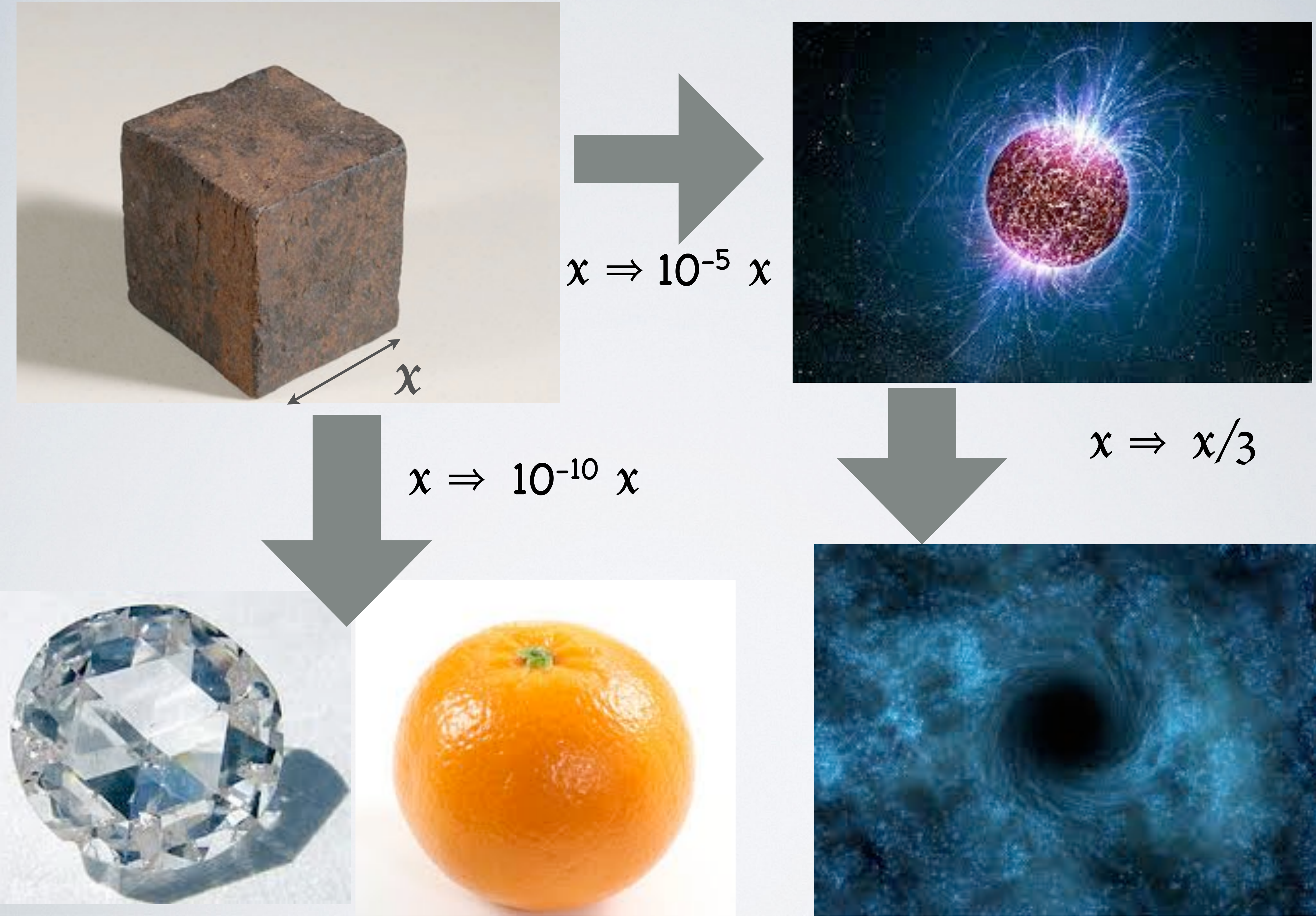
Lecture 2:

Dense Matter and the Astrophysics of Supernovae and Neutron Stars

Cold Compression

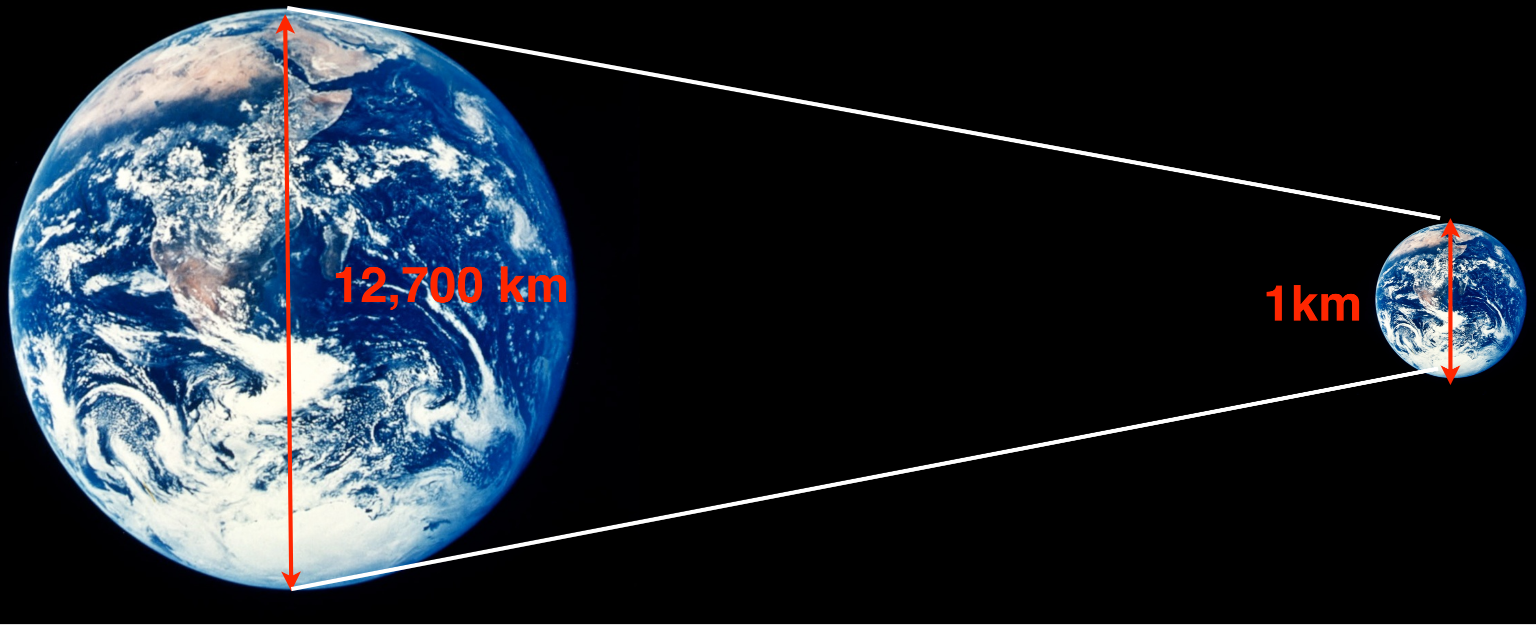


$x \Rightarrow 10^{-5}\ x$

$x \Rightarrow x/3$

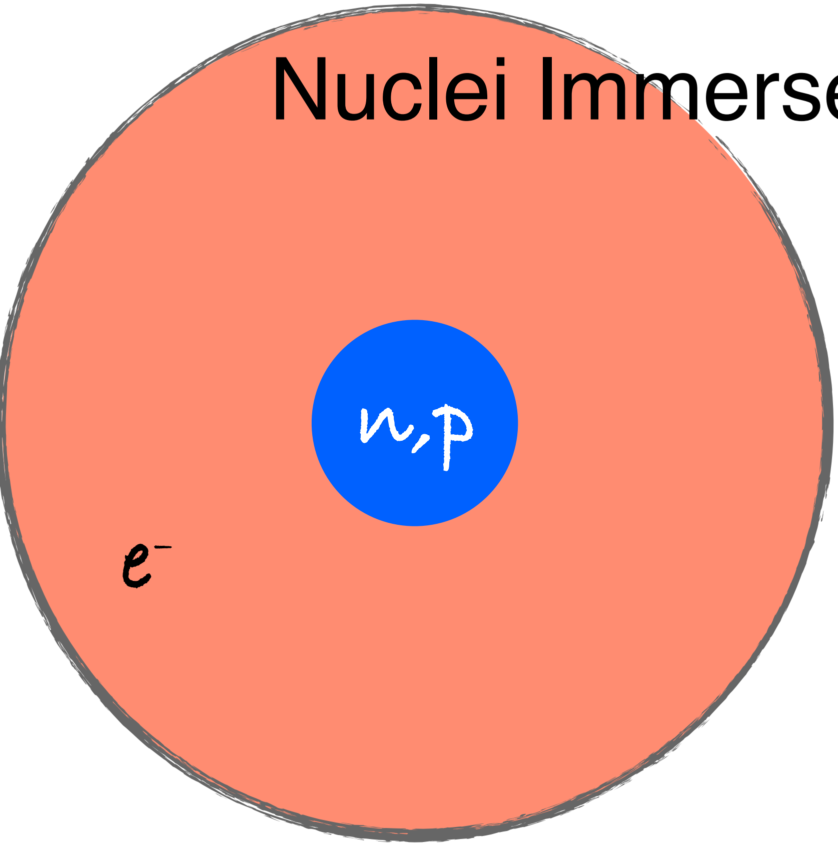
$x \Rightarrow 10^{-10}\ x$

Compression: Frustration and Liberation



Density	Energy	Phenomena
10^3 - 10^6 g/cm^3	Electron Chemical Pot. μ_e= 10 keV– MeV	Ionization
10^6 - 10^{11} g/cm^3	Electron Chemical Pot. μ_e= 1–25 MeV	Neutron-rich Nuclei
10^{11} - 10^{14} g/cm^3	Neutron Chemical Pot. μ_n= 1–30 MeV	Neutron-drip
10^{14} - 10^{15} g/cm^3	Neutron Chemical Pot. μ_n=30–1000 MeV	Nuclear matter Hyperons or Quarks ?

Nuclei Immersed in a dense electron gas



Beta Equilibrium:

$$e^- + p \rightarrow n + \nu_e, \quad n \rightarrow p + e^- + \bar{\nu}_e$$

$$\mu_n - \mu_p = \mu_e \simeq 4\ \alpha_{\rm sym}(1 - 2\ x_p)$$

$$x_p \simeq \frac{1}{2}\left(1 - \frac{\mu_e}{4\ \alpha_{\rm sym}}\right)\left(1 + \frac{\alpha_{\rm C}\ A^{2/3}}{4\ \alpha_{\rm sym}}\right)^{-1}$$

Neutron Fermi levels rise :

$$\mu_n \simeq -\alpha_{\rm bulk} + 2\alpha_{\rm sym}[(1 - 2x_p) - \frac{1}{2}(1 - 2x_p)^2]$$

Neutrons drip at : $x_p \simeq \frac{1}{2}\sqrt{1 - \frac{\alpha_{\rm bulk}}{\alpha_{\rm sym}}} \approx 0.34$

Table 1 Nuclides in the ground state of cold matter as a function of density, from Haensel & Pichon (21)

Element	Z	N	Z/A	$\rho_{\max}^{a}$ (g cm^{-3})	μ_e^{b} (MeV)	$\Delta\rho/\rho^{c}$ (%)
Using experimental nuclear masses						
^{56}Fe	26	30	0.4643	$7.96\ 10^{6}$	0.95	2.9
^{62}Ni	28	34	0.4516	$2.71\ 10^{8}$	2.61	3.1
^{64}Ni	28	36	0.4375	$1.30\ 10^{9}$	4.31	3.1
^{66}Ni	28	38	0.4242	$1.48\ 10^{9}$	4.45	2.0
^{86}Kr	36	50	0.4186	$3.12\ 10^{9}$	5.66	3.3
^{84}Se	34	50	0.4048	$1.10\ 10^{10}$	8.49	3.6
^{82}Ge	32	50	0.3902	$2.80\ 10^{10}$	11.44	3.9
^{80}Zn	30	50	0.3750	$5.44\ 10^{10}$	14.08	4.3
^{78}Ni	28	50	0.3590	$9.64\ 10^{10}$	16.78	4.0
From the mass formula of Möller (1992), unpublished results						
^{126}Ru	44	82	0.3492	$1.29\ 10^{11}$	18.34	3.0
^{124}Mo	42	82	0.3387	$1.88\ 10^{11}$	20.56	3.2
^{122}Zr	40	82	0.3279	$2.67\ 10^{11}$	22.86	3.4
^{120}Sr	38	82	0.3167	$3.79\ 10^{11}$	25.38	3.6
^{118}Kr	36	82	0.3051	$(4.33\ 10^{11})^{d}$	(26.19)	

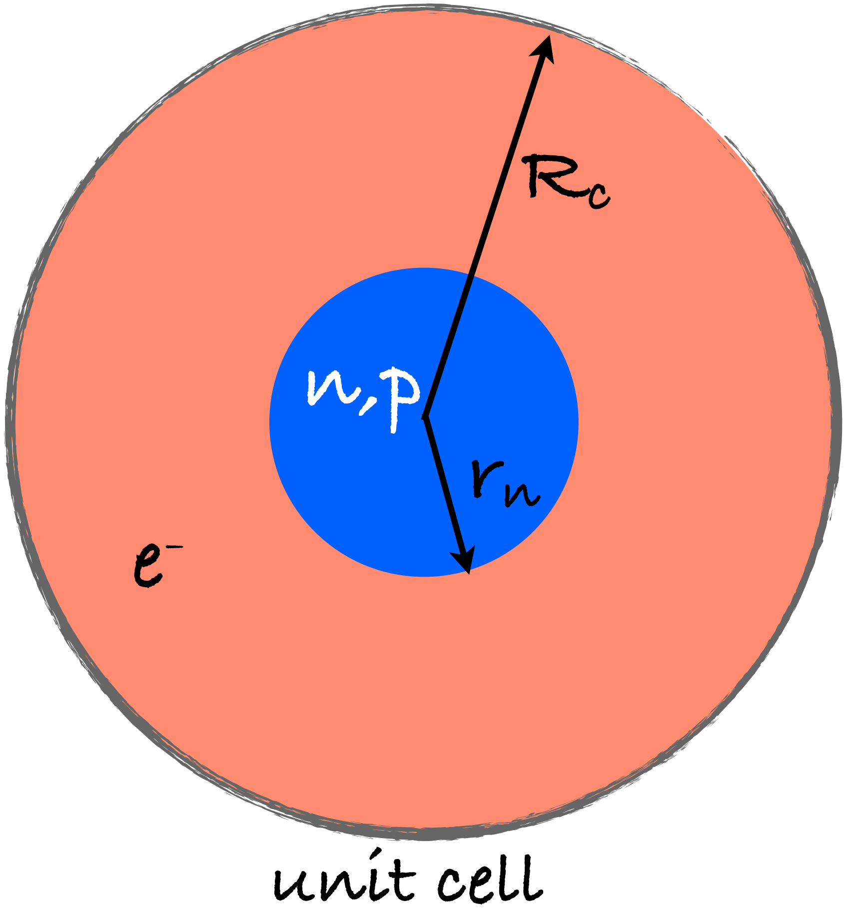
[a] $\rho_{\max}$ is the maximum density at which the nuclide is present.

[b] μ_e is the electron chemical potential (including electron rest mass) at that density.

[c] $\Delta\rho/\rho$ is the fractional increase in the mass density in the transition to the next nuclide.

[d] The lines with $\rho_{\max}$ in parentheses correspond to the neutron drip point.

Electron-nucleus Interaction and Lattice Energy



To good approximation electron charge distribution is uniform.

$$E_{\rm C} = \frac{3}{5}\frac{Z^2\alpha}{r}\left(1-\frac{3}{2}\frac{r}{R}+\frac{1}{2}\frac{r^3}{R^3}\right)$$

Nucleus becomes unstable to deformations when

$$E_{\rm C}^0 = \frac{3}{5}\frac{Z^2\alpha}{r} > 2\ E_S$$

or $\left(1-\frac{3}{2}\frac{r}{R}+\frac{1}{2}\frac{r^3}{R^3}\right) < \frac{1}{4}$

Bohr-Wheeler (1938)

Prblm 1.5 : Show that the Coulomb energy per unit cell is given by the above expression.

Non-spherical nuclei or Pasta

For spherical nuclei $$E_{\mathrm{C}} = \frac{3}{5}\frac{Z^2\alpha}{r}\left(1 - \frac{3}{2}\frac{r}{R} + \frac{1}{2}\frac{r^3}{R^3}\right)$$

For "d" dimensional structures:

$$\boxed{\frac{E_C}{V} = 2\pi\ \alpha\ n_p^2\ r^2\ u\ f_d(u)}$$

$$\boxed{\frac{E_S}{V} = \frac{d\ u\ \sigma}{r}}$$

where:

$$f_3(u) = \frac{1}{5}(2 - 3u^{1/3} + u) \simeq \frac{2}{5},$$

$$f_2(u) = \frac{1}{4}\left(\ln\frac{1}{u} - 1 + u\right) \simeq \frac{1}{4}\ln\frac{1}{eu}$$

$$f_1(u) = \frac{1}{3}\left(\frac{1}{u} - 2 + u\right) \simeq \frac{1}{3u}.$$

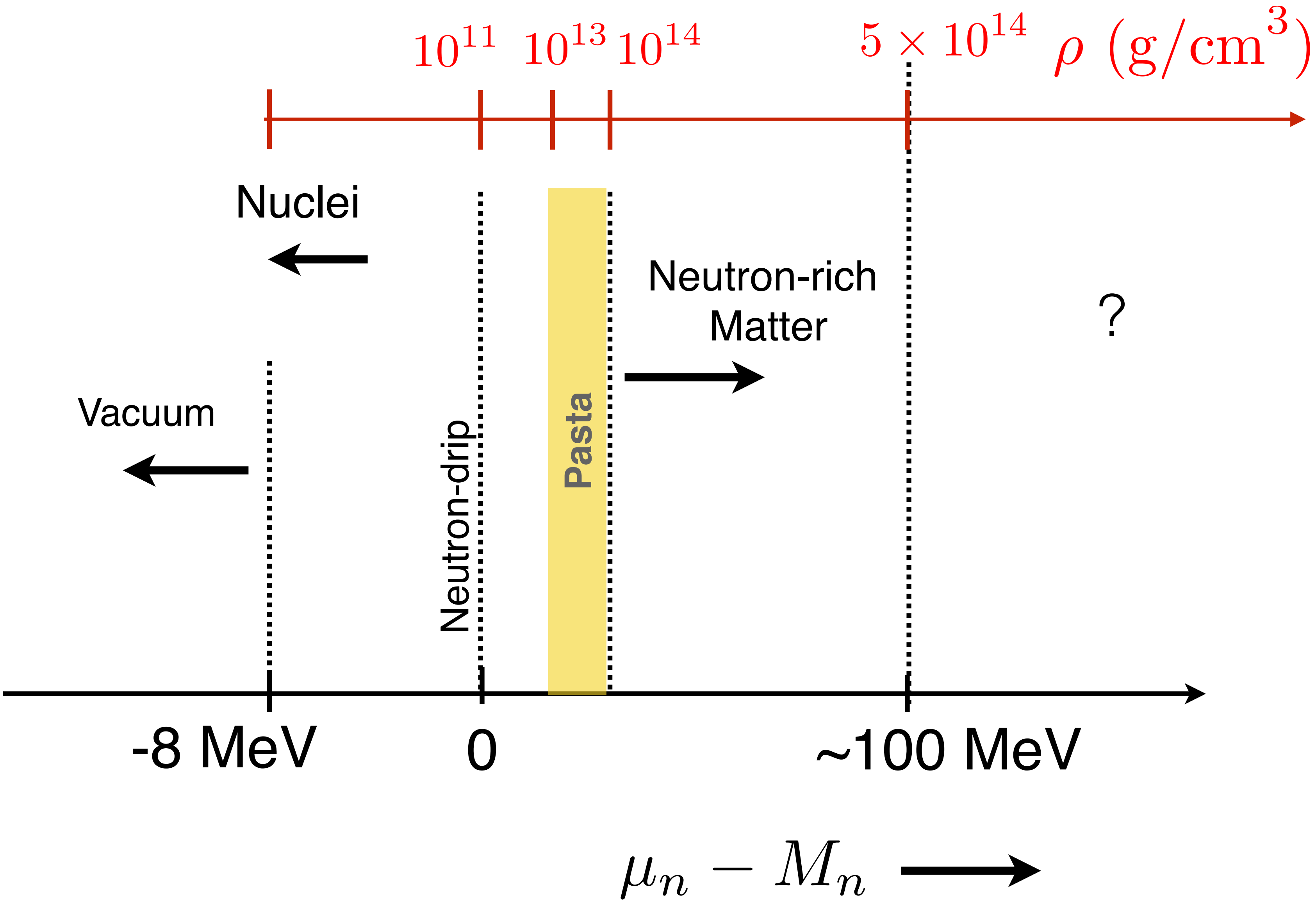
For small surface tension pasta is favored.

Baym, Bethe, Pethick (1971)

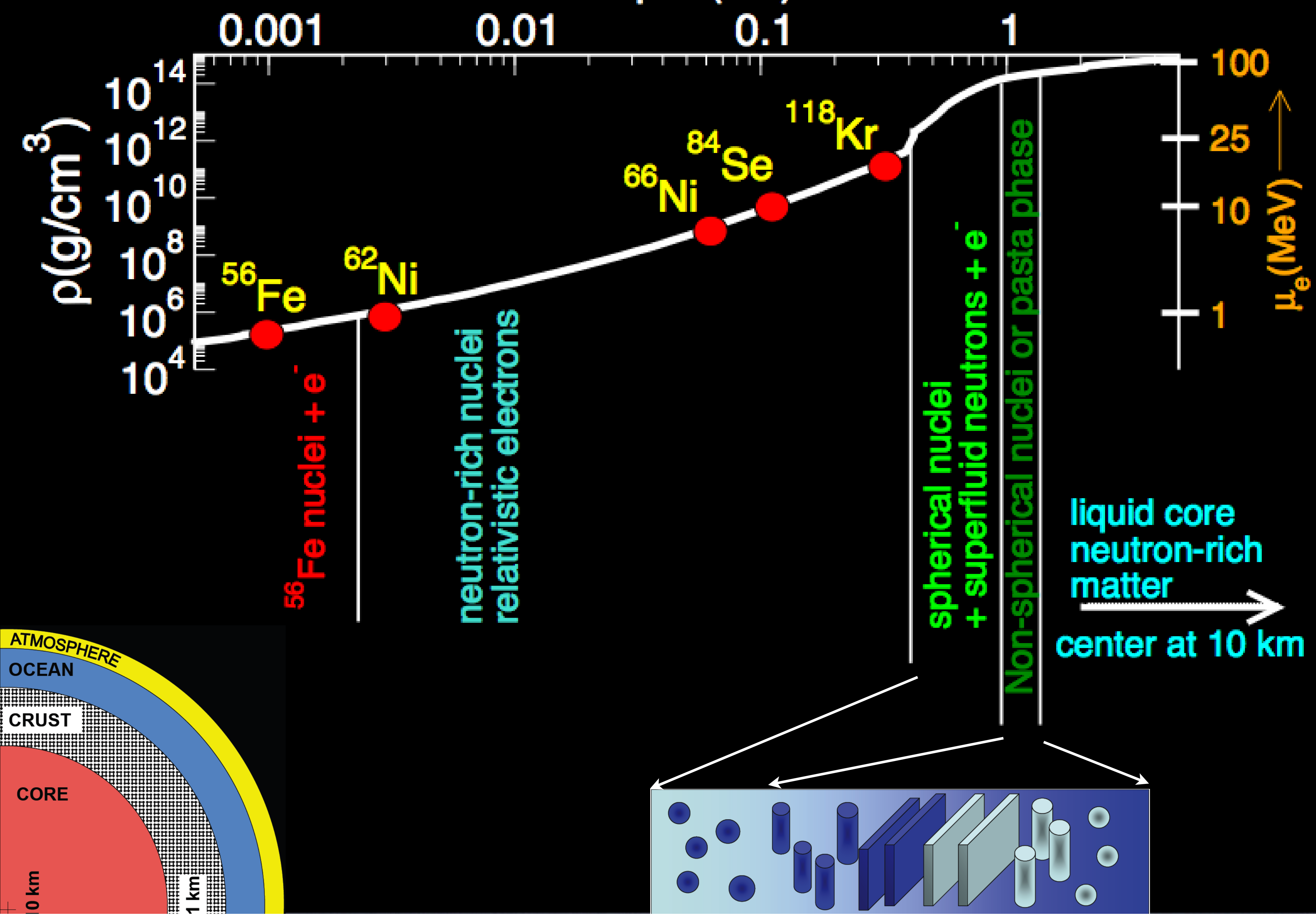
Bulk Matter at T=0

Weak Equilibrium : $\mu_n = \mu_p + \mu_e$

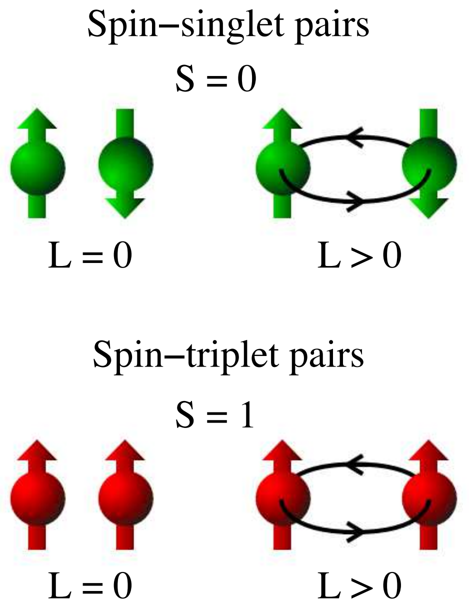
+ Charge neutrality : $n_e = n_p$

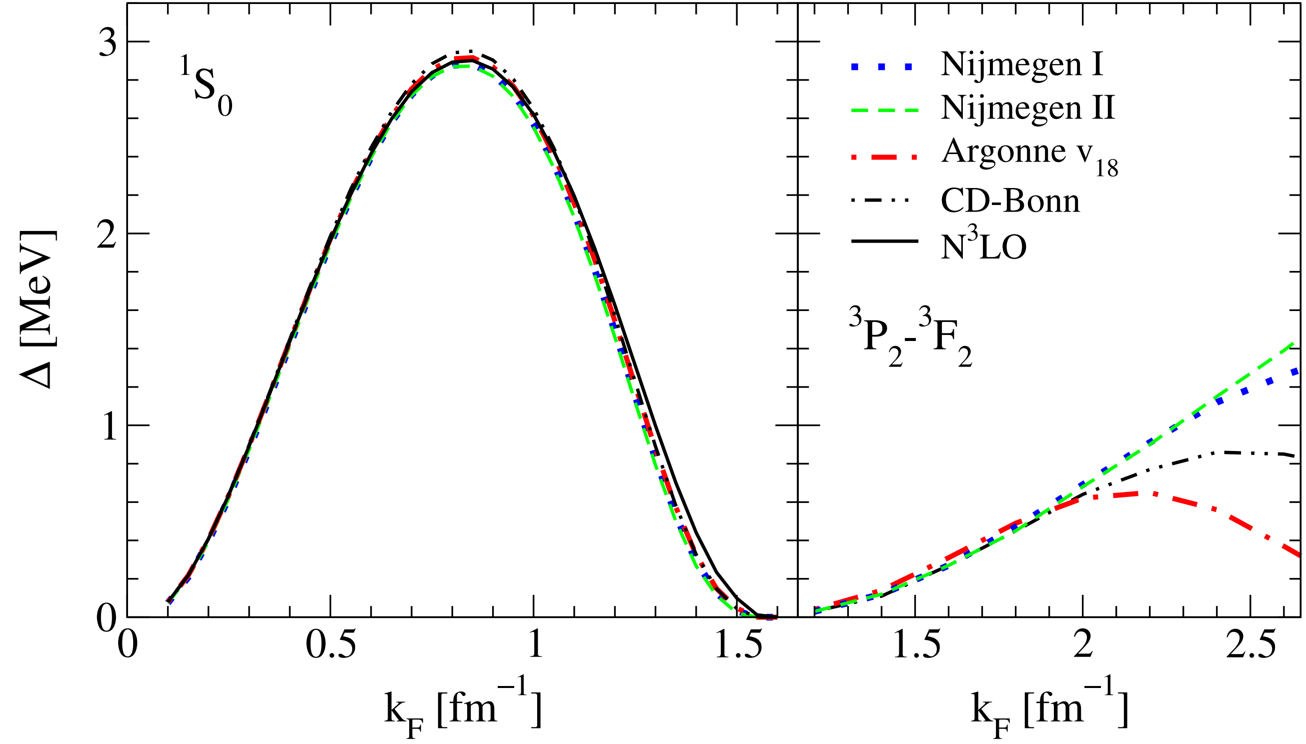


Neutron Star in Depth (km)



Nuclear Pairing



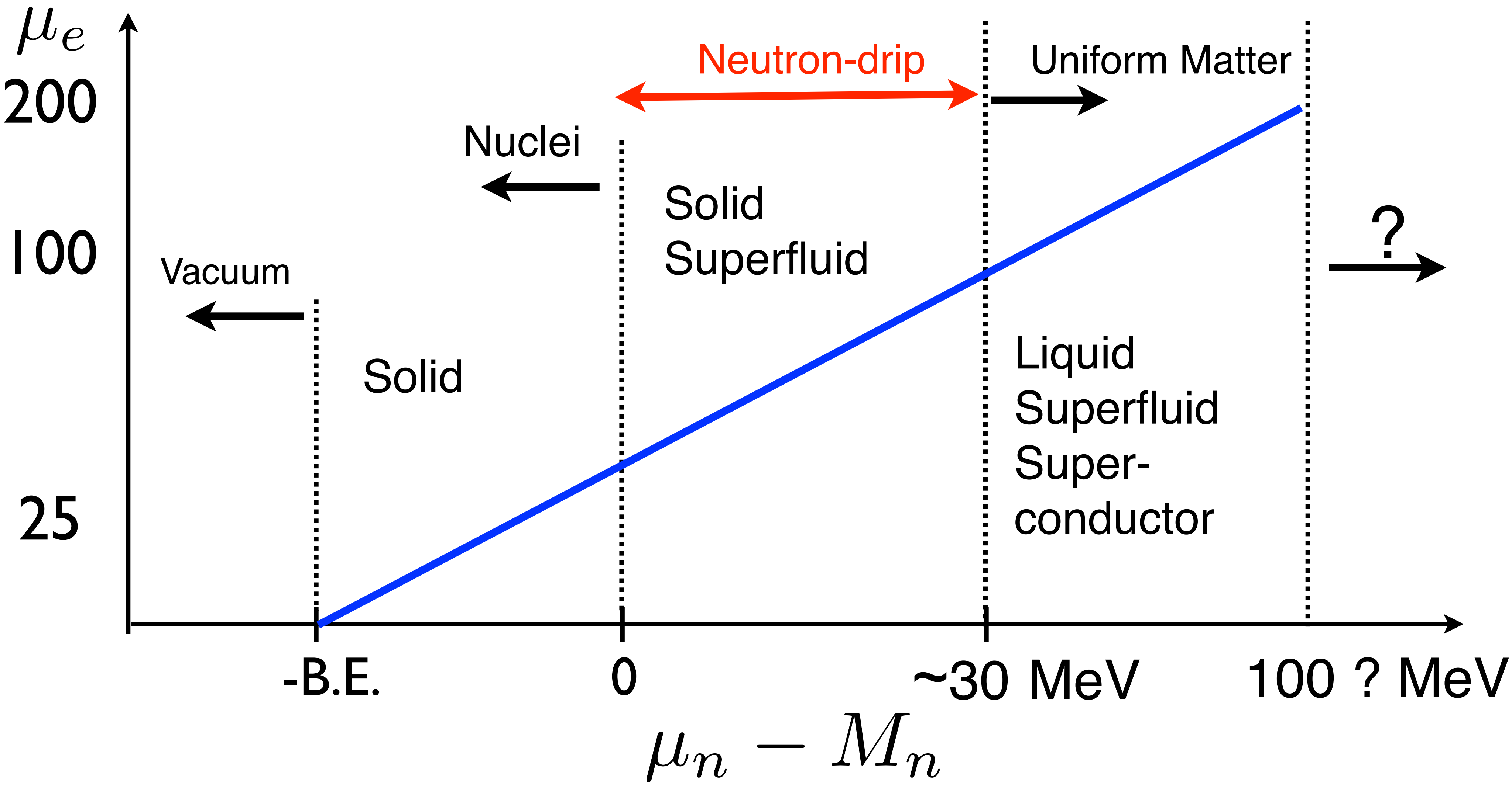

Gezerlis, Pethick, Schwenk (2016)

S-wave interactions are attractive at low density, and is repulsive at high density.

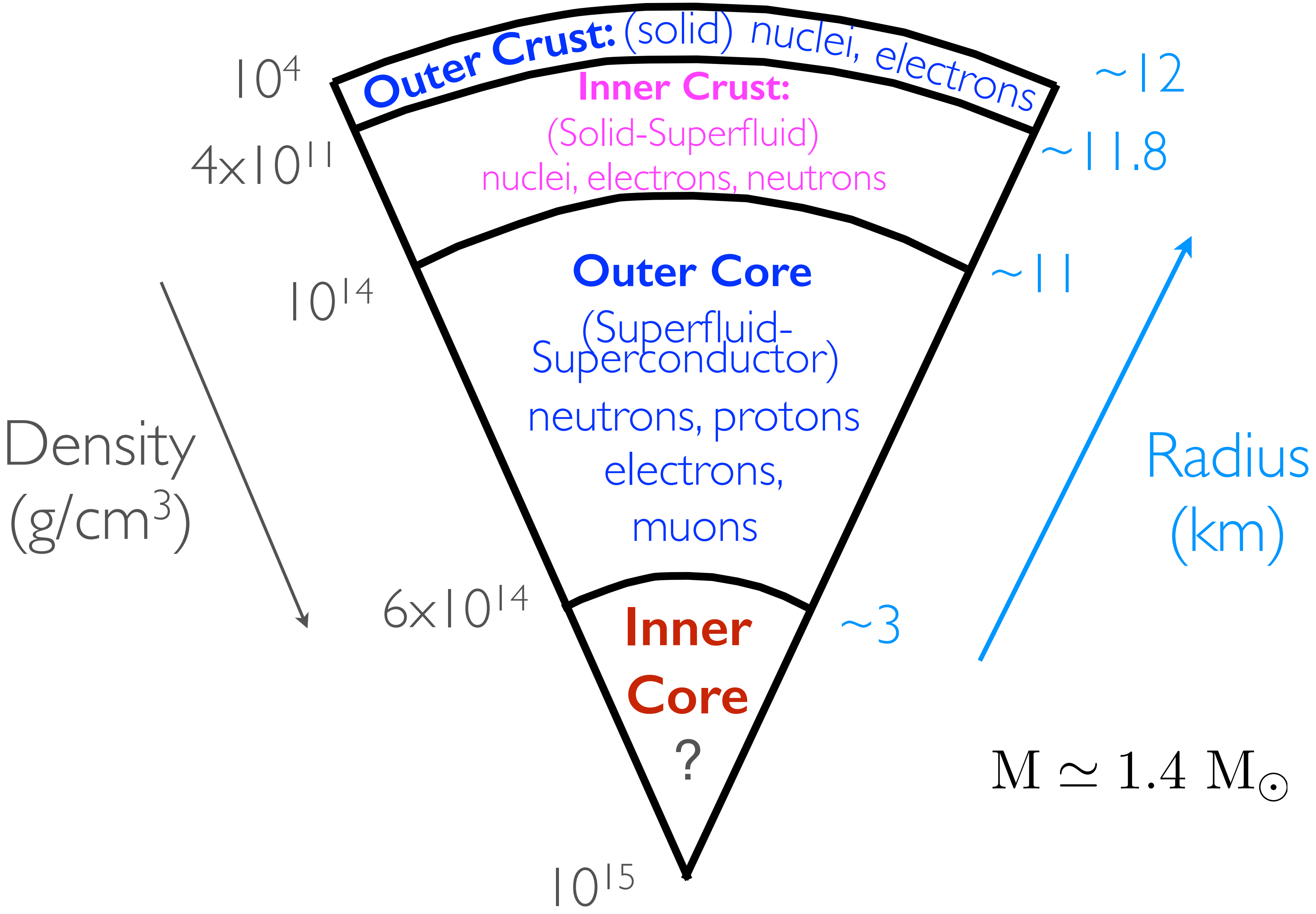
P-wave interaction in spin 1 channel is attractive at high density.

P-wave gap is quite uncertain and likely to be small.

Phase Structure at T=0



Neutron Star Interiors



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

4×10^{11}

10^{14}

6×10^{14}

10^{15}

Radius (km)

~12

~11.8

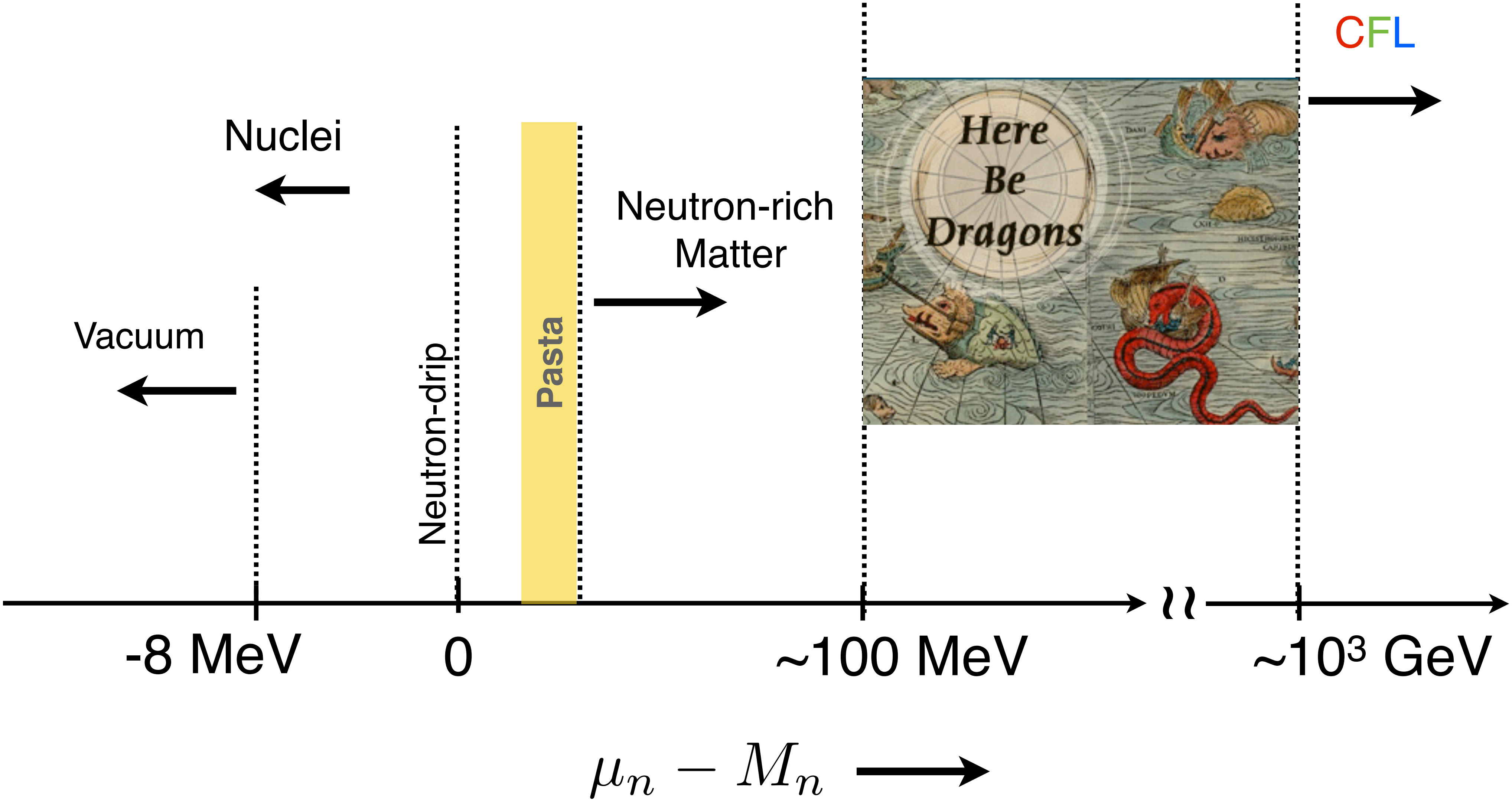
~11

~3

$$M \simeq 1.4\ M_\odot$$

Phases at High Density

- Hyperons
- Quark matter


Nuclei

Vacuum

Neutron-drip

Pasta

Neutron-rich Matter

CFL

-8 MeV

0

~100 MeV

~10^3 GeV

$\mu_n - M_n \longrightarrow$

Hyperons

At high density hyperons may appear because:

$\mu_n > M_\Lambda$
$\mu_n + \mu_e > M_{\Sigma^-}$

Energy to create a hyperon in dense matter is

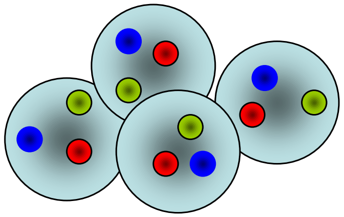
$$e_B(k) = M_B + \frac{k^2}{2M_B} + U_B(k)$$

Strong repulsive forces between nucleon-hyperon can disfavor their appearance at high density.

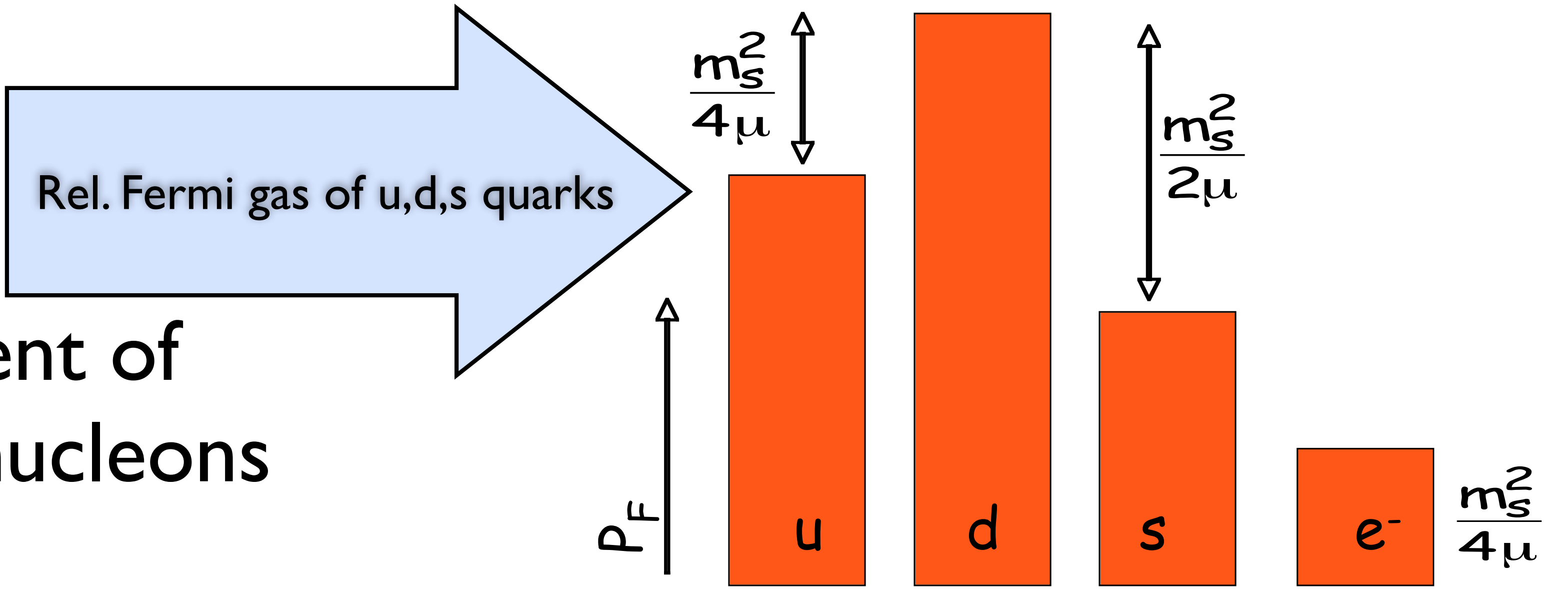
The hyperon-nucleon and hyperon-nucleon-nucleon interactions are not well constrained to draw definite conclusions.

If hyperons appear they will reduce the pressure of dense matter - we shall discuss its implications for neutron star masses.

Quarks Matter at Extreme Density and T=0



De-confinement of quarks from nucleons

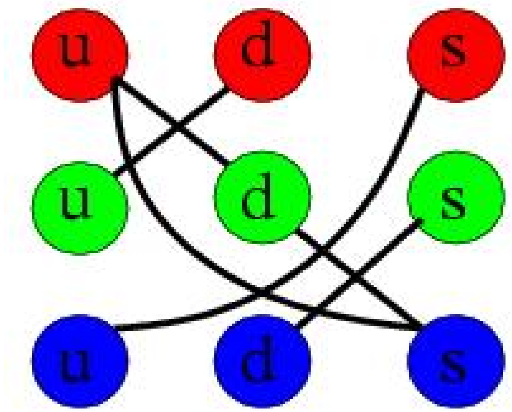


Rel. Fermi gas of u,d,s quarks

Interactions lead to pairing and color superconductivity

Strongest attraction in color-antisymmetric channel:
Color-Flavor-Locking

$$\Delta \gg \frac{m_s^2}{4\mu}$$



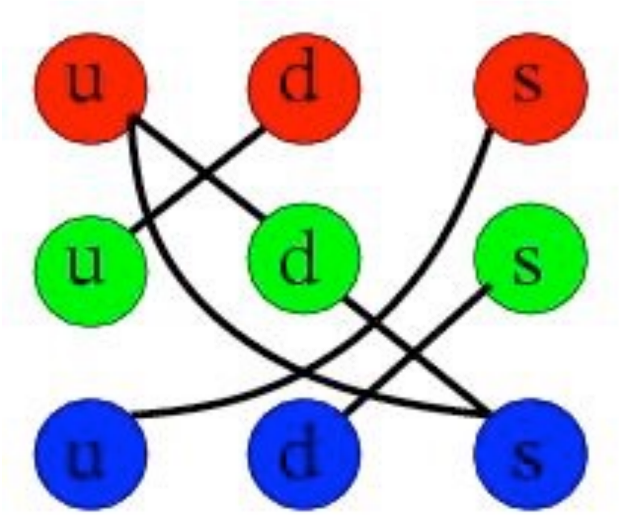
$$n_u = n_d = n_s$$

Alford, Rajagopal, Wilczek (1999)

Color-Flavor Locked Phase

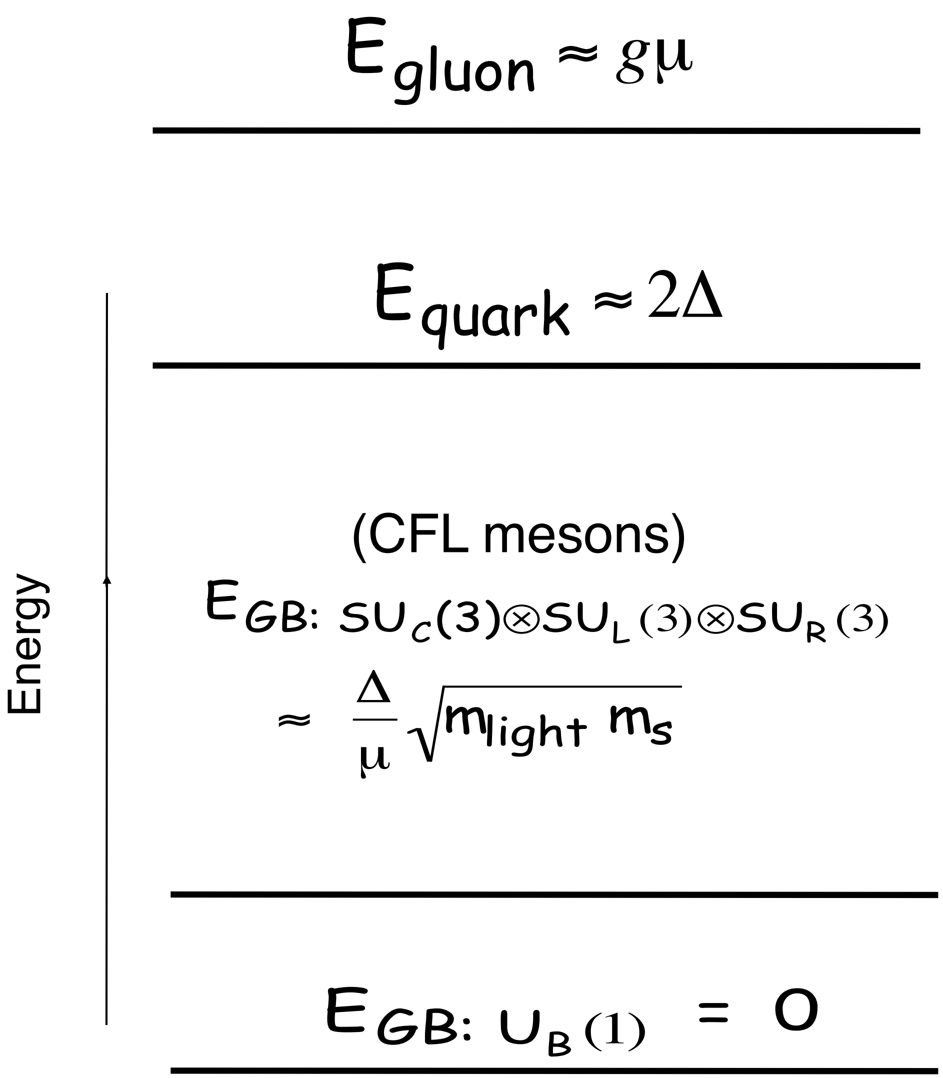
BCS pairing of all 9 quarks:

$\Delta \approx 100$ MeV !



$$SU(3)_{color} \otimes SU(3)_L \otimes SU(3)_R \otimes U(1)_B$$
$$\Downarrow$$
$$SU(3)_{color+L+R} \otimes Z_2$$

Color superconductor and transparent insulator.



$E_{gluon} \approx g\mu$

$E_{quark} \approx 2\Delta$

(CFL mesons)

$E_{GB:\ SU_C(3)\otimes SU_L(3)\otimes SU_R(3)}$

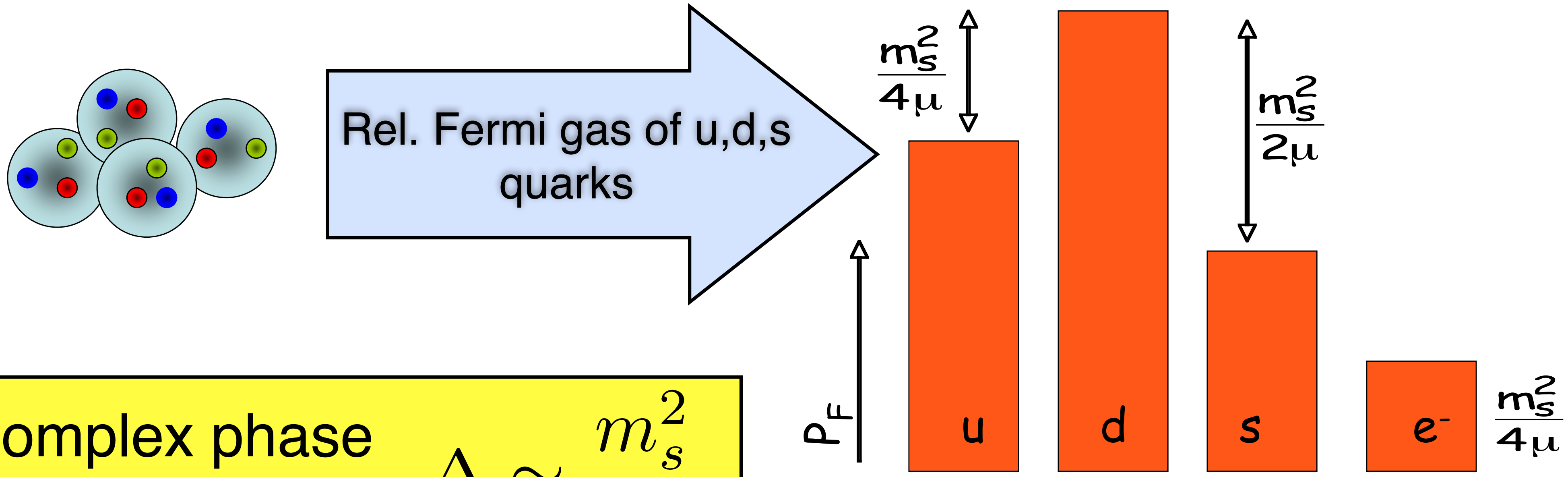
$$\approx \frac{\Delta}{\mu}\sqrt{m_{light}\, m_s}$$

$E_{GB:\ U_B(1)} = 0$

Excitation Spectrum

Alford, Rajagopal & Wilczek, (1999)

Quark Matter in Neutron Stars



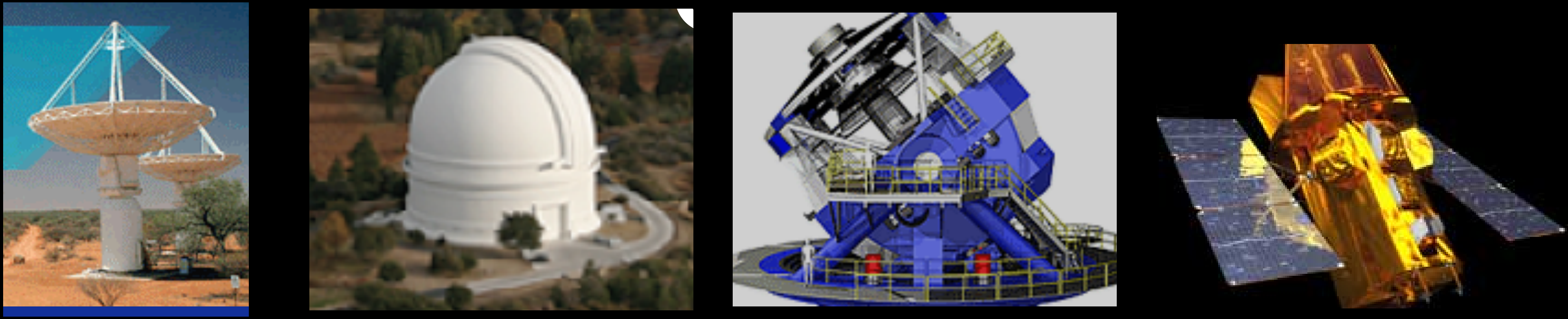
Rel. Fermi gas of u,d,s quarks

Complex phase structure when $\Delta \simeq \frac{m_s^2}{4\mu}$

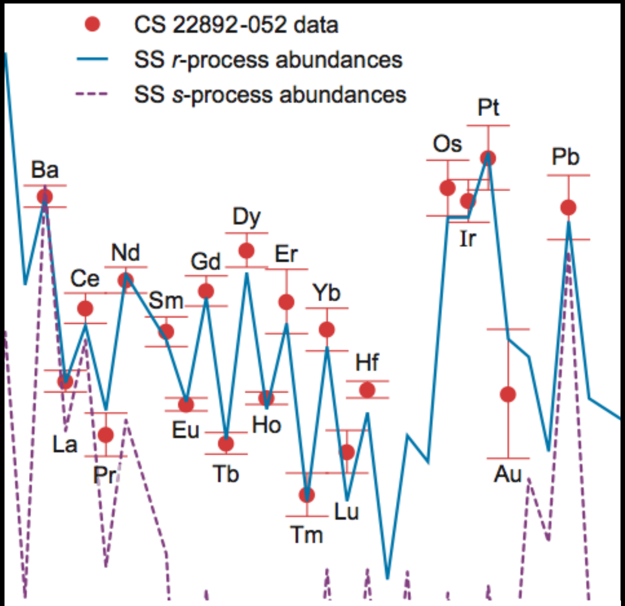
- Competition between chiral and di-quark condensation.
- Strong correlations and Fermi liquid effects.
- Need to rely on models.

Rich phase diagram but difficult to the predict ground state with current techniques.

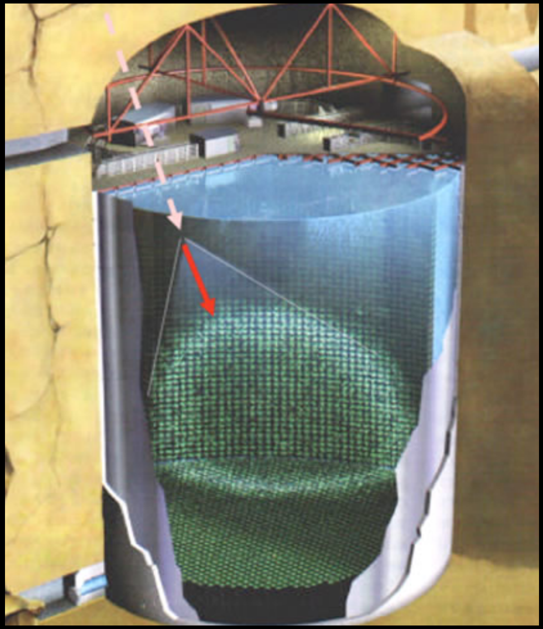
(Multi-)Messengers



Photons



Abundances

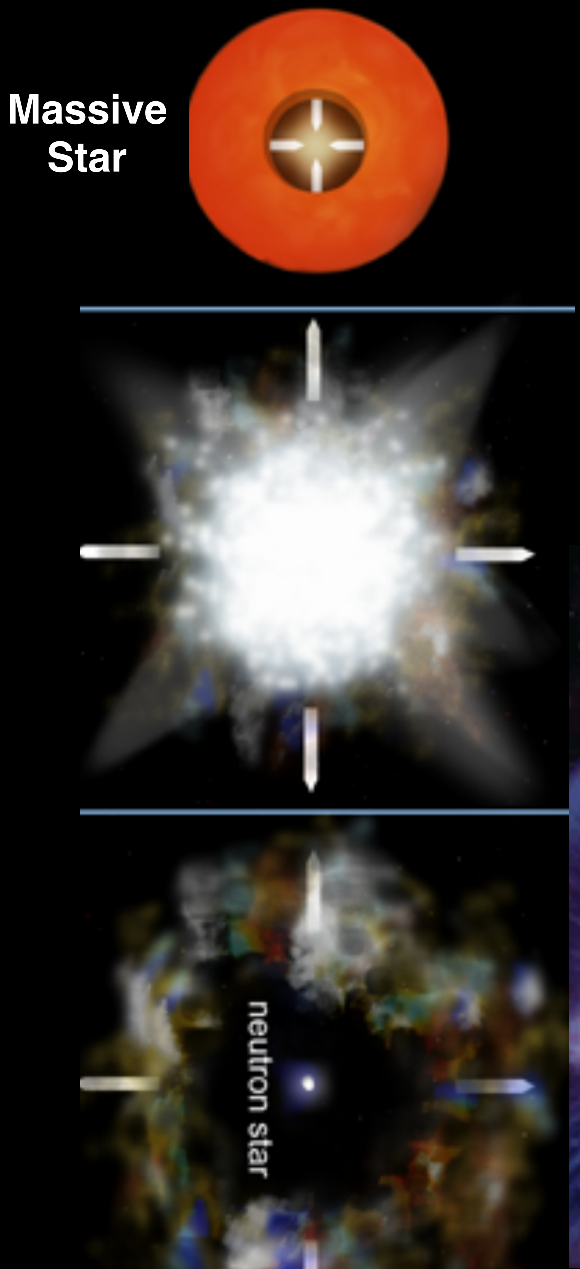


Neutrinos

Gravitational Waves

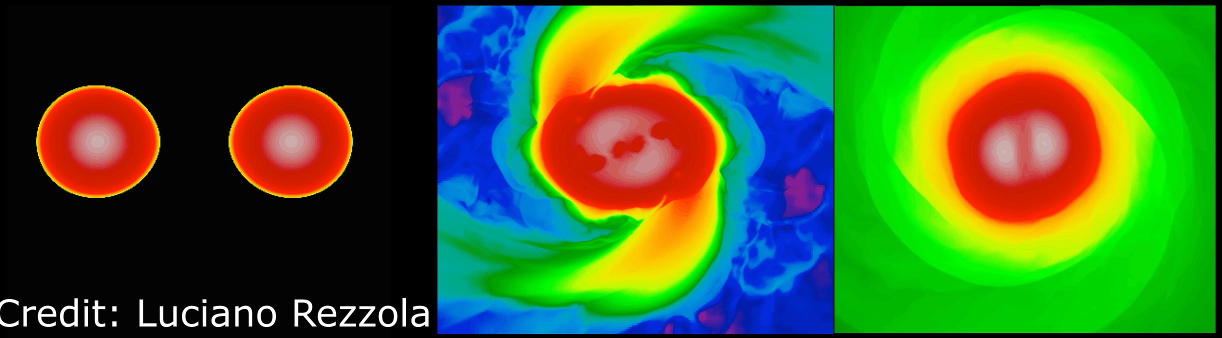
Neutron Stars: Bona fide Multi-messenger Sources

Supernova



Credit: NASA/CXC/S Lee

Binary Neutron Star Mergers

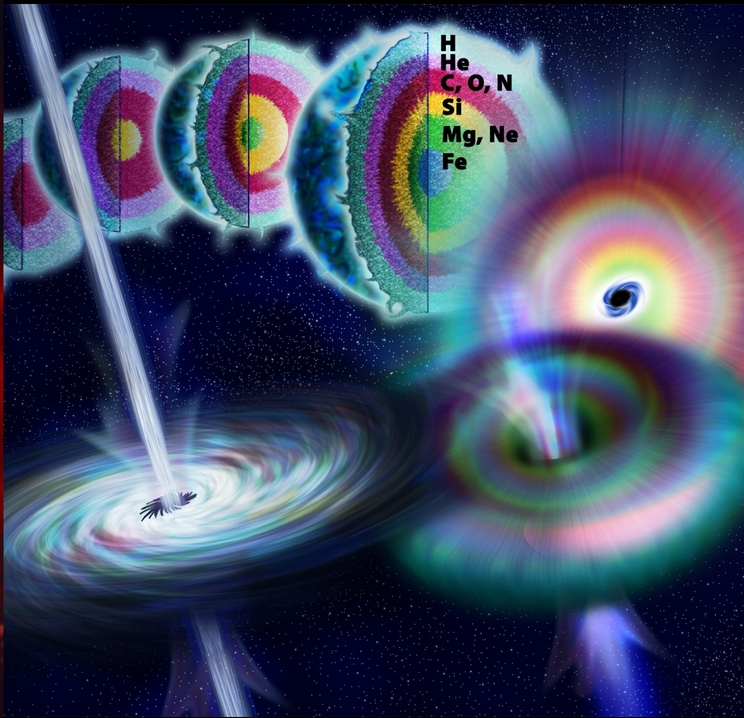


Credit: Luciano Rezzola

Accreting Neutron Stars

Credit: David Hardy & PPARC

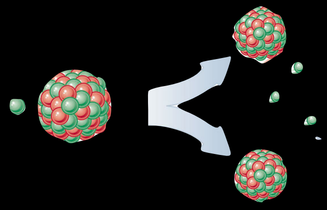
Gamma-Ray Bursts

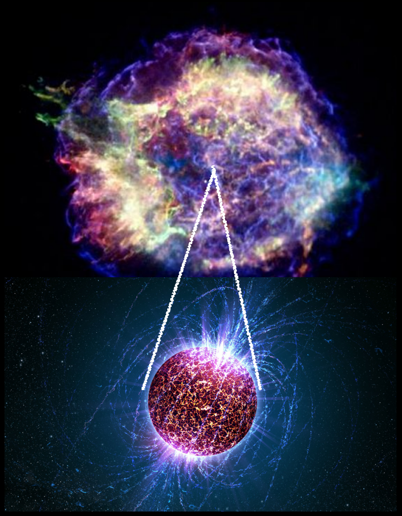


Credit: Nicolle Rager Fuller/NSF

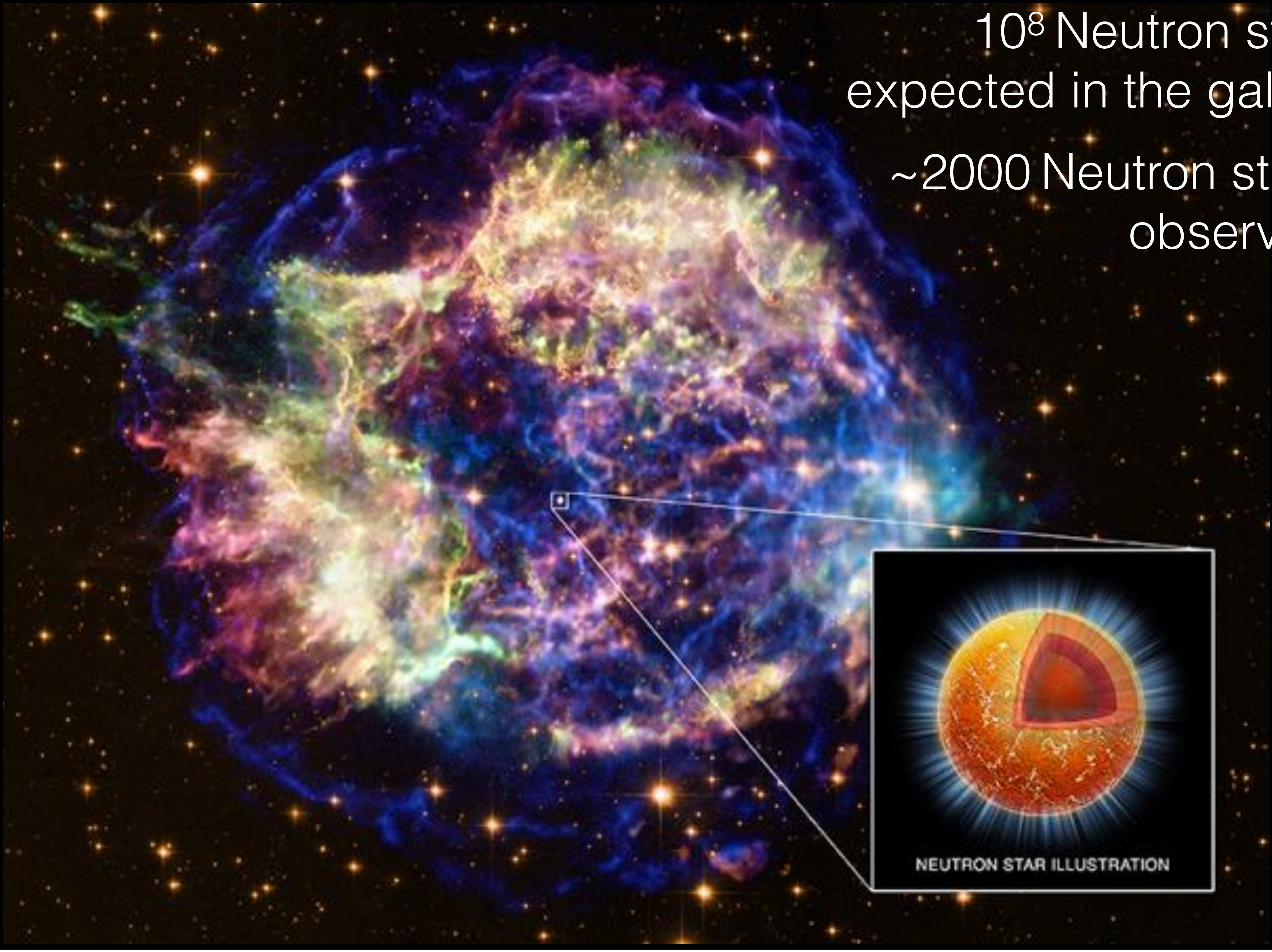
Some Big Questions

1. What are the nuclear and neutrino processes that shape the cosmos ?
2. How do supernovae explode ?
3. What should we expect from NS mergers ?
4. Where and how are the heavy elements synthesized ?
5. Are there new states of matter inside neutron stars ?
6. Can we interpret multi-messenger signals to extract fundamental physics ?





Stellar Evolution, Supernova & Neutron Stars

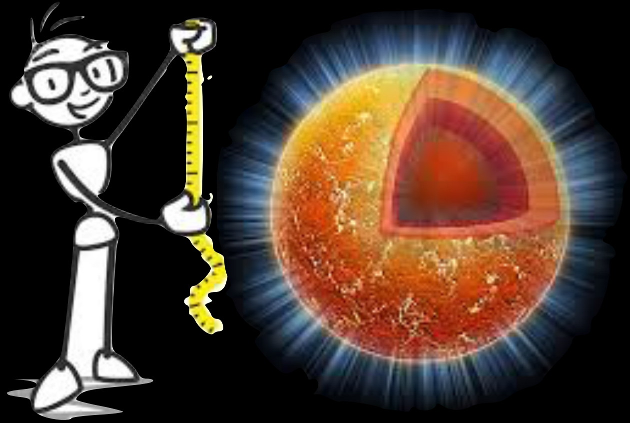


10^8 Neutron stars expected in the galaxy

~2000 Neutron stars observed

Measuring Neutron Stars

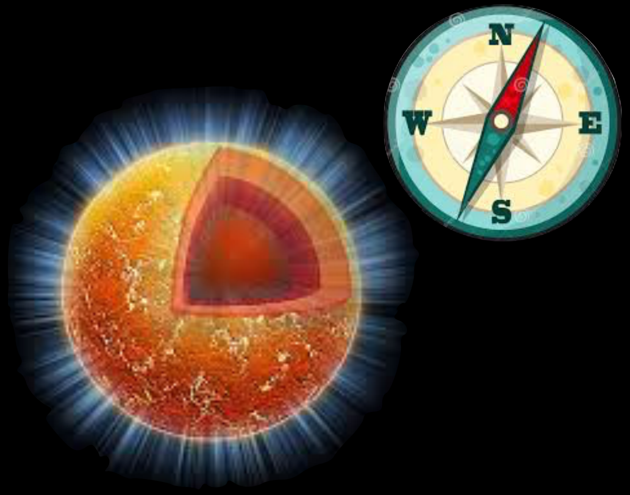
Thermal Evolution



Radius

Mass

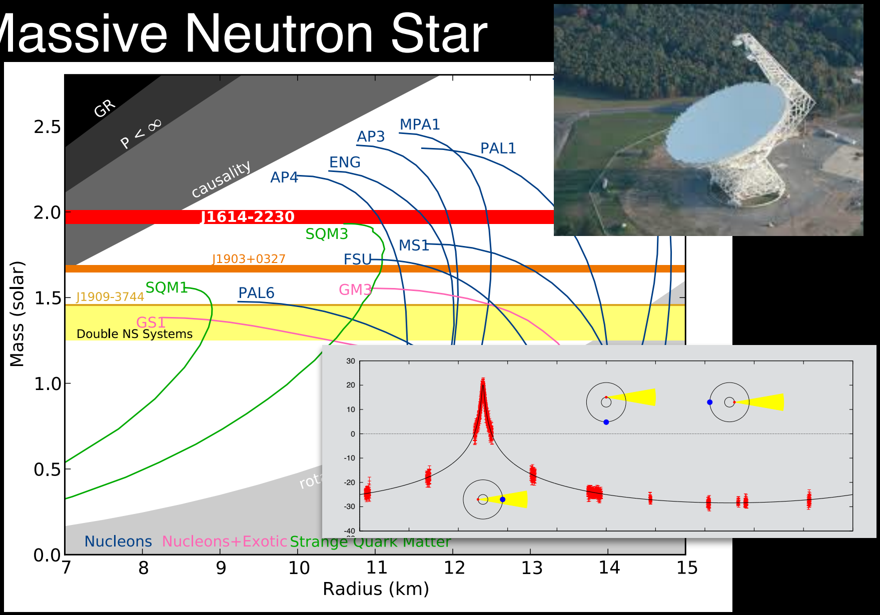
Seismology



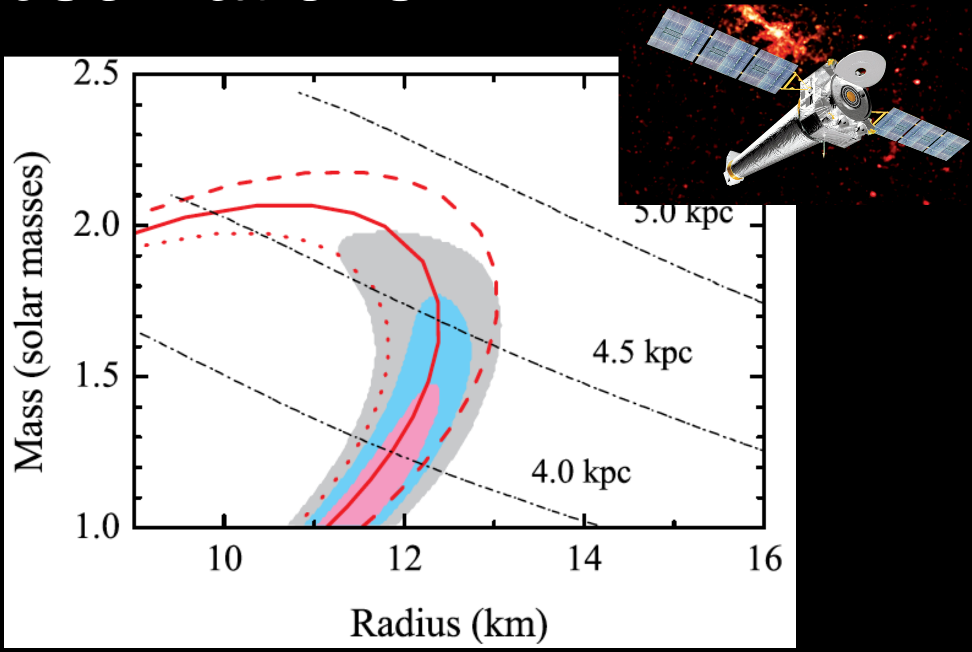
Magnetic Field Evolution

Some Recent Observations

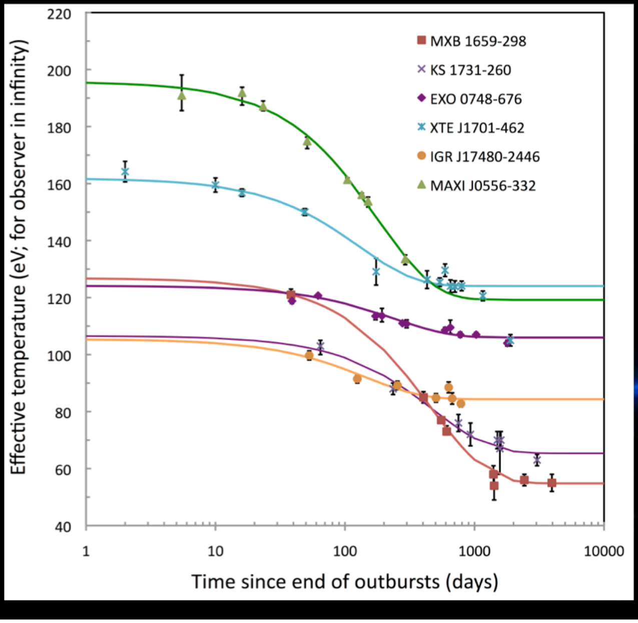
Massive Neutron Star



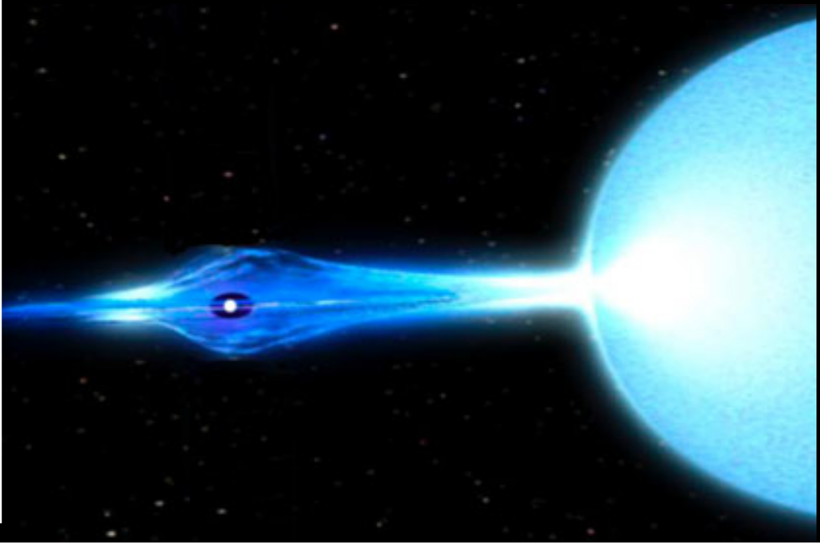
2 Solar Mass NS measured using Shapiro-delay. Demorest et al. (2010)



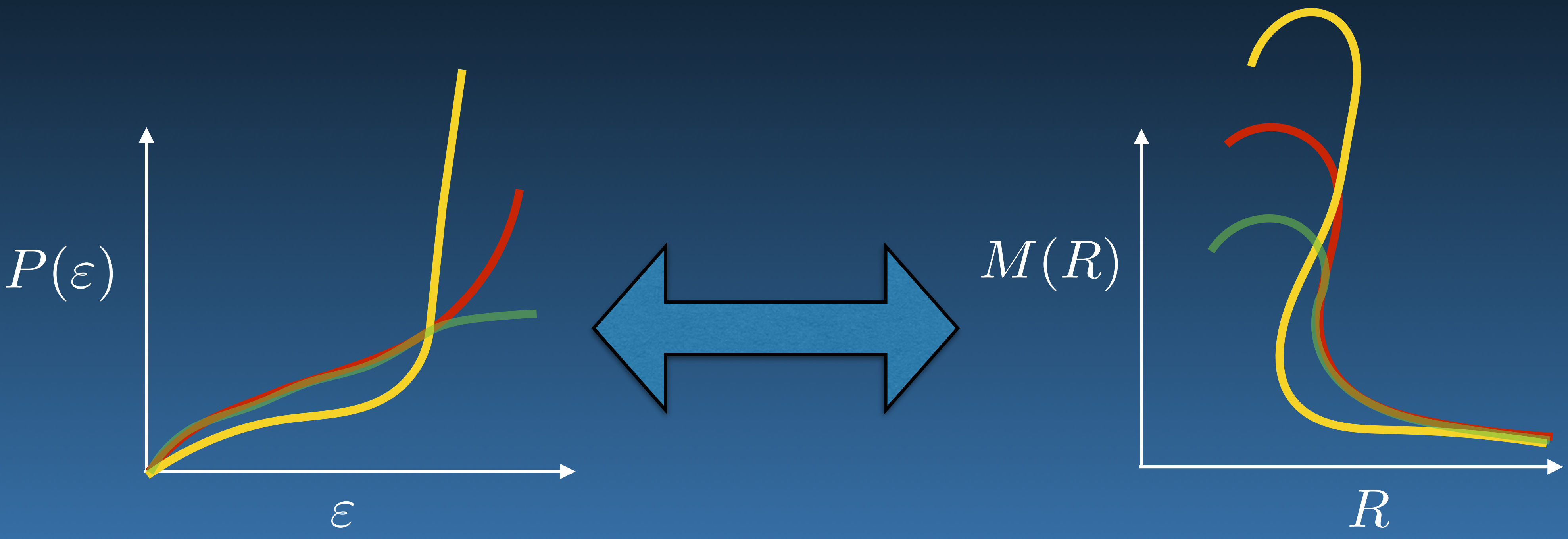
Modeling observed thermal surface emission suggests radii in the range 10-13 km. Poutanen et al. (2015)



Cooling Accreting Neutron Stars



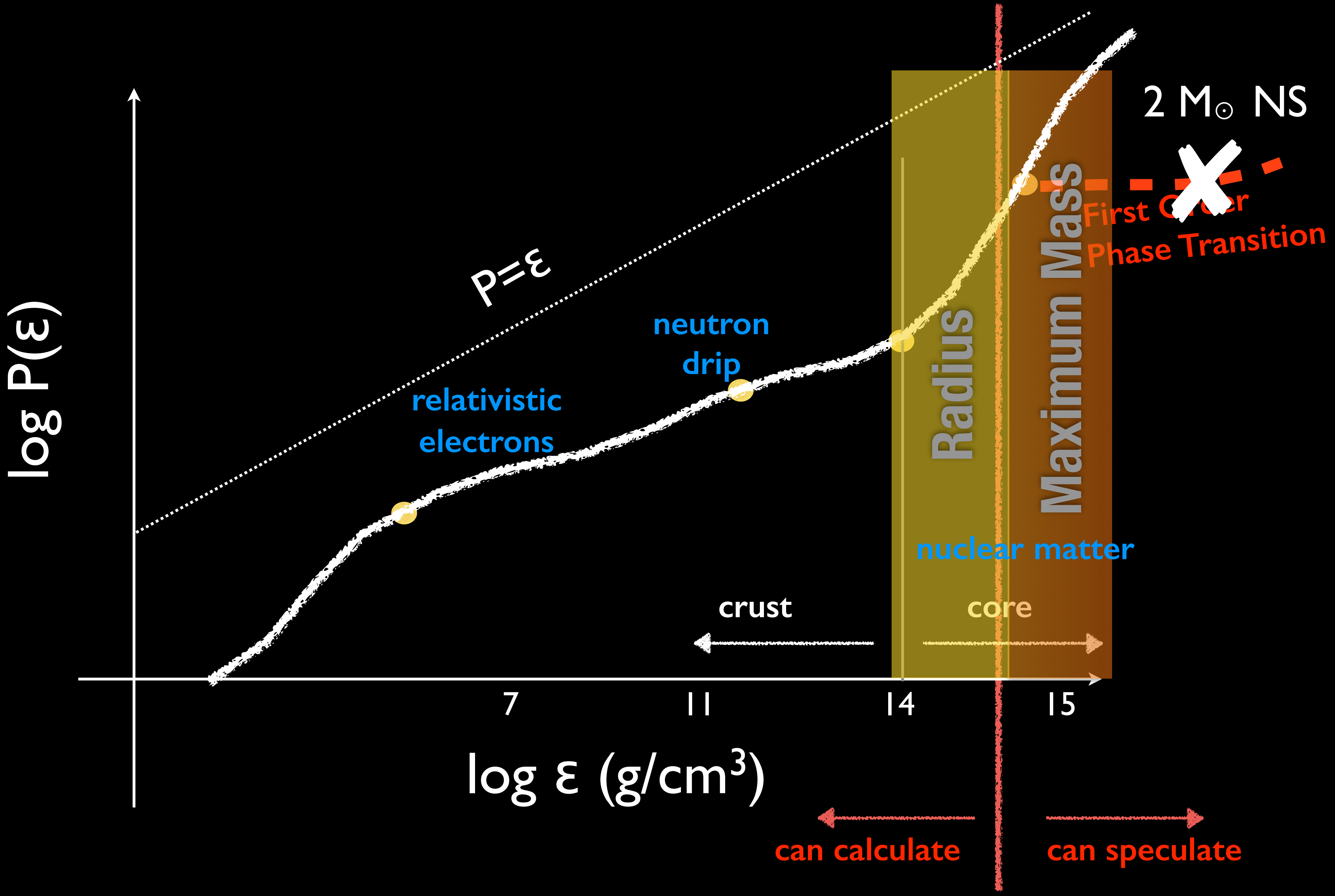
Equation of State and Neutron Star Structure



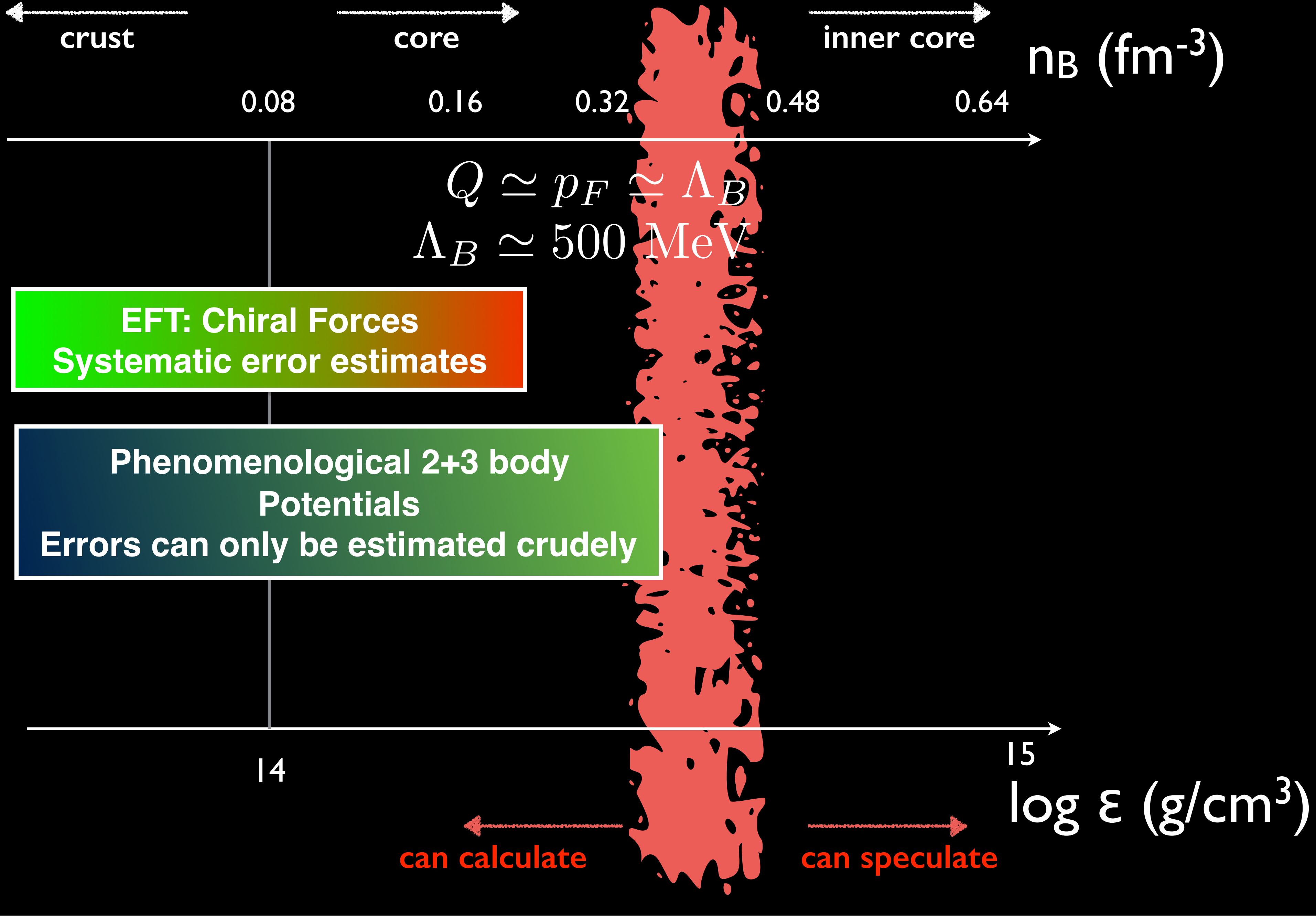
$$P(\varepsilon) + \text{Gen.Rel.} = M(R)$$

Small radius and large maximum mass implies a rapid transition from low pressure to high pressure with density.

Pressure v/s Energy Density (EoS)



EFT and Phenomenological Models



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

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

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

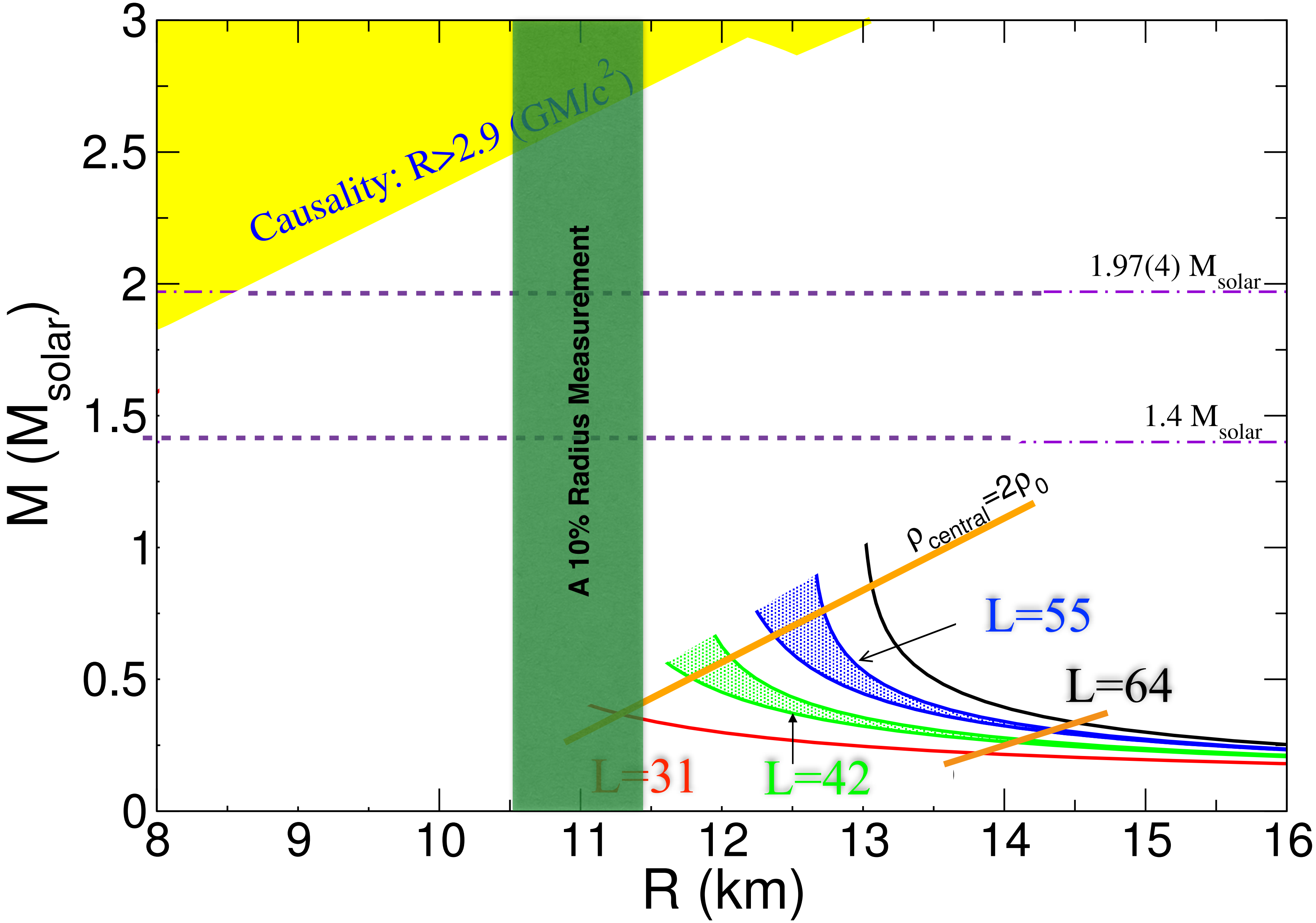
(Parameterization suggested by Gandolfi, 2009)

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

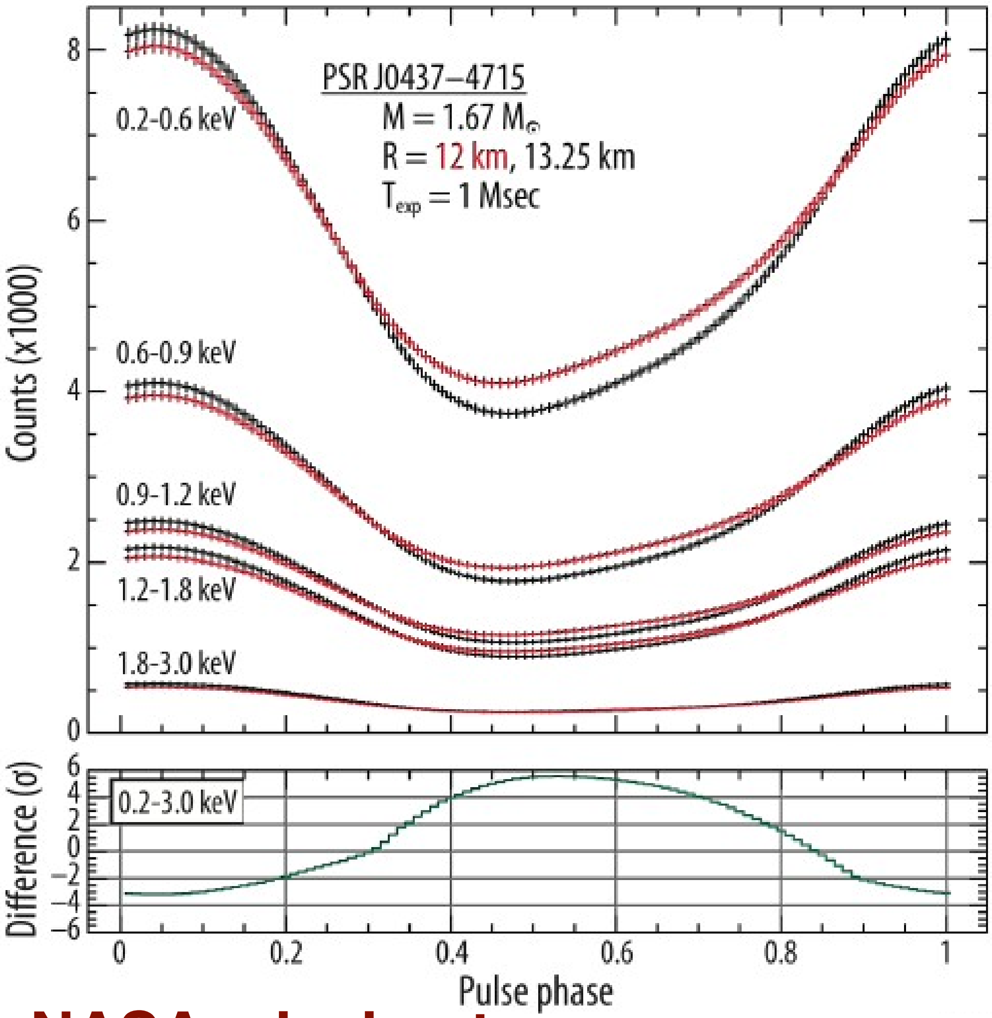
$b = 4 \pm 2 \text{ MeV} \quad \beta = 2.3 \pm 0.3$ → 2 & 3-body interactions

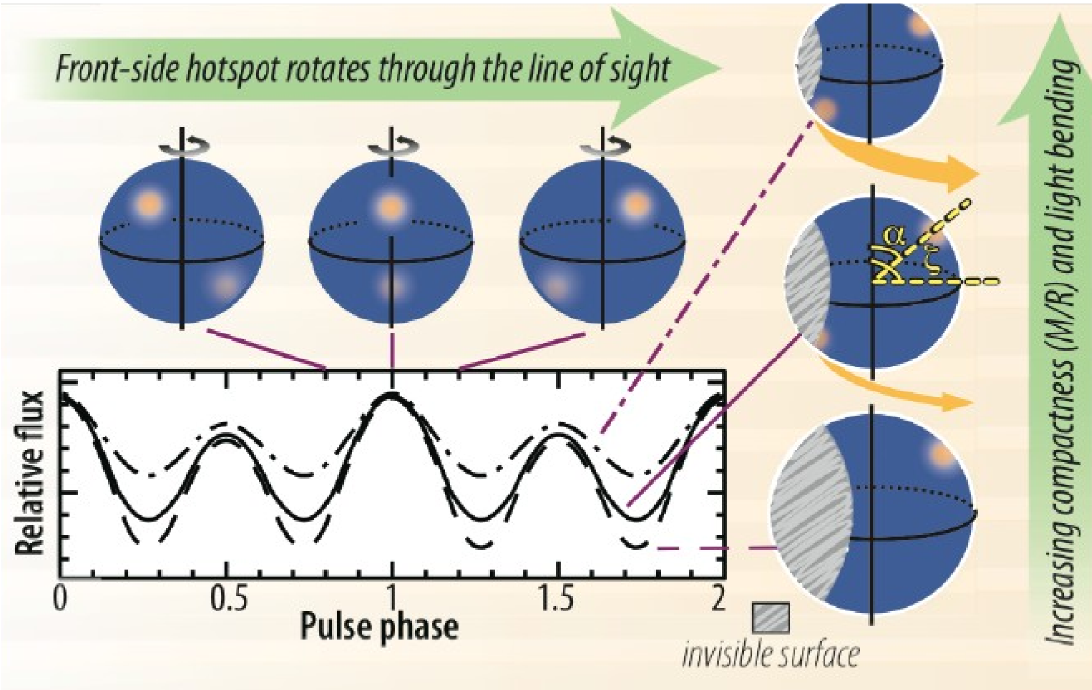
Akmal & Pandharipande 1998, Hebeler and Schwenk 2009, Gandolfi, Carlson, Reddy 2010, Tews, Kruger, Hebeler, Schwenk (2013), Holt Kaiser, Weise (2013), Roggero, Mukherjee, Pederiva (2014), Wlazlowski, Holt, Moroz, Bulgac, Roche (2014),

Neutron Star Structure



Radii from Hot Spots:





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

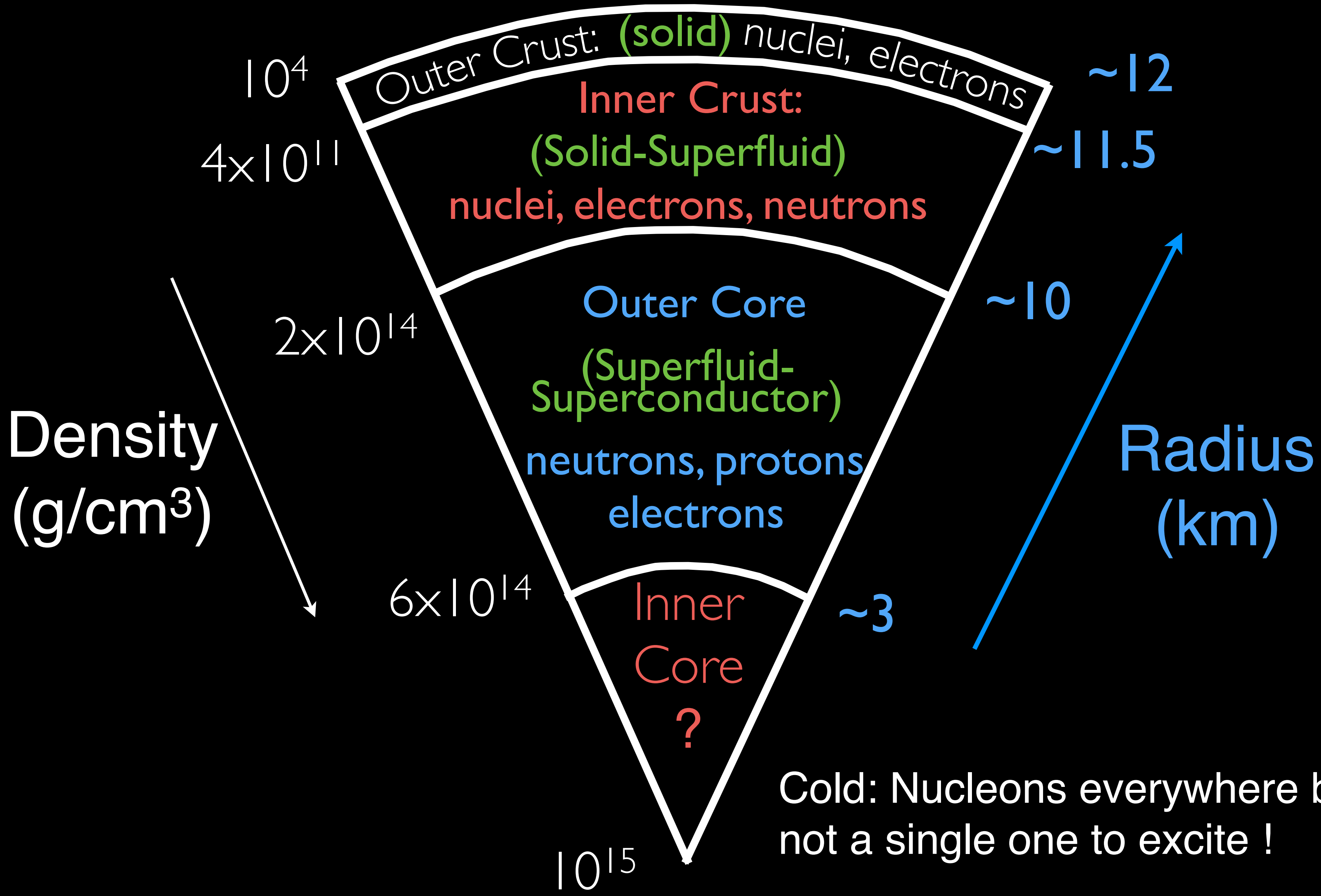
With about 10^6 photons a 10% radius measurement seems possible.

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

NASA mission to launch Feb. 2017.

Neutron Star Thermal Evolution

Phases of Cold Dense Matter in Neutron Stars



Outer Crust: (solid) nuclei, electrons

Inner Crust:
(Solid-Superfluid)
nuclei, electrons, neutrons

Outer Core
(Superfluid-Superconductor)
neutrons, protons
electrons

Inner
Core
?

10^4

4×10^{11}

2×10^{14}

6×10^{14}

10^{15}

Density
(g/cm^3)

~12

~11.5

~10

~3

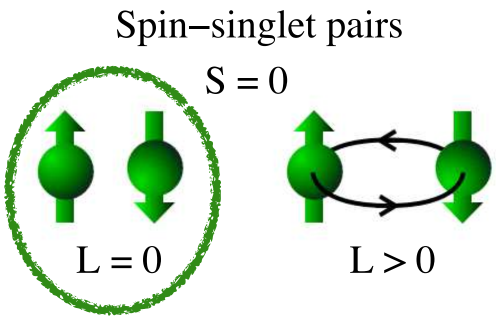
Radius
(km)

Cold: Nucleons everywhere but
not a single one to excite !

Pairing in the Core

- ✳ Proton pair due to s-wave interaction. $\Delta_p \approx 0.1 - 1 \text{ MeV}$
- ✳ Neutrons pair in p-waves with spin-1 channel. $\Delta_n \approx 0.01 - 0.1 \text{ MeV}$

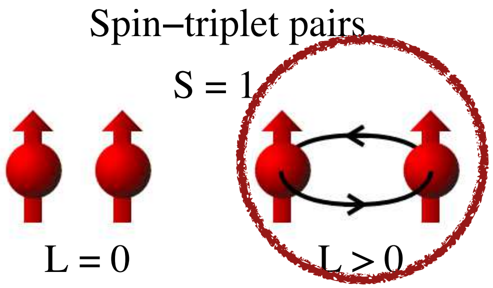
Protons:



$$\langle \psi_p^T \psi_P \rangle = \Delta_p^0 \; e^{i2\theta_p}$$

Action is invariant under: $\theta_p \to \theta_p + \phi_p$

Neutrons:



$$\langle \psi_n^T \sigma_2 \sigma^i \overleftrightarrow{\nabla}^j \psi_n \rangle = \Delta_n^{ij} \; e^{i2\theta_n}$$

Action is invariant under: $\theta_n \to \theta_n + \phi_n$

$$\Delta_n^{ij} \to \mathcal{R}(\beta) \Delta^{ij} \mathcal{R}^T(\beta)$$

Low energy excitations are described by fluctuations of:

$$\phi_p(x,t), \quad \phi_n(x,t), \quad \beta(x,t)$$

Low energy modes in the core

4 Goldstone modes:

1 neutron density mode (n-phonon).

1 electron-proton mode (ep-phonon).

2 modes associated with fluctuations of spin and angular momentum of neutron cooper pairs (angulons).

Neutron star seismology and thermal properties are qualitatively different due to pairing.

Bedaque, Rupak, Savage, (2003), Bedaque and Reddy (2013).

Effective Lagrangian for Phonons and Angulons

Phonons:

$$\mathcal{L}_0 = \frac{1}{2}(\partial_t\phi_n)^2 - \frac{v_n^2}{2}\,(\partial_i\phi_n)^2 + \frac{1}{2}(\partial_t\phi_p)^2 - \frac{v_p^2}{2}(\partial_i\phi_p)^2$$

$$\boxed{+\, g_{pn}\;\partial_t\phi_n\;\partial_t\phi_p - v_{pn}^2\;\partial_i\phi_n\;\partial_i\phi_p}$$

Bedaque and Reddy (2013). Kobyakov, Pethick, Reddy, Schwenk (2017)

Angulons:

$$\mathcal{L}_{\text{ang}} = \sum_{i=1,2}\left[\frac{1}{2}(\partial_0\beta_i)^2 - \frac{1}{2}{v_\perp^i}^2((\partial_x\beta_i)^2 + (\partial_y\beta_i)^2) + v_\parallel^2(\partial_z\beta_i)^2\right.$$

$$+\,\frac{e g_n f_\beta}{2M\sqrt{-\nabla_\perp^2}}\left[\mathbf{B}_1\partial_0(\partial_y\beta_1 + \partial_x\beta_2) + \mathbf{B}_2\partial_0(\partial_x\beta_1 - \partial_y\beta_2)\right]$$

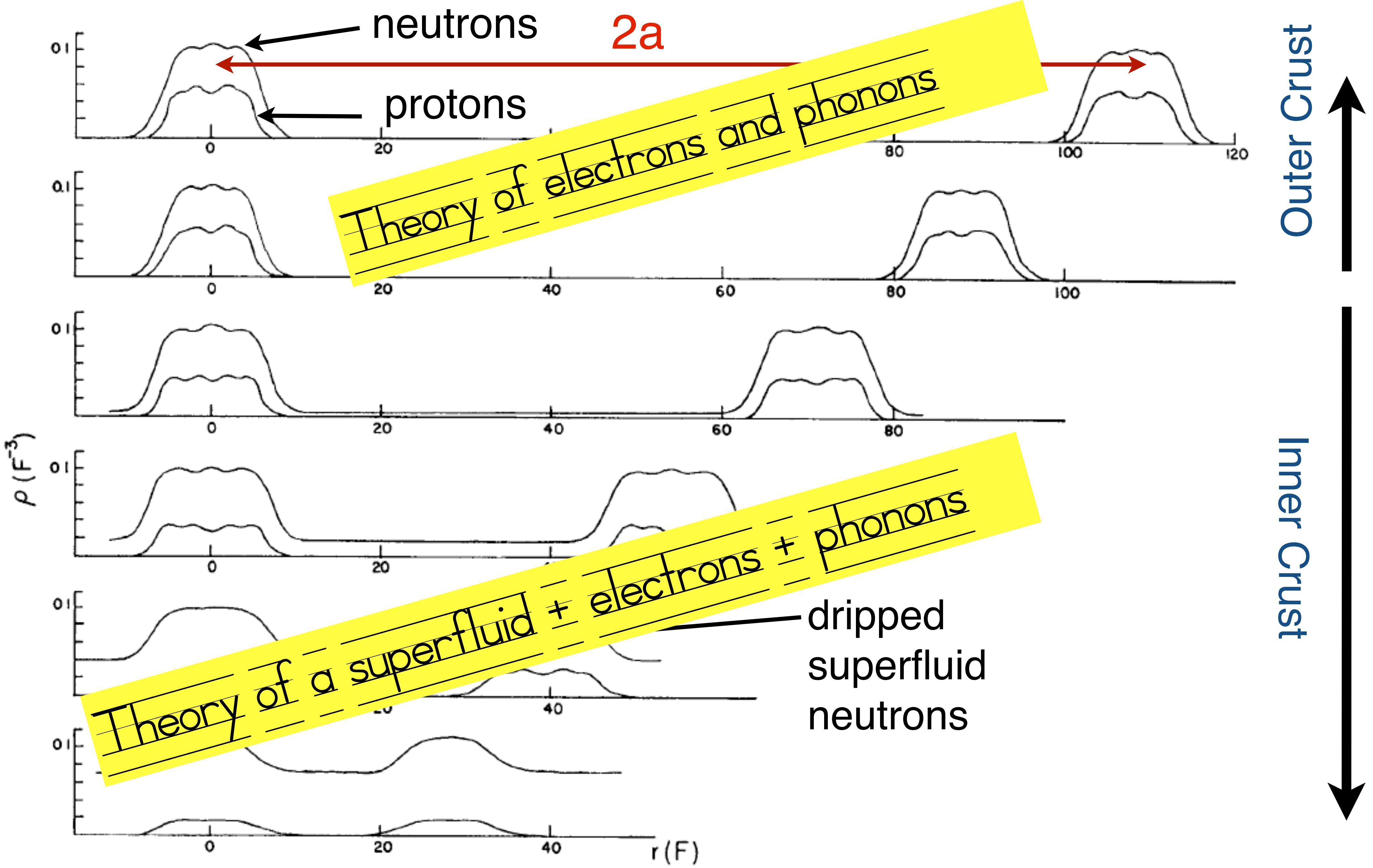
Bedaque, Nicholson (2013)

Higher order terms of the derivative expansion are highly suppressed.

Expansion parameter is $p/\sqrt{Mk_F}$

Breakdown scale is $\omega \approx 2\Delta$

Low energy excitations in the crust



Theory of electrons and phonons

Theory of a superfluid + electrons + phonons

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

Phonons in the Inner Crust

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

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

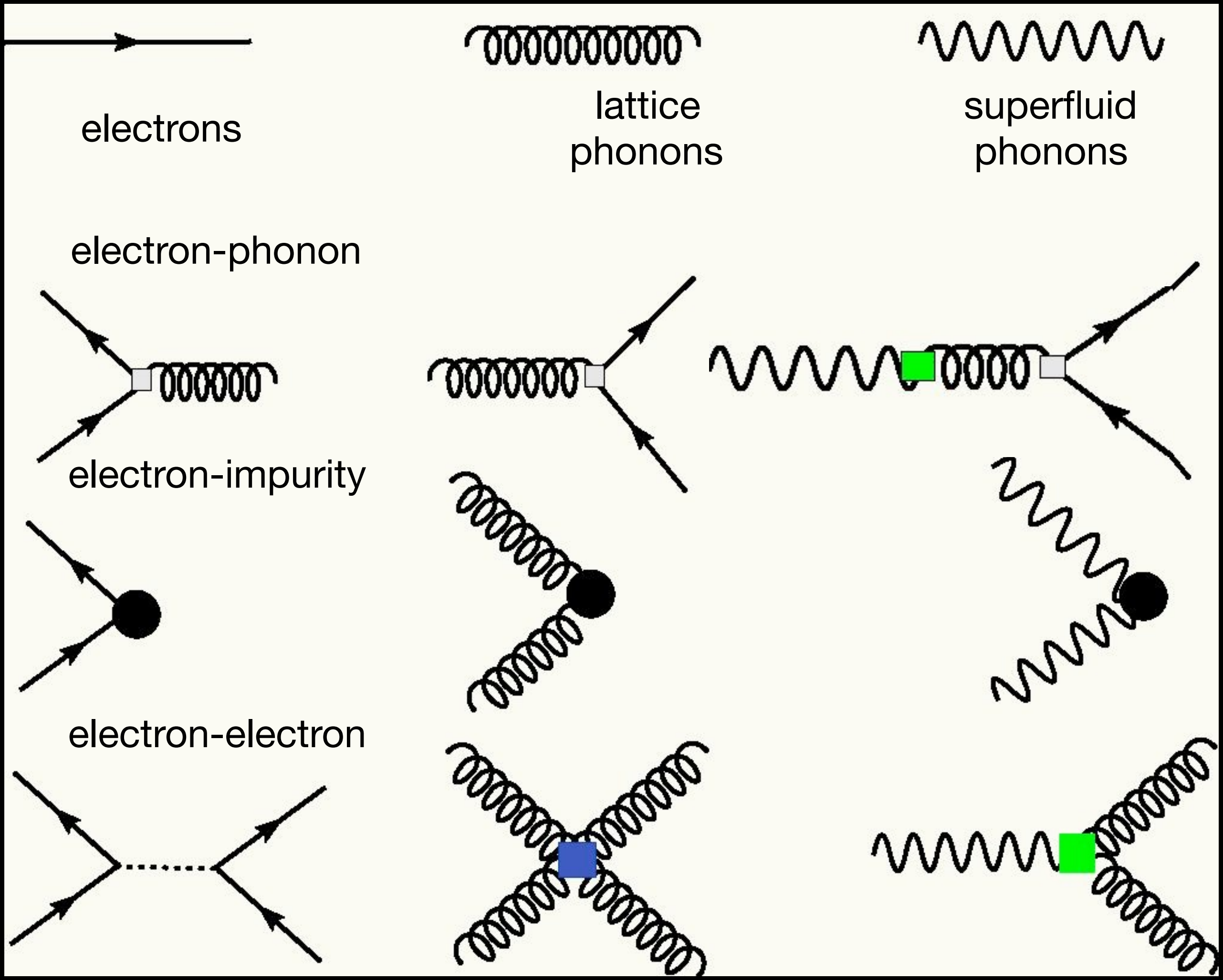
Vector Field: $\xi_i(r,t)$
Scalar Field: $\phi(r,t)$

Excitations and Interactions in the Inner Crust

Electrons and 2 longitudinal and 2 transverse phonons are the relevant excitations.

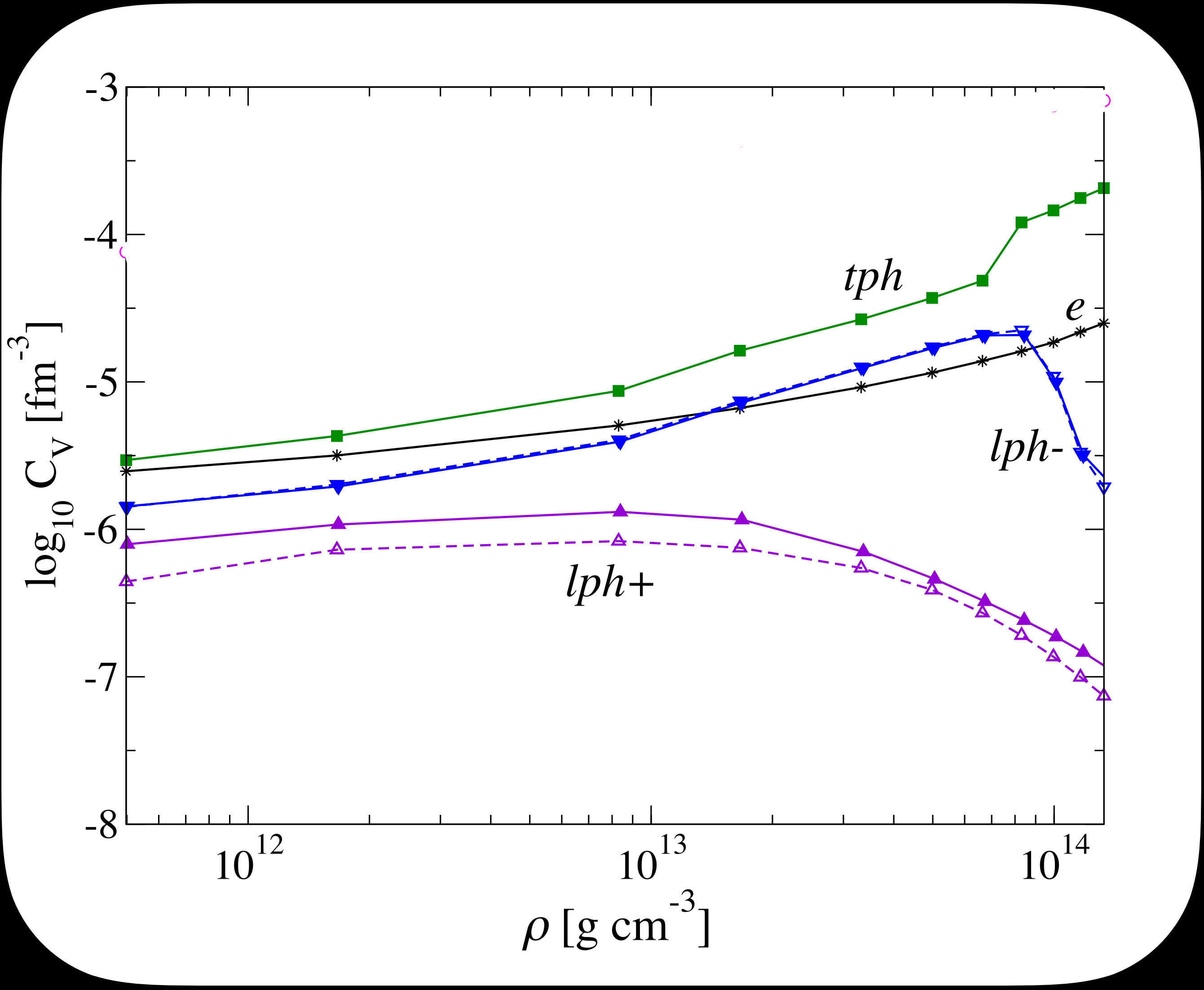
Thermal and transport properties of the solid and superfluid crust can be calculated using an effective field theory.

Mixing between phonons leads to strong Landau damping. Phonon conduction is highly suppressed.



Cirigliano, Reddy & Sharma (2011), Page & Reddy (2012), Chamel, Page, & Reddy (2013), Roggero & Reddy (2016)

Crustal Specific Heat



Electrons:

$$C_V^e \simeq \mu_e^2\, T$$

Phonons:

$$C_V^i \simeq \frac{T^3}{v_i^3}$$

If neutrons were normal

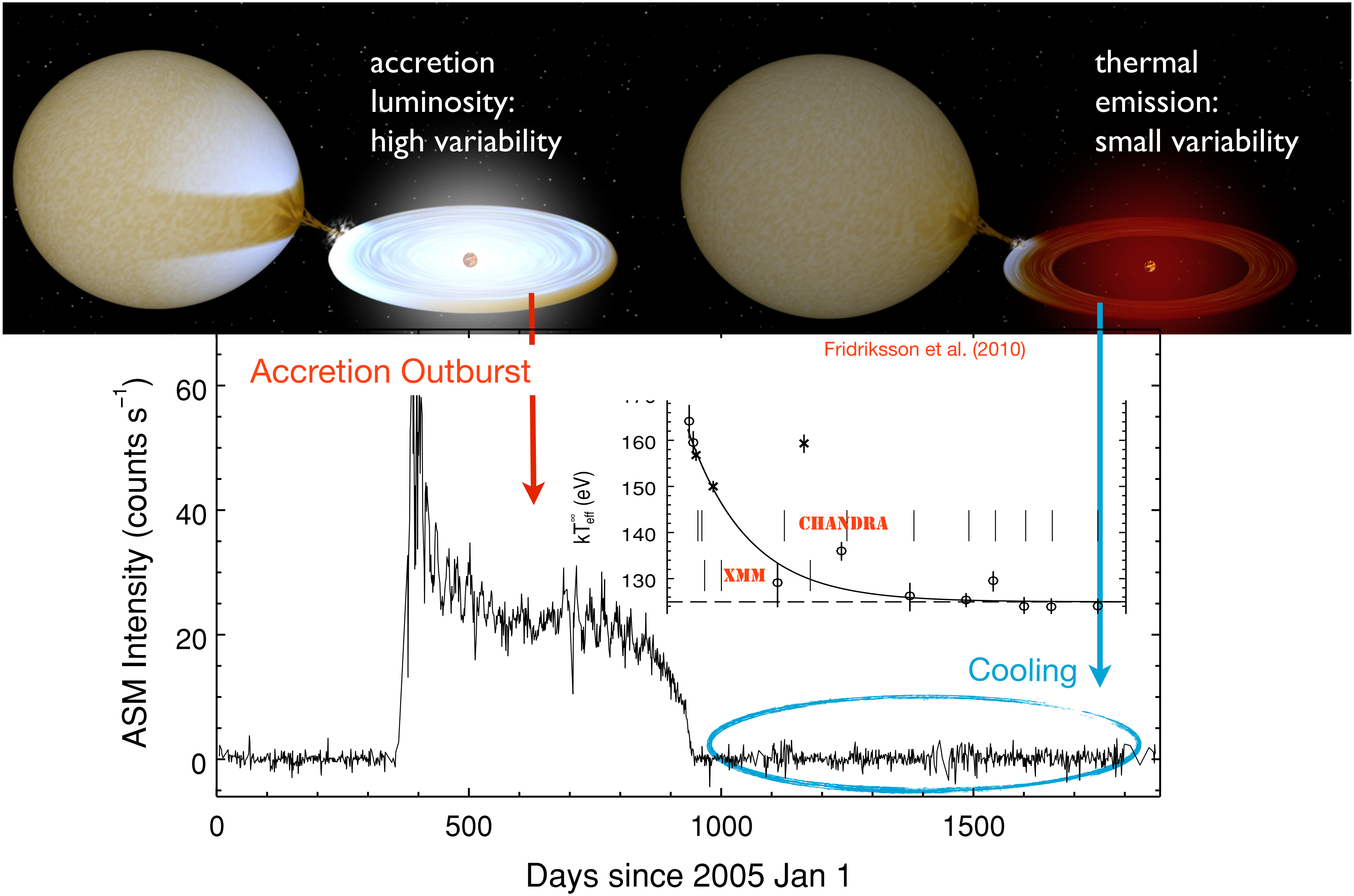
$$C_V^n \simeq M\ k_{Fn}\ T$$

their contribution would overwhelm.

Page & Reddy (2012), Chamel, Page, Reddy (2013)

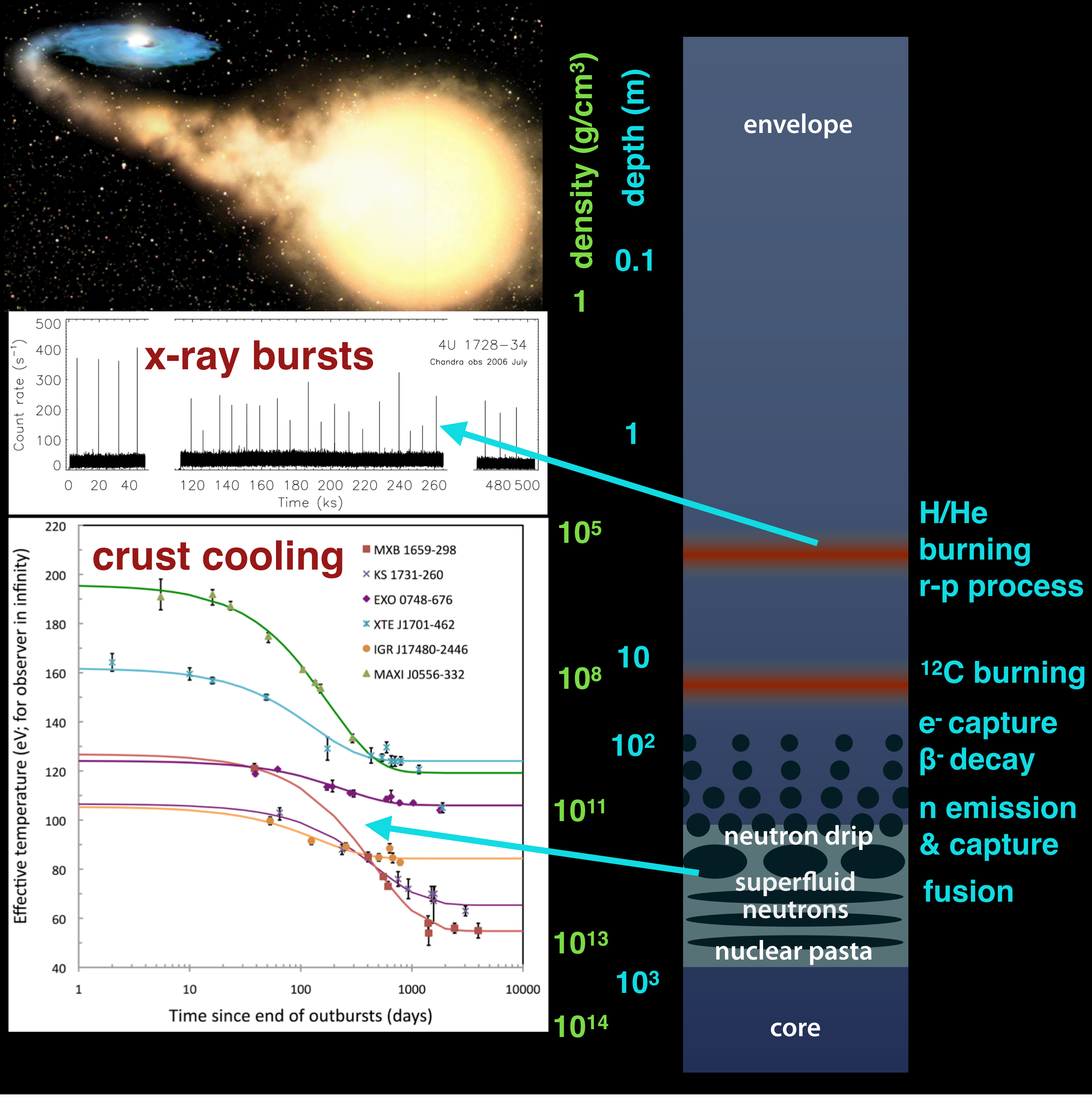
Transiently Accreting Neutron Stars

(Nature’s low temperature dense matter laboratory)



Physical Processes in Accreting Neutron Stars

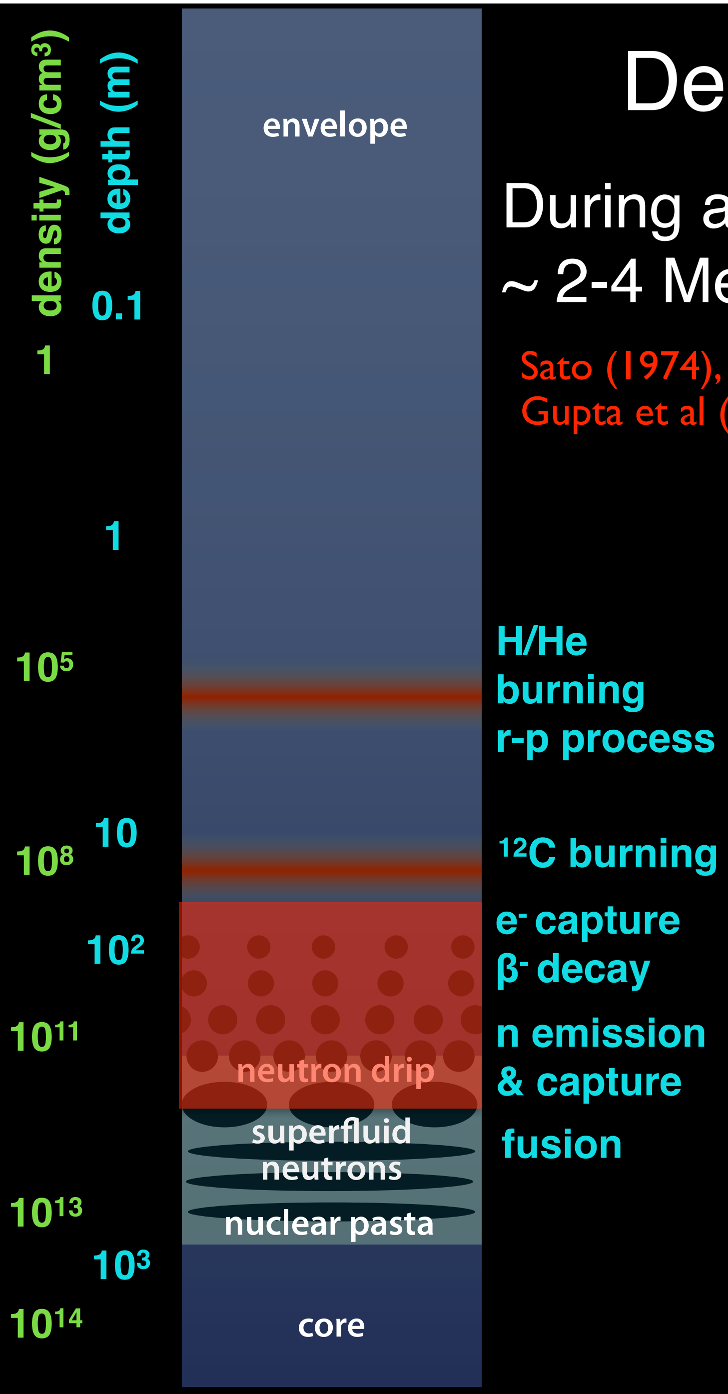
- Accreting neutron stars host phenomena that uniquely probe the physics of its ultra dense interior.
- It is a data driven field.
- Interpreting this data requires a coordinated effort that combines theory, experiment and observations. JINA-CEE has played a key role.

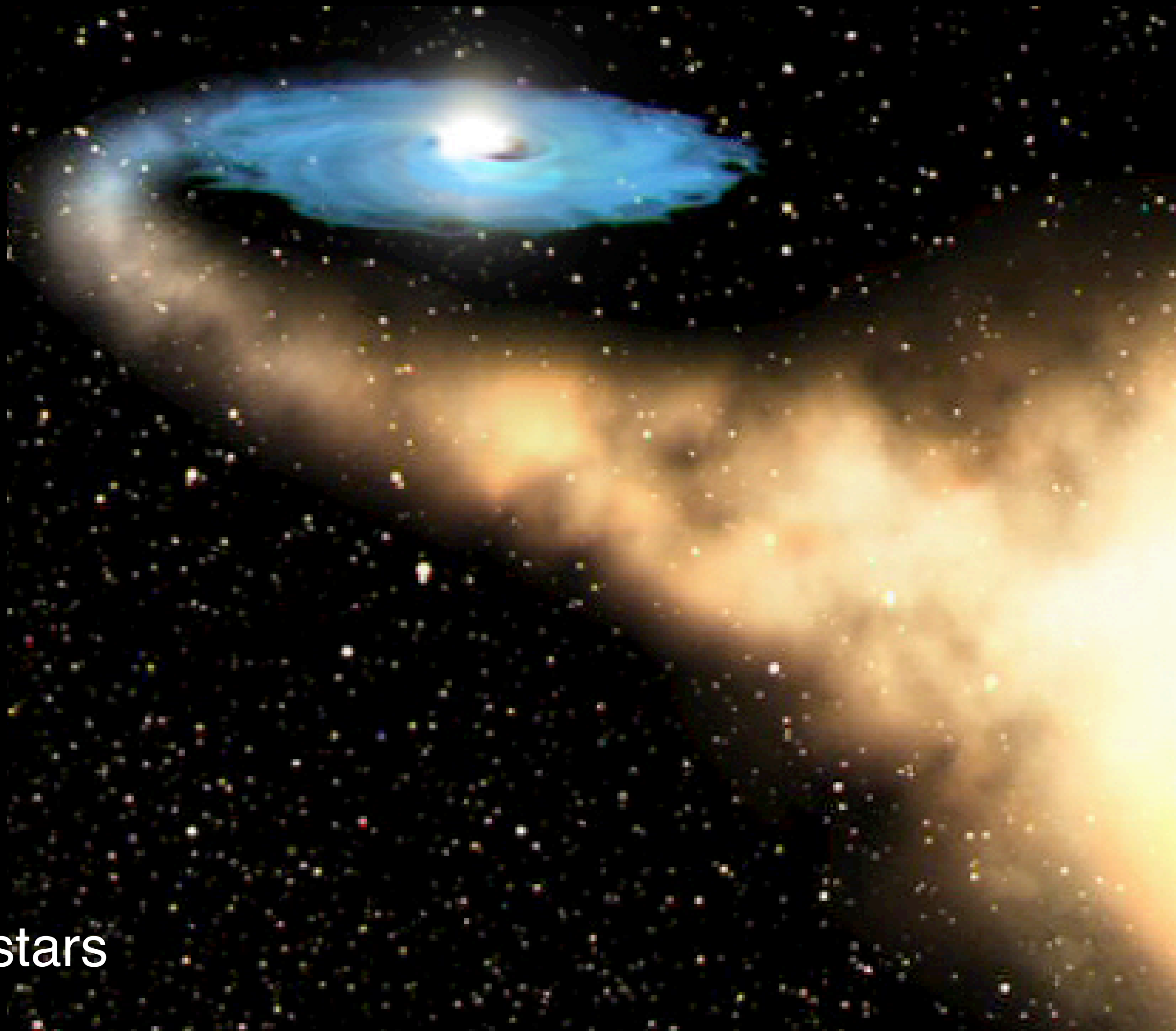


Deep Crustal Heating

During accretion nuclear reactions release:
~ 2-4 MeV / nucleon

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





Warms up old neutron stars

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 ~1000 days.

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

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

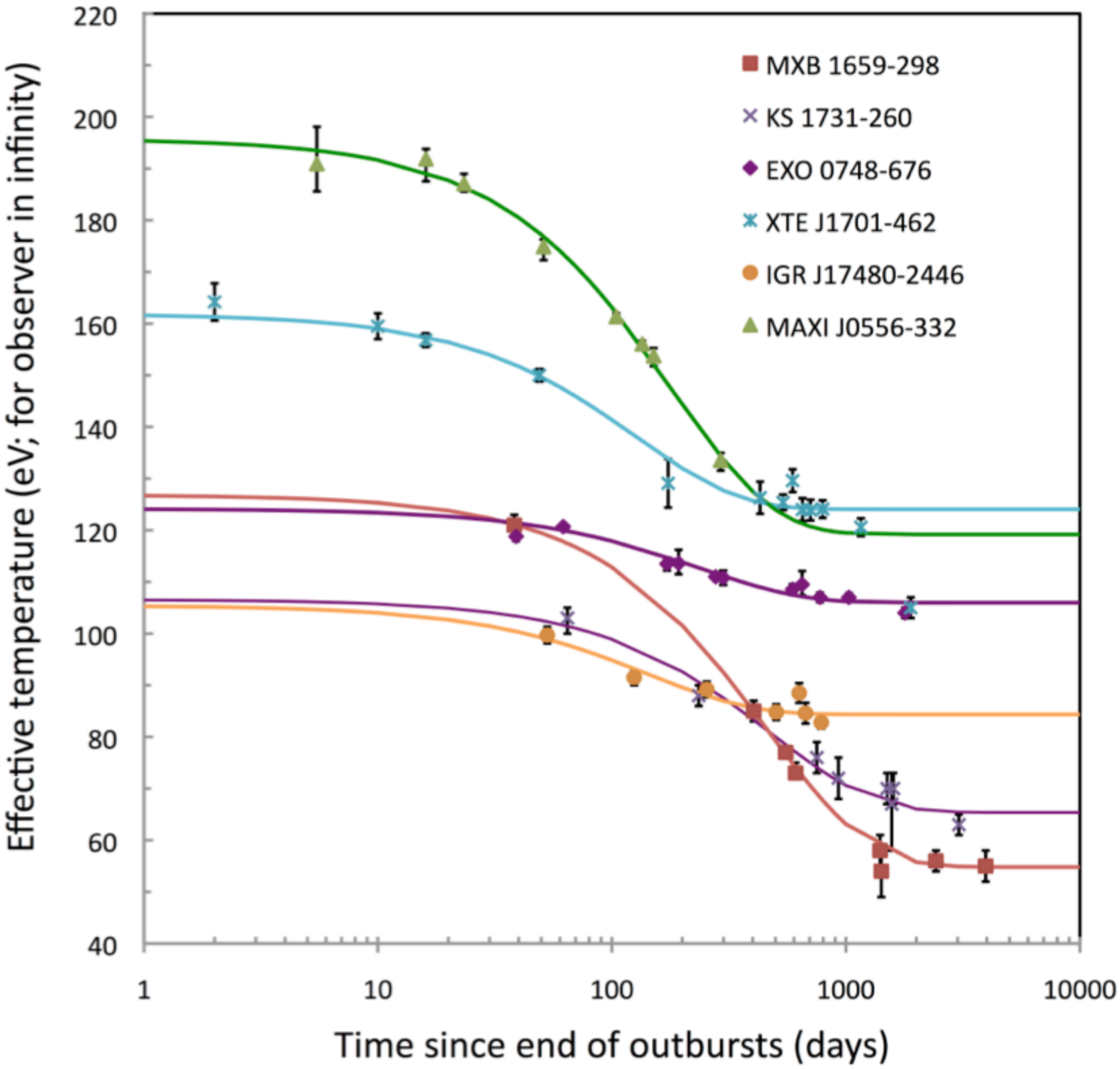


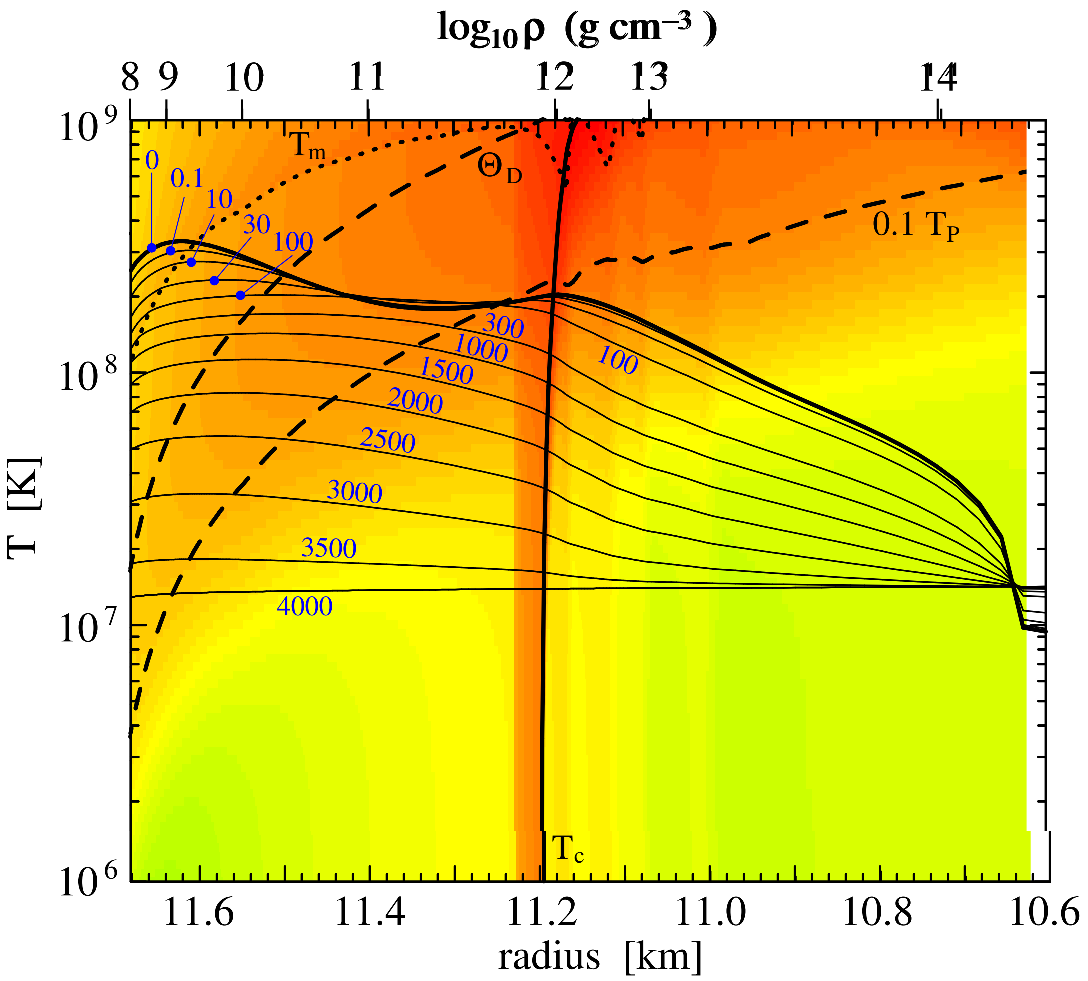
Figure from Rudy Wijnands (2013)

Thermal Evolution of the Crust

Temperature profile in the crust depends on the duration of the accretion phase.

When accretion ends heat flows into the core and is radiated away as neutrinos.

Timescale for cooling is set by the heat diffusion time.



Shternin & Yakovlev (2007) Cumming & Brown (2009) Page & Reddy (2011)

Connecting to Crust Microphysics

Crustal Specific Heat

Crust Thickness

$$\tau_C \simeq \frac{C_V}{\kappa}\ \Delta R^2$$

Thermal Conductivity

- Observed timescales are short.
- Requires small specific heat and large thermal conductivity.
- Favors a solid (with small impurity fraction) and superfluid inner crust.

Measuring the Heat Capacity of the Core

Heat the star, allow it to relax, and observe the change in temperature: $C_{NS}\ dT = dQ$

When $C_{NS} = \alpha\, T$: $\frac{\alpha}{2}\,(T_f^2 - T_i^2) = \Delta Q$

Lower limit: $C_{NS}(T_f) > 2\frac{\Delta Q}{T_f}$

$$\Delta Q = \dot{H} \times t_H - L_\nu \times (t_H + t_{obs})$$

heating rate

duration of heating

neutrino cooling rate

time of observation (after heating ceases)

Cumming et al. (2016)

Observations of KS 1731-260

Quiescent Surface Temperature (post relaxation): $T_s = 63.1$ eV
Accretion Phase: 12 yrs at dM/dt $\approx 10^{17}$ g/s
Thermal Relaxation: t ≈ 8 yrs

Wijnands et al. (2002) Cackett et al. (2010)

Inferred Core Temperature:

Insulating envelope supports a temperature gradient near the surface.

Heavy element envelope: $T_c^\infty = 7.0 \times 10^7\ \mathrm{K}\ \left(\frac{T_s^\infty}{63.1\ \mathrm{eV}}\right)^{1.82}$

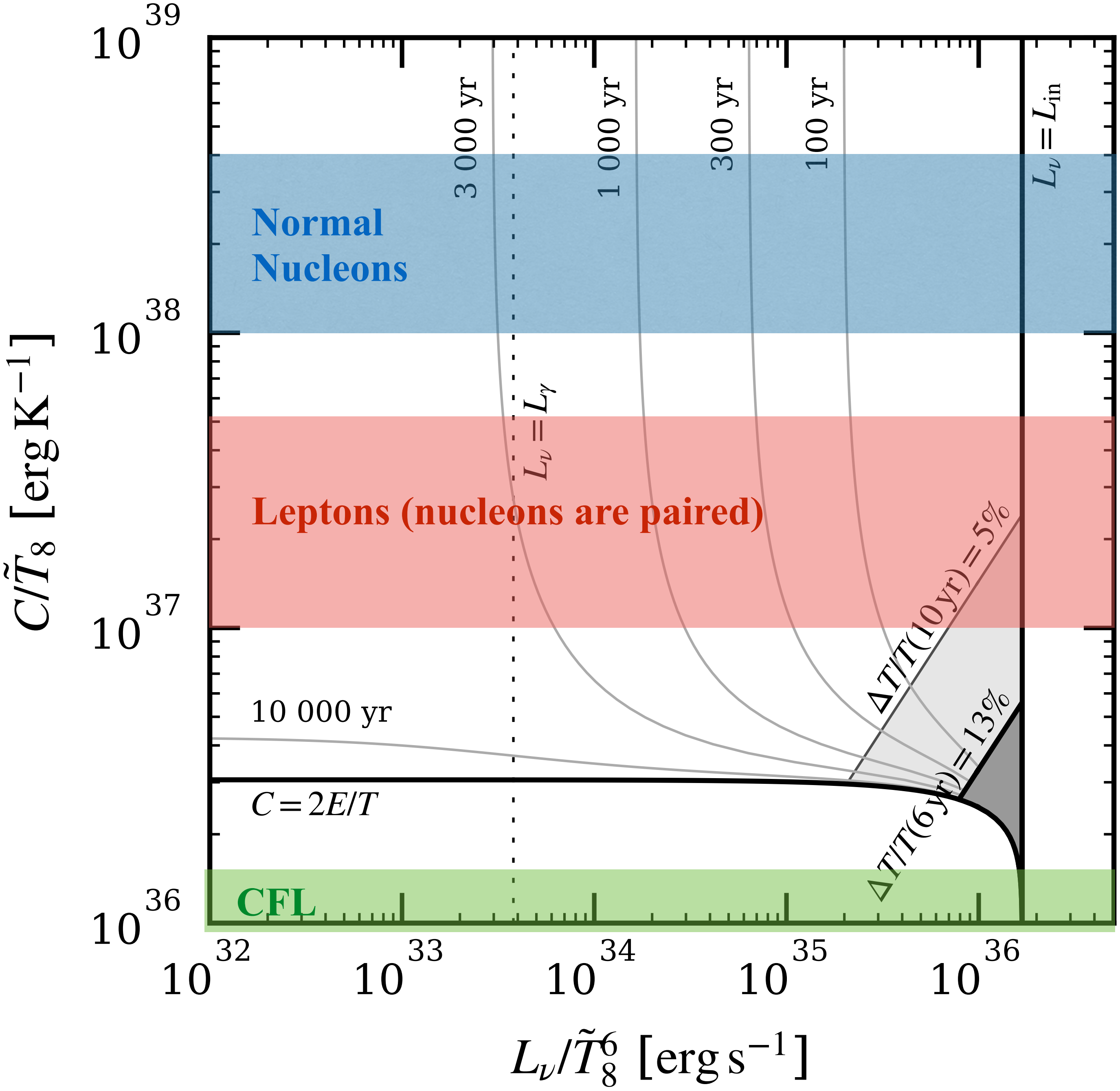
Light element envelope: $T_c^\infty = 3.1 \times 10^7\ \mathrm{K}\ \left(\frac{T_s^\infty}{63.1\ \mathrm{eV}}\right)^{1.65}$

Inferred Energy Deposition:

$$\Delta Q = \dot{H} \times t_H = 6 \times 10^{43}\ \mathrm{ergs}\ \left(\frac{Q_{nuc}}{2\ \mathrm{MeV}}\right)\left(\frac{\dot{M}}{10^{17}\ \mathrm{g/s}}\right)\left(\frac{t_H}{10\ \mathrm{yrs}}\right)$$

Cumming, Page, Brown, Reddy, Horowitz and Fatttoyev (2016)

Limits: Current & Future



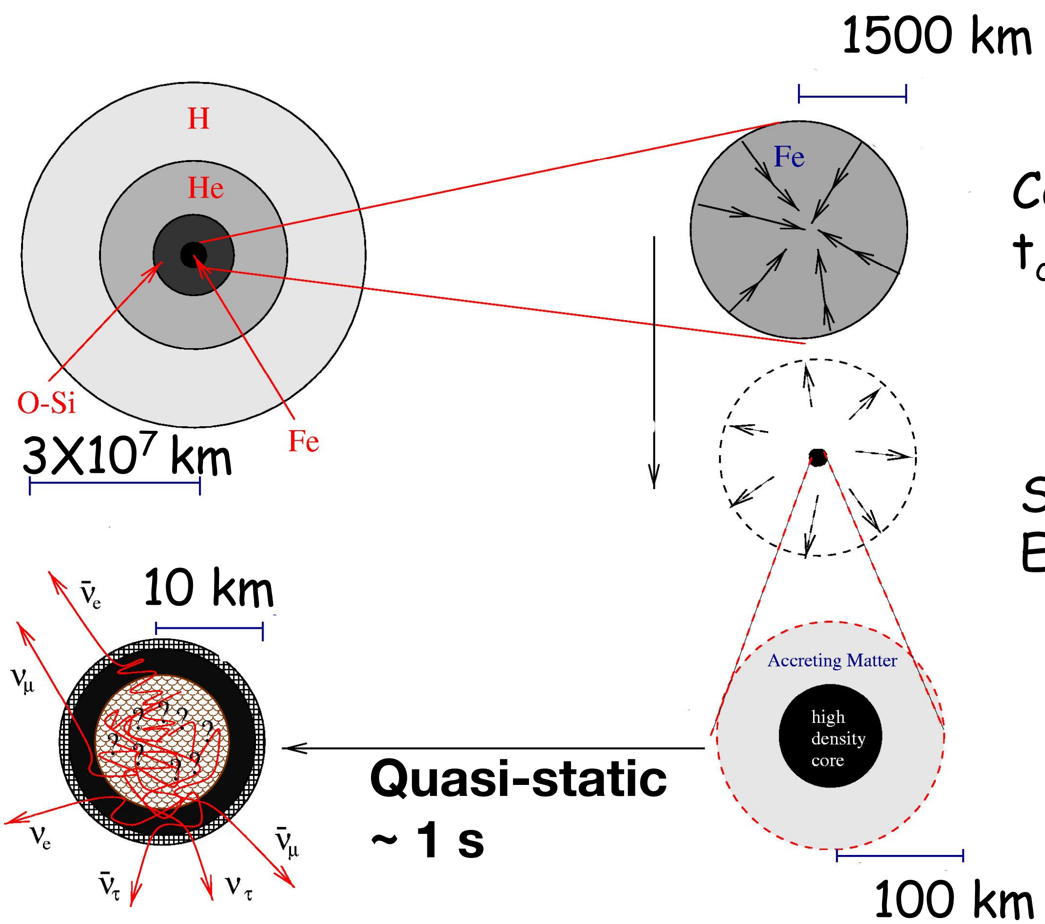
Cumming, Page, Brown, Reddy, Horowitz and Fatttoyev (2016)

The other messengers

- Neutrinos
- Nucleosynthesis
- Gravitational Waves

Nuclear interactions and the equation of state of neutron-rich dense matter plays role. Is essential to interpret observations and unravel correlations.

Core Collapse Supernova



Core collapse
$t_{collapse}$ ~100 ms

Shock wave
E_{shock}~10^{51}ergs

neutrinos diffuse out of the dense newly born neutron star

carry away ~ 3 x 10^{53} ergs

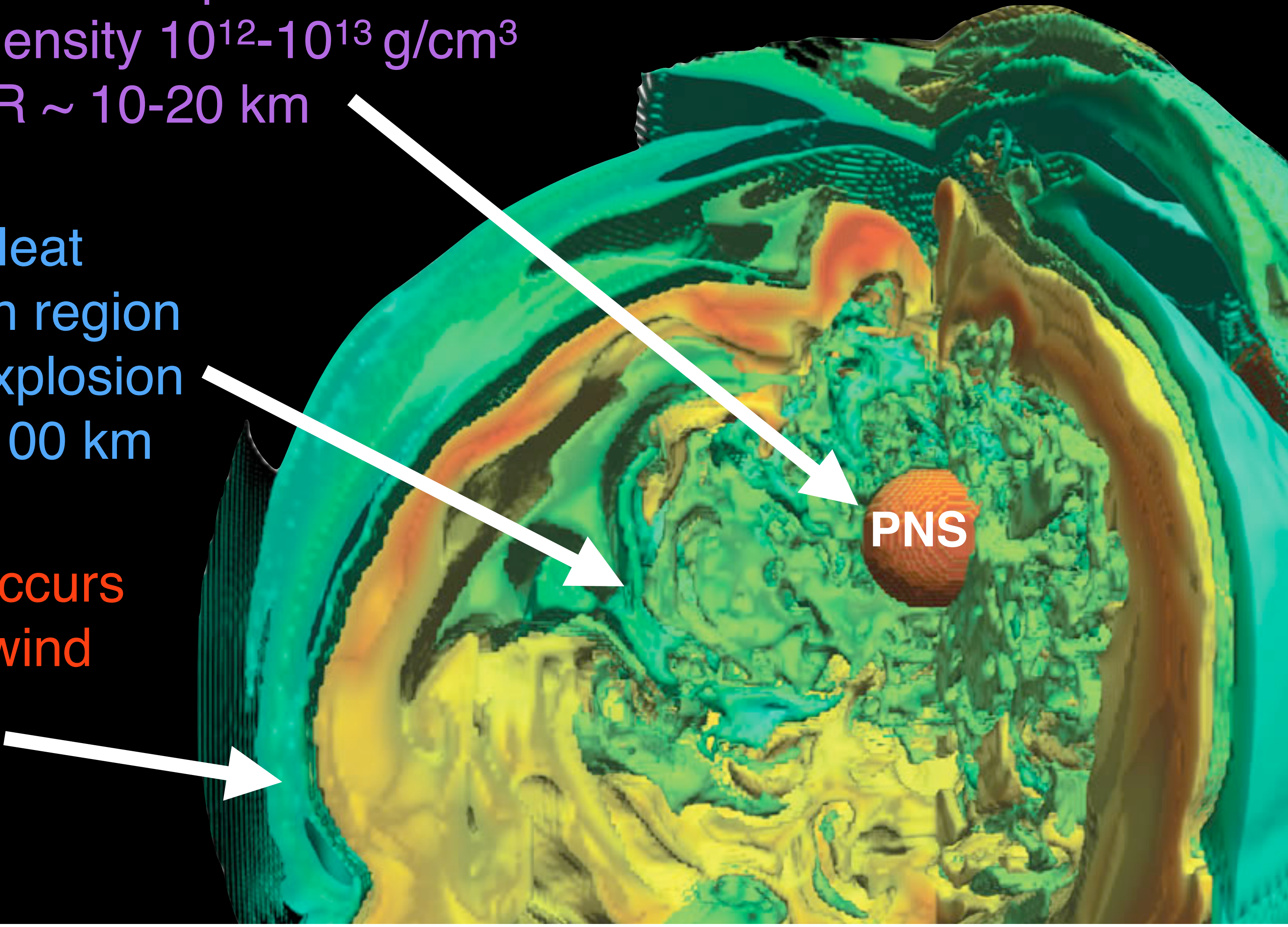
Quasi-static ~ 1 s

- 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.

Supernova Neutrinos

Neutrino spectrum and luminosity is crucial to:

- Supernova explosion mechanism
- Heavy-element nucleosynthesis
- Neutrino detection



Neutrino-sphere: Neutrino spectra is determined at high density 10^{12}-10^{13} g/cm^3 and T~ 4-8 MeV at R ~ 10-20 km

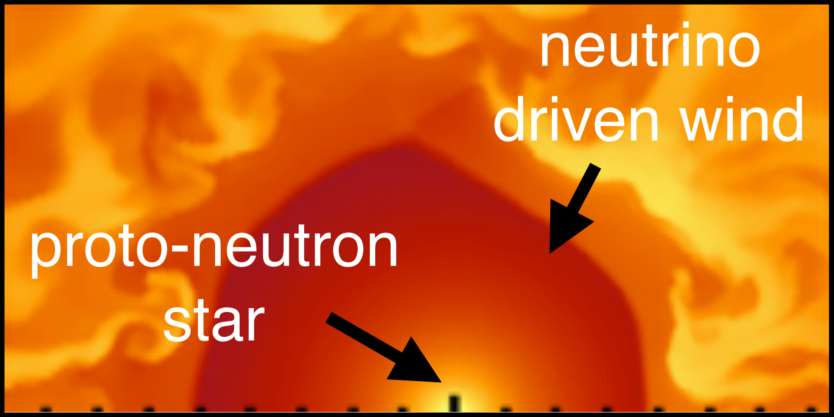
Neutrino heating: Heat deposition in the gain region is essential for the explosion mechanism. R~ 50-100 km

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

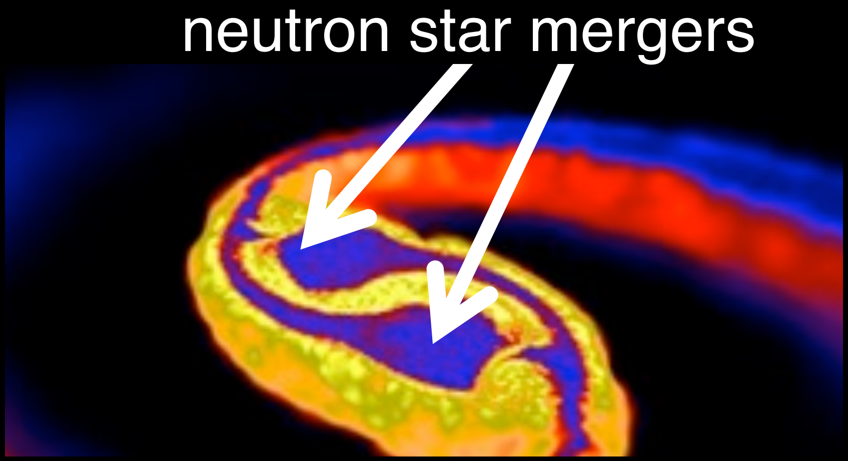
Where does the r-process occur ?

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 abundance peaks at A~130 and A ~ 190.

This requires:

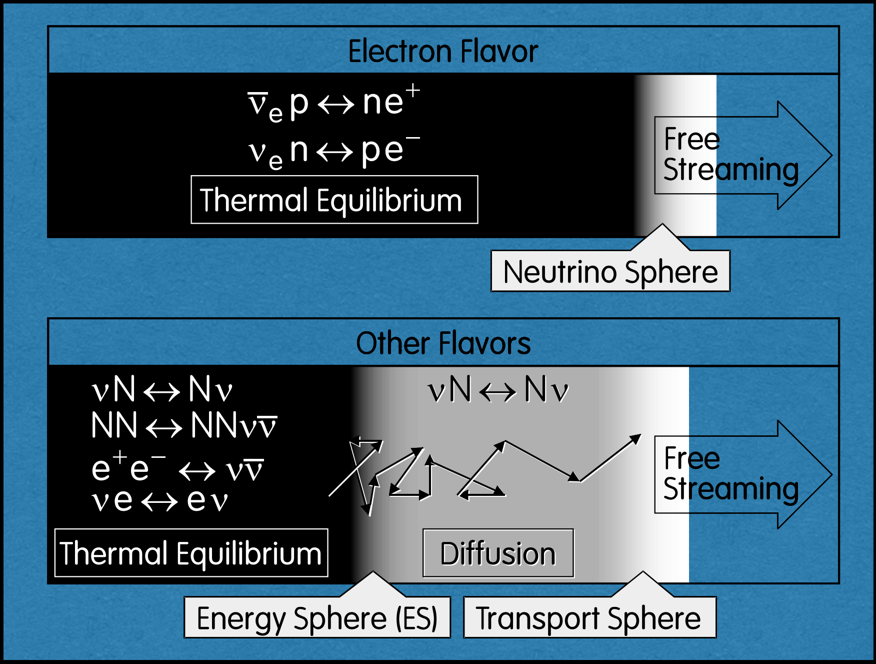
- High entropy per baryon.
- Short expansion time.
- Neutron-rich ejecta.

} Hydrodynamics,
Magnetic Fields, etc

} Neutrino Spectra

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

Neutrino Spectra and its Impact



Raffelt (2001)

hotter neutrinos enhance heating and aid the explosion

cooler electron neutrinos and hotter anti-neutrinos increase the neutron fraction and aids nucleosynthesis

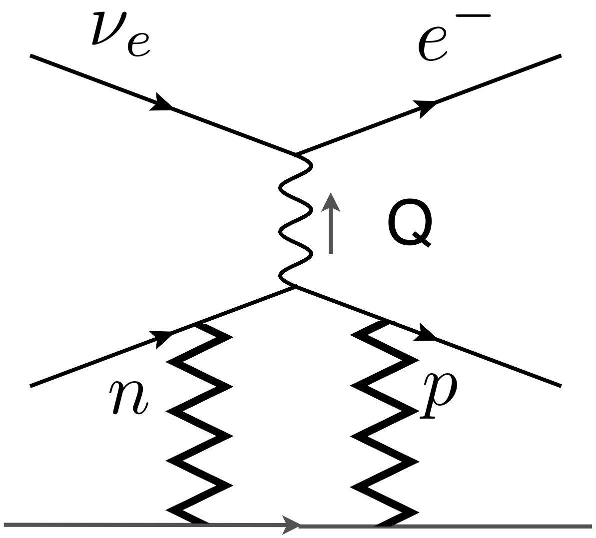
Radius

Spectrum of ν_e and $\bar{\nu}_e$ are most relevant.

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

$$\nu_e + n \rightarrow p + e^-$$

Charged Currents and Symmetry Energy

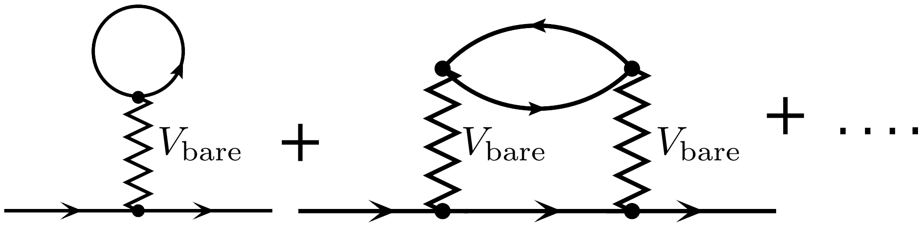


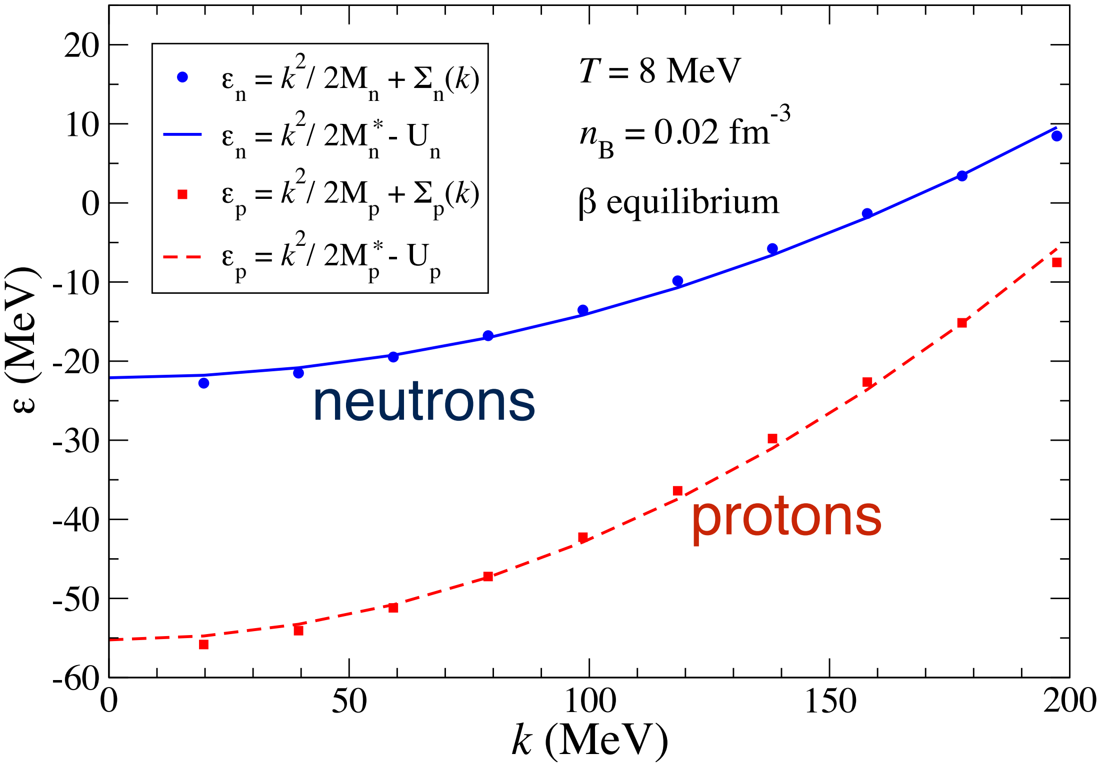
Nuclear Medium

Energy difference between neutrons and protons in neutron-rich matter is large.

$$\mathrm{Q} = \varepsilon_n(\vec{k}) - \varepsilon_p(\vec{k} - \vec{q})$$
$$\cong M_n - M_p + \Sigma_n(k) - \Sigma_n(k - q)$$

Due to large scattering lengths, a shallow bound state, and large effective range, interactions are non-perturbative at low density and moderate temperature.





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

Modified Mean Free Paths and Neutrino Decoupling

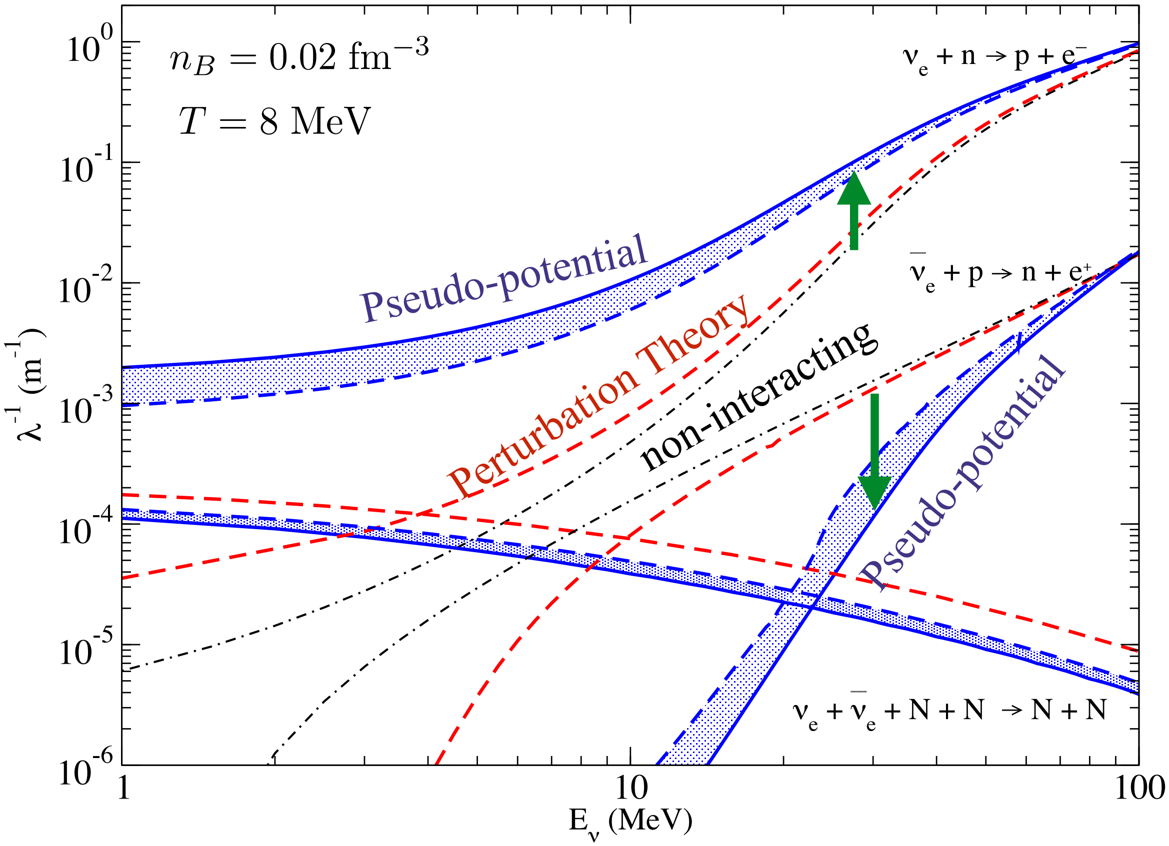
Modest changes to the single particle energies has a large effect on neutrino mean free paths and their spectra.

$$\nu_e + n \rightarrow p + e^-$$

Potential energy gain associated with converting neutrons into protons helps overcome electron final state blocking. Spectrum gets colder.

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

Energy needed to convert neutrons into protons reduces the phase space and the reaction cross-section. Spectrum get hotter.

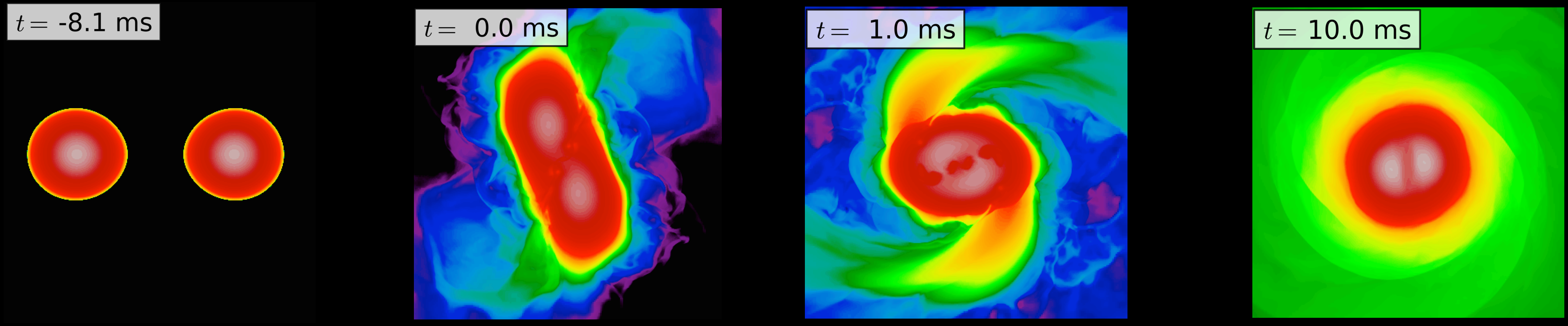


Implication for supernova neutrino detection: More events in water Cherenkov detectors and fewer events in Liquid Argon.

Neutron Star Merger Dynamics

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

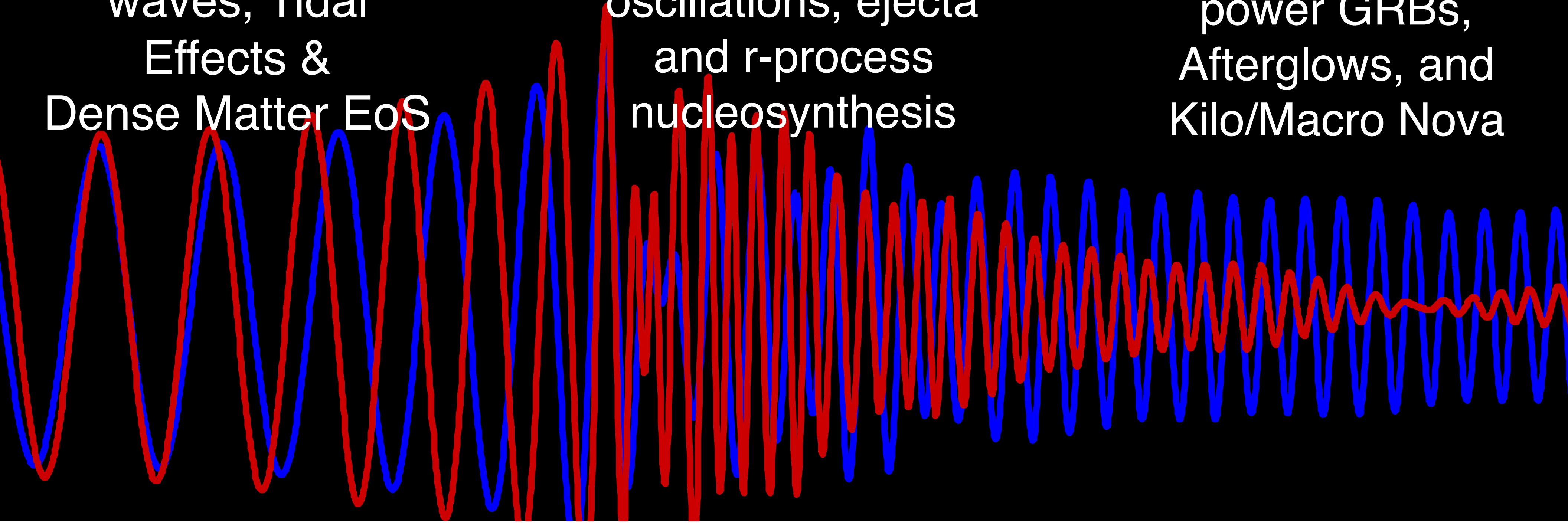
Simulations: Rezzola et al (2013)



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

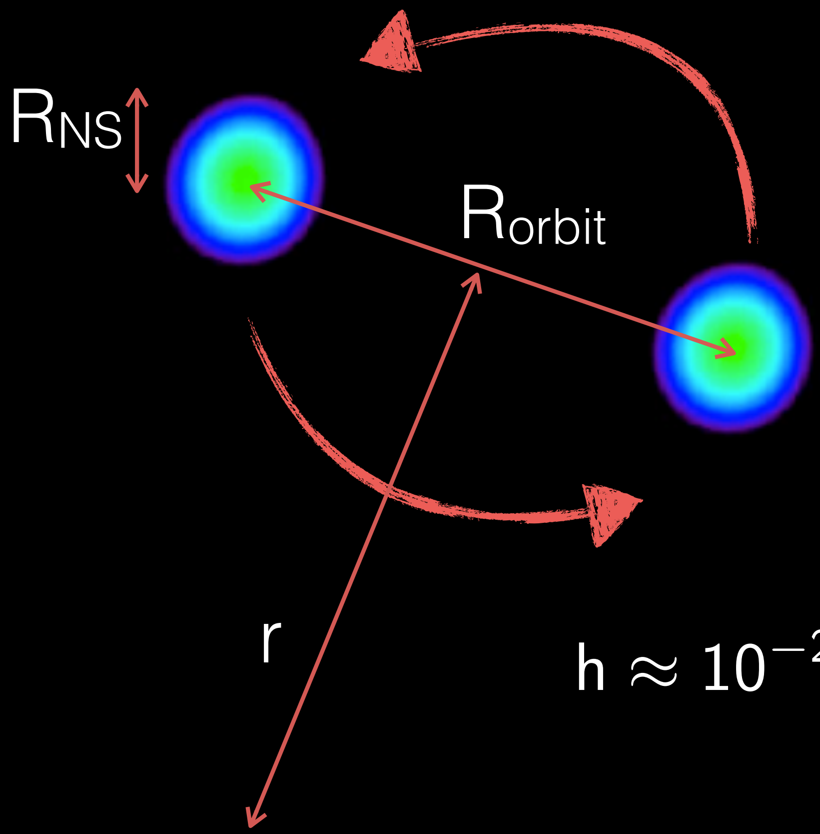
Merger:
Disruption, NS oscillations, ejecta and r-process nucleosynthesis

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



Binary inspiral and gravitational waves

GWs are produced by fluctuating quadrupoles.



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

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

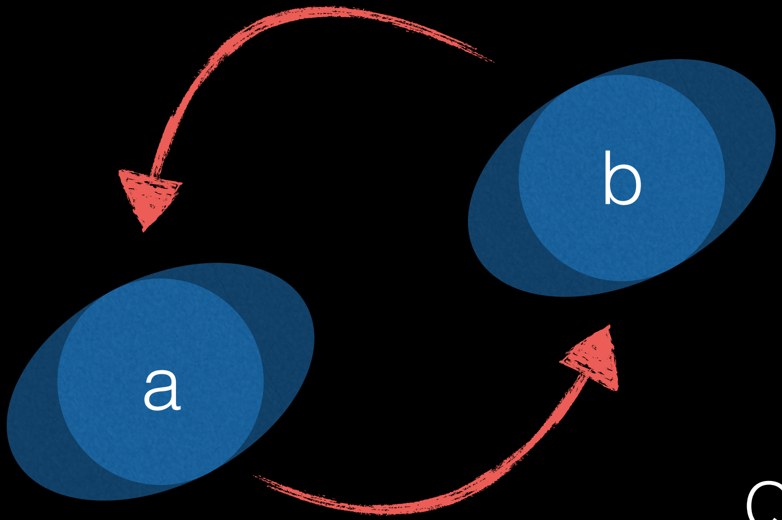
For $R_{orbit} >> R_{NS}$:

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

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

- Advanced LIGO can detect the last 100 or so orbits of a neutron star merger.
- Detection expected 2017 - 2018!

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})

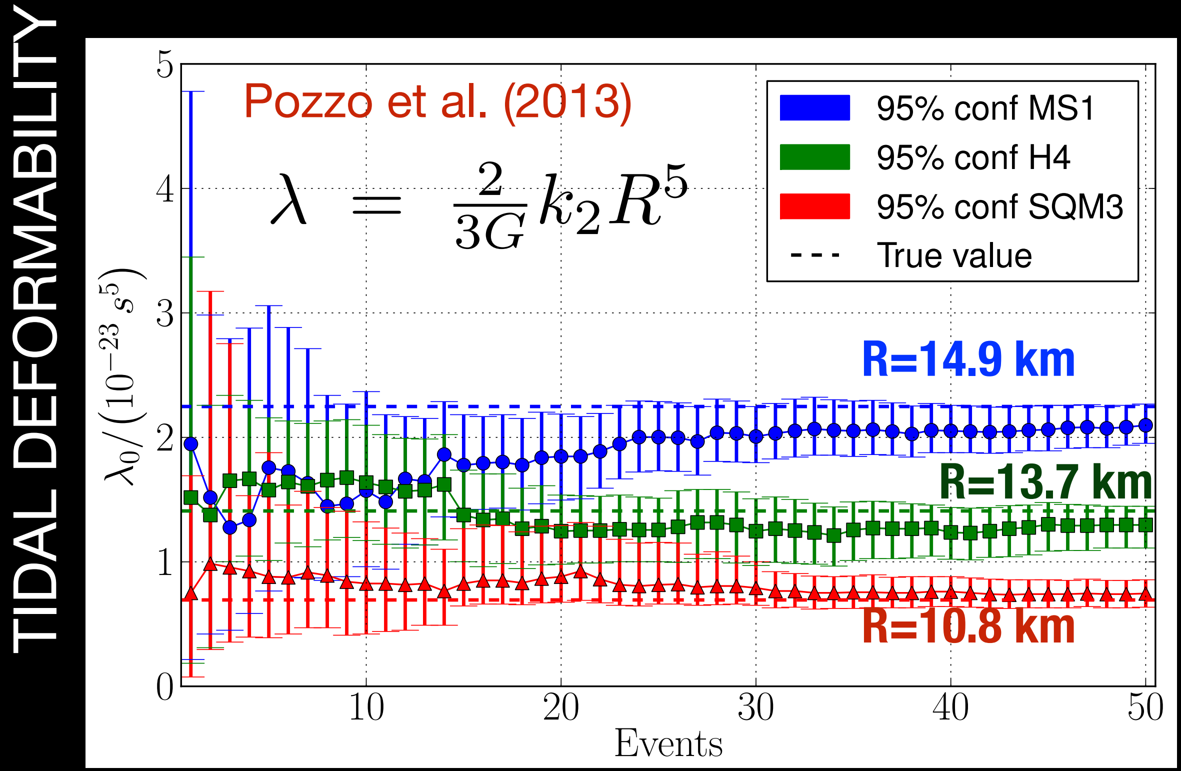
Quadrupole polarizability: $\lambda = k_2(\beta, \bar{y})\ R_{NS}^5$

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

This advances the orbit and changes the rotational phase.
Larger radii imply larger tidal effects.

Neutron Star Radii From Pre Merger Signal

Tidal polarizability or deformability can be extracted from the 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. This would provide strong constraints on the nuclear symmetry energy and the dense matter EOS.

Summary & Outlook

- Neutron stars are central engines for a large class of phenomena and the underlying nuclear and neutrino physics is rich, tractable and testable.
- Observations of accreting neutron stars are providing new insights about neutron star interiors.
- Intriguing correlations between neutron star radii, GWs from mergers, supernovae neutrino spectra, and r-process nucleosynthesis are emerging.
- GWs are here and neutron star mergers are up next. Multi-messenger astronomy has much more to reveal.