Chasing Hagedorn's Dream

Mapping the QCD Phase Diagram at RHIC

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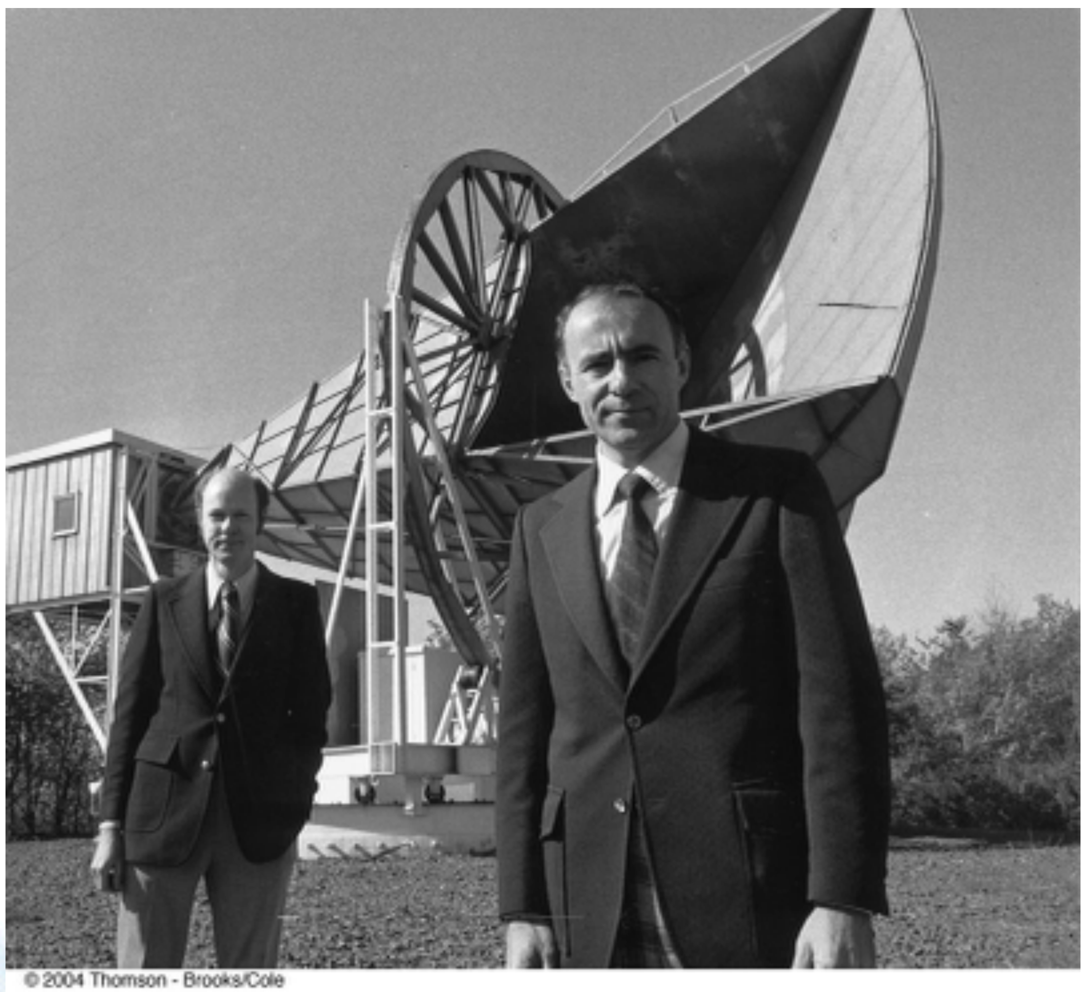
USQCD Meeting
BNL
29 April 2016

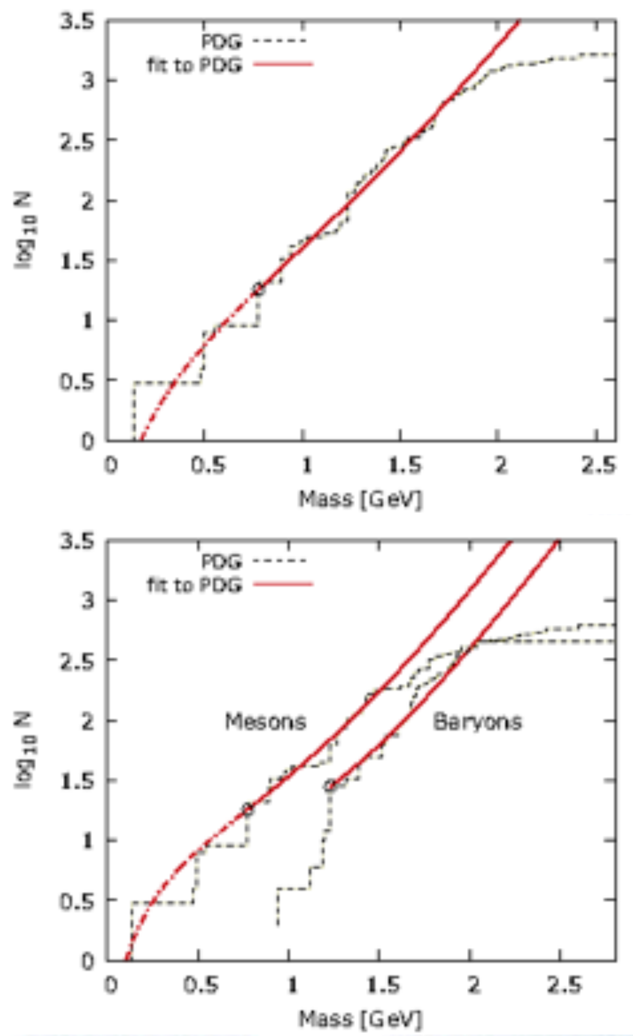
BROOKHAVEN NATIONAL LABORATORY
a passion for discovery

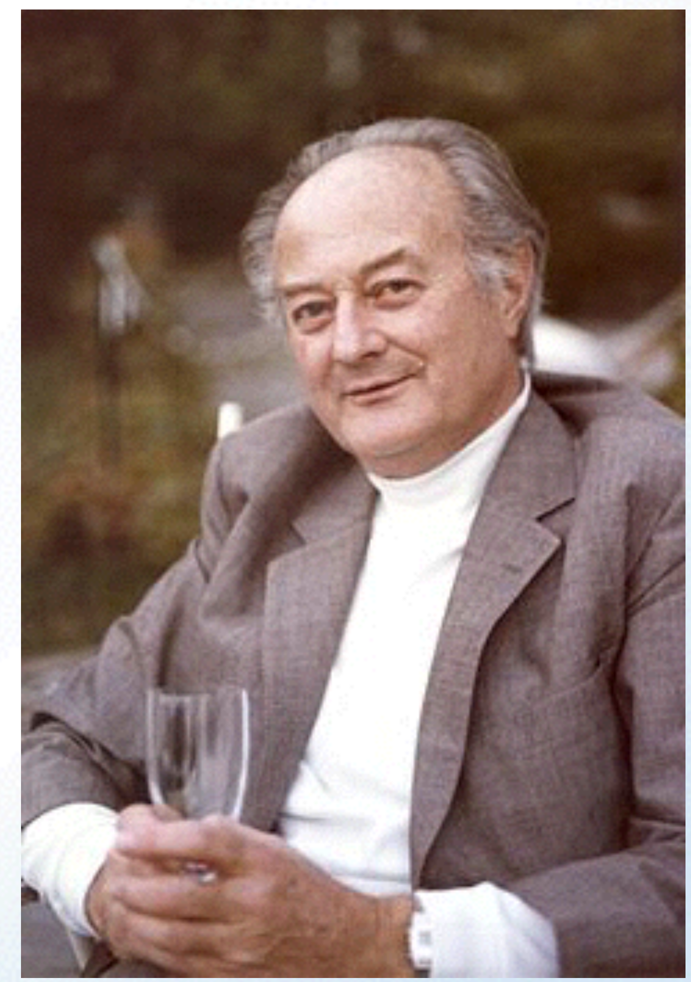
Office of Science
U.S. DEPARTMENT OF ENERGY

1965

was a momentous year





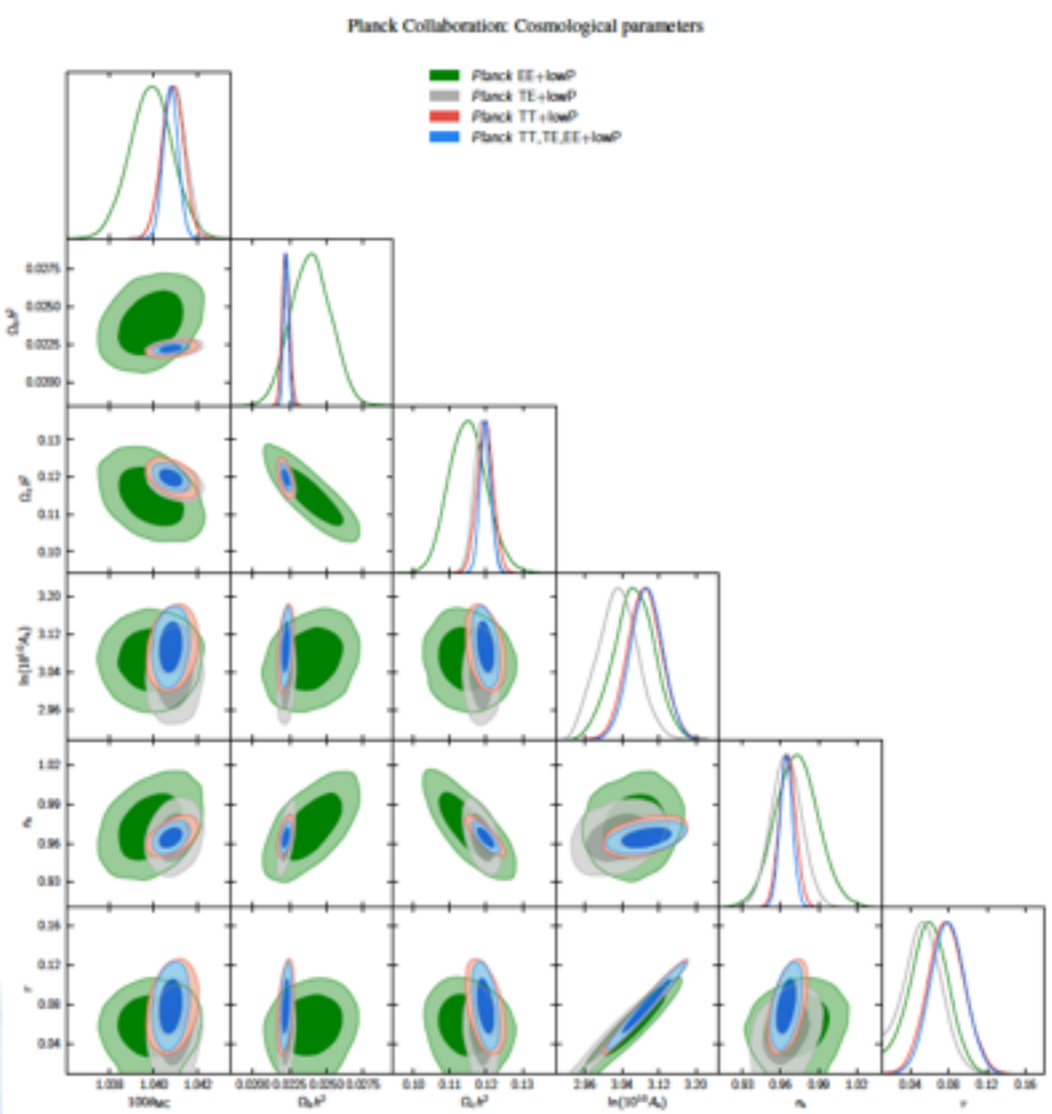


cosmic microwave background

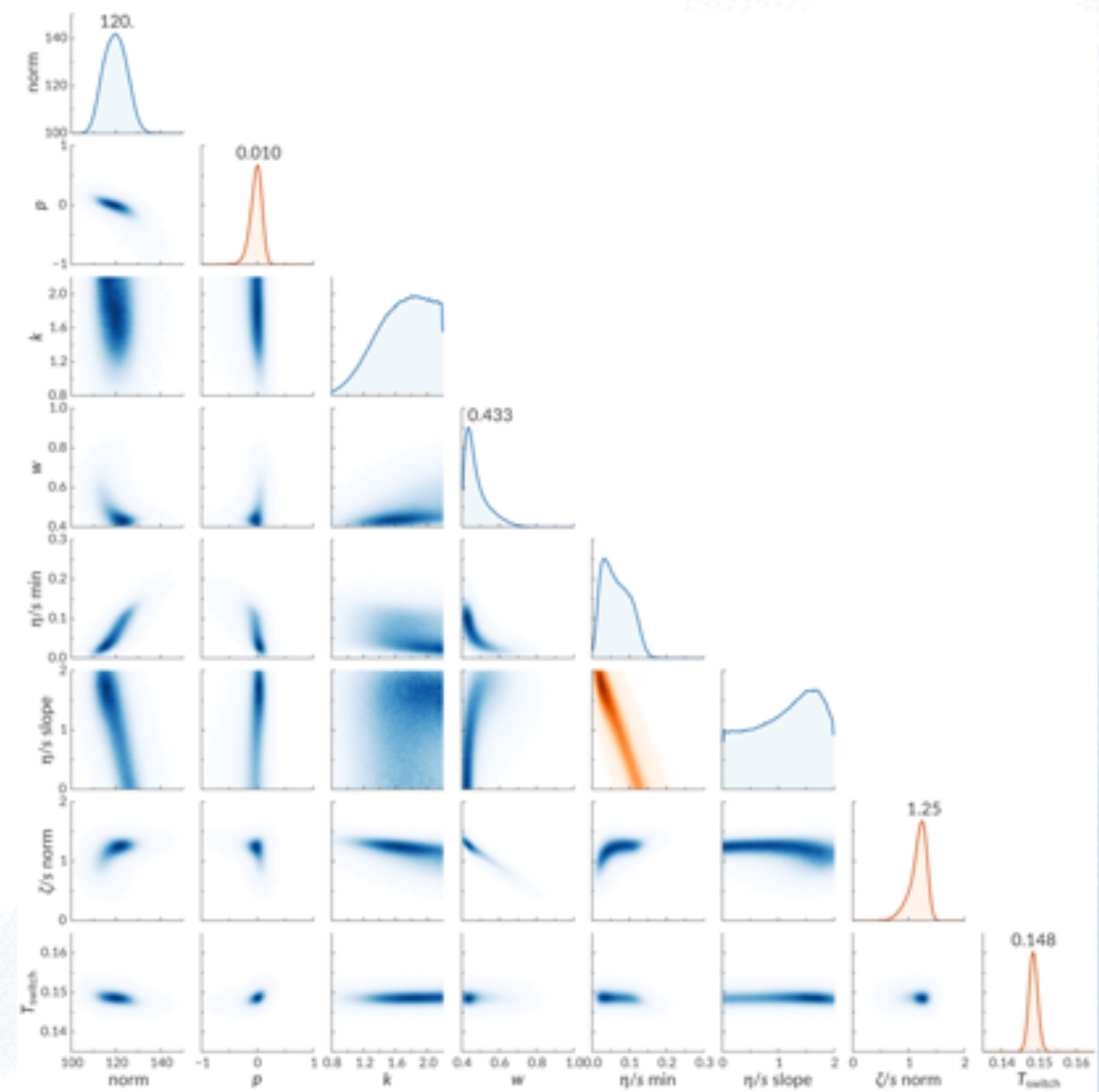
Hagedorn’s temperature “limit”

51 years later

almost unimaginable progress

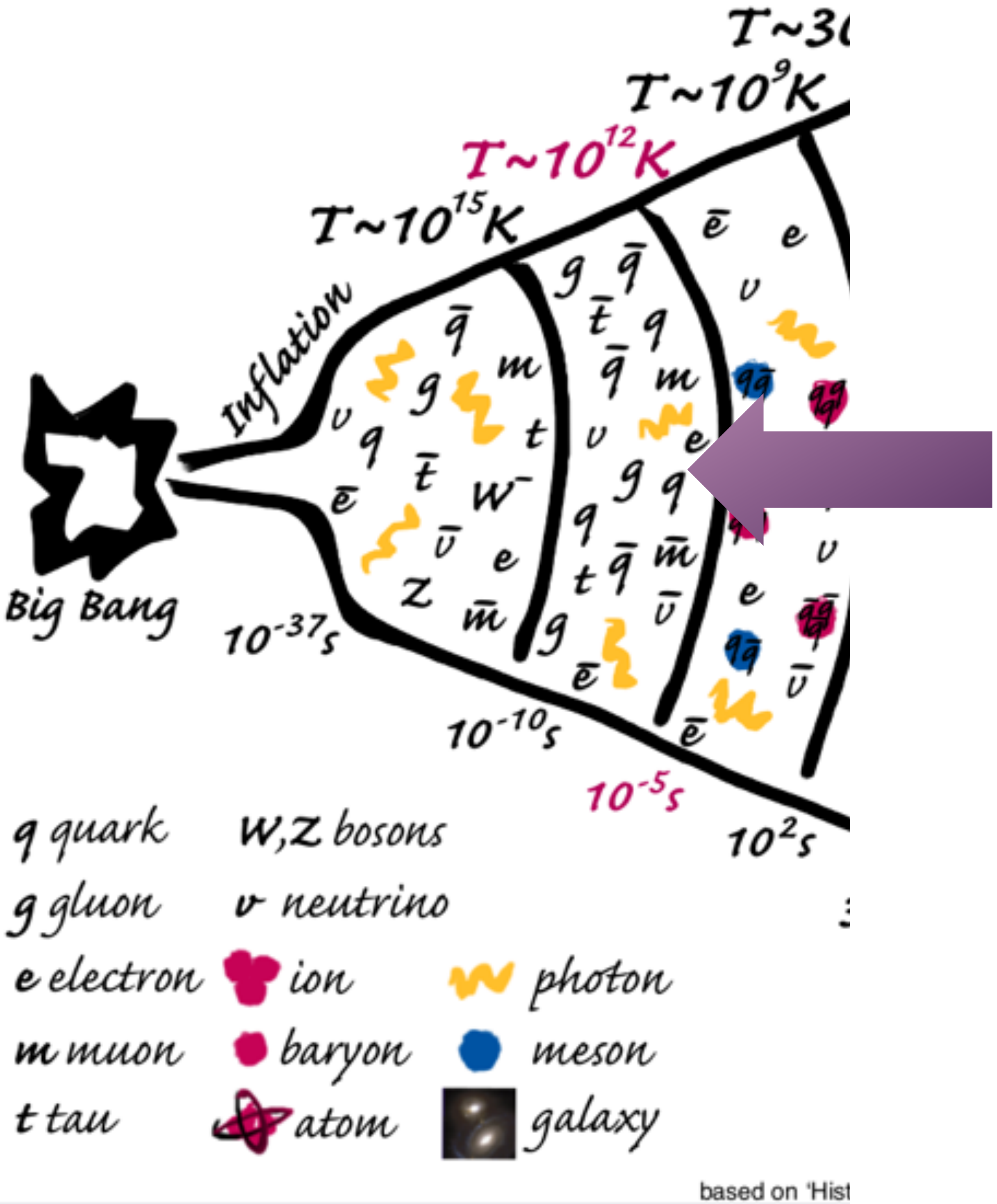


Planck: cosmological parameters



MADAI: Multiparameter analysis of heavy ion data

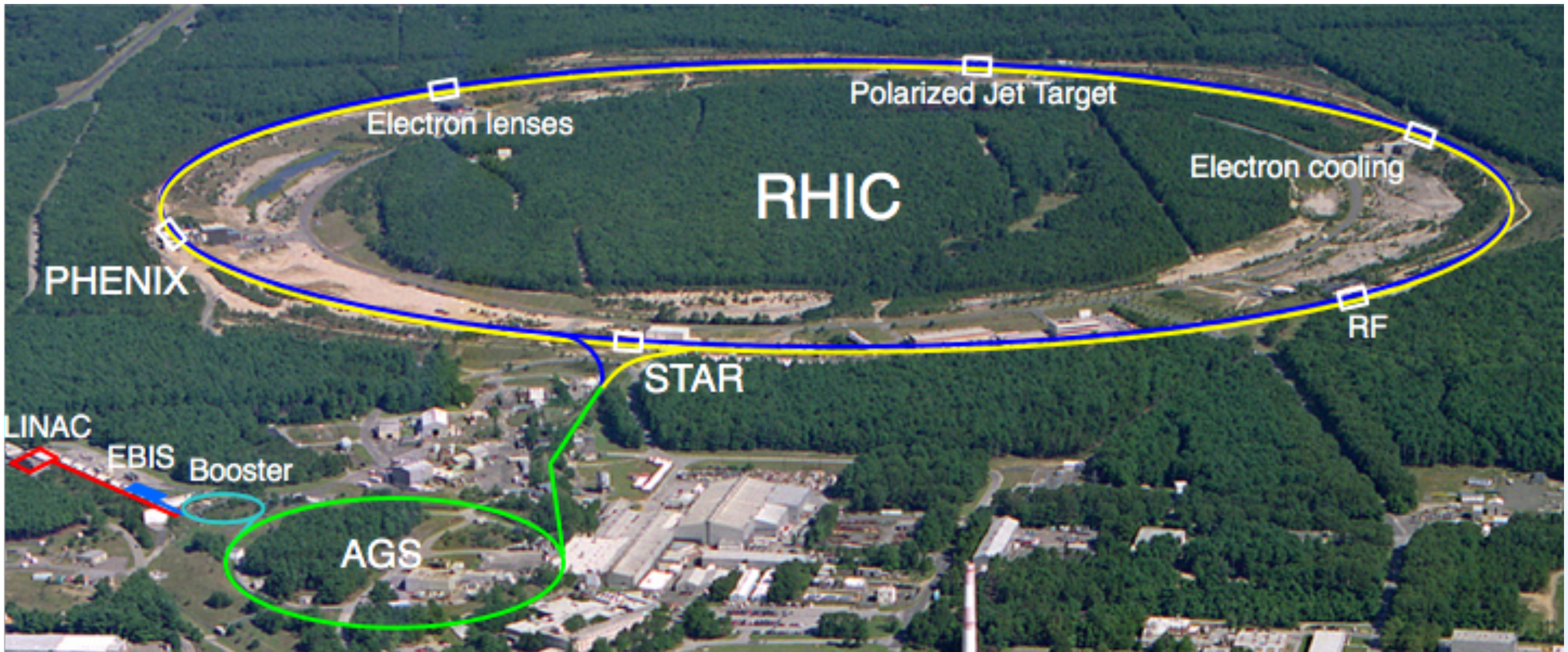
Evolution of the universe

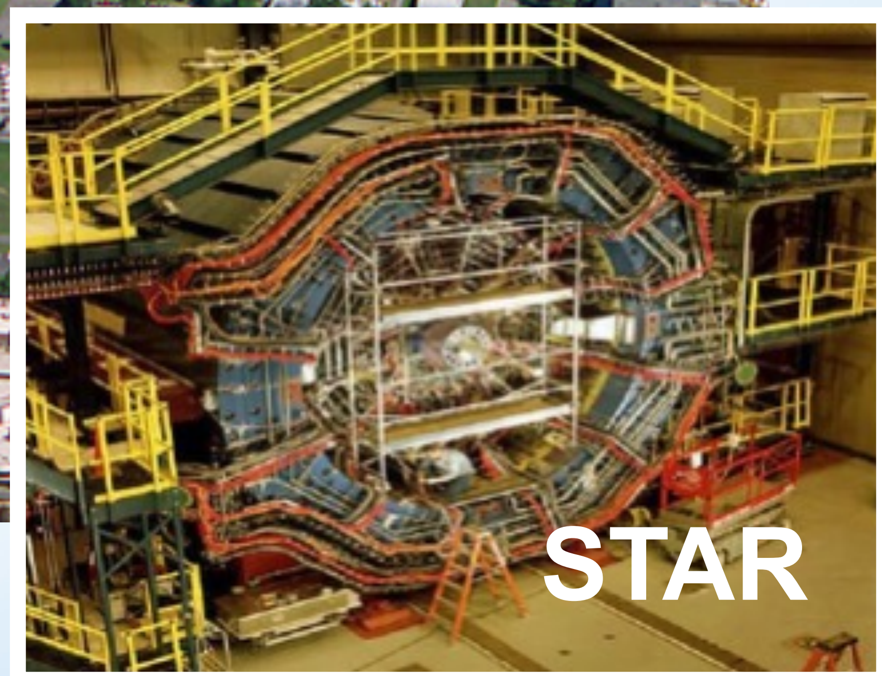


after the Big Bang

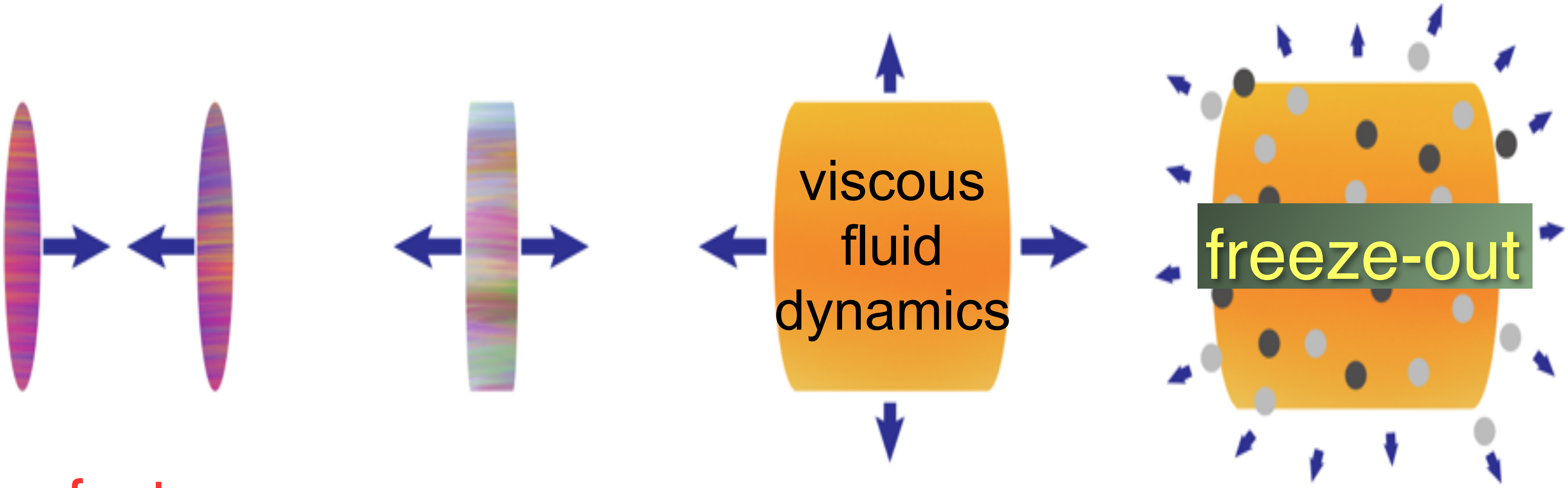
~ 70000 x hotter than the center of the sun

The Relativistic Heavy Ion Collider





Recreating QGP on Earth in Little bangs



fast moving nuclei

nuclei collide

expanding & cooling QGP

hadrons re-formed

observed in experiments

Comprehensive framework based on transport theory provides description of reaction from start to finish

Equation of State of QCD Matter

Equation of State

EOS of flowing matter has conservative and dissipative contributions:

$$T_{\mu\nu} = T_{\mu\nu}^{(\mathrm{cons})} + T_{\mu\nu}^{(\mathrm{diss})}$$
$$= \varepsilon u_\mu u_\nu + p\left(u_\mu u_\nu - g_{\mu\nu}\right)$$
$$+ \eta\left(\partial_\mu u_\nu + \partial_\nu u_\mu - \tfrac{2}{3} g_{\mu\nu} \partial_\alpha u^\alpha\right) + \zeta \partial_\alpha u^\alpha \left(g_{\mu\nu} - u_\mu u_\nu\right)$$

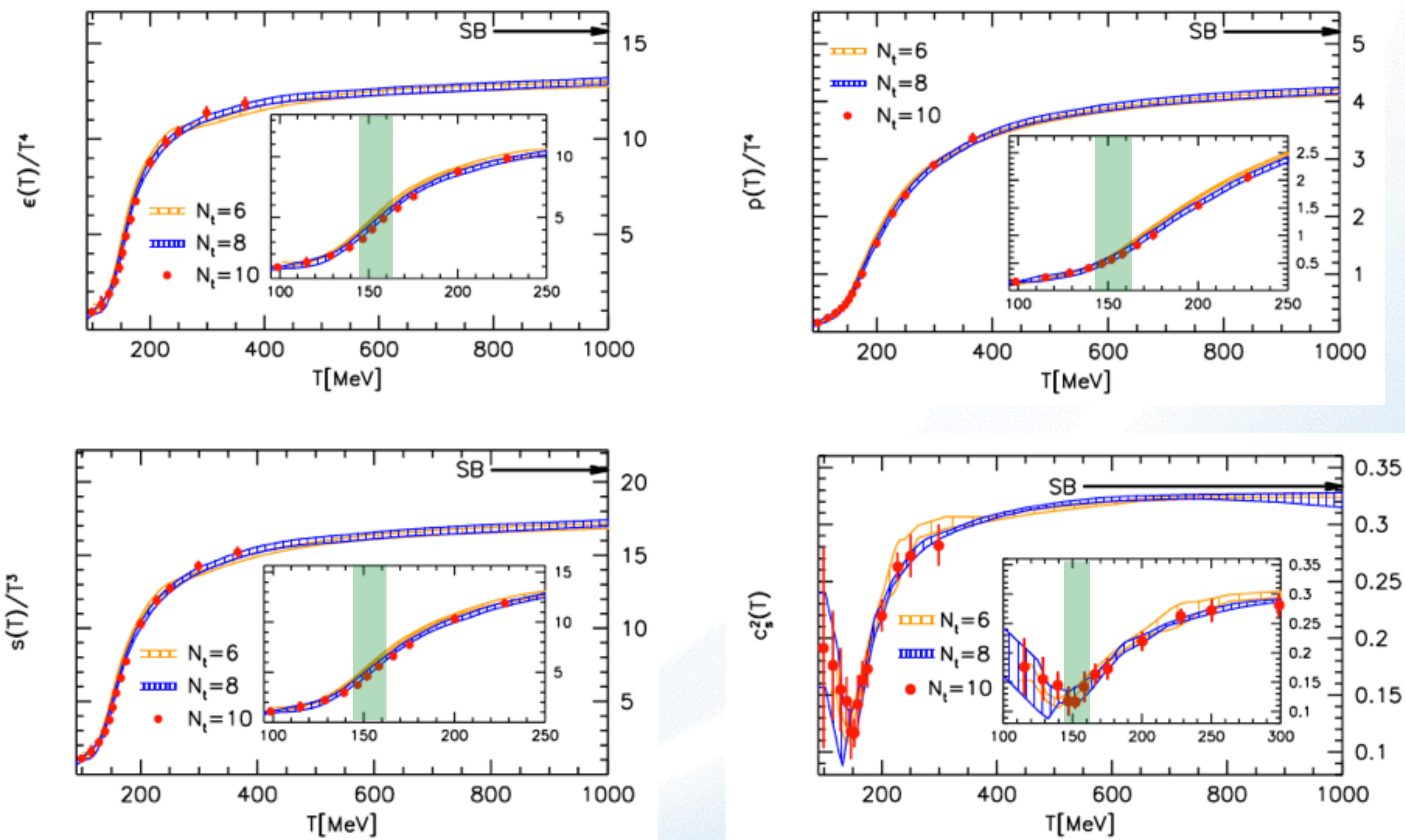
When $\zeta(\partial_\alpha u^\alpha) > p$, the matter becomes unstable and cavitates.

In general, $T_{\mu\nu}$ is a dynamical quantity that relaxes to its equilibrium value on a time scale τ_π that itself is related to the viscosity.

While the shear viscosity η has a lower quantum bound, the bulk viscosity ζ vanishes for conformally invariant matter.

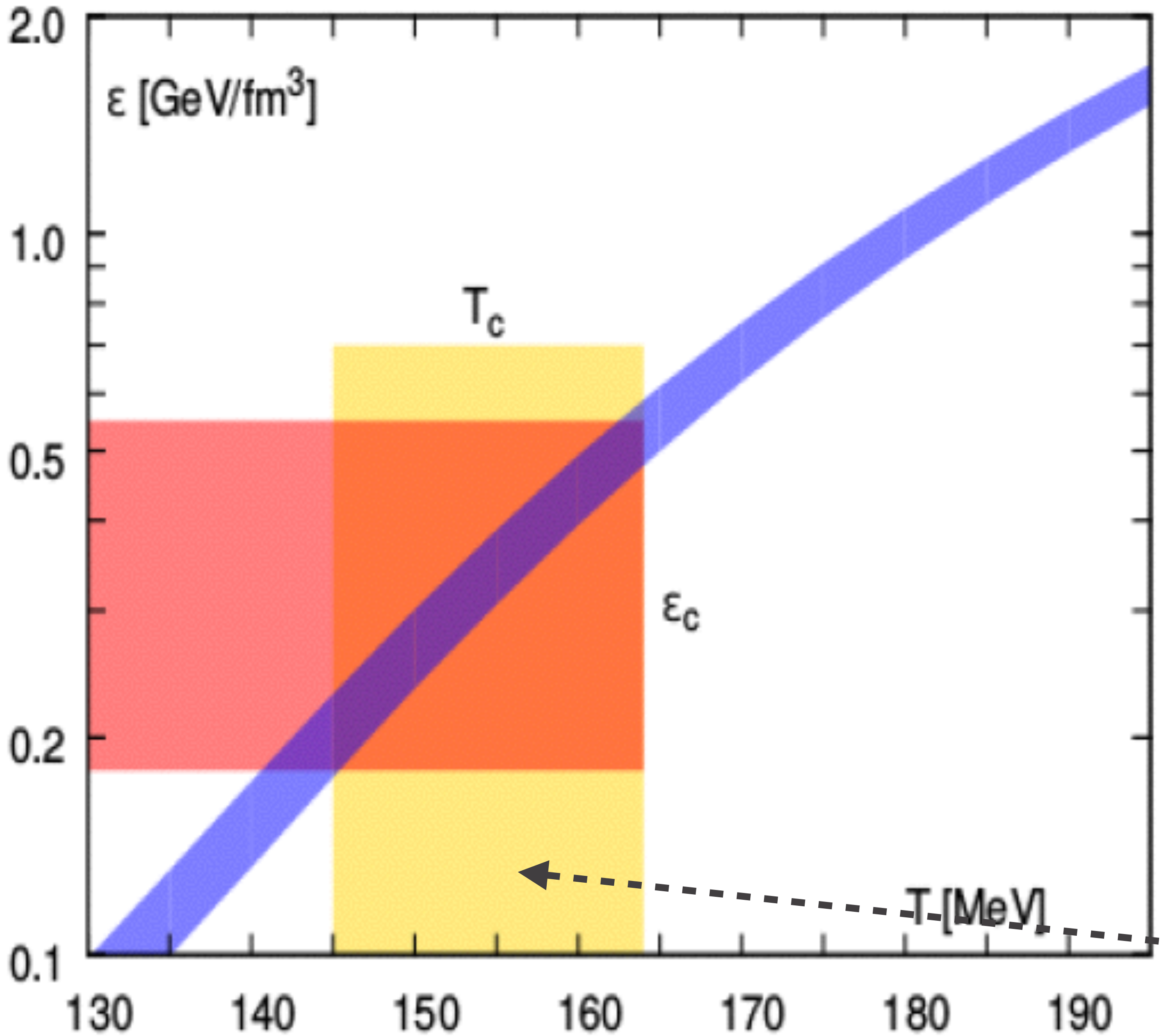
QCD EOS at $\mu_B = 0$

Results (true quark masses, continuum extrapolated) have converged; full agreement found between groups (HotQCD, Wuppertal-Budapest) using different quark actions.



(Pseudo-) Critical temperature

Transition between hadron gas and quark-gluon plasma is a **cross-over** at $\mu_B = 0$ and for small μ_B. Precise value of T_c depends on the quantity used to define it.



HotQCD: arXiv:1407.6387

Pseudo-critical temperature from chiral susceptibility peak:

T_c = 154 ± 9 MeV

critical energy density:

$\epsilon_c = 0.18 - 0.50\ \mathrm{GeV/fm^3}$

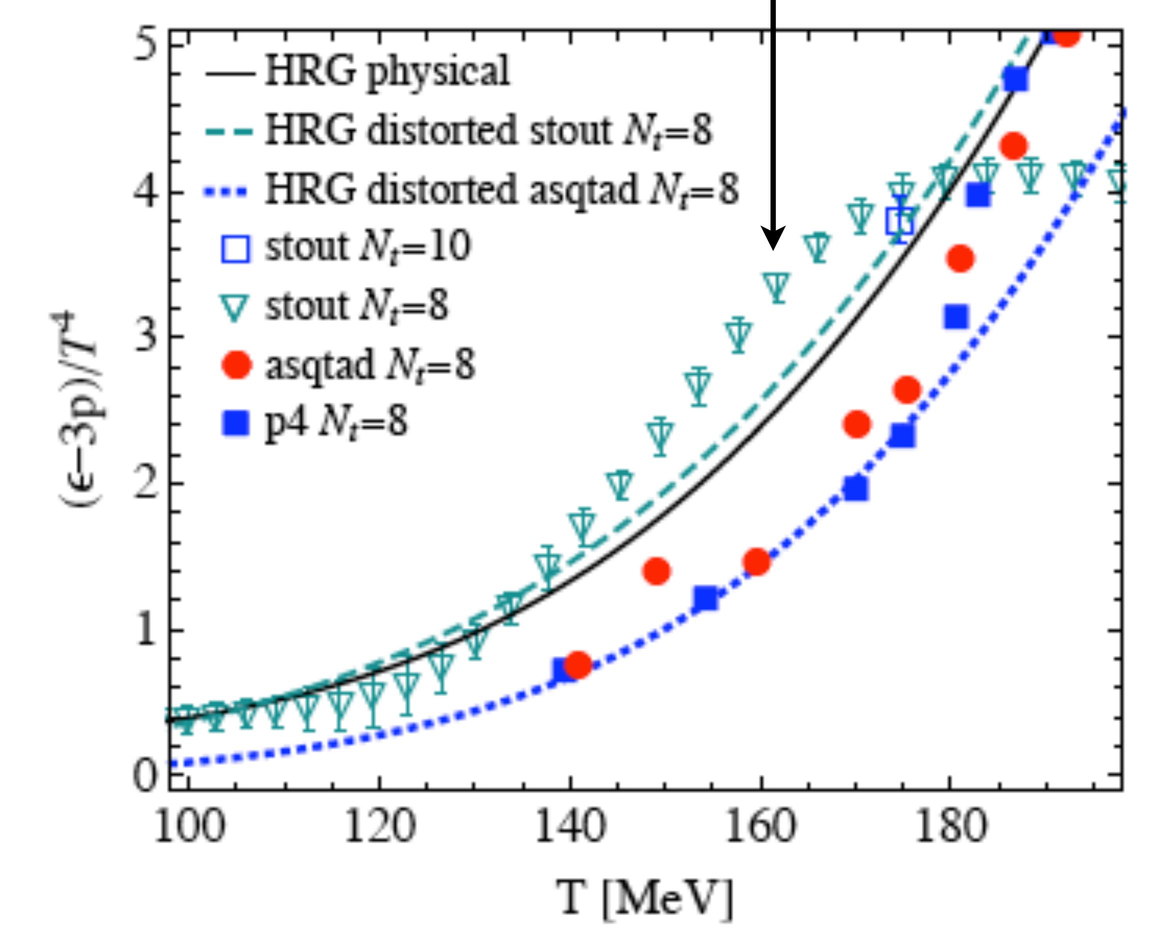
$\epsilon_c = (1.2 - 3.3)\,\rho_{nuclear}$

Uncertainty in T_c, not width of cross-over region!

Hadron mass spectrum

Below T_c, the quantity $(\varepsilon - 3p)/T^4$ measures the level density of massive hadronic excitations of the QCD vacuum.

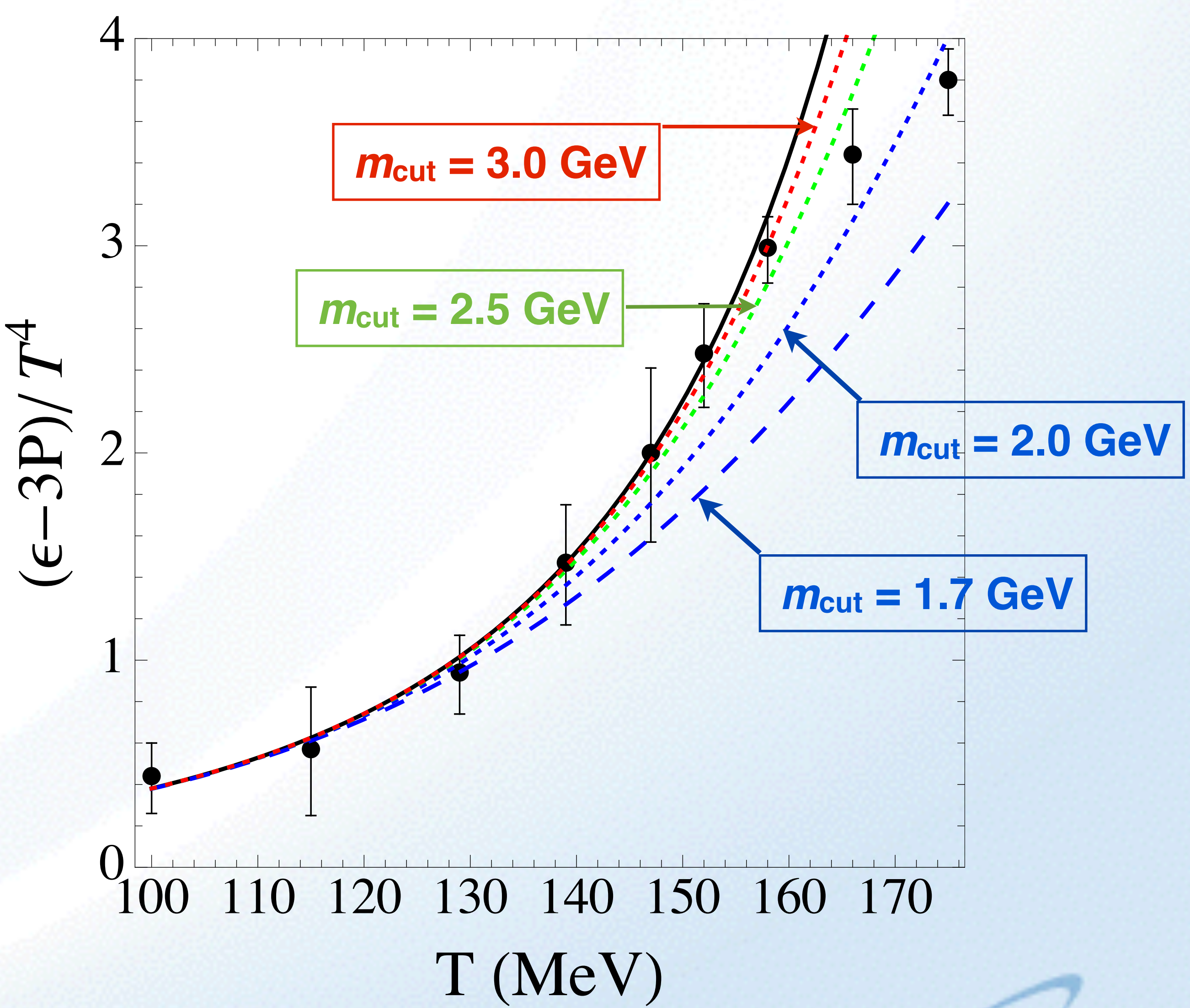
Lines: Hadron resonance gas using only PDG resonances
Data points: Lattice QCD
LQCD lies above HRG for T > 140 MeV
Indicates additional hadron resonances



Hagedorn spectrum ($T_H \approx$ 180 MeV):

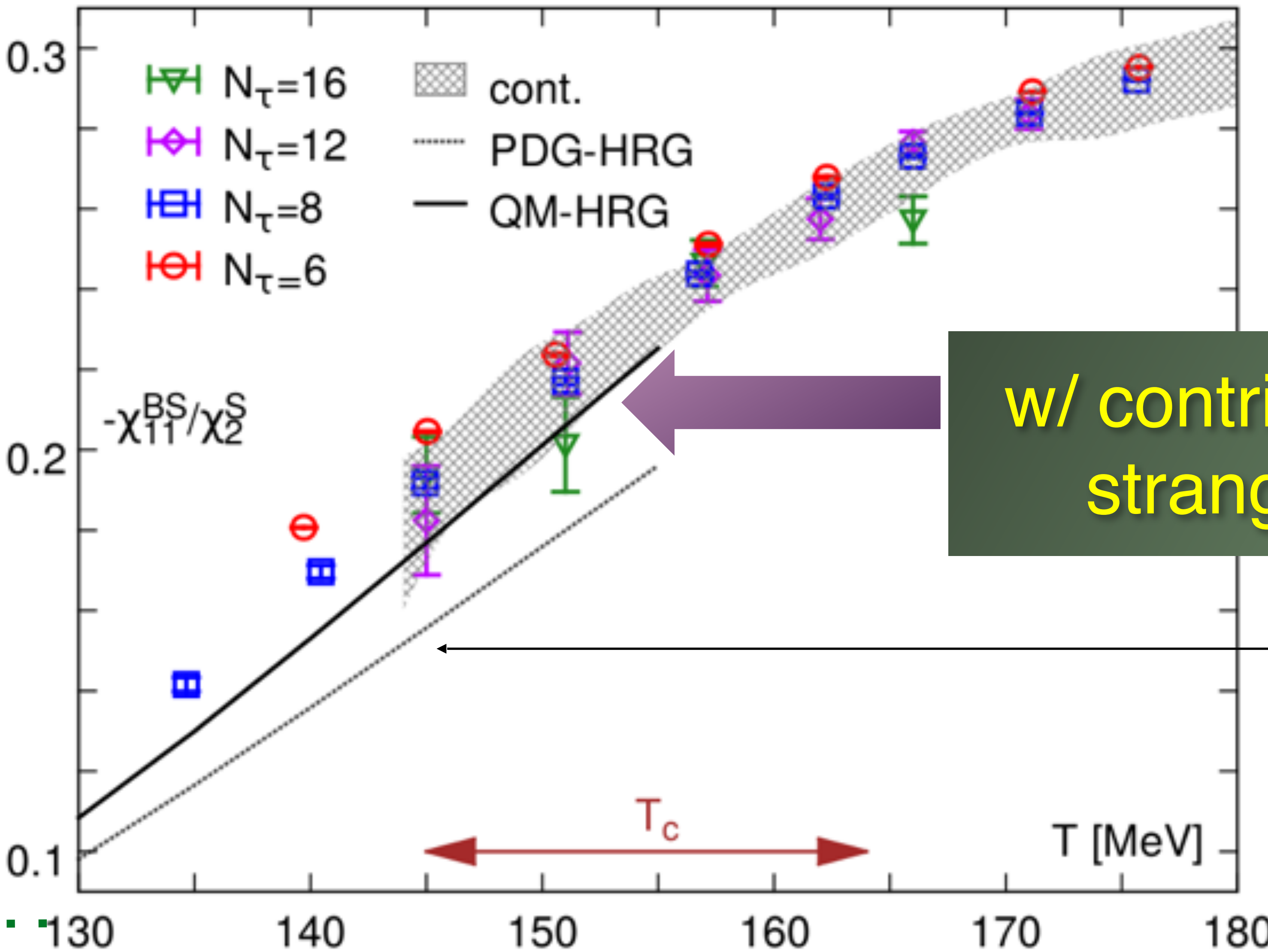
$$\rho_H(m) = \frac{A\, e^{m/T_H}}{\left(m^2 + m_0^2\right)^{5/4}}$$

In good agreement with lattice results
Hadrons up to 3 GeV mass contribute



Lattice evidence for strange baryons

$\frac{\text{strange baryons}}{\text{strange hadrons}}$ contr. to pressure



w/ contrib. of unobserved strange baryons

contr. of all expt. observed strange hadrons

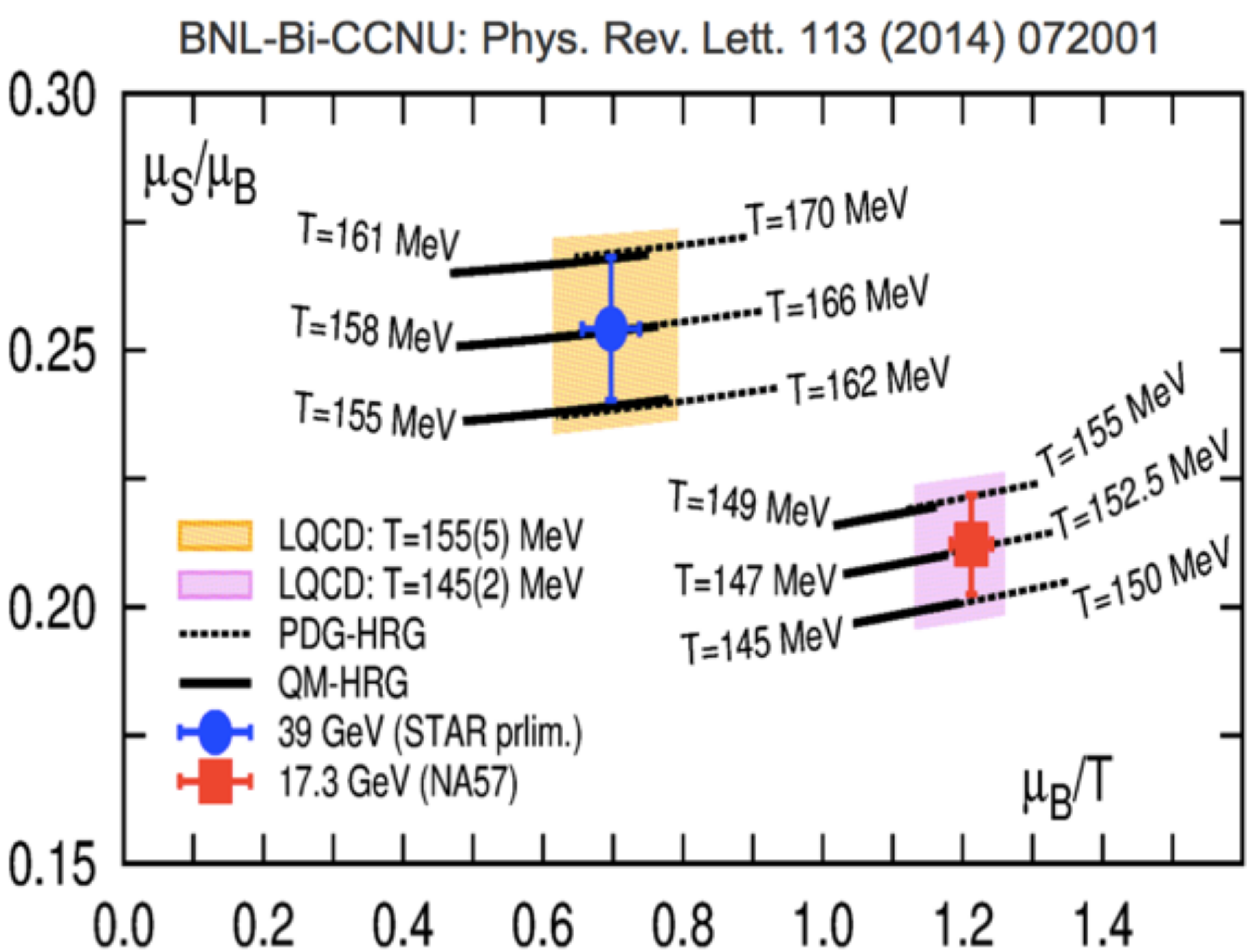
temperature [MeV]

indirect signatures in heavy-ion experiments

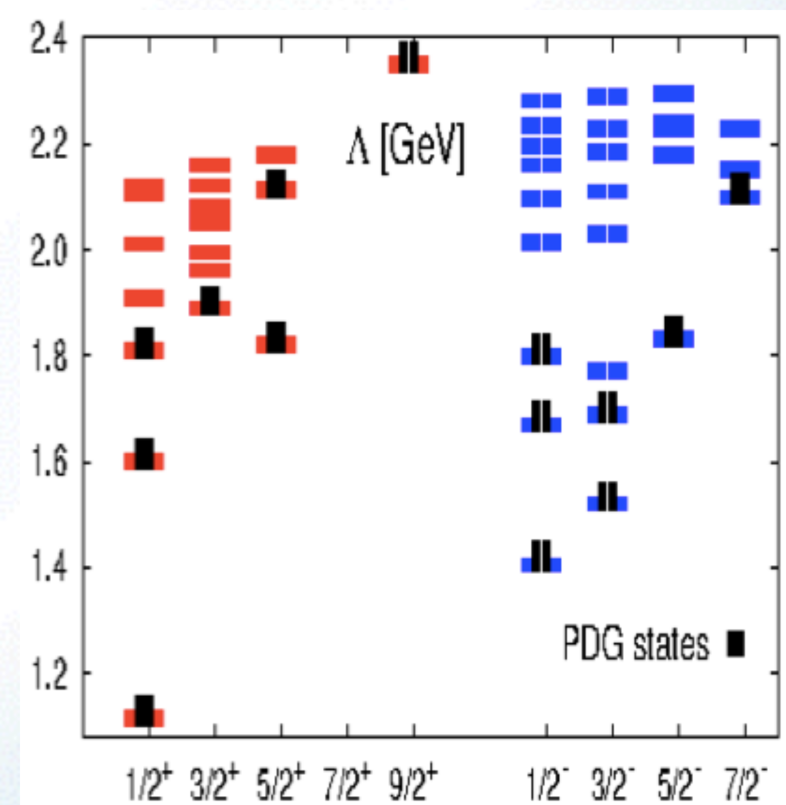
BNL-Bielefeld-CCNU: Phys. Rev. Lett. 113, 072001 (2014)

Probing the baryon spectrum

Consistency of μ_S/μ_B and μ_B/T with chemical composition of emitted hadrons and Lattice QCD requires additional strange baryon resonances beyond those in the PDG tables.

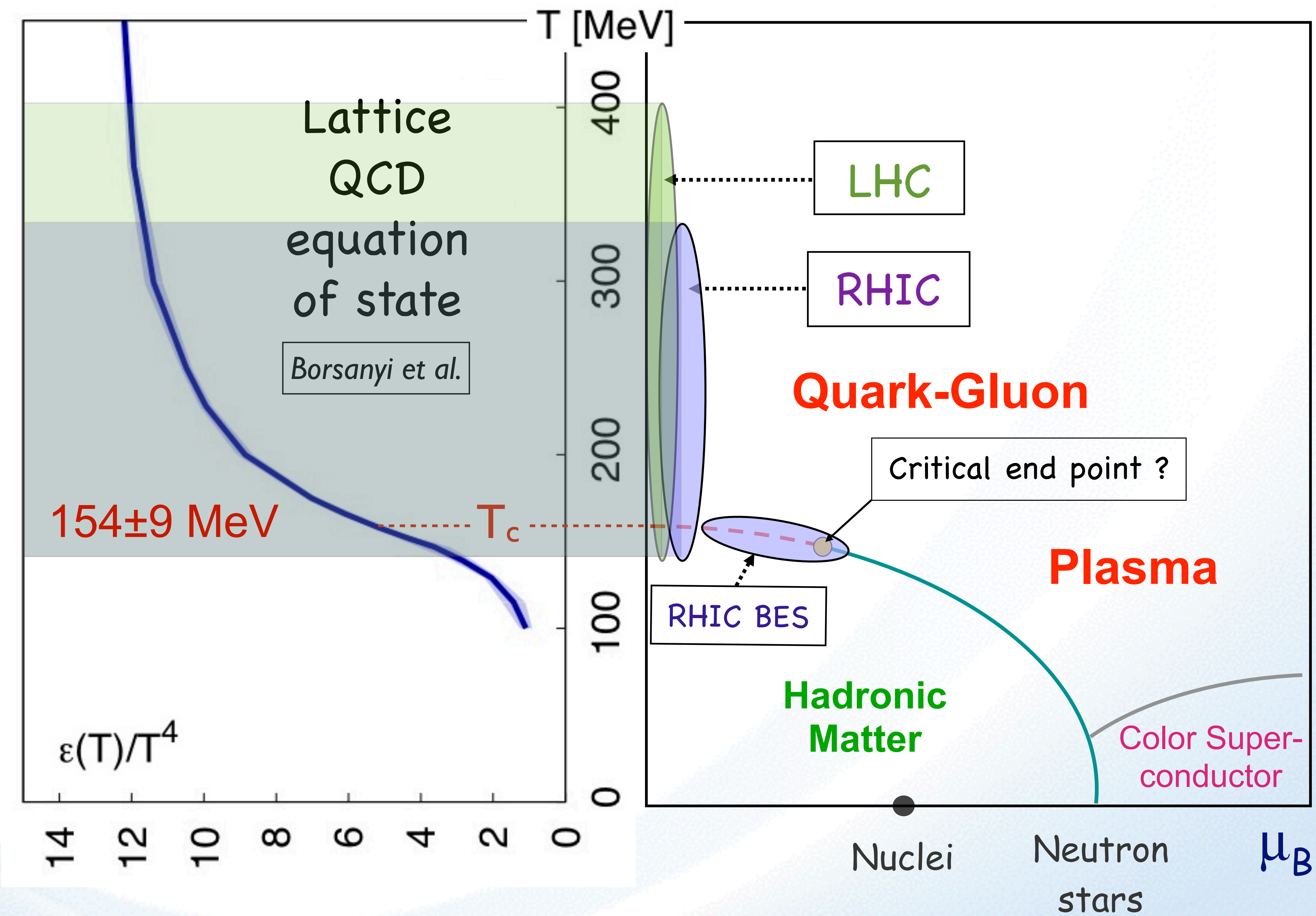


Quark model states of strange baryons



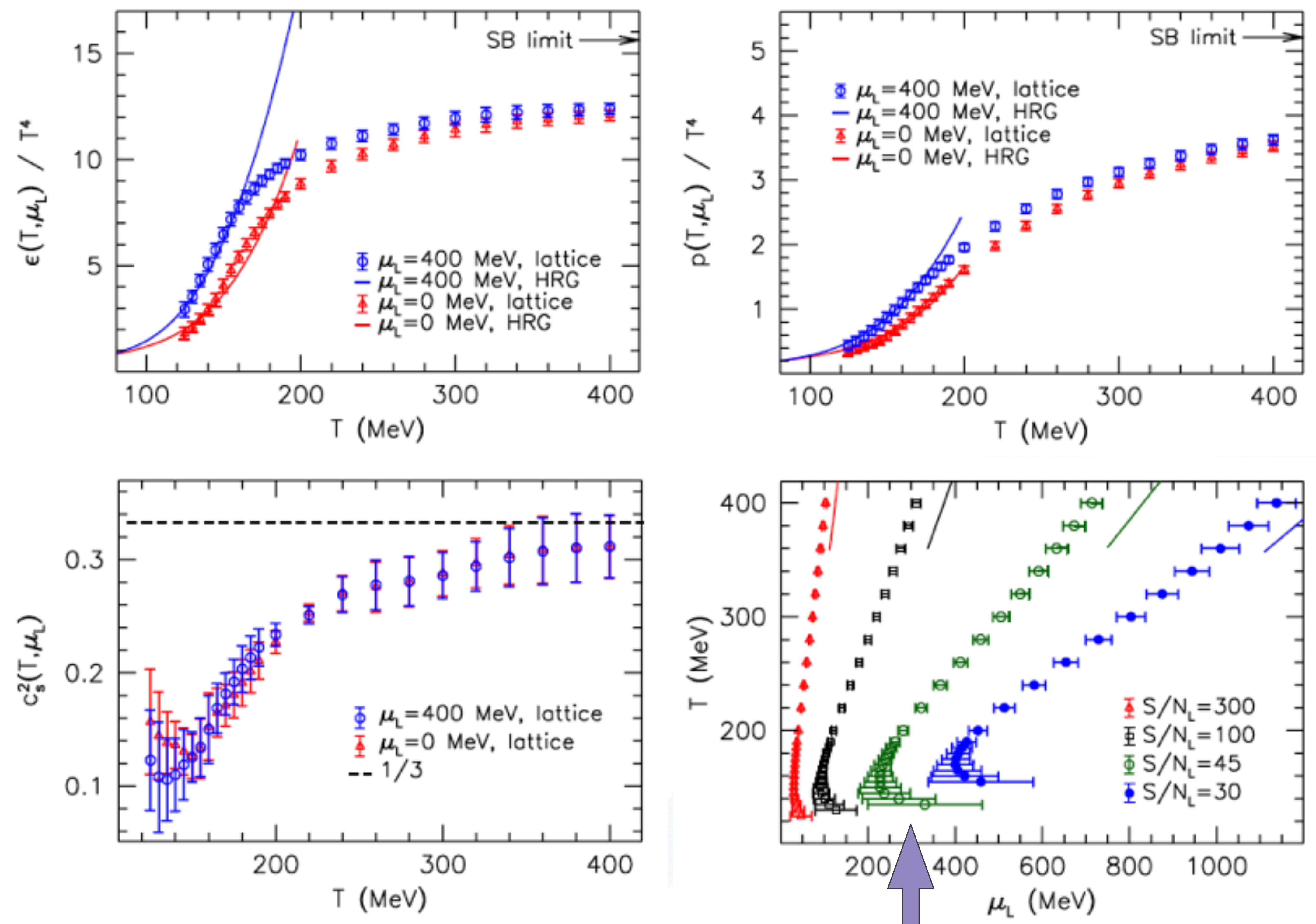
Probing the QCD Phase Boundary

QCD Phase Diagram



QCD EOS at $\mu_B \neq 0$

Borszanyi et al., arXiv:1204:6710



Approximate trajectories in QCD phase diagram

Thermodynamic fluctuations

Susceptibilities measure thermodynamic fluctuations.
Interesting because they exhibit singularities at a critical point.
Fluctuations of conserved quantities (charge *Q*, baryon number *B*,…) cannot be changed by local final-state processes.

Expt.: mean: M_Q
variance: σ_Q^2
skewness: S_Q
kurtosis: κ_Q

$$\sqrt{s} \Leftrightarrow (T, \mu_B)$$

Lattice gauge theory:

$$\chi_n^X(T, \mu_X) = \frac{\partial^n \left(p(T, \mu_X)/T^4 \right)}{\partial (\mu_X/T)^n}$$

Ratios are independent of the (unknown) freeze-out volume:

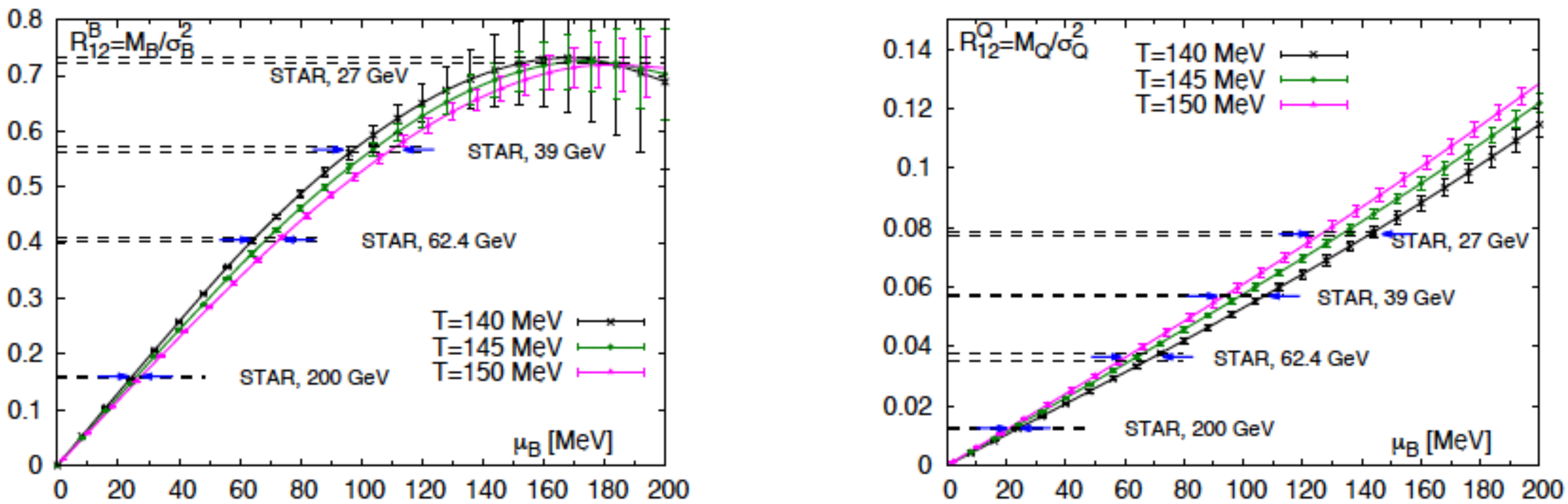
$$\frac{M_Q(\sqrt{s})}{\sigma_Q^2(\sqrt{s})} = \frac{\chi_1^Q(T, \mu_B)}{\chi_2^Q(T, \mu_B)} \qquad \frac{S_Q(\sqrt{s})\sigma_Q^3(\sqrt{s})}{M_Q(\sqrt{s})} = \frac{\chi_3^Q(T, \mu_B)}{\chi_1^Q(T, \mu_B)}$$

Chemical freeze-out

… from fluctuations of conserved quantum numbers (*Q*, *B*):

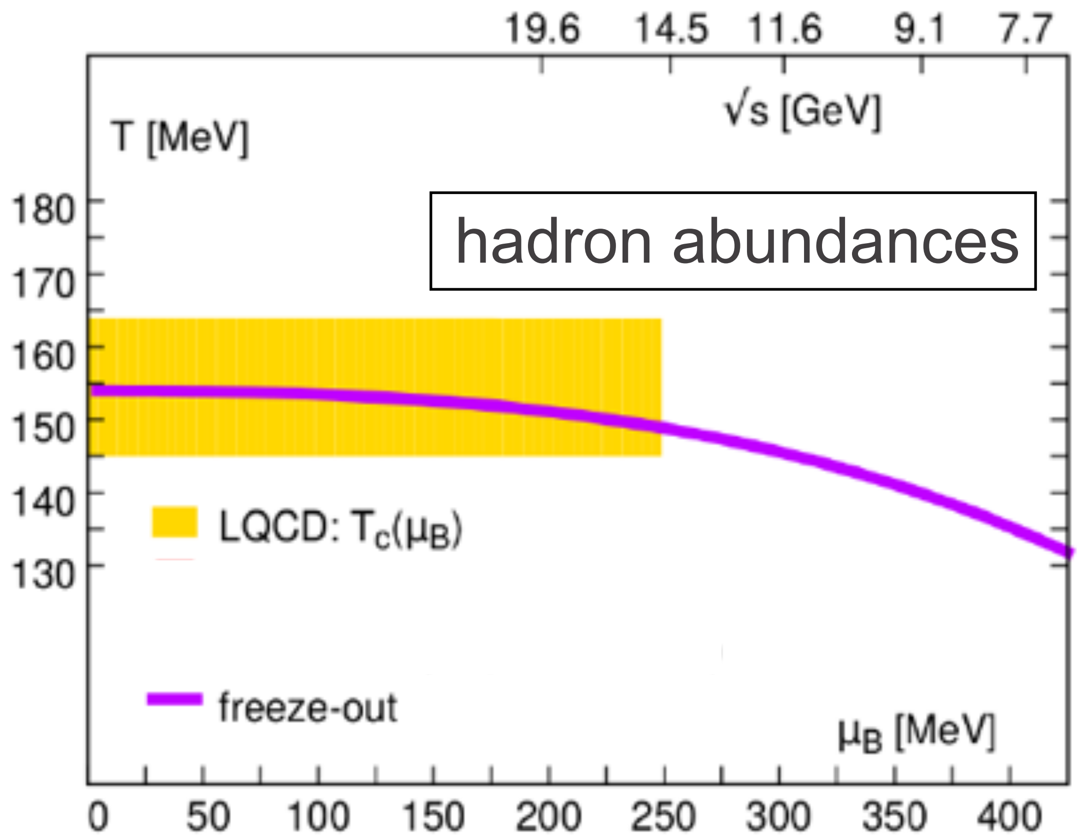
Borsanyi et al. Wuppertal-Budapest Coll. Phys.Rev.Lett. 111, 062005 (2013); Phys.Rev.Lett. 113, 052301 (2014)

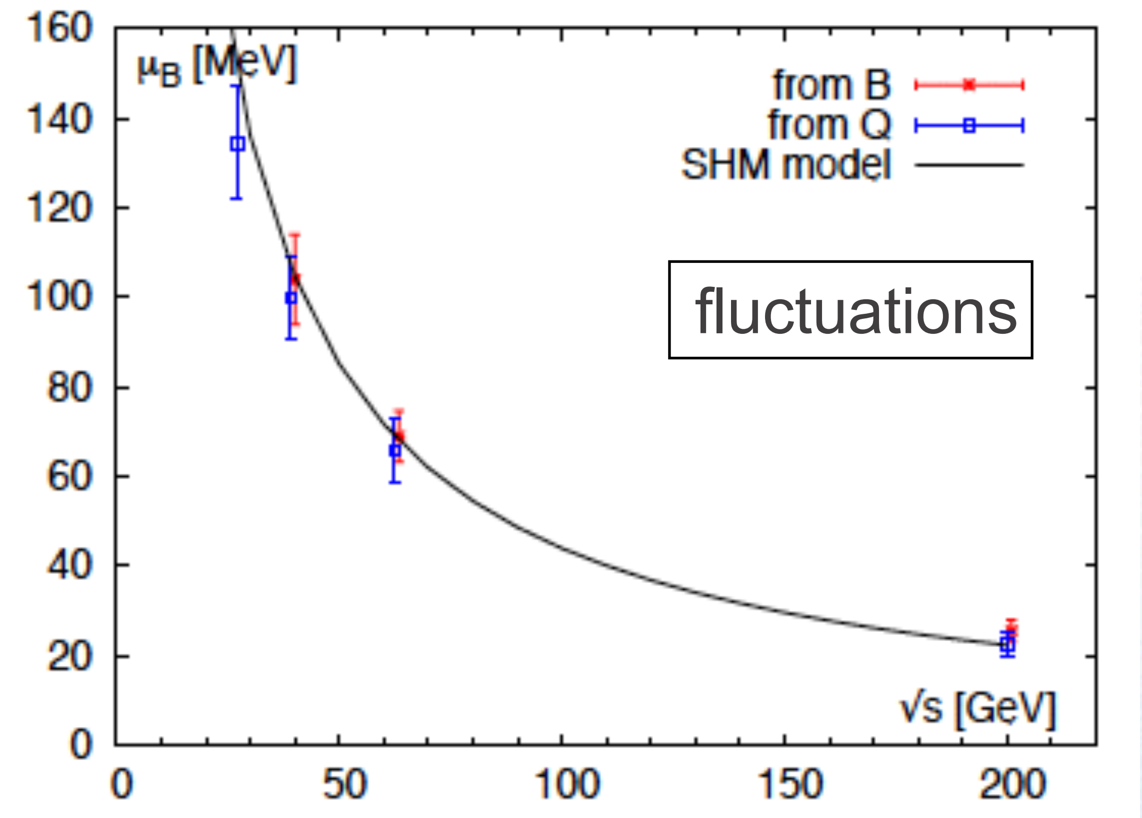
use M/σ^2 both in the baryon and in the charge sector



Compare lattice results with the STAR data for the fluctuation ratios in the temperature range 140−150 MeV permits to read off μ_B.
Both methods are consistent with each other and with the measured baryon/antibaryon ratios, if additional strange baryon states beyond those in the PDG tables (e.g. in the quark model) are accounted for.

Chemical freeze-out





Consistency of freeze-out parameters from mean hadron abundances and from fluctuations (*Q*, *B*) opens the door to search for a critical point in the QCD phase diagram by looking for enhanced critical fluctuations as function of beam energy.

The “perfect” fluid

Viscous hydrodynamics

Hydrodynamics = effective theory of energy and momentum conservation

energy-momentum tensor = **ideal fluid** + **dissipation**

$$\partial_\mu T^{\mu\nu} = 0 \quad \text{with} \quad T^{\mu\nu} = (\varepsilon + P)u^\mu u^\nu - P g^{\mu\nu} + \Pi^{\mu\nu}$$

$$\tau_\Pi \left[\frac{d\Pi^{\mu\nu}}{d\tau} + \left(u^\mu \Pi^{\nu\lambda} + u^\nu \Pi^{\mu\lambda} \right) \frac{du^\lambda}{d\tau} \right] = \eta \left(\partial^\mu u^\nu + \partial^\nu u^\mu - \text{trace} \right) - \Pi^{\mu\nu}$$

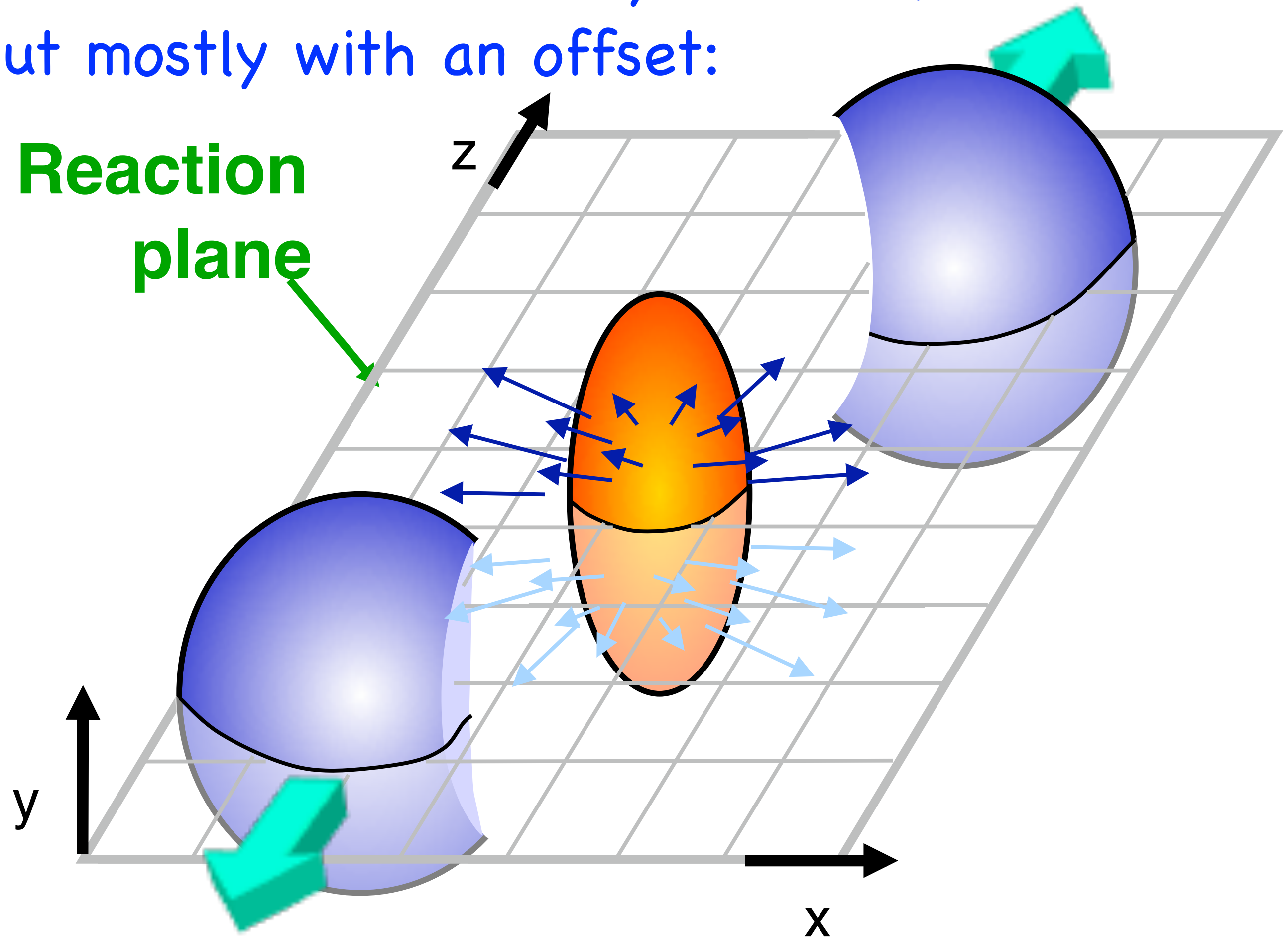
Input: Equation of state P(ε), shear viscosity, initial conditions ε(x,0), u^μ(x,0)

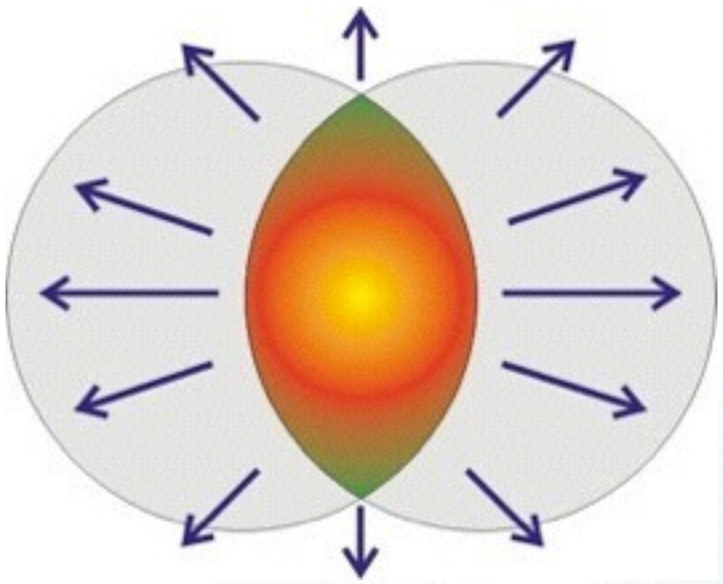
Shear viscosity **η** is normalized by density: **kinematic viscosity η/ρ**.

Relativistically, the appropriate normalization factor is the **entropy density** s = (ε+P)/T, because the particle density is not conserved: **η/s**.

Elliptic flow

- two nuclei collide rarely head-on, but mostly with an offset:





only matter in the overlap area gets compressed and heated

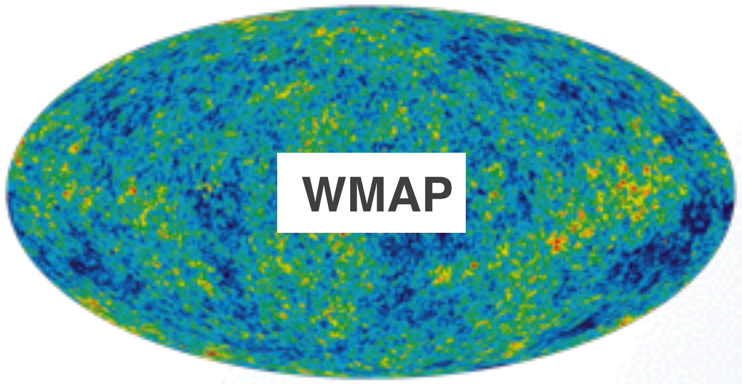
$$2\pi \frac{dN}{d\phi} = N_0 \left(1 + 2 \sum_n v_n(p_T, \eta) \cos n\left(\phi - \psi_n(p_T, \eta)\right) \right)$$

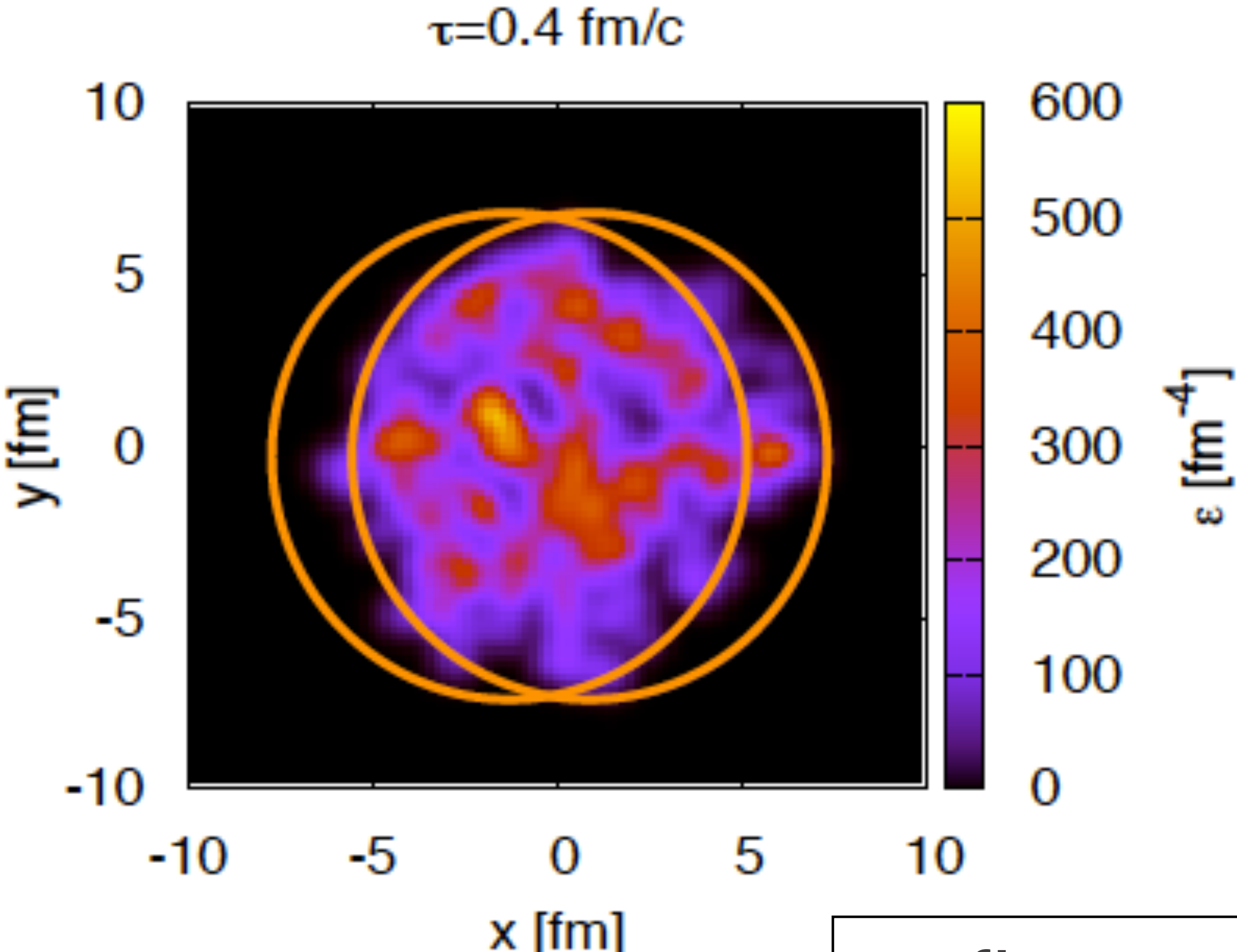
anisotropic flow coefficients

event plane angle

Event-by-event fluctuations

Initial state generated in A+A collision is grainy
event plane ≠ reaction plane
⇒ eccentricities ε_1, ε_2, ε_3, ε_4, etc. ≠ 0





Idea: Energy density fluctuations in transverse plane from initial state quantum fluctuations. These thermalize to different temperatures locally and then propagate hydrodynamically to generate angular flow velocity fluctuations in the final state.

⇒ flows v_1, v_2, v_3, v_4,…

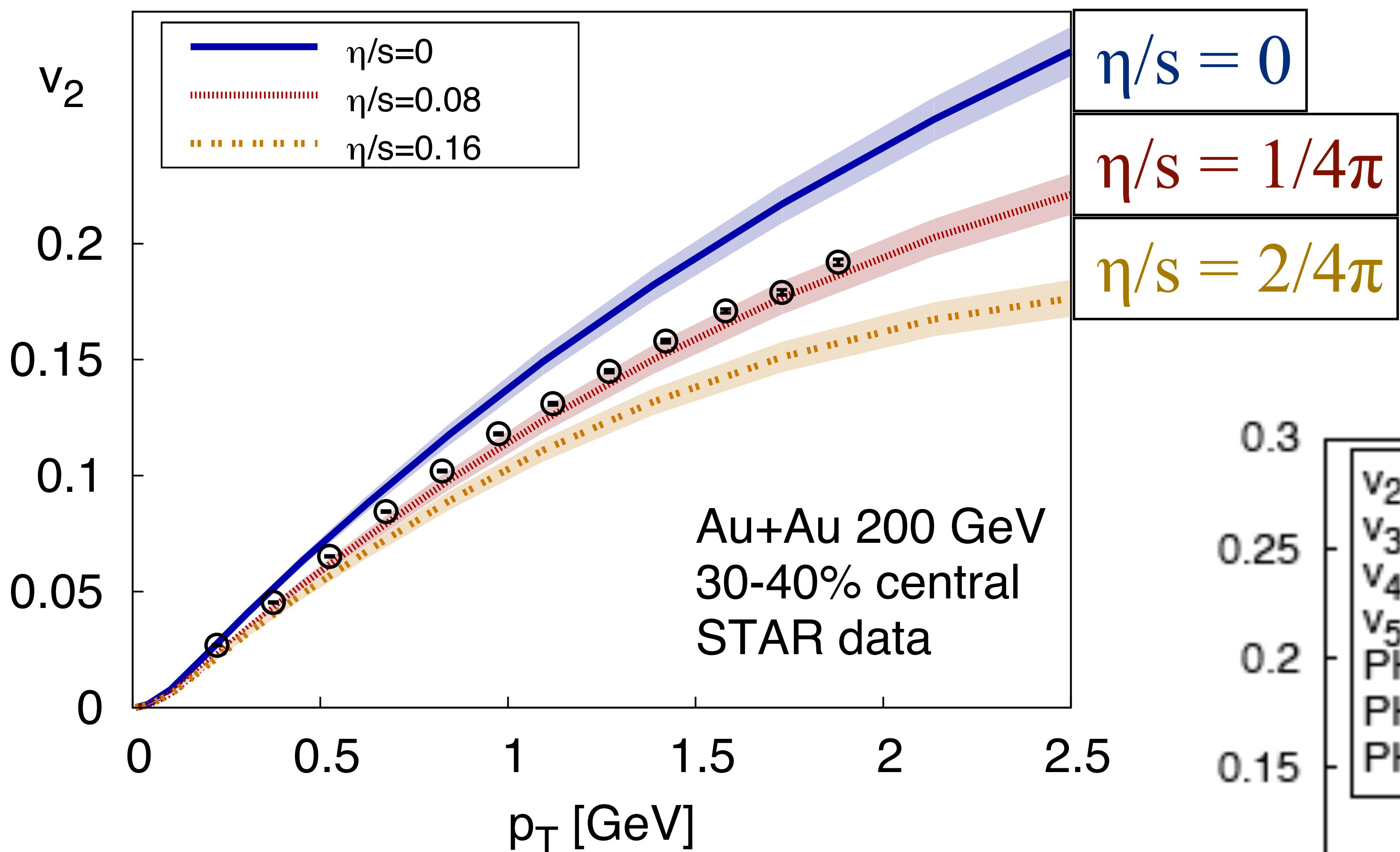
Elliptic flow "measures" η_{QGP}

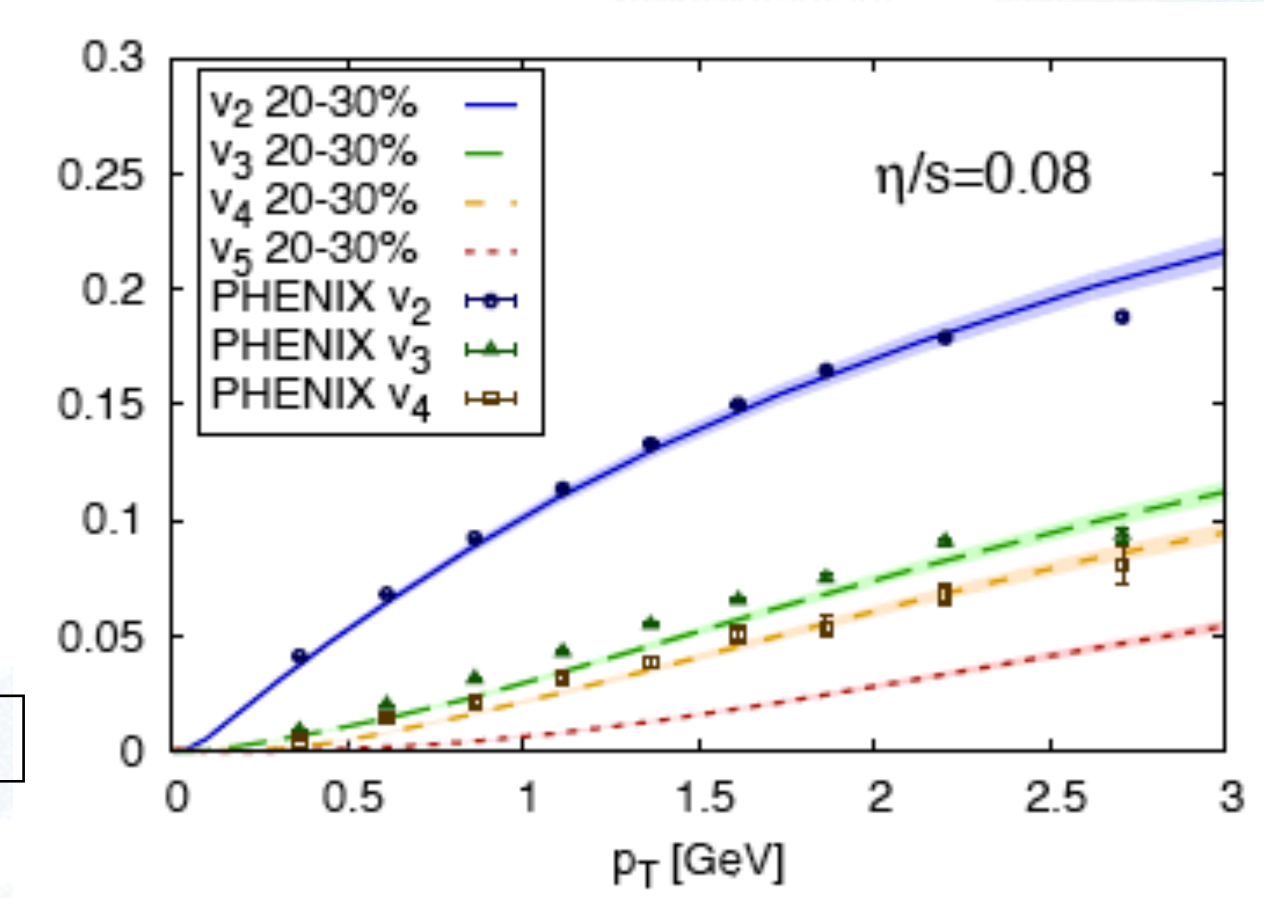
Universal strong coupling limit of non-abelian gauge theories with a gravity dual:

$\eta/s \rightarrow 1/4\pi$

aka: the "perfect" liquid

Schenke, Jeon, Gale, PRL 106 (2011) 042301

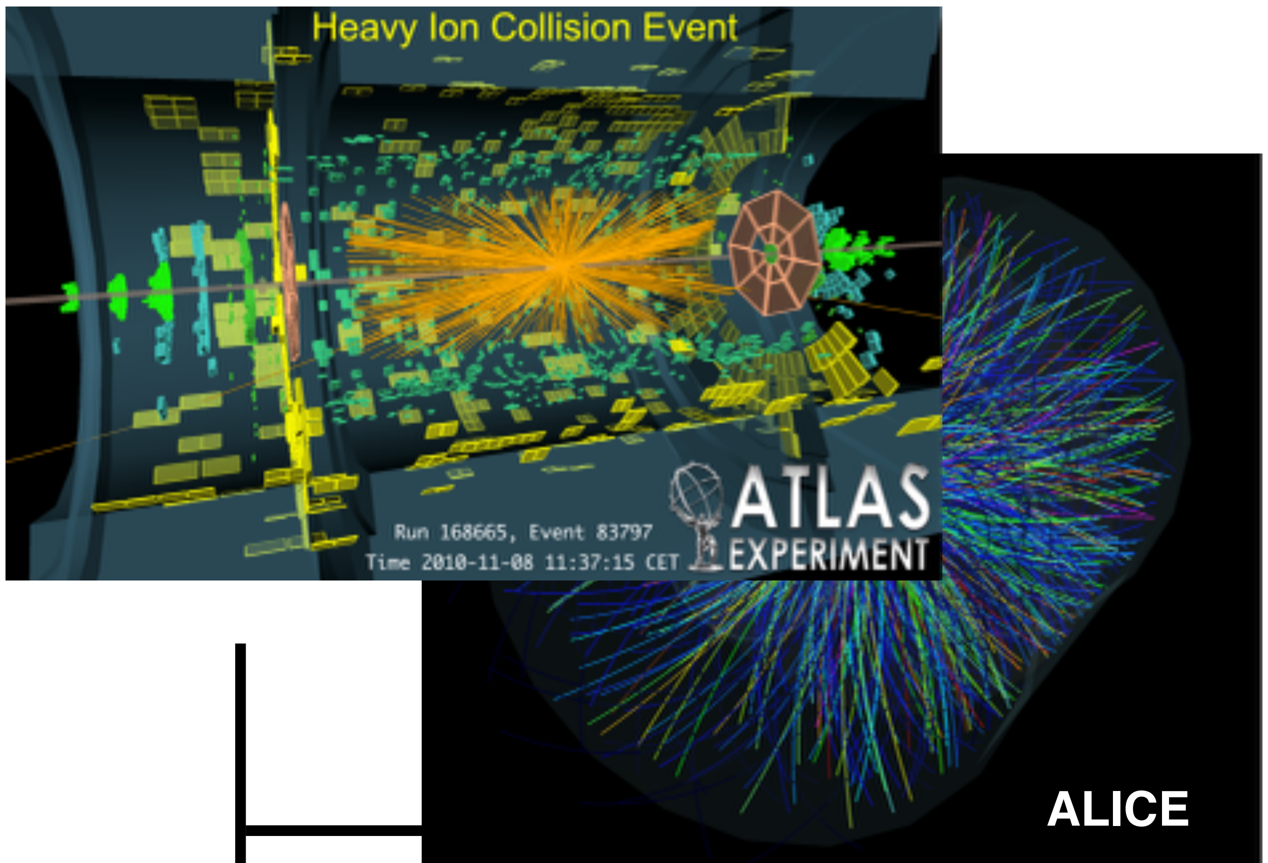


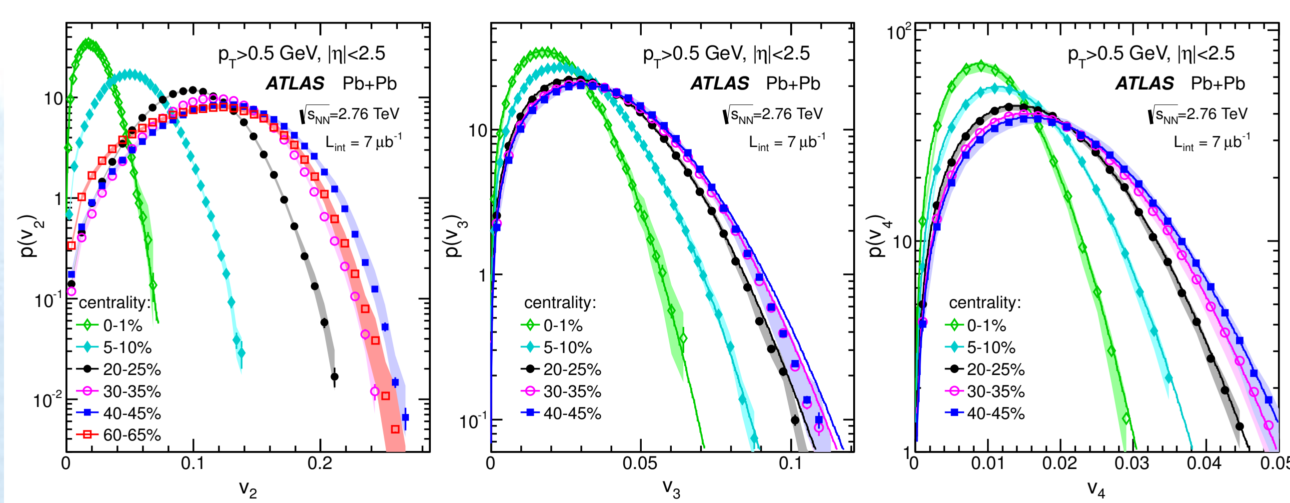


Schenke, Jeon, Gale, PRC 85 (2012) 024901

Discovery by model-data comparison

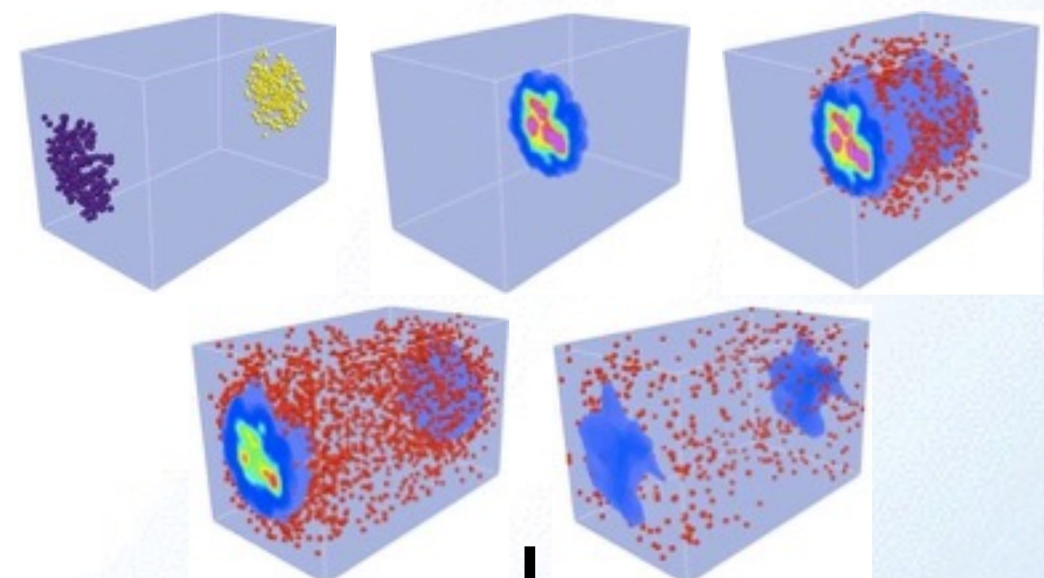
Data:

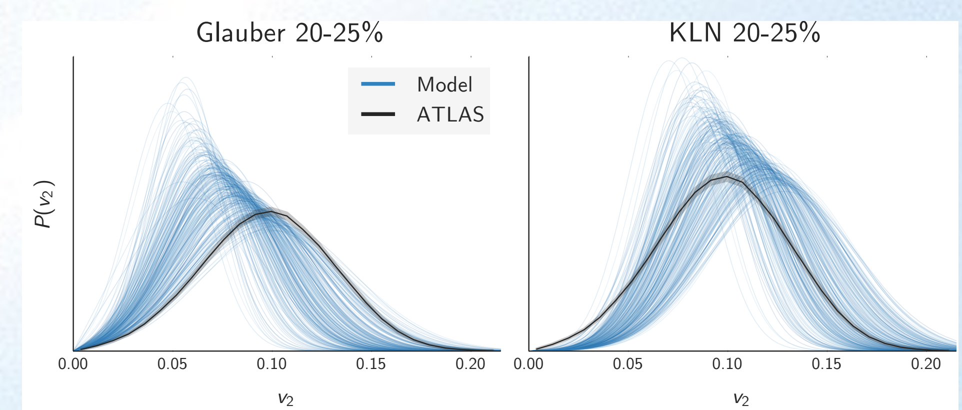




Model:

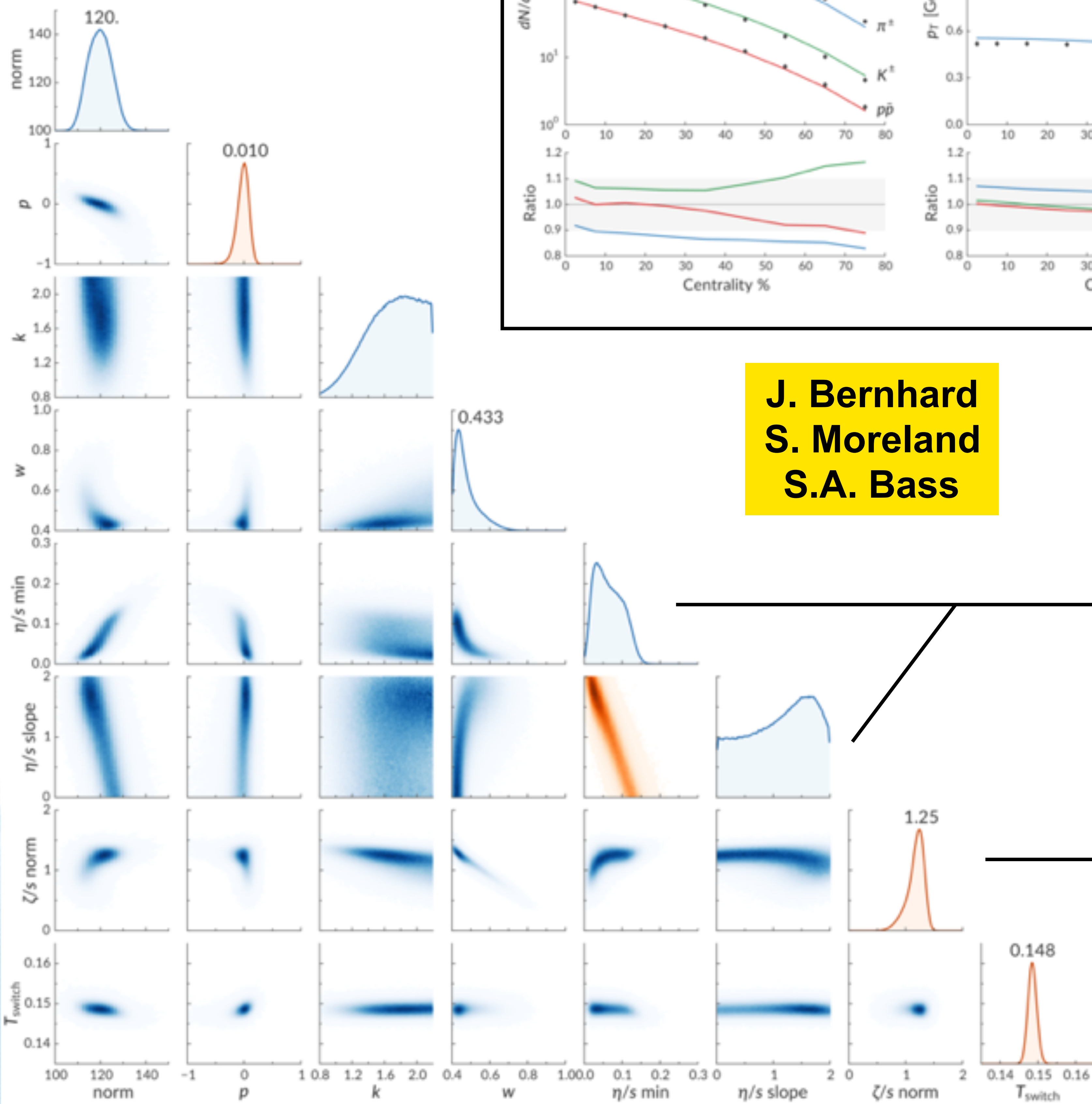
initial conditions, τ_0, η/s, ζ/s, ….



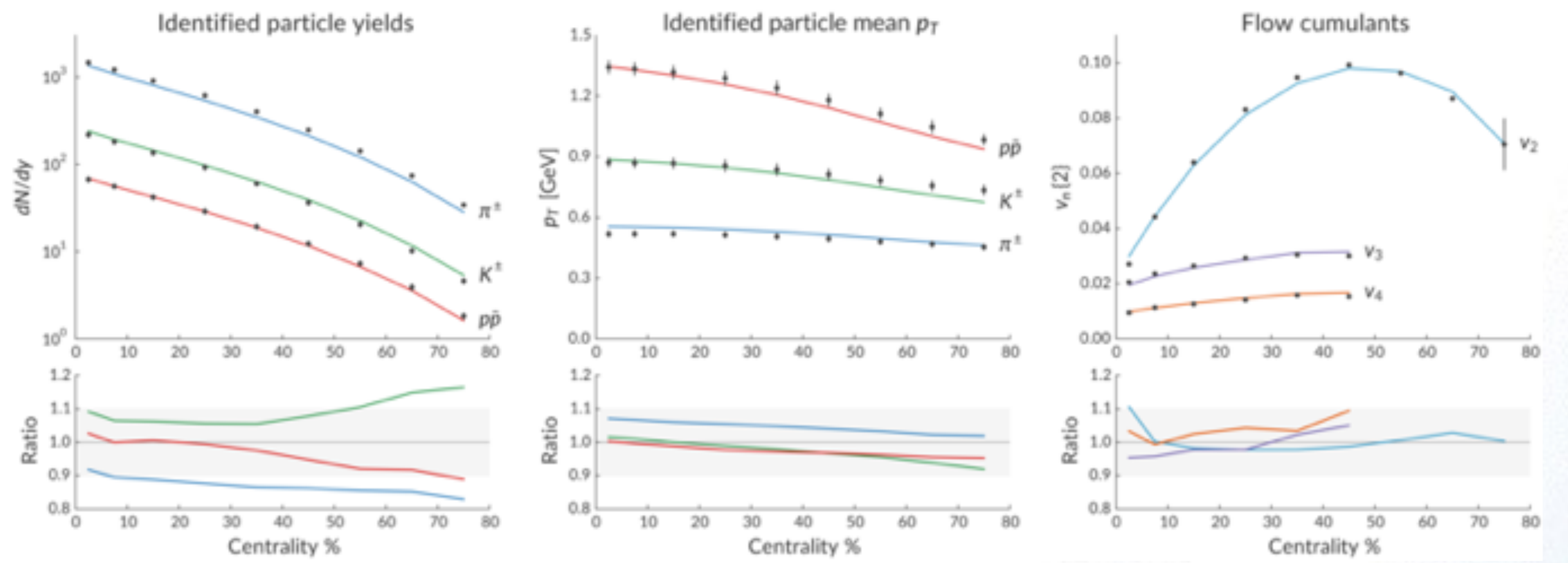


extracted QGP properties: η/s, …

Calibrated posterior distributions:

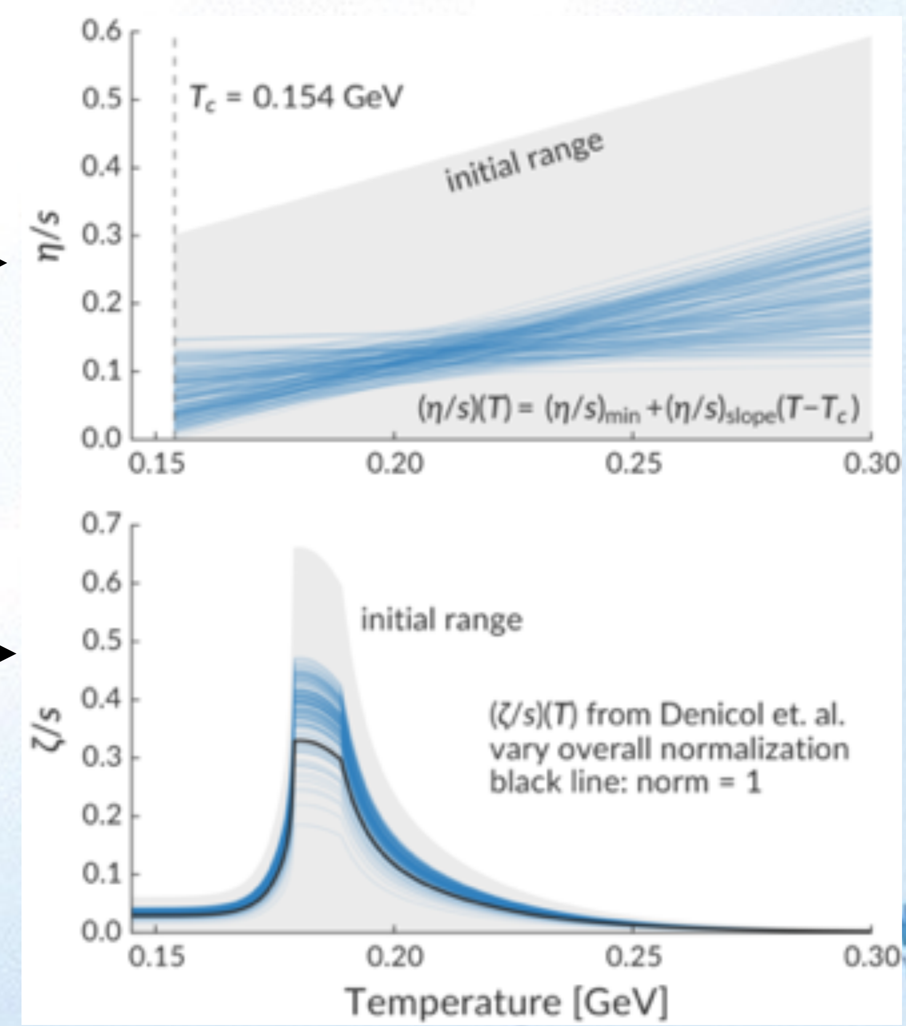


Explicit model calculations (no emulator):



J. Bernhard
S. Moreland
S.A. Bass

Temperature-dependent viscosities from the calibrated posterior:



Probing the Quark-Gluon Plasma

Hot QCD matter properties

Which **properties of hot QCD matter** can we hope to determine and how ?

Easy for LQCD

$$T_{\mu\nu} \quad \Leftrightarrow \quad \varepsilon, p, s$$

Equation of state: spectra, coll. flow, fluctuations

$$\eta = \frac{1}{T}\int d^4x \left\langle T_{xy}(x) T_{xy}(0) \right\rangle$$

Shear viscosity: anisotropic collective flow

Very Hard for LQCD

$$\hat{q} = \frac{4\pi^2\alpha_s C_R}{N_c^2 - 1}\int dy^- \left\langle U^\dagger F^{a+i}(y^-) U F_i^{a+}(0) \right\rangle$$

$$\hat{e} = \frac{4\pi^2\alpha_s C_R}{N_c^2 - 1}\int dy^- \left\langle i U^\dagger \partial^- A^{a+}(y^-) U A^{a+}(0) \right\rangle$$

$$\kappa = \frac{4\pi\alpha_s}{3N_c}\int d\tau \left\langle U^\dagger F^{a0i}(\tau) t^a U F^{b0i}(0) t^b \right\rangle$$

Momentum/energy diffusion: parton energy loss, jet fragmentation

Hard for LQCD

$$\Pi_{\mathrm{em}}^{\mu\nu}(k) = \int d^4x\, e^{ikx} \left\langle j^\mu(x) j^\nu(0) \right\rangle$$

QGP Radiance: Lepton pairs, photons

Easy for LQCD

$$m_D = -\lim_{|x|\to\infty} \frac{1}{|x|} \ln \left\langle U^\dagger E^a(x) U E^a(0) \right\rangle$$

Color screening: Quarkonium states

Future of RHIC

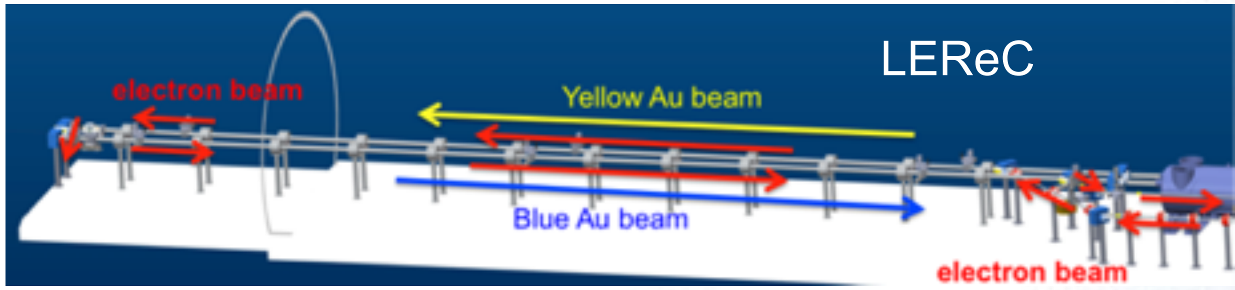
Completing the RHIC science mission

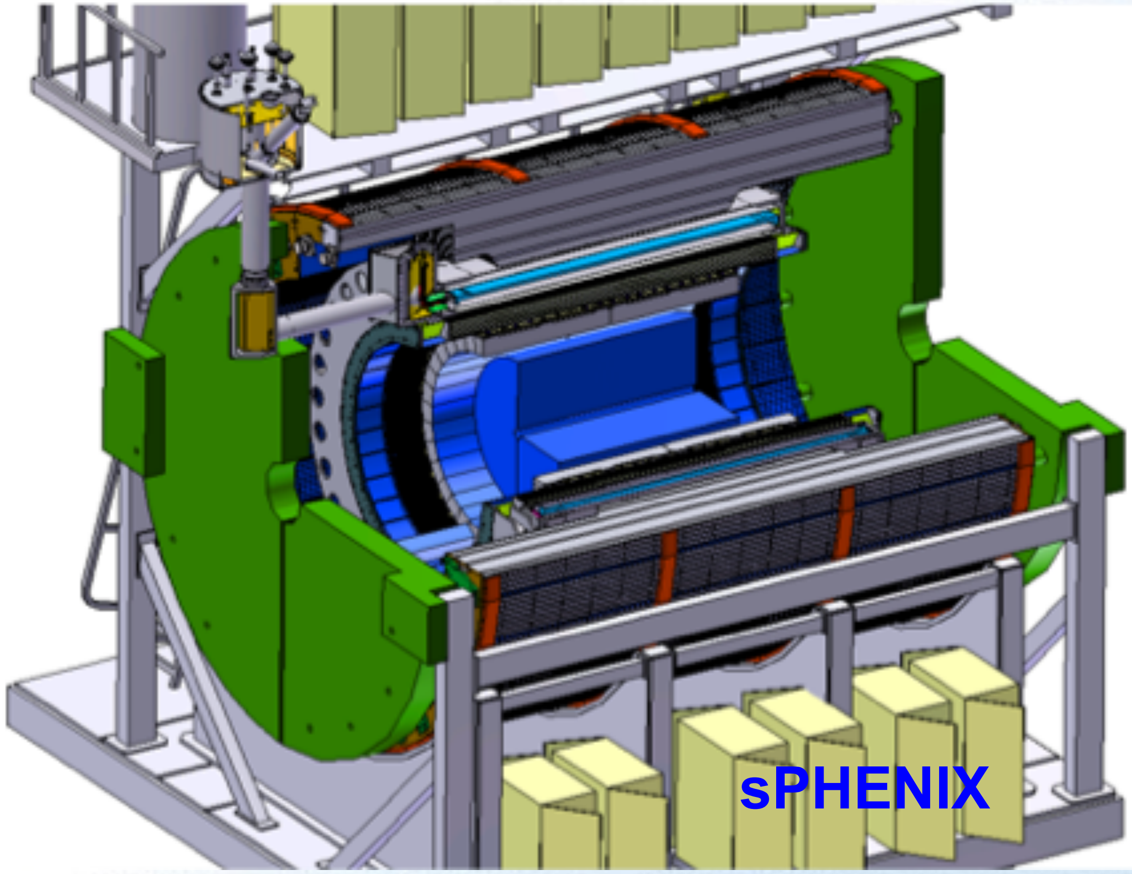
Status: RHIC-II configuration is complete

- Vertex detectors in STAR (HFT) and PHENIX
- Luminosity reaches 25x design luminosity

Plan: Complete RHIC mission in 3 campaigns:

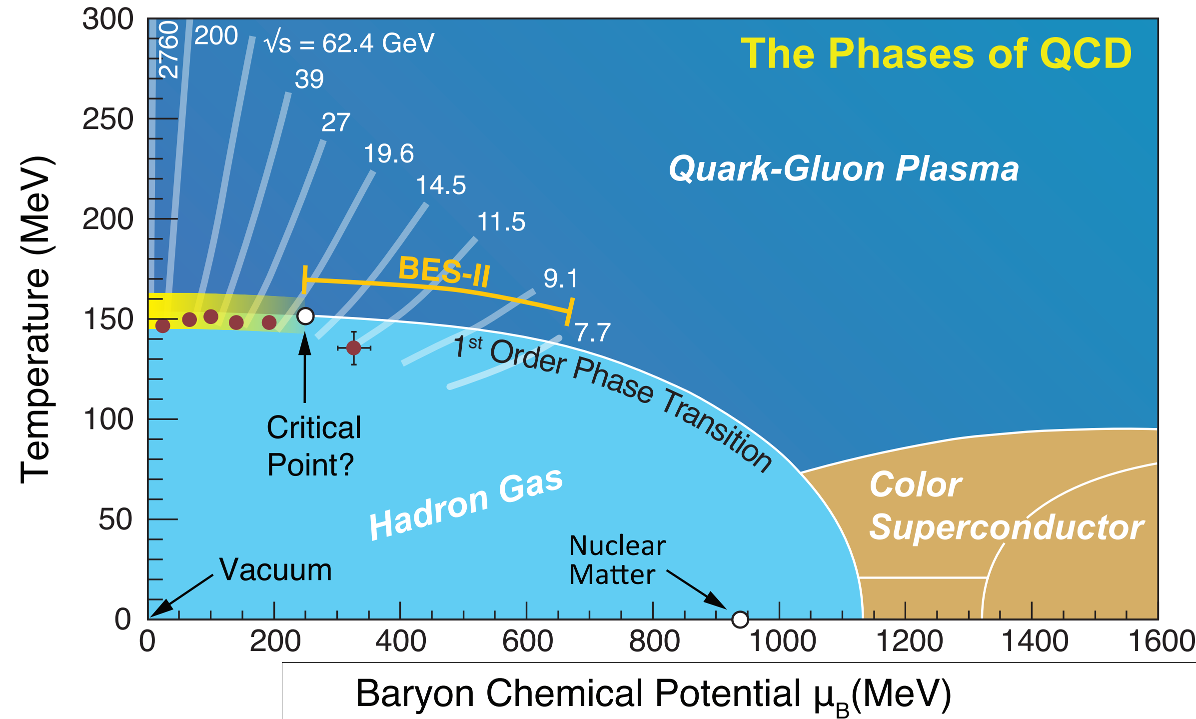
- **2014–17: Heavy flavor probes of the QGP using the micro-vertex detectors; Transverse spin physics**
- *2018: Install low energy e-cooling*
- **2019/20: High precision scan of the QCD phase diagram & search for critical point**
- *2021: Install sPHENIX*
- **2022-23: Probe perfect liquid QGP with precision measurements of jet quenching and Upsilon suppression**
- *Transition to eRHIC?*



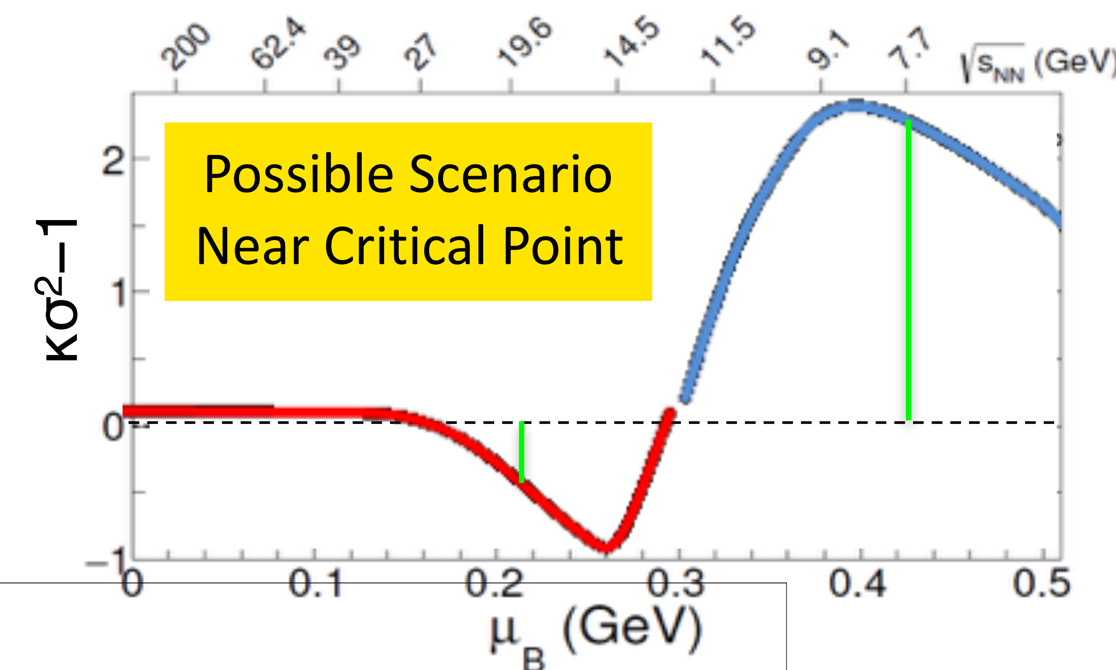


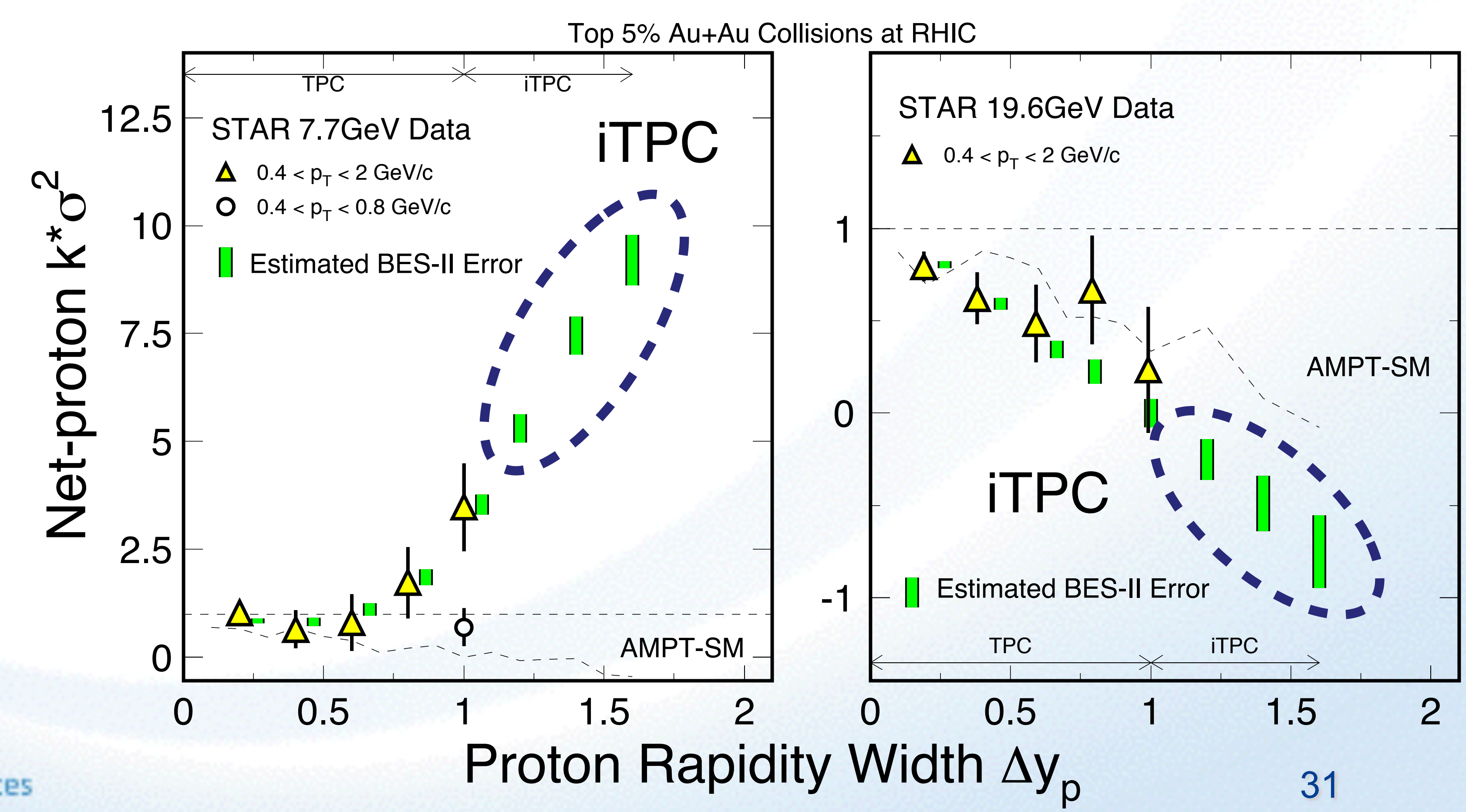
RHIC remains a unique discovery facility

Critical fluctuations in BES-II



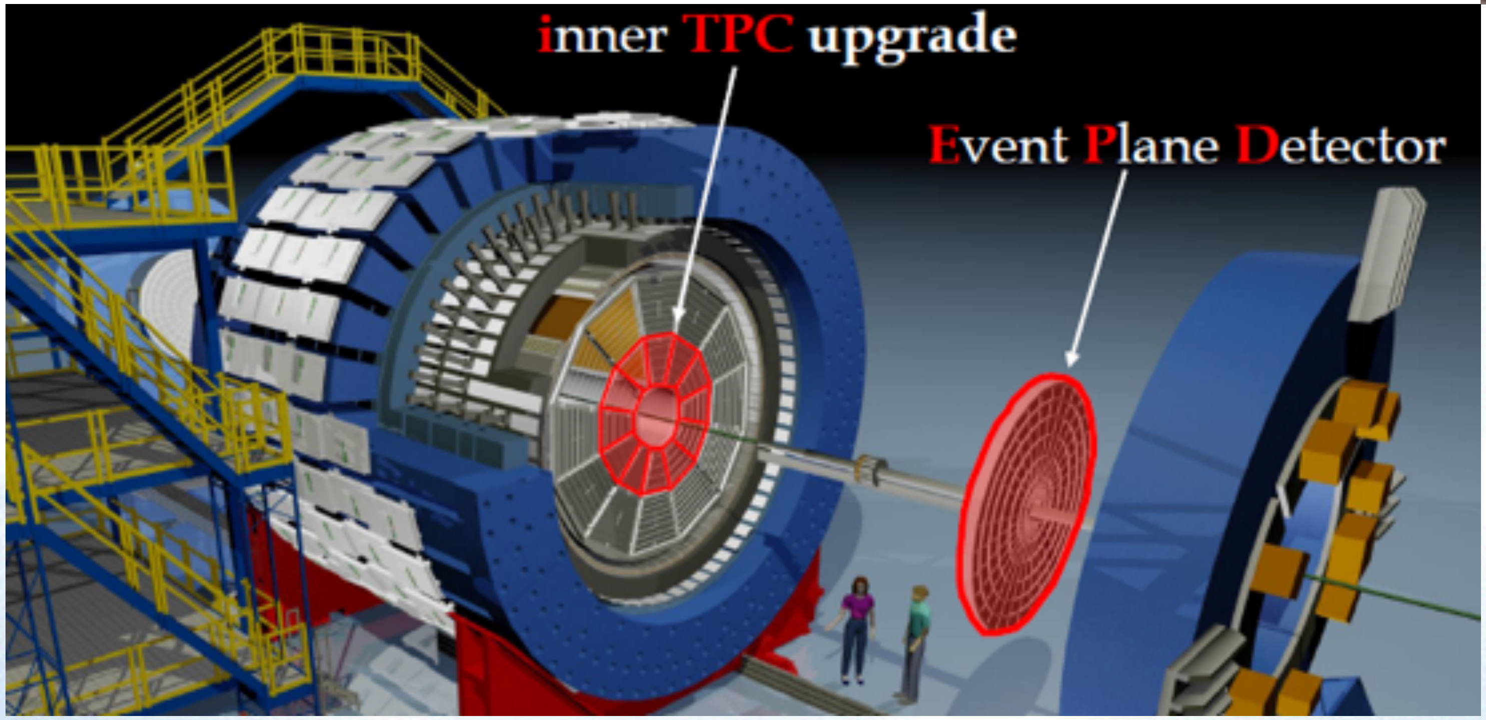
Model independent structure of net baryon number kurtosis





STAR Upgrades for BES II

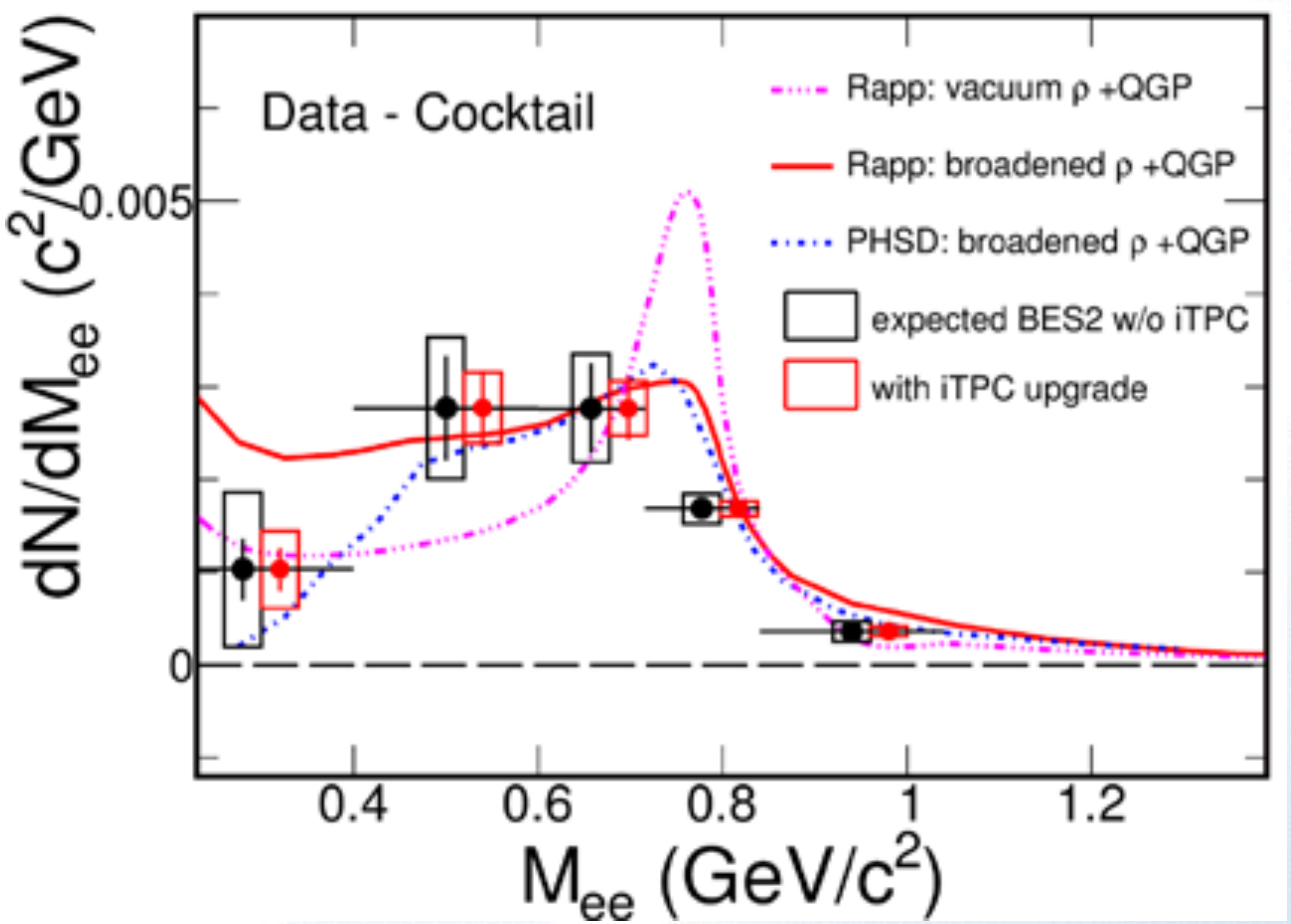
iTPC upgrade (2018)
Replace inner TPC Sectors
Extend rapidity coverage
Better particle ID
Low p_T coverage



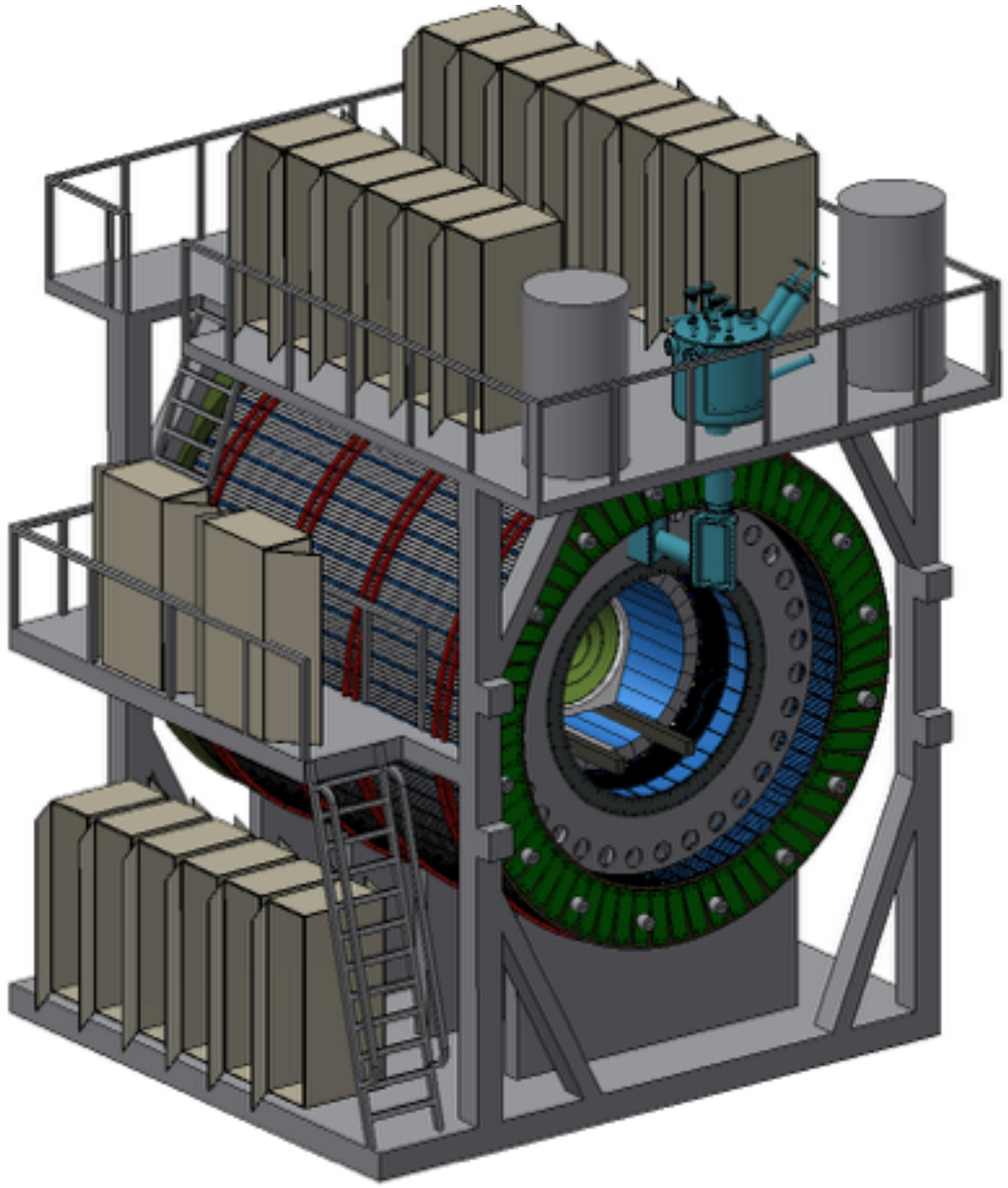
Event Plane Detector (2018)
Improved Event Plane Resolution
Centrality definition
Improved trigger
Background rejection

Photon spectral function

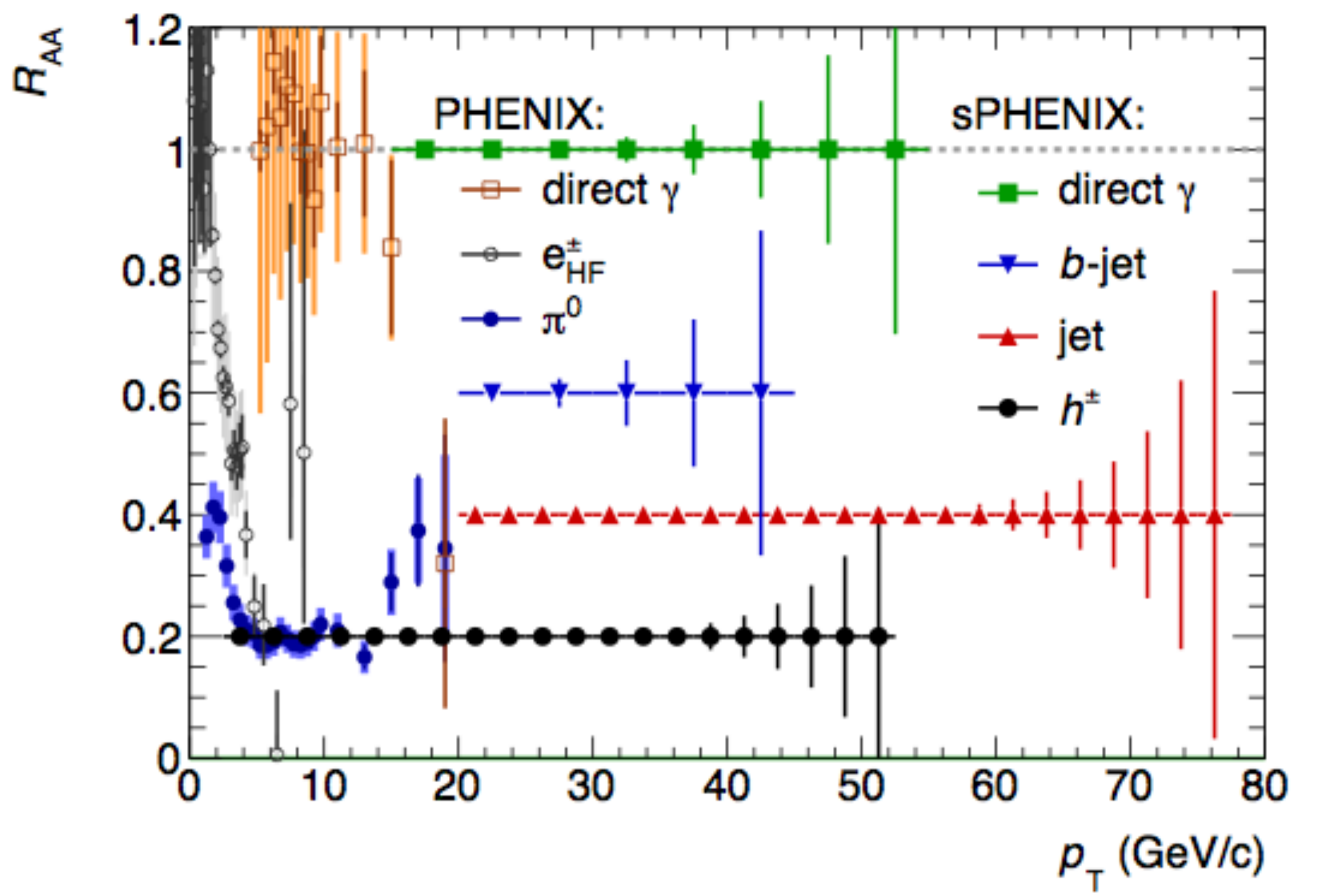
The iTPC will also enable a more precise measurement of the photon spectral function at masses below 1 GeV



sPHENIX



A large-acceptance detector to make precision measurements of hard probes (jets and Upsilon states) of the QGP at strongest coupling (near T_c). Replacing PHENIX and upgradable to EIC detector.



Built around the BaBar solenoid – undergoing testing at BNL

Completing the RHIC science mission

- **A unique forefront science program with tremendous discovery potential that is ONLY possible with RHIC:**
- **Quantify the transport properties of the QGP *near T_c* using heavy quarks as probes** (together with LHC)
- **Measure gluon and sea quark contributions to proton spin and explore coupled momentum-spin dynamics of QCD**
- **High statistics map of the QCD phase diagram, including possible discovery of a critical point**
- **Probe internal structure of the *most liquid* QGP using fully reconstructed jets and resolved Upsilon states as probes** (together with LHC)
- **Refine the physics program of an EIC with studies of *polarized* pp and pA collisions in forward kinematics**
- **RHIC enabled R&D to retire major risks of eRHIC design**