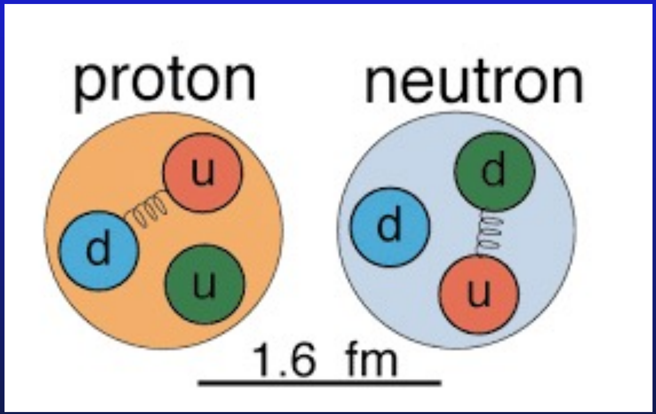
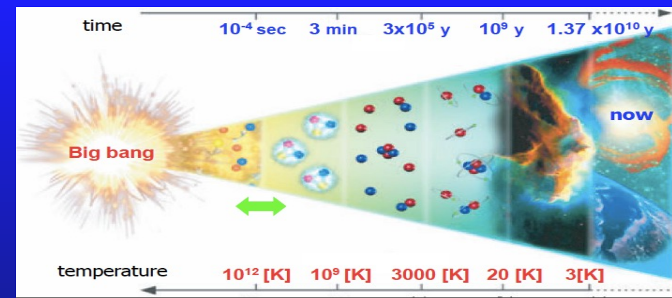
Quark degrees of freedom in neutron stars



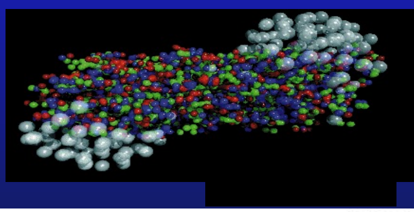
Gordon Baym
University of Illinois
Urbana, Illinois

32nd Texas Symposium on Relativistic Astrophysics
15 December 2023

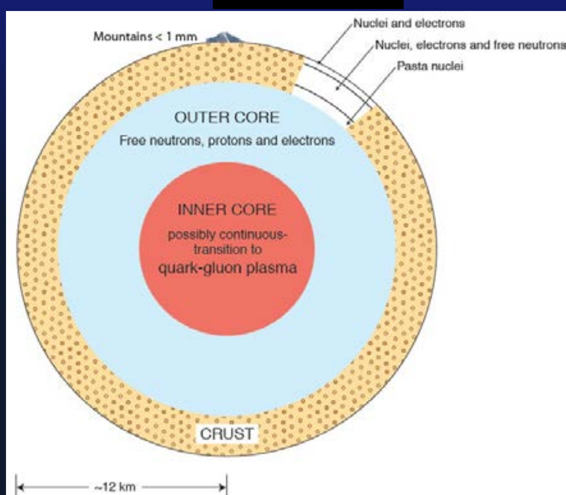
Quarks in dense matter



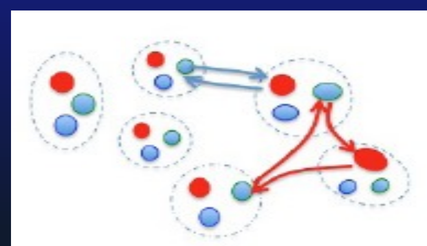
The early universe before one microsecond after the big bang -- hot quark gluon plasma



and created in ultrarelativistic heavy ion collisions



Cold quark matter in cores of high mass neutron stars



Quarks (and gluons) in nuclei will be mapped by future Electron-Ion Collider

Strongly interacting system: cannot do exact calculations at finite density, low temperature.

Modelling neutron stars: first construct equation of state

$E(n_b)$ = energy density = ρc^2

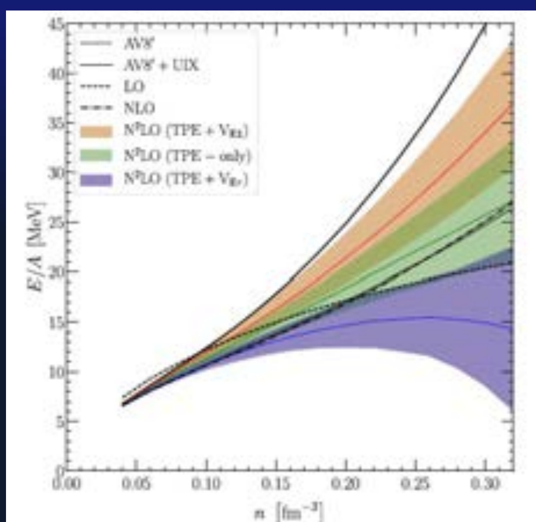
n_b = baryon density

$P(r)$ = pressure = $n_b^2\, d(E/n_b)/dn_b$

$$\frac{\partial P(r)}{\partial r} = -G\frac{\rho(r) + P(r)/c^2}{r\,(r - 2Gm(r)/c^2)}[m(r) + 4\pi r^3 P(r)/c^2]$$

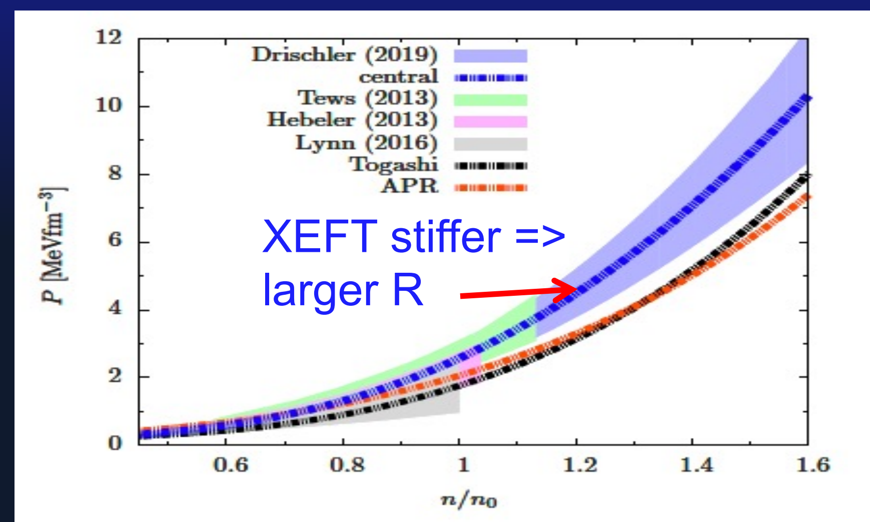
TOV equation $M = \int_0^R 4\pi r^2 dr\, \rho(r)$

Time-honored procedure is to calculate matter with neutrons and protons



Chiral effective field theory - E/A vs n_b

n_0 = density in center of large nuclei = 0.16/fm^3



Pressure vs density

Modelling neutron stars: first construct equation of state

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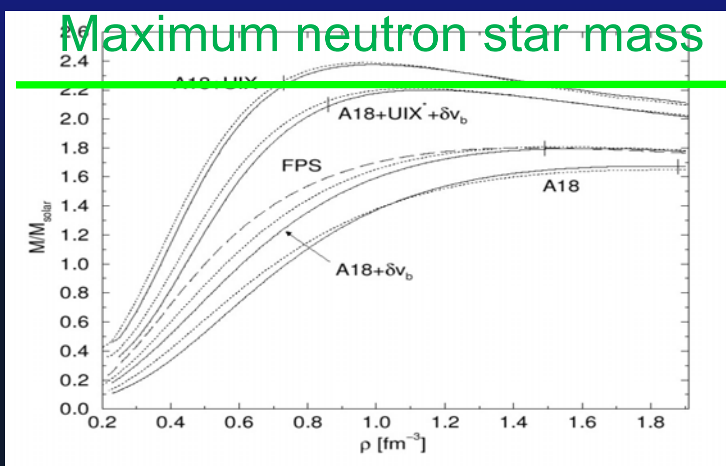
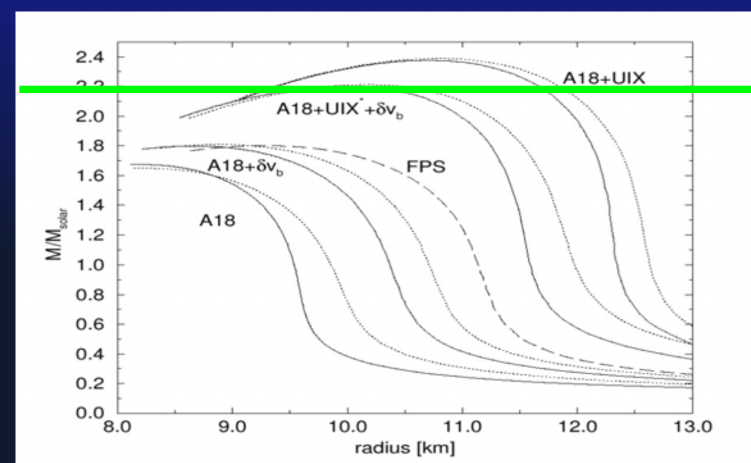


Mass vs. central density

Families of neutron stars



Mass vs. radius

Akmal, Pandharipande and Ravenhall (APR) nuclear equation of state

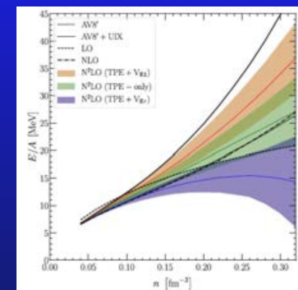
Fundamental limitations of eq. of state based on NN interactions

Accurate for $n \sim n_0$ = density in center of large nuclei. But for $n \gg n_0$:

-sound speed becomes greater than speed of light

-importance of 3 (4,5...) body forces grows with n

-chiral effective theory breaks down above $n \sim 1.5\text{-}2n_0$



-can forces be described with static few-body potentials?

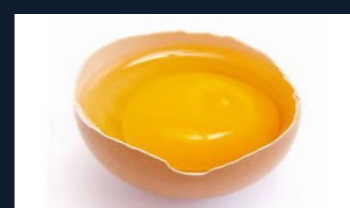
-can one describe system in terms of well-defined “asymptotic" laboratory particles?

Given all information on Nb+Nb atomic scattering could one predict that Nb is a superconductor?

Early percolation of nucleonic volumes! New degrees of freedom enter!!

Squeeze matter

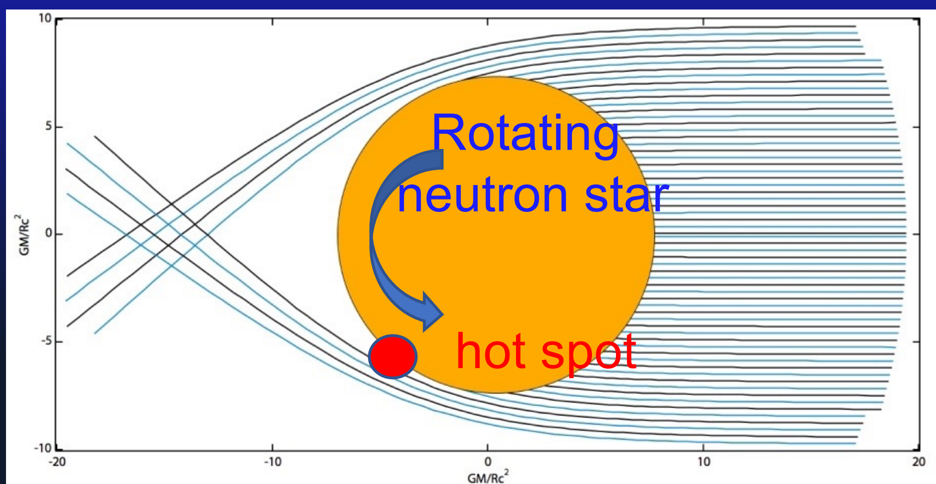
=>

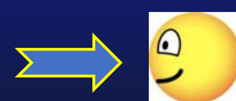


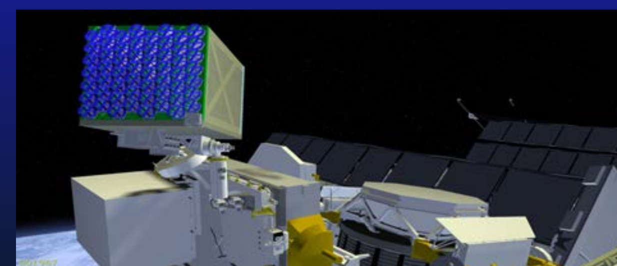
Quark soup

NICER = Neutron star Interior Composition ExploreR

Track hot spots on neutron star in X-ray. (300 nsec, 0.12-12 KeV)
Light bending => see "behind" star. Bending depends on M, R and Ω.
Amplitudes + phases in different frequencies + modelling of hot spots

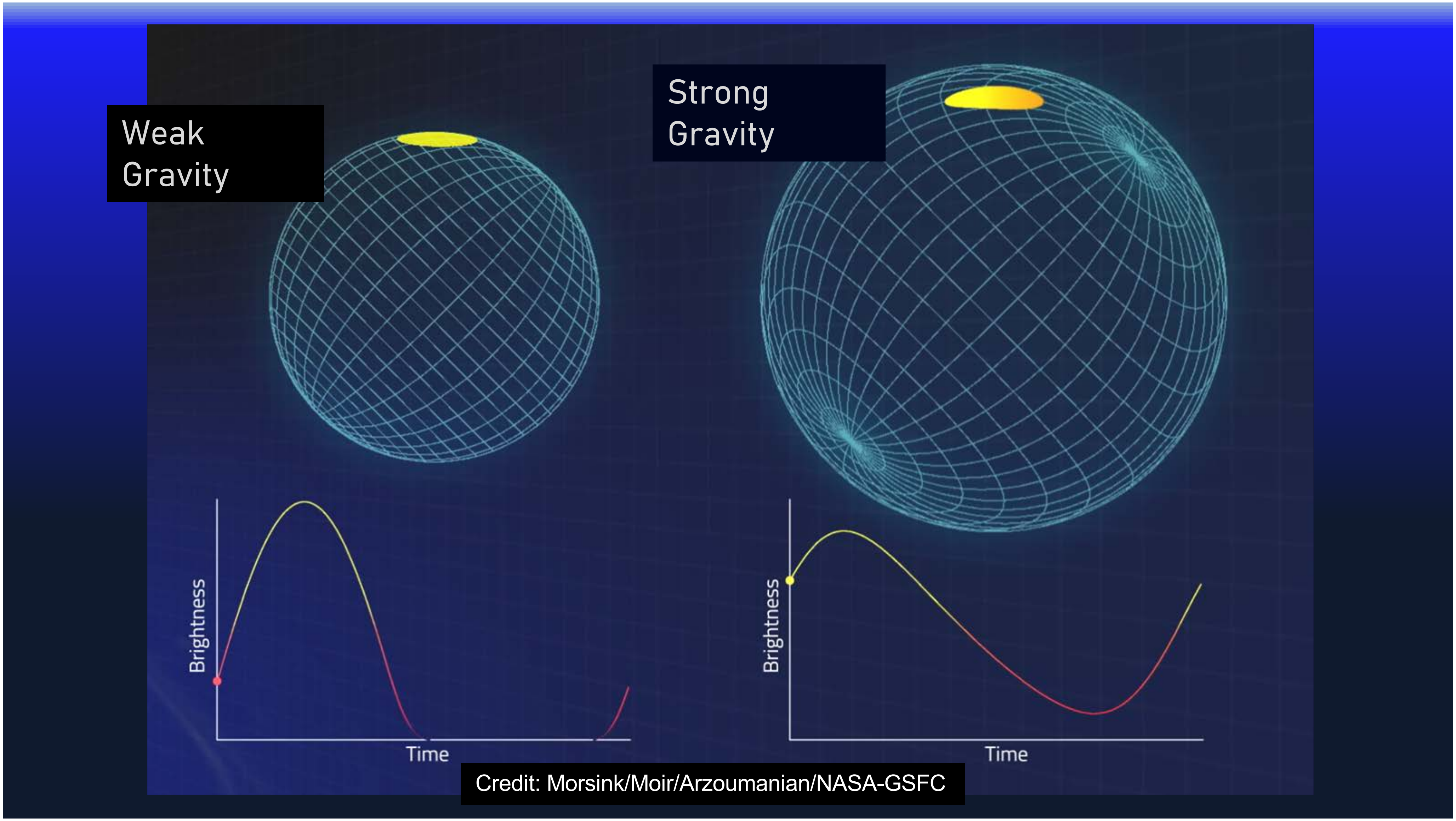






On Int'l Space Station since 2017

Results for two neutron stars
PSR J0740+6620 : M_{nstar} = 2.08 ± 0.07 $M_\odot$, R_{nstar} ~12-13 km
PSR J0030+0451 : = 1.44 ± 0.15 $M_\odot$, ~12-13 km

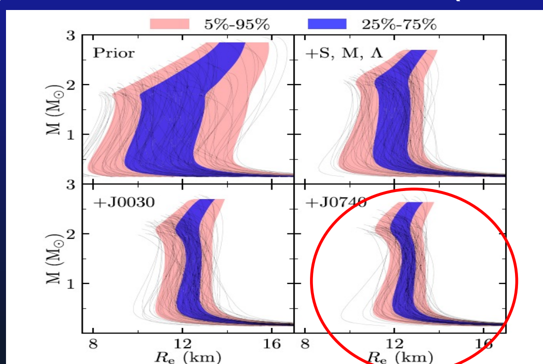

Weak
Gravity
Strong
Gravity
Brightness
Time
Brightness
Time
Credit: Morsink/Moir/Arzoumanian/NASA-GSFC

NICER determinations of radius and mass of PSR J0740+6620

$M = 2.08 \pm 0.07 M_{\odot}$ Greenbank/CHIME radio pulsar measurements

M.C. Miller et al., UMd/UIUC

Ap. J. Lett., 918, L28 (2021)



M vs R from fits to eq of state

$R_{eq} = 13.7\ ^{+2.4}_{-1.5}$ km (1σ)

$M = 2.062\ ^{+0.090}_{-0.091}\ M_{\odot}$

from NICER/XMM data alone

=> R ⇨ 12.3 ± 0.7 km (1σ)

with nuclear + other astro data

$R(1.4\ M_{\odot}) = 12.4 \pm 0.6$ km

T. E. Riley et al., UVAmsterdam

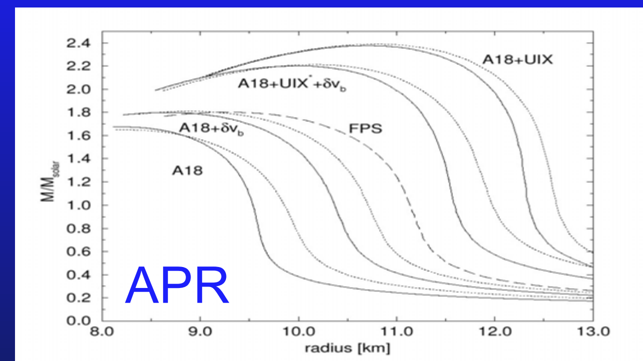
Ap. J. Lett. 918, L27 (2021)

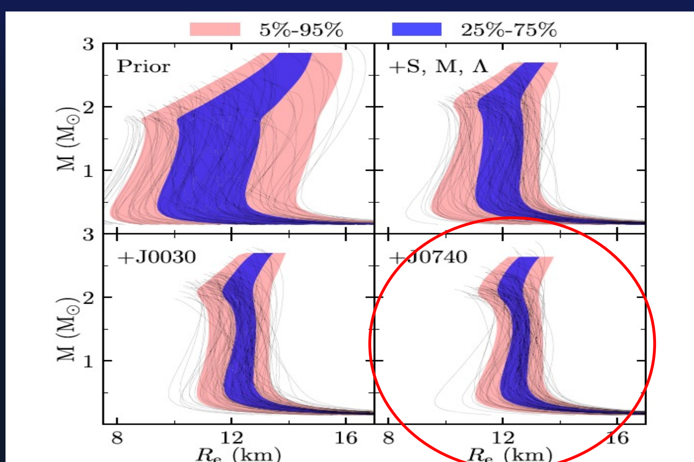
R_{eq} = 12.39 (+1.30-0.98) km

M = 2.072 (+0:067- 0.066) $M_{\odot}$

Messages from NICER

Would expect that adding mass to neutron star decreases its radius.
All eqns of state based on interacting nucleons show this behavior.
But inferred eqn of state shows radius from ~1.4-2.1 M_{sun} changes little.

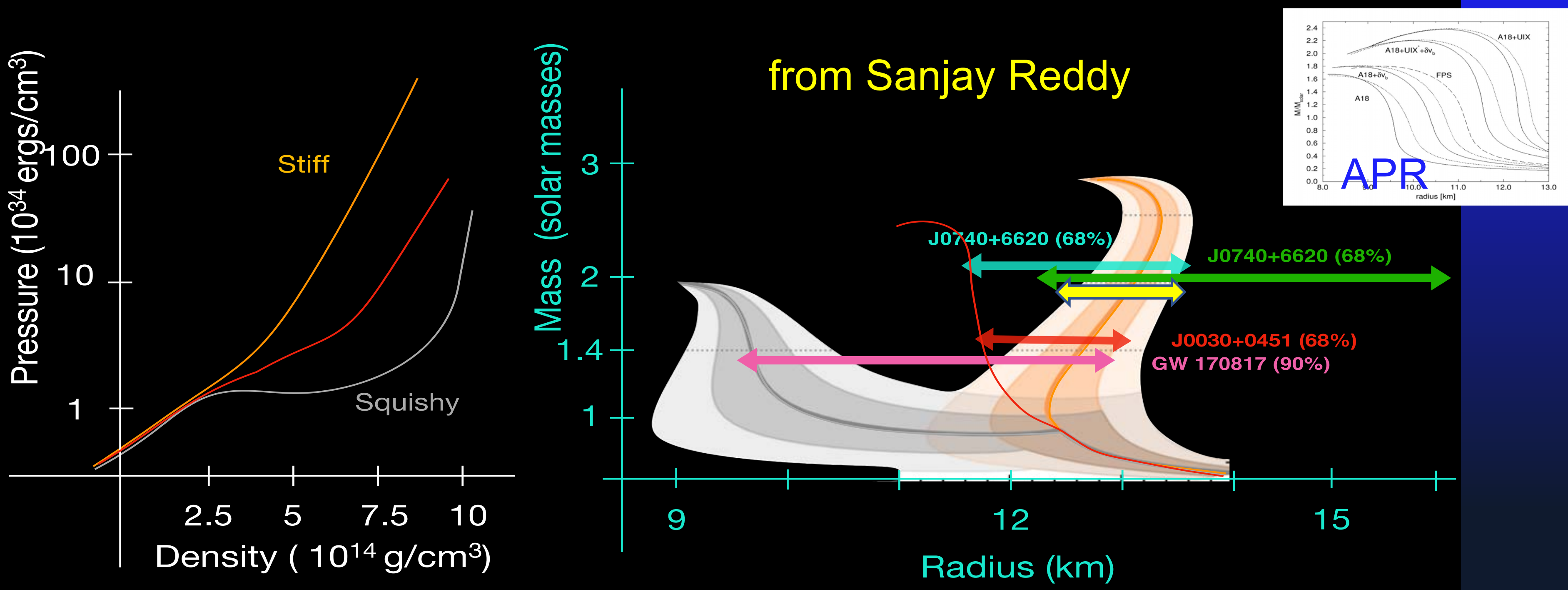




Points to rapid stiffening of nuclear matter, and onset of higher momentum degrees of freedom.

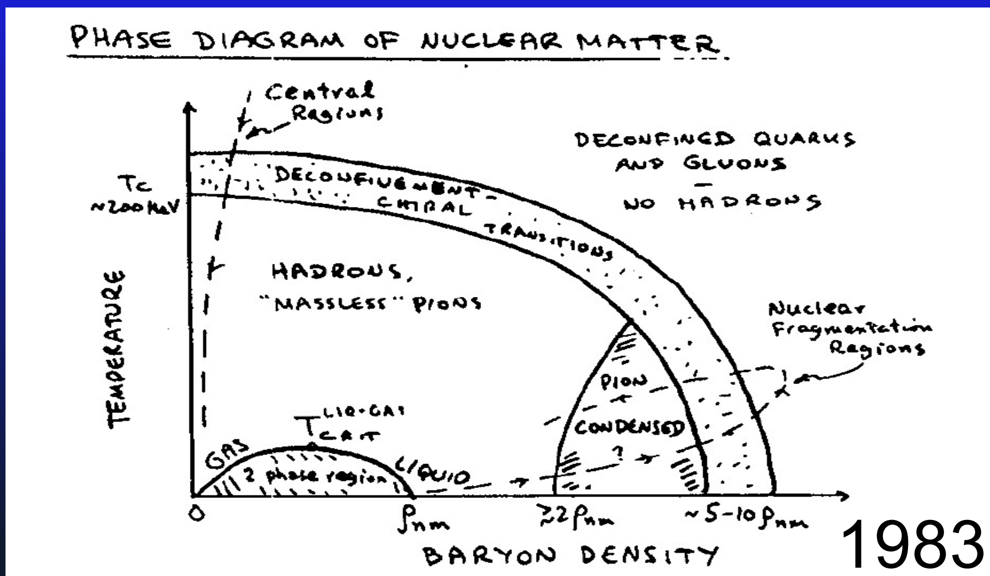
Nucleons beginning transition to quark matter. Pauli blocking of quarks pushes quarks to become relativistic, and start to contribute directly to the pressure, well before quark Fermi sea develops.

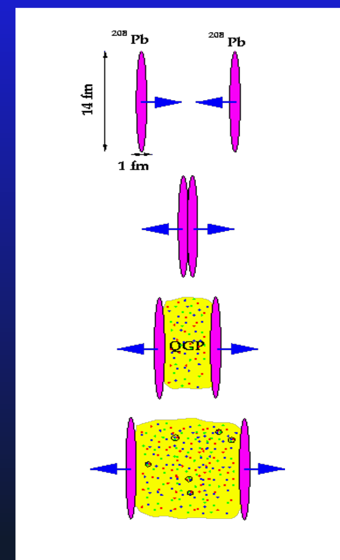
The size of neutron stars ⟷ Pressure of dense matter



NICER radius range with LIGO, nuclear and other astro information excludes soft equations of state and large first order phase transition

Matter under extreme conditions: baryon density/temperature

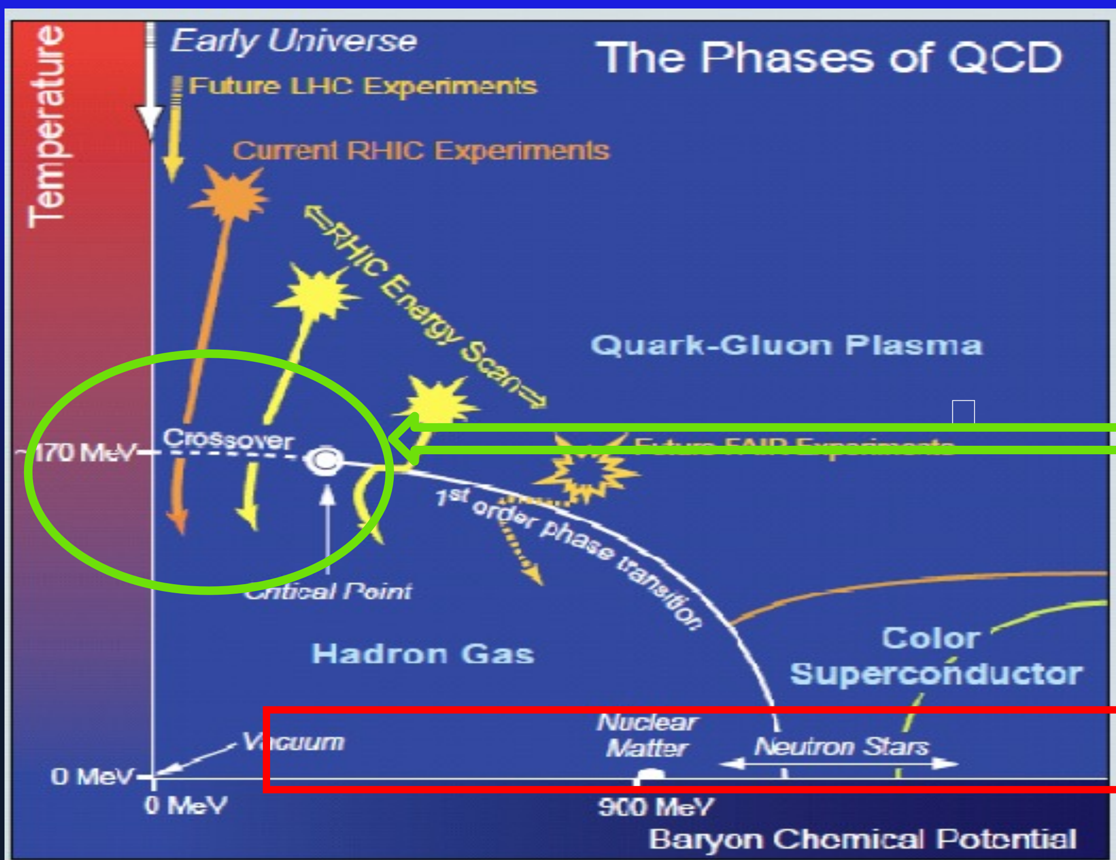




Ultrarelativistic heavy ion collision

Brookhaven Relativistic Heavy Ion Collider (RHIC) and the LHC at CERN study nuclear matter under extreme energy density – finding hot quark gluon plasma

More modern phase diagram



QCD lattice gauge theory predicts crossover from Confined phase at lower T to deconfined phase at higher T.

Do quarks roam freely in the deconfined phase? If so, they must also roam freely at lower T.

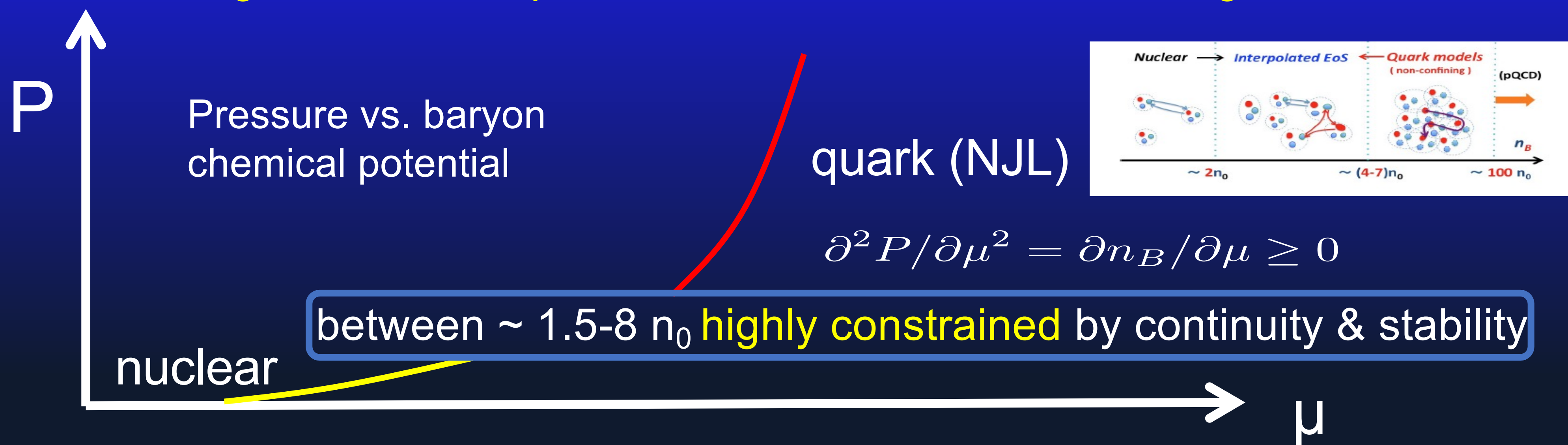
Are there really quarks running about freely in the room?

Strongly interacting system: cannot do lattice quantum chromodynamic simulations at finite density, zero temperature, owing to fermion sign problem.

QHC21 (quark-hadron crossover) equation of state

T. Kojo, GB, & T. Hatsuda,, Ap.J. 934:46 (2022)

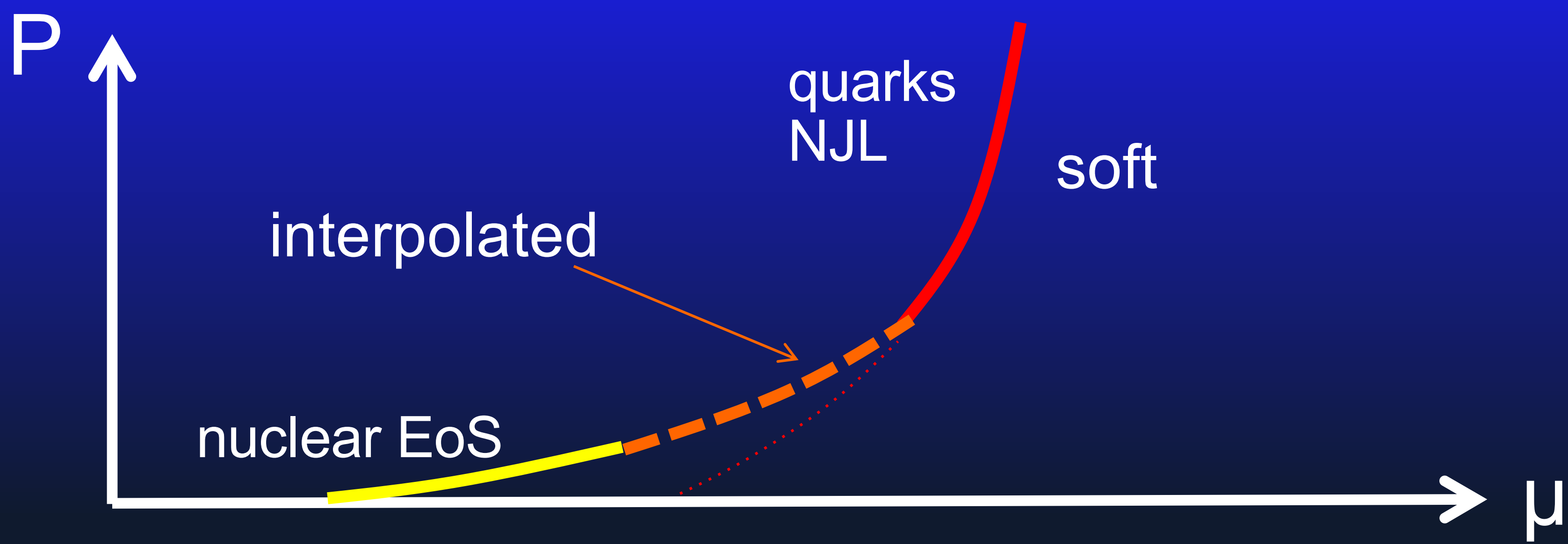
Have good idea of equation of state at nuclear and at high densities



Nuclear matter equation of state below 1.5 n_0

Quarks in Nambu-Jona-Lasinio (NJL) model with universal repulsive short-range qq coupling g_V and s-wave quark-quark pairing interaction H

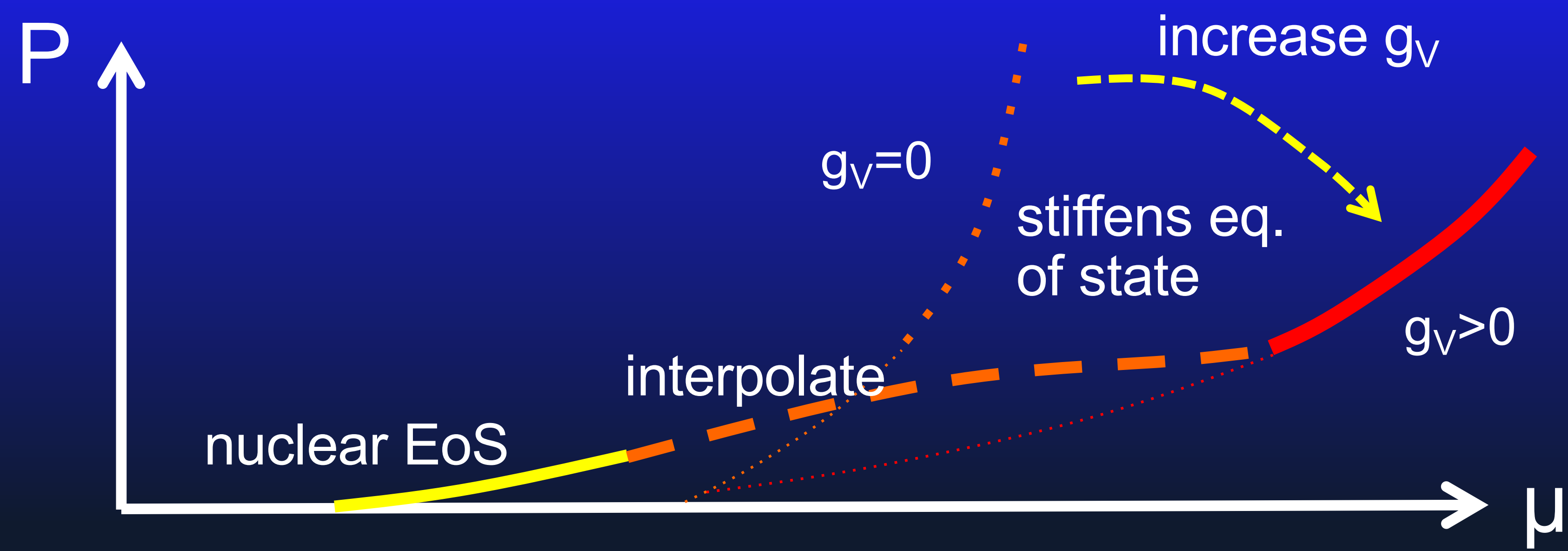
Minimal model: free quarks g_V = H = 0



Soft quark equation of state does not allow high mass neutron stars.

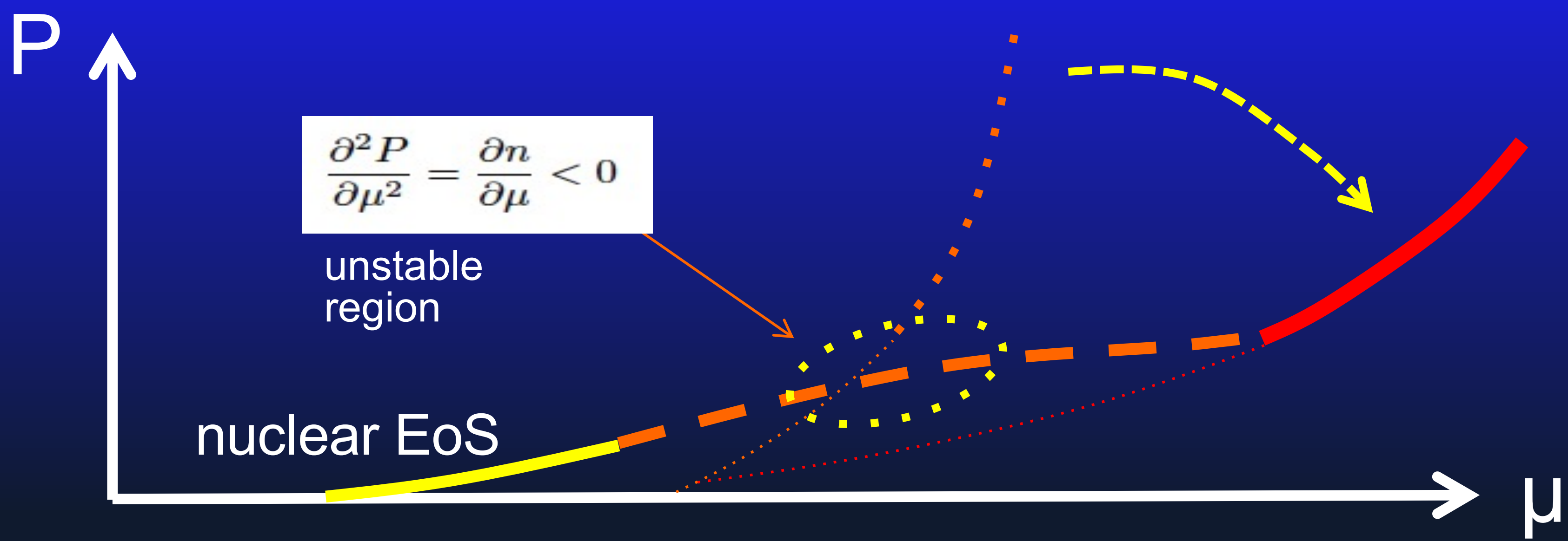
Need large quark repulsion g_V to reach high mass.

Short range repulsion stiffens eq. of state



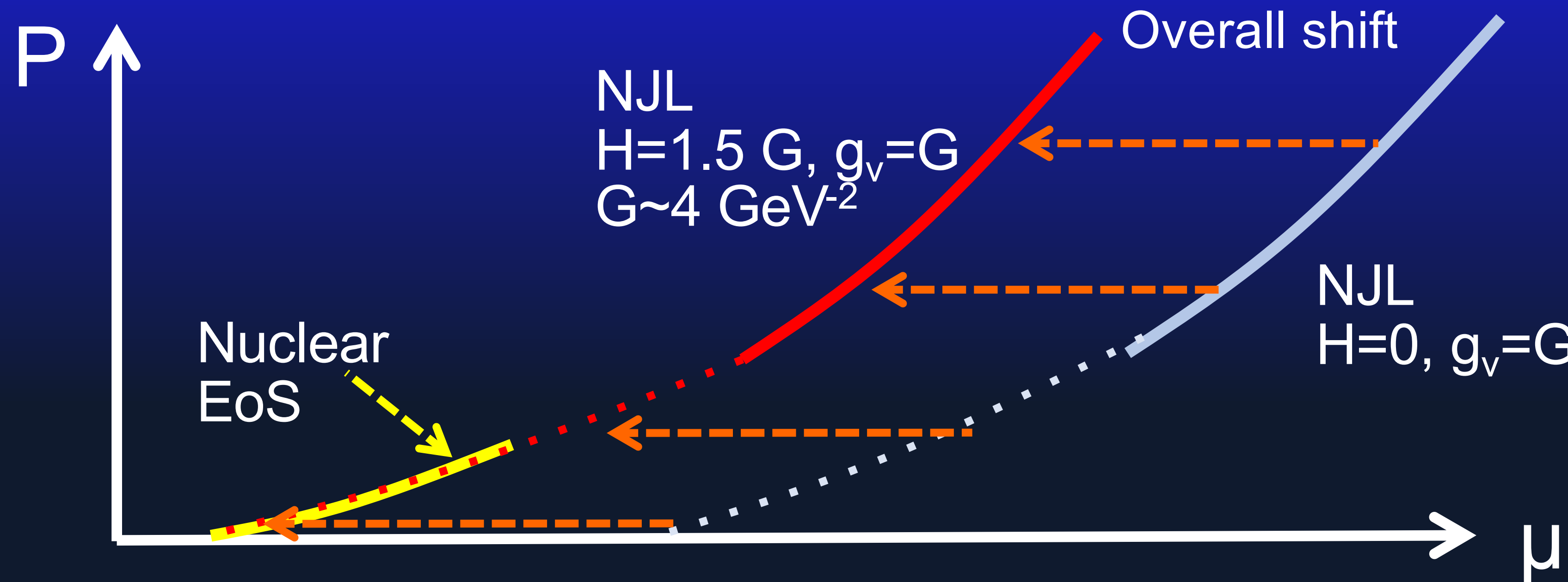
Shift of pressure in quark phase towards higher μ

Short range repulsion stiffens eq. of state



But larger g_V leads to unphysical thermodynamic instability

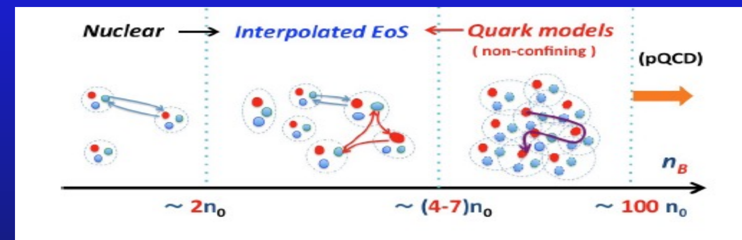
Thermodynamic stability requires large diquark s-wave pairing interaction, H



Expect increased pairing (onset of stronger 2-body correlations) as quark matter comes nearer to becoming confined – quarks want to form neutrons and protons

QHC21 (quark-hadron crossover) eqn of state

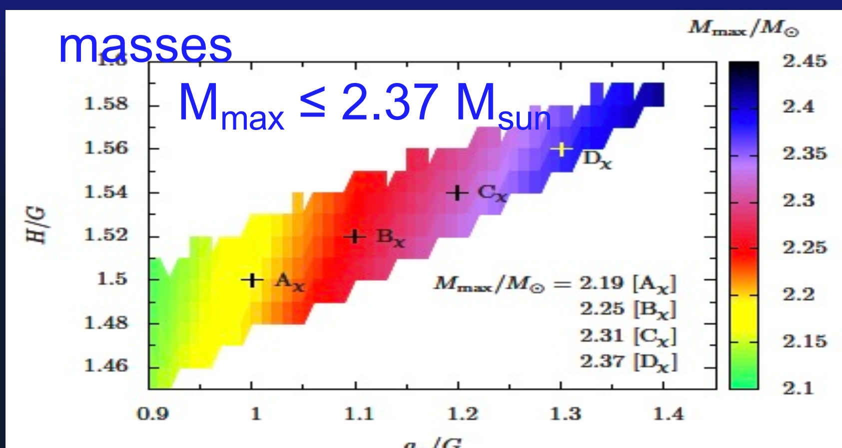
T. Kojo, GB, & T. Hatsuda, Ap. J. 934:46 (2022) https://compose.obspm.fr.



Parameters g_v and H must be in colored region so that
speed of sound ≦ speed of light.

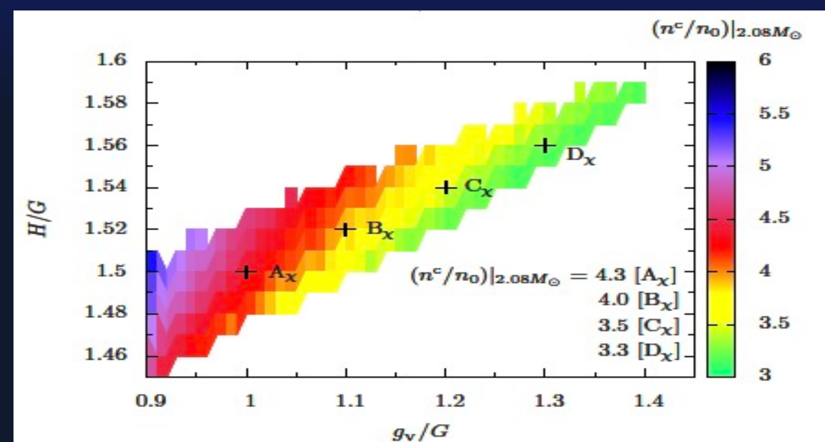
masses

$M_{max} \leq 2.37\ M_{sun}$



Strange quarks included

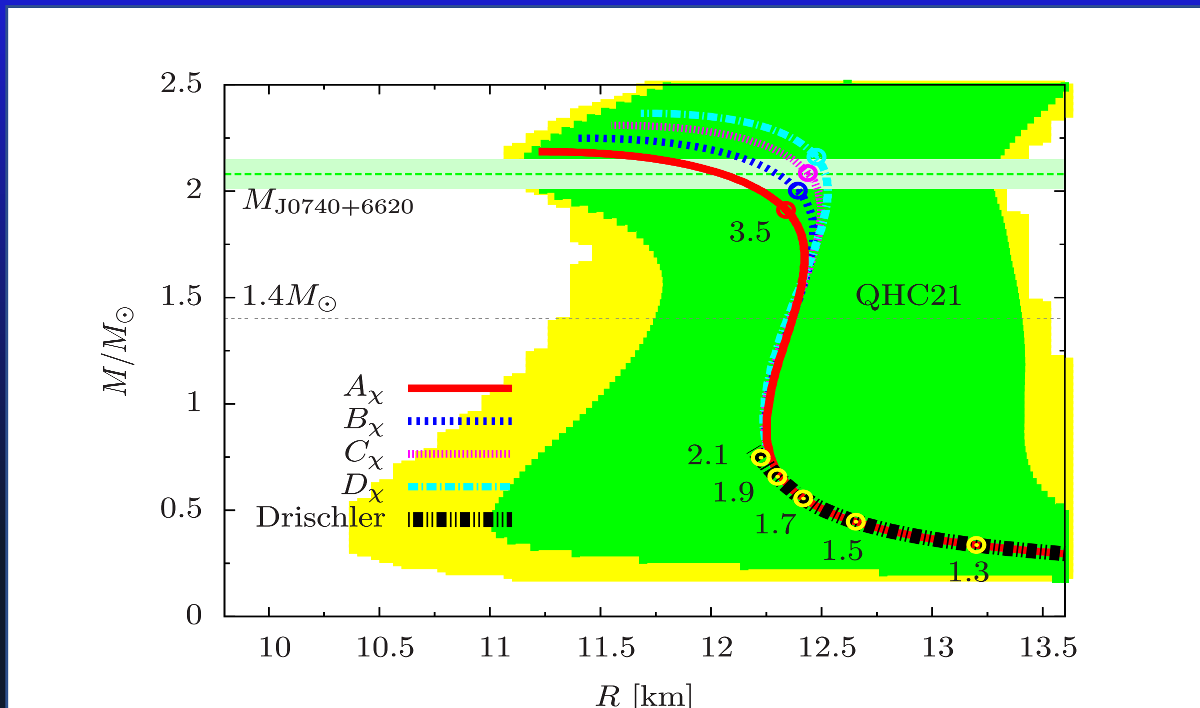
Further restricted by maximum neutron star mass > 2.08 M_{sun}



2.08 M_{sun} => $g_v \gtrsim 0.9$ G

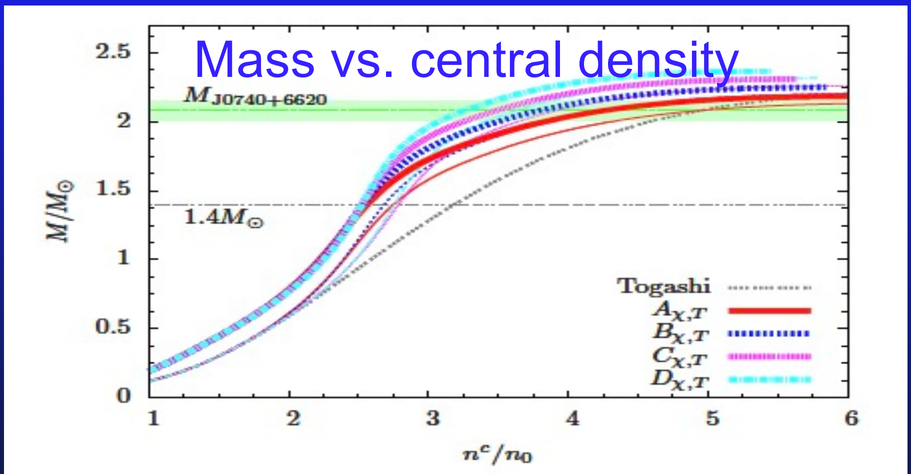
QHC21 (quark-hadron crossover) eqn of state

T. Kojo, GB, & T. Hatsuda, Ap. J. 934:46 (2022) *https://compose.obspm.fr.*



Chiral effective field theory to describe nuclear matter at densities below $1.5n_0$ +transition to quark matter in satisfactory agreement with NICER inferences of radii. Rapid pressure rise!

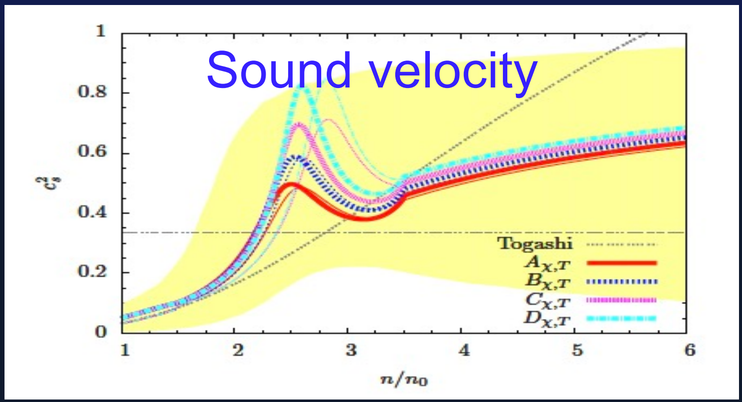
Quarks beginning to enter neutron stars



Central density of PSR J0740+6620 ~$5n_0$.
Maximum mass ~ 2.3 – 2.4 M_{sun}

Well above densities where pure hadronic calculations are valid. Entering transition to strongly interacting quark matter.

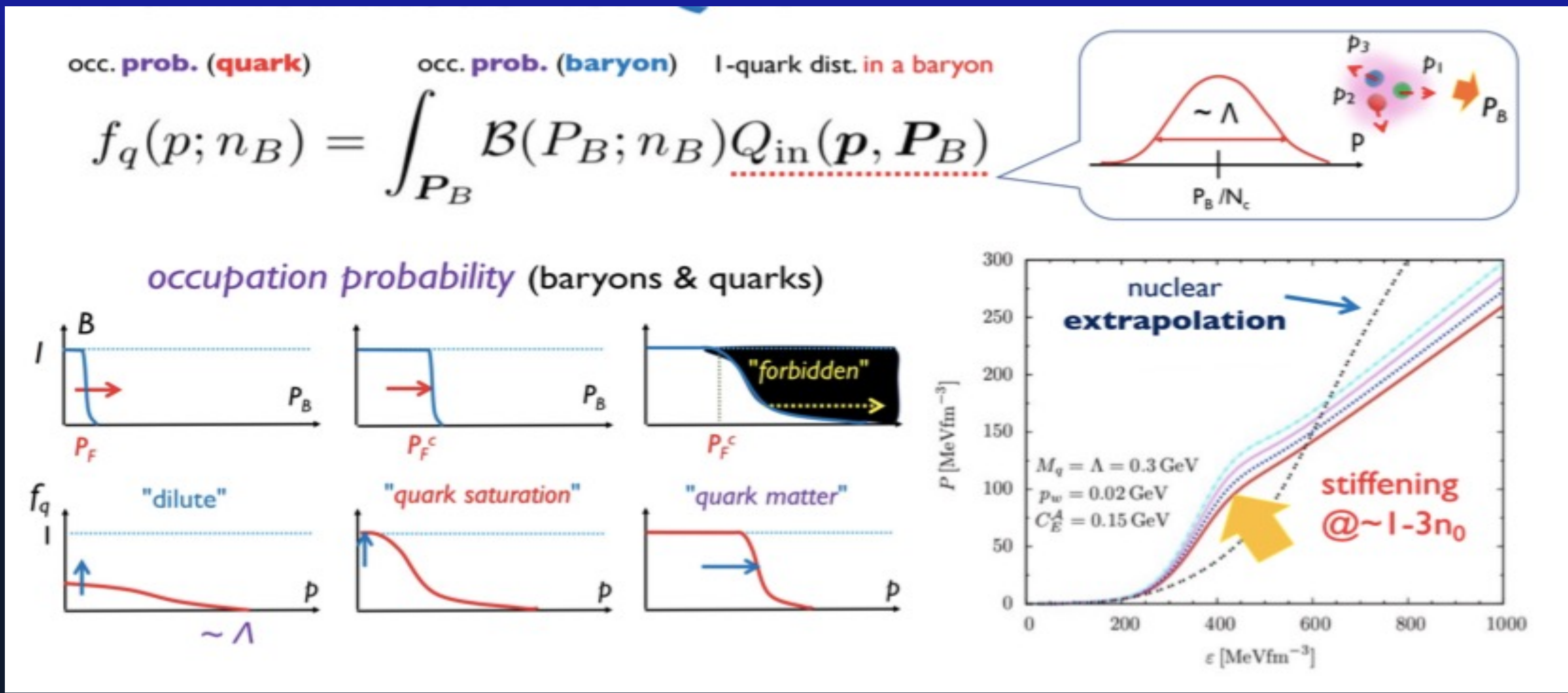
Cores of higher mass stars could reach beyond transition. Fully developed quark matter in cores? Need fully microscopic calculations of matter undergoing transition from nucleonic to quark degrees of freedom.



Peak not seen in nucleonic eq. of state

Pauli principle at high densities forces quarks in nucleons to higher energy states, stiffening matter

T. Kojo,,Phys. Rev. D105, 074005 (2021)



Challenges for future:

Build consistent phenomenological picture of matter above nuclear matter density from both gravitational radiation and NICER data.

Develop microscopic pictures of transition from hadronic to quark degrees of freedom in the regime 1.5-8 n_0.

Not good enough to draw a curve $P(\rho)$ that fits data. Must understand microscopic physics at QCD level.

What are the lightest and heaviest neutron stars, and lightest black holes?
(cf. LIGO/Virgo ~2.59 M_{sun} in GW190814)

Future NICER data and eventual gravitational wave data
(3rd generation detectors, to 400 Mpc => ~ 10^2 BNS mergers/year)
will continue to clarify physics of matter under extreme conditions.

Neutron stars are becoming quark 小笼包