New States of Quantum Matter:
Many particle physics from the hottest to the densest to the coldest places in the universe

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International Workshop on Quantum Many-Body Problems in Particle, Nuclear, and Atomic Physics

Duy Tan University, Danang

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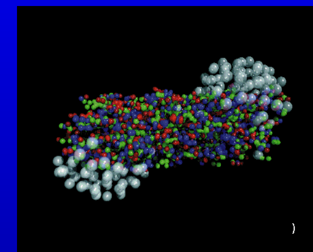
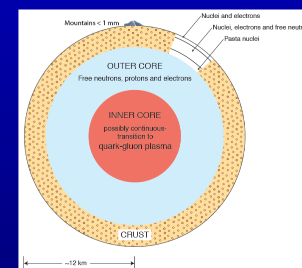
Two new forms of matter

Quark-gluon plasmas



1) made in ultrarelativistic heavy ion collisions at temperatures ~ 10^2 MeV ~ 10^{12} K (the temperature of early universe at one microsecond after the BIG BANG)

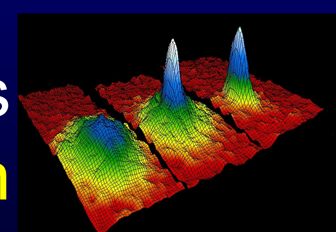


2) The stuff in the deep interiors of neutron stars, at temperatures << 1 MeV. Densest in universe.

and ultracold trapped atomic systems

Bose-condensed superfluids

Bardeen-Cooper-Schrieffer (BCS) superfluids

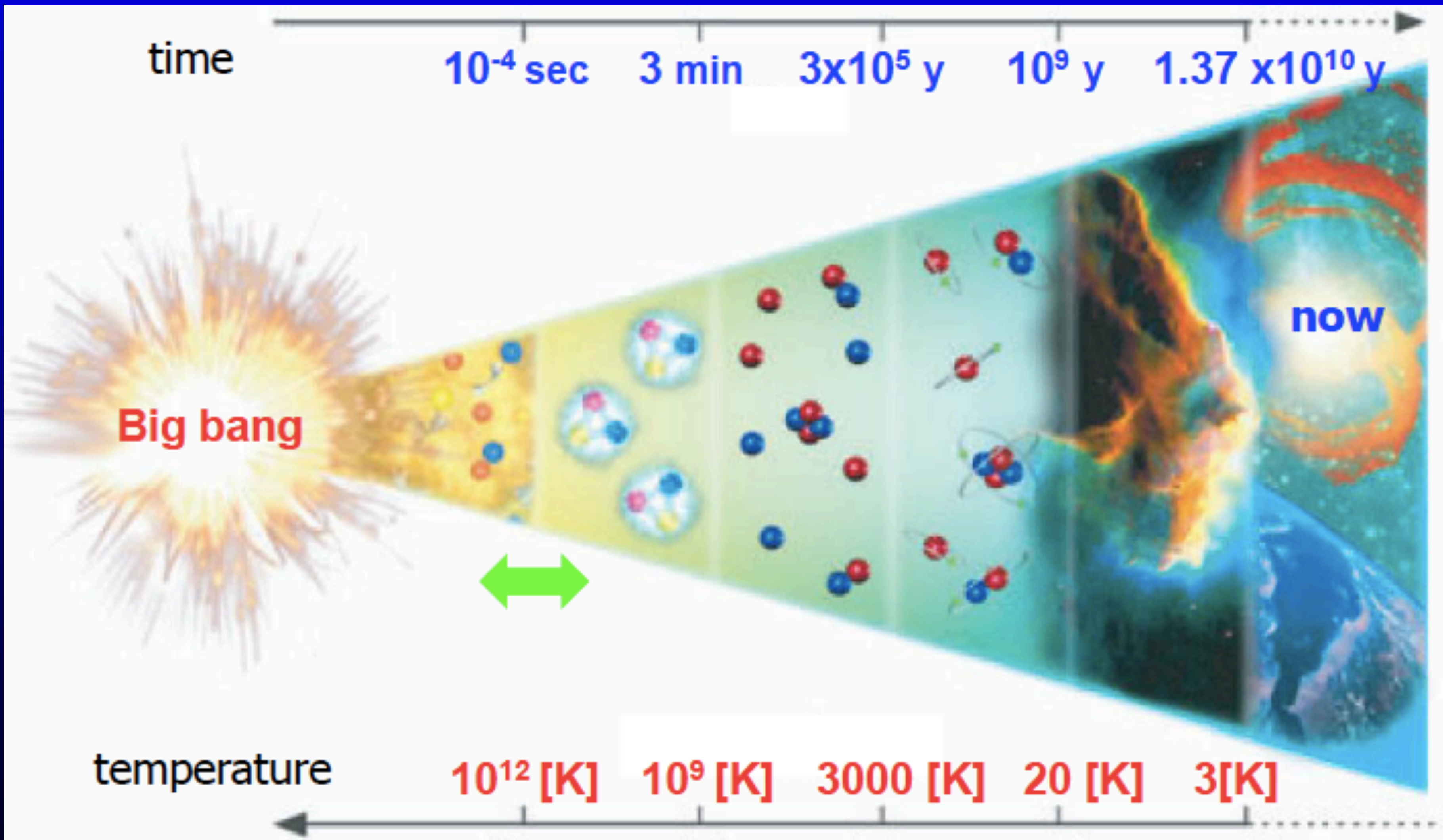


Temperatures from microkelvin to nanokelvin

Absolutely the coldest places in the universe

Even though 20 orders of magnitude difference in energies, see intriguing similarities among these two forms of matter

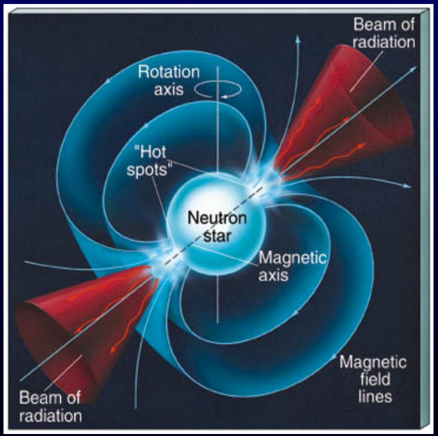
The early universe before one microsecond was made of quark matter

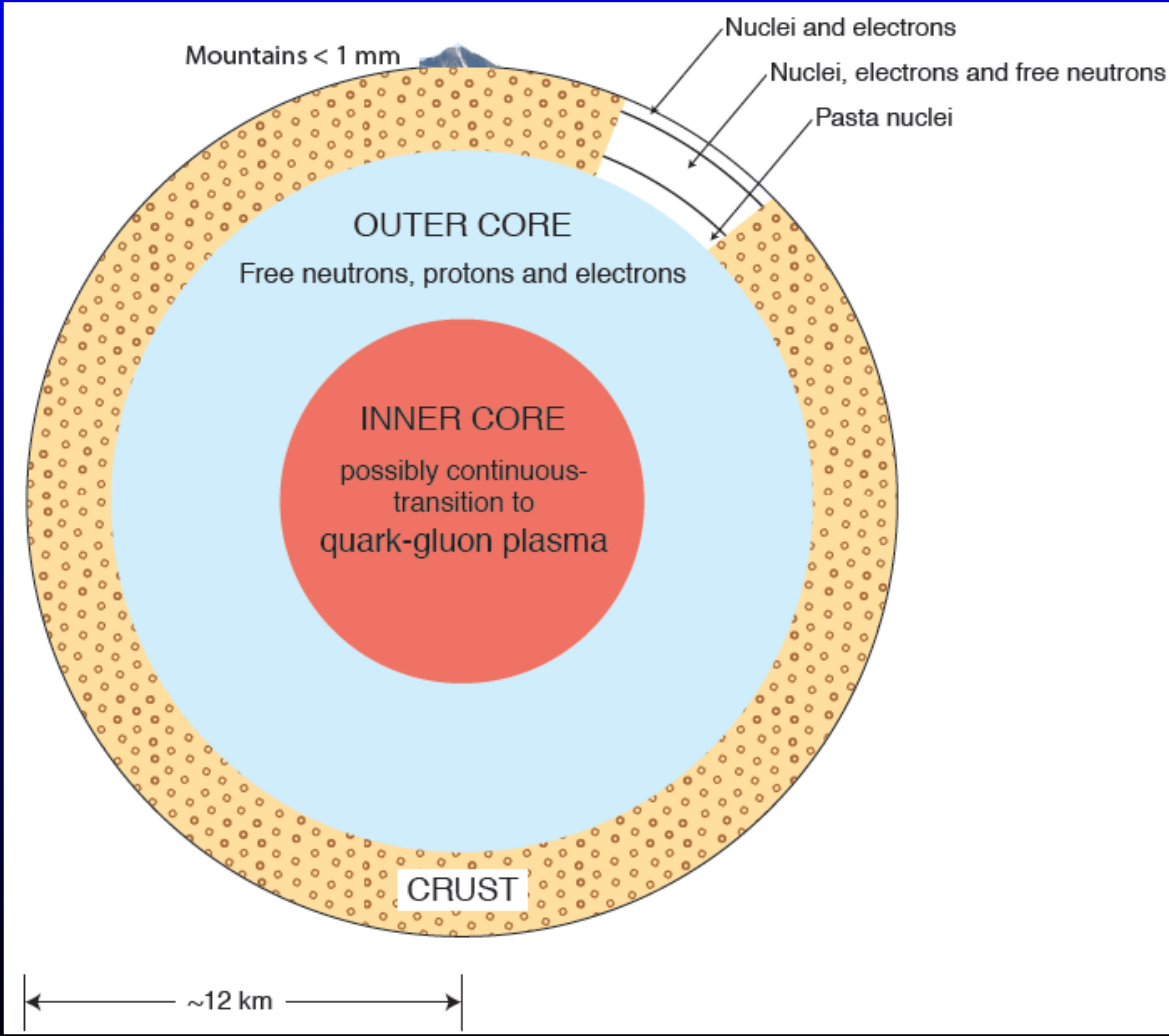


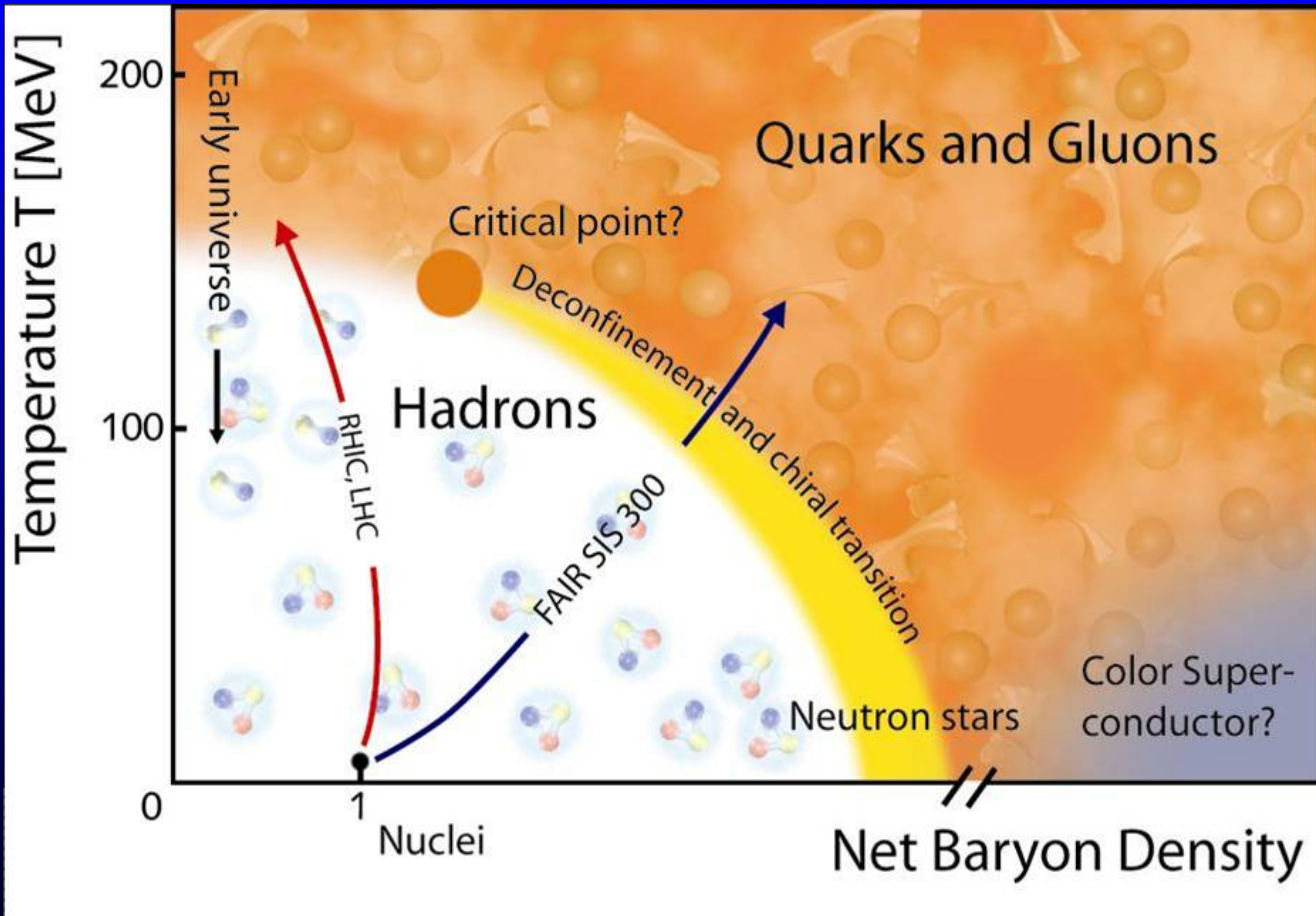
Neutron star interior

Mass ~ 1.4-2 M_{sun}
Radius ~ 10-12 km
Temperature
~ 10^6-10^9 K

Surface gravity
~10^{14} that of Earth
Surface binding
~ 1/10 mc^2



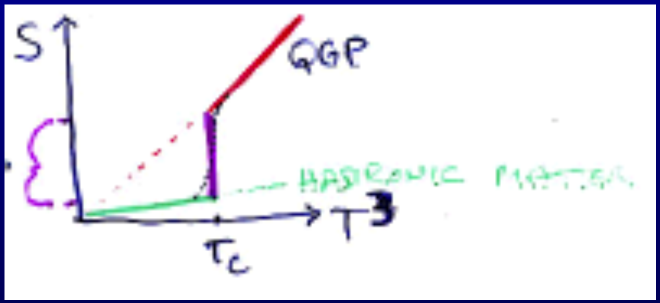



Temperature T [MeV]
200
100
0
1
Nuclei
Net Baryon Density
Early universe
RHIC, LHC
FAIR SIS 300
Hadrons
Critical point?
Quarks and Gluons
Deconfinement and chiral transition
Neutron stars
Color Super-
conductor?

Quark-gluon plasma state

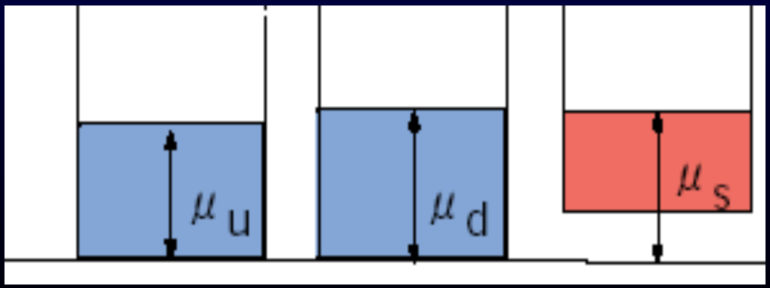
Degrees of freedom are deconfined quarks and gluons

Many more degrees of freedom than hadronic matter
(color, spin, particle-antiparticle, & flavor);
much larger entropy at given temperature.



<= Large latent heat
(or sharp rise at least)

At low temperatures form Fermi
seas of degenerate u,d, and s quarks:
(e.g., in neutron stars)



A few crucial heavy ion experimental observations :

Produce matter with energy densities ~ 5 GeV/fm^3

~ 10-30 X energy density of ordinary nuclei ~ 0.15 GeV/fm^3

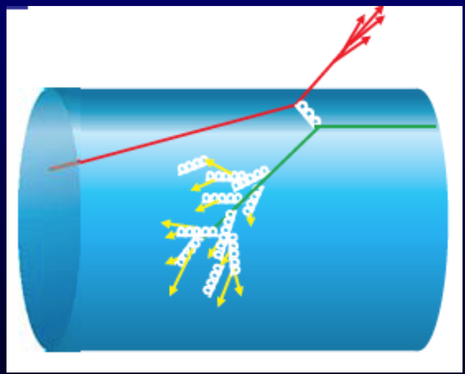
Certainly produce quark-gluon plasma.

Fast quarks traversing medium lose energy rapidly. “Opaque” medium

Very rapid build-up of pressure in collisions:

Large collective flow, fast thermalization,

large interaction cross sections.



off-axis jets

Hydrodynamics => small viscosity

Many body physics challenges

Solving QCD to construct:

Phase diagram for hot and dense quark matter

Equation of state for low temperature (neutron star) matter
- Pairing, chiral symmetry breaking
- Allow for 2 solar mass neutron stars
- Role of strangeness

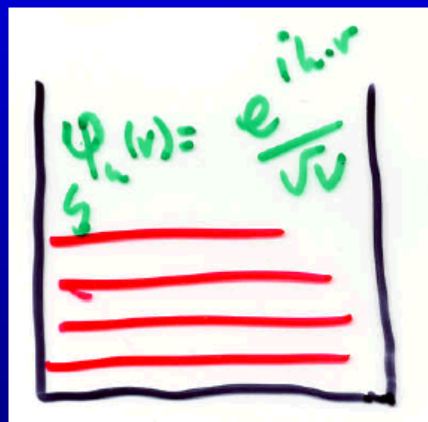
(Lattice gauge theory not yet well implemented for finite baryon density!!)

Dynamics

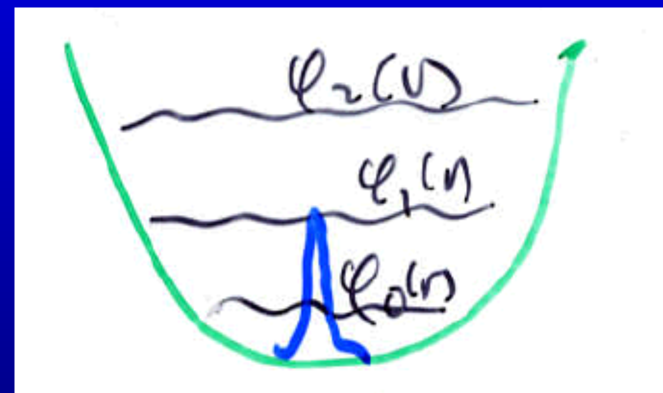
Non-equilibrium problems: Thermalization and transport

Initial conditions in heavy ion collisions

A very brief introduction to cold atoms: trapped bosons and fermions



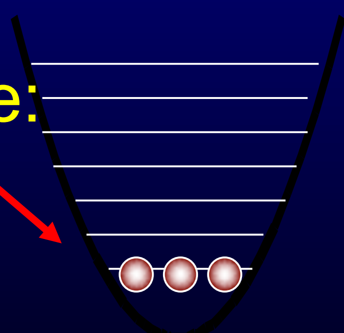
Box

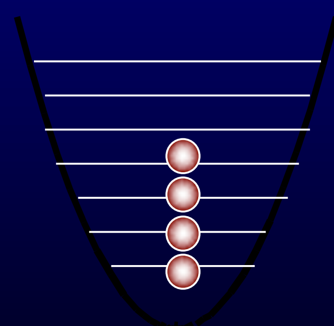


Potential well (trap)

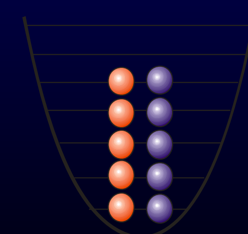
Statistics:

Bose condensate: macroscopic occupation of single mode (generally lowest)





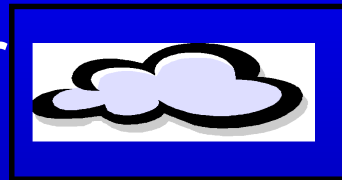
Degenerate Fermi gas



=> BCS pairing

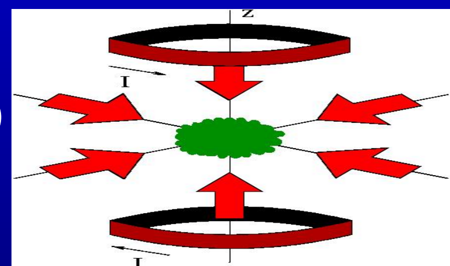
Trapped atomic experiments in a nutshell

Warm atomic vapor



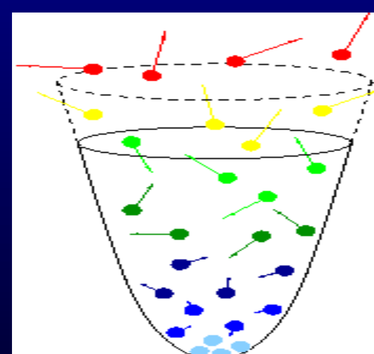
$T=300K$, $n \sim 3\times10^6/cm^3$

Magneto-optical trap



Laser cool to $T \sim 50\mu K$
$n \sim 10^{11}/cm^3$

Evaporatively cool in magnetic (or optical) trap

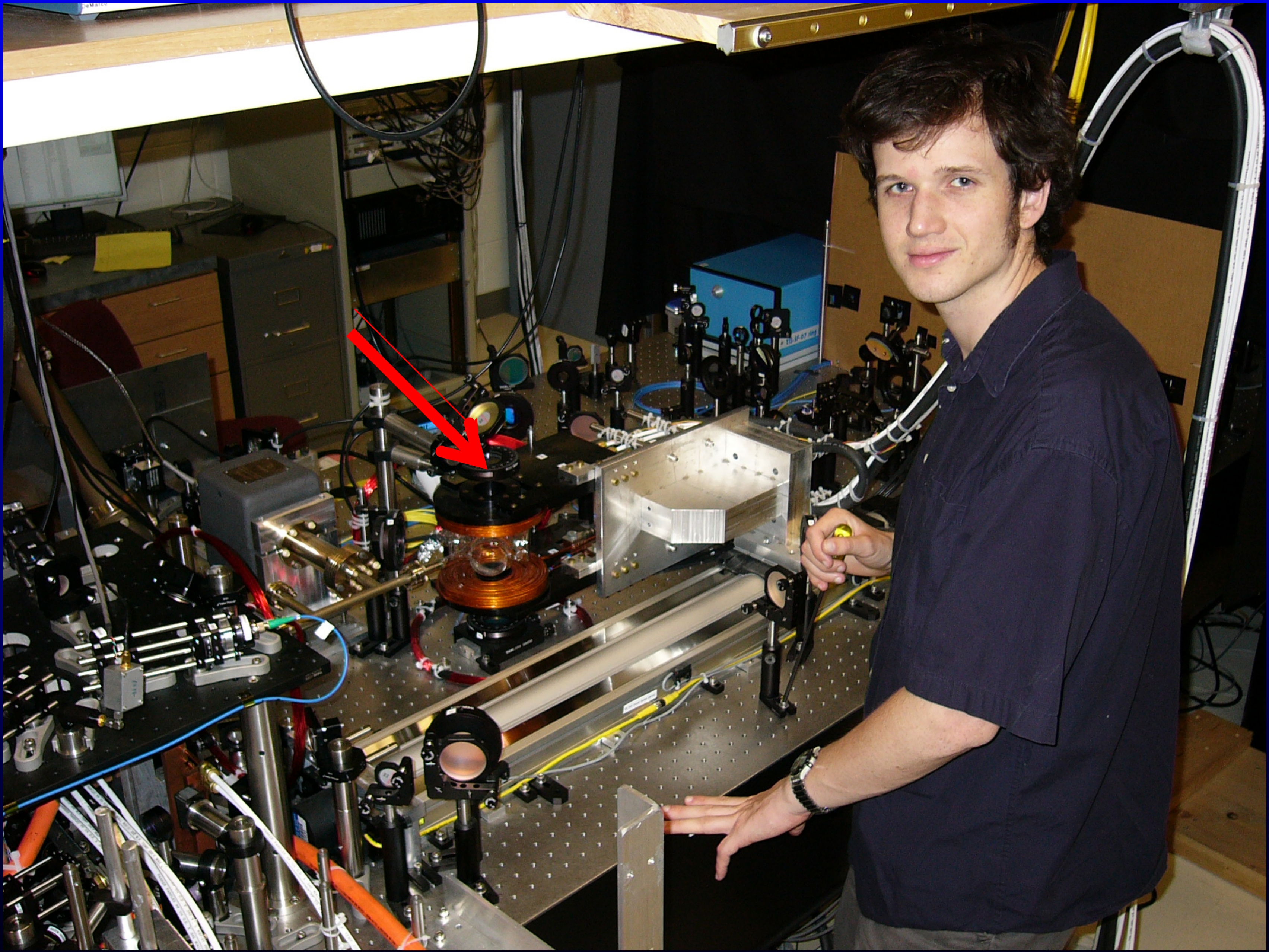


Bosons condense,
Fermions BCS-pair
$T_c \sim 1\text{-}10^3$ nK
$n \sim 10^{14-15}/cm^3$
$N \sim 10^5\text{-}10^8$

Experiment, and then measure :

The door to Brian DeMarco’s lab in Illinois Physics Department

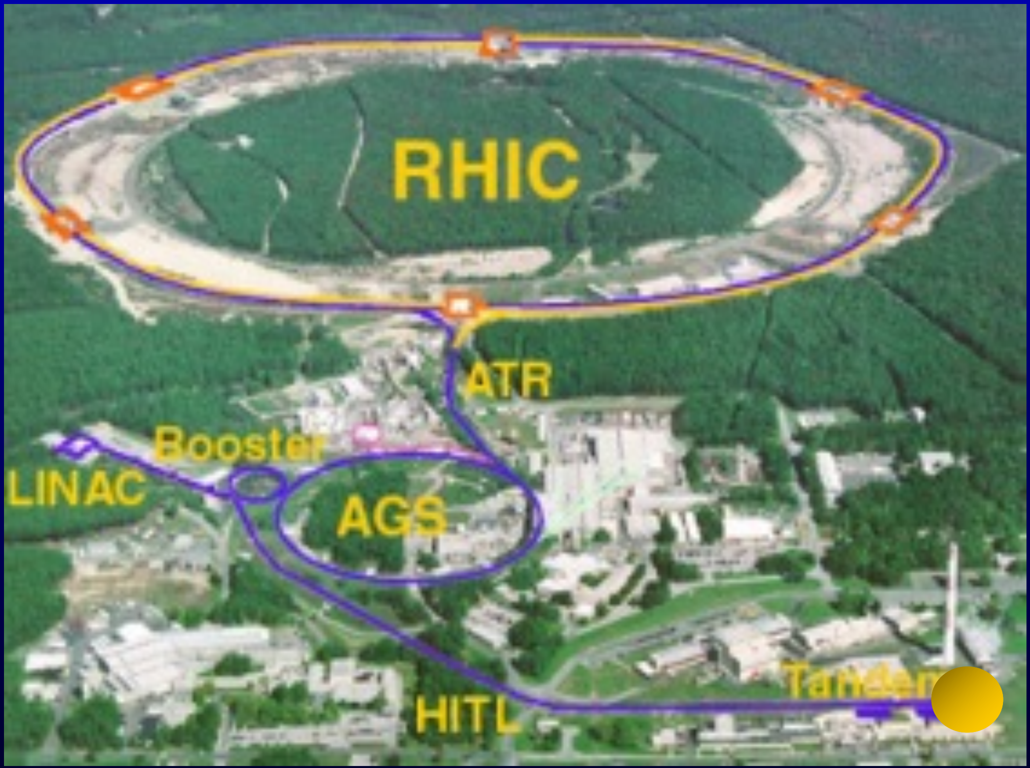
Trapped atom experiments done on table tops

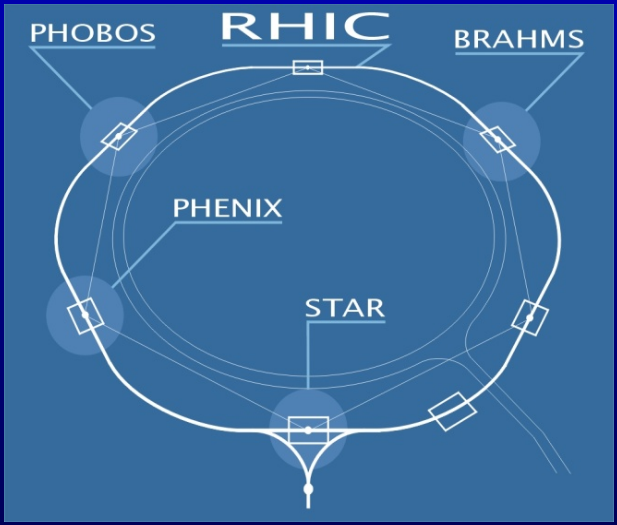


Former grad student David McKay in DeMarco's lab in Urbana

Creating high energy density matter in the lab

Relativistic Heavy Ion Collider (Brookhaven) since 2000	Beams 100 GeV/A
Large Hadron Collider (CERN) since 2010	now 2760 GeV/A
HADES at GSI	~1.25 GeV/A
FAIR (GSI) ca. 2018	to 45 GeV/A





T. Hirano

Au(197×100GeV)+Au(197×100GeV)

Dense nuclear matter and cold atom systems

Both heavy ion and atomic systems are small clouds with many degrees of freedom $\sim 10^4 - 10^7$

Strongly interacting systems (QGP always, atoms by choice)

QCD phase diagram:
hadron ⇔ quark-gluon plasma and BEC ⇔ BCS crossover

Viscosity: heavy-ion elliptic flow ⇔Fermi gases near unitarity

Cold atom analogs of QCD and nuclear systems

Artificial magnetic fields

Ultracold ionized atomic plasma physics: study strongly interacting plasma dynamics in lab

Superfluidity and pairing in unbalanced systems:
trapped fermions ⇔ color superconductivity (neutron stars)

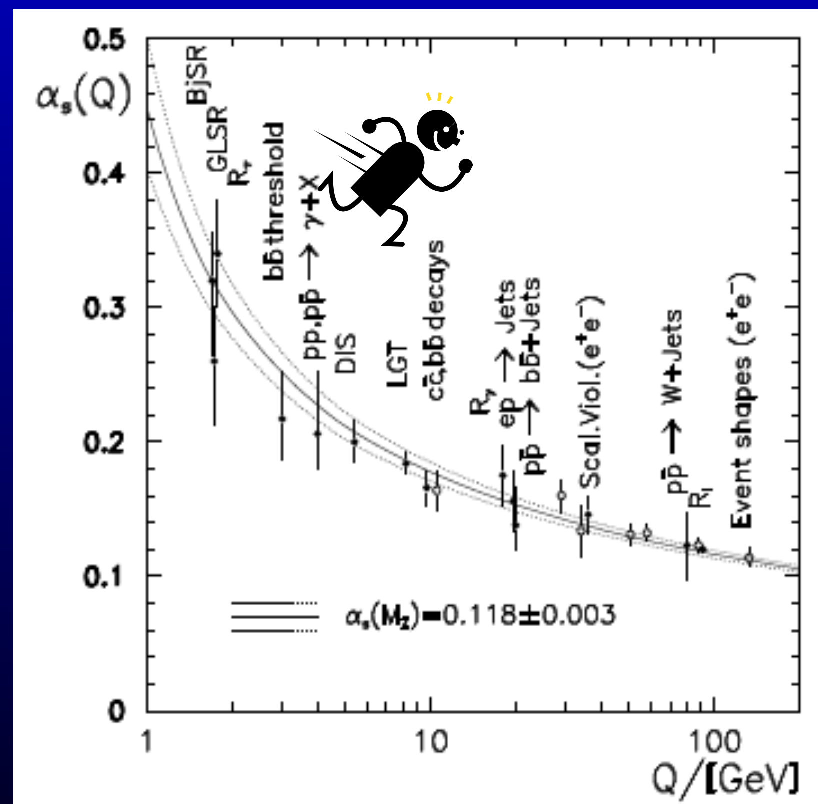
Strong interactions in qgp

In quark-gluon plasma,

$$\alpha_s(p) = \frac{g_s^2}{4\pi} = \frac{6\pi}{(33 - 2N_f)\ln(p/\Lambda)}$$

$\Lambda \sim 150$ MeV

Even at Grand Unified (GUT) scale, 10^{15}GeV, $g_s \sim 1/2$
(cf. electrodynamics:
$e^2/4\pi = 1/137 \Rightarrow e \sim 1/3$)



QGP is always strongly interacting

Running coupling constant

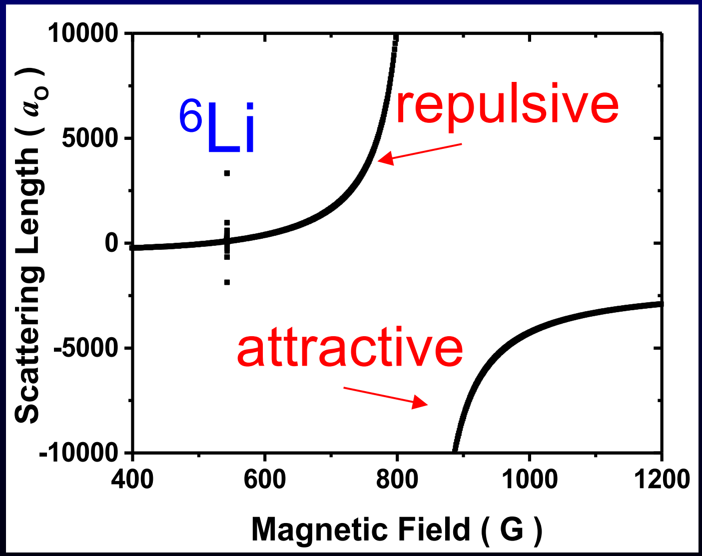
Strong interactions in cold atoms

In cold atoms, effective atom-atom interaction is short range and s-wave:

$$V(r-r') = [4\pi\hbar^2 a/m]\,\delta(r-r')$$

a = s-wave atom-atom scattering length.
Cross section: $\sigma=4\pi a^2$

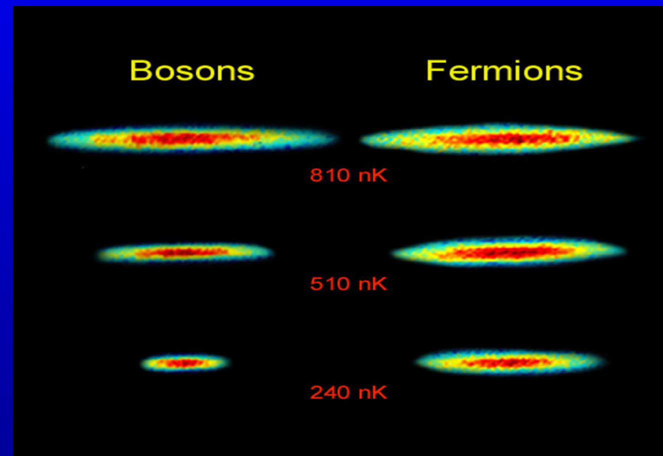
Go from weakly repulsive to strongly repulsive to strongly attractive to weakly attractive by dialing external magnetic field through Feshbach resonance



Resonance at B= 830 G

Degenerate ultracold atomic Fermi gases

Produce trapped degenerate Fermi gases: ^{6}Li, ^{40}K



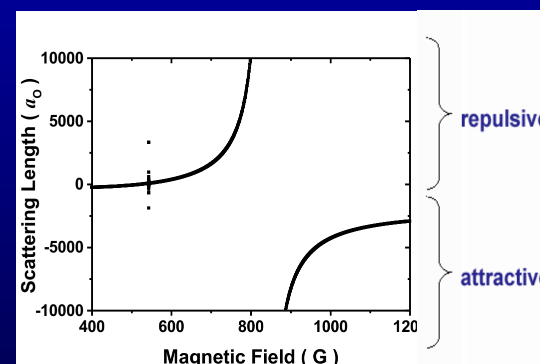
^{7}Li vs. ^{6}Li

810 nK

510nK

240nK

Increase attractive interaction with Feshbach resonance



At resonance have "unitary regime,"
force range << interparticle spacing << scattering length,
only relevant length scale is the interparticle spacing.

At temperatures ~ 0.2 of the degeneracy temperature T_f, create BCS paired superfluids.

Both systems scale-free in strongly coupled regime

$F_{qgp} \sim \text{const } n_{exc}^{4/3}$ $\qquad$ $E_{\text{cold atoms}} \sim \text{const } n^{2/3}/m$

In cold atoms near resonance only length-scale is density.
No microscopic parameters enter equation of state:

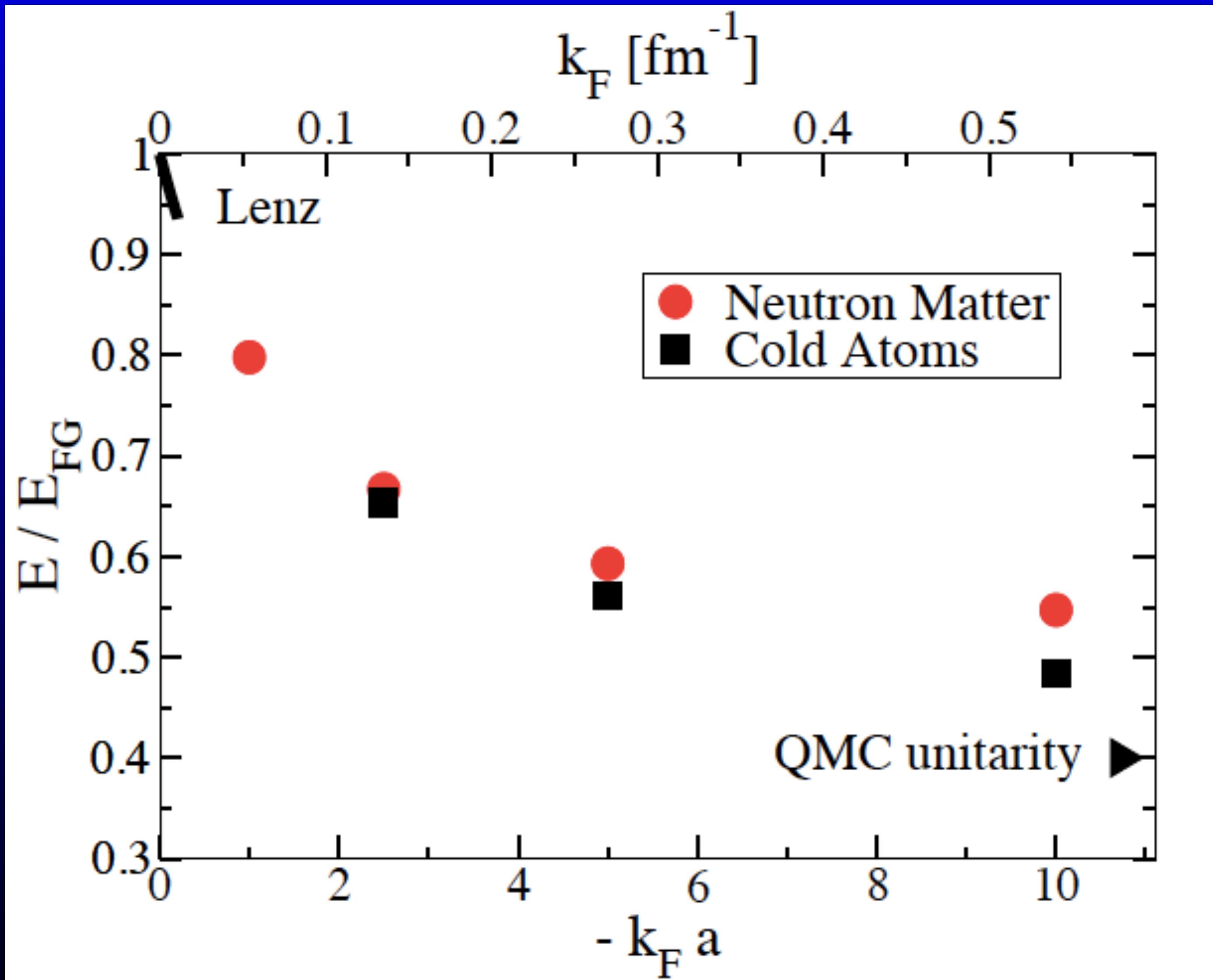
$$\frac{\mathbf{E}}{\mathbf{N}} = \frac{\mathbf{3}}{\mathbf{5}}\mathbf{E_F}(\mathbf{1}+\beta)$$

β is a universal parameter. No systematic expansion

Theory: β = -0.60 *Green's Function Monte Carlo -- Gezerlis & Carlson (2008)*

Experiment: -0.61 *Duke (2008)*

Remarkably similar behavior of ultracold fermionic atoms and low density neutron matter (a_{nn}= -18.5 fm)

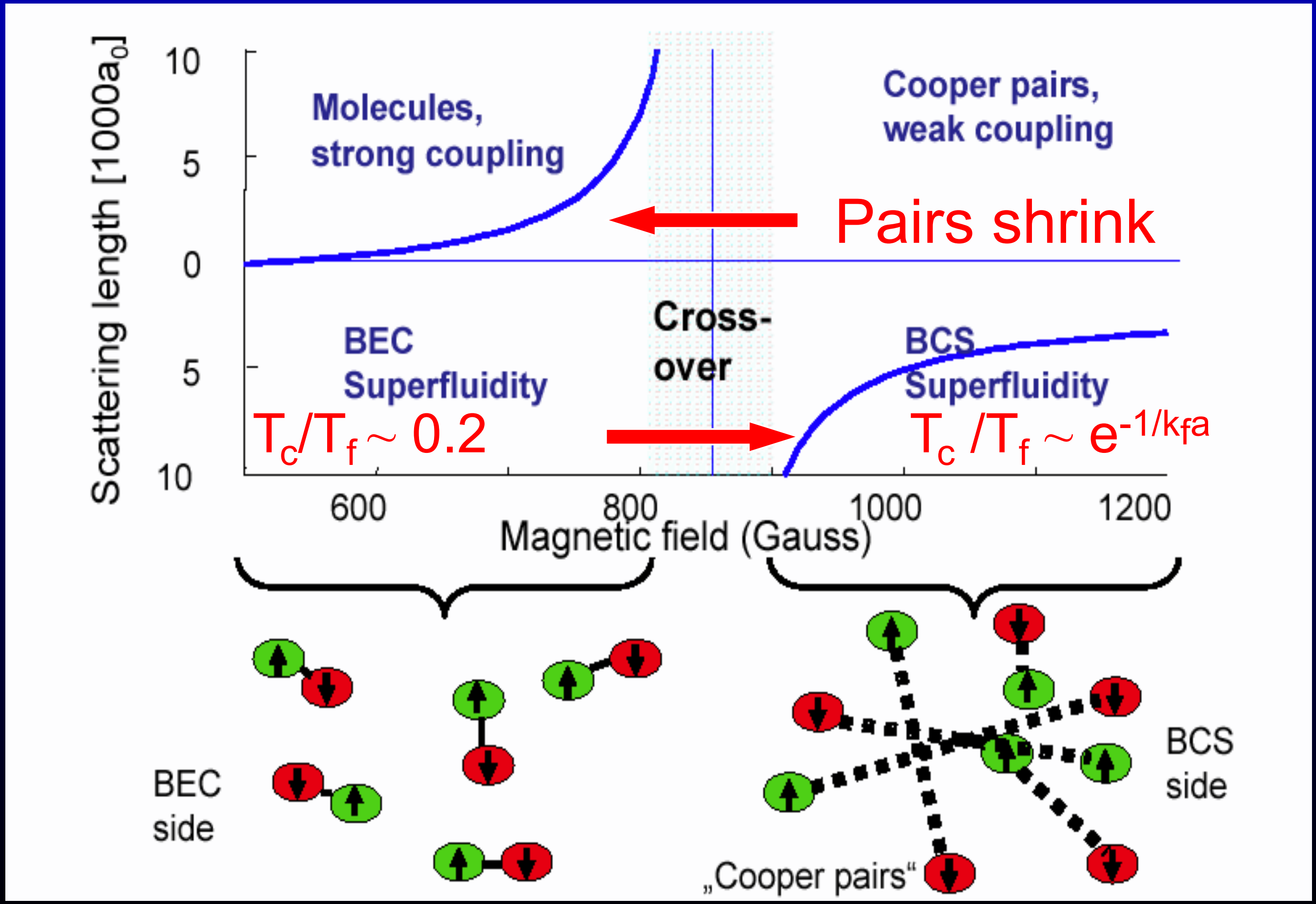


A. Gezerlis and J. Carlson, Phys. Rev. C 77, 032801(R) (2008)

BEC-BCS crossover in Fermi systems

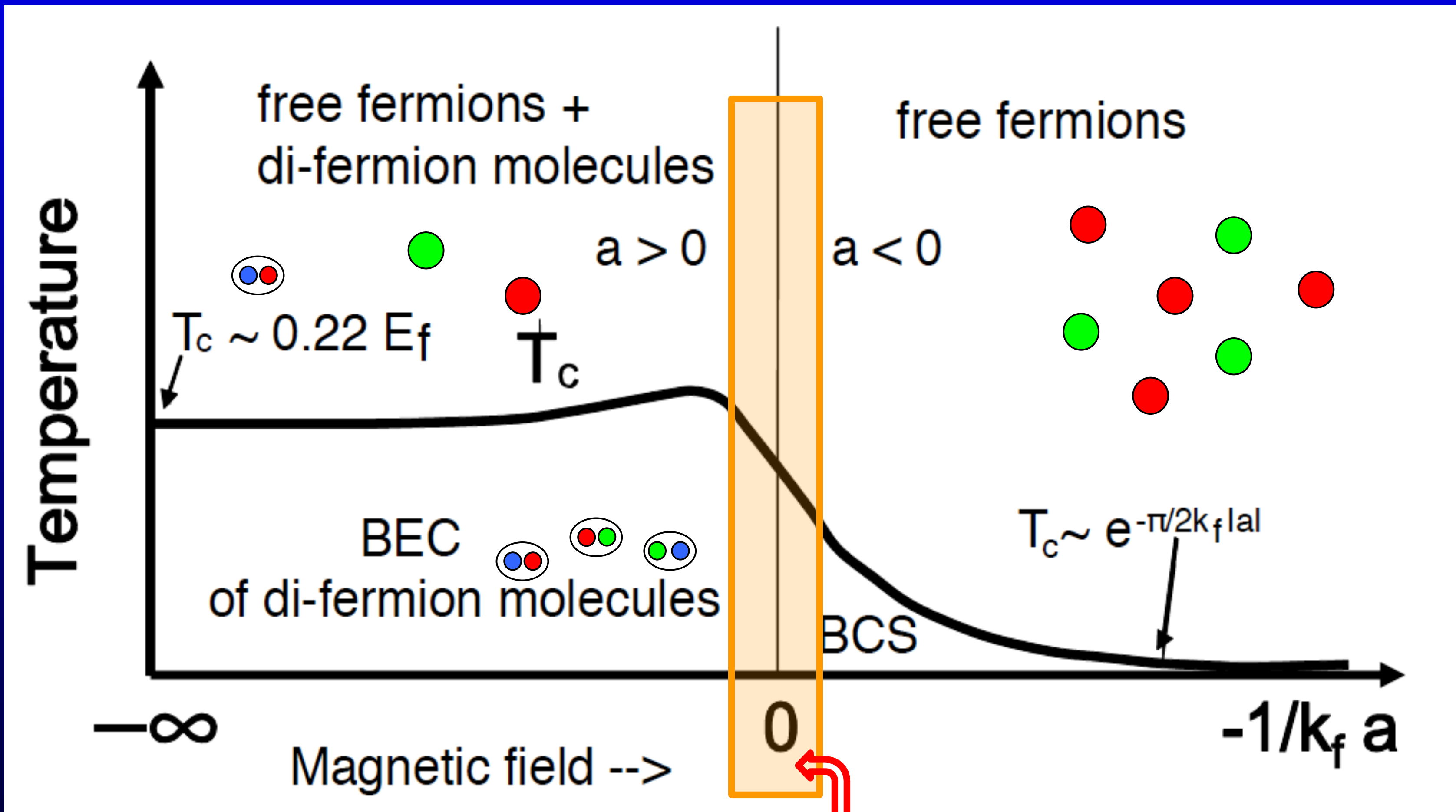
Continuously transform from molecules to Cooper pairs:

D.M. Eagles (1969)
A.J. Leggett, J. Phys. (Paris) C7, 19 (1980)
P. Nozières and S. Schmitt-Rink, J. Low Temp Phys. 59, 195 (1985)



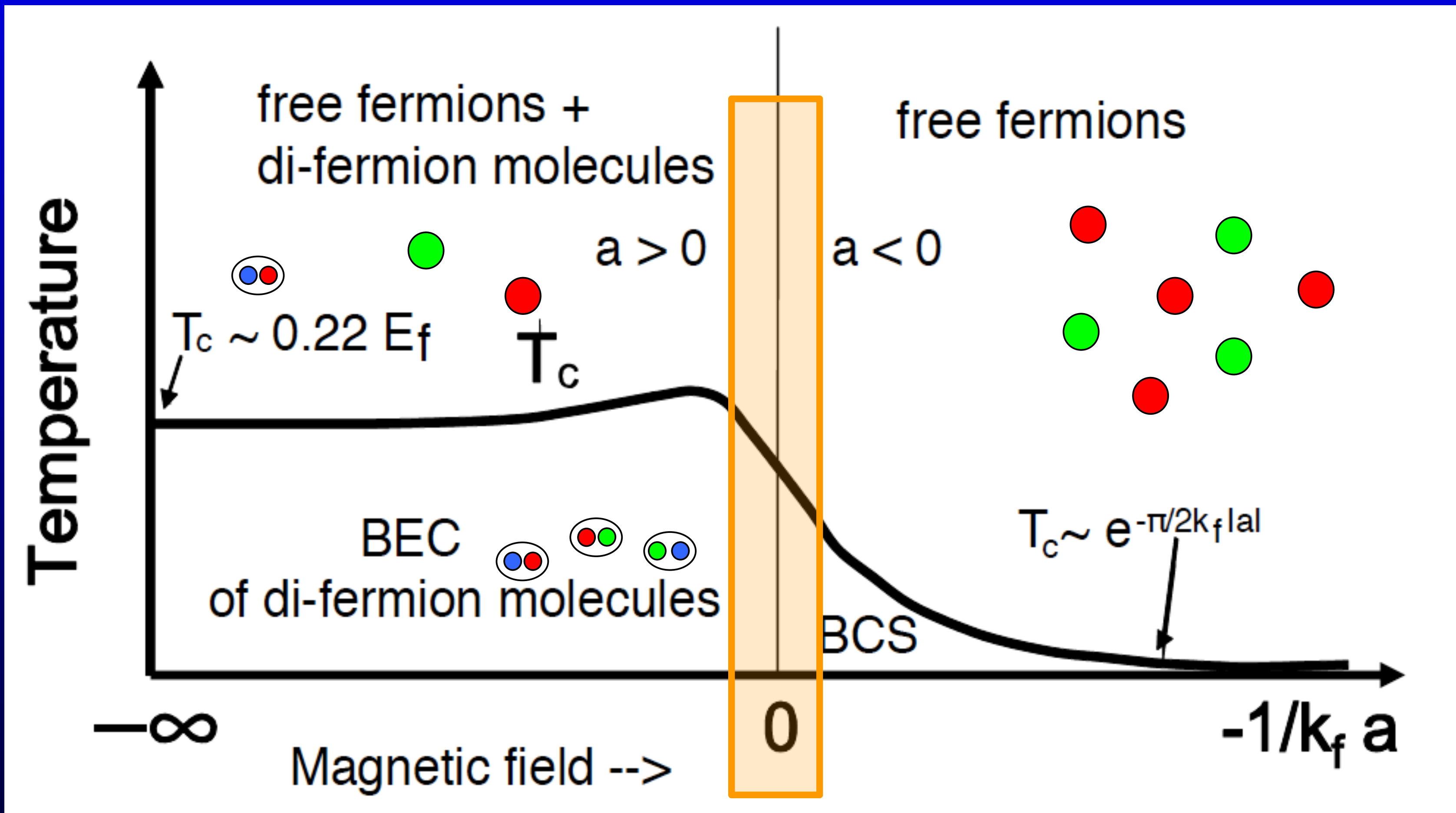
^{6}Li

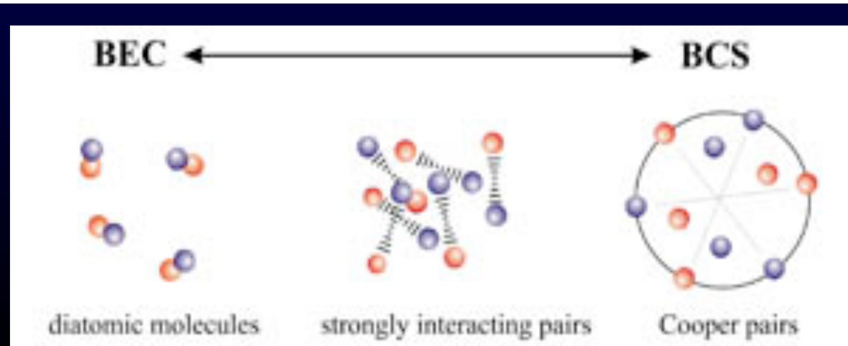
Phase diagram of ultracold atomic fermion gases: in T and strength of the particle interactions



Unitary regime (Feshbach resonance) – BEC-BCS crossover. No phase transition through crossover

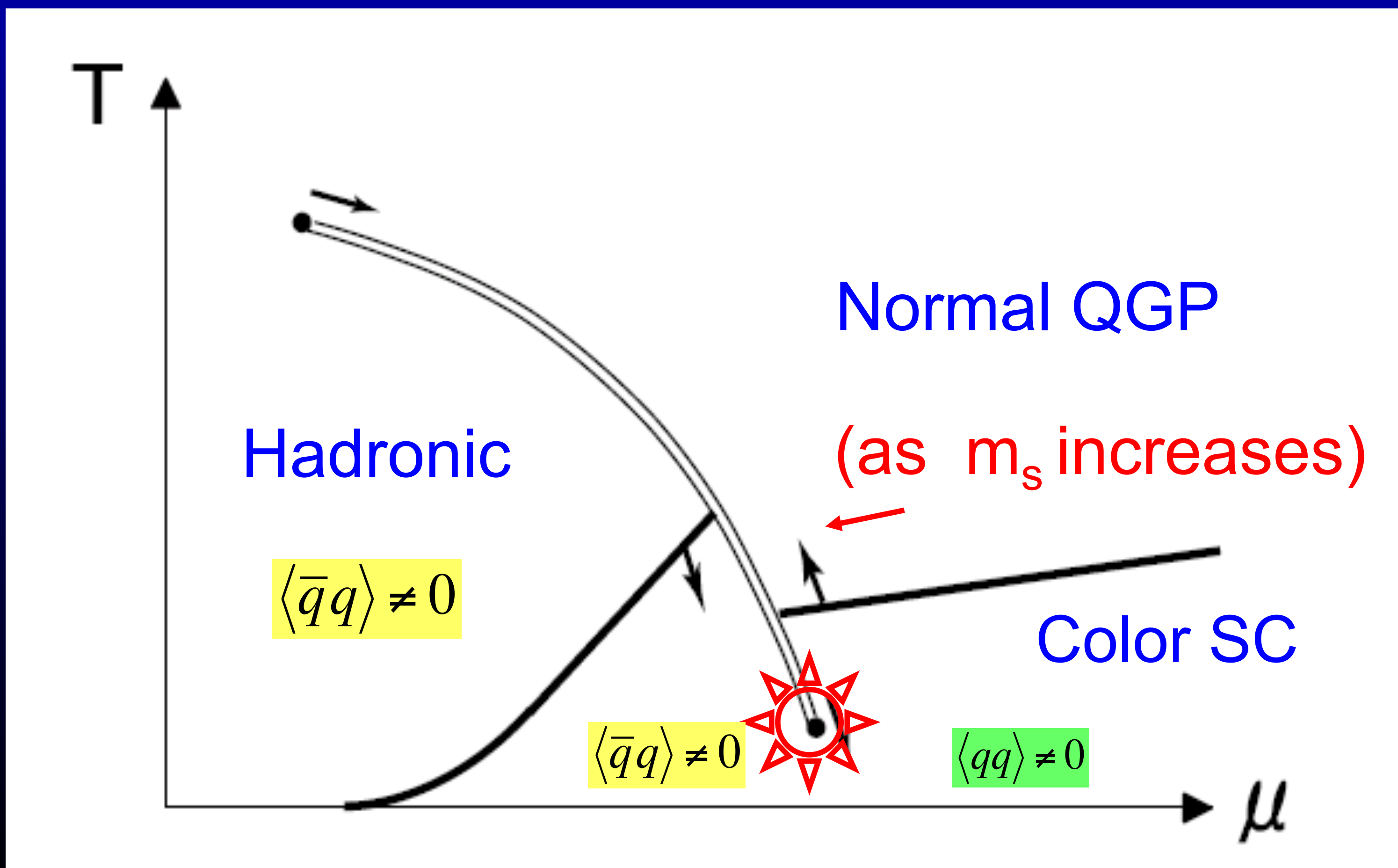
Phase diagram of ultracold atomic fermion gases: in T and strength of the particle interactions

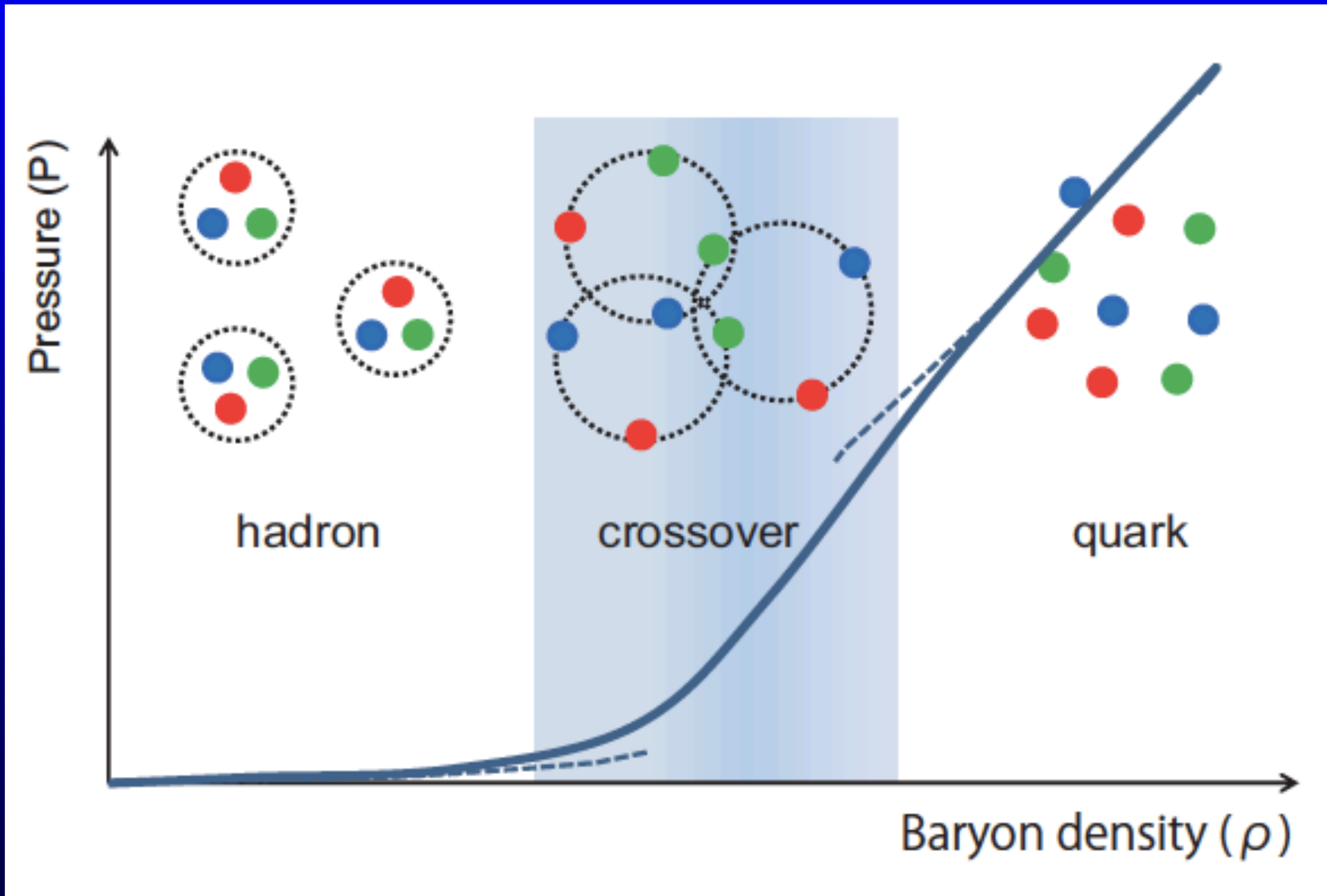




New critical point in dense matter phase diagram:
induced by chiral condensate – diquark pairing coupling via axial anomaly

Hatsuda, Tachibana, Yamamoto & GB, PRL 97, 122001 (2006)
Yamamoto, Hatsuda, Tachibana & GB, PRD76, 074001 (2007)
GB, Hatsuda, Tachibana, & Yamamoto. J. Phys. G: Nucl. Part. 35 (2008) 10402
Abuki, GB, Hatsuda, & Yamamoto,Phys. Rev. D81, 125010 (2010)





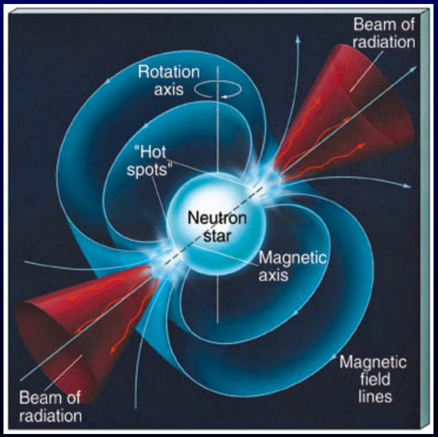
"Continuous" evolution from nuclear to quark matter

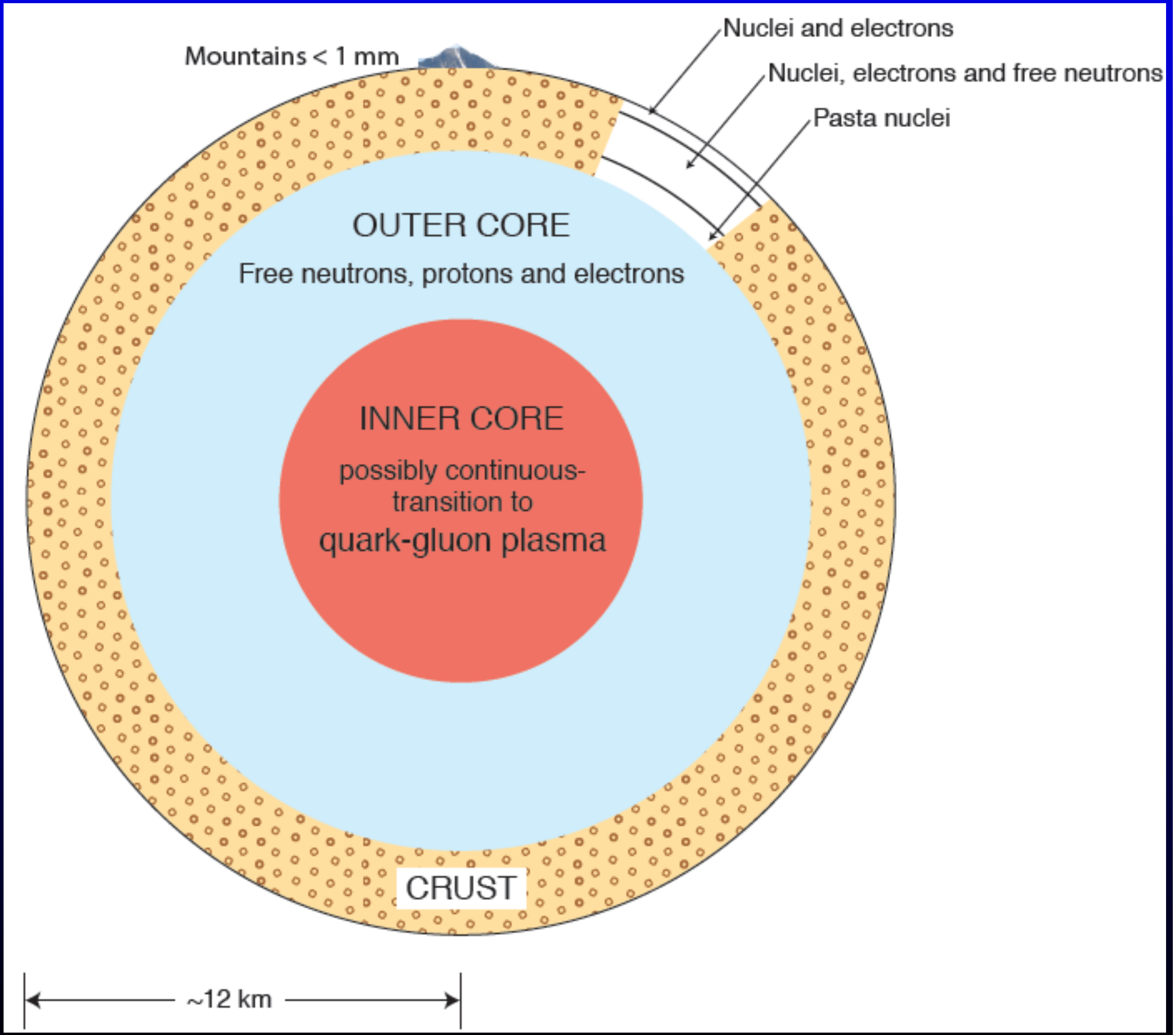
K. Masuda, T. Hatsuda, & T. Takatsuka, Ap. J.764, 12 (2013)

Neutron stars

Mass ~ 1.4-2 M_{sun}
Radius ~ 10-12 km
Temperature
~ 10^6-10^9 K

Surface gravity
~10^{14} that of Earth
Surface binding
~ 1/10 mc^2





Neutron star masses

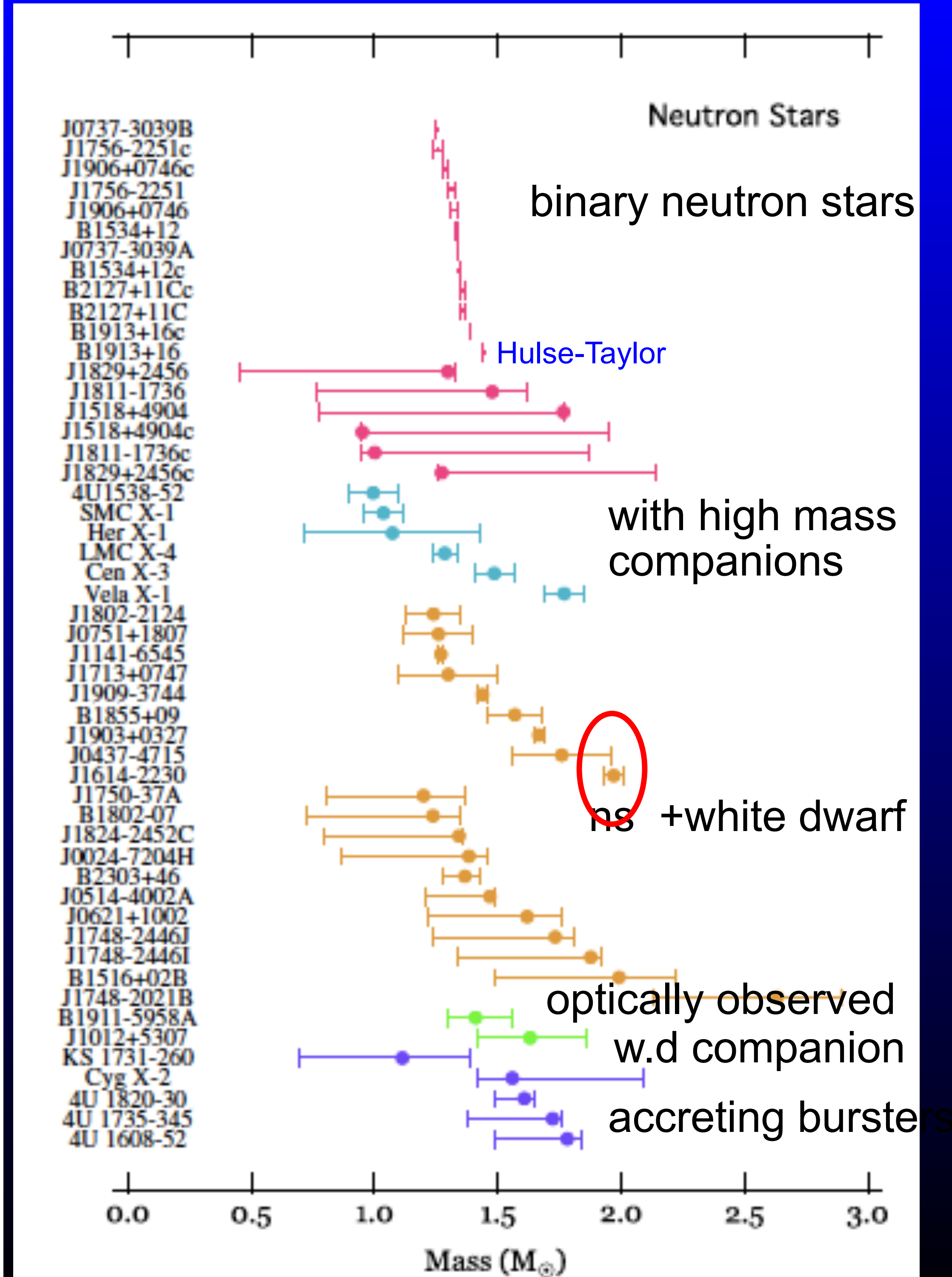
F. Özel et al, Ap.J.757, 1 (2012)

PSR J1614-2230 :

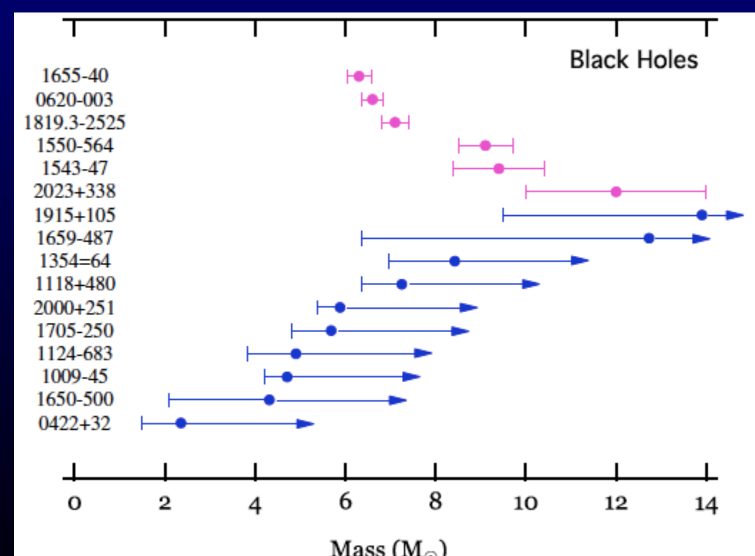
$M_{nstar} = 1.97 \pm 0.04 M_{\odot}$

PSR J0348+0432:

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



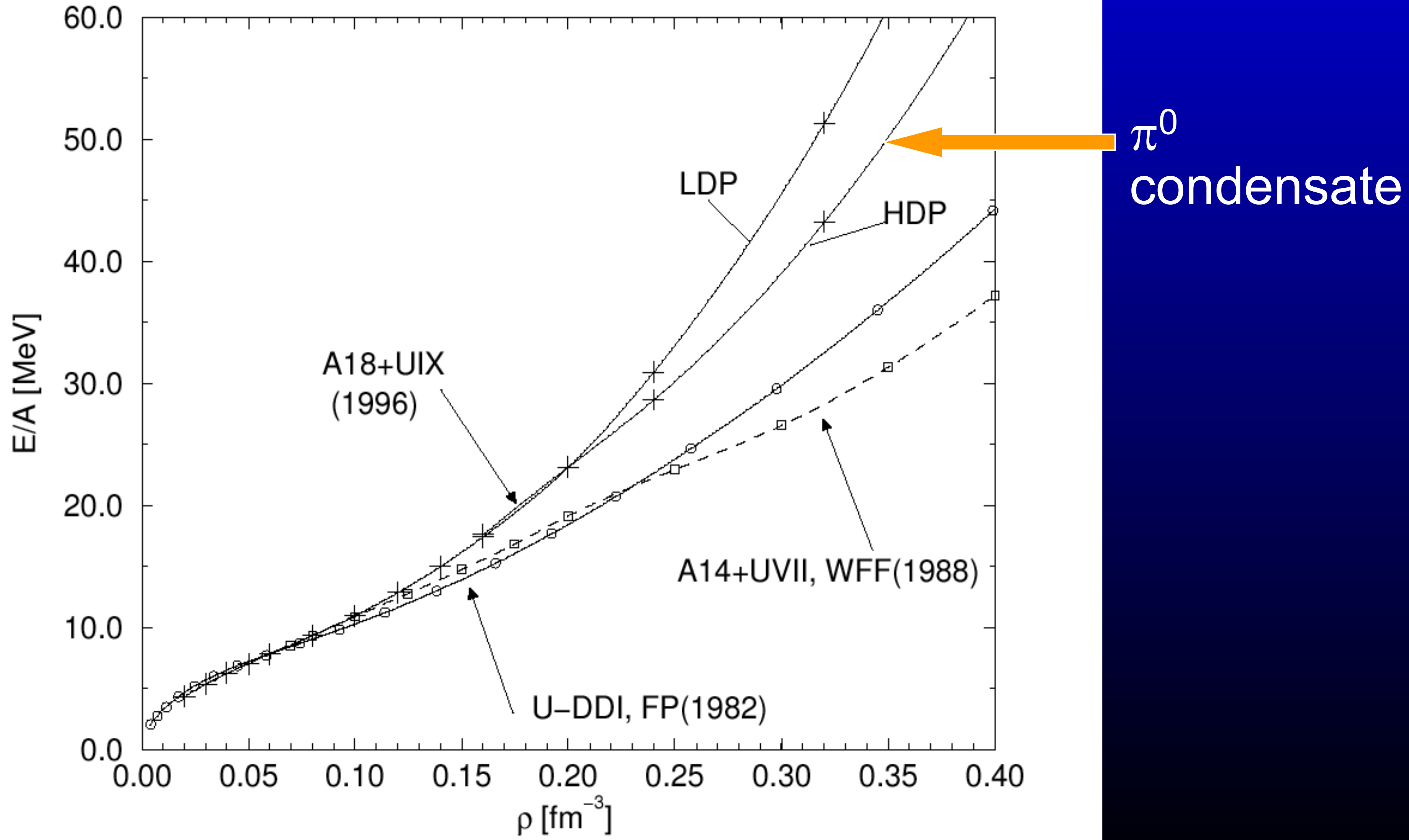
Galactic black hole masses



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



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

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

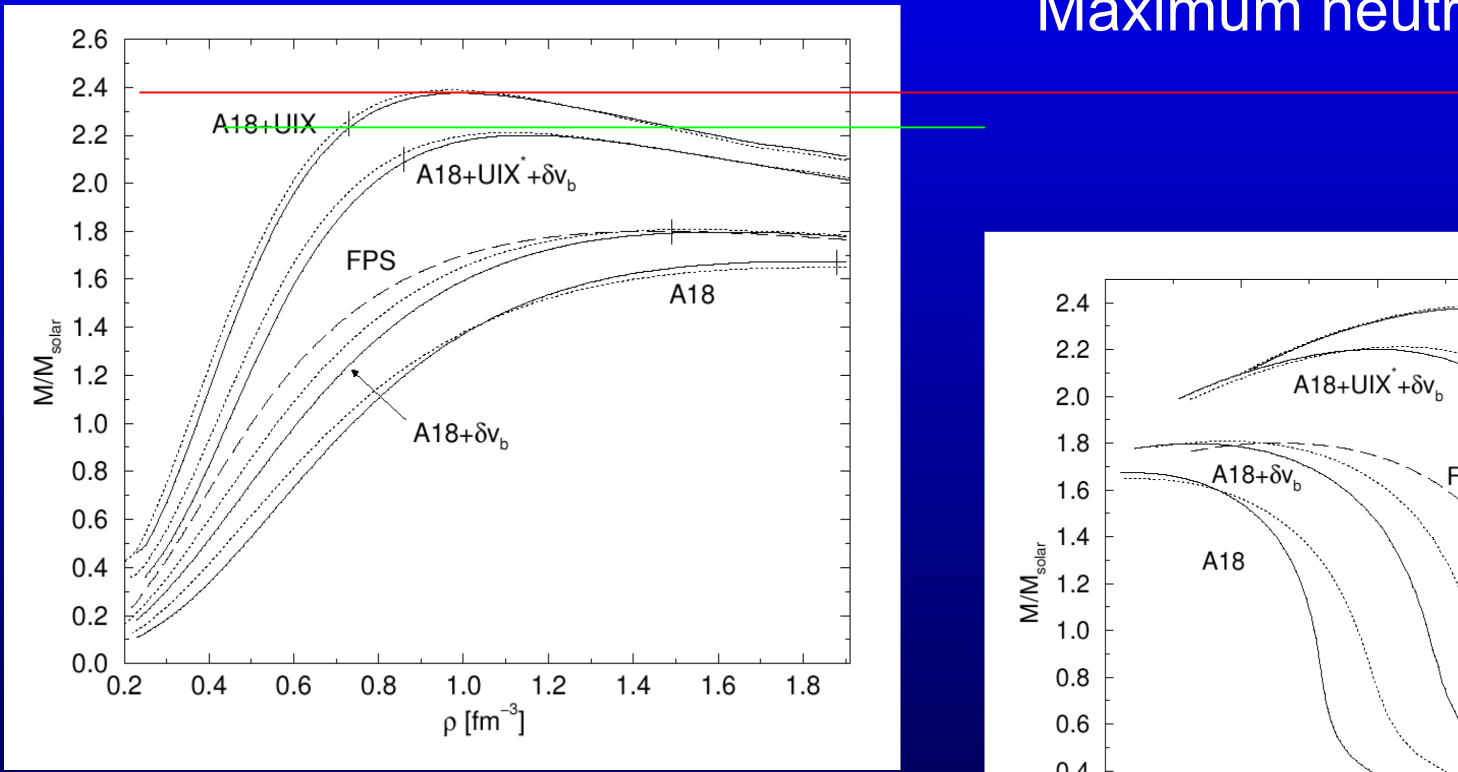
= mass within radius r

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

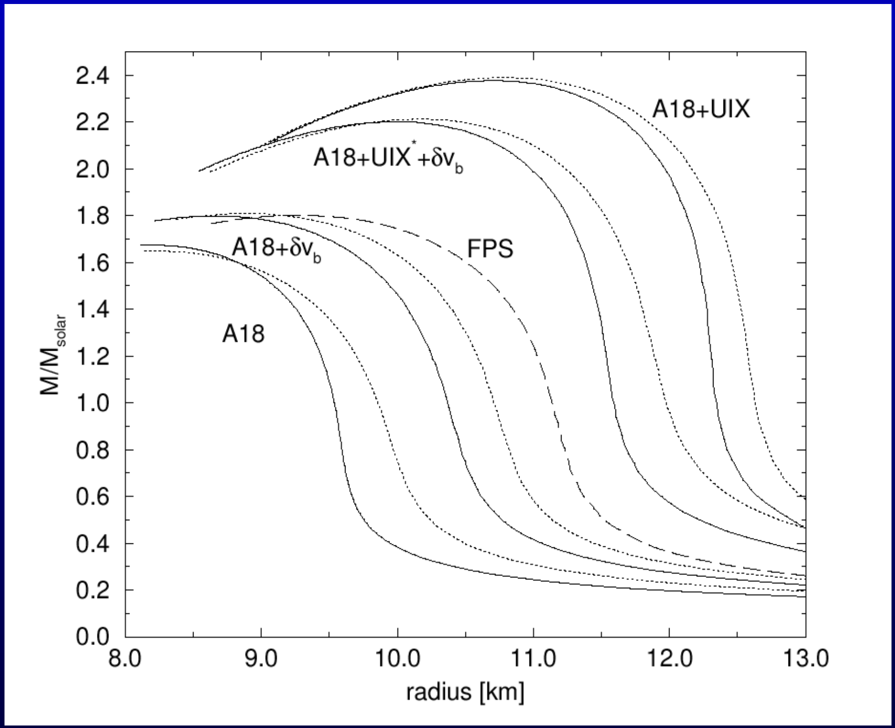
$$M = \int_0^R \rho(r)4\pi r^2 dr$$

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

Maximum neutron star mass



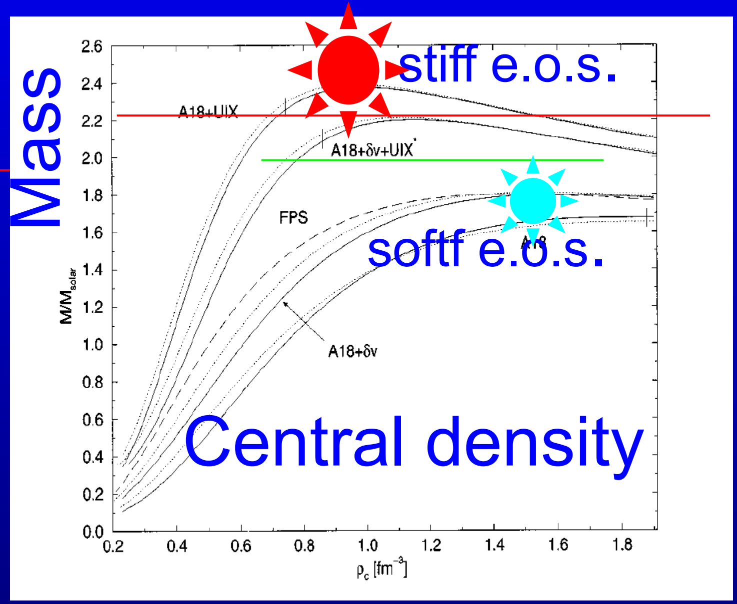
Mass vs. central density



Mass vs. radius

Akmal, Pandharipande and Ravenhall, 1998

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?

Neutron stars: cold quark matter

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

Accurate for $n \sim n_0$. But for $n >> n_0$:

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

-Force range $\sim 1/2m_\pi$ => relative importance of 3 (and higher) body forces $\sim n/(2m_\pi)^3 \sim 0.4n_{\text{fm}^{-3}}$.

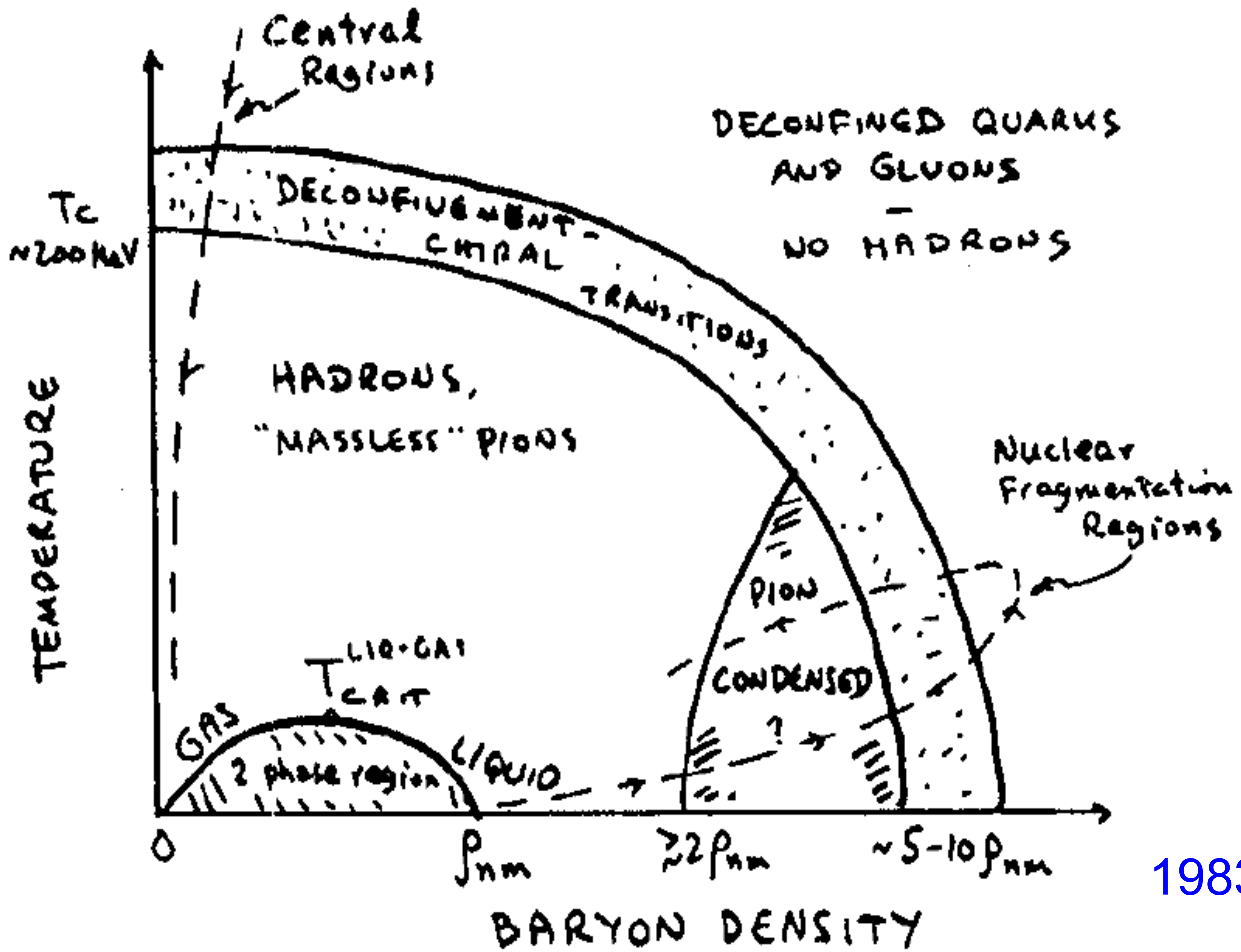
-No well defined expansion in terms of 2,3,4,...body forces.

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

How can quark matter give stiff eq. of state, to explain large masses?

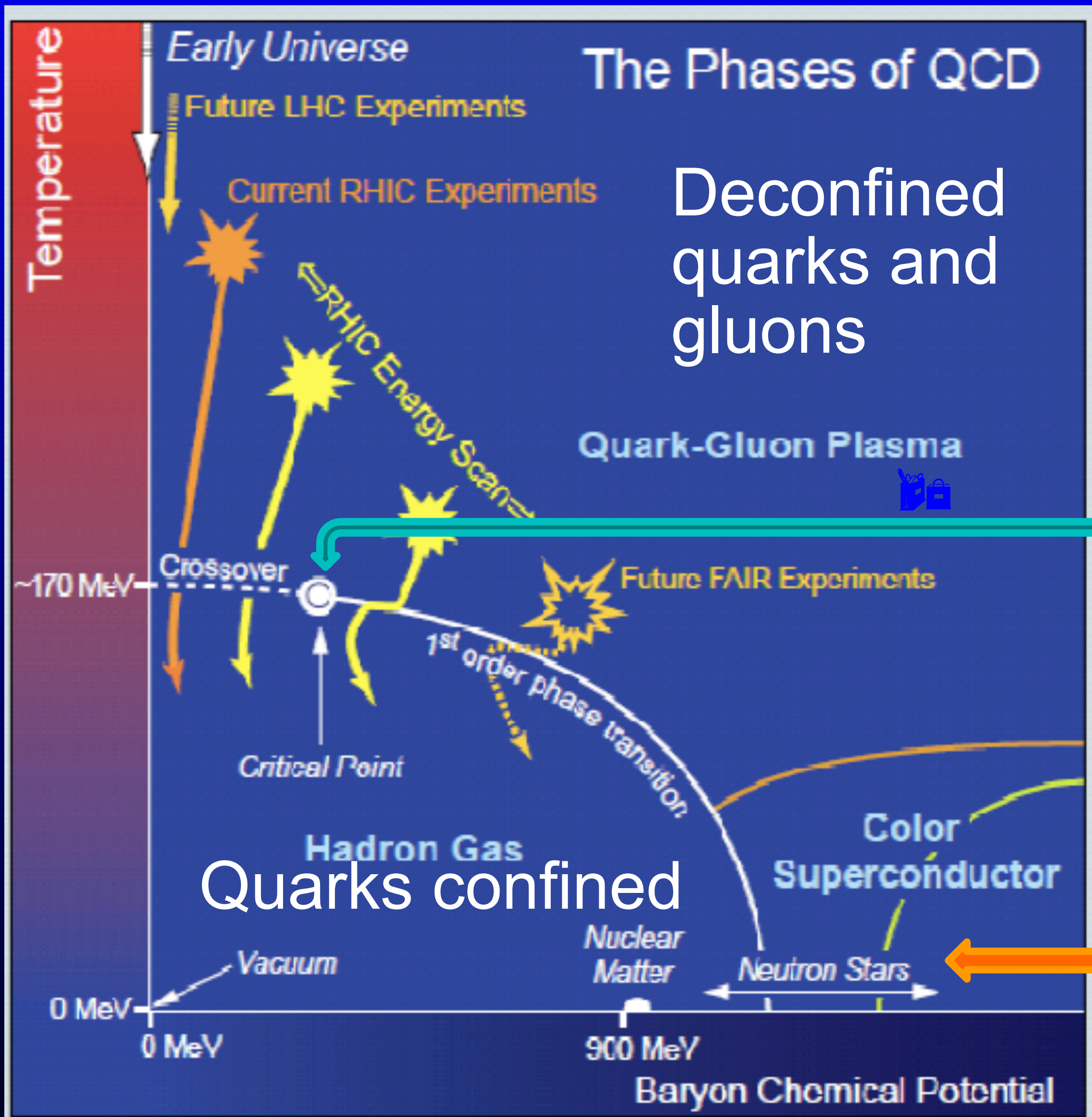
Construct neutron star from equation of state (pressure vs. baryon chemical potential. We do not know much about the transition region from hadronic to quark degrees of freedom – between about 2 to 8 times nuclear matter saturation density n_0.

PHASE DIAGRAM OF NUCLEAR MATTER



1983

Modern phase diagram



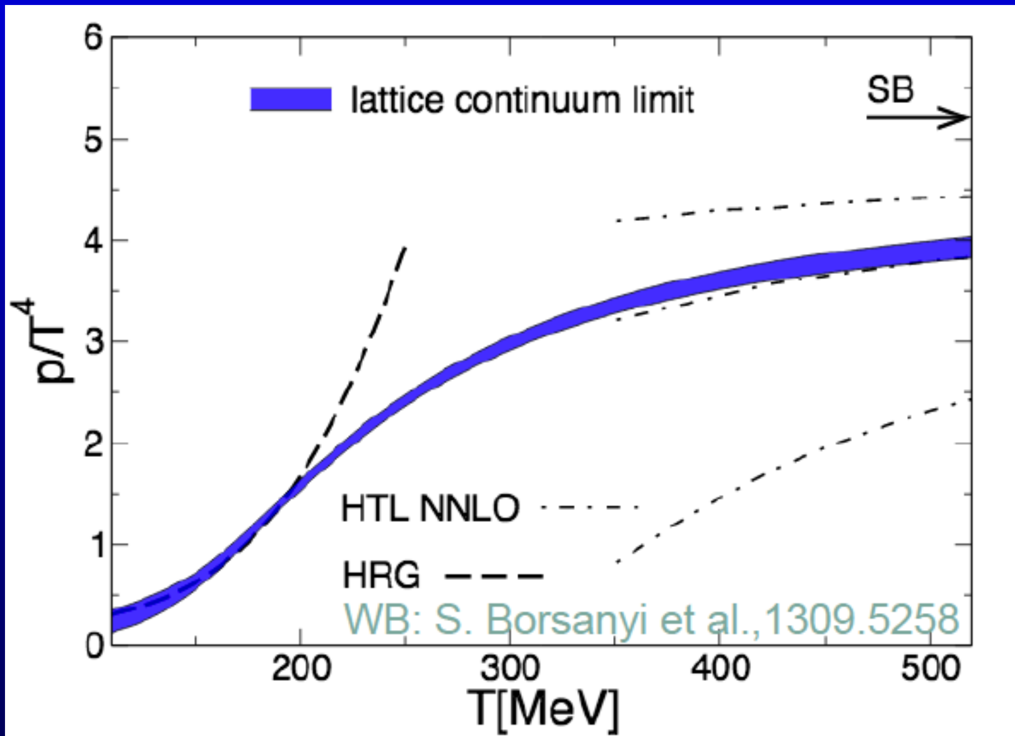
Asakawa-Yazaki critical point (1989)

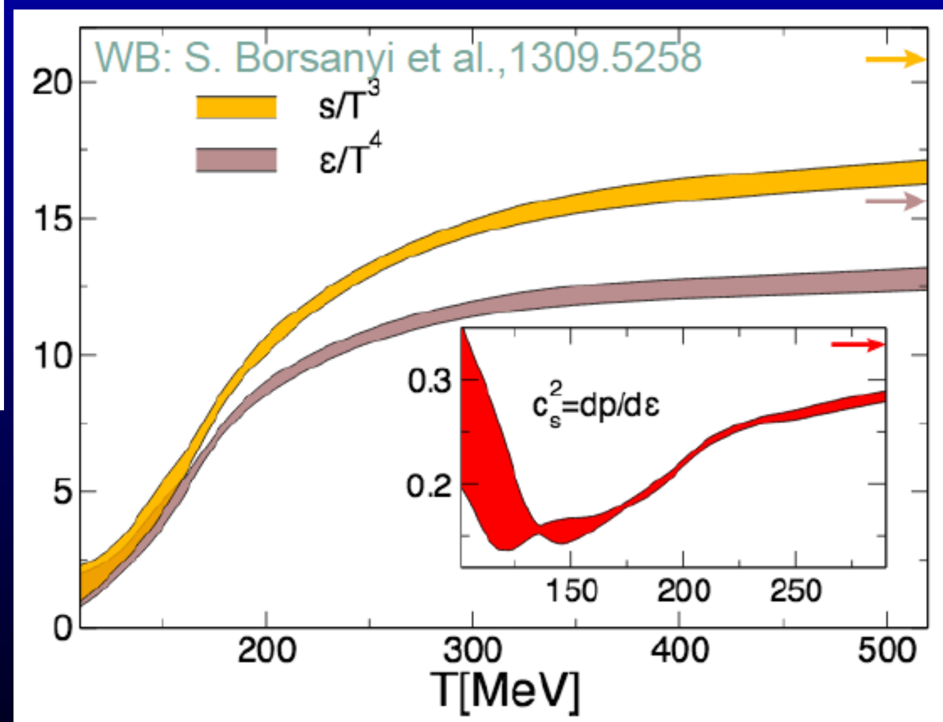
Search in RHIC & SPS energy scans.

States of color superconductivity – diquark BCS pairing

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

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

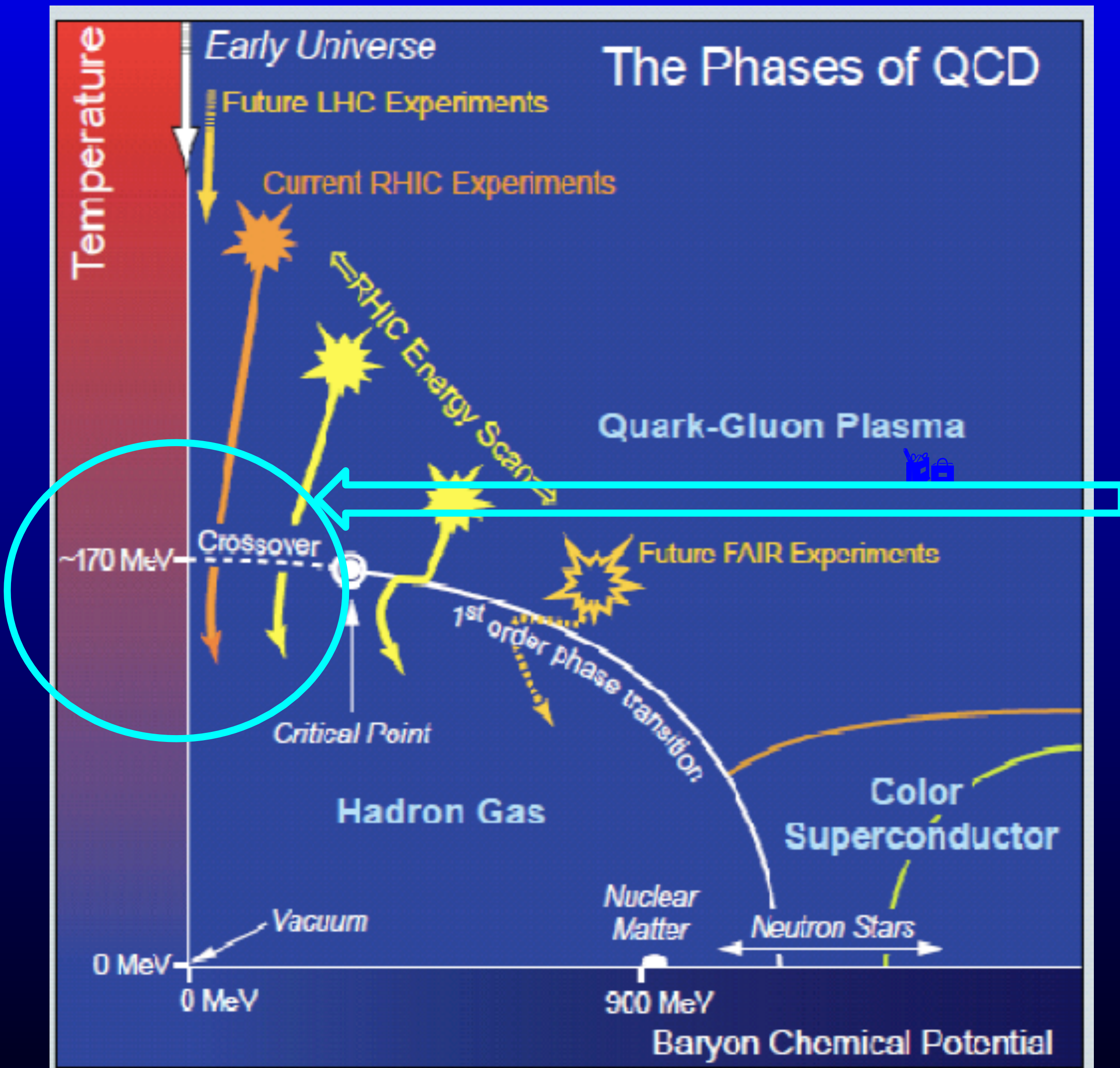




Wuppertal-Budapest
lattice collaboration

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

Crossover at zero net baryon density



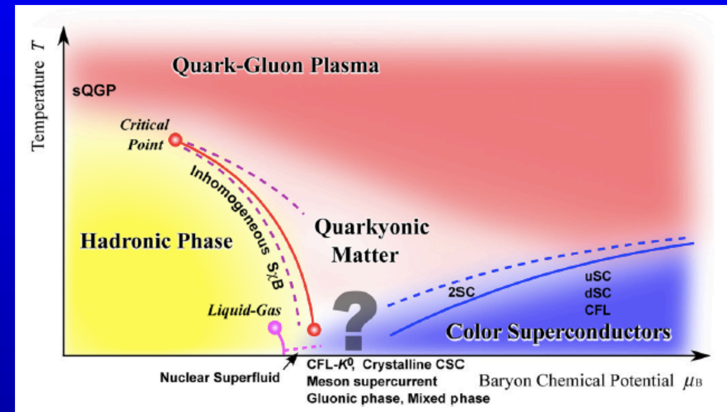
QCD lattice gauge theory -- for finite light quark masses -- predicts crossover from confined phase at lower T to deconfined phase at higher T.

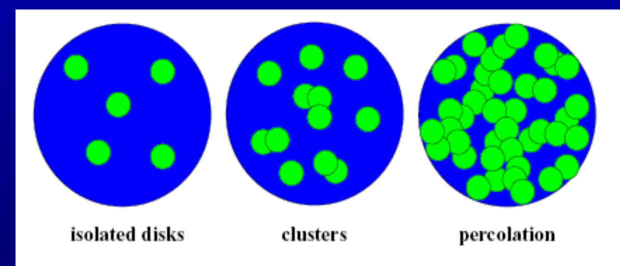
Do quarks roam freely in the deconfined phase? If so, they must also roam freely at lower T.

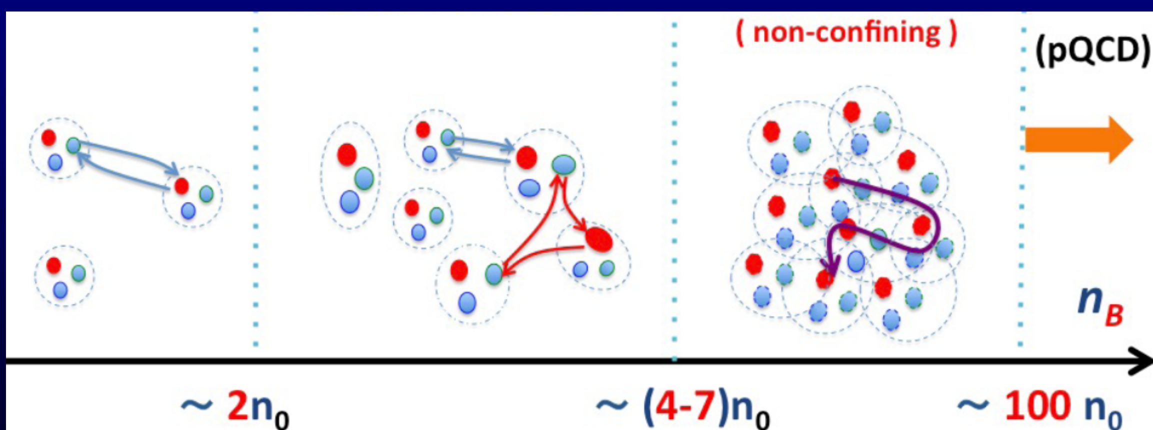
Are there really quarks running about freely in this room?

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

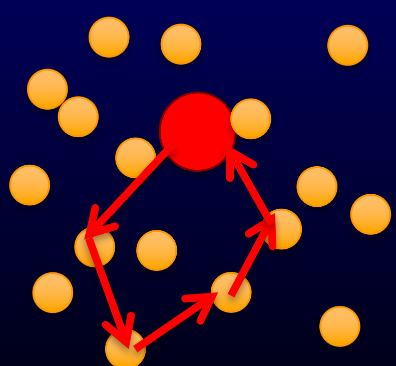
Percolation of clusters along the density axis, at zero temperature. n_0 is the density of matter inside a large nucleus. Quarks can still be bound even if deconfined.

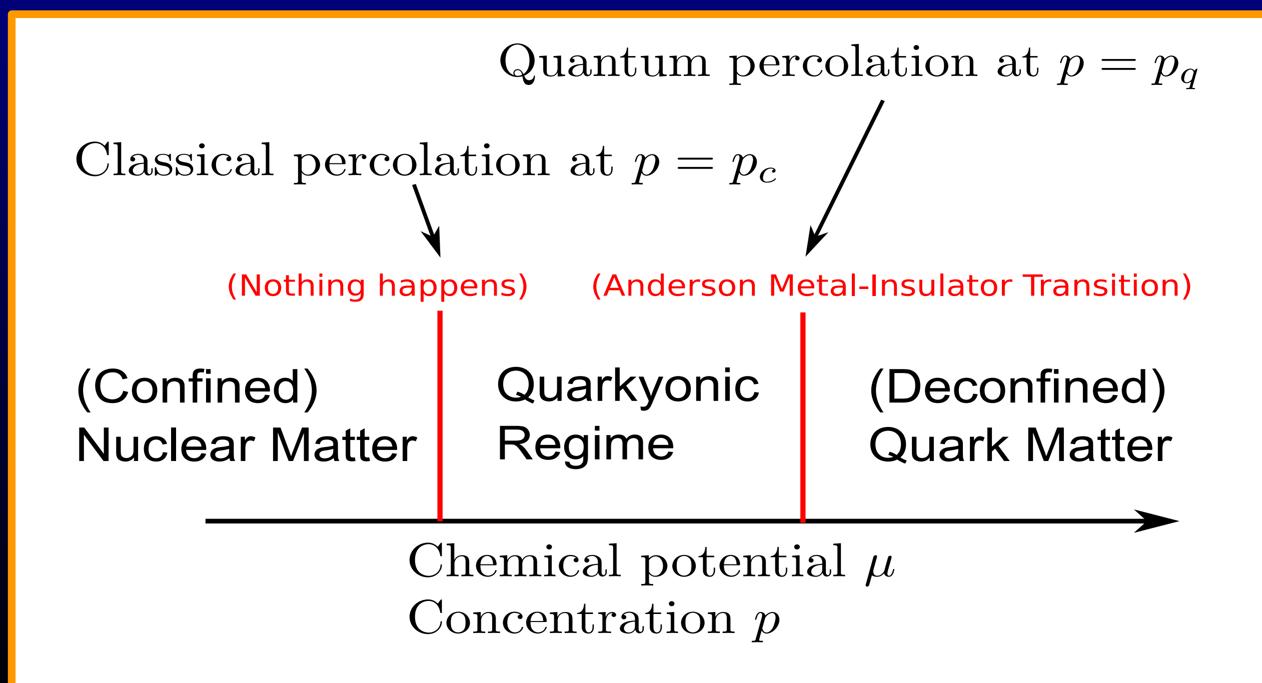
But aren't nucleons, with long distance cloud of mesons always overlapping?

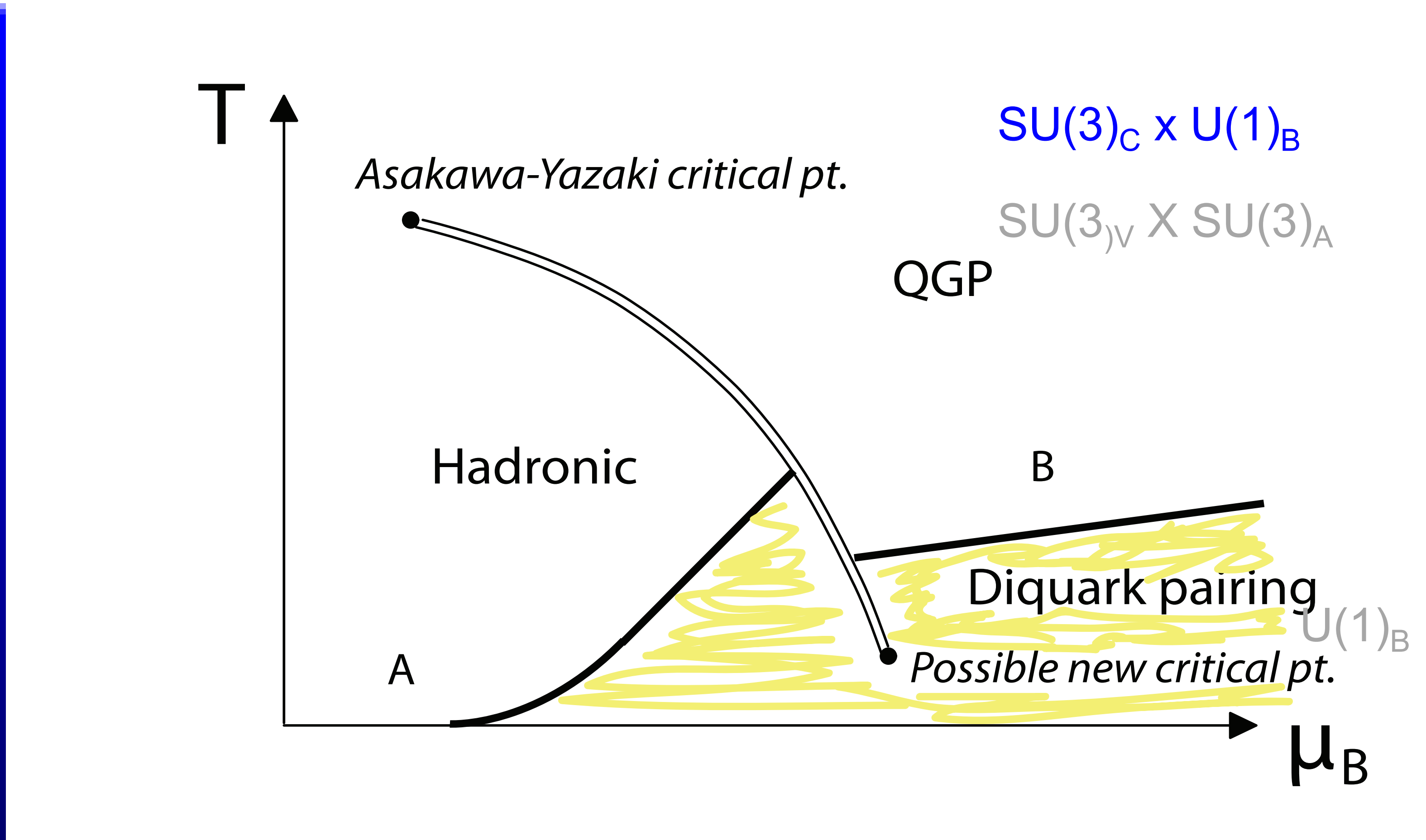
Does anything actually happen at classical percolation transition? No obvious lattice calculation to do!

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

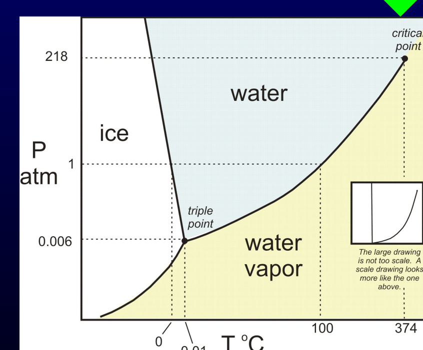
Deconfinement as (inverse) Anderson localization
(K. Fukushima):







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



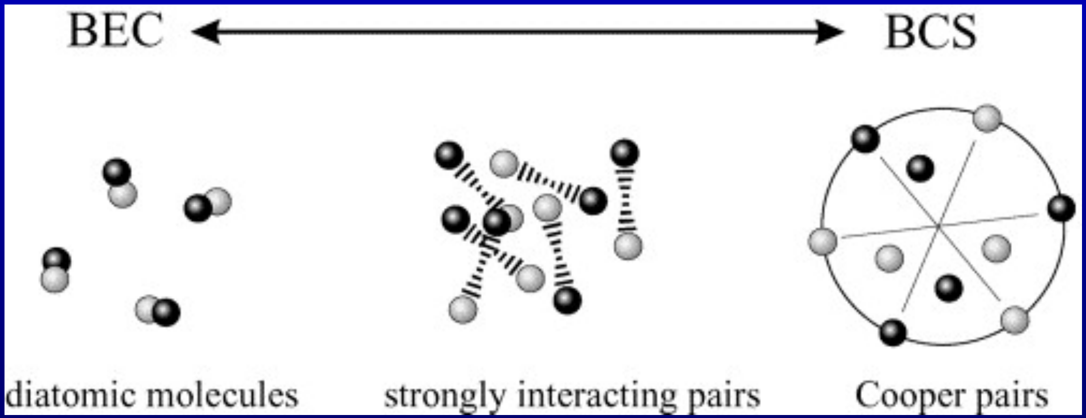
Can go continuously from A to B around the upper critical point. Liquid-gas phase transition.

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

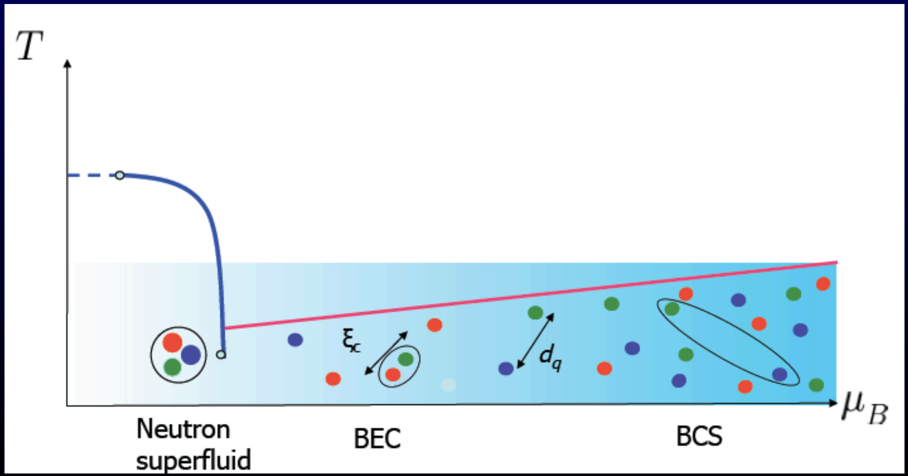
Smooth evolution of states in atomic clouds and nuclear matter

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:

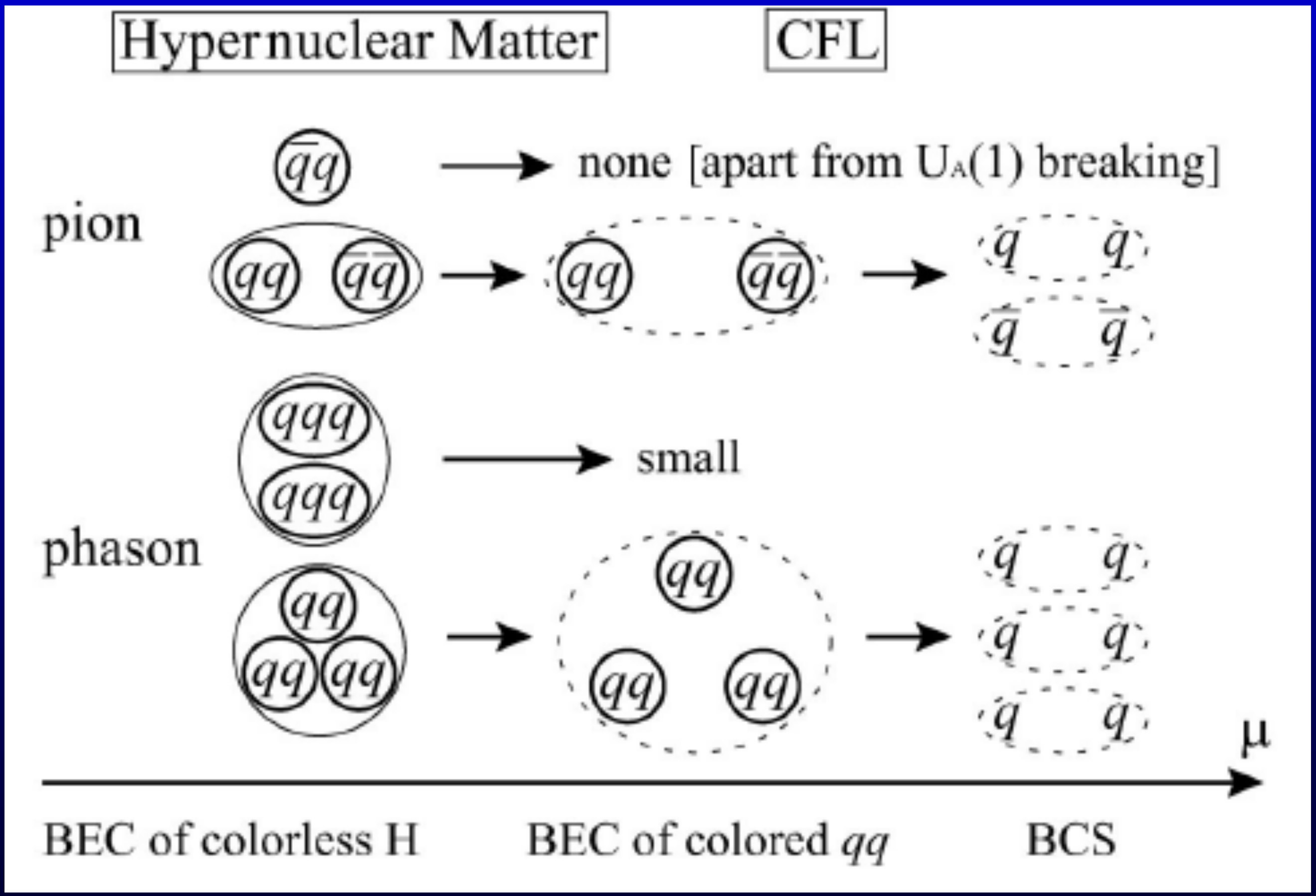


denser →

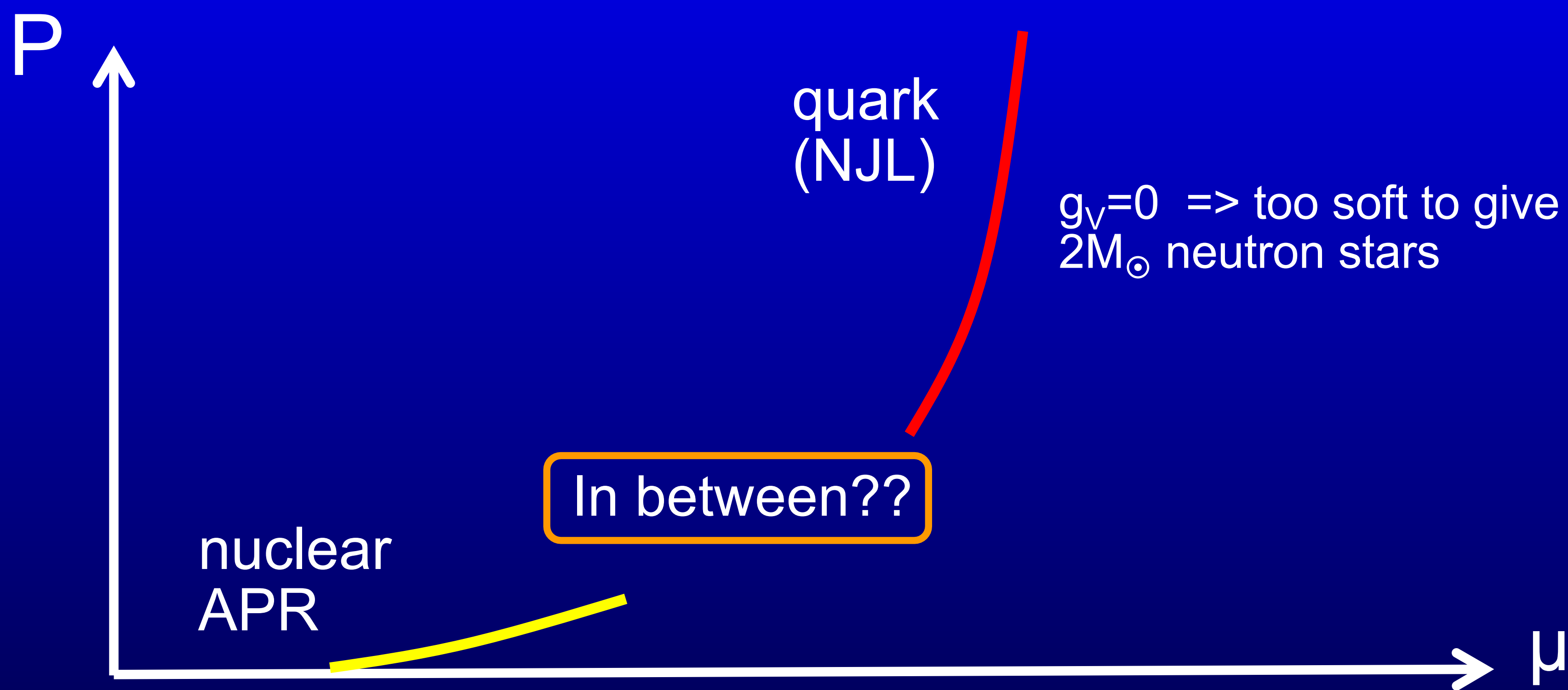
K. Masuda, T. Hatsuda, & T. Takatsuka, Ap. J.764, 12 (2013)

Smooth evolution of pairing states in dense nuclear matter

K. Fukushima, PRD (2004)



Have good idea of equation of state at nuclear densities and at high densities. Look at pressure vs. baryon chemical potential



Quarks in Nambu-Jona-Lasinio (NJL) model with universal repulsive short-range qq coupling (*Kunihiro*)

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

APR = Akmal, Pandharipande, Ravenhall nucleonic equation of state with nucleonic potentials (2 and 3 body) fit to NN scattering and light nuclei

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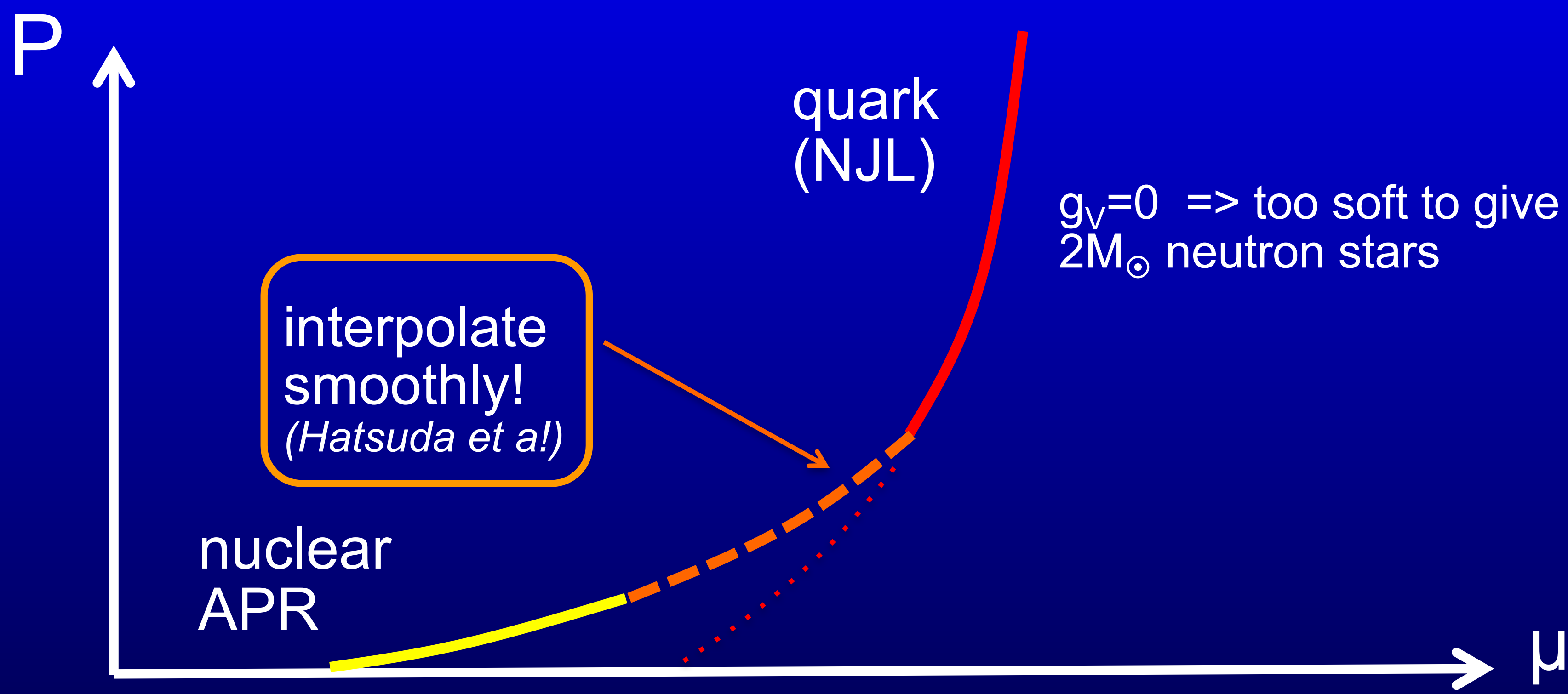

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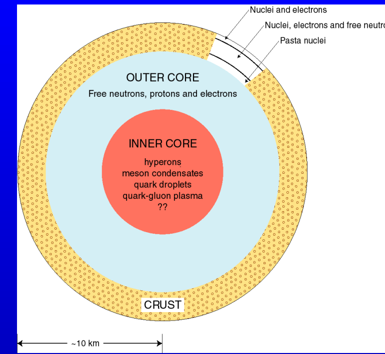
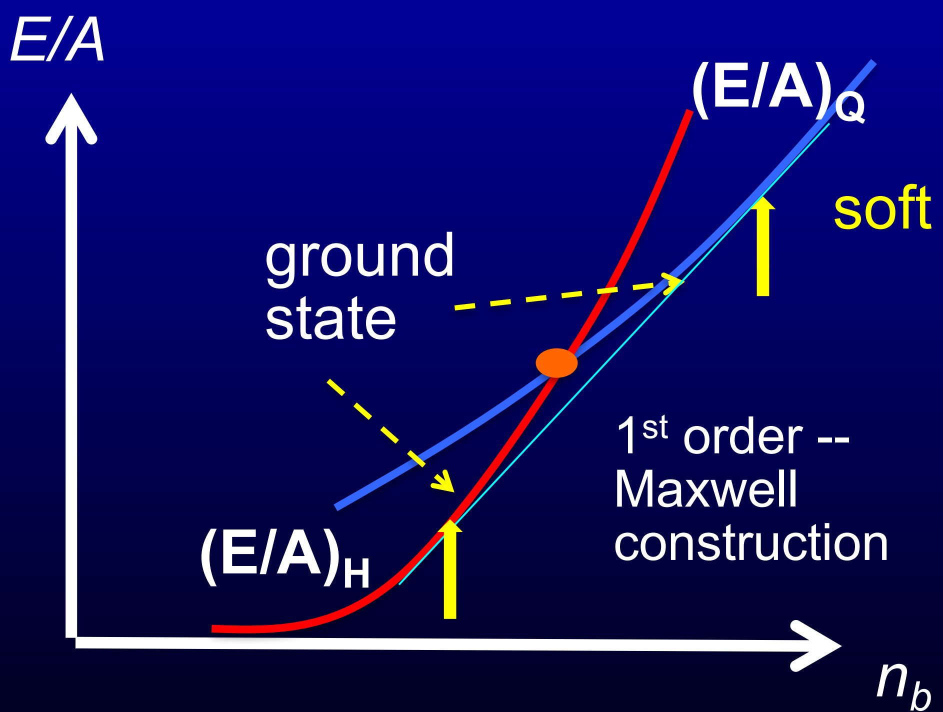
Quark matter cores in neutron stars



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.



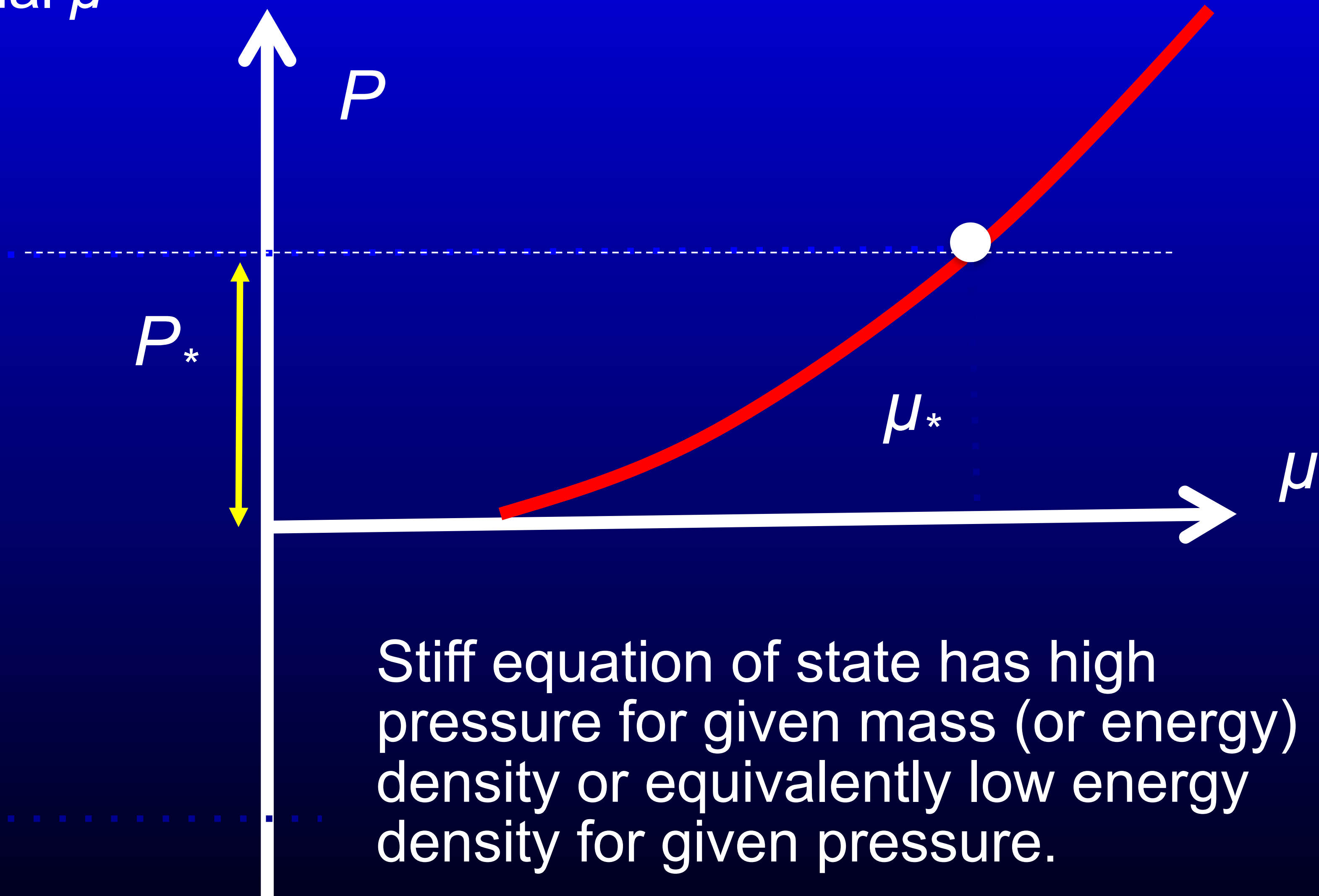
Assumes hadronic state at high densities – not possible when hadrons substantially overlap

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 $n \sim 10 n_{nm}$ -- would not be reached even in high mass neutron stars => at most small quark matter cores

How can QCD give large mass neutron stars?

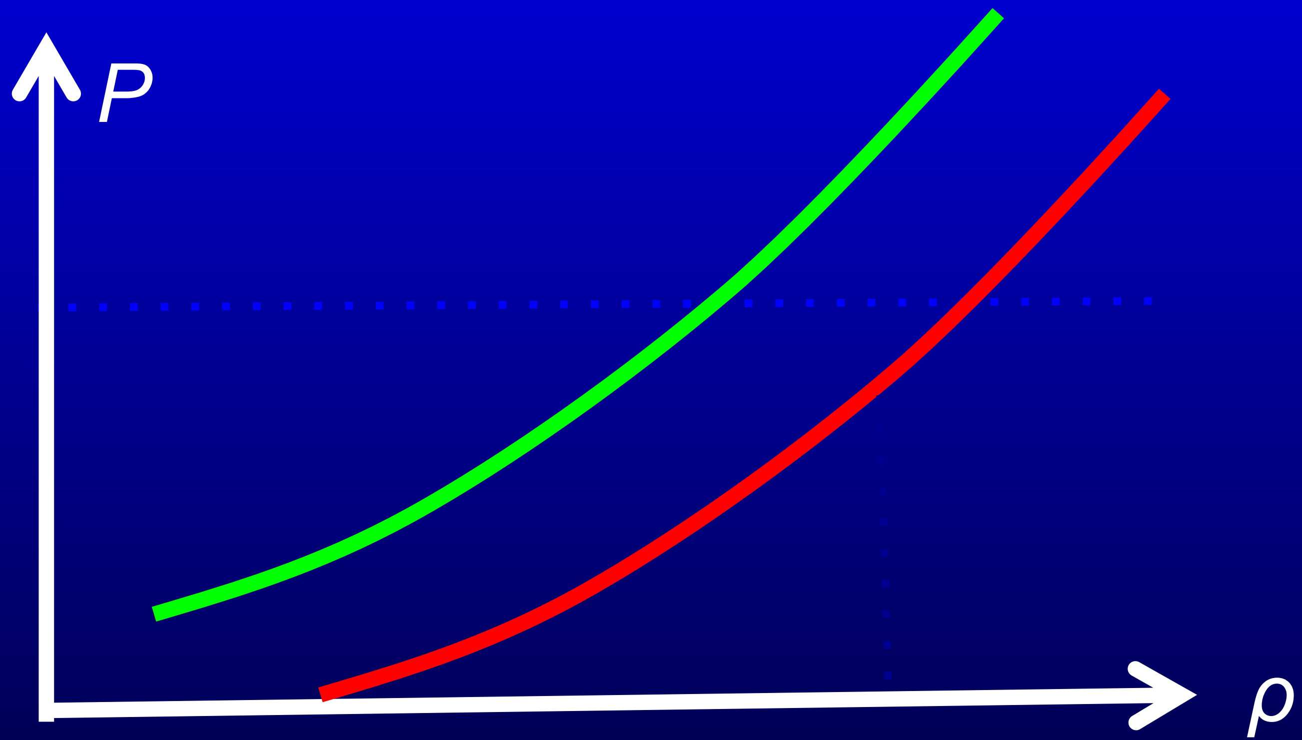
Pressure P is a continuous function of baryon chemical potential μ



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)

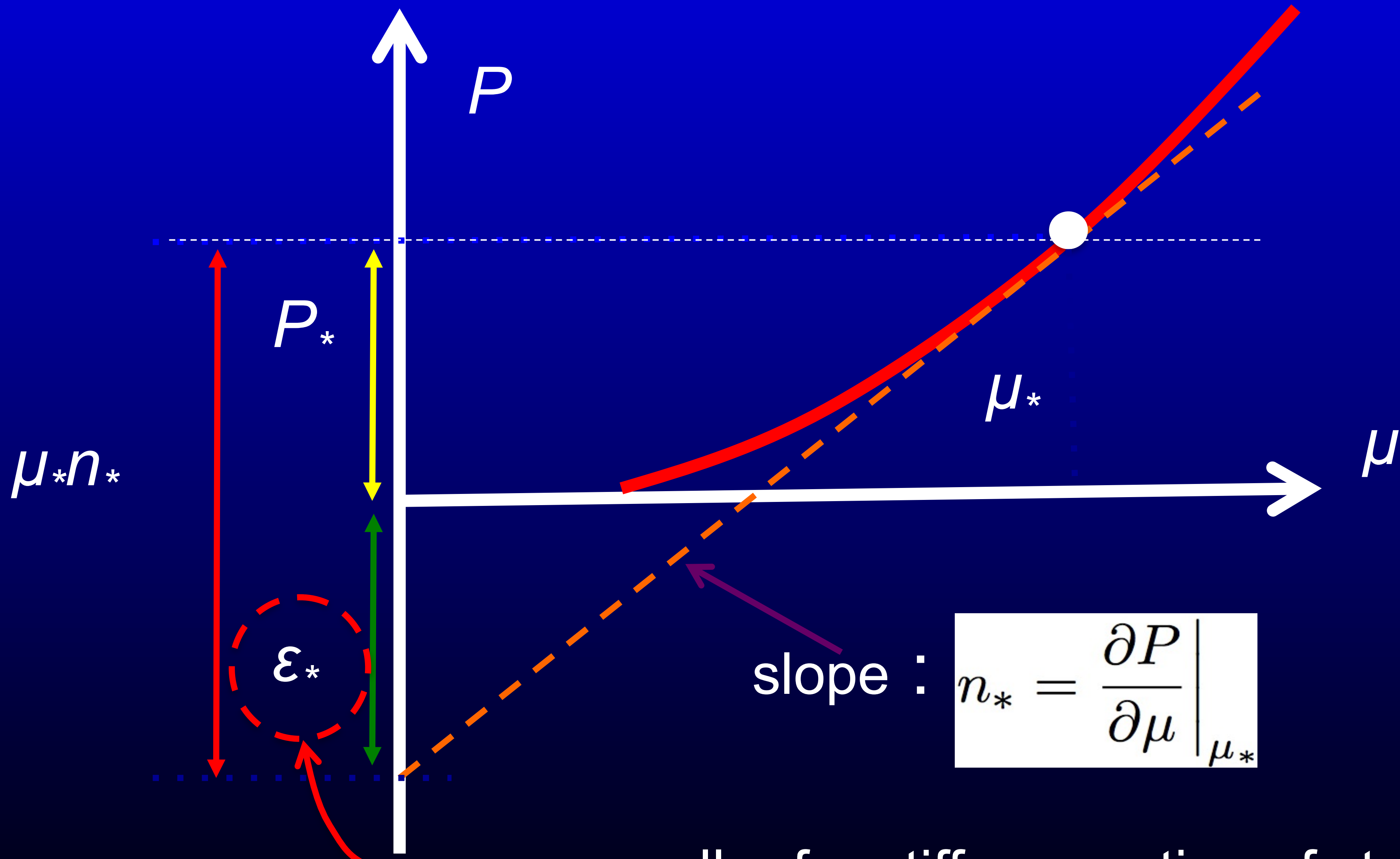
Stiffer equations of state given more massive neutron stars, with lower central densities



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 $\varepsilon = \rho c^2 = \mu n - P$

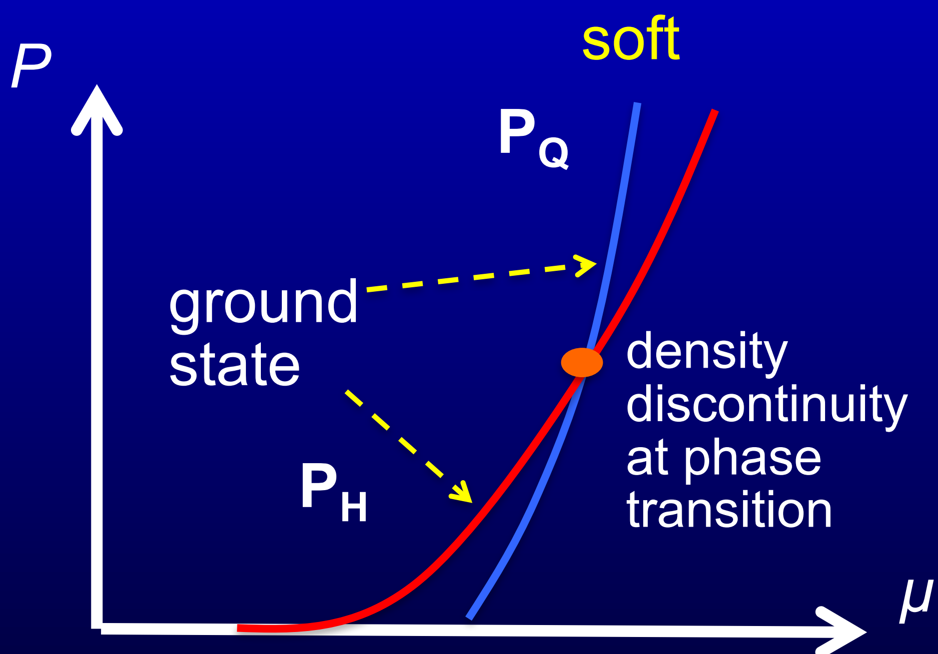


slope : $n_* = \left.\frac{\partial P}{\partial \mu}\right|_{\mu_*}$

smaller for stiffer equation of state

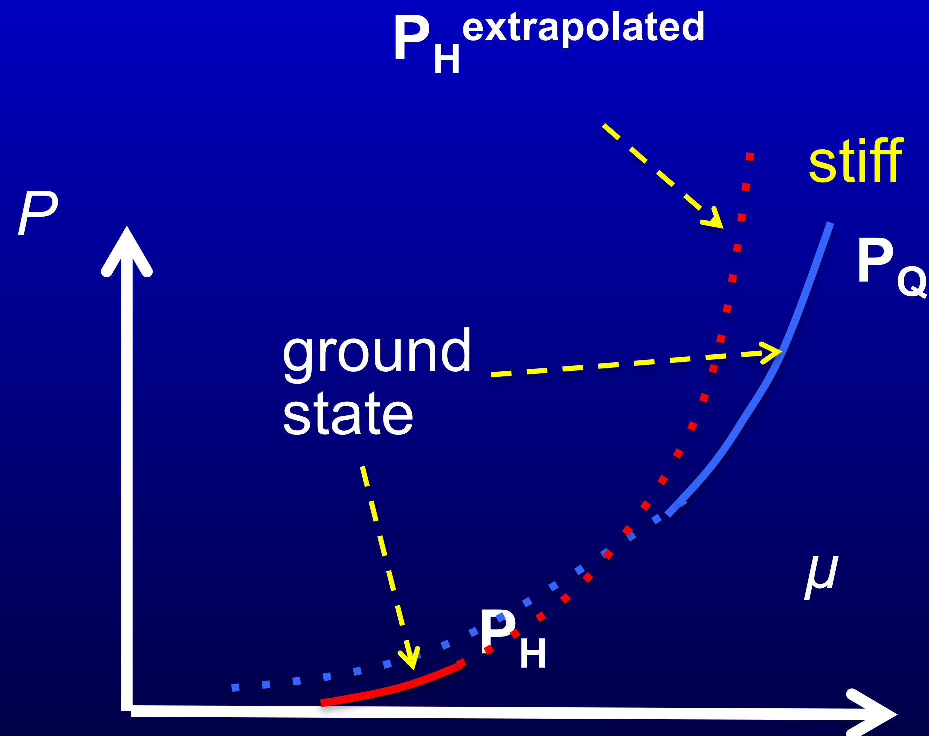
Hybrid eqs. of state
are intrinsically softer

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

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

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

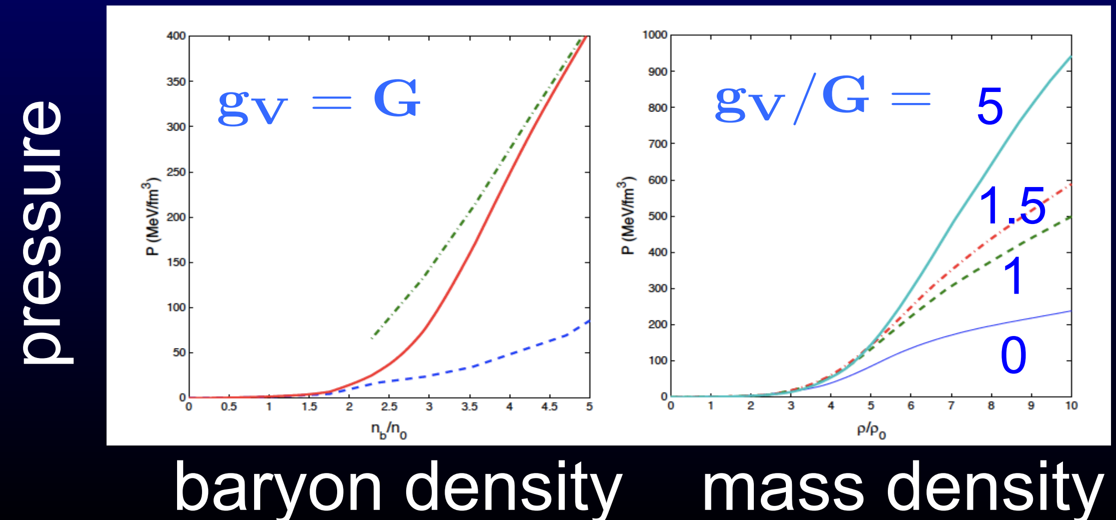
$\mathcal{L}^{(6)}$ = Kobayashi-Maskawa-‘t Hooft six quark axial anomaly

plus universal repulsive quark-quark vector coupling

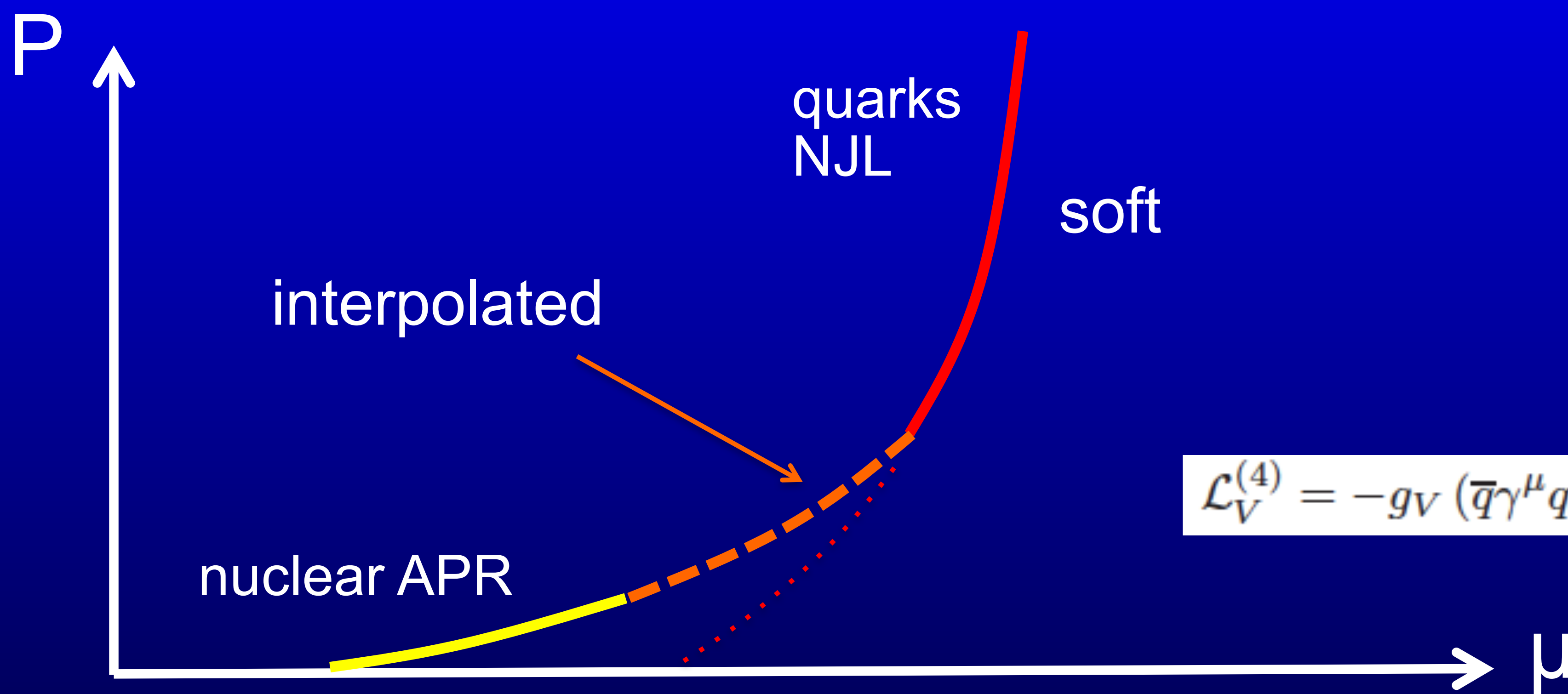
$\mathcal{L}_V^{(4)} = -g_V\left(\overline{q}\gamma^\mu q\right)^2$ *T. Kunihiro*

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)



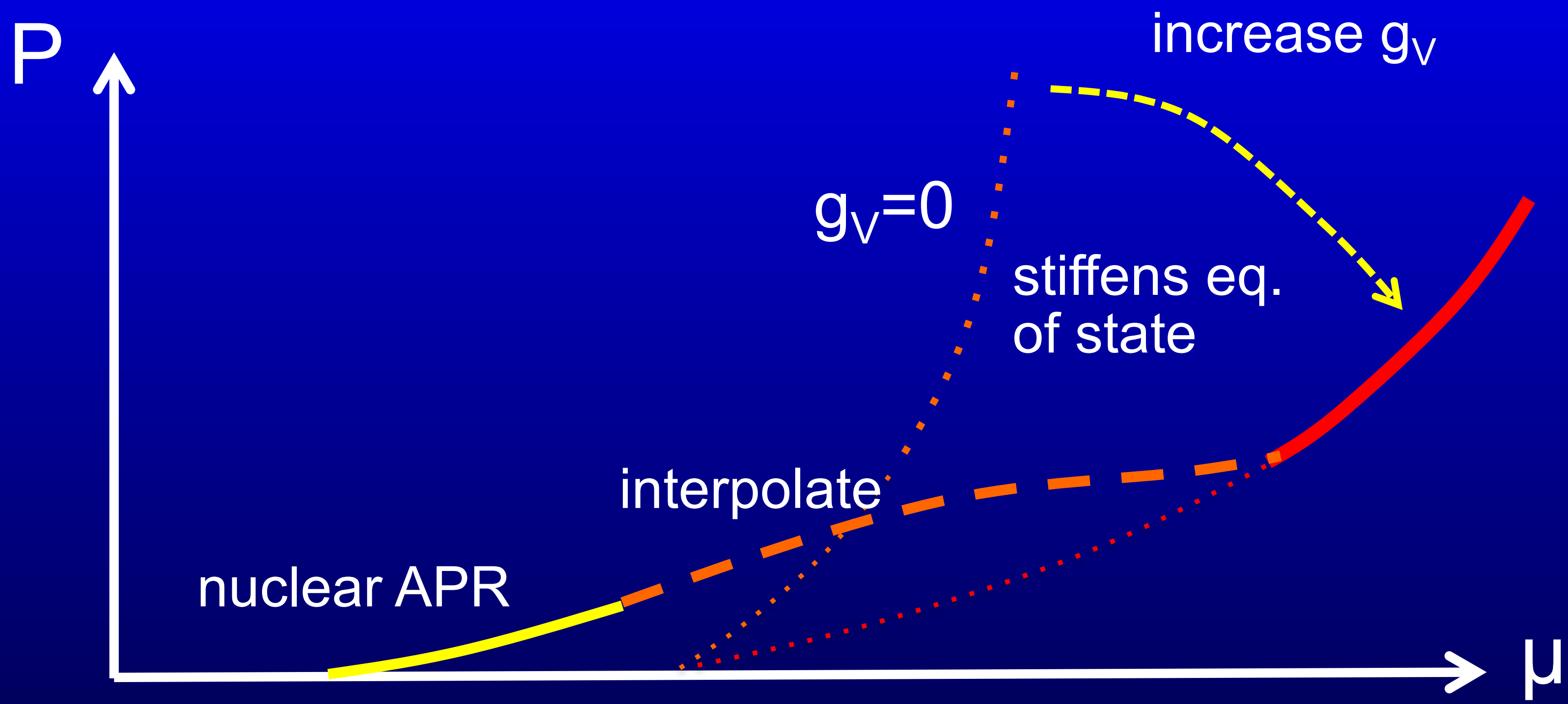
Minimal model: $g_V = 0$



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

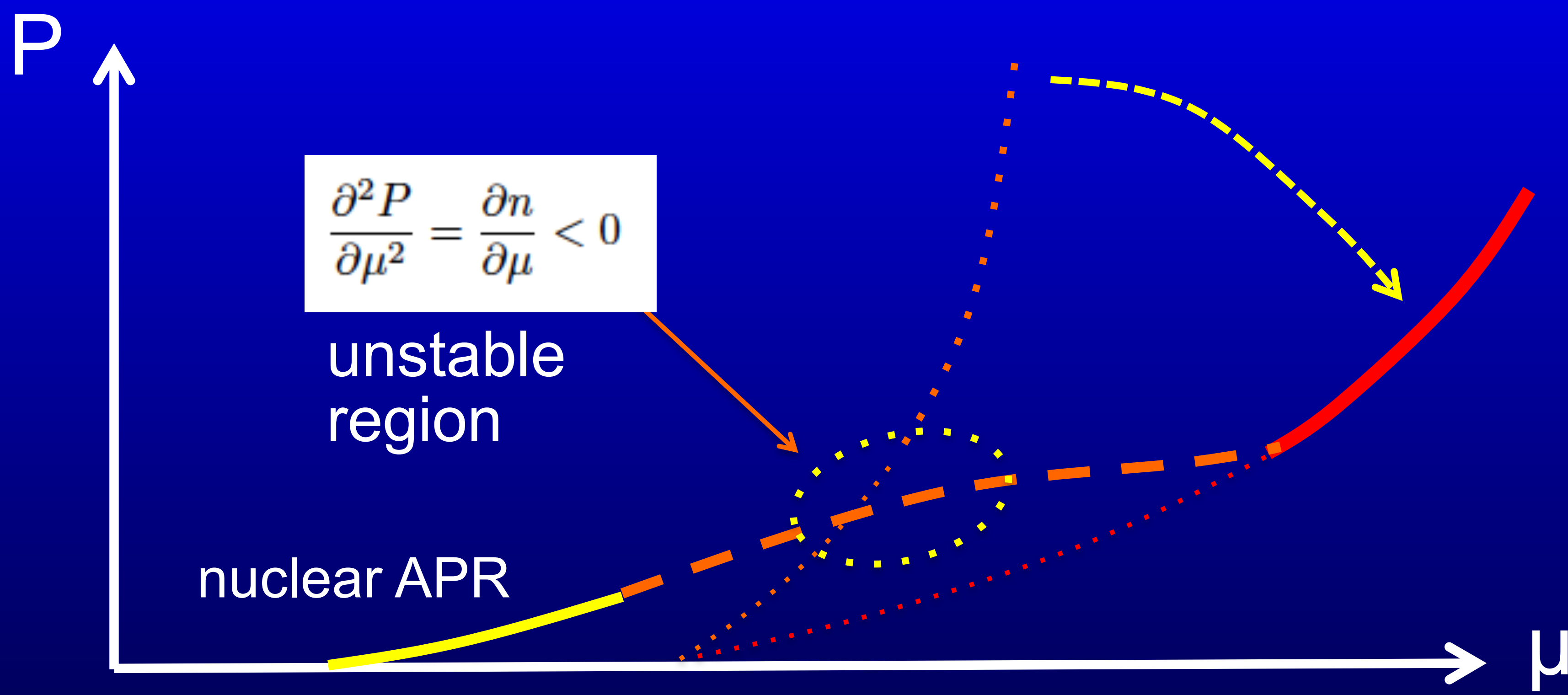
Soft quark equation of state does not allow high mass neutron stars

Vector interaction stiffens eq. of state

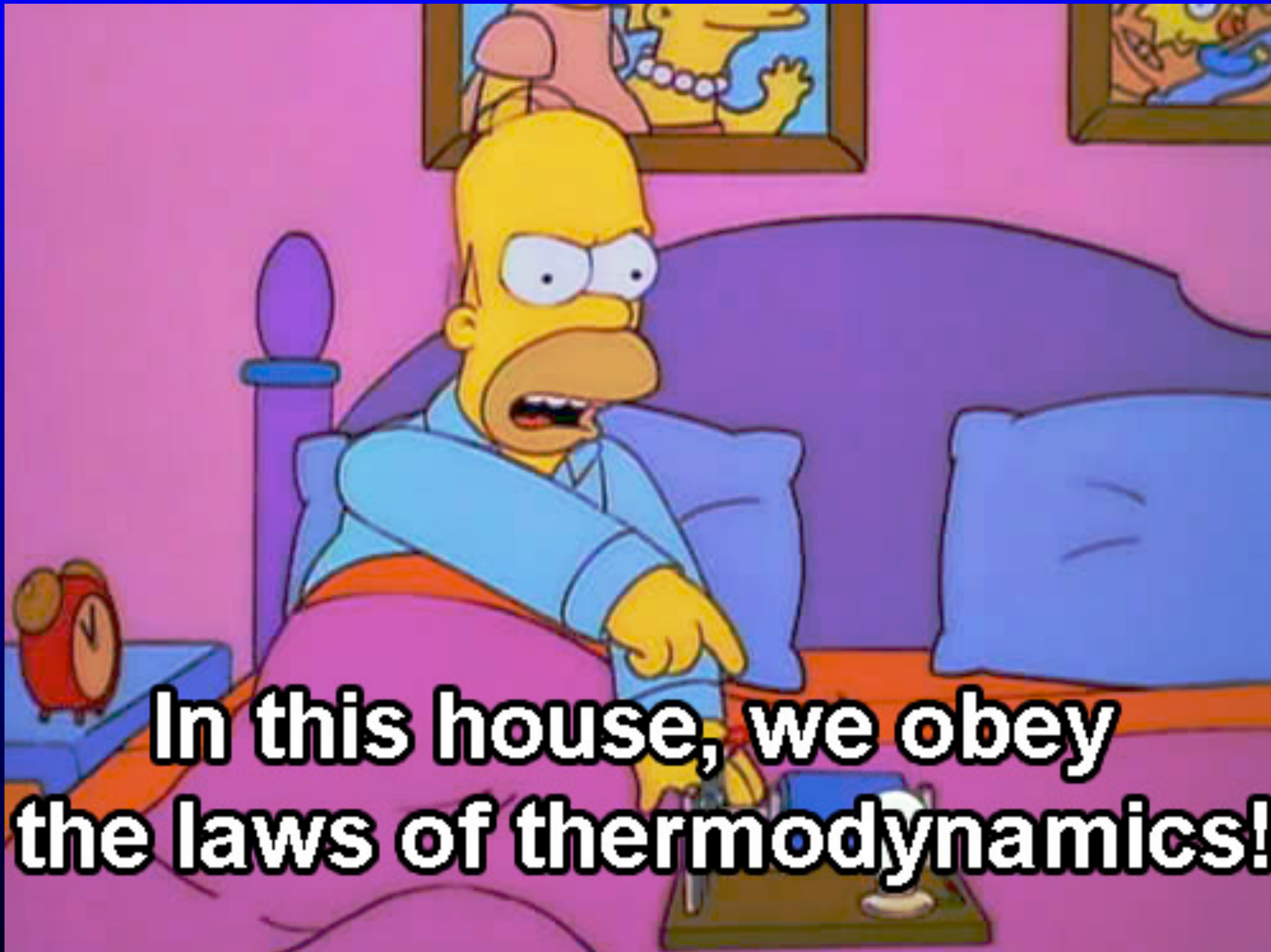


Shift of pressure in quark phase towards higher μ

Vector interaction stiffens eq. of state

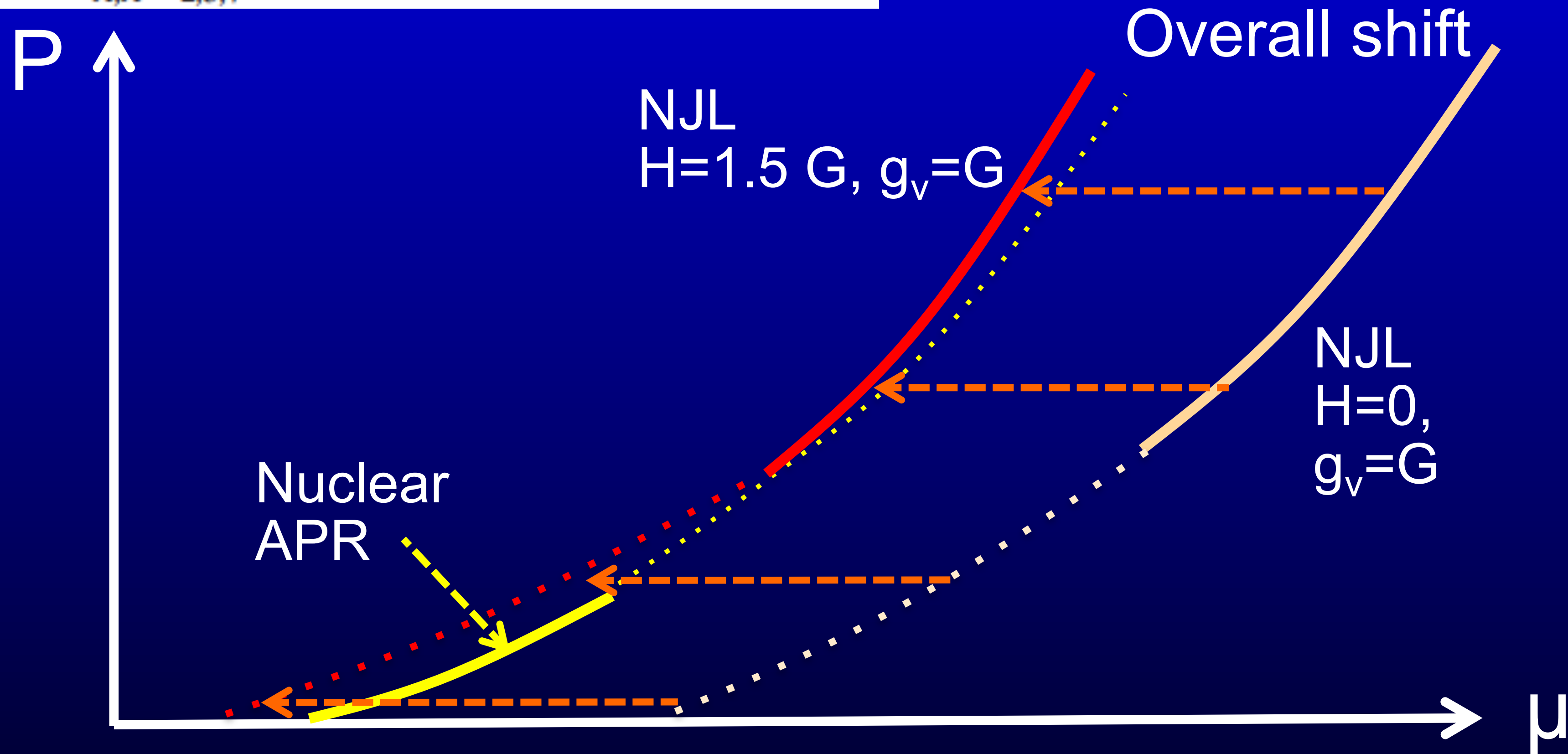


Larger g_V leads to unphysical thermodynamic instability


In this house, we obey
the laws of thermodynamics!

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

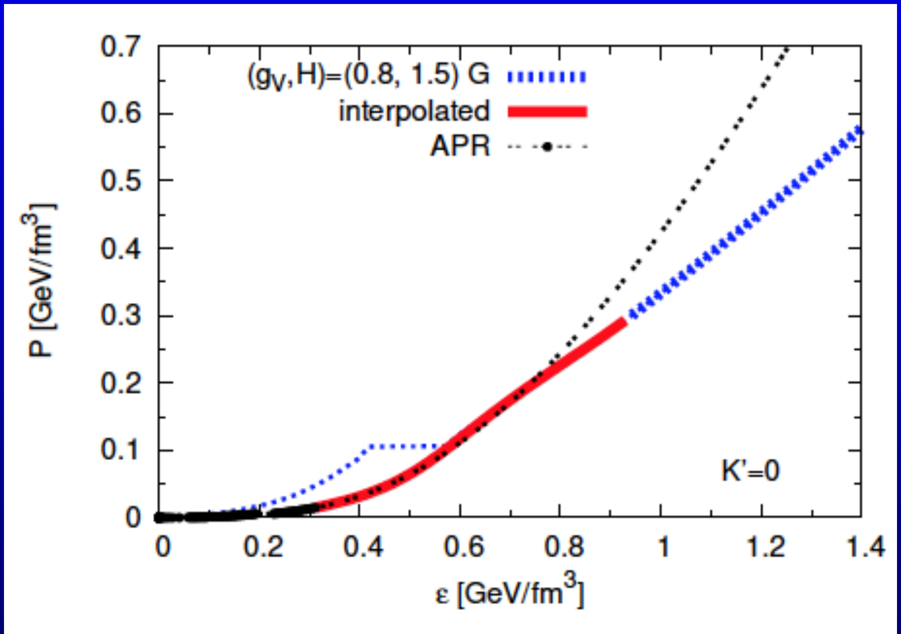
$$\mathcal{L}_d^{(4)} = H \sum_{A,A'=2,5,7} [(\bar{q} i\gamma_5 \tau_A \lambda_{A'} C \bar{q}^T)(q^T C i\gamma_5 \tau_A \lambda_{A'} q)$$

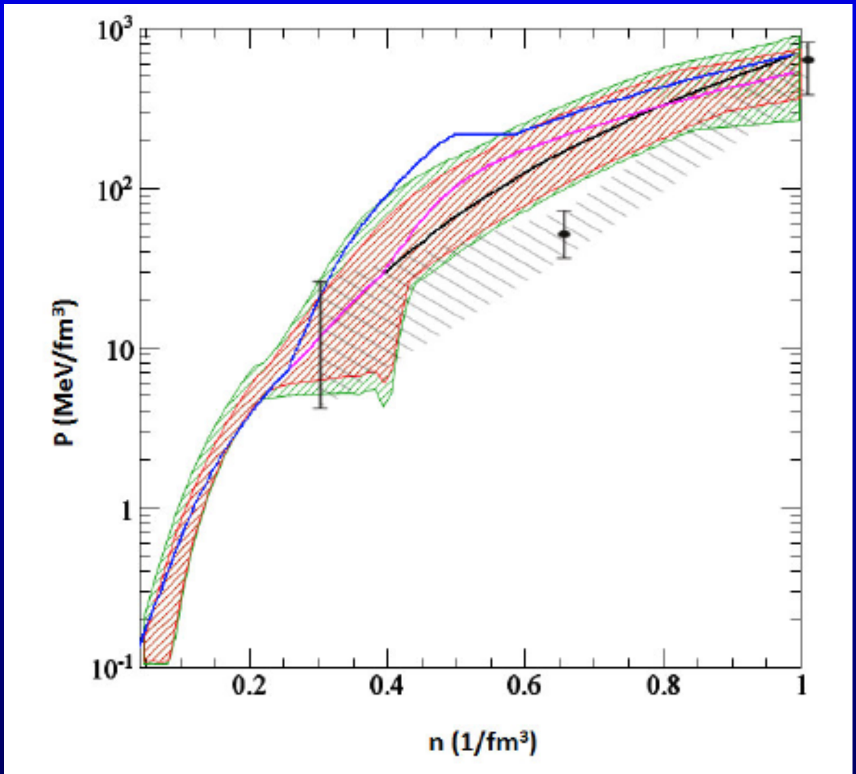


Increased BCS pairing (onset of stronger 2-body correlations) as quark matter comes nearer to becoming confined

Sample "unified" equation of state

T. Kojo et al.





Reasonable agreement with eq. of state inferred from M vs. R observations

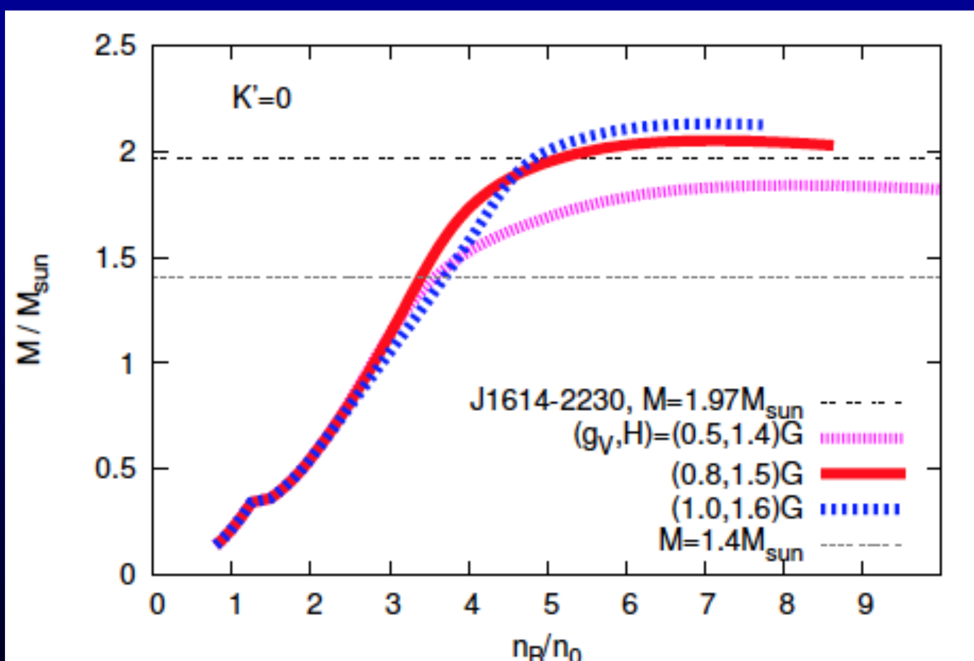
Quark eqs. of state can be stiffer than previously thought: allow for n.s. masses > 2 $M_\odot$, and with substantial quark cores in neutron stars!!!

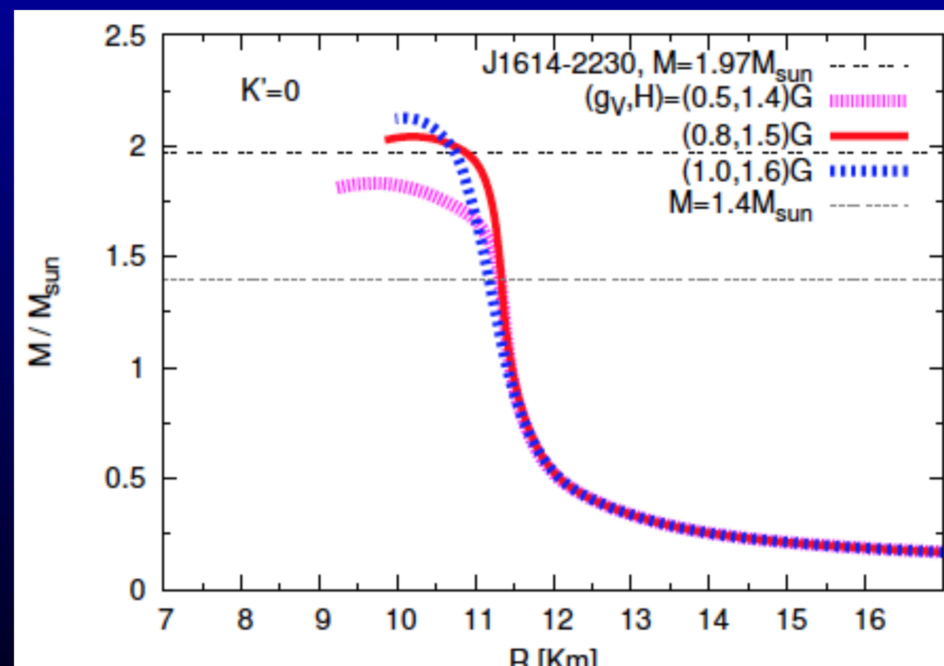
Masses and radii of neutron stars vs. central mass density from integrating the TOV equation

T. Kojo, P.D. Powell, Y. Song, & GB, PR D91, 054003 (2015)

Include stronger corelations between quarks by increasing the effective pairing interaction H between quarks beyond standard NJL
H ~ 1.5 G

Increased vector repulsion between quarks: g_V ~ 0.5-1.0 G





Mass vs. central baryon density: Mass vs. radius:

Summary

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

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 $\sim g_v \sim G_s^{vac}$

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* cảm ơn