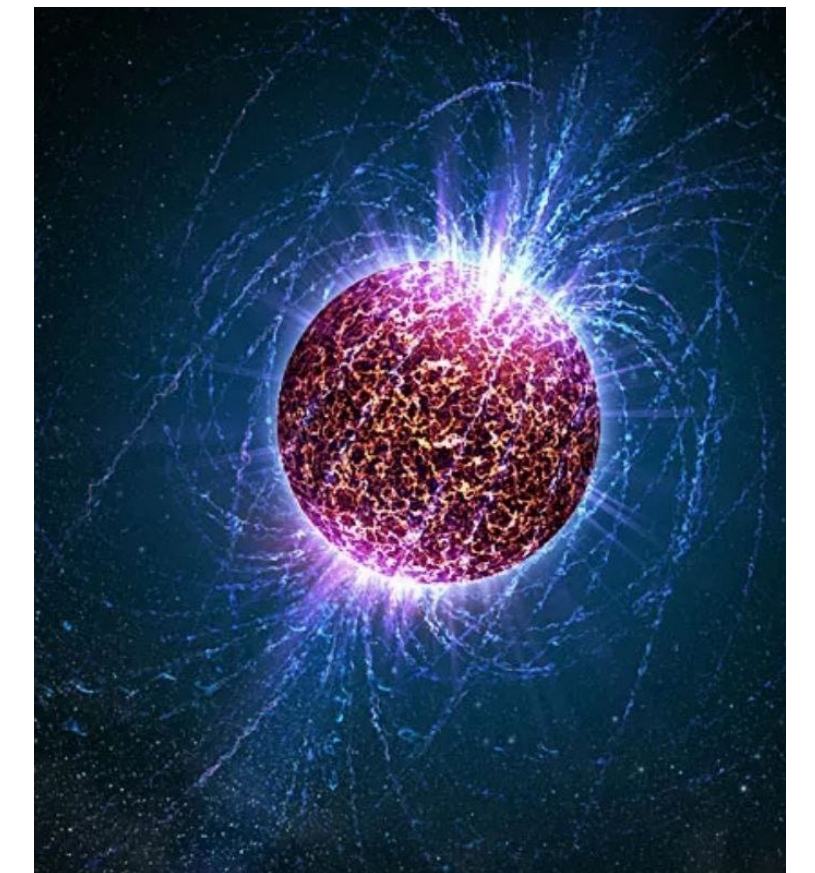
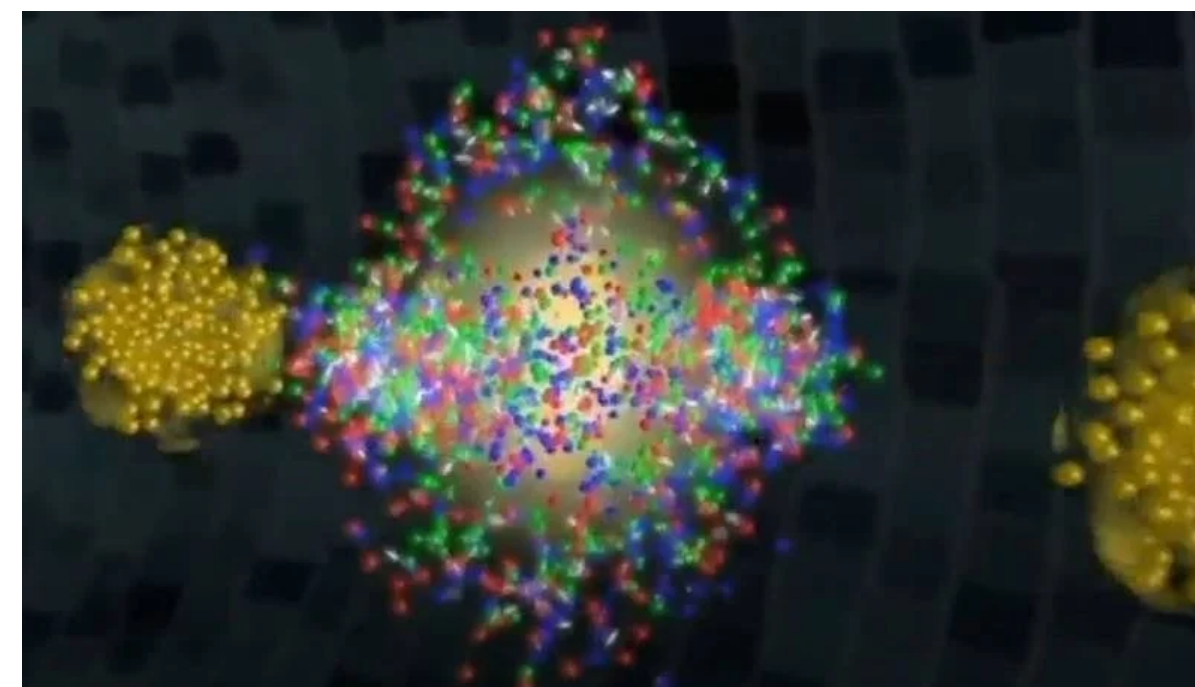
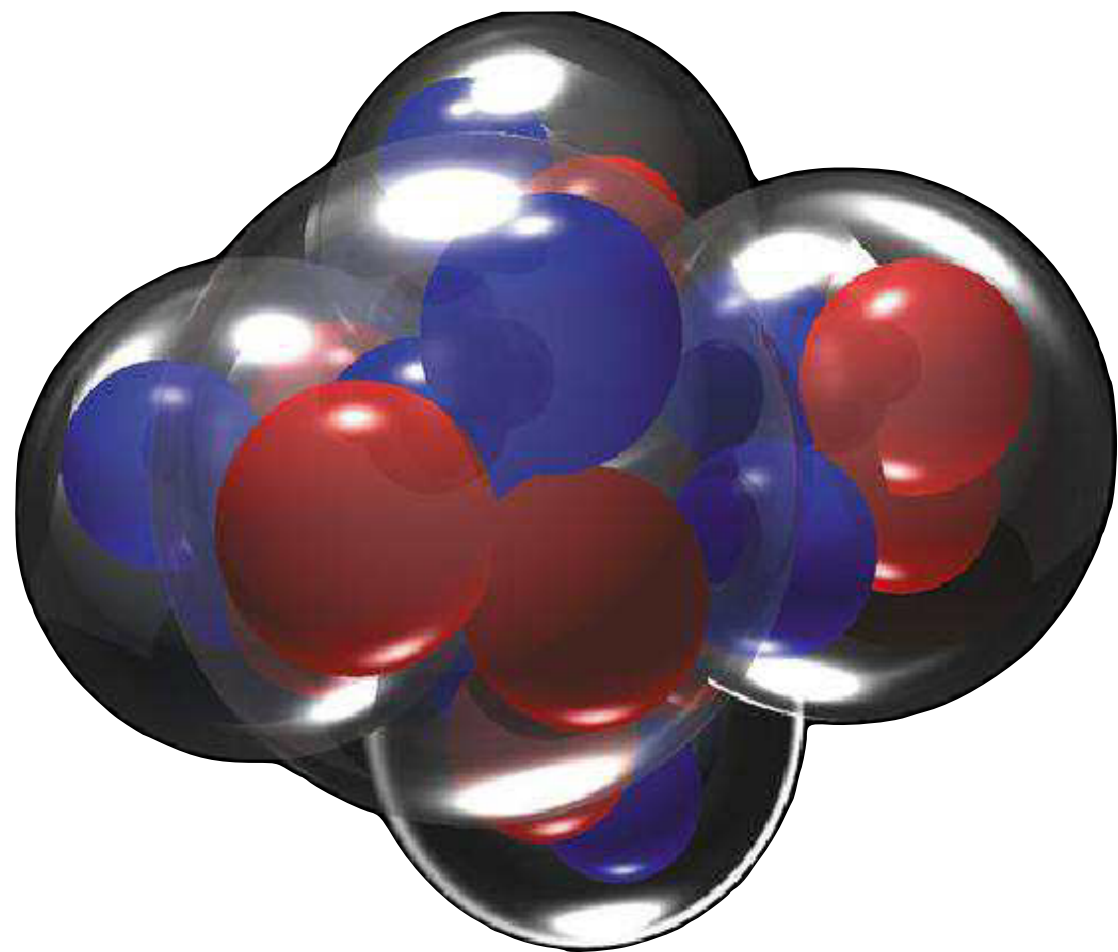




Lasting Science Impact of RHIC

Jacquelyn Noronha-Hostler

RHIC & AGS User's Meeting - 22nd May, 2025



Starting my PhD in 2004, during the White Papers (2005)

Early days of RHIC

Hanging out around Columbia University circa 2009



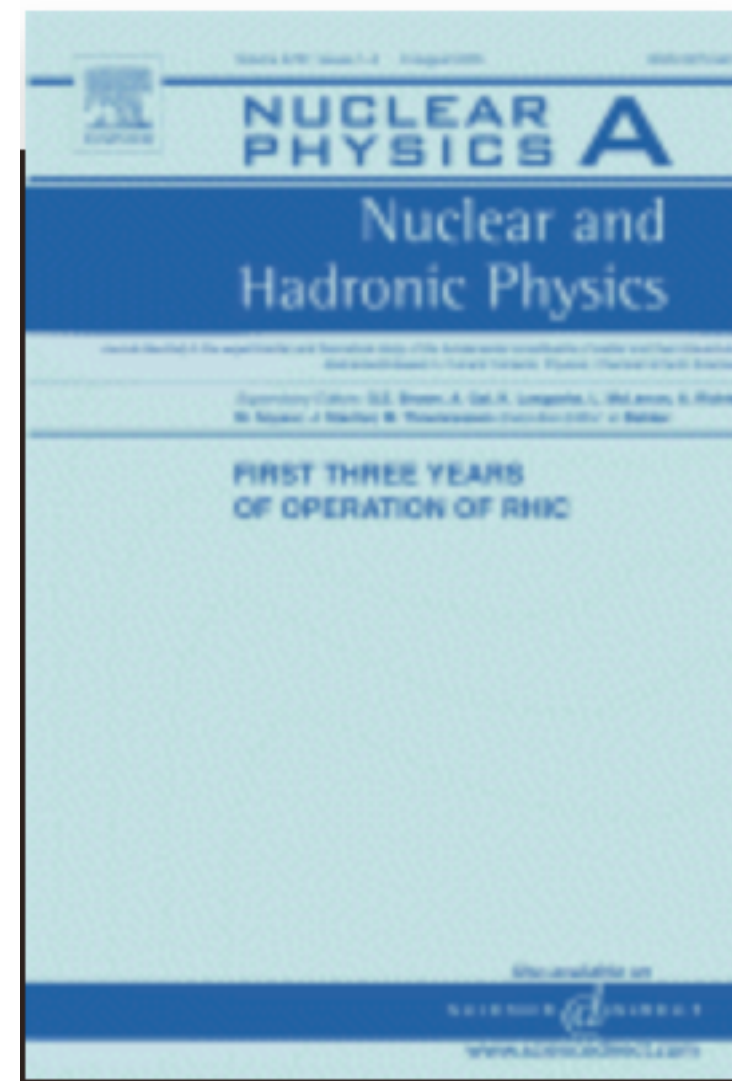
Me, Jorge Noronha, Georgio Torrieri, Miklos Gyulassy

J. Noronha-Hostler UIUC

The New York Times

At One Trillion Degrees, Even Gold Turns Into the Sloshiest Liquid

My own much smaller contribution:
 $\eta/s \rightarrow 0.08$ in the HRG
Phys.Rev.Lett. 103 (2009) 172302



~13,000 citations!

$$(\eta/s)_{min} \sim \frac{1}{4\pi}$$

PRL 94, 111601 (2005)

PHYSICAL REVIEW LETTERS

week ending
25 MARCH 2005

Viscosity in Strongly Interacting Quantum Field Theories from Black Hole Physics

P. K. Kovtun,¹ D. T. Son,² and A. O. Starinets³

¹Kavli Institute for Theoretical Physics, University of California, Santa Barbara, California 93106, USA

²Institute for Nuclear Theory, University of Washington, Seattle, Washington 98195-1550, USA

³Perimeter Institute for Theoretical Physics, Waterloo, Ontario N2L 2Y5, Canada

(Received 20 December 2004; published 22 March 2005)

The ratio of shear viscosity to volume density of entropy can be used to characterize how close a given fluid is to being perfect. Using string theory methods, we show that this ratio is equal to a universal value of $\hbar/4\pi k_B$ for a large class of strongly interacting quantum field theories whose dual description involves black holes in anti-de Sitter space. We provide evidence that this value may serve as a lower bound for a wide class of systems, thus suggesting that black hole horizons are dual to the most ideal fluids.

DOI: 10.1103/PhysRevLett.94.111601

PACS numbers: 11.10.Wx, 04.70.Dy, 11.25.Tq, 47.75.+f

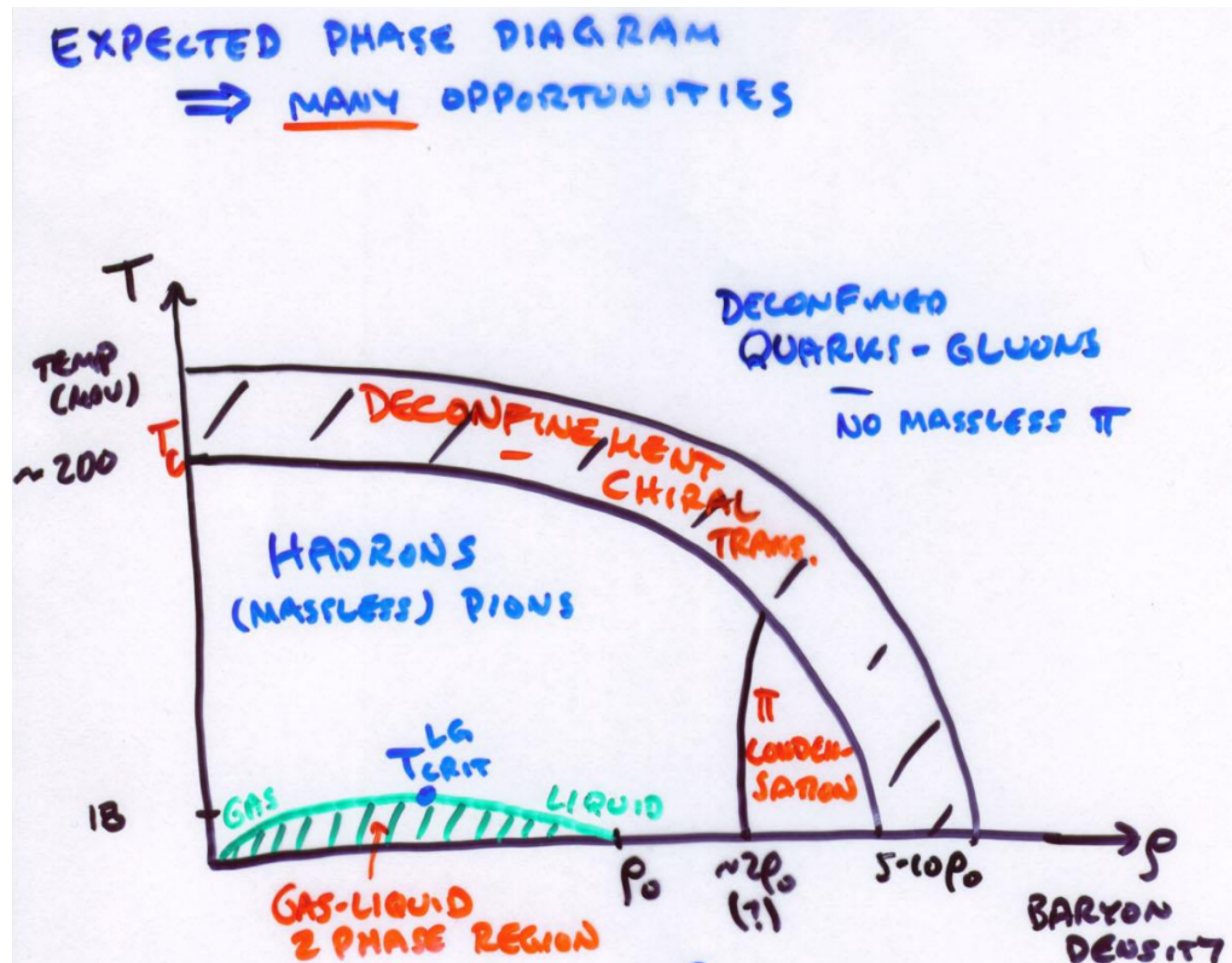
Over 3,000 citations!

Heavy-ion collisions is about **DISCOVERY** science

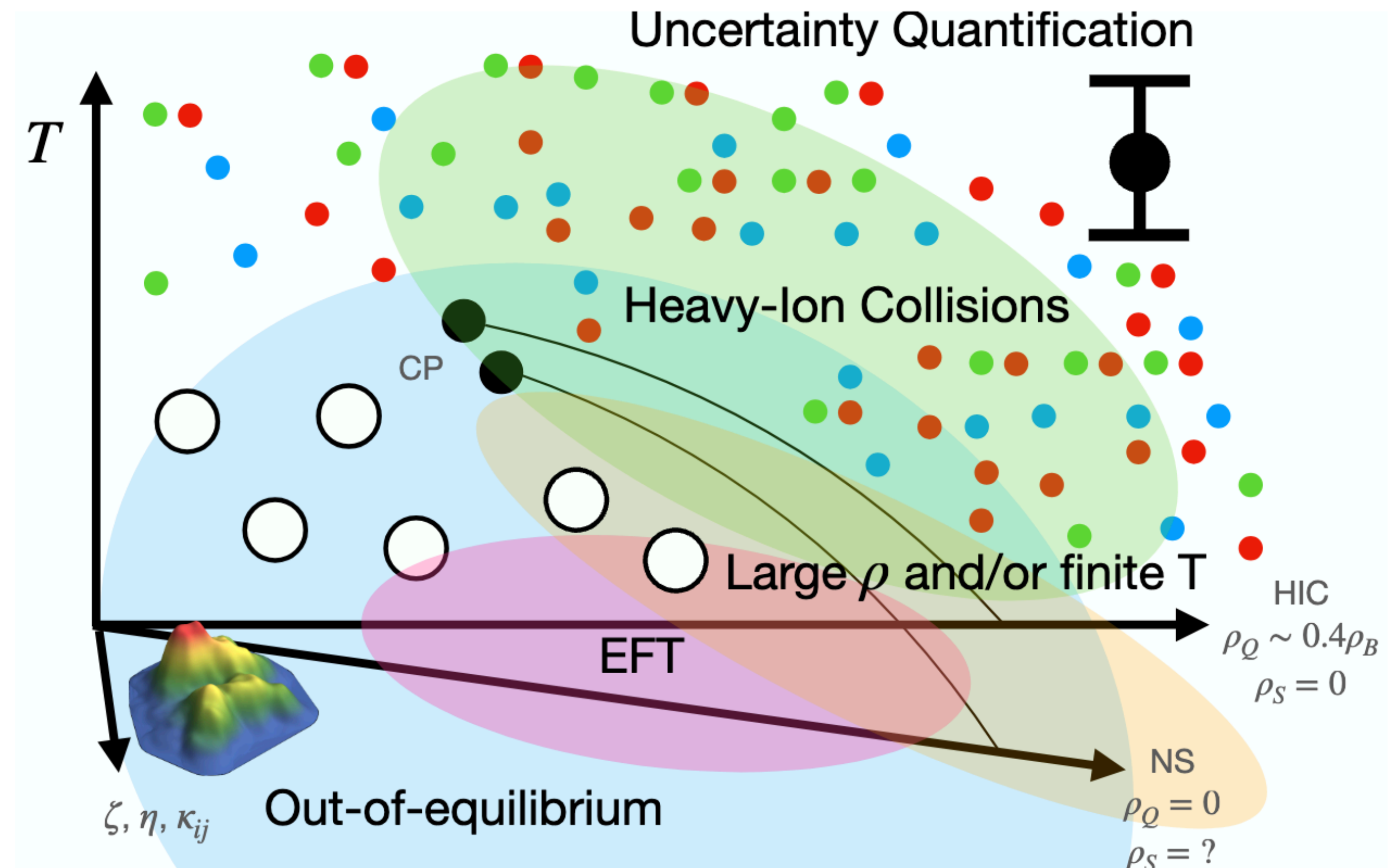
Heavy-ions are like a box of chocolates, you never know what you're going to get



Gordon Baym 1980's



More modern cartoon, we still don't have it all figured out yet...



We don't have the answers, maybe we don't even have all the questions, but we keep finding cool stuff!

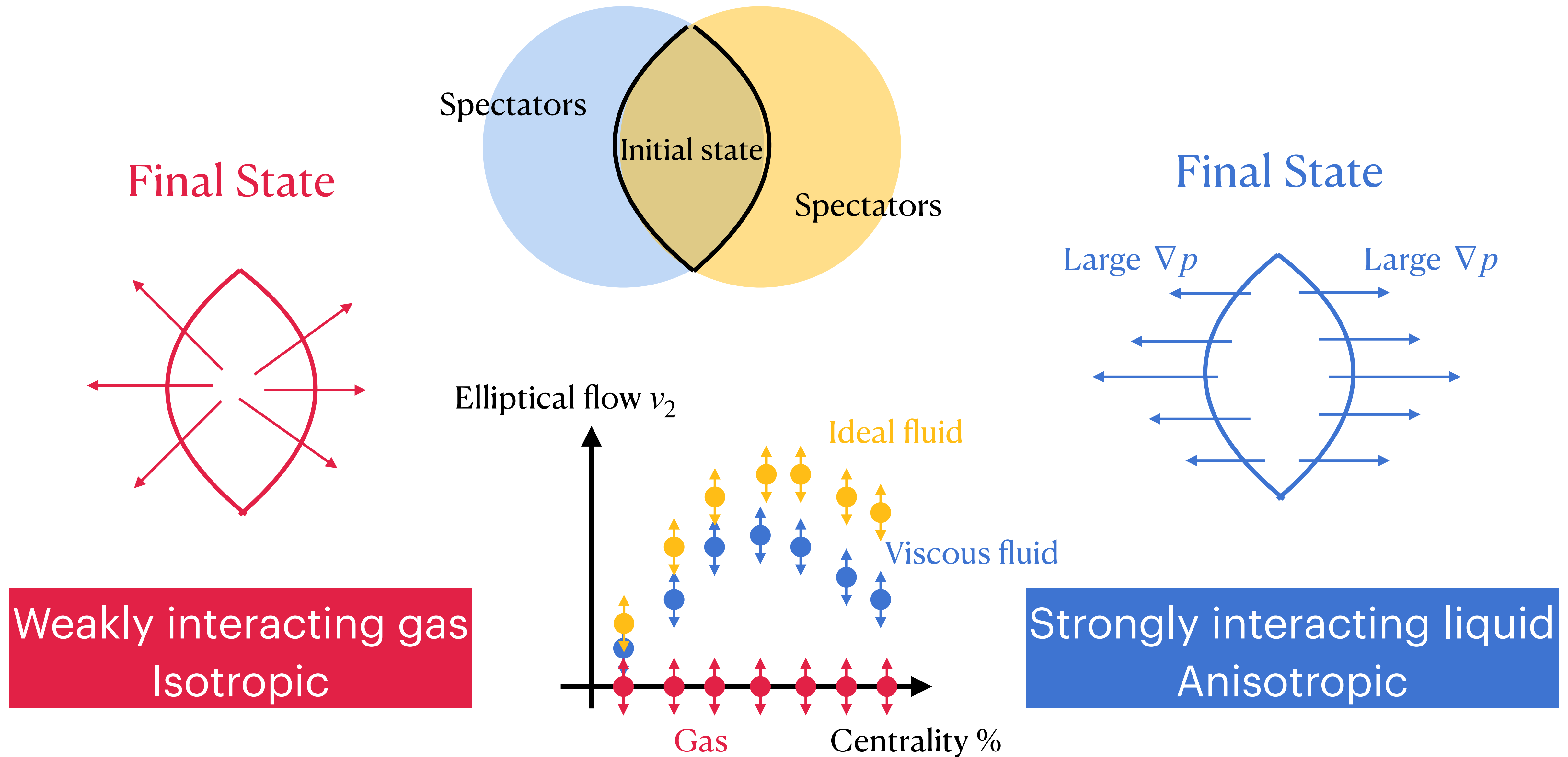
Pandora's box of physics

Theorist's job: *Hope* of understanding the data



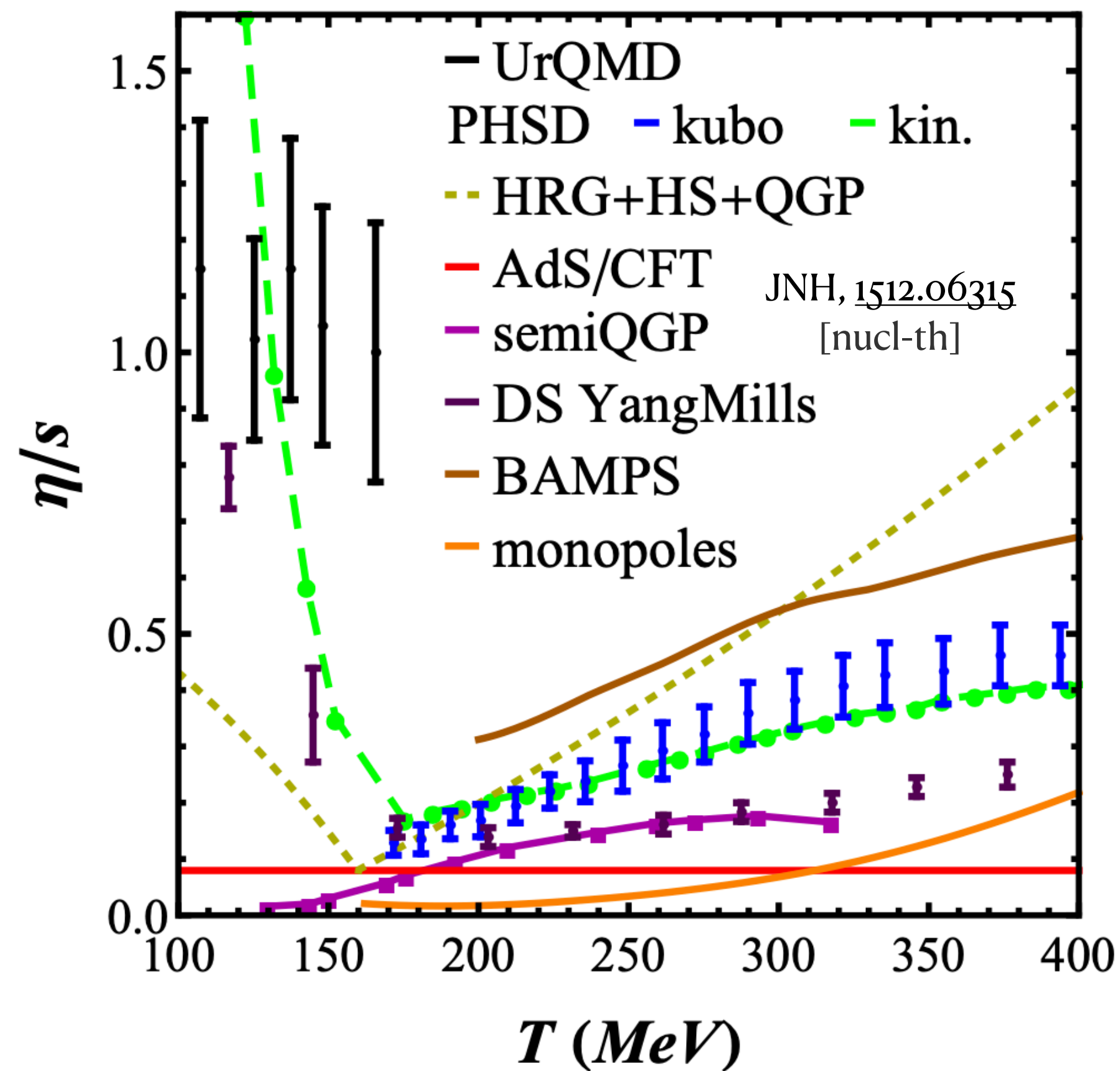
- Understanding RHIC is hard. Many-body physics across many scales; strongly interacting, relativistic, and very, very small
- “It doesn't matter how beautiful your theory is, it doesn't matter how smart you are. If it doesn't agree with experiment, it's wrong” - Feynman
- Over the years, heavy-ion collision data has challenged our theories, eliminating many good ideas. We're still figuring this out.
- I'm going to focus on things we've exported to (not imported from) other fields. *This is hardly a comprehensive talk!*

QGP: dilute, weakly interacting gas or a dense, strongly interacting liquid?

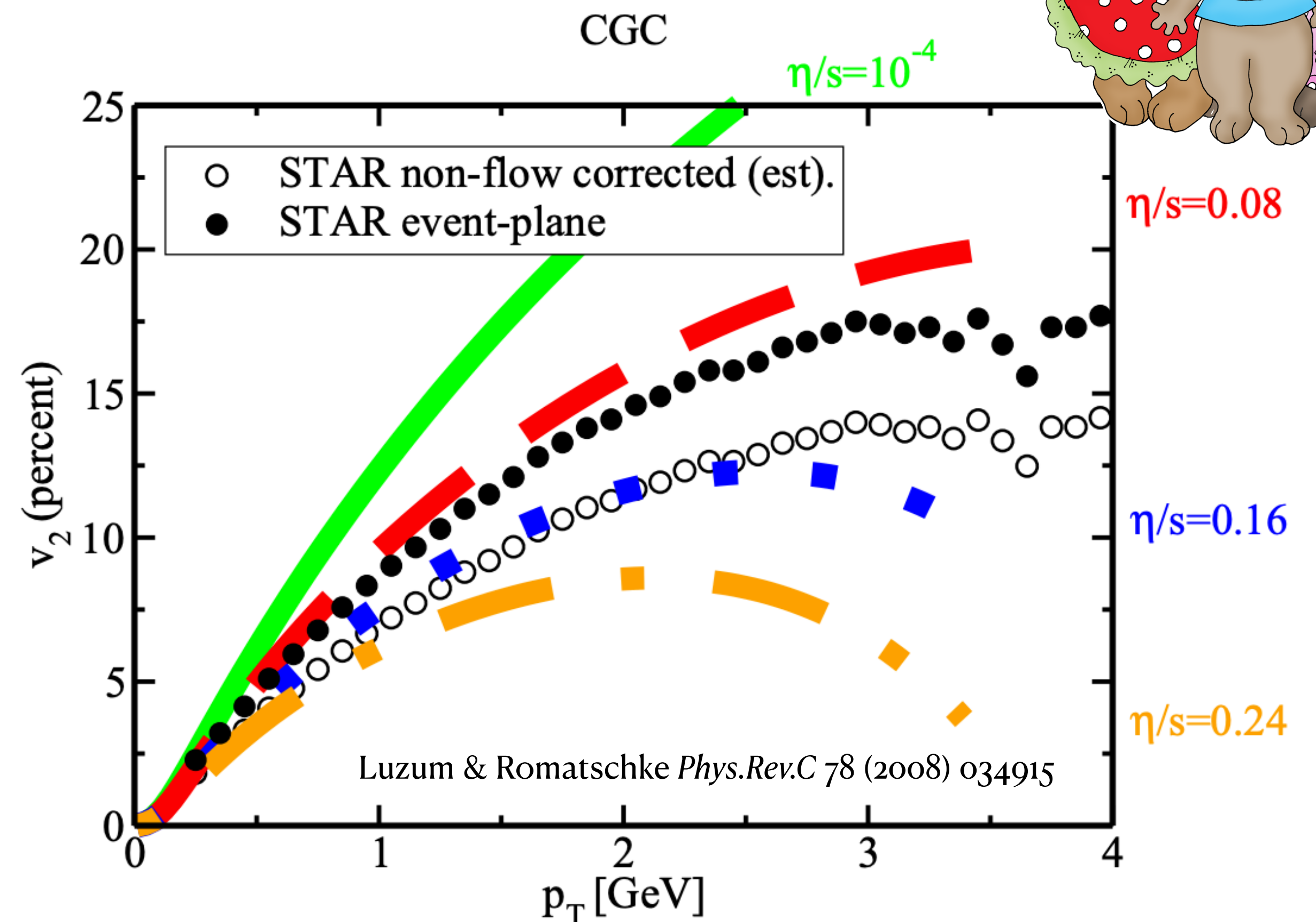


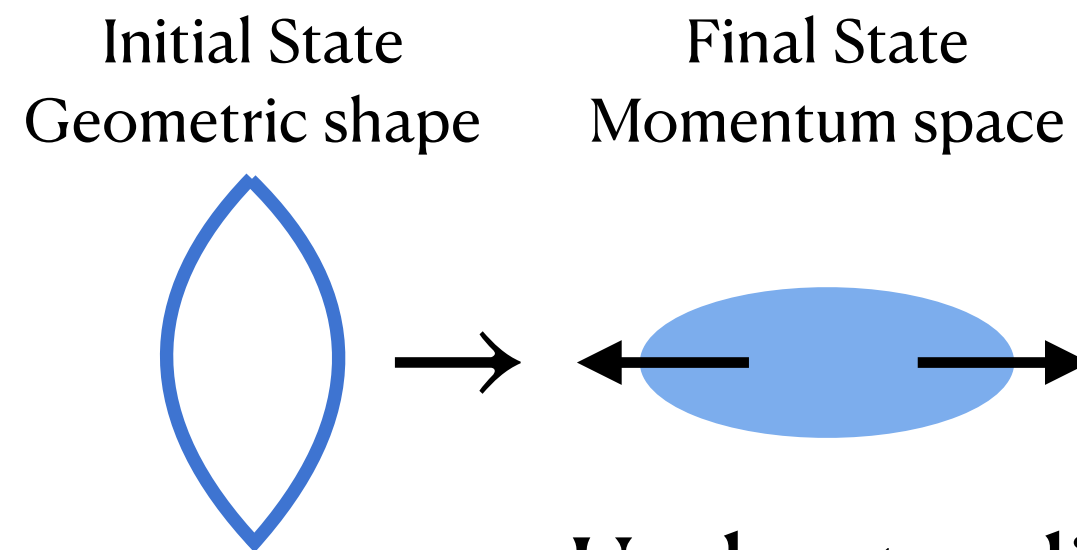
Impact 1: Nearly perfect fluid, relativistic **viscous** hydrodynamics

Early calculations of η/s from various theories



Quark Gluon Plasma require an extremely small but non-zero shear viscosity (η/s)



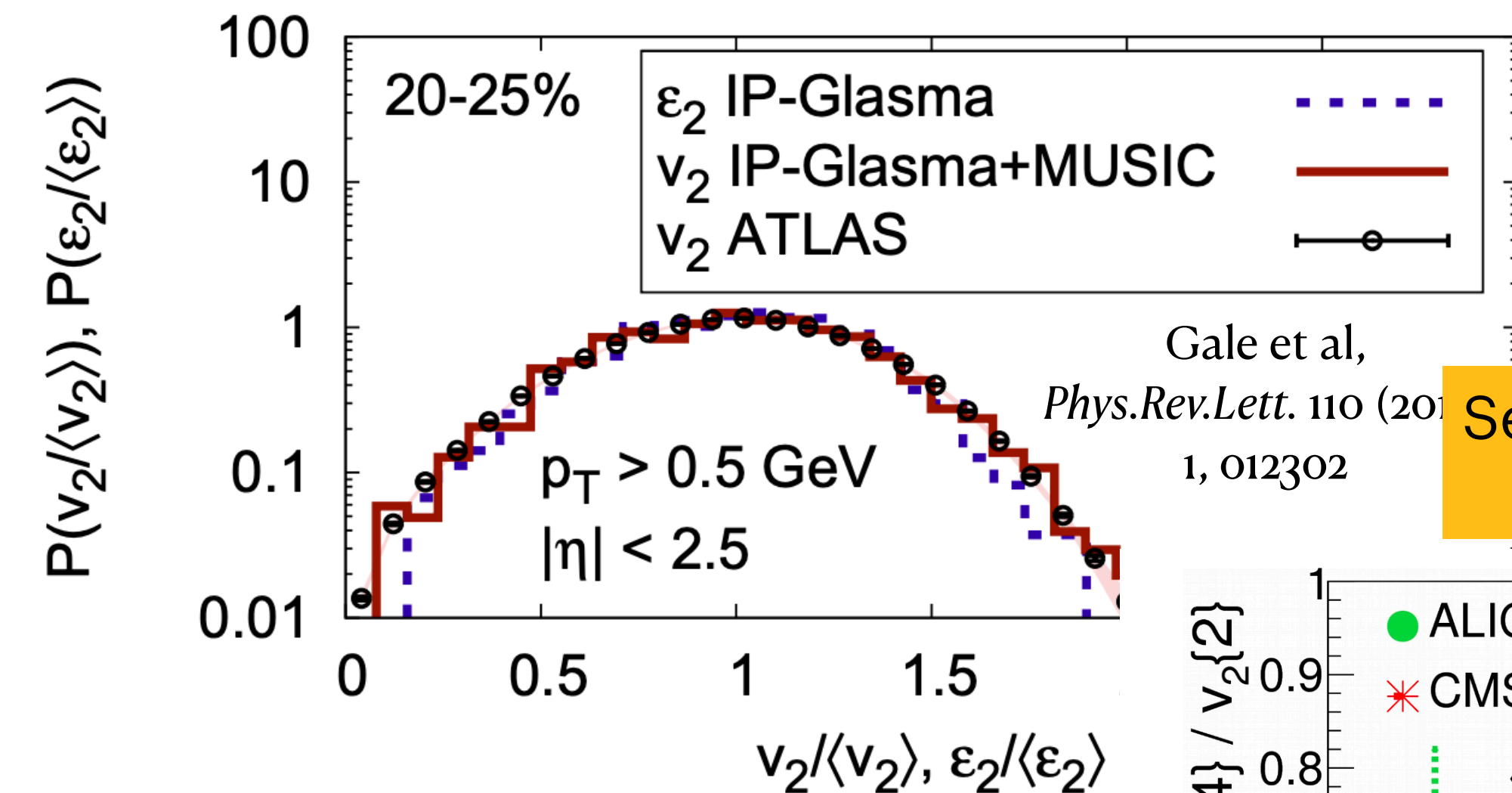


Event-by-event: Initial to final state connection

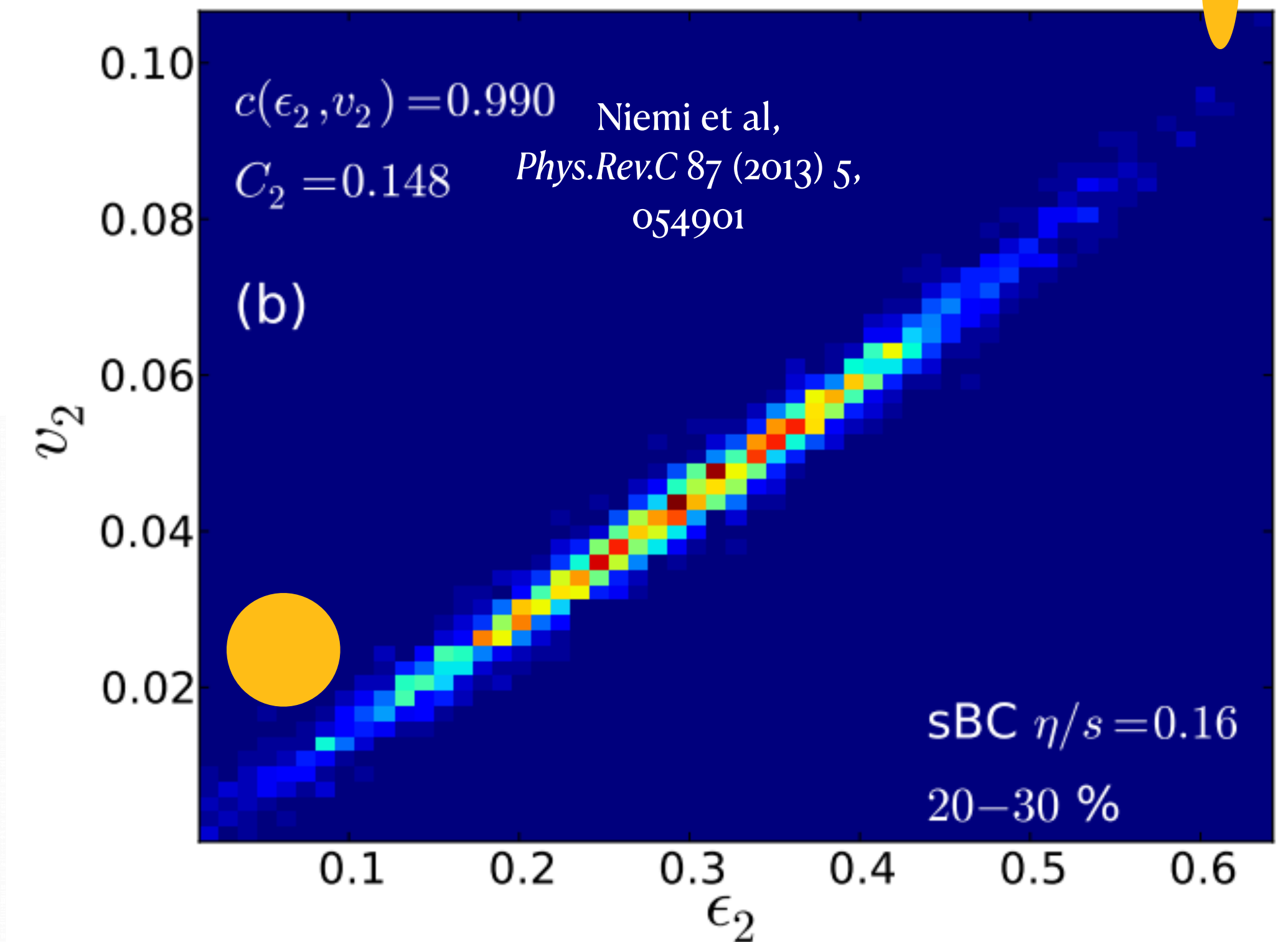
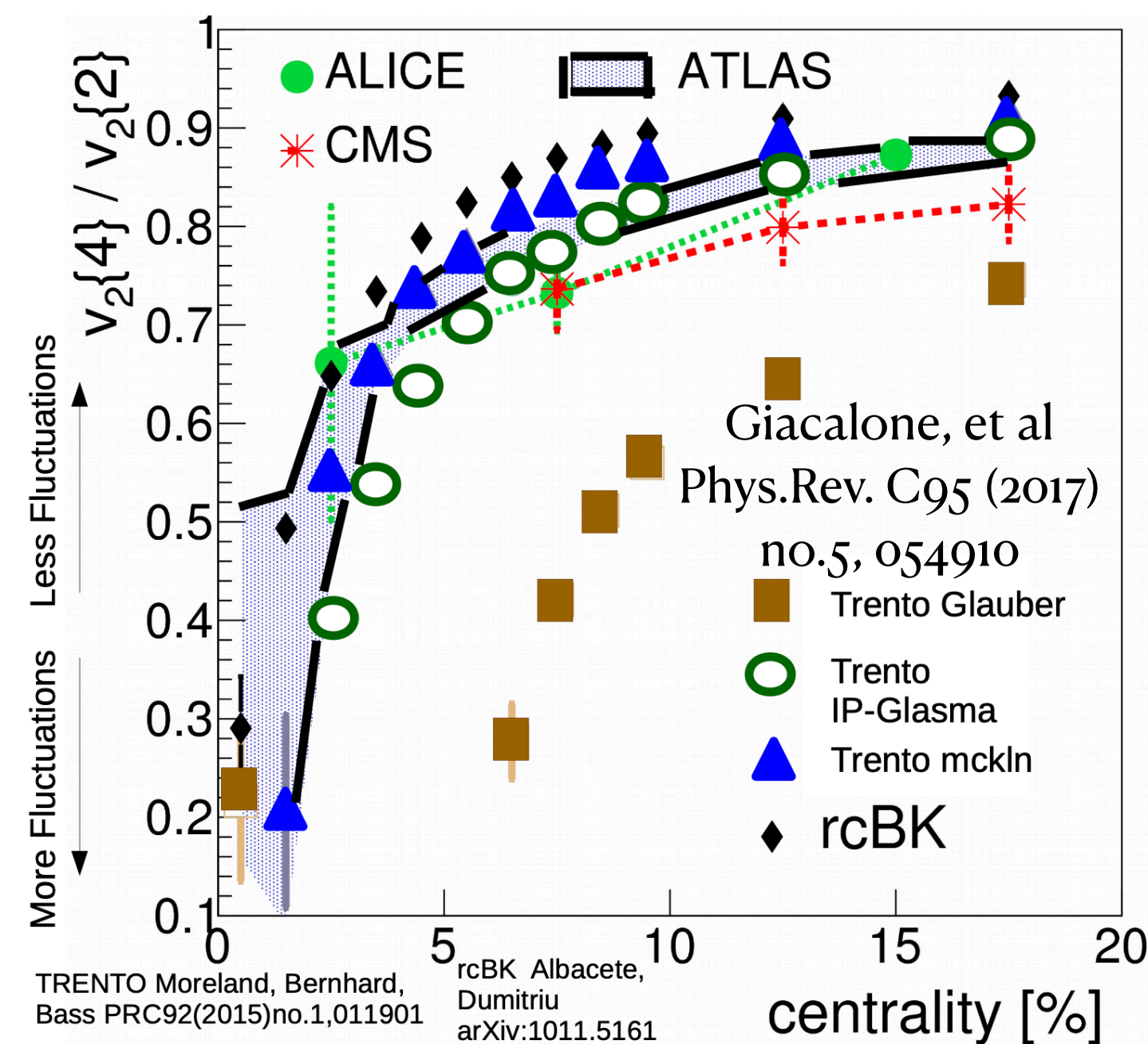
Imprints of the initial geometry

History of Event-by-Event from Belmont Weds

Understanding viscosity only works if there is a strong mapping from the initial to final state



See Niseem Magdy talk on Tuesday



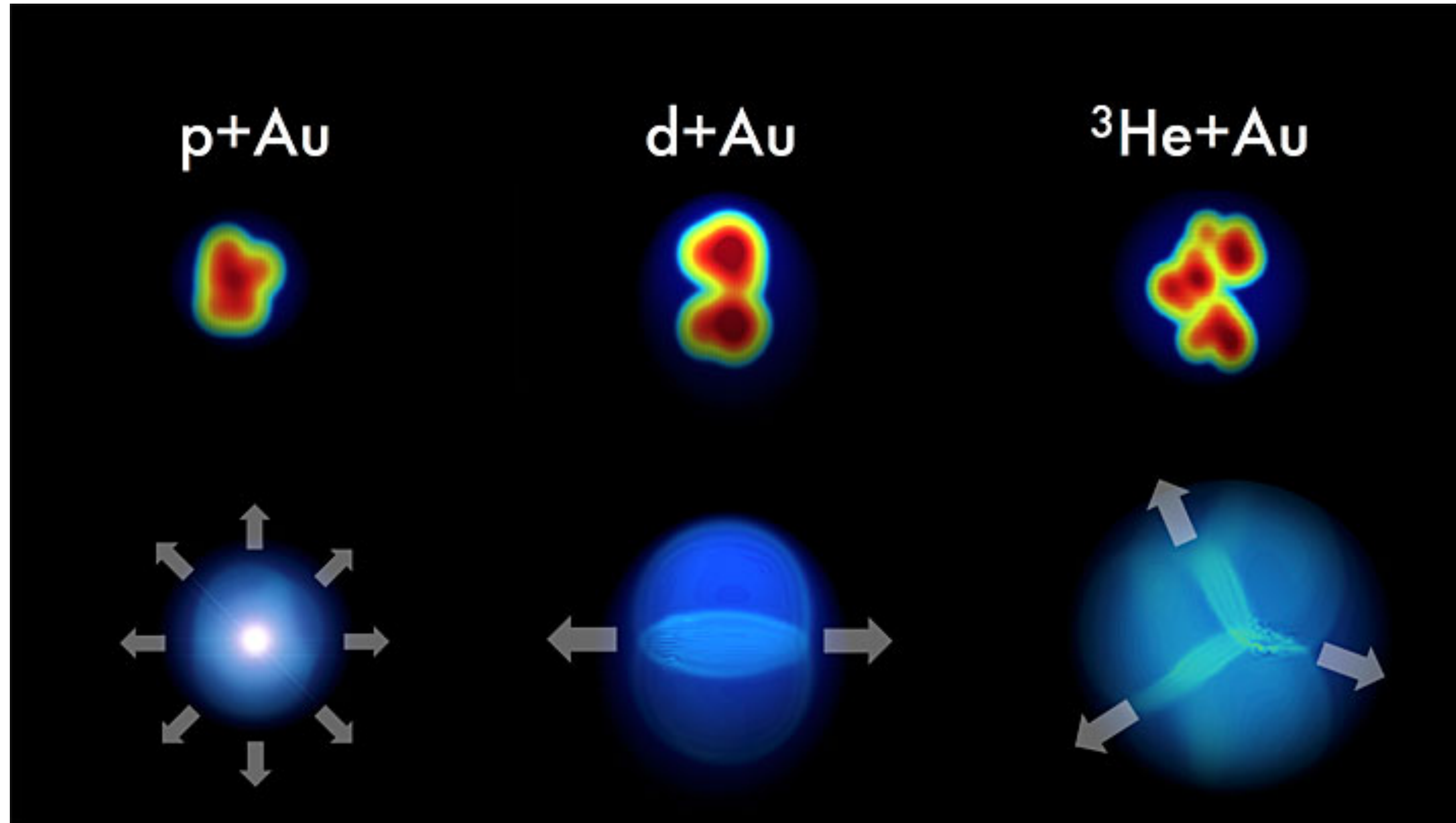
Nearly perfect linear correlation for v_2 and v_3 !

Also works for BSQ charges: Sousa, Sievert, JNH, Luzum, to appear tonight!

Initial state reproduces fluctuations, not just mean values

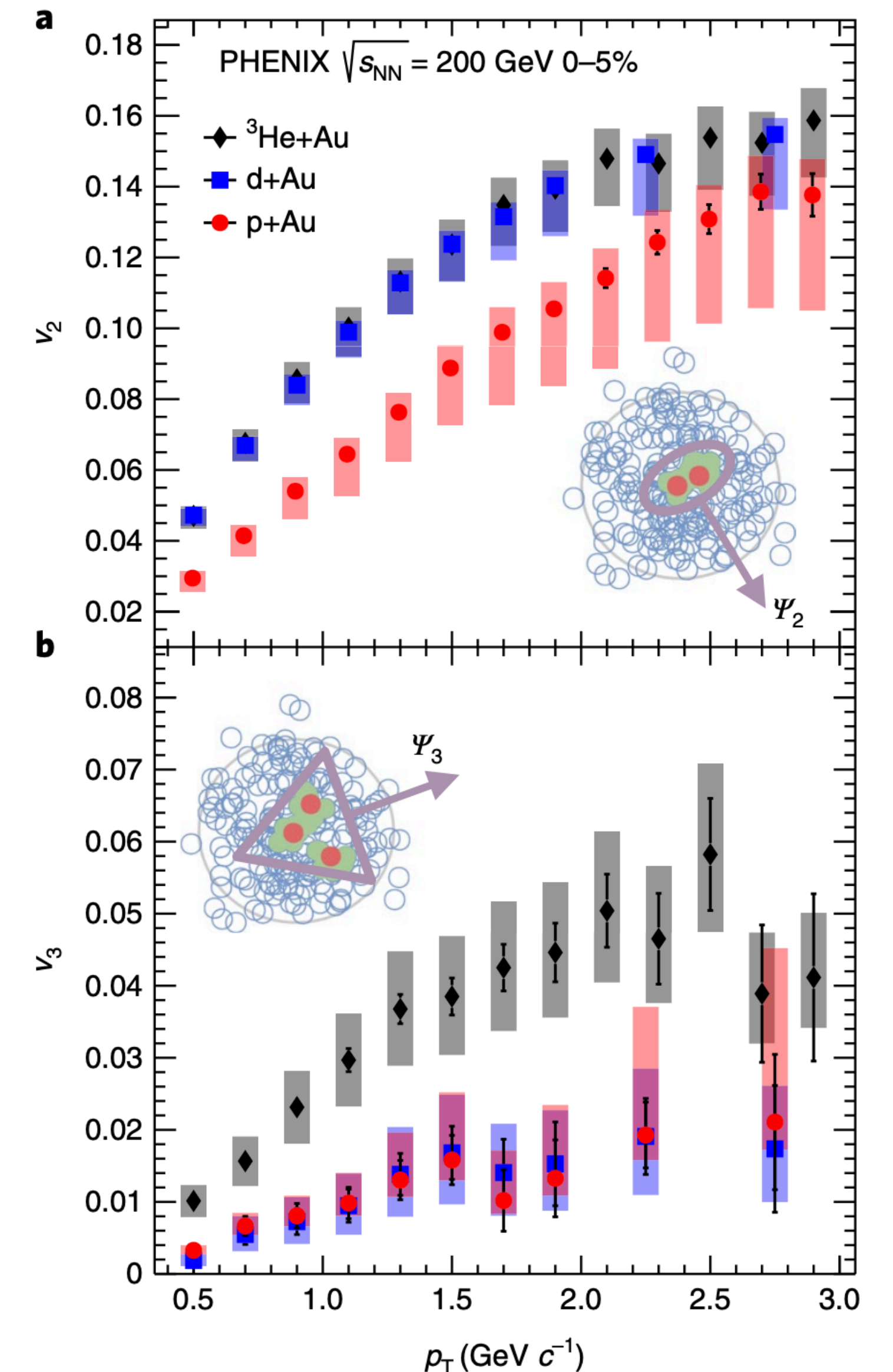
RHIC pushing our understanding to the extreme

Small systems and far-from-equilibrium hydrodynamics



PHENIX *Nature Physics* volume 15, pages 214–220 (2019)

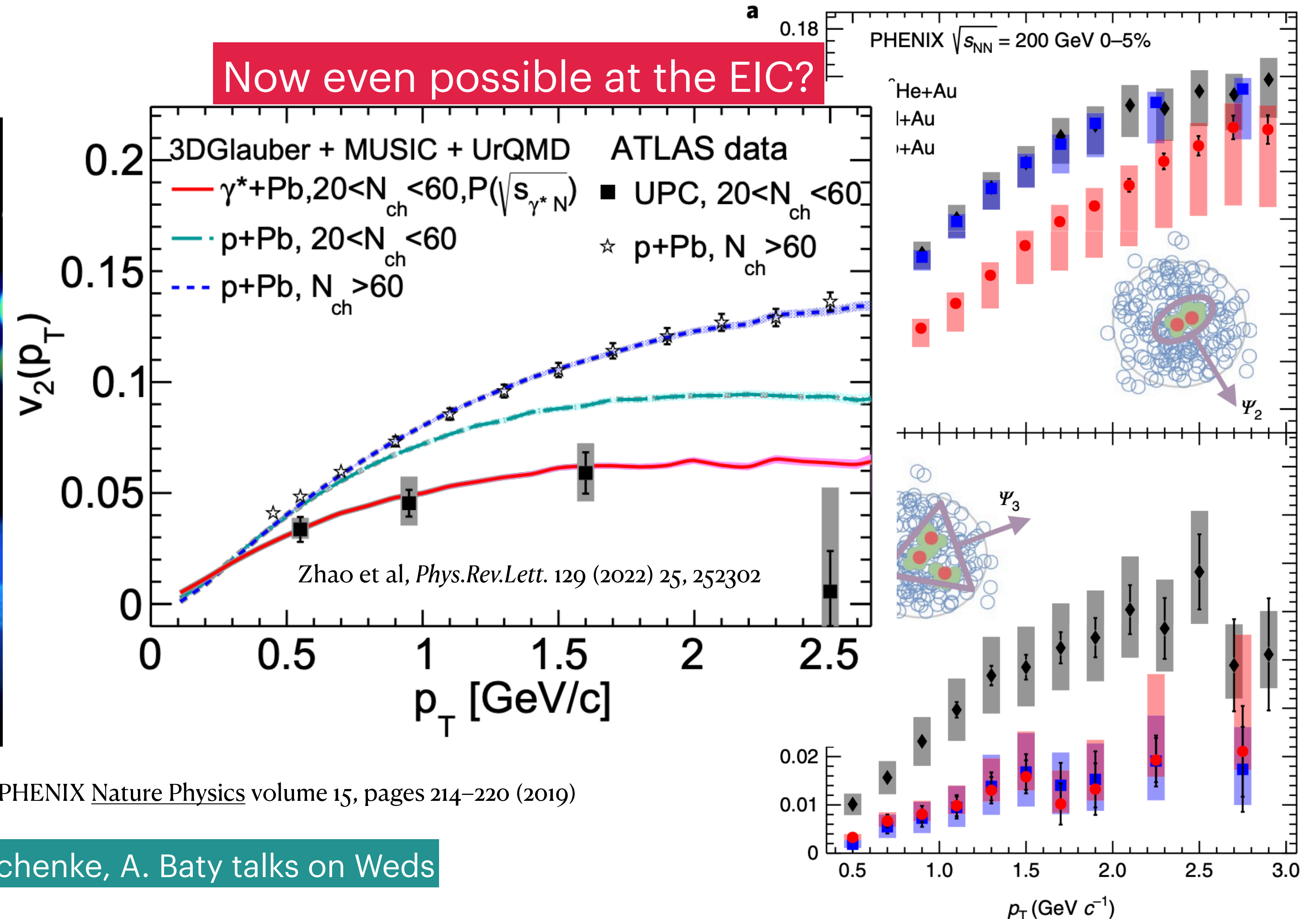
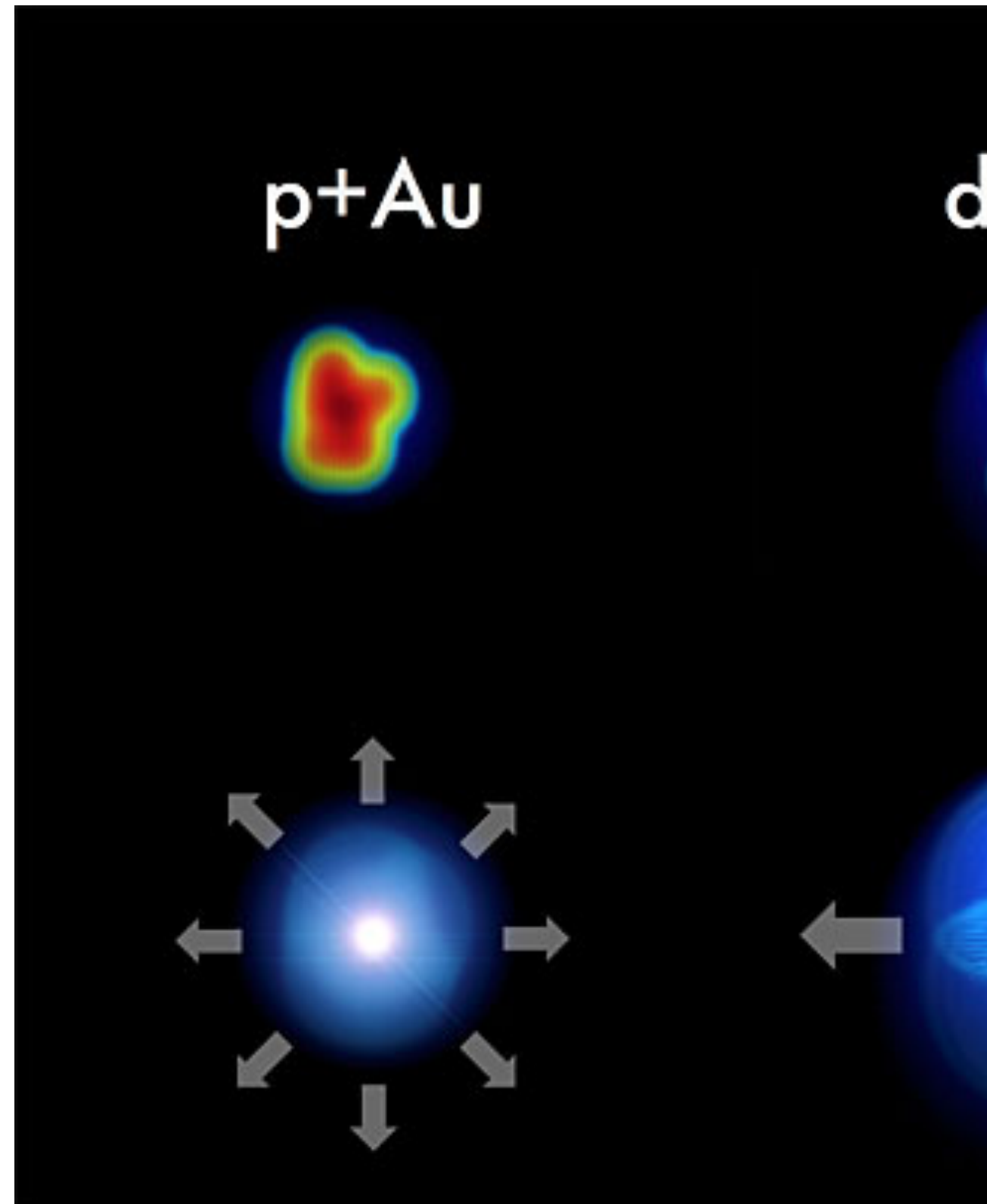
See R. Belmont, S. Paul, B. Seidlitz, B. Schenke, A. Baty talks on Weds



RHIC pushing our understanding to the extreme

Small systems and far-from-equilibrium hydrodynamics

Now even possible at the EIC?



PHENIX *Nature Physics* volume 15, pages 214–220 (2019)

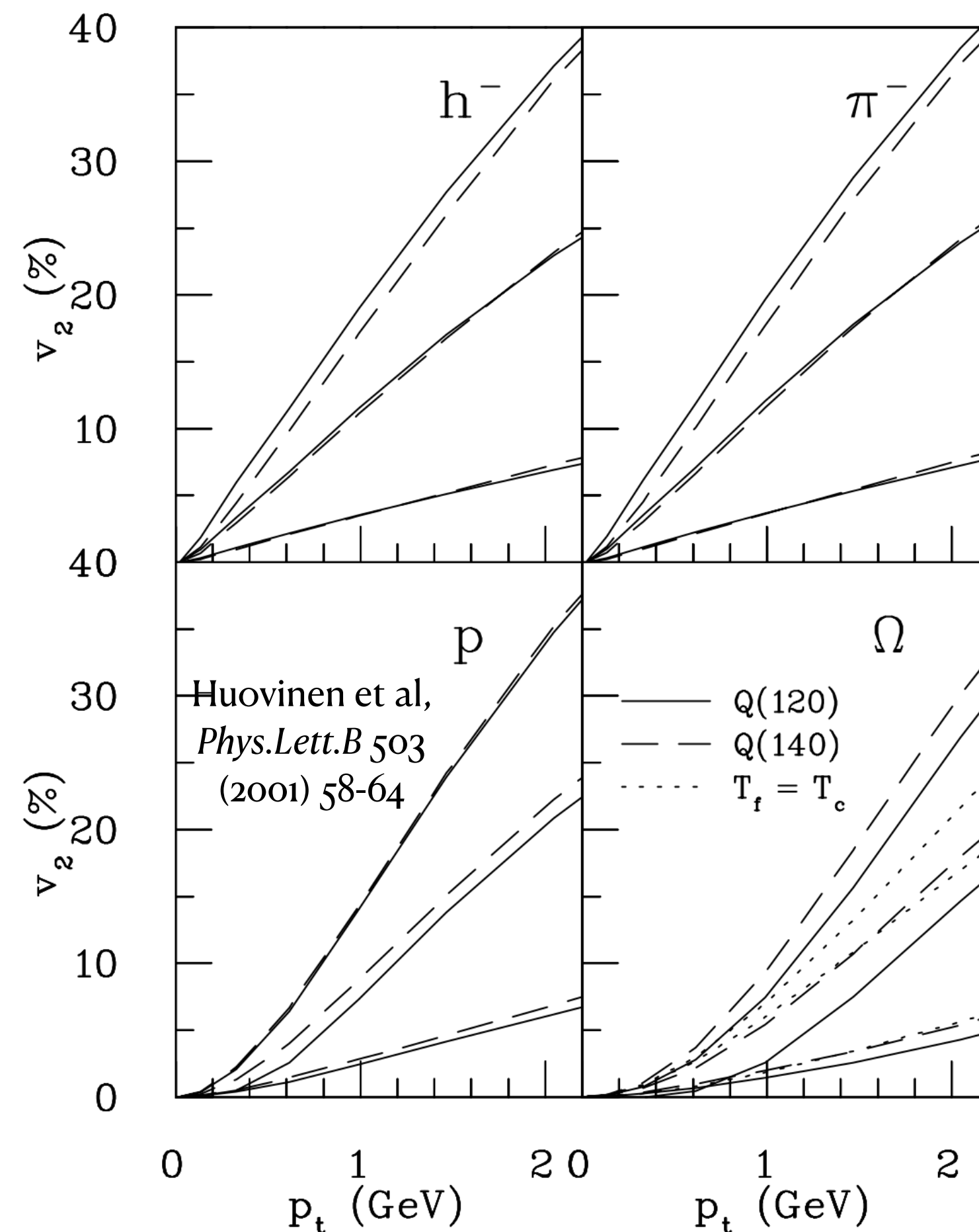
See R. Belmont, S. Paul, B. Seidlitz, B. Schenke, A. Baty talks on Weds

Rapid development of computational tools

Focus on fast runs for event-by-event initial conditions

Ideal $\rightarrow$ 2+1 shear $\rightarrow$ 2+1 shear+bulk $\rightarrow$ 3+1 shear+bulk+conserved charges (BSQ) $\rightarrow$ 3+1 shear+bulk+BSQ diffusion

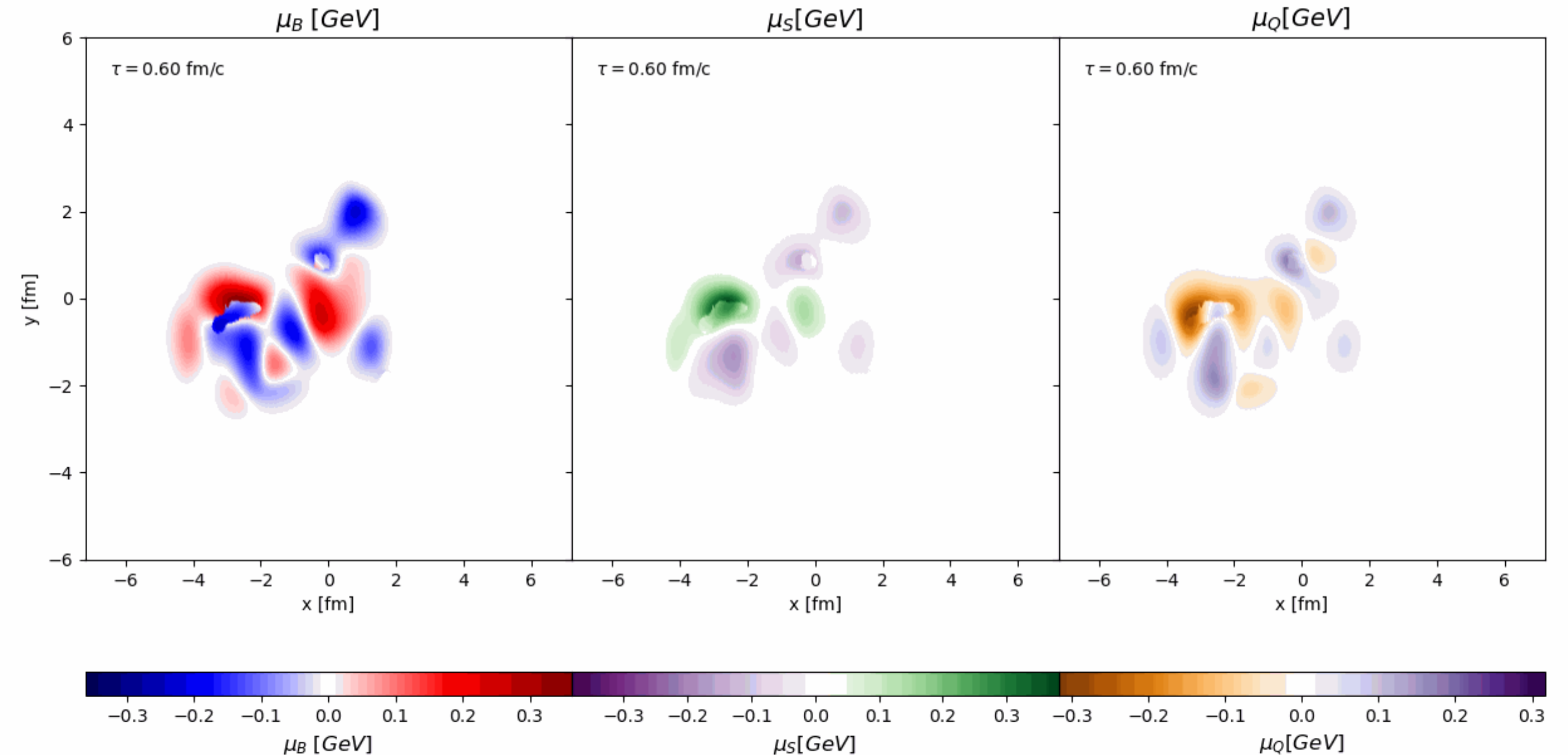
Ideal hydro



J. Noronha-Hostler UIUC

Trento+ICCING+CCAKE 2.0 (3+1 BSQ diffusion)

Pala, Kaur Virk, Almaalol, Danhoni, Yao, Long, Salinas san Martin, Serone, Gardim, Plumberg, JNH to appear



See Lipei Du's
talk on Tuesday

Simulation of PbPb collisions with full BSQ
diffusion matrix+shear and bulk viscosity

BSQ diffusion coefficients from : Greif et al *Phys.Rev.Lett.* 120 (2018) 24, 242301;

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

Theoretical description of relativistic fluids

Different methods to derive the equations of motion

Israel-Stewart

Annals Phys. 118 (1979) 341-372

Enforce 2nd law of thermo

$$\tau_\pi \pi^{\dot{\mu}\nu} + \pi^{\mu\nu} = 2\eta\sigma^{\mu\nu} + \frac{\tau_\pi \dot{\beta}_\pi}{2\beta_\pi} \pi^{\mu\nu}$$

Israel-Stewart only

DNMR

Denicol, et al, *Phys.Rev.D* 85 (2012) 114047

Expansion in applicability of hydro

$$\tau_\pi \pi^{\dot{\mu}\nu} + \pi^{\mu\nu} = 2\eta\sigma^{\mu\nu} + \frac{\tau_\pi}{2} \pi^{\mu\nu} \theta + \frac{\eta \delta_{\Pi\pi}}{2} \Pi \sigma^{\mu\nu}$$

Couples shear-bulk viscosity

BDNK

Bemfica et al, *Phys.Rev.D* 98 (2018) 10, 104064

1st-order, generalized frame

$$\pi^{\mu\nu} = 2\eta\sigma^{\mu\nu}$$

Picks up acceleration terms

ADNH=IS+DNMR

Almaalol et al, *Phys.Rev.D* 111 (2025) 1, 014020

Recovers most DNMR terms from 2nd law method

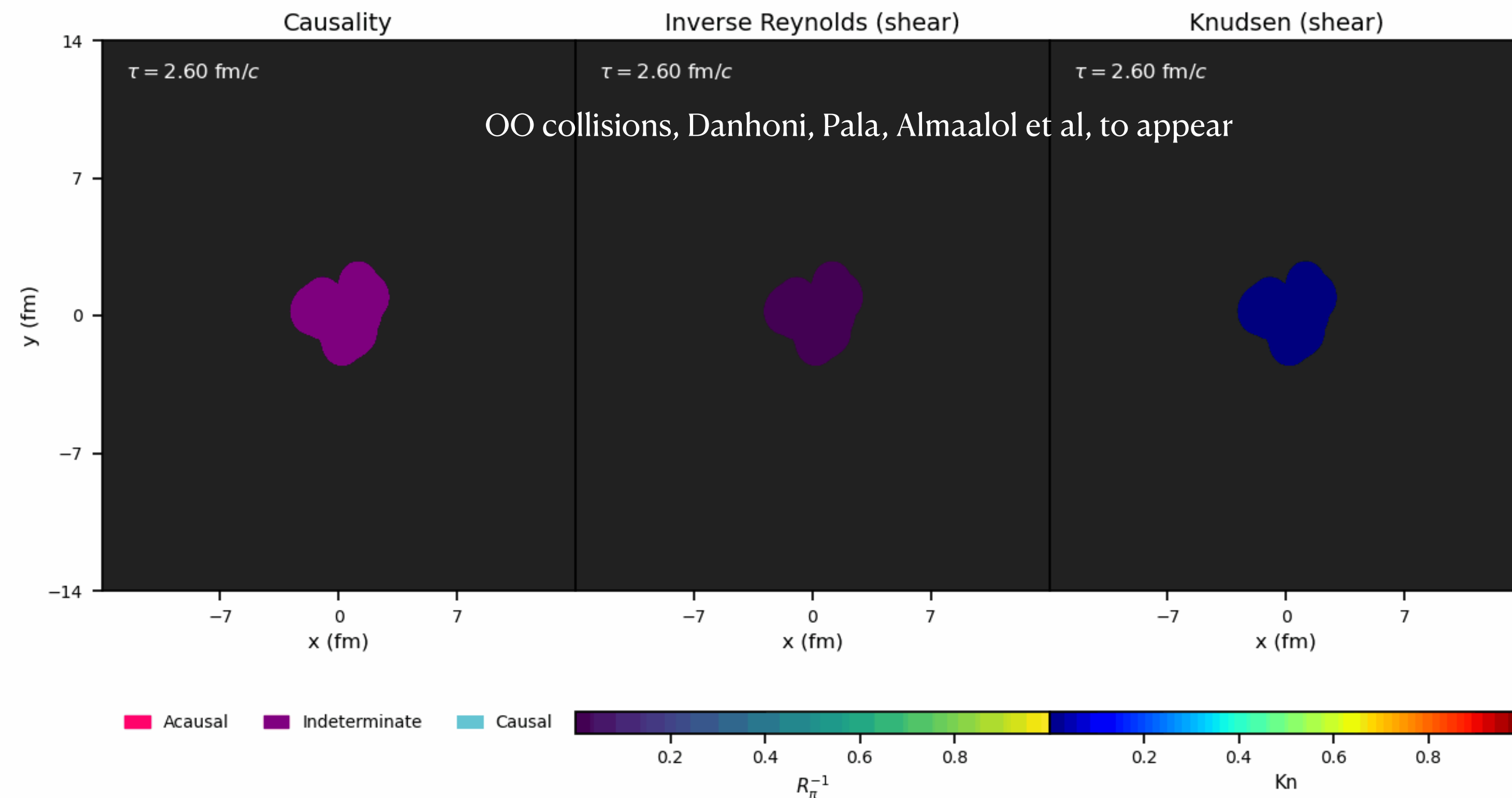
$$\tau_\pi \pi^{\dot{\mu}\nu} + \pi^{\mu\nu} = 2\eta\sigma^{\mu\nu} + \frac{\tau_\pi \dot{\beta}_\pi}{2\beta_\pi} \pi^{\mu\nu} + \frac{\tau_\pi}{2} \pi^{\mu\nu} \theta + \frac{\eta \delta_{\Pi\pi}}{2} \Pi \sigma^{\mu\nu}$$

Larger body of work, studying attractors (see original Heller Spalinski *PRL* 115 (2015) 7, 072501), applicability in different systems, finite densities, magnetic fields, coupled to general relativity etc

Causality and Stability: math-physics collaborations

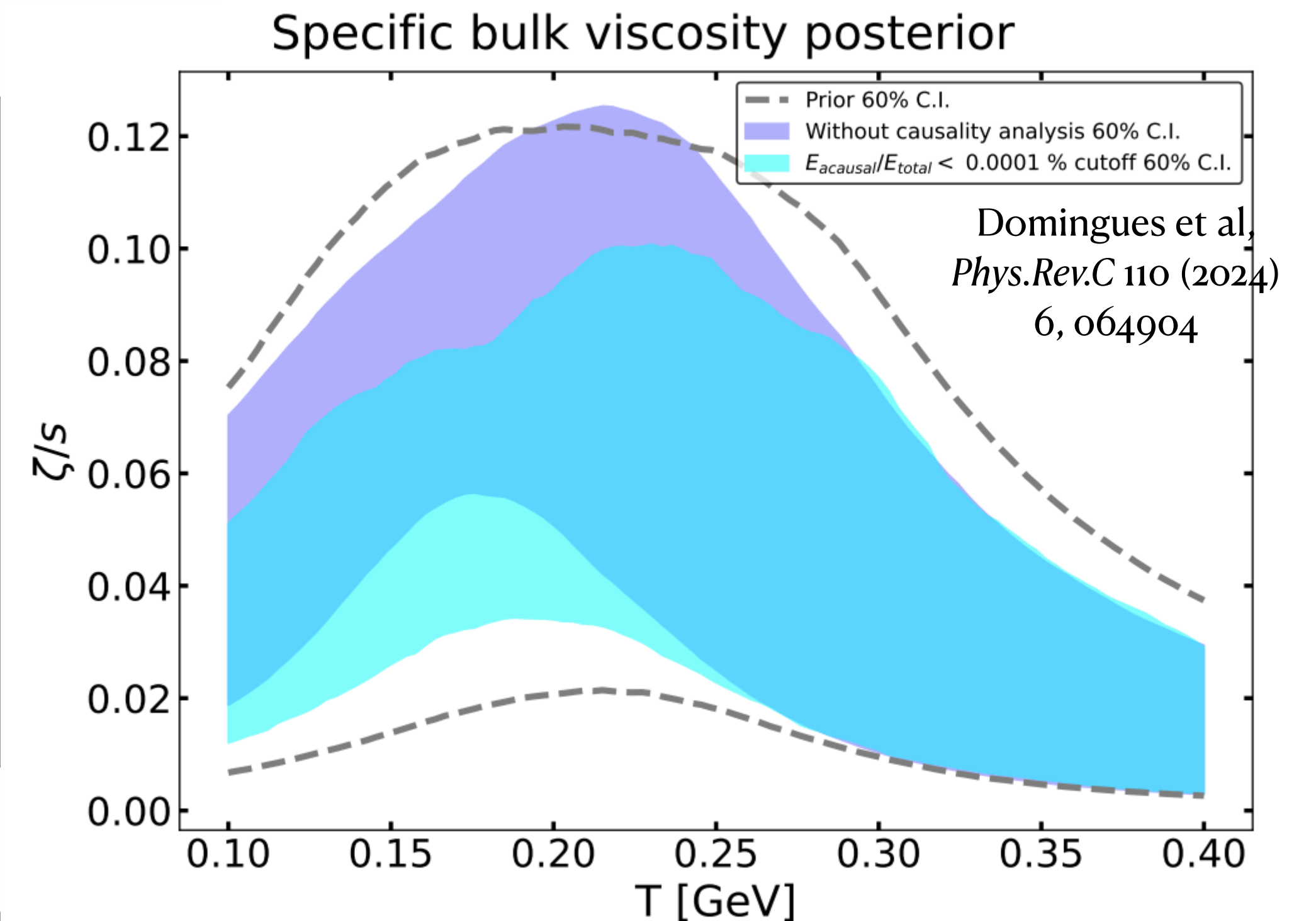
Mathematical constraints from nonlinear causality and stability

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



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

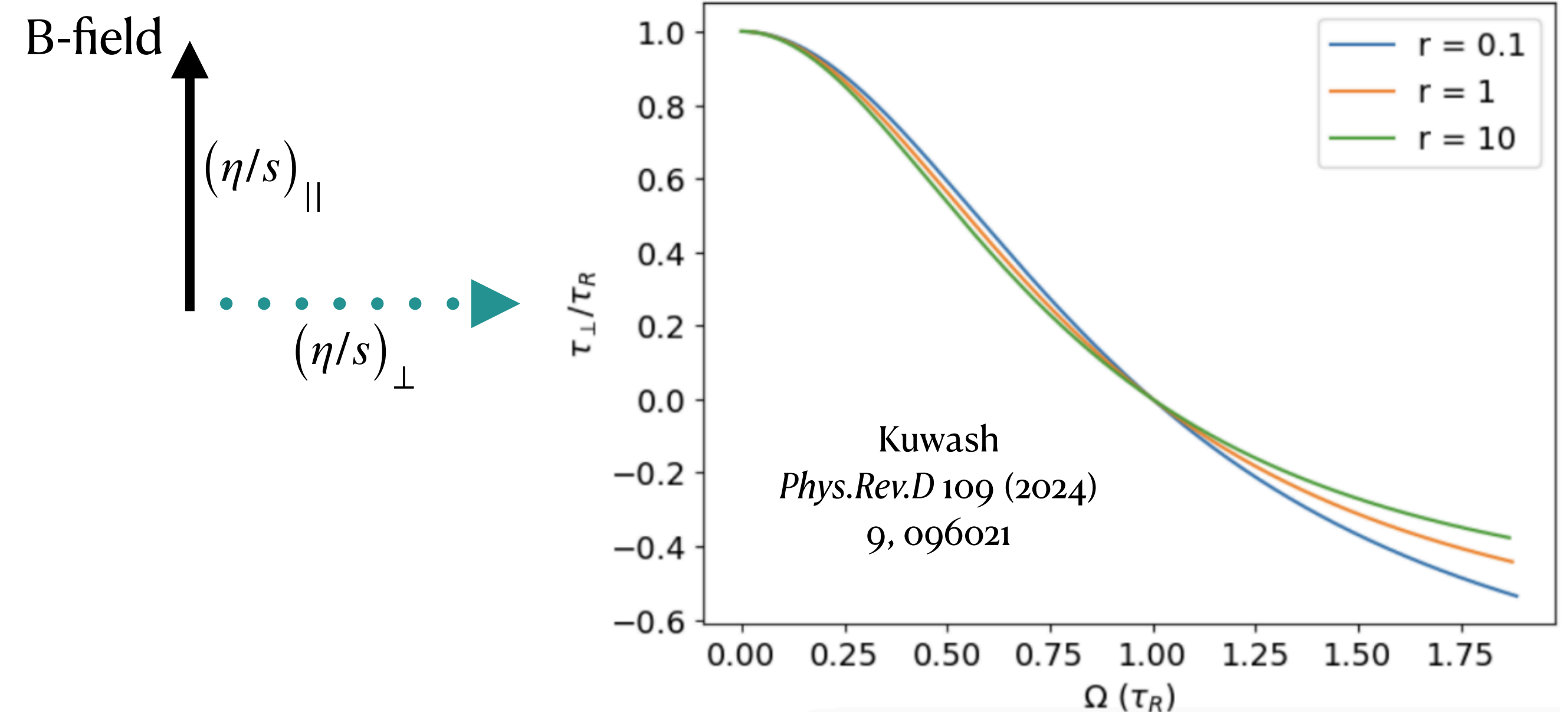
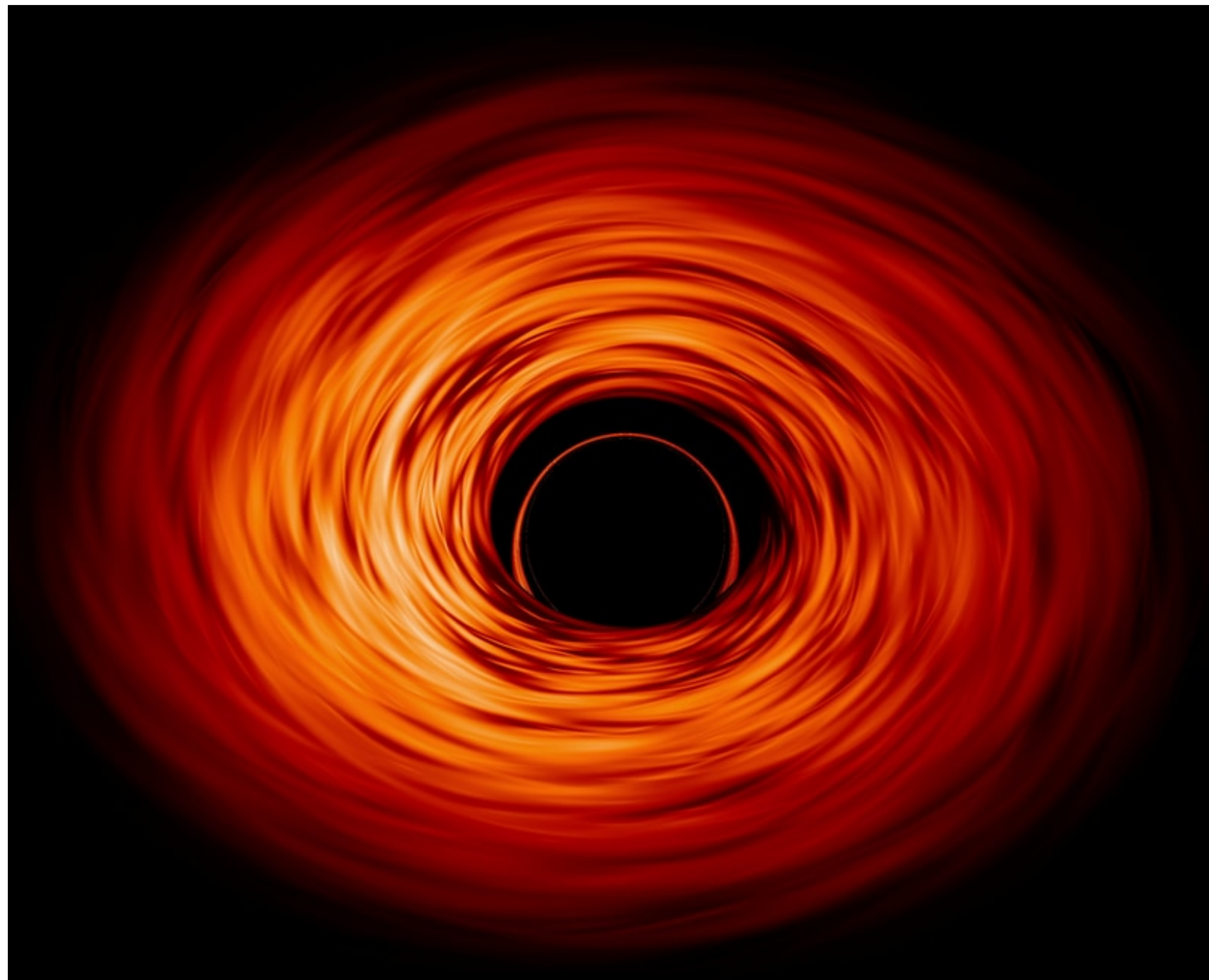


BUT, this goes WAY beyond just heavy-ion collisions!

Causality/stability constraints in astrophysics!

Magnetohydrodynamics for black hole accretion disks

High $T \sim 100$ MeV, extremely dilute (electrons and light ions), large magnetic fields



(a) $\tau_\perp$ assuming negative values for $\varphi(\Omega) > 0.5$.

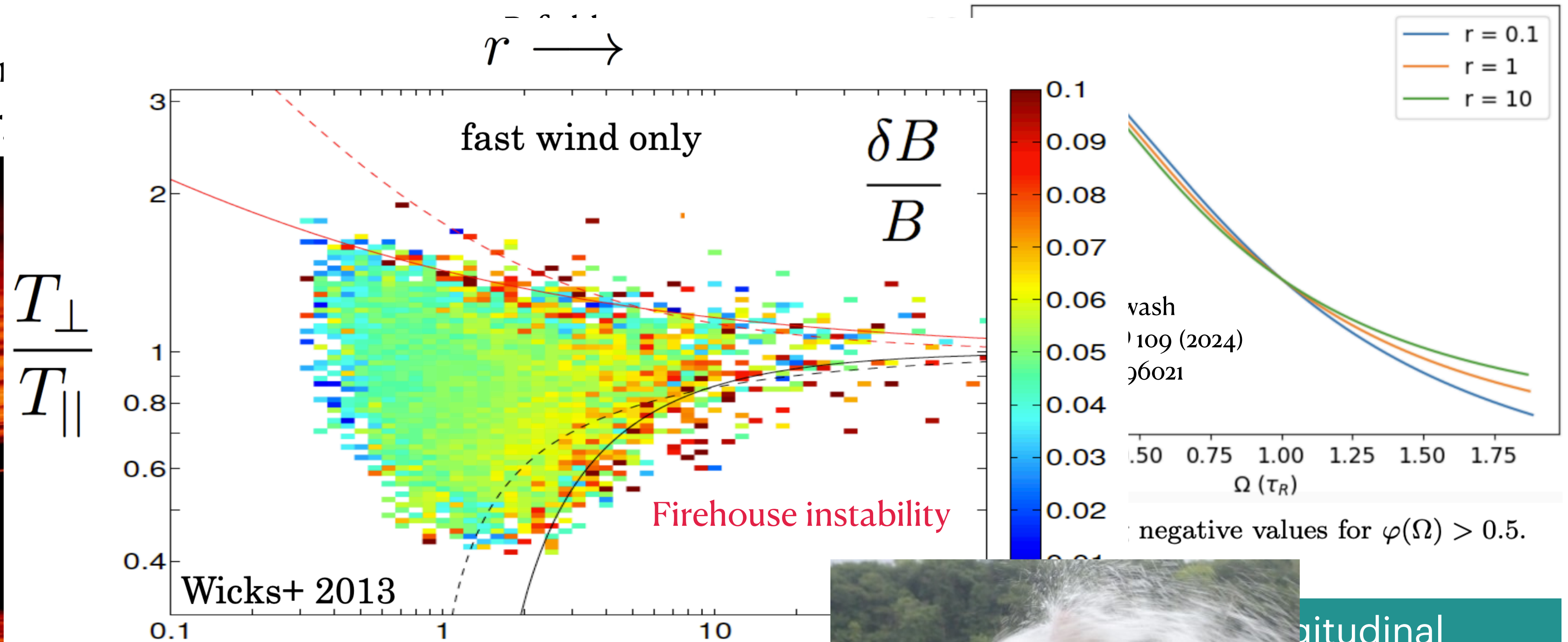
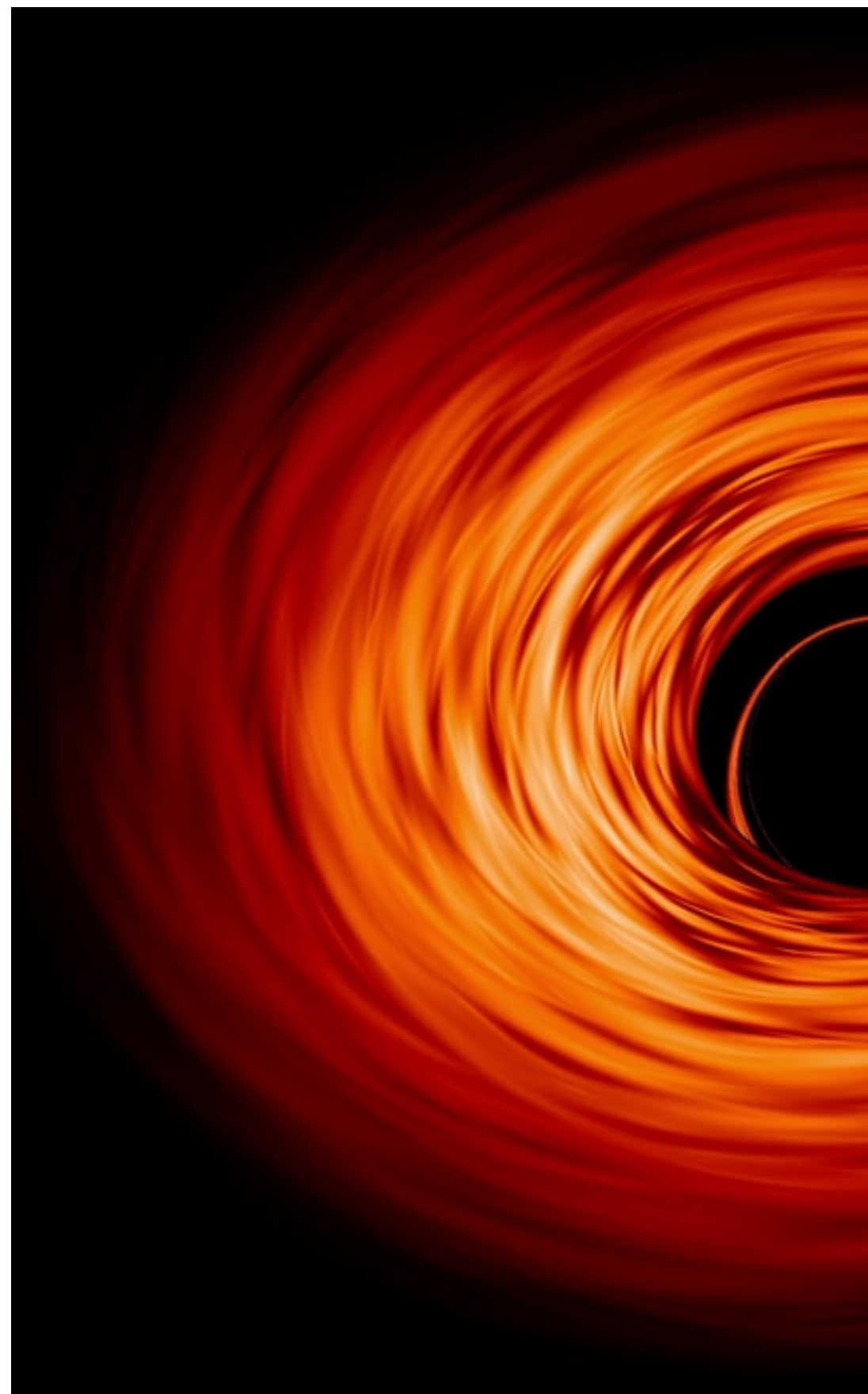
Astrophysical plasmas only longitudinal components of $\pi^{\mu\nu}$, this assumption may not be valid in certain regimes (firehouse instability)

Brito et al, [2505.10397](#) [nucl-th]

Causality/stability constraints in astrophysics!

Magnetohydrodynamics for black hole accretion disks

High $T \sim 100$ MeV, exti
and light ions), lar



$$\beta_{\parallel} = \frac{8\pi n T_{\parallel}}{B^2}$$

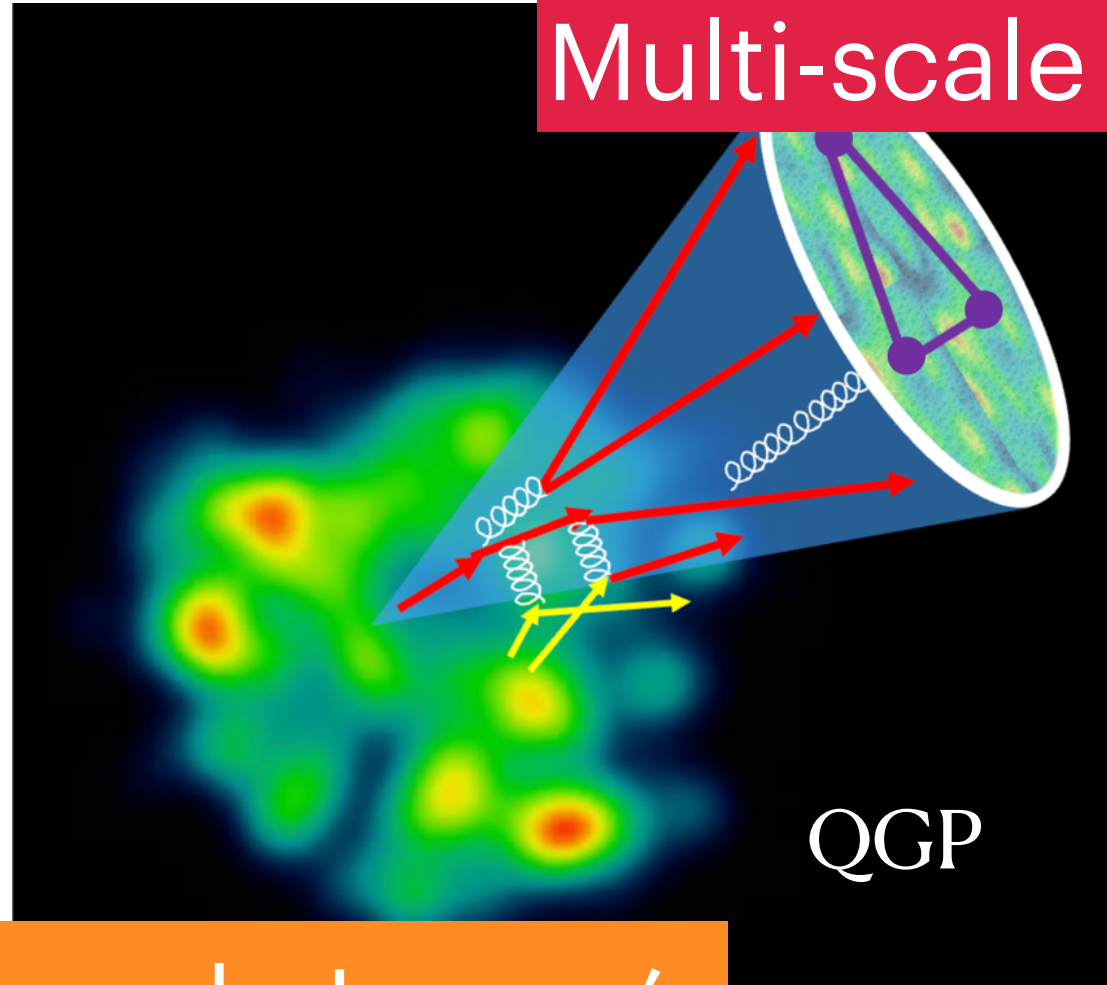


itudinal
n may not be
instability)

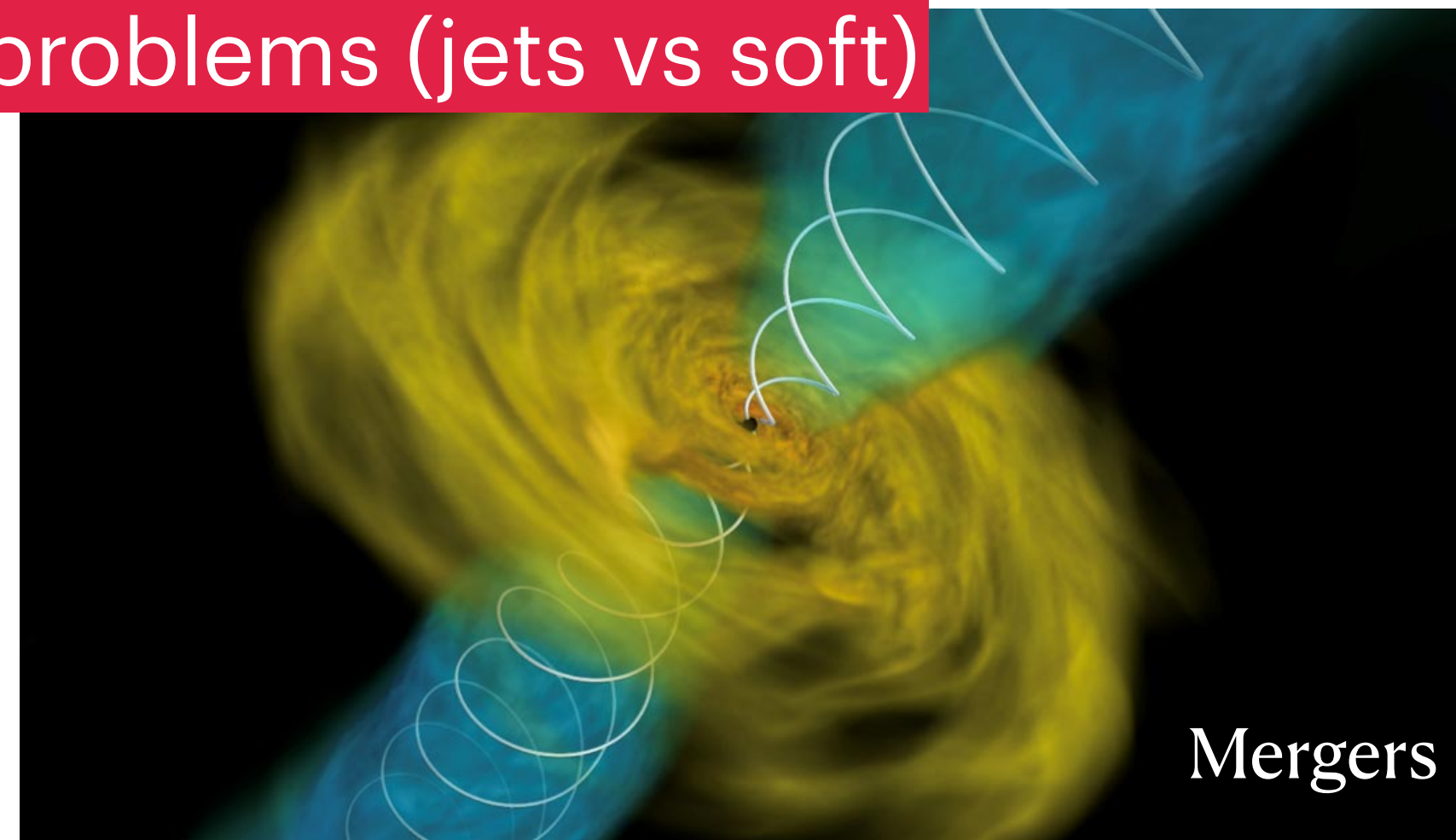
Brito et al, [2505.10397](#) [nucl-th]

Still much to do: nuclear, astro, gravity, strings...

Multi-scale problems (jets vs soft)



QGP



Mergers

Riccardo Longo's
talk on Weds

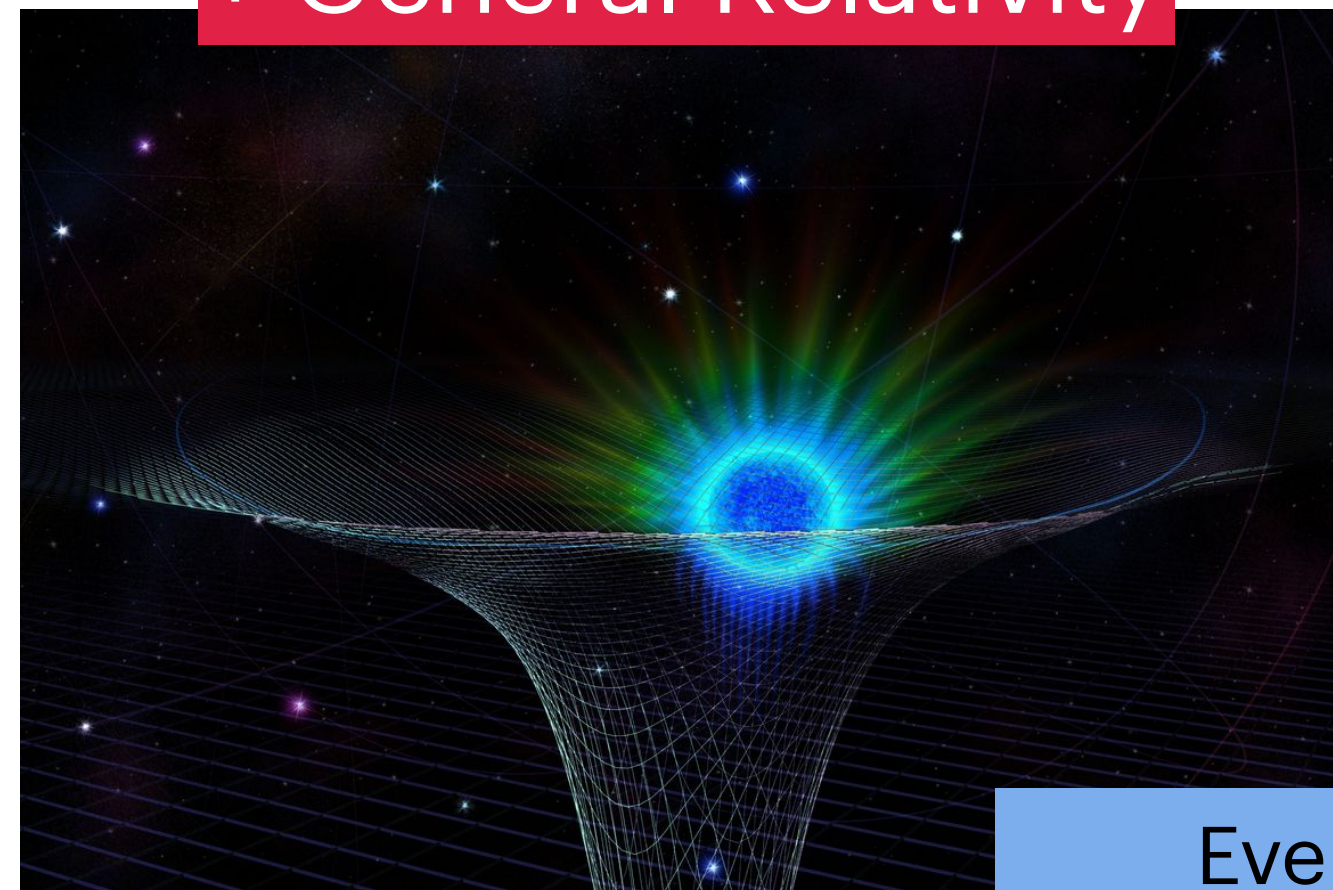
Diffusion Wake: Chen
et al, Physics Letters B
777 (2018) 86–90

Criticality/phase transitions
in relativistic fluids



J. Noronha-Hostler UIUC

+ General Relativity



Even used to studied modified gravity
Ciambelli et al, Phys.Rev.D 108 (2023) 12, 126019



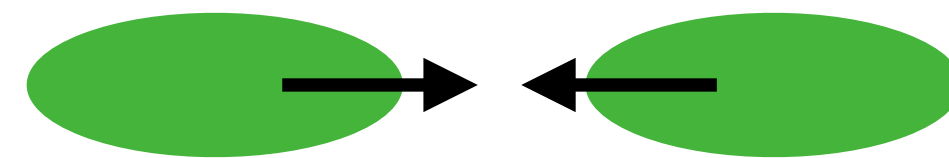
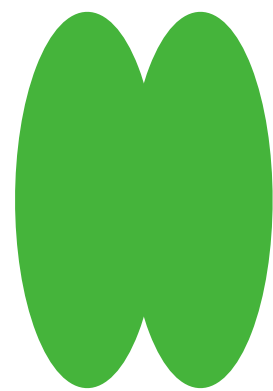
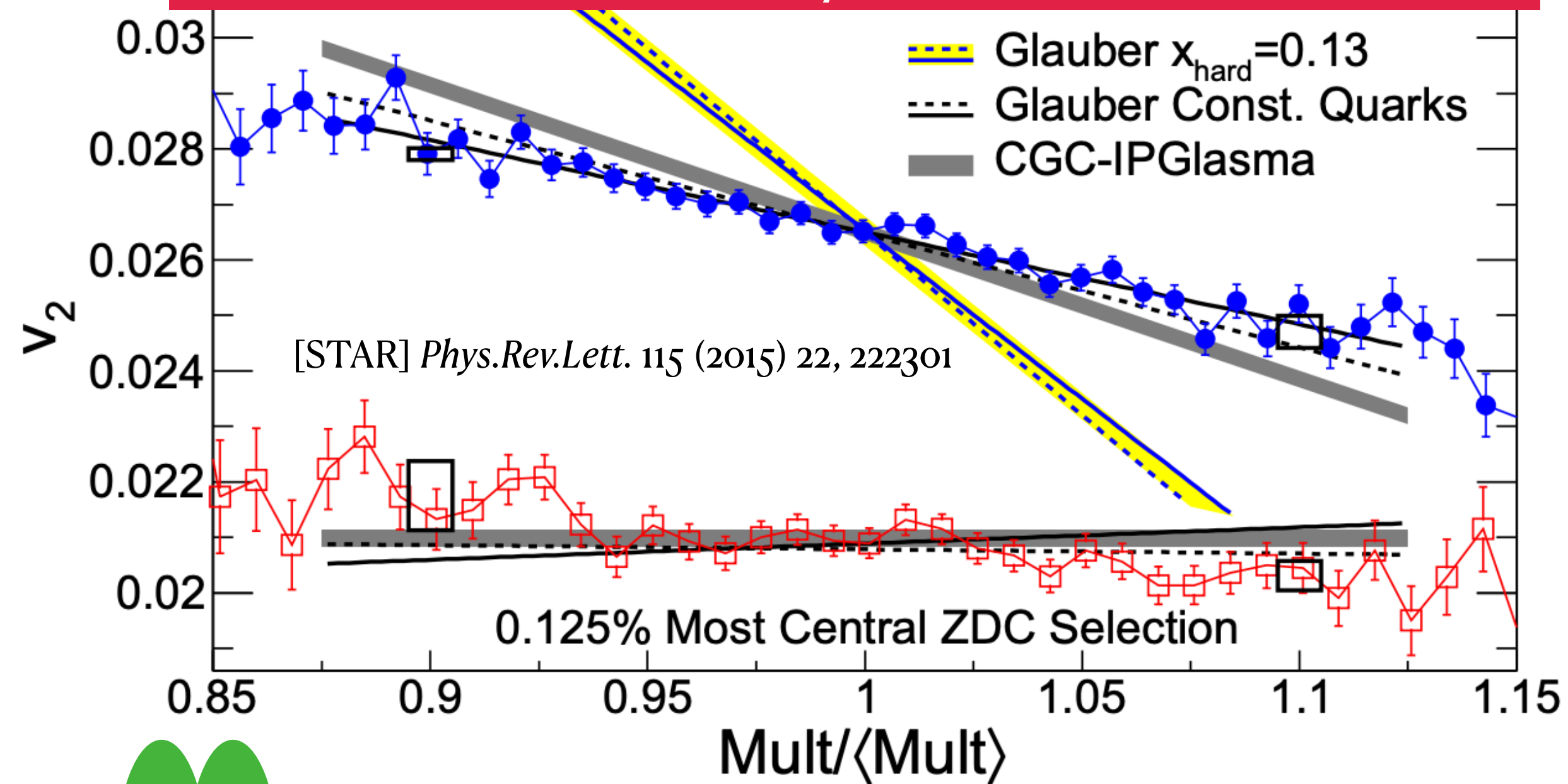
The Many Faces of Relativistic Fluid Dynamics

Coordinators: Michal P. Heller, Pavel Kovtun, Jacquelyn Noronha-Hostler, and Jorge Noronha
Scientific Advisors: Ulrich Heinz, Mukund Rangamani, Dam Son, and Bill Zajc

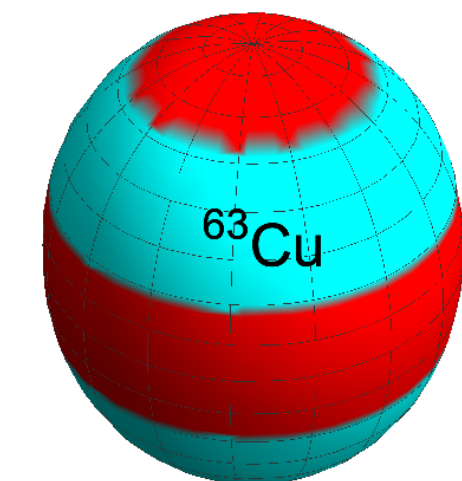
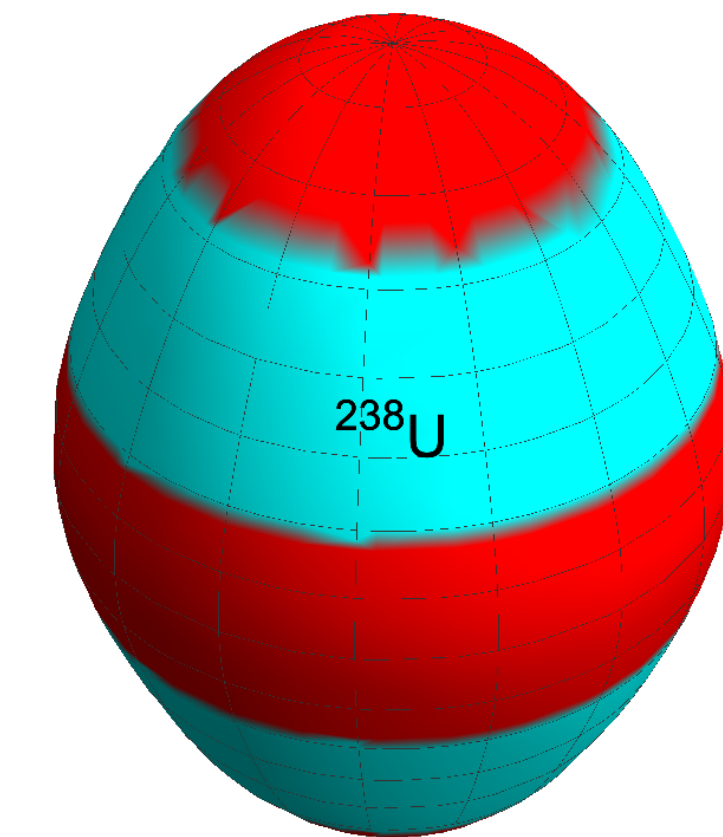
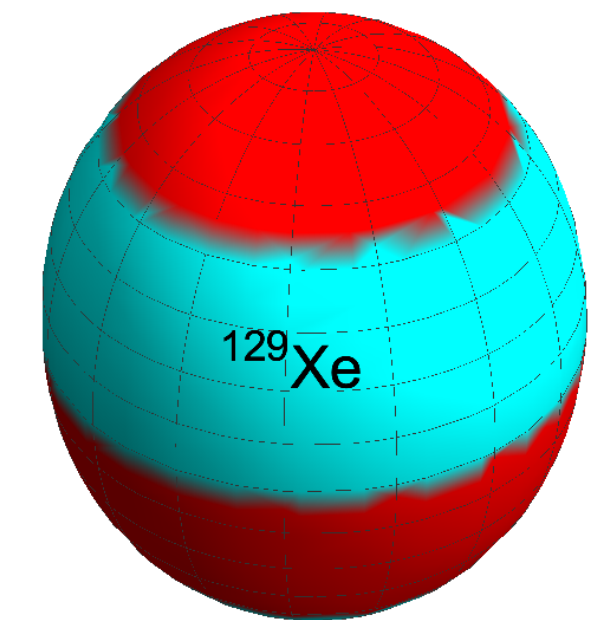
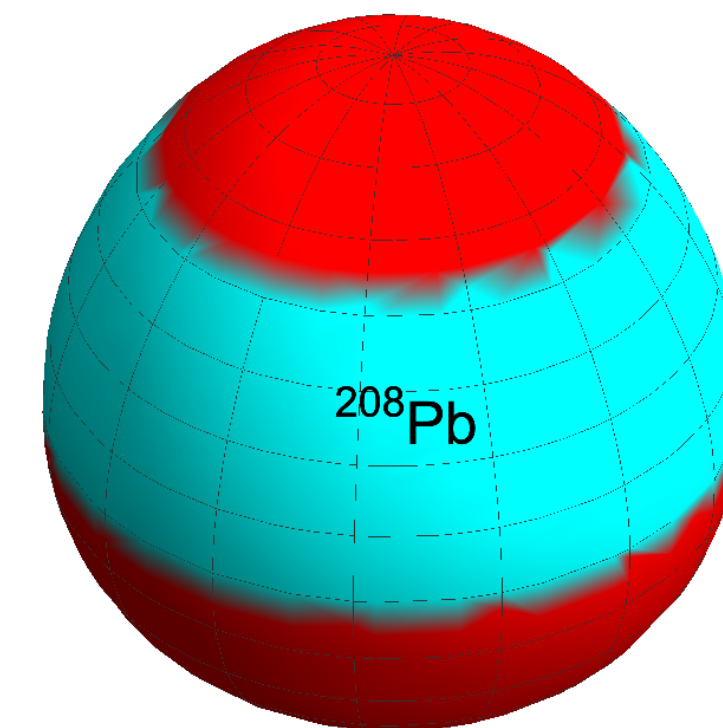


Impact 2: Finding nuclear structure in unexpected places

Idea from STAR, using ultra central collisions to study nuclear structure!



^{238}U is roughly football shaped

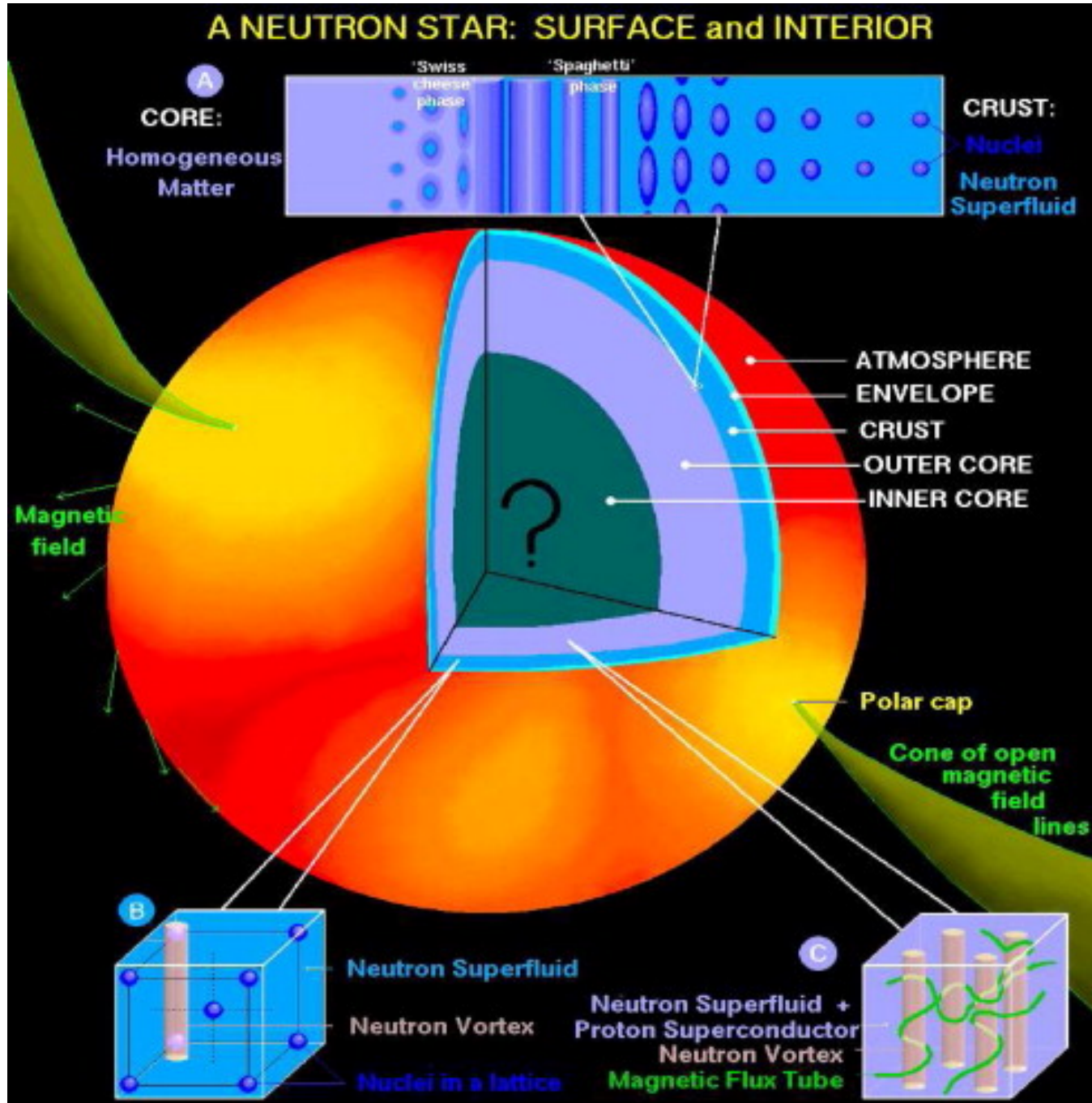


Recent study on hexadecupole constraints from the ^{238}U data

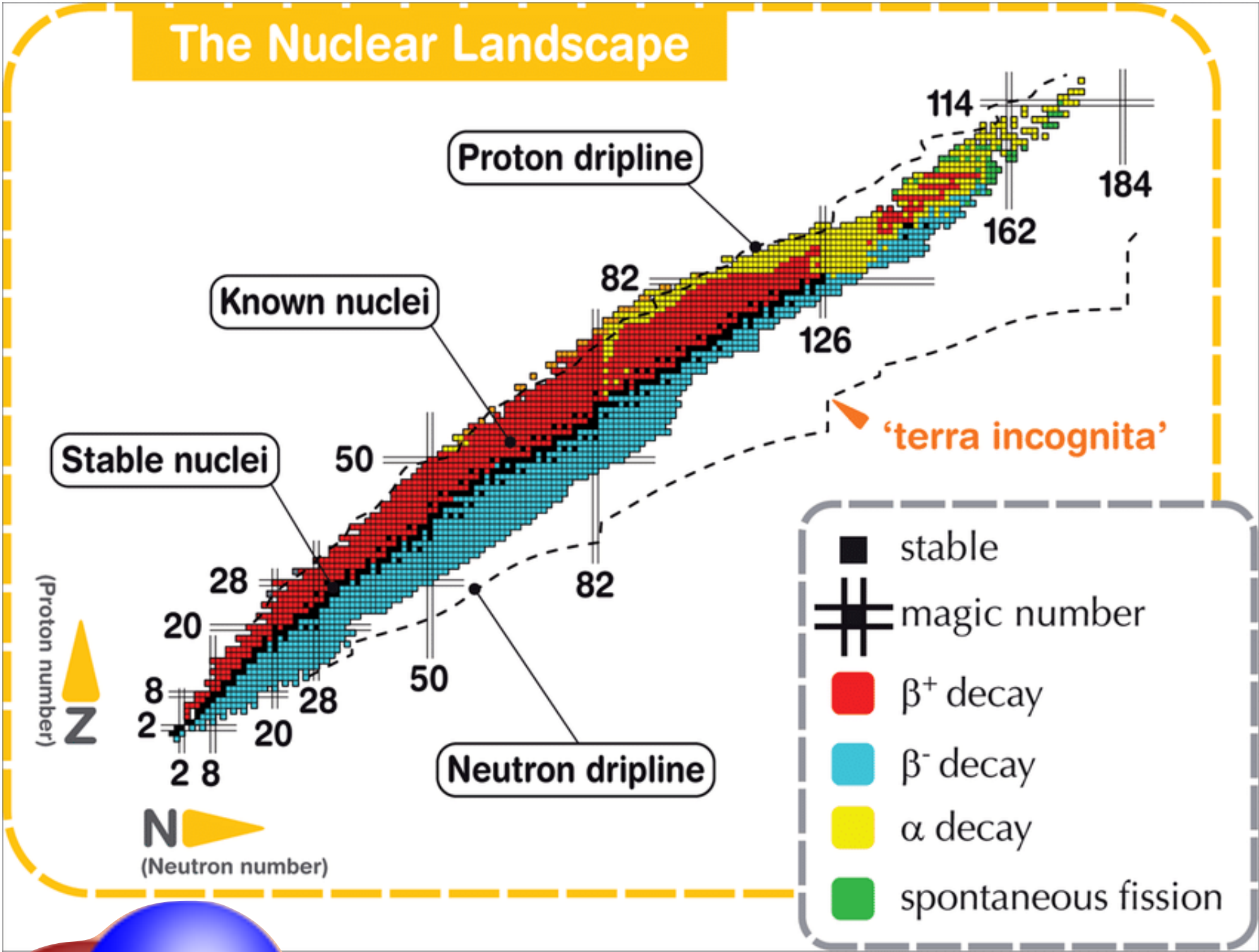
Ryssens et al, Phys.Rev.Lett. 130 (2023) 21, 212302

Why is nuclear structure interesting?

Neutron Stars



Correlations

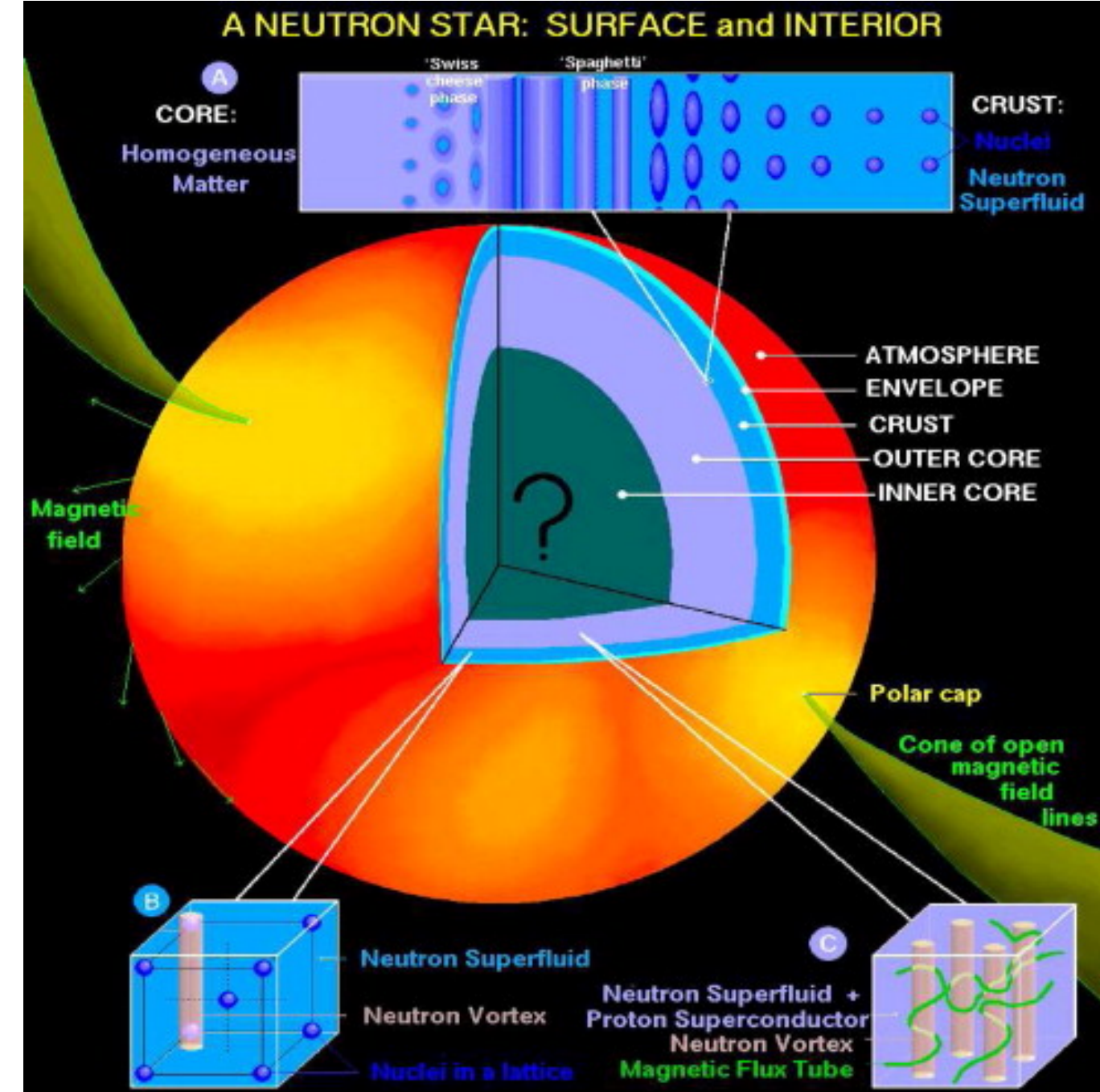


Connecting 2 pillars of DOE NP

Many-Body Physics

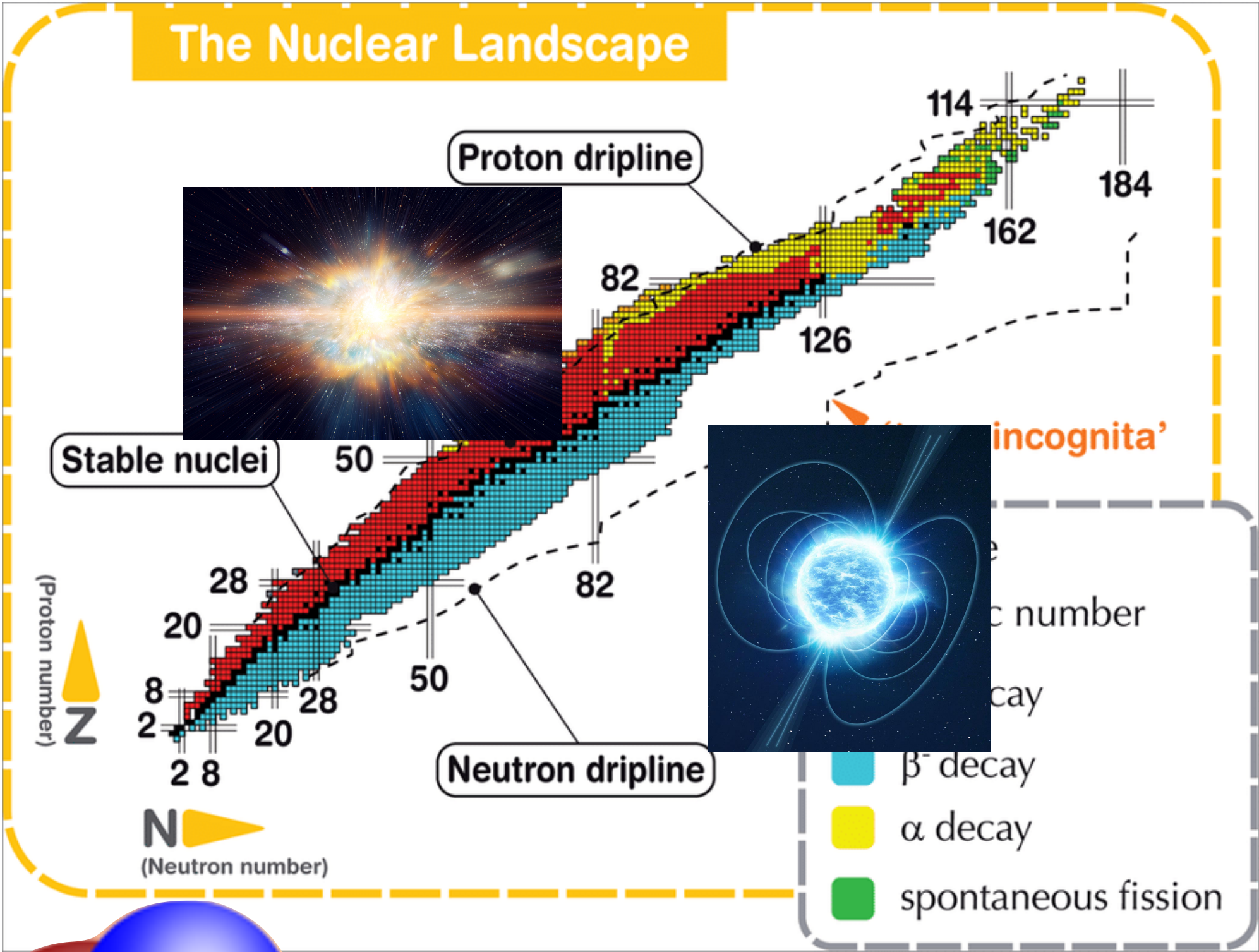
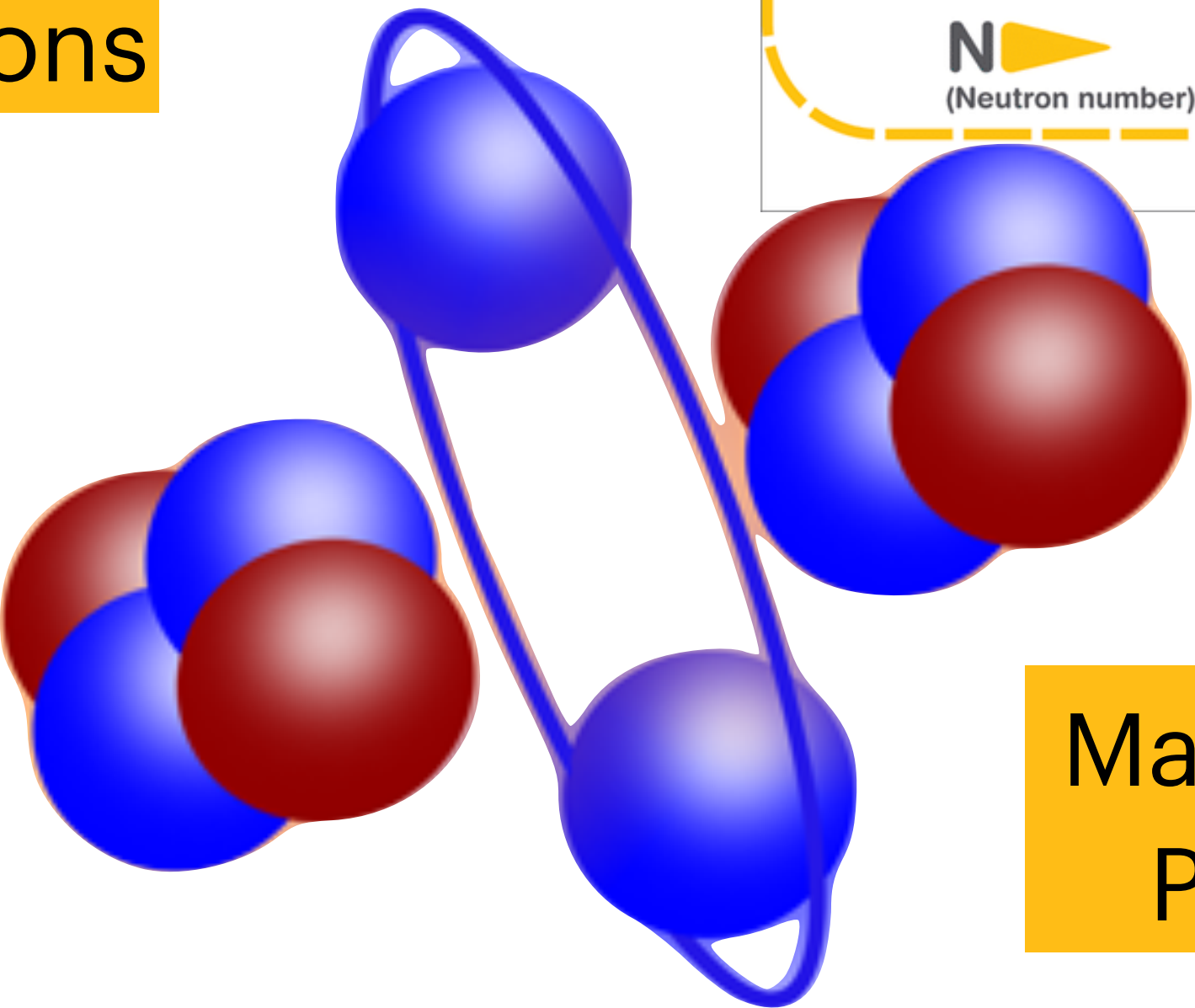
Why is nuclear structure interesting?

Neutron Stars



J. Noronha-Hostler UIUC

Correlations

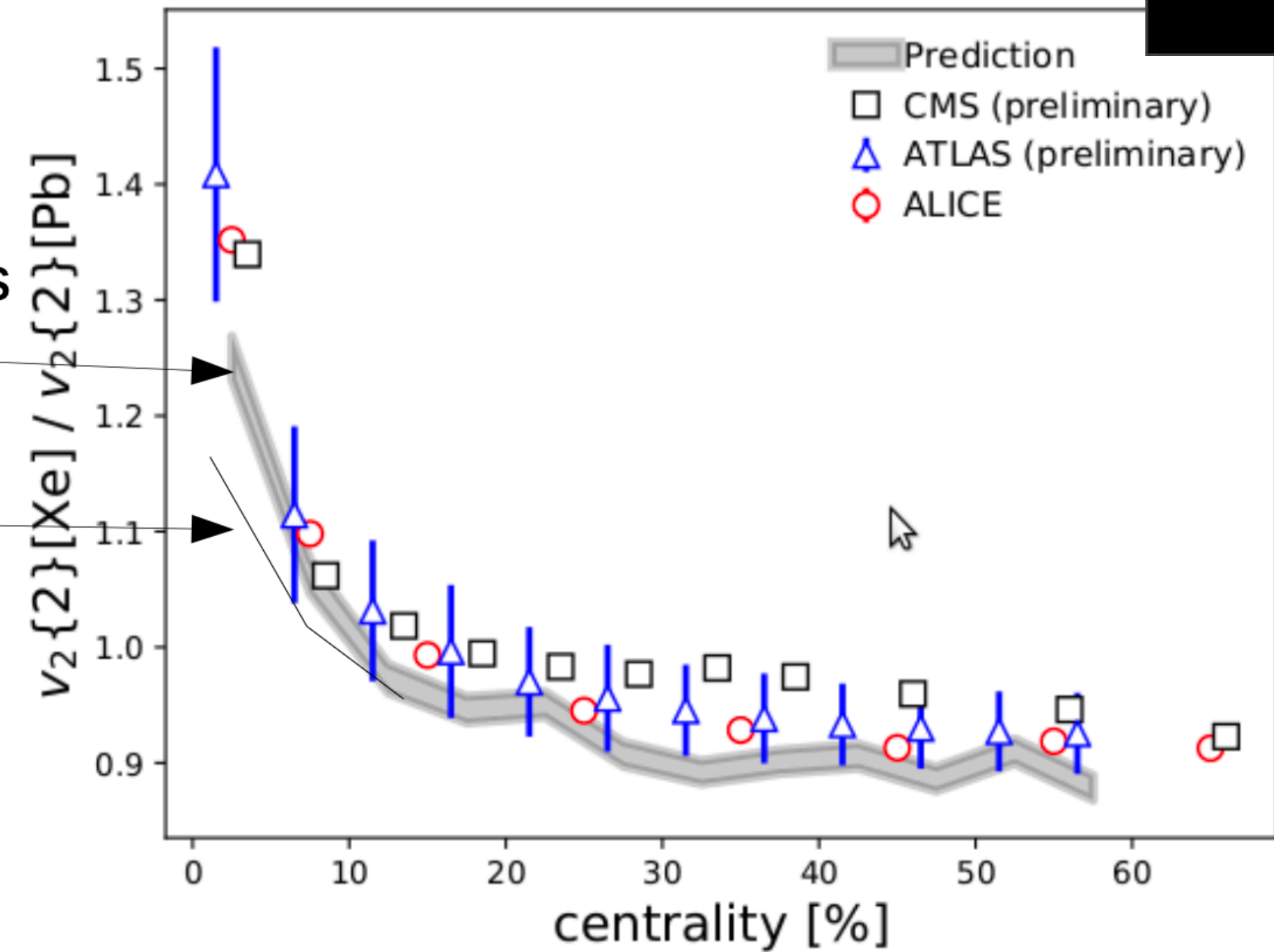
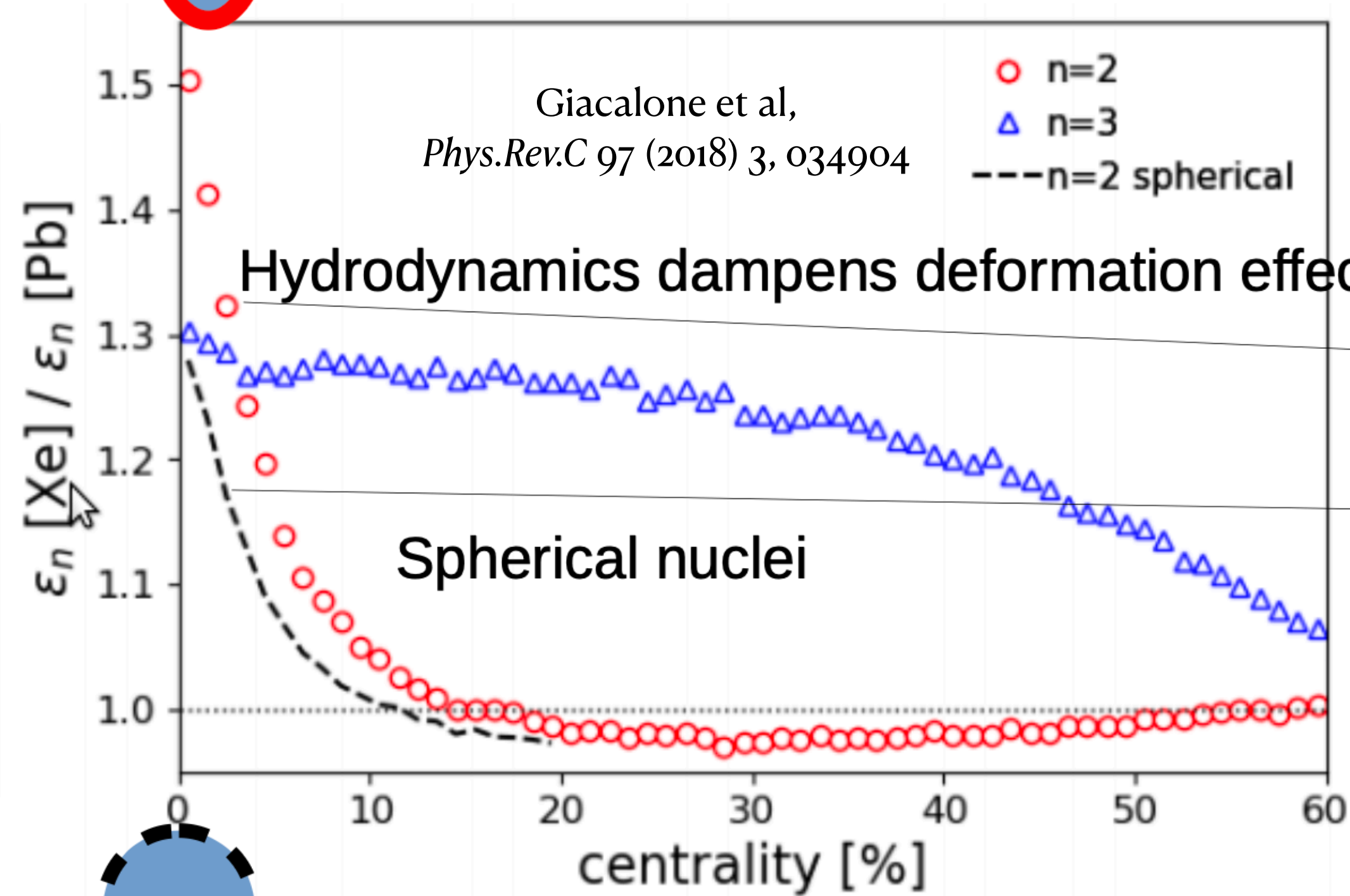


Connecting 2 pillars of DOE NP

Many-Body Physics

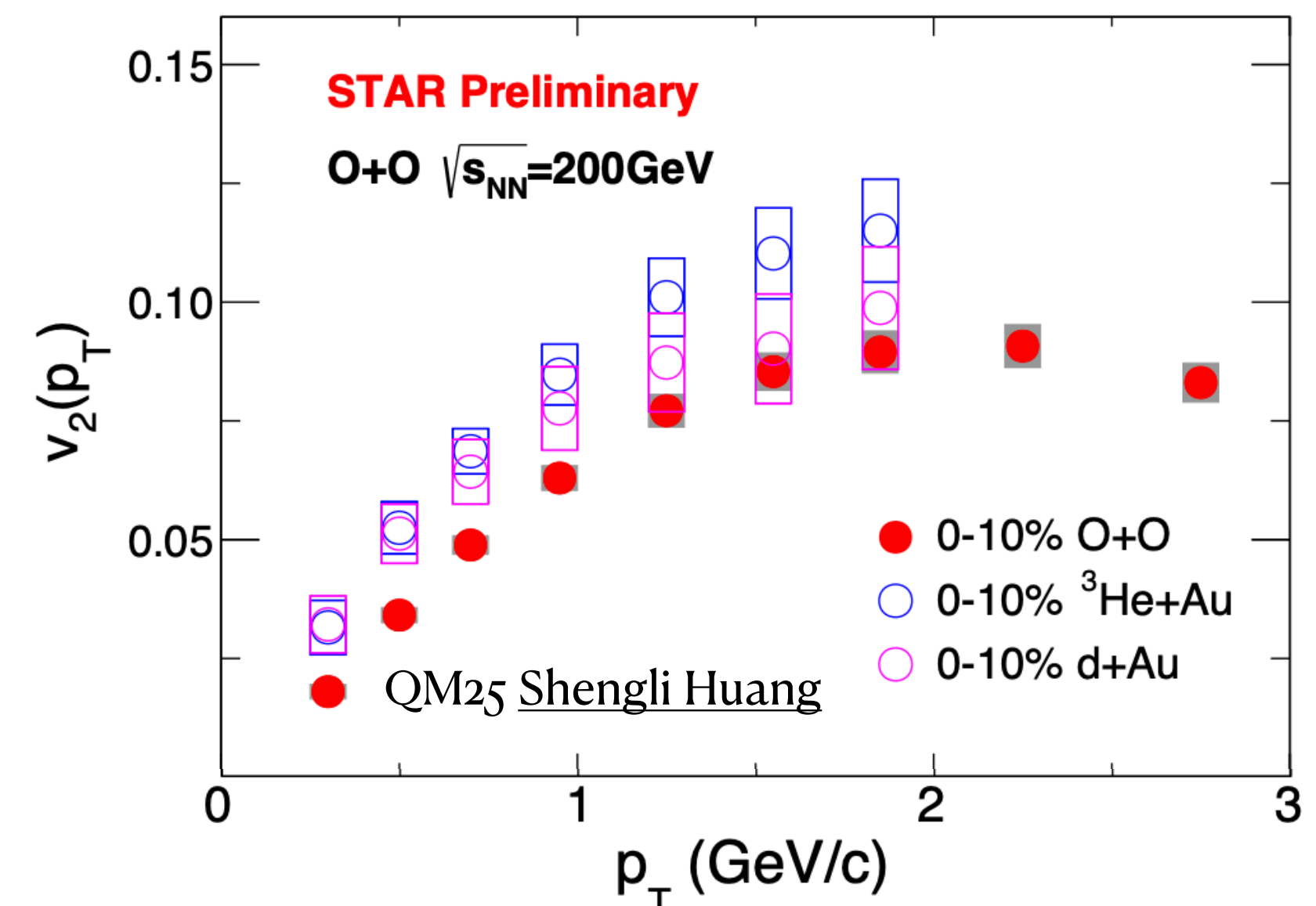
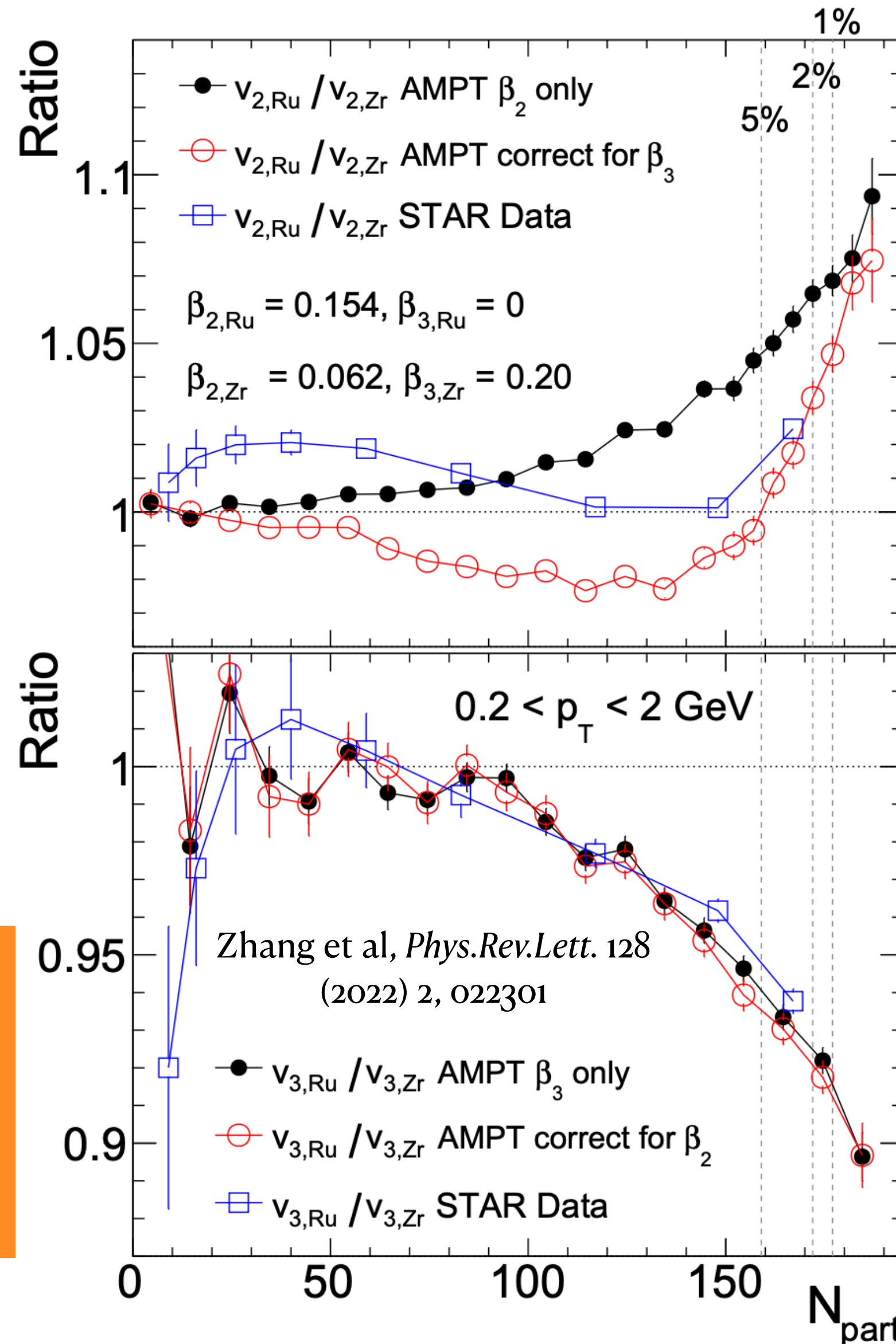
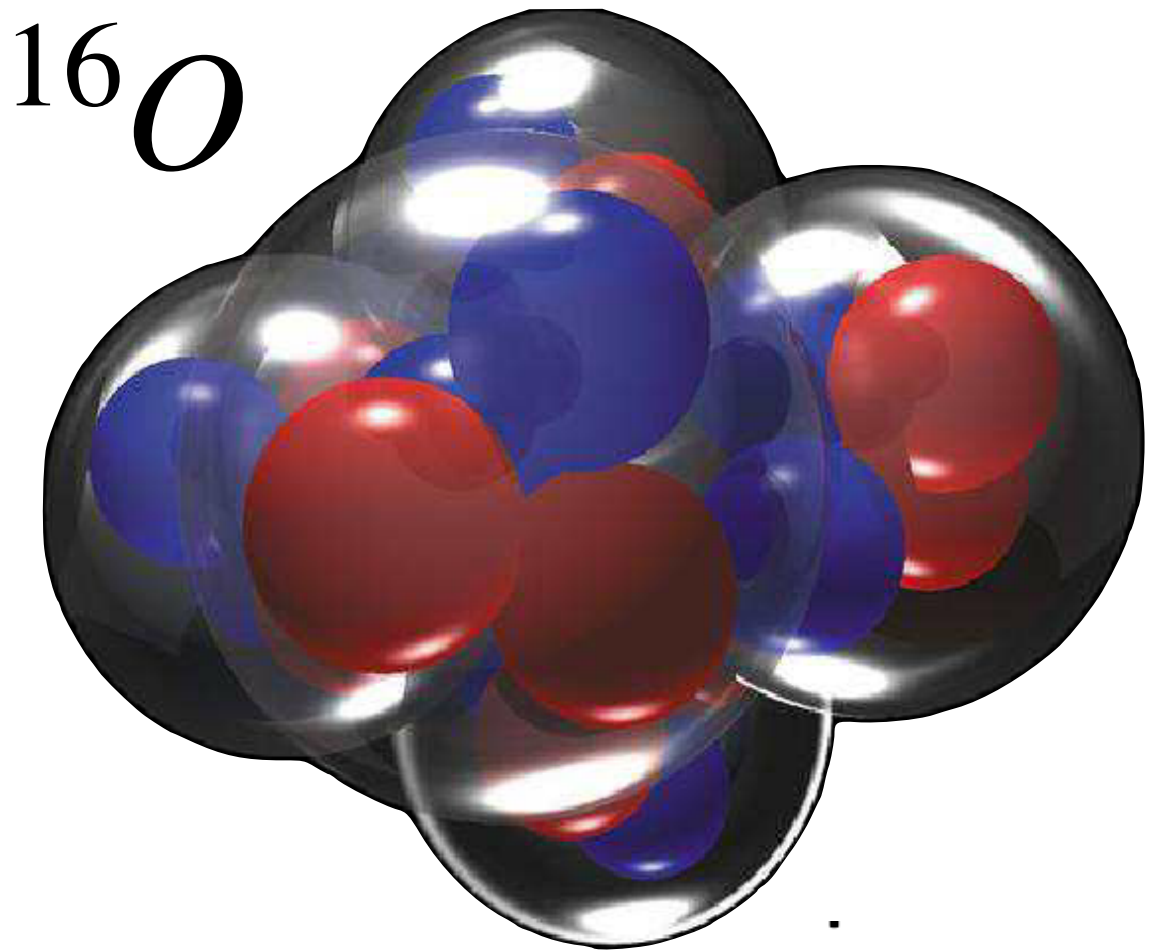
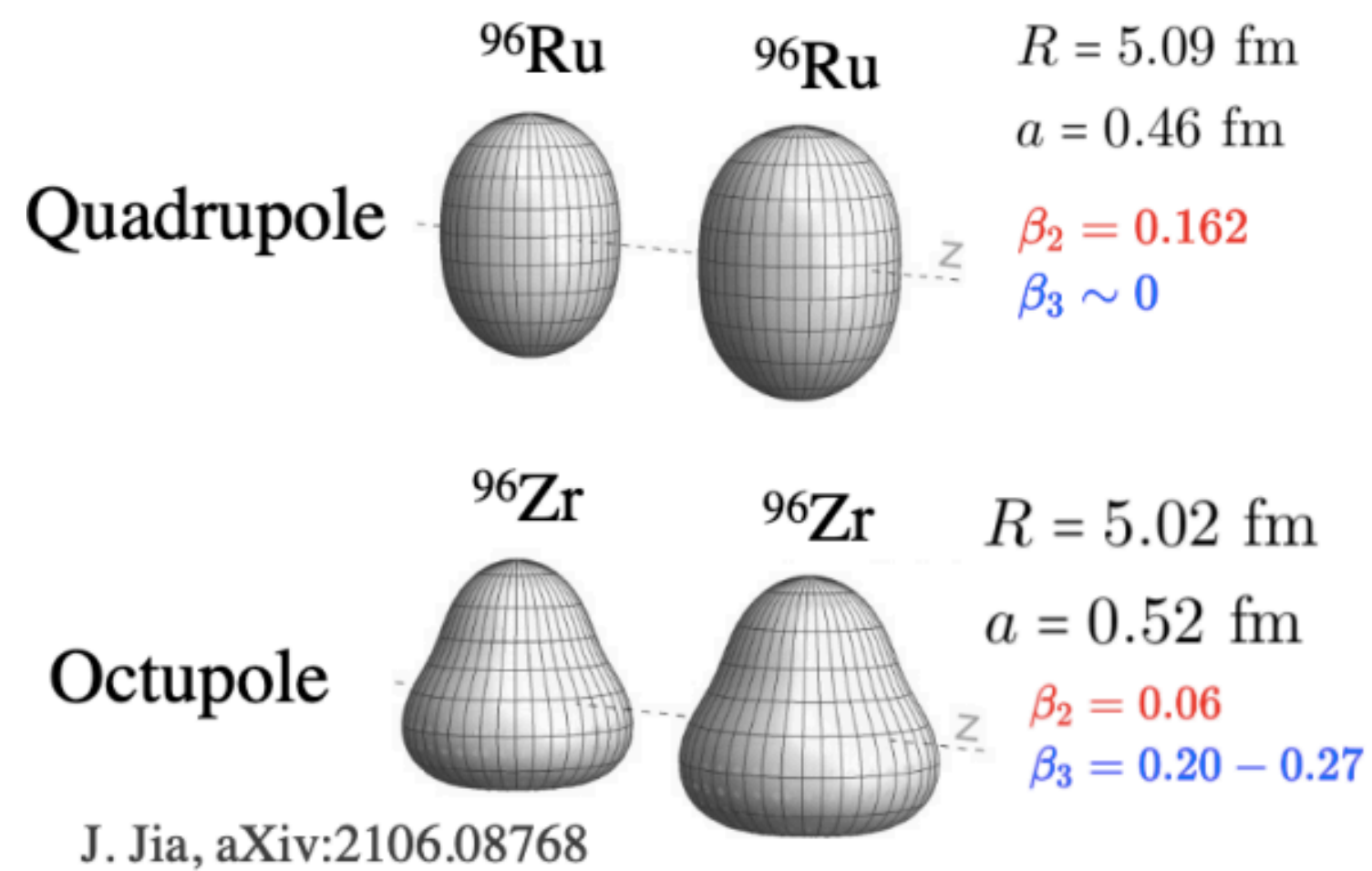
^{238}U set the stage for understanding ^{129}Xe results from the LHC

Central collisions most important for nuclear structure



Now: structure of isobars and peering inside ^{16}O

Using ratios to
extract deformation
parameters



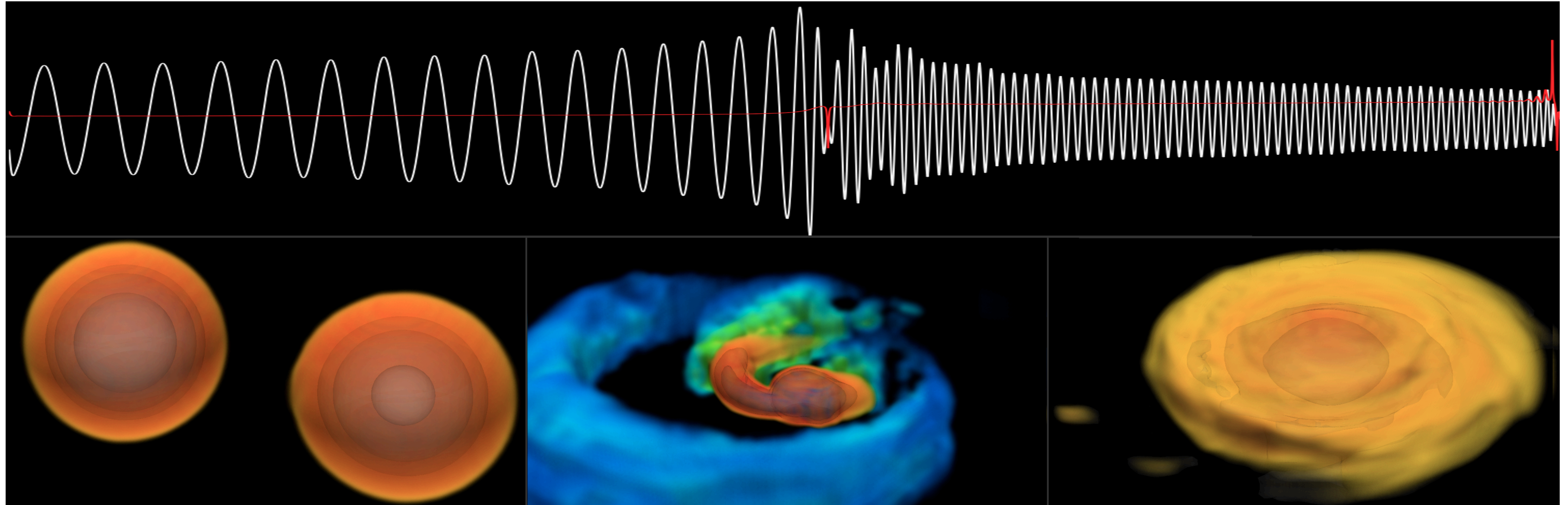
More O-O data at sPHENIX
would be invaluable to
understand intermediate
systems

Nice ideas for nuclear structure in
Ultra-peripheral collisions and the
EIC!

Mäntysaari et al, *Phys.Rev.C* 109 (2024) 2, 024908; *Phys.Lett.B* 858 (2024) 139053

Impact 3: influence of RHIC on neutron stars

Stages of binary neutron star mergers



Cold (inspiral)

$$T \sim 10^6 \text{ K}$$

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

Hot (post-merger)

$$T \sim 10^{12} \text{ K}$$

$$T \sim 100 \text{ MeV}$$

Currently have inspiral data, but hopefully future detectors will probe mergers

Combined inference of the equation of state

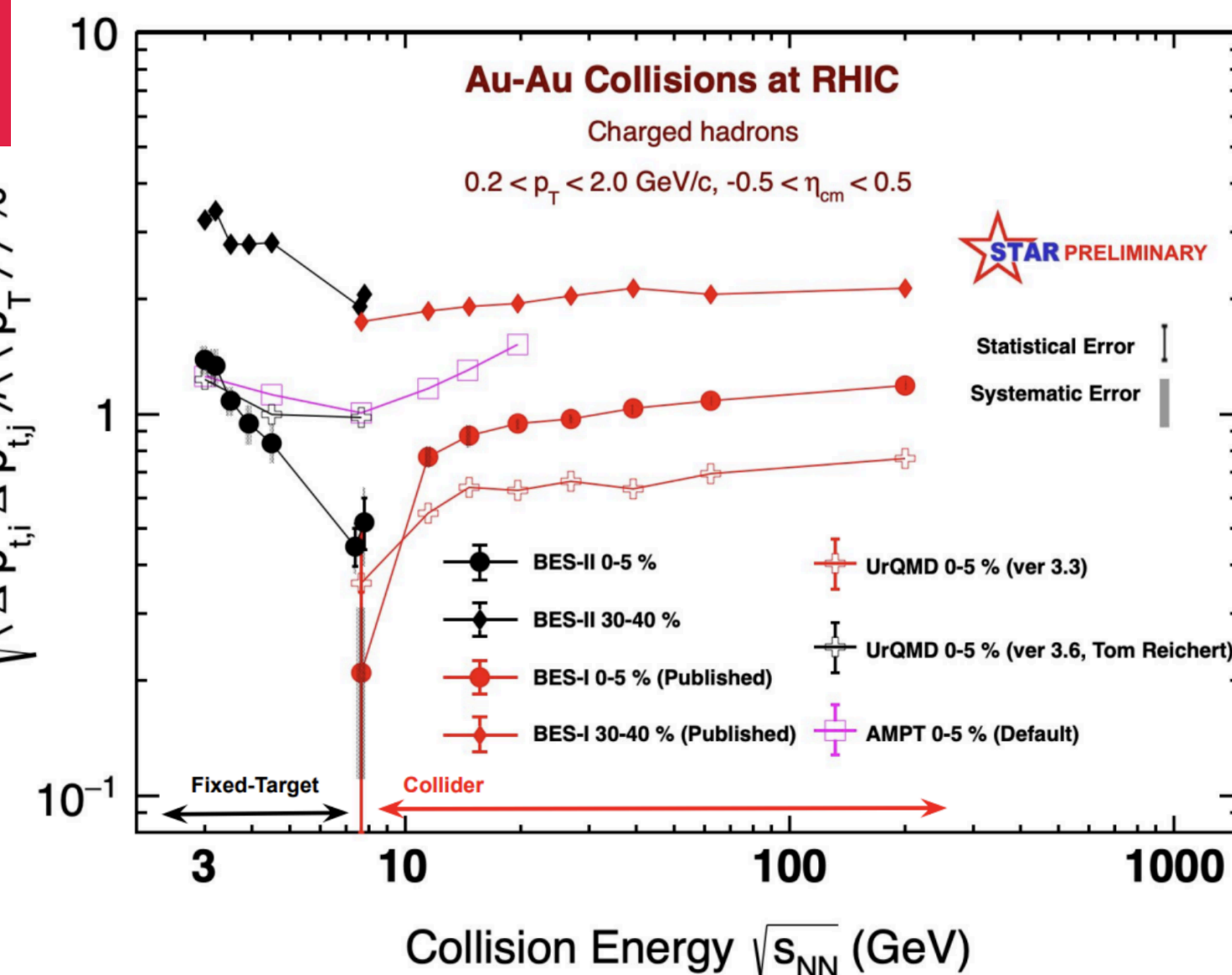
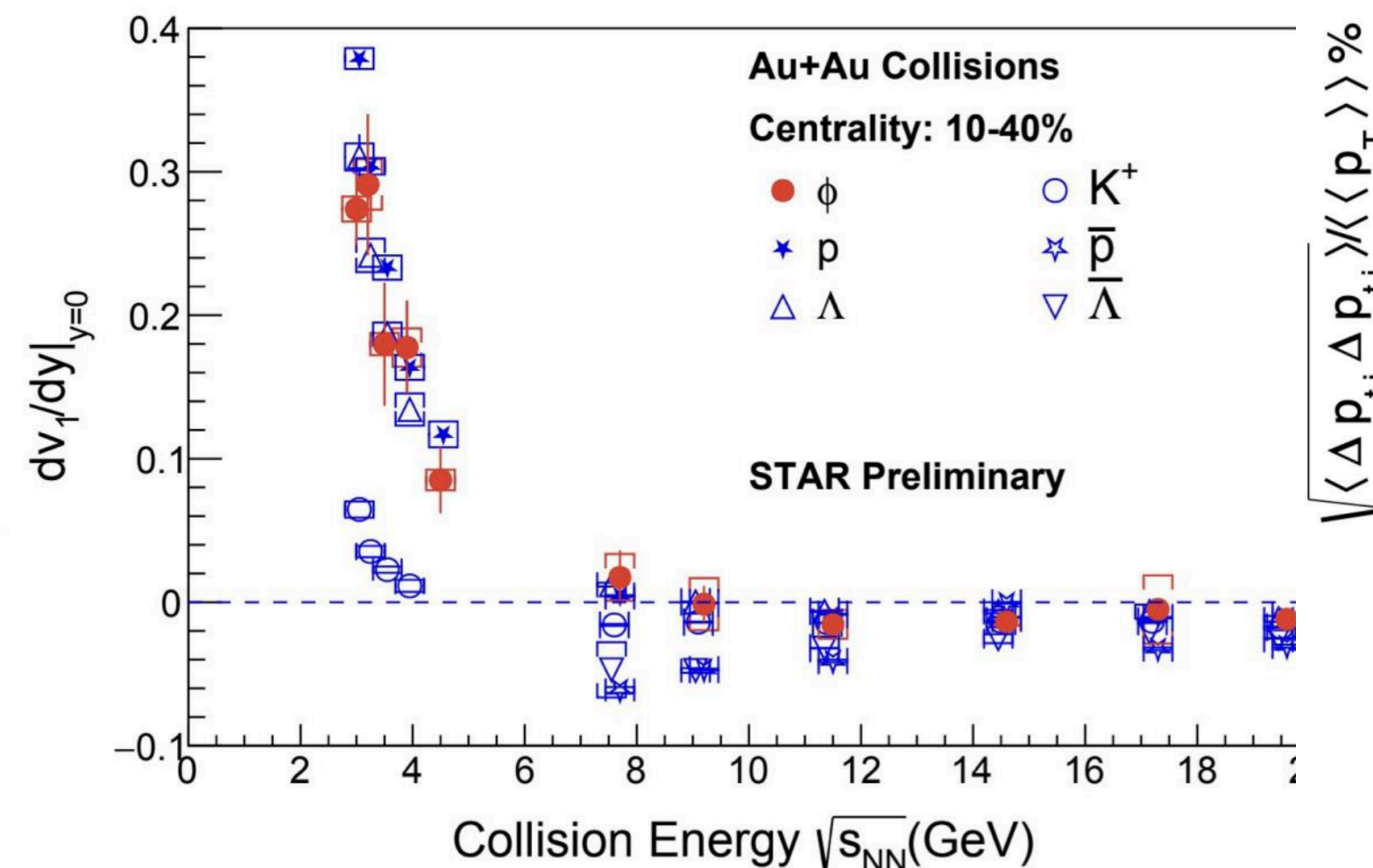
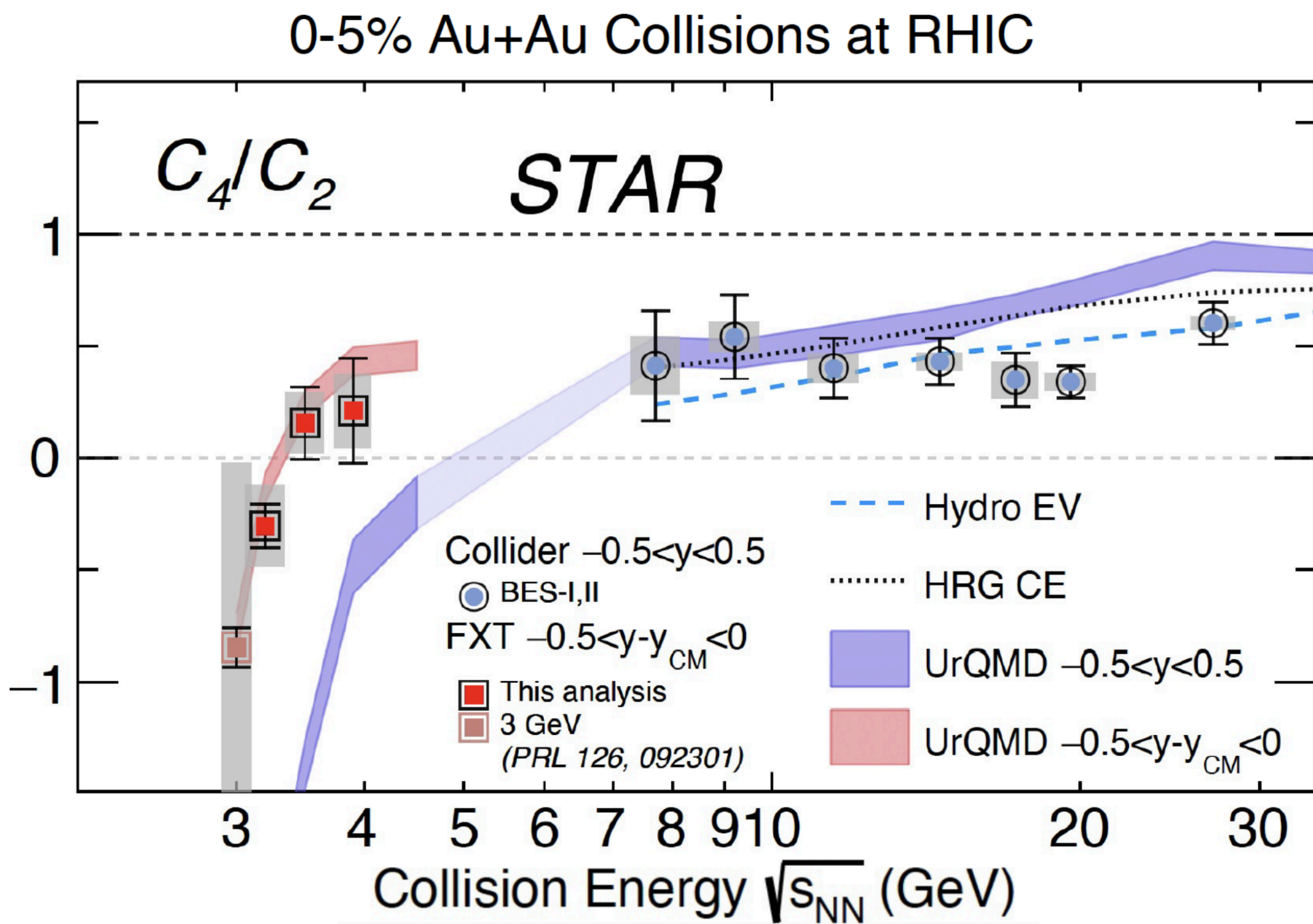
From the lab to the cosmos

DATA: See Lijuan Ruan's talk on Tuesday

Huge amount of data from the Beam Energy Scan II.

Hydrodynamics, equation of state, analysis tools still being built, but this data will certainly be vital in our understanding of the dense matter EOS

Theory: See Lipei Du's and Johannes Jahan's talk on Tuesday



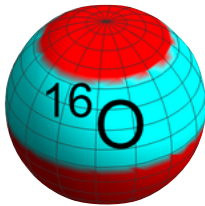
Connections related to charge fraction

See Nanxi Yao's talk on Tuesday

Mroczek et al, 2404.01658 [astro-ph.HE]; Nana et al, 2411.03705 [nucl-th]

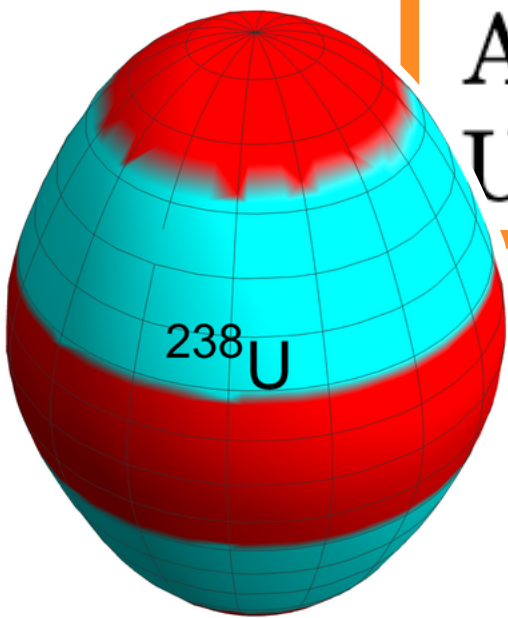
Measurements varying Z/A

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



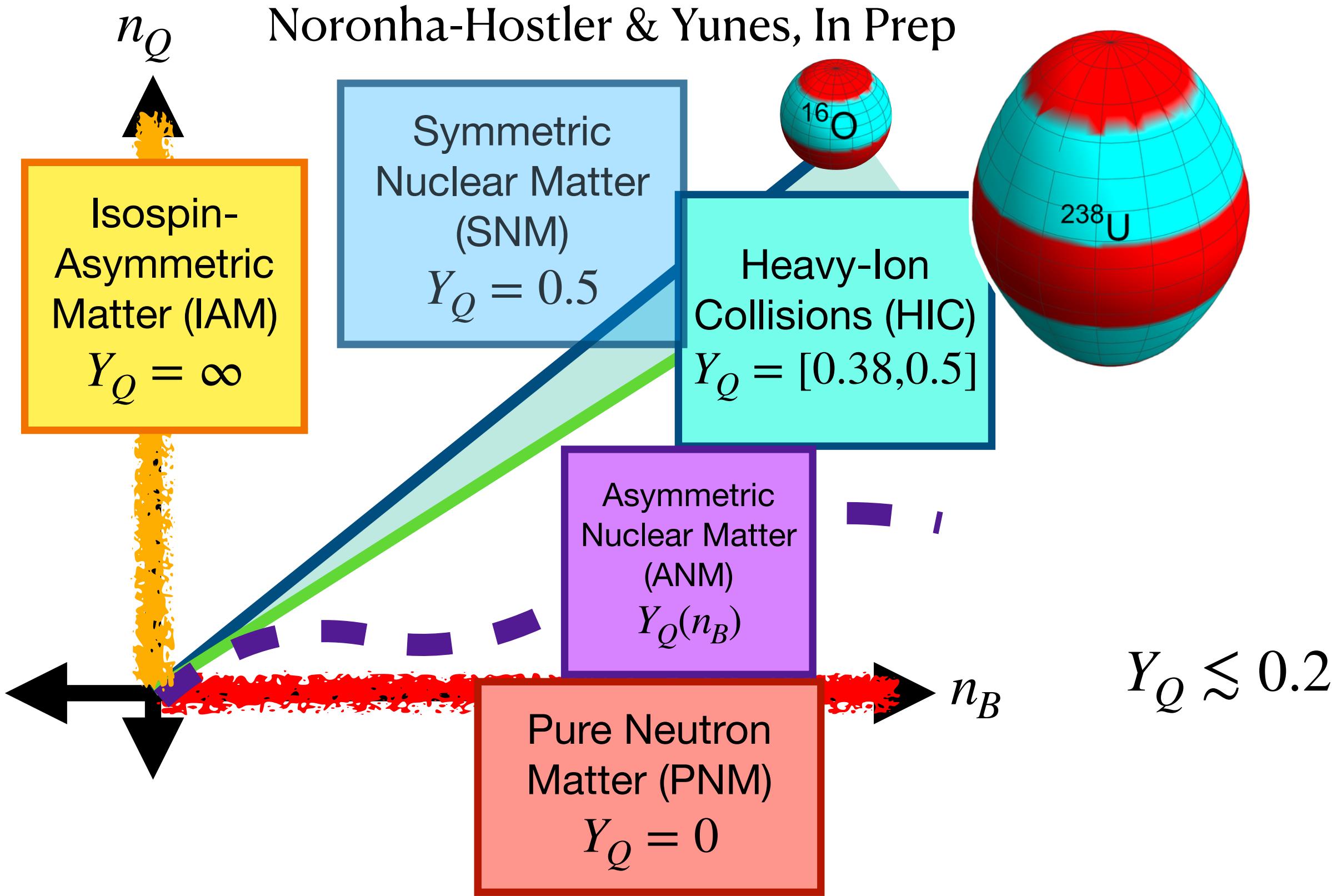
System	Z	A	Y_Q	Data?
O+O	8	16	0.5	some
Ne+Ne	10	20	0.5	no
Mg+Mg	12	24	0.5	no
Ca+Ca	20	40	0.5	no
Cu+Cu	29	63	0.46	yes
Ru+Ru	44	96	0.458	some
Ar+Ar	18	40	0.45	no
Xe+Xe	54	128	0.419	yes
Zr+Zr	40	96	0.417	some
Au+Au	79	198	0.399	yes
U+U	92	238	0.387	yes

RHIC



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

How is this charge stopped? Pihan et al, *Phys.Rev.Lett.* 133 (2024) 18, 182301



Neutron skin vs charge radius

$$R_n - R_p = 0.17 \pm 0.03(stat) \pm 0.08(syst) \text{ for } ^{197}\text{Au}$$

$$R_n - R_p = 0.44 \pm 0.05(stat) \pm 0.08(syst) \text{ for } ^{238}\text{U}$$

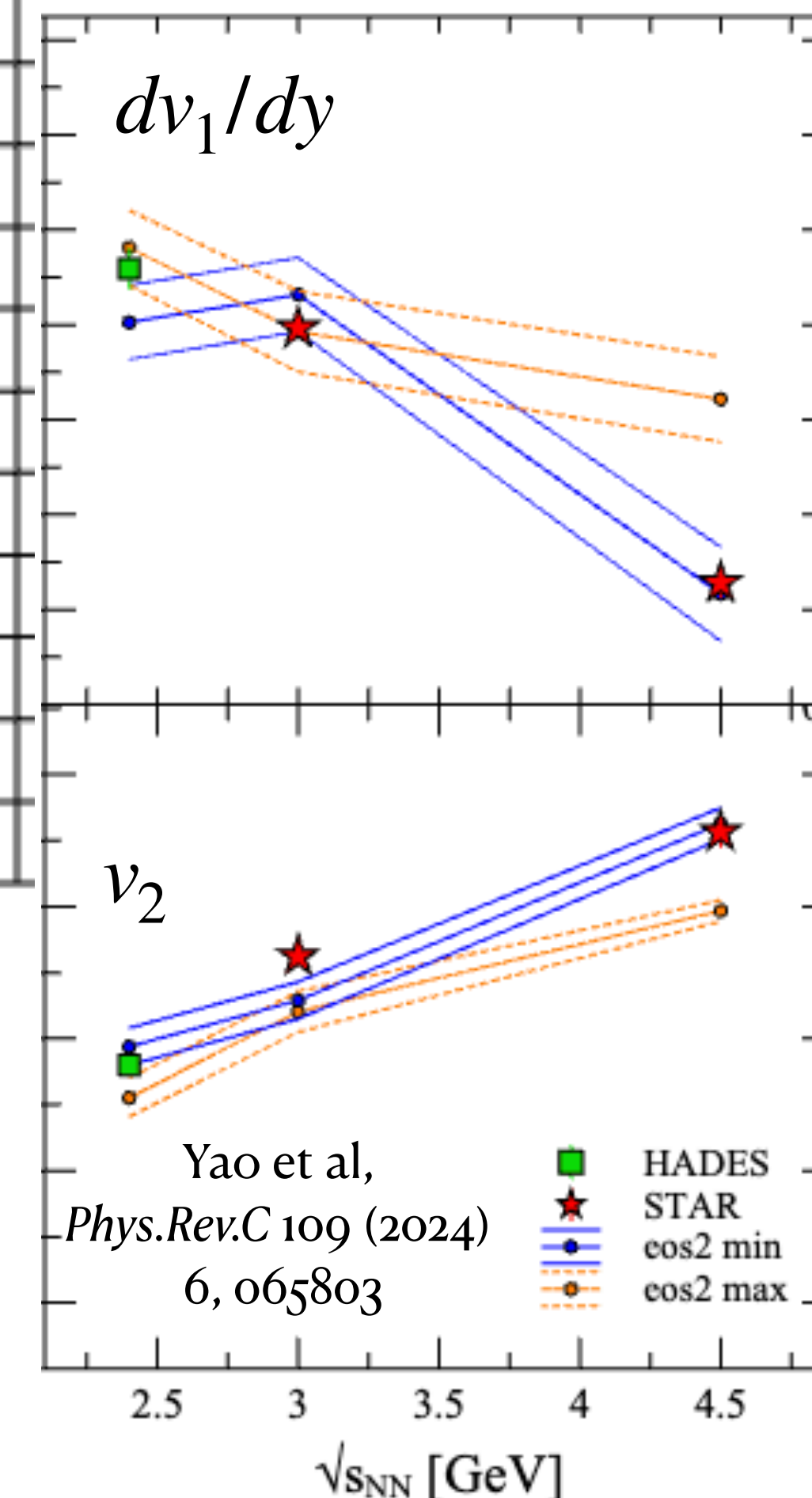
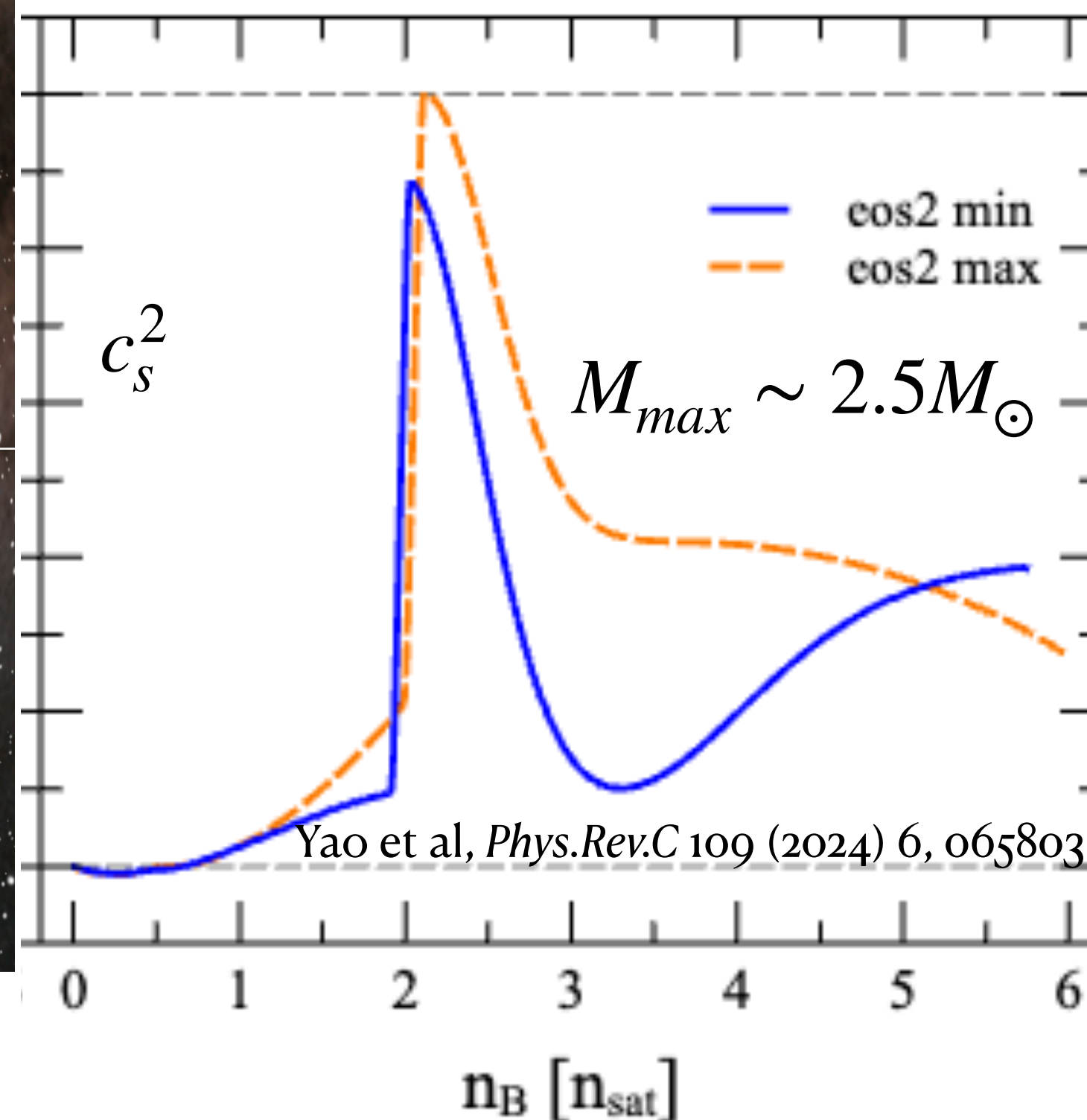
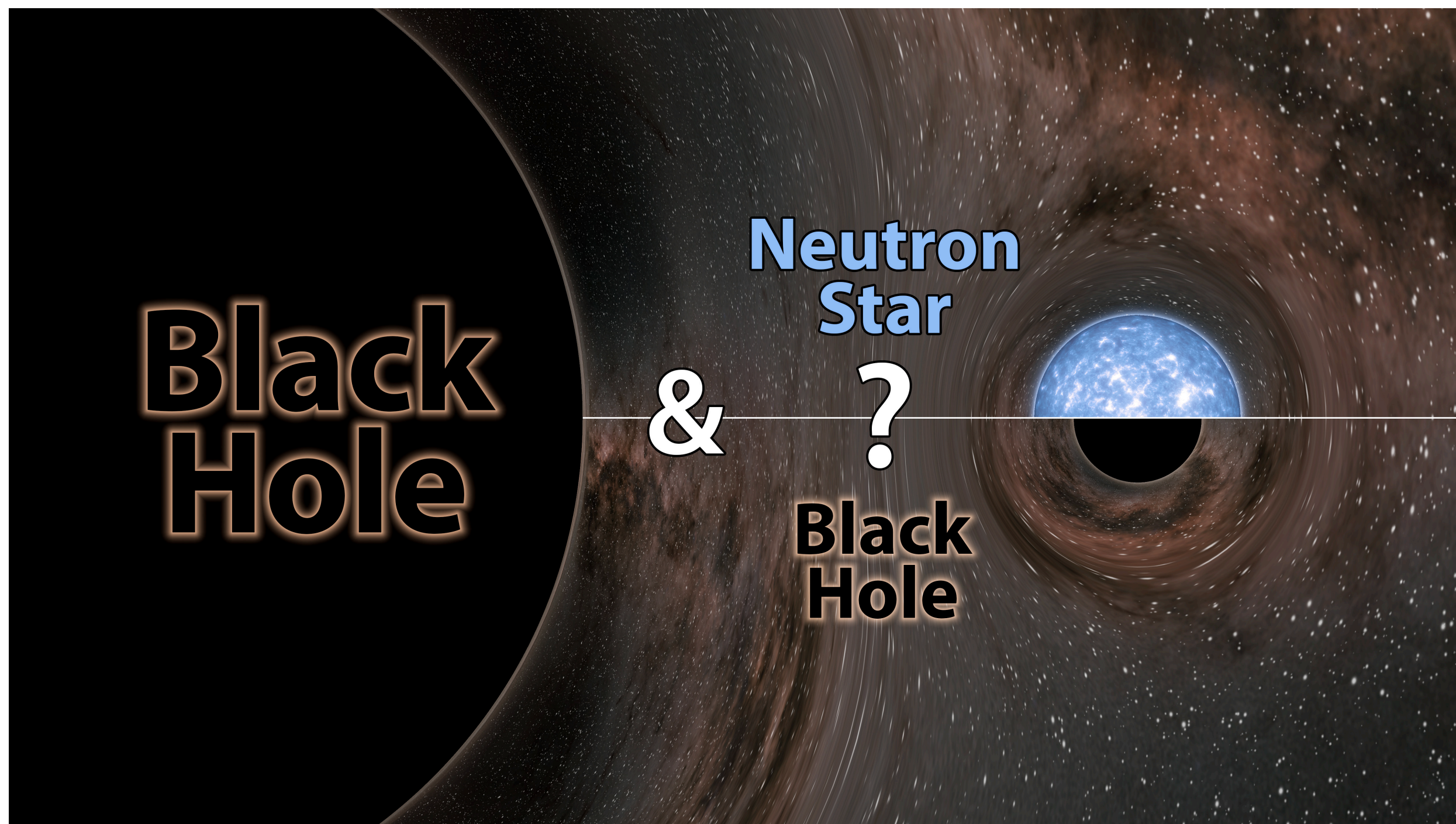
[STAR] *Sci.Adv.* 9 (2023) 1, eabq3903

Heavy neutron stars vs heavy-ion collisions

The mystery of the mass-gas

GW190814 Mystery object of $M \sim 2.6M_{\odot}$

STAR fixed-target IS consistent with ultra-heavy neutron stars!



Quarkyonic matter?

McLerran & Reddy *Phys.Rev.Lett.* 122 (2019) 12, 122701

Preference of peak at $2 - 3 n_{sat}$

Oliinychenko et al,
Phys.Rev.C 108 (2023) 3, 034908

[1] argued “heavy-ion data” inconsistent with ultra heavy neutron stars. BUT not “data”, not a Bayesian analysis, didn’t use STAR data, only considered nucleons in EOS

[1] Fattoyev et al,

J. Noronha-Hostler UIUC

Phys.Rev.C 102 (2020) 6, 065805

Viscous effects from neutron star mergers

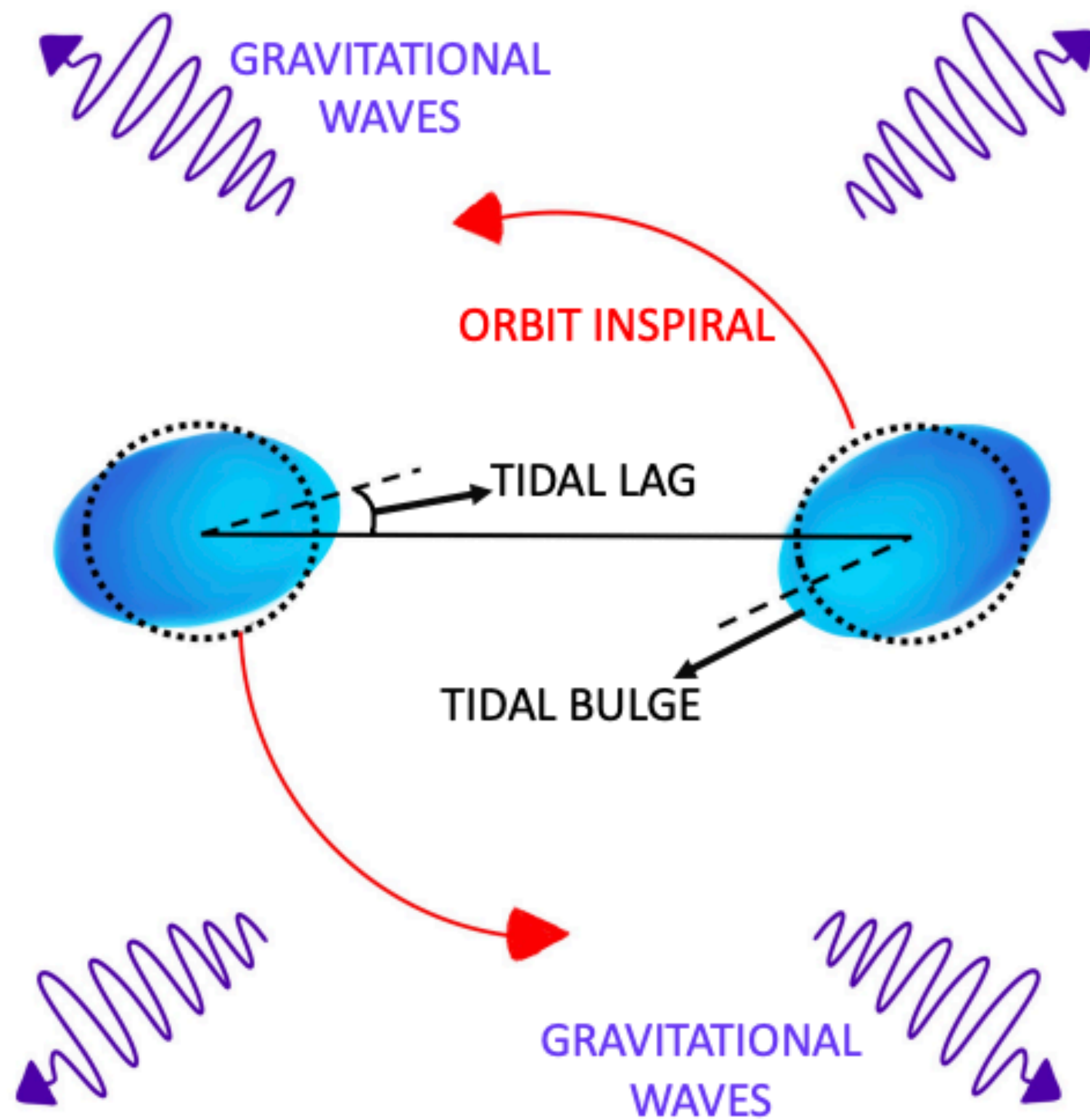
Learning from heavy-ion collisions



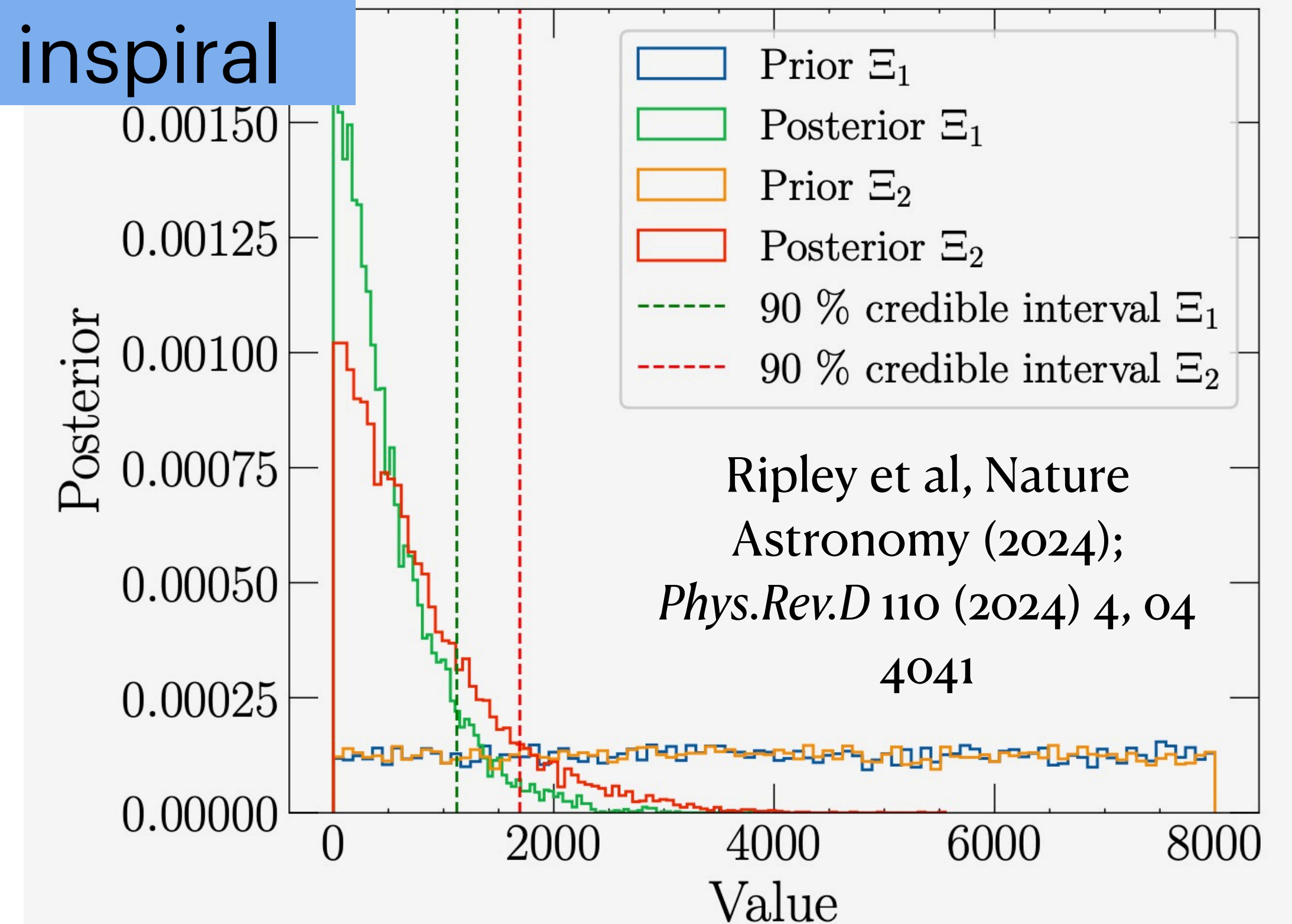
Out-of-equilibrium: misalignment of tidal bulge

First constraints on viscosity from gravitational wave data!

“Averaged” viscosity within the inspiral



Ripley, Hegade, Chandramouli,
Nature Astronomy (2024)

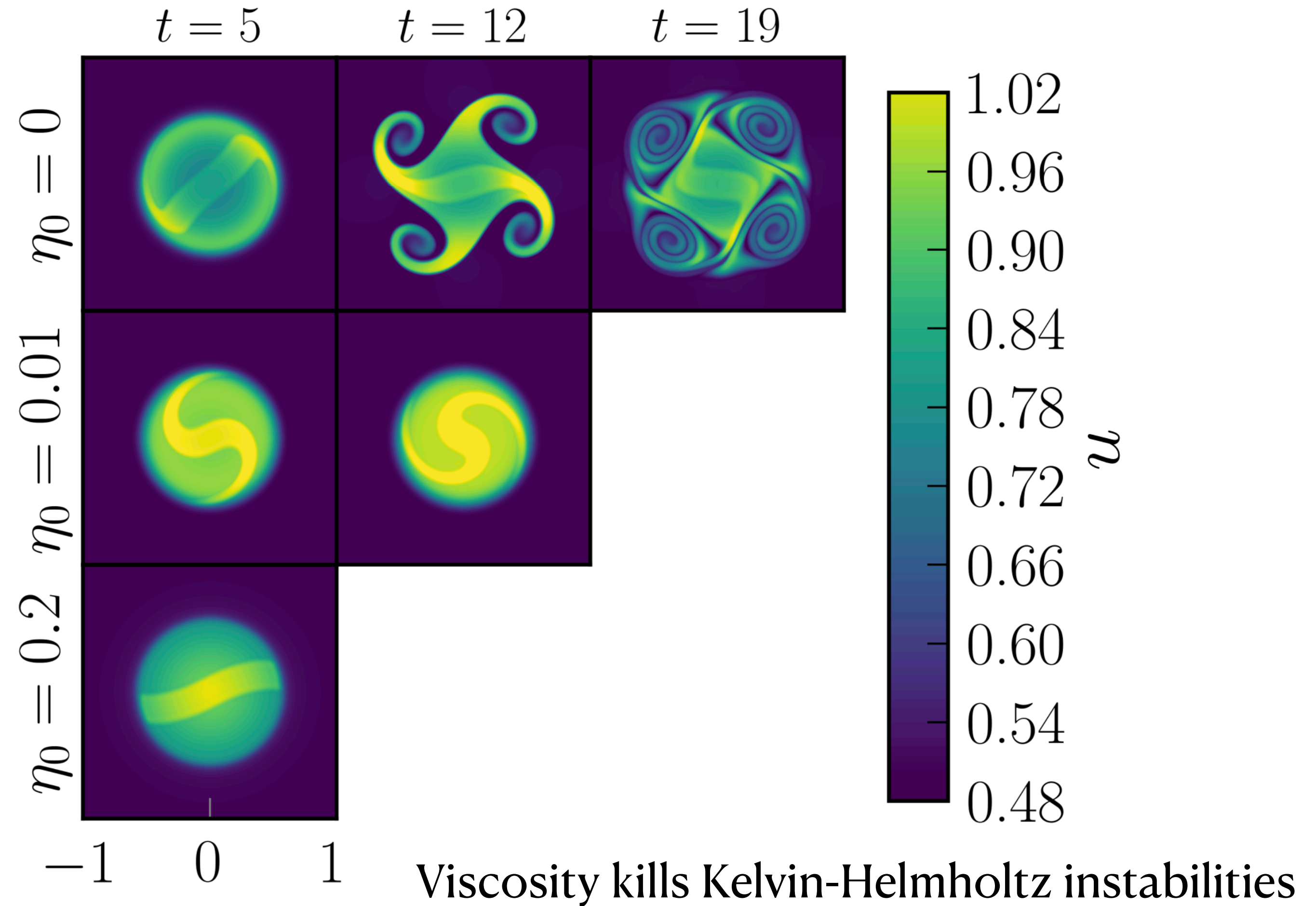
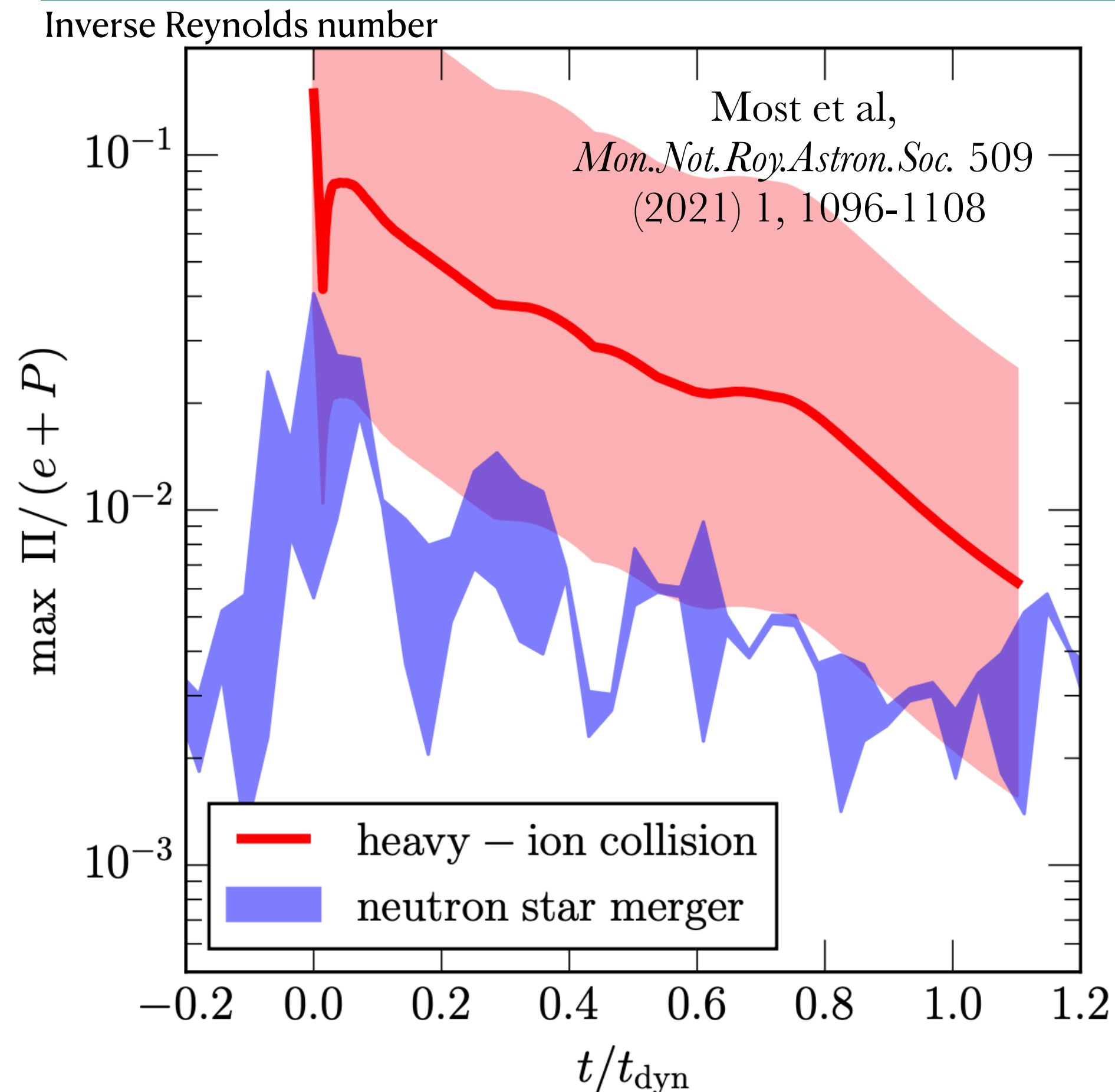


Out-of-equilibrium measurements provide new way to probe neutron star degrees-of-freedom!

Bulk viscosity: heavy-ions vs neutron stars

Comparisons of inverse Reynolds numbers

State-of-the-art heavy-ion collision simulations vs neutron star mergers find comparable effects from bulk viscosity



Future detectors/runs able to better constrain the averaged viscosity in the inspiral. Potential for future collaborations!

Conclusions and Outlook

- Heavy-ion collisions. Might be “little bangs” but there’s been a enormous return on investment. So many unexpected finds!
- The story isn’t yet over, we still have many unanswered questions even as BNL looks to the future EIC and current sPHENIX. Jets/heavy flavor are a great example of a multi-scale problem (soft and hard sector that interact) where I think our text book physics is still being developed.
- Much to do still for relativistic viscous hydrodynamics: next frontier magneto-viscous-hydrodynamics, spin, and phase transitions. Implications for astrophysics!
- What more can we get from nuclear structure? Possibilities at the EIC? Internal structure?
- STAR BES II will certainly play a role in constraints of the dense matter EOS → waiting on better theoretical frameworks
- **Many other lasting impacts:** technological advances, the workforce, medical advancements, computational advances etc