Neutron stars & multi-messenger physics

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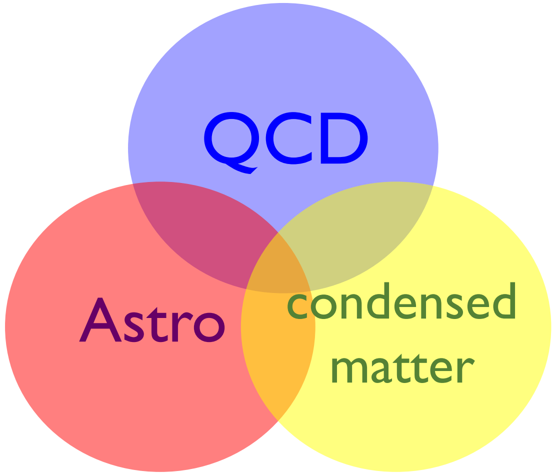
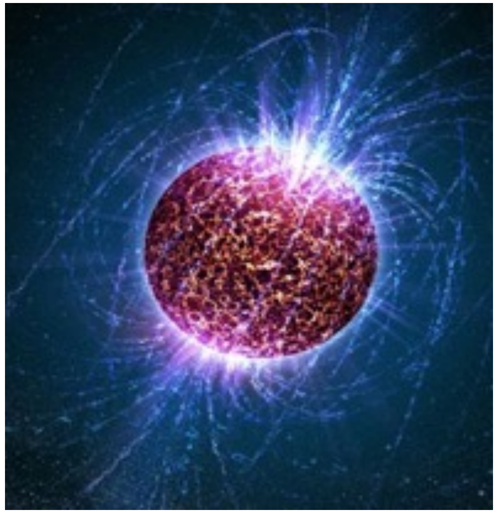
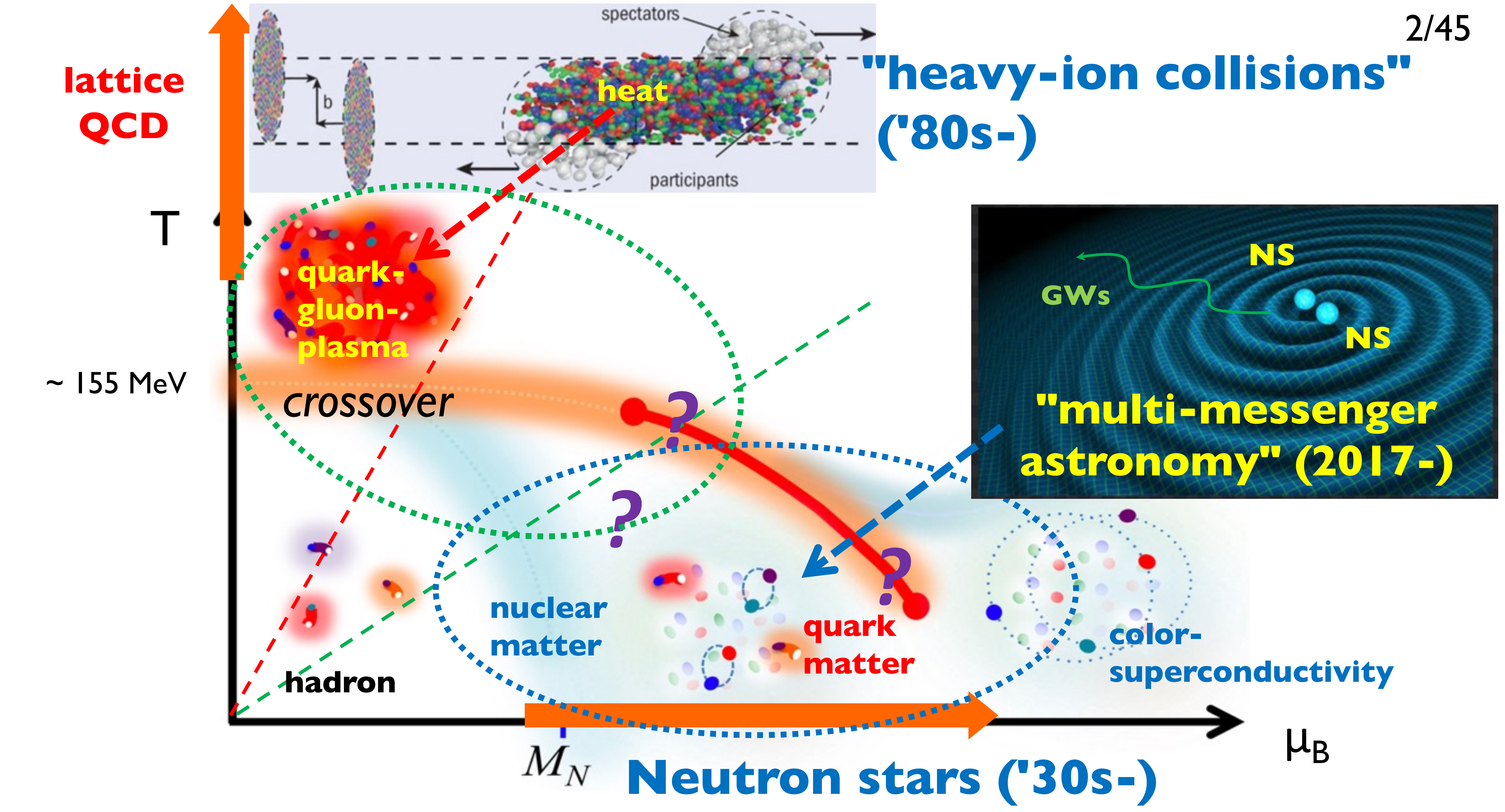




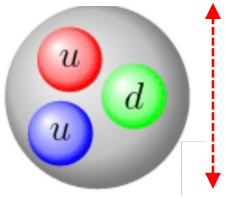

lattice
QCD
spectators
b
heat
participants
"heavy-ion collisions"
('80s-)
T
quark-
gluon-
plasma
~ 155 MeV
crossover
?
?
?
NS
GWs
NS
"multi-messenger
astronomy" (2017-)
nuclear
matter
quark
matter
color-
superconductivity
hadron
M_N
μ_B
Neutron stars ('30s-)

Scales & units to be used

dynamical scale

- $\Lambda_{QCD} \sim 200$ MeV $\sim 1\,\mathrm{fm}^{-1}$

proton



$\sim \Lambda_{QCD}^{-1}$

mass

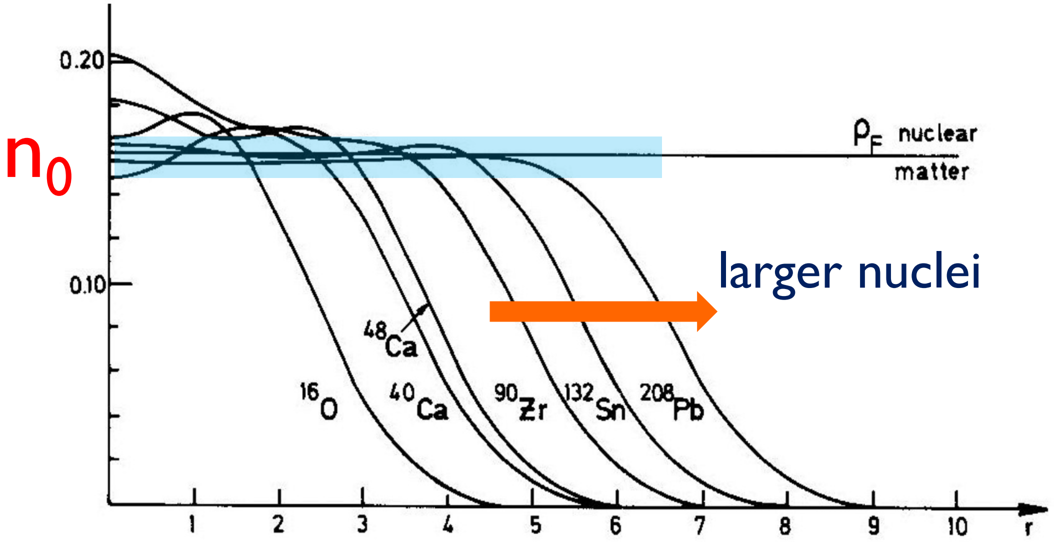
$M_N \sim N_c \Lambda_{QCD} \sim 1$ GeV

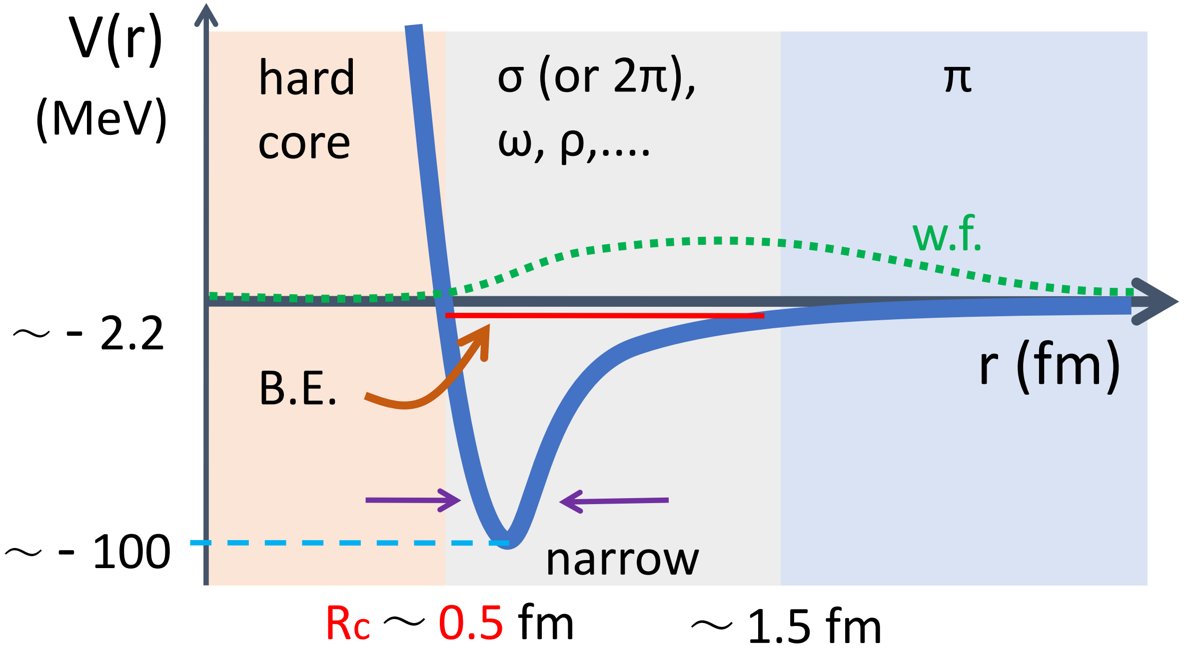
- saturation density: $n_0 = 0.16\ \mathrm{fm}^{-3}$

(~ central density of nuclei)

- nuclear binding E : O(1-10) MeV

(unnaturally small !!)

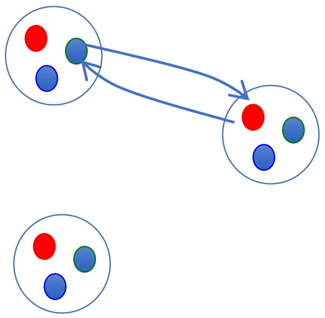




State of matter: overview

(n_0 = 0.16 fm^{-3}) [Masuda+ '12; TK+ '14]

- few meson exchange
- nucleons only

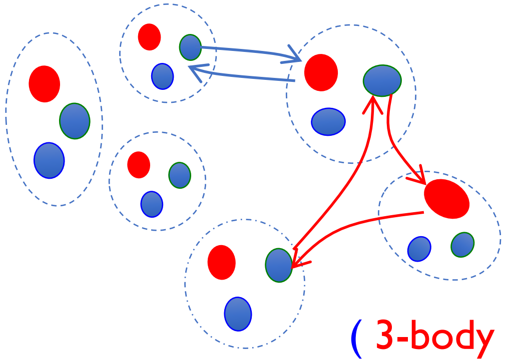


ab-initio nuclear cal.

laboratory experiments

steady progress

- many-quark exchange
- structural change,...
- hyperons, Δ, ...

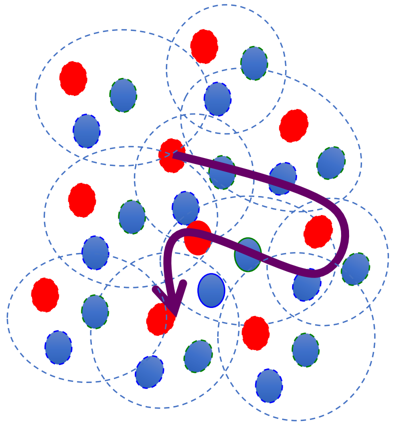


(3-body)

most difficult

(d.o.f ??)

- Baryons overlap
- Quark Fermi sea



strongly correlated

(d.o.f : quasi-particles??)

not explored well

(pQCD)

[Freedman-McLerran, Kurkela+, Fujimoto+...]

n_B

~ 1.4 $M_\odot$ ~ 2 $M_\odot$

~ $2n_0$ **Hints from NS** ~ $5n_0$ ~ $40n_0$

Plan

Lect 1) Overview: NS phenomenology & QCD

- glancing at NS properties
- M-R relation and EOS
- $R_{1.4}$ & low density EOS

Lect 2) NS-NS mergers

- gravitational waves
- pre-mergers [inspiral & tidal deformation]
- post-mergers [EM-counterparts]

Lect 3) From hadrons to quarks in NS

- quark matter
- 3-window modeling
- stiffening of matter in quark-hadron continuity

Glancing at neutron star properties

Neutron stars (NSs)

rot. period : $P \sim$ 1ms – 1s (~ 10^{-9} – 10^{-6} $P_\odot$)

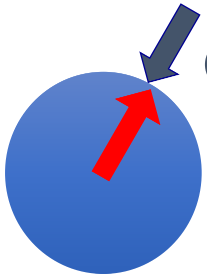
Mass : $M \sim$ 1-2 $M_\odot$

Radius : $R \sim$ 11-13 km (~10^{-6} $R_\odot$)

n_p/n_B : $Y_p \sim$ 0.05 (neutron rich)

Temp. : $T \sim$ KeV (<< p_F of nucleons)

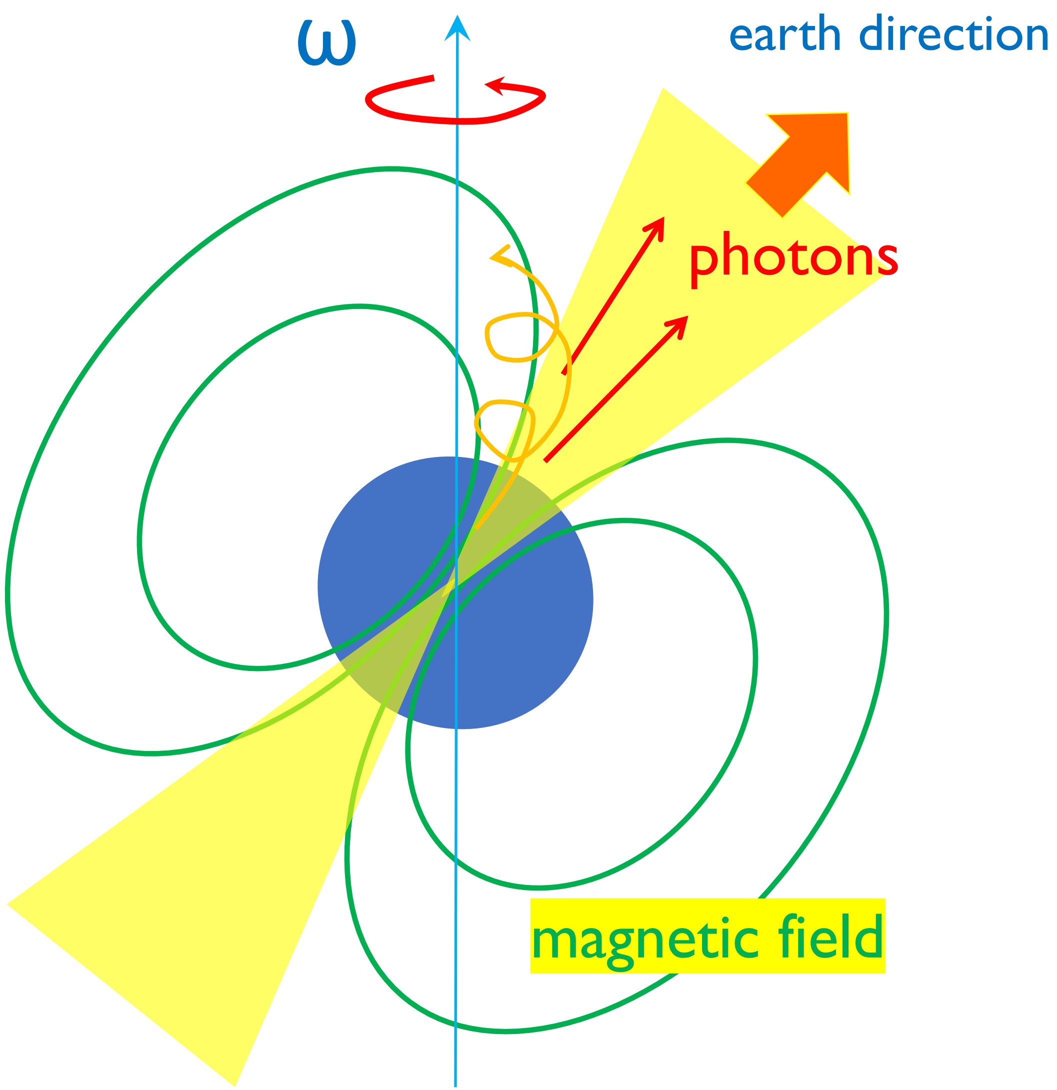
mag. field : $B \sim$ 10^6-10^{15} Gauss (~ 10^5 – 10^{11} $B_\odot$)



gravitationally bound

how can we infer
these extreme properties ?

fast rotating pulsars & NS



the **existence** of pulsars with

pulse period (for earth) < 1s

(very quickly rotating, large ω)

with constraints

$v_{surf} = \omega R < 1$ (light velocity)

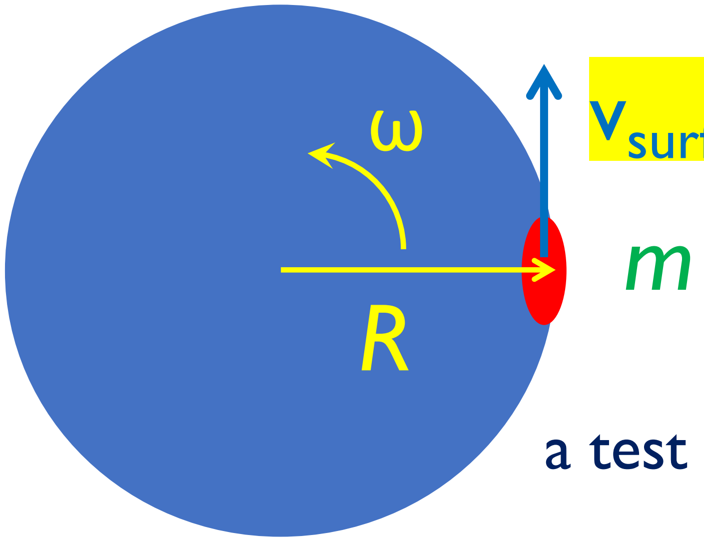
→ R ~ 10-100 km (!)

compact objects !!

fast rotating pulsars & NS

pulse periods are known to be extremely stable & precise

how can such compact objects be stable ?



$v_{surf} = \omega R$

$GMm/R^2 = mR\omega^2$ mechanical balance

→ $\omega = [GM/R^3]^{1/2}$ *Kepler frequency*

large ω → $M_{pulsar} \sim M_{sun}$

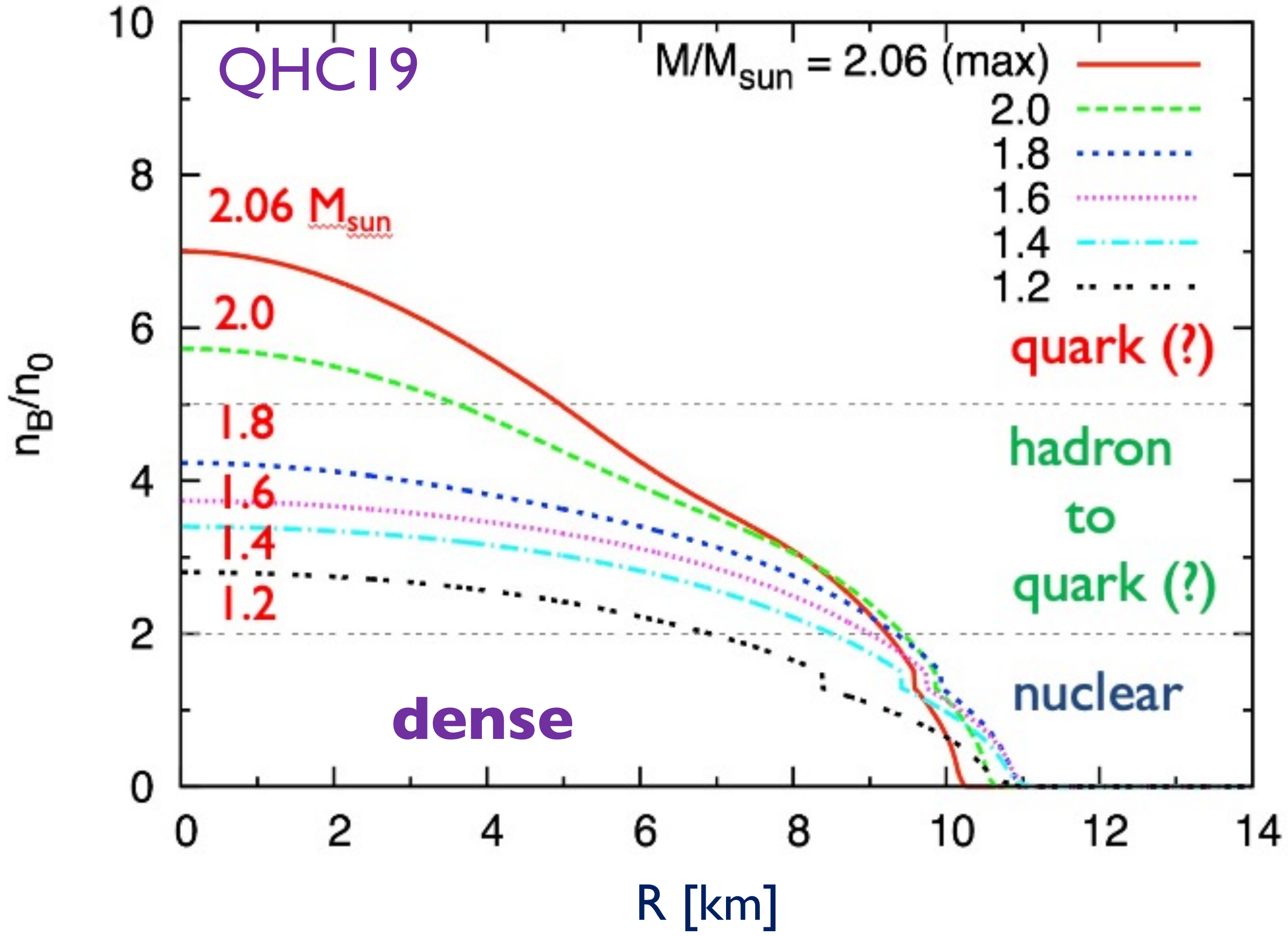
(unless R is extremely small < ~10 km)

massive & compact → *hardly affected by other objects*

How dense?

very dense

For $M \sim M_{sun}$ & $R \sim 10$ km ➔ $n_B \sim M/(4\pi R^3 \times m_N) \sim O(0.1\text{-}1)$ fm^{-3}

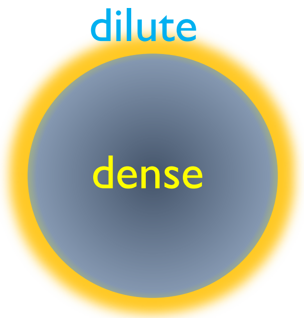


density distribution

from the surface to the center

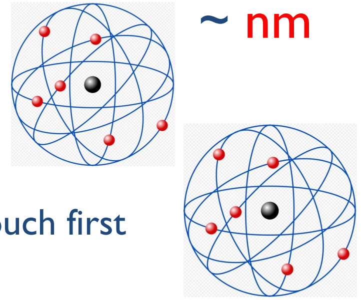
for $M \sim M_{sun}$

the majority of matter is very dense, $n_B > n_0$



gravitational compression & matter content

atom
(nucleus + electrons)



~ nm

e- touch first

compressions

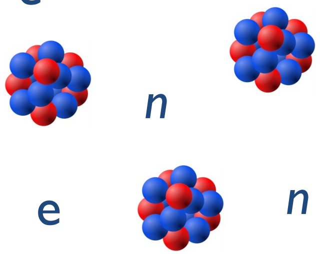
e-dripped

e + p → n + ν_e

(see below)

nuclei + dripped n & e

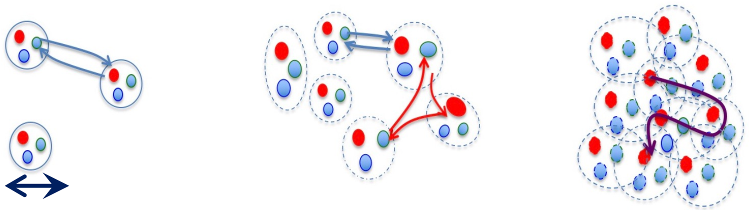
e *n* e *n* e *n*



~ 5 fm

nuclear liquid to **quark matter**

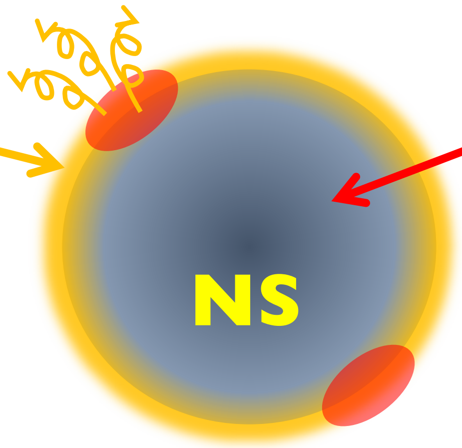
n or p



~ 1-2 fm

n_B ~ $10^{-9}\, n_0$ ~ $10^{-3}\, n_0$ ~ **1-2**n_0 ~ **2-5**n_0 ~ **5-10** n_0

crust **core**



surface phenomena

M-*R* relation

why "neutron" stars ?

assuming ideal gases of rela. electrons + non-rela. nucleons

charge neutrality → n_p $(= Y_p\, n_B)$ = n_e or $p_F^{\,p} = p_F^{\,e}$

β-equilibrium → $m_N + (p_F^{\,n})^2/2M_N = m_N + (p_F^{\,p})^2/2M_N + p_F^{\,e} + \ldots$

$(\mu_n = \mu_p + \mu_e)$ small $(= p_F^{\,p})$

$m_N \gg p_F^{\,p}$ large scale

→ $(p_F^{\,n})^2 = 2M_N\, p_F^{\,p} + \ldots$ $(\, p_F^{\,n} \gg p_F^{\,p}\,)$ **neutron rich !**

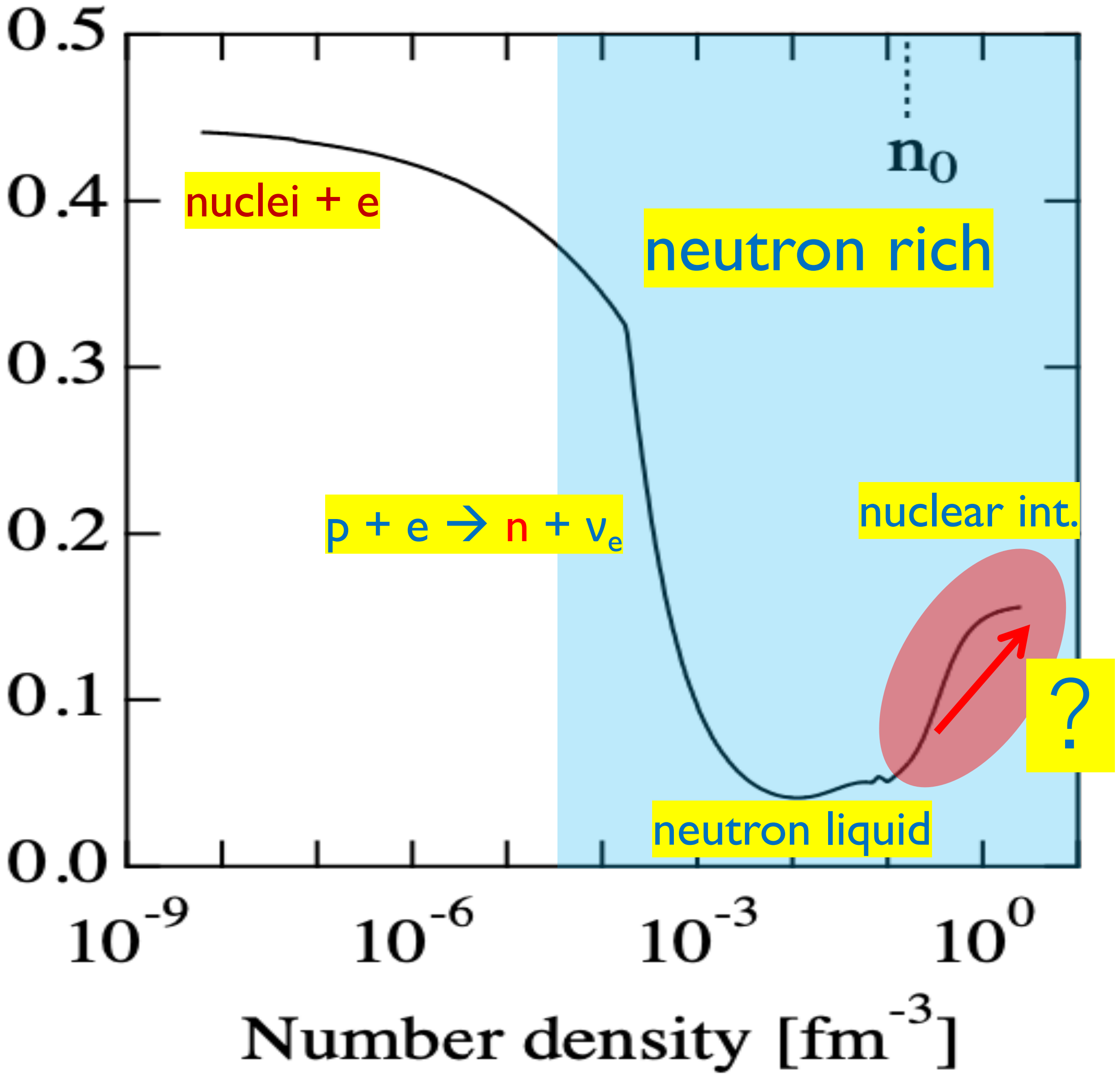
in intuitive terms,

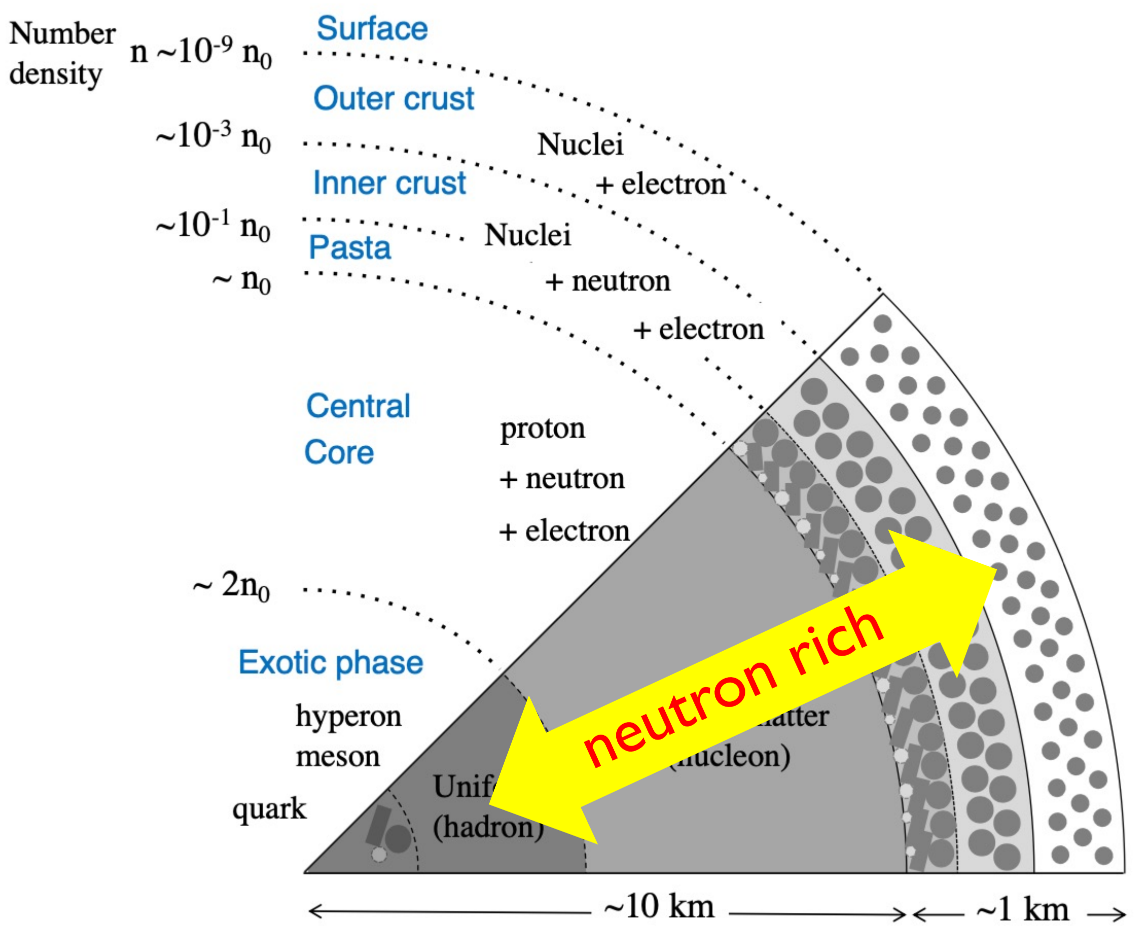
electron kin. energy cost is sensitive to Y_p, while nucleon kin E cost is NOT (tempered by $1/M_N$)

→ the priority is to reduce electron density as much as possible → small Y_p

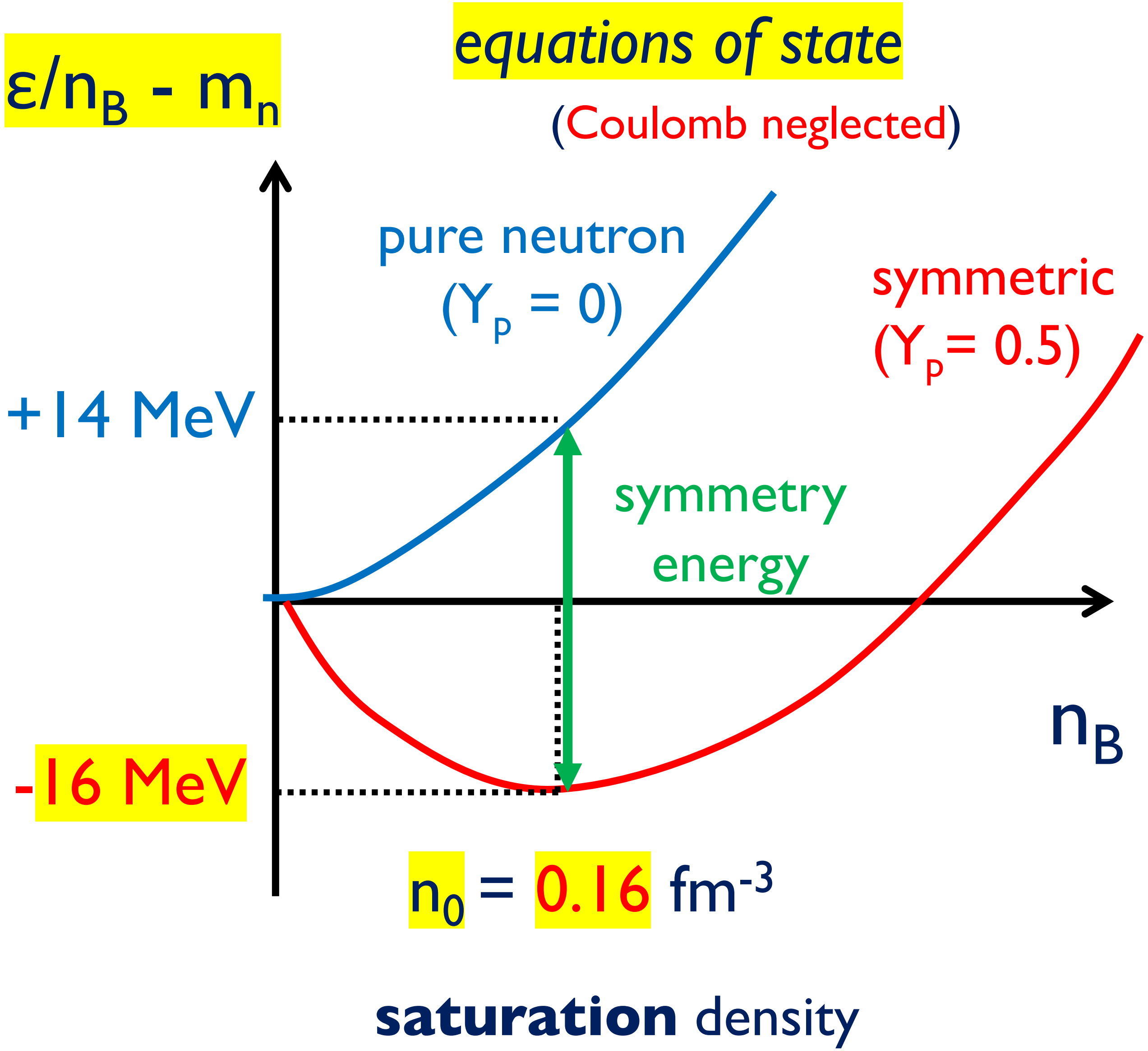
the trend continues until nucleon interactions become important

how wide neutron rich domain?





Y_p in nuclear sector becomes important at $\sim n_0$



- *nuclear liquid* at $n_B > \sim 0.5 n_0$

  (clusters are all dissolved)

- SNM is self-bound

  $$P = \mu_B n_B - \varepsilon = n_B^2 \, \partial(\varepsilon/n_B)/\partial n_B$$

  $\rightarrow P(n_0) = 0$

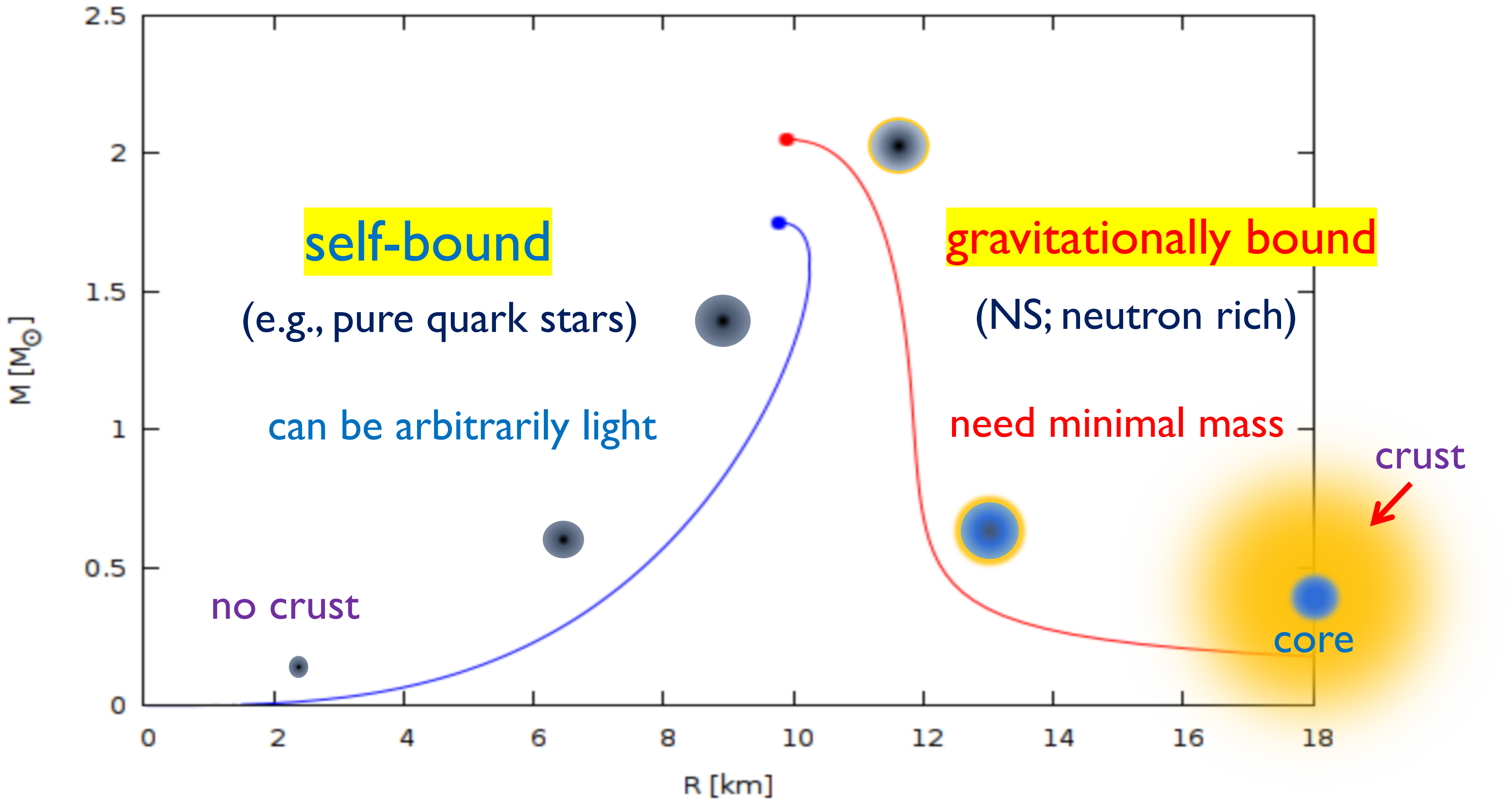
  (finite density without pressure!)

- PNM is **NOT** self-bound

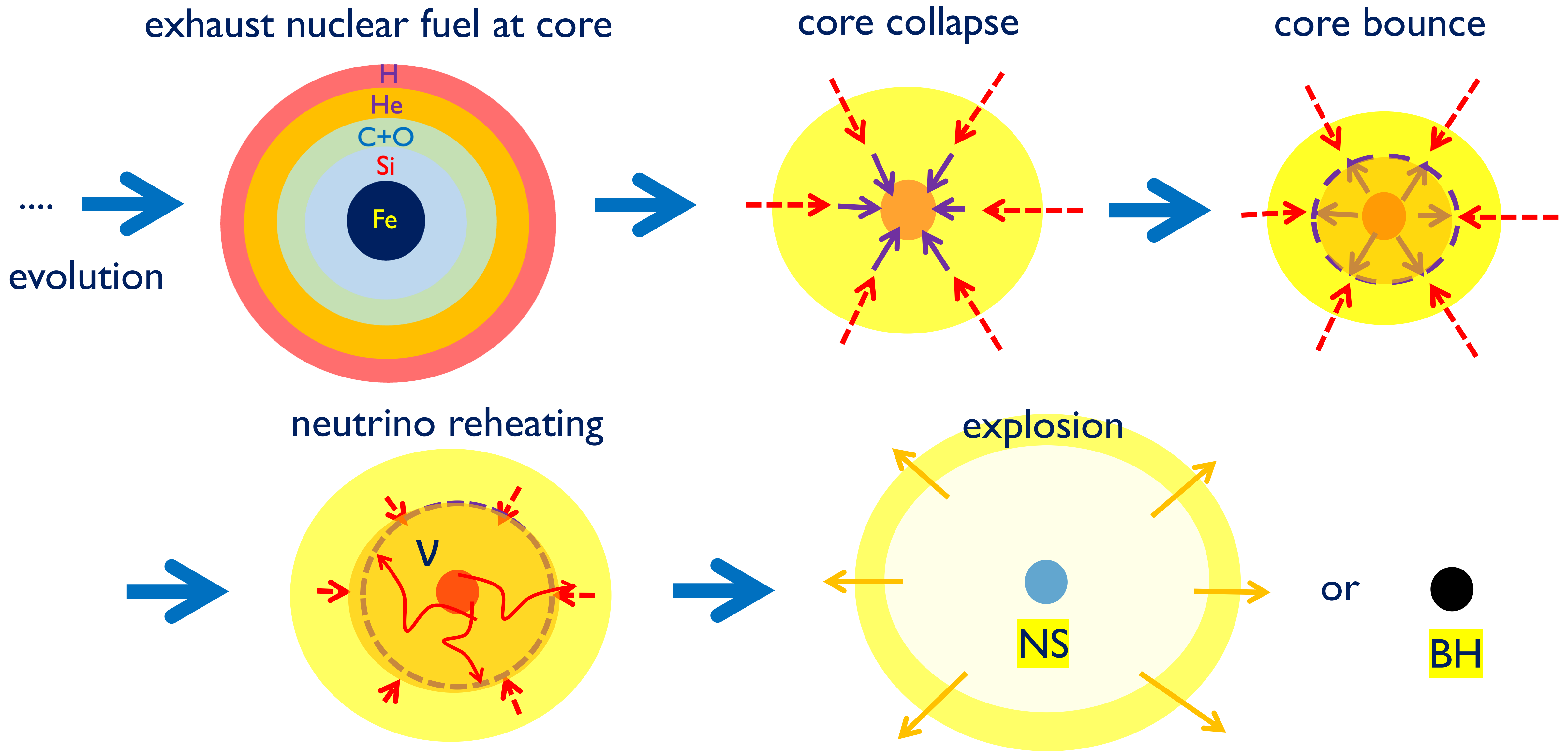
  (finite density needs external pressure!)

the external force → gravity

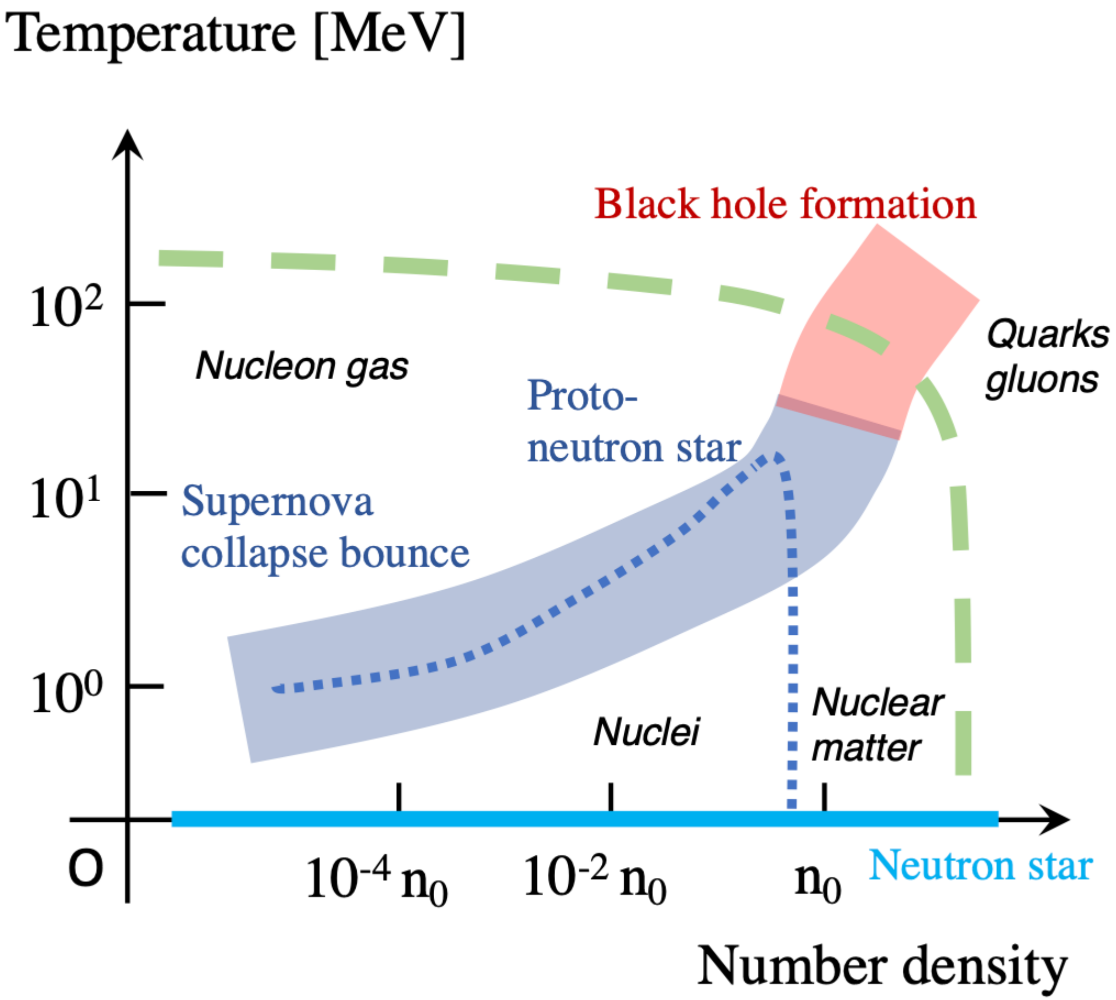
self-bound vs gravitationally bound stars

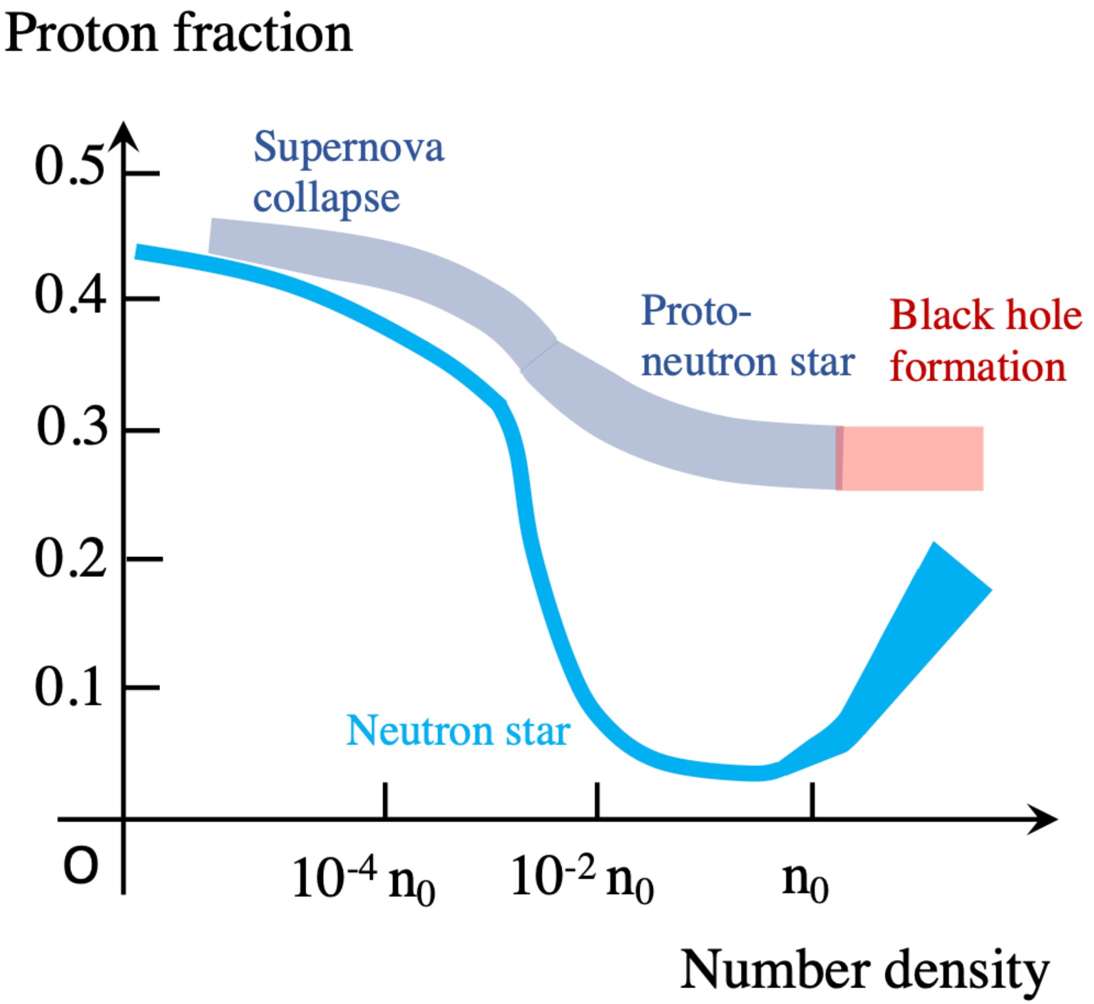


Core collapse supernovae: birth of NS

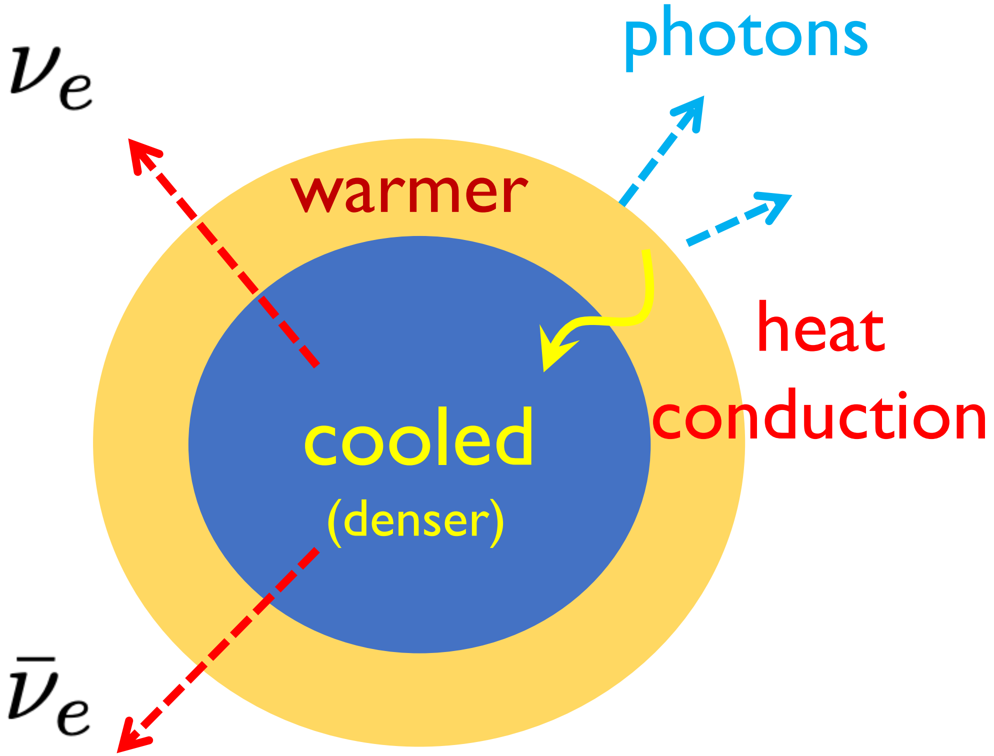


Supernova matter & proto-NS





Temperature in NSs



in the core:

- thermal nucleons lose energy via

direct URCA (**Fast**):

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

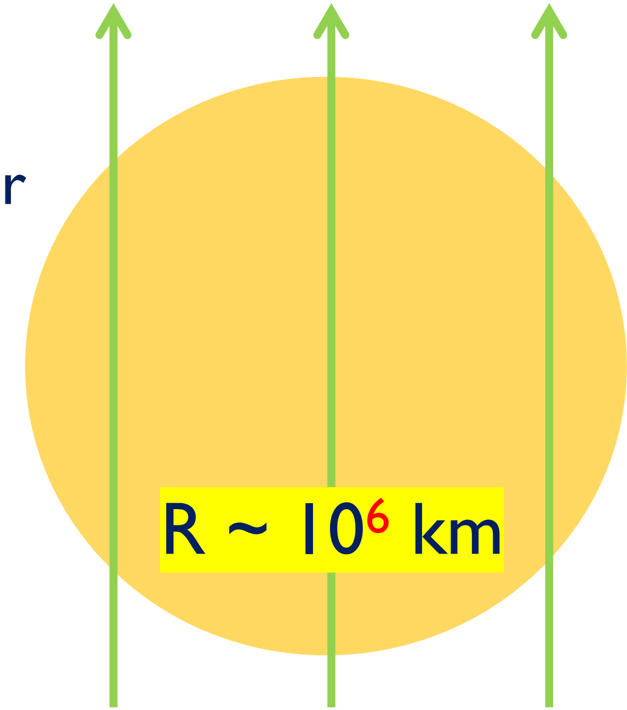
modified URCA (**Slow**):

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

~10-100s after the birth, the T_{surf} drops to ~ keV

magnetic fields & angular momentum

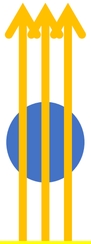
progenitor



$R \sim 10^6$ km

core collapse supernovae

squeezing fluxes



NS

$R \sim 10$ km ($\sim 10^{-5} R_{before}$)

BR^2 = const.

$B \sim 10^2$ G → $B \sim 10^{12}$ G

typical initial conditions

$I\omega \sim R^2\omega$ = const.

$P \sim 10^7$ s → $P \sim 10^{-3}$ s

size consistent with obs.

Neutron stars (NSs)

rot. period : $P \sim$ 1ms – 1s (~ $10^{-9} - 10^{-6}\ P_{\odot}$)

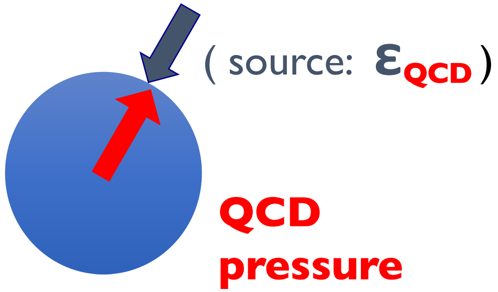
Mass : $M \sim$ 1-2 $M_{\odot}$

Radius : $R \sim$ 11-13 km (~$10^{-6}\ R_{\odot}$)

n_p/n_B : $Y_p \sim$ 0.05 (neutron rich)

Temp. : $T \sim$ KeV (<< p_F of nucleons)

mag. field : $B \sim$ 10^6-10^{15} Gauss (~ $10^5 - 10^{11}\ B_{\odot}$)



now we have (very) rough ideas on NS

gravitationally bound

How many NSs?

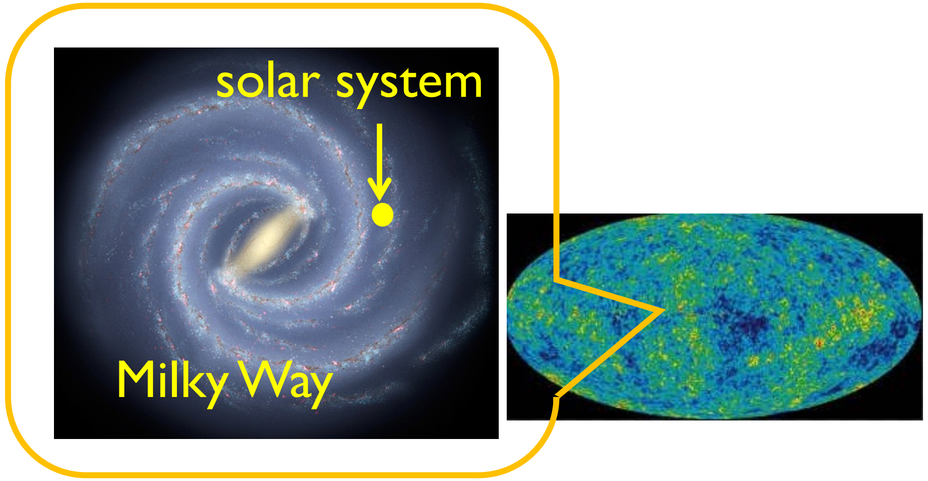
1 parsec (**pc**) = 3.26.. light year

earth to sun: ~ 10^{-8} pc ~ 10^{8} km

diameter of Milky Way galaxy: ~ 10^{4} pc

range of GW detection (aLIGO): ~ 10^{8} pc

diameter of visible universe (CMB): ~ 10^{10} pc



In our Milky Way galaxy:

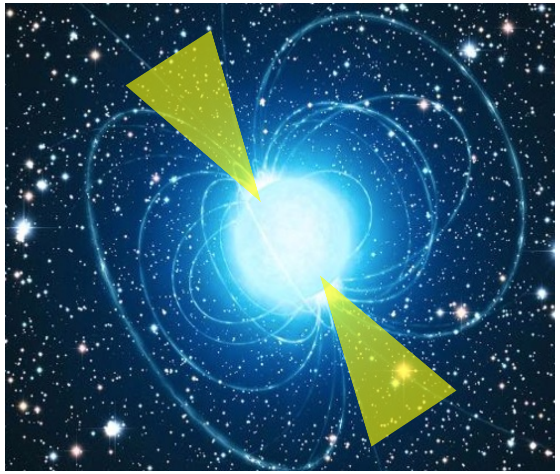
- NS formation (SNe) → a few events per century
- age of the galaxy → ~ 10^{9} years

the num. of NSs ~ 10^{8} – 10^{9}; only ~ 2×10^{3} were observed

Types of NSs?

observed ~ 2 x 10^3 pulsars

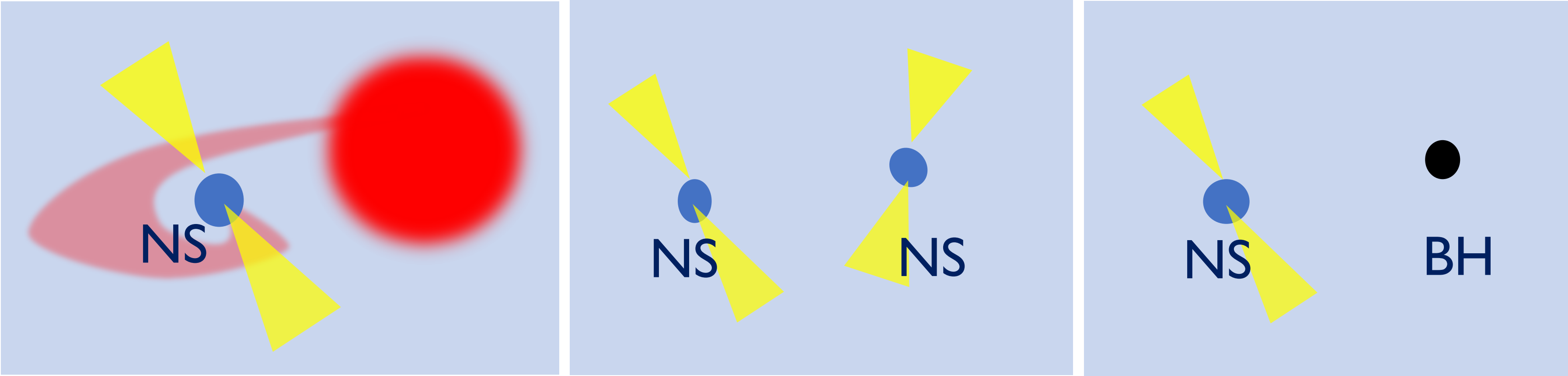
isolated radio pulsars



> 1500 NS

(including ~ 400 millisec. pulsars)

pulsars in binaries



~ 100 NSs (pulsars) : member of binaries

... + many invisible NSs (**old**, age > ~10^8 yrs)

which have exhausted the rot. energy to power radio pulses

EOS & NS structure

NS: brief history --- where are we now?

1934) Zwicky & Baade (prediction) [1931: neutron discovered (Chadwick)]

"*supernova: ordinary star → NS*"

1967) Bell & Hewish: discovery of a pulsar (NS)

"*existence of NS*"

1974) Taylor & Hulse: a binary pulsar (double NSs)

"*indirect confirmation of gravitation waves (GWs)*"

2010) Demorest+: discovery of $2M_{\odot}$ -NS

"*new guide on high density equations of state*"

2017) LIGO-Virgo: GWs from NS mergers (+ electromagnetic counterparts)

"*dawn of multi-messenger (GW, EM, neutrino) astronomy*"

The **first** (established) ~$2M_\odot$ NS : **PSR J1614-2230**

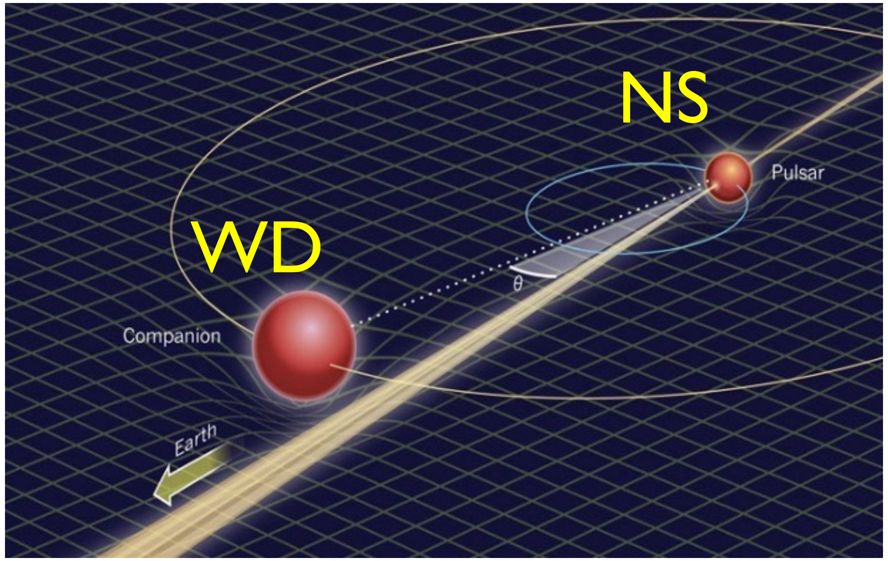
NS – WD (white dwarf) binary [v1) Demorest+ (2010); v2) Fonseca+ (2016)]

spin period = 2.15 ms; orbital period = 8.7 days

inclination angle = **89.17** ± 0.02 ; edge on

M_{NS} = **1.928** ± 0.017 $M_\odot$

M_{WD} = 0.500 ± 0.006 $M_\odot$

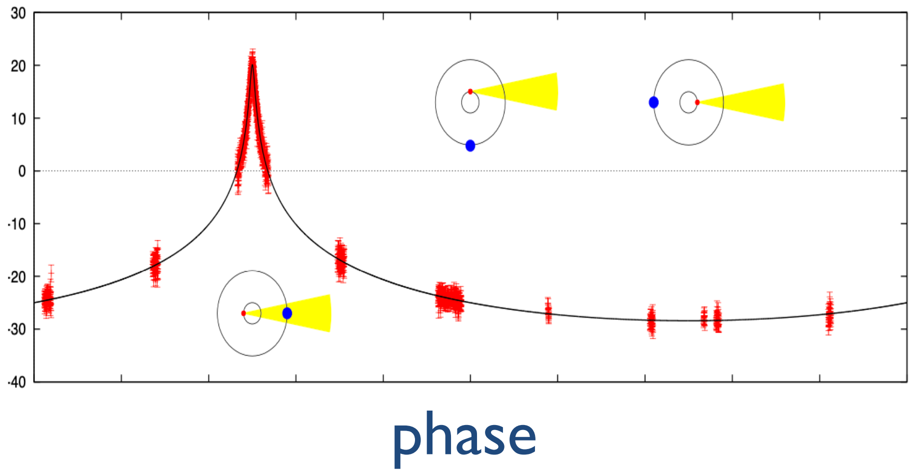


1) **binary orbit** → relations btw M_{NS} & M_{WD}

2) WD **in the direction of pulses** (!)

Shapiro delay of light

1 & 2 → separate determination of M_{NS} & M_{WD}



The **heaviest** NS known: **PSR J0740+6620**

NS – WD (white dwarf) binary [v1) Cromartie+ (2019); v2) Fonseca+ (2021)]

spin period = 2.89 ms; orbital period = 4.77 days

inclination angle = **87.56** $\pm$ 0.17 ; edge on

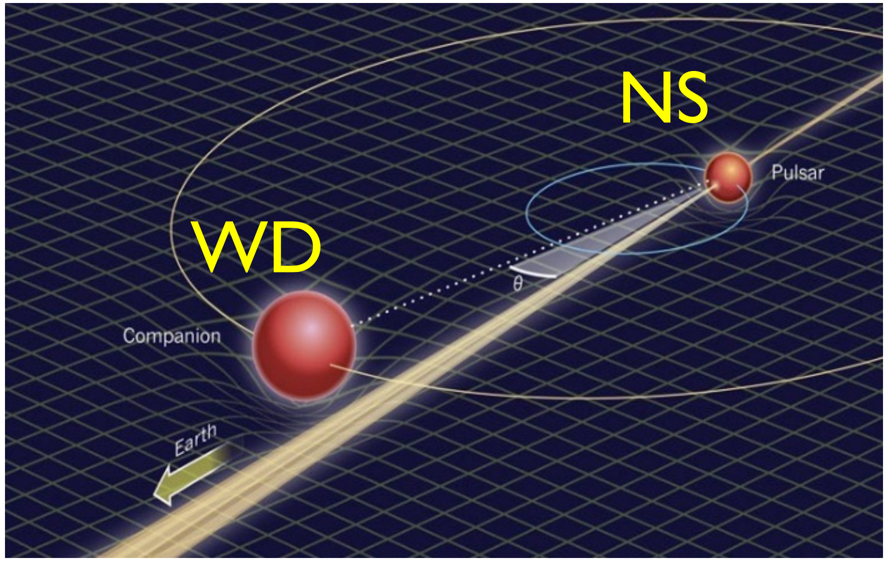
M_{NS} = **2.08** $\pm$ 0.07 $M_\odot$

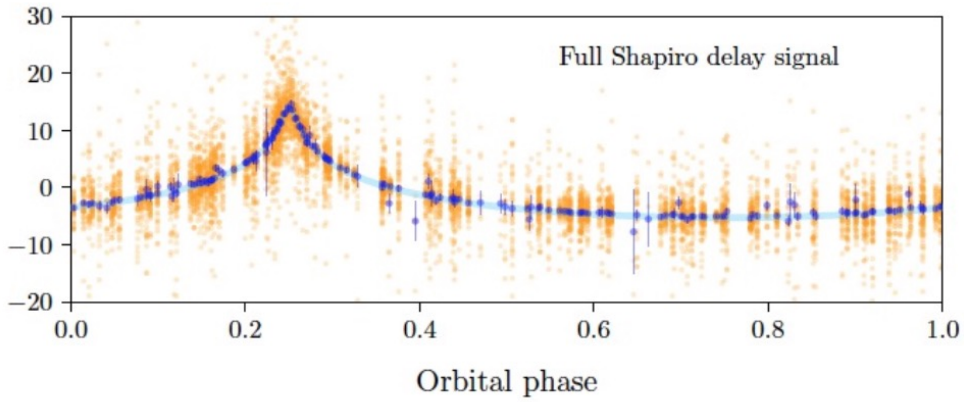
M_{WD} = 0.253 $\pm$ 0.005 $M_\odot$

distance from the earth : 1.14 kpc

Also, a target of NICER

M & **R** (see below)





Mass-Radius (M-R) relations

Tolman-Oppenheimer-Volkoff (TOV) eq.

Einstein eq. QCD EoS

$$G_{\mu\nu} = 8\pi G T_{\mu\nu}$$

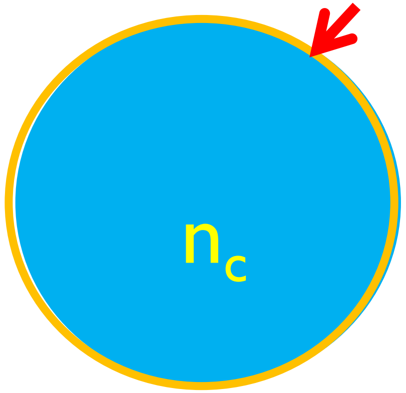
→ static & spherical sym.

$$\begin{cases} \dfrac{dP(r)}{dr} = -\dfrac{GM(r)\varepsilon(r)}{r^2}\left(1+\dfrac{P}{\varepsilon}\right)\left(1+\dfrac{4\pi r^3 P}{M(r)}\right)\left(1-\dfrac{2GM(r)}{r}\right)^{-1} \\ \dfrac{\mathrm{d}M(r)}{\mathrm{d}r} = 4\pi r^2 \varepsilon(r) \end{cases}$$

GR effects (> 1)

r → integrated

→ $n_c = n_B(r = 0)$

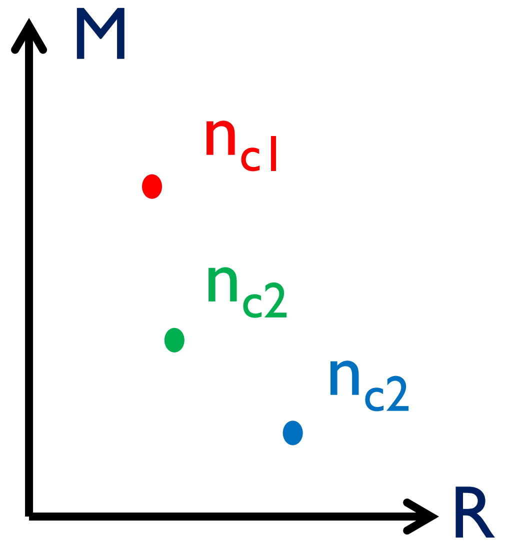


$P(r=R) = 0$ (def. of R)

→

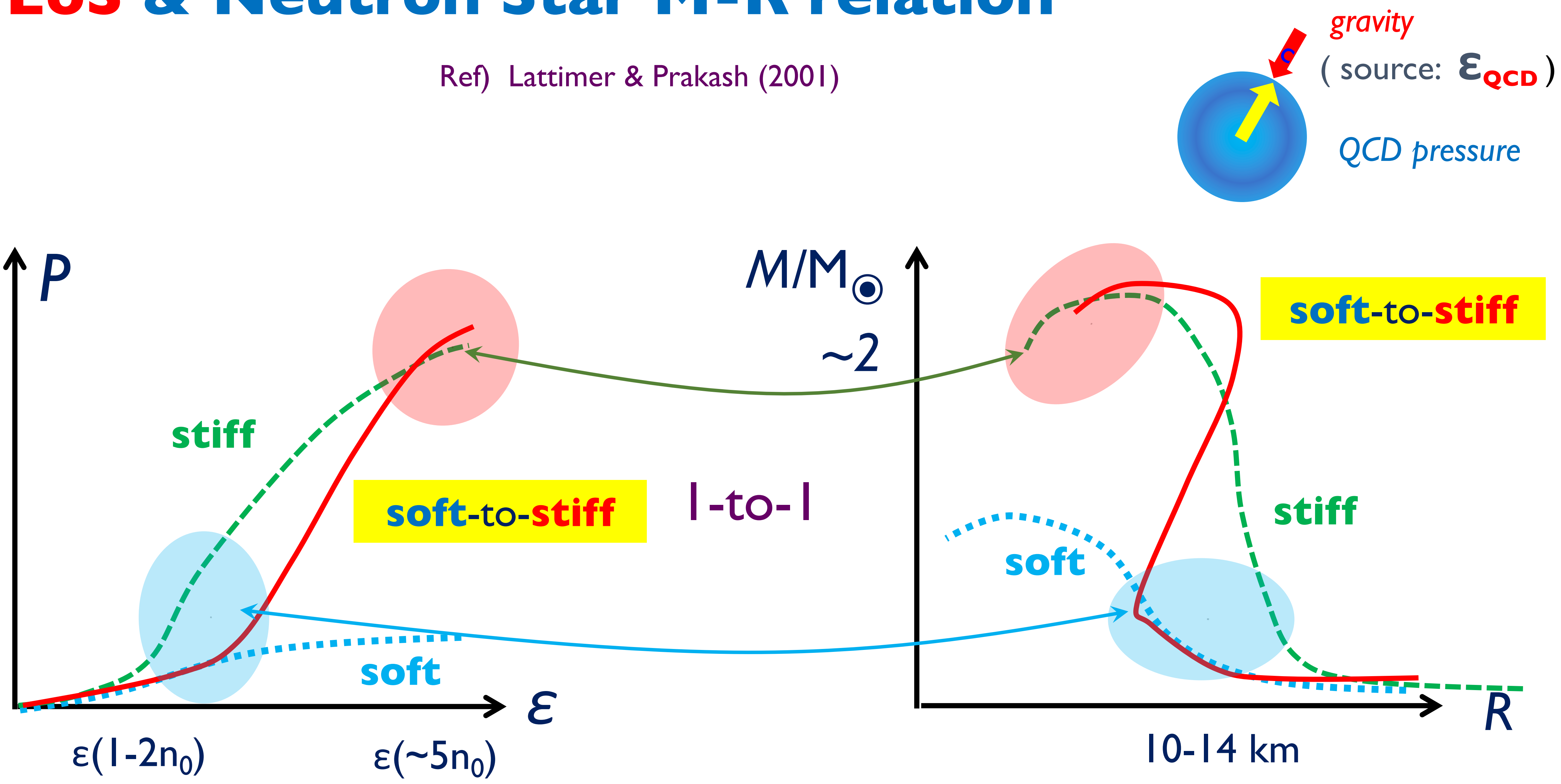
$$\begin{cases} M(n_c) \\ R(n_c) \end{cases}$$

at *given* n_c



EoS & Neutron Star M-R relation

Ref) Lattimer & Prakash (2001)



Density vs *M-R* curves

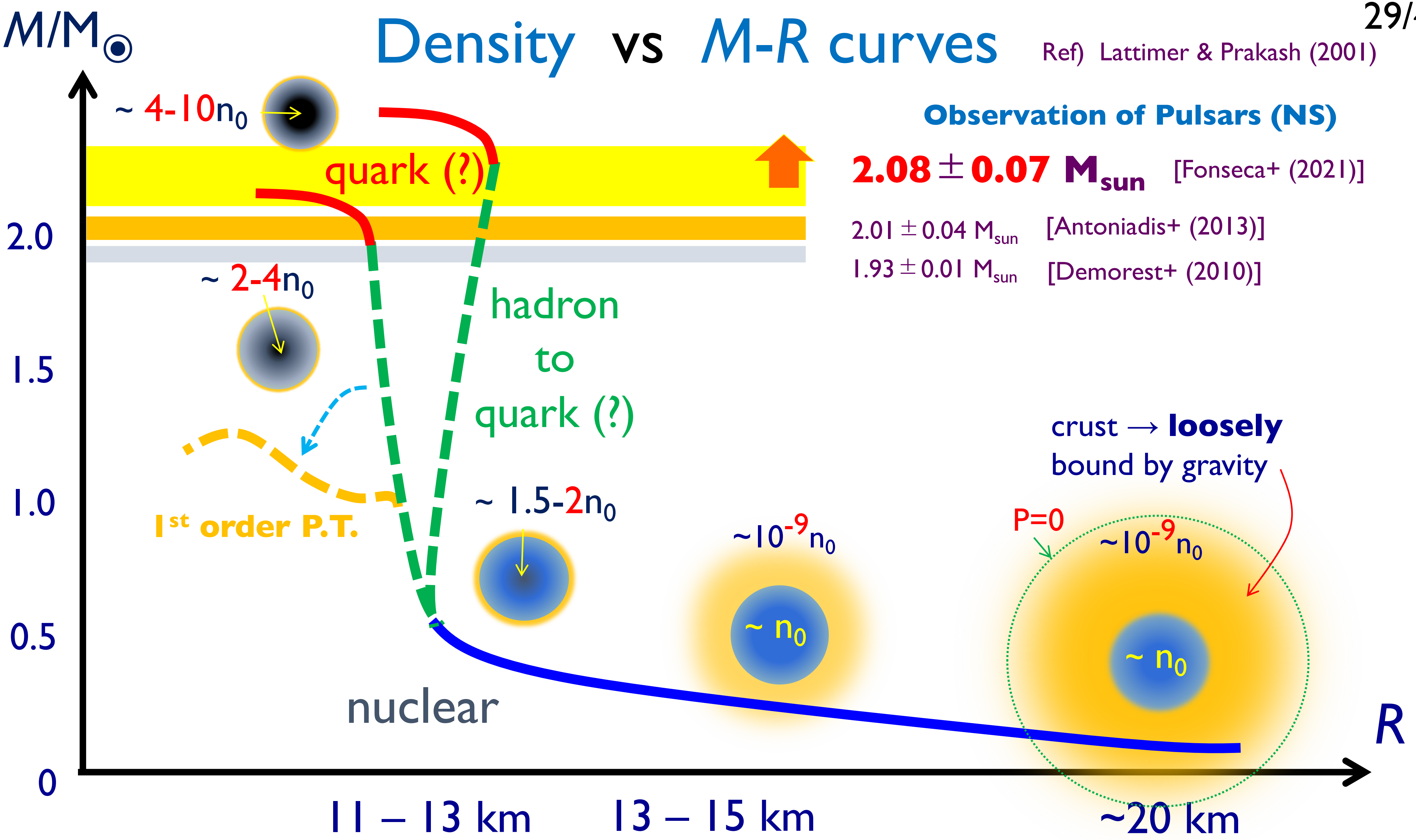
Ref) Lattimer & Prakash (2001)

Observation of Pulsars (NS)

$2.08 \pm 0.07\ M_{sun}$ [Fonseca+ (2021)]

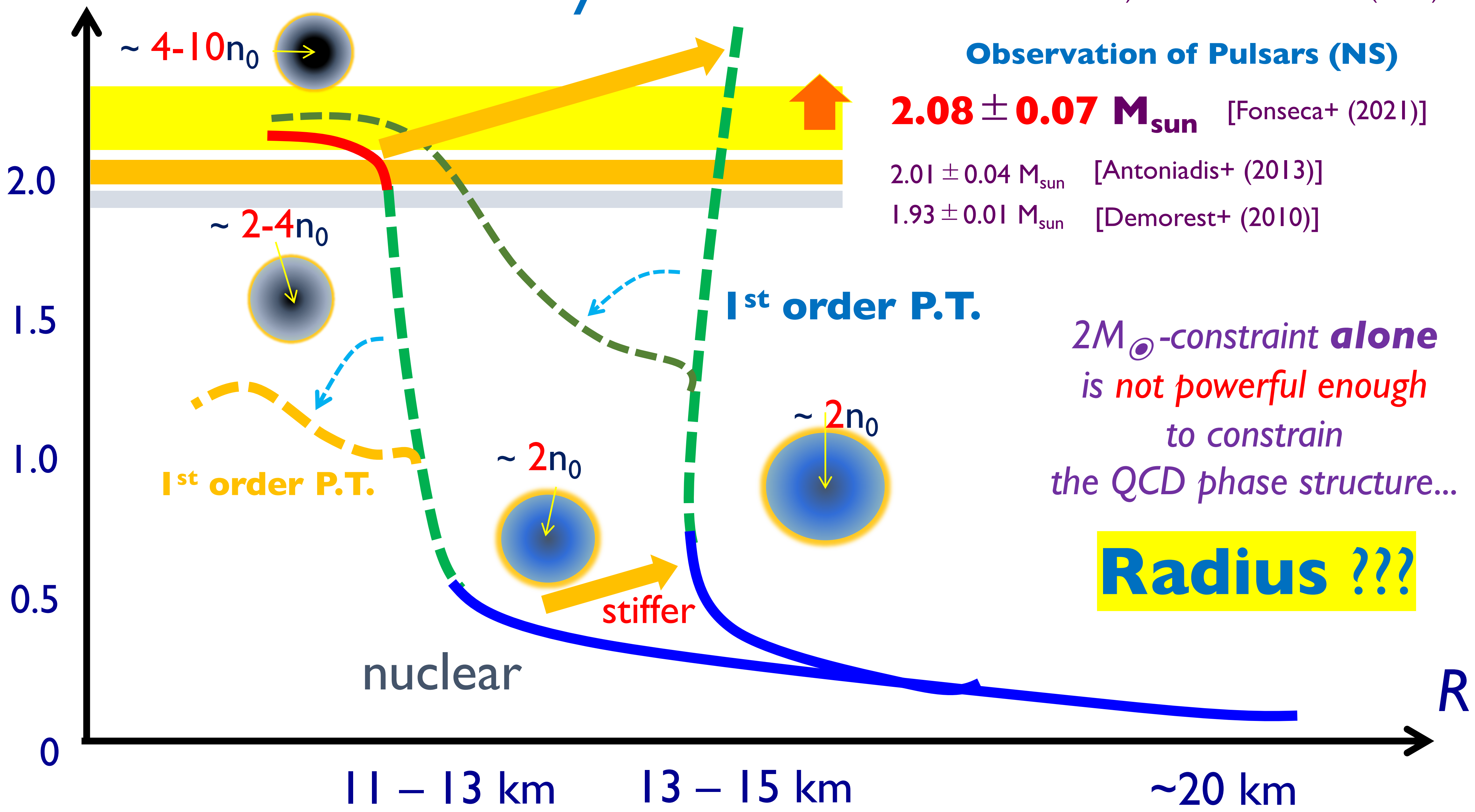
$2.01 \pm 0.04\ M_{sun}$ [Antoniadis+ (2013)]

$1.93 \pm 0.01\ M_{sun}$ [Demorest+ (2010)]



Density vs *M*-*R* curves

Ref) Lattimer & Prakash (2001)



Observation of Pulsars (NS)

2.08 ± 0.07 M_{sun} [Fonseca+ (2021)]

2.01 ± 0.04 M_{sun} [Antoniadis+ (2013)]

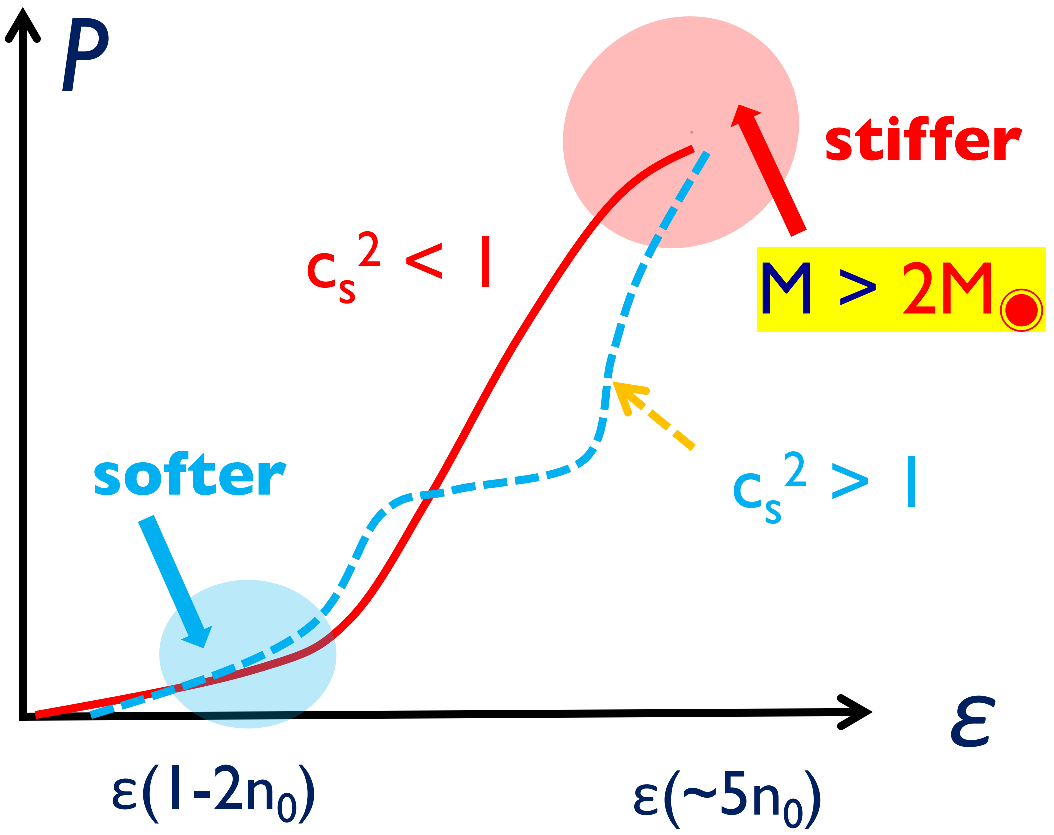
1.93 ± 0.01 M_{sun} [Demorest+ (2010)]

*$2M_\odot$-constraint **alone** is not powerful enough to constrain the QCD phase structure…*

Radius ???

Correlating **low** ($<\sim 2n_0$) & **high** ($>\sim 5n_0$) density EOS

speed of sound: $c_s^2 = dP/d\varepsilon < 1$ (causality)



The constraints are tighter
if

- **high** density EOS is **stiffer**
- **low** density EOS is **softer**

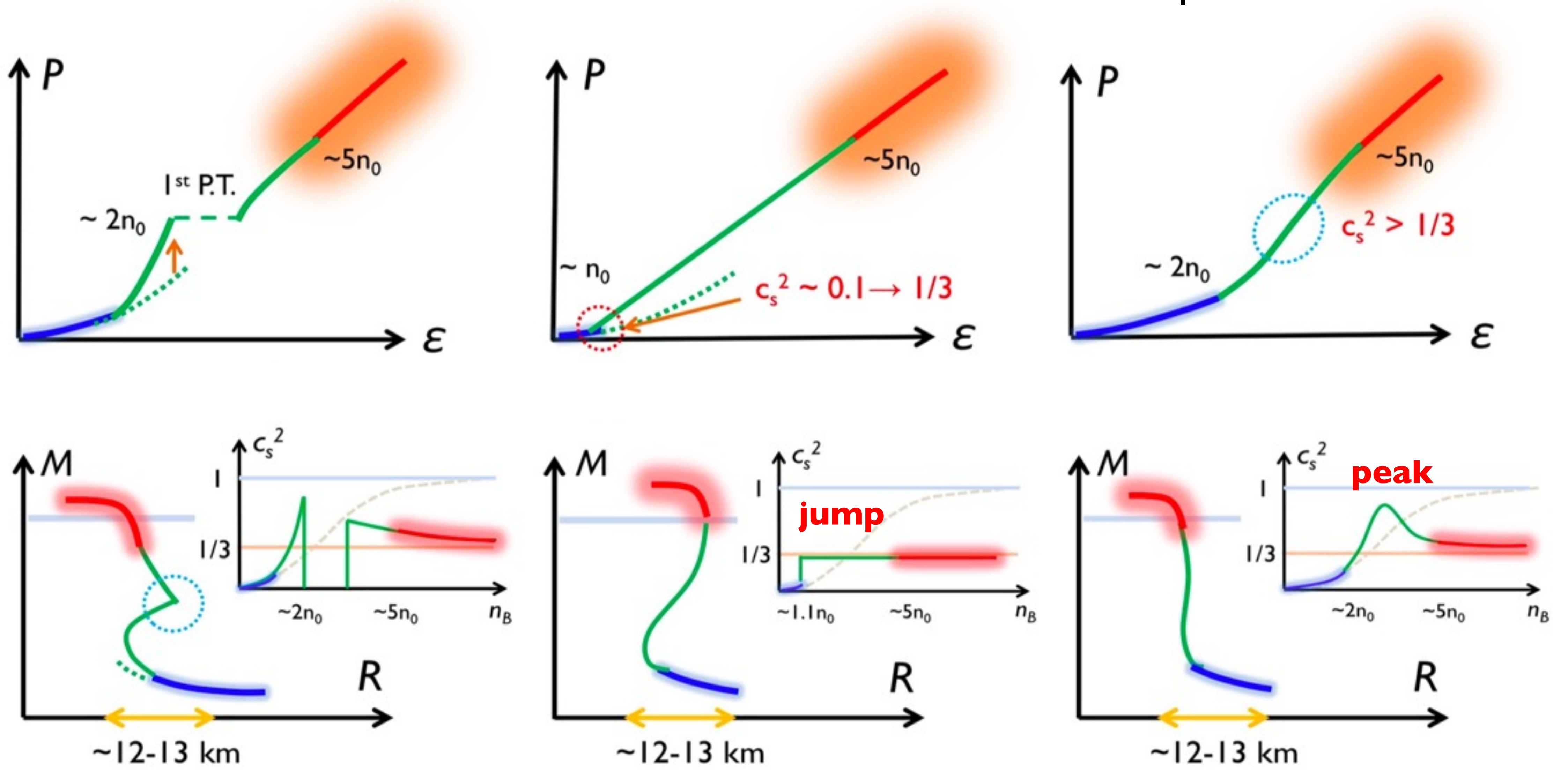
" *soft-to-stiff* " combination
is theoretically challenging

(but *likely* from *observations* & *nuclear physics*)

Several possible scenarios

[e.g. TK '21, mini-review]

→ topics in **Lect. 3**



Key questions to be addressed

- low density: ($n_B < \sim 2n_0$)
  - **observational** constraints for $\mathbf{R_{1.4}}$?
  - **domain** of **applicability**? (1.1-2.0n_0?)
  - **precision** of low density **calculations**?

  → **see below**

- high density: ($n_B > \sim 5n_0$)
  - **mechanisms** for **stiff EOS**?
  - effective **d.o.f**? Hadrons or quarks or..?
  - **when** matter becomes **weakly coupled**?

- Inbetween:
  - hadron-to-quark **phase transitions**?
  - **mechanism** for stiffening? **peaks in c_s^2** ?

  → **Lect.3**

$R_{1.4}$ & low density EOS ($<\sim 2n_0$)

Soft vs stiff low density EOS (n_B < ~ $2n_0$)

sources of info

NS observations : $R_{1.4}$ → EOS at 1-3n_0

[Y_p for β-equilibrium]

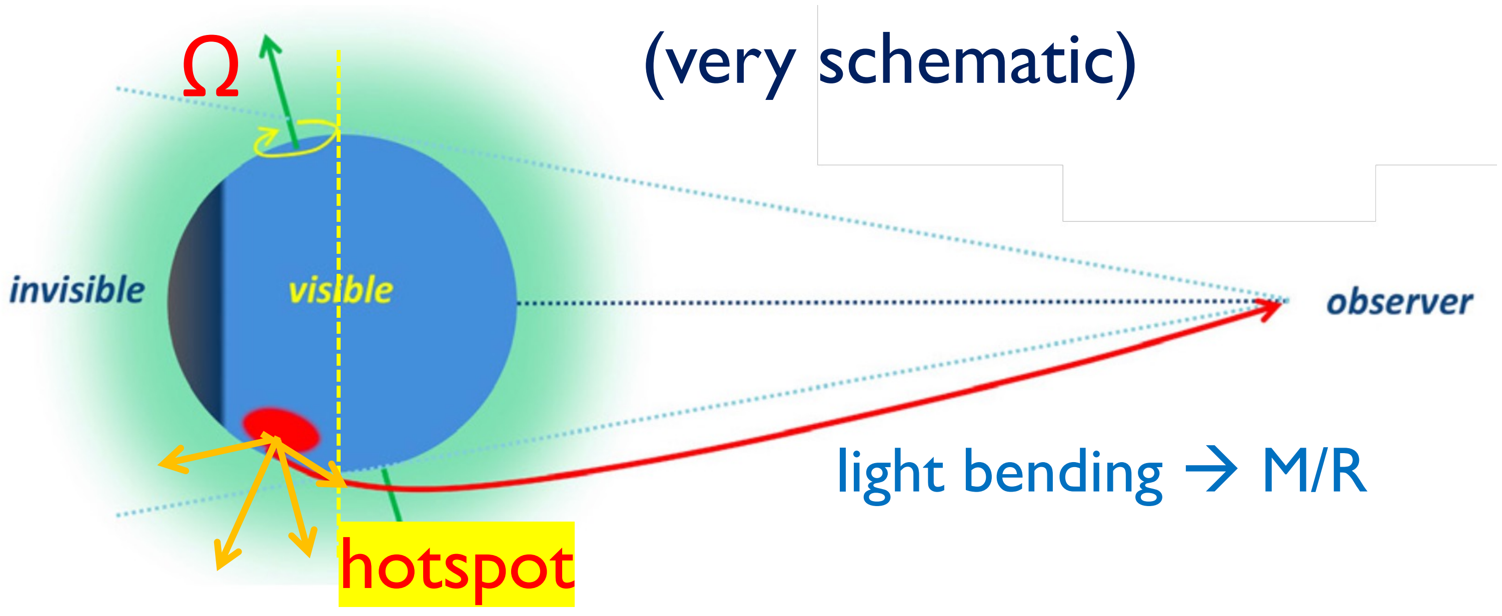
Nuclear physics : EOS at < ~2n_0

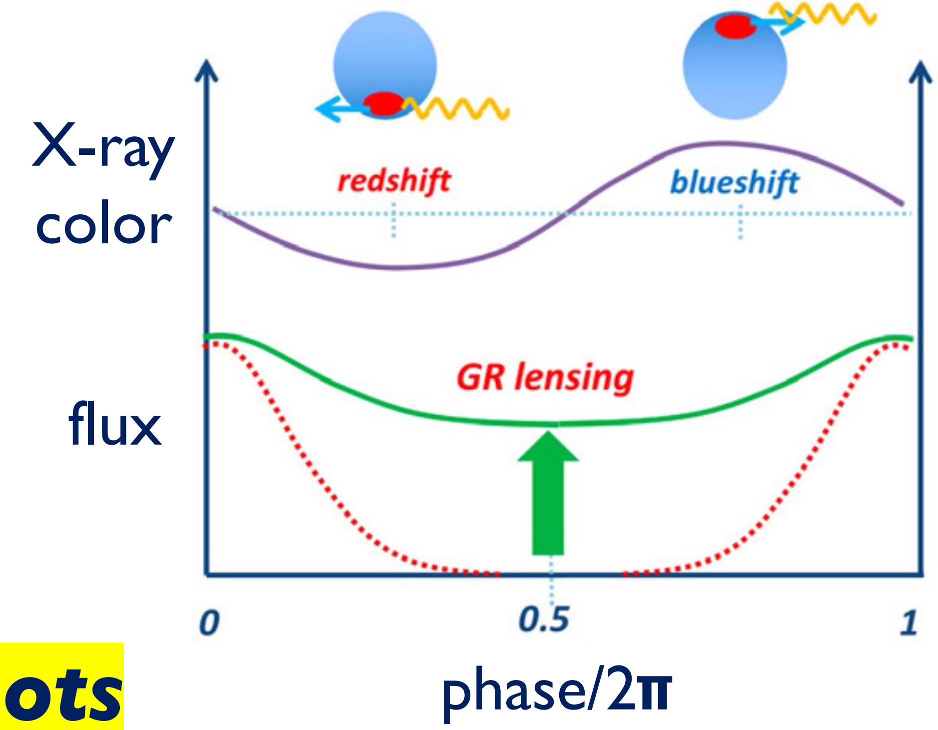
[theory for all Y_p , exp. for Y_p~ 0.5]

Heavy Ion experiments : "EOS" for 2-5(?)n_0

[but Y_p ~0.5 & T ~20-100 MeV,
considerable extrapolations needed]

NICER (Neutron star Interior Composition Explorer, 2017-)

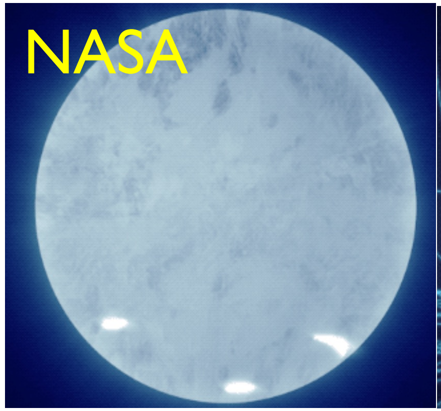


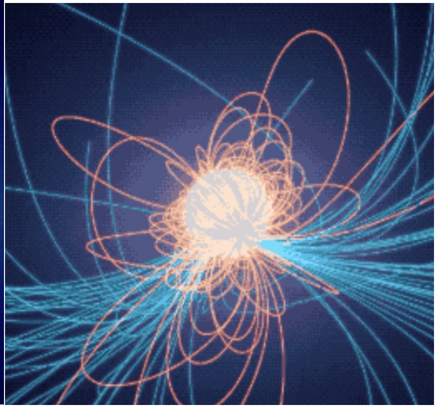


idea: *follow hot spots*

period		Ω (pulse period)
Doppler shifted spectra	→	RΩ (surface velocity)
GR lensing	(in principle)	M/R (red shift)

NICER analyses for R (&M)





...reality is more complicated

hot spots → not simple dipole types

shapes? numbers of spots?

[examined by two teams]

PSR J0030+0451

$M = 1.44^{+0.15}_{-0.14}\, M_\odot$

$R = 13.02^{+1.24}_{-1.06}$ km

Miller+ '19

$M = 1.34^{+0.15}_{-0.16}\, M_\odot$

$R = 12.71^{+1.14}_{-1.19}$ km

Riley+ '19

PSR J0740+6620

$M = 2.08^{+0.07}_{-0.07}\, M_\odot$

NICER + XMM Newton

$R = 13.7^{+2.6}_{-1.5}$ km — Miller+ '21

$R = 12.39^{+1.30}_{-0.98}$ km — Riley+ '21

Nuclear calculations (microscopic)

1) Prepare **NN** + **3N** forces + ...

a) meson exchange models (traditional) [e.g., Illinois, Bonn, Argonne, Nijmegen,...]

b) Chiral EFT (ChEFT) for π & N [e.g., Weinberg, Epelbaum, Meissner, Schwenk,...]

c) Lattice QCD for NN, NY, YY int. [e.g., HAL collaboration,...]

2) Use the microscopic forces in **many-body methods**

a) variational [e.g., Pandharipande, Takano, Togashi, ...] (w. soft nucleons $p^2/m_N < m_\pi$)

b) Quantum Monte-Carlo [e.g., Carlson, Gandolfi,...]

c) Hartree-Fock + many-body perturbation [e.g., Schwenk, Drischler, ...]

Advantage: can check how *systematic uncertainties* propagate;

→ the methods can predict *the domains of applicability*.

Domain of nuclear methods: rough estimate

$\varepsilon(n_B)$

2-body int. ~ n_B^2 (contact) & $n_B^{4/3}$ (long-range)

3-body int. ~ n_B^3 (contact) & $n_B^{5/3}$ (long-range)

Interactions **dominate** over kin. E (NR) ~ $n_B^{5/3}/m_N$

e.g.1) Akmal-Pandharipande-Ravenhall EoS (**APR**)

PNM n_B	2 –body int. $\langle v_{ij}^{\pi} \rangle$	2 –body int. $\langle v_{ij}^{R} \rangle$	3 –body int. $\langle V_{ijk}^{2\pi} \rangle$	3 –body int. $\langle V_{ijk}^{R} \rangle$
n_0	−4.1	−29.9	1.2	4.5
$2\ n_0$	−25.1	−36.4	−17.4	30.6
$3\ n_0$	−35.7	−44.7	−34.1	78.0
$4\ n_0$	−52.2	−41.1	−76.9	160.3

grow rapidly!

e.g.2) parameterized **pure neutron** matter EoS

[Gandolfi+ '09]

fit to Quantum Monte-Carlo

~kin. + 2-body ~3-body

$$\varepsilon = n_0 \left[(12 \pm 1\,\mathrm{MeV}) \left(\frac{n_B}{n_0} \right)^{1.45 \pm 0.05} + (4 \pm 2\,\mathrm{MeV}) \left(\frac{n_B}{n_0} \right)^{3.3 \pm 0.3} \right]$$

$n_B \sim 2n_0$ is the upper bound

Chiral EFT [Weinberg 1990-]

chiral symmetry

1) **pions must** appear together with derivatives or explicit sym. breaking terms

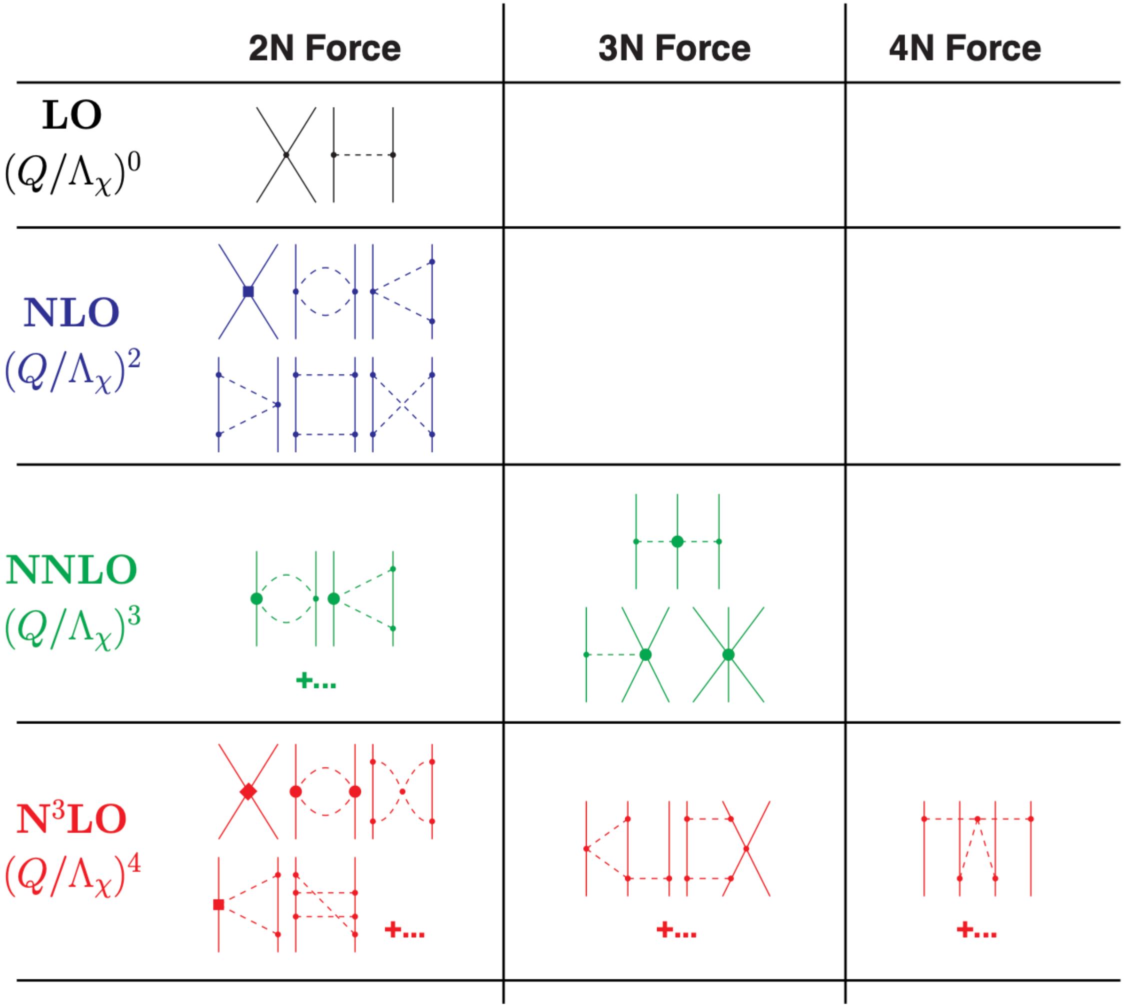
2) **Short distance** nucleon **contact** terms

3) other heavy d.o.fs :“**integrated out**”

→ systematic organization of terms in Lagrangian (!)

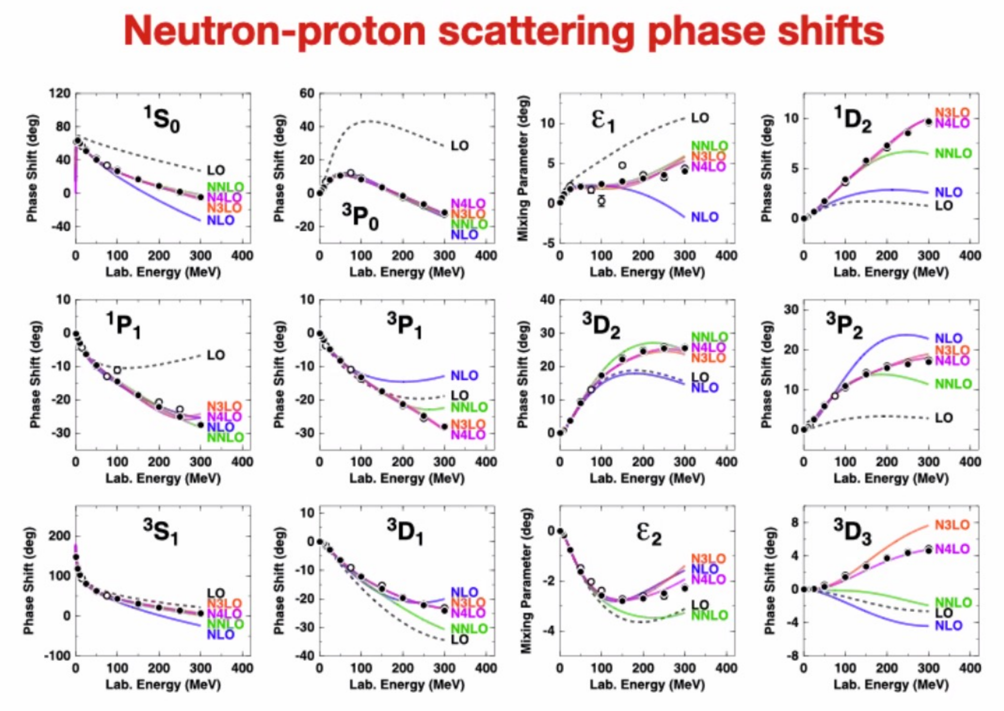
advantages especially in organizing **many-body forces**

expansions of Q/Λ_χ , m_π/Λ_χ



Low energy constants

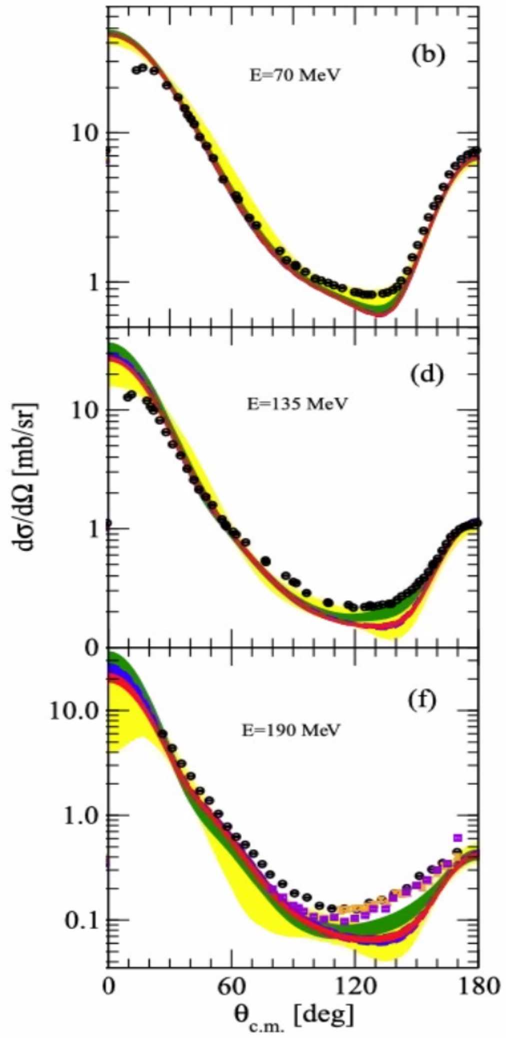
2N forces (well determined)



excellent fits (~6000 data)

~40 LECs (N^{4}LO, 2NF)

3N forces (progressing)

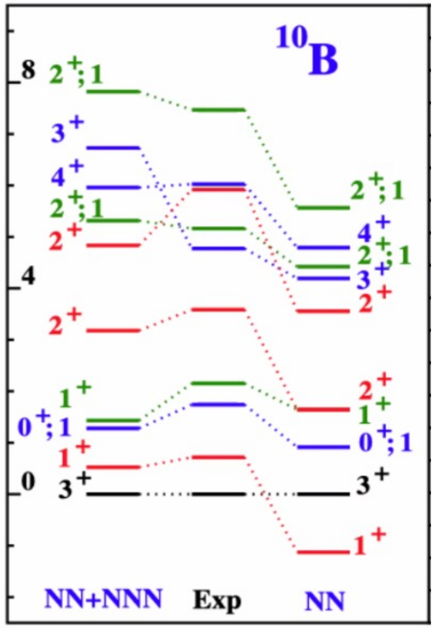


d(np) – p scatt. [Sekiguchi+ '17]

2NF to N^{4}LO
miss some contributions

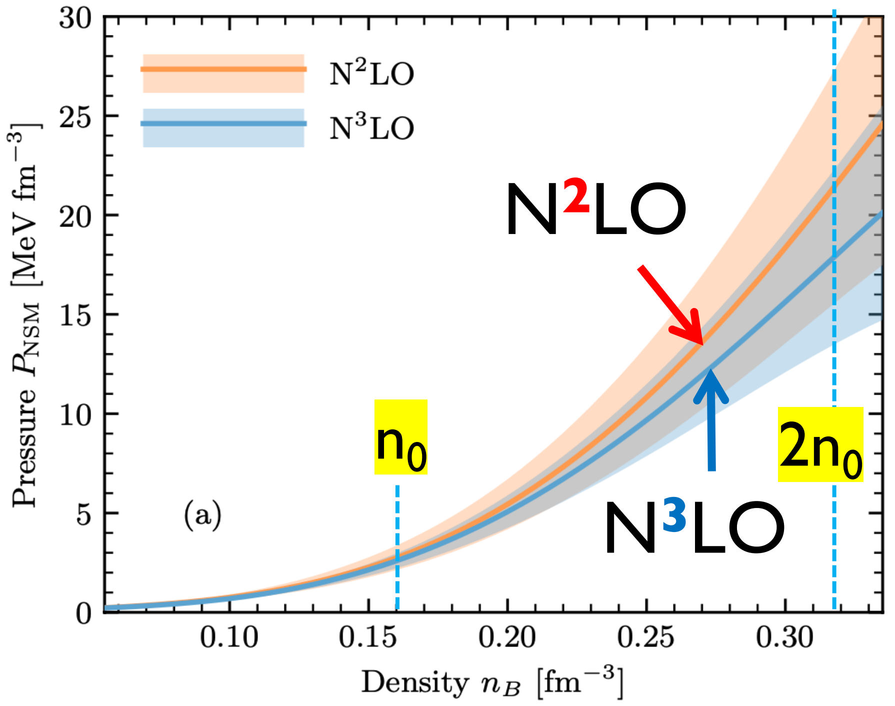
spectra of light nuclei

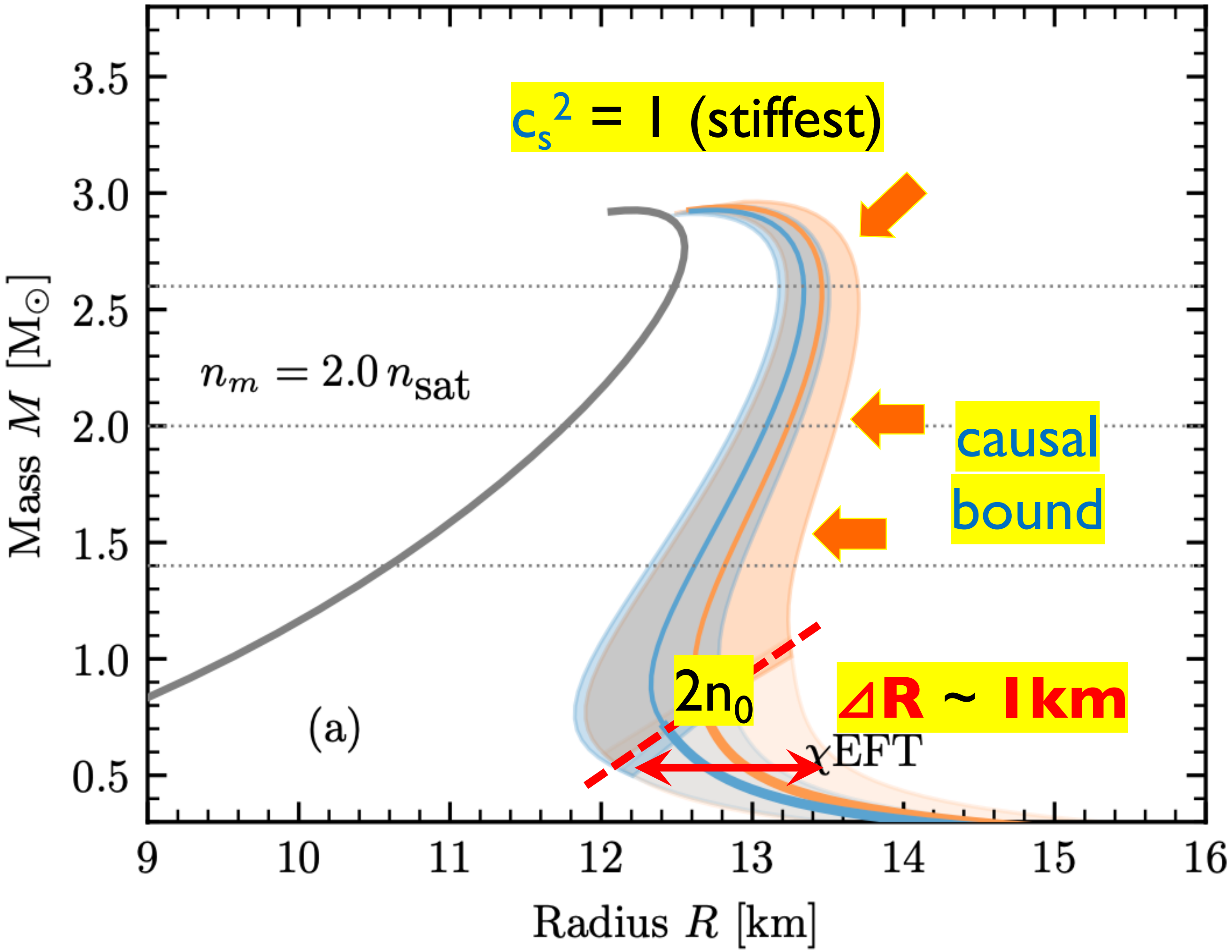
significant
improvement
with 3NF



EOS with N³LO ChEFT band

[Drischler+ '21]





EOS: $P = P_\chi|_{2n0} + c_s^2\,(\,\varepsilon - \varepsilon_\chi|_{2n0}\,)$

if we trust ChEFT to $2n_0$, the causality → $R_{1.4}$ < ~12.9 km

NICER + XMM + GW + nuclear physics (+ "$c_s^2 < 1$")

(see Lect.2)

NICER + XMM Newton

$R_{2.08} = 13.7^{+2.6}_{-1.5}$ km

Miller+ '21

+ GW + nuclear ($0.5n_0$) [Miller+ '21]

$R_{2.08} = 12.35^{+0.75}_{-0.75}$ km

$R_{1.4} = 12.45^{+0.65}_{-0.65}$ km

reduction of errors (!)

NICER + XMM Newton

$R_{2.08} = 12.39^{+1.30}_{-0.98}$ km

Riley+ '21

+ GW + ChEFT ($0.5\text{-}1.1n_0$) [Raajimakers+ '21]

$R_{1.4} = 12.33^{+0.76}_{-0.81}$ km

reduction of errors (!)

$$R_{2.08} \sim R_{1.4}\ (!)$$

Summary of Lecture 1

- glancing at NS properties; M, R, Y_p, B, T, ...
- EOS and M-R relations
- EOS at low density; NICER $R_{1.4}$ and ChEFT

$$R_{2.08} \sim R_{1.4} \ (!)$$ hints for soft-to-stiff EOS

Lect. 2 : Gravitational waves & NS-NS mergers

Lect. 3 : From hadrons to quarks in NS