Connections between heavy-ion collisions and neutron star mergers

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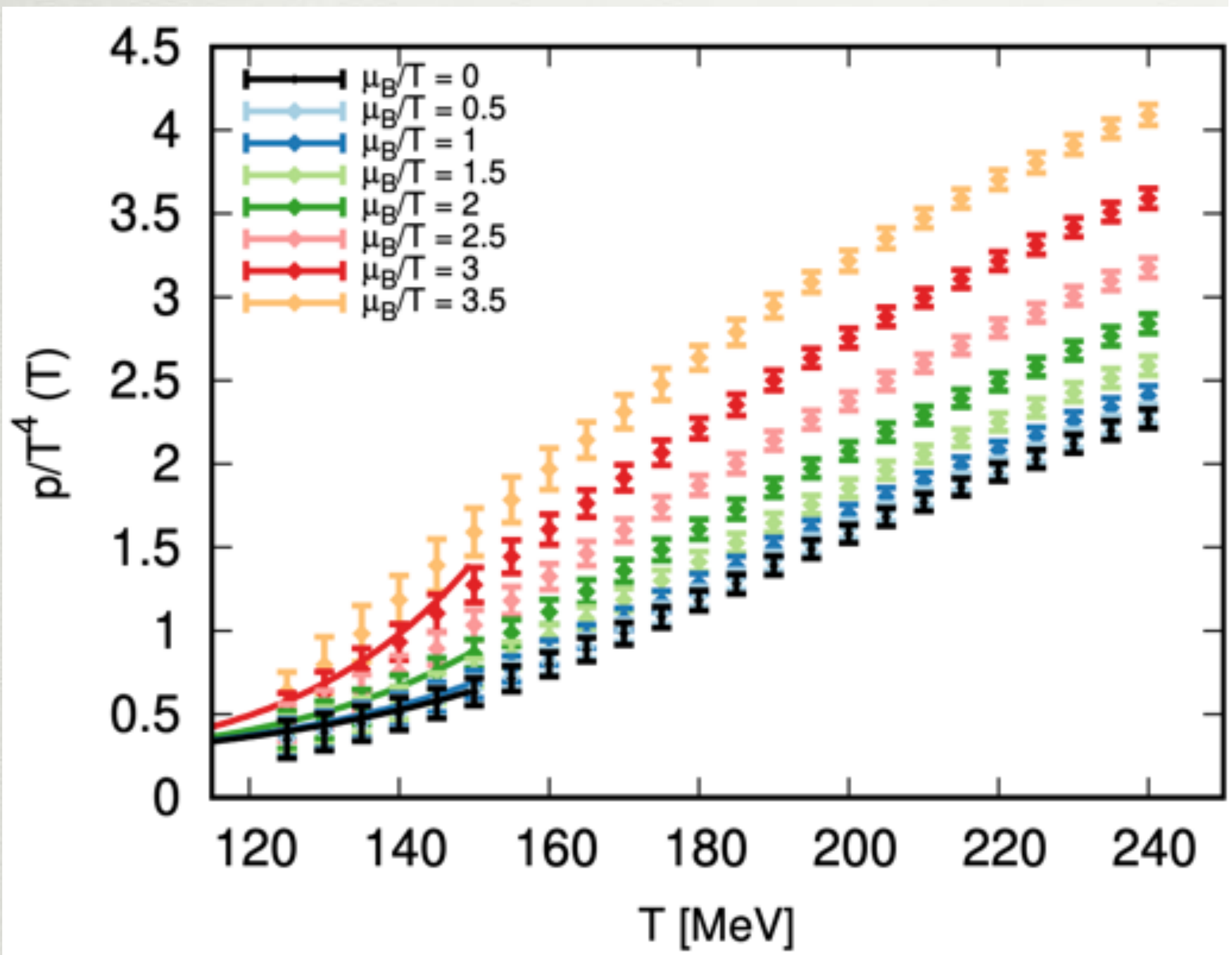
RHIC & AGS User's Meeting 2021

QCD Phase Diagram in Equilibrium

Lattice QCD and holography

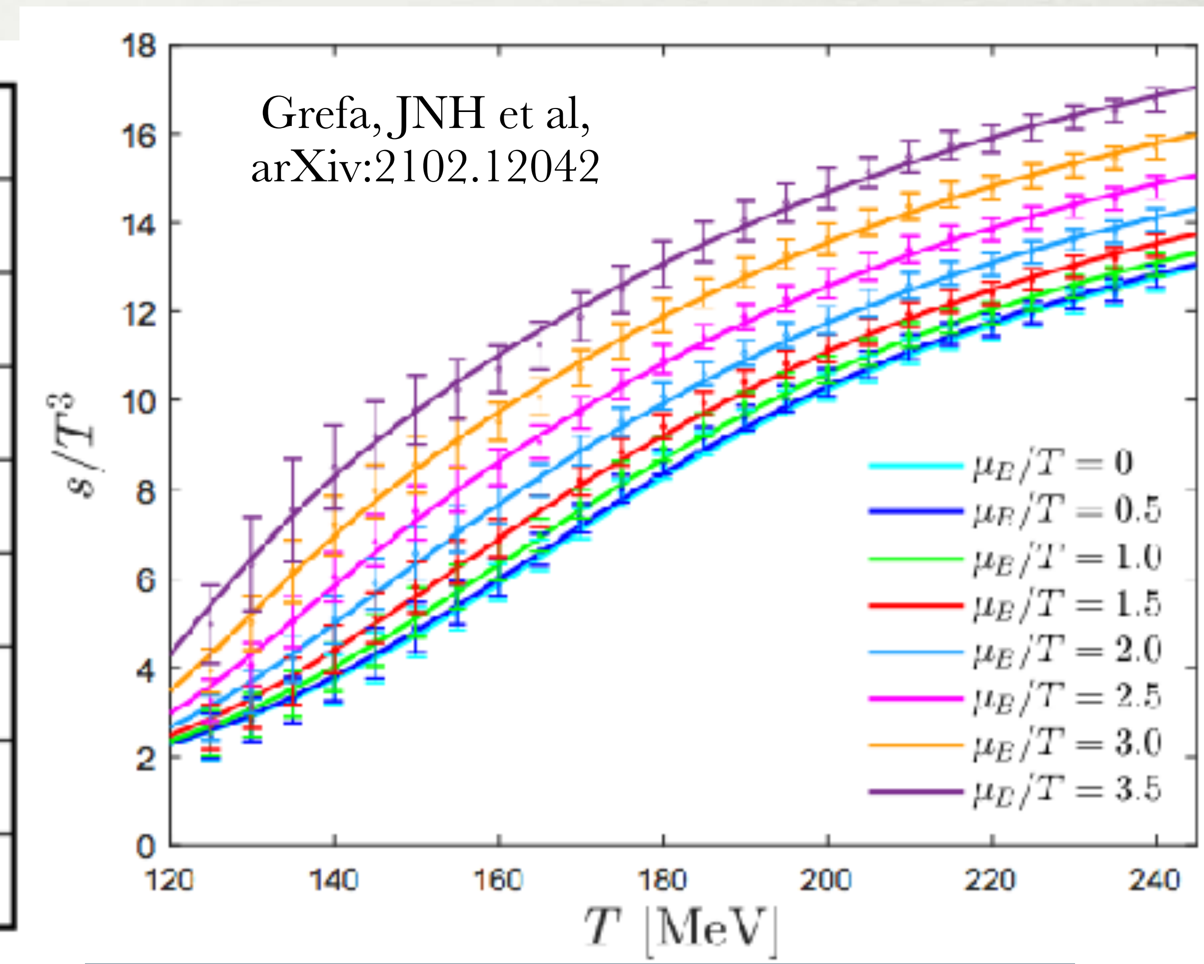
Joaquin Grefa
UH PhD Student

New resummation scheme to reach larger μ_B



For $T \sim 150$MeV reaches $\mu_B \sim 525$MeV

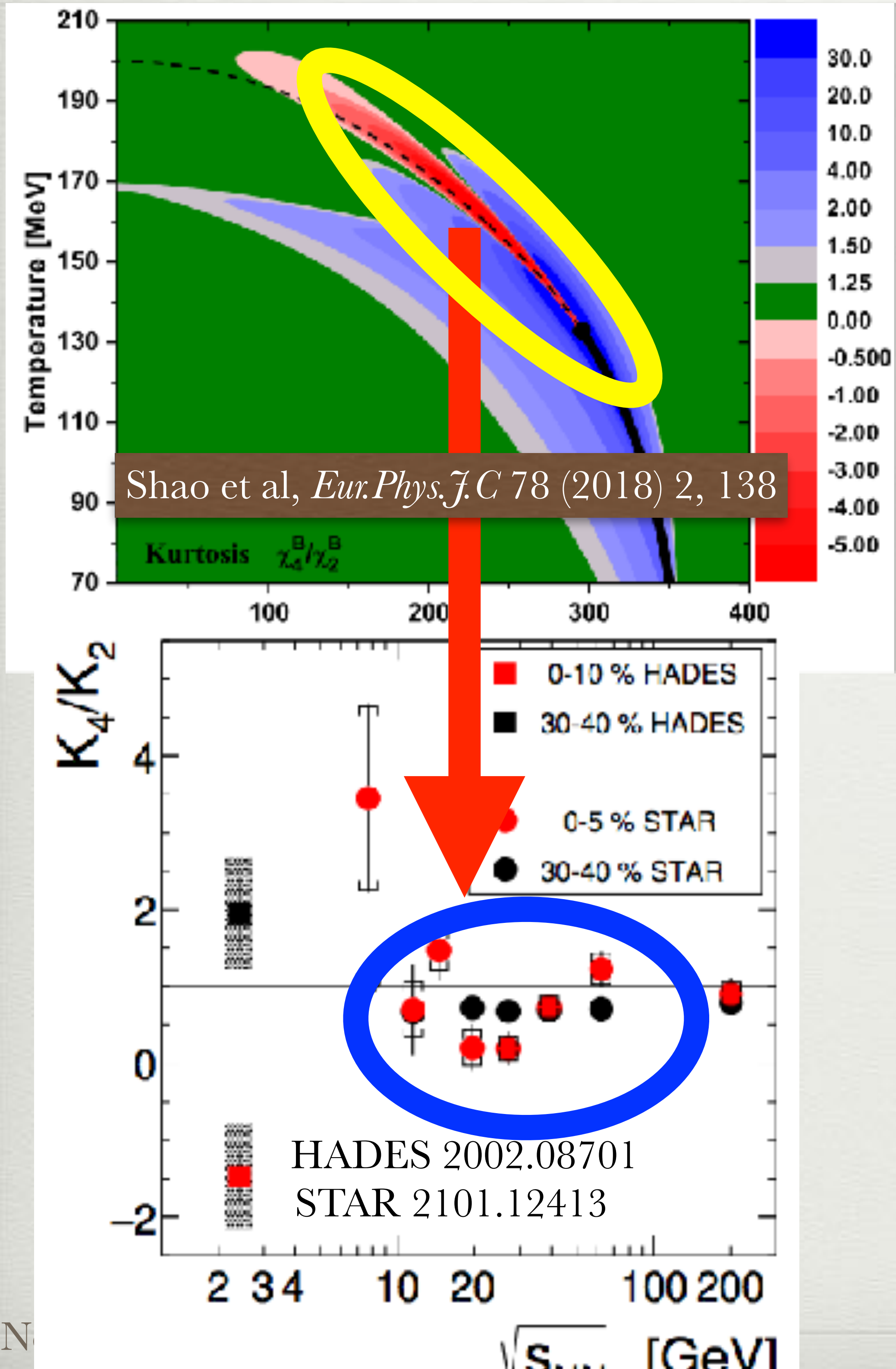
Predicts CP at $\{T_c = 89, \mu_B = 724\}$ MeV

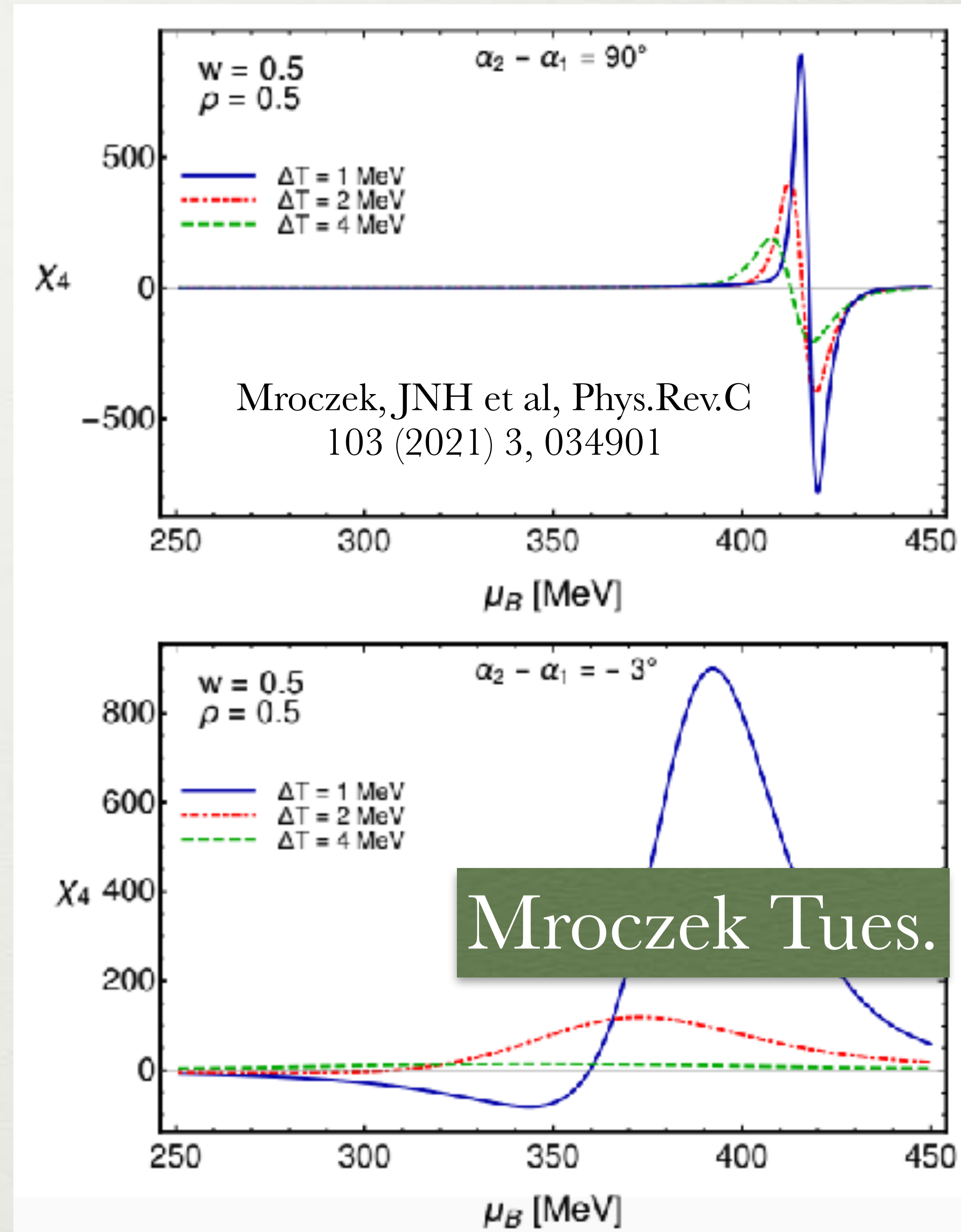


Fitting to just Lattice QCD at $\mu_B = 0$ captures $\mu_B > 0$ EOS

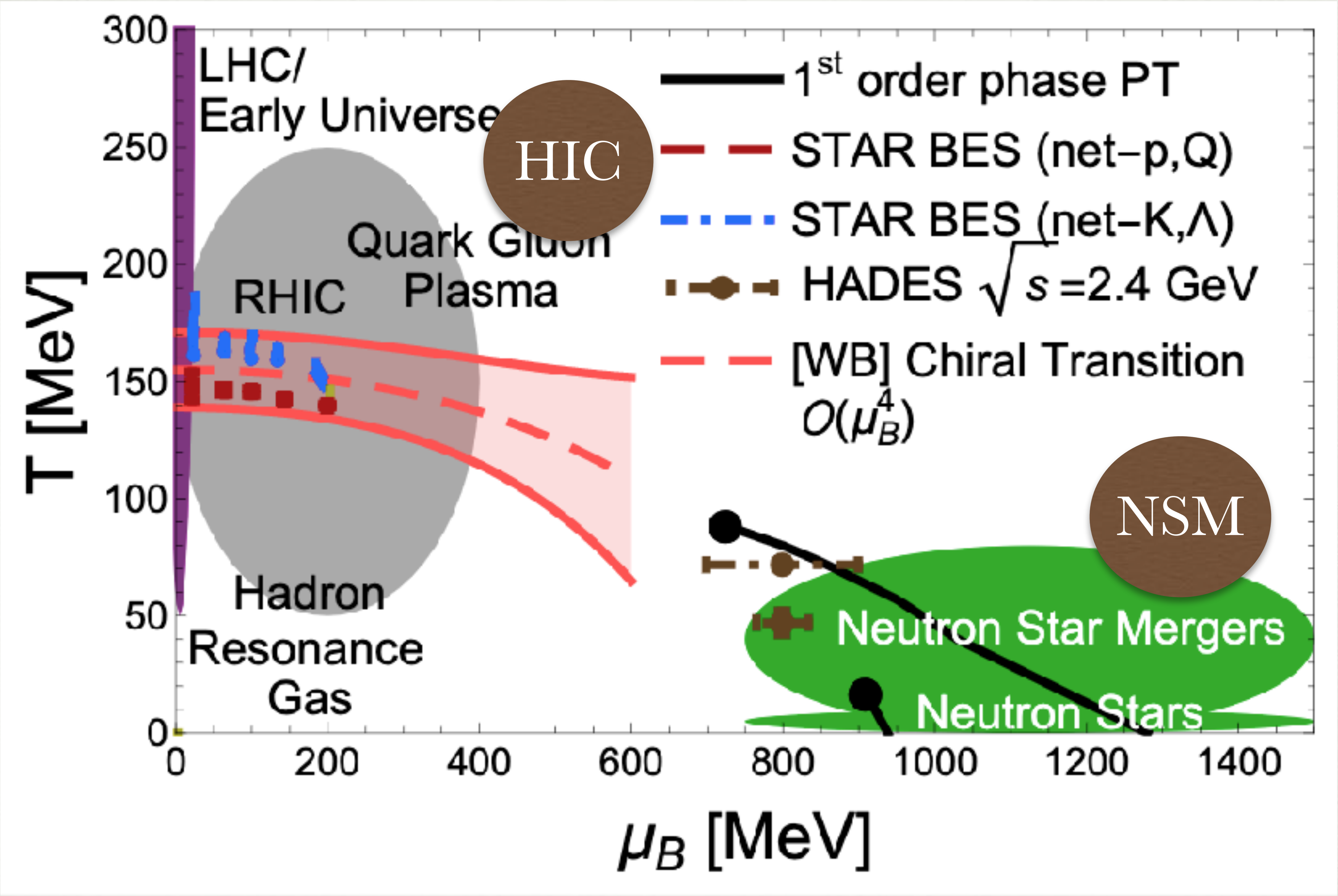
Critical Point:
Peak in κ_4/κ_2 only clear signature

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

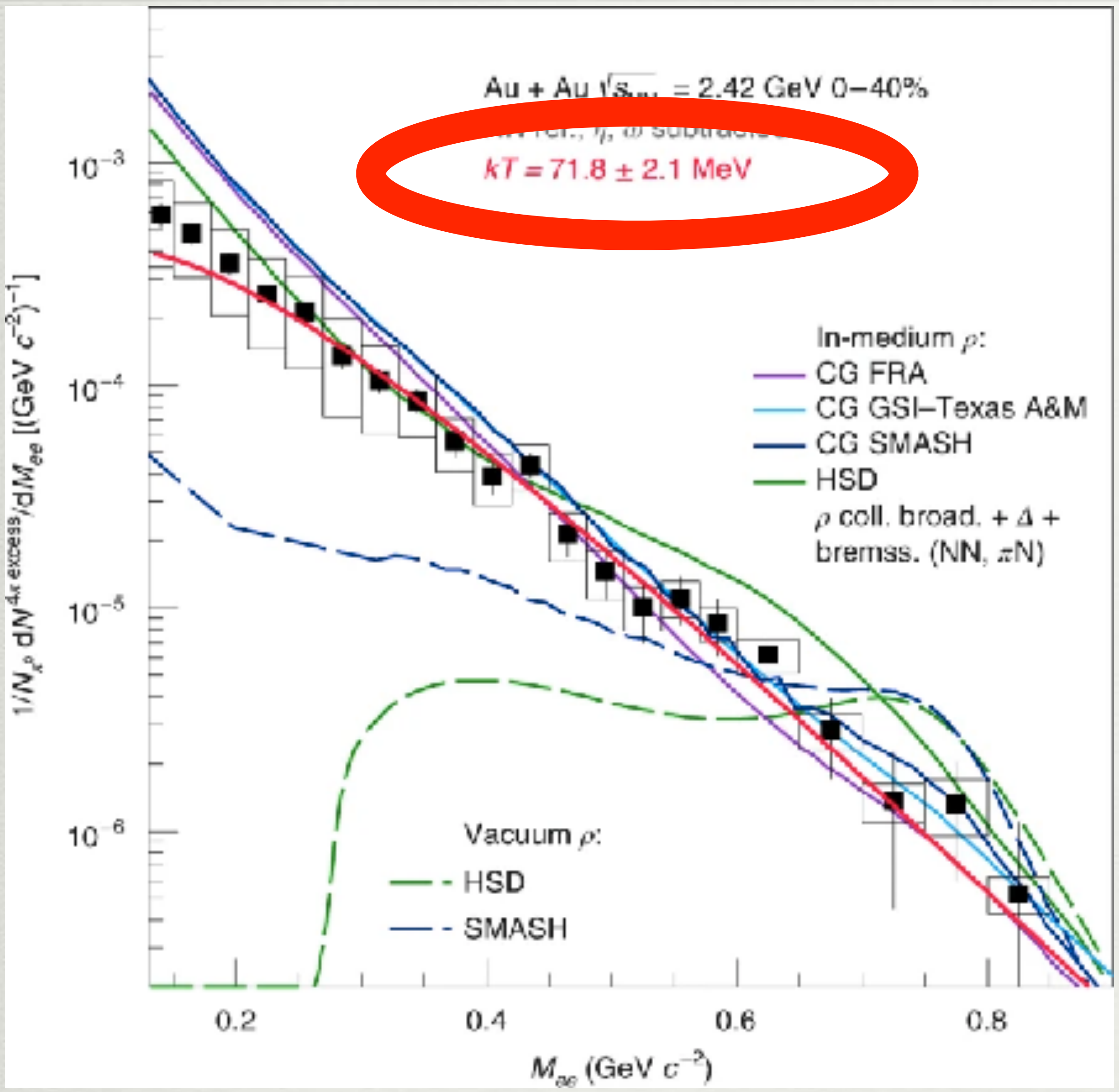




QCD phase diagram



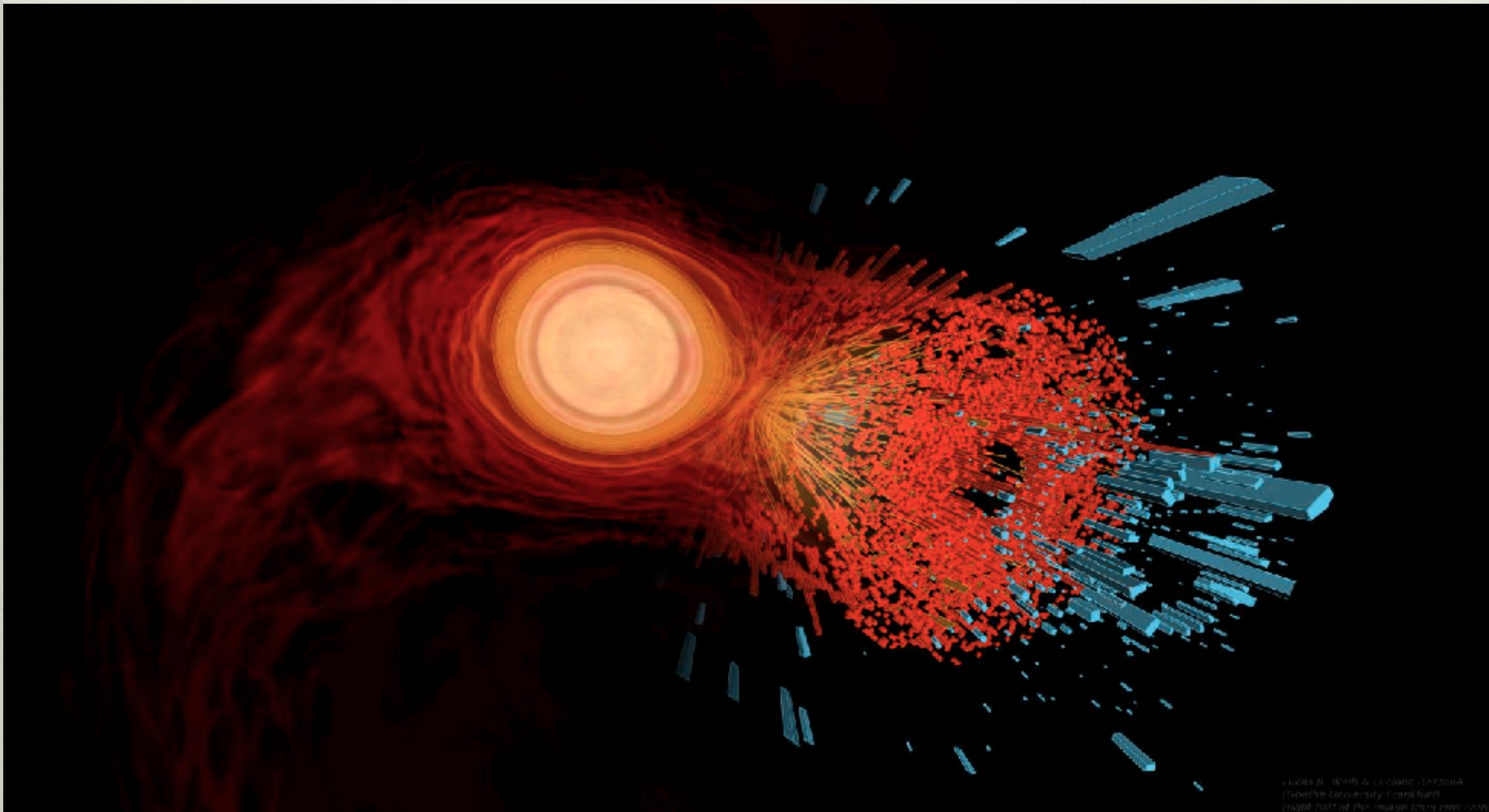
HADES best for EOS at finite T



[HADES] Nature Physics volume 15, pages 1040–1045(2019)

- Extracted average temp $T = 71 \pm 2.1$ MeV
- Density estimates highly model dependent but $\rho \sim 2\rho_0$
- Min. Measurable T from thermal fits: $\{T_{chem}, \mu_B^{chem}\} = \{47 \pm 5, 799 \pm 22\}$

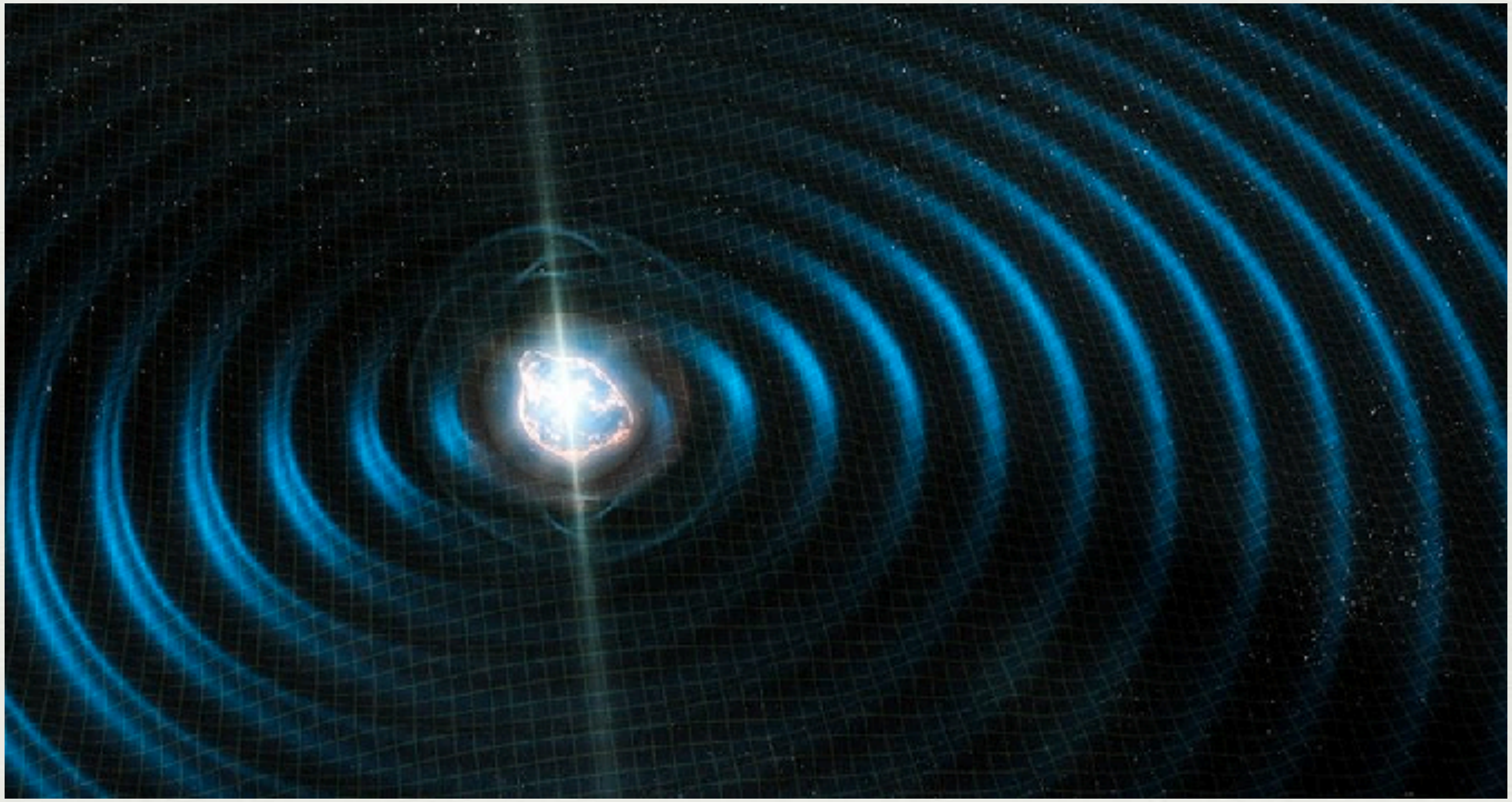
Nucleus-Nucleus collisions = mini-neutron star mergers?



Neutron star mergers combine the fundamental forces

Electromagnetism
Large B field, visual signals

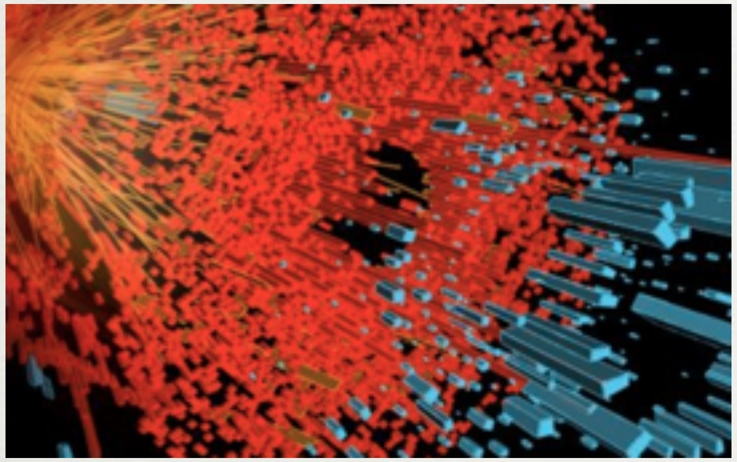
Gravity
Gravitational Waves



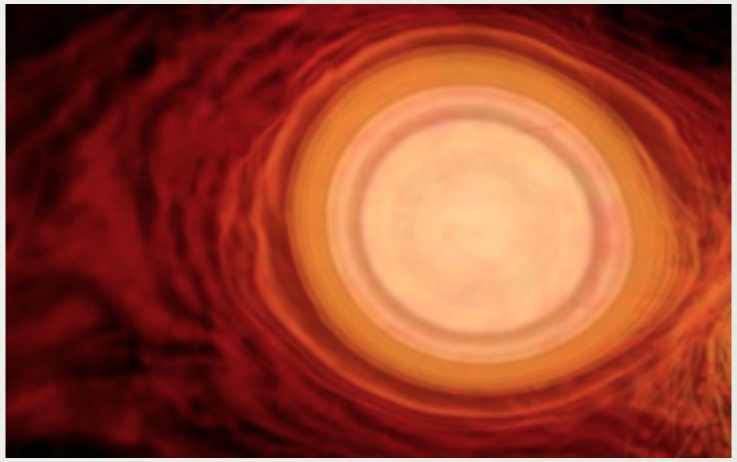
Strong Force
Nuclei, nucleons, quarks

Weak Force
Neutrinos, Strange decays

Caveats: Strangeness and Electric Charge

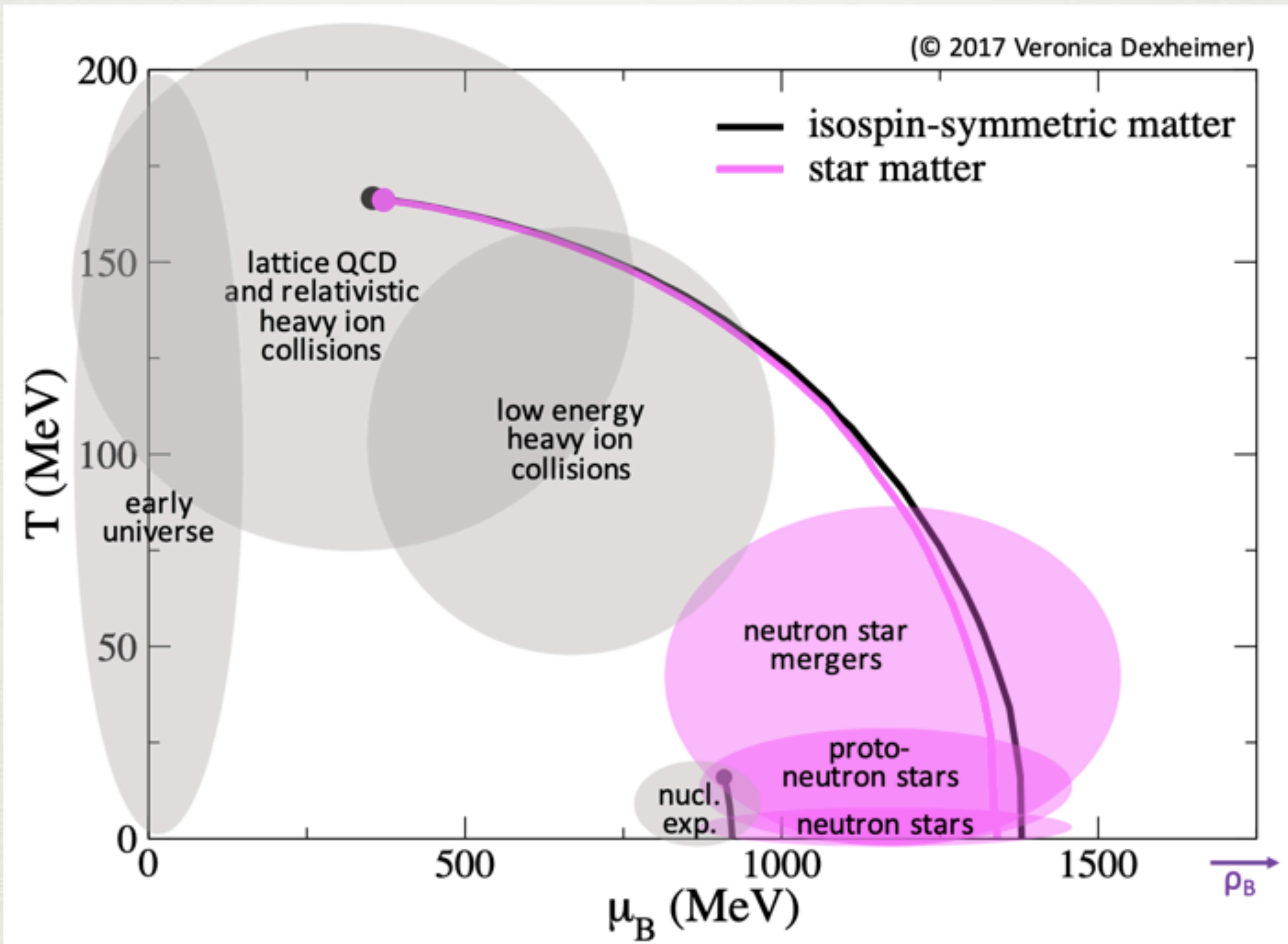


- Strangeness neutrality $\langle \rho_S \rangle = 0$
- Short lifetime, strangeness conserved
- Charge: p vs. n in ions $0.4\langle \rho_Q \rangle \sim \langle \rho_B \rangle$



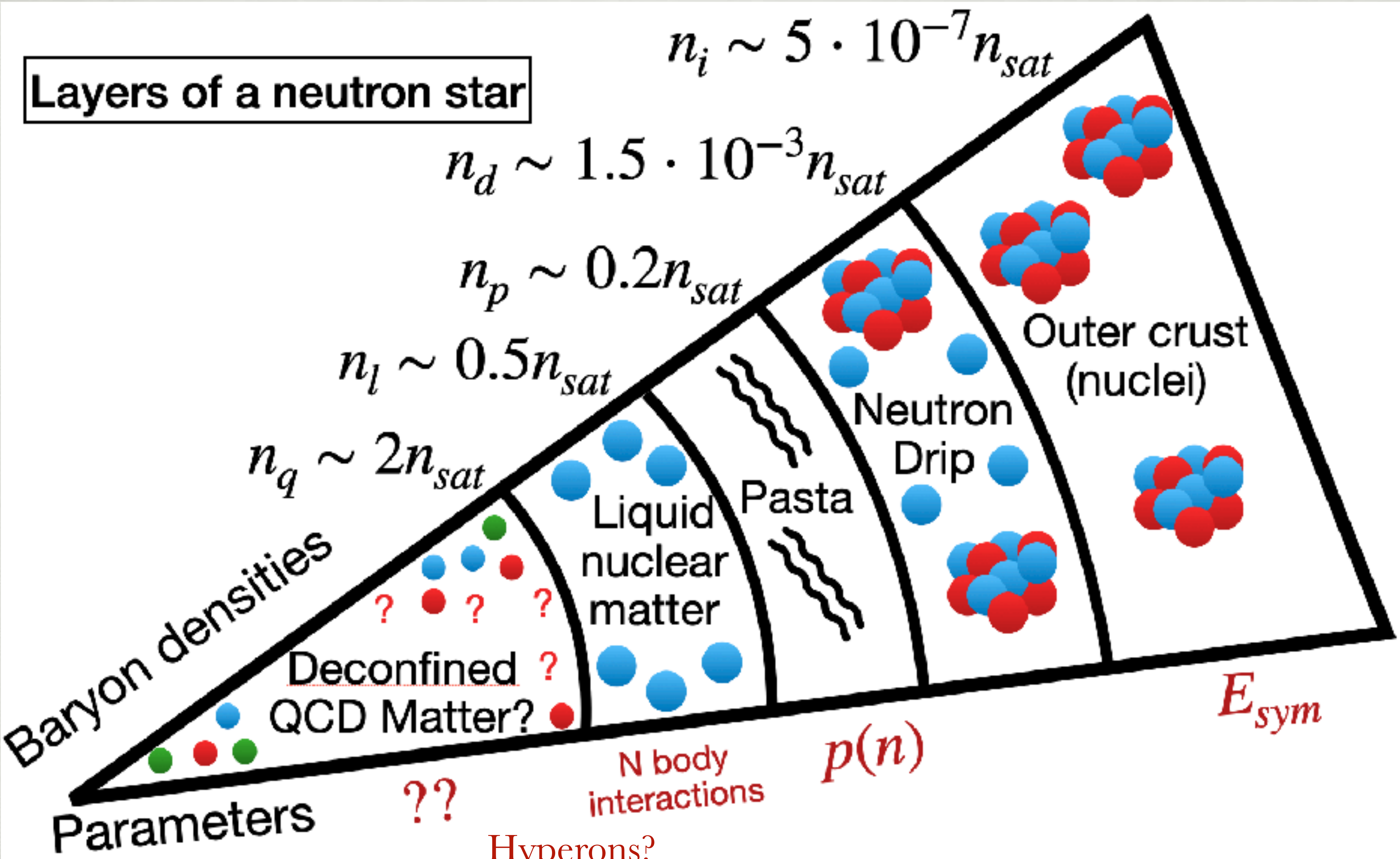
- Long lifetime, weak decay: $s \rightarrow u + W^-$
- Strangeness most likely *not* in equilibrium
- Electrically neutral for stability $\langle \rho_Q \rangle = 0$

Heavy-ions: phase transition at larger μ_B

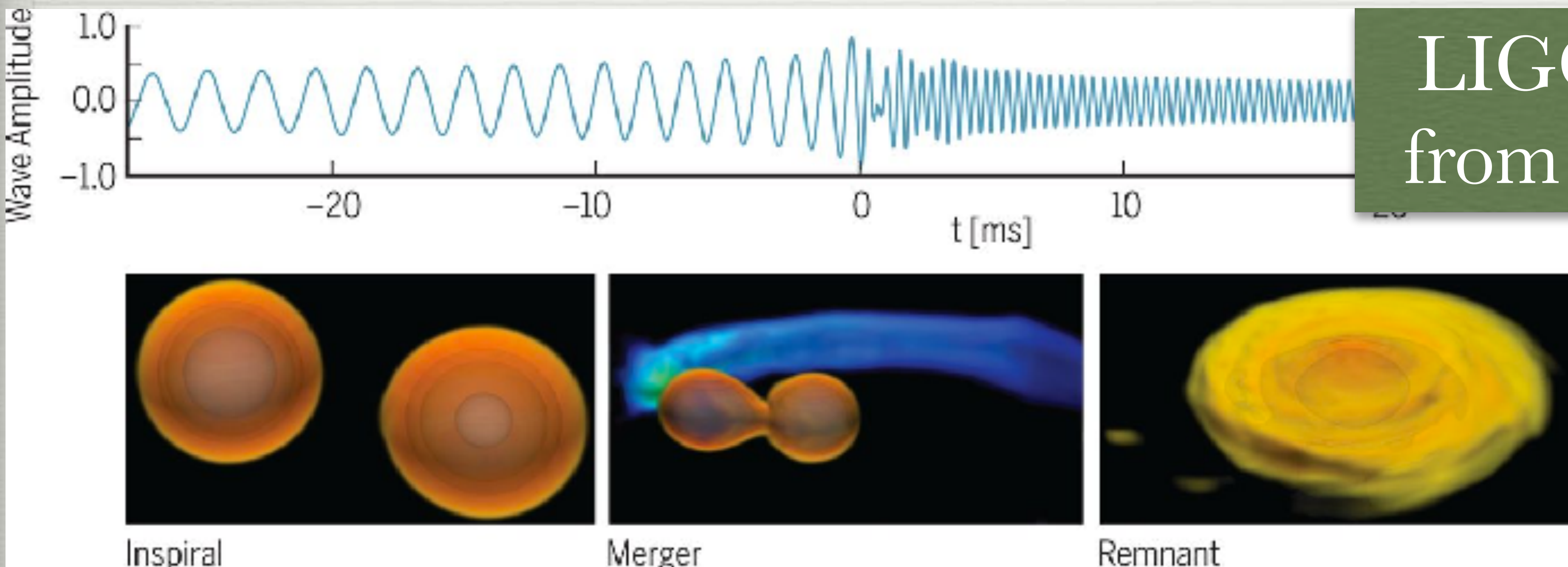


Dexheimer et al, *Astron.Nachr.* 342 (2021) 1-2, 347-351

Degrees of freedom by density



Constraints at low T and large ρ_B



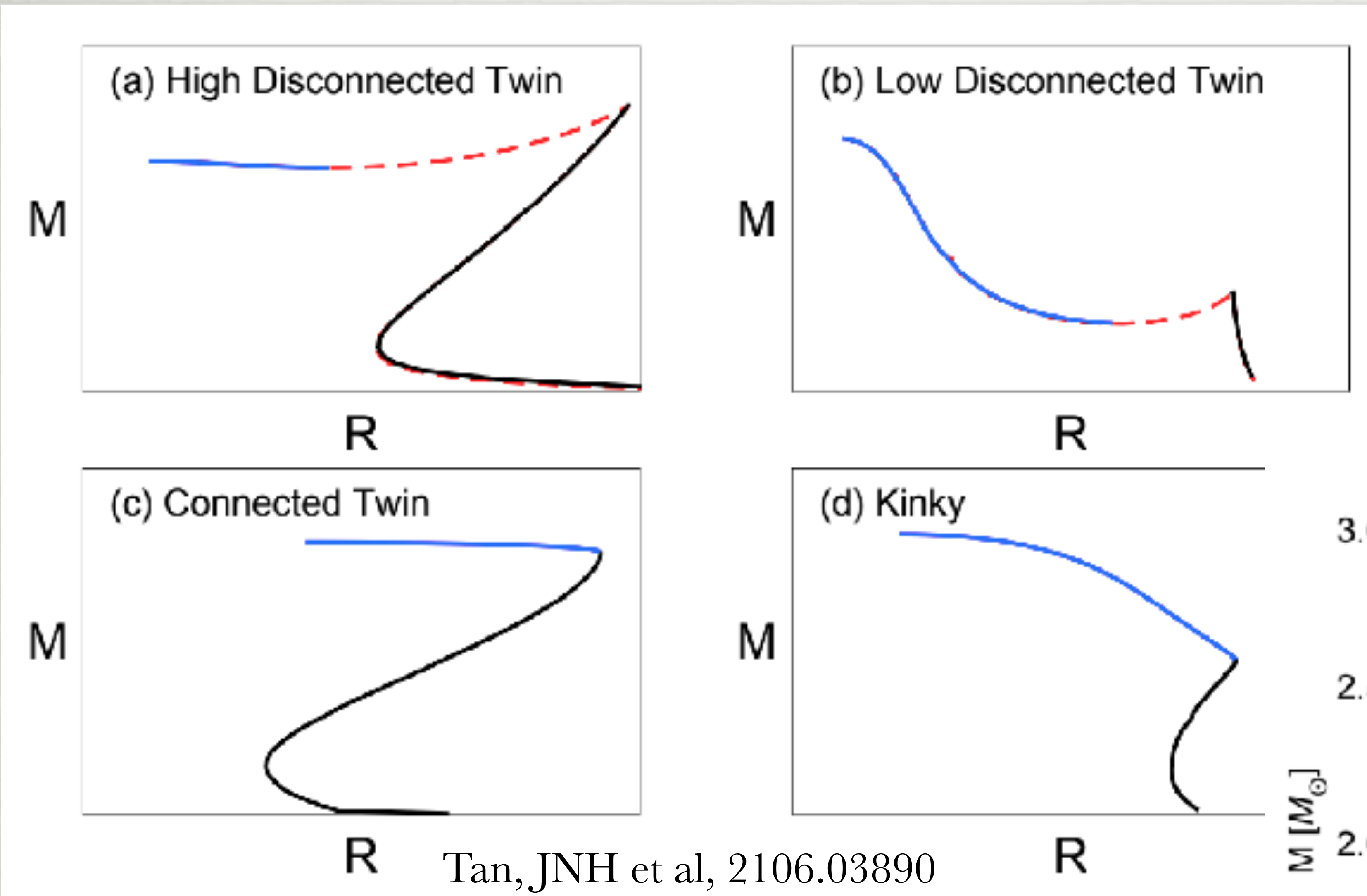
LIGO/VIRGO: Inspiral from Gravitational Waves

NICER: Observations of isolated Neutron Star

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

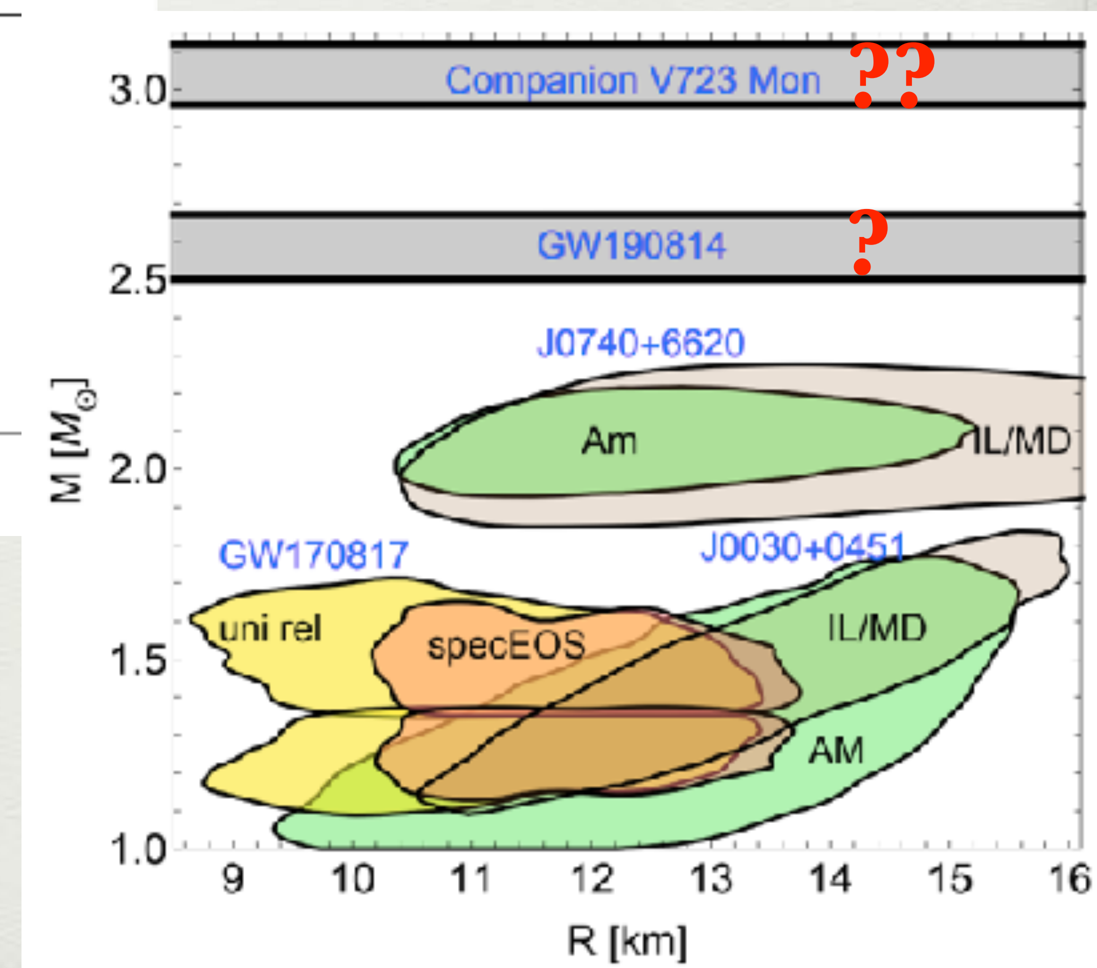
J. Noronha-Hostler

Mass Twins: 1st-order PT in Neutron Stars



Tan, JNH et al, 2106.03890

Current constrain not yet precise enough to confirm/ deny

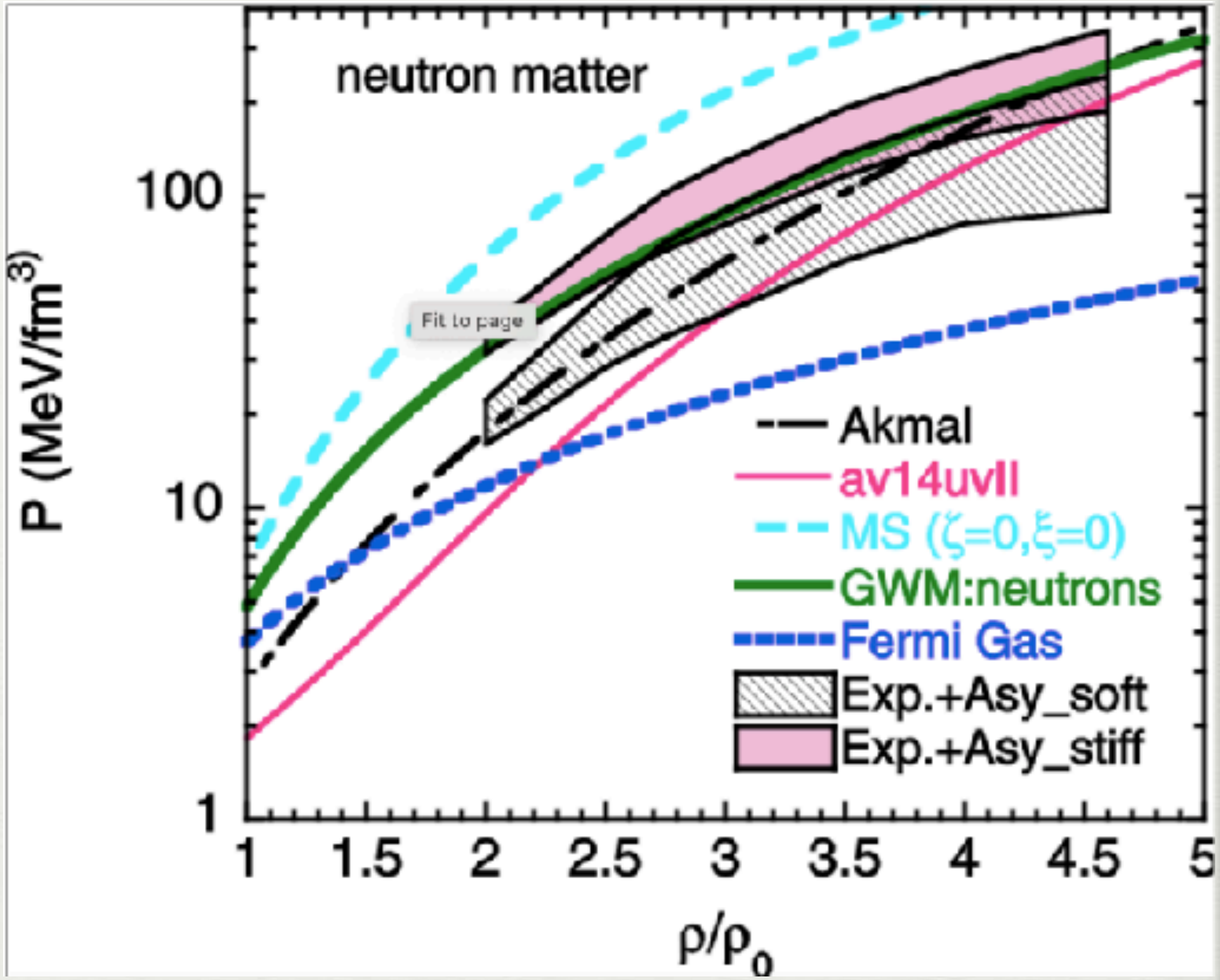


See also Alford, Han, Prakash *Phys.Rev.D* 88 (2013) 8, 083013

Can we directly compare heavy-ions to neutron stars?

Previous attempts: Heavy-Ion “Data”

- Fermi-liquid/π, p, n transport assumed
- quarks d.o.f not checked
- Extrapolate to T=0, neutron matter
- Compare to v_1 and v_2 only in mid-central collisions $\sqrt{s_{NN}} = 1.5 - 4.7$ GeV

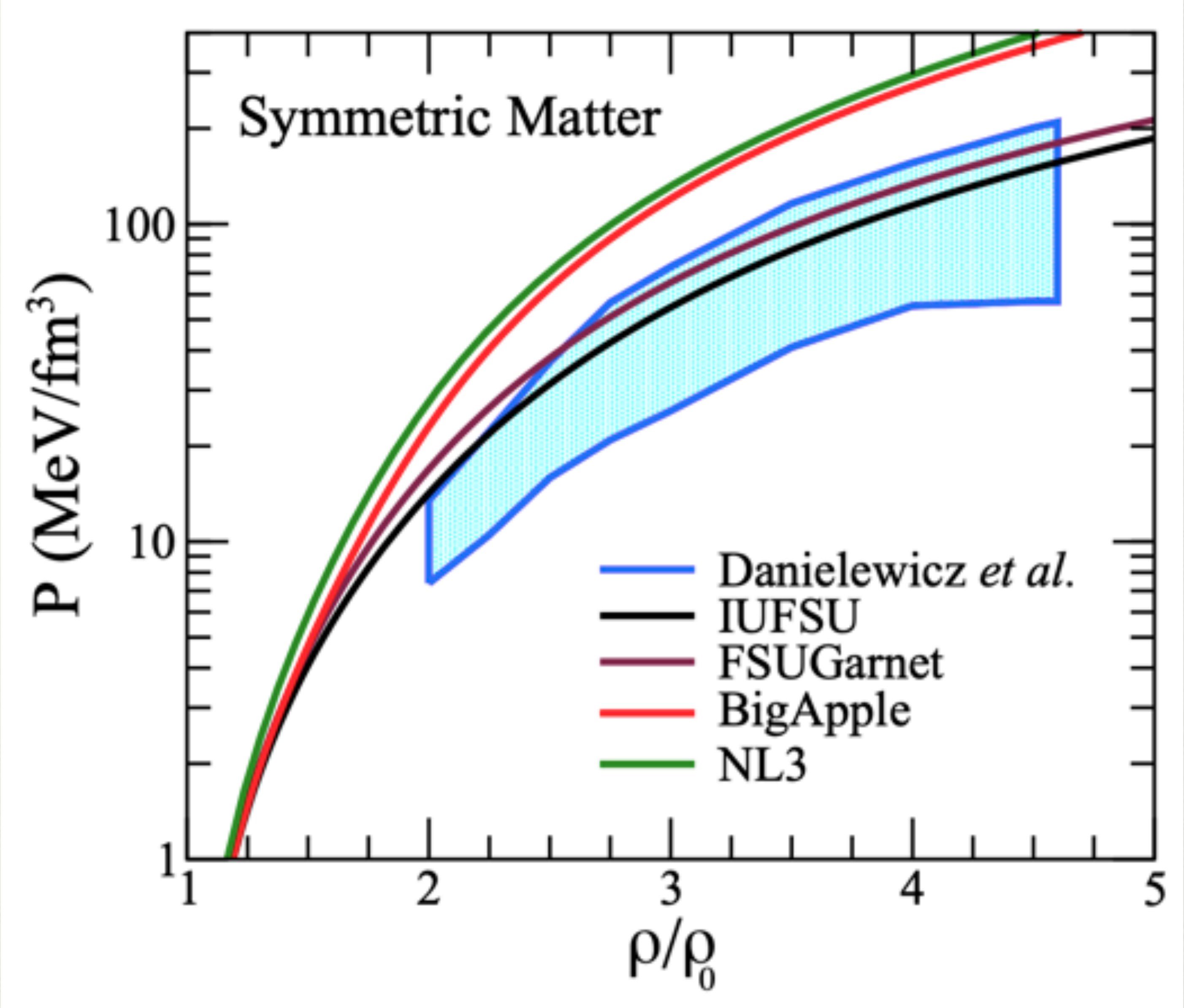


Danielewicz, Lacey, Lynch *Science* 298 (2002) 1592-1596

Used **extensively** in nuclear astrophysics to exclude EOS

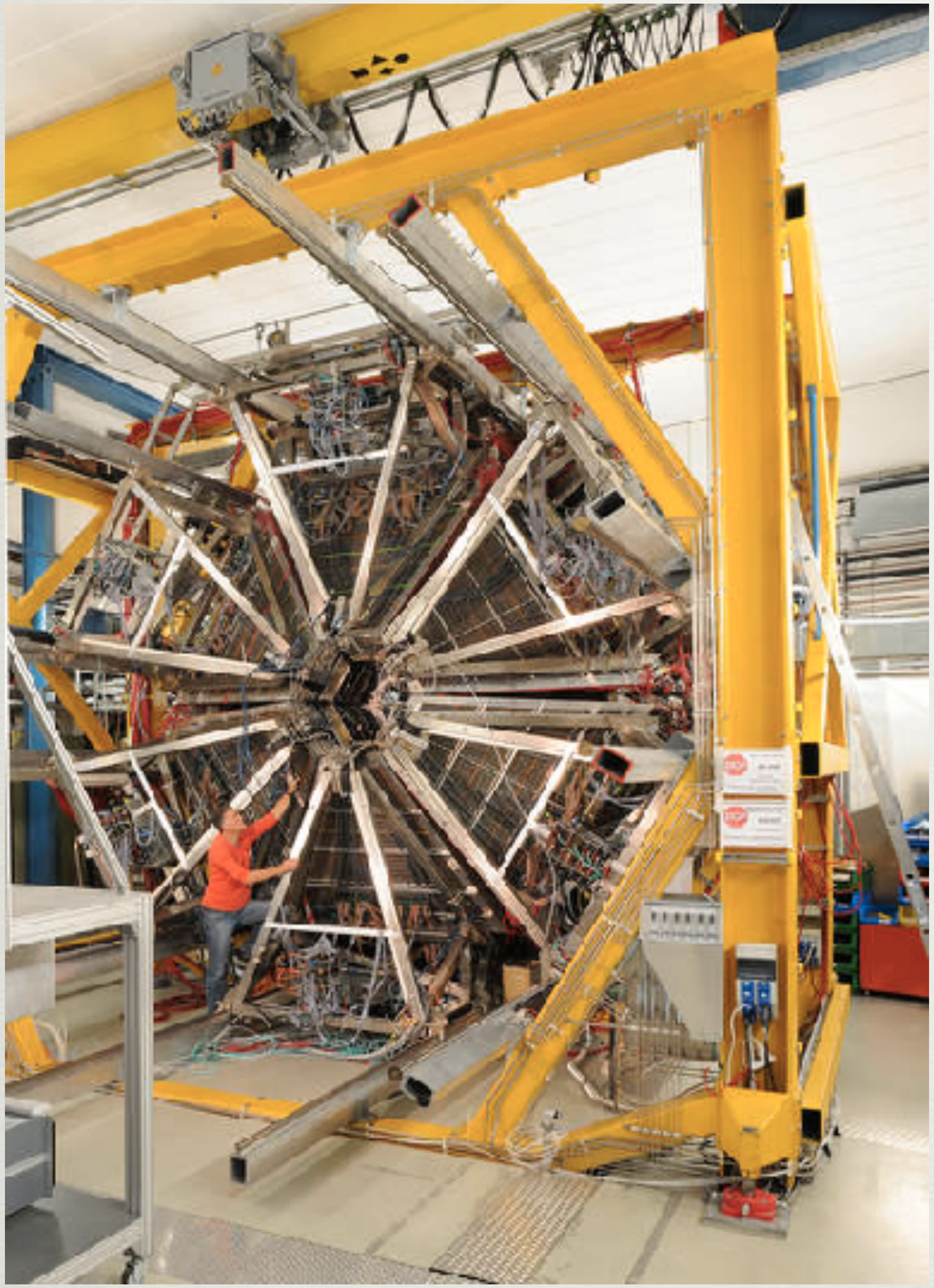
20 year old heavy-ion "data" used to exclude $M > 2.5M_{\odot}$

- Stiff EOS are excluded because of this heavy-ion "data"
- Does a hadronic transport model/fermi-liquid actually work well compared to modern low-energy heavy-ion collisions?



Horowitz et al, *Phys.Rev.C* 102 (2020) 4, 044321

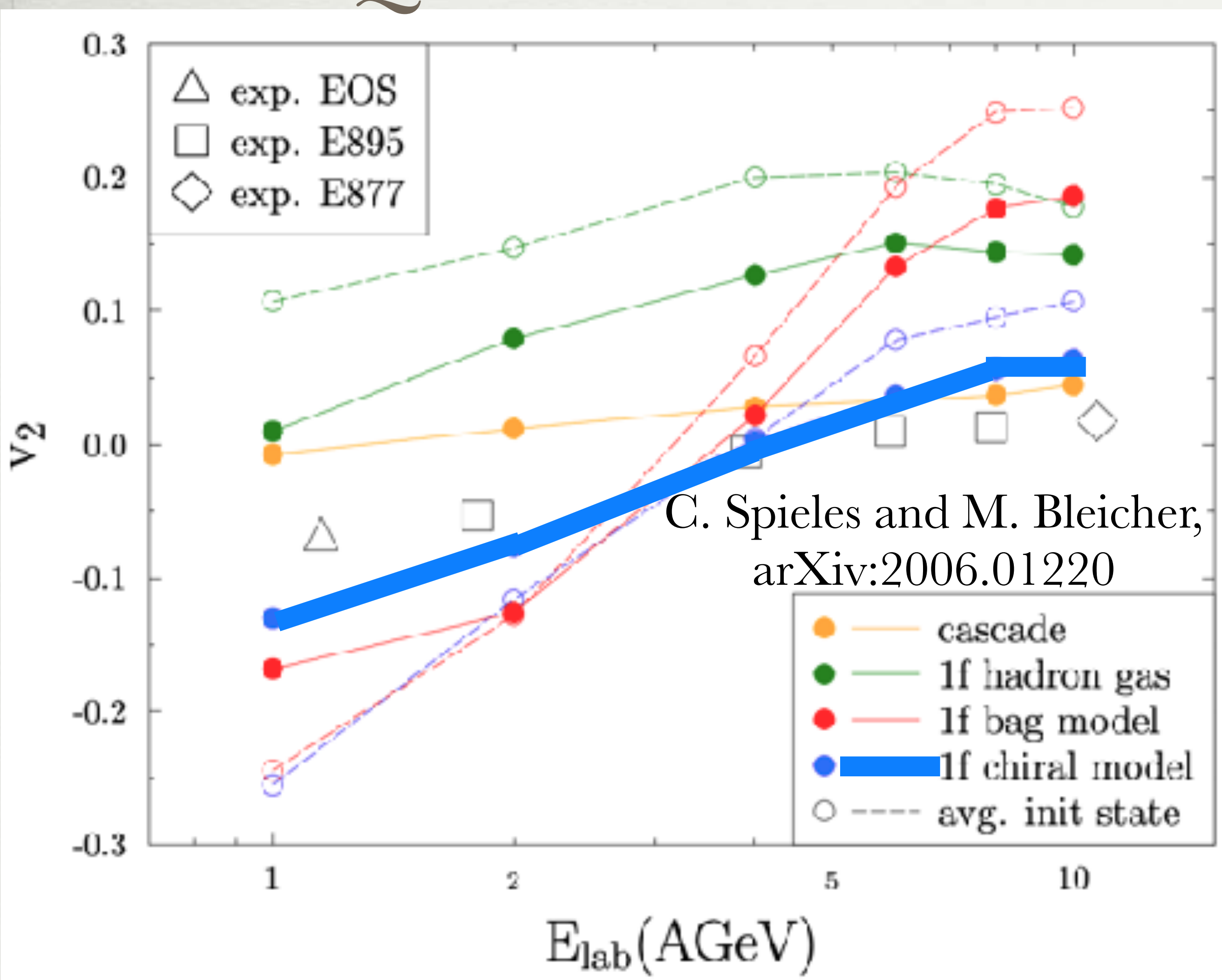
HADES can shed-light on the heavy-ions to neutron stars?



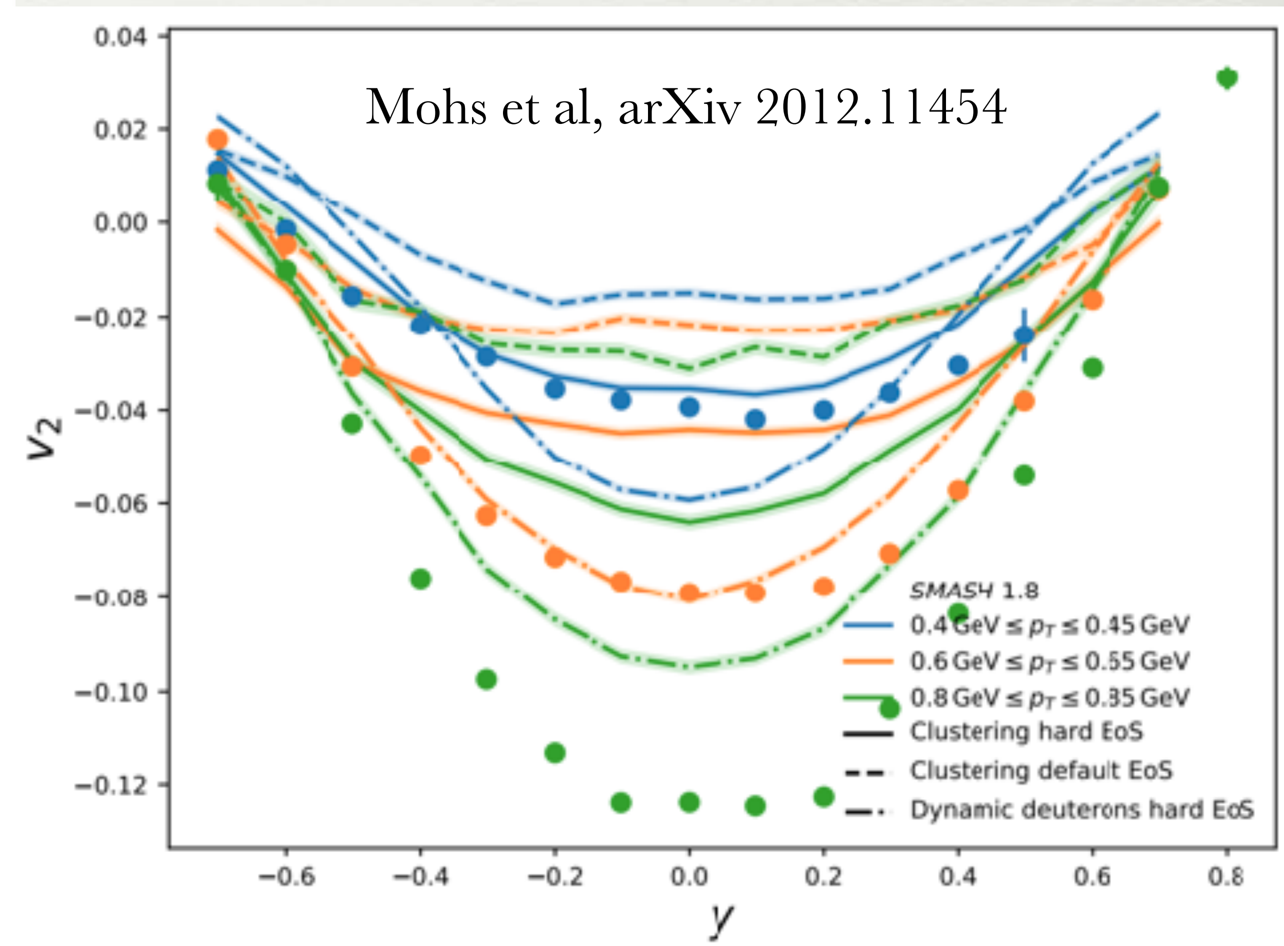
- $\sqrt{s_{NN}} = 1 - 3$ GeV
- Modern flow measurements
- Studies of kurtosis (looking for 1st order phase transition)
- Multi-particle flow cumulants
- More centralities, p_T, η dependence

HADES *almost* a mini NS-NS merger

QGP+Hadrons



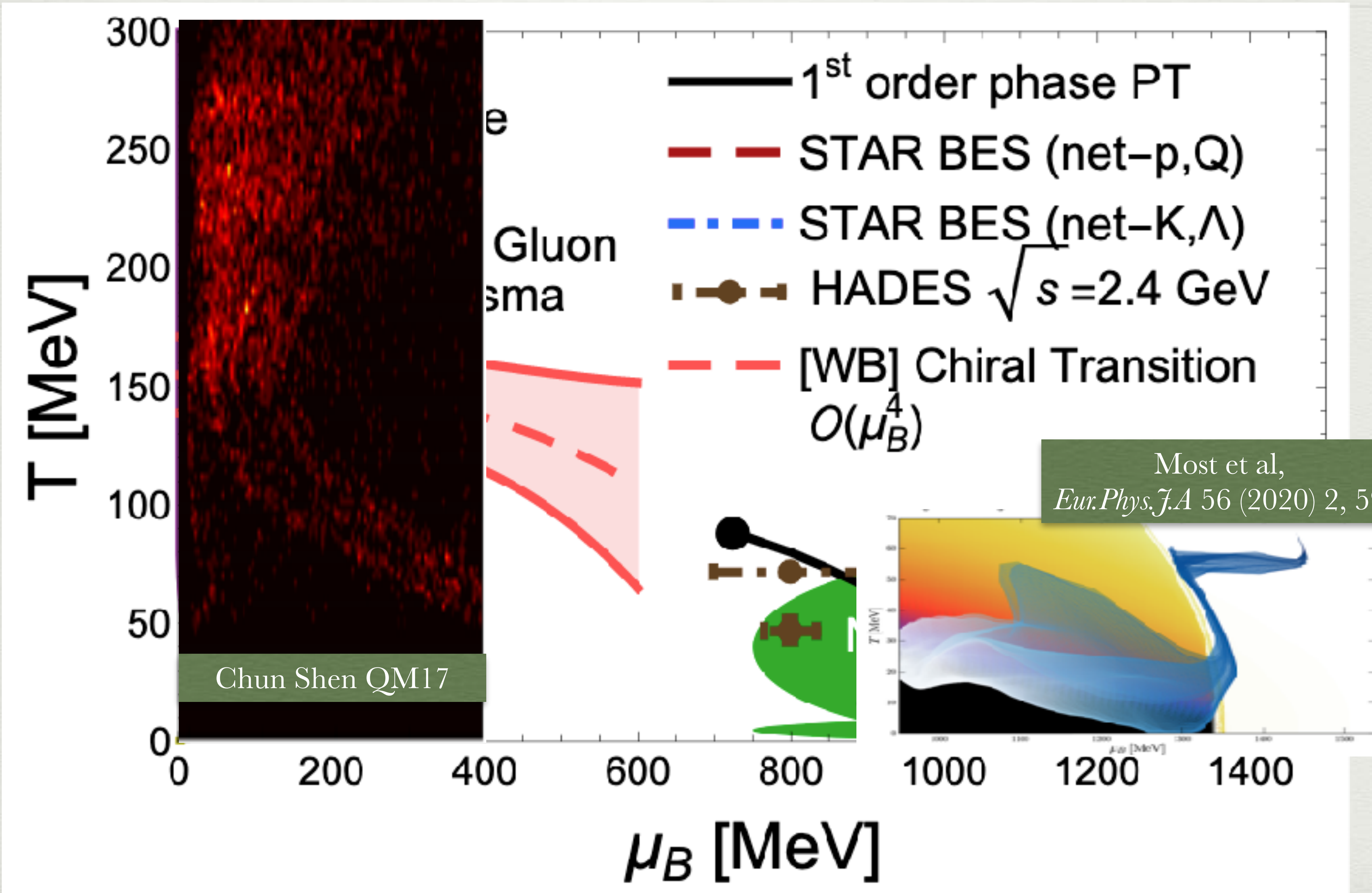
Hadrons only



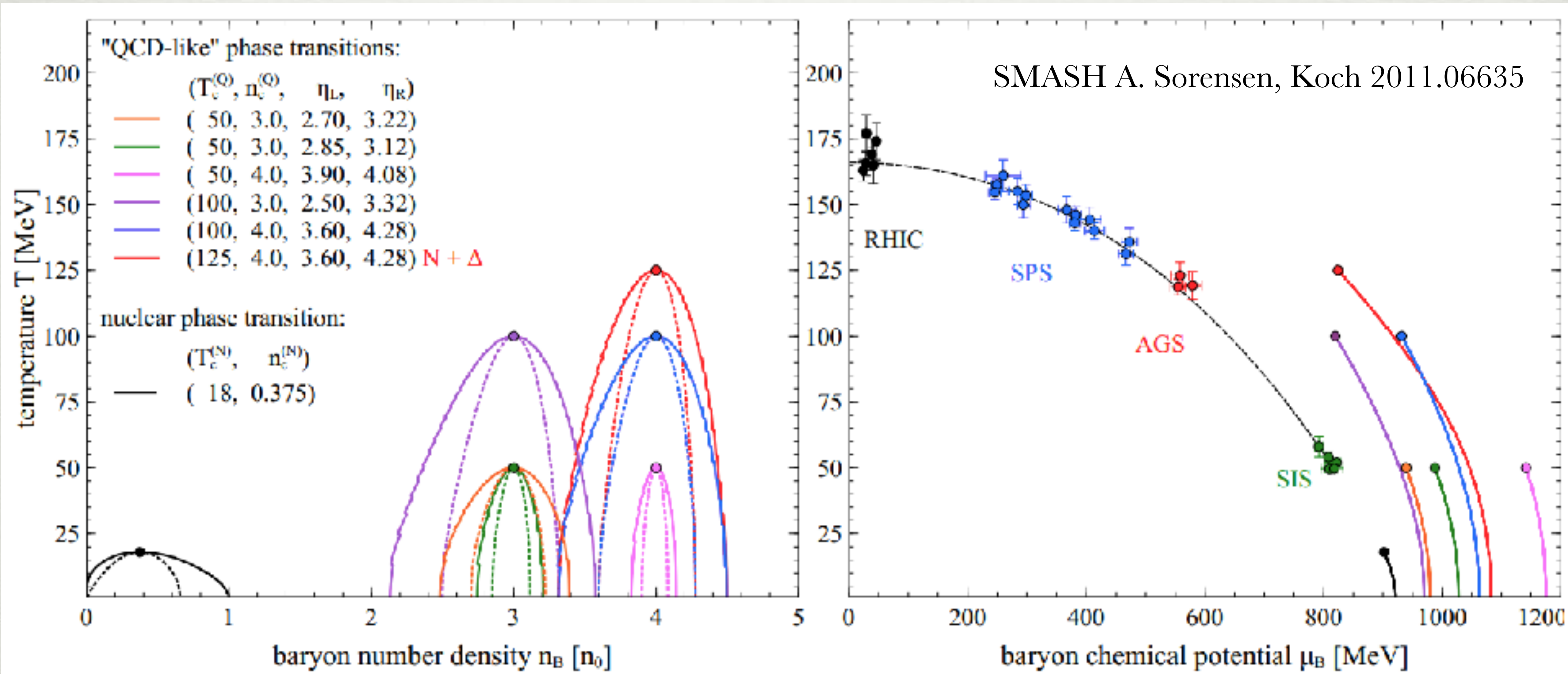
Not clear if HADES can be best described by transport or hydrodynamics + transport. Neither fits all data.

QCD Phase Diagram in Out-of-Equilibrium

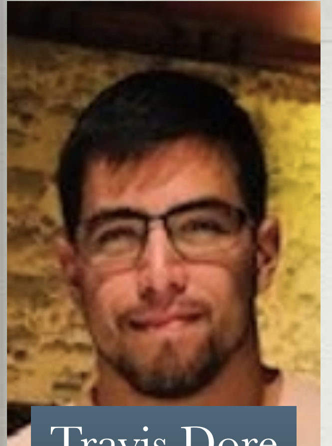
QCD Phase Diagram Out-of-Equilibrium



Phase transitions in hadronic transport



Such an approach allows for better systematic checks

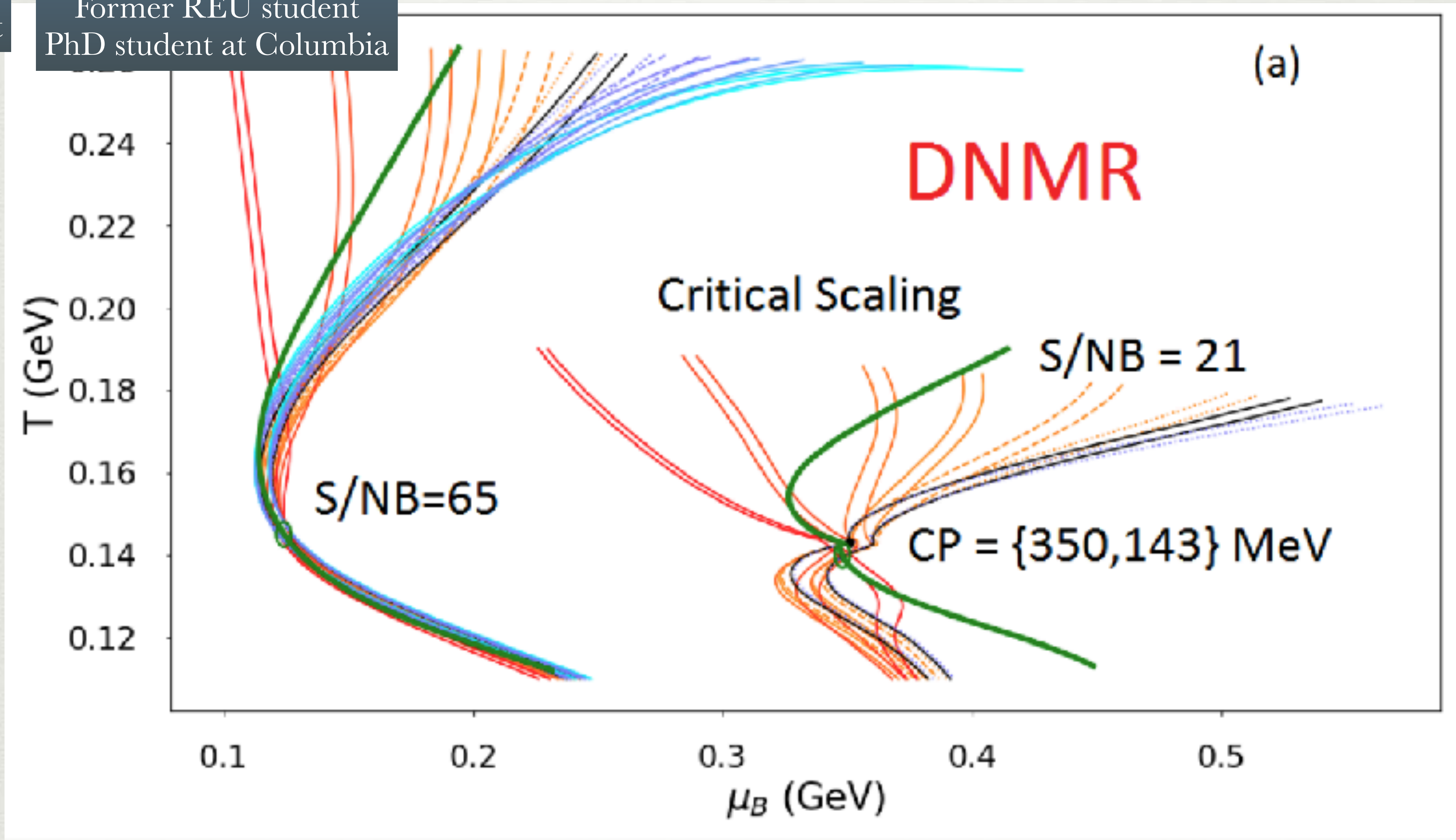


Travis Dore
PhD student

Emma McLaughlin
Former REU student
PhD student at Columbia

Far from equilibrium

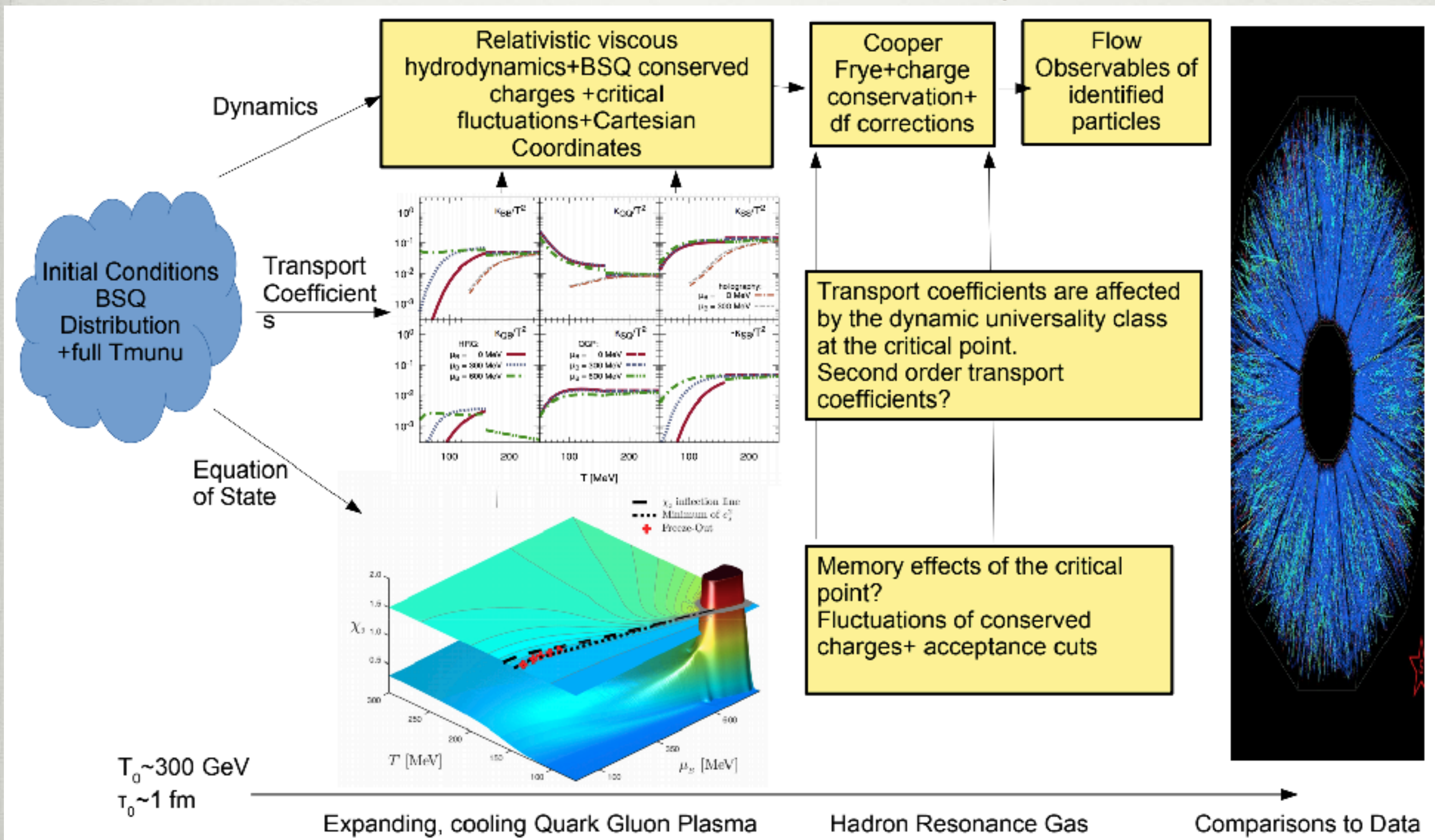
Dore, McLaughlin, JNH 2007.15083



Far-from-equilibrium initial conditions in heavy-ion collisions can dramatically affect the extraction of the EOS

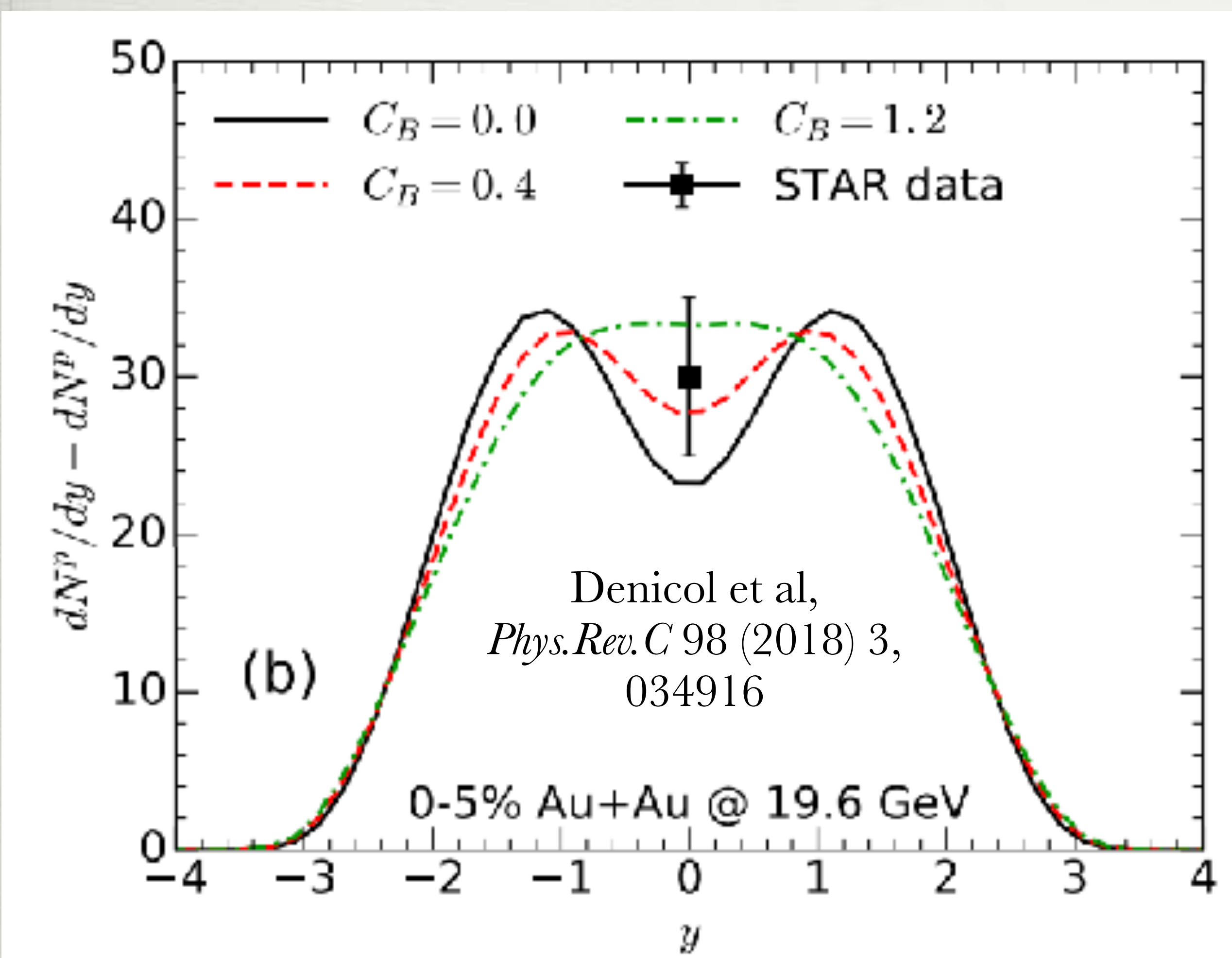
3+1 BSQ hydro needed for low-beam energies

Dexheimer, Noronha, JNH, Ratti, Yunes arXiv:2010.08834



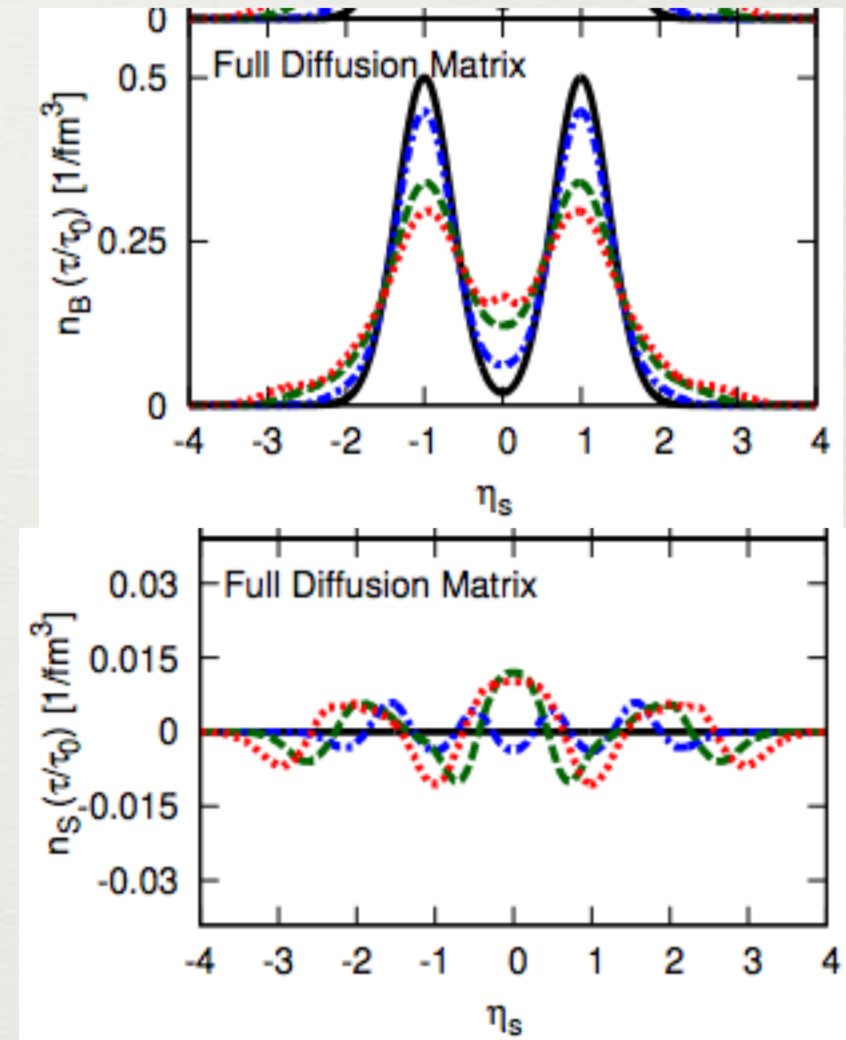
Initial hydro results

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

$_B = 0$, shear+bulk viscosity gives 11 coupled
ren

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

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

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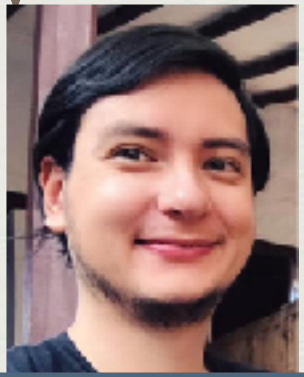

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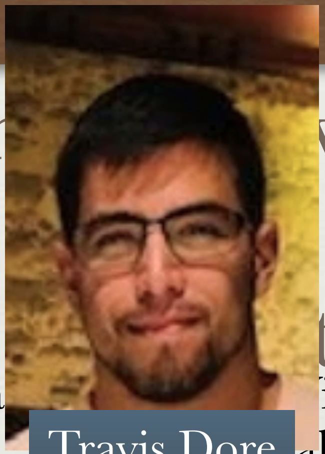
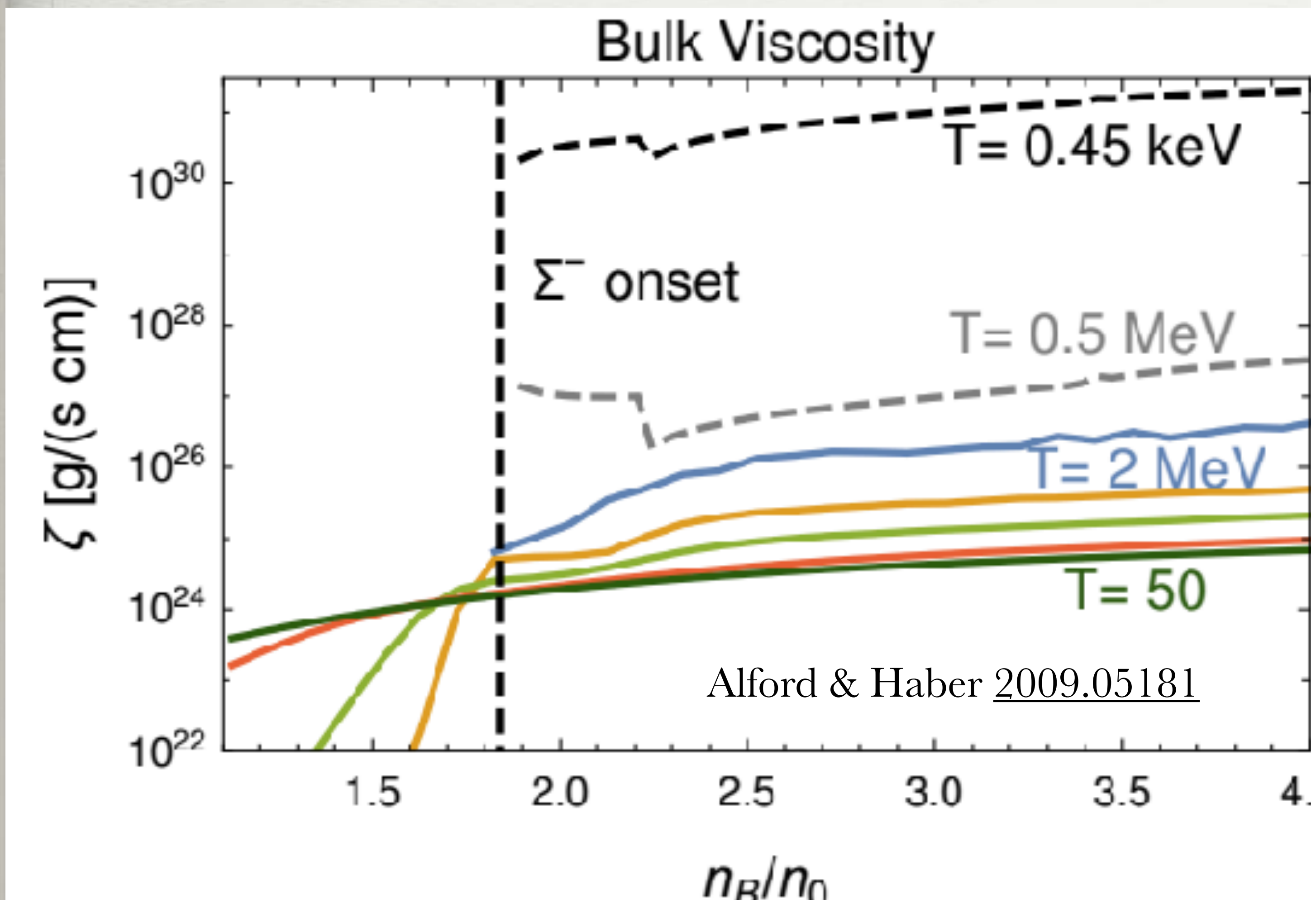
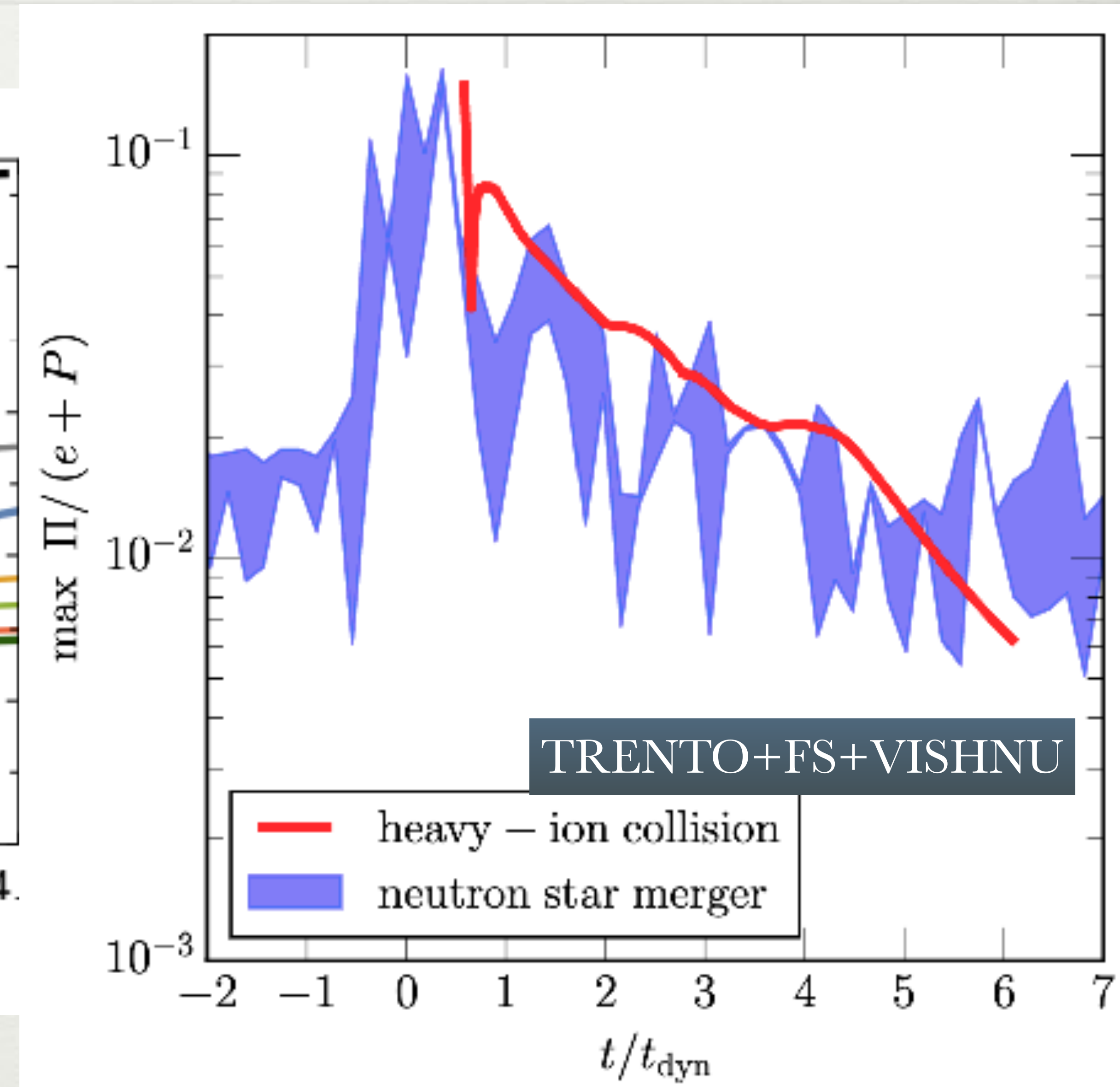
Stephanov, Na… in, Schaeffer, Yee, An, Marti… matsu, Yan,
… al, Weller, Ridgway, Du, He…



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





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

Alford, Harris, Most, Noronha, JNH, Pretorius, Plumberg, Witek, Yunes
To appear soon

Summary

- STAR Fixed Target: NEED for low-energy heavy-ion collisions to constrain EOS at finite T
  - What is important to mesure? Spectra, fluctuations, flow, HBT, …
- Equation of State: lots of progress but hydrodynamics needs a wider range of μ_B, μ_S, μ_Q
- BSQ hydrodynamics needed, critical fluctuations.
- Neutron star mergers now incorporating viscosity