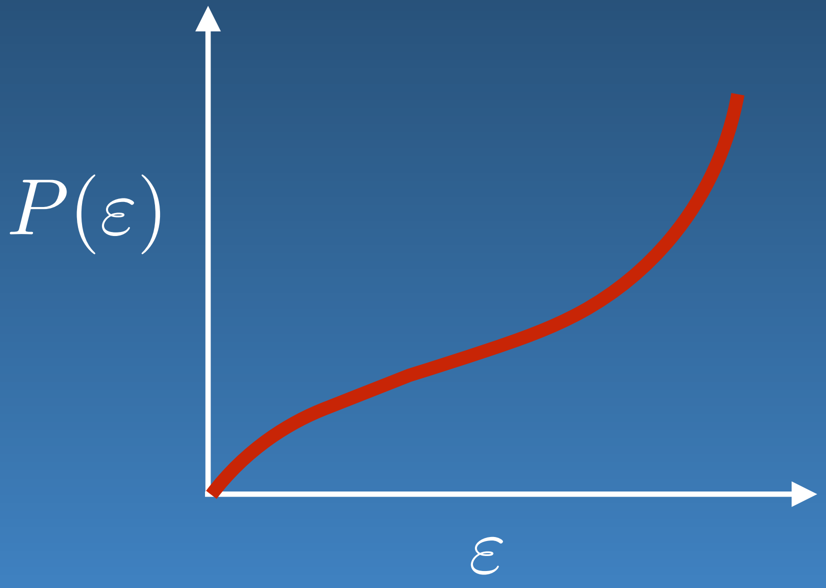
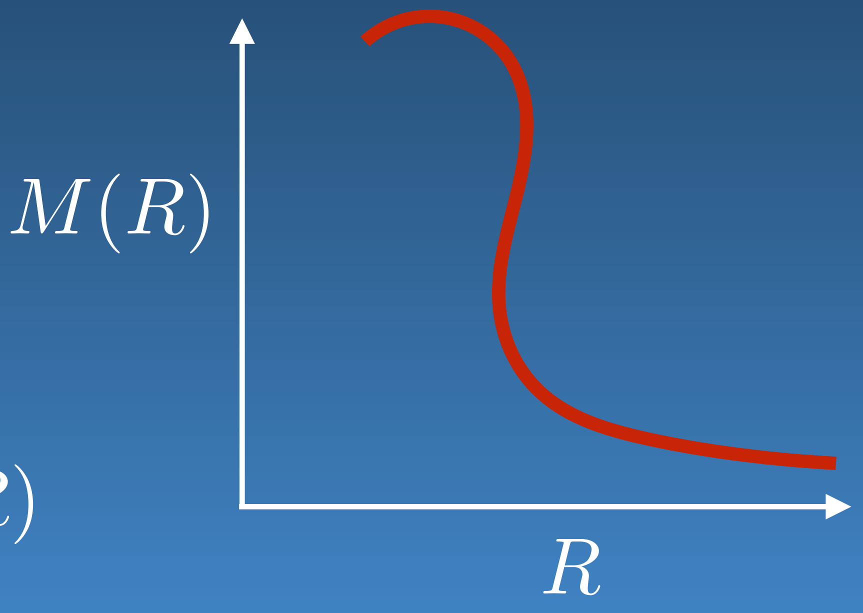
Astrophysical constraints on the high density EOS: Current status and near term prospects.

Sanjay Reddy
Univ. of Washington, Seattle.



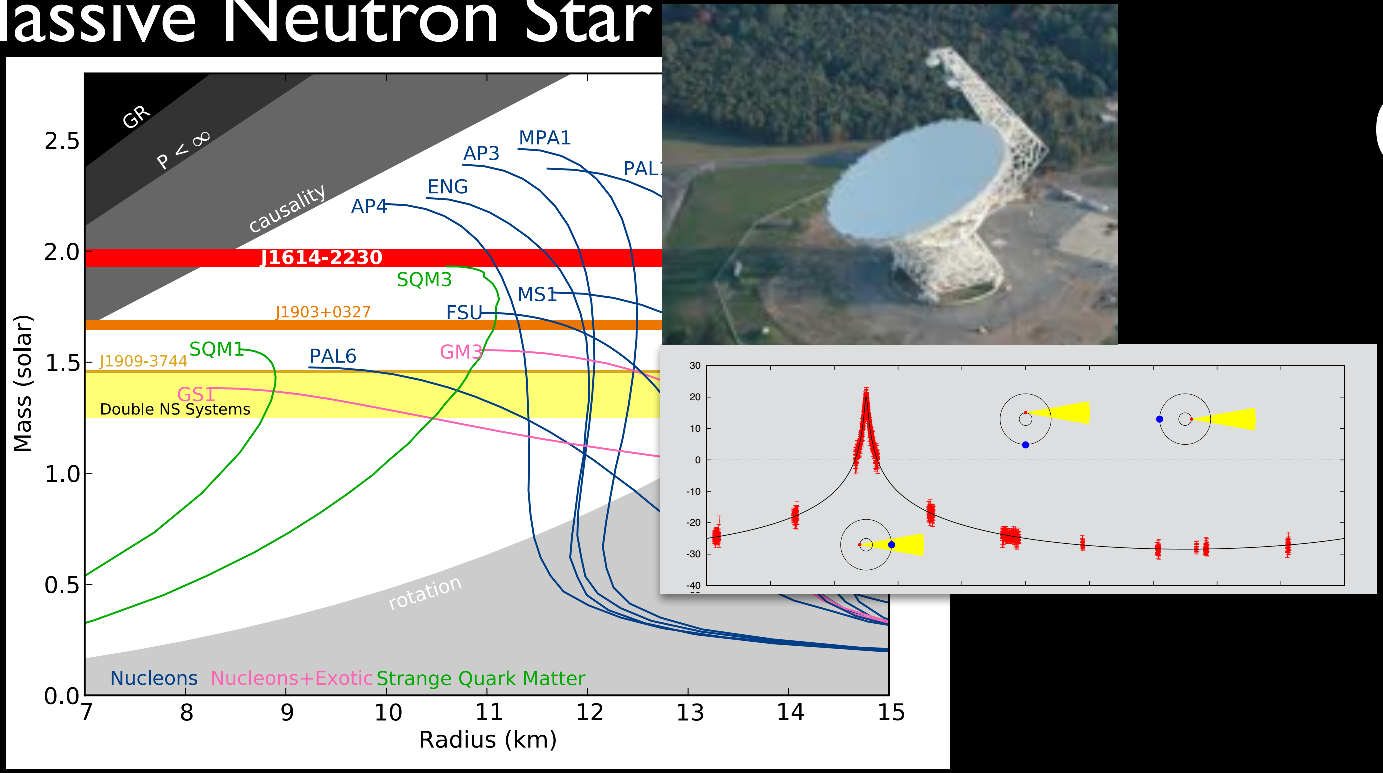
$$P(\varepsilon) + \mathrm{Gen.Rel.} = M(R)$$



INSTITUTE for
NUCLEAR THEORY

Recent Observations

Massive Neutron Star



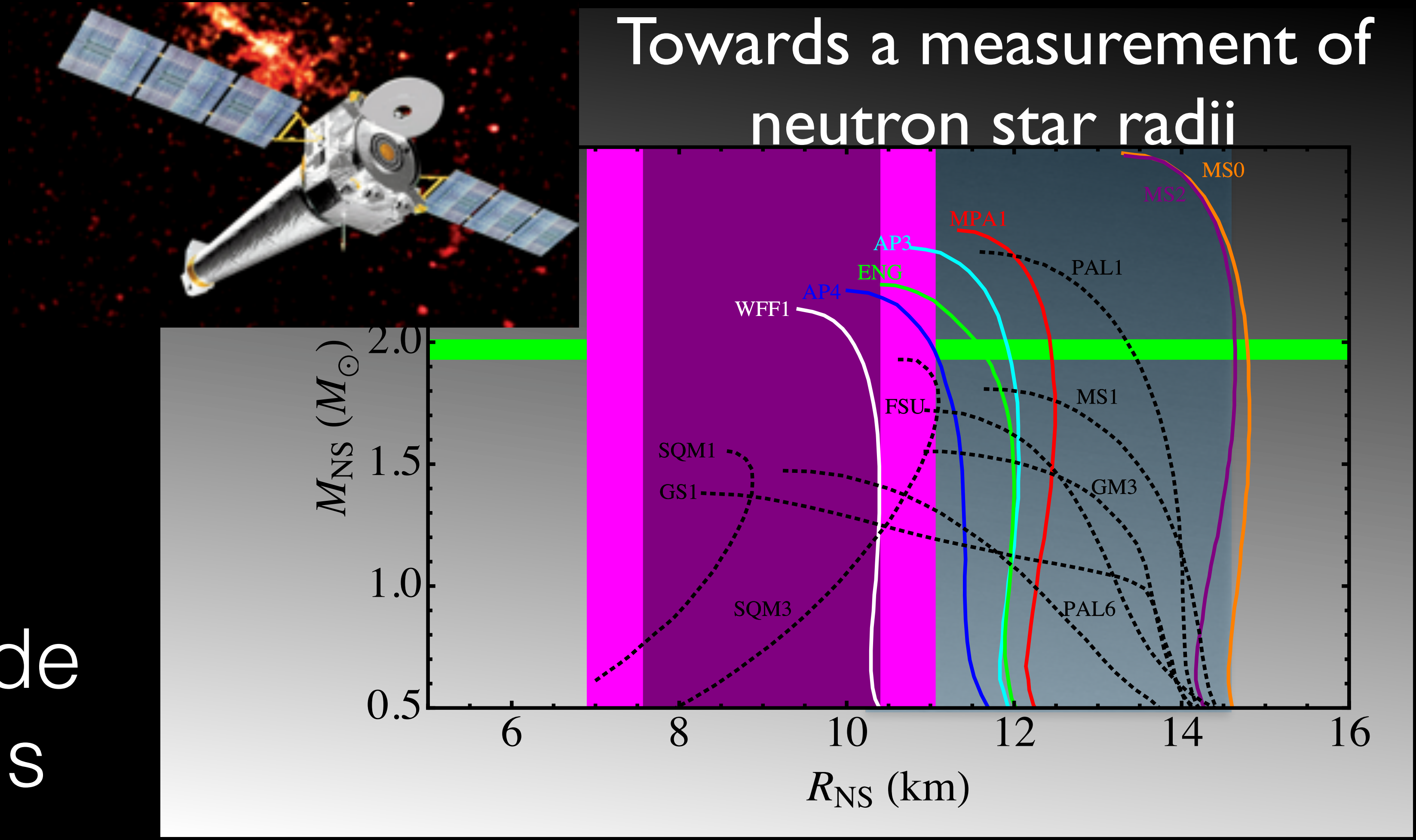
Convincing evidence for

$$M_{\rm NS}^{\rm max} > 2\,M_\odot$$

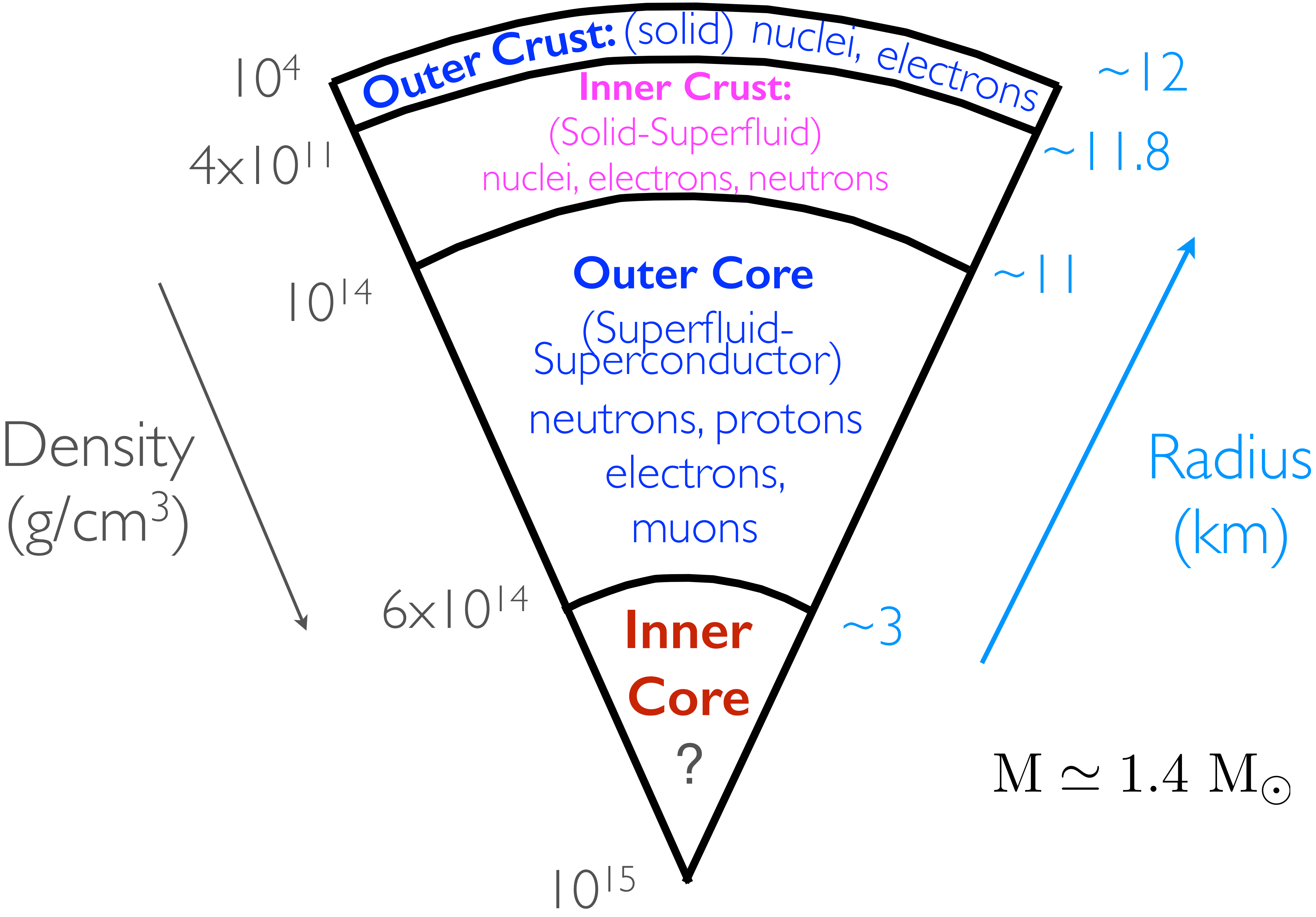
Hints that NS radii are small

$R < 13$ km

Systematic errors preclude drawing firm conclusions


Towards a measurement of neutron star radii

Phases of Dense Matter in Neutron Stars



Outer Crust: (solid) *nuclei, electrons*

Inner Crust:

(Solid-Superfluid)

nuclei, electrons, neutrons

Outer Core

(Superfluid-Superconductor)

neutrons, protons

electrons,

muons

Inner Core

?

Density (g/cm^3)

10^4

$4x10^{11}$

10^{14}

$6x10^{14}$

10^{15}

Radius (km)

~12

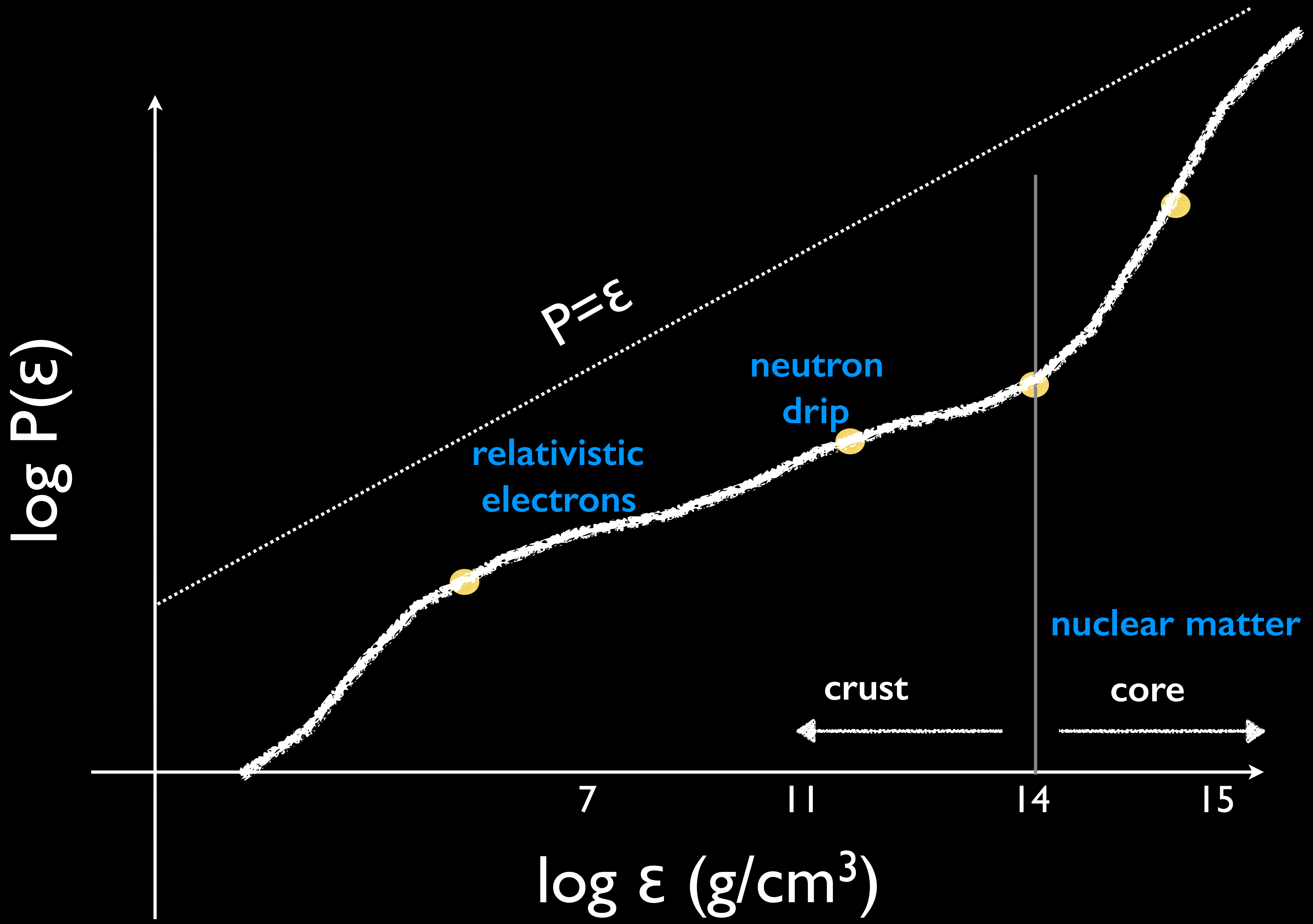
~11.8

~11

~3

$M \simeq 1.4 \ M_\odot$

Pressure v/s Energy Density (EoS)



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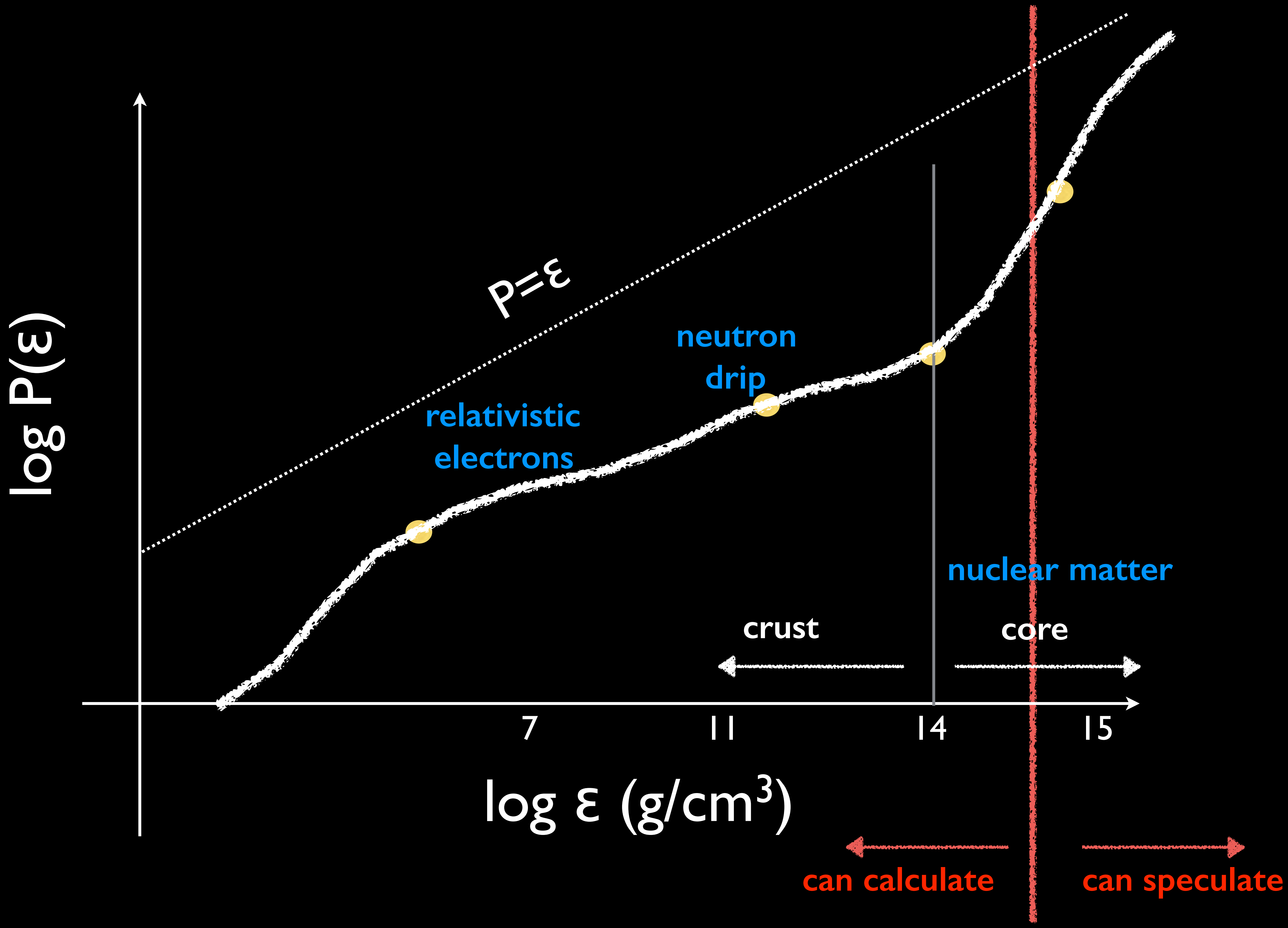

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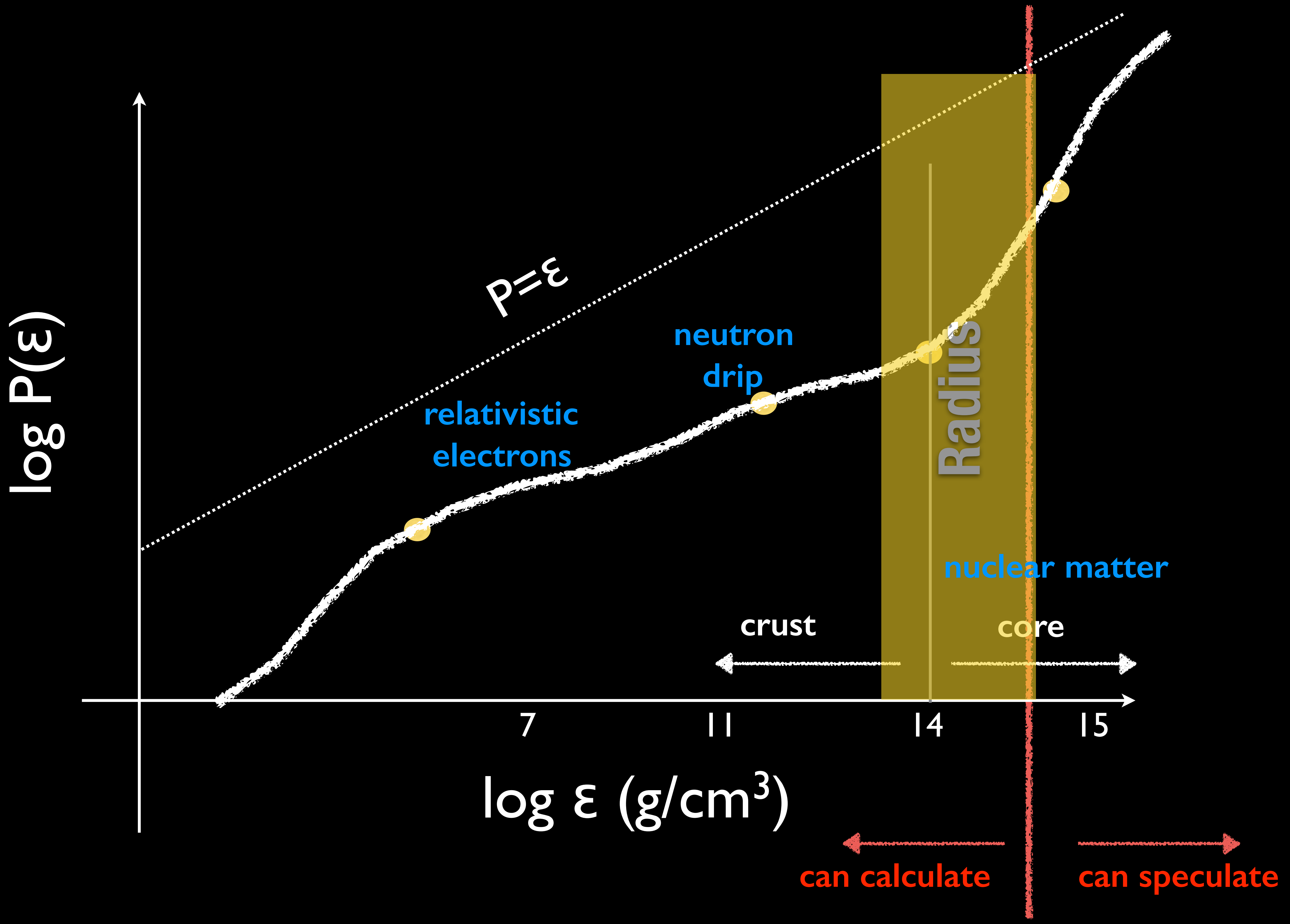

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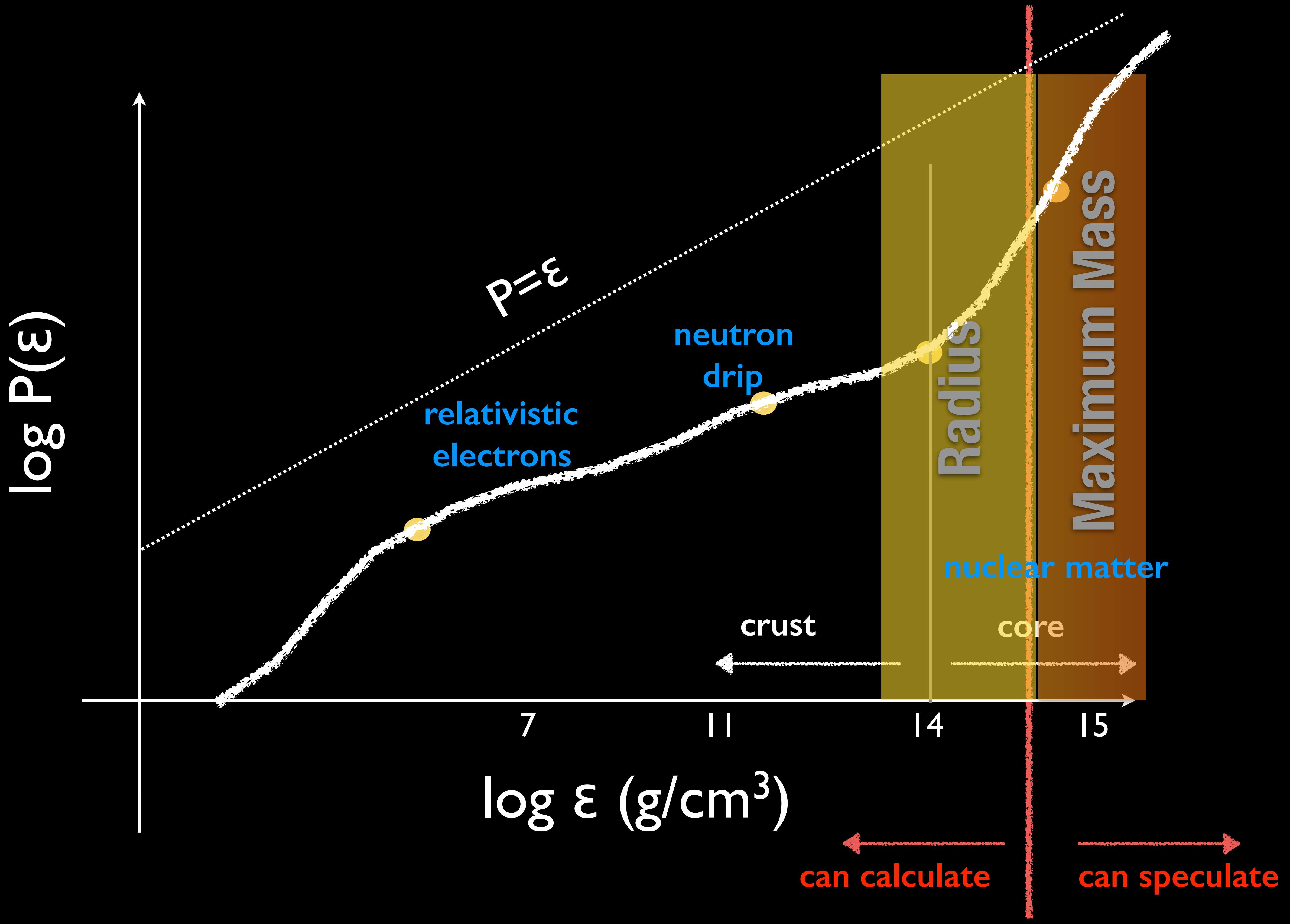

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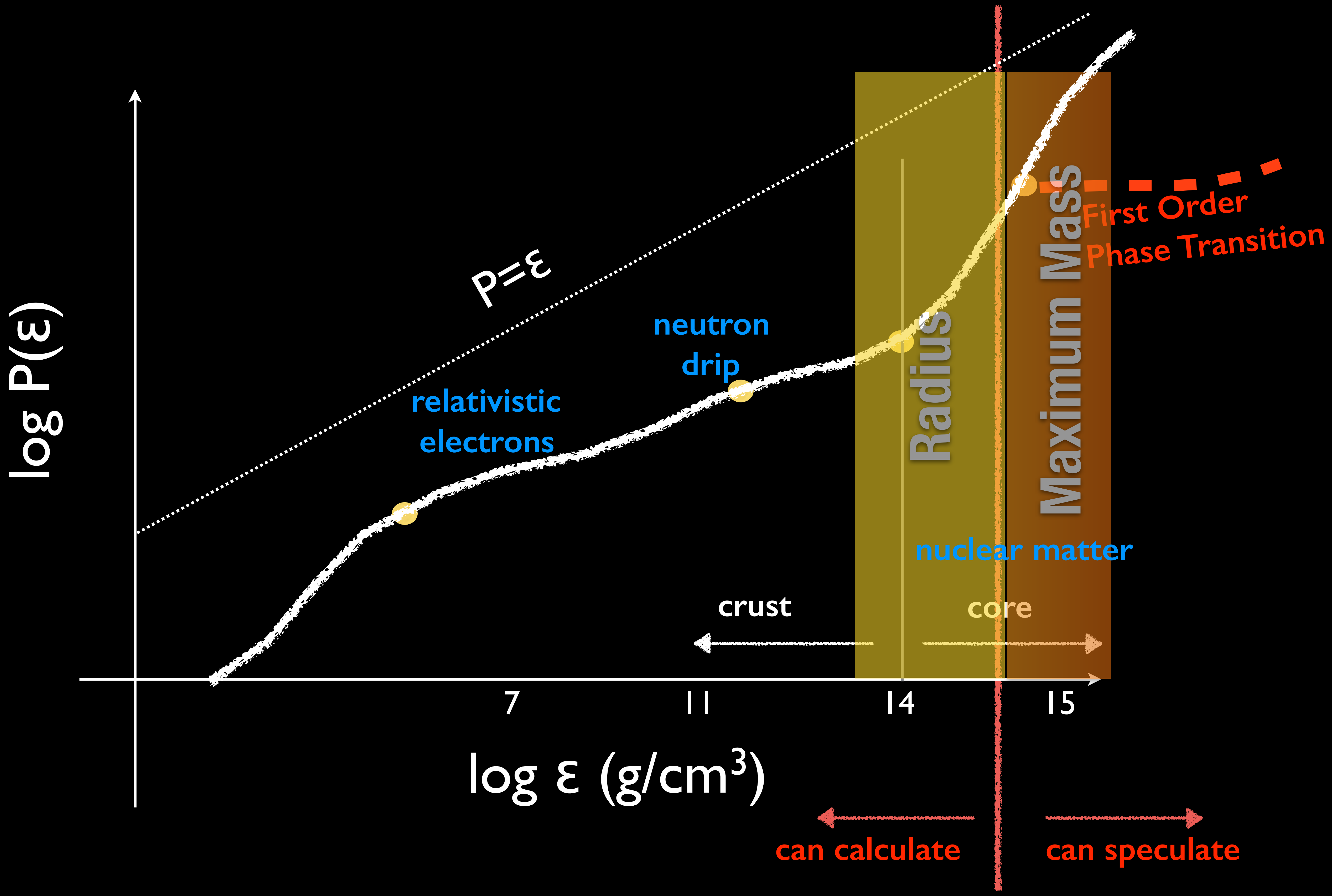

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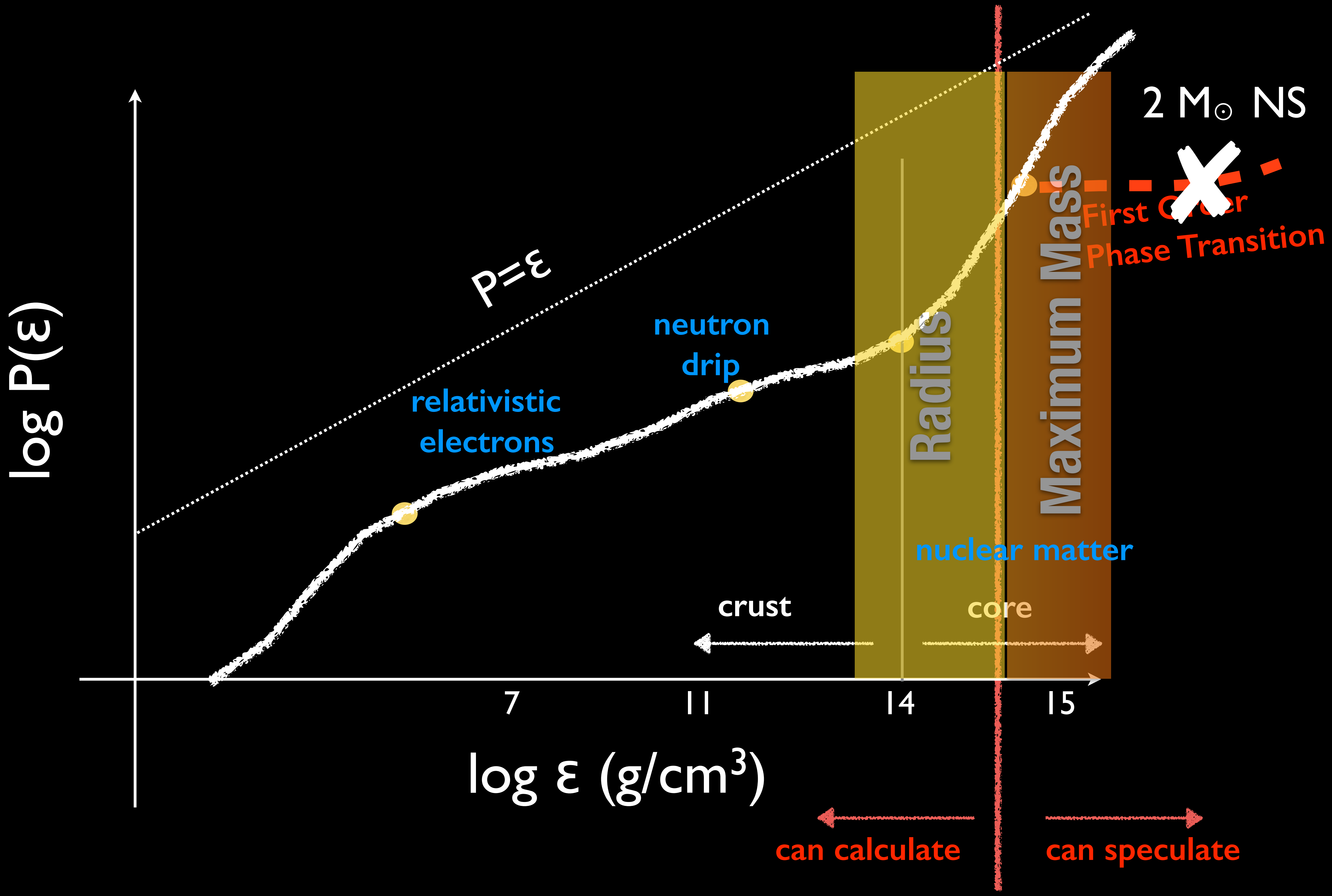

Nuclear Many Body Theory

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

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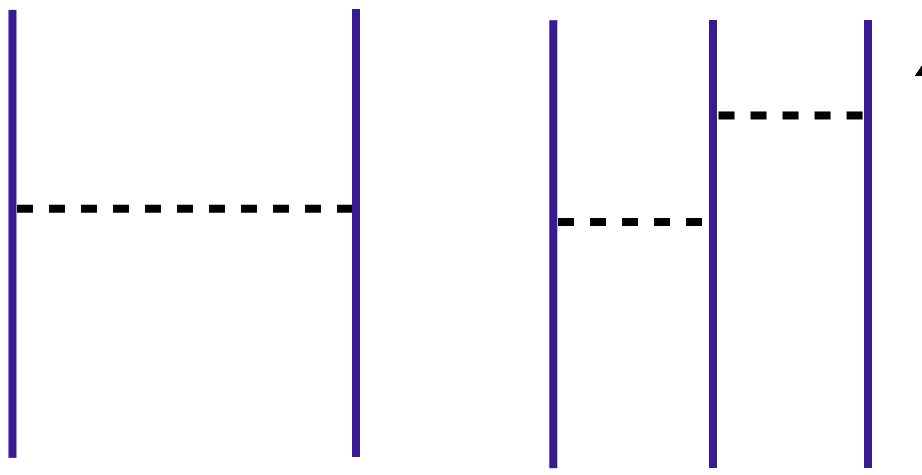

two-body nucleon-nucleon potential is well constrained by scattering data.

Nuclear Many Body Theory

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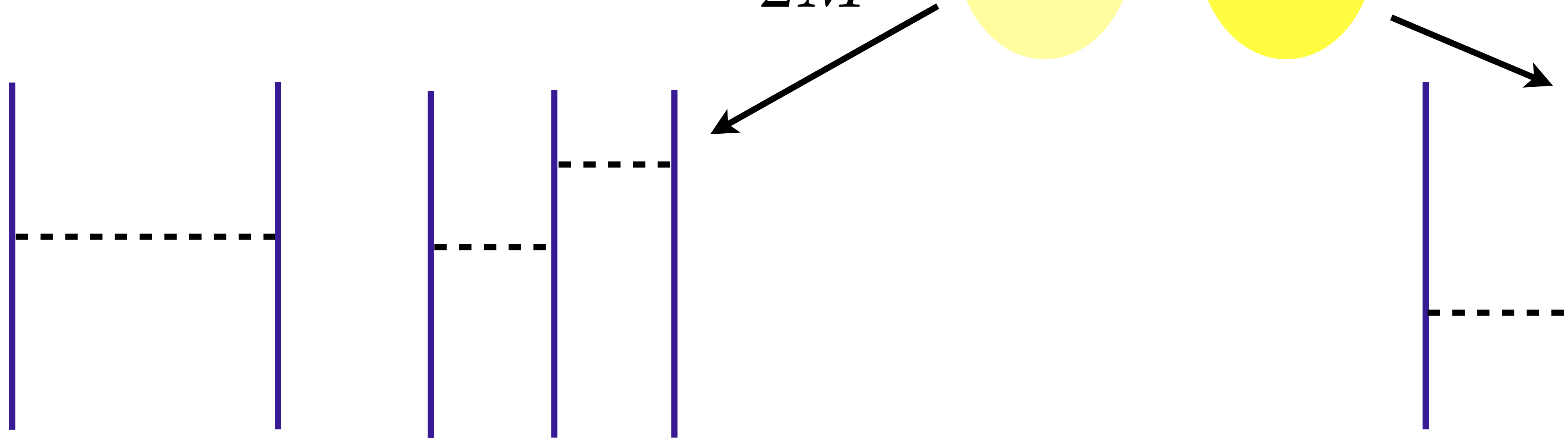

two-body nucleon-nucleon potential is well constrained by scattering data.

three-neutron potential is not well constrained by nuclear data.

Nuclear Many Body Theory

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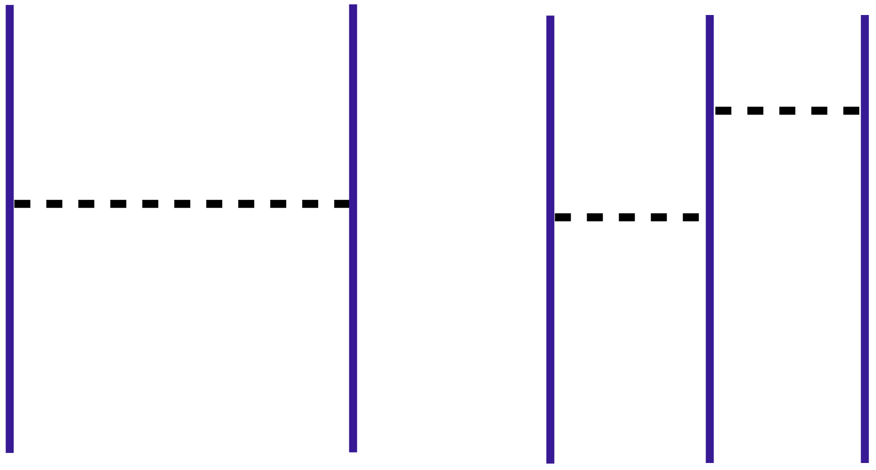

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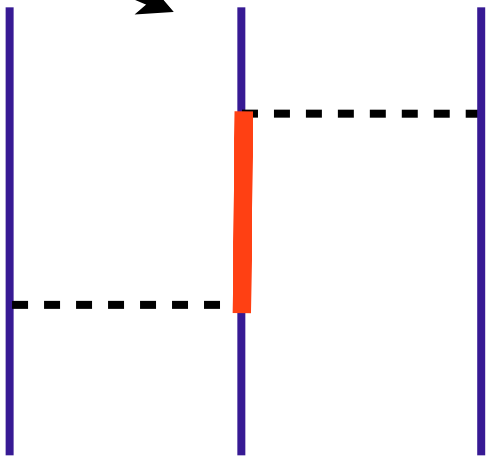


three-neutron potential is not well constrained by nuclear data.

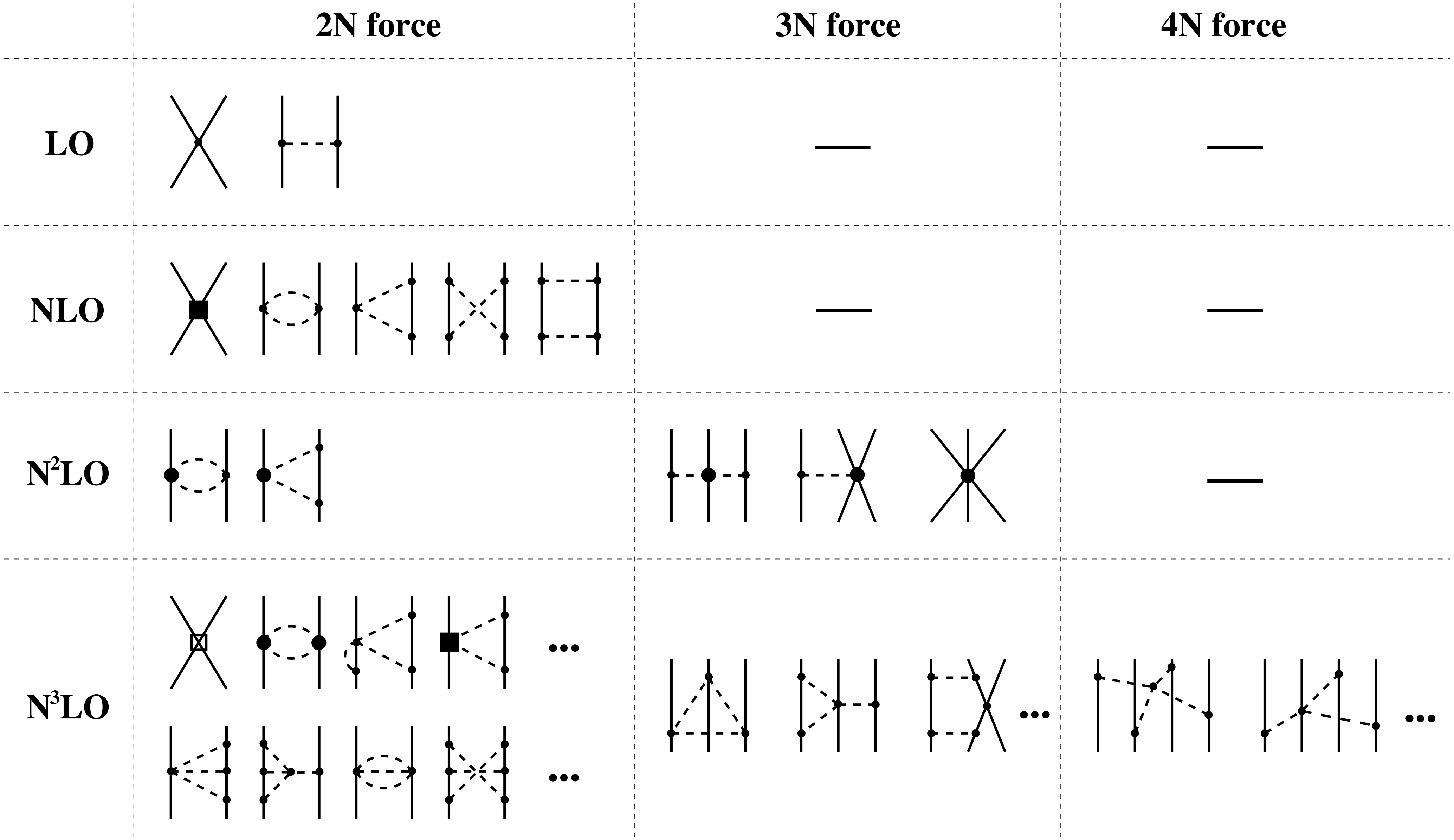
Quantum Many-Body Theory:

Quantum Monte Carlo

$$E(\rho_n, \rho_p)$$: Energy per particle

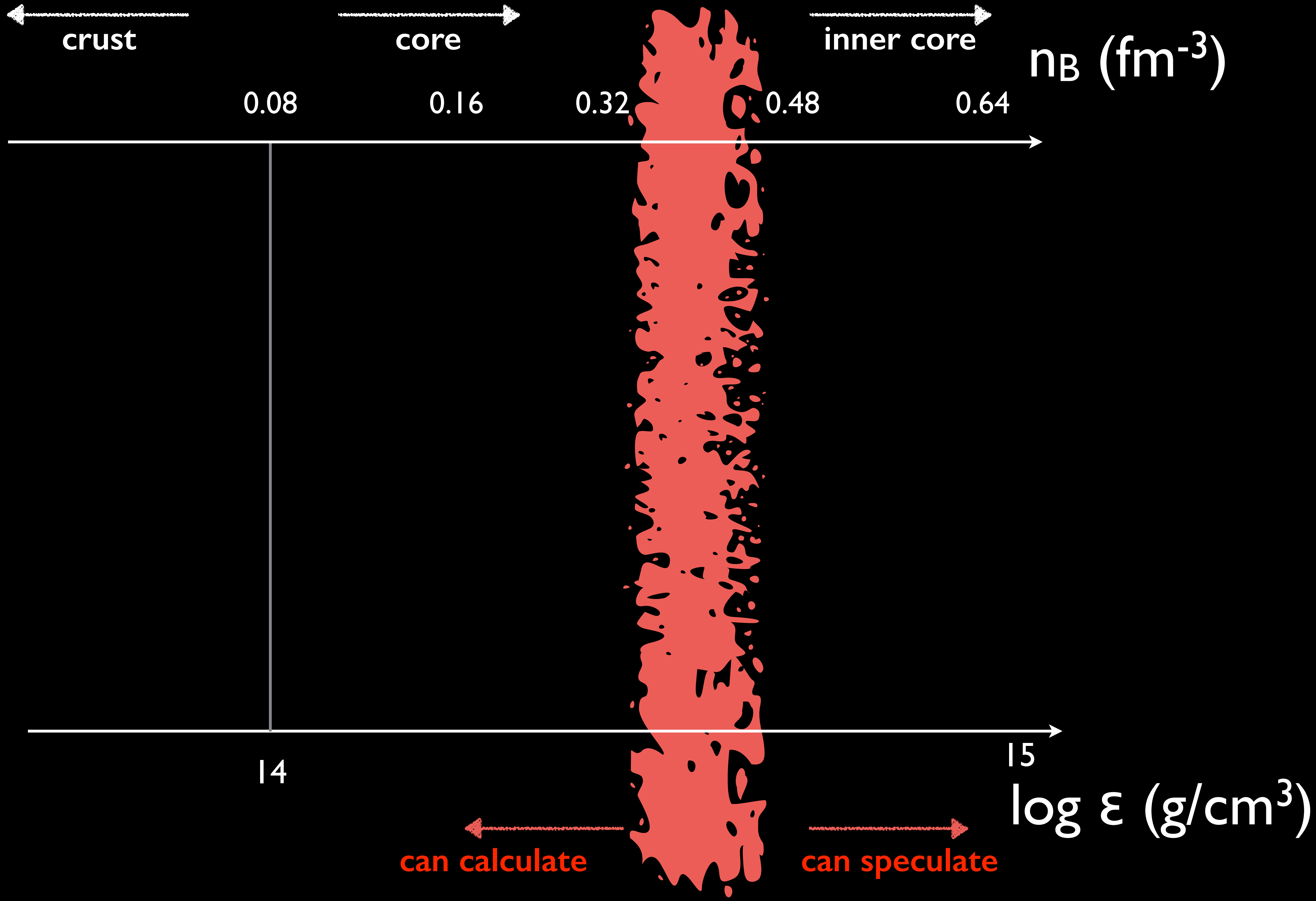
Effective Field Theory: Chiral NN & NNN Forces

Organizes the nuclear Hamiltonian in powers of the momentum exchange: $\dfrac{Q}{\Lambda_B}$



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

EFT and Phenomenological Models



crust

core

inner core

n_B (fm^{-3})

0.08 0.16 0.32 0.48 0.64

14

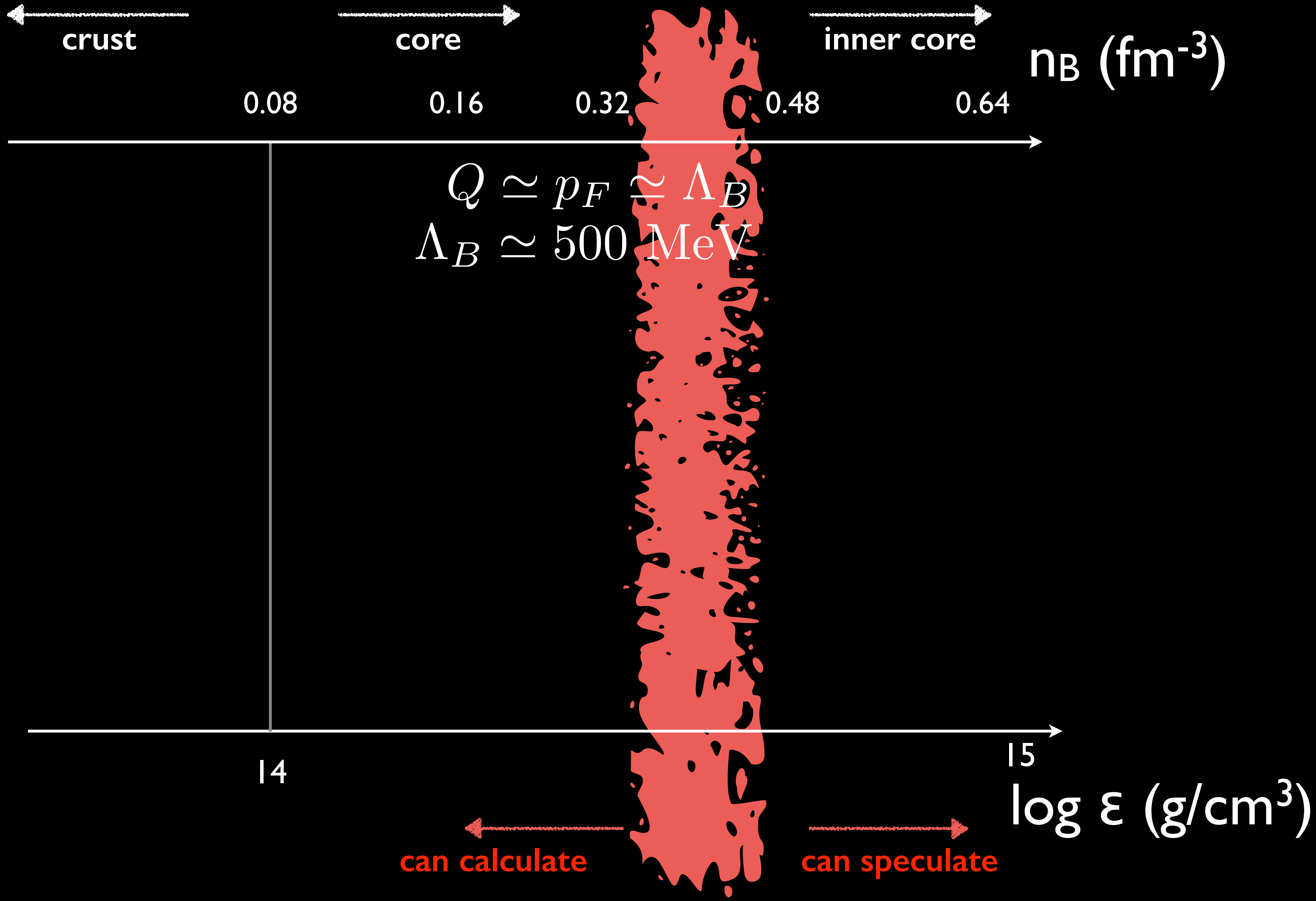
15

log ε (g/cm^3)

can calculate

can speculate

EFT and Phenomenological Models



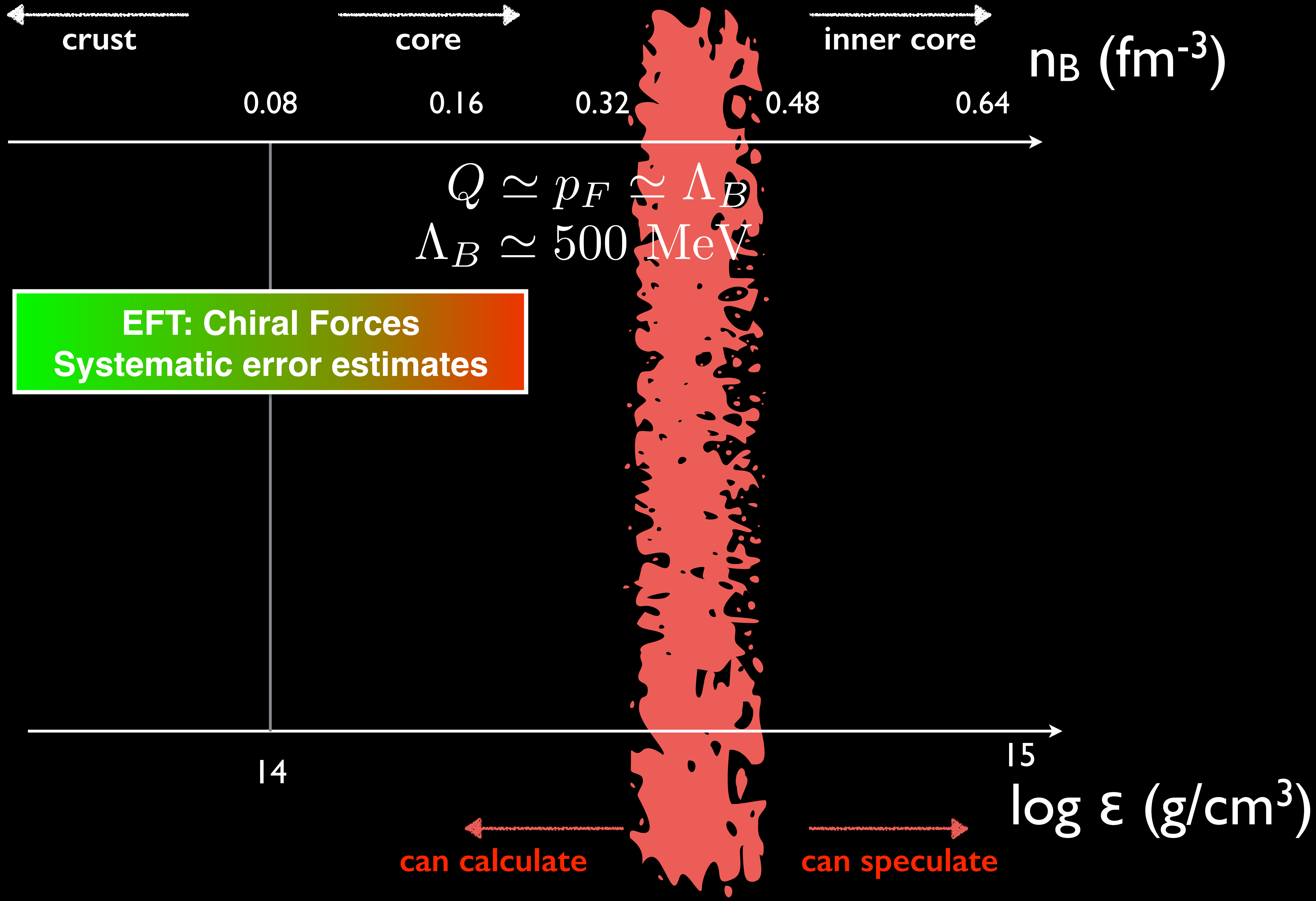
$$Q \simeq p_F \simeq \Lambda_B$$

$$\Lambda_B \simeq 500 \text{ MeV}$$

can calculate

can speculate

EFT and Phenomenological Models



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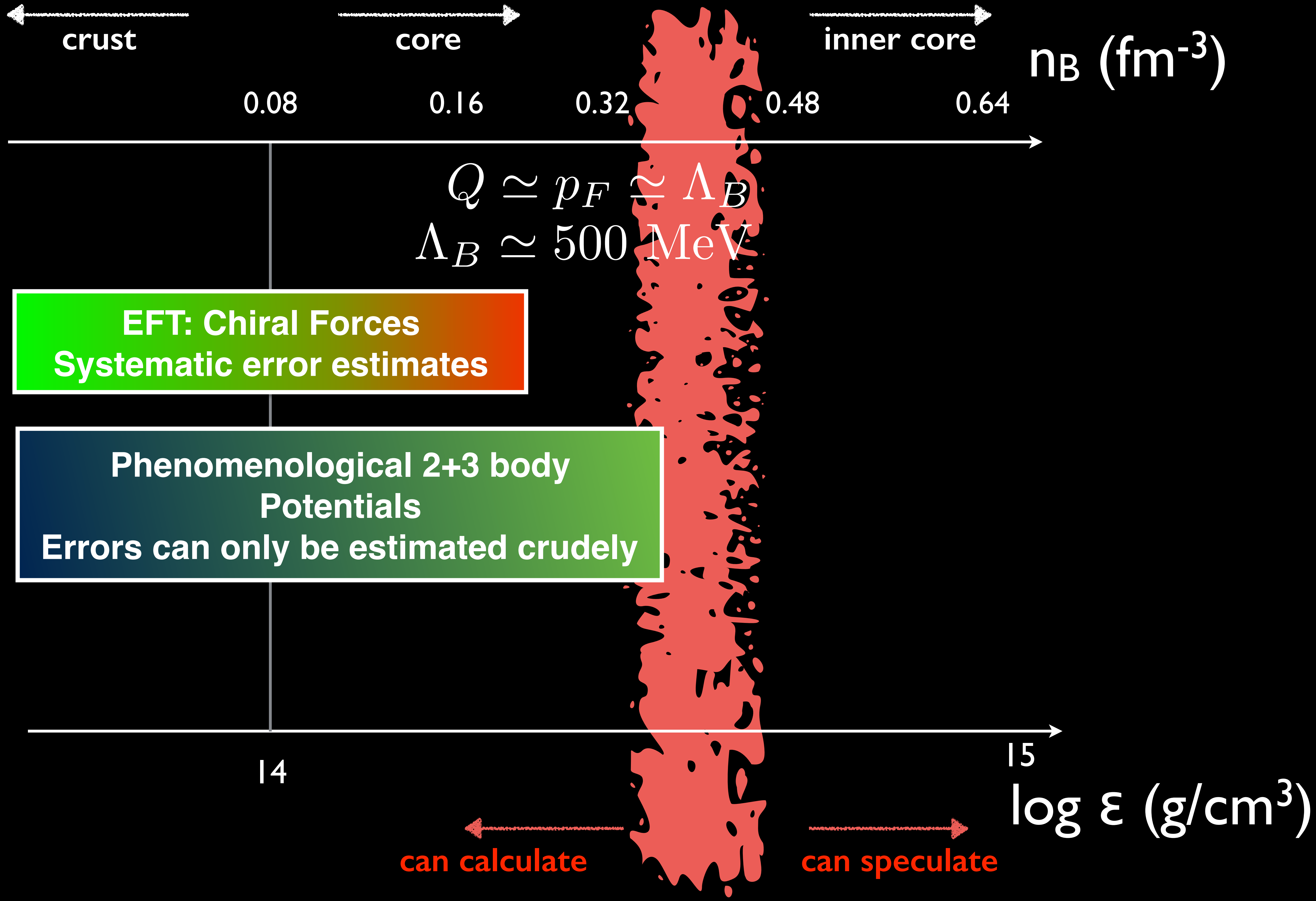
EFT: Chiral Forces
Systematic error estimates

can calculate

can speculate

EFT and Phenomenological Models



$$Q \simeq p_F \simeq \Lambda_B$$
$$\Lambda_B \simeq 500\ \mathrm{MeV}$$

EFT: Chiral Forces
Systematic error estimates

Phenomenological 2+3 body Potentials
Errors can only be estimated crudely

can calculate

can speculate

Equation of State of Neutron Matter

$$\epsilon(n) = n\ (M_n + E_n(n)) \qquad P(\epsilon) = n^2\ \frac{\partial E_n(n)}{\partial n}$$

Predictions of microscopic theories:

Energy per baryon: $$E_n(\rho) = a\ \left(\frac{n}{n_0}\right)^{\alpha} + b\ \left(\frac{n}{n_0}\right)^{\beta}$$

(Parameterization suggested by Gandolfi, 2009)

$a = 12 \pm 1\ \mathrm{MeV}$ $\quad \alpha = 0.45 \pm 0.05$ → 2-body interactions

$b = 4 \pm 2\ \mathrm{MeV}$ $\quad \beta = 2.3 \pm 0.3$ → 2 & 3-body interactions

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),

Neutron Matter Constraints from Nuclear Experiment

Near nuclear density $$E_n(n \approx n_0) = -16\ \mathrm{MeV} + S + \frac{L}{3}\left(\frac{n-n_0}{n_0}\right)$$

where
$$S = a + b + 16\ \mathrm{MeV}$$
$$L = 3(a\alpha + b\beta)$$

Nuclear measurements correlate S & L:

nuclear masses

neutron skin

dipole polarizability

giant-dipole resonances

heavy-ion phenomenology

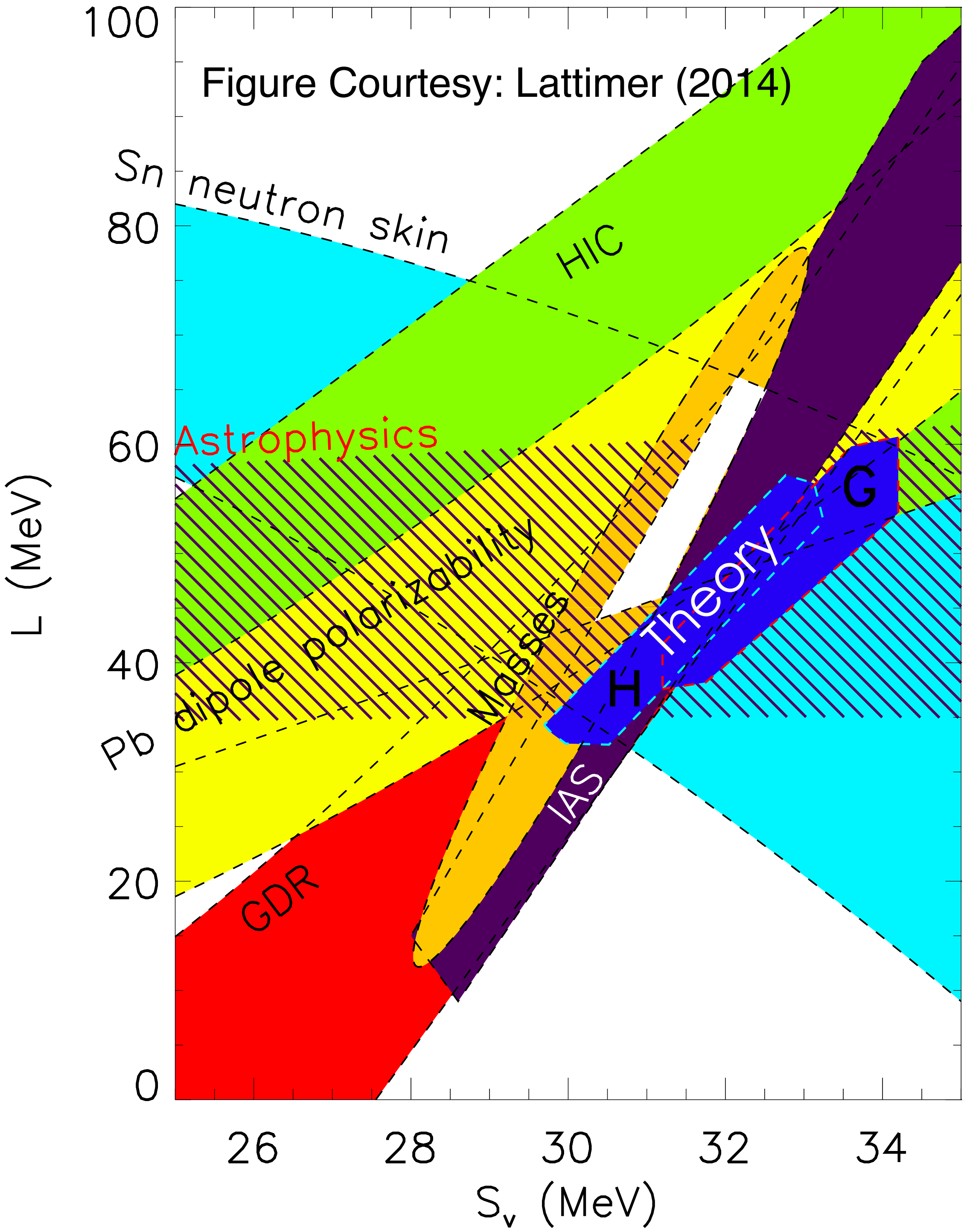


Figure Courtesy: Lattimer (2014)

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Near nuclear density $$E_n(n \approx n_0) = -16 \text{ MeV} + S + \frac{L}{3}\left(\frac{n - n_0}{n_0}\right)$$

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Nuclear measurements correlate S & L:

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Neutron Star radius is sensitive to L.

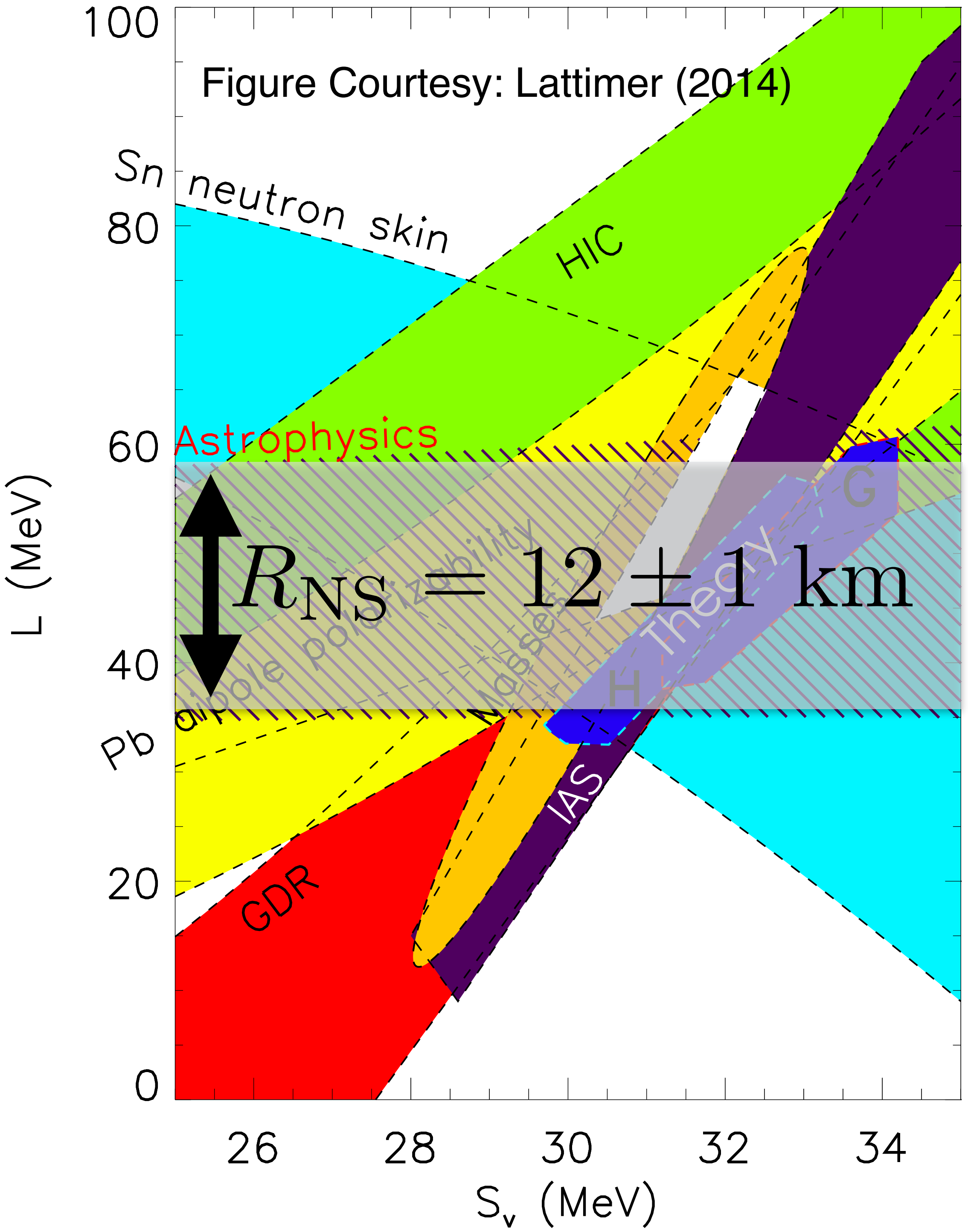
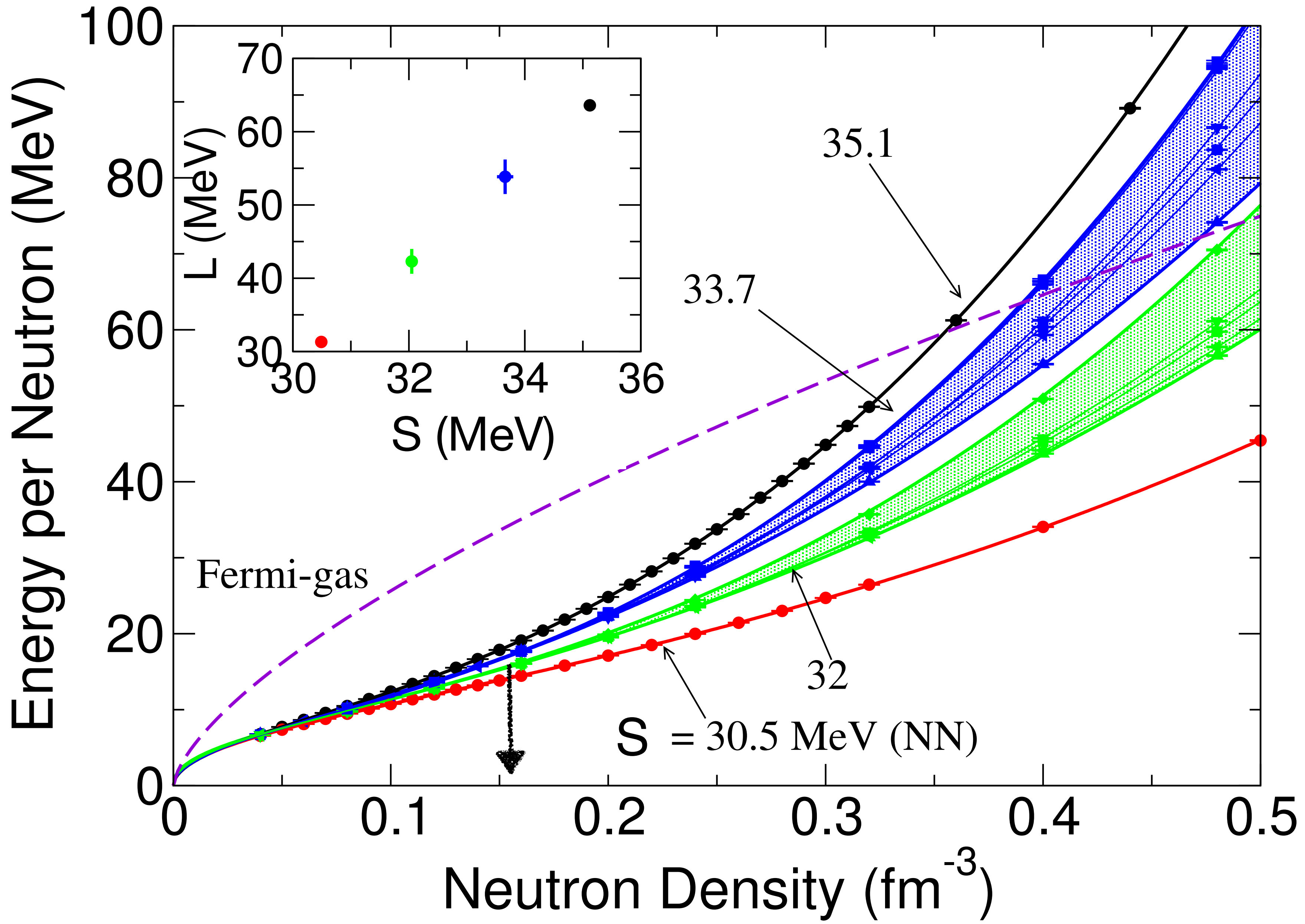


Figure Courtesy: Lattimer (2014)

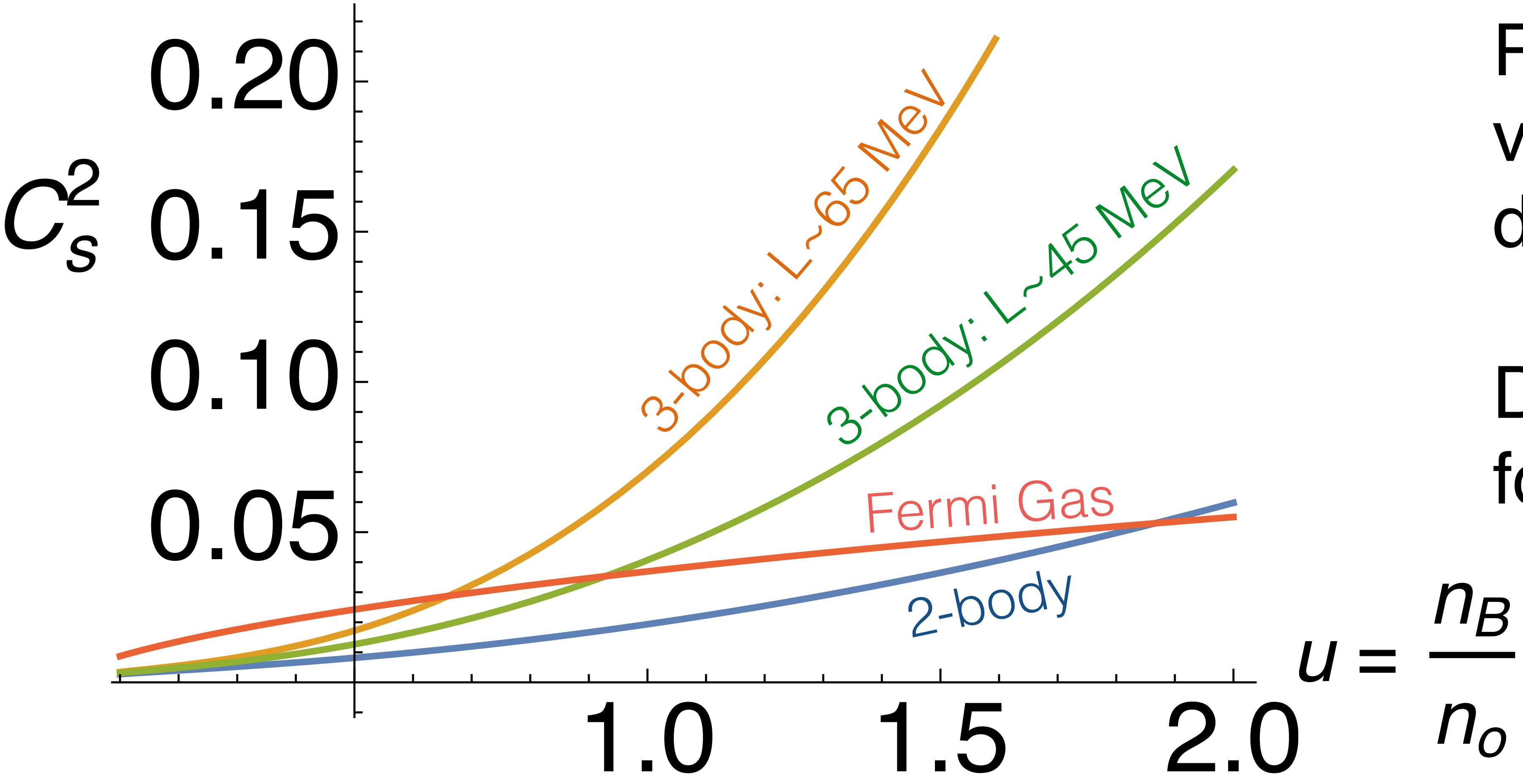
EoS with Phenomenological Potentials



An attempt at estimating extrapolation errors in phenomenological models - constrained variations of three-body forces.

Gandolfi, Carlson, Reddy (2012)

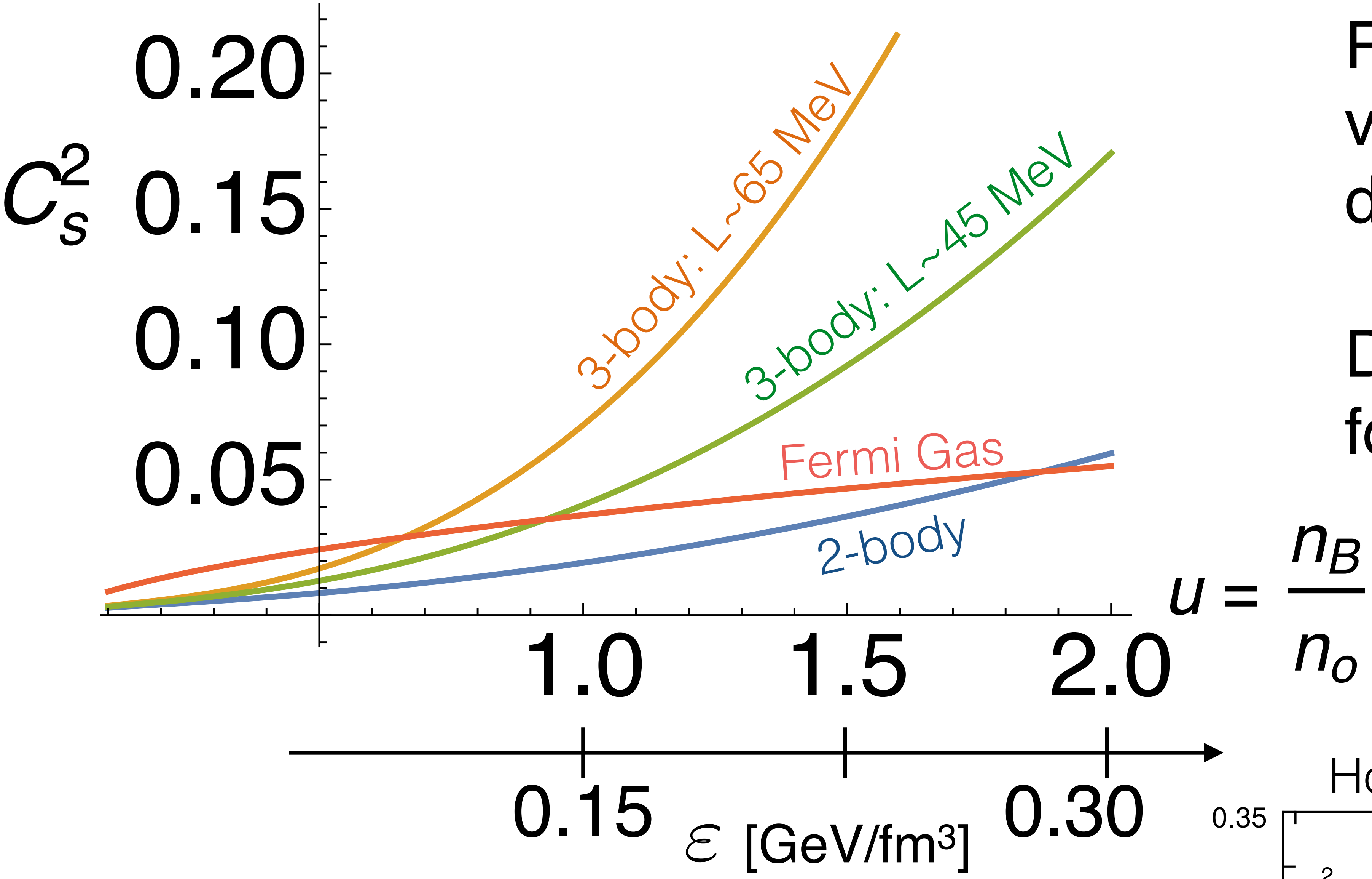
Speed of Sound



Rapid increase in the vicinity of nuclear density.

Driven by three-body forces and frustration.

Speed of Sound

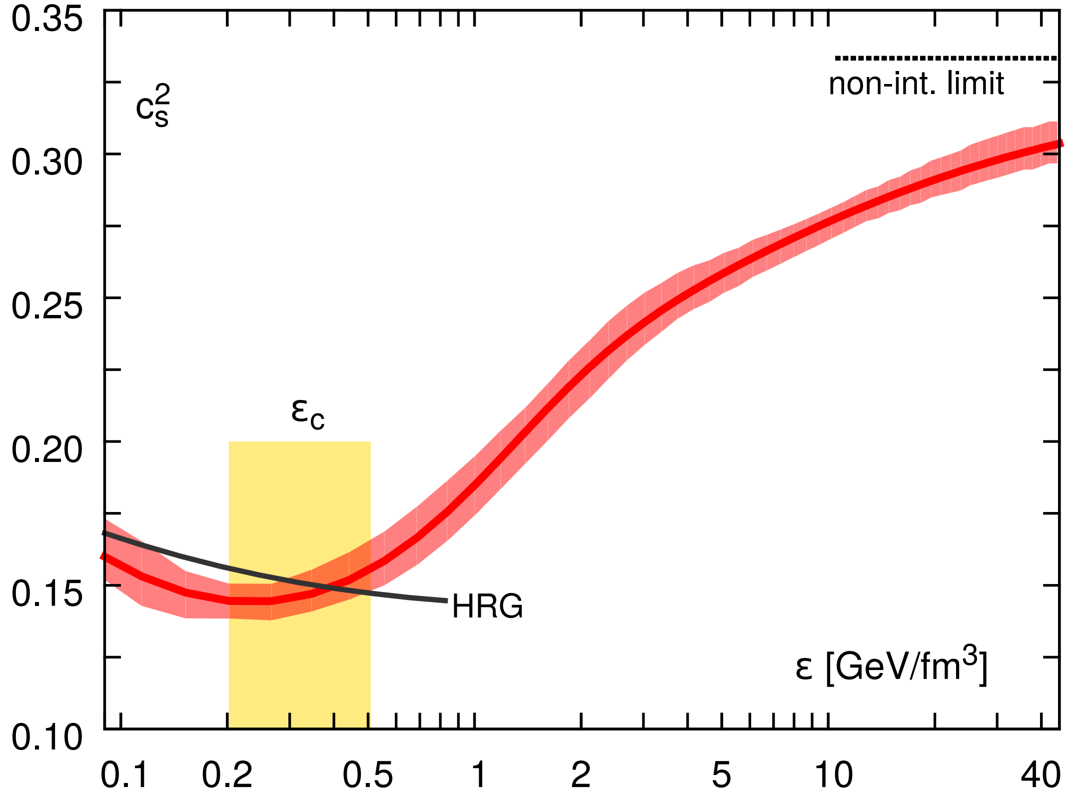


Rapid increase in the vicinity of nuclear density.

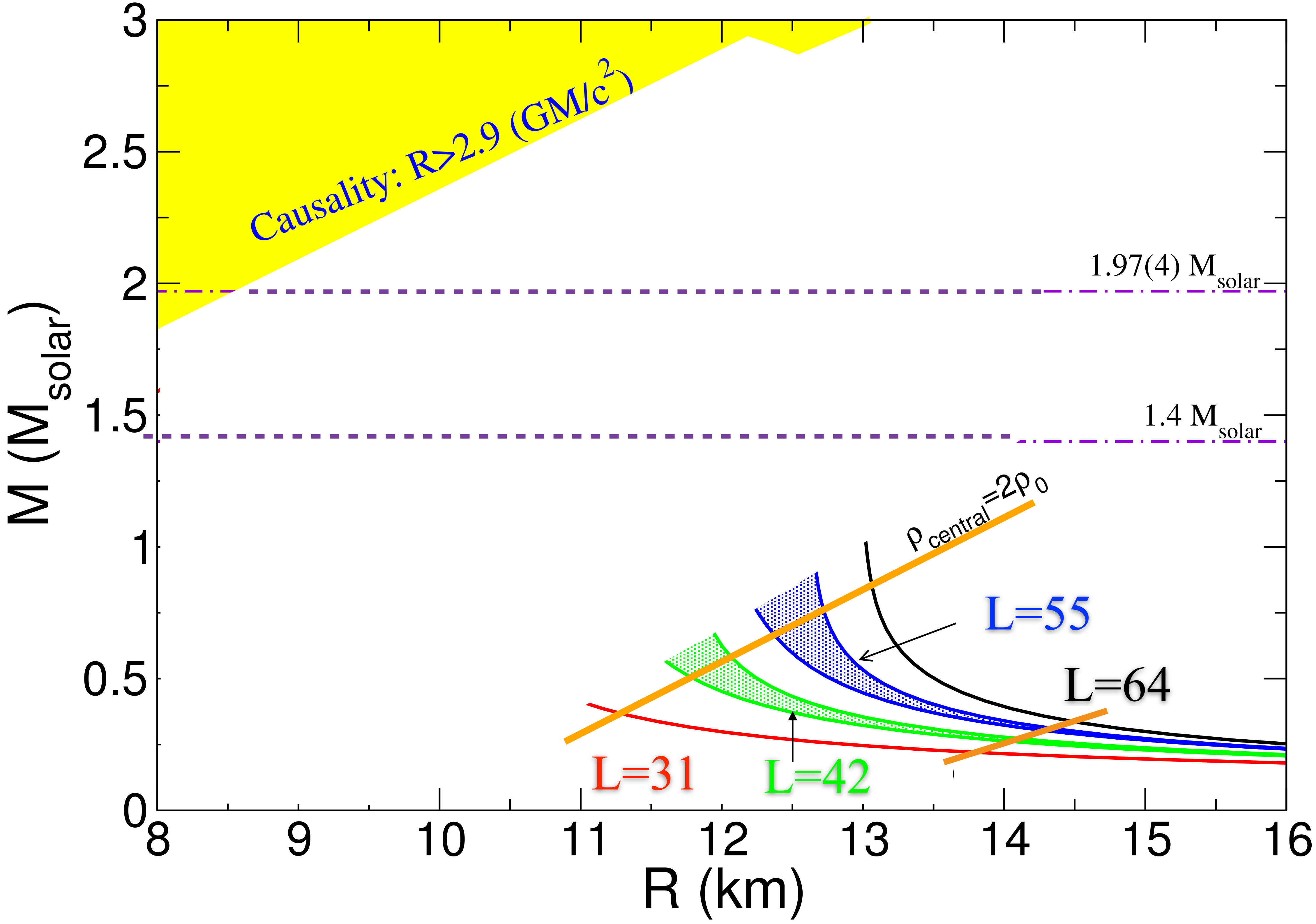
Driven by three-body forces and frustration.

At n_B=0 and finite temperature, lattice QCD predictions for C_s are interesting and different.

Many mesonic states in the spectrum to access with increasing temperature.


Hot QCD Collaboration (2015)

Neutron Star Structure



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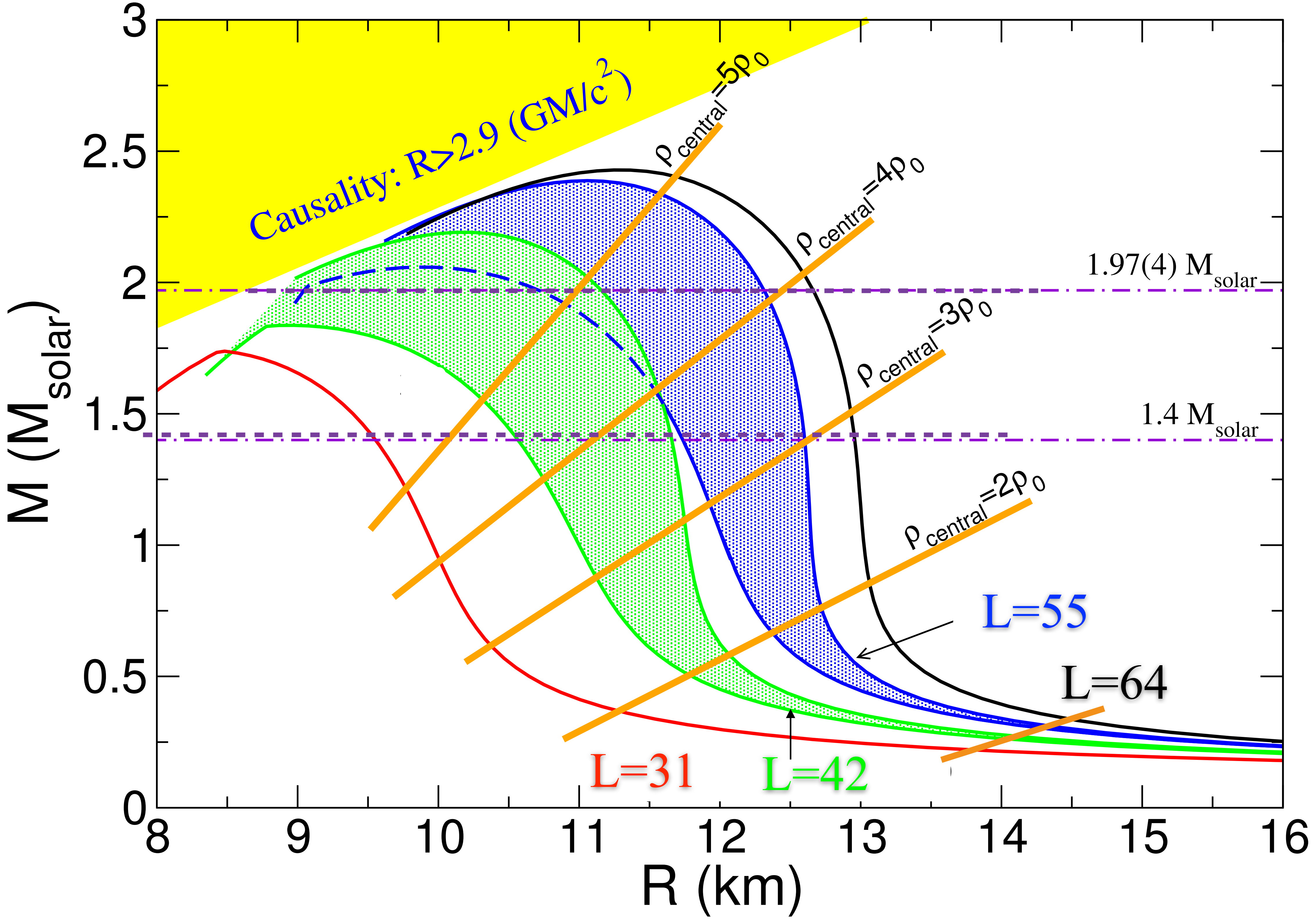

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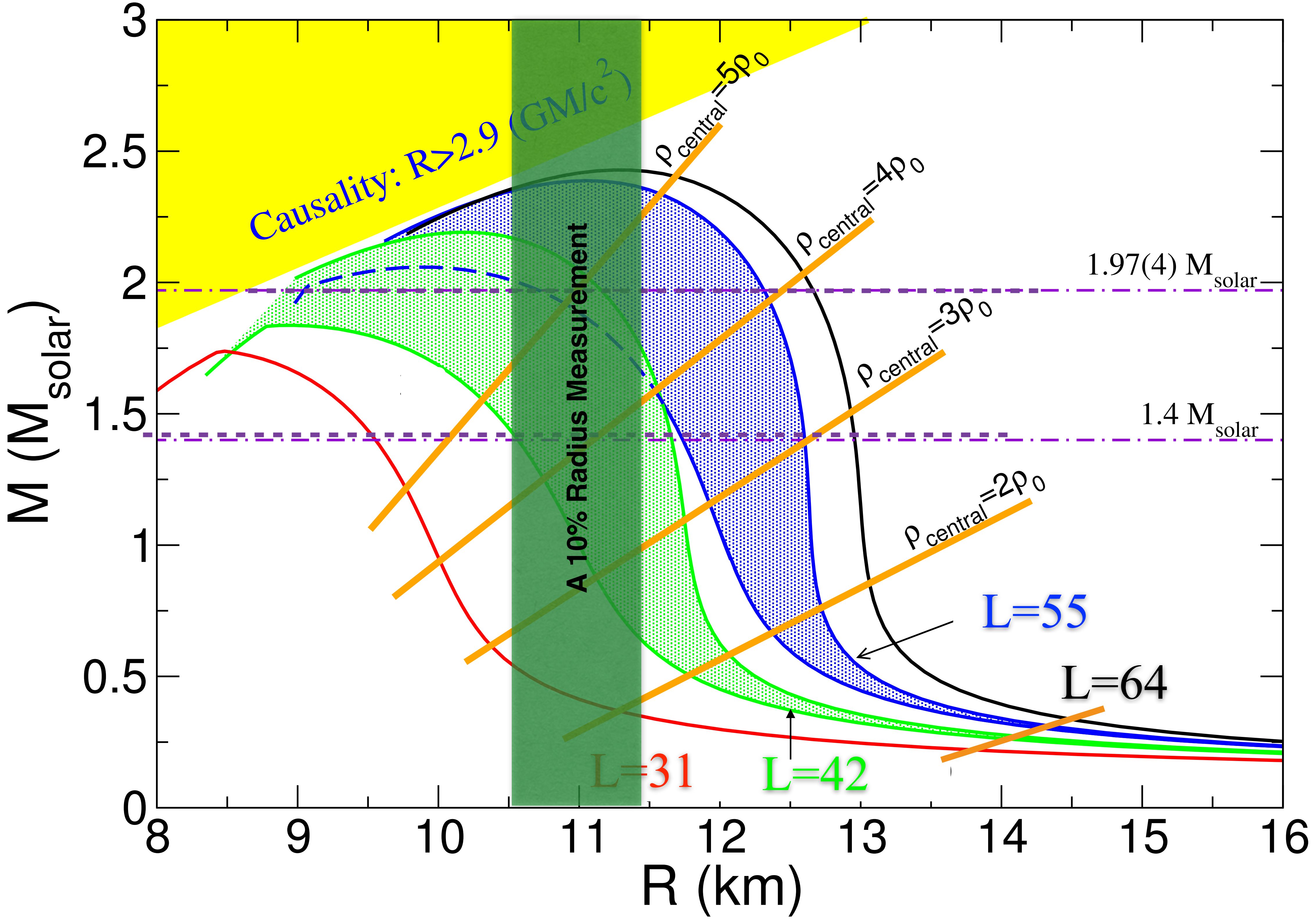
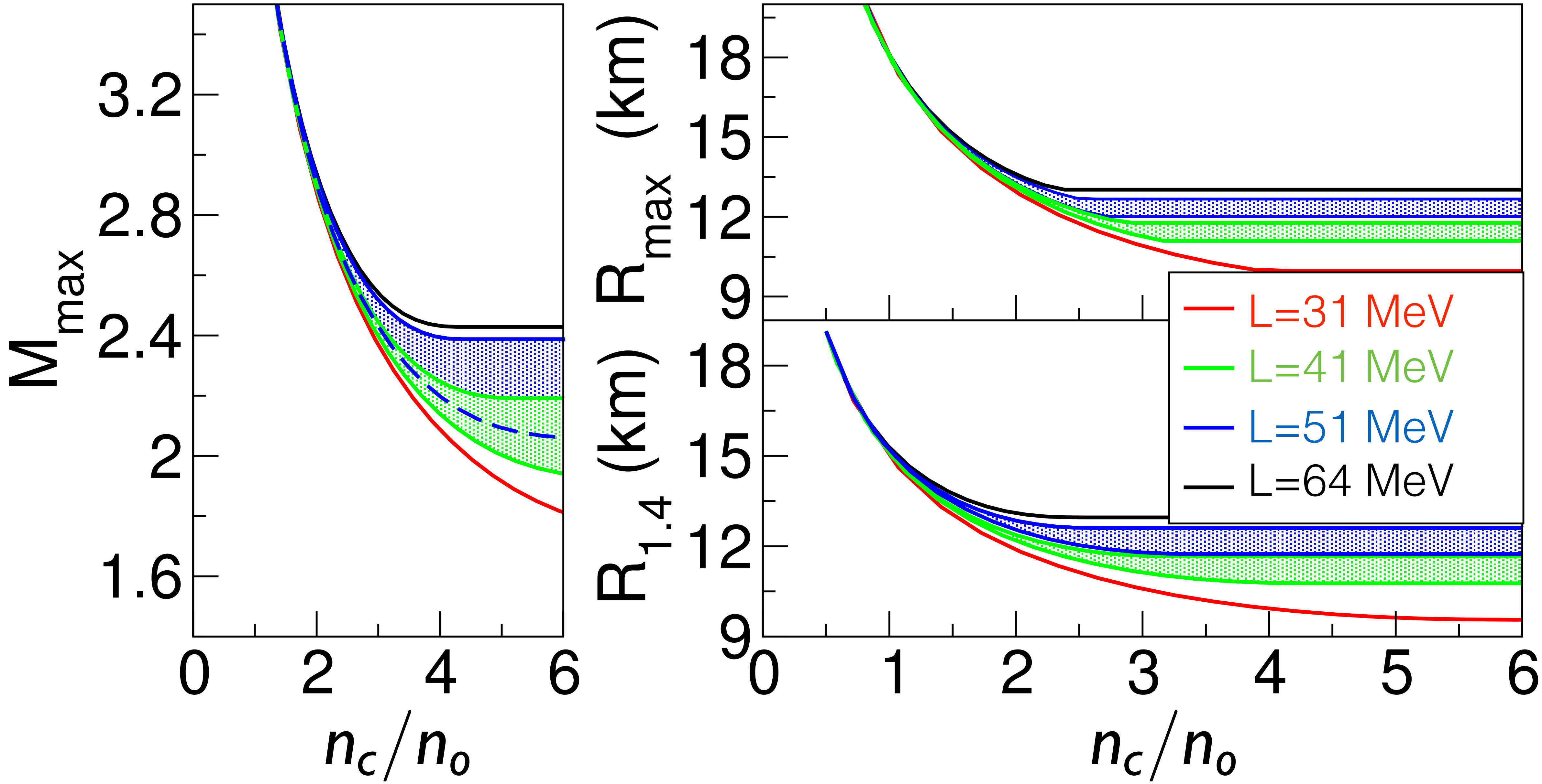


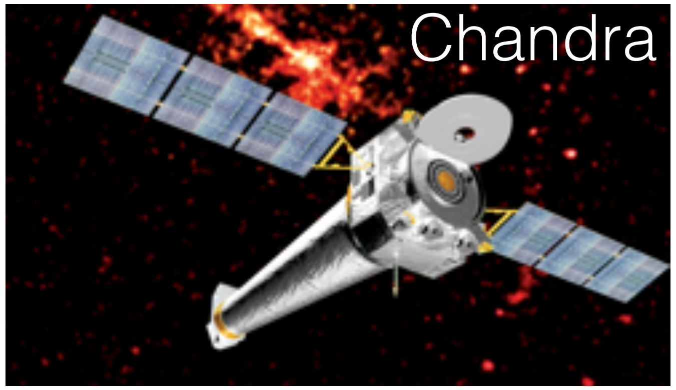
Upper Bounds on Neutron Star Masses & Radii

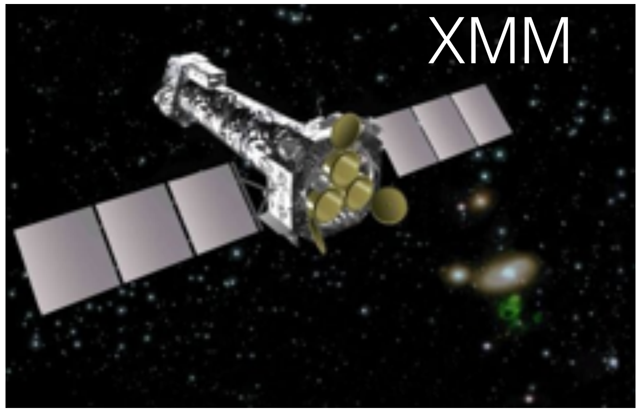
Given an EOS up to a n_B=n_c the largest and most massive neutron stars are obtained if $p(\varepsilon > \varepsilon_c) = \varepsilon - (\varepsilon_c - p_c)$



Gandolfi, Carlson, Reddy (2012)

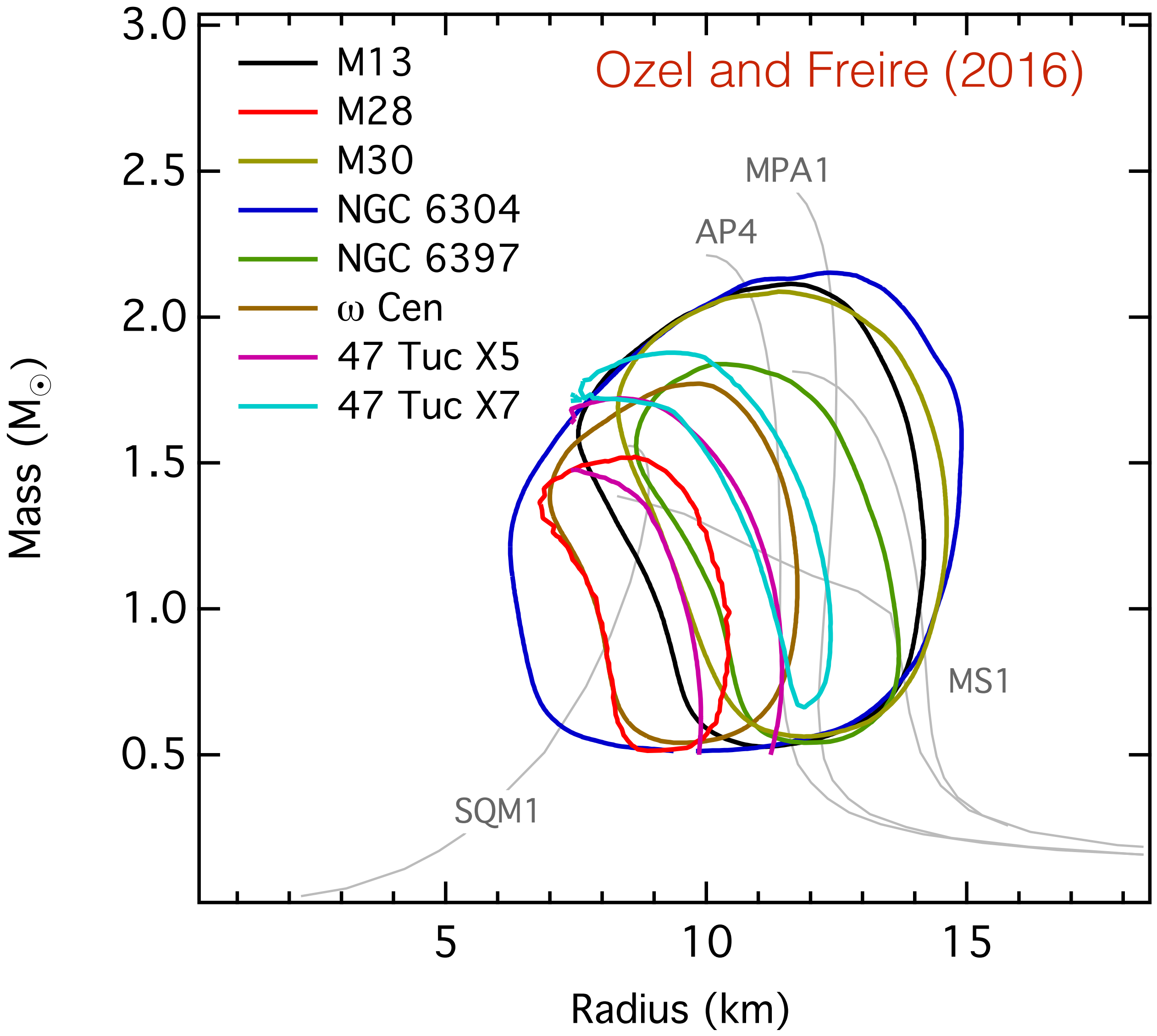
Radii from Quiescent NS





$$F_\infty = \left(\frac{R_\infty}{D}\right)^2 \sigma_B \, T_{\rm eff}^4 \qquad R_\infty = \frac{R}{\sqrt{1 - 2GM/Rc^2}}$$

Can extract “radius” subject to assumptions:
(i) surface temperature is uniform
(iii) atmosphere composition is known
(iii) distance and inter-stellar absorption is measured.

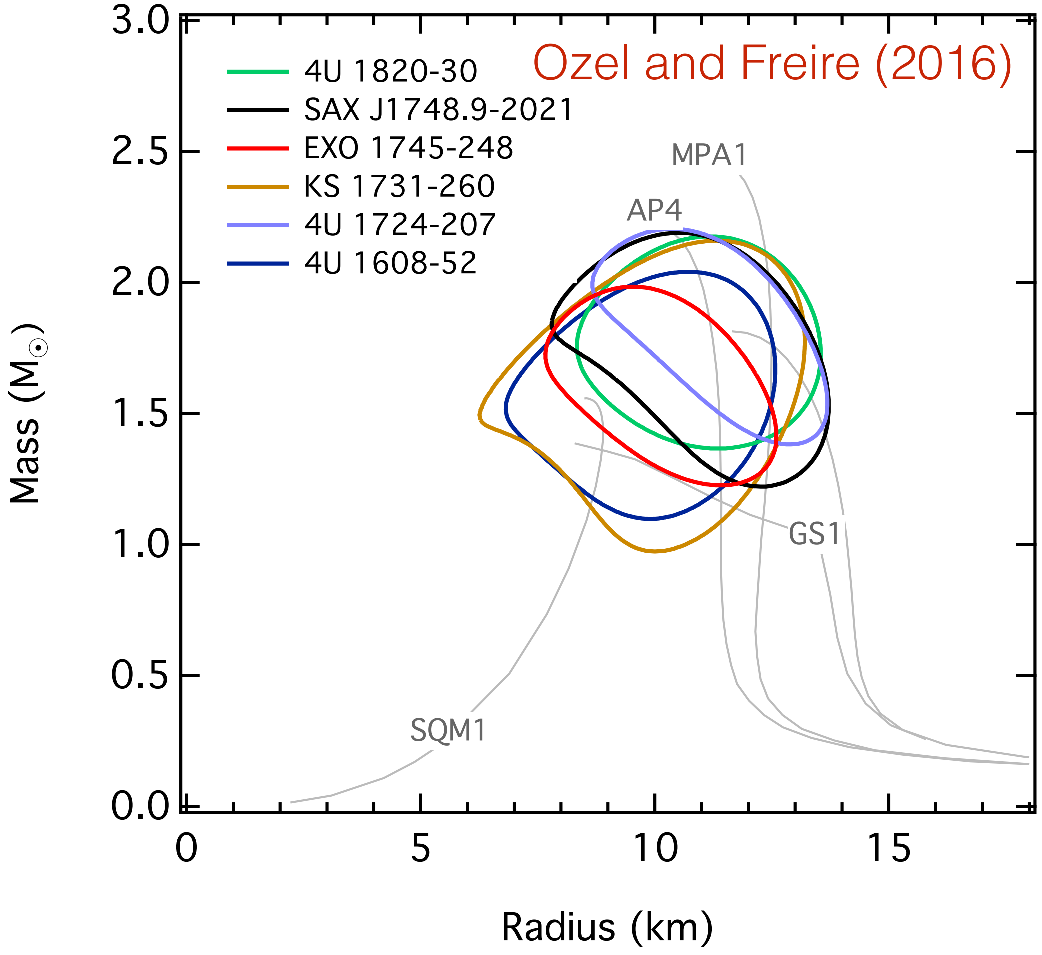


Radii from X-Ray Bursts:

Photosphere radius expansion is observed in some x-ray bursts:

$$F_{\mathrm{Edd}} = \frac{GMc}{\kappa_e\, D} \sqrt{1 - 2GM/Rc^2}$$

$$F_\infty = \left(\frac{R_\infty}{D}\right)^2 \sigma_B\, T_{\mathrm{eff}}^4$$



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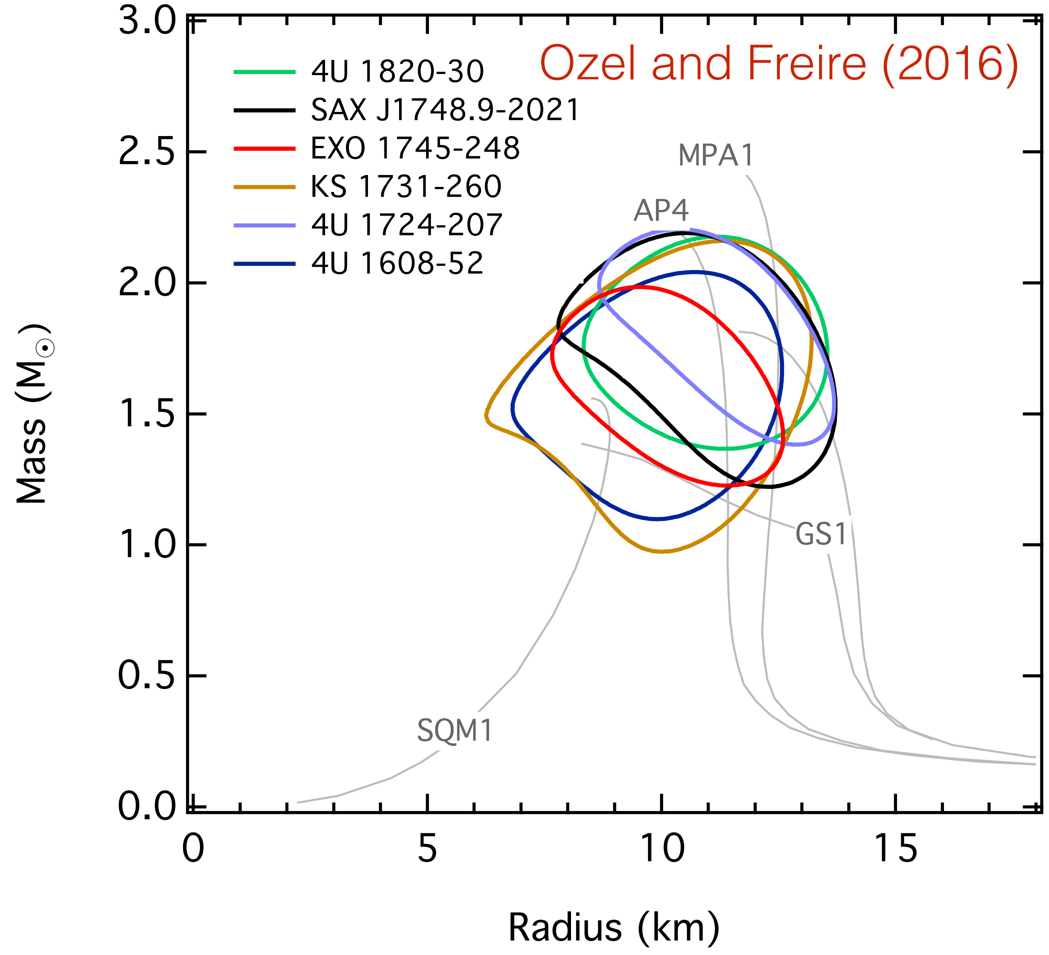
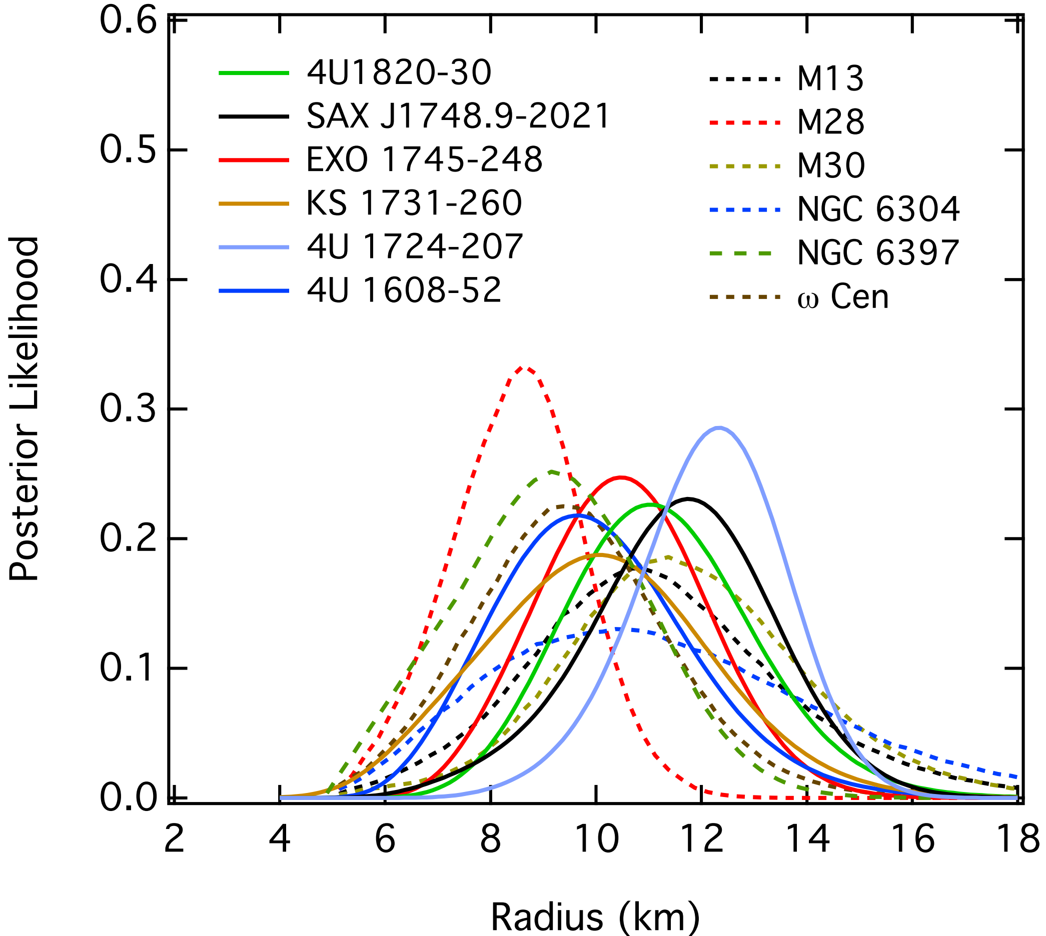
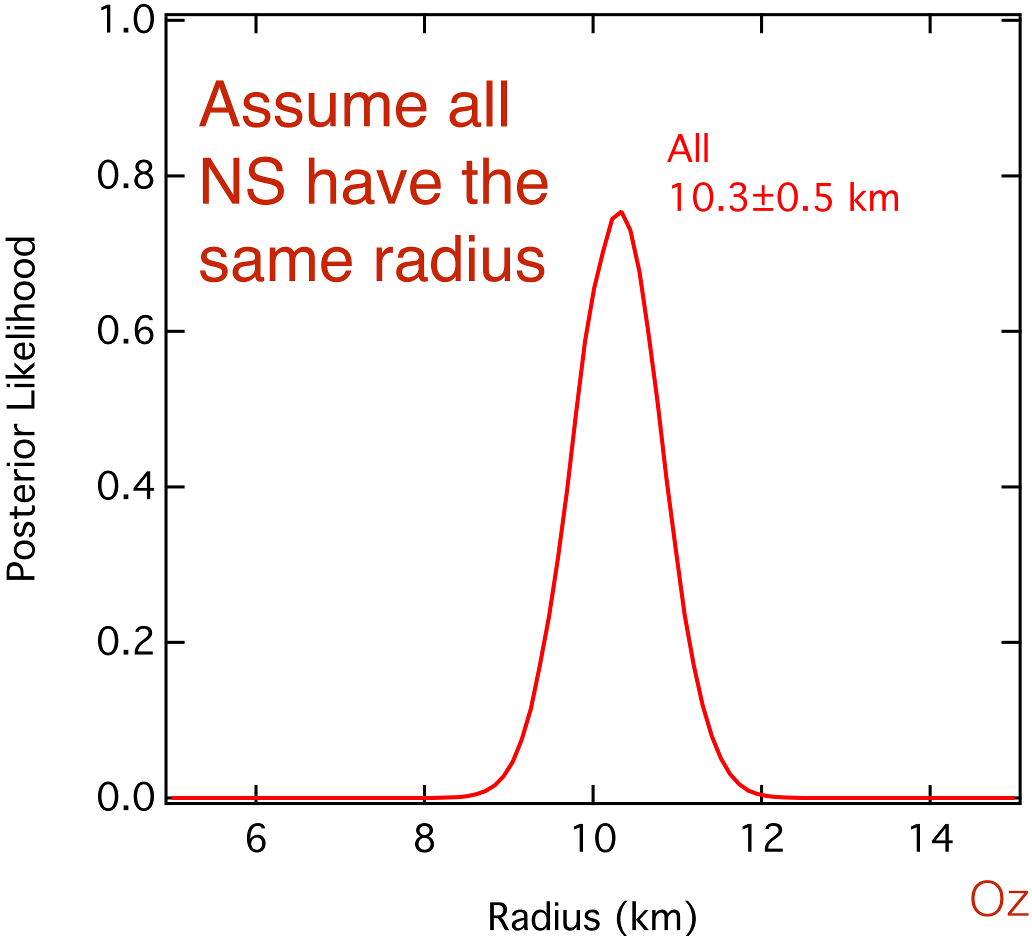


Combining data using observed neutron star mass distribution:



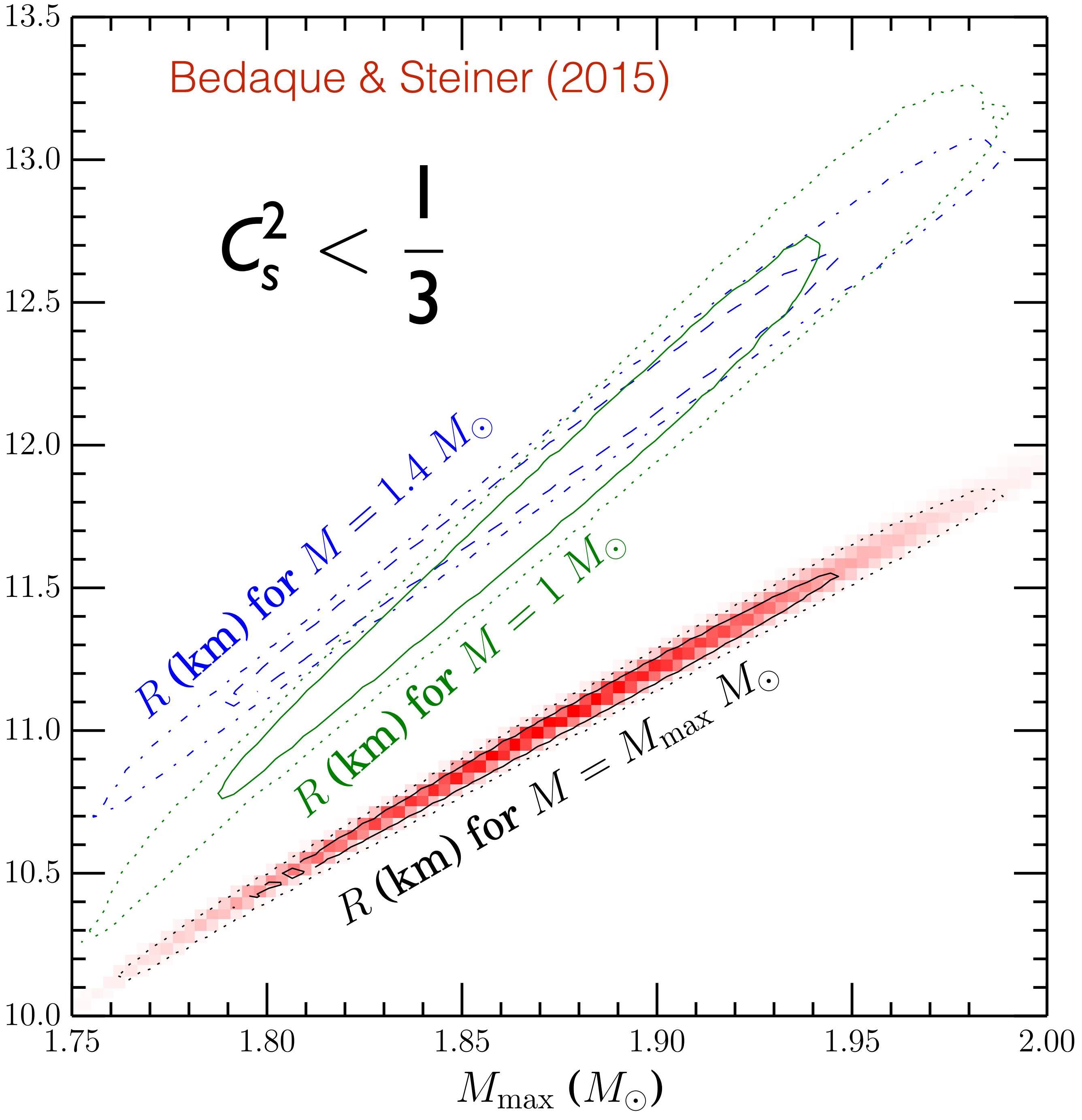


Assume all NS have the same radius

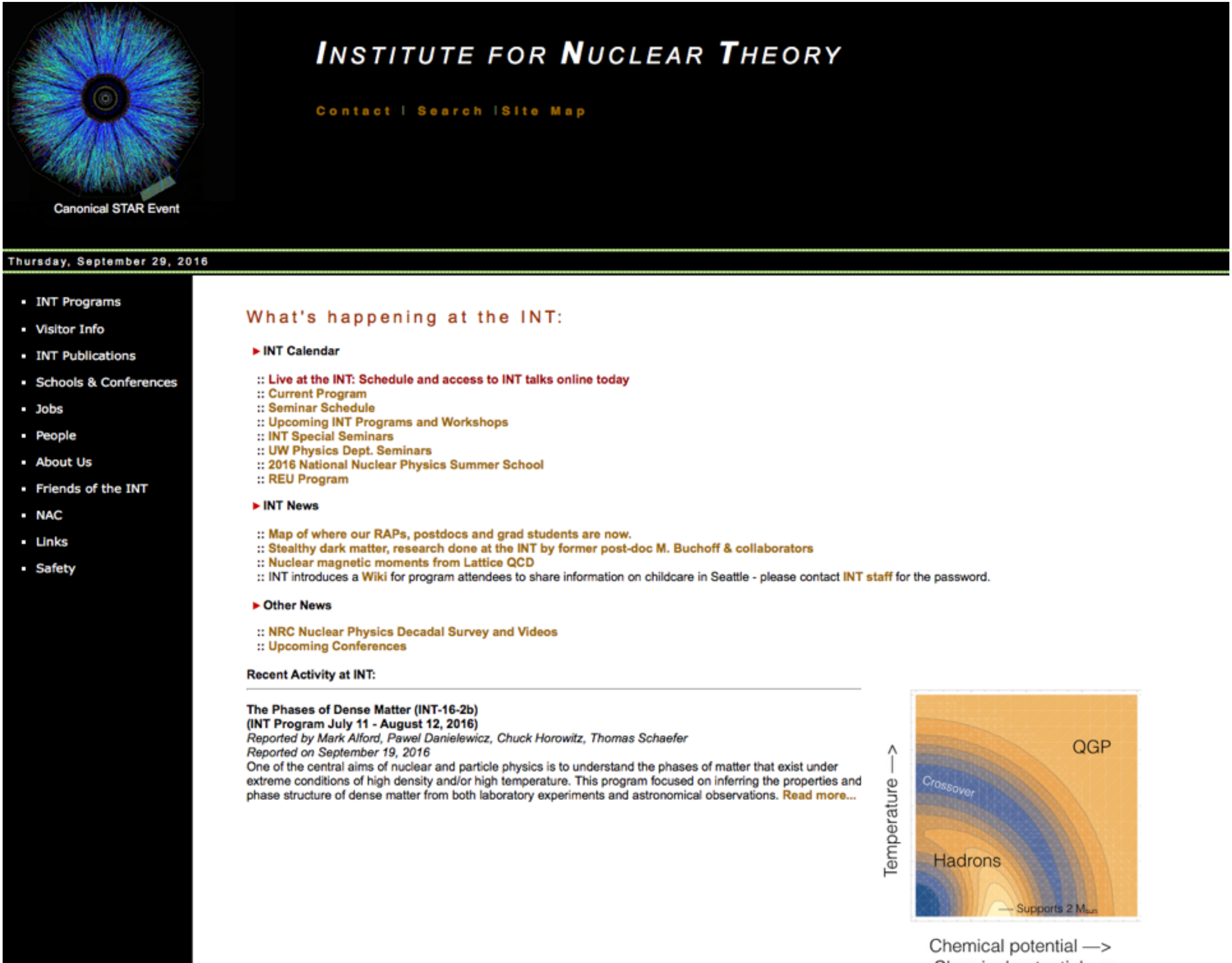
Ozel et al. (2015)

Tension between “small” radii and large masses

- Small radii require a relatively soft EOS around saturation density. Smaller values of L.
- High masses require a stiff EOS.
- Transition from soft to stiff must occur rapidly - favoring a larger speed of sound.
- If the nuclear EOS (with associated errors) is used up to 2 n_o and $C_s^2=1/3$ for $n_B > 2\ n_o$ then: $M_{max} < 2\ M_{solar}$.



Corollary: If observations establish that $R_{1.4} < 13$ km then the existence of a NS with M = 2 M_{solar} requires that somewhere inside the neutron star $C_s^2 > 1/3$!



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What's happening at the INT:

▸ **INT Calendar**

:: Live at the INT: Schedule and access to INT talks online today
:: Current Program
:: Seminar Schedule
:: Upcoming INT Programs and Workshops
:: INT Special Seminars
:: UW Physics Dept. Seminars
:: 2016 National Nuclear Physics Summer School
:: REU Program

▸ **INT News**

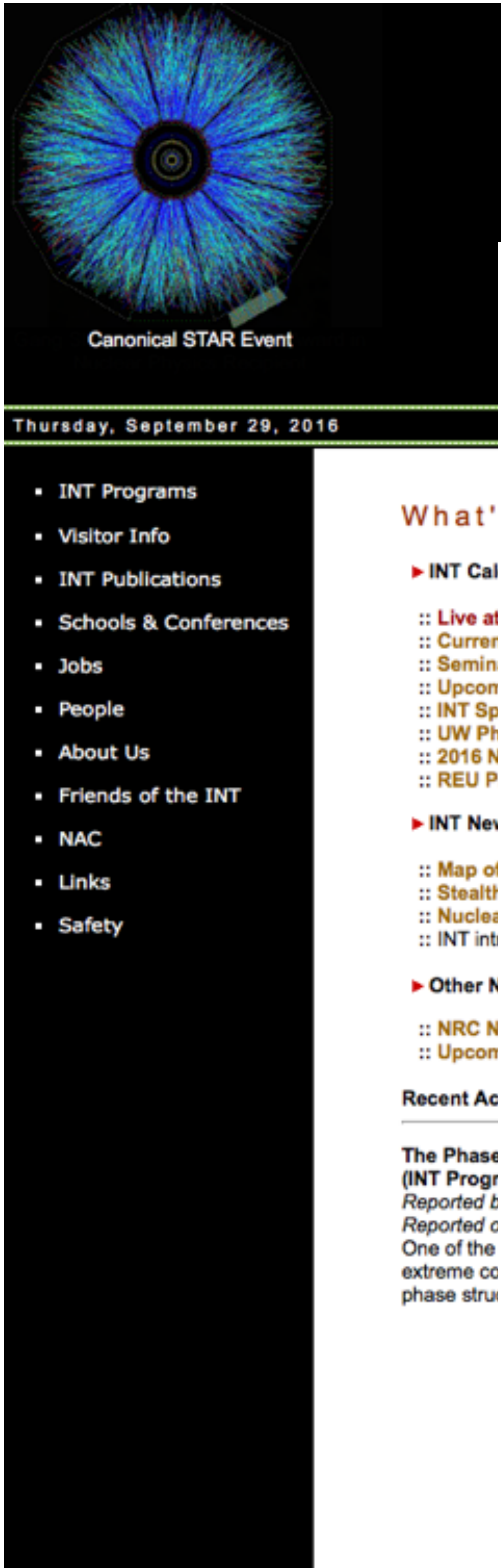
:: Map of where our RAPs, postdocs and grad students are now.
:: Stealthy dark matter, research done at the INT by former post-doc M. Buchoff & collaborators
:: Nuclear magnetic moments from Lattice QCD
:: INT introduces a Wiki for program attendees to share information on childcare in Seattle - please contact INT staff for the password.

▸ **Other News**

:: NRC Nuclear Physics Decadal Survey and Videos
:: Upcoming Conferences

Recent Activity at INT:

The Phases of Dense Matter (INT-16-2b)
(INT Program July 11 - August 12, 2016)
Reported by Mark Alford, Pawel Danielewicz, Chuck Horowitz, Thomas Schaefer
Reported on September 19, 2016
One of the central aims of nuclear and particle physics is to understand the phases of matter that exist under extreme conditions of high density and/or high temperature. This program focused on inferring the properties and phase structure of dense matter from both laboratory experiments and astronomical observations. Read more...



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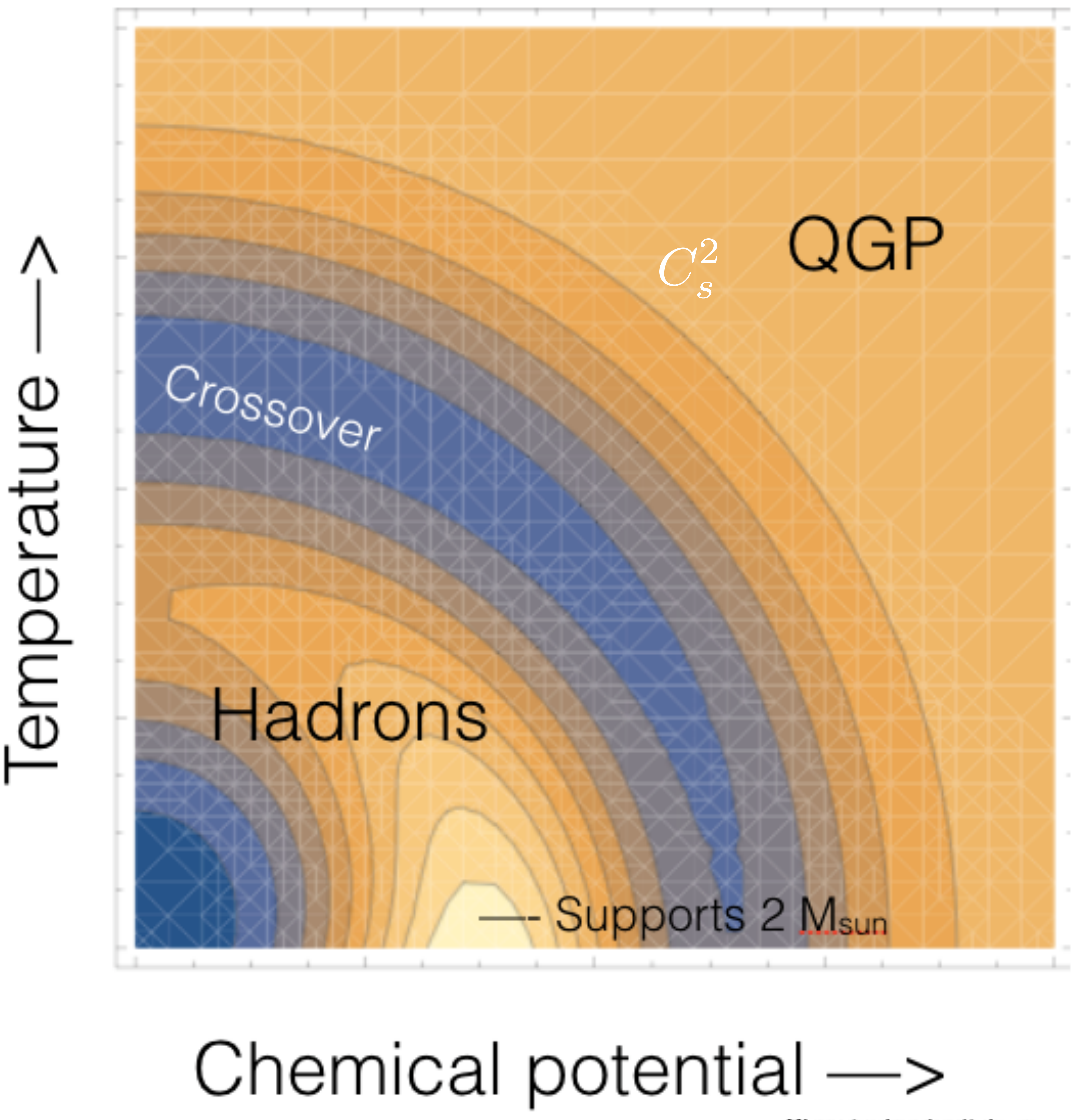
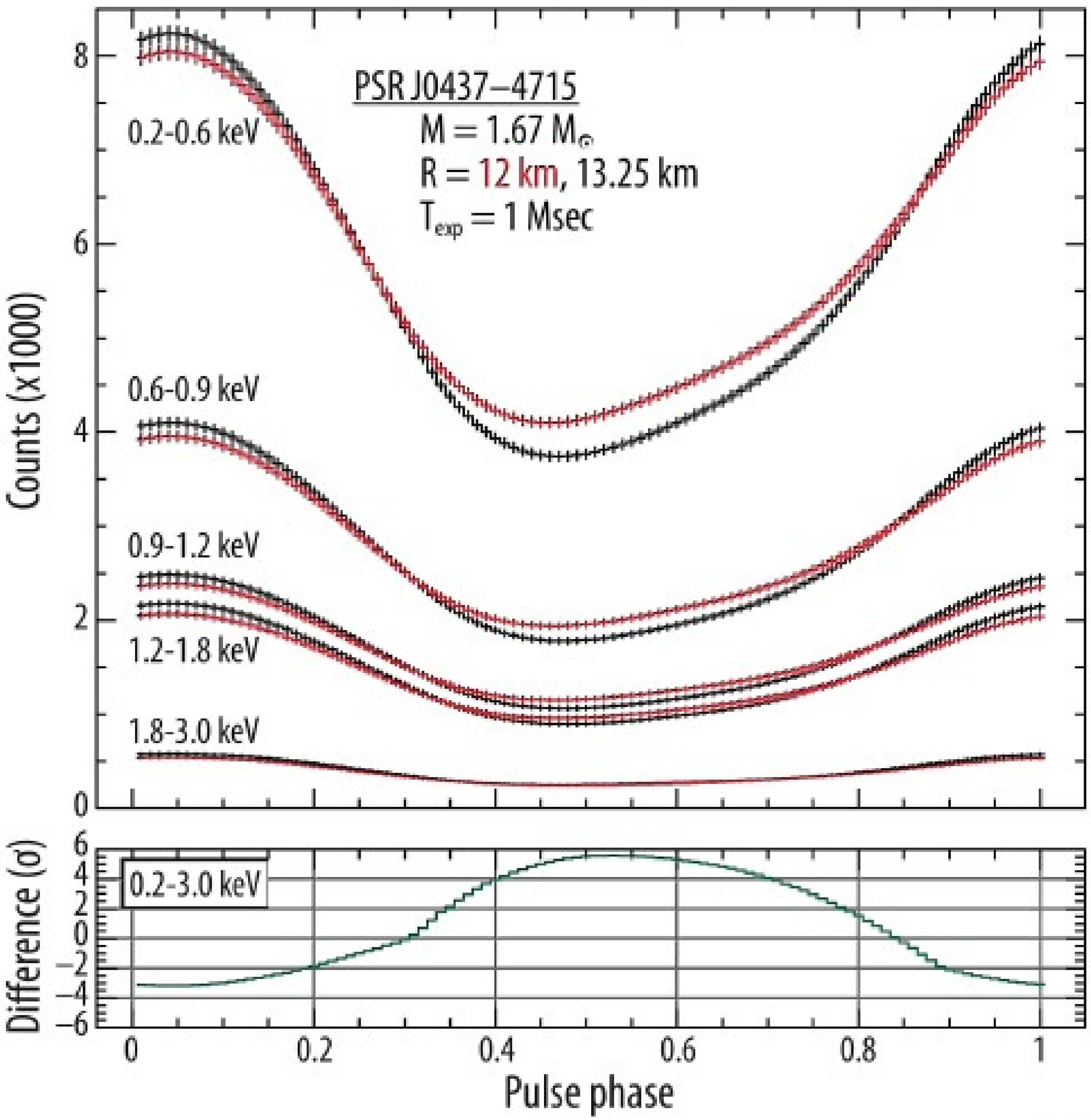
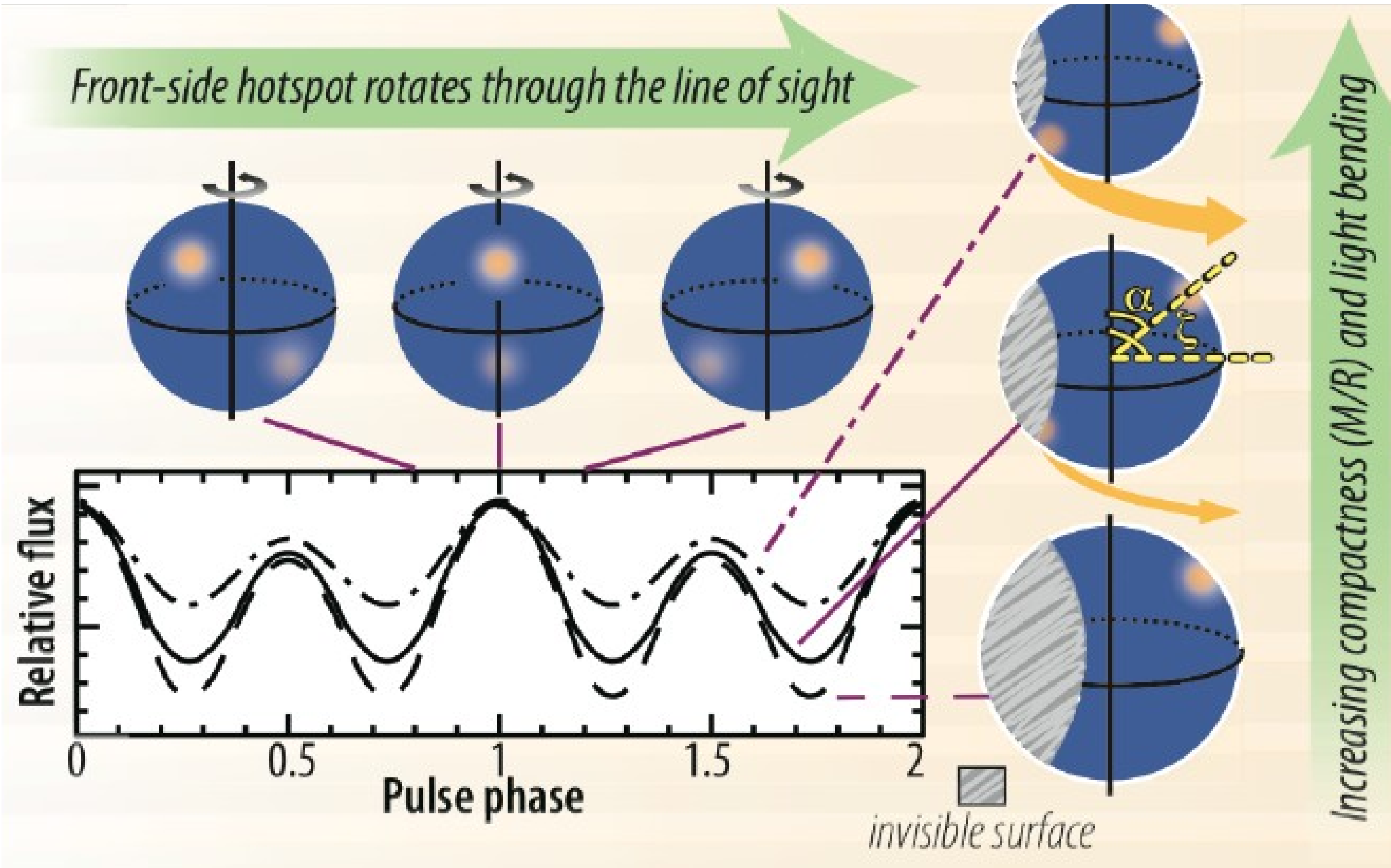


Near Term (1-10 yrs) Prospects

Radii from Hot Spots:



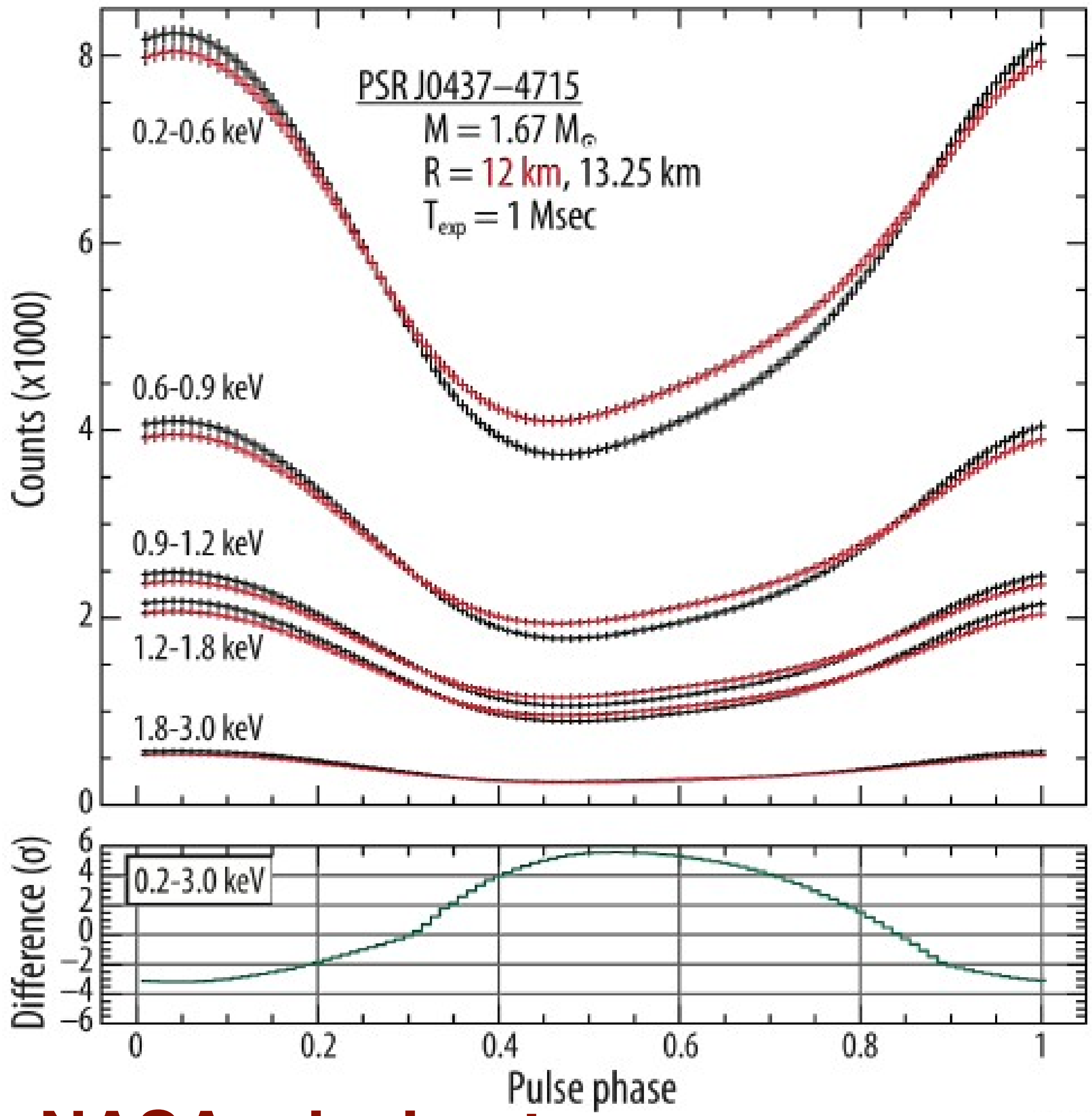


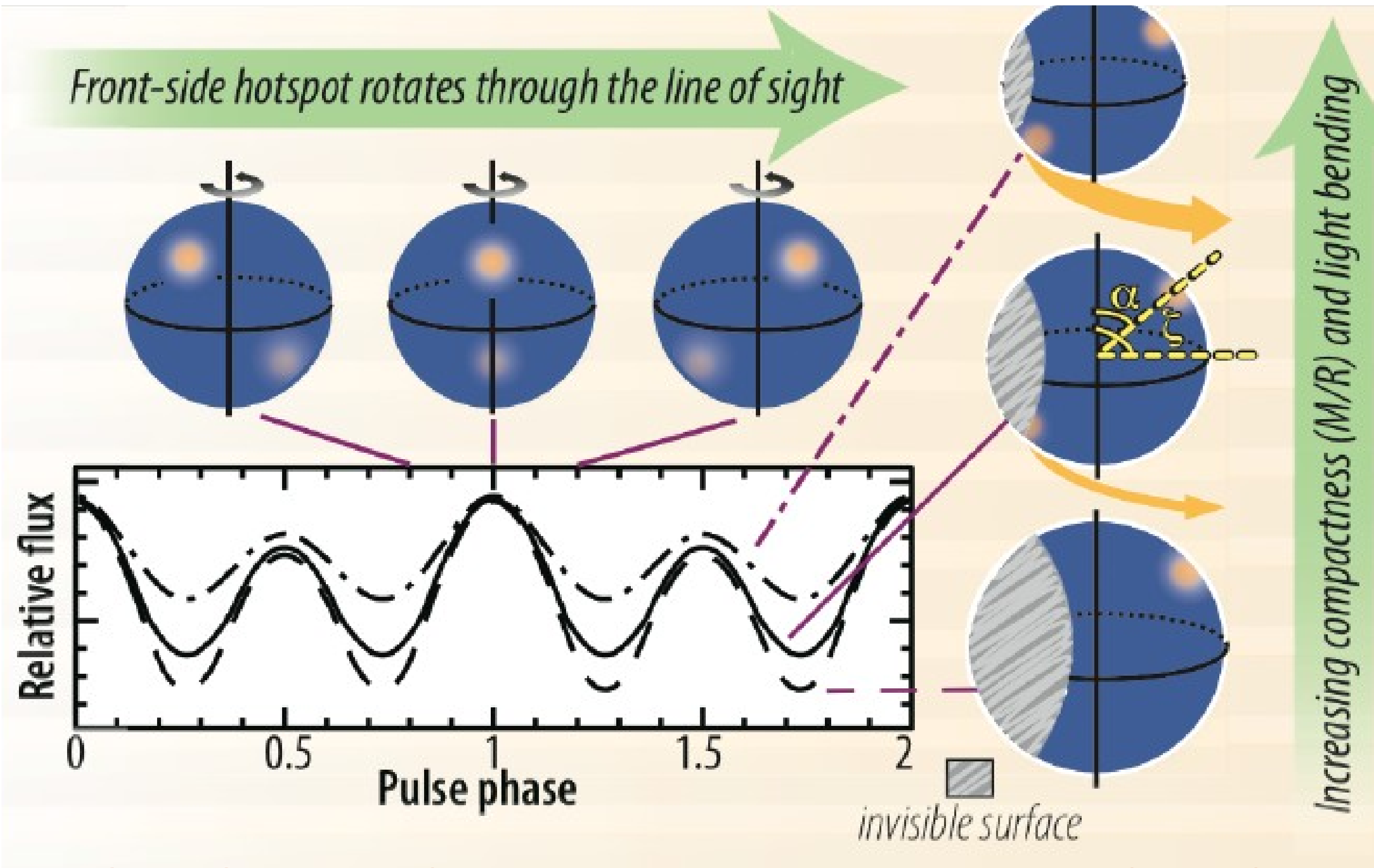
NICER Science Overview Arzoumanian, et. al. (2014)

With about 10^6 photons a 10% radius measurement seems possible. For details see the talk by Fred Lamb:

www.int.washington.edu/talks/WorkShops/int_16_2b/People/Lamb_F/Lamb.pdf

Radii from Hot Spots:





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NASA mission to launch Feb. 2017.

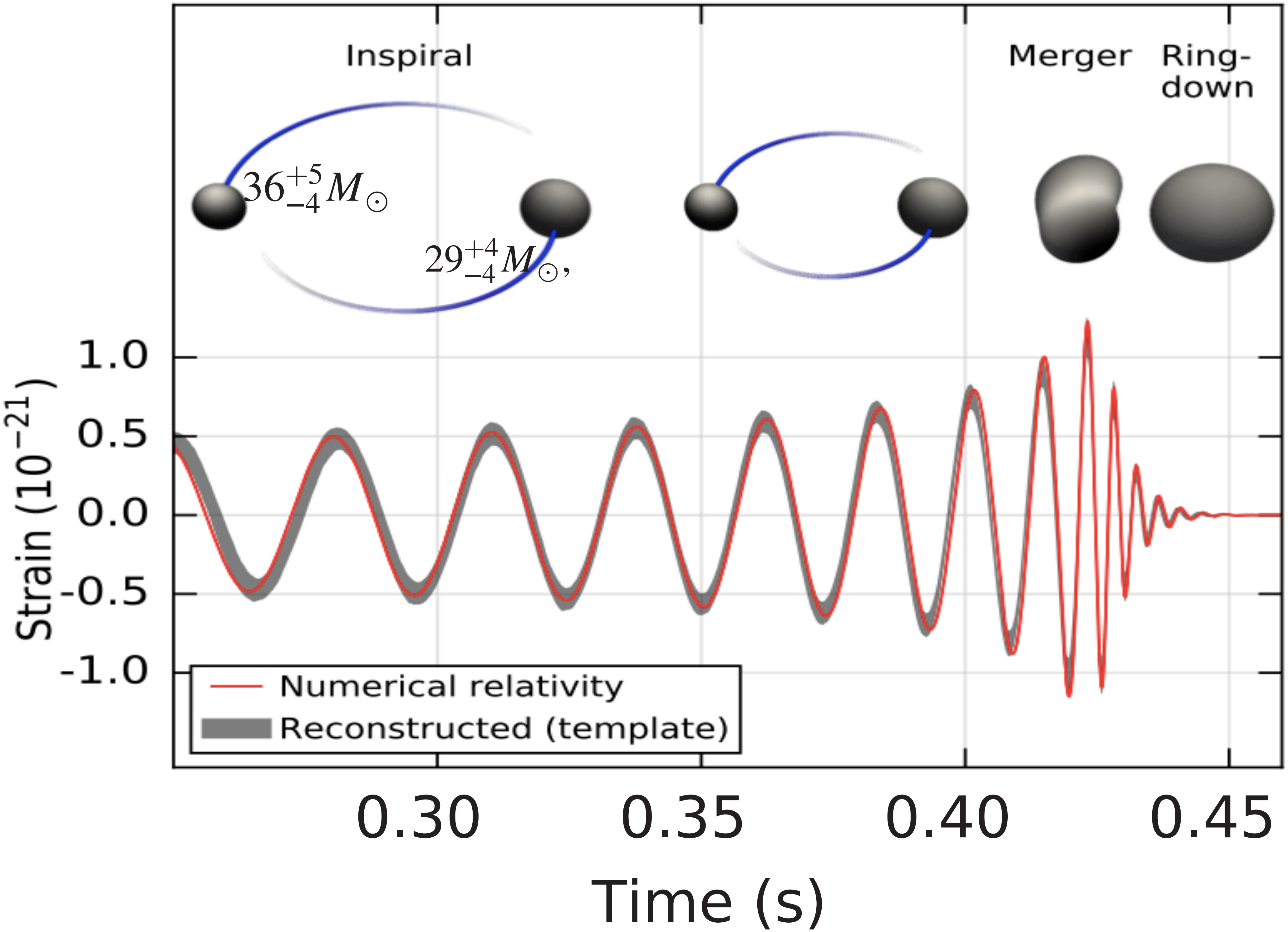
Gravitational are here !
GW150914

PRL 116, 061102 (2016) PHYSICAL REVIEW LETTERS 12 FEBRUARY 2016

Observation of Gravitational Waves from a Binary Black Hole Merger

B. P. Abbott *et al.*[*]
(LIGO Scientific Collaboration and Virgo Collaboration)

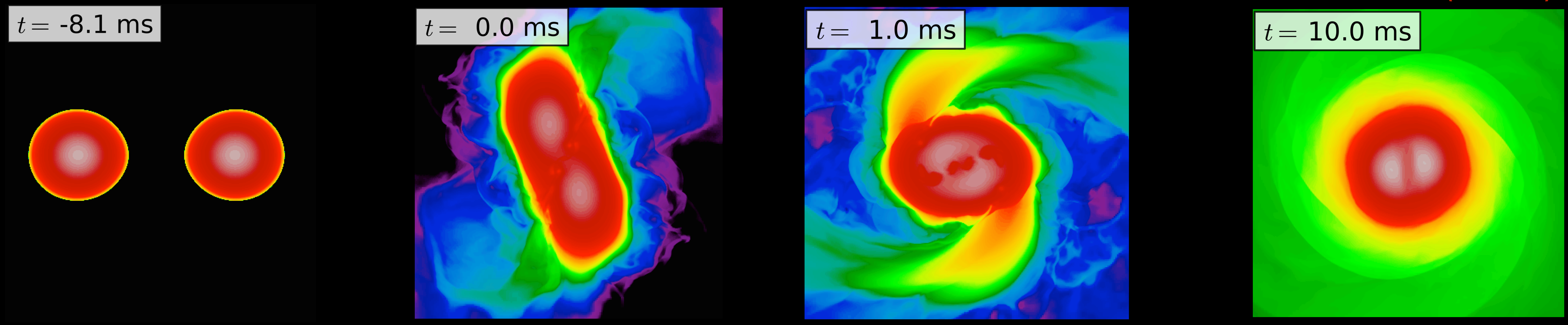
(Received 21 January 2016; published 11 February 2016)



Neutron Star Merger Dynamics

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

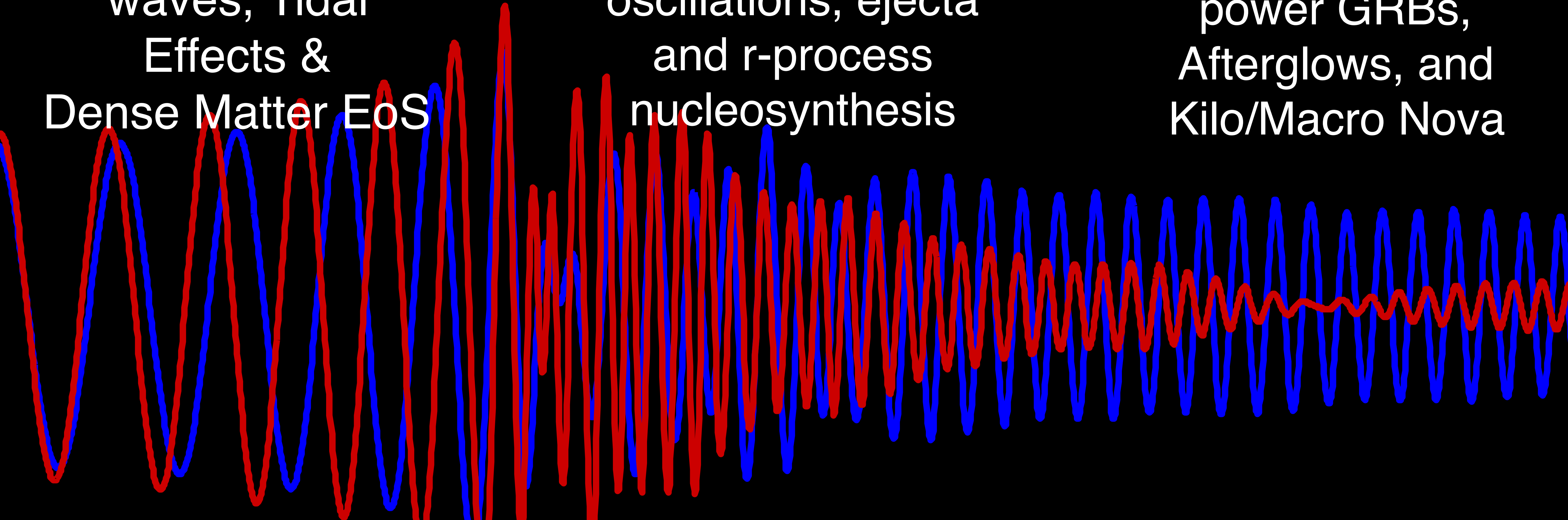
Simulations: Rezzola et al (2013)



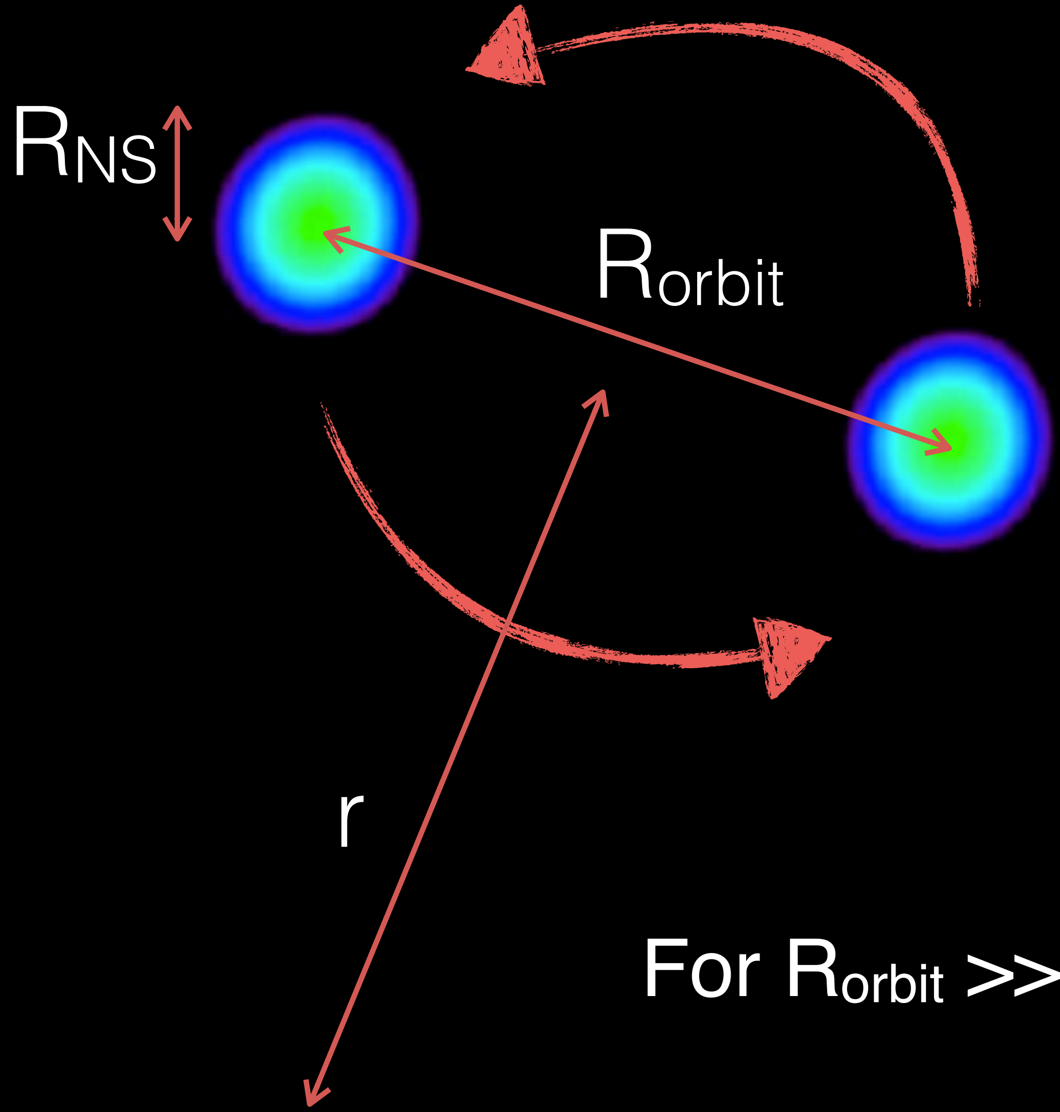
Late Inspiral:
Gravitational
waves, Tidal
Effects &
Dense Matter EoS

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

Post Merger:
Ambient conditions
power GRBs,
Afterglows, and
Kilo/Macro Nova



Binary inspiral and gravitational waves



GWs are produced by fluctuating quadrupoles.

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

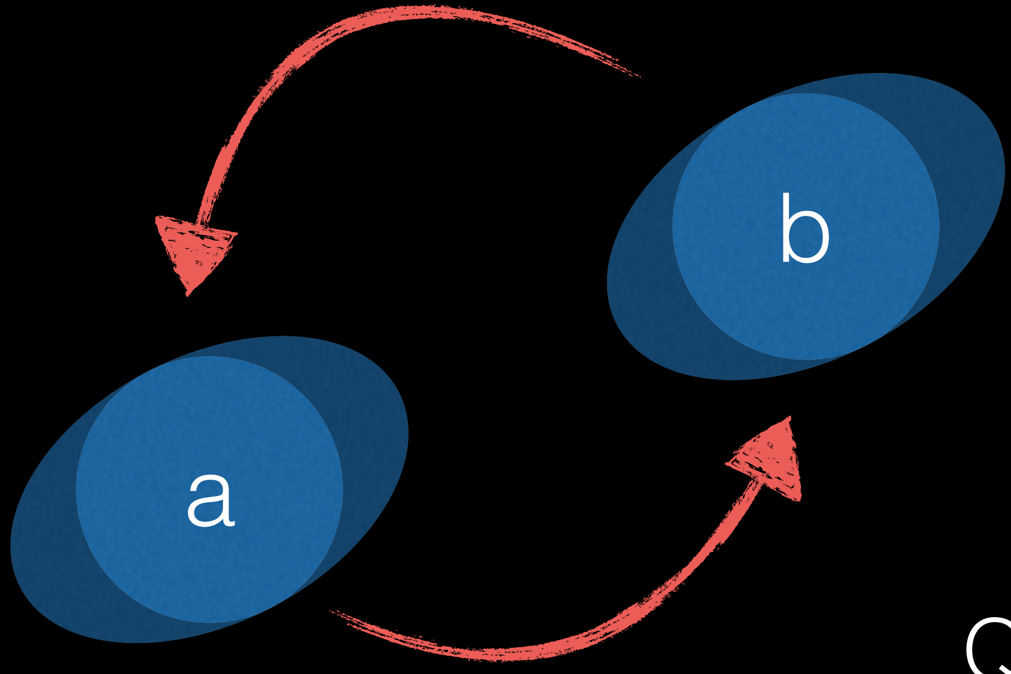
$$h_{\mu\nu}(r,t) = \frac{2G}{r}\,\ddot{I}_{ij}(t_R)$$

$$I_{ij}(t) = \int d^3x\ \rho(t,\vec{x})\ x_i\ x_j$$

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

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

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 (λ)

↑ External field (E_{ij})

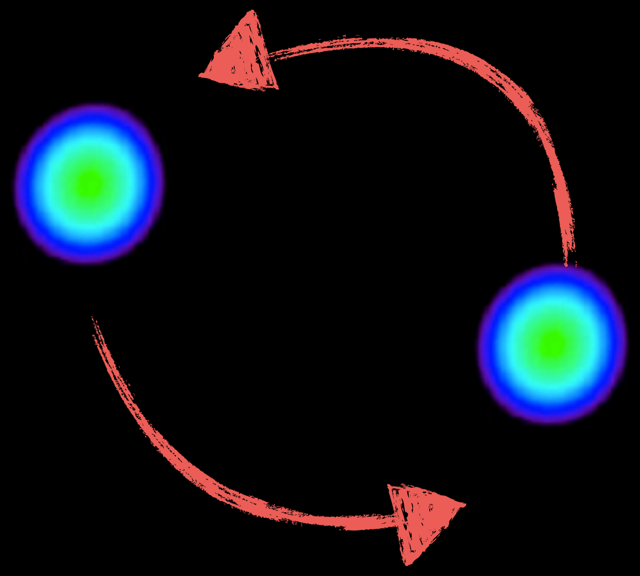
$$V(r) \simeq -\frac{GM_a}{r} - \frac{GQ_a}{r^3} \approx -\frac{GM_a}{r} - \frac{G\lambda M_b}{r^6}$$

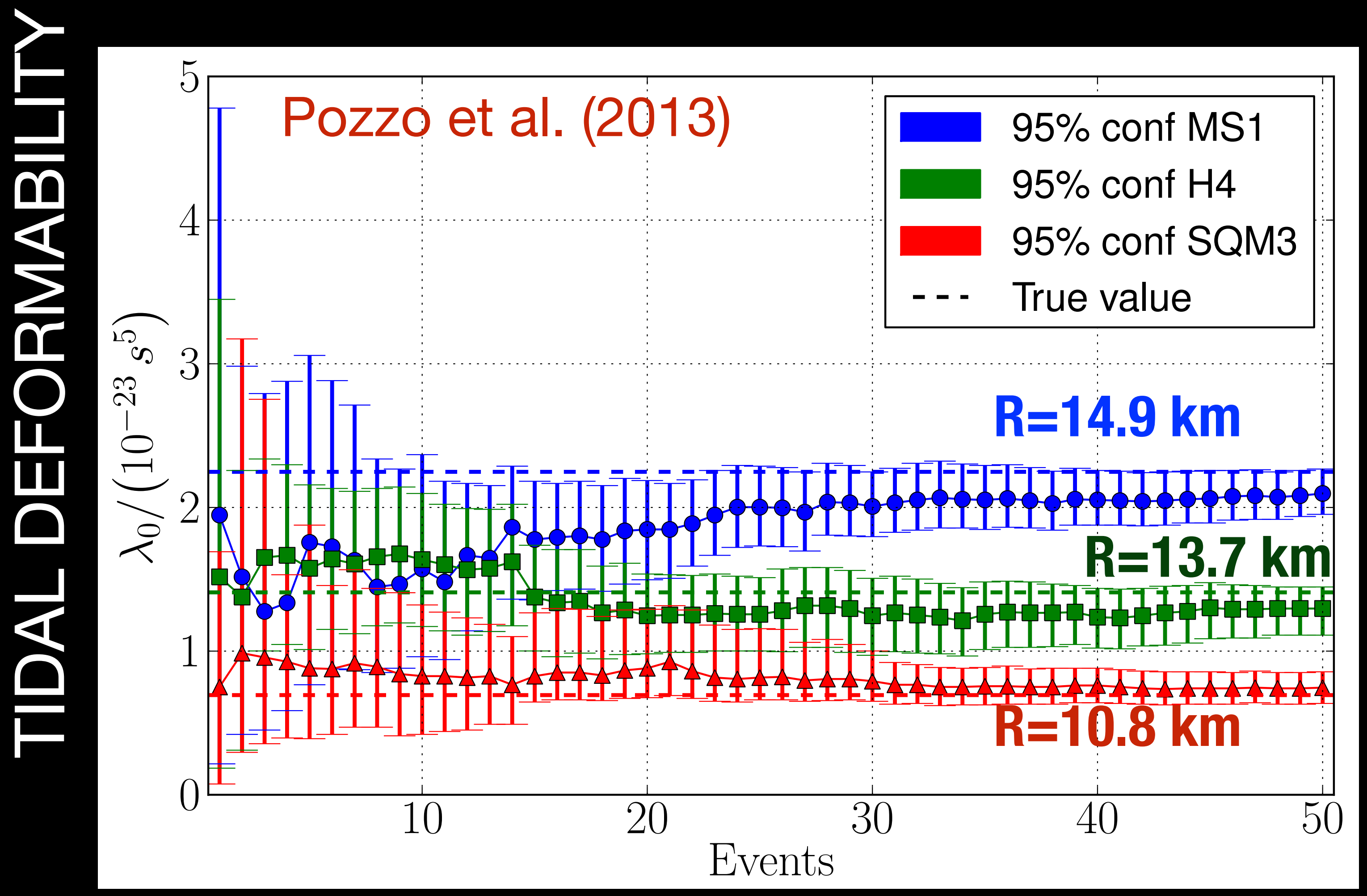
This advances the orbit and changes the rotational phase.

Quadrupole polarizability: $\lambda = k_2(\beta, \bar{y})\ R_{NS}^5$

tidal love number: depends weakly on the matter distribution
(approximately NS have no-hair !)

Neutron Star Radii From Pre Merger Signal





Realistic data analysis by injecting events in a volume between 100-250 Mpc demonstrates discriminating power between EOSs. Pozzo et al. (2013)

With tens of events the radius can be extracted to better than 10% if the waveforms can be modeled.

SUMMARY & OUTLOOK

- Observation of massive NSs and hints at relatively small NS radii imply a rapid transition from soft to stiff EOS in the NS core.

- Neutron matter calculations predict such a transition in the vicinity of n_o due to three body forces.

- Terrestrial experiments have the potential to probe this transition, but currently, the errors are large.

- Better determinations of the neutron star radii seems imminent. Different methods with different systematics.

- Gravitational waves from neutron star mergers can potentially provide information about neutron star radius and maximum mass.