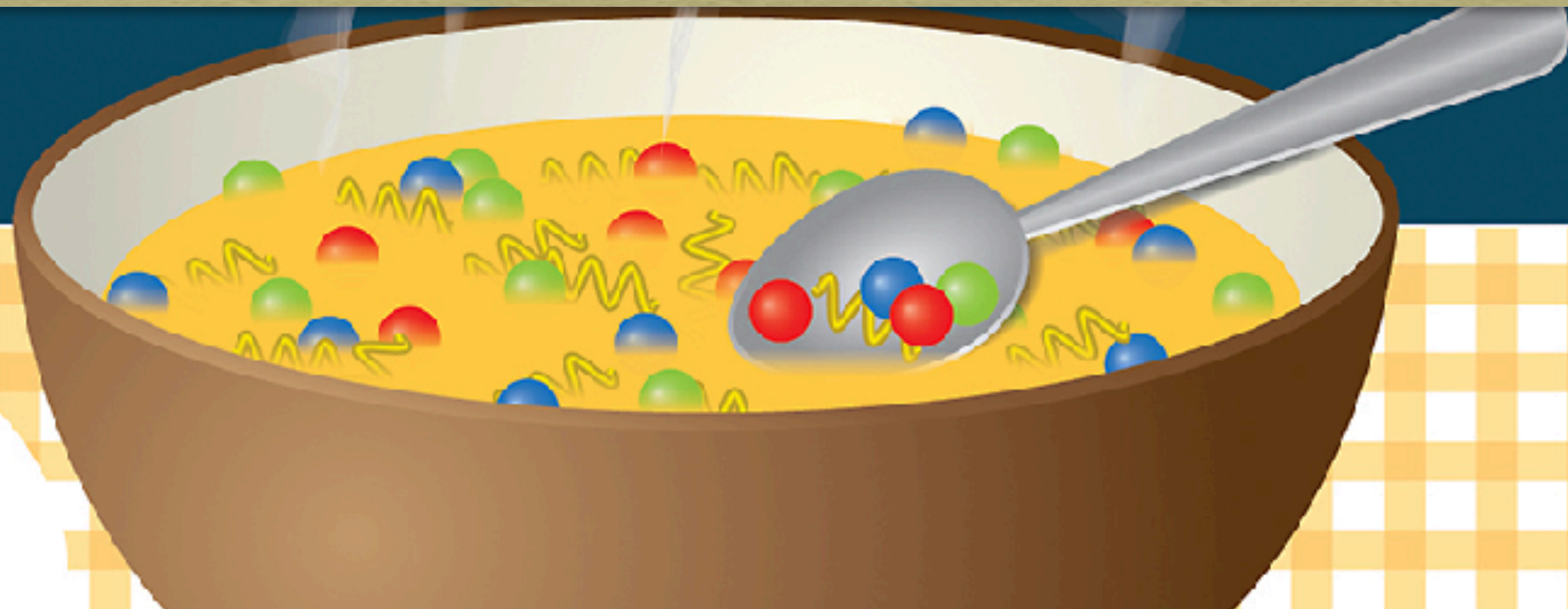
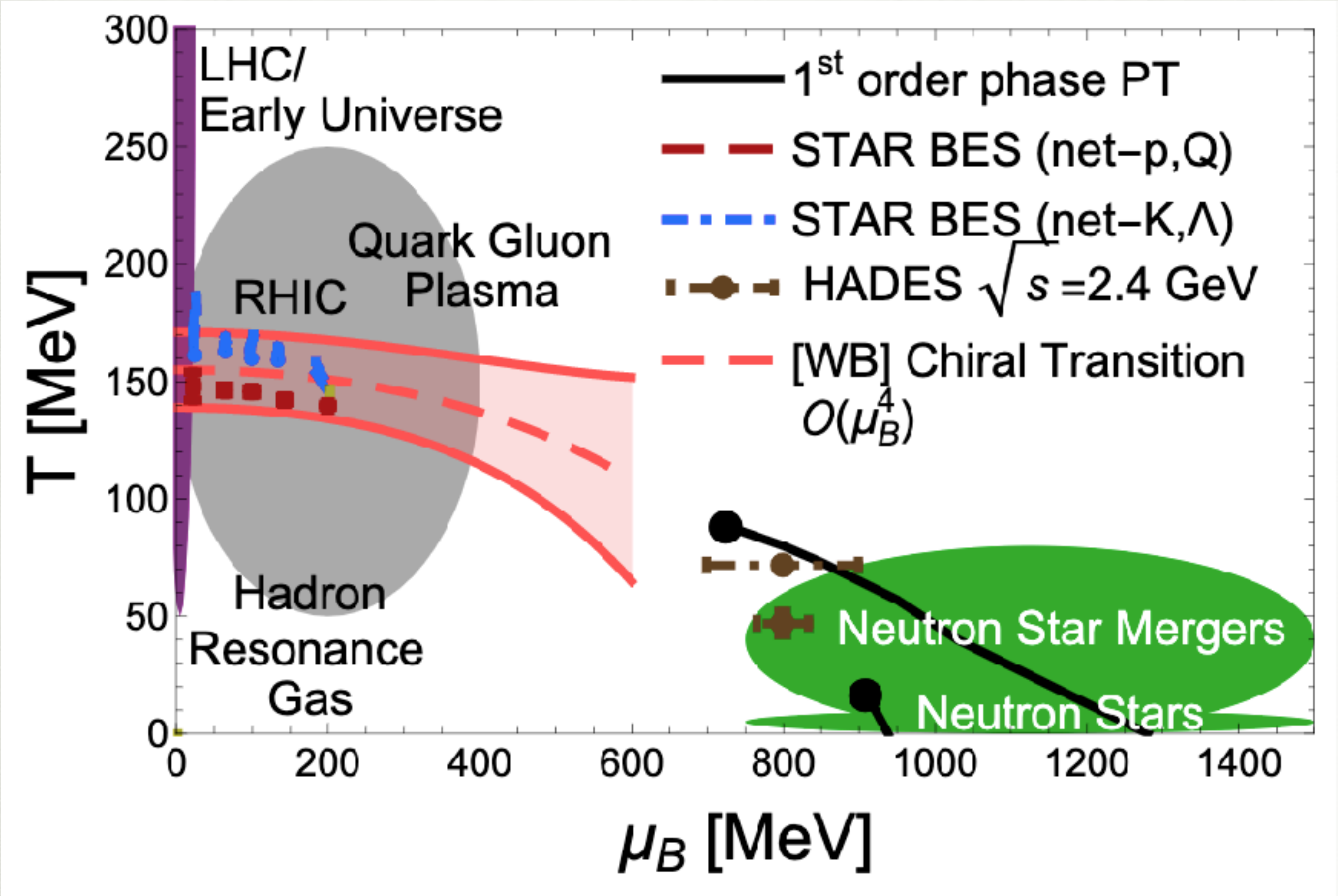
Illinois Center for Advanced Studies of the Universe

Hydrodynamics, QGP, and the QCD phase diagram



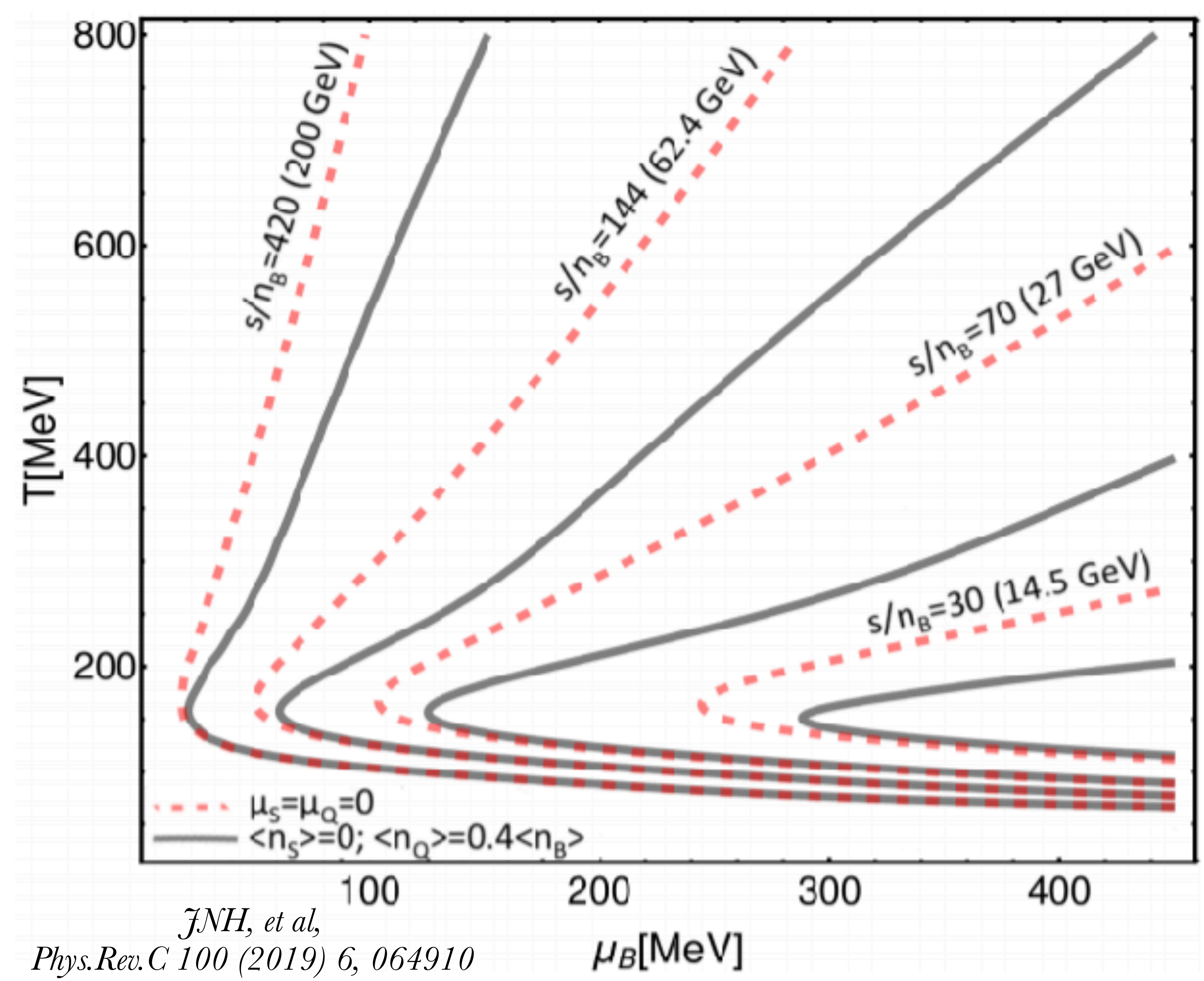
Jacquelyn Noronha-Hostler
University of Illinois Urbana-Champaign

RHIC-BES on-line seminar series



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*

Ideal hydrodynamics: Isentrope trajectories



JNH, et al, Phys.Rev.C 100 (2019) 6, 064910

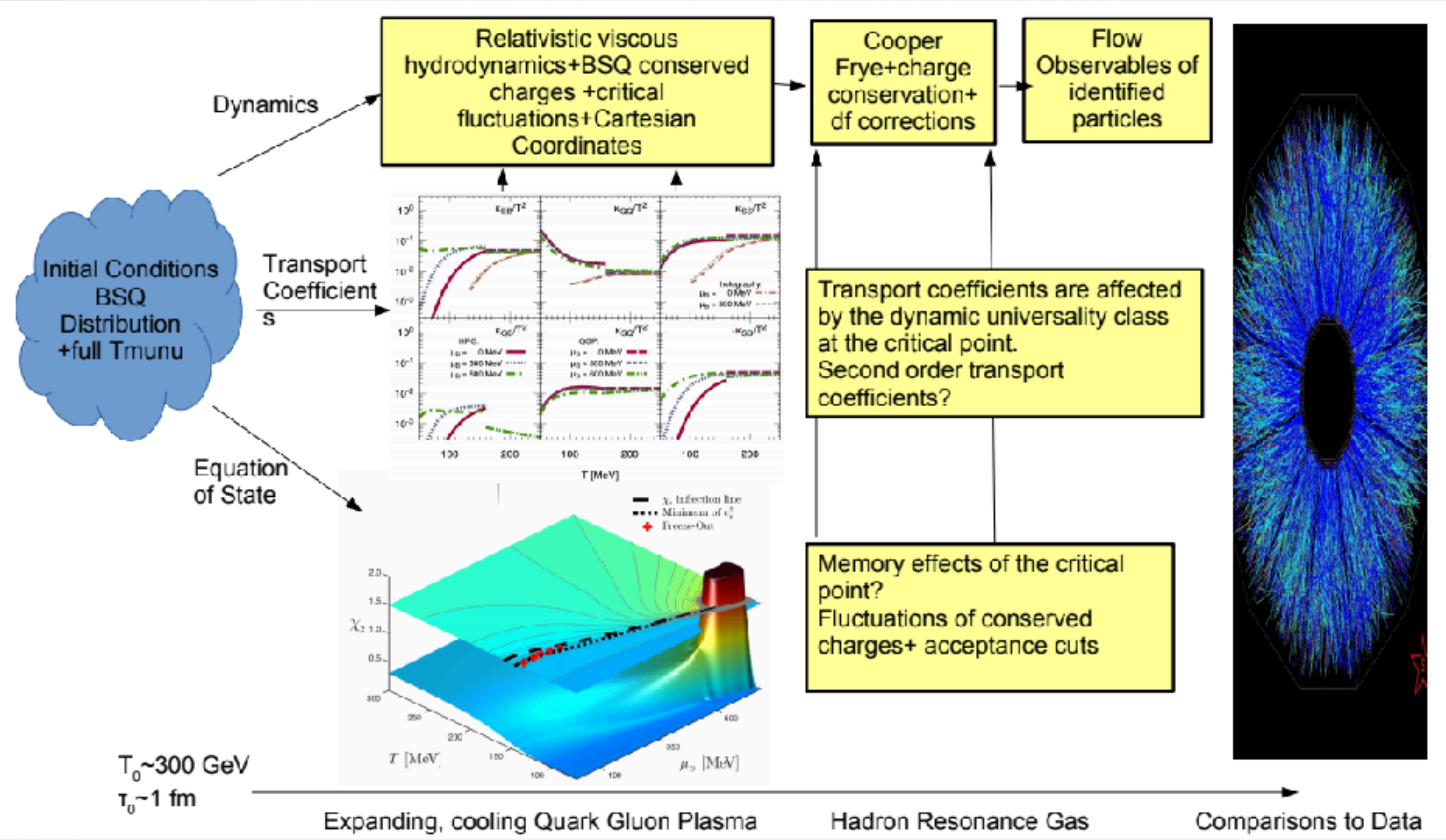
Ideal hydro= no entropy production

$S/N_B = const$

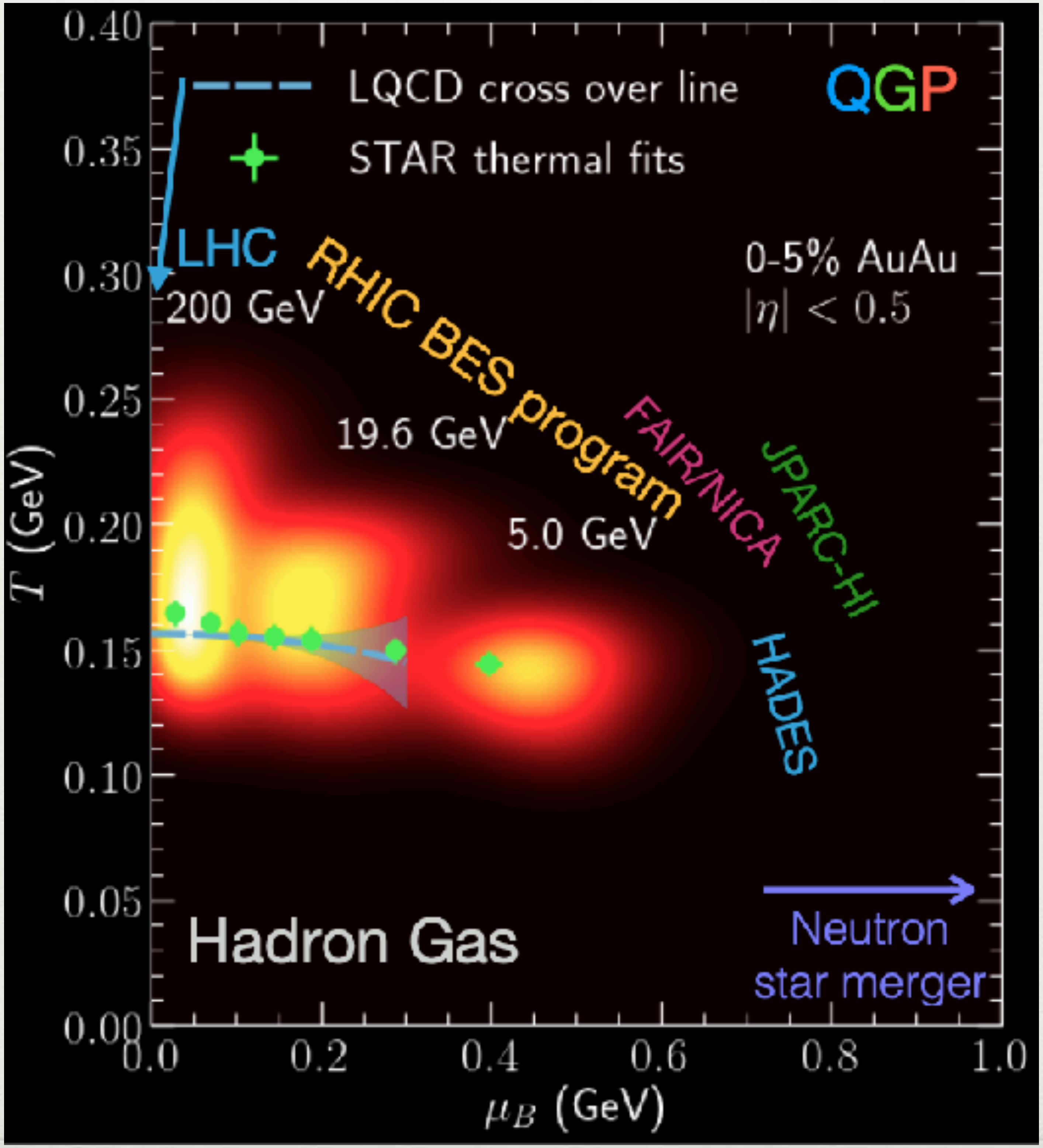
How does out-of-equilibrium effects (entropy production) influence the trajectories?

Need relativistic viscous hydrodynamics + 3 conserved charges (BSQ)

Review: Dexheimer, Noronha, JNH, Ratti, Yunes, *J.Phys.G* 48 (2021) 7, 073001 BEST: 2108.13867 [nucl-th]



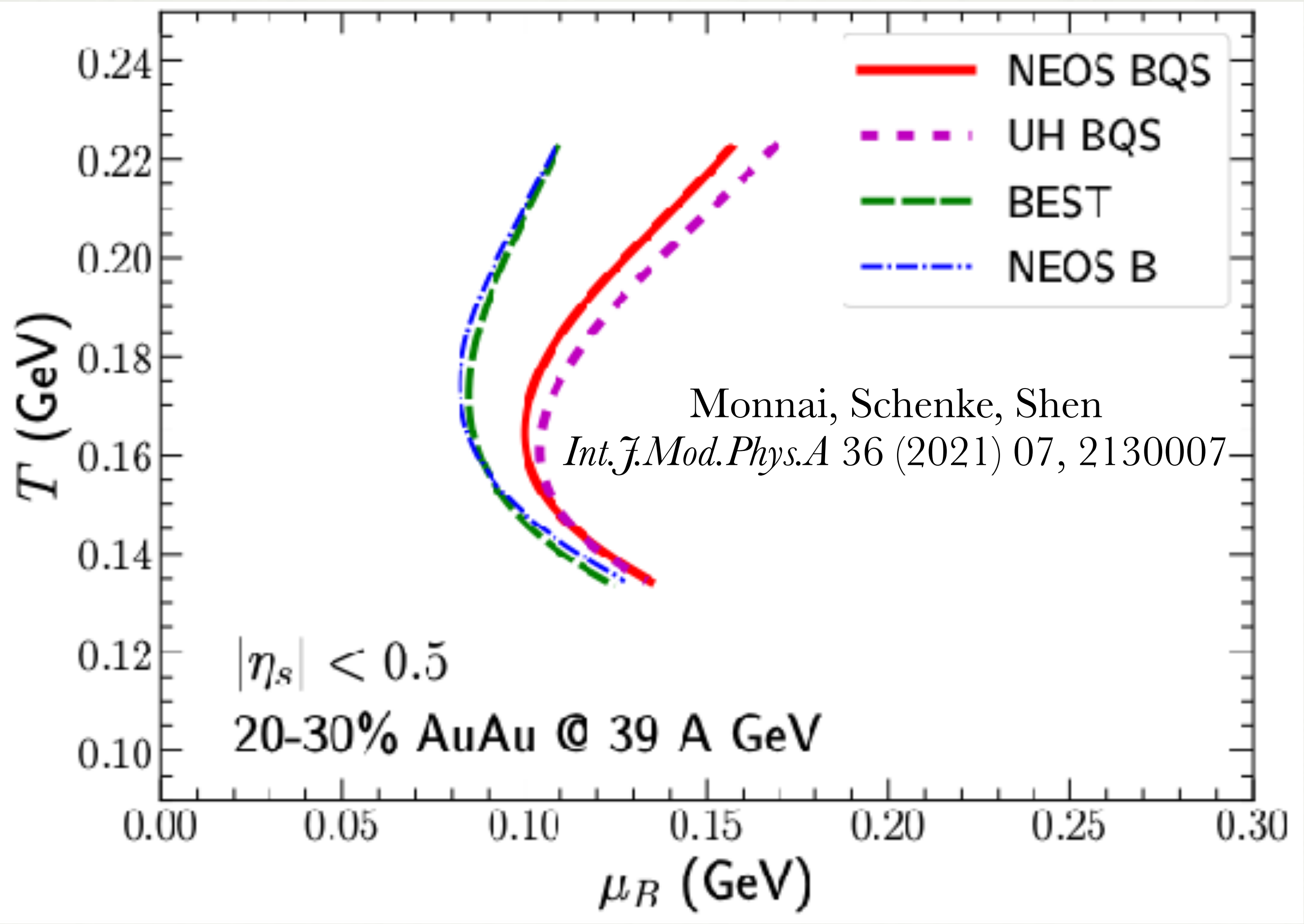
Hydrodynamics is a field, don't just probe one trajectory in (T, μ_B)



Courtesy Chun Shen

Averaged trajectories vs. EOS

Differences between only baryon conservation vs. BSQ influence the trajectories through the QCD phase diagram. Shown with $\eta/s = 0.08$



J. Noronha-Hostler

0+1D Hydrodynamics+baryon current

Dore, et al, *Phys.Rev.D* 102 (2020) 7, 074017

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

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

Baryon density: $\rho_B = \frac{\rho_0}{\tau}$

Shear Viscosity

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

Israel-Stewart: $\tau_\pi \dot{\pi}_\eta^\eta + \pi_\eta^\eta = \frac{1}{\tau}\left[\frac{4\eta}{3} - \frac{\eta T \pi_\eta^\eta}{2}\left(\beta_\pi + \tau\dot{\beta}_\pi\right)\right]$

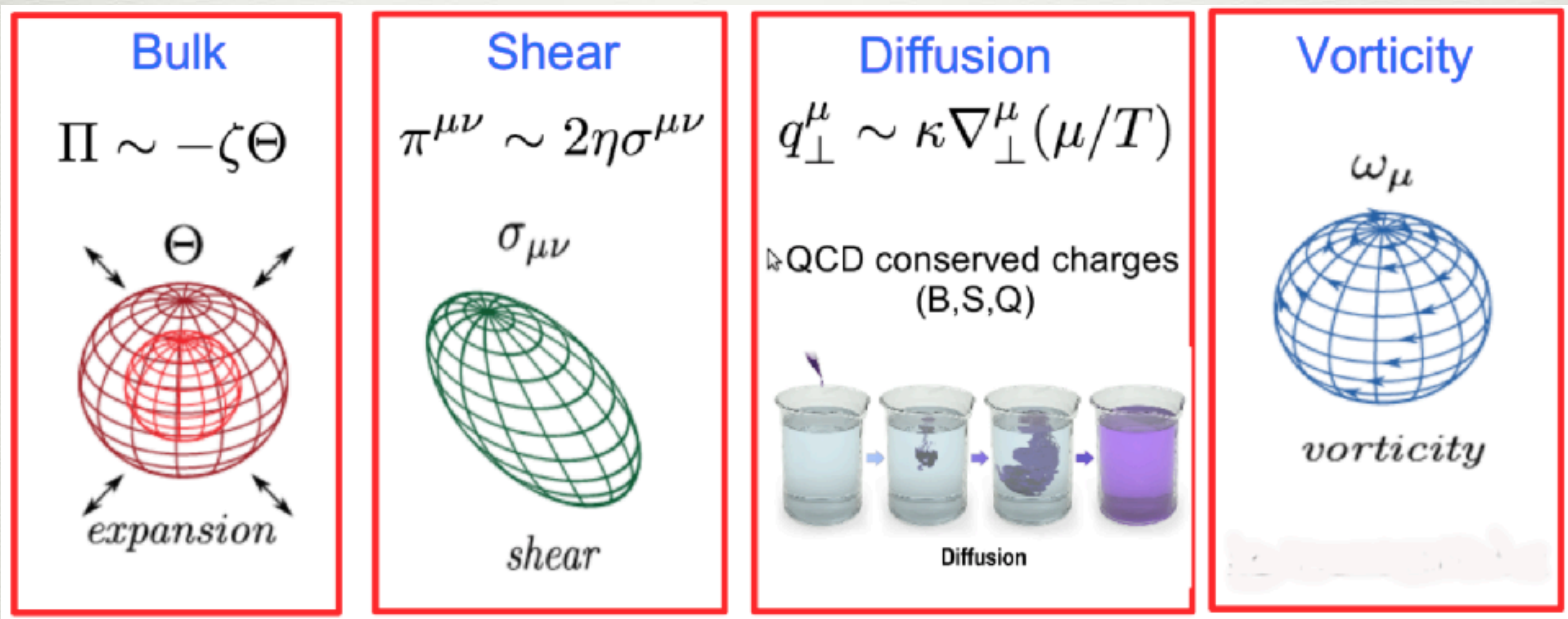
Bulk Viscosity

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

Israel-Stewart: $\tau_\Pi \dot{\Pi} + \Pi = -\frac{1}{\tau}\left[\zeta + \frac{\zeta T \Pi}{2}\left(\beta_\Pi + \tau\dot{\beta}_\Pi\right)\right]$

Transport coefficients/viscosities

Transport coefficient: Perturb the fluid from equilibrium- how quickly does it return to equilibrium?



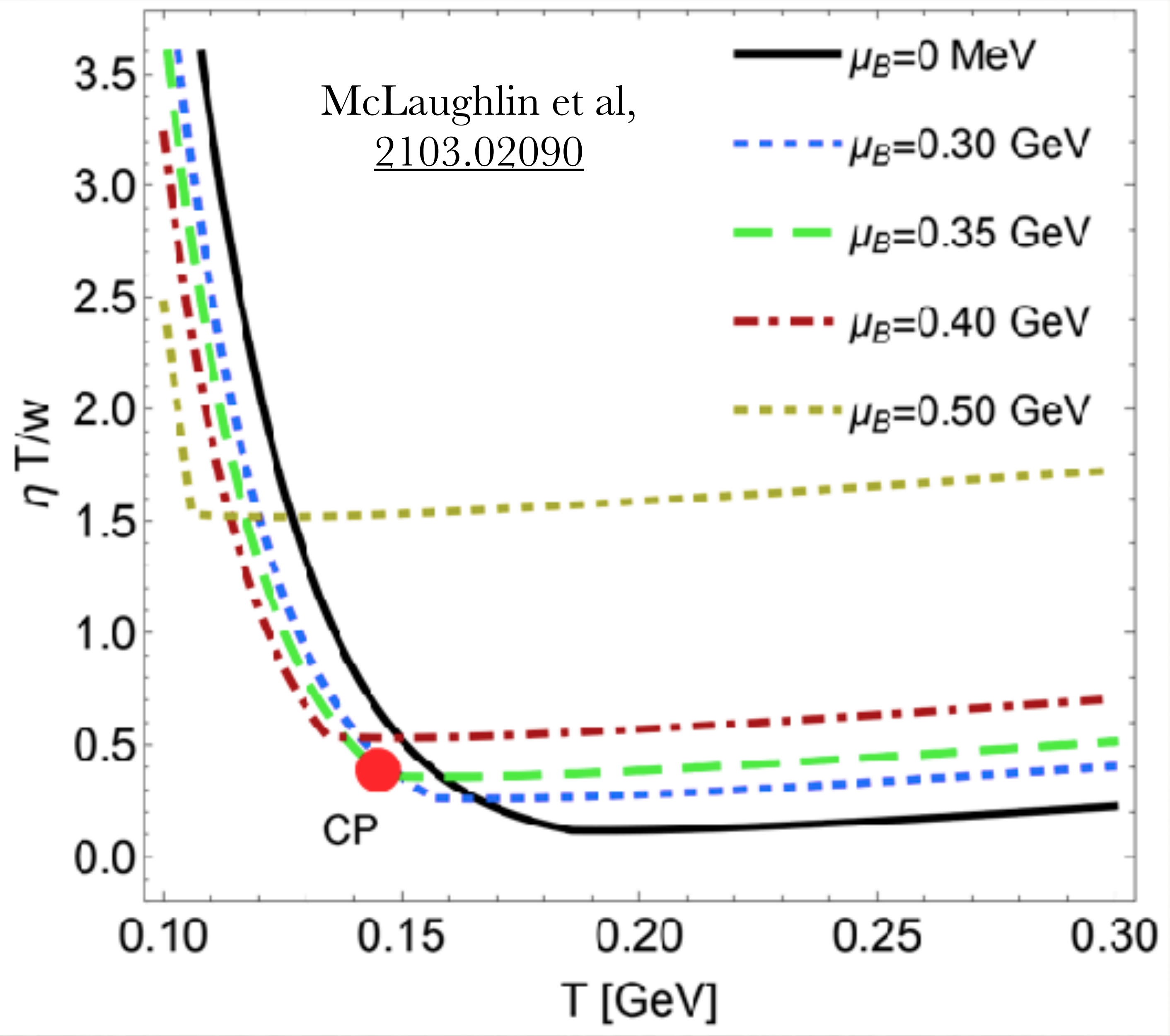
Viscosity - resistance to deformation or "thickness" of liquid

Shear viscosity at $\mu_B > 0$

Dore, et al, *Phys.Rev.D* 102 (2020) 7, 074017

Hadron resonance gas + Parameterized QGP phase

JNH, Noronha, Greiner Phys.Rev. C86 (2012) 024913 *Dubla et al, Nucl.Phys. A979 (2018) 251-264*



Bulk Viscosity at $\mu_B > 0$

Non-critical bulk: $\dfrac{\zeta T}{w} = 36 \times \dfrac{1/3 - c_s^2}{8\pi}$

Critical Scaling: $\left(\dfrac{\zeta T}{w}\right)_{CS} = \dfrac{\zeta T}{w}\left[1 + \left(\dfrac{\xi}{\xi_0}\right)^3\right]$

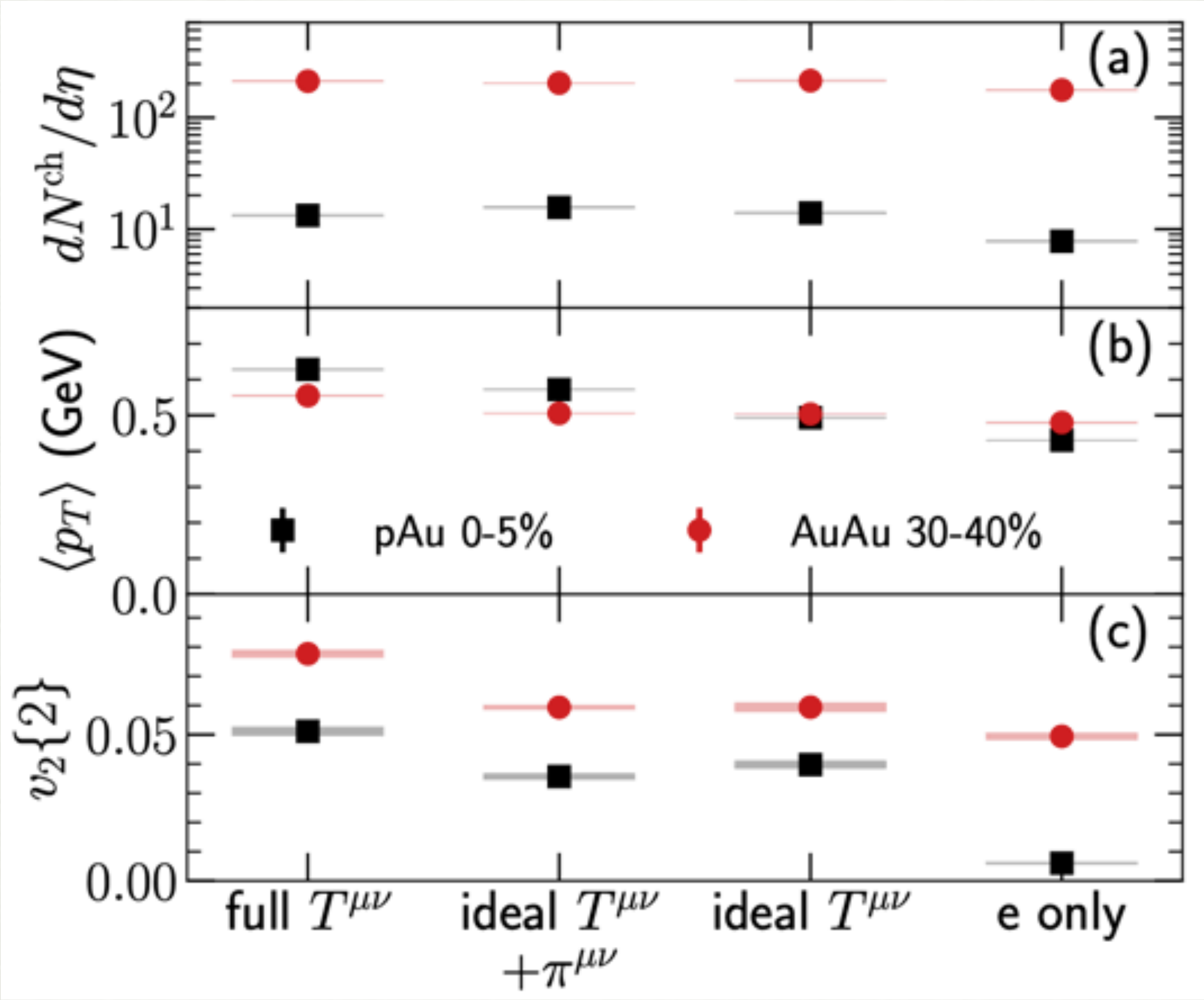
Critical Scaling: Monnai, Mukherjee, Yin; Phys.Rev.C 95 (2017) 3, 034902

Correlation length: $\xi^2 = \dfrac{1}{H_0}\left(\dfrac{\partial M(r,h)}{\partial h}\right)_r$

Correlation Length to $\mathcal{O}(\theta^5)$: Dore, et al, *Phys.Rev.D* 102 (2020) 7, 074017

See also: Martinez et al Phys.Rev.D 100 (2019) 7, 074017; Rajagopal et al Phys.Rev.D 102 (2020) 9, 094025

Simulations: full $T^{\mu\nu}$ small effect

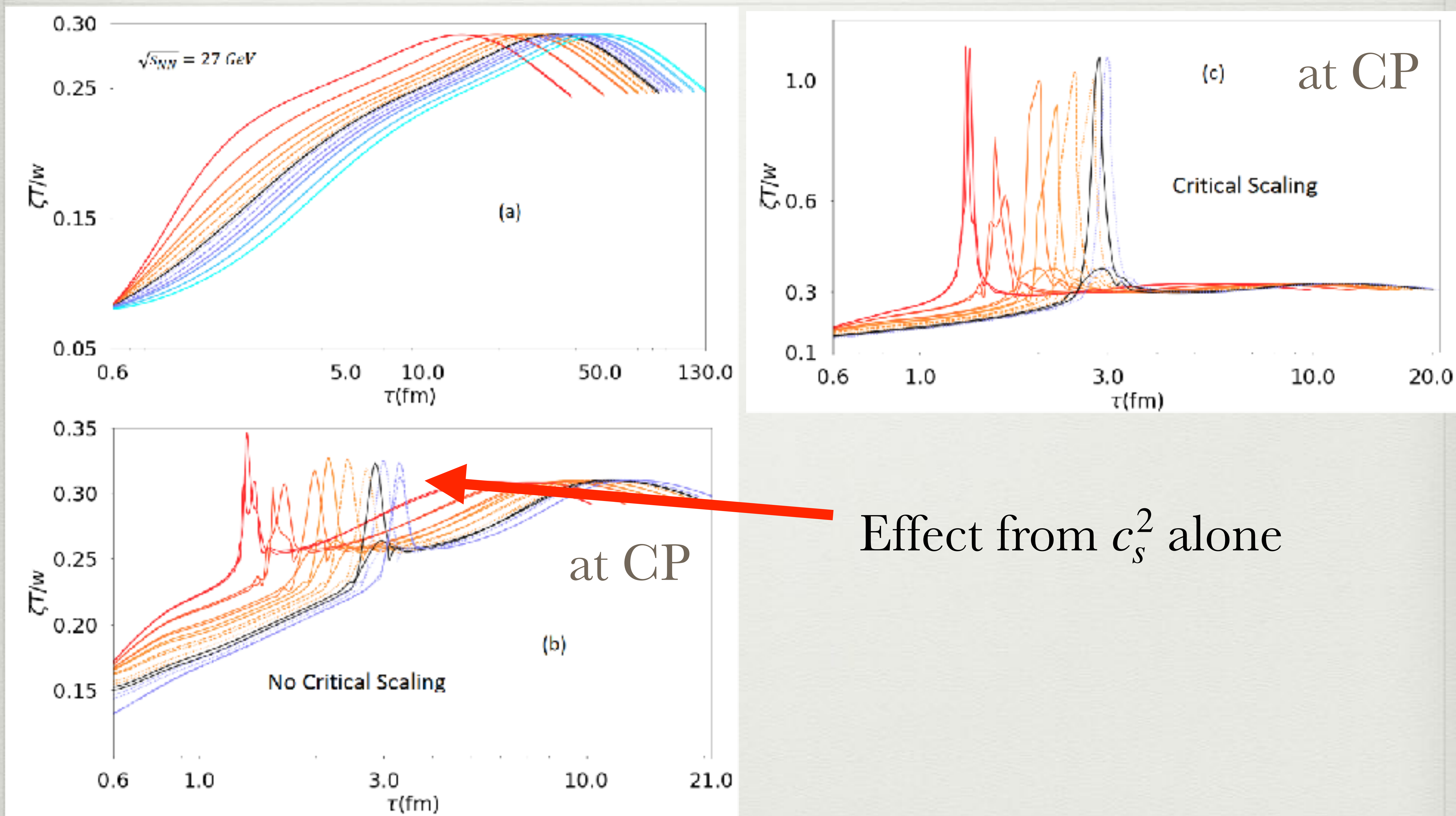


Schenke et al, *Phys.Lett.B* 803 (2020) 135322

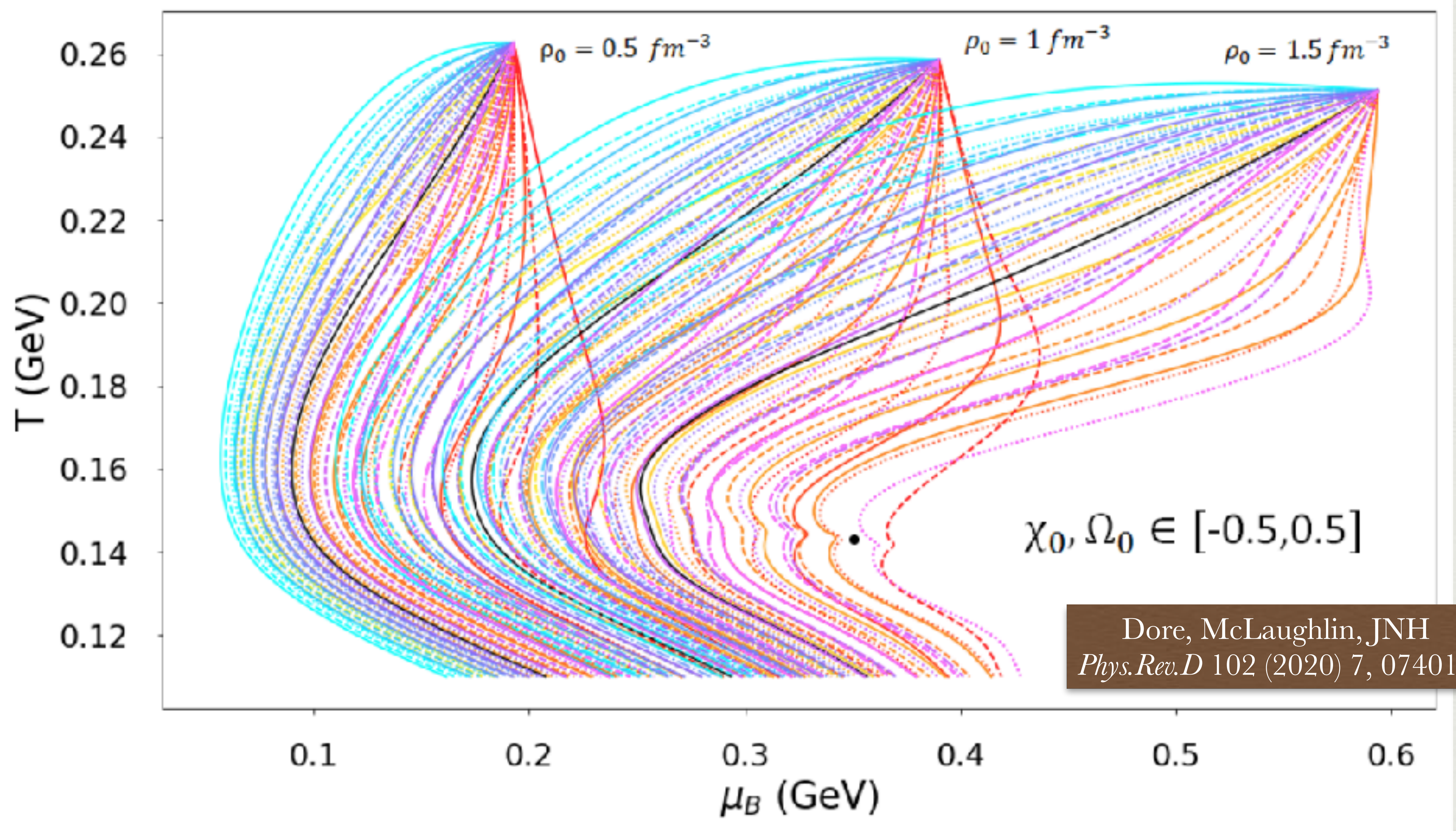
J. Noronha-Hostler

Bulk viscosity, varying $\left(\pi_\eta^\eta, \Pi_0\right)$

Dore, et al, *Phys.Rev.D* 102 (2020) 7, 074017

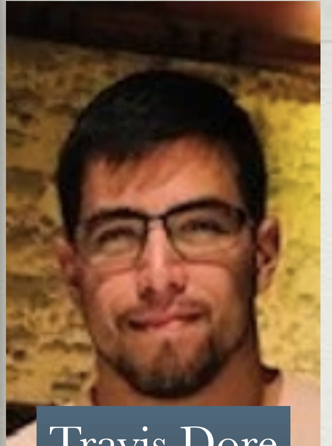


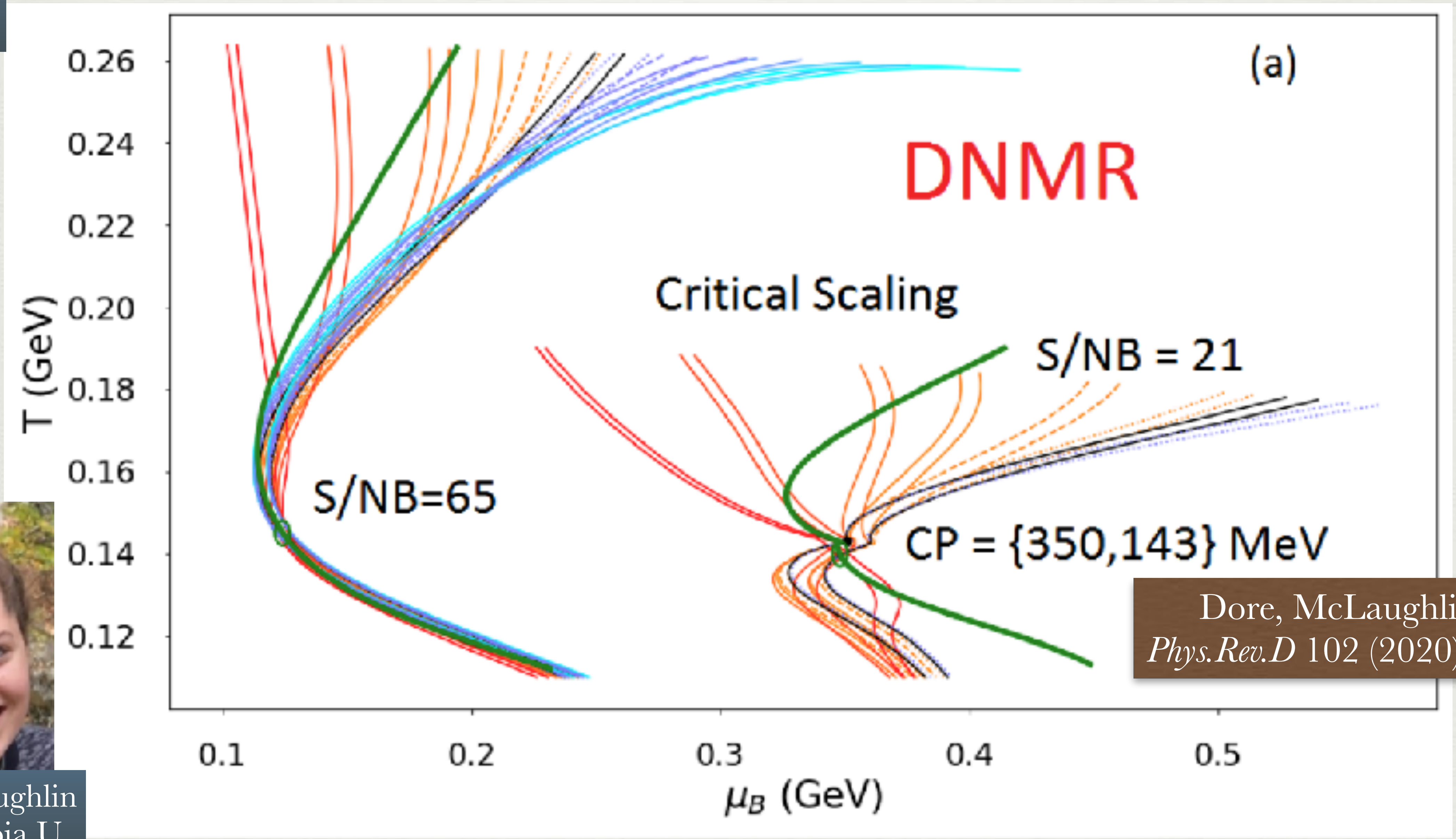
Fixed initial condition $(\varepsilon_0, \rho_B^0)$, vary $\left(\pi_\eta^\eta, \Pi_0\right)$



Dore, McLaughlin, JNH
Phys.Rev.D 102 (2020) 7, 074017

Far from equilibrium causes further deviations from ideal


Travis Dore
PhD UIUC

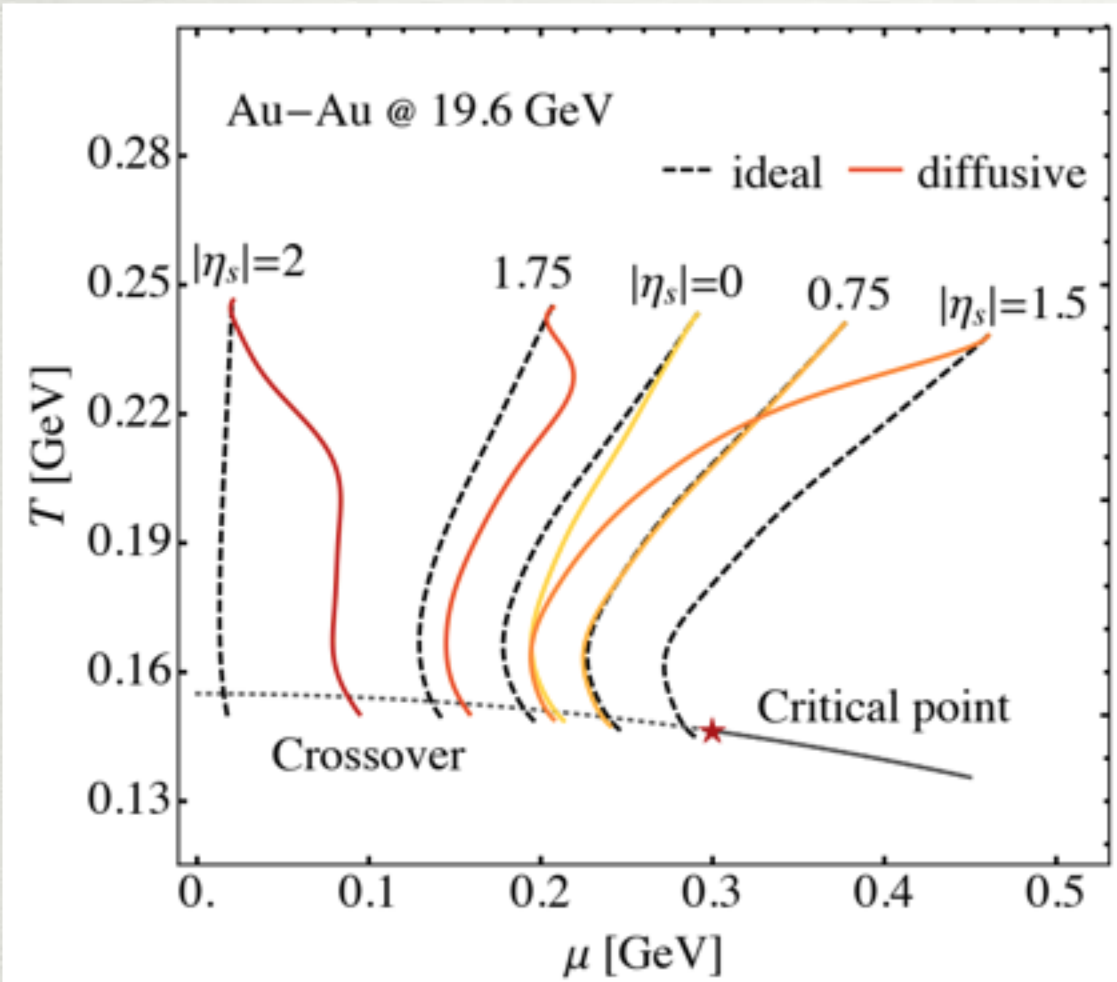


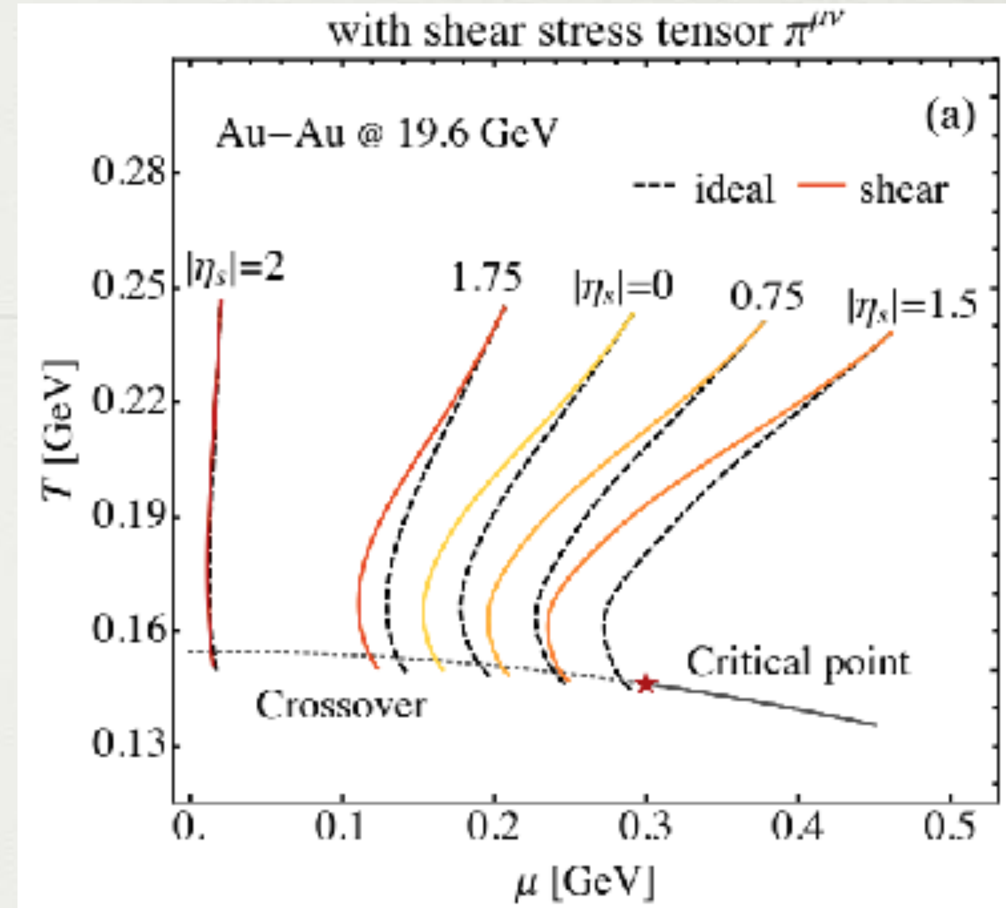
Dore, McLaughlin, JNH
Phys.Rev.D 102 (2020) 7, 074017

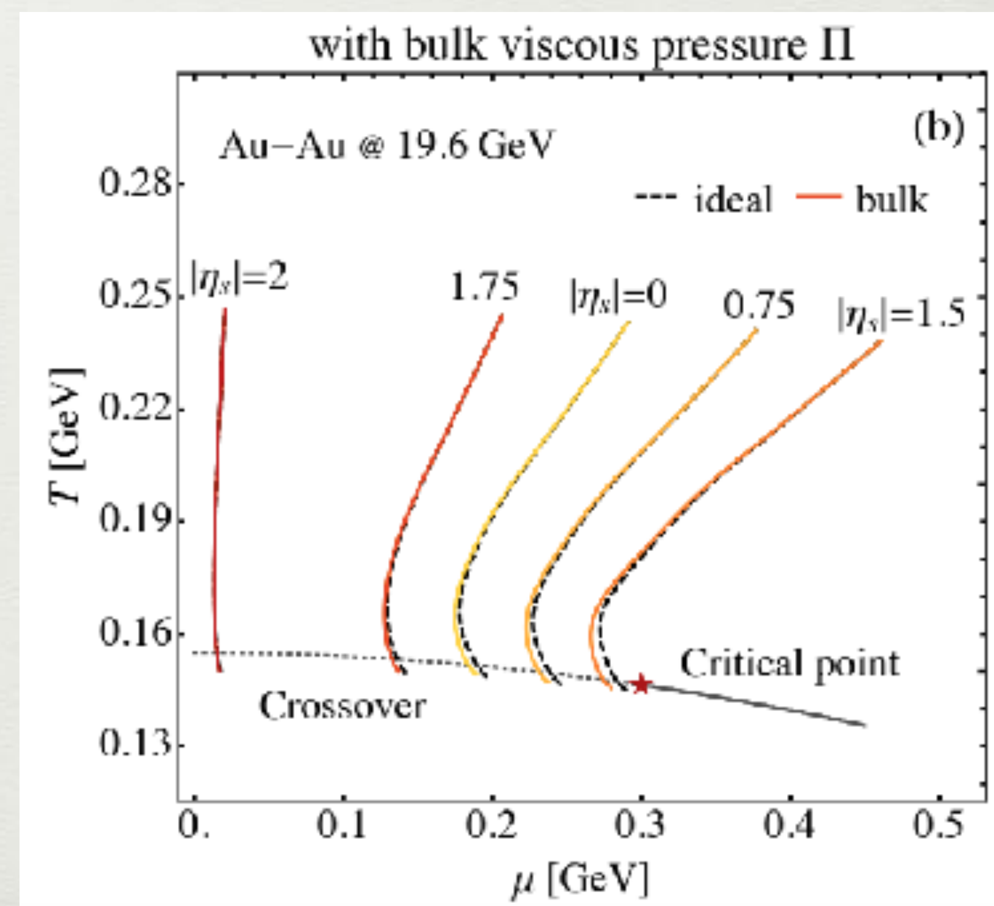

Emma McLaughlin
PhD Columbia U.

Assuming we know the point of freeze-out (from thermal models/ fluctuations), initial conditions then unknown

Beyond 0+1D studies





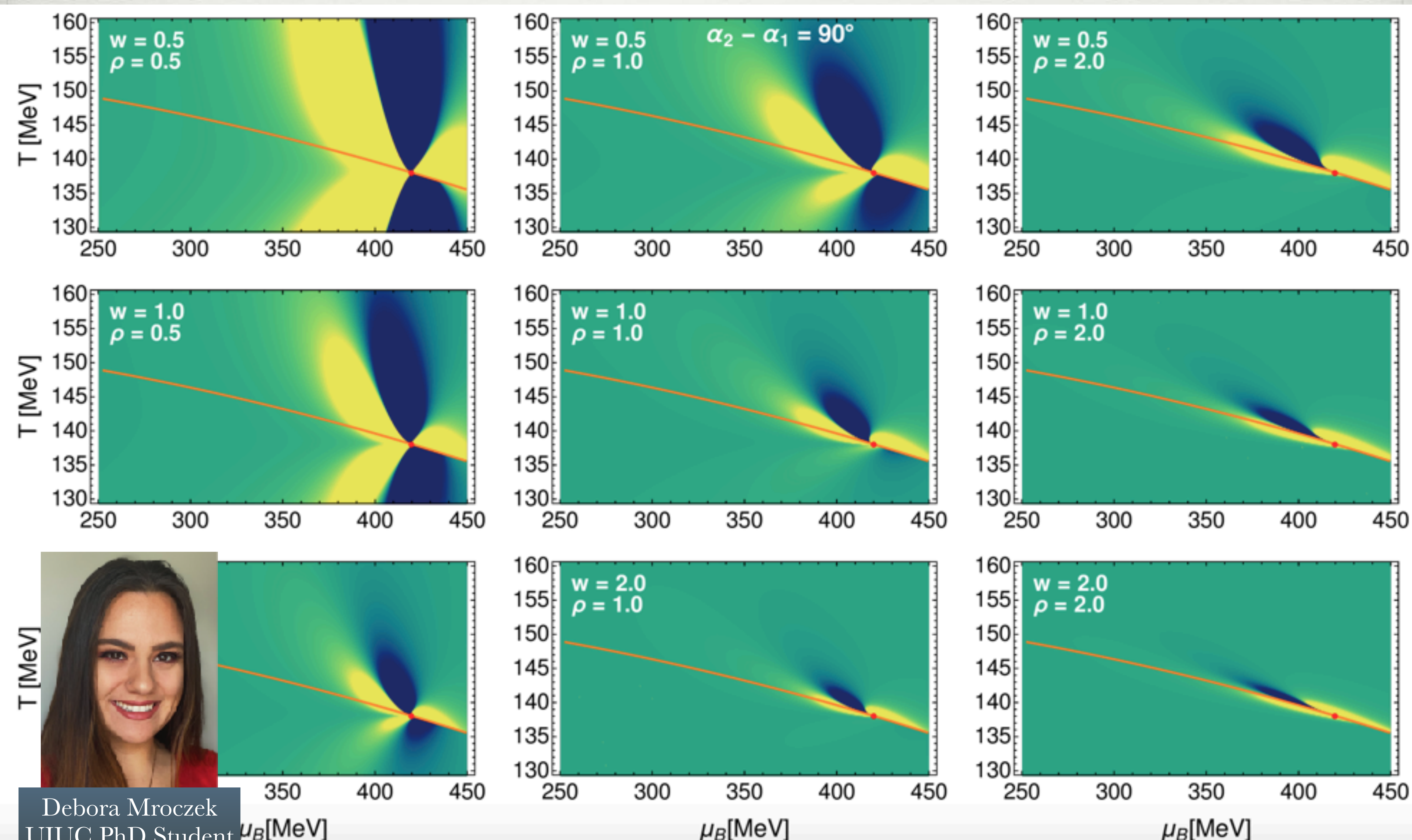


1+1D study, if initial start in equilibrium, diffusion and shear play biggest role

See also Du & Schlichting *Phys.Rev.Lett.* 127 (2021) 12, 122301

All critical points not created equally

Mroczek et al, *Phys.Rev.C* 103 (2021) 3, 034901



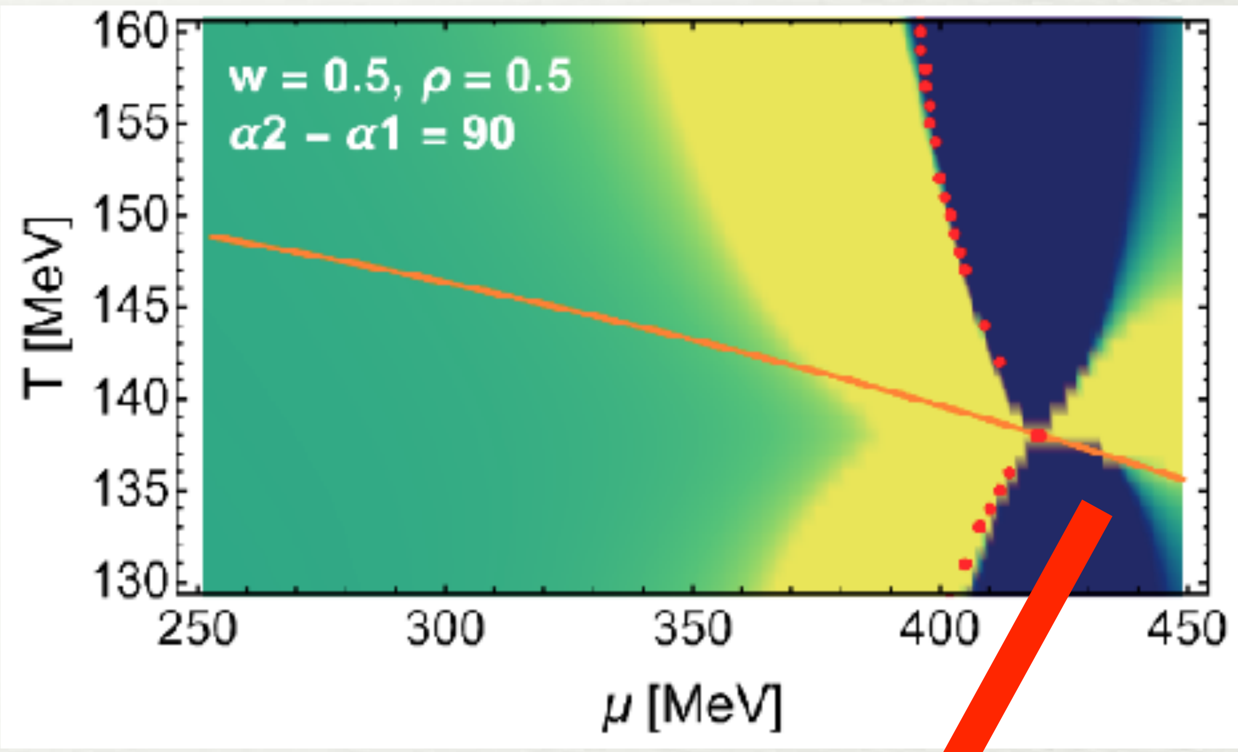
Debora Mroczek
UIUC PhD Student

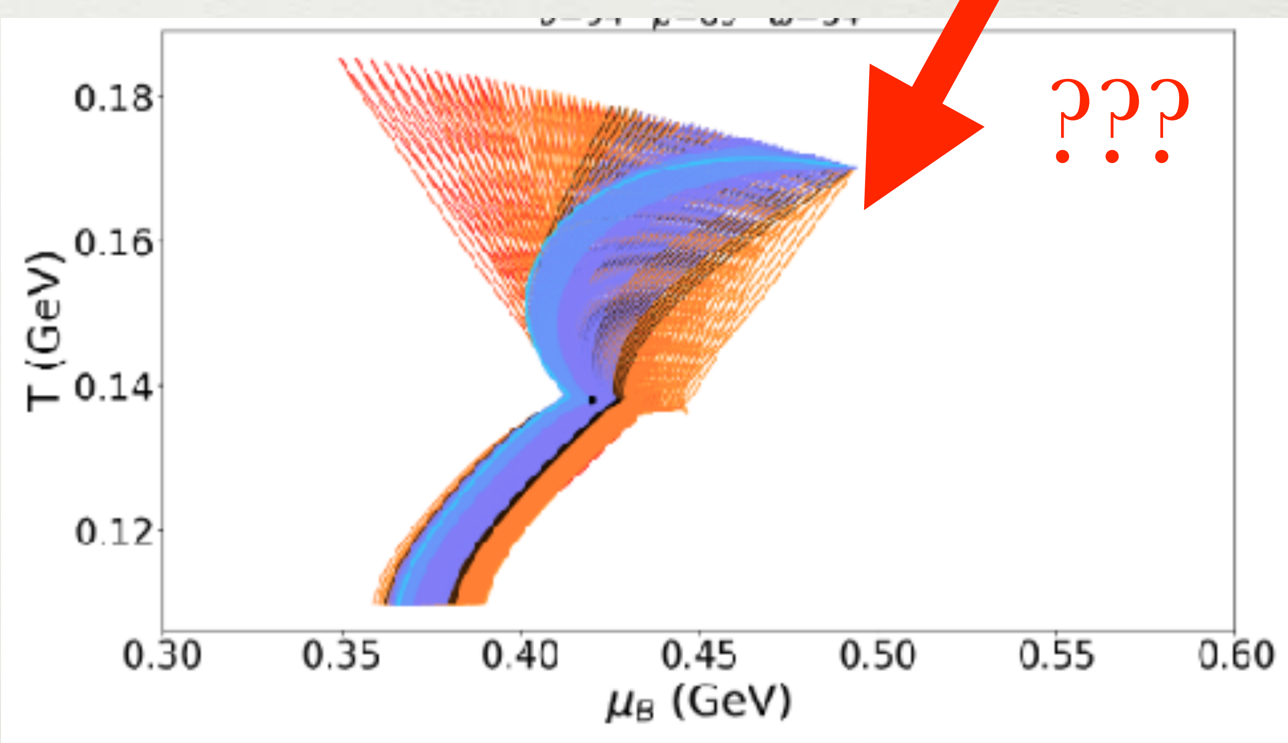
Effect of critical region on hydro?

Travis Dore, Isaac Long, Debora Mroczek, Yukari Yamauchi, Paolo Parotto, Claudia Ratti, JNH, to appear soon

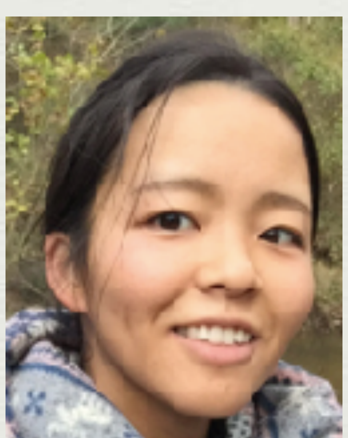
Travis Dore
PhD UIUC

Isaac Long
UIUC REU



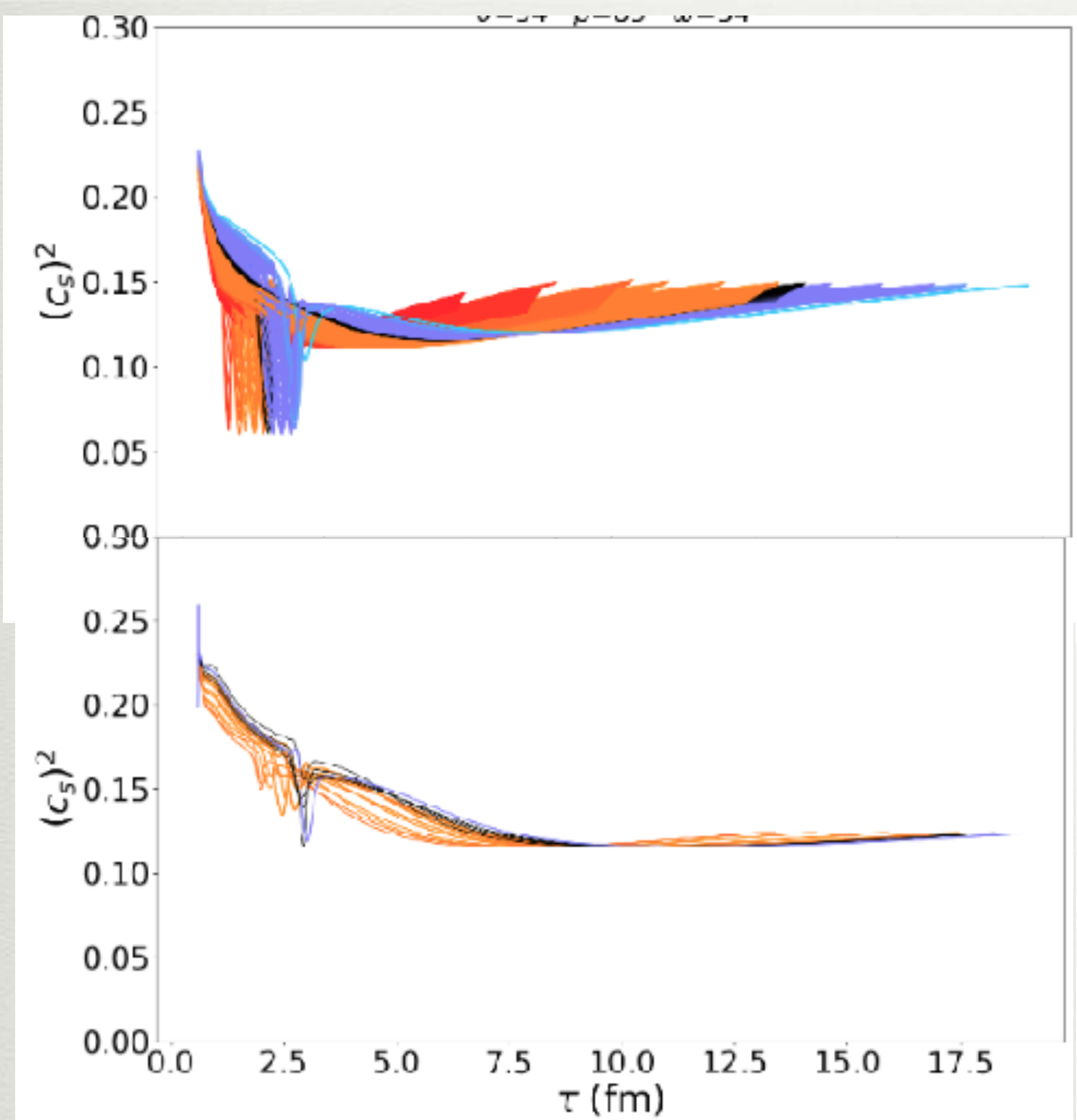


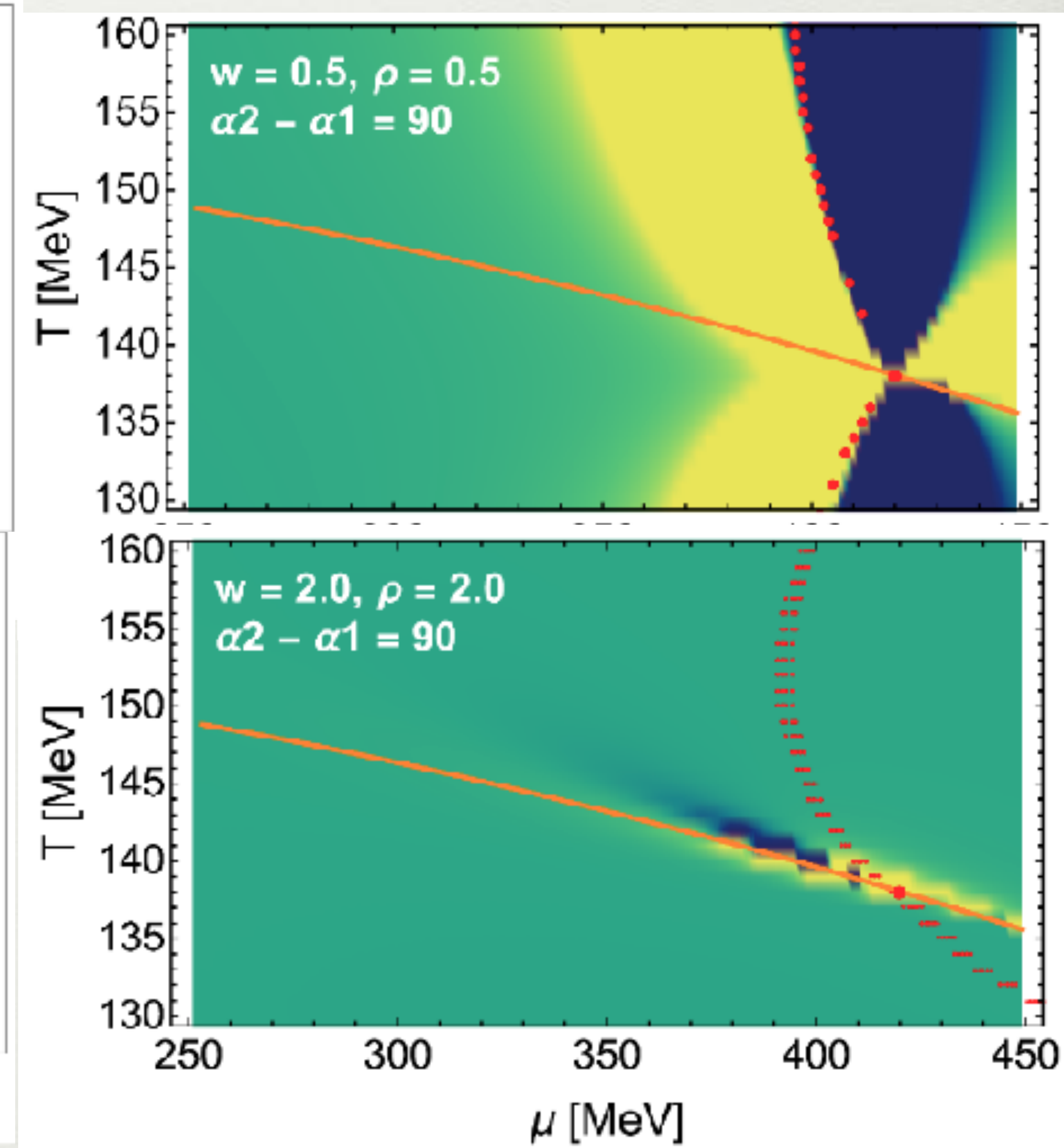
Debora Mroczek
UIUC PhD Student



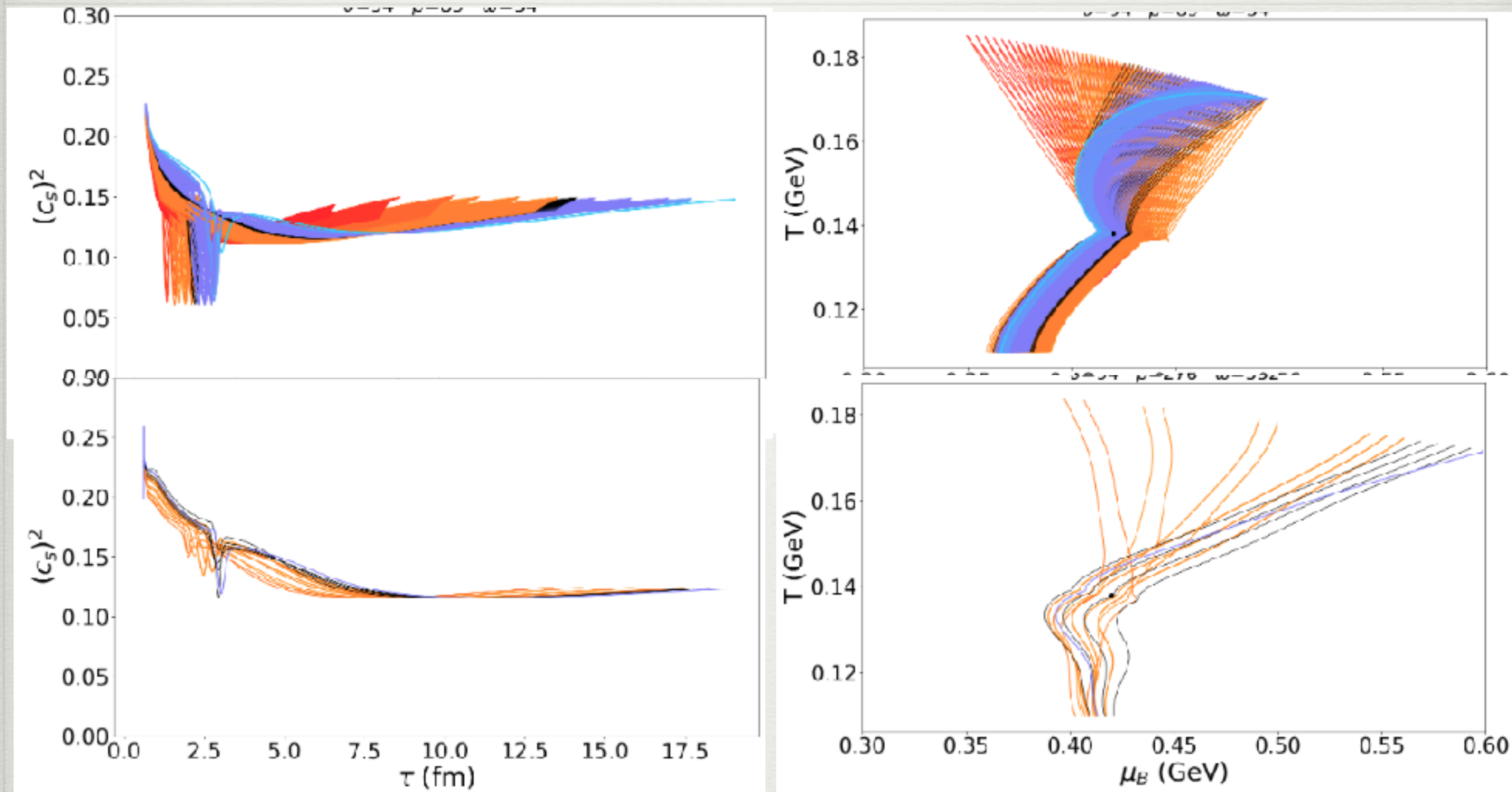
Yukari Yamauchi
Maryland PhD Student

Spread in critical region vs dip in c_s^2





c_s^2 dip → critical point trajectories attractor

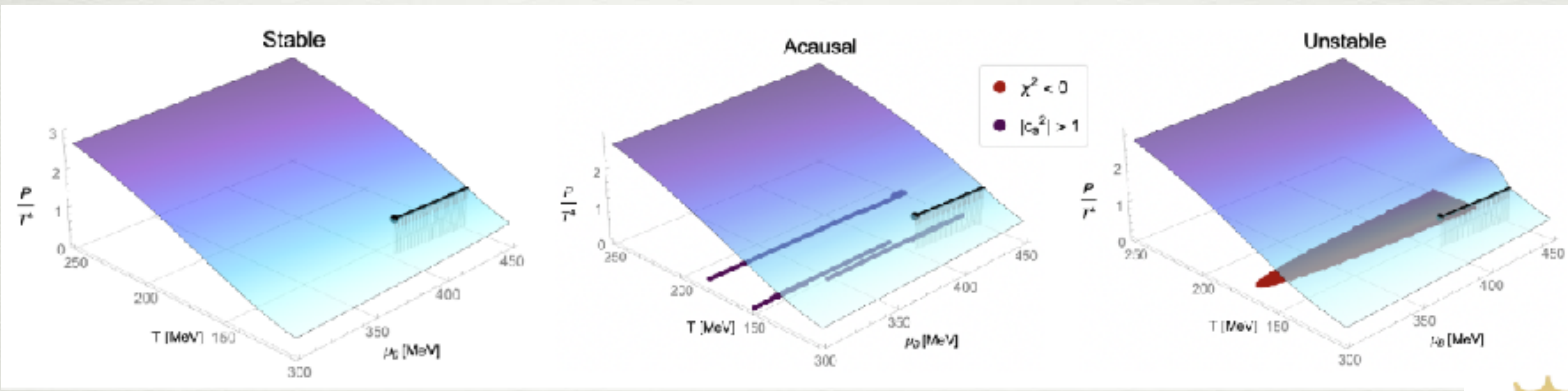


Orientation of critical region affects observability of critical region

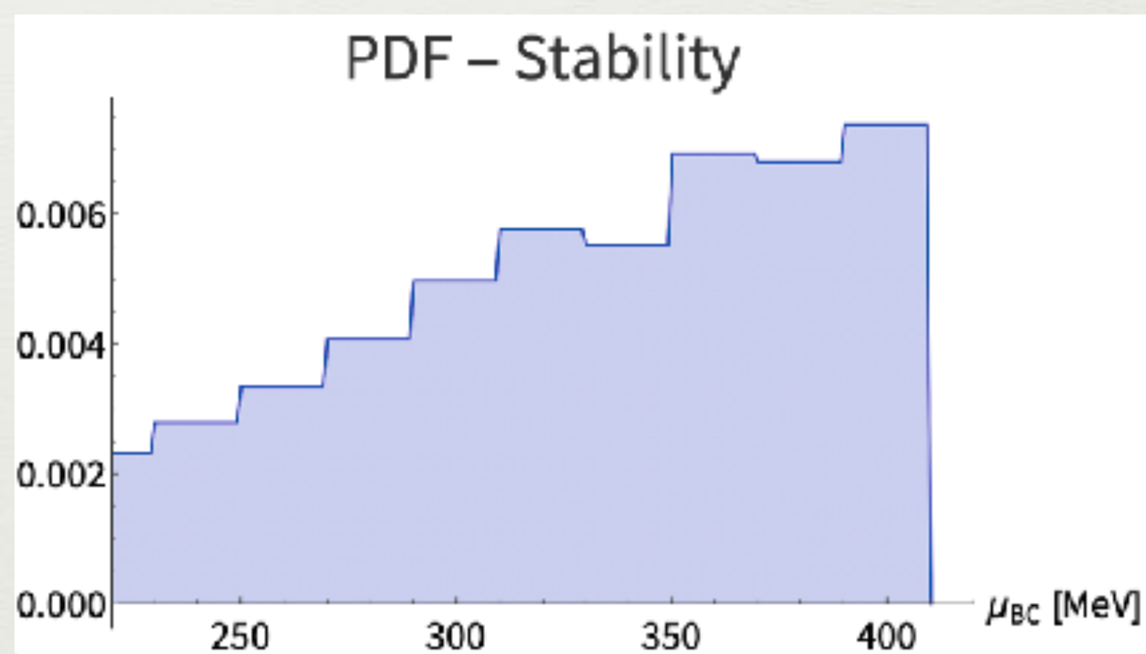
EoS: Constraining the 4 free parameters

Mroczek, Parotto, Hjorth-Jensen, JNH, Ratti, Vilalta to appear soon

Using active learning+machine learning to label viable EOS

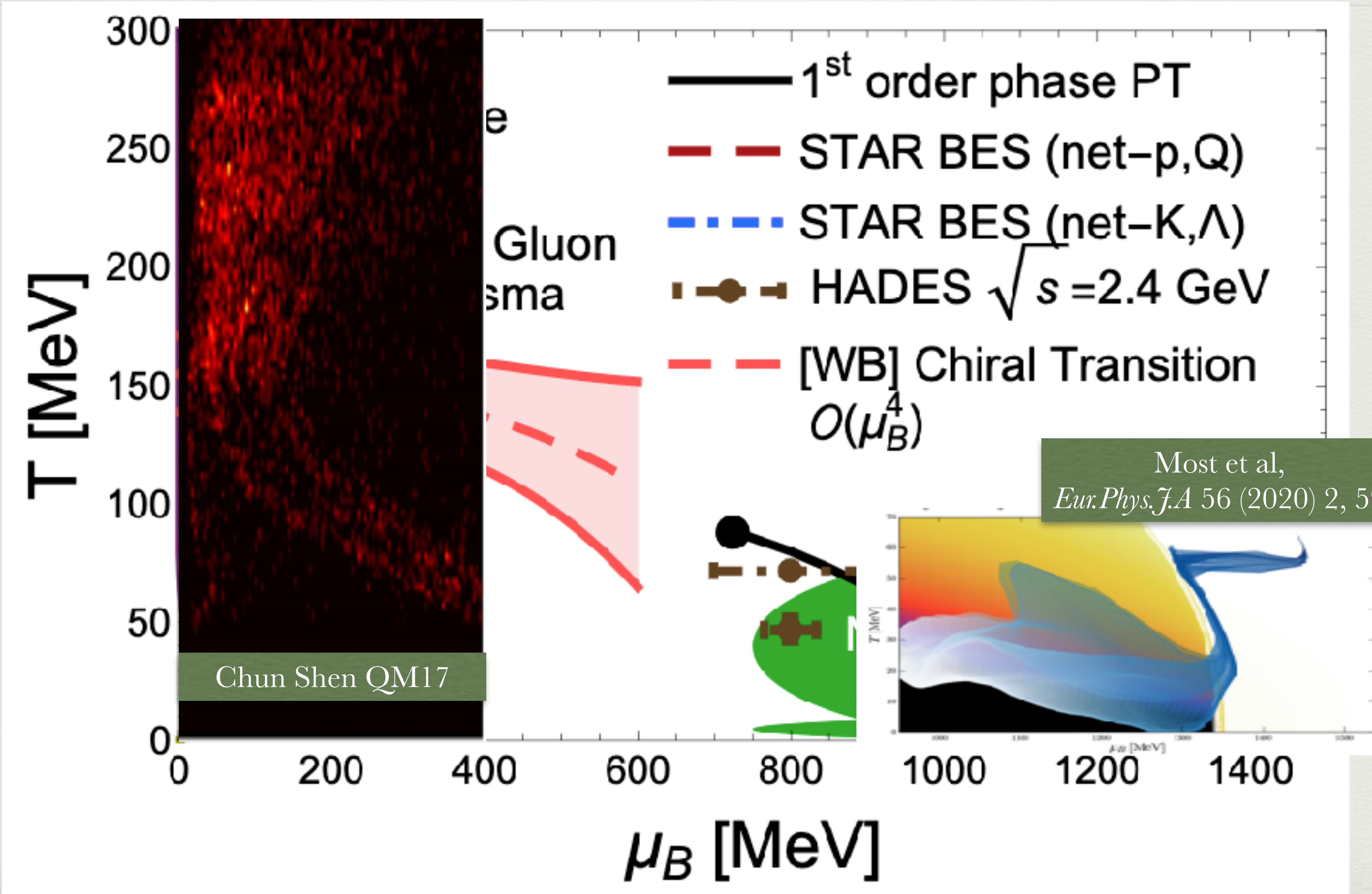


Most efficient method: random forrest with margin sampling



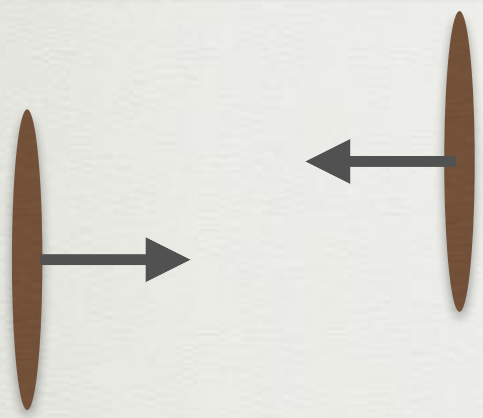
Debora Mroczek
UIUC PhD Student

Full 2+1 & 3+1 BSQ hydro



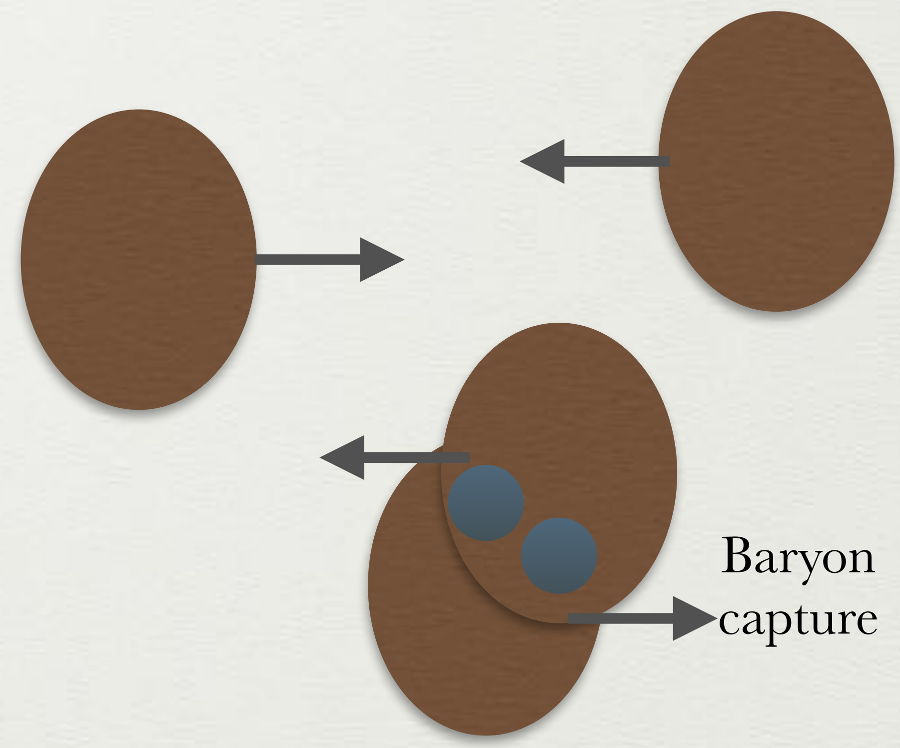
Heavy-ion Collisions: $\sqrt{s_{NN}}$ vs ρ_B

Large $\sqrt{s_{NN}}$



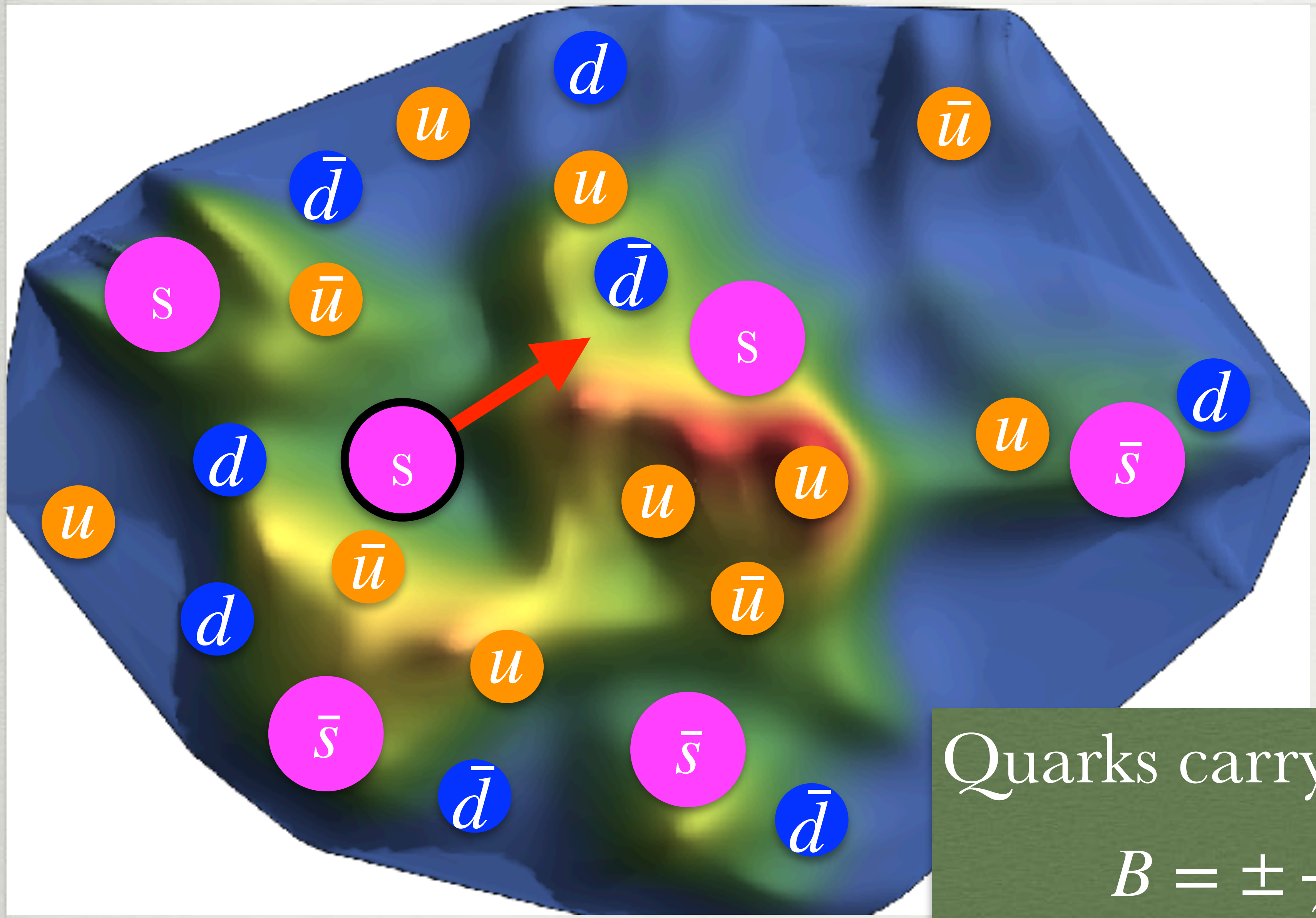
- Lorentz contracted (2D)
- Nuclei pass through instantaneously
- Too quick to capture baryons

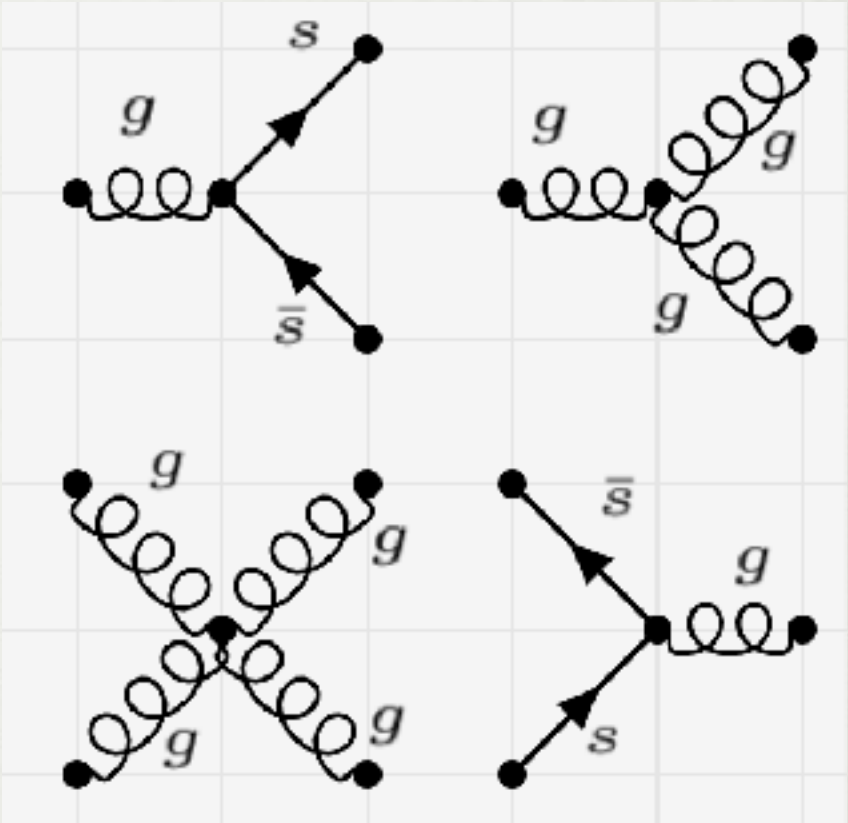
Small $\sqrt{s_{NN}}$



- 3D nuclei pass slowly
- Time to capture baryons

Initial conditions: Local charge fluctuations





Quarks carry ~3 conserved charges:

$$B = \pm\frac{1}{3} \text{ Baryon number}$$

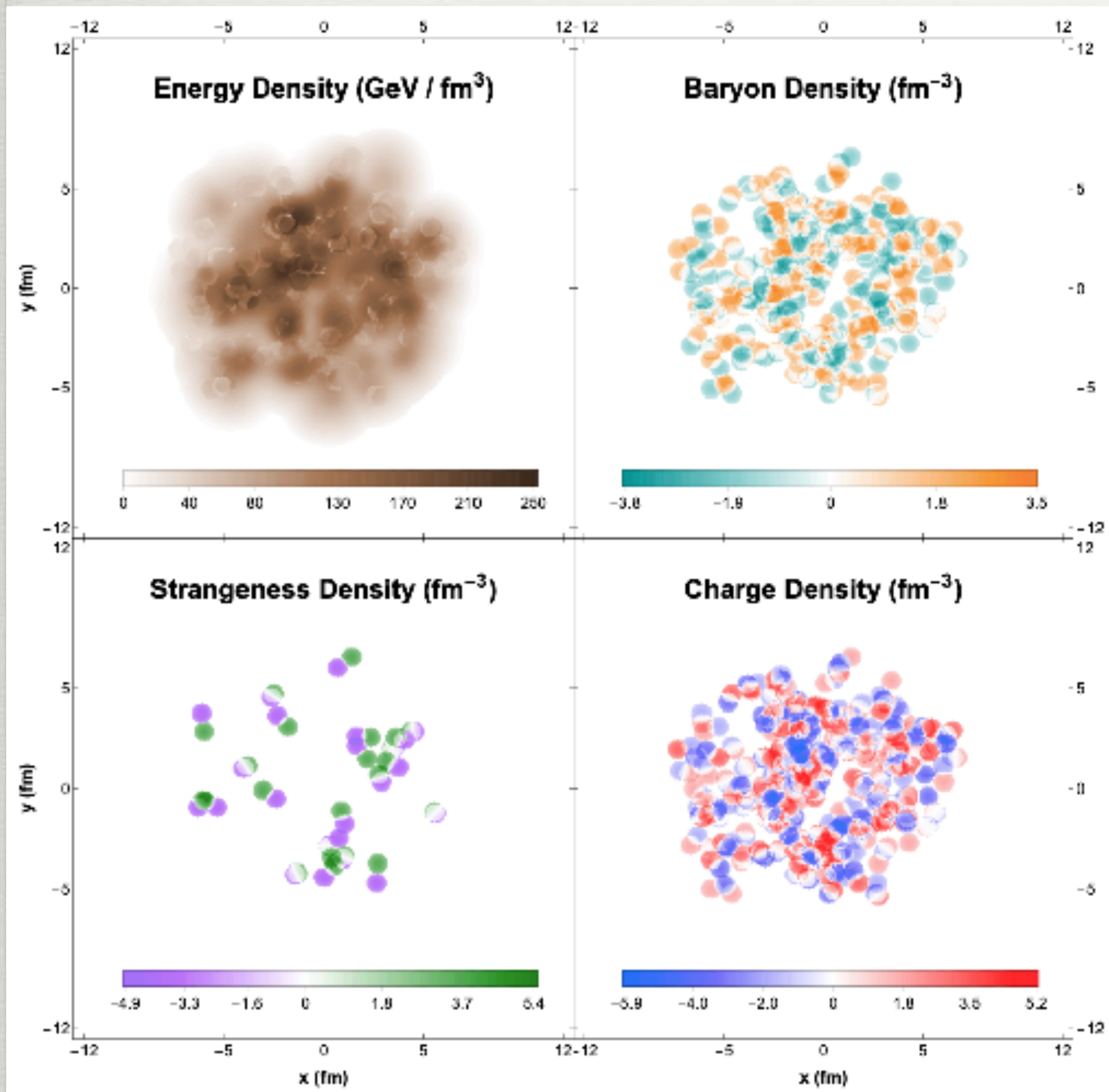
$$S = \pm 1 \text{ Strangeness}$$

$$Q = \pm\frac{1}{3} \text{ (d,s) or } Q = \pm\frac{2}{3} \text{ (u)}$$

Each grid point in an initial condition needs to initialize

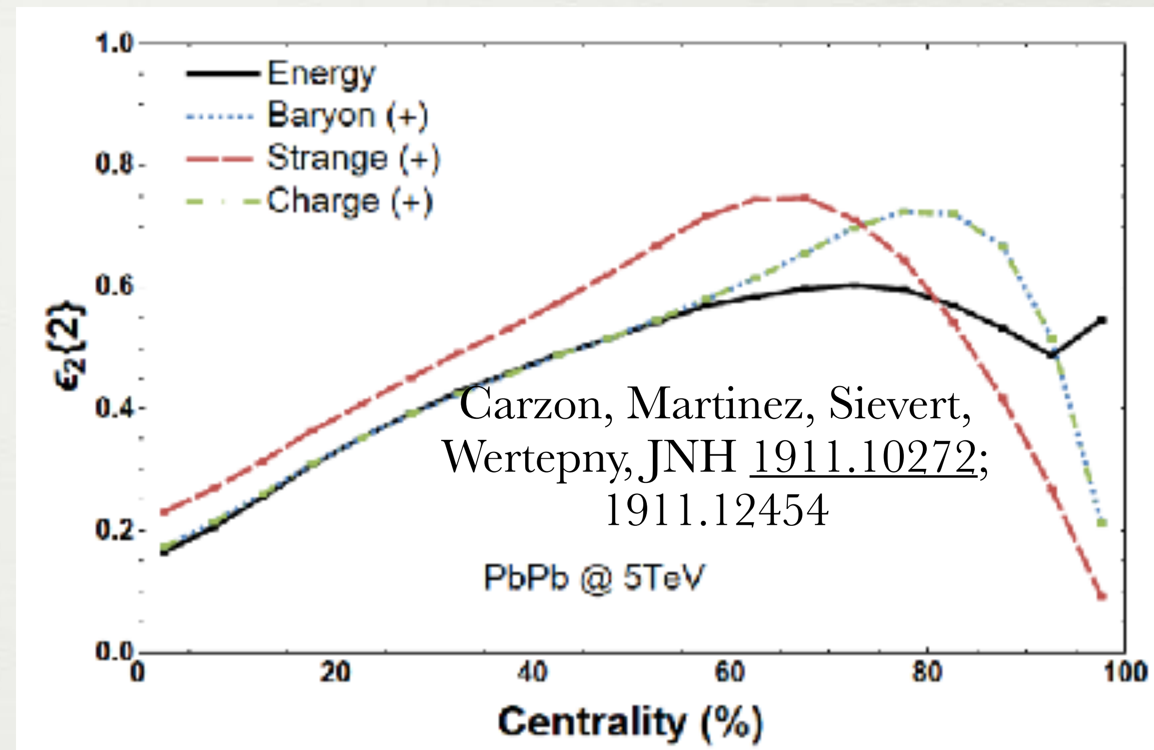
$$\left\{T, \rho_B, \rho_S, \rho_Q\right\}$$

Initial conditions: ICCING- Initializing Conserved Charges in Nuclear Geometries

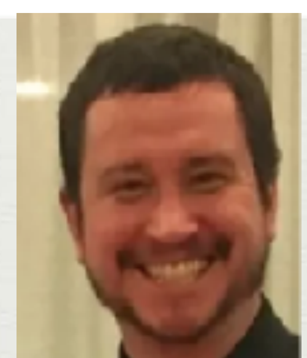


Theoretical development
Martinez, Sievert, Wertepny
JHEP 02 (2019) 024;JHEP 1807 (2018) 003

$g \leftrightarrow q\bar{q}$



Carzon, Martinez, Sievert, Wertepny, JNH 1911.10272; 1911.12454



Matt Sievert
Former Postdoc UIUC
Faculty NMSU

Patrick Carzon
PhD UIUC

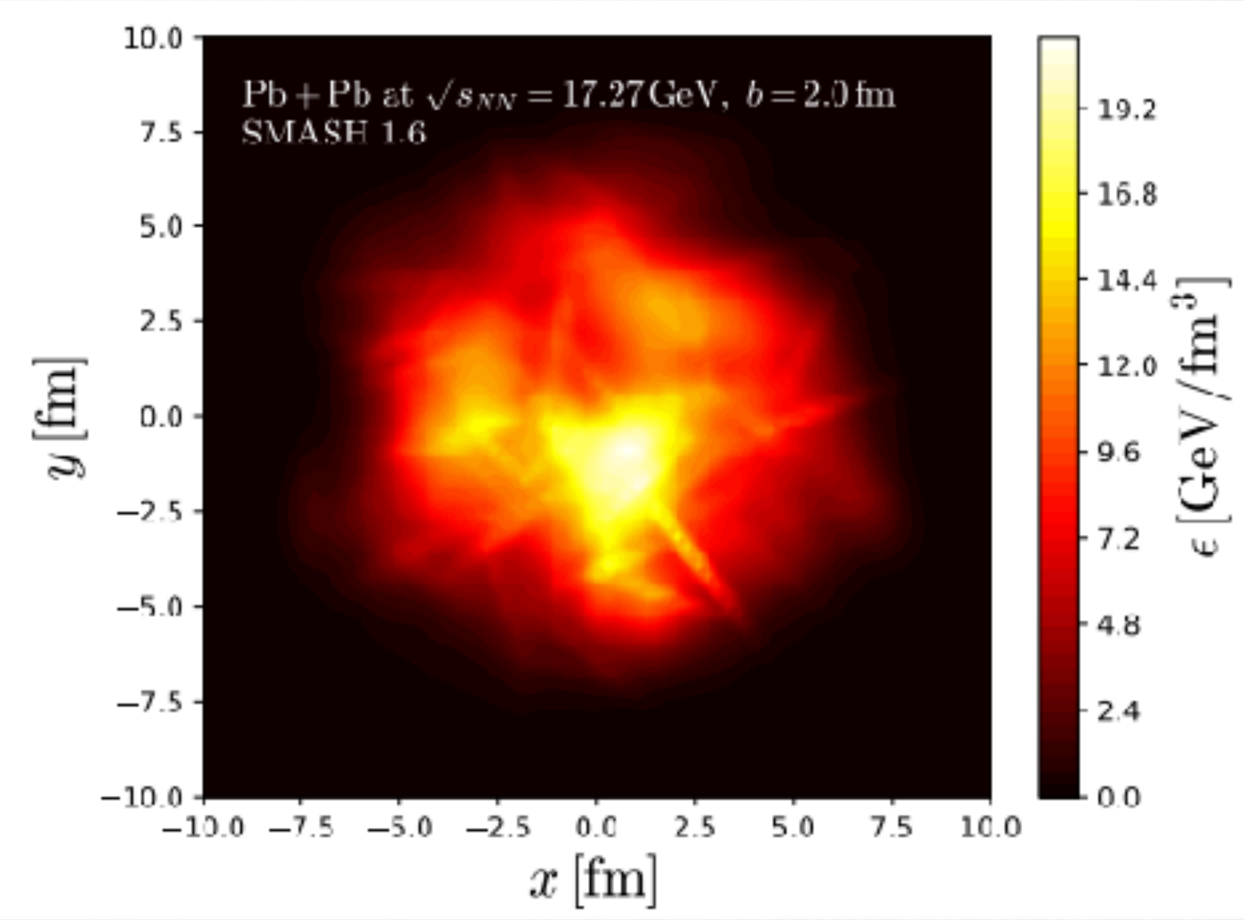
Initializing finite baryon density with nucleons

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

Transport (UrQMD/SMASH)

Karpenko, et al;Phys.Rev. C91 (2015) no.6, 064901



Mohs et al, J.Phys.G 47 (2020) 6, 065101

What about at the quark/gluon level?

Initial Conditions: What are we missing?

- Definition of eccentricities for BSQ: what is the eccentricity of the initial baryon density? How does that translate to a v_2 of protons?
  - Eccentricities are calculated in the center of mass frame, can't do a center of charge frame when $\rho_B \to 0$
- Full $T^{\mu\nu}$ at finite μ_B. Need initial q^μ as well
- What are the right degrees of freedom? Just nucleons?
- Should we be modeling the initial conditions as fluids?

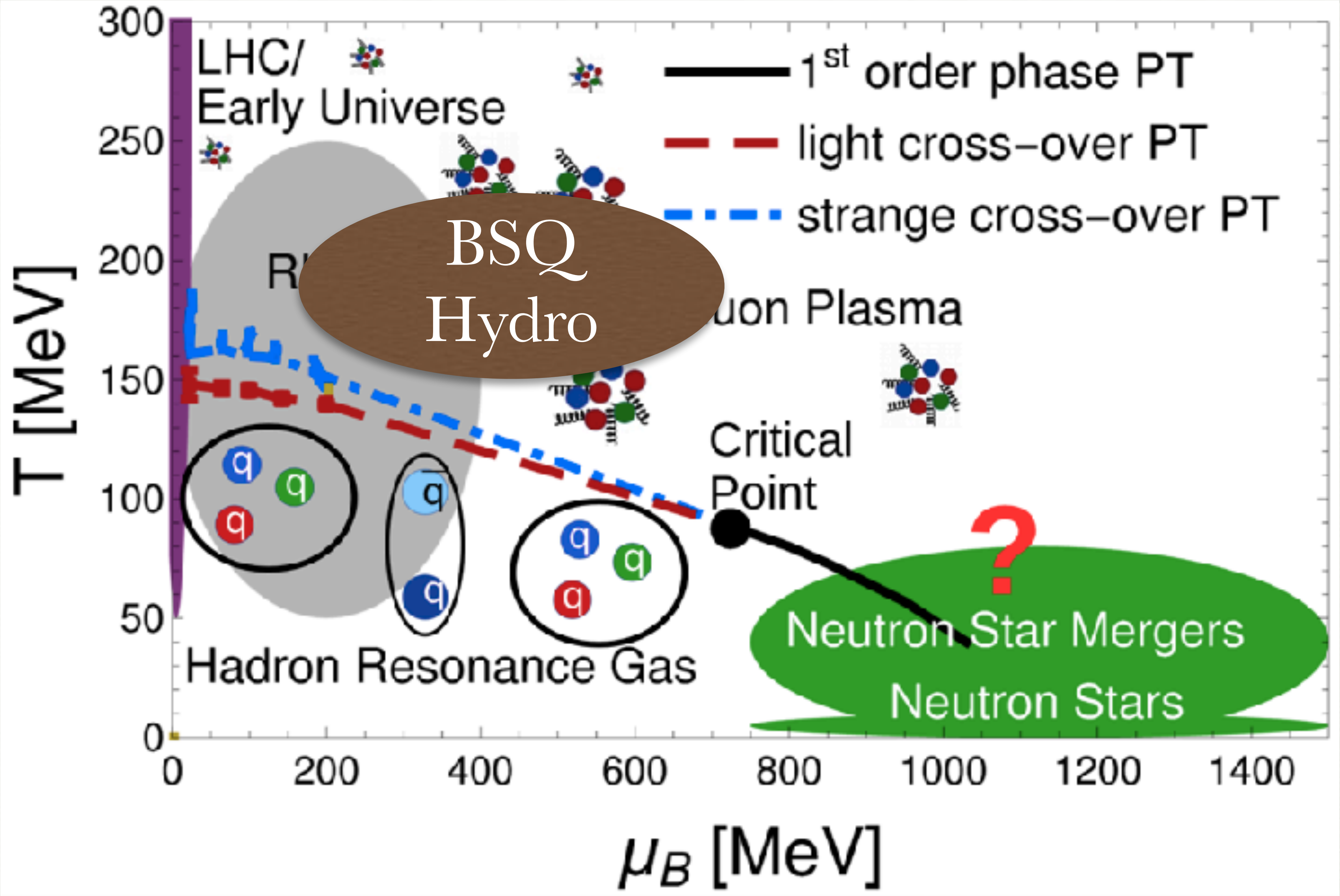
Initial state: $\{e, u_0, \pi^{\mu\nu}, \Pi, q^\mu\}$

- Current simulations at finite μ_B include initial conditions for $\{e, u_0\}$
- Very common to still run ideal hydro at low $\sqrt{s_{NN}}$
- *Some* include transport coefficients: $\eta T/w$, $\zeta T/w$, κ_{XY} where X,Y=BSQ. *Some* include 2nd order

E.g. Du & Heinz Comput.Phys.Commun. 251 (2020) 107090

- None include initial conditions from $\{\pi^{\mu\nu}, \Pi, q^\mu\}$

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*

Upgrades to Hydrodynamics

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

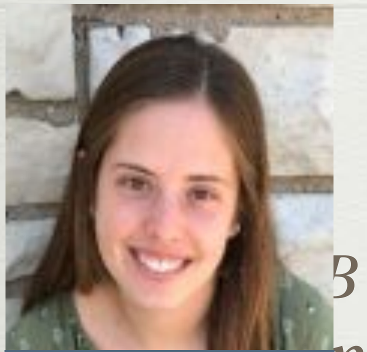
Transport Coefficients
Shear and bulk viscosity
$\eta T/w(T,\mu_B,\mu_S,\mu_Q)$
BSQ Diffusion
$\kappa_{BB},\ \kappa_{BS},\ \dots$

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

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

J. Noronha-Hostler

Full BSQ hydro simulations



$_B = 0$, shear+bulk viscosity gives 10 coupled
ren

- Additio … new
  pled … er
  usio

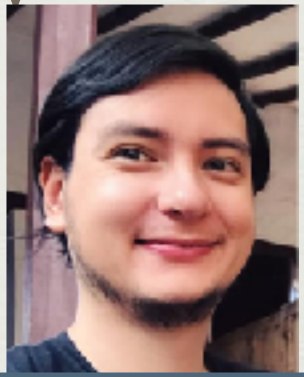
  dif
  thermodynar … vatives

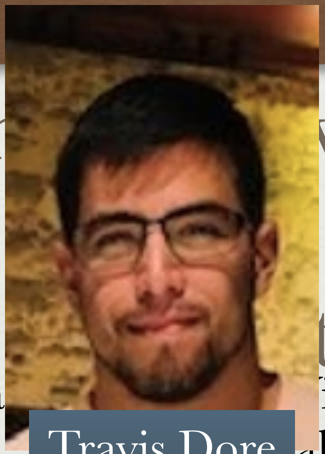
- Criticality + … tic viscous hyd … pen question!

Stephanov, Na … in, Schaeffer, Yee, An, Marti … matsu, Yan,
… al, Weller, Ridgway, Du, He

2+1 BSQ relativistic viscous hydrodynamics+ICCING Coming Soon!

Almaalol, Carzon, Cruz Camacho, Dore, Mroczek, Plumberg, Spychalla, Sievert, JNH

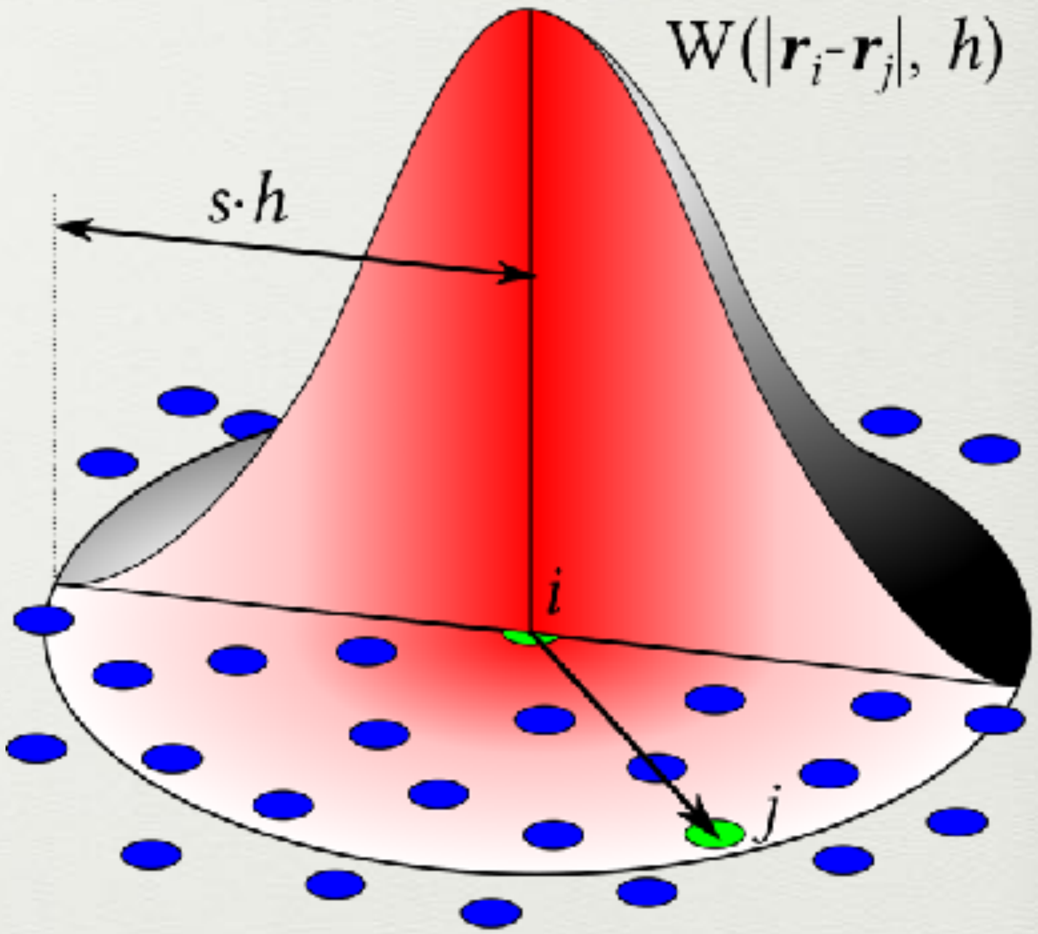




Dynamics: Smoothed Particle Hydrodynamics (SPH) for BSQ

With BSQ diffusion, the charge current becomes

$$N^{\mu}_{B,S,Q} = \underbrace{\rho_{B,S,Q} u^{\mu}}_{ideal} + \underbrace{n^{\mu}_{B,S,Q}}_{diffusion}$$



However, SPH requires one to divide by ρ_{BSQ}, in heavy-ions ρ_{BSQ} may be 0!

Define $\rho^{*}_{BSQ} \equiv \rho_{B,S,Q} u^{\mu} + n^{\mu}_{B,S,Q}$ where $\rho^{*}_{BSQ} = \sqrt{J^{\mu} J_{\mu}} > 0$

BSQ hydrodynamic simulations coming soon!

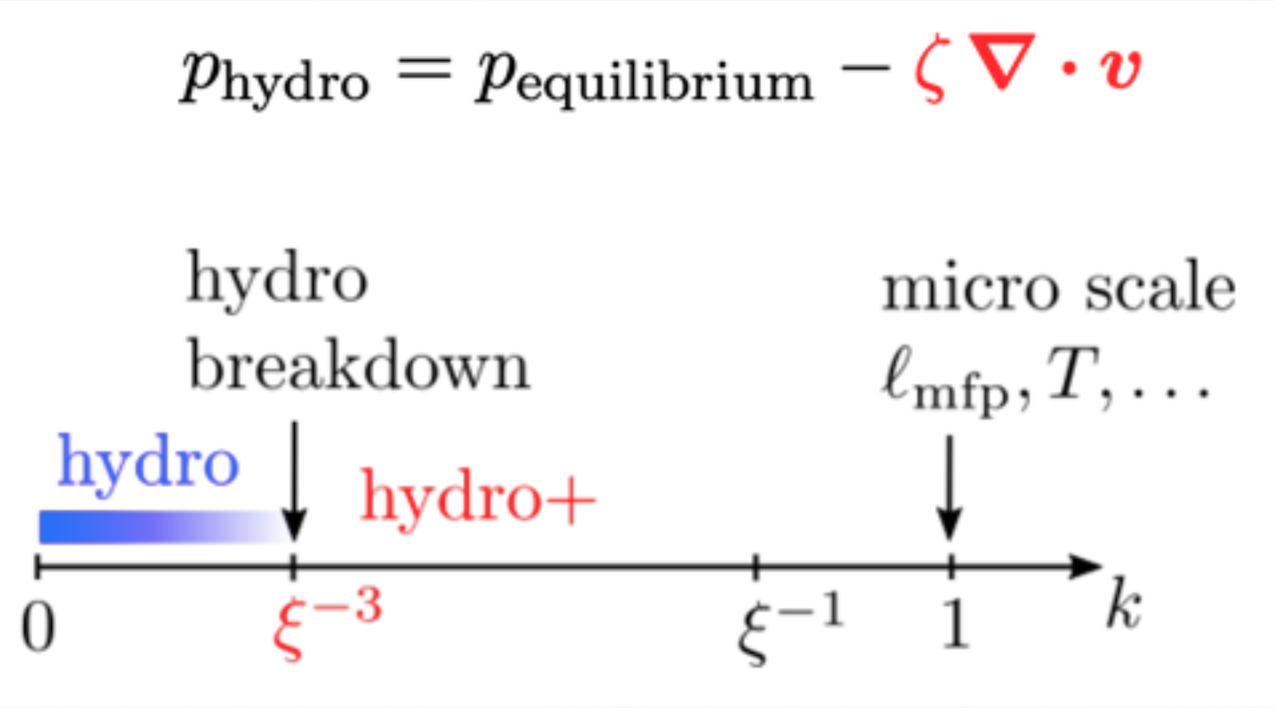
Hydro $\neq$ Hydro $\neq$ Hydro

How are the hydrodynamic equations of motion derived?

- Phenomenological Israel-Stewart: derived from the 2nd law of thermodynamics i.e. entropy *always* ⇑
- DNMR: power counting in Kn and Re^{-1}
  - "Standard in the field"
- BDNK: frame choice neither Ekhart nor Landau, first-order hydrodynamics
  - Fewer transport coefficients
  - Near equilibrium

Hydro as we approach a critical point

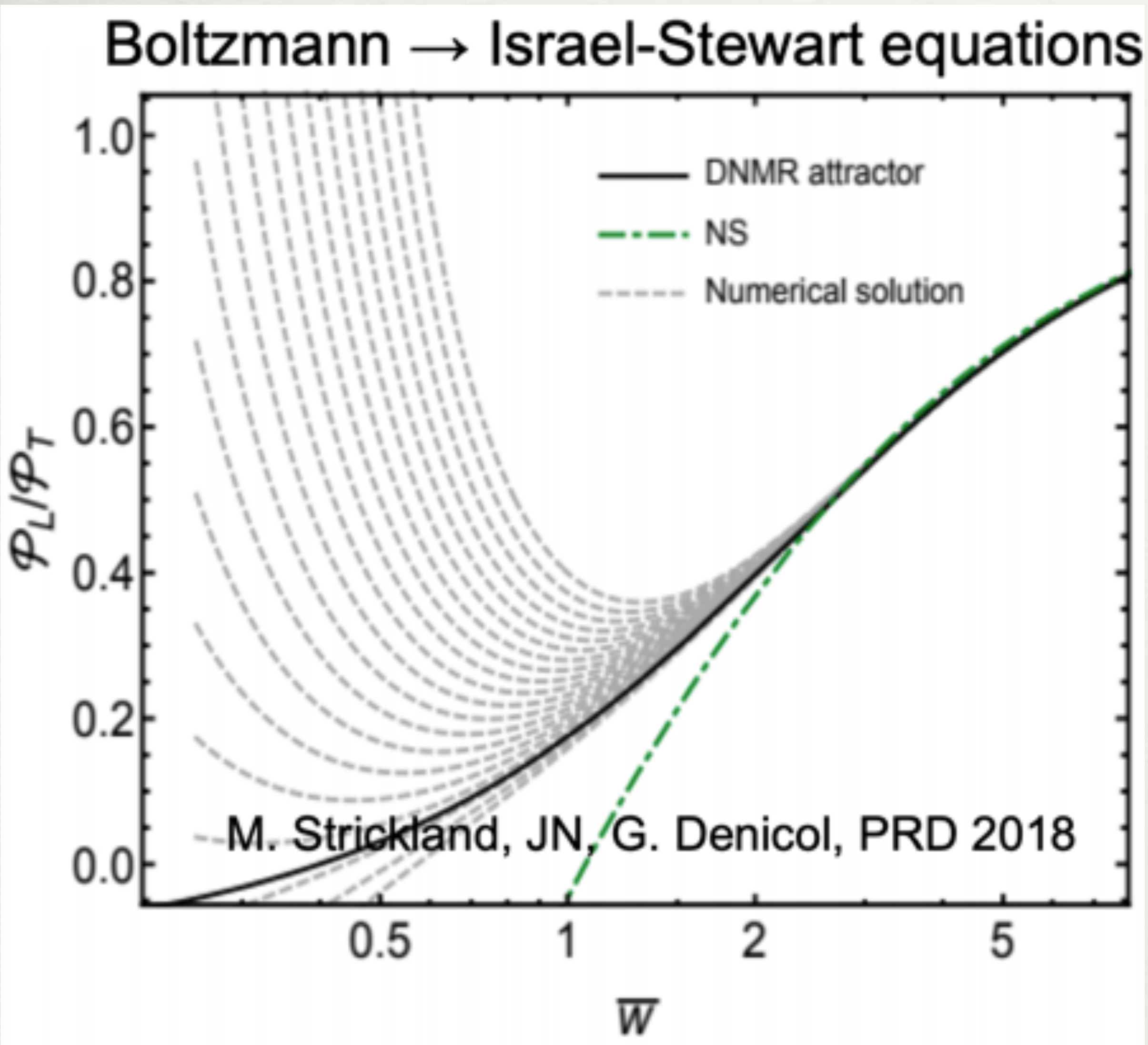
Hydro breaks down as → critical point



Stephanov, Yin Phys. Rev. D 98, 036006 (2018)

However, what theory works best for as long as possible?

How well-behaved in hydro near a CP? Do attractors exist?



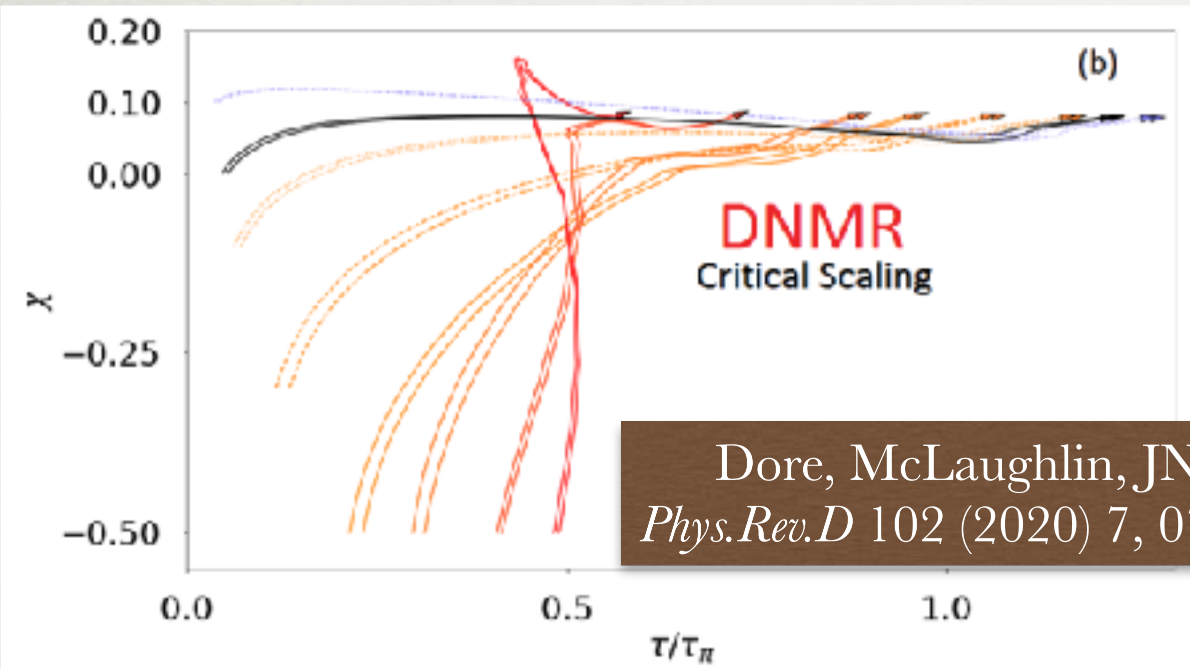
First work from Heller & *Spalinski Phys.Rev.Lett.* 115 (2015) 7, 072501

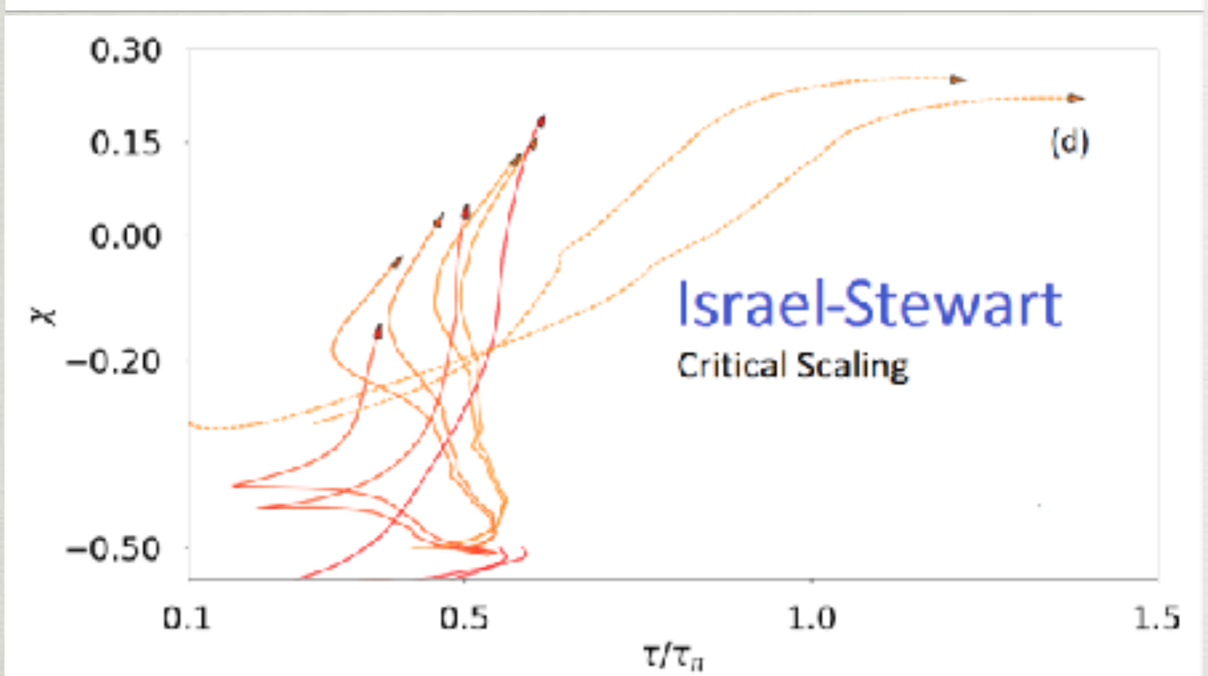
- Attractors at $\mu_B = 0$ imply out-of-equilibrium contributions to the initial conditions are washed out
- Mostly only ε_n's matter

In Holography: Critelli *Phys.Rev.D* 99 (2019) 6, 066004

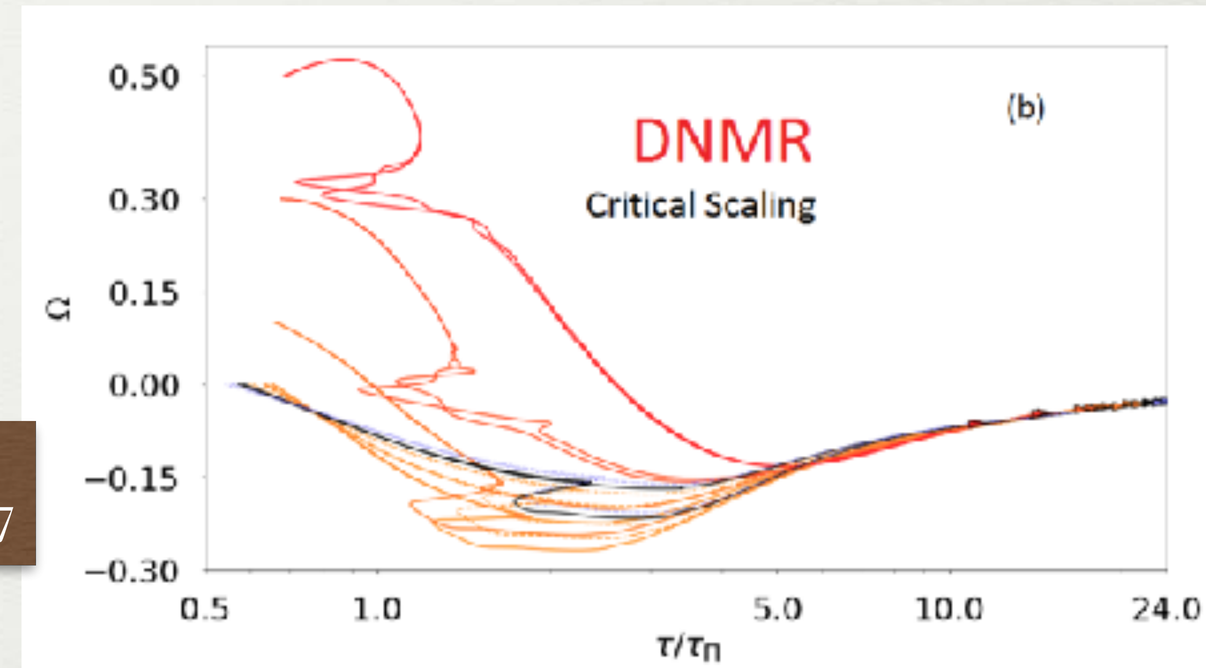
Critical point and equations of motion and attractors, varying $\left(\pi_\eta^\eta, \Pi_0\right)$

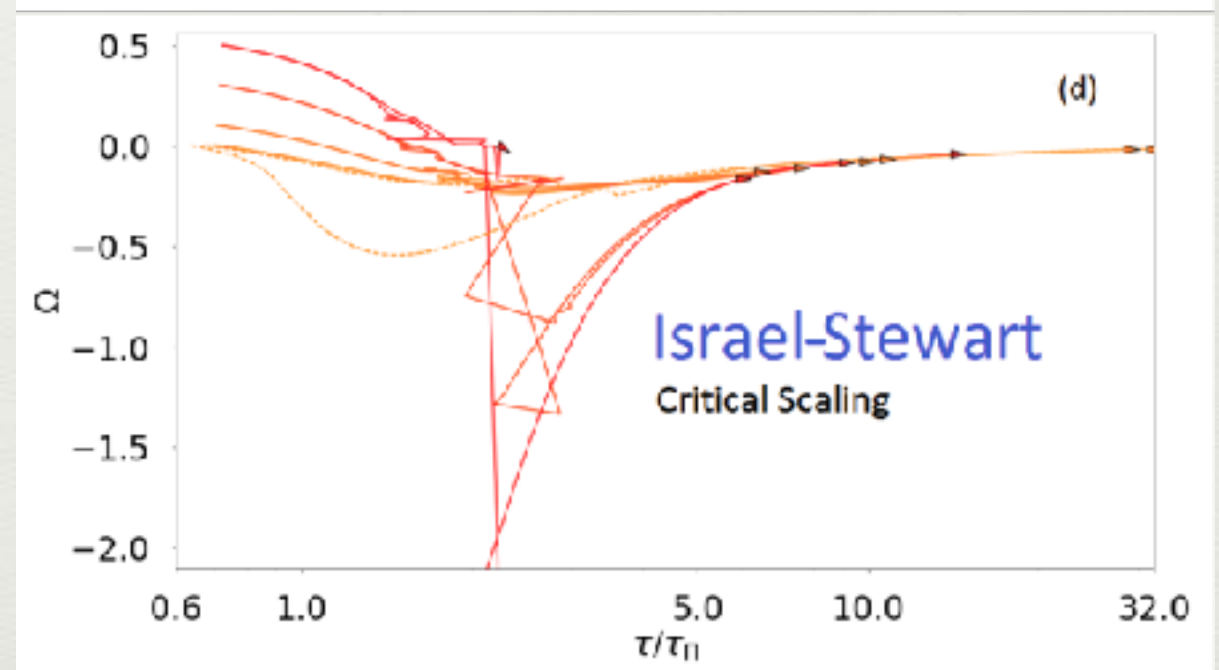
Shear stress tensor





Bulk pressure





Dore, McLaughlin, JNH
Phys.Rev.D 102 (2020) 7, 074017

Dynamics: BSQ diffusion in relativistic hydrodynamics

Ensure only positive entropy production

Many new terms that couple shear, bulk, and BSQ diffusion!

$$\tau_\pi \dot{\pi}^{\mu\nu} + \pi^{\mu\nu} = 2\eta\sigma^{\mu\nu} + \frac{\tau_\pi \pi^{\mu\nu}}{2}\theta - \frac{\tau_\pi}{2\beta_\pi}\dot{\beta}_\pi \pi^{\mu\nu} - \frac{2\eta}{\beta}\left(\gamma_1^q \nabla^{\langle\mu} n_q^{\nu\rangle} + \frac{1}{2} n_q^{\langle\mu}\nabla^{\nu\rangle}\gamma_1^q\right)$$

$$\tau_\Pi \dot{\Pi} + \Pi = -(\zeta + \frac{\tau_\Pi}{2}\Pi)\theta - \frac{\tau_\Pi}{2\beta_\Pi}\dot{\beta}_\Pi \Pi - \frac{\zeta}{\beta}\left(\gamma_0^q D_\mu n_q^\mu + \frac{1}{2} n_q^\mu \nabla_\mu \gamma_0^q\right)$$

$$\tau_{qq'}\dot{n}_{q'}^\mu + n_q^\mu = -\kappa_{qq'}\nabla^\mu \alpha_{q'} + \frac{\tau_{qq'} n_{q'}^\mu}{2}\theta - \frac{\tau_{qq'}}{2\beta_{qq'}}\dot{\beta}_{qq'} n_{qq'}^\mu - \frac{\kappa_{qq'}}{\beta}\left(\gamma_0^{qq'}\nabla^\mu \Pi - \frac{\Pi}{2}\nabla^\mu \gamma_0^{qq'}\right) - \frac{\kappa_{qq'}}{\beta}\left(\gamma_1^{qq'}\nabla_\nu \pi^{\mu\nu} + \frac{\pi^{\mu\nu}}{2}\nabla_\nu \gamma_1^{qq'}\right)$$

Dore, Mroczek, Almaalol, Sievert, JNH to appear soon

See also Monnai *Nucl.Phys.A* 847 (2010) 283-314

BSQ diffusion from DNMR/DBNK

DNMR

Fotakis, Niemi, Denicol, Greiner, Greif

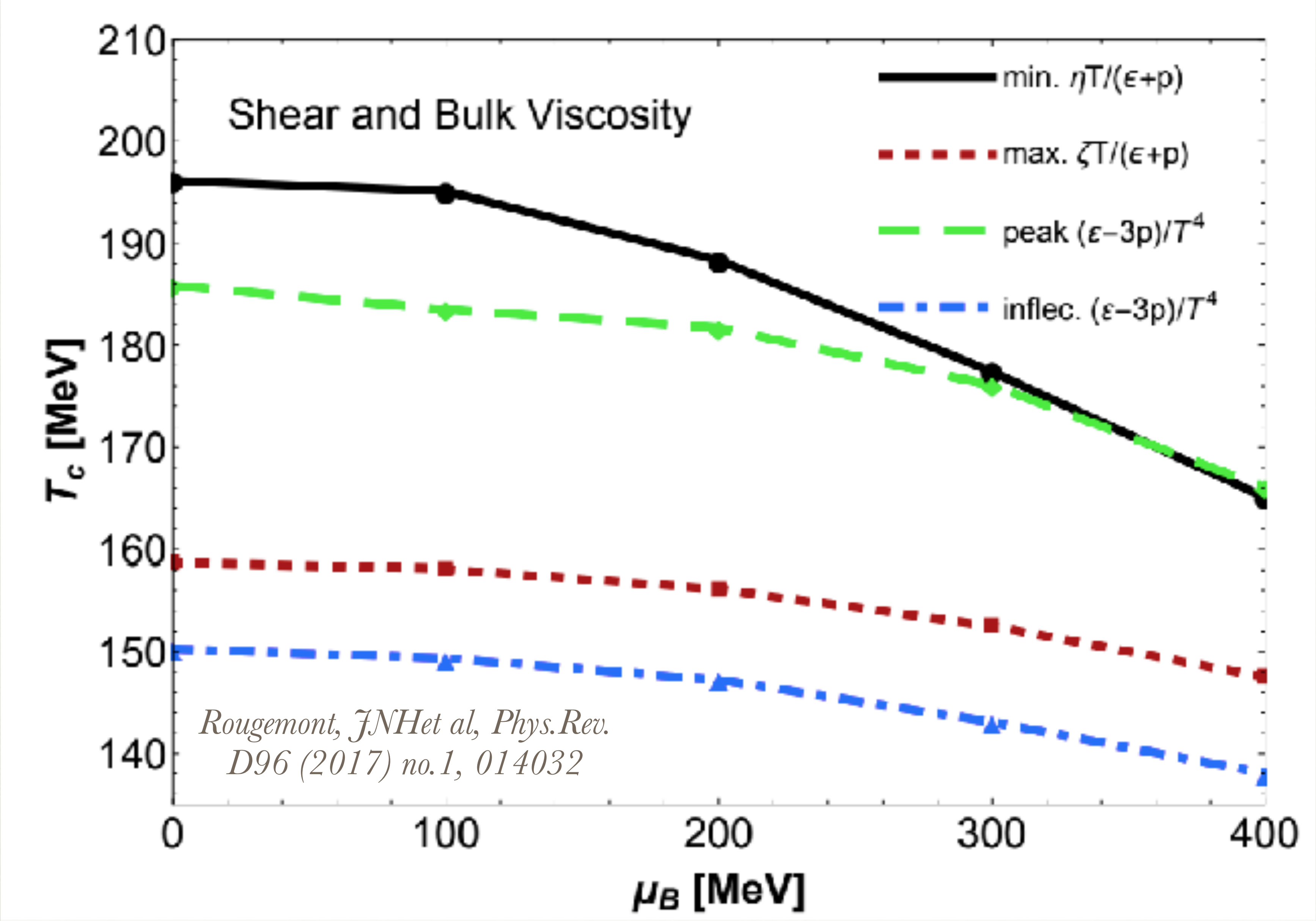
DBNK

Disconzi, Bemfica, Noronha, Kovtun

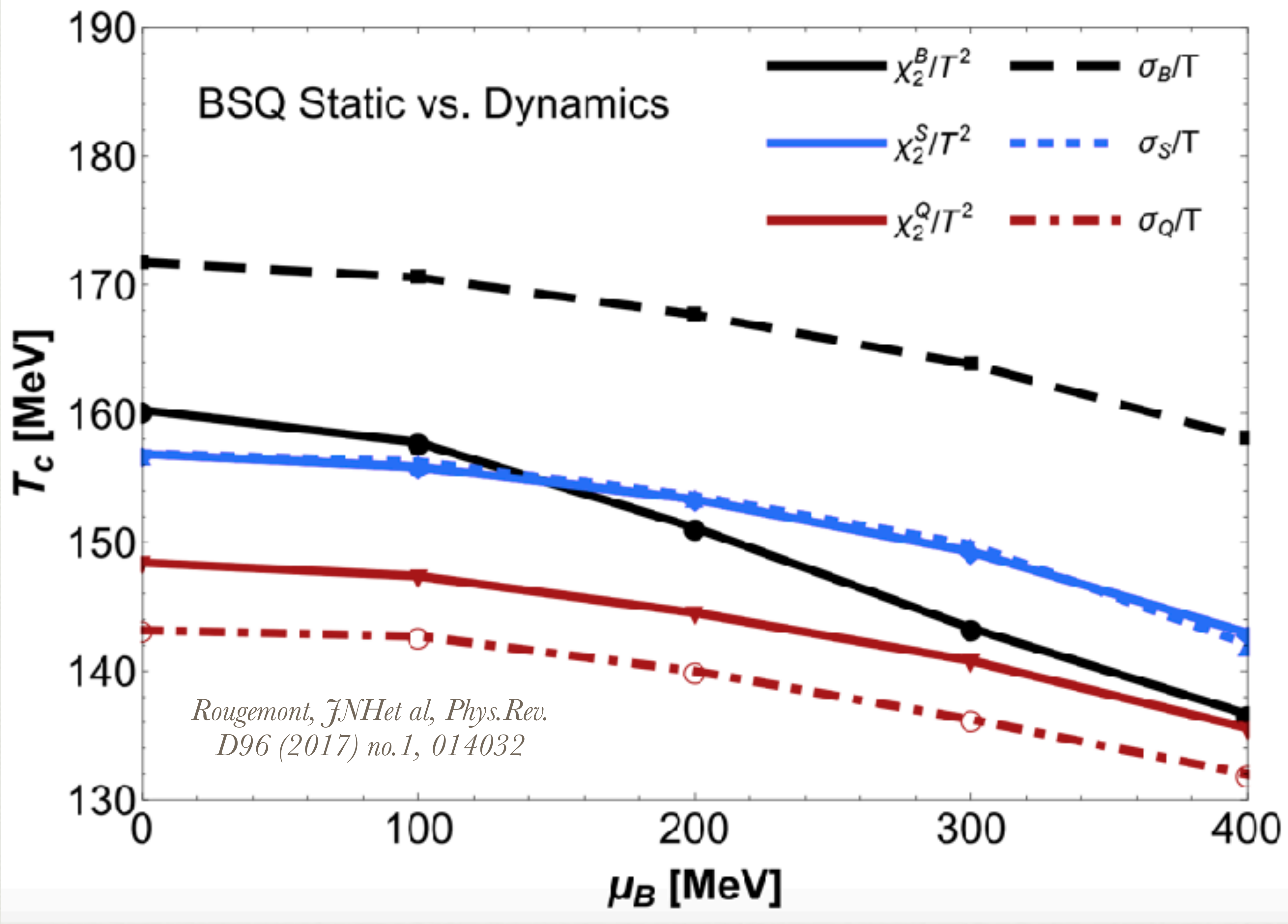
Pseudo-critical temperatures

Example: T at $(\eta/s)_{min}$

Guidance from holography



BSQ T_{pc} in and out of equilibrium



Pseudo critical temperatures of transport coefficients

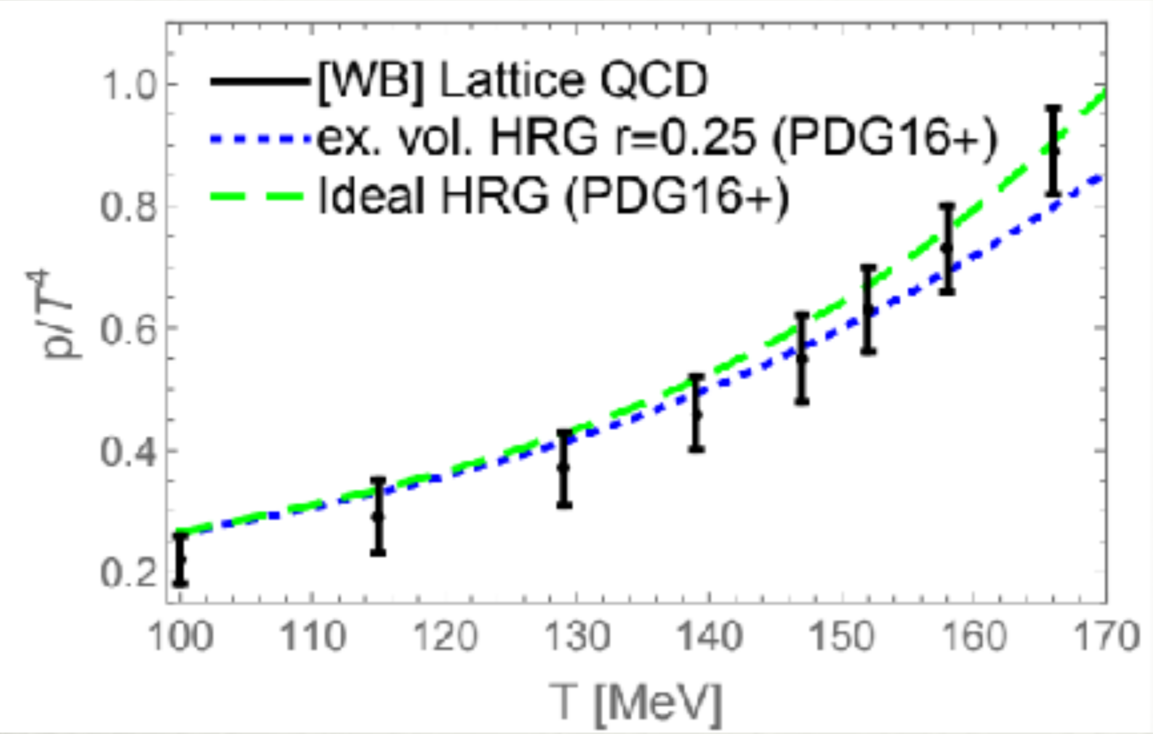
- Should all converge all the critical point
- Large spread at low μ_B
- Equilibrium ($\chi_{B,S,Q}$) vs. Out-of-Equilibrium ($\sigma_{B,S,Q}$) quantities do not, necessarily, have the same pseudo critical temperatures
- How does this affect simulations????

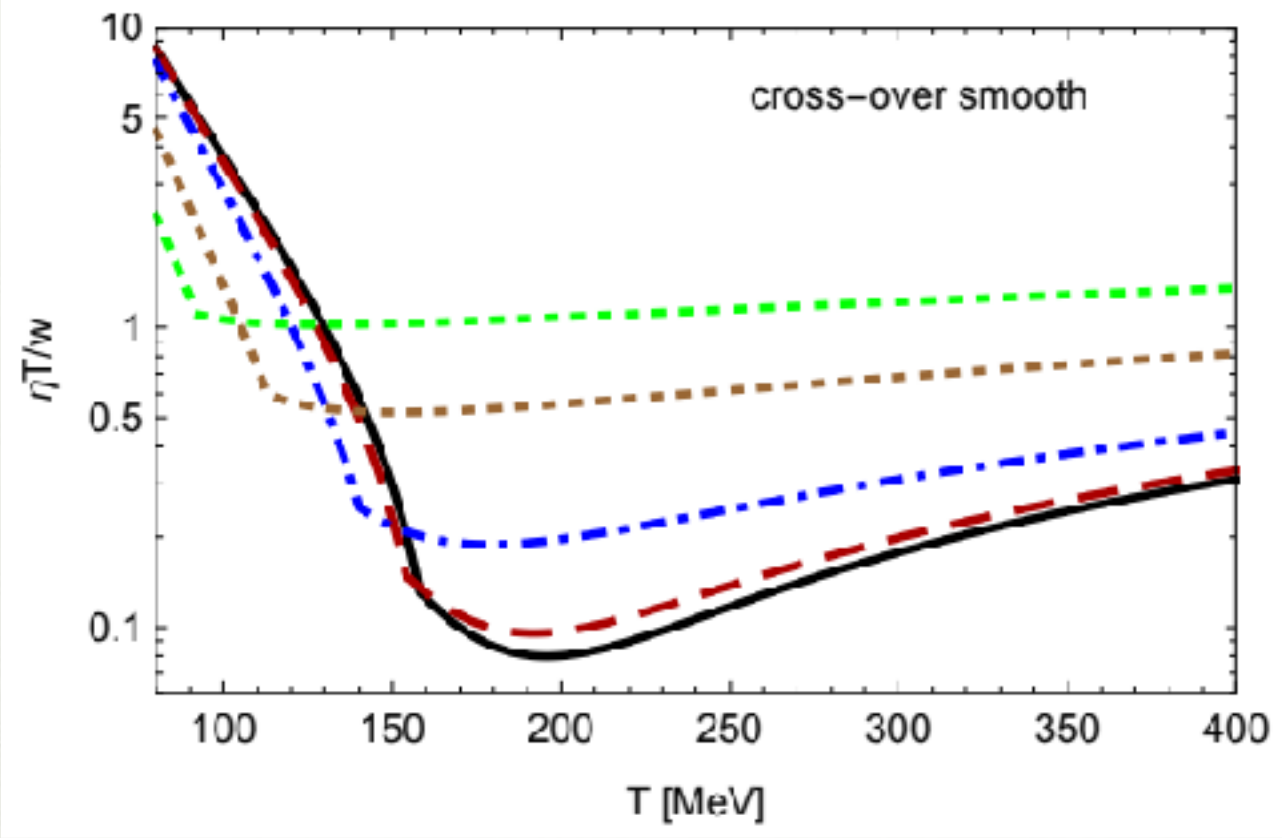
Testable shear viscosity $\eta T/w(T,\mu_B)$

McLaughlin, JNH, et al, 2103.02090

Constrain the Excluded volume from Lattice QCD

Matched to parameterized QGP shear using a variety of methods

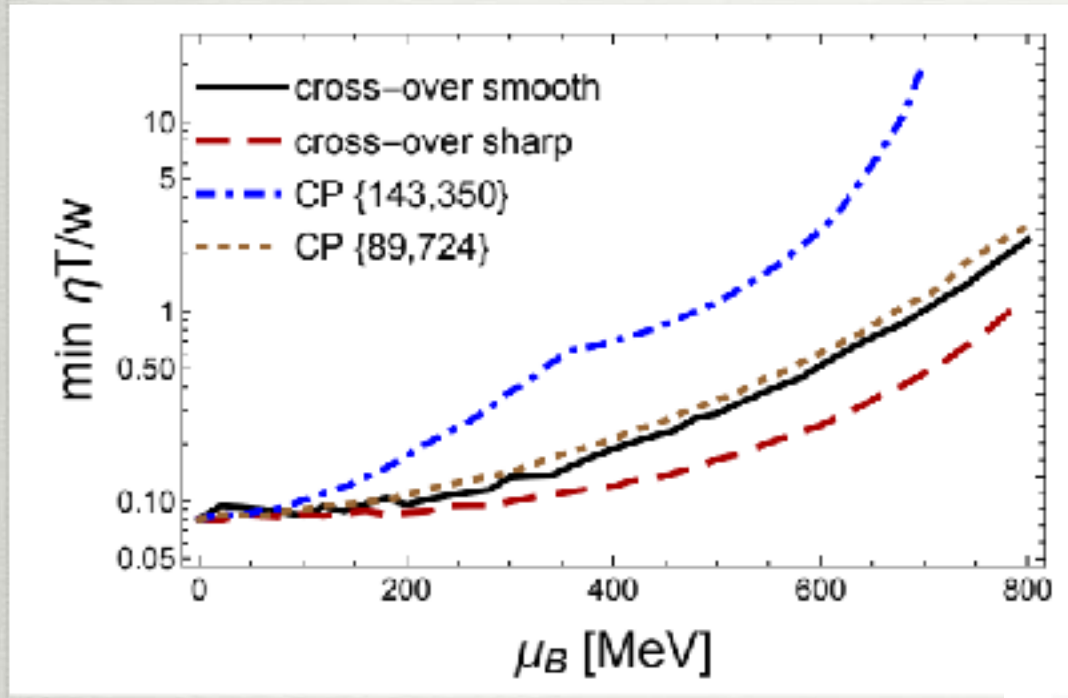




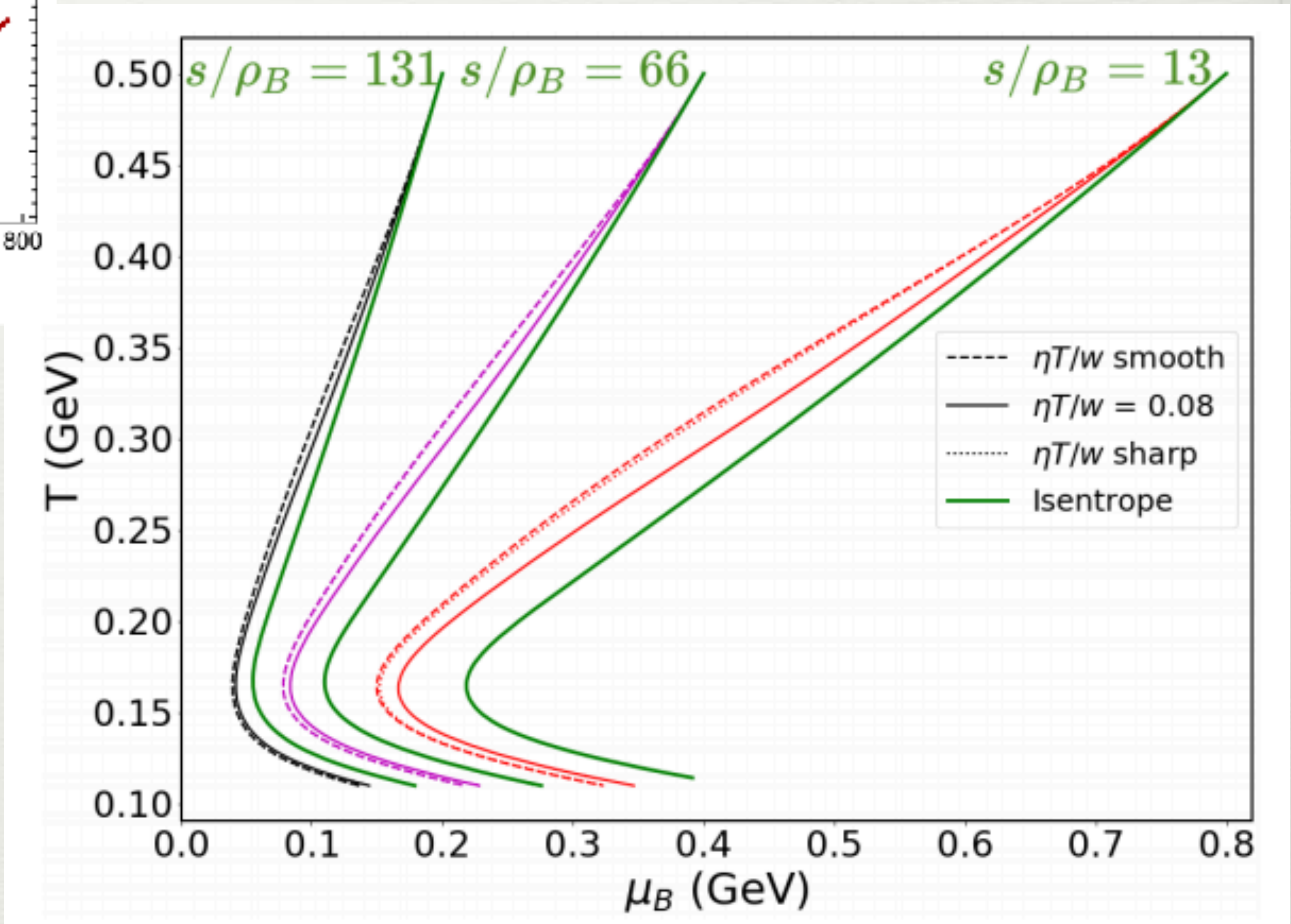
Include critical point (different locations) and sharp vs. smooth cross-over

Consequences of $\eta T/w$ across μ_B

McLaughlin, JNH, et al, 2103.02090

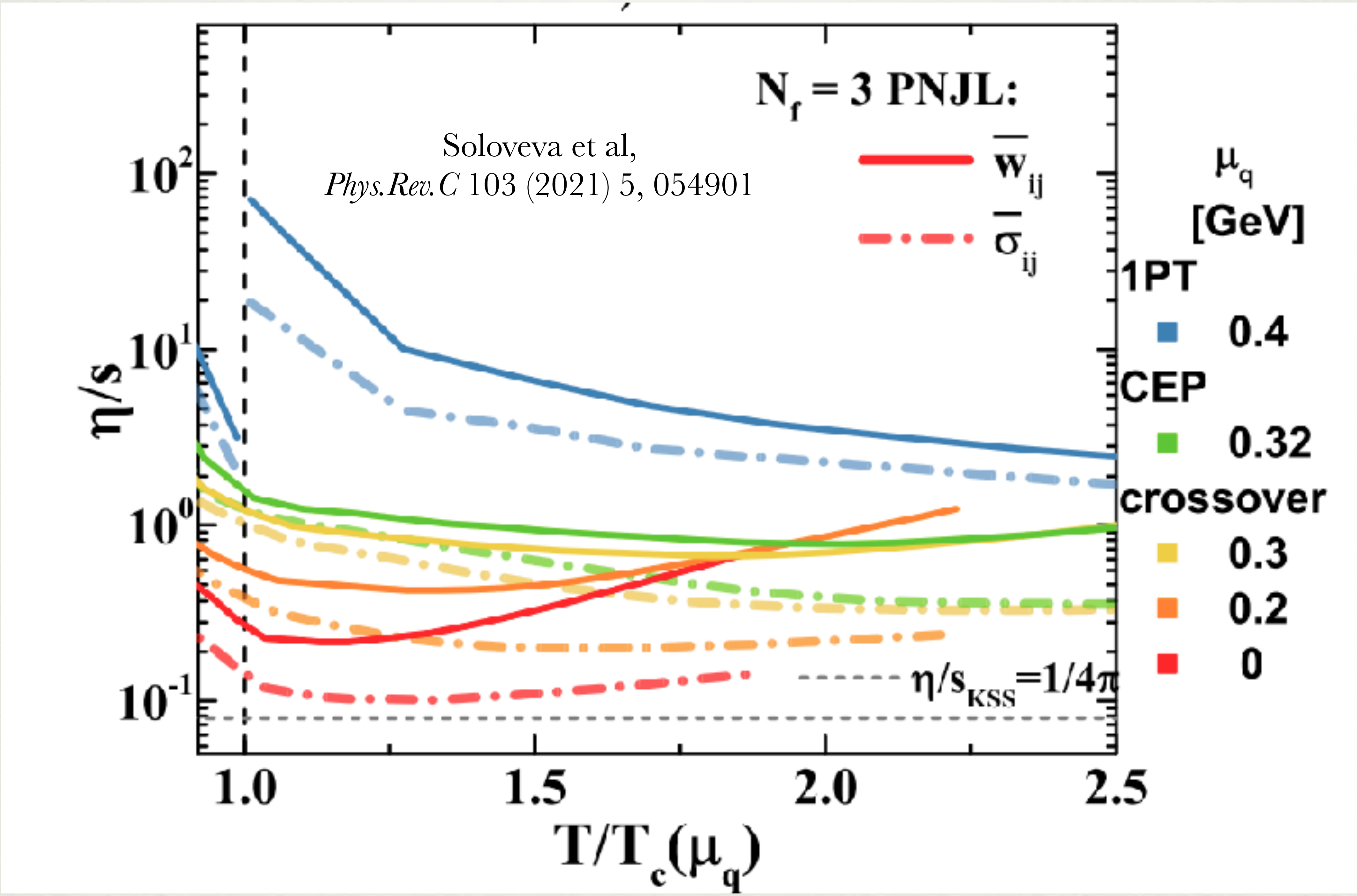


Transition line affects magnitude of $\eta T/w$

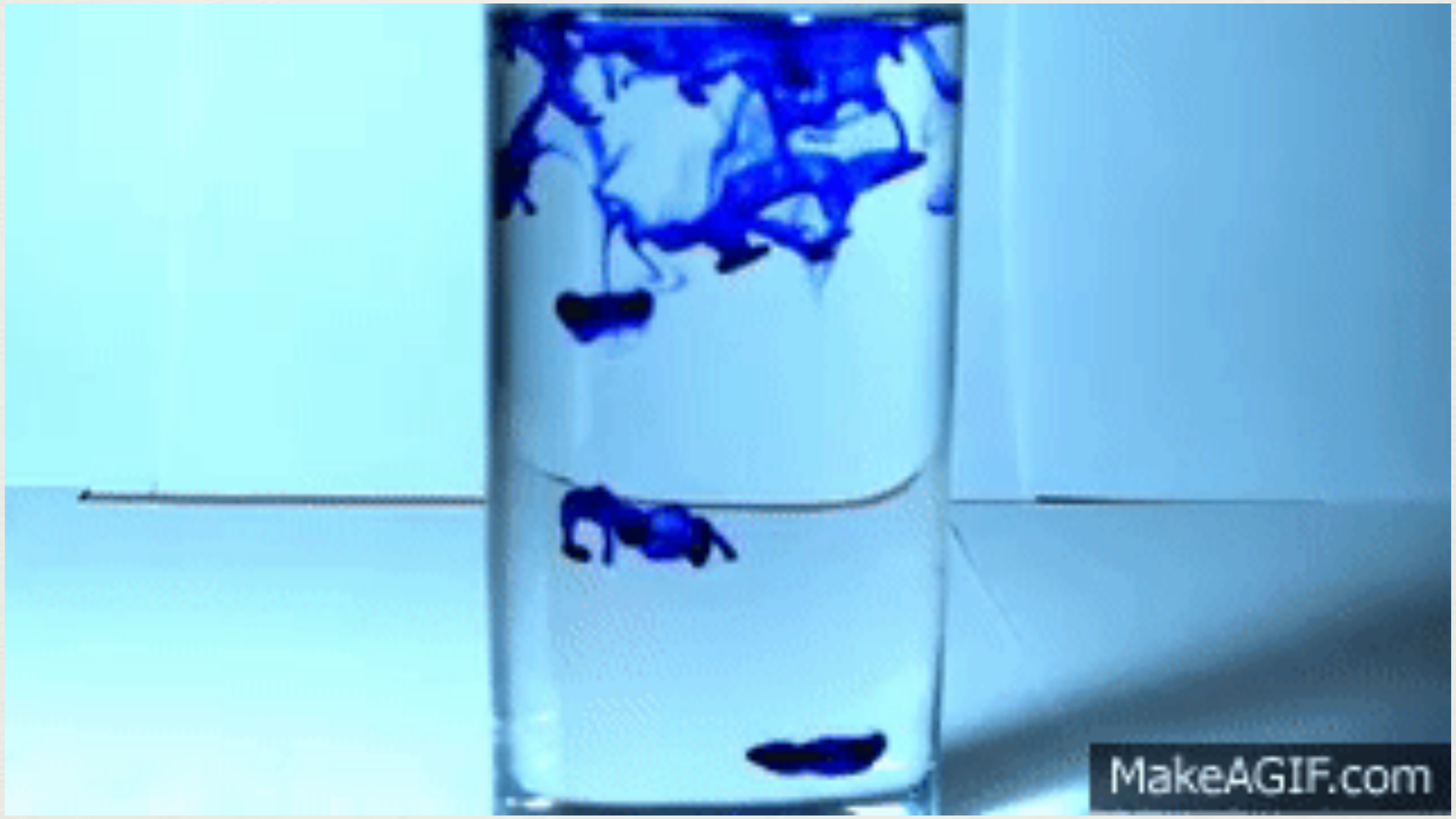


Viscous effects more prevalent at low beam energies

Jump in η/s across a 1st-order phase transition?

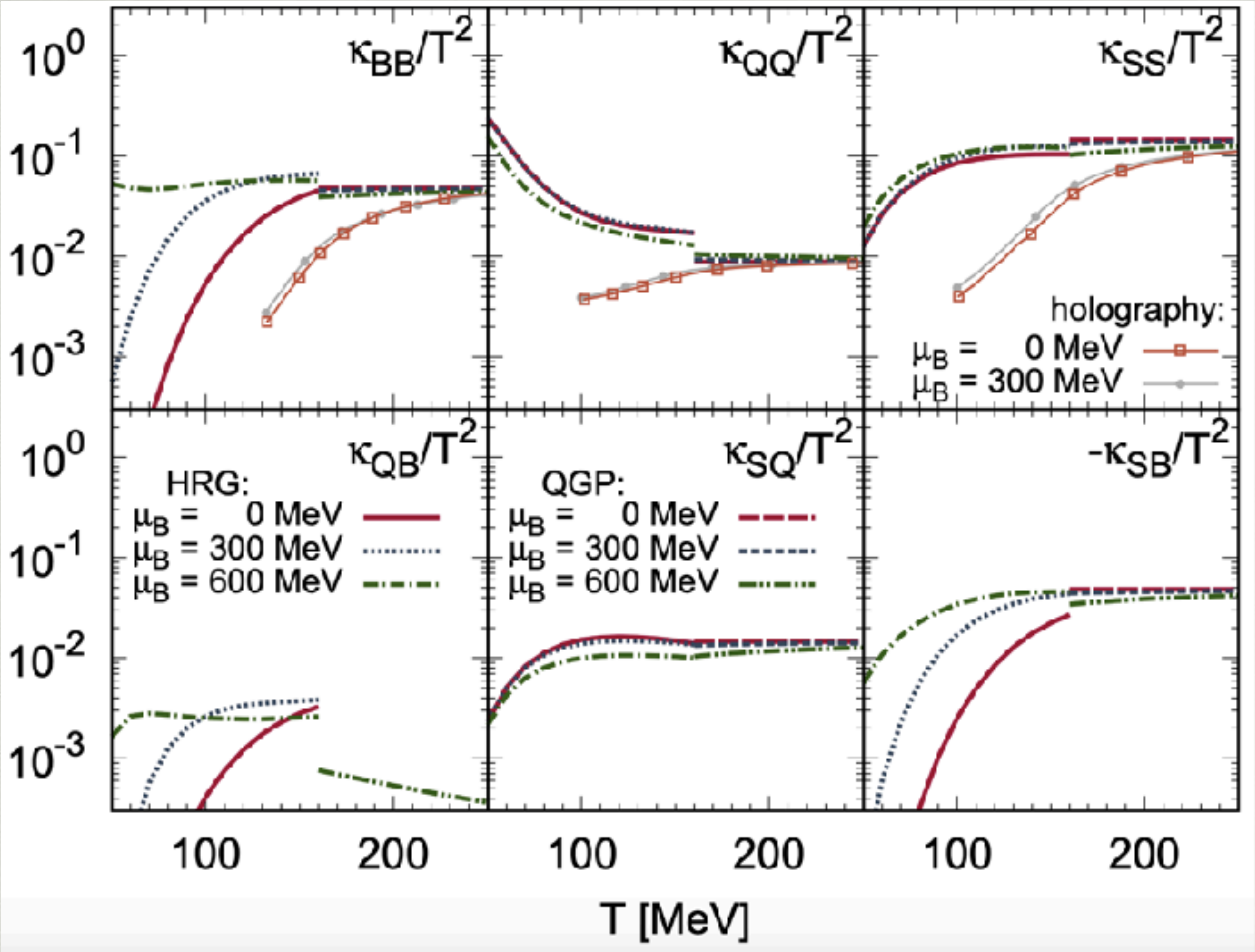


BSQ diffusion



How do quarks spread out over time? How quickly do u, d, s quarks diffuse through out the QGP since they carry multiple conserved charges?

BSQ Diffusion



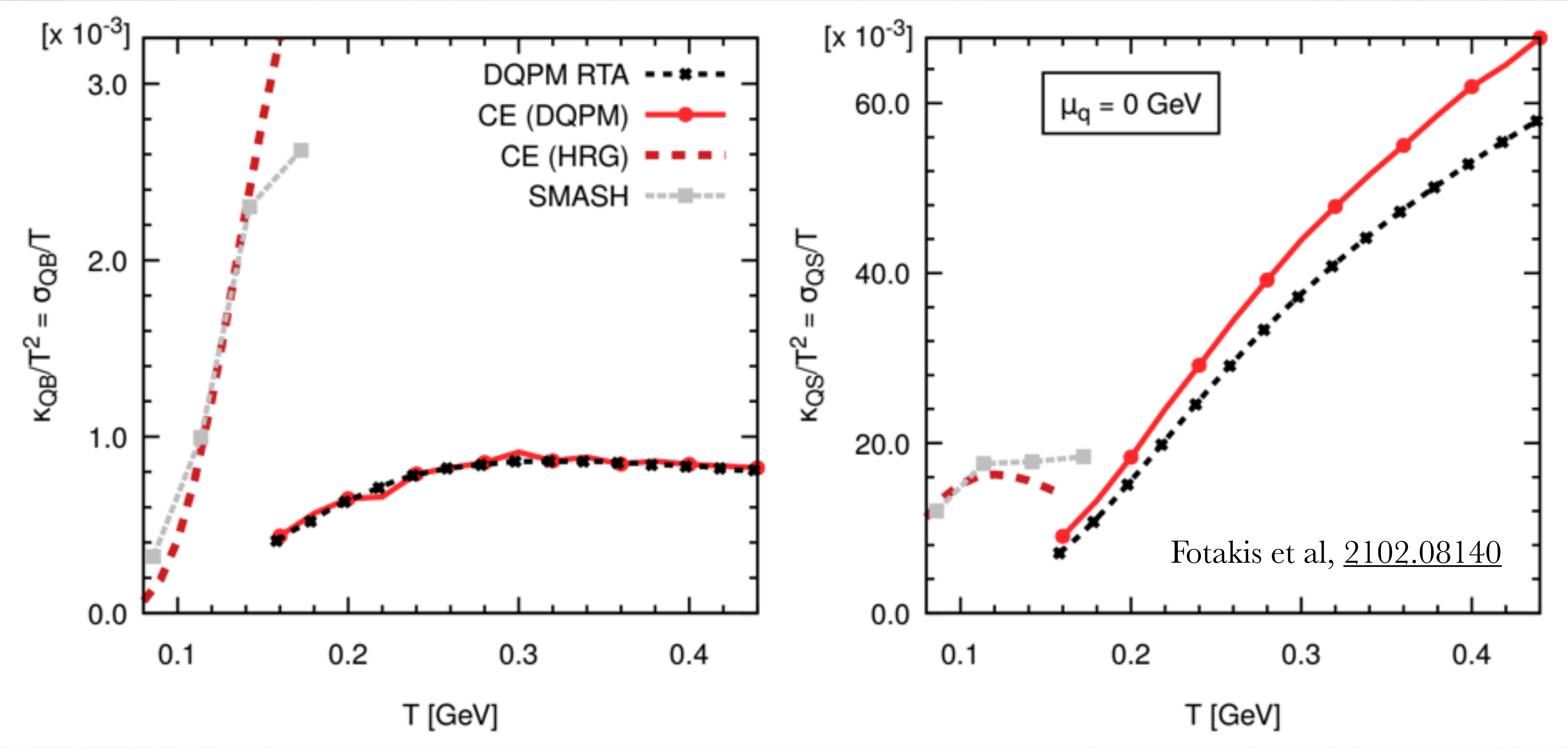
Kinetic Theory

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

Diffusion: HRG to QGP?

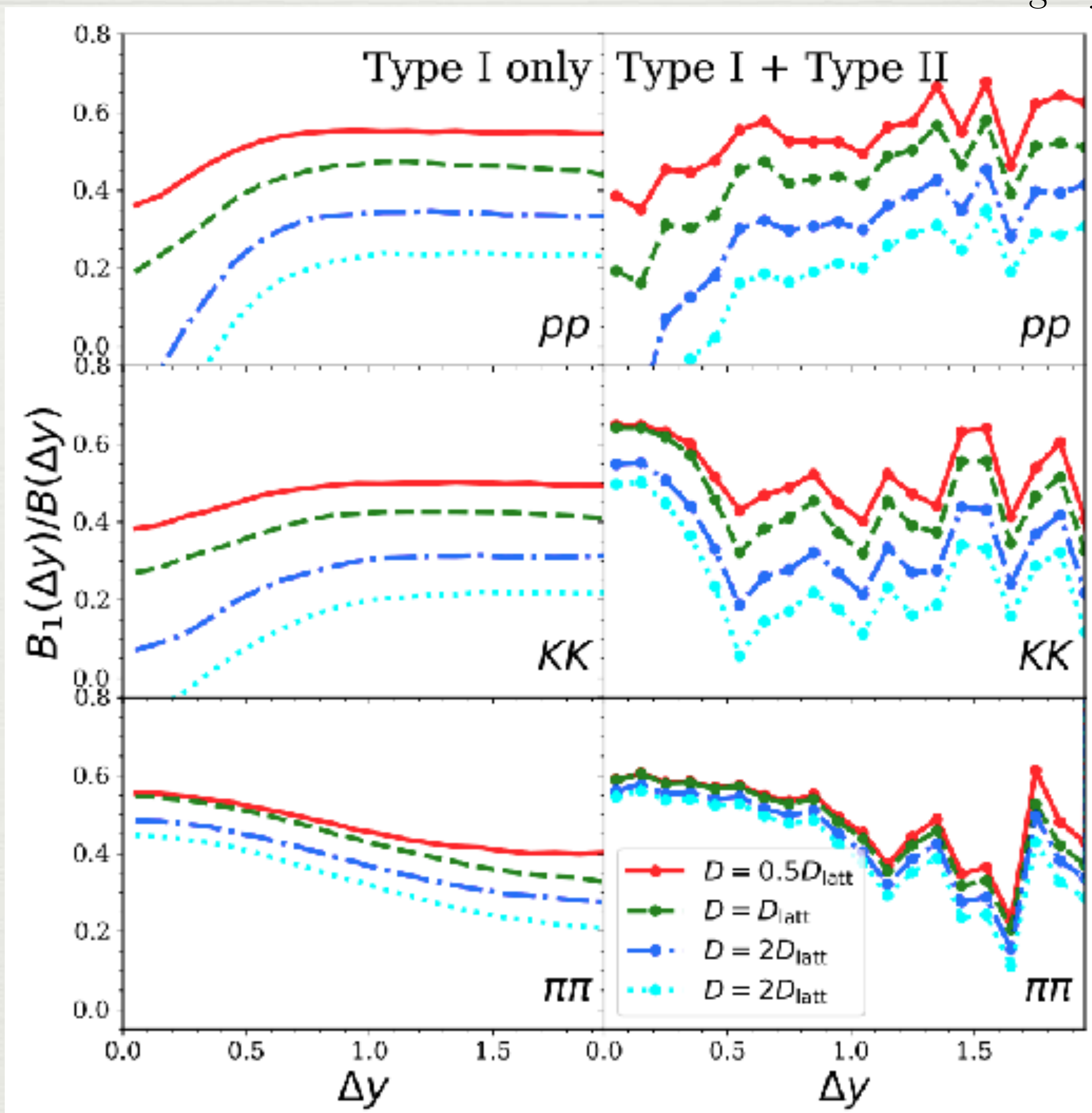


Fotakis et al, 2102.08140

J. Noronha-Hostler

Charge Balance functions: potential probe of diffusion?

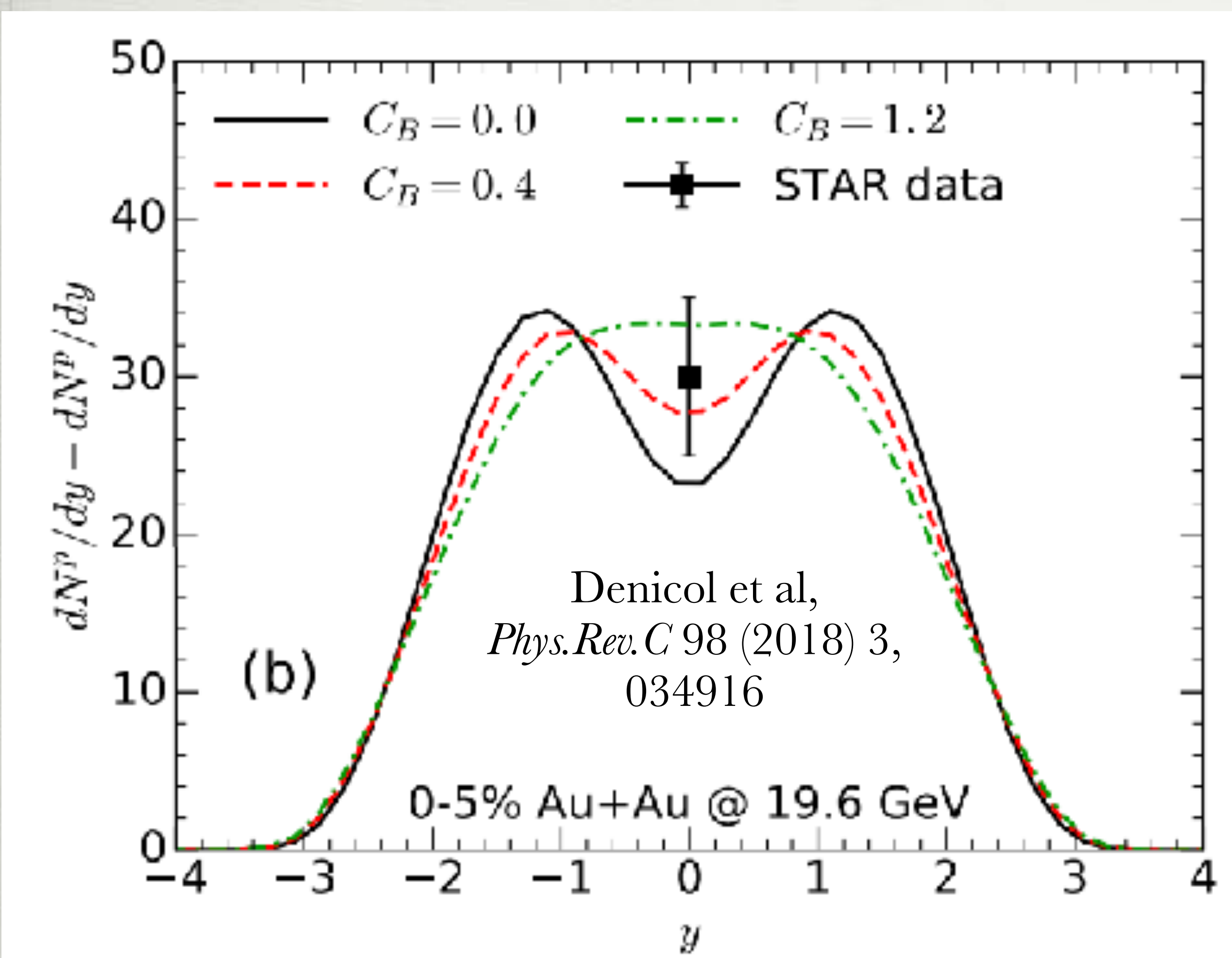
Pratt and Plumberg *Phys.Rev.C* 104 (2021) 1, 014906



J. Noronha-Hostler

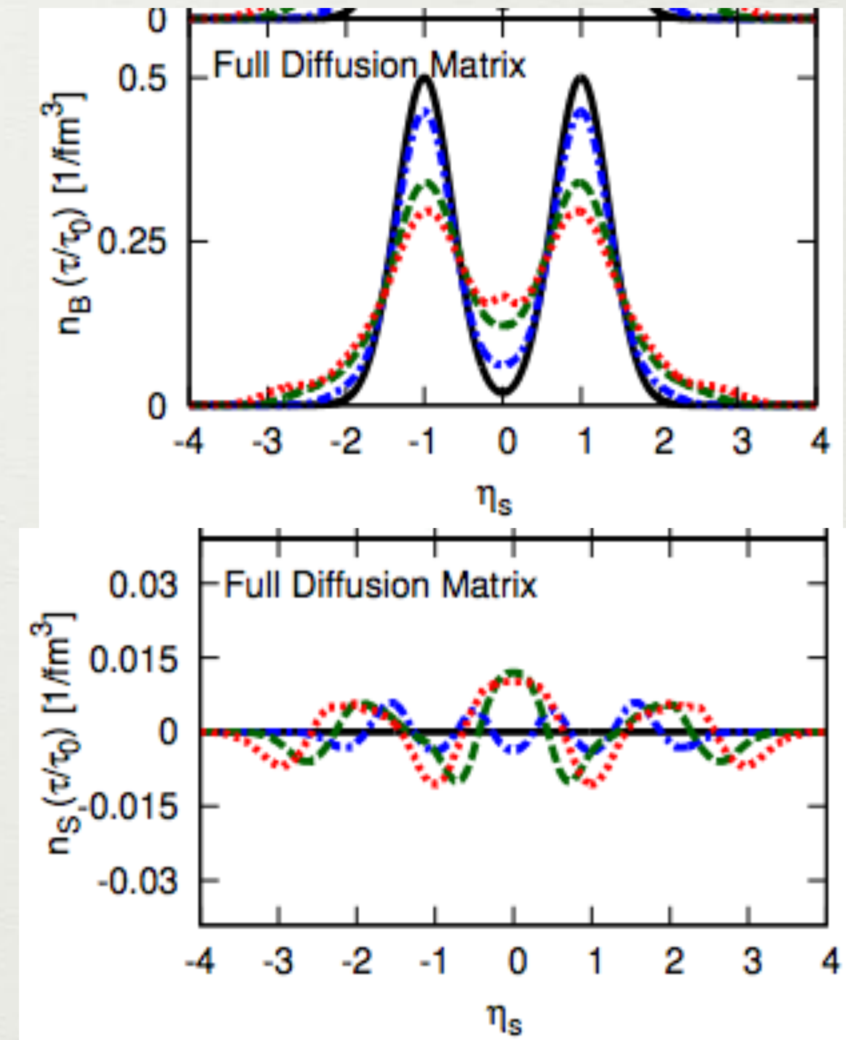
Initial hydro results

3+1 B hydro



Denicol et al, *Phys.Rev.C* 98 (2018) 3, 034916

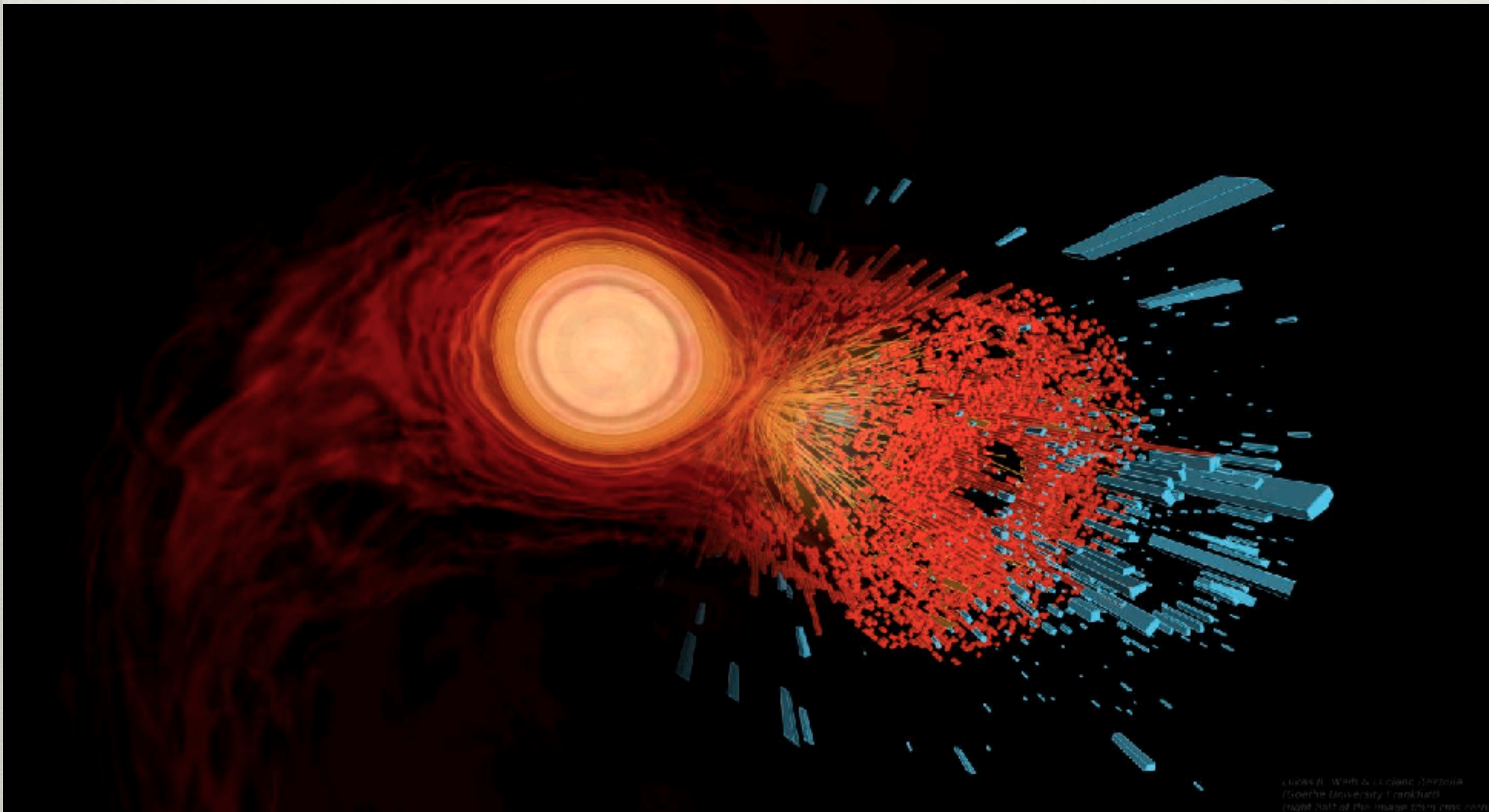
1+1 BS hydro



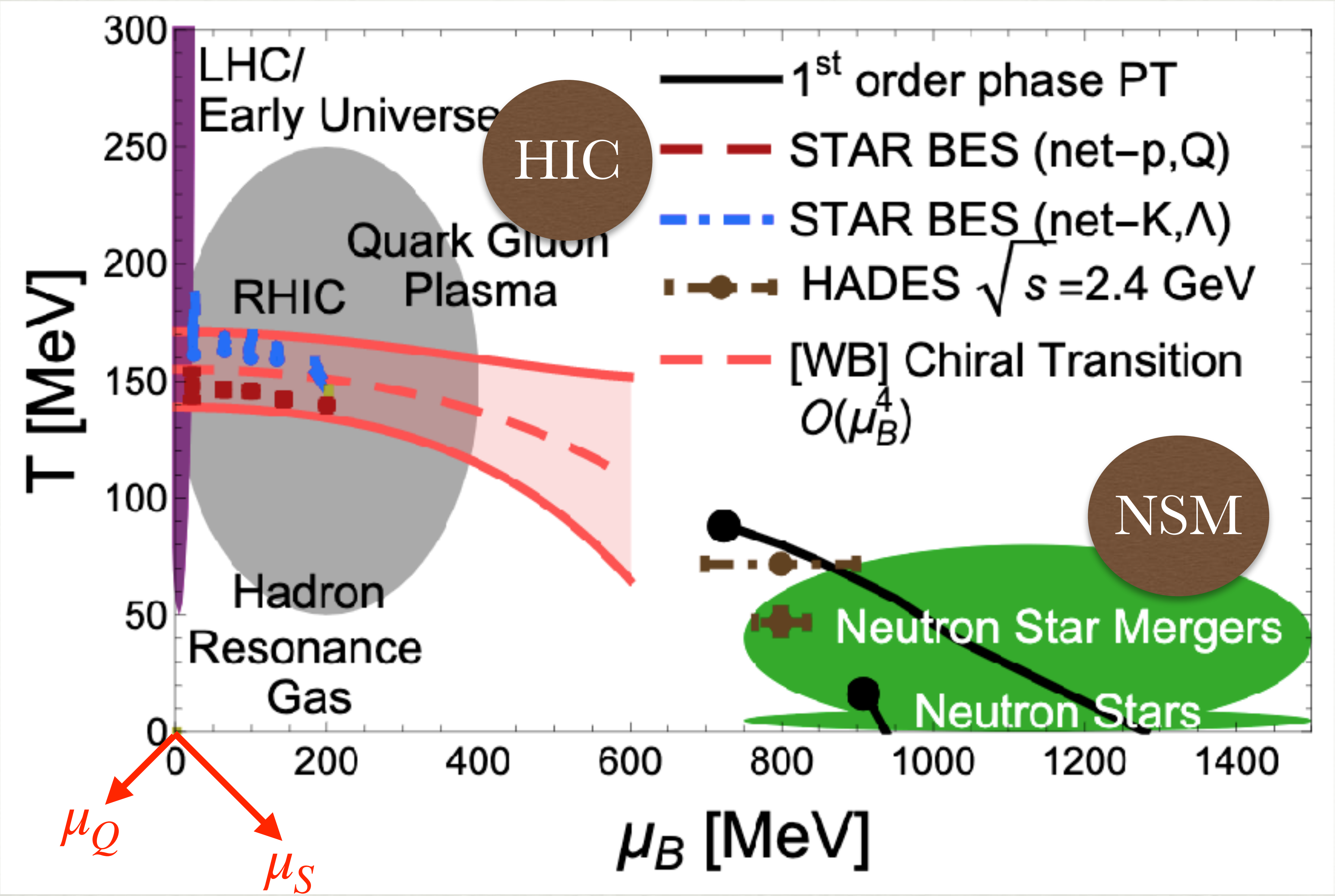
See also, Du, Heinz Comput.Phys.Commun. 251 (2020) 107090

Fotakis et al *Phys.Rev.D* 101 (2020) 7, 076007

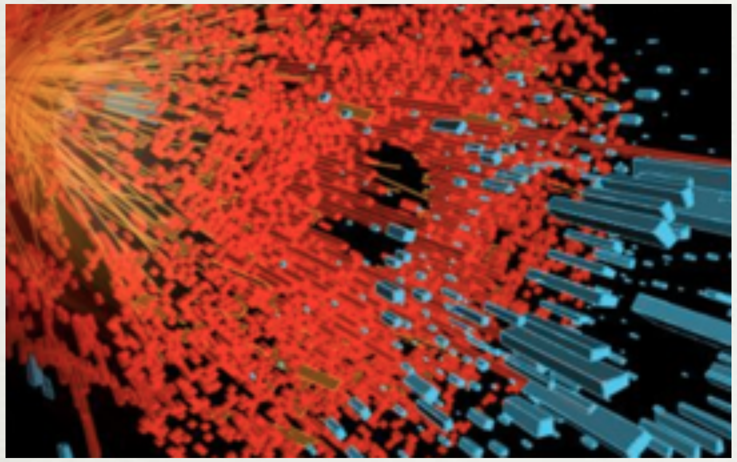
Nucleus-Nucleus collisions= mini-neutron star mergers?

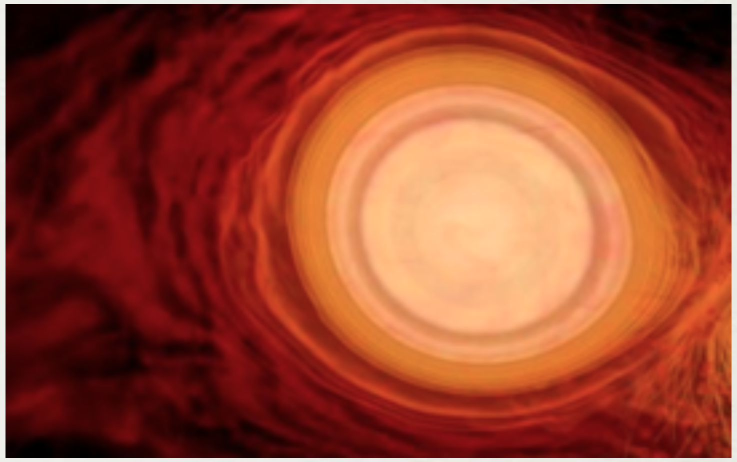


How do we connection the heavy-ion and neutron star EOS?



Key differences between heavy-ions and neutron star (mergers)

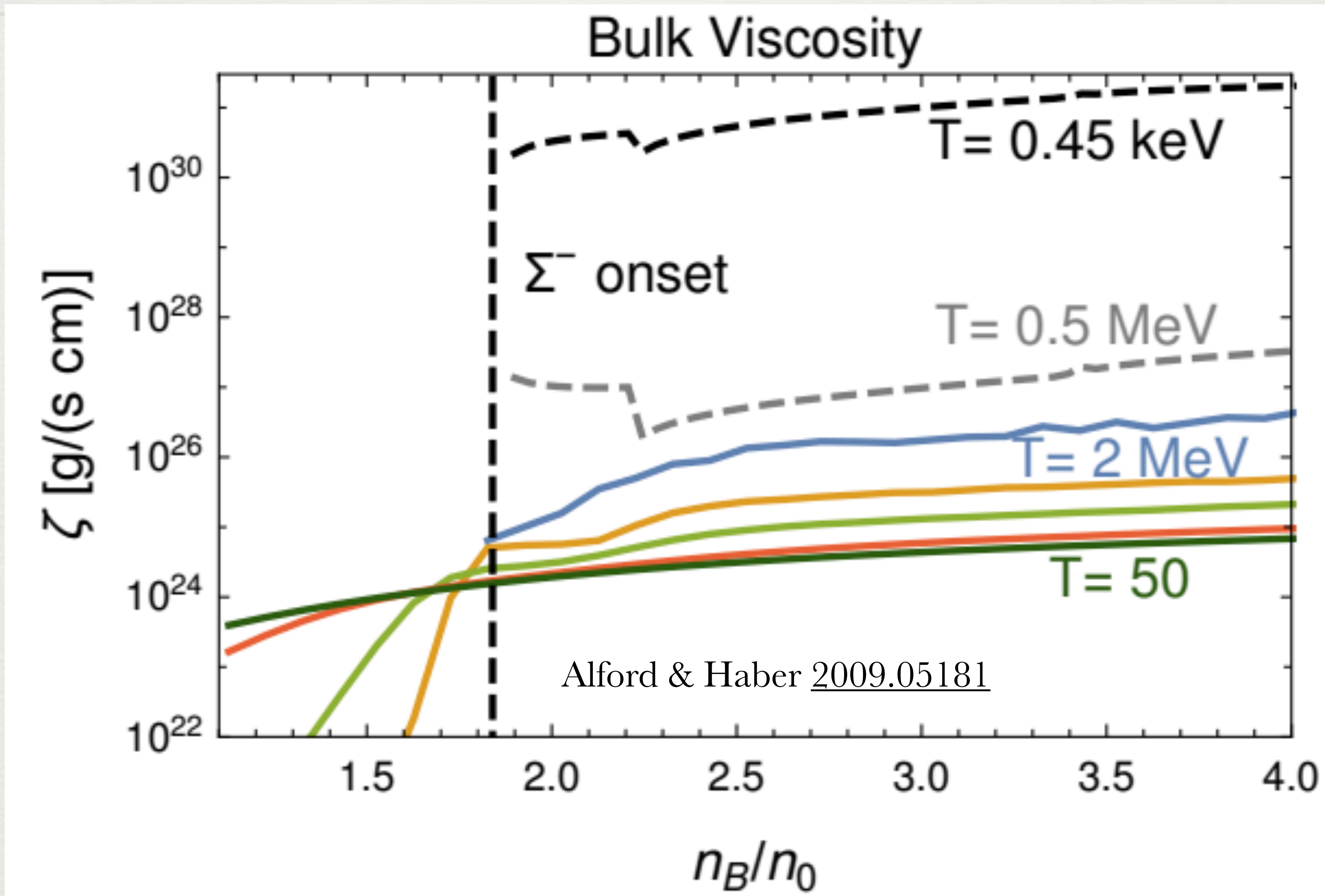




- Strangeness neutrality $\langle S \rangle = N_S - N_{\bar{S}} = 0$
- Short lifetime, strangeness conserved
- Charge: p vs. n in ions $0.4\langle Q \rangle \sim \langle B \rangle$

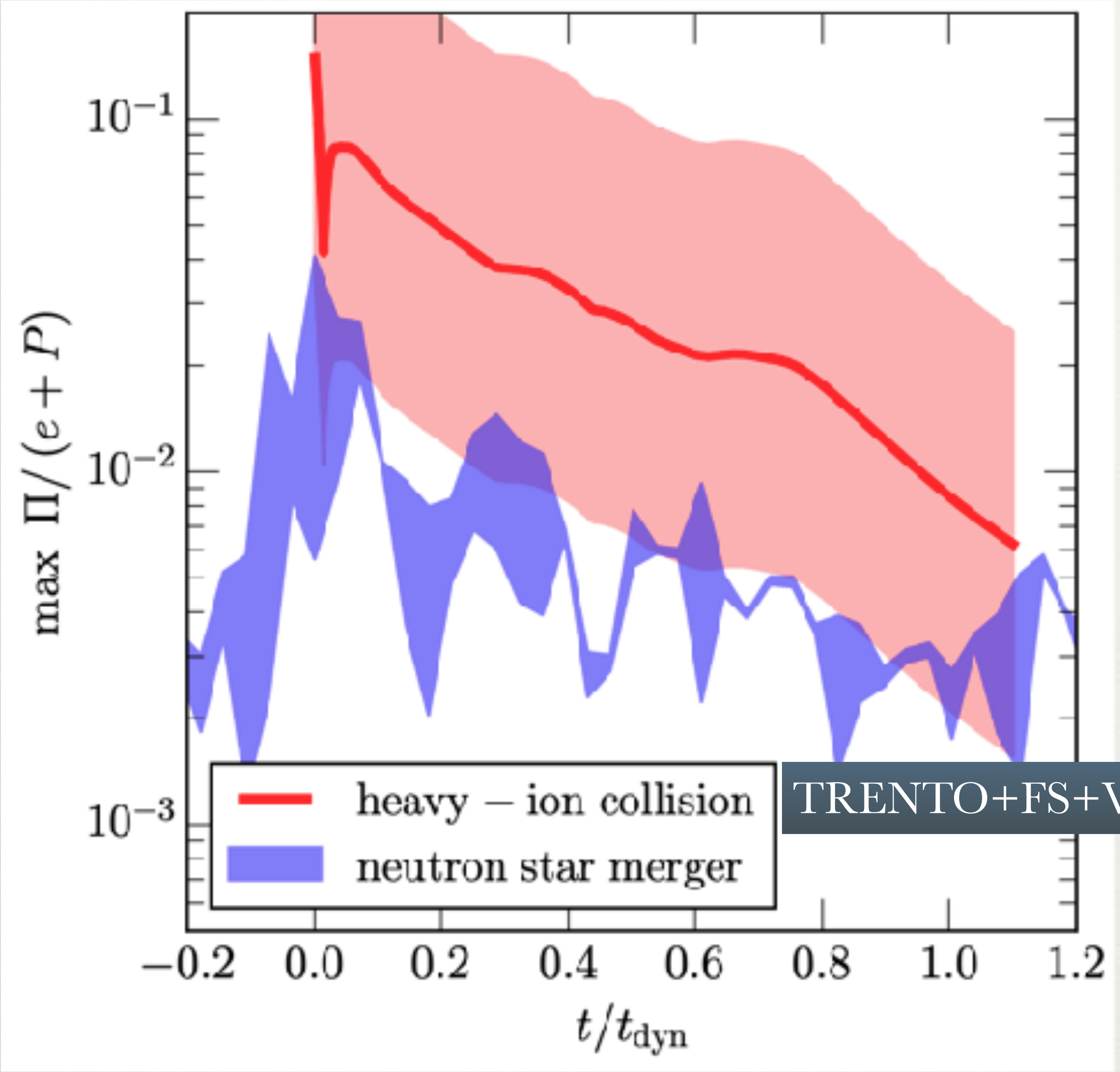
- Long lifetime, weak decay: $s \rightarrow u + W^-$
- Strangeness most likely *not* in equilibrium
- Electrically neutral for stability $\langle Q \rangle = 0$

Bulk viscosity in neutron star mergers



New approach to understand the microscopic degrees of freedom in neutron stars

Bulk viscosity in neutron star mergers, comparable to heavy-ions!



TRENTO+FS+VISHNU

- Collaborations with relativistic viscous hydrodynamics needed
- +GR, what new observables?
- Effects on lifetime? QCD phase transition?

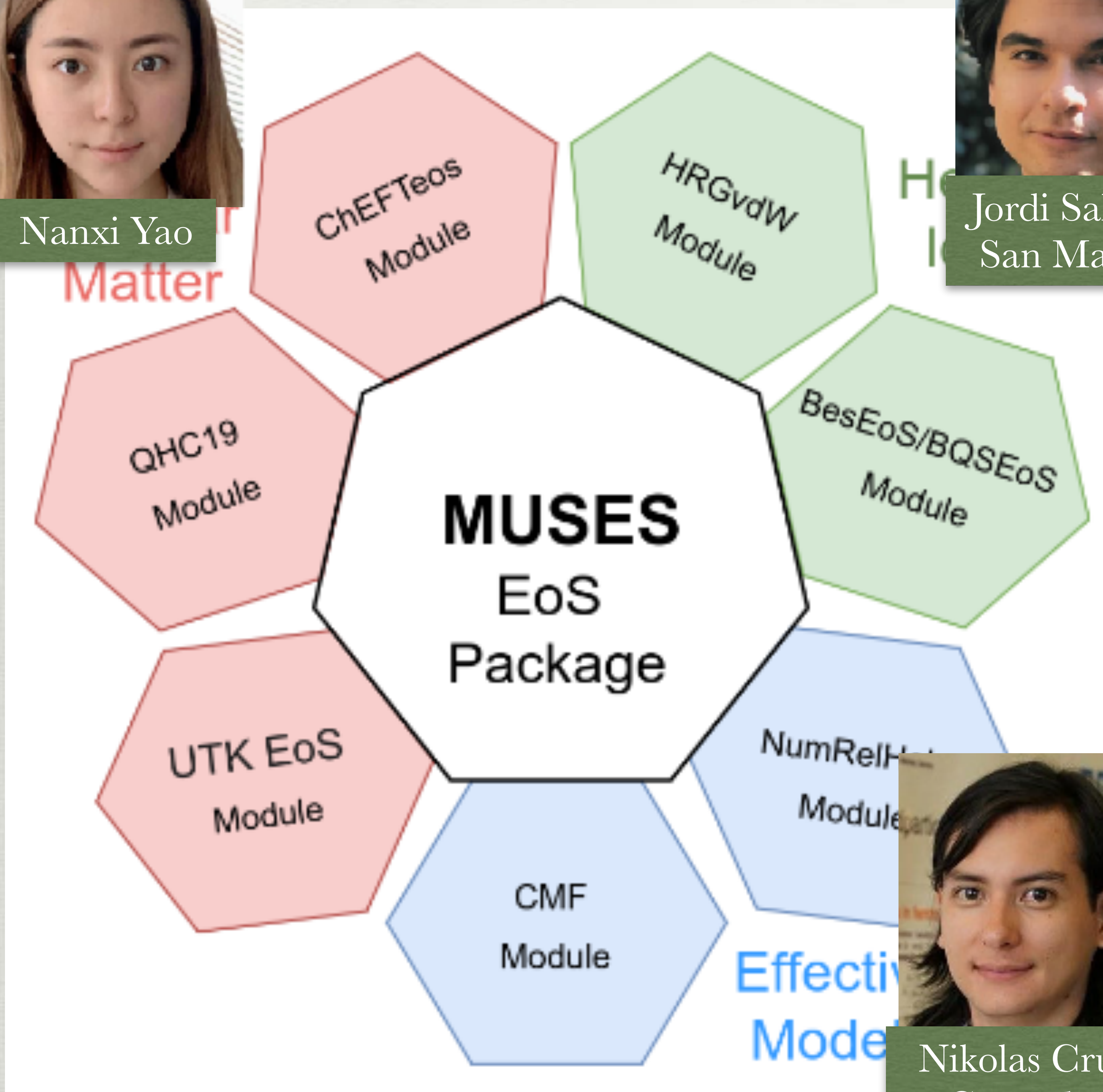
Alford, Harris, Most, Noronha, JNH, Pretorius, Plumberg, Witek, Yunes 2107.05094 [astro-ph.HE]

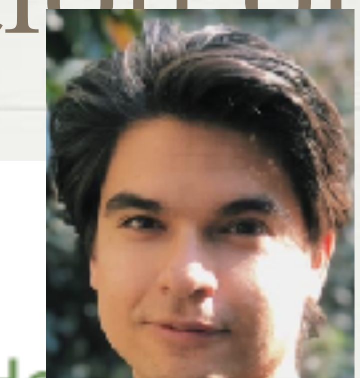
Viscosity in heavy-ions to neutron stars

- Very different sources.
  - Heavy-ions: directly from QCD
  - Neutron star mergers: neutrino oscillations, truculence
- Differences in codes.
  - Heavy-ions: focus on fast codes, short timescales, negative densities
  - Neutron star mergers: precision, adaptive hydrodynamics

MUSES: Modular Unified Solver of the Equation of State

Nanxi Yao




Jordi Salinas San Martín

Nikolas Cruz Camacho

Recommended for funding by the NSF

16+ institutions, combines nuclear/computer science/ gravity/astro/particle

Conclusions and Outlook

- Critical region along T axis creates a trajectory attractor
- BSQ charges likely will affect final flow harmonics
- Studies of BSQ viscous hydrodynamics underway
- Unanswered questions about transport coefficients at finite μ_B
- Overlap in heavy-ion collisions and neutron star mergers, but need viscosity in future simulations