Initializing Conserved Charges for BSQ hydrodynamics

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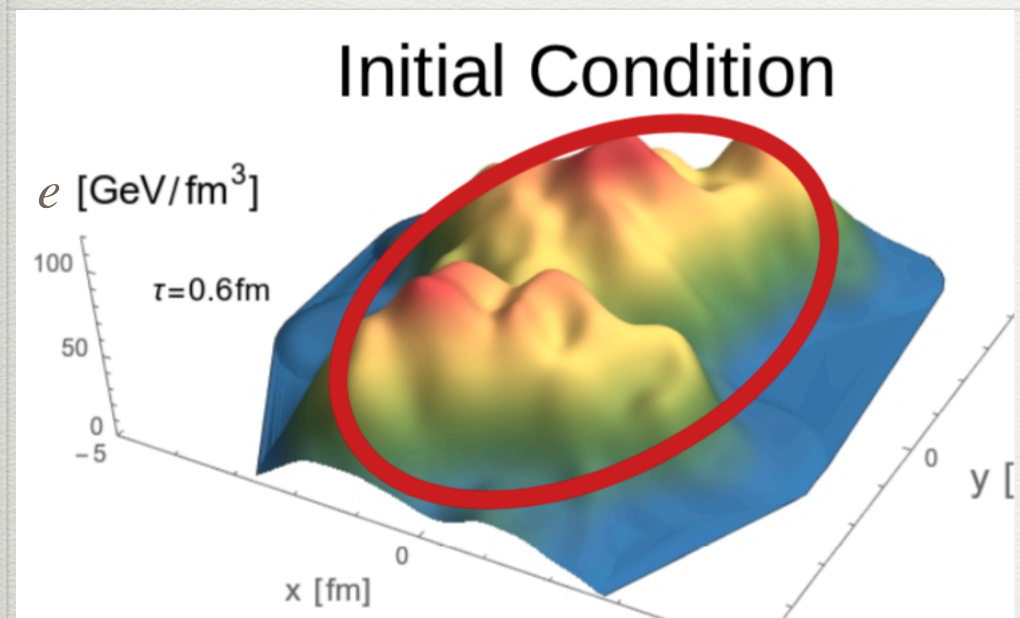
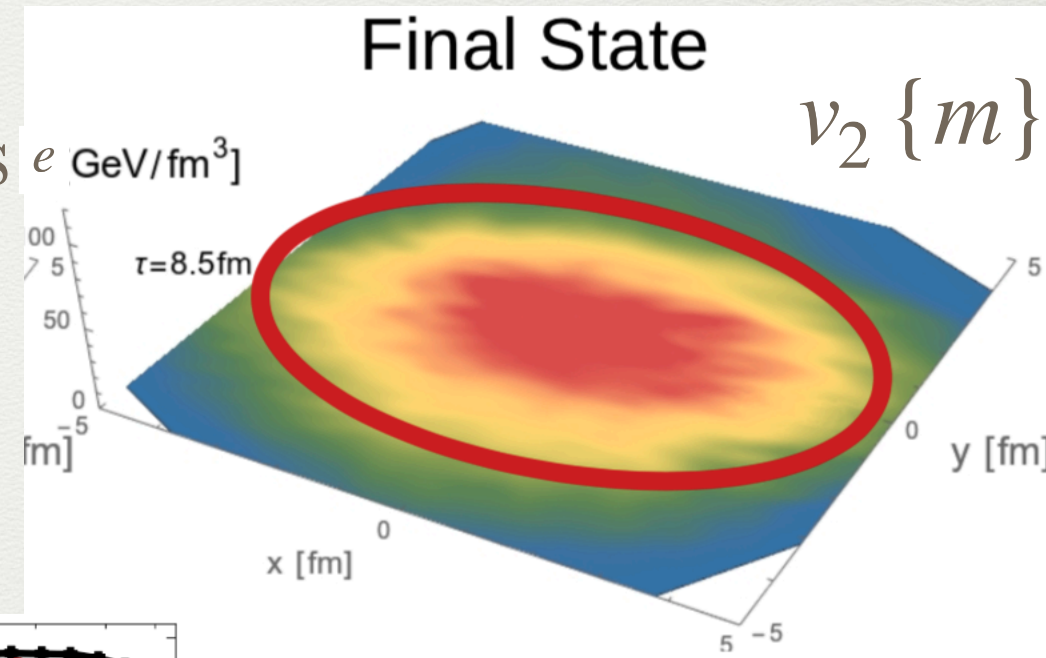
Non-conformal EOS $\eta T/w(T,\mu_B)$, $\zeta T/w(T,\mu_B)$: Travis Dore
(BSQ initial state) ICCING: Martinez, Sievert, Wertepny
arXiv:1911.10272,+long paper on arXiv on Sunday

Initial state: energy density only *e*

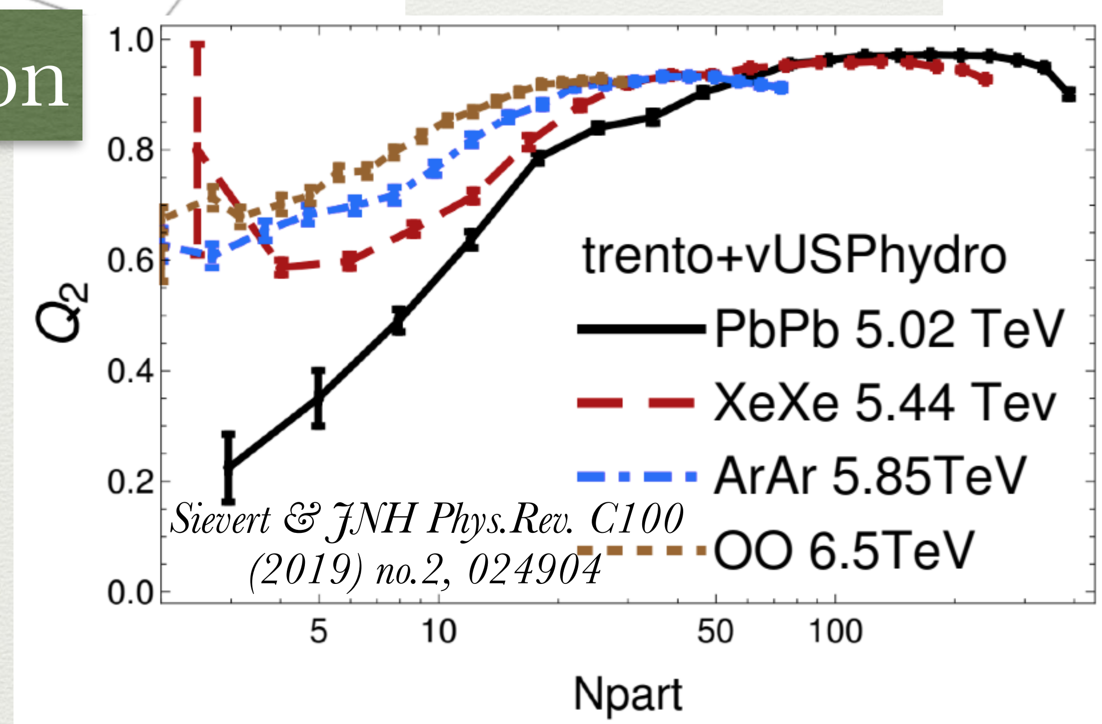


Eccentricities

$\varepsilon_n\{m\}$



Perfect correlation



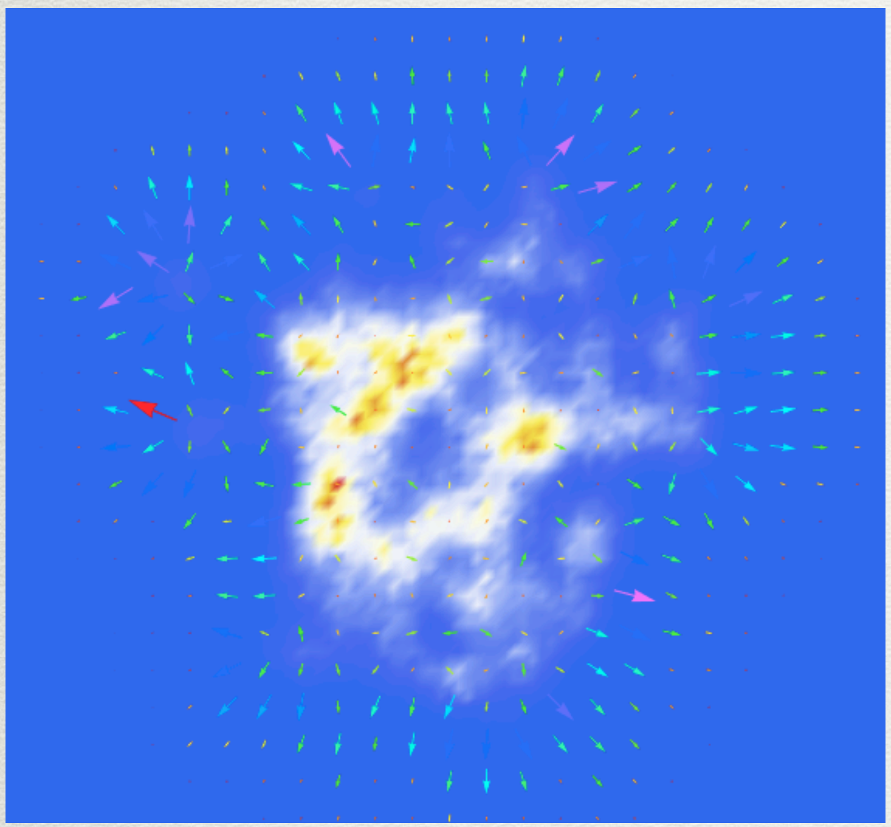
No correlation

Pearson coefficient between initial energy density to final flow harmonic

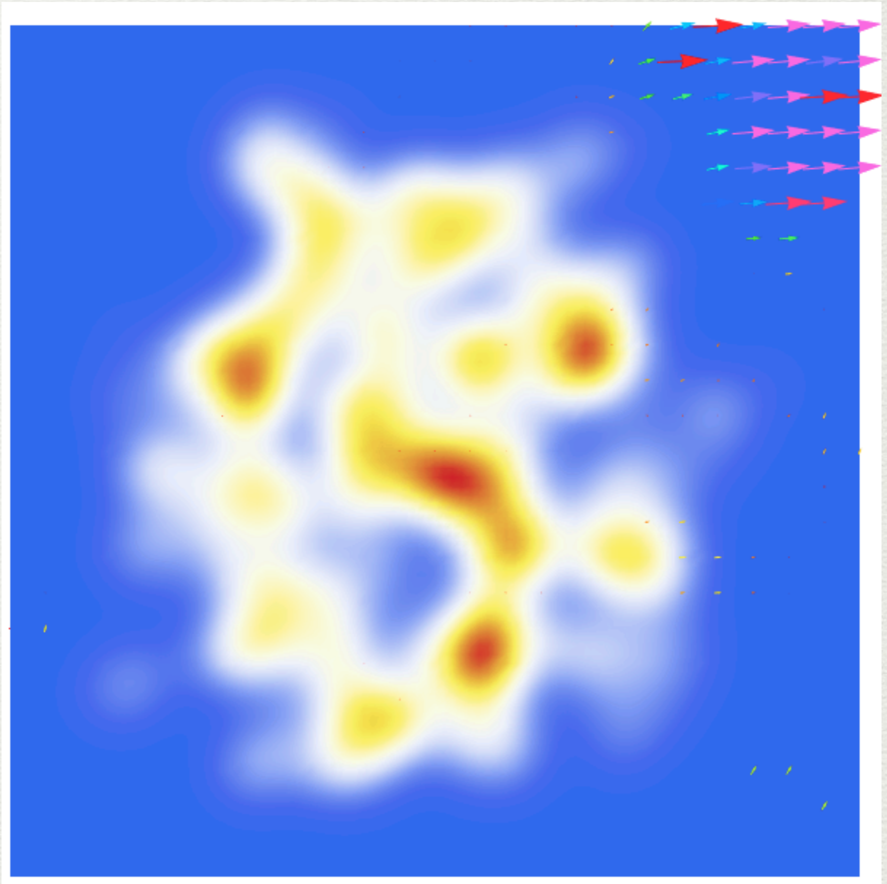
Hirano et al, PRC84 (2011) 011901; Qiu PLB707 (2012) 151-155; Cao et al PRC 88, 044907 (2013); Teaney et al, PRC 83, 064904 (2011), PRC 86, 044908 (2012); Qiu et al, PRC 84, 024911 (2011); Gardim et al, PRC85(2012)024908;PRC91(2015)3,034902; Niemi et al, PRC 87, no. 5, 054901 (2013) ; JNH et al Phys.Rev. C93 (2016) no.1, 014909; Phys.Rev. C95 (2017) no.4, 044901; Gardim et al, Phys.Rev. C97 (2018) no.6, 064919; Sievert & JNH Phys.Rev. C100 (2019) no.2, 024904

Initial state: e, u_0

IP-Glasma



Nexus

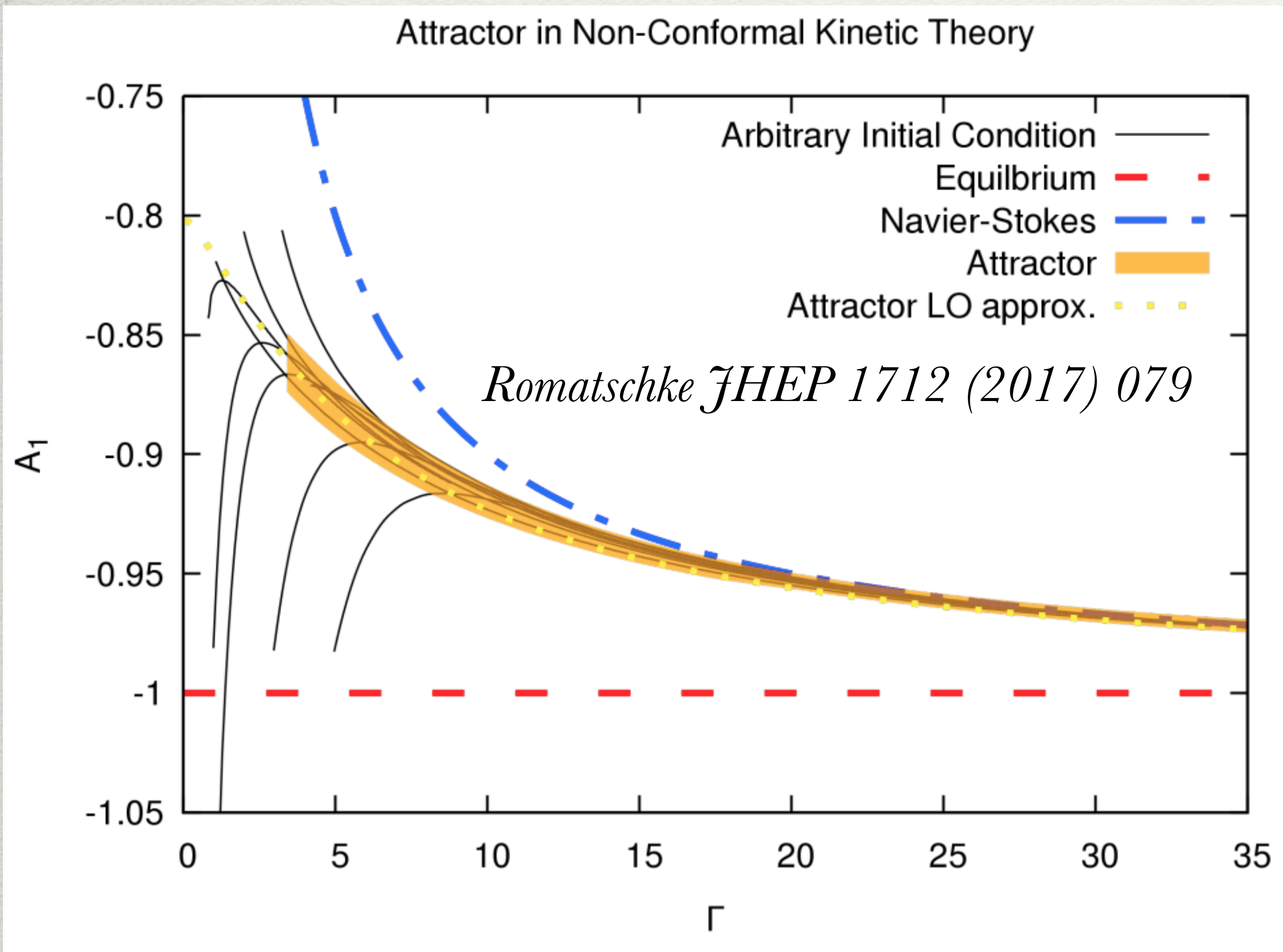


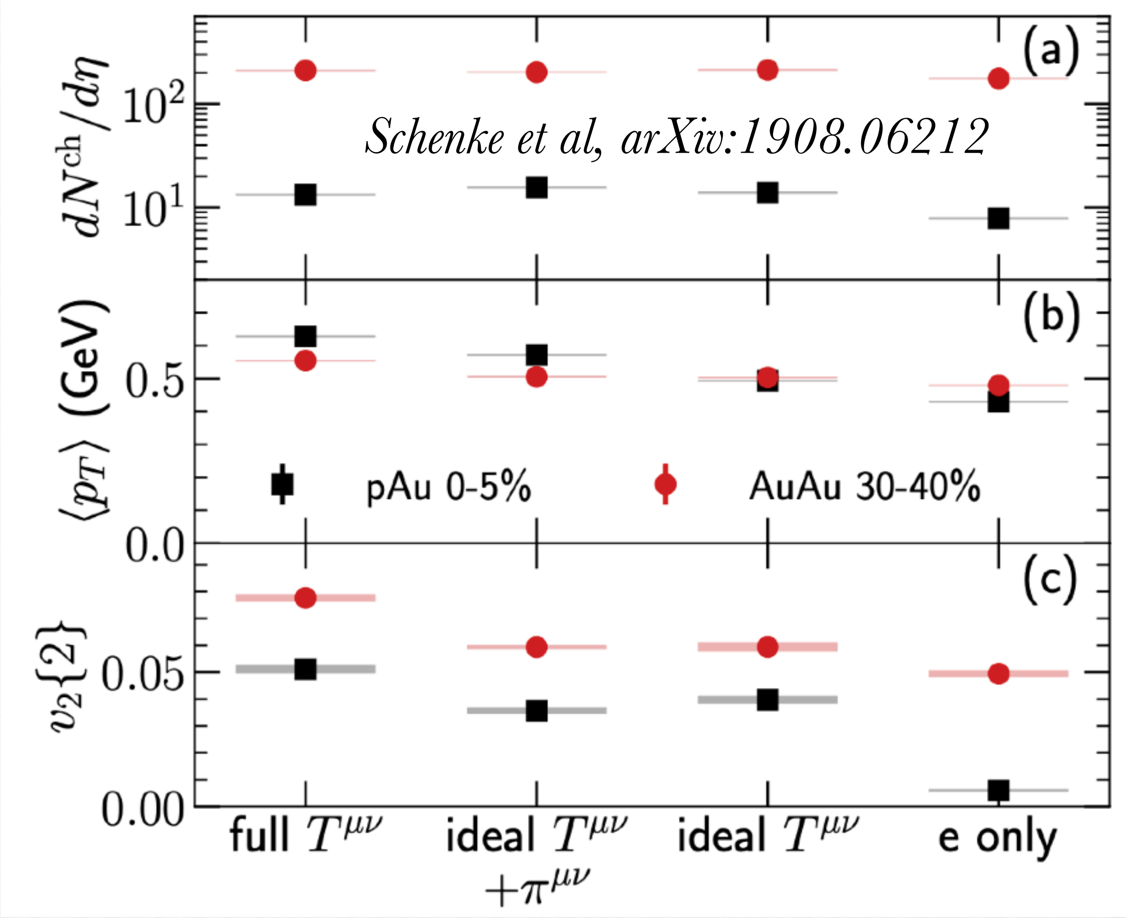
Initial flow $\{e, u_0\}$ → **Small ⇑ in $v_2\{2\}$ in large systems**

Mapping: Gardim et al, Phys.Rev. C85 (2012) 024908

Small systems: Weller & Romatschske Phys.Lett. B774 (2017) 351-356; Mäntysaari et al Phys.Lett. B772 (2017) 681-686

Initial state: $\{e, u_0, \pi^{\mu\nu}, \Pi\}$





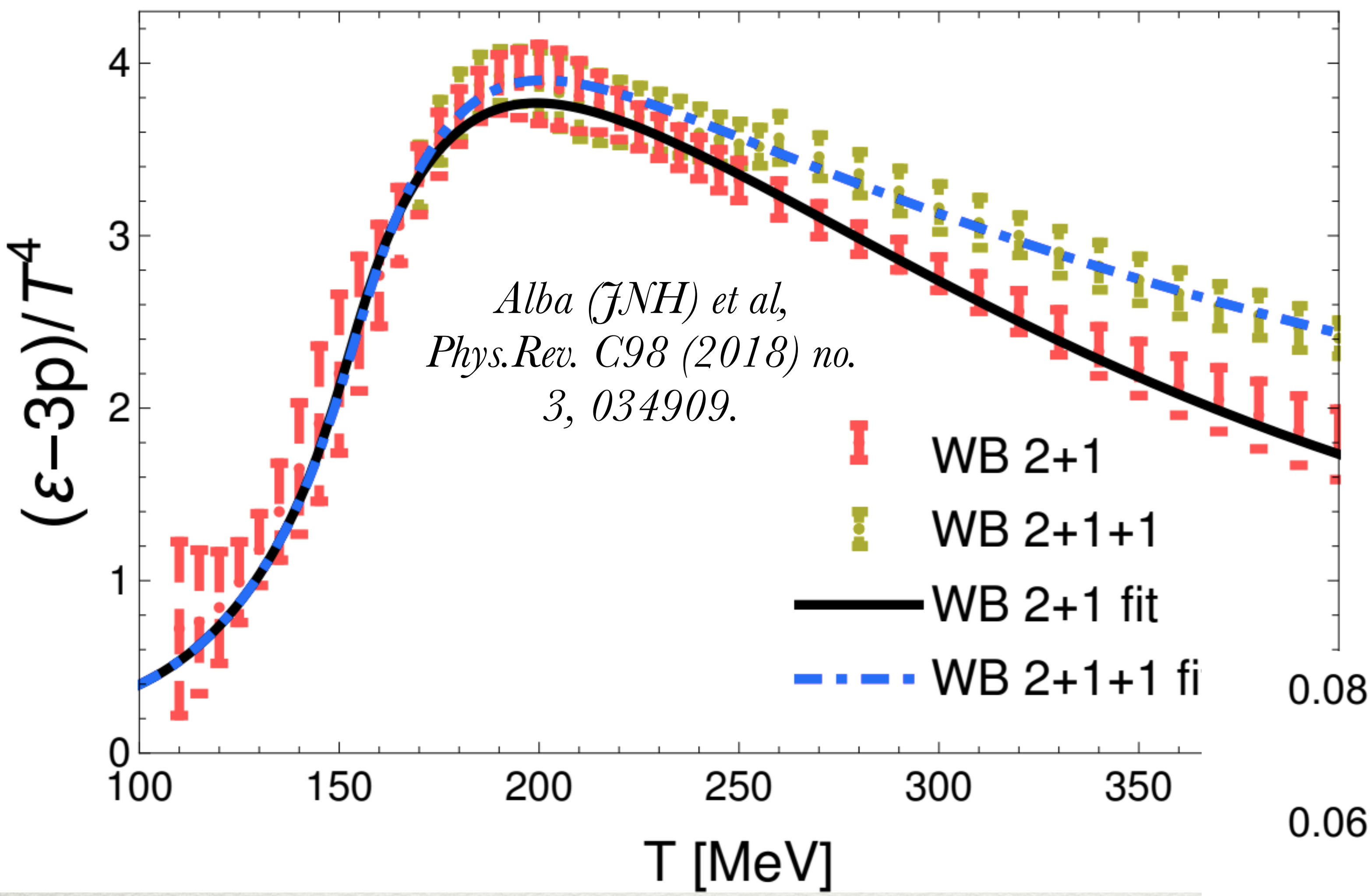
Full $T_{\mu\nu}$ i.e. $\{e, u_0, \pi^{\mu\nu}, \Pi\}$ → **Attractors, decorrelation with $\varepsilon_n\{m\}$ in small systems**

Free Streaming: Liu et al, Phys.Rev. C91 (2015) no.6, 064906; Bernhard et al Nature Phys. 15 (2019) no.11, 1113-1117
Kinetic theory: Kurkela et al, Phys.Rev.Lett. 122 (2019) no.12, 122302

Mapping: Luzum (QM19) & Noronha in preparation

- **Attractors with realistic Equation of State+transport coefficients** *Dore, McLaughlin, JNH to appear soon*
    - What happens to attractors with both shear and bulk viscosities?
    - How does a full $T^{\mu\nu}$ affect the path to the critical point?
- **Initializing conserved charges (baryon number, strangeness, and electric charge)** *Sievert, Martinez, Wertepny, JNH arXiv:1911.10272*
    - Do conserved charges have the same geometries?
    - How does this affect the mapping between initial and final state?

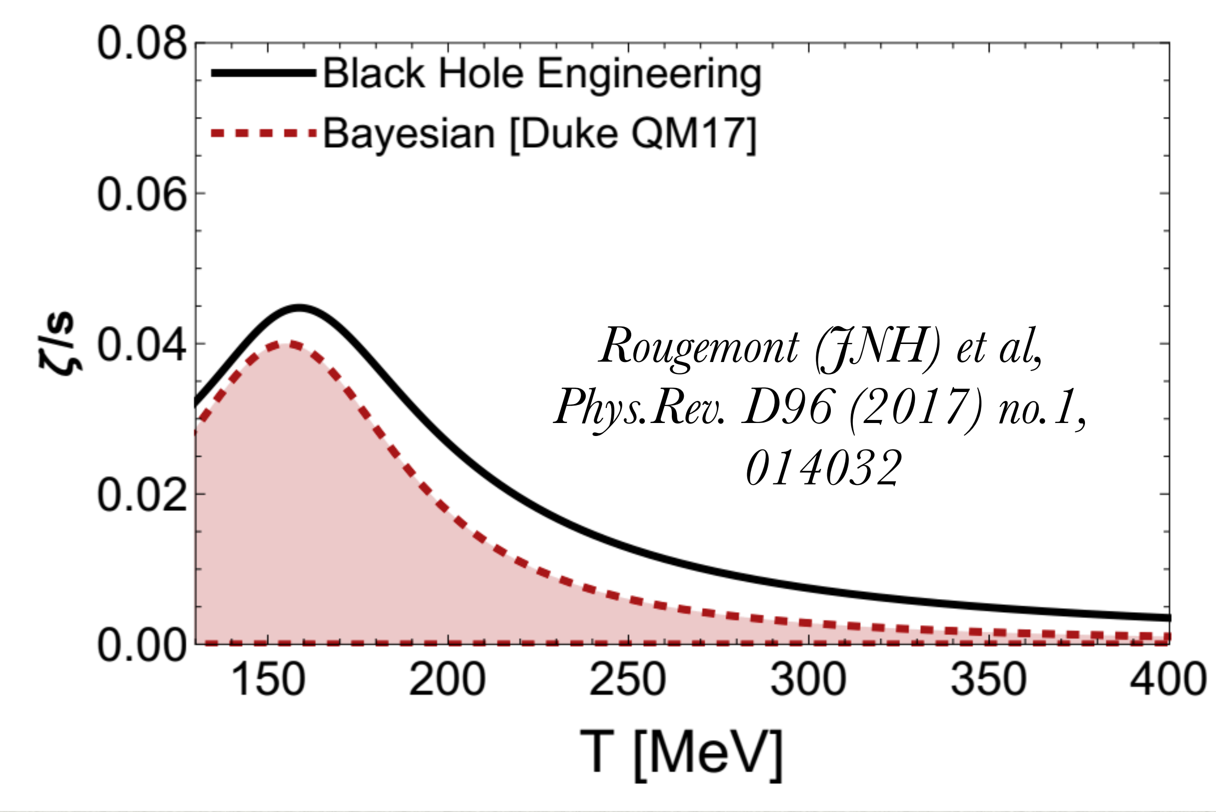
Attractors: QCD EOS+Bulk viscosity?



Alba (JNH) et al, Phys.Rev. C98 (2018) no. 3, 034909.

EOS definitely not conformal even at high T

Bulk connected to $e \neq 3p$ but magnitude and shape unclear



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

Bernhard et al Nature Phys. 15 (2019) no.11, 1113-1117

Equations of Motion

Energy density

$$\dot{\epsilon} = -\frac{1}{\tau}\left[e + p + \Pi + \pi_\eta^\eta\right]$$

Shear

$$\tau_\pi \dot{\pi}_\eta^\eta + \pi_\eta^\eta = -\frac{4\eta}{3\tau} - \frac{1}{\tau}\left[\left(\frac{4}{3} + \lambda\right)\pi_\eta^\eta + \frac{2}{3}\lambda_{\pi\Pi}\Pi\right]$$

Bulk

$$\tau_\Pi \dot{\Pi} + \Pi = -\frac{\zeta}{\tau} - \frac{1}{\tau}\left(\delta_{\Pi\Pi}\Pi + \frac{2}{3}\lambda_{\Pi\pi}\pi_\eta^\eta\right)$$

Baryon Density

$$\rho_B = \frac{\rho_0}{\tau}$$

Denicol, Jeon, Gale Phys.Rev. C90 (2014) no.2, 024912

Transport coefficients

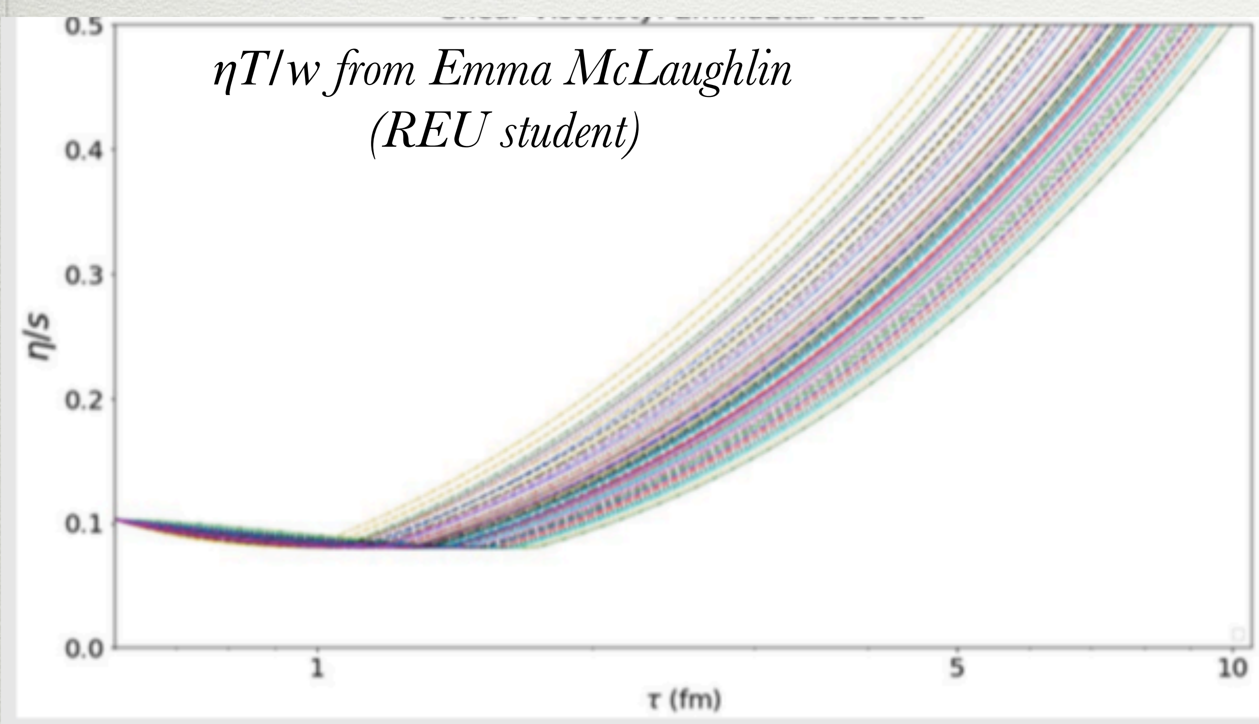
$$\tau_\Pi = \frac{\zeta}{15(e+p)\left(\frac{1}{3} - c_s^2\right)^2}$$

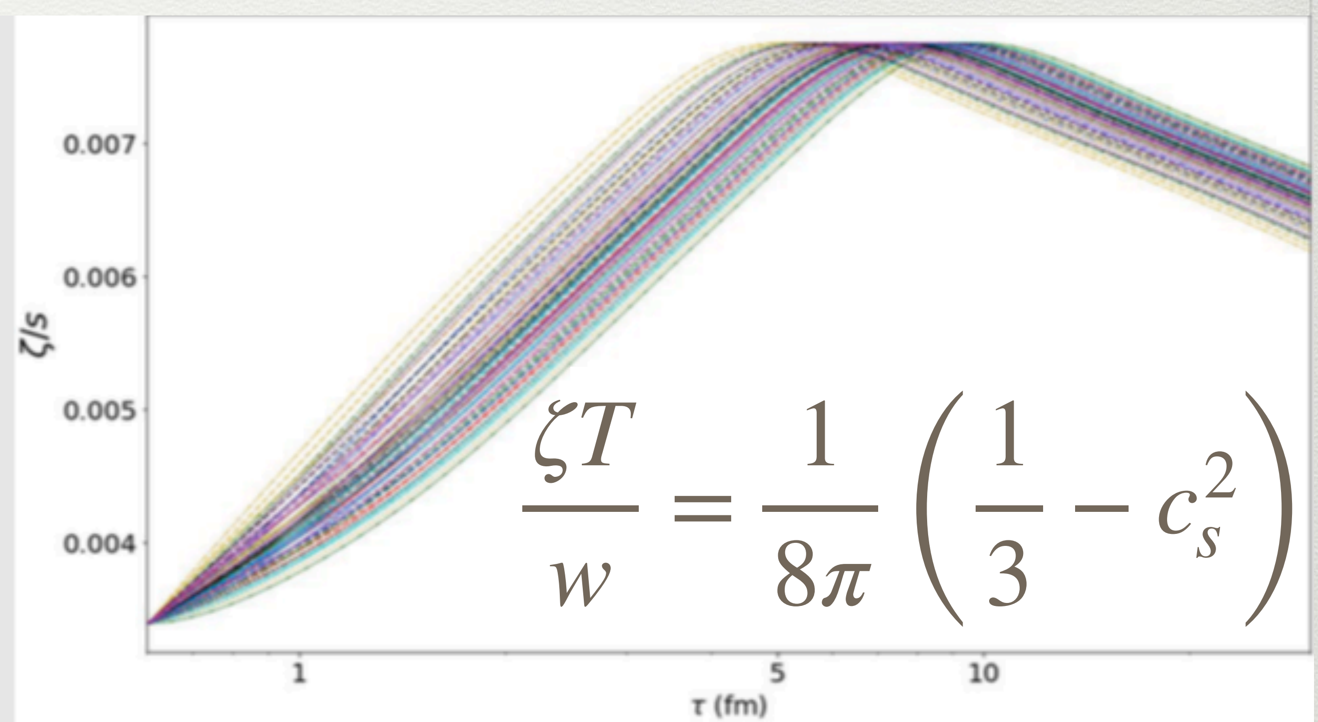
$$\tau_\pi = \frac{5\eta}{e+p}$$

Diffusion vanishes in Bjorken flow. 1+1D future study.

PhD student Travis Dore

Transport coefficients versus τ



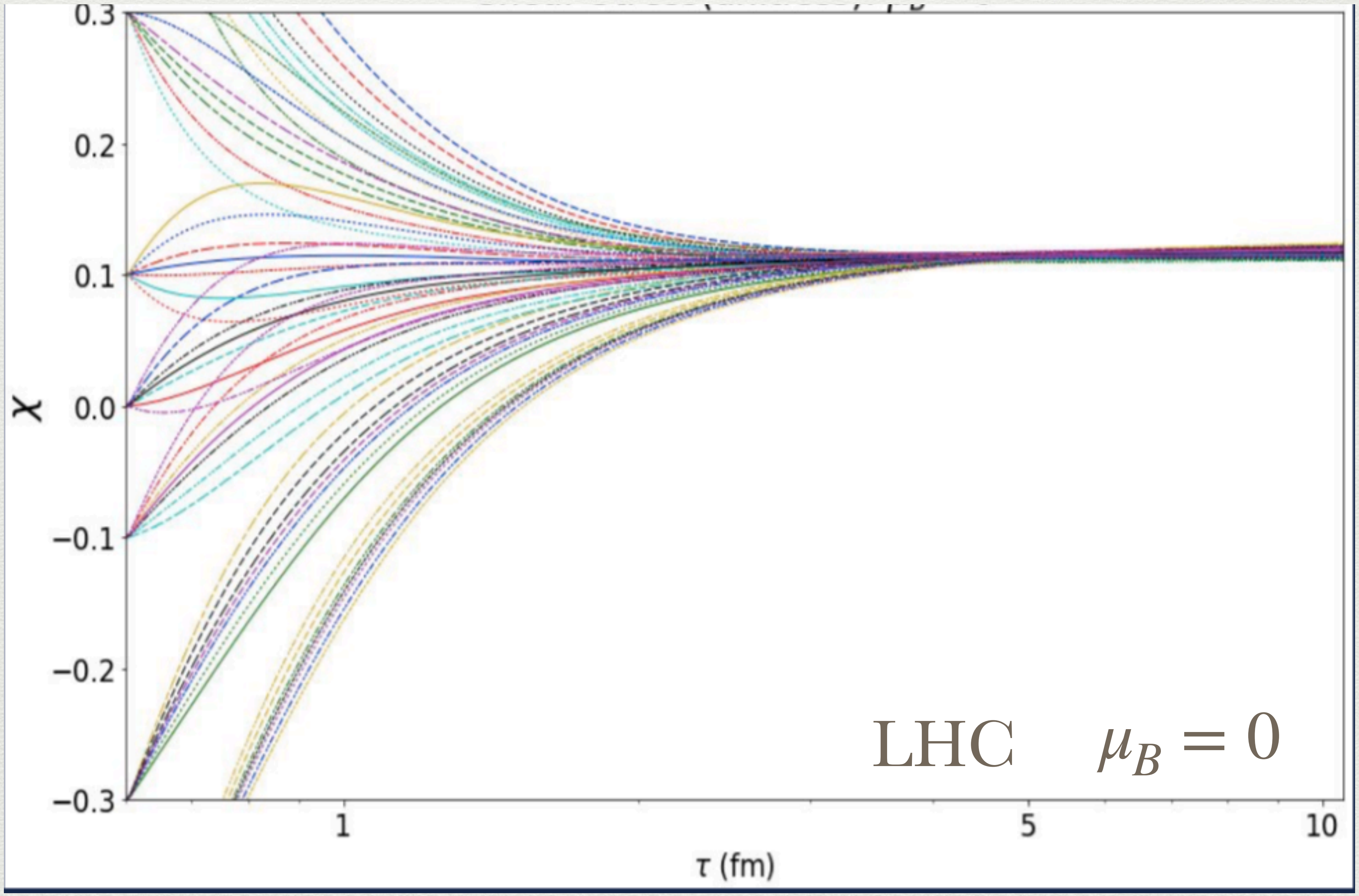


$$\frac{\zeta T}{w} = \frac{1}{8\pi}\left(\frac{1}{3} - c_s^2\right)$$

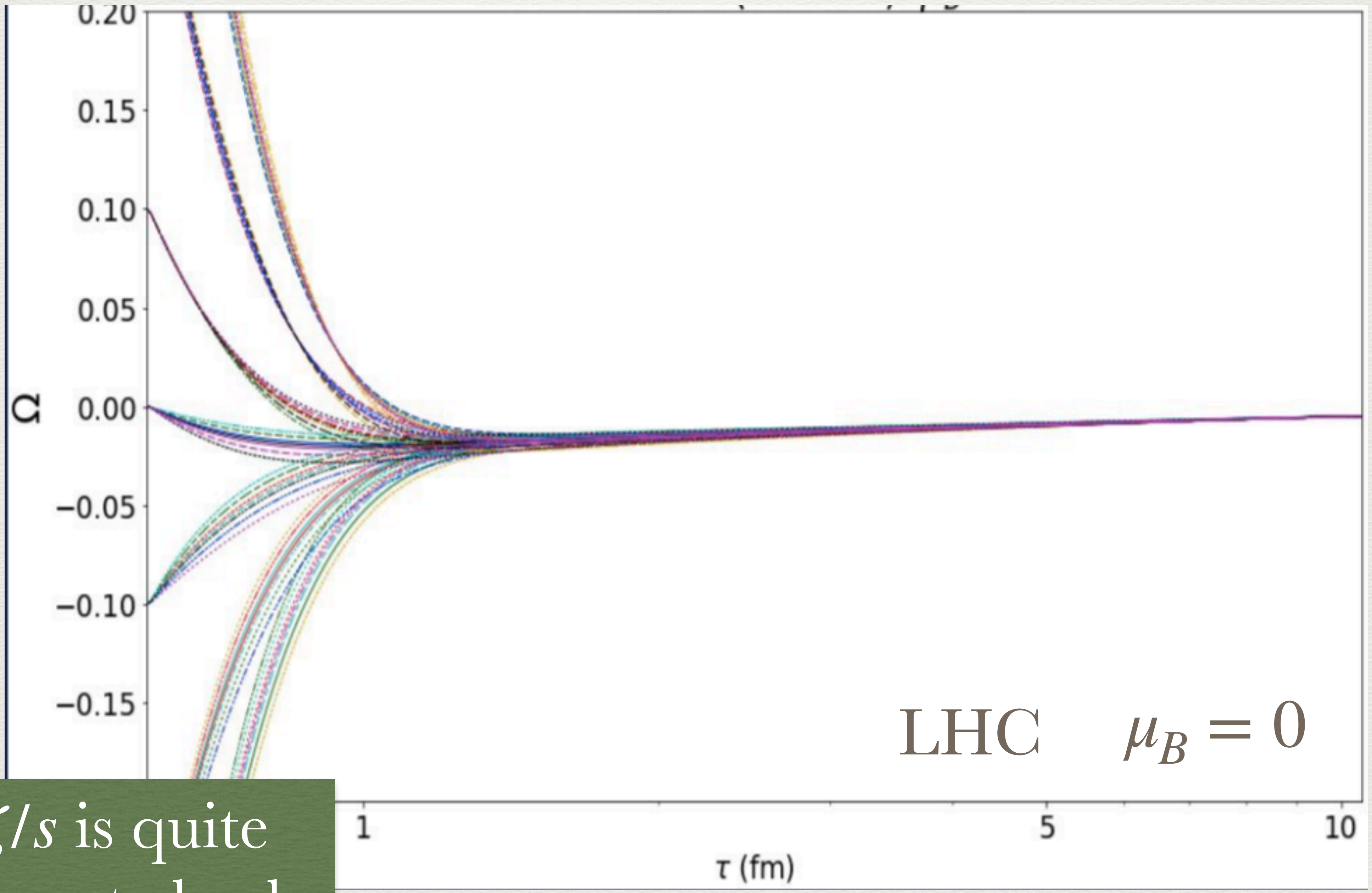
- $(\eta/s)_{min}$ occurs at early times
- $(\zeta/s)_{max}$ occurs at late times (driven by $\downarrow$ in c_s^2 at the T_{pc})

At finite densities we'll use $w = e + p$

Shear stress evolution $\chi = \dfrac{\pi^\eta_\eta}{e+p}$



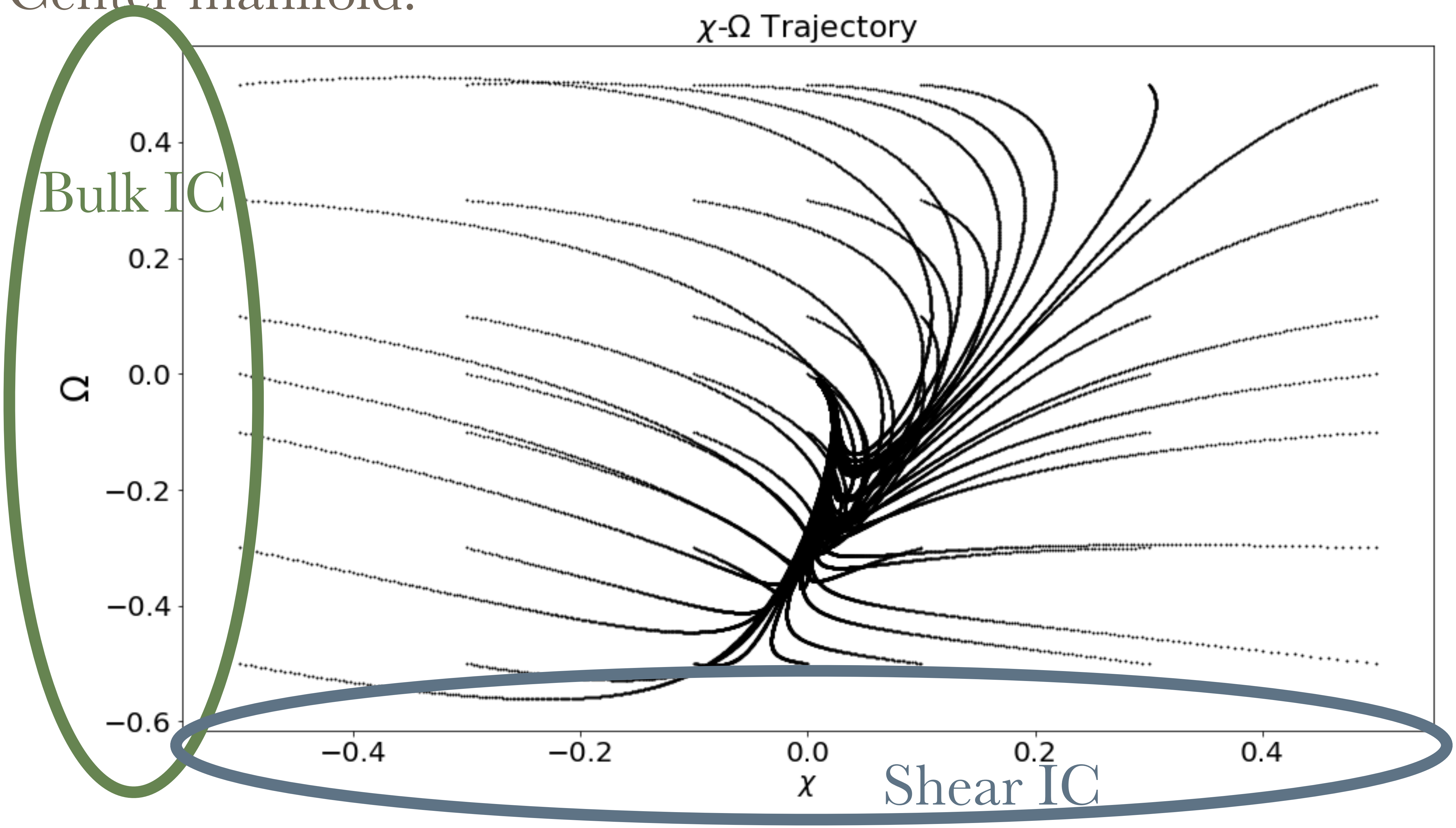
Bulk evolution $\Omega = \dfrac{\Pi}{e+p}$



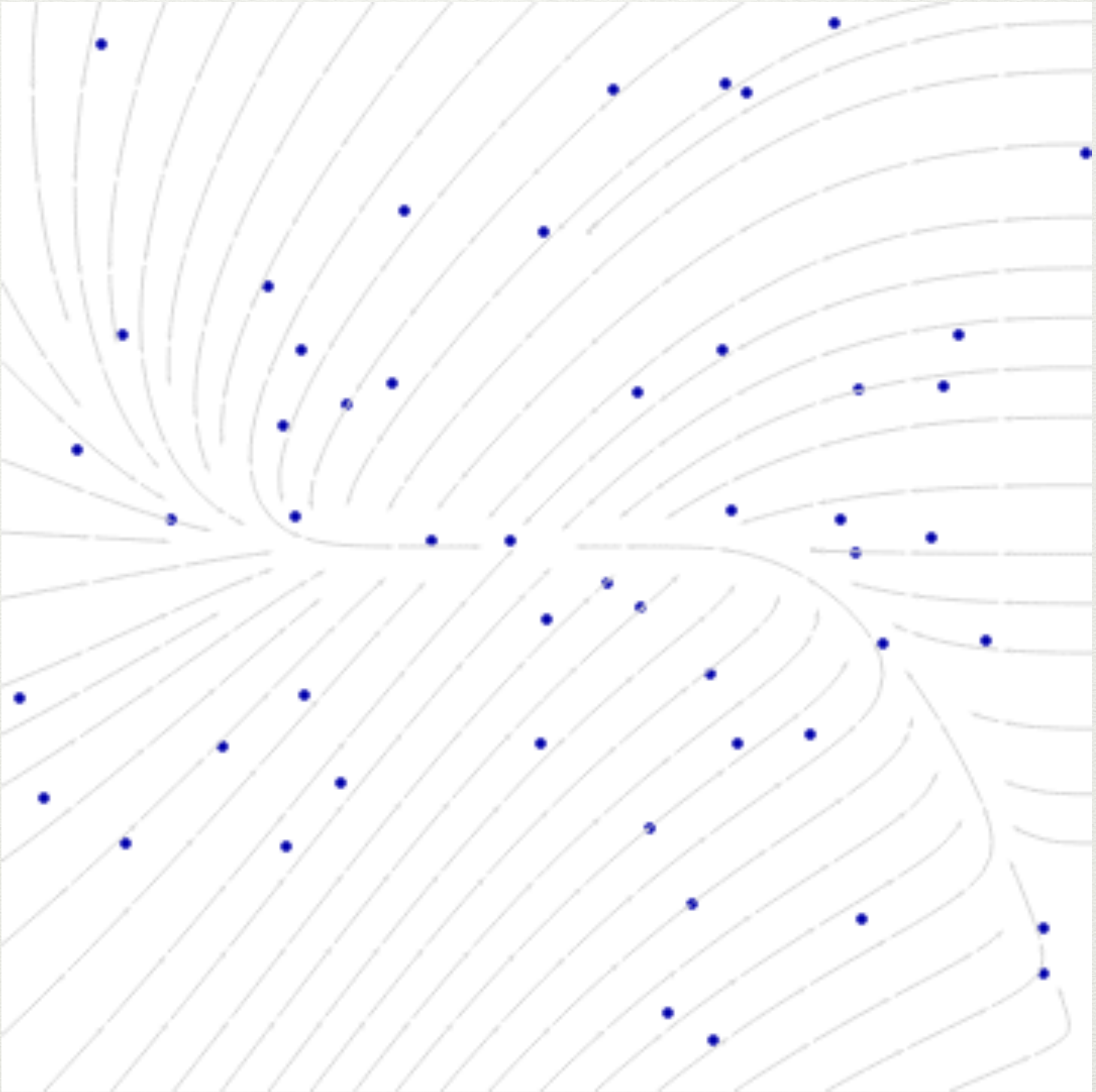
Our ζ/s is quite small, must check with a larger one

Shear versus bulk initial conditions

Center manifold?



Center Manifold?

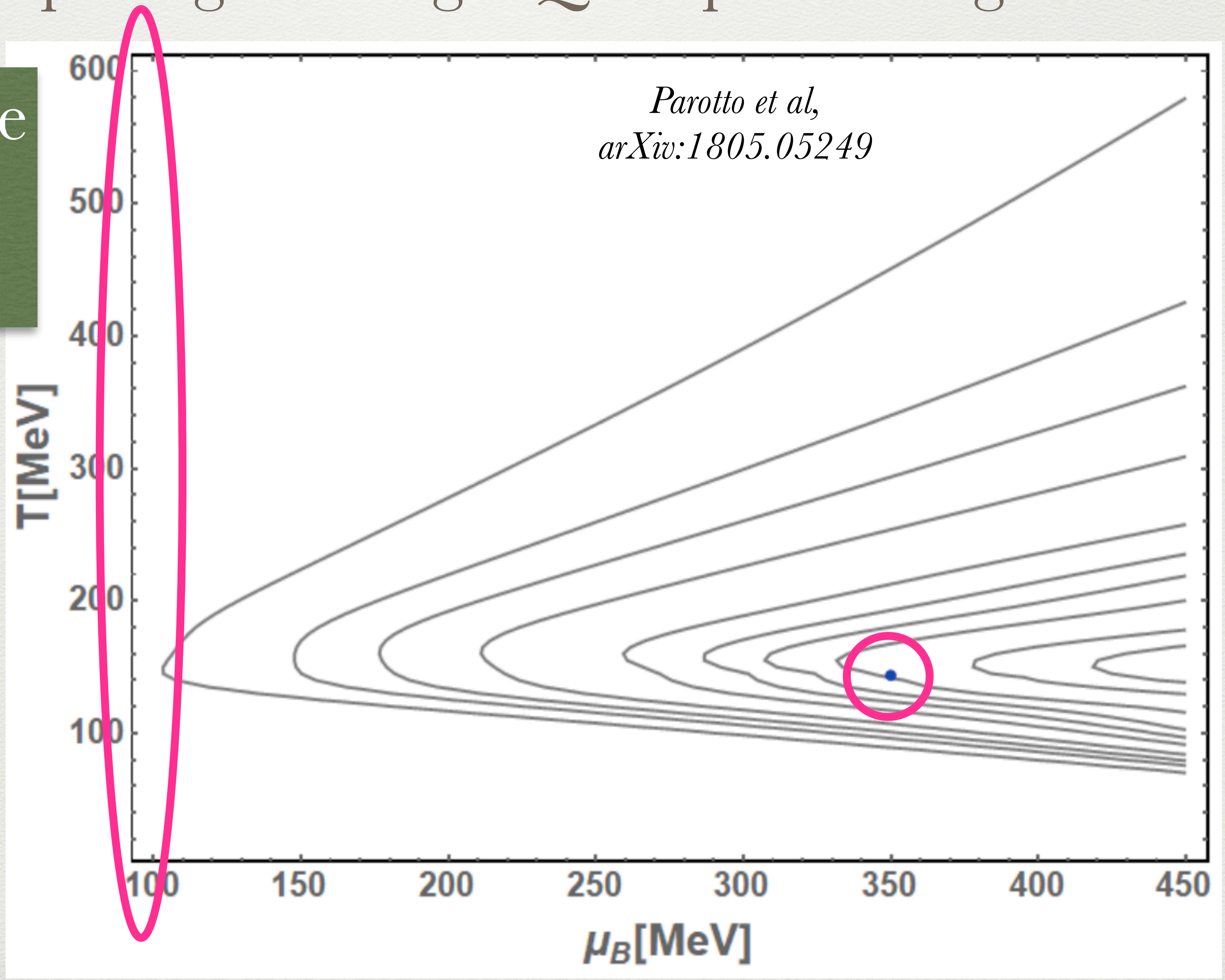


Viktor’s talk

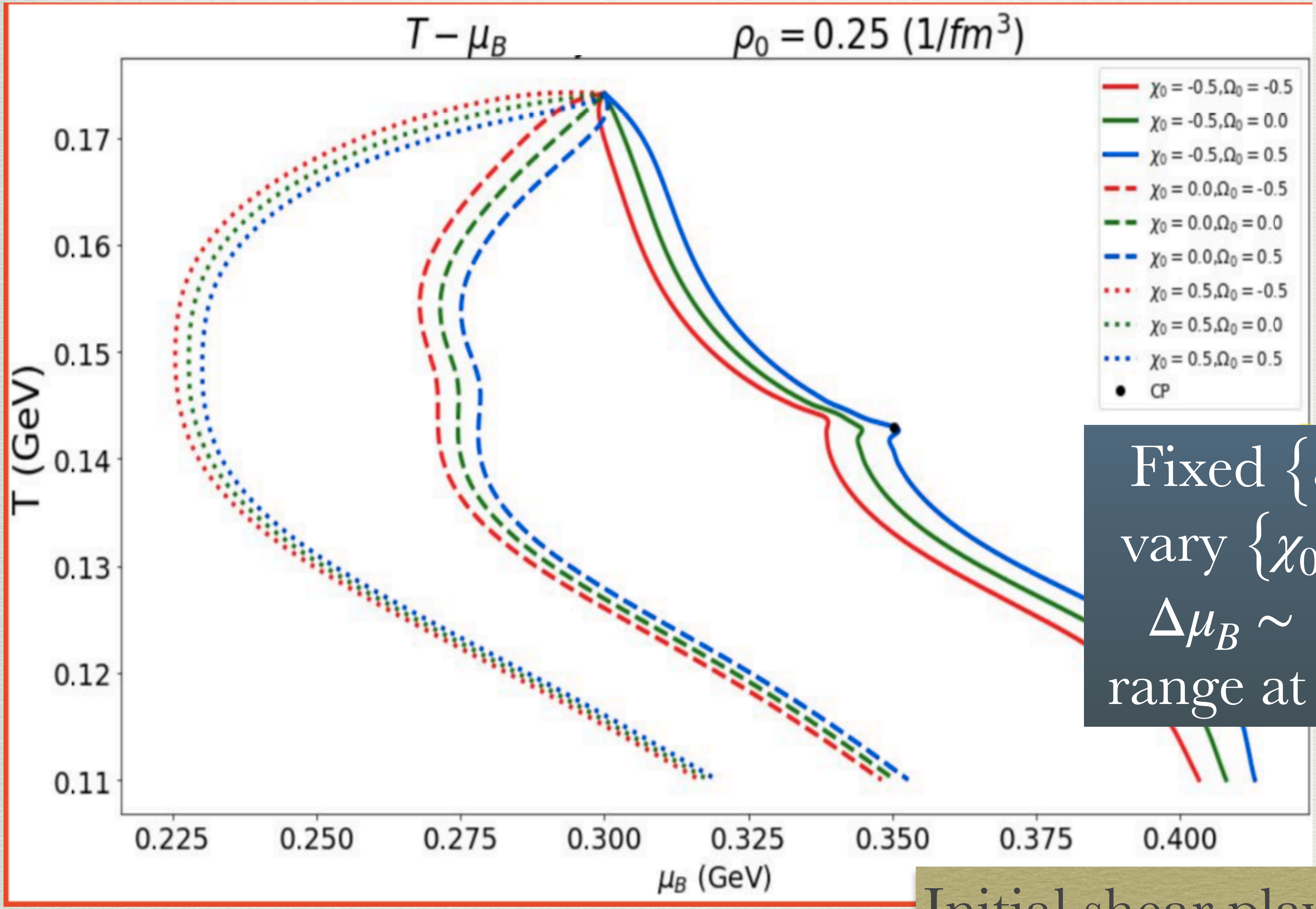
Search for the critical point

Lattice QCD uses isentropes (assumes ideal hydro) to map out passage through QCD phase diagram

Attractors have only been checked here



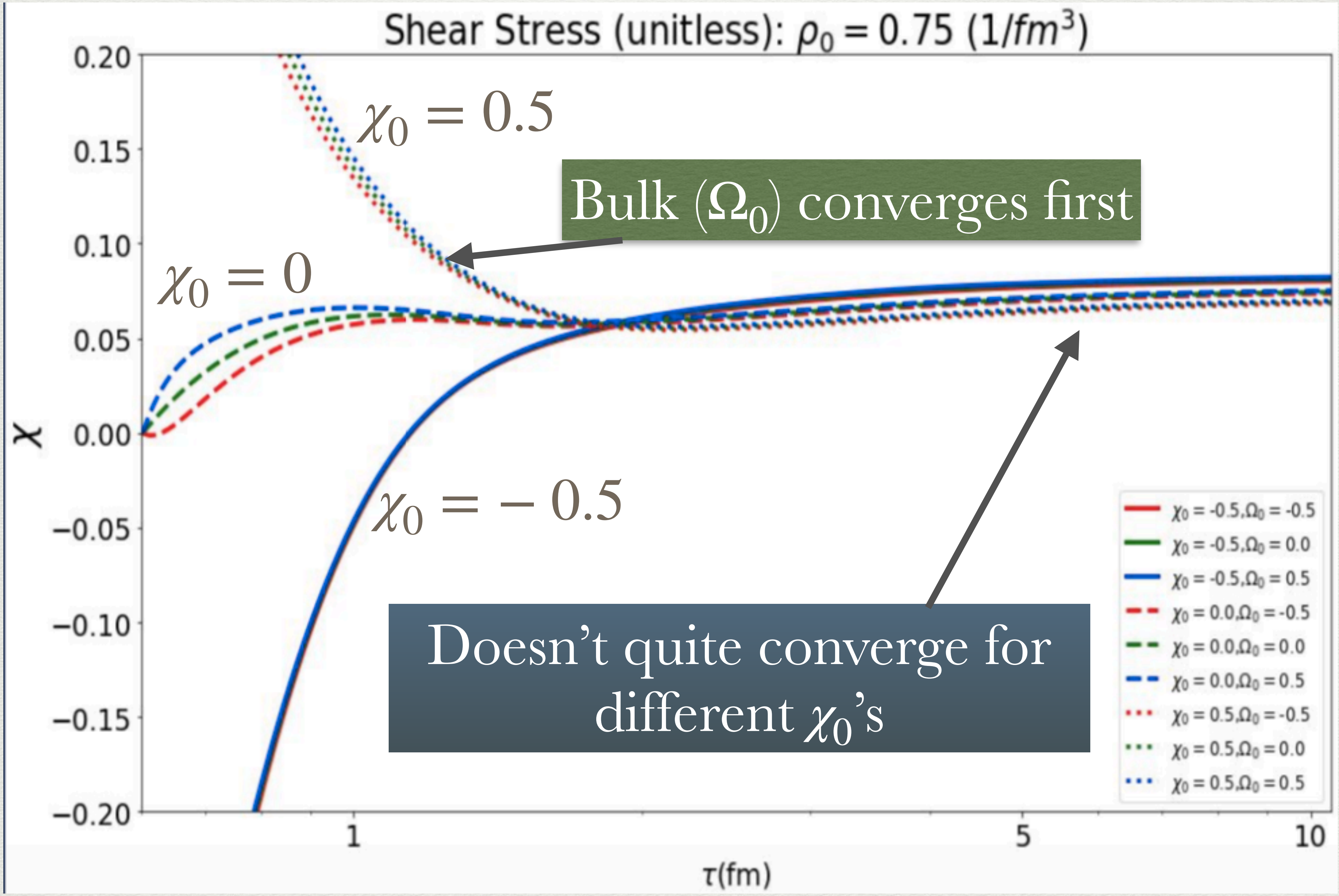
Full $T^{\mu\nu}$ at the Beam energy scan



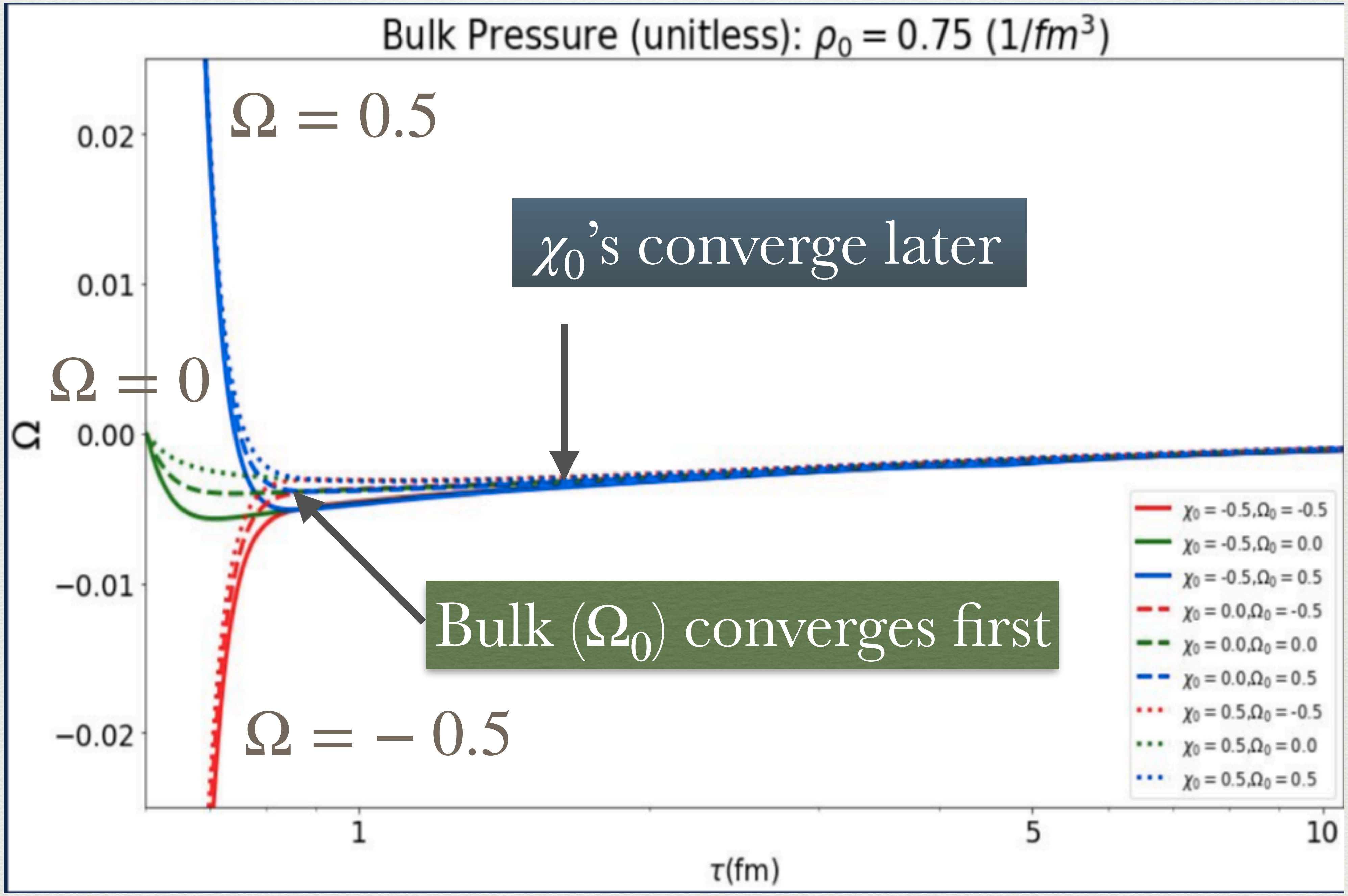
Fixed $\{\varepsilon_0, \rho_0\}$ but vary $\{\chi_0, \Omega_0\}$, find $\Delta\mu_B \sim 125$ MeV range at freeze-out.

Initial shear plays largest role

Shear evolution at finite μ_B



Bulk evolution at finite μ_B



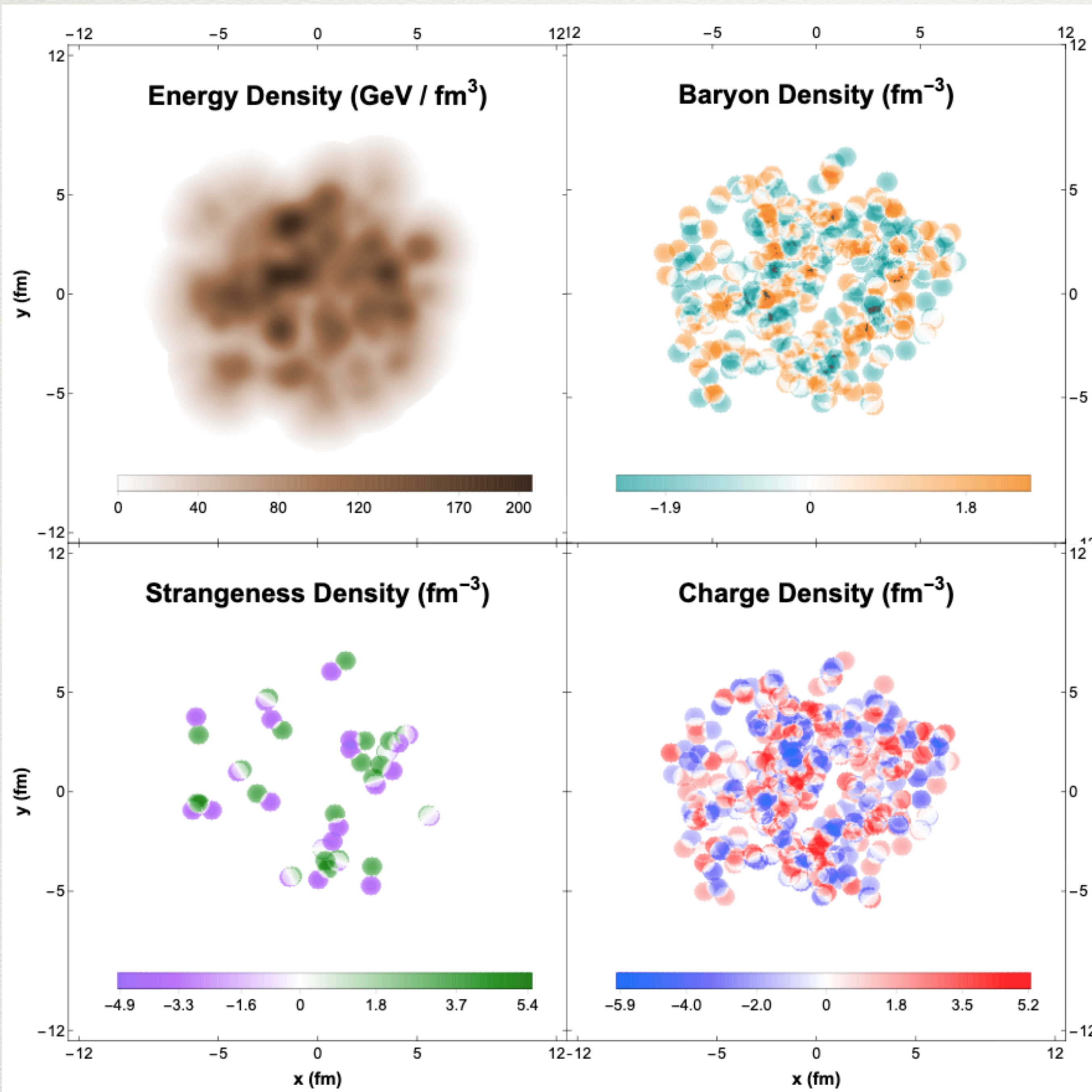
Mini-summary

- At $\mu_B = 0$ with a non-conformal EOS, shear appears to have a convergence whereas bulk converges to zero
- At $\mu_B > 0$ bulk converges, shear converges for a fixed π_η^η while varying bulk, but not varying both
- Full $T^{\mu\nu}$ dramatically changes $\{T, \mu_B\}$ trajectories, as does choice in $\eta T/w(T, \mu_B)$
- Future: rapidity dependence of $\{T, \mu_B\}$ trajectories (see J. Brewer Phys.Rev. C98 (2018) no.6, 061901)

Initial conditions: $\{e, u_0, \pi^{\mu\nu}, \Pi\} + \left\{\rho_B, \rho_S, \rho_Q\right\}$

Sievert, Martinez, Wertepny, JNH arXiv:1911.10272

ICCING: Initial Conserved Charges in Nuclear Geometry

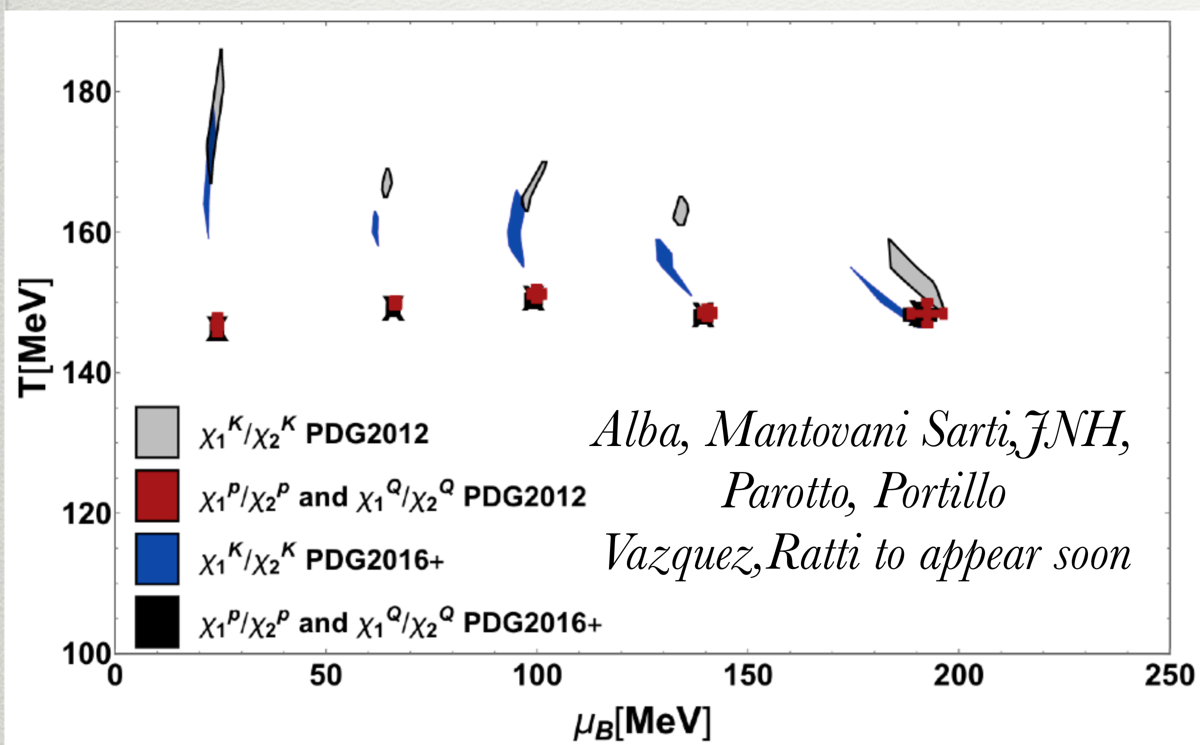


We consider fluctuations at LHC energies

$\mu_B = 0$

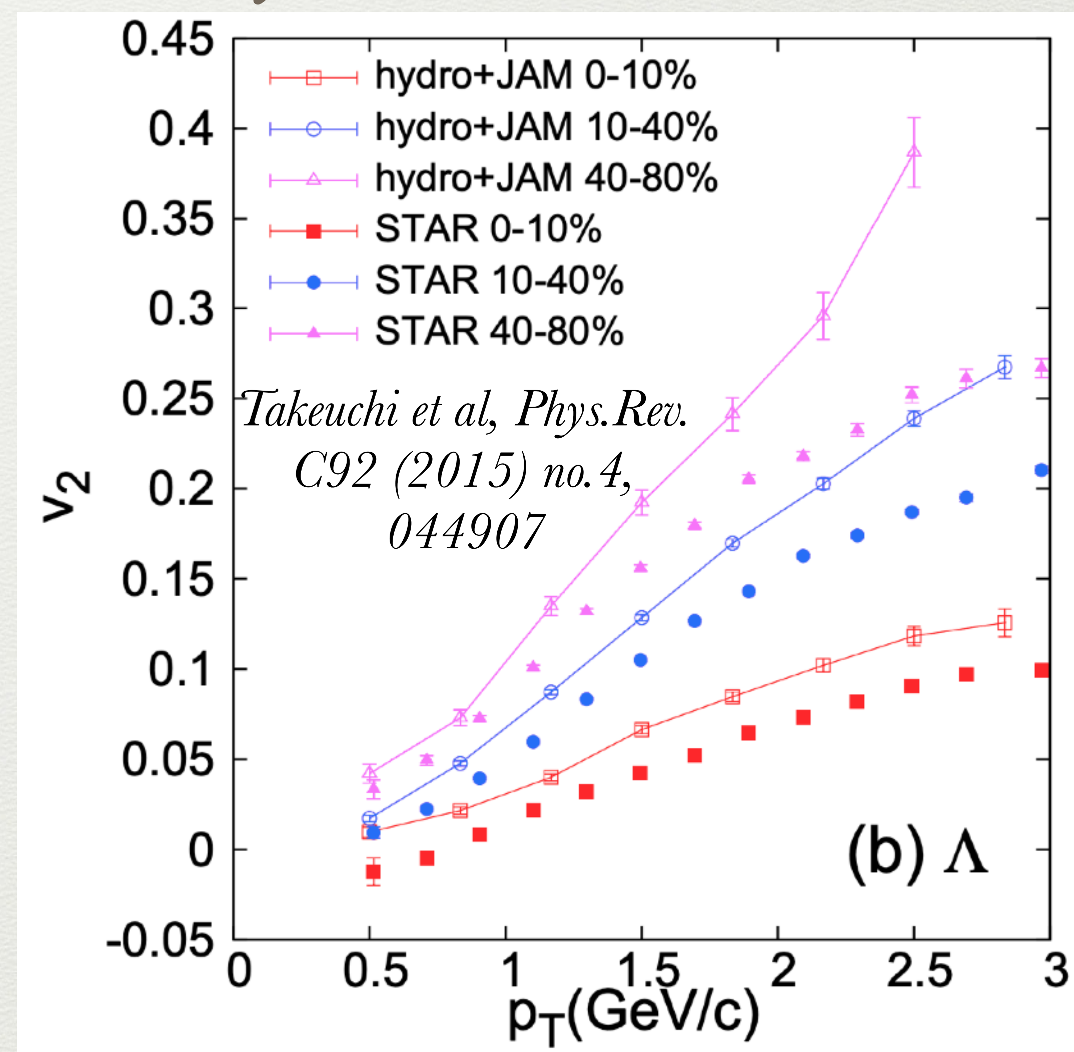
Why do this at $\mu_B = 0$?

Indications of $T_{FO}^{str} > T_{FO}^{light}$



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

$\frac{dN}{dy}$ vs. v_2 for S>0



Understand S>0 in small systems

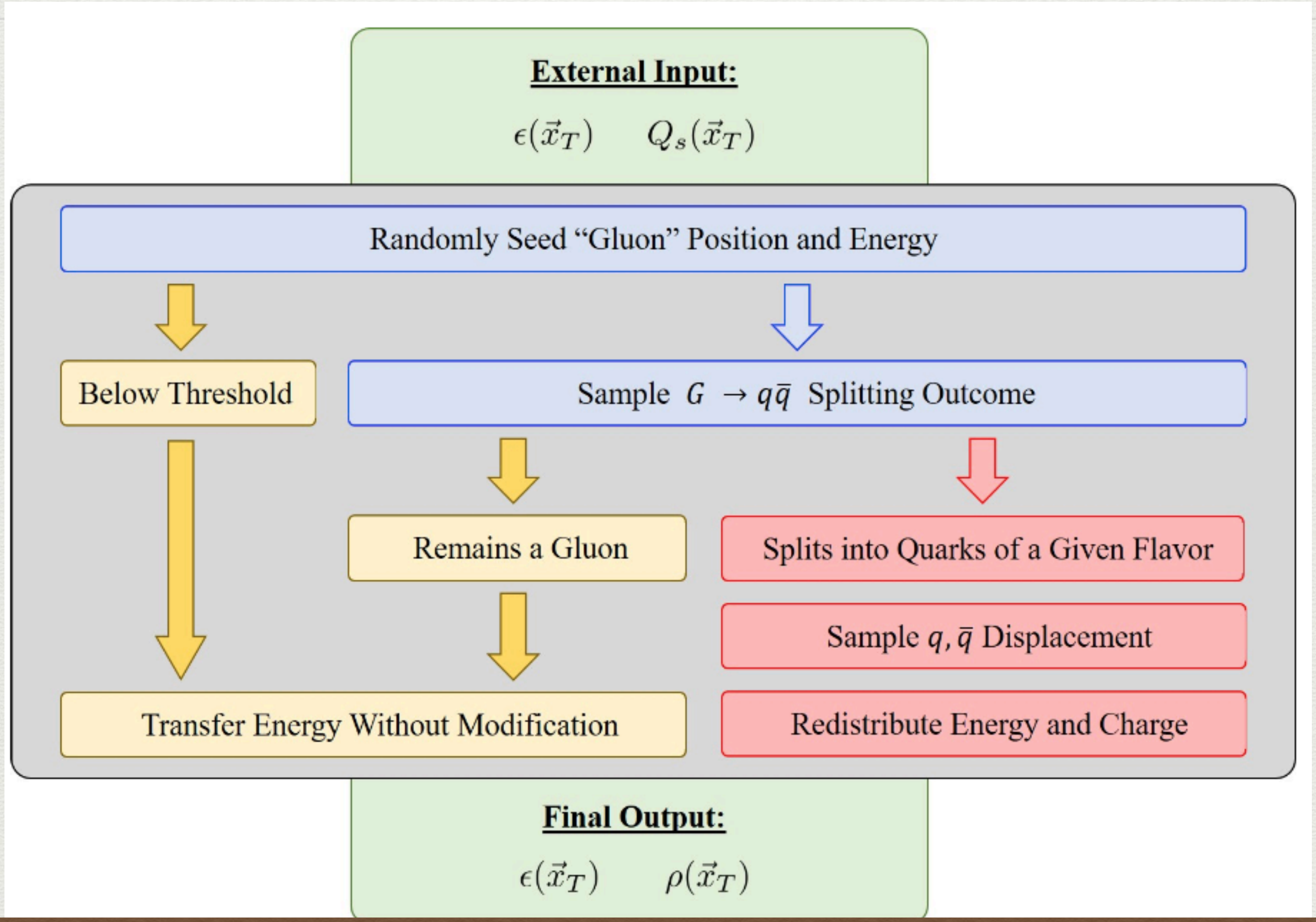
[ALICE] Nature Physics 13 (2017) 535-539

Different core/corona ratio in small systems

Kanakubo et al, arXiv:1910.10556

Study κ_{BSQ} with high statistics

General algorithm



Despite complicated cross-sections, quark mass effects appear to play the largest role

Strangeness eccentricities

Quantifying the initial state is non-trivial here.

Bulk eccentricity:

r in respect to center of mass

$$\varepsilon_2 \equiv \left| \frac{\int d^2r \, (\boldsymbol{r} - \boldsymbol{r}_{CMS})^2 \, \epsilon(\boldsymbol{r})}{\int d^2r \, |\boldsymbol{r} - \boldsymbol{r}_{CMS}|^2 \, \epsilon(\boldsymbol{r})} \right|$$

$$\boldsymbol{r}_{CMS} \equiv \frac{\int d^2r \, \boldsymbol{r} \, \epsilon(\boldsymbol{r})}{\int d^2r \, \epsilon(\boldsymbol{r})}$$

Charge eccentricities:

r in respect to center of *charge*

$$\varepsilon_2^{(\mathcal{X}^+)} \equiv \left| \frac{\int d^2r \left(\boldsymbol{r} - \boldsymbol{r}_{COC}^{(\mathcal{X}^+)}\right)^2 \rho^{(\mathcal{X}^+)}(\boldsymbol{r})}{\int d^2r \left|\boldsymbol{r} - \boldsymbol{r}_{COC}^{(\mathcal{X}^+)}\right|^2 \rho^{(\mathcal{X}^+)}(\boldsymbol{r})} \right|$$

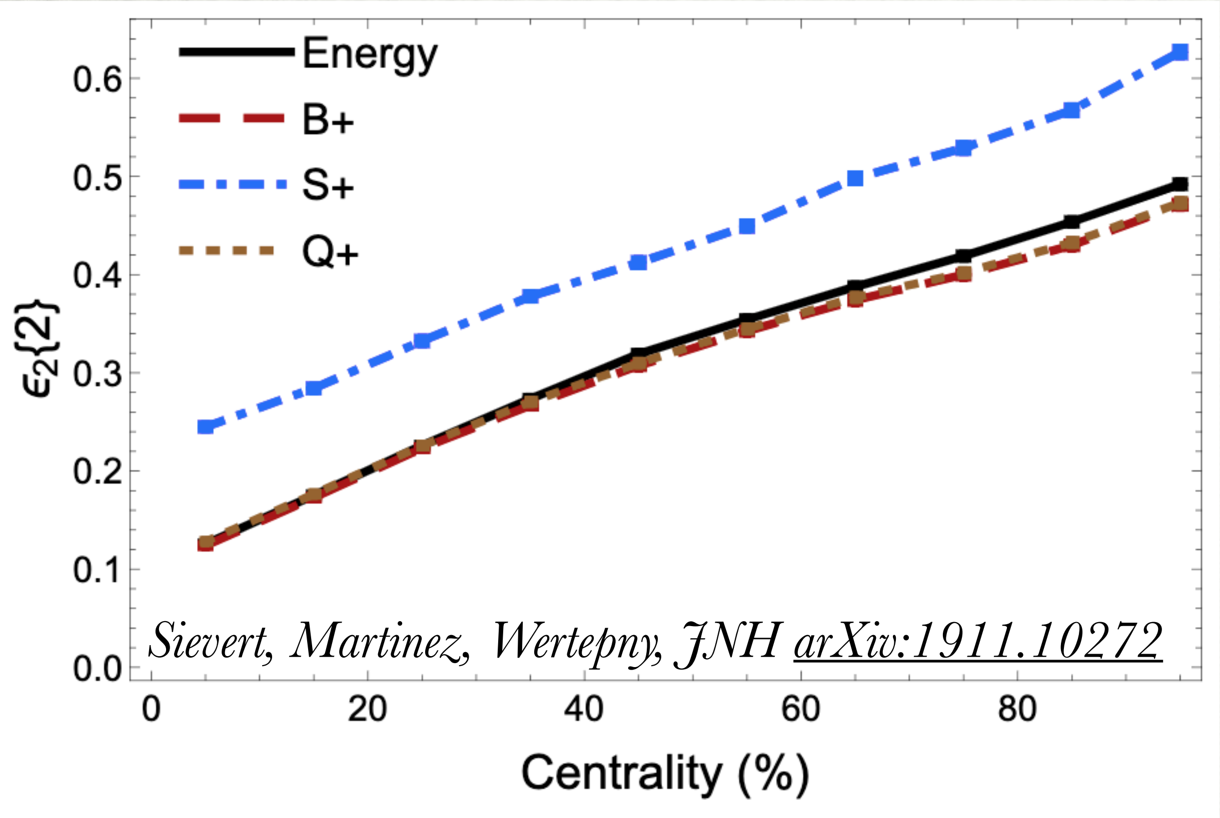
$$\varepsilon_2^{(\mathcal{X}^-)} \equiv \left| \frac{\int d^2r \left(\boldsymbol{r} - \boldsymbol{r}_{COC}^{(\mathcal{X}^-)}\right)^2 \rho^{(\mathcal{X}^-)}(\boldsymbol{r})}{\int d^2r \left|\boldsymbol{r} - \boldsymbol{r}_{COC}^{(\mathcal{X}^-)}\right|^2 \rho^{(\mathcal{X}^-)}(\boldsymbol{r})} \right|$$

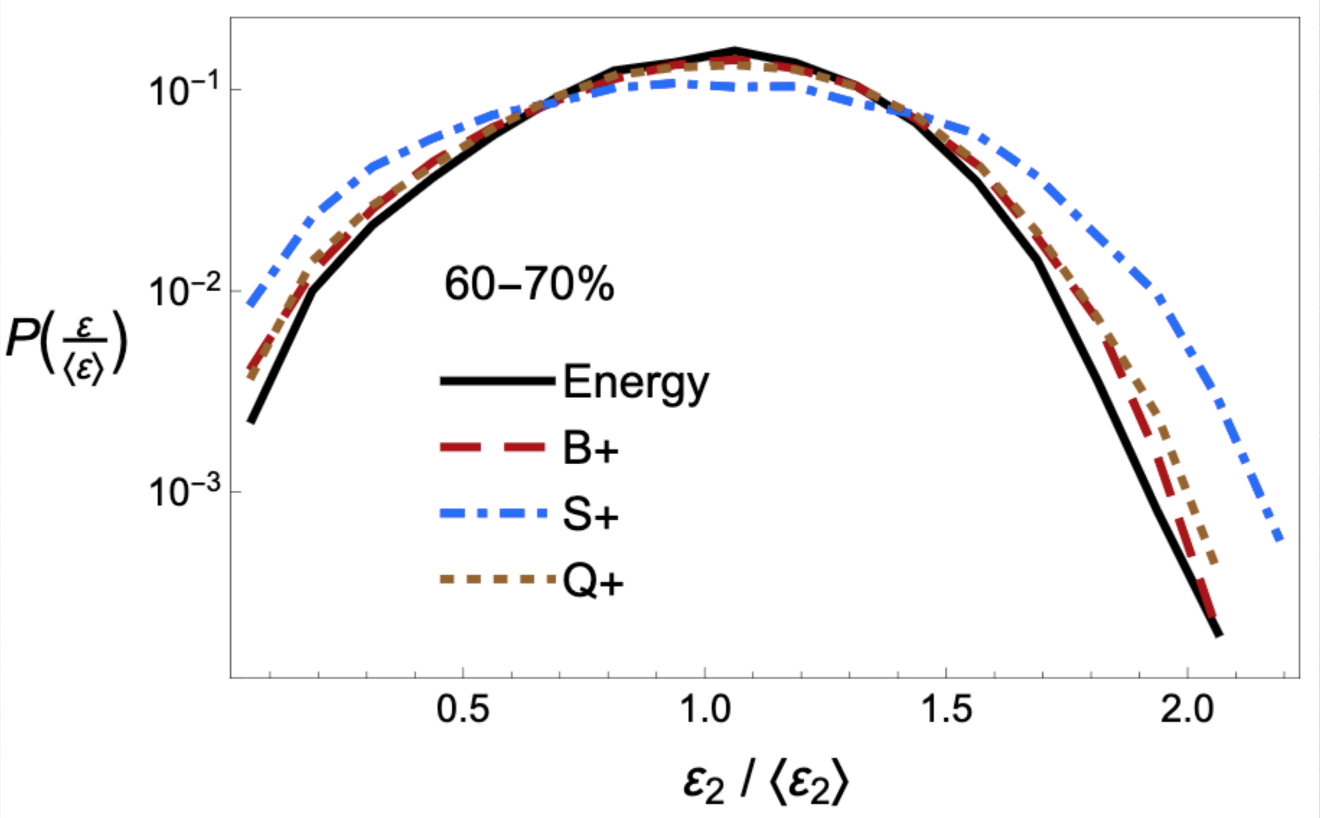
Can only consider + or -, not net because net charge can be =0!!

$$\boldsymbol{r}_{COC}^{(\mathcal{X}^\pm)} \equiv \frac{\int d^2r \, \boldsymbol{r} \, \rho^{(\mathcal{X}^\pm)}(\boldsymbol{r})}{\int d^2r \, \rho^{(\mathcal{X}^\pm)}(\boldsymbol{r})}$$

Strangeness eccentricities

Strangeness doesn't follow the energy density eccentricities



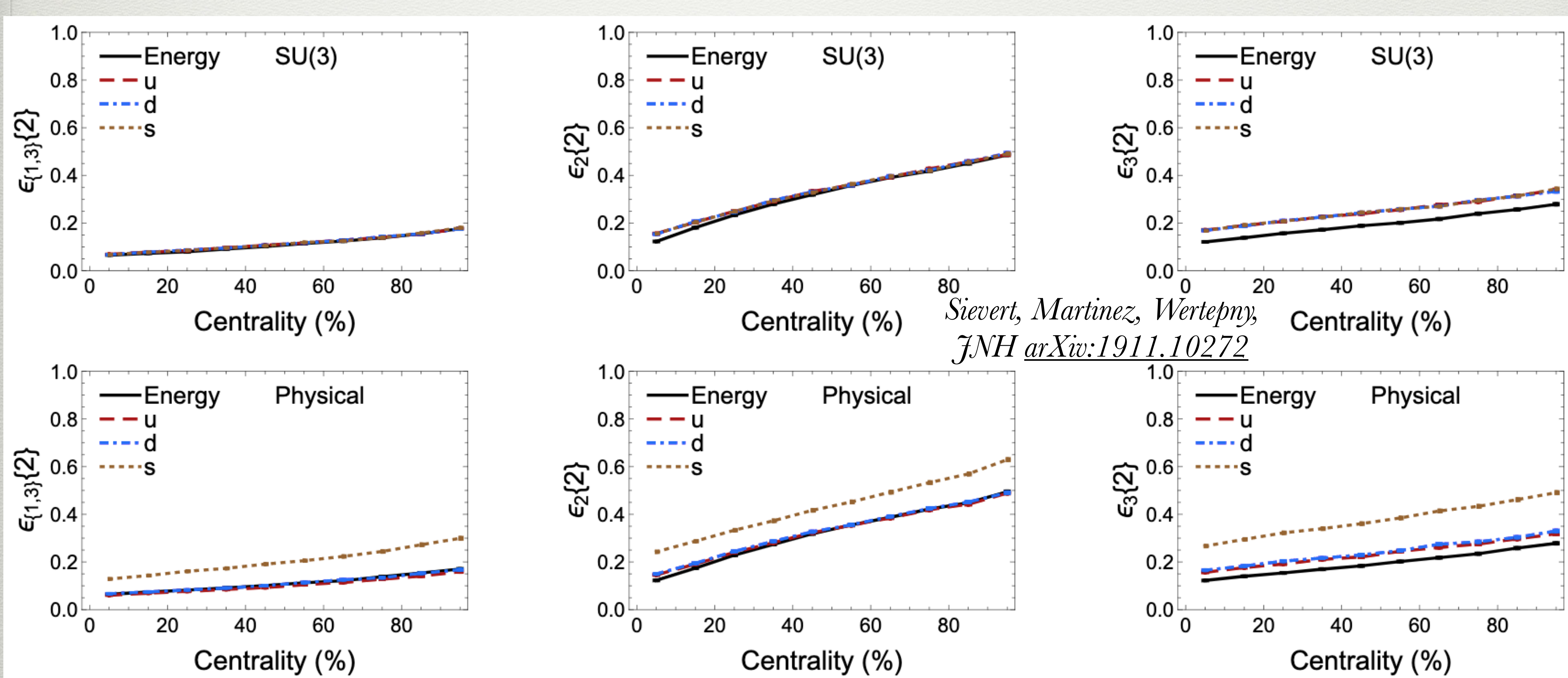


Using physical quark masses, we find the strangeness "eccentricity" is much larger than the energy density eccentricities.

Experimentalist: so kaons have a larger v_2??
ICCING: we're not sure yet how initial $\rho_S(x, y) \rightarrow v_2^K$

Why is it a quark mass effect?

Assume $m_u = m_d = m_s$, all eccentricities converge



Sievert, Martinez, Wertepny, JNH *arXiv:1911.10272*

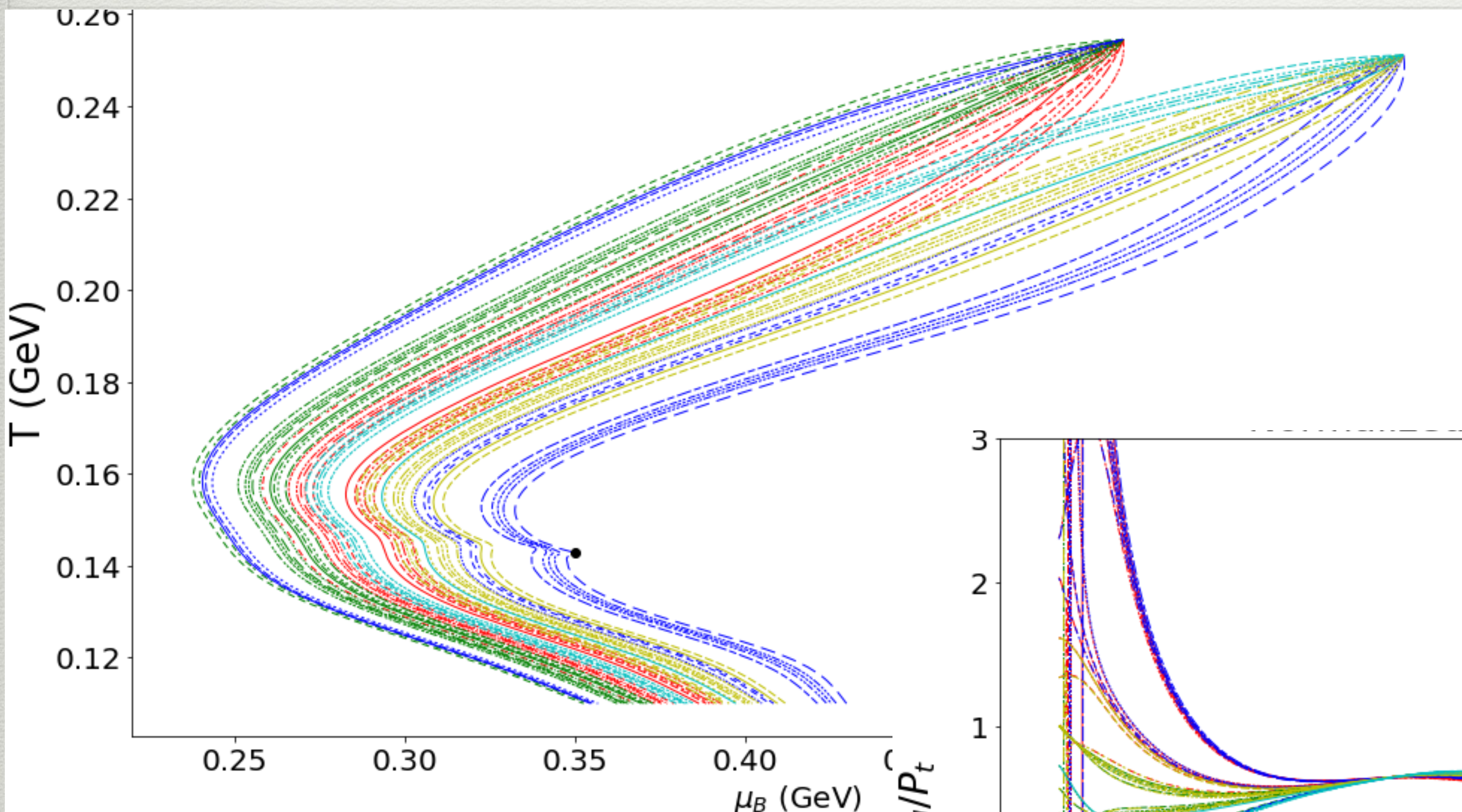
Physical masses, see eccentricity hierarchy

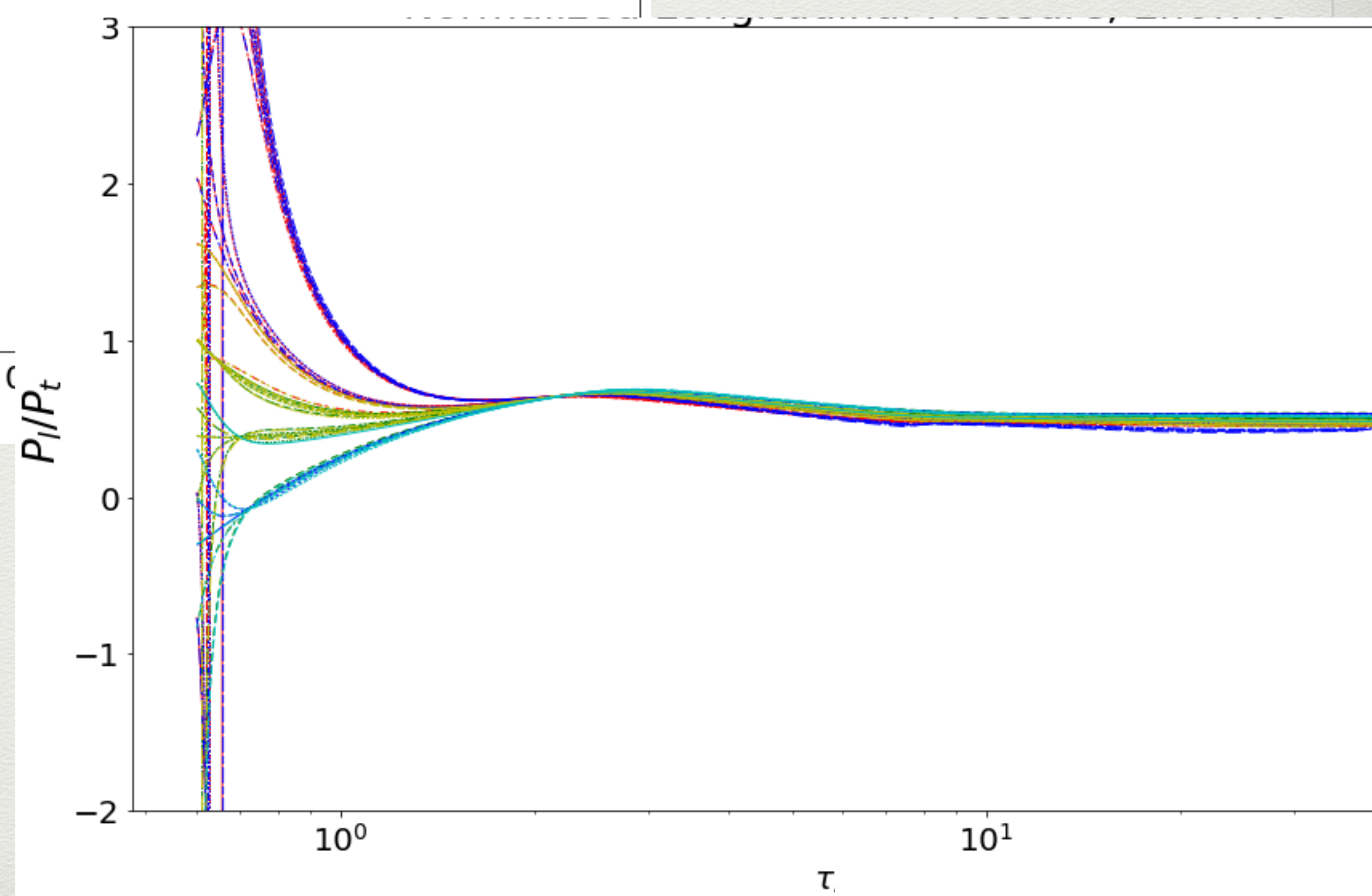
Future

- Understanding attractors in full BSQ hydrodynamics
  - Need at least 1+1D for BSQ diffusion transport coefficients+cross terms (see J. Fotakis QM19)
  - Incorporate critical fluctuations effects
- Kaon=1 light + 1 strange, how does ρ_S contribute to the final state? What about $\Omega(sss)$? Initial state versus $s\bar{s}$ production in the QGP?
- System size dependence? (see Y. Ikeshita QM19)

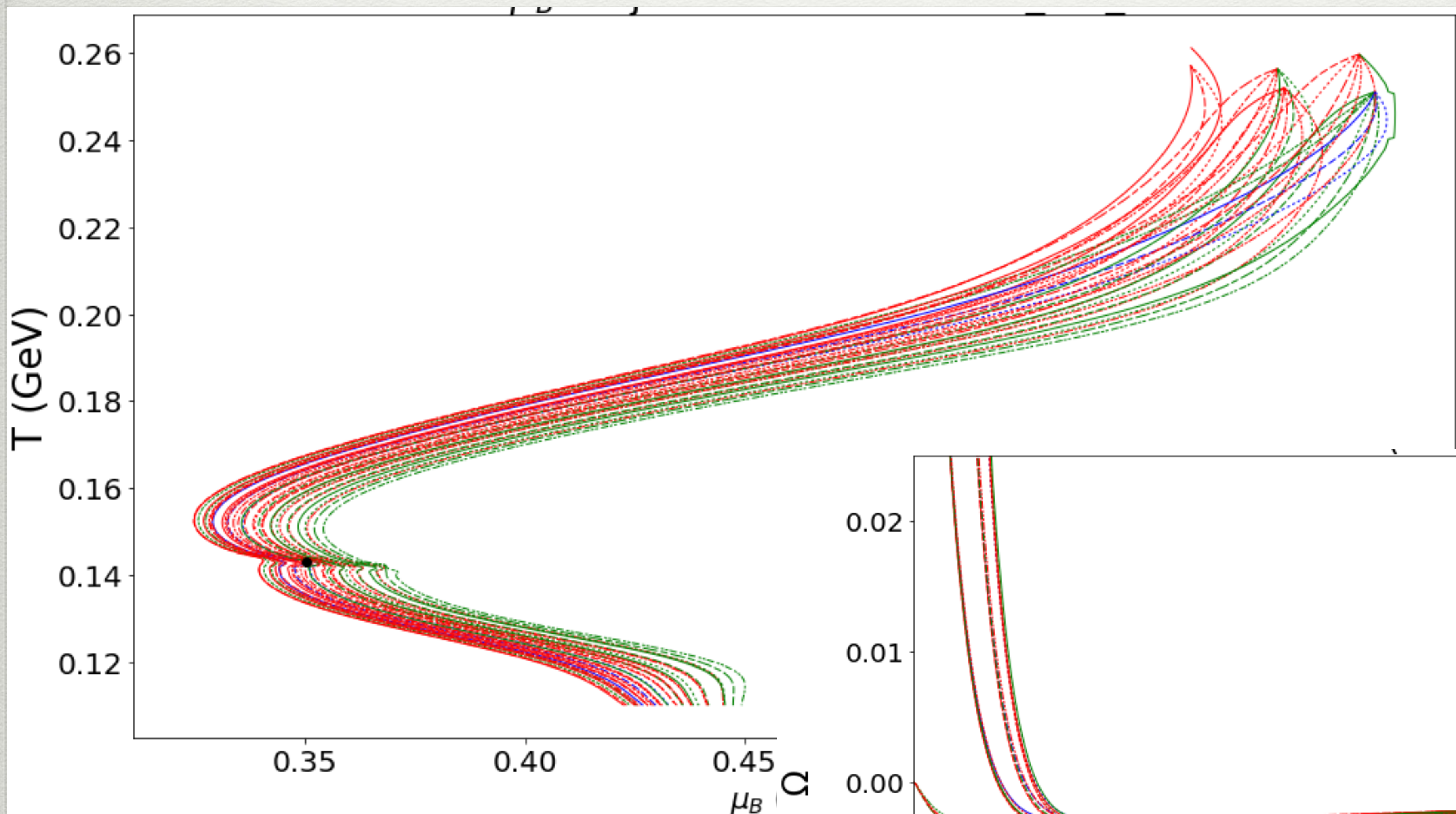
Backup

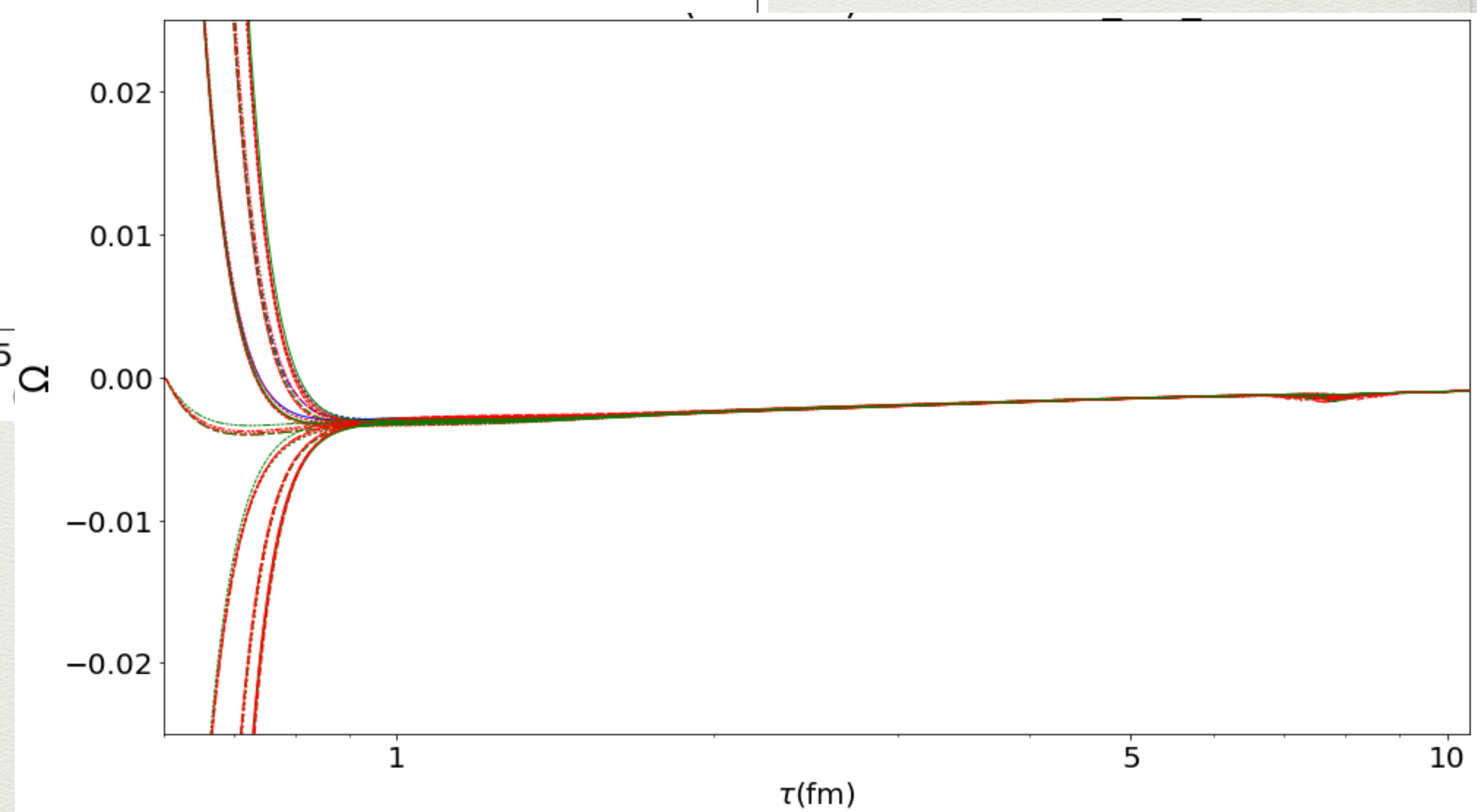
Beam Energy Scan



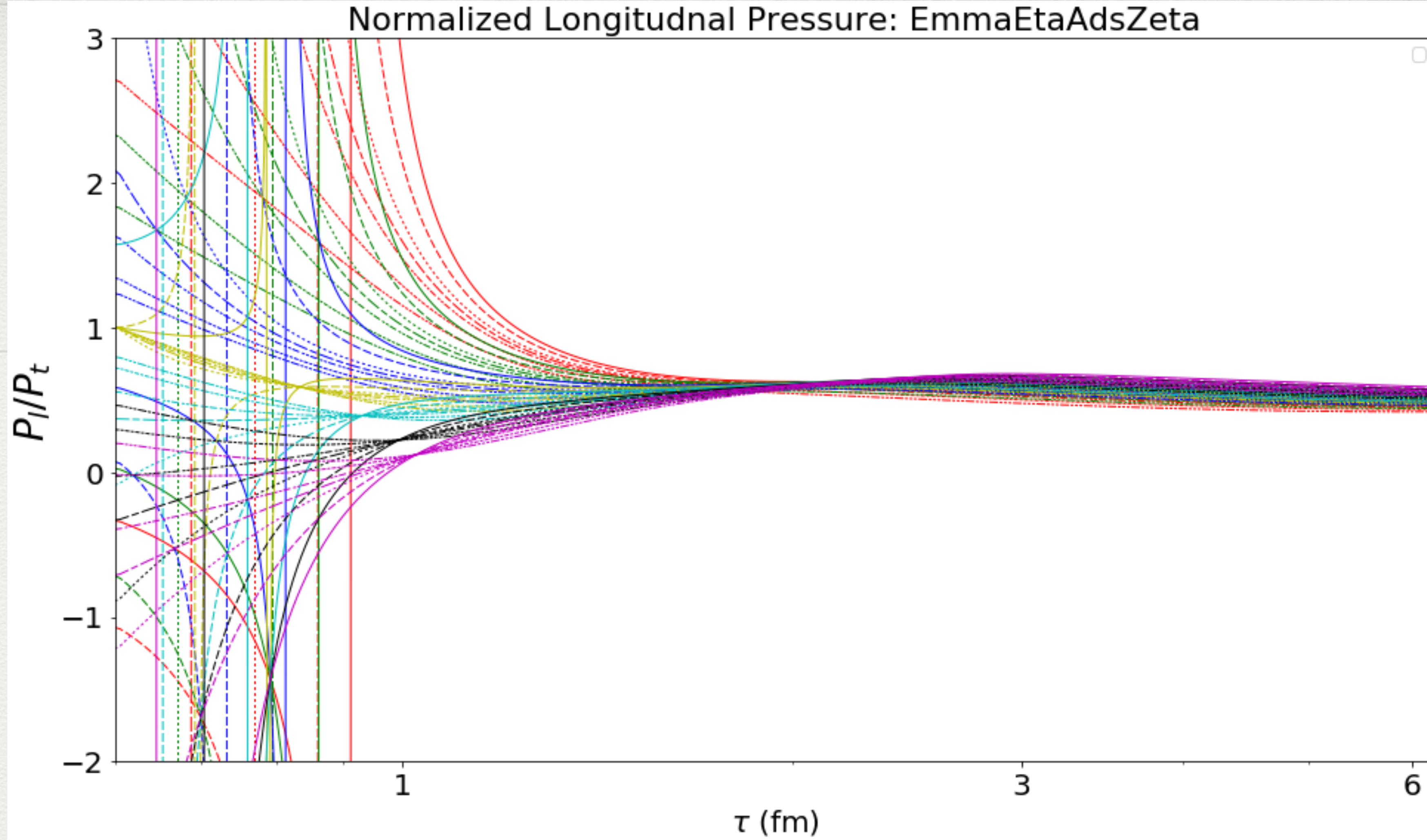


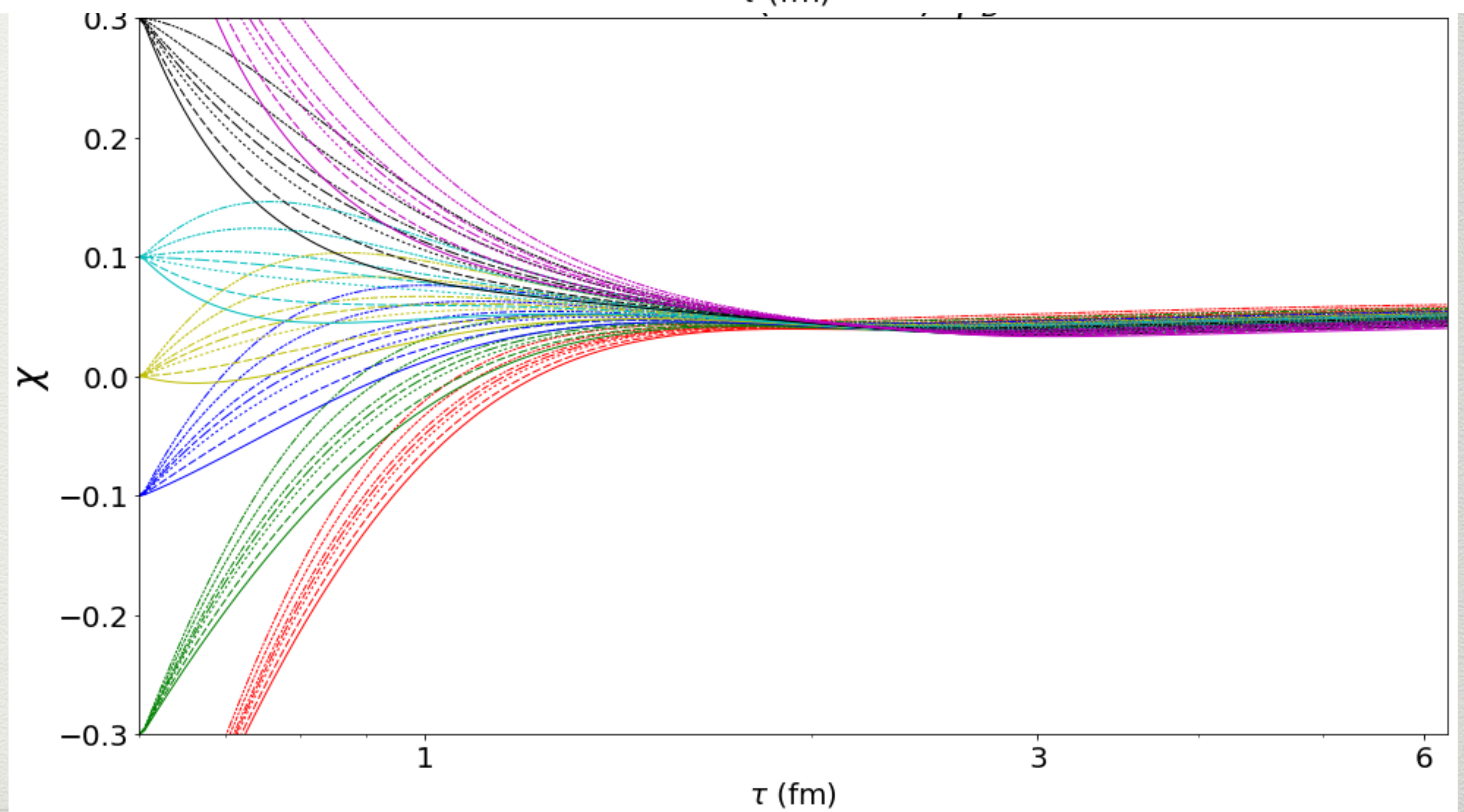
Passage through the CP





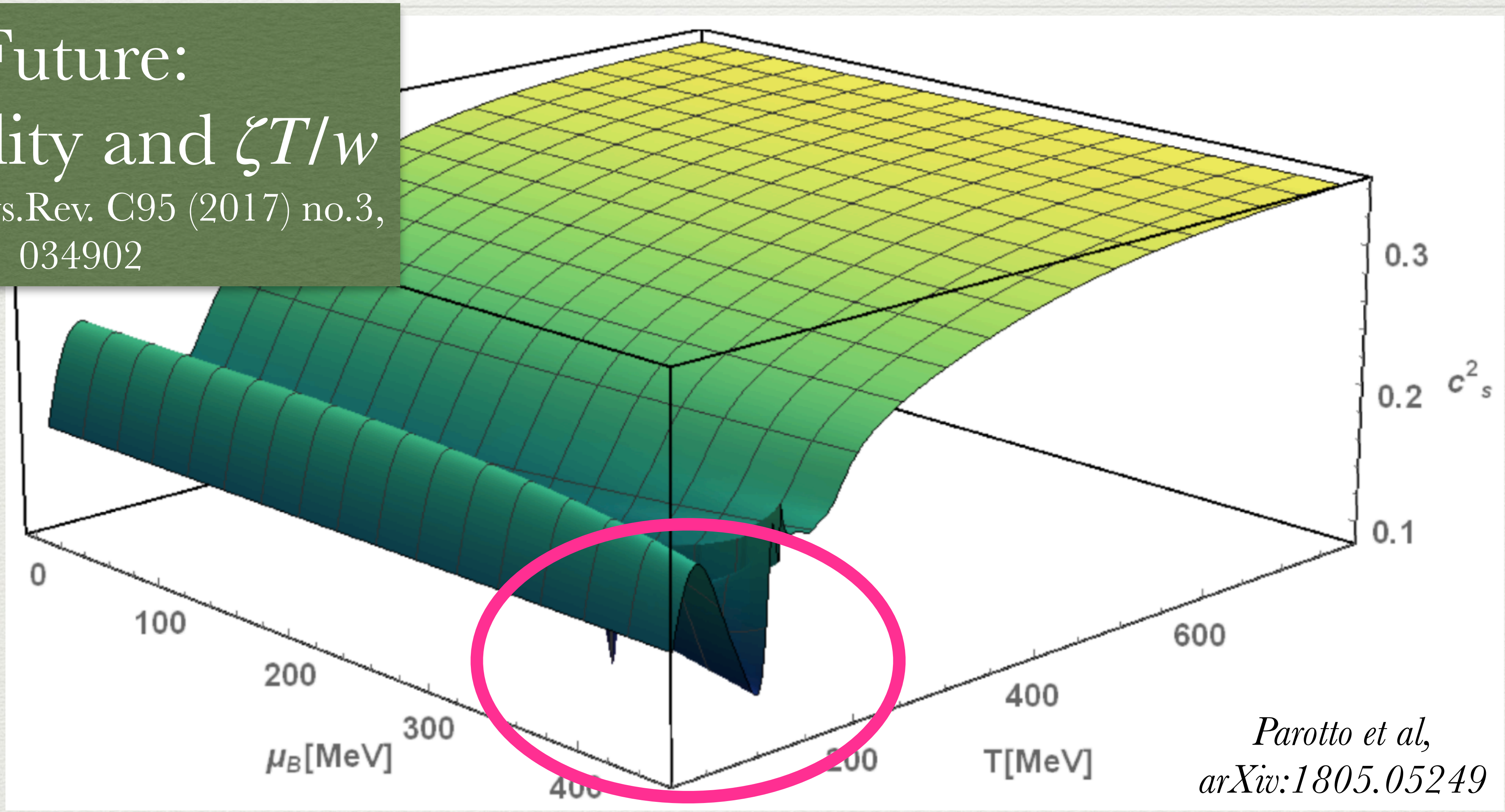
$$\left(\frac{\zeta}{s}\right)_{max} \sim 0.05$$





Realistic Equation of State

Future:
Criticality and $\zeta T/w$
Yin et al, Phys.Rev. C95 (2017) no.3, 034902



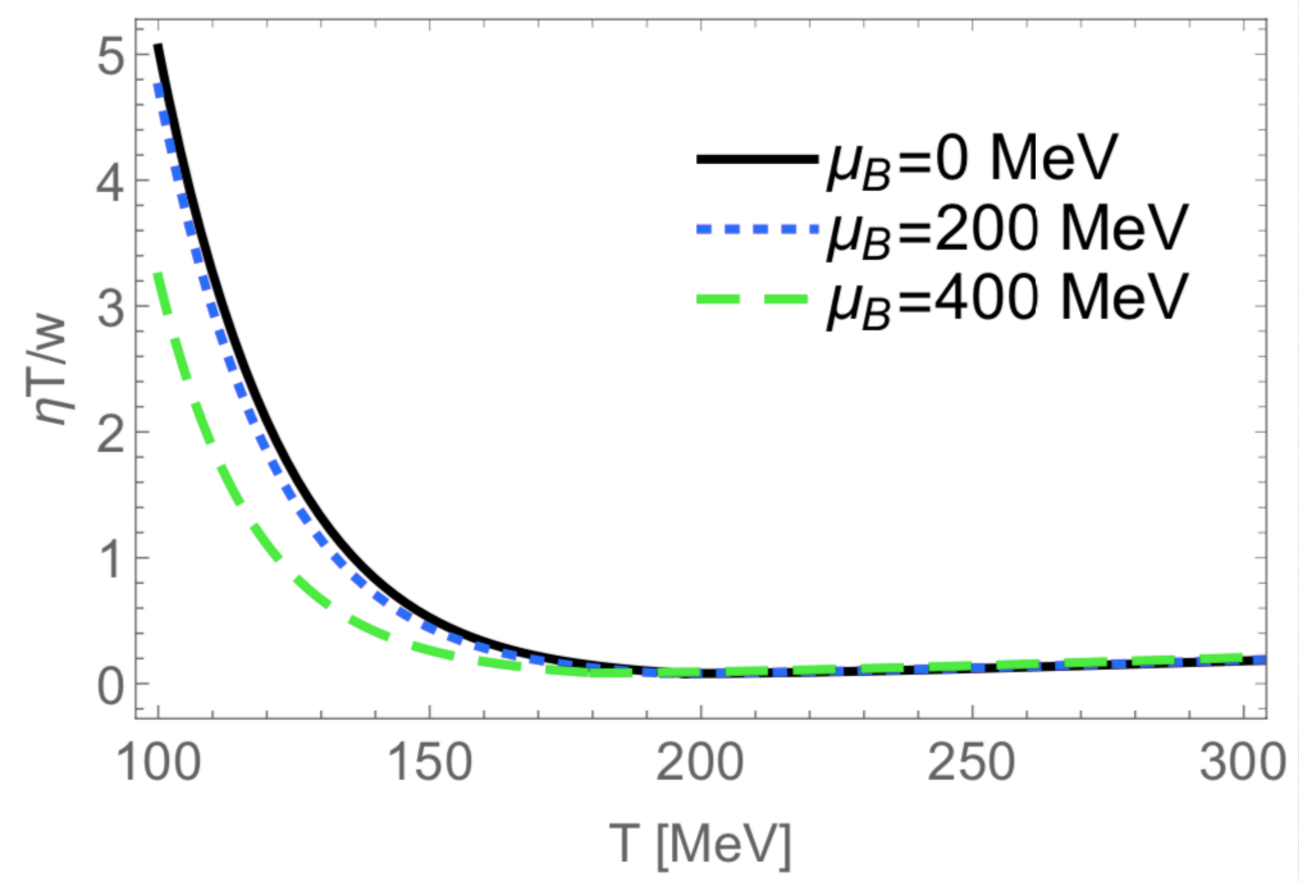
Parotto et al, arXiv:1805.05249

Lattice QCD up to 4th order+3D Ising model

Bulk viscosity depends on c_s^2 since we use $\dfrac{\zeta T}{w} = \dfrac{1}{8\pi}\left(\dfrac{1}{3} - c_s^2\right)$

$\eta T/w(T, \mu_B, \mu_S, \mu_Q)$

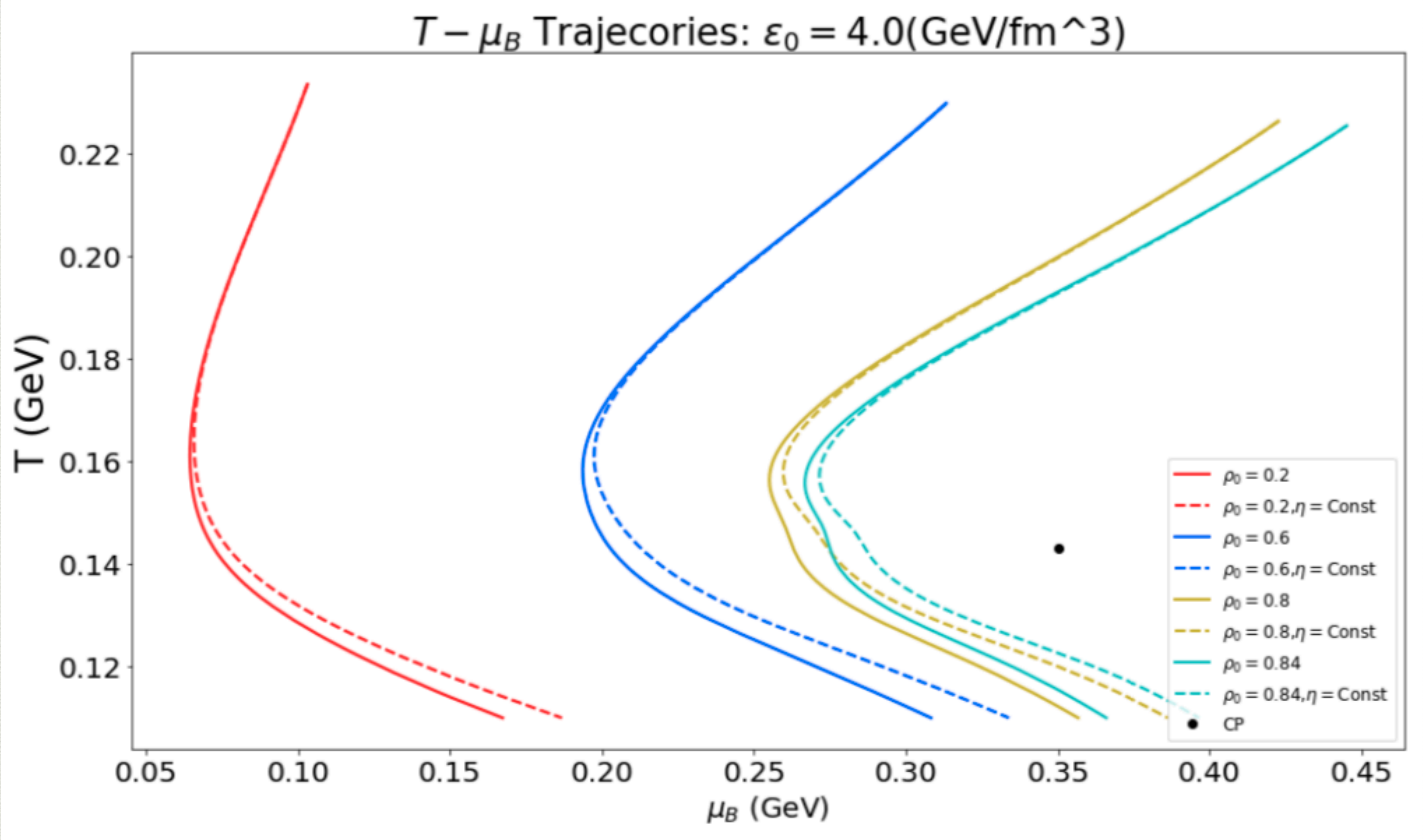
Work in preparation with Emma McLaughlin (REU student)



- Hadron resonance gas $T < T_{\eta T/w\ min}$
- Switching temperature $T_{\eta T/w\ min}$ follows inflection point of the chiral condensate from Lattice QCD *Bazavov et al, PLB795, pp. 15–21, 2019*
- Parameterized QCD-motived η/s from *Christiansen et al, PRL 115, no. 11, p. 112002, 2015*

Effect of $\eta T/w = const$ vs. $\eta T/w\left\{T, \mu_B\right\}$

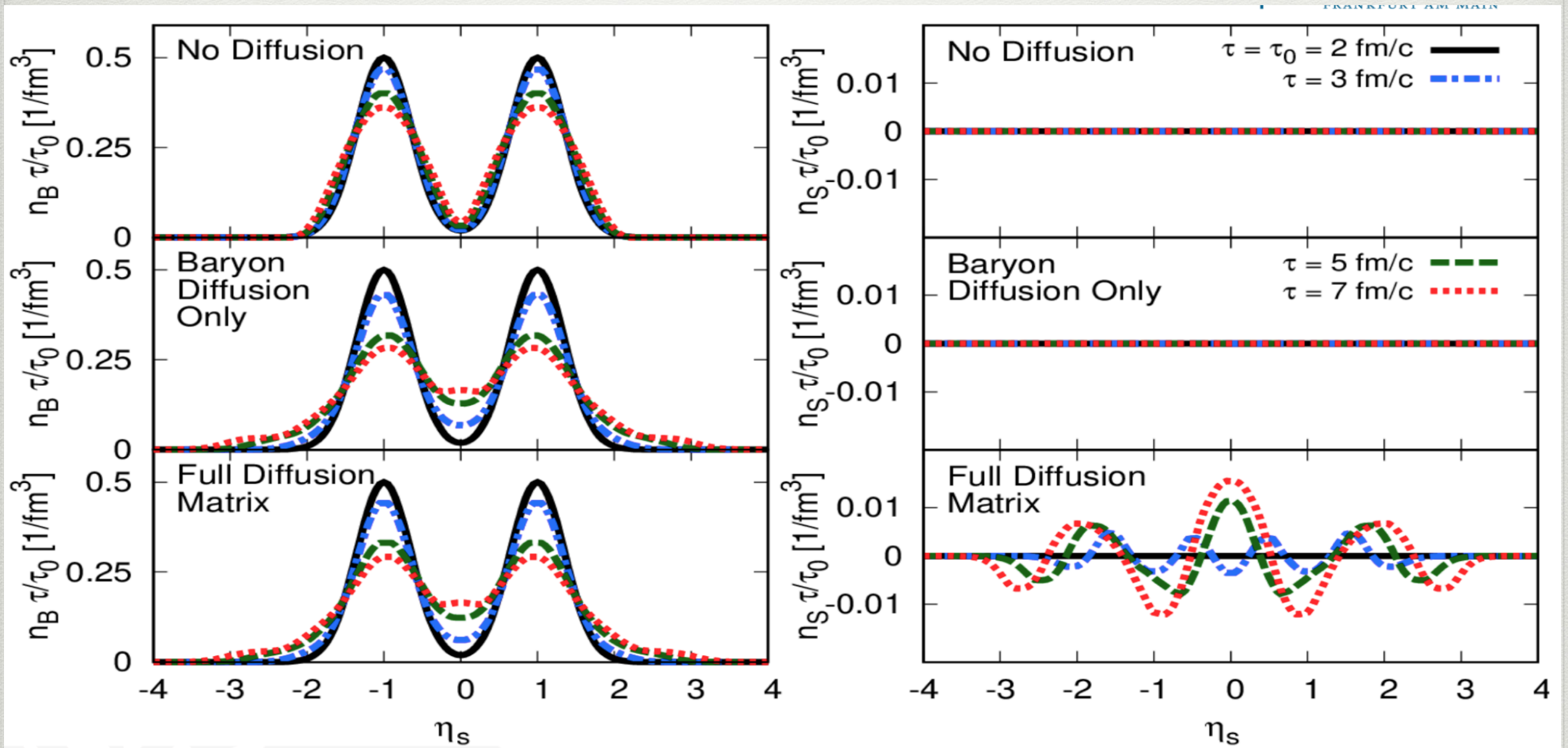
First, assume initial condition is only e_0, ρ_0



$\eta T/w = const$ pushes to larger μ_B

Full BSQ diffusion

$$\begin{pmatrix} j_B^\mu \\ j_Q^\mu \\ j_S^\mu \end{pmatrix} = \begin{pmatrix} \kappa_{BB} & \kappa_{BQ} & \kappa_{BS} \\ \kappa_{QB} & \kappa_{QQ} & \kappa_{QS} \\ \kappa_{SB} & \kappa_{SQ} & \kappa_{SS} \end{pmatrix} \cdot \begin{pmatrix} \nabla^\mu \alpha_B \\ \nabla^\mu \alpha_Q \\ \nabla^\mu \alpha_S \end{pmatrix}$$



J. Fotakis QM19