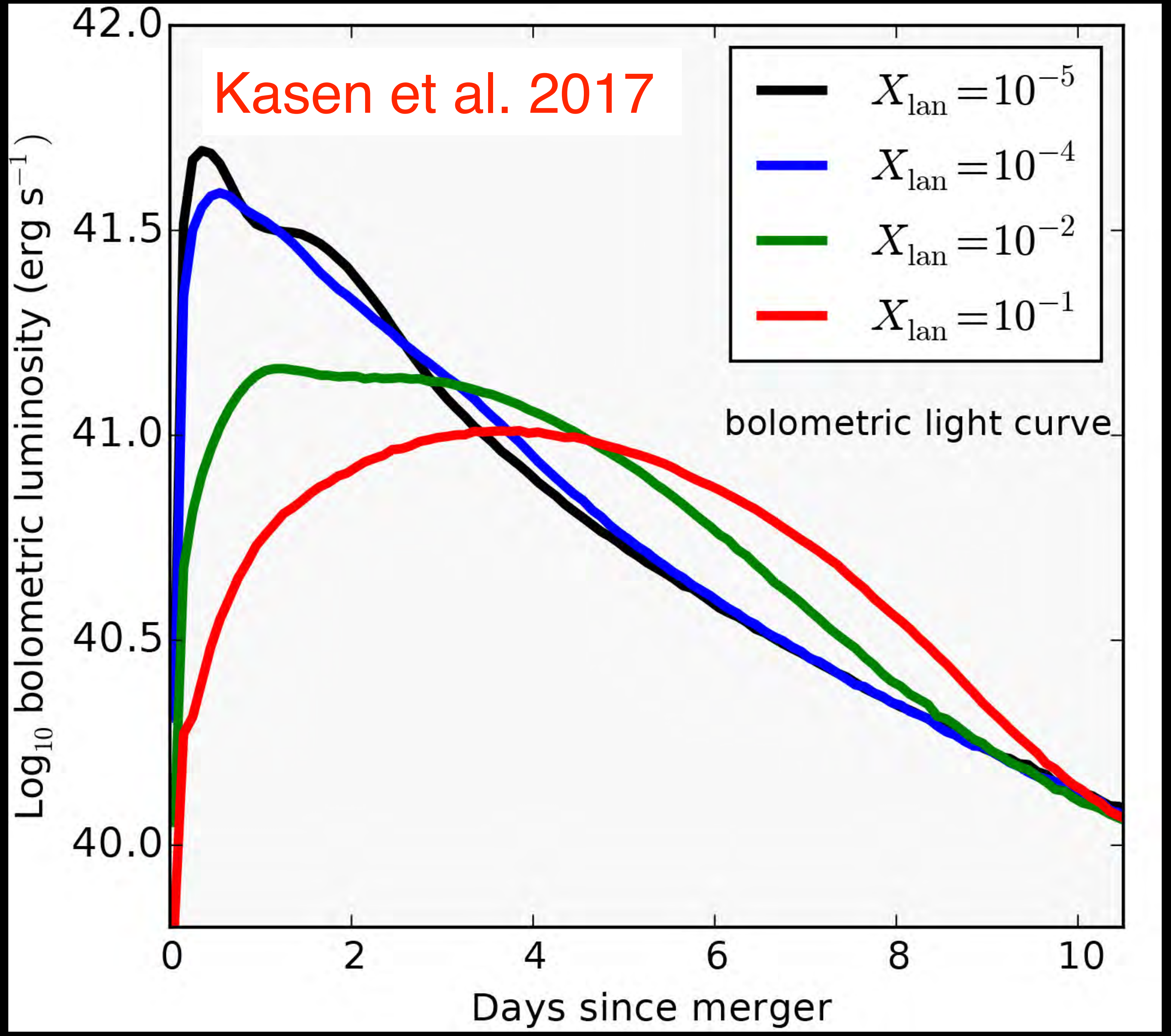
$$\kappa_{\text{Fe-like}} \sim 1 \text{ cm}^2/\text{g}$$

(d-shell electrons contribute to transitions)

- Heavy r-process with lanthanides is made for $Y_e < 0.2$ 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)



Conclusions and Outlook

- NSs merge and emit GWs. The detection rate is likely to be greater than a few per year.
- Connection between EM signals (especially the Kilonova) and GWs will rely on our understanding of dense matter, neutrino physics, nuclear structure and reactions.
- EOS, weak interactions and transport at extreme density are critical to model mergers and interpret observations.
- Details worth pursuing with multi-physics merger simulations. Multi-messenger astronomy is here had has much to reveal.