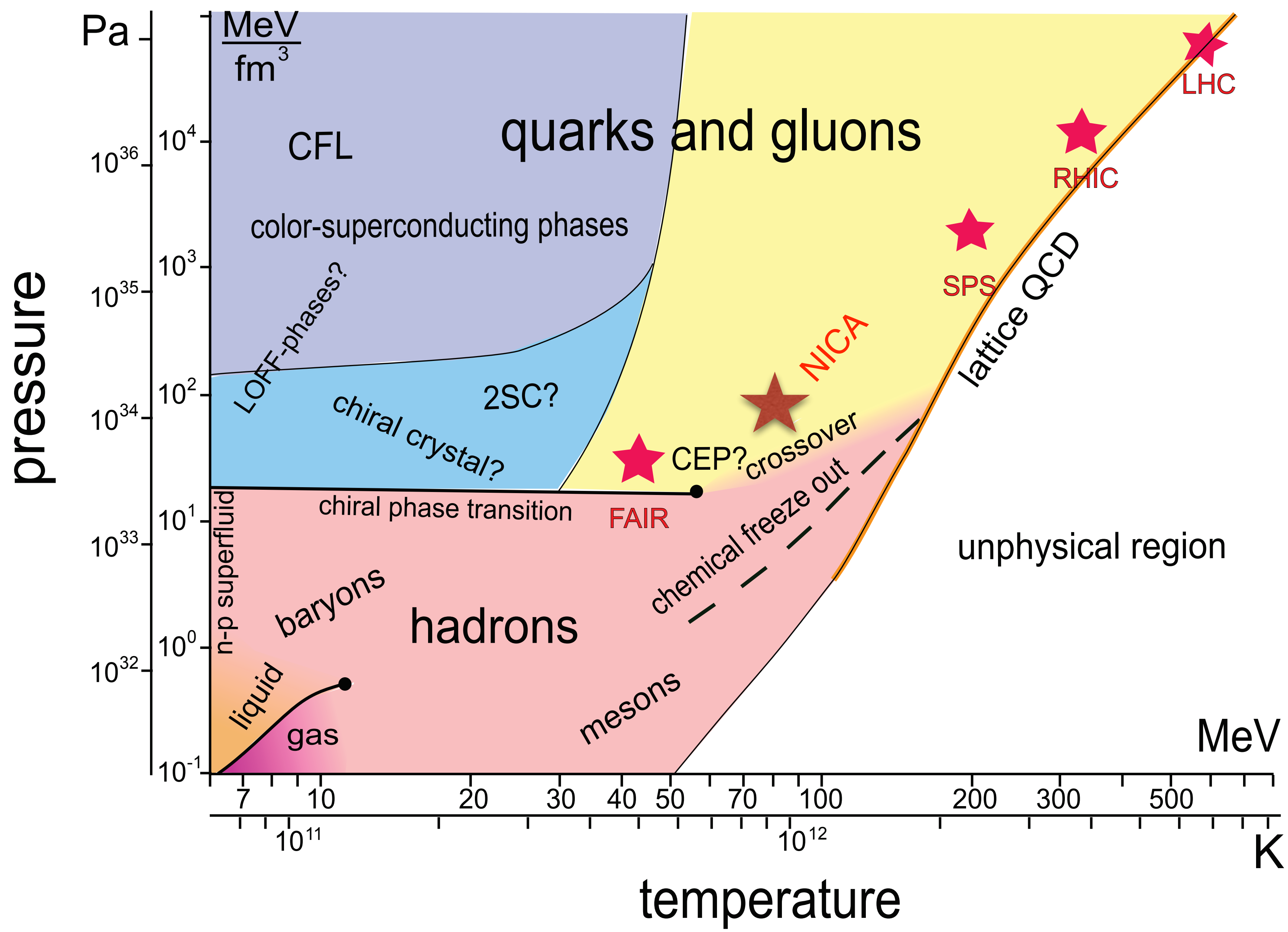
Nuclear and quark matter:
exploring the QCD phase diagram

Bengt Friman
GSI



Phase diagrams

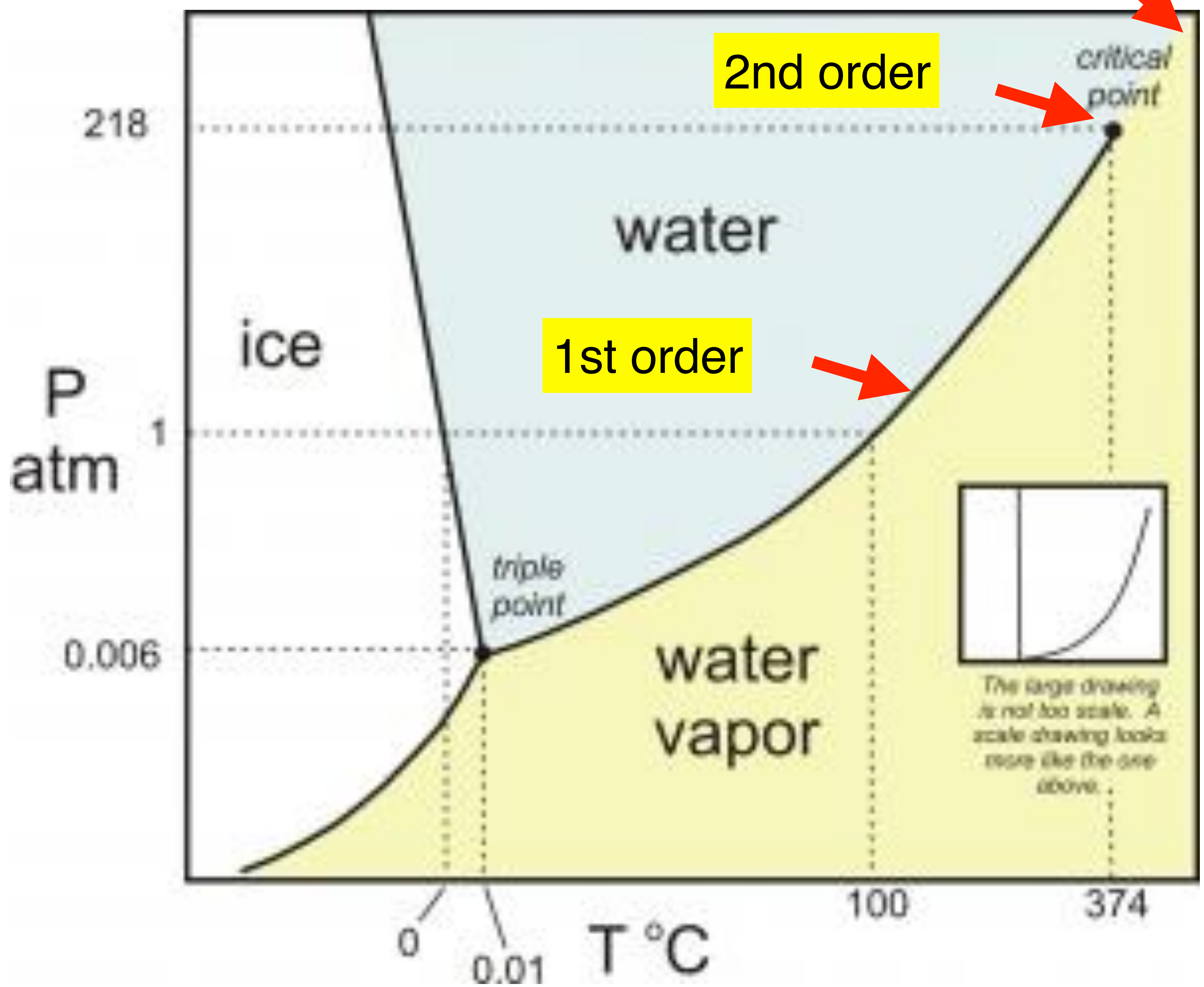
- Maps showing the state of a substance in equilibrium conditions

- Phase boundaries: phase transitions

- 1st order:
  - Latent heat
- 2nd order:
  - Fluctuations
- Cross over:
  - Smooth transition

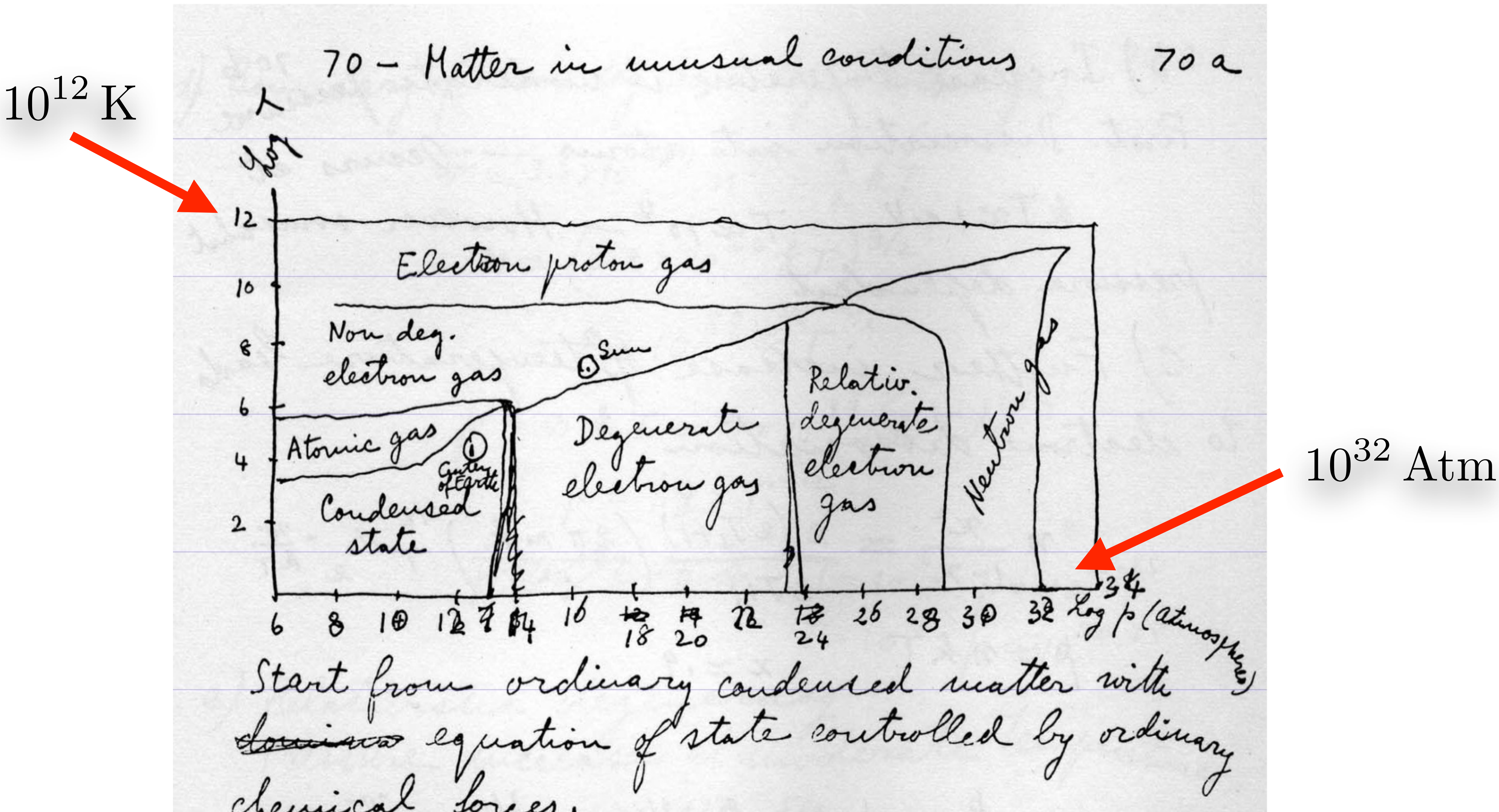
Continuous

Cross over



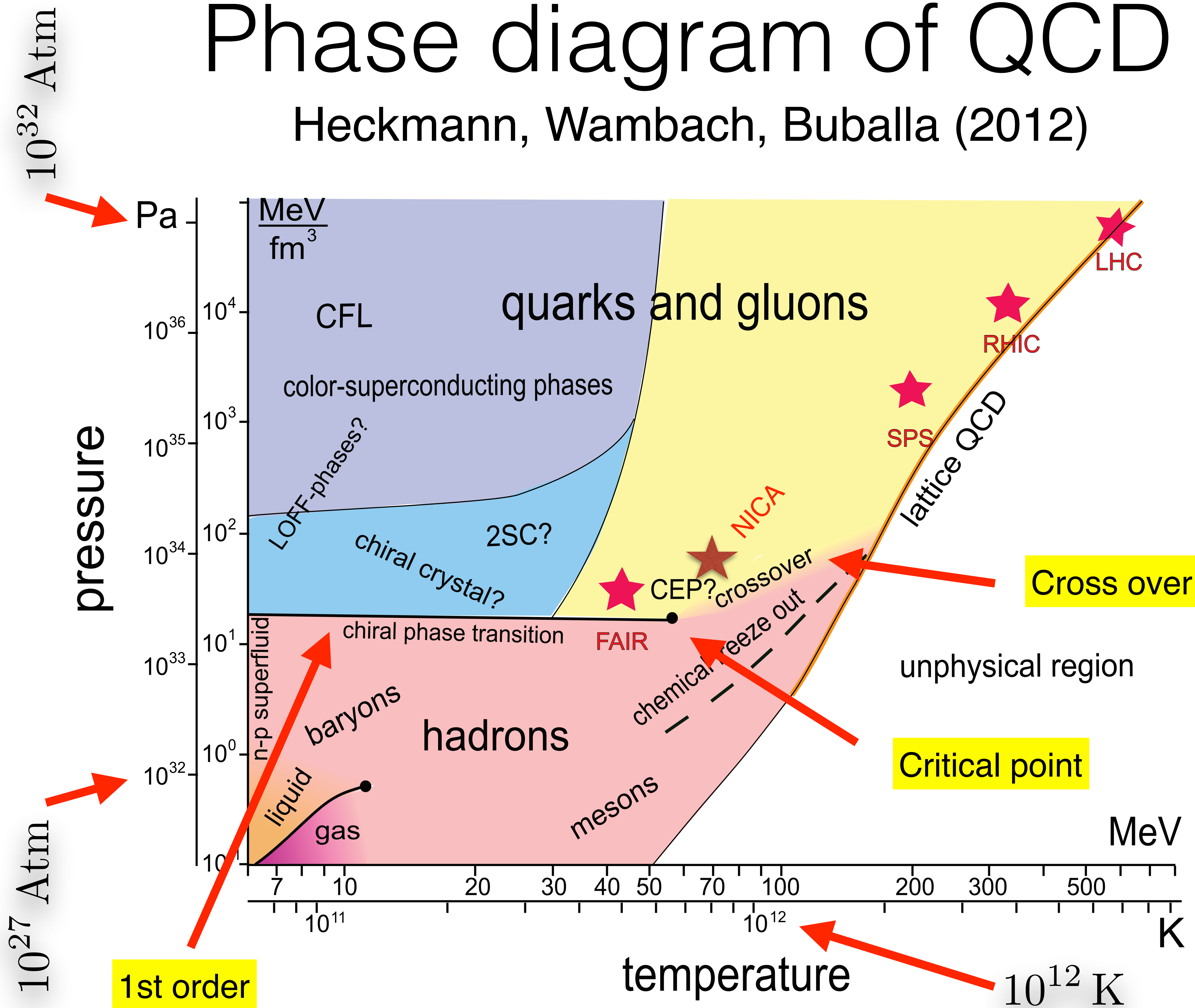
Matter in “unusual conditions”

Enrico Fermi (1953)



Phase diagram of QCD

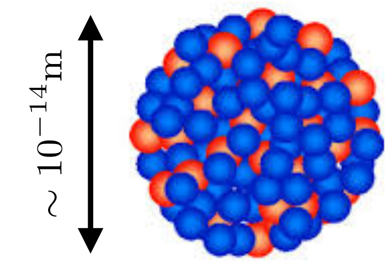
Heckmann, Wambach, Buballa (2012)



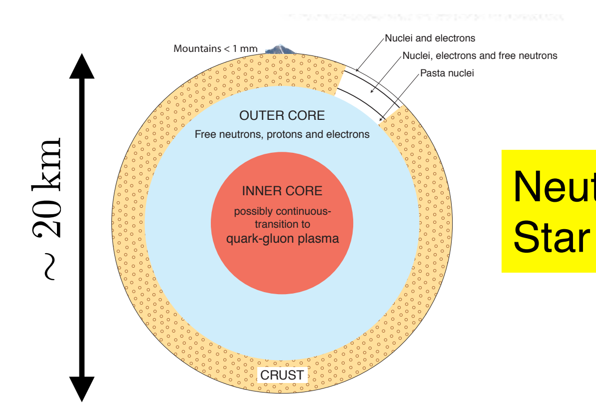
Matter at the extreme

- Densest and hottest substances being studied

  - Nuclear/Quark Matter:
    interior of nuclei, neutron stars
    (cold and dense)



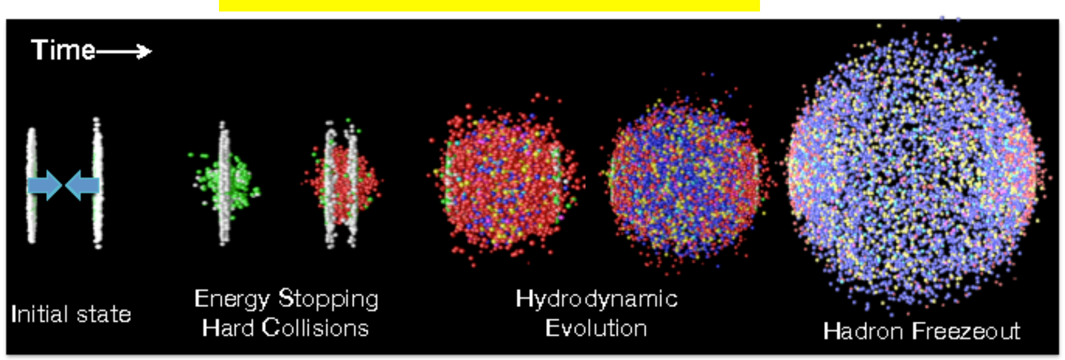
Nucleus



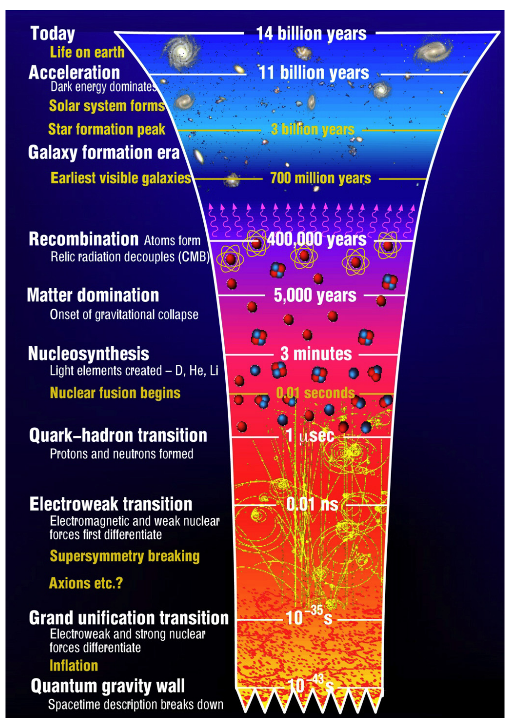
Neutron Star

  - Quark-Gluon plasma:
    ultra-relativistic nucleus-nucleus collisions, early universe (hot and dense)

Nucleus-nucleus collisions



Early Universe



Quantum Chromo Dynamics

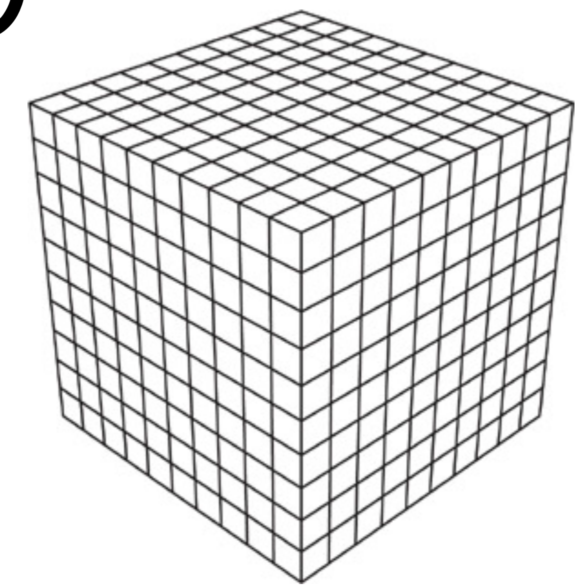
- Describes the interaction between quarks and gluons, the strong interaction

- Quarks and gluons carry color charge

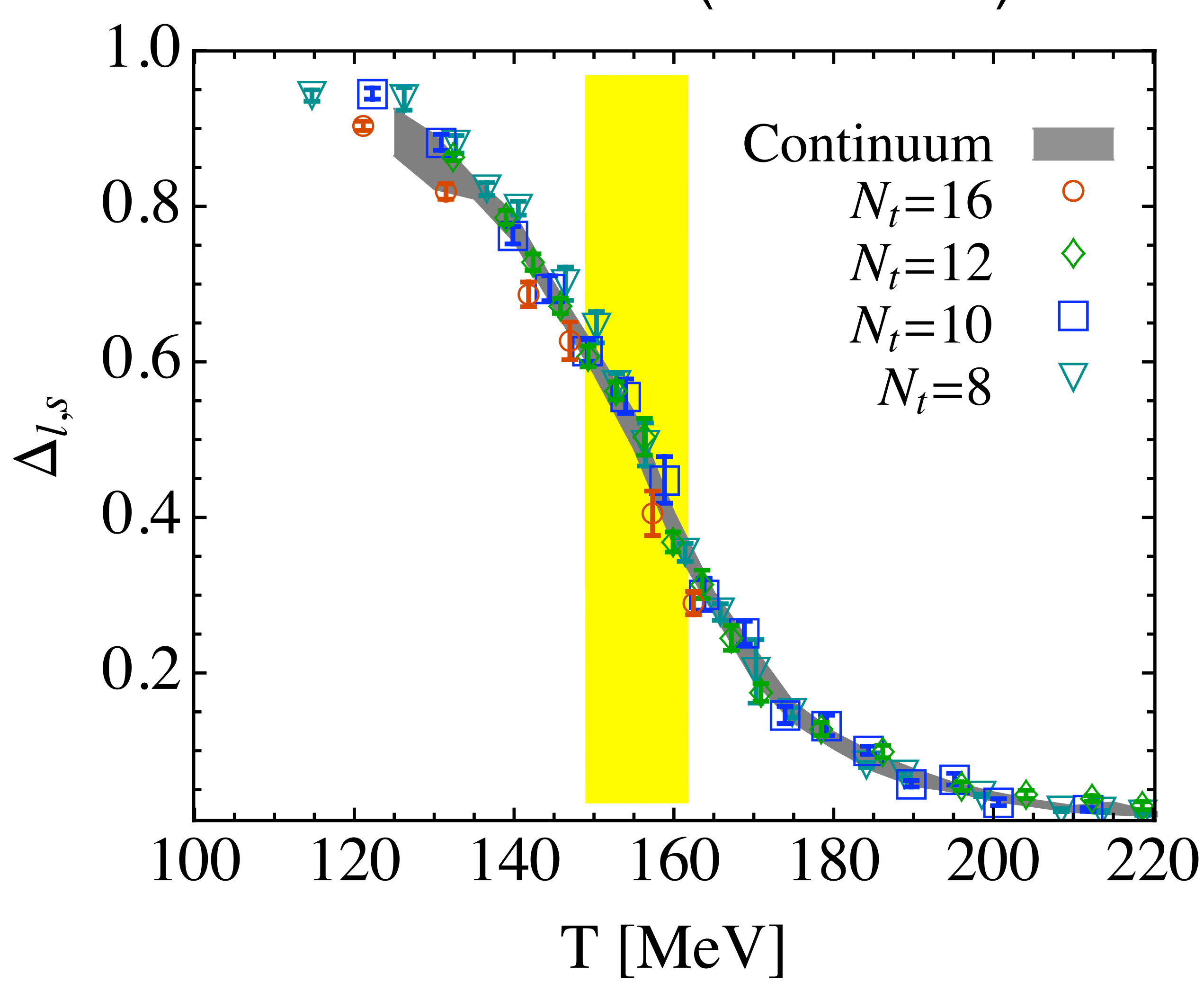
- Symmetries of QCD
  - Color SU(3): confinement of colored dof's
  - Chiral symmetry: right & left handed light quarks do not mix, spontaneously broken in vacuum
  - Expect two transitions @ large T: deconfinement + chiral restoration

Lattice QCD

QCD on a space-time grid

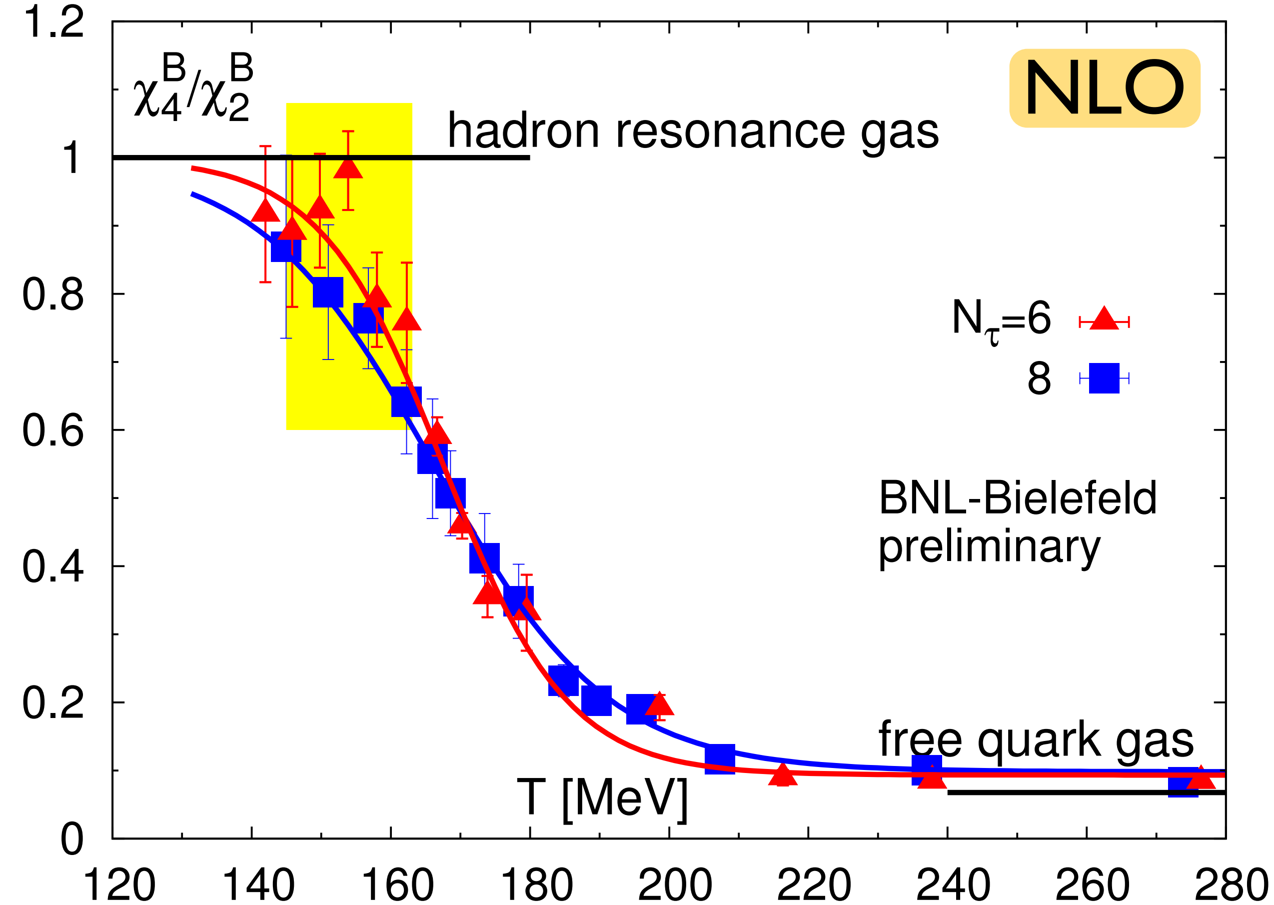


Chiral transition (cross over)



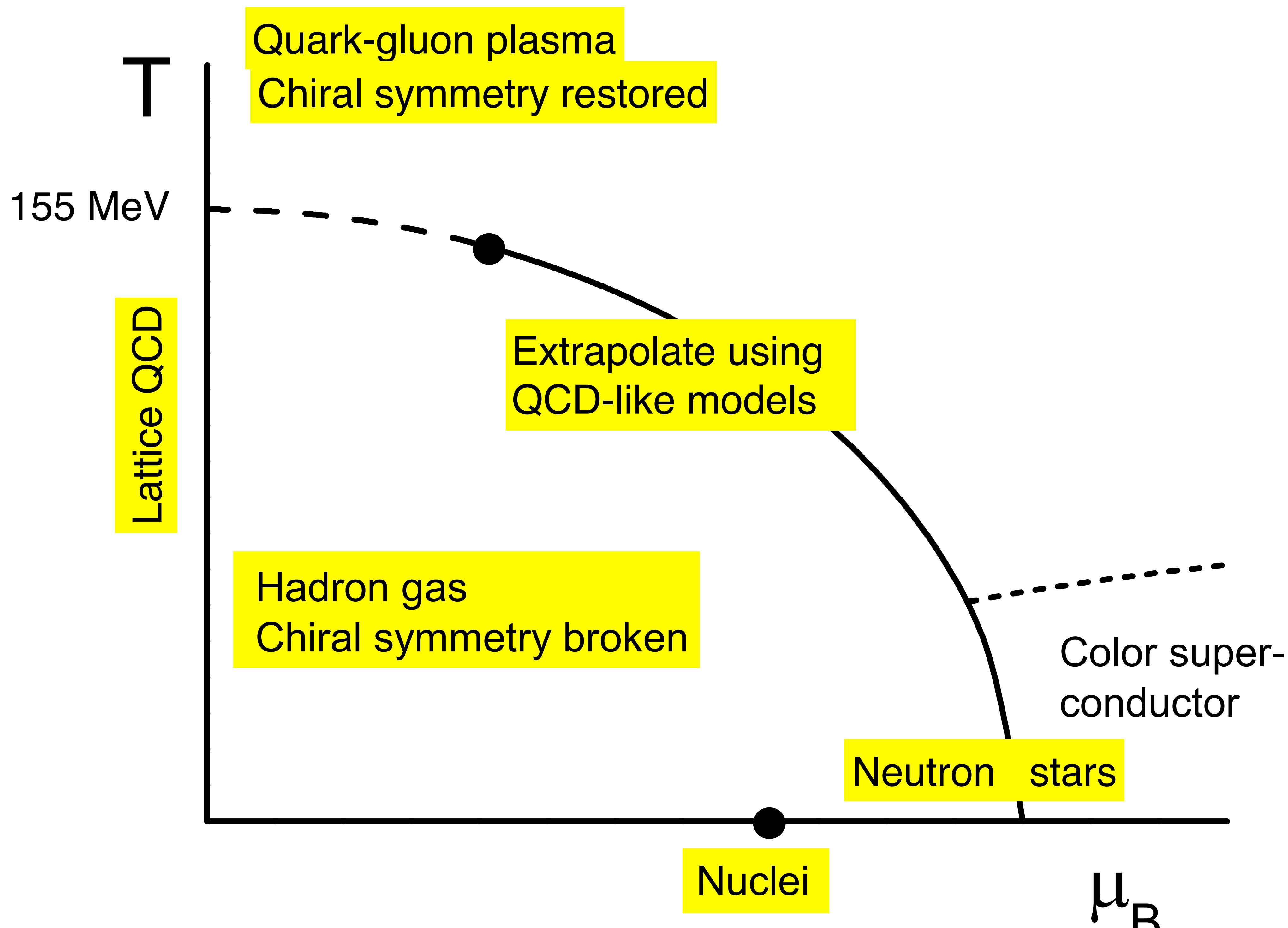
Borsanyi *et al. 2010*

Deconfinement (cross over)



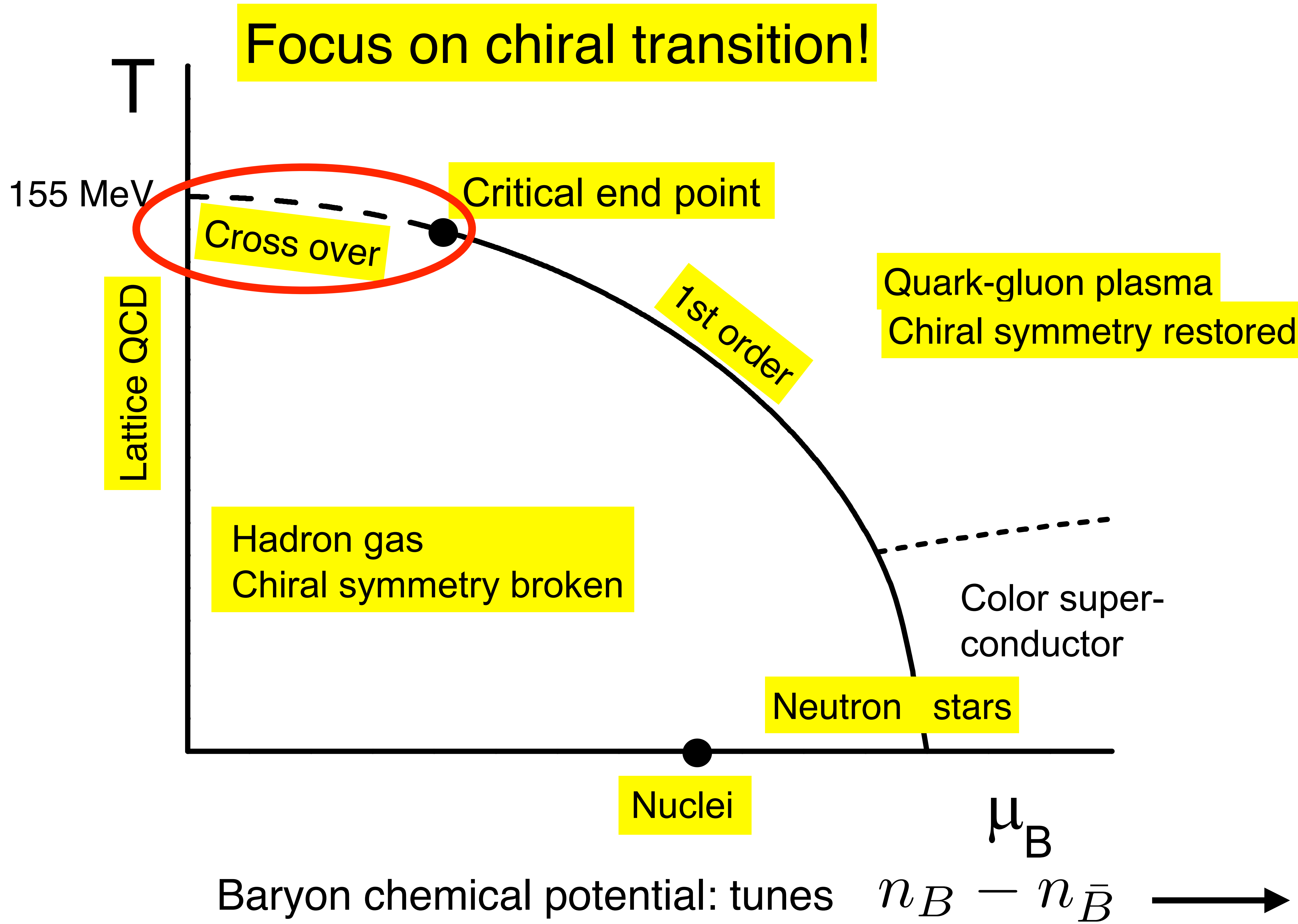
Bazavov *et al. 2012*

Phases of QCD matter?

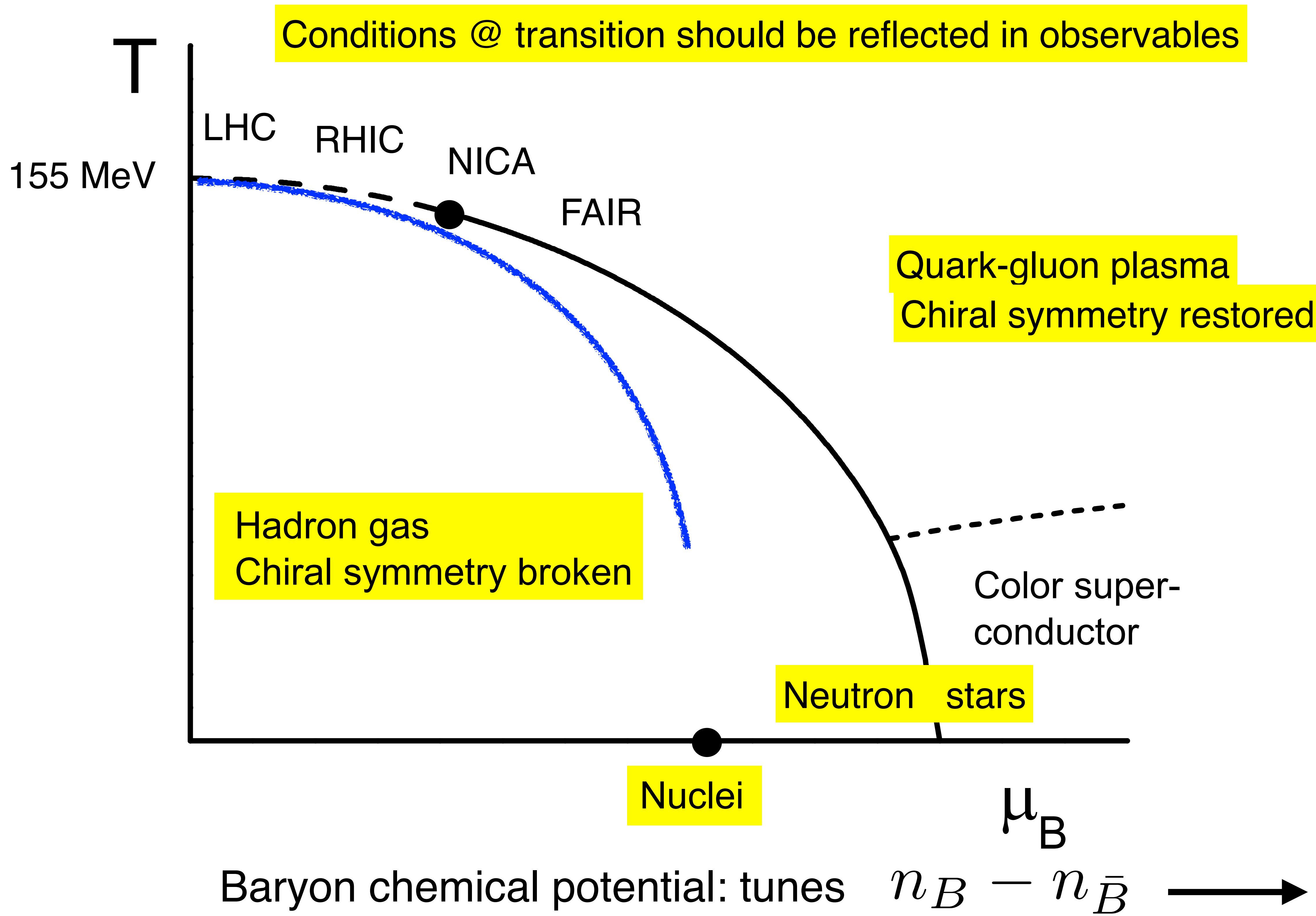


Baryon chemical potential: tunes $n_B - n_{\bar{B}}$ →

Phases of QCD matter?

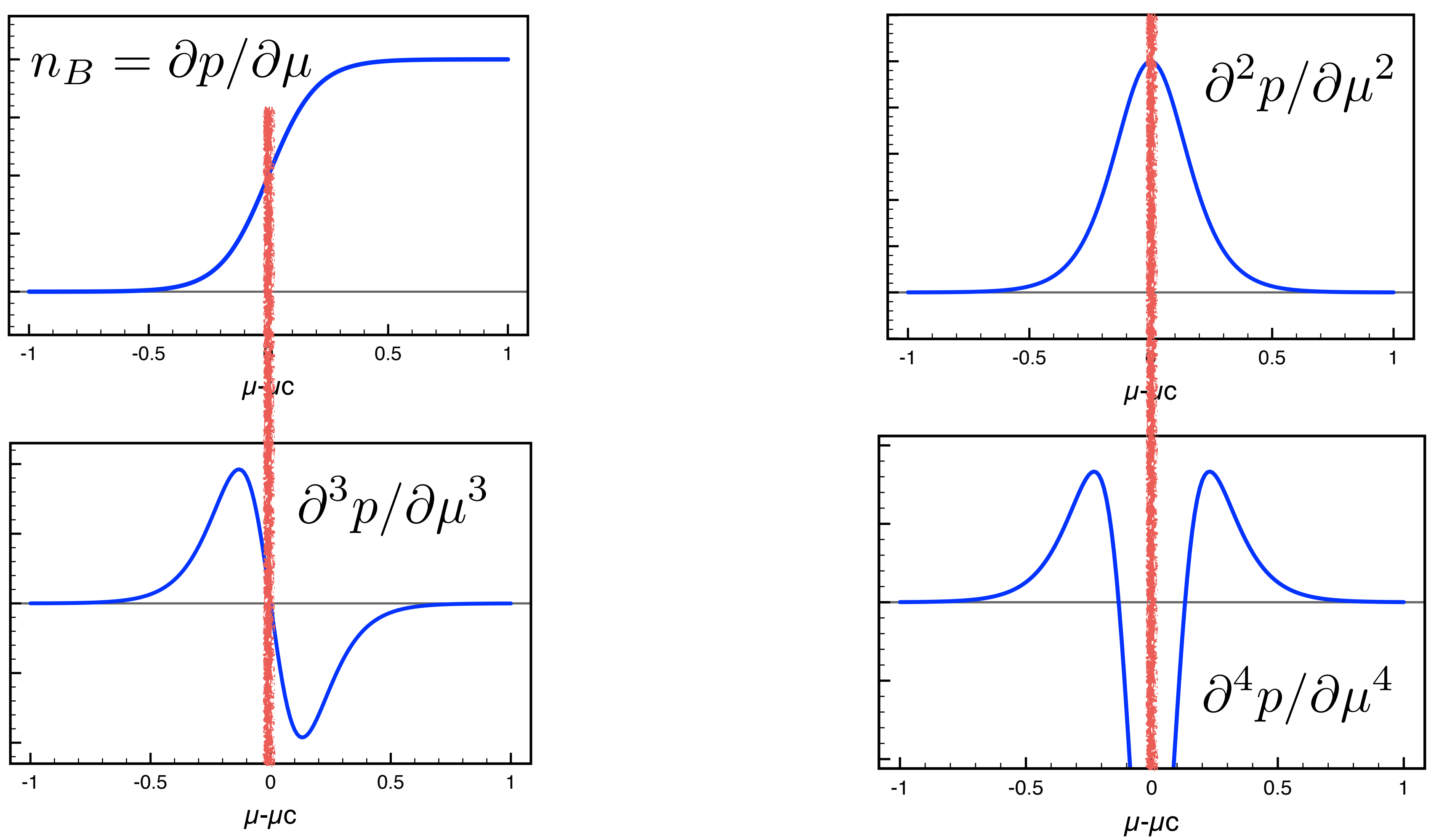


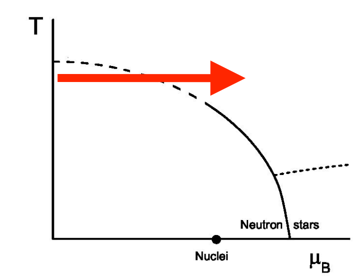
Freeze-out curve



Finding a smooth cross over?

- Explore phase diagram using critical fluctuations
- Fluctuations diverge @ critical point
- Smooth cross over → derivatives help!





Higher derivatives reveal criticality

Measuring derivatives?

- $$Z = \mathrm{Tr}\, e^{-(\hat{E}-\mu\hat{N}_B)/T} \qquad\qquad p = \frac{T}{V}\,\ln Z$$

- $$\langle N_B\rangle = \frac{1}{Z}\,\mathrm{Tr}\,\hat{N}_B\, e^{-(\hat{E}-\mu\hat{N}_B)/T} = \frac{\partial}{\partial\mu/T}\,\ln Z$$

- $$\chi_B^2 = \langle(\Delta N_B)^2\rangle = \langle N_B^2\rangle - \langle N_B\rangle^2 = \left(\frac{\partial}{\partial\mu/T}\right)^2 \ln Z$$

$$\Delta N_B = N_B - \langle N_B\rangle$$

- $$\chi_B^n = \langle(\Delta N_B)^n\rangle - \cdots = \left(\frac{\partial}{\partial\mu/T}\right)^n \ln Z$$

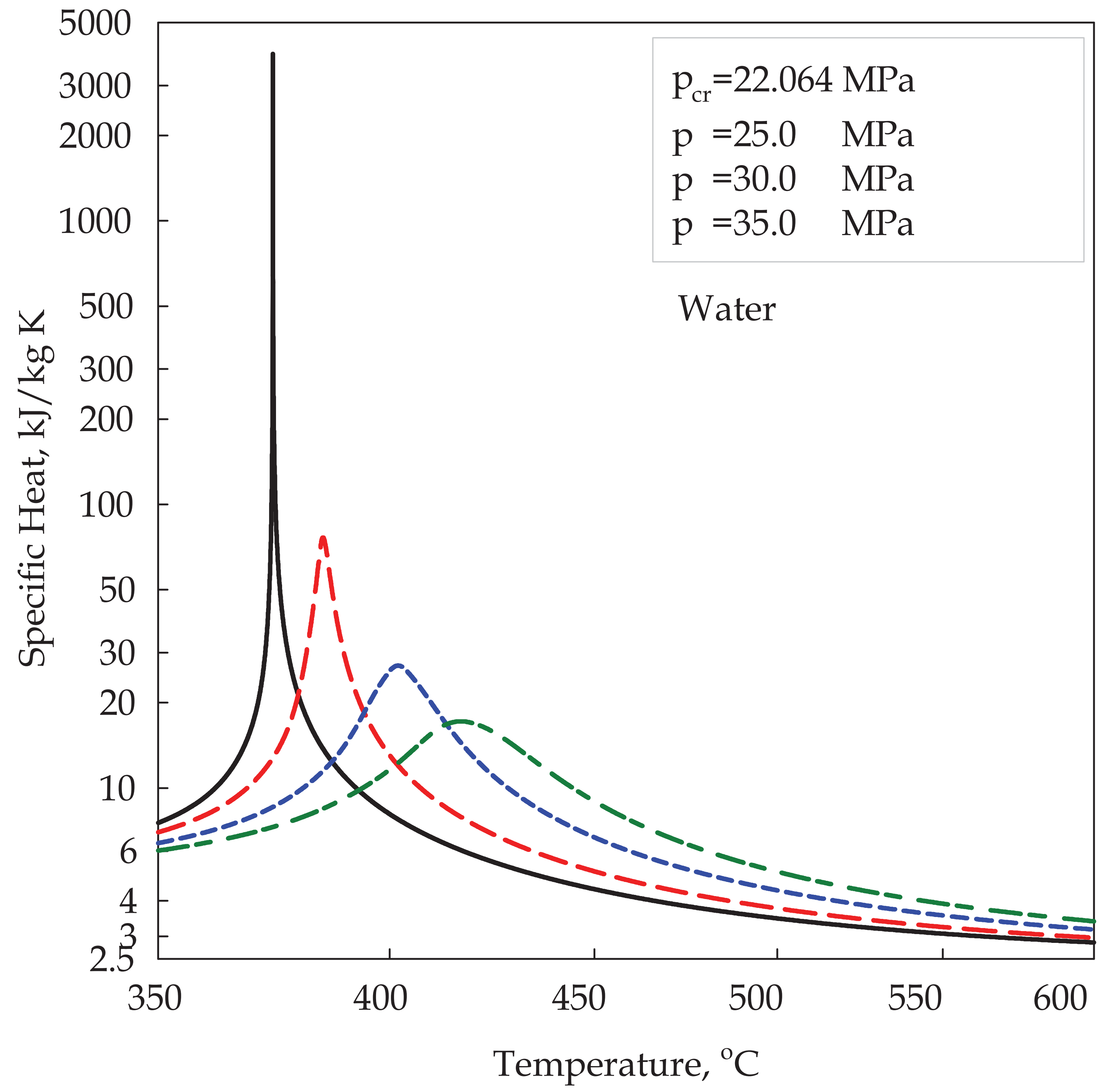
- Cumulants of baryon number fluctuations measure μ derivatives cross over transition!

Fluctuations in H_2O

- Specific heat near critical point of H_2O
- Fluctuation of Entropy diverges at CP!

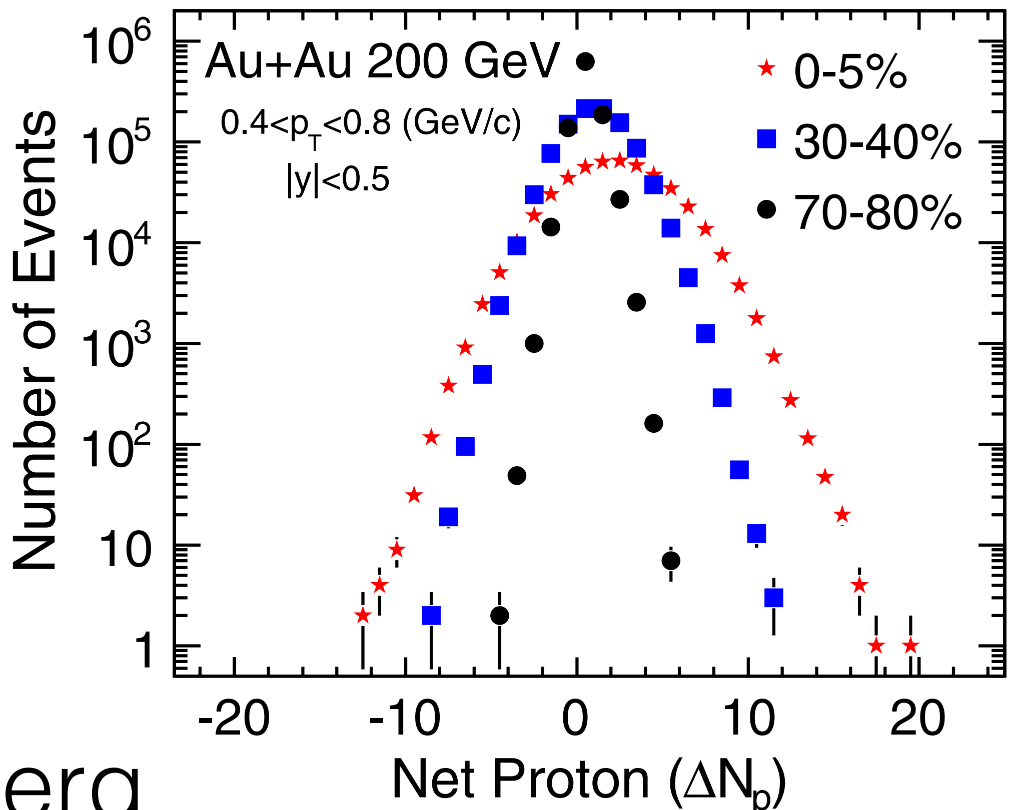
$$C_p = \langle S^2 \rangle - \langle S \rangle^2$$

- Fluctuations peaked at cross over trans.
- Explore fluctuations to localize continuous phase transitions



Where is the snag?

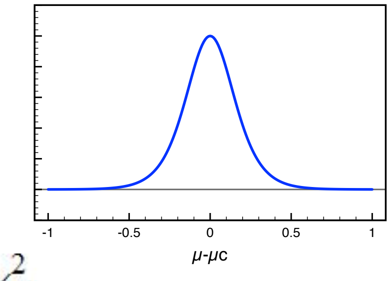
- Higher cumulants probe the tail of the distribution
    - Need high statistics both in experiment & theory
- Experiments don't measure neutrons
- Finite size & time effects: no diverg. Need to understand <u>all</u> other (non-critical) sources of fluctuations!
- Other complications: momentum space cuts, non-equilibrium effects …..

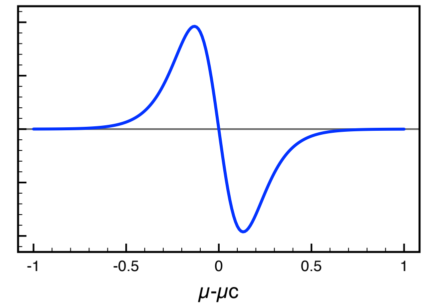


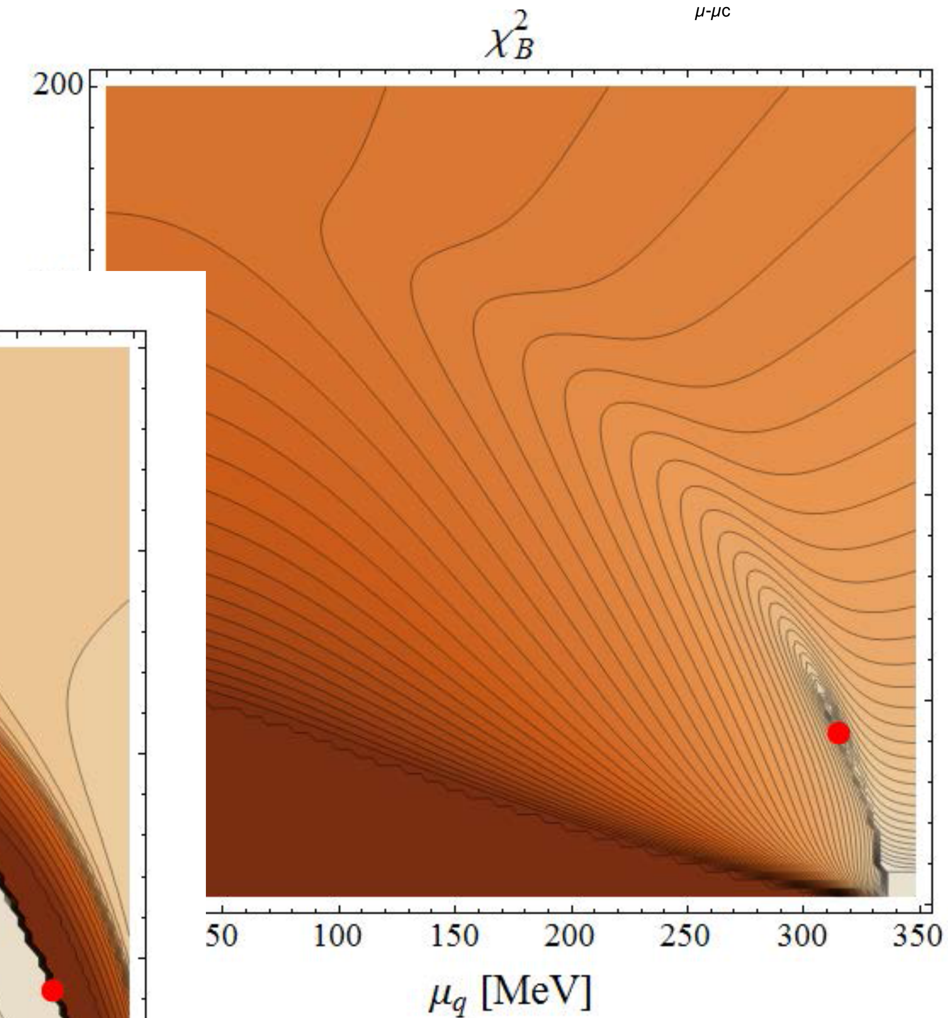
$$\Delta N_p = N_p - N_{\bar{p}}$$

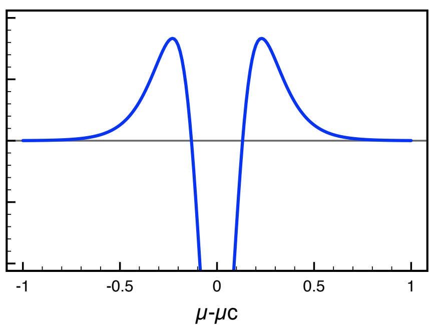
Model calculation

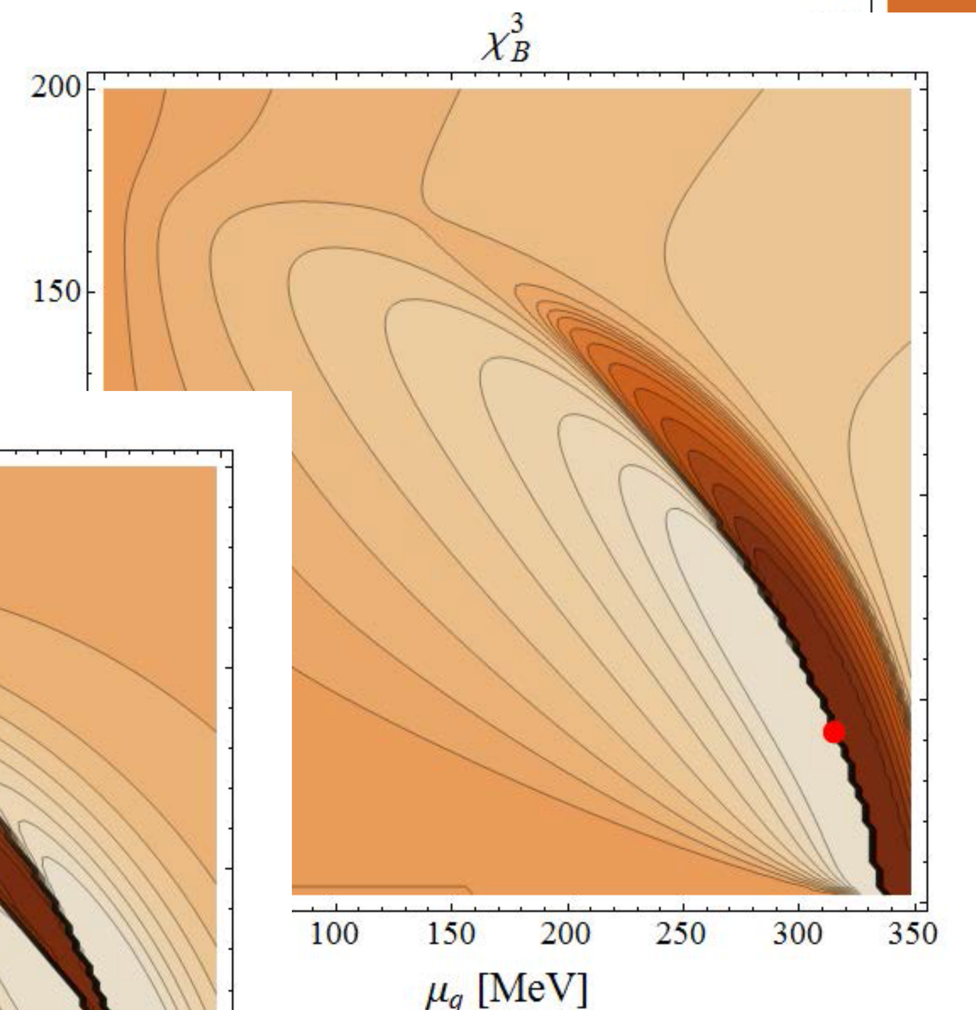
$$\chi_B^n = \left(\frac{\partial}{\partial \mu / T}\right)^n \ln Z$$

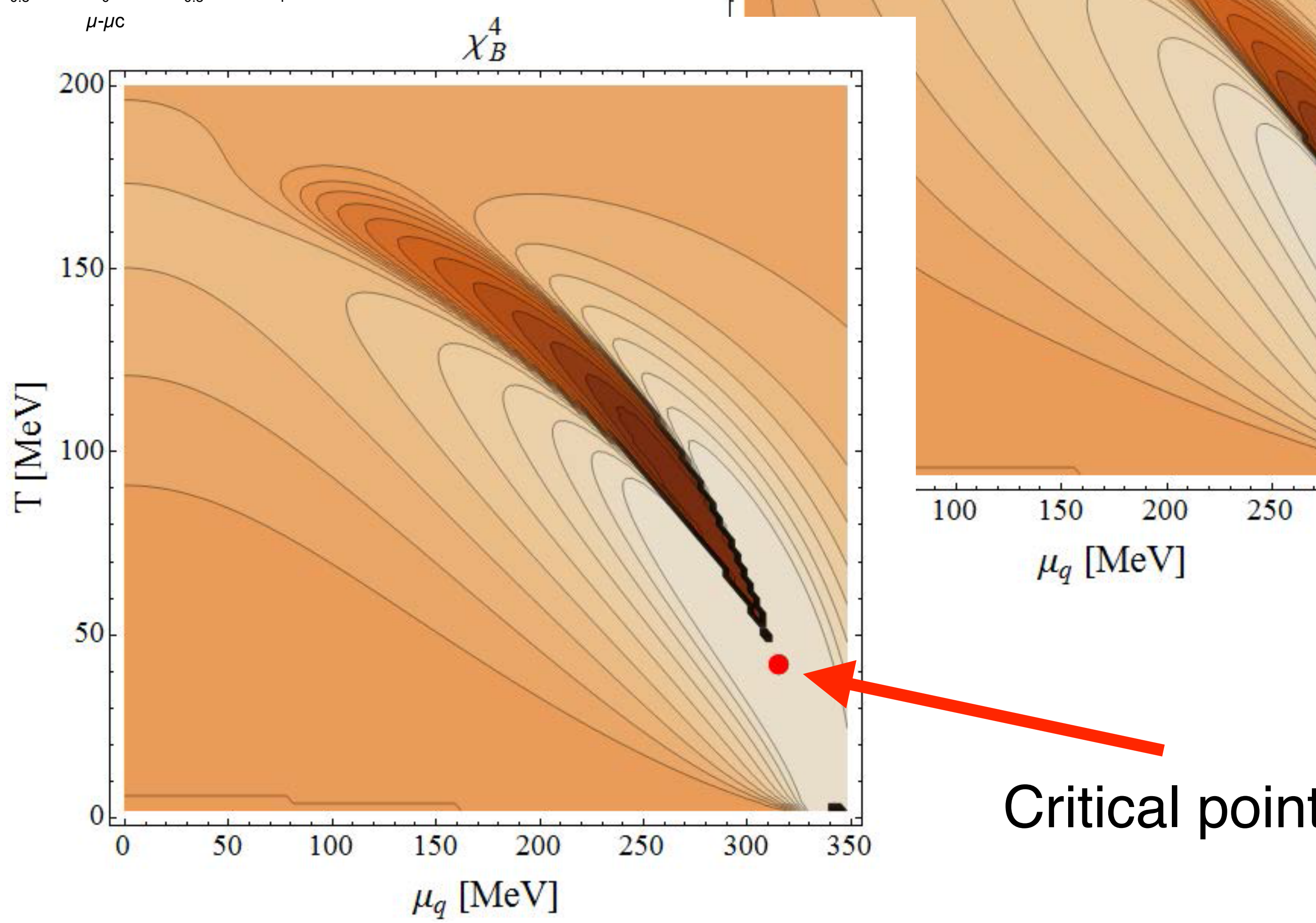








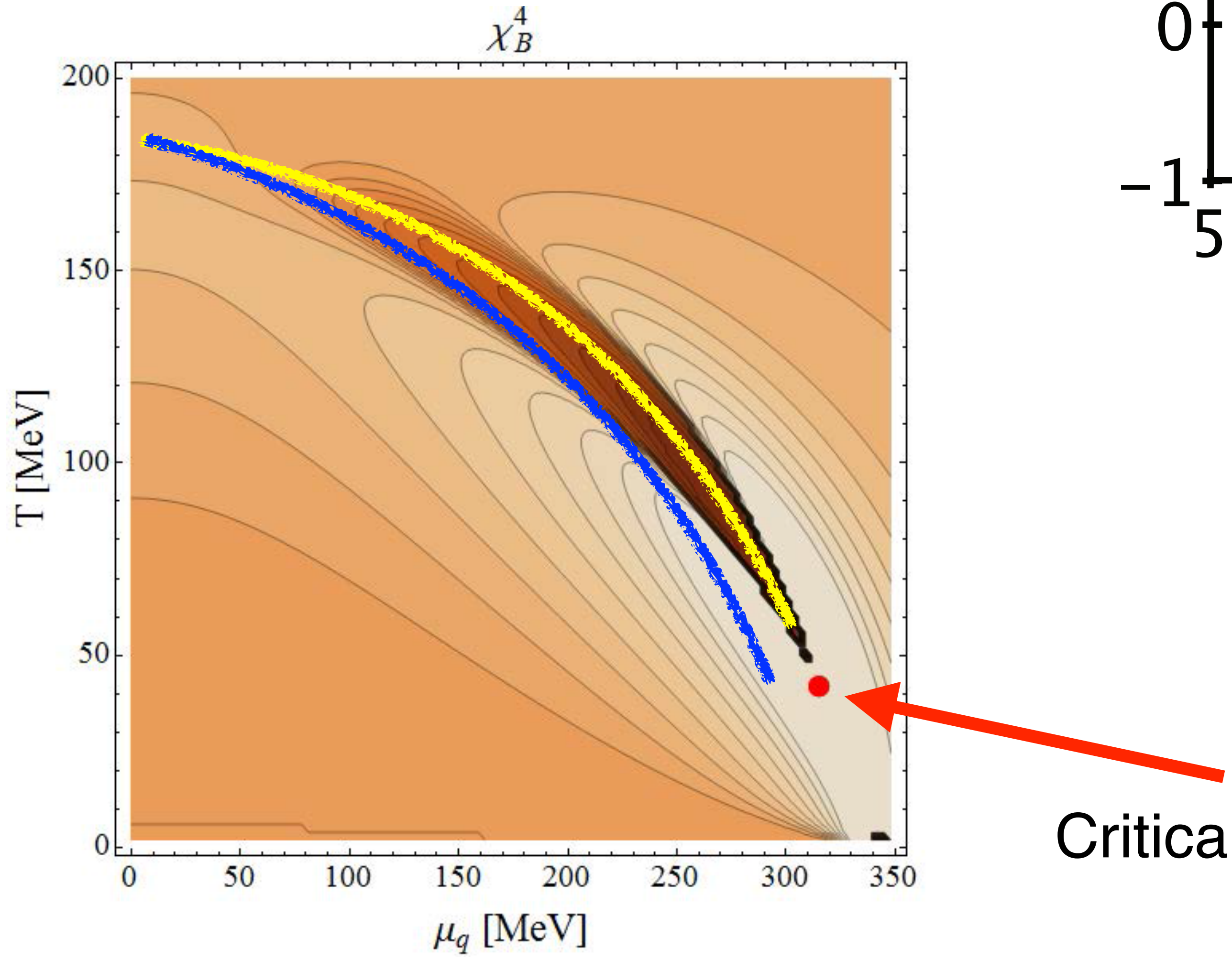


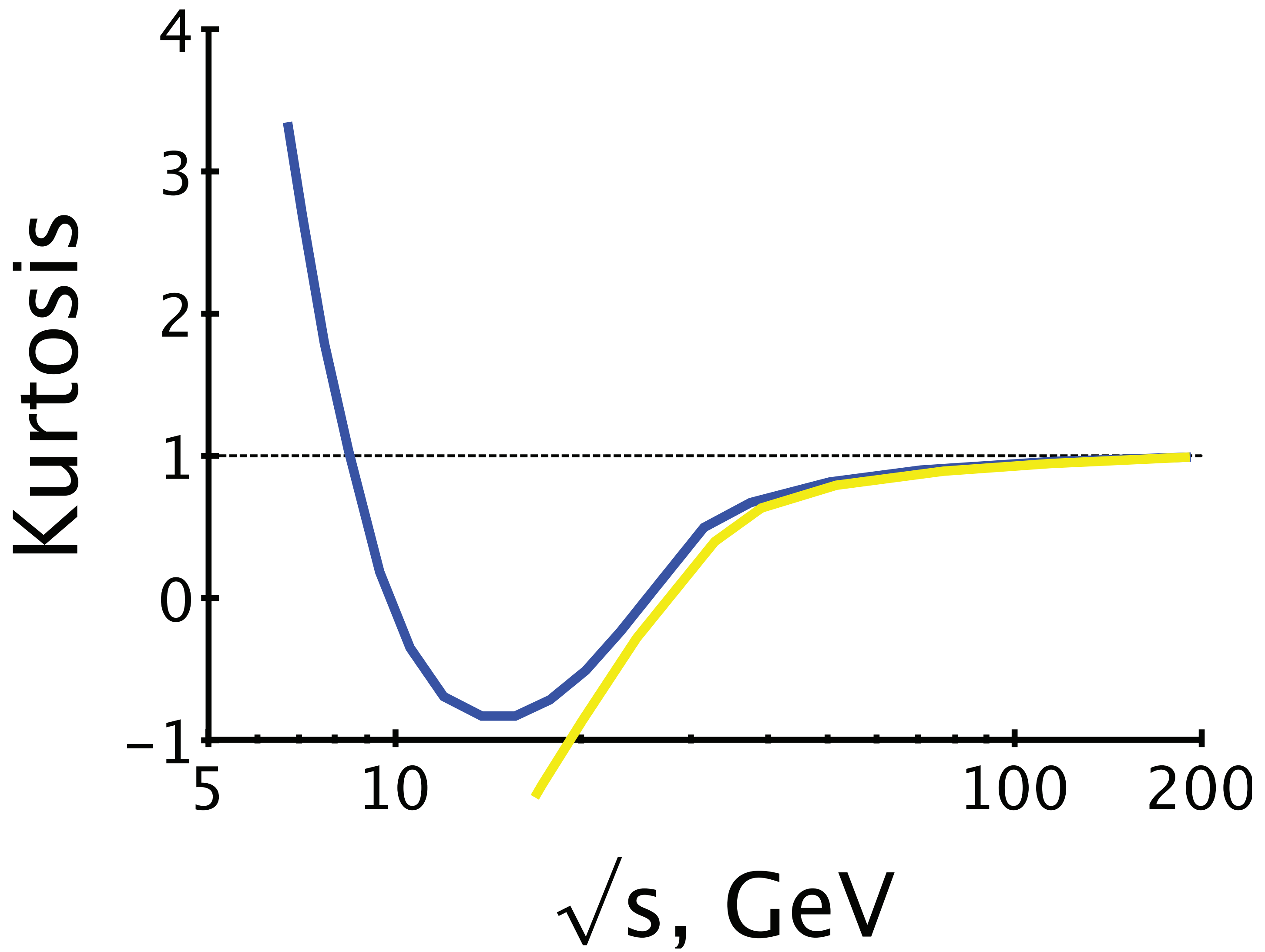


Structure sharpened as CP approached

Dependence on freeze-out line

$$\text{Kurtosis} = \chi_B^4/\chi_B^2$$



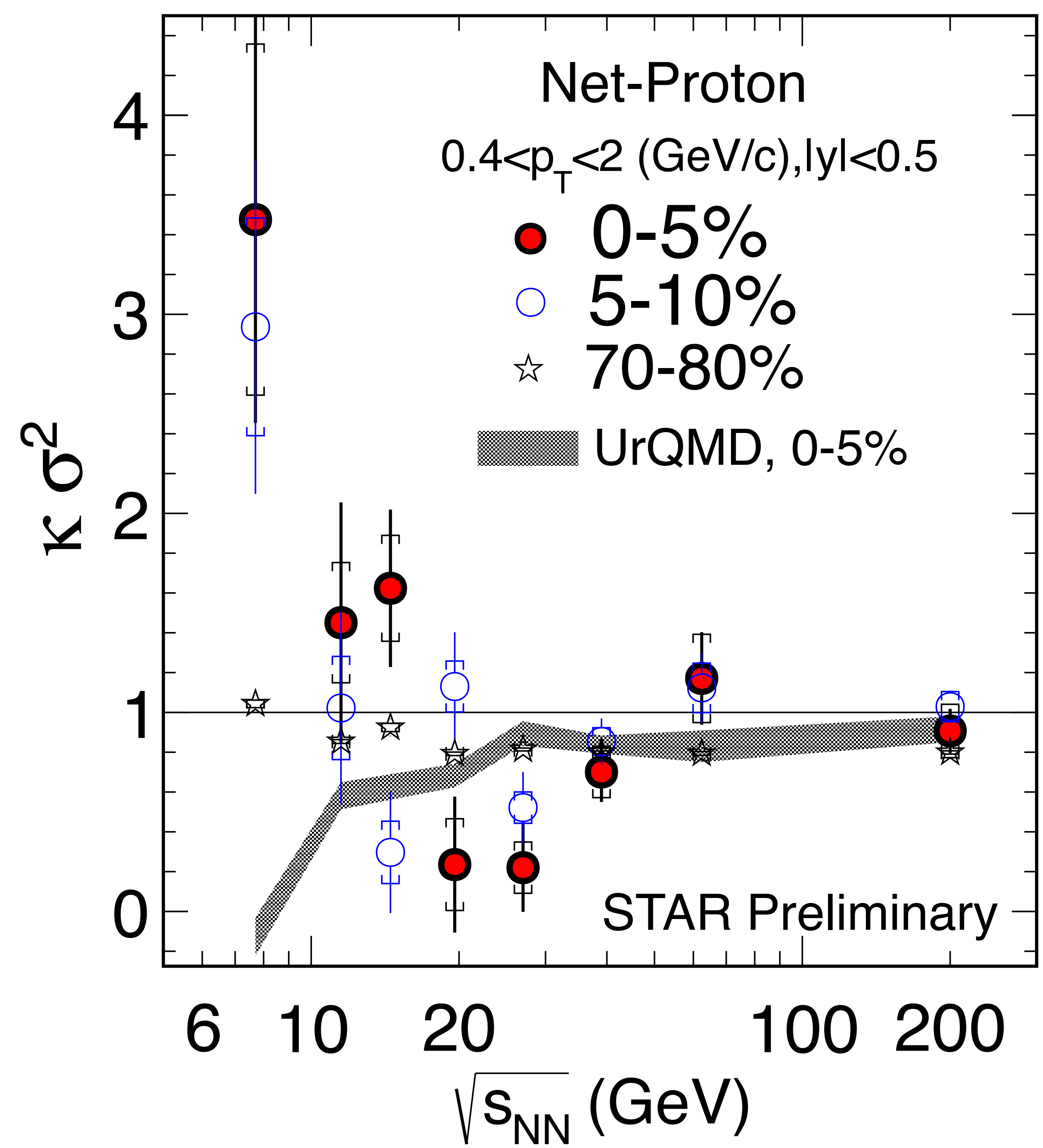


Critical point

STAR data on fluctuations

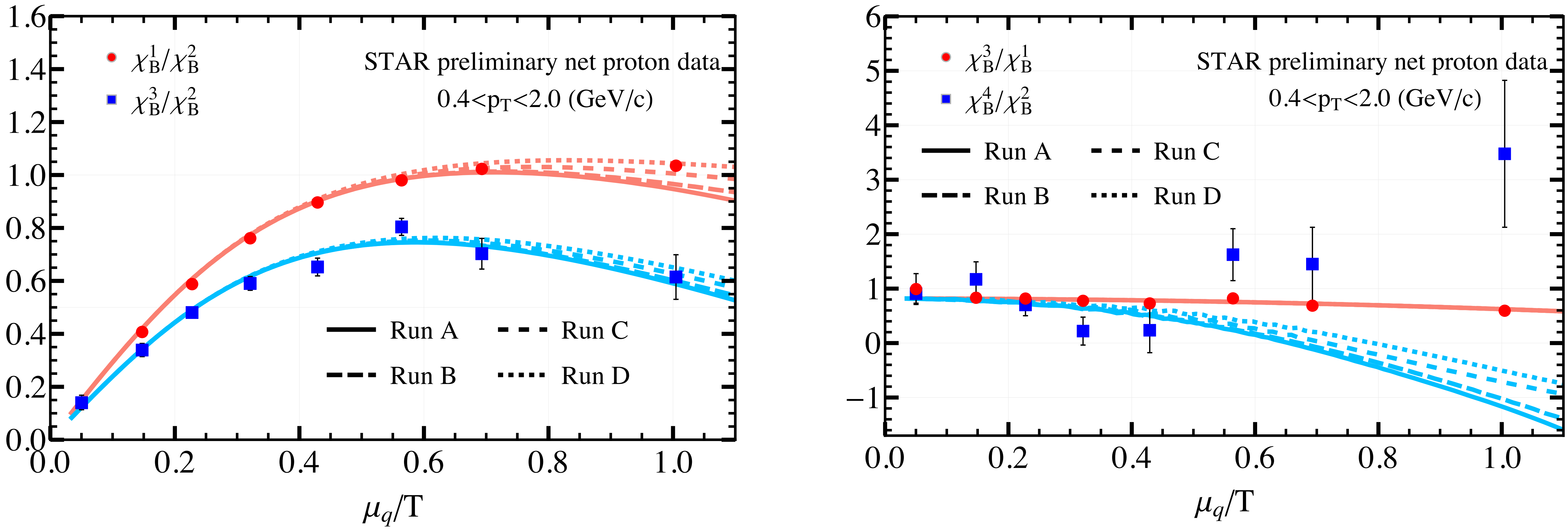
- Transport theory (no criticality) yields only suppression!
- Can enhancement at low energies be due to the chiral critical point?
- Are other cumulants consistent?

$$\kappa\,\sigma^2 = \chi_B^4/\chi_B^2$$



Self consistent freeze-out

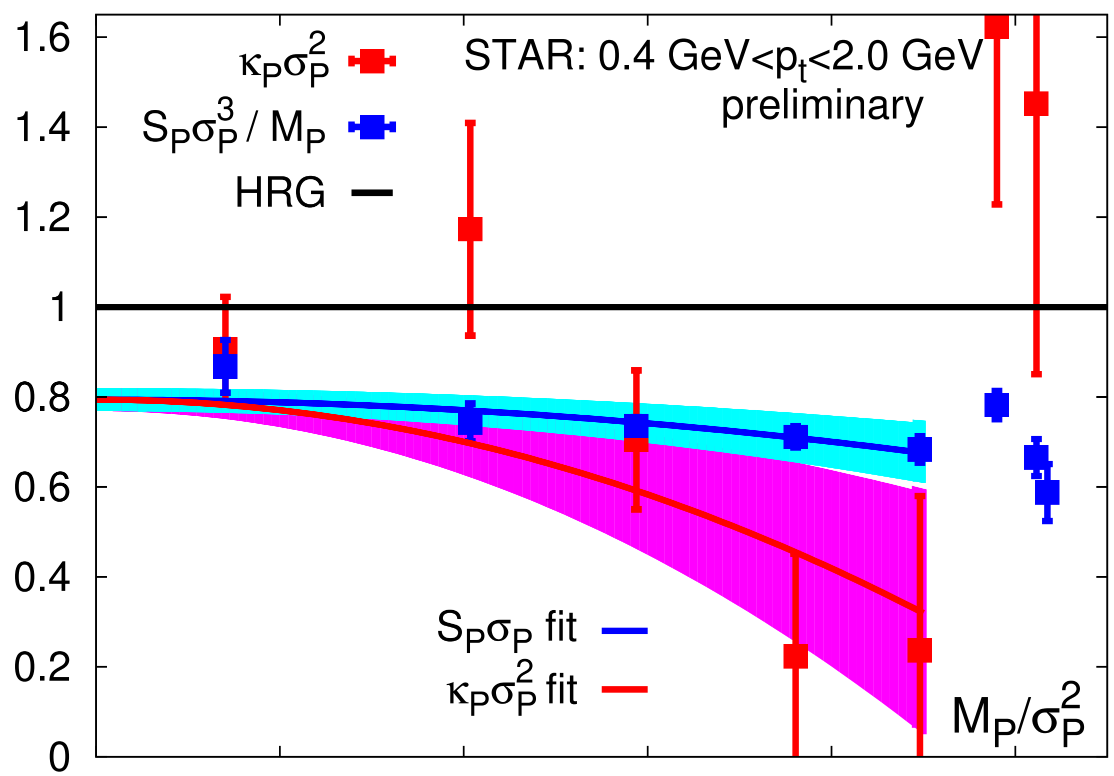
- Freeze-out line determined by fitting χ_B^3/χ_B^1 to data
- Yields good description of χ_B^1/χ_B^2 and χ_B^3/χ_B^2
- Enhancement of χ_B^4/χ_B^2 not reproduced!



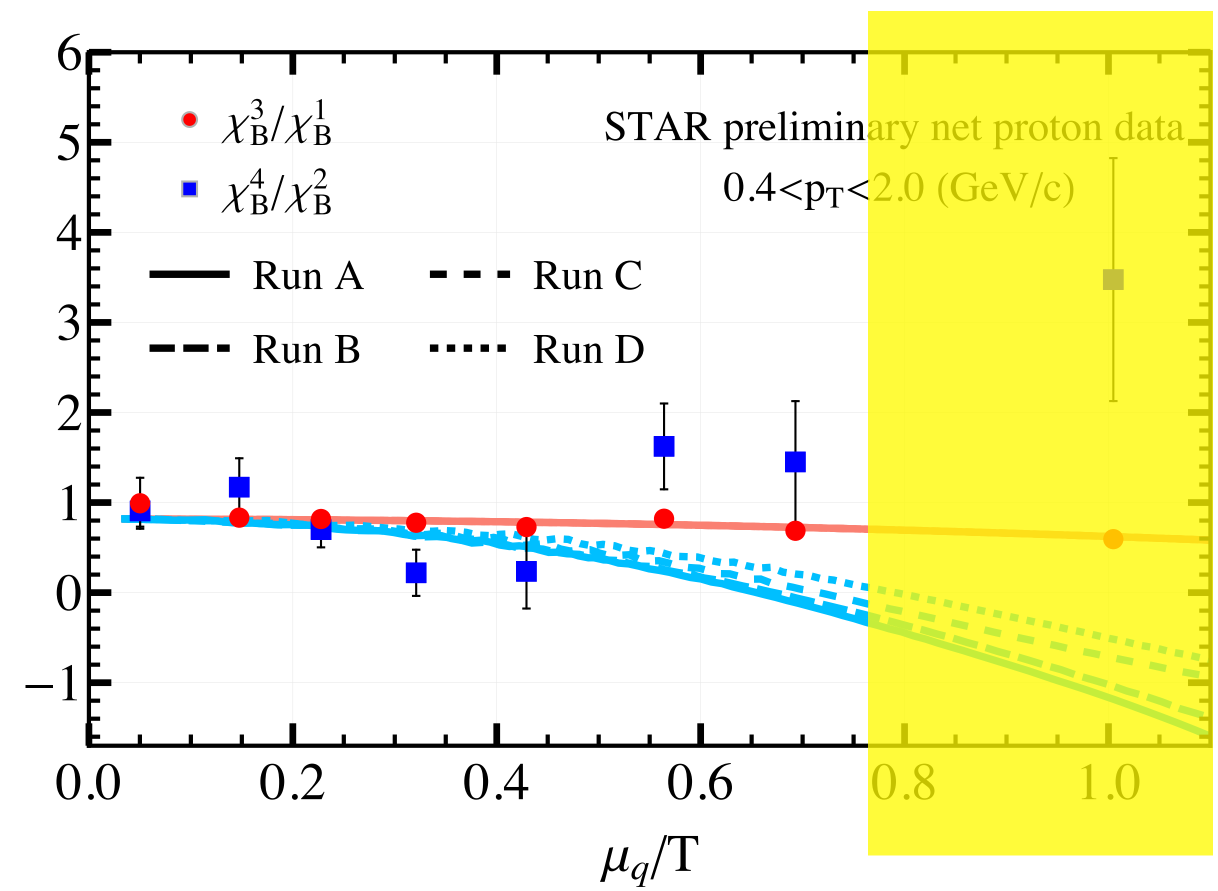
Gabor Almasi, Krzysztof Redlich & BF

Lattice extrapolation

- Freeze-out line determined by fitting χ_B^3/χ_B^1 to data
- Yields good description of χ_B^1/χ_B^2 and χ_B^3/χ_B^2
- Enhancement of χ_B^4/χ_B^2 not reproduced!



F. Karsch



Summary

- Prospects for exploring the phase diagram of QCD in nuclear collisions with fluctuations
- Low cumulants described by model/lattice $(n \leq 3)$
- χ_B^4/χ_B^2 cannot be reproduced in model
- Numerous effects not yet understood:
  - Non-critical sources of fluctuations (e.g. volume)
  - Non-equilibrium effects?
  - Momentum cuts
  - Protons vs. baryons?