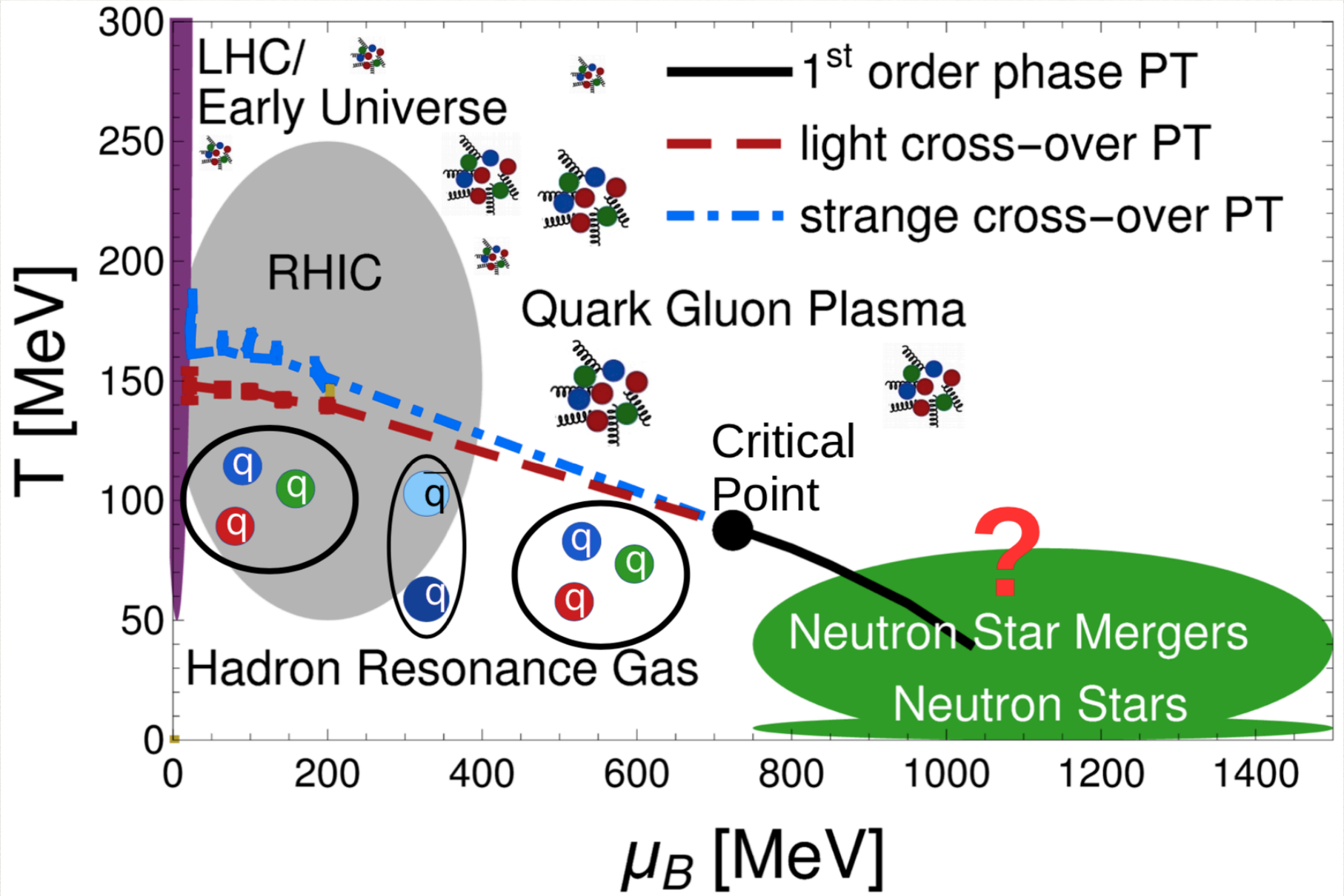
EXPLORING THE QCD PHASE DIAGRAM ACROSS BARYON NUMBER, STRANGENESS, AND ELECTRIC CHARGE

Jacquelyn Noronha-Hostler
Initial Conditions: Patrick Carzon, Mauricio Martinez, Skanda Rao, Matt Sievert, Doug Wertepny
Hydro: Travis Dore, Emma McLaughlin
Freeze-out/EOS: Paolo Parotto, Israel Portillo Vazquez, Claudia Ratti, Jamie Stafford

QCD Phase Diagram



Light transition *Phys.Lett. B738 (2014) 305-310;* ***Strange Transition*** *Bellwied, JNH, Parotto, Vazquez, Ratti, Stafford, arXiv:1805.00088 ;* ***Neutron Star (mergers)*** *V. Dexheimer ariXiv:1708.08342;* ***Holography*** *Critelli, JNH, et al, Phys.Rev. D96 (2017) no.9, 096026*

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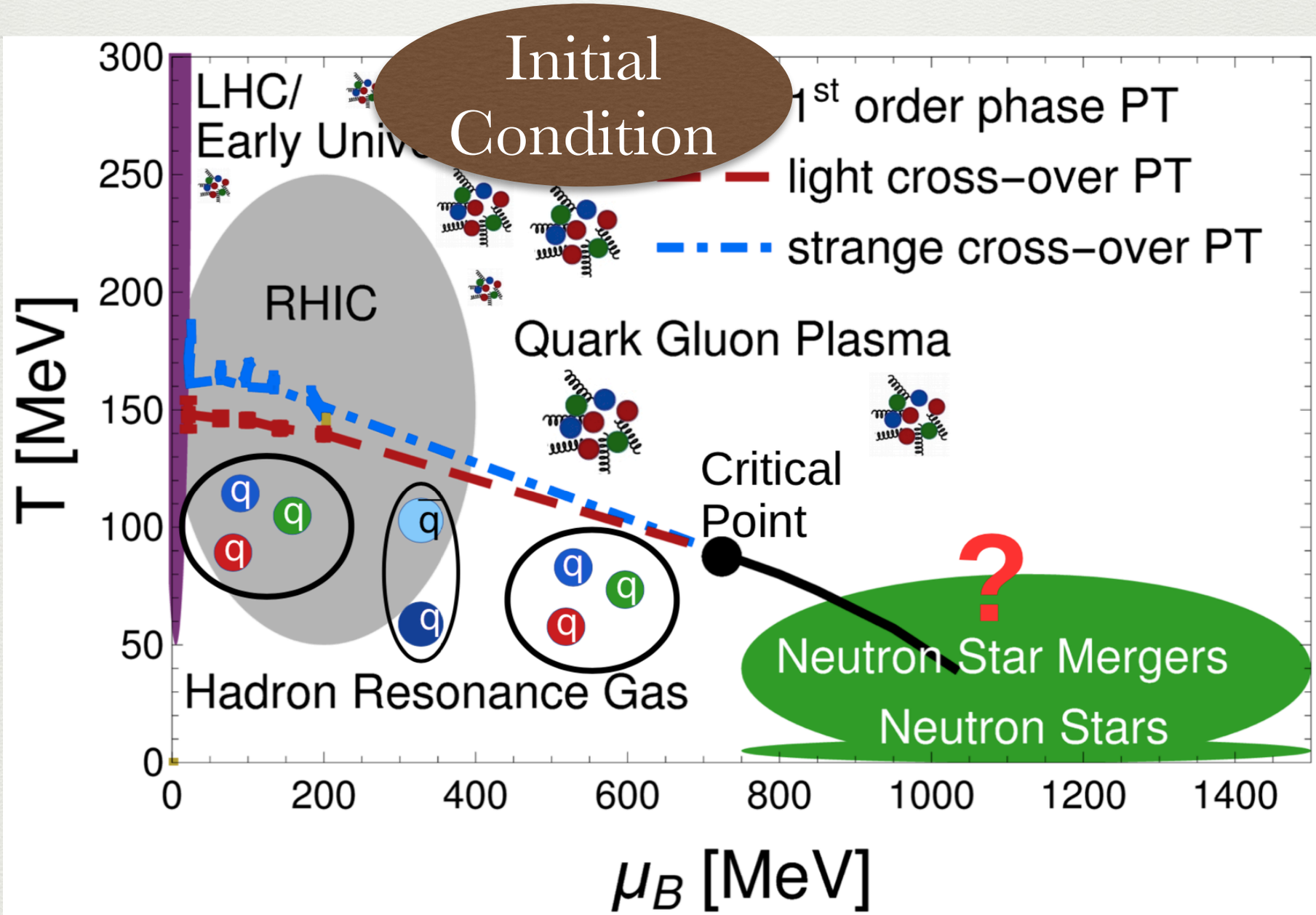

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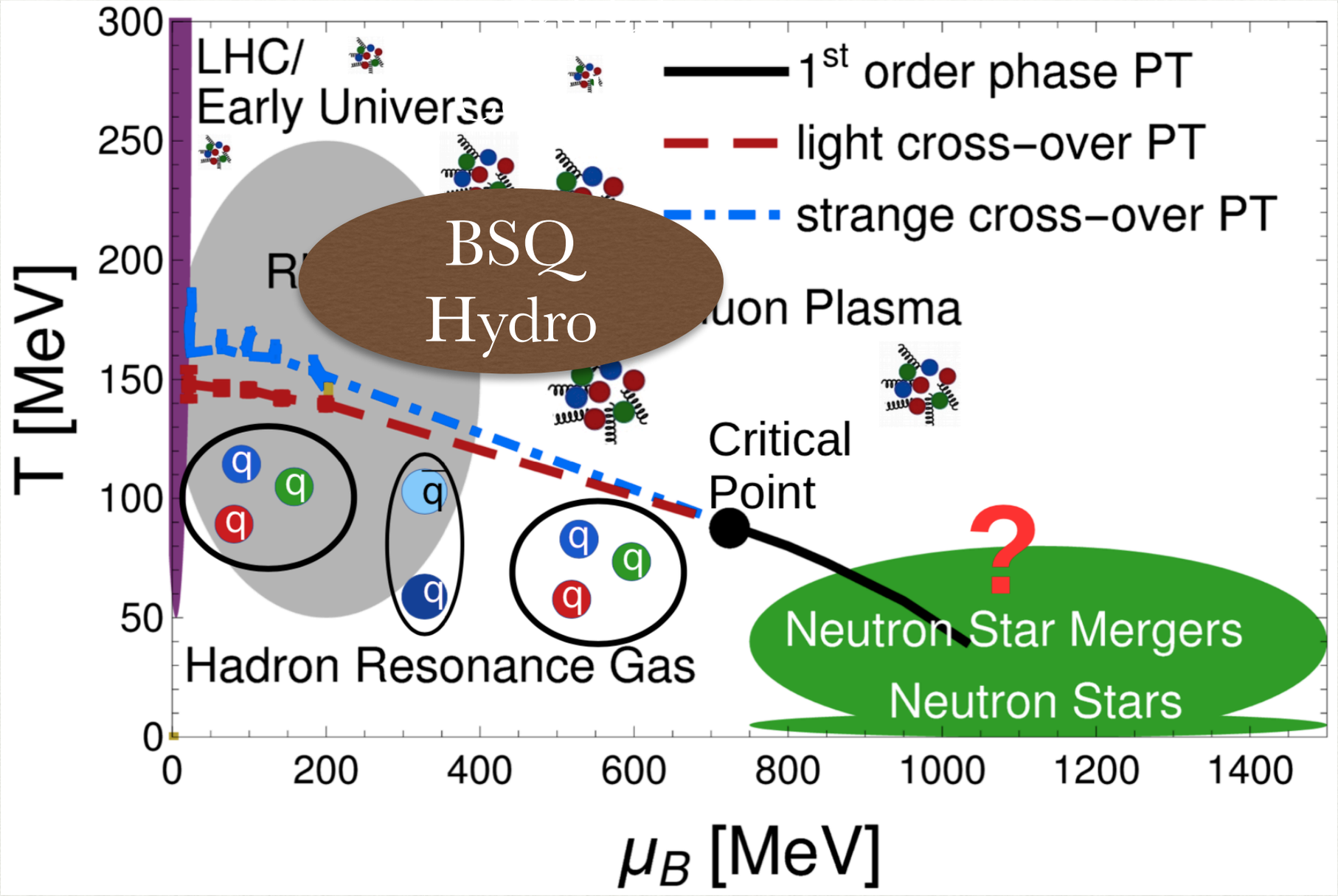

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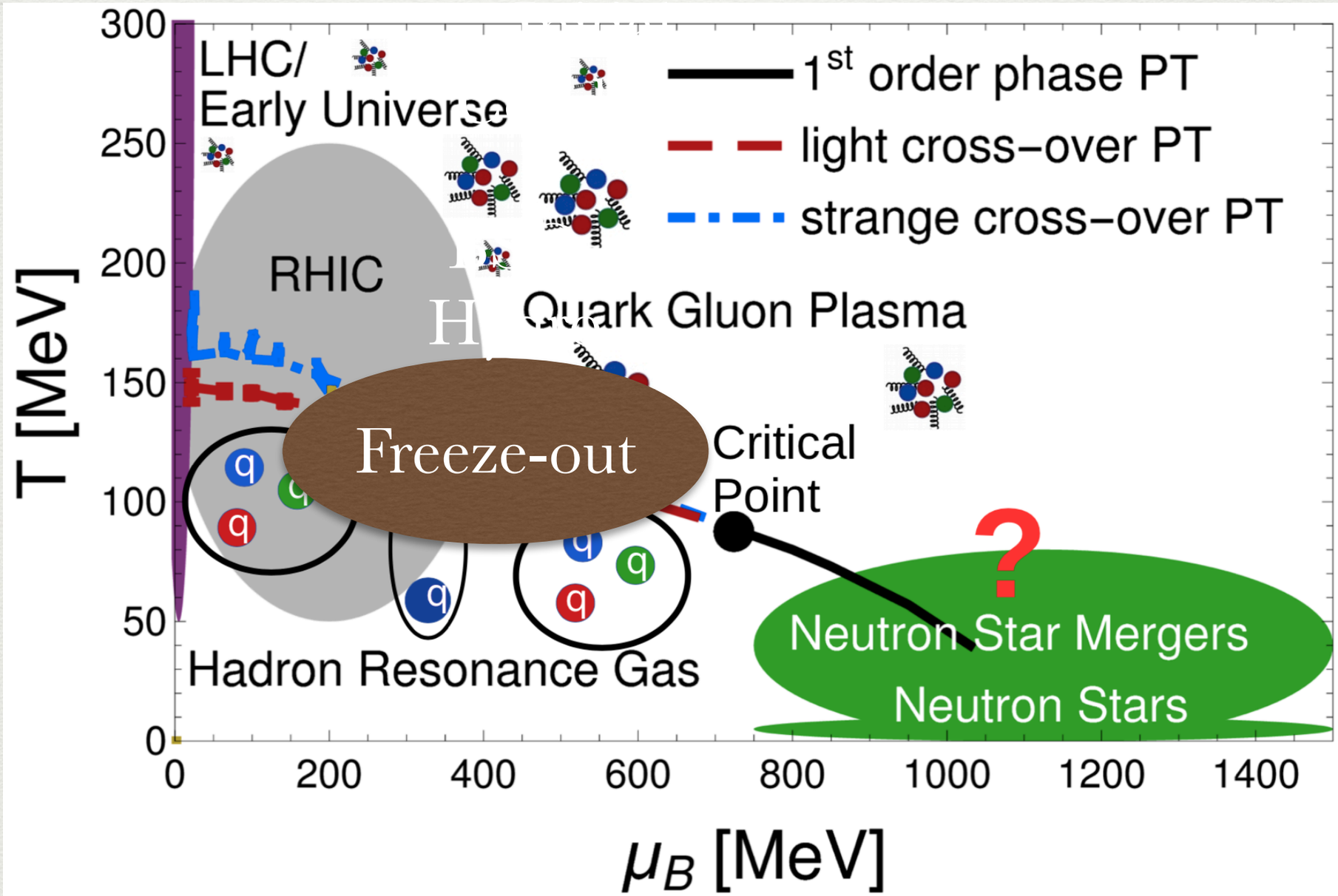

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How do initial conditions vary by Beam Energy?

Strings between nucleons to simulate baryon stopping

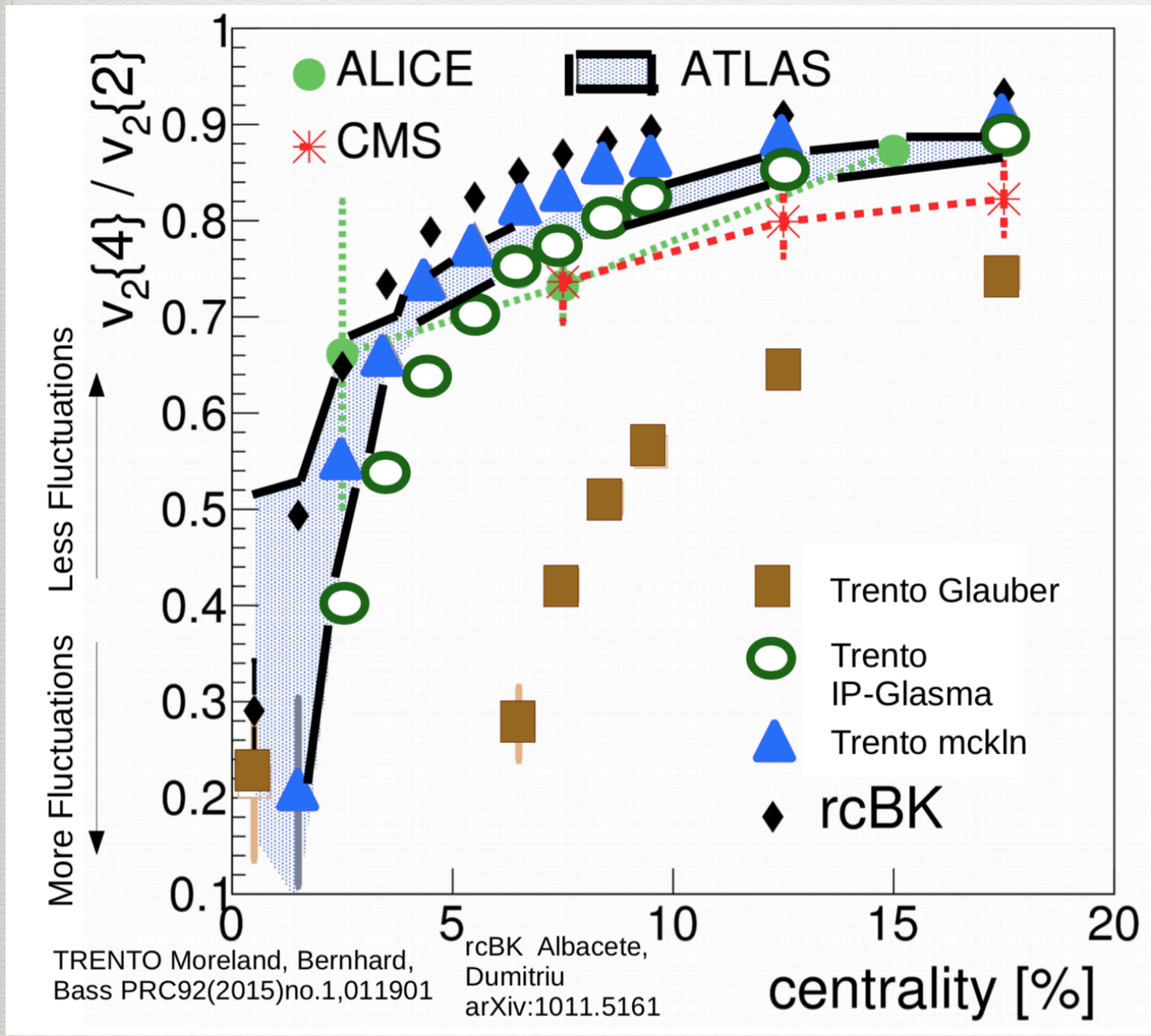
Werner, Phys.Rept. 232 (1993) 87-299 ; Jeon and Kapusta, Phys.Rev. C56 (1997) 468-480 ; Bialis, Bzdak, Bozek, Acta Phys.Polon. B49 (2018) 103; Schenke and Shen Phys.Rev. C97 (2018) no.2, 024907

Tranport (UrQMD)

Karpenko, P. Huovinen, H. Petersen, M. Bleicher;Phys.Rev. C91 (2015) no.6, 064901

But the question we want to ask, is how different are they from the LHC/top RHIC energies?

Flow fluctuations constrain Initial Conditions



Linear response works well in central LHC PbPb collisions

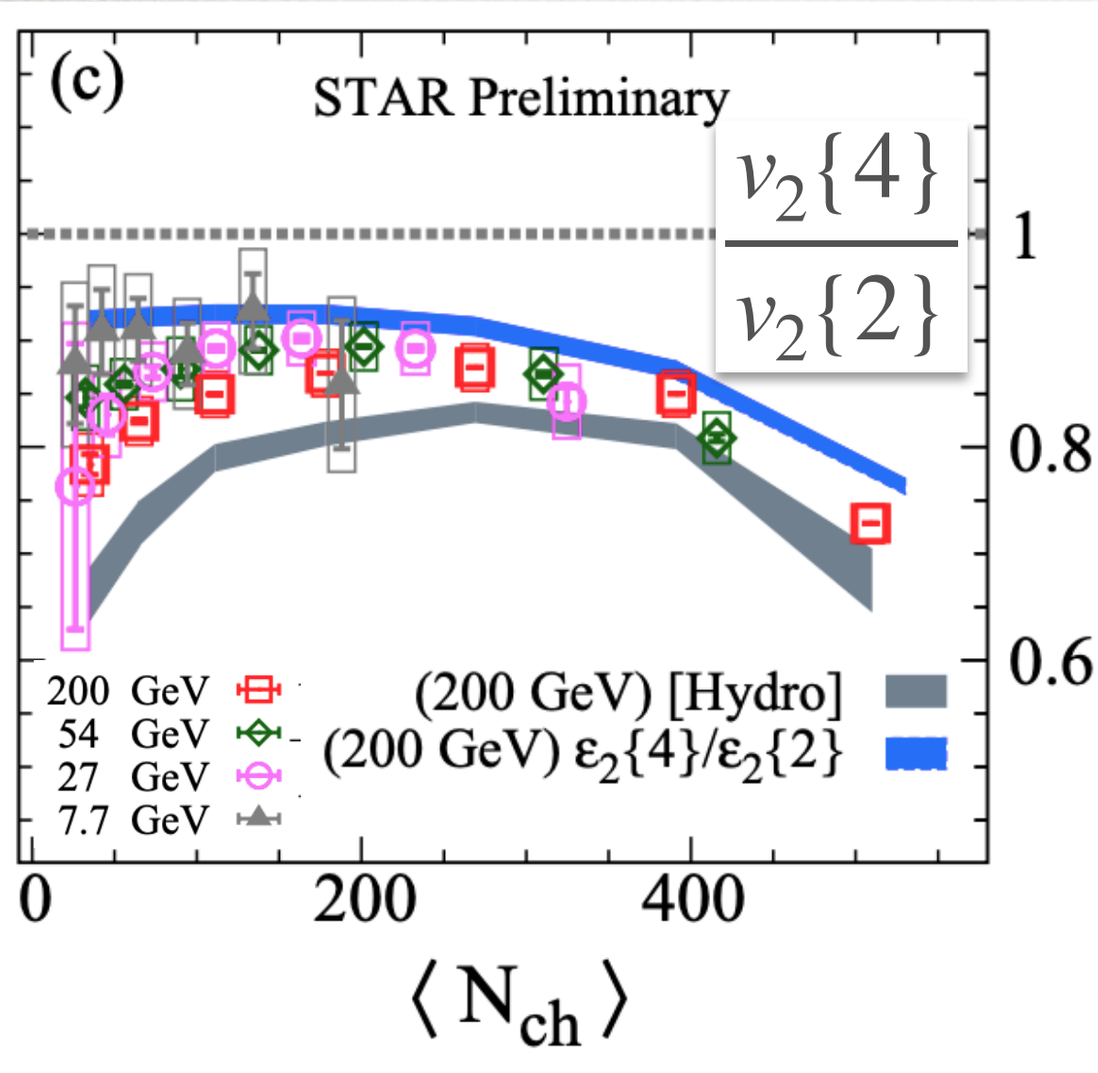
$$\frac{v_2\{4\}}{v_2\{2\}} \sim \frac{\varepsilon_n\{4\}}{\varepsilon_n\{2\}}$$

Smaller systems require cubic response, what about lower beam energies?

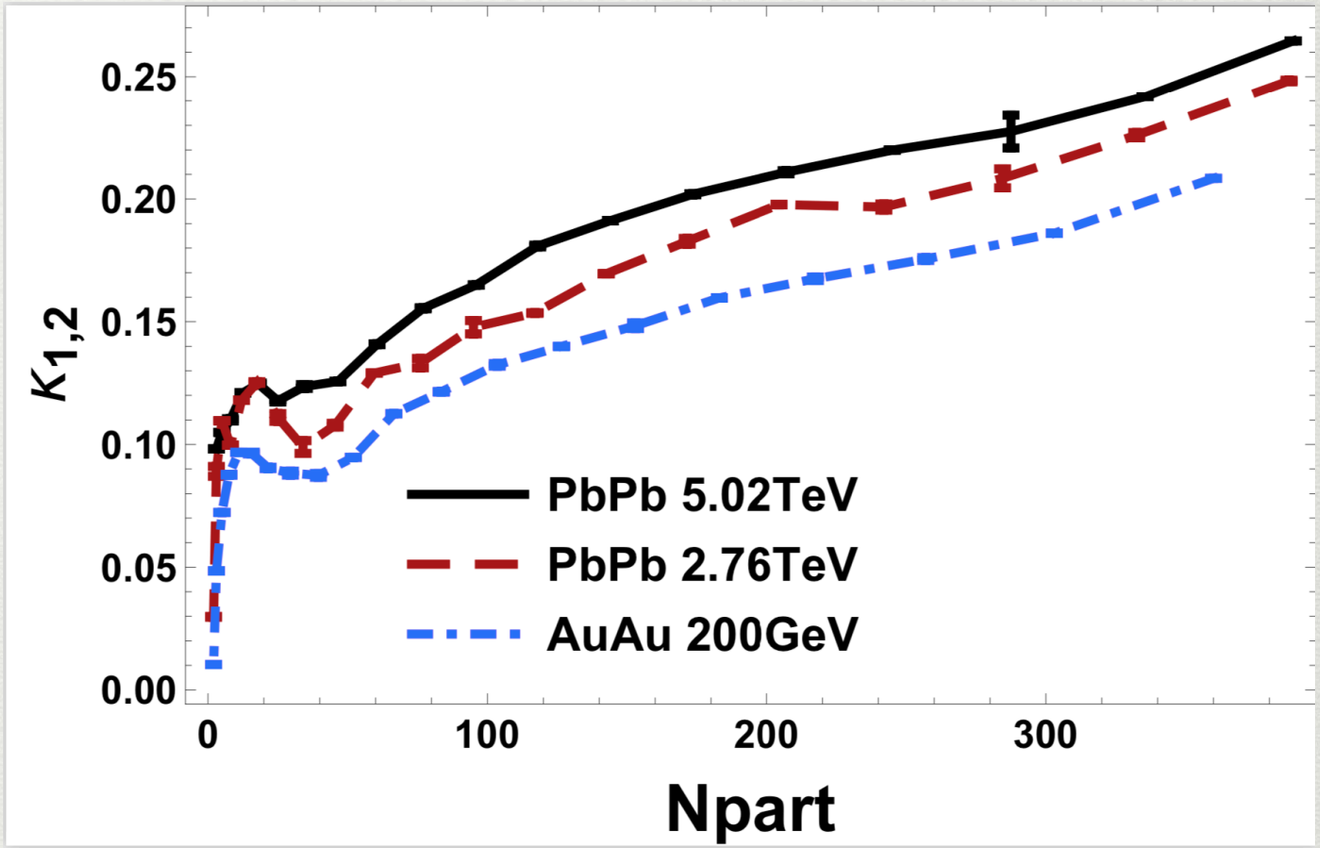
Giacalone, JNH, Ollitrault Phys.Rev. C95 (2017) no.5, 054910

Sievert and JNH, arXiv:1901.01319

Flow fluctuations at the Beam Energy Scan



Linear response $\Downarrow$ *with* $\Downarrow$ $\sqrt{s_{NN}}$



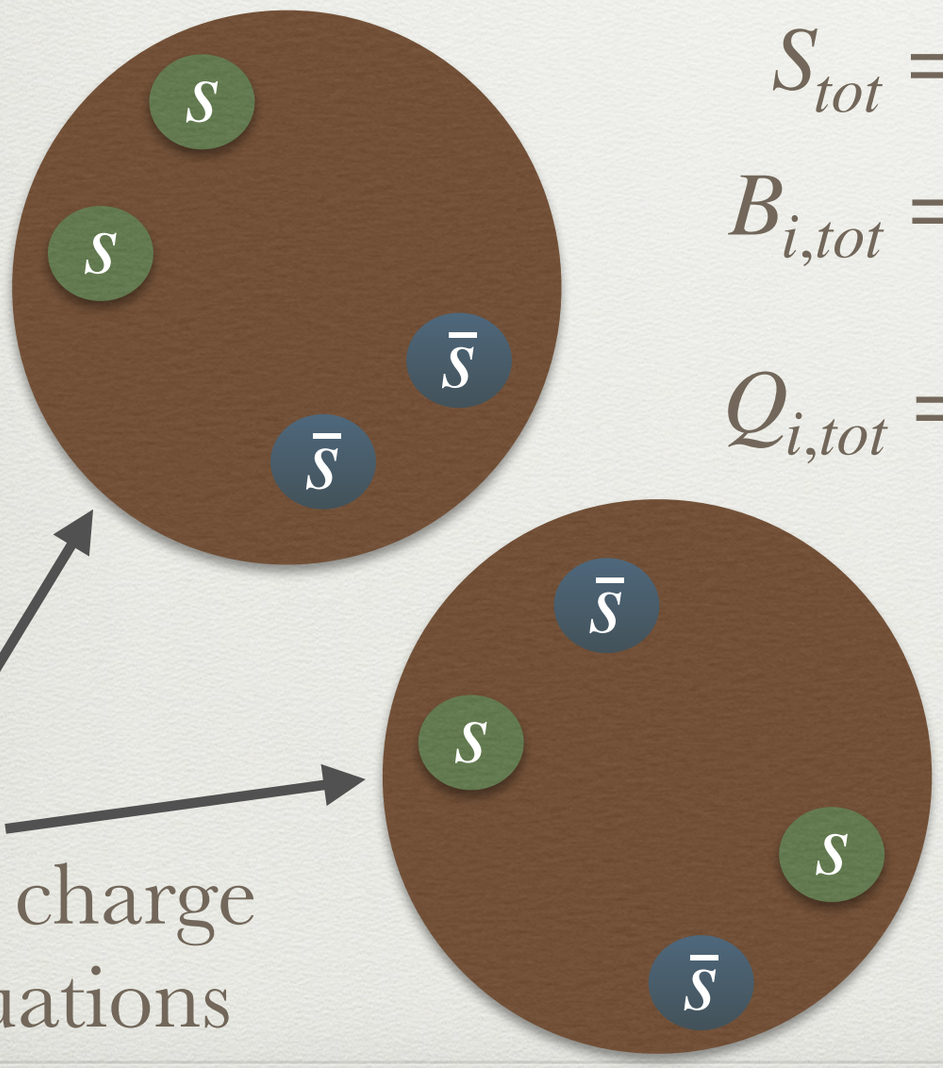
[STAR] Magdy, Nucl.Phys. A982 (2019) 255-258

See Skanda Rao's poster

3 conserved charges

QCD has not only baryon number but strangeness and electric charge conservation

Quark Gluon Plasma



$$S_{tot} = 0$$

$$B_{i,tot} = B_{f,tot}$$

$$Q_{i,tot} = Q_{f,tot}$$

Local charge fluctuations

Each grid point in an initial condition needs to initialize

$$\left\{ T, \rho_B, \rho_S, \rho_Q \right\}$$

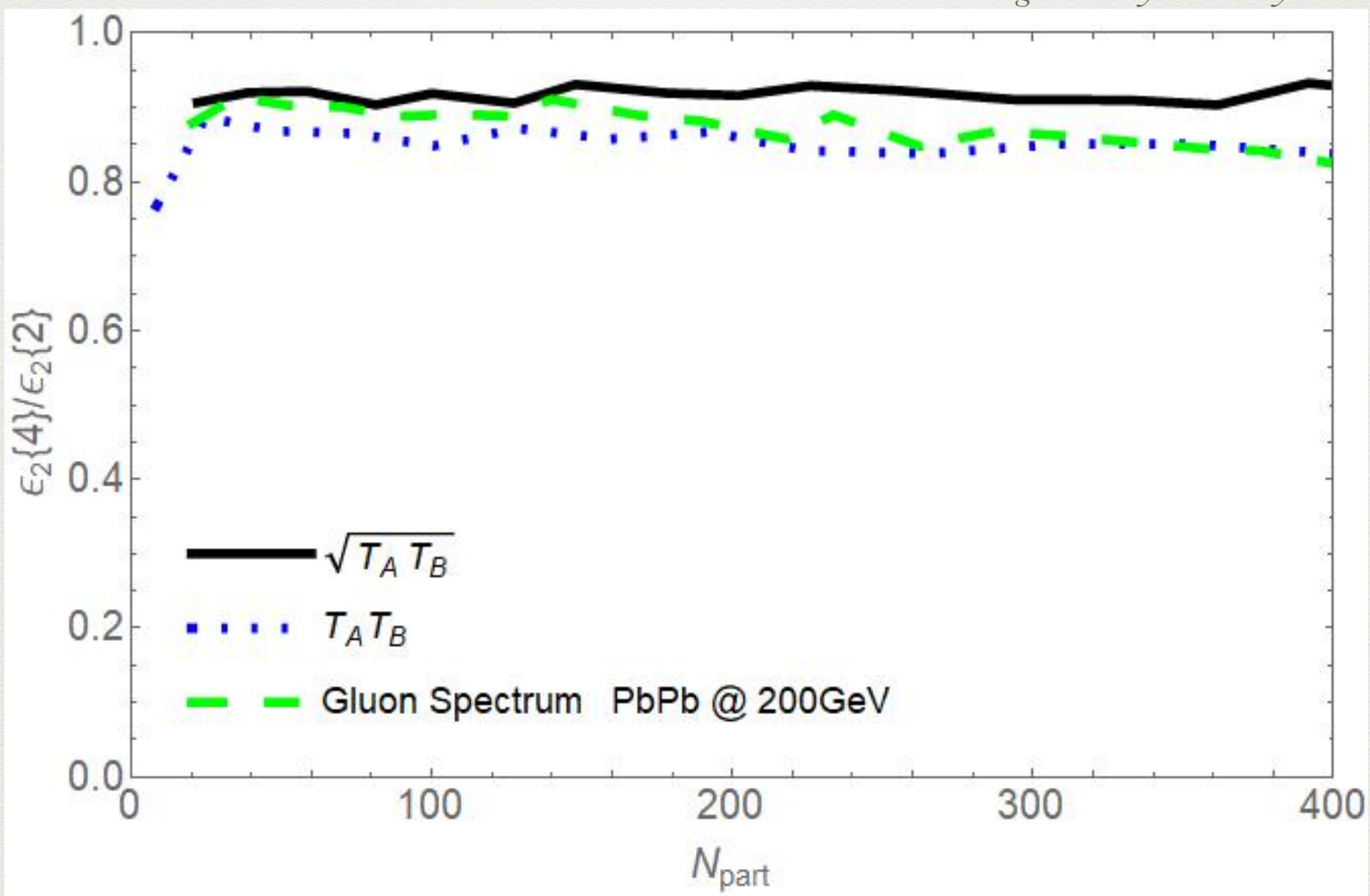
Initial Conditions+Conserved Charges

- Need a sampling function that consider the mass of the quarks
- Gluon Spectrum Sampling in Trento (Patrick Carzon)
- Gluon spectrum & the quark correlations derived within a (semi)dilute-dense approximation (Martinez, Sievert, Wertepny)
- Must coincide with the background (i.e. very statistically unlikely to produce a charm quark in a low density region)
- Zero-sum game (only limited amount of energy at each coordinate)
- Fine grid spacings

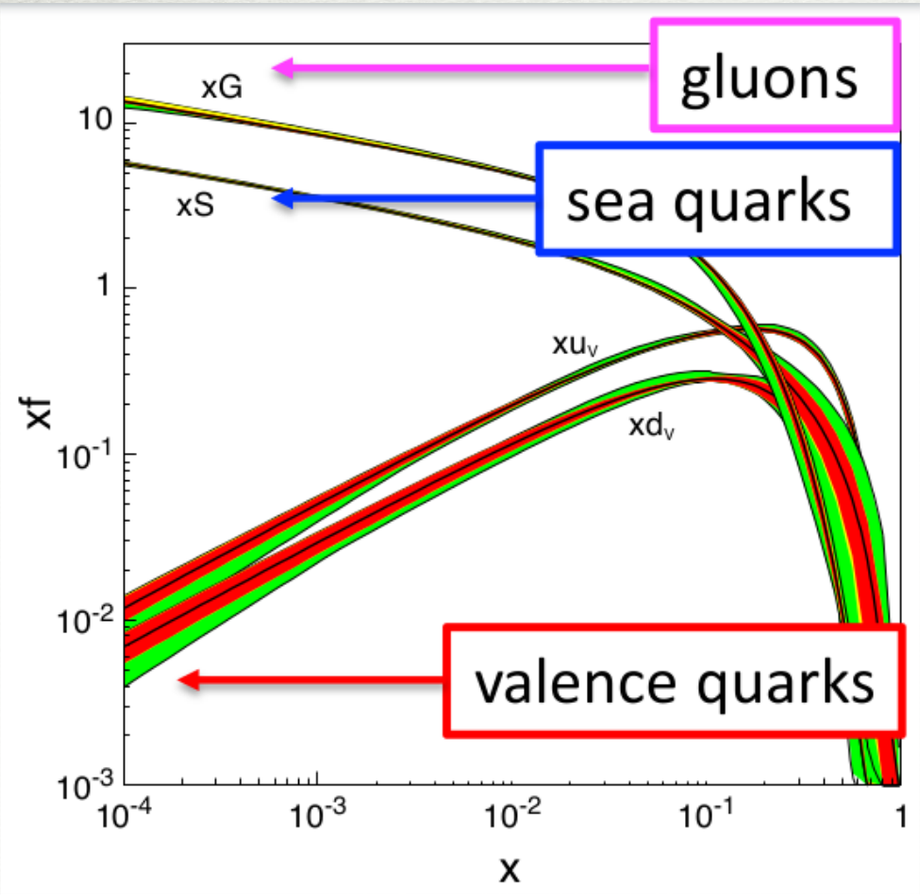
Gluon Spectrum (Preliminary)

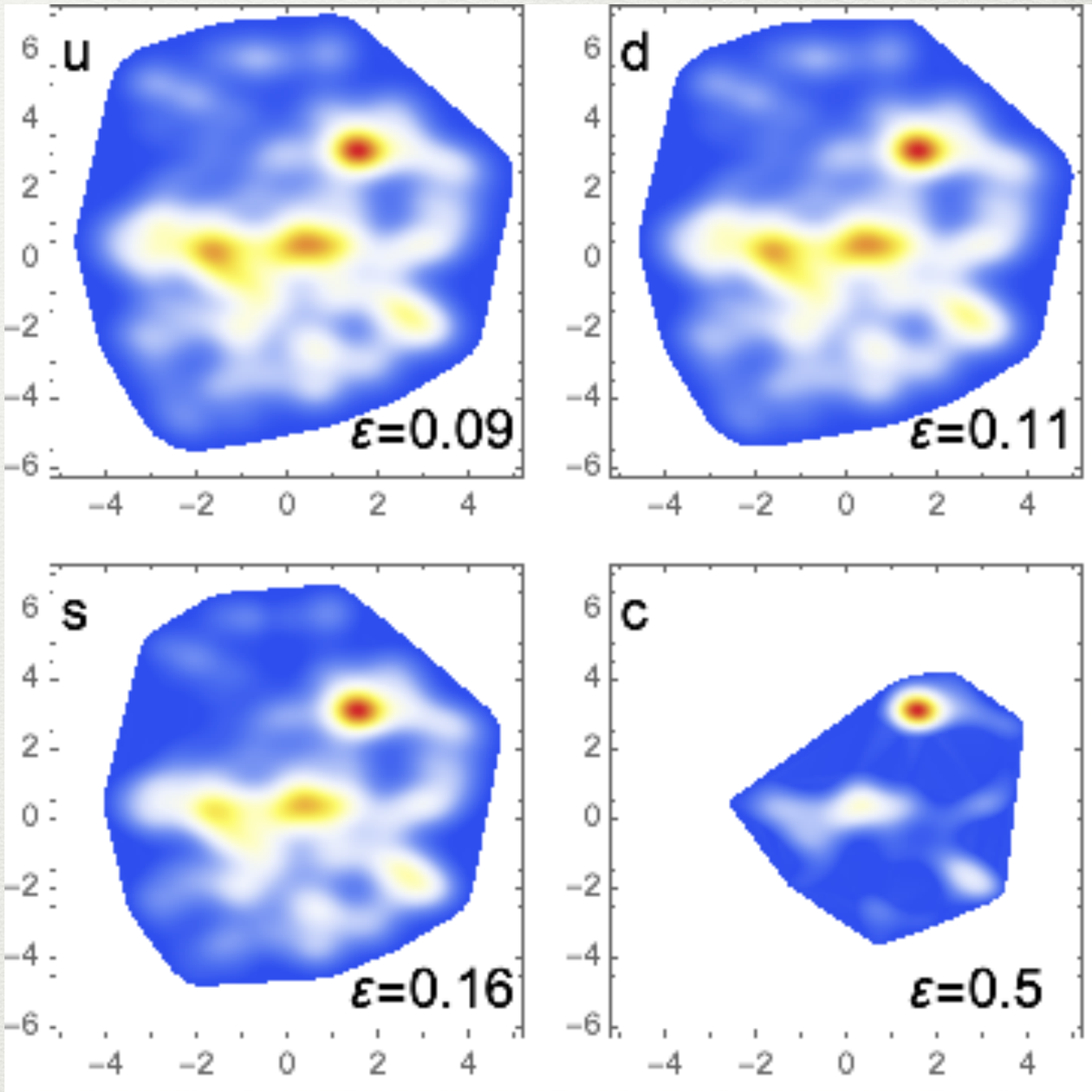
$$\frac{dn^G}{d^2x} = \frac{\kappa_A N_c^2 \Delta Y}{32\pi^5 \alpha_s^2 \sigma_{inel}} \int d^2b \frac{T_A(\underline{b})}{|x-b|_T^2} \left[1 - \exp\left(-\frac{1}{2}\kappa_B |x-b|_T^2 T_B(\frac{x+b}{2})\right)\right] \Theta(1 - |x-b|_T \Lambda)$$

Camb.Monogr.Part.Phys.Nucl.Phys.Cosmol. 33 (2012) 1-350



ICCING- Initializing Conserved Charges in Nuclear Geometries





Initialize quark anti-quark pairs from gluon splittings

Martinez, Sievert, Wertepny

arXiv:1808.04896;

JHEP 1807 (2018) 003

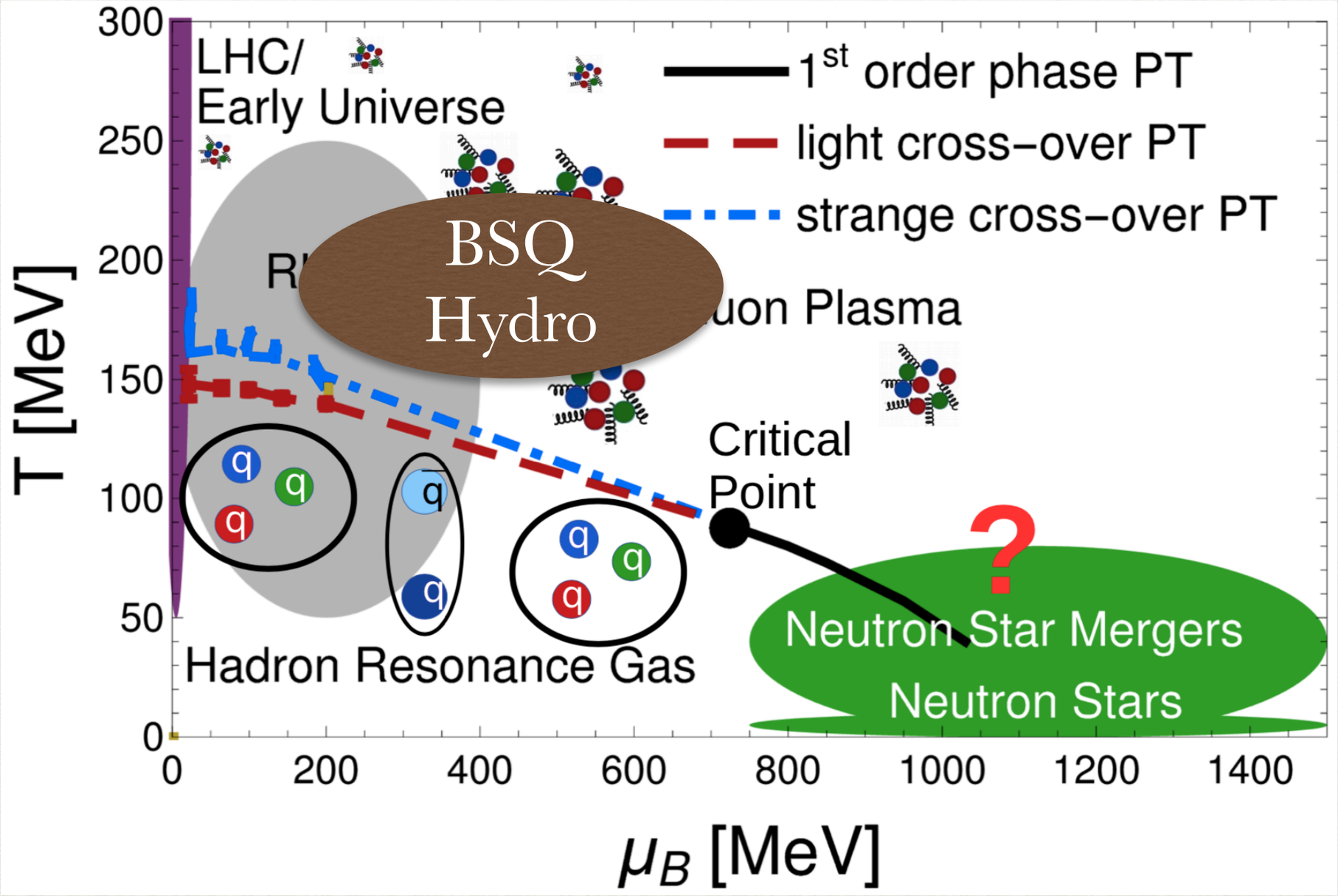
Future for ICCING

- Open-Source code (being built to run with TRENTO)
- Baryon stopping (not clear how to do yet)
- Gluons into gluons $g \rightarrow gg$
- Initialized initial flow (and eventually $T^{\mu\nu}$)

e.g. Lappi, Phys.Lett. B643 (2006) 11-16

See M. Martinez's Talk in Small Systems

QCD Phase Diagram



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Upgrades to Hydrodynamics

Equation of State
Baryon, Strangeness,
Electric Charge
EOS+CP

Transport Coefficients
Shear and bulk viscosity
$\eta T/w(T, \mu_B, \mu_S, \mu_Q)$
BSQ Diffusion
$\kappa_{BB}, \kappa_{BS}, \ \cdots$

BSQ Hydro
Ideal BSQ
$\partial_\mu B^\mu = 0, \ B^\mu = \rho_B u^\mu + n_B^\mu$
Diffusion
$\kappa_{BB} \Delta^{\mu\nu} \partial_\nu \left(\mu_B / T\right)$
BSQ cross terms

$\kappa_{BS} \Delta^{\mu\nu} \partial_\nu \left(\mu_B / T\right)$

Equation of State

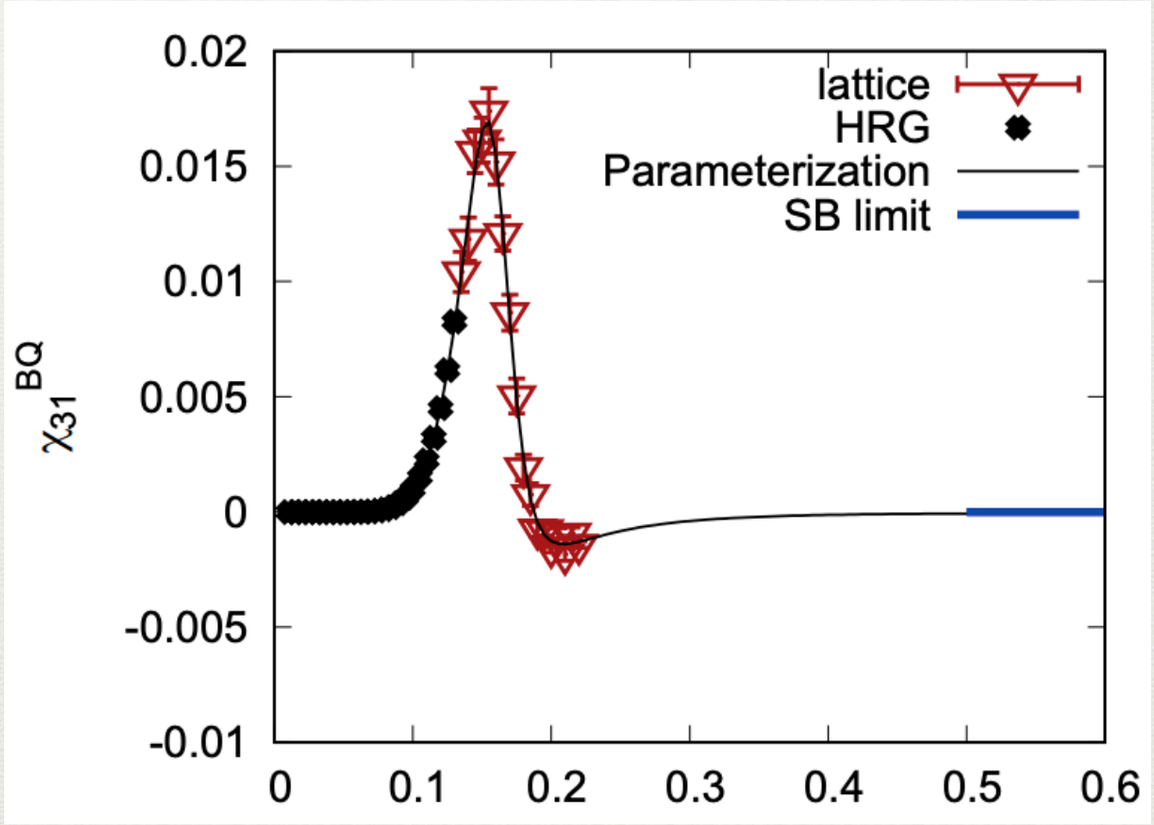
JNH, Paolo Parotto, Israel Portillo Vazquez, Claudia Ratti, Jamie Stafford 1902.06723

$$\frac{p(T,\mu_B,\mu_Q,\mu_S)}{T^4} = \sum_{i,j,k} \frac{1}{i!j!k!} \chi_{ijk}^{BSQ} \left(\frac{\mu_B}{T}\right)^i \left(\frac{\mu_Q}{T}\right)^j \left(\frac{\mu_S}{T}\right)^k$$

Create interpolation functions of all χ_{ijk}^{BSQ}

where $i + j + k \leq 4$

Constrain with Lattice QCD results, HRG, and Stefan-Boltzmann limit

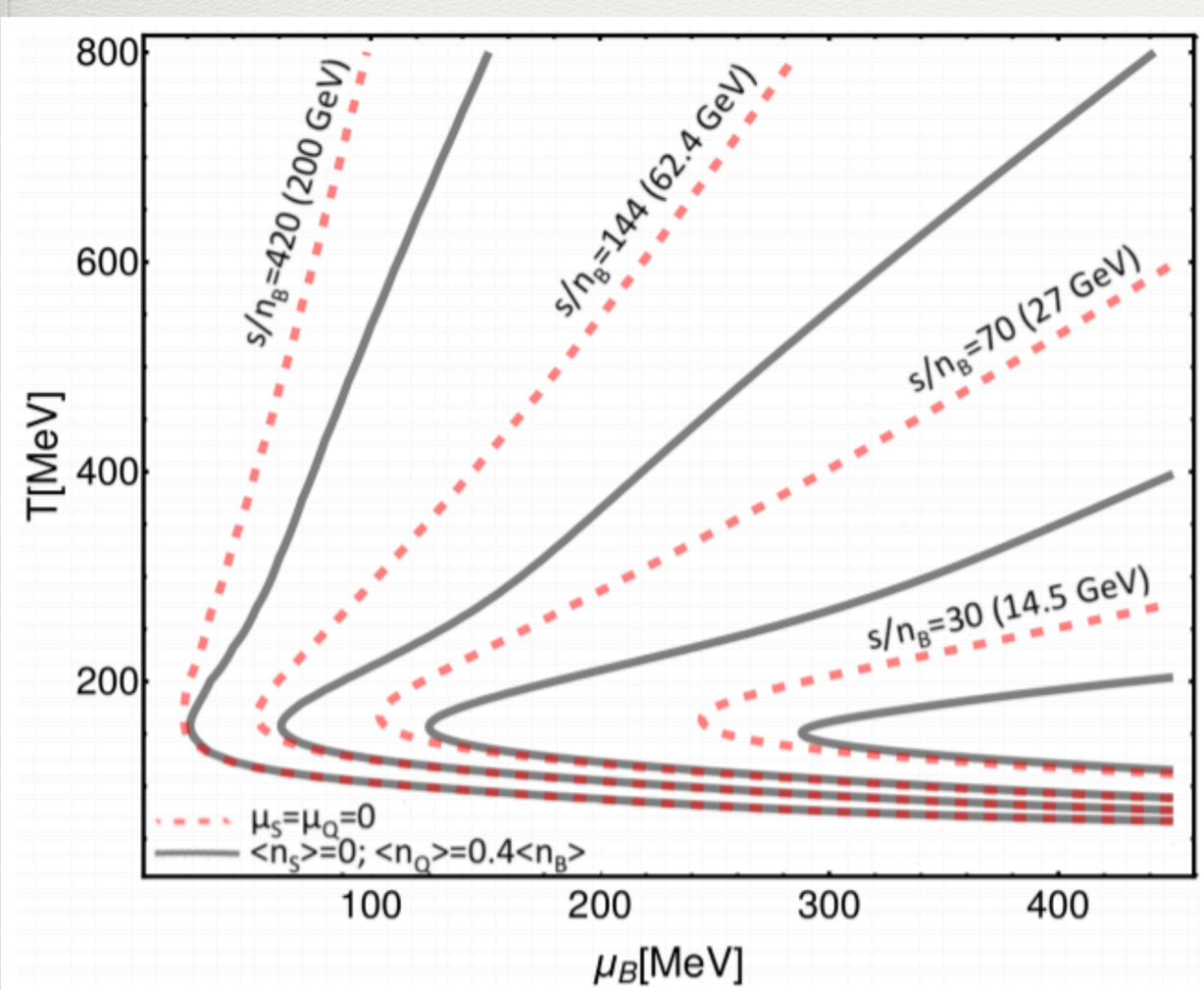


T [MeV]

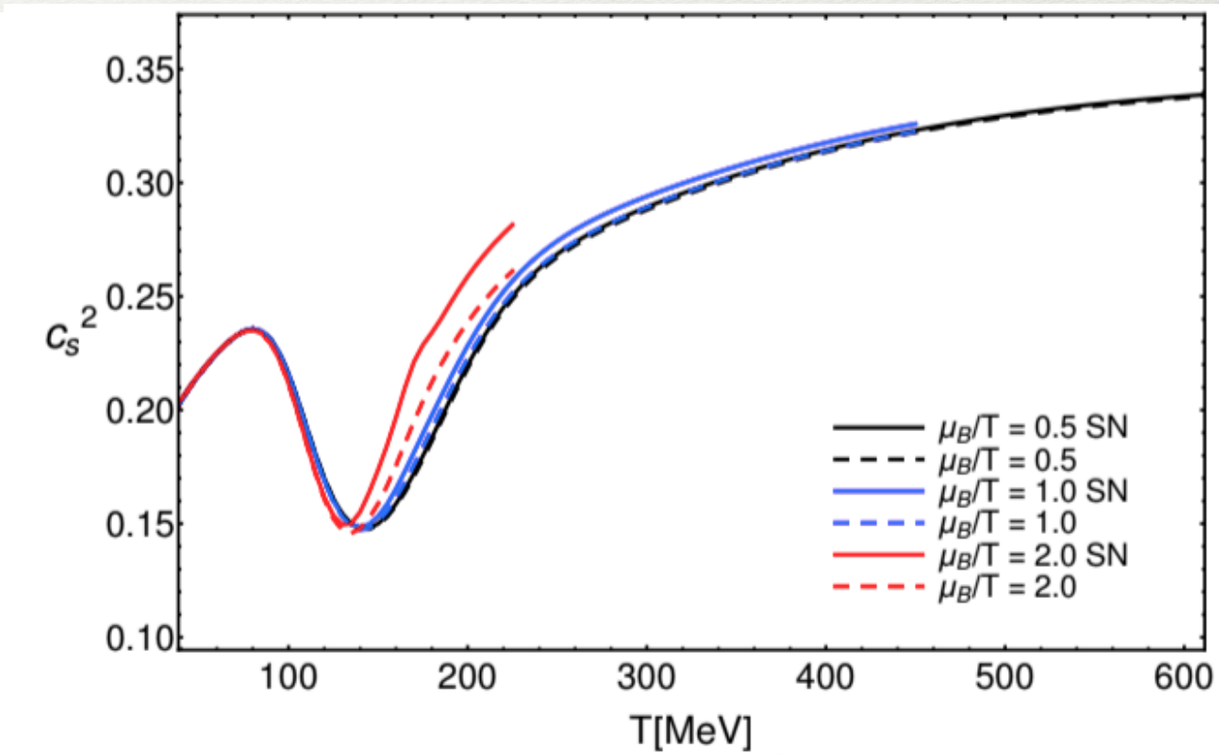
Speed of sound

JNH, Paolo Parotto, Israel Portillo Vazquez, Claudia Ratti, Jamie Stafford 1902.06723

Isentrope trajectories



Steeper speed of sound



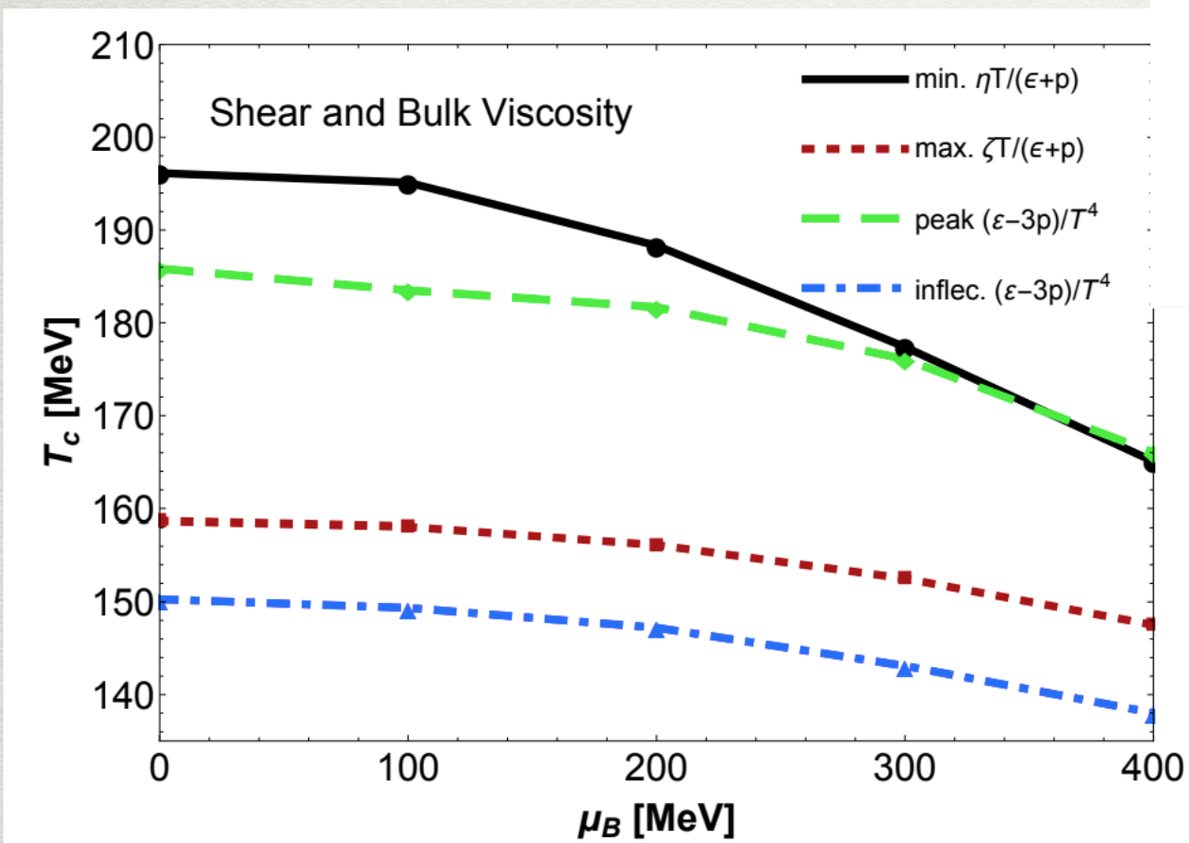
$$c_s^2 = \left.\frac{\partial p}{\partial \epsilon}\right|_{n_i} + \sum_i \frac{n_i}{\epsilon + p} \left.\frac{\partial p}{\partial n_i}\right|_{\epsilon, n_j}$$

Reaches larger chemical potentials

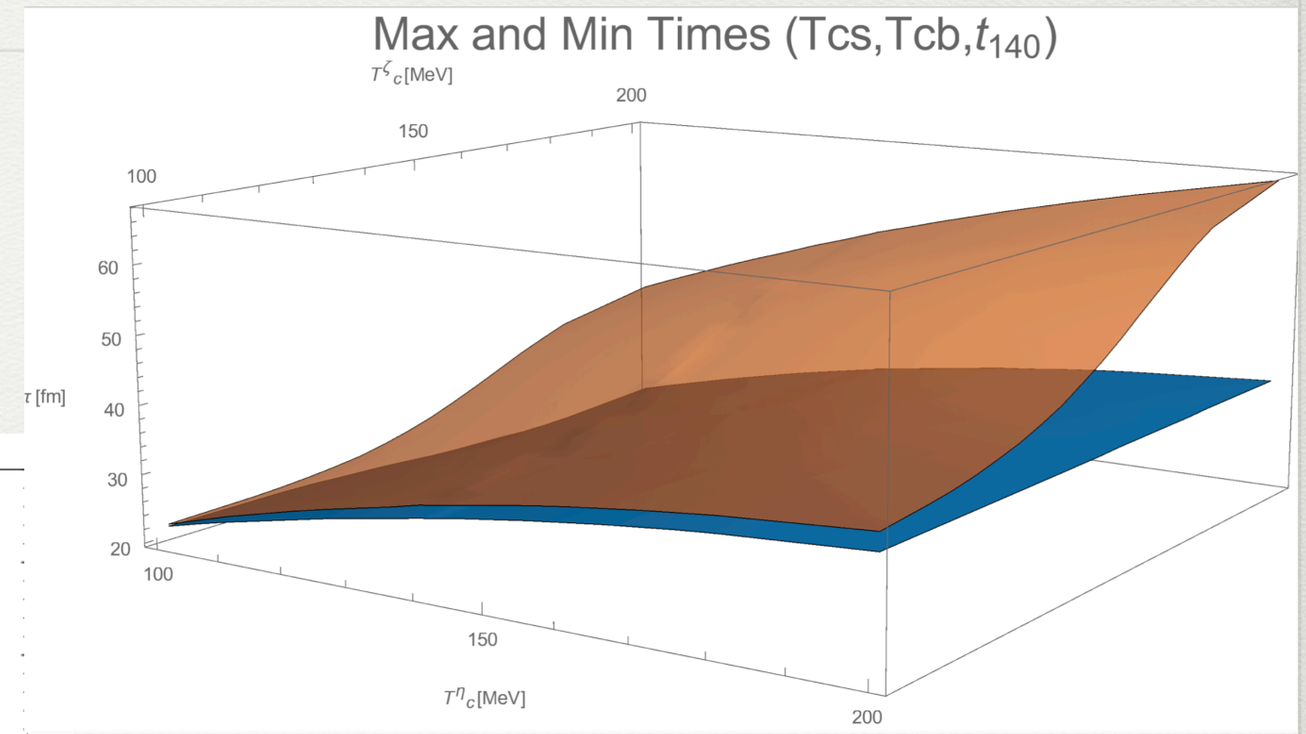
See also Monnai, Schenke, Shen, arXiv:1902.05095

Viscosity at finite densities

Temperature of minimum of shear and maximum of bulk viscosity



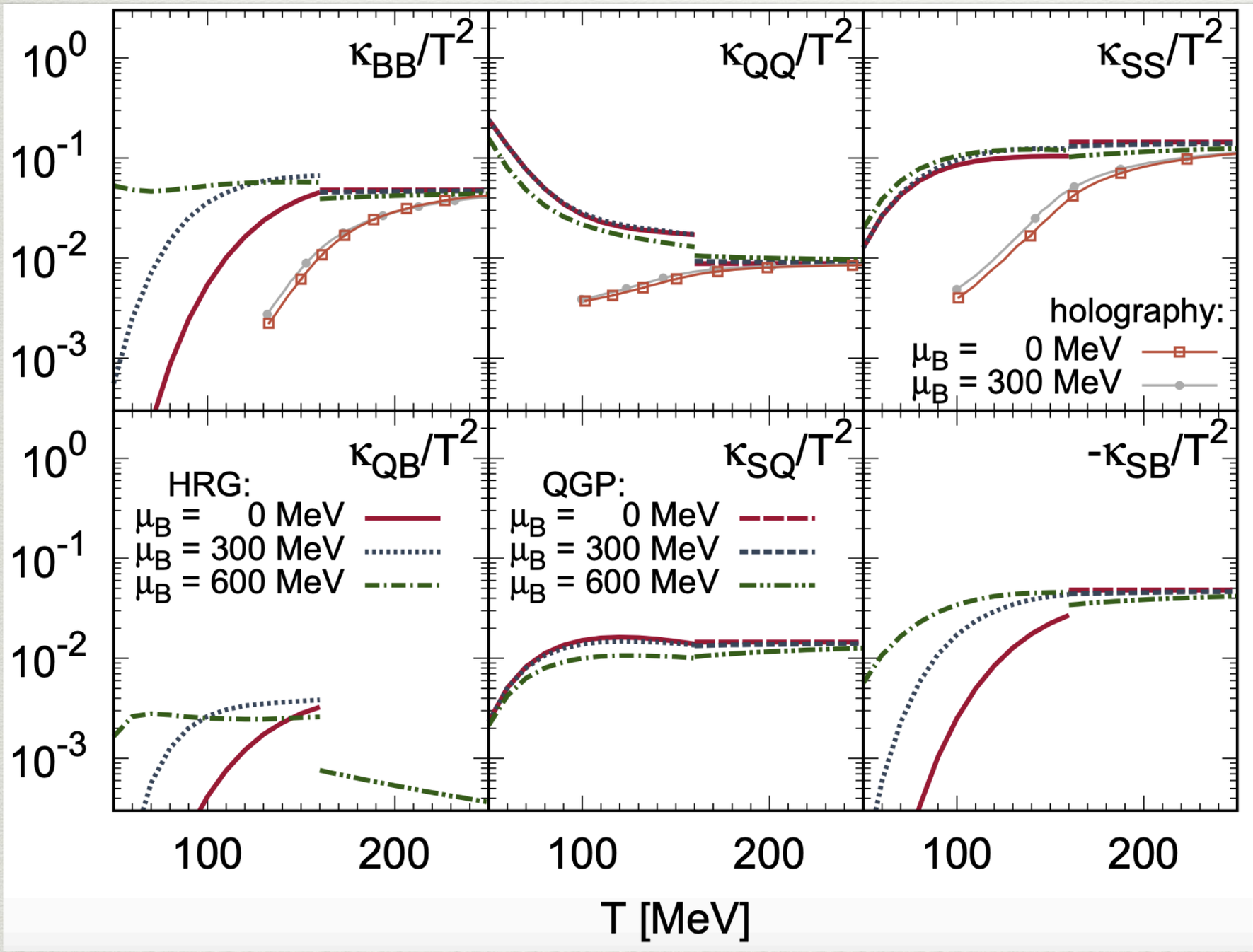
Rougemont, JNHet al, Phys.Rev. D96 (2017) no.1, 014032



See Travis Dore's Poster

Varying characteristic temperatures significantly change hydrodynamical evolution times

BSQ Diffusion



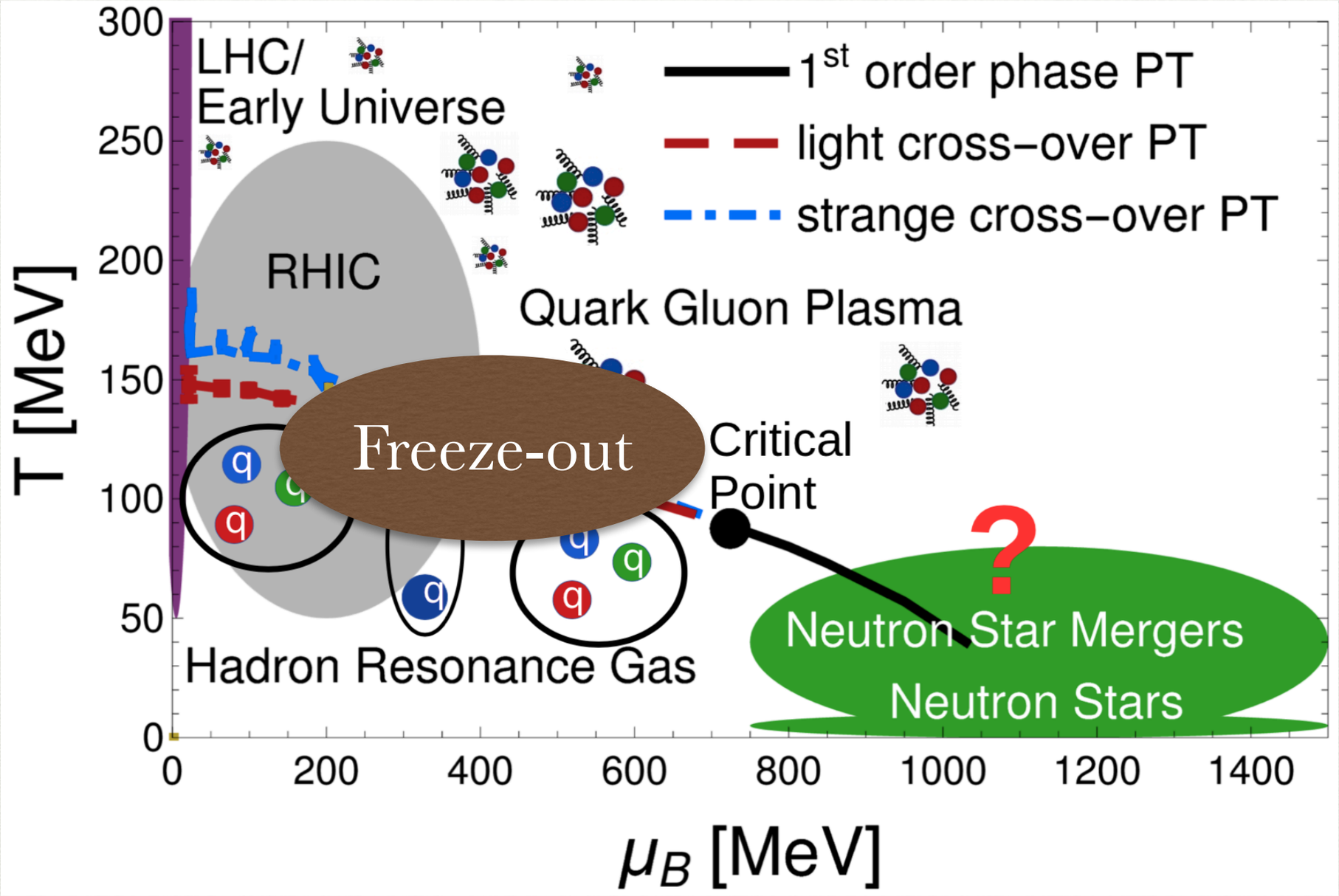
Kinetic Theory

Greif, Fotakis, Denicol, Greiner Phys.Rev.Lett. 120 (2018) no.24, 242301

Holography (black hole engineering)

Rougemont, Critelli, JNH, Noronha, Ratti Phys.Rev. D96 (2017) no.1, 014032

QCD Phase Diagram



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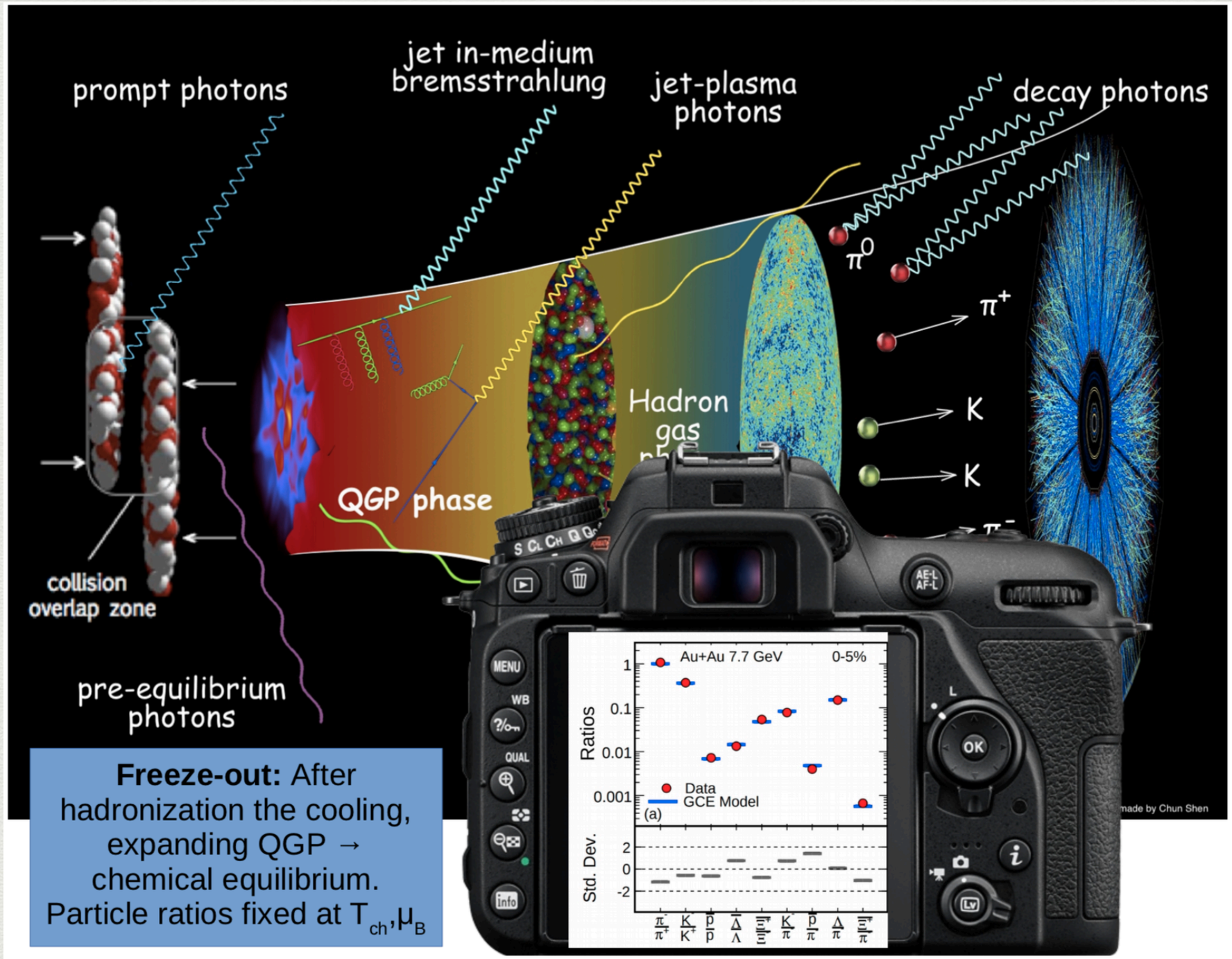
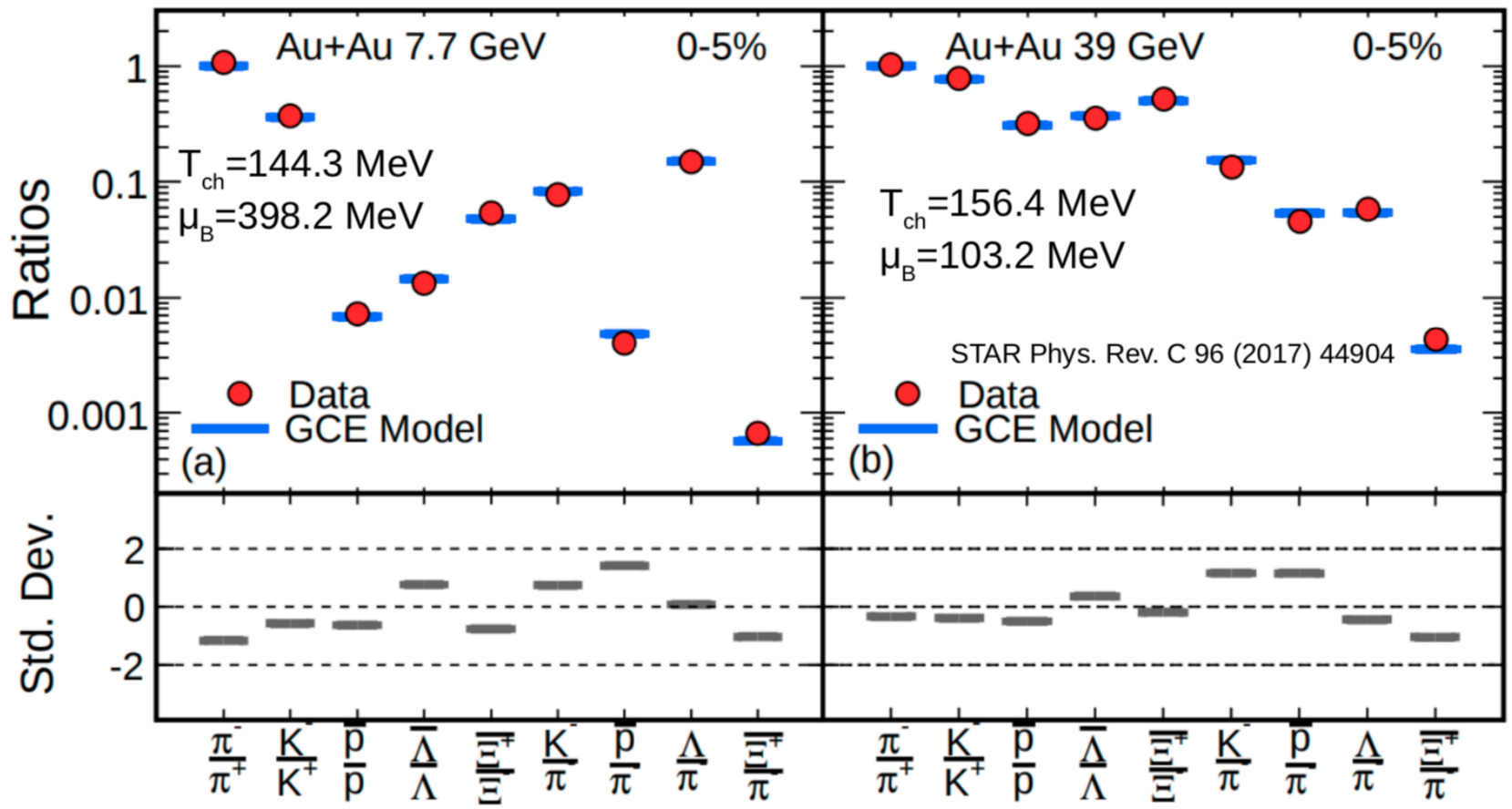
Freeze-out: finding the cross-over temperature



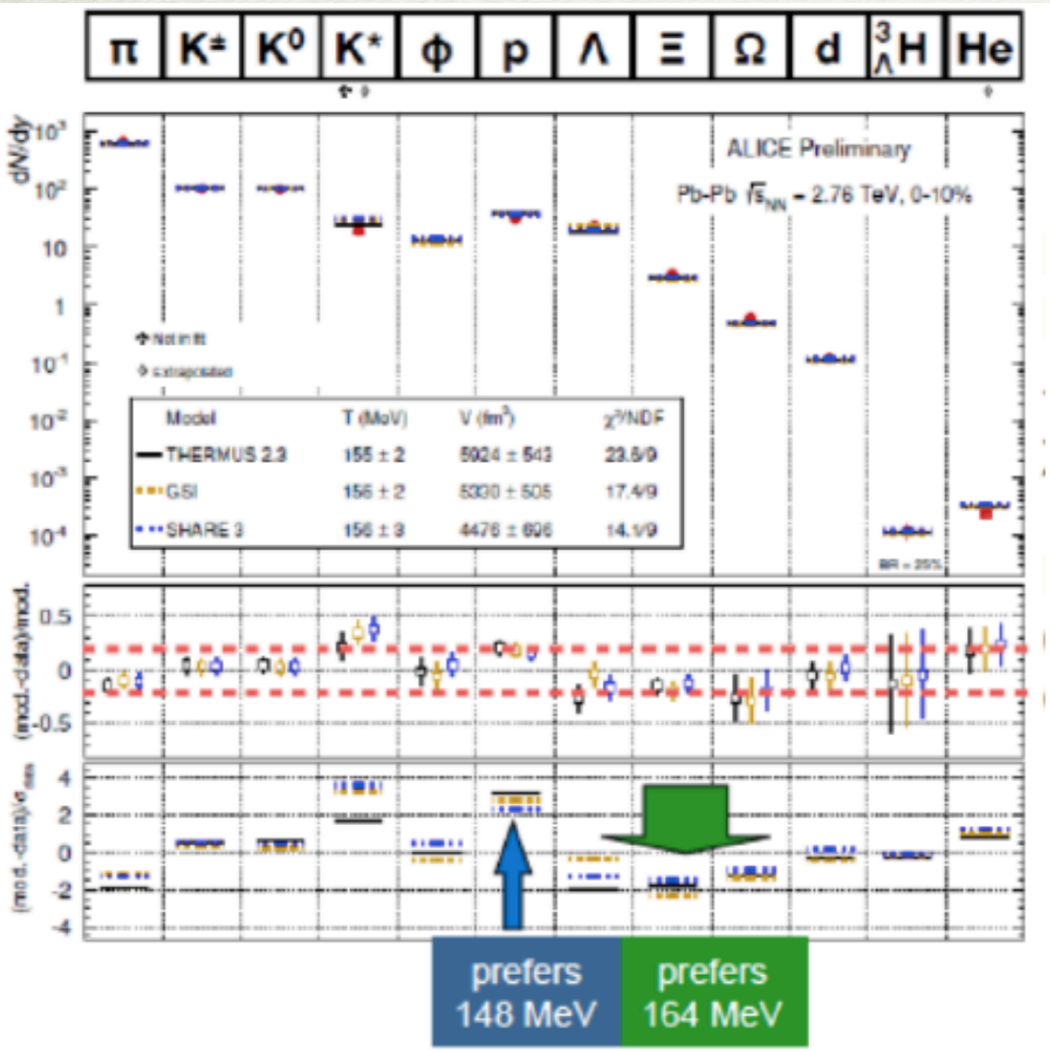
Freeze-out: After hadronization the cooling, expanding QGP → chemical equilibrium. Particle ratios fixed at T_{ch},μ_B

Thermal fits: position on the phase diagram



- Assume particles are in thermal and chemical equilibrium (Grand Canonical Ensemble)
- Calculate ratios of particles in HRG across T and μ_B (volume cancels)
- Extract chemical equilibrium T & μ_B, $\rightarrow$ shortly after hadronization
- Lower Beam Energies=Larger μ_B Beam Energy Scan

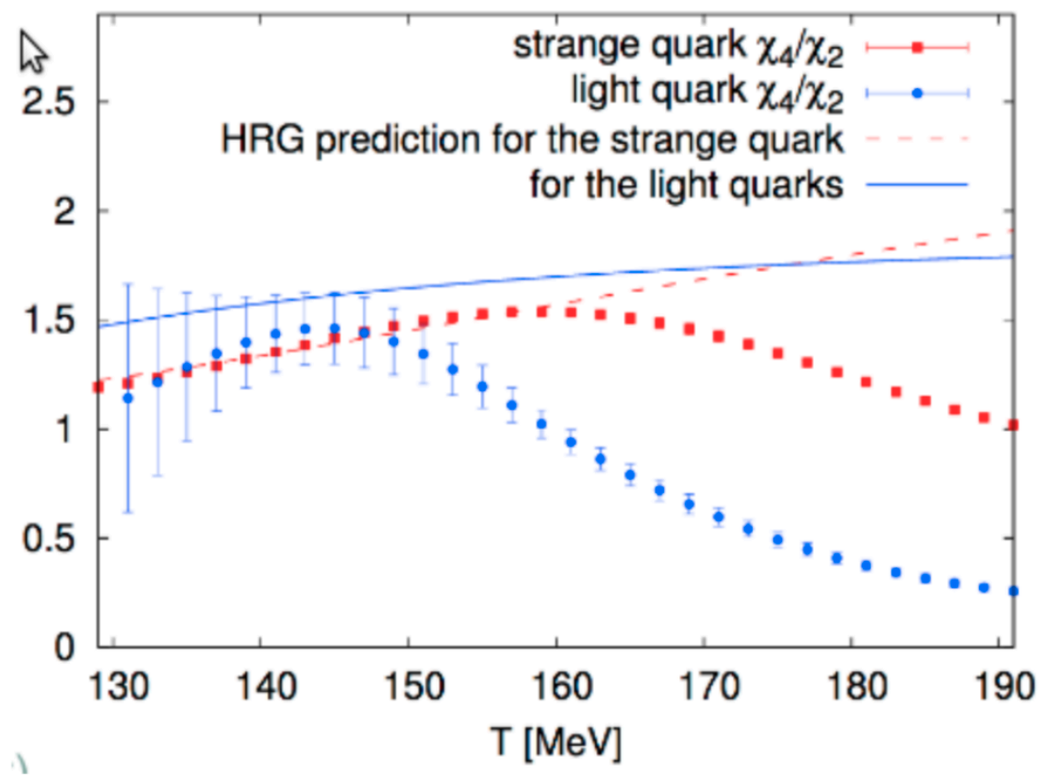
Caveats



Floris Nucl.Phys. A931 (2014) 103-112

Hadronization

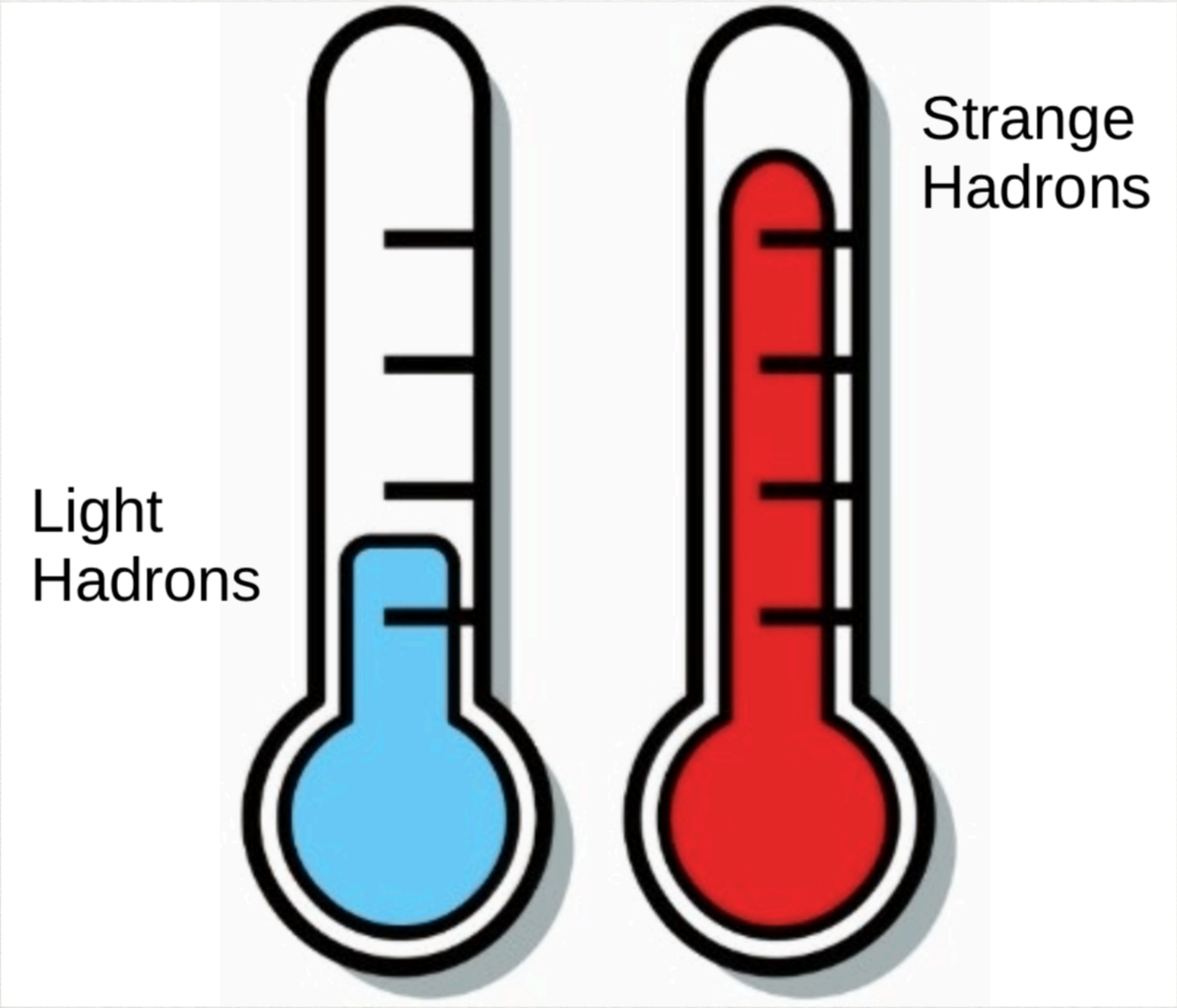
R. Bellwied et al. (WB Collaboration): PRL2013



Bellwied et al, Phys.Rev.Lett. 111 (2013) 202302

- Assumes a single freeze-out temperature
- Tension between light and strange particles

Should light freeze-out = strange hadrons freeze-out?



Look to fluctuations of conserved charges

Susceptibilities

Taking derivatives of the pressure gives further information

$$\chi_{lmn}^{BSQ} = \frac{\delta^{l+m+n} p/T^4}{\delta\left(\mu_B/T\right)^l \delta\left(\mu_S/T\right)^m \delta\left(\mu_Q/T\right)^n}$$

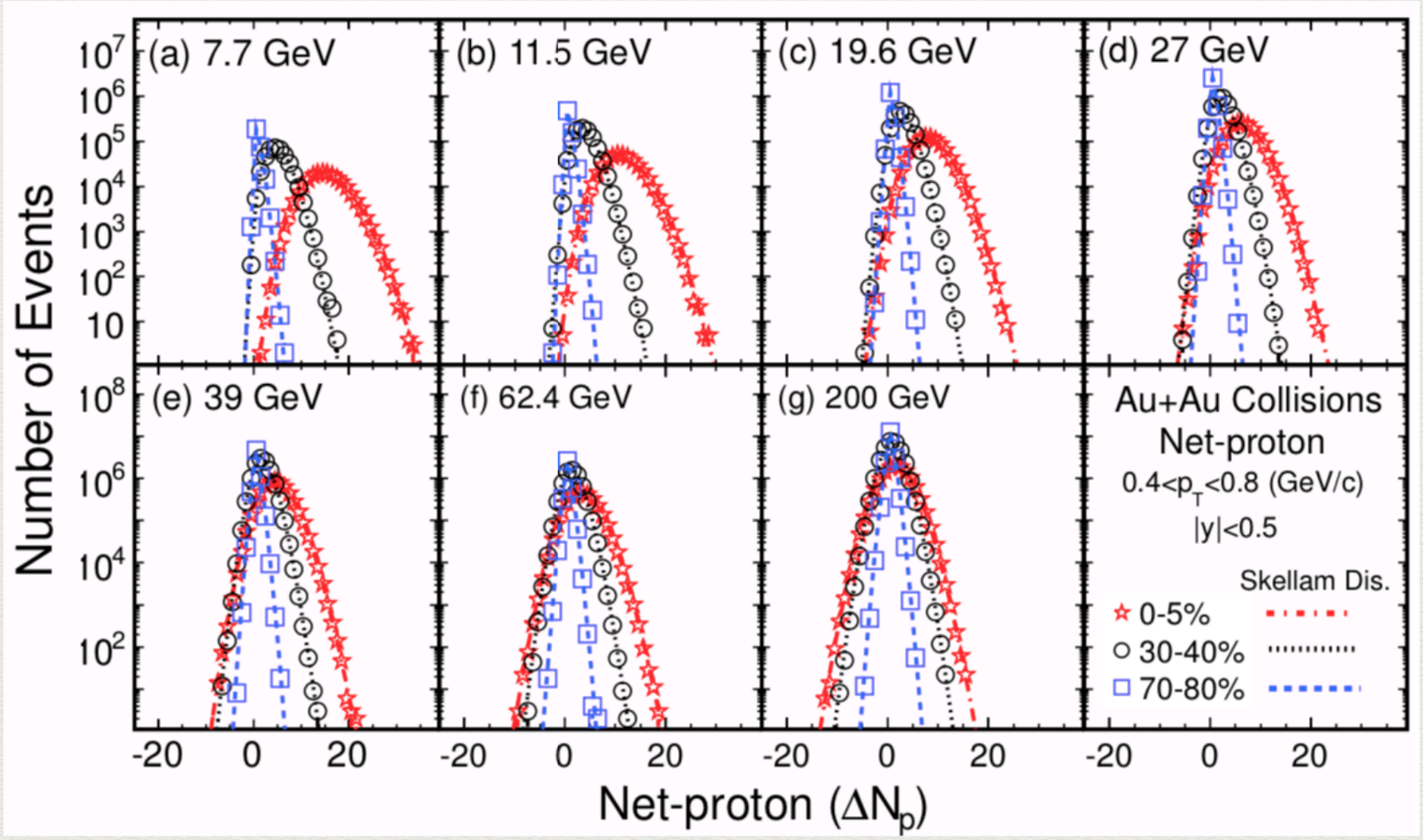
- partial derivatives respect to Strangeness selects on only strange hadrons

- The chemical potentials are constrained by experiments
$$\langle \rho_S \rangle = 0 \text{ and } \langle \rho_Q \rangle = 0.4 \langle \rho_B \rangle$$
- Higher-order susceptibilities more sensitive to critical behavior

Connecting the Beam Energy Scan to Lattice QCD

RHIC measures Mean $M = \chi_1 V$ Variance $\sigma^2 = \chi_2 V$

Skewness $S = \chi_3 V / (\chi_2 V)^{3/2}$ Kurtosis $\kappa = \chi_4 V / (\chi_2 V)^2$



 [STAR] Phys.Rev.Lett. 112 (2014) 032302

Removing the volume

To make direct comparison to Lattice QCD we need volume independent quantities

$$\frac{\sigma^2}{M} = \frac{\chi_2}{\chi_1}$$

$$\kappa\sigma^2 = \frac{\chi_4}{\chi_2}$$

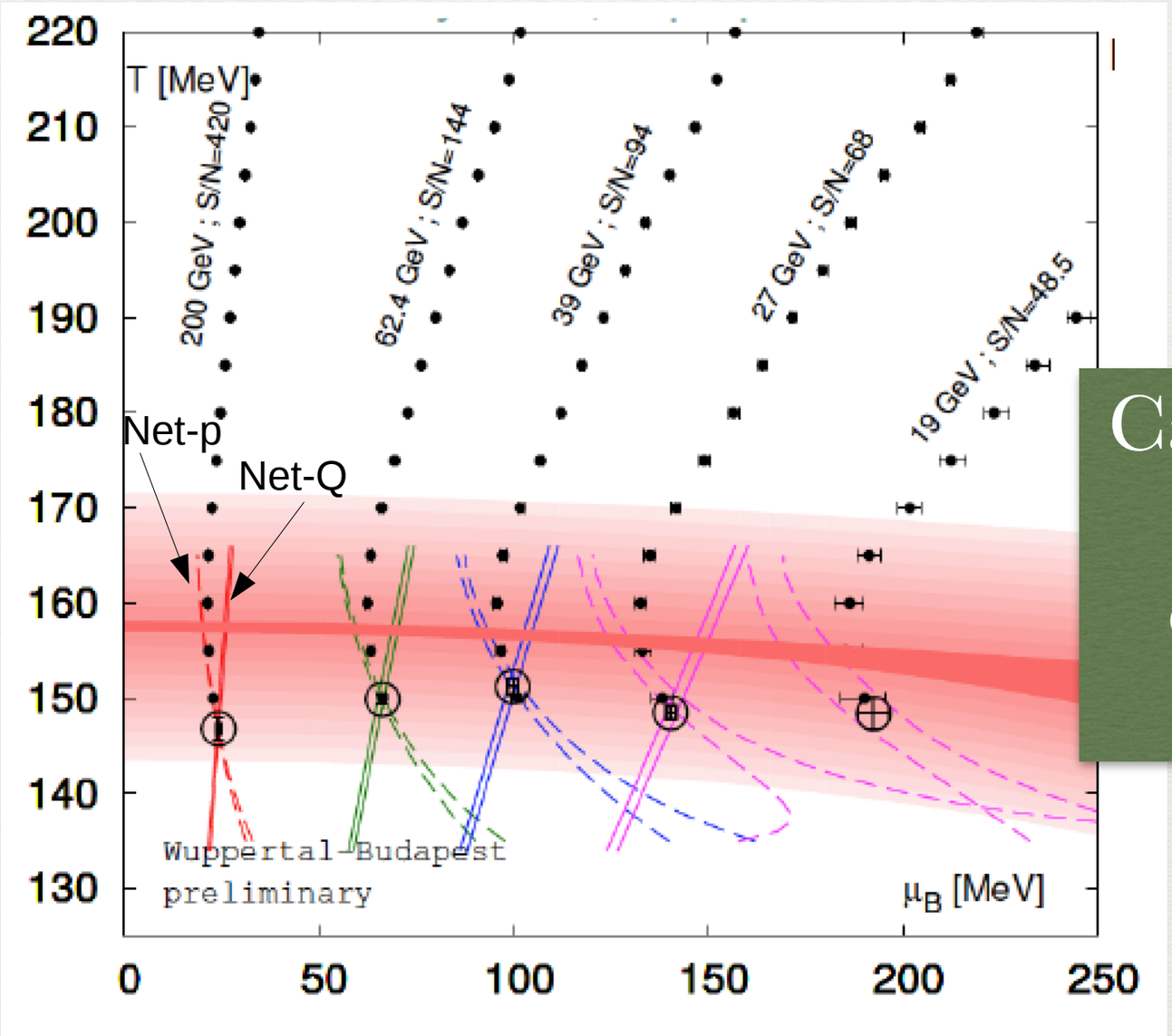
$$S\sigma = \frac{\chi_3}{\chi_2}$$

$$\frac{S\sigma^3}{M} = \frac{\chi_3}{\chi_1}$$

Karsch Central Eur.J.Phys. 10 (2012) 1234-1237

Freeze-out baryon chemical potential from Lattice

Ratios of baryon susceptibilities compared to experimental data



Caveats: effects from acceptance cuts, decays, finite size effects etc

Selecting only charged kaons in Lattice QCD

Experiments measure charged kaons, Lattice QCD includes K^0, Λ, Σ, Ω

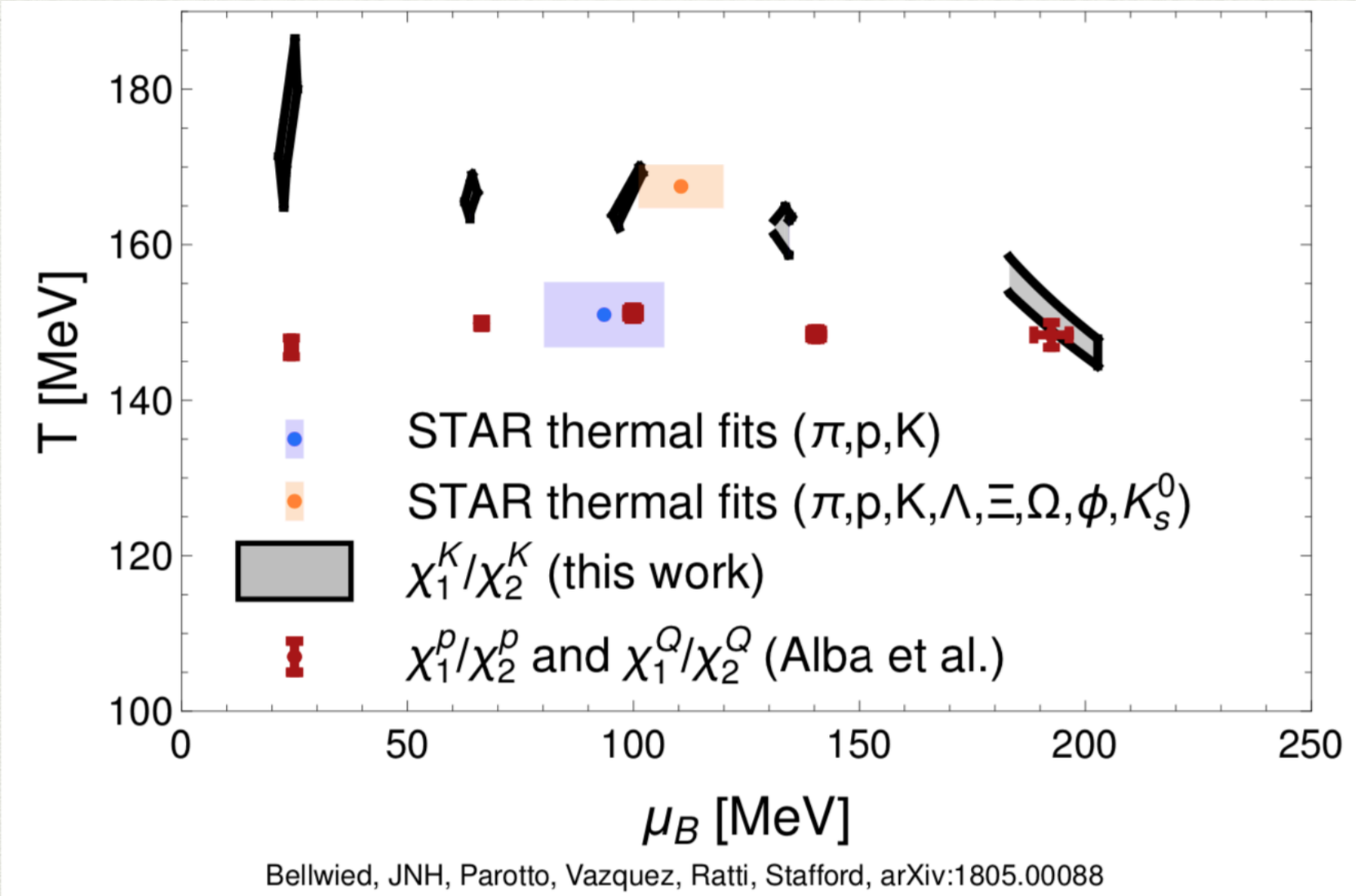
Partial pressure of charged kaons

$$P_{K^{+/-}} = P_{0|1||1|} \cosh(\hat{\mu}_S + \hat{\mu}_Q) \text{ where } P_{0|1||1|} = \chi_2^S - \chi_{22}^{BS}$$

The, the derivatives can be written as

$$\frac{\chi_2^K}{\chi_1^K} = \frac{\cosh(\hat{\mu}_S + \hat{\mu}_Q)}{\sinh(\hat{\mu}_S + \hat{\mu}_Q)}$$

Flavor hierarchy seen compared to STAR data at RHIC

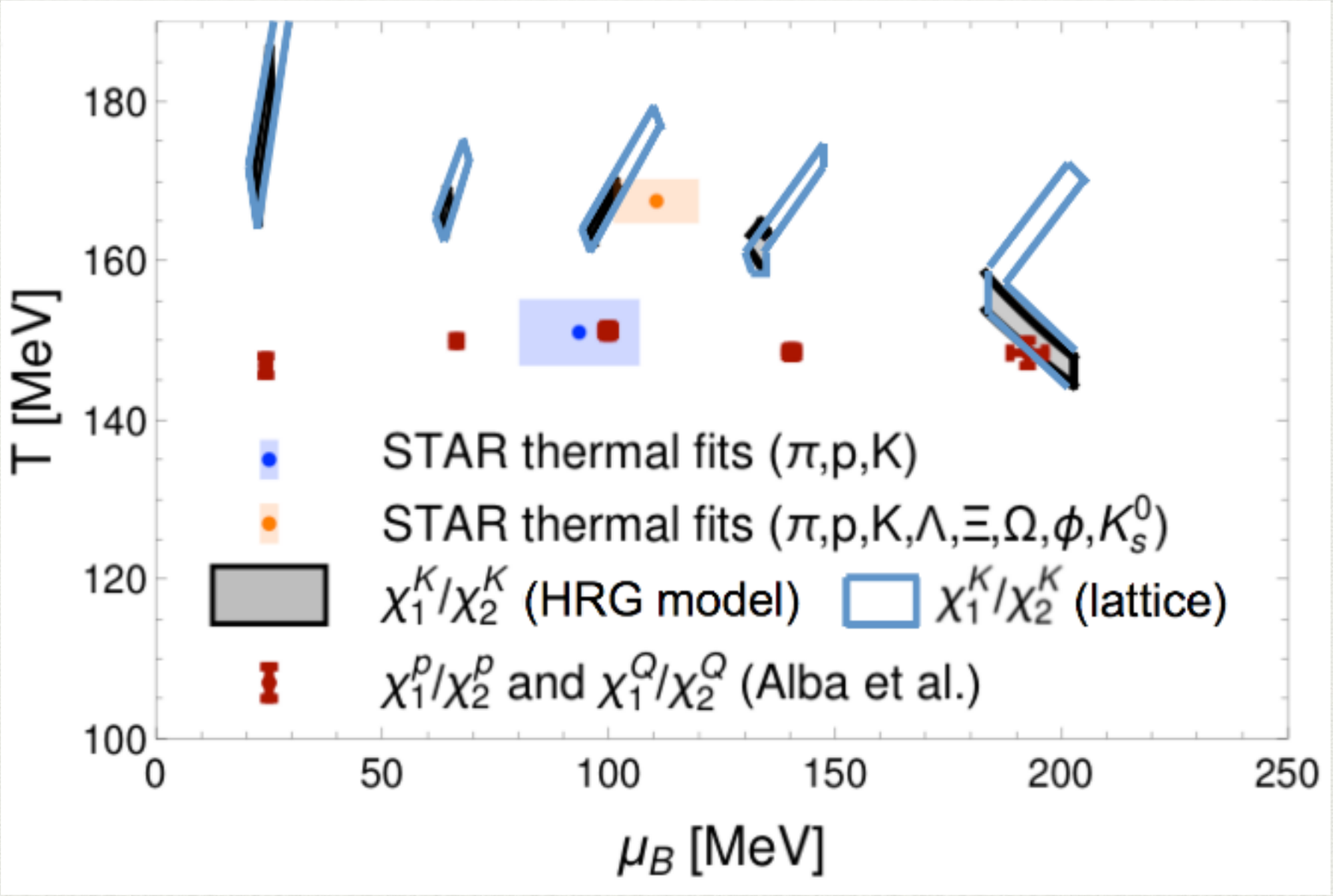


Phys.Rev. C99 (2019) no.3, 034912

Thermal fits also see flavor hierarchy

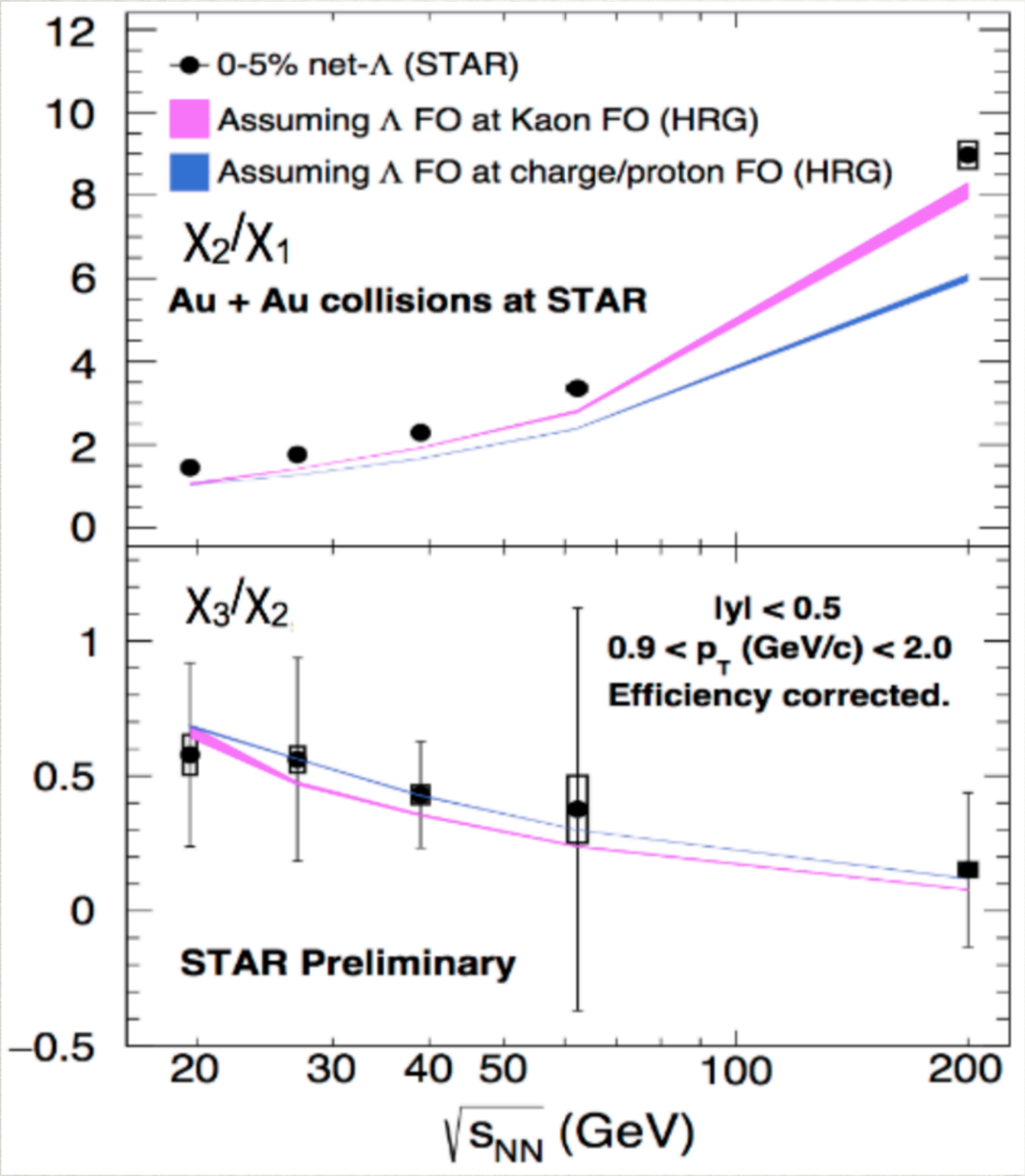
[STAR] Phys. Rev. C 96 (2017) 44904

With Lattice QCD partial pressures



net-Lambda fluctuations

Bellwied, JNH et al, Phys.Rev. C99 (2019) no.3, 034912



Lambda fluctuations also appear to prefer 2 flavor freeze-out.

Mudiyanselage QM Poster 2018

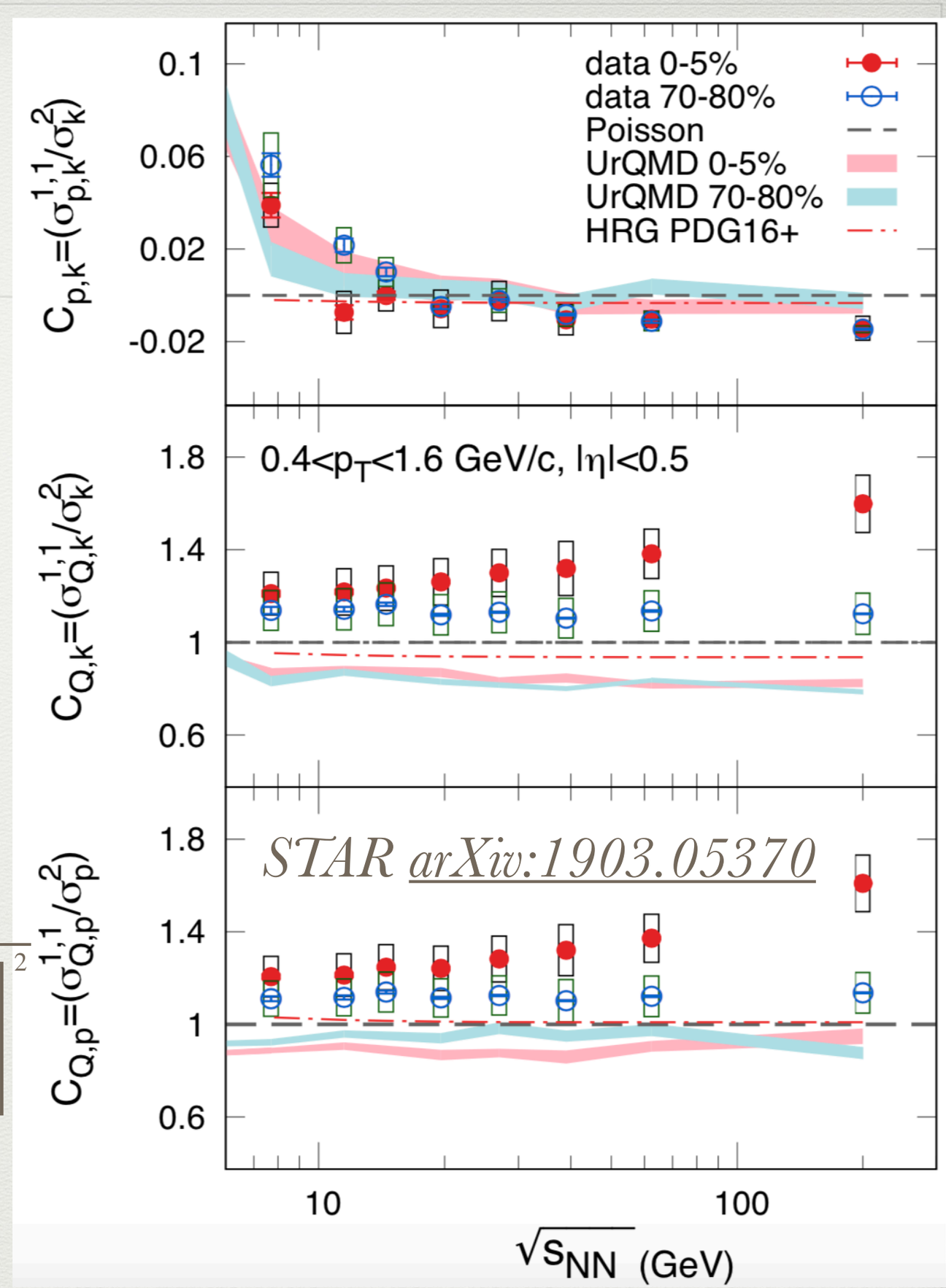
Mixed susceptibilities

Charge correlations not well understood

$$\chi_{11}^{\Delta A \Delta B} = \sum_{i}^{N_{HRG}} \left(Pr_{i\to A^{\pm}} X_i\right)\left(Pr_{i\to B^{\pm}} Y_i\right) \frac{d_i}{4\pi^2} \cdot$$

$$\cdot \int_{-0.5}^{0.5} d\eta \int_{0.2}^{1.6} dp_T \times \frac{p_T^2 \mathrm{Cosh}[\eta] \exp\left(\frac{\sqrt{p_T^2 \mathrm{Cosh}^2[\eta] + m_i^2}}{T} - \hat{\mu}\right)}{\left[(-1)^{B_k+1} + \exp\left(\frac{\sqrt{p_T^2 \mathrm{Cosh}^2[\eta] + m_i^2}}{T} - \hat{\mu}\right)\right]^2}$$

To appear soon



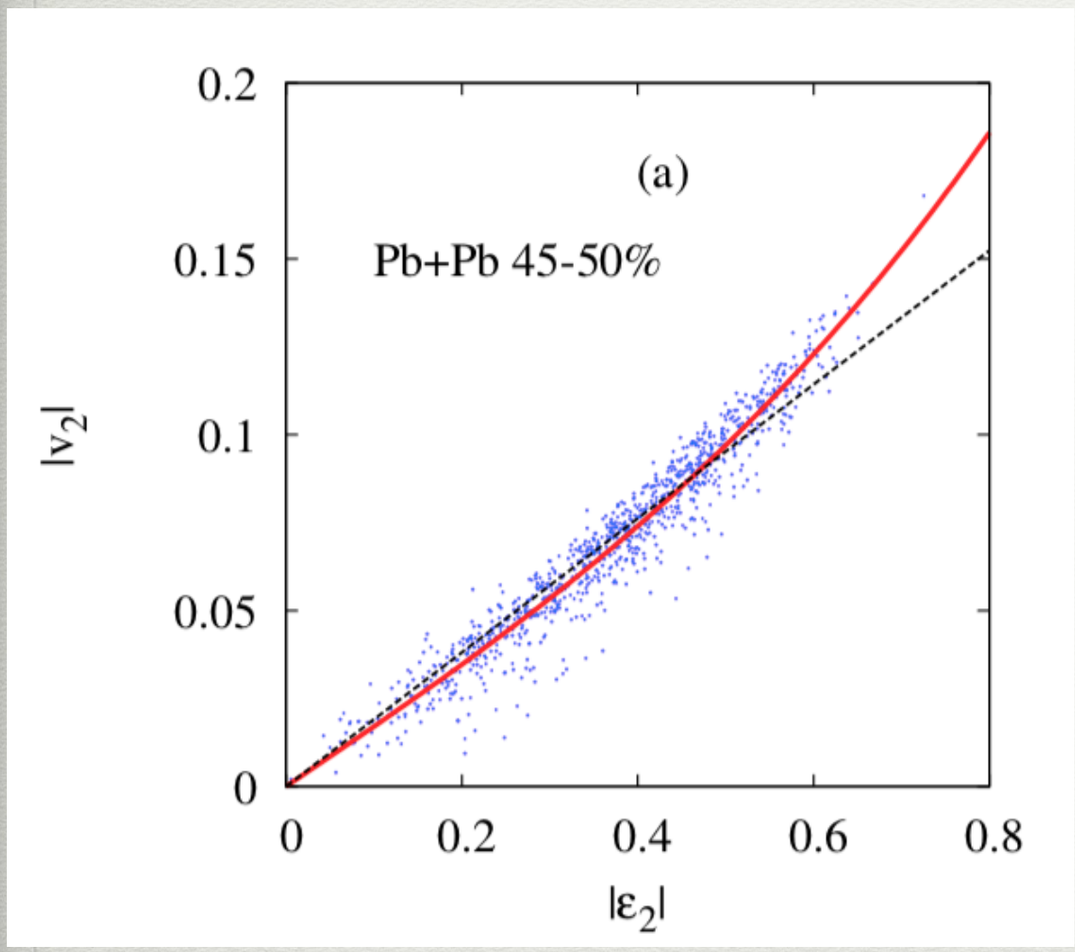
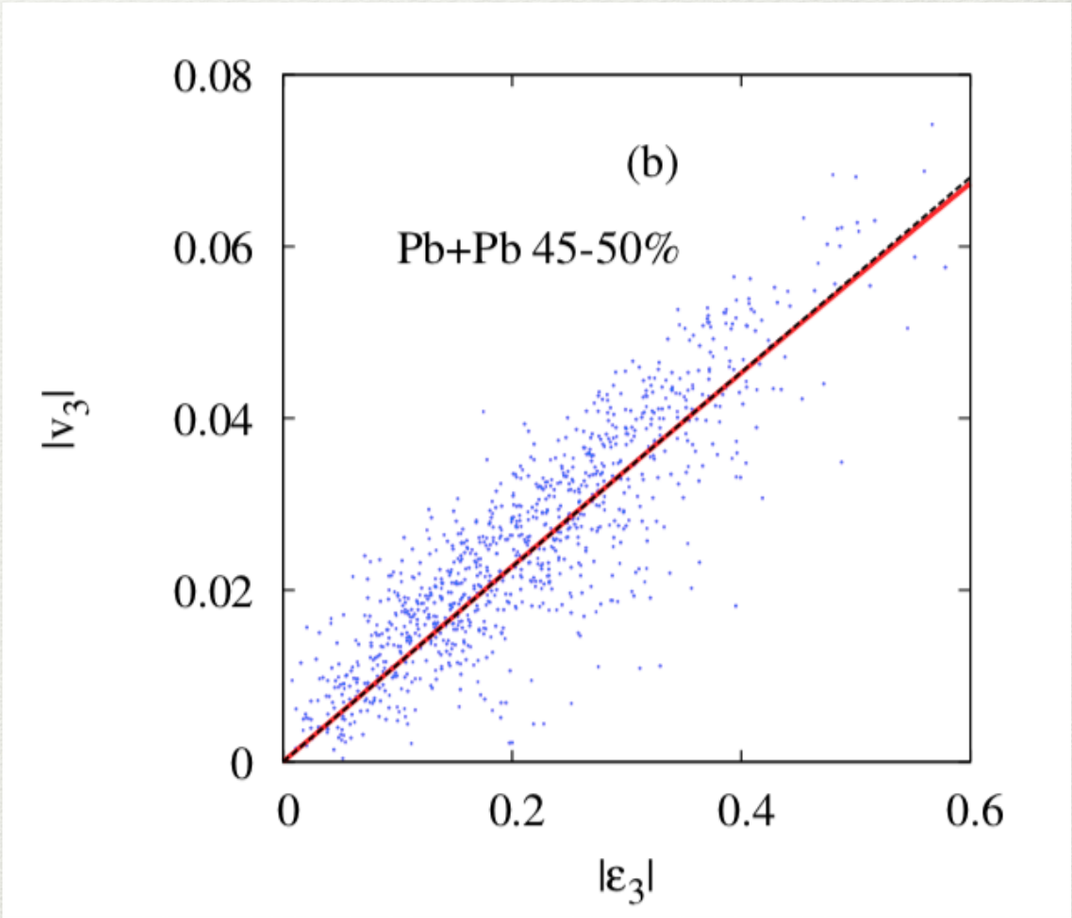
Conclusions and Outlook

- Predictions of flow fluctuations at lower beam energies coming soon!
- ICCING- initializes conserved charges using CGC
  - Flavor dependent eccentricities
- Many unanswered questions about transport coefficients at finite densities
- Possible signs of a flavor hierarchy at freeze-out, mixed susceptibilities need to be better understood

Linear vs. Cubic response

Linear response $$V_n^{pred} = \gamma_n \mathscr{E}_n$$

Teaney,Yan,PRC83(2011)064904;Gardim,et al,PRC85(2012)024908;PRC91(2015)3,034902

Linear+cubic response $$V_n^{pred} = \kappa_{1,n} \mathscr{E}_n + \kappa_{2,n} |\varepsilon_n|^2 \mathscr{E}_n$$

JNH,Yan,Gardim,Ollitrault Phys. Rev. C 93, 014909 (2016)