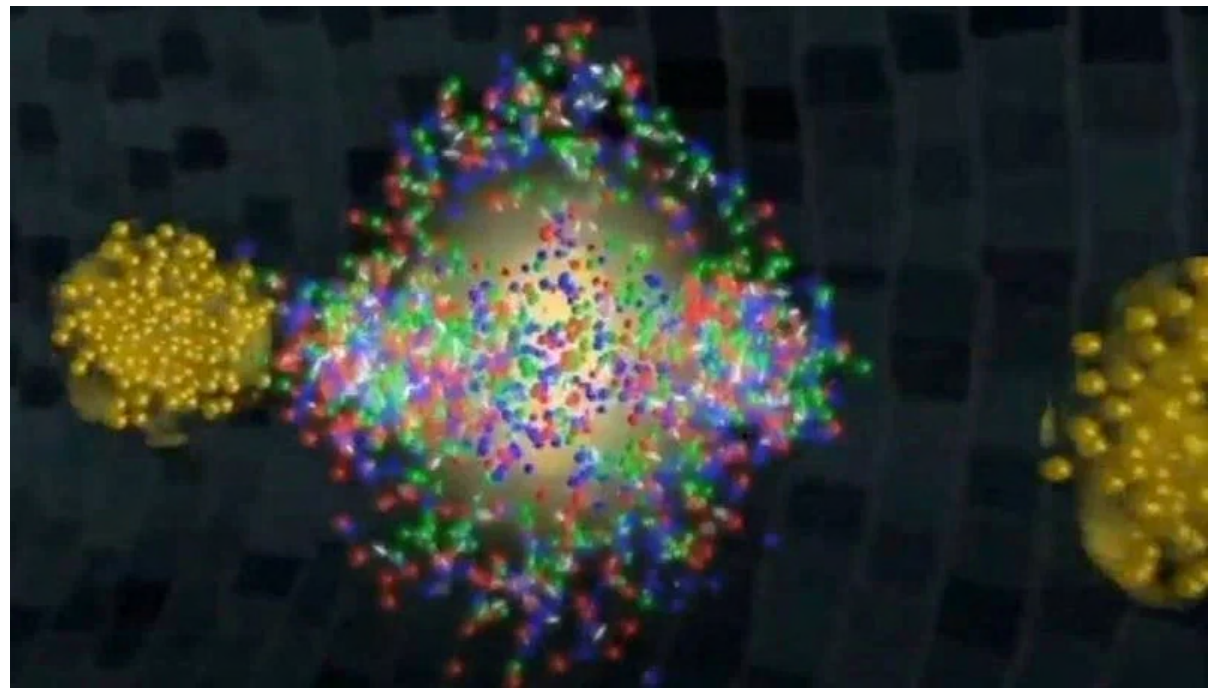
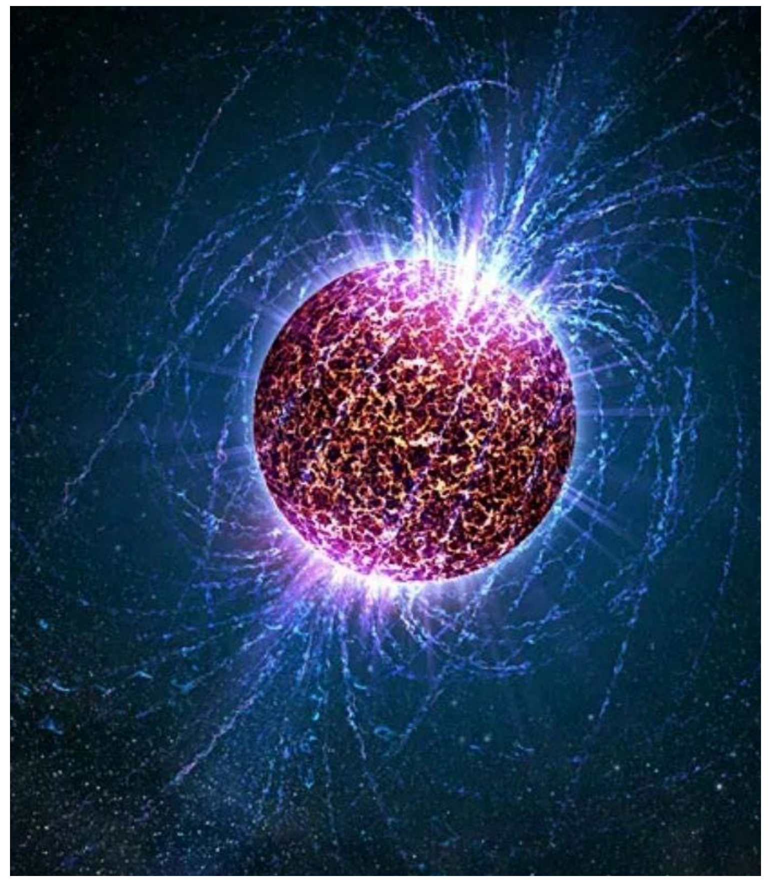
How do we connect the dense matter EOS to heavy-ion data?

Jacquelyn Noronha-Hostler

INT 25-94W Sept, 2025





Main takeaway: heavy-ion collisions are complicated.

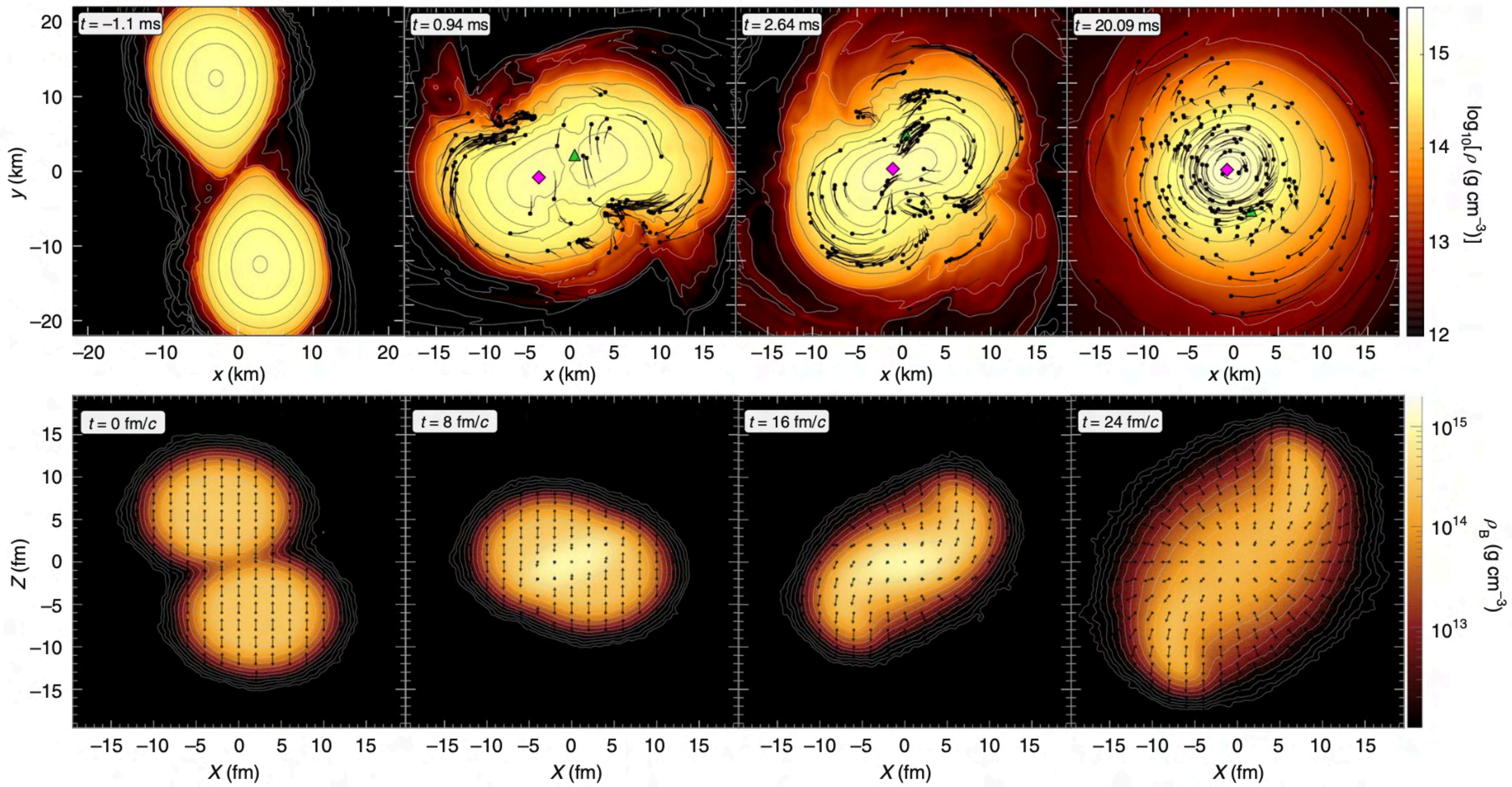
Don't trust anyone who tells you they know the large n_B EOS.

But there's hope we will with enough time and effort!

Heavy-ion collisions (HIC) vs Binary neutron star (NS) mergers

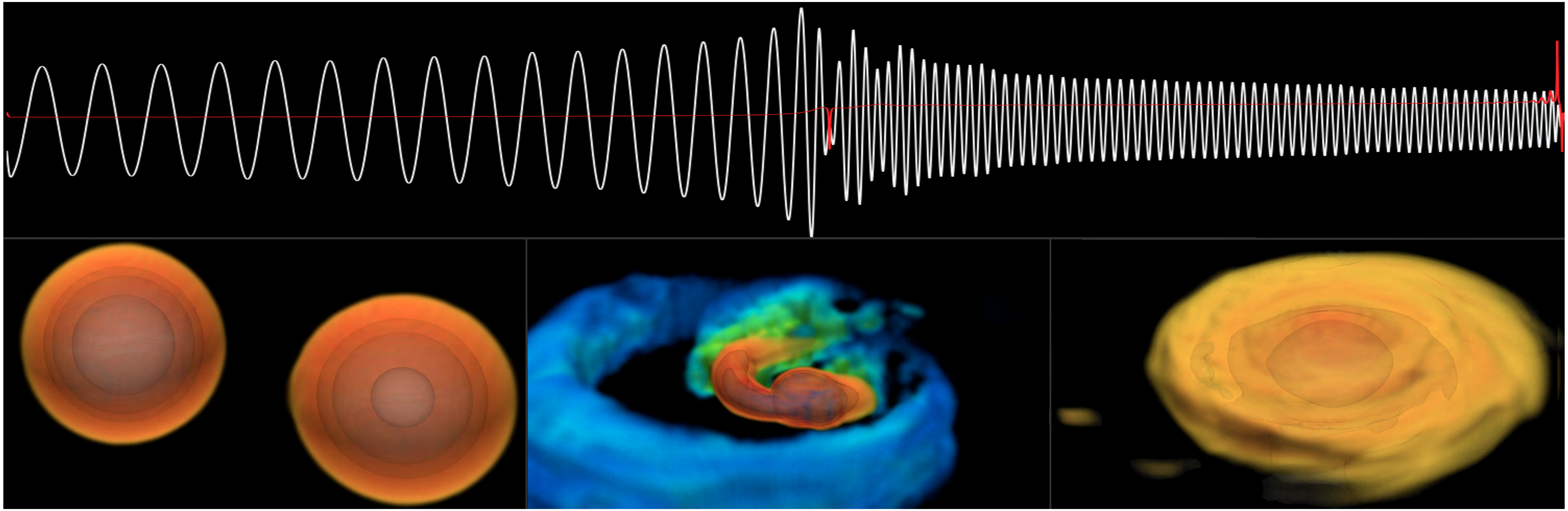
Neutron Star Mergers (Numerical Relativity)

[HADES] Nature Phys. 15 (2019) 10, 1040-1045



Low-energy Heavy-Ion Collisions (hadron transport)

Stages of a binary neutron star (NS) merger



Cold (inspiral)

$T \sim 10^{-5}\ MeV$

Hot (merger)

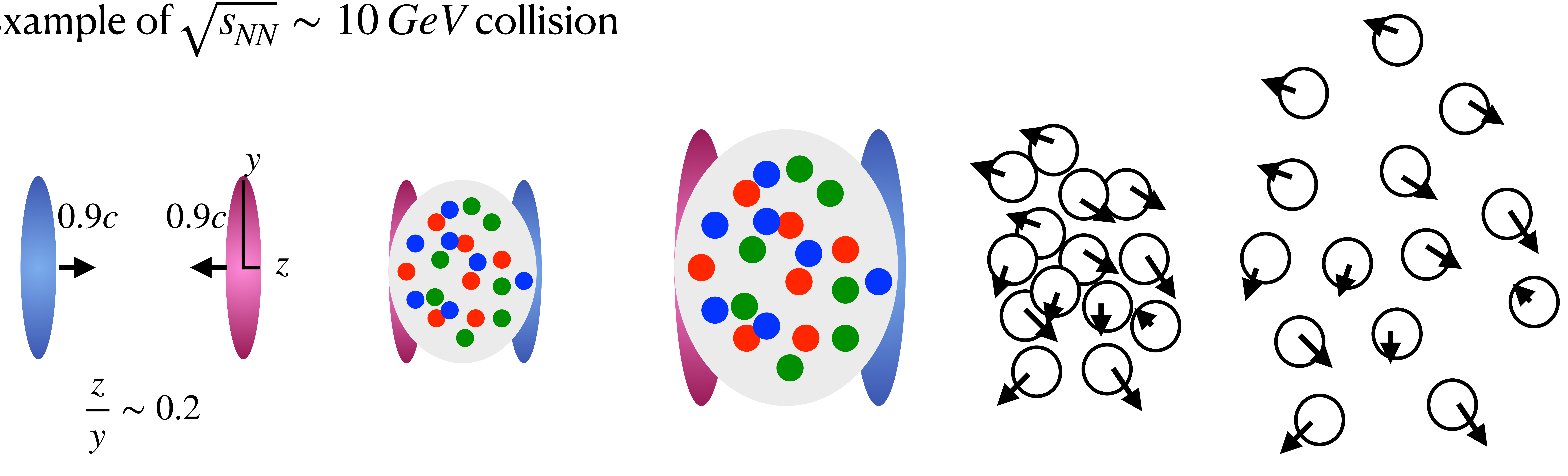
$T \sim 100\ MeV$

Observations here

Not yet measured

Stages of a heavy-ion collision (HIC)

Example of $\sqrt{s_{NN}} \sim 10\,GeV$ collision



Initial State | Hydrodynamics | Hadron gas | Freeze-out

$T \sim 0\,MeV, \quad n_B \sim n_{sat}$

$T_{max} \sim 200\,MeV \quad \mu_B^{max} \sim 300\,MeV$

$T_{FO} \sim 140\,MeV, \quad \mu_B \sim 200\,MeV$

"Archeology"

Data obtained here

System size BNS vs HIC

Difference $L_{NS}/L_{HIC} \sim 10^{18}$

$L_{NS} \sim 10^4\, m$

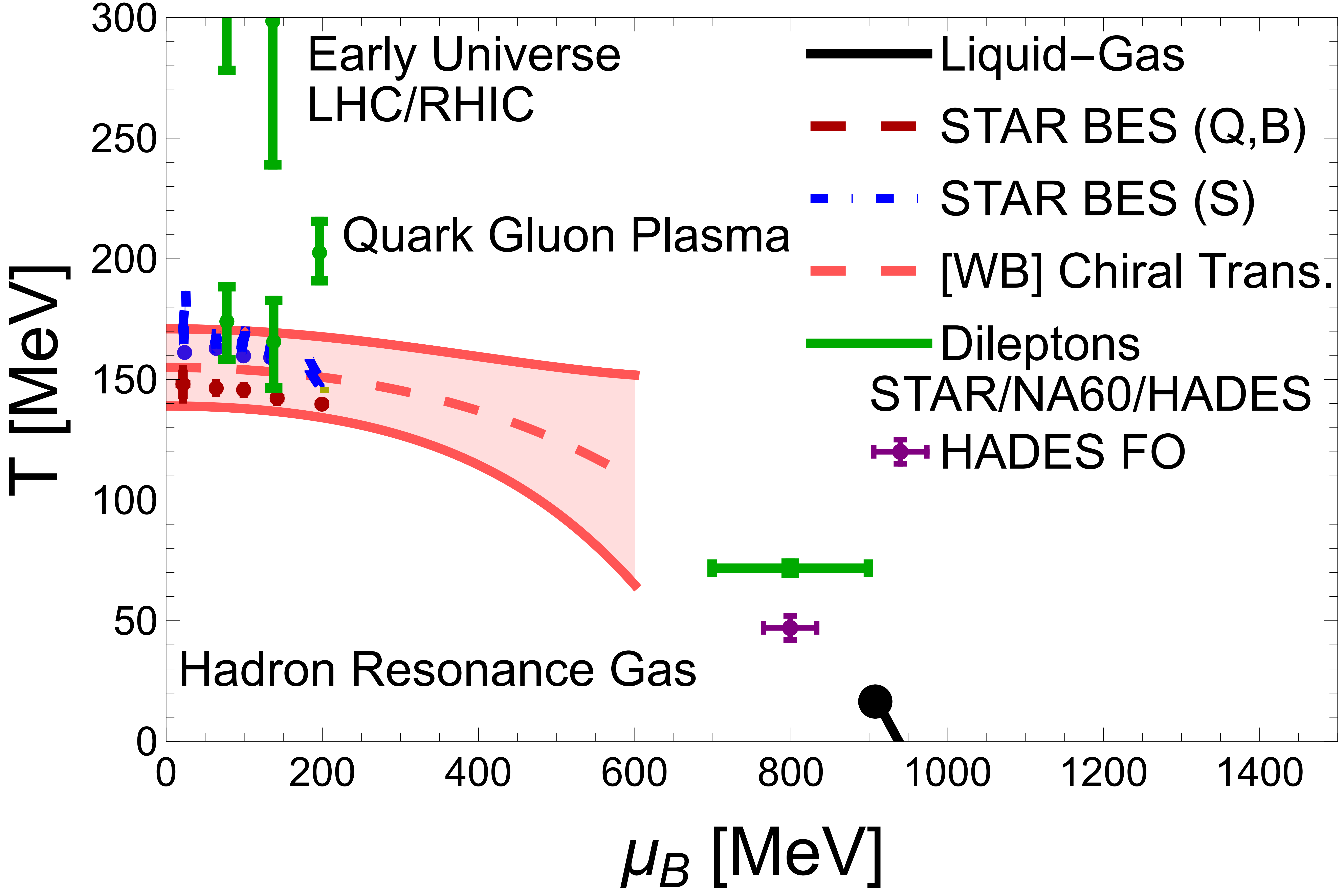
- Neutrinos and leptons matter
- Magnetic fields $\gg$ viscosity
- Convergence issues (Nils talk)
- Time scales milliseconds (10^{-3} sec)
- Causality?
- EOS has constraints a $T = 0$
- EOS ***unknown*** at finite T??
- $n_B \lesssim 6\, n_{sat}, T \lesssim 50\, MeV, Y_Q \lesssim 0.2$
- $\mu_S = 0$
- Ignore anti-matter

$L_{HIC} \sim 10^{-14}\, m$

- QCD (hadrons/quarks) matters
- Viscosity $\gg$ magnetic fields
- Converges
- Time scales femtometer (10^{-23} sec)
- Causality challenges with viscosity
- EOS is ***known*** nearly exactly at high energies
- EOS unknown-***ish*** at finite n_B, n_S, n_Q
- $n_B \lesssim 2\, n_{sat}, T \gtrsim 50\, MeV, Y_Q \gtrsim 0.38$
- $n_S = 0$
- We have a TON of anti-matter

Jamie's talk

HIC: what we know, what we don't



Hydro simulations from $\sqrt{s} = [3,7.7,27]\ GeV$
Shen&Schenke, Phys. Rev. C 105, 064905 (2022)

(T, μ_B) extracted from STAR net-(p,π,K), net-p, net-K fluctuations
Alba, et al, Phys. Rev. C 101, 054905 (2020)

Chiral transition from lattice QCD
[WB] Phys. Rev. Lett. 125, 052001 (2020)

Dilepton measurements from
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[HADES] Nature Phys. 15, 1040 (2019)
[NA60] Eur.Phys.J.C59:607-623,2009

Statistical Hadronization Model
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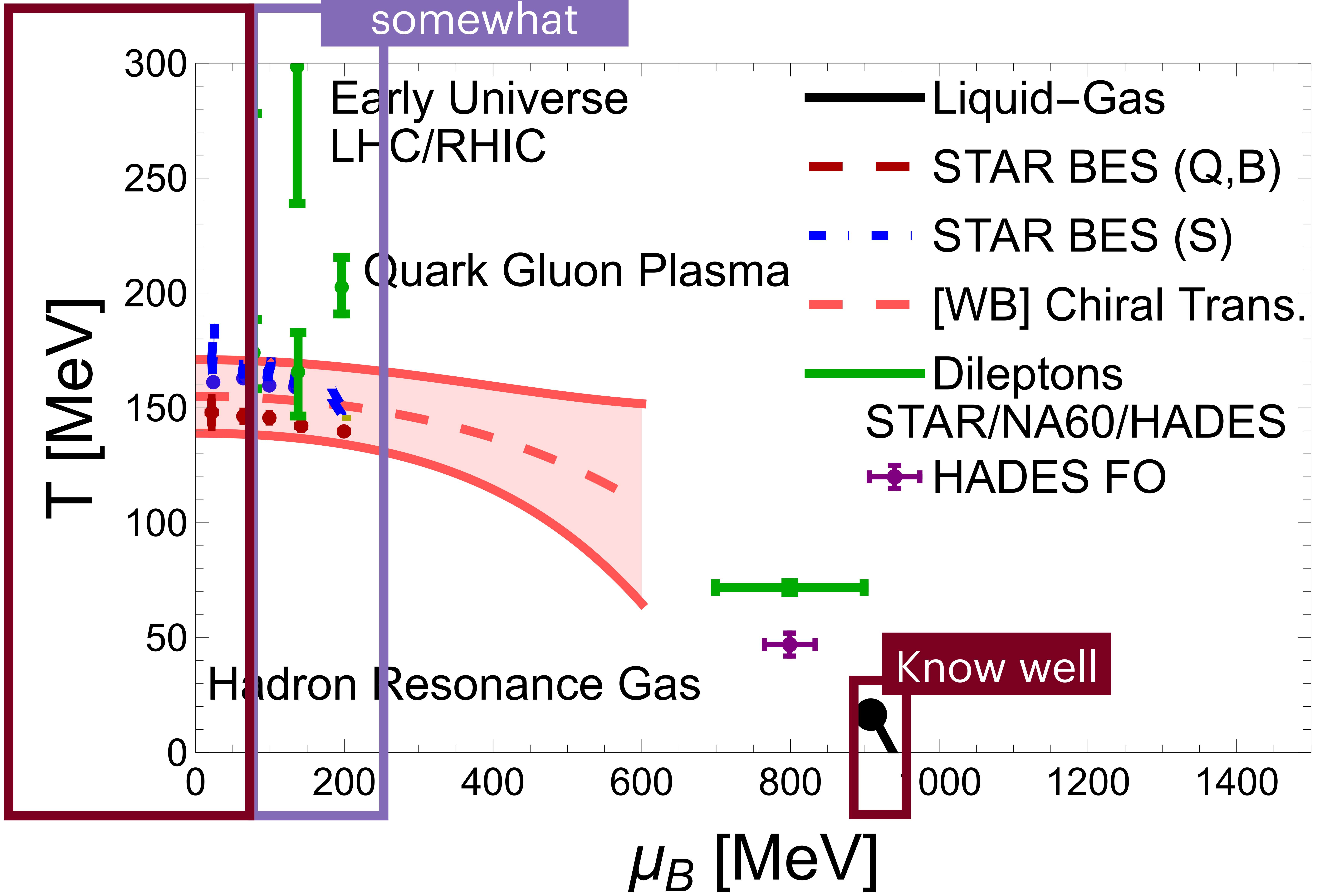
μ_B estimate Vovchenko, et al, Phys. Rev. Lett. 118, 182301 (2017)

Hints of a QCD critical point beginning to appear…

…at we know, what we don't



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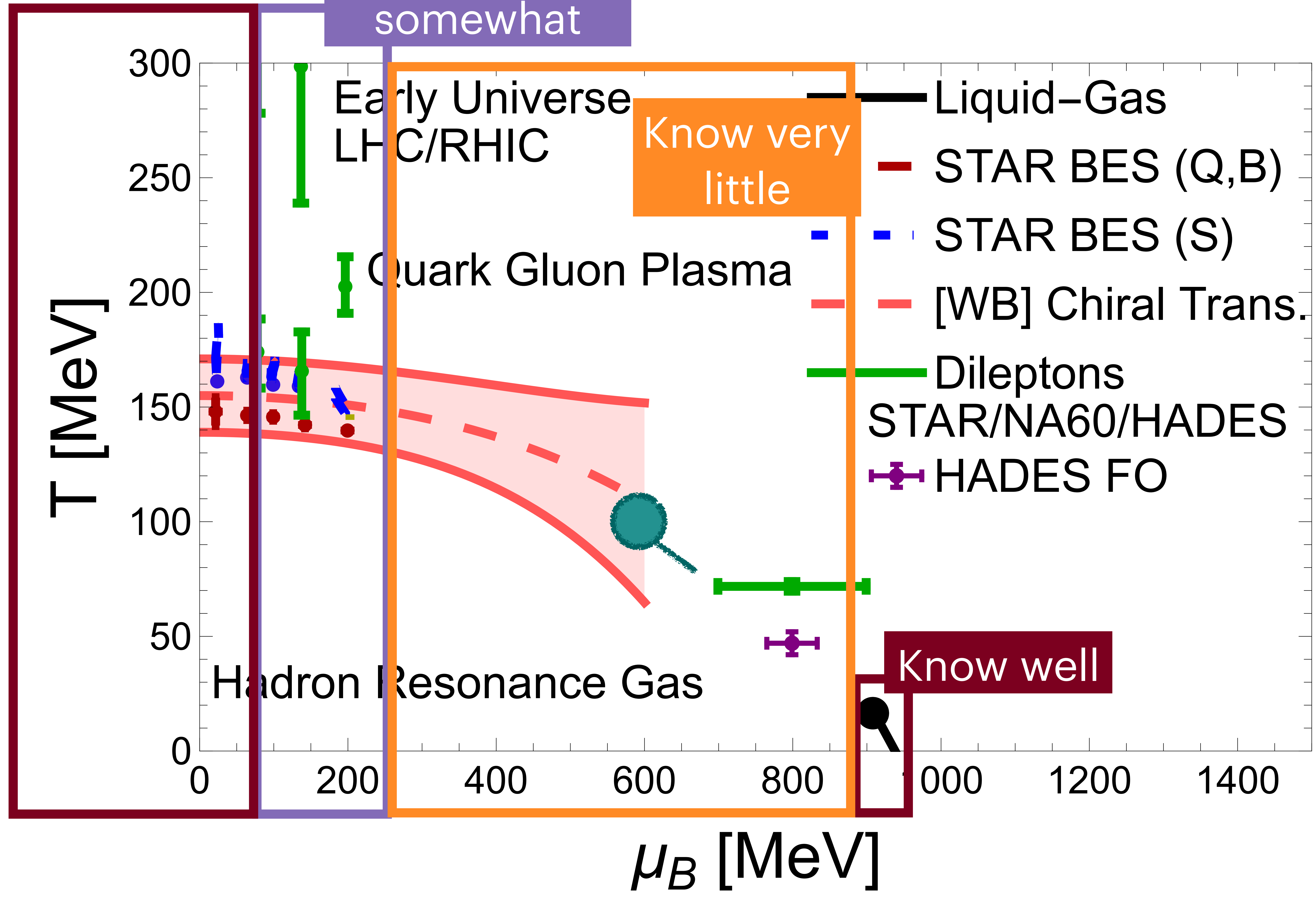

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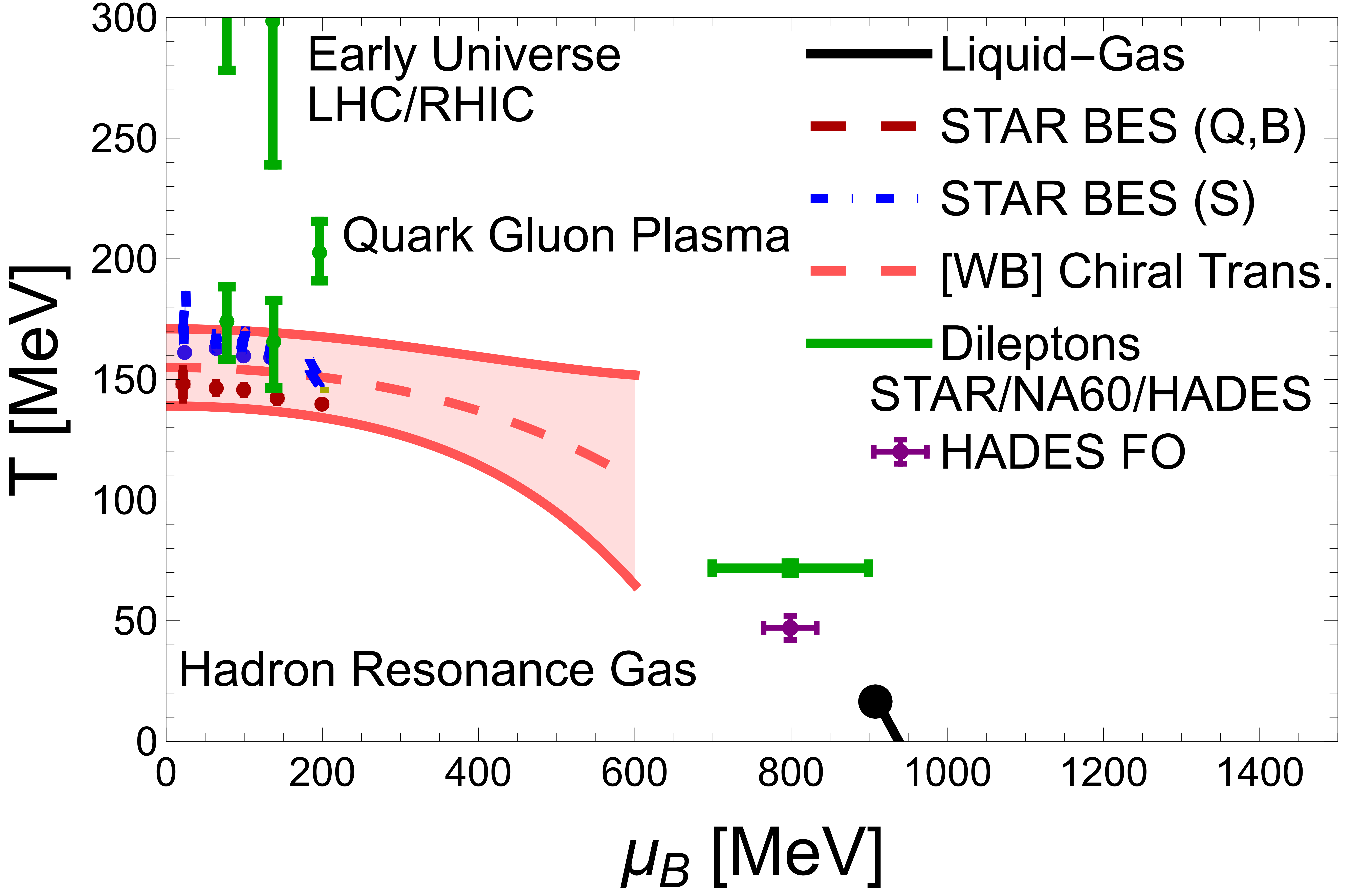
History of HIC: why don't we understand large n_B?



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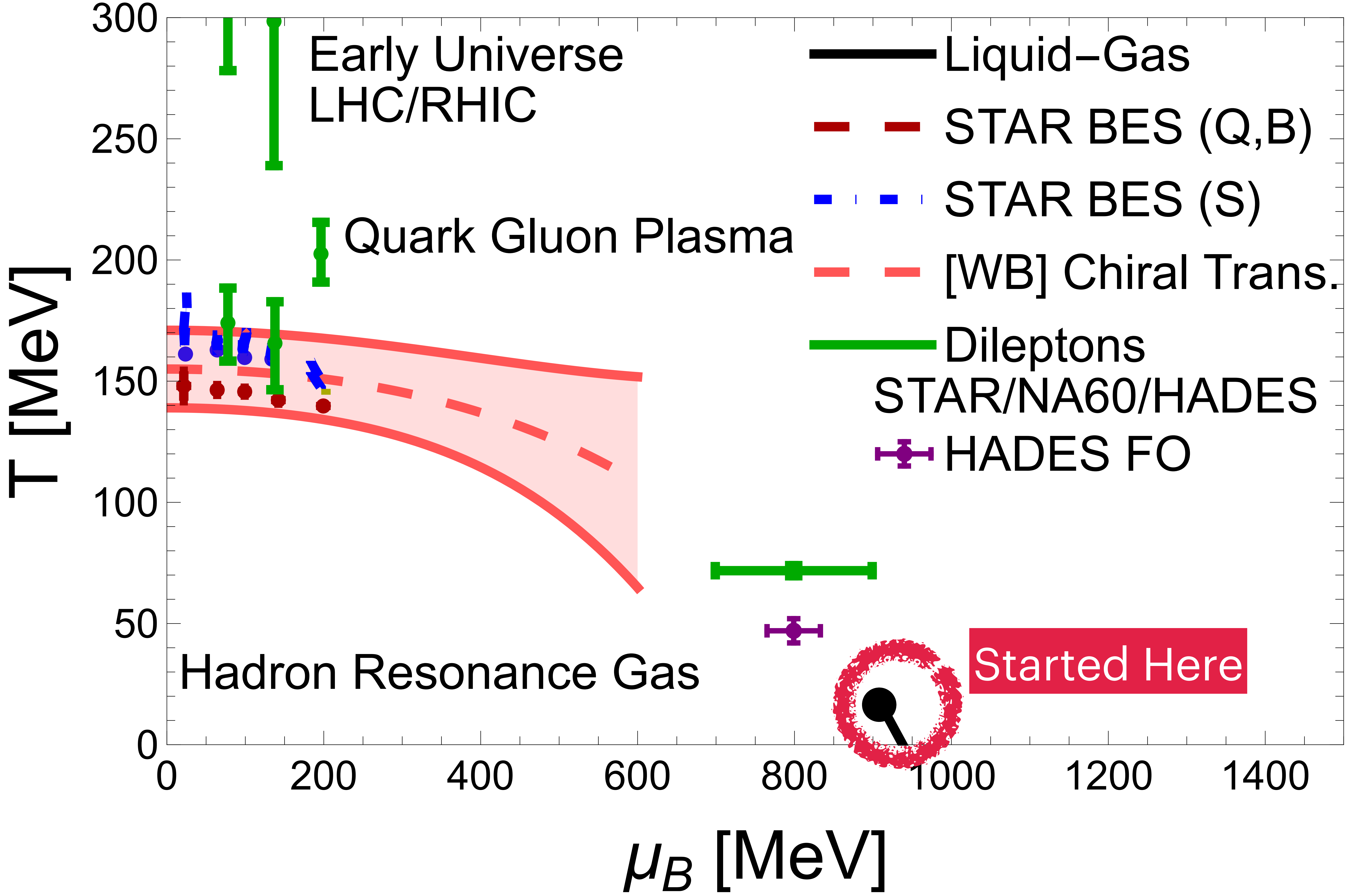

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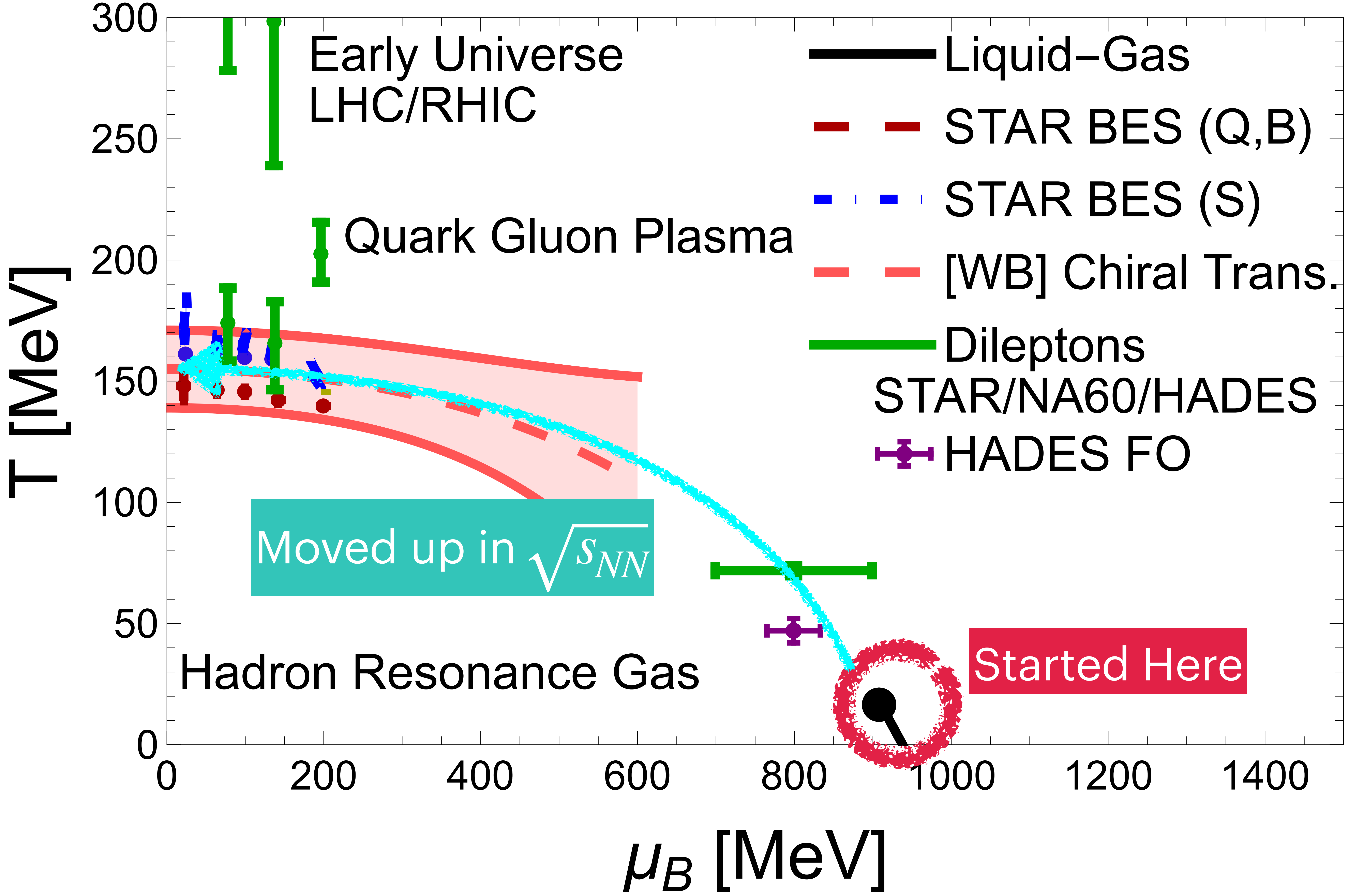

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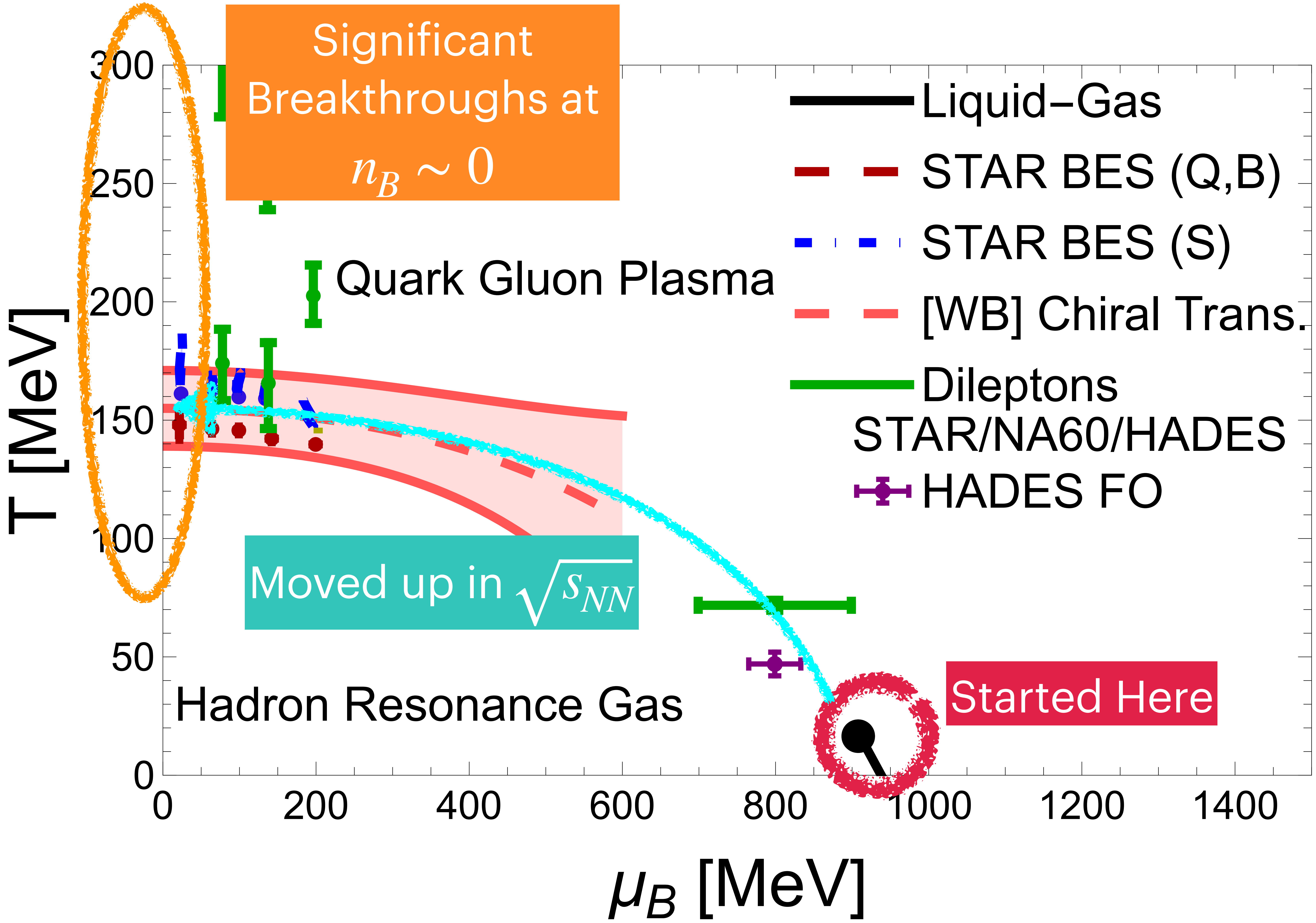

Breakthroughs:

- Event-by-event
- Relativistic viscous hydro
- Lattice QCD EOS
- Cross-over EOS
- Hadron improvements
- Constrained initial state
- Nuclear structure
- Open-source frameworks
- Bayesian Analyses
- Quantitative Predictions

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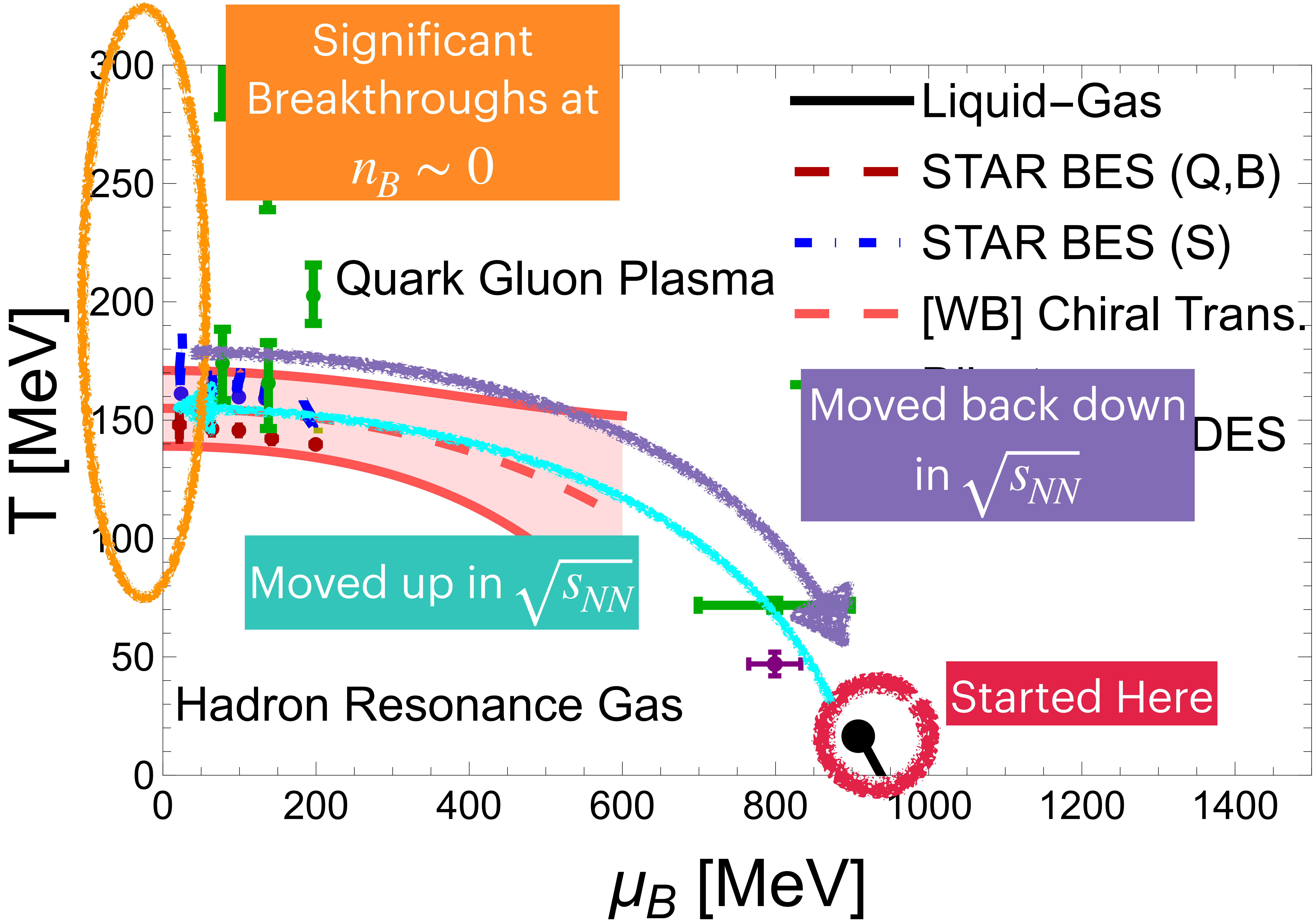

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Beam energy Scan/ HADES/SPS

Rest of this talks

Before proceeding , need to understand how we connect the EOS (equilibrium) to data

Heavy-Ion Collisions: Equilibrium vs Out-of-Equilibrium

Energy-Momentum Tensor

$$T^{\mu\nu} = T_0^{\mu\nu} + \Pi + \pi^{\mu\nu}$$

Equation of State (EOS)

Local rest frame

$$T_0^{\mu\nu} = \begin{bmatrix} \varepsilon & 0 & 0 & 0 \\ 0 & p & 0 & 0 \\ 0 & 0 & p & 0 \\ 0 & 0 & 0 & p \end{bmatrix}$$

Bulk Pressure $\Pi = Tr\left[T^{\mu\nu} - T_0^{\mu\nu}\right]$

Shear stress tensor $\pi^{\mu\nu} = T^{\mu\nu} - T_0^{\mu\nu} - \Pi$

Conserved Currents

Baryon Current $N_B^\mu = n_B u^\mu + q_B^\mu$

Strangeness Current $N_S^\mu = n_S u^\mu + q_S^\mu$

Electric Charge Current $N_Q^\mu = n_Q u^\mu + q_Q^\mu$

Diffusion

Contains diffusion matrix and gradients of μ/T

$$\kappa = \begin{bmatrix} \kappa_{BB} & \kappa_{BS} & \kappa_{BQ} \\ \kappa_{SB} & \kappa_{SS} & \kappa_{SQ} \\ \kappa_{QB} & \kappa_{QS} & \kappa_{QQ} \end{bmatrix}$$

Ignoring magnetic fields and rotation

Heavy-Ion Collisions: Equilibrium vs Out-of-Equilibrium

Energy-Momentum Tensor

$$T^{\mu\nu} = T_0^{\mu\nu} + \Pi + \pi^{\mu\nu}$$

Local rest frame

$\begin{bmatrix} \varepsilon & 0 & 0 & 0 \end{bmatrix}$

Conserved Currents

Baryon Current $N_B^\mu = n_B u^\mu + q_B^\mu$

Strangeness Current $N_S^\mu = n_S u^\mu + q_S^\mu$

Diffusion

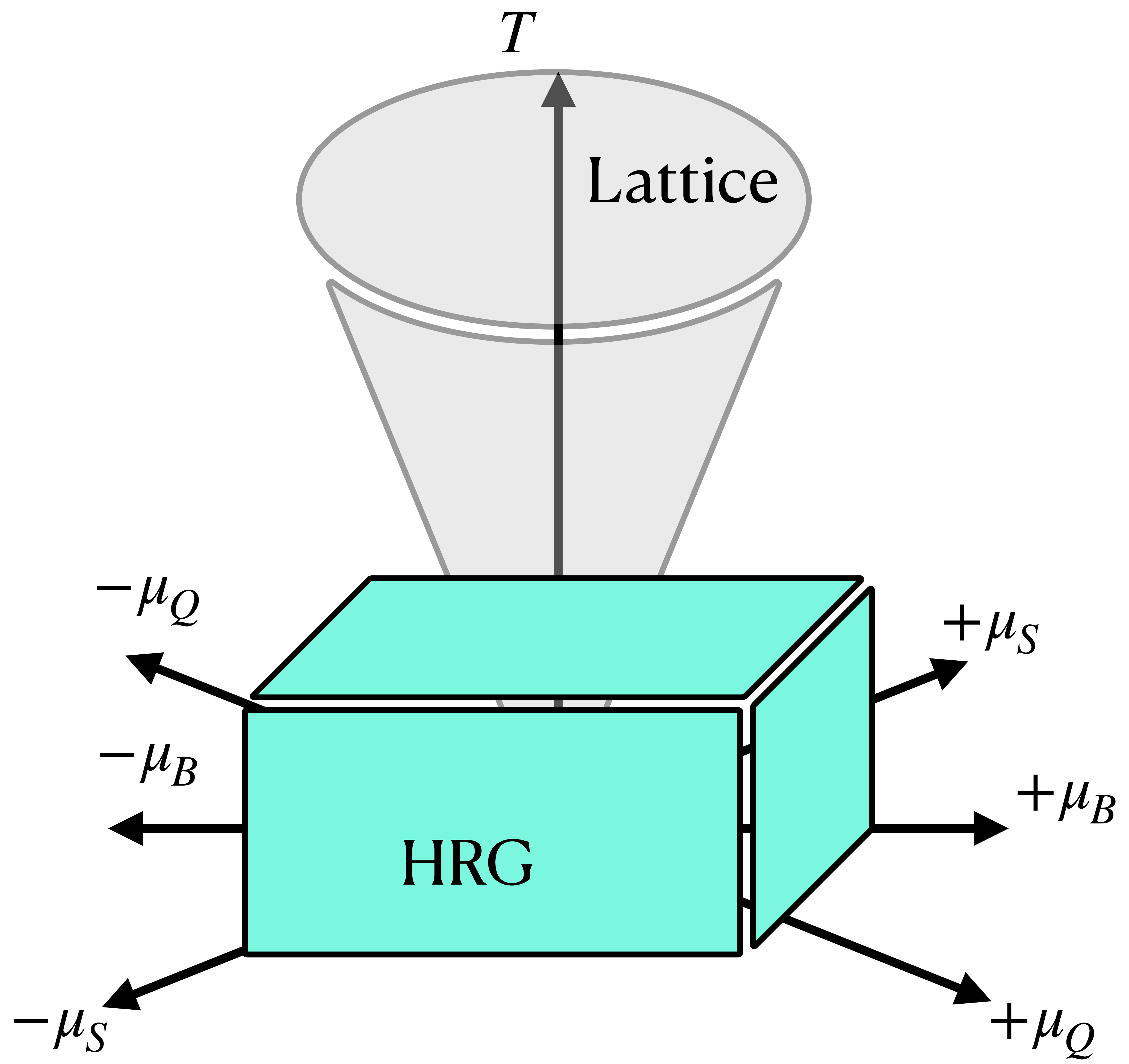
Heavy-ion collisions are NOT in equilibrium, out-of-equilibrium effects must be properly accounted for to extract the EOS!

$$\kappa = \begin{bmatrix} \kappa_{BB} & \kappa_{BS} & \kappa_{BQ} \\ \kappa_{SB} & \kappa_{SS} & \kappa_{SQ} \\ \kappa_{QB} & \kappa_{QS} & \kappa_{QQ} \end{bmatrix}$$

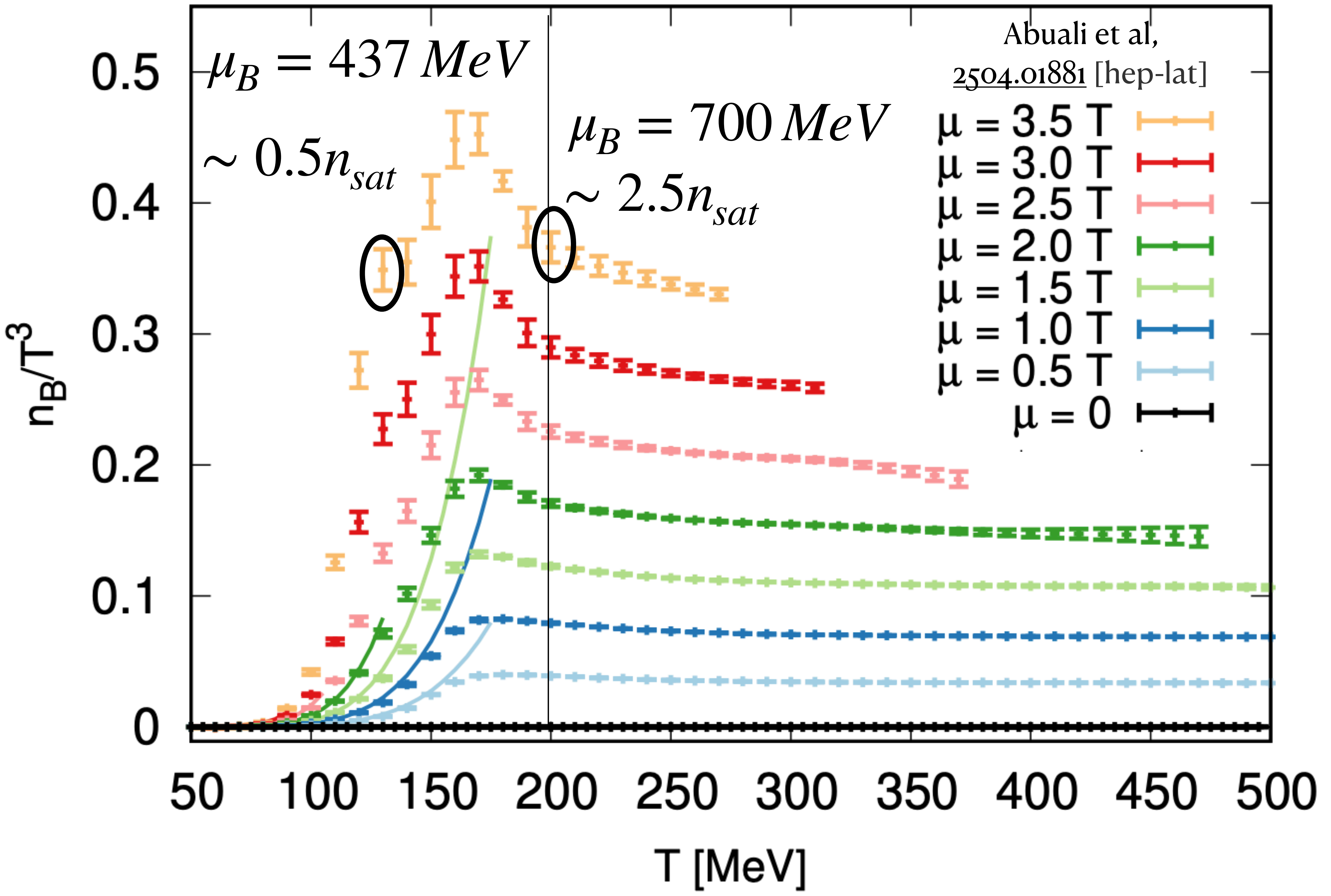
Shear stress tensor $\pi^{\mu\nu} = T^{\mu\nu} - T_0^{\mu\nu} - \Pi$

Ignoring magnetic fields and rotation

4d EOS of heavy-ions T, n_B, n_S, n_Q



Lattice QCD



Reasonable estimates: $\mu_S/\mu_B \sim 1/3$

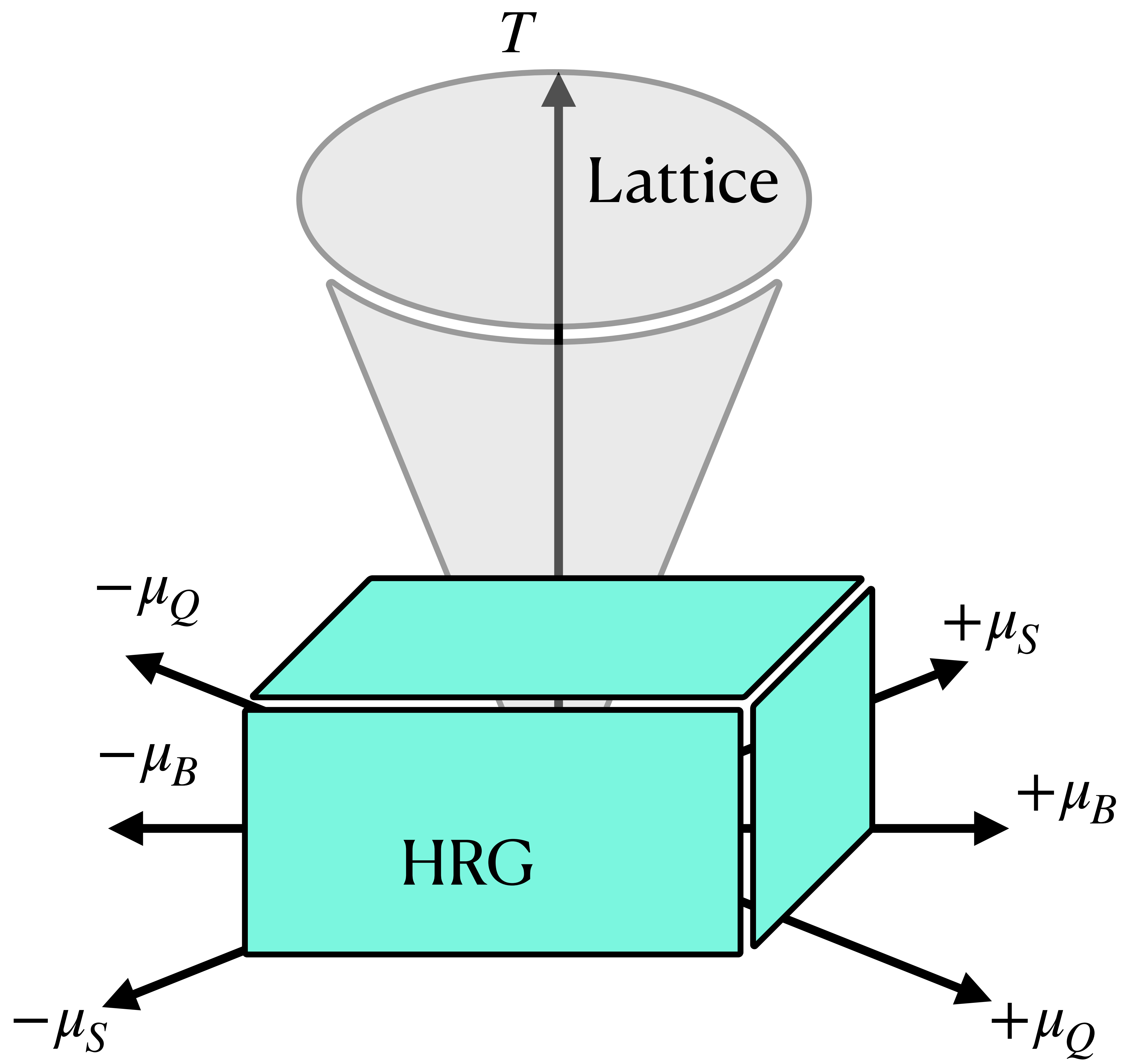
$\mu_Q/\mu_B \sim -0.1$

But these are fields, with large fluctuations!

Lines are ideal hadron resonance gas (HRG)

Data bars come from lattice QCD

4d EOS of heavy-ions T, n_B, n_S, n_Q



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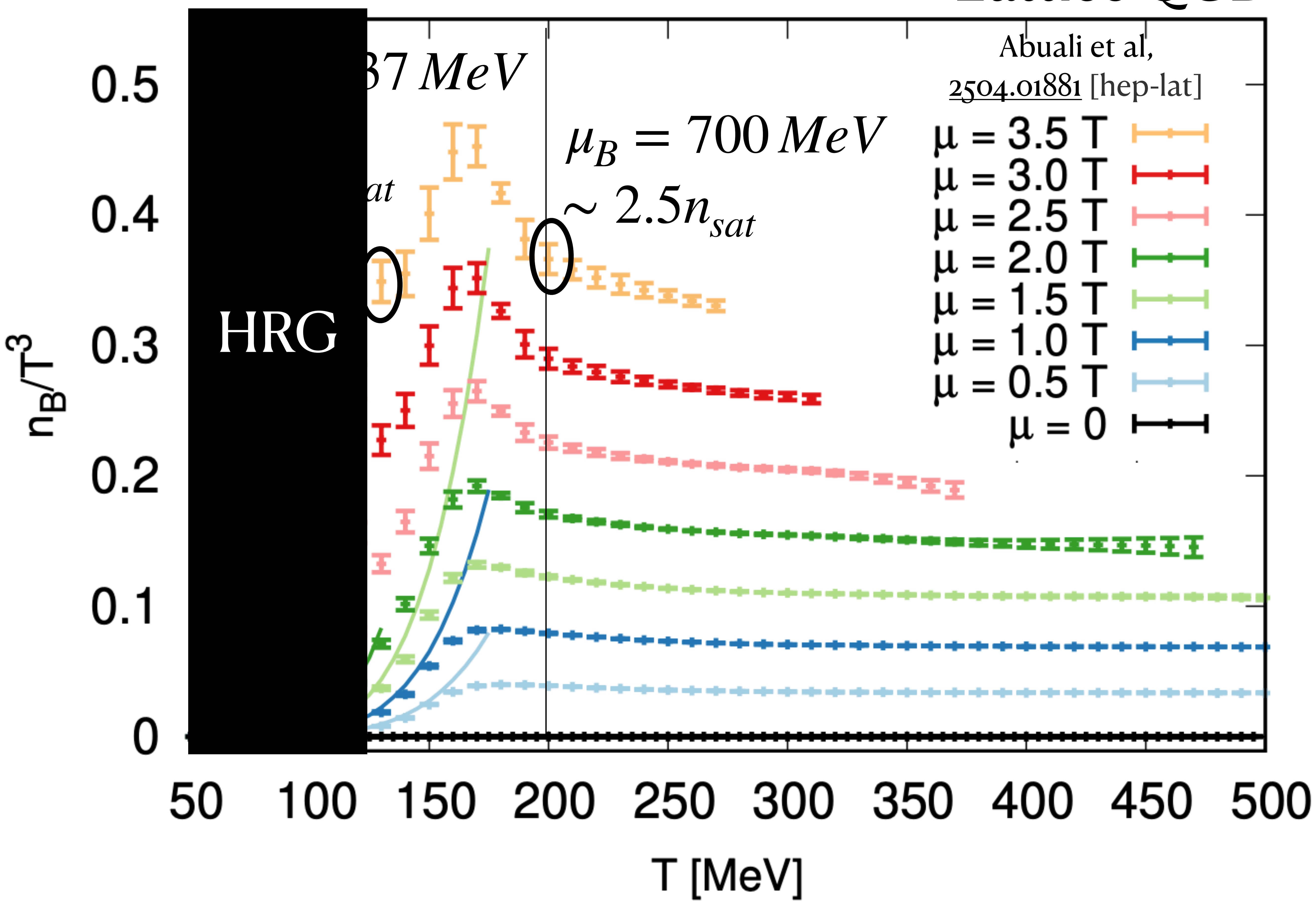

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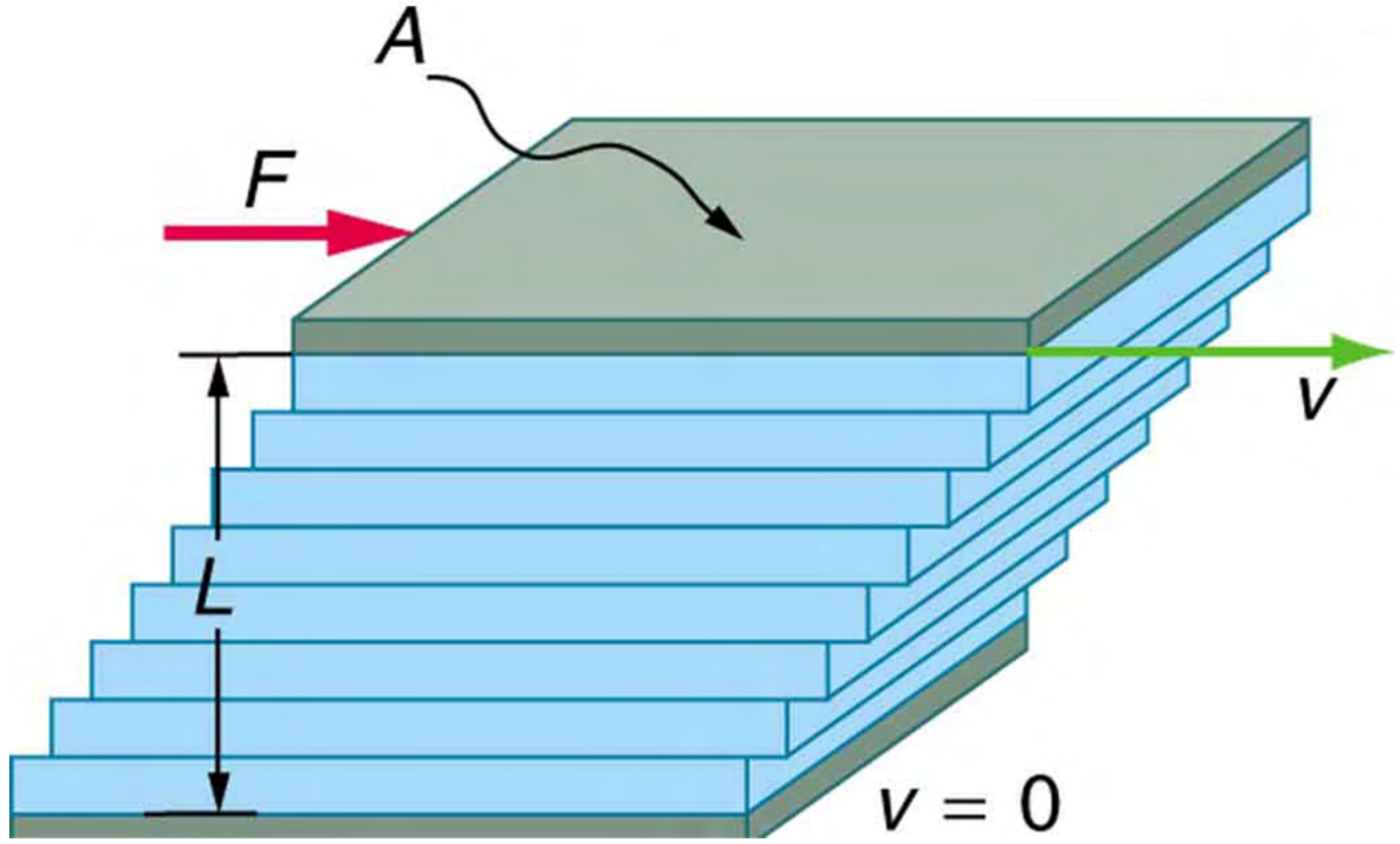
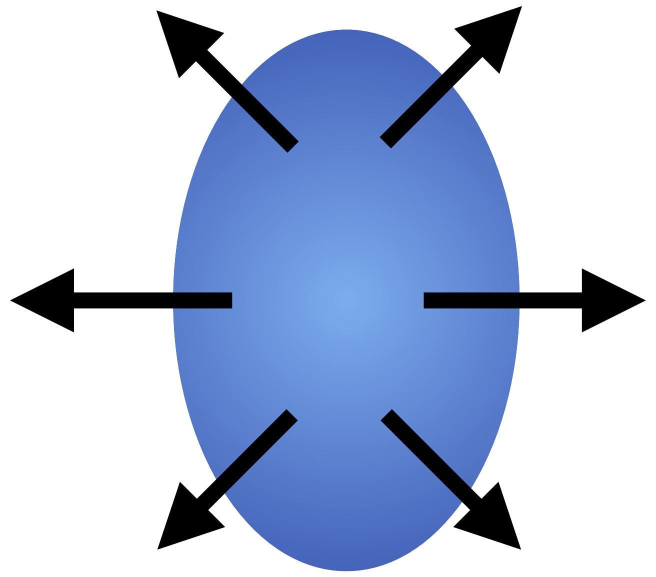
Equations of motion for out-of-equilibrium pieces


Almaalol, Dore, JNH *Phys.Rev.D* 111 (2025) 1, 014020

Equations NOT unique: Derived from enforcing only positive entropy production



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



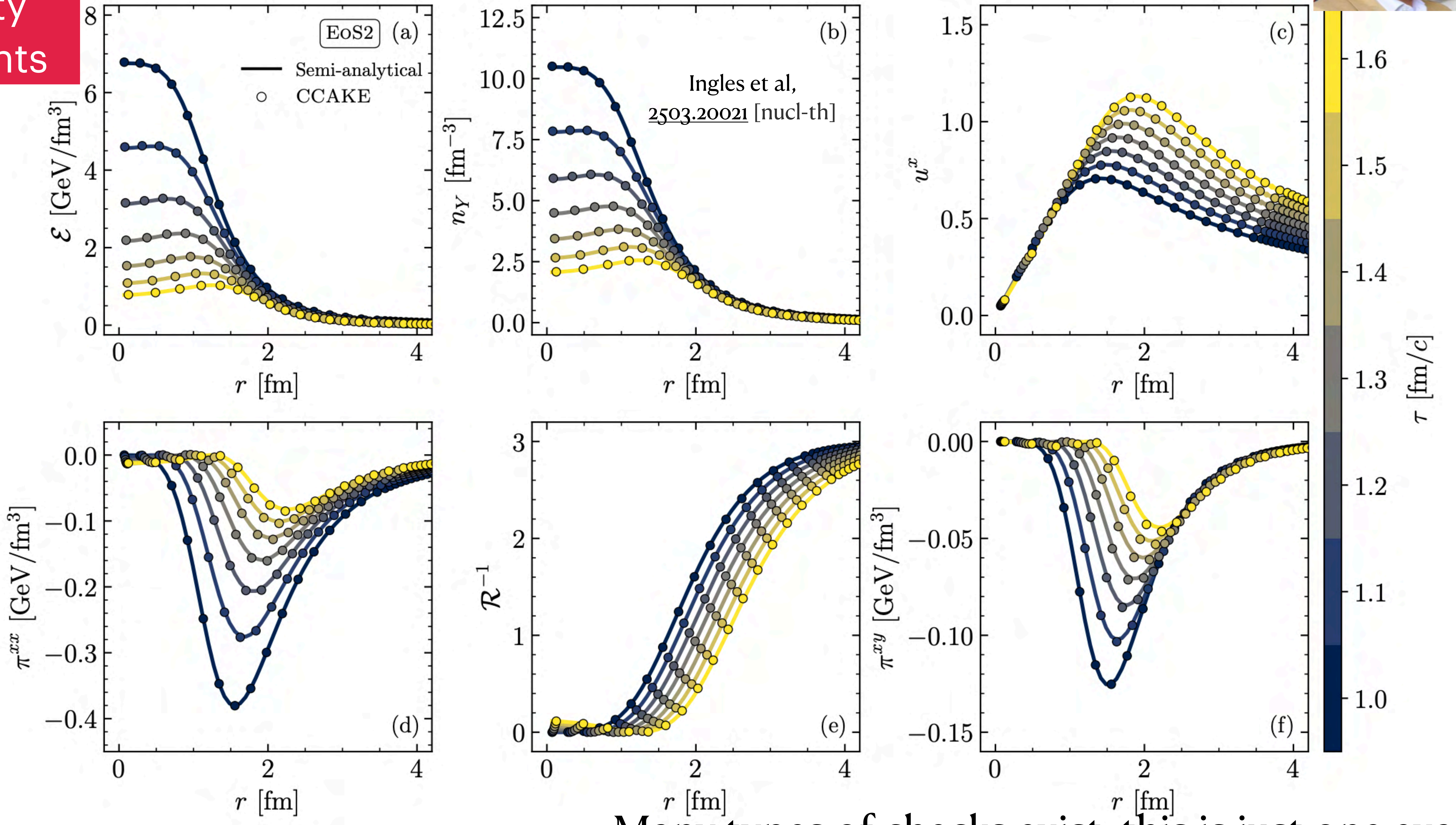
$$\tau_\Pi \dot{\Pi} + \Pi = -(\zeta + \frac{\tau_\Pi}{2}\Pi)\theta - \frac{\tau_\Pi}{2\beta_\Pi}\dot{\beta}_\Pi \Pi - \frac{\zeta}{\beta}\left(\gamma_0^q D_\mu n_q^\mu + \frac{1}{2} n_q^\mu \nabla_\mu \gamma_0^q\right)$$

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

Ask about Causality +stability constraints

Does this actually work? Analytical checks

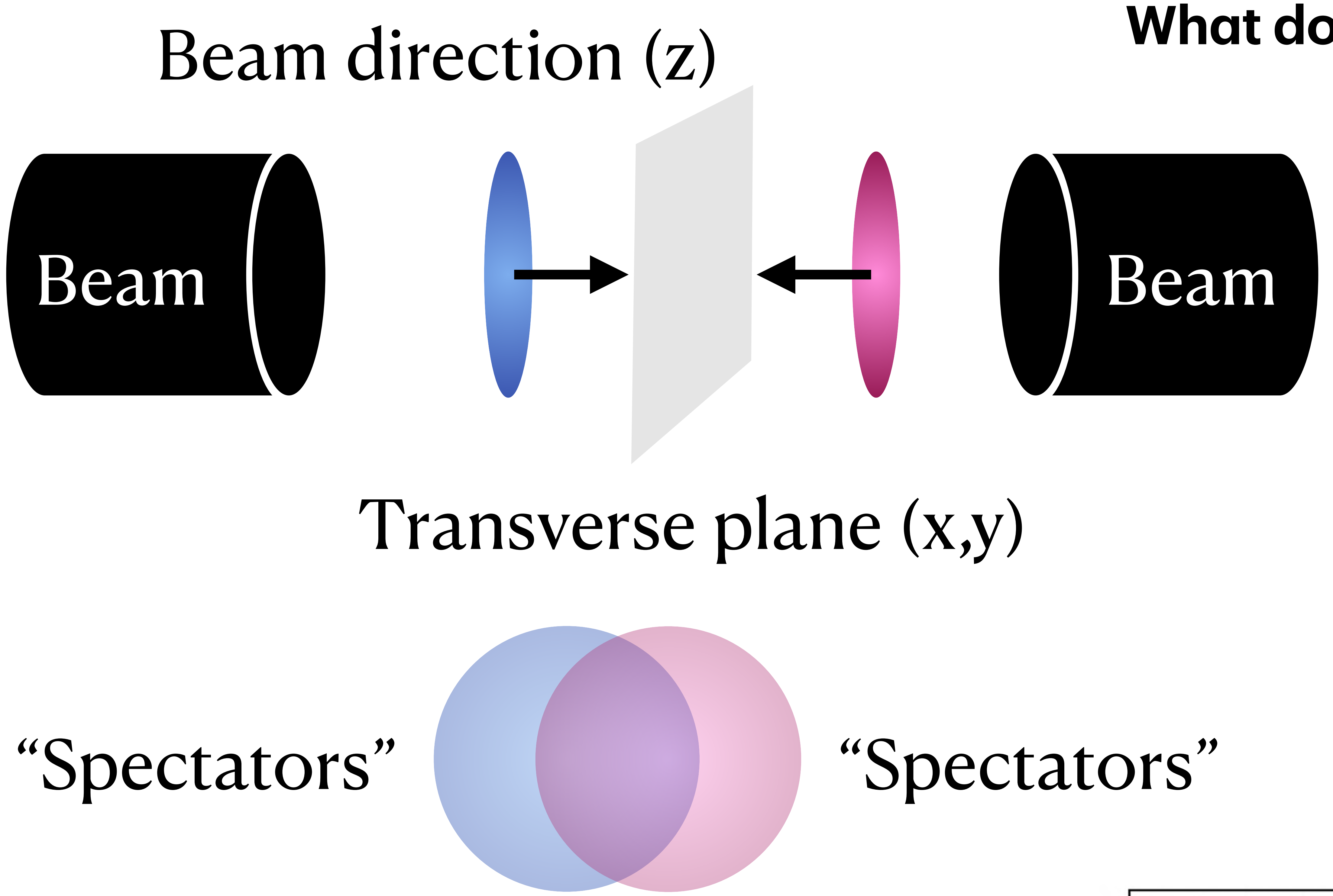
With viscosity, at finite densities



Many types of checks exist, this is just one example

Comparing to data: dynamics of HIC

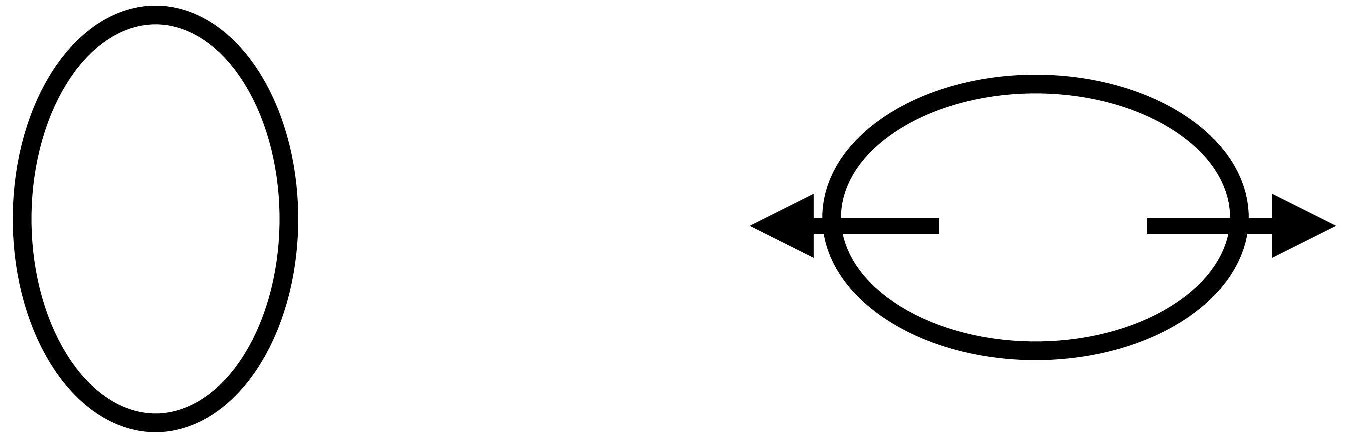
What do pressure gradients do?

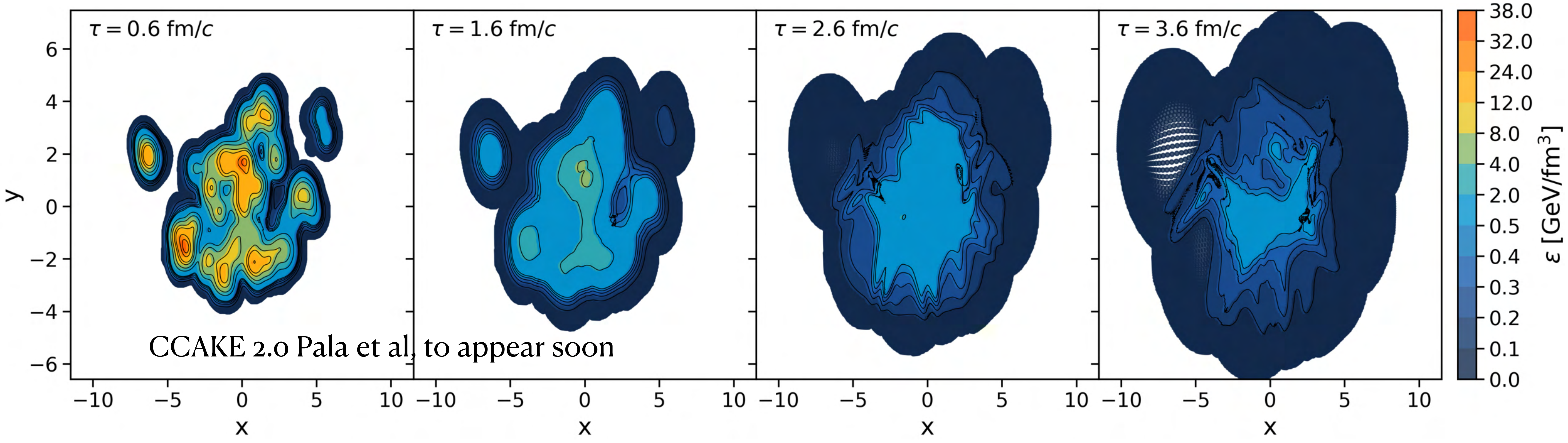


Geometric shape or "eccentricity", propagated to final state in momentum space

(∇p drive hydro response)

Initial State | Final State





CCAKE 2.0 Pala et al, to appear soon

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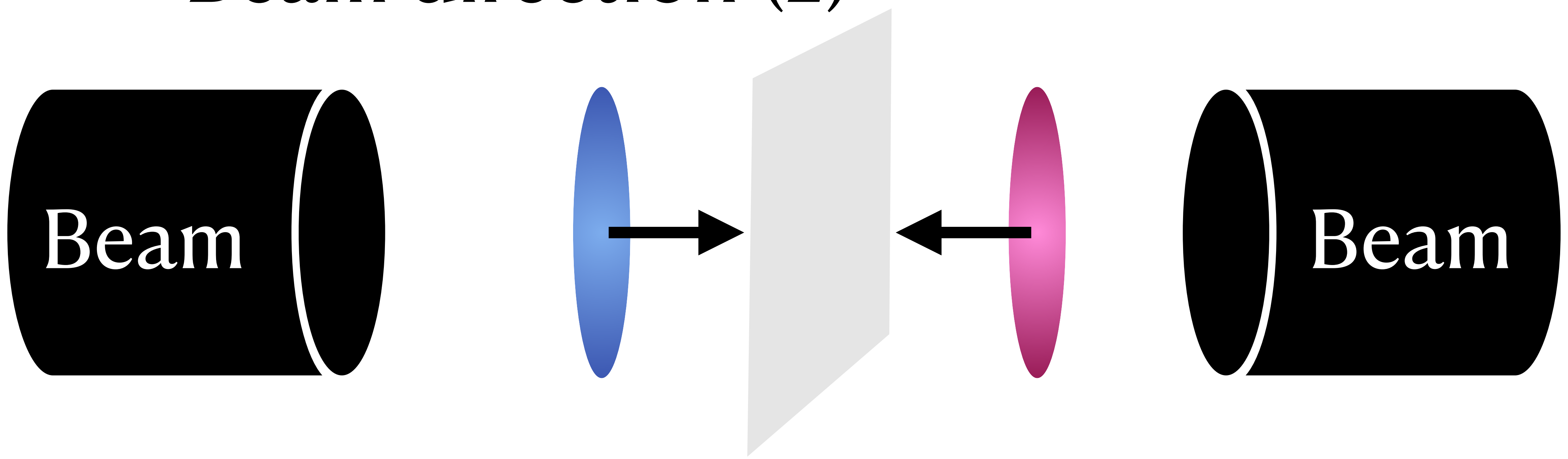
What do pressure gradients do?

Beam direction (z)



Transverse plane (x,y)

Geometric shape or "eccentricity", propagated to final state in momentum space

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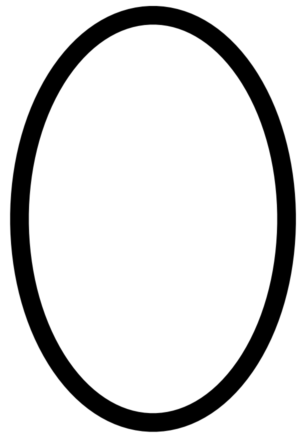
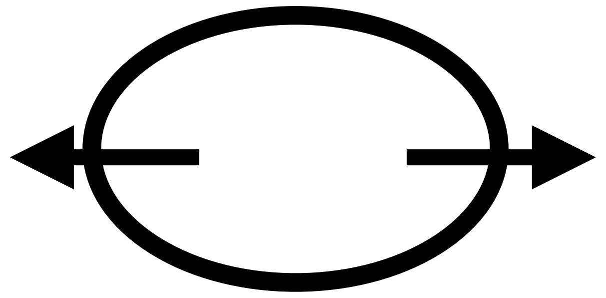
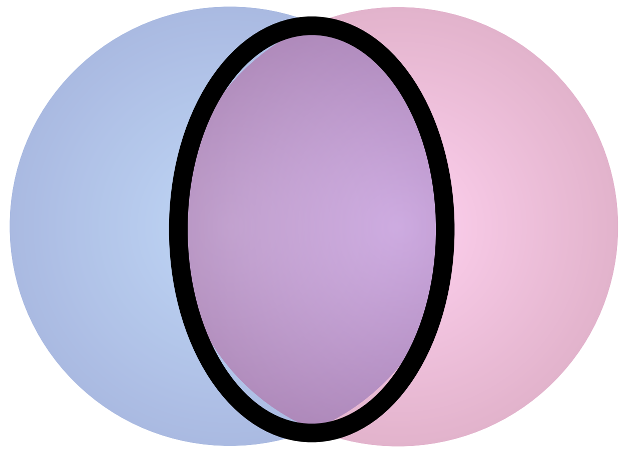


Final State

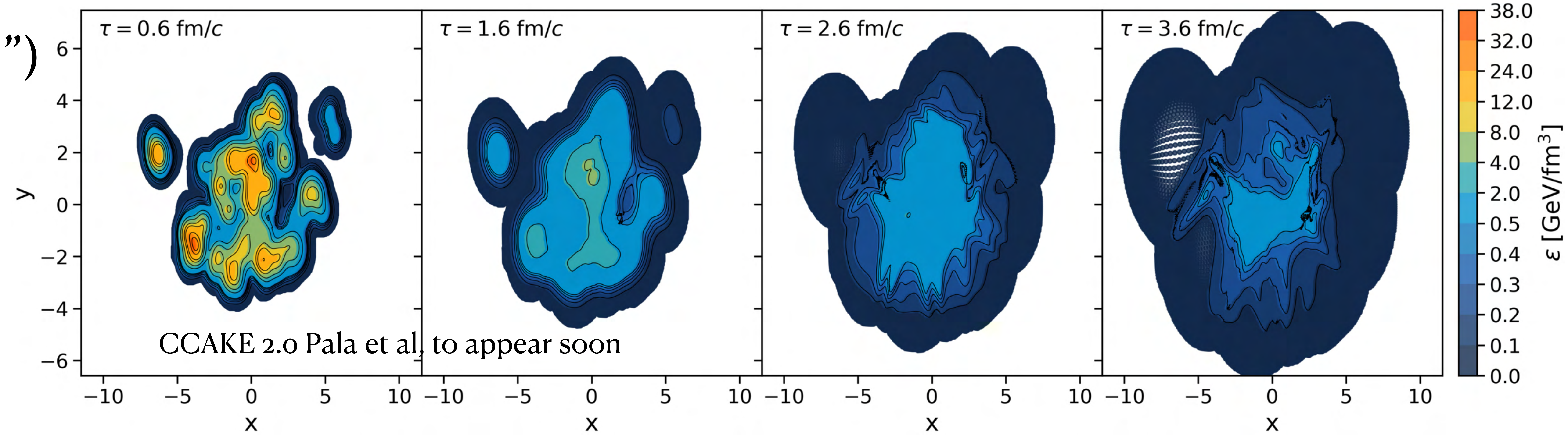


"Spectators"



"Spectators"

Overlap region ("participants")
This is the initial condition!



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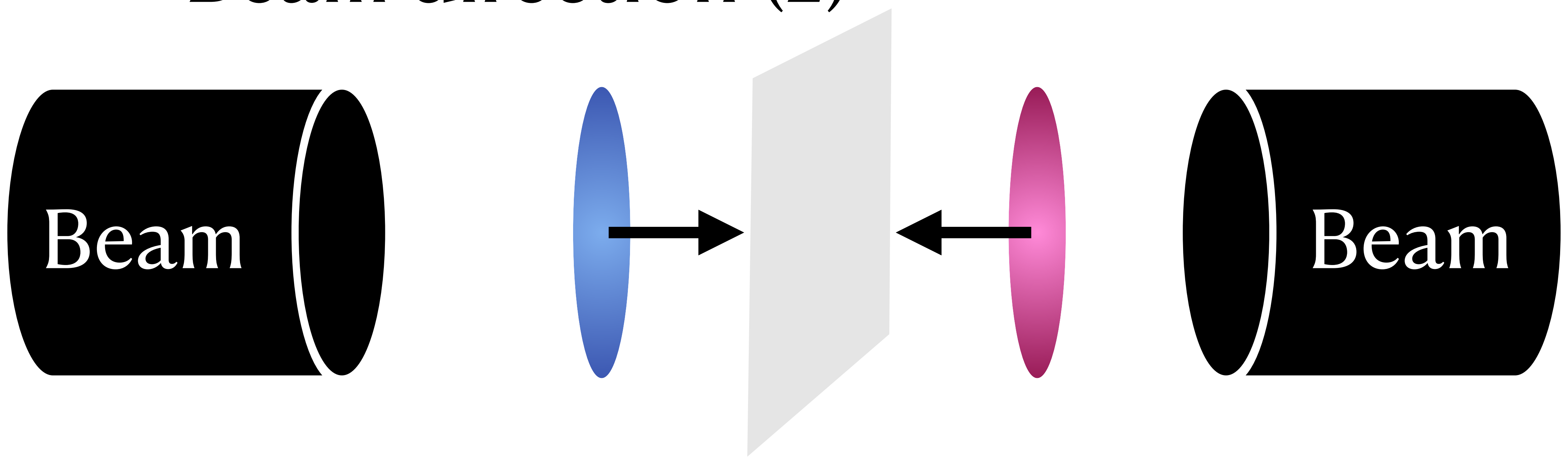

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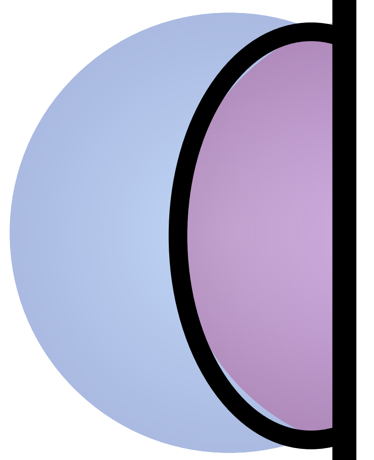

Since final state is measured in momentum, and the transverse plane is where most of the “action” occurs, we talk about the transverse momentum p_T

Overlap region (“participants”)
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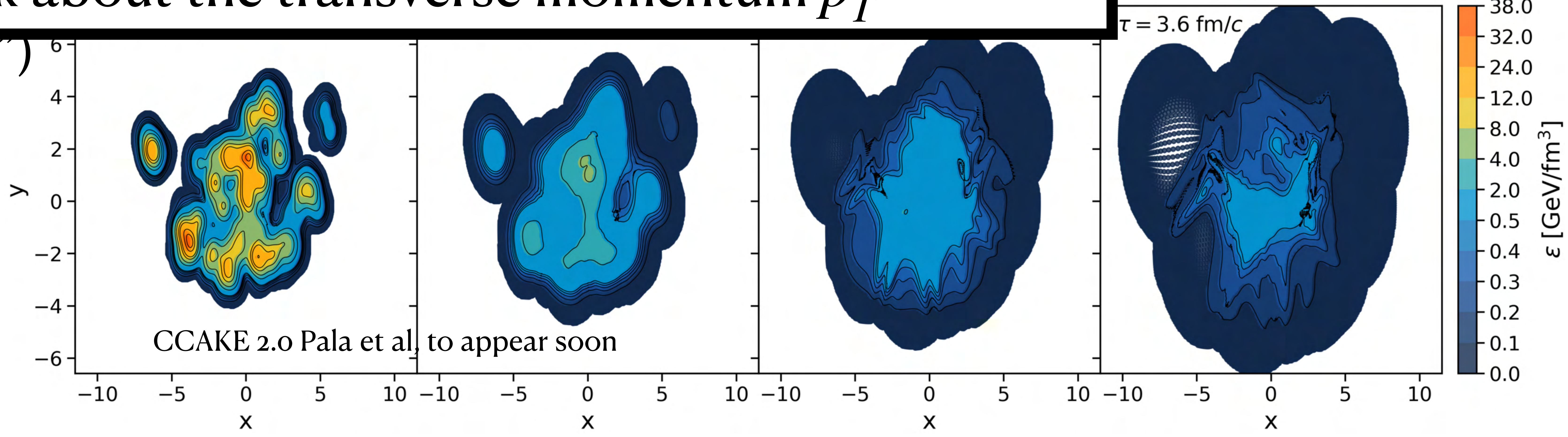


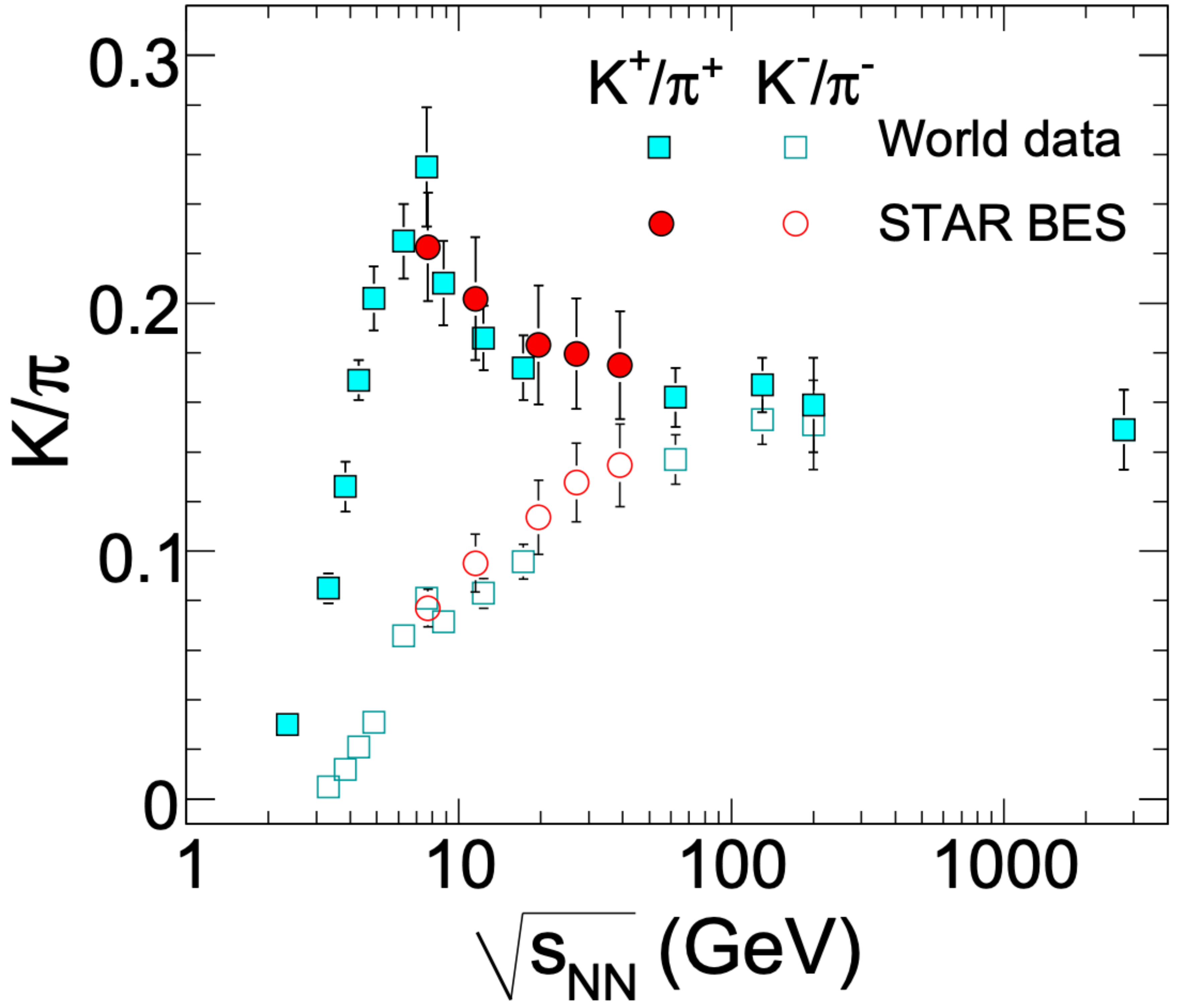
CCAKE 2.0 Pala et al, to appear soon

Multiplicity and collective flow

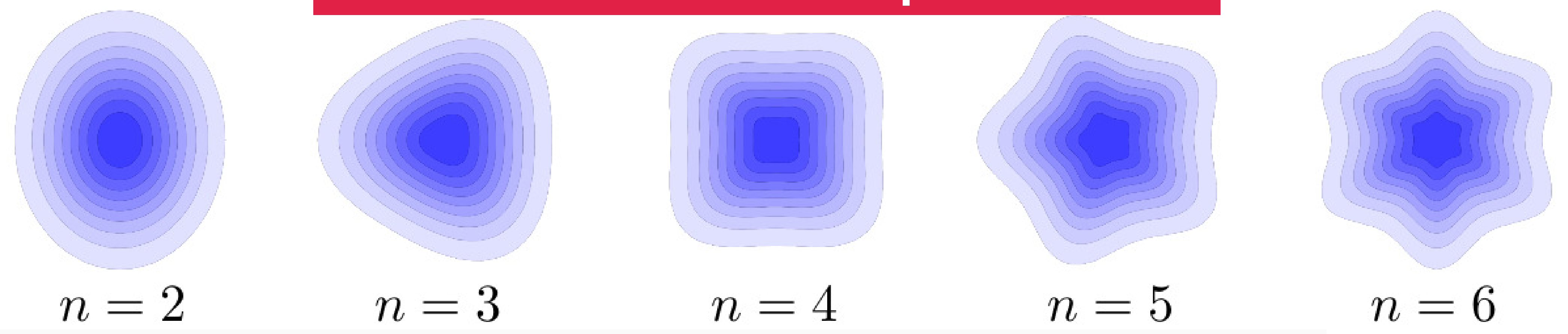
Counting of particles, Fourier analyses: oh my!

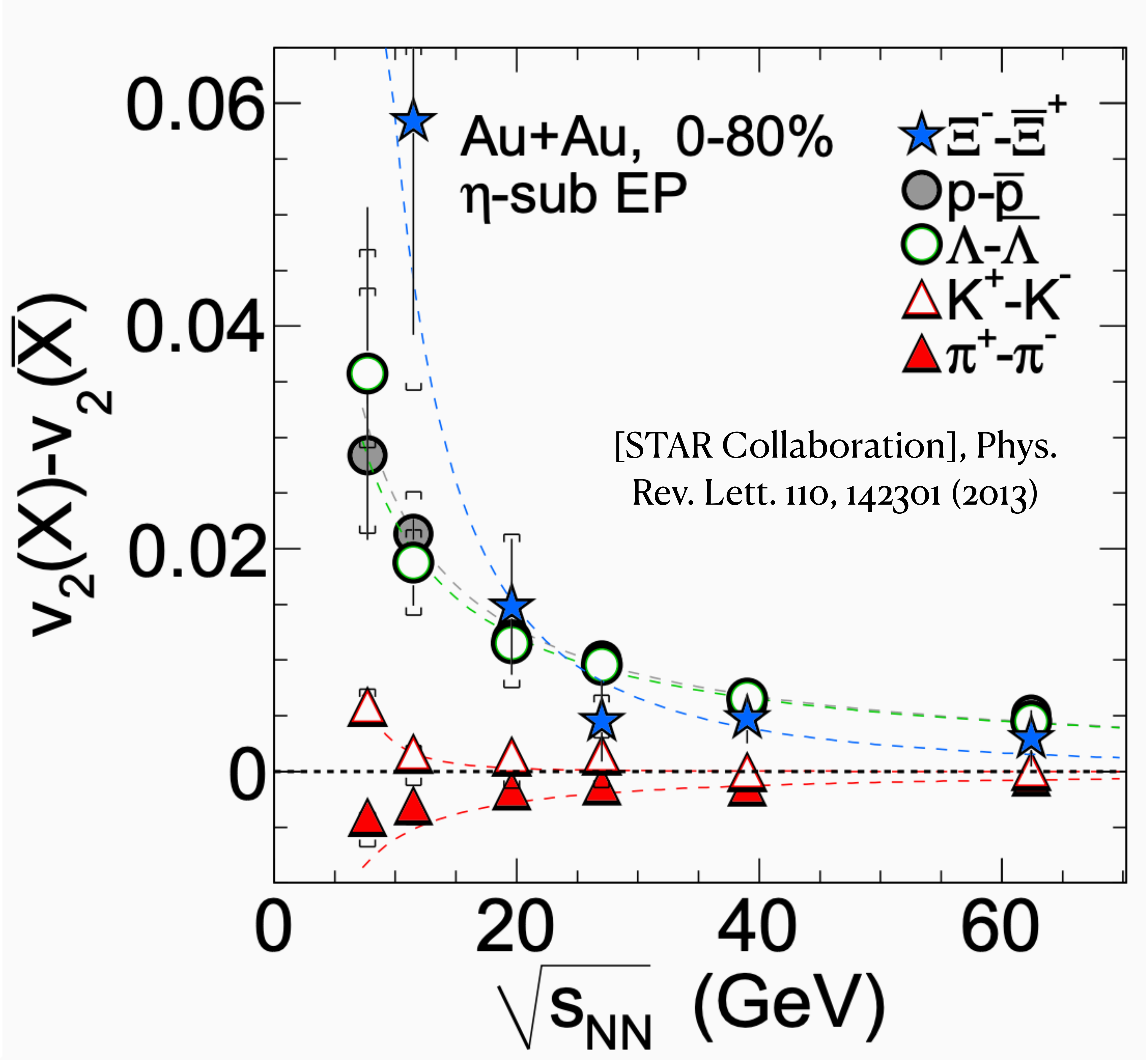
Count up particles

Can compare across p_T or rapidity (more well-defined relativistically "z" direction)



Fourier decomposition





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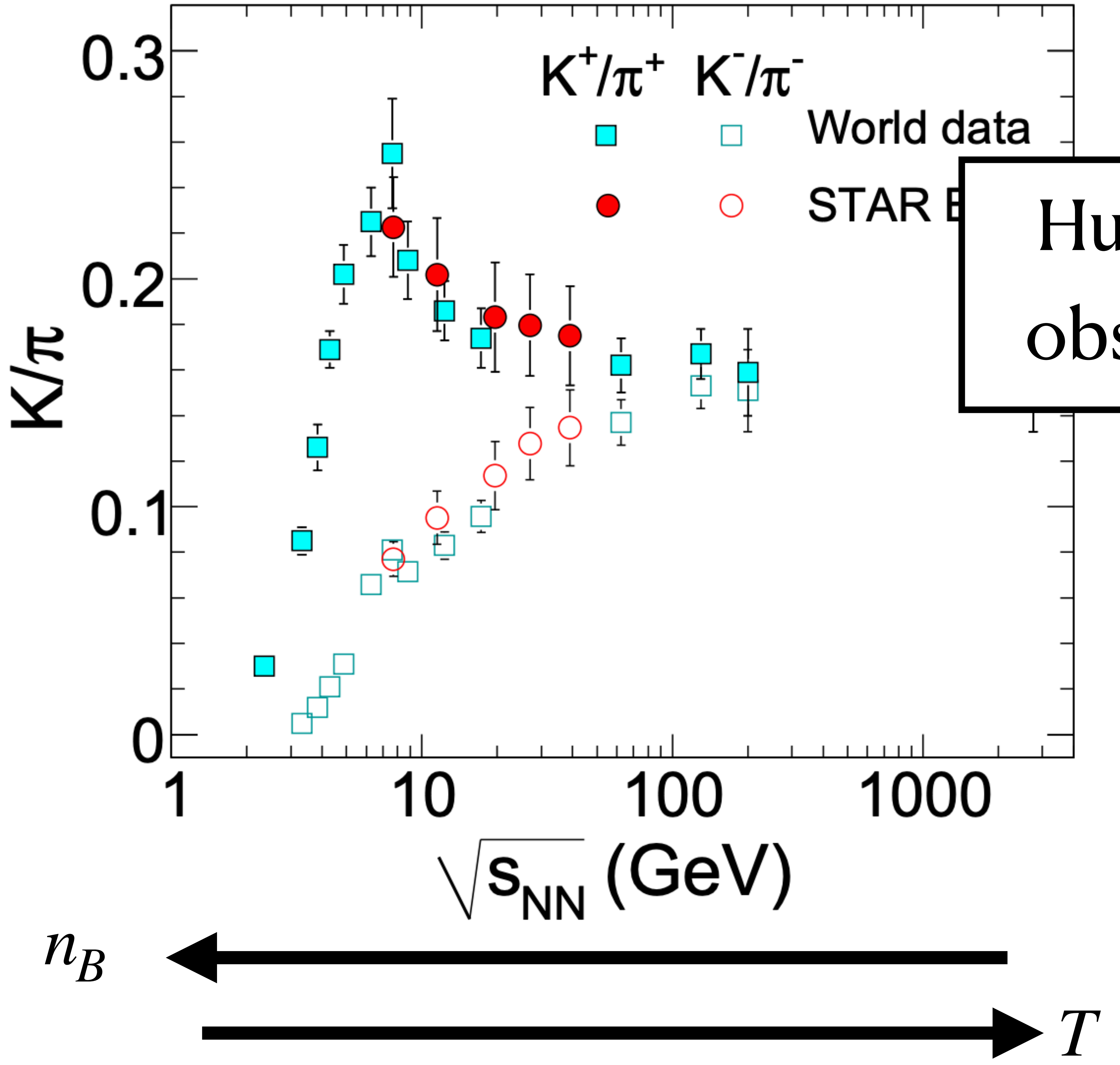
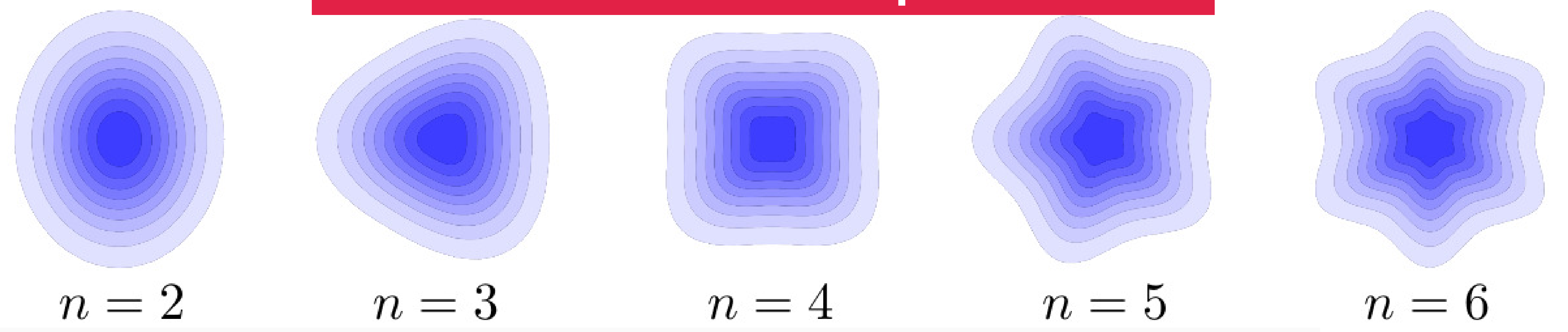
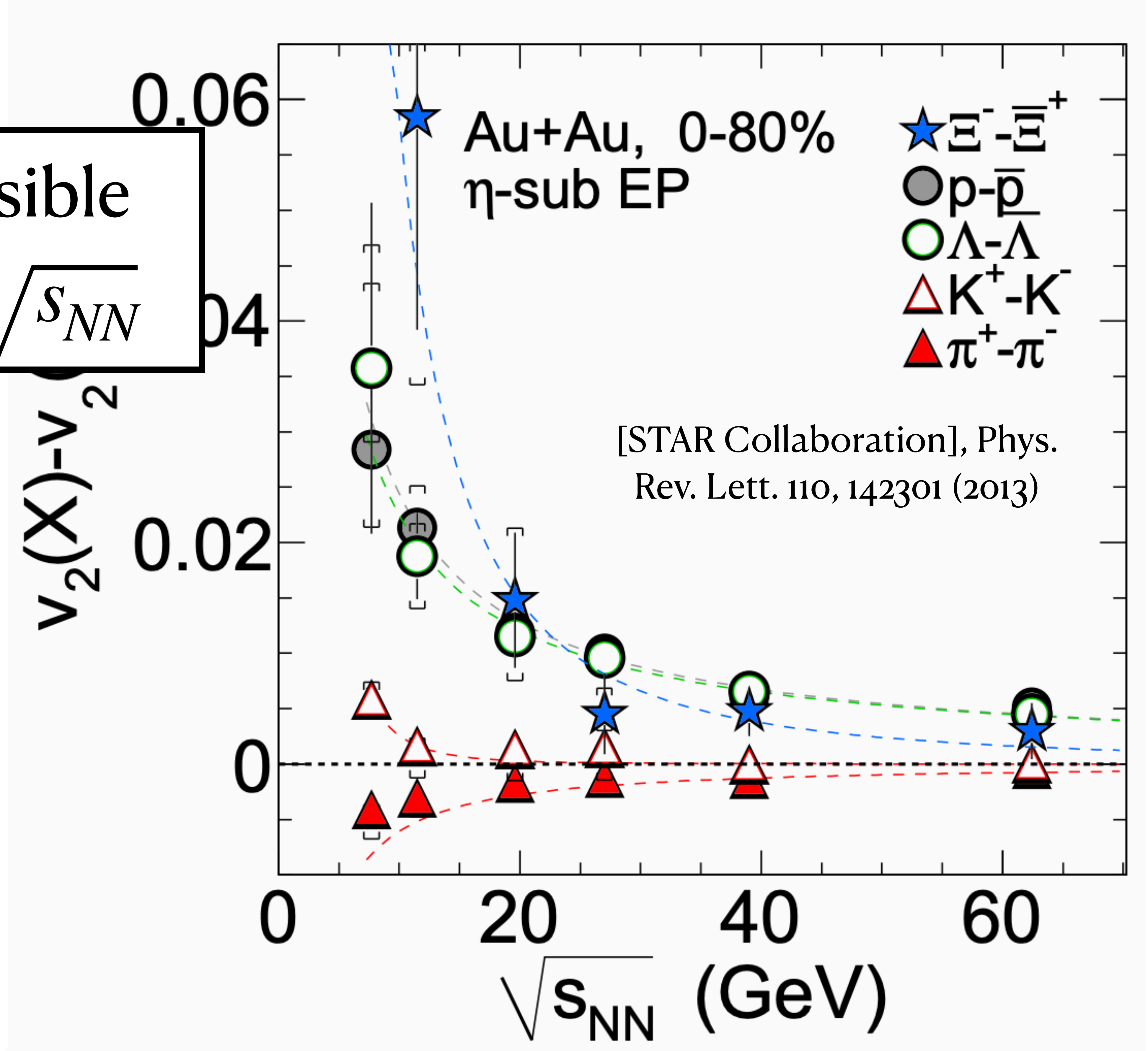


Hundreds of possible observables per $\sqrt{s_{NN}}$

Fourier decomposition

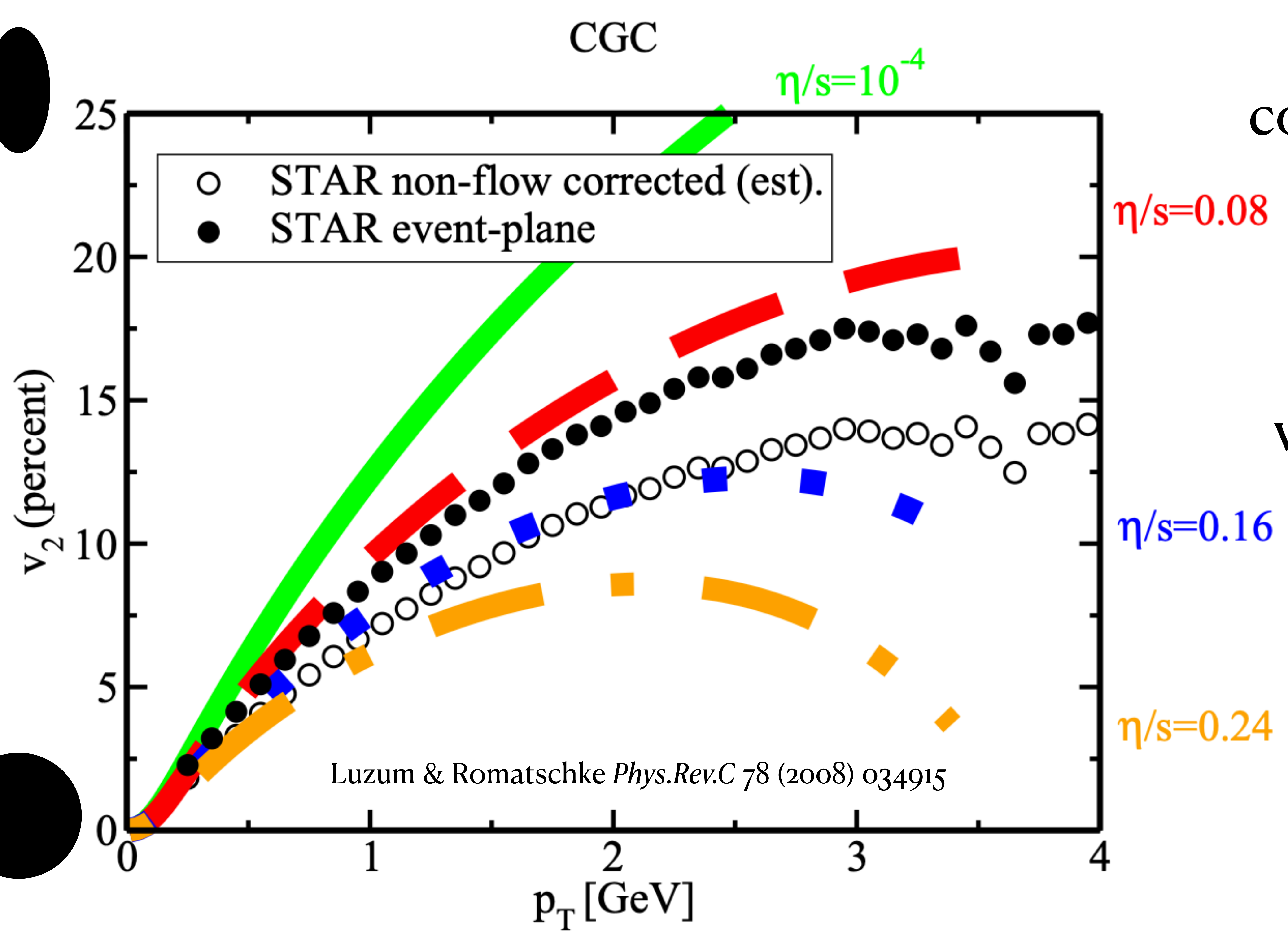




[STAR Collaboration], Phys. Rev. Lett. 110, 142301 (2013)

Collective flow and viscosity

Out-of-equilibrium and EOS intertwined!



Shear viscosity vital to reproducing collective flow observables at $n_B = 0$ bulk and diffusion are sub-dominate there.

At finite n_B, systematic studies of EOS variations+ all transport coefficients for realistic hydro ***DO NOT EXIST***.

Simpler studies of fixing EOS varying $\eta/s = const$, sometimes ζ/s do

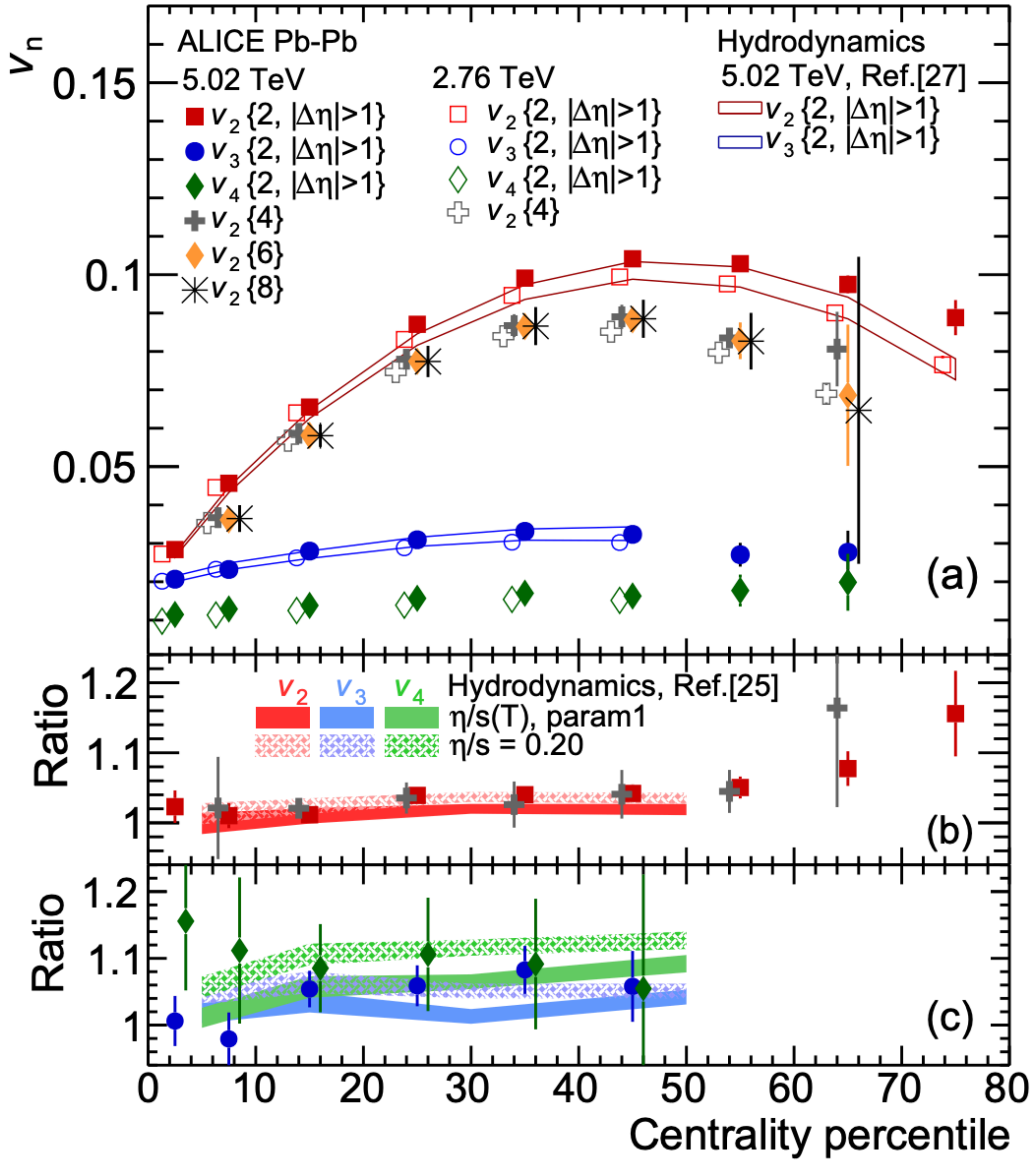
Simpler studies of varying EOS with transport coefficients in 0+1D or 1+1D exist

How well to HIC models reproduce data?

$\sqrt{s_{NN}} \sim [200\,GeV, 6\,TeV]$ RHIC/LHC

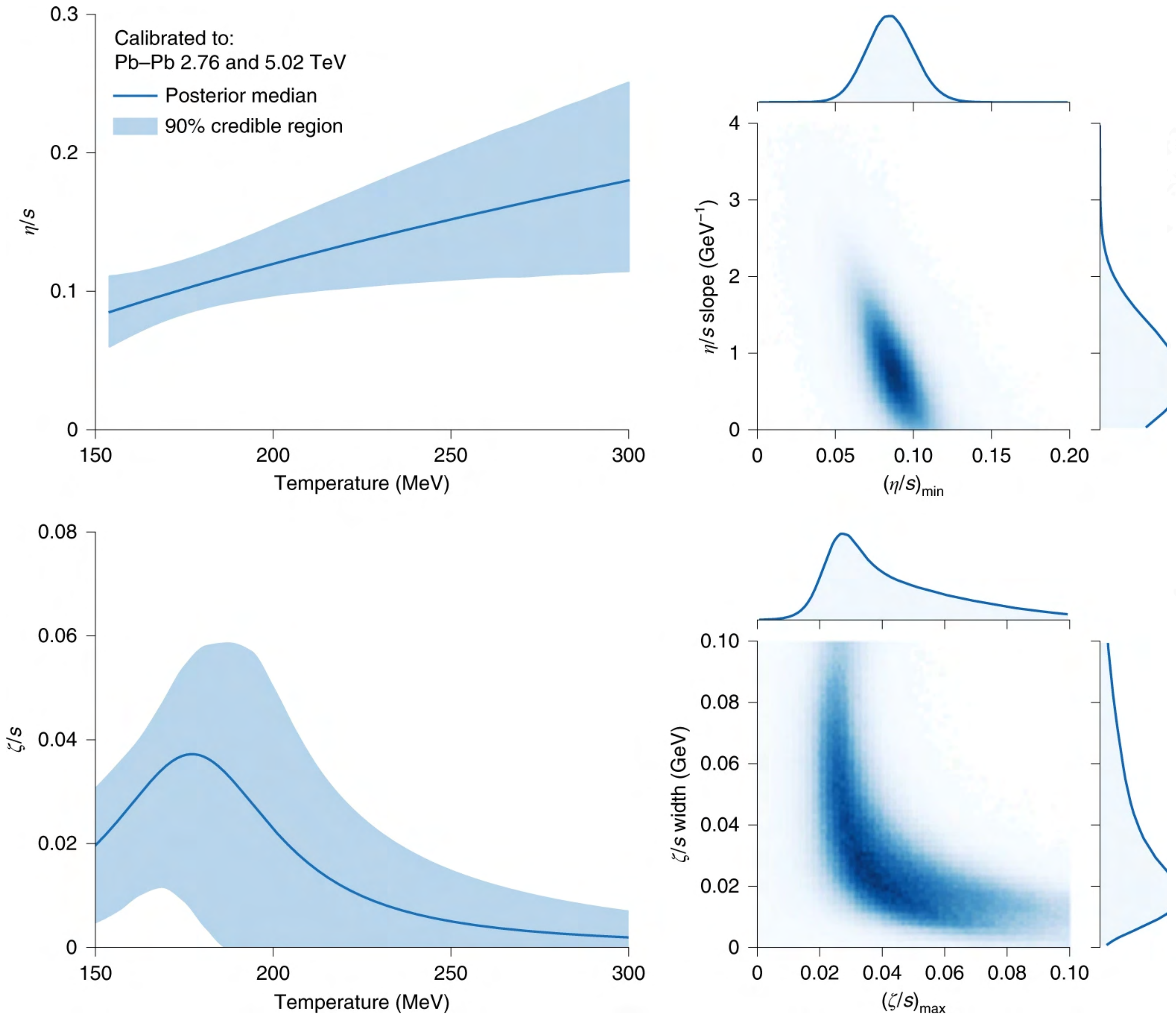
2016 Theory predictions confirmed at the % level.

[ALICE] *Phys.Rev.Lett.* 116 (2016) 13, 132302

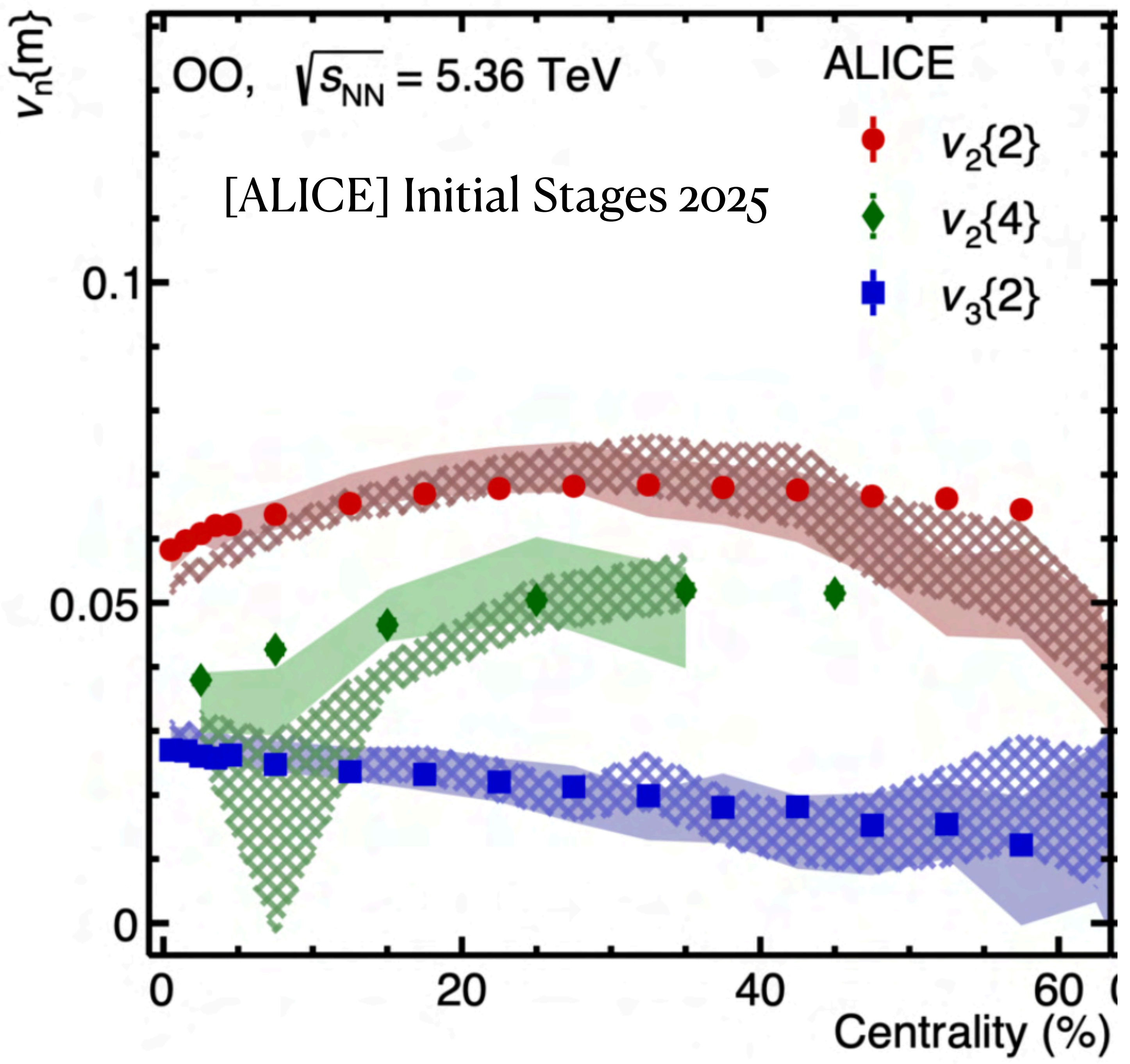


2016-2020 Bayesian parameter estimates begin

Bernhard et al, *Nature Phys.* 15 (2019) 11, 1113-1117



2025 Bayesian posteriors accurately predict OO data!



https://alice-collaboration.web.cern.ch/2025-ALICE-Initial-Stages

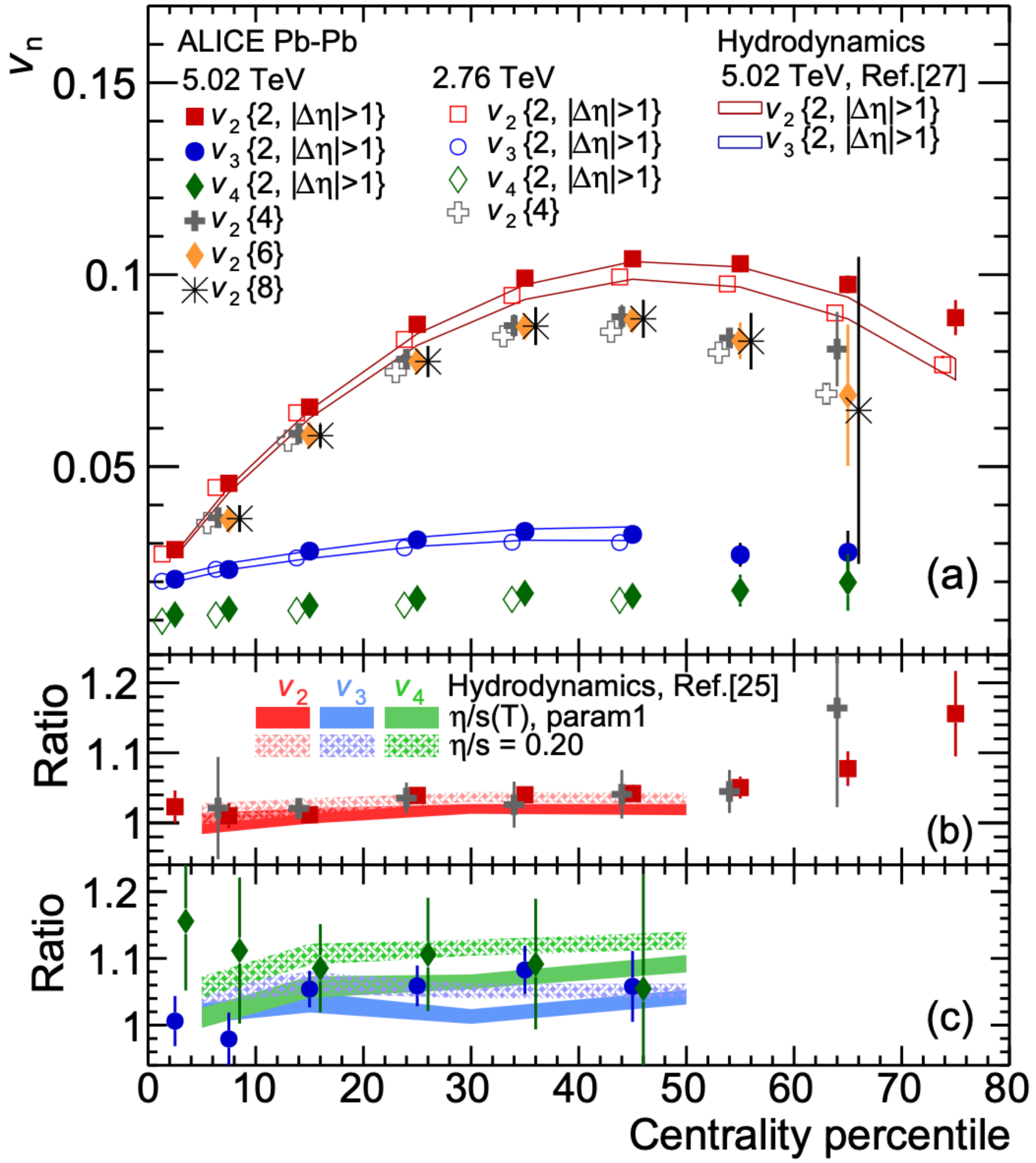
How well to HIC models reproduce data?

Know extremely well

$\sqrt{s_{NN}} \sim [200\, GeV, 6\, TeV]$ RHIC/LHC

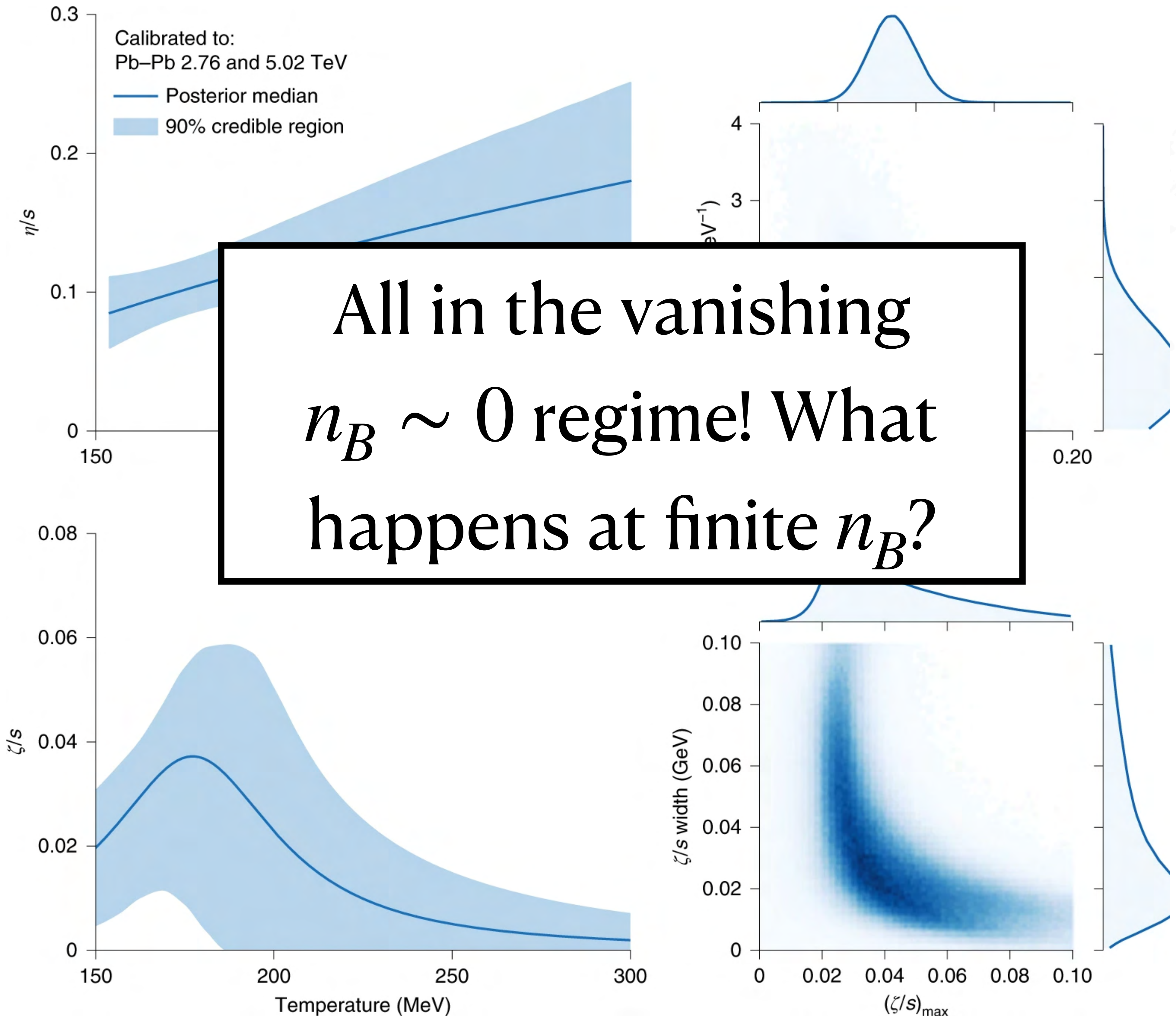
2016 Theory predictions confirmed at the % level.

[ALICE] *Phys.Rev.Lett.* 116 (2016) 13, 132302



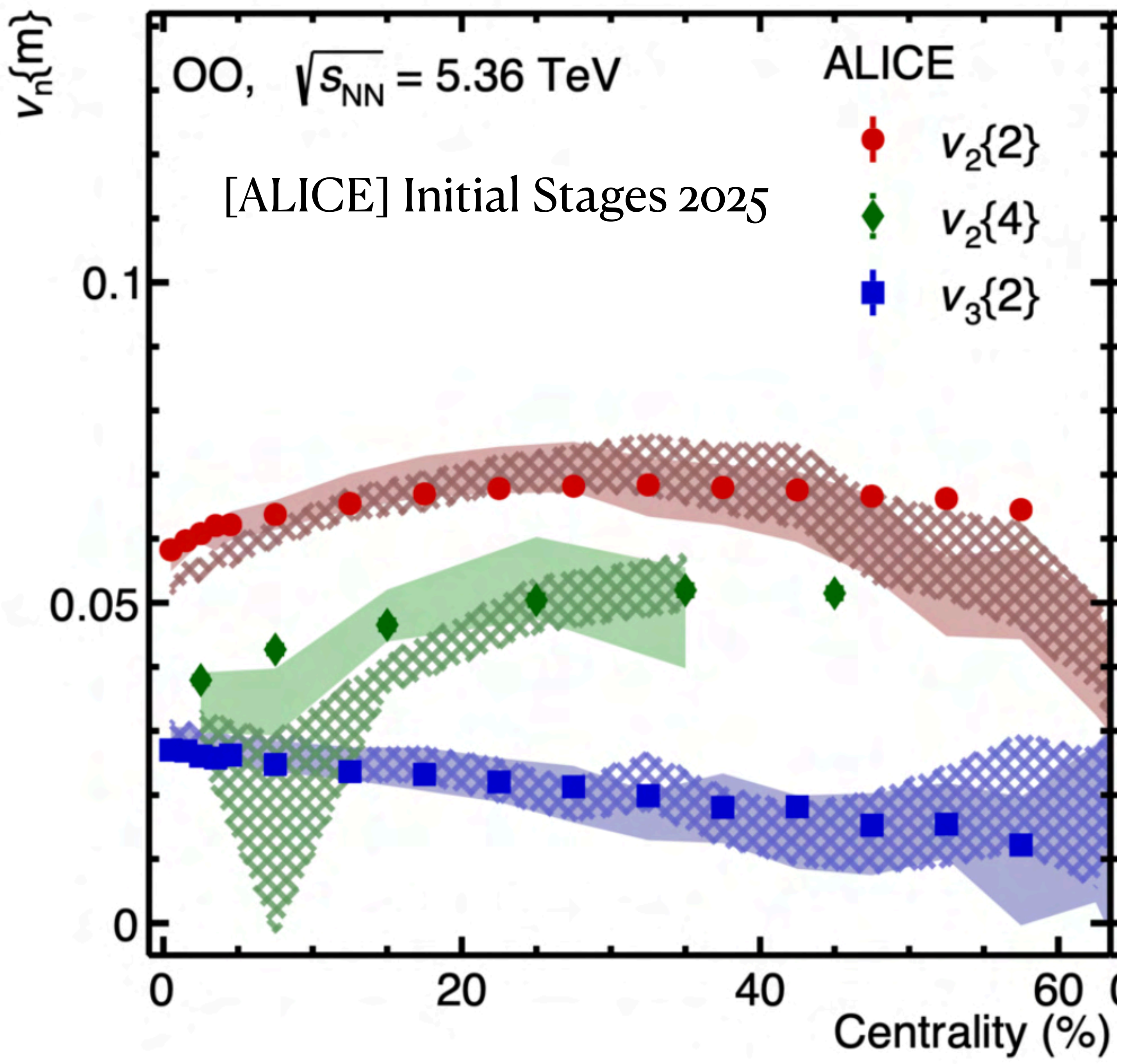
2016-2020 Bayesian parameter estimates begin

Bernhard et al, *Nature Phys.* 15 (2019) 11, 1113-1117



All in the vanishing $n_B \sim 0$ regime! What happens at finite n_B?

2025 Bayesian posteriors accurately predict OO data!

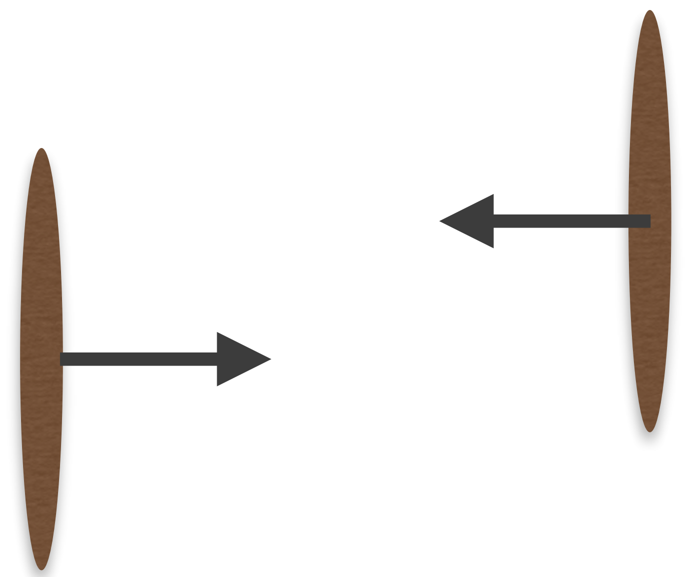


https://alice-collaboration.web.cern.ch/2025-ALICE-Initial-Stages

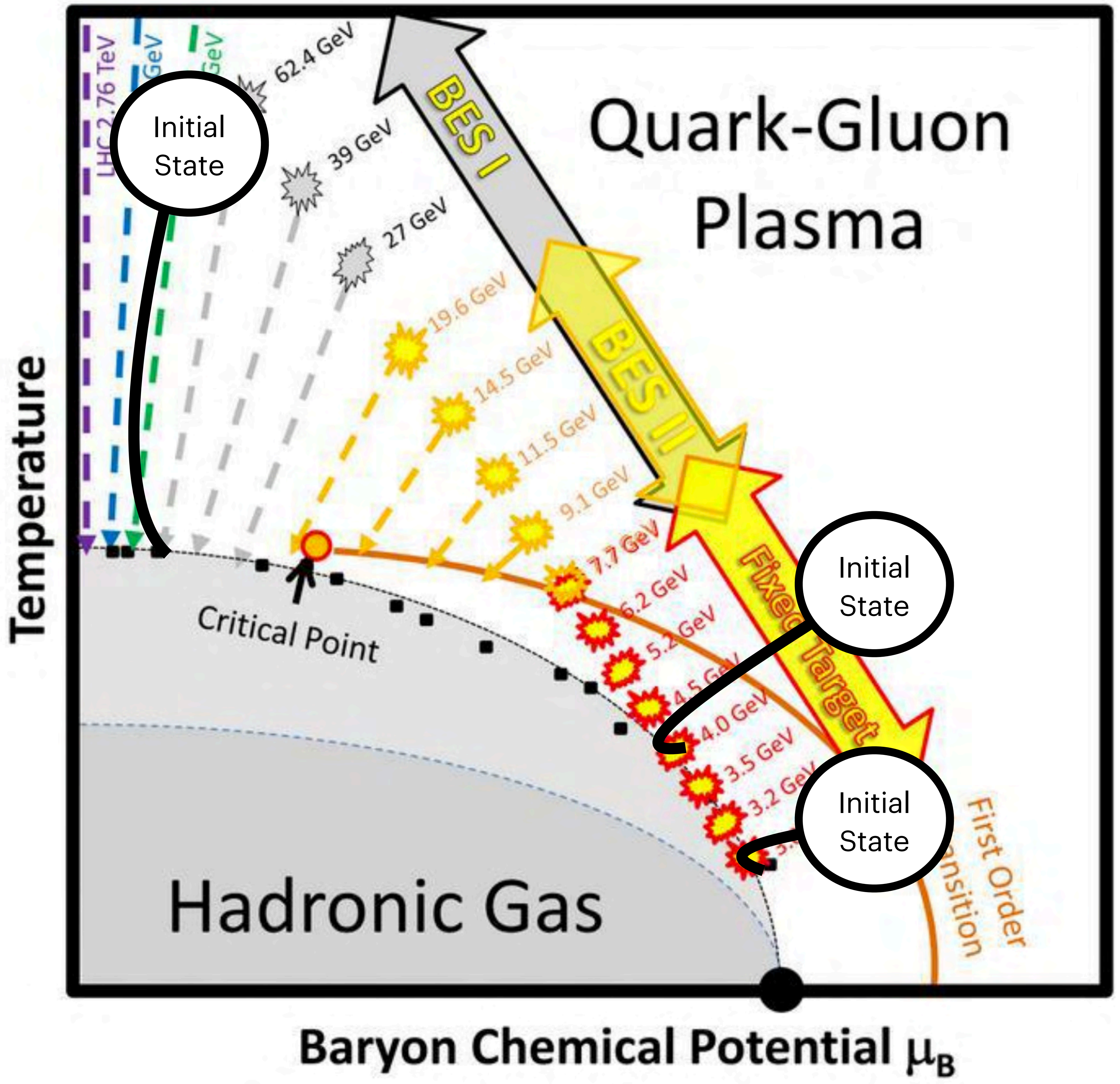
Differences as you lower $\sqrt{s}$ in HIC

Quark-gluon degrees of freedom may matter significantly less

Large $\sqrt{s_{NN}}$

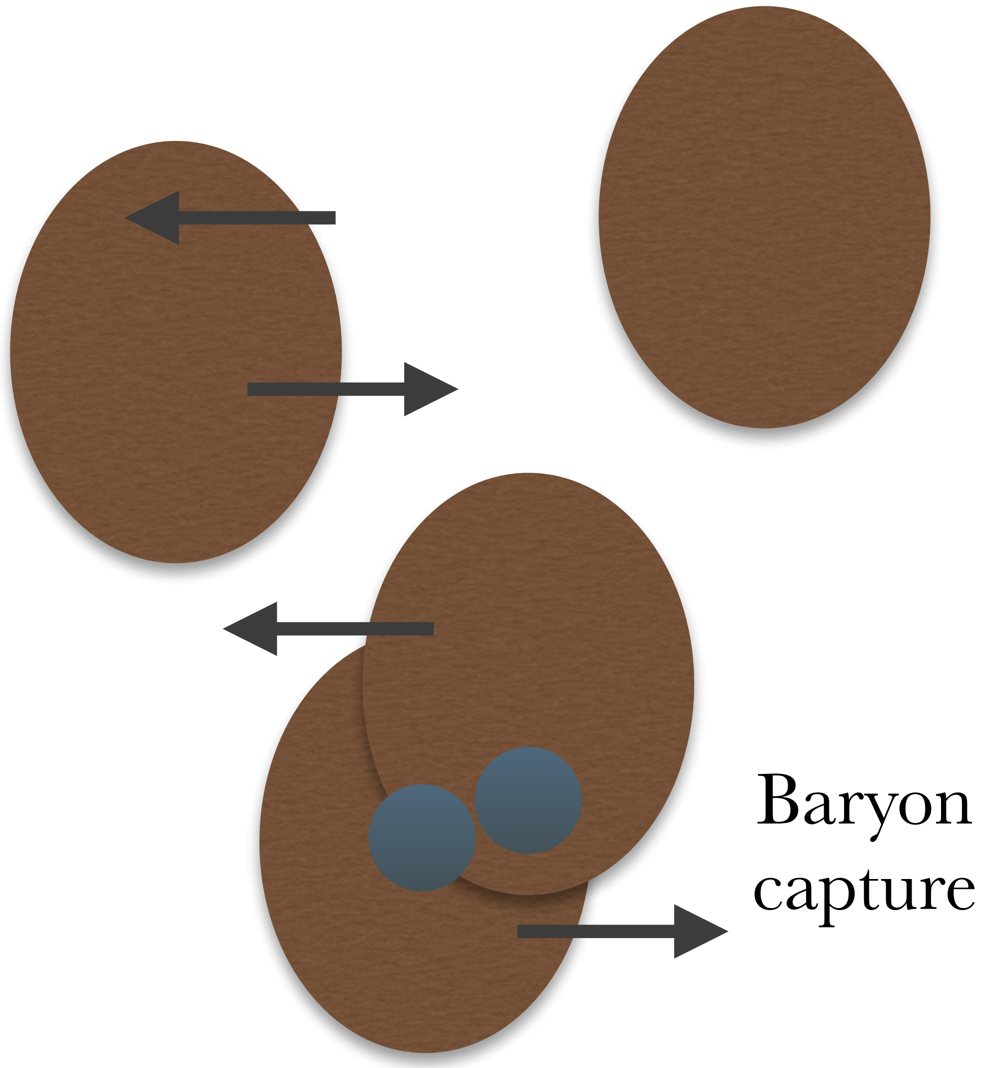


- Lorentz contracted (2D)
- Nuclei pass through instantaneously
- Too quick to capture baryons
- Simulations best understood



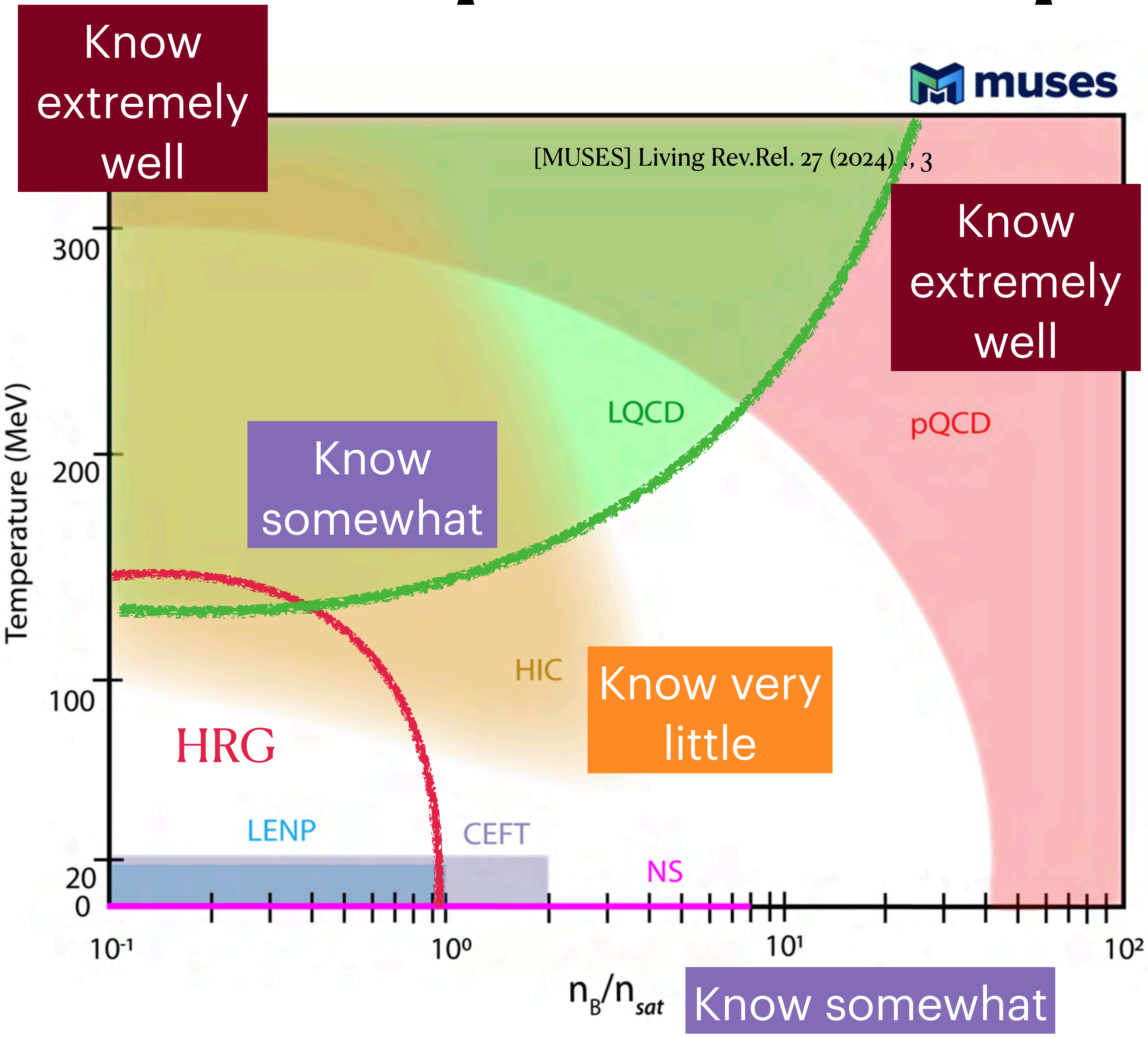
With $\sqrt{s_{NN}}$, different time spent in quark/gluon phase vs hadron phase

Small $\sqrt{s_{NN}}$



- 3D nuclei pass slowly
- Time to capture baryons
- Diffusion, phase transitions matter

Equilibrium: Complexity at low $\sqrt{s_{NN}}$



Large parts of heavy-ion collisions outside of the regime of validity for lattice QCD and the HRG

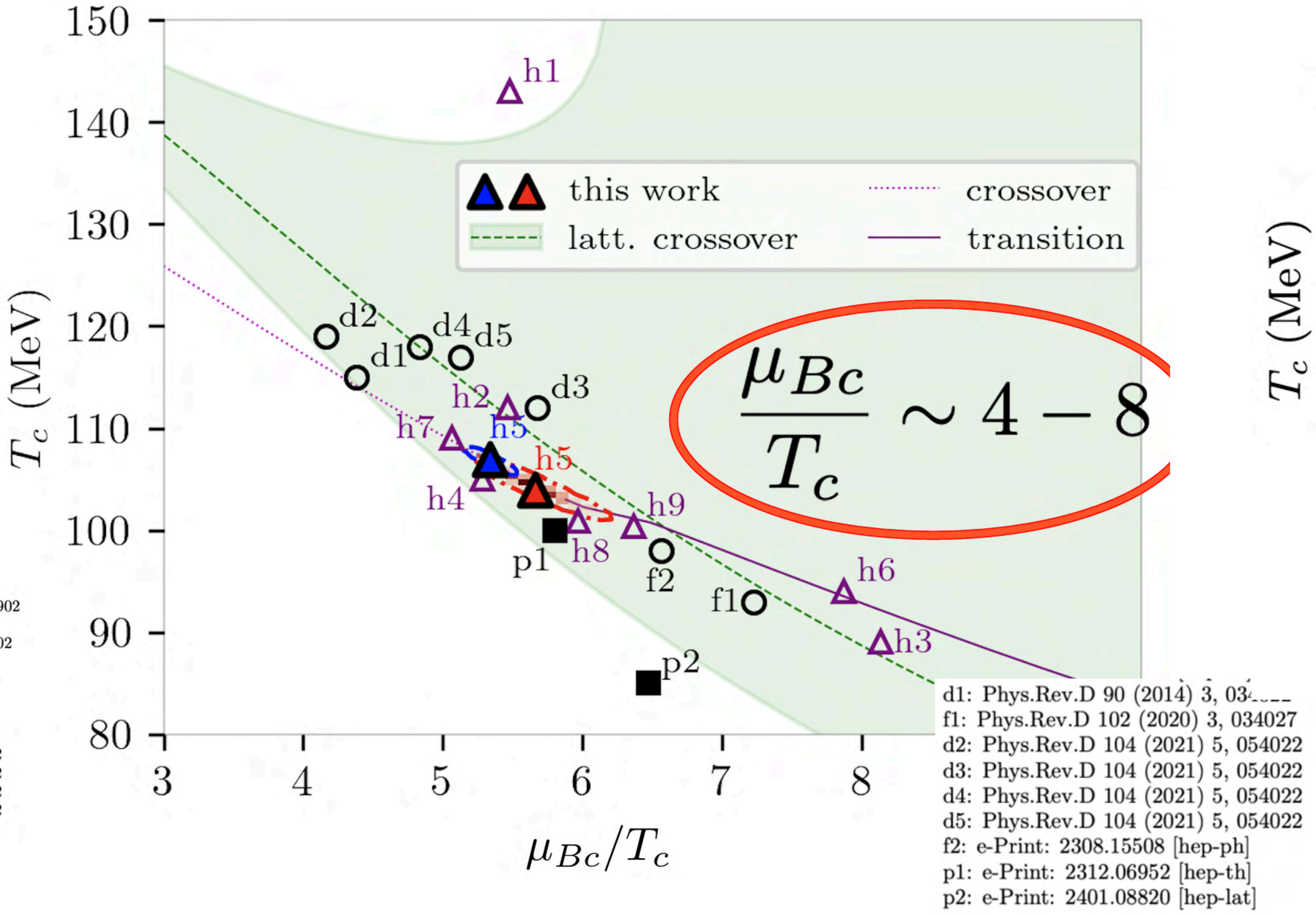
Jamie's talk

Need to smoothly match to lattice QCD/HRG, include search for critical point/first-order line, match to NS, requires 4D EOS as well!

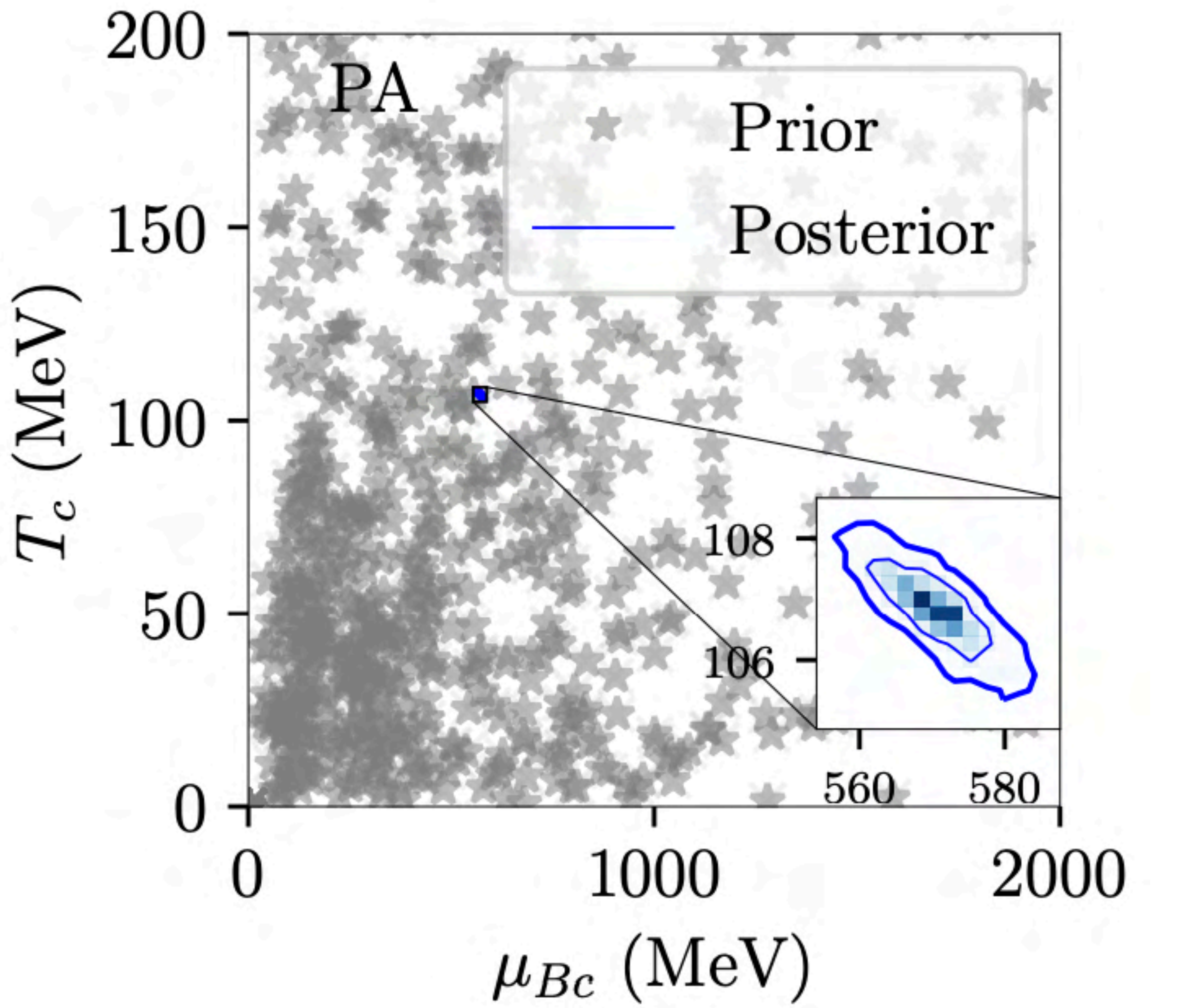

Hints of a critical point

Know somewhat

Using lattice QCD+models (holography, functional renormalization group, data etc)



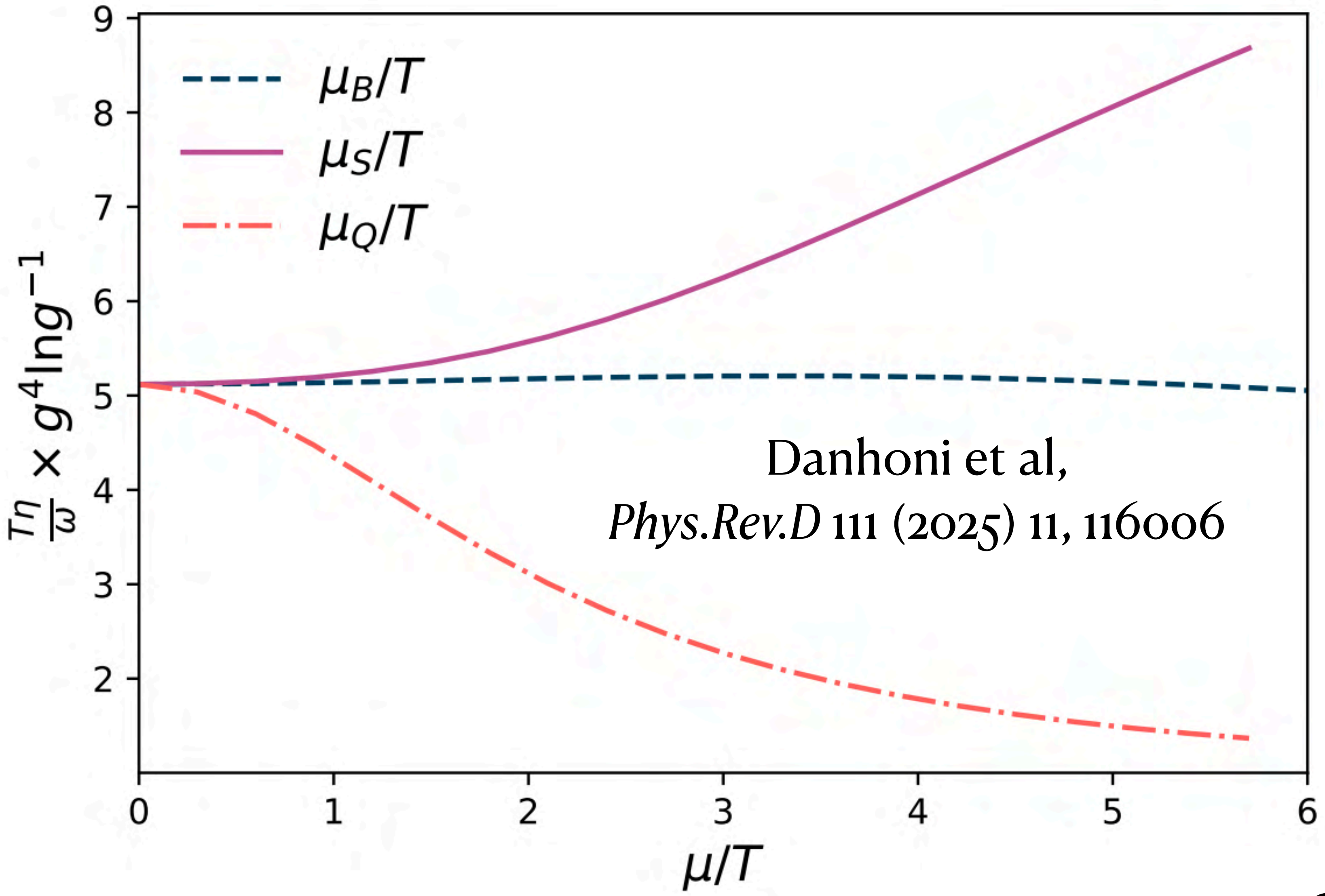
Hippert et al, *Phys.Rev.D* 110 (2024) 9, 094006



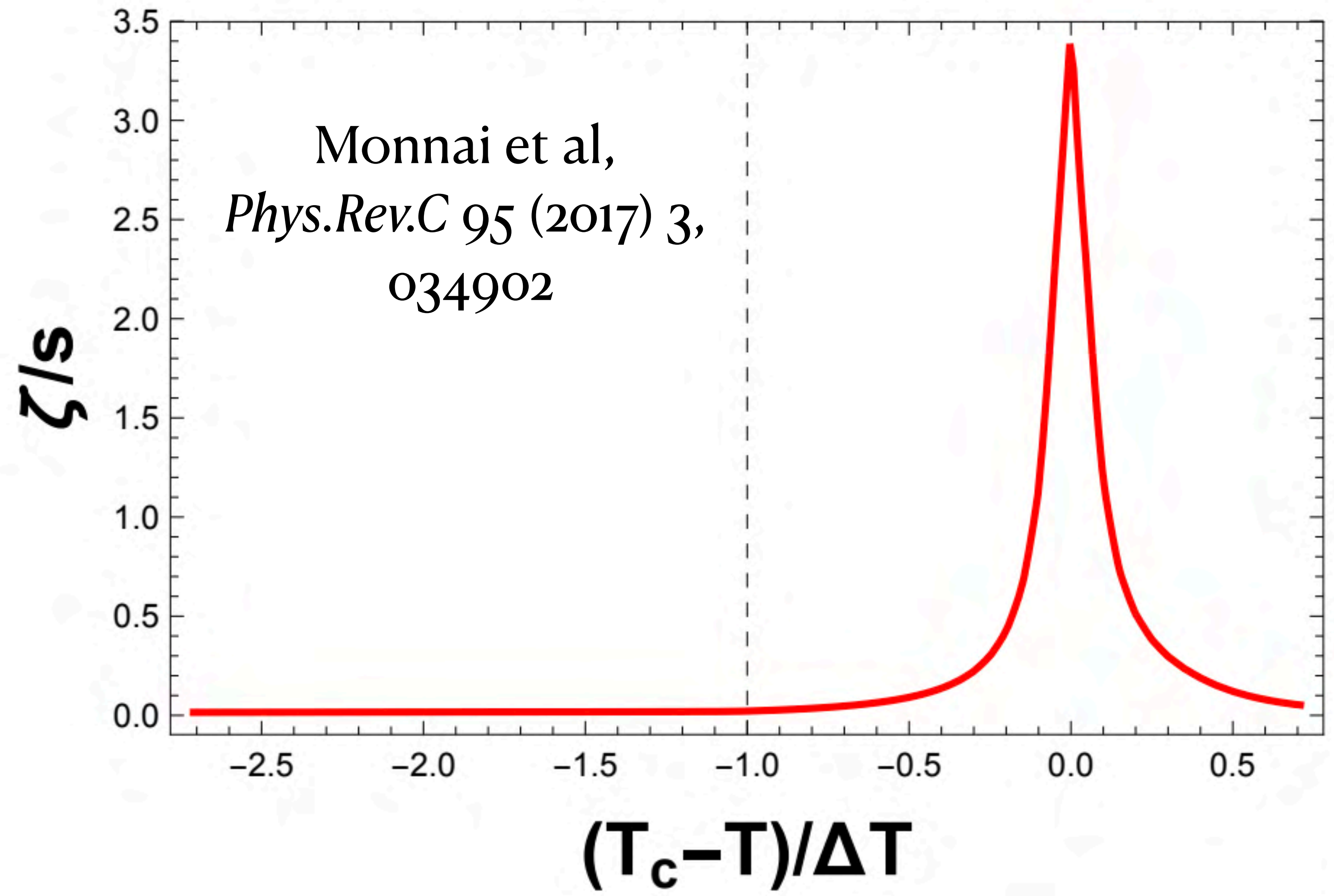
Bayesian analysis to reproduce lattice QCD, finds highly constrained critical point!

Out-of-Equilibrium: Complexity at low $\sqrt{s_{NN}}$

Shear viscosity of pQCD

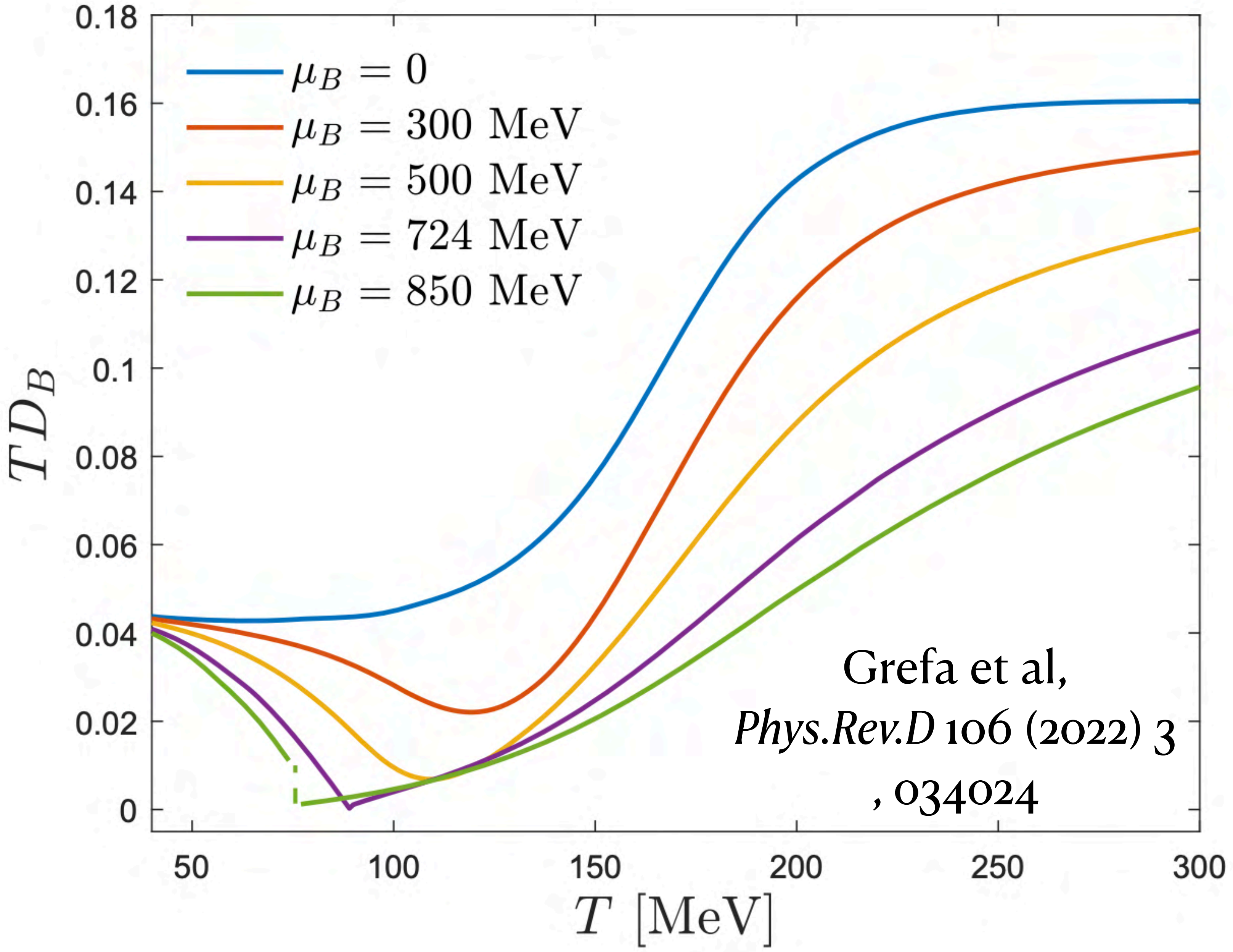


Bulk viscosity at a critical point

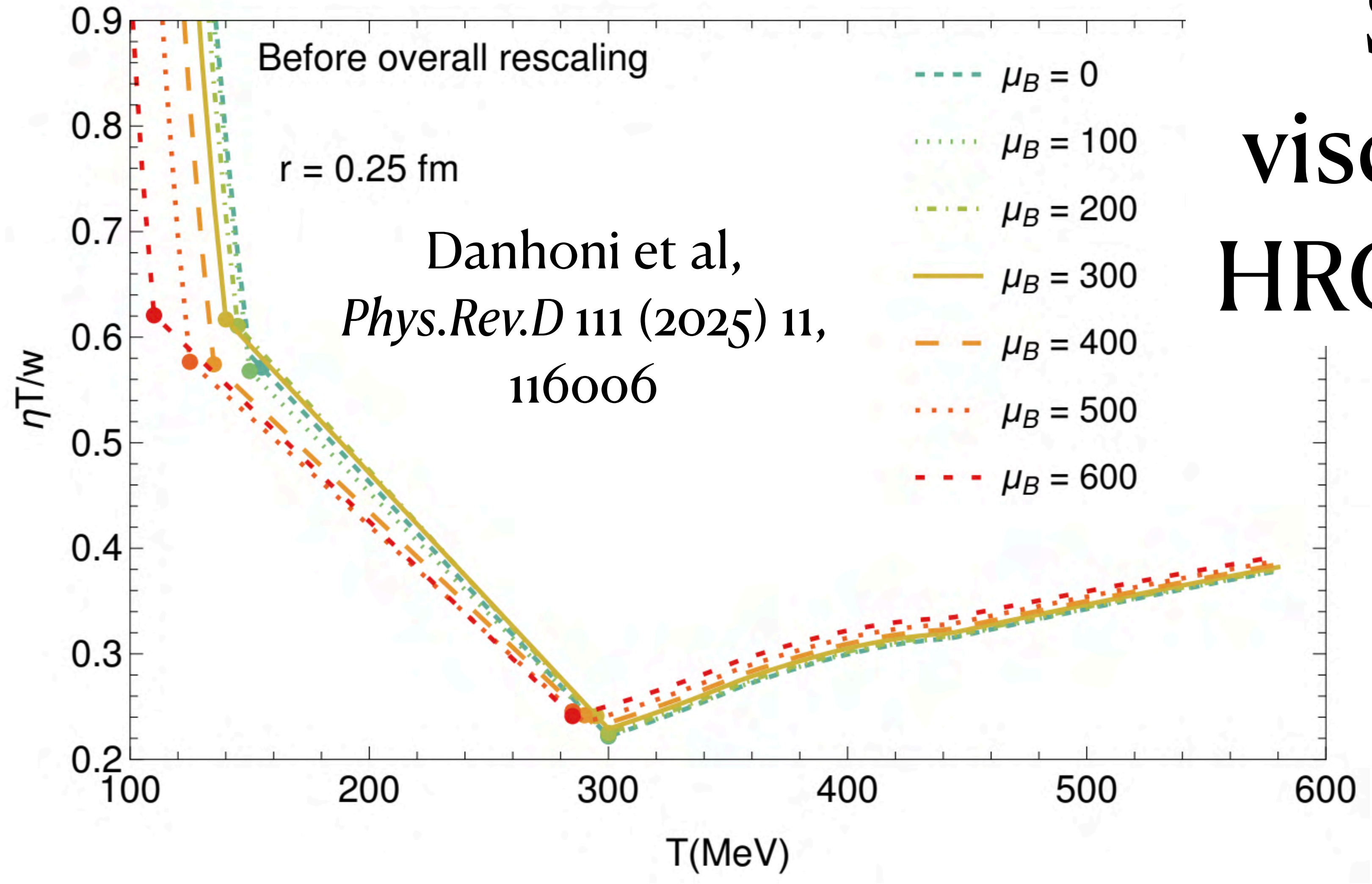


BSQ diffusion matrix ???

Baryon diffusion at a critical point

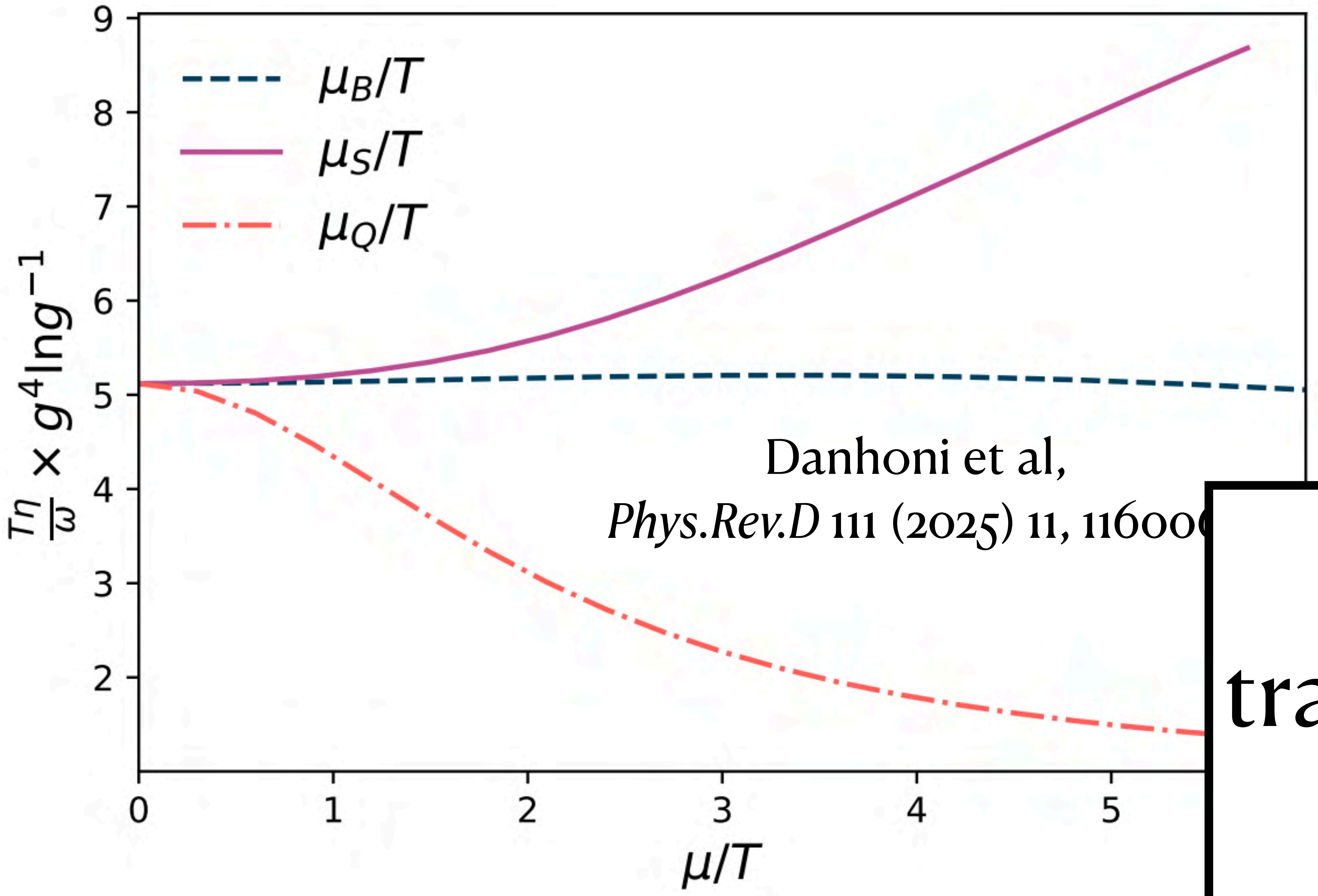


Shear viscosity of HRG+pQCD

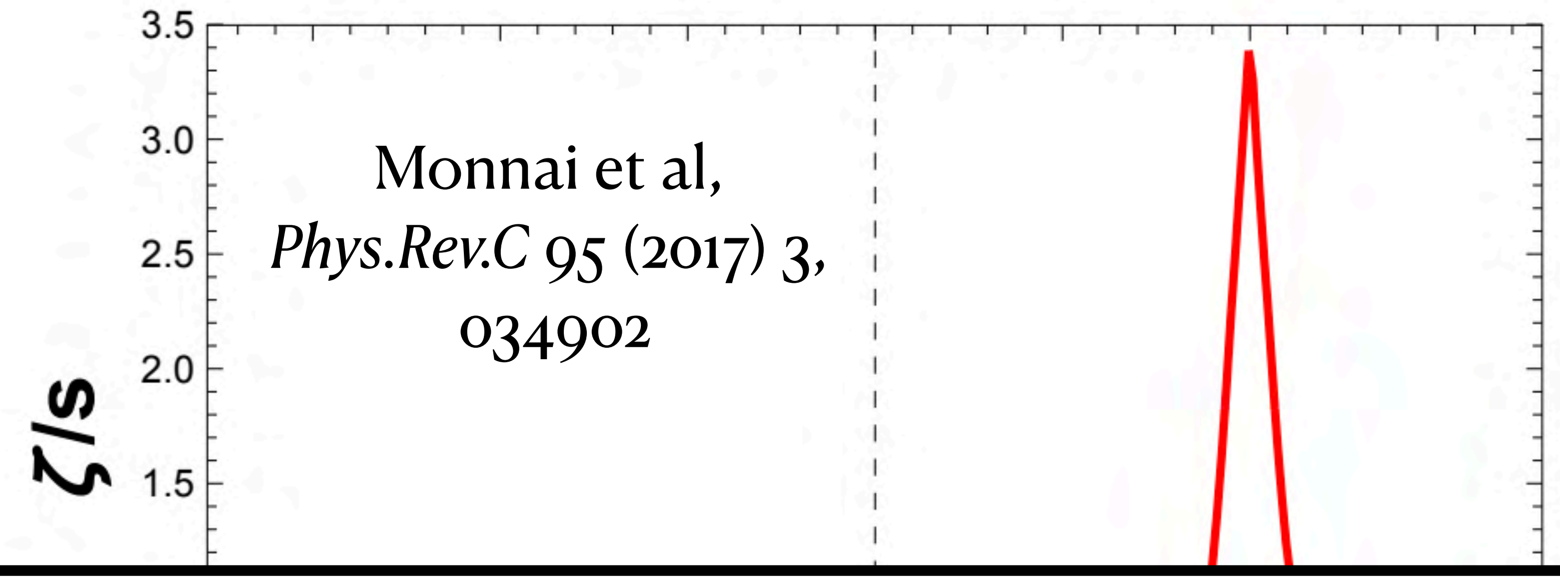


Out-of-Equilibrium: Complexity at low $\sqrt{s_{NN}}$

Shear viscosity of pQCD



Bulk viscosity at a critical point

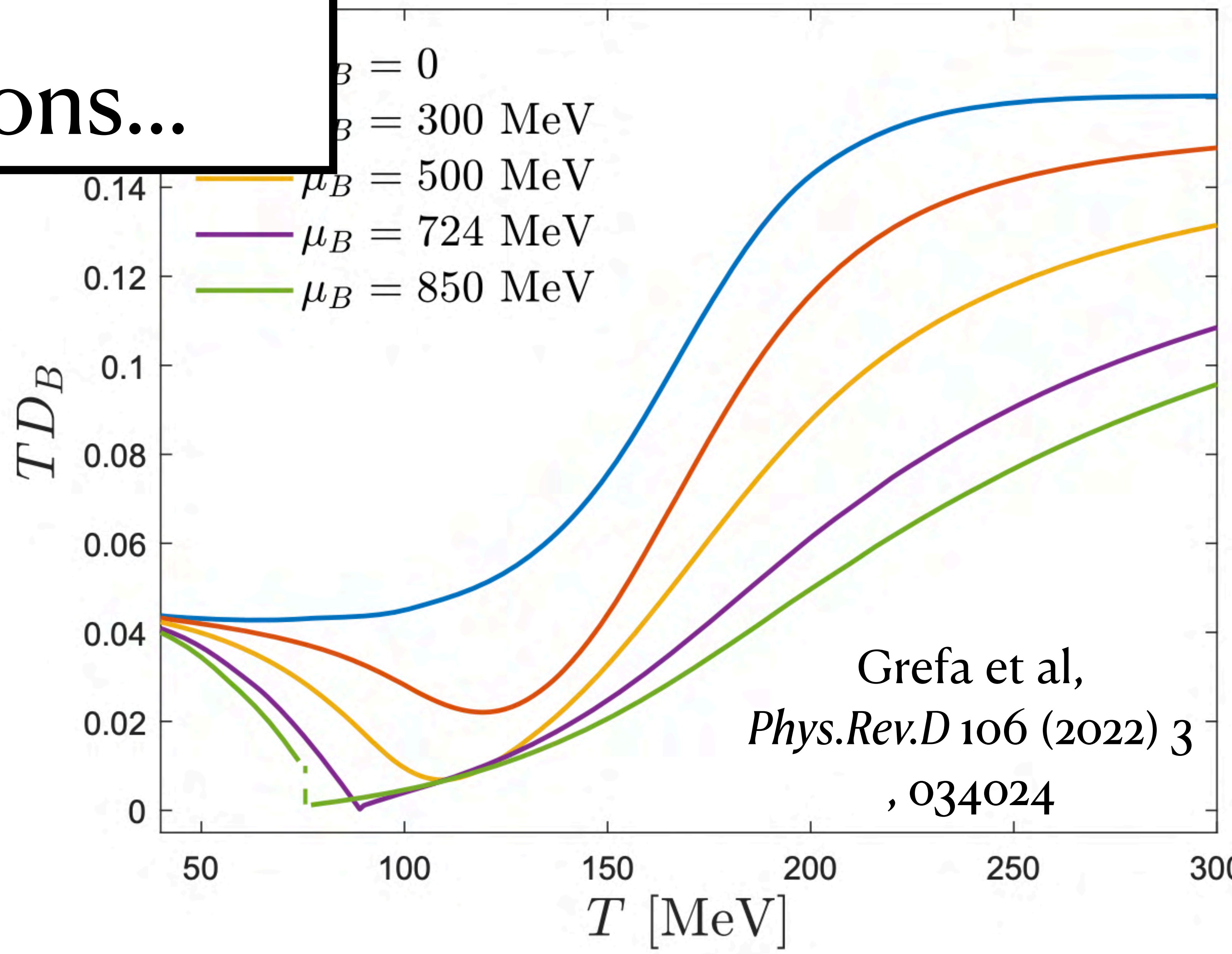


BSQ diffusion matrix ???

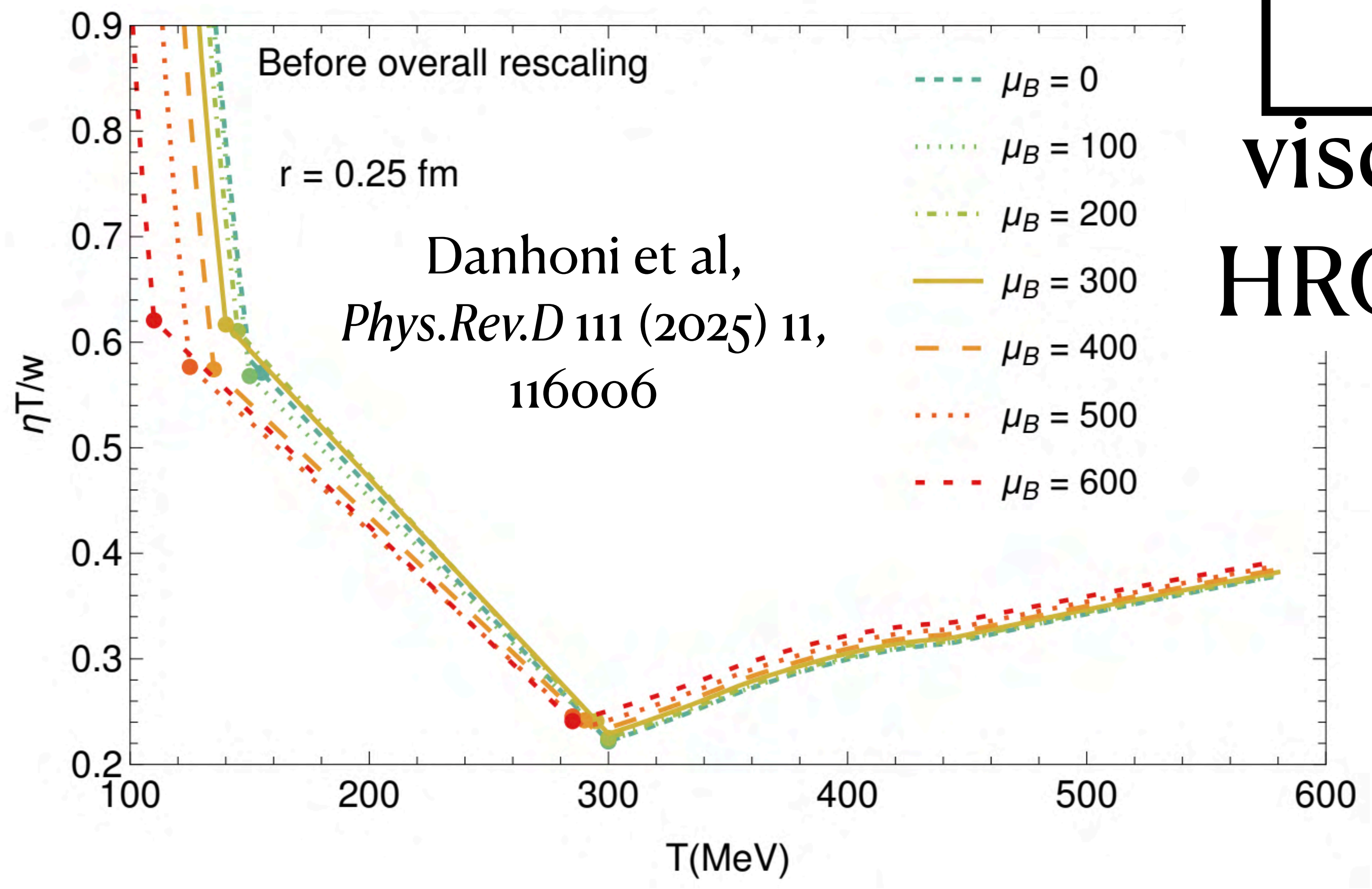
Recall, cross-correlations between transport coefficients, this is all very non-trivial!

Also, no lattice QCD calculations…

aryon diffusion at a critical point

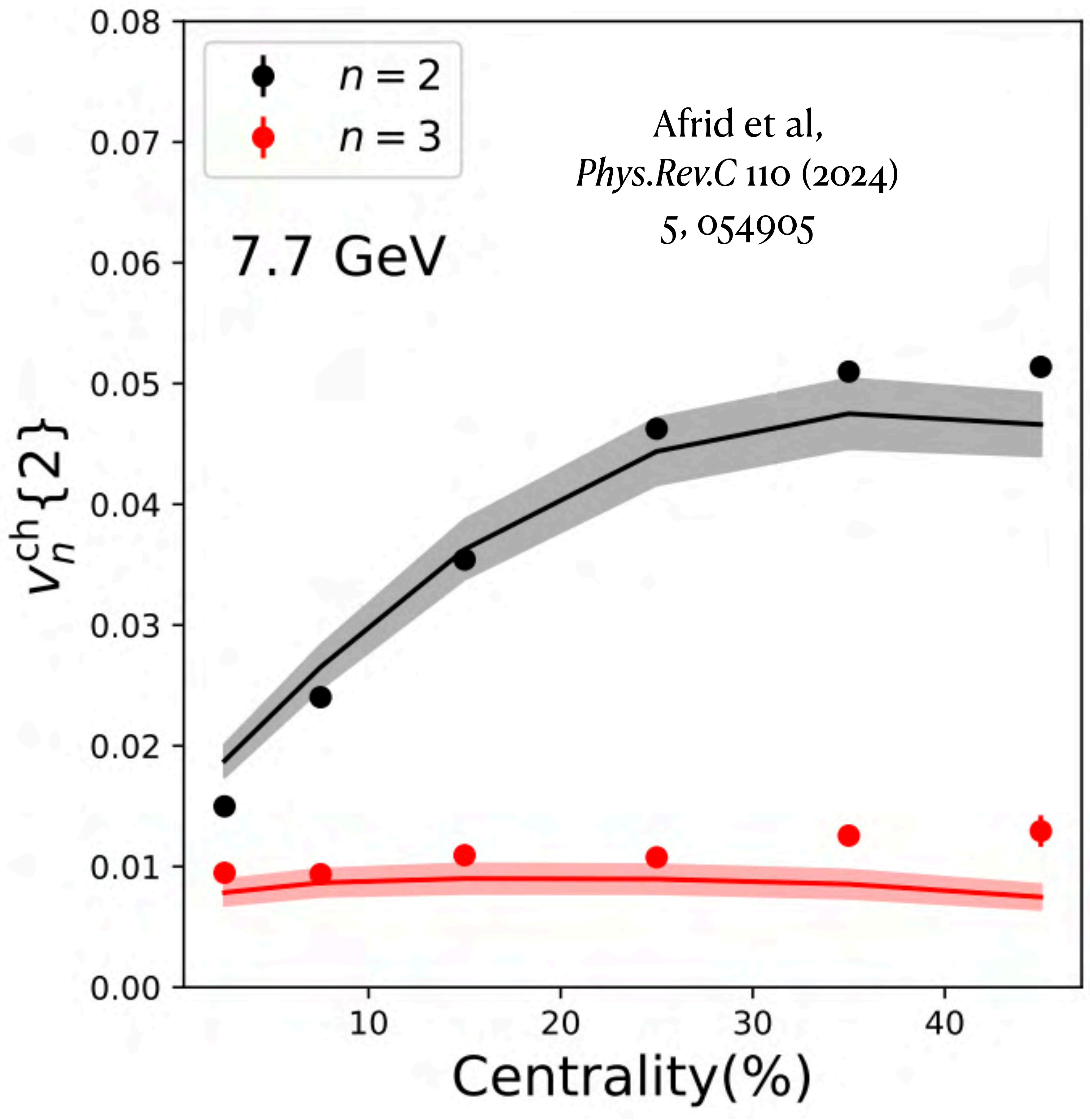


viscosity of HRG+pQCD

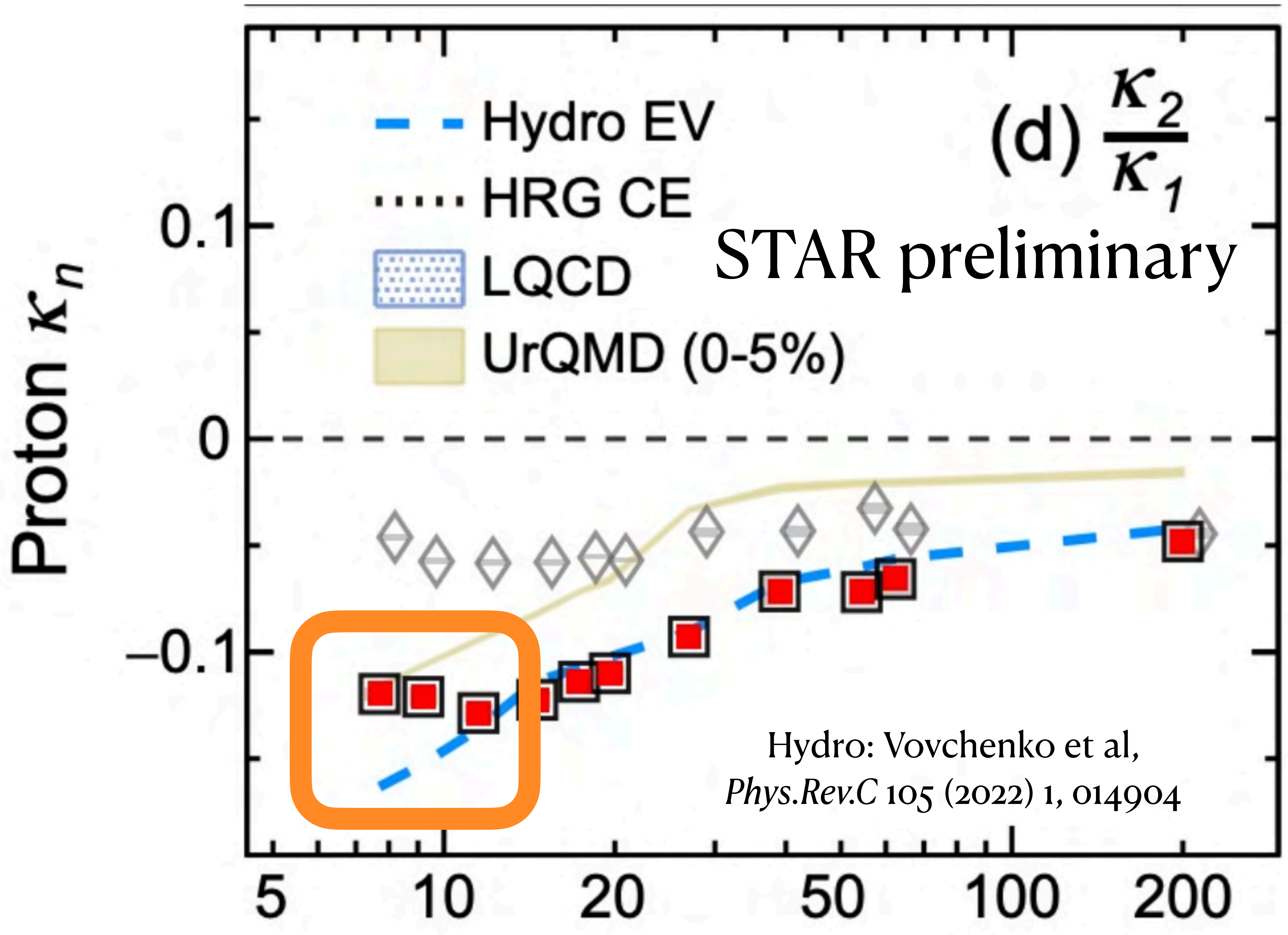


Baseline calculations (cross-over all the way down)

Most recent Bayesian analysis with fixed (lattice QCD+HRG) EOS, vary (simplified) transport coefficients



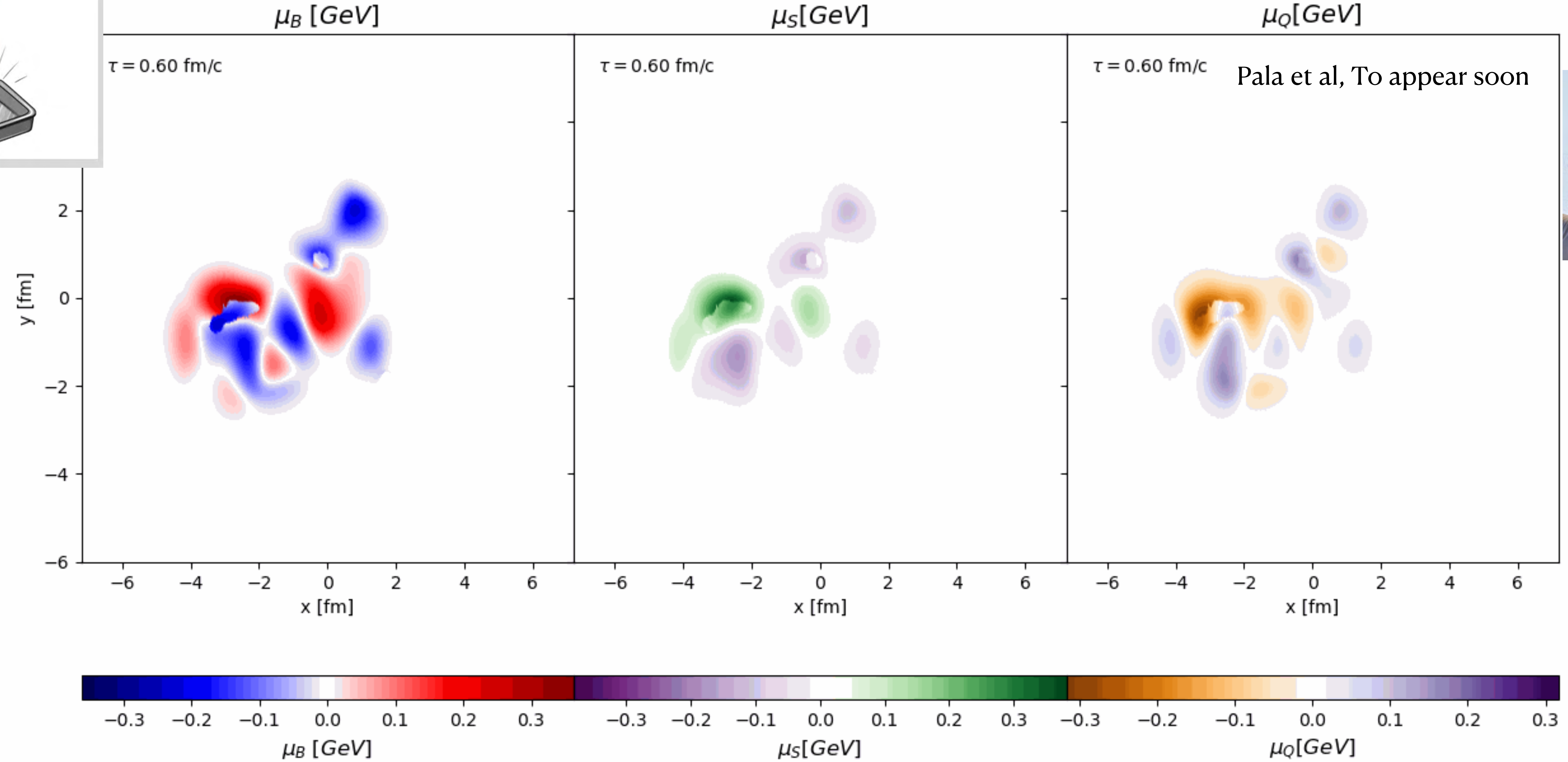
Search for the QCD critical point



Deviations exactly at $\sqrt{s_{NN}} = 7.7\ GeV$, hydro still works. Sign of a critical point?

Coming soon: CCAKE 2.0

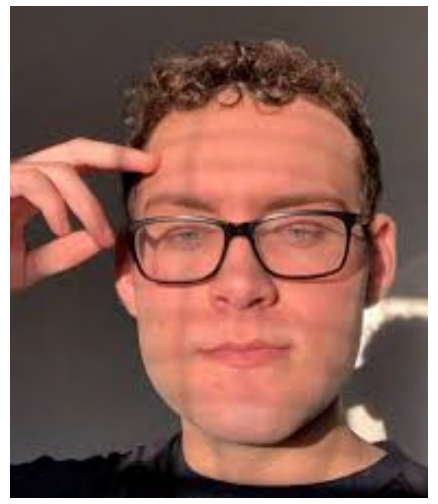
3+1D simulations with BSQ diffusion, on CPUs/GPUs, generalized coordinates











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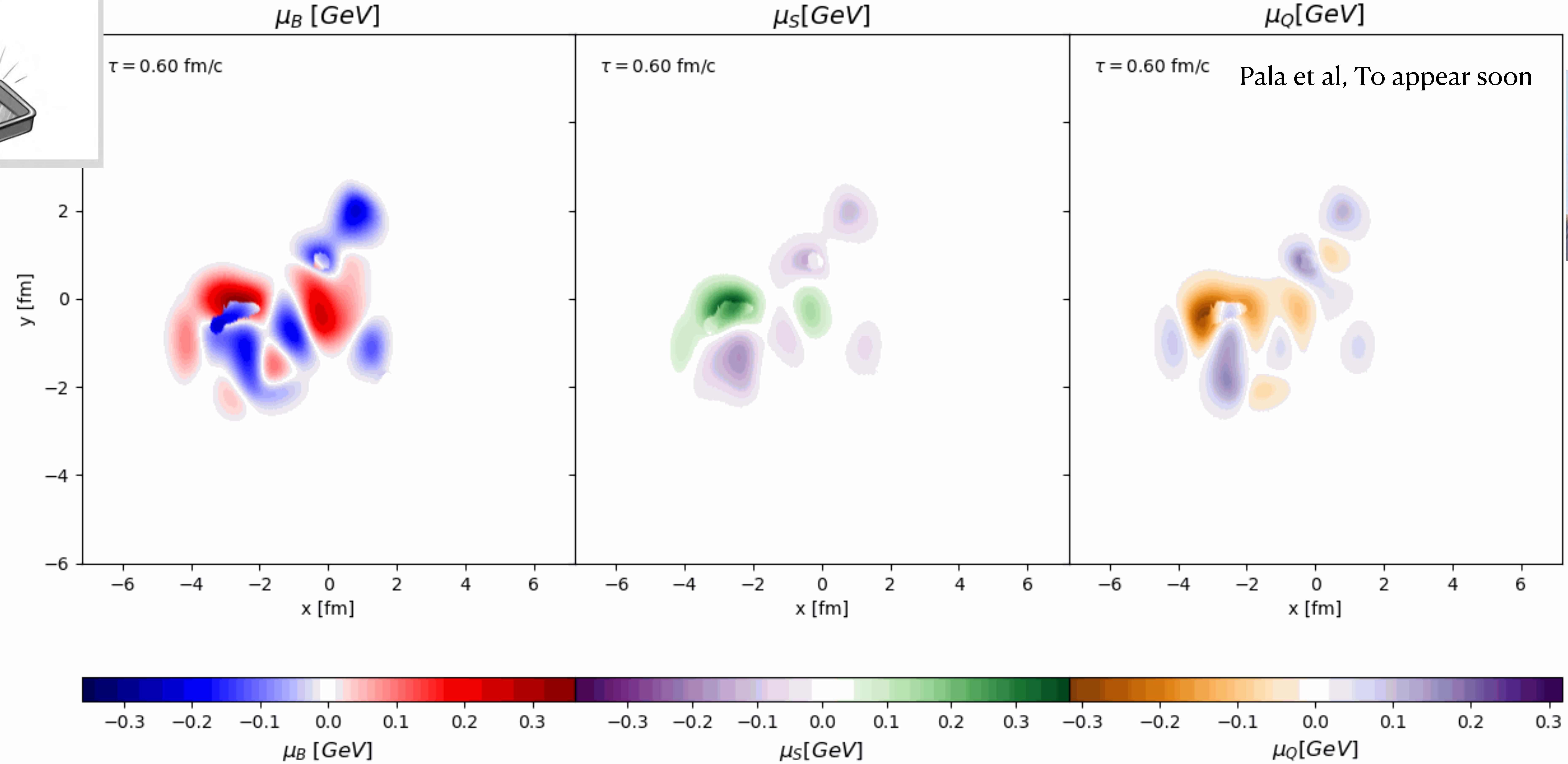
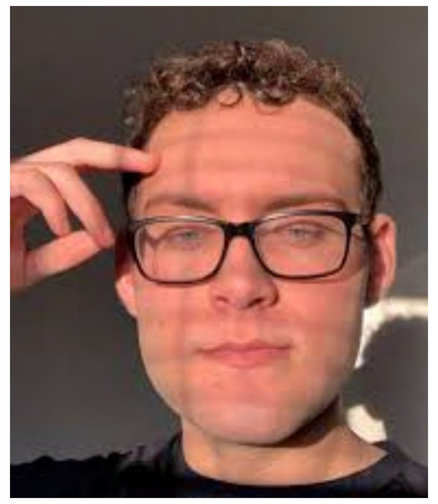










What do we do in the meantime?

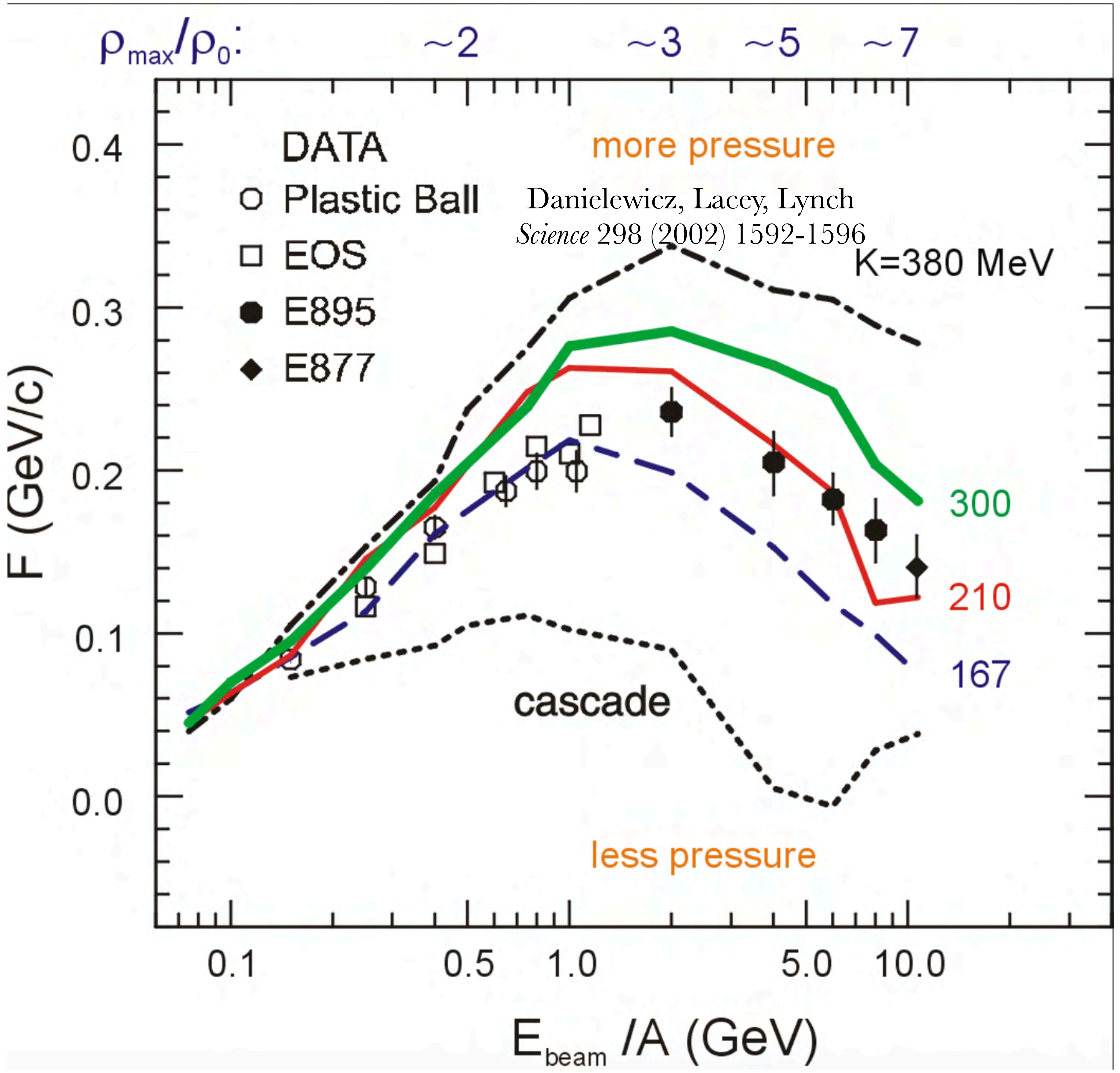
Need to work out the math to connect HIC to NS, this isn’t very trivial…

2002 Collective flow & extracting the heavy-ion EOS

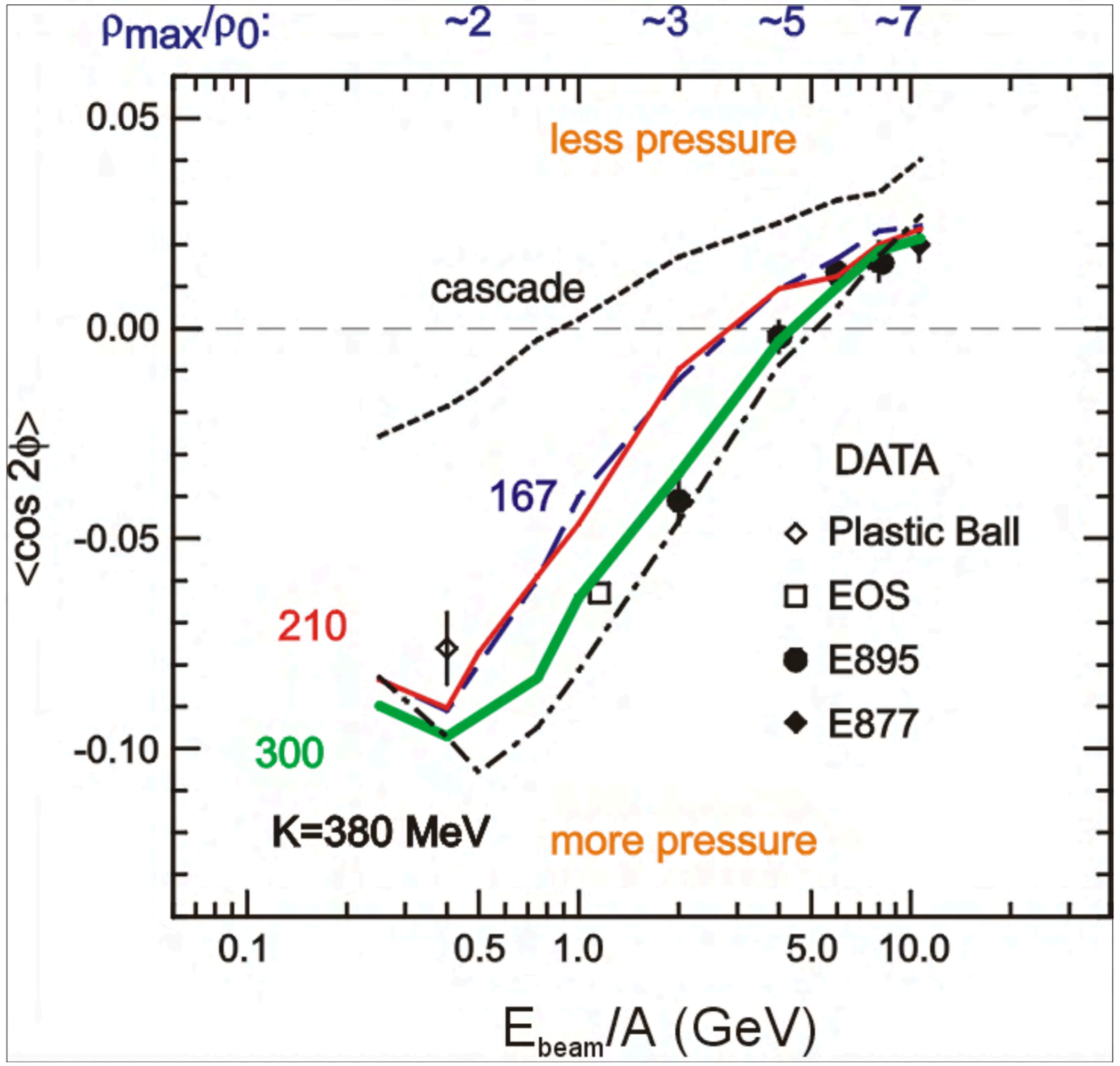
Varied Symmetry energy properties, extrapolated EOS to $T = 0$

Extremely hard to fit both dv_1/dy and v_2

$\frac{dv_1}{dy}$



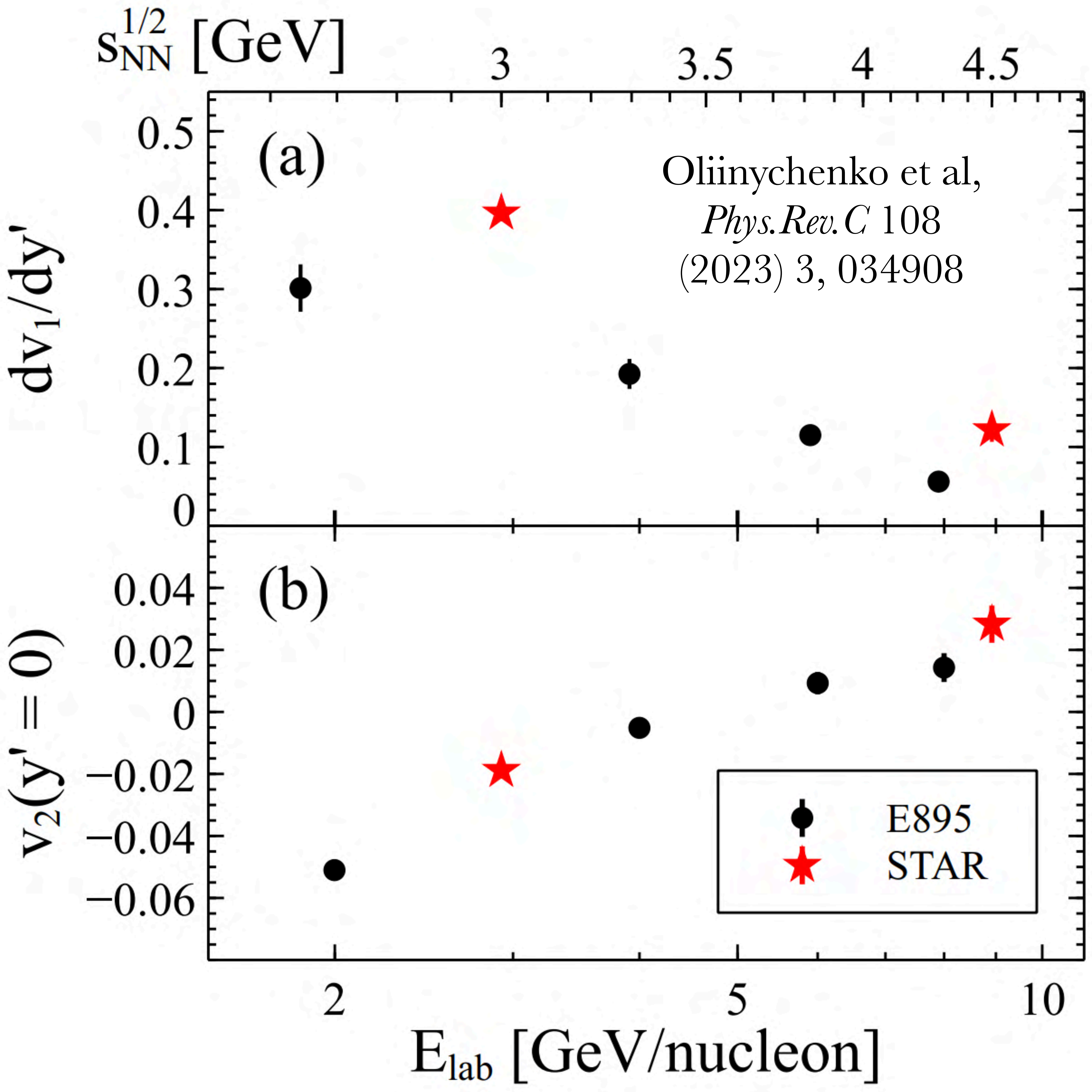
v_2

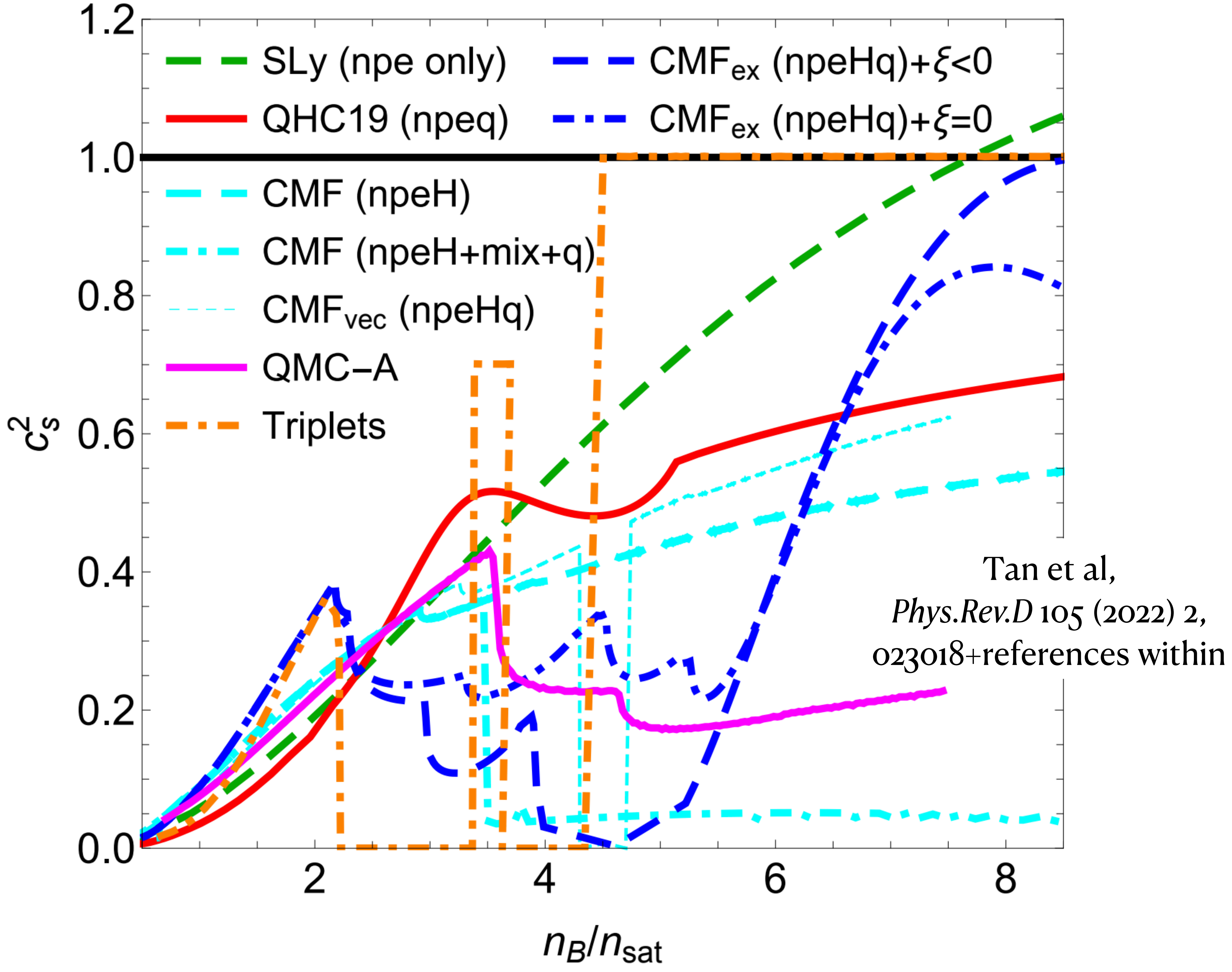


Fermi-liquid/π, p, n transport assumed
What does modern HIC find?

A lot has happen in 20+ years

New data, insights from neutron stars and high-energy HIC



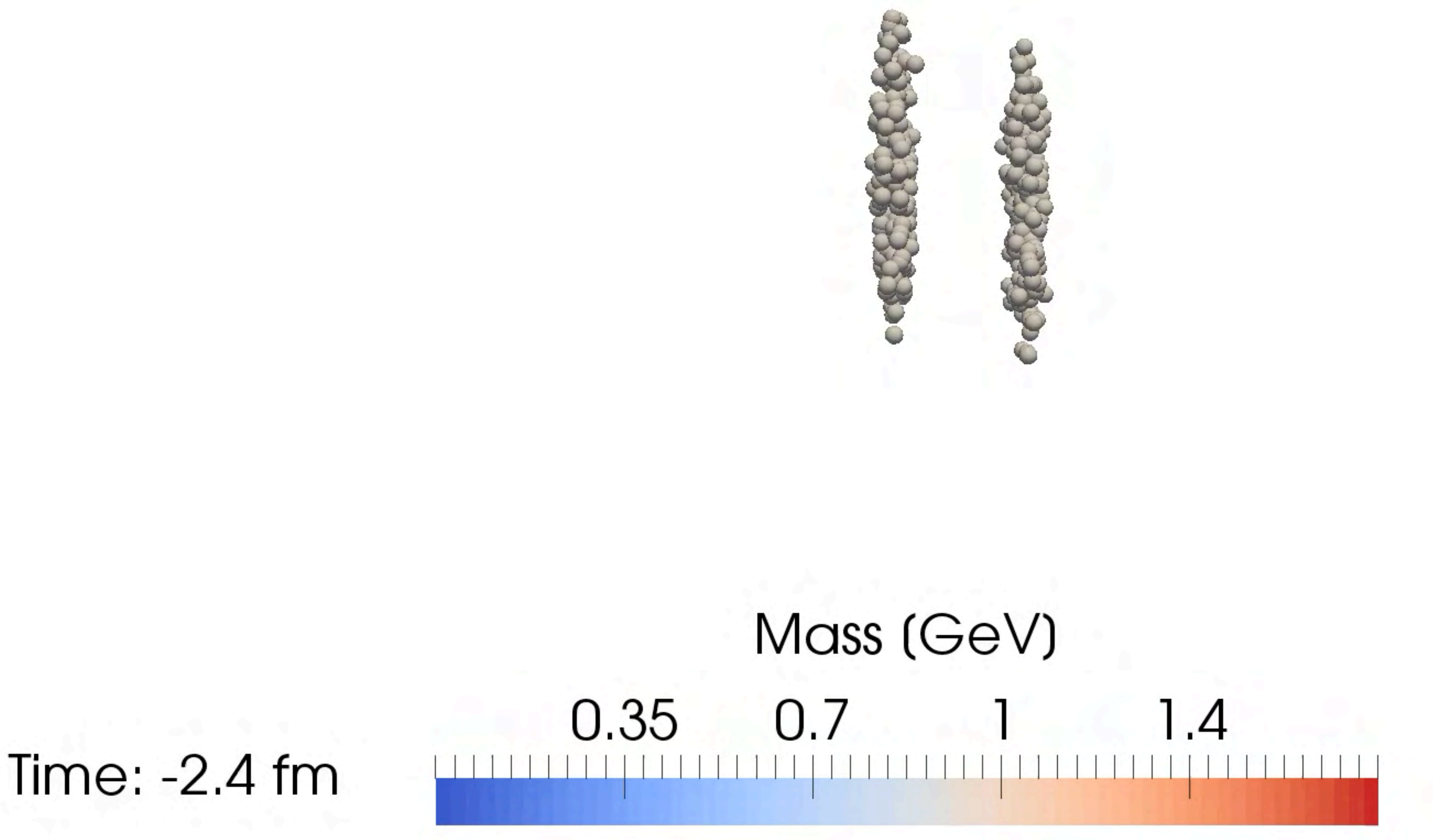


New STAR data not identical to old HIC data, bumps in c_s^2, but 20 years of knowledge from HIC…

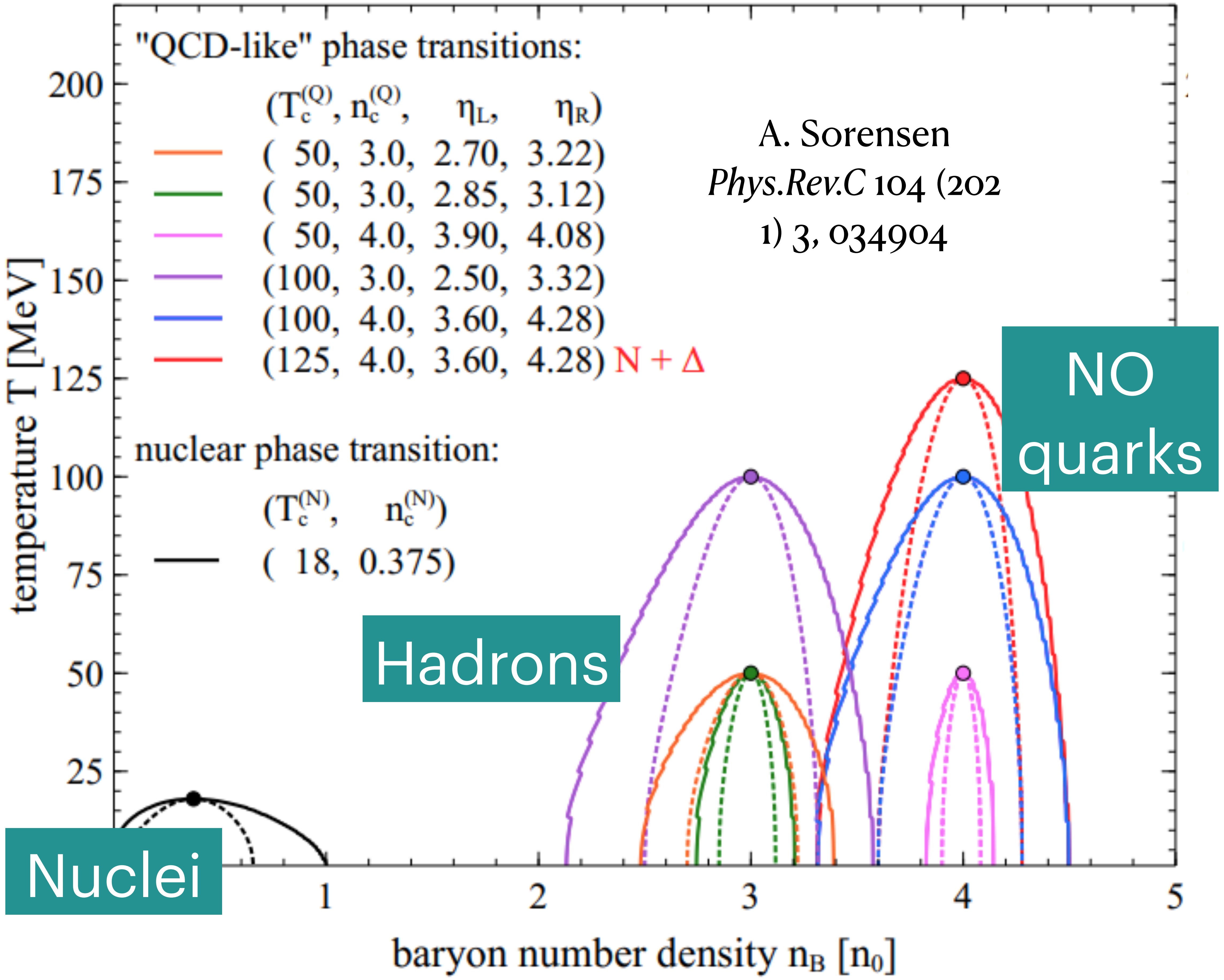
2020's Low-energy $\sqrt{s} \leq 7.7\ GeV$ HICs

New STAR data, new interpretations

Do quark-gluons d.o.f. matter?
Build phase transitions into hadron transport



Flexible potentials → phase transitions



A. Sorensen
Phys.Rev.C 104 (2021) 3, 034904

2020's Low-energy $\sqrt{s} \leq 7.7\, GeV$ HICs

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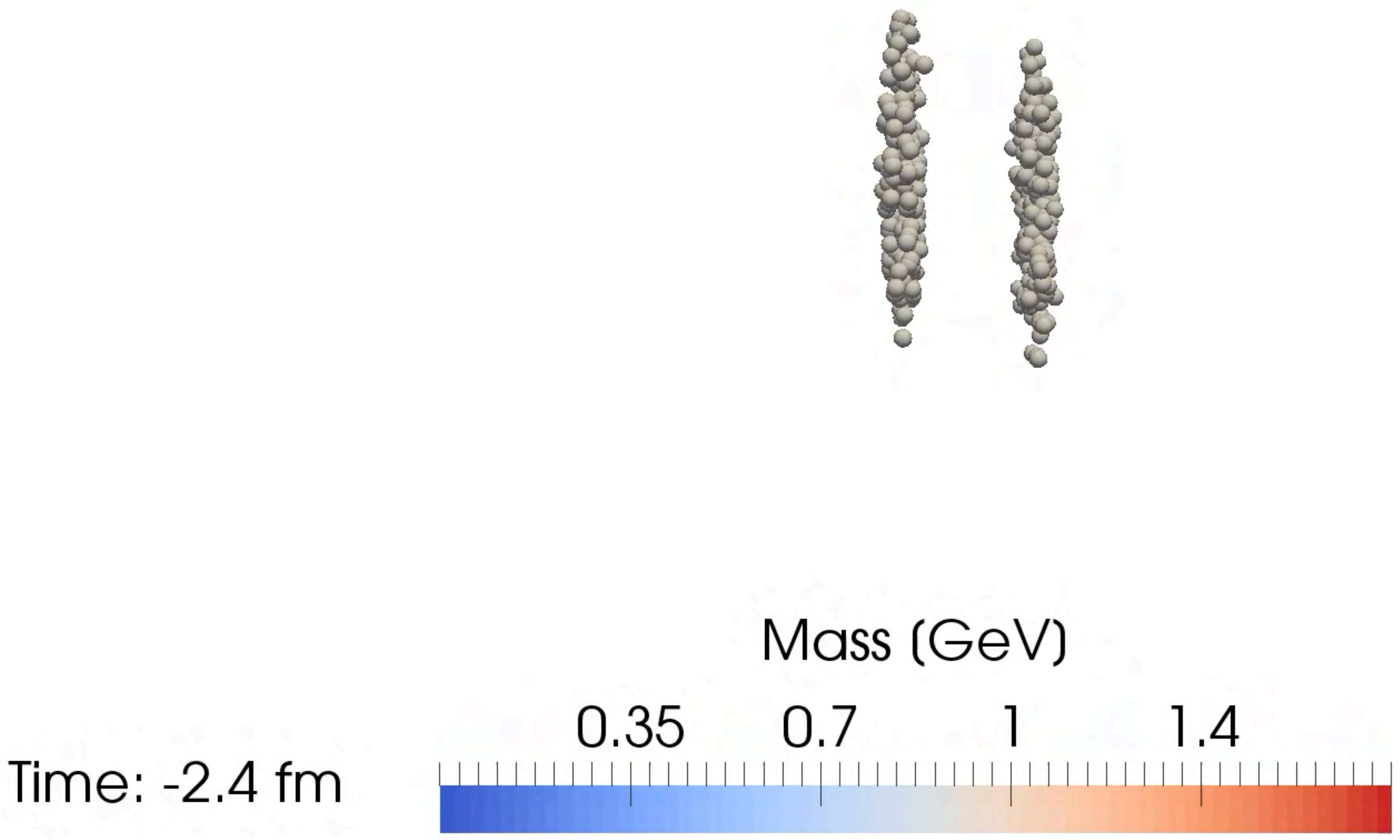

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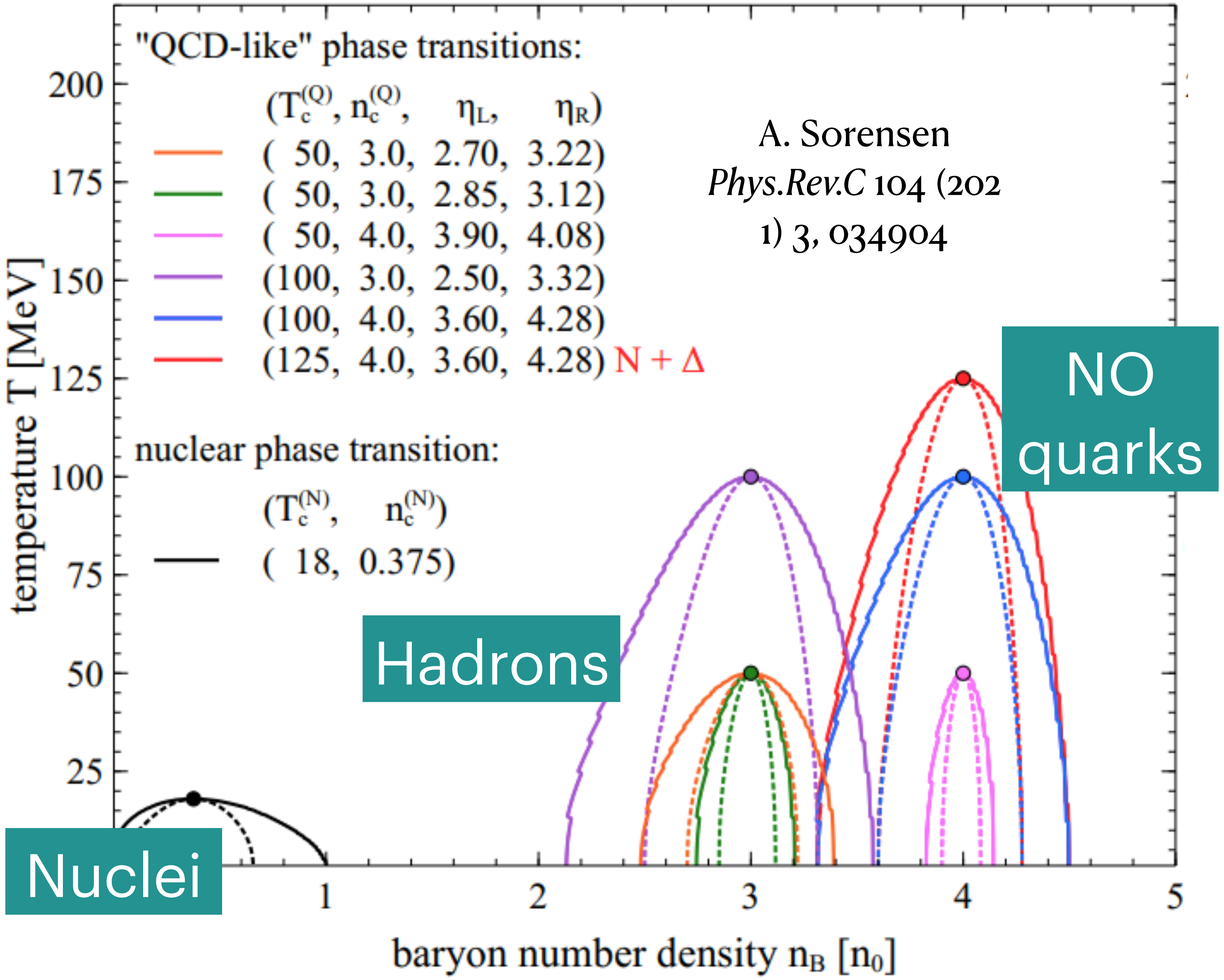
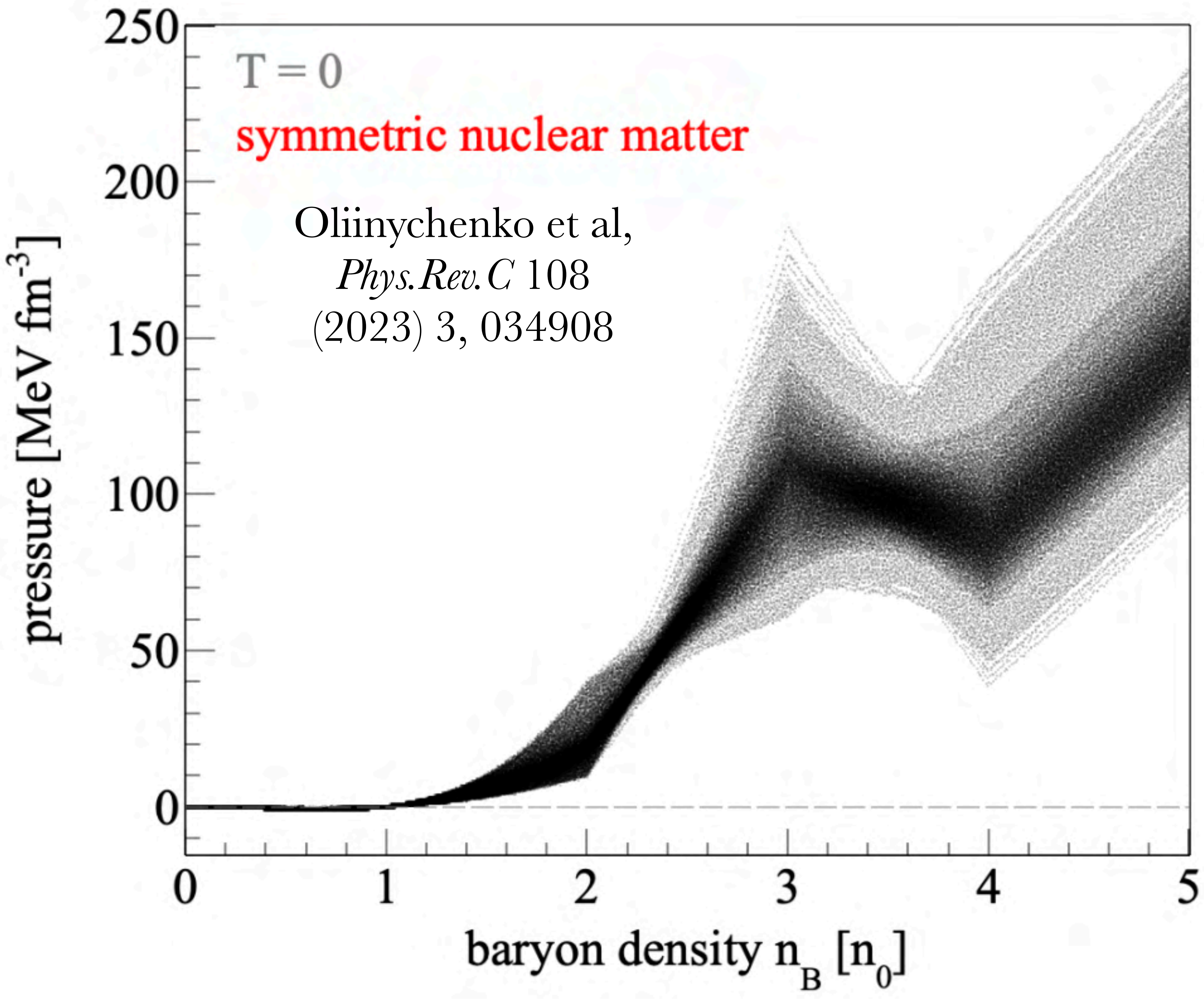
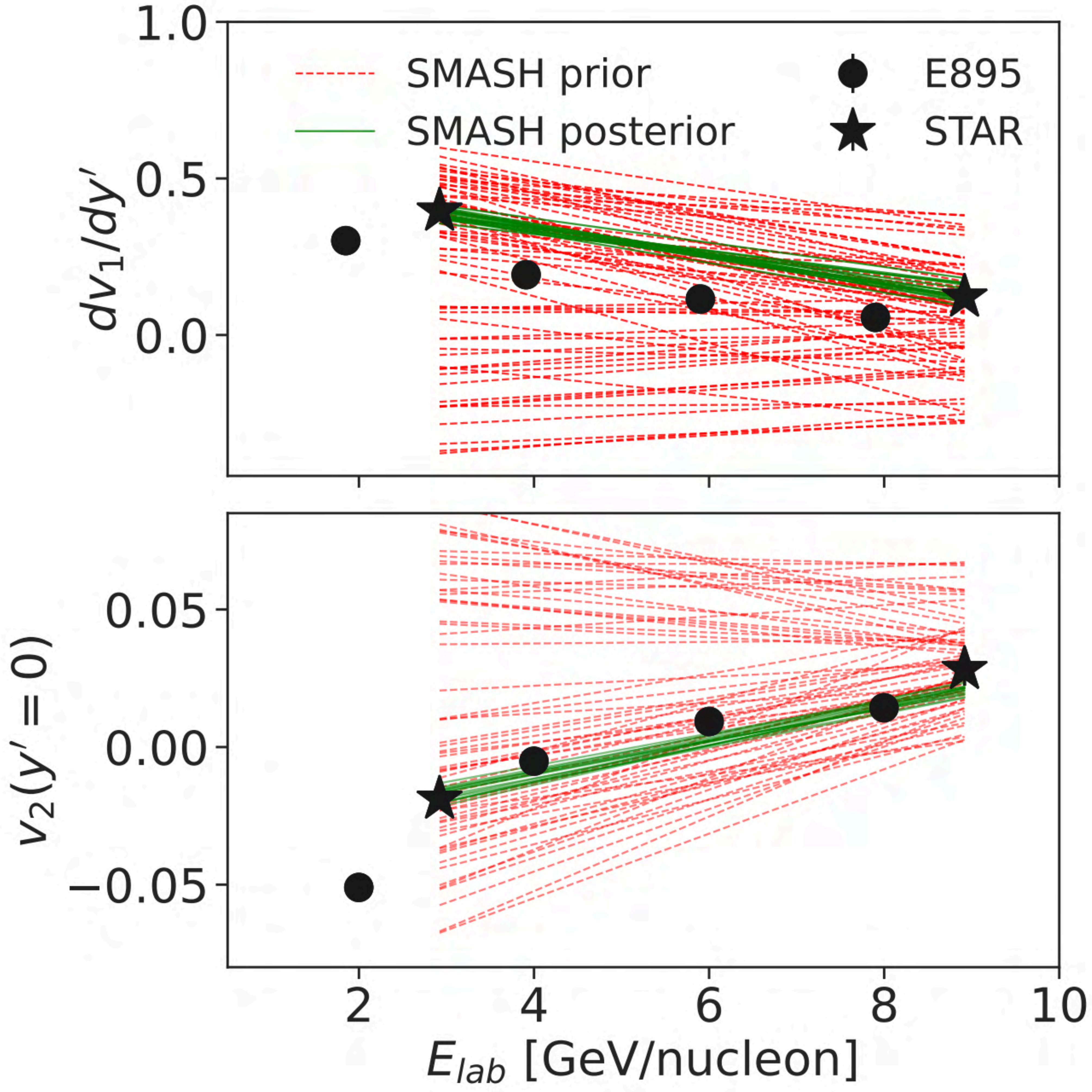


Peak in c_s^2 at $n_B^{peak} = [2,3]\, n_{sat}$ for HIC





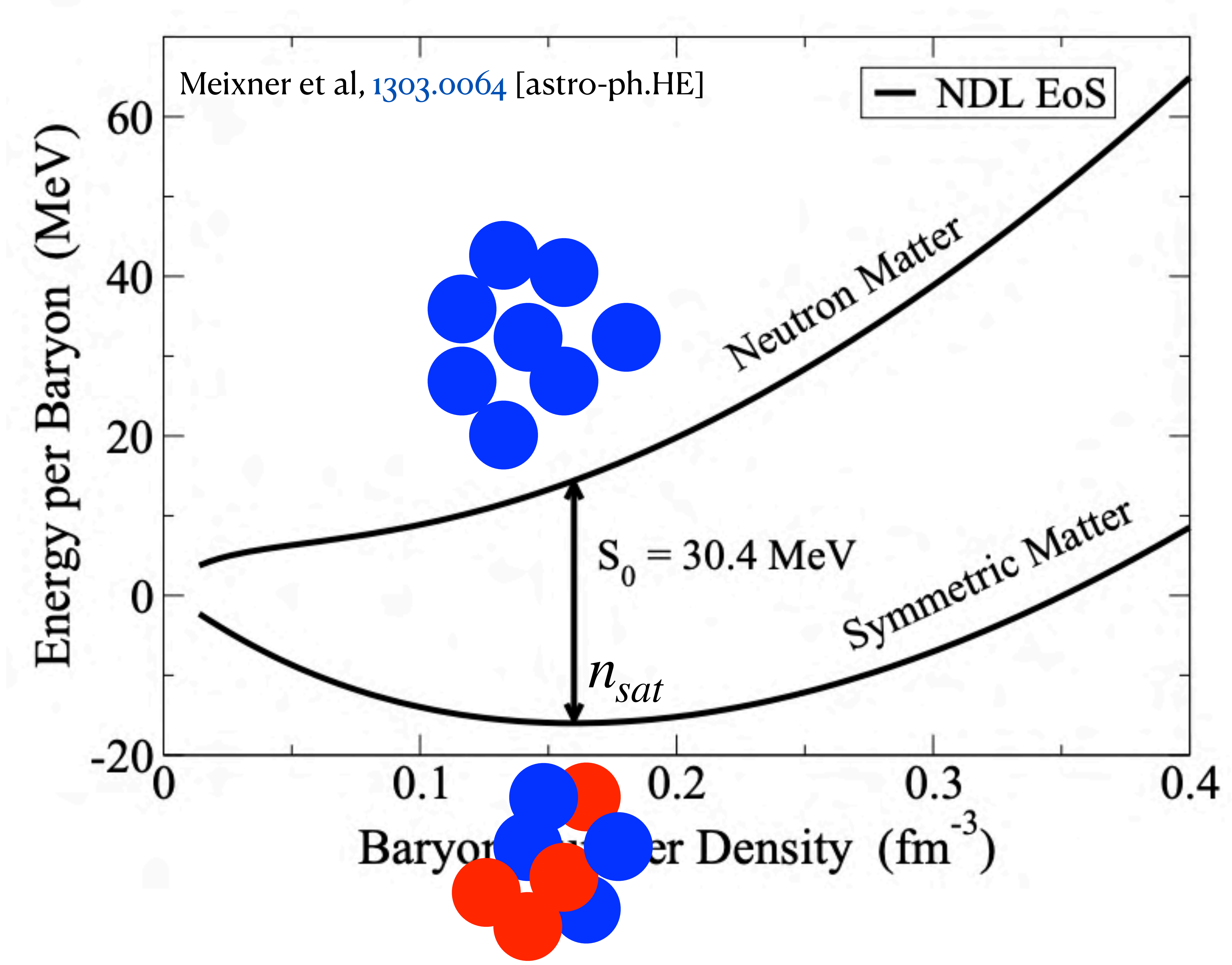
See also *Phys.Rev.Lett.* 131 (2023) 20, 202303

Systematic Hydro studies still needed

How do we connect HIC to NS?

Symmetric nuclear matter vs Pure neutron Matter

"Symmetry Energy"



Symmetric nuclear matter

$\mu_Q = 0$

Isospin asymmetry $\delta = 1 - 2Y_Q = 0$

$Y_Q = 0.5$

ONLY true for neutrons and protons!

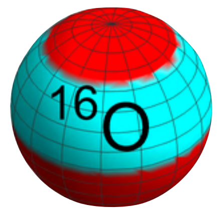
Symmetry energy

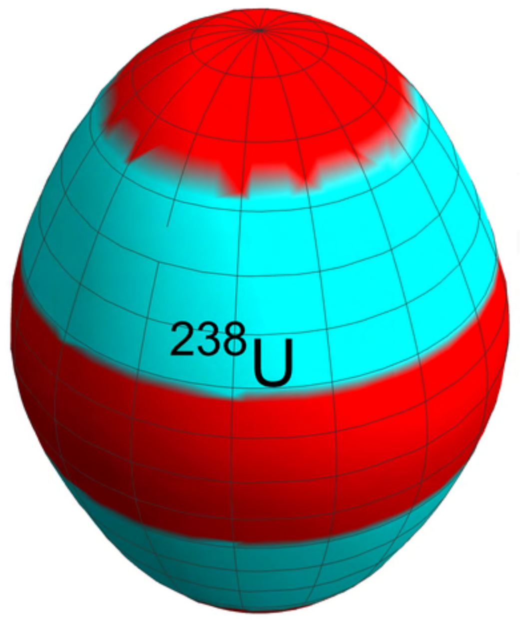
$$S(n_B) = \frac{\varepsilon_{PNM}}{n_B} - \frac{\varepsilon_{SNM}}{n_B}$$

Charge fraction of ions

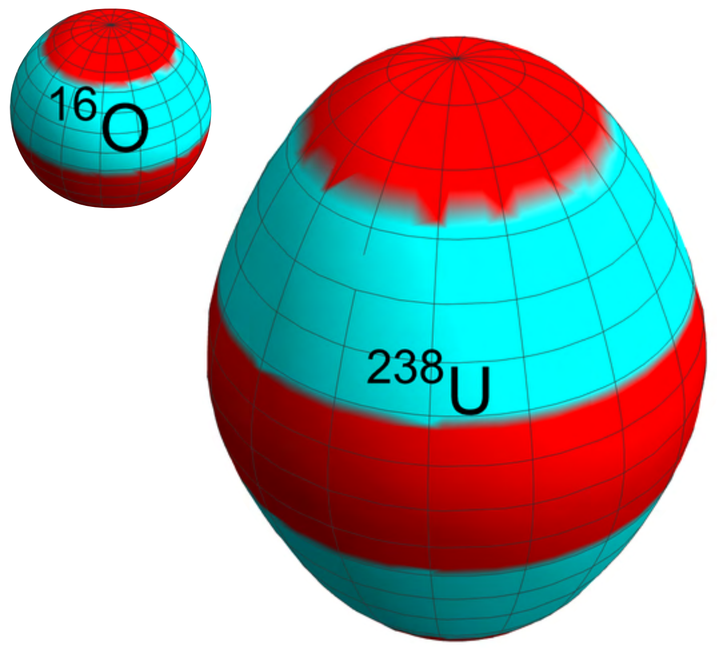
Isospin asymmetry

$$Y_Q = \frac{Z}{A} = \frac{n_Q}{n_B}$$





System	Z	A	Y_Q	Data?
O+O	8	16	0.5	some
Ne+Ne	10	20	0.5	no
Mg+Mg	12	24	0.5	no
Ca+Ca	20	40	0.5	no
Cu+Cu	29	63	0.46	yes
Ru+Ru	44	96	0.458	some
Ar+Ar	18	40	0.45	no
Xe+Xe	54	128	0.419	yes
Zr+Zr	40	96	0.417	some
Au+Au	79	198	0.399	yes
U+U	92	238	0.387	yes



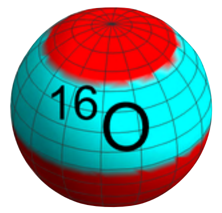
$Y_Q \lesssim 0.2$

Heavy-Ions and Neutron Stars are all on the same phase diagram, but very different Y_Q

Charge fraction of ions

Isospin asymmetry

$$Y_Q = \frac{Z}{A} = \frac{n_Q}{n_B}$$



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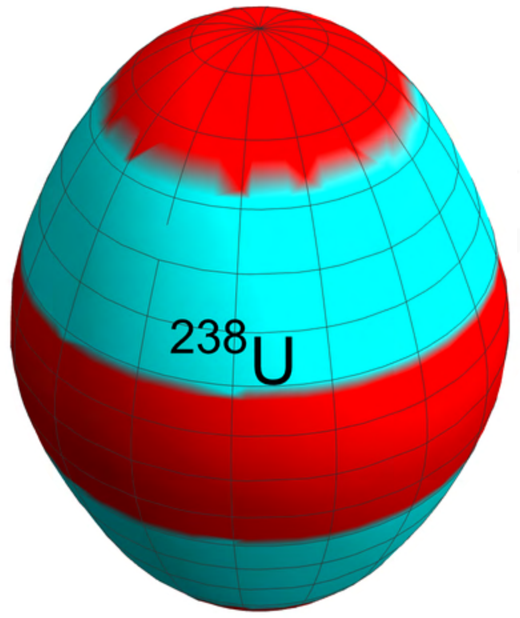
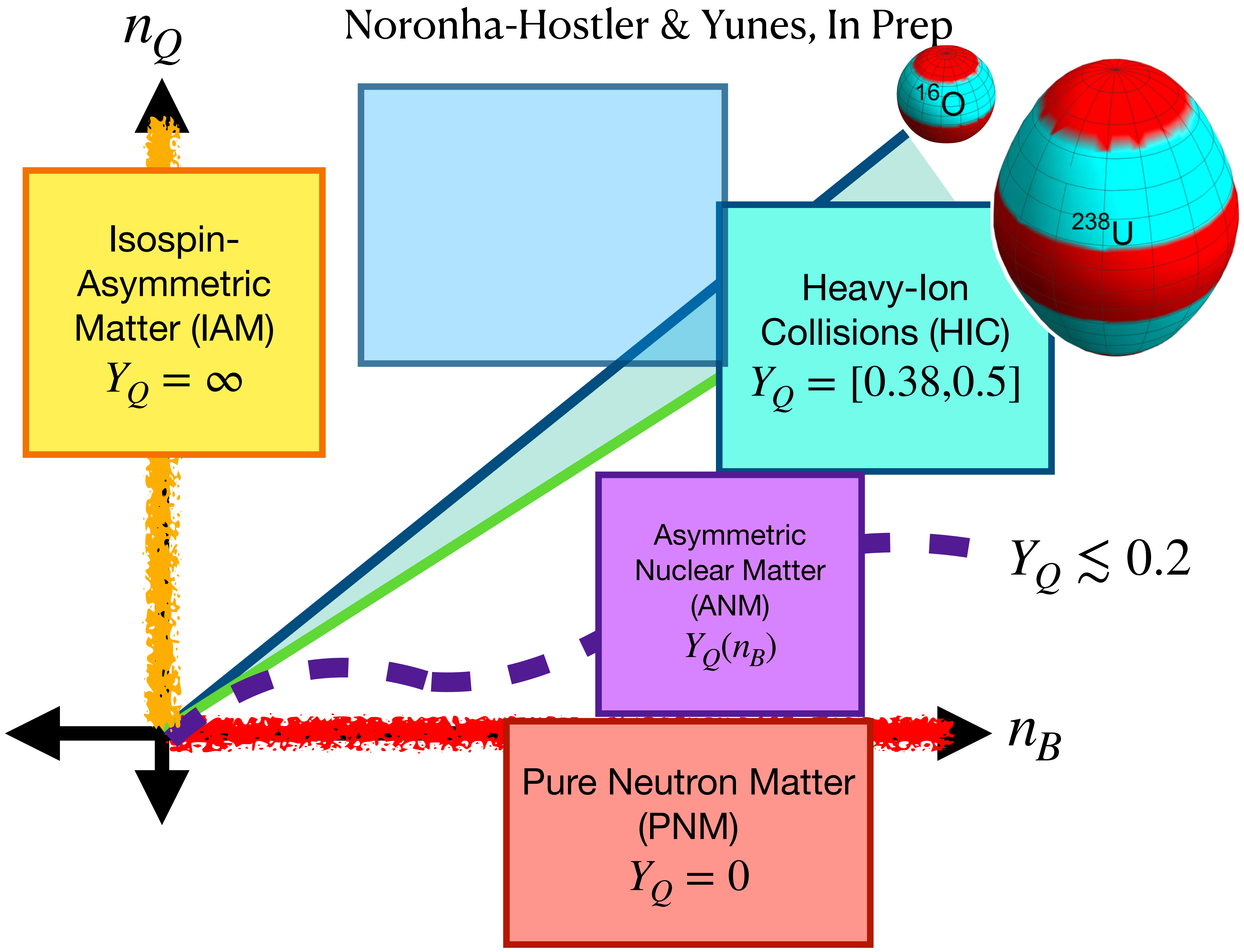


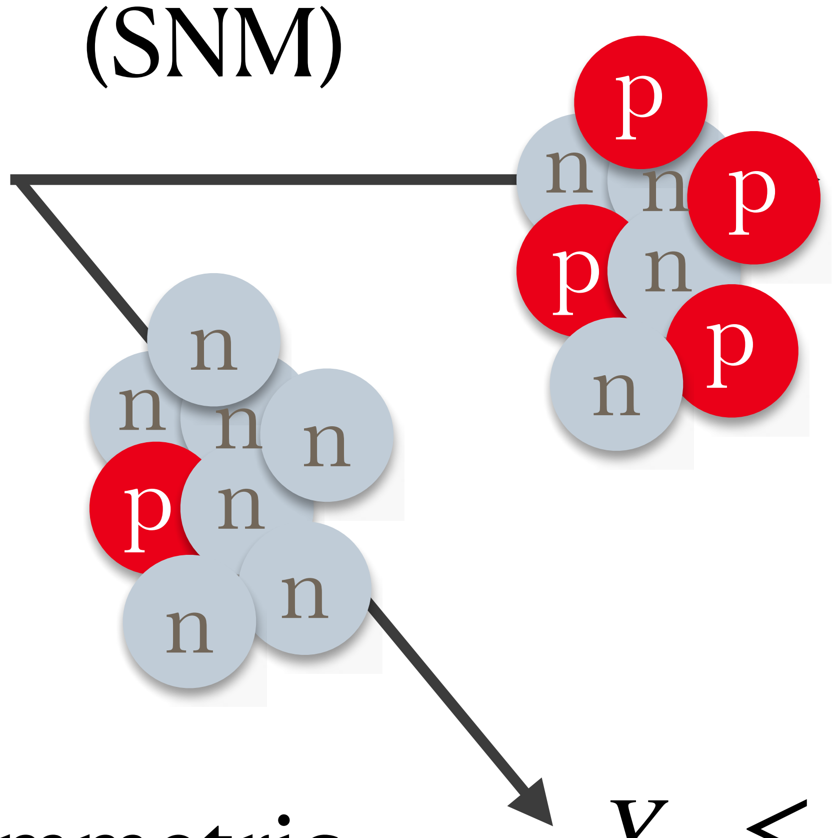


Heavy-Ions and Neutron Stars are all on the same phase diagram, but very different Y_Q

IGNORE Strange: Symmetry Energy Expansion

Connecting NS to HIC across Y_Q

Symmetric matter (SNM)



$Y_Q = 0.5$

$Y_Q \lesssim 0.1$

Asymmetric matter (ANM)

Original symmetry energy expansion from binding energies
Bombaci & Lombardo *Phys.Rev.C* 44 (1991) 1892-1900

Isospin asymmetry $\delta = 1 - 2Y_Q$

where $\delta = 0$ for SNM and $\delta = 1$ for PNM

$$\frac{E_{ANM}}{N_B} = \frac{E_{SNM}}{N_B} + E_{sym,2}\delta^2 + \mathcal{O}(\delta^4)$$

Expand in δ where odd terms drop due to isospin symmetry

Convert EOS from NS to HIC, expand around n_{sat}

$$\varepsilon_{HIC} = \varepsilon_{NS} - 4n_B\left[E_{sym,sat} + \frac{L}{3}\left(\frac{n_B}{n_{sat}} - 1\right) + \frac{K}{18}\left(\frac{n_B}{n_{sat}} - 1\right)^2 + \frac{J}{162}\left(\frac{n_B}{n_{sat}} - 1\right)^3\right]\left[\left(Y_Q^{HIC} - Y_{Q,NS}\right) + \left(Y_{Q,NS}^2 - \left(Y_Q^{HIC}\right)^2\right)\right]$$

$E_{sym,2}(n_B)$ 4 unknowns

To varing Y_Q^{HIC}
Yao et al, *Phys.Rev.C* 109 (2024) 6, 065803

What about hyperons?

Symmetry energy expansion with strangeness

Yang et al, 2504.18764 [nucl-th]

Original symmetry energy expansion considered only protons, neutrons

isospin asymmetry: $\delta_Q \equiv 1 - 2\,Y_Q$

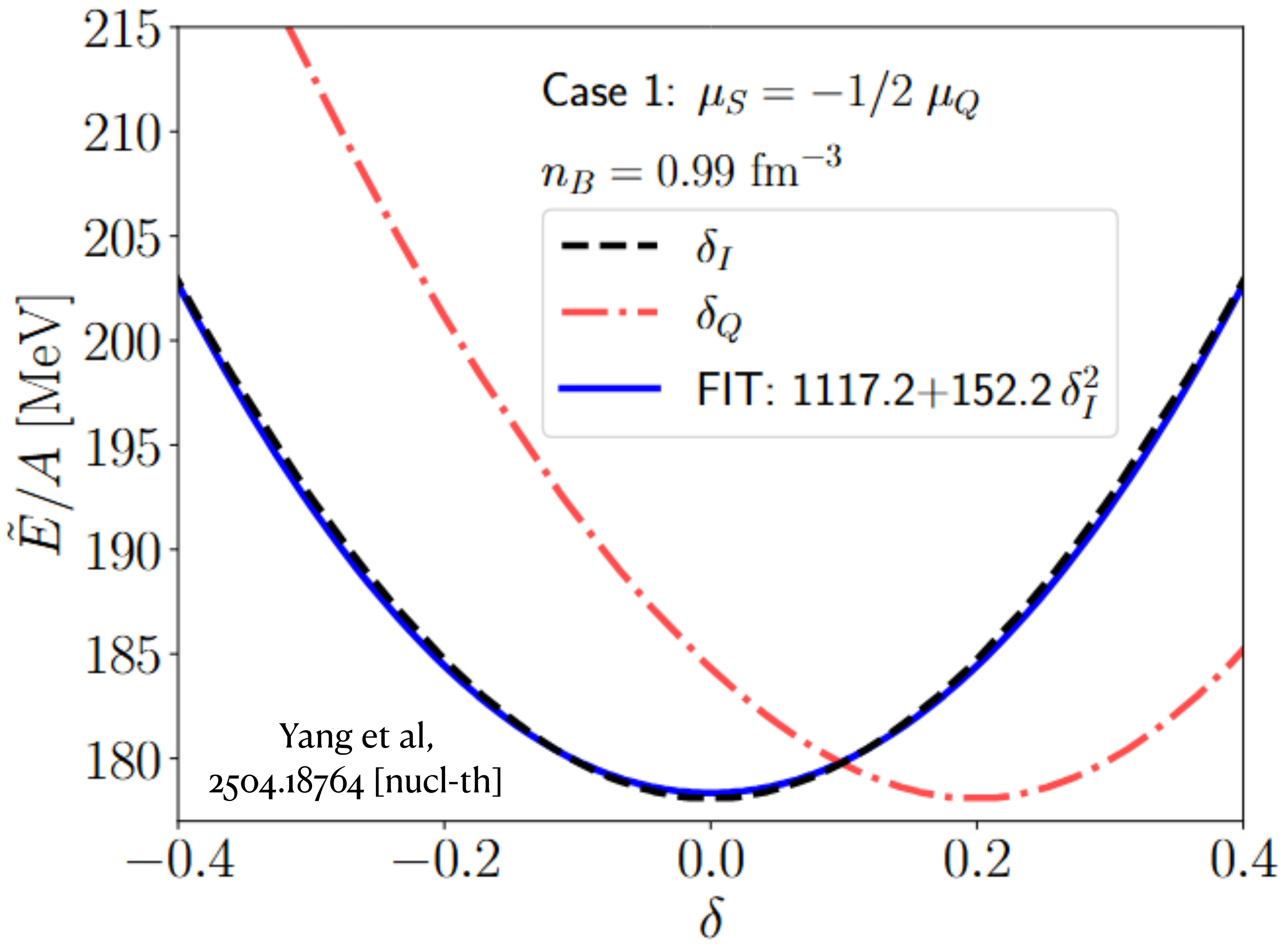
Gell-Mann-Nishijima formula

$$Q = I_z + \frac{1}{2}(B + \mathcal{S})$$

Corrected isospin asymmetry

$$\delta_I \equiv 1 + Y_S - 2\,Y_Q$$

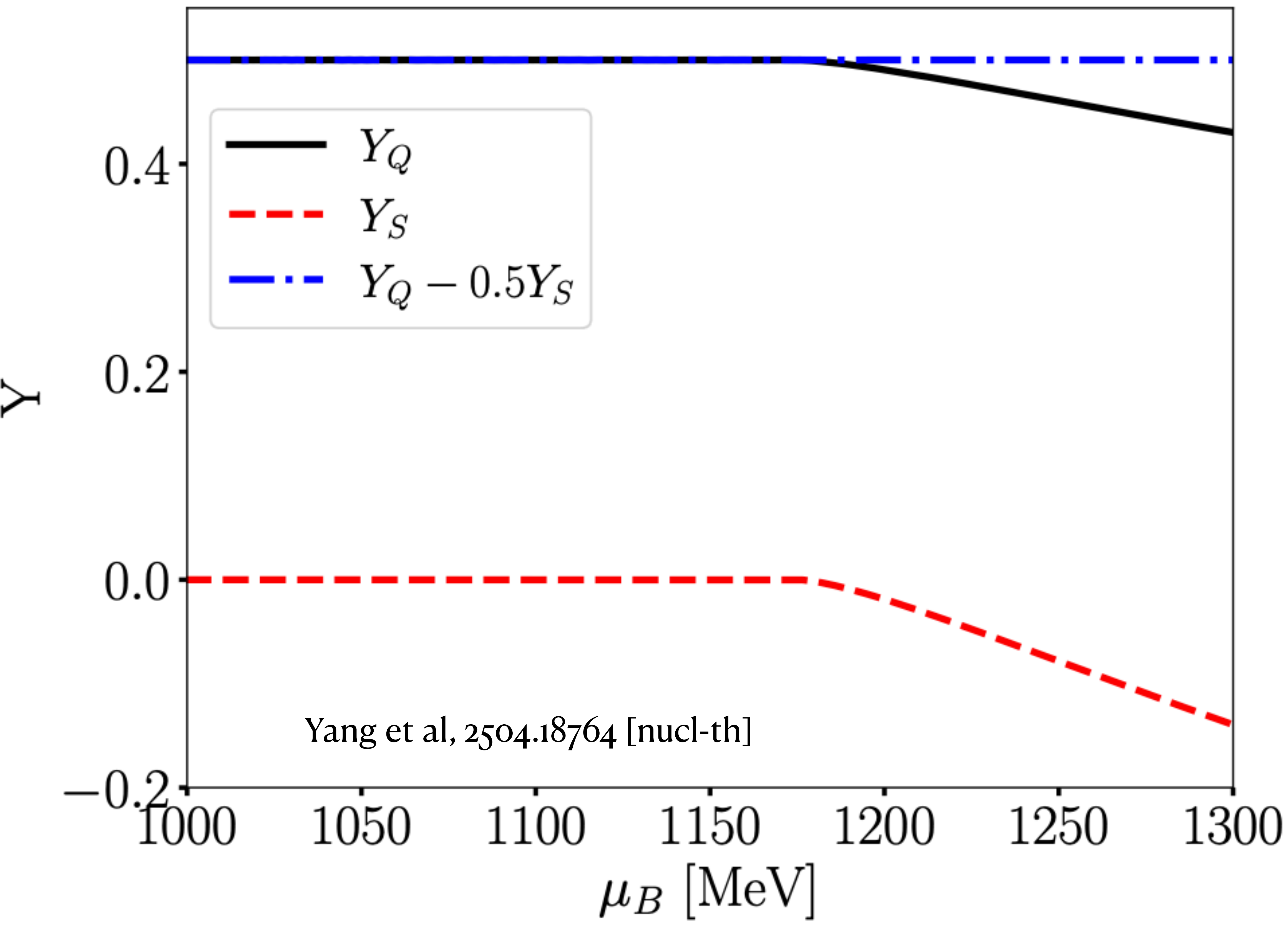
Original symmetry energy expansion misses the ground state of nuclear matter when hyperons are present



Strangeness contribution to SNM

You really CANNOT ignore it

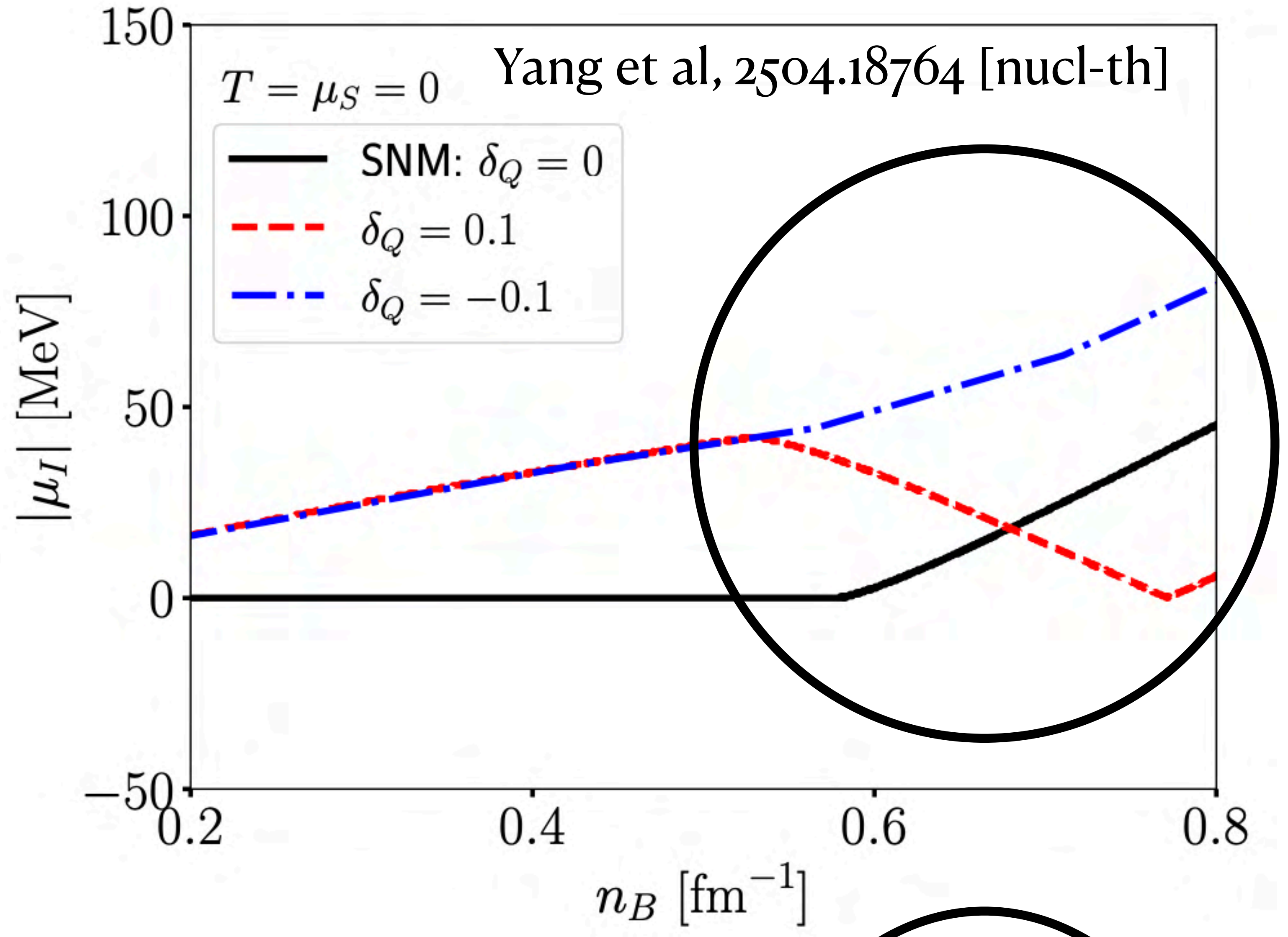
For SNM, $Y_Q \neq 0.5$



Wrong isospin asymmetry

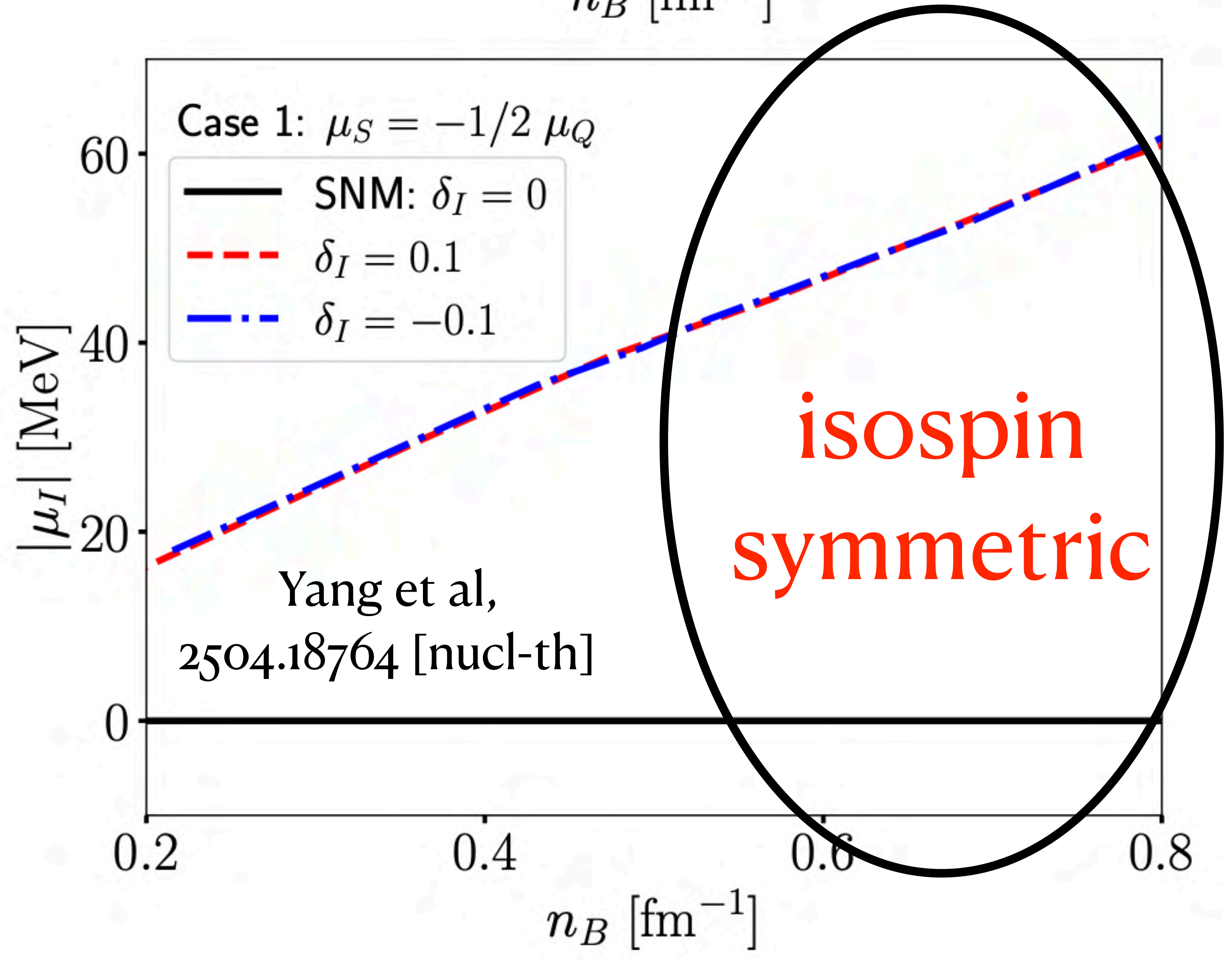
$\delta_Q = 1 - 2Y_Q$

NOT isospin symmetric



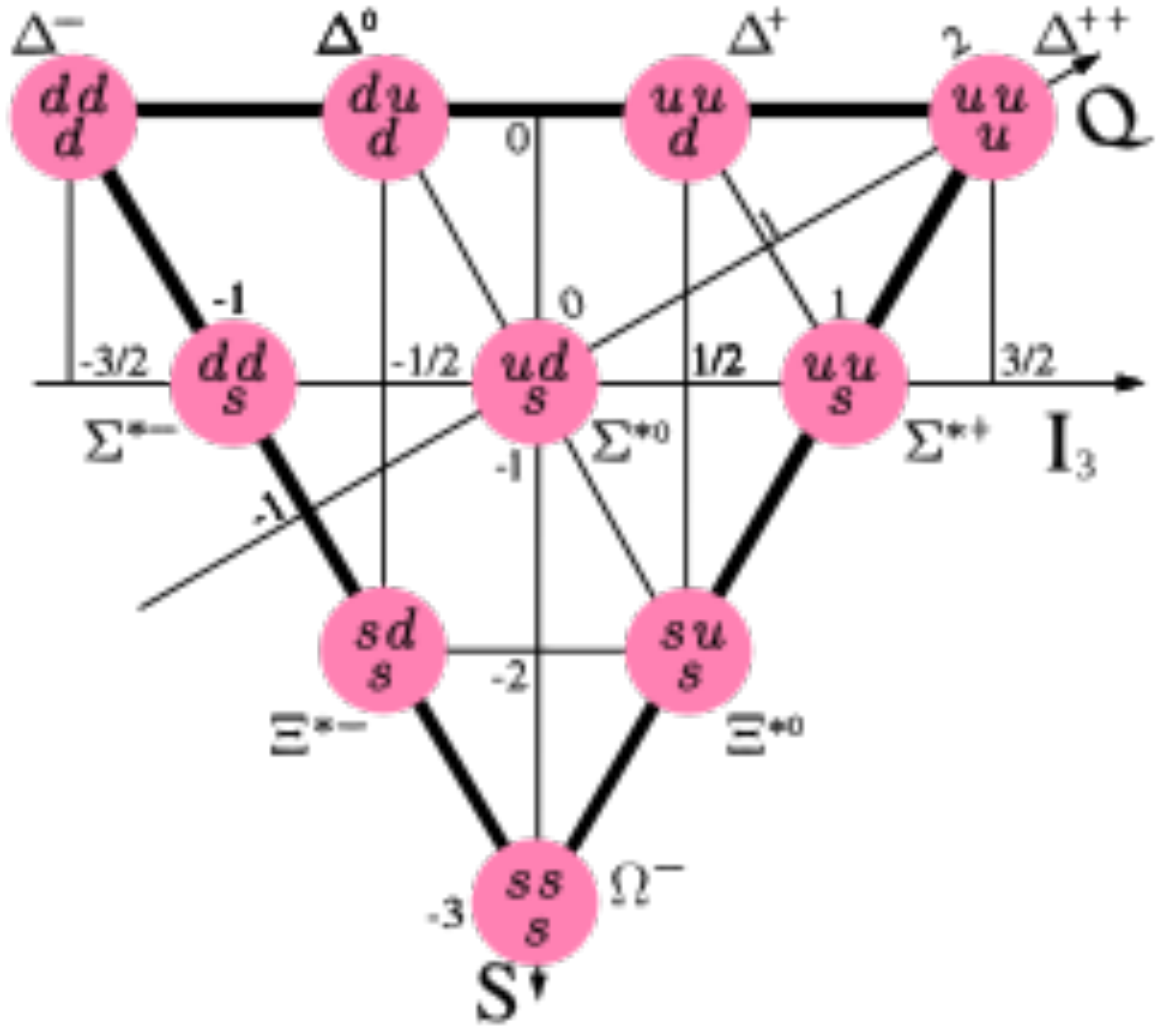
Correct isospin asymmetry

$\delta_I = 1 - 2Y_Q + Y_S$

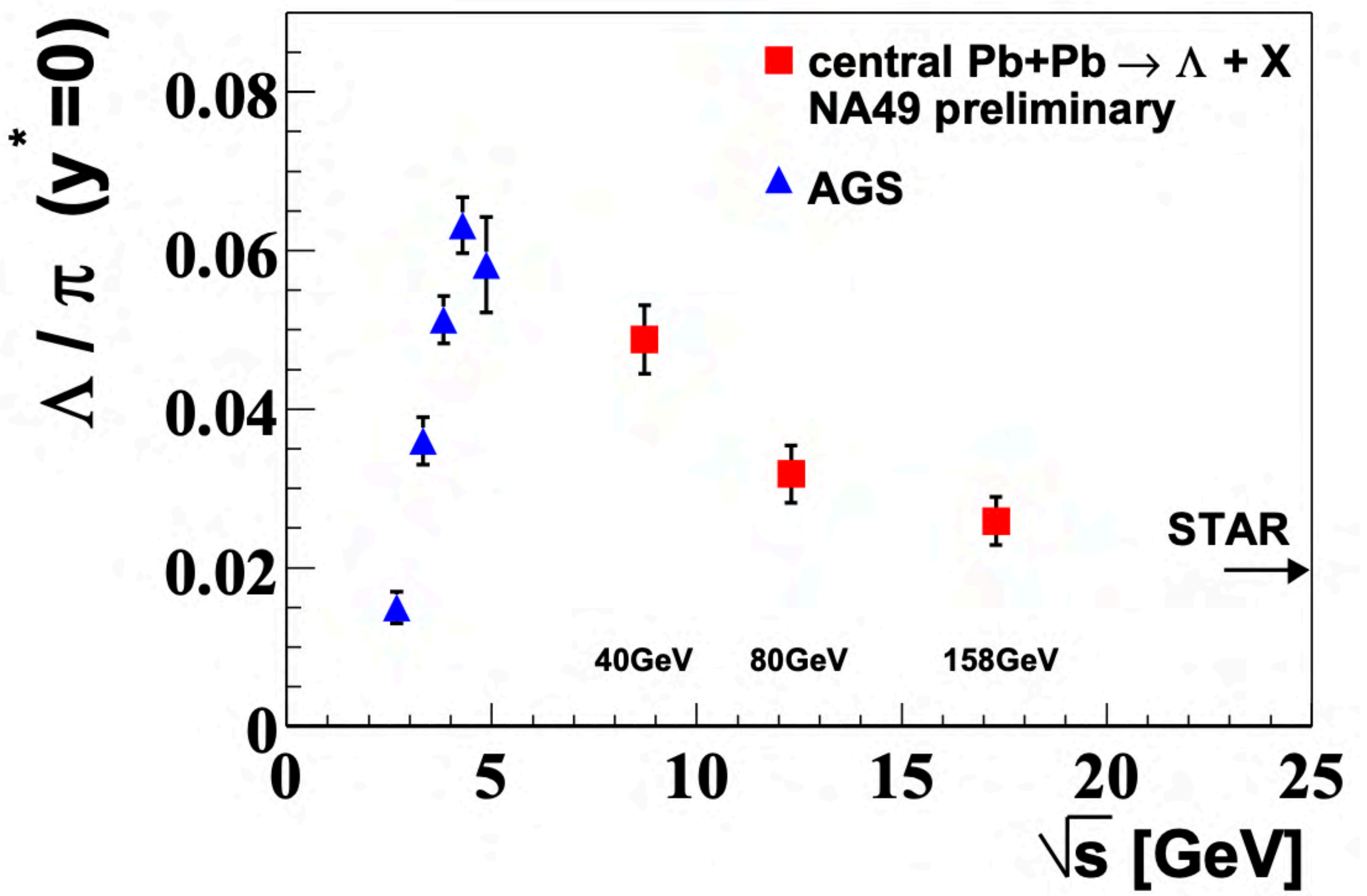


PNM is meaningless for $\delta_I = 1$, then $Y_S = 2Y_Q$

Ignoring strangeness



[NA49] *J.Phys.G* 28 (2002) 1761-1768

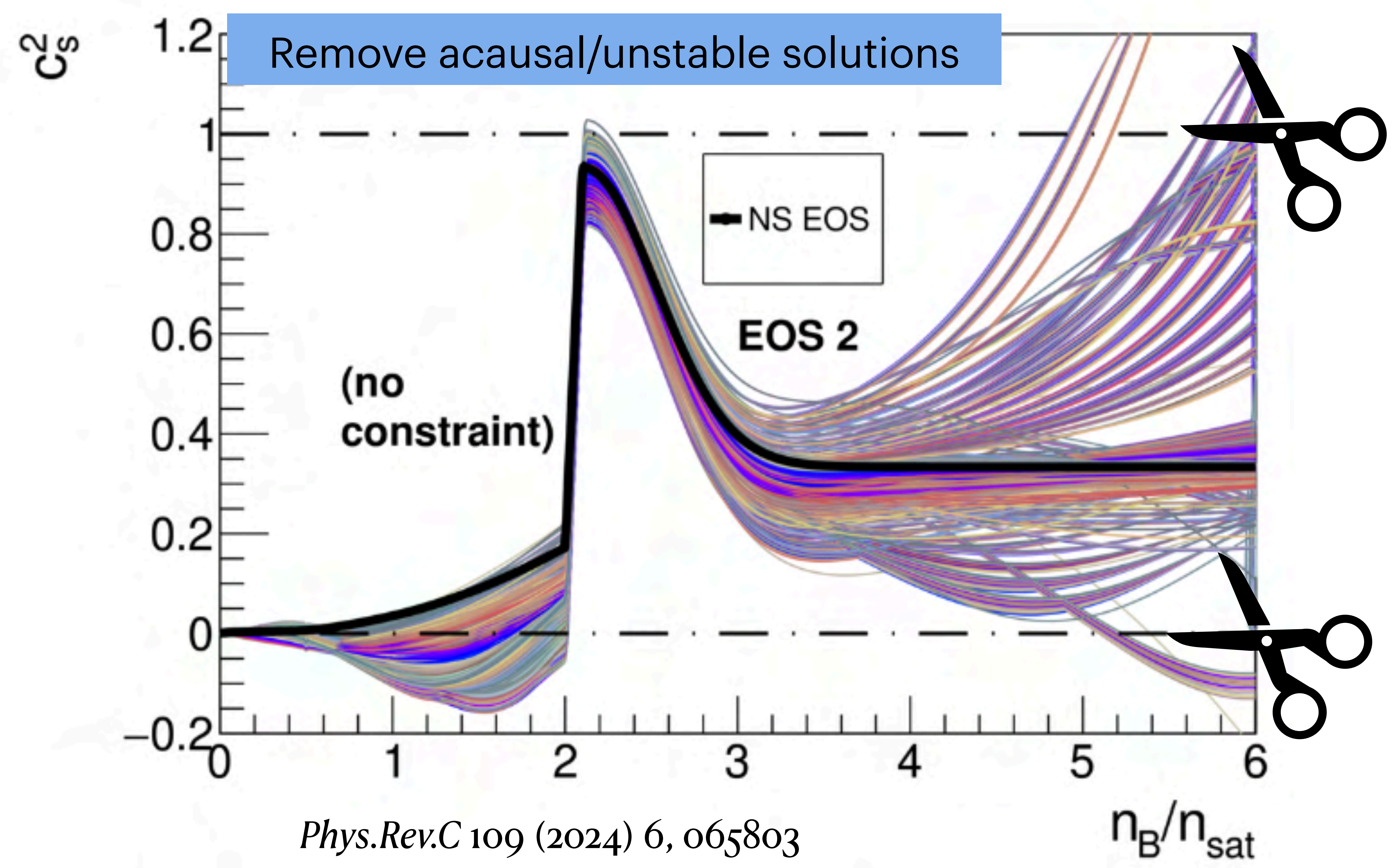


How do low-energy heavy-ion collisions at $T = 0$ connect to neutron stars?

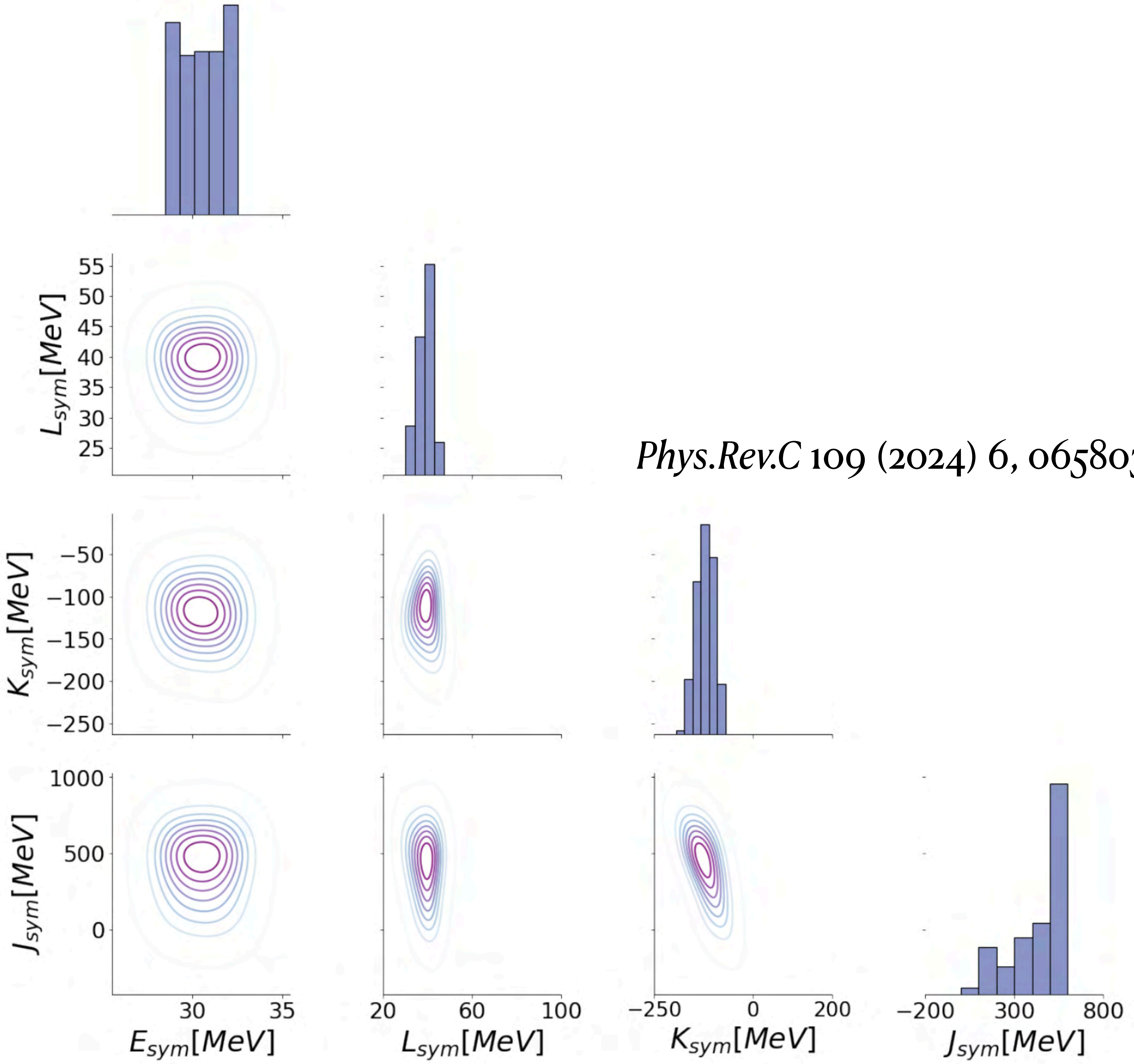
Symmetry energy expansion

Given neutron star equation of state → convert to HIC and can constrain by $0 \leq c_s^2 \leq 1$ and saturation properties.

n_B



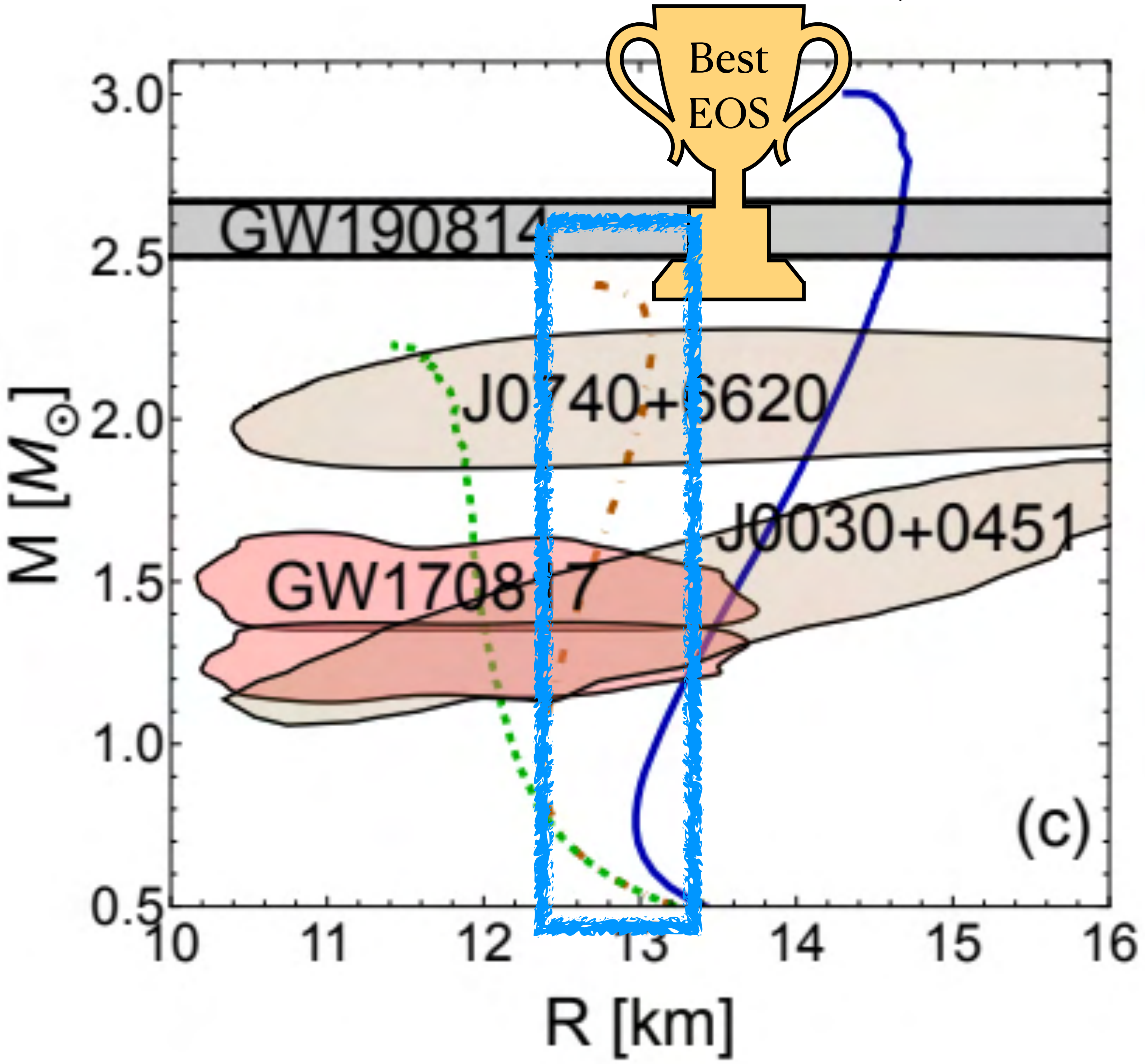
Phys.Rev.C 109 (2024) 6, 065803

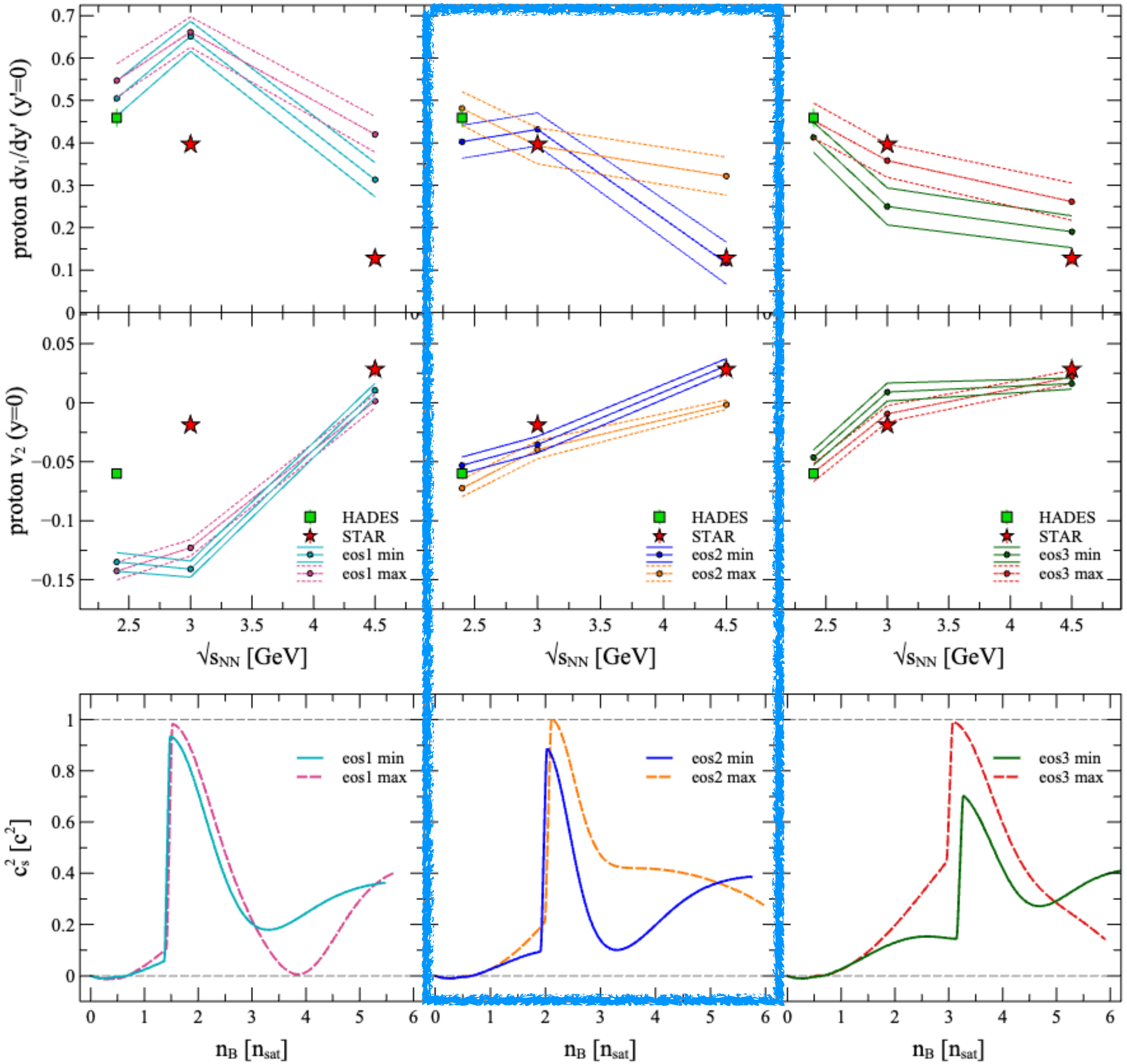


Phys.Rev.C 109 (2024) 6, 065803

Ultra heavy neutron star EOS works HIC

Phys.Rev.C 109 (2024) 6, 065803

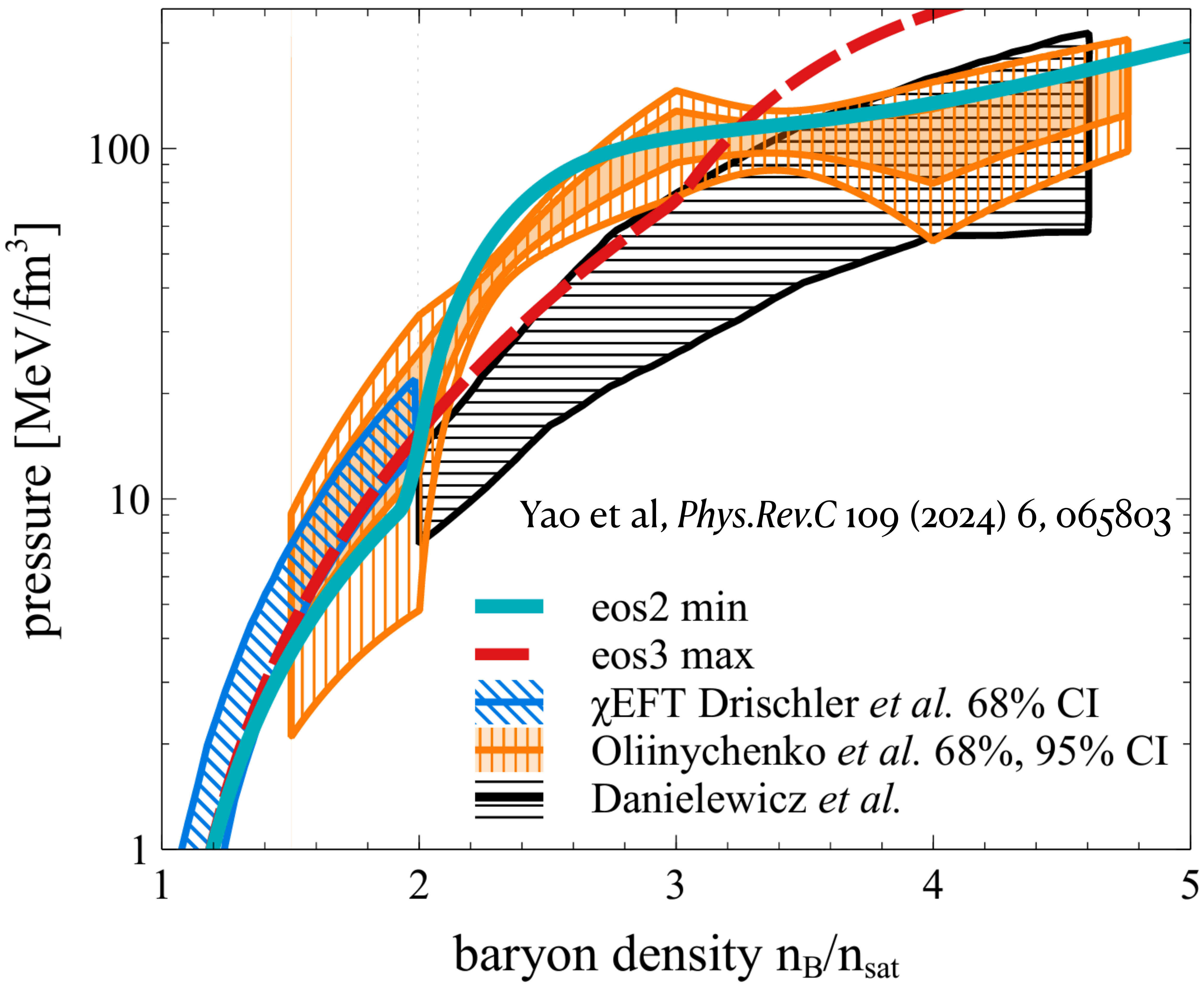




Take extremes of the EOS band derived for heavy-ion collisions, run in hadron transport, and compare to heavy-ion collision flow data

Ultra heavy neutron star EOS works HIC

But, this does NOT match hadron only transport models



But, this is NOT the end of the story..

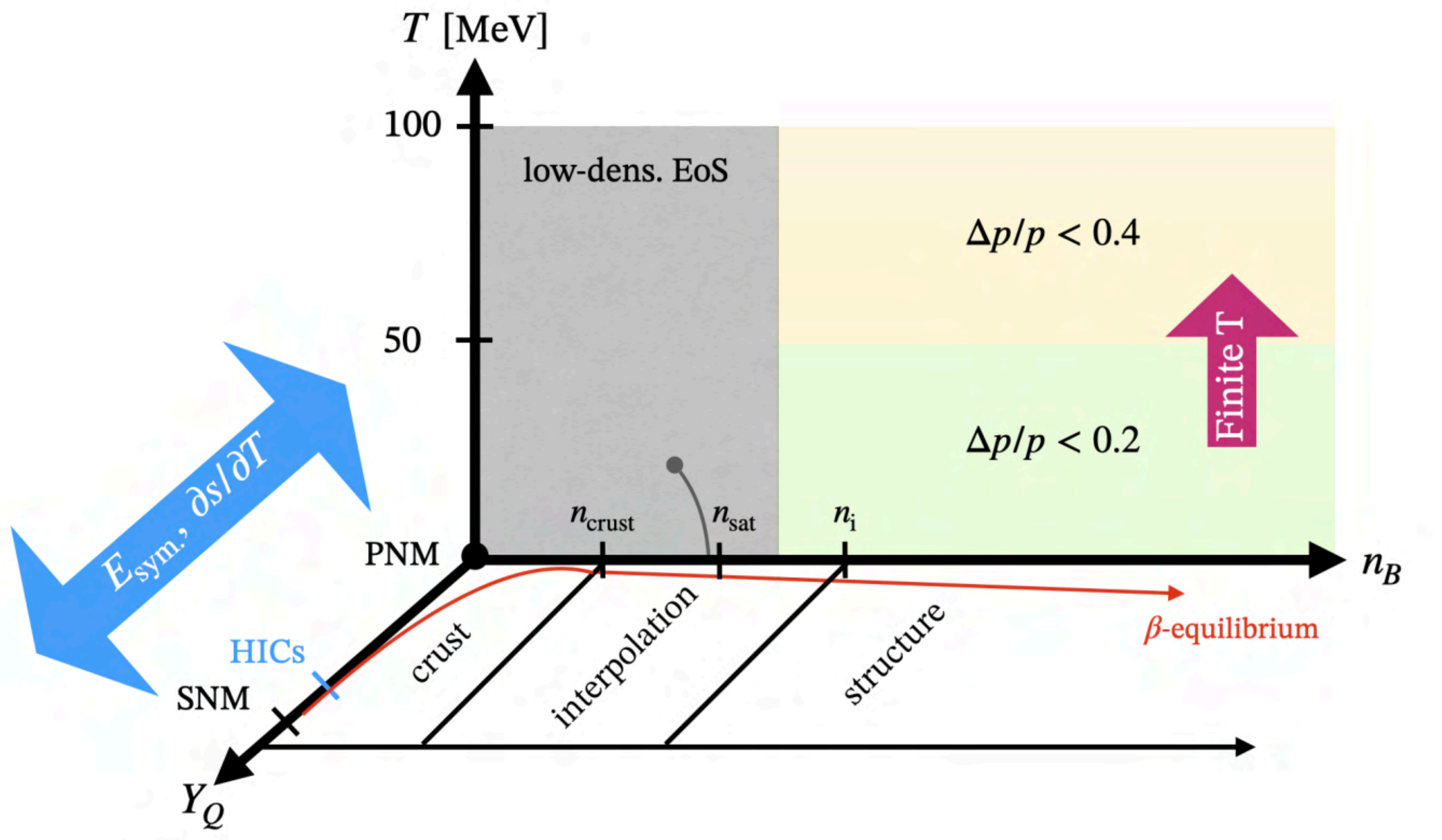
- Strangeness symmetry energy expansion
- Redo with hydrodynamics
- Properly include quarks
- Bayesian analysis BOTH with NS and HIC + symmetry energy coefficients
- Momentum dependence potentials
- A lot of unused HIC data still…

Proposal: isospin HIC scan

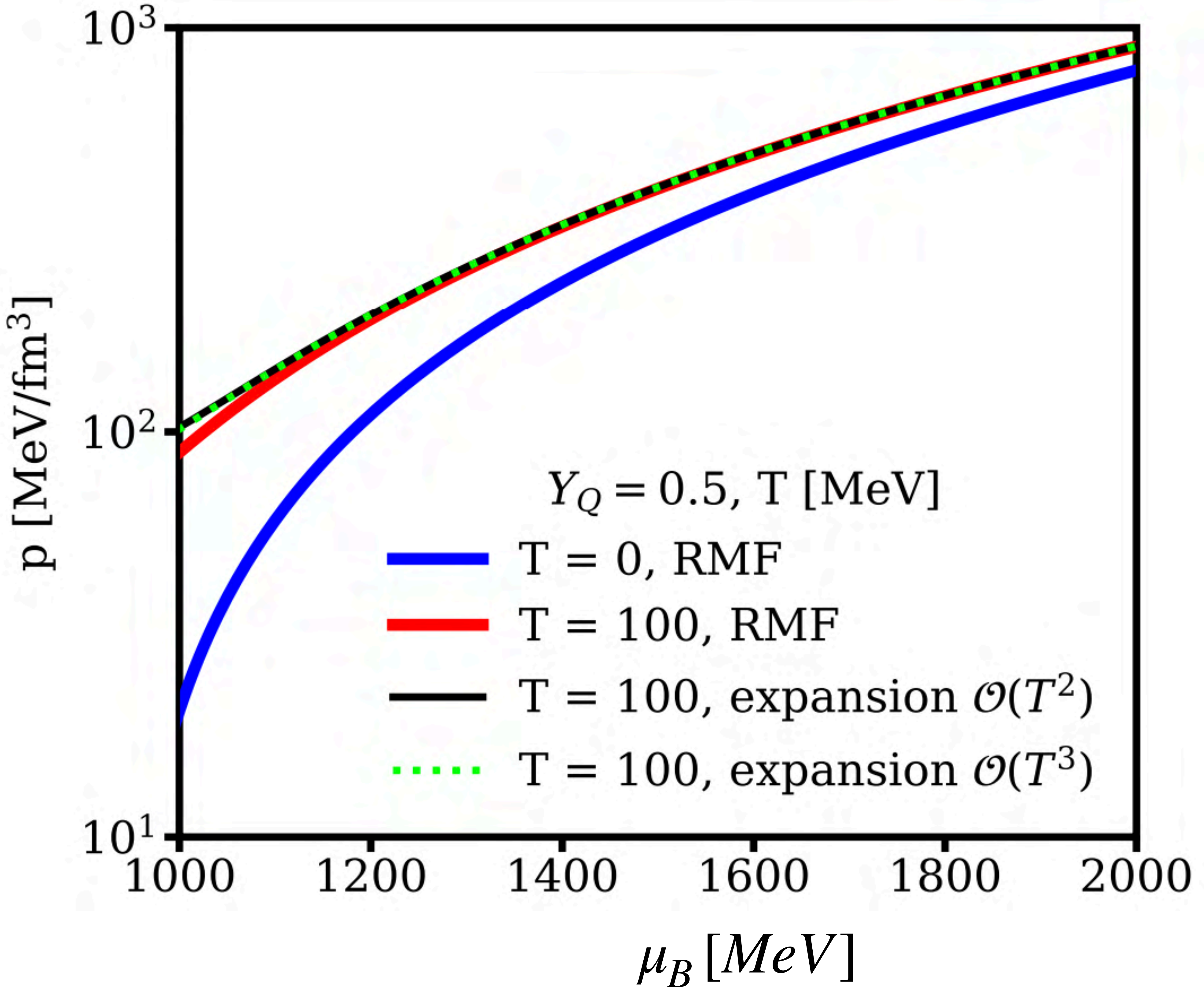
New finite T expansion

1D EOS → 3D EOS

Mroczek, Yao et al, 2404.01658 [astro-ph.HE]



+Liam, Alex, Elias (in this room!)



Expand from a cold, neutron star EOS

$$p(T,\vec{\mu}) = p_{T=0} + \frac{1}{2}\frac{\partial s}{\partial T}\Big|_{T=0,\vec{\mu}} T^2 + \mathcal{O}(T^3)$$

Yields across $\frac{Z}{A}$ and the neutron star equation of state

Repurposing isobars

Nana, Salinas san Martin, JNH 2411.03705 [nucl-th]

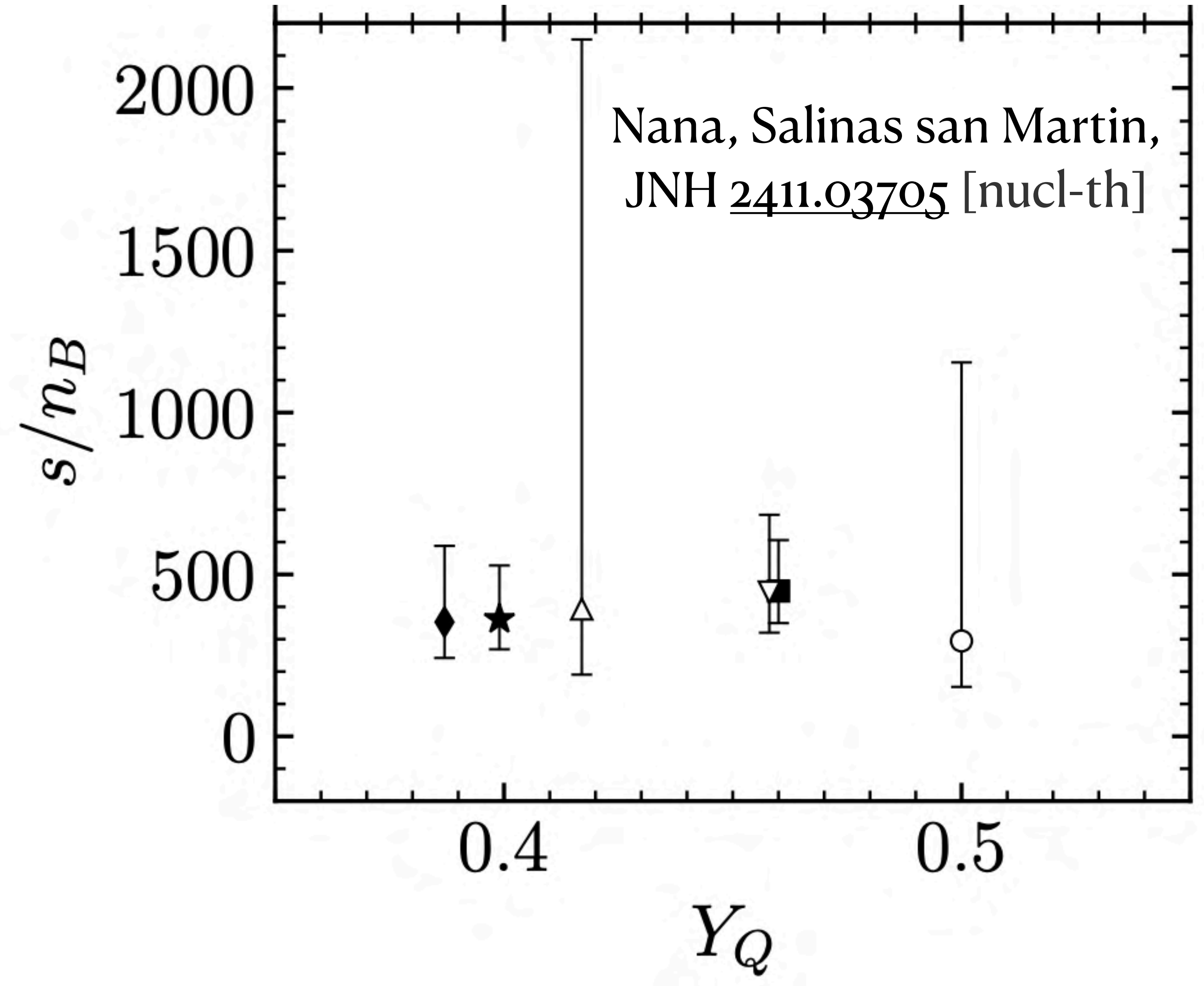
Need information about how $\partial s/\partial T$ varies with Y_Q

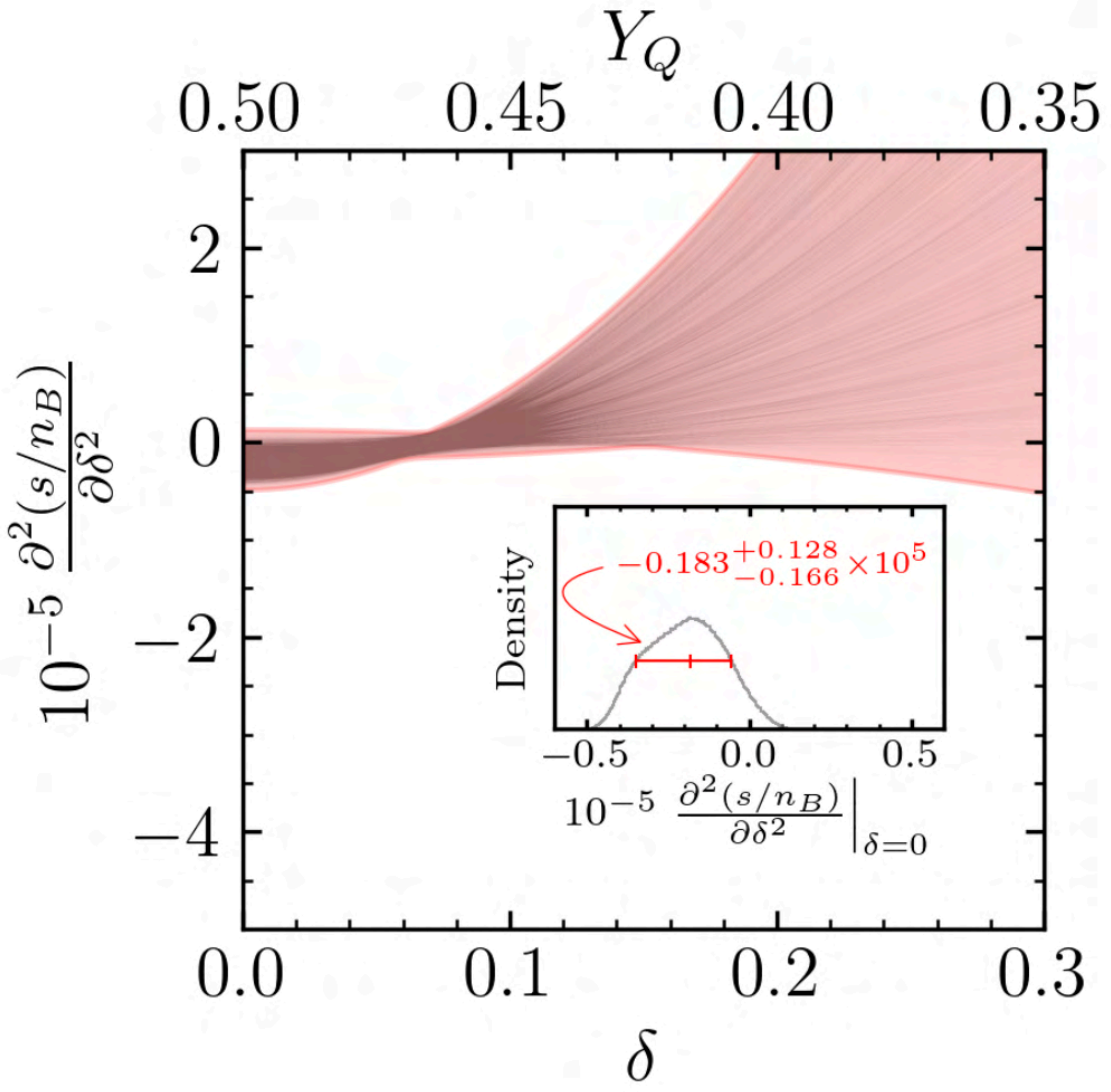
$$\left.\frac{\partial s/n_B(T,n_B,Y_Q)}{\partial T}\right|_{T=0} = \frac{1}{n_B}\left.\frac{\partial s_{\rm HIC}(T,n_B,Y_Q)}{\partial T}\right|_{T=\delta_{\rm HIC}=0} + \frac{1}{2}\left(1-\frac{Y_Q}{Y_Q^{\rm HIC}}\right)^2 \left.\frac{\partial^3 (s/n_B)_{\rm HIC,2}(T,n_B,\delta_{\rm HIC})}{\partial T \partial \delta^2_{\rm HIC}}\right|_{T=\delta_{\rm HIC}=0}$$

How do we get this information?

Thermal models from heavy-ion collisions and varying Y_Q!

Proof-of-principle from RHIC $\sqrt{s} = 200$ GeV



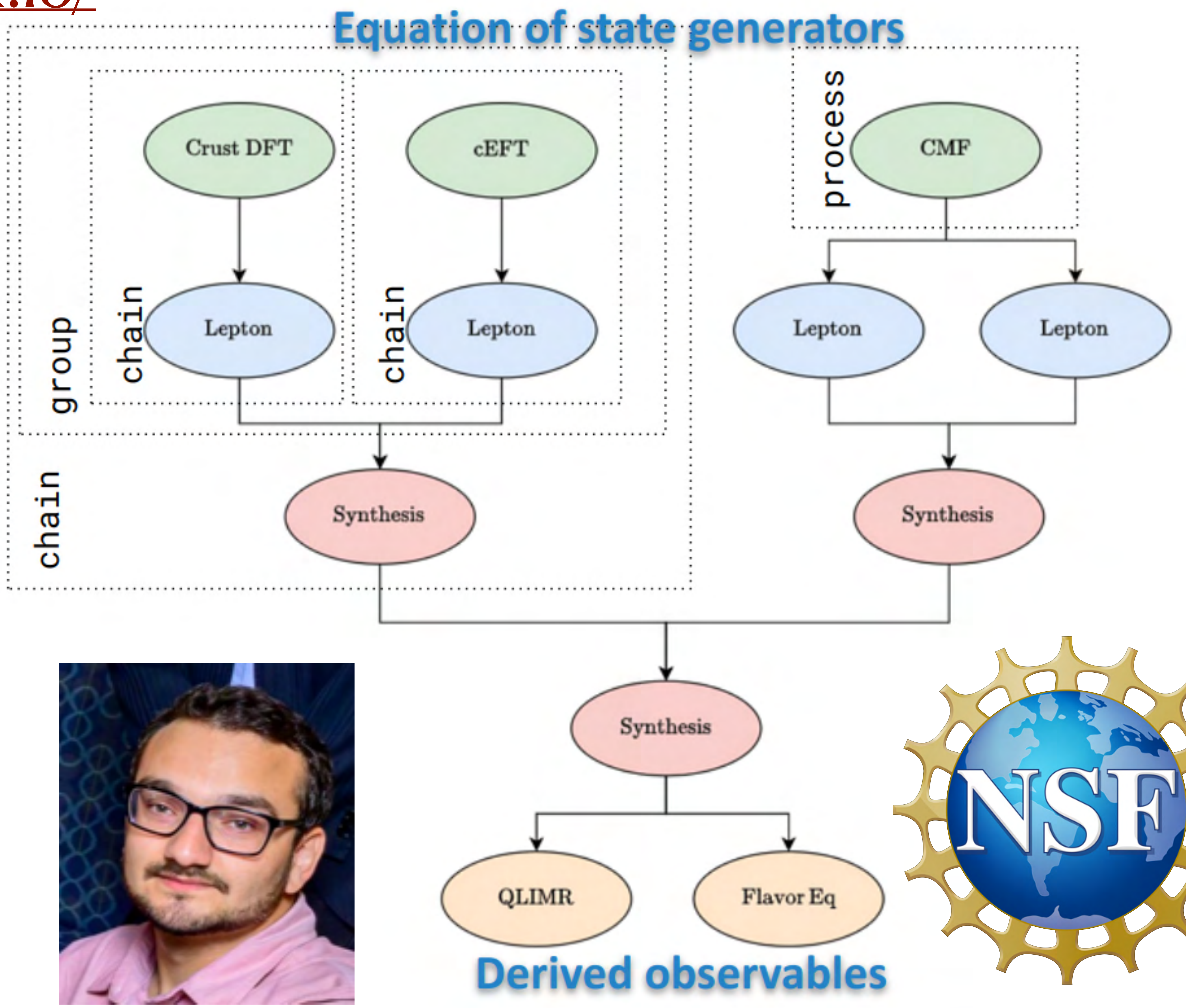


Open-source tools for more cross-disciplinary connections!

muses https://ce.musesframework.io/

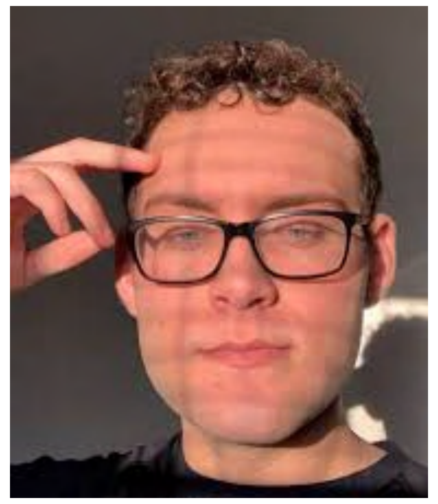
- 7 available equation of state (EOS) modules
- 6 new EOS modules in next year+2D synthesis
- 3 available observable modules (2+ coming soon)
- Both heavy-ion and neutron star EOS available
- β-release out and available! Possible to run crust to core of a neutron star+calculate mass, radius, tidal deformability etc
- Looking for new collaborators!

Software across the QCD phase diagram



Later releases will connect heavy-ion and neutron star EOS across the entire phase diagram!

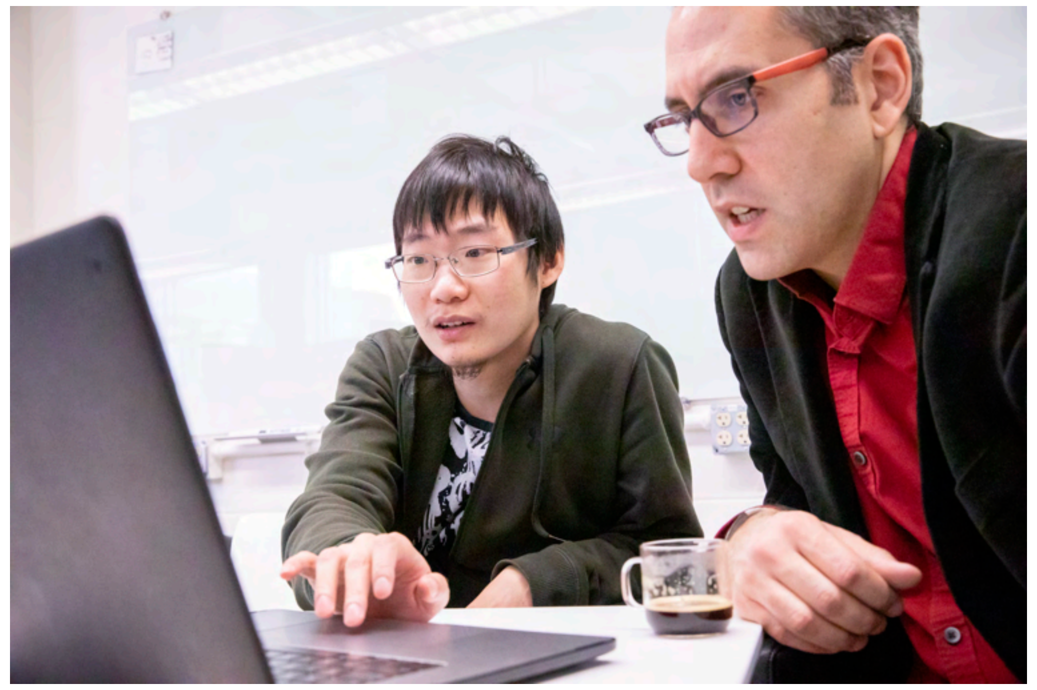
Thank you to my group + collaborators!



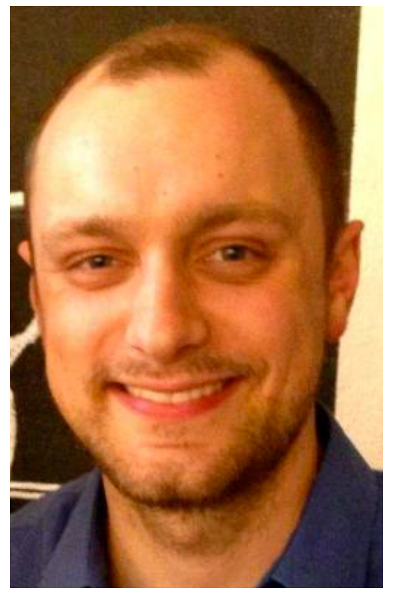








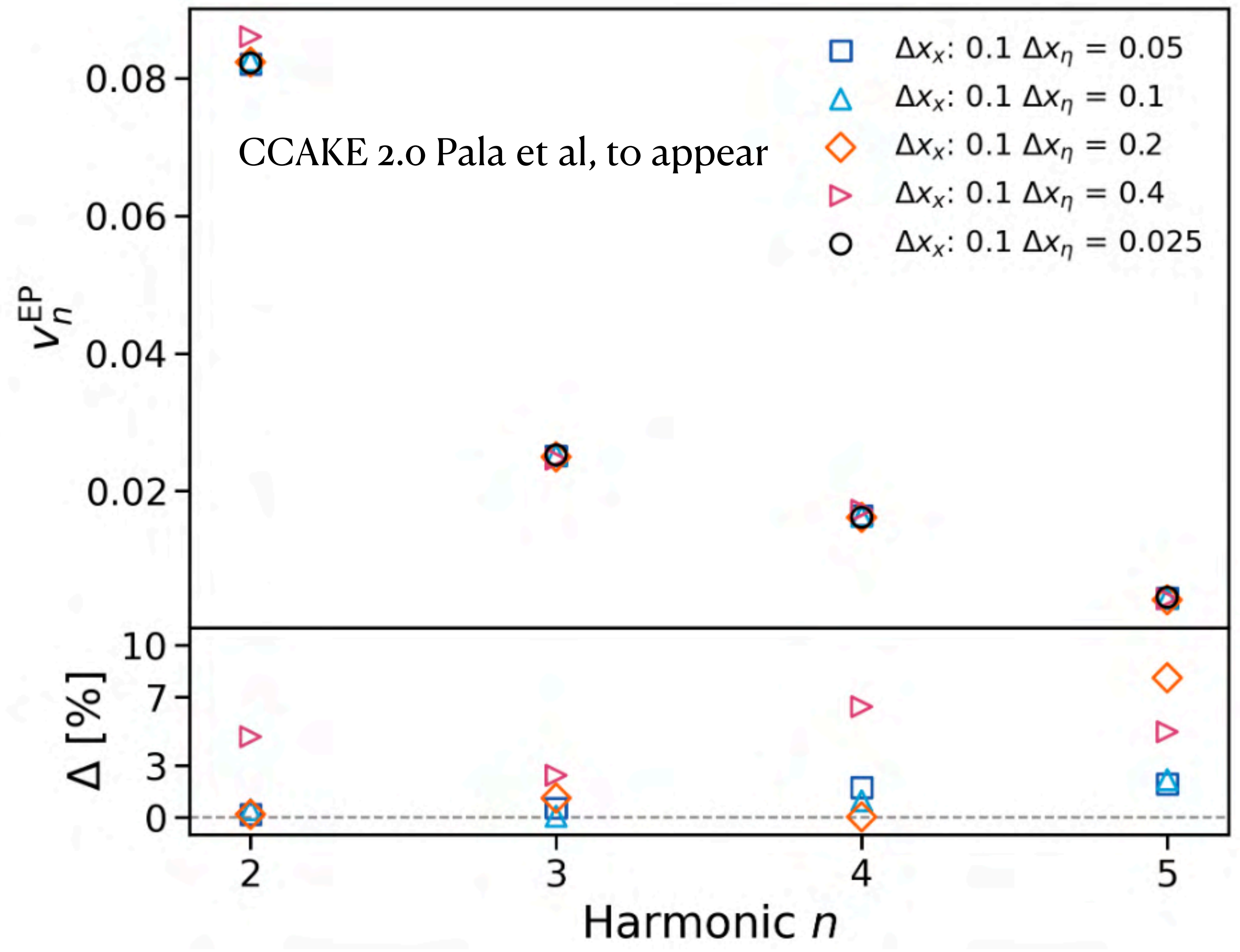




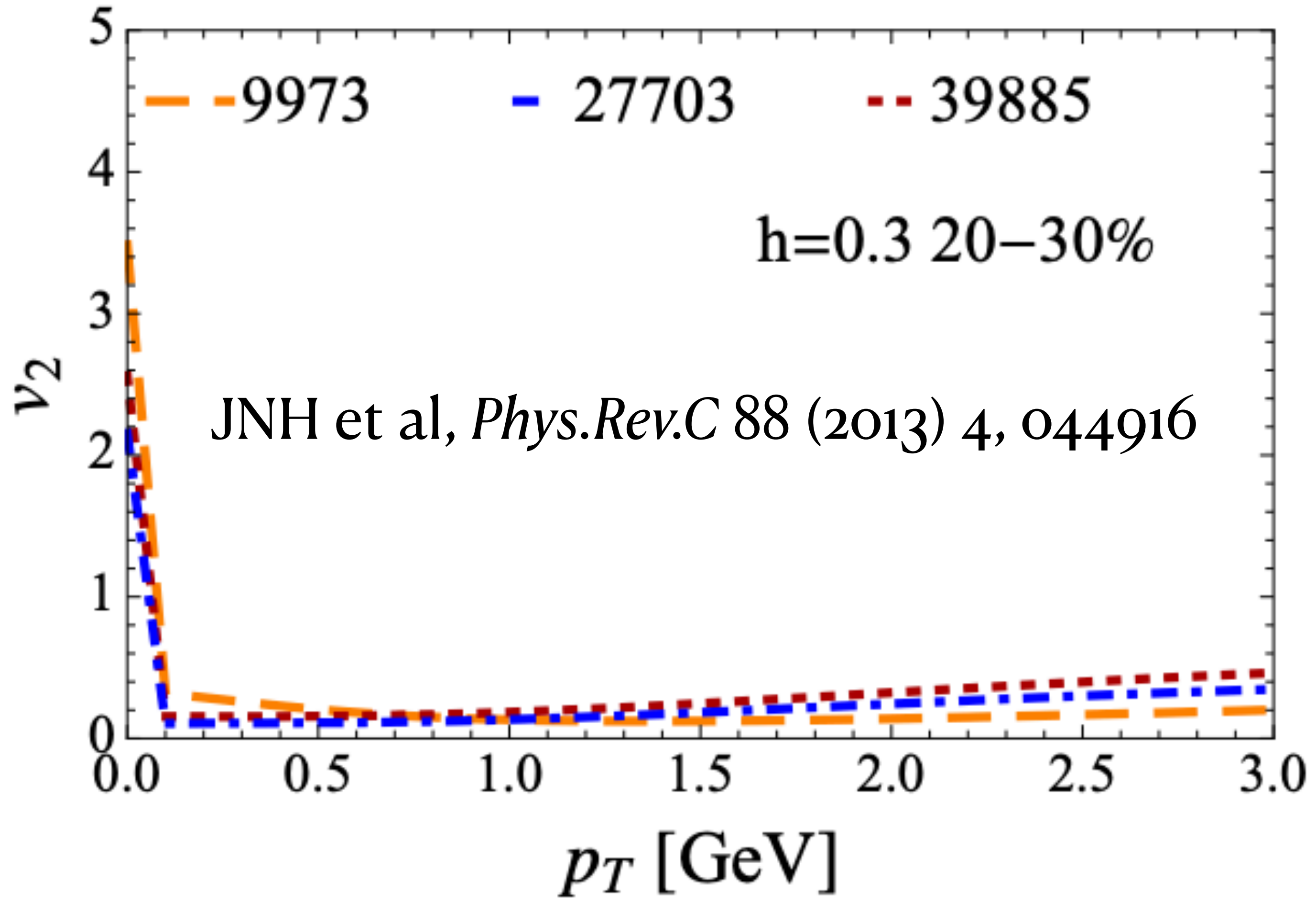

Summary and Outlook

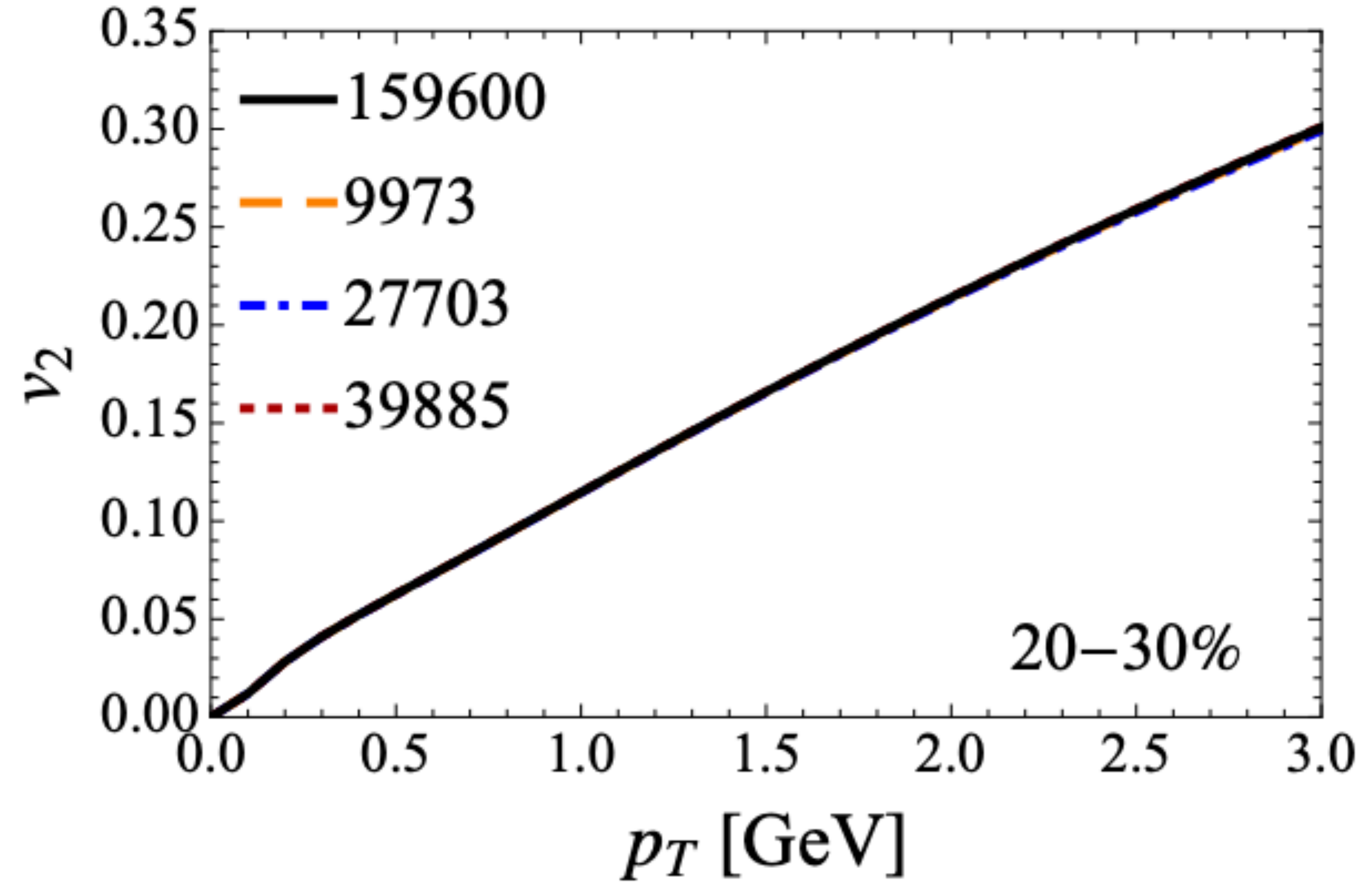
- We do NOT know the large n_B EOS probed in heavy-ion collisions, but there's hope
- We DO understand high-energies ($n_B \sim 0$) HIC extremely well: precision studies, Bayesian analyses, predictions possible
- Large n_B has many moving parts (EOS + transport coefficients), slowly working our way towards better models.
  - Biggest limitations: time, computational resources, personnel, $$
  - Joint Bayesian analyses in HIC and NS desperately needed, but it's **<u>really</u>** hard
- Need to understand HIC (assumptions, limitations) before applying to astrophysical data
- CMB at FAIR in Germany is being built to study the regime between heavy-ions and neutron stars → scans of Z/A
- Possibilities at other fixed target experiments? Here at CERN? AGS? FRIB400?

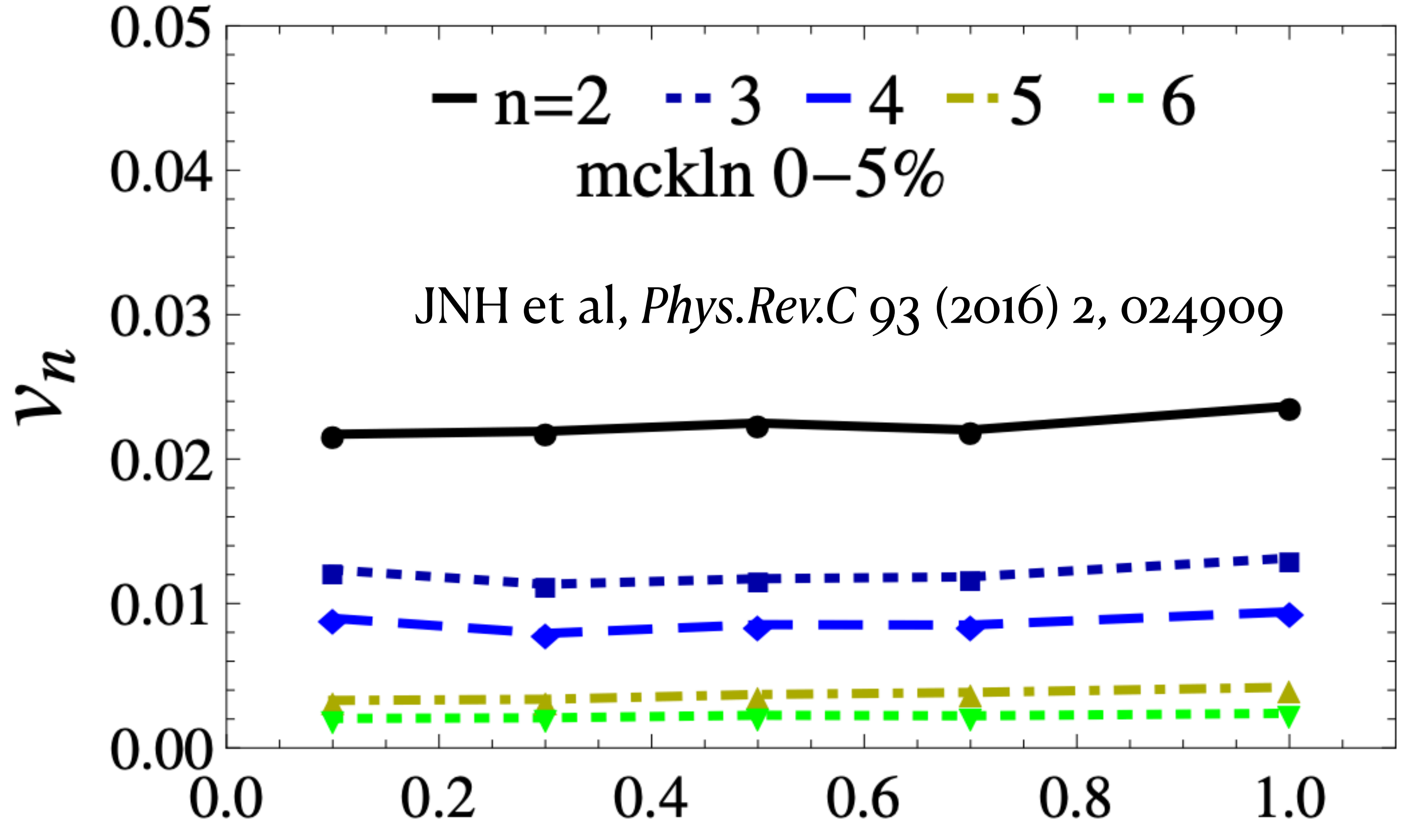
Robustness to grid-size changes, smoothing scale h



Number of SPH particles







Smoothing scale: λ [fm]

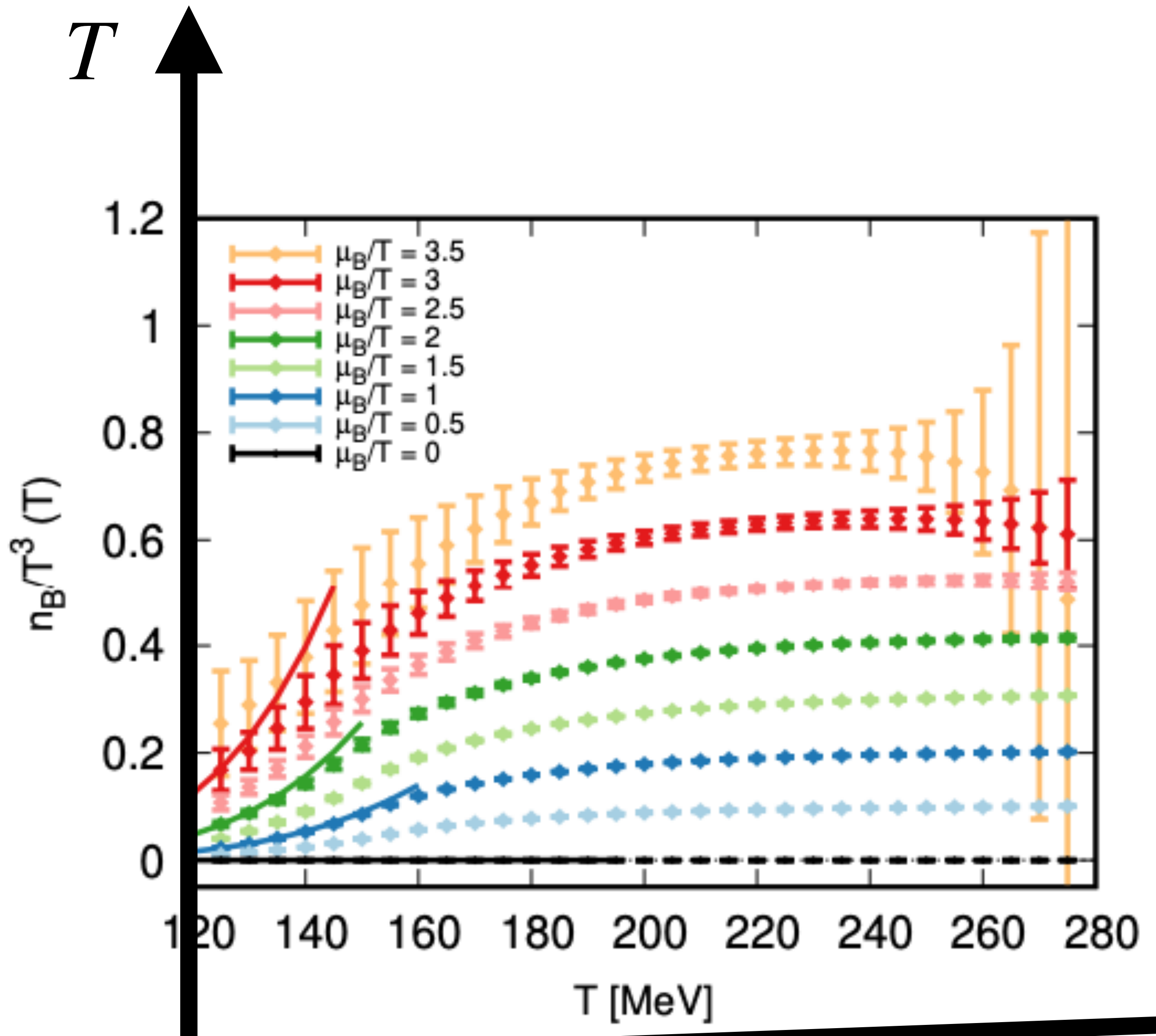
Summary of theory and experimental constraints [MUSES] Living Rev.Rel. 27 (2024) 1, 3

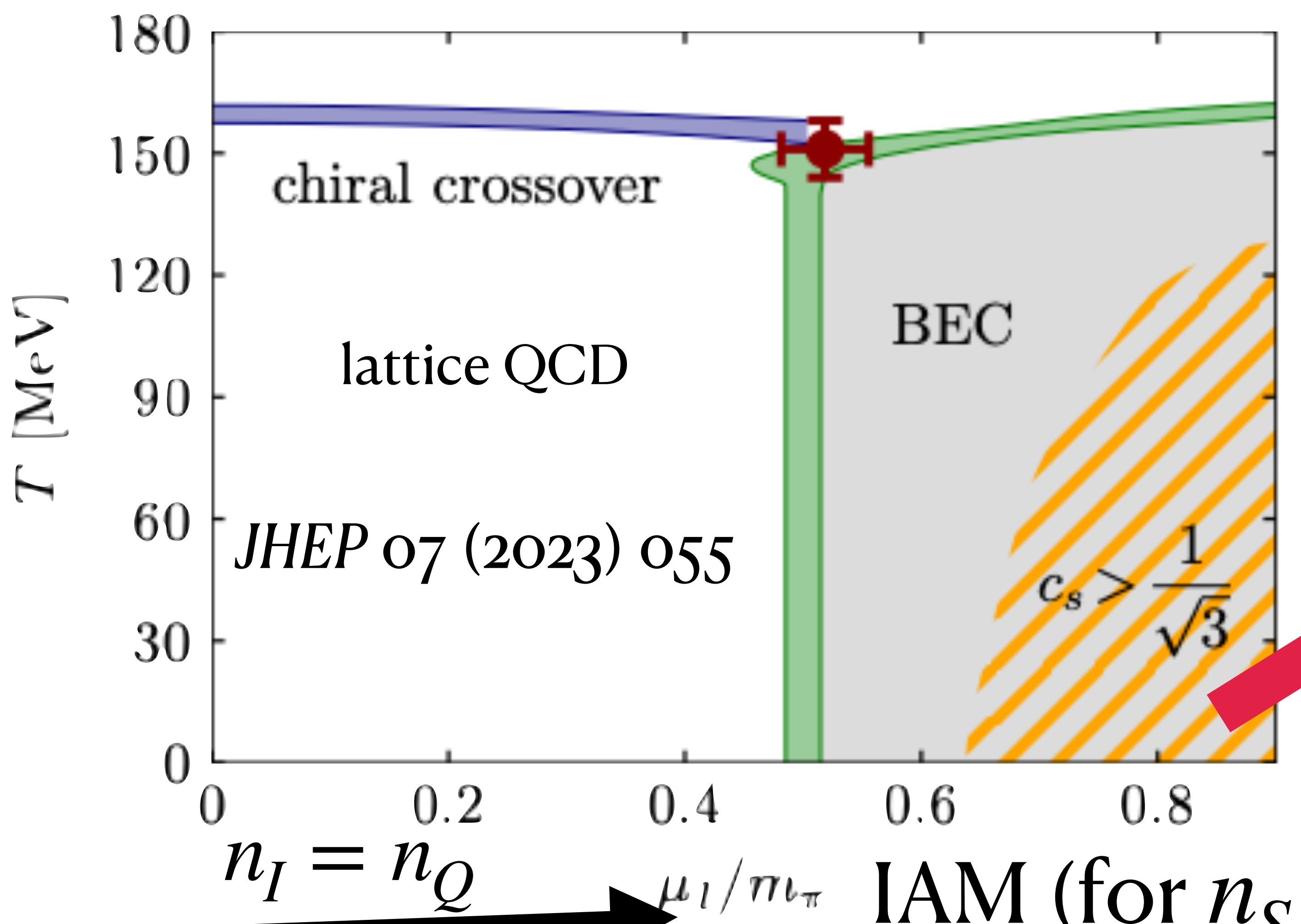
First principle QCD constraints

Equation of State (EOS)

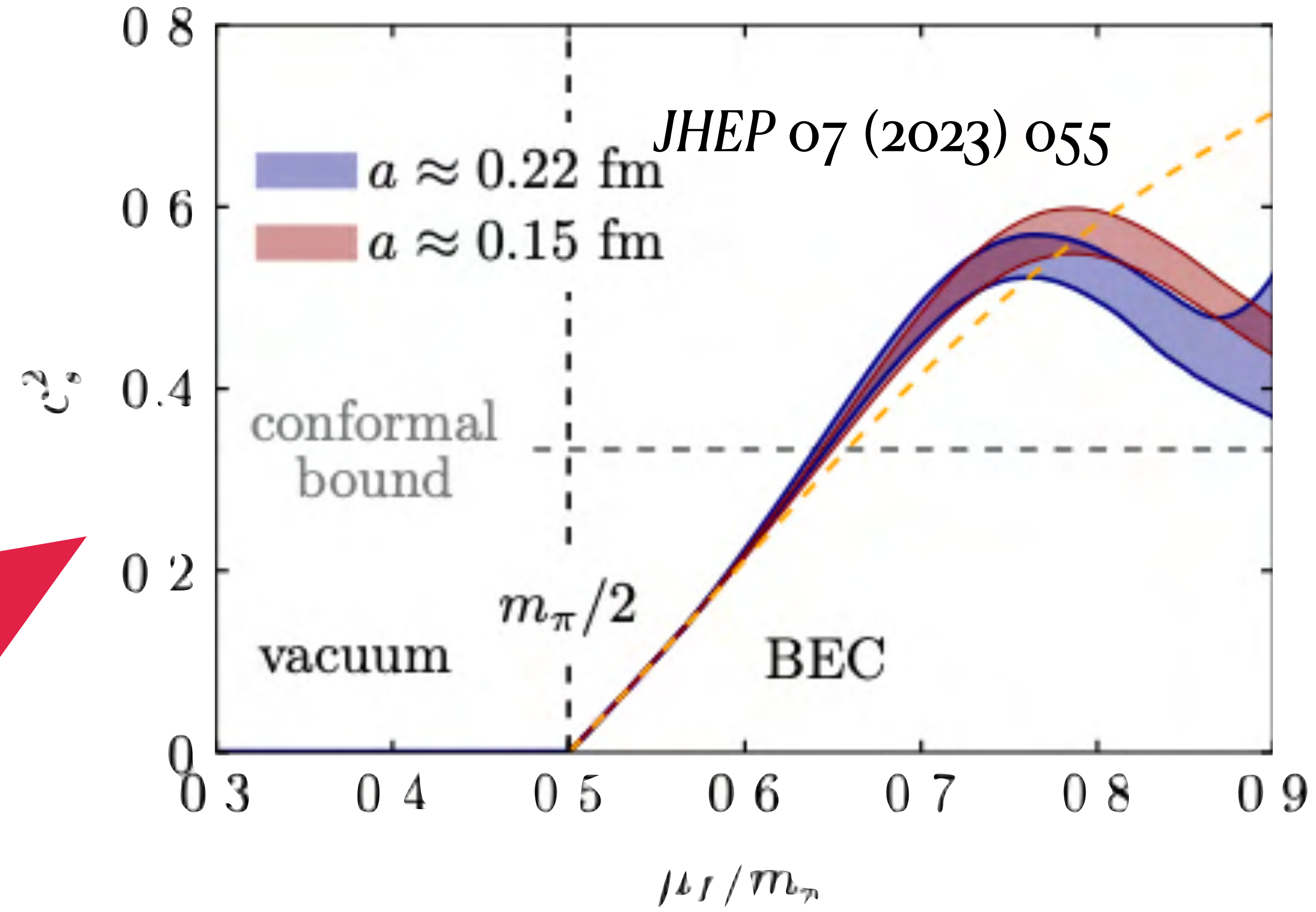
Resumed lattice QCD

Lattice *Phys.Rev.Lett.* 126 (2021) 23, 232001; *Phys.Rev.D* 105 (2022) 11, 114504
Open-source code *Phys.Rev.D* 109 (2024) 9, 094046

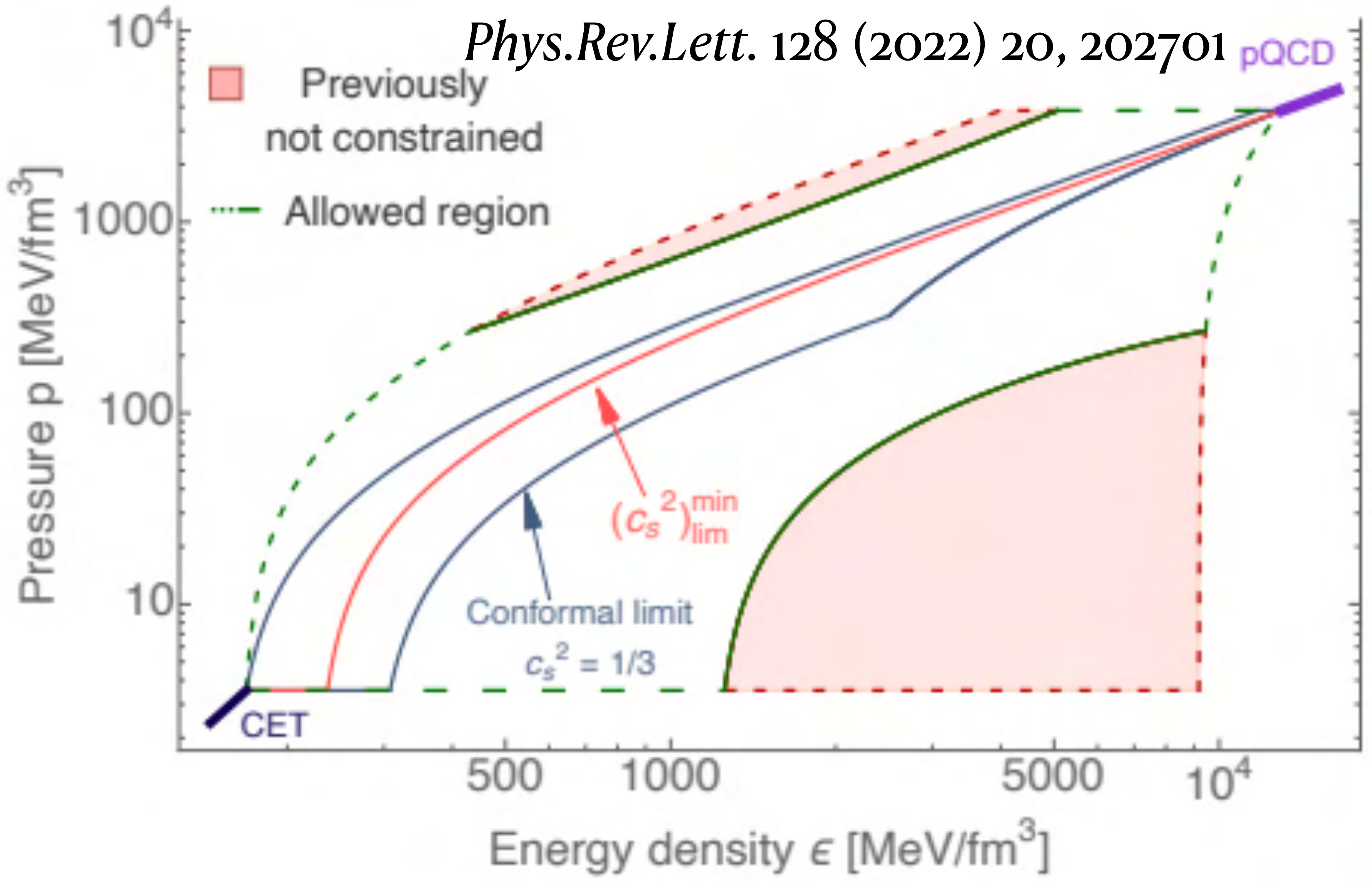




$n_I = n_Q$ IAM (for $n_S = n_B = 0$)



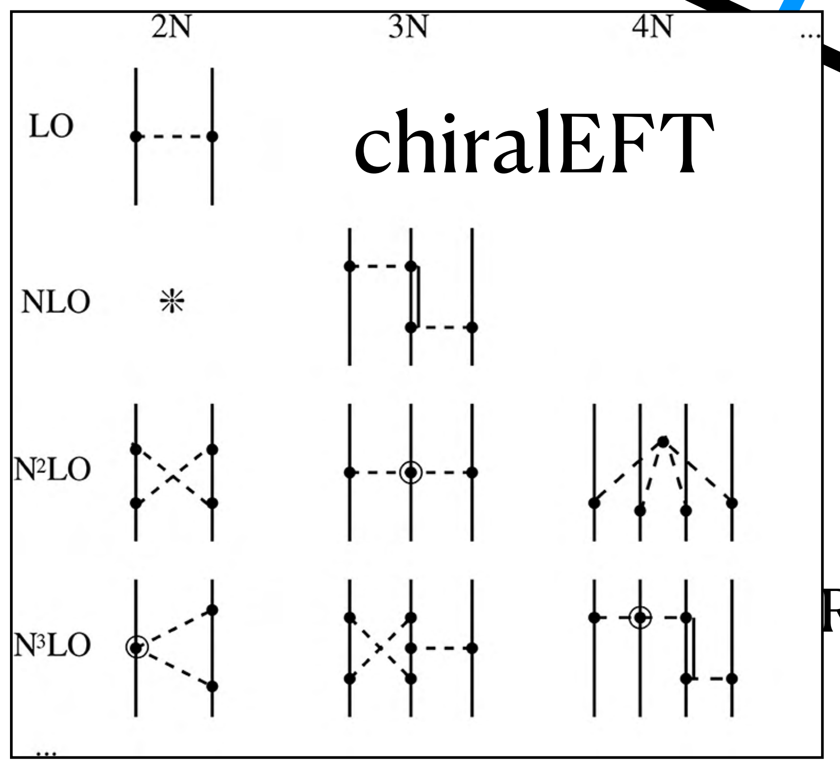
Perturbative QCD $n_B \gtrsim 40\, n_{sat}$



$\sim n_{sat}$

SNM $Y_Q = 0.5$

n_B



Review: *Phys.Rept.* 503 (2011) 1-75
+ many, many works

n_B

PNM $Y_Q = 0$

Filling gaps in our knowledge

Expansions: symmetry energy, finite T or μ, etc

Lattice QCD $\mu_B = 0$, then $p(T, \hat{\mu} = \vec{\mu}/T) = T^4 \sum_{i,j,k} \frac{1}{i!j!k!} \chi^{BQS}_{ijk} \hat{\mu}^i_B \hat{\mu}^j_S \hat{\mu}^k_Q$

Cold neutron stars $T = 0$, then $p(T, \vec{\mu}) = p_{T=0} + \frac{1}{2} \frac{\partial s}{\partial T}\Big|_{T=0,\vec{\mu}} T^2 + \mathcal{O}(T^3)$ 2404.01658 [astro-ph.HE]

Connect heavy-ions to neutron stars: $\frac{E_{ANM}}{N_B} = \frac{E_{SNM}}{N_B} + E_{sym}\delta^2 + \mathcal{O}(\delta^4)$ *& expansion around n_{sat}*

Caveat: breaks down outside of regime of validity, struggles with phase transitions

Effective Models: relativistic mean field, NJL, quarkyonic, etc

Qualitative features: bump in c_s^2, phase transitions, ...

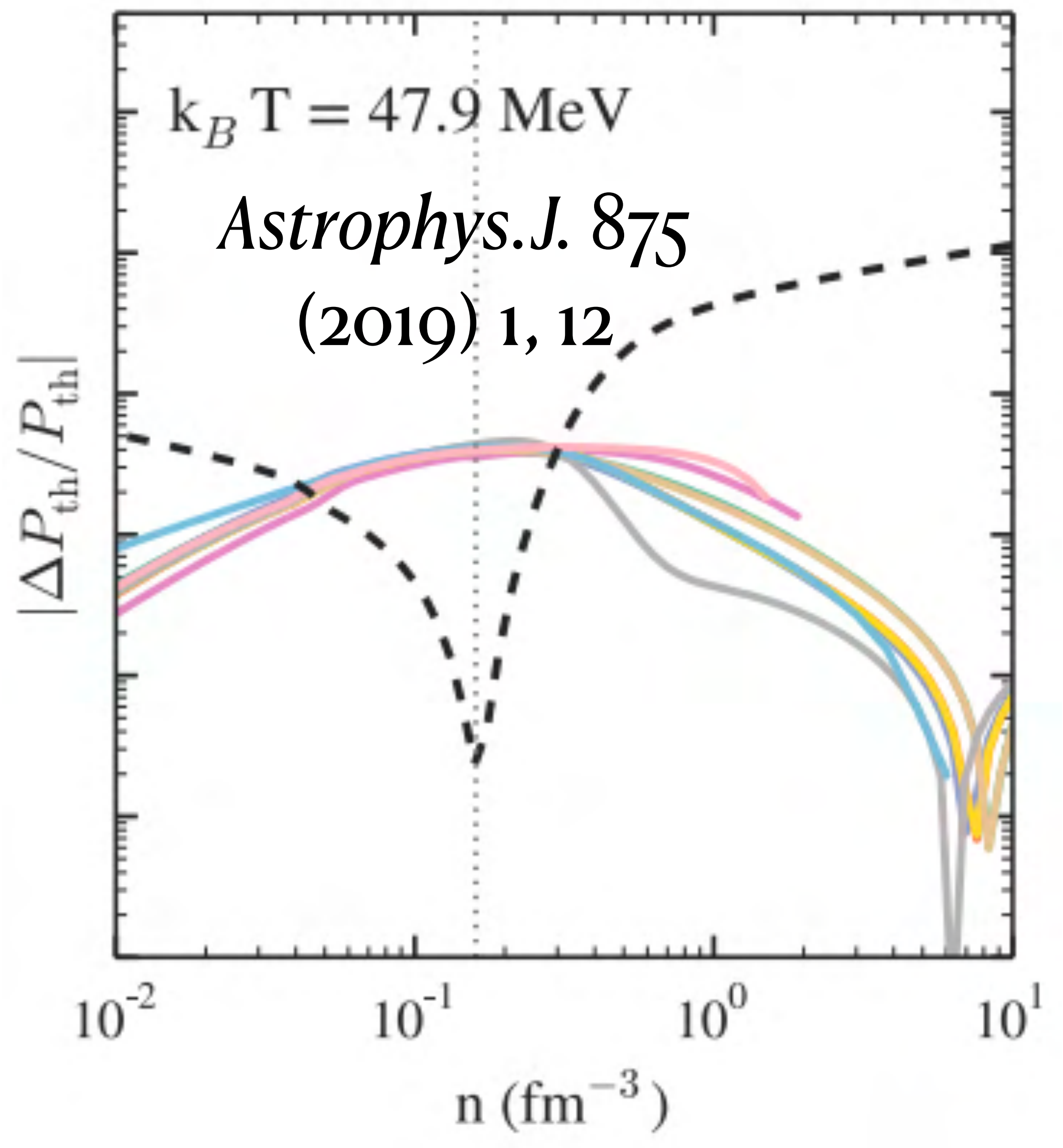
Constrain theory vs data; vary free parameters

Caveat: model assumptions and degrees of freedom

Minimalist models based on nuclear parameters

Effective Mass approach for neutron, proton, electron matter

Caveat: breaks down outside of regime of validity, no phase transitions, hyperons etc



Head on collisions and deformations

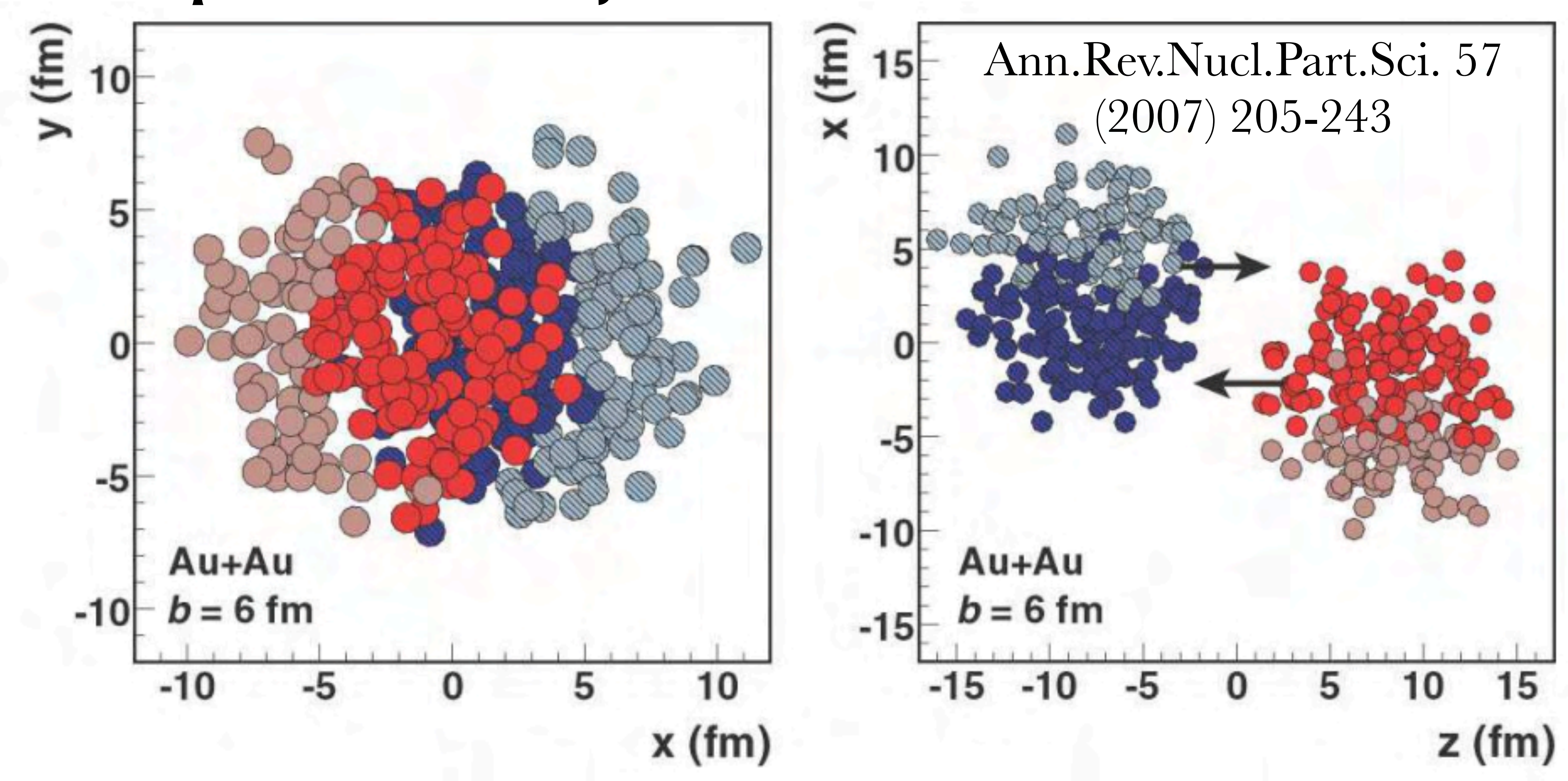
Centrality $\% = 0$ for head on collisions

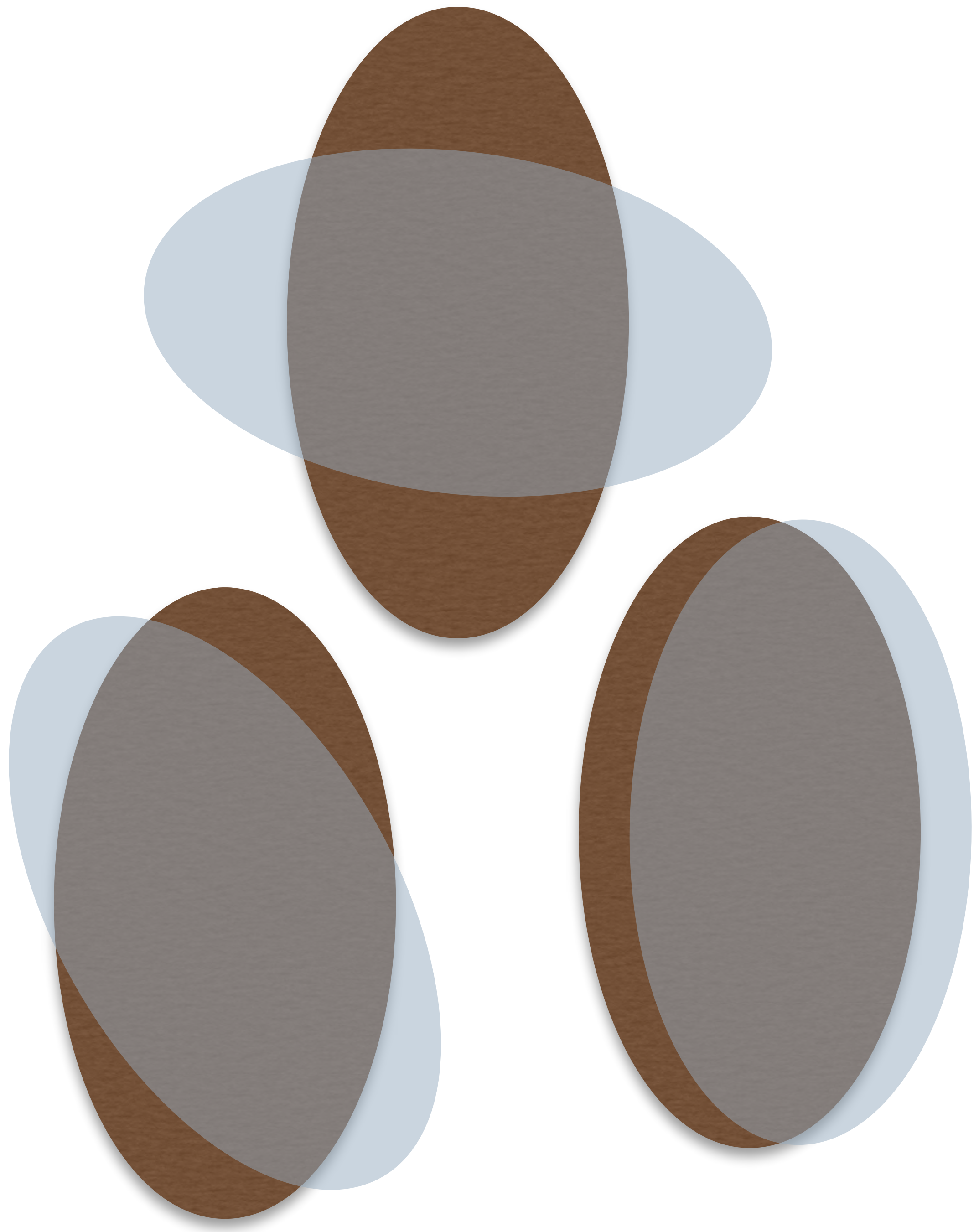
Terminology:

-participants (colliding nucleons)

-spectators (fly off to the detector)

All $b = 0$ impact parameters, very different shapes





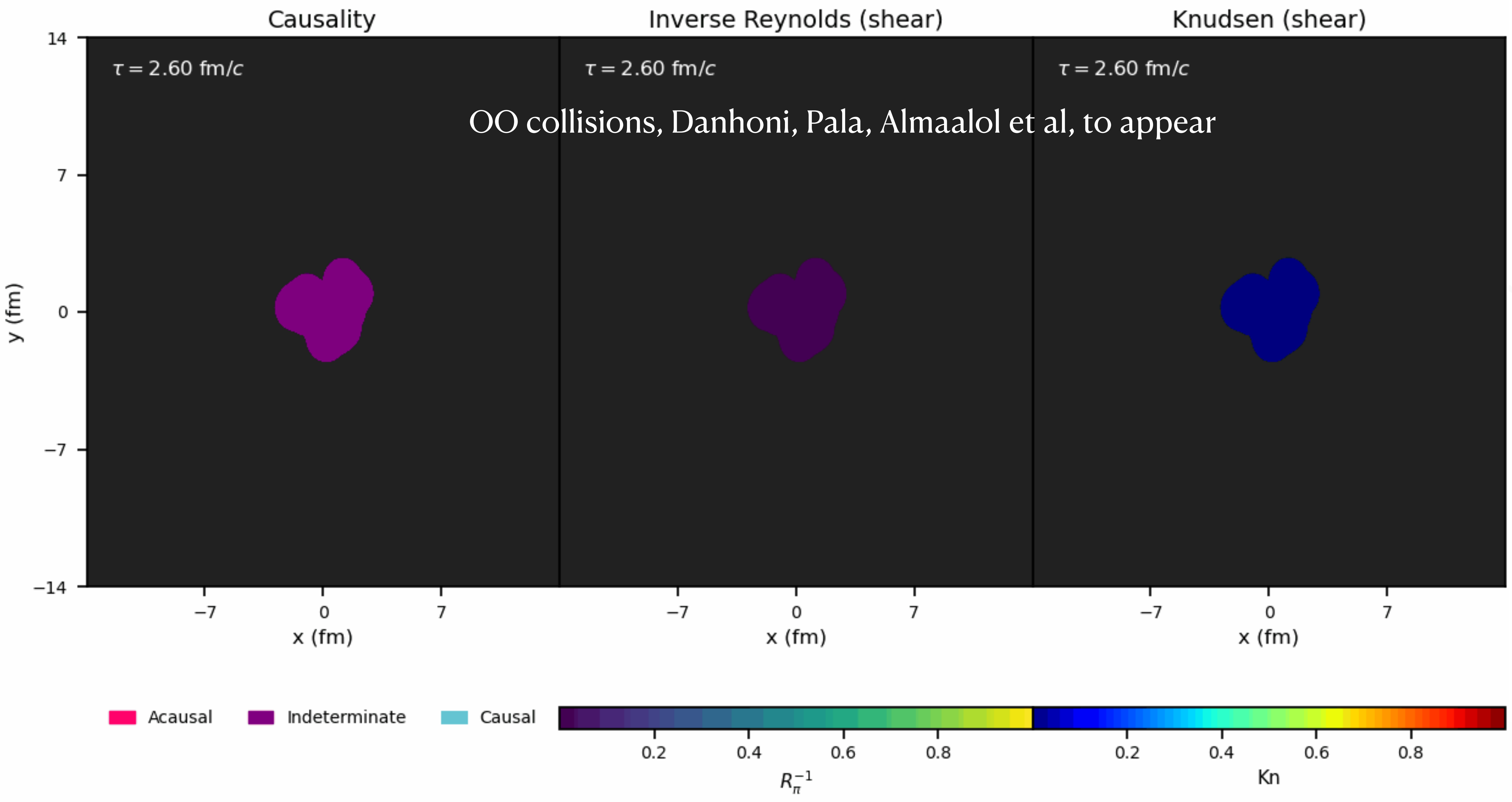
Head-on collisions most sensitive to structure, but $b = 0$ does not necessarily mean ultra central!

Causality and Stability: math-physics collaborations

Mathematical constraints from nonlinear causality and stability

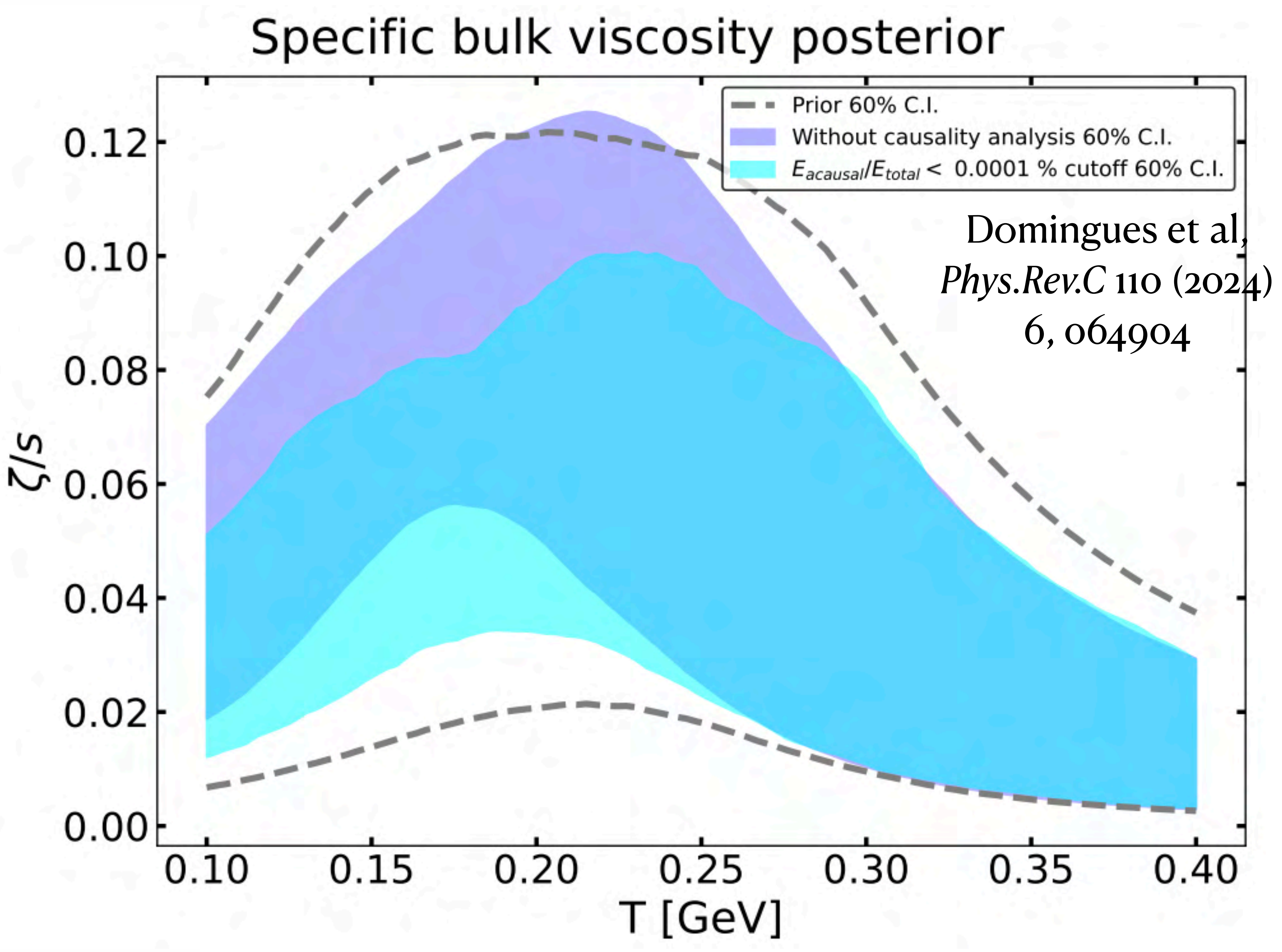
Derivation: Bemfica et al, *Phys.Rev.Lett.* 126 (2021) 22, 222301 ;

OO collisions, Danhoni, Pala, Almaalol et al, to appear



Other related works in HIC: Plumberg et al, *Phys.Rev.C* 105 (2022) 6, L061901; Chiu et al, *Phys.Rev.C* 103 (2021) 6, 064901, Gavassino QM25, Cordeiro QM25

Effects on transport coefficient extraction



Domingues et al, *Phys.Rev.C* 110 (2024) 6, 064904

BUT, this goes WAY beyond just heavy-ion collisions!

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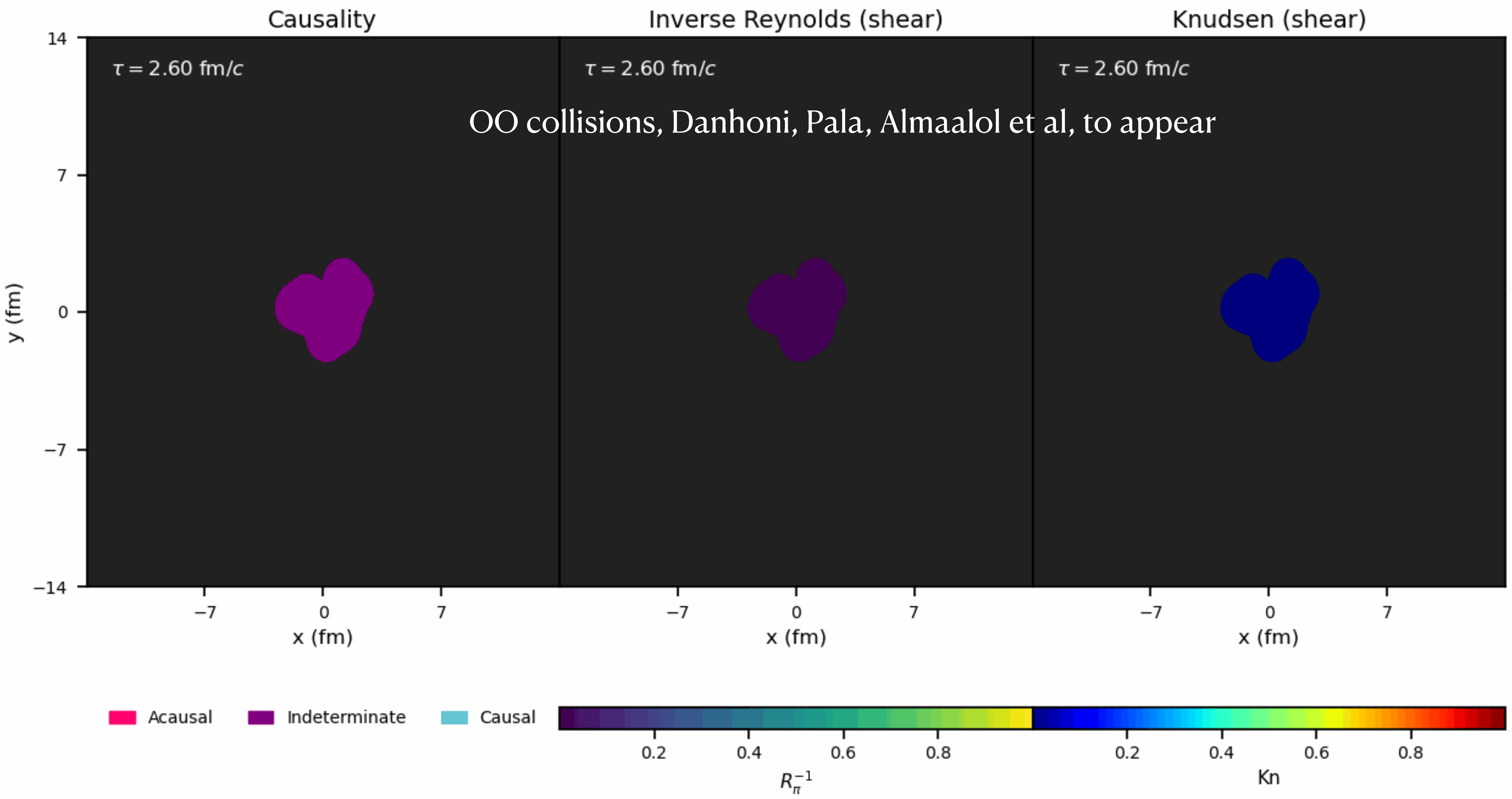

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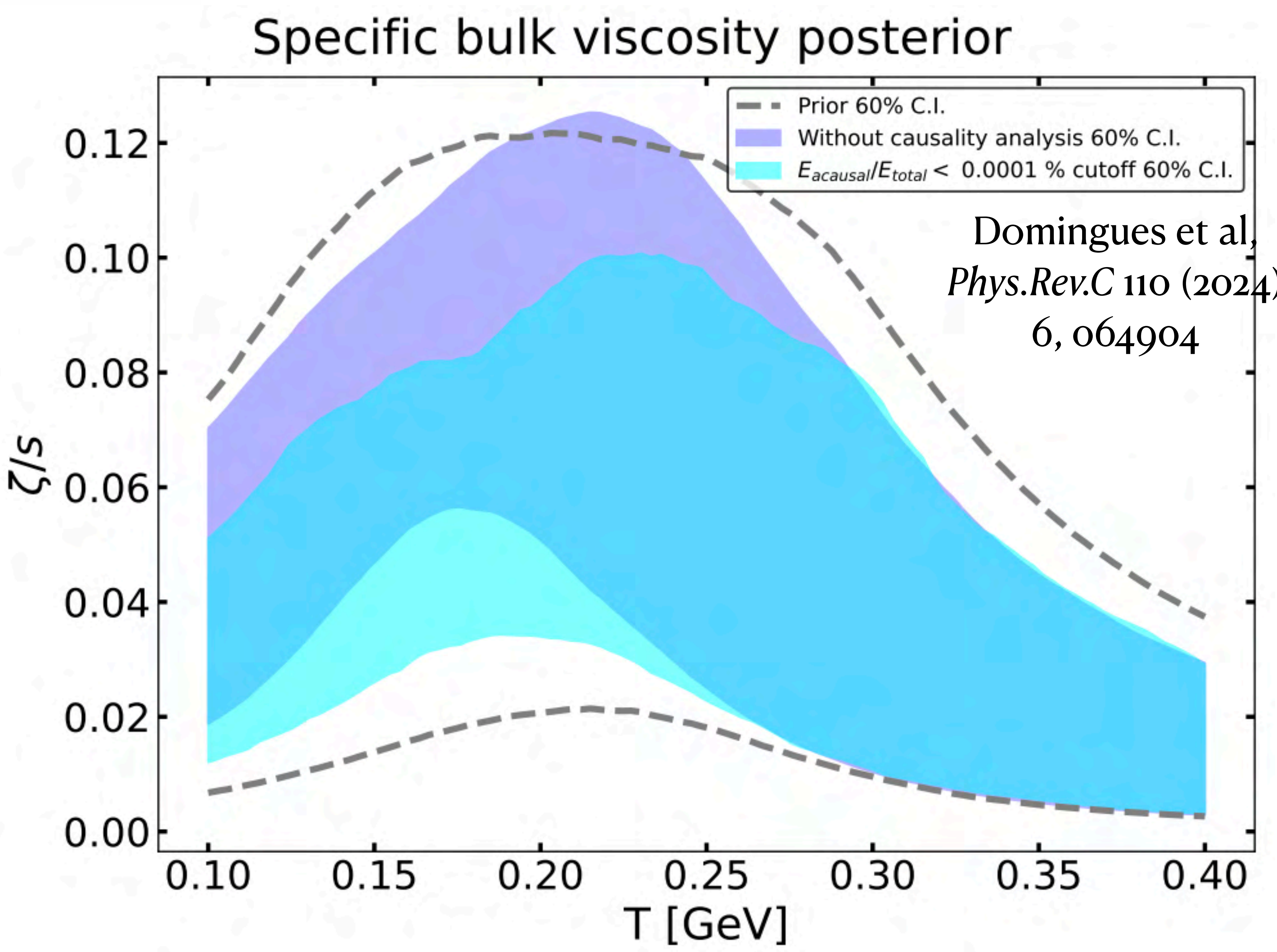

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