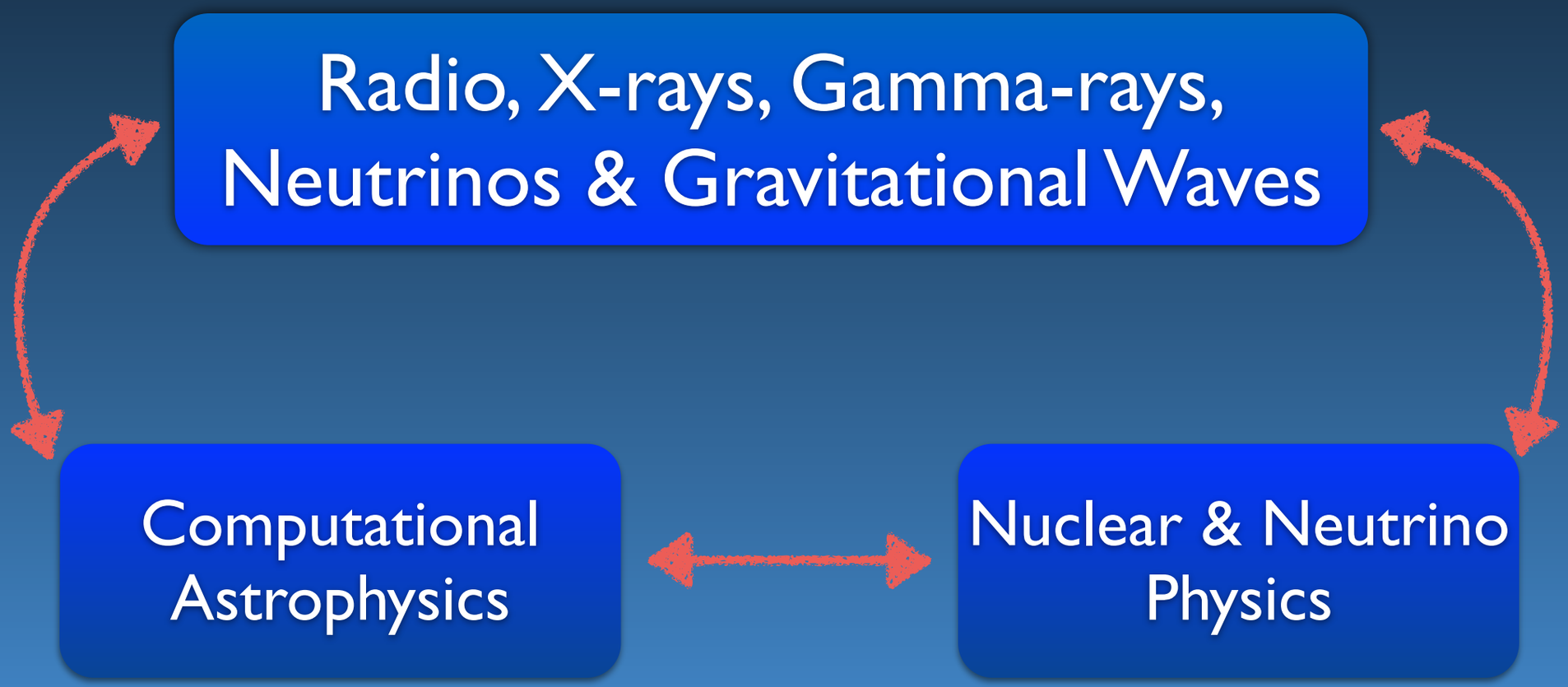
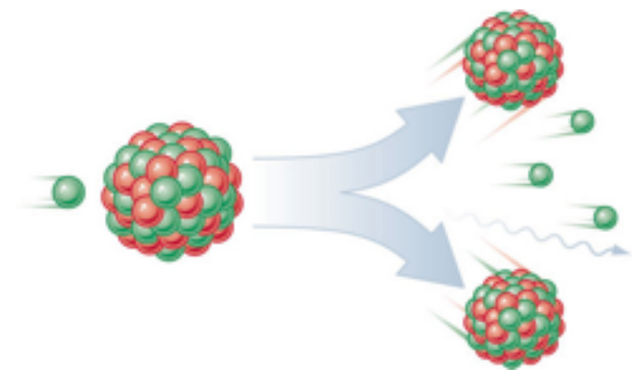
Neutron Stars in the Multi-Messenger Era: Extreme Matter & Extreme Phenomena

Sanjay Reddy
Univ. of Washington, Seattle

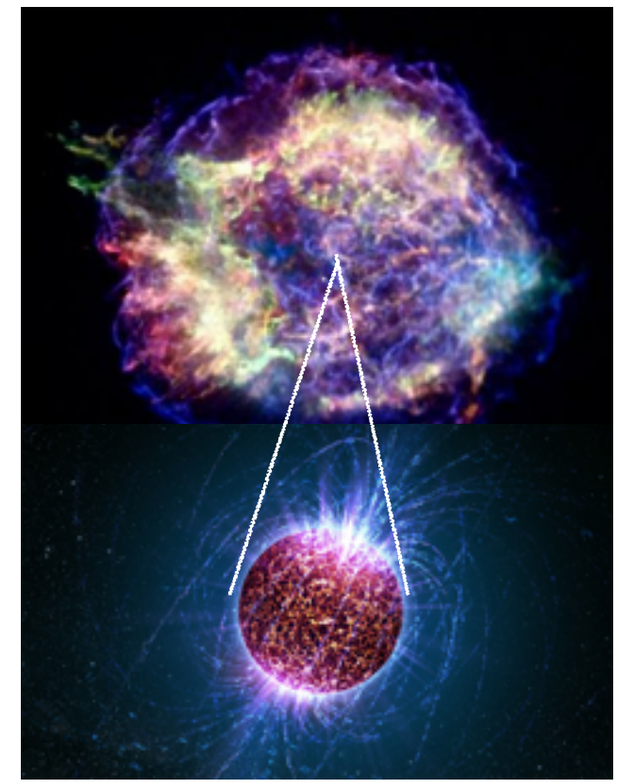


INSTITUTE for NUCLEAR THEORY

Big Questions

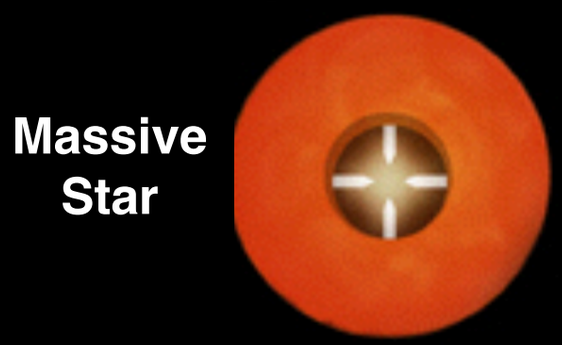


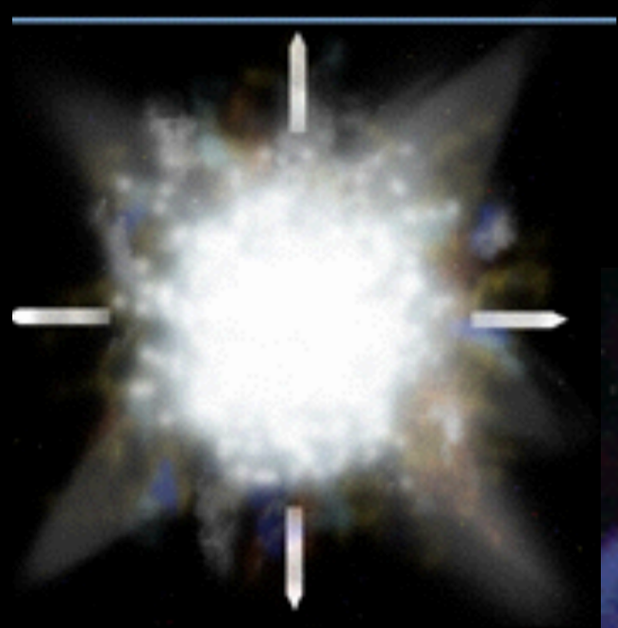
1. What are the nuclear and neutrino processes that shape cosmic explosions and nucleosynthesis ?
2. What are the phases and properties of matter encountered in neutron stars, supernova and binary neutron star mergers ?
3. Where and how are the heavy elements synthesized ?
4. **Can we interpret multi-messenger signals with advanced modeling and simulations to extract fundamental nuclear physics ?**

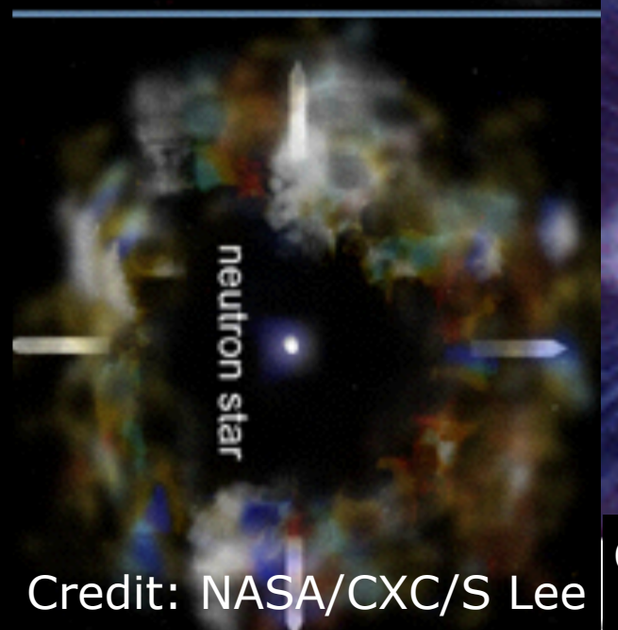


Sources

Supernova

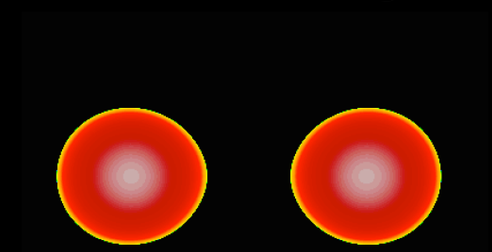


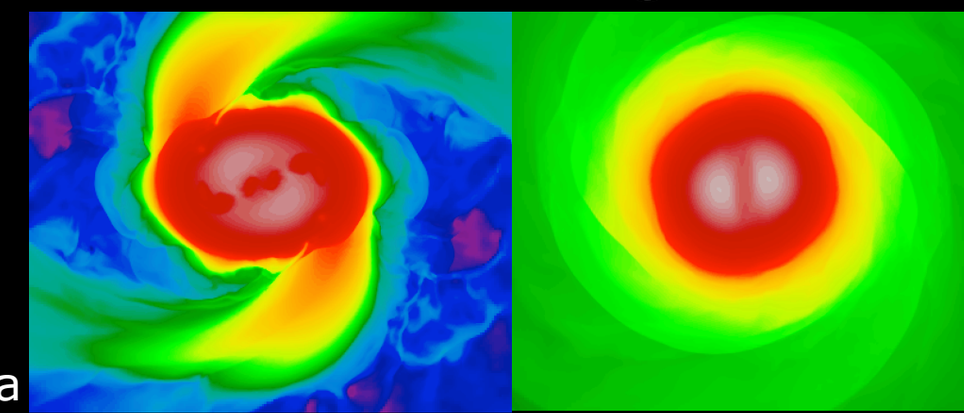




Credit: NASA/CXC/S Lee

Binary Neutron Star Mergers



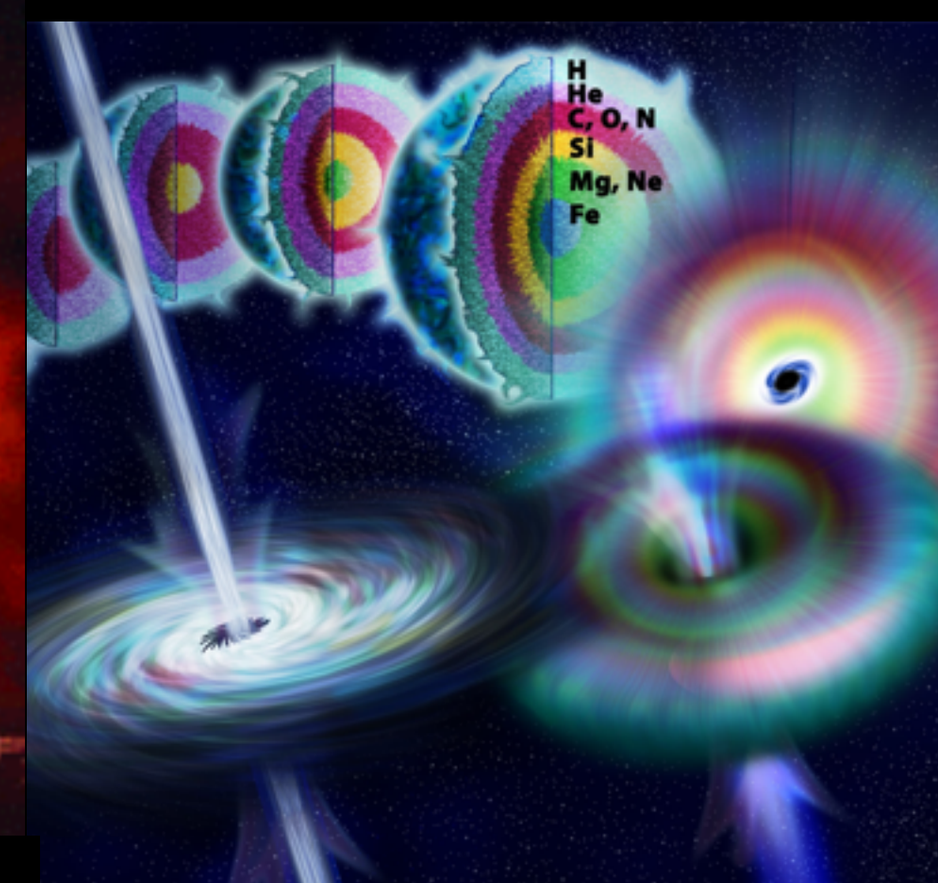


Credit: Luciano Rezzola

Accreting Neutron Stars, Magnetars

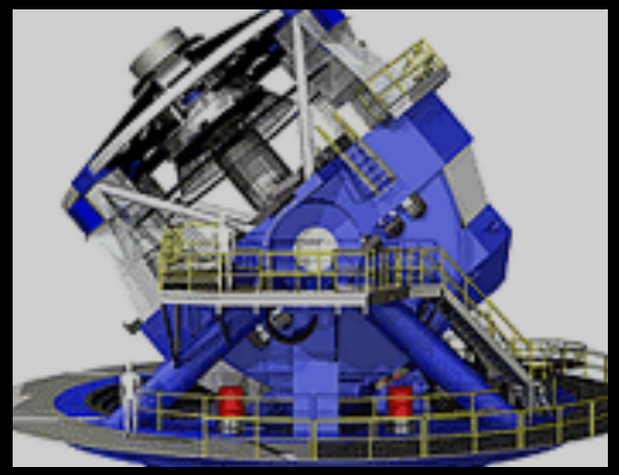
Credit: David Hardy & PPARC

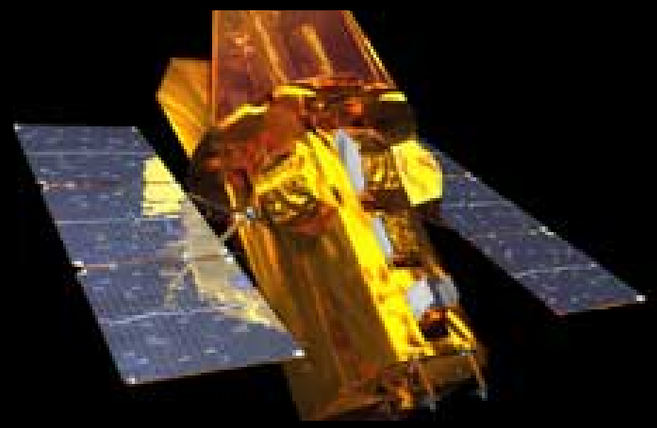
Gamma-Ray Bursts



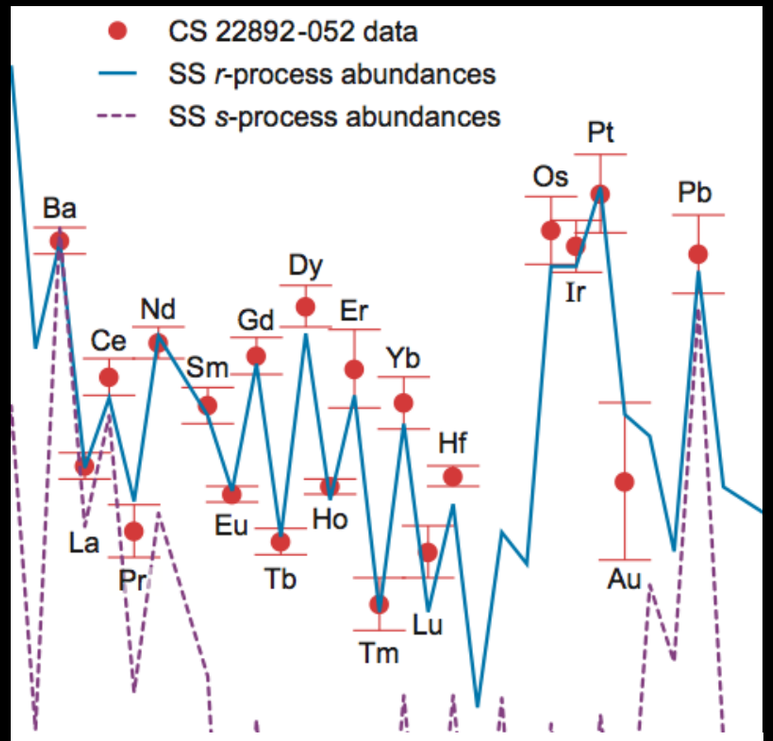
Credit: Nicolle Rager Fuller/NSF

Signals

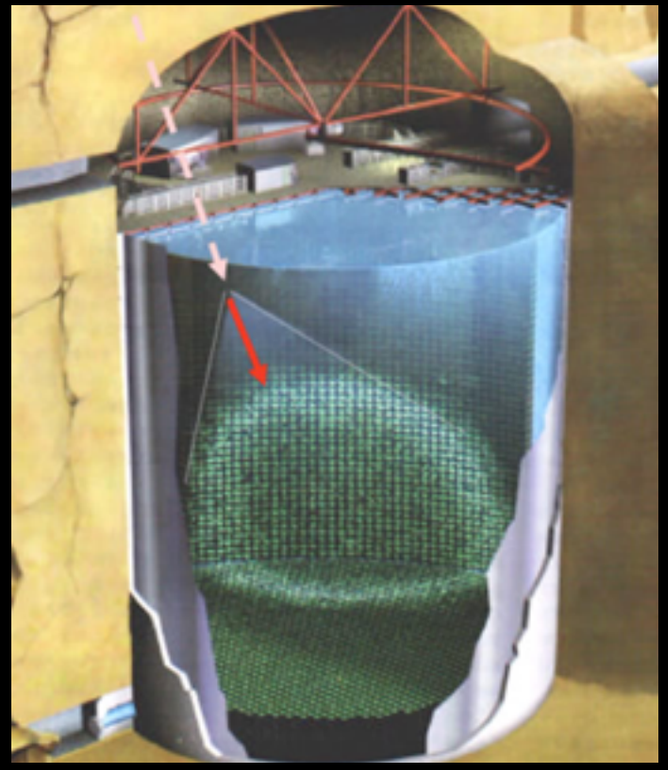




Photons



Abundances

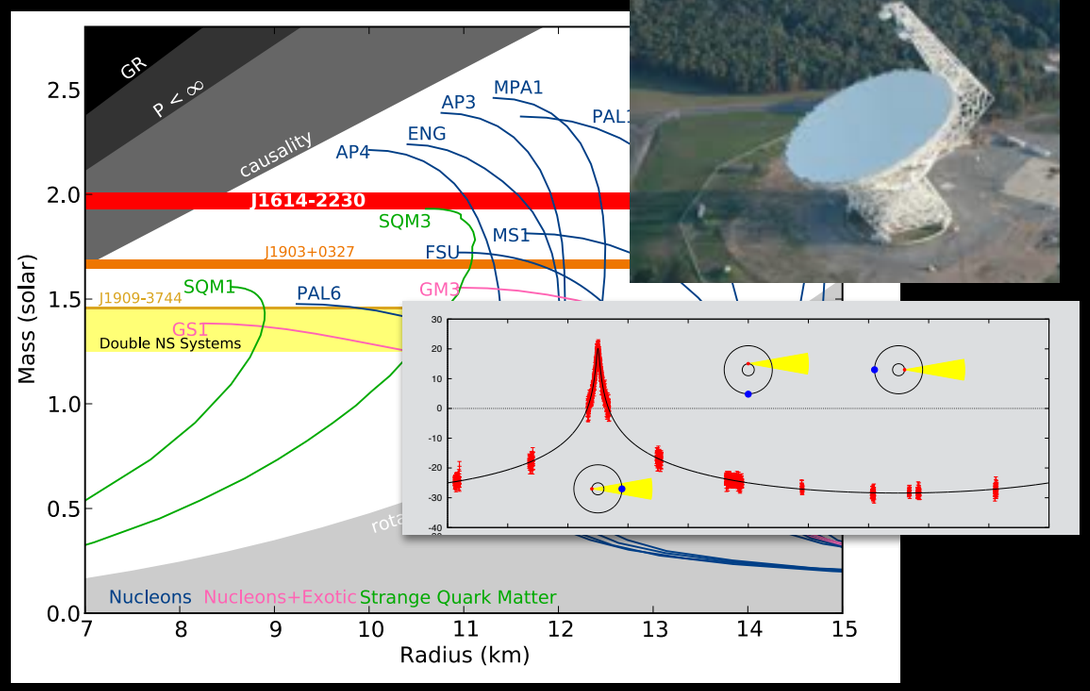


Neutrinos

Gravitational Waves

Recent Observations

Massive Neutron Star



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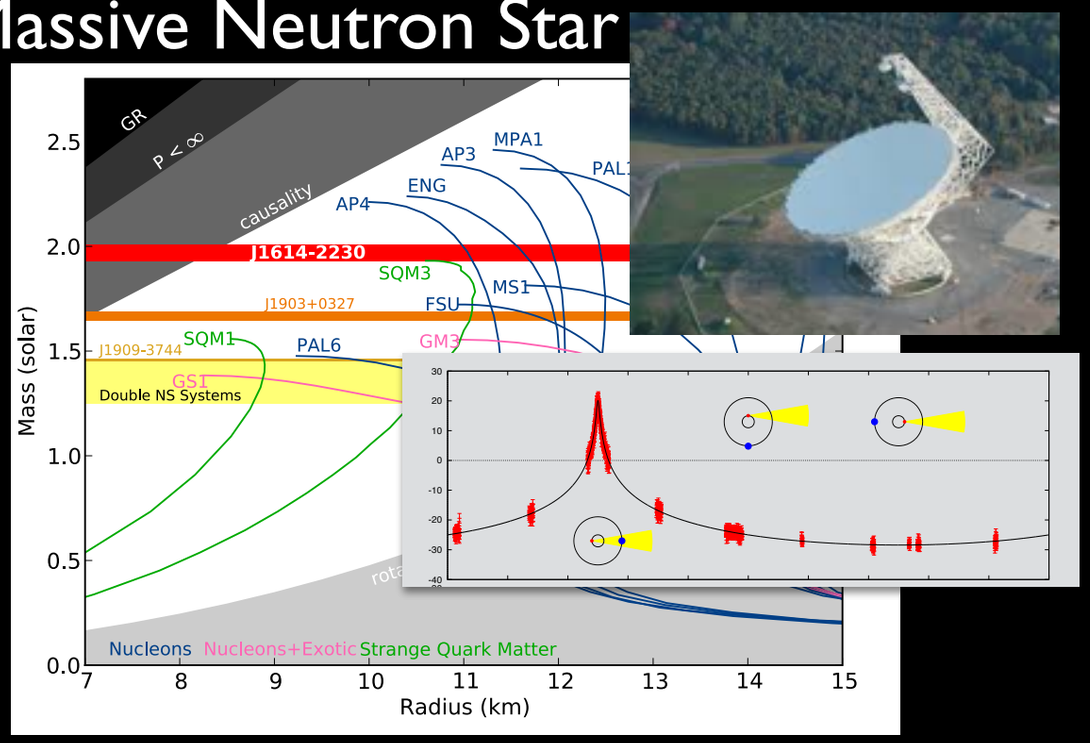
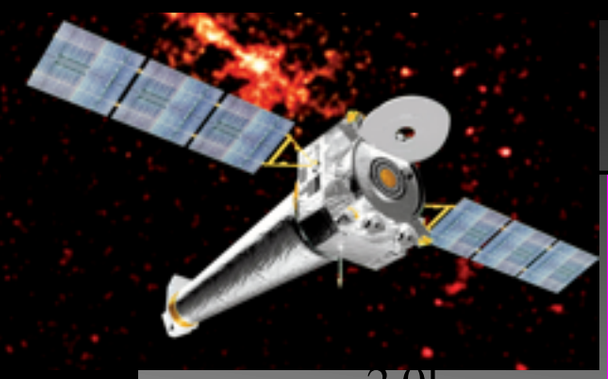
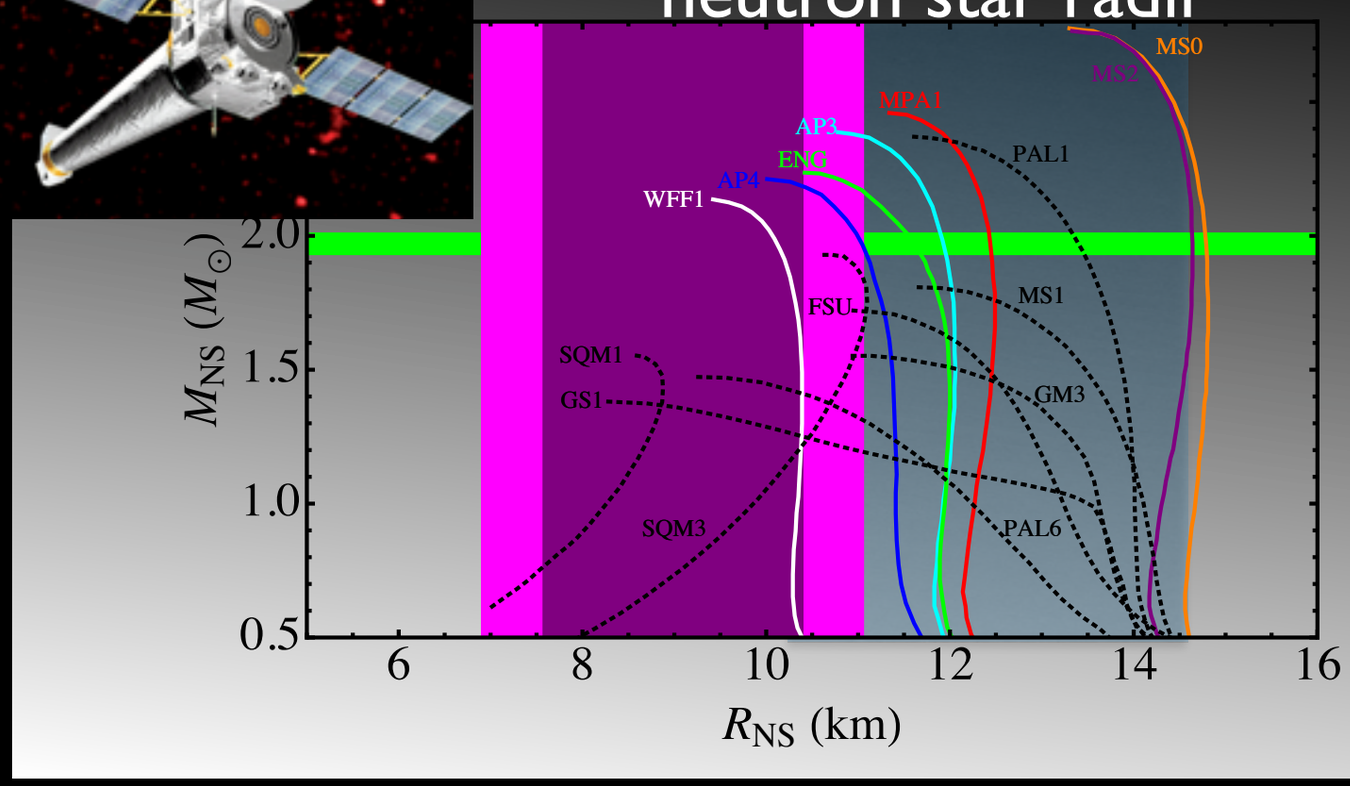




Towards a measurement of neutron star radii



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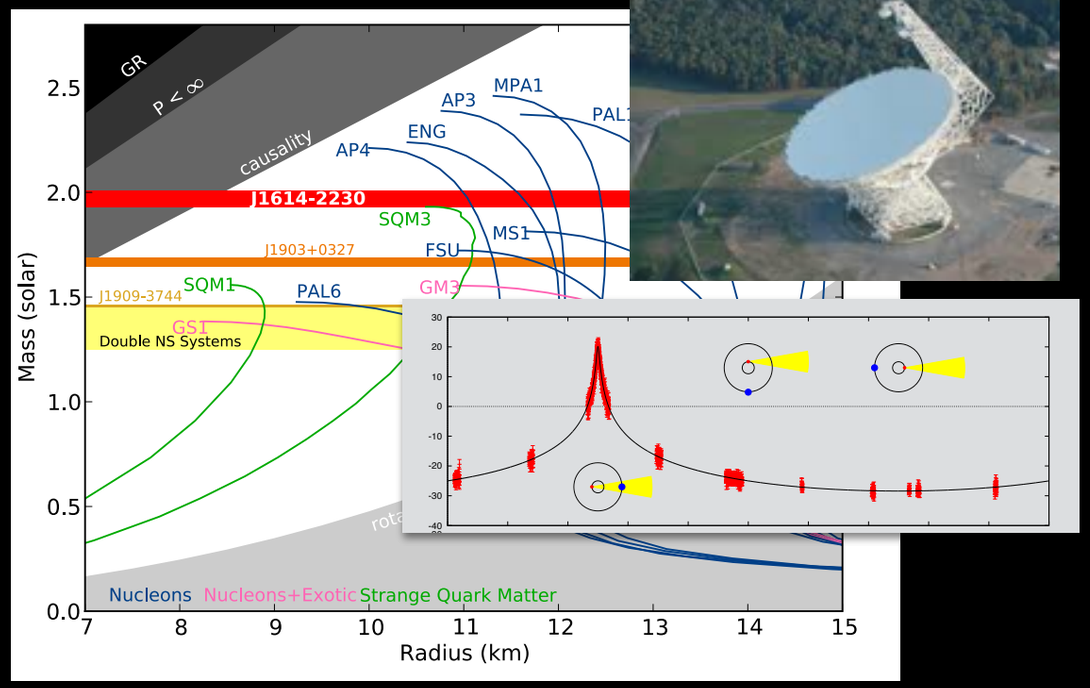
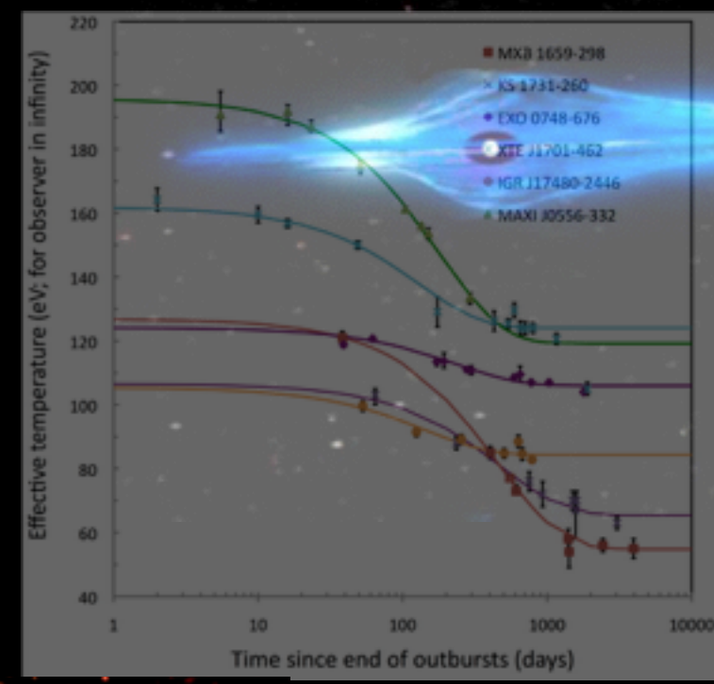


Thermal Relaxation in Accreting Neutron Stars



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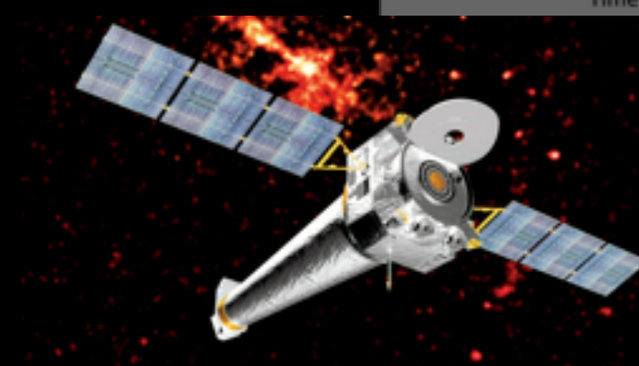

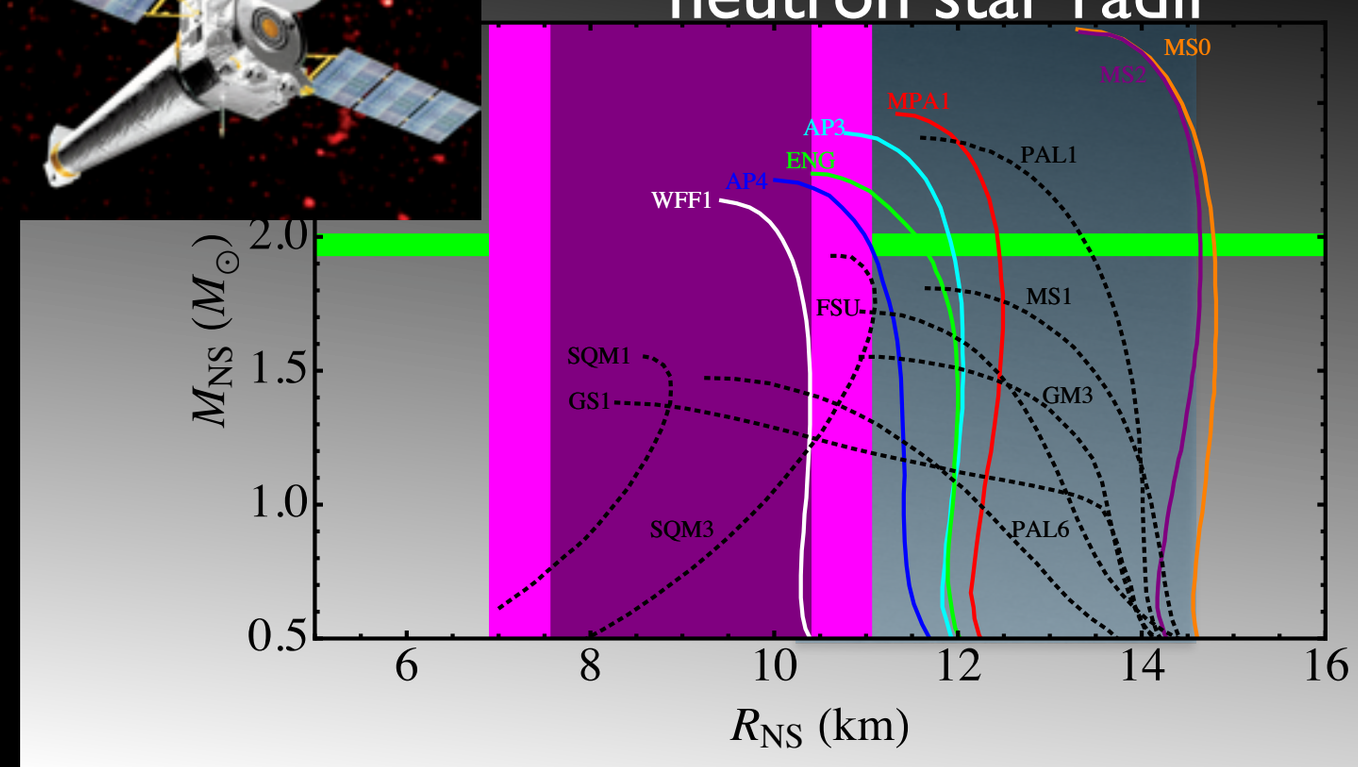

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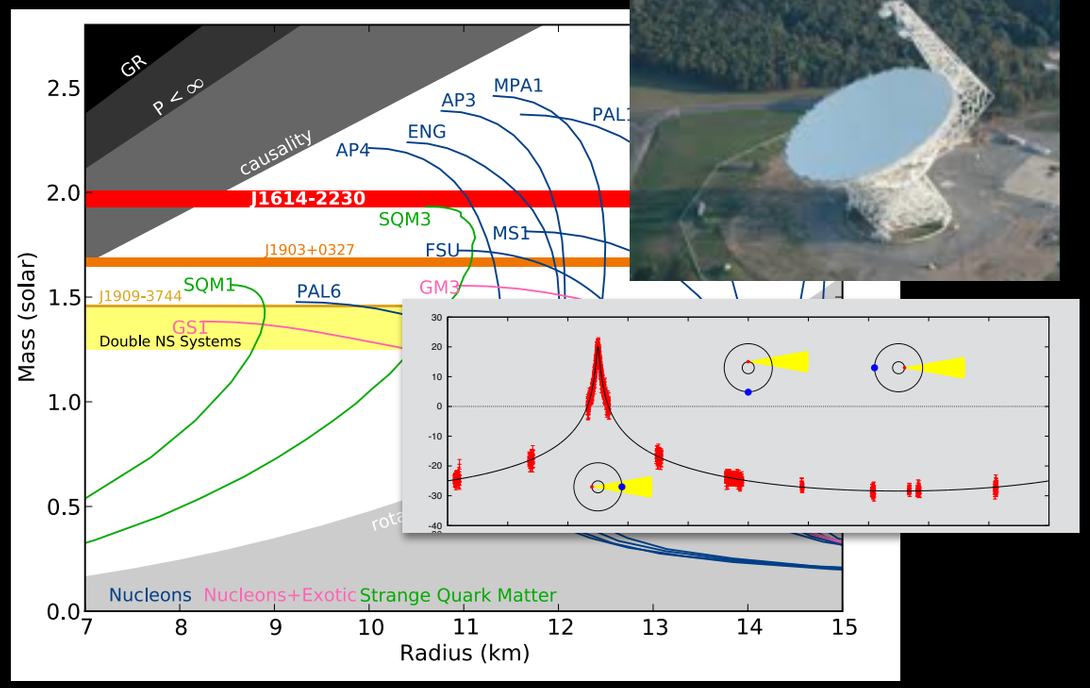

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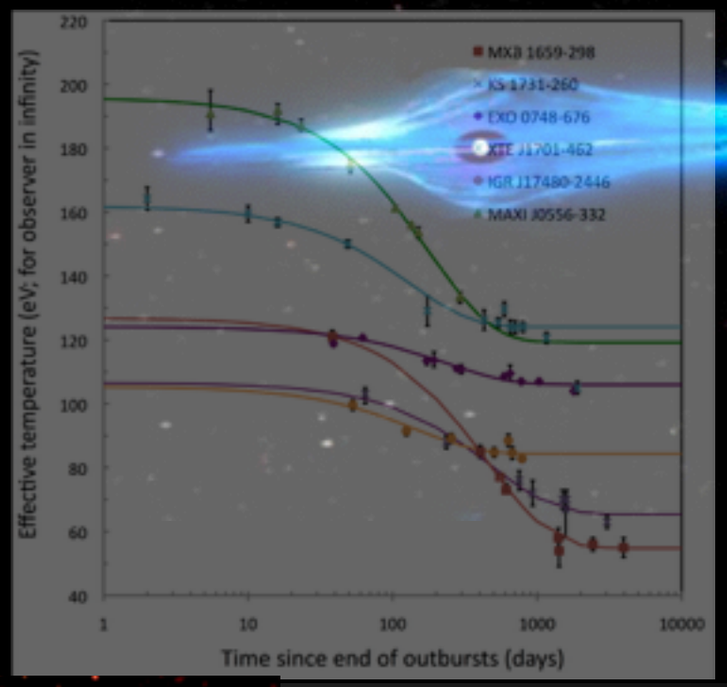
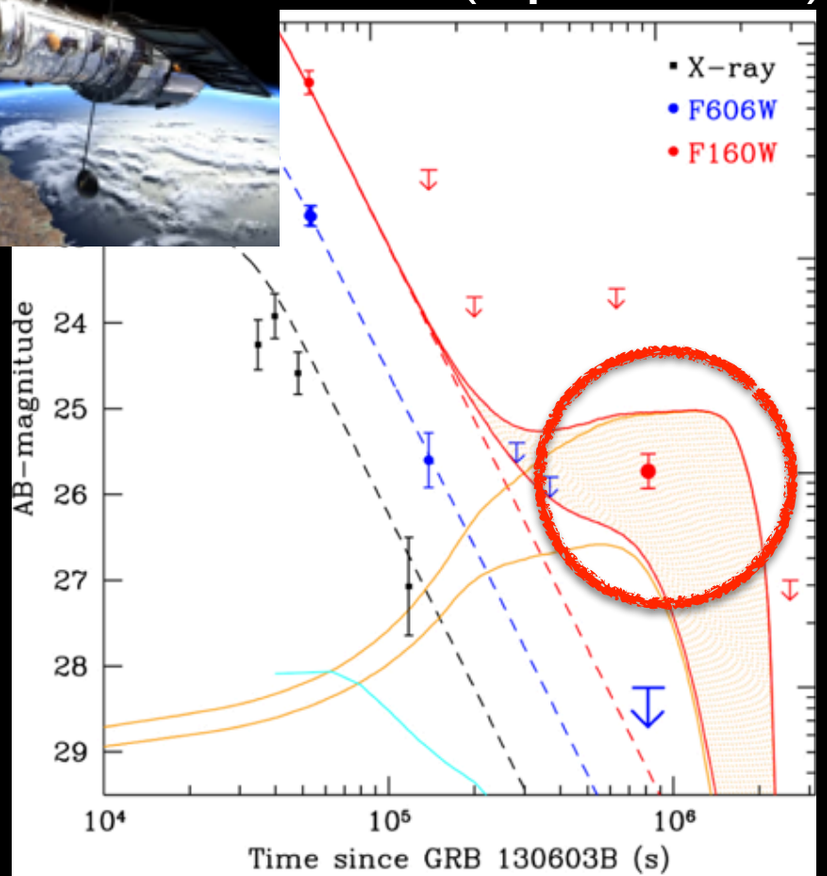
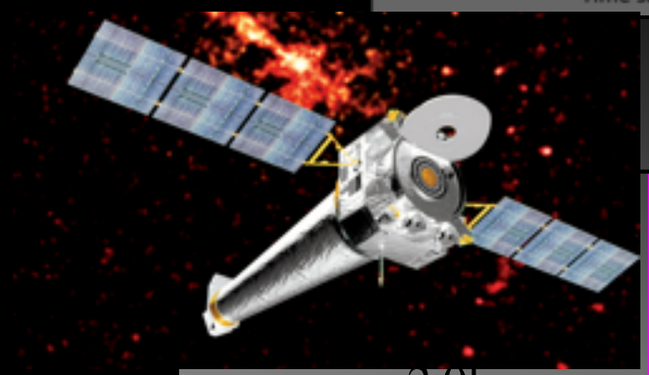


Kilo Nova (r-process ?)





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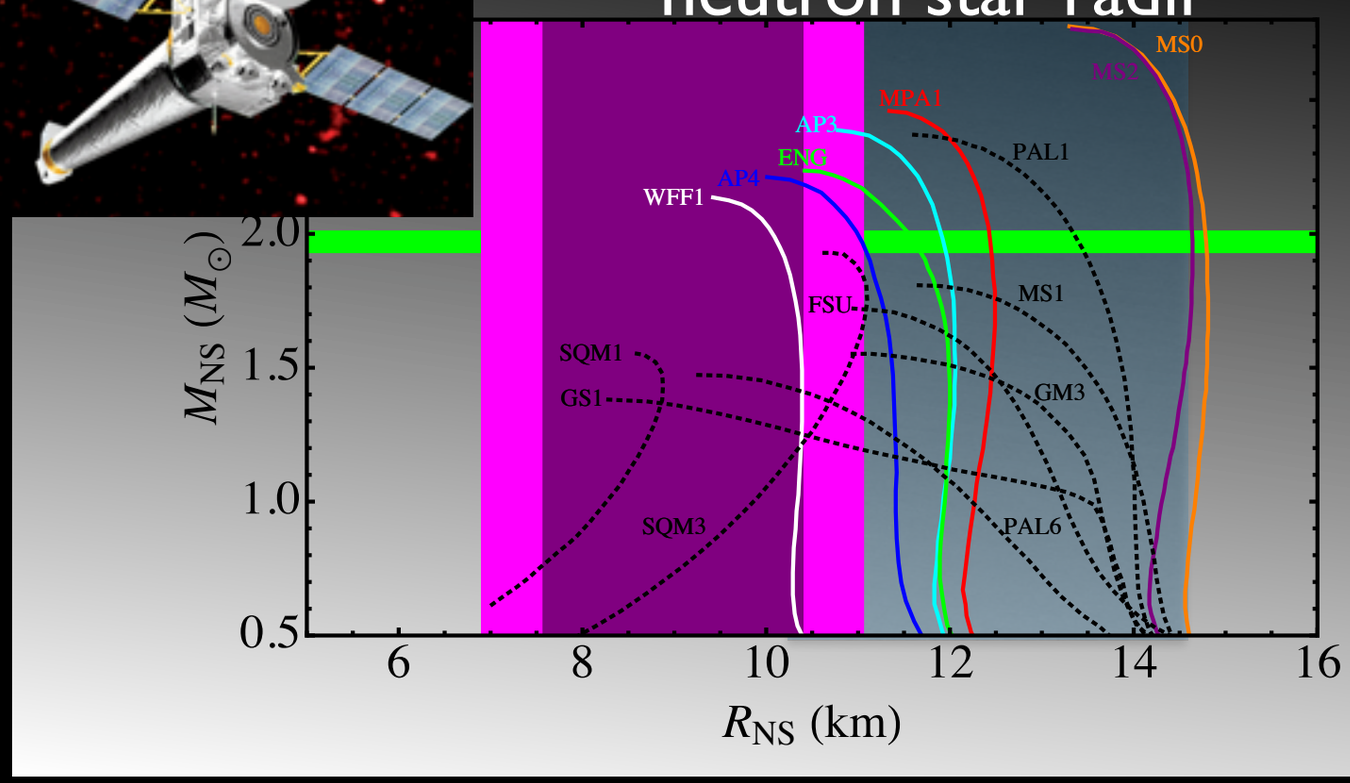
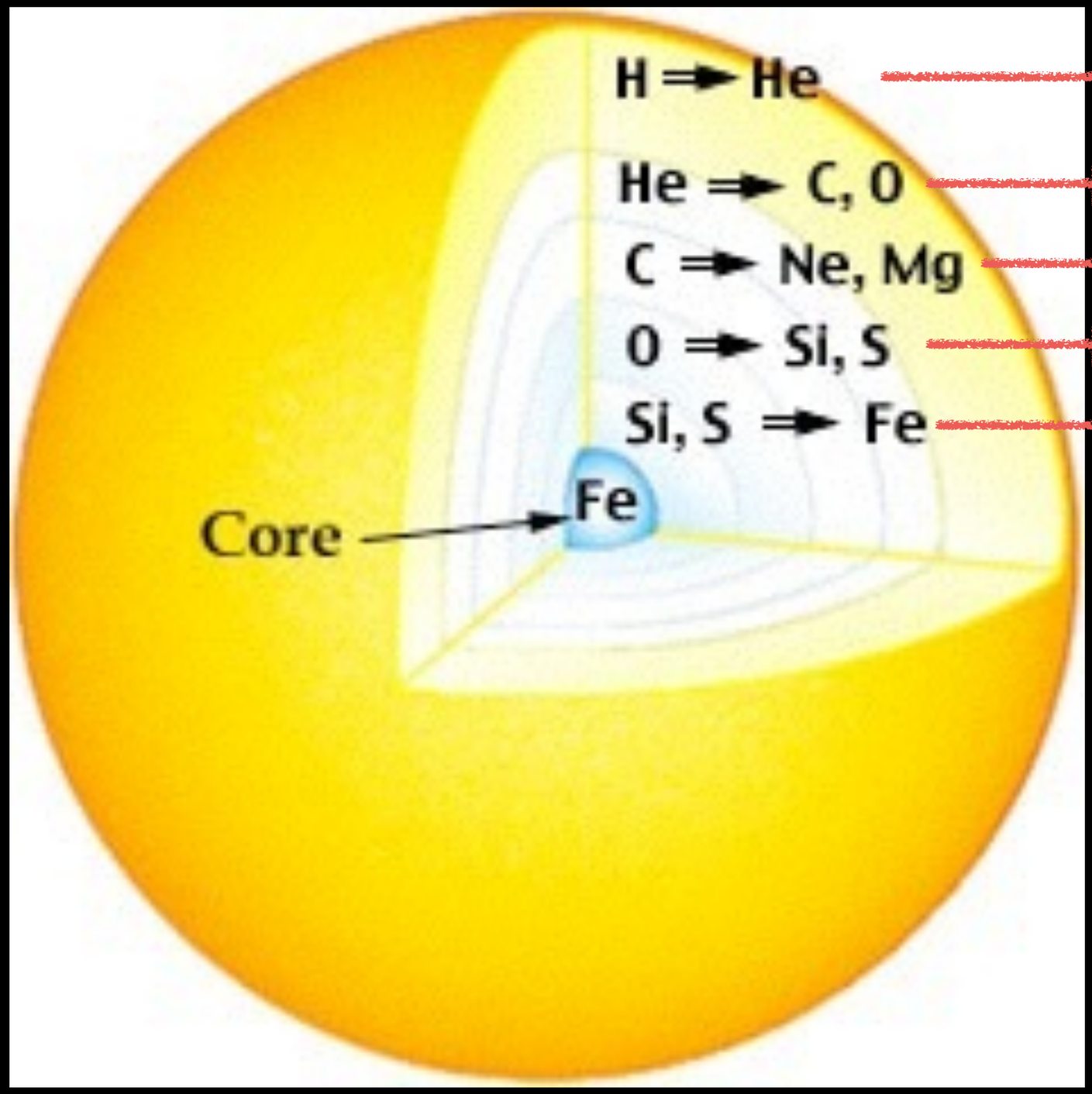


Stellar Evolution, Supernova & Neutron Stars



10 Million Years

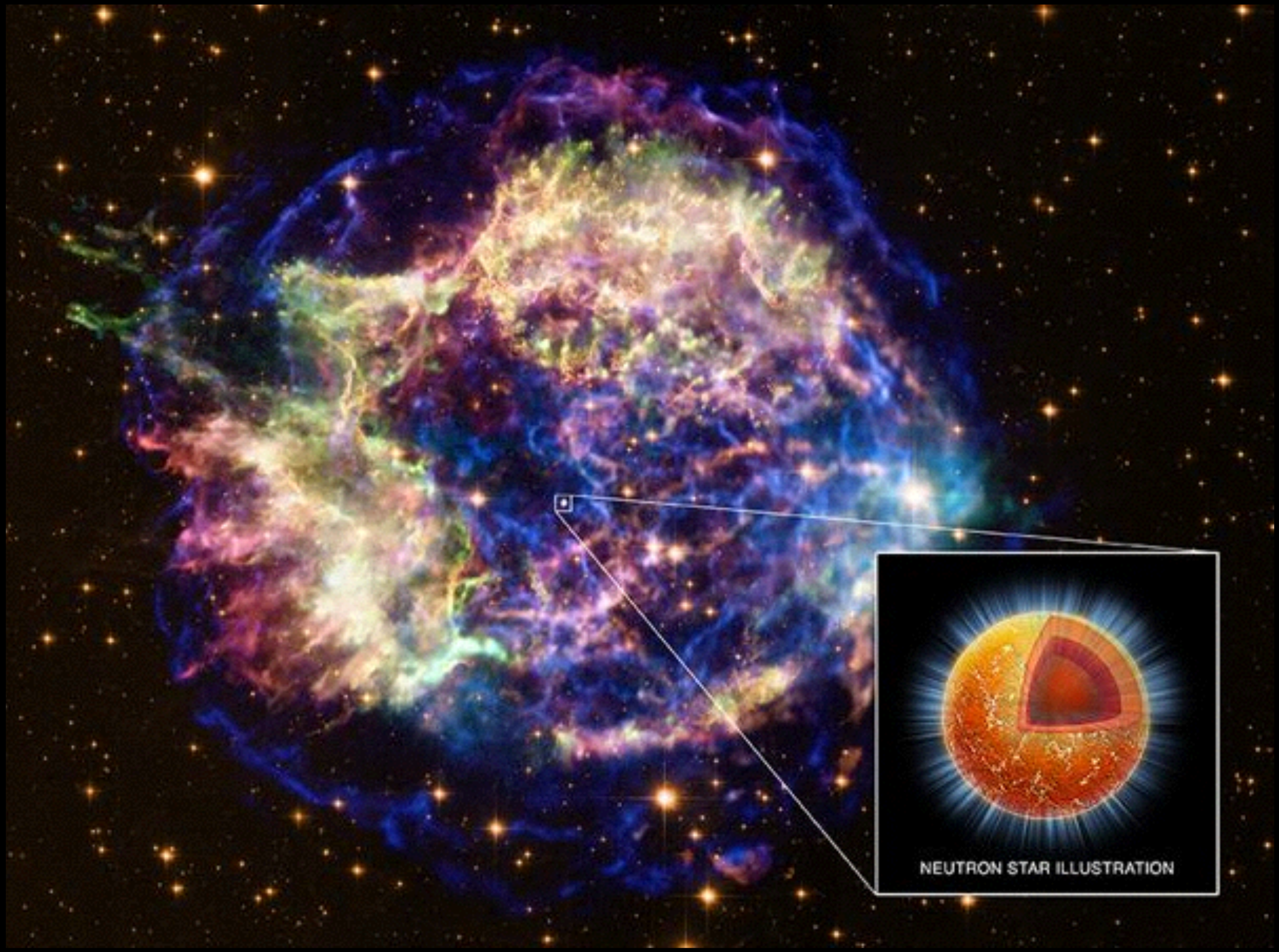
1 Million Years

1000 Years

1 Year

1 day

Stellar Evolution, Supernova & Neutron Stars



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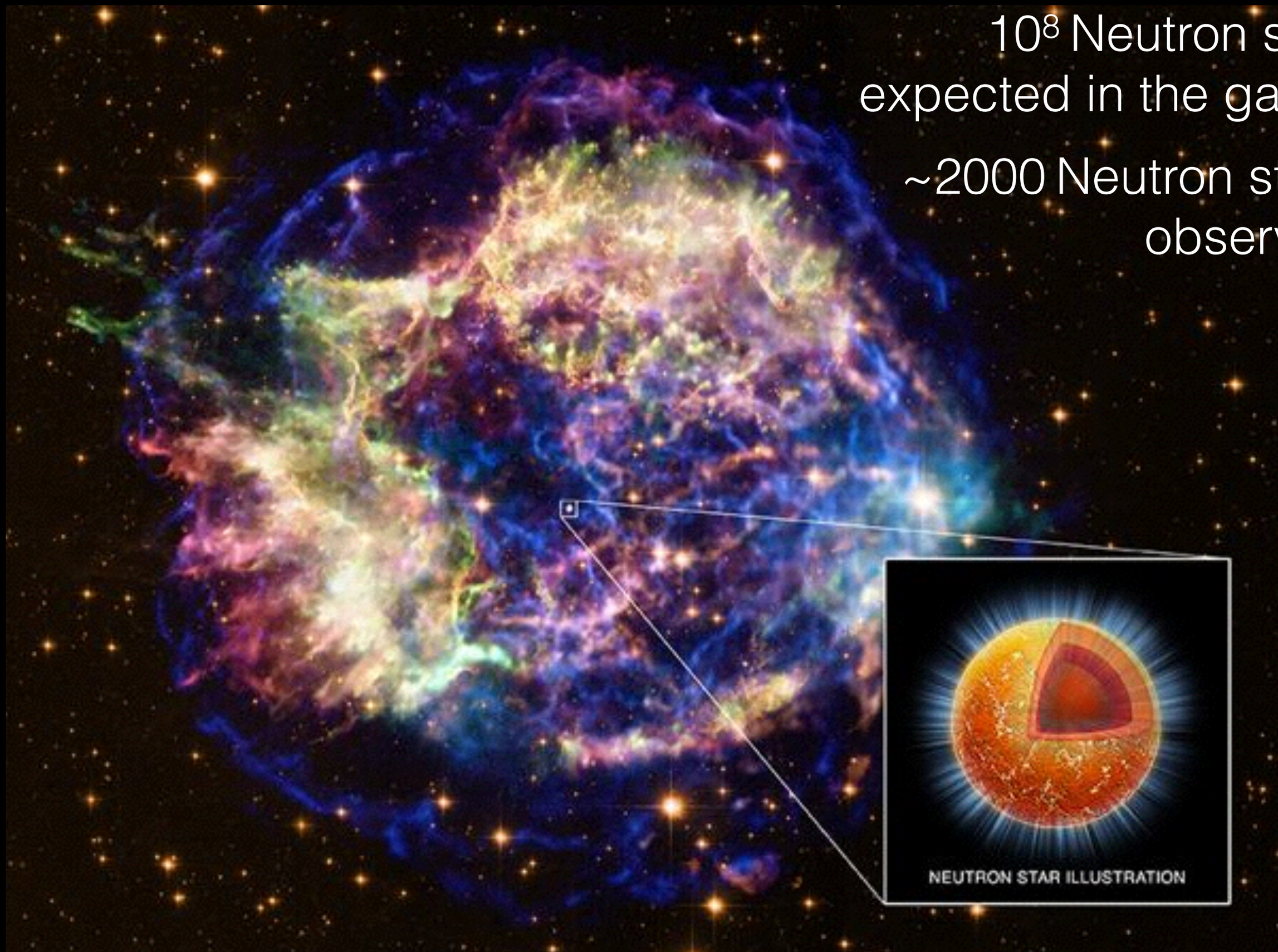
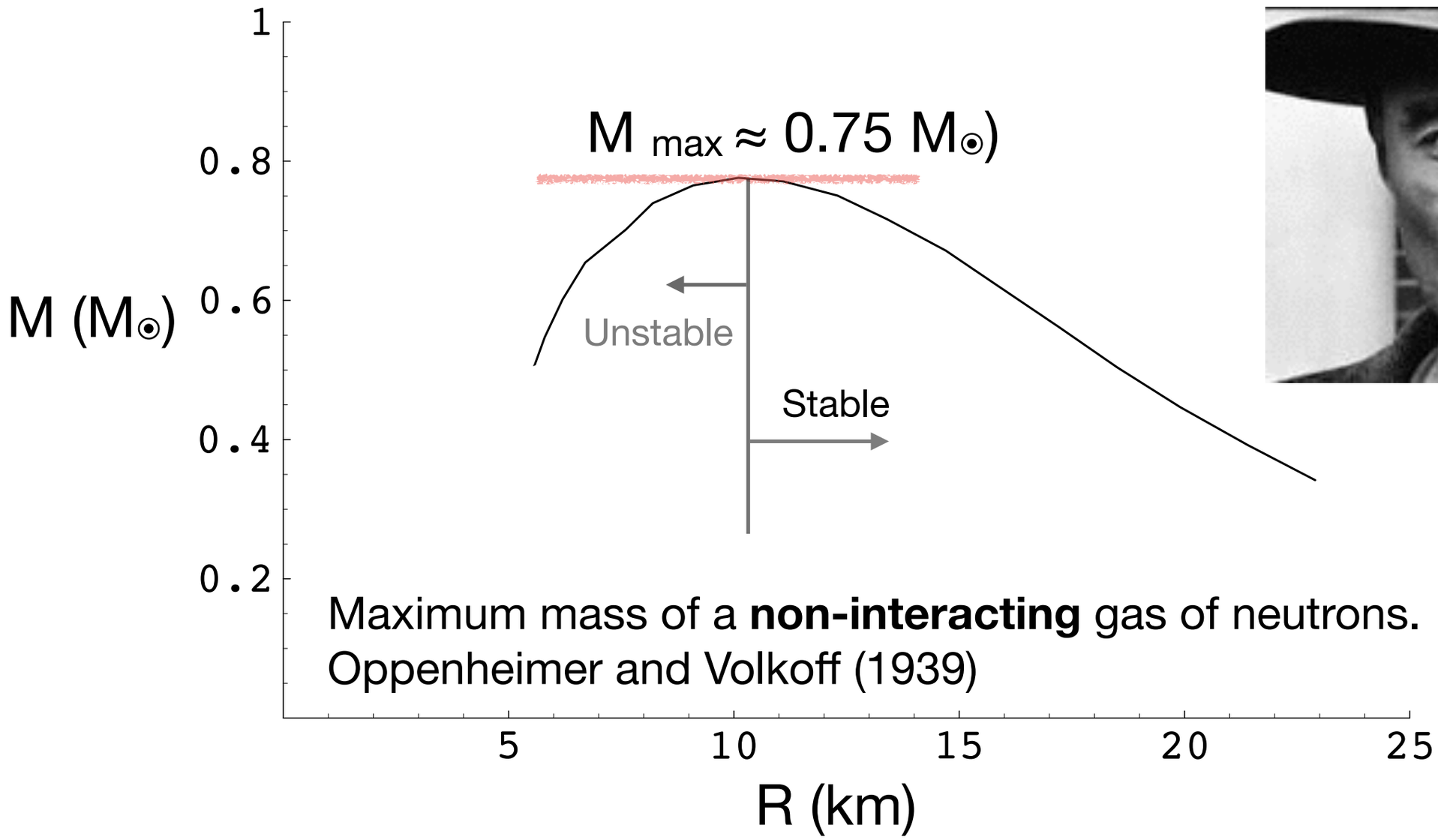


10^8 Neutron stars expected in the galaxy

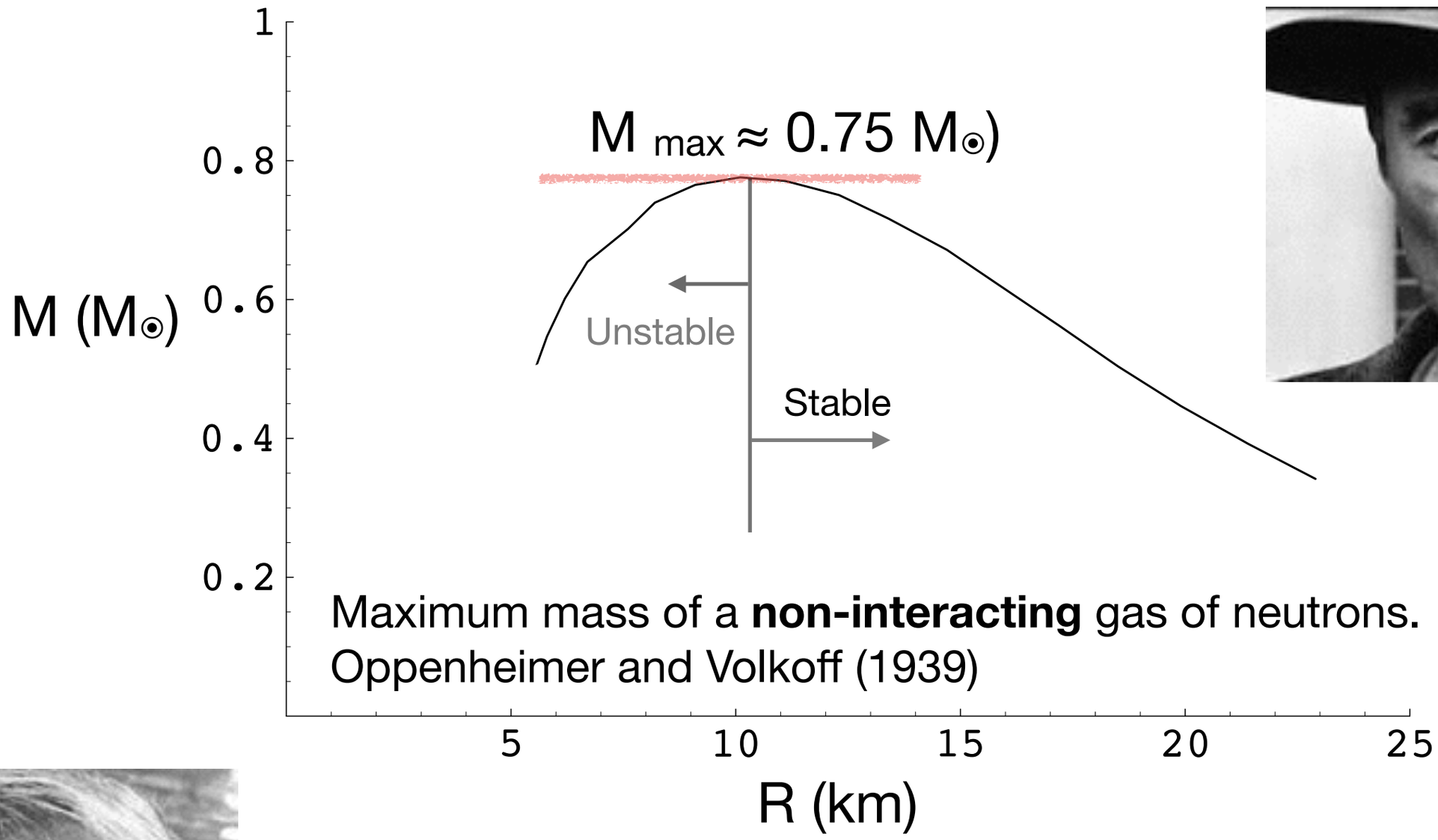
~2000 Neutron stars observed

Nuclear physics matters



Maximum mass of a **non-interacting** gas of neutrons.
Oppenheimer and Volkoff (1939)

Nuclear physics matters



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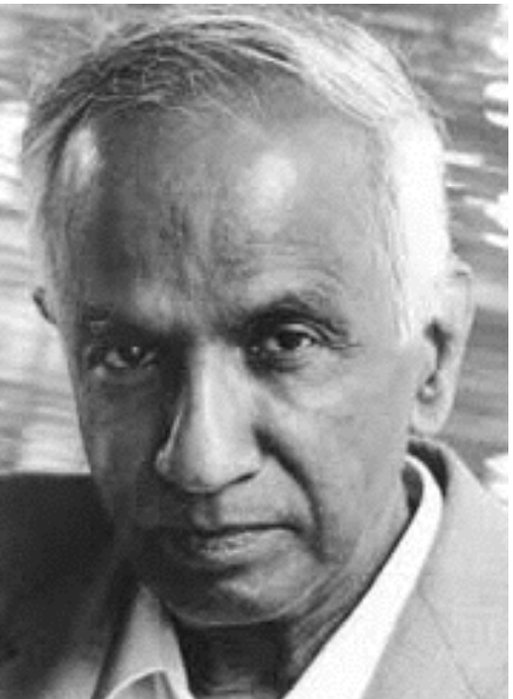
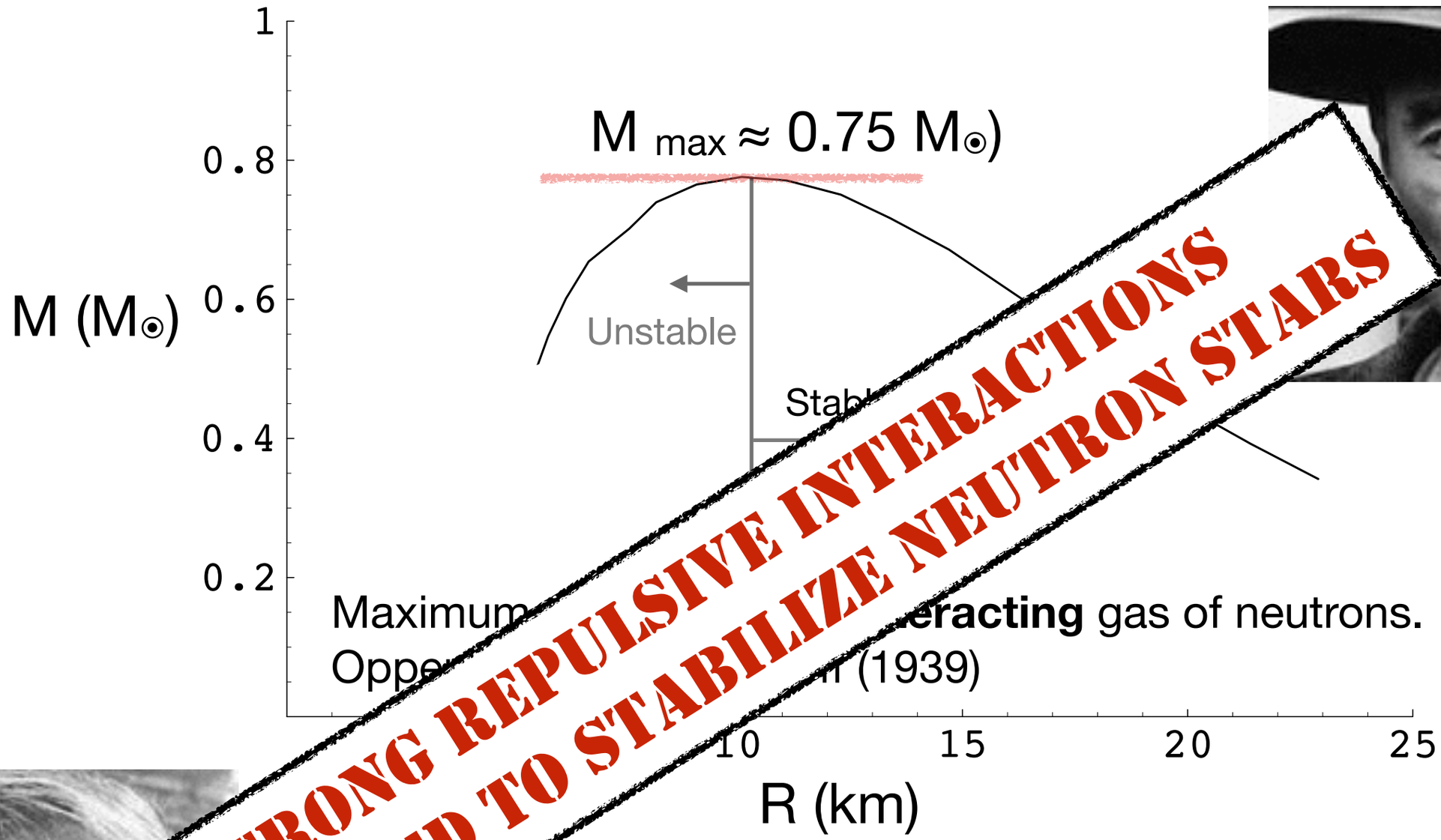


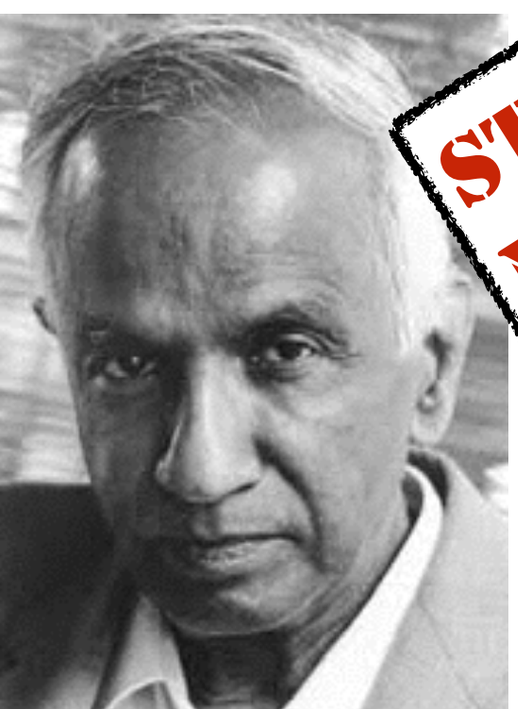
Chandrashekar had already shown that electron degeneracy pressure would support an iron core ~ 1.4 $M_\odot$ in massive stars.

If Oppenheimer's calculation of the maximum mass was correct neutron stars would not exist ! Neither would supernova !

Nuclear physics matters



STRONG REPULSIVE INTERACTIONS NEEDED TO STABILIZE NEUTRON STARS



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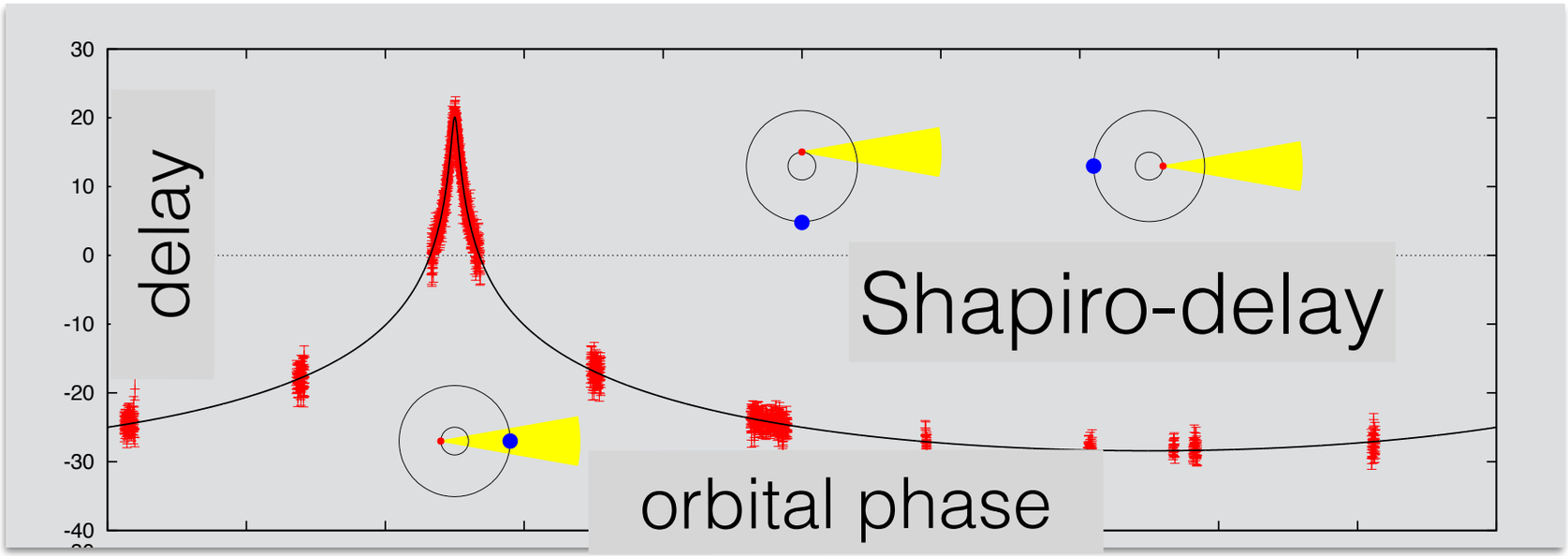
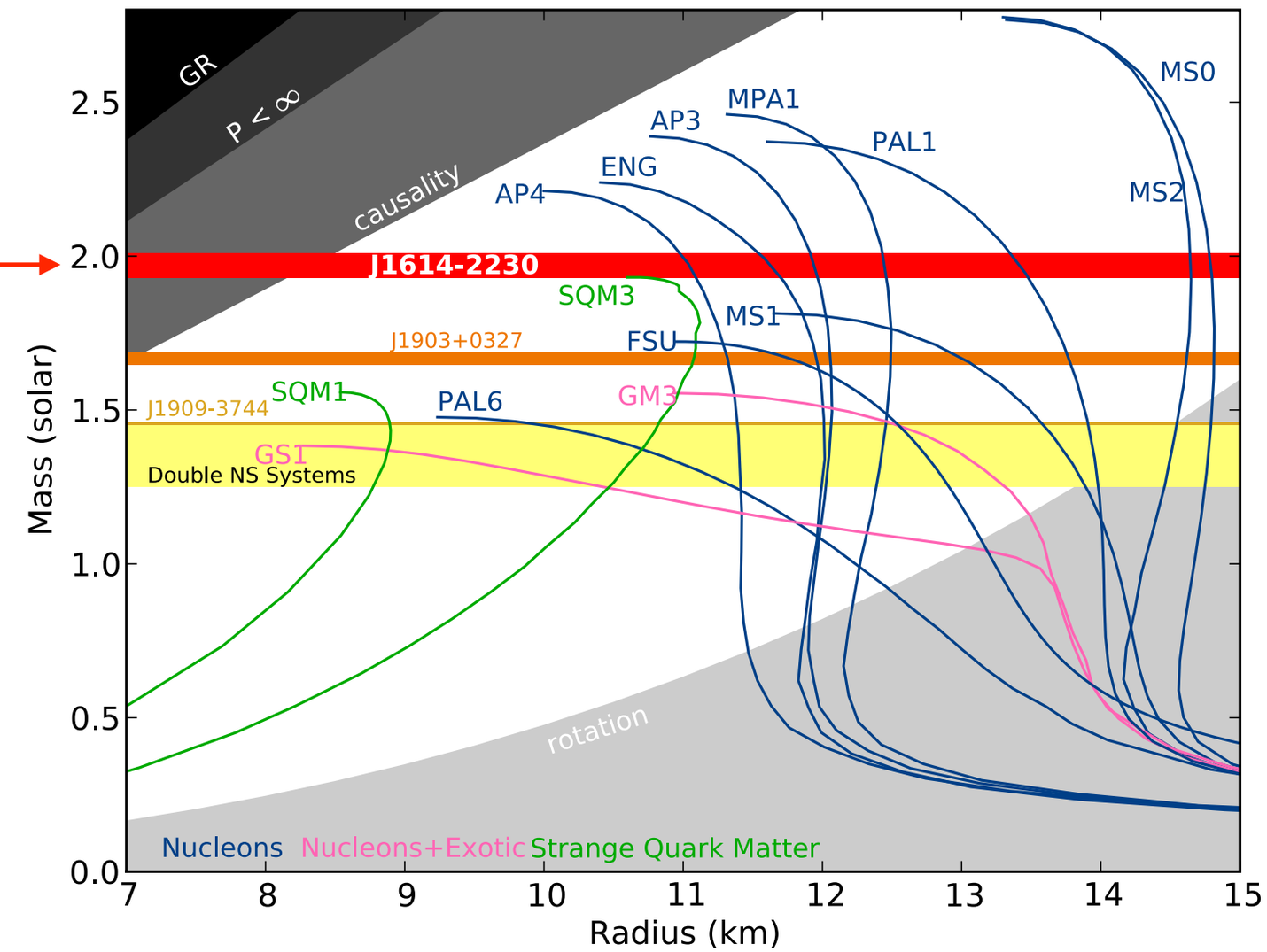
Part I:
Equation of State (EOS)

- EOS of cold dense matter uniquely determines neutron star structure.
- Pressure v/s Energy Density ↔ Mass v/s Radius

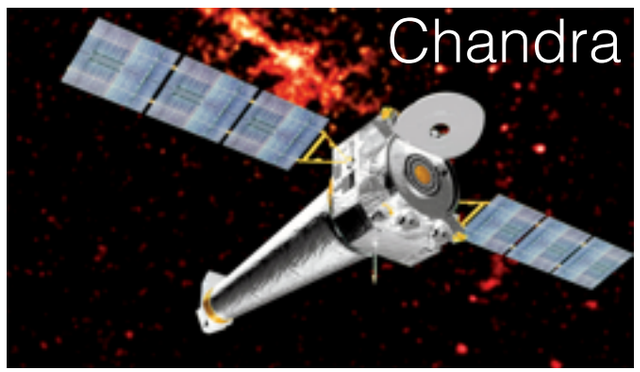
2 Solar Mass Neutron Star

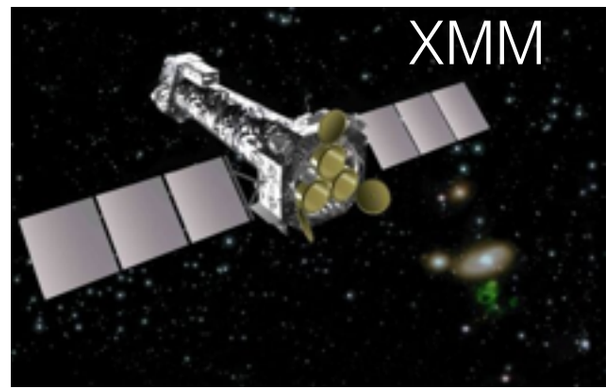


Demorest et al. (2010) discovered a massive neutron star in a binary system- using pulsar timing.
A precise mass determination was possible because Shapiro-delay was detectable.



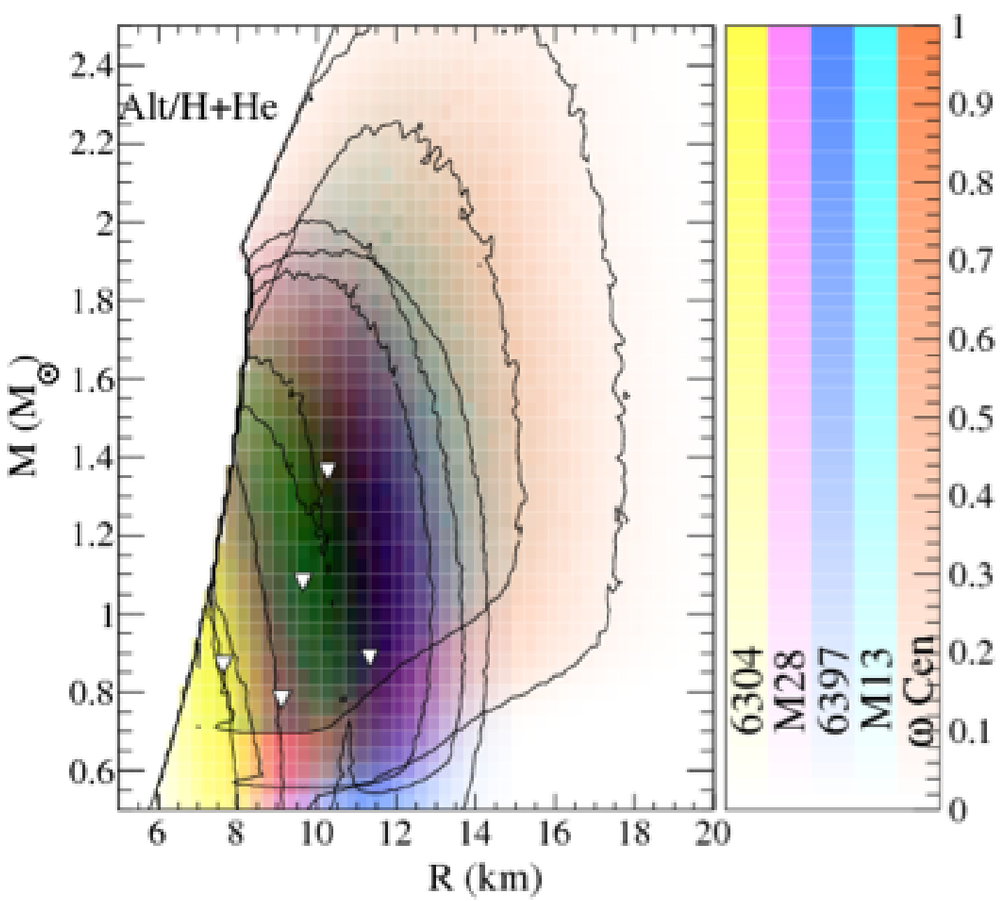
Radii from Quiescent NS





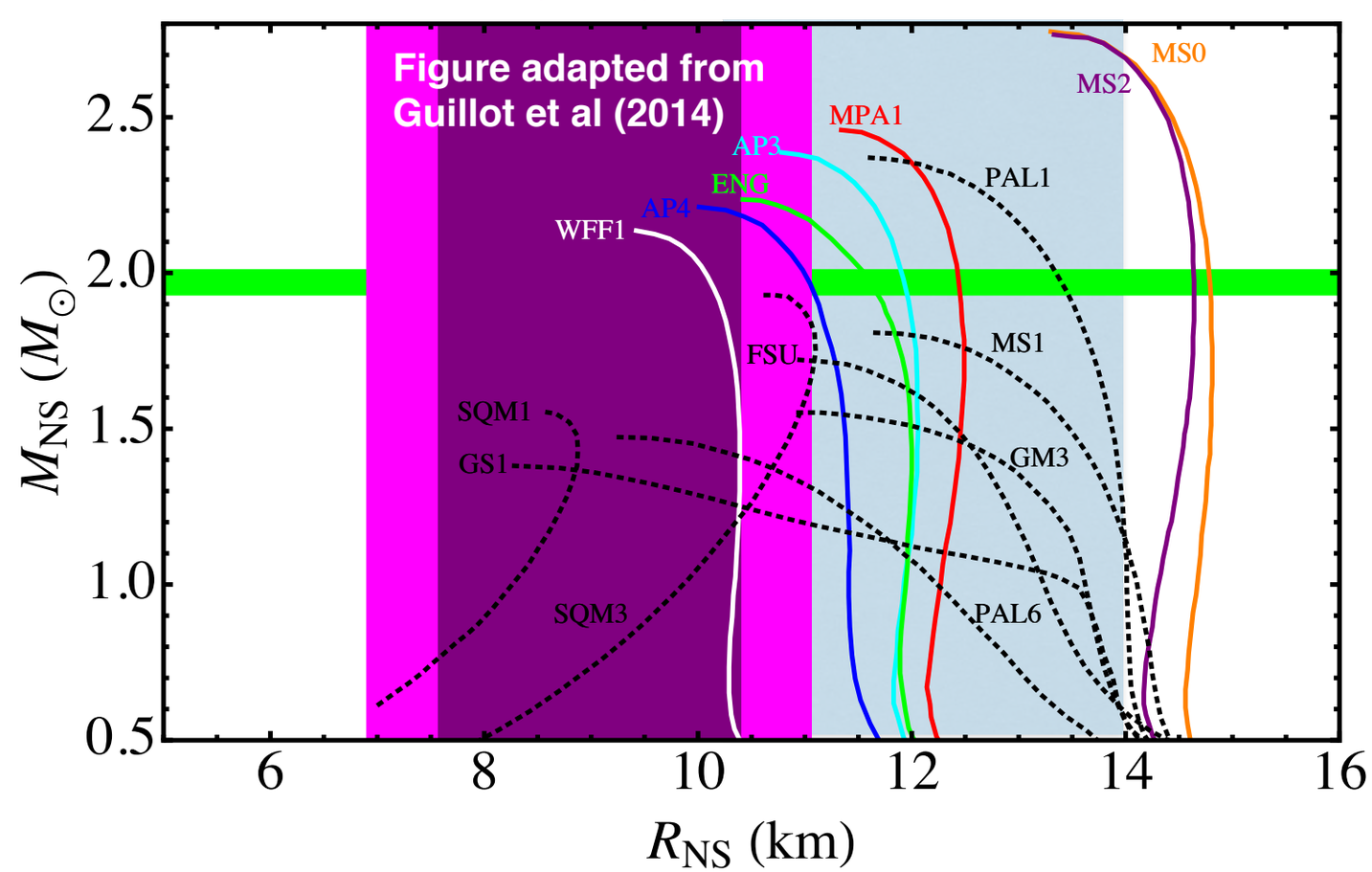
- Can extract radius subject to the assumptions: (i) surface temperature is uniform; (iii) atmosphere composition is known and (iii) distance and inter-stellar absorption is measured.

Heinke et al, and Steiner & Lattimer (2014)

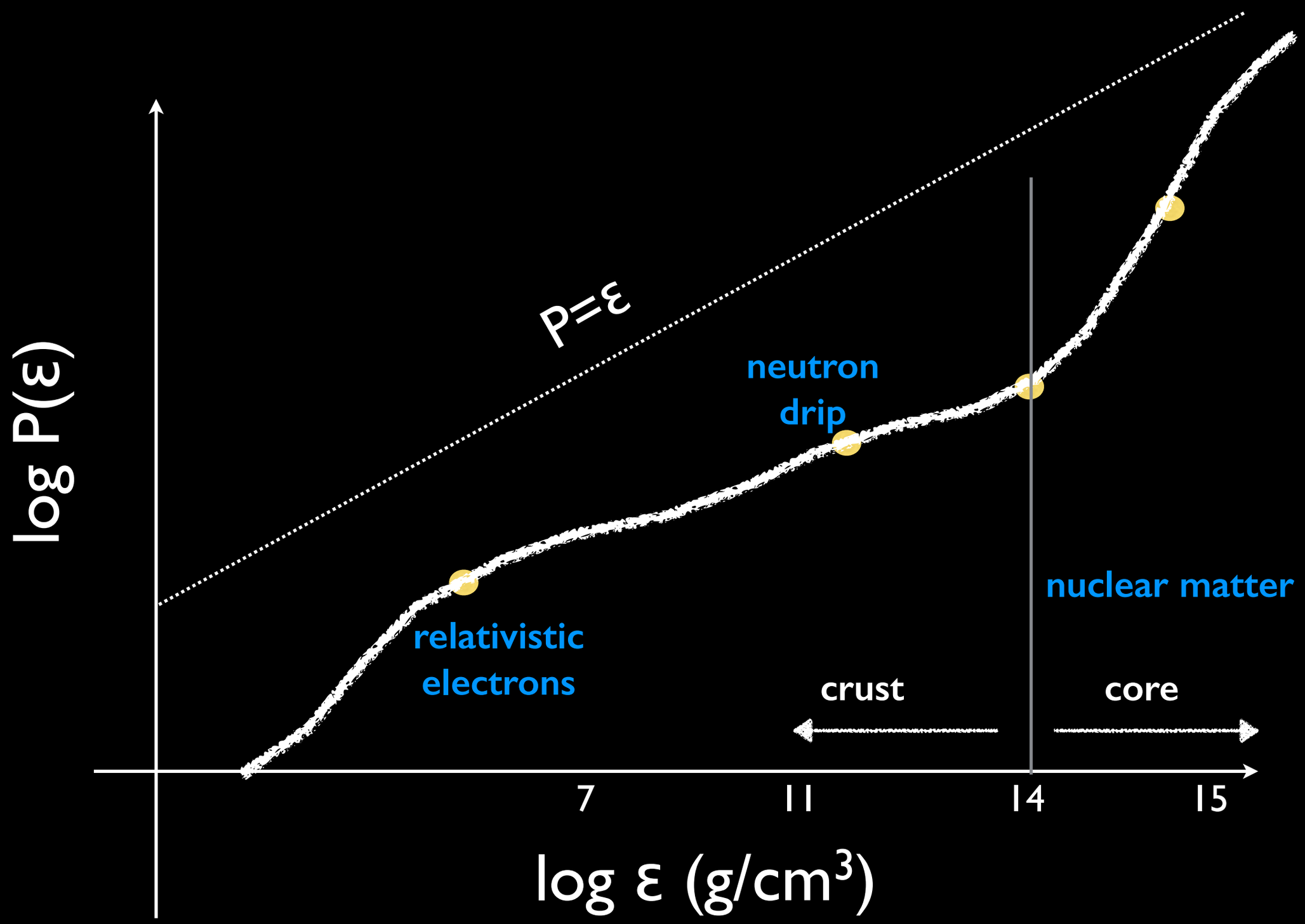


Guillot et al (2014)

Steiner et al, Heinke et al (2014)



PRESSURE V/S ENERGY DENSITY (EOS)



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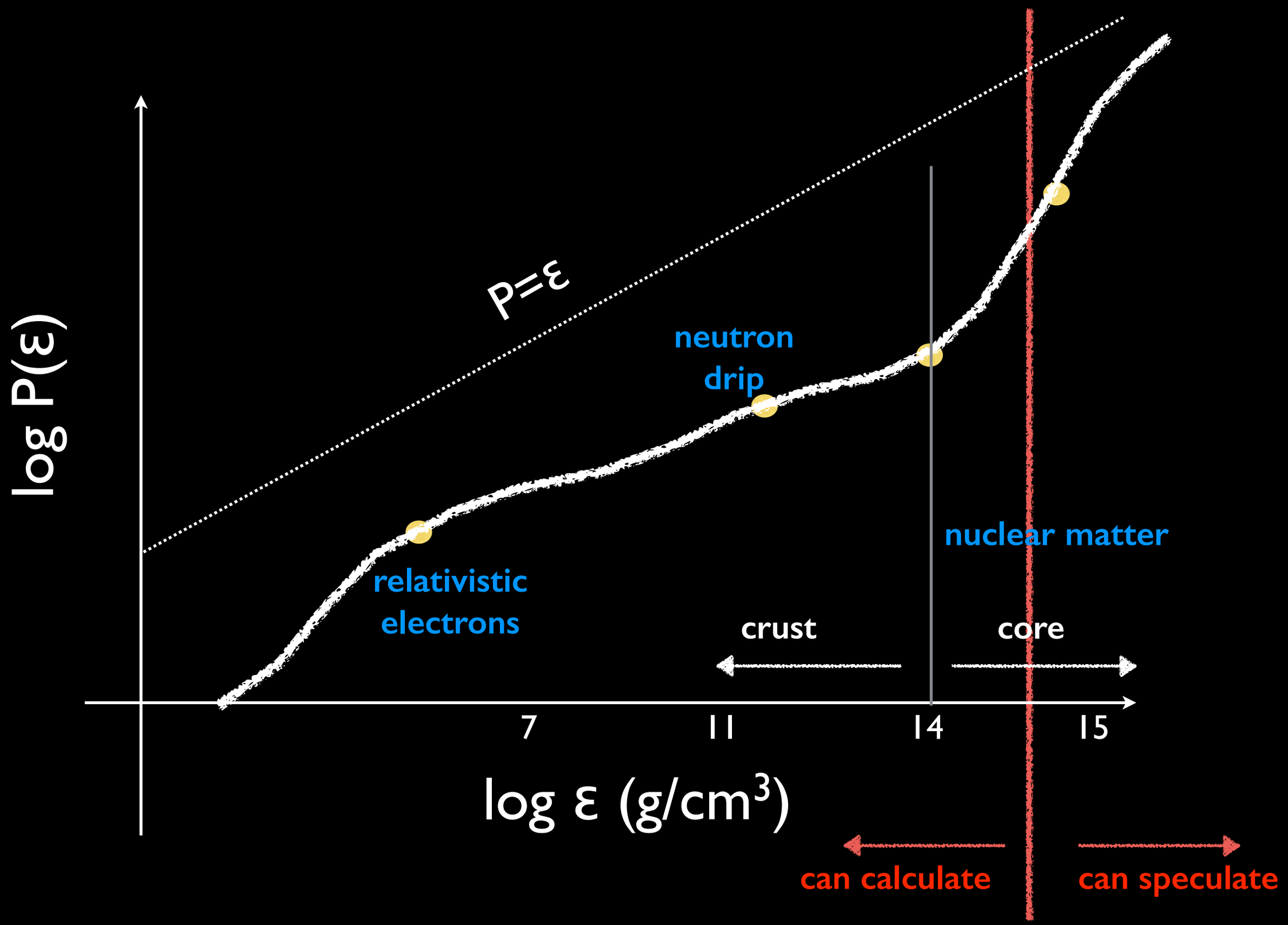

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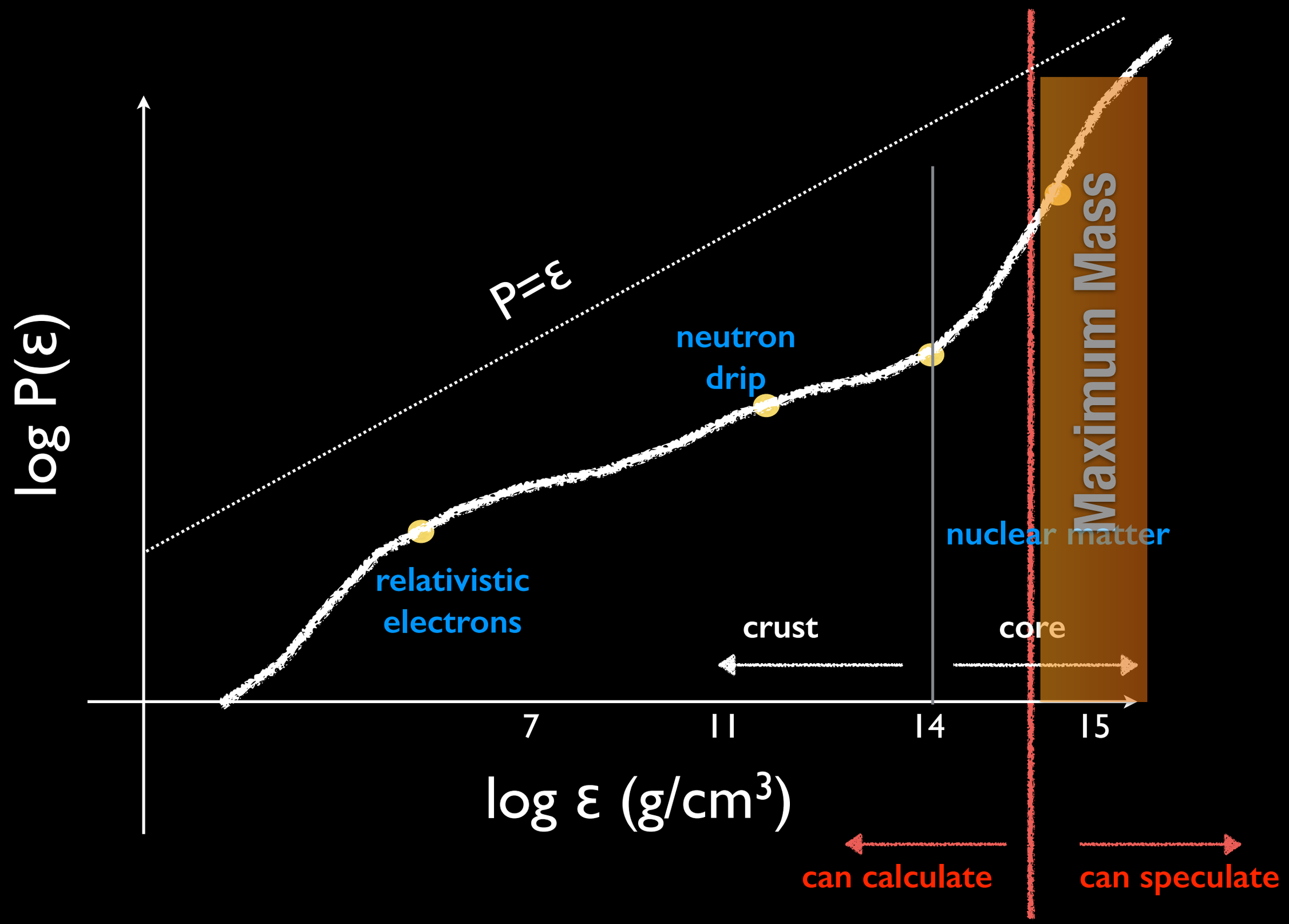

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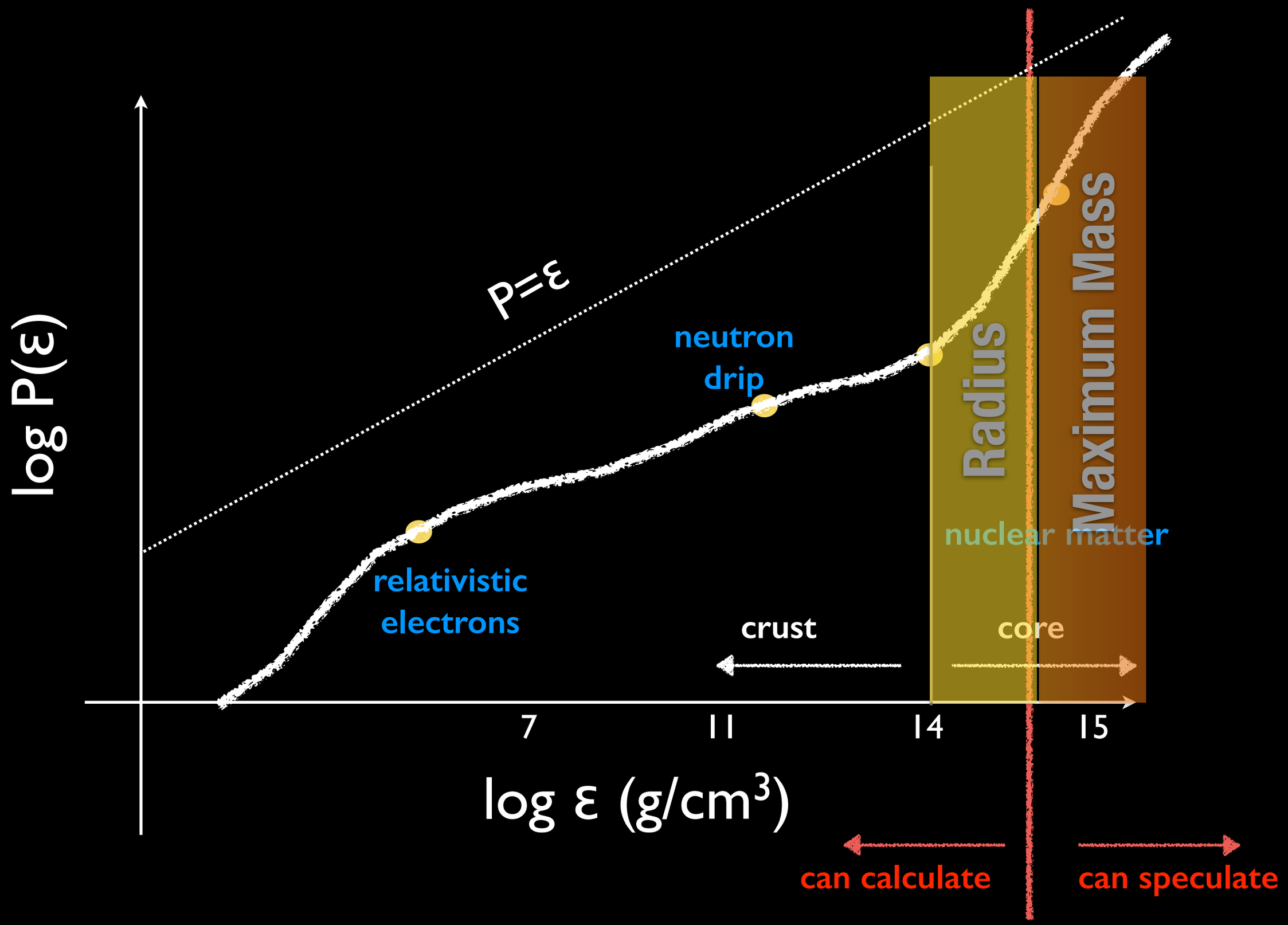

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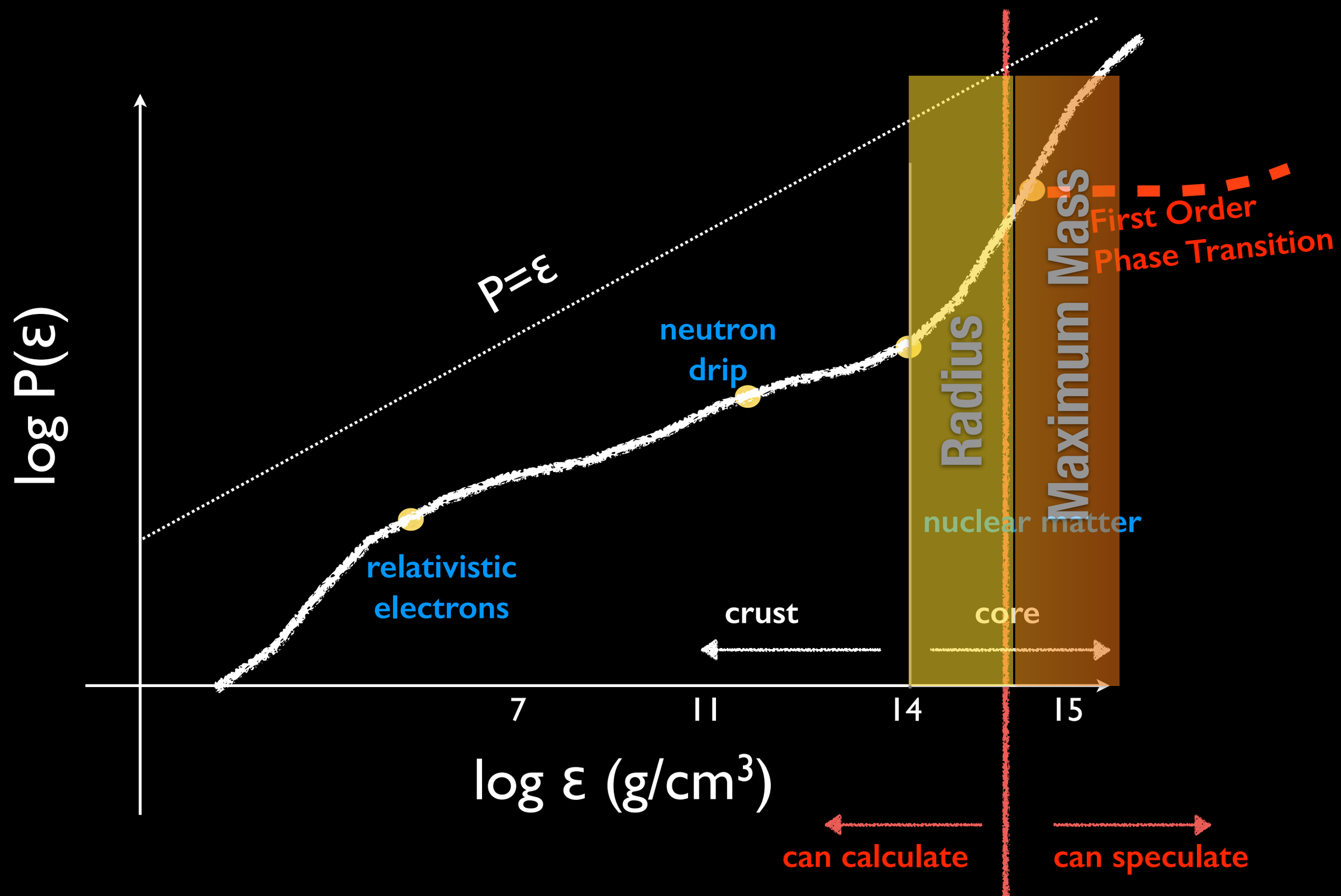

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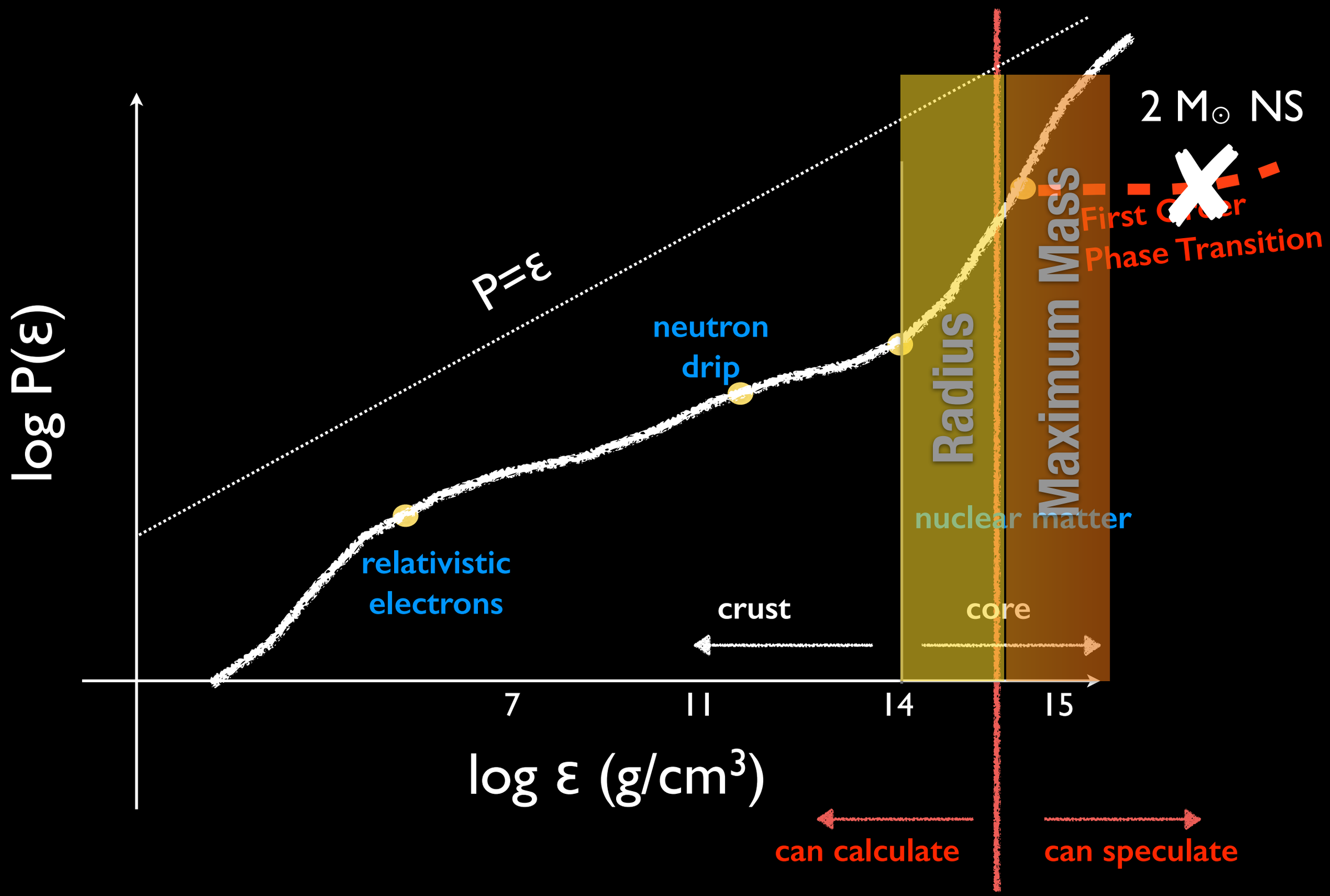
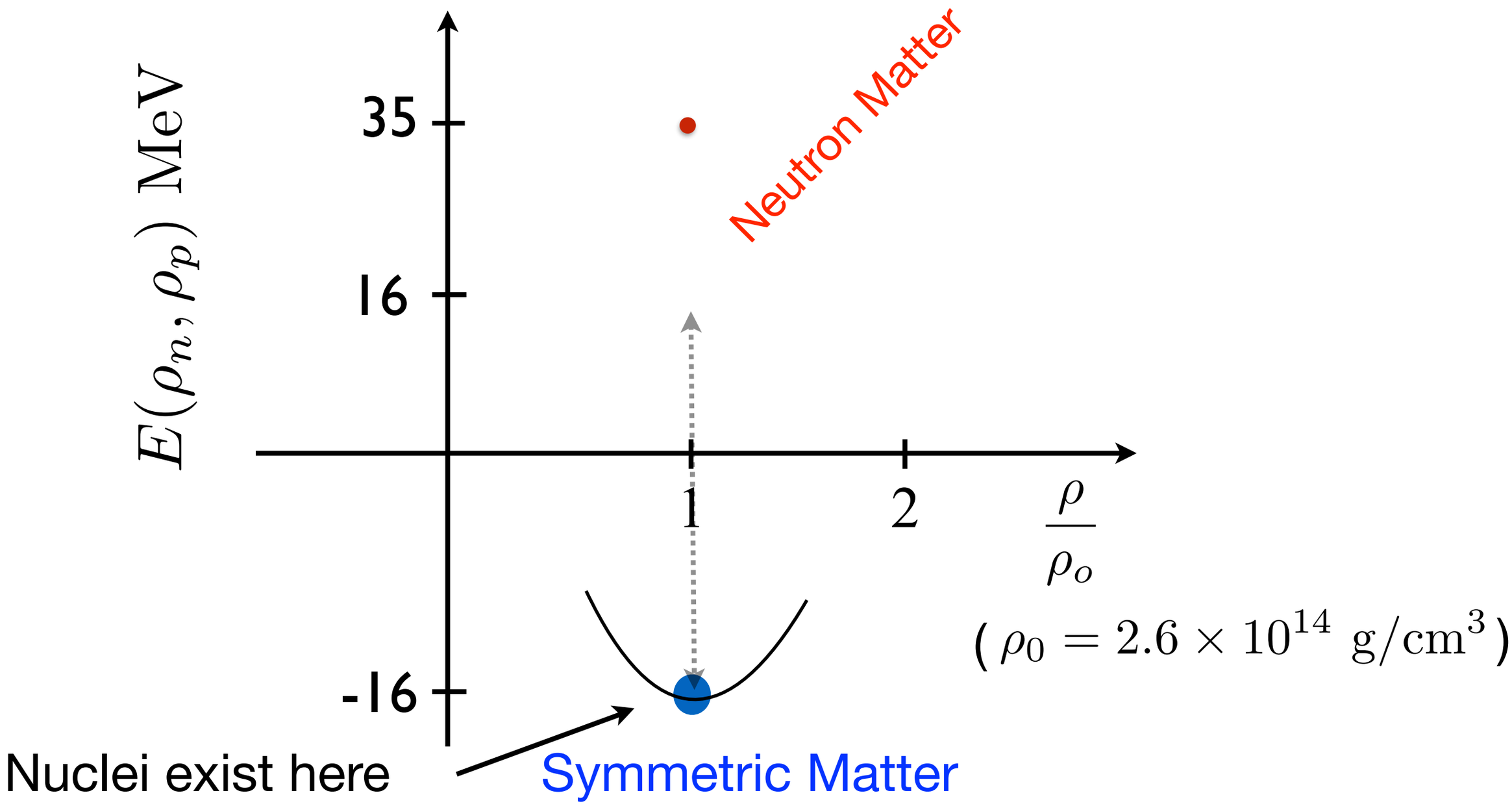


Equation of State of Neutron Matter

$$\varepsilon(\rho) = \rho\, E(\rho) \qquad P(\rho) = \rho^2 \frac{\partial E(\rho)}{\partial \rho}$$



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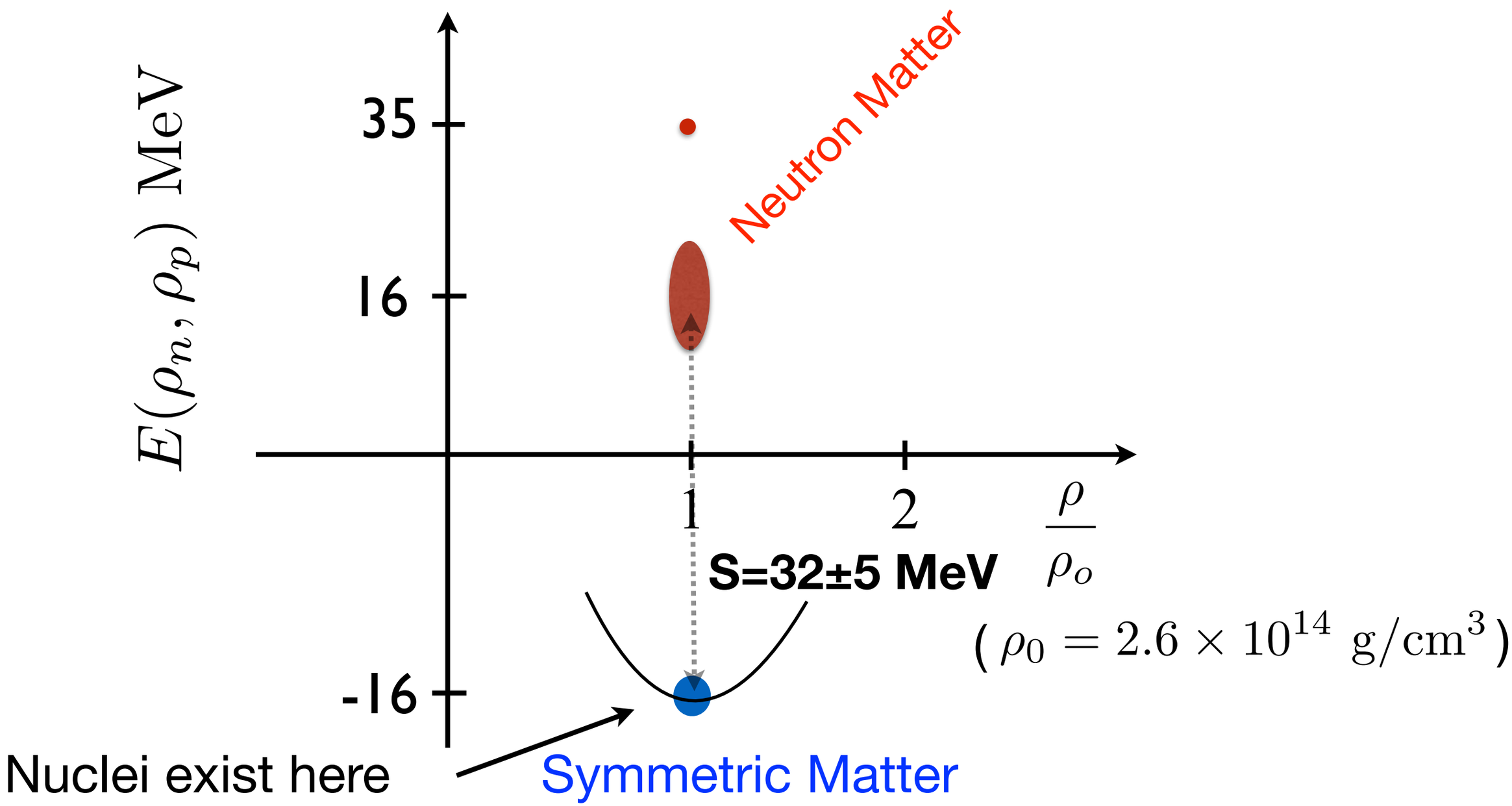

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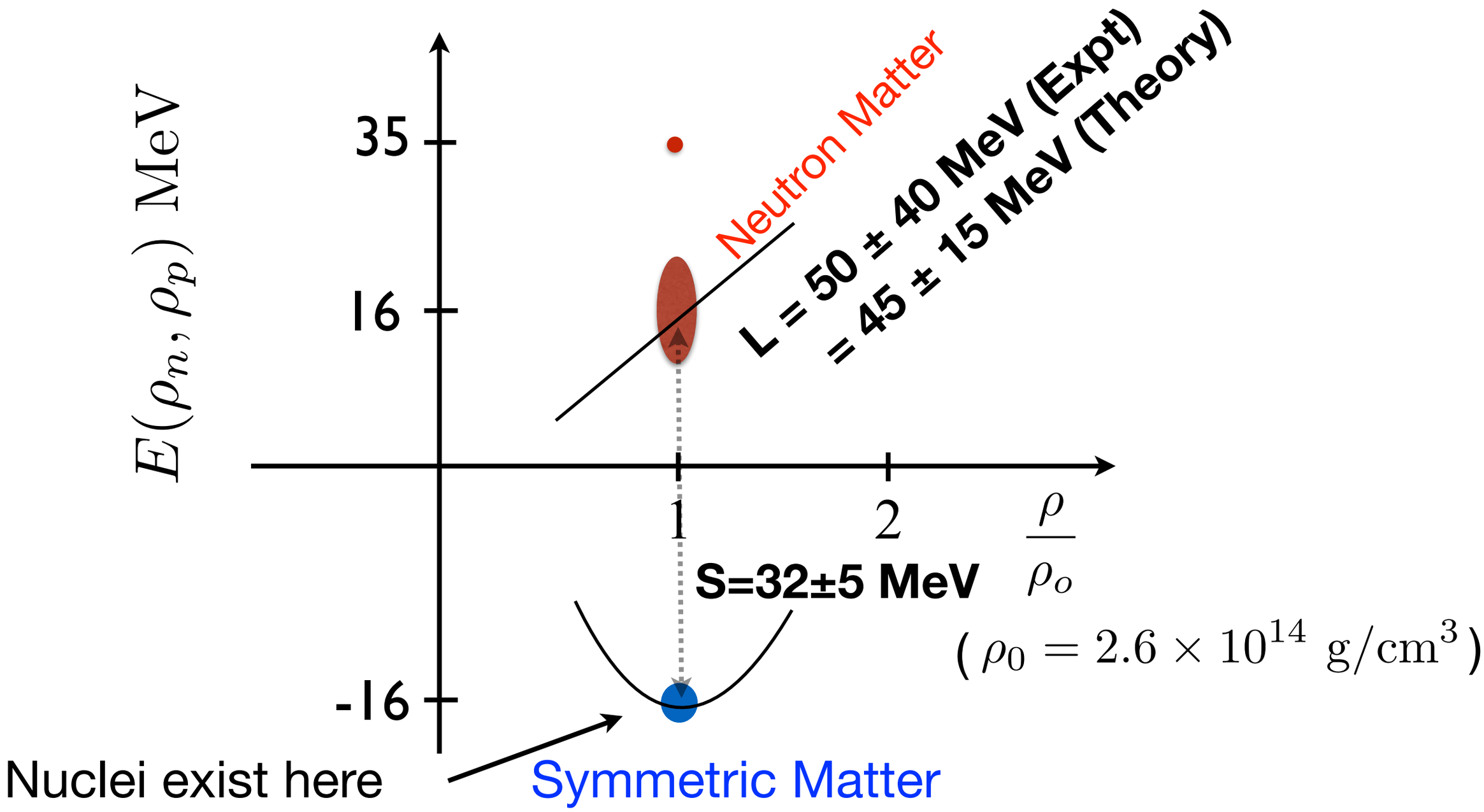

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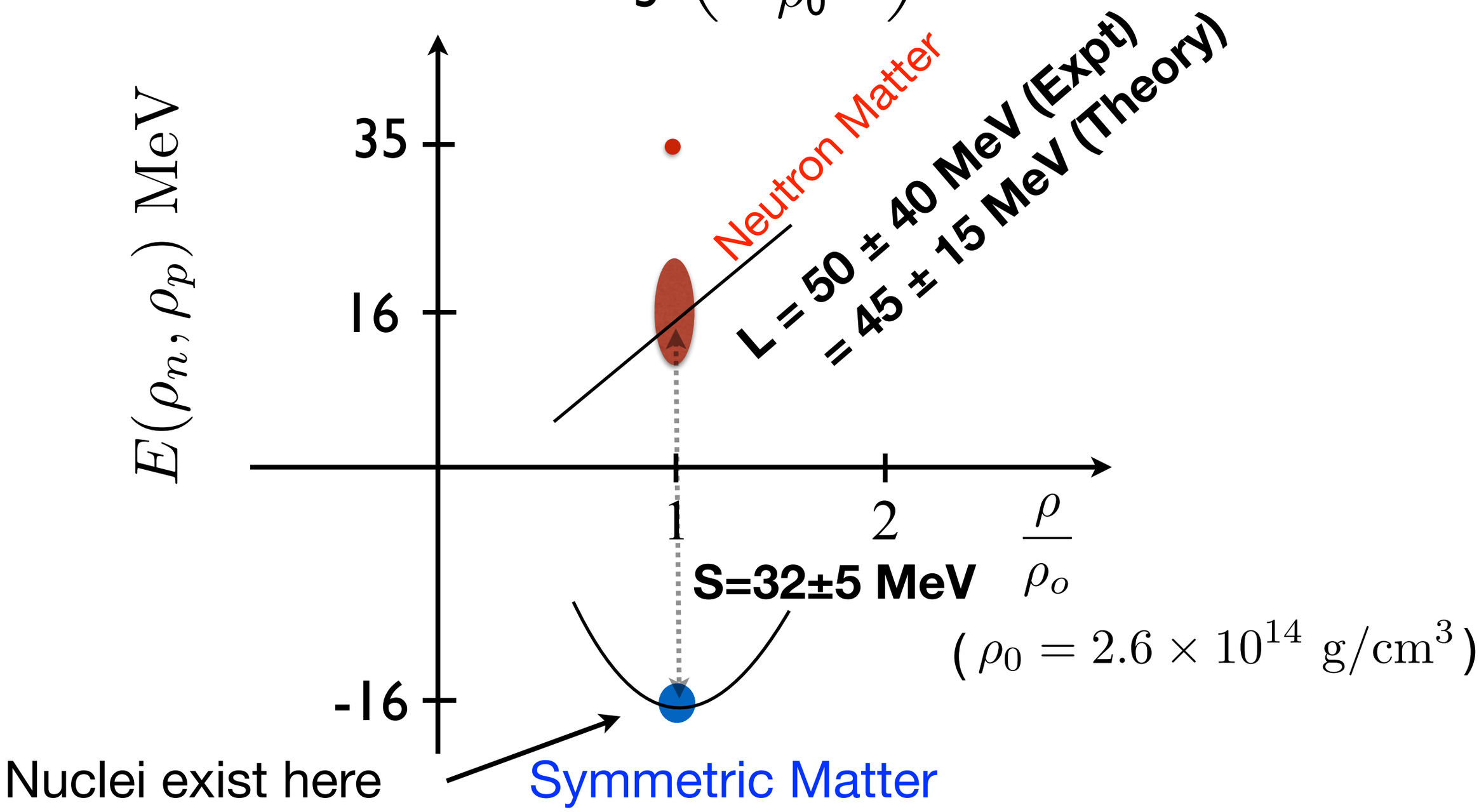
$$E(\rho \simeq \rho_0) = m_n + S - 16 + \frac{L}{3}\left(\frac{\rho - \rho_0}{\rho_0}\right)$$



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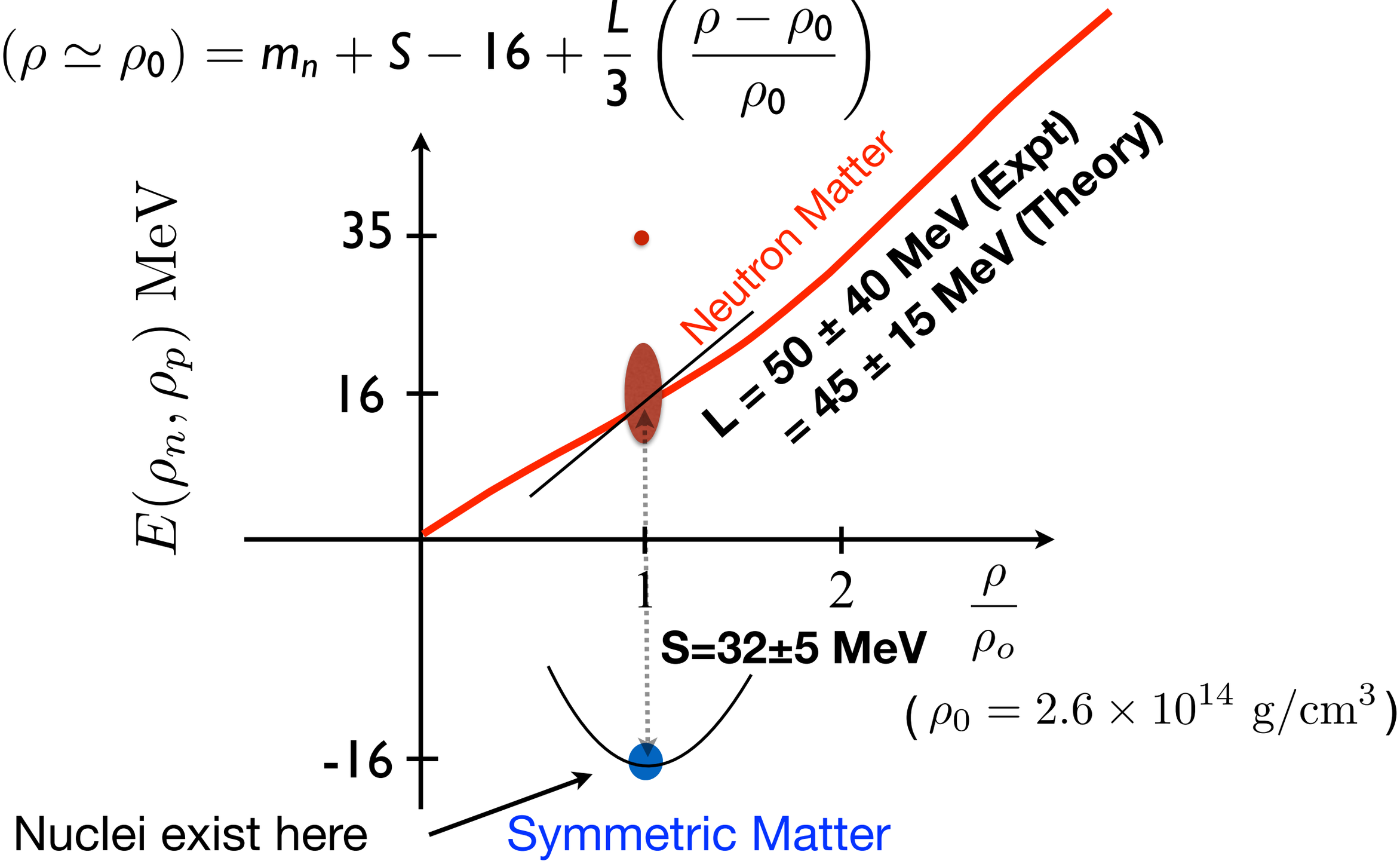

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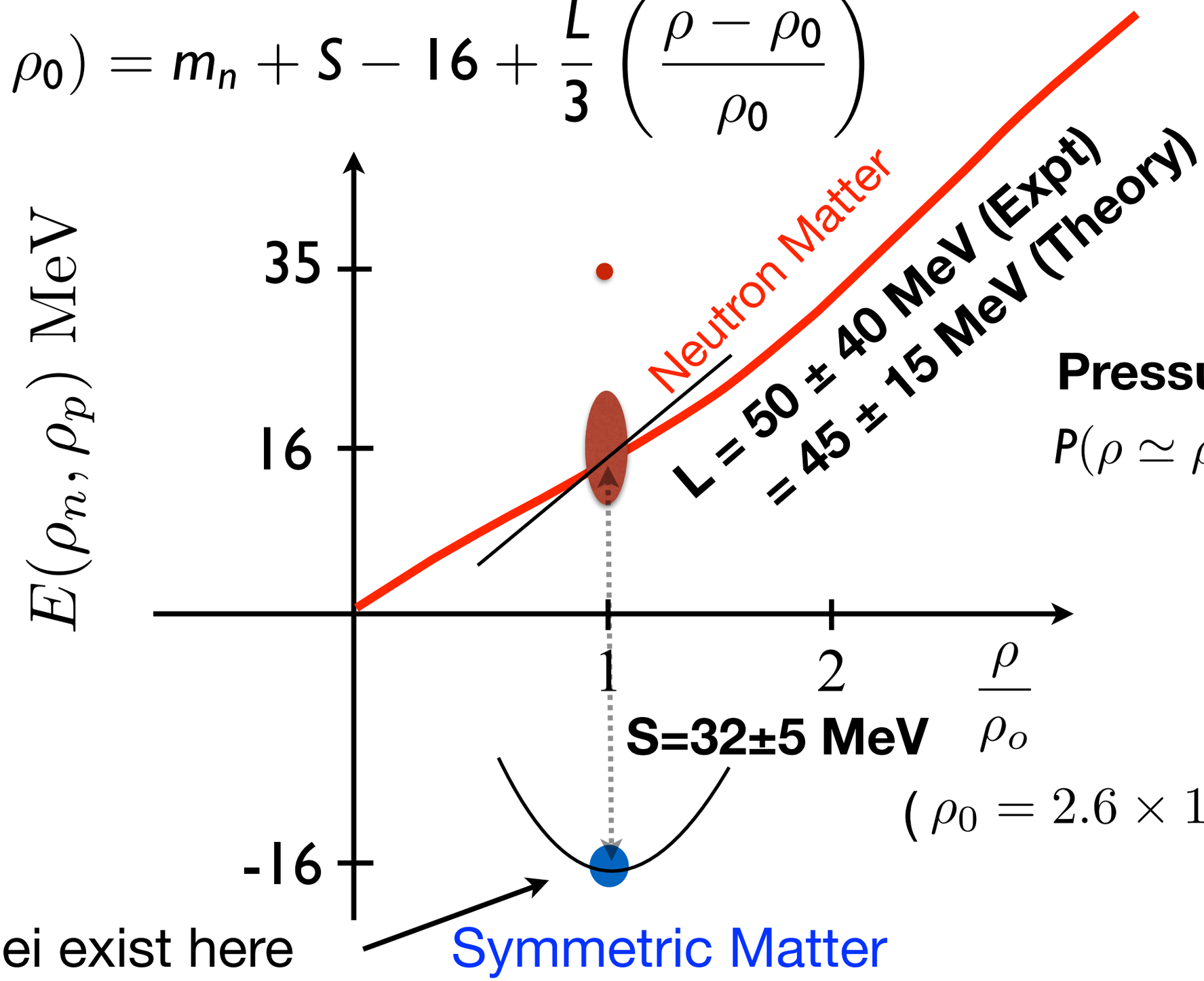

Pressure:

$$P(\rho \simeq \rho_0) \approx \frac{L\,\rho^2}{\rho_0}$$

$$(\rho_0 = 2.6 \times 10^{14}\ \mathrm{g/cm^3})$$

Neutron Matter and Symmetry Energy

To get from nuclei to neutron stars:

$$S(\rho) = E(\rho, x = 0) - E(\rho, x = 1/2)$$

$$E(\rho, x) = E(\rho, 1/2) + (1 - 2x)^2 S_2(\rho) + ..$$

$$S_2(\rho) = \mathbf{S_v} + \frac{\mathbf{L}}{3} \frac{\rho - \rho_s}{\rho_s} + \ldots$$

Simplest parameterization to characterize the extrapolation in isospin and baryon density.

Neutron Matter and Symmetry Energy

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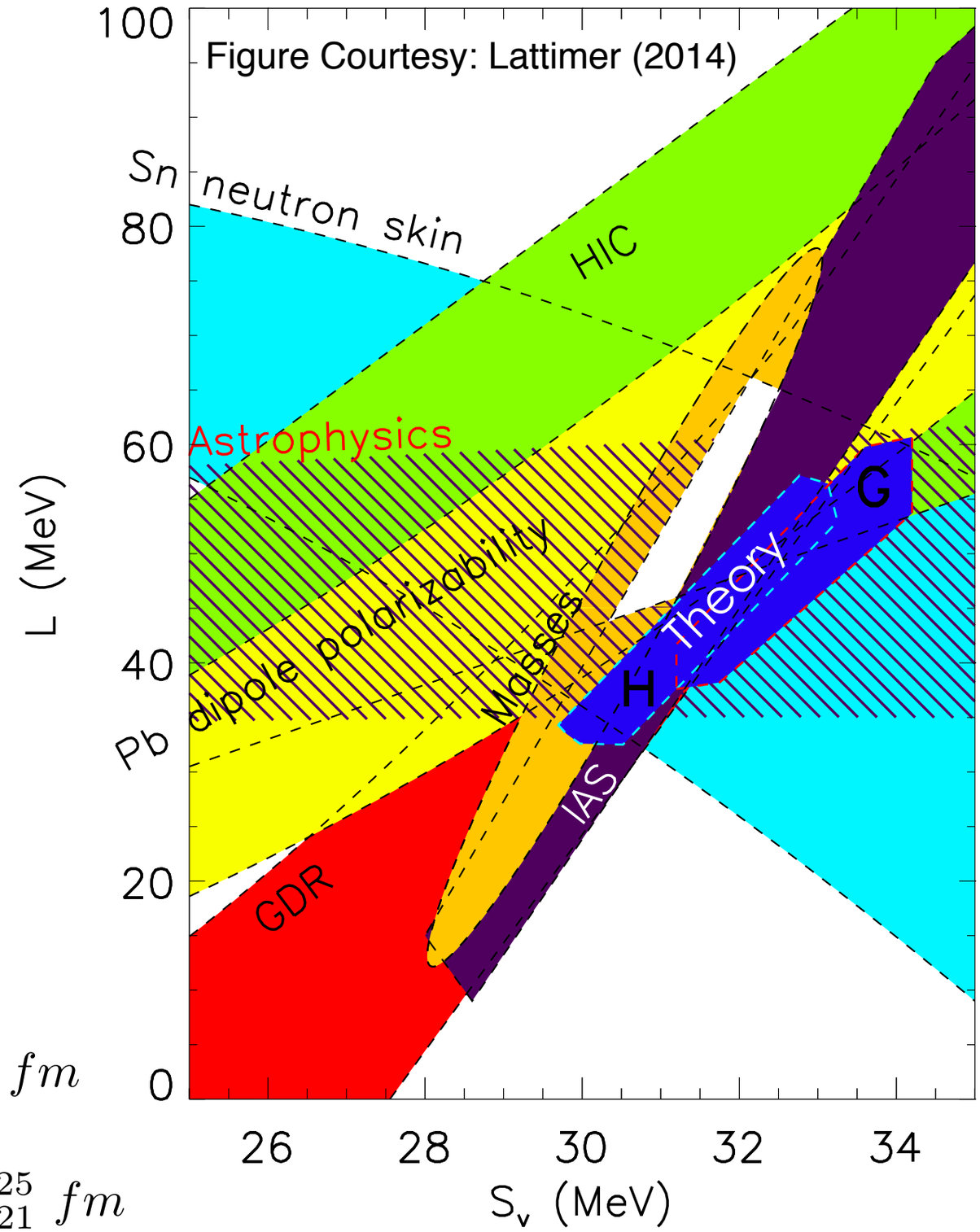
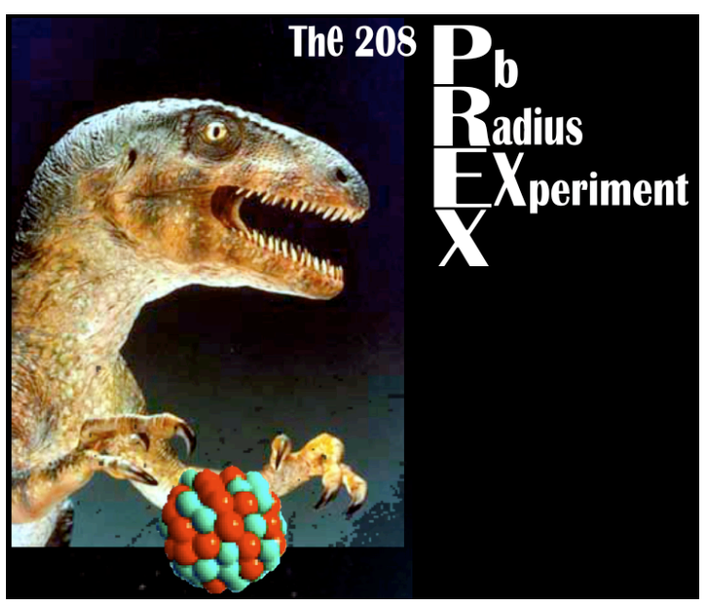
Symmetry Energy, Experiment & Radius

Nuclear measurements:

- nuclear masses
- neutron skin
- dipole polarizability
- giant-dipole resonances
- heavy-ion phenomenology

correlate S & L.





^{208}Pb r_{skin}

PREX: $0.34^{+0.15}_{-0.17}\,fm$

αD (Tamii et al.) $0.156^{+0.025}_{-0.021}\,fm$

Theory: $0.168 \pm 0.022\,fm$

Symmetry Energy, Experiment & Radius

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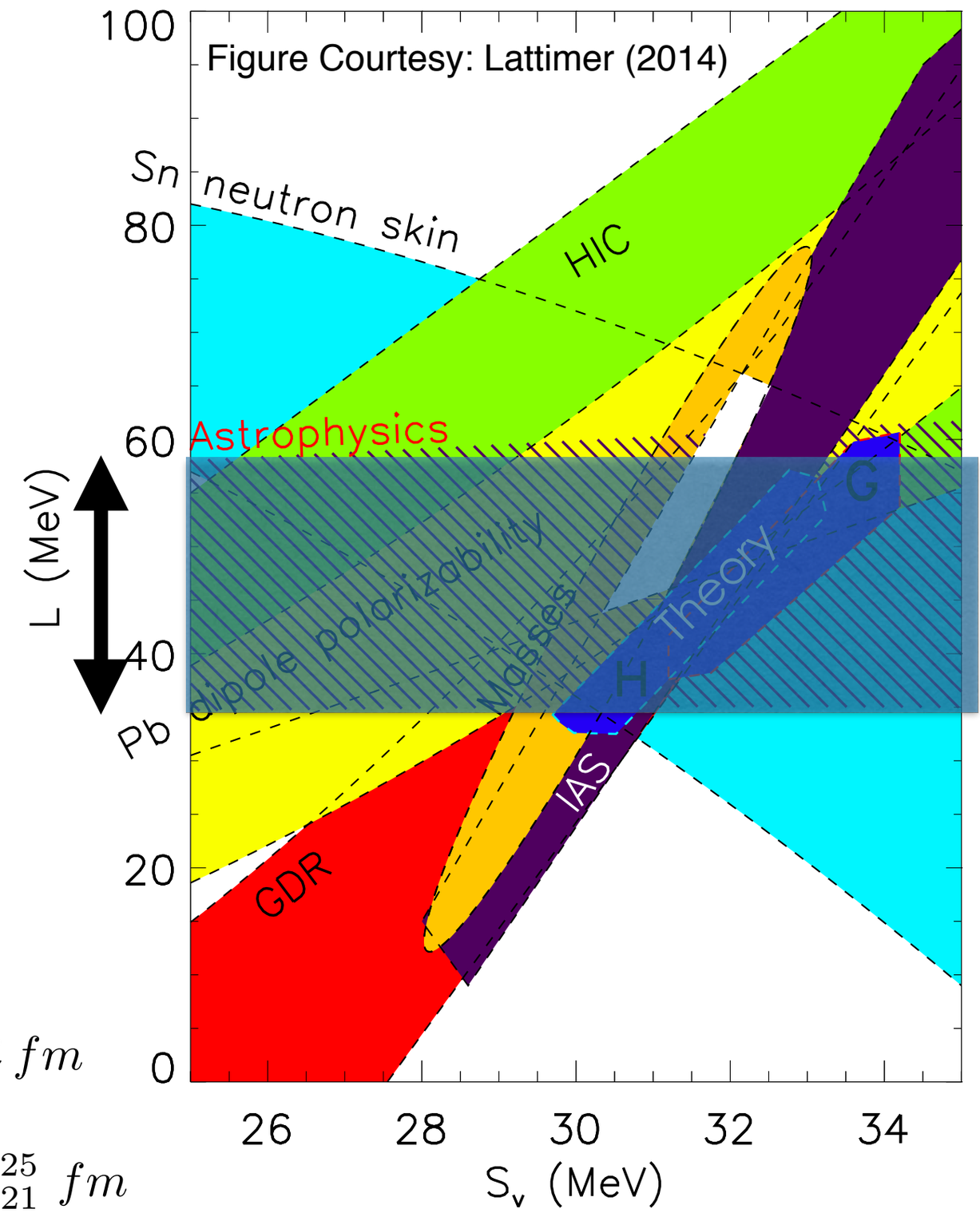
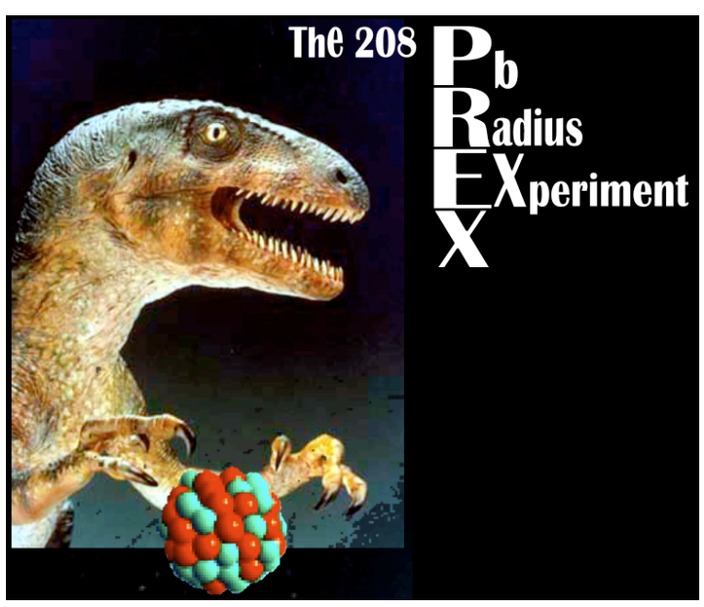
correlate S & L.

Neutron Star radius is sensitive to L.





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Many Body Theory for Neutron Matter

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

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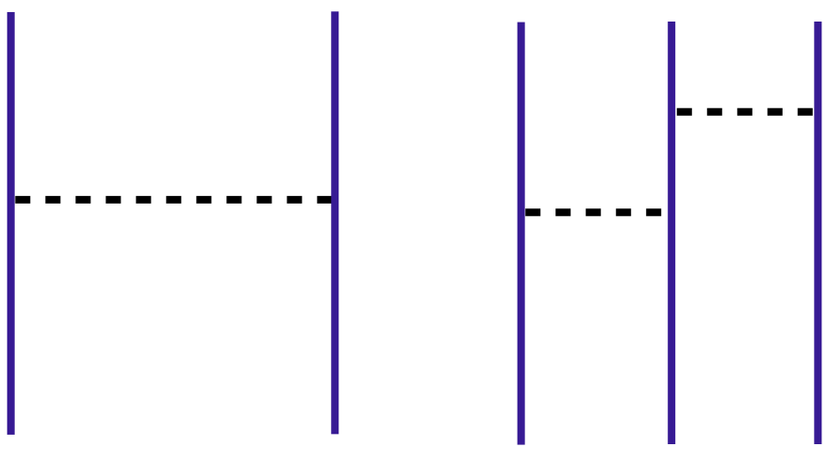

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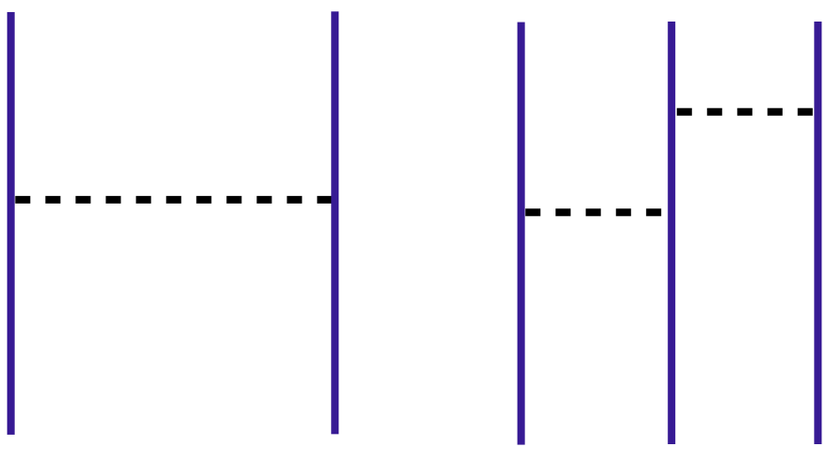

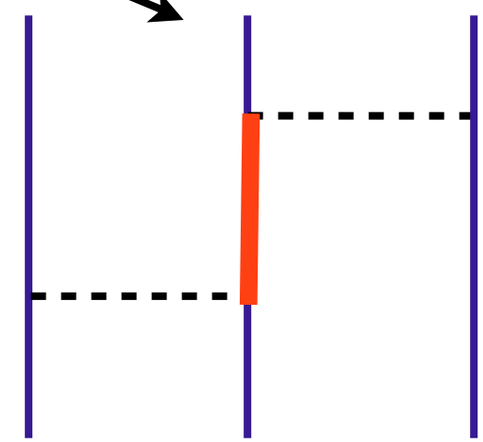

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three-neutron potential is not well constrained by nuclear data (yet).

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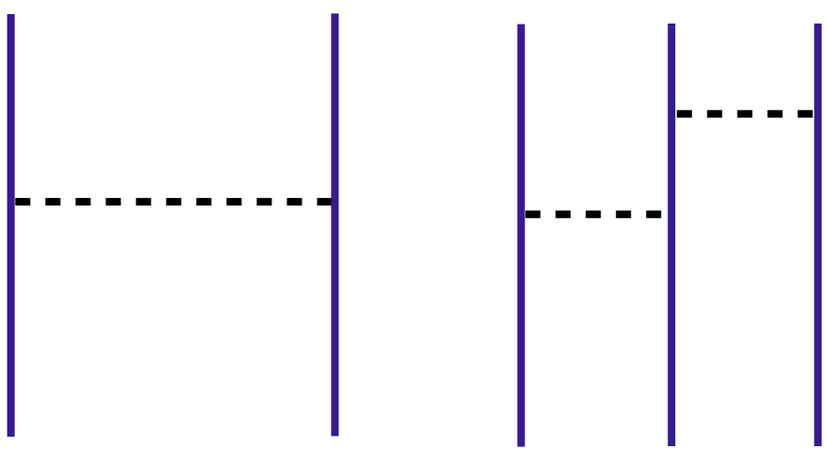

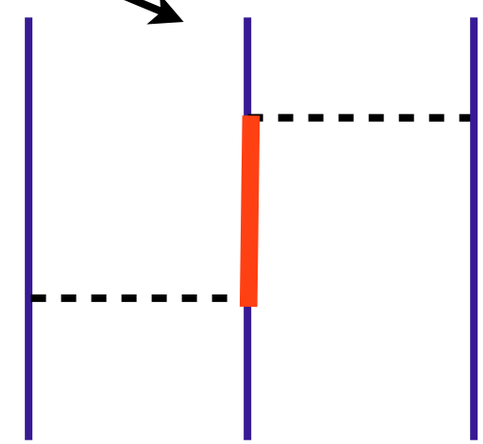

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Quantum Many-Body Theory:

Quantum Monte Carlo

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

Nucleon-Nucleon Potential

$$V_{ij} = \sum_p v_p(r_{ij})\, O^p_{ij}$$

Intricate spin, isospin and tensor structure.

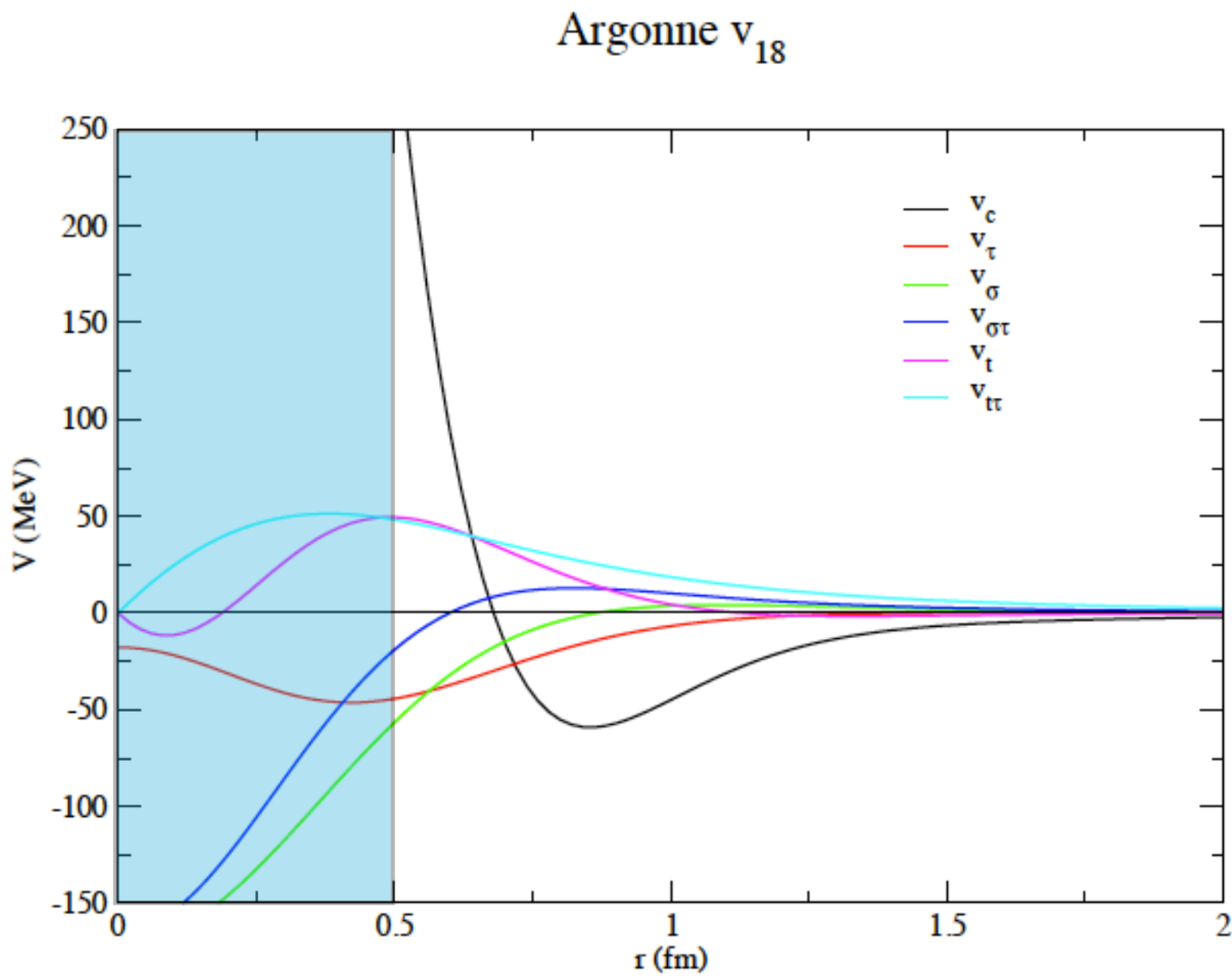
$$\begin{aligned} O^p_{ij} = {} & [1, \sigma_i \cdot \sigma_j, S_{ij}, \mathbf{L}\cdot\mathbf{S}, \mathbf{L}^2, \mathbf{L}^2(\sigma_i\cdot\sigma_j), (\mathbf{L}\cdot\mathbf{S})^2] \\ & + [1, \sigma_i \cdot \sigma_j, S_{ij}, \mathbf{L}\cdot\mathbf{S}, \mathbf{L}^2, \mathbf{L}^2(\sigma_i\cdot\sigma_j), (\mathbf{L}\cdot\mathbf{S})^2] \otimes \tau_i \cdot \tau_j \\ & + [1, \sigma_i \cdot \sigma_j, S_{ij}, \mathbf{L}\cdot\mathbf{S}] \otimes T_{ij} \\ & + [1, \sigma_i \cdot \sigma_j, S_{ij}, \mathbf{L}\cdot\mathbf{S}] \otimes (\tau_i + \tau_j)_z \end{aligned}$$

$$S_{ij} = 3\sigma_i \cdot \hat{r}_{ij}\sigma_j \cdot \hat{r}_{ij} - \sigma_i \cdot \sigma_j \qquad T_{ij} = 3\tau_{iz}\tau_{jz} - \tau_i \cdot \tau_j$$

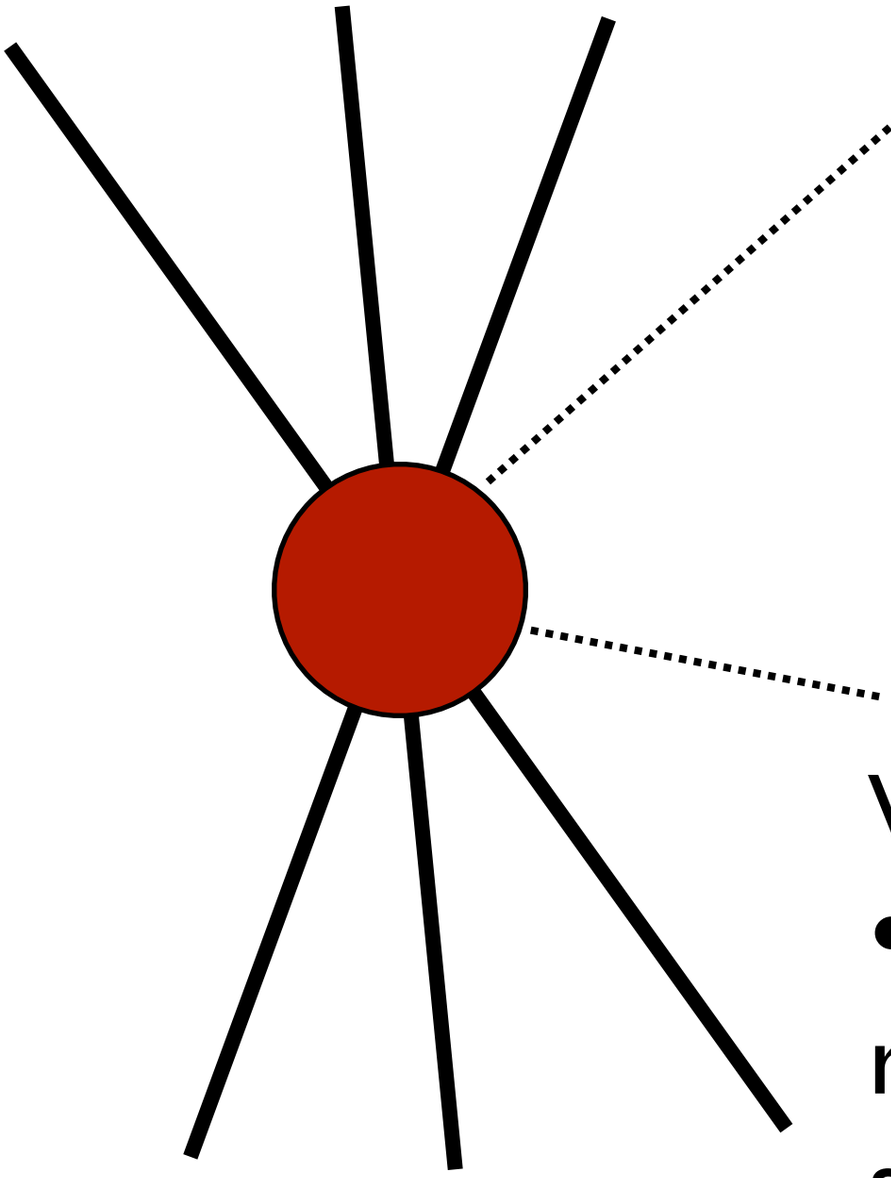
Interaction is scale dependent:

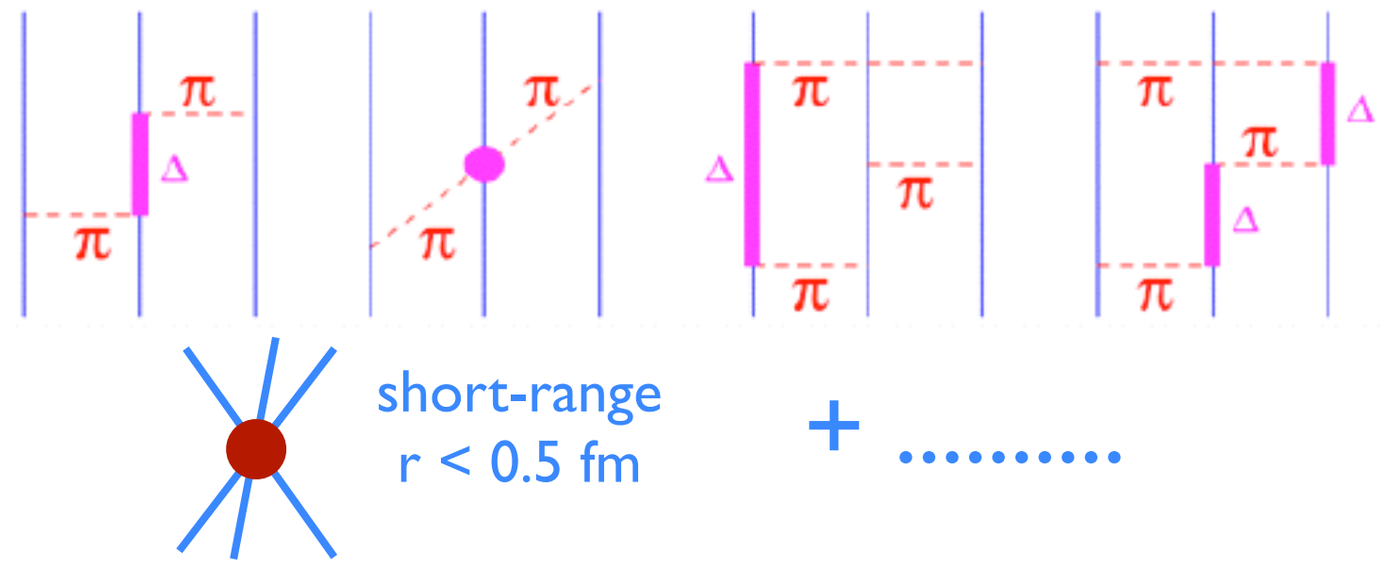
Potential is not unique.

Potentials with different short-distance behavior can fit low-energy NN phase shifts.



Phenomenological Three-Nucleon Force



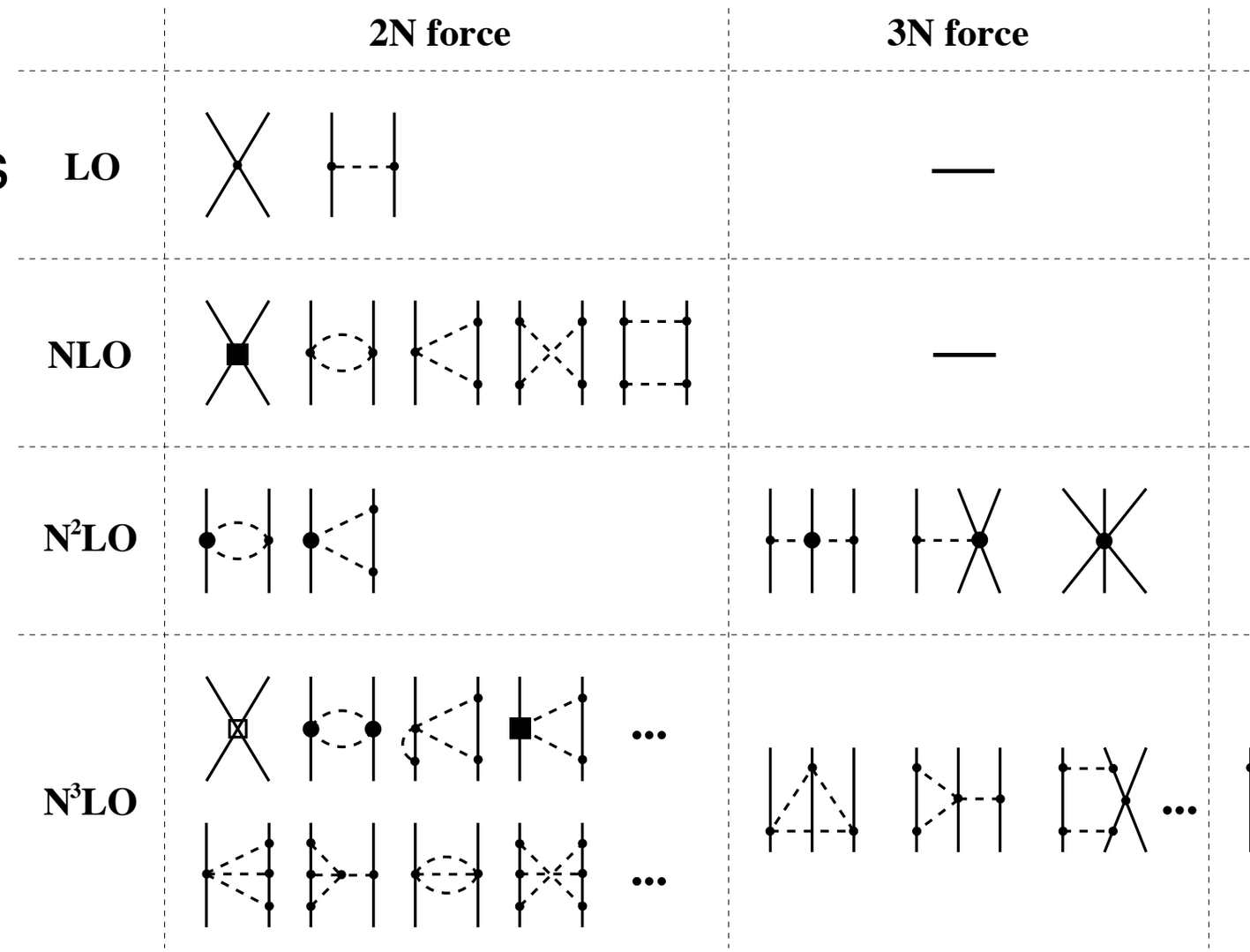


We know it exists ... but

- Its magnitude depends on the renormalization scheme and the specific choice of the 2-body potential.
- Difficult to constrain full structure from expt.
- High quality 2-body potentials require relatively large 3-body forces.

Hierarchy and Effective Field Theory: Chiral NN & NNN Potentials

- A potential based on pion exchanges, contact interactions and their derivates.
- Separation of scales (between long and short range physics) allows for a systematic parametrization of short-distance physics - momentum expansion.
- Hierarchy of many-body forces and higher dimension operators.



Weinberg, van Klock, Kaplan, Savage, Wise, Meißner, Epelbaum, Entem, Machleidt

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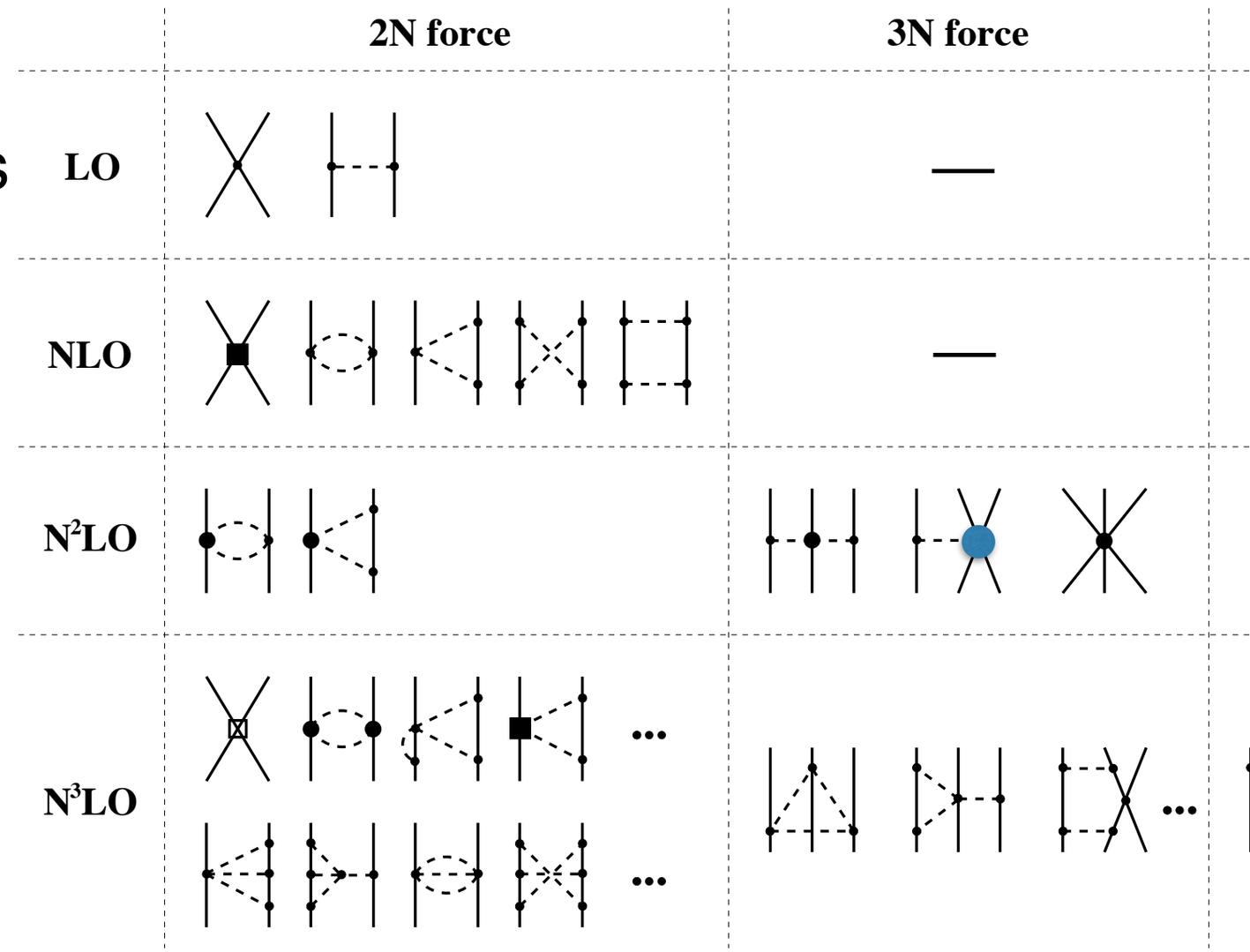

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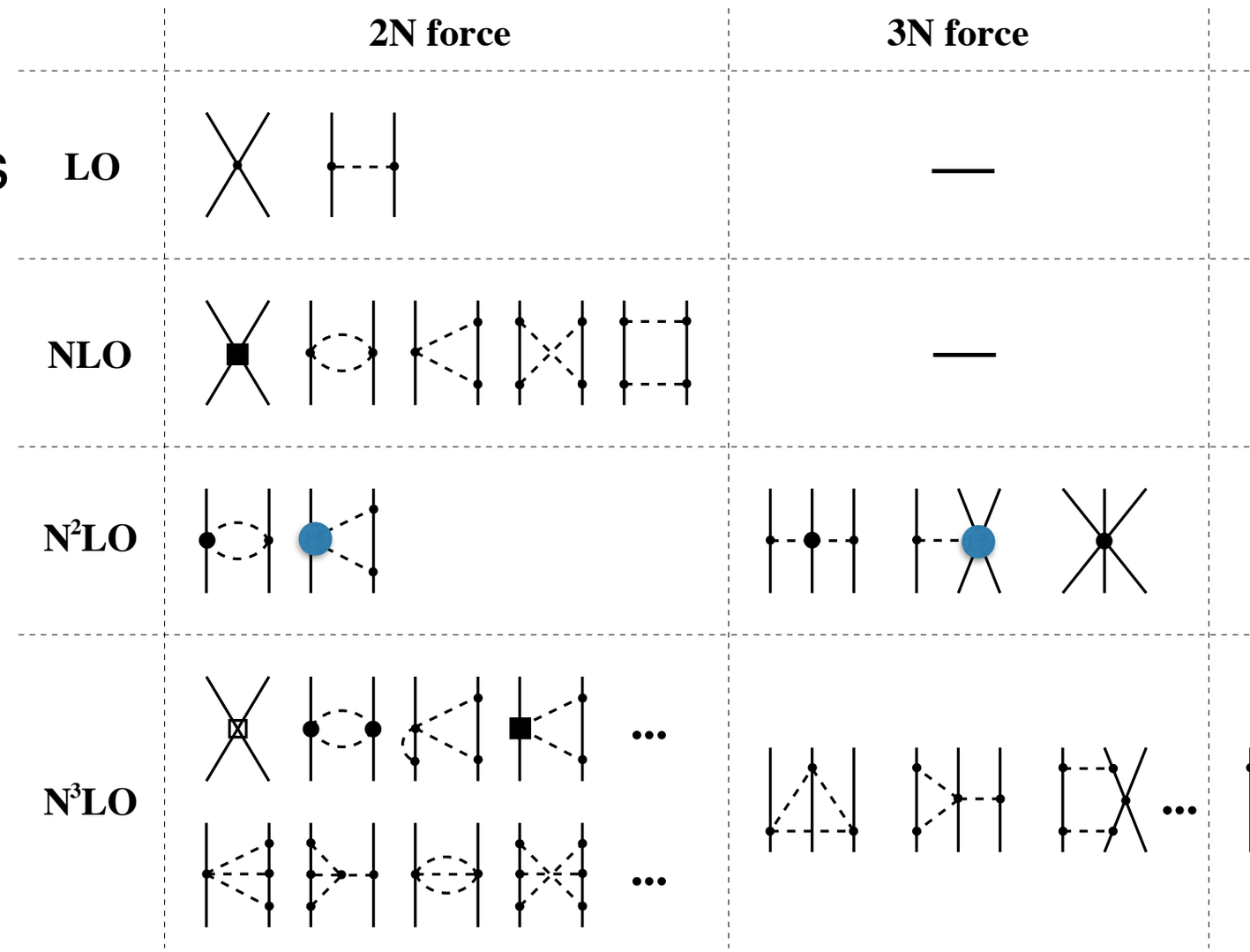
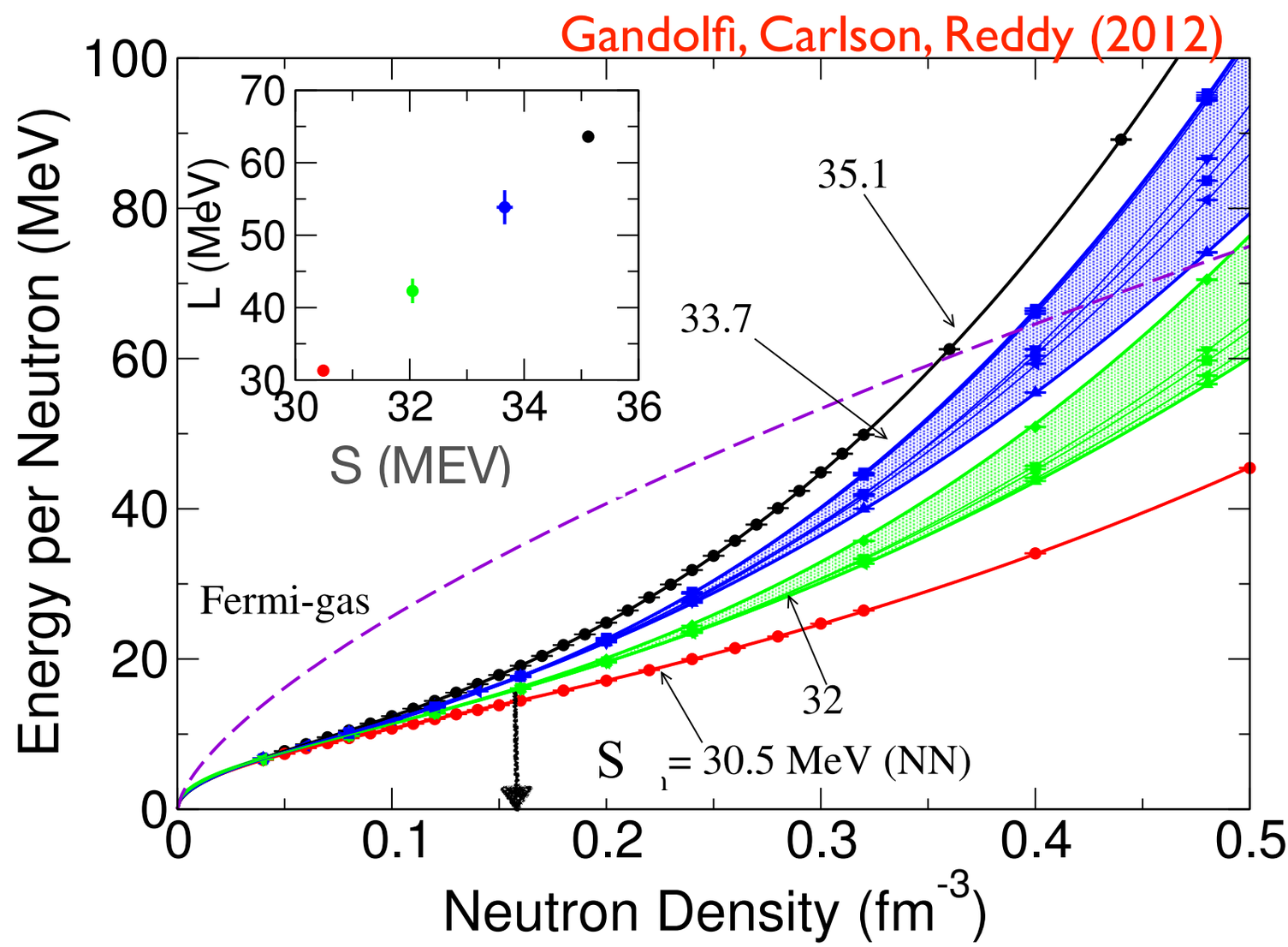


Weinberg, van Klock, Kaplan, Savage, Wise, Meißner, Epelbaum, Entem, Machleidt

QMC Predictions & 3N Forces

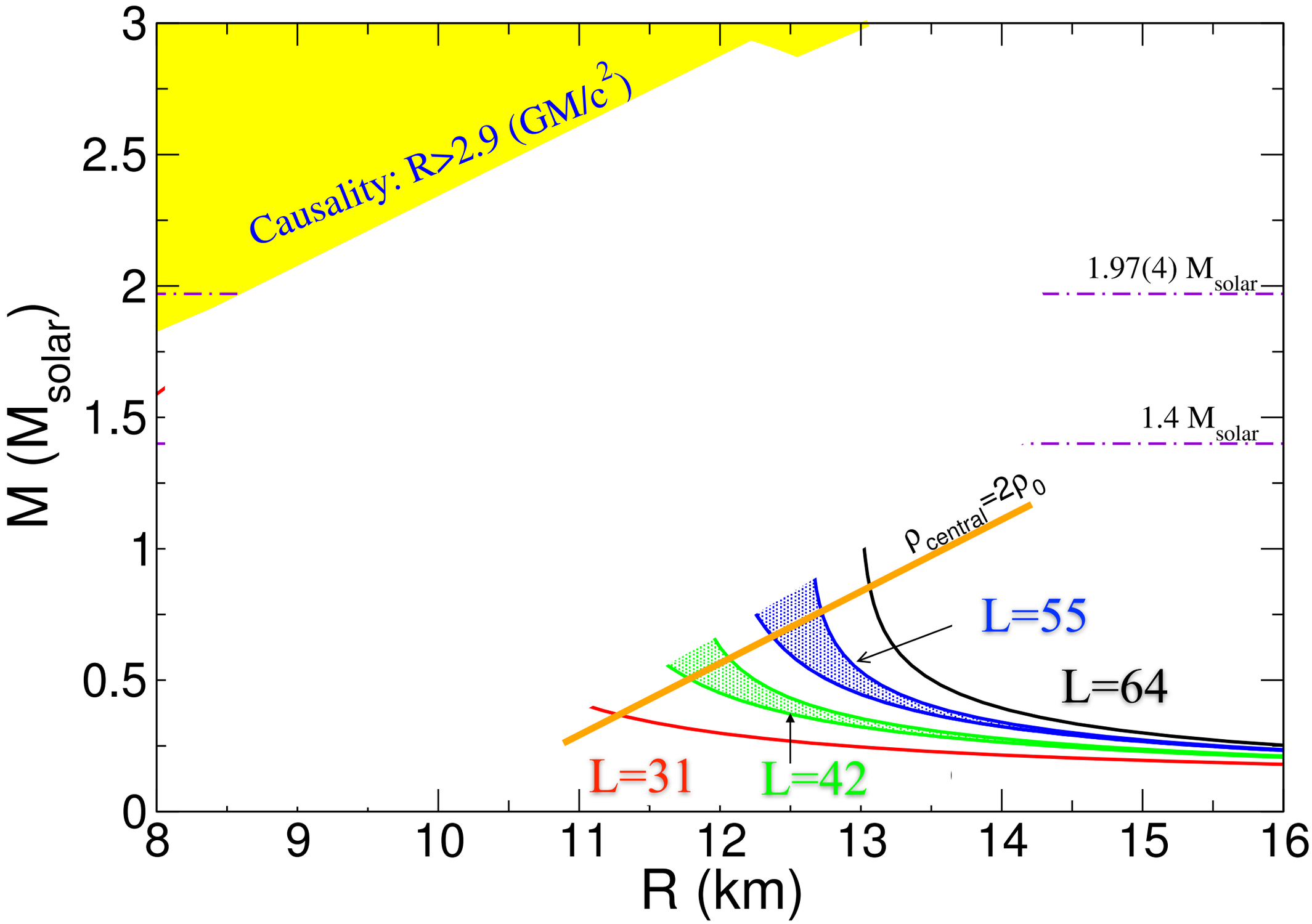
- QMC correlates S & L.
- Measuring both S & L with error ~ 1 MeV would be useful.



For $\rho < 2\ \rho_0$: 3-body contribution is small but important.

A large cancellation between the kinetic energy and two-body (attraction) potential energy.

EoS & Neutron Star Structure



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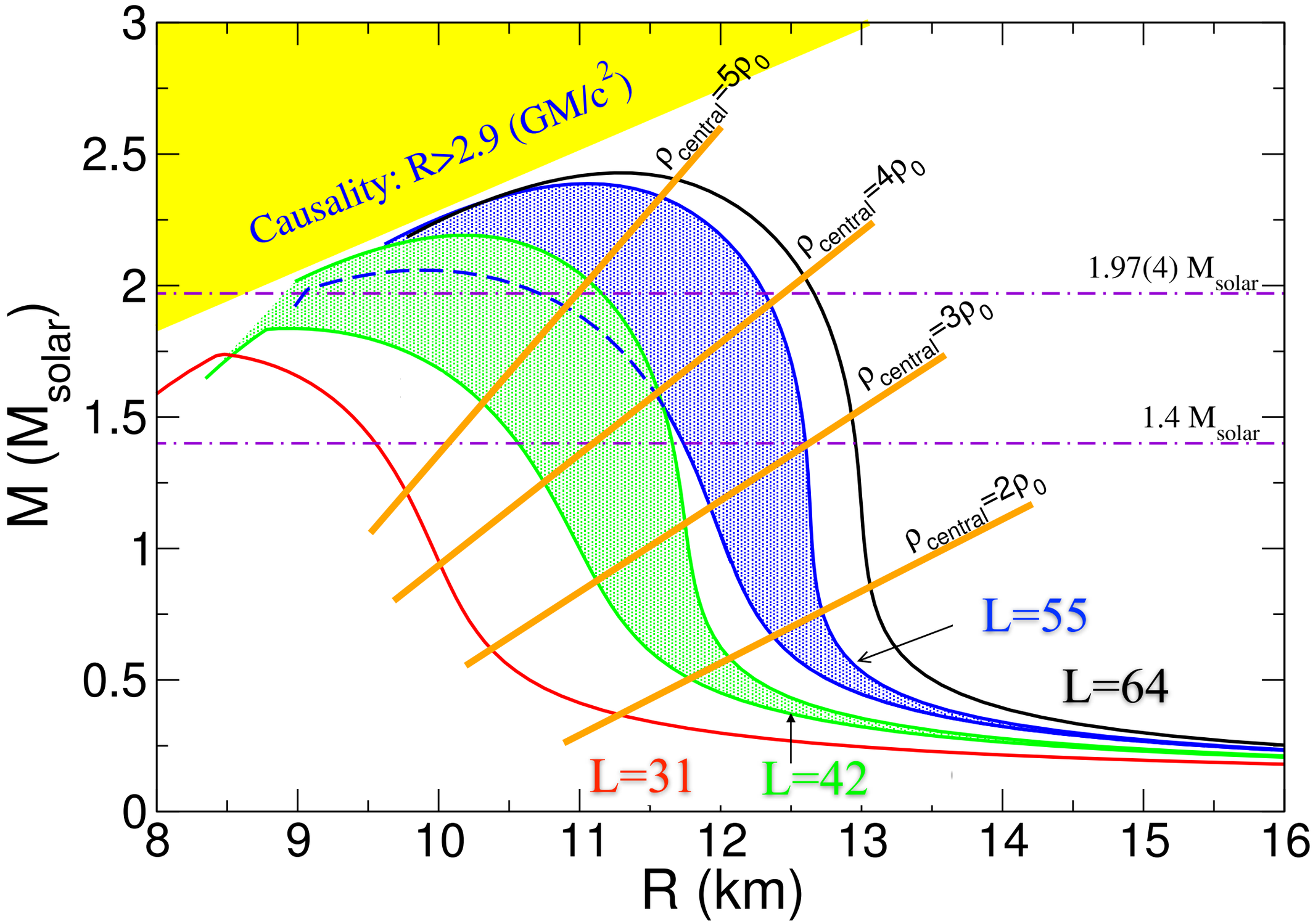
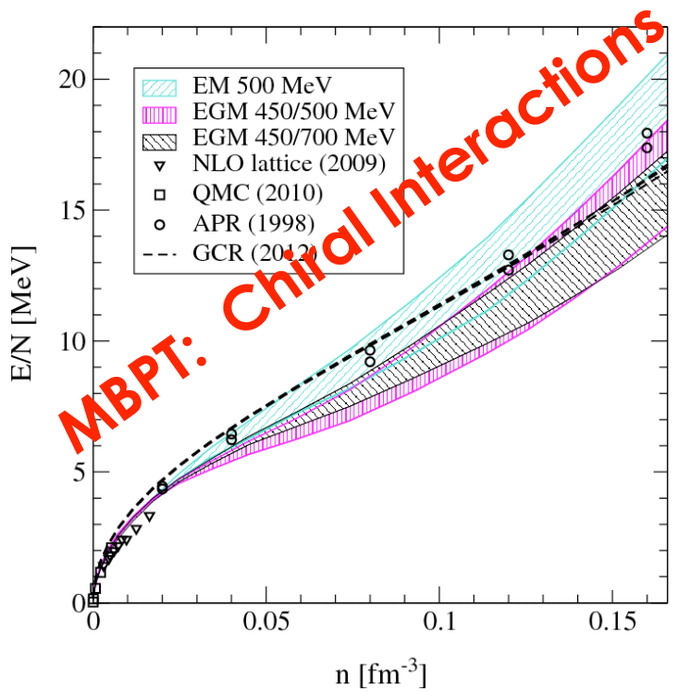
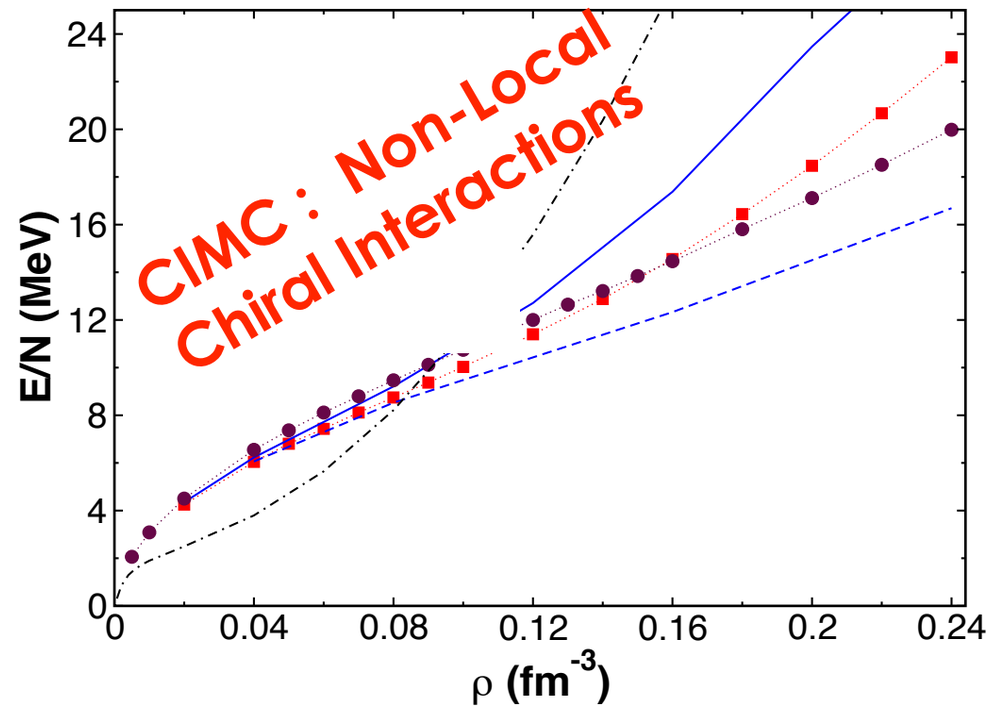


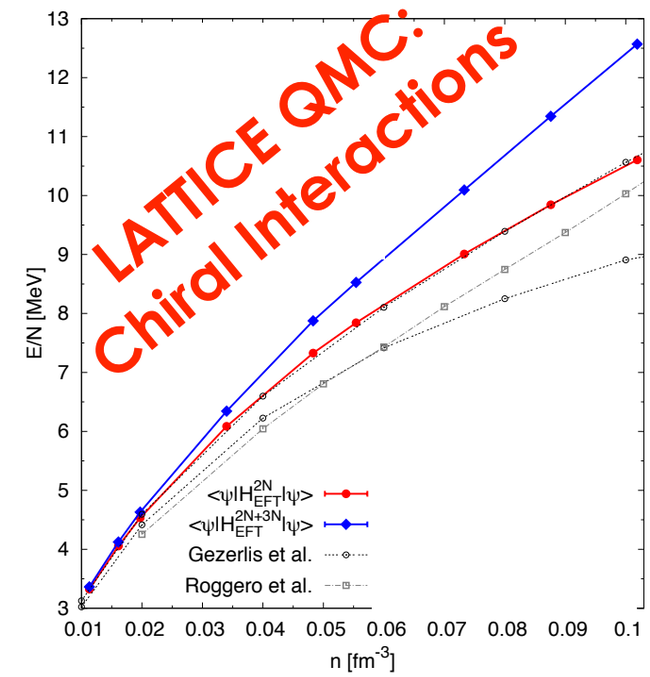
Converging on the EoS and Radius



Tews, Kruger, Hebeler, Schwenk (2013)



Roggero, Mukherjee, Pederiva (2014)

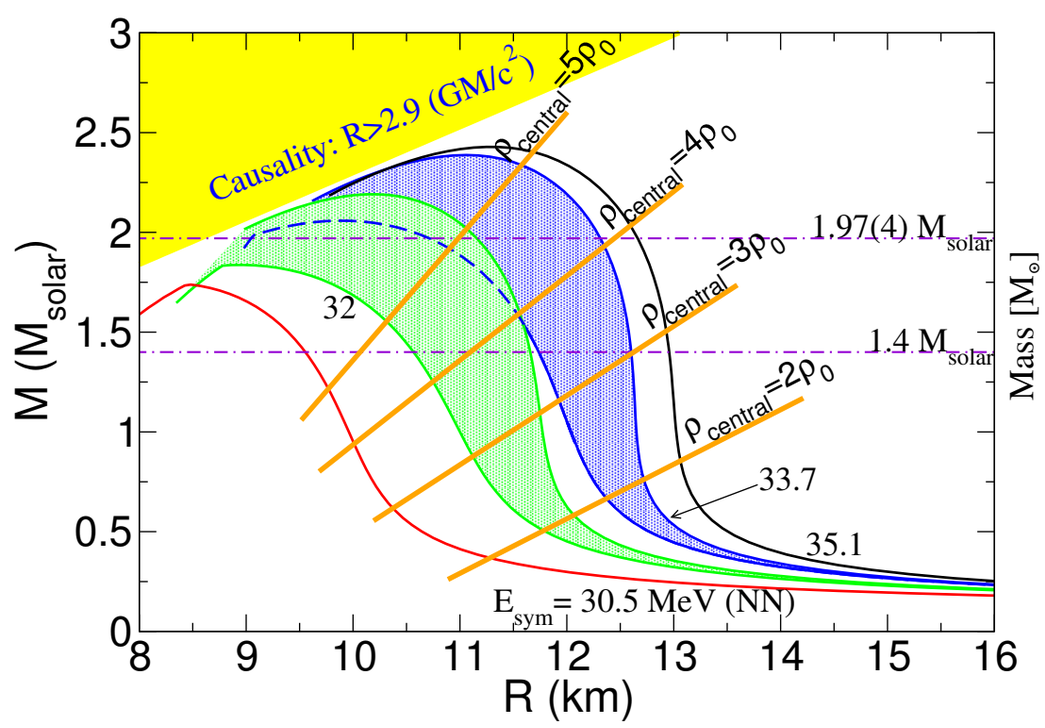


Wlazlowski, Holt, Moroz, Bulgac, Roche (2014)

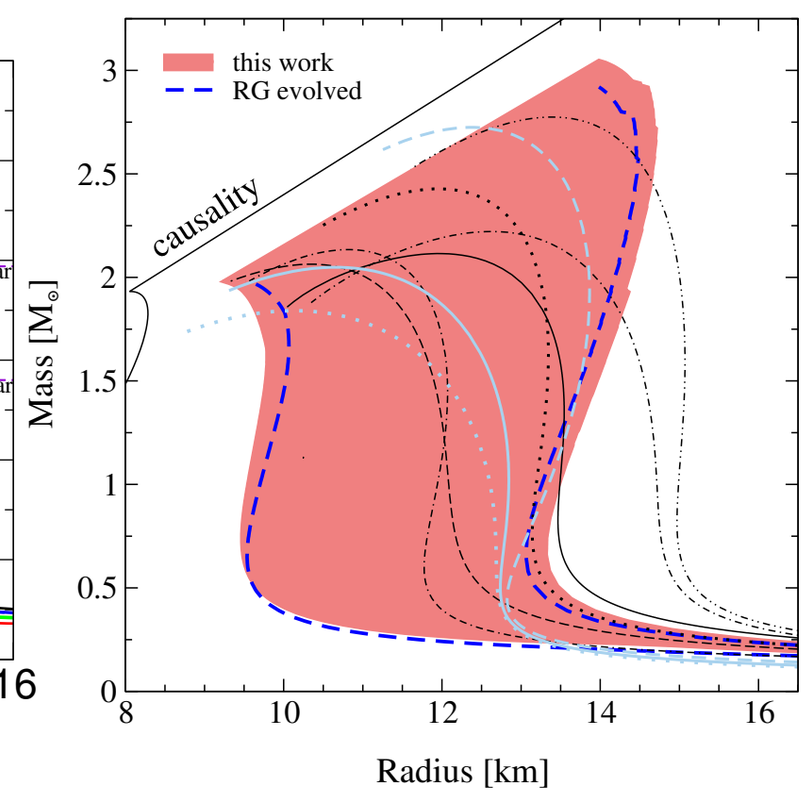
Quantifying uncertainties due to the interaction and many-body approximations.

With implications for NS radius: R = 12 ± 2 km

QMC: Local Interactions



MBPT: Chiral Interactions

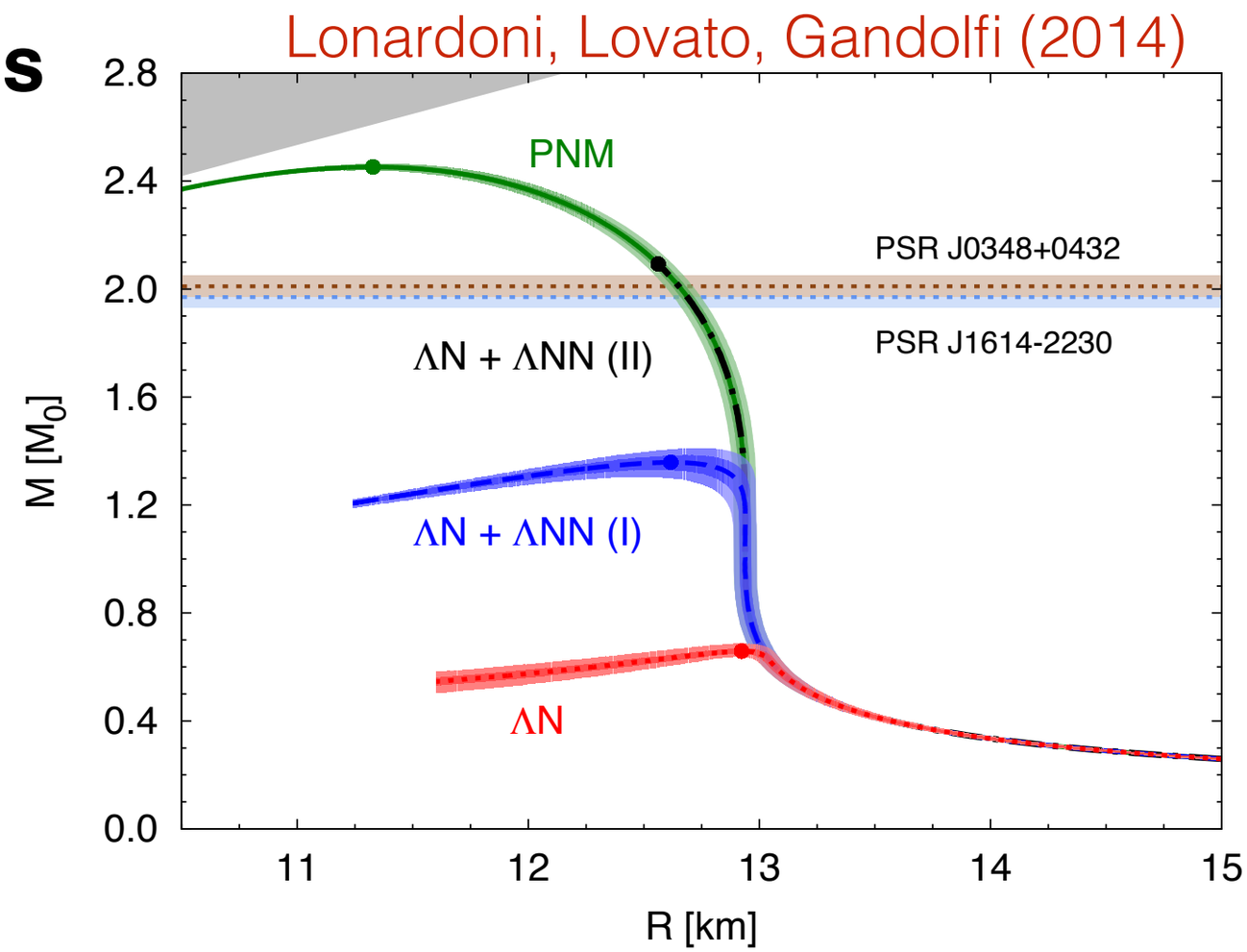


Matter at Supra-nuclear Density

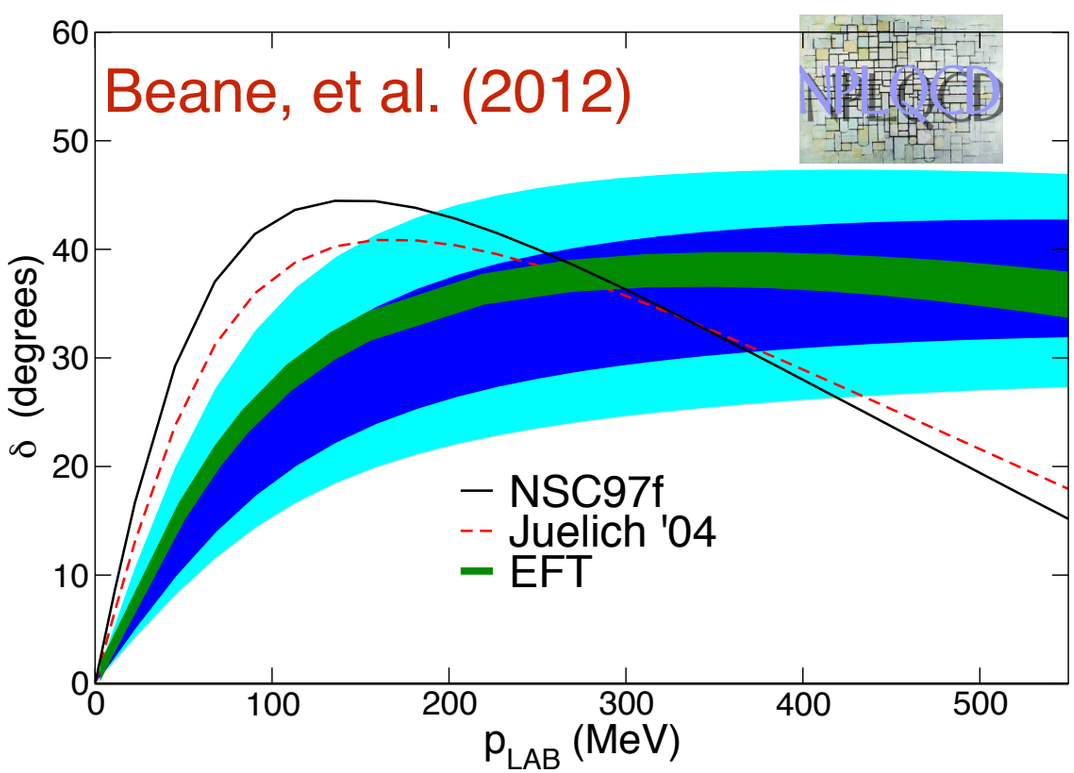
2 solar mass star poses serious challenges:

Rules out strong first-order phase transitions. But,

- How are hyperons suppressed ?
- When and how do quarks emerge ?



$^1S_0$ $n\Sigma^-$ phase shift from LQCD



Path Forward:

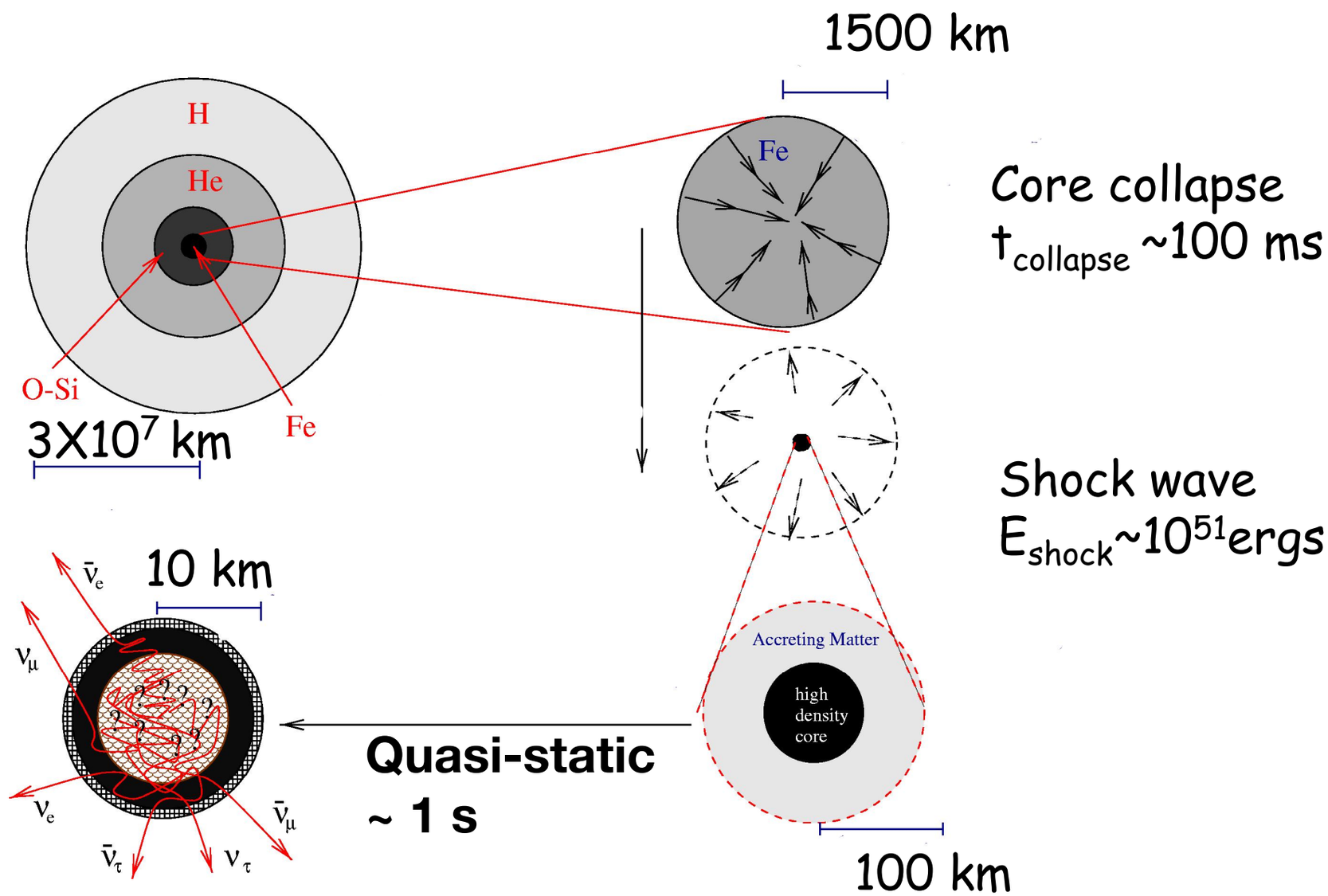
- Hyper-nuclear phenomenology
- Lattice QCD input for hyperon-nucleon interactions and nucleon three-body forces
- Heavy-ion phenomenology and transport theory.

Part II: Dynamics

SUPERNOVA AND NEUTRON STAR MERGERS

- Supernova: Neutrinos & nucleosynthesis
- NS Mergers: Gravitational waves, radius, nucleosynthesis.

Supernova Neutrinos



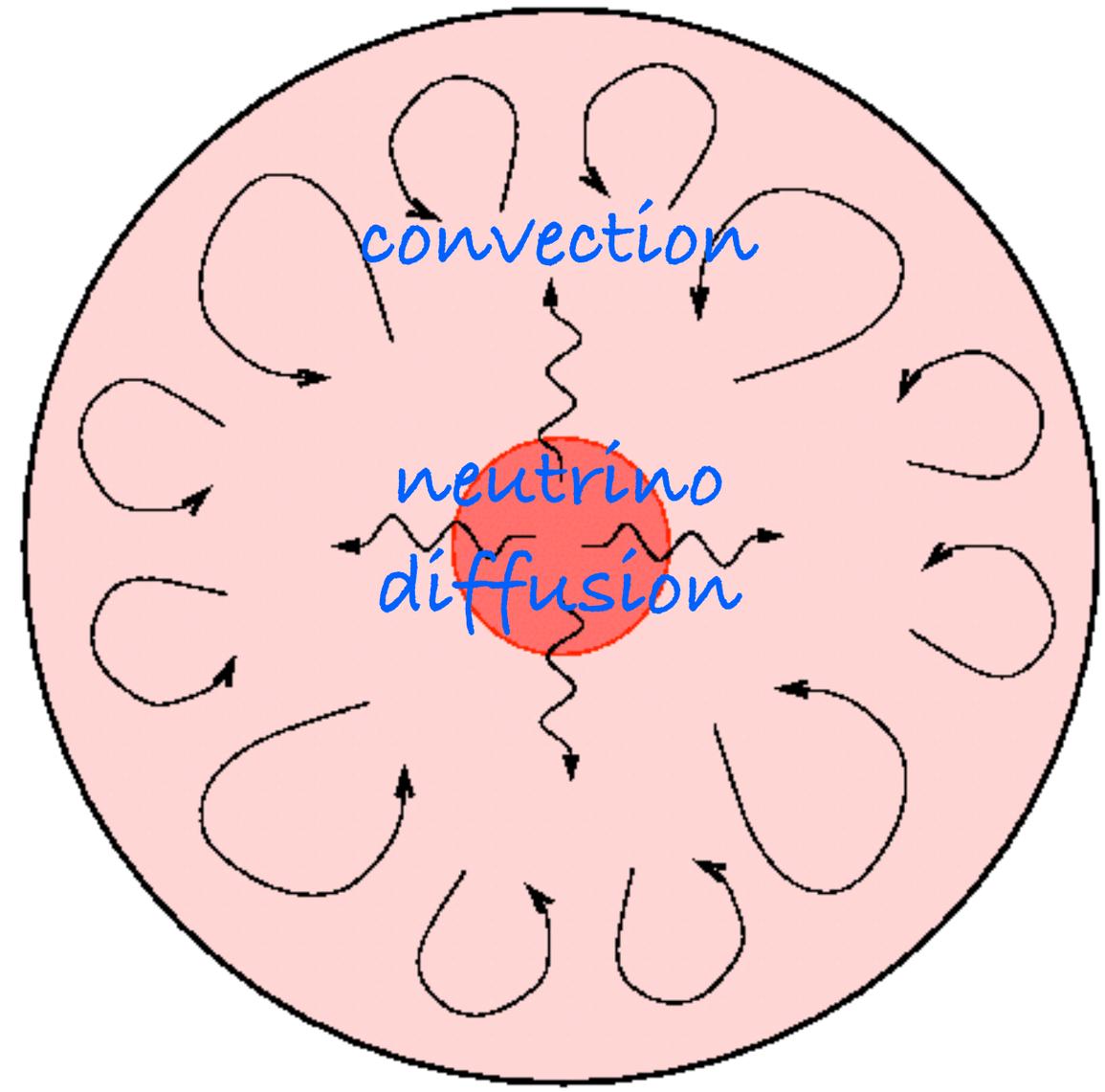
neutrinos diffuse out of the dense newly born neutron star carry away ~ 3 x 10^{53} ergs

- The time structure of the neutrino signal depends on how heat is transported in the neutron star core.
- The spectrum is set by scattering in a hot (T=3-6 MeV) and not so dense (10^{12}-10^{13} g/cm^3) neutrino-sphere.

Neutrino Emission Timescales & EoS.

Heat transport : Neutrino diffusion + convection

Diffusion: $\tau_{\rm diff} \simeq \frac{R^2}{c\,\lambda_\nu} \approx 3-5\ {\rm s}$



Convection:

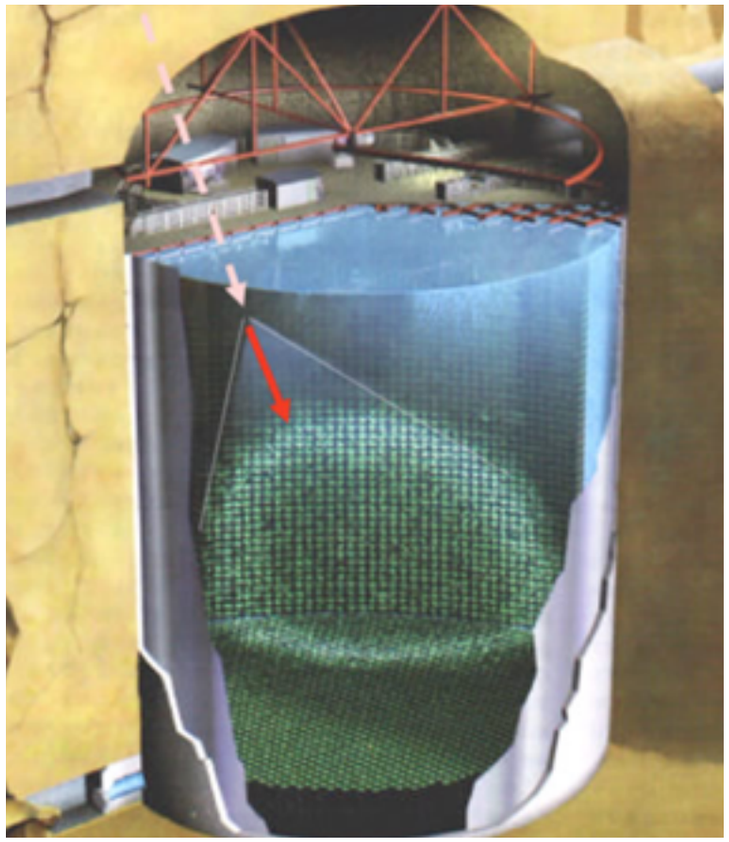
Convection driven by composition gradients can accelerate neutrino transport.

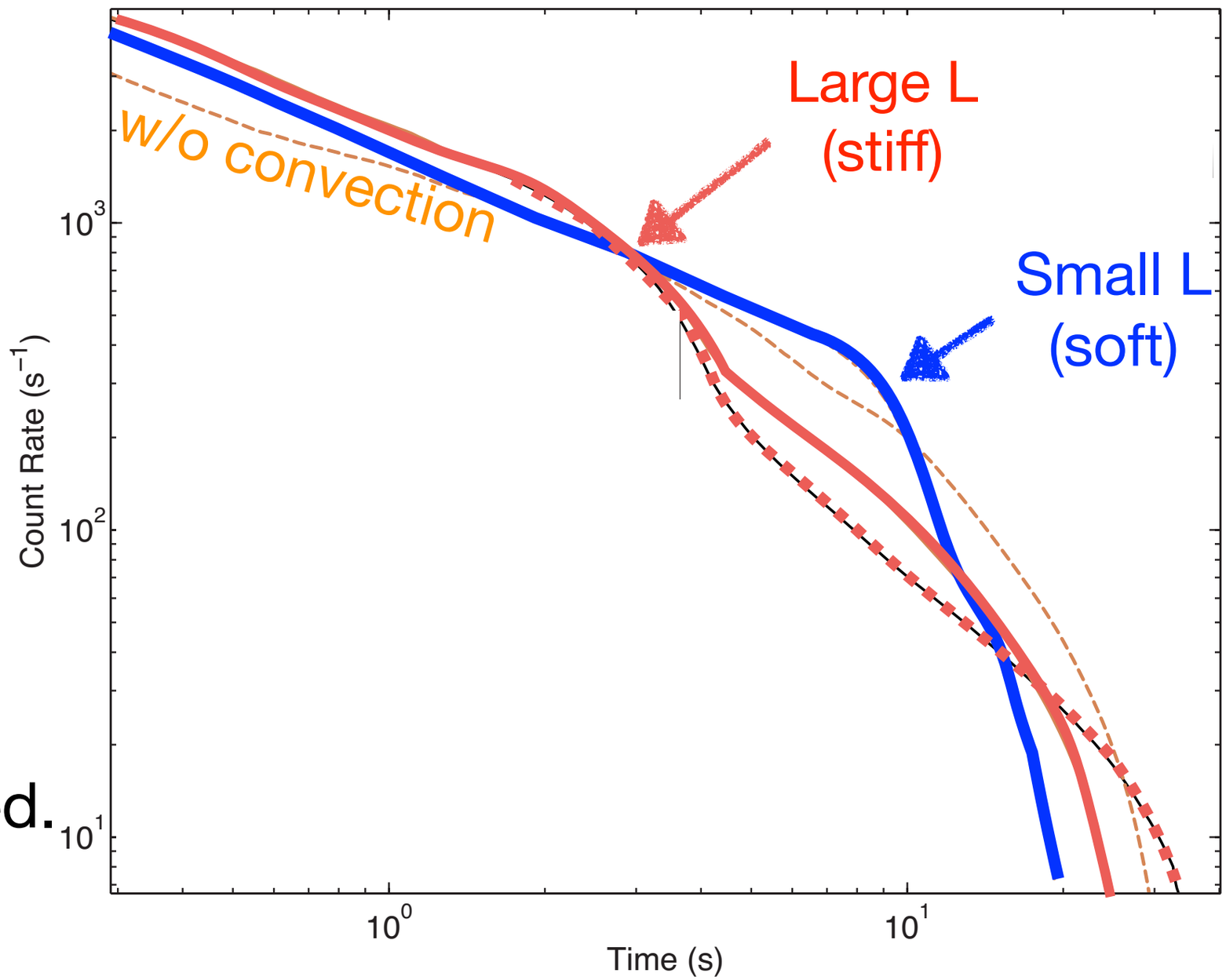
Buoyancy of matter depends on the pressure of neutron matter - is sensitive to L

Large L drives convection.
Small L suppress it.

Roberts, Cirigliano, Pons, Reddy, Shen, Woosley (2012)

Signatures of Convective Transport





- Neutrino flux is enhanced.
- Break in the light curve (when convection ends).
- Fraction of events between 3-10 s provides good discrimination.

Count rate in Super-Kamiokande for galactic supernova at 10 kpc.

Roberts, Cirigliano, Pons, Reddy, Shen, Woosley (2012)

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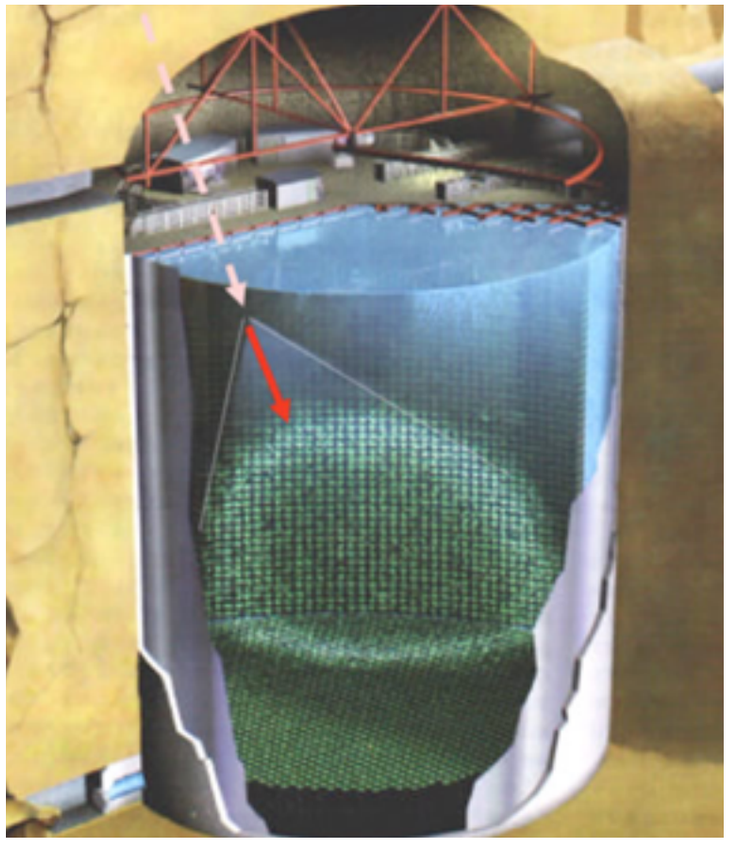

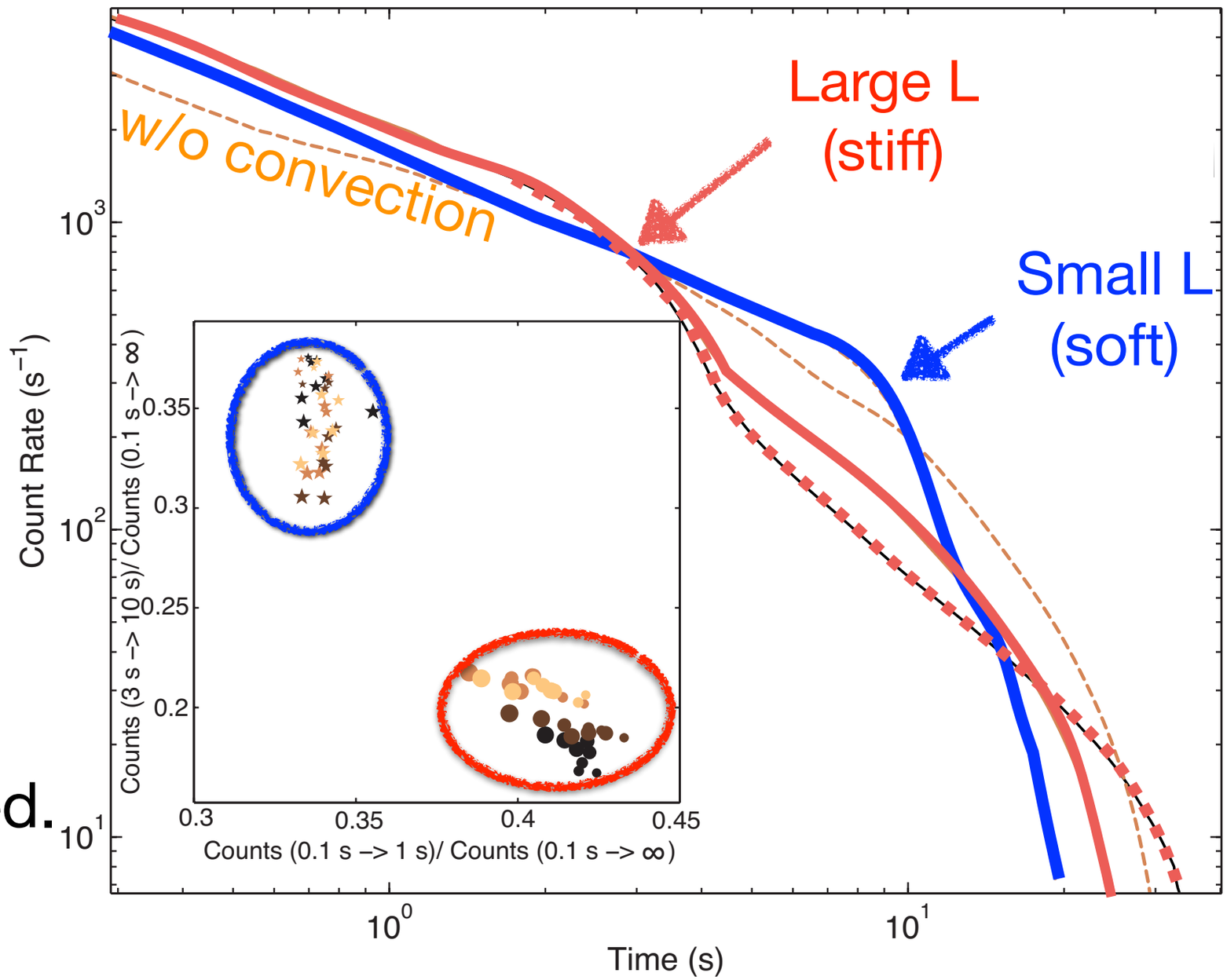

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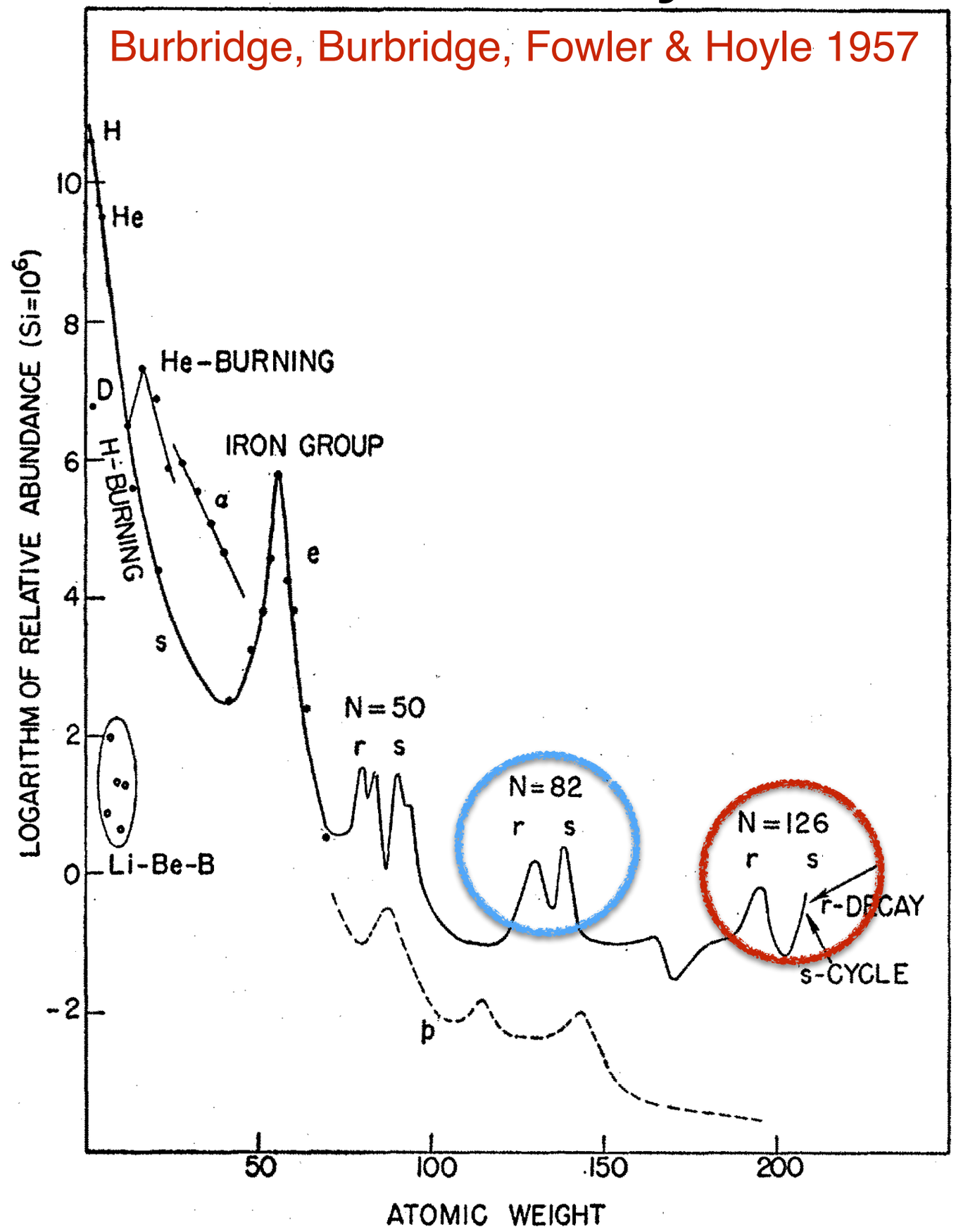
Roberts, Cirigliano, Pons, Reddy, Shen, Woosley (2012)

Dense Matter, Neutrinos & Nucleosynthesis

In extreme environments rapid neutron capture (r-process) on seed nuclei can produce heavy elements.

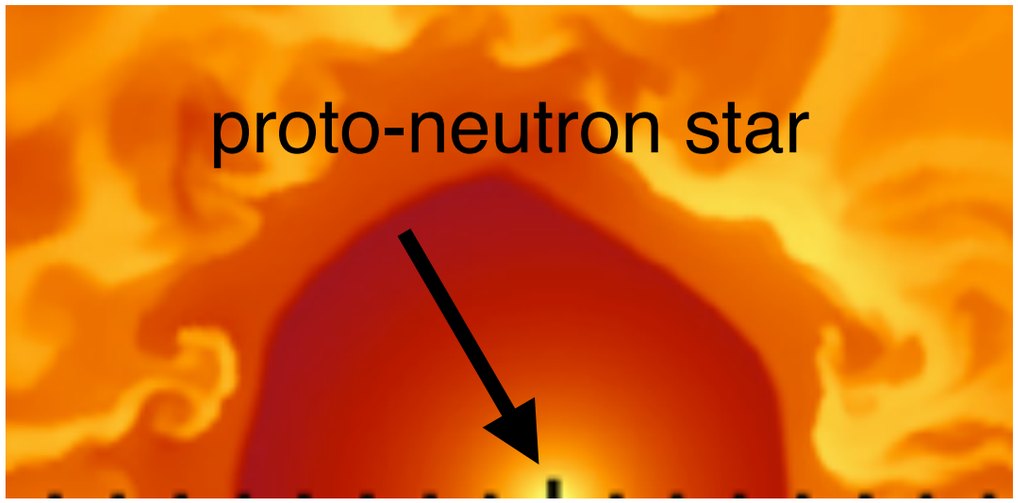
Properties of dense matter and neutrinos influence where and how heavy elements are synthesized.



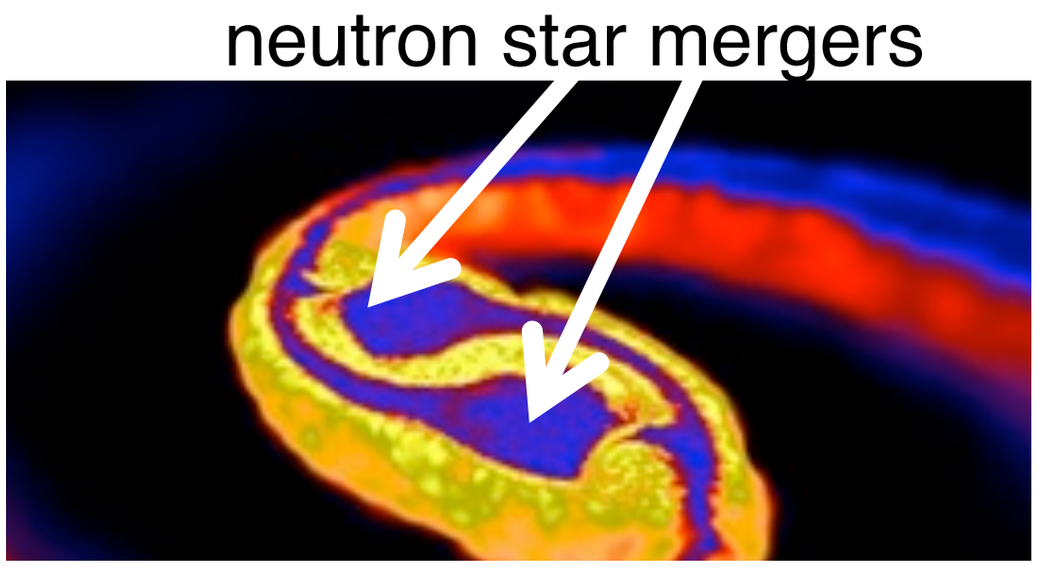
Where does the r-process occur ?

There is general consensus that it involves either one or two neutron stars.

- The one neutron star scenario: Neutrino driven wind in a core-collapse supernova. [Fragile]



- The two neutron star scenario: Dynamical ejection of matter in binary neutron star mergers. [Robust]



R-process: Necessary Conditions

High neutron to seed ratio is needed to populate the observed A~130 and A ~ 190 peaks.

This requires:

- High entropy per baryon.
- Short expansion time.

} Hydrodynamics, Magnetic Fields, etc

- Low electron fraction (Y_e).

} Neutrino Spectra

Dense matter properties determine the neutrino spectra emerging from the hot neutron star.

Y_e in the Neutrino Driven Wind

Is set by the charged current reactions in two regions.

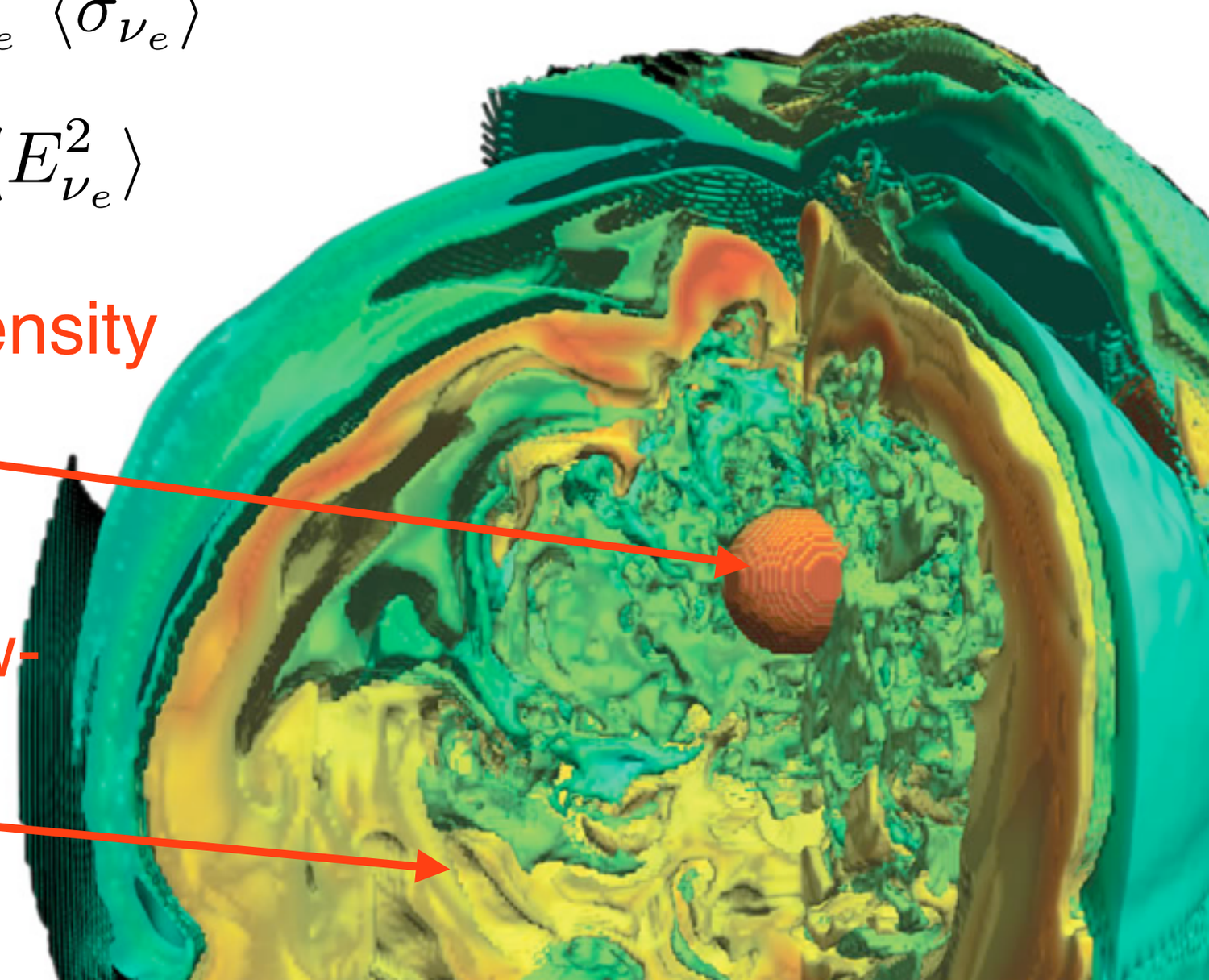
$$\begin{cases} \bar{\nu}_e + p \rightarrow n + e^+ \\ \nu_e + n \rightarrow p + e^- \end{cases}$$

$$Y_e^{\mathrm{NDW}} \approx \frac{\dot{N}_{\nu_e} \langle \sigma_{\nu_e} \rangle}{\dot{N}_{\bar{\nu}_e} \langle \sigma_{\bar{\nu}_e} \rangle + \dot{N}_{\nu_e} \langle \sigma_{\nu_e} \rangle}$$

$$\langle \sigma_{\bar{\nu}_e} \rangle \propto \langle E^2_{\bar{\nu}_e} \rangle \qquad \langle \sigma_{\nu_e} \rangle \propto \langle E^2_{\nu_e} \rangle$$

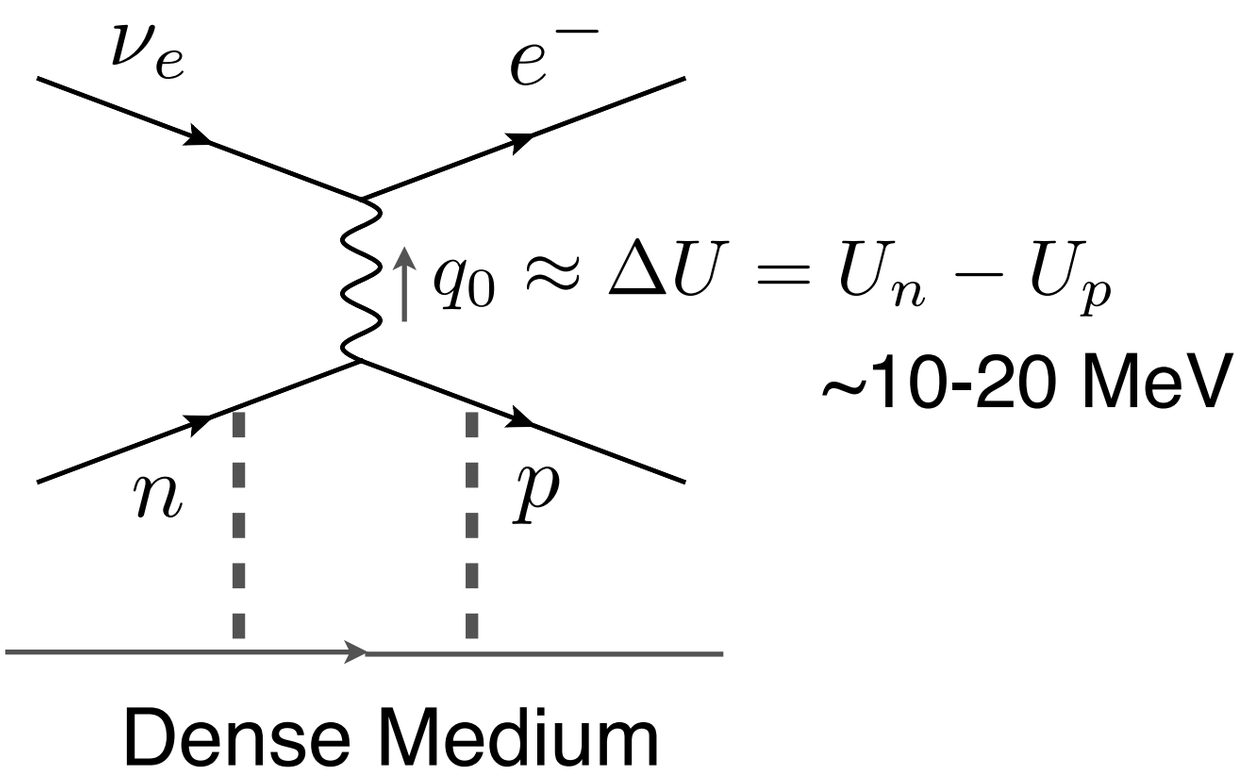
Neutrino-sphere at high density and moderate entropy.
R ~ 10-20 km

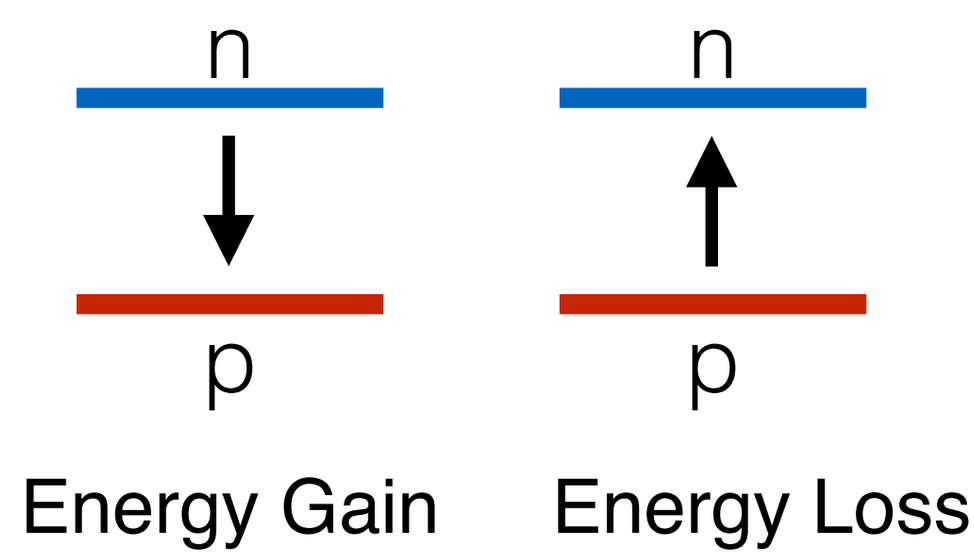
Neutrino driven wind at low-density and high entropy.
R ~ 10^3-10^4 km



Charged Current Opacity

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



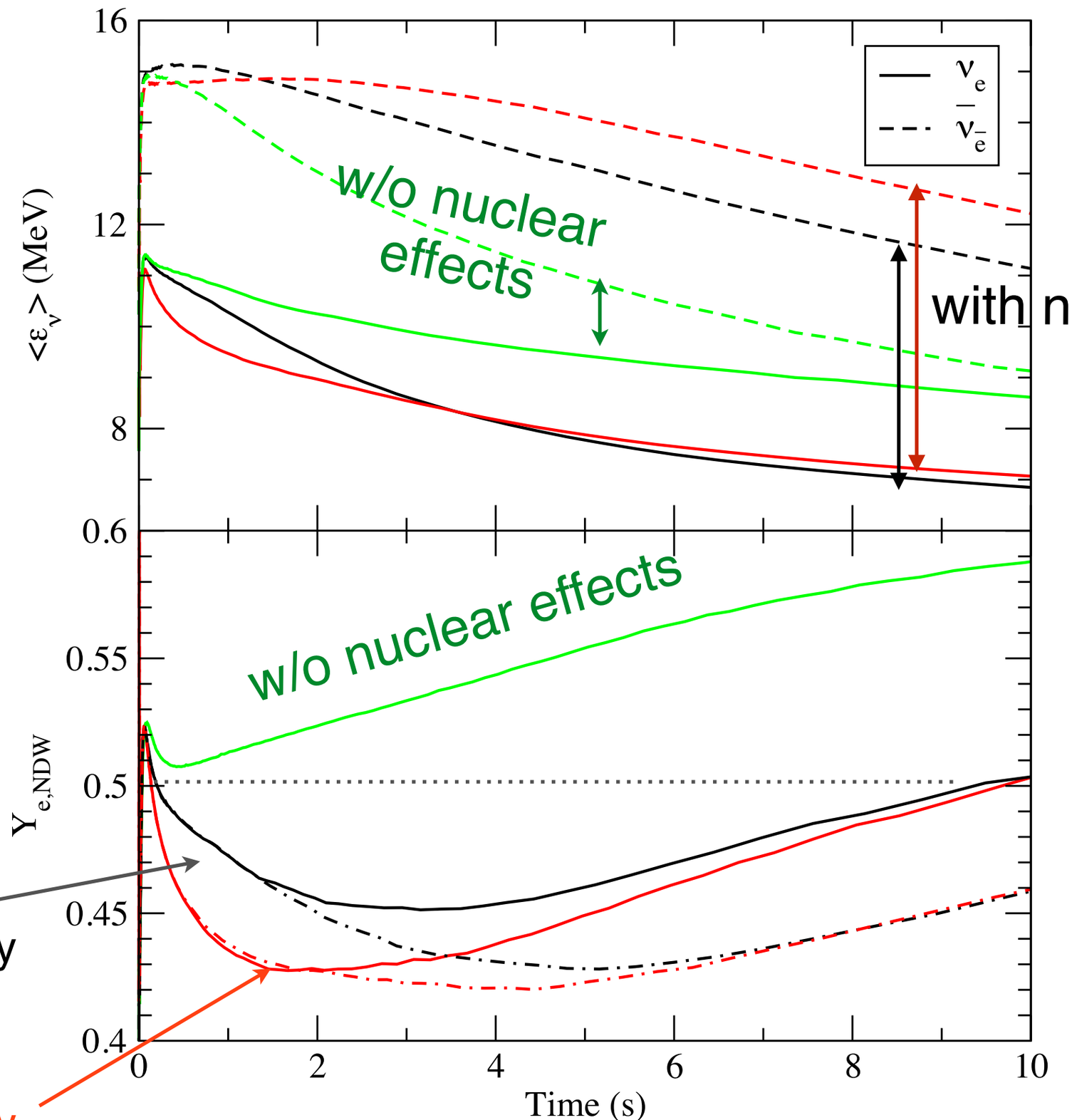


Dense medium changes the “Q” value of the reaction.

- Protons experience larger attraction in neutron-rich matter.
- Large symmetry energy favors electron neutrino absorption and disfavors anti-electron neutrino absorption.

Reddy, Prakash & Lattimer (1998), Roberts (2012), Martinez-Pinedo et al. (2012), Roberts & Reddy (2012)

Spectra & Nucleosynthesis



proton-rich ejecta

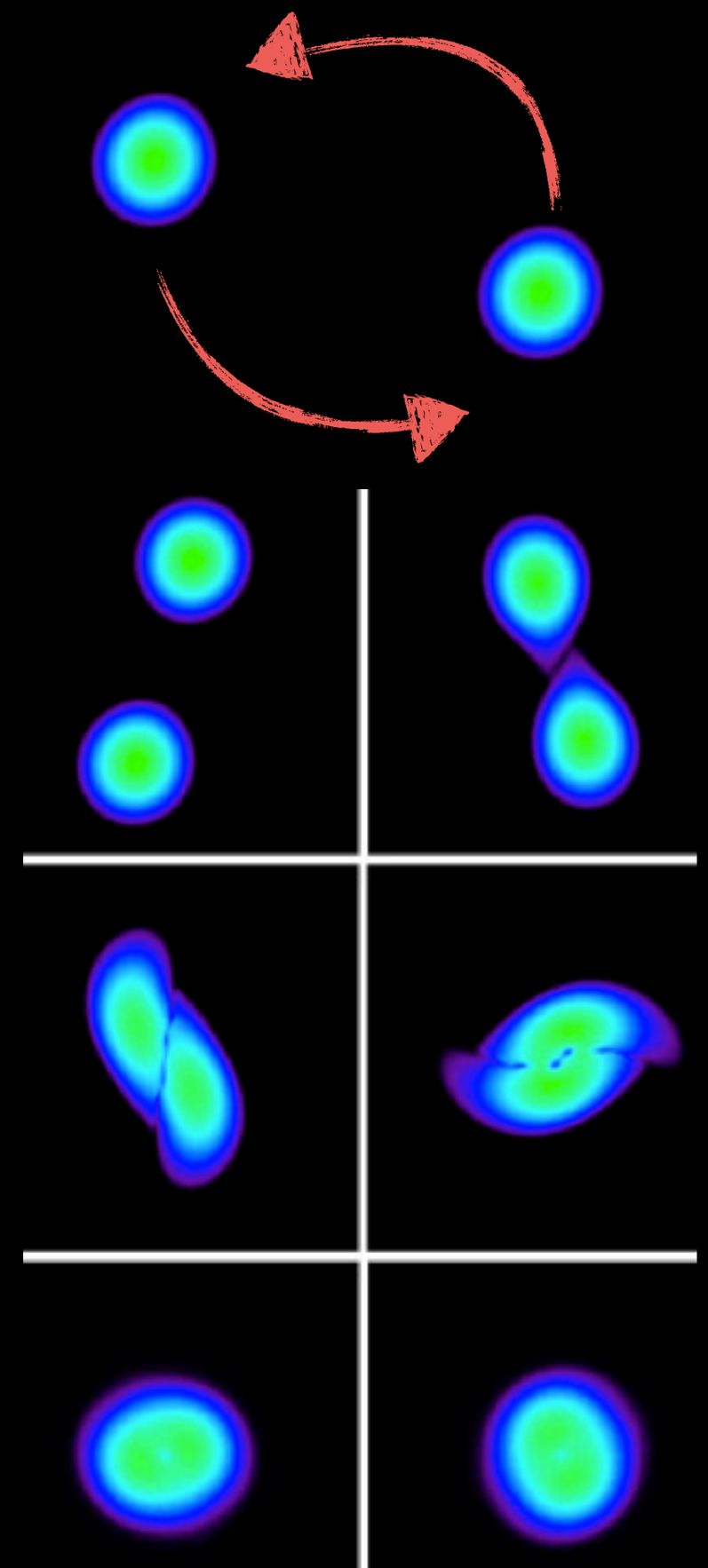
neutron-rich ejecta

EoS: Small Symmetry Energy

EoS: Large Symmetry Energy

Roberts, Reddy & Shen (2012)

NS Collisions - Gravitational Waves

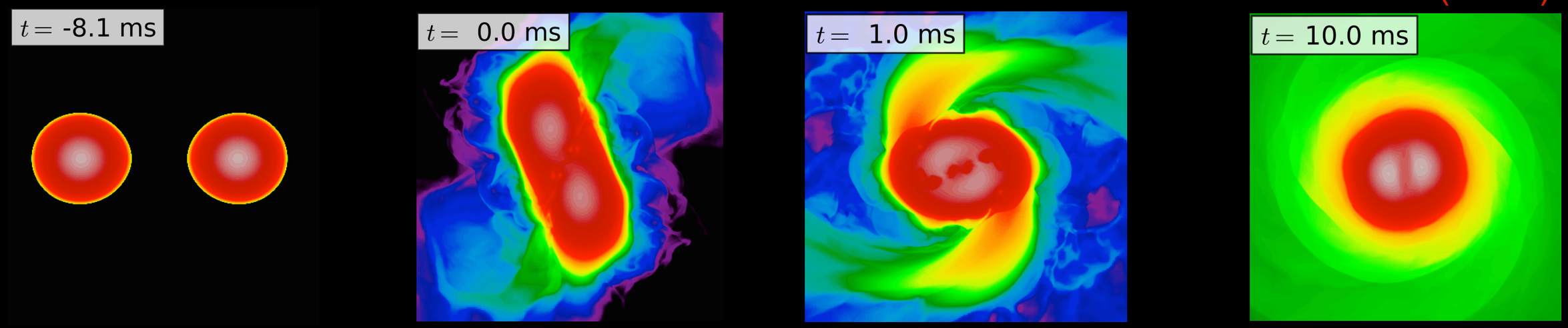


The gravitational waves, EM counterparts, and nucleosynthesis are sensitive nuclear and neutrino physics.

Neutron Star Merger Dynamics

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

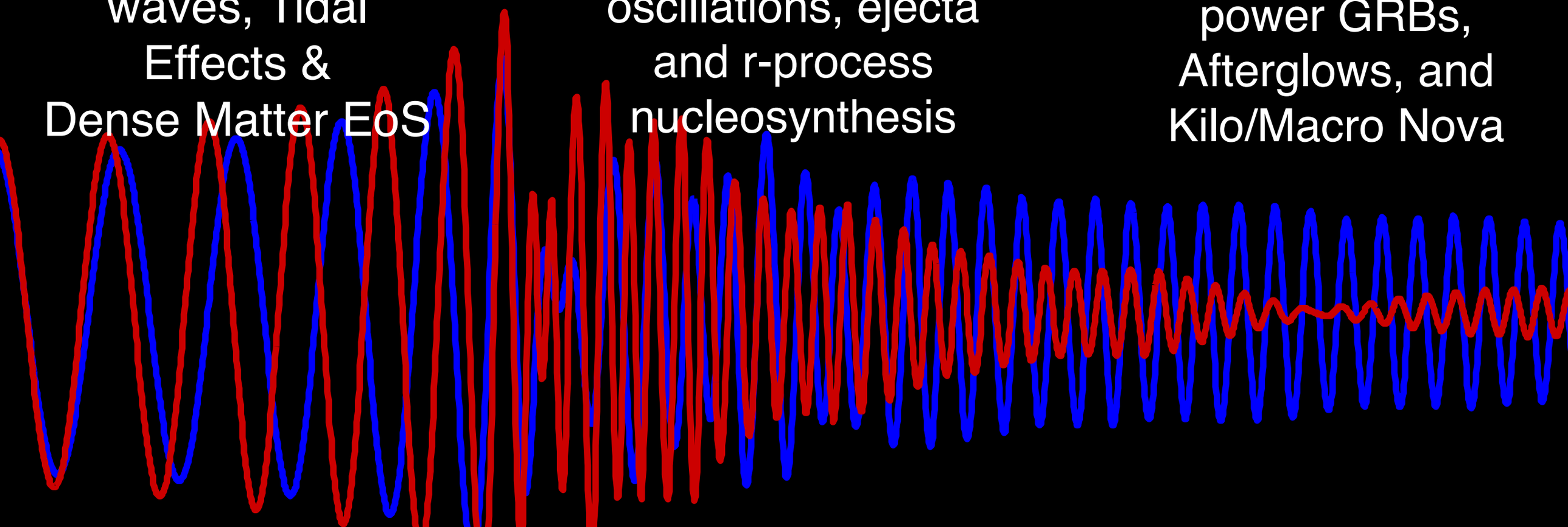
Simulations: Rezzola et al (2013)



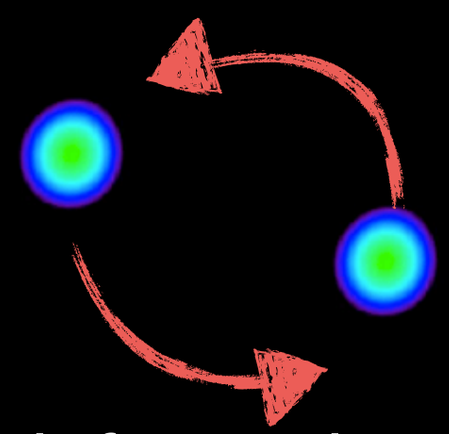
Inspiral: Gravitational waves, Tidal Effects & Dense Matter EoS

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

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

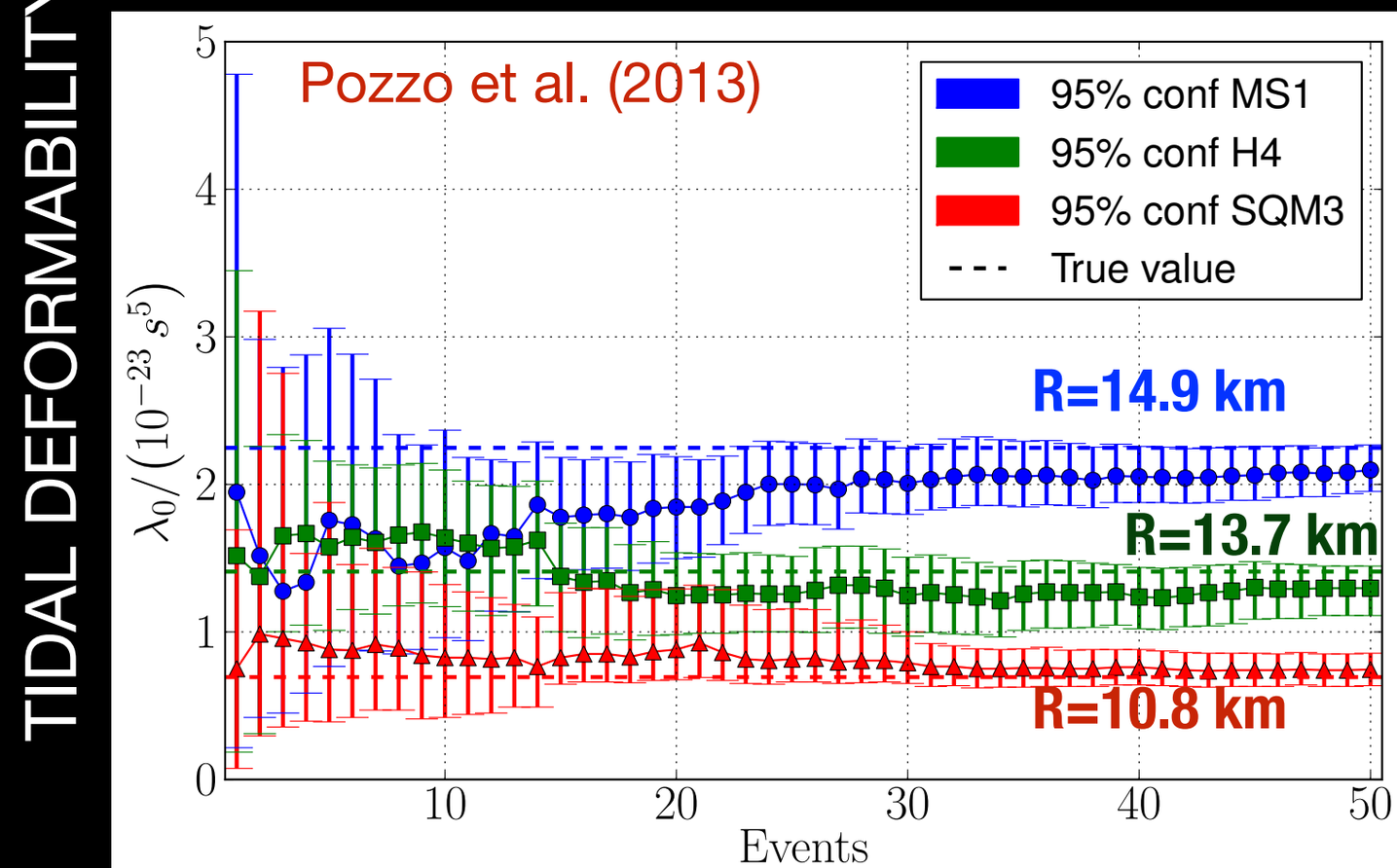


NEUTRON STAR RADII FROM PRE MERGER SIGNAL



Tidal deformation induces quadrupole moment.

$$\lambda = \frac{2}{3G} k_2 R^5$$

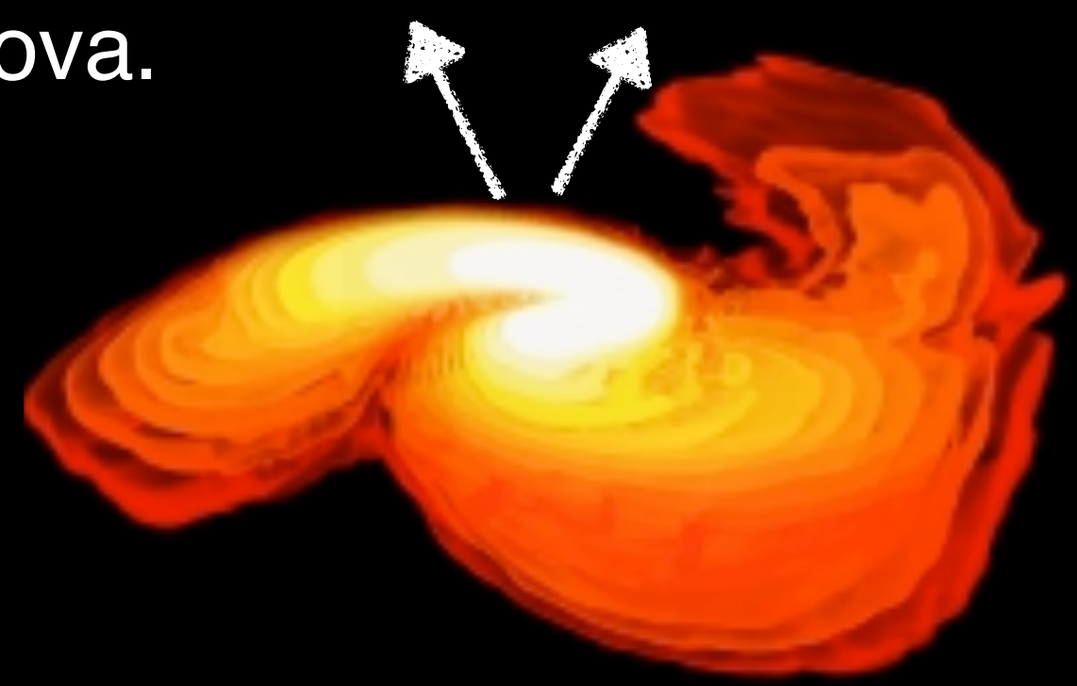


Realistic data analysis by injecting events in a volume between 100-250 Mpc demonstrates discriminating power between EOSs. Pozzo et al. (2013)

With a few tens of events the radius can be extracted to better than 10%.

Merger Ejecta & Nucleosynthesis

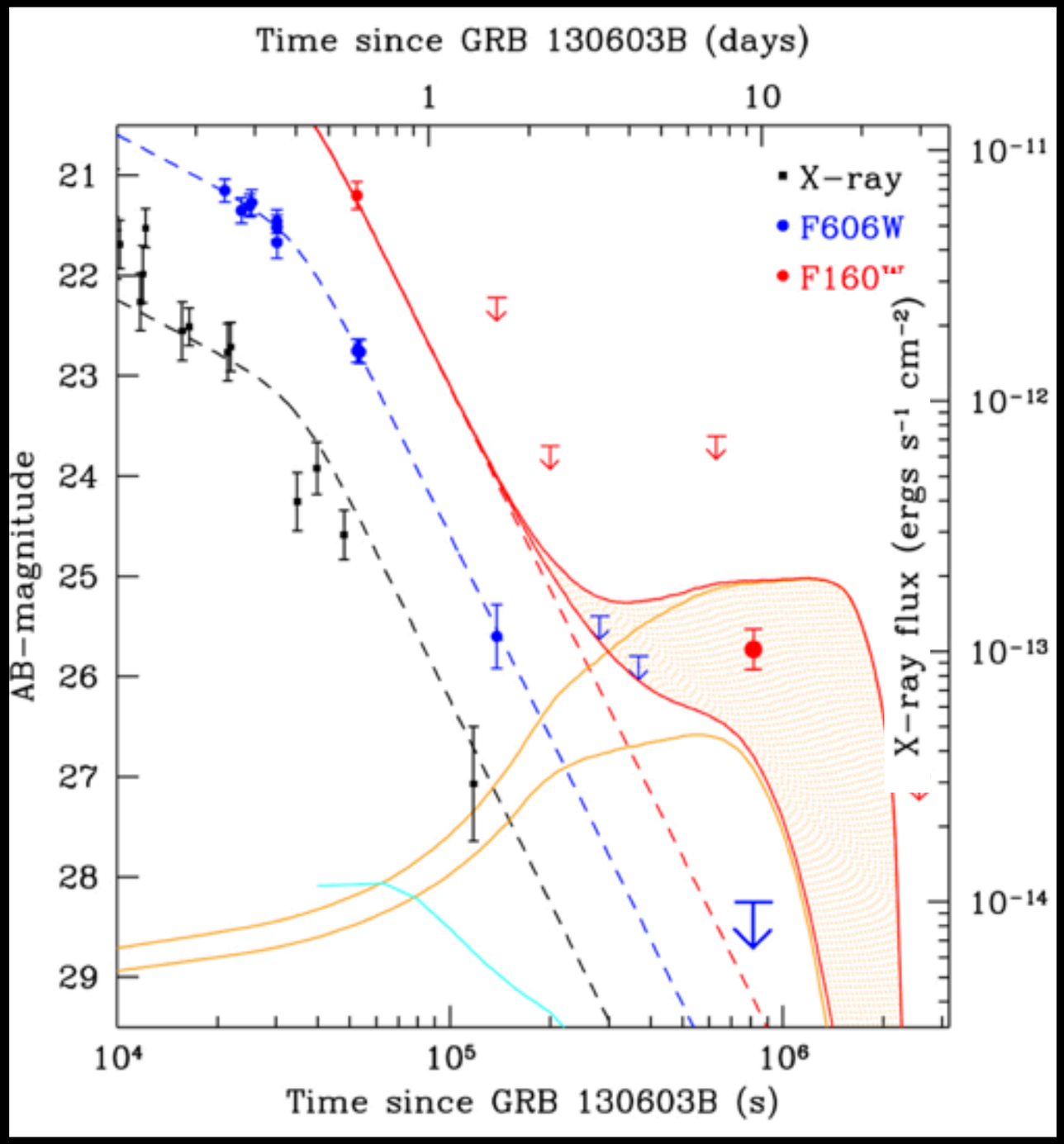
Shocked ejecta:
Processed by neutrinos, much like in a supernova.



Tidal ejecta:
Early, and very neutron-rich.
Robust r-process.

Amount and composition of the material ejected depends on the neutron star radius and neutrino interactions in dense matter.

Ejecta and GRB afterglow: Kilonova



Detection of a Kilonova

Tanvir et al. 2013

- Radioactive heavy elements synthesized and ejected can power an EM signal

  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

Summary & Outlook

- Diverse explosive and transient phenomena are driven by similar nuclear and neutrino processes.
- Simulations and dense matter theory has begun to identify robust connections to guide observations and interpretation.
- Multi-wavelength, multi-messenger astronomy can probe source properties at microscopic scales.
- GWs from neutron star mergers - an exciting near term prospect with important implications for neutron stars, dense matter theory and nucleosynthesis.

Reactions in the Neutrino-sphere

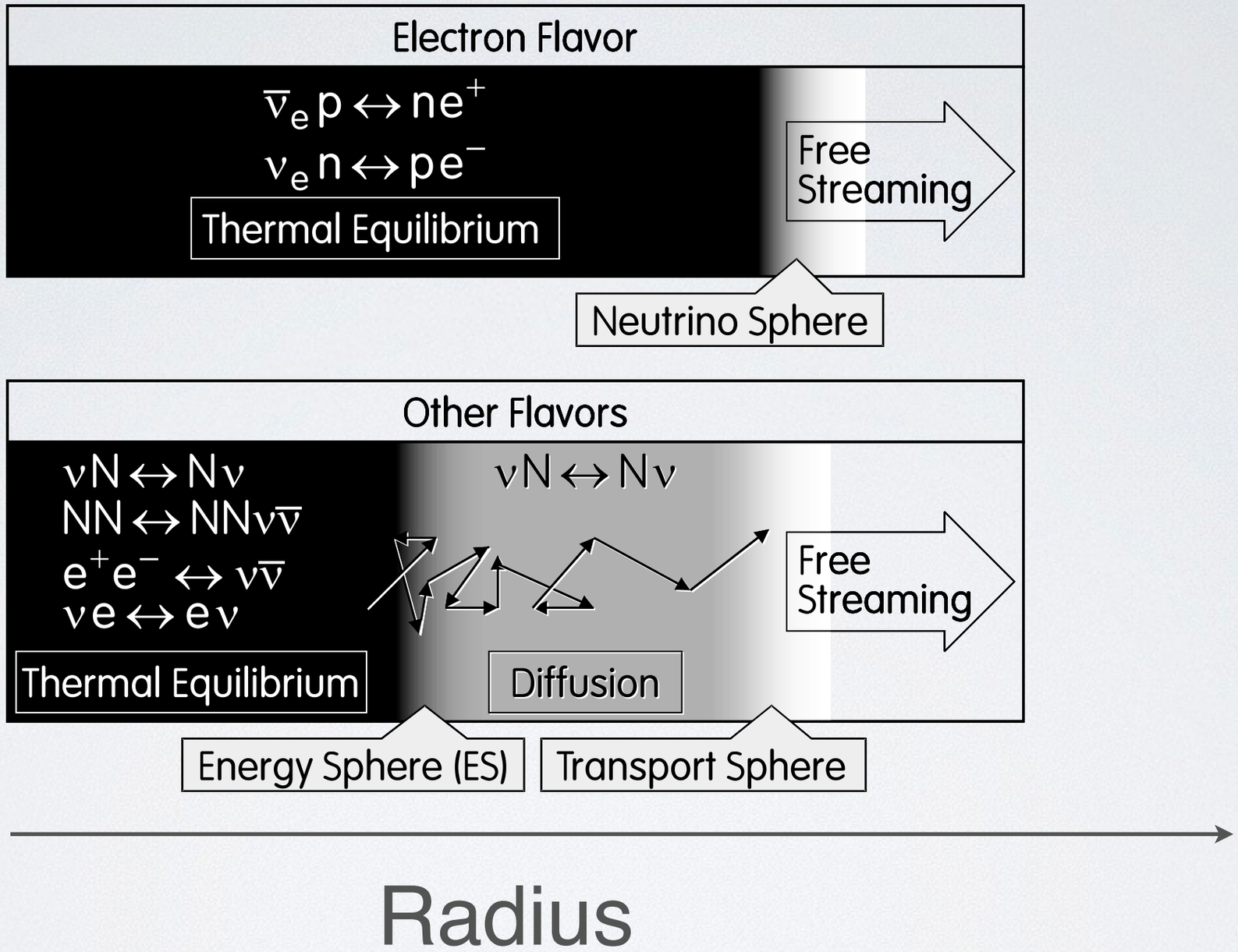
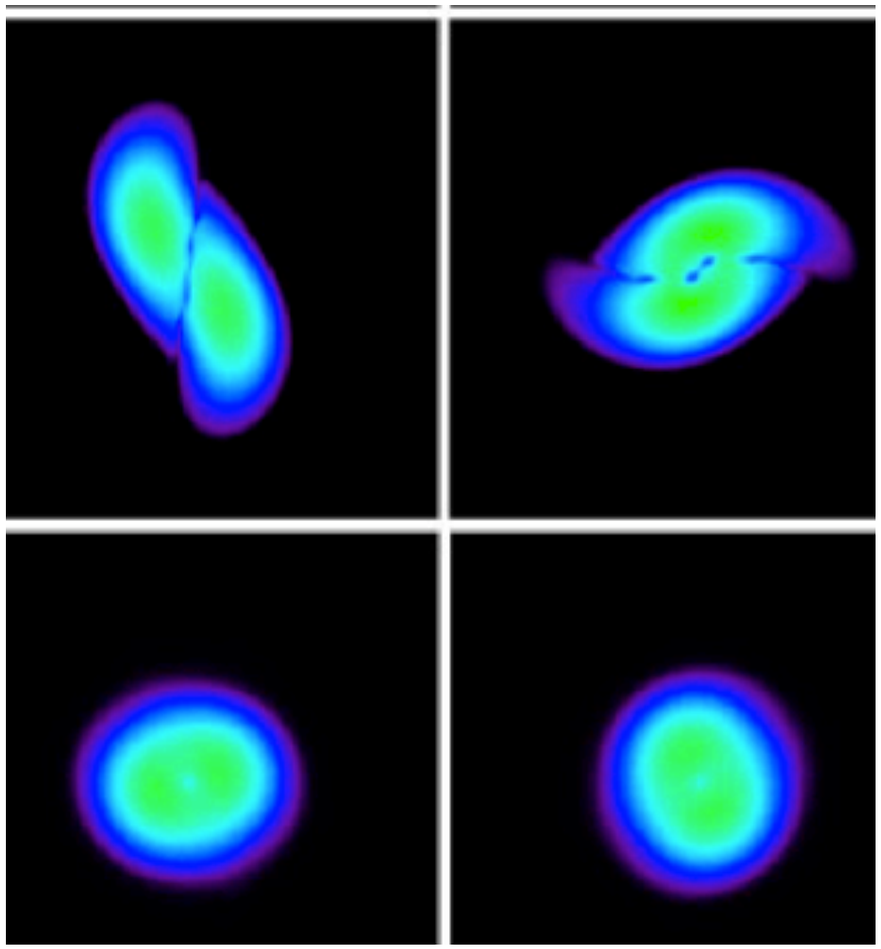
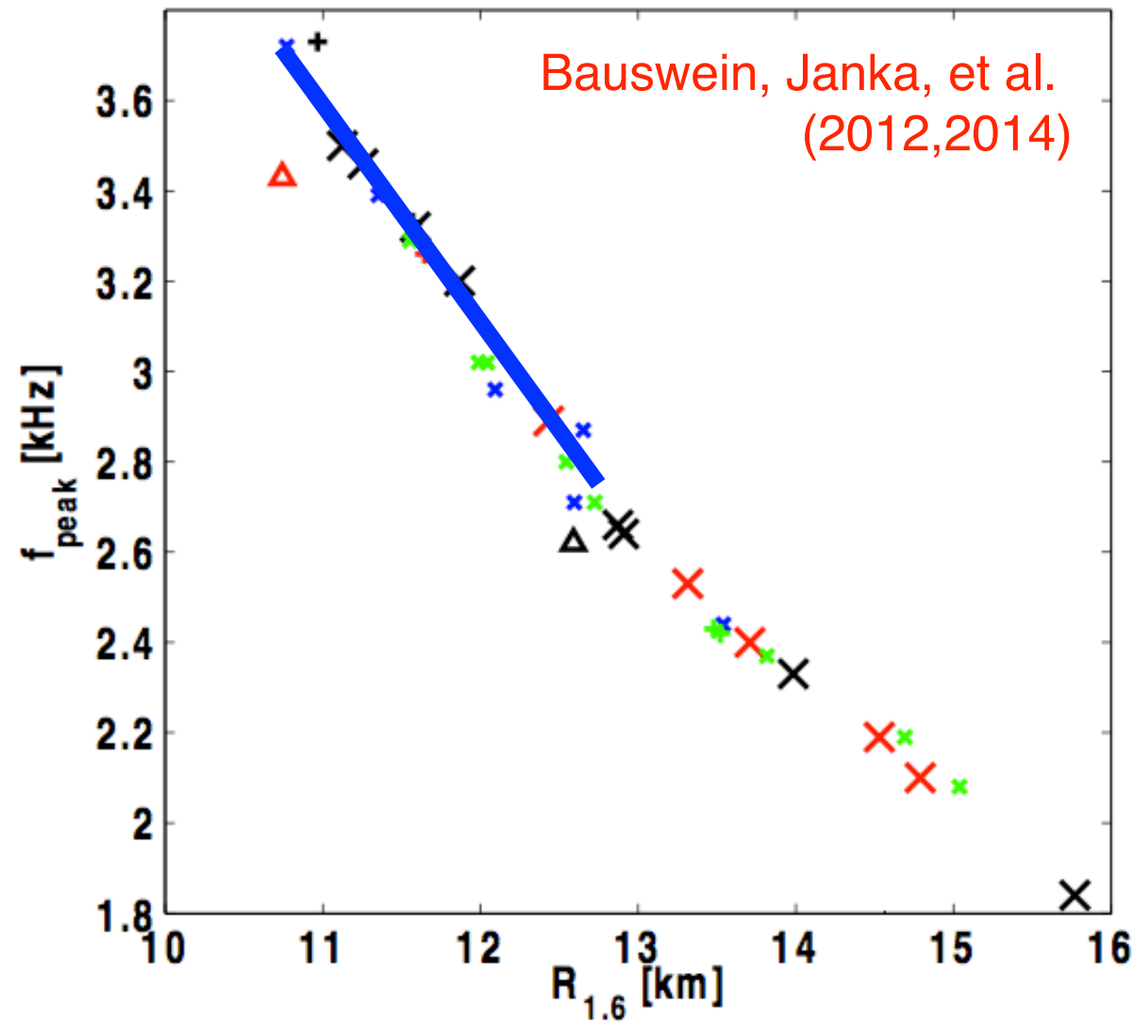


Fig: From Raffelt (2001)

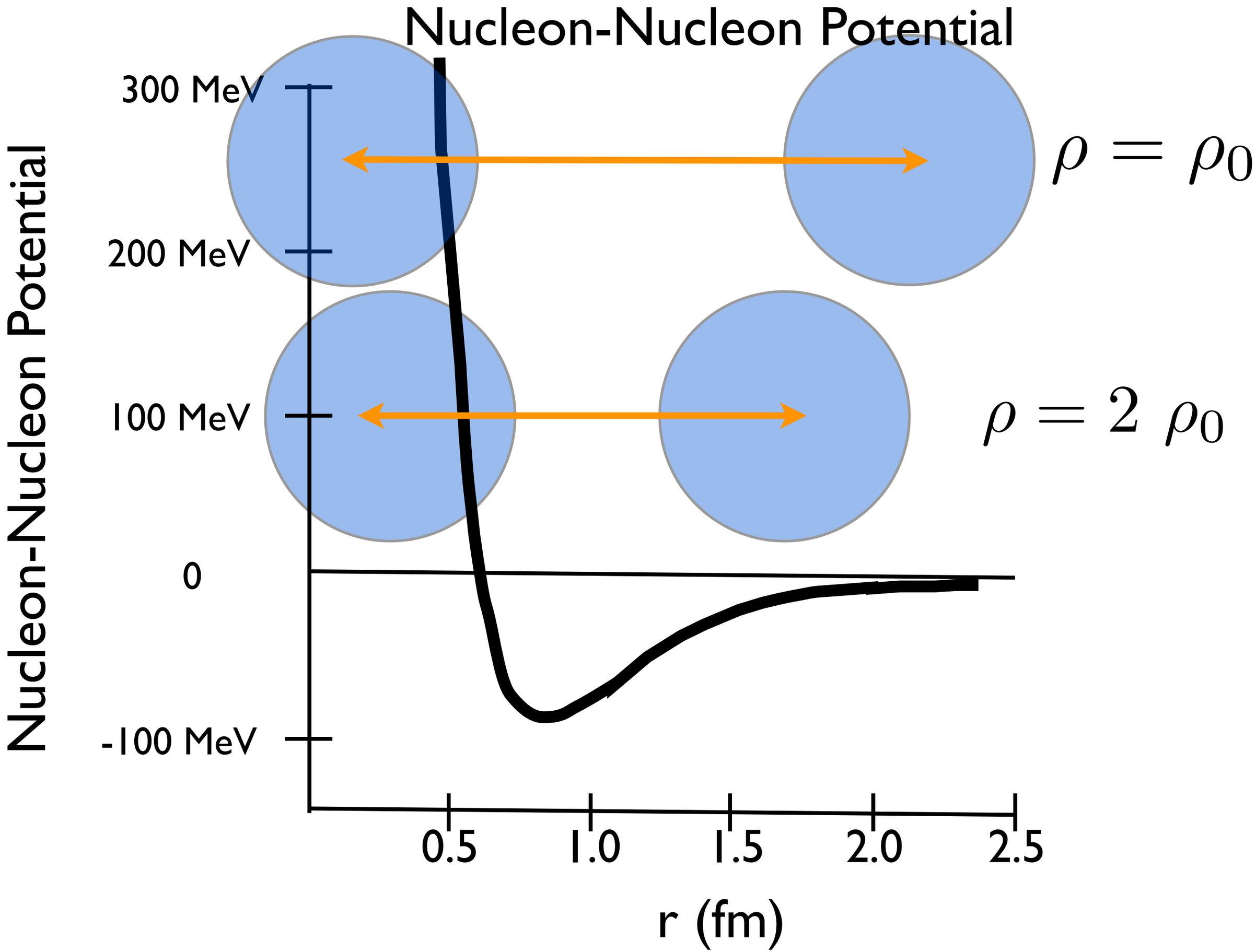
Post Merger Dynamics





- Peak frequency of neutron star oscillations post merger is correlated with neutron star radius.

- Black-hole formation, nucleosynthesis in the ejecta are also sensitive to dense matter properties.


Nucleon-Nucleon Potential
300 MeV
200 MeV
100 MeV
0
-100 MeV
Nucleon-Nucleon Potential
$\rho = \rho_0$
$\rho = 2\ \rho_0$
0.5
1.0
1.5
2.0
2.5
r (fm)