Dense Matter in Neutron Stars:
New Insights from Theory and Observations.

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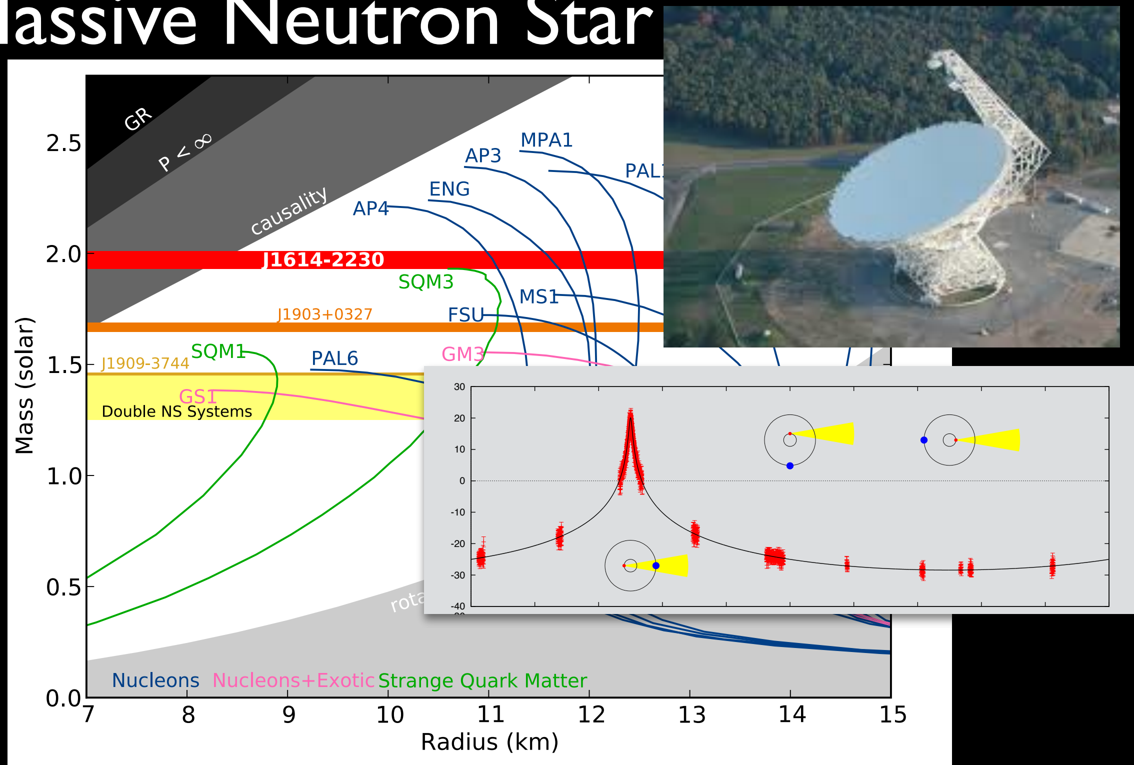
INT & Univ. of Washington, Seattle

EMMI workshop on "Cold dense nuclear matter from short-range correlations to neutron stars", GSI, Darmstadt.

INSTITUTE for NUCLEAR THEORY

Recent Observations

Massive Neutron Star



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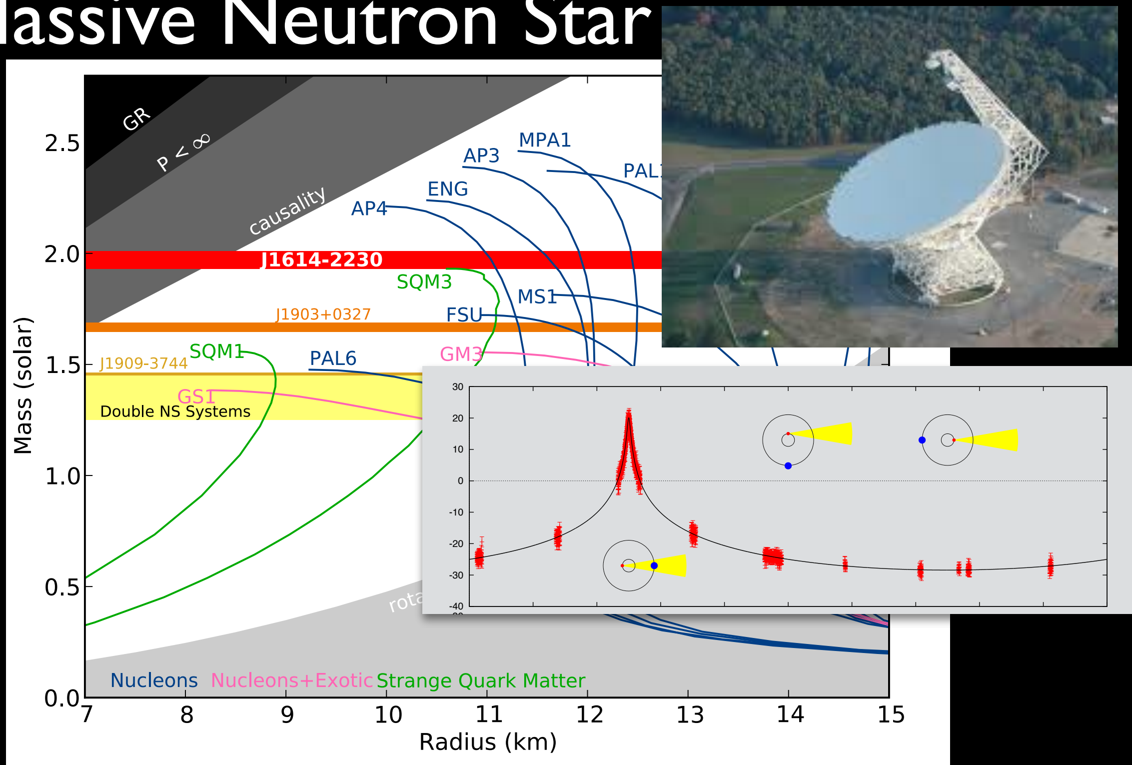
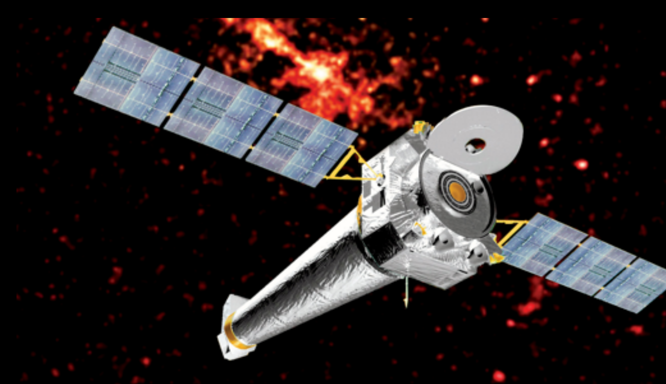
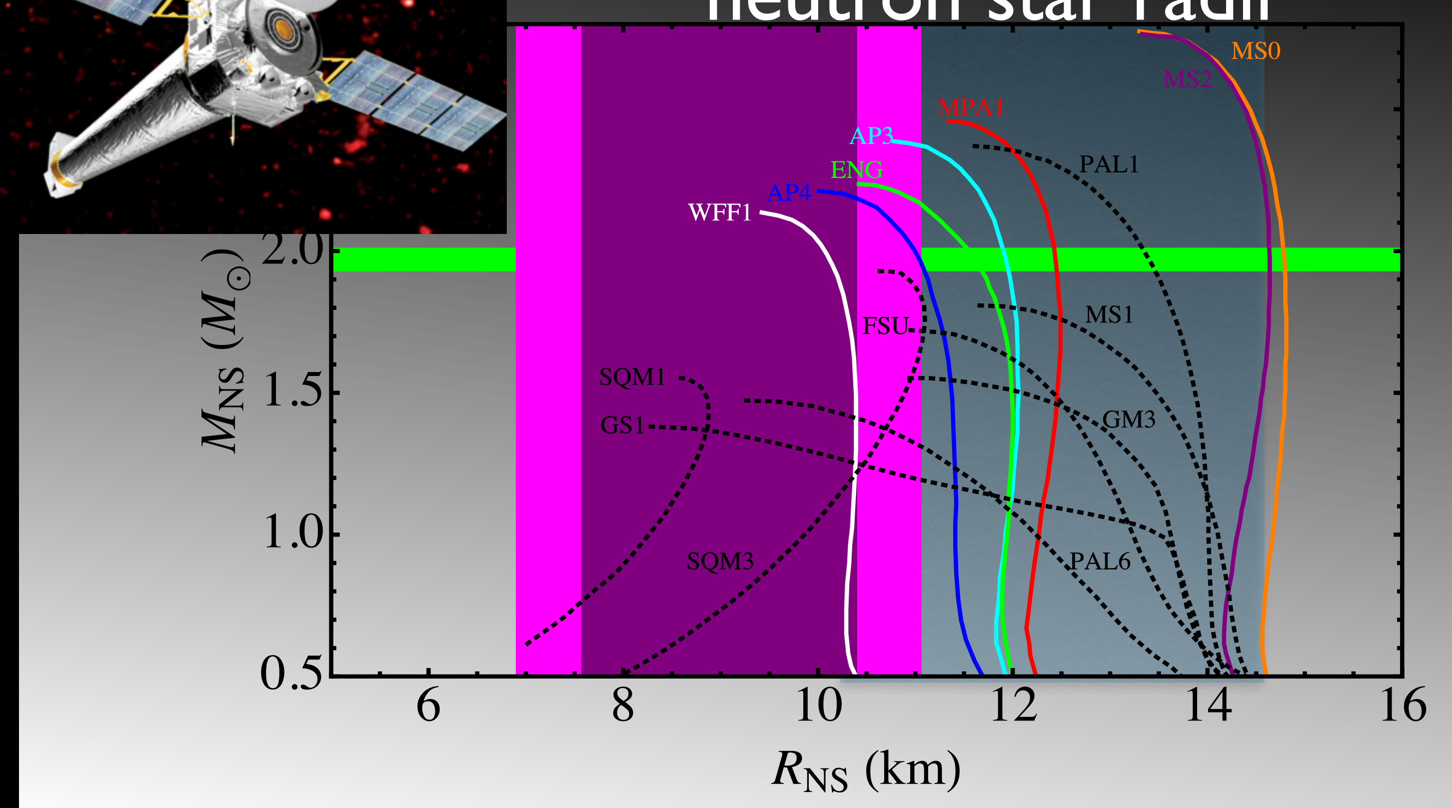




Towards a measurement of neutron star radii



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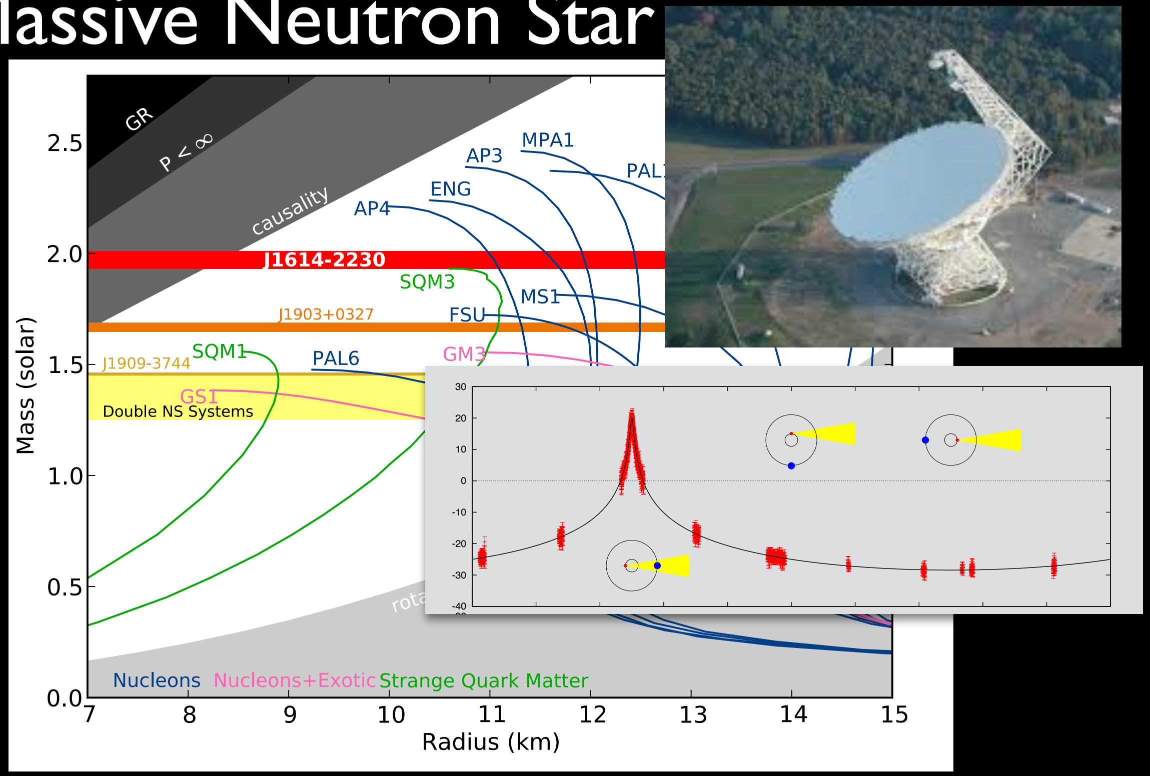
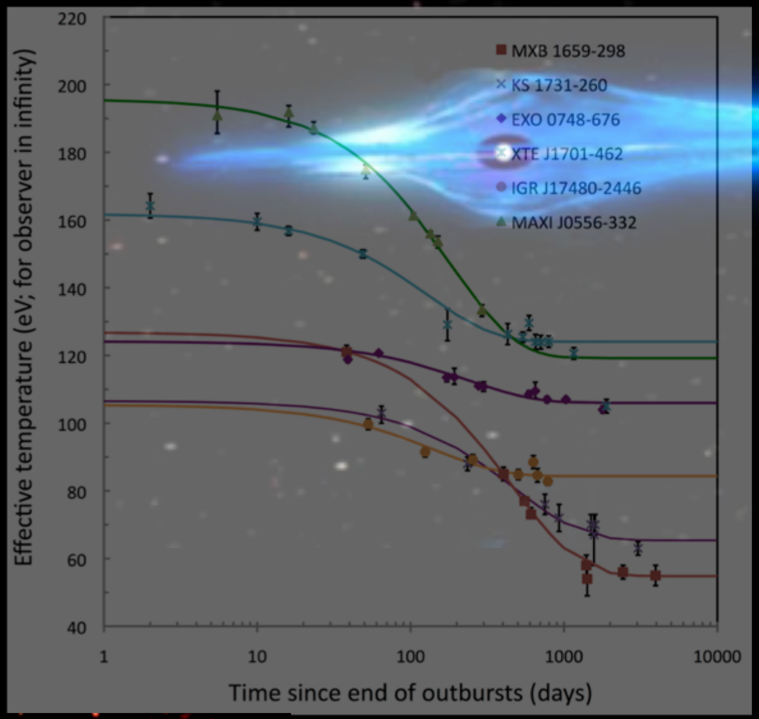
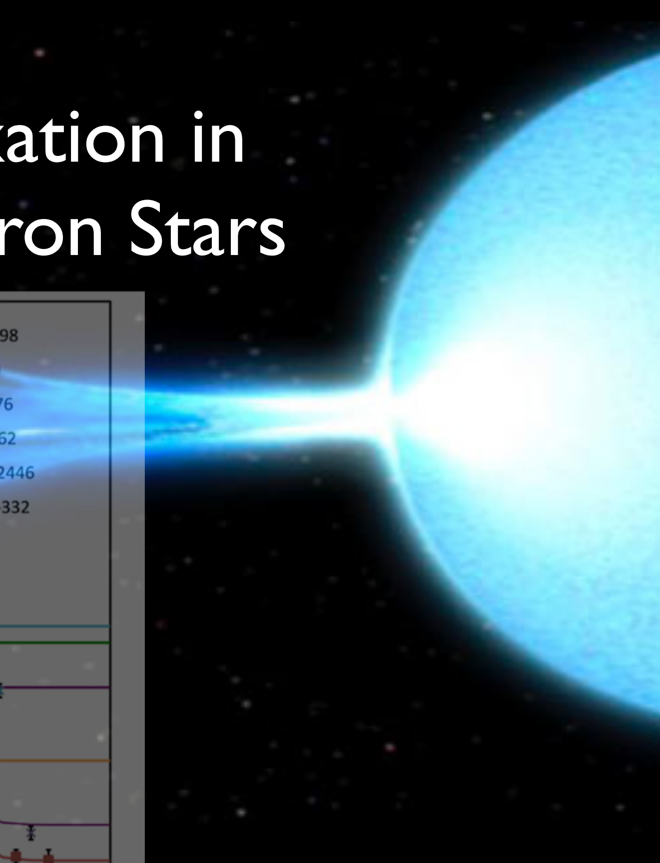
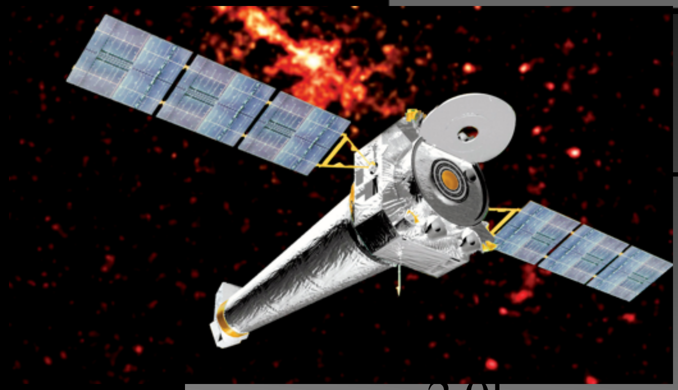


Thermal Relaxation in Accreting Neutron Stars







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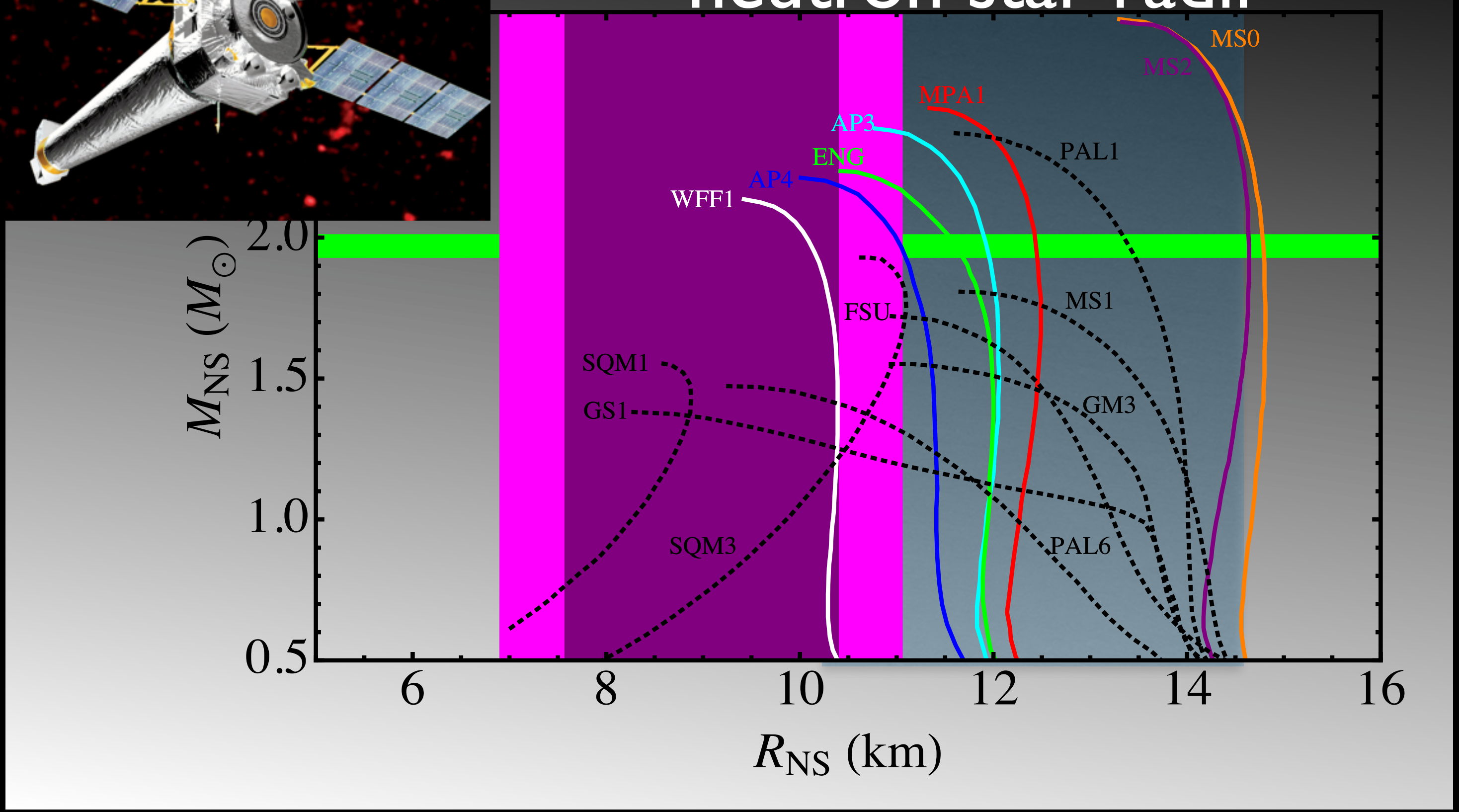

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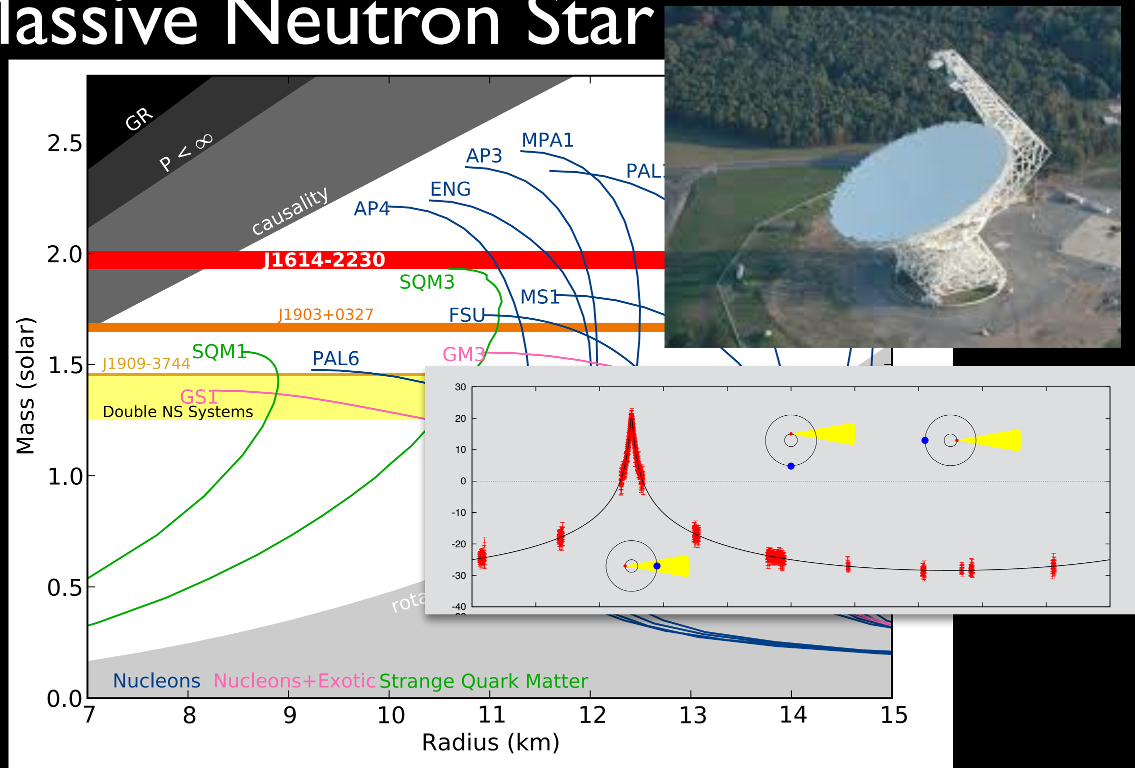

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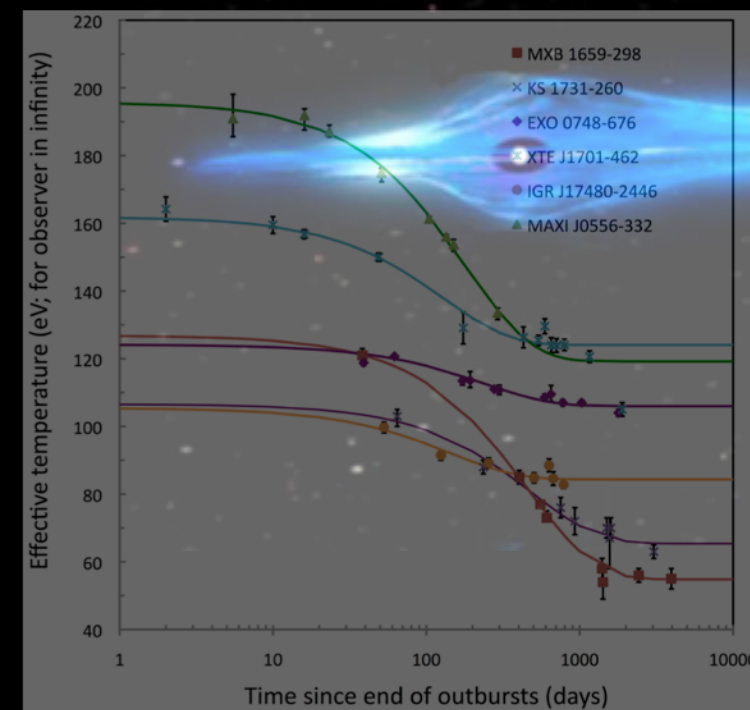
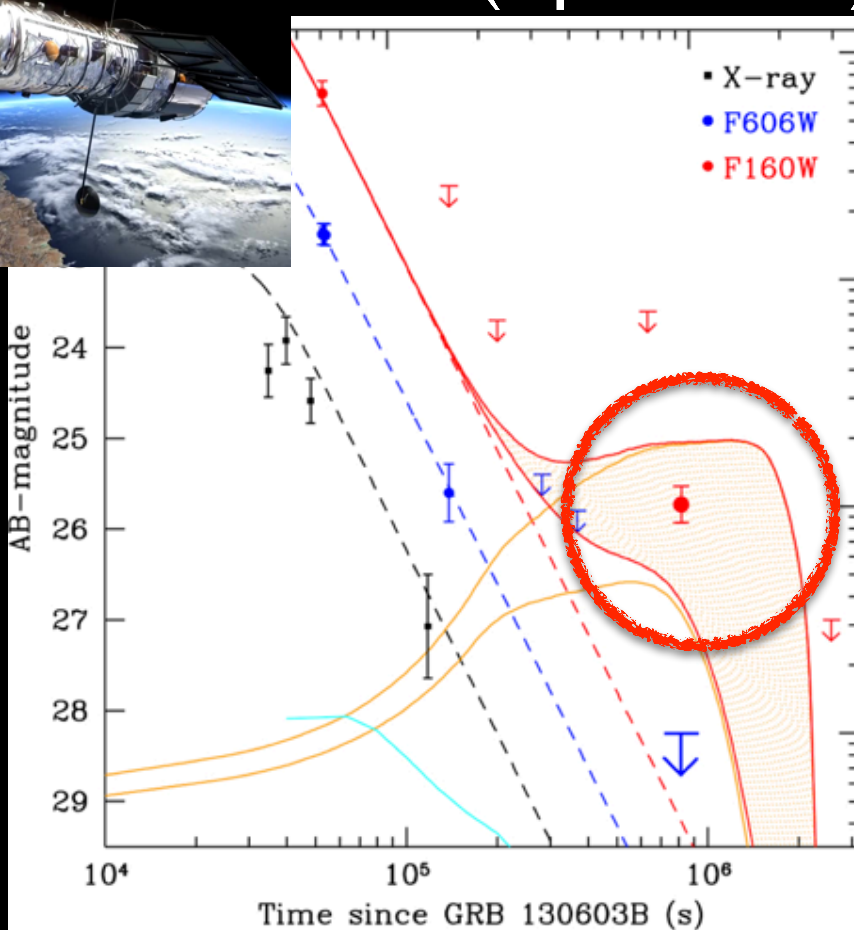
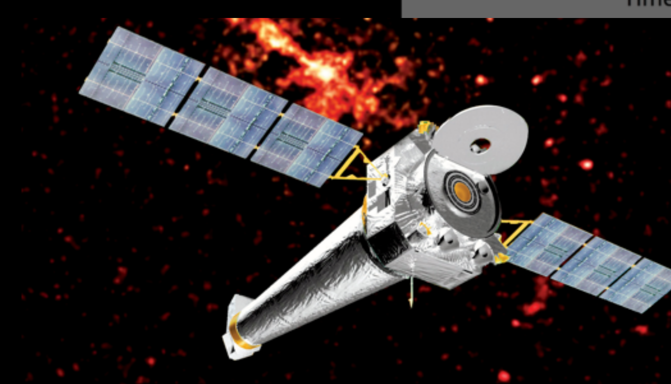


Kilo Nova (r-process ?)





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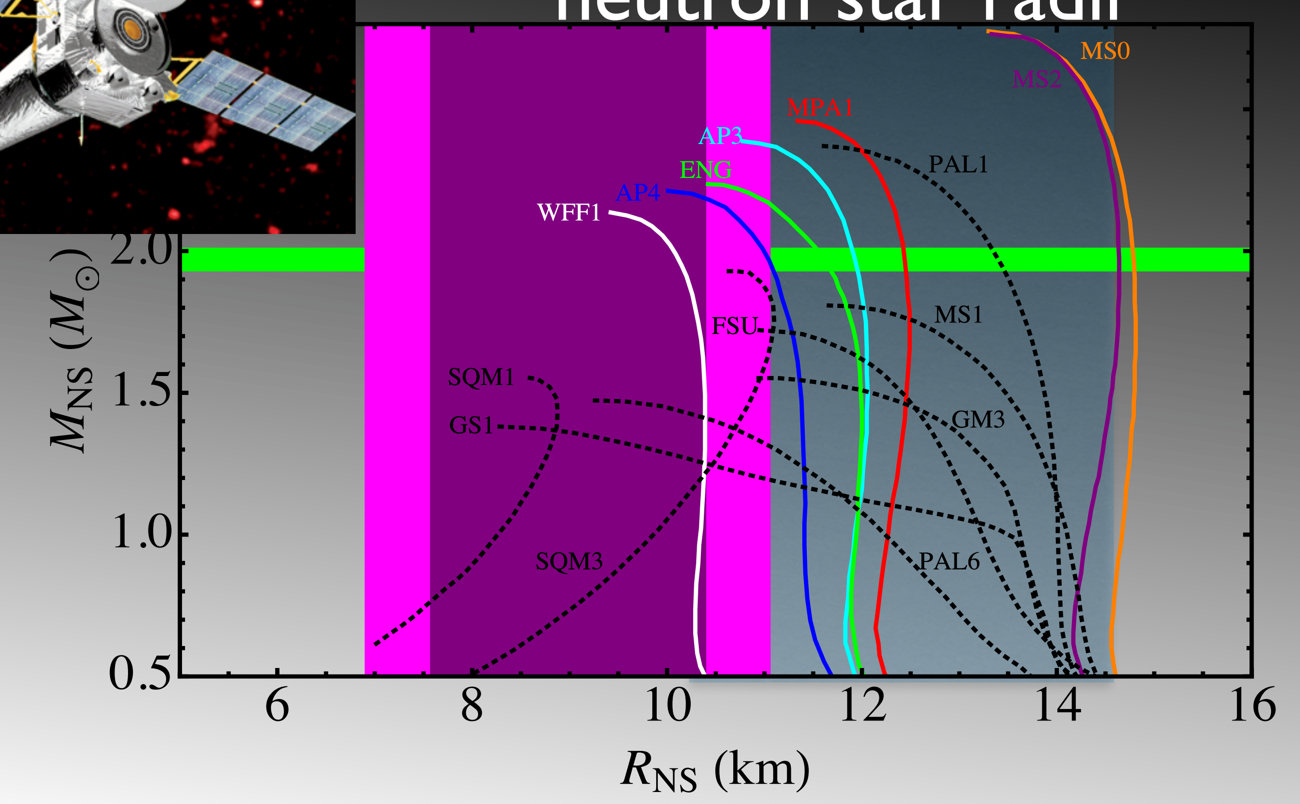
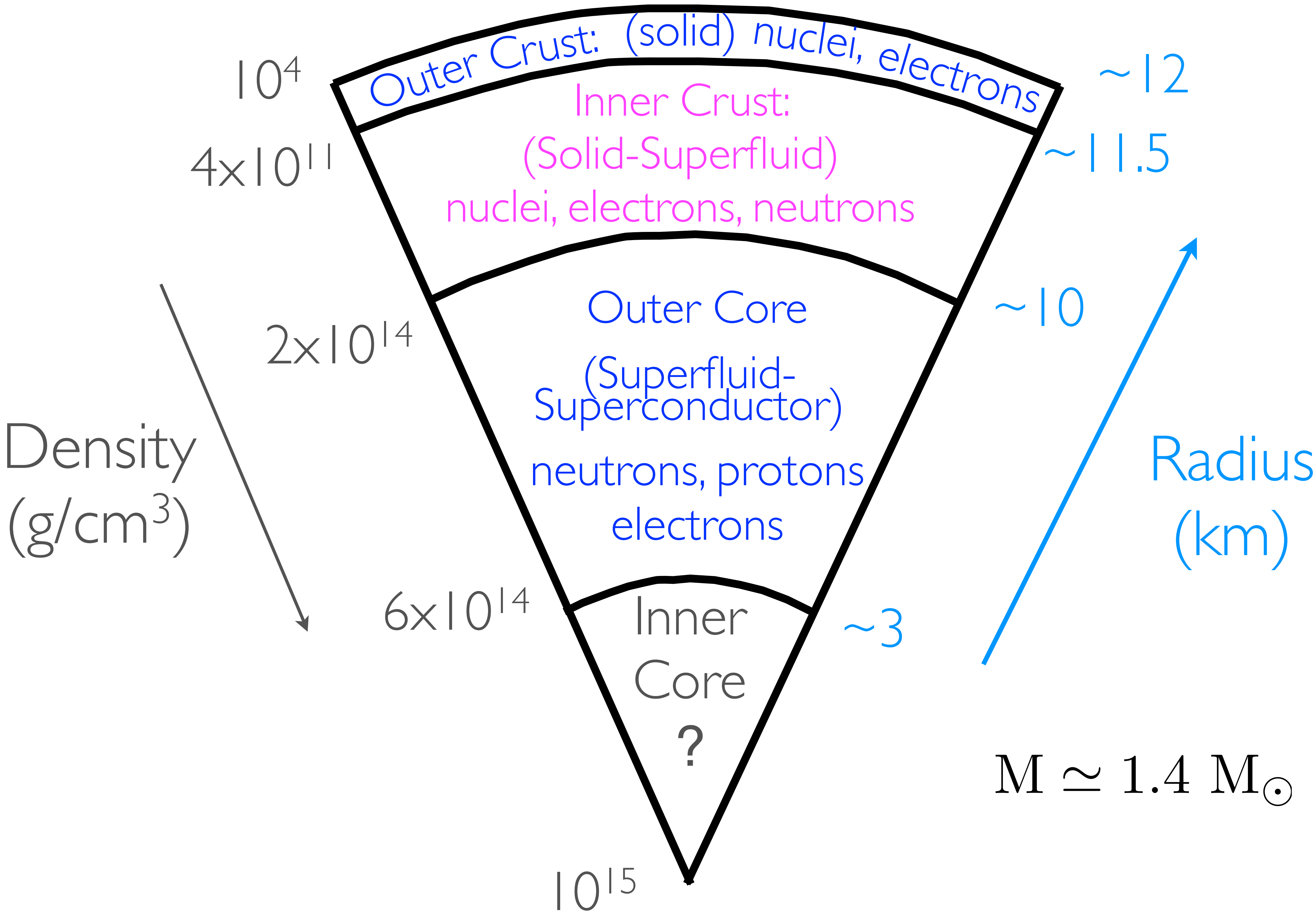
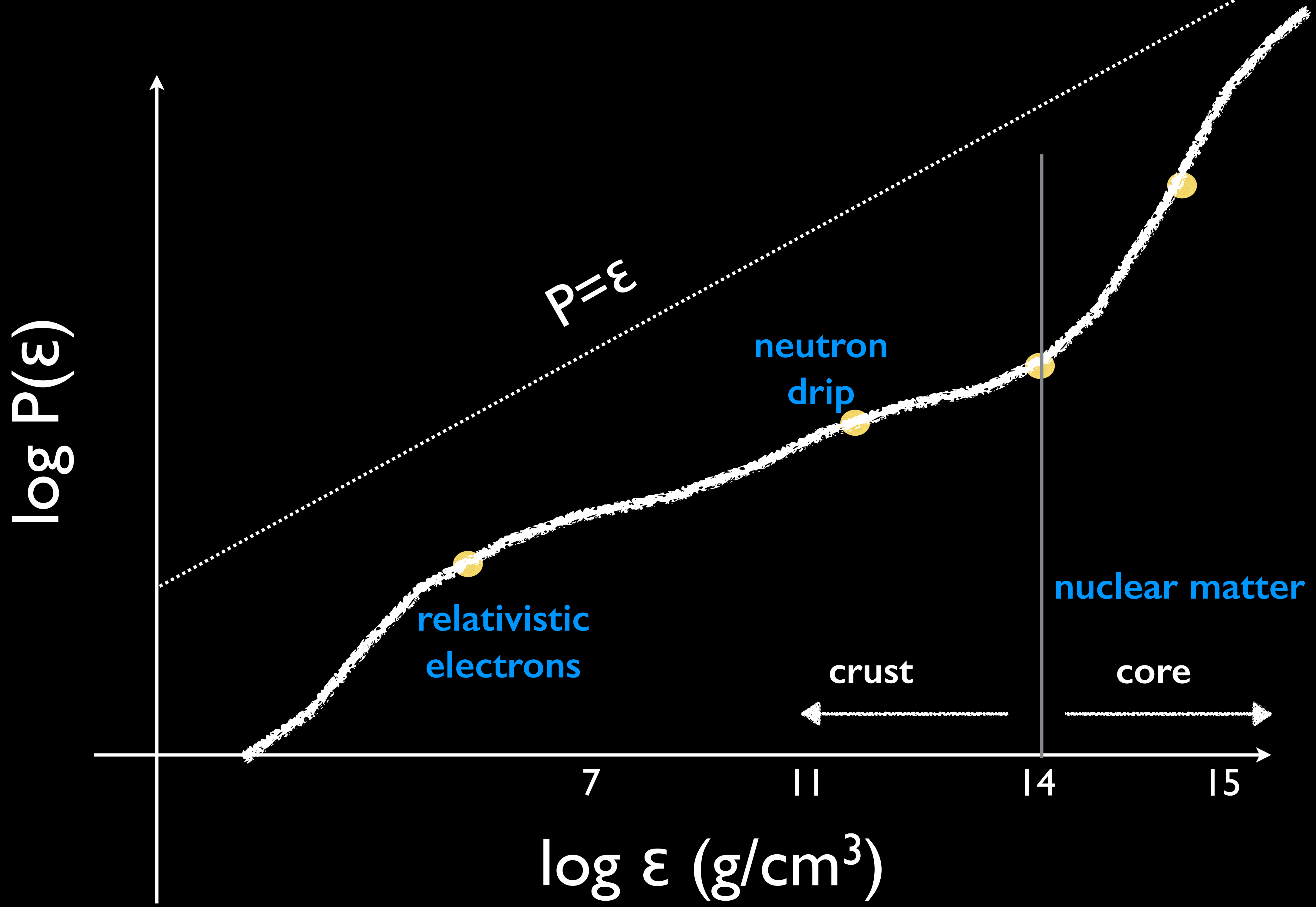


Phases of Dense Matter in Neutron



Pressure v/s Energy Density (EoS)



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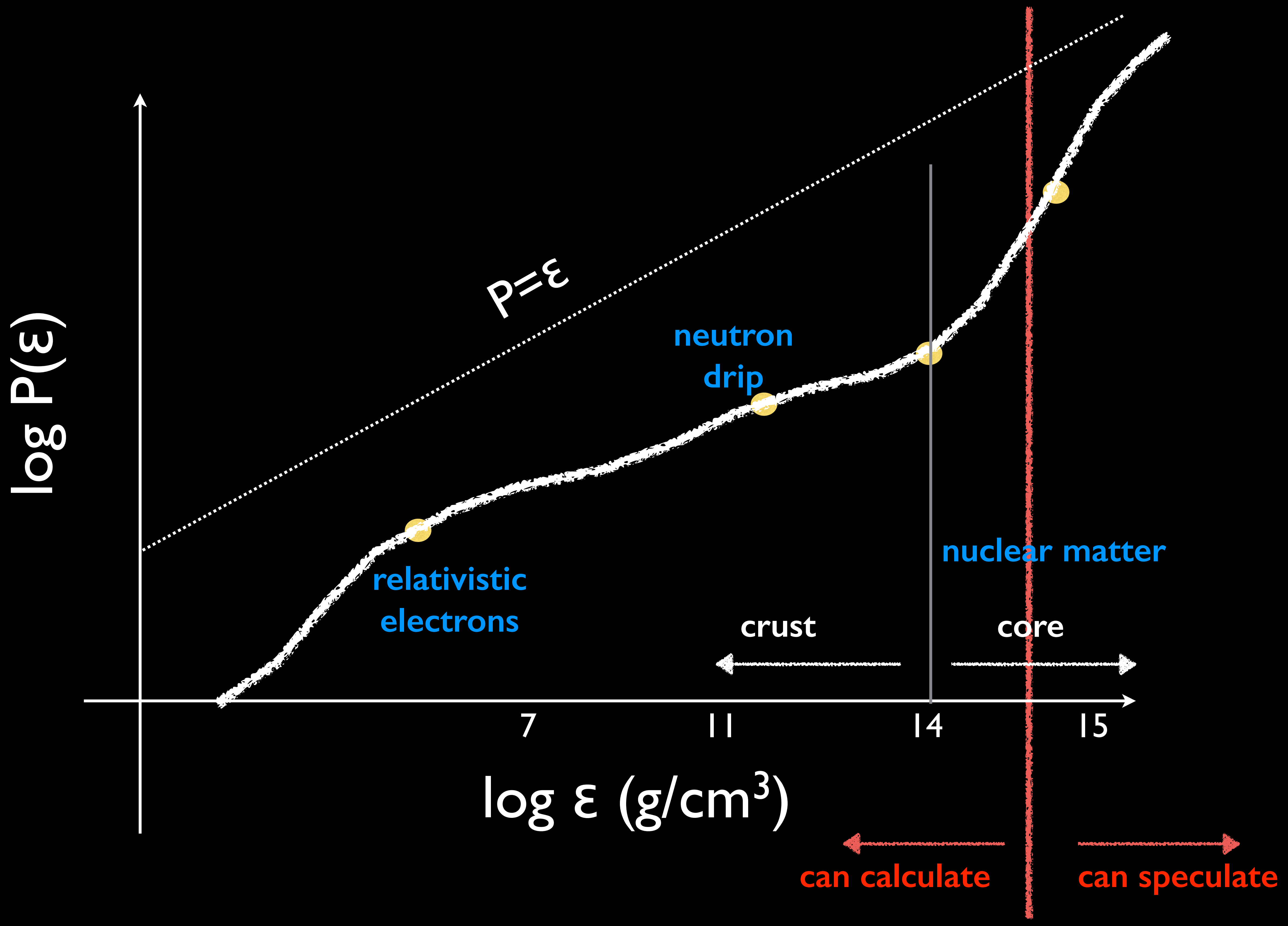

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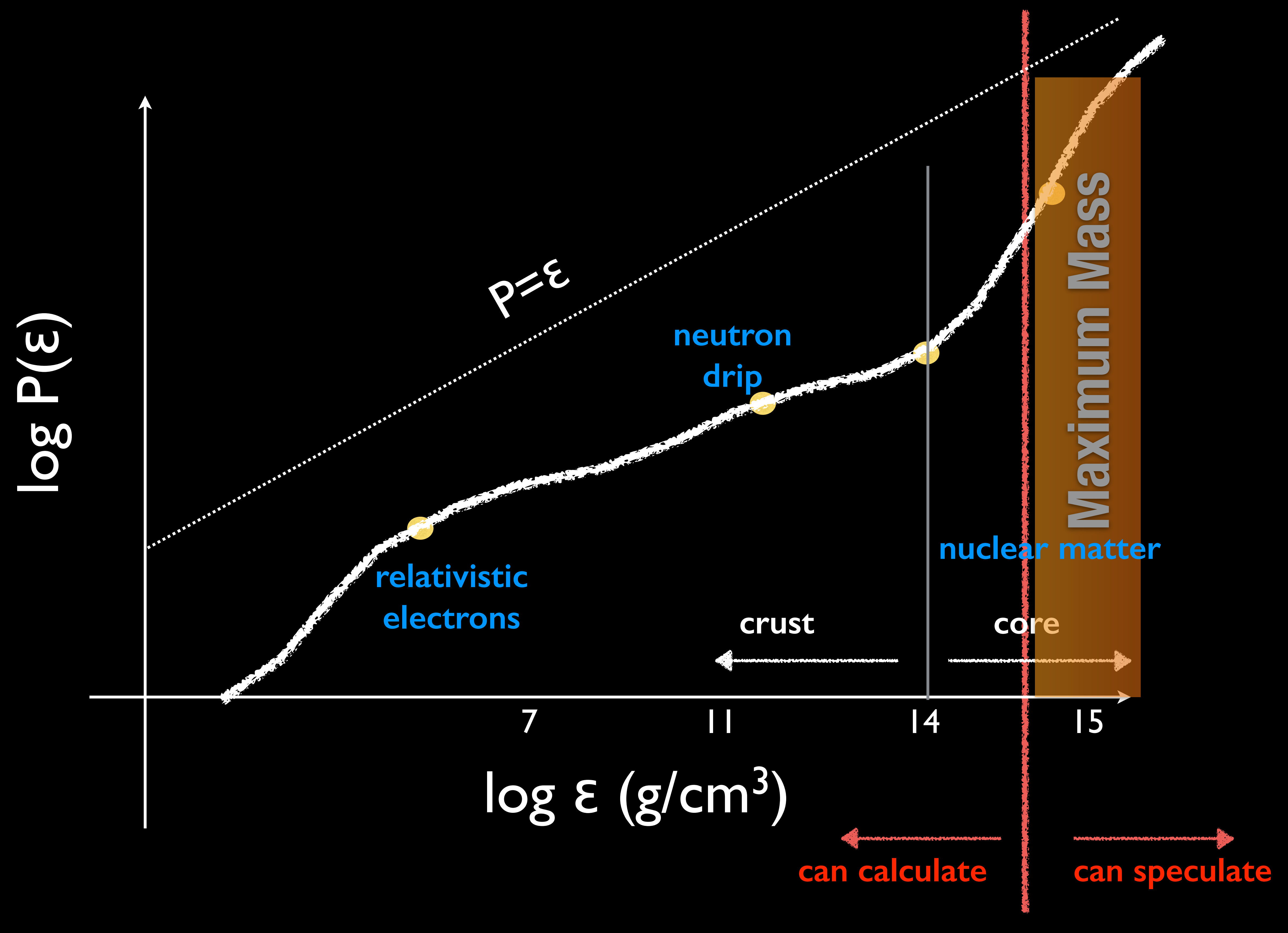

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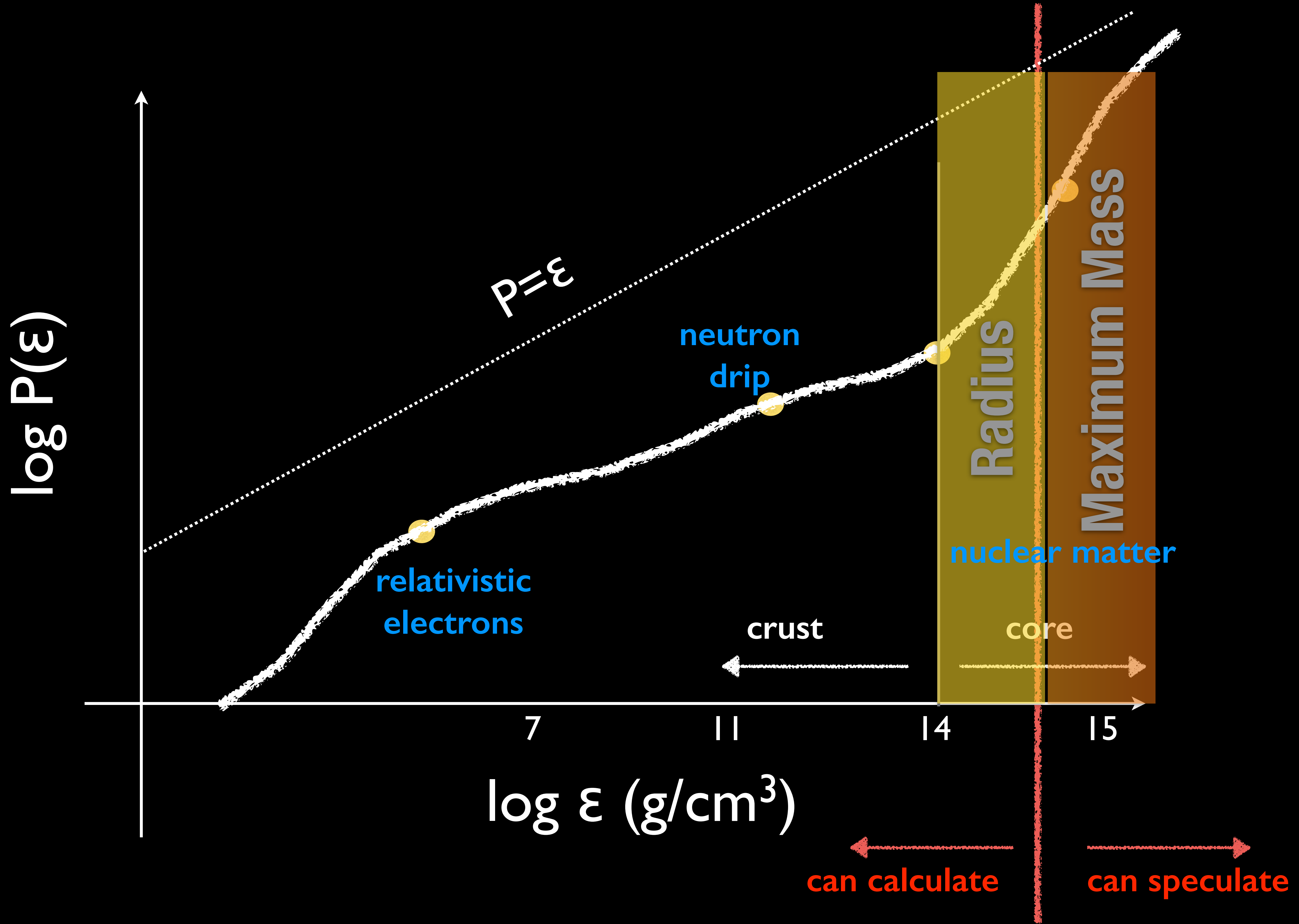

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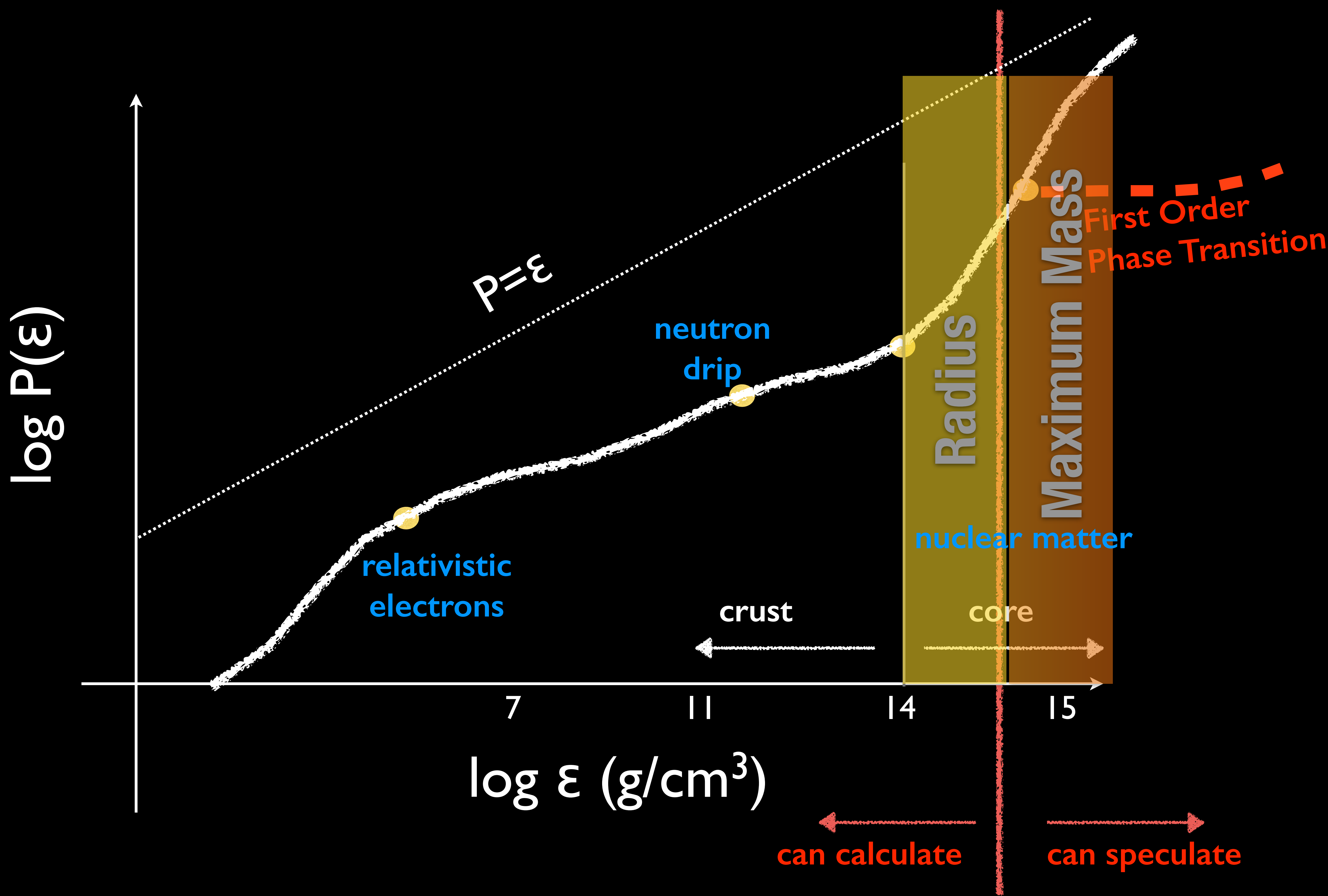

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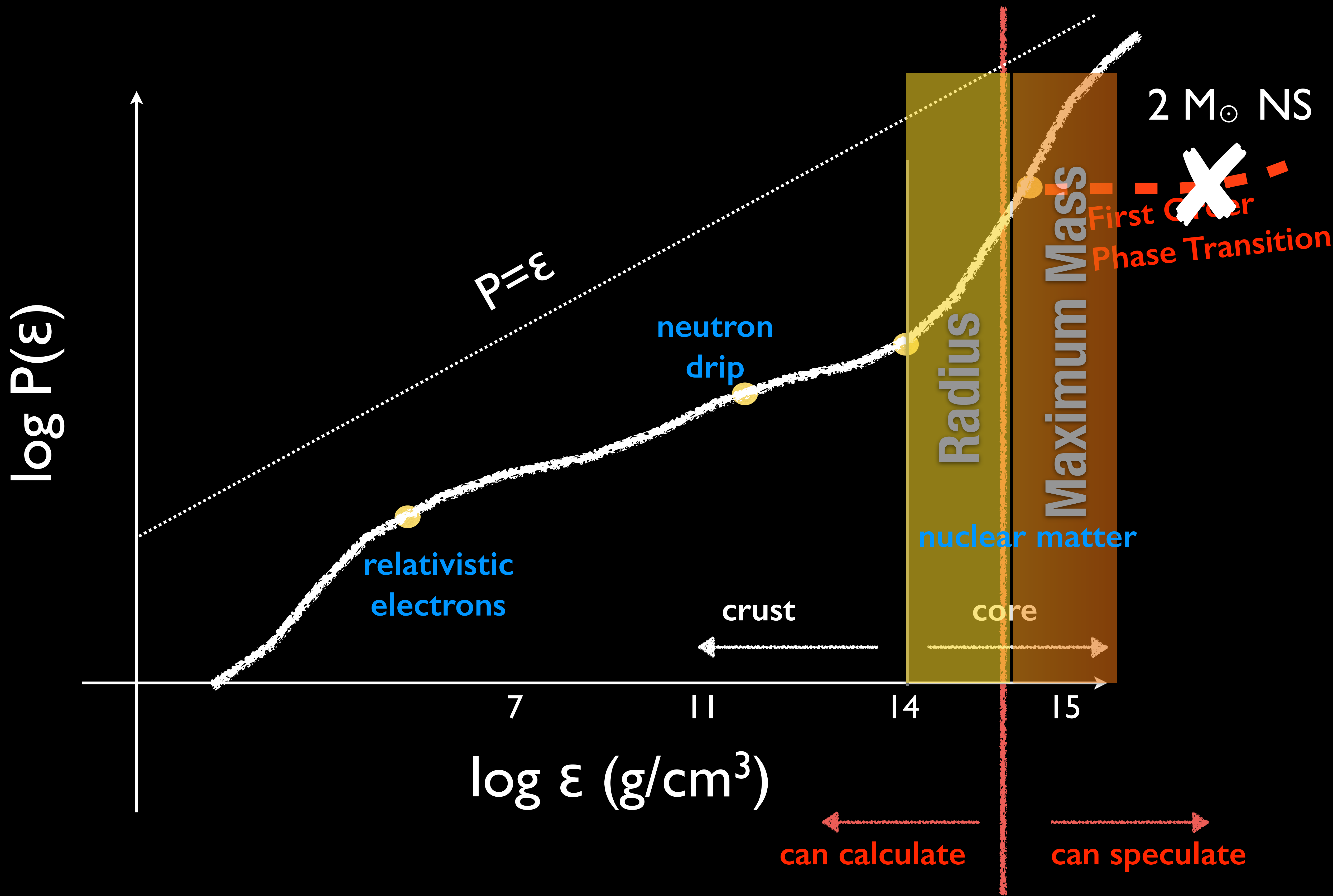
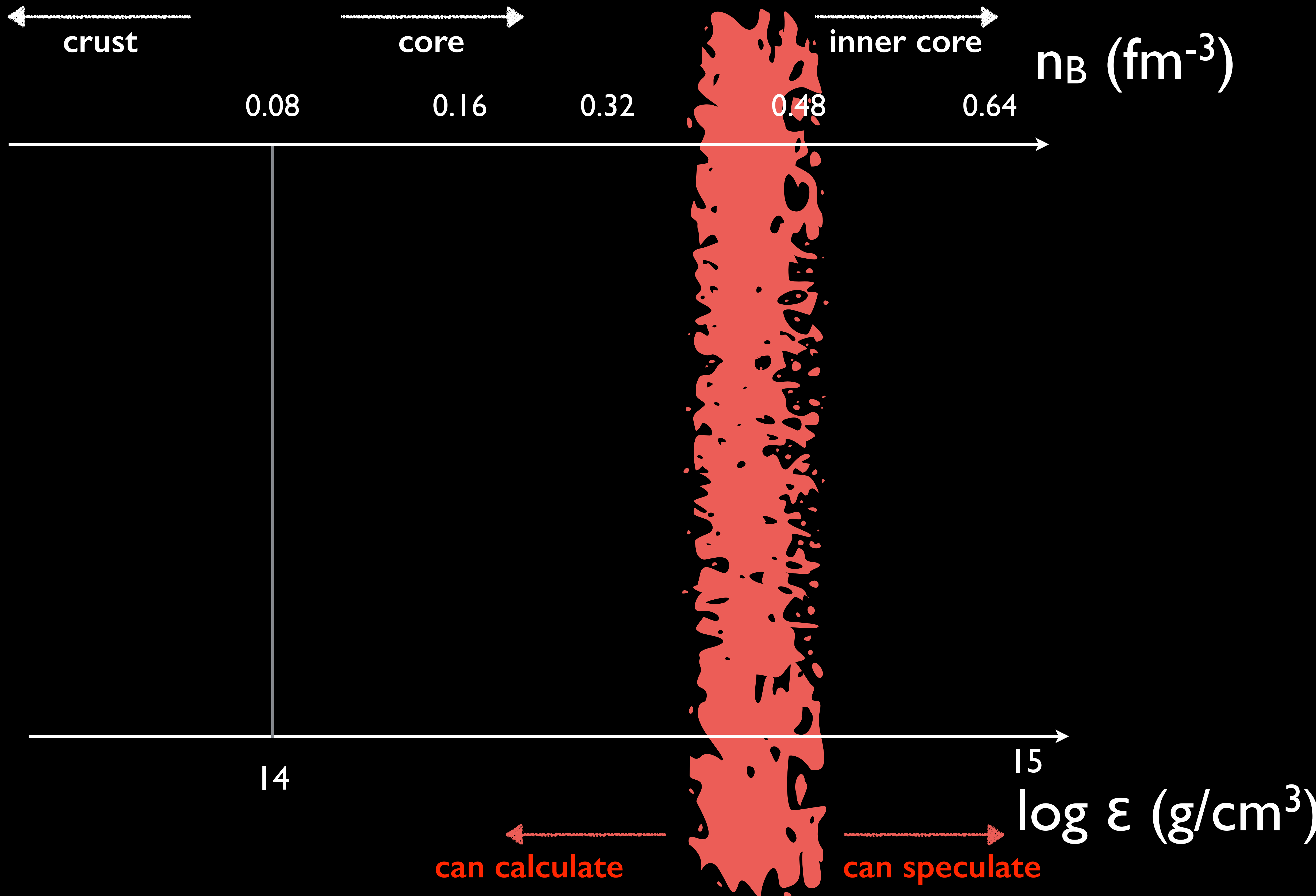


EFT and Phenomenological Models



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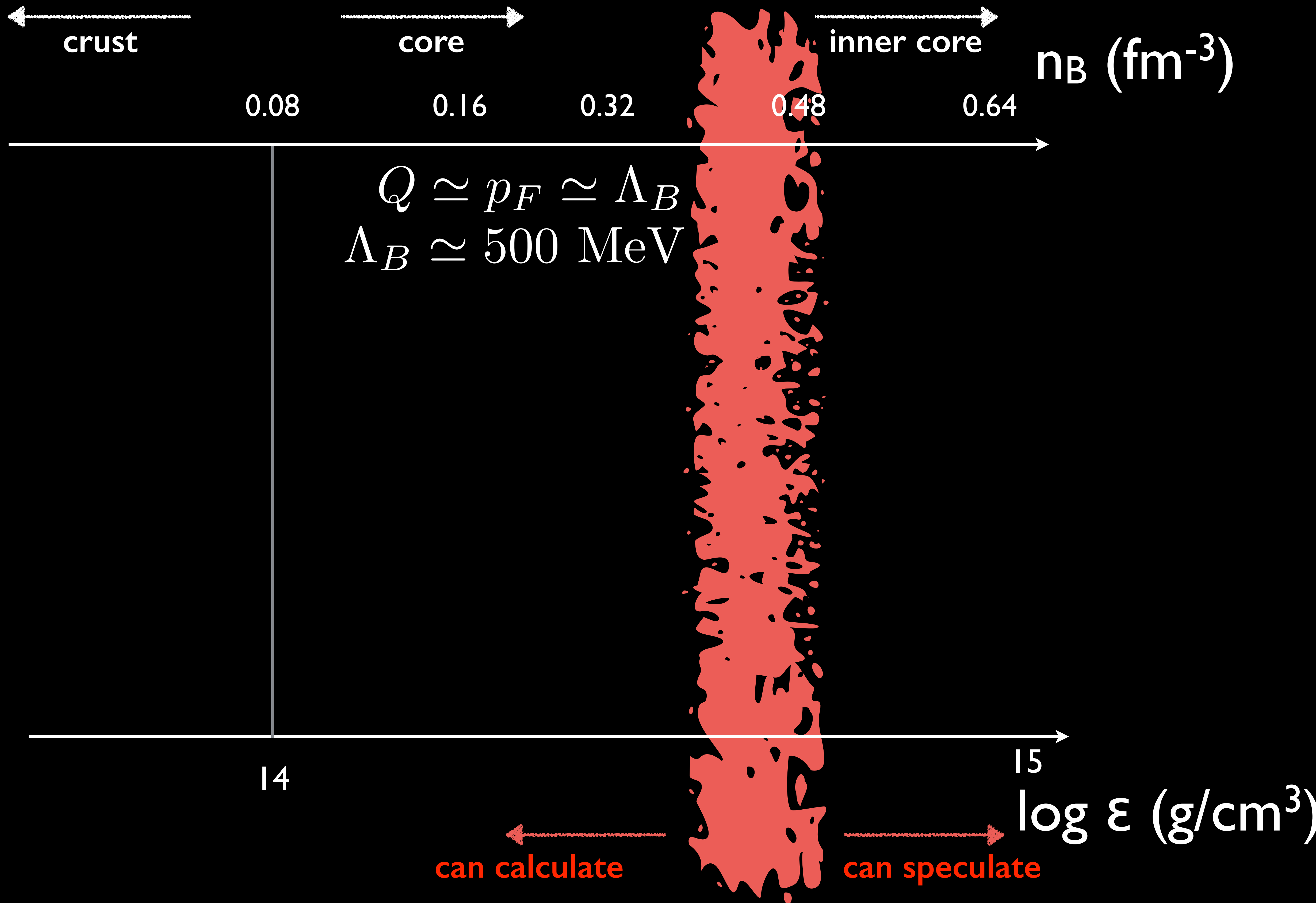

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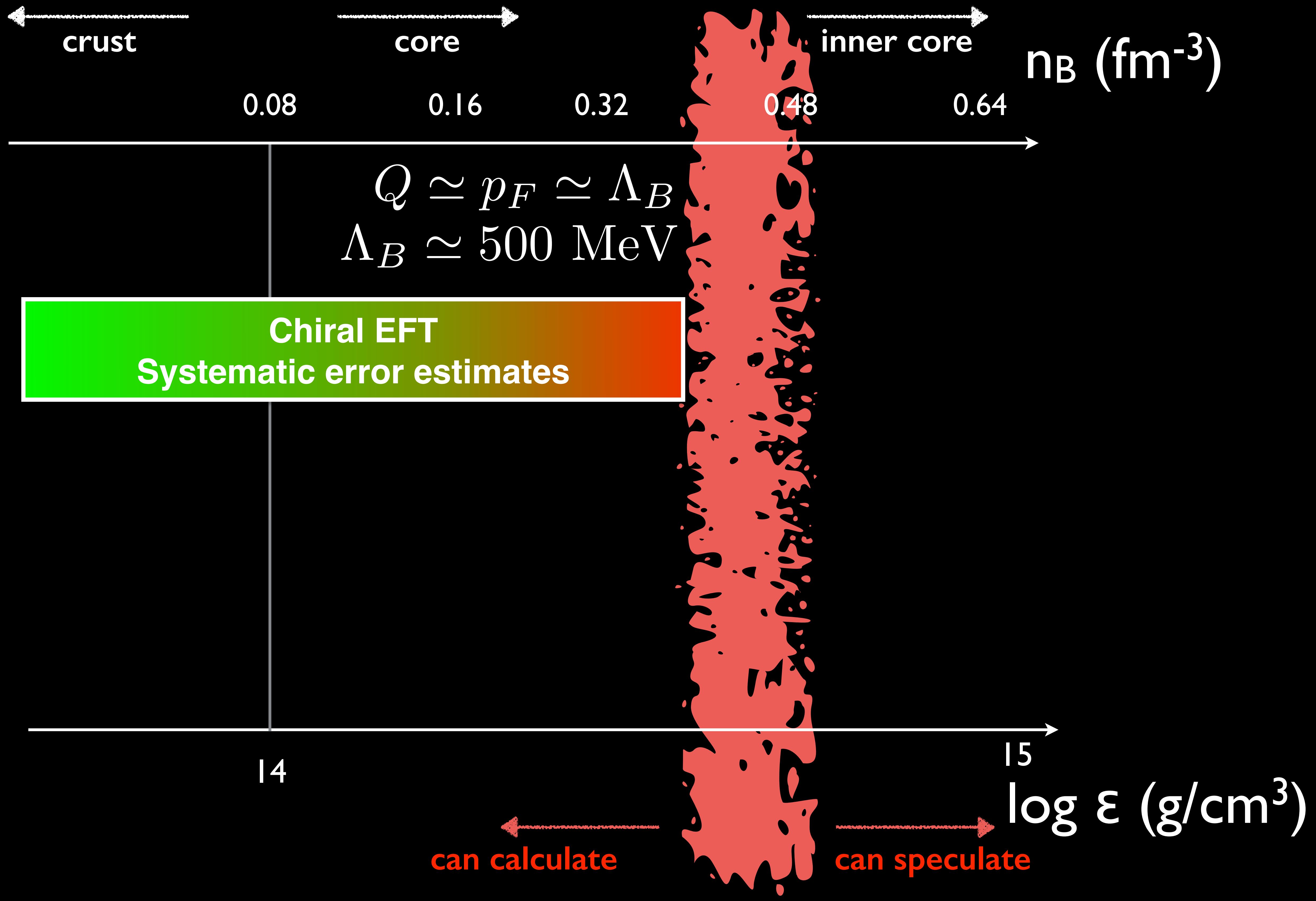

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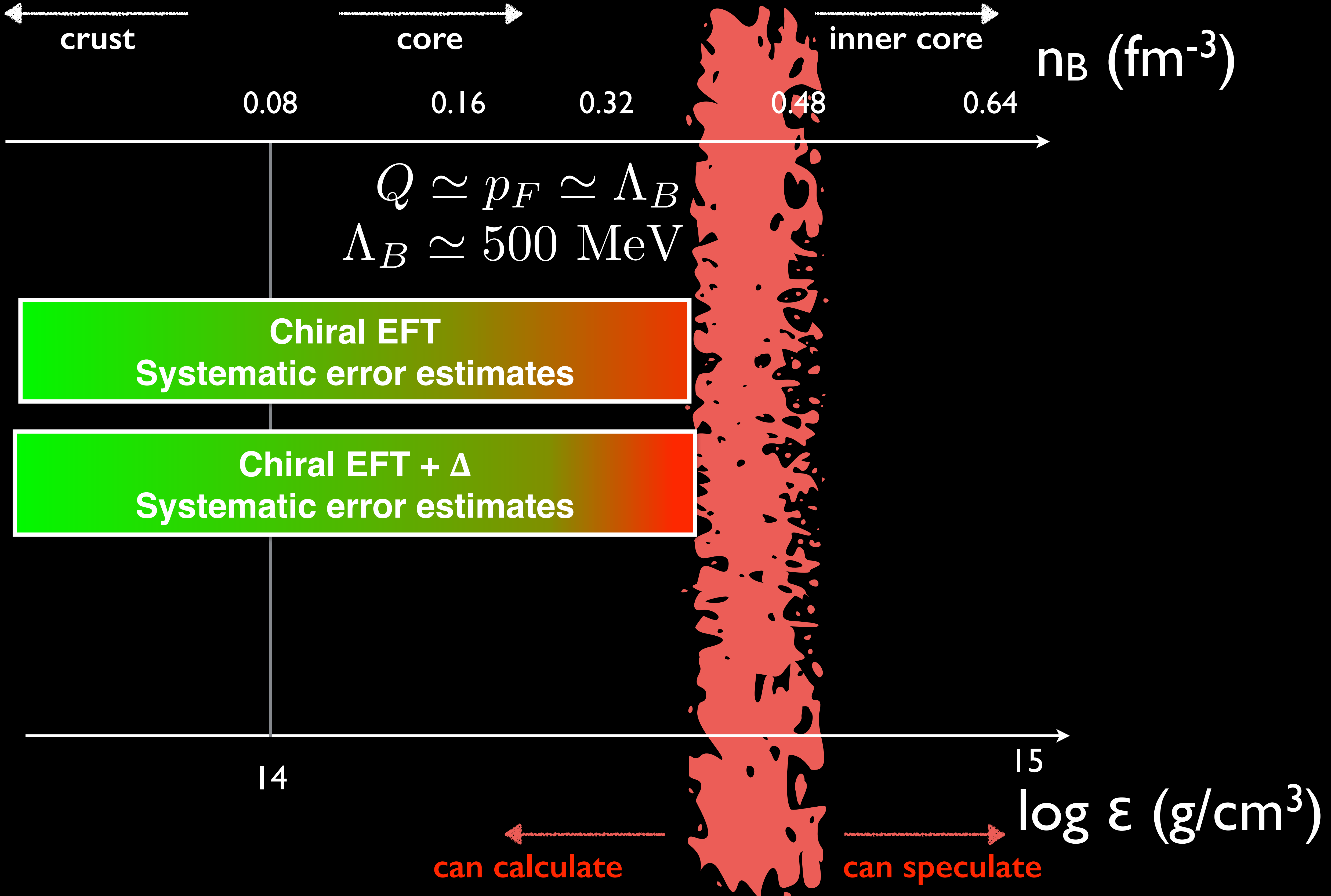

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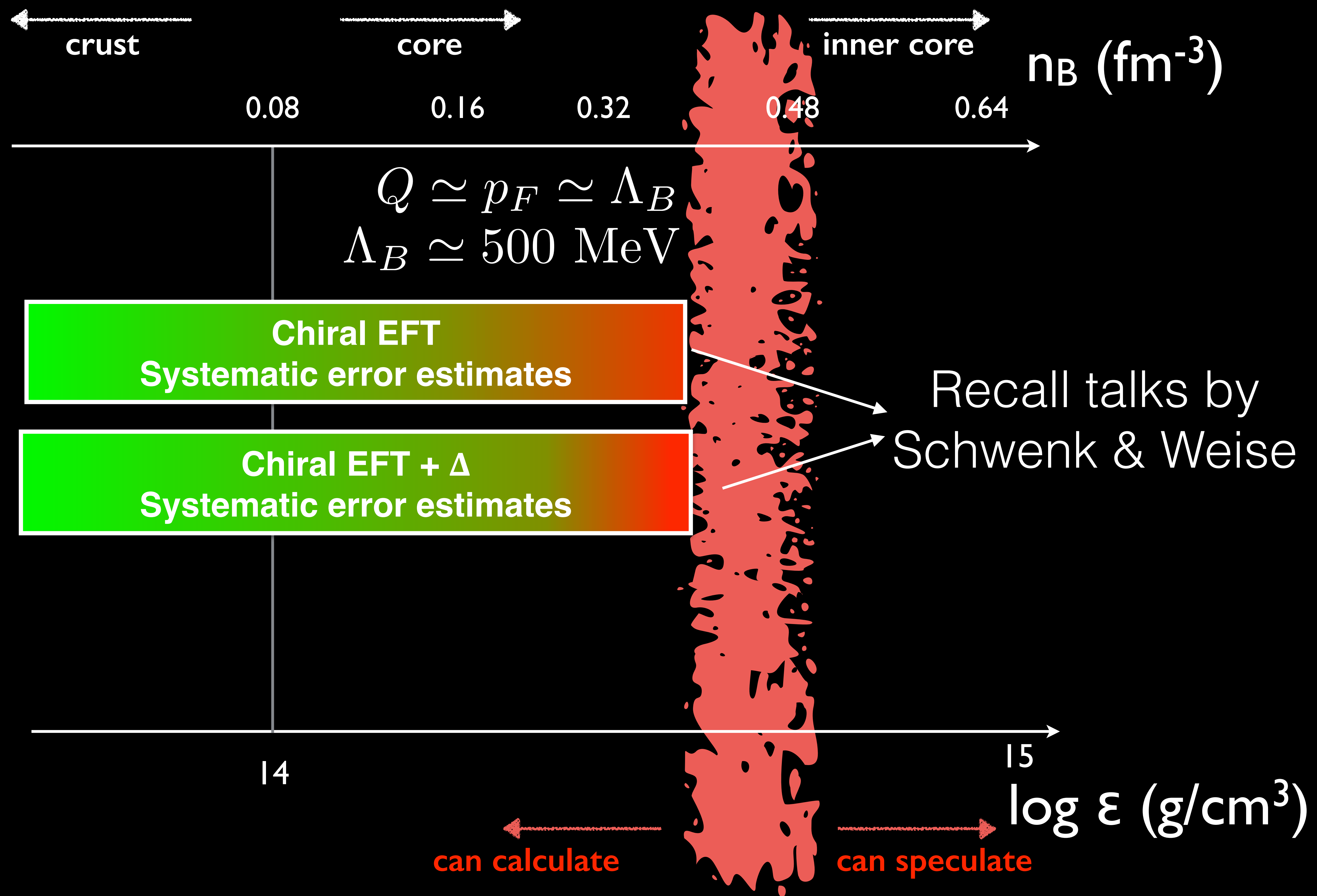

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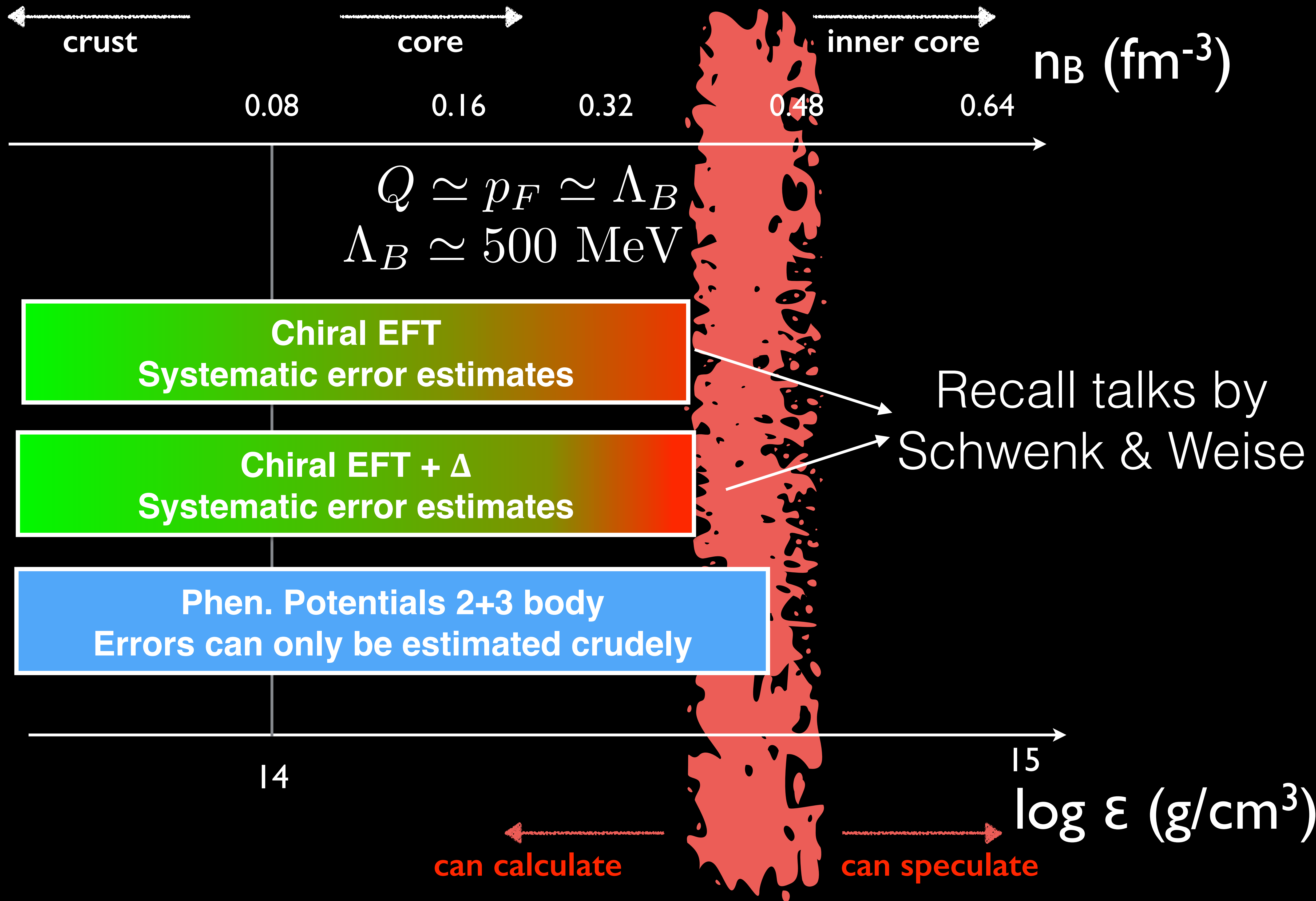
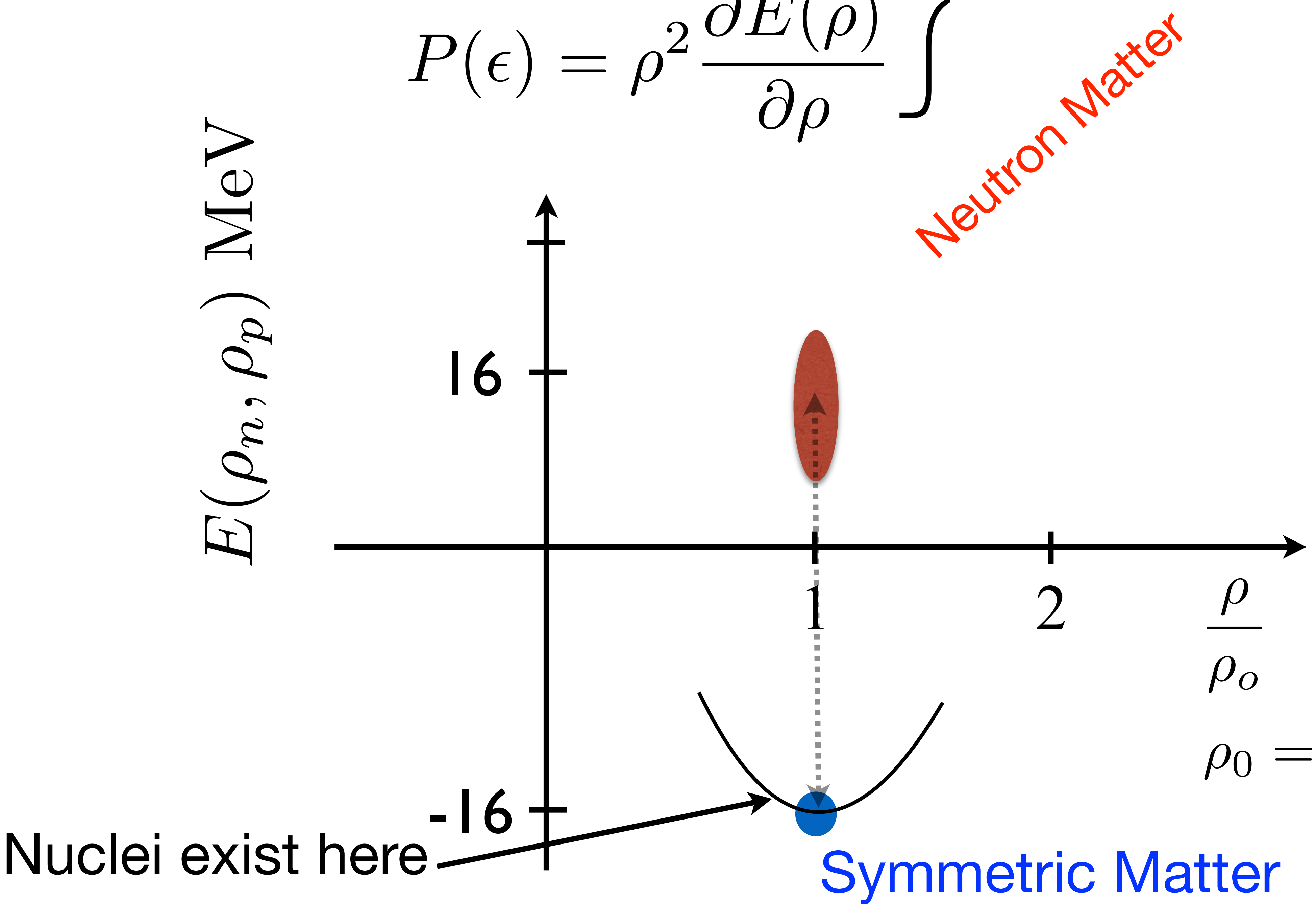


S, L & Equation of State of Neutron Matter

$$\left.\begin{aligned} \epsilon &= \rho\ E(\rho) \\ P(\epsilon) &= \rho^2 \frac{\partial E(\rho)}{\partial \rho} \end{aligned}\right\}$$



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

$$E_n(\rho \simeq \rho_0) \simeq -16\ \mathrm{MeV} + S + \frac{L}{3}\ \frac{(\rho - \rho_0)}{\rho_0}$$

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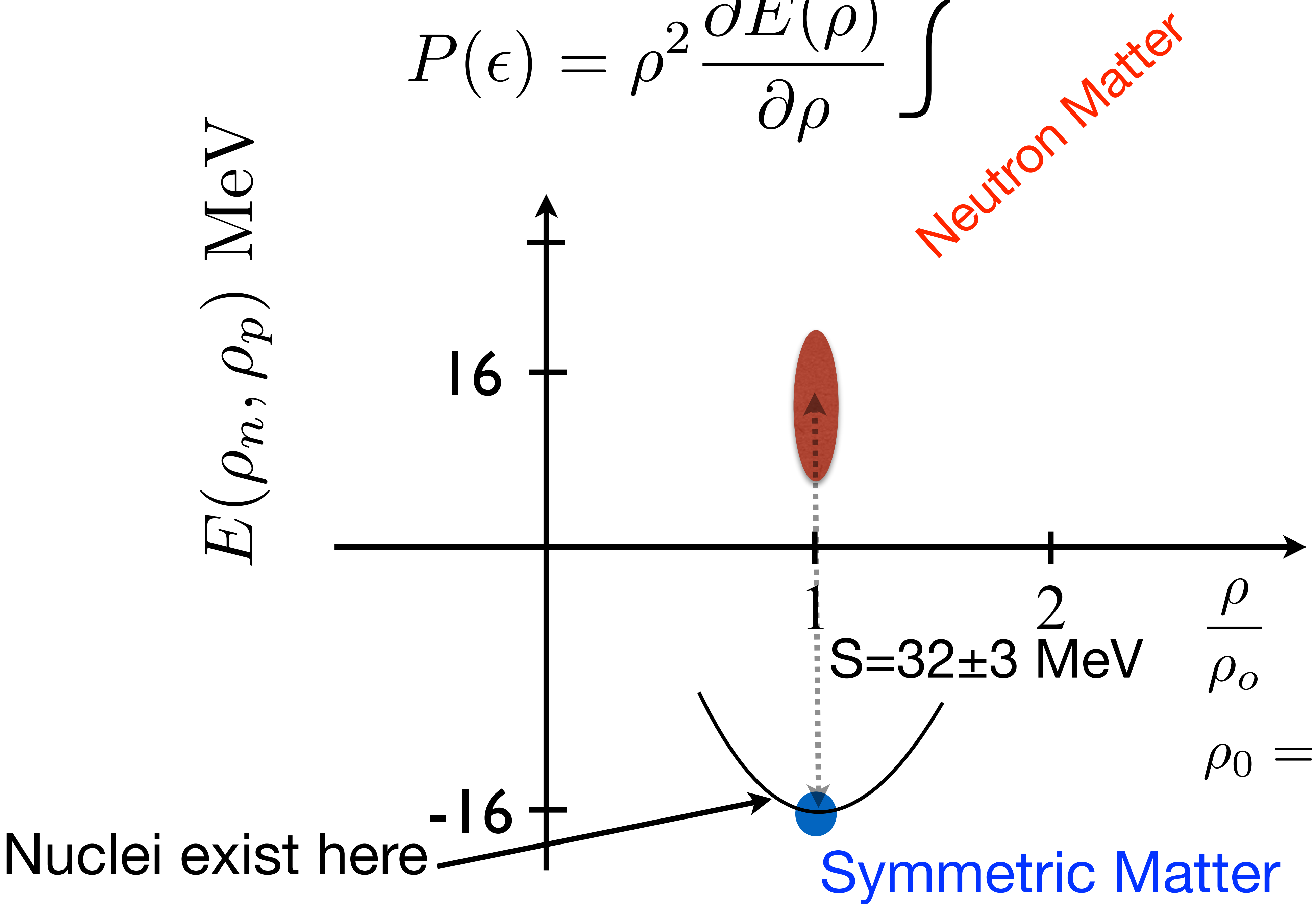

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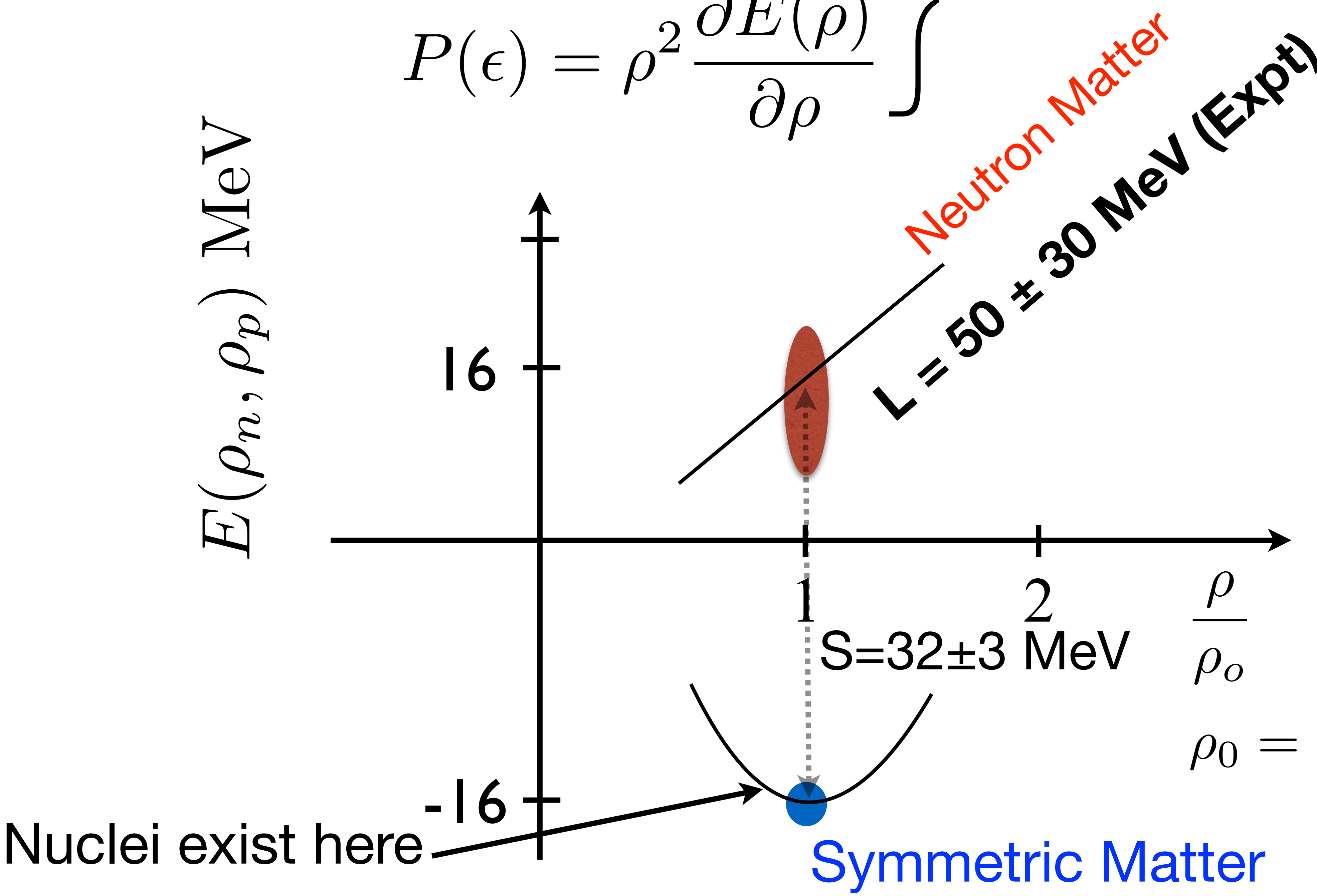

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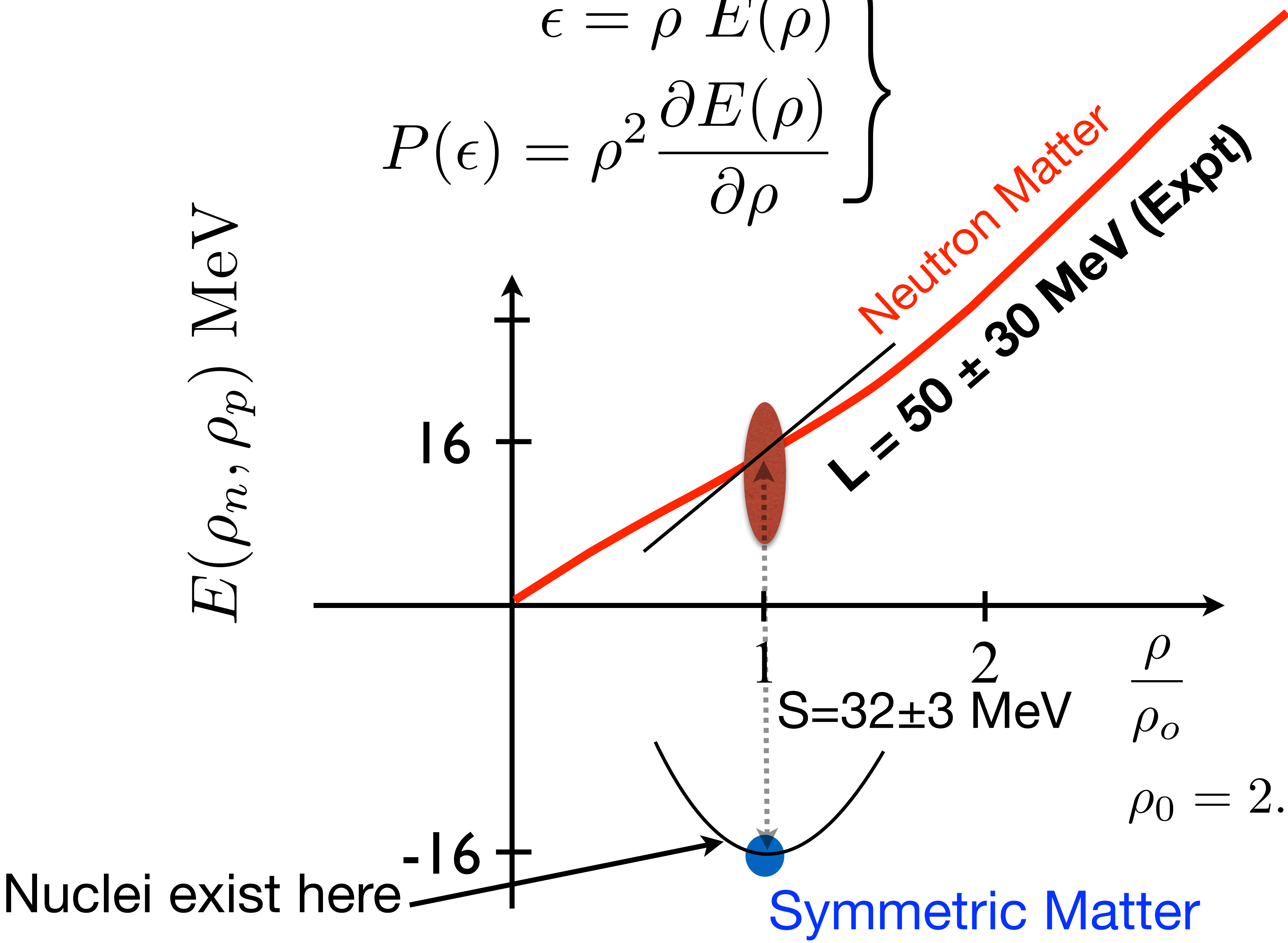

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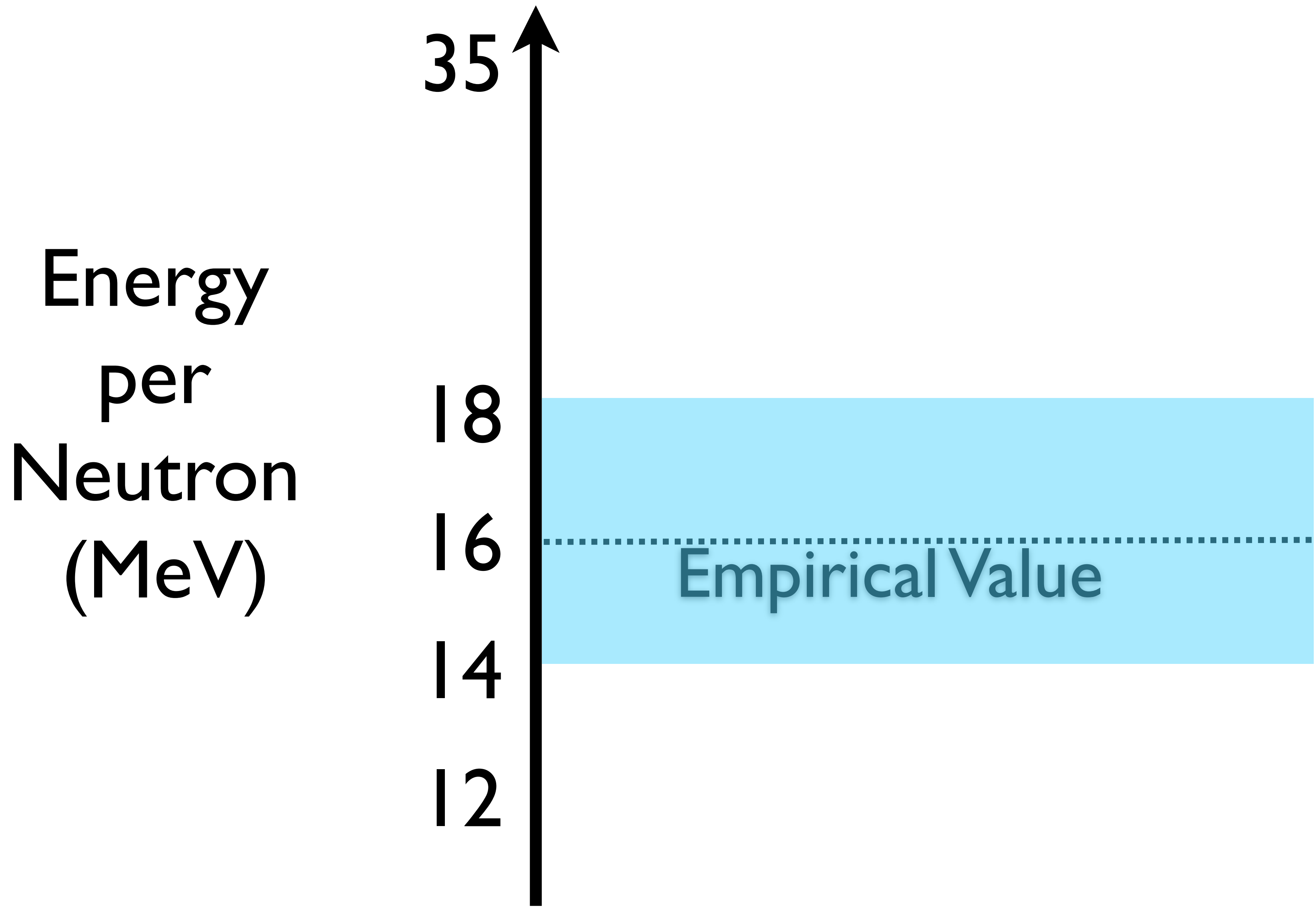
Neutron Matter from Ab-initio Theory
(at nuclear saturation density)



Caveat: Separation between 2N and 3N contributions is resolution scale and model dependent.

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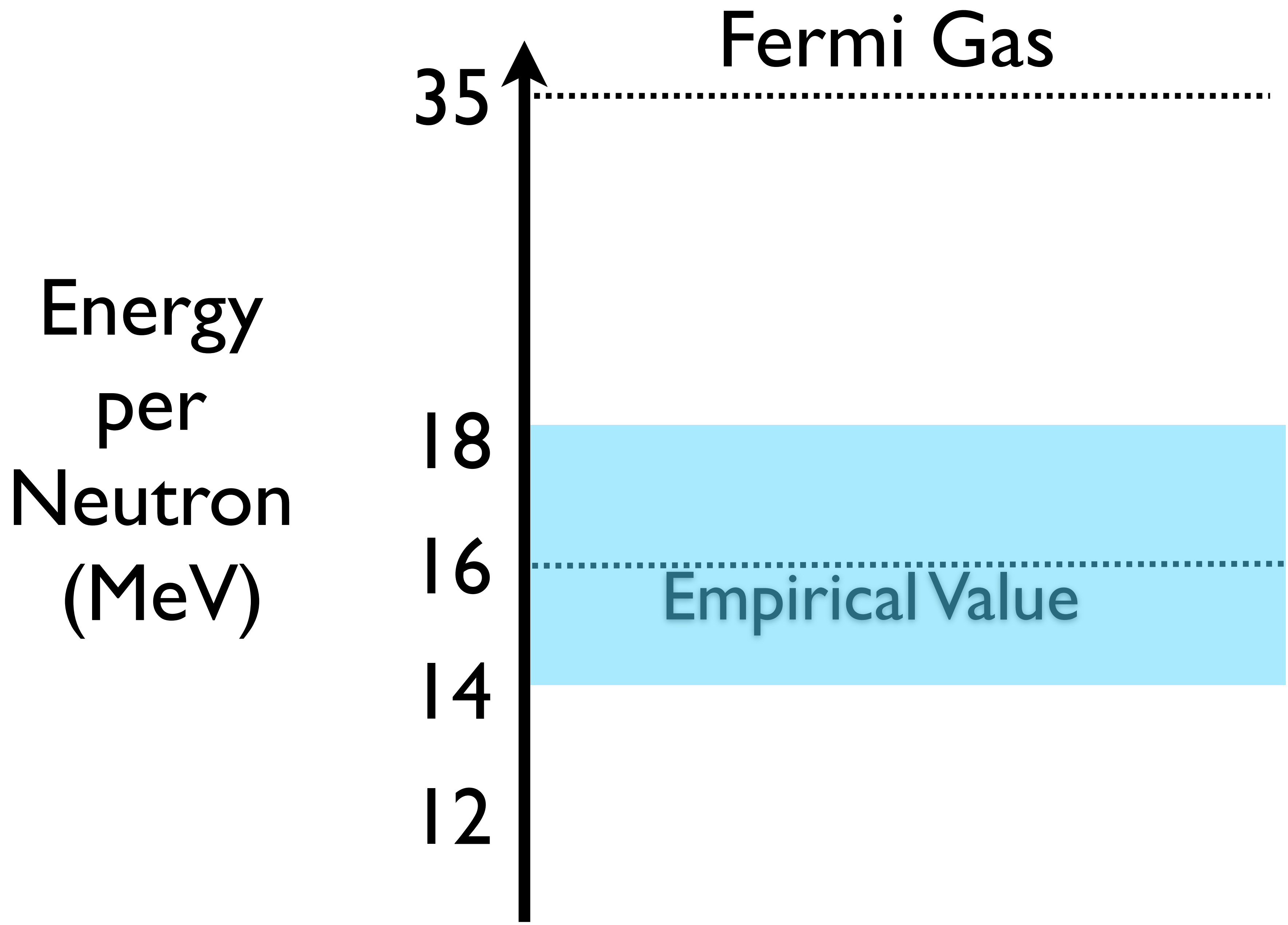

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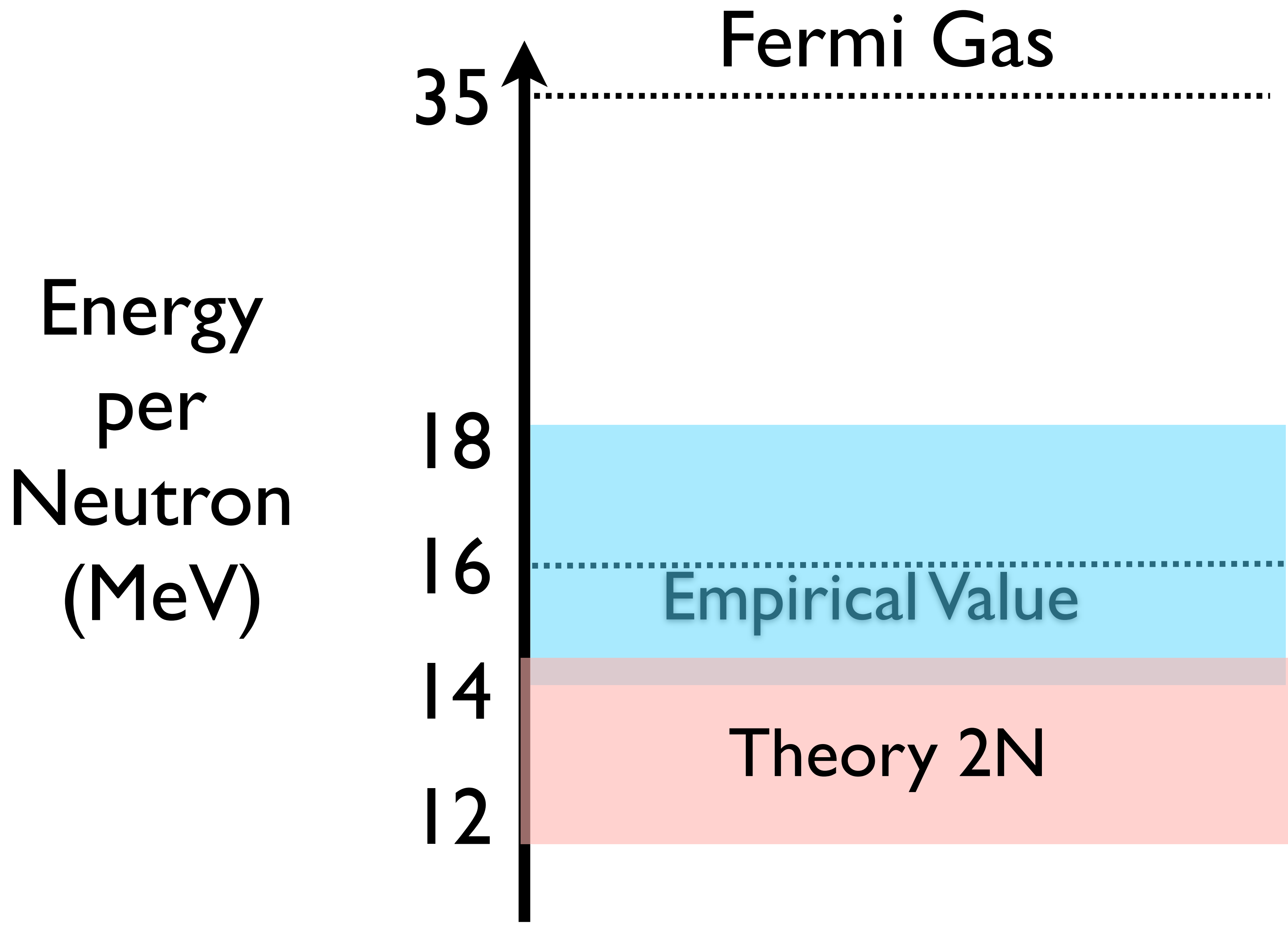

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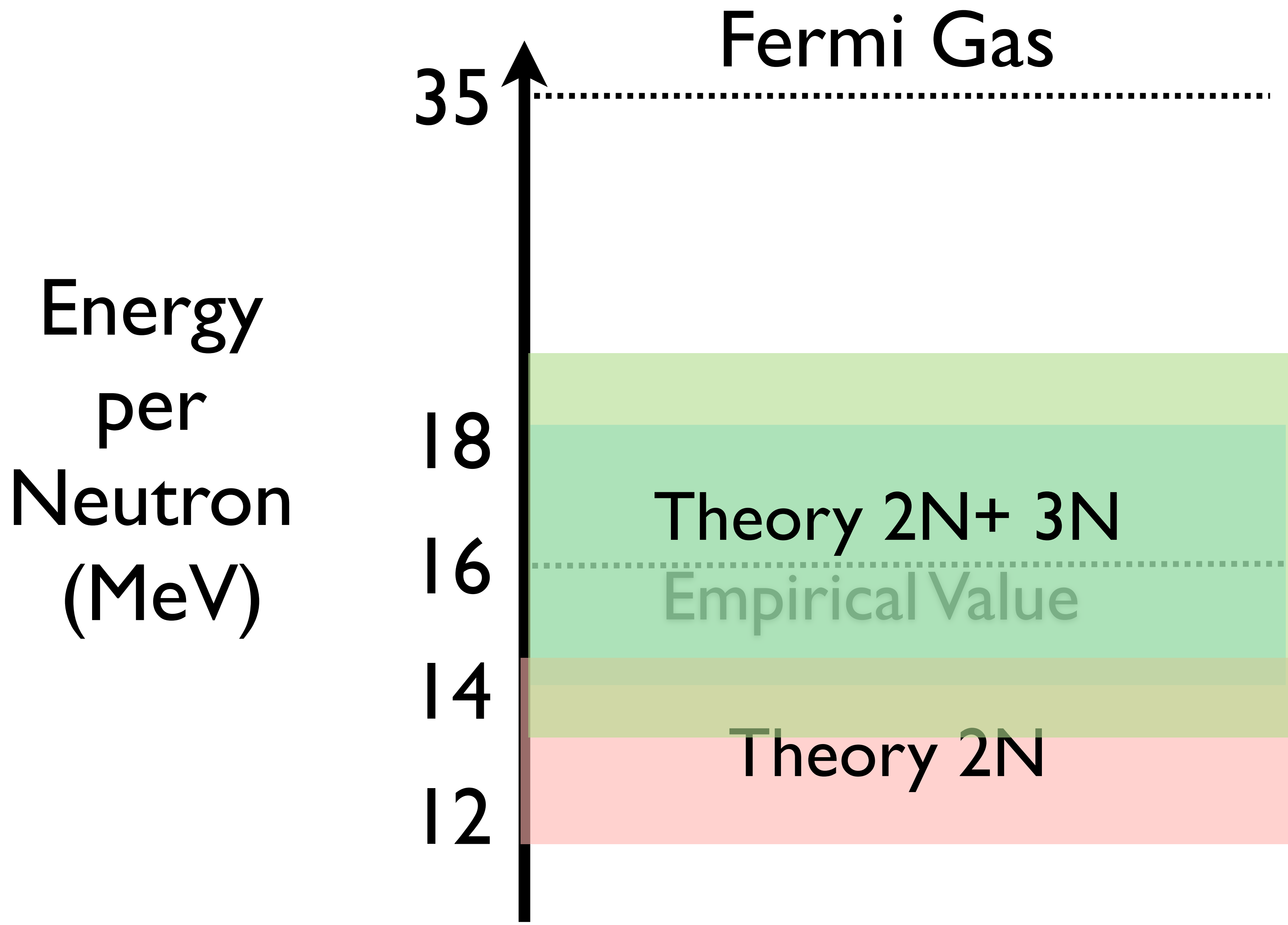

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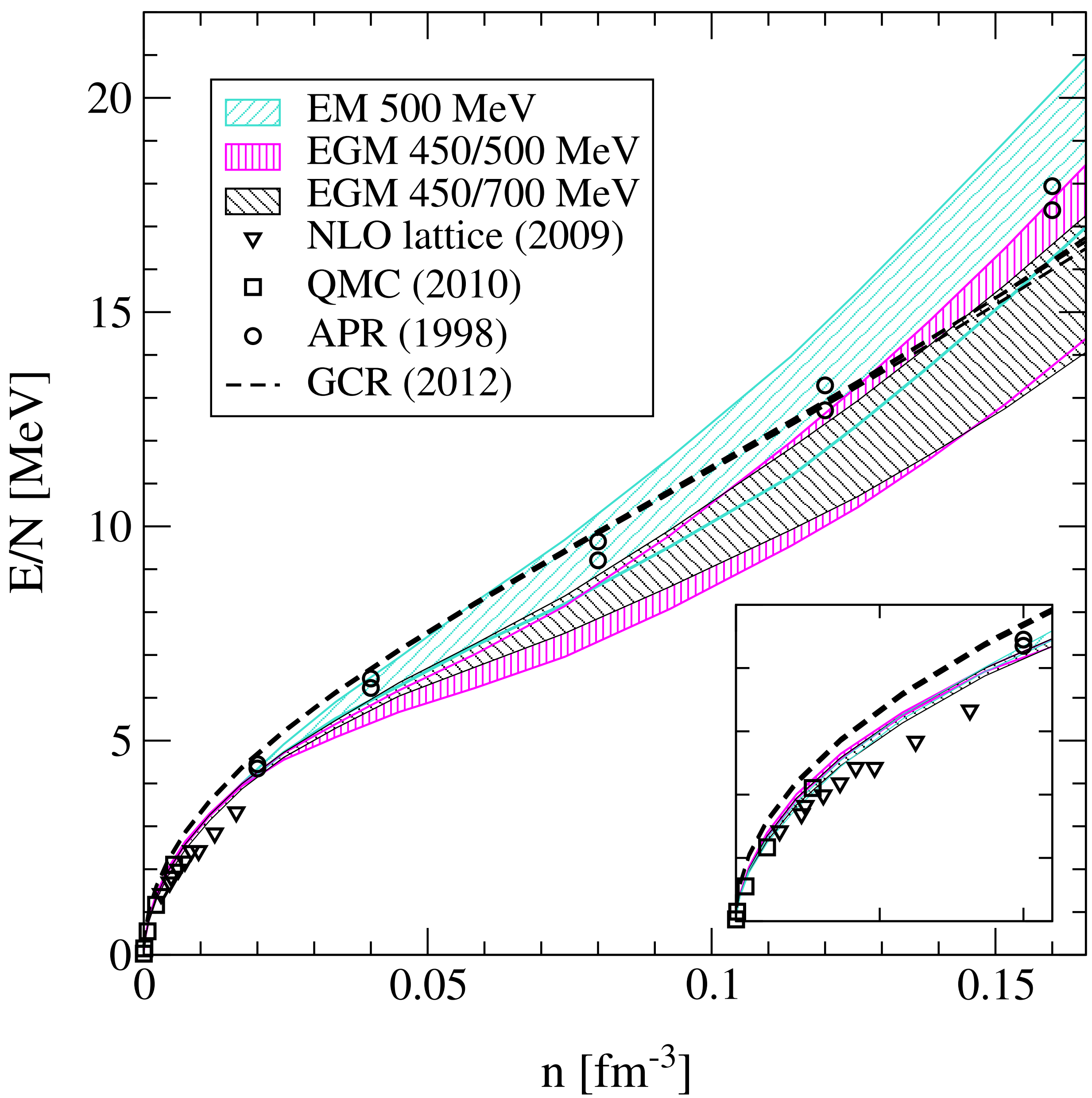
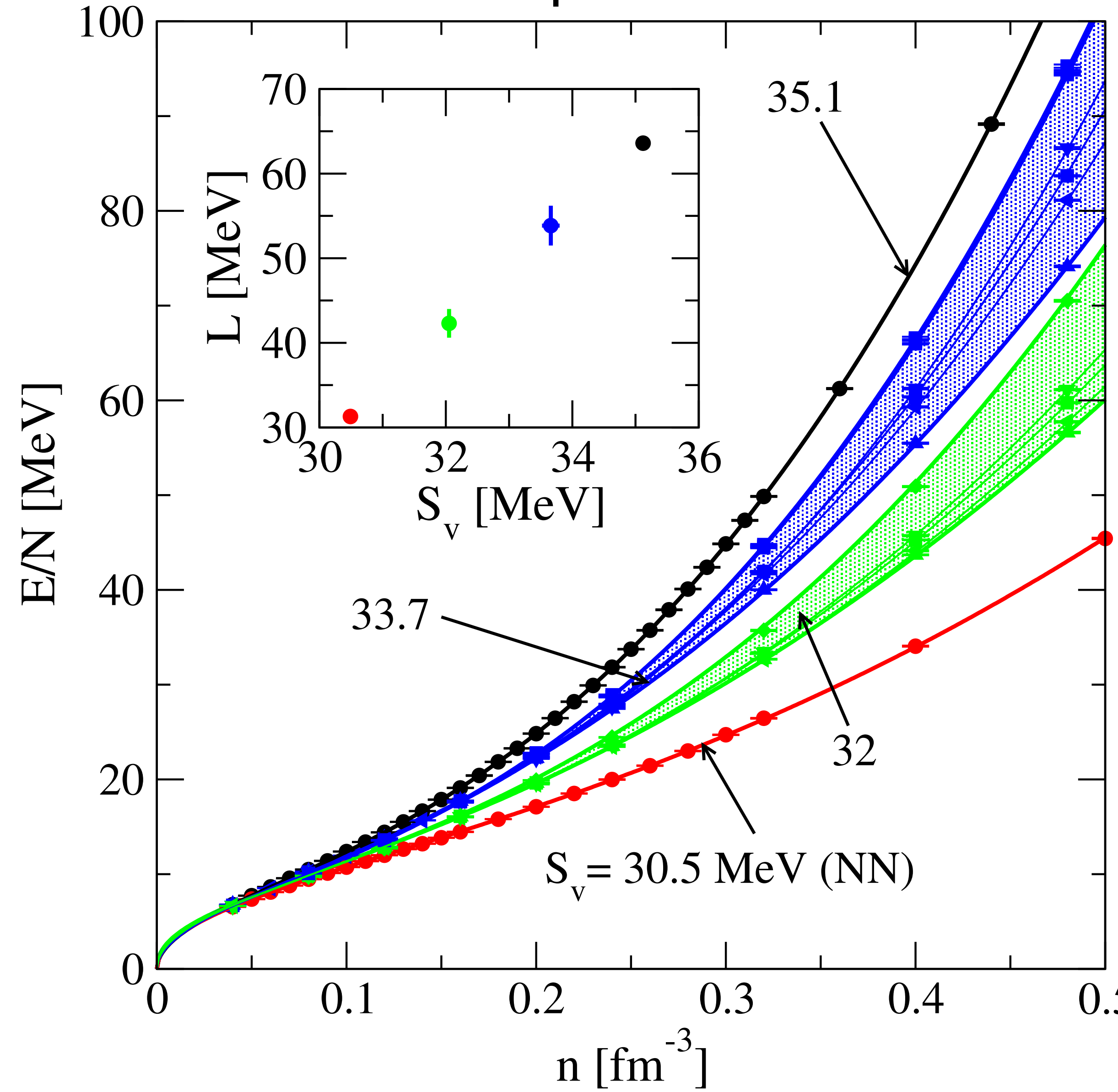
Current Status of Neutron Matter EoS Studies

Prediction



Hebeler, Schwenk,Furnstahl, Tews, …
Holt, Kaiser, Weise, …
Hagen, Papenbrock, …

Extrapolation



Gandolfi, Carlson, Reddy

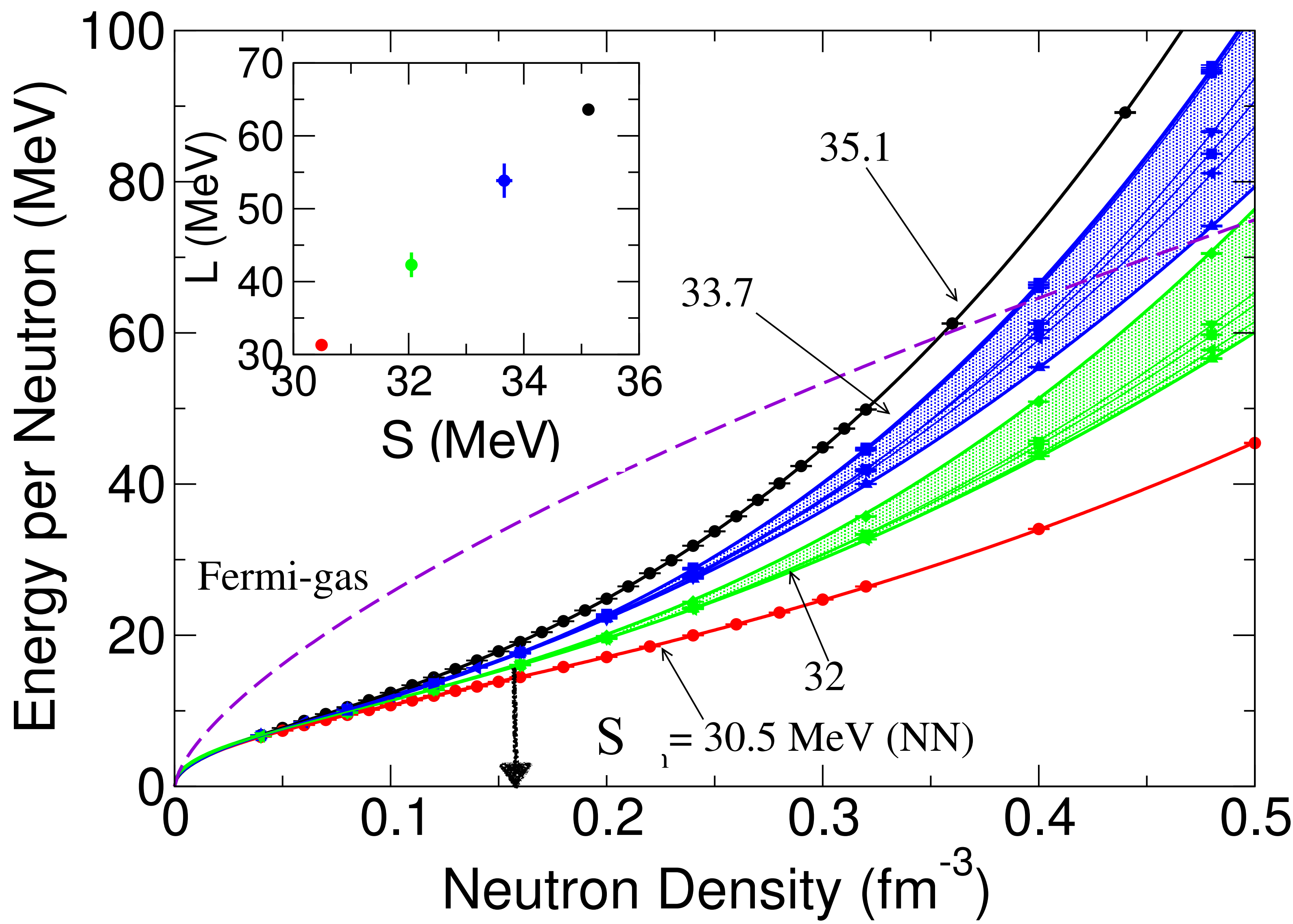
Implications for NS radius: R = 12 ± 2 km

QMC with Phenomenological Potentials

Gandolfi, Carlson, Reddy (2010)

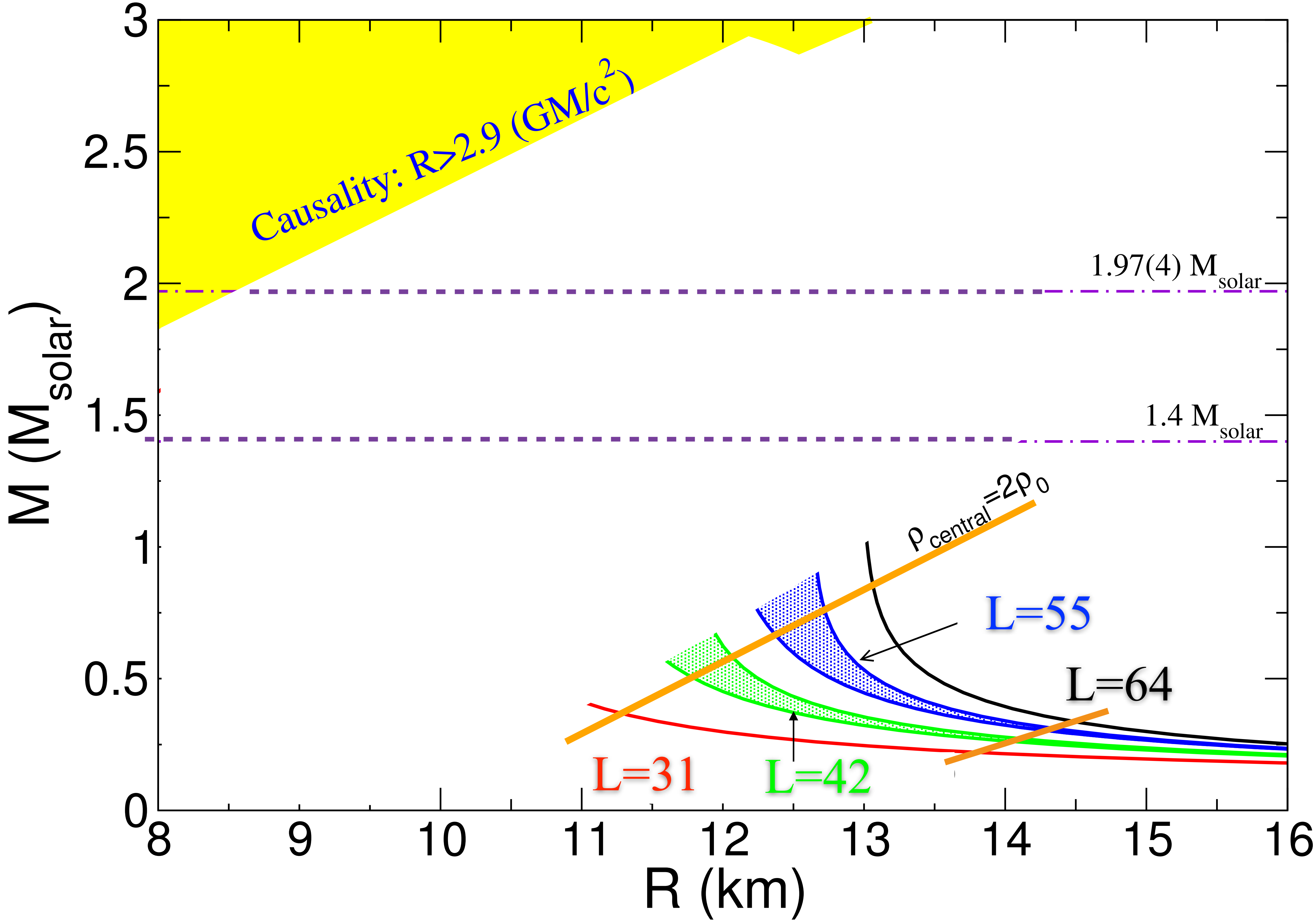
- S & L are correlated by the model.
- Experimental measurement of L & S with ~ 1 MeV error needed to test the model.

Up to about twice saturation density, the 3-body contribution is smaller than the 2-body force.



This was a first attempt at estimating extrapolation errors in phenomenological models.
Need to understand how to quantify uncertainties of this extrapolation by varying the short-distance behavior of both 2 and 3 body forces together.

Neutron Star Structure



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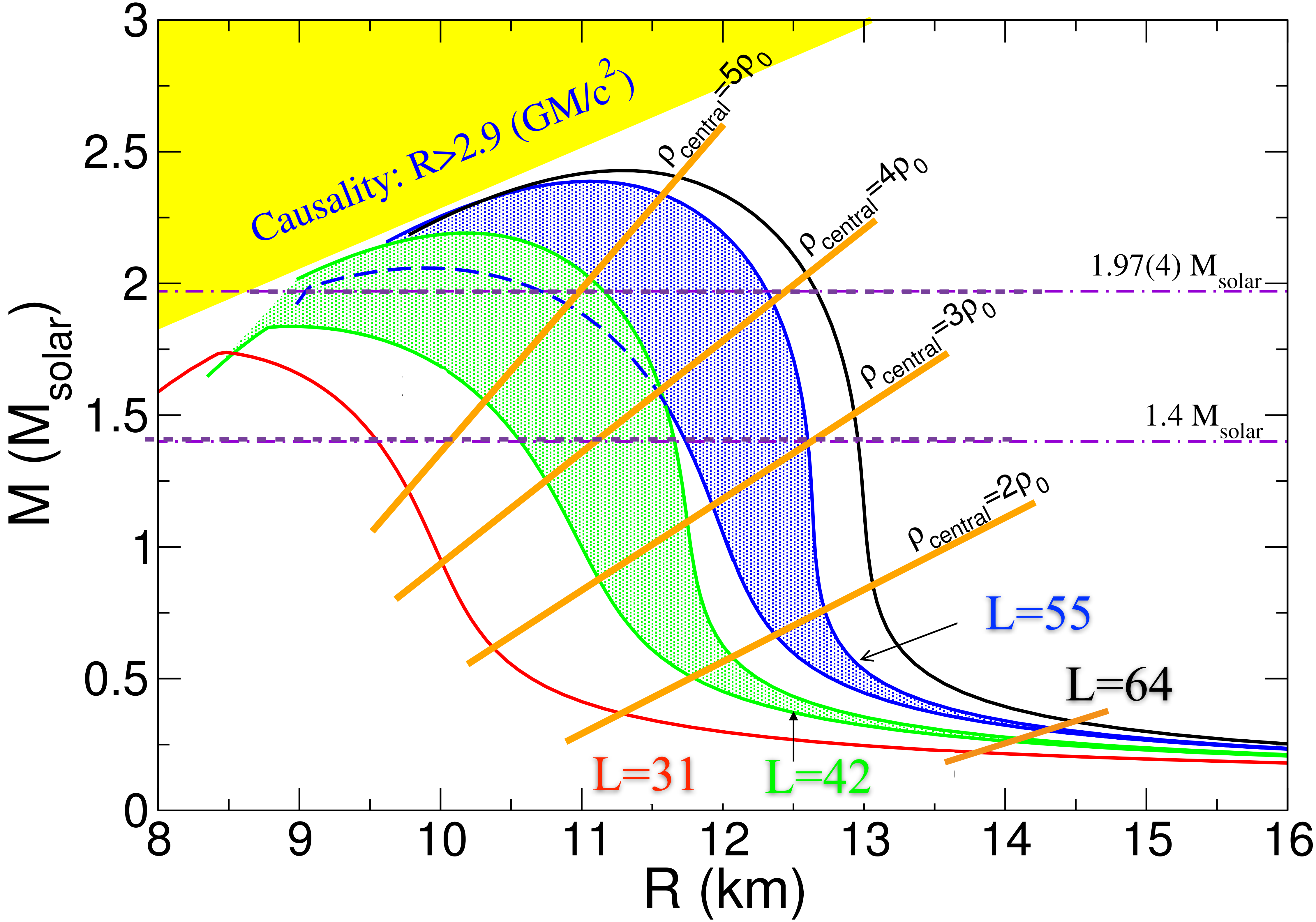

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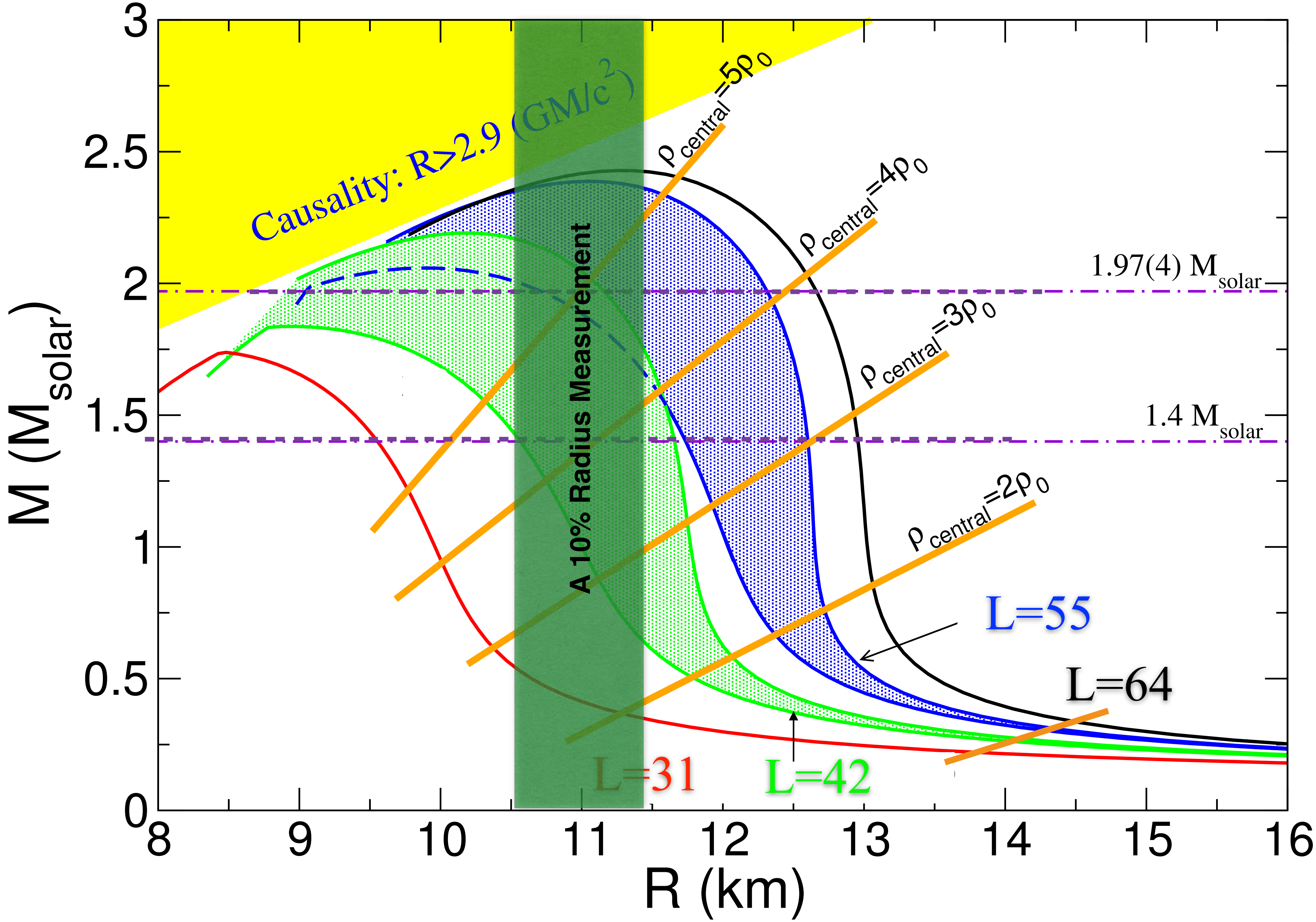
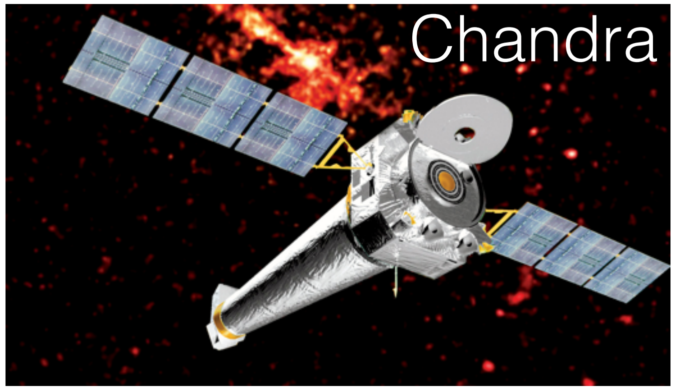
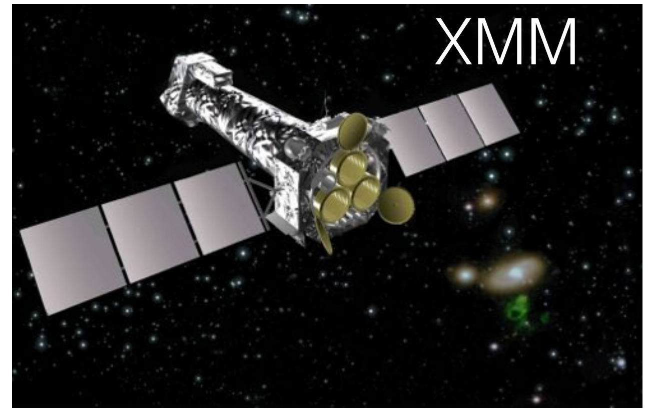


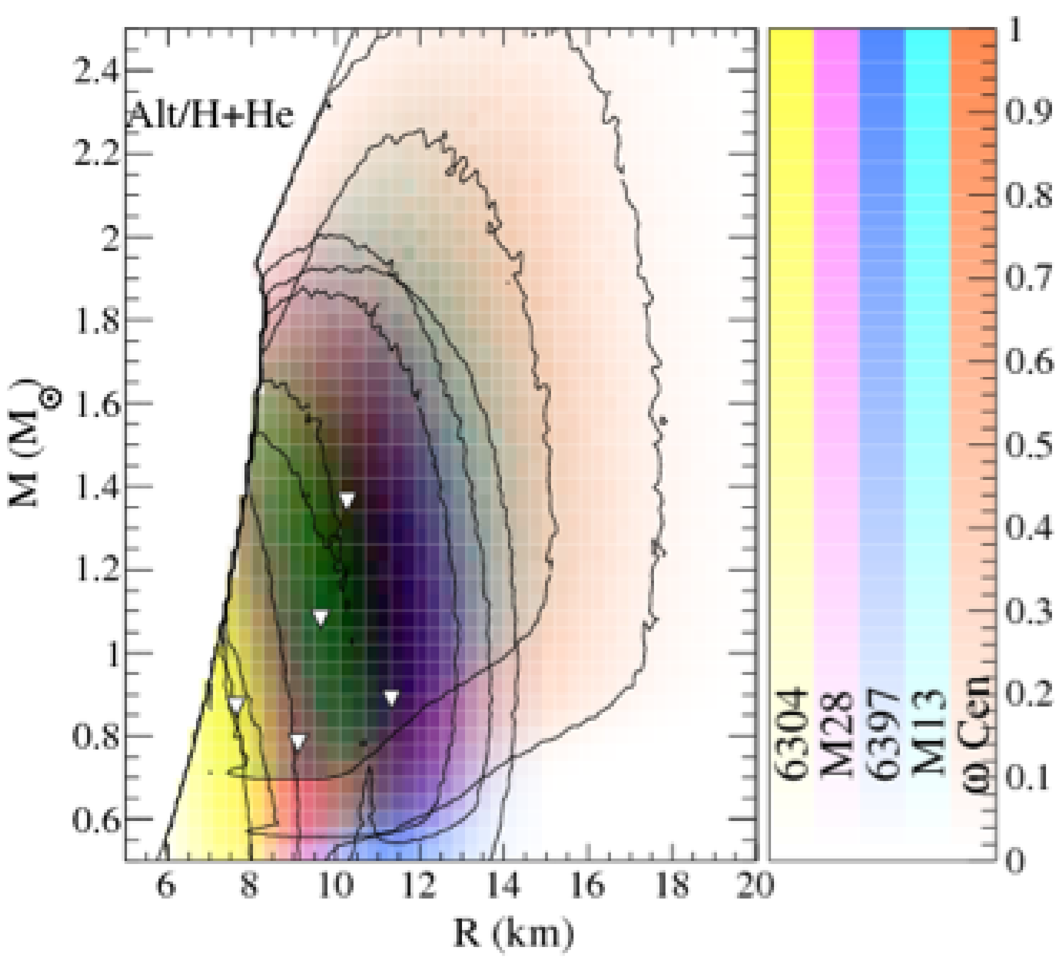
Radii from Quiescent NS





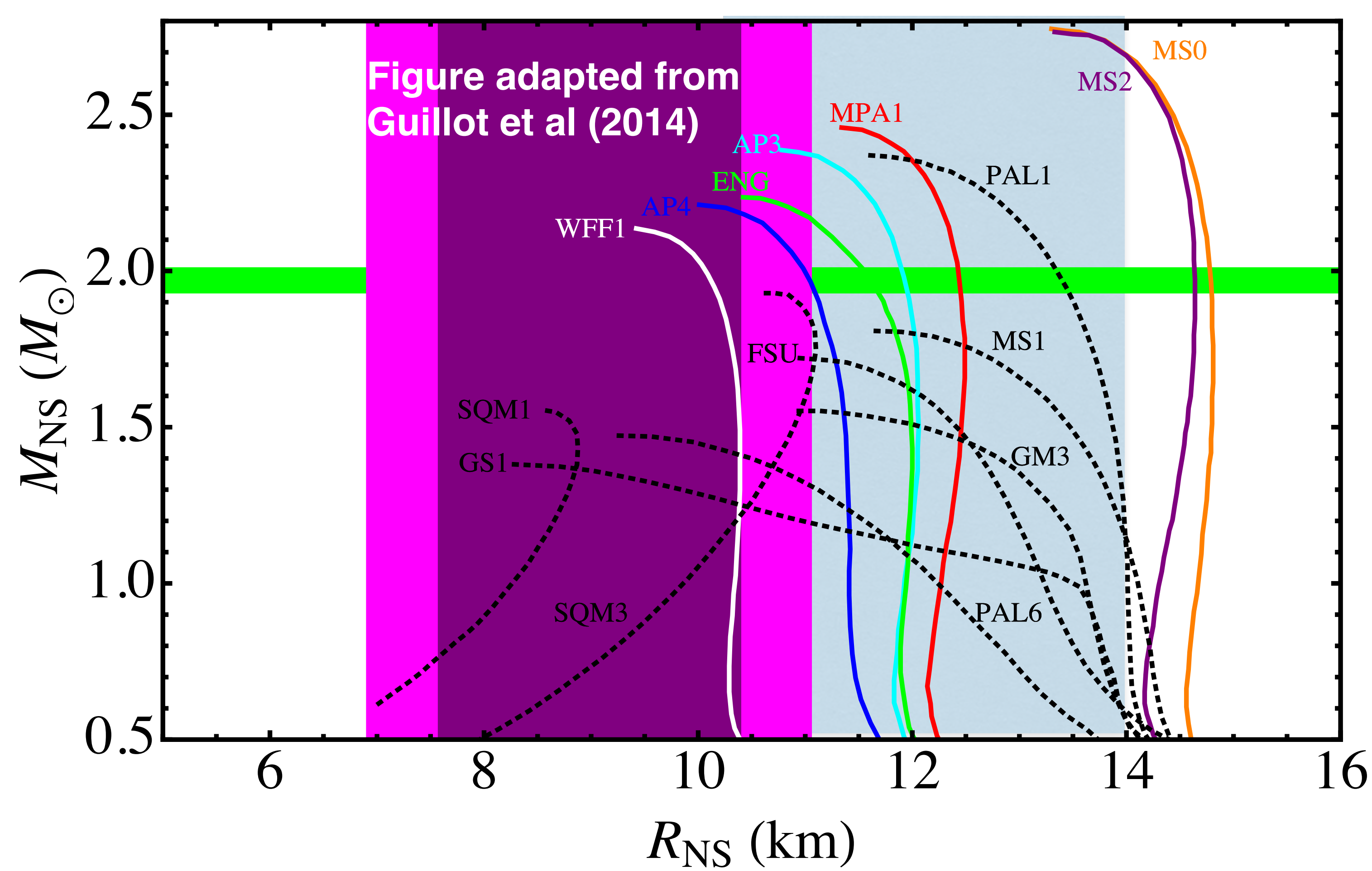
- Can extract radius subject to the assumptions: (i) surface temperature is uniform; (iii) atmosphere composition is known and (iii) distance and inter-stellar absorption is measured.

Heinke et al, and Steiner & Lattimer (2014)



Guillot et al (2014)

Steiner et al, Heinke et al (2014)



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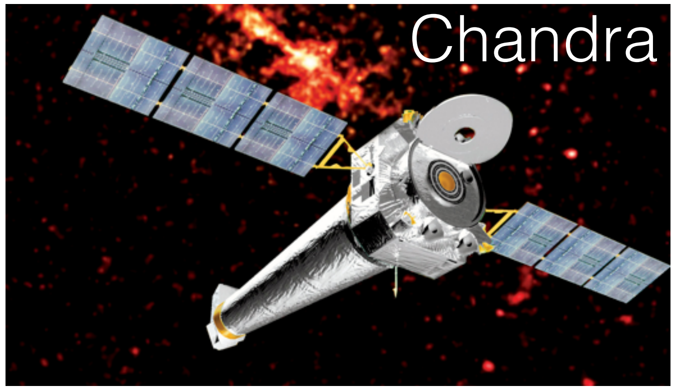

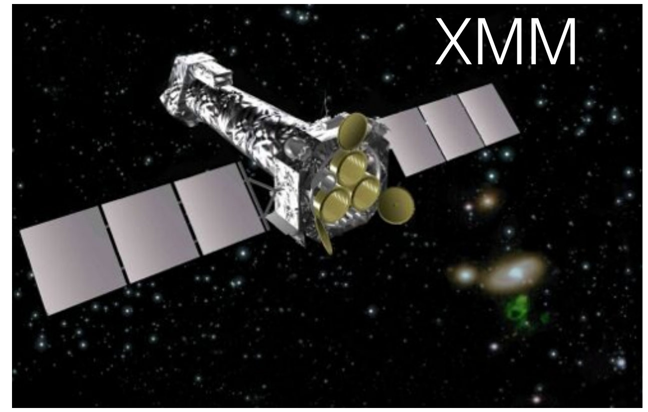

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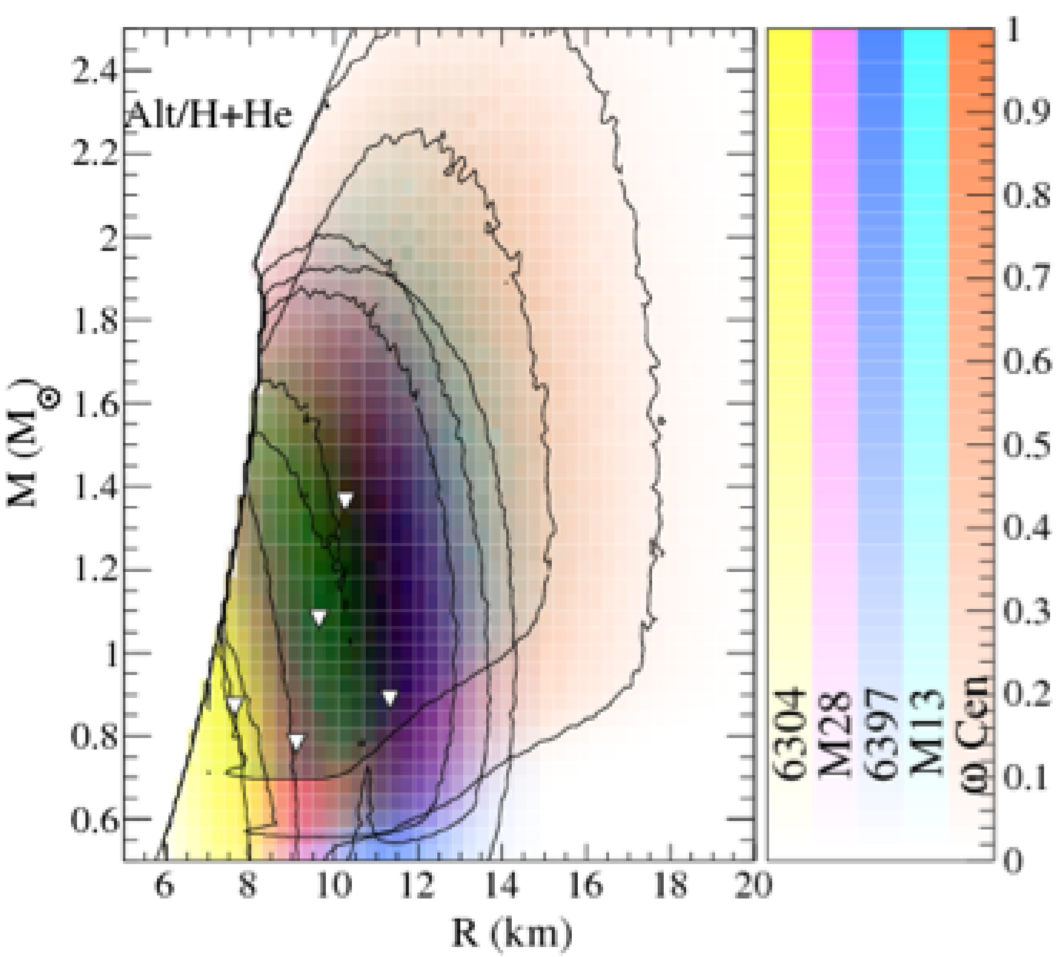
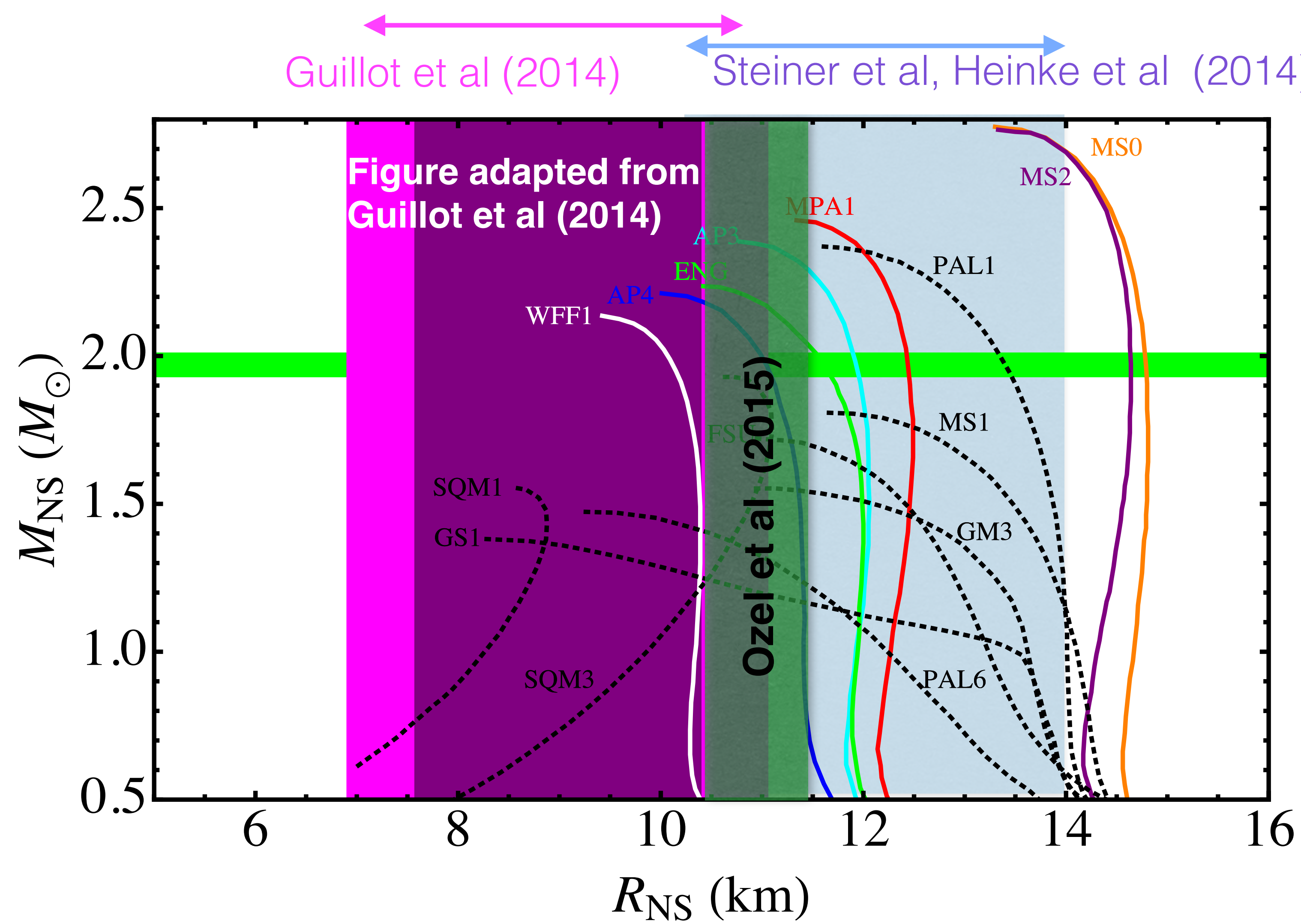
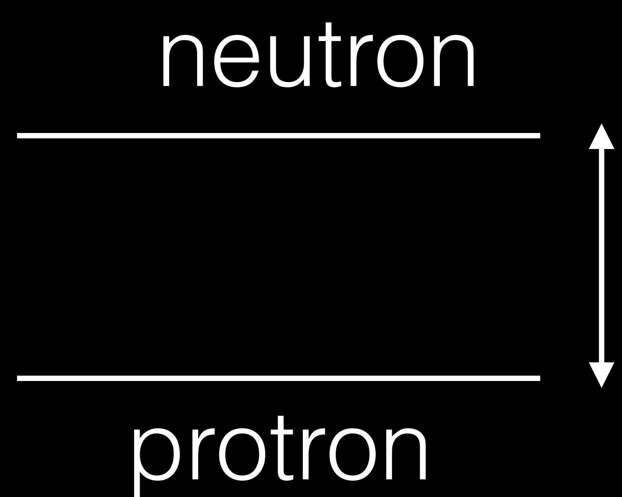




Symmetry Energy: Impact on Dynamics



$$\Delta E(p,q) = E_n(p) - E_p(p+q)$$

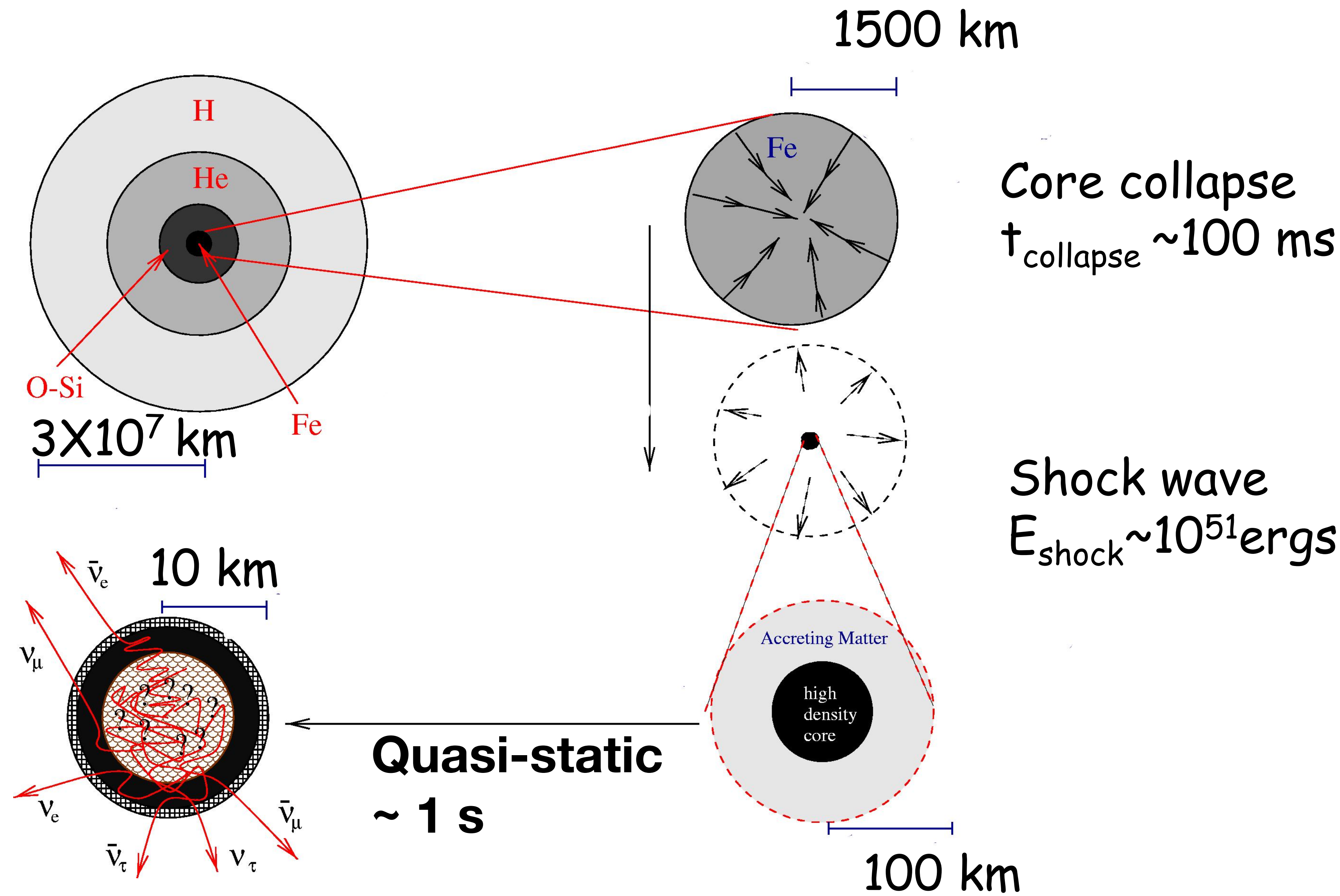
The energy associated with converting a neutron to a proton in neutron-rich matter has important implications for astrophysics:

- 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

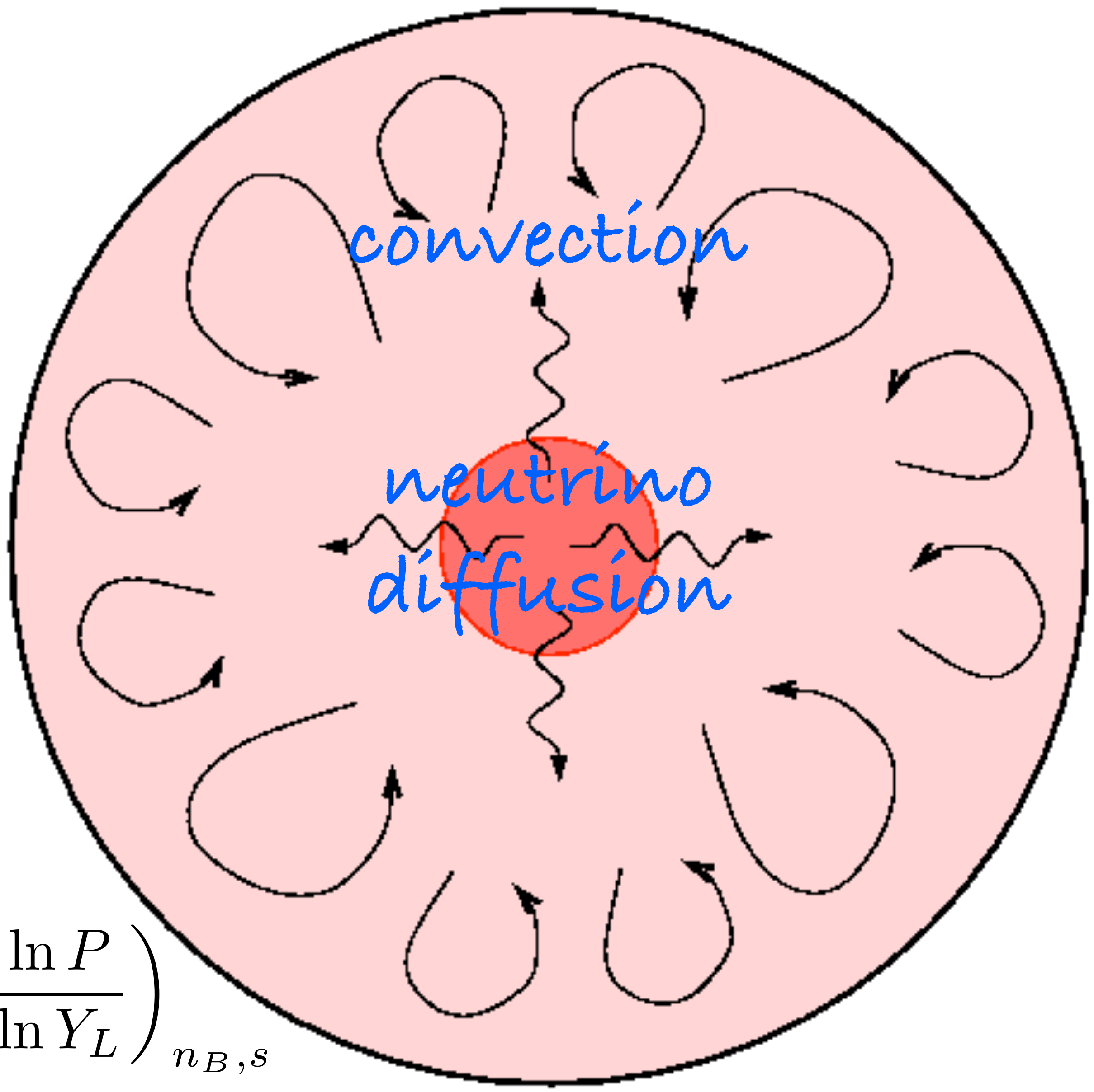


- The time structure of the neutrino signal depends on how heat is transported in the neutron star core.
- The spectrum is set by scattering in a hot (T=3-6 MeV) and not so dense (10^{12}-10^{13} g/cm^3) neutrino-sphere.

Modeling PNS evolution with different EoS.

Heat transport : Neutrino diffusion + convection

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



Convection: Driven by composition gradients. Buoyancy of matter depends on the pressure or neutron matter. Convective growth rate:

$$\omega^2 = -\frac{g}{\gamma_{n_B}}\left(\gamma_s \nabla \ln(s) + \gamma_{Y_L} \nabla \ln(Y_L)\right)$$

$$\gamma_{n_B} = \left(\frac{\partial \ln P}{\partial \ln n_B}\right)_{s,Y_L} \gamma_s = \left(\frac{\partial \ln P}{\partial \ln s}\right)_{n_B,Y_L} \gamma_{Y_L} = \left(\frac{\partial \ln P}{\partial \ln Y_L}\right)_{n_B,s}$$

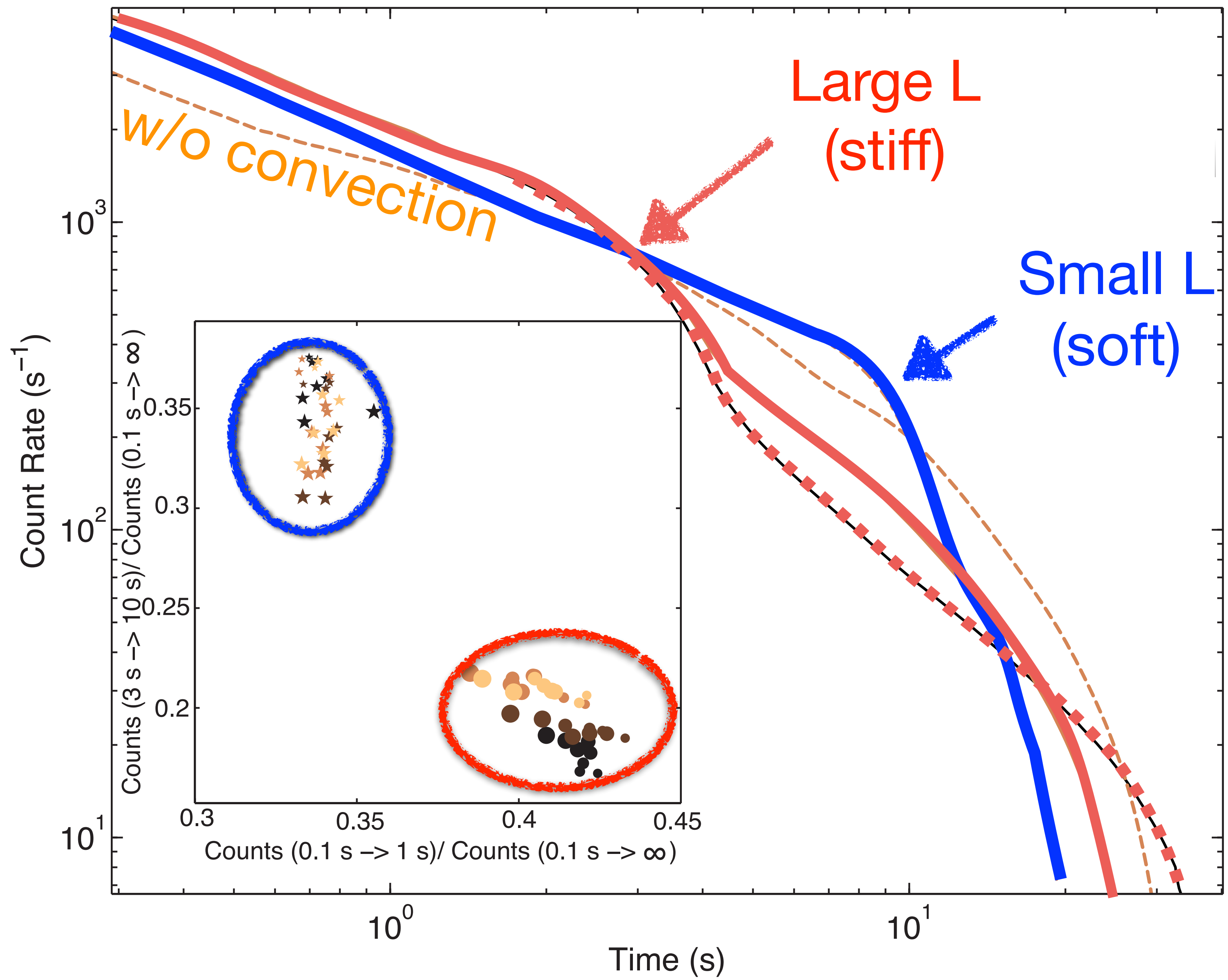
$$\left(\frac{\partial P}{\partial Y_L}\right)_{n_B} \simeq n_B^{4/3} Y_e^{1/3} - 4 n_B^2 E'_{\rm sym}(1-2Y_e)$$

Large values of L suppress convection.

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

Observable signatures of convective transport

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



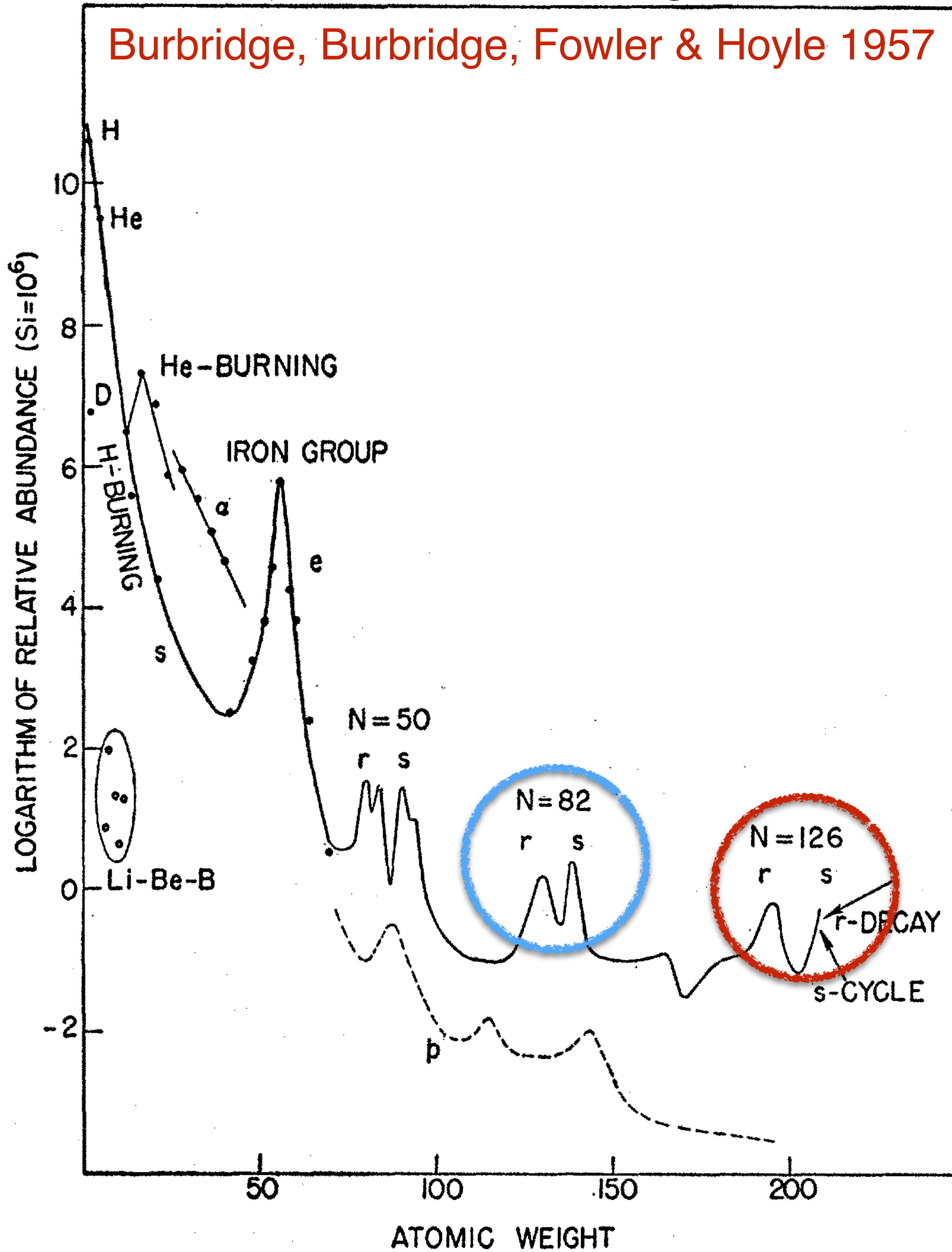
Count rate in Super-Kamiokande for galactic supernova at 10 kpc.

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

Dense Matter, Neutrinos & Nucleosynthesis

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

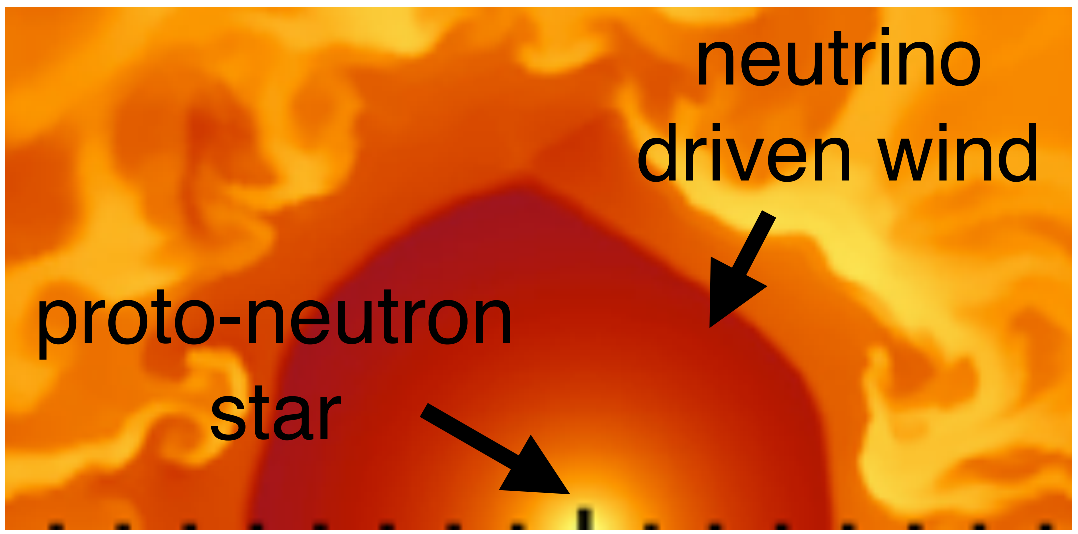
Properties of dense
matter and neutrinos
influence
where and how heavy
elements are
synthesized.



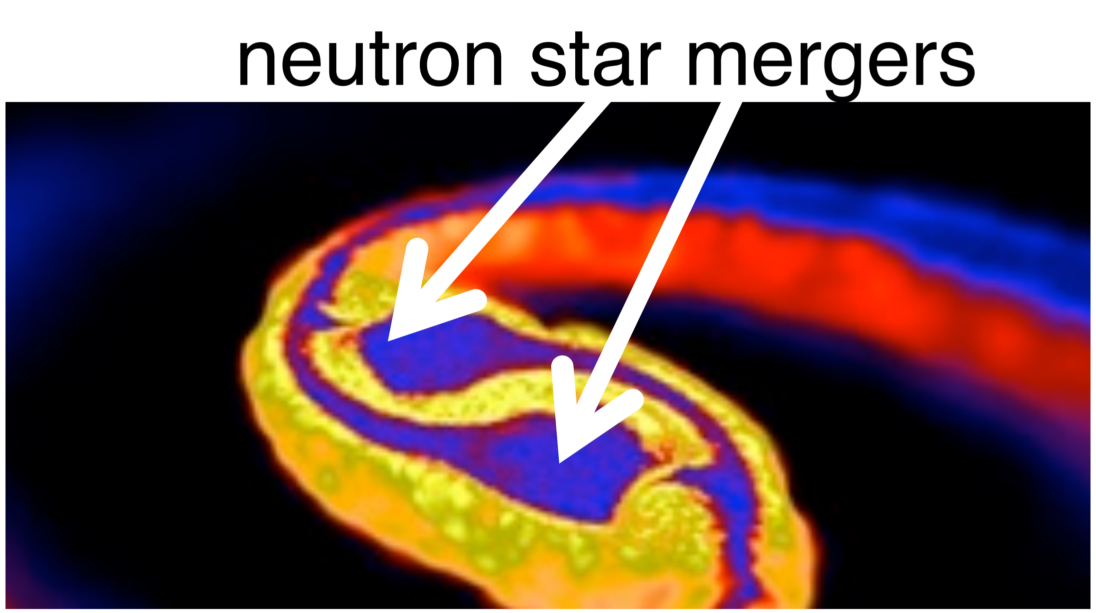
Where does the r-process occur ?

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]



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.
- Low electron fraction (Y_e).

} Hydrodynamics, Magnetic Fields, etc

} 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.

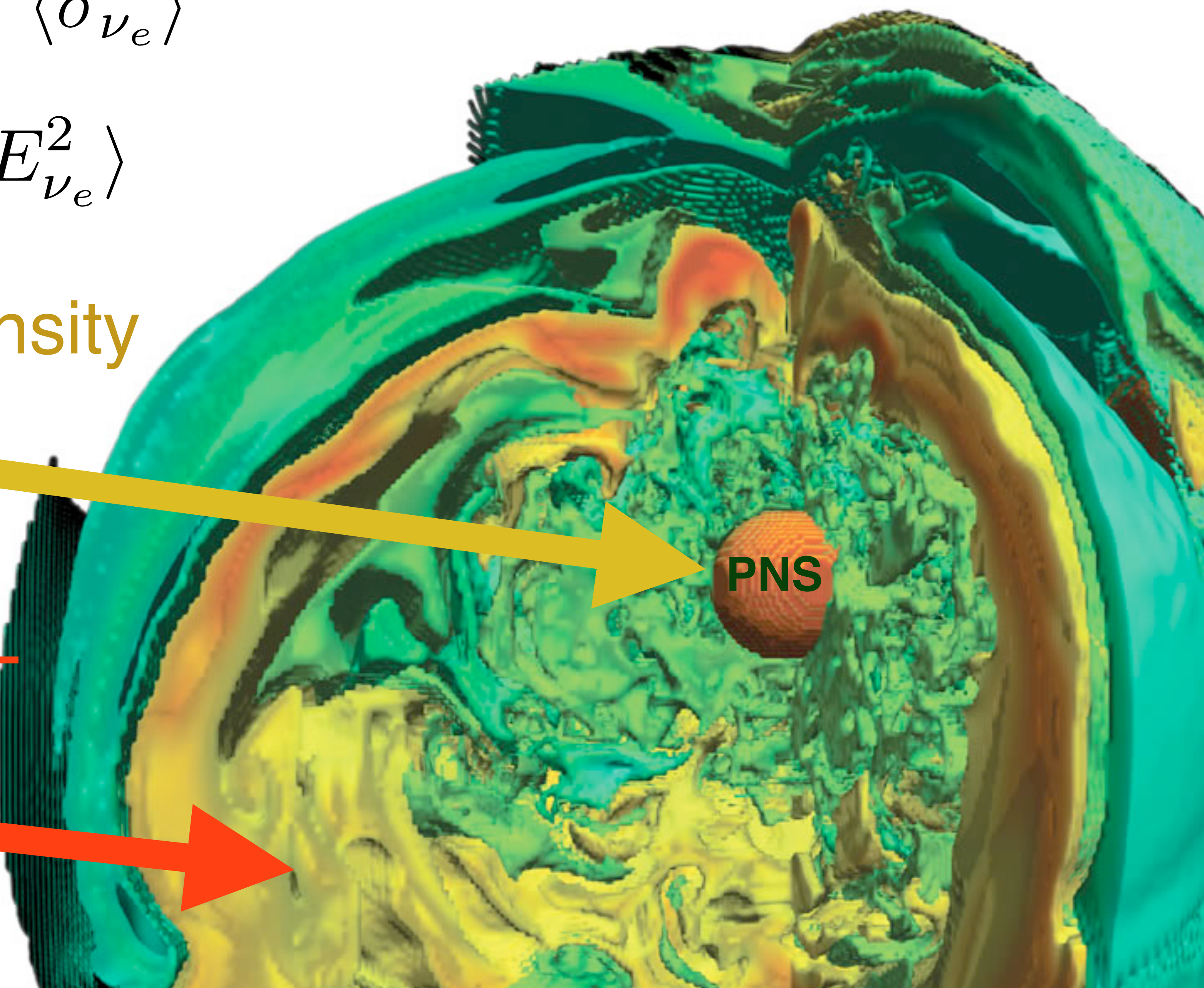
$$\begin{cases} \bar{\nu}_e + p \rightarrow n + e^+ \\ \nu_e + n \rightarrow p + e^- \end{cases}$$

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

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

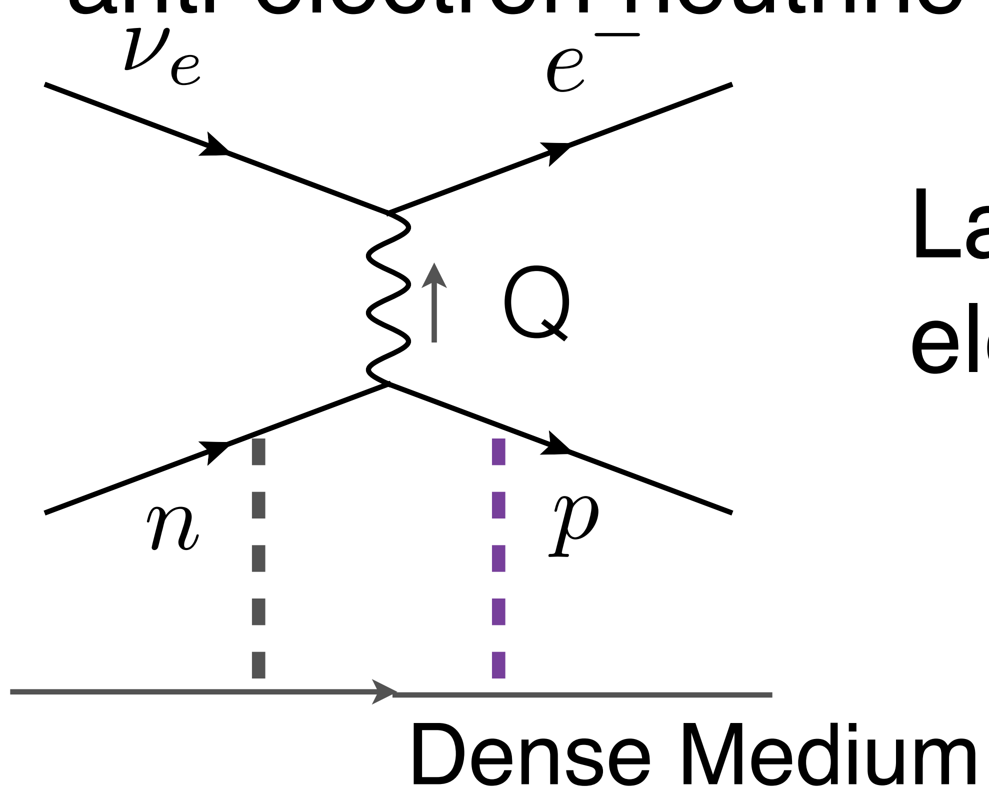
Neutrino-sphere at high density and moderate entropy.
R ~ 10-20 km

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



Charged Current Opacity

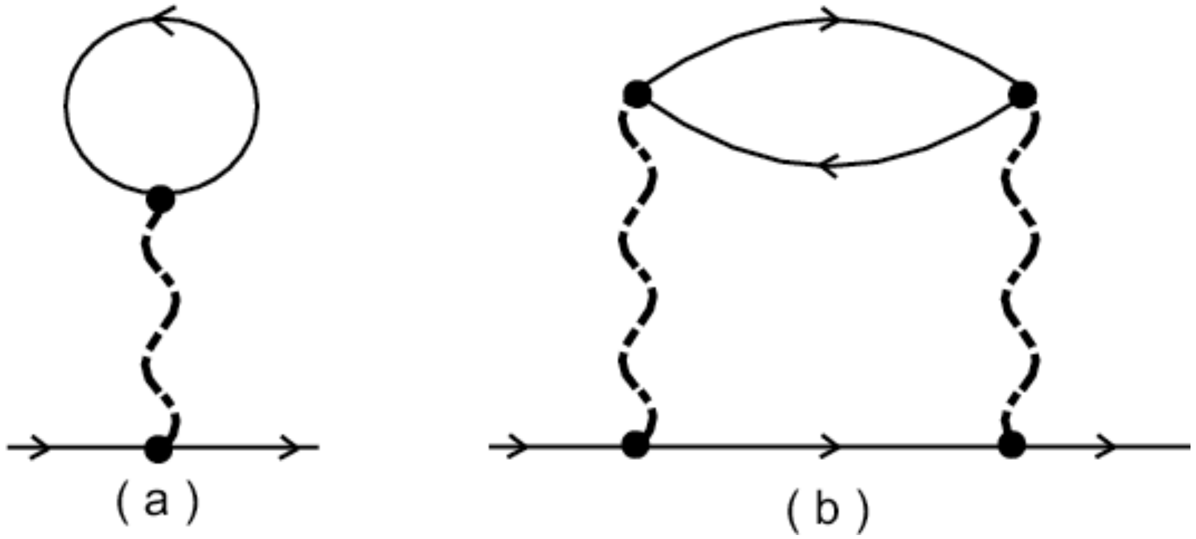
- Asymmetry between neutrons and proton interactions in neutron-rich matter determines the Q value of the reaction.
- A large symmetry energy (S) implies a large +Q value for change neutrons to protons and a large -Q value for changing protons to neutron.
- Large S favors electron neutrino absorption and disfavors anti-electron neutrino absorption.



Large Q crucial to overcome electron final state blocking

Reddy, Prakash & Lattimer (1998)
Roberts (2012)
Martinez-Pinedo et al. (2012)
Roberts & Reddy (2012)
Rrapaj, Bartl, Holt, Reddy, Schwenk (2015)

SINGLE PARTICLE ENERGY SHIFT & DAMPING



$$E_n(p) \approx m_n + \frac{p^2}{2m_n^*} + U_n + i\ \Gamma_n$$

$$E_p(p+q) \approx m_p + \frac{(p+q)^2}{2m_n^*} + U_p + i\ \Gamma_p$$

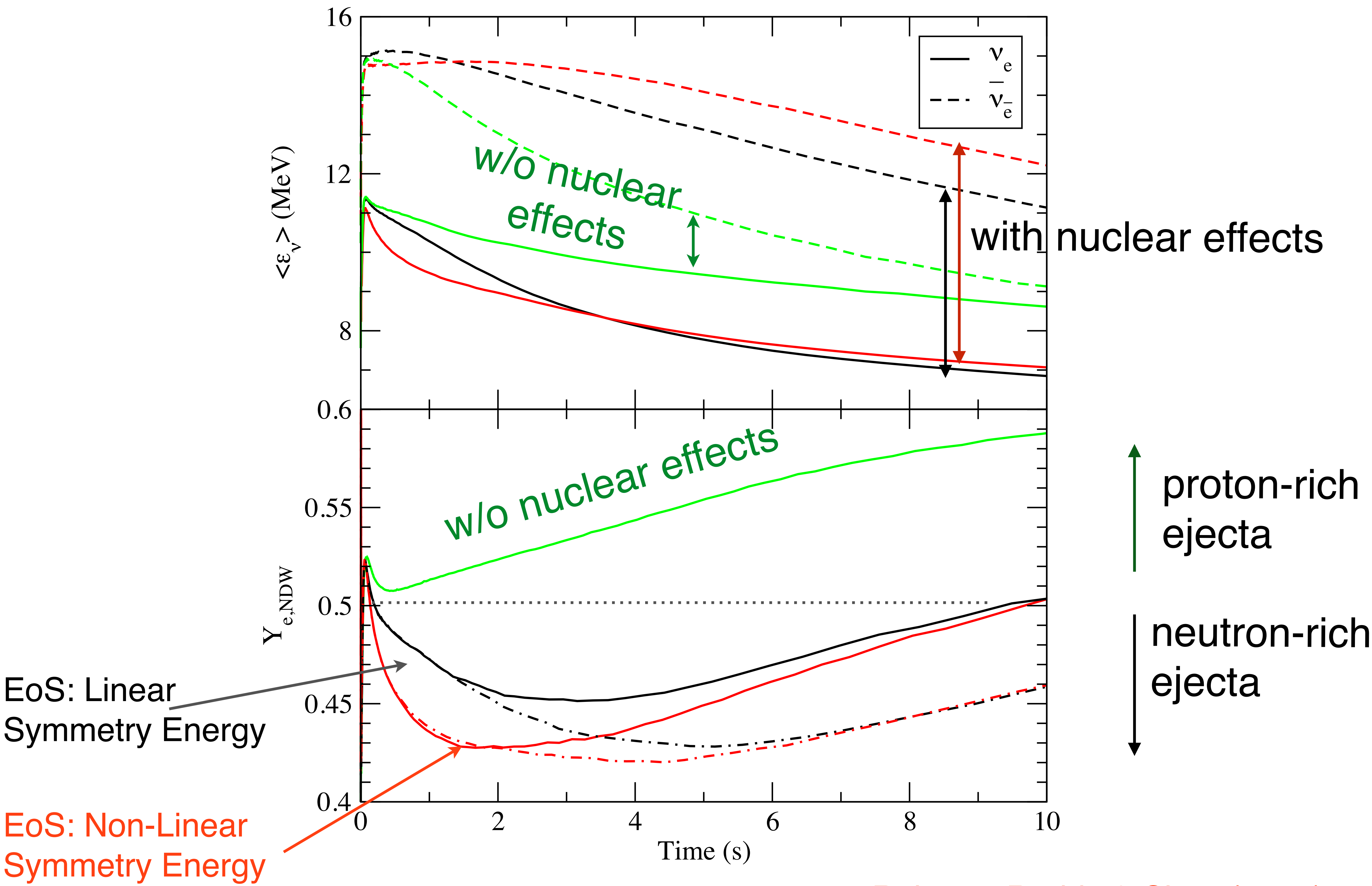
Energy Transfer in the Charged Current Process:

$$q_0 = E_n(p) - E_p(p+q) \simeq \frac{pq}{2m_n^*} + (m_n - m_p) + (U_n - U_p)$$

$$\approx 0 \qquad \simeq 1.3\ \mathrm{MeV}$$

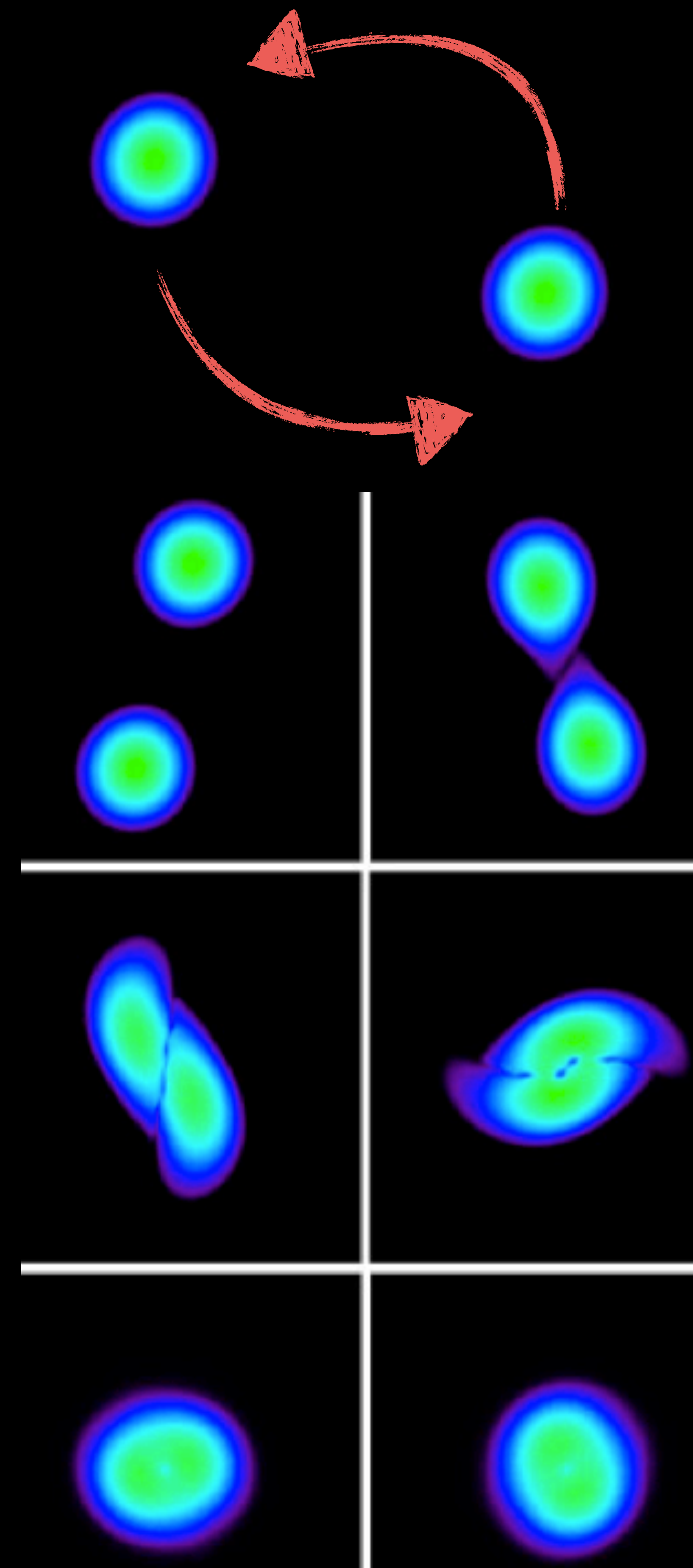
$$\Delta U = U_n - U_p \approx 40\ \frac{n_n - n_p}{n_0}\ \mathrm{MeV}$$

Spectra & Nucleosynthesis



Roberts, Reddy & Shen (2012)

NS Collisions - Gravitational Waves

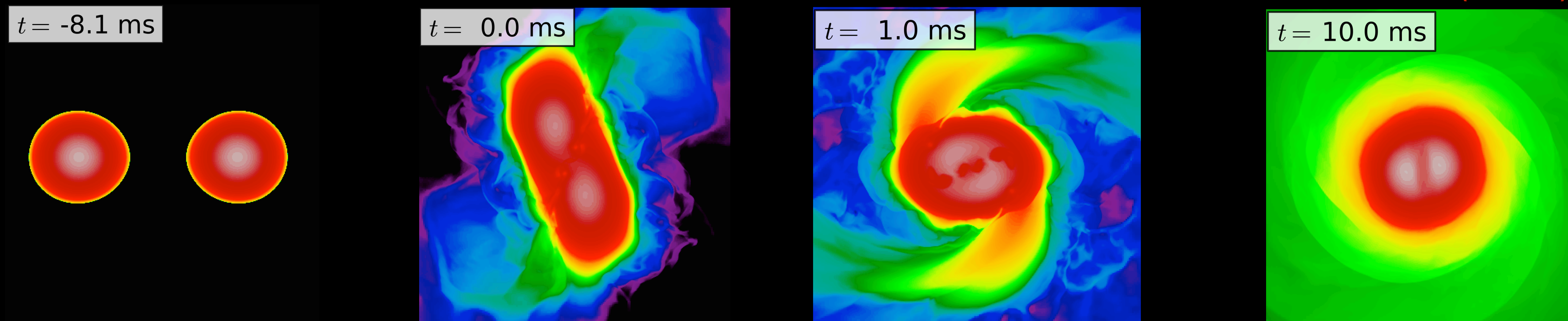


The gravitational waves, EM counterparts, and nucleosynthesis are sensitive nuclear and neutrino physics.

Neutron Star Merger Dynamics

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

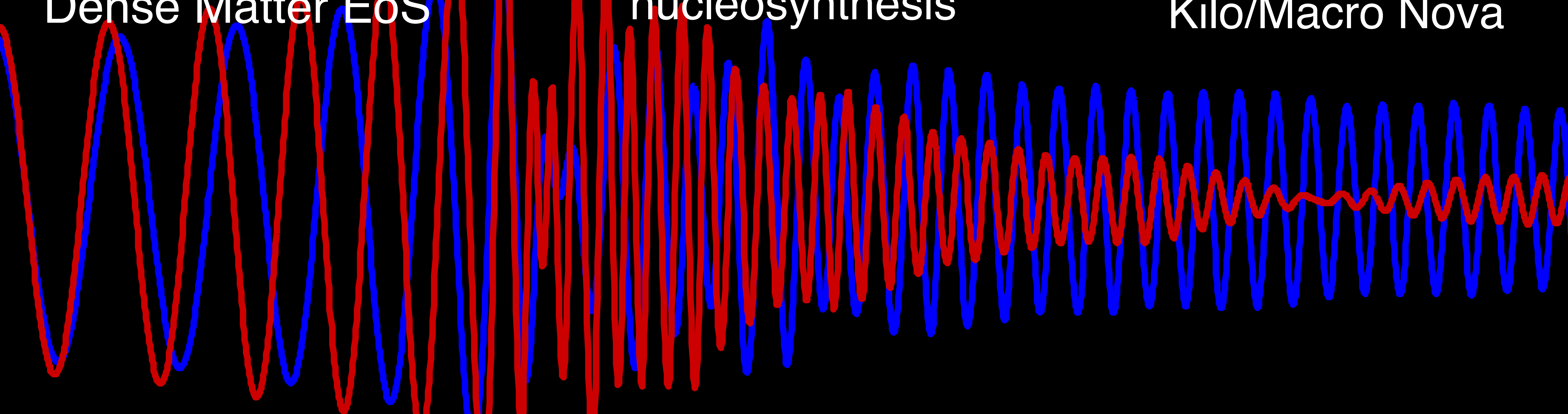
Simulations: Rezzola et al (2013)



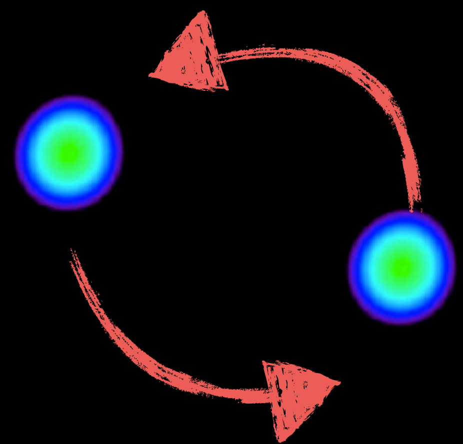
Inspiral:
Gravitational waves, Tidal Effects & Dense Matter EoS

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

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



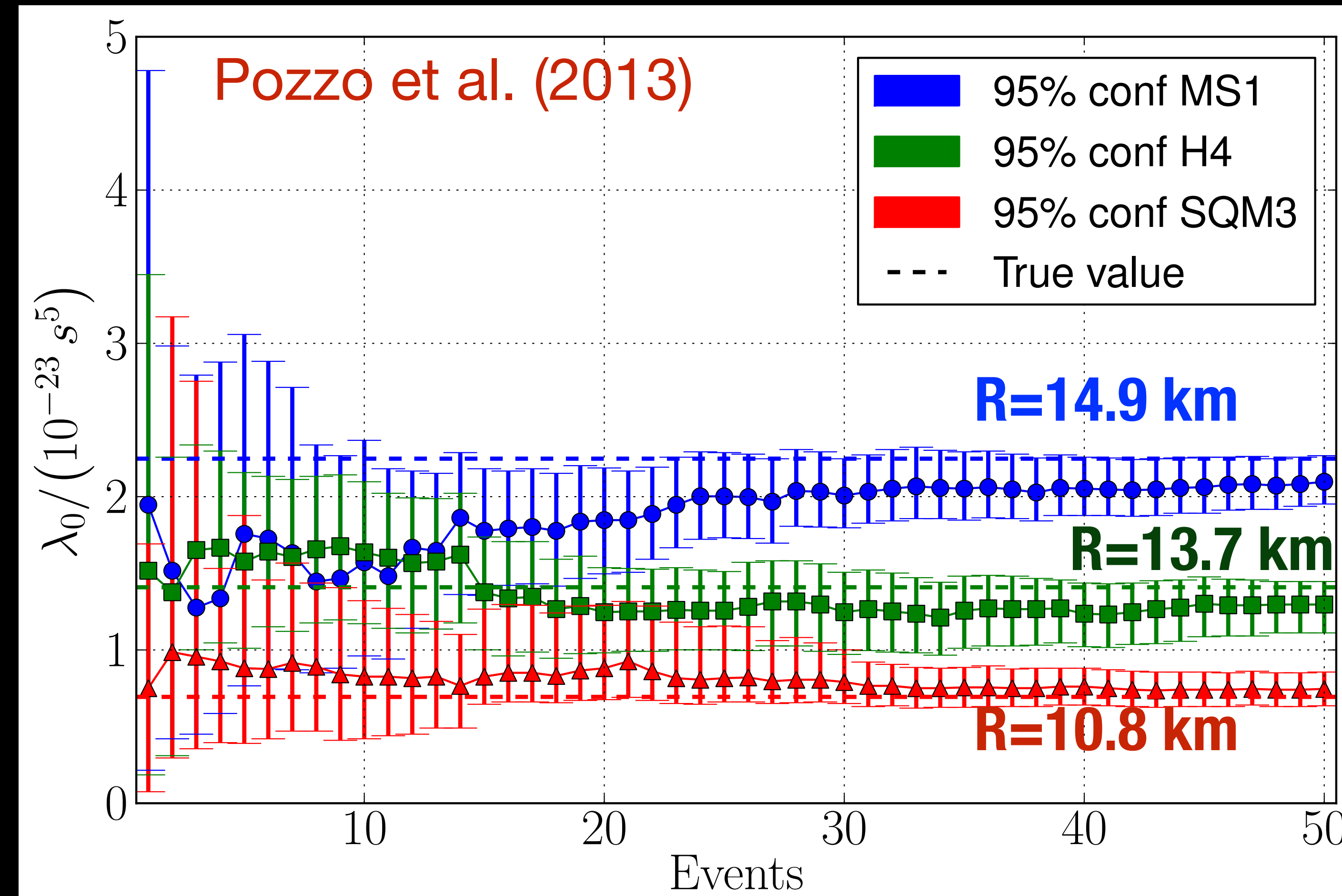
Neutron Star Radii From Pre Merger Signal



Tidal deformation induces quadrupole moment.

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

TIDAL DEFORMABILITY

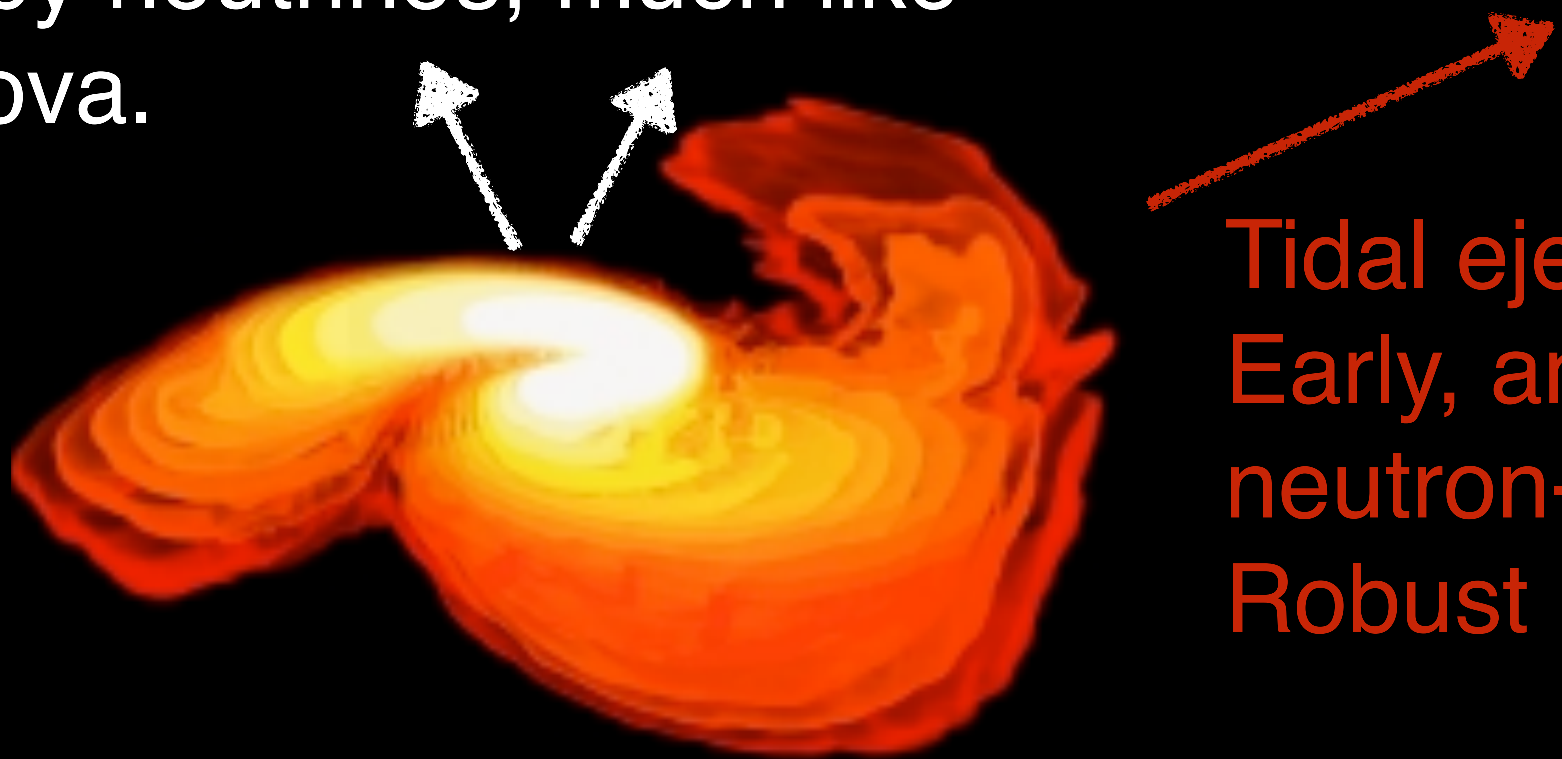


Realistic data analysis by injecting events in a volume between 100-250 Mpc demonstrates discriminating power between EOSs. Pozzo et al. (2013)

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

Merger Ejecta & Nucleosynthesis

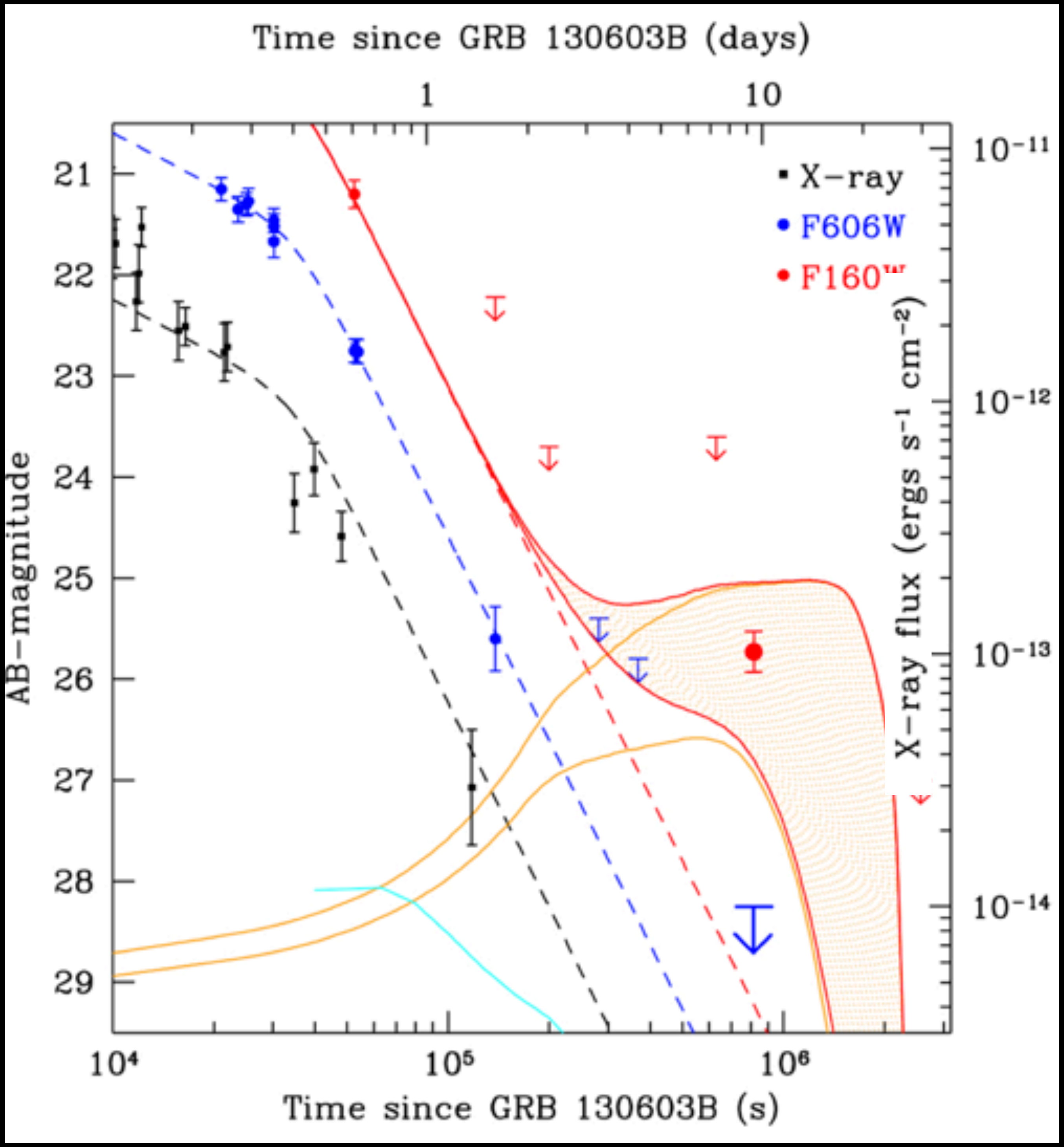
Shocked ejecta:
Processed by neutrinos, much like in a supernova.



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.

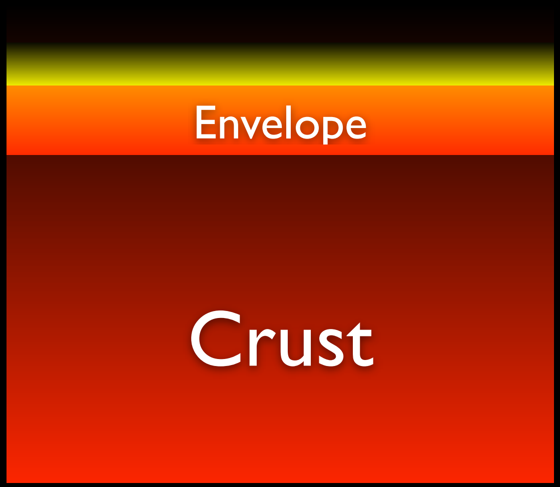
Kasen 2013

Observing and Interpreting Transport Phenomena in Neutron Stars

- Key to discovering new phases of matter in neutron stars.
- Novel phases at low (crust) and high density (core) influence neutron star cooling.
- Neutron stars in binaries accrete matter form a companion and are subject to episodic heating and subsequent cooling cycles.

Transiently Accreting NSs

SXRTs: High accretion followed by periods of quiescence



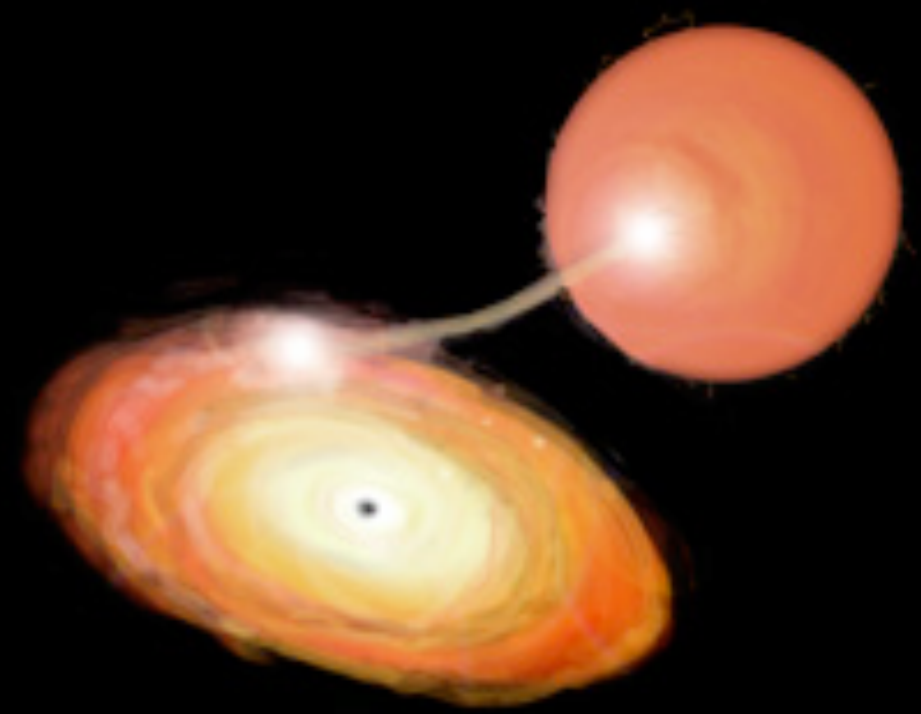
During accretion
Nuclear reactions
release: ~
1.5 MeV / nucleon

Deep crustal heating.

Brown, Bildsten Rutledge (1998)
Sato (1974), Haensel & Zdunik (1990),
Gupta et al (2007,2011).

Electron capture, electron capture induced neutron emission, pycno-nuclear fusion reactions play a role

Warms up old neutron stars



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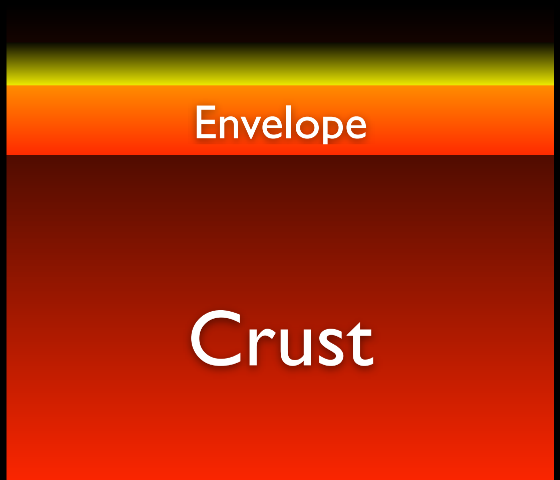

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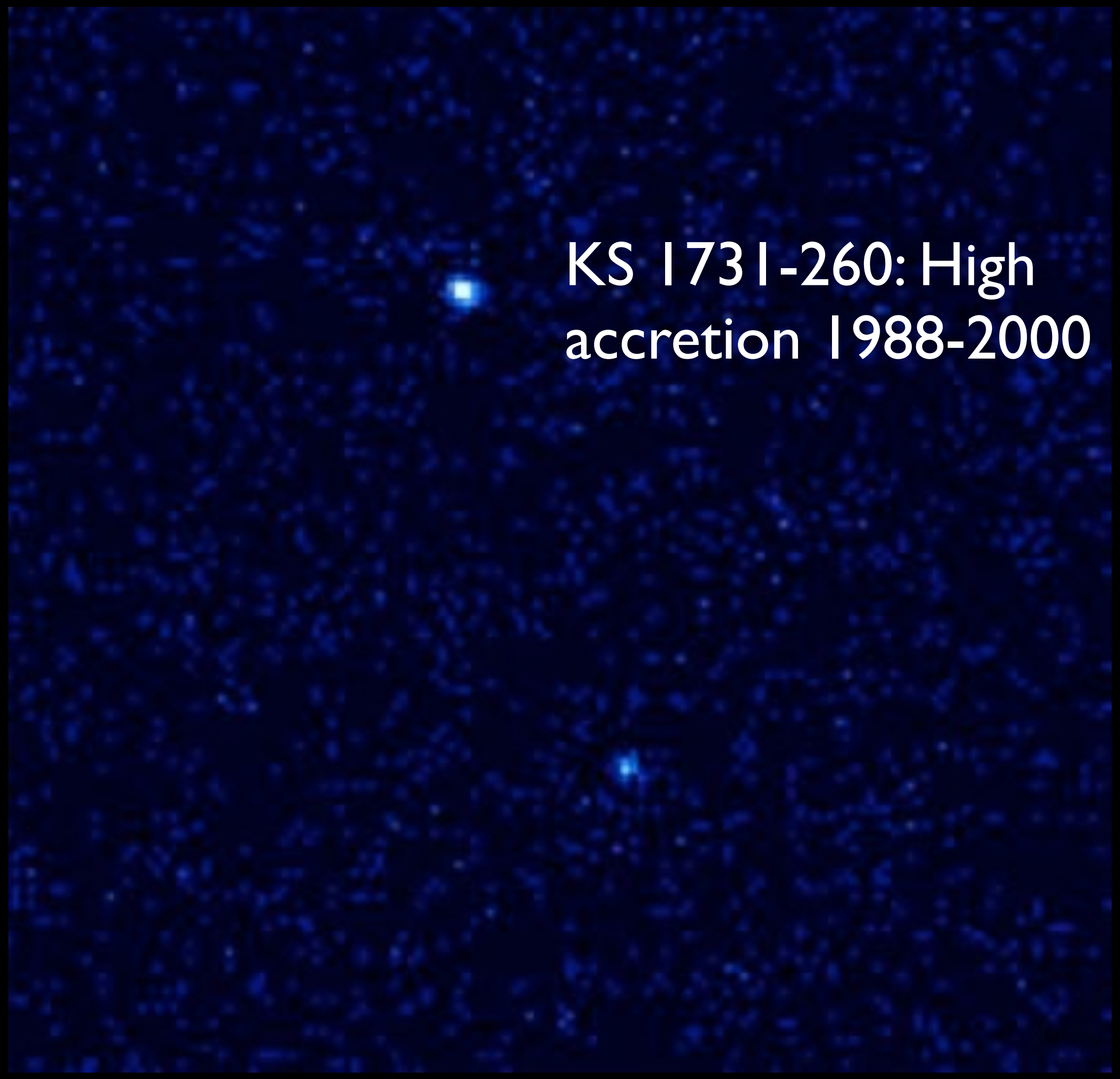
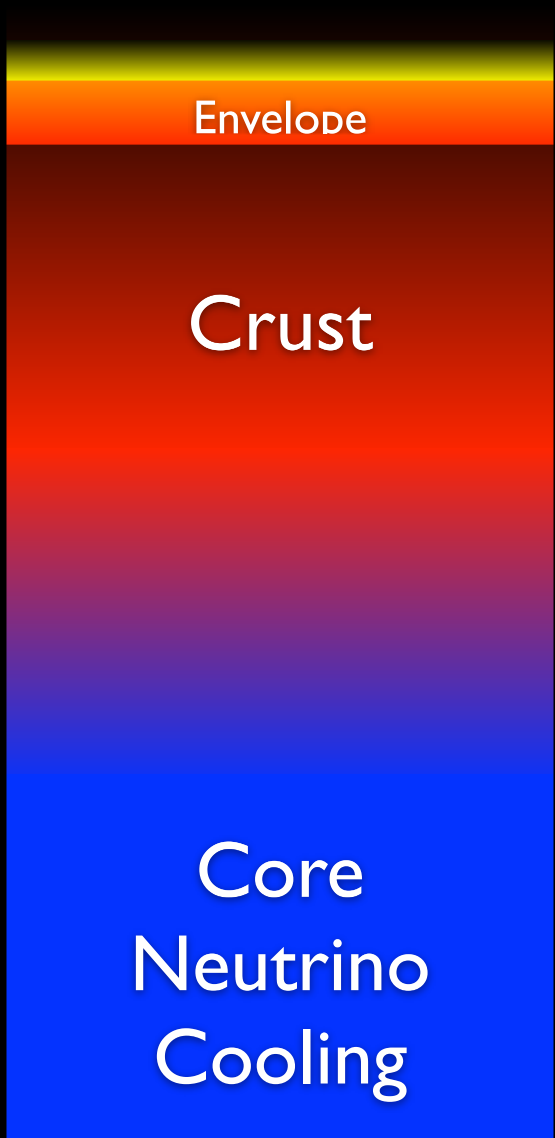


Image credit: NASA/CXC/Wijnands et al.

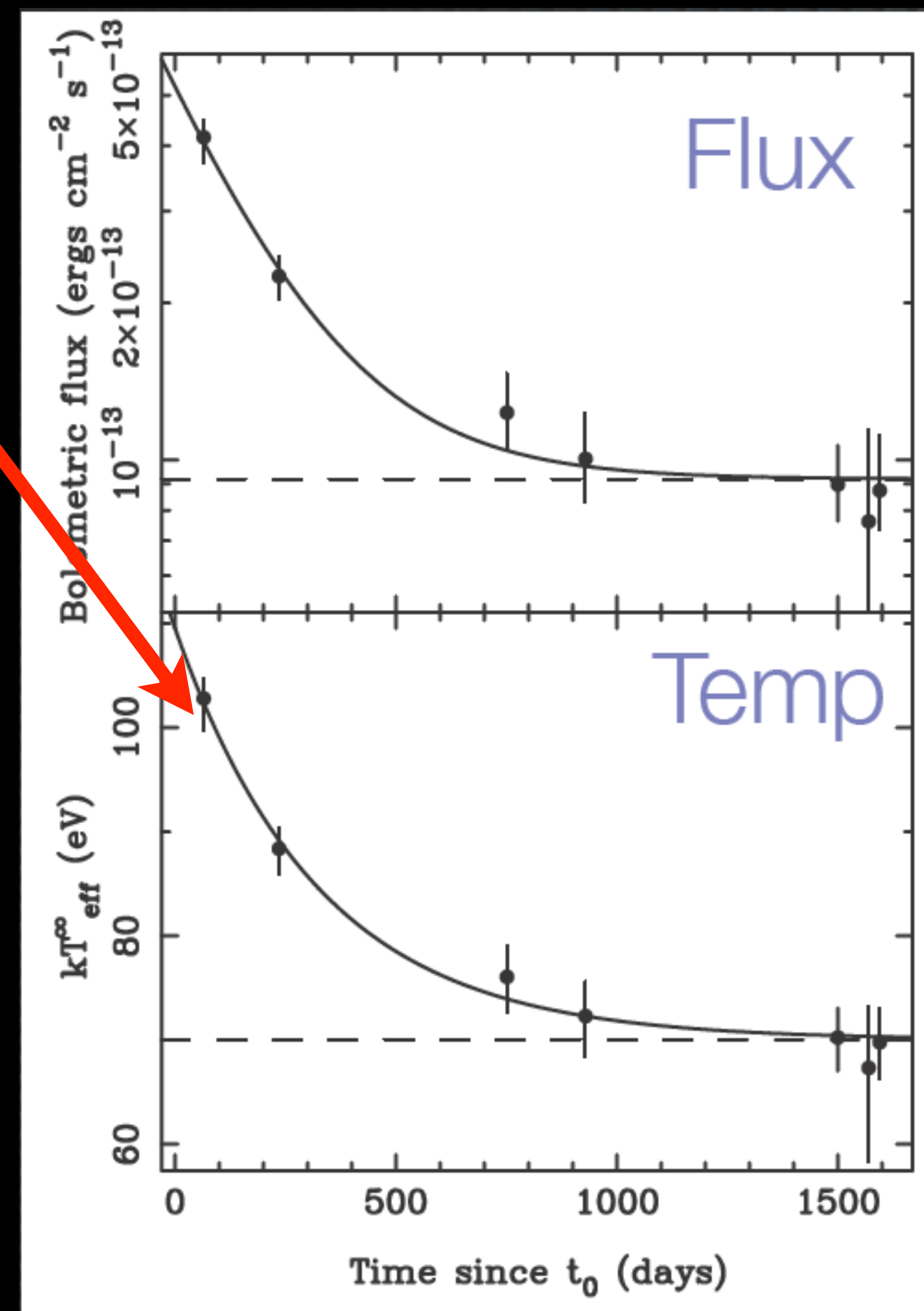
Crust Cooling

Watching NSs immediately after accretion ceases !



Crust Relaxation:

1. Initial temperature profile.
2. Thermal conductivity.
3. Heat capacity.



Shternin & Yakovlev (2007)
Cumming & Brown (2009)

Cackett, et al. (2006)

Cooling Post Accretion

All known Quasi-persistent sources show cooling after accretion

- After a period of intense accretion the neutron star surface cools on a time scale of 100s of days.

- This relaxation was first discovered in 2001 and 6 sources have been studied to date.

- Expected rate of detecting new sources ~ 1/year.

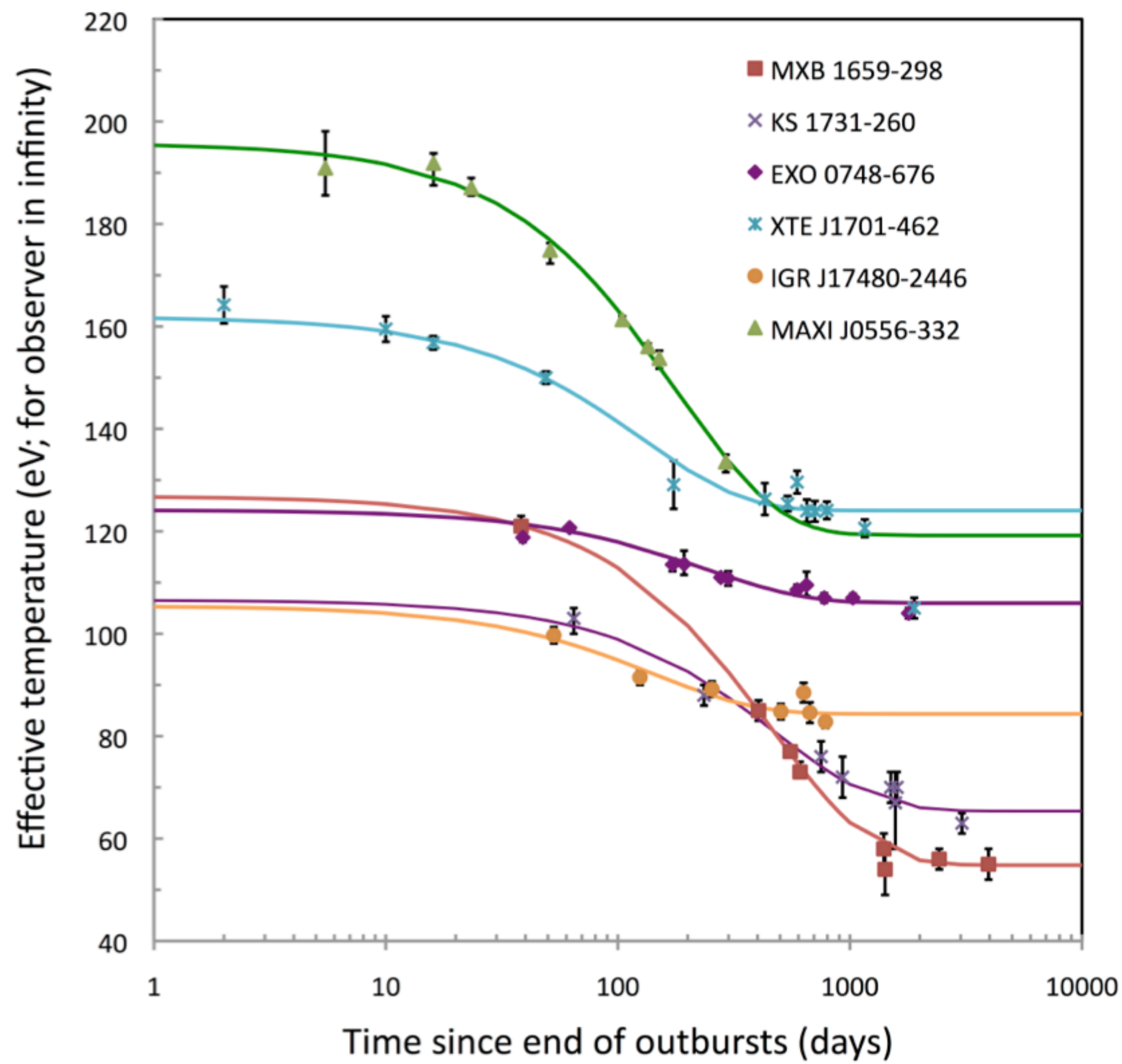


Figure from Rudy Wijnands (2013)

Connecting to Crust Microphysics

Crustal Specific Heat

Crust Thickness

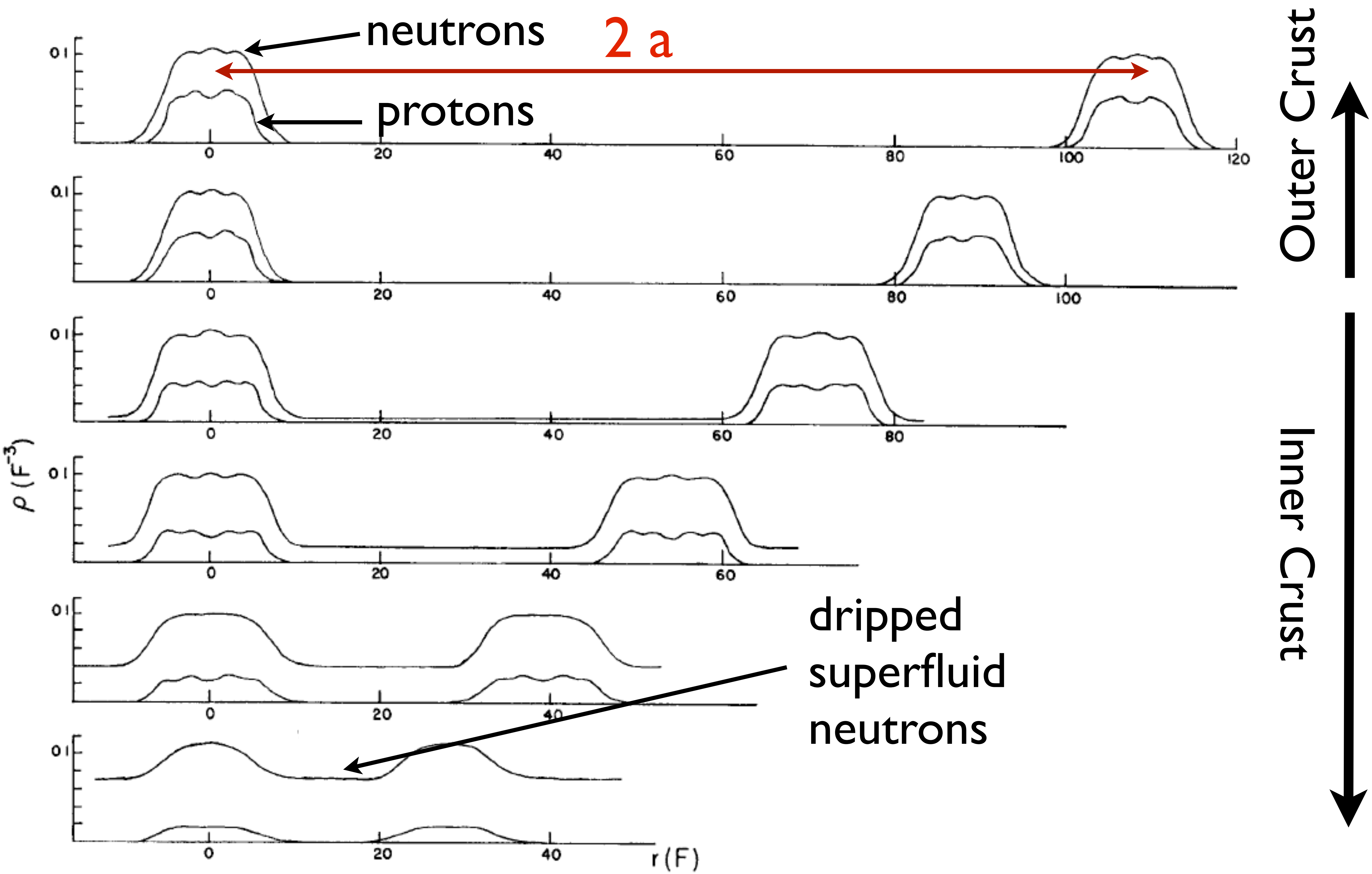
$$\tau_{\rm C} = \langle \frac{C_V}{\kappa} \rangle \; \Delta R^2$$

Thermal Conductivity

The shape of the light curve is a probe of the local thermal time. In principle a collection of light curve can map the thermal and transport properties at each depth.

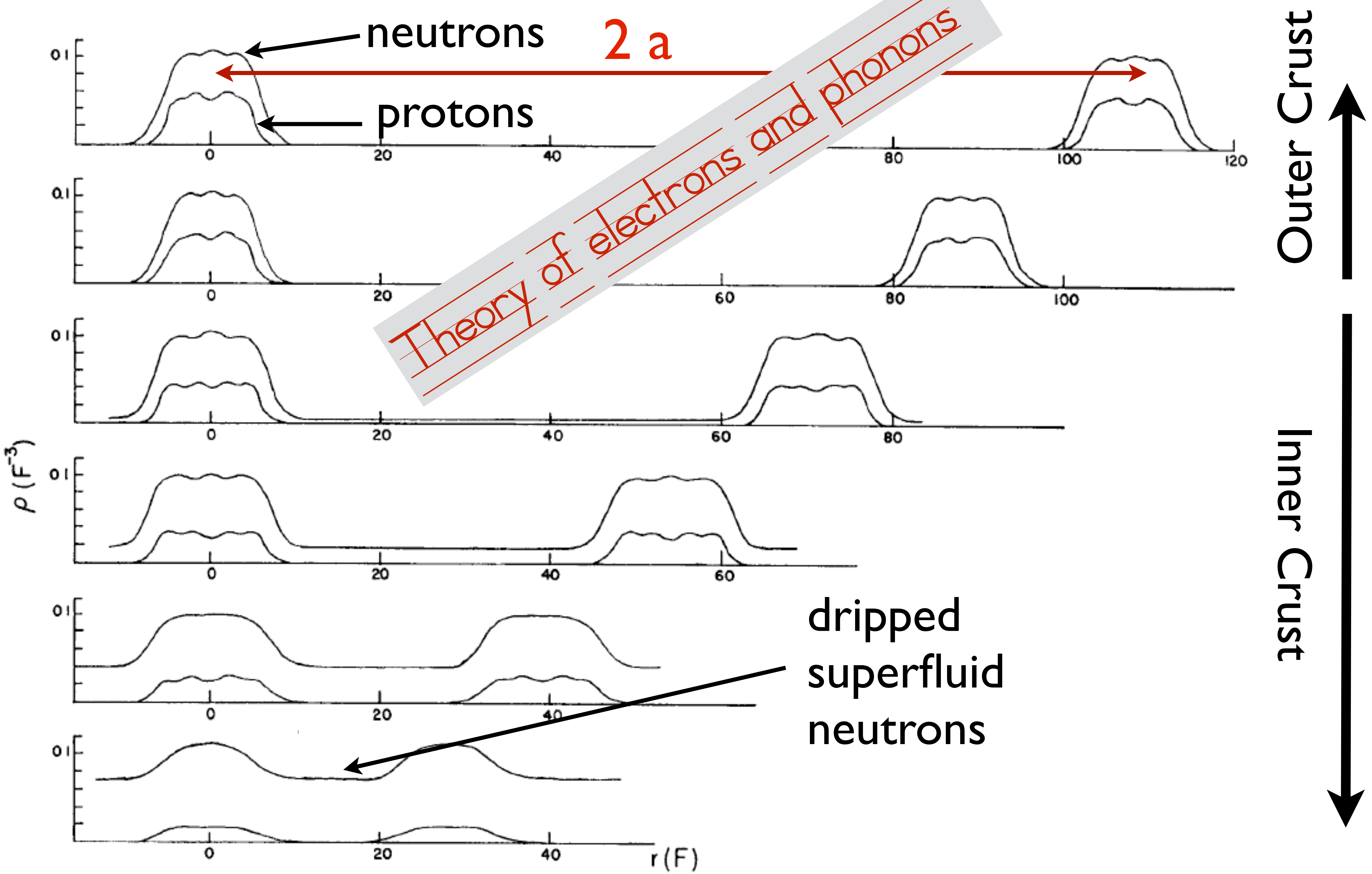
$$\tau_{\rm th}(\rho, T) = \frac{C_V}{\kappa}$$

Microscopic Structure of the Crust



Baym Pethick & Sutherland (1971)   Negele & Vautherin (1973)

Microscopic Structure of the Crust



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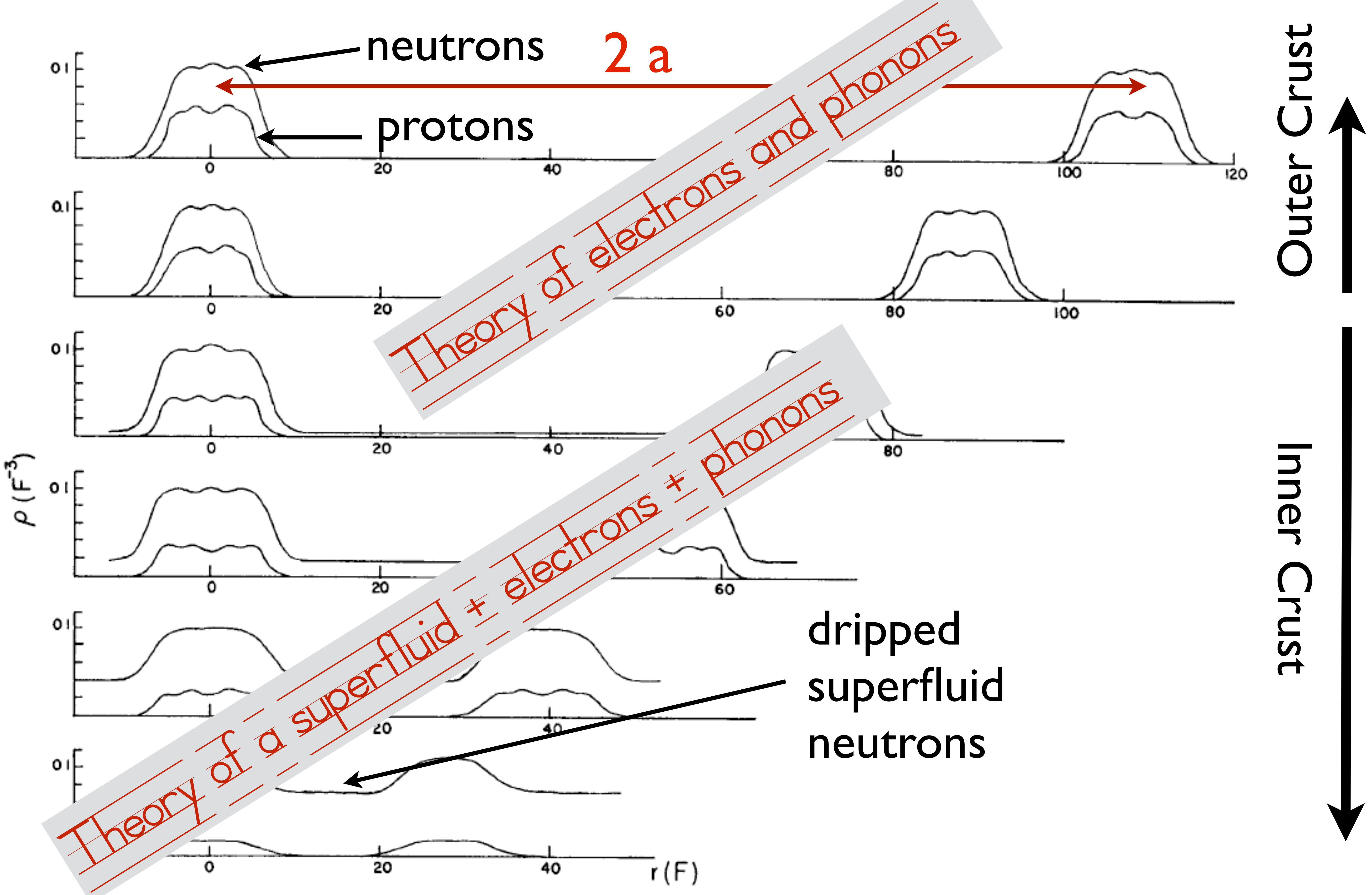
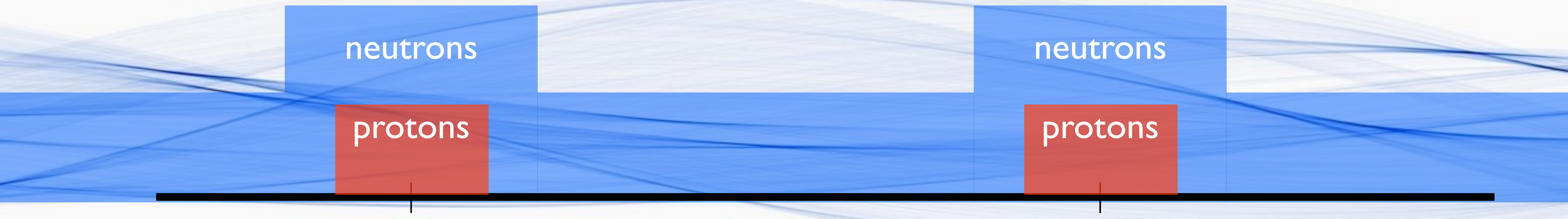
Microscopic Structure of the Crust



Baym Pethick & Sutherland (1971)   Negele & Vautherin (1973)

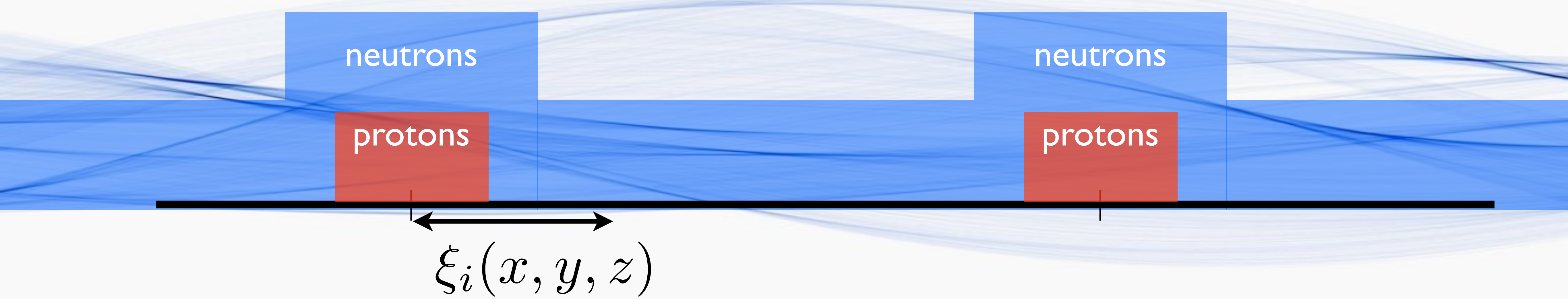
Low Energy Theory of Phonons



Proton (clusters) move collectively on lattice sites. Displacement is a good coordinate.

Neutron superfluid: Goldstone excitation is the phase of the condensate.

Low Energy Theory of Phonons



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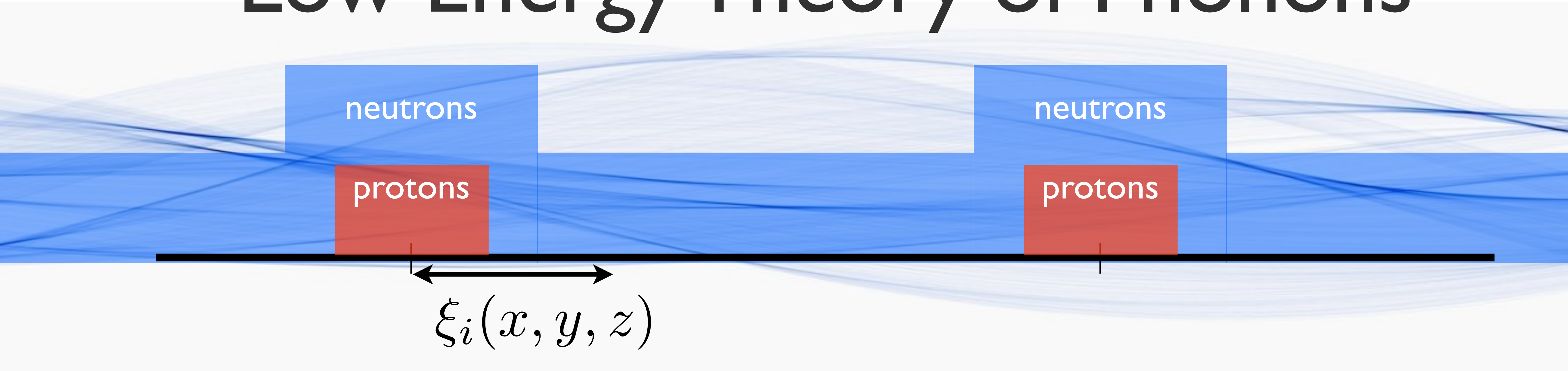
Low Energy Theory of Phonons



Proton (clusters) move collectively on lattice sites. Displacement is a good coordinate.

Neutron superfluid: Goldstone excitation is the phase of the condensate.

$$\langle \psi_\uparrow(r)\psi_\downarrow(r)\rangle = |\Delta| \ \exp\left(-2i \ \theta\right)$$

"coarse-grain"

Collective coordinates:

Vector Field: $\xi_i(r,t)$
Scalar Field: $\phi(r,t)$

A Low Energy Effective for the Inner Crust

Symmetries of the underlying Hamiltonian

$$\begin{cases} \xi^{a=1..3}(\mathbf{r},t) \to \xi^{a=1..3}(\mathbf{r},t) + a^{a=1..3} \\ \phi(\mathbf{r},t) \to \phi(\mathbf{r},t) + \theta \end{cases}$$

Only derivative terms are allowed. Lagrangian density for the phonon system with cubic symmetry:

$$\mathcal{L} = \frac{f_\phi^2}{2}(\partial_0\phi)^2 - \frac{v_\phi^2 f_\phi^2}{2}(\partial_i\phi)^2 + \frac{\rho}{2}\partial_0\xi^a\partial_0\xi^a - \frac{1}{4}\mu(\xi^{ab}\xi^{ab}) - \frac{K}{2}(\partial_a\xi^a)(\partial_b\xi^b)$$
$$- \frac{\alpha}{2}\sum_{a=1..3}(\partial_a\xi^a\partial_a\xi^a) + g_{\rm mix} f_\phi\sqrt{\rho}\;\partial_0\phi\partial_a\xi^a + \frac{1}{f_{\rm ep}}\;\partial_0\xi\;\psi_{\rm e}^\dagger\;\psi_{\rm e} + \cdots$$

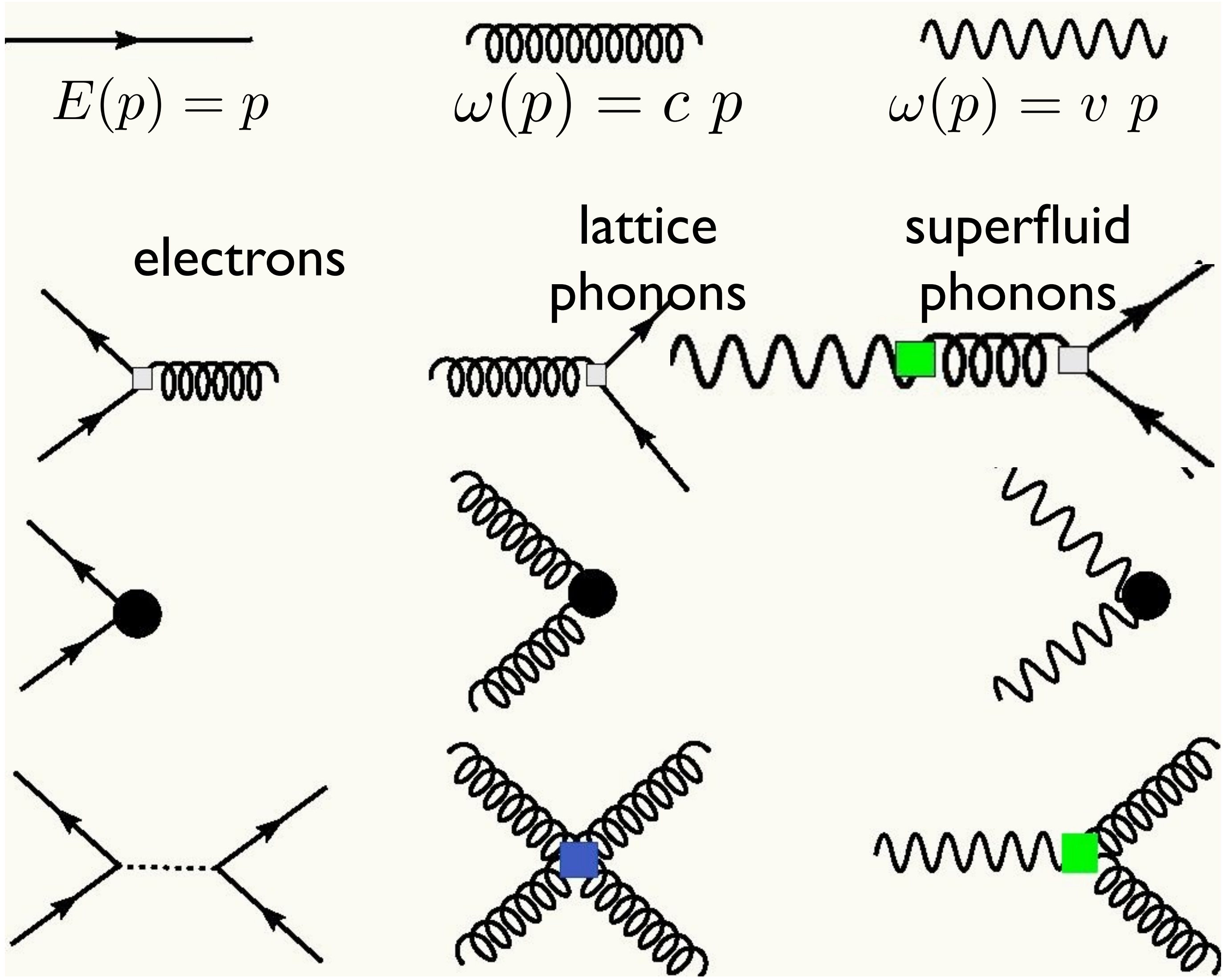
Low energy coefficients are related to static properties and are obtained as derivatives of the equation of state.

Cirigliano, Reddy, Sharma 2011

Transport: Thermal Conduction

$$\kappa = \frac{1}{3}\, C_v \times v \times \lambda$$

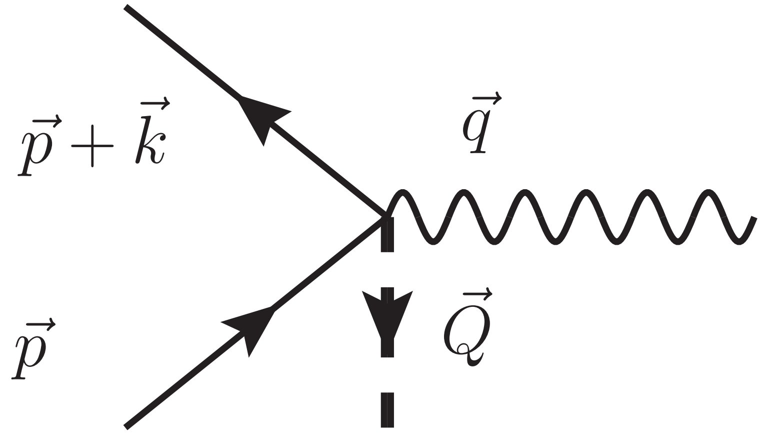
- Dissipative processes:



Cirigliano, Reddy & Sharma (2011)

- Umklapp is important:

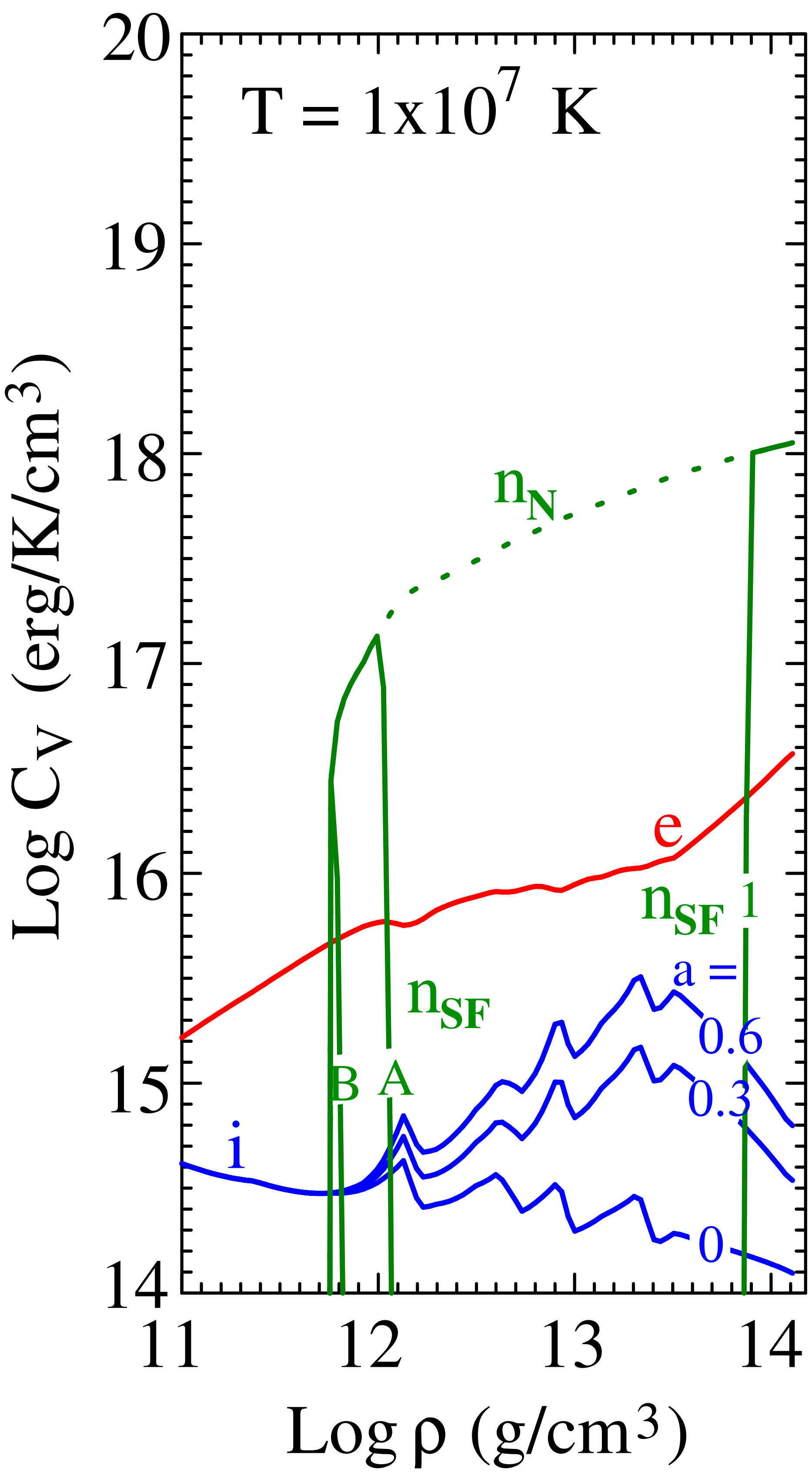
$$\frac{k_{\rm Fe}}{q_{\rm D}} = \left(\frac{Z}{2}\right)^{1/3} > 1$$



Electron Bragg scatters and emits a transverse phonon.

Flowers & Itoh (1976)

Crustal Specific Heat



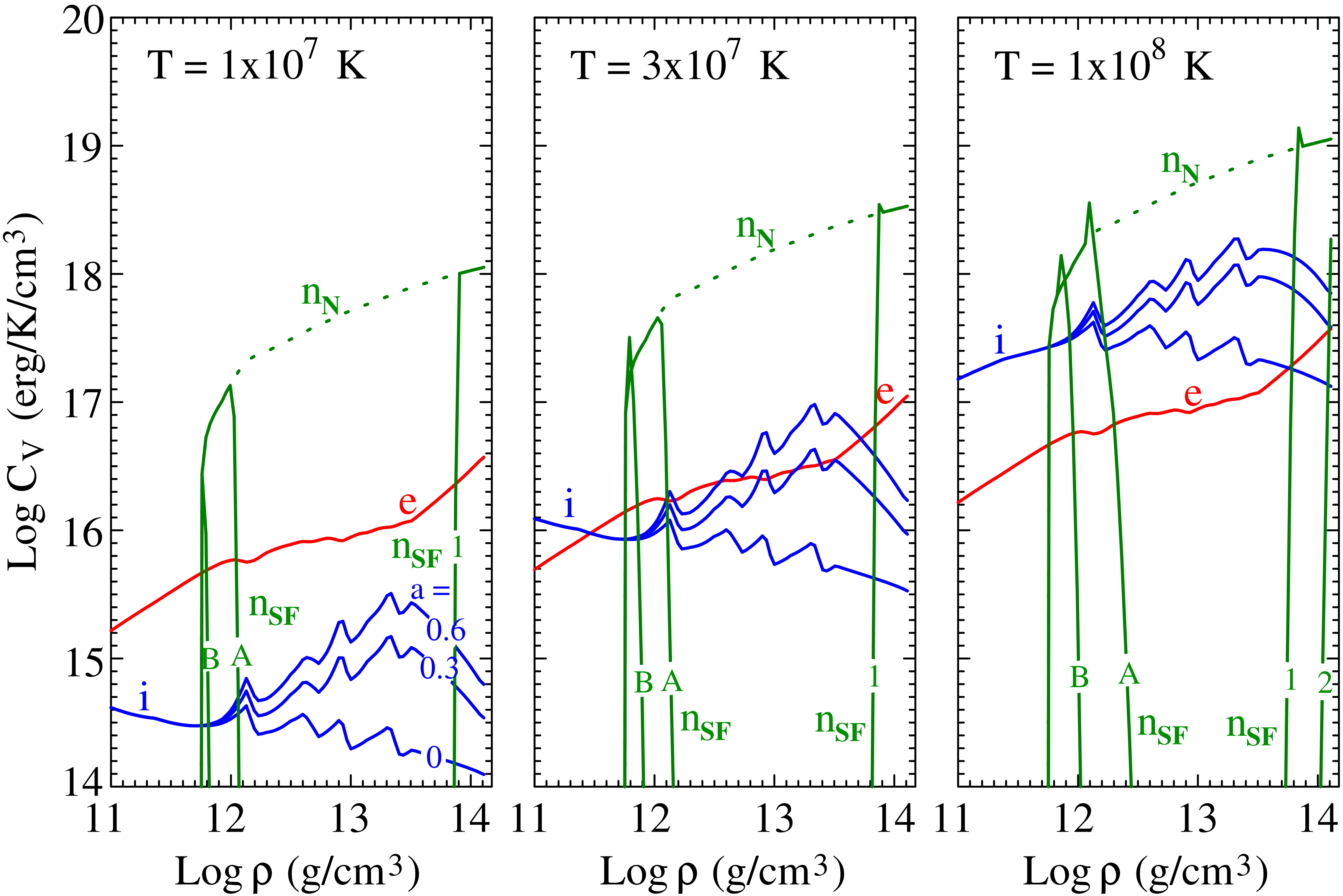
Electrons: $$C_v^e = \frac{1}{3}\mu_e^2\, T$$

Ions: $$C_v^{\rm lph} = \frac{2\pi^2}{15}\left(\frac{T^3}{v_l^3} + \frac{2\,T^3}{v_t^3}\right)$$

Neutrons:
$$\begin{cases} C_v^{\rm sph} = \dfrac{2\pi^2}{15}\dfrac{T^3}{v_\phi^3} & (T \ll T_c) \\ C_v^{\rm neutron} = \dfrac{1}{3}\, m_n\, k_{\rm Fn}\, T & (T > T_c) \end{cases}$$

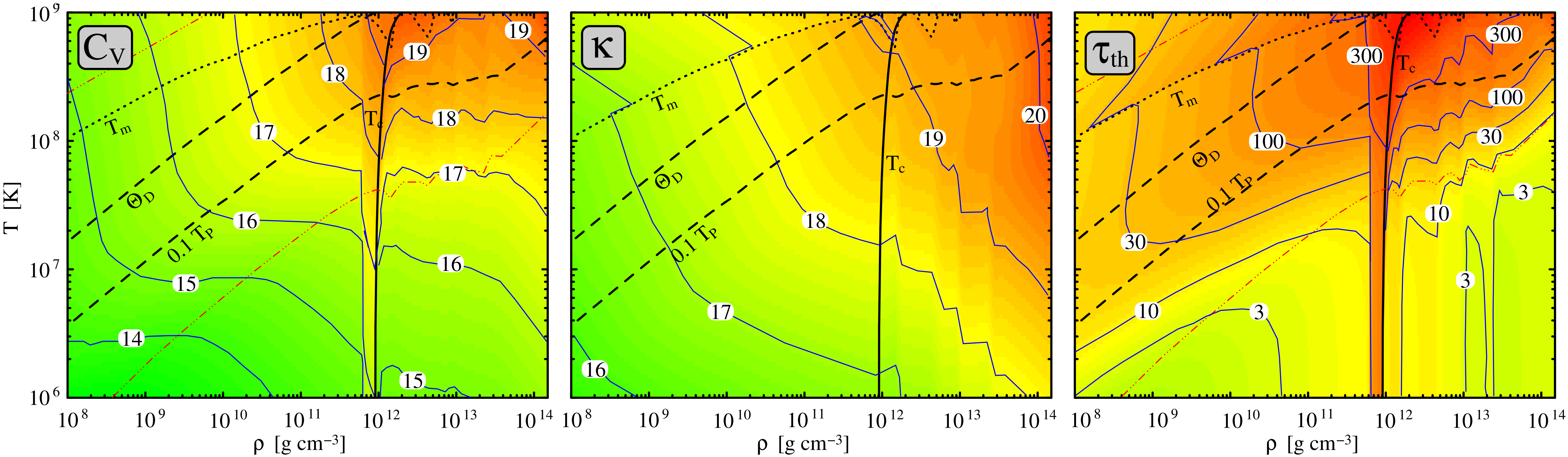
Page & Reddy (2012)

Crustal Specific Heat



Page & Reddy (2012)

Revealing the Inner Crust



- Late time signal is sensitive to inner crust thermal and transport properties.
- Data favors relatively high thermal conductivity and low specific heat.
- Inner crust is crystalline, not too dirty, and neutrons must be in a superfluid state.

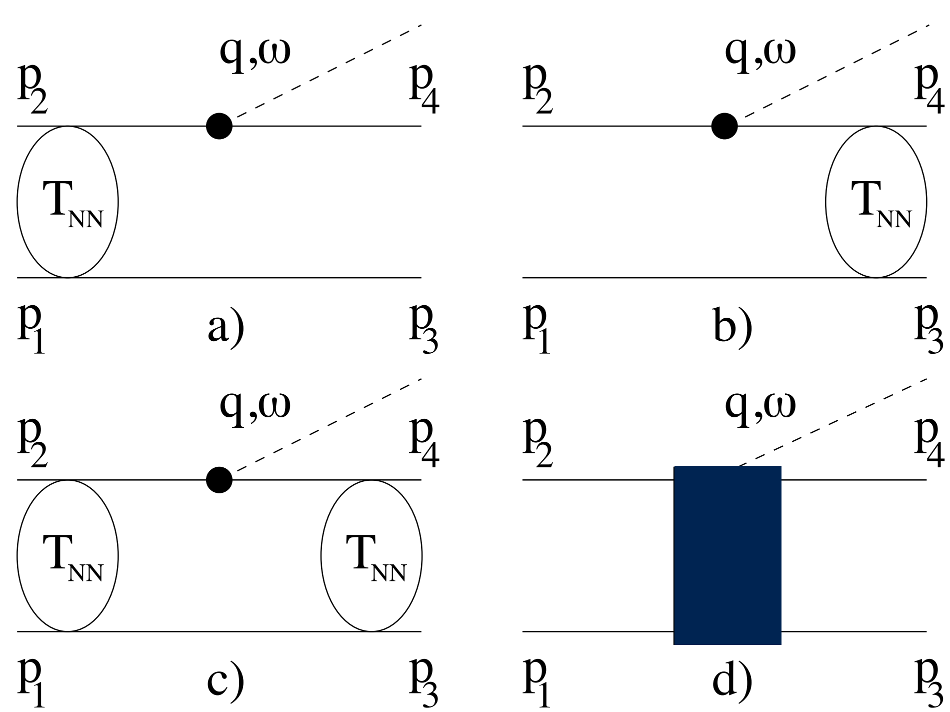
Shternin & Yakovlev (2007), Brown & Cumming (2009), Page & Reddy (2012,2014)

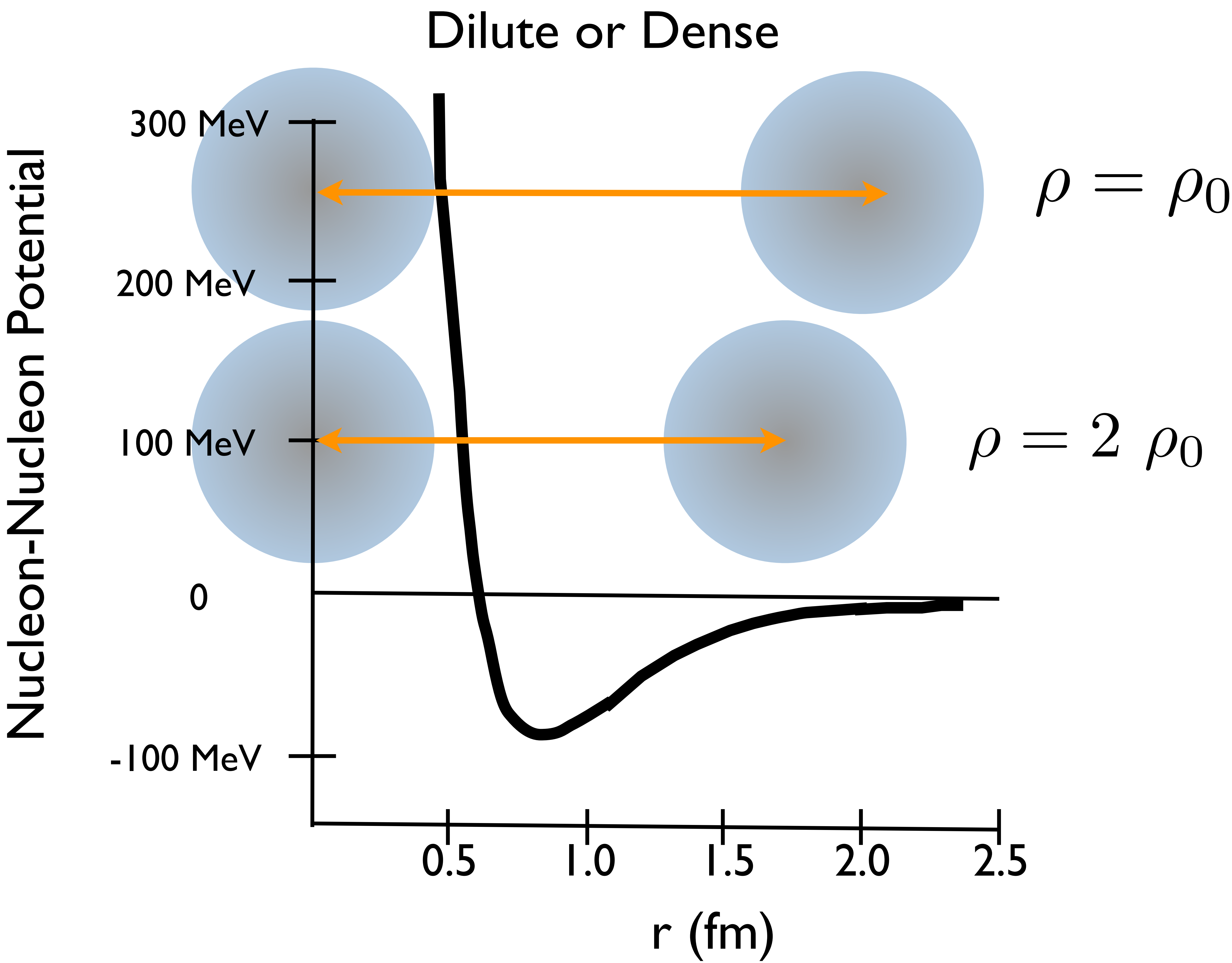
Summary & Outlook

- Three nucleon forces are key to to understanding the EOS for neutron stars and supernova.
- If small NS radii are confirmed, we need to a mechanism to stiffen the equation of state rapidly and must persist to high density.
- Properties of matter at densities accessible to nuclear many-body theory has wide ranging implications for astrophysics - mergers, supernovae, and nucleosynthesis.
- Thermal evolution of accreting neutron stars is providing new insights about thermal and transport properties of the crust - revealing its phase structure
- The core remains even more mysterious.

"So what does all this have to do with short-range correlations ? "

I do not know. As a first step it would be useful to ask if electron-nucleus scattering data can constrain the two-body potential at high momentum. Disentangling the probe dependent two-body current from the two-body nucleon-nucleon potential is model and resolution scale dependent.




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