High Density QCD Matter

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Take any macroscopic piece of matter, crush them until nuclei touch. You will get

dense QCD matter

Cold, baryon number density:

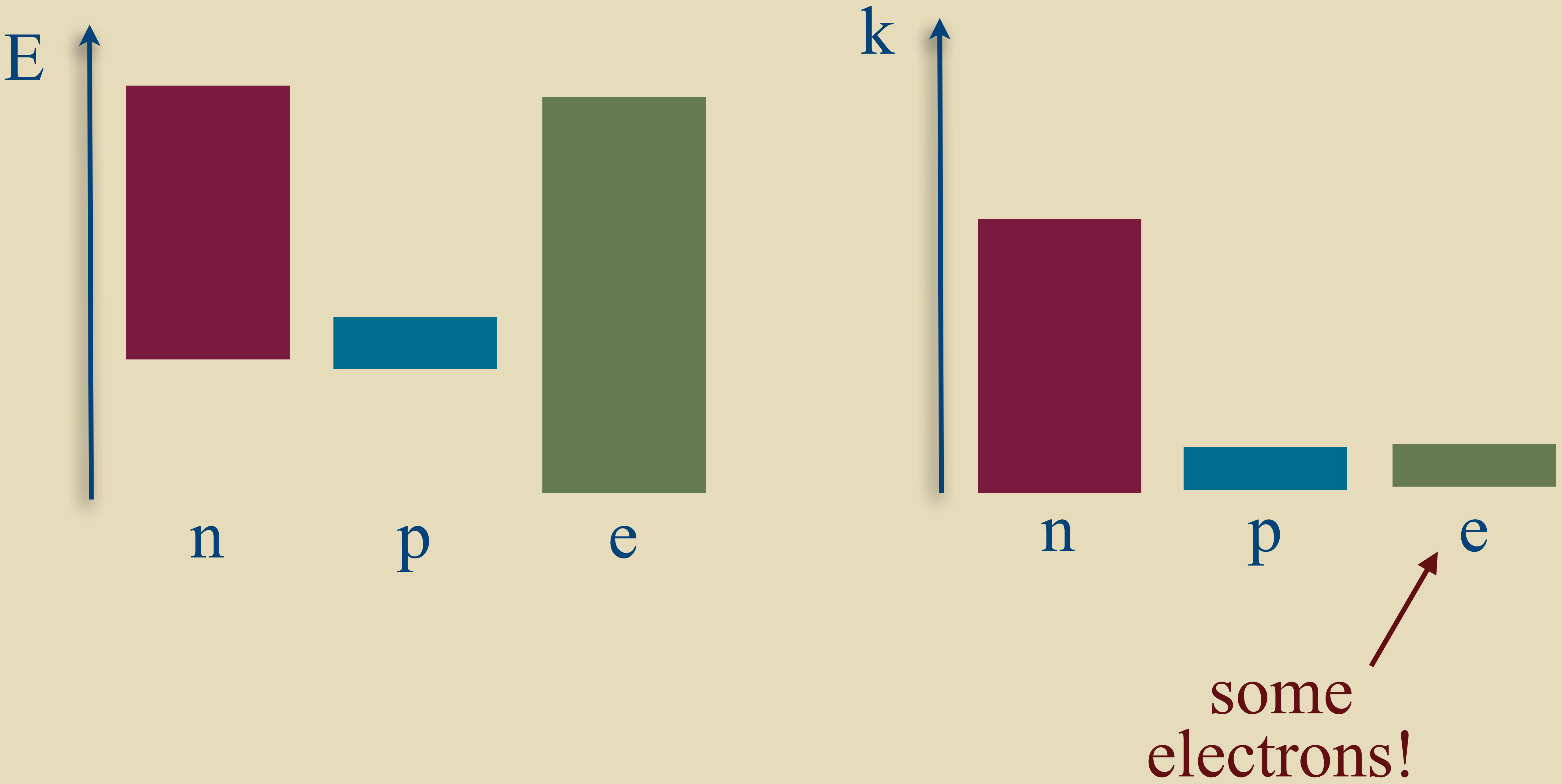
$$\frac{0.1}{fm^3} < n < \frac{10}{fm^3}$$

clumps into nuclei

does not occur anywhere

- nuclei
- neutron stars (except crust)

Dense matter is (mostly) neutron matter or …



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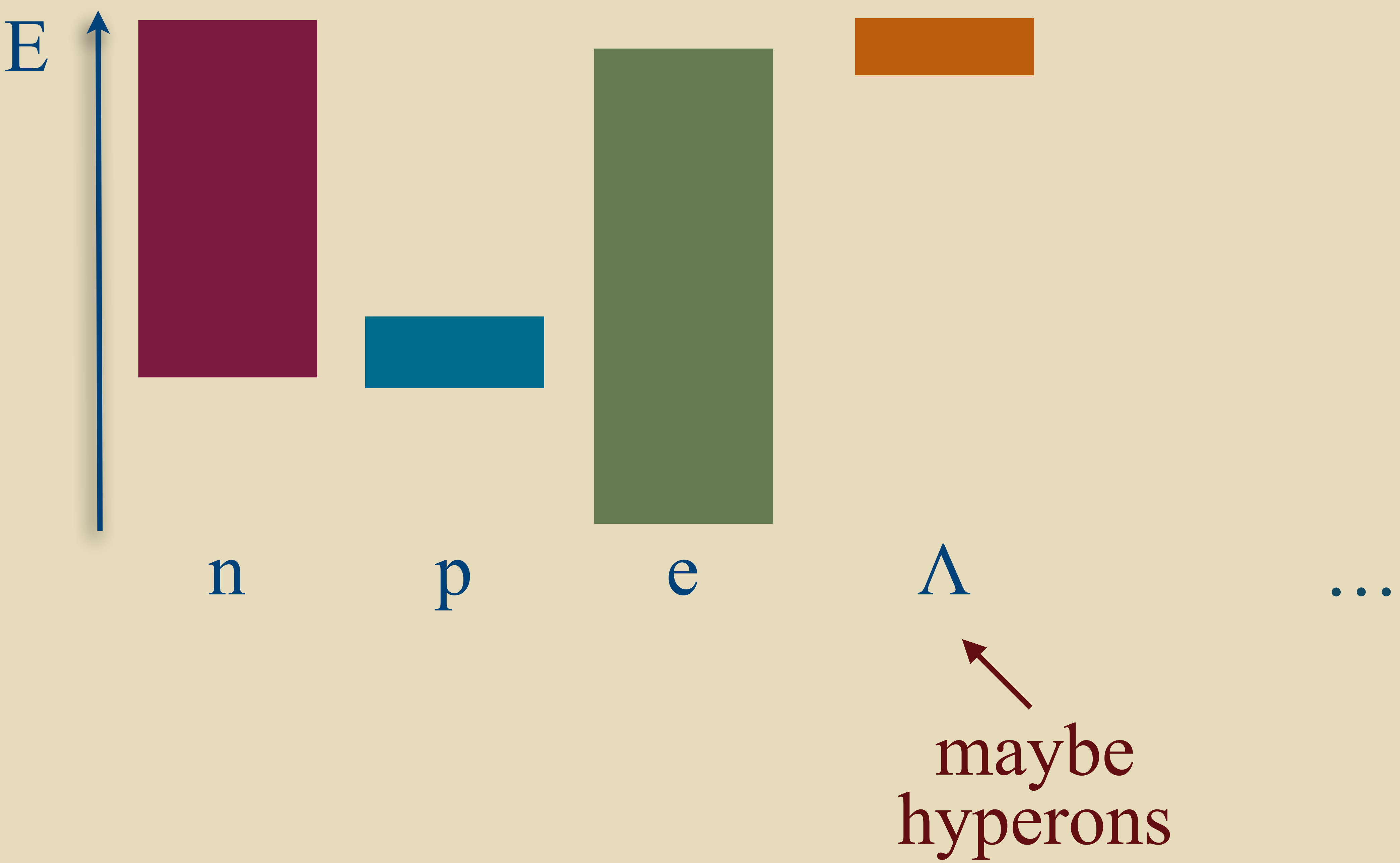
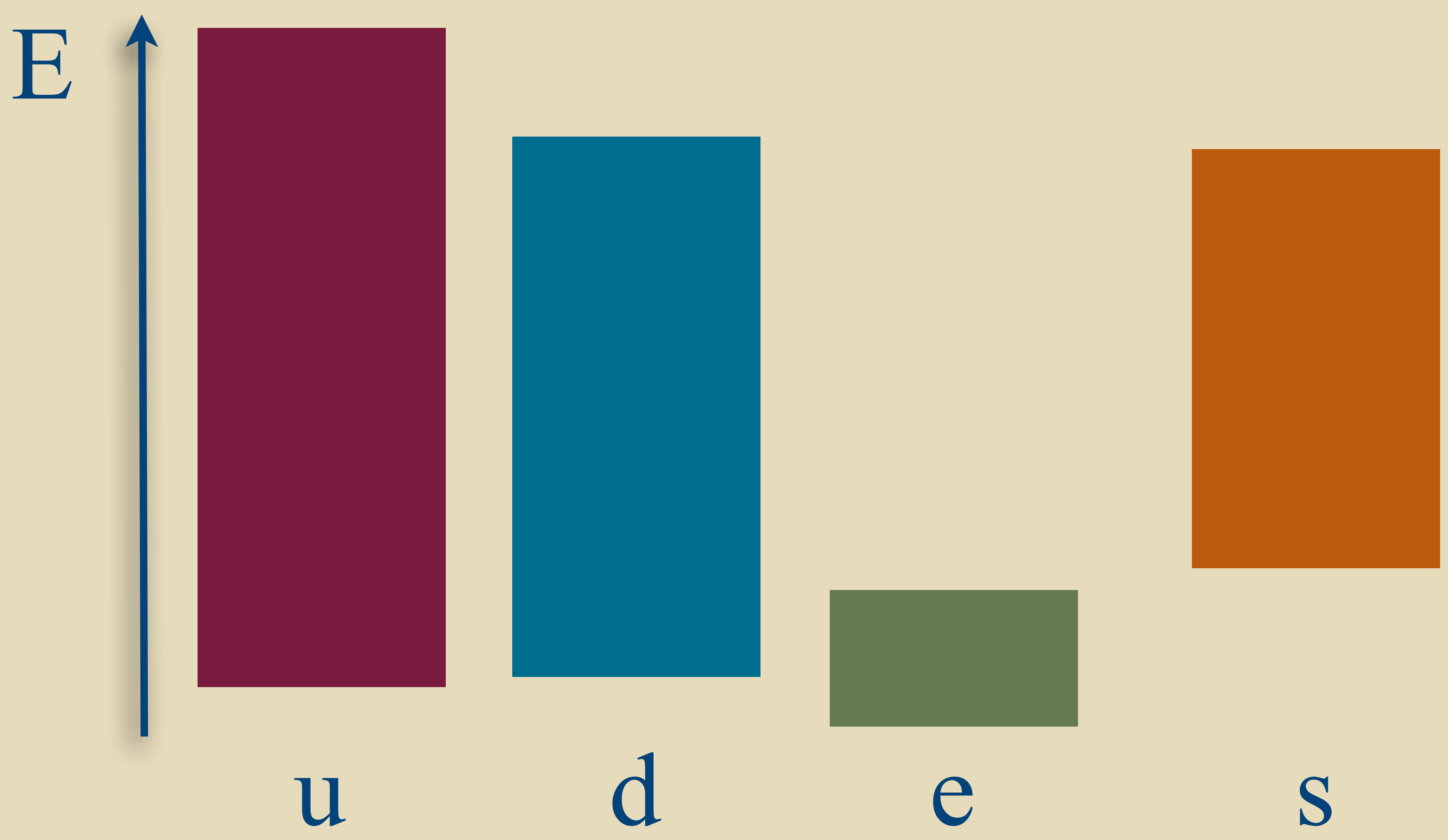


… or quark matter



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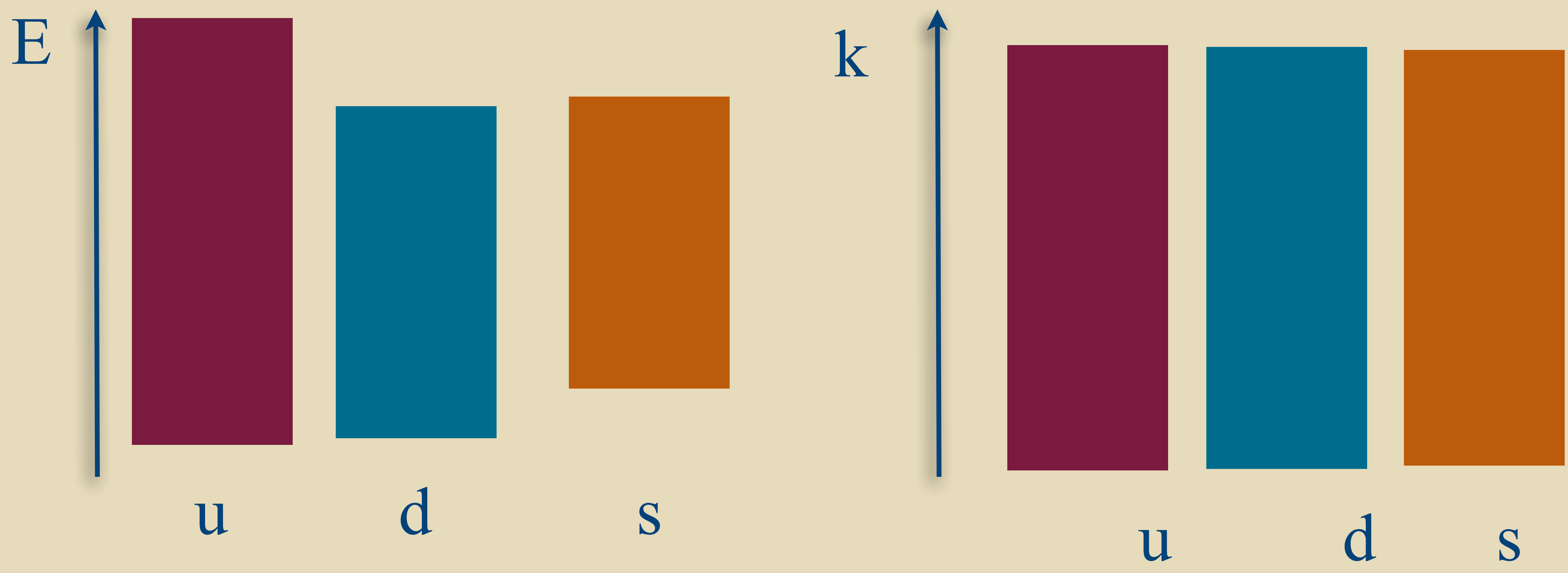


including pairing (CFL or K_0-CFL)
there maybe be no e^-

Theoretical Methods

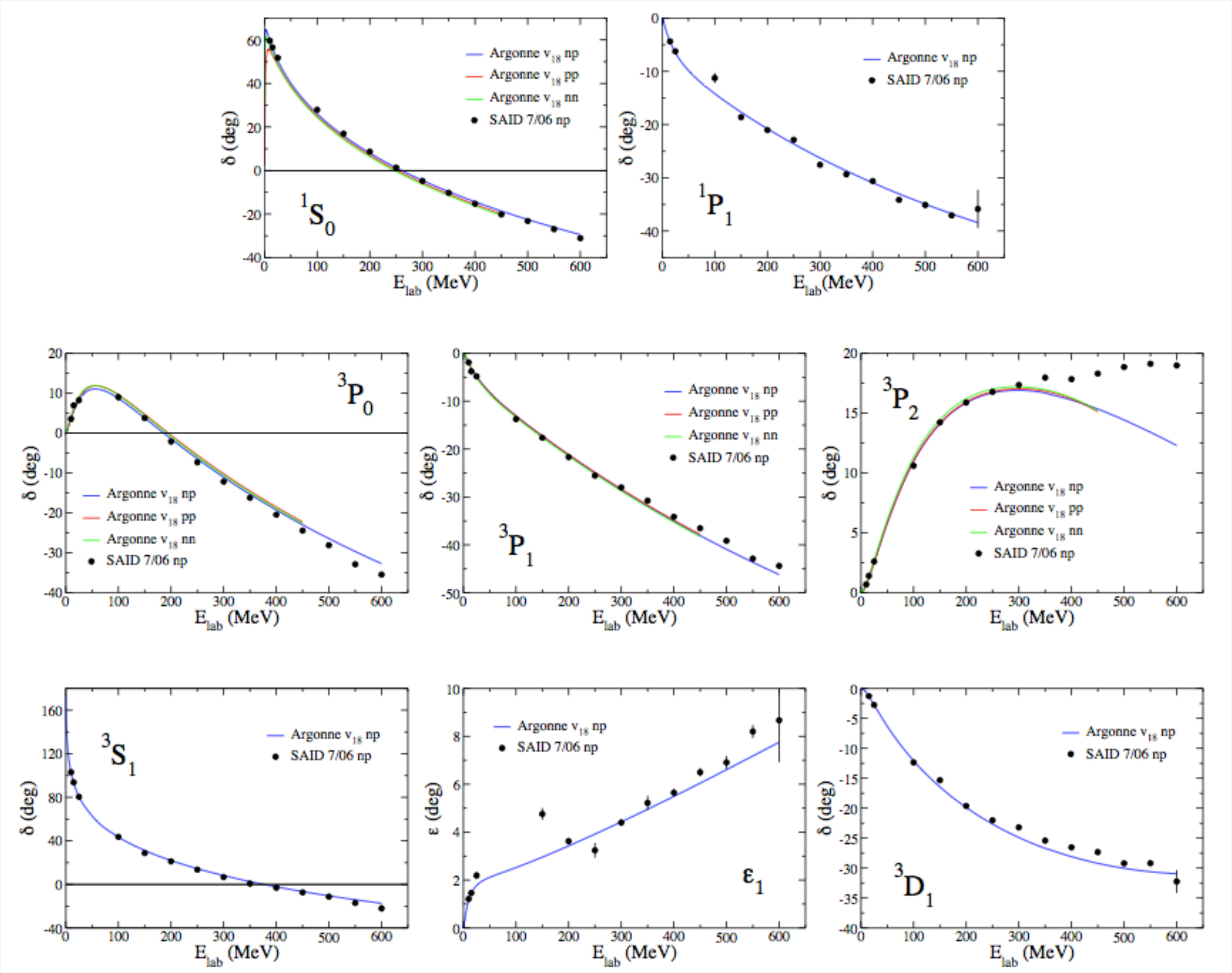
- lattice QCD: plagued by sign problem, but complex Langevin progress (?) (Aarts, Seiler, Stamatescu, Sexty, Bongiovanni, …) and Lefshets thimble (?) (Cristoforetti, Renzo, Scorzato, …)

$$Z_{QCD} = \int DA \, e^{-S_{glue}} \underbrace{det(\gamma.D + i\mu\gamma^0)}_{complex}$$

- perturbative QCD: α_s^2, $m_s > 0$ calculation completed (Kurkela, Romatschke, Vuorinen); relatively hard, valid for $n > 100\, n_0$

• Equation of state from nucleon scattering

Fancy potential (some “theory”+ fitting NN data), in this case, AV18 (Wiringa et al. ‘95)



Equation of state from nucleon scattering

Fancy potential (some "theory") fitting NN data (in this case, AV18)

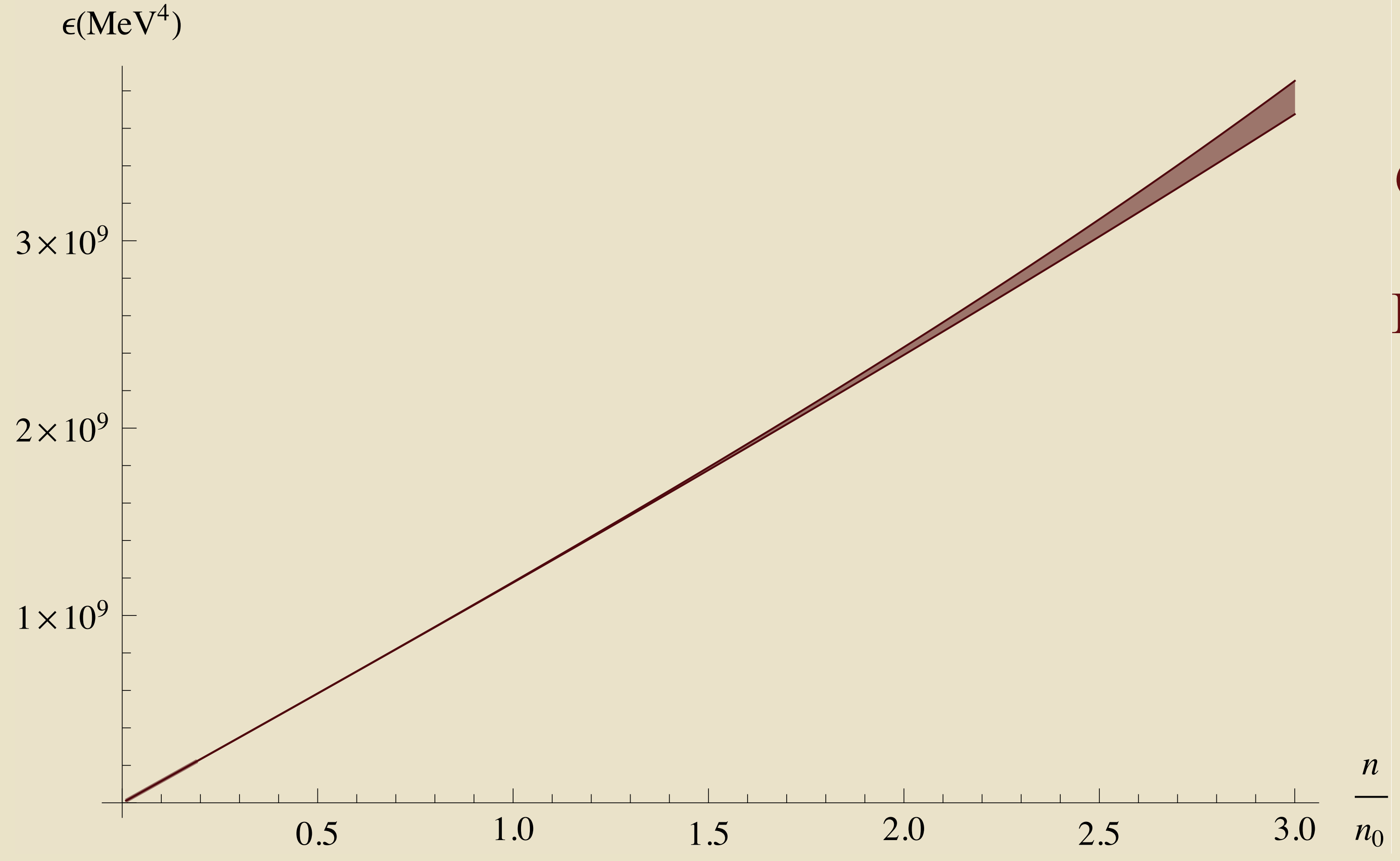
+

3-body force fitted to small nuclei

A lot of uncertainty here!
(functional form unknown)

Equation of state from nucleon scattering

Numerical, Monte Carlo method to solve the Schroedinger eq. (in this case Auxiliary Field Greens Function Monte Carlo Schmidt&Fantoni,'99)



Gandolfi et al.,'13 compatible with Hebeler et al., '13, …

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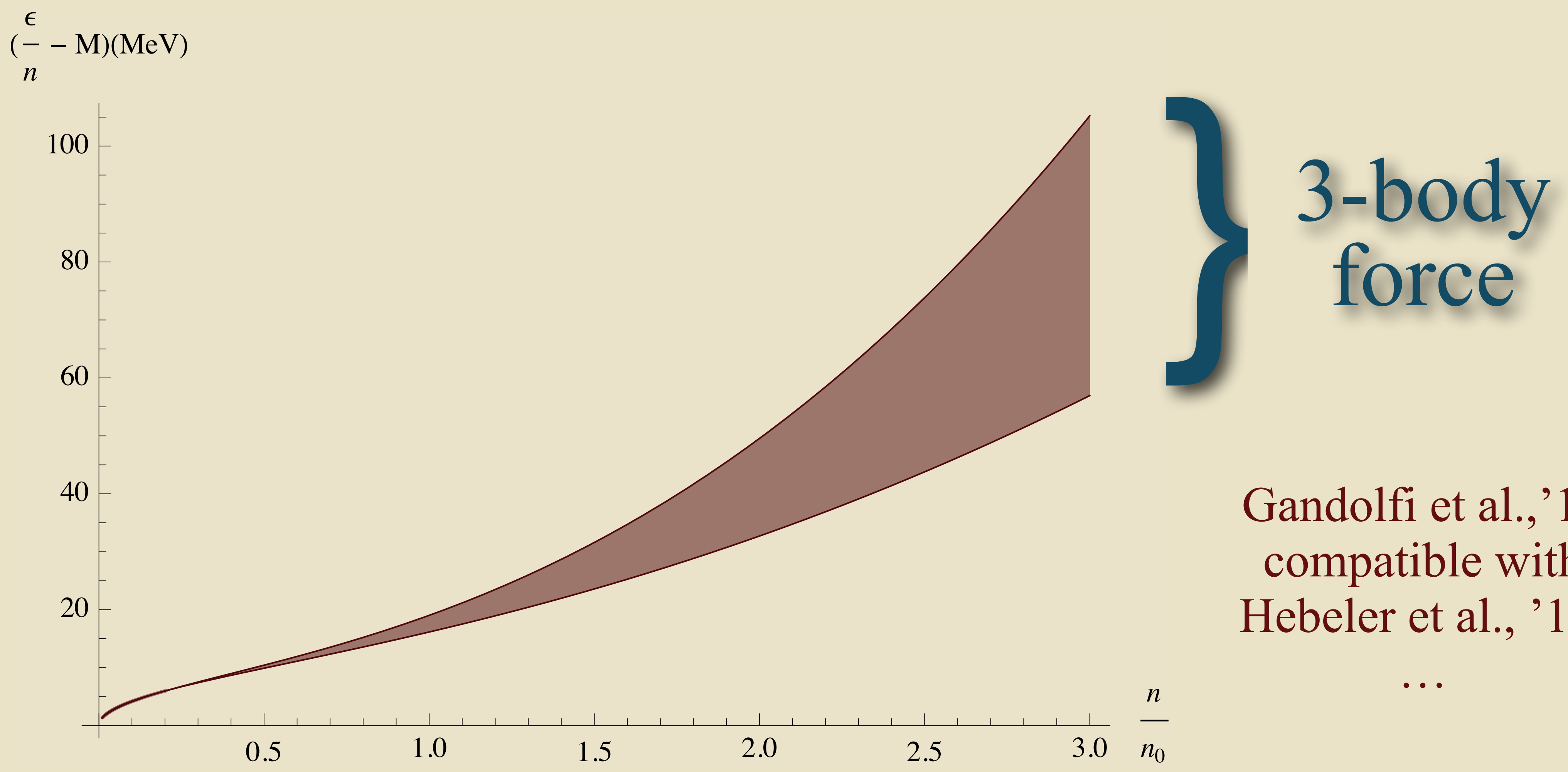

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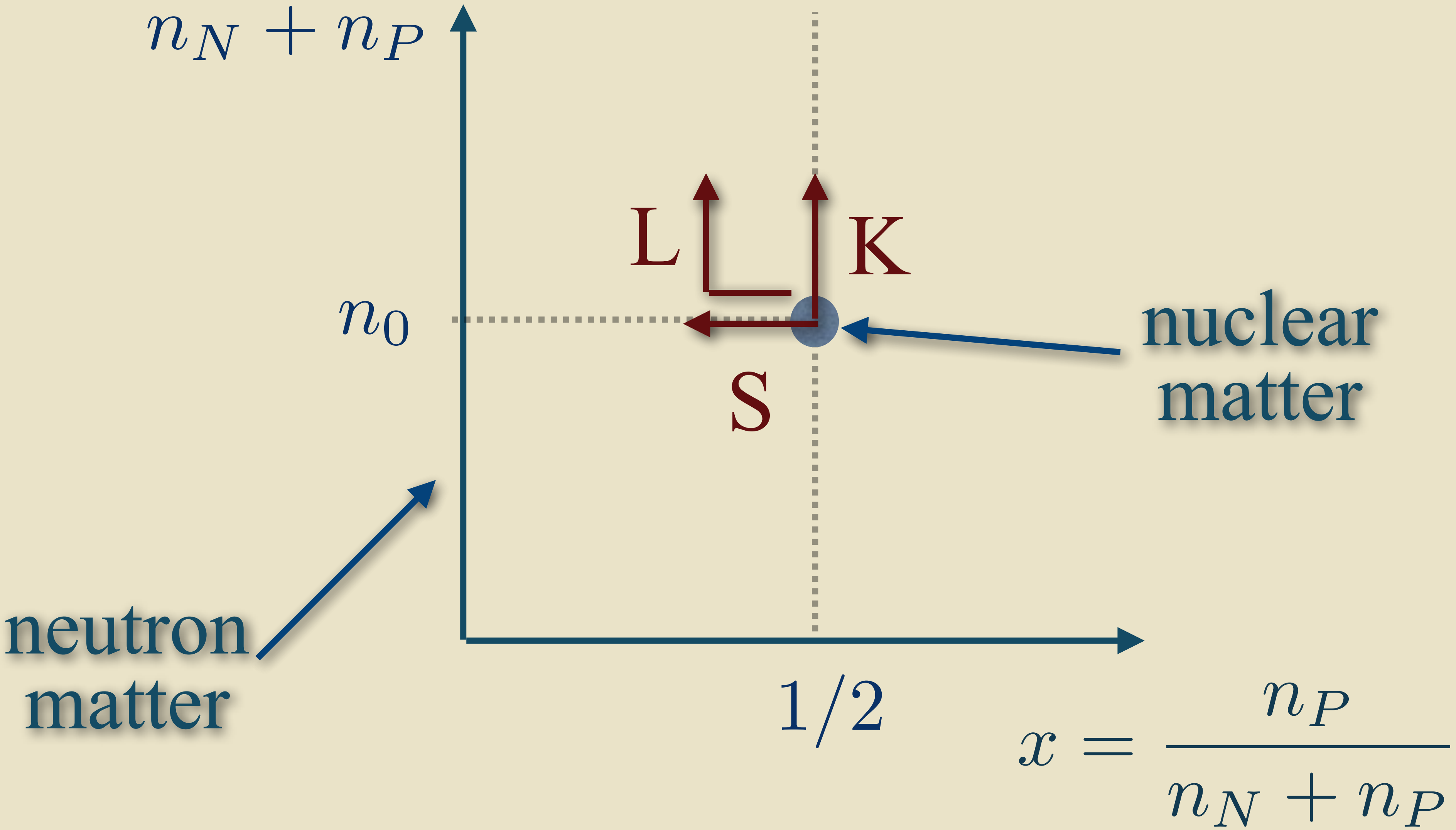
- Mass formula and extrapolations



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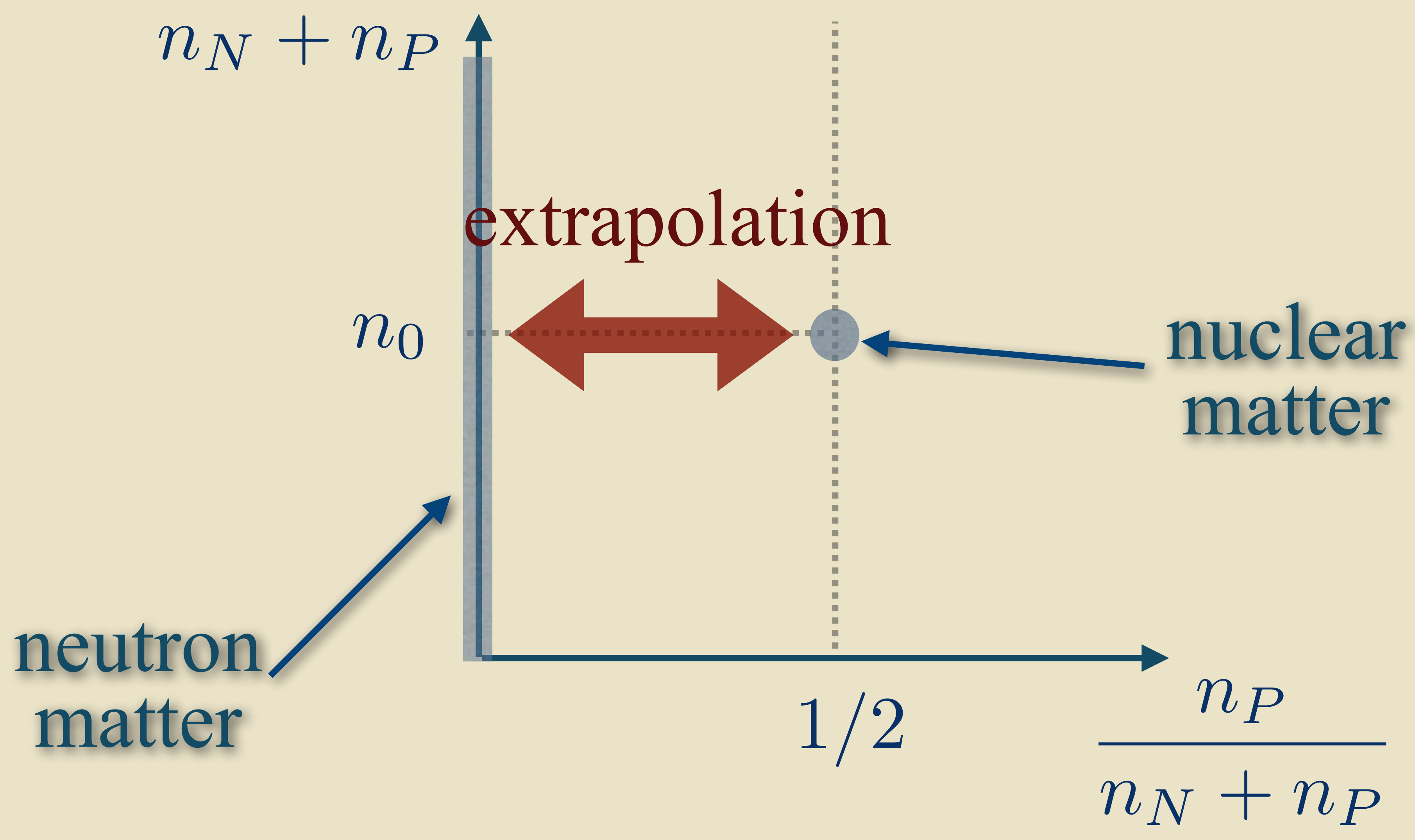


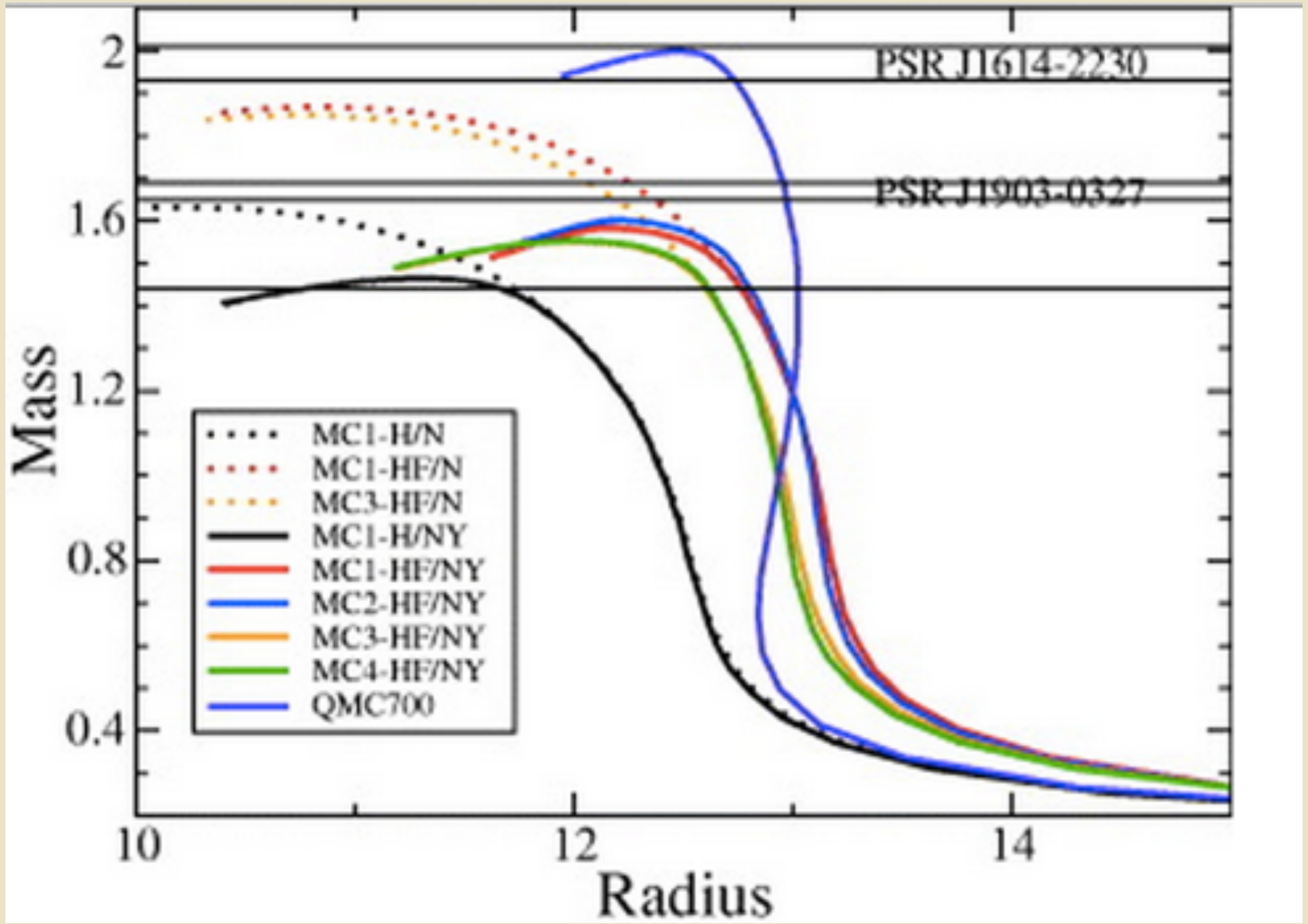
uncertainty due to 3-body force ~ uncertainty in S,L (PREX)

Neutron Stars

ε(p)
general relativity

→

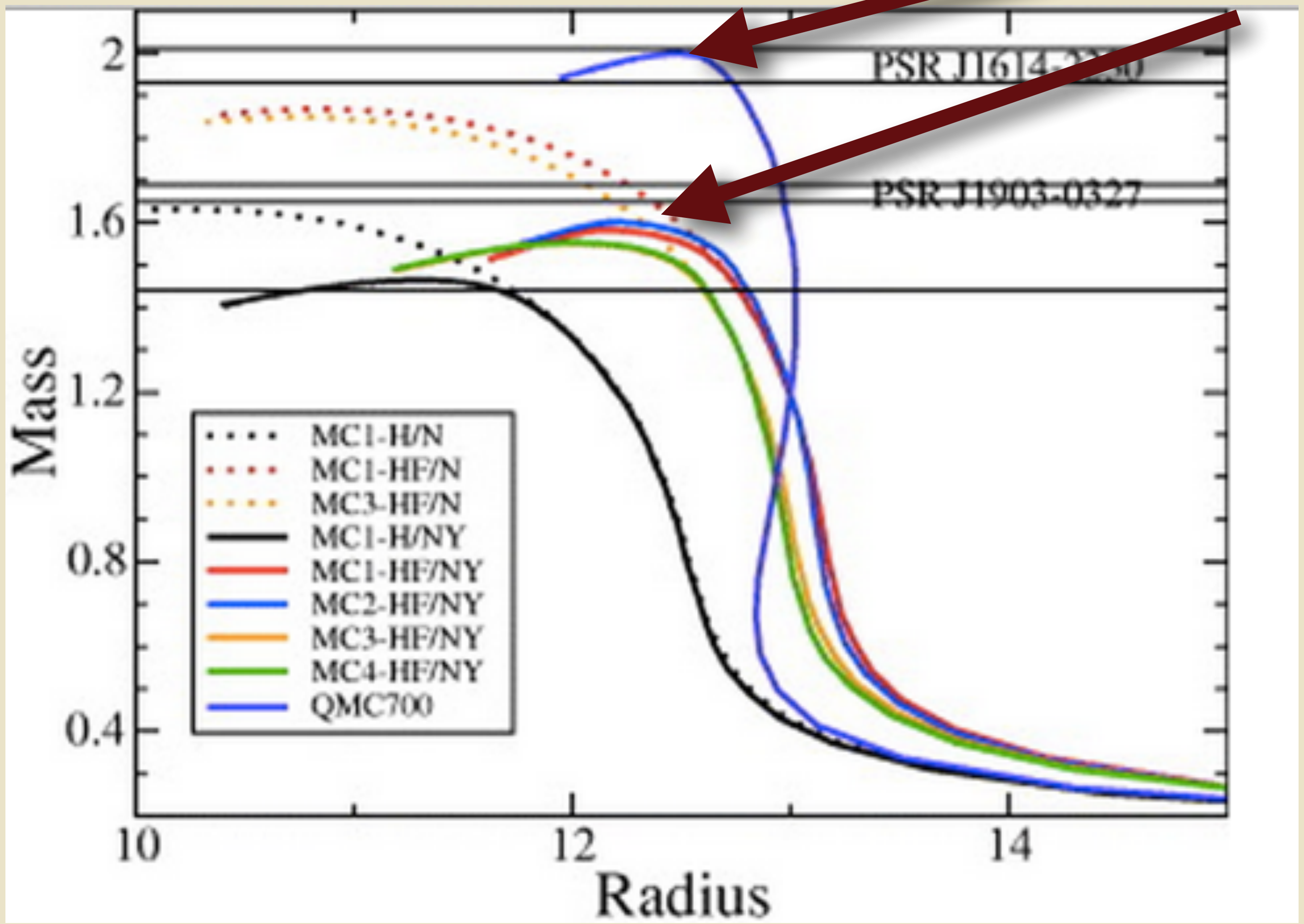
M x R



Neutron Stars

ε(p)
general relativity → M x R

maximum mass



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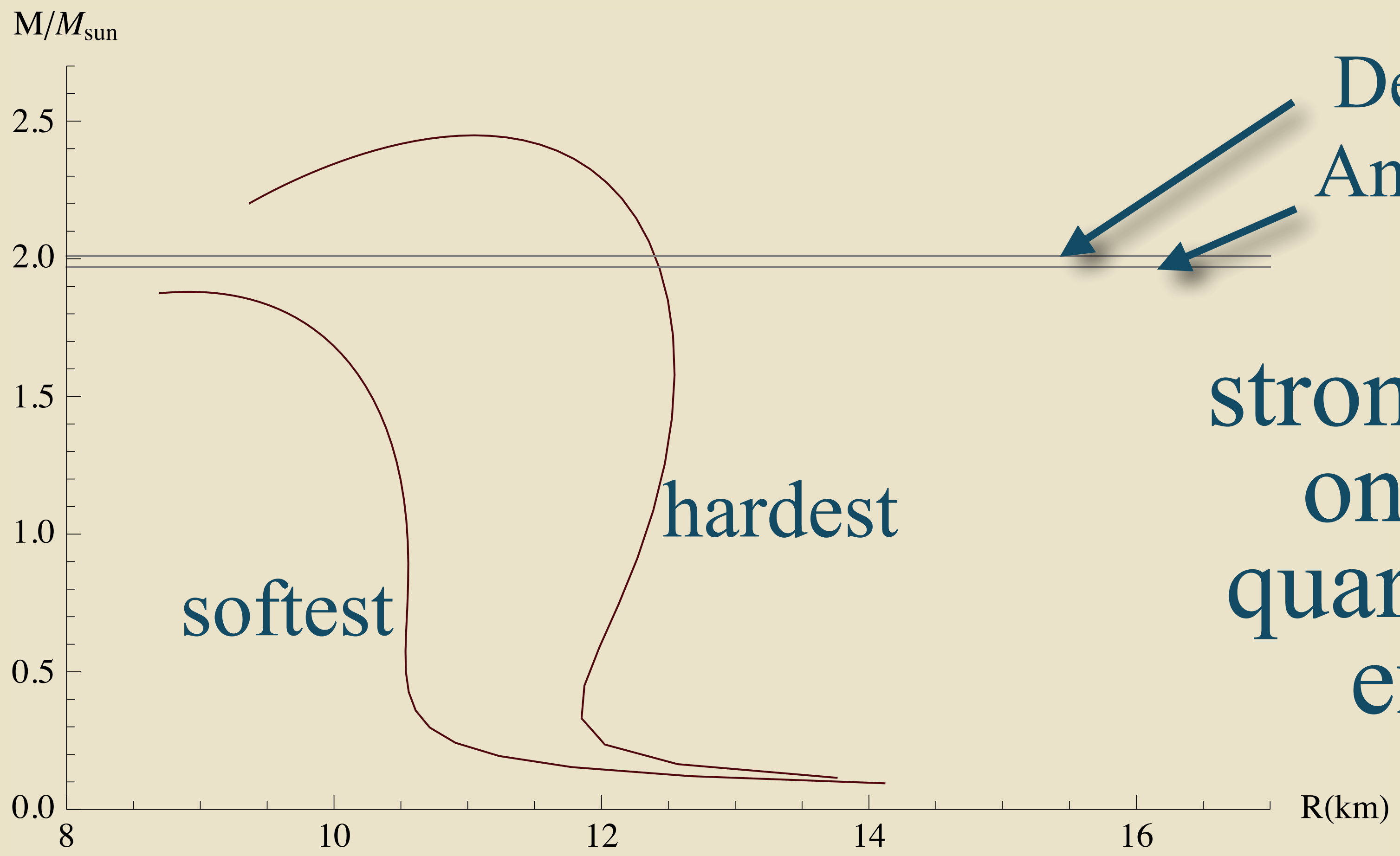
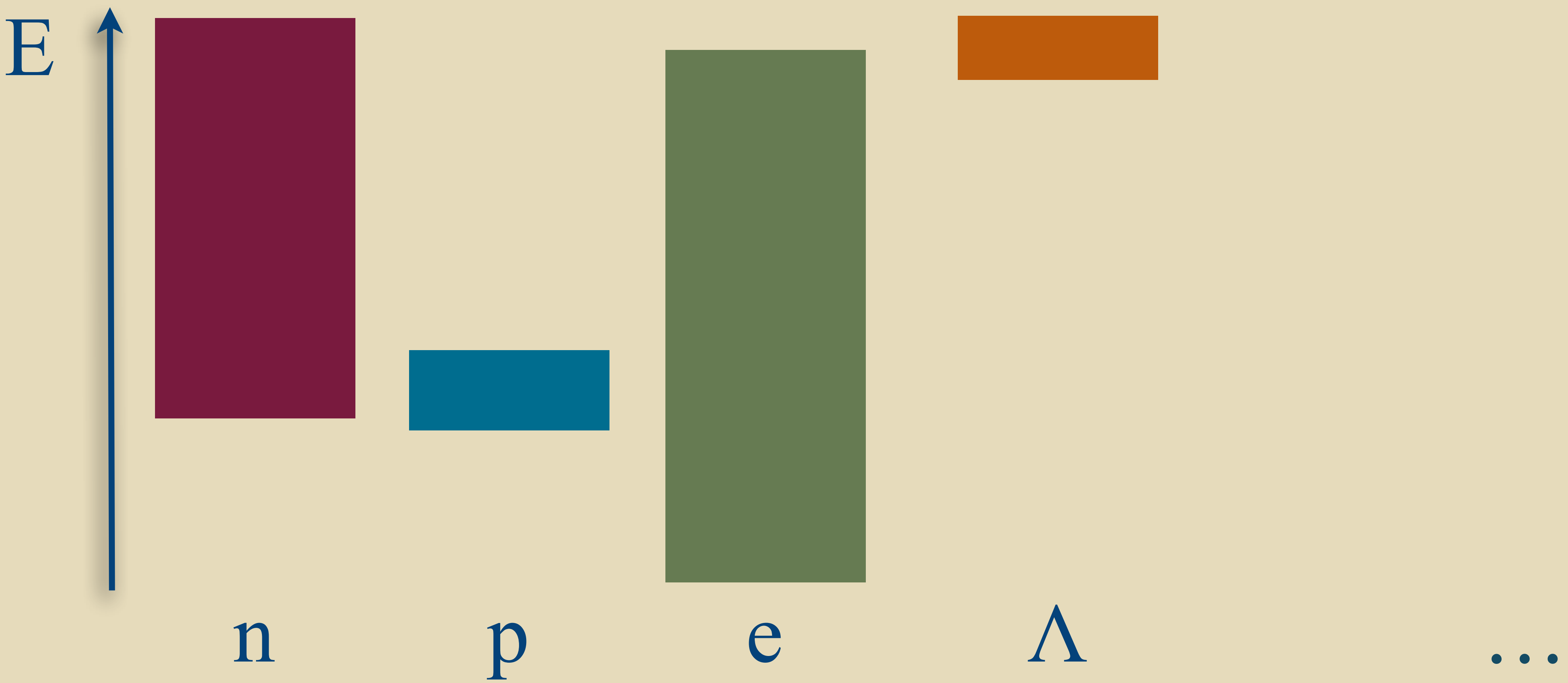


Demorest et al., '10
Antoniadis et al., '13

strong constraint on e.o.s. but quark matter no excluded!

Hyperons in dense matter



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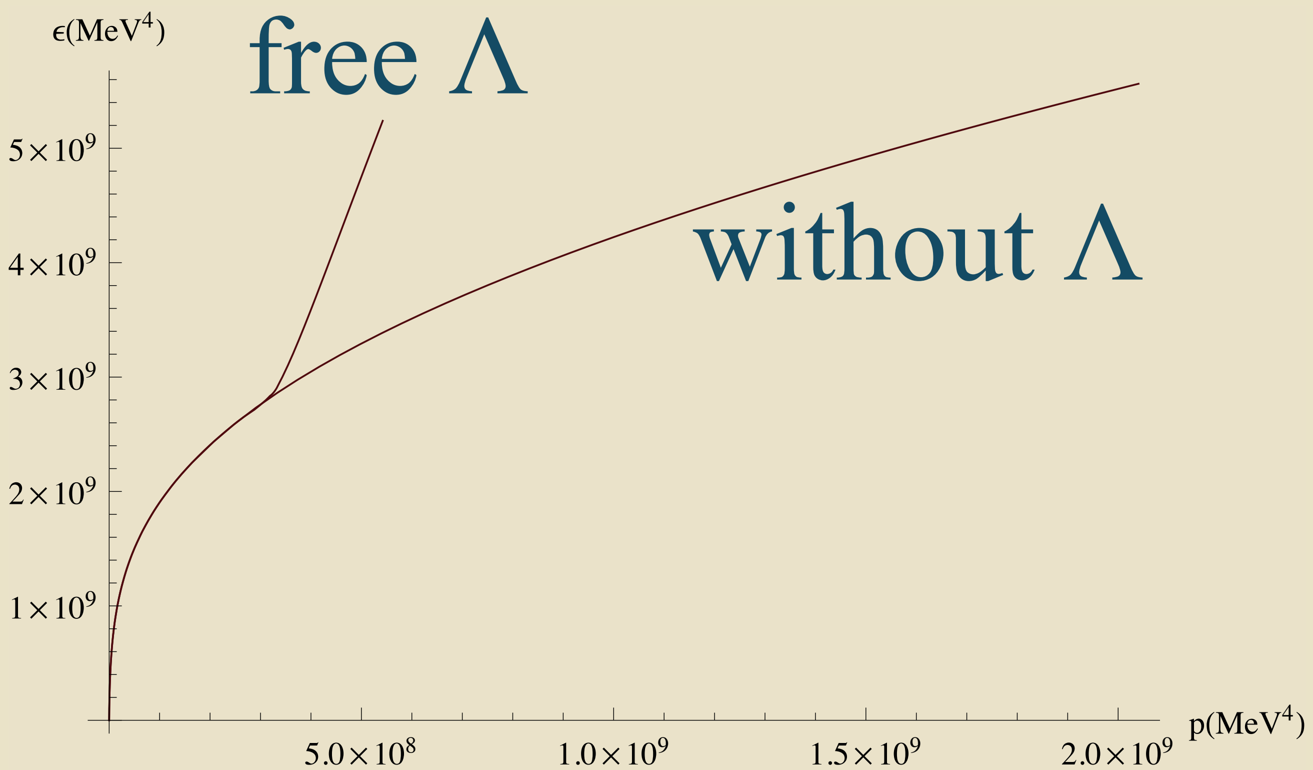

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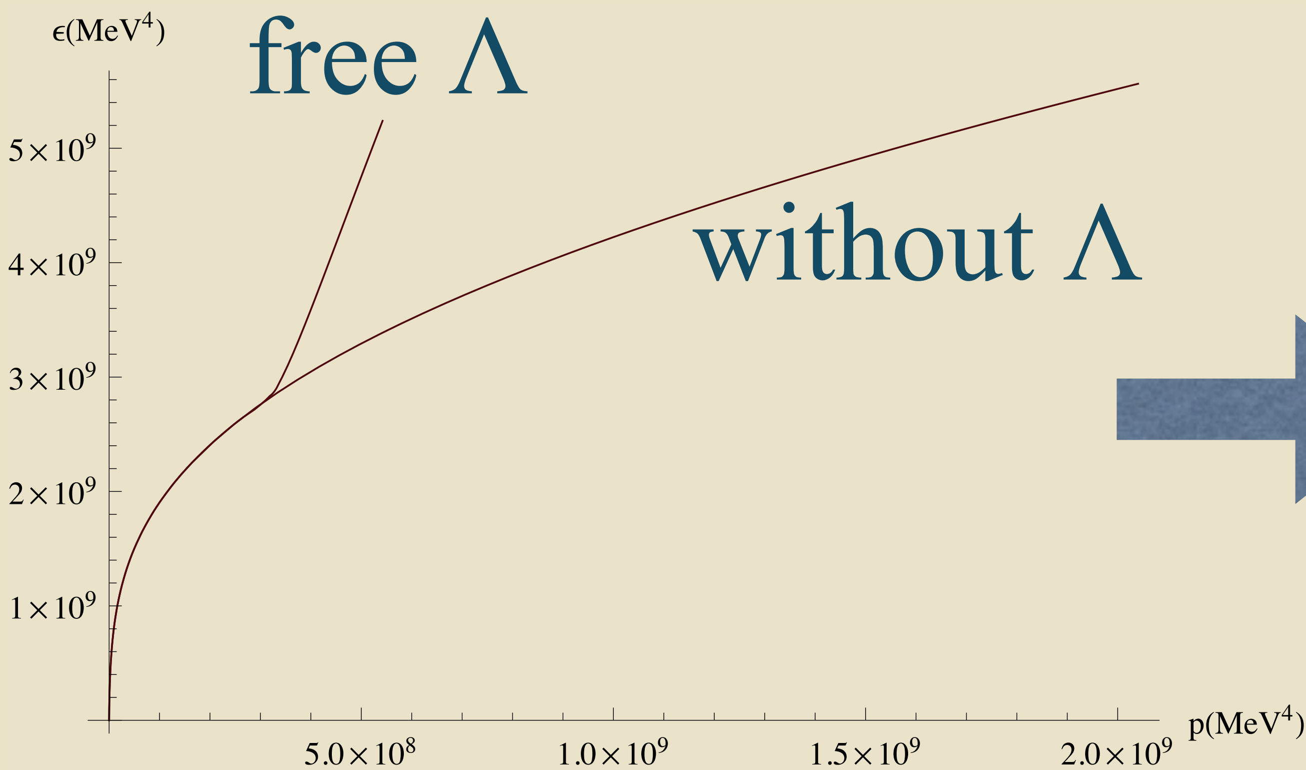
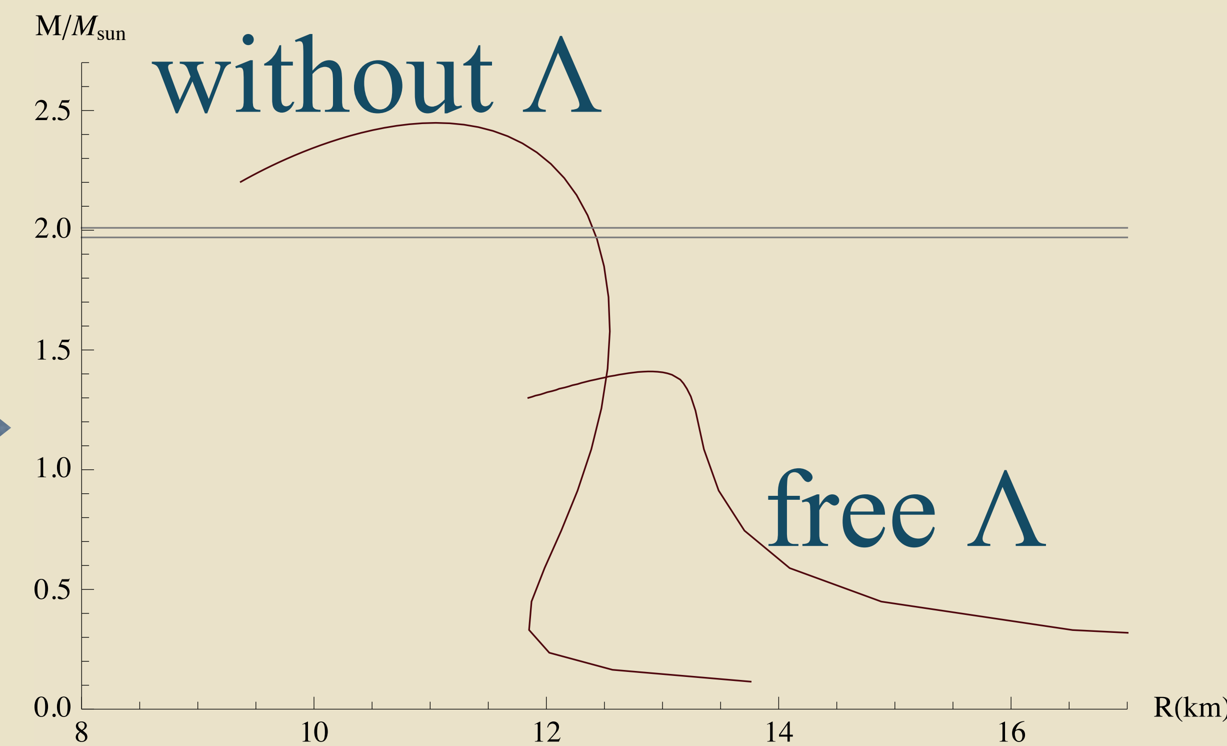




from hyper nuclei: ΛN is *attractive!*

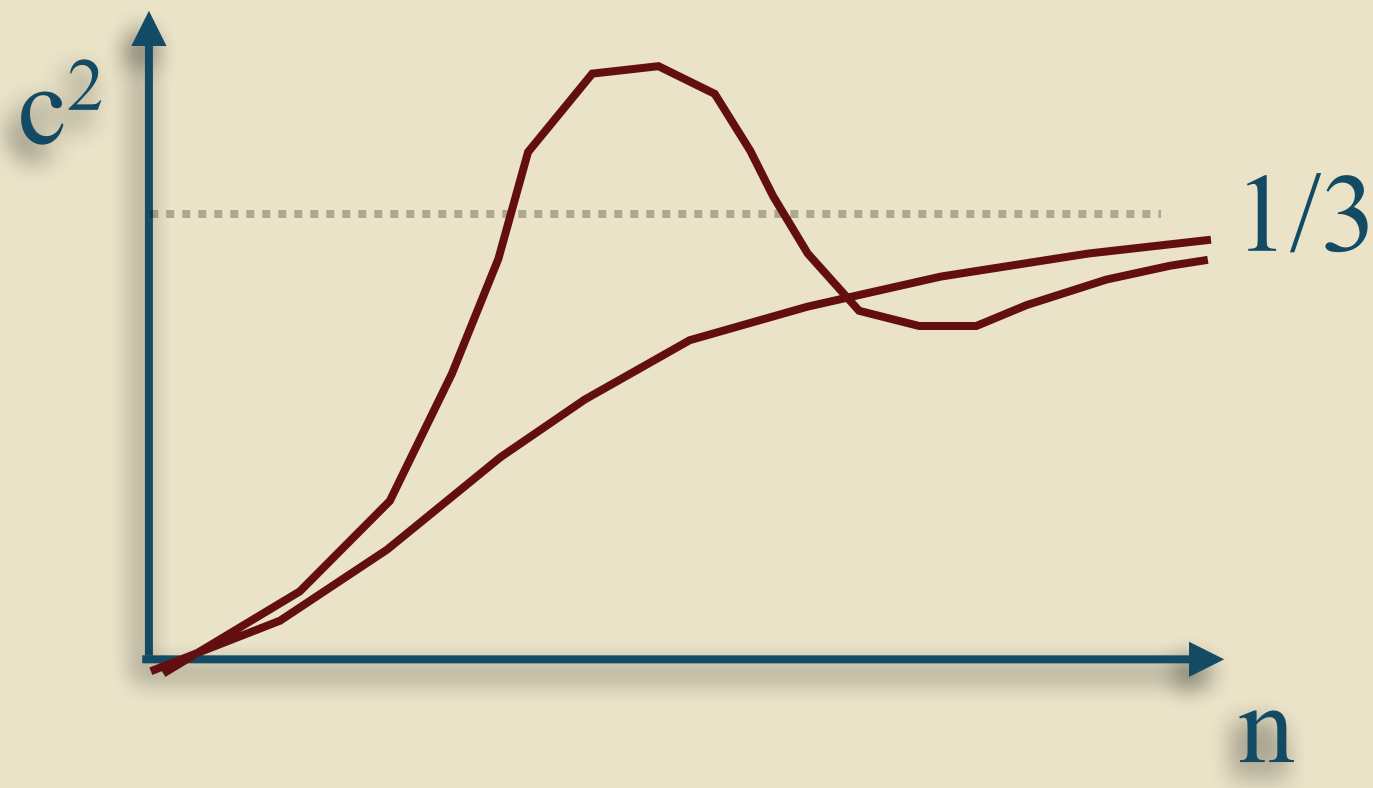
ΛNN strongly repulsive?

There are such forces that reproduce hypernuclei

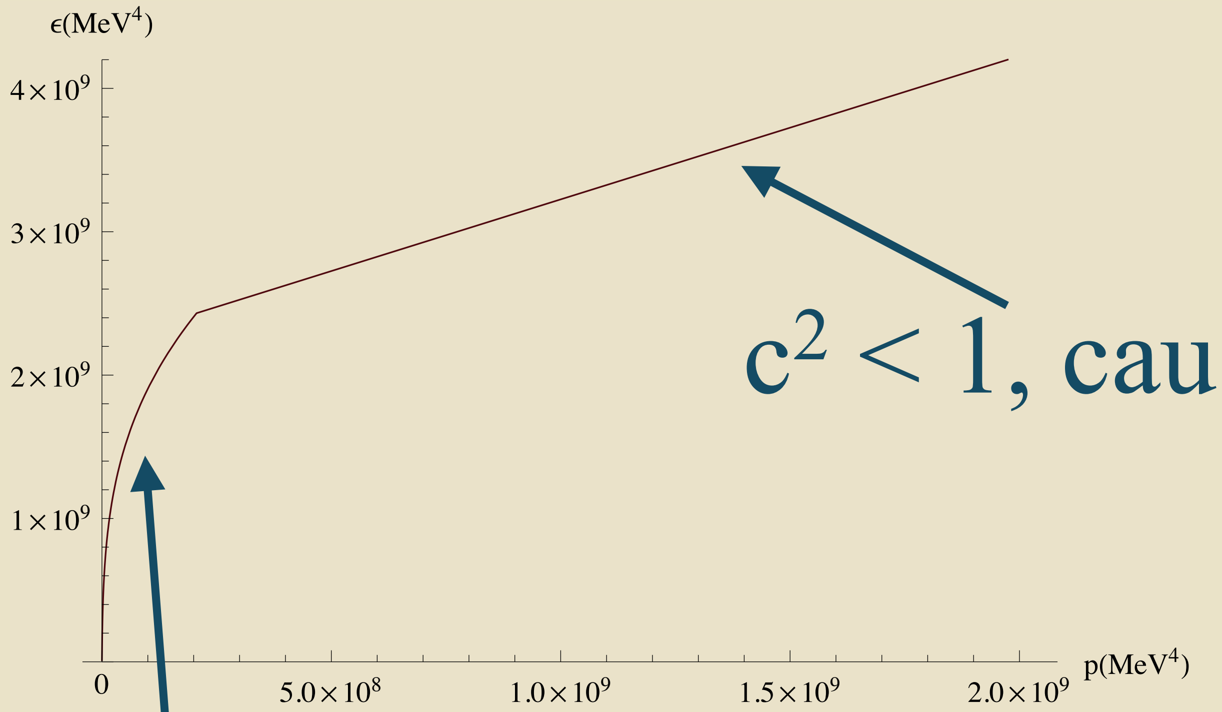
(Lonardoni et a., ‘14)

What is the maximum speed of sound ?

speed of sound → $$c^2 = \frac{dp}{d\epsilon}$$



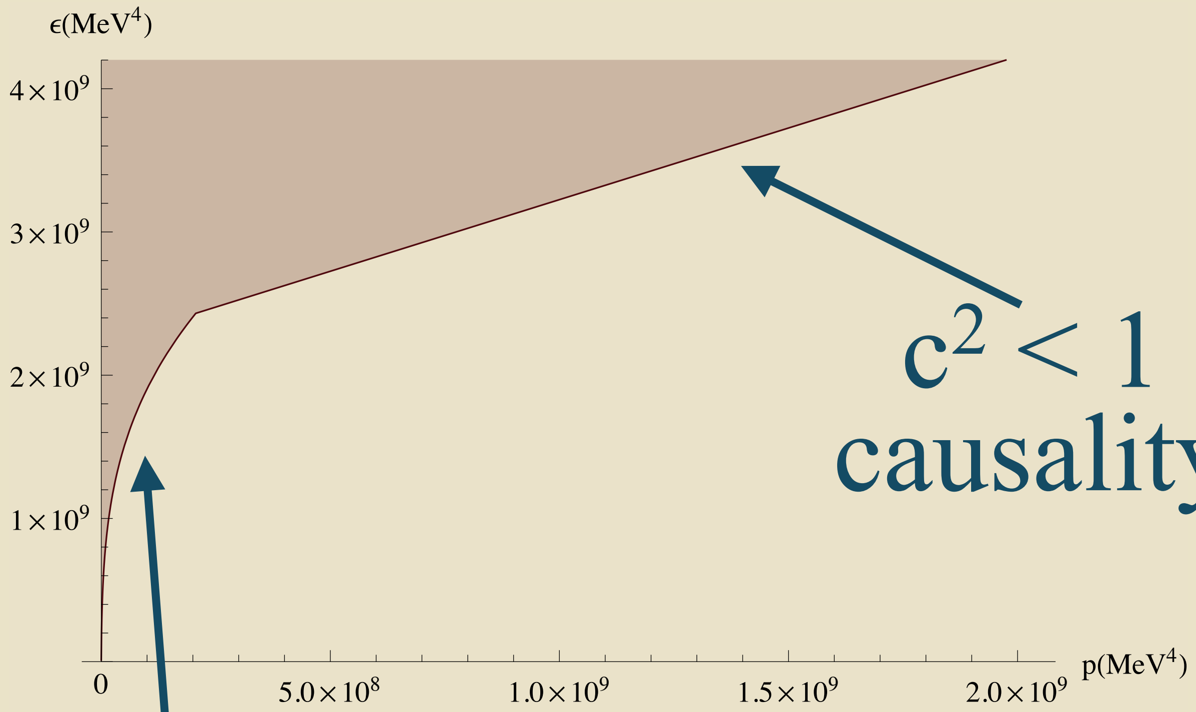
for sure $c^2 \leq 1$



$c^2 < 1$, causality

"known" low density

for sure $c^2 \leq 1$



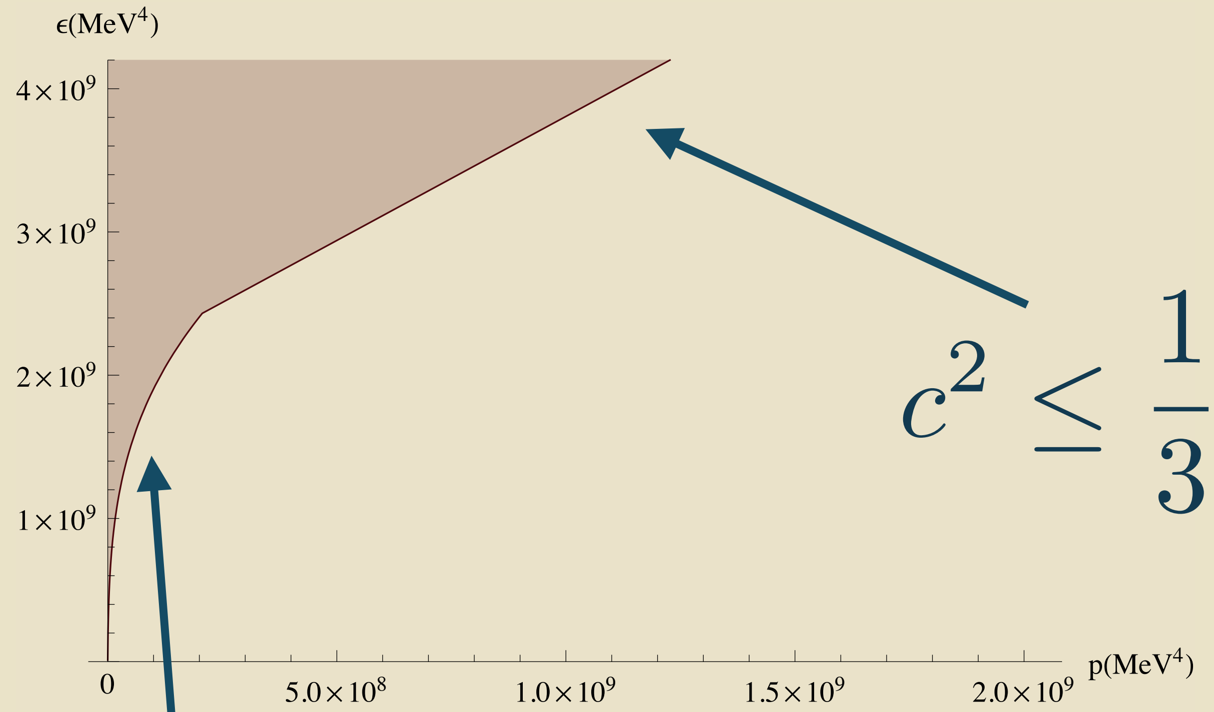
$c^2 < 1$
causality

"known" low
density

$M < 3.2\ M_{sun}$

Ruffini bound

$$c^2 \leq \frac{1}{3} \; ?$$



$$c^2 \leq \frac{1}{3} \Rightarrow M < 2\ M_{sun}$$

(Alford et al., P.B,Steiner, ‘14)

“known” low density

$c^2 < 1/3$ for free Fermi gas, weakly coupled gas, several holographic models, high T QCD, conformal theories, …

Beyond the eos: other observables probe more subtle aspects of dense matter

cooling curves
(anti) glitches
flare oscillations
r-modes
gravitational waves from mergers
...

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cooling curves (anti) glitches flare oscillations r-modes gravitational waves from mergers ...	↔	neutrino emissivity specific heat viscosities heat conduction superfluidity/ conductivity ...

Beyond the eos: other observables probe more subtle aspects of dense matter

cooling curves
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flare oscillations
r-modes
gravitational waves from mergers

neutron star seismology
...

↔

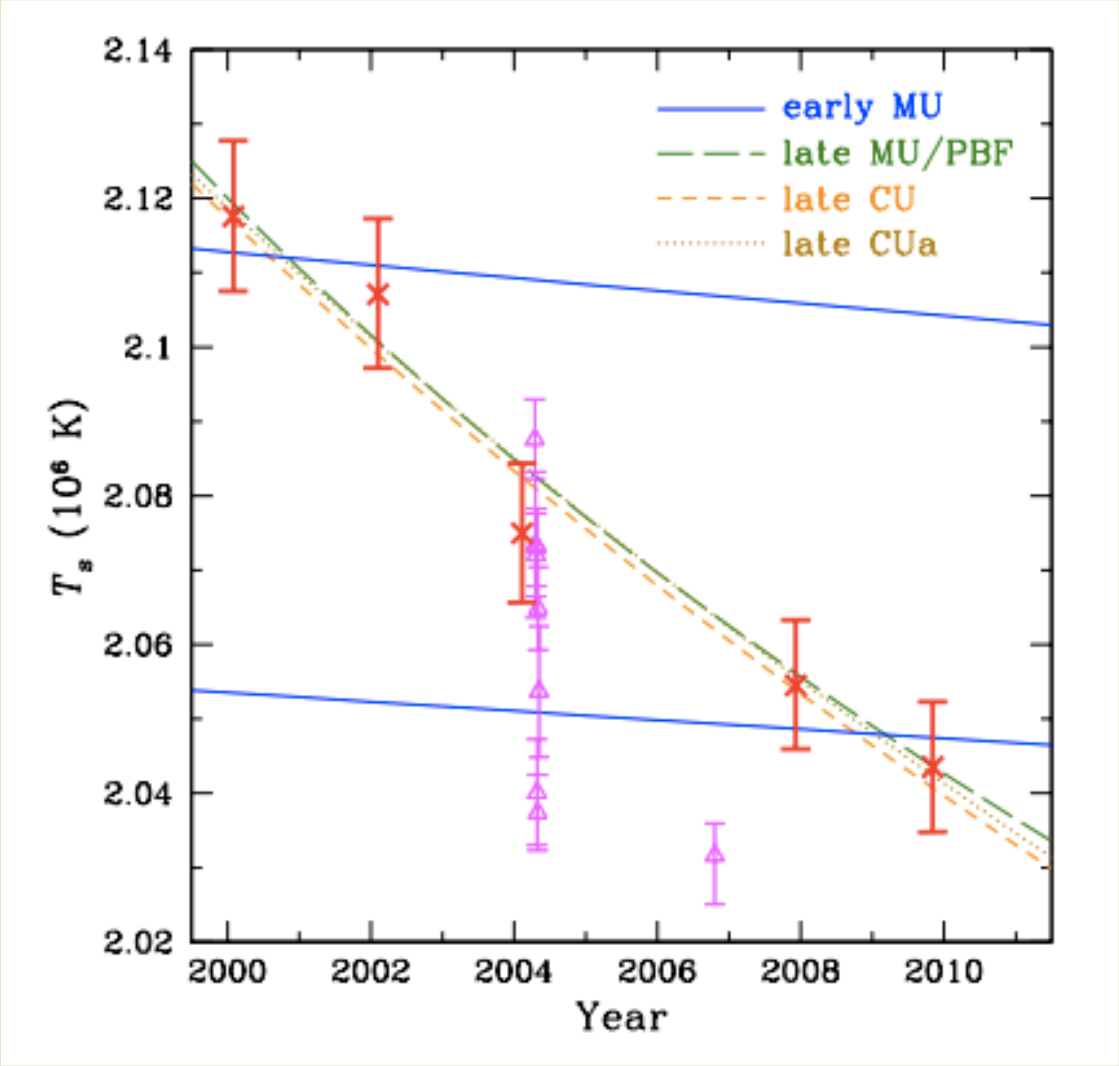
ν emissivity
specific heat
viscosities
heat conduction
superfluidity/conductivity
...

←

low lying excitations (unpaired fermions, Goldstones)

neutron matter is superfluid

Cooling of Cassiopeia A:

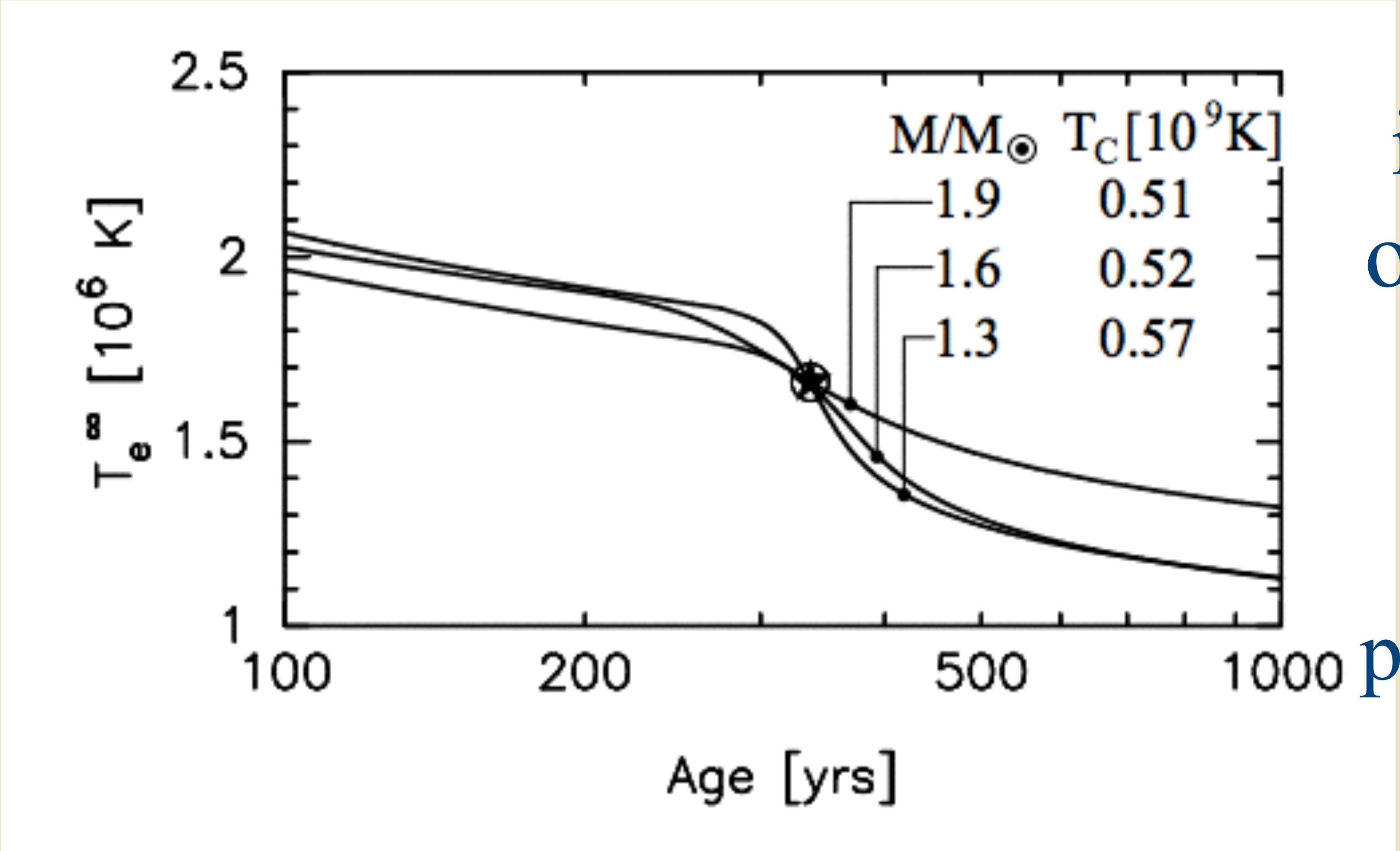


Heinke&Ho, 2007

interpreted as the result of formation/breaking of Cooper pairs (Shternin et al.,Page et al. ,'11)
but other interpretations possible (Blaschke, Sedrakian,…)

low temperature fact: neutron matter is superfluid

Cooling of Cassiopeia A:



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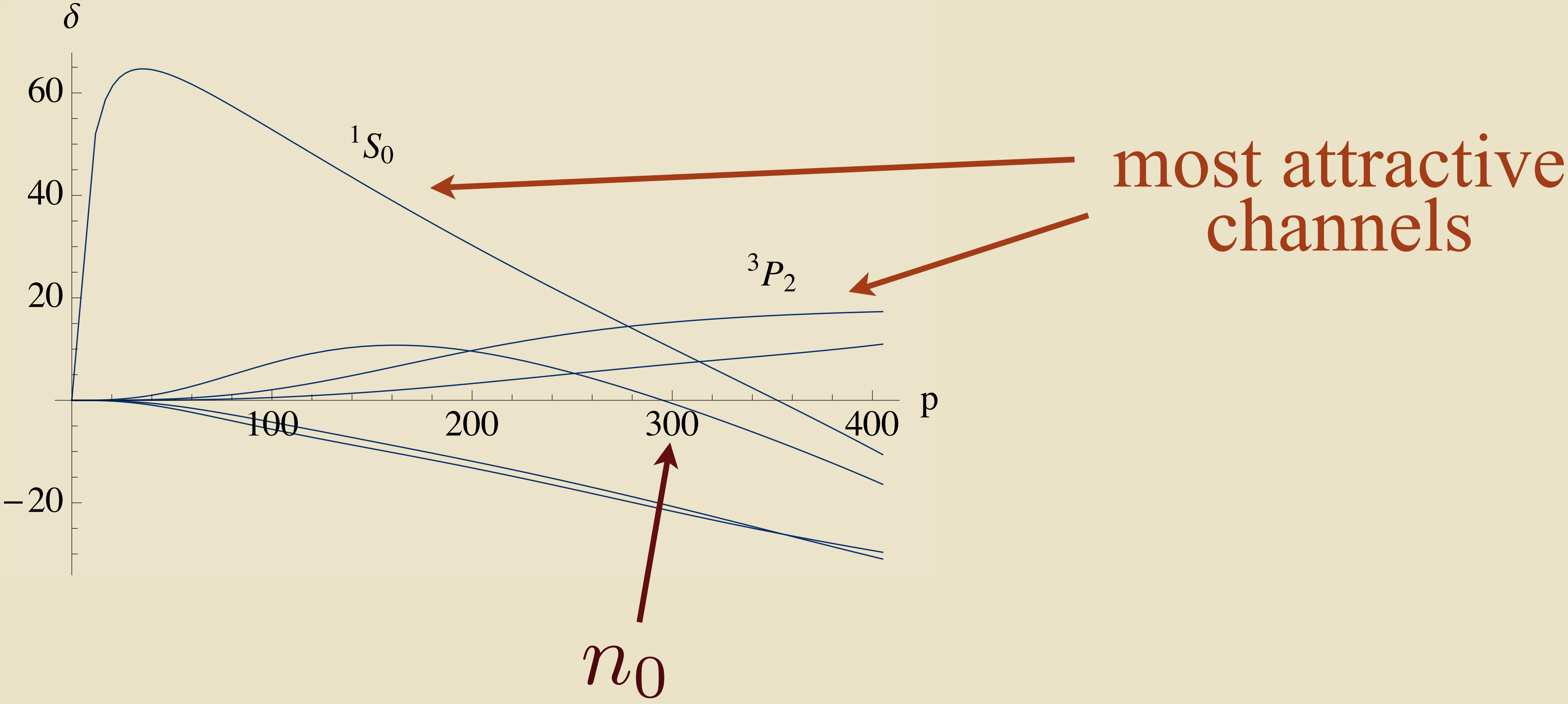
What are the attractive forces?



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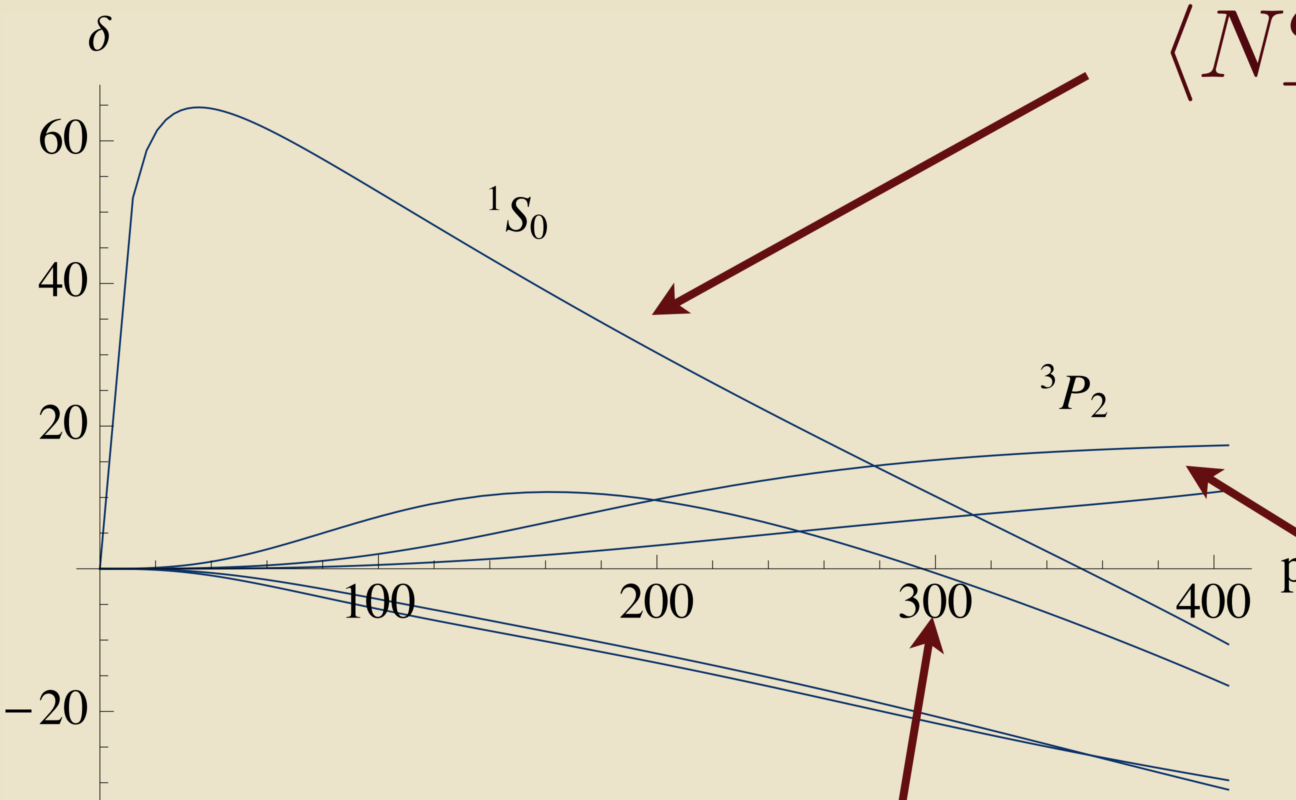
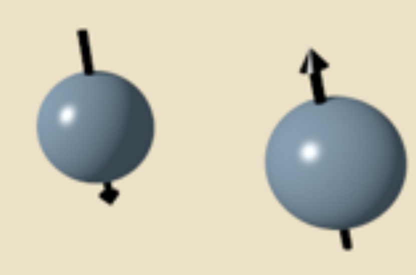
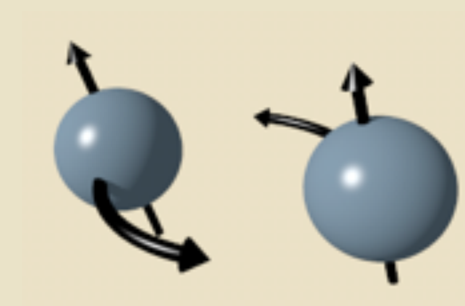


nuclear density

$$\langle N^{\alpha}_{-p} N^{\beta}_{p} \rangle = \Delta \ \delta_{\alpha\beta}$$



$$\langle N^{\alpha}_{-p} N^{\beta}_{p} \rangle = \Delta^{ij} \ (\sigma_2 \sigma^i)_{\alpha\beta} p^j$$



Spontaneous symmetry breaking

$$\langle N^T \sigma_2 N \rangle = e^{i\alpha}$$

$U_B(1) \to \mathbb{Z}_2$

1 Goldstone boson (phonon)

$$\langle N^T \sigma_2 \sigma_i \nabla_j N \rangle = e^{i\alpha} \Delta_{ij}$$

$SO(3) \to U_z(1) \times \mathbb{Z}_2$

traceless, symmetric tensor

1+2 Goldstone bosons (phonon +“angulons")

P.B., Rupak,Savage, ‘03

soft GBs couple weakly so they have large mean free paths but:

$$n_e \sim \mu_e^2 T \ll n_{GB} \sim T^3$$

too many electrons!

The importance of the superfluid phonon in transport in neutron matter is being debated (P.B, Reddy, Tolos, Manuel, …)

In quark matter it is definitely important

In a nutshell:

- 2 M_{sun} stars put a strong constraint on e.o.s (but quark matter still alive)
- Cas A cooling suggests superfluidity
- $n < 2\ n_0$ very constrained by nuclear physics
- at what density quark matter appears ?
- hyperon problem

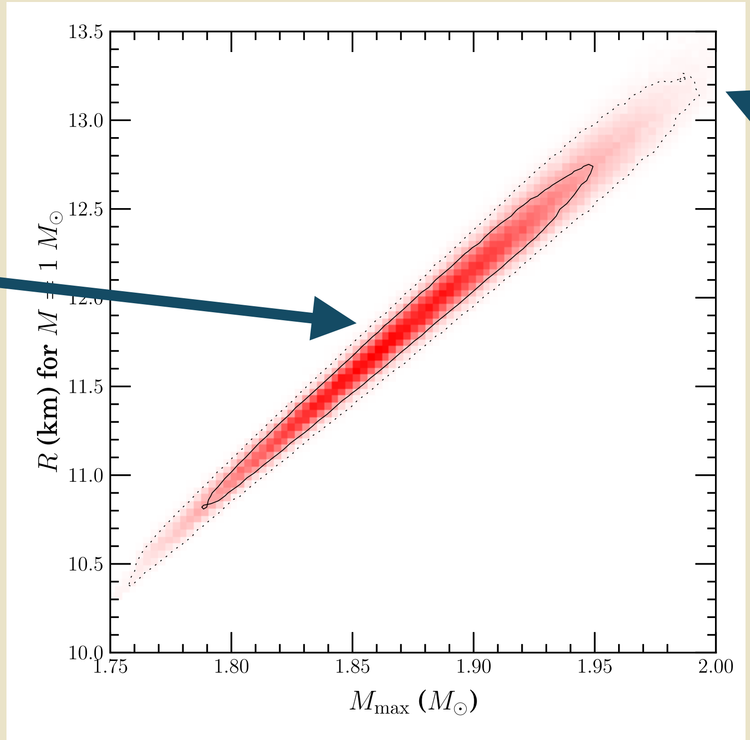
Speed of sound bound?

$$c^2 = \frac{d\epsilon}{dp} \leq \frac{1}{3} \;?$$

speed of sound

for free Fermi gas, weakly coupled gas, several holographic models, high T QCD, conformal theories, …

Probably not:
"reasonable models" for $n<2n_0$, $c^2=1/3$ for $n>2\, n_0$



$M=2M_{sun}$ nearly excluded
(Alford et al., P.B,Steiner, '14)