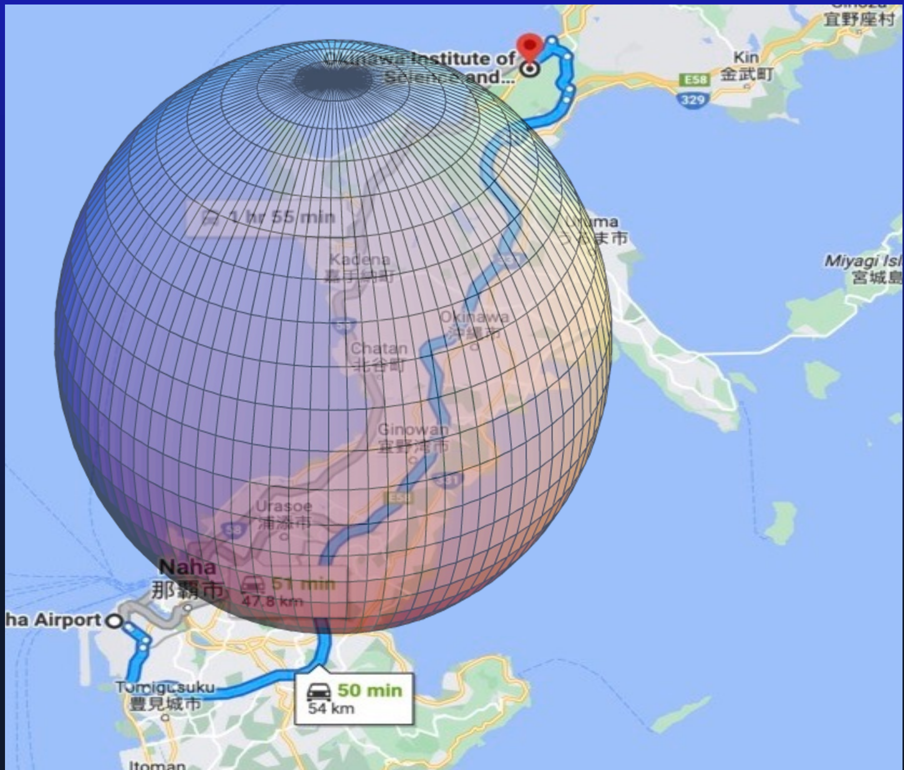
Matter under extreme conditions in neutron stars



neutron star over Okinawa

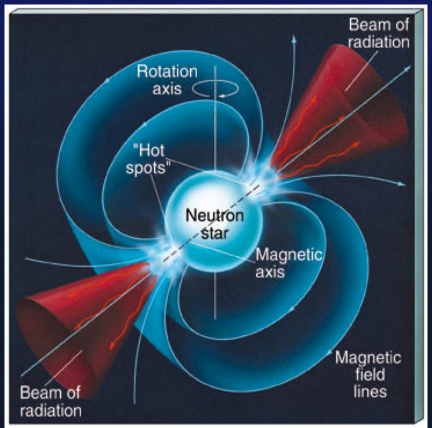
Gordon Baym
University of Illinois
Urbana, Illinois
&
RIKEN iTHEMS

ISCO 2023, OIST, Okinawa

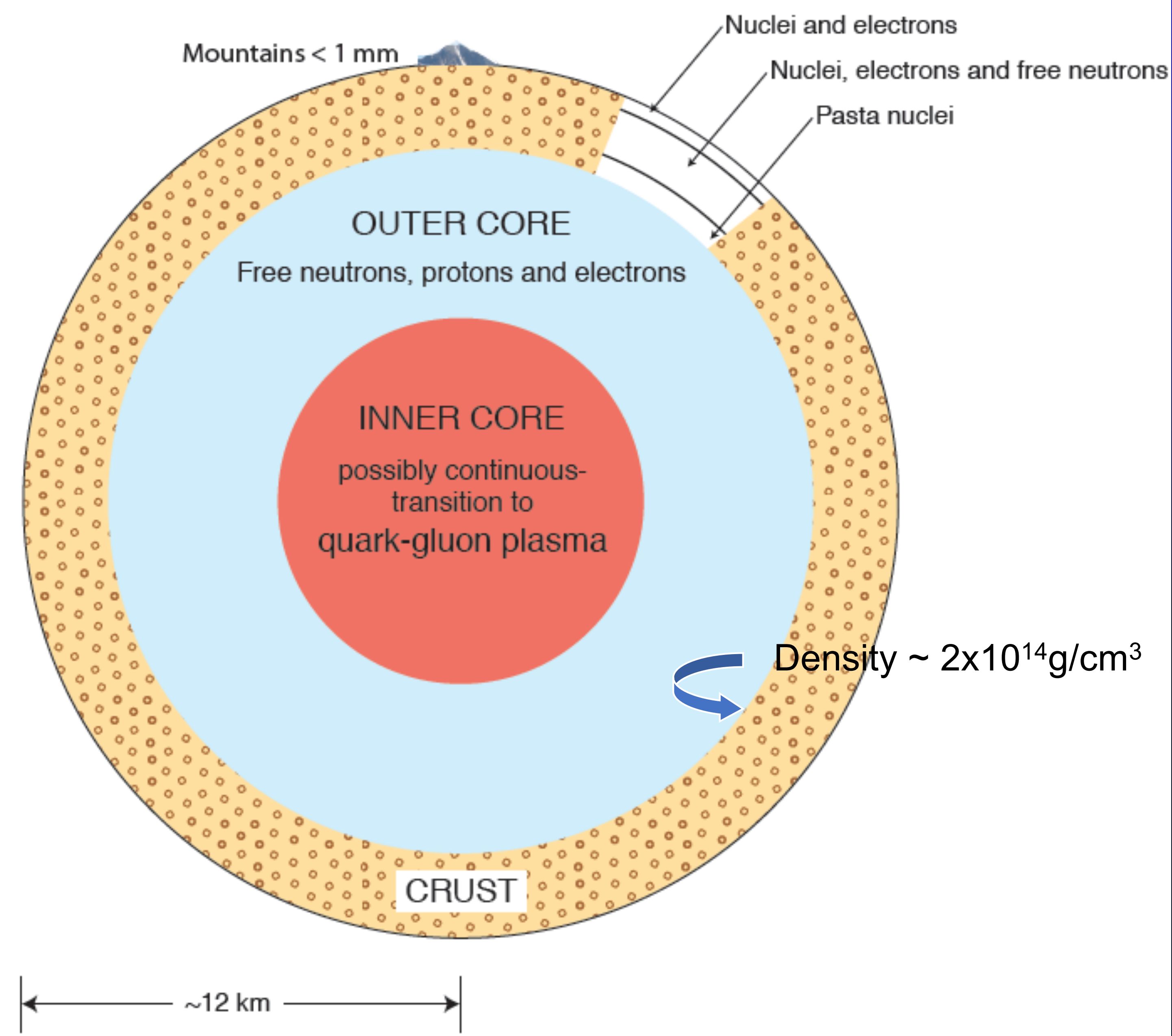
28 February 2023

Inside a neutron star

Mass ~ 1-2+ M_{sun}
Radius ~ 12-13 km
Temperature
 ~ 10^6-10^9 K
Baryon no. ~ 10^{57}
Magnetic fields
 ~ 10^6 – 10^{16} G



Surface gravity
 ~10^{11} that of Earth
Surface binding
~ 1/10 mc^2



Chadwick to Bohr, 24 Feb. 1932 announcing the discovery of the neutron

Cavendish Laboratory,
Cambridge.

24 February 1932.

Dear Bohr.

I enclose the proof of a letter I have written to "Nature" and which will appear either this week or next. I thought you might like to know about it beforehand.

The suggestion is that α particles eject from beryllium (and also from boron) particles which have no nett charge, and which probably have a mass about equal to that of the proton. As you will see, I put this forward rather cautiously, but I think the evidence is really rather strong. Whatever the radiation from Be may be, it has most remarkable properties. I have made many experiments which I do not mention in the letter to "Nature" and they can all be interpreted readily on the assumption that the particles are neutrons. Feather has taken some pictures in the expansion chamber and we have already found about 20 cases of recoil atoms. About 4 of these show an abrupt bend or fork and it is almost certain that in this one arm of the fork represents a recoil atom and the other some other particle, probably an α particle. These are disintegrations due to the capture of the neutron by N_{14} or O_{16}. I enclose two photographs, one of which shows the simple recoil atom, and the other what we suppose is a disintegration. The photographs are not very good but they were printed in a hurry.

With best regards
Yours sincerely
J. Chadwick.

"I enclose the proof of a letter I have written to Nature and which will appear within this week or next.
The suggestion is that α particles eject from Be ... particles which have a mass almost equal to that of the proton …"

09/05/32

Special Cable to THE NEW YORK TIMES.
YORK, England, Sept. 5.—The belief that the neutron is a new ultimate particle like an electron or proton was challenged today by Dr. James Chadwick, young Cambridge scientist who discovered the elusive neutron last Winter.

Dr. Chadwick only smiled, however, when asked if his discovery had practical importance.
"I am afraid neutrons will not be of any use to any one," he said.

NY Times
02/29/32

Baade & Zwicky propose neutron stars, made in supernovae
APS Bulletin Dec. 1933

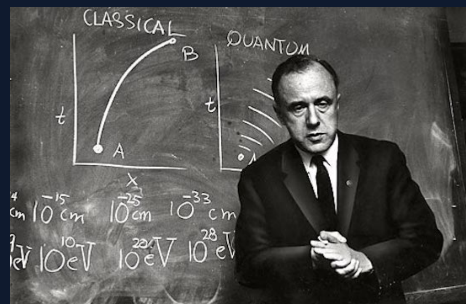
Cosmic Rays from Super-novae
PNAS 20, 259 (1934)

Oppenheimer & Volkoff (1939) calculate neutron star made of free neutrons ($M = 0.7\ M_\odot$)

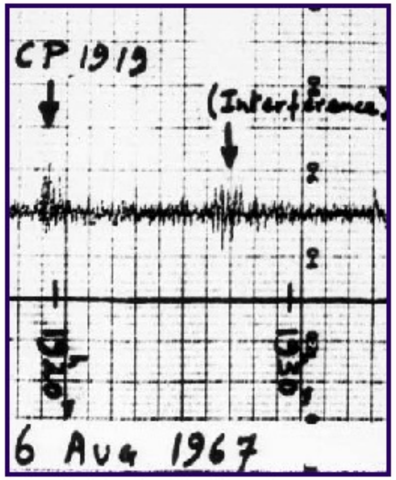
. . .

Wheeler, 1966 (Ann. Rev. Astron. Astrophys.)

A ``cool" superdense star ... is fainter than the 19th magnitude and therefore hardly likely to be seen. The rapidity of cooling makes detection even more difficult.

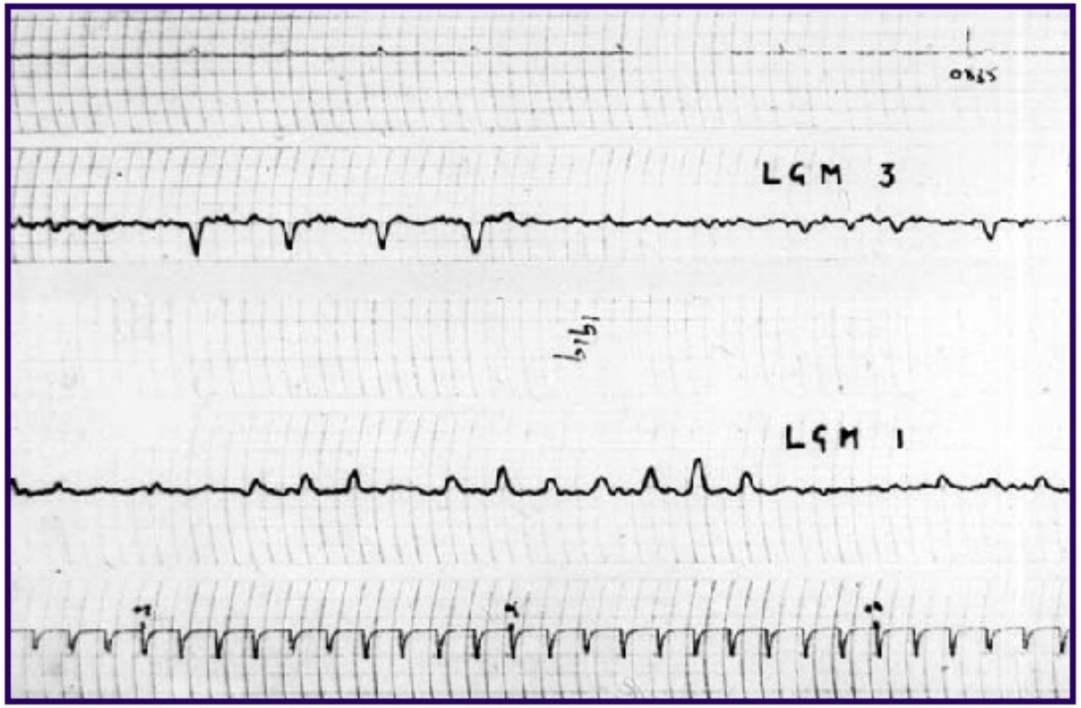


Nov. 1967 First pulsar detection: 1919+21 *Bell & Hewish*



2: The first detection of the first pulsar, occupying about one-quarter inch of chart paper. About five minutes later is a short burst of low level interference. This signal has been high-pass filtered, to remove the telescope's interference pattern. (Mullard Radio Astronomy Observatory.)

Jocelyn Bell



3: The bottom trace is of broadcast one-second time pips. The middle trace shows the first recording to reveal the pulsed nature of the pulsar PSR1919. The top trace is of the third pulsar discovered, PSR0834.

1968 (Spring): Pulsars identified as rotating neutron stars by Tommy Gold (Cornell) and Franco Pacini (Florence)

Made in gravitational collapse of massive stars (supernovae)
and can be a remnant of binary neutron star mergers

Matter in neutron stars is densest in universe:
baryon density n up to ~ 5-10 n_0

$n_0 = 0.16$ /fm^3 <-> 3 X10^{14} g/cm^3 = density of matter in atomic nuclei
[cf. white dwarfs: $\rho \sim 10^5$-10^9 g/cm^3] 1 fm = 10^{-13} cm

Supported against gravitational collapse by nucleon
(and at higher densities quark) degeneracy pressure

Central engines in variety of compact energetic systems:
pulsars, binary X-ray sources, Soft Gamma Repeaters,
magnetars, ultraluminous X-ray sources, Fast Radio Bursts (FRB),
binary neutron star (and ns-black hole) mergers

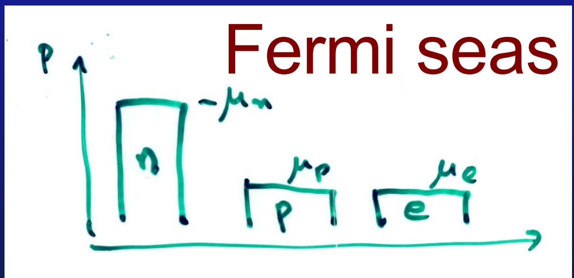
Astrophysical laboratory for study of cold high-density matter and
Quantum Chromodynamics (QCD)

Nuclei before neutron drip (outer crust)

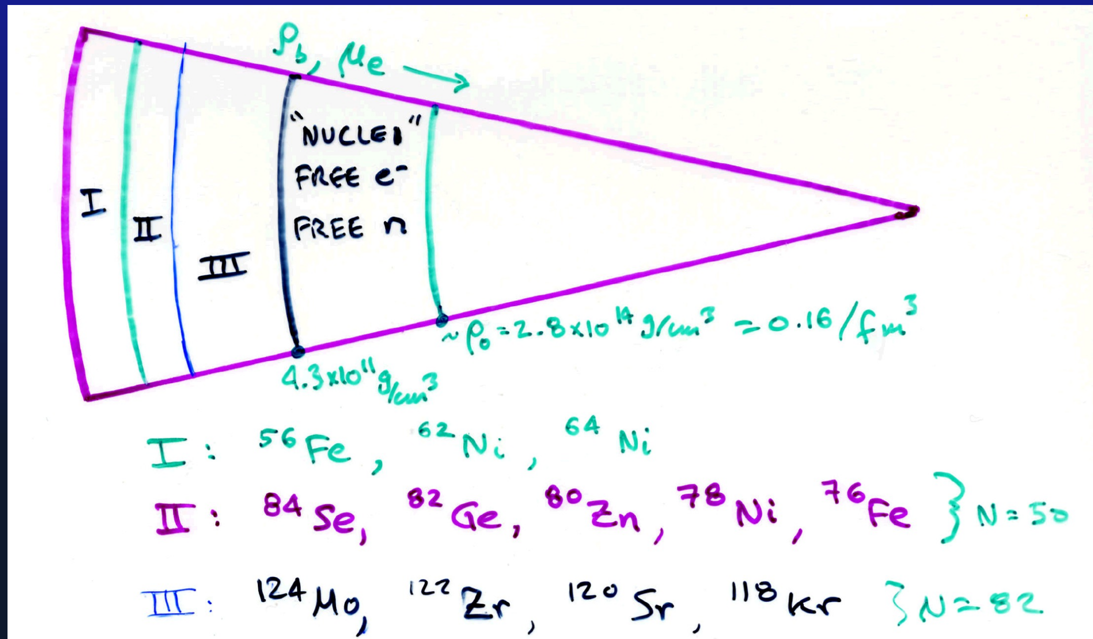
$e^- + p \longrightarrow n + \nu$: makes nuclei neutron rich as electron Fermi energy increases with depth

$n \longrightarrow p + e^- + \bar{\nu}$: not allowed if e^- state already occupied

Beta equilibrium: $\boxed{\mu_n = \mu_p + \mu_e}$



GB, C.J.Pethick, and P. Sutherland, Ap.J. (1971)



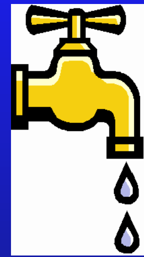
Shell structure (spin-orbit forces) for very neutron rich nuclei?

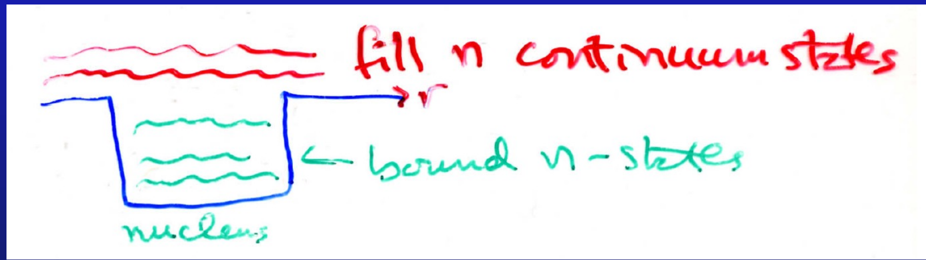
Do N=50, 82 remain neutron magic numbers? Proton shell structure?

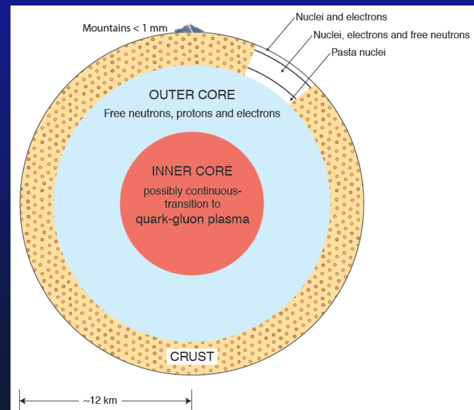
Being explored at rare isotope accelerators: RIKEN Rare Ion Beam Facility (RIBF), and later GSI (MINOS), FRIB, RAON (KoRIA)

Neutron drip

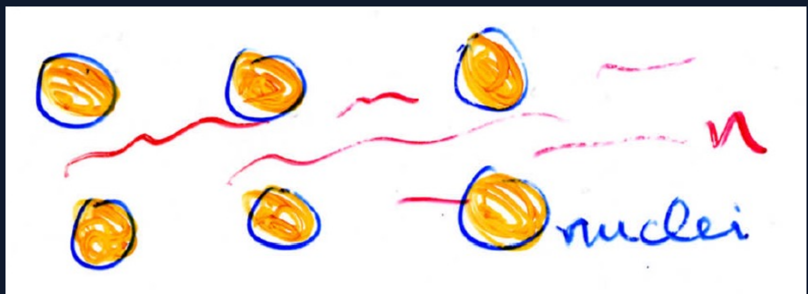
Beyond density ρ_{drip} ~ 4.3 X 10^{11} g/cm^3 neutron bound states in nuclei become filled. Further neutrons must go into continuum states. Form degenerate neutron Fermi sea.







Neutrons in neutron sea are in equilibrium with those inside nucleus (common μ_n)



How do the nuclei turn into liquid at higher densities?

Protons appear not to drip, but remain in bound states until nuclei merge in liquid interior.

The liquid interior near nuclear matter density

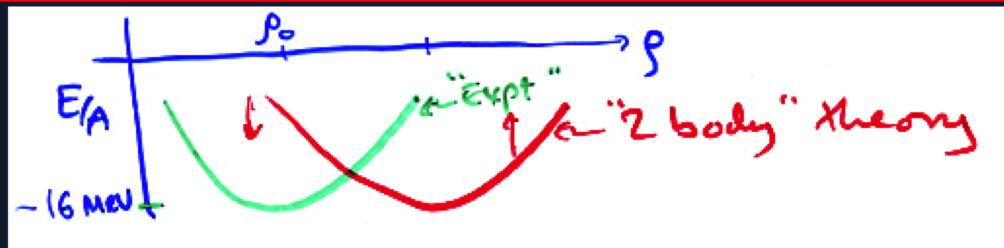
Theoretical extrapolation from low energy laboratory nuclear physics near nuclear matter density up to $2n_0$ or higher.

Determine the equation of state:
Pressure $P(\varepsilon)$
as function of energy density, ε :

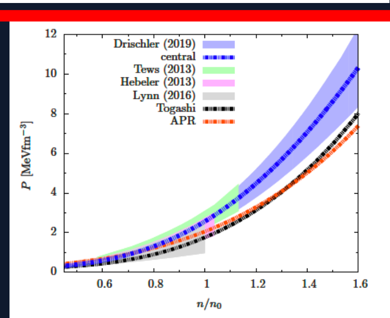
ε = energy density = ρc^2
n_b = baryon density
$P(r)$ = pressure = $n_b^2\, d(\varepsilon/n_b)/dn_b$

1) Determine N-N potentials from scattering expts E < 300 MeV, +deuteron, 3 body nuclei (^3He, ^3H); solve Schrödinger eq. variationally

Two body potential alone fails!!
Fix with three body forces.



2) Chiral effective theory approach -- best now
Expansion in low energy processes, e.g., one π exch.



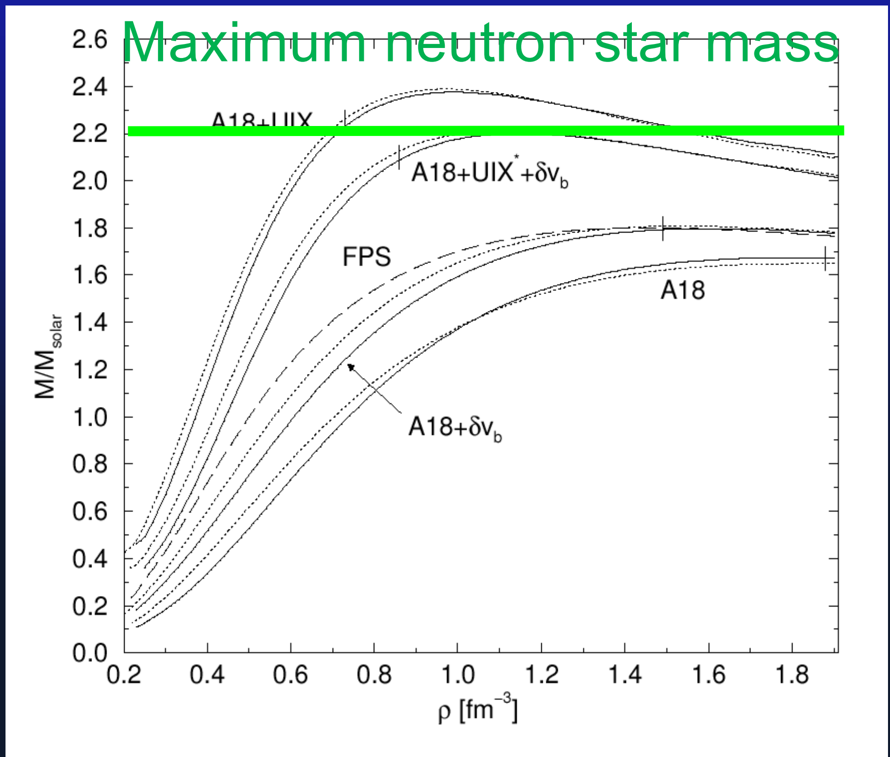
Construct neutron star models

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

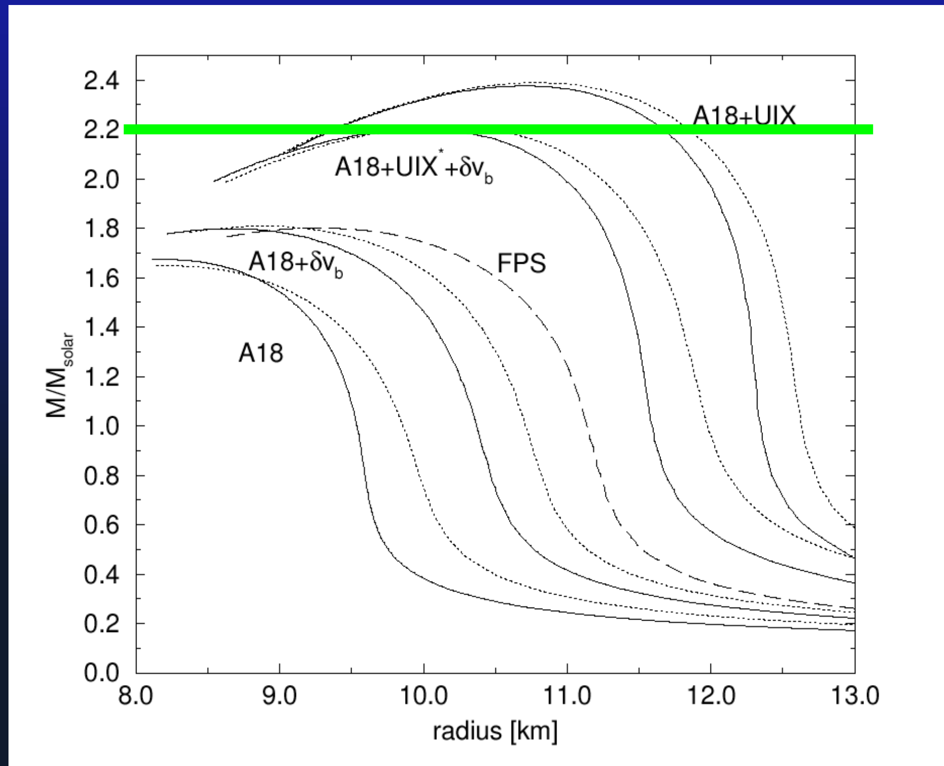
$$\frac{\partial P(r)}{\partial r} = -G\frac{\rho(r) + P(r)/c^2}{r\,(r - 2Gm(r)/c^2)}[m(r) + 4\pi r^3 P(r)/c^2]$$

TOV equation

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



Mass vs. central density



Mass vs. radius

Akmal, Pandharipande and Ravenhall (APR) 1998 nuclear equation of state

Fundamental limitations of eq. of state based on NN interactions

Accurate for n~ n_0.   But for n >> n_0:

-sound speed becomes greater than speed of light

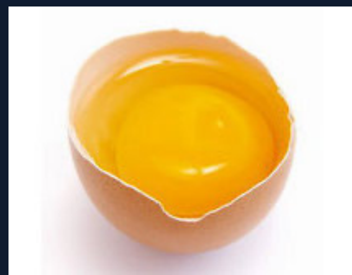
-importance of 3 (4,5...) body forces grows with density

-chiral effective theory breaks down above n ~ 1.5-2n_0.

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

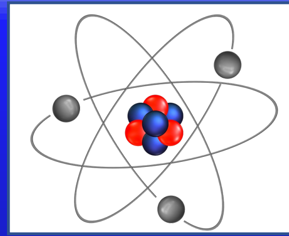
-can one even describe system in terms of well-defined “asymptotic" laboratory particles?

New degrees of freedom enter! QUARKS

Squeeze:  => 

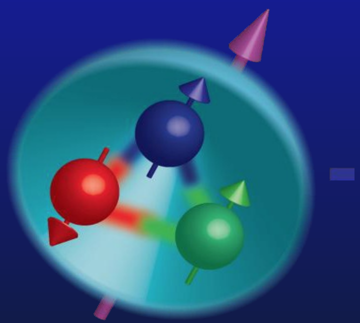
Given all information on Nb+Nb atomic scattering could one predict that Nb is a superconductor?

Atoms are made of electrons and nuclei.
Similarly neutrons, protons, and nuclei are made of
quarks and gluons



Quarks = fractionally charged spin-1/2 fermions, baryon no. = 1/3,
with internal SU(3) color degree of freedom.

Flavor	Charge/|e|	Mass(MeV)
u	2/3	~2
d	-1/3	~5
s	-1/3	~ 94
c	2/3	~1280
b	-1/3	~4200
t	2/3	~175,000



proton = u + u + d
neutron = u + d + d
$\pi^+ = u + \bar{d}$, etc.

Quark matter (baryonic) in the early universe at t < 1 microsec
(T > 100 MeV), and in the deep interiors of heavier neutron stars.

Can’t calculate strongly interacting matter exactly – technical problem

The Golden Age of Neutron Stars:

Wealth of new observational data, and even Gold

The Golden Age of Neutron Stars:

Wealth of new observational data, and even Gold

Detections of heavy neutron stars in pulsars
Equation of state relatively stiff

Masses and radii of neutron stars
NICER measuring M, R directly for a few pulsars

Gravitational waves from ns-ns and ns-black hole mergers explore masses, radii, and tidal deformabilities
Production of heavy elements via r-process: Au, Pt, Ag, U, Sr

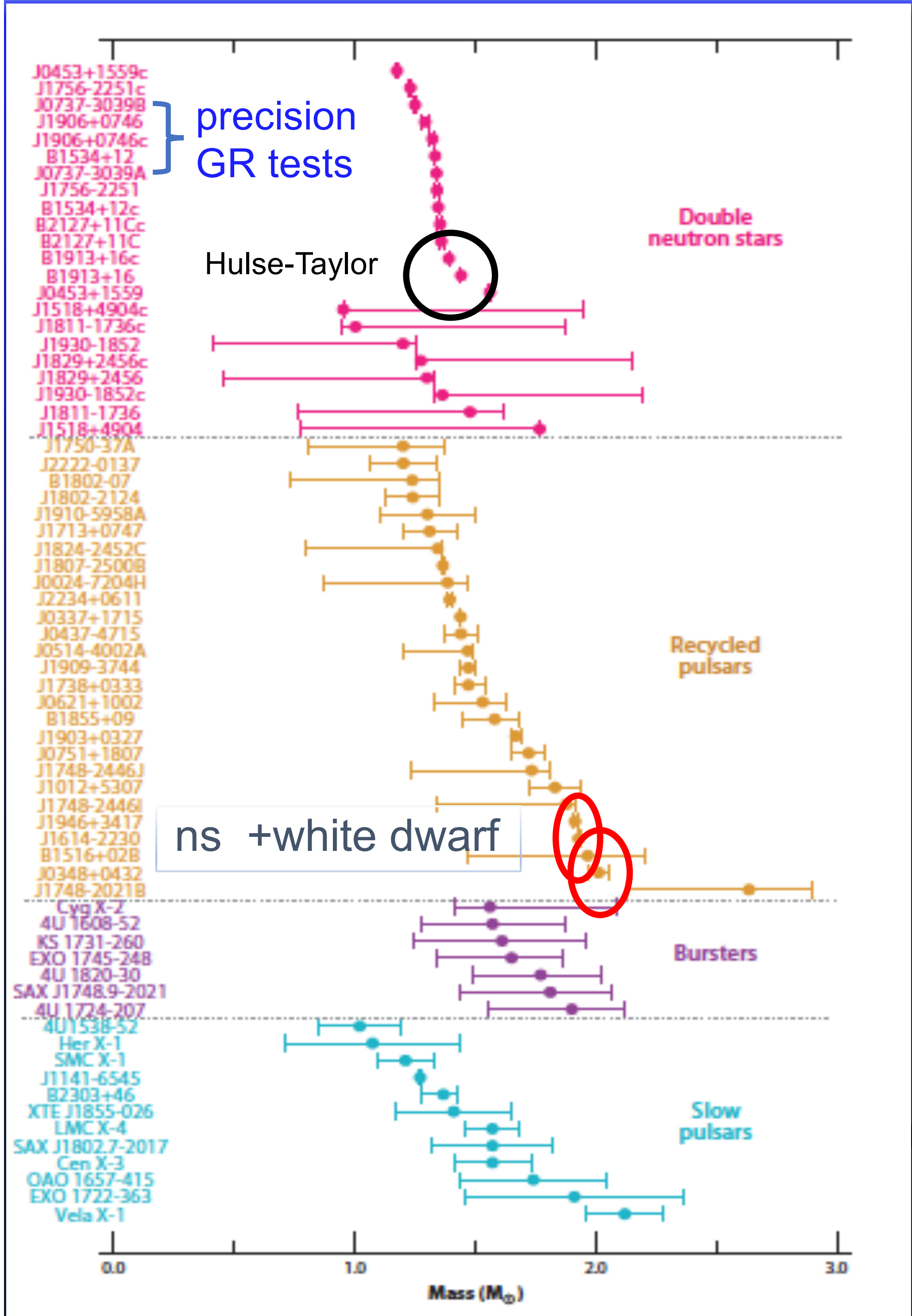
LIGO/Virgo/KAGRA (Run 4 - 05/23)
Eventually Cosmic Explorer, Einstein Telescope, LISA

Glitches: probe n,p superfluidity and crust

Cooling of n-stars: search for rapid cooling from exotic states, measuring equation of state in crust

Neutron star masses

Özel & Freire, Ann Rev AA (2016)



PSR J1614-2230 :

$M_{nstar} = 1.928 \pm 0.017 M_\odot$

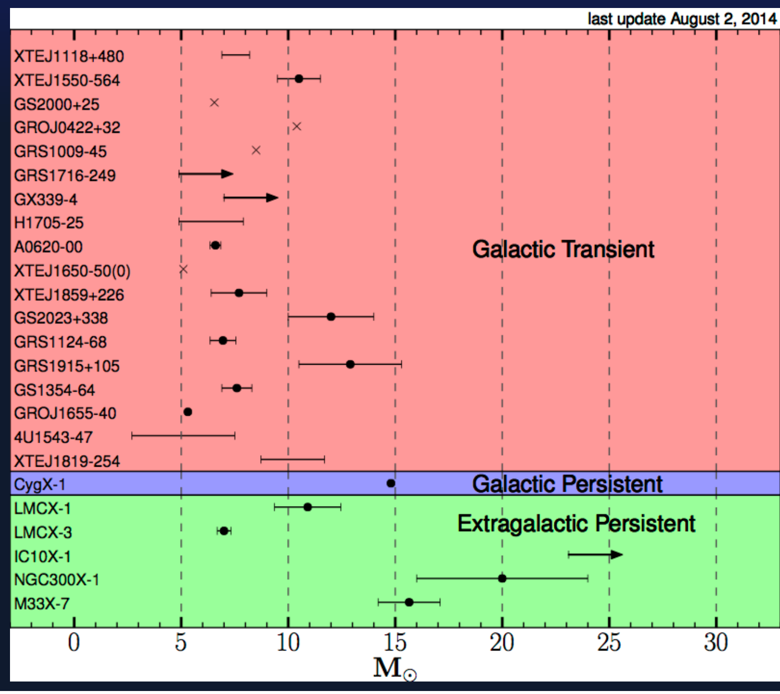
PSR J0348+0432:

$M_{nstar} = 2.01 \pm 0.04 M_\odot$

PSR J0740+6620 :

$M_{nstar} = 2.08 \pm 0.07 M_\odot$

Galactic black hole masses



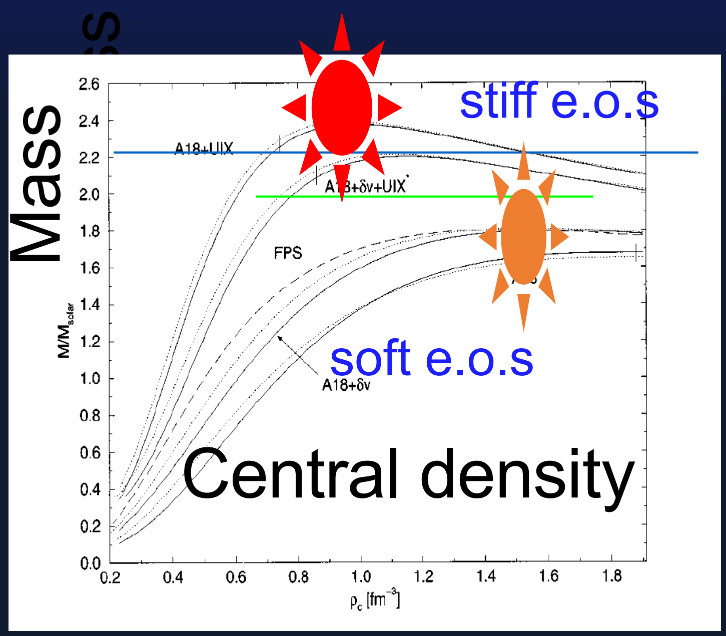
Mass determinations of three high mass neutron stars (pulsars in binaries)

PSR J0348+0432: $M_{neutron\ star} = 2.01 \pm 0.04 M_\odot$ 2013

PSR J1614-2230 : $1.93 \pm 0.02 M_\odot$ 2016

PSR J0740+6620 : $2.08 \pm 0.07 M_\odot$ 2019

=> the equation of state is stiff



Softer equation of state => lower maximum mass and higher central density

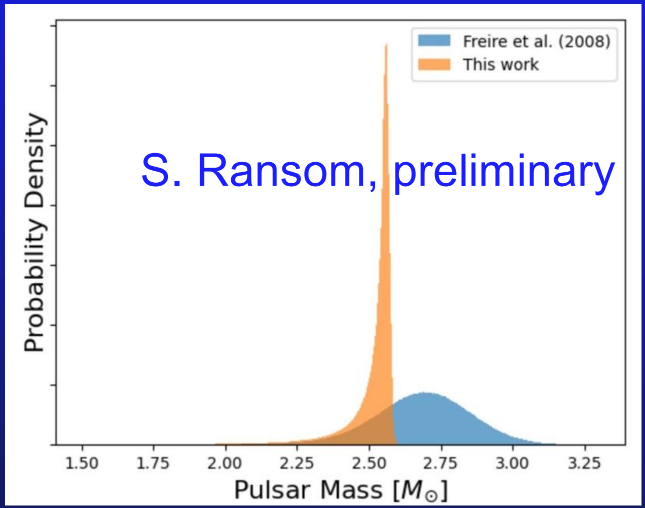
Binary neutron stars ~ 1.4 $M_\odot$: consistent with soft eq. of state

Can quarks support two solar masses?

Two further massive neutron stars

PSR 1748-2021B (Arecibo, 1998)

Binary pulsar in globular cluster M5.
P = 16.7 msec.
Companion light and small. Awaiting detection by James Webb Space Telescope



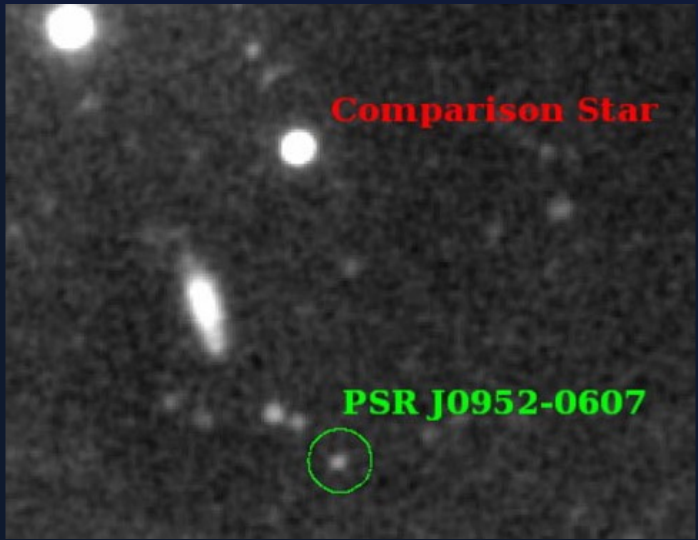
$M<2.5\ M_{sun}$

PSR J0952-0607

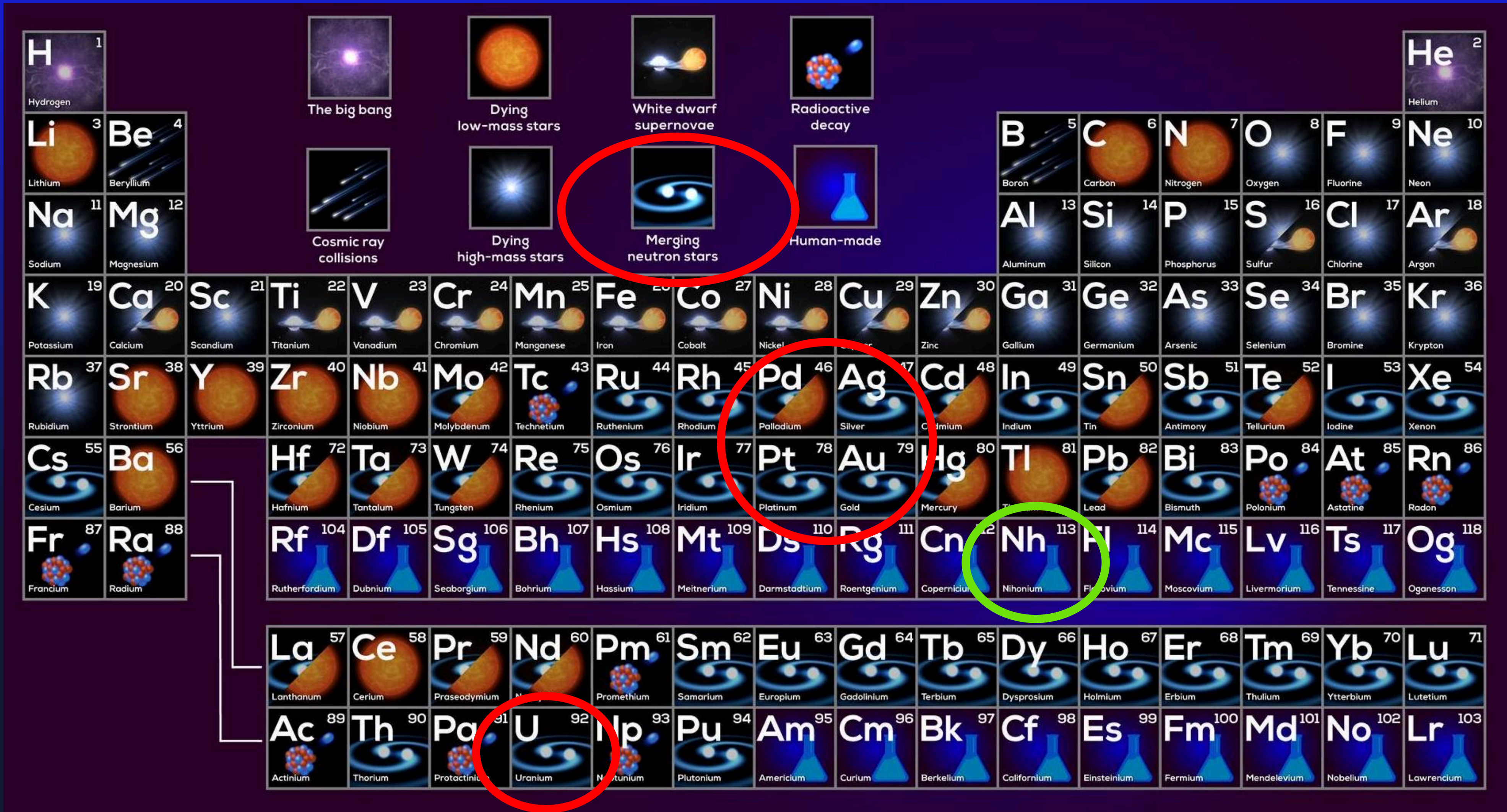
(R. Romani, Ap.J. Lett. 934:L17, 2022)

Black widow pulsar, P =14.1 msec.
Mass of companion = $0.032 \pm 0.002\ M_{sun}$

$M = 2.35 \pm 0.17\ M_{sun}$



Binary neutron star mergers likely site of heavy element production (via r-process)



Periodic table of the elements with their “origins”

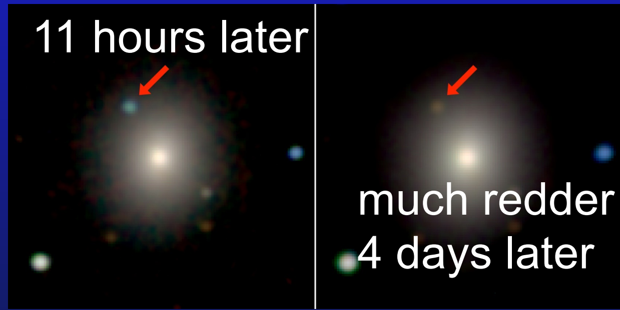
Gravitational radiation: new window on neutron stars

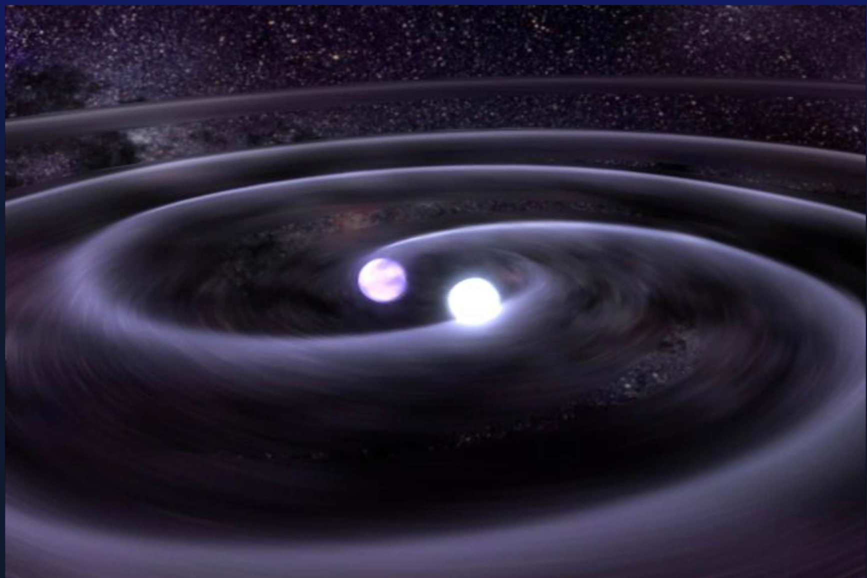
GW170817: Initial spectacular event – Multi-messenger astronomy

Neutron star – neutron star (BNS) merger observed on 17 Aug. 2017 by LIGO and Virgo (gravitational radiation), FERMI (gamma ray telescope) and ~ 70 other electromagnetic observatories.

$m_1 \sim 1.36\text{-}1.60\ M_\odot$, $m_2 \sim 1.17\text{-}1.36\ M_\odot$

radii ~ 11.9 ± 0.7 km

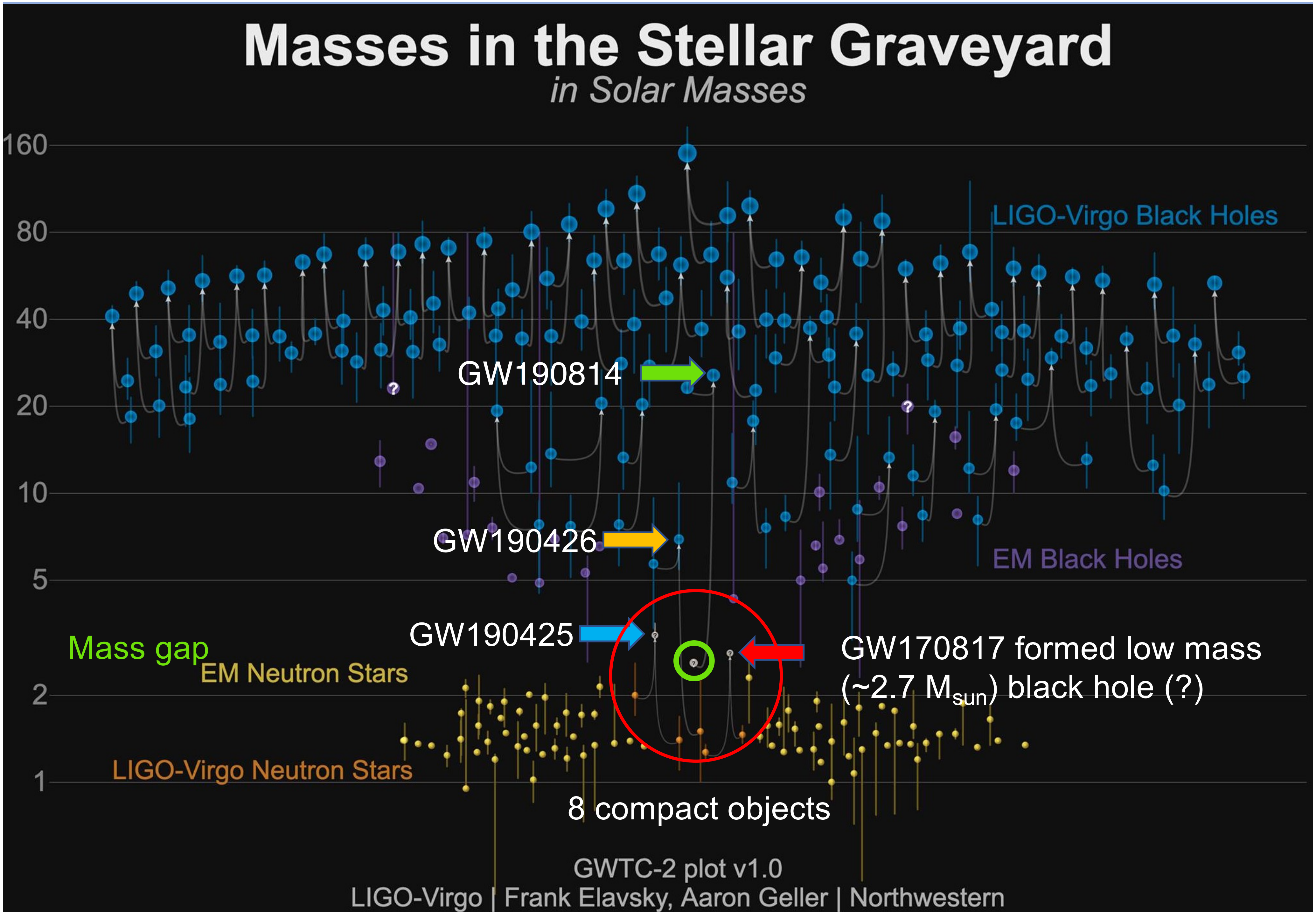




Two neutron stars merging, emitting gravitational radiation and. post-merger, forming:

Kilonova: neutron-rich site of r-process

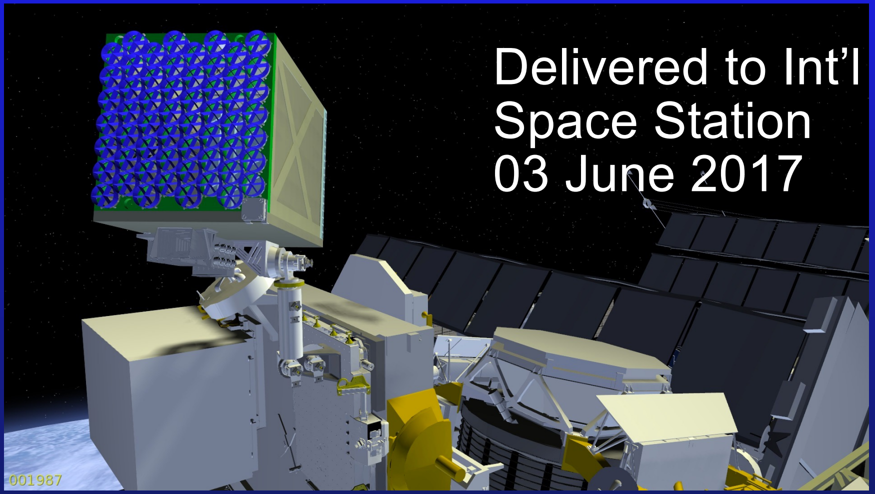
Masses in the Stellar Graveyard



"GW19…" objects involve neutron stars

NICER = Neutron star Interior Composition ExploreR

X-ray timing (to 300 nsec)
& spectroscopy (0.12-12 KeV)



Measure masses and radii (5%) by monitoring X-ray pulse profiles of nearby neutron stars (J0437, ...)

Properties of n.s. crusts via astroseismology

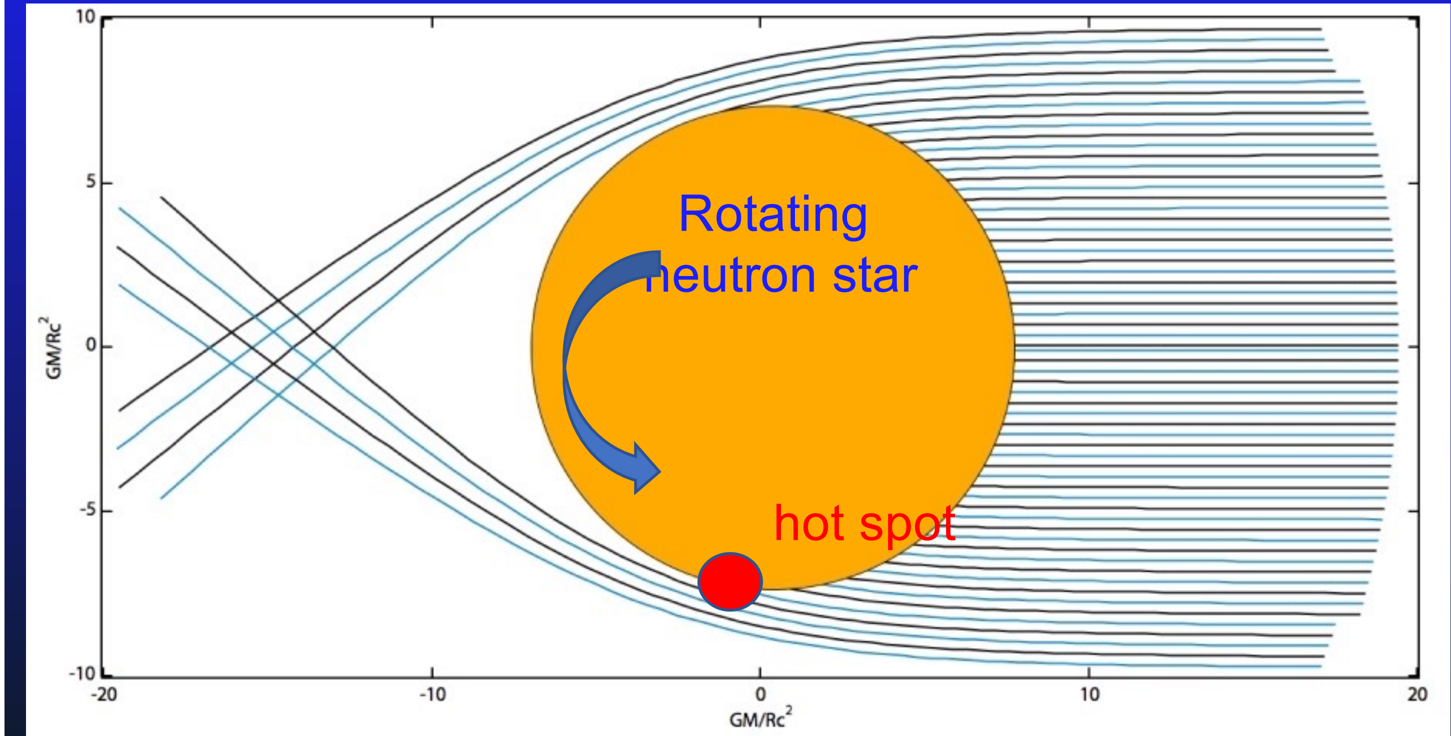
Periodic pulsations from transient & steady systems

Results for two neutron stars

PSR J0740+6620 : $M_{nstar} = 2.08 \pm 0.07\ M_{\odot}$, R_{nstar} ~12-13 km

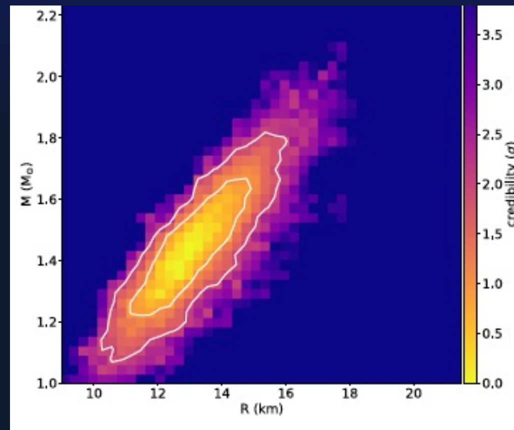
PSR J0030+0451 : $= 1.44 \pm 0.15\ M_{\odot}$, ~12-13 km

Track hot spots on neutron star. Light bending by star enables one to see spot "behind" star. Bending depends on M and R.



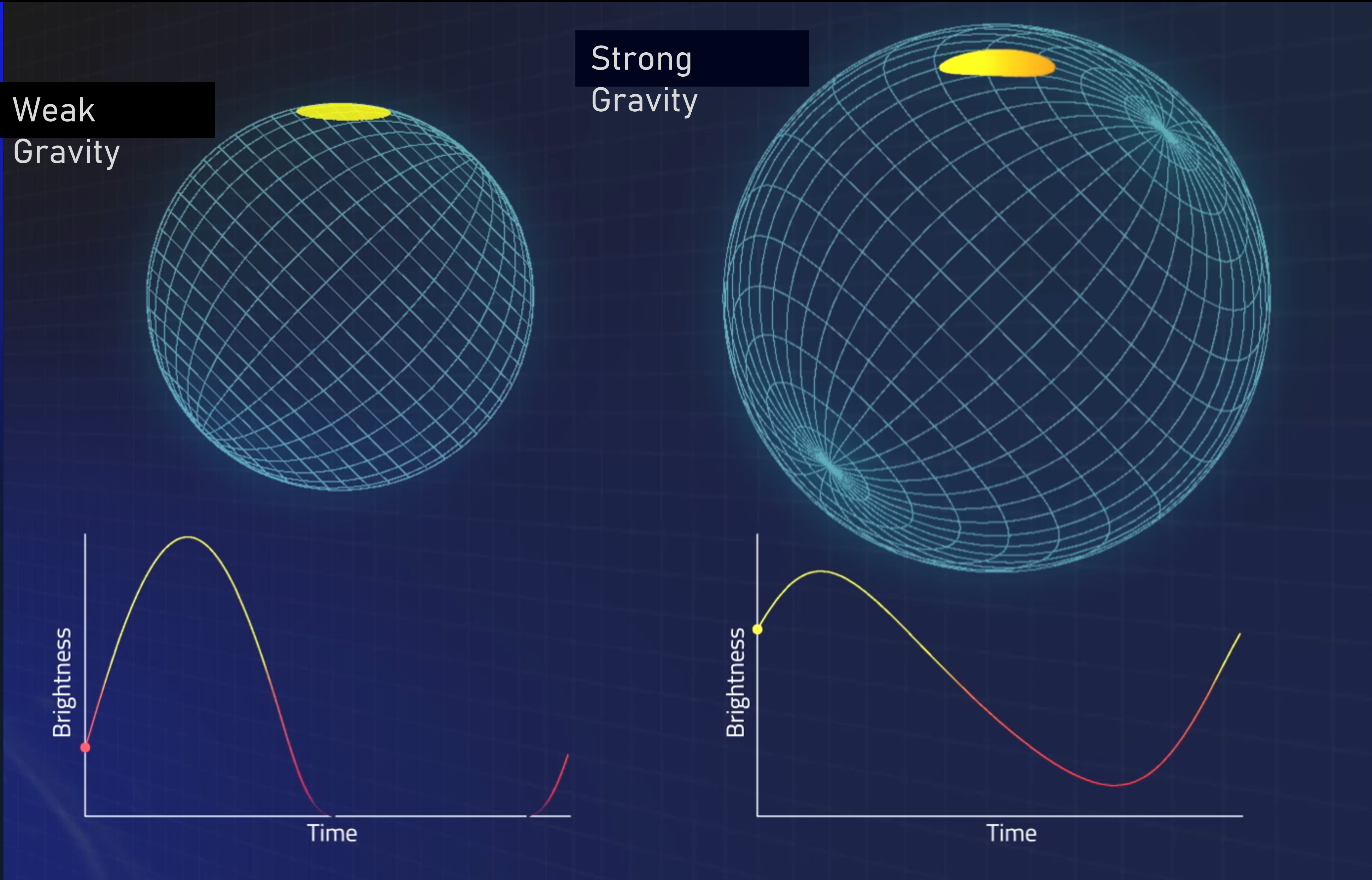
Observer = NICER

Measure amplitudes and phases in different frequencies, construct model of hot spots to interpret data



PSR J0030+0451
Mass vs Radius
Miller et al.,Ap.J. (2019)

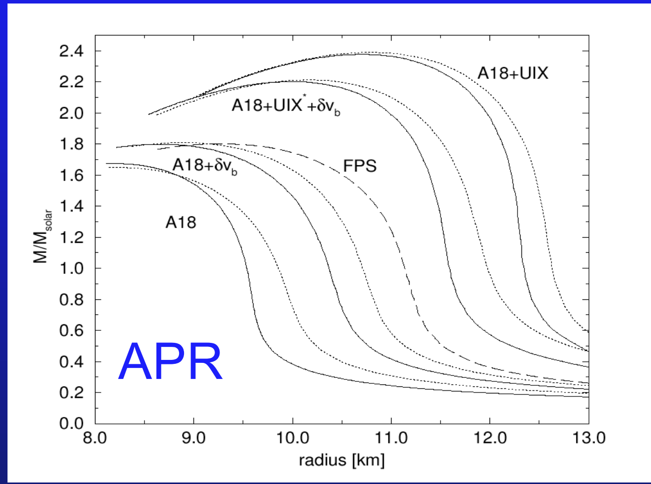
Pulse Profile Modeling (PPM)

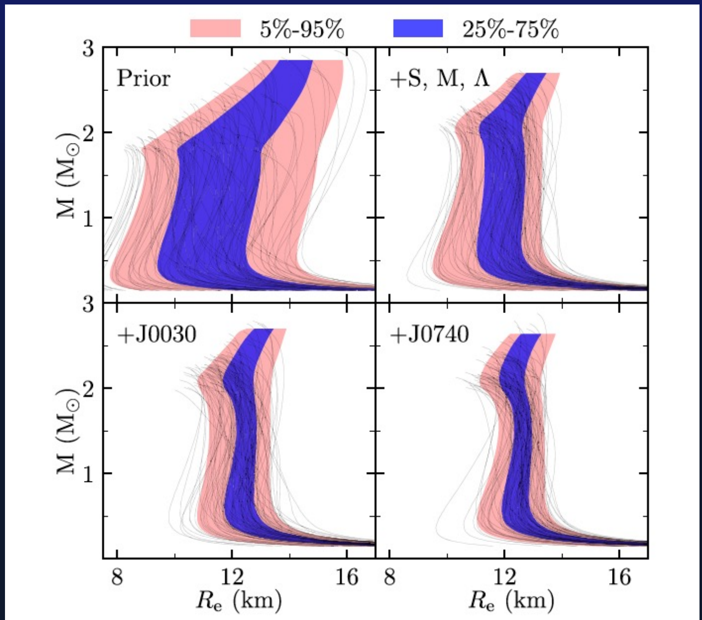


Credit: Morsink/Moir/Arzoumanian/NASA-GSFC

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} changing little.



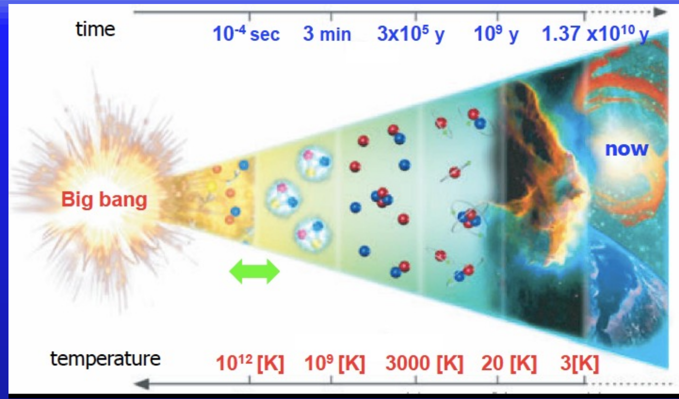


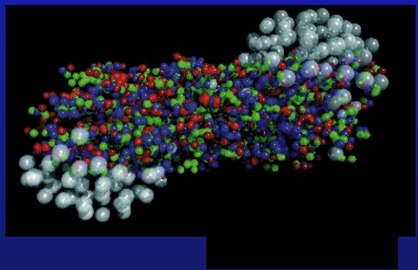
Points to rapid stiffening of nuclear matter, and onset of higher momentum degrees of freedom.

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.

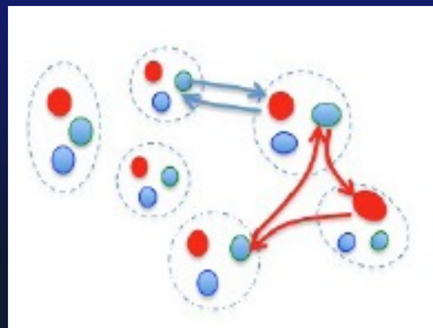
Quarks in dense matter

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

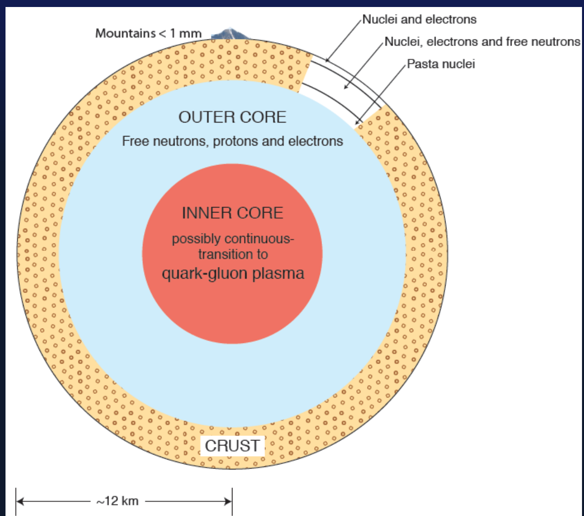




and created in ultrarelativistic heavy ion collisions



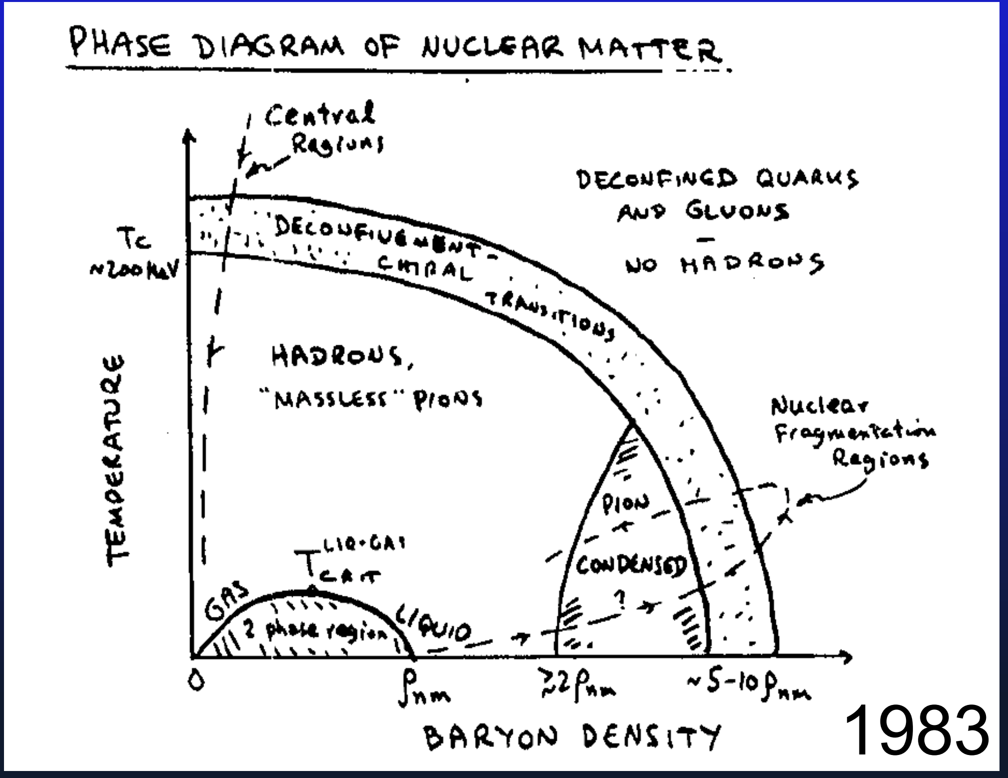
Quarks (and gluons) in nuclei will be mapped by future Electron-Ion Collider

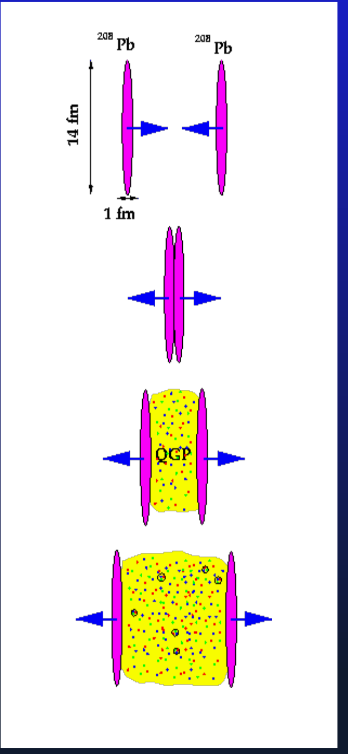


Cold quark matter cores of high mass neutron stars –

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

Matter under extreme conditions: baryon density/ temperature

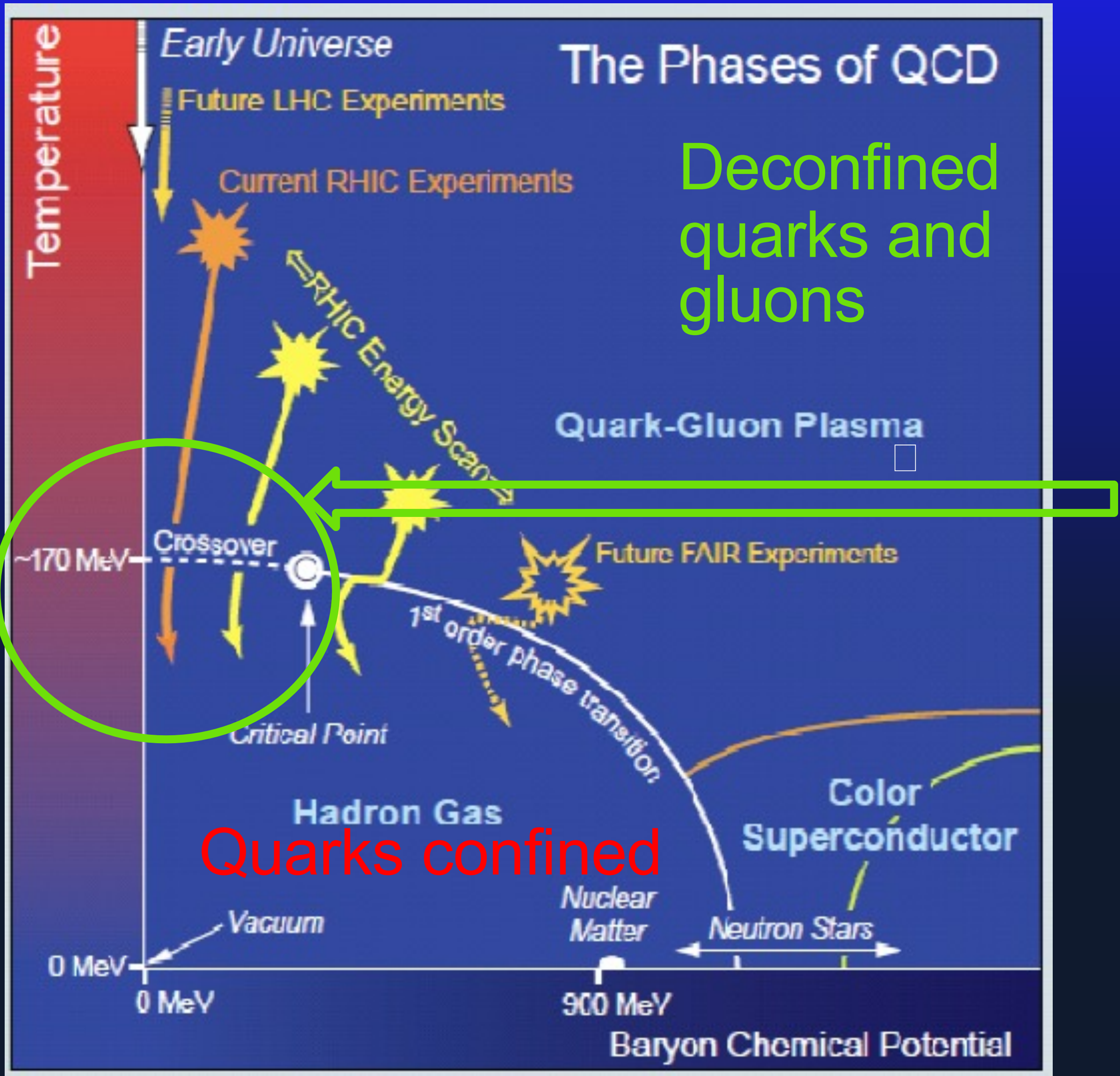




Ultrarelativistic heavy ion collisions (B. Jacak talk Friday)

Building of Brookhaven Relativistic Heavy Ion Collider (RHIC) 1983-2000, to study nuclear matter under extreme energy density – finds hot quark gluon plasma

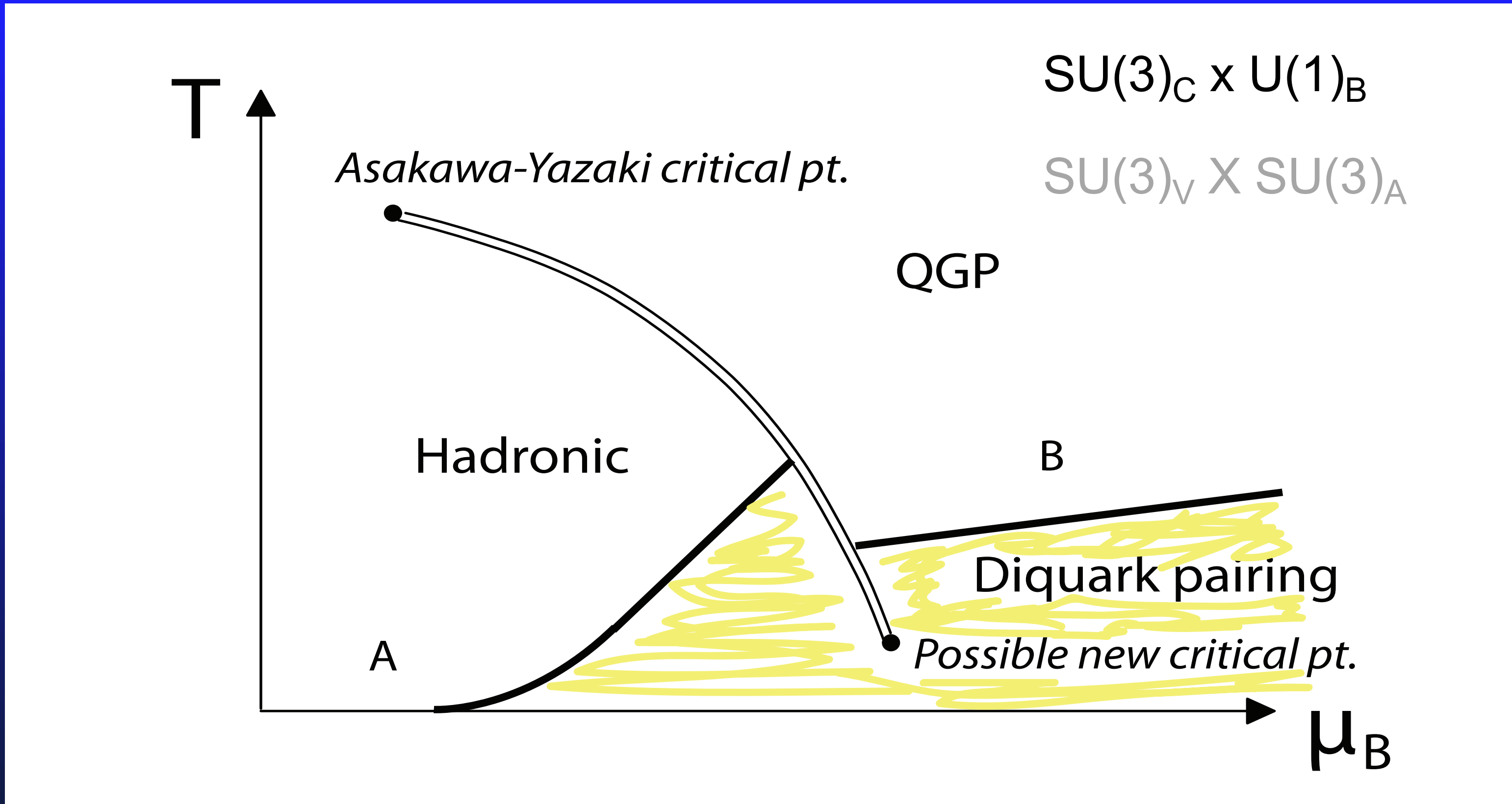
More modern phase diagram



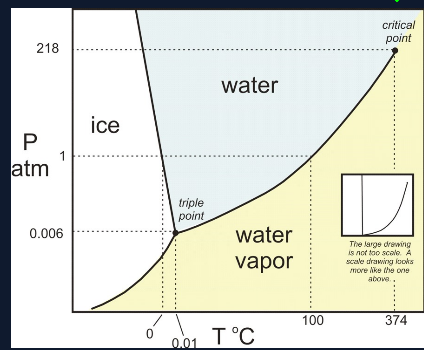
QCD lattice gauge theory -- for finite light quark masses -- predicts crossover from confined phase at lower T to deconfined phase at higher T.

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?

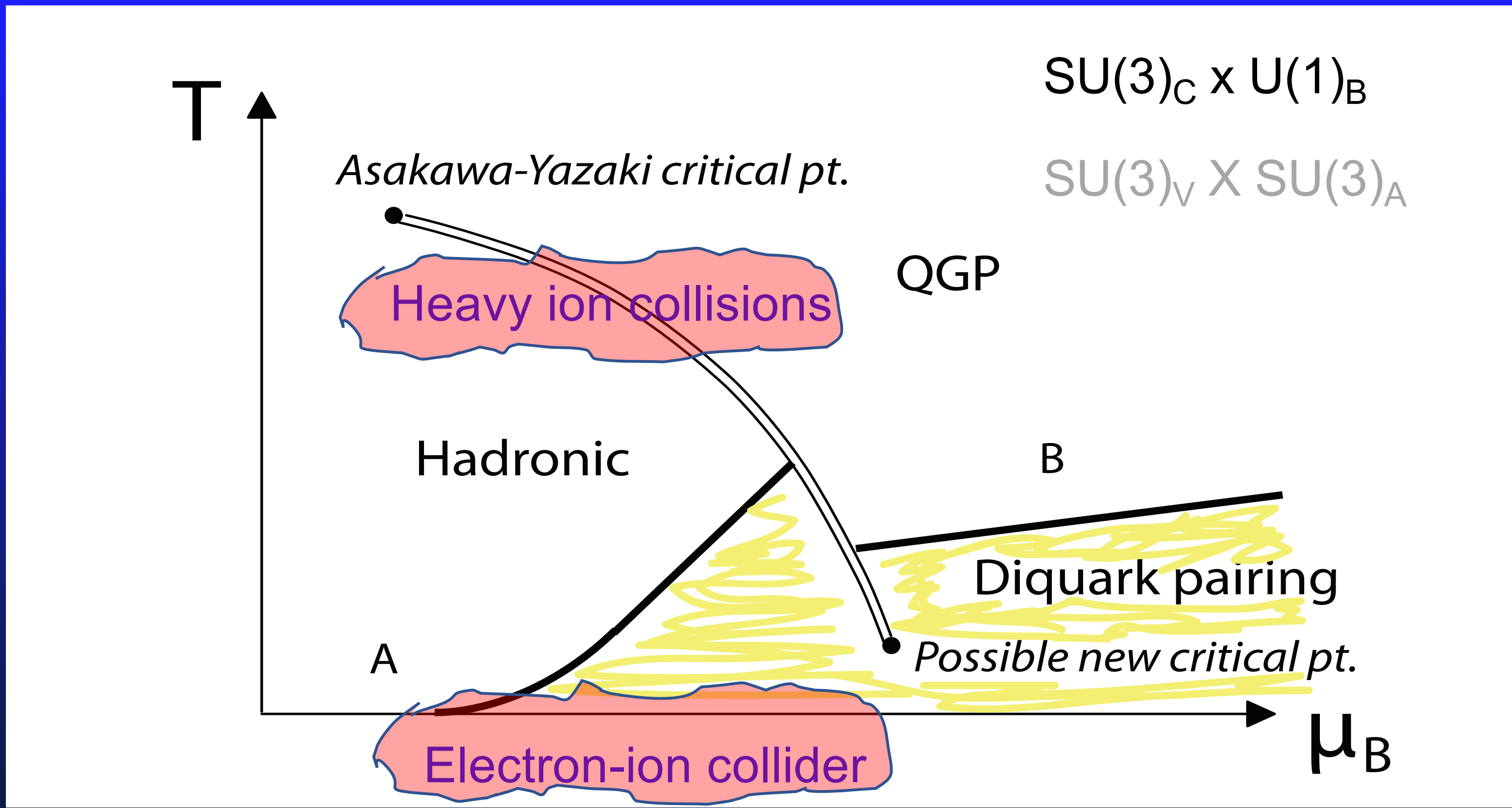


Critical points similar to those in liquid-gas phase diagram (H_2O). Neither critical point necessary!!



Can go continuously from A to B around the upper critical point. Liquid-gas phase transition.

In lower shaded region have BCS pairing of nucleons, of quarks, and possibly other states (meson condensates, quarkyonic). Different symmetry structure than at higher T.



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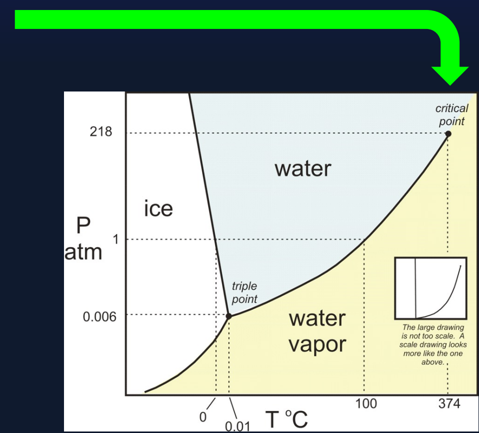

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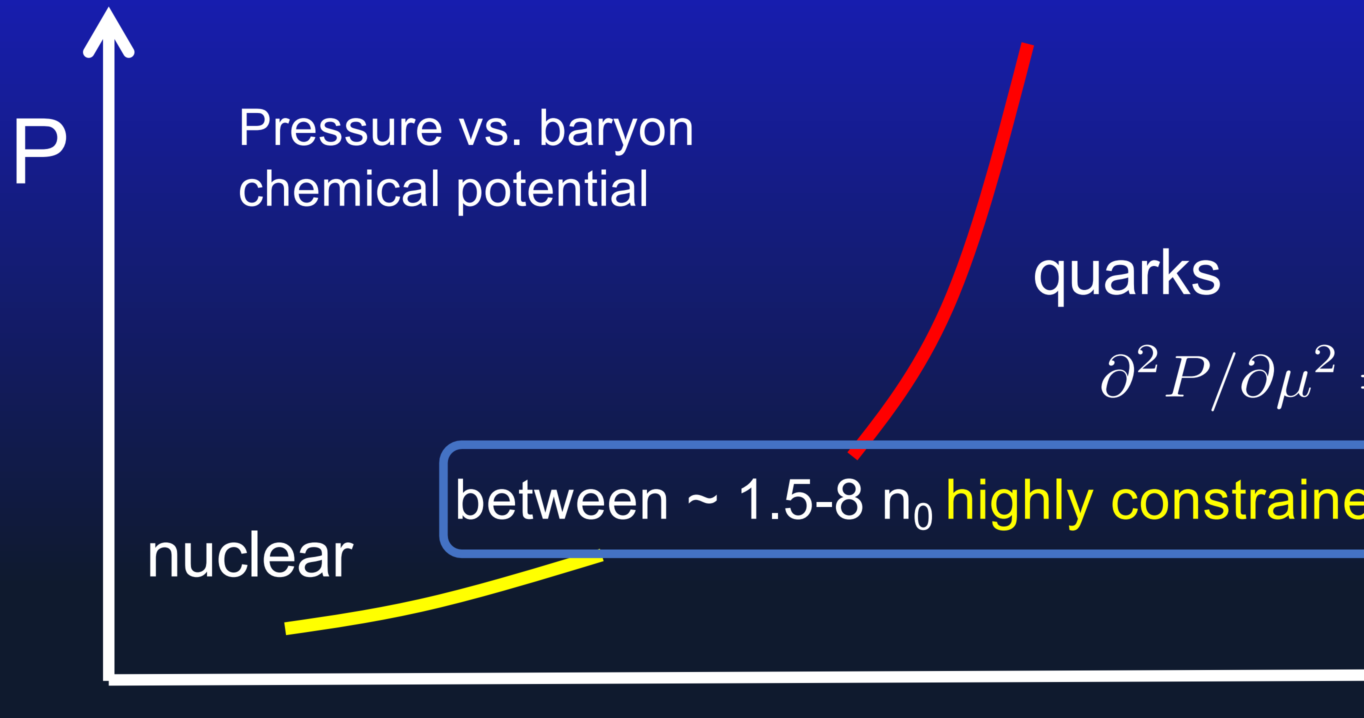
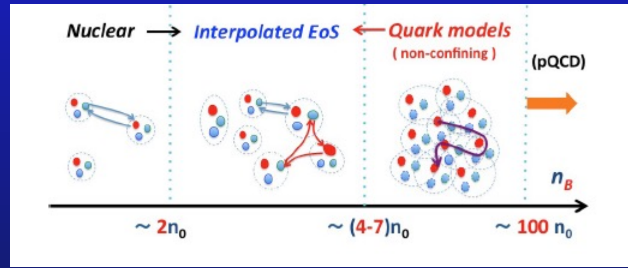
QHC21 (quark-hadron crossover) equation of state:

QHC19 --GB, S. Furusawa, T. Hatsuda, T. Kojo & H. Togashi, Ap.J. 885:42 (2019)

QHC21 --T. Kojo, GB, &T. Hatsuda,, Ap.J. 934:46 (2022).

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

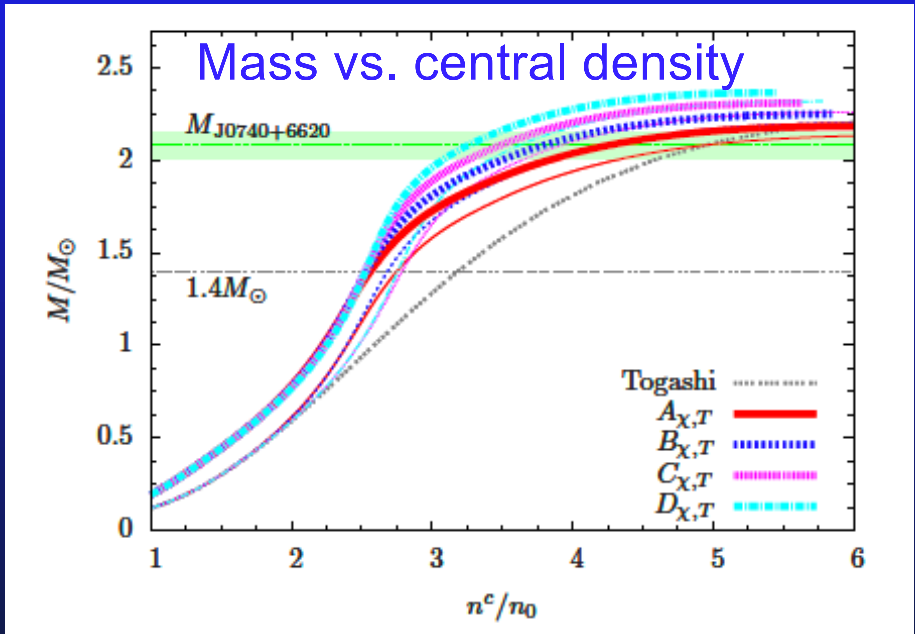




Simplified picture of quarks with
universal repulsive short-range qq coupling (*Kunihiro*)
and diquark (BCS) pairing interaction

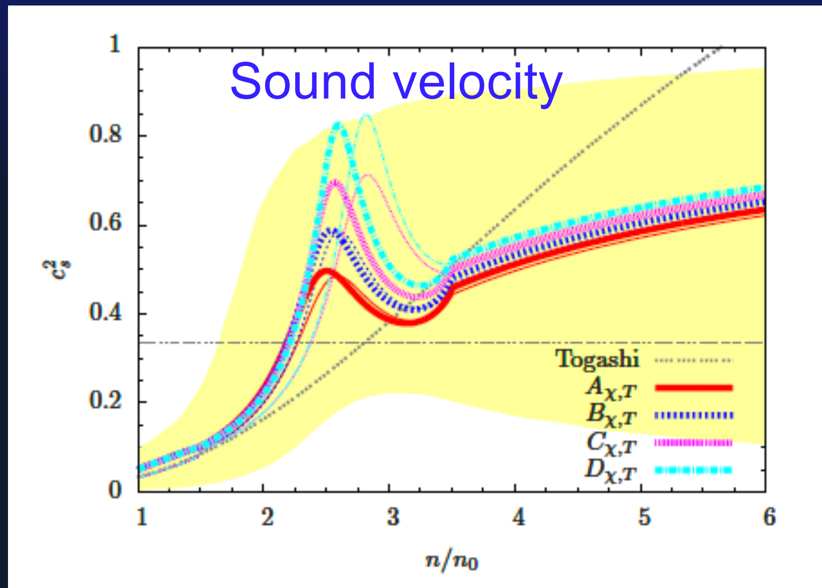
Nuclear equation of state up to $1.5n_0$ (chiral effective theory)

Quarks beginning to enter neutron stars



Central density of PSR J0740+6620 ~5n_0.
Well above densities where pure hadronic calculations are valid. Entering transition to strongly interacting quark matter.

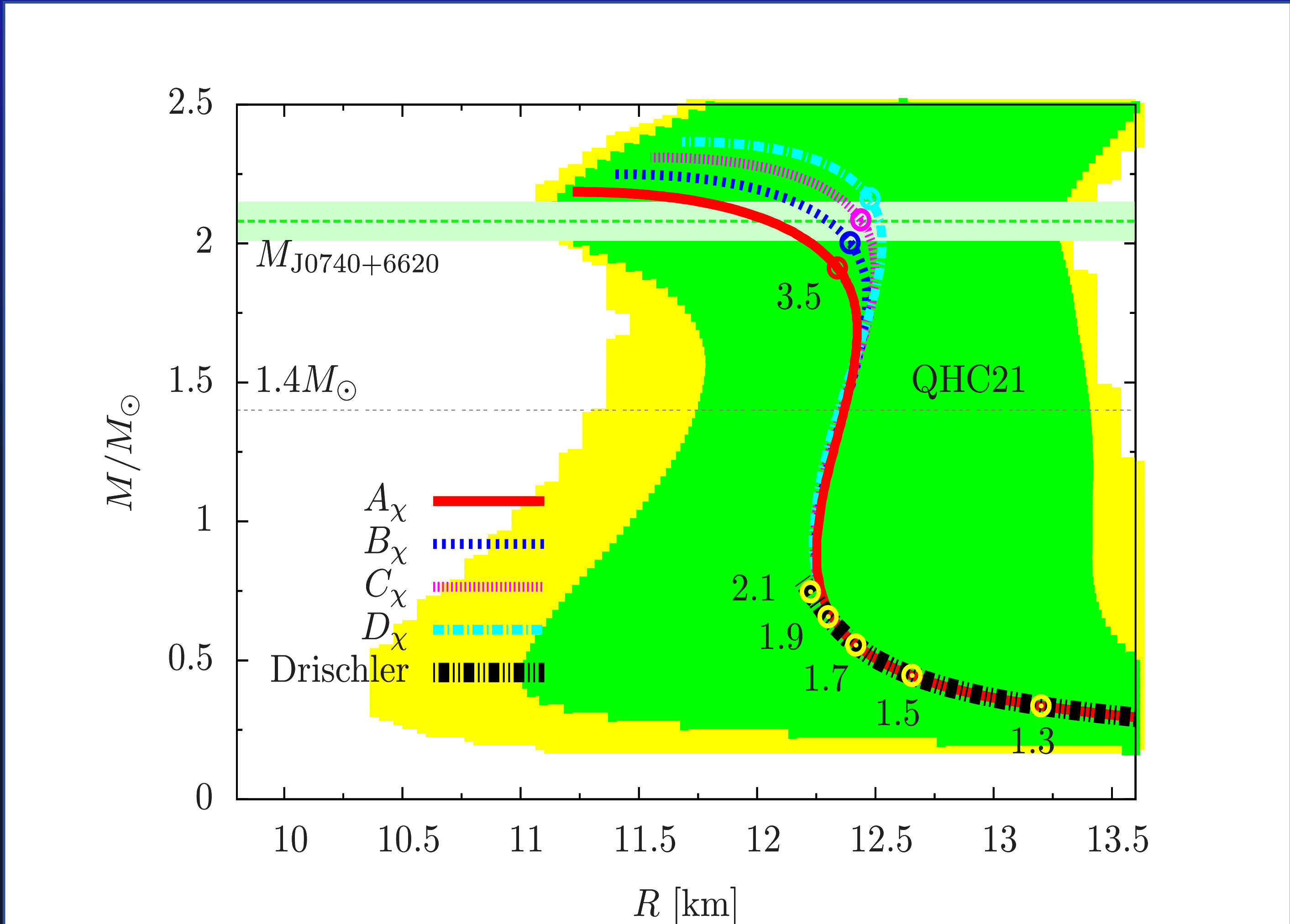
Cores of higher mass stars could reach beyond transition.
Fully developed quark matter in cores? Need fully microscopic calculations of matter undergoing transition from nucleonic to quark degrees of freedom.



Peak not seen in nucleonic eq. of state

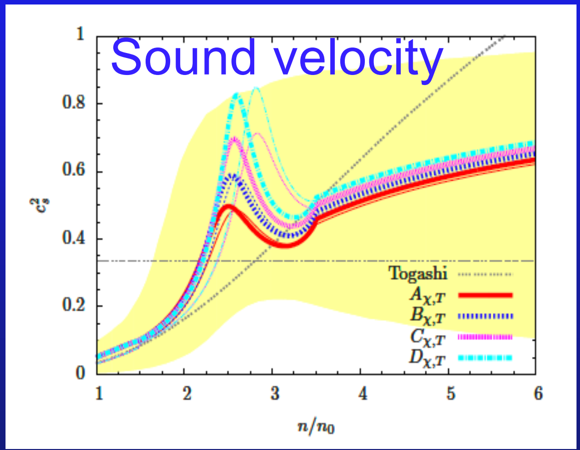
Nuclear matter based on chiral EFT + transition to quark matter in excellent agreement with NICER inferences of radii. Rapid pressure rise!

Central density for 2.08 M_{sun} ~ 3.6 n_0



QHC21

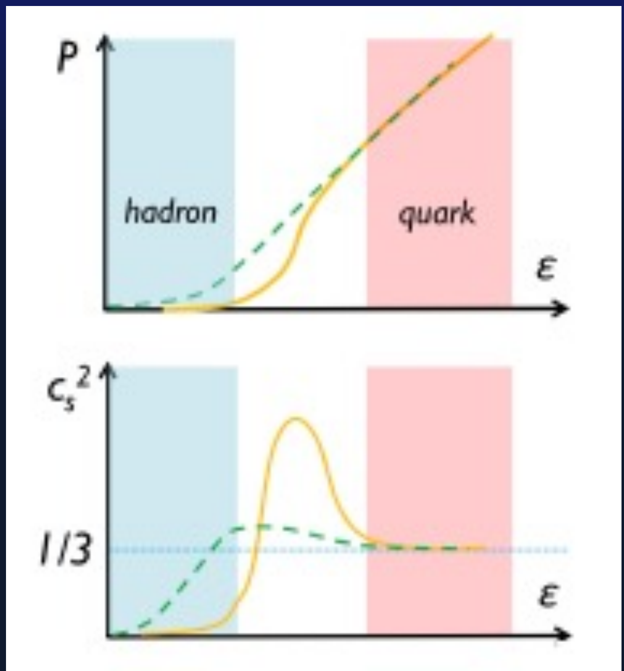
Sound velocity reflects stiffness of matter



$$c_s^2 = \partial P / \partial \varepsilon$$

c_s = sound velocity
P – pressure
ε = energy density (including rest mass)

Structure from stiffening nuclear matter followed by superfluid quark matter



Toru Kojo

Rise for $n < 2n_0$ characteristic of nuclear matter. But nuclear matter eventually has $c_s > c$ = speed of light.

Sound velocity in superfluid quark matter (BCS pairing) falls until one enters perturbative regime ($\alpha_s << 1$ <=> $\mu >> \Lambda_{qcd} \sim 300$ MeV) then flattens out at $c_s \sim c/\sqrt{3}$ (conformal limit).

Eventually sound velocity -> $c/\sqrt{3}$ from below!!

NICER has provided first empirical tests of theories of neutron rich nuclear matter

1) Chiral Effective Field Theory of nuclear matter points toward stiff neutron rich matter in nuclear regime (up to 1.5 n_0), adequate to allow 12-13 km neutron stars.

2) Effective equality of radii of neutron stars of 1.4 and 2.08 M_{sun}

3) Future NICER measurements of radii of neutron stars of intermediate masses, with improved precision,

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's eight compact objects)

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.

どうもありがとう

[redacted]