UNIVERSITY OF ILLINOIS URBANA-CHAMPAIGN

Illinois Center for Advanced Studies of the Universe

Hot and Dense Quark-Gluon Plasma from Black Hole Engineering

JORGE NORONHA

In collaboration with

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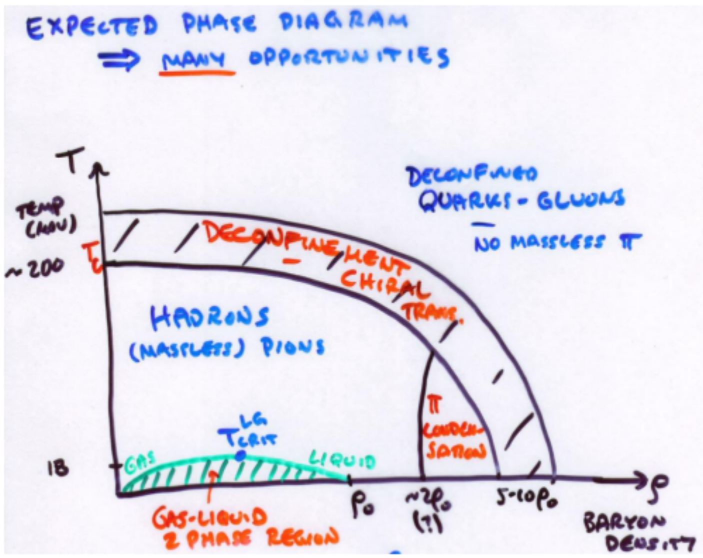
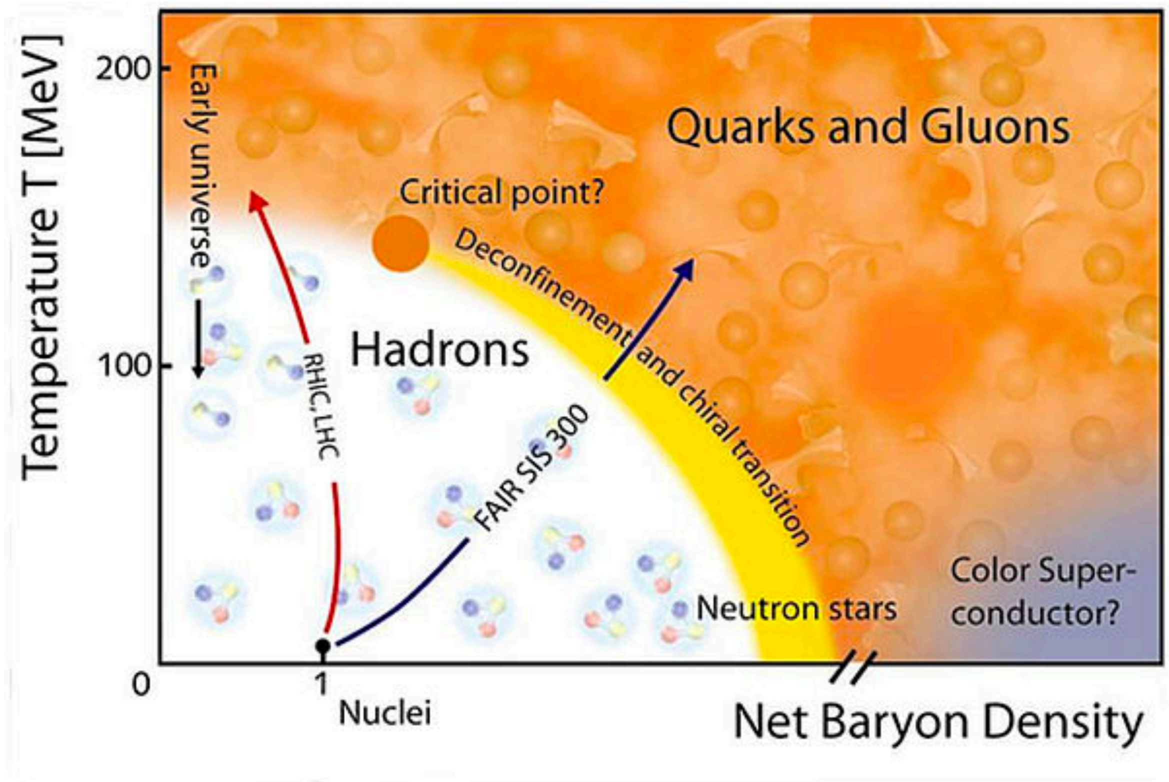
RHIC-BES Online Seminar Series, Nov. 2021

QCD Phase Diagram (from cartoon to reality)



From Gordon Baym, circa 1980

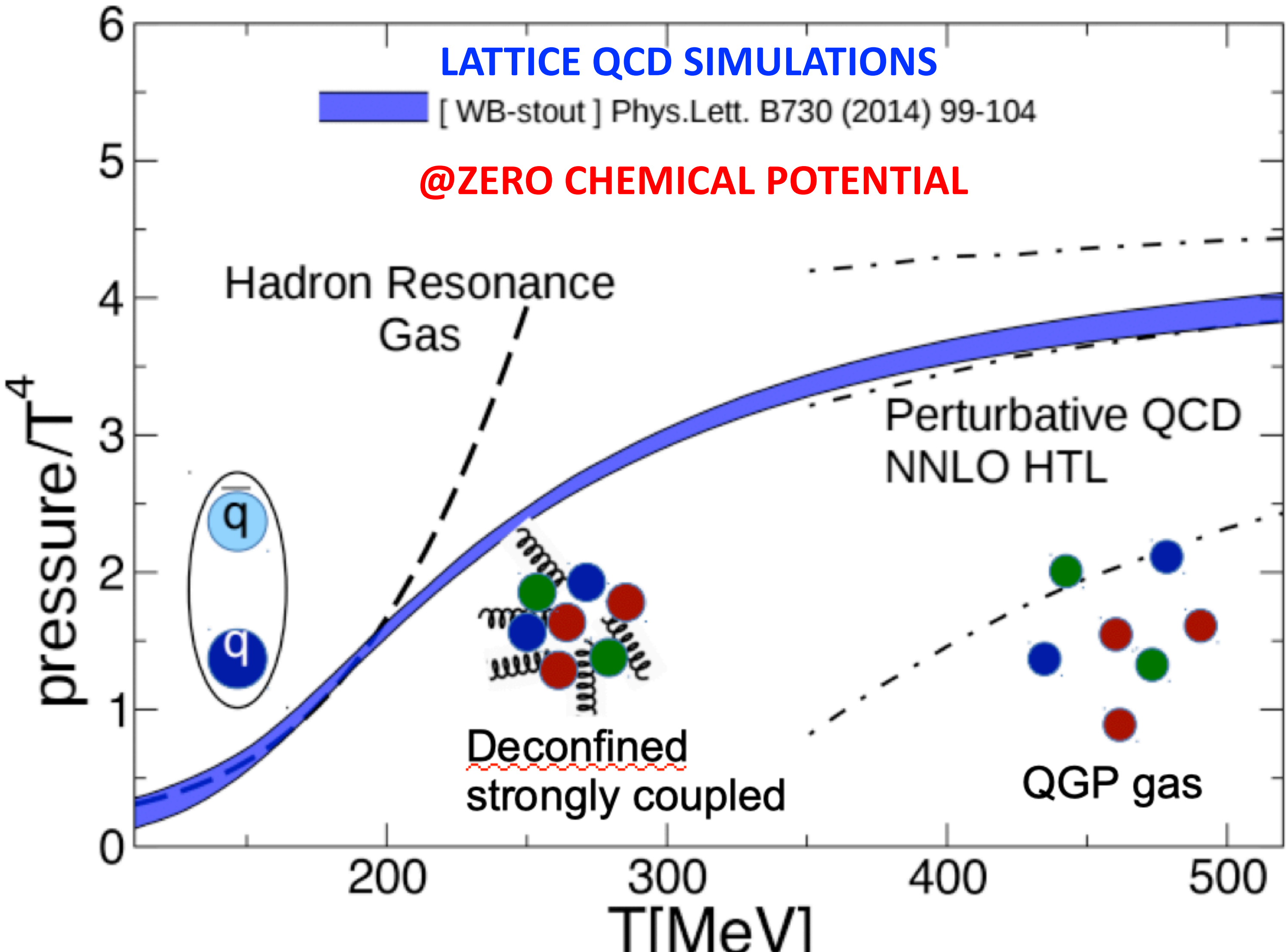


Focus (past 20 years):

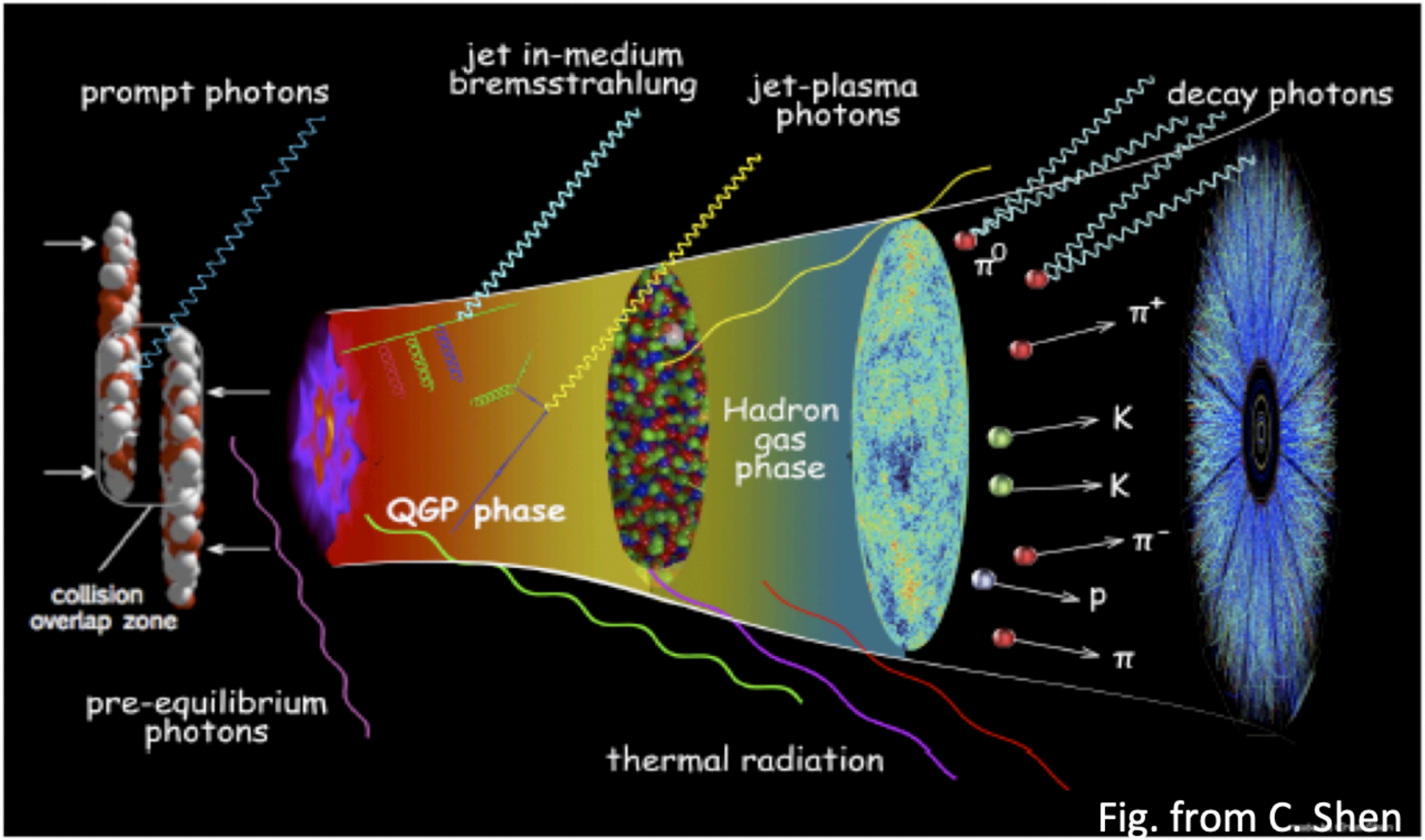
- Primordial quark-gluon plasma $T > m_\pi, \mu_B \sim 0$
- Investigation of in and out of equilibrium phenomena

Quark-Gluon Plasma (QGP) in equilibrium

QCD phase transition in the early universe was a crossover



Recreating the Primordial Liquid: Heavy-Ion Collisions



QGP = The hottest, densest, smallest, most perfect liquid

Nearly Perfect Fluidity: An Emergent Property of QCD

QGP behaves as a strongly coupled liquid !!!!

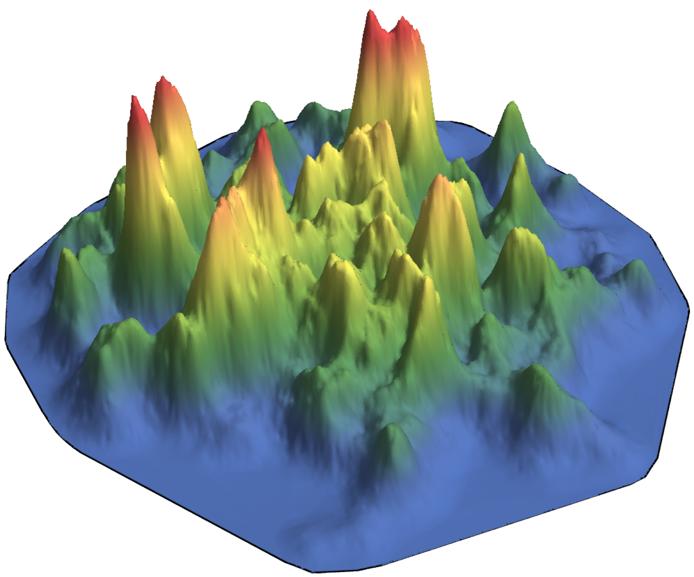
Shear viscosity to entropy density ratio

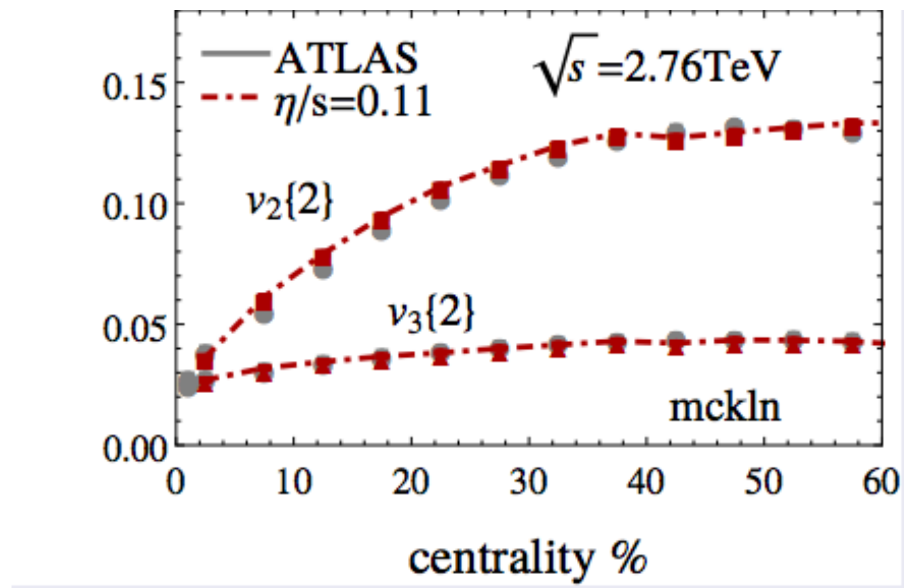
$$\eta/s \sim 0.05 - 0.2$$

Relativistic Hydrodynamics

Example:

Energy density



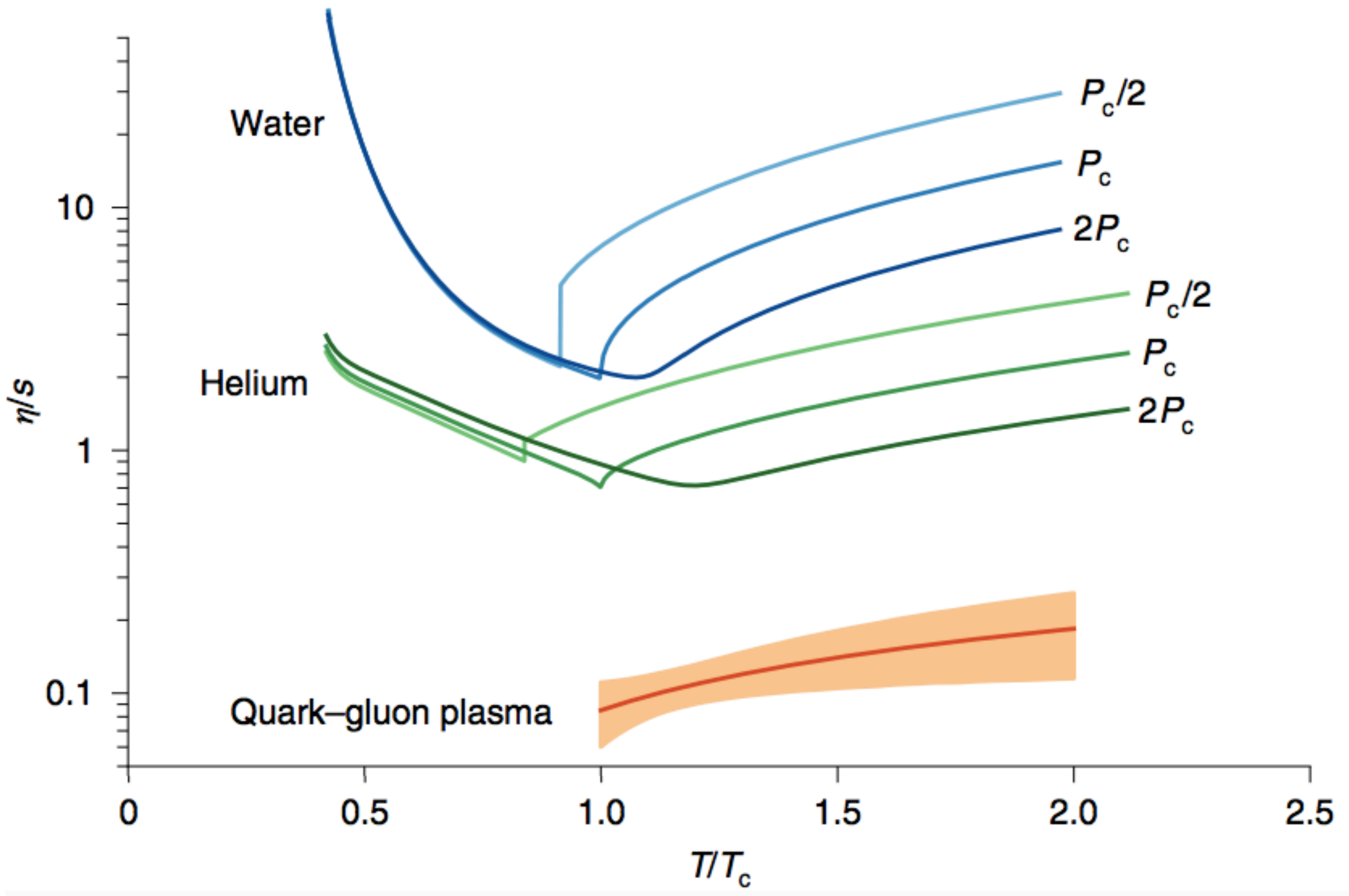


Noronha-Hostler, Betz, JN, Gyulassy, PRL 2016

(Nearly) Perfect Fluidity: An Emergent Property of QCD

QGP behaves as a strongly coupled relativistic fluid !!!

Bayesian analysis from Bernhard, Moreland, Bass, Nature Phys., 2019



- Nearly perfect fluidity of deconfined QCD matter is the defining feature of the QGP formed in heavy-ion collisions (“QGP book”).

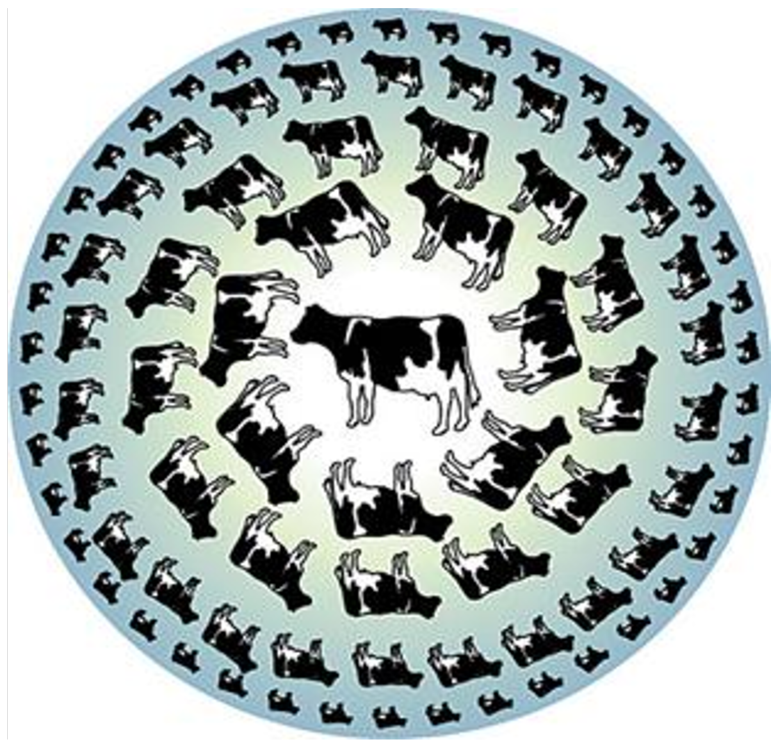
- This is an emergent property of the QCD liquid, i.e., its existence is not at all obvious when one stares at the QCD Lagrangian.

- Explanation is currently beyond the scope of ab initio lattice calculations.

- Likely beyond the scope of a consistent quasiparticle description as well.

However, even before the first modern viscous hydro simulations were done (Romatschke & Romatschke, 2007)

Nearly perfect fluidity had already been ***predicted*** to occur in a large class of systems using the holographic duality*



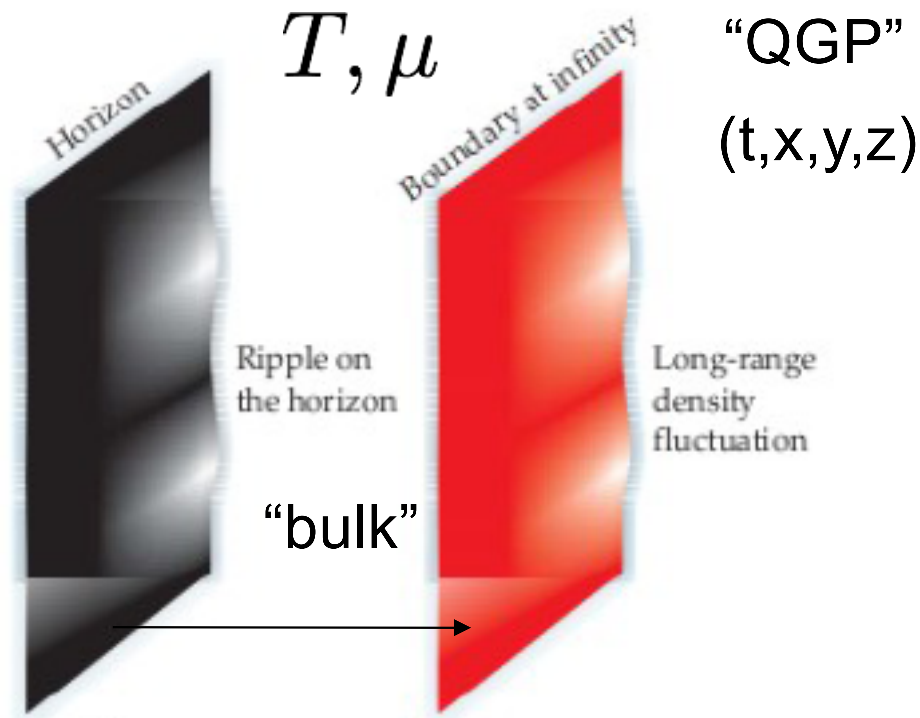
*Also known as:

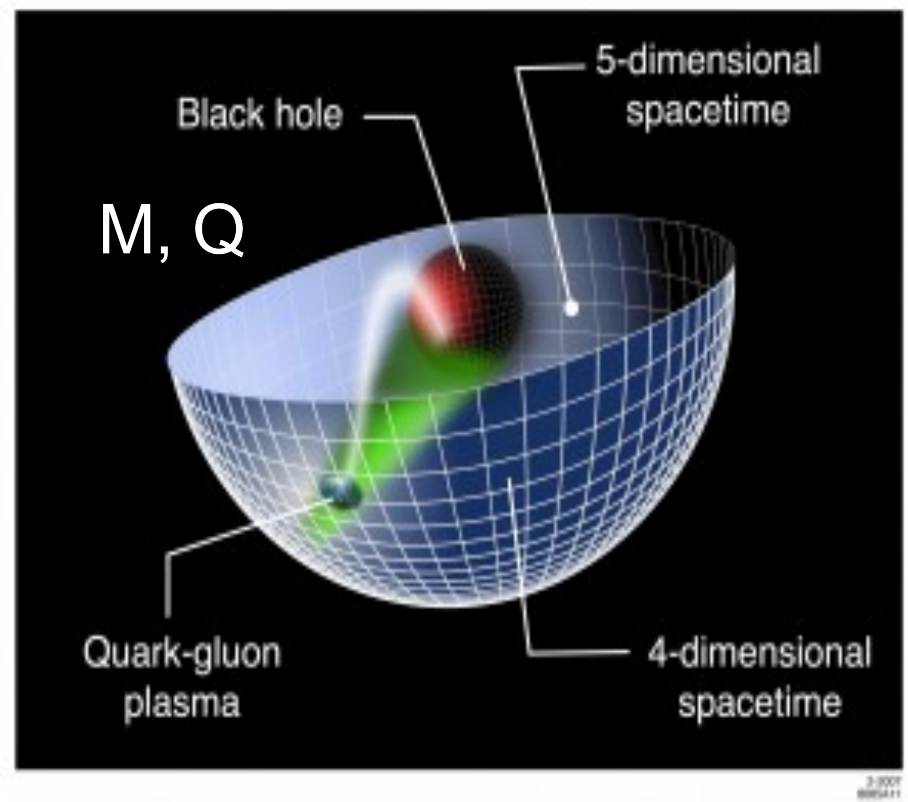
AdS/CFT correspondence
Maldacena duality
Gauge/gravity correspondence
Holography

Holographic correspondence (gauge/gravity duality)

Maldacena 1997; Witten 1998; Gubser, Polyakov, Klebanov 1998

Strongly coupled gauge theory ⟷ **String Theory/Classical gravity**





- **Fluid dynamics from black hole physics**
- **Quasiparticles "replaced" by curved geometry**

Key input from holography: Universality of Transport

Kovtun, Son, Starinets; Buchel, Liu (2003 - 2005), and MANY OTHERS

$\lambda \gg 1$ in QFT $\rightarrow$ string theory in weakly curved backgrounds

d.o.f. / vol. $\rightarrow \infty$ in QFT $\rightarrow$ vanishing string coupling

$T,\ \mu$ in QFT $\rightarrow$ spatially isotropic black brane

Corrections appear from anisotropy/inhomogeneities or higher order derivatives in the bulk action

$$\frac{\eta}{s} = \frac{1}{4\pi}$$

Nearly Perfect Fluid

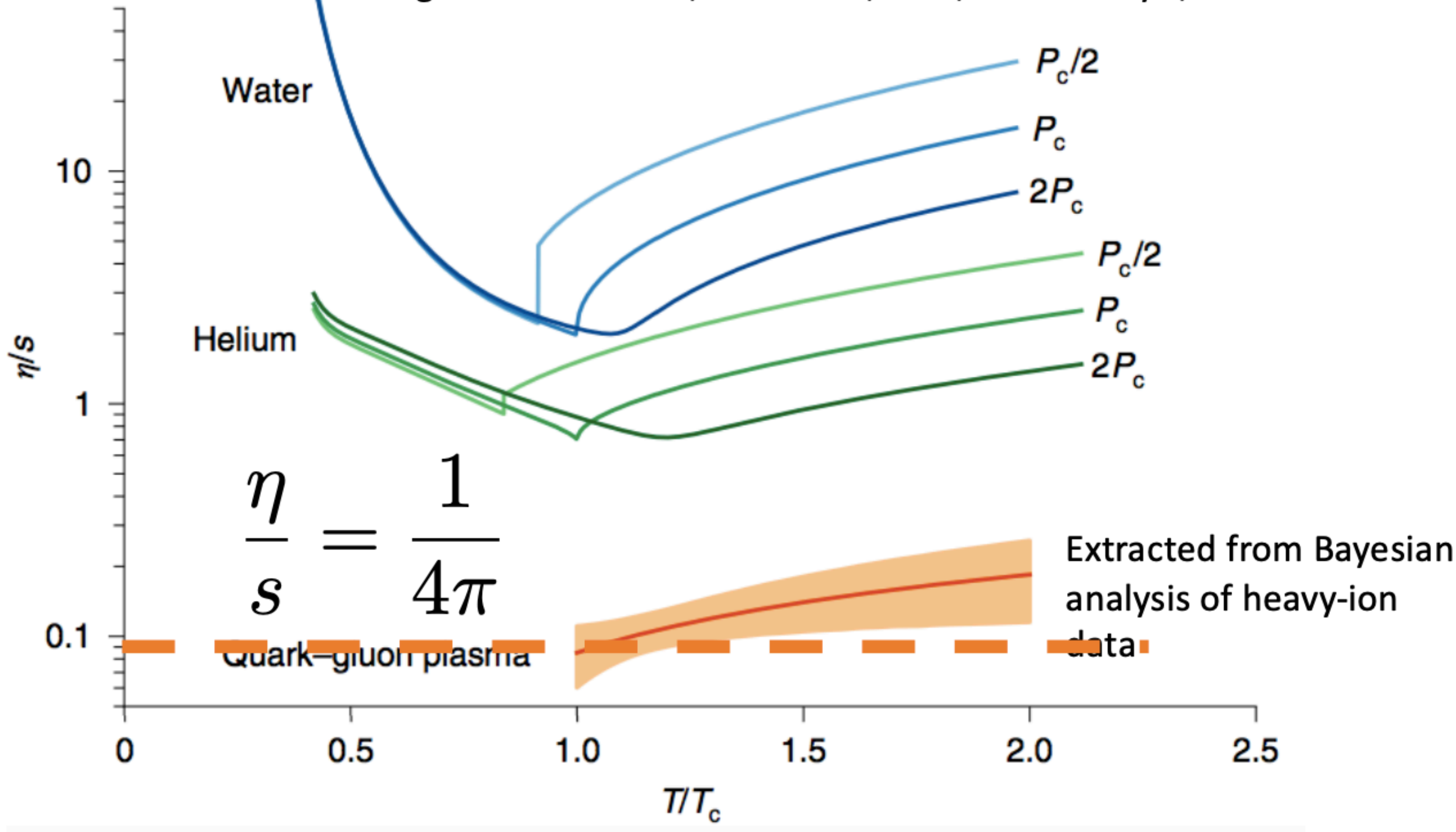
Right ballpark for the QGP!

Universality of black hole horizons $\Rightarrow$ **HOLOGRAPHY** $\Rightarrow$ Universality of transport coefficient in QFT

(Nearly) Perfect fluidity: an emergent property of QCD

QGP behaves as a strongly coupled relativistic fluid !!!

Fig. from Bernhard, Moreland, Bass, Nature Phys., 2019



Holography has been important in heavy-ion collisions:

- Paradigm change (from weakly to a strongly coupled QGP).

calculation of 20+ transport coefficients!!

- Equilibrium and near-equilibrium physics beyond quasiparticles.

Rougemont, Finazzo, JN, et al (2014-2017)

- Motivated a number of other developments and applications.

(e.g. jet energy loss/quenching in a strongly coupled QGP).

- Led to new developments in relativistic hydrodynamics

(e.g. fluid/gravity duality, higher order derivative expansions, attractors).

- Motivated further studies about the role of anomalies and topology in strongly coupled gauge theories.

- Our only practical way to study strongly coupled gauge theories far from equilibrium (numerical relativity in AdS spacetime).

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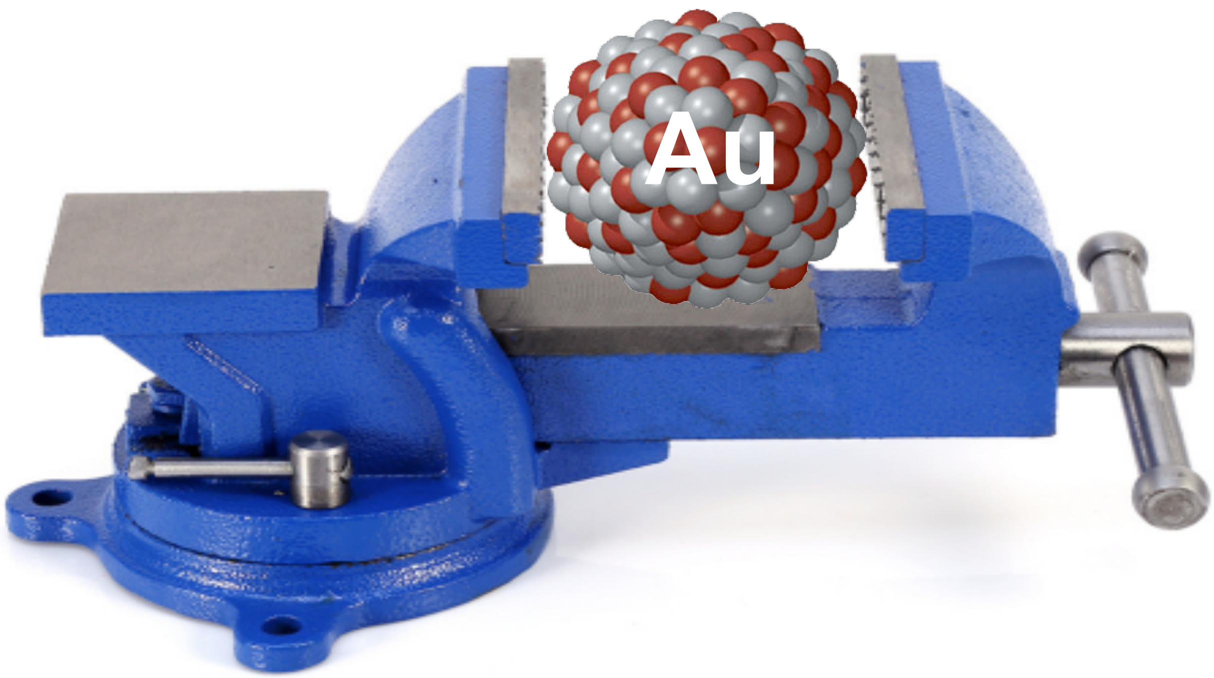
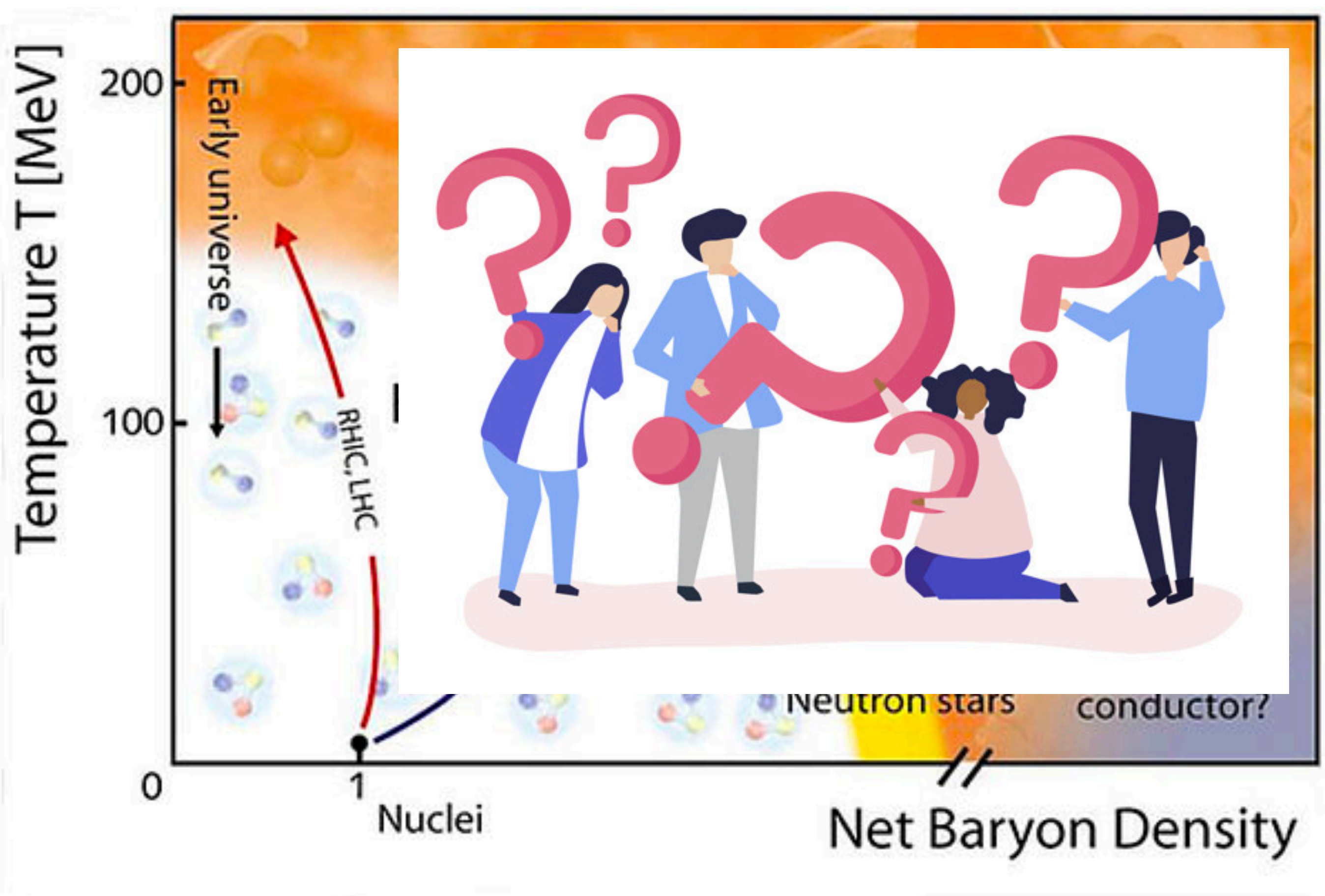
QCD at Large Net Baryon Density

A major focus of our community for the next 20 years (RHIC, FAIR, NICA)

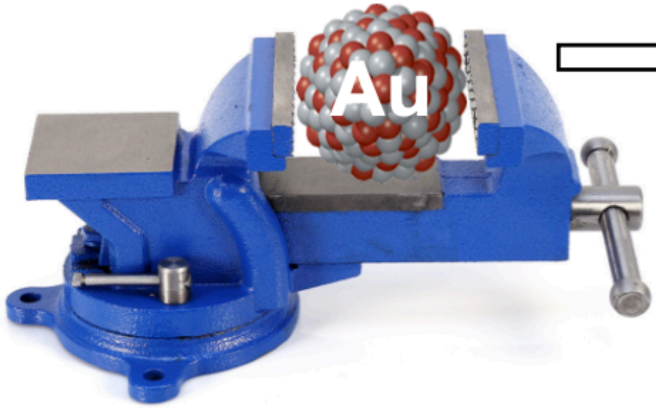


Properties of matter at <u>*extreme*</u> baryon densities (core of neutron stars) remain unknown even in equilibrium

QCD Phase Diagram

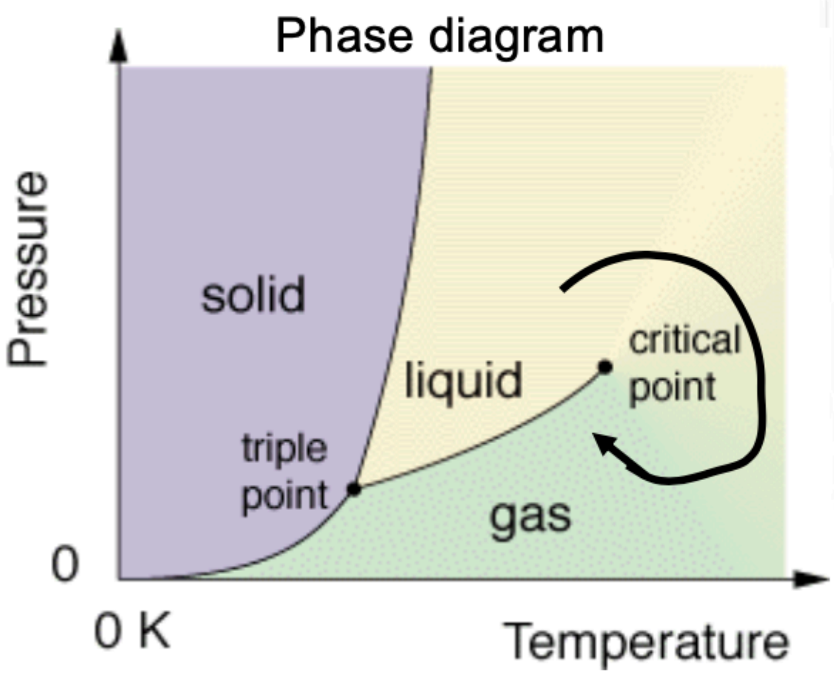


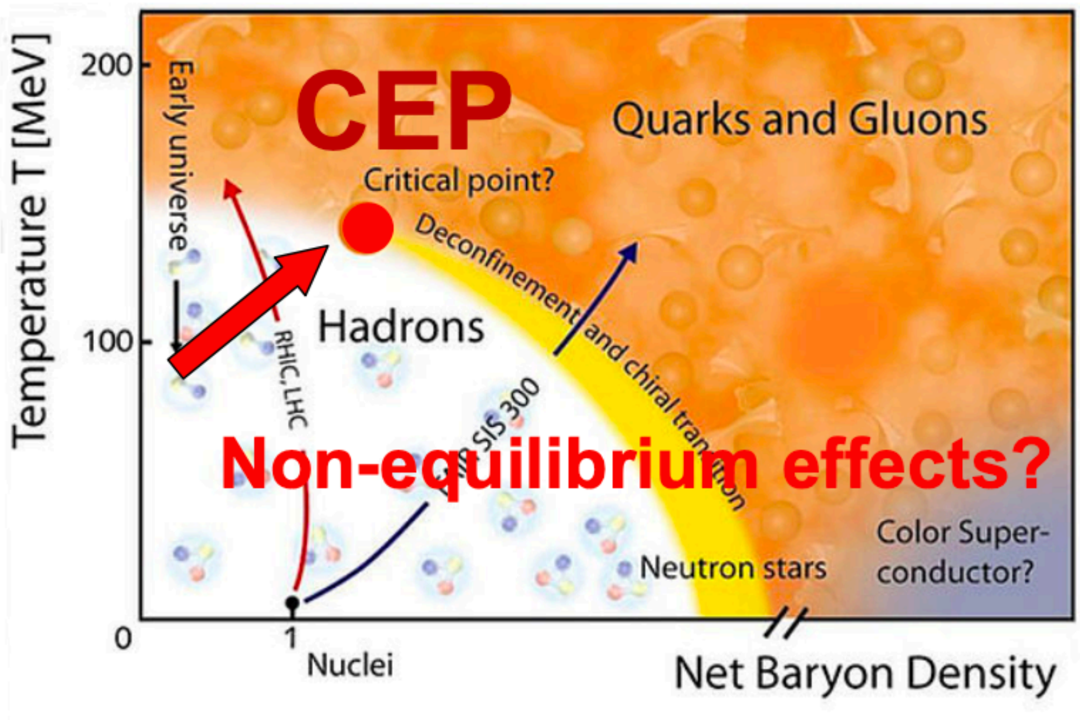
2019+ → QCD at large baryon densities (RHIC, FAIR, NICA)



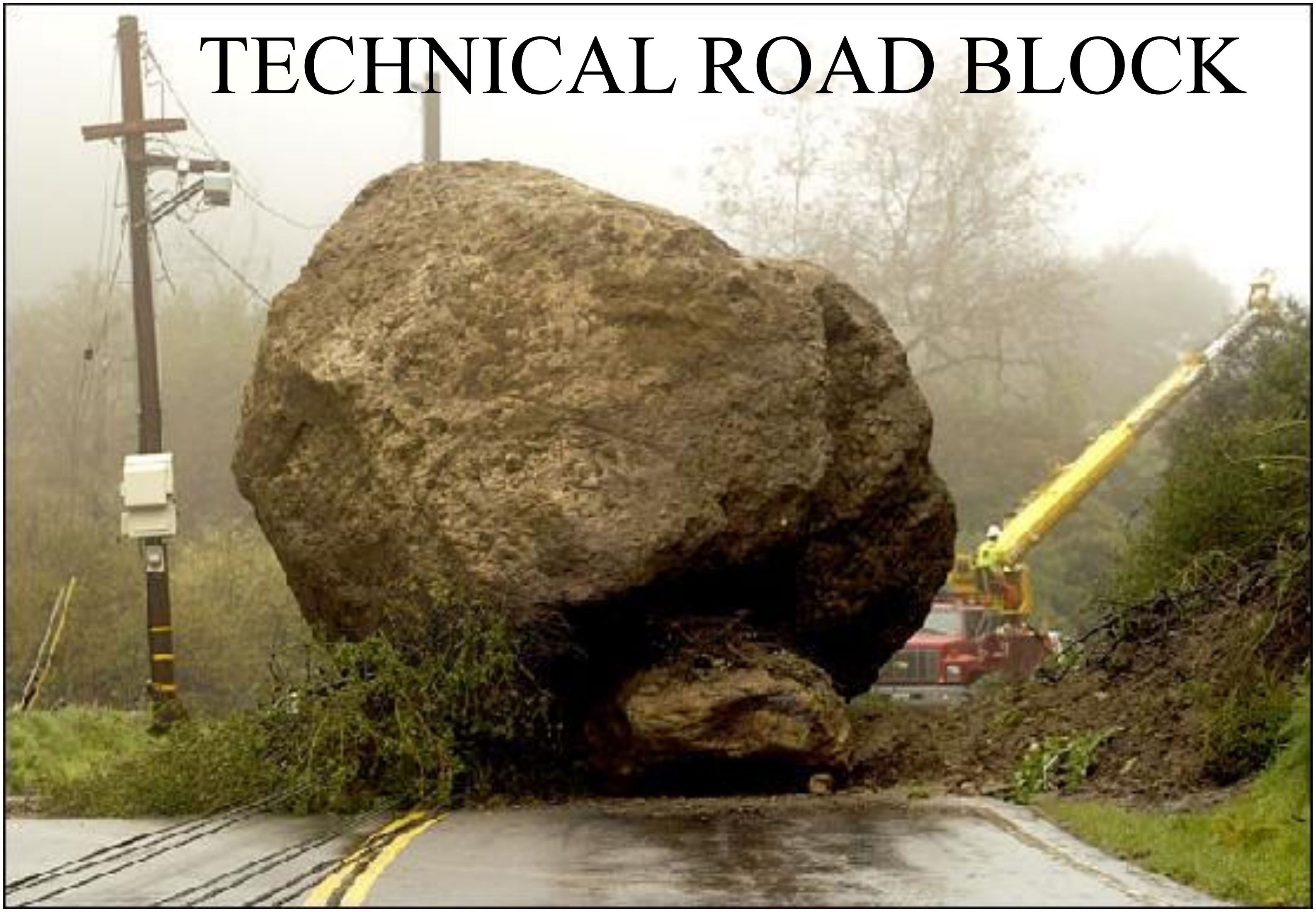
Signatures of critical phenomena in QCD?

RHIC Beam Energy Scan (BES) II

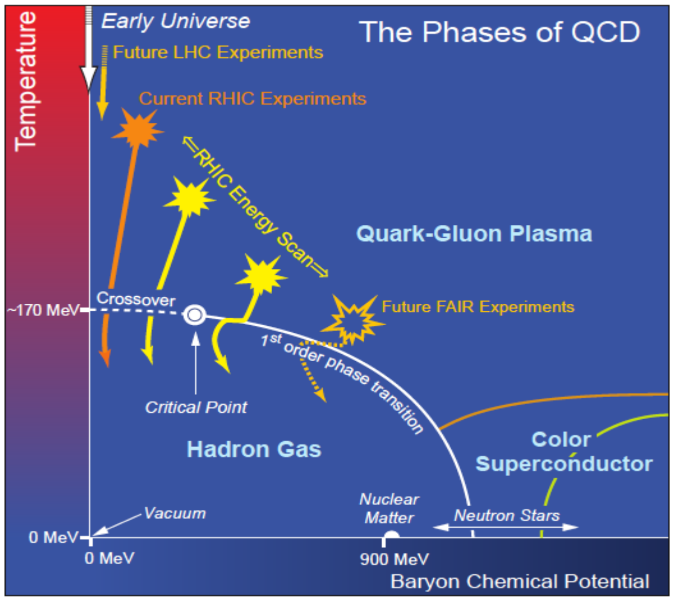


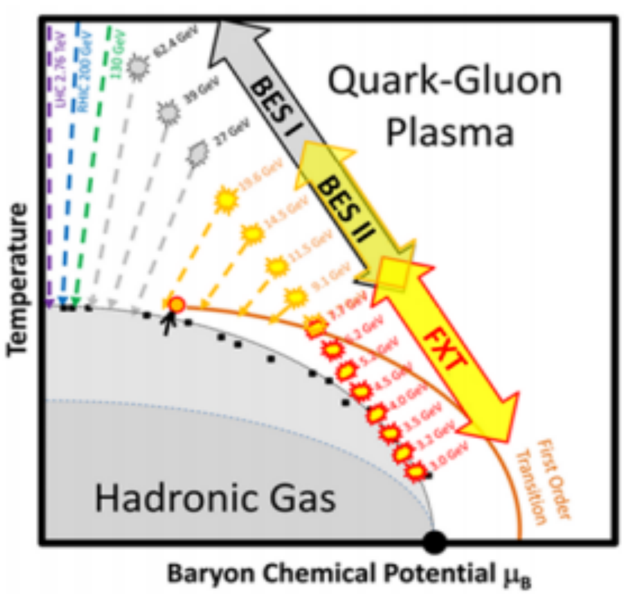


The Sign Problem



Consequences of the Fermion Sign Problem in QCD





- Majority of QCD phase diagram: unknown
- EOS for neutron stars and mergers: unknown
- Location/existence of high T critical point: unknown

RHIC Beam Energy Scan (BES) II

Major experimental effort to search for the critical point using heavy ion collisions (STAR experiment)

QCD thermodynamics from a Taylor expansion

Expand the QCD partition function in a Taylor series around $\mu_B = 0$

$$\frac{P(T,\mu_B) - P(T,0)}{T^4} = \sum_{n=1}^{\infty} \frac{1}{(2n)!} \chi_{2n}(T) \left(\frac{\mu_B}{T}\right)^{2n}$$

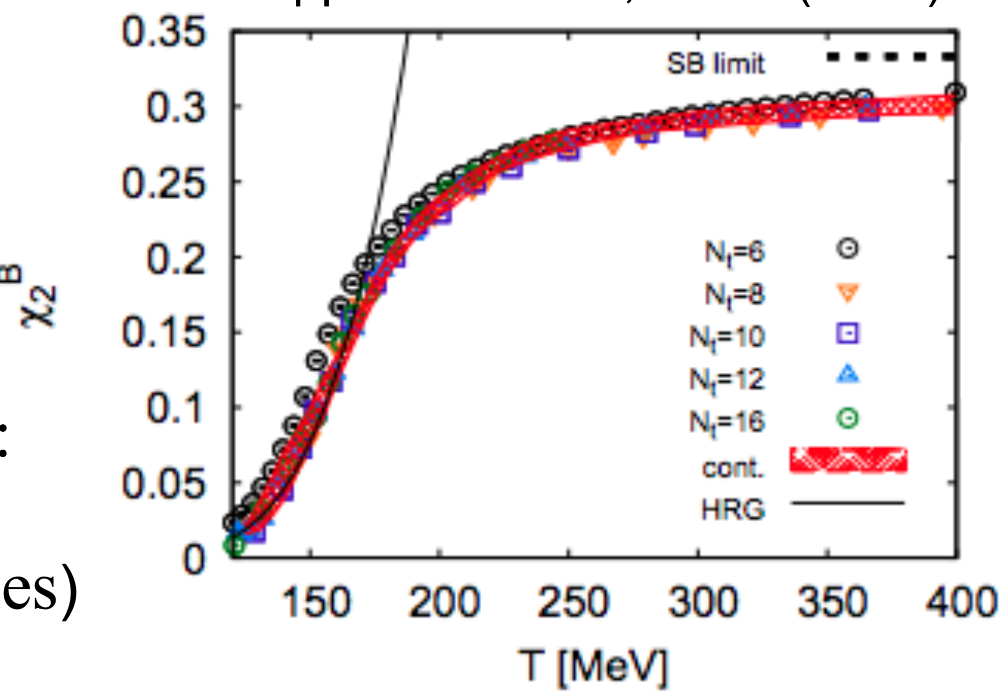
Baryon susceptibilities

$$\chi_n^B(T,\mu_B) = \frac{\partial^n (P/T^4)}{\partial(\mu_B/T)^n}$$

- Few coefficients are known
- Multitude of new approaches:

(imaginary chemical potential resummations, Lefschetz-thimbles)

Wuppertal Collab., JHEP (2012)



Ab initio approaches, valid in the strongly coupled regime in and out-of-equilibrium, remain unavailable especially in the baryon-rich regime.

What do we need?

- An effective theory for hot deconfined matter with at least one conserved charge (baryon charge)
- Approach where nearly perfect fluidity is manifest
- Agreement with known lattice thermodynamics results
- Ability to perform calculations even far from equilibrium

How would we construct such an effective theory?

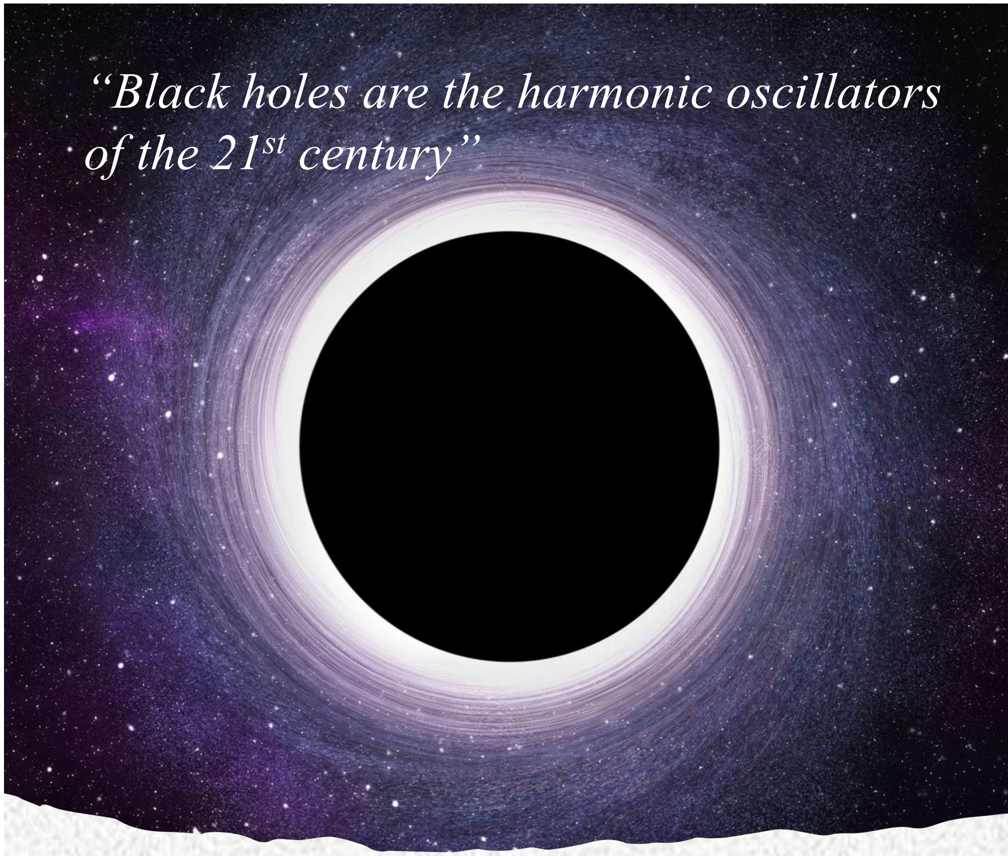
- At low energies, the relevant operators are:

$$J_B^\mu \qquad \langle \bar{\psi}\psi \rangle \qquad \mathrm{Tr}\, F^2 \qquad T_{\mu\nu} \qquad \mathrm{Tr}\, F\tilde{F}$$

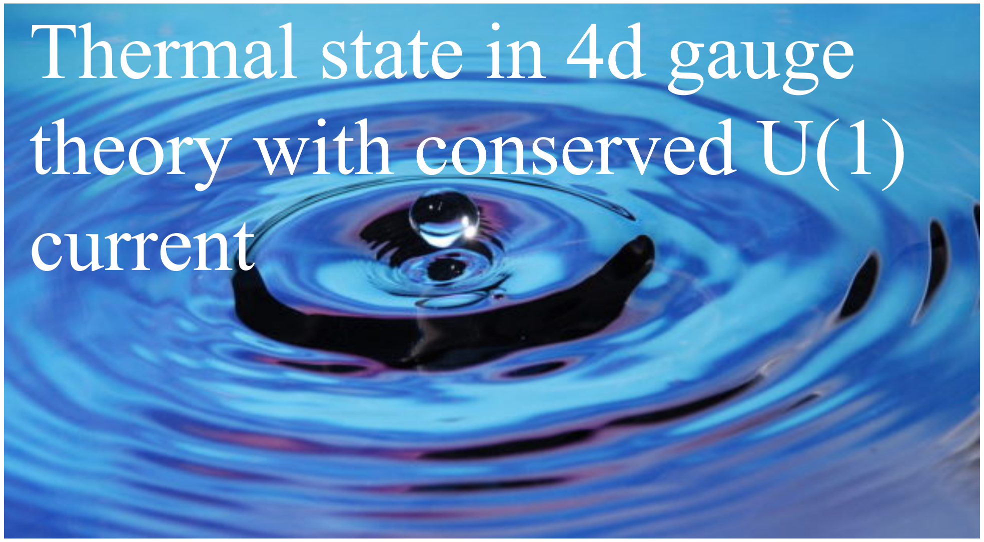
- Quasiparticle description is not mandatory in the regime we are interested in, but nearly perfectly fluidity is.

- In principle, the effective theory does not need to be described in d=4 dimensions (examples exist, especially at strong coupling).

- Effective theory does not need to be local in those variables.



Black Hole Engineering



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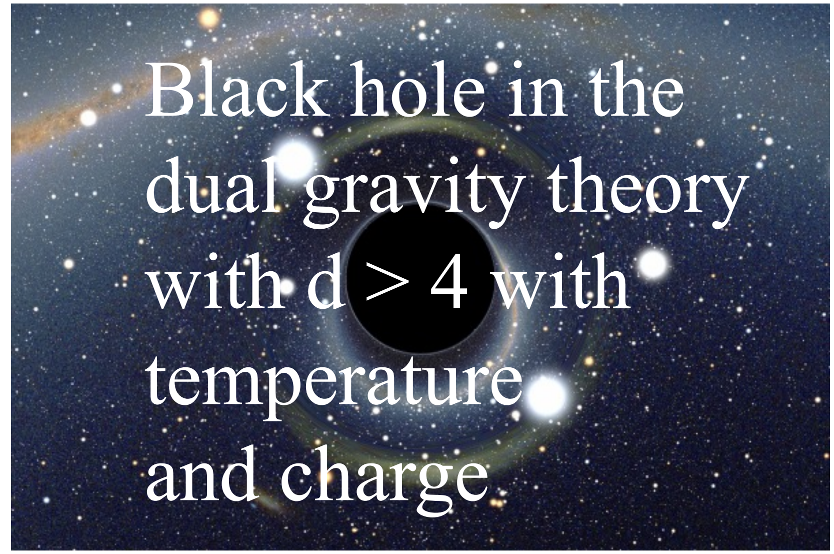


Strongly coupled gauge theory at large Nc:

- Dual gravitational description becomes local and semi-classical.

Classical gravity action

$$Z_{QFT}(T,\mu) \sim e^{-S_{gravity}}$$

Quantum partition function

with a black hole

In this regime, it is simple to take into account the operators

Gauge theory in 4d:	$J^\mu_B(x)$	$T_{\mu\nu}(x)$	$\mathrm{Tr}\, F^2(x)$
	↓	↓	↓
Gravity in 5d:	$A^M(x,r)$	$g_{MN}(x,r)$	$\phi(x,r)$

Most general gravitational effective action

$$\mathcal{S} = \frac{1}{2\kappa^2}\int d^5x\sqrt{-g}\left[R - \frac{1}{2}(\partial_M\phi)^2 - V(\phi) - \frac{1}{4}f(\phi)F^2_{MN}\right]$$

Thermodynamics in QFT ⟷ Solutions of Einstein's equations with a black hole

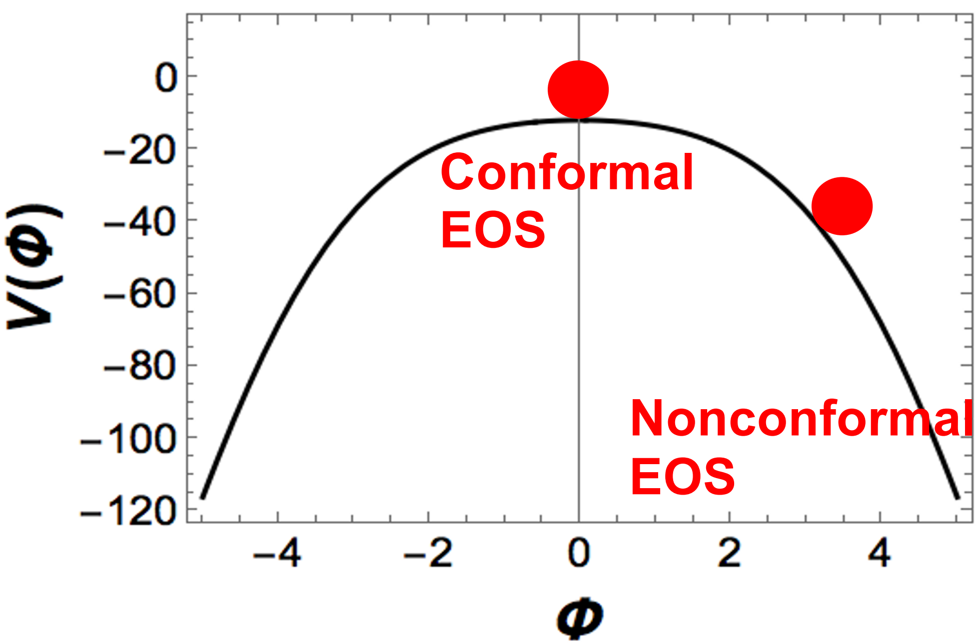
Black hole engineering and the non-conformal QGP

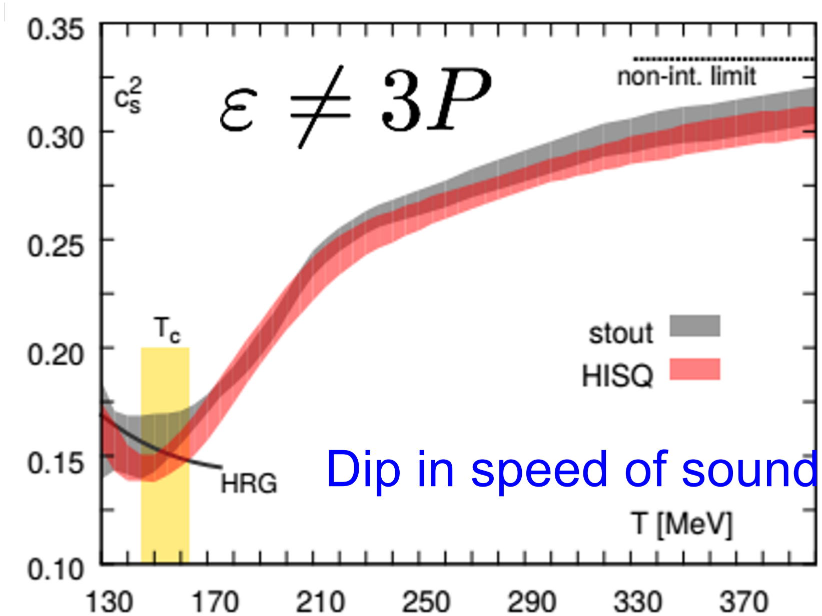
Minimal 5d bulk holography for a non-conformal plasma at $\mu_B = 0$

Gursoy, Kiritsis, Mazzanti, Nitti (2008)
Gubser and Nellore, (2008)
JN, (2009)

$$\mathcal{S} = \frac{1}{2\kappa^2}\int d^5x\sqrt{-g}\left[R - \frac{1}{2}(\partial_M\phi)^2 - V(\phi)\right]$$

Potential engineering: description of $\mu_B = 0$ thermal QCD

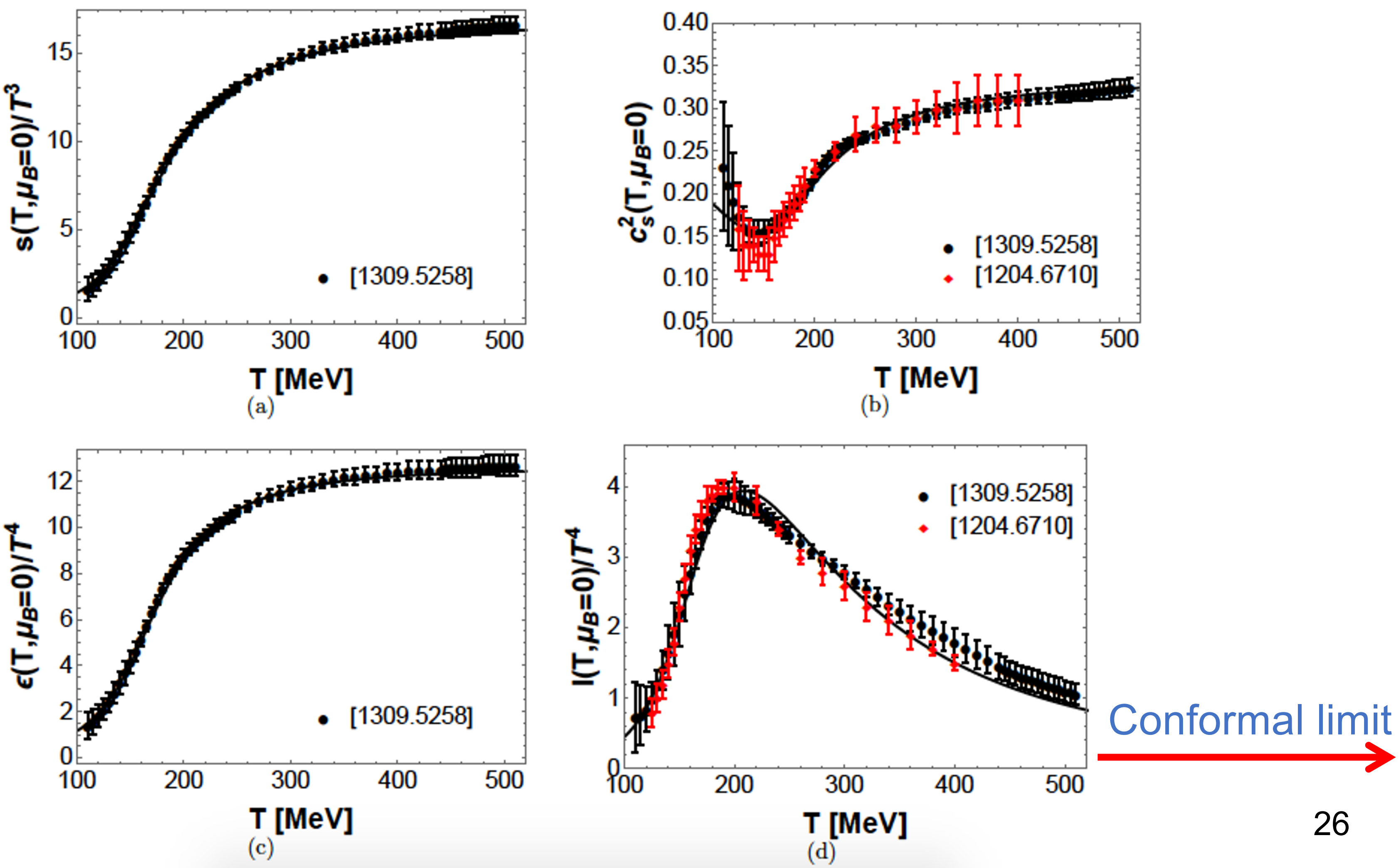




Black hole engineering and the non-conformal QGP

Critelli, JN, Noronha-Hostler, Portillo, Ratti, Rougemont, PRD 2017

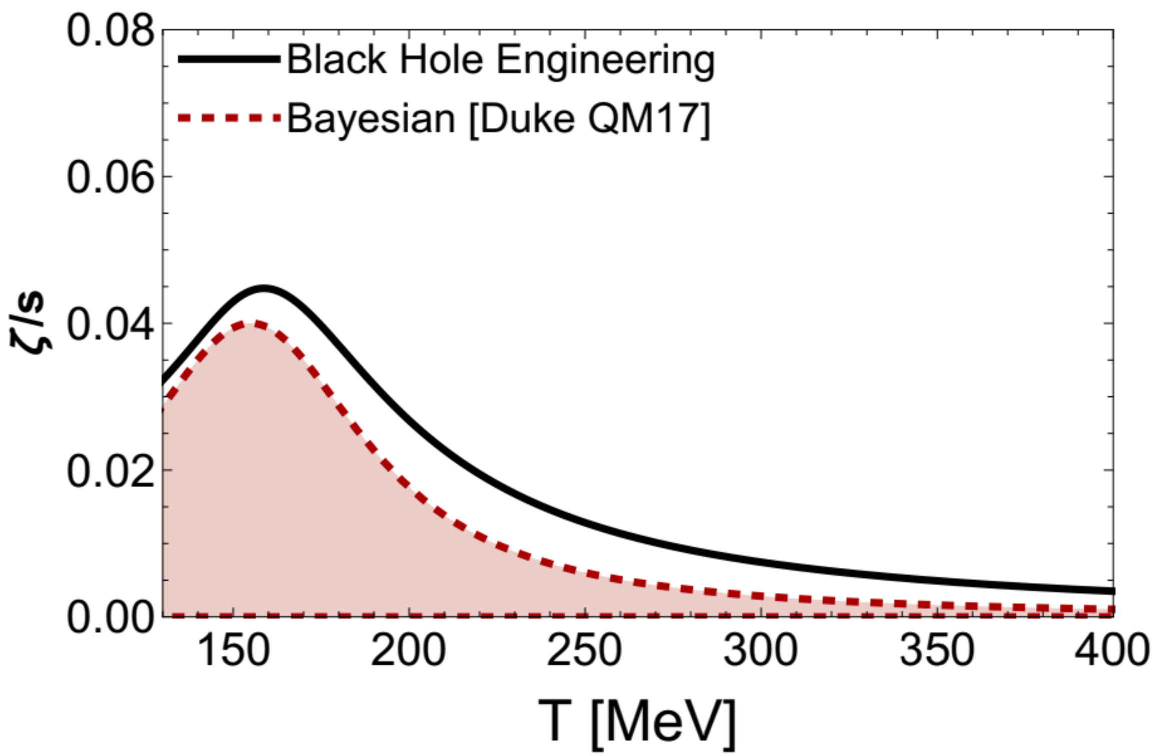
Match to lattice data around crossover (zero baryon density)



- Agreement with thermal QCD at zero chemical potential *by construction*

- However, any real time property computed from such an approach is a *prediction of the model*

- For instance, while $\eta/s = 1/4\pi$, for bulk viscosity



Black hole engineering at finite baryon density

Critelli, JN, Noronha-Hostler, Portillo, Ratti, Rougemont, PRD 2017

Following DeWolfe, Gubser, Rosen (2011)

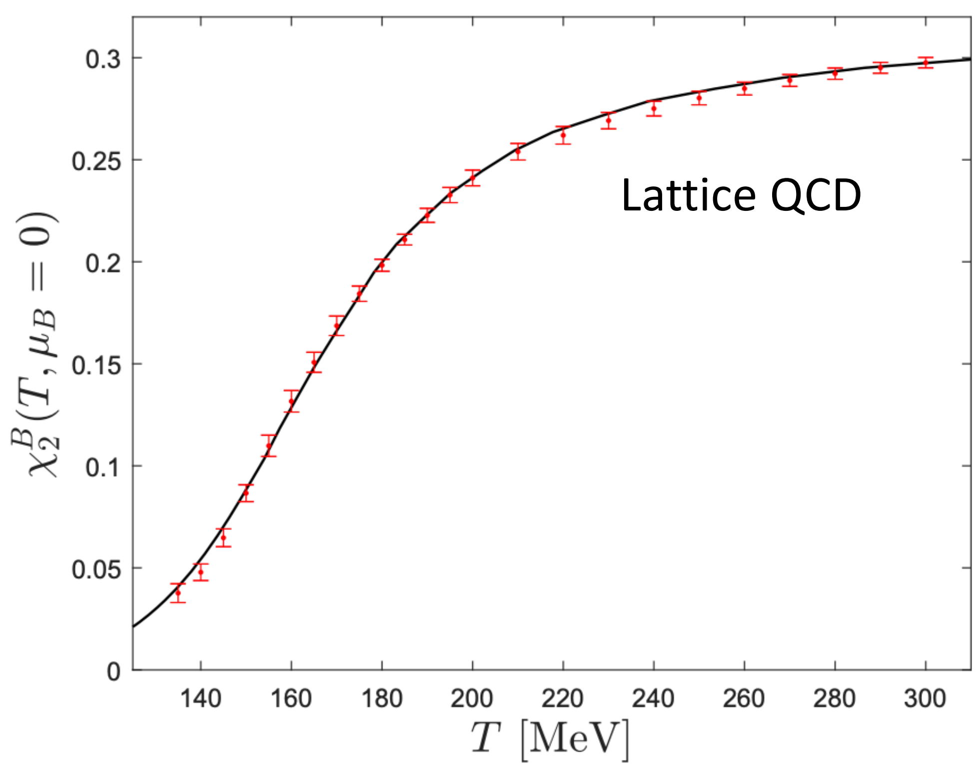
$$\mathcal{S} = \frac{1}{2\kappa^2}\int d^5x\sqrt{-g}\left[R - \frac{1}{2}(\partial_M\phi)^2 - V(\phi) - \frac{1}{4}f(\phi)F_{MN}^2\right]$$

Engineer the coupling $f(\phi)$

to match $\chi_2^B(T, \mu_B = 0)$

Any calculation at $\mu_B \neq 0$

is a PREDICTION!!!

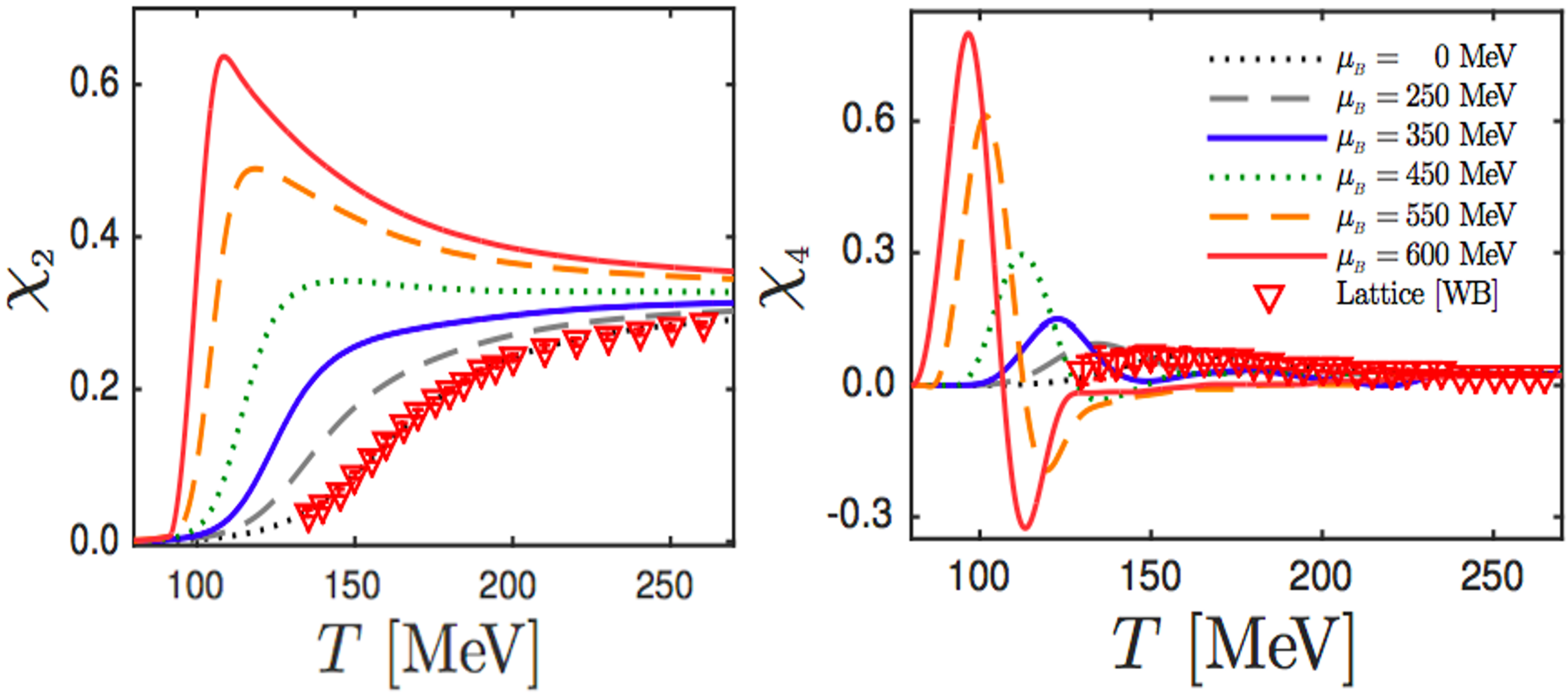


Realistic calculations of baryon susceptibilities

Critelli, JN, Noronha-Hostler, Portillo, Ratti, Rougemont, PRD 2017

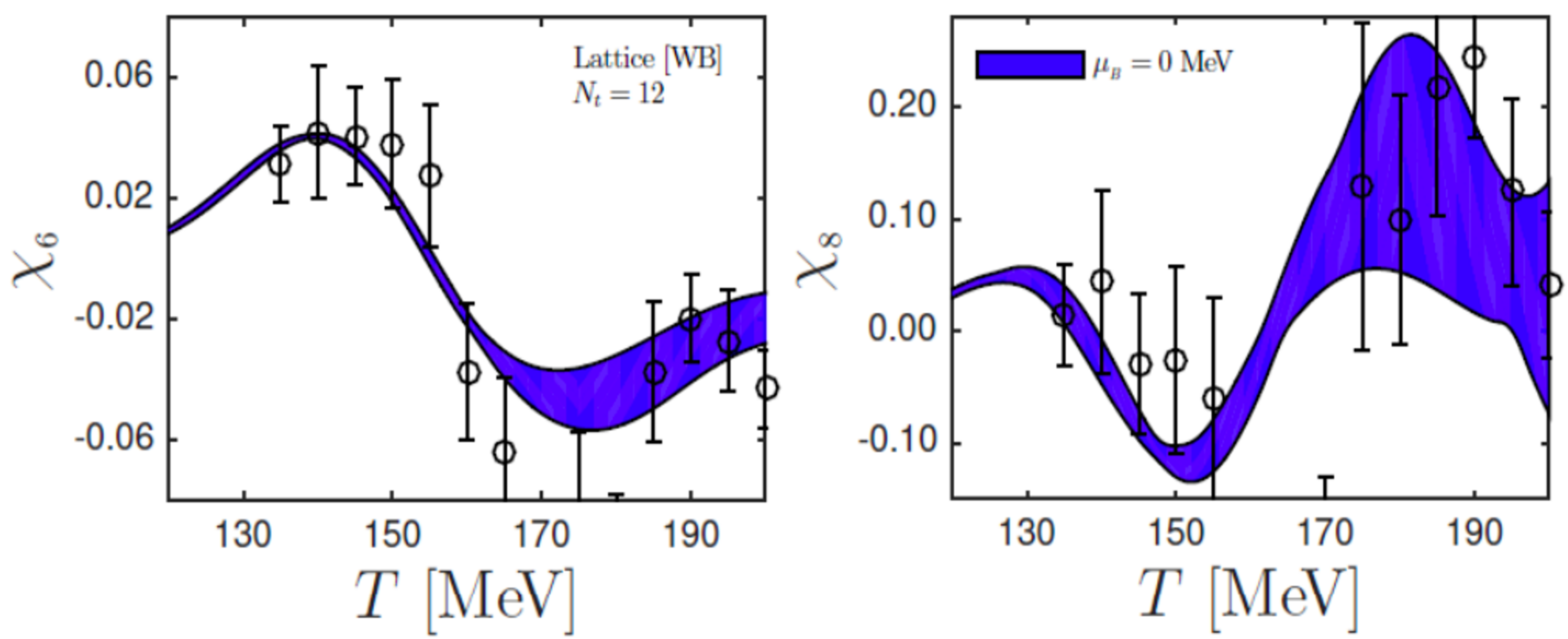
Charged black hole

Peak in χ_2 for $\mu_B > 400$ MeV



Predictions for the higher order susceptibilities

Critelli, JN, Noronha-Hostler, Portillo, Ratti, Rougemont, PRD 2017

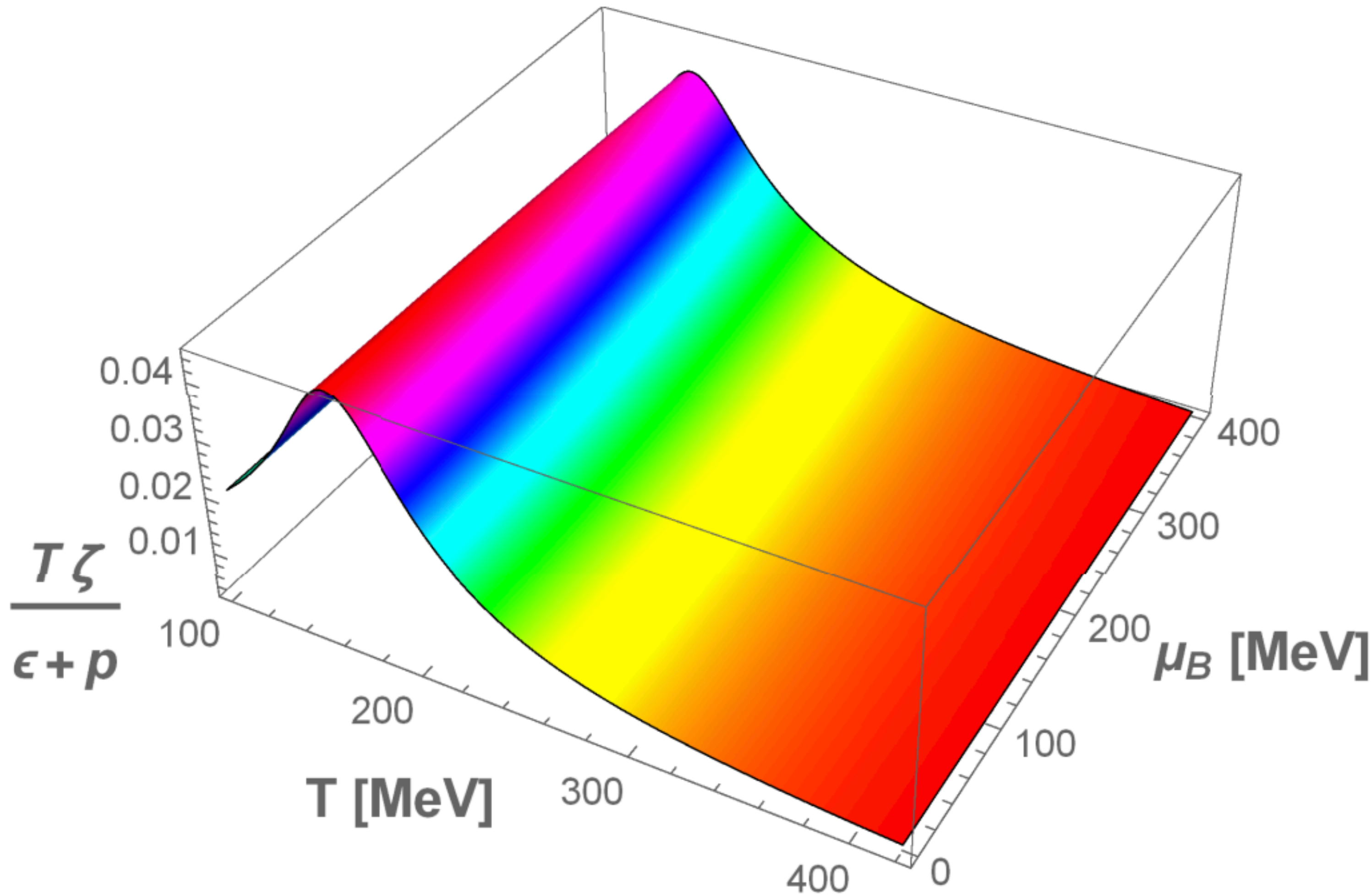


Consistent with lattice calculations in 2018 !!

S. Borsanyi et al., JHEP 1810 (2018) 205

Evolution of bulk viscosity with baryon density

Critelli, JN, Noronha-Hostler, Portillo, Ratti, Rougemont, PRD 2017

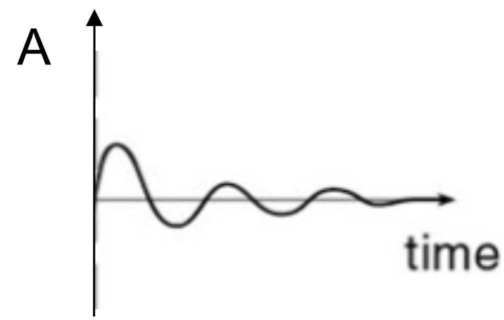


Evolution of quasinormal spectrum with density

Rougemont, Critelli, JN, PRD 2018

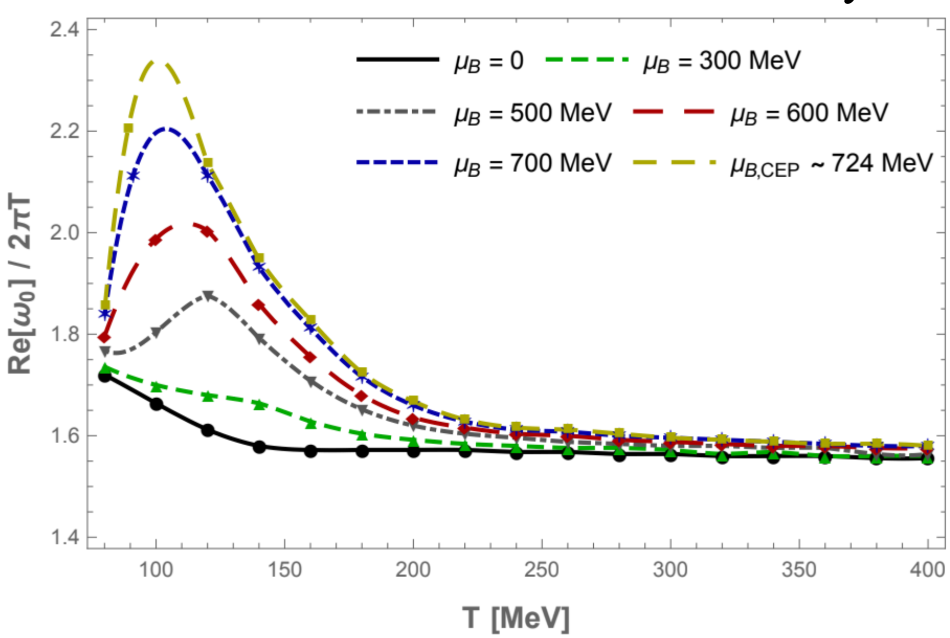
Dual black hole

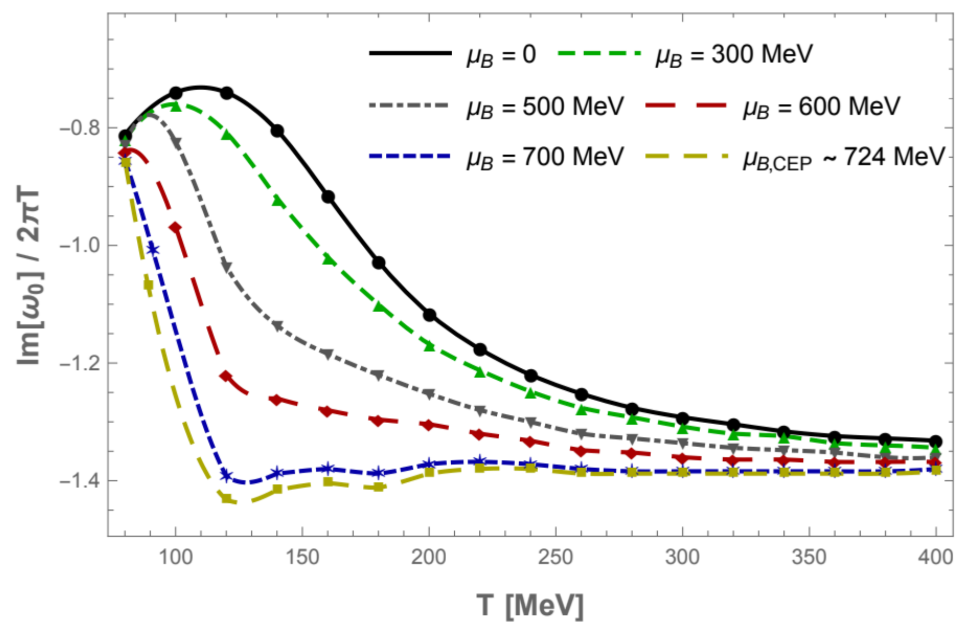
Quasinormal mode



Ringdown

Lowest non-hydro quasinormal mode

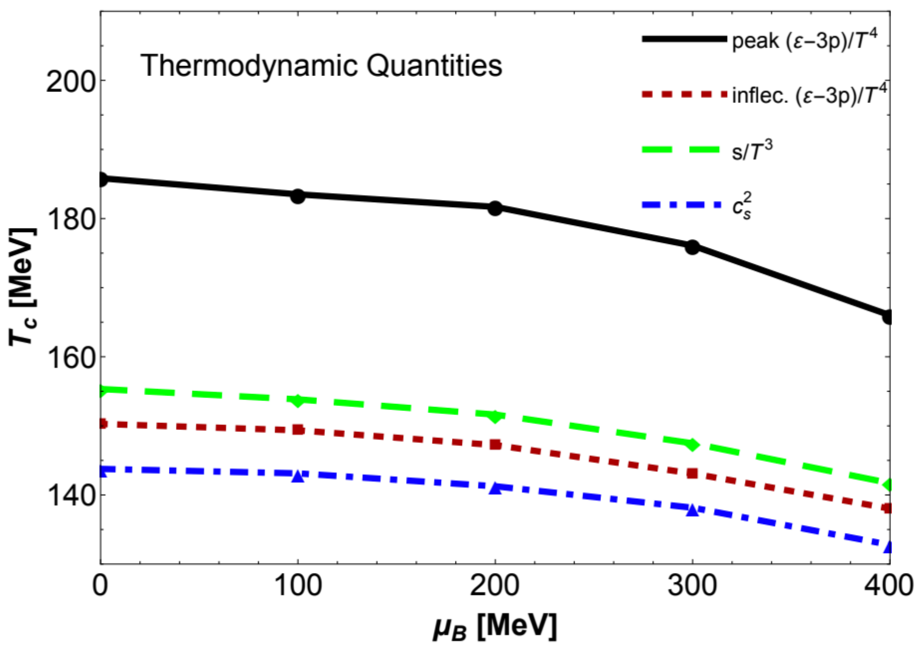


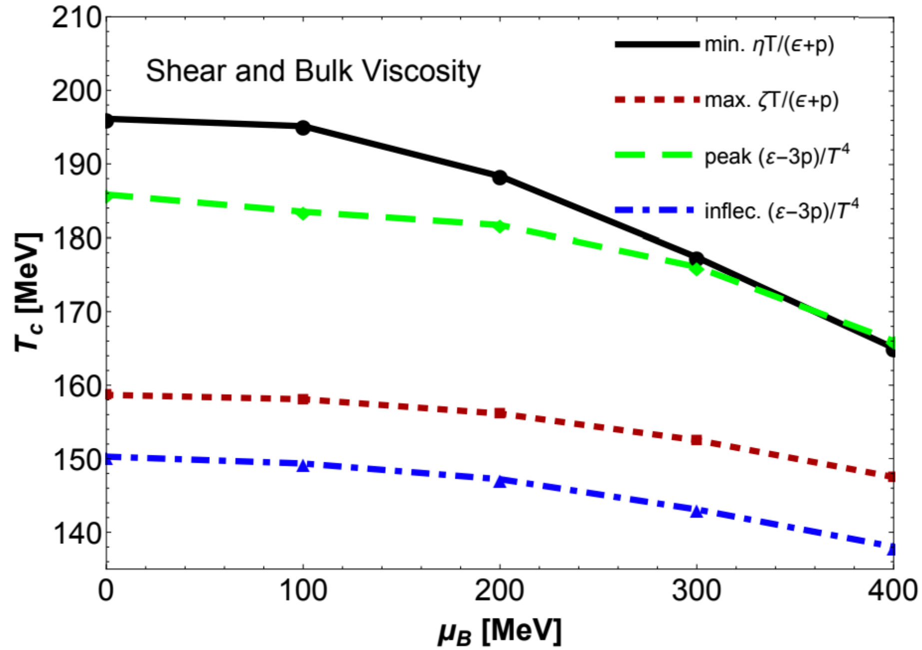


Evolution of characteristic temperatures

Critelli, JN, Noronha-Hostler, Portillo, Ratti, Rougemont, PRD 2017

Peaks, minima, inflection points of several quantities



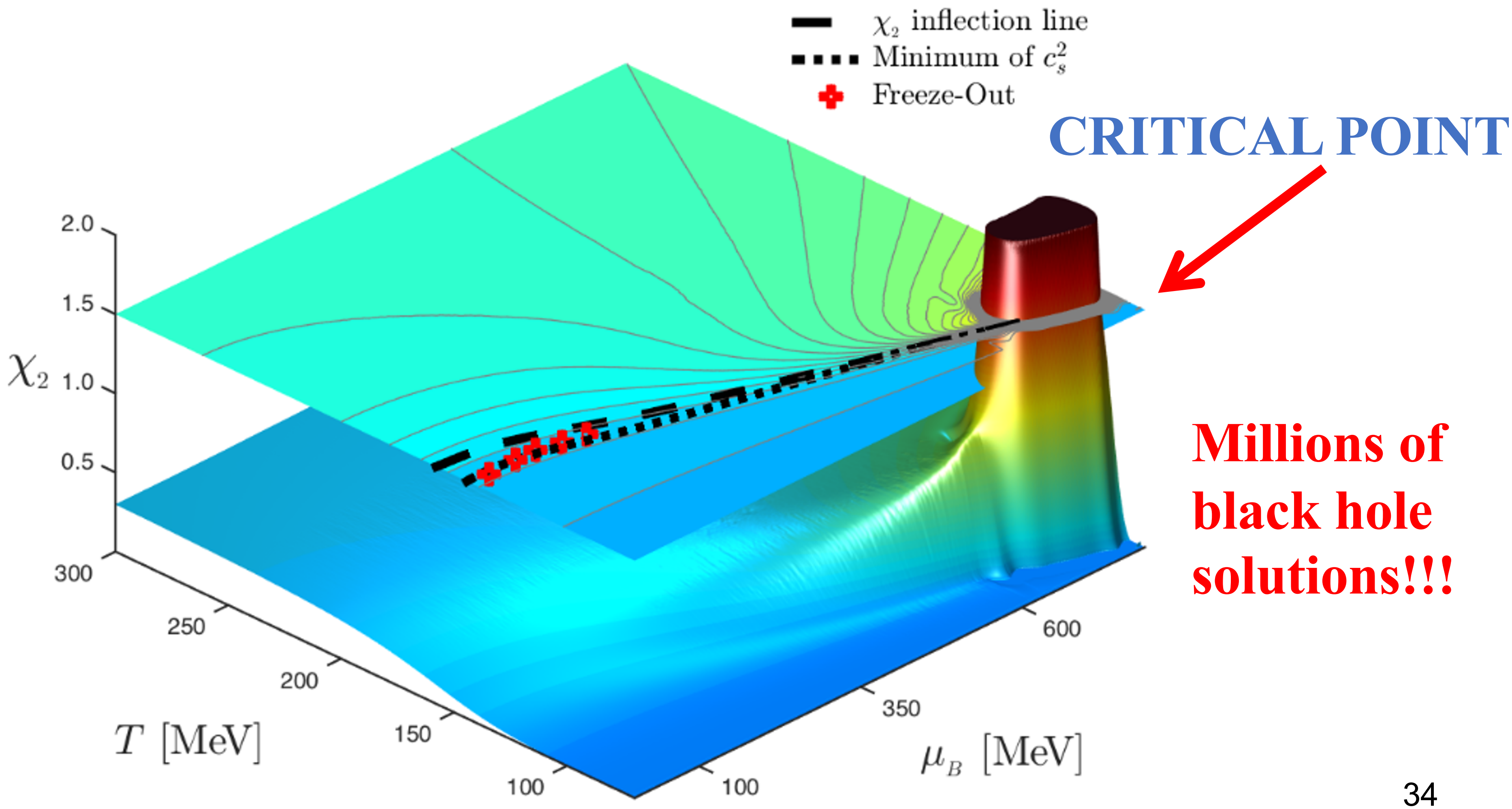


Convergence at large chemical potential expected to occur at the critical point.

Location of the QCD critical point from black holes

Critelli, JN, Noronha-Hostler, Portillo, Ratti, Rougemont, PRD 2017

2[nd] baryon susceptibility diverges at: $T_{CEP} = 89$ MeV, $\mu_B^{CEP} = 724$ MeV



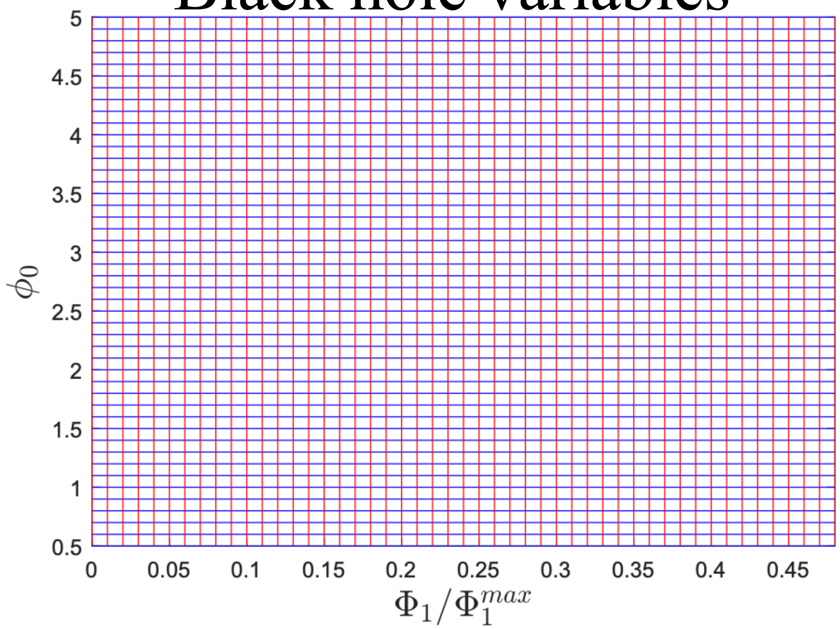
Millions of black hole solutions!!!

What about the phase diagram or the first-order line?

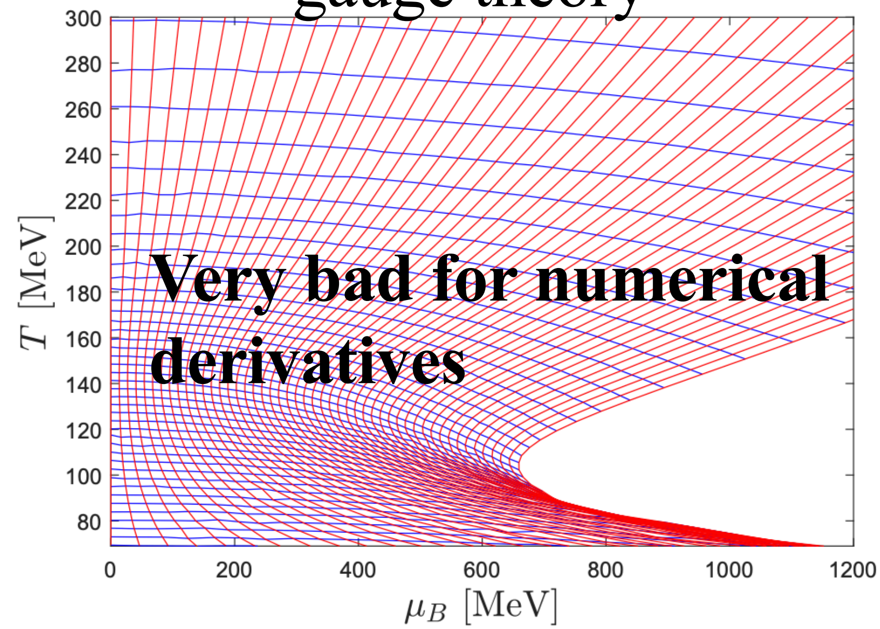
- Previous calculations (done in 2017) were limited to some restricted range in T, μ_B plane.

- This was a numerical issue due to highly nonlinear mapping between black hole variables and T, μ_B

Black hole variables



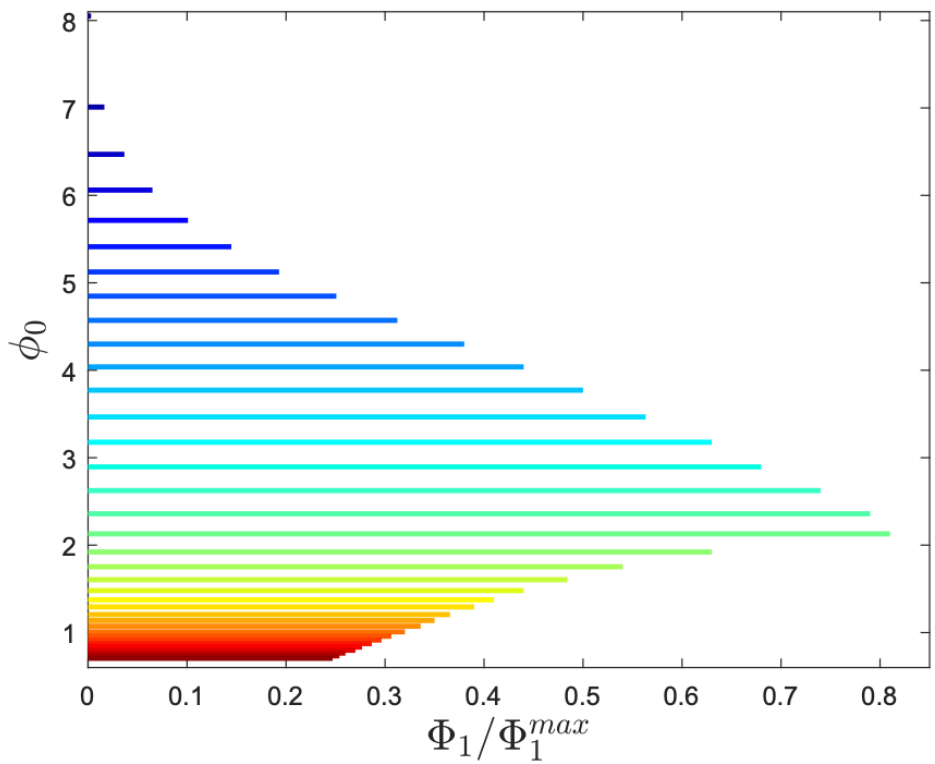
gauge theory

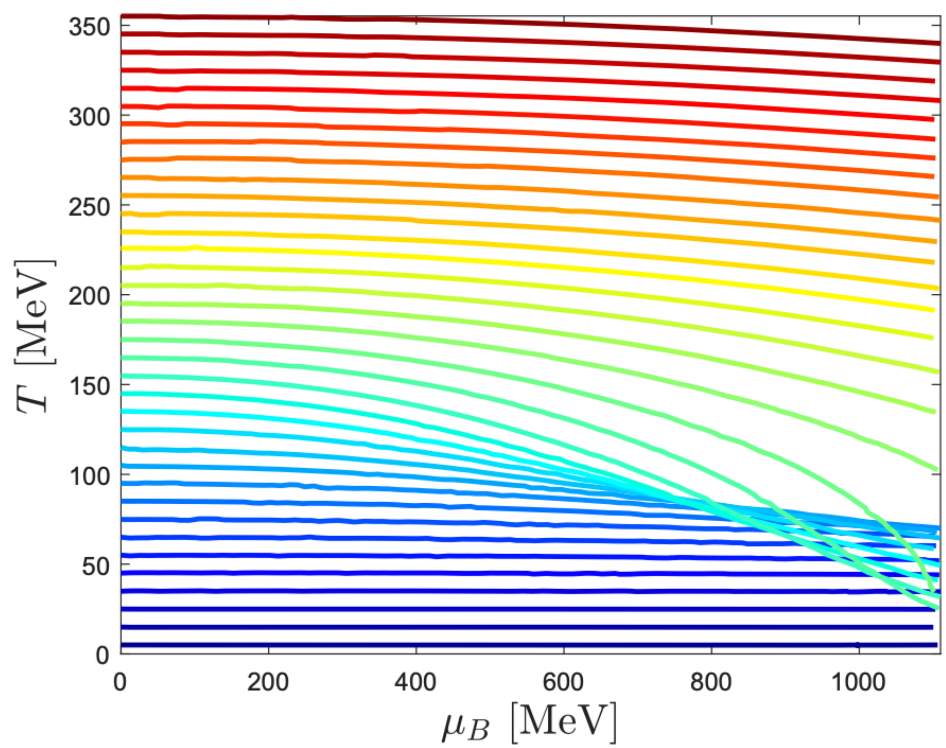


New thermodynamic results and the 1st order line

Grefa, JN, Noronha-Hostler, Portillo, Ratti, Rougemont, PRD 2021

New numerical algorithm! Lines of constant ϕ_0 + variation of Φ_1





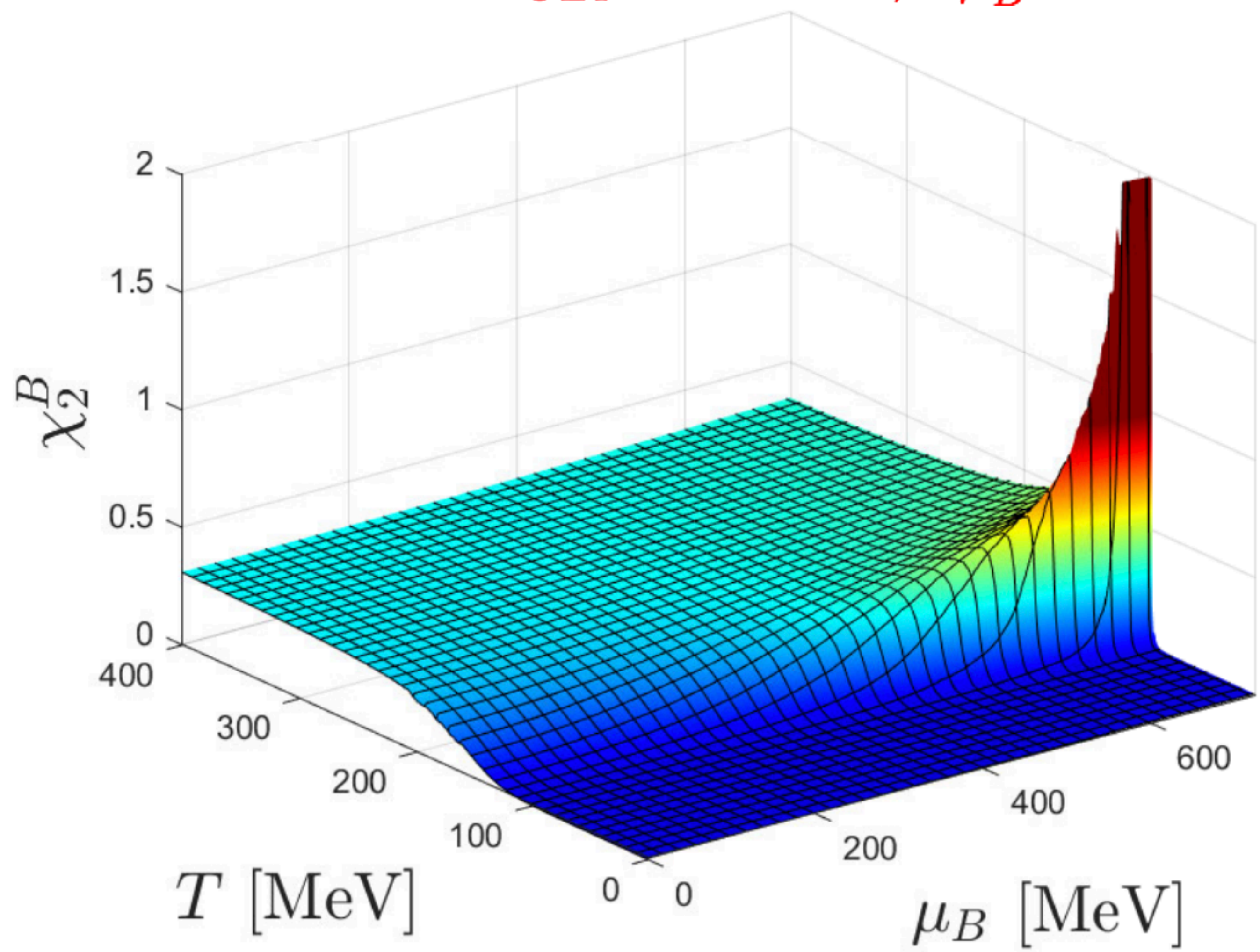
Thermodynamics computable in a wide region of phase diagram!!

$$T \in [2, 550]\,\text{MeV},\ \mu_B \in [0, 1100]\,\text{MeV}$$

New thermodynamic results and the 1st order line

Grefa, JN, Noronha-Hostler, Portillo, Ratti, Rougemont, PRD 2021

$T_{CEP} = 89$ MeV, $\mu_B^{CEP} = 724$ MeV



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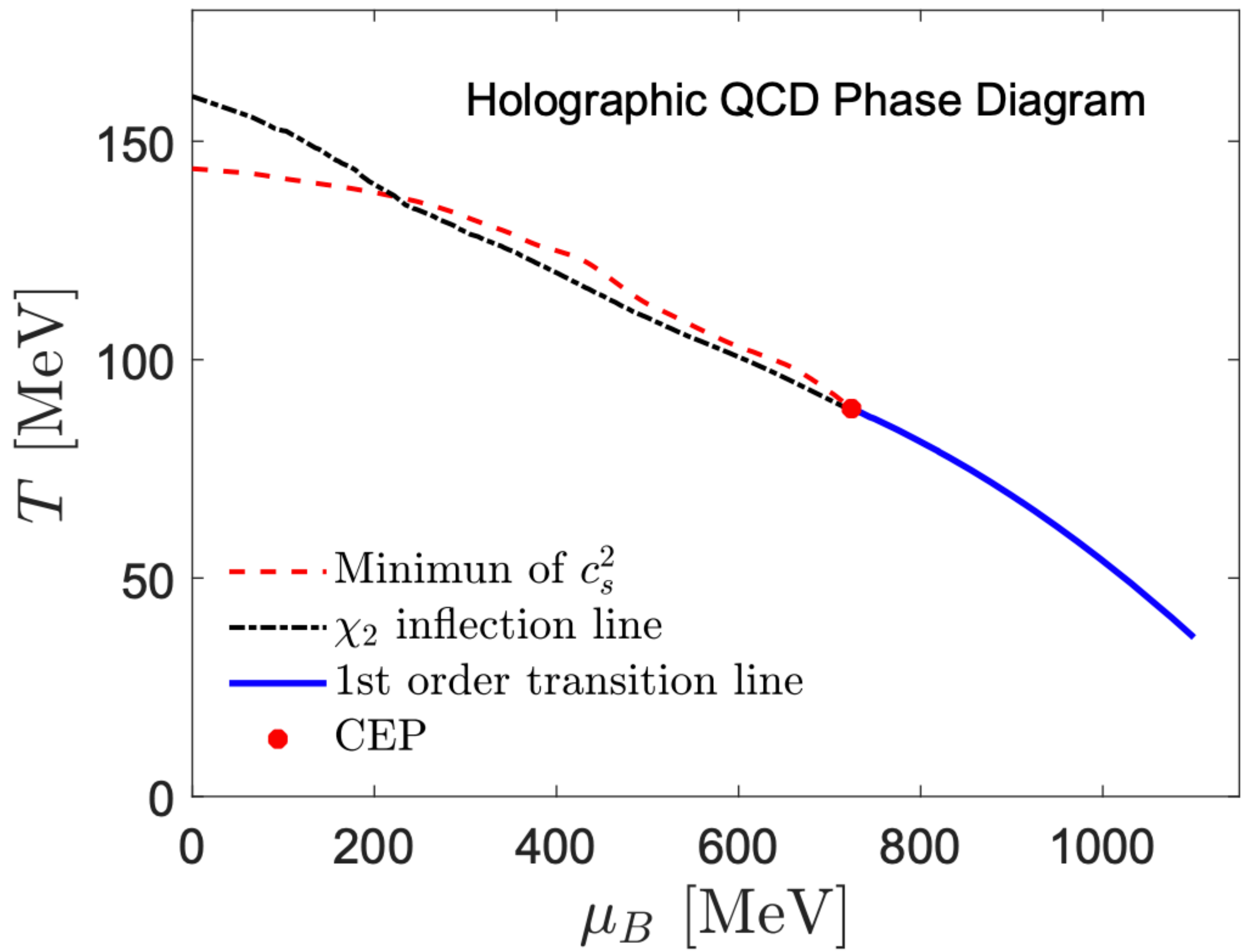

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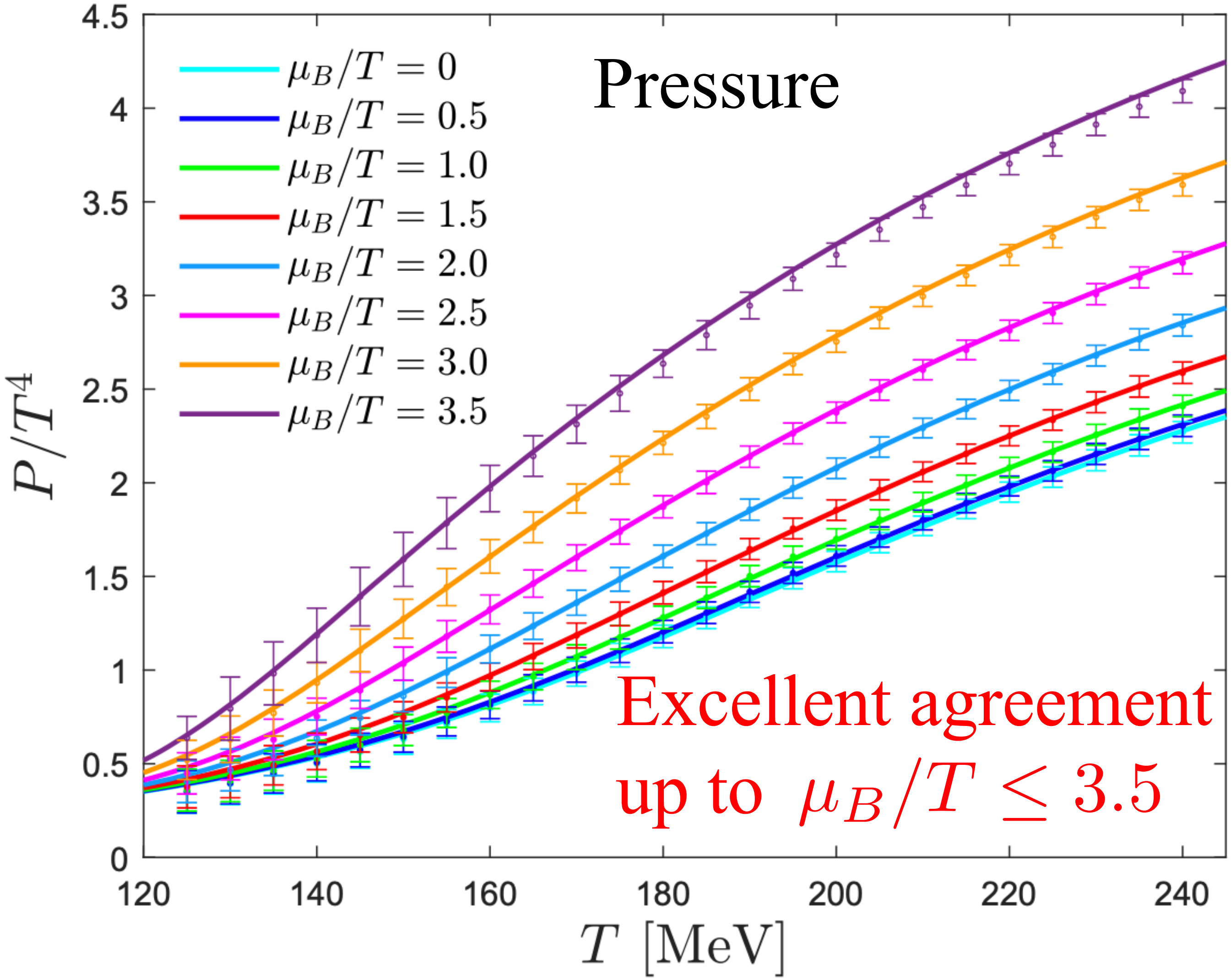
Comparison to lattice results from Borsanyi et al, PRL (2021)



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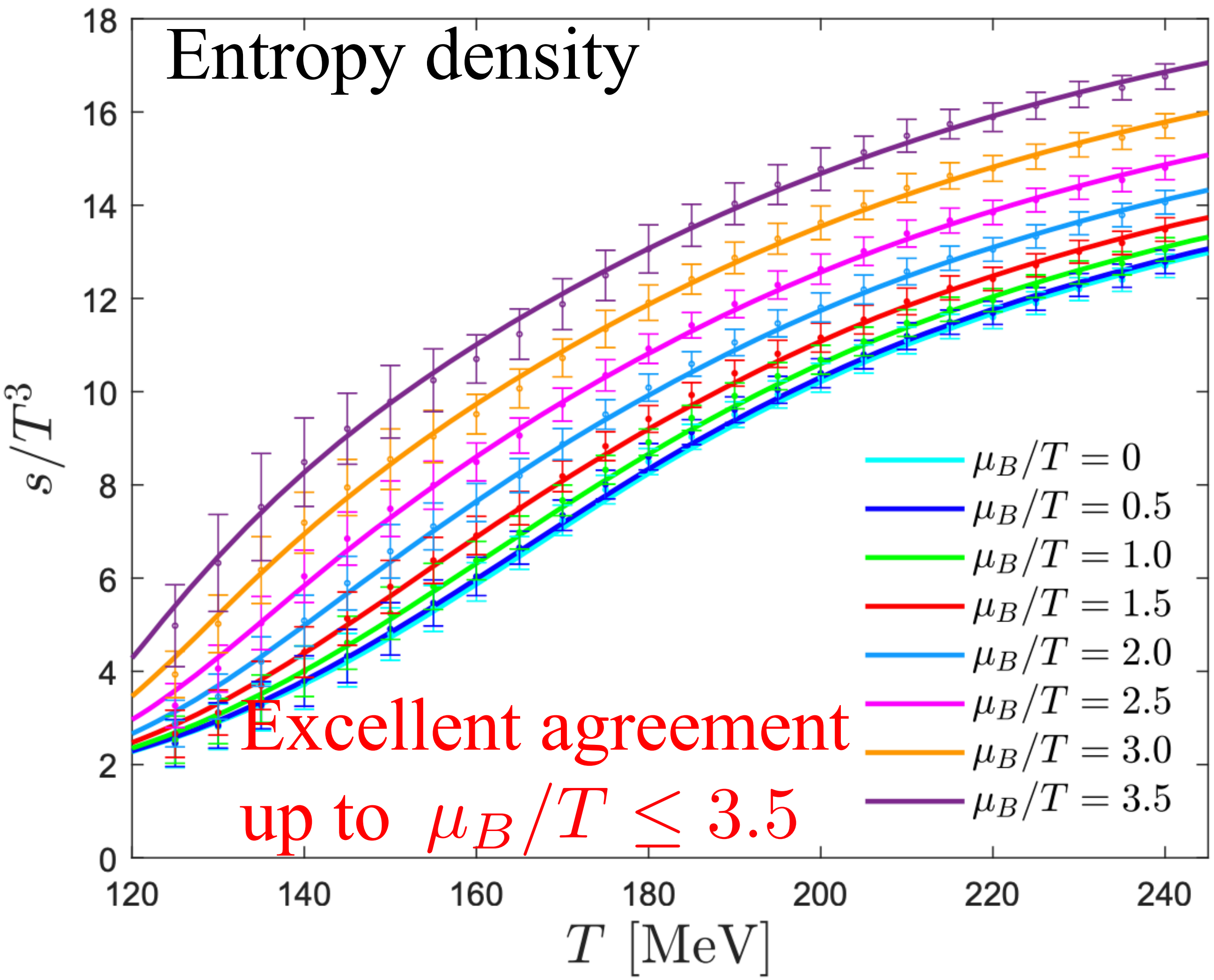
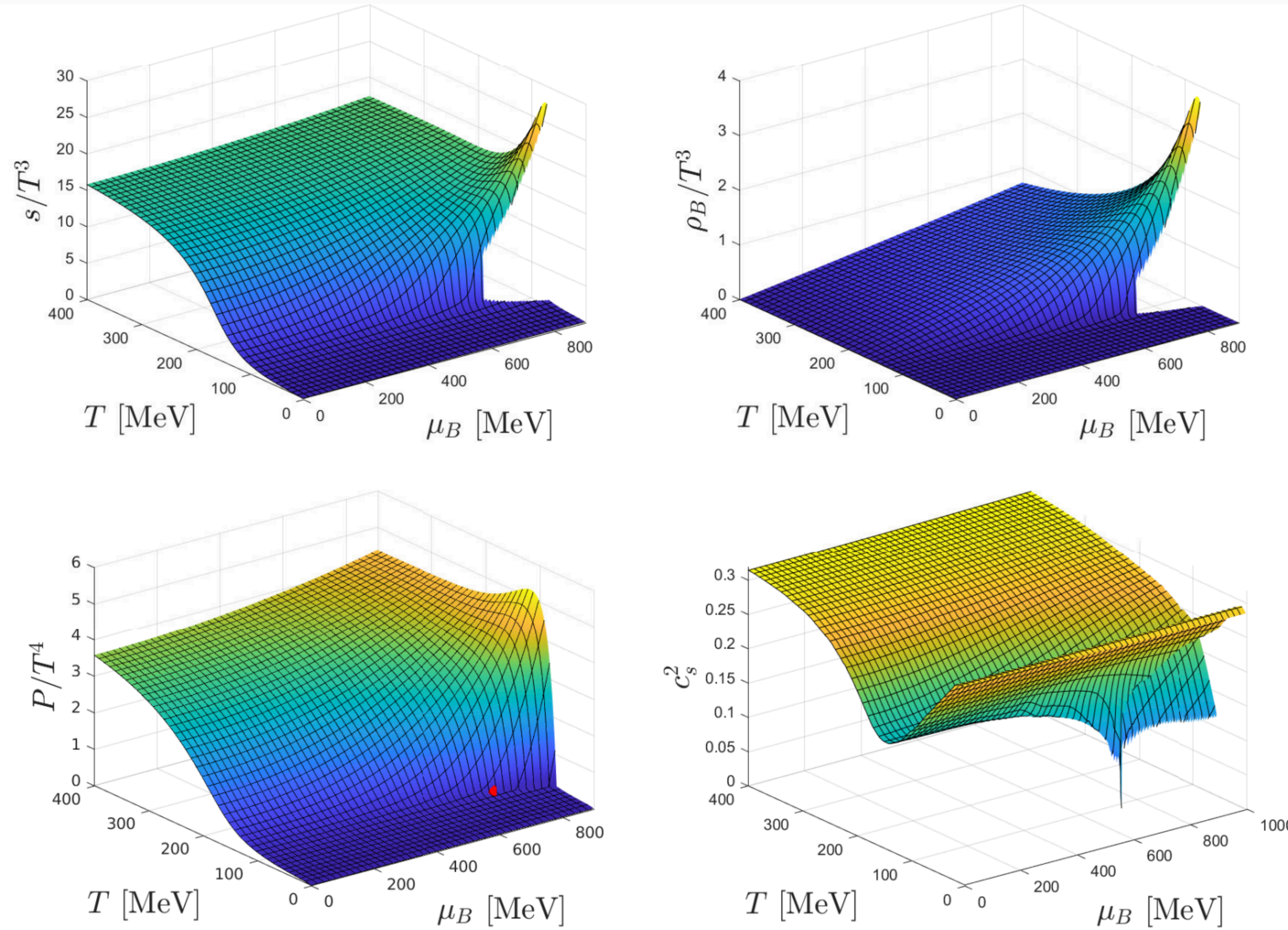


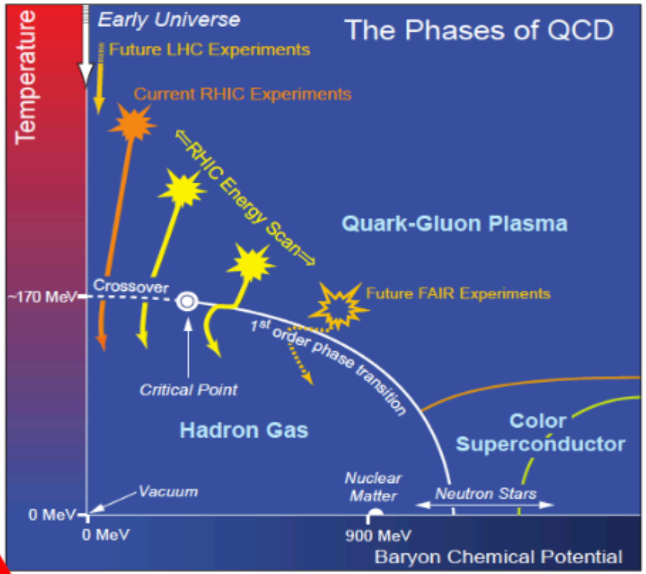
New thermodynamic results and the 1st order line

Grefa, JN, Noronha-Hostler, Portillo, Ratti, Rougemont, PRD 2021



Challenges for the discovery of QCD critical point?

- High T critical point may not really exist in QCD.
- Heavy-ion system not large enough (correlation length ξ finite).
- Very short lifetime of the system (out of equilibrium effects!)



Far-from-equilibrium effects:

Can they distort (or erase) critical behavior?

???

"Out-of-equilibriumness"

(new axis)

See T. Dore, J. Noronha-Hostler, E. McLaughlin PRD (2020).

Far-from-equilibrium hydrodynamics near a critical point

R. Critelli, R. Rougemont, JN, PRD (2019)

How does hydrodynamic behavior emerge in the vicinity of a critical point in the phase diagram?

Simplest scenario: Bjorken expanding holographic system

- Toy model of heavy-ion collisions

$$ds^2_{bdy} = -d\tau^2 + dx^2 + dy^2 + \tau^2 d\eta^2$$

Bjorken flow

$u^\mu = (1,0,0,0)$

Rapidly expanding anisotropic fluid

Holography: $T_{\mu\nu}(\tau) = \mathrm{diag}(\varepsilon, p_\perp, p_\perp, p_\parallel)$

Far-from-equilibrium hydrodynamics near a critical point

R. Critelli, R. Rougemont, JN, PRD (2019)

Top-down holographic model: 1 R-charged black hole (1RCBH)

Gubser, 1999; Behrndt, Cvetic, and W. A. Sabra, 1999

N=4 SYM charged under a U(1) subgroup of the global SU(4) R-symmetry

Einstein-Maxwell-Dilaton
(a limit of STU model)

$$2\kappa_5^2 \mathcal{L} = R - \frac{(\partial_\mu \phi)^2}{2} - V(\phi) - \frac{f(\phi)(F_{\mu\nu})^2}{4}$$

$$V(\phi) = -8e^{\frac{\phi}{\sqrt{6}}} - 4e^{-\sqrt{\frac{2}{3}}\phi}$$

$$f(\phi) = e^{-2\sqrt{\frac{2}{3}}\phi}$$

For a general discussion of this model (and generalizations):

DeWolfe, Gubser, Rosen, PRD 83 (2011); 84 (2011); 86 (2012).

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1RCBH: Analytical equilibrium solution with a critical point (2nd order phase transition)

$$\mu_c/T_c = \pi/\sqrt{2}$$

Far-from-equilibrium hydrodynamics near a critical point

R. Critelli, R. Rougemont, JN, PRD (2019)

Holographic Bjorken flow (infalling Eddington-Finkelstein): Chesler, Yaffe, PRD 2010

$$ds^2 = 2d\tau\left[dr - A(\tau,r)d\tau\right] + \Sigma(\tau,r)^2\left[e^{-2B(\tau,r)}d\xi^2 + e^{B(\tau,r)}\left(dx^2+dy^2\right)\right]$$

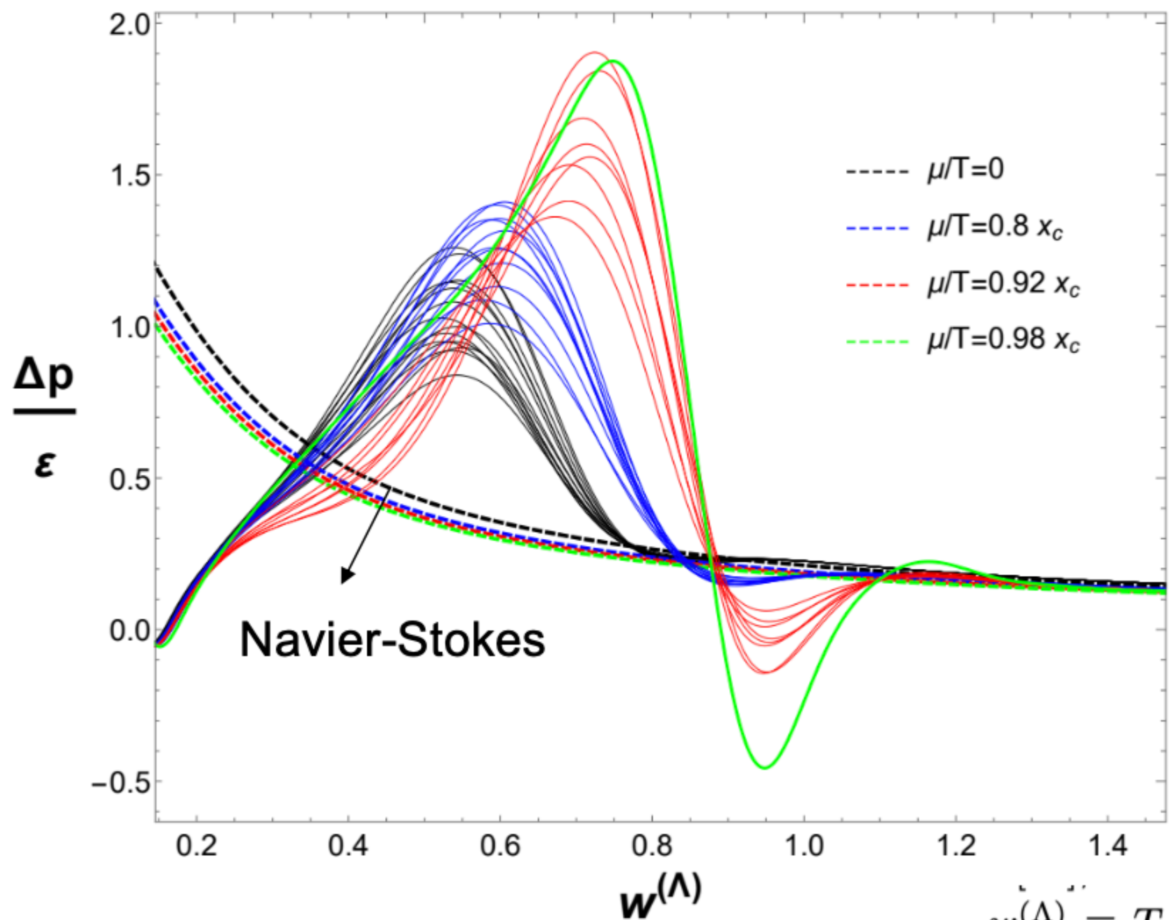
$\phi = \phi(\tau,r)$ $\quad A_\mu dx^\mu = \Phi(\tau,r)d\tau$ $\quad$ Dynamical fields: $\{A, \Sigma, B, \phi, \Phi\}$

- Full far-from-equilibrium problem can be investigated.
- Vary chemical potential from zero to $\mu_c/T_c = \pi/\sqrt{2}$
- Emergence of hydro behavior + critical phenomena

Far-from-equilibrium hydrodynamics near a critical point

R. Critelli, R. Rougemont, JN, PRD (2019)

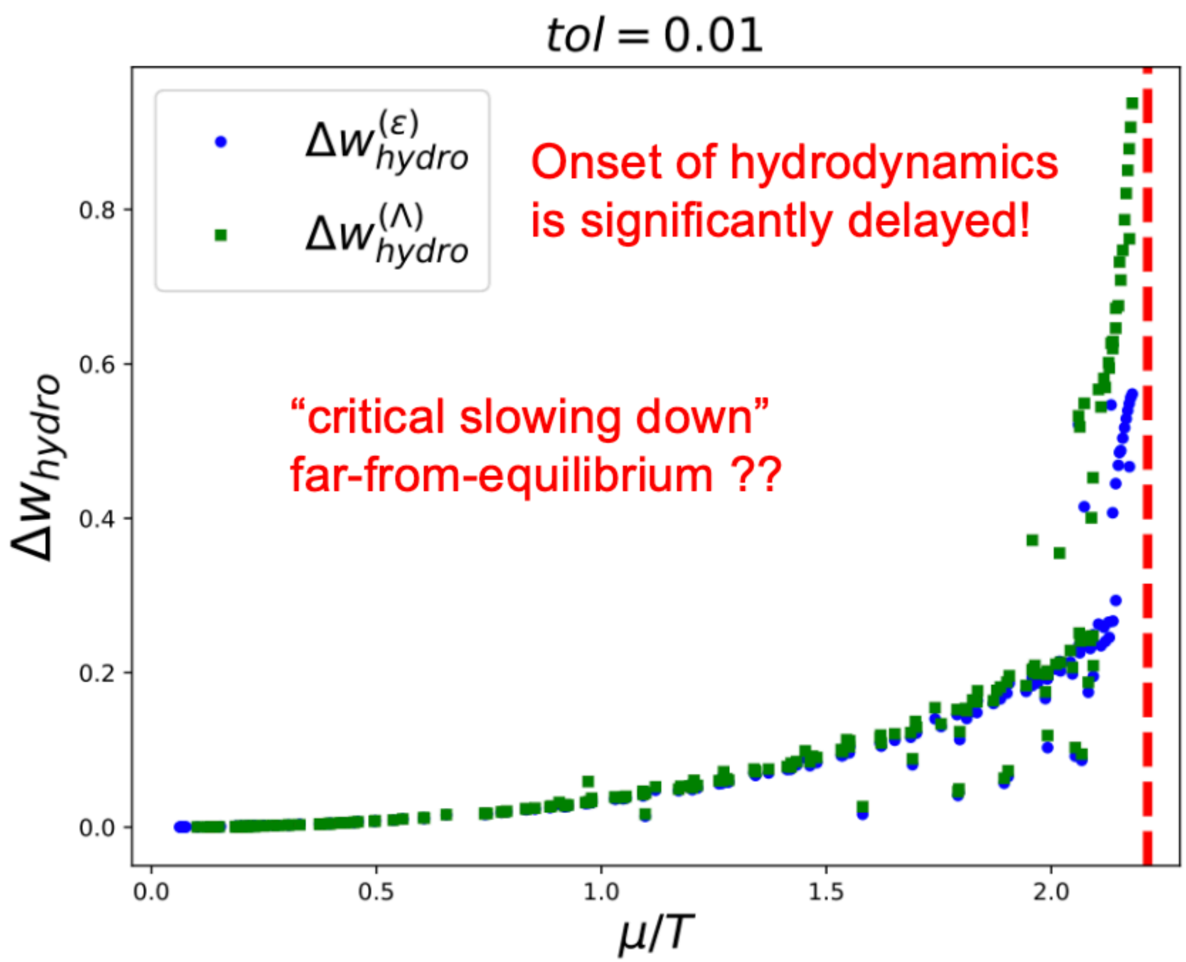
Pressure anisotropy $$\frac{\Delta p}{\varepsilon} \equiv \frac{p_T - p_L}{\varepsilon} = 2 + \frac{3}{2}\tau\frac{\partial_\tau \varepsilon}{\varepsilon}.$$



$$w^{(\Lambda)} \equiv T_{\text{asym}}(\tau)\tau = (\Lambda\tau)^{2/3}$$

Hydrodynamization: $\left|\left(\frac{\Delta p}{\varepsilon}\right)_{\text{numerical}} - \left(\frac{\Delta p}{\varepsilon}\right)_{\text{hydro}}\right| \leq 0.01 \left(\frac{\Delta p}{\varepsilon}\right)_{\text{hydro}}$

$$\Delta w_{\text{hydro}}^{(\varepsilon/\Lambda)} \equiv \frac{w_{\text{hydro}}^{(\varepsilon/\Lambda)}(\mu/T) - w_{\text{hydro}}^{(\varepsilon/\Lambda)}(0)}{w_{\text{hydro}}^{(\varepsilon/\Lambda)}(0)}.$$



Next Decade: Synergy between QGP and holography will continue

PHASE 1

(2005 -)
RHIC experiments
Strongly coupled QGP
Hydrodynamics, jet quenching

Motivated the understanding of near equilibrium properties of holographic fluids + holographic jet quenching

PHASE 2

(2010 -)
RHIC, LHC
Highly inhomogeneous QGP
Small systems (pp, pA)

Motivated the understanding of far-from-equilibrium holography (advent of numerical relativity)

PHASE 3

(2020 -)
RHIC, LHC, FAIR, NICA
QCD critical point
Connection to neutron star mergers
Electron-Ion Collider (EIC)

Holography in real time far-from-eq. dynamics + critical phenomena

?????????????

Conclusions & Outlook

- Holographic model provides a good starting point to investigate the nearly perfect fluid regime of hot and baryon dense QGP.

- Predictions for susceptibilities and for the location of critical endpoint $T_{CEP} = 89$ MeV, $\mu_B^{CEP} = 724$ MeV

- Differently than other approaches, holography can be naturally solved also far from equilibrium (Num. Rel.).

- One can study not only thermal state but also the onset of hydrodynamic behavior consistently in the same method.

Conclusions & Outlook

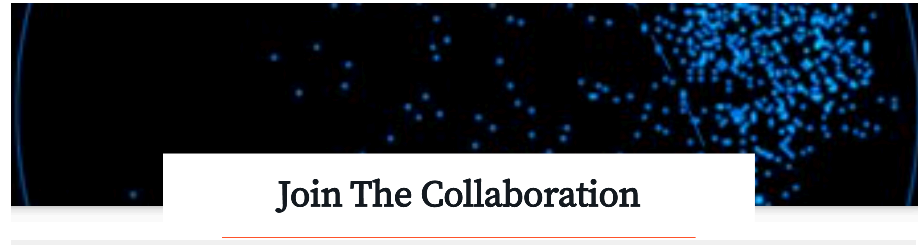
- EOS from the model can be used in heavy-ion simulations.

- Model will be extended to incorporate the thermodynamics and the out of equilibrium behavior of QCD's charges B,S,Q.

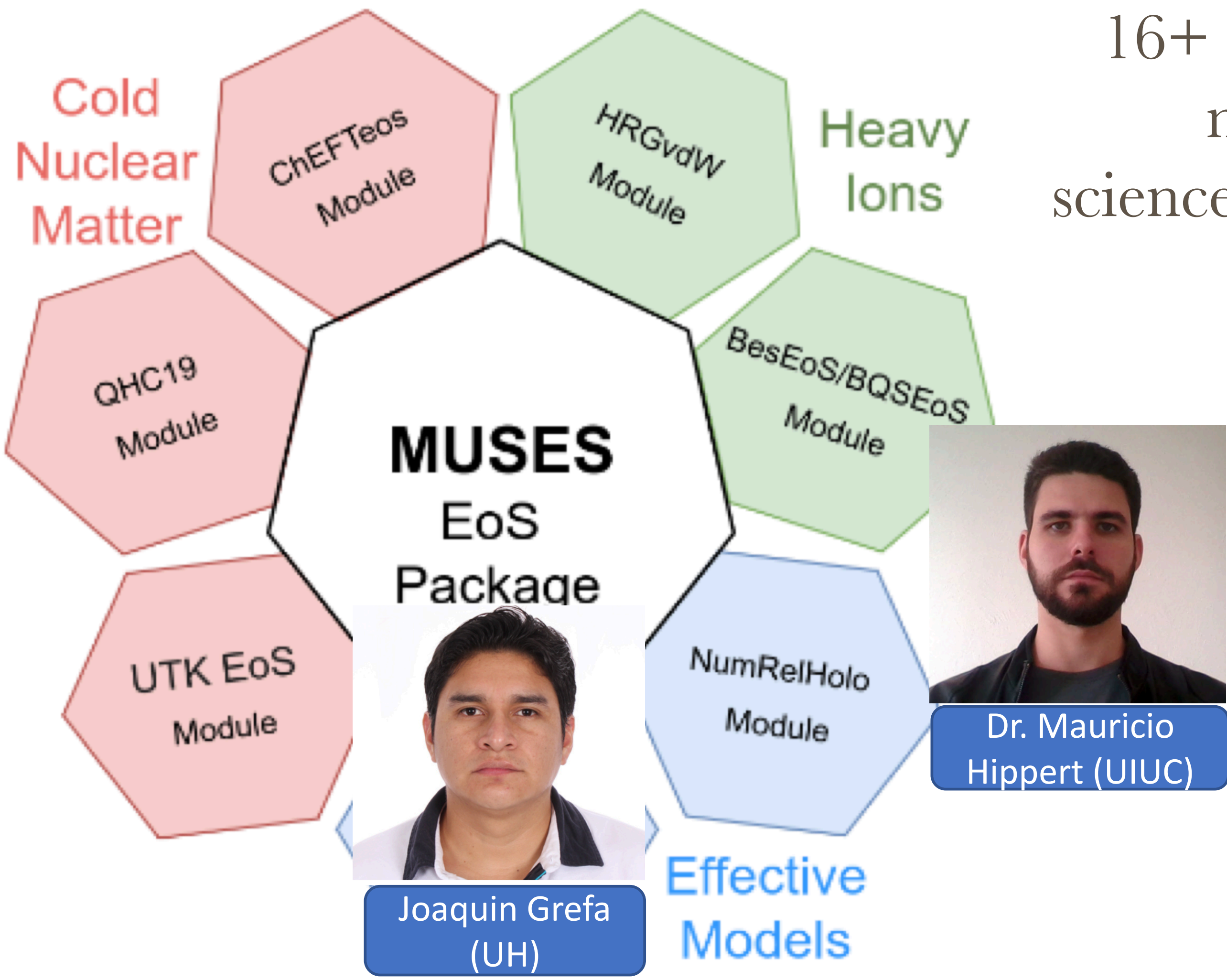
- Model will be extended to incorporate the physics and effects from the chiral condensate.

- Once those extensions are done, framework will provide a comprehensive way to describe hot and dense QGP from heavy ions towards the neutron star regime.

MUSES



Modular Unified Solver of the Equation of State



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