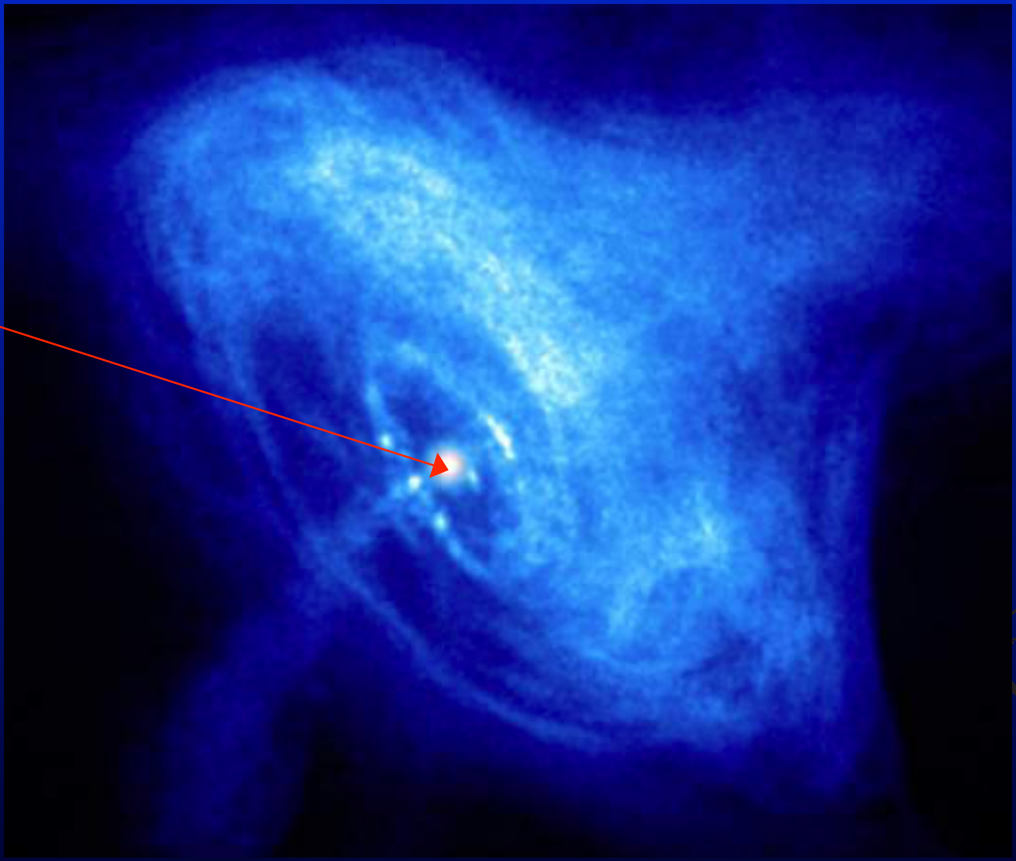
Inside neutron stars: from hadrons to quarks

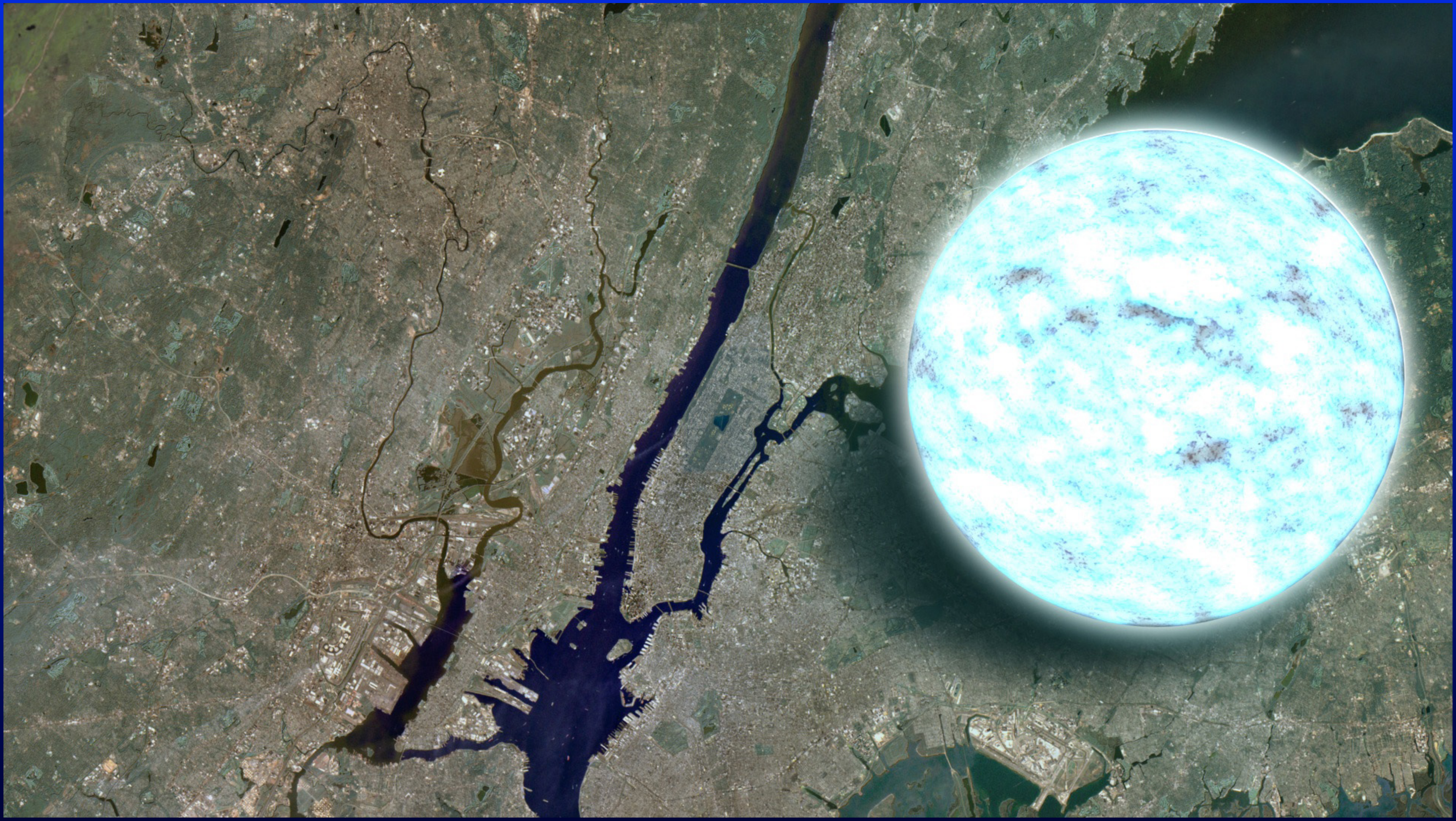
Gordon Baym
University of Illinois



Crab nebula
in X-ray

GSI
22 November2016

Compress the sun (radius 700,000 km) down to a radius of 10-12 km



Neutron star over New York City

Neutron stars

Mass ~ 1.3-2 M_{sun}

Baryon no. ~ 10^{57}

$$\sim (\mathbf{G m_p^2}/\hbar \mathbf{c})^{-3/2}$$

Radius ~ 10-12 km

Temperature

~ 10^6-10^9 K

Surface gravity

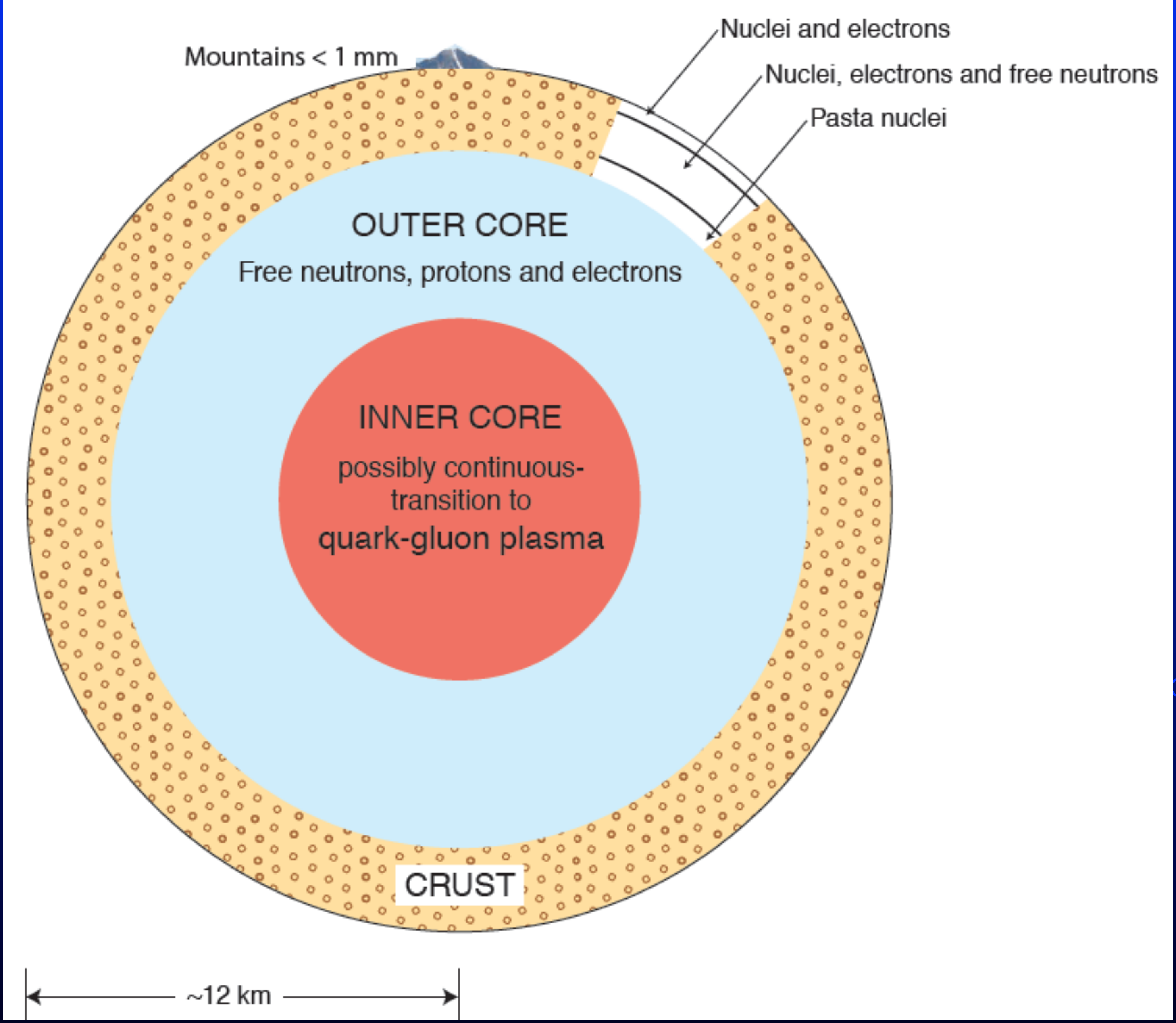
~10^{14} that of Earth

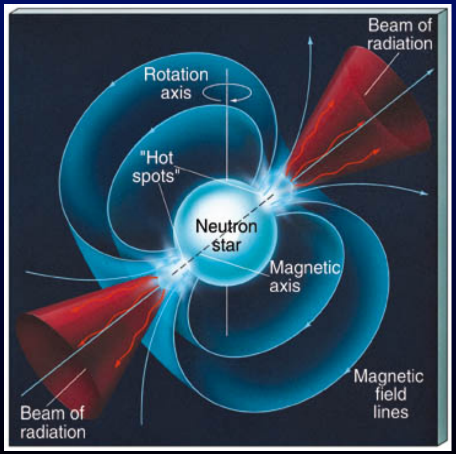
Surface binding

~ 1/10 mc^2

Magnetic fields

~ 10^6 – 10^{15} G





Properties of liquid interior near nuclear matter density

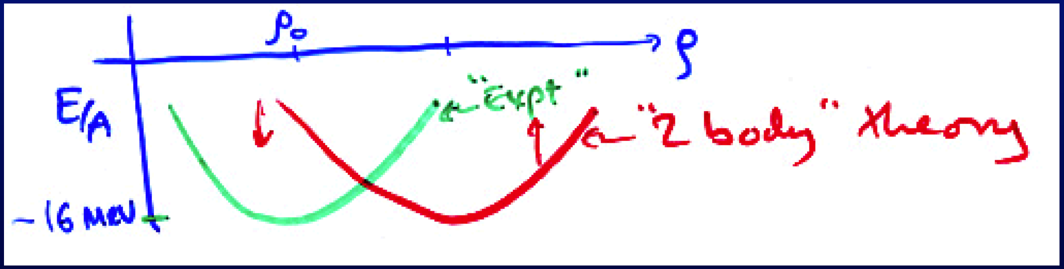
Determine N-N potentials from
- scattering experiments E<300 MeV
- deuteron, 3 body nuclei (^{3}He, ^{3}H)

ex., Paris, Argonne, Urbana 2 body potentials

Solve Schrödinger equation by variational techniques

Large theoretical extrapolation from low energy laboratory nuclear physics at near nuclear matter density

Two body potential alone:



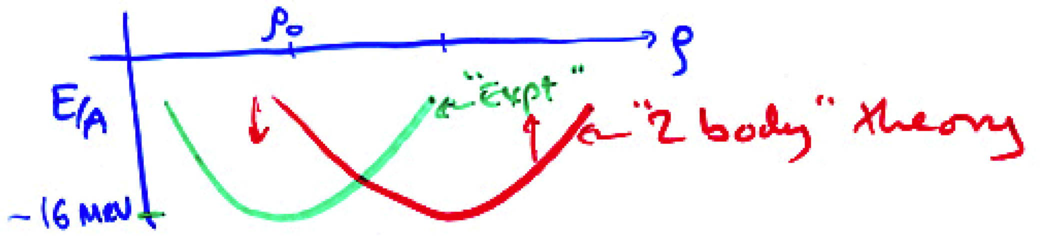
Underbind ^{3}H: Exp = -8.48 MeV, Theory = -7.5 MeV

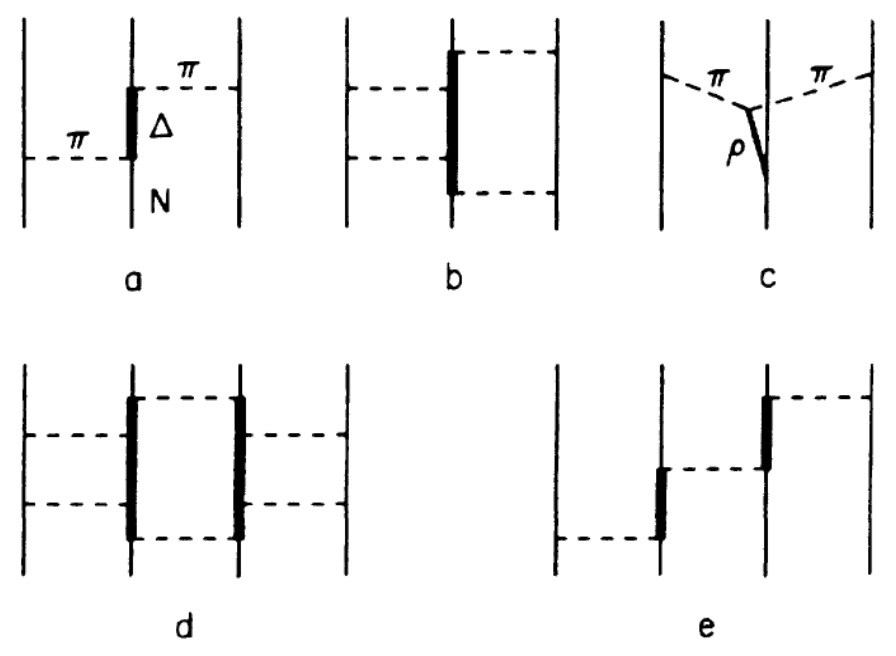
^{4}He: Exp = -28.3 MeV, Theory = -24.5 MeV

Importance of 3 body interactions

Attractive at low density

Repulsive at high density





Various processes that lead to three and higher body intrinsic interactions (not described by iterated nucleon-nucleon interactions).

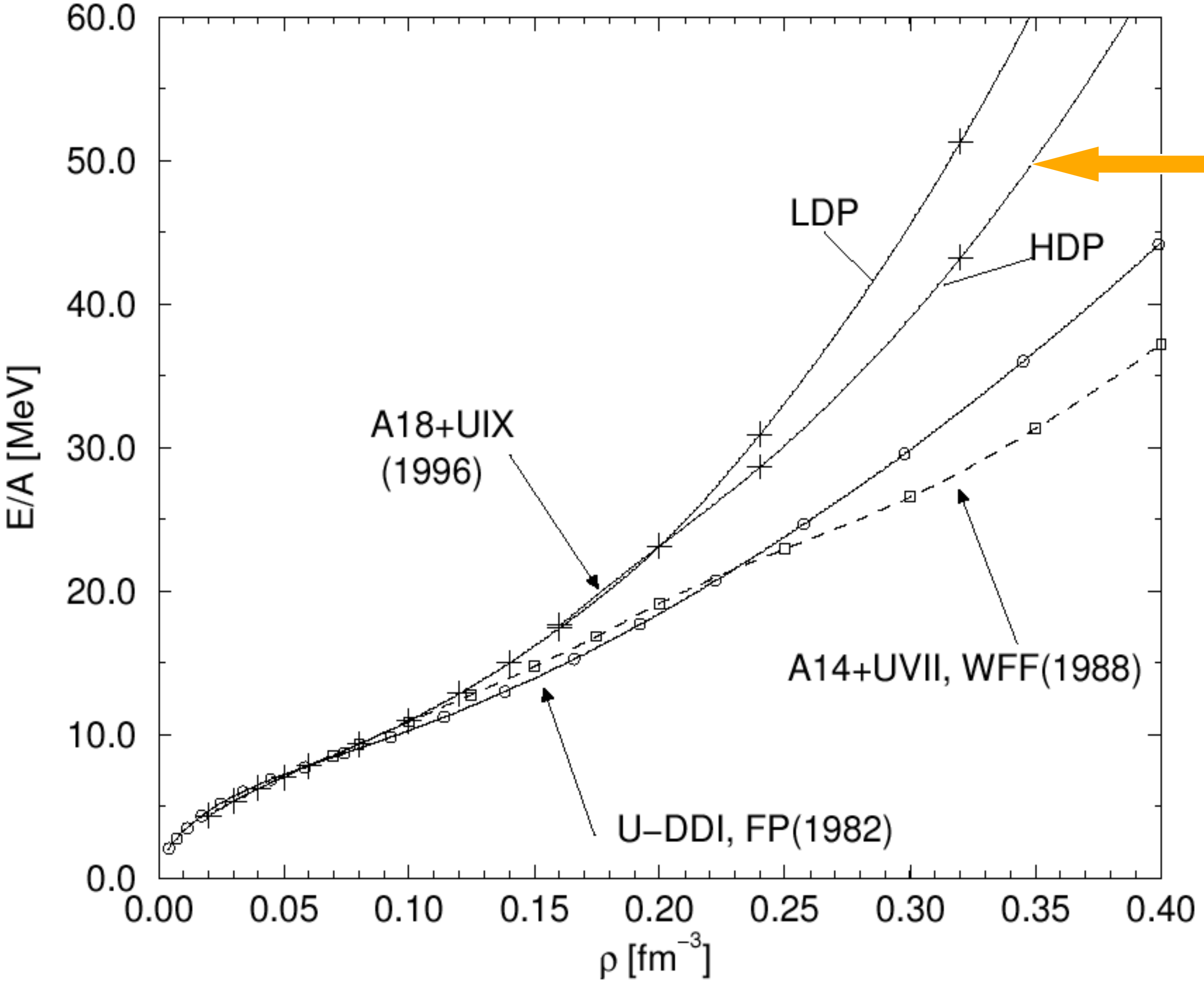
Stiffens equation of state at high density

Large uncertainties!

Standard construction of neutron star models

1) Compute energy per nucleon in neutron matter (pure or in beta equilibrium: $\mu_n = \mu_p + \mu_e$). Include 2 and 3 body forces between nucleons.

Akmal, Pandharipande & Ravenhall, Phys. Rev. C58 (1998) 1804



π^0 condensate

2) Determine the equation of state, $P(\rho)$

E = energy density = ρc^2
n_b = baryon density
$P(\rho)$ = pressure = $n_b^2\, \partial(E/n_b)/\partial n_b$

3) Integrate the Tolman-Oppenheimer-Volkoff equation of hydrostatic balance:

$$\frac{\partial P(r)}{\partial r} = -\frac{G}{r^2}\frac{\left(\rho(r) + \boxed{P(r)/c^2}\right)}{1 - \boxed{2m(r)G/rc^2}}\left(m(r) + \boxed{4\pi P(r) r^3/c^2}\right)$$

general relativistic corrections

$$m(r) = \int_0^r \rho(r')4\pi r'^2 dr'$$

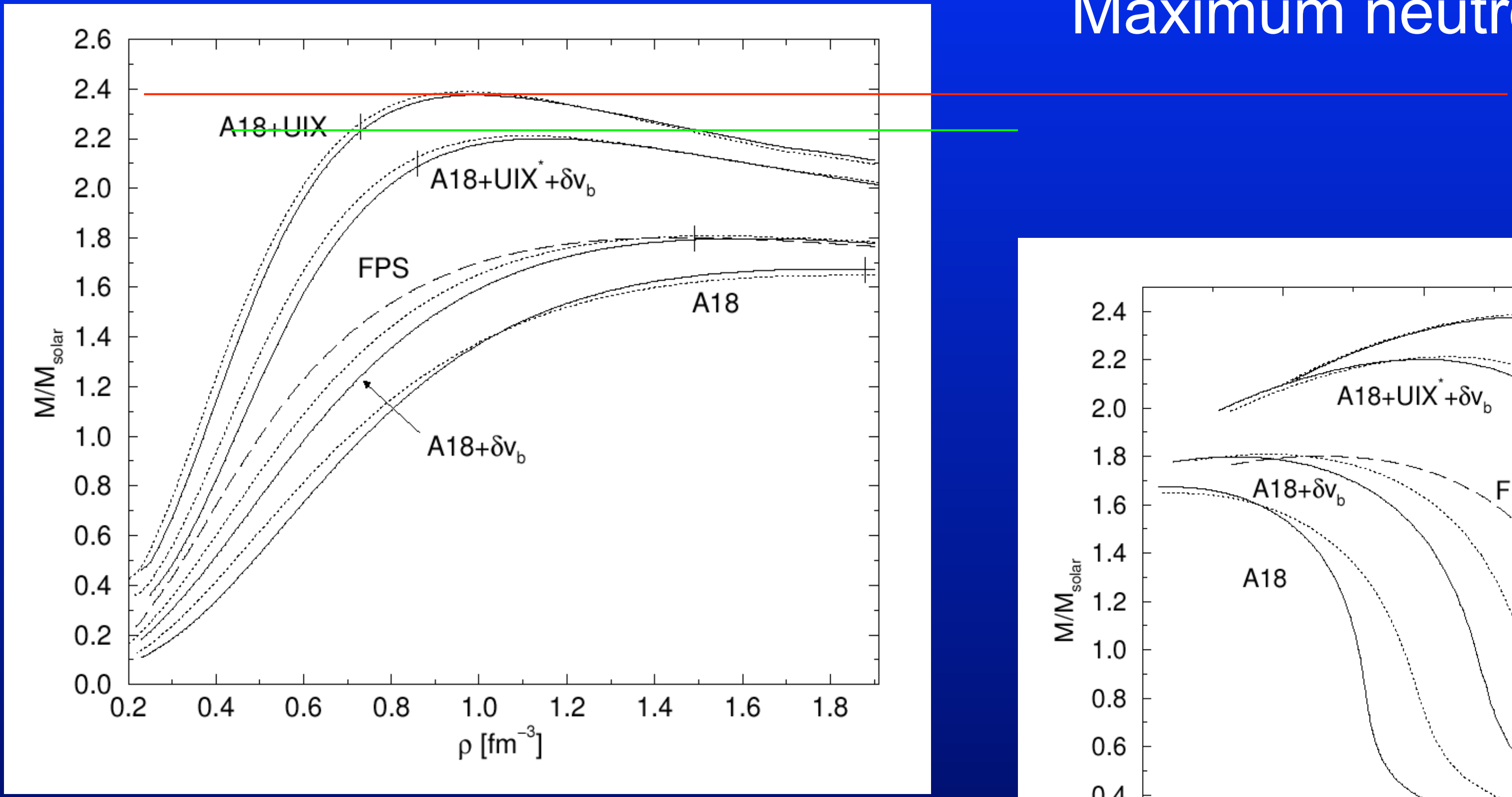
= mass within radius r

a) Choose central density: $\rho(r=0) = \rho_c$
b) Integrate outwards until $P=0$ (at radius R)
c) Mass of star

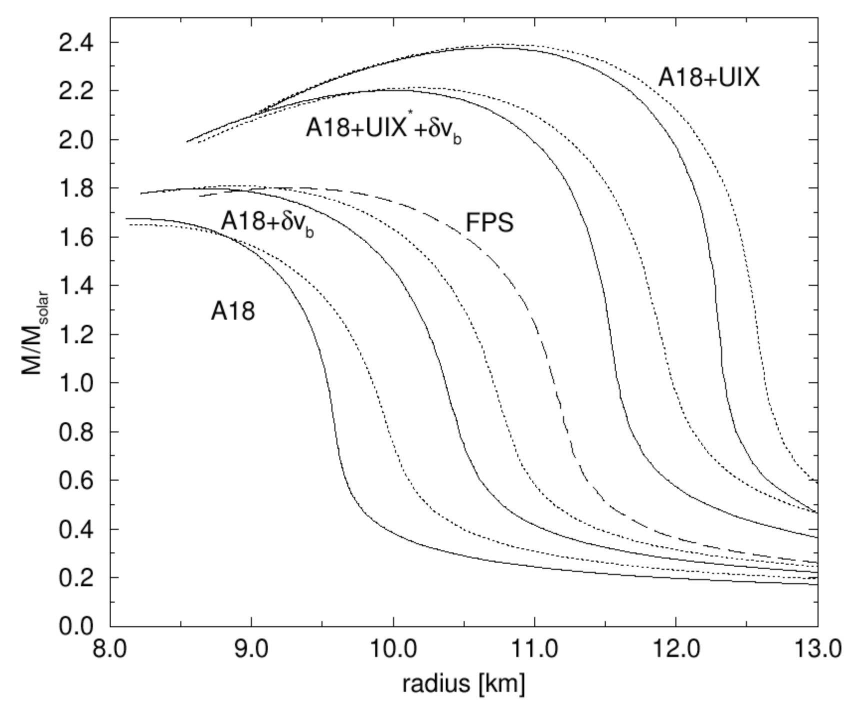
$$M = \int_0^R \rho(r) 4\pi r^2 dr$$

Neutron star models using *static interactions* between *nucleons*

Maximum neutron star mass



Mass vs. central density



Mass vs. radius

Akmal, Pandharipande and Ravenhall, 1998

Going beyond this picture:

Discovery of high mass (2 $M_{\odot}$) neutron stars indicates high density in neutron stars and a stiff equation of state

Programs to observe masses and radii simultaneously:
in low mass x-ray binaries, and NICER.

Onset of new degrees of freedom at higher densites: mesonic, Δ' s, quarks and gluons, including strange quarks...

Properties of matter in this extreme regime determine maximum neutron star mass, nut large uncertainties!!

Fundamental limitations of equation of state based on nucleon-nucleon interactions alone

Fundamental limitations of equation of state based on nucleon-nucleon interactions alone:

Accurate for n~ n_0= nuclear saturation density = $0.16/\mathrm{fm}^3$

But for n >> n_0:

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

-Force range ~ $1/2m_\pi$ => relative importance of 3 (and higher) body forces ~ $n/(2m_\pi)^3$ ~ 0.3 n/n_0. Estimate from chiral effective field theory possibly lower.

-No well defined expansion in terms of 2,3,4,...body forces.

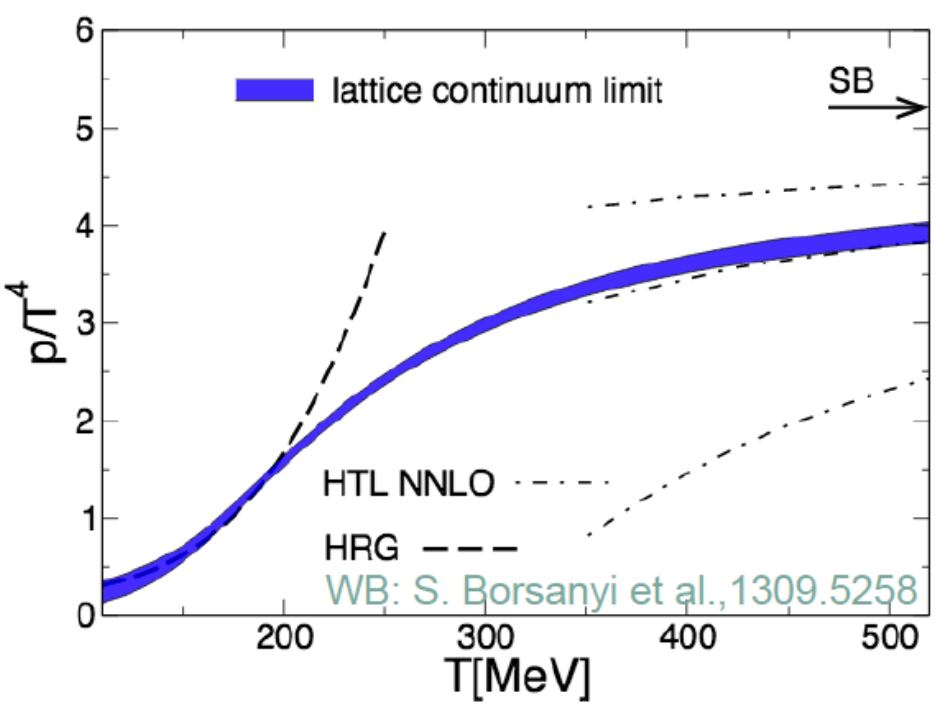
-Can one even describe system in terms of well-defined ``asymptotic'' laboratory particles? Early percolation of nucleonic volumes!

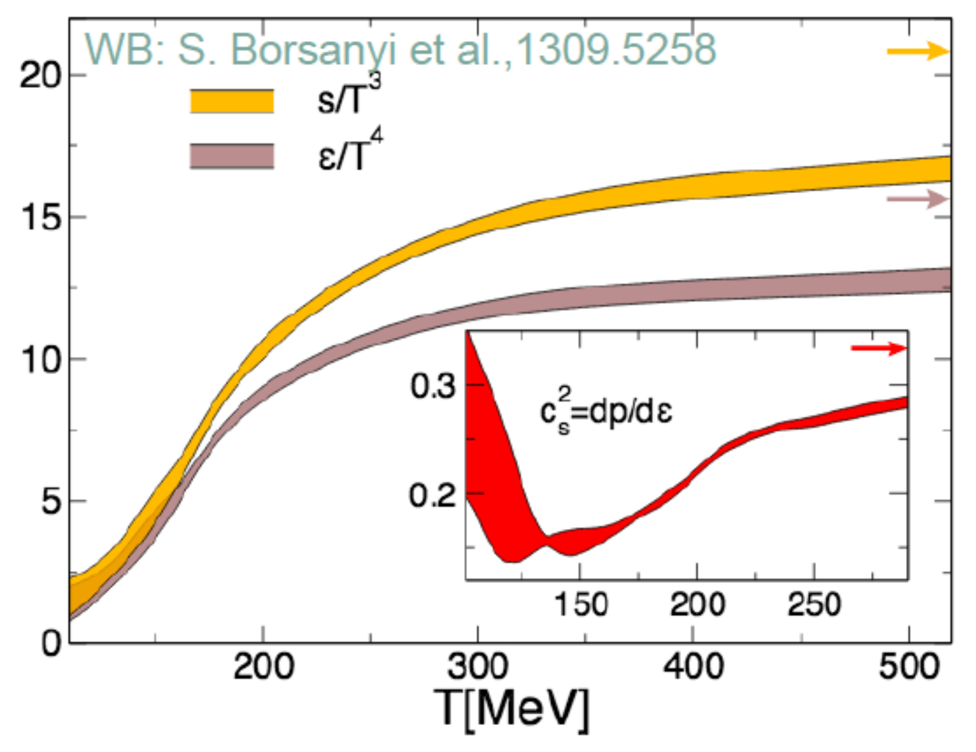
Must take quarks degrees of freedom seriously at densities n >> n_0

Lattice gauge theory calculations of equation of state of QGP

Limited, because of “fermion sign problem” to zero baryon density and nearby.

Can’t systematically calculate yet for realistic chemical potentials



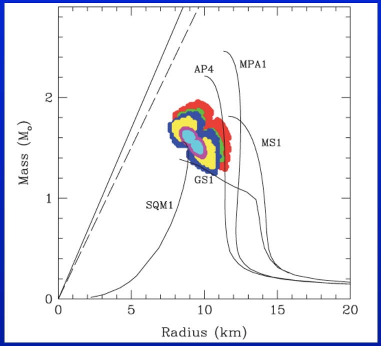


Learning about dense matter from neutron star observations

Masses of neutron stars

Binary systems: stiff e.o.s

Thermonuclear bursts in X-ray binaries => Mass vs. Radius, strongly constrains eq.of state



Glitches: probe n,p superfluidity and crust

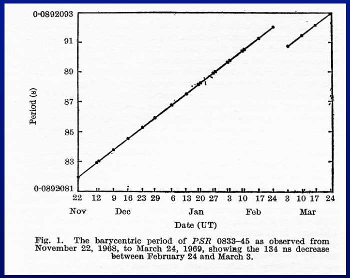
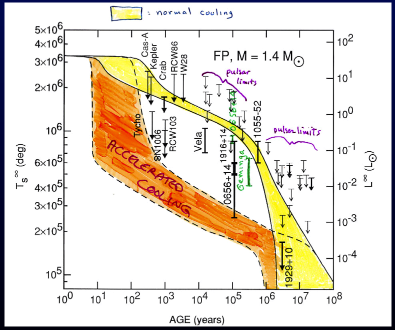


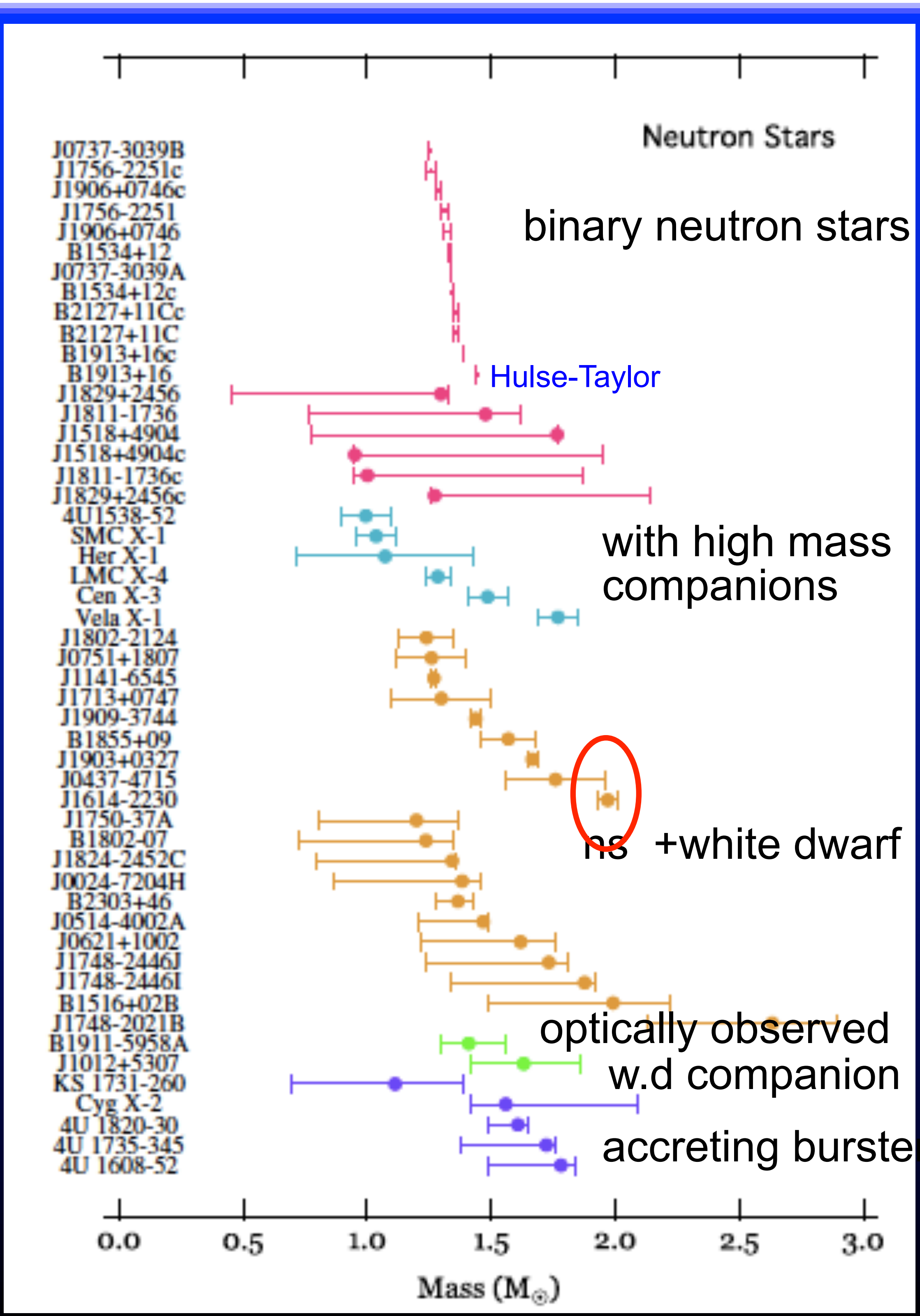
Fig. 1. The barycentric period of *PSR* 0833–45 as observed from November 22, 1968, to March 24, 1969, showing the 134 ns decrease between February 24 and March 3.

Cooling of n-stars: search for exotica



Neutron star masses

F. Õzel et al, Ap.J.757, 1 (2012)



binary neutron stars

Hulse-Taylor

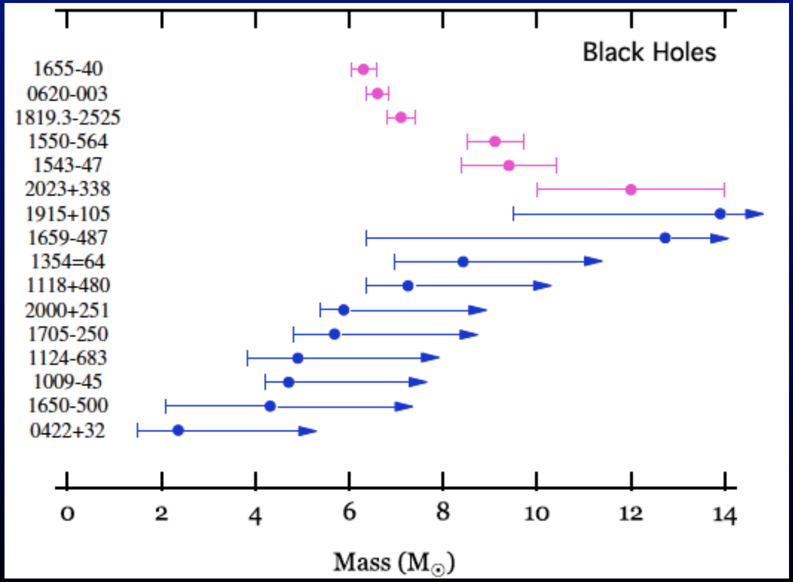
with high mass companions

ns +white dwarf

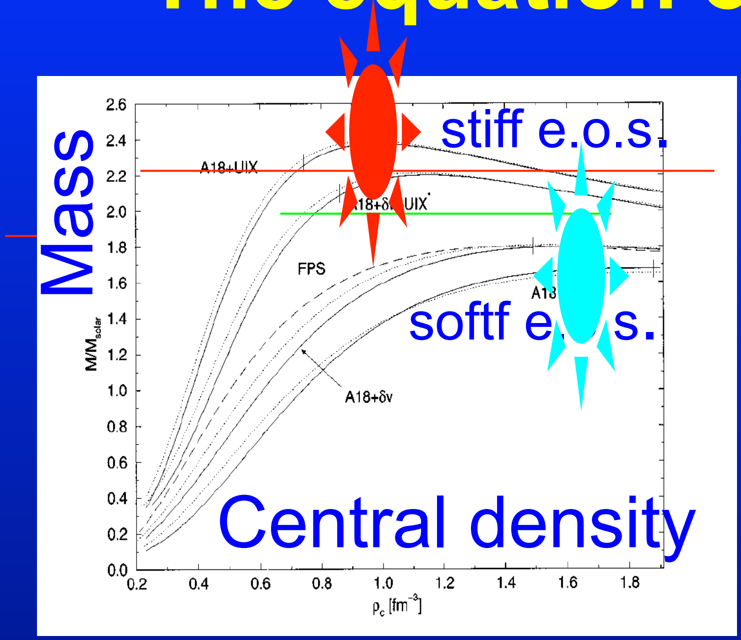
optically observed w.d companion

accreting bursters

Galactic black hole masses



The equation of state is very 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

PSR J1614-2230 : $M_{\text{neutron star}} = 1.97 \pm 0.04 M_\odot$

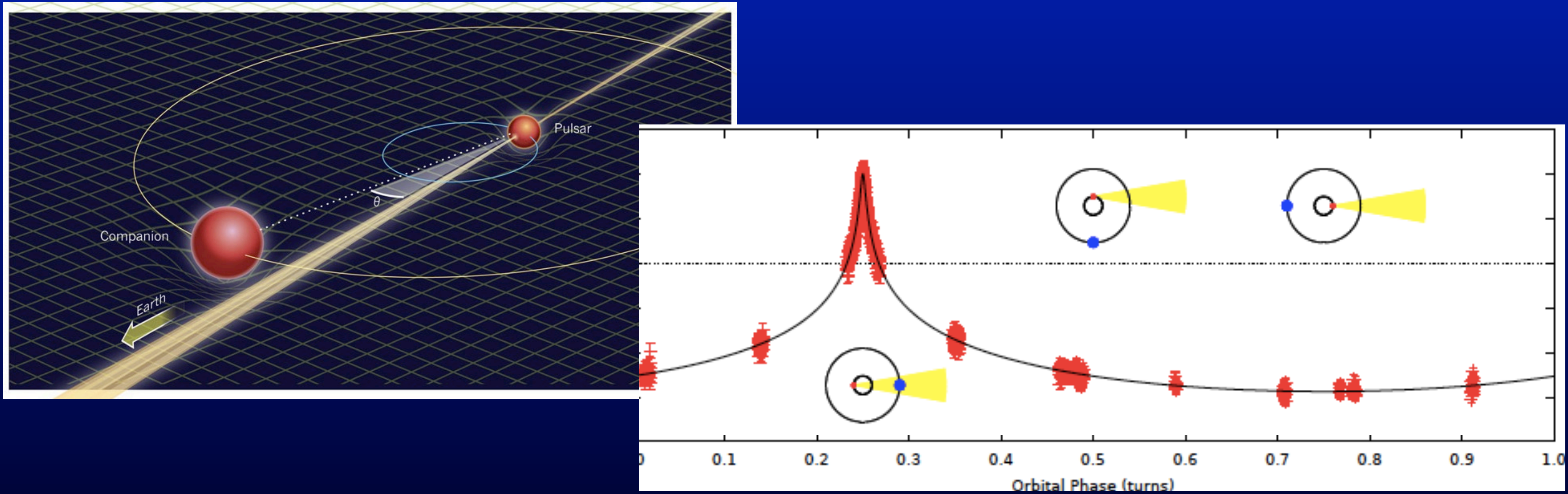
PSR J0348+0432: $M_{\text{neutron star}} = 2.01 \pm 0.04 M_\odot$

require very stiff equation of state! How possible?

High mass neutron star, PSR J1614-2230 -- in neutron star-white dwarf binary

Demorest et al., Nature 467, 1081 (2010); Ozel et al., ApJ 724, L199 (2010).

Spin period = 3.15 ms; orbital period = 8.7 day
Inclination = 89:17° ± 0:02° : edge on
$M_{\text{neutron star}} = 1.97 \pm 0.04 M_\odot$; $M_{\text{white dwarf}} = 0.500 \pm 0.006 M_\odot$

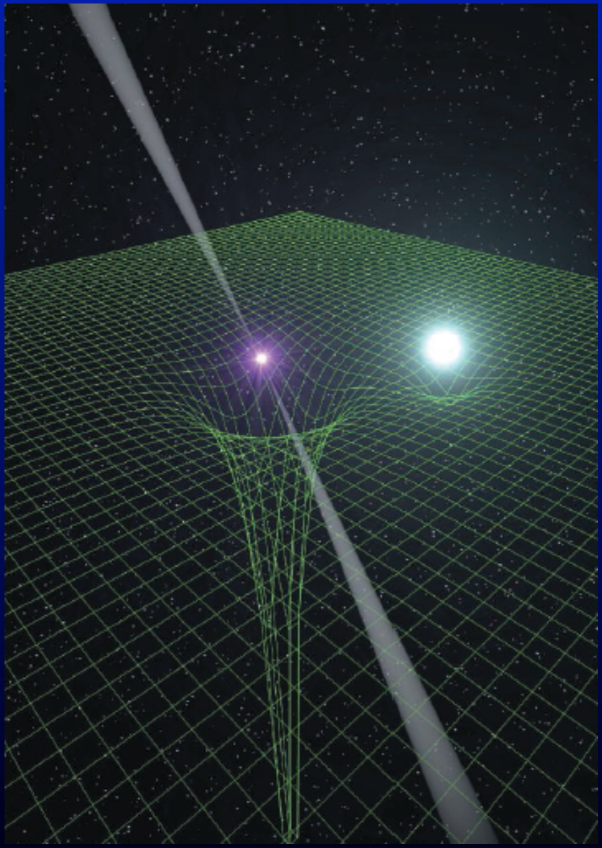


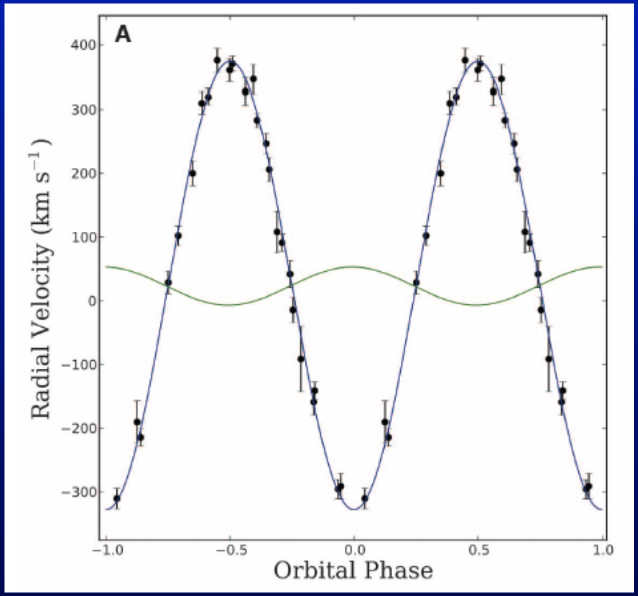
(Gravitational) Shapiro delay of light from pulsar when passing the companion white dwarf

Second high mass neutron star, PSRJ0348+0432 -- in neutron star-white dwarf binary

Antonidas et al., Science 340 1233232 (2013)

Spin period = 39 ms; orbital period = 2.46 hours
Inclination =40.2°
$M_{\text{neutron star}} = 2.01 \pm 0.04 M_\odot$; $M_{\text{white dwarf}} = 0.172 \pm 0.003 M_\odot$





Significant gravitational radiation

$$\dot{\mathrm{P}}/\dot{\mathrm{P}}_{\mathrm{GR}} = 1.05 \pm 0.18$$

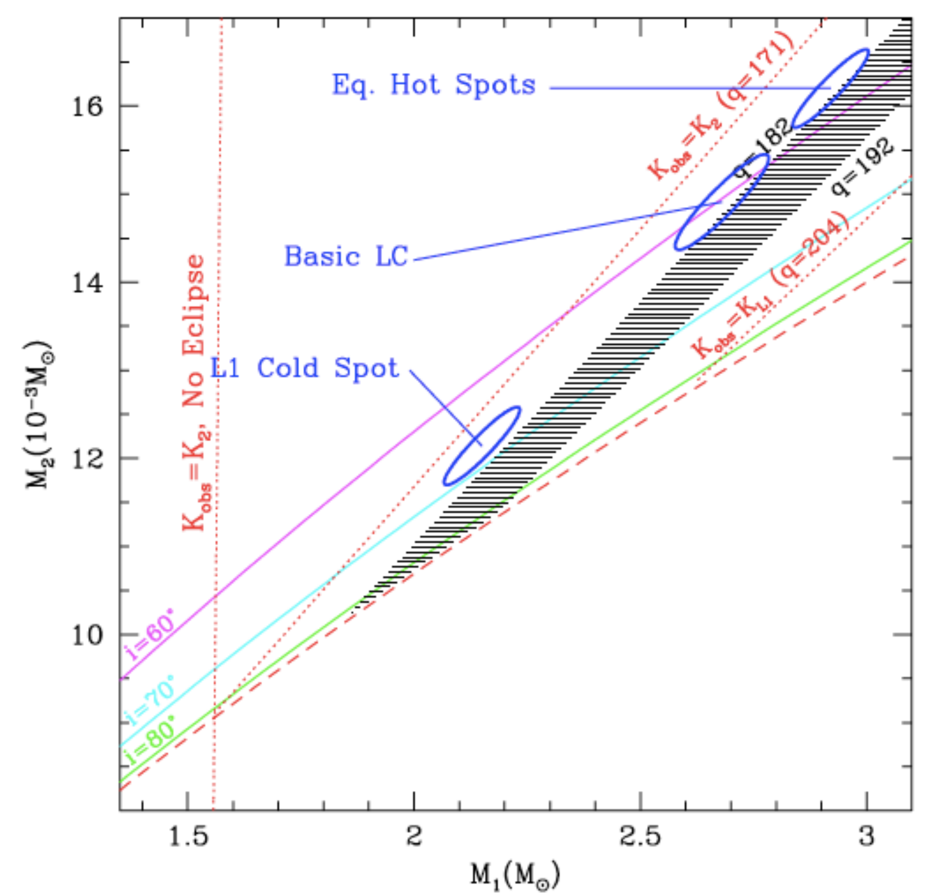
400 Myr to coalescence!

Possible third high mass neutron star in “black widow pulsar” PSR J1311-3430 – neutron star - He star binary

Romani et al., Ap. J. Lett., 760:L36 (2012), Ap. J. 804:115R (2015)

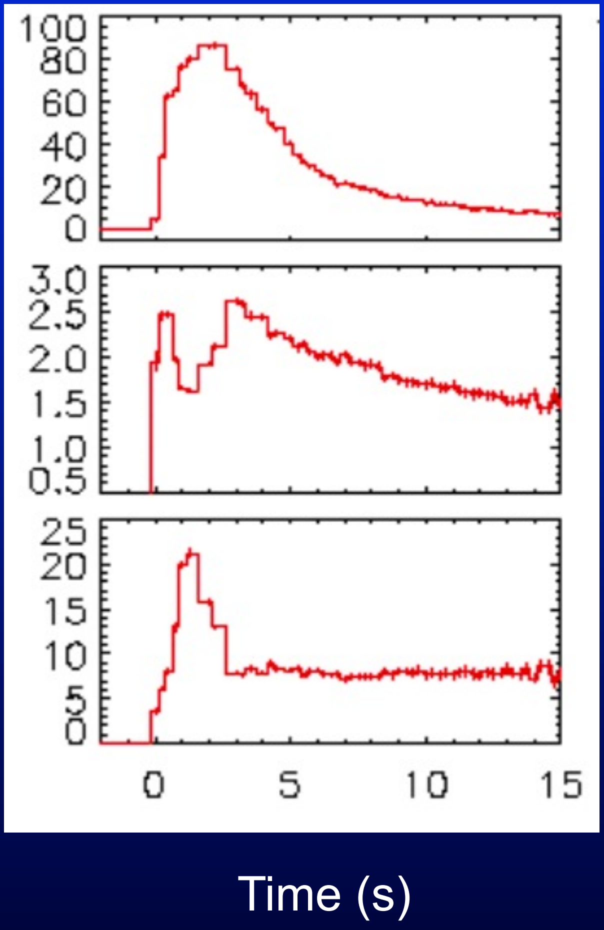
$M_{\text{neutron star}} \sim 1.8 - 2.7\ M_\odot$; $M_{\text{companion}} \sim 0.01 M_\odot$

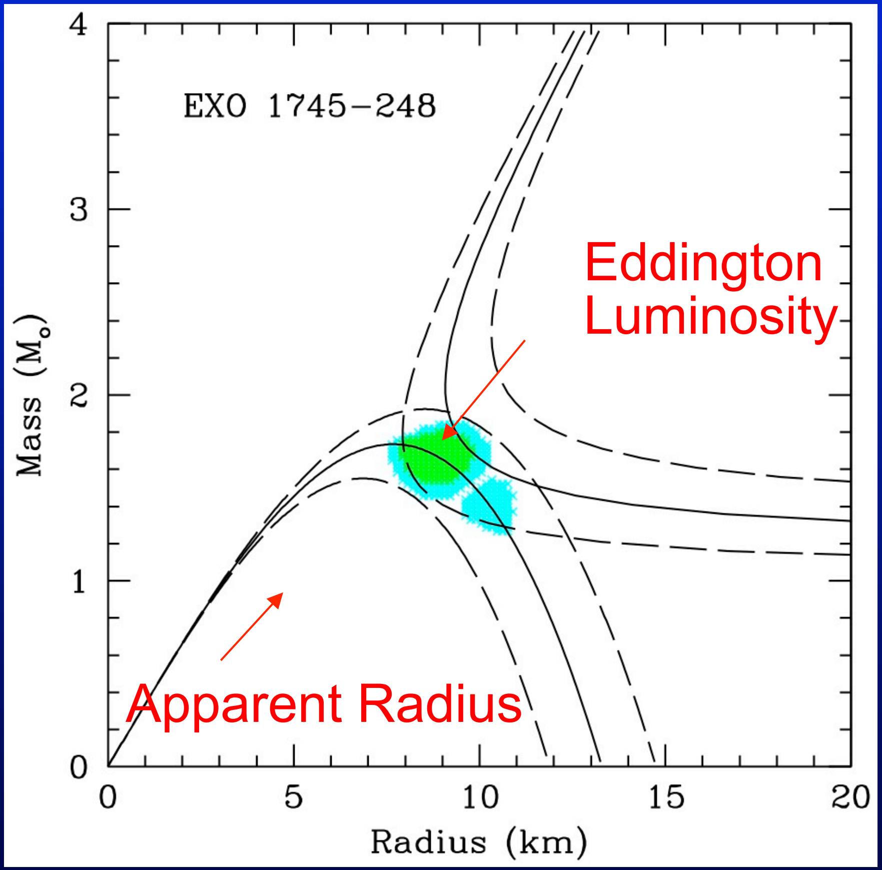
Uncertainties arising from internal dynamics of companion



Measuring masses and radii of neutron stars in thermonuclear bursts in X-ray binaries

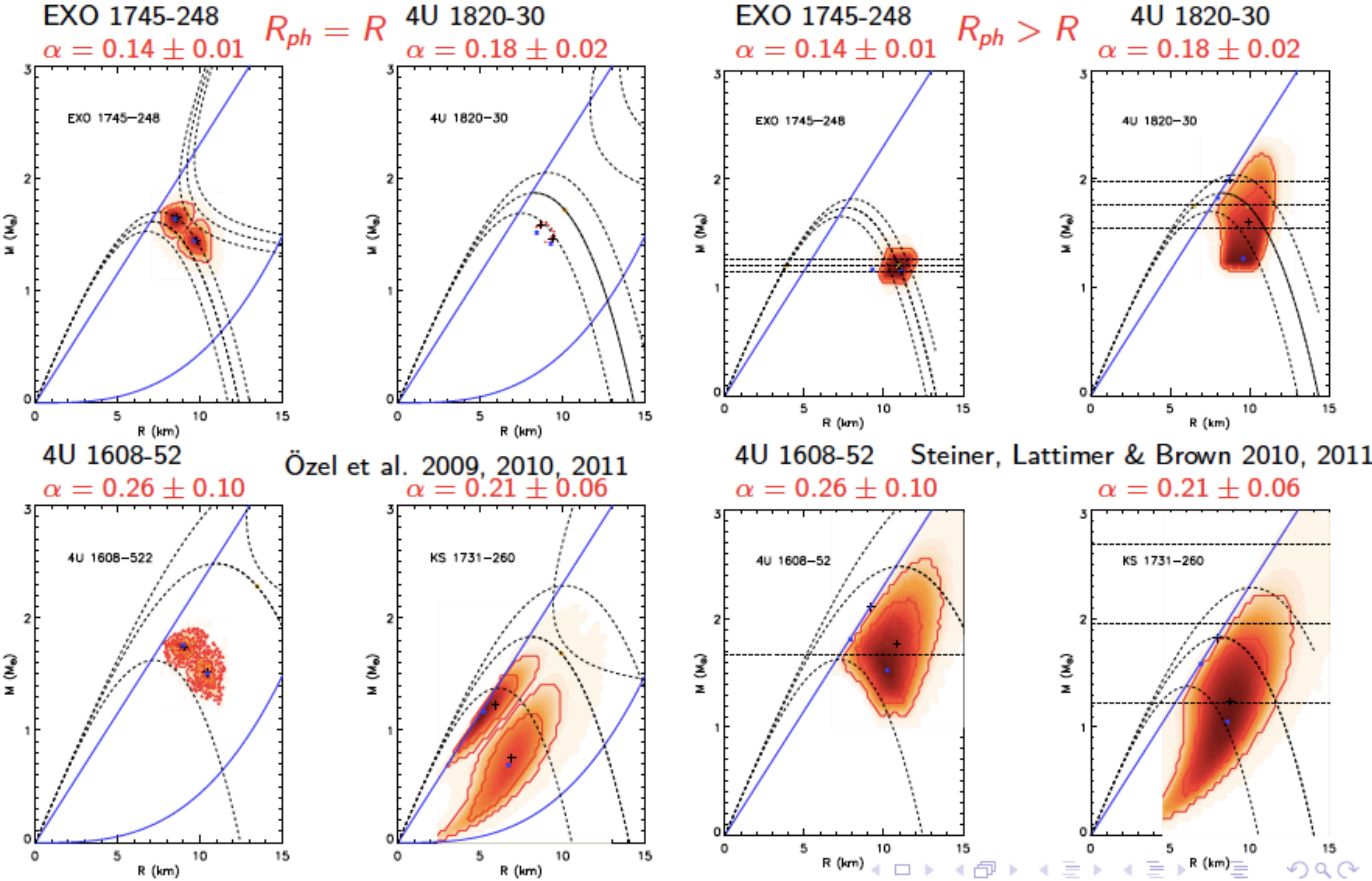
Özel et al., 2006-20l6
Steiner et al. 2010-2013



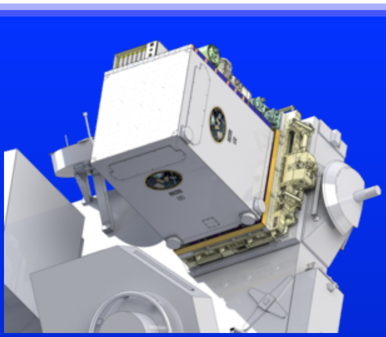


Measurements of *apparent* surface area, flux at Eddington limit (radiation pressure = gravity), combined with distance to star, constrains M and R.

M vs R from bursts (*Özel et al., Steiner et al.*)



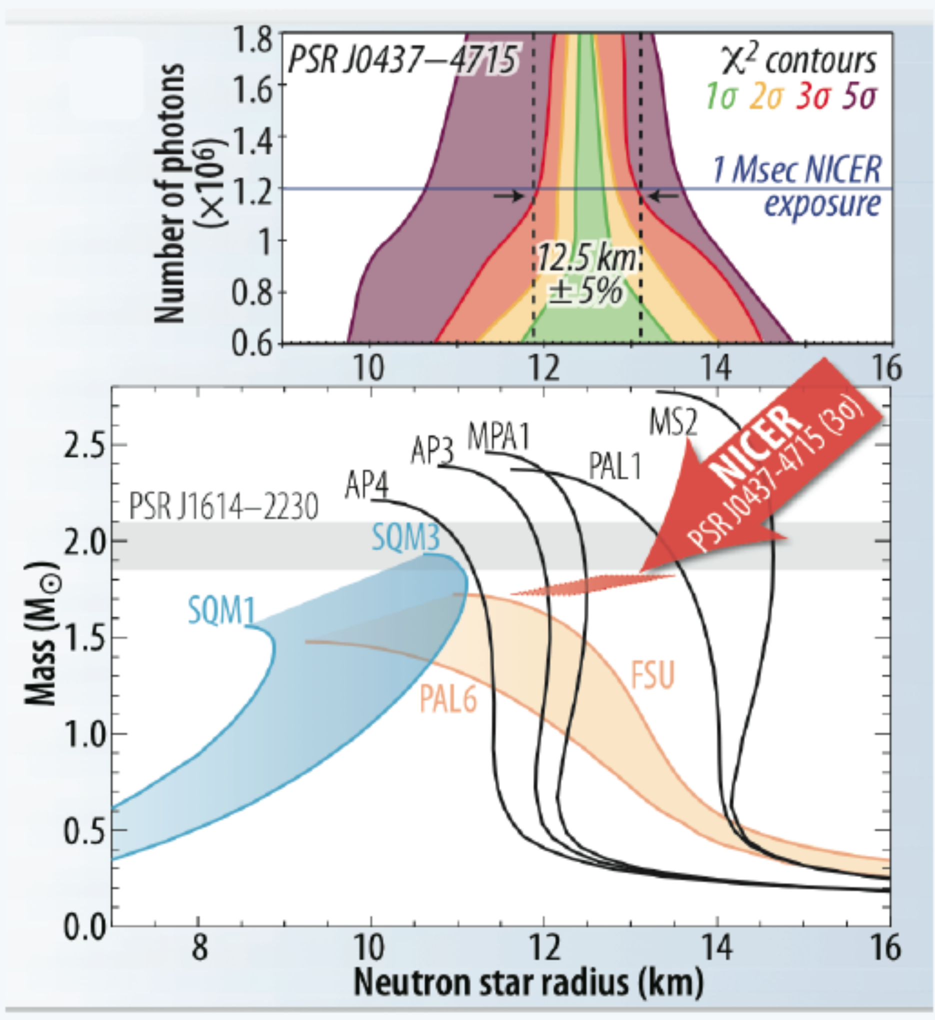
NICER =
Neutron star Interior Composition ExploreR

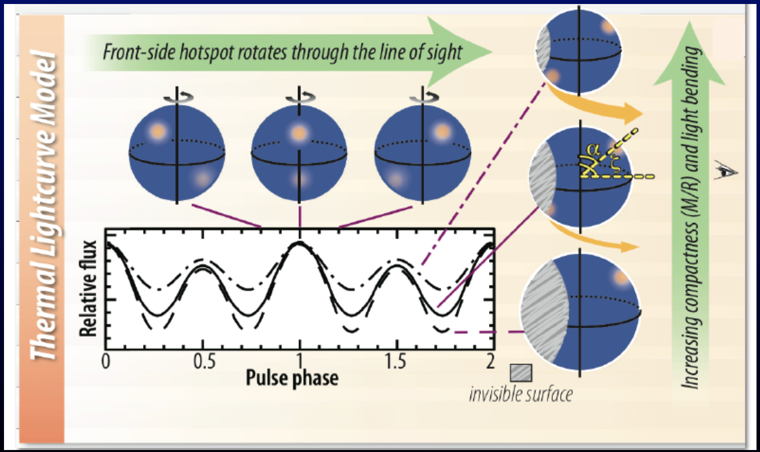


To be delivered to Int. Space Station (Space-X) Feb. 2017

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

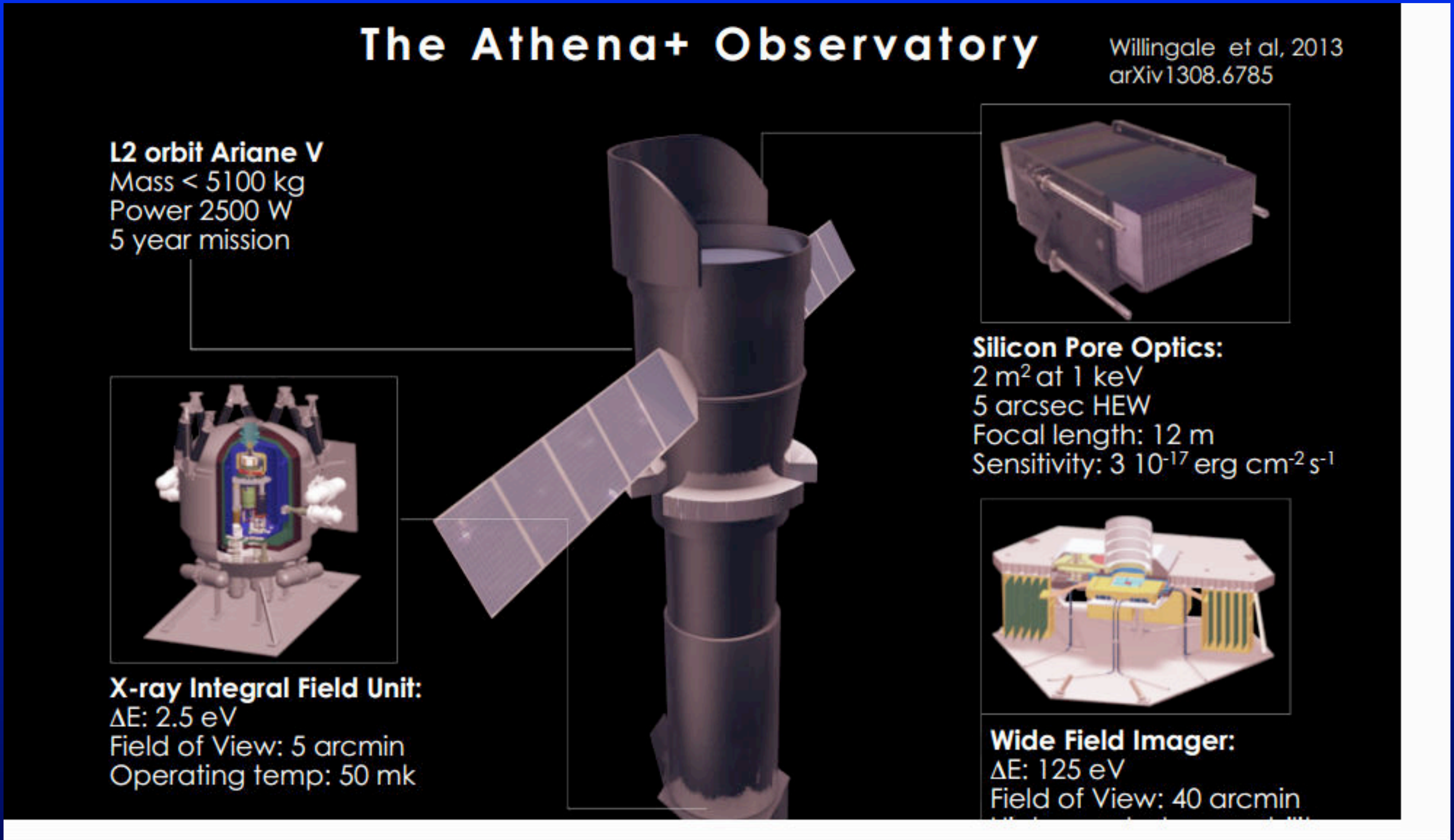
Measure radii and masses
Pulsar timing stability
Radiation spectra and
  luminosities





ATHENA = Advanced Telescope for High ENergy Astrophysics

ESA ~ 2028



The Athena+ Observatory

Willingale et al, 2013
arXiv1308.6785

L2 orbit Ariane V
Mass < 5100 kg
Power 2500 W
5 year mission

Silicon Pore Optics:
2 m^2 at 1 keV
5 arcsec HEW
Focal length: 12 m
Sensitivity: 3 10^{-17} erg cm^{-2} s^{-1}

X-ray Integral Field Unit:
ΔE: 2.5 eV
Field of View: 5 arcmin
Operating temp: 50 mk

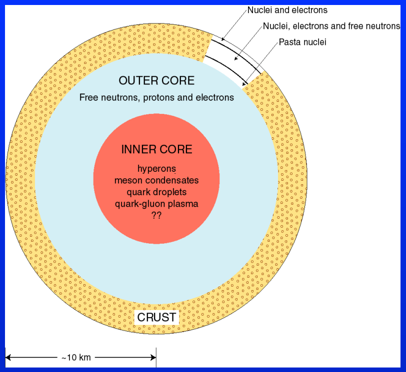
Wide Field Imager:
ΔE: 125 eV
Field of View: 40 arcmin

microsec time resolution of X-rays

-accretion
-magnetic processes from millisec pulsars to magnetars

-internal energy; cooling neutron stars.

Quark matter cores in neutron stars

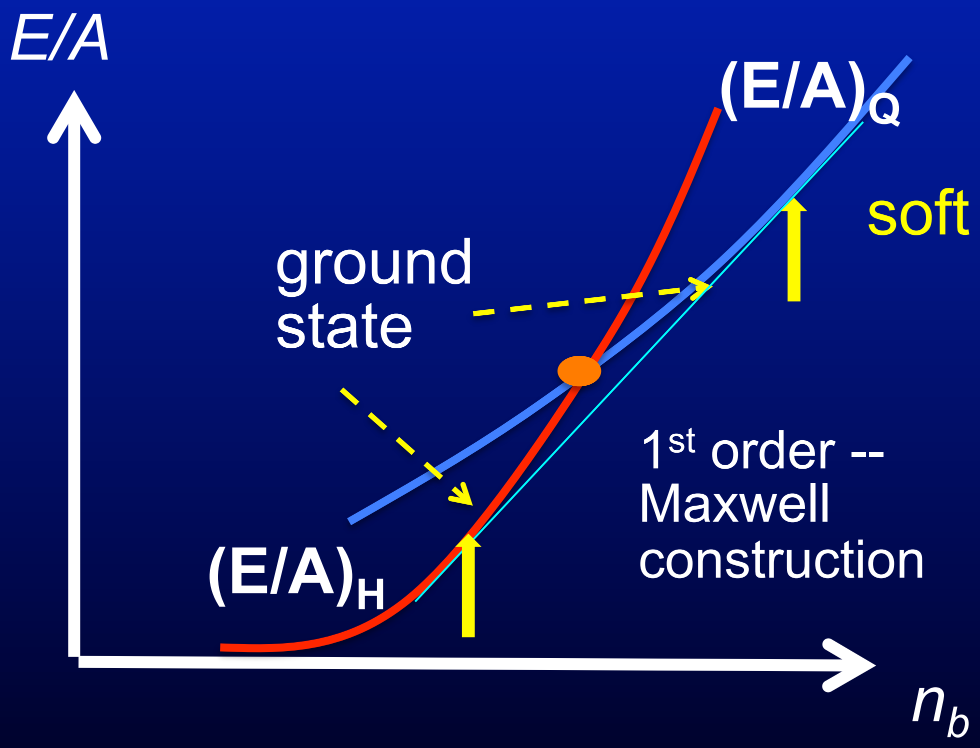


Canonical picture: compare calculations of eqs. of state of hadronic matter and quark matter.

GB & S.A. Chin (1976)

Crossing of thermodynamic potentials => first order phase transition.

ex. nuclear matter using 2 & 3 body interactions, vs. perturbative expansion or bag models.

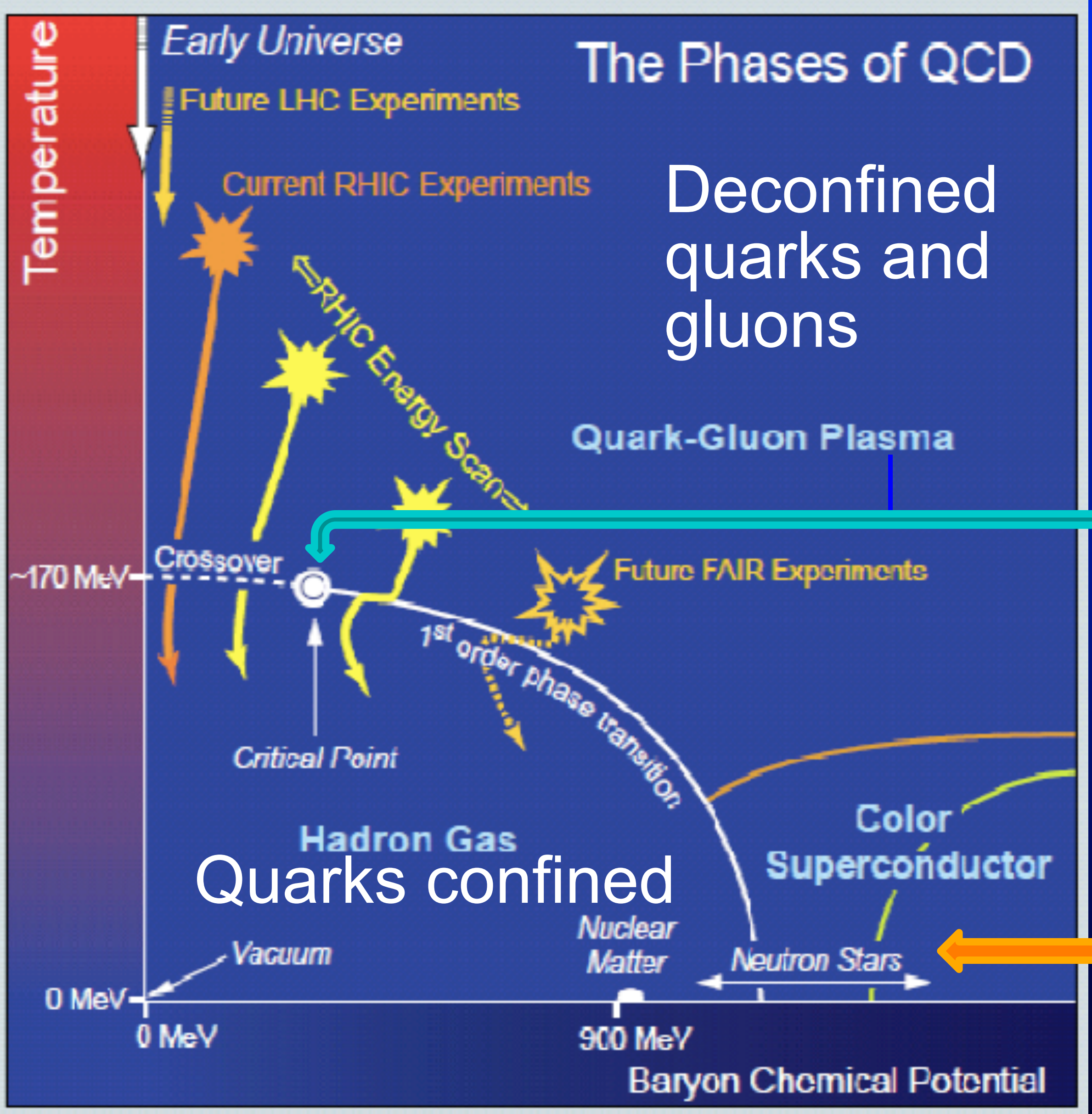


Assumes hadronic state at high densities – not possible when hadrons substantially overlap

Allows only quark equations of state lying under hadronic at high density. Soft only and therefore can't support two solar mass stars.

Typically conclude transition at n~10n_{nm} -- would not be reached even in high mass neutron stars => at most small quark matter cores

Modern phase diagram



Deconfined quarks and gluons

Quarks confined

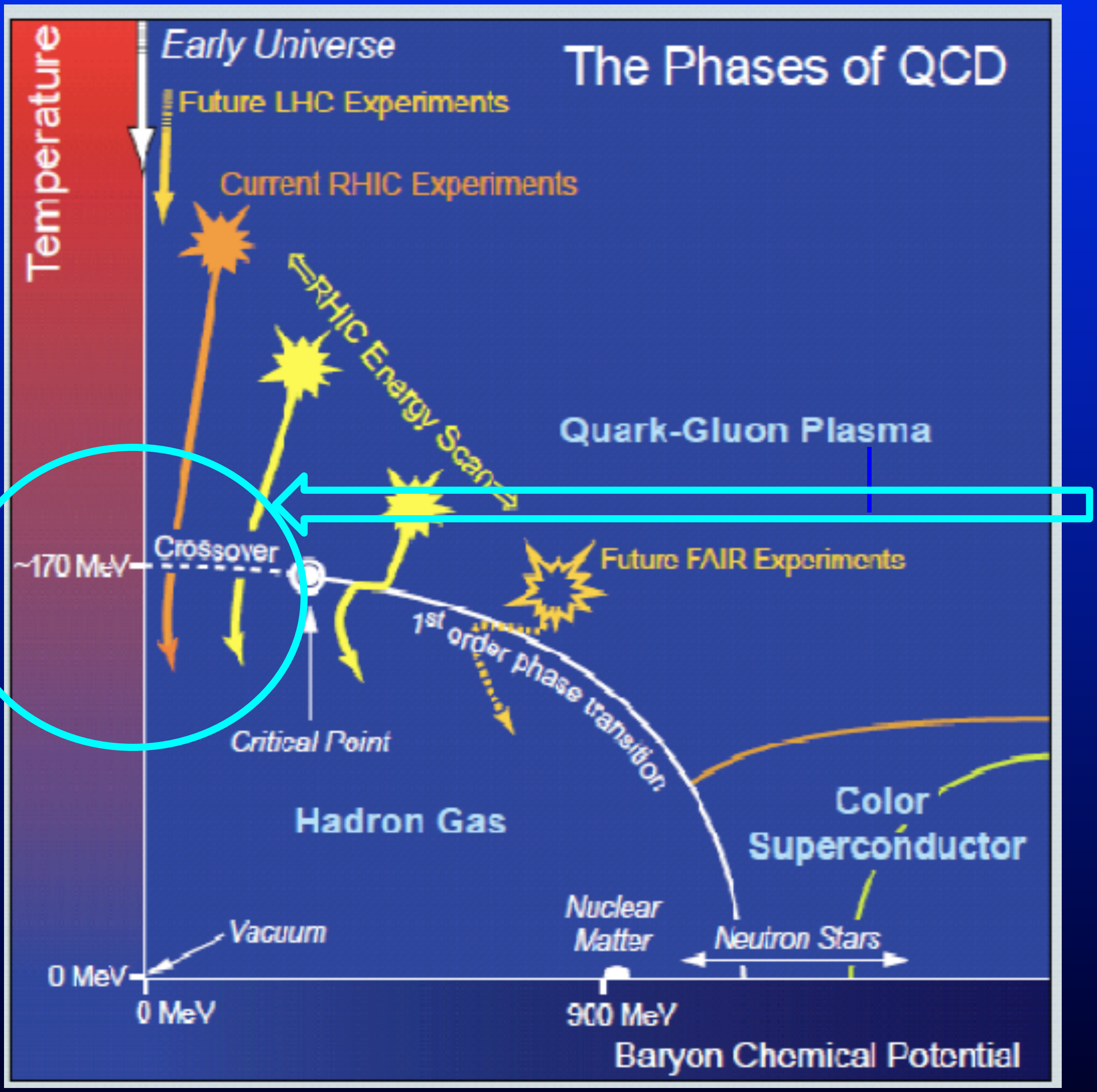
Asakawa-Yazaki critical point (1989)

Search in RHIC & SPS energy scans.

States of color superconductivity – diquark BCS pairing

2SC / Color flavor locked
(Alford, Rajagopal, Wilczek, ...)

Crossover at zero net baryon density

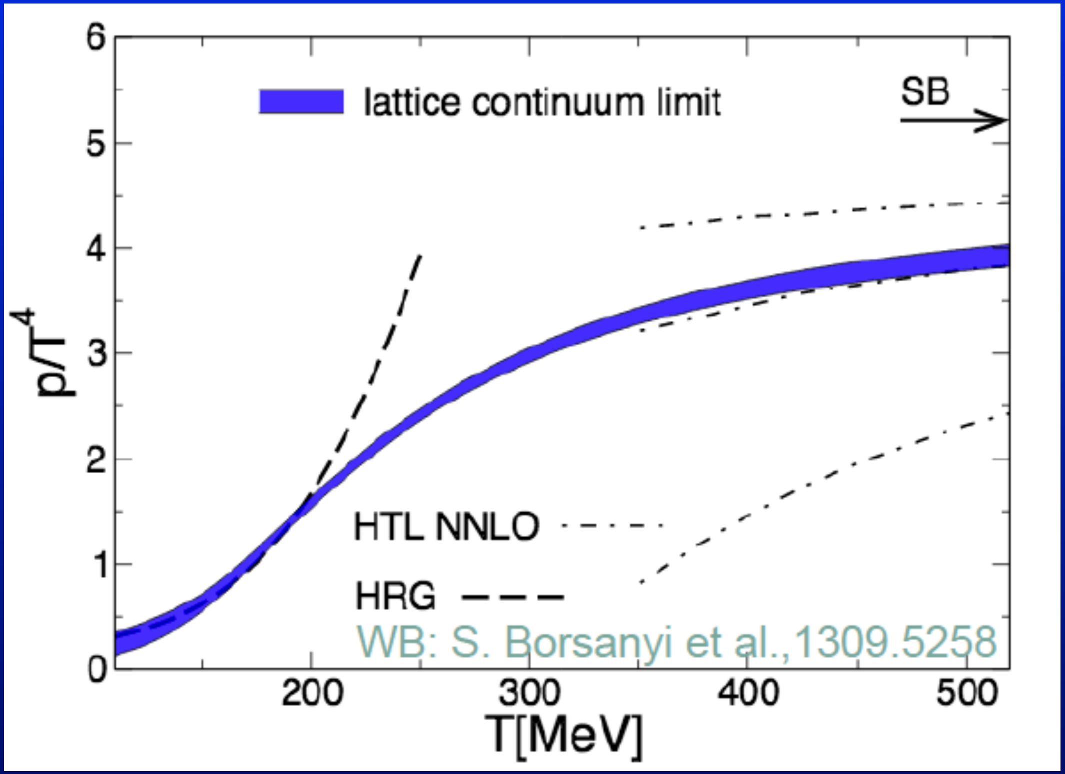


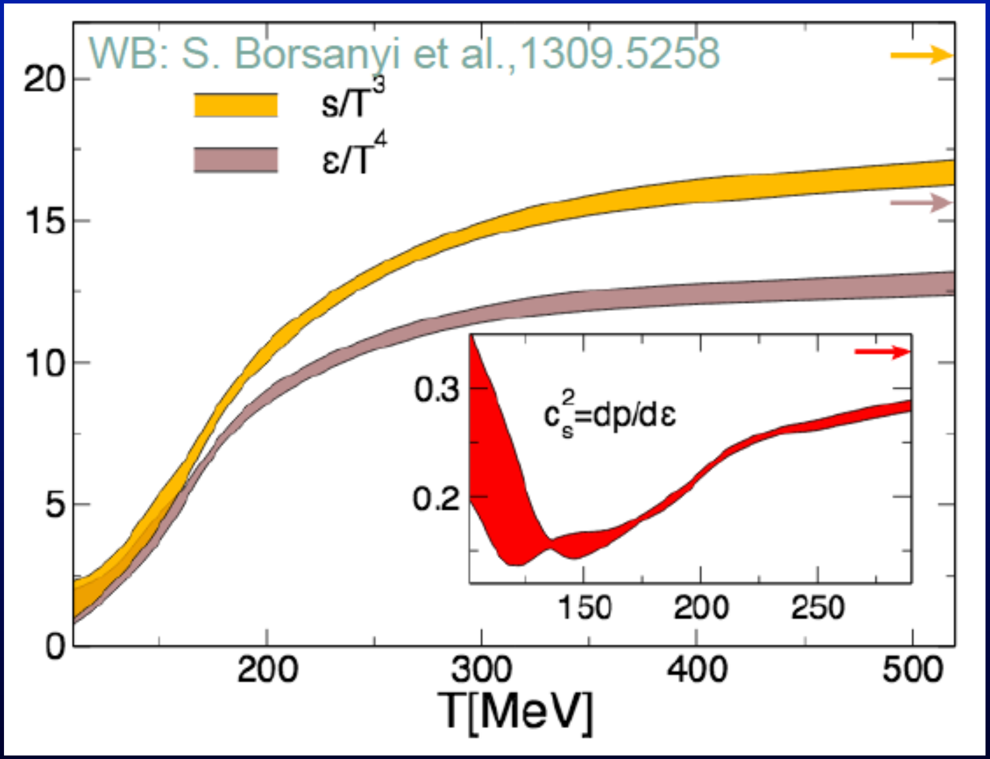
QCD lattice gauge theory -- for finite light quark masses -- predicts crossover from confined phase at lower T to deconfined phase at higher T.

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 this room?

Crossover at zero net density: see no evidence of phase transition in pressure, entropy, or energy density.



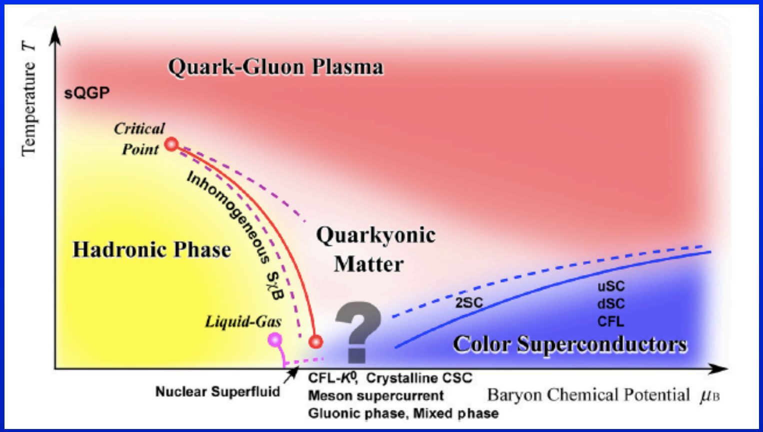


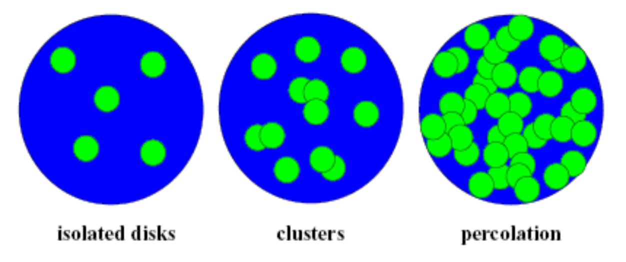
Wuppertal-Budapest
lattice collaboration

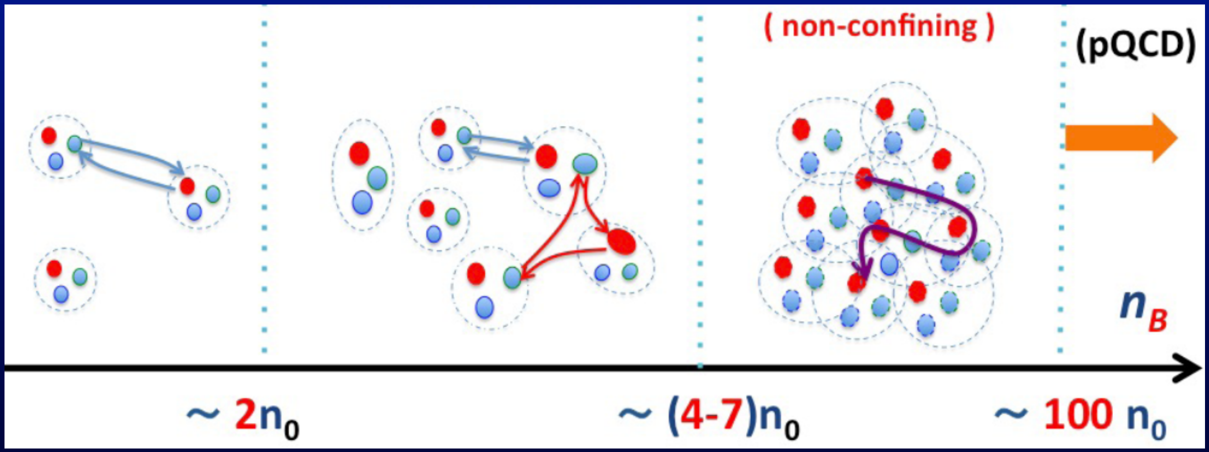
WB: S. Borsanyi et al., PLB (2014)
HotQCD: A. Bazavov et al., PRD (2014)

No free quarks even above the crossover!

In confined region quarks are inside hadrons. Also have quarks and antiquarks in the QCD forces between hadrons. With higher density or temperature, form larger clusters, which percolate at the crossover. In deconfined regime clusters extending across all of space.





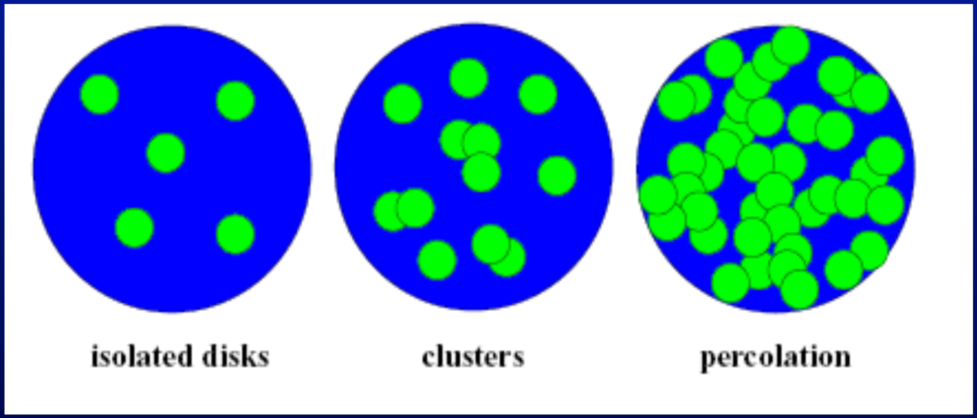


$$n_{perc} \sim 0.34\ (3/4\pi\ r_n^{3})\ \ \mathrm{fm}^{-3}$$

r_n = nucleon radius

Percolation of clusters along the density axis, at zero temperature. n_0 is the density of matter inside a large nucleus. Quarks can still be bound even if deconfined.

Classical percolation



$n_{perc} \sim 0.34\ (3/4\pi\ r_n^3)\ \ \mathrm{fm}^{-3}$

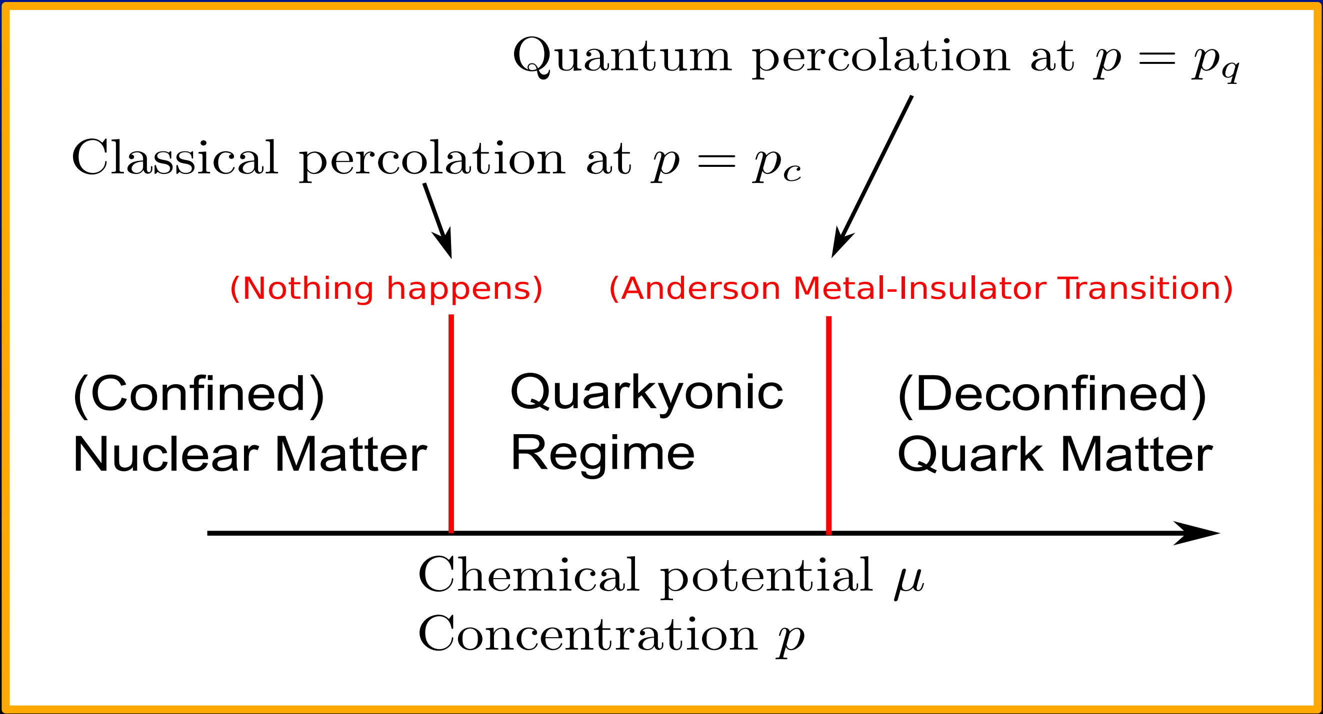
Quarks can still be bound even if deconfined.

But aren't nucleons, with long distance cloud of wee partons always overlapping?

Does anything actually happen at classical percolation transition? No obvious lattice calculation to do!

Distinguish classical (geometric) percolation
from quantum percolation in terms of wave functions

Deconfinement as (inverse) Anderson localization
(Kenji Fukushima):



Quantum percolation at $p = p_q$

Classical percolation at $p = p_c$

(Nothing happens)

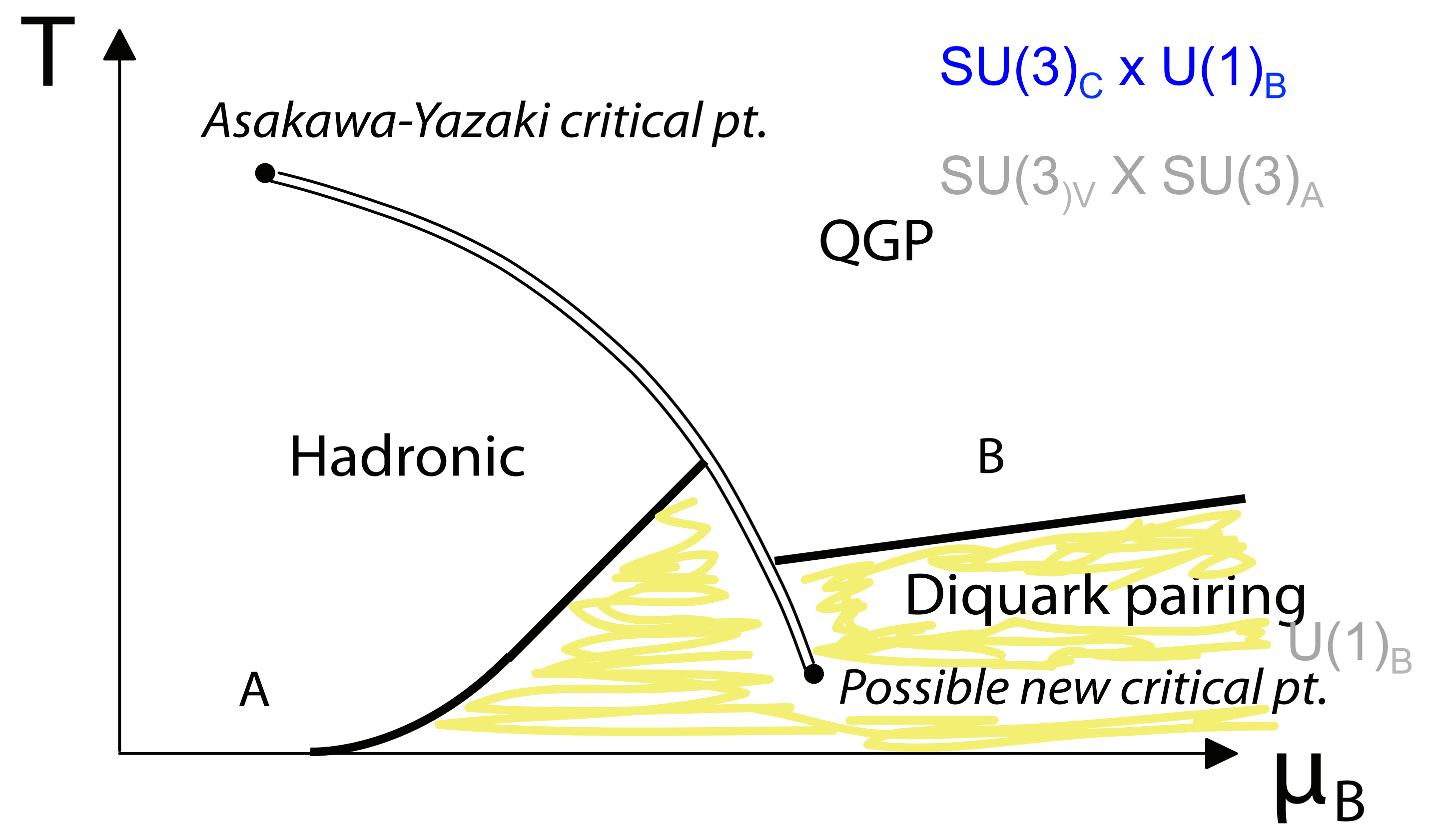
(Anderson Metal-Insulator Transition)

(Confined)
Nuclear Matter

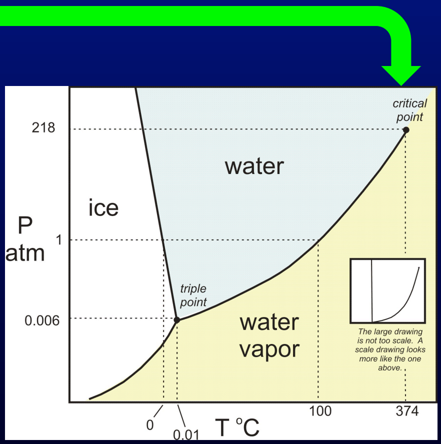
Quarkyonic
Regime

(Deconfined)
Quark Matter

Chemical potential μ
Concentration p



Critical points similar to those in liquid-gas phase diagram (H_2O)



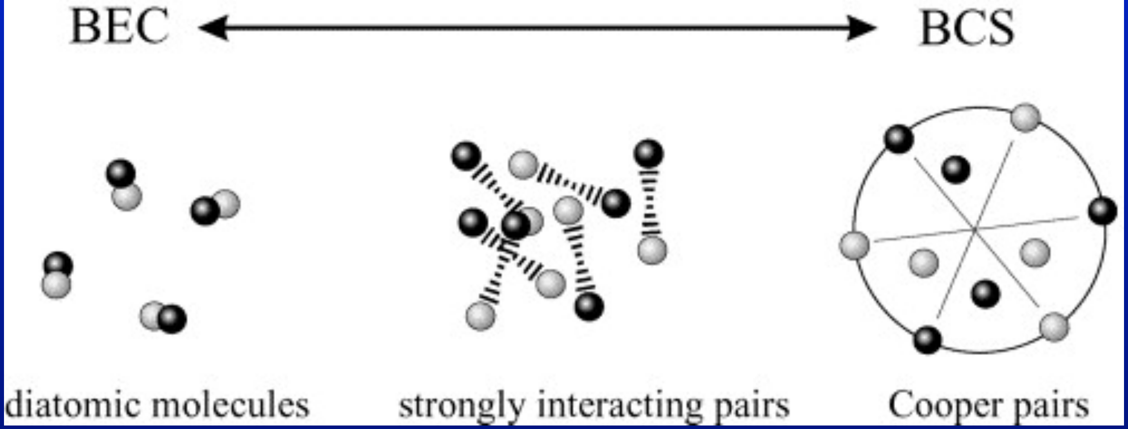
Can go continuously from A to B around the upper critical point. Liquid-gas phase transition.

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

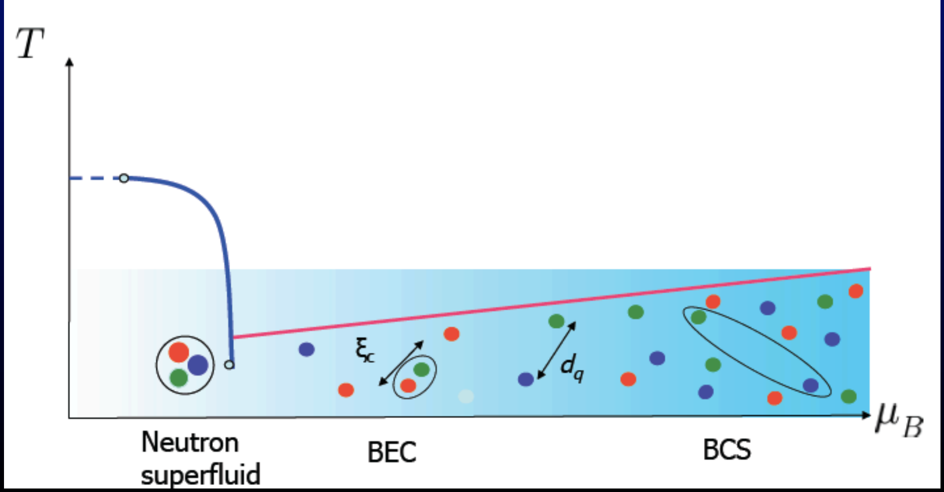
Smooth evolution of states in atomic clouds and nuclear matter

GB, T.Hatsuda, M.Tachibana, & Yamamoto. J. Phys. G: Nucl. Part. 35, 10402 (2008)
H. Abuki, GB, T. Hatsuda, & N. Yamamoto,Phys. Rev. D81, 125010 (2010)

Evolution of Fermi atoms with weakening attraction between atoms:



Similarly, as nuclear matter becomes denser have “continuous” evolution from hadrons (nucleons) to quark pairs (diquarks) to quark matter:

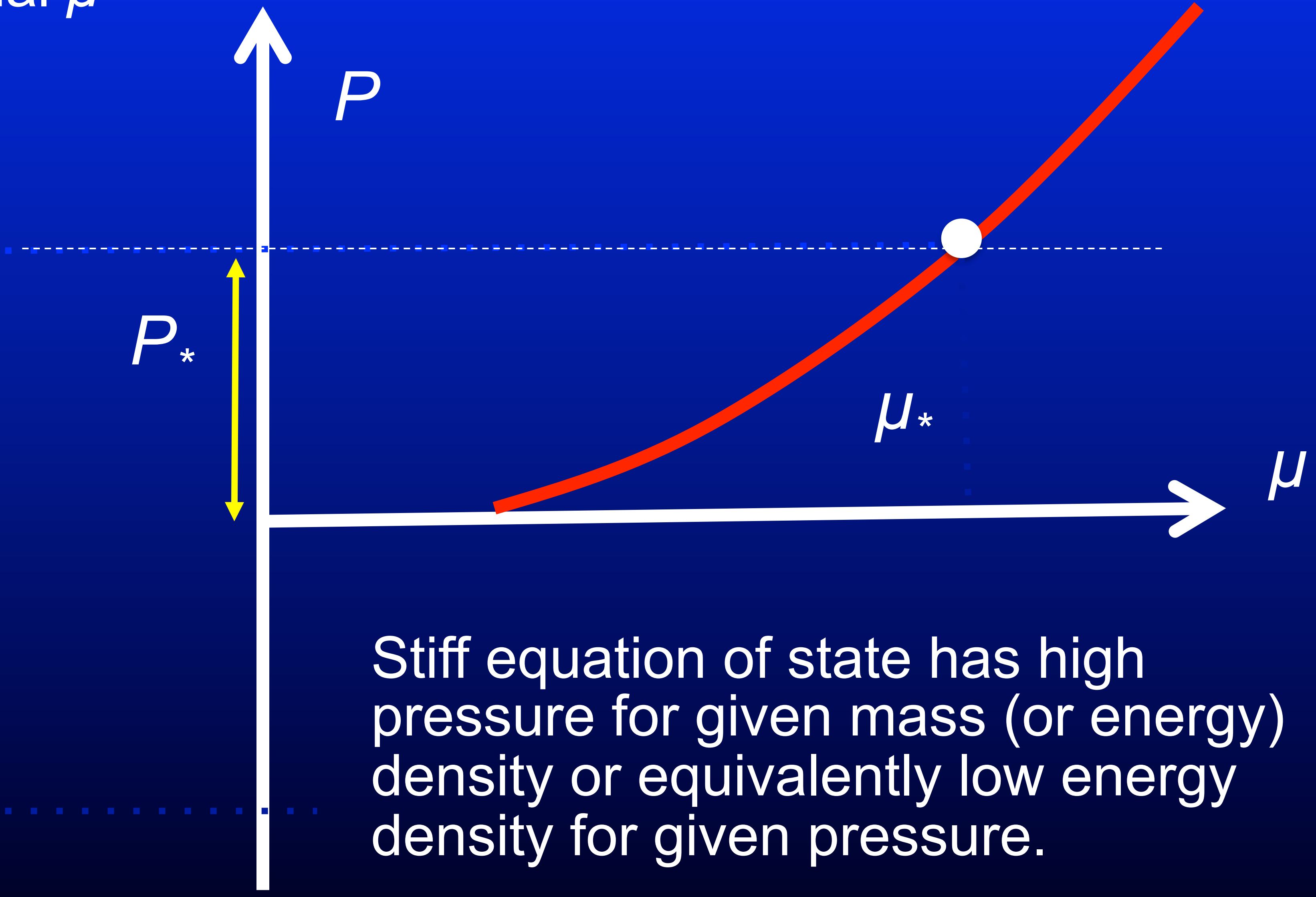


denser →

K. Masuda, T. Hatsuda, & T. Takatsuka, Ap. J.764, 12 (2013)

How can QCD give large mass neutron stars?

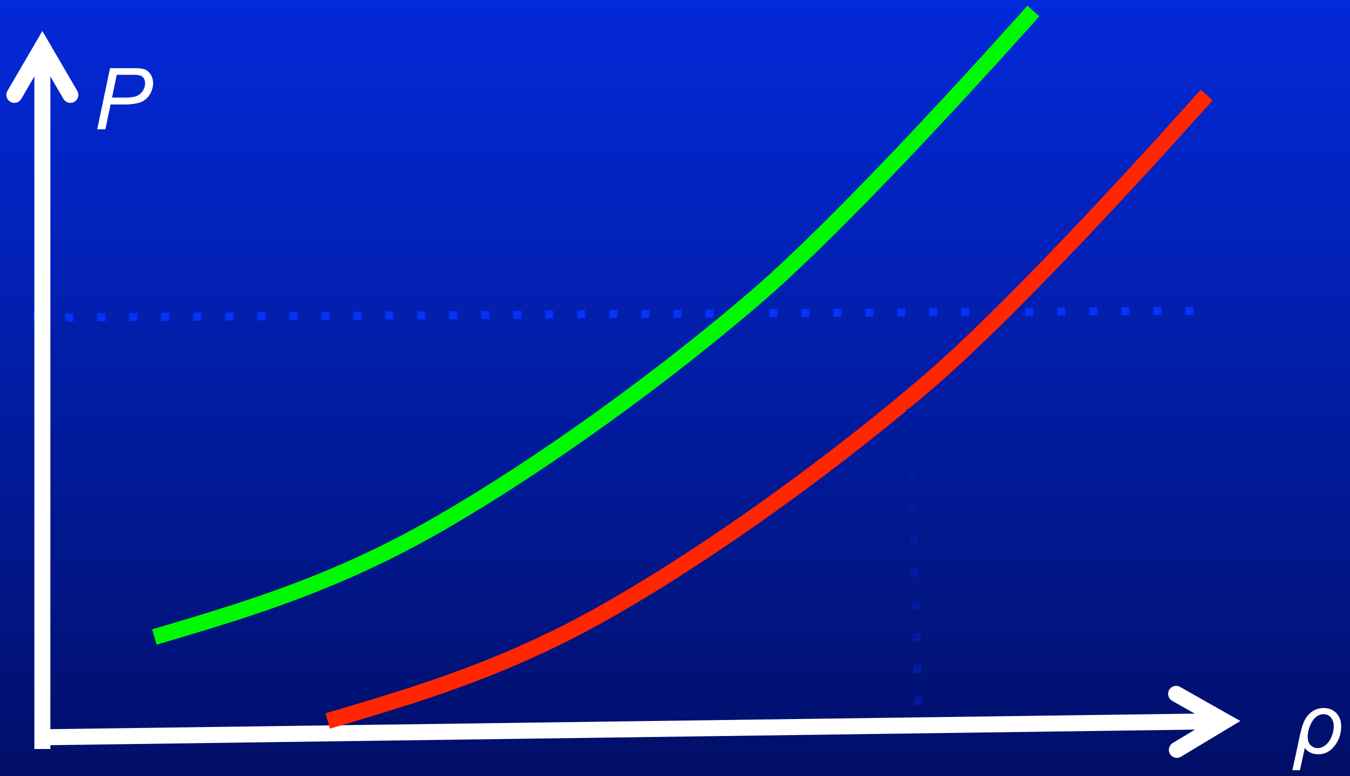
Pressure P is a continuous function of baryon chemical potential μ



Stiff equation of state has high pressure for given mass (or energy) density or equivalently low energy density for given pressure.

T. Kojo, P. D. Powell, Y. Song, & GB, PR D 91, 045003 (2015)

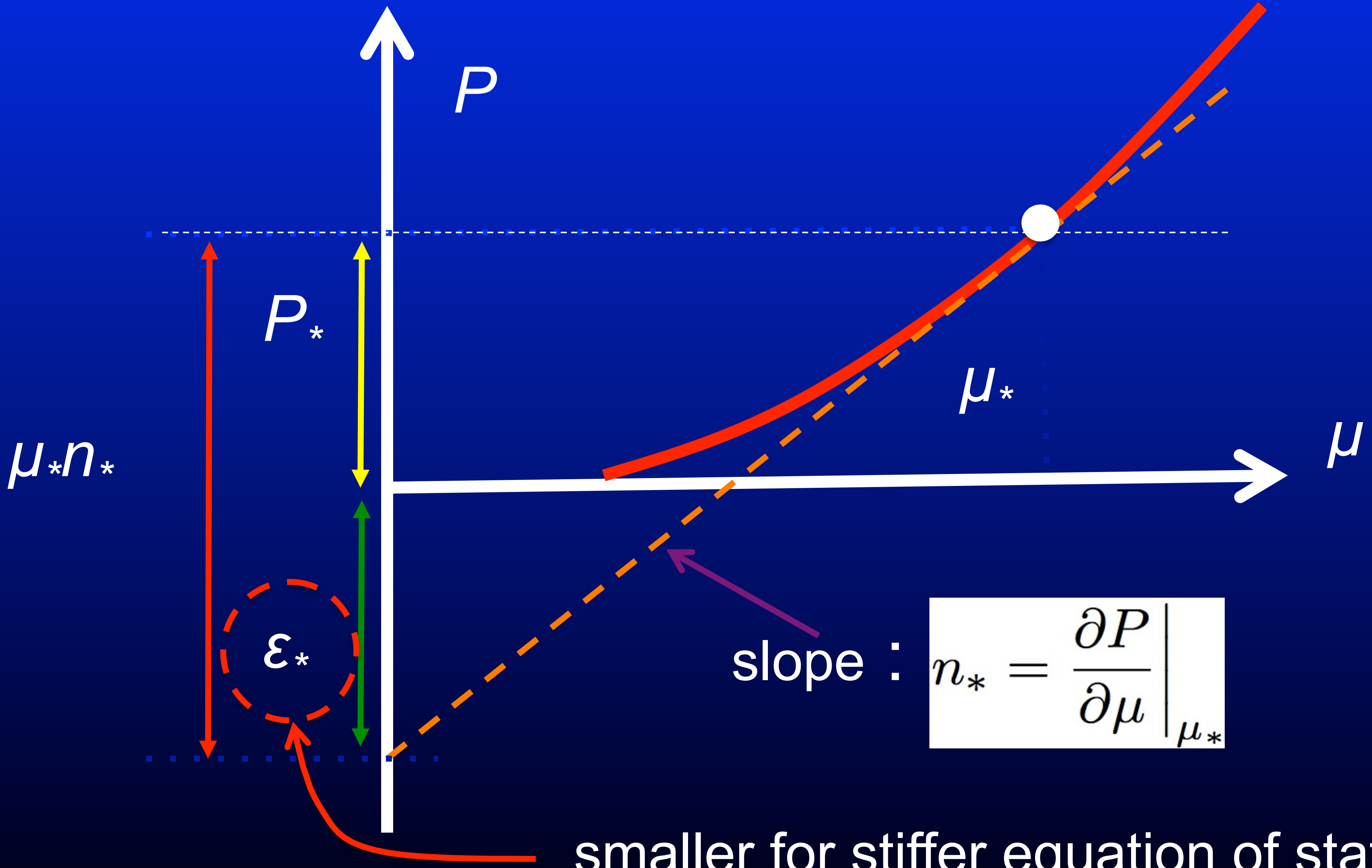
Stiffer equations of state given more massive neutron stars, with lower central densities



Green equation of state is stiffer than red.
Has larger pressure for given mass density *ρ*,
and has smaller *ρ* for given pressure P

How can QCD give large mass neutron stars?

Energy or mass density $\varepsilon = \rho c^2 = \mu n - P$

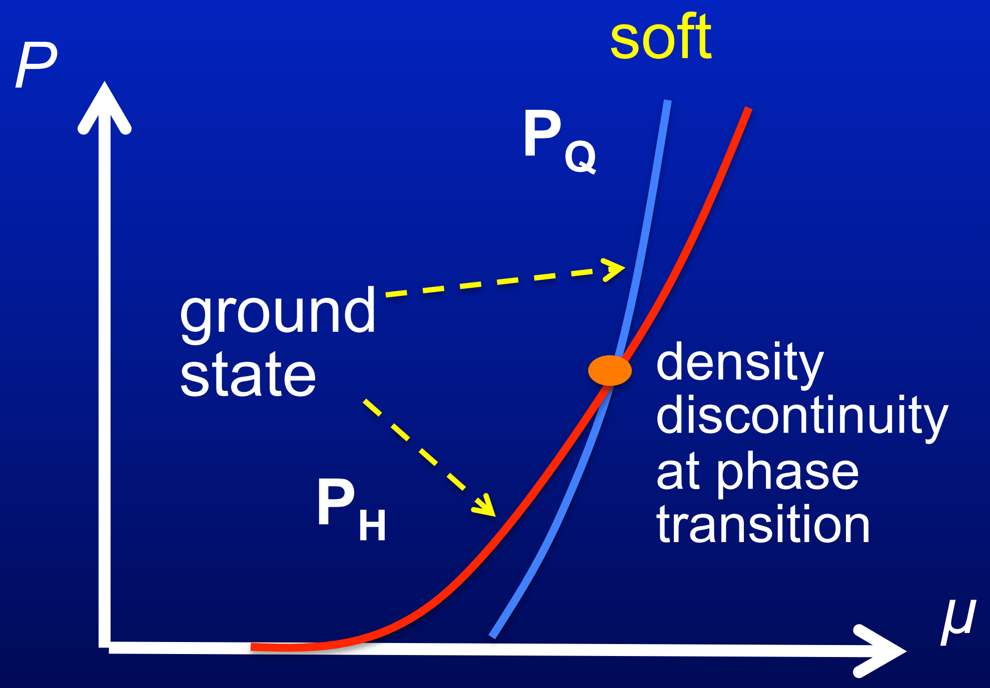


slope : $n_* = \left.\frac{\partial P}{\partial \mu}\right|_{\mu_*}$

smaller for stiffer equation of state

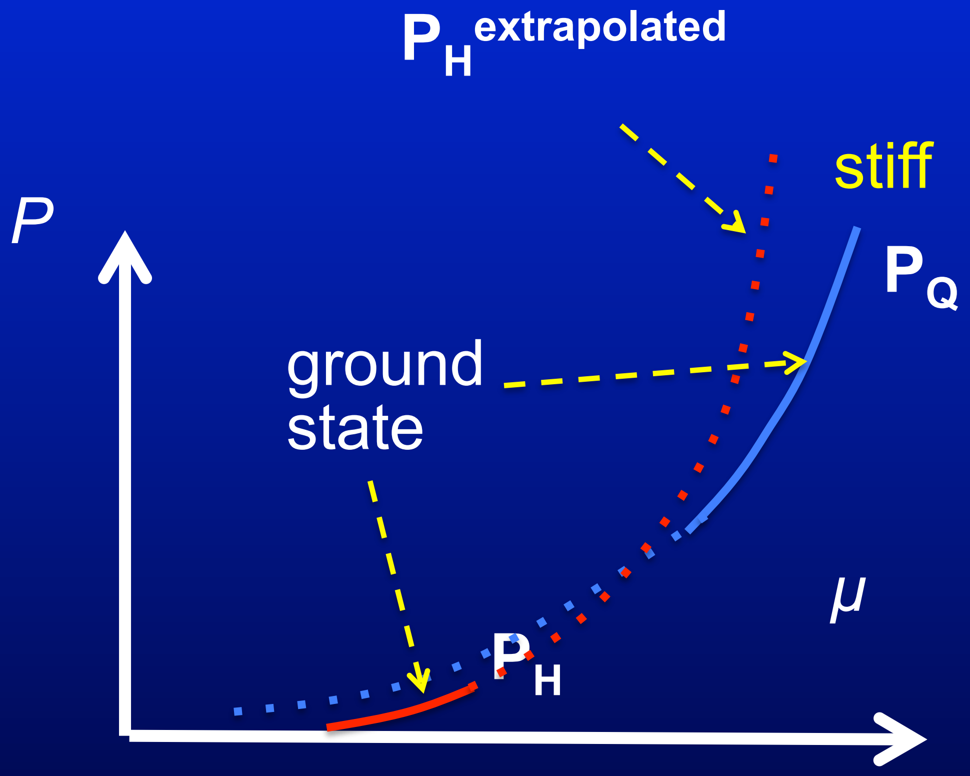
Hybrid eqs. of state are intrinsically softer

Phase with larger P at given μ thermodynamically preferred



Assumes hadronic state at high densities – not possible when hadrons substantially overlap

Continuous eqs. of state can be much stiffer



Hadrons only at low density and quark matter at high density. In between???

Model calculations of neutron star matter within NJL model

NJL Lagrangian $\mathcal{L} = \bar{q}(i\gamma_\mu\partial^\mu - m_q + \mu\gamma_0)q + \mathcal{L}^{(4)} + \mathcal{L}^{(6)}$

$\mathcal{L}^{(4)}_\chi = G\sum_{a=0}^{8}[(\bar{q}\tau_a q)^2 + (\bar{q}i\gamma_5\tau_a q)^2]$ chiral interactions

$\mathcal{L}^{(4)}_d = H\sum_{A,A'=2,5,7}[(\bar{q}i\gamma_5\tau_A\lambda_{A'}C\bar{q}^T)(q^T C i\gamma_5\tau_A\lambda_{A'}q)$ BCS pairing interactions

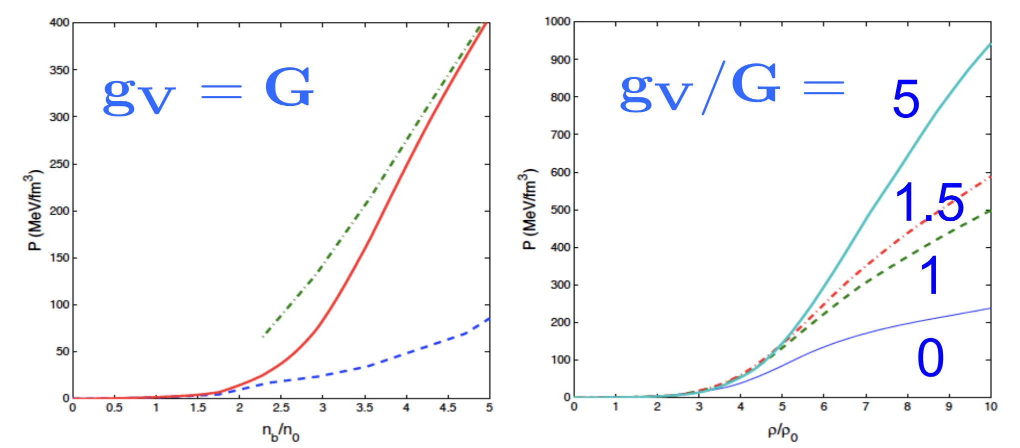
$\mathcal{L}^{(6)}$ = Kobayashi-Maskawa-'t Hooft six quark axial anomaly

plus universal repulsive quark-quark vector coupling

$\mathcal{L}^{(4)}_V = -g_V(\bar{q}\gamma^\mu q)^2$ *T. Kunihiro*

K. Masuda, T. Hatsuda, & T. Takatsuka, Ap. J.764, 12 (2013)

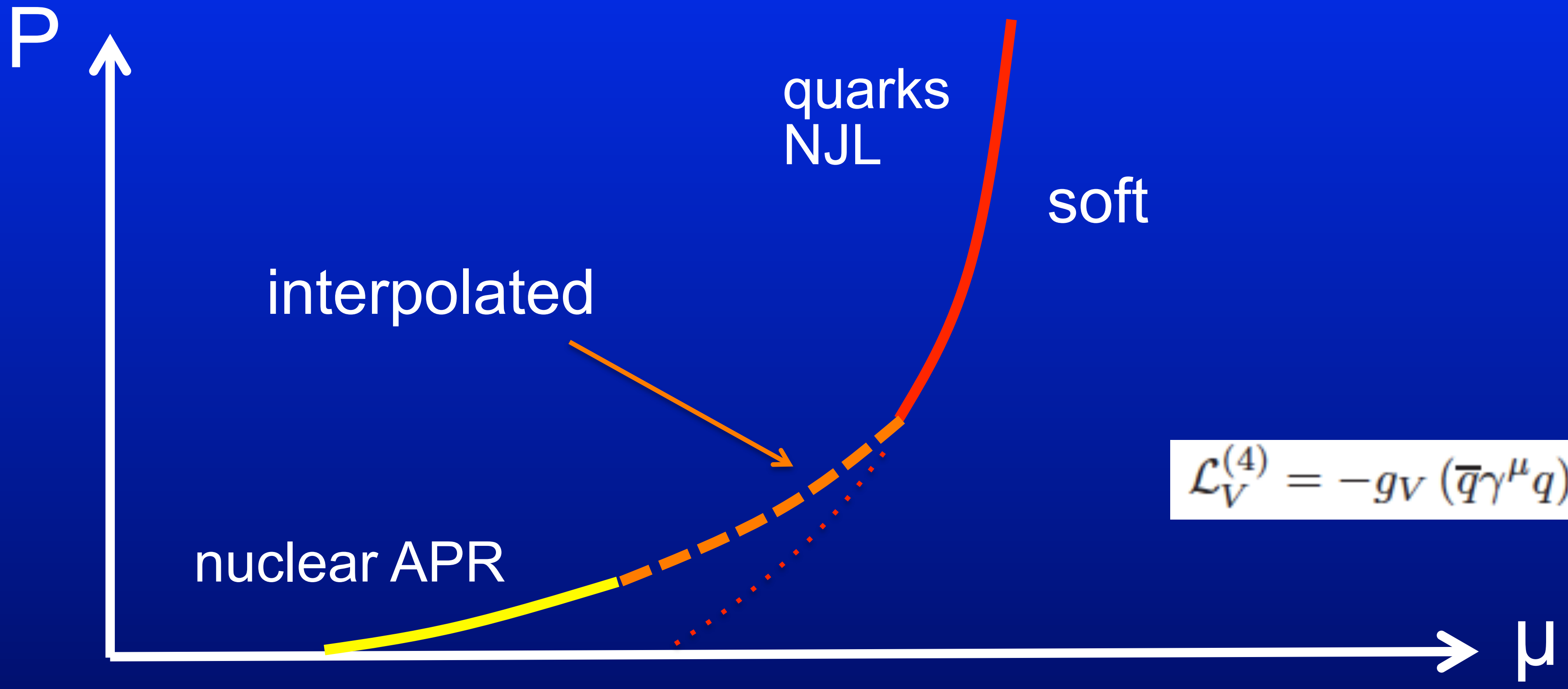
GB, T. Kojo, T. Hatsuda, C.J. Pethick, T. Takatsuka, Y. Song (to be published)



pressure

baryon density mass density

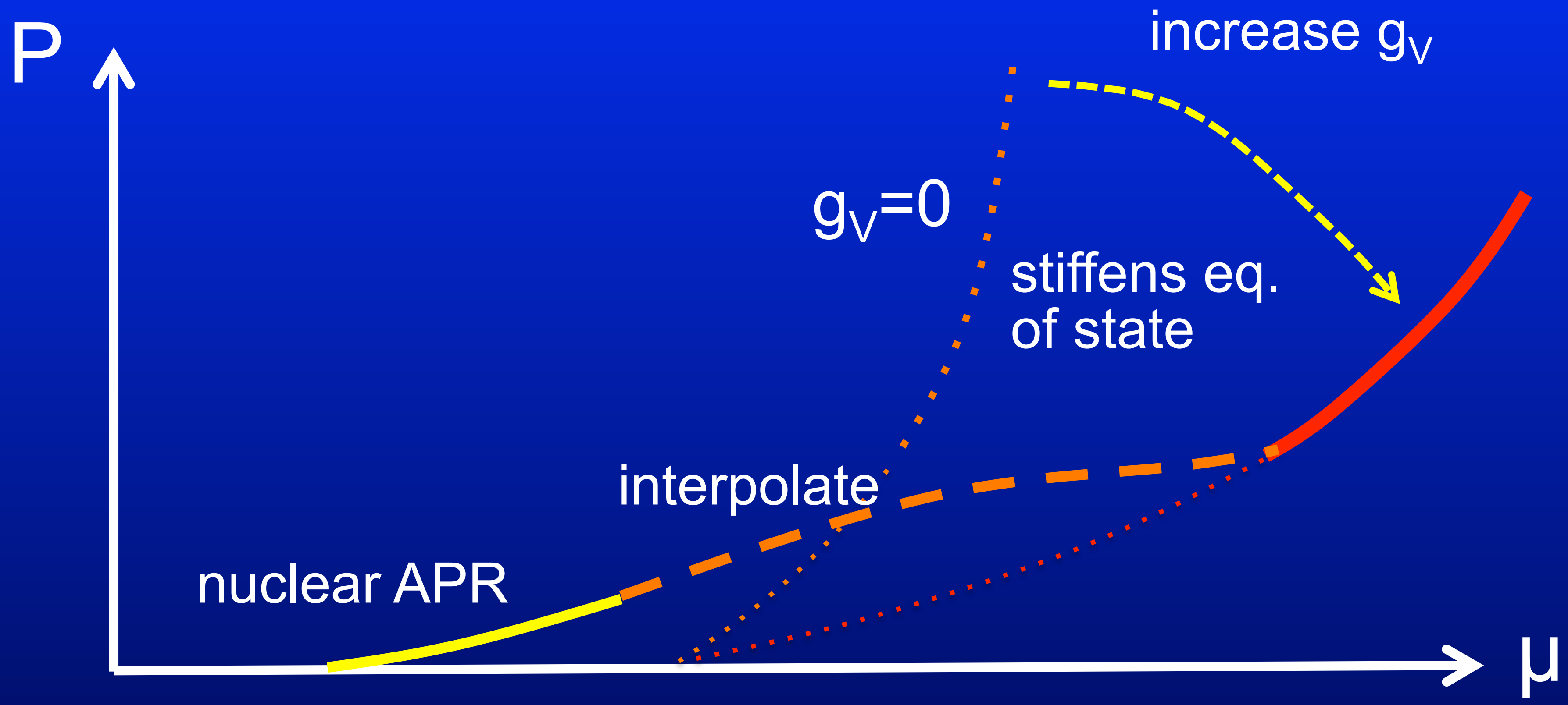
Minimal model: $g_V = 0$



$$\mathcal{L}_V^{(4)} = -g_V \left(\overline{q}\gamma^\mu q\right)^2$$

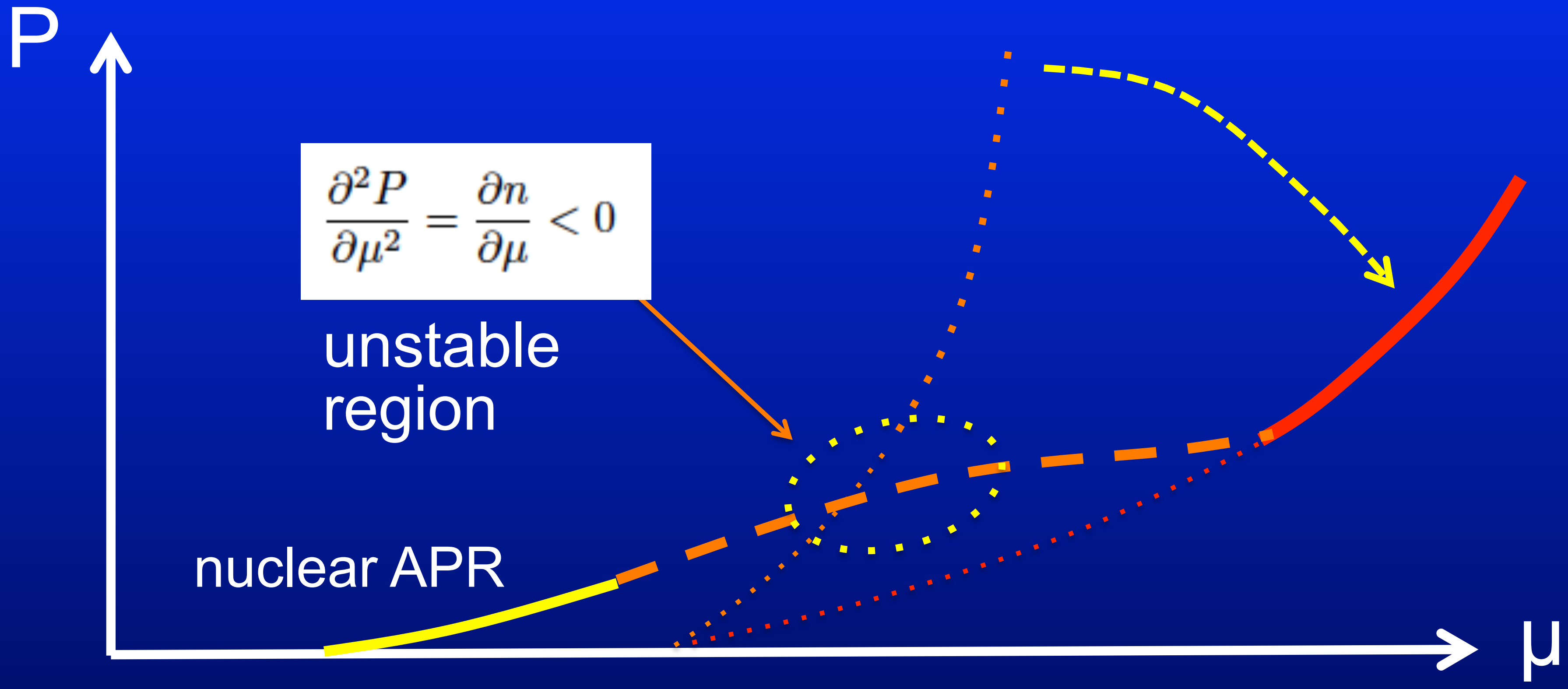
Soft quark equation of state does not allow high mass neutron stars

Vector interaction stiffens eq. of state



Shift of pressure in quark phase towards higher μ

Vector interaction stiffens eq. of state



$$\frac{\partial^2 P}{\partial \mu^2} = \frac{\partial n}{\partial \mu} < 0$$

unstable
region

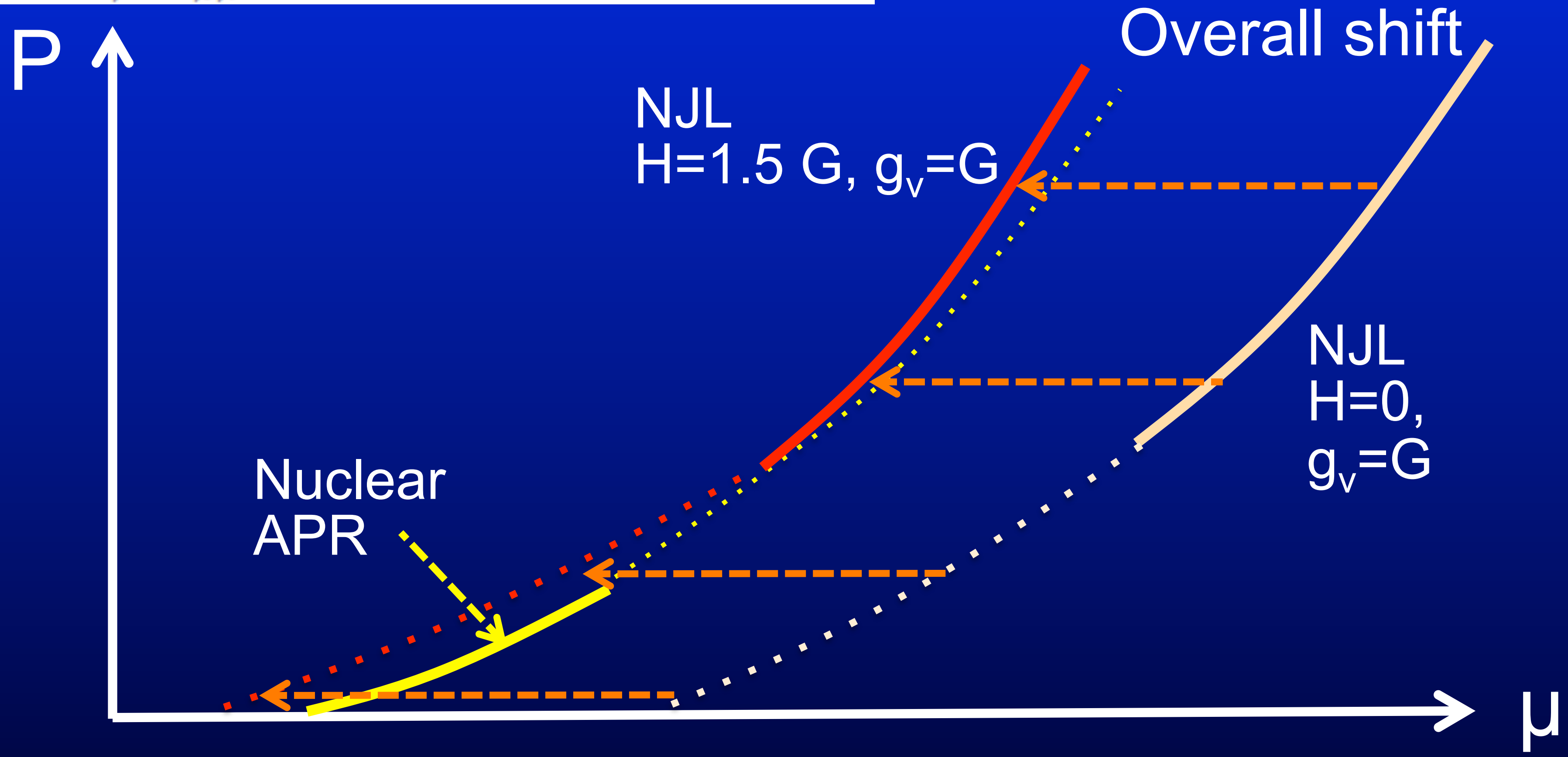
nuclear APR

Larger g_V leads to unphysical thermodynamic instability


In this house, we obey
the laws of thermodynamics!

Restore stability with increased BCS (diquark) pairing interaction, H

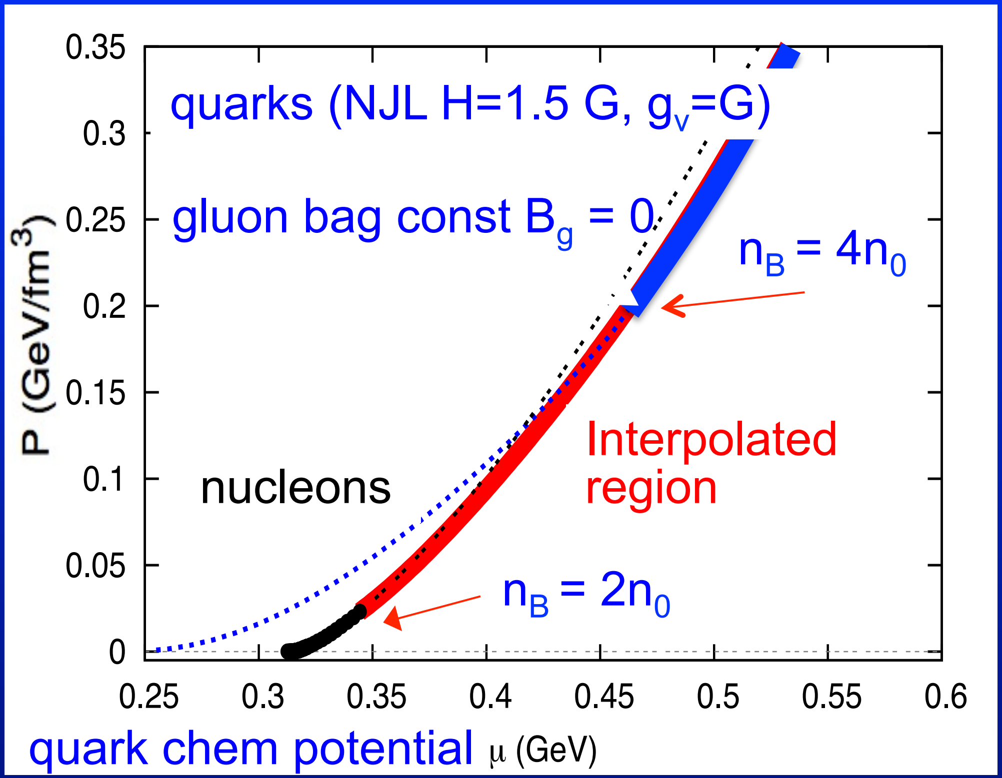
$$\mathcal{L}_d^{(4)} = H \sum_{A,A'=2,5,7} [(\bar{q} i\gamma_5 \tau_A \lambda_{A'} C \bar{q}^T)(q^T C i\gamma_5 \tau_A \lambda_{A'} q)$$

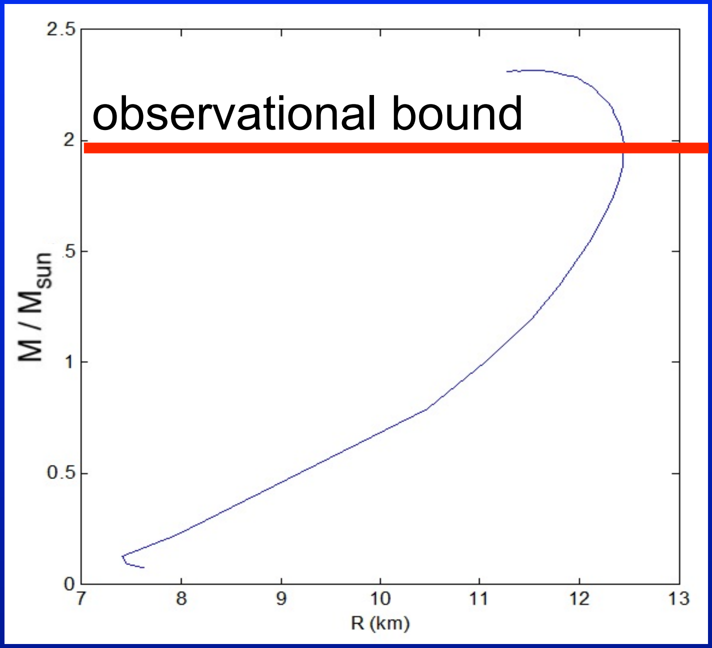


Increased BCS pairing (onset of stronger 2-body correlations) as quark matter comes nearer to becoming confined

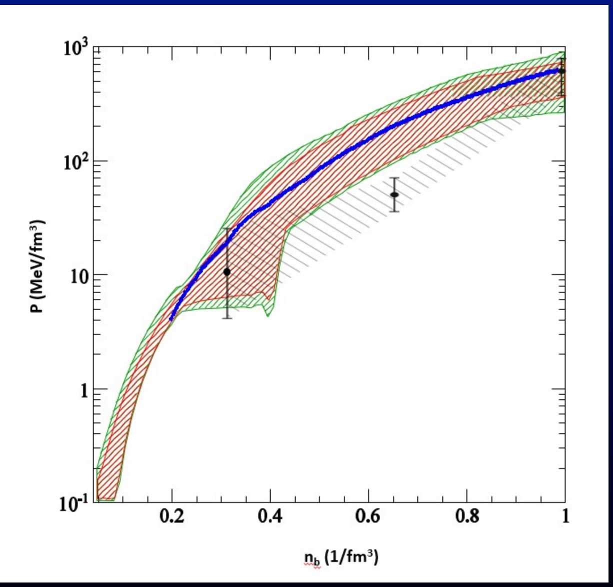
Sample “unified” equation of state

T. Kojo et al.





M-R relation similar to results of nucleonic (APR) equation of state but with correct high density degrees of freedom



<= Reasonable agreement with eq. of state inferred from M vs. R measurements.

Quark eqs. of state can be stiffer than previously thought: allow for n.s. masses > 2 $M_\odot$, and with substantial quark cores in neutron stars!!!

Summary

For 2 $n_0 < n_B <$ 7-8 n_0 mattter is intermediate between purely hadronic and purely quark: “quarkyonic”

Quark model eqs. of state can be stiffer than previously thought, allowing for neutron star masses > 2 $M_\odot$

Interaction parameters of order vacuum values $H \sim g_v \sim G_s^{vac}$

Gluonic bag constant is small; gluons remain non-perturbative at densities in neutron stars. Else significant softening of equation of state. Vacuum gluon condensate persists.

But much more to do:

Uncertainties in nuclear matter equation of state (APR, etc.)

Uncertainties in interpolating from nuclear matter to quark matter lead to errors in maximum neutron star masses and radii

Uncertainties in the vector coupling and pairing forces;

Going beyond the NJL model -- running g_v (Fukushima-Kojo)

Need to produce finite temperature equation of state (≤ 50 MeV) for modelling neutron star -- neutron star (or black hole) mergers as sources of gravitational radiation.

K. Masuda, T. Hatsuda, and T. Takatsuka, Prog. Theor. Exp. Phys. ***2016****, 021D01*

Forthcoming workshops on:

Neutron Stars: linking nuclear physics of the interior to electromagnetic observations and gravitational radiation

GB, T. Hatsuda, K. Kokkotas, and F. Özel
Aspen Center for Physics
June 18-July 8, 2017

Applications due Jan. 31, 2017 (aspenphys.org)

New perspectives on neutron star interiors

G. Barnaföldi, GB, and L. Tolos
ECT*, Trento
Oct. 9-13, 2017