QCD in Heavy-Ion Collisions

Kenji Fukushima

The University of Tokyo

"QCP" in Heavy-Ion Collisions

(+ Astrophysical Constraints)

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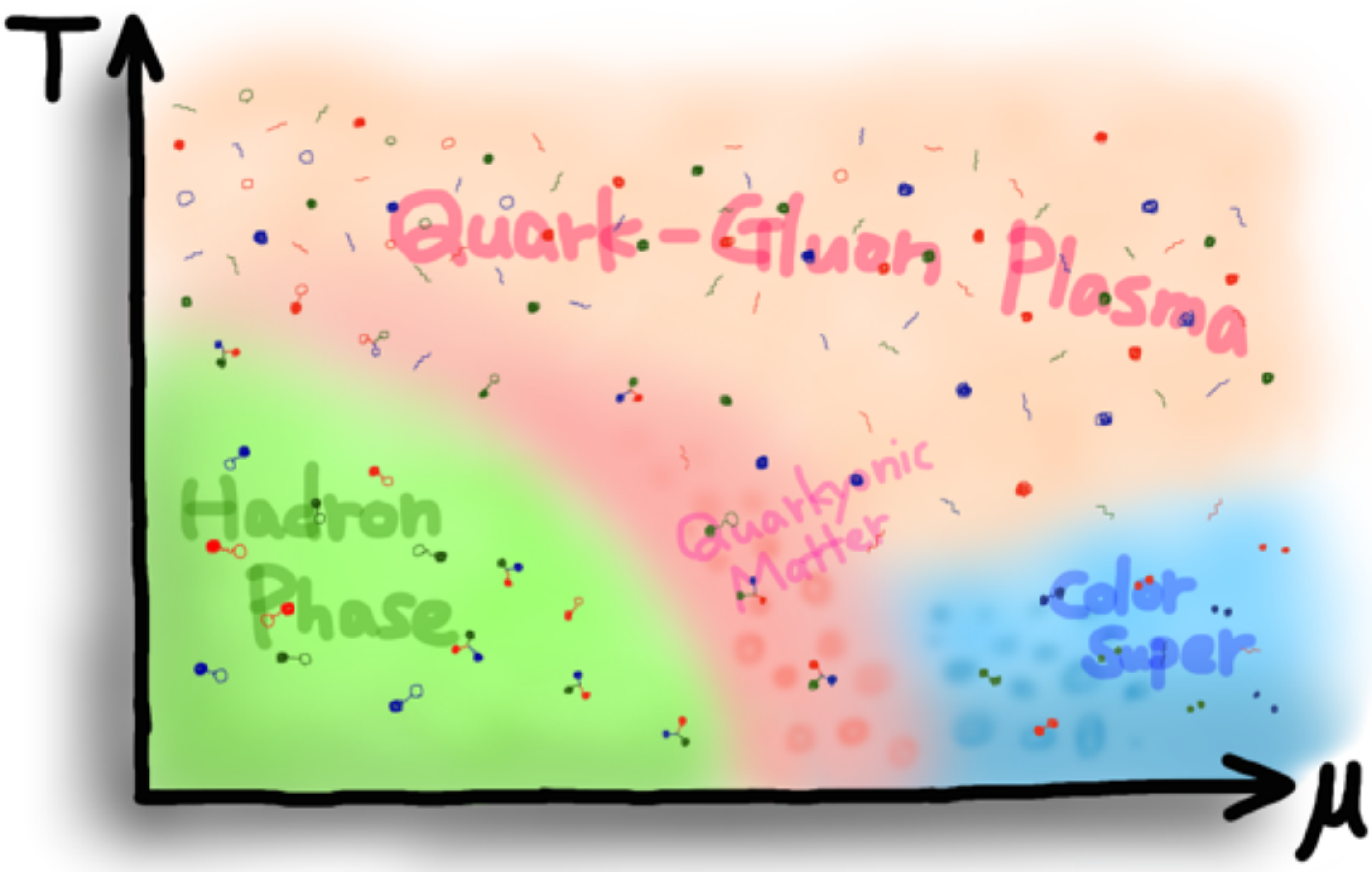
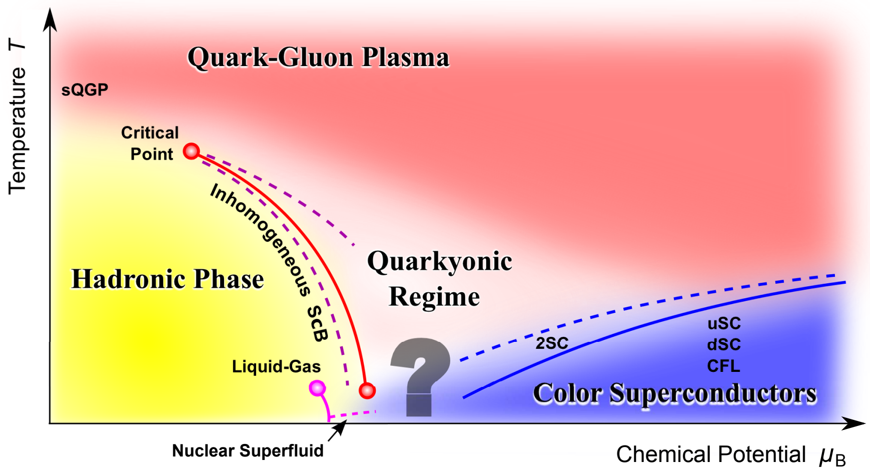
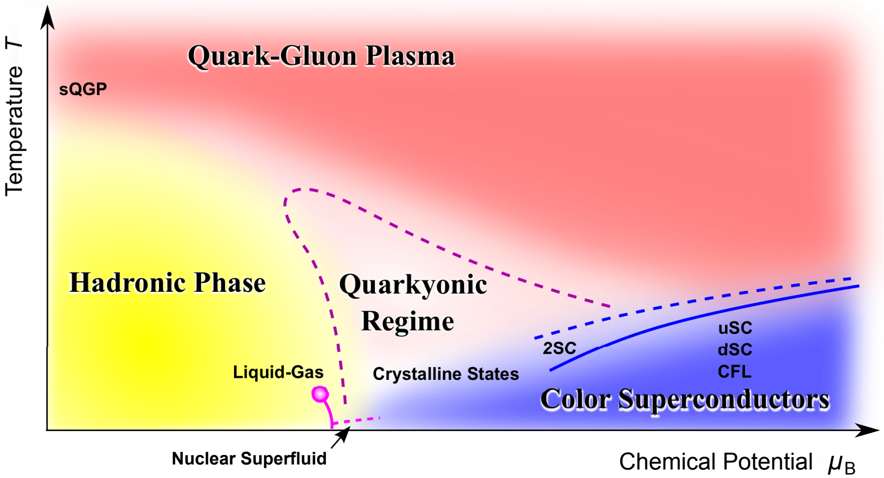
QCD Phase Diagram on iPad



Figures from Fukushima-Sasaki (2013)



V.S.



QCD Critical Point (summary)

- **State-of-the-art experiment**
  - **Plenary Report by Xiaofeng Luo**
    No positive signal in Kurtosis for $0.4 < p_T < 0.8$ GeV
    Positive signal in Kurtosis for $0.4 < p_T < 1.2$ GeV
- **State-of-the-art theory**
  - No new proposal / No progress in lattice
    (People more interested in heavy-flavor sector)
  - **Plenary Report by Marlene Nahrgang**
    Analogies to known systems / known results
    Dynamical aspects assuming QCP
    Useful simulations *if it exists*

Neutron Star EoS (summary)

State-of-the-art EoS constraint to neutron matter

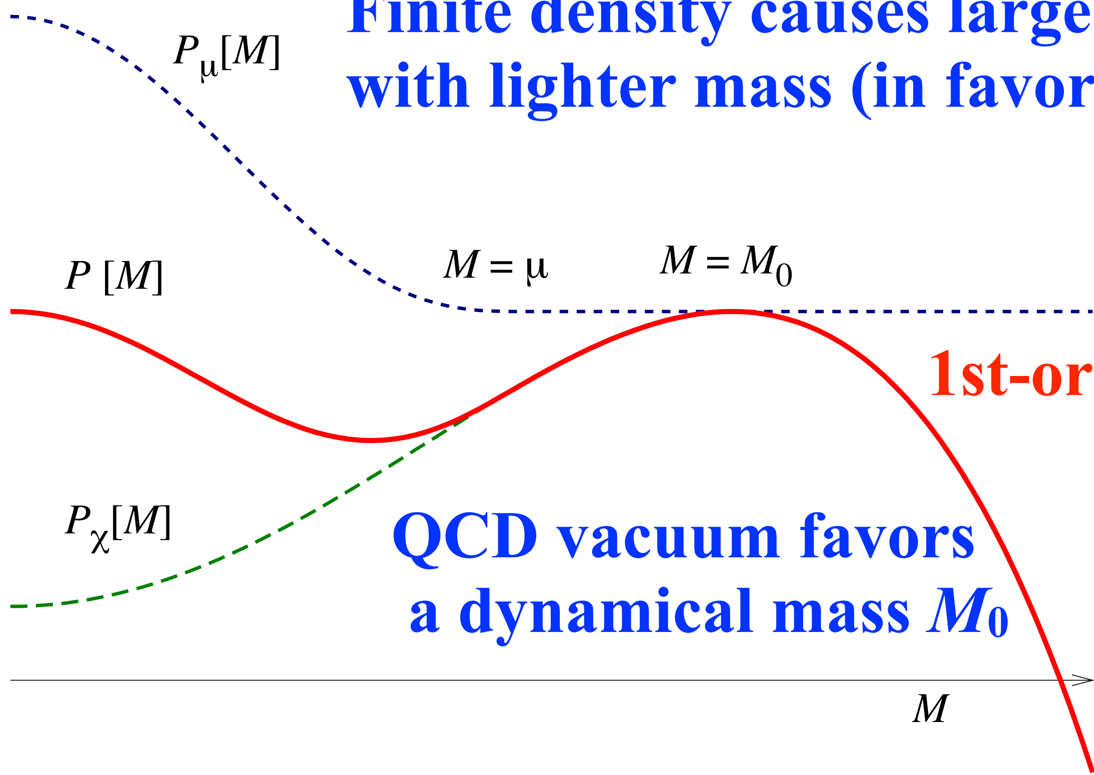
- **Report by Eduardo Fraga**
  No assumption about the EoS (matching to pQCD)
  Allowed EoS systematically identified incl. 1st-order

- **Report by Kota Masuda**
  Three window model
  Smooth interpolation without any 1st-order

- **Report by *Toru Kojo***
  A variant of three window model
  Smooth interpolation with/without 1st-order
  Nuclear matter with many-body int. = quark matter

Robust Picture in favor of QCP

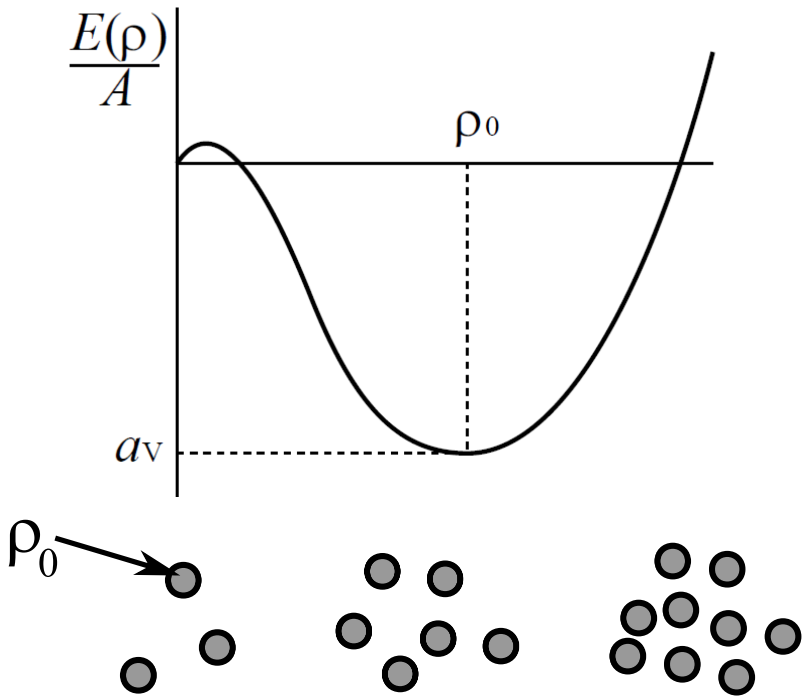
Finite density causes larger pressure with lighter mass (in favor of small *M*)



1st-order transition!

QCD vacuum favors a dynamical mass M_0

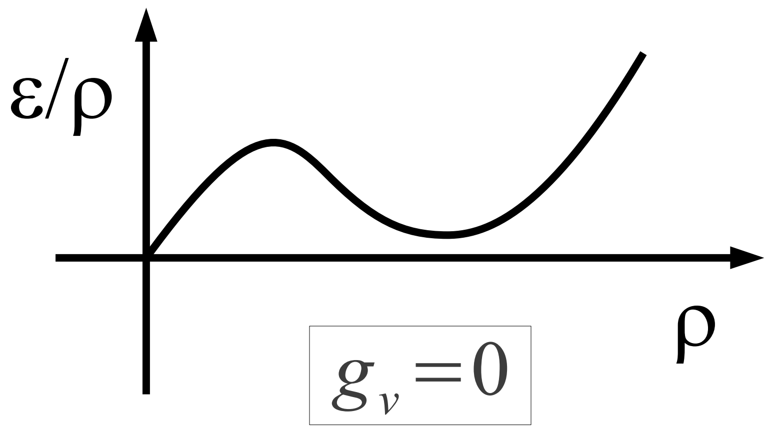
Self-bound Fermionic Systems



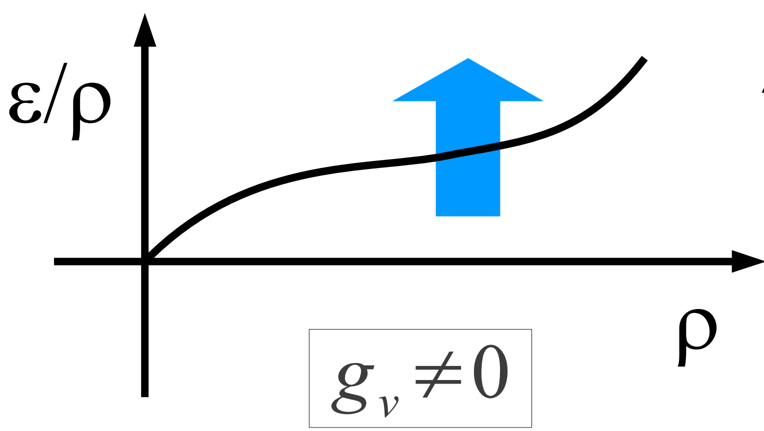
Self-bound fermionic systems have a preferred density.
Diluteness is realized as a "mixed phase" of nuclei.

No argument about whether quarks are self-bound?
Quark EoS is constrained by neutron stars > $2M_\odot$

Sufficient Cond. for QCP



Meta-stable quark matter can have a 1st-order

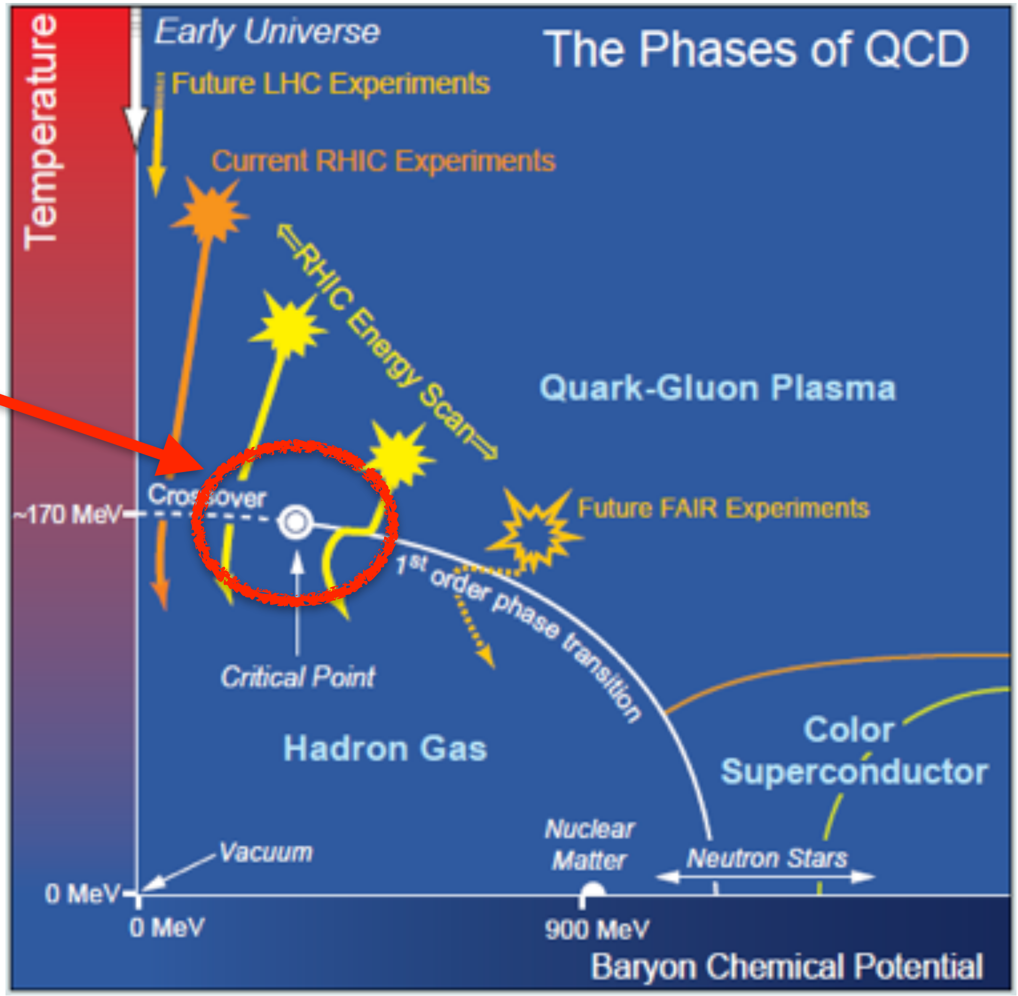


$$\Delta\varepsilon = g_v \rho^2$$

This term is chiral inv.
Difficult to constrain
(susceptibility?)

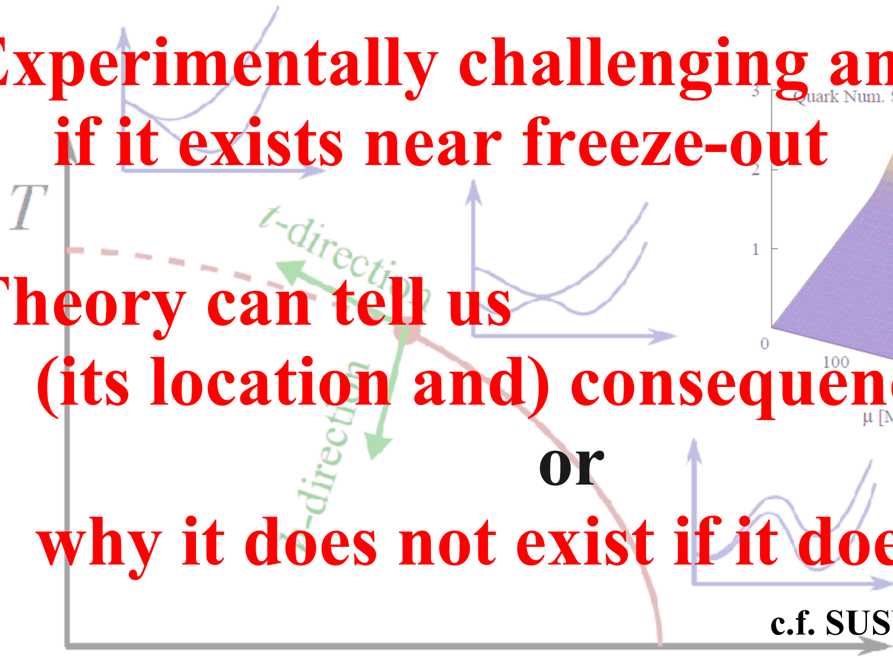
Landmark on Phase Diagram

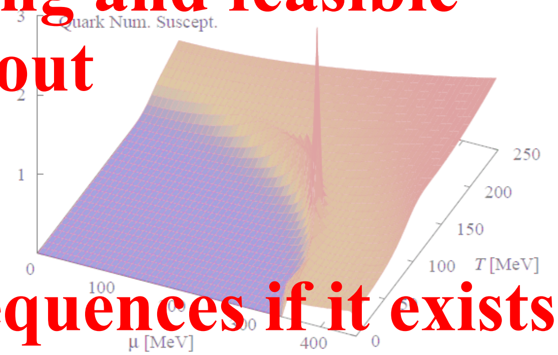
QCD CP or anything?



Models cannot predict the existence of QCP but density always favors 1st-order.

QCP is more likely than supersymmetry
but less likely than dark matter.





Experimentally challenging and feasible
if it exists near freeze-out

Theory can tell us
(its location and) consequences if it exists
or
why it does not exist if it does not

Fukushima at INPC (2010)

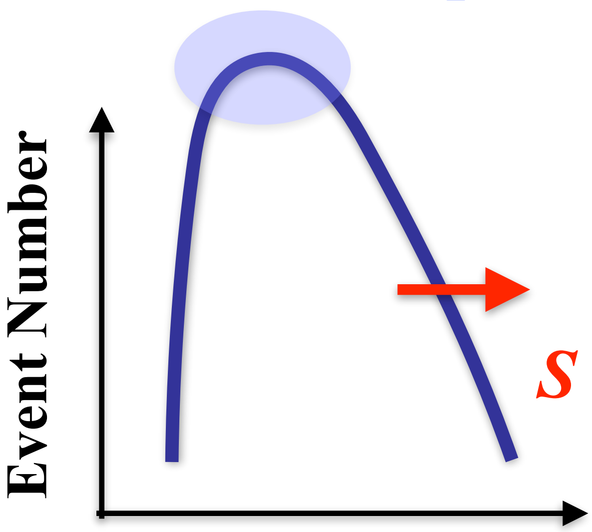
c.f. SUSY, Extra-Dimension, etc...

Fluctuations

$$\frac{\sigma^2}{M} \equiv \frac{\chi_B^{(2)}}{\chi_B^{(1)}}, \quad S\sigma \equiv \frac{\chi_B^{(3)}}{\chi_B^{(2)}}, \quad \kappa\sigma^2 \equiv \frac{\chi_B^{(4)}}{\chi_B^{(2)}}$$

Skewness **Kurtosis**

κ ~ **how sharp**



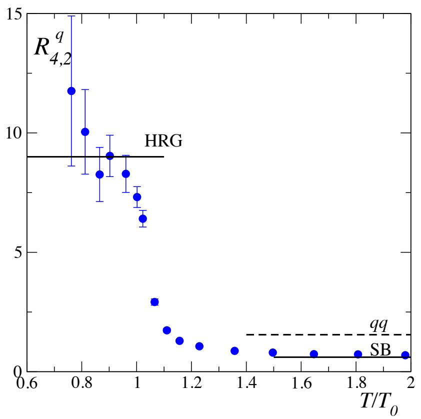
S ~ **how distorted**

Discovery of QCP???

→ Talks by X. Luo / J. Deng on Thurs.

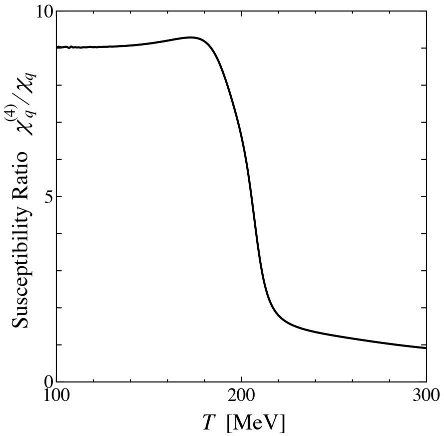
Comment on Kurtosis

Historically, Kurtosis was proposed as an order parameter for deconfinement :



Ejiri et al. (2005)

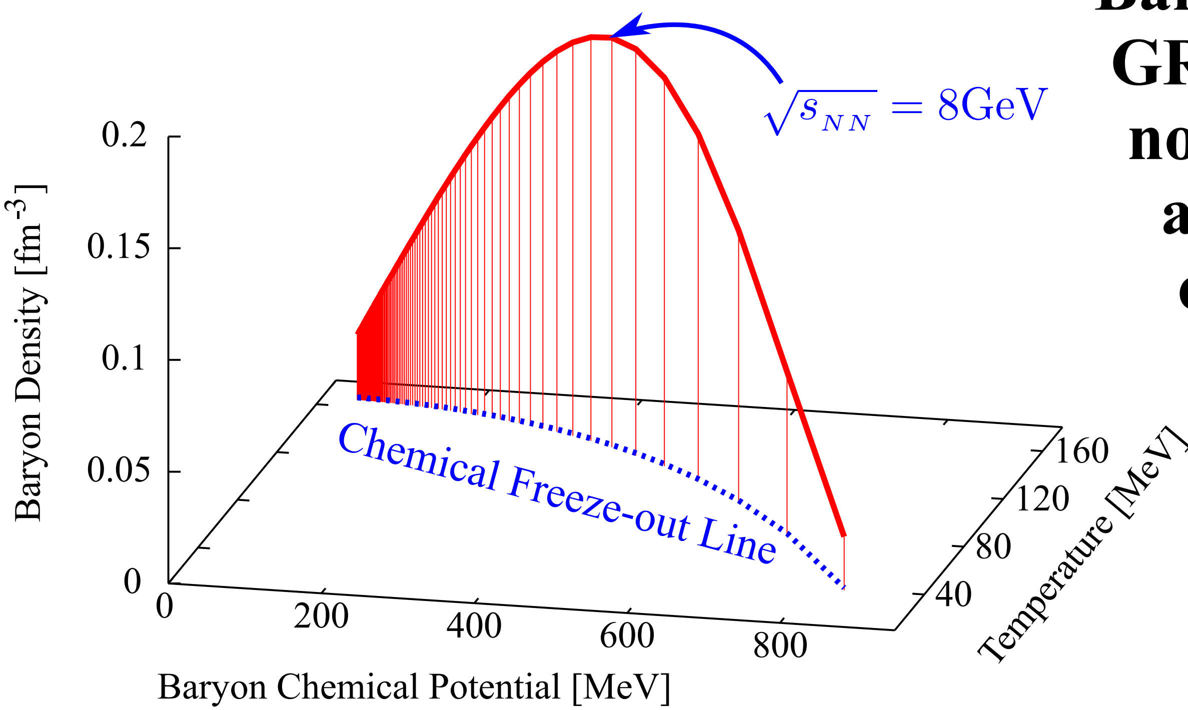
As long as fluctuations are dominated at the chemical freezeout, no way to see such fluctuations in the deconfined phase (small suppression?)



Model result (2008)

Landmark on Phase Diagram

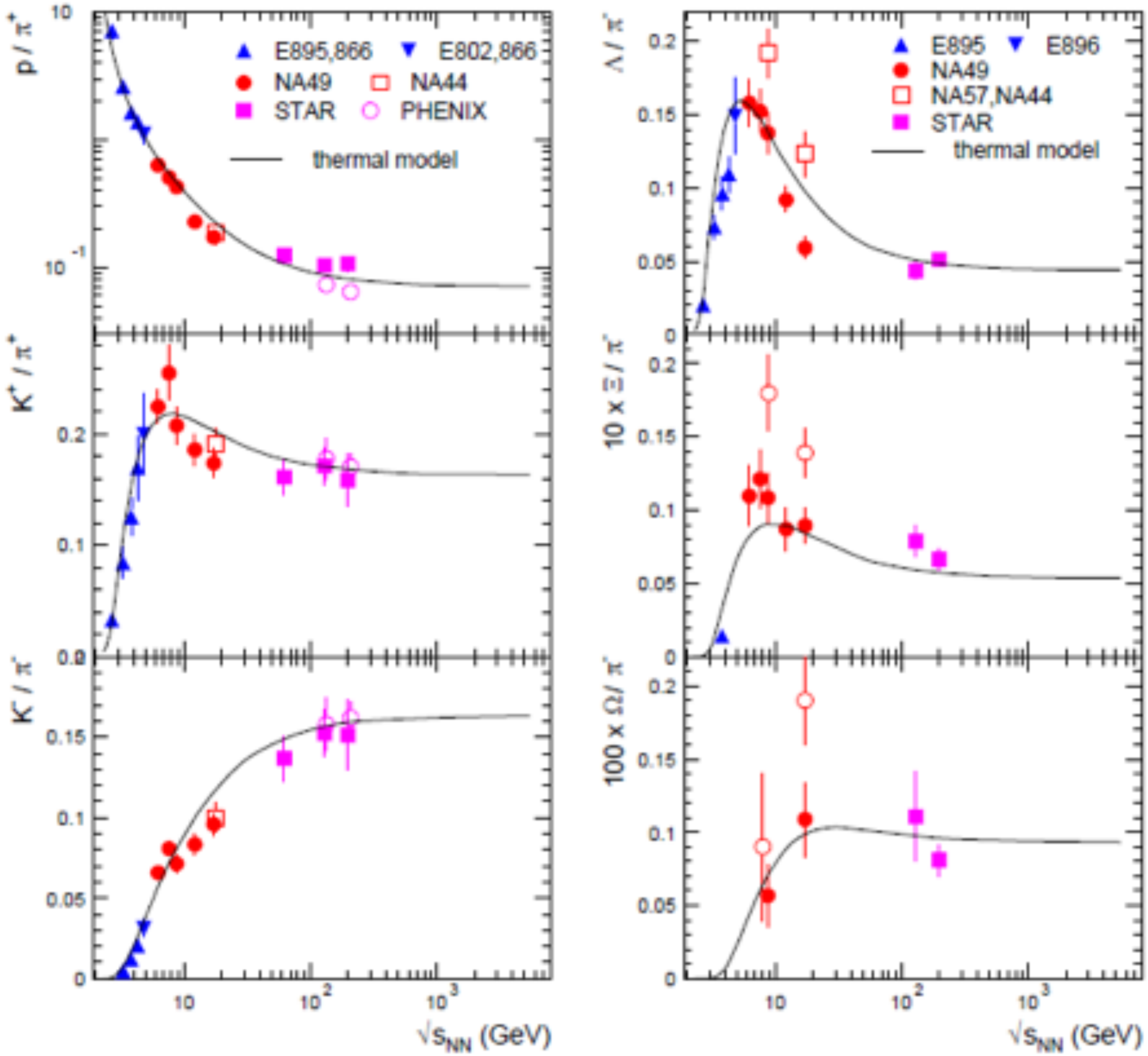
Estimate from HRG (w/o QCP)



Baryon density is GREATER than normal nuclear density around where people conjecture QCP!?

QCD Triple Point

Densest = Strangest



More baryons

↓

More Λ, Ξ, Ω

↓

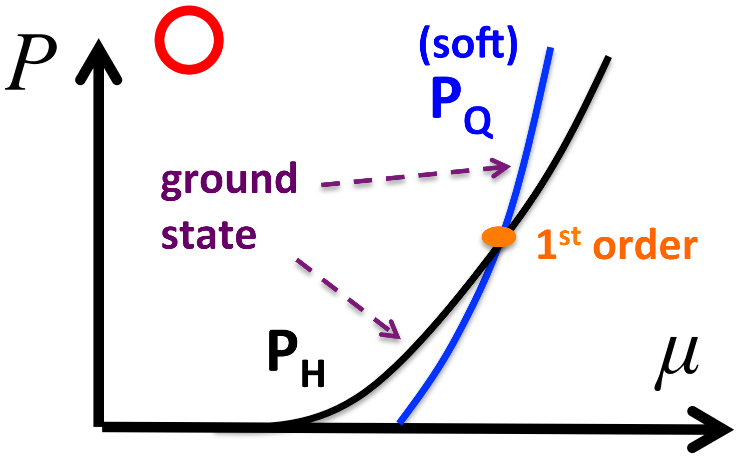
More K^+

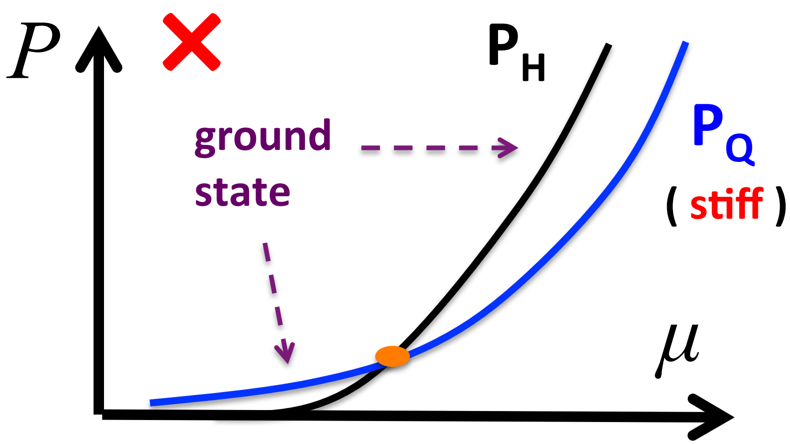
$(n_s = 0)$

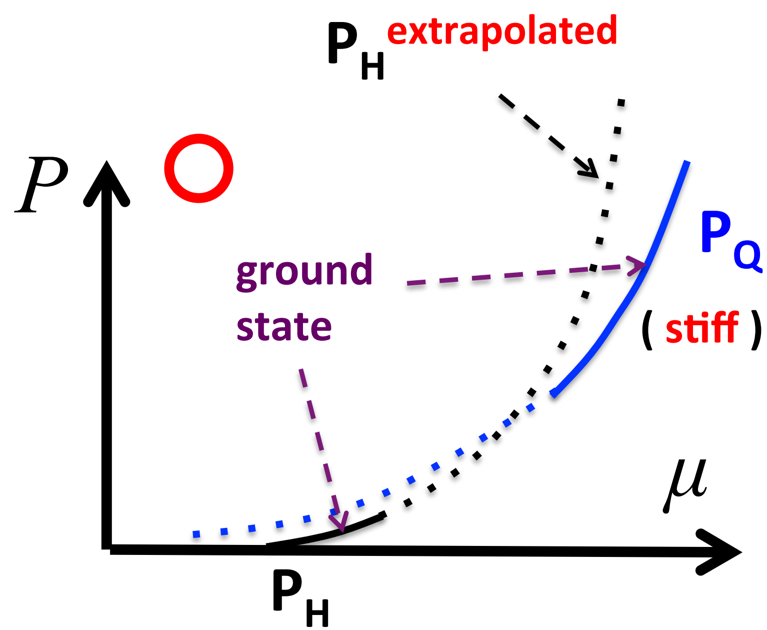
Serious problem
in neutron star phys.
* Soft EoS
* Fast cooling

Neutron Star EoS

QM talk by Toru Kojo



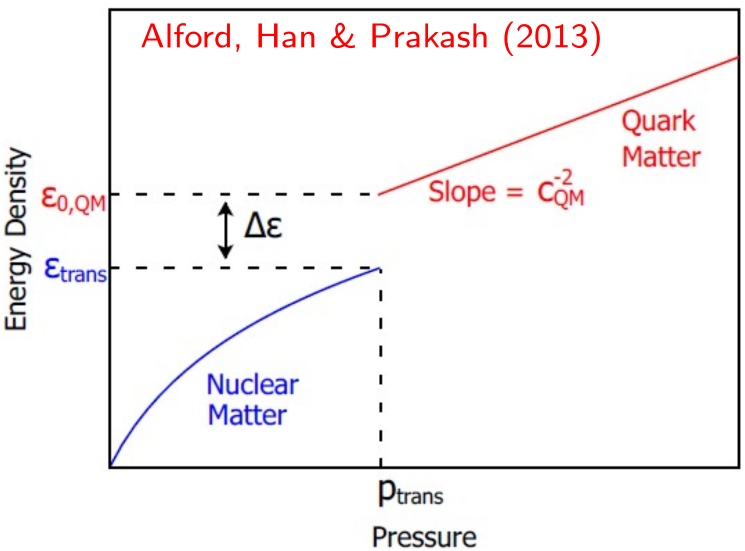


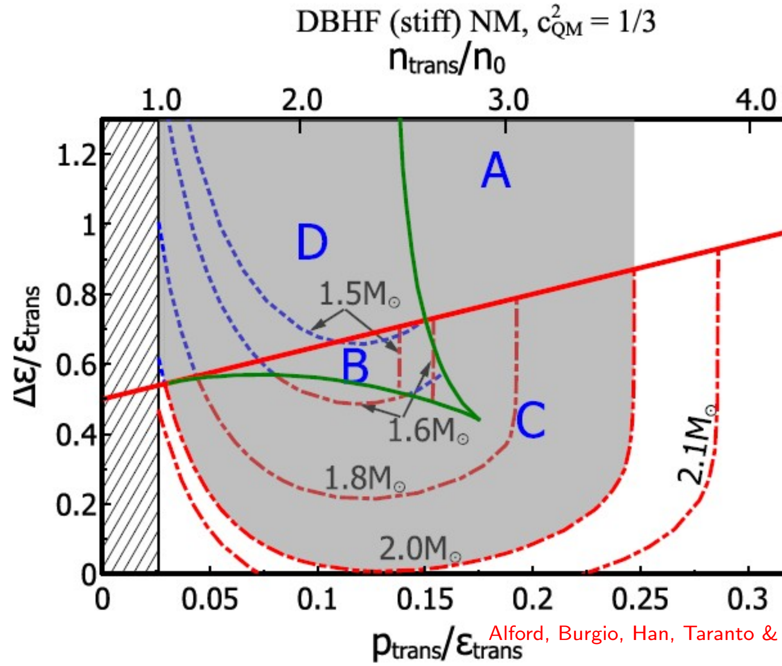


stiff **quark EoS** ***possible***

Researcher, physicist and astronomer James Lattimer

No quark matter in NS!





Alford, Burgio, Han, Taranto & Zappalá (2015)

No (very weak) 1st-order
1st-order at very high density

Question

No Microscopic Dynamics…

You can say nothing about :

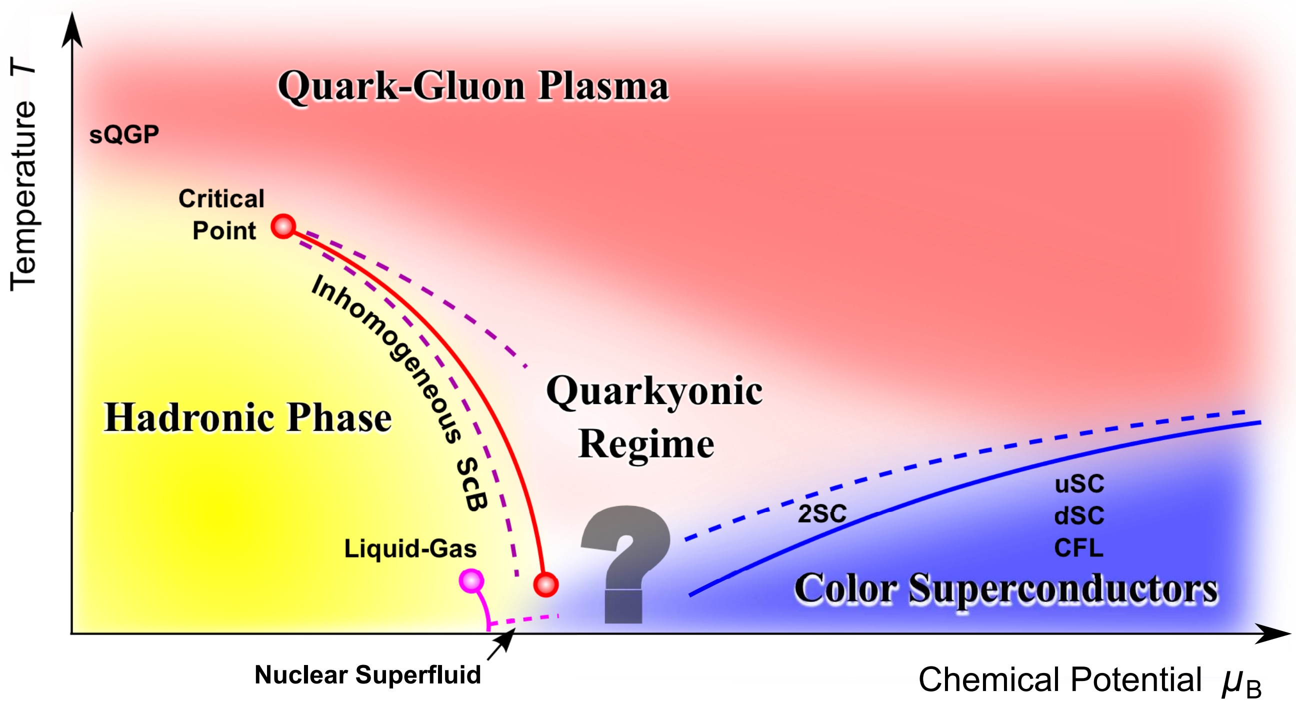
Whether you have nuclear / quark matter?
How much strangeness you have?
What is the rate of cooling you expect?

We need something more concrete!

Larry's Puzzle

fishy, fishy, fishy…
QCP consistent with NS?

Possible answer
↓
Another CP



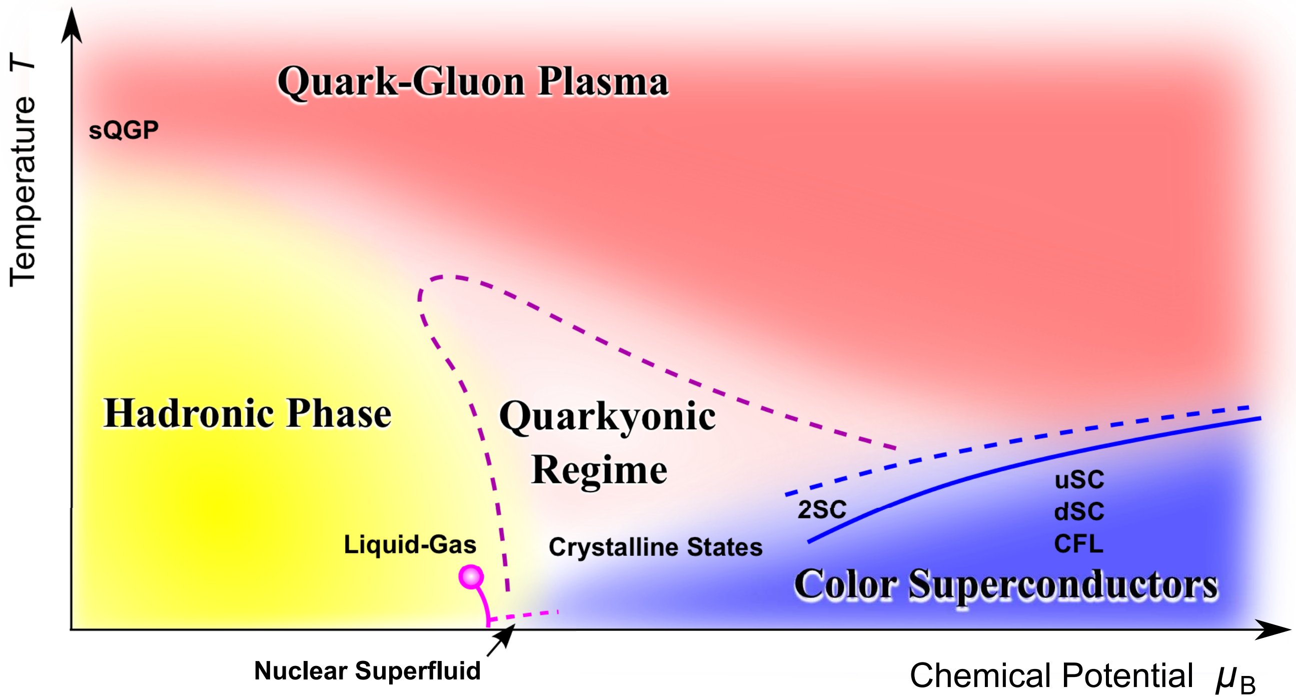
Larry's Puzzle

fishy, fishy, fishy…
QCP consistent with NS?

Possible answer

↓

NO CP



Nuclear Matter = Quark Matter

What if a diquark condensates

$\langle ud \rangle$ does not break any symmetry

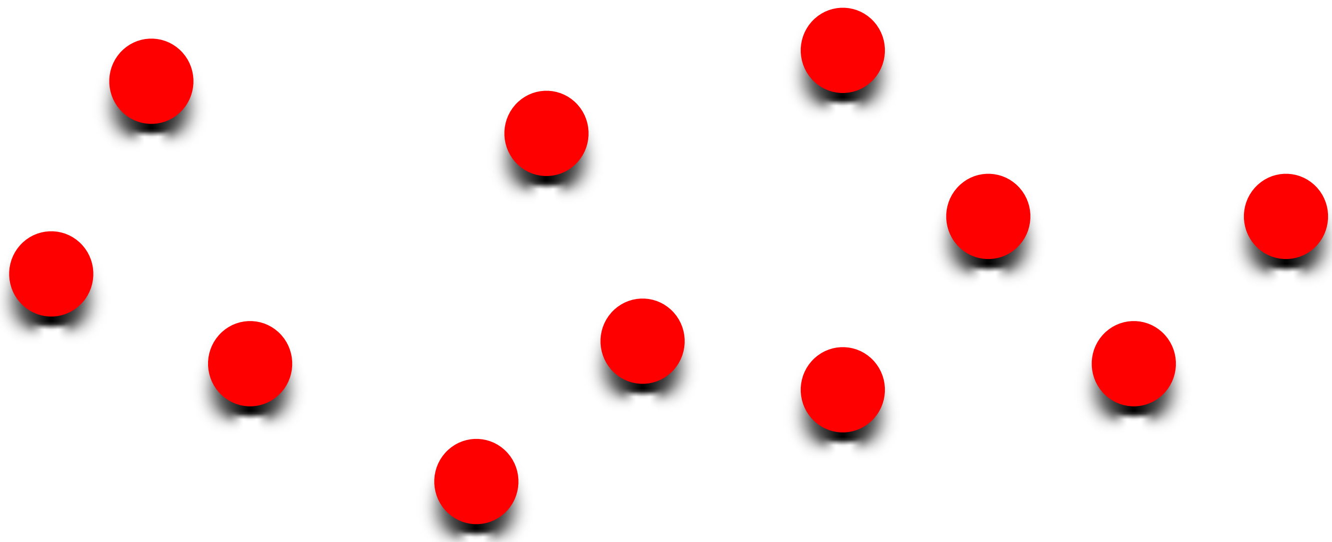
2SC can coexist in nuclear matter !? (Fukushima-Kojo)

$\langle ud \rangle, \ \langle \bar{u}u \rangle, \ \langle \bar{d}d \rangle$ can coexist

Quark Matter (CSC) and Nuclear Matter : indistinguishable

(3-flavor symmetric) CFL has more elegant arguments

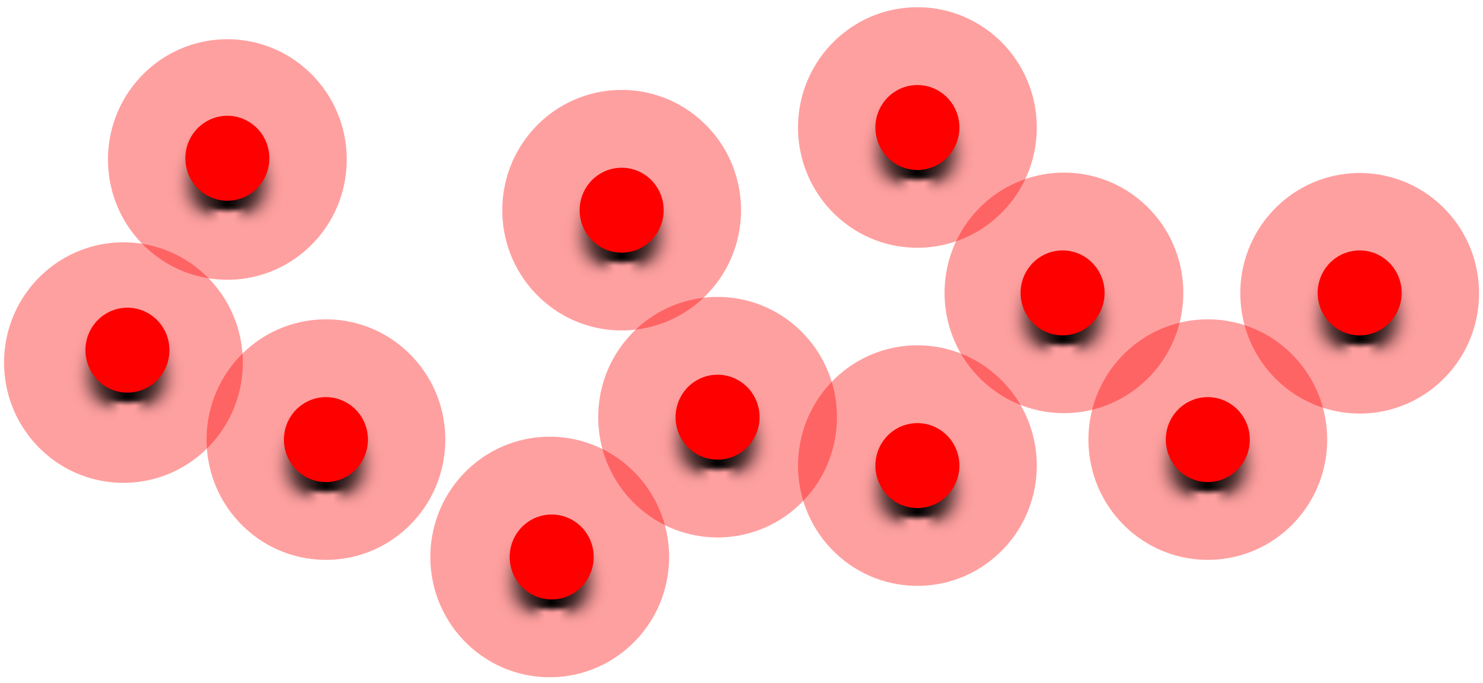
Deconfinement at High T



No interaction $\longrightarrow$ No saturation

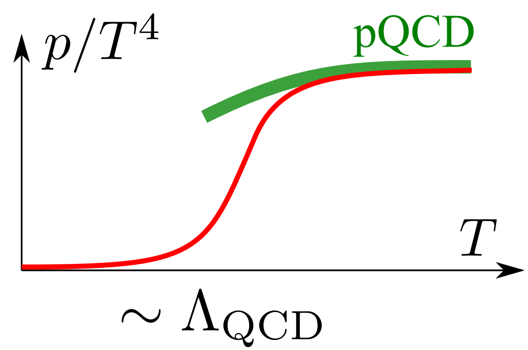
(Large-N_c QCD : Non-interacting mesons)

Deconfinement at High T



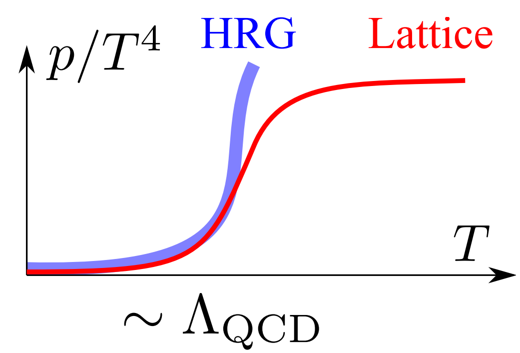
Crossover = Almost free gas + Finite extent

Dual Descriptions at High T



Introduction of Polyakov loop
(center-symmetric model: Vuorinen-Yaffe)

Introduction of confinement
(Gribov-Zwanziger: talk by Nan Su)

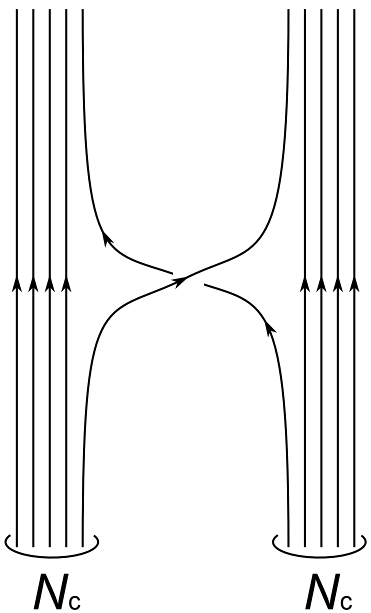


Hadronic EoS can be reproduced in terms of partonic degrees of freedom

Very useful for smooth extrapolation to high *T*

Deconfinement at High N_B

Interaction never goes off



Quarks exchanged in *NN* int.
Confined? Deconfined?

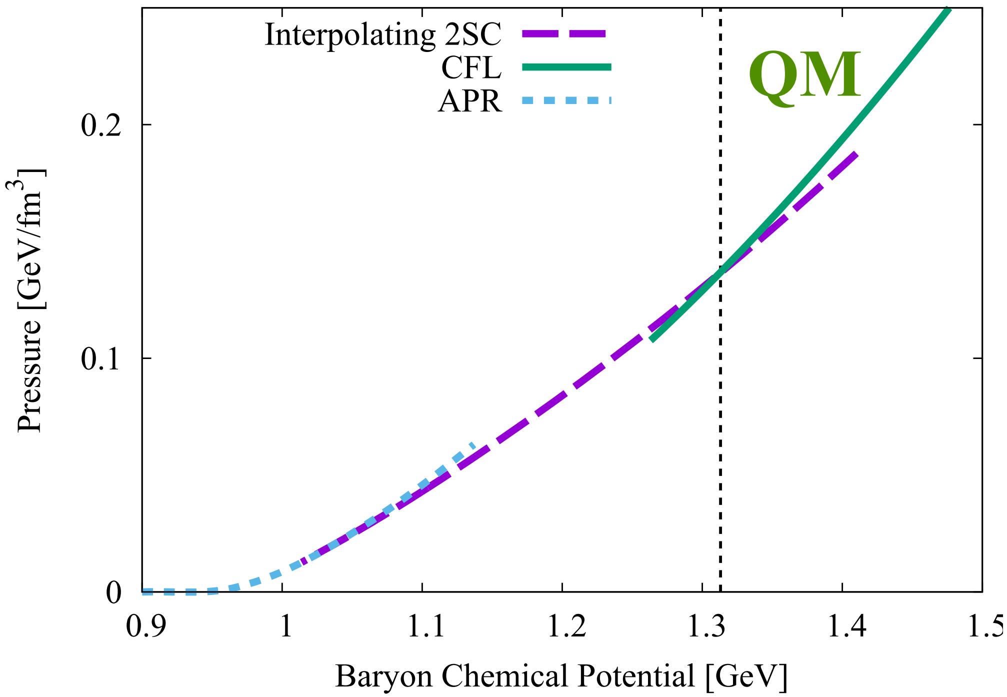
Deconfined when *NN*, *NNN*, *NNNN*…
all become of the same order

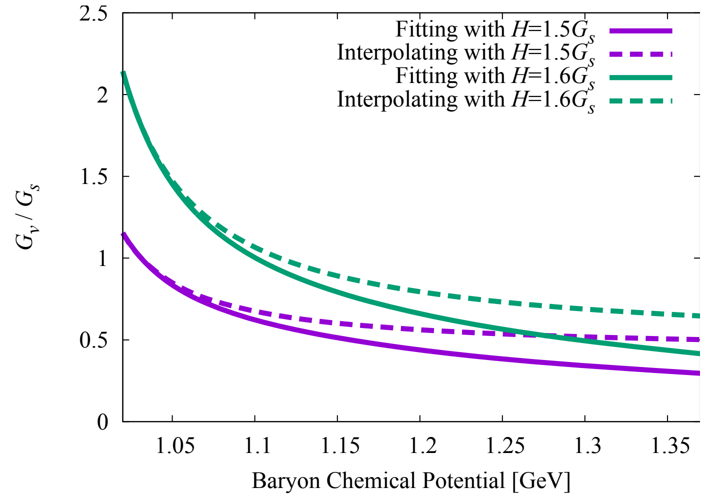
Kojo et al. (2014)

Nuclear matter is already deconfined

~ quarkyonic matter

Dual Descriptions at High N_B





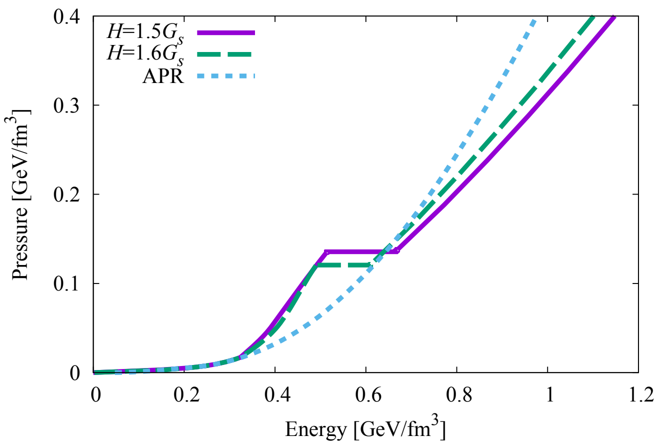
$$G_{\rm v}(\mu_{\rm B})/G_{\rm s} = \frac{a}{\log[(\mu_{\rm B}-b)/c]} + d$$

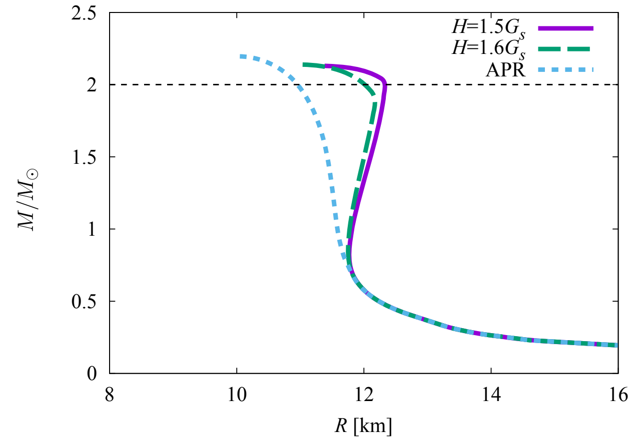
Established NM EoS

Conventional inverse-log naturally appears from the fit to NM EoS… accidental???

Fukushima-Kojo (2015)

Quarkyonic Star

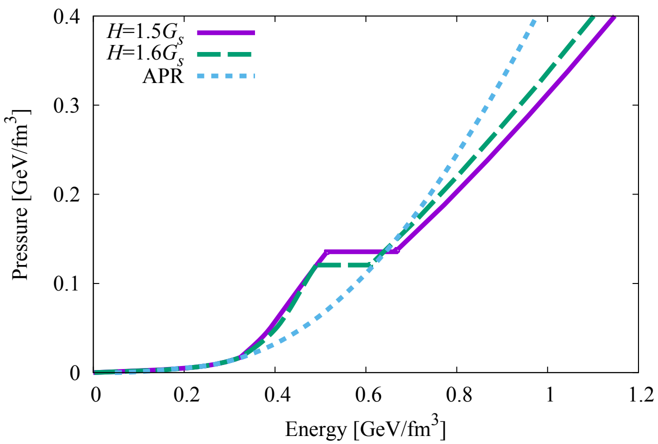


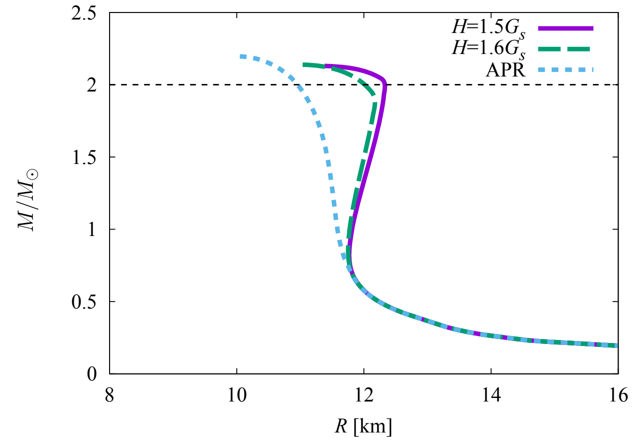


Severe constraint onto model space

* g_v (vector) should be large to support $>2M_\odot$
* H (diquark) should be large to be dual to NM
* H (diquark) should be small not to violate causality
* 1st-order from 2SC to CFL unavoidable (strangeness)

Quarkyonic Star





Severe constraint onto model space

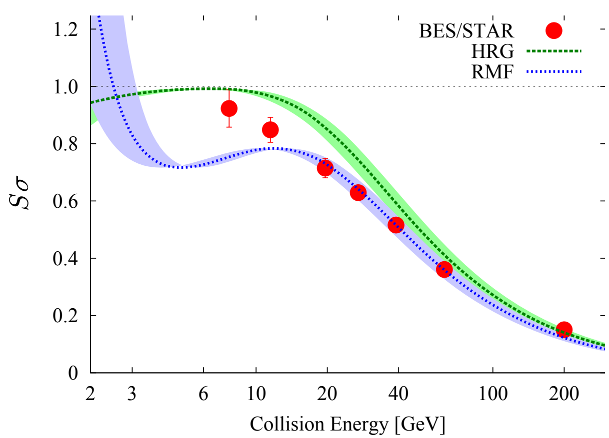
*** g_v (vector) should be large to support $>2M_\odot$**

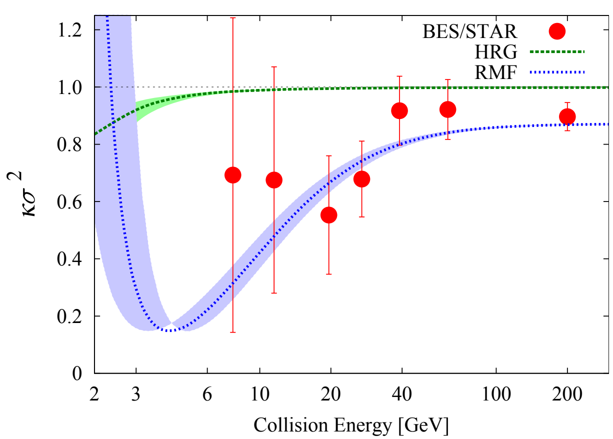
Impossibly difficult to build a model that has
- Diquark-driven quarkyonic matter
- QCD critical point

Coming back to HIC

Astrophysical constraints are quite useful
Once we have a reliable description of nuclear/quark matter, we can easily extrapolate it to finite *T* accessed by BES.

***One example*: what happens if we calculate Kurtosis using a conventional NM model (Walecka-model).**





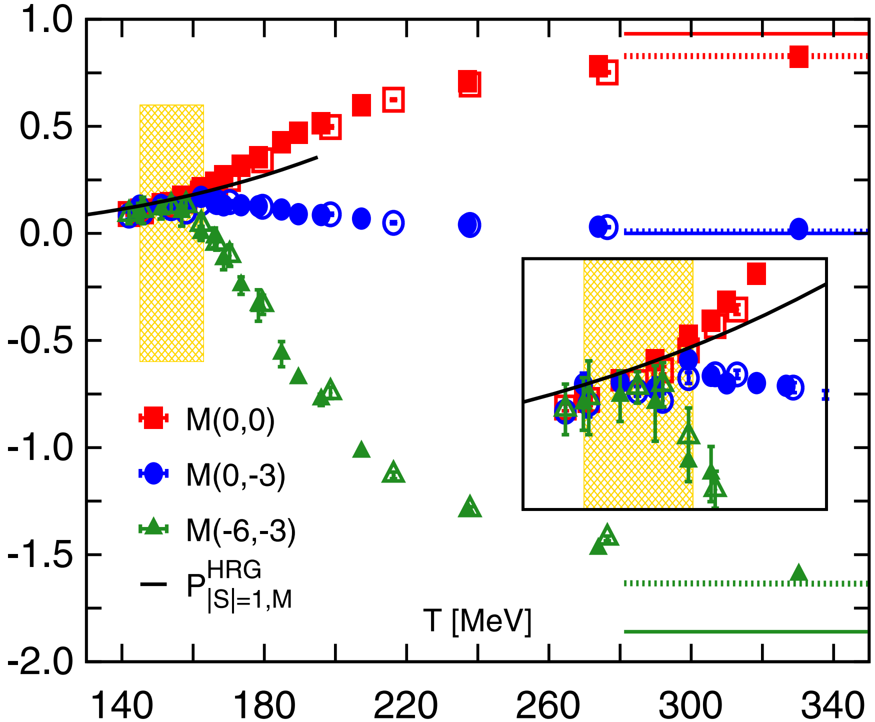
Comparison with "old" STAR data

Fukushima (2014)
cf. Floechinger-Wetterich

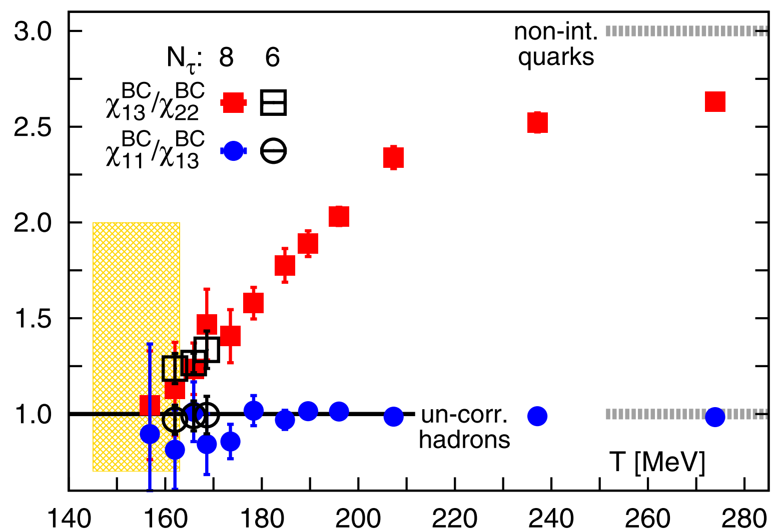
Key Questions

- **IF the QCP signal in Kurtosis is real, what happens for Skewness? Similar anomaly seen?**
- **Inhomogeneous phase? ALL models favor inhomogeneous phases than the QCP so far…**
- **Signal for 1st-order phase transition? Mixed phase / inhomogeneous phase**
- **Strangeness??? Heavier flavor???**

Still need more digestions



BNL-Bielefeld (2014/15)



Deviations from HRG in the strange/charm sectors

Talk Slide of Maezawa (Bielefeld-BNL)

Non-interacting Meson-Baryon gas system

$$\frac{P^{\mathrm{HRG}}}{T^4} = \sum_{i\in\mathrm{meson}} \frac{g_i}{\pi^2}\left(\frac{m_i}{T}\right)^2 K_2\left(\frac{m_i}{T}\right)\cosh(S_i\hat{\mu}_S) + \sum_{i\in\mathrm{baryon}} \frac{g_i}{\pi^2}\left(\frac{m_i}{T}\right)^2 K_2\left(\frac{m_i}{T}\right)\cosh(B_i\hat{\mu}_B + S_i\hat{\mu}_S)$$

$$\underbrace{=M_0}_{\pi^\pm,\pi^0,\rho,\cdots} + \underbrace{M_1\cosh(-\hat{\mu}_S)}_{K,K^\pm,\bar{K}\cdots}$$

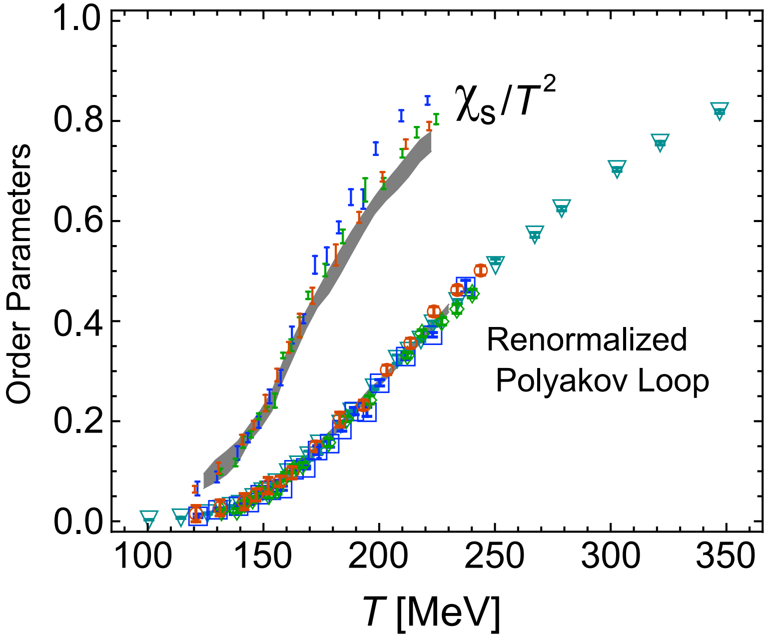
$$+\underbrace{B_0\cosh(\hat{\mu}_B)}_{N,\Delta,N^*,\cdots} + \underbrace{B_1\cosh(\hat{\mu}_B-\hat{\mu}_S)}_{\Lambda,\cdots} + \underbrace{B_2\cosh(\hat{\mu}_B-2\hat{\mu}_S)}_{\Xi,\cdots} + \underbrace{B_3\cosh(\hat{\mu}_B-3\hat{\mu}_S)}_{\Omega,\cdots}$$

Relation to susceptibilities (up to 4th order)

$$\begin{array}{rclcccc}
\chi_2^B & = & & B_0 + & B_1 + & B_2 + & B_3 \\
\chi_4^B & = & & B_0 + & B_1 + & B_2 + & B_3 \\
\chi_{11}^{BS} & = & & & (-1)B_1 + & (-2)B_2 + & (-3)B_3 \\
\chi_{31}^{BS} & = & & & (-1)B_1 + & (-2)B_2 + & (-3)B_3 \\
\chi_2^S & = & (-1)^2M_1 & + & (-1)^2B_1 + & (-2)^2B_2 + & (-3)^2B_3 \\
\chi_{22}^{BS} & = & & & (-1)^2B_1 + & (-2)^2B_2 + & (-3)^2B_3 \\
\chi_{13}^{BS} & = & & & (-1)^3B_1 + & (-2)^3B_2 + & (-3)^3B_3 \\
\chi_4^S & = & (-1)^4M_1 & + & (-1)^4B_1 + & (-2)^4B_2 + & (-3)^4B_3
\end{array}$$

$\chi_2^B - \chi_4^B = 0$: constraint for u, d quarks

Strangeness



Strangeness fluctuations
~ Deconfinement order param.

Zero net strangeness
→ No fluctuation
Strong correlation of *B* and *S*

Strangeness fluctuation ~ Probe for sQuarkyonic
Calculations (predictions) in progress using HRG