New developments to localize the QCD critical point

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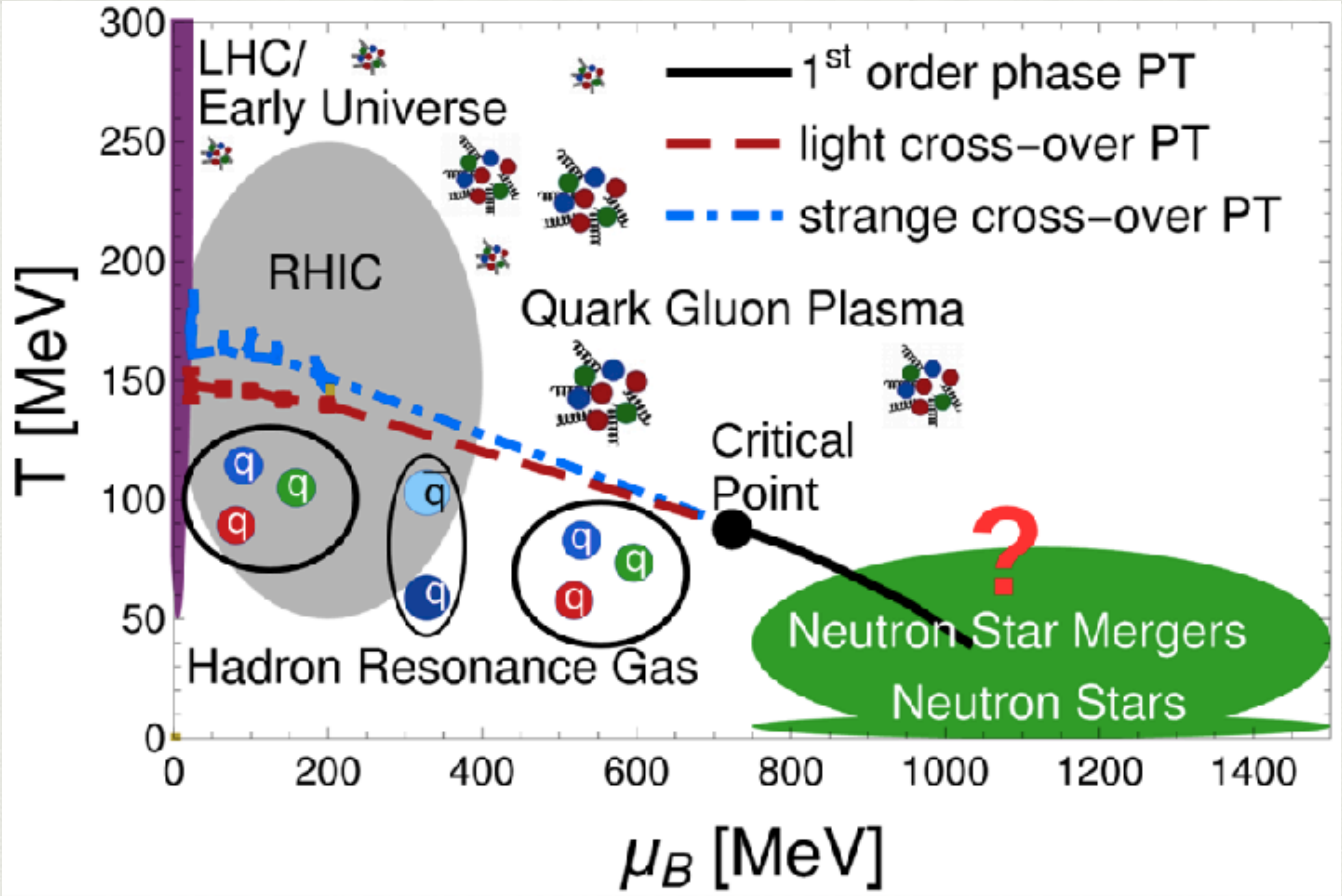
HADRON 2021, Mexico City

Illinois Center for Advanced Studies of the Universe

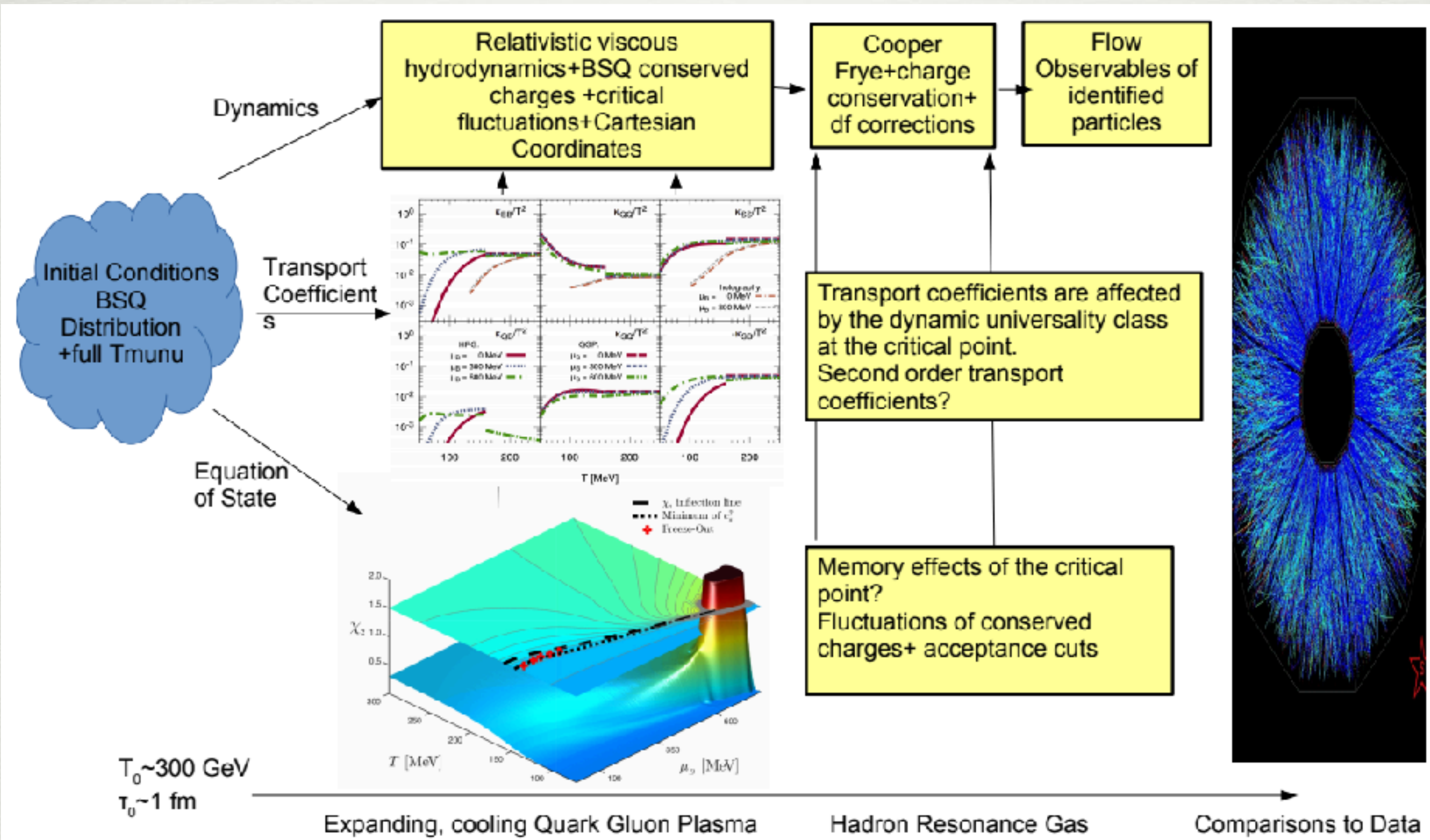
QCD Phase Diagram



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*

Needed Theoretical development

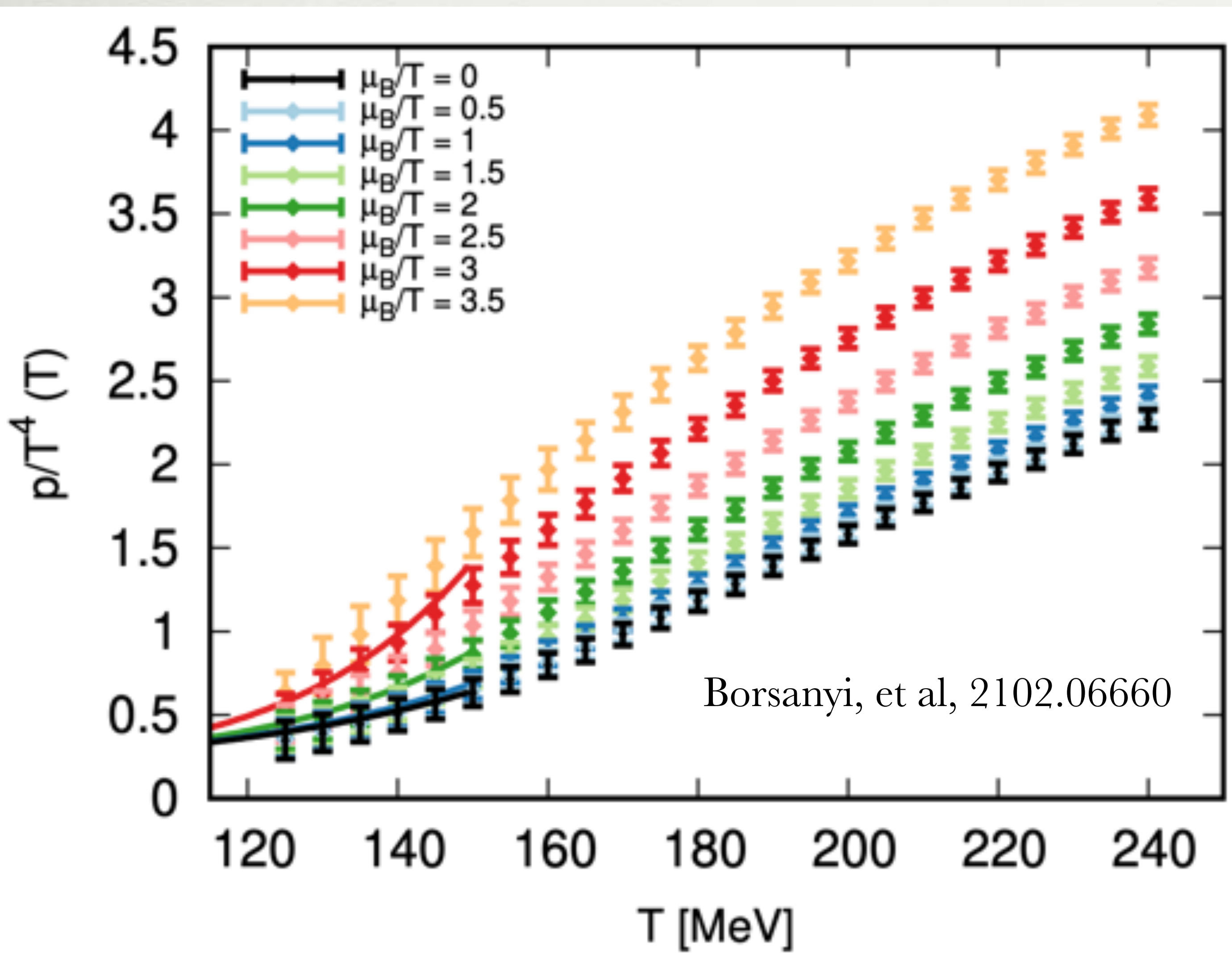
Review: Dexheimer, Noronha, JNH, Ratti, Yunes, *J.Phys.G* 48 (2021) 7, 073001

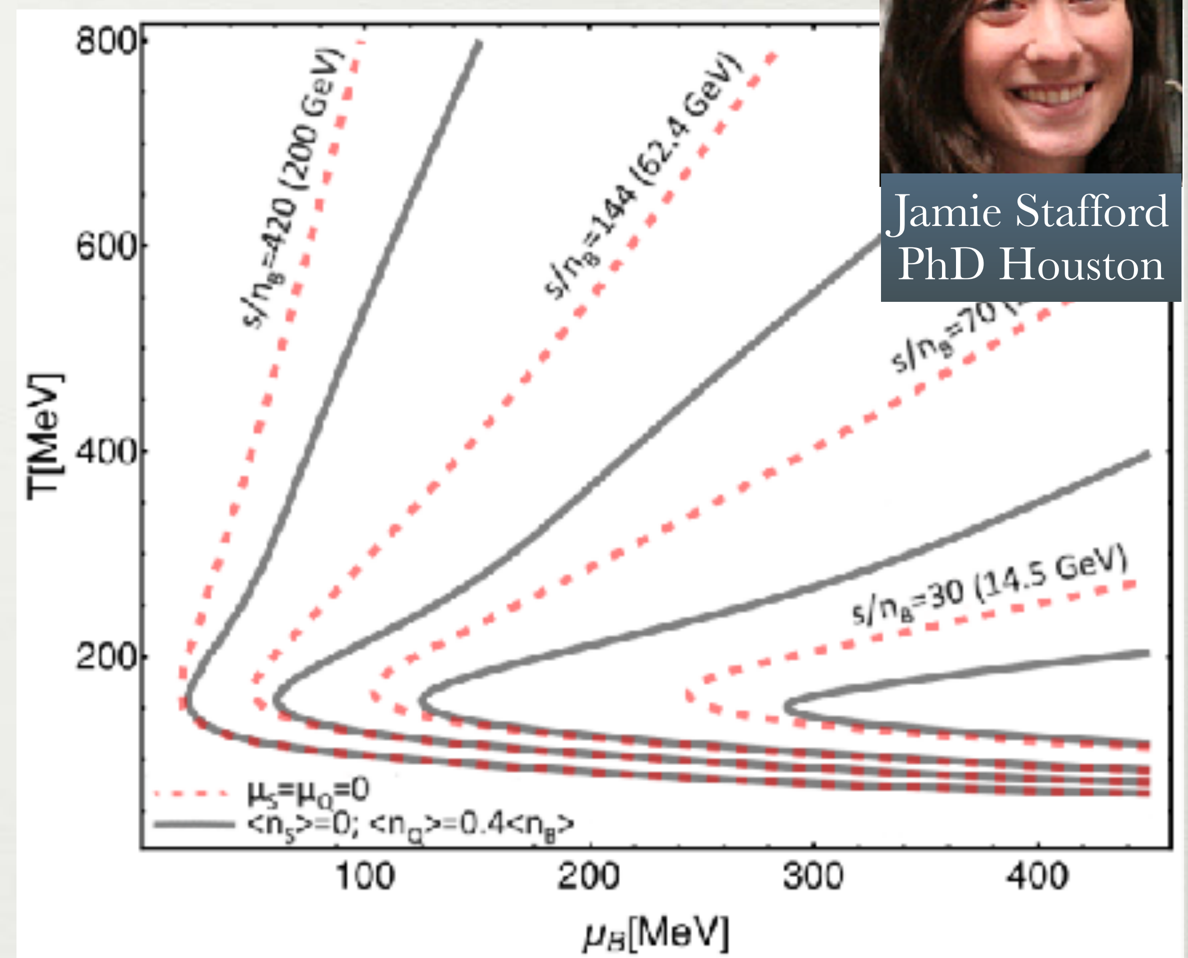


$\mu_B^{max} \sim 525\text{MeV}$

EOS: Lattice QCD (only)

New resummation scheme to reach larger μ_B





Jamie Stafford
PhD Houston

2 open-source codes that reconstruct the BSQ EOS

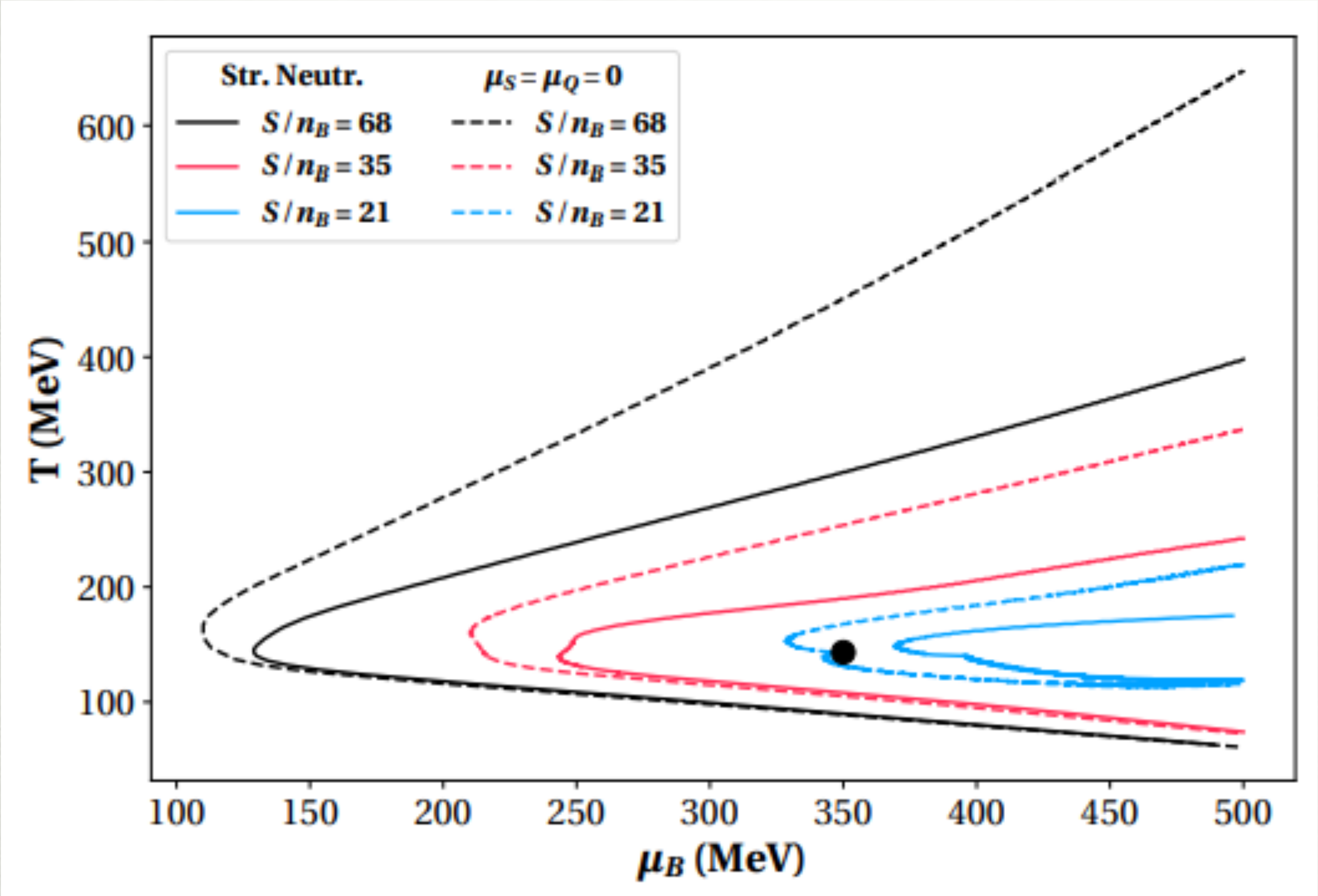
JNH, Stafford, et al, *Phys.Rev.C* 100 (2019) 6, 064910
Monnai et al, *Phys.Rev.C* 100 (2019) 2, 024907

$\mu_B^{max} \sim 450 - 600\text{MeV}$

EOS: Lattice + criticality

Taylor series does not capture criticality

Couple Lattice QCD to 3D Ising model



Stafford, JNH et al, arXiv:2103.08146
Parotto, JNH et al, *Phys.Rev.C* 101 (2020) 3, 034901

2 conditions:

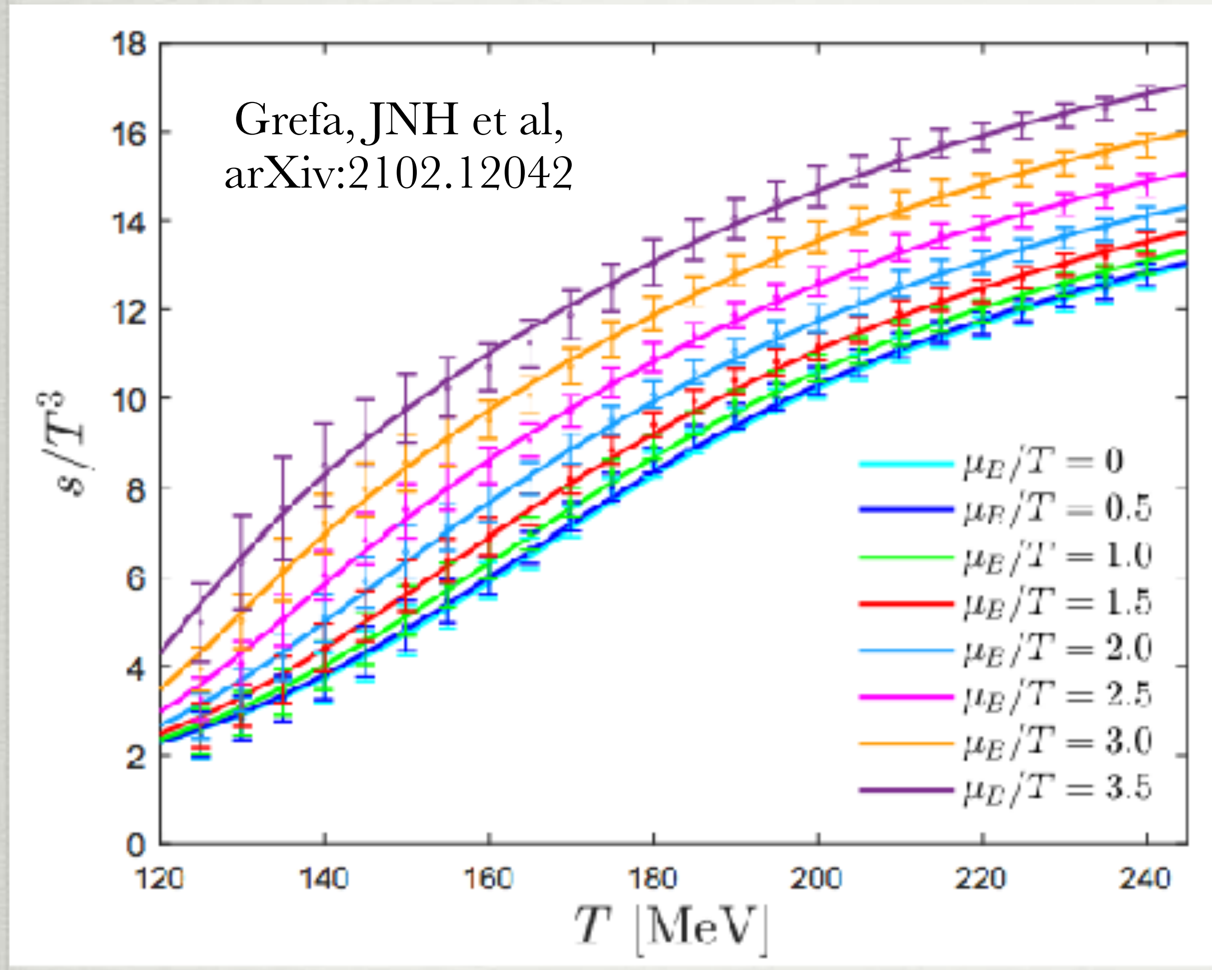
- Baryon conservation: $\mu_B > 0, \mu_S = \mu_Q = 0$
- Heavy-Ion Trajectory: $\mu_B > 0, \langle\rho_S\rangle = 0, \langle\rho_Q\rangle = 0.4\langle\rho_B\rangle$

Debora Mroczek
UIUC PhD Student

Paolo Parotto
PD Wuppertal

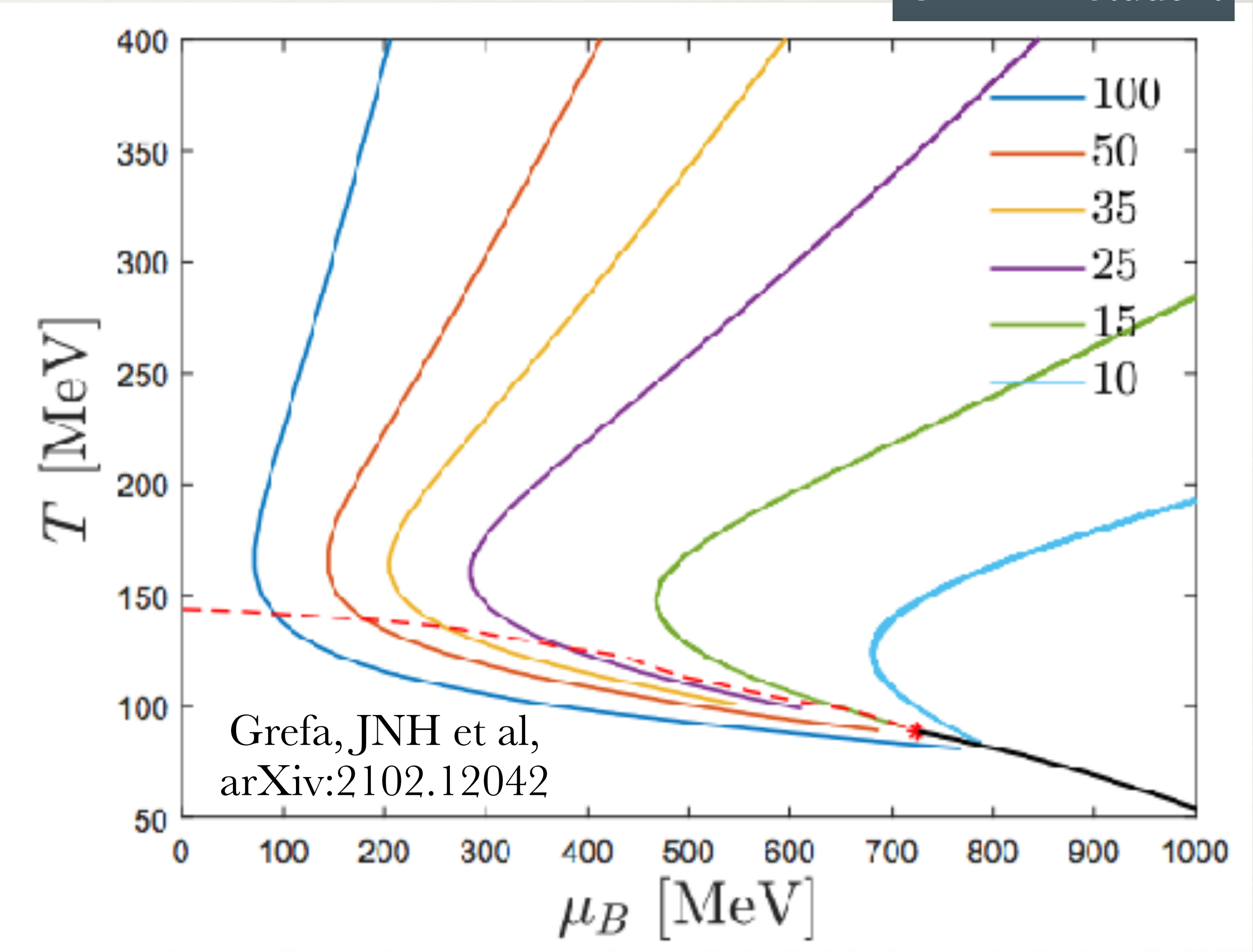
$\mu_B^{max} \sim 1100$ MeV

EOS: holography



Predicts CP at
$\{T_c = 89, \mu_B = 724\}$ MeV

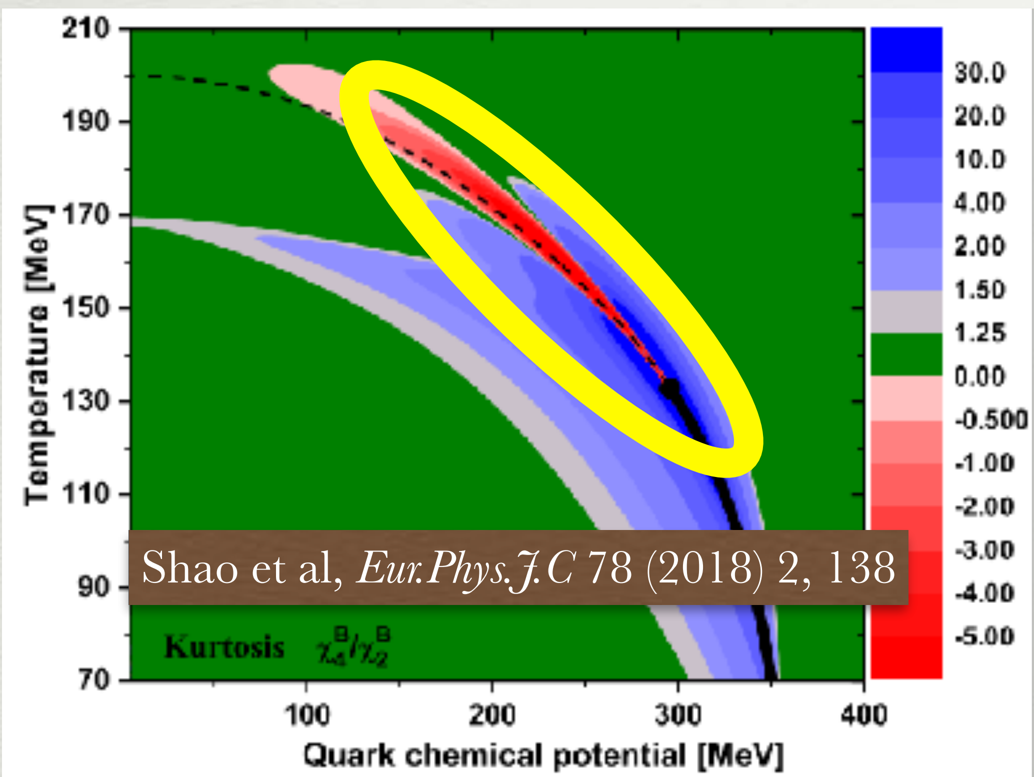
Joaquin Grefa
UH PhD Student

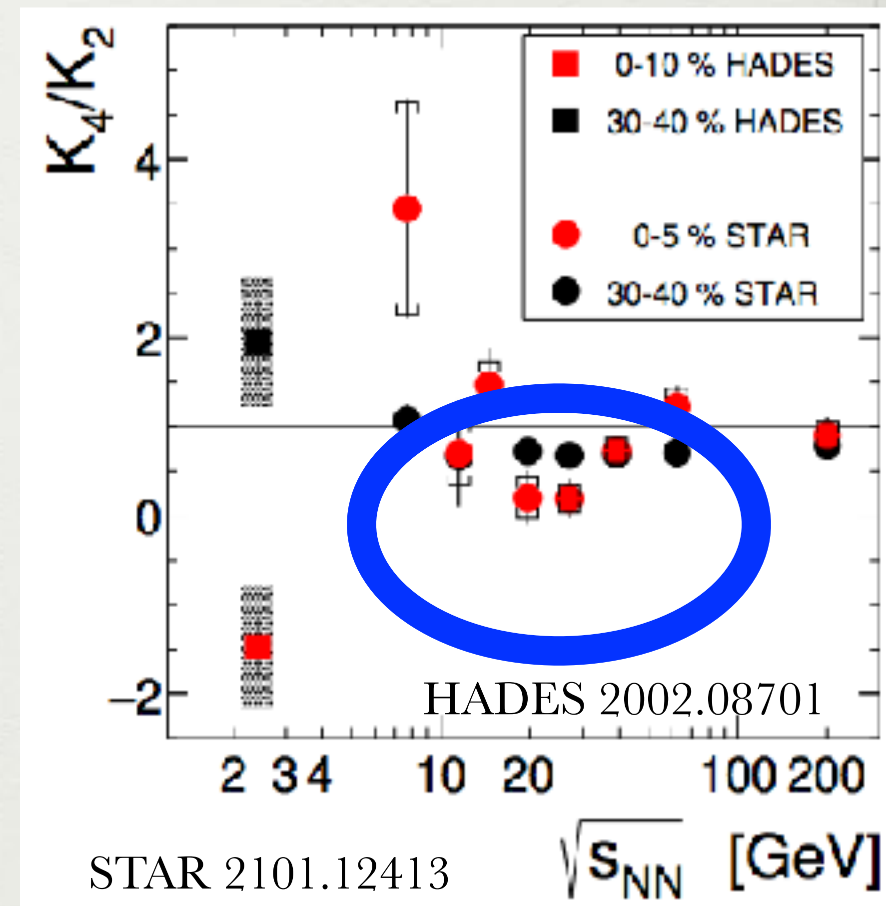


Fitting to just Lattice QCD at $\mu_B = 0$ captures $\mu_B > 0$ EOS

Signature of the critical point: Kurtosis

3D Ising (leading order terms only) Stephanov. PRL 107 (2011)





Non-monotonic approach to CP, thought to be signature

Still signature in 3D Ising model with all sub-leading terms?
Generic signature in all models?

Dip **NOT** a clear CP signature

Models without criticality already see a dip

- Baryon conservation

Braun-Munzinger et al, Nucl. Phys. A960, 114 (2017); arXiv:2007.02463, see also Bzdak et al *Phys.Rev.C* 87 (2013) 1, 014901

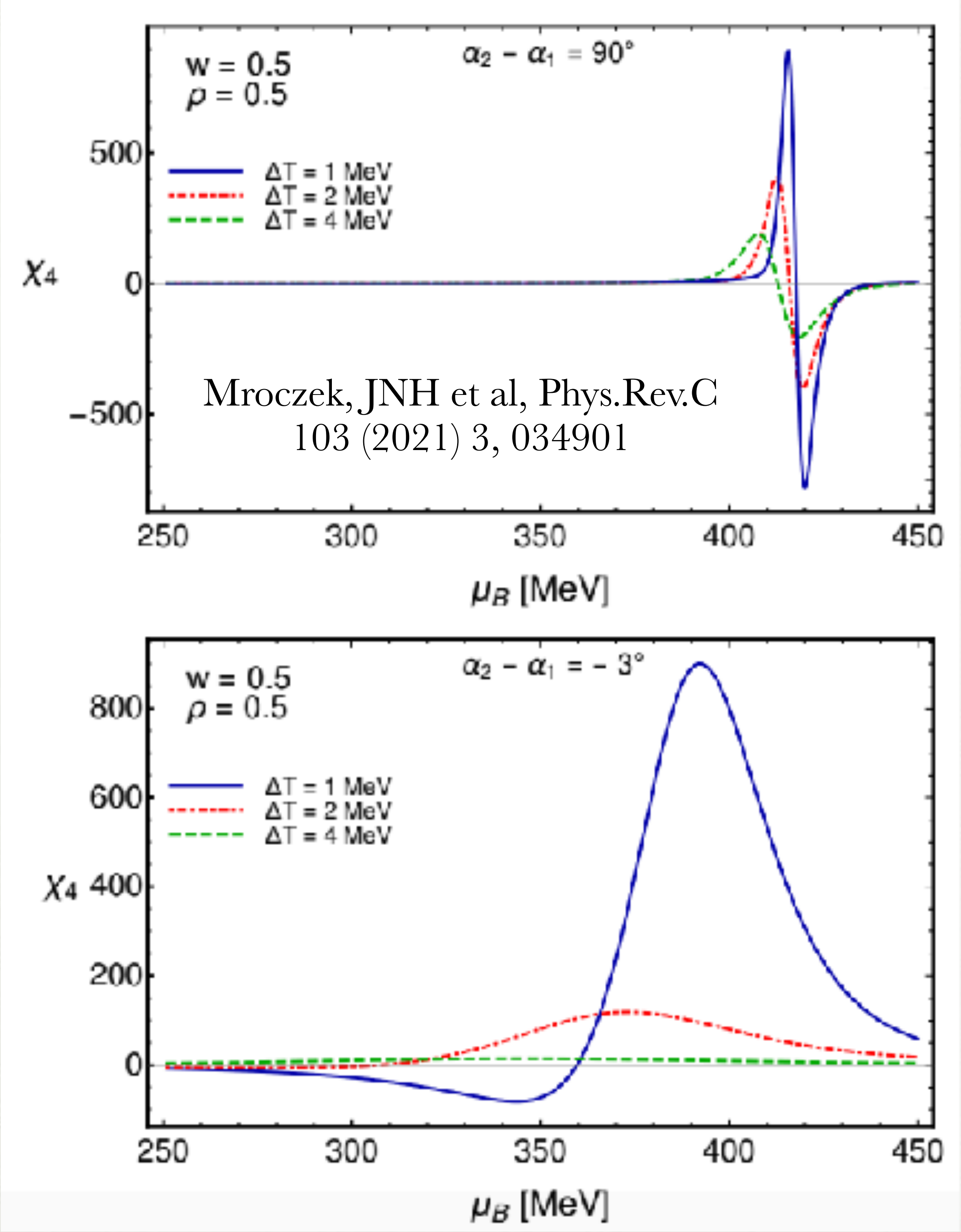
- Lattice QCD Taylor series

Braun-Munzinger et al, Nucl. Phys. A960, 114 (2017); arXiv:2007.02463, see also Bzdak et al *Phys.Rev.C* 87 (2013) 1, 014901

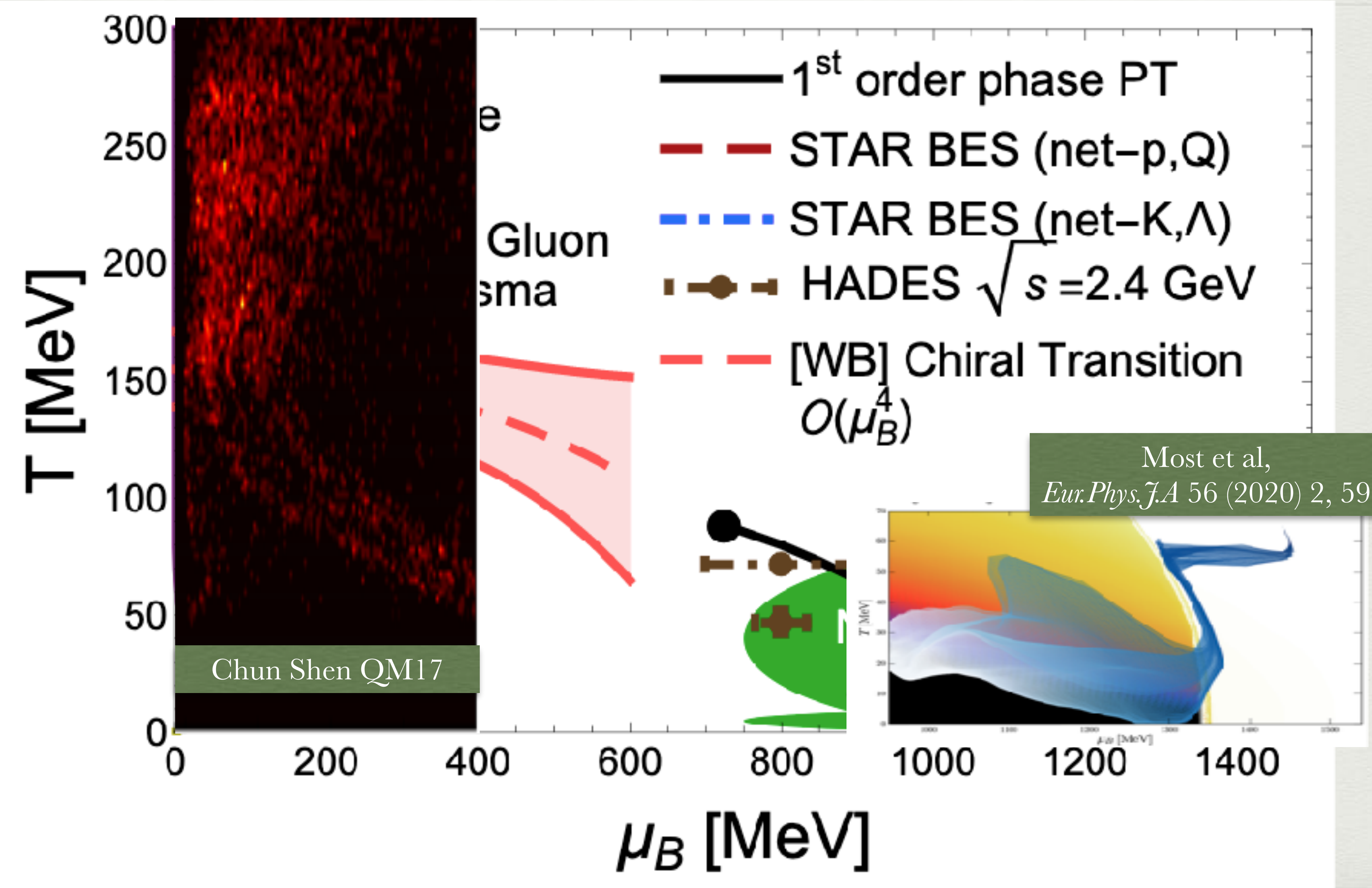
- UrQMD

Braun-Munzinger et al, Nucl. Phys. A960, 114 (2017); arXiv:2007.02463, see also Bzdak et al *Phys.Rev.C* 87 (2013) 1, 014901

3D Ising+sub-leading terms, only peak clear signature!

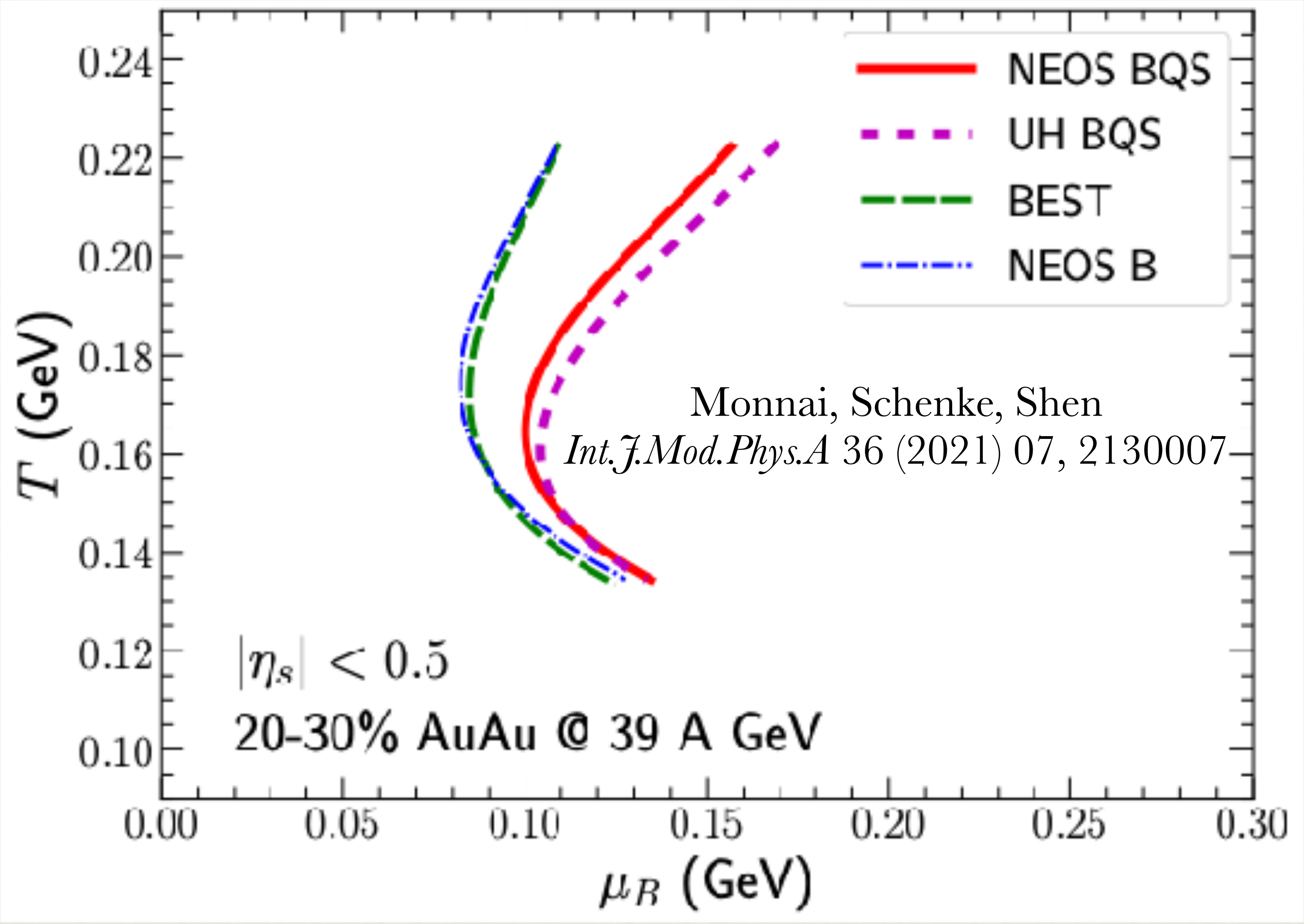


QCD Phase Diagram Out-of-Equilibrium

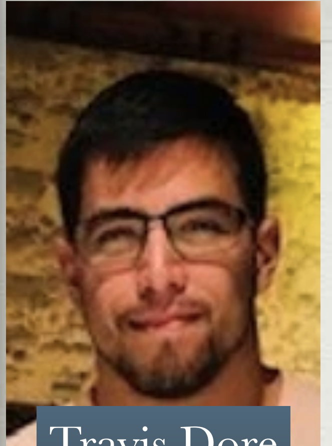


Averaged trajectories vs. EOS

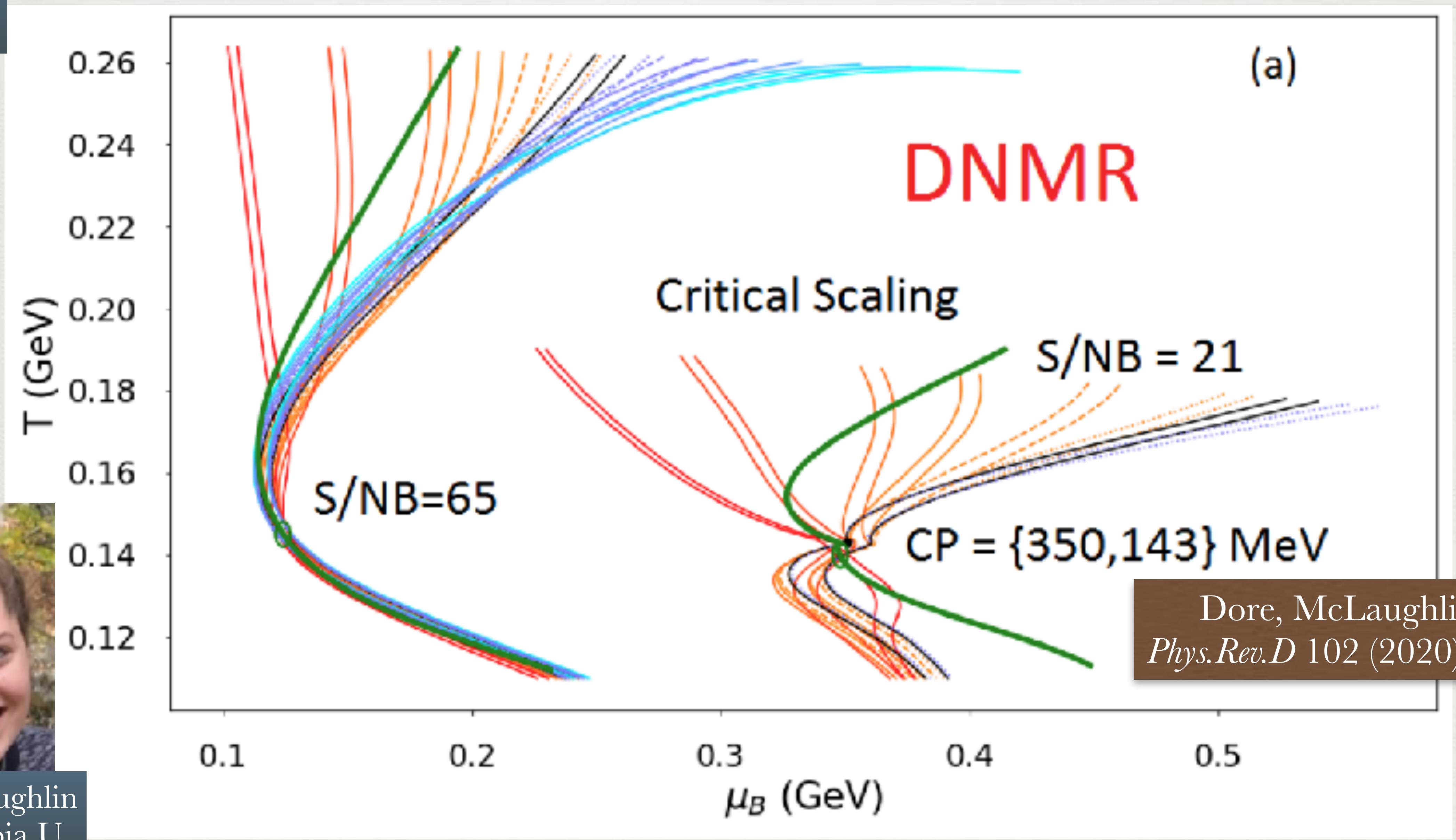
Differences between only baryon conservation vs. BSQ influence the trajectories through the QCD phase diagram. Shown with $\eta/s = 0.08$



Far from equilibrium causes further deviations from ideal



Travis Dore
PhD UIUC

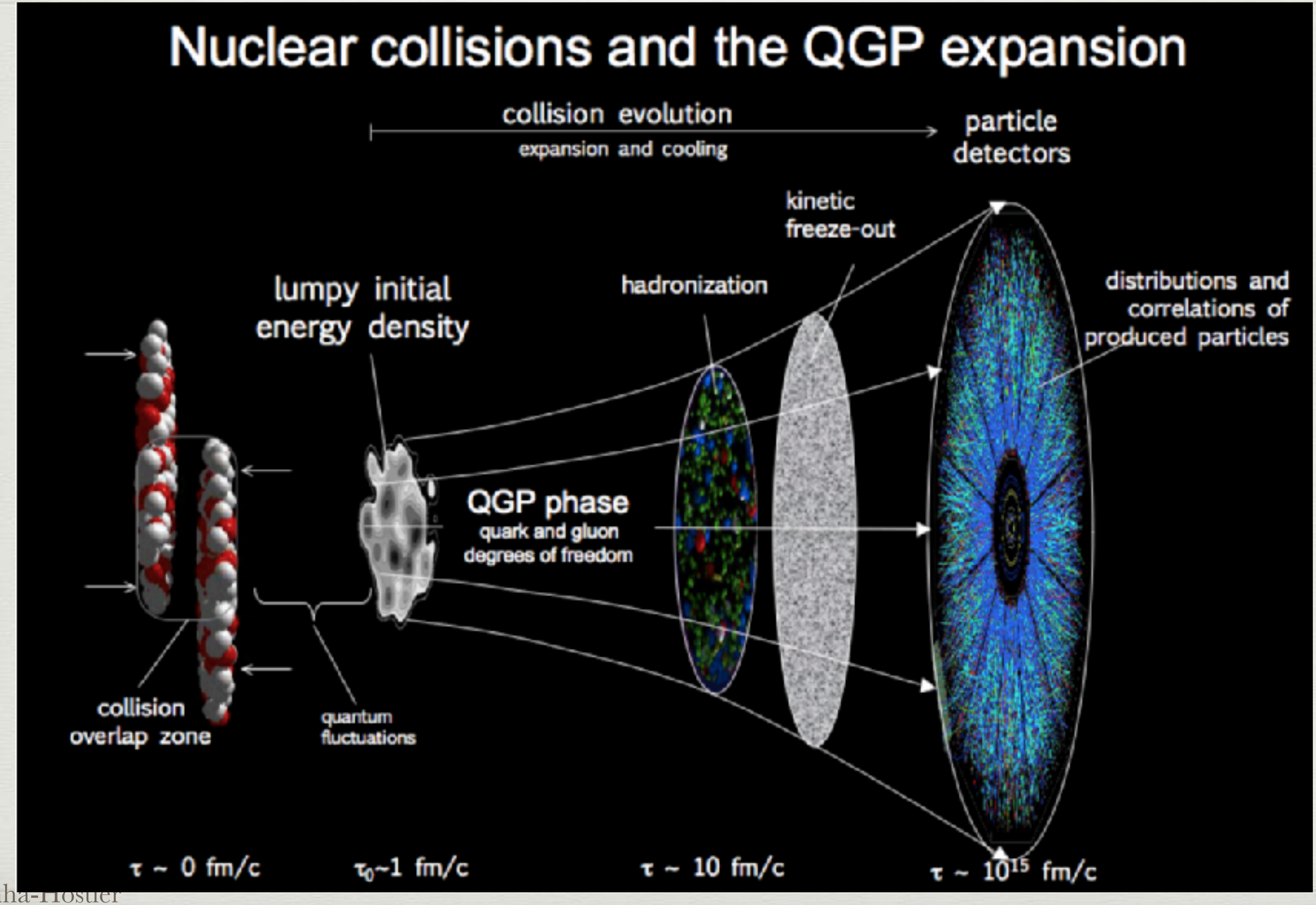


Dore, McLaughlin, JNH
Phys.Rev.D 102 (2020) 7, 074017

Emma McLaughlin
PhD Columbia U.

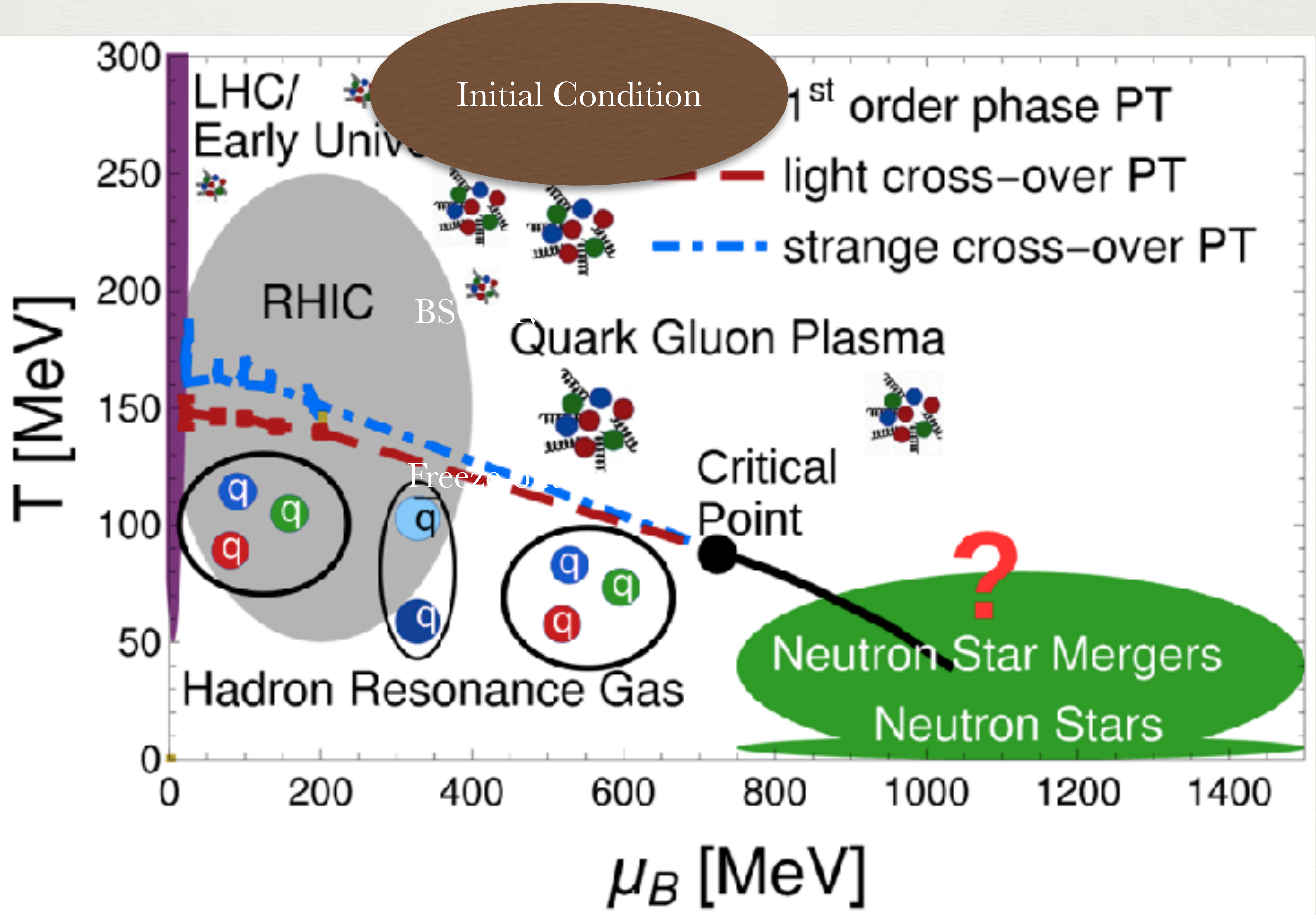
Far-from-equilibrium initial conditions in heavy-ion collisions can dramatically affect the passage through the phase diagram

Heavy-ion collisions explore the QCD phase diagram *dynamically*



J. Noronha-Hostler

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*

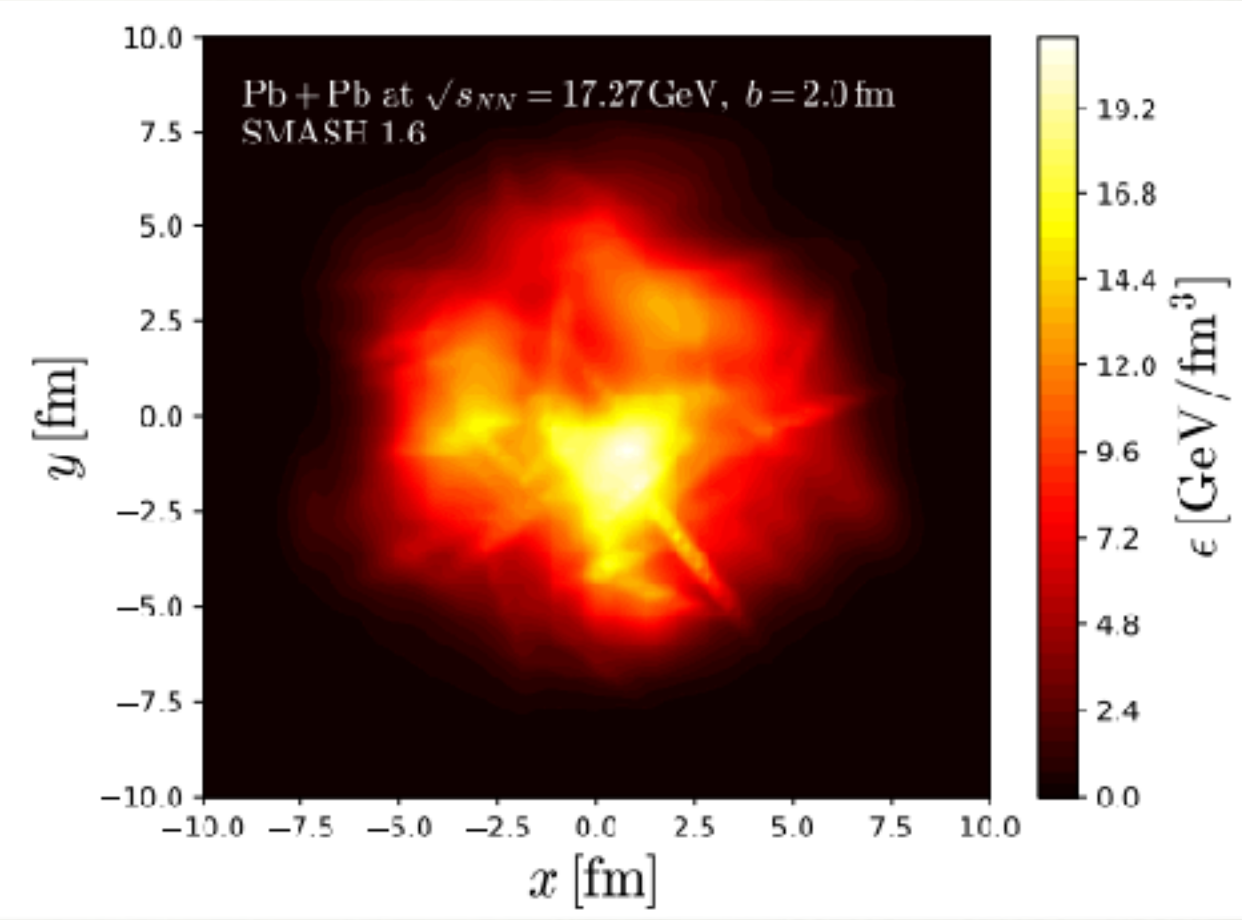
Initializing finite baryon density with nucleons

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



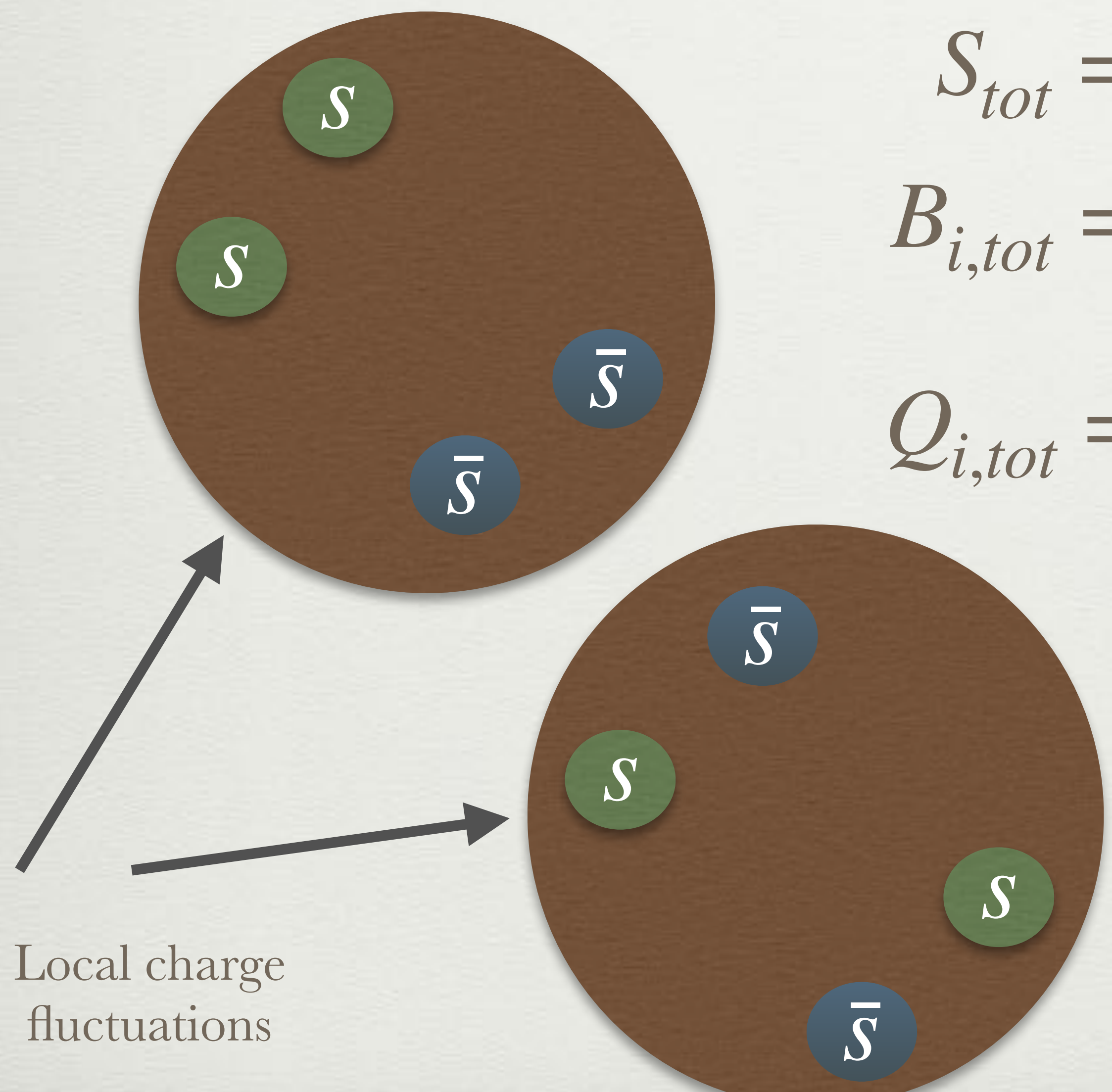
Mohs et al, J.Phys.G 47 (2020) 6, 065101

What about at the quark/gluon level?

3 conserved charges: BSQ

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

Quark Gluon Plasma



$$S_{tot} = 0$$

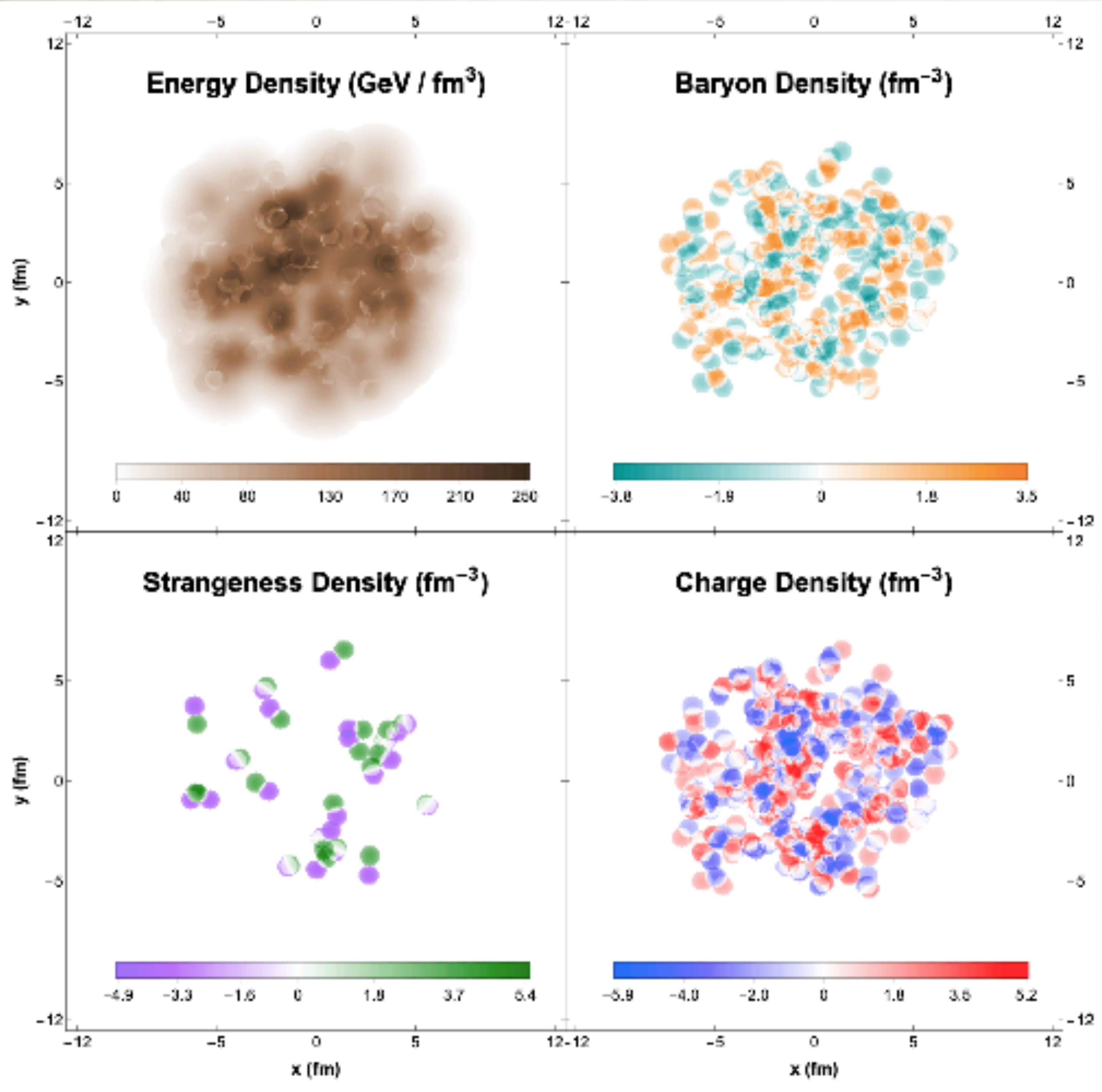
$$B_{i,tot} = B_{f,tot}$$

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

Each grid point in an initial condition needs to initialize

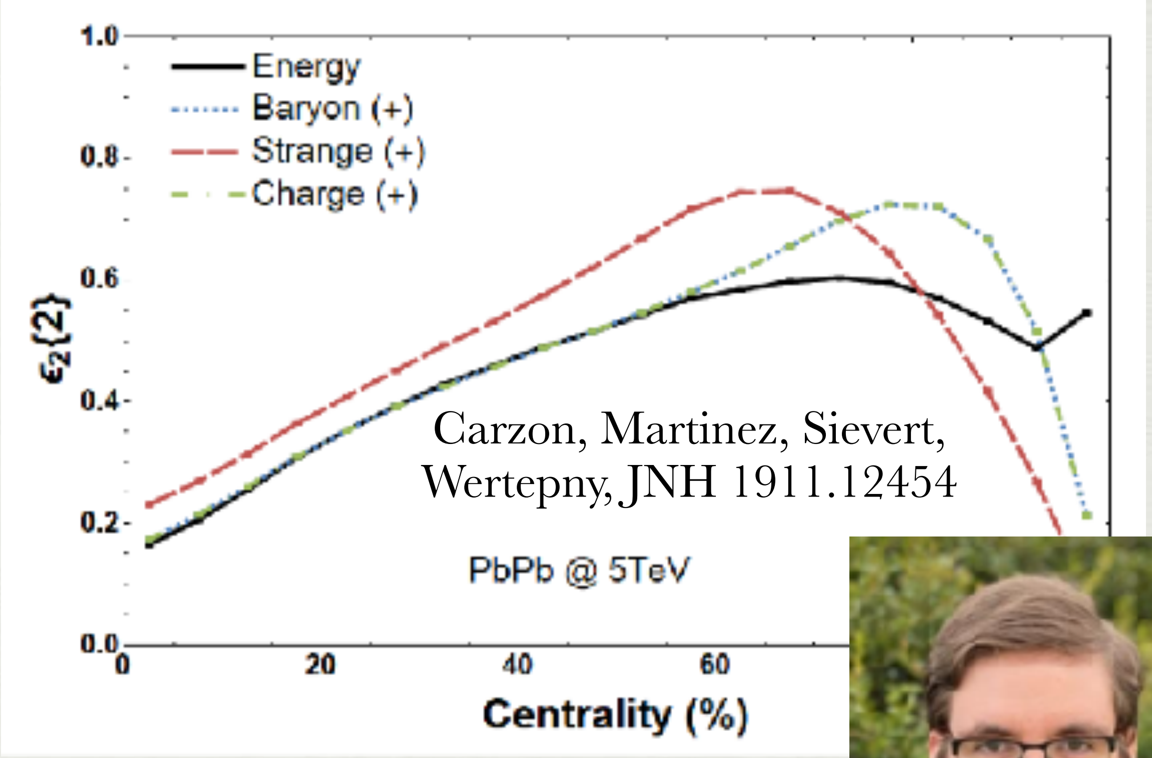
$$\left\{ T, \rho_B, \rho_S, \rho_Q \right\}$$

ICCING- Initializing Conserved Charges in Nuclear Geometries

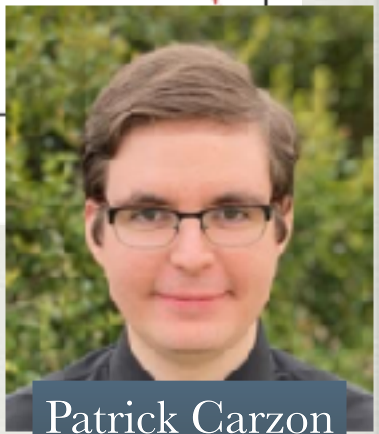


Theoretical development
Martinez, Sievert, Wertepny
JHEP 02 (2019) 024;JHEP 1807 (2018) 003

$g \to q\bar{q}$



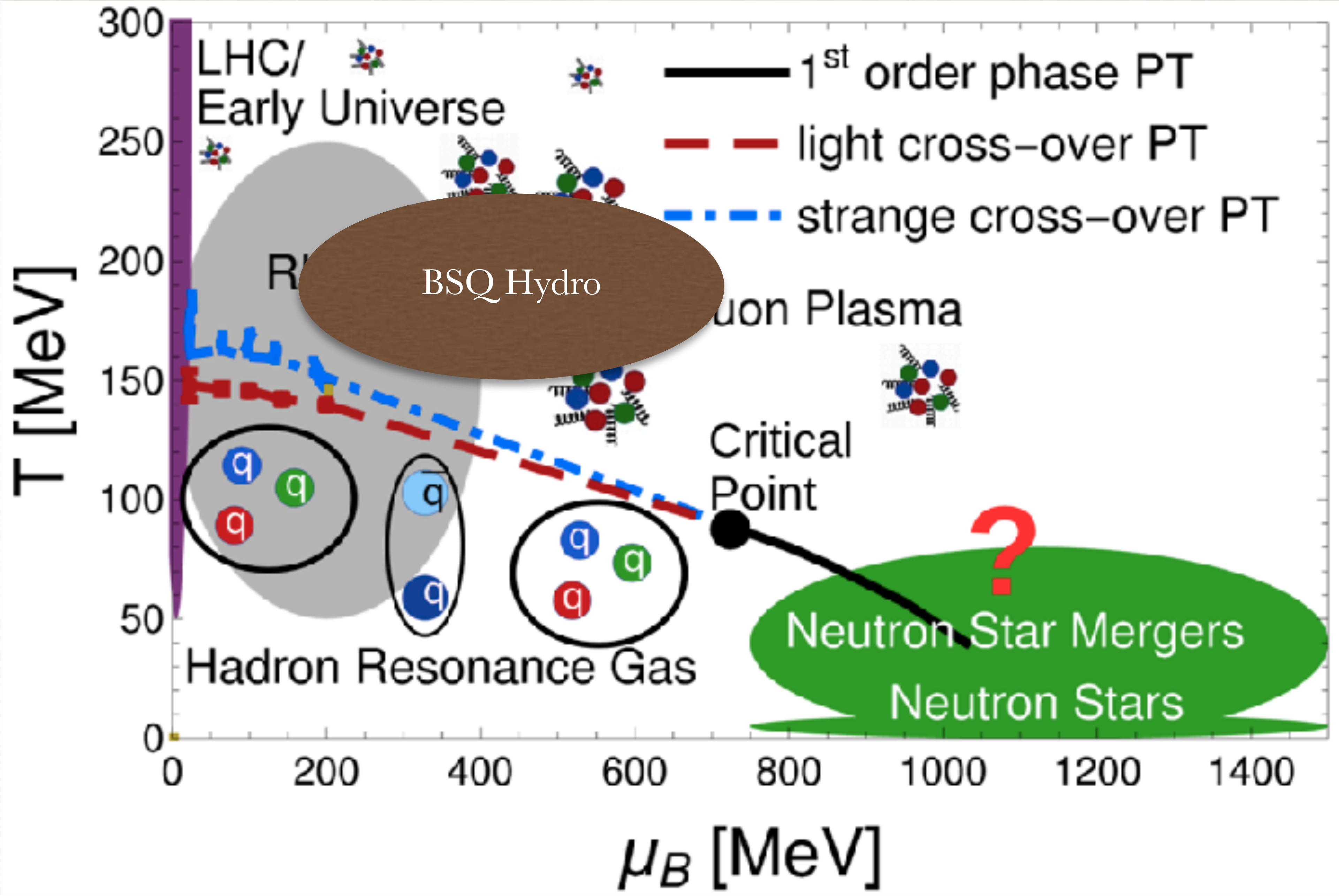
Carzon, Martinez, Sievert, Wertepny, JNH 1911.12454



Patrick Carzon
PhD UIUC

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

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
$\kappa_{BB}, \kappa_{BS}, \ \ldots$

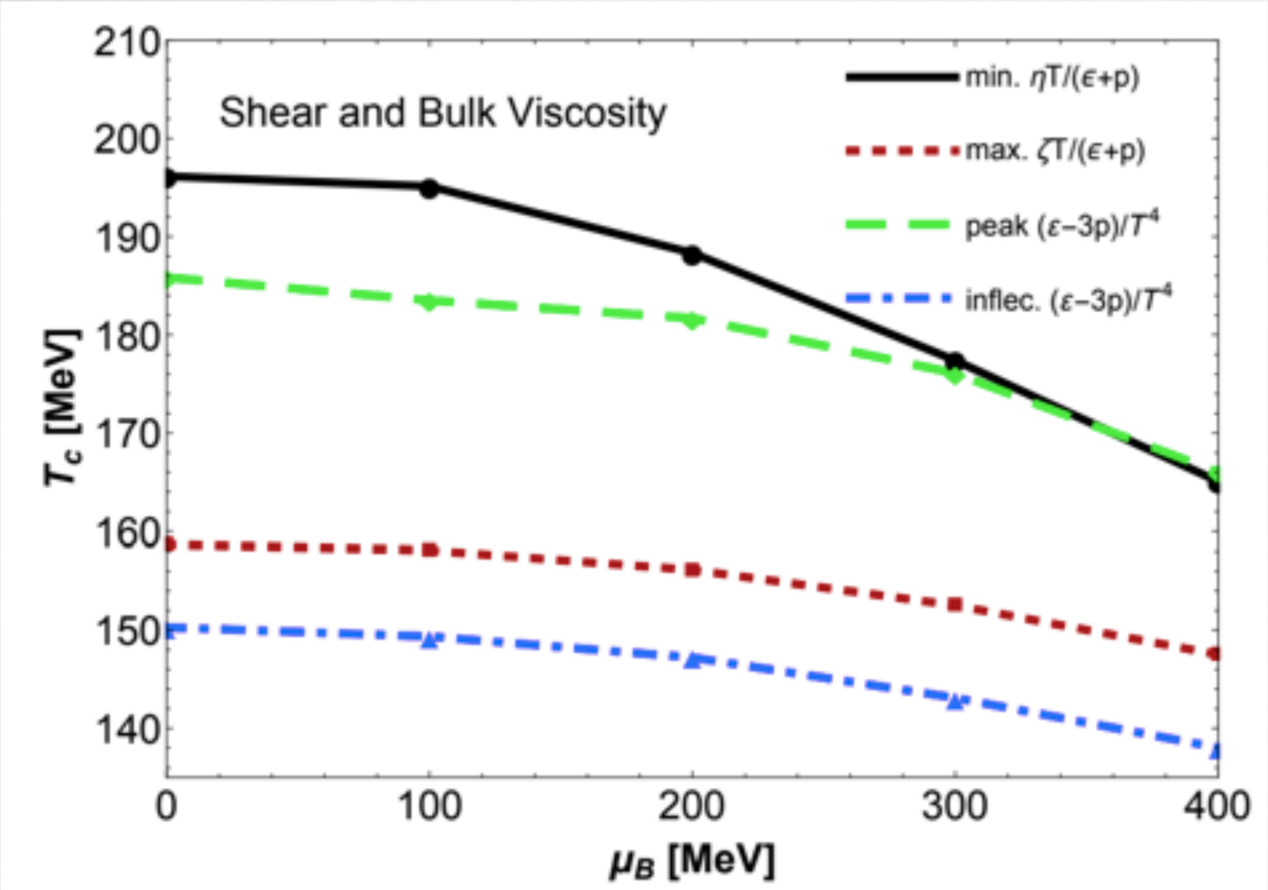
BSQ Hydro
Ideal BSQ
$\partial_\mu B^\mu = 0,\ B^\mu = \rho_B u^\mu + n_B^\mu$
Diffusion
$\kappa_{BB}\Delta^{\mu\nu}\partial_\nu\left(\mu_B/T\right)$
BSQ cross terms
$\kappa_{BS}\Delta^{\mu\nu}\partial_\nu\left(\mu_B/T\right)$

Viscosity at finite densities

Temperature of minimum of shear and maximum of bulk viscosity

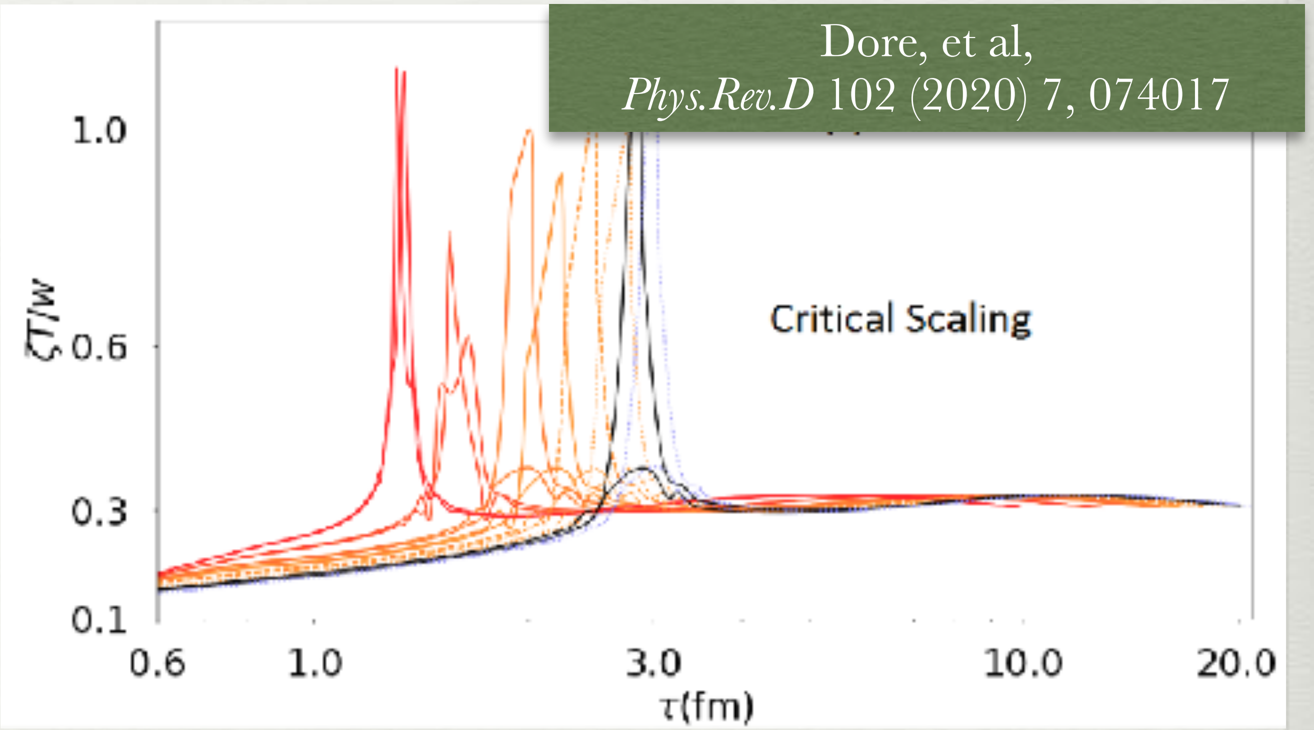
Critical Scaling:

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



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

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

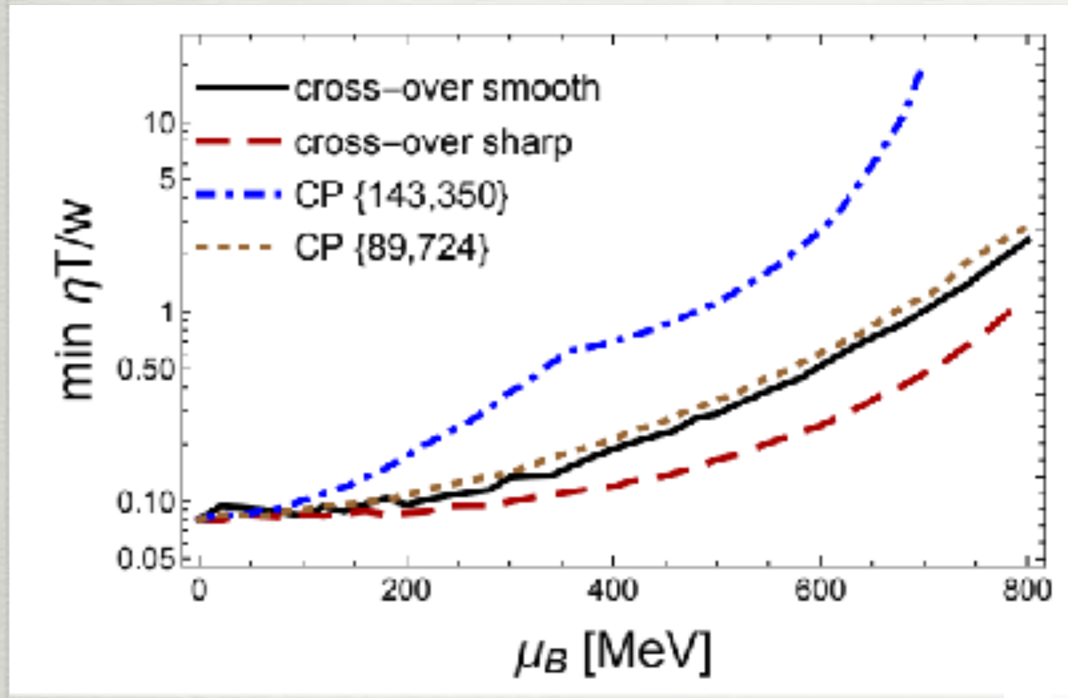


Dore, et al, *Phys.Rev.D* 102 (2020) 7, 074017

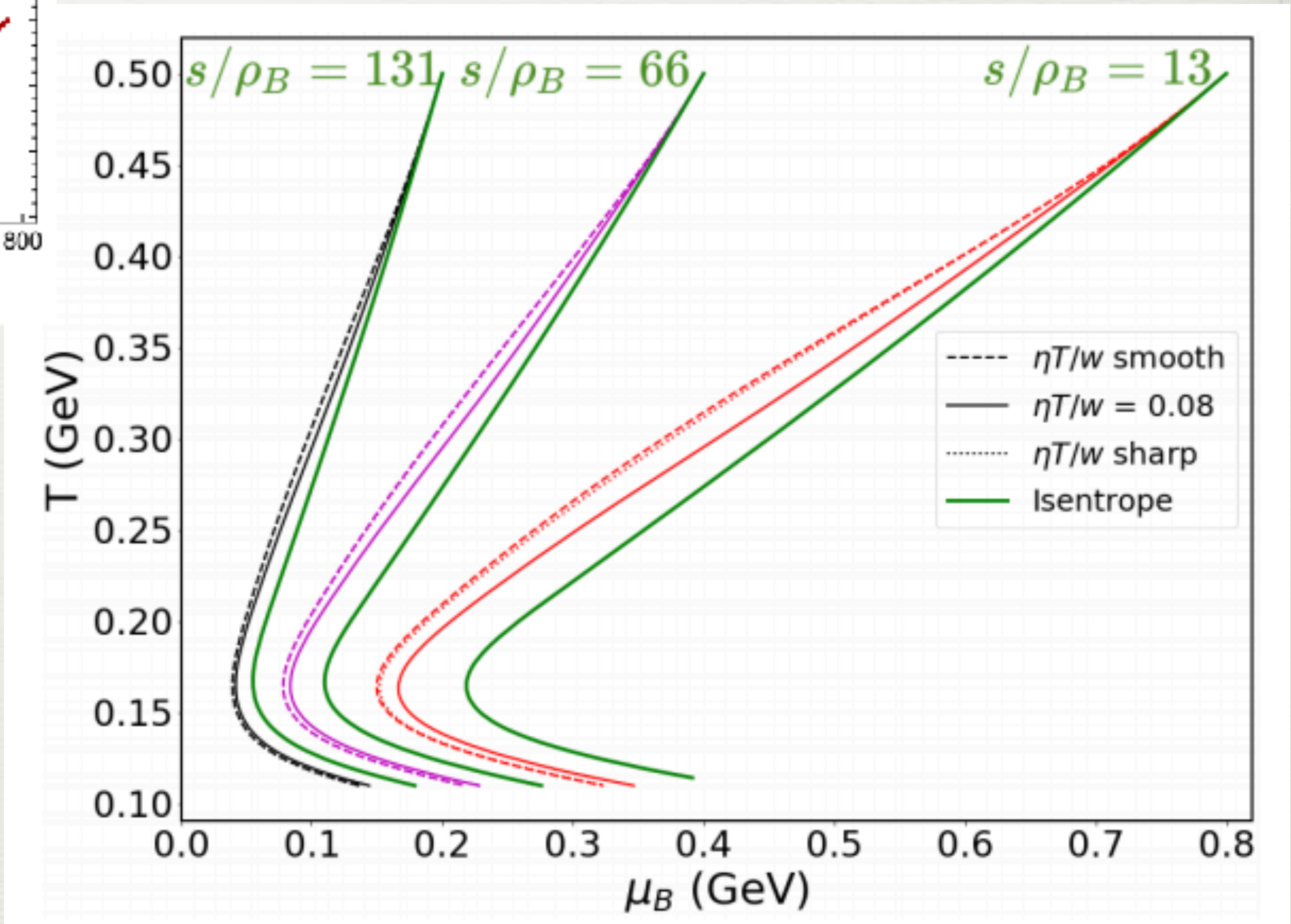
Note $\zeta T/w \propto 1/3 - c_s^2$

Consequences of $\eta T/w$ across μ_B

McLaughlin, JNH, et al, 2103.02090

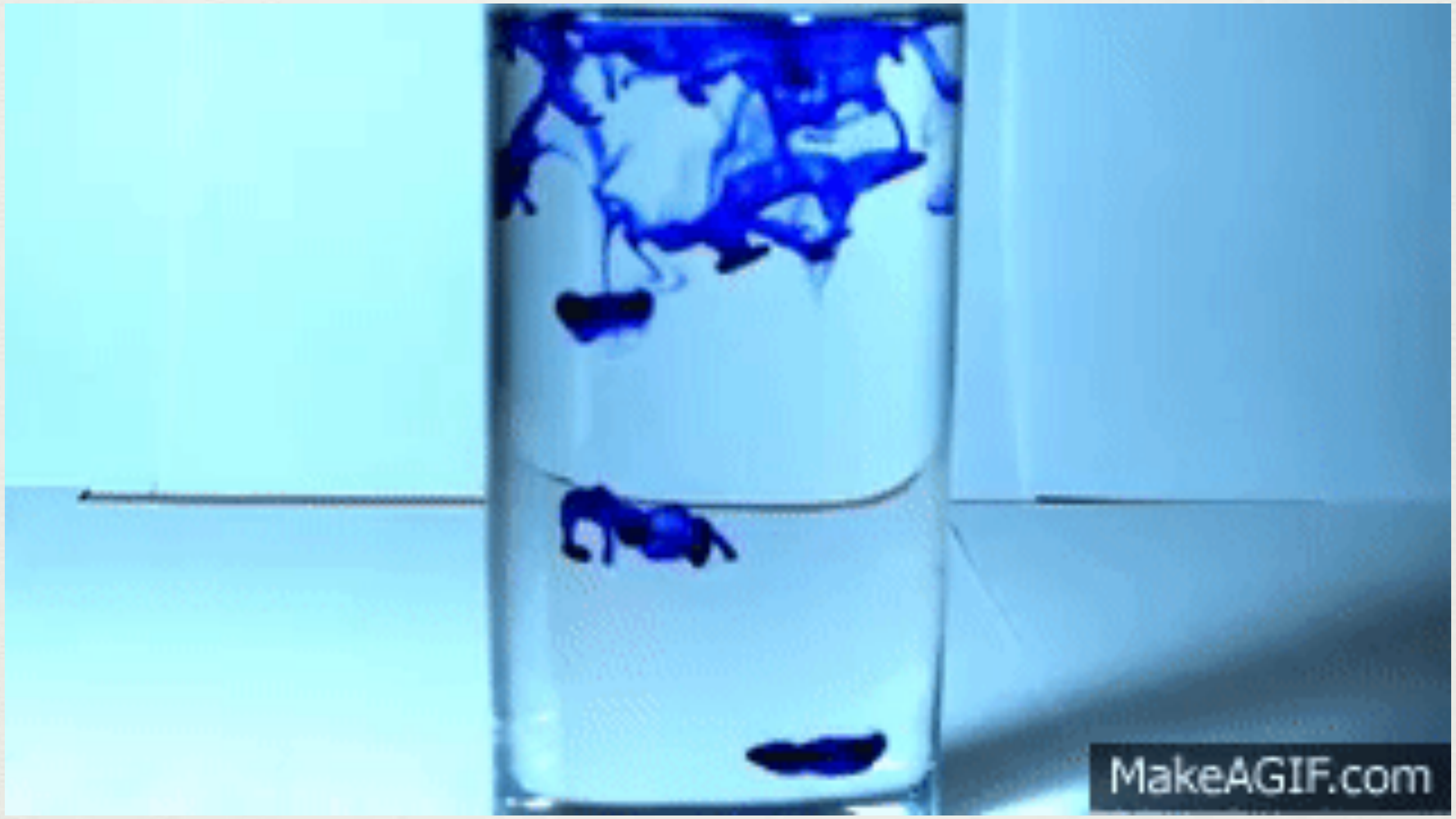


Transition line affects magnitude of $\eta T/w$



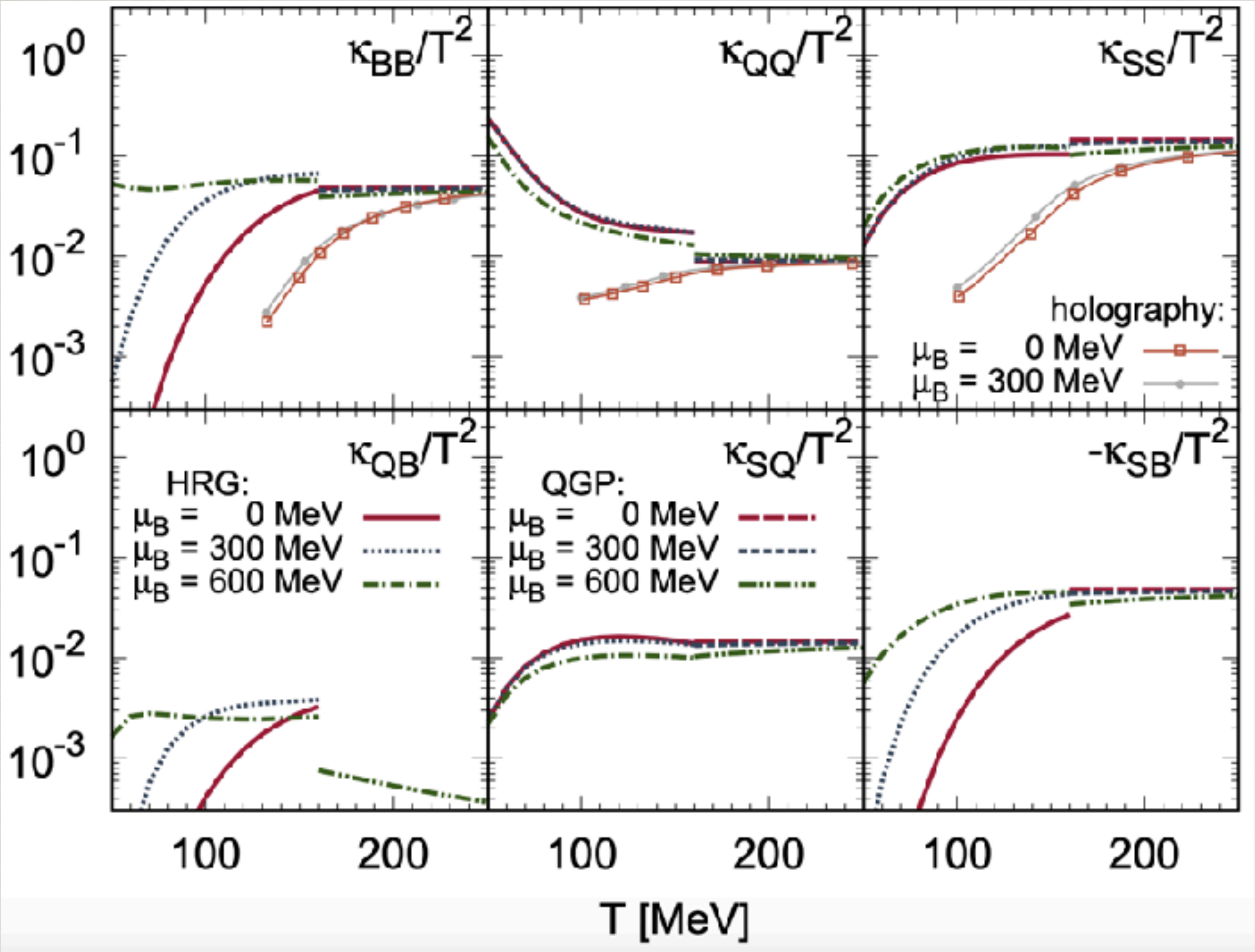
Viscous effects more prevalent at low beam energies

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 Matrix



Kinetic Theory

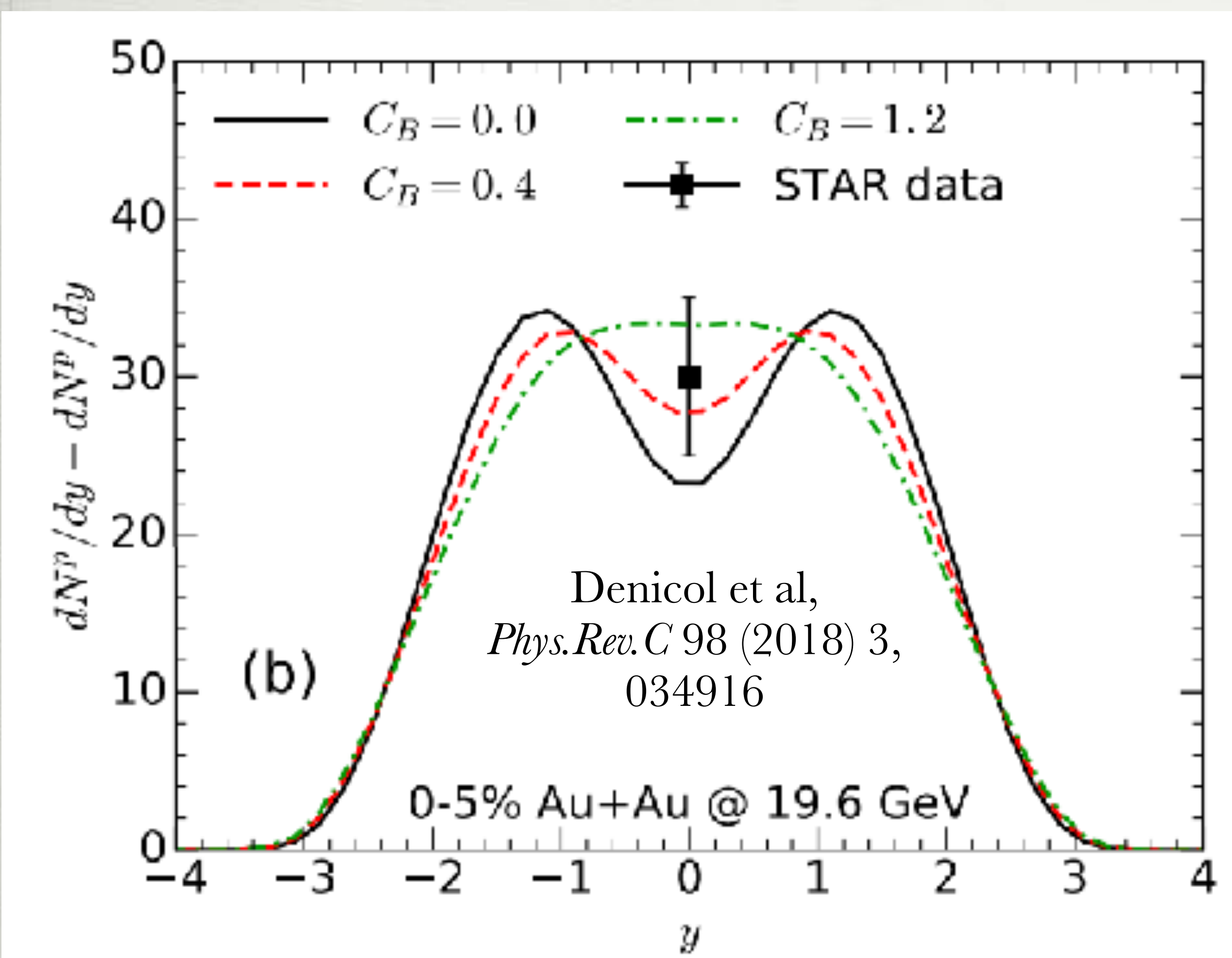
Greif, Fotakis, Denicol, Greiner Phys.Rev.Lett. 120 (2018) no.24, 242301

Holography (black hole engineering)

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

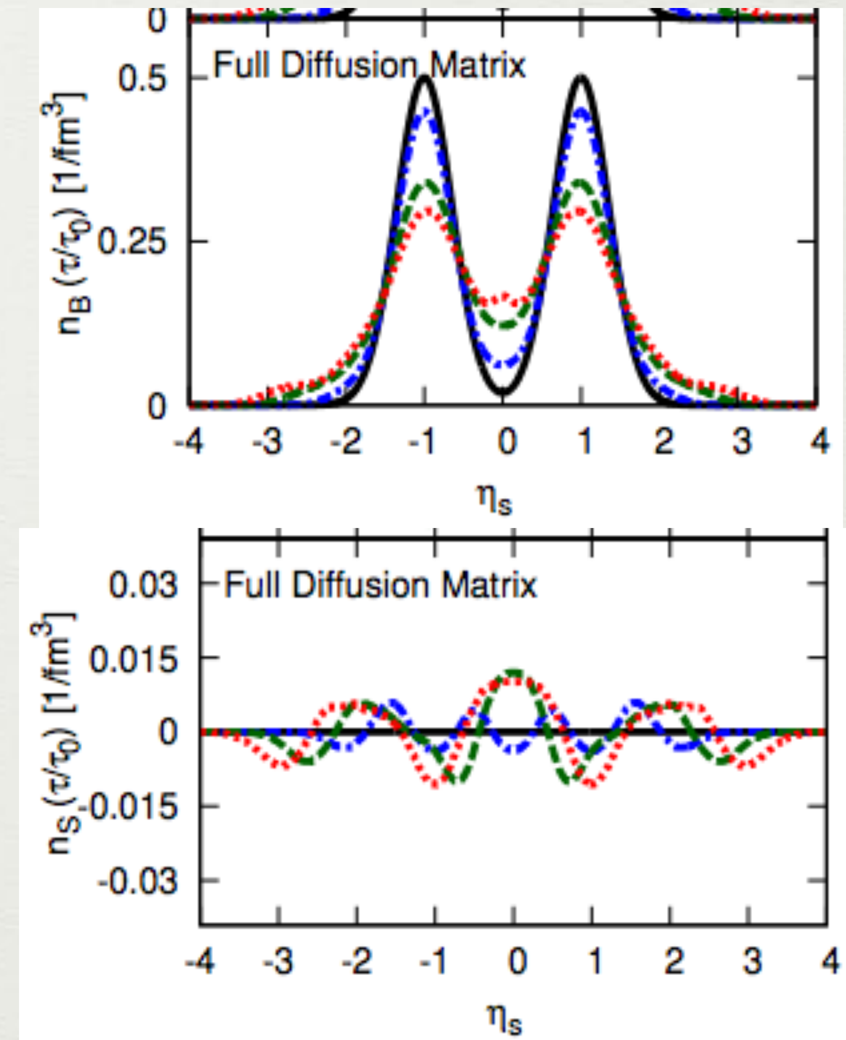
Initial hydro results

3+1 B hydro



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

1+1 BS hydro



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

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

BSQ equations of motion


Lydia Spychalla
REU UIUC


Dekra Almaalol
PhD Kent
Soon UIUC postdoc

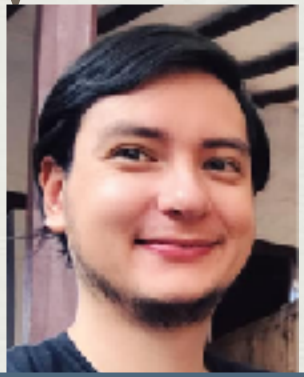
$_B = 0$, shear+bulk viscosity gives 10 coupled
ren

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

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

- Additio ... new
  pled ... er
  usio


Christopher Plumberg
UIUC postdoc

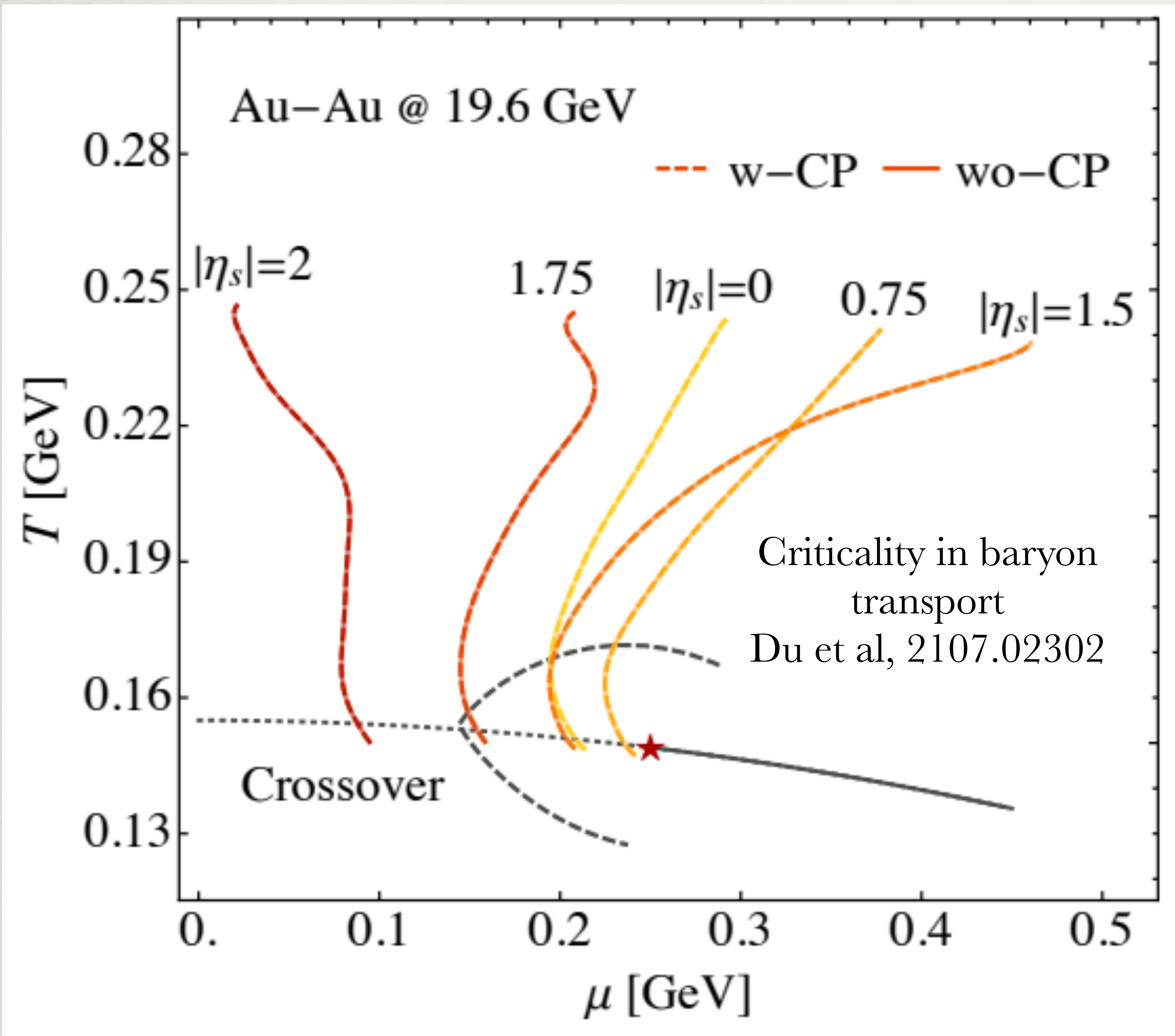

Nikolas Cruz Camacho
PhD UIUC

dif
thermodynamic derivatives

- Criticality + relativistic viscous hydro still open question!

Stephanov, Nahrgang, Basar, Yin, Schaeffer, Yee, An, Martinez, Teaney, Akamatsu, Yan, Rajagopal, Weller, Ridgway, Du, Heinz, Song

Critical fluctuations in 1+1D hydro



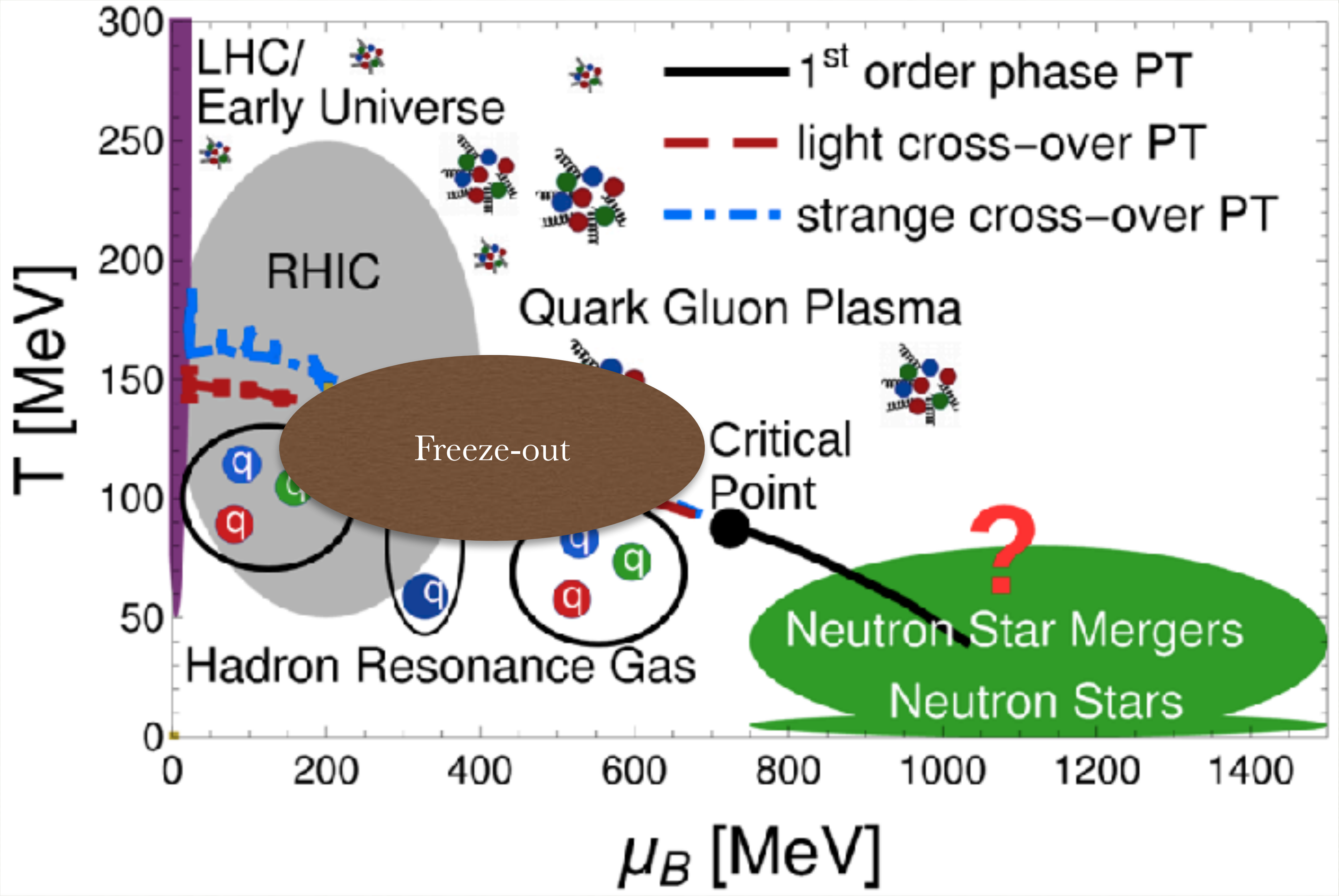
Critical slow down (from baryon transport), no noticeable affect.

Bulk viscous effects still relevant

$\eta \sim \xi^{-19}$, $D_B \sim \xi^{-1}$, $\zeta \sim \xi^{3}$

Monnai et al, *Phys.Rev.C* 95 (2017) 3, 034902; Dore, McLaughlin, JNH *Phys.Rev.D* 102 (2020) 7, 074017; Du et al, 2107.02302

QCD Phase Diagram



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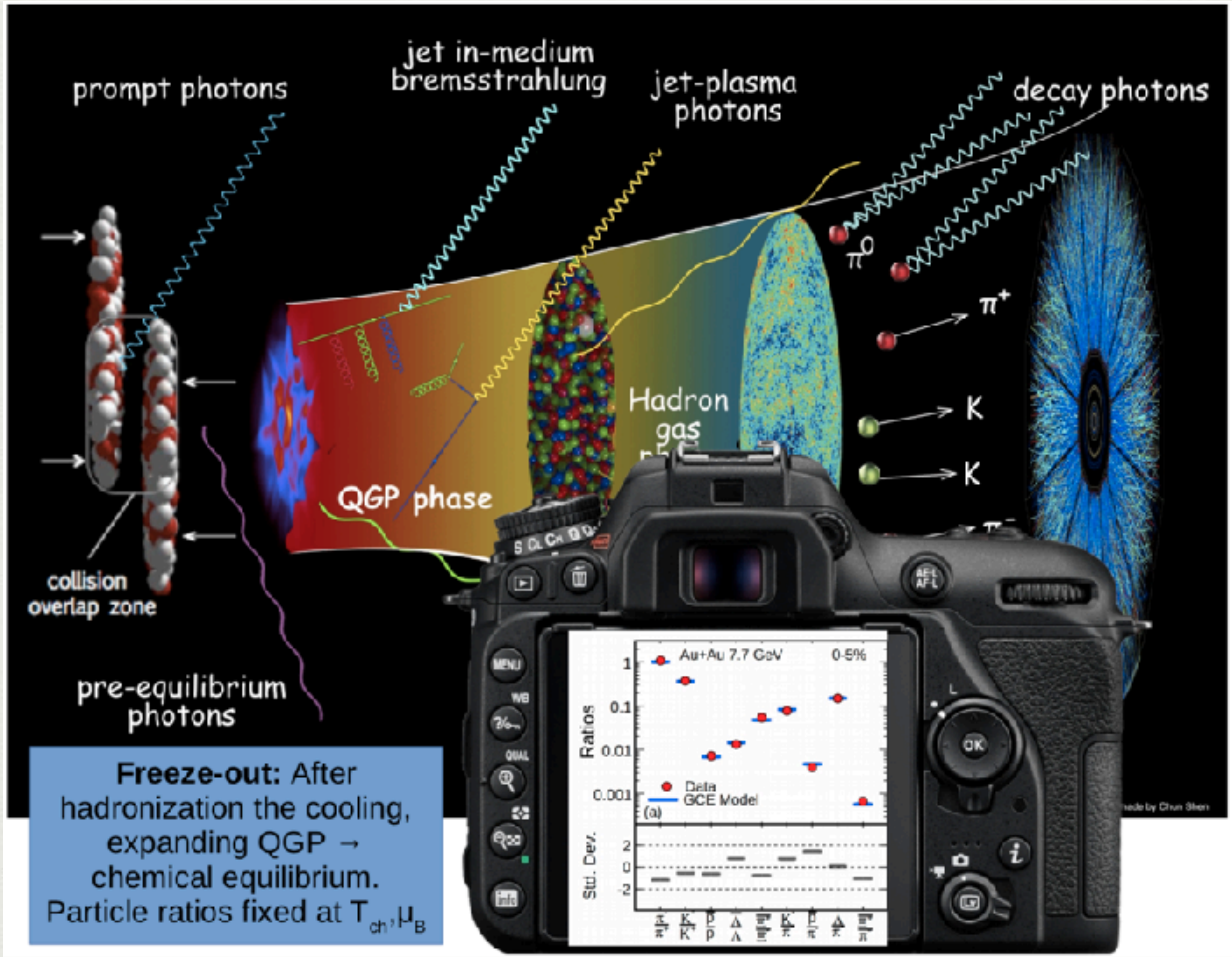
Freeze-out: finding the cross-over temperature



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Hadron resonance gas at large ρ_B

- Conservation of B,S,Q in MC sampling

D. Oliinychenko *et al*, *Phys.Rev.C* 102 (2020) 3, 034904

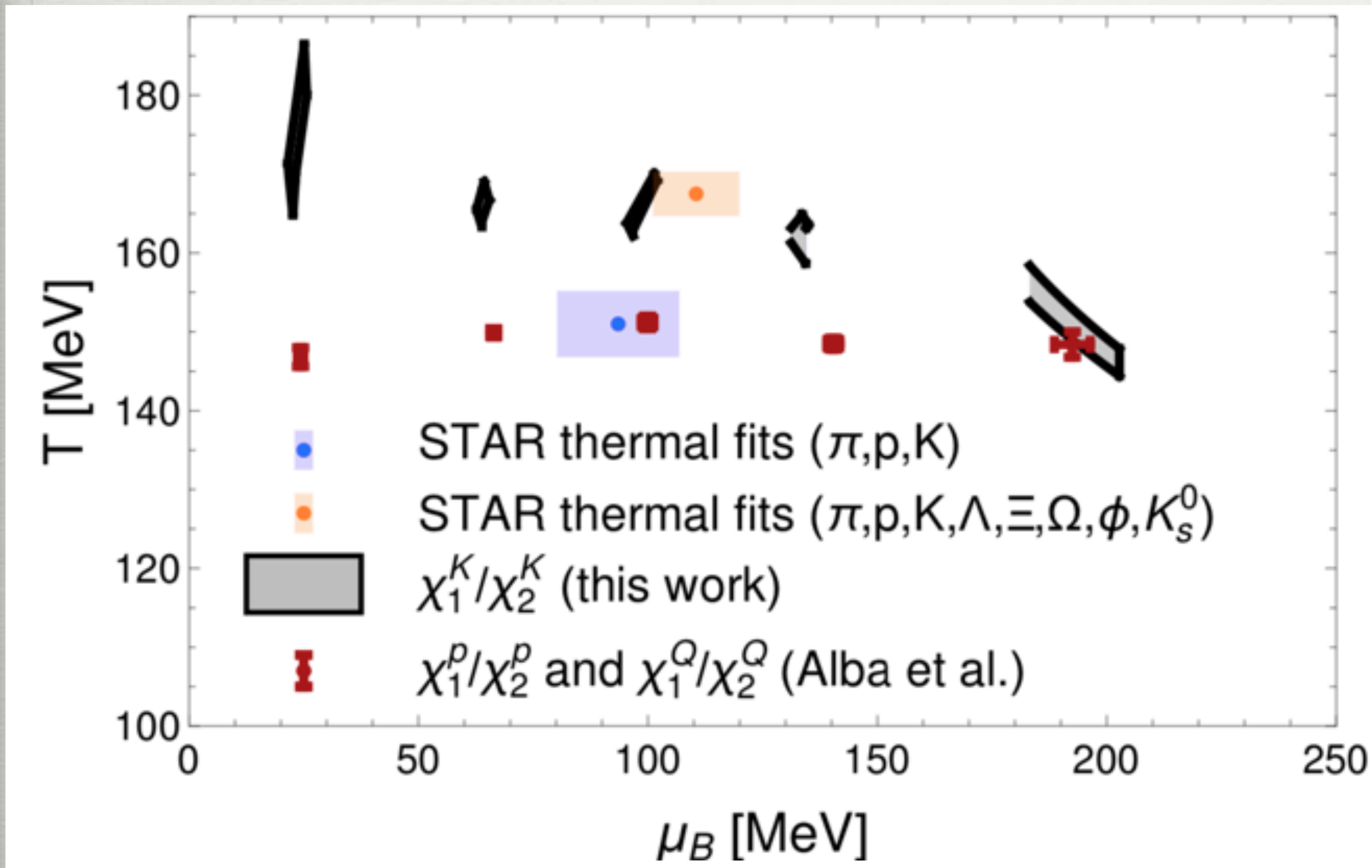
- Cooper Fry diffusion corrections

$$f(T,\mu_B,\mu_s,\mu_Q)+\delta f_\eta+\delta f_\zeta+\delta f_{D_{B,S,Q}}$$

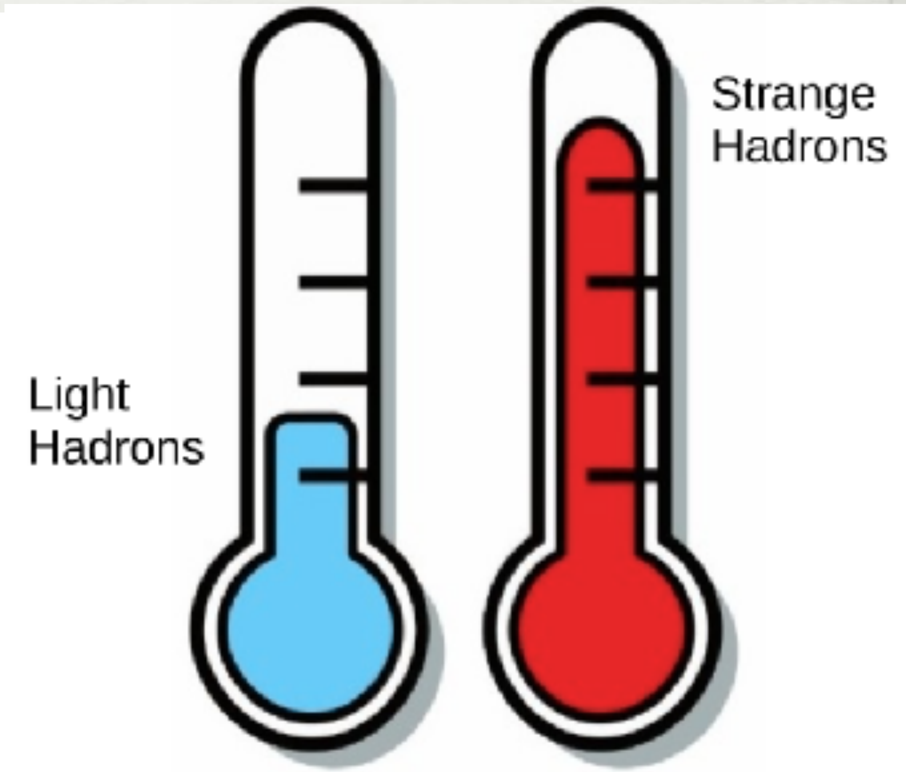
- N-body interactions/potentials

SMASH A. Sorensen, Koch 2011.06635

Flavor hierarchy in freeze-out



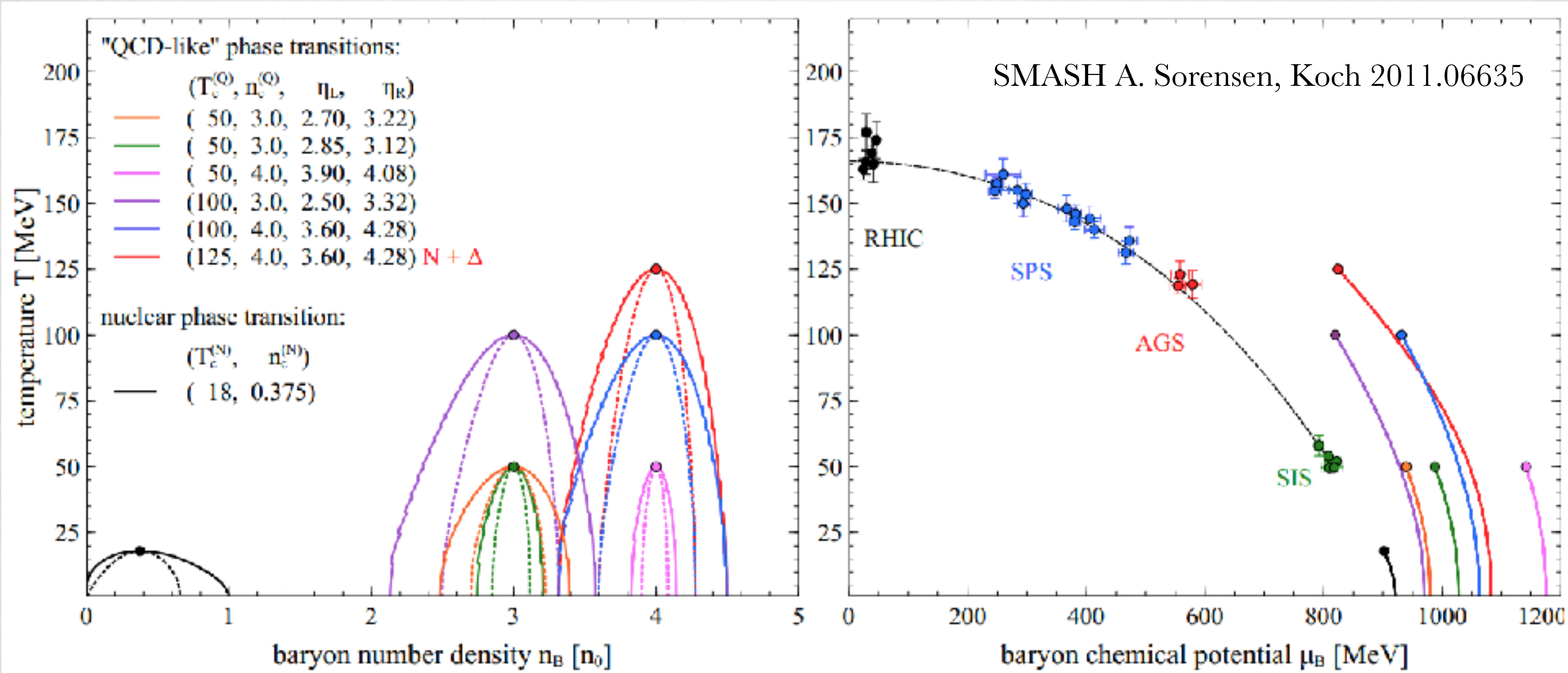
Bellwied, JNH, et al, Phys.Rev. C99 (2019) no.3, 034912



Thermal fits also see flavor hierarchy

[STAR] Phys. Rev. C 96 (2017) 44904; Alba et al, Phys.Rev.C 101 (2020) 5, 054905,Flor et al, Phys.Lett.B 814 (2021) 136098

Phase transitions in hadronic transport



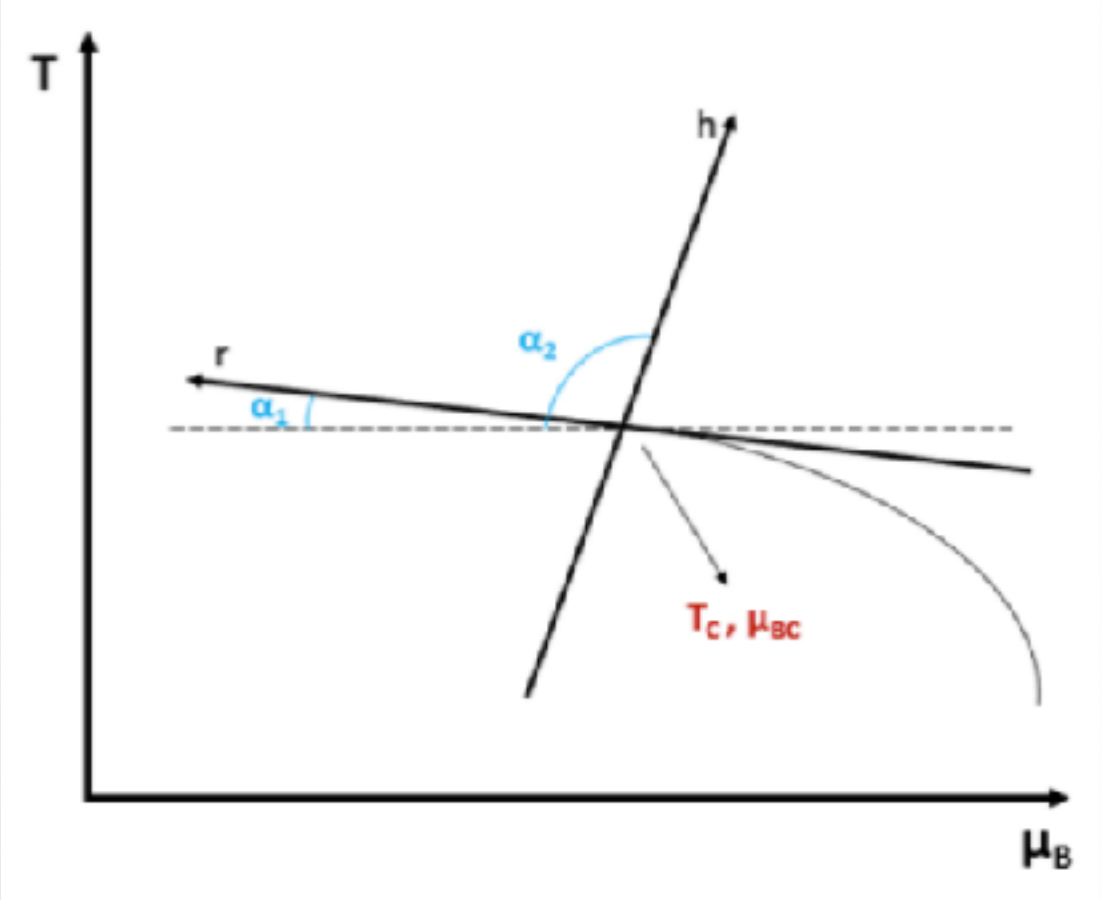
Such an approach allows for better systematic checks

Conclusions and Outlook

- EOS from Lattice QCD reaching larger μ_B, models hint at a CP
- BSQ charges likely will affect final flow harmonics
- Studies of BSQ viscous hydrodynamics underway
- Unanswered questions about transport coefficients at finite μ_B
- Possible signs of a flavor hierarchy at freeze-out

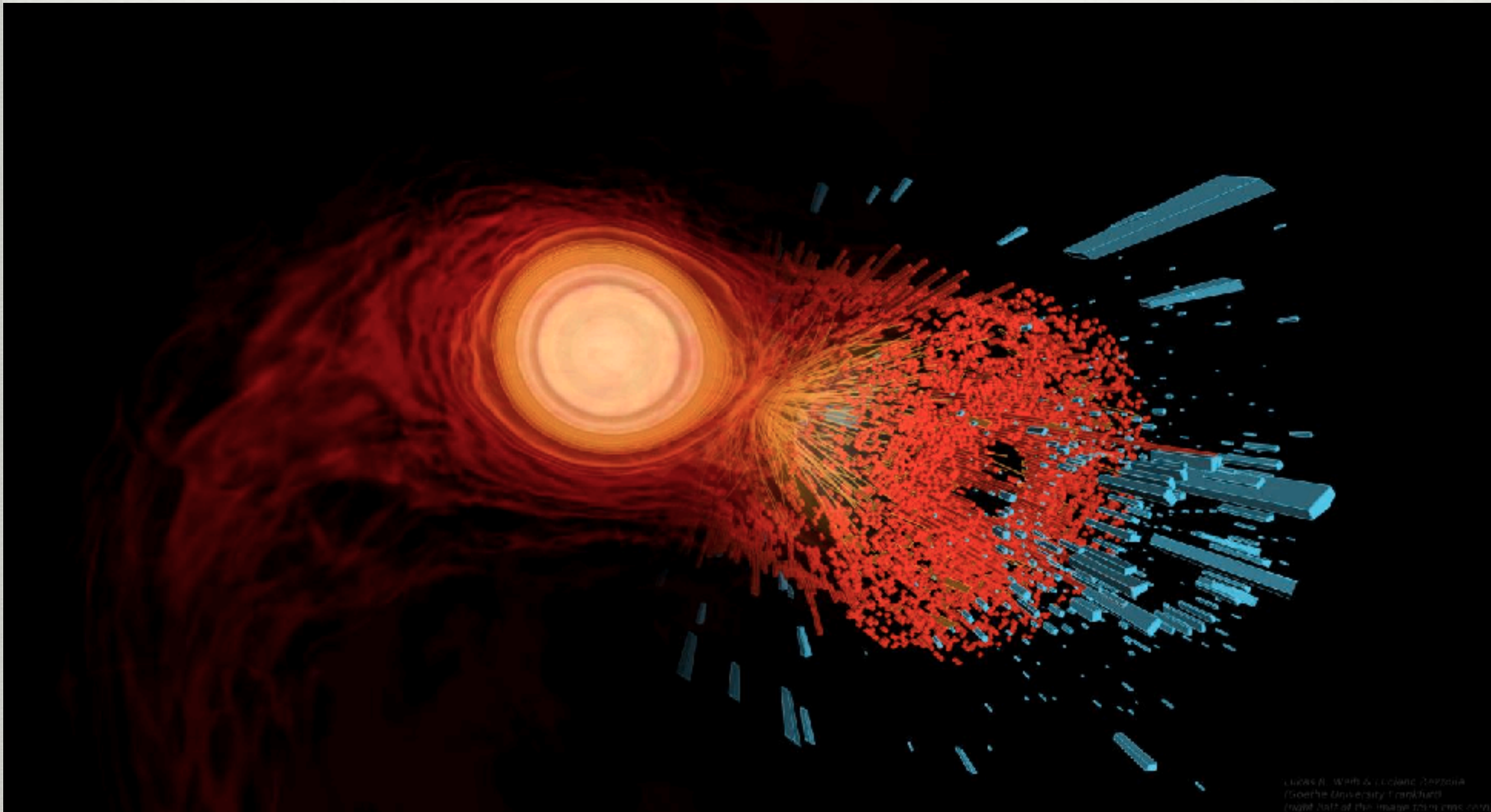
BES-EOS: 6 unknown parameters

- 2 location: $\{T_c, \mu_B^c\}$
- Angles:
  - α_1 between transition line & r
  - α_2 between r & h
- Strength of critical region: ρ, ω

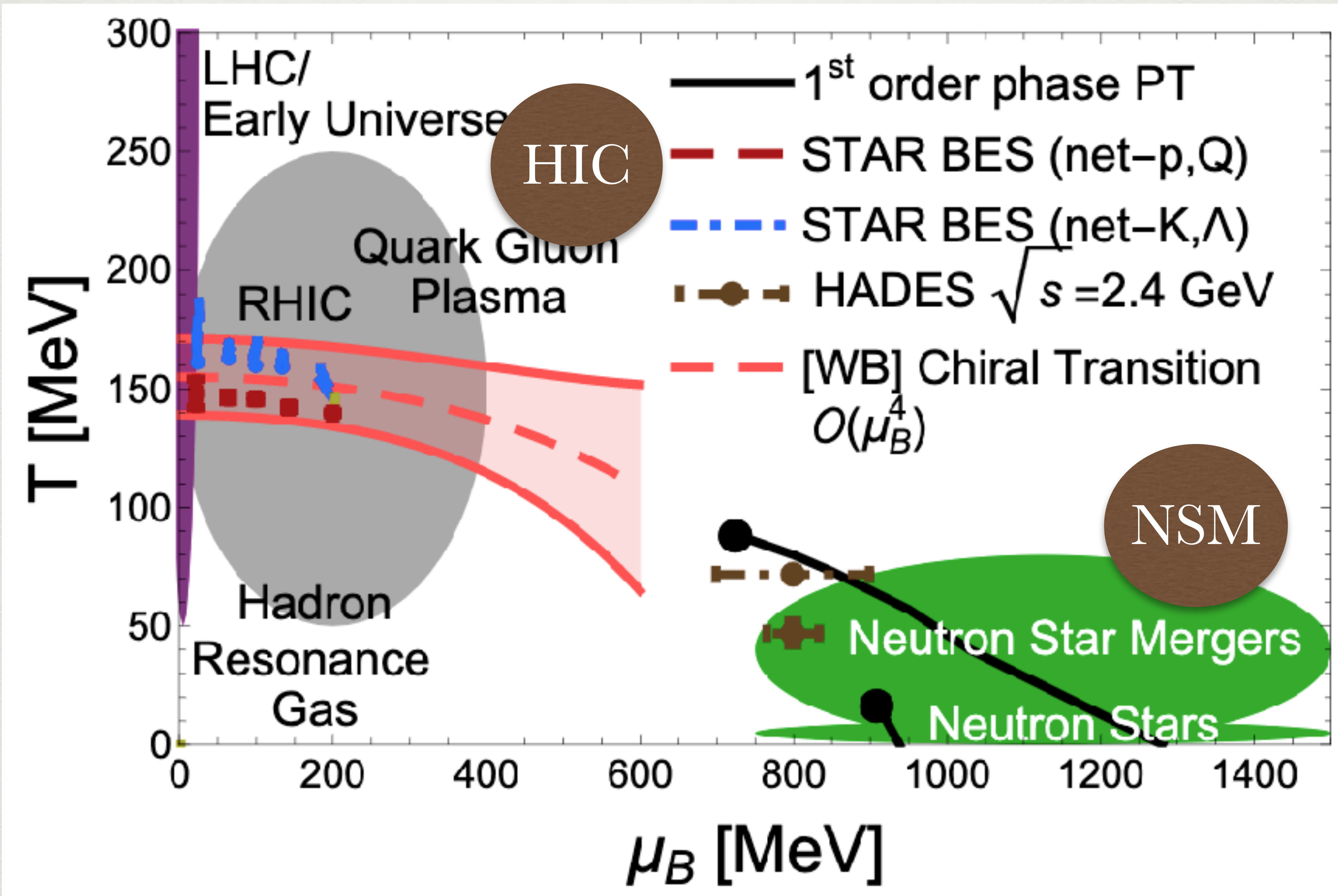


Eliminate 2: chiral transition line
Machine Learning in progress!
Debora Mroczek et al

Nucleus-Nucleus collisions= mini-neutron star mergers?



Can heavy-ions be used to constrain the NS EOS?



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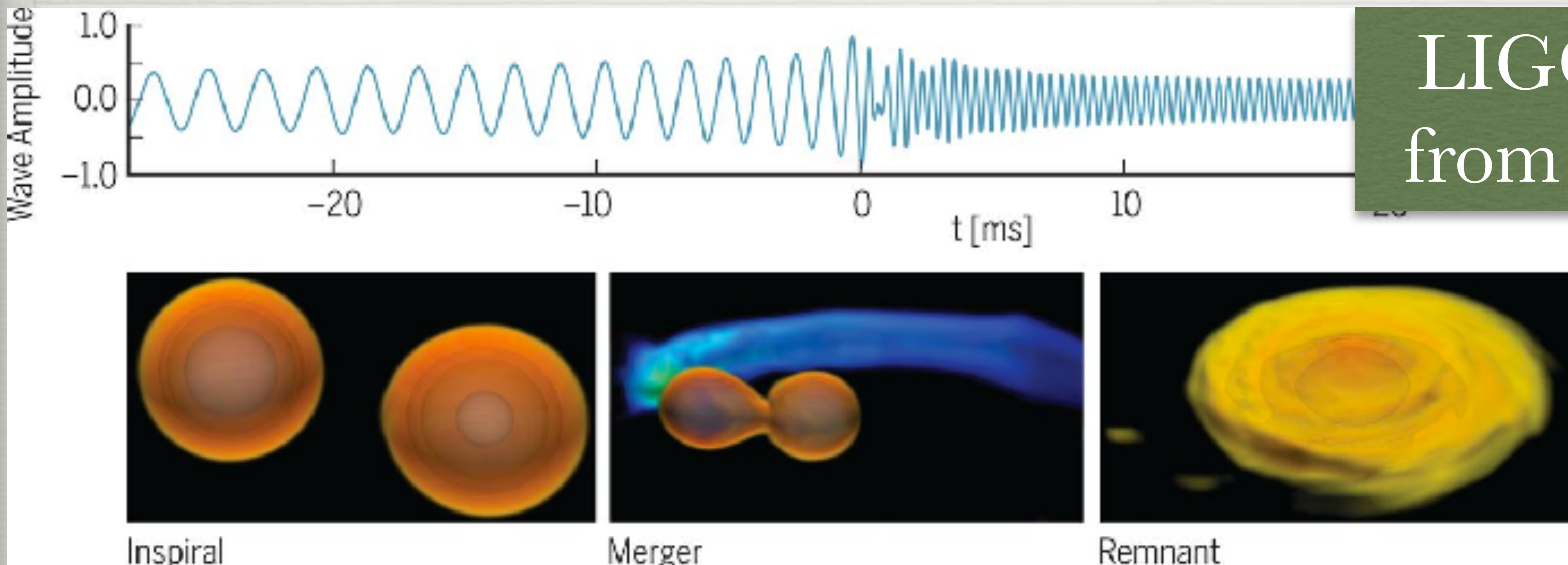
Constraints at low T and large ρ_B

LIGO/VIRGO: Inspiral from Gravitational Waves

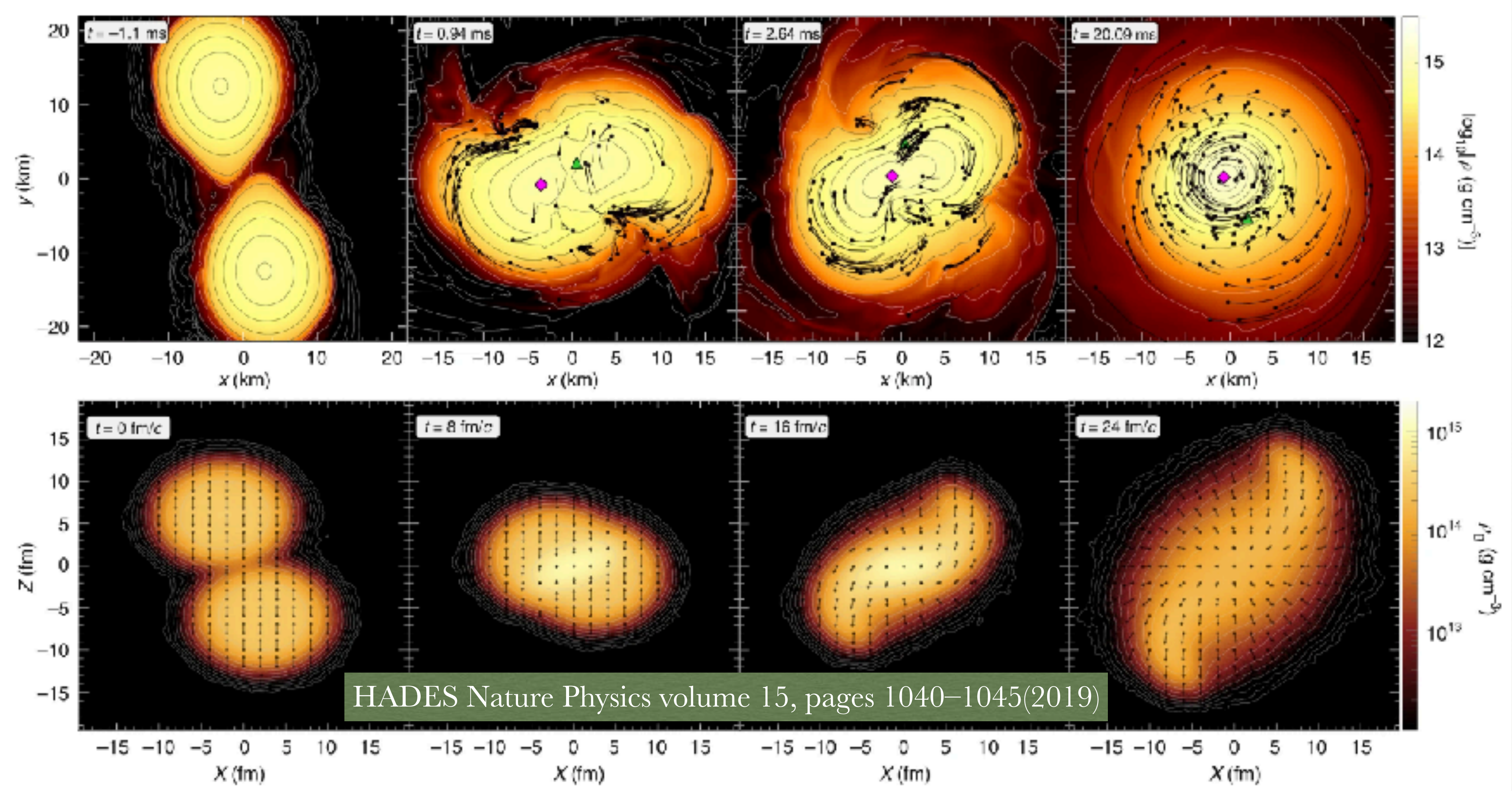


NICER: Observations of isolated Neutron Star

Late-stage Inspiral, Merger, Post-merger, …

HADES: Heavy-Ion Collisions vs. Neutron Stars

Comparable T, ρ_B between low-E heavy-ions (HADES) and top T's in neutron star ***mergers***.



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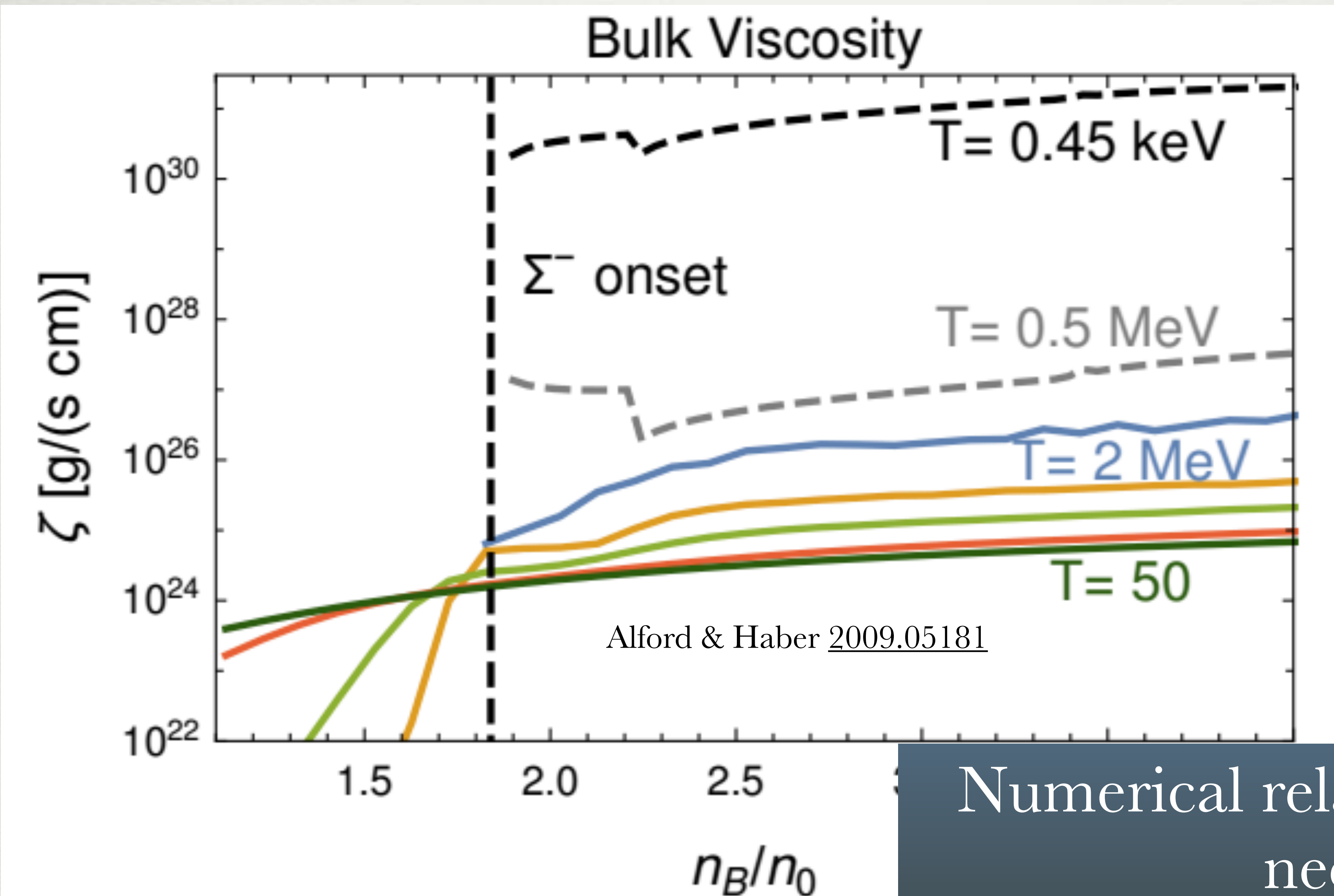
Viscosity revolution

Viscosity was a game changer for heavy-ion collision - what about neutron star mergers?

Bulk viscosity in neutron star mergers

Bulk viscosity also plays a significant role in neutron star mergers



Alford & Haber 2009.05181

Numerical relativity+viscosity needed

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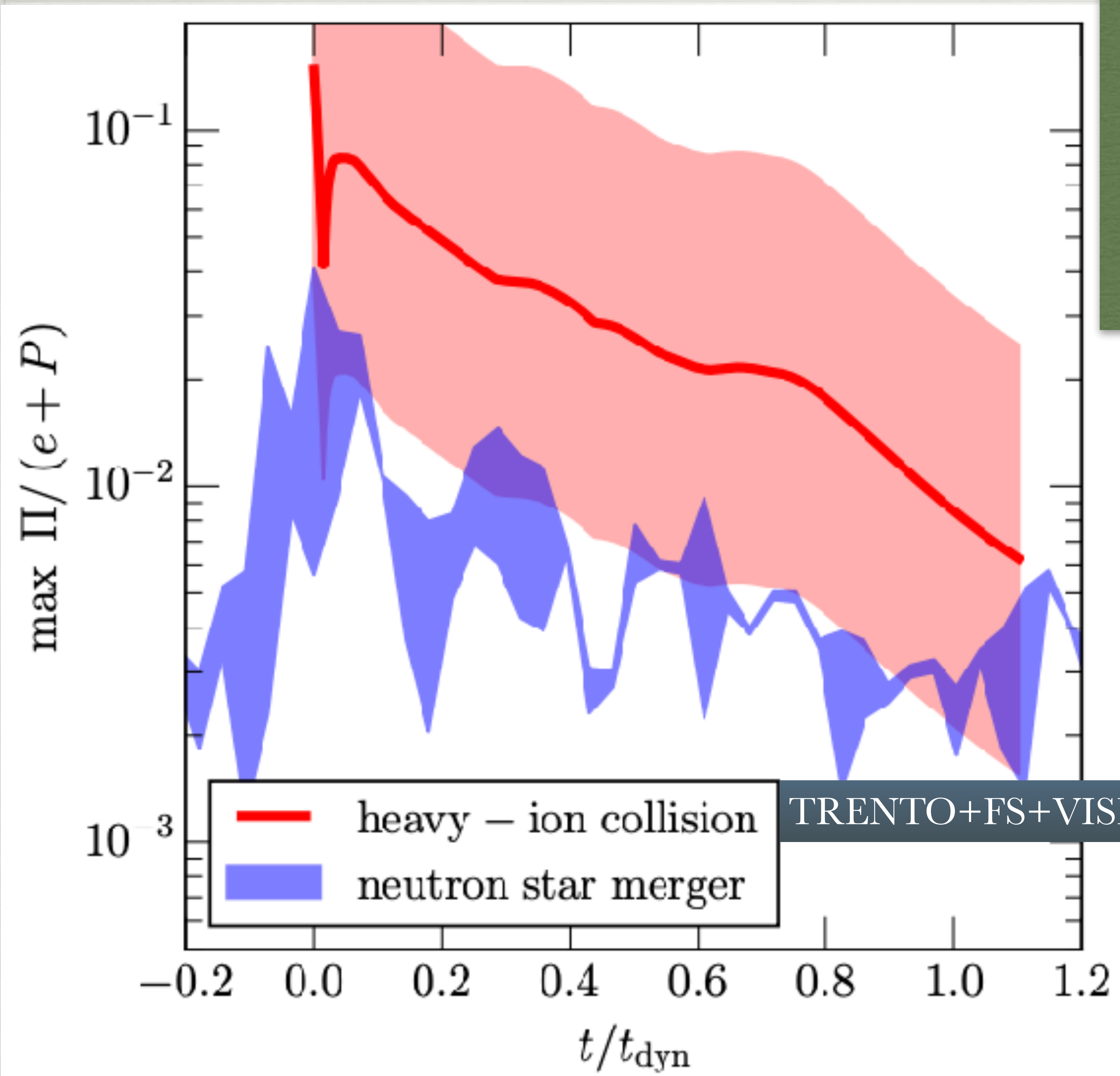
Bulk Viscosity: Heavy-ions vs. Neutron Star Mergers



TRENTO+FS+VISHNU

Alford, Harris, Most, Noronha, JNH, Pretorius, Plumberg, Witek, Yunes 2107.05094

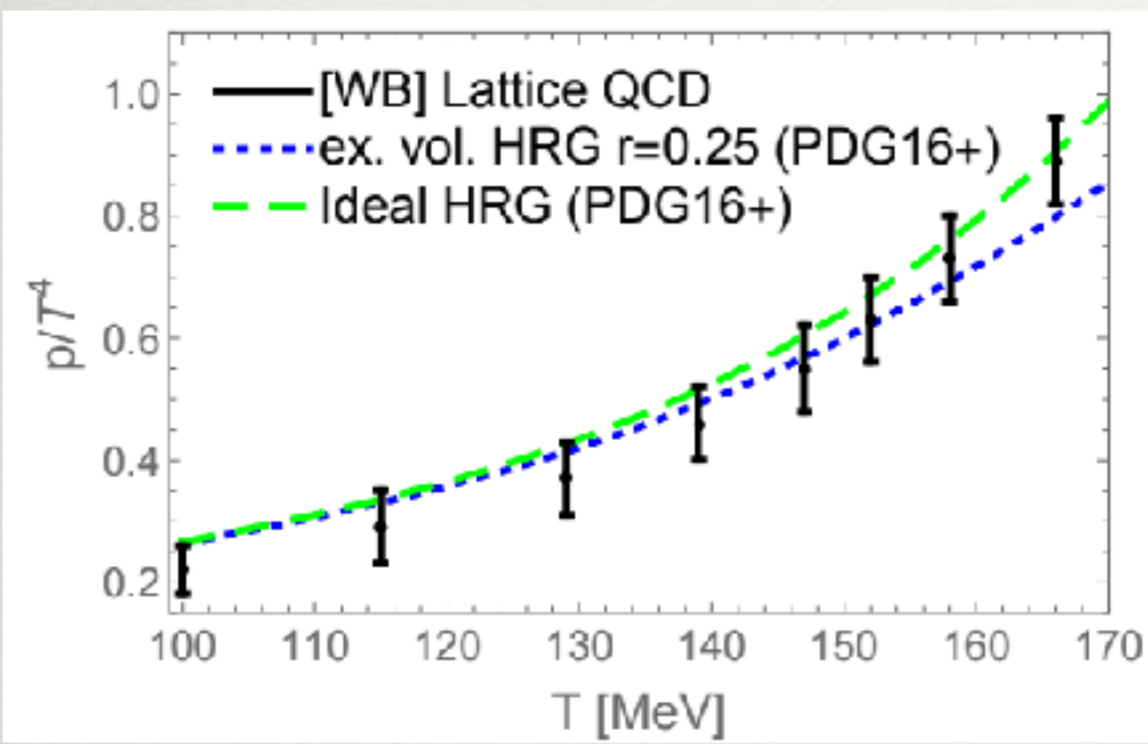
See also Pandya & Pretorius 2104.00804

Most influential post-merger

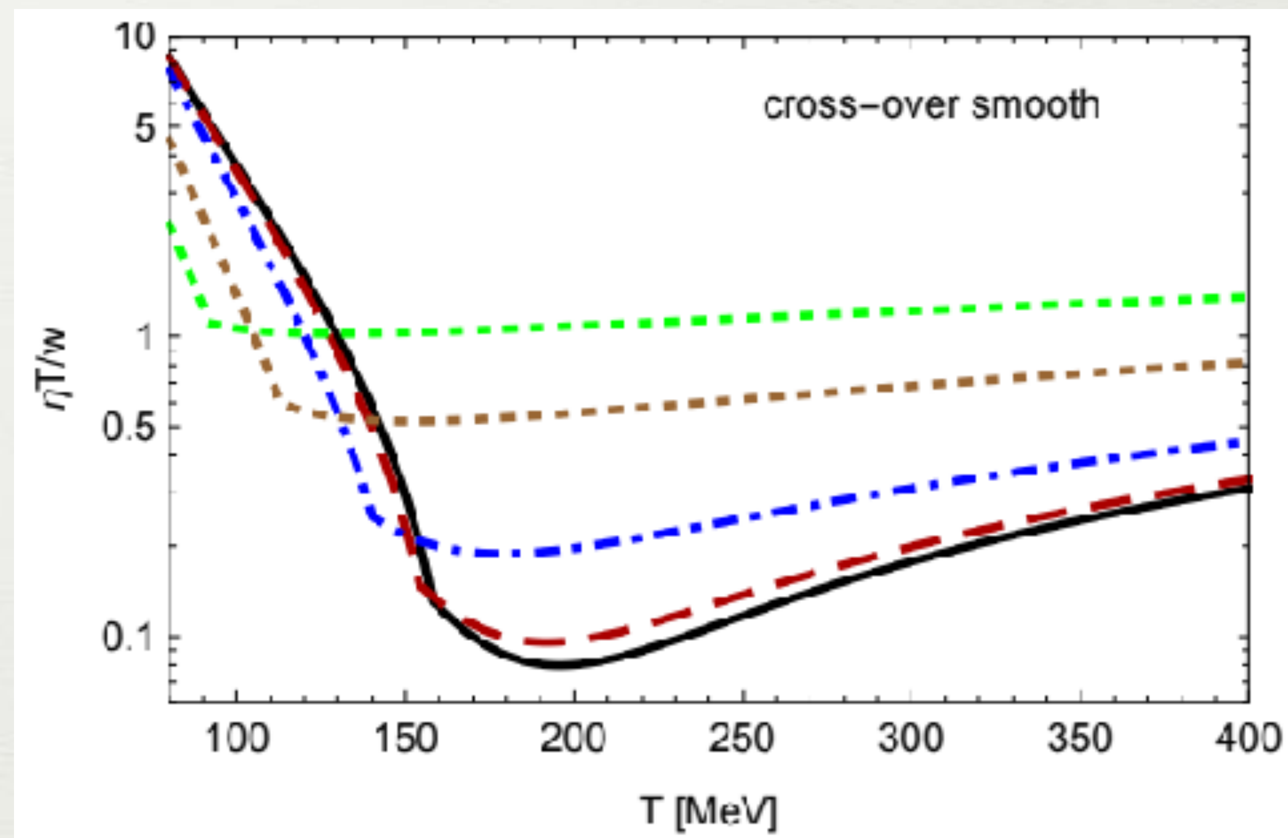
Testable shear viscosity $\eta T/w(T,\mu_B)$

McLaughlin, JNH, et al, 2103.02090

Constrain the Excluded volume from Lattice QCD



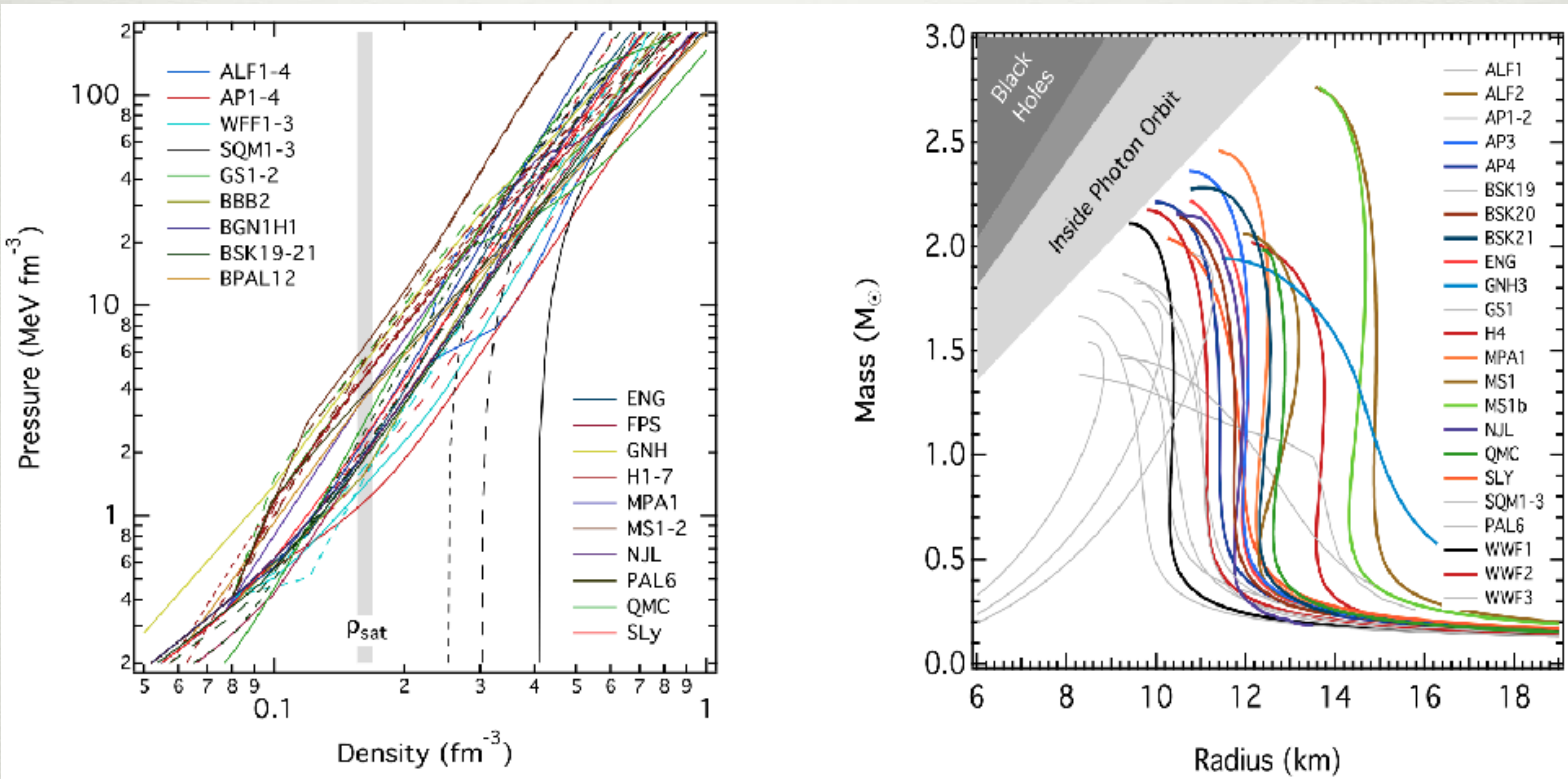
Matched to parameterized QGP shear using a variety of methods



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

EOS at T=0 connected to Mass vs. Radius

Plug EOS into Tolman–Oppenheimer–Volkoff (TOV) equation



Feryal Özel, Paulo Freire, Ann.Rev.Astron.Astrophys. 54 (2016) 401-440

Heavy neutron stars

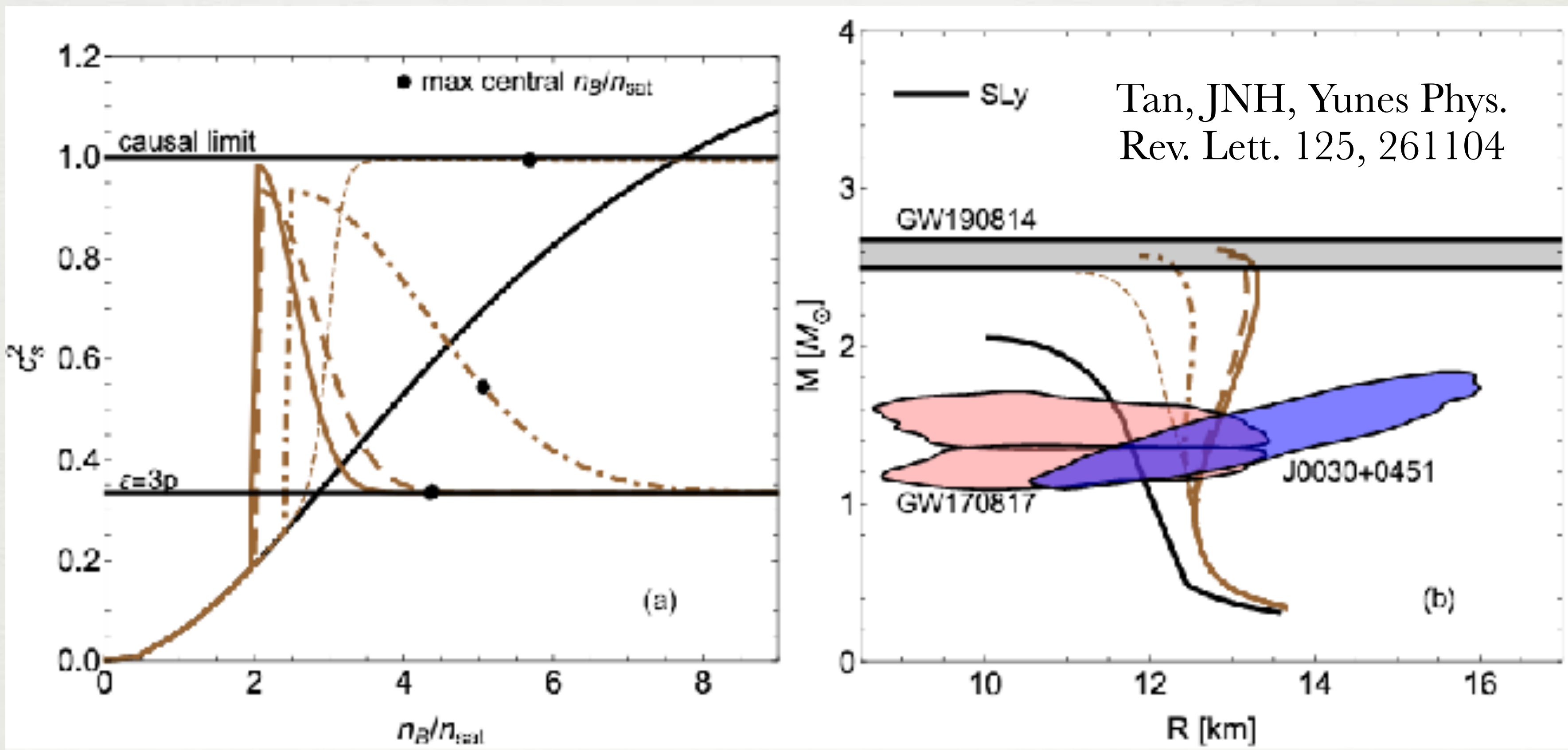
GW190814 [LIGO, Virgo], Astrophys. J. 896, L44 (2020)

Nico Yunes
ICASU director

Hung Tan
UIUC PhD Student

+Dore and Dexheimer (to appear soon)

Compact object of $M \geq 2.5M_{\odot}$ measured, is it a neutron star?



Bump in $c_s^2 > 1/3$?

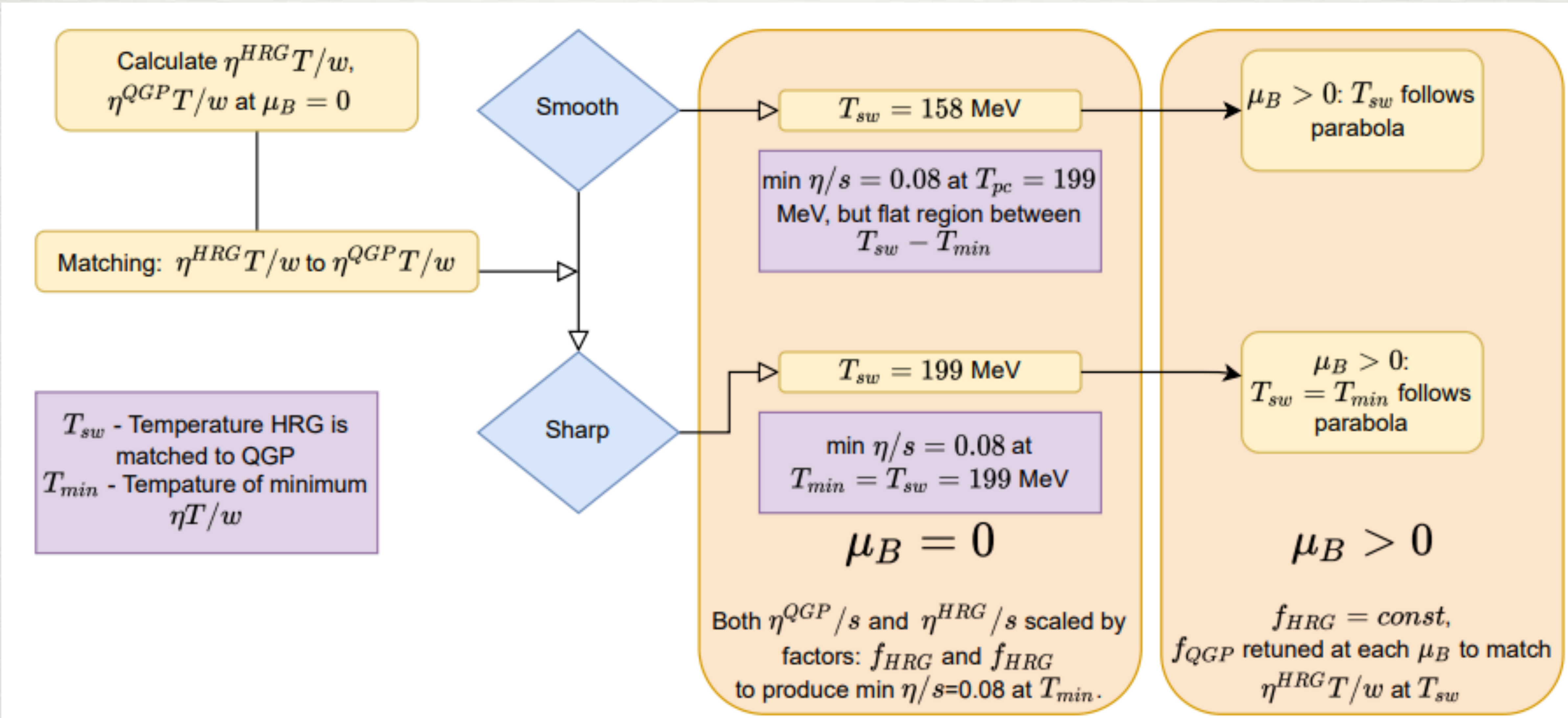
Bedaque & Steiner, Phys.Rev.Lett. 114 (2015) 3, 031103; Alford et al, Phys. Rev. D92, 083002 (2015), Ranea-Sandoval, et al, Phys. Rev. C93, 045812 I. Tews, et al, Phys. Rev. C98, 045804 (2018); McLerran & Reddy, Phys. Rev. Lett.122, 122701 (2019); Dexheimer & Schramm, Phys. Rev. C81, 045201 (2010); Jakobus, et al, arXiv:2004.07026 [nucl-th]; Baym et al, Astro-phys. J.885, 42 (2019)

Alternatives: spin/new strange interactions

Zhang & Li *Astrophys.J.* 902 (2020) 1, 38; Dexheimer et al, *Phys.Rev.C* 103 (2021) 2, 025808; Tsokarus *et al, Astrophys.J.* 905 (2020) 1, 48; Tews et al, Astrophys.J.Lett. 908 (2021) 1

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

McLaughlin et al, 2103.02090



Excluded volume in HRG

$$\eta^{HRG}=\frac{5}{64\sqrt{8}}\frac{1}{r^2}\frac{1}{n}\sum_i n_i\frac{\int_0^\infty p^3 e^{-\sqrt{p^2+m_i^2}/T+\tilde{\mu}_i}dp}{\int_0^\infty p^2 e^{-\sqrt{p^2+m_i^2}/T+\tilde{\mu}_i}dp}$$

Parameterized QGP phase

$$\eta^{QGP}/s=f\left[\frac{a}{\alpha^{\gamma}_{s,HQ}(cT/T_{YM})}+\frac{b}{(T/T_{YM})^{\delta}}\right]$$

Linear vs. Cubic response

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

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

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

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