Brookhaven National Laboratory

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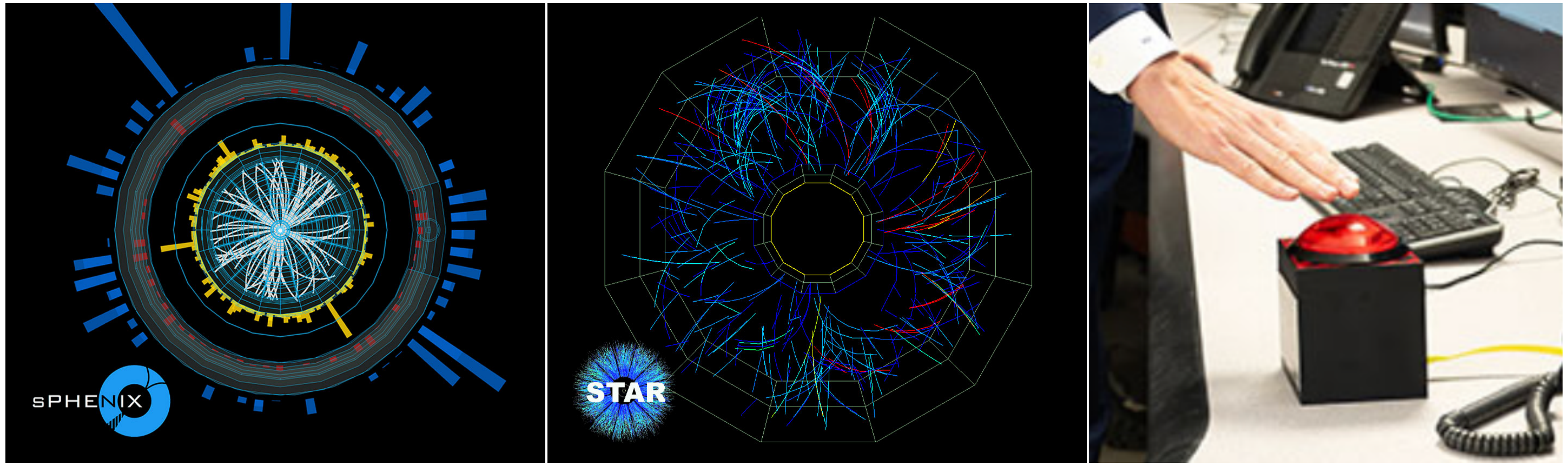
COMPLETING THE RHIC SCIENCE MISSION: THEORY

2026 RHIC/AGS ANNUAL USERS' MEETING
RHIC SCIENCE SYMPOSIUM
May 11-15, 2026

Thanks to my colleagues from the BNL Nuclear Theory Group for input

RHIC RUNNING ENDED. RHIC SCIENCE DID NOT.

- New measurements from STAR, sPHENIX and PHENIX will keep coming out
- Qualitative understanding and quantitative constraints require theory advances



work continues

~ 10+ years

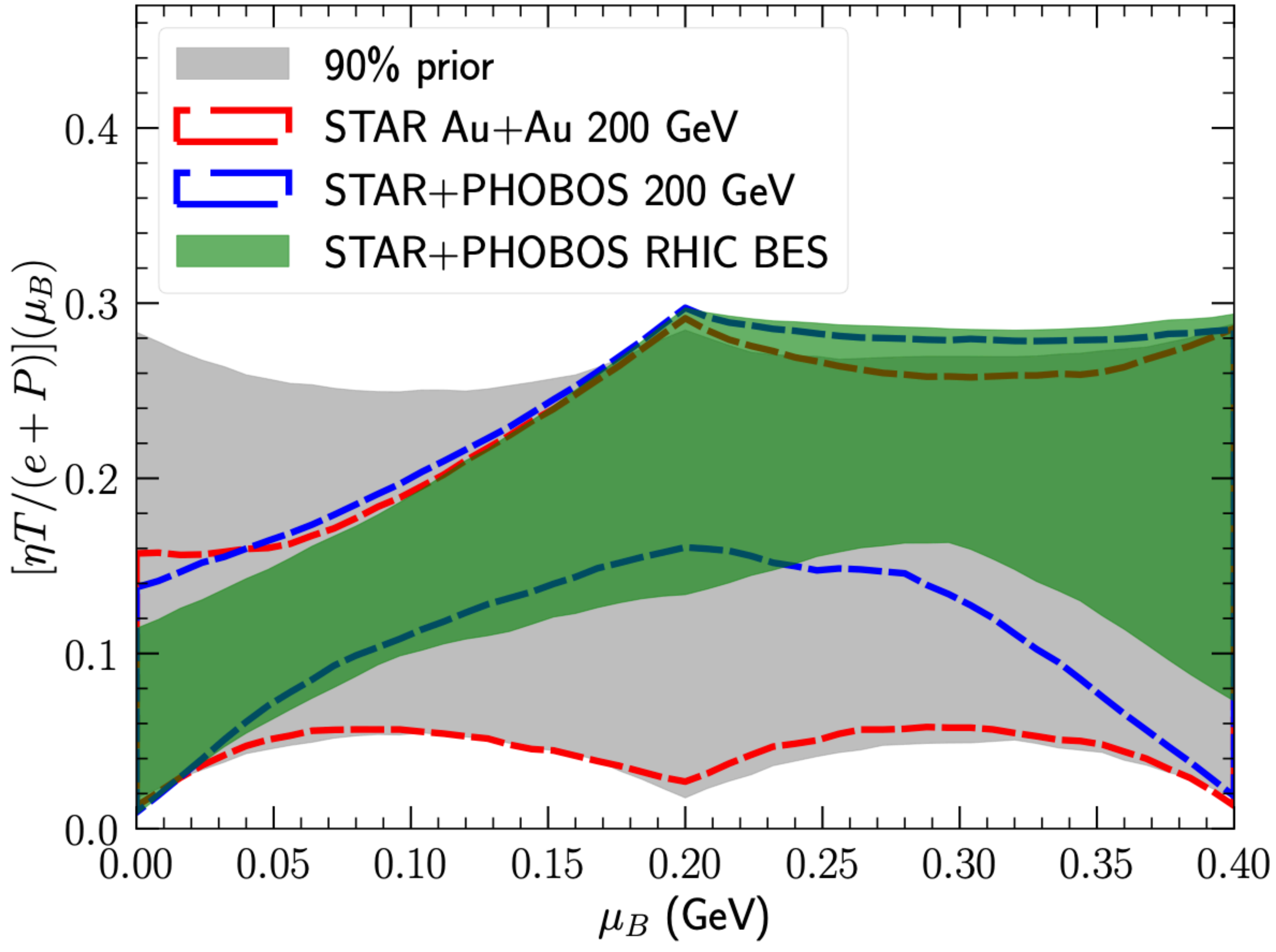
February 6, 2026

- What theory advances are needed to complete the RHIC science mission?

3+1D COLLISION DYNAMICS

- **What we can do now**
  - Realistic 3+1D multistage simulations
  - Bayesian inference at finite μ_B
  - Increasing attention to causality/stability of viscous hydrodynamics

C. Shen, B. Schenke, W. Zhao, Phys.Rev.Lett. 132 (2024) 7, 072301
S. Afrid Jahan, H. Roch, C. Shen, Phys.Rev.C 110 (2024) 5, 054905
JETSCAPE Collaboration, Phys.Rev.C 103 (2021) 5, 054904



Including rapidity dependent data from PHOBOS and RHIC BES data improves constraints on $(\eta/s)(\mu_B)$

3+1D COLLISION DYNAMICS

- **What needs improvement**
  - Conserved charge (BQS) diffusion
  - Stage (initial/final) matching uncertainties
  - EOS uncertainties (especially high T and μ_B)
- **Will unlock**
  - Quantitative BES interpretation
  - QCD phase structure constraints

MACHINE LEARNING

- Fast surrogate models for full evolution of 2+1 and 3+1D hydrodynamics
- 3+1D needs more sophisticated ML model
- 100x to 1000x speed-up
- Typically < 2% relative error
- Will enable:
  - Fast simulation
  - Inference of QGP properties in global analysis
  - Application for studies with hard probes

see presentation by S. Lee on Monday

H. Huang et. al. Phys. Rev. Research 3, 023256
D. Stewart, J. Putschke, Phys.Rev.C 113 (2026) 1, 014904
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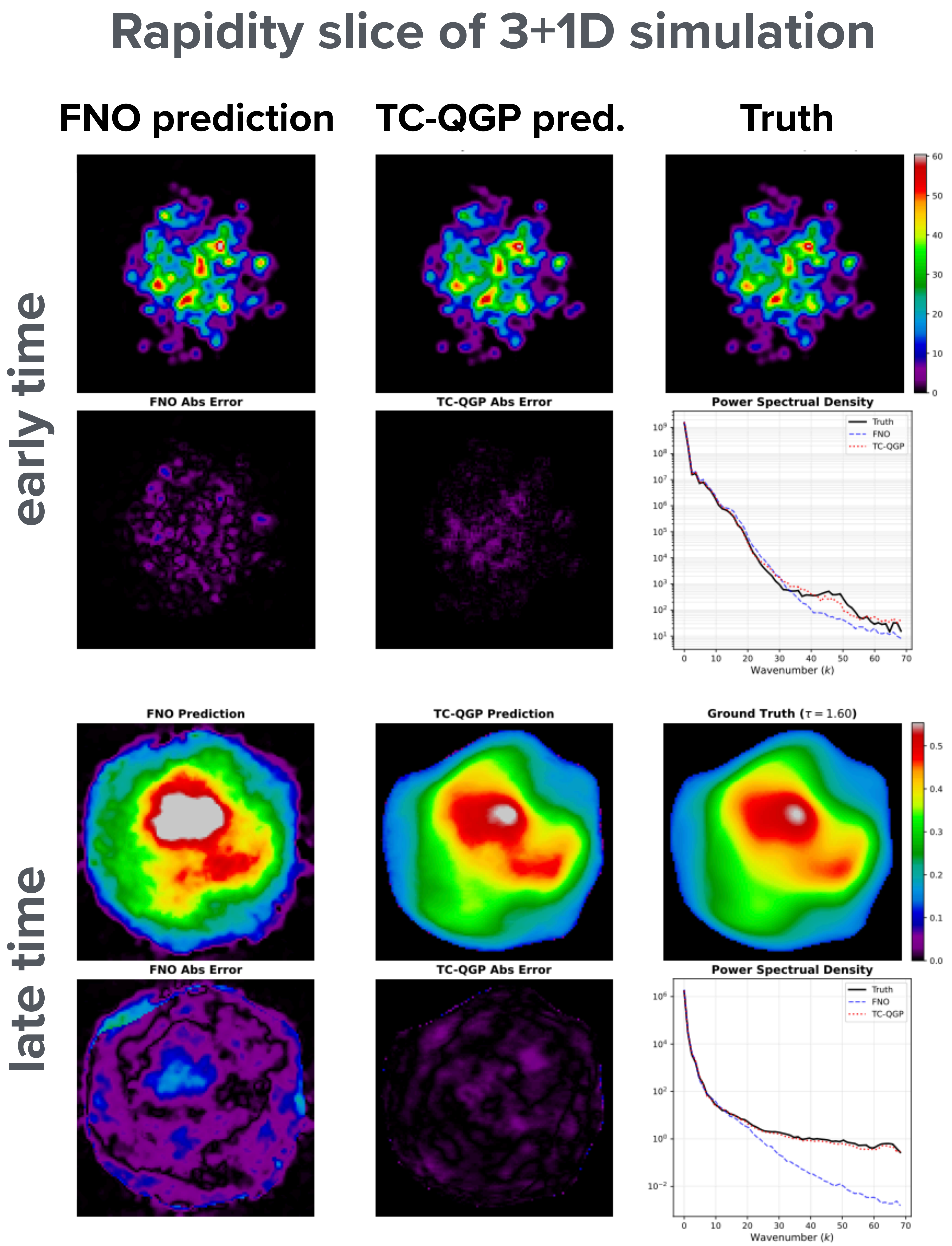
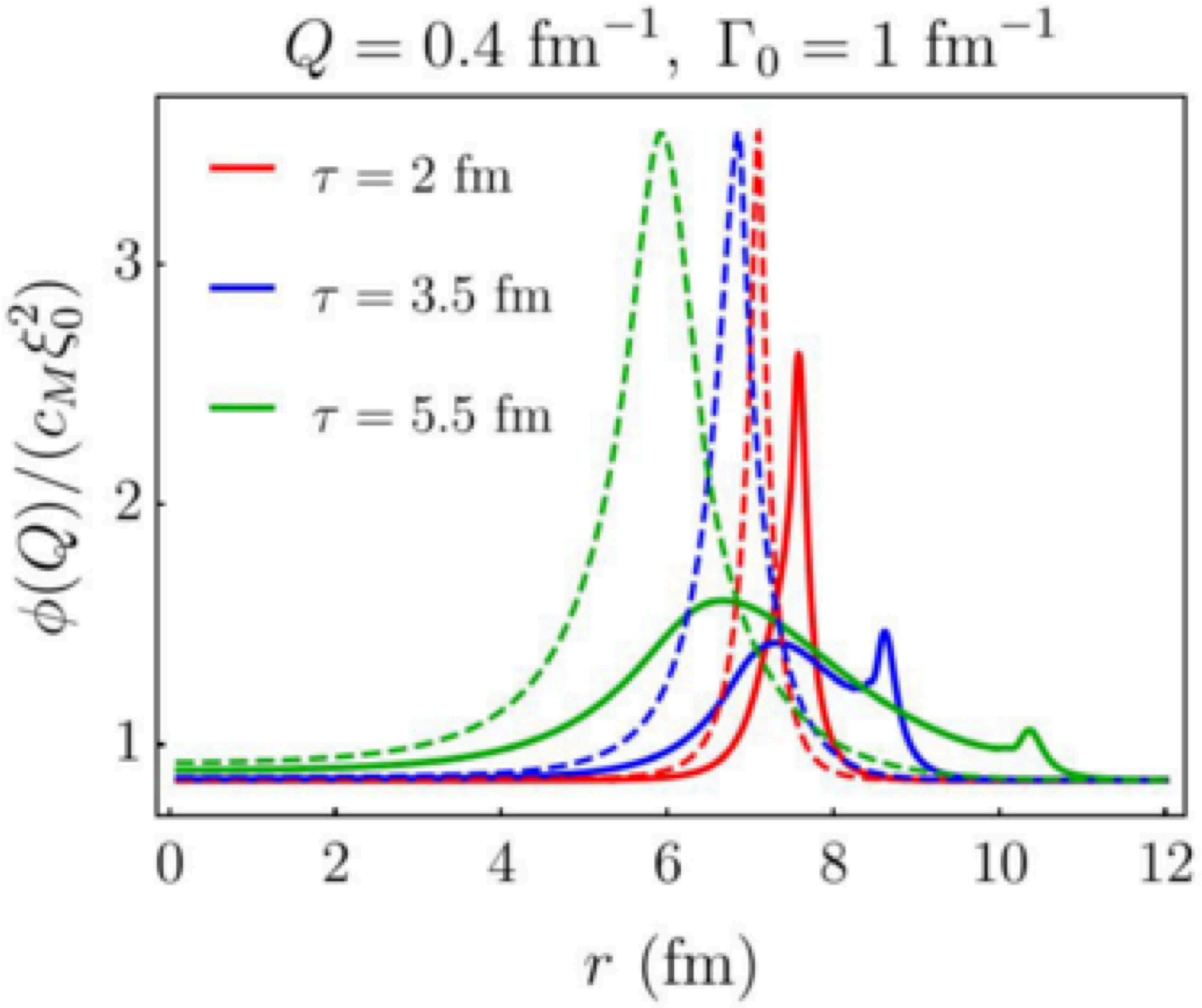


PHASE DIAGRAM AND CRITICAL POINT

X. An et al, Nucl.Phys.A 1017 (2022) 122343
M. Stephanov, Y. Yin, Phys.Rev.D 98 (2018) 3, 036006
M. Stephanov, *EPJ Web Conf.* 314 (2024) 00042
D. Oliinychenko, V. Koch, Phys.Rev.Lett. 123 (2019) 18, 182302
K. Rajagopal, G. Ridgway, R. Weller, Y. Yin
Nucl. Phys. A 1005 (2021) 121796

- **What we can do now**
  - BEST Collaboration - theory toolchain
  - Lattice-informed finite-density EOS some with tunable critical point
  - Hydrodynamic fluctuation theory
  - Hydro+ = relativistic hydrodynamics + a slow non-equilibrium critical mode
- **What needs improvement**
  - Critical fluctuations embedded in realistic 3+1D simulations; implementation of freeze-out
  - Volume, conservation-law and hadronic afterburner effects
  - Bayesian inference over critical-point location
  - A robust “no critical point in this region” statement if warranted

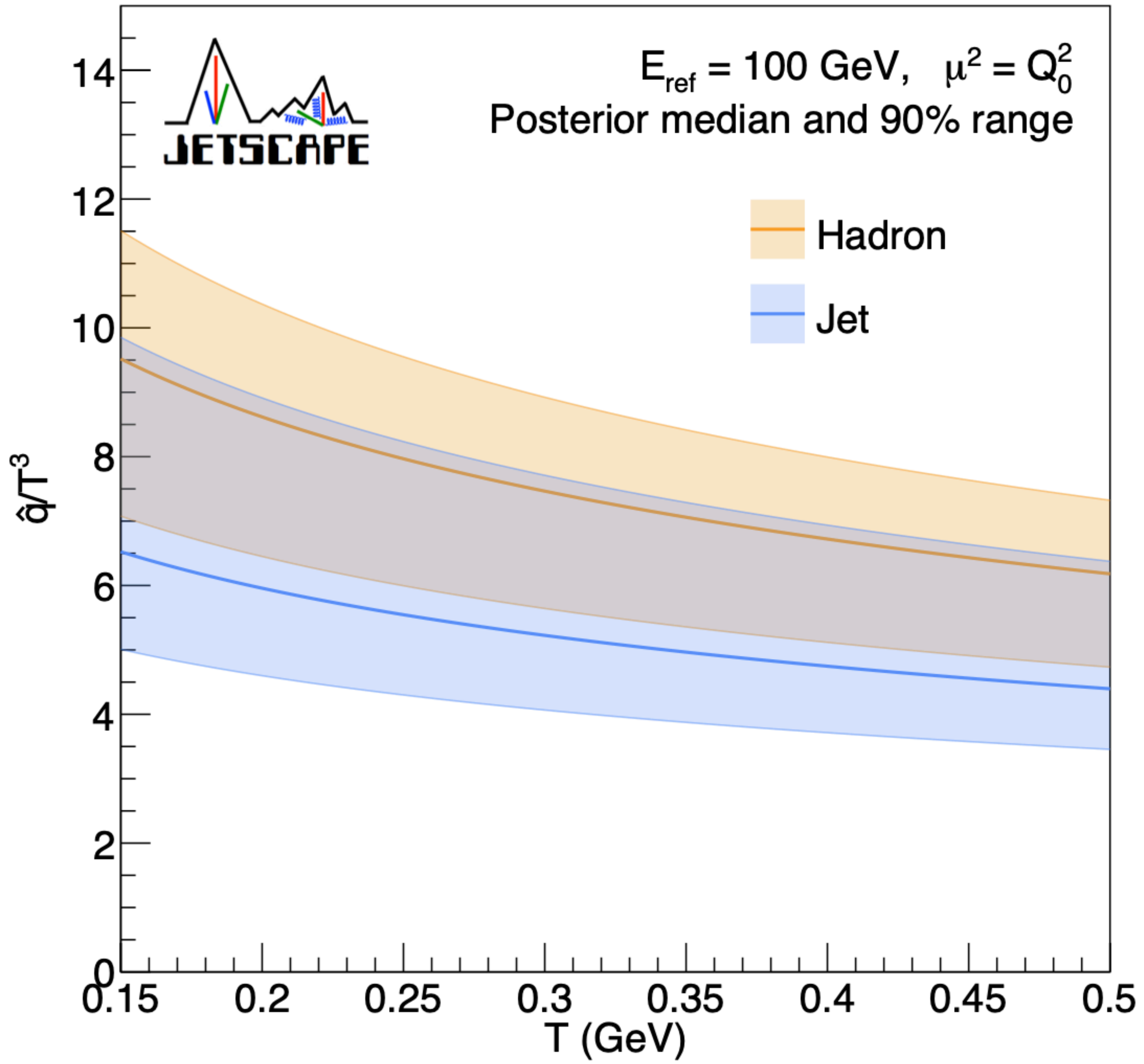
Magnitude of critical fluctuations



Dashed: equilibrium
Solid: Hydro+ with off-equilibrium lag

JETS AND HIGH-p_T PROBES

- **What we can do**
  - sPHENIX-focused prediction program
  - JETSCAPE Bayesian extraction of $\hat{q}$
  - Self-similar energy transfer from hard modes to the plasma's temperature scale
  - Renormalization of the jet quenching parameter, following non-linear renormalization equation
  - Growing use of jet substructure, photon+jet, heavy-flavor jets, and energy correlators



Y. Mehtar-Tani, arXiv:2509.26394
JETSCAPE Collaboration, Phys.Rev.C 111 (2025) 5, 054913

JETS AND HIGH-p_T PROBES

- **What needs improvement**
  - Implement recent theory developments in phenomenological frameworks
  - Extract $\hat{q}$ as a function of temperature, energy, virtuality, and path length — not one number
  - Consistent medium response and recoil treatment
  - Understand uncertainties from soft-background and hadronization effects
  - Study QGP at different length scales; are there quasiparticles?
  - Learn about thermalization from jets

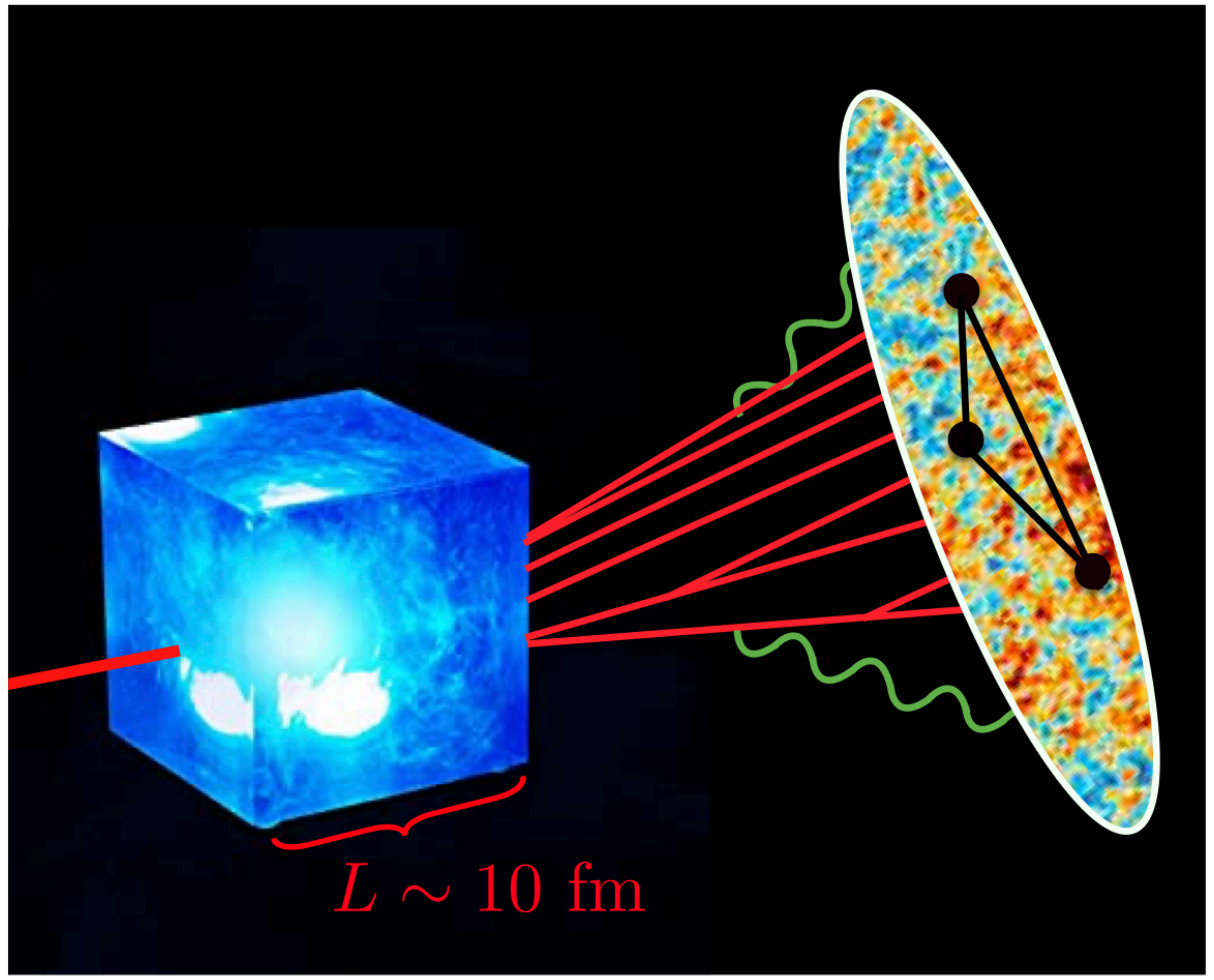


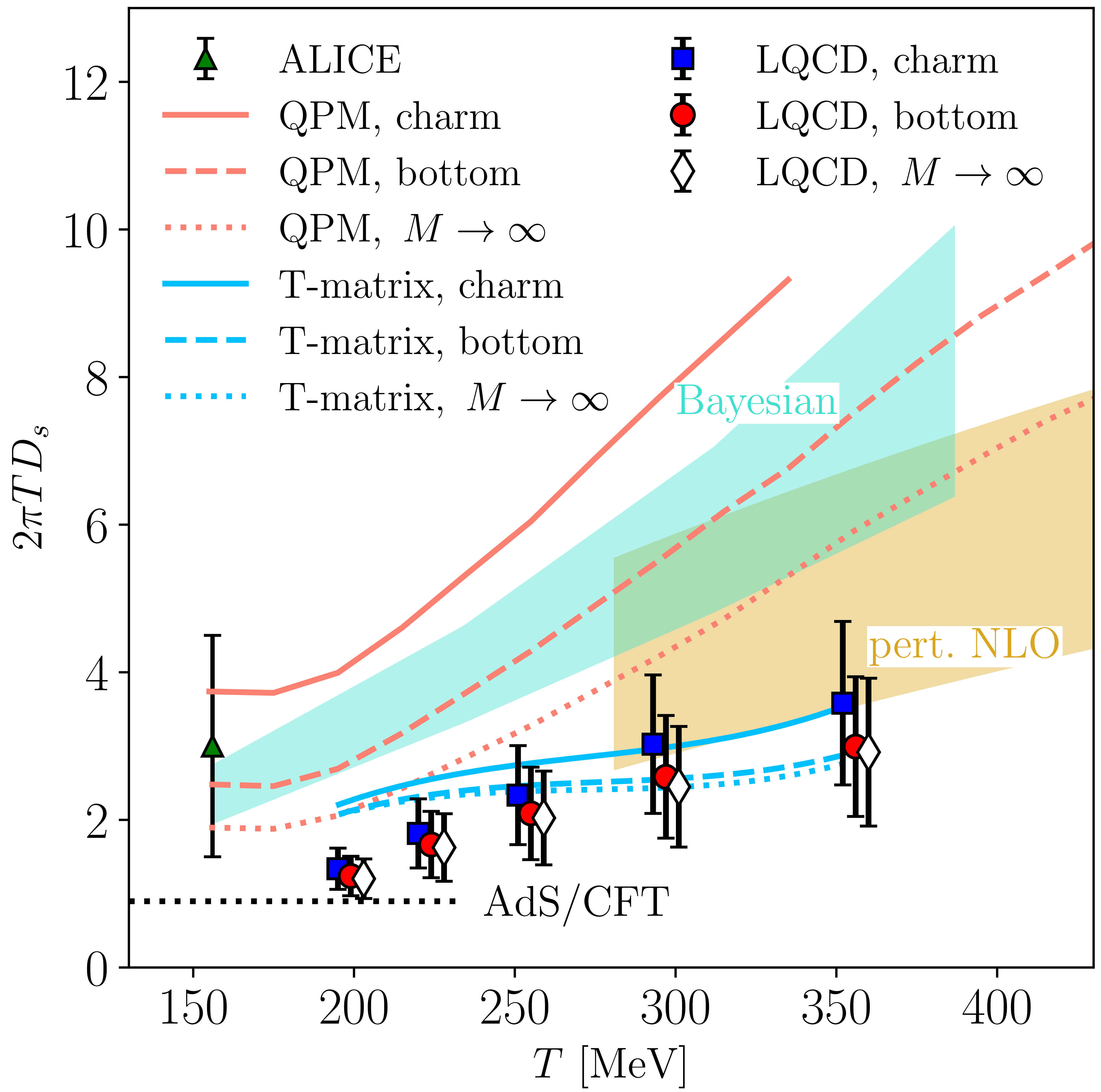
FIG. 1: The scales of the QGP are imprinted into the scales of the substructure of final state jets. These can be naturally extracted through the use of correlation functions of energy flux.

Y. Mehtar-Tani, arXiv:2509.26394
C. Andres, F. Dominguez, R. Kunnawalkam Elayavalli, J. Holguin, C. Marquet, I. Moult, Phys. Rev. Lett. 130, 262301 (2023)

HEAVY FLAVOR

- **What we can do**
  - HEFTY: comprehensive heavy-flavor theory framework
  - Lattice-QCD constraints on heavy-quark diffusion and in-medium potentials
  - Quantum transport, open quantum systems, and T-matrix approaches
- **What needs improvement**
  - Hadronization of heavy flavor, the role of in-medium heavy flavor resonances
  - Simultaneous constraints from R_{AA}, v_n, correlations, jets, and quarkonia
  - Good understanding of early time effects on heavy flavor evolution
  - Pin down heavy-quark transport coefficients from QCD as functions of temperature and momentum

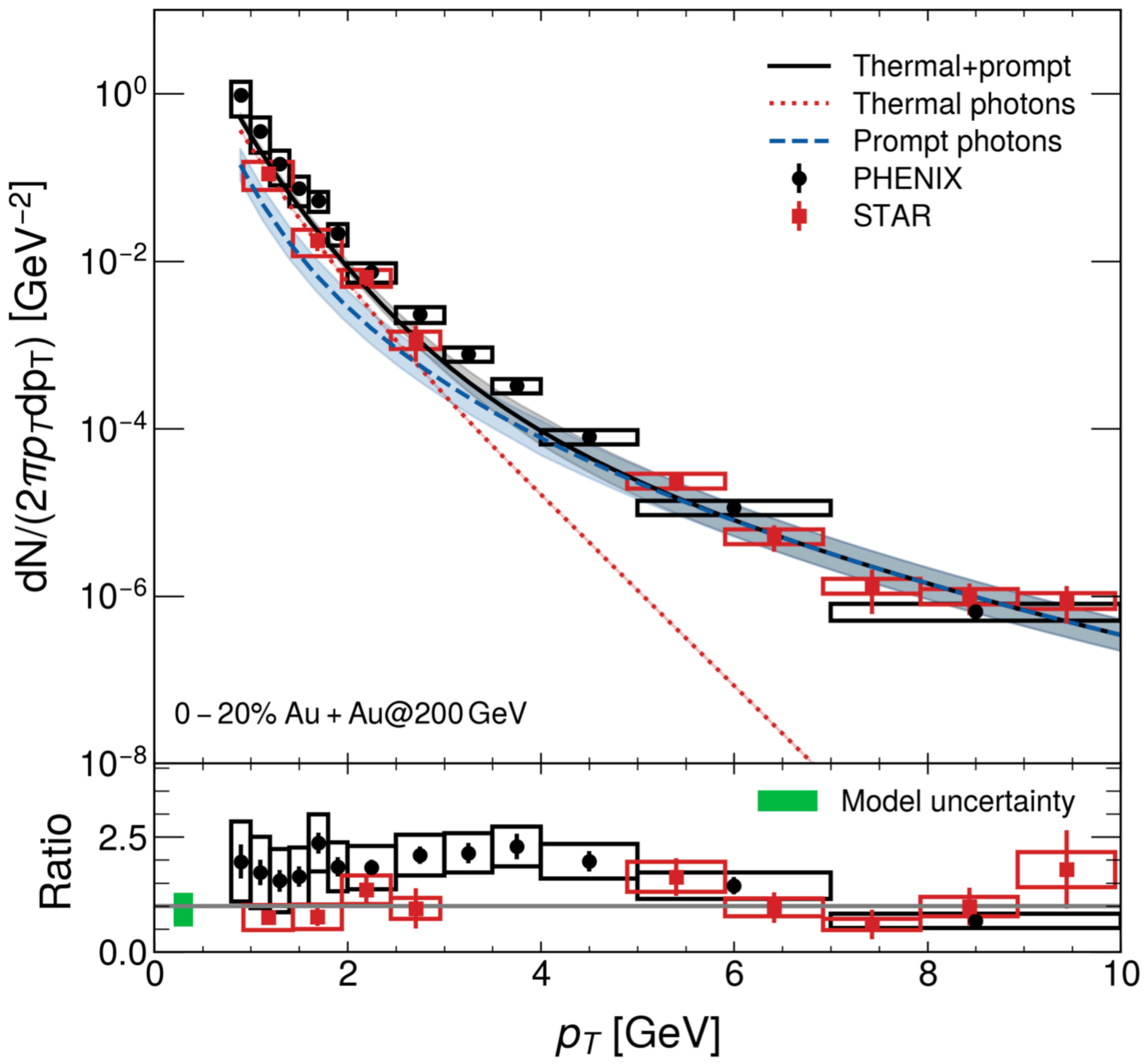
HotQCD Collaboration, PRL 132, 051902 (2024)



ELECTROMAGNETIC PROBES

- **What we can do**
  - Event-by-event 3+1D calculations that include prompt, pre-equilibrium, thermal QGP, hadron gas photon and dilepton production
  - First lattice QCD estimates of thermal photon production rate from the QGP
- **What needs improvement**
  - Lattice QCD dilepton and photon rates using physical pion mass and for different T
  - Complete set of rates with off-equilibrium corrections
  - Understanding of photon anisotropic flow
- **Will unlock**
  - More precise temperature measurements
  - Deeper insight into earliest stages

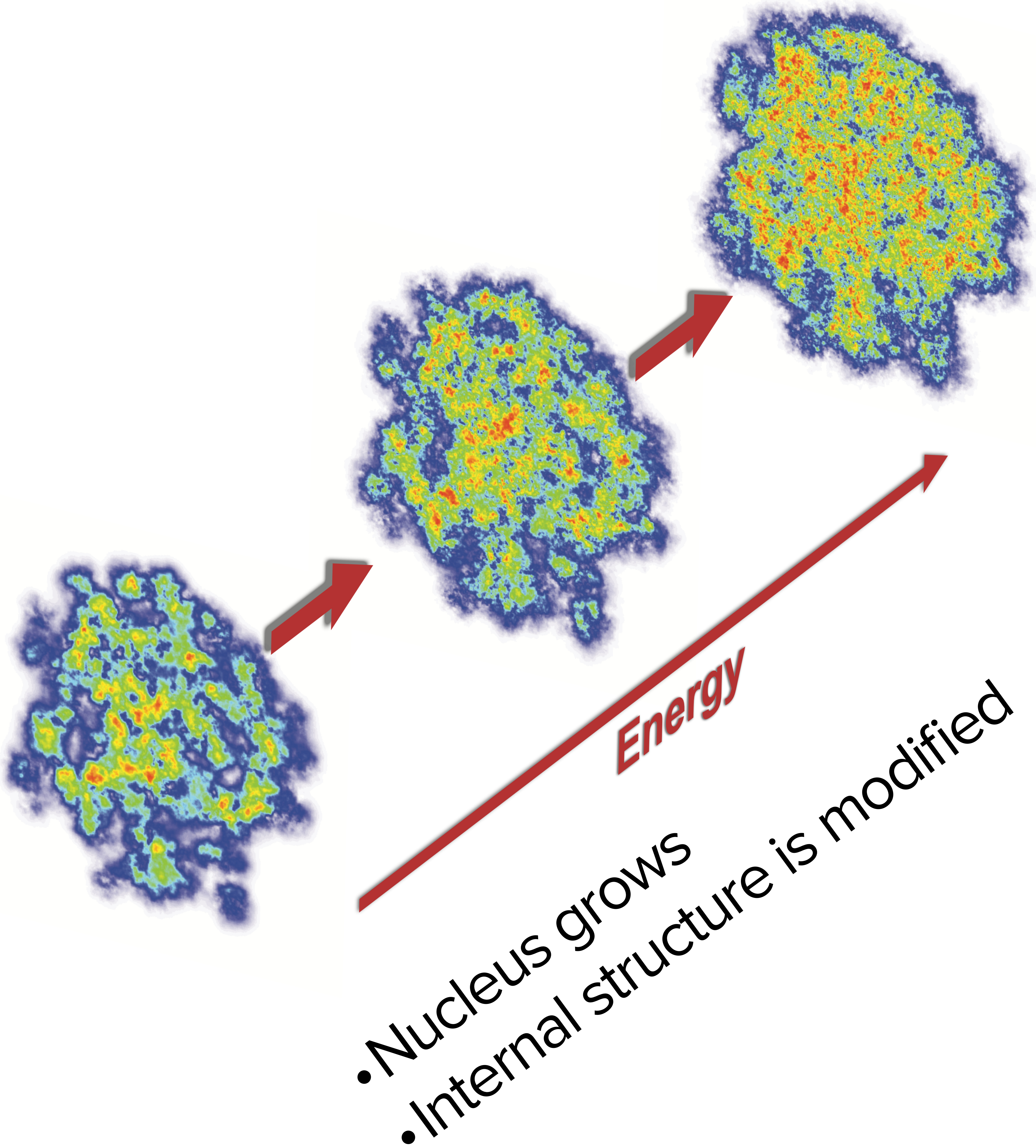
Event-by-event 3+1D calculations reproduce RHIC direct-photon spectra



X.-Y. Wu, C. Gale, S. Jeon, J.-F. Paquet, B. Schenke, C. Shen, arXiv:2511.08773
A. Adare et al. (PHENIX), Phys. Rev. C 91, 064904 (2015)
B. L. Adamczyk et al. (STAR), Phys. Lett. B 770, 451–458 (2017)

COLD QCD AND INITIAL STATE

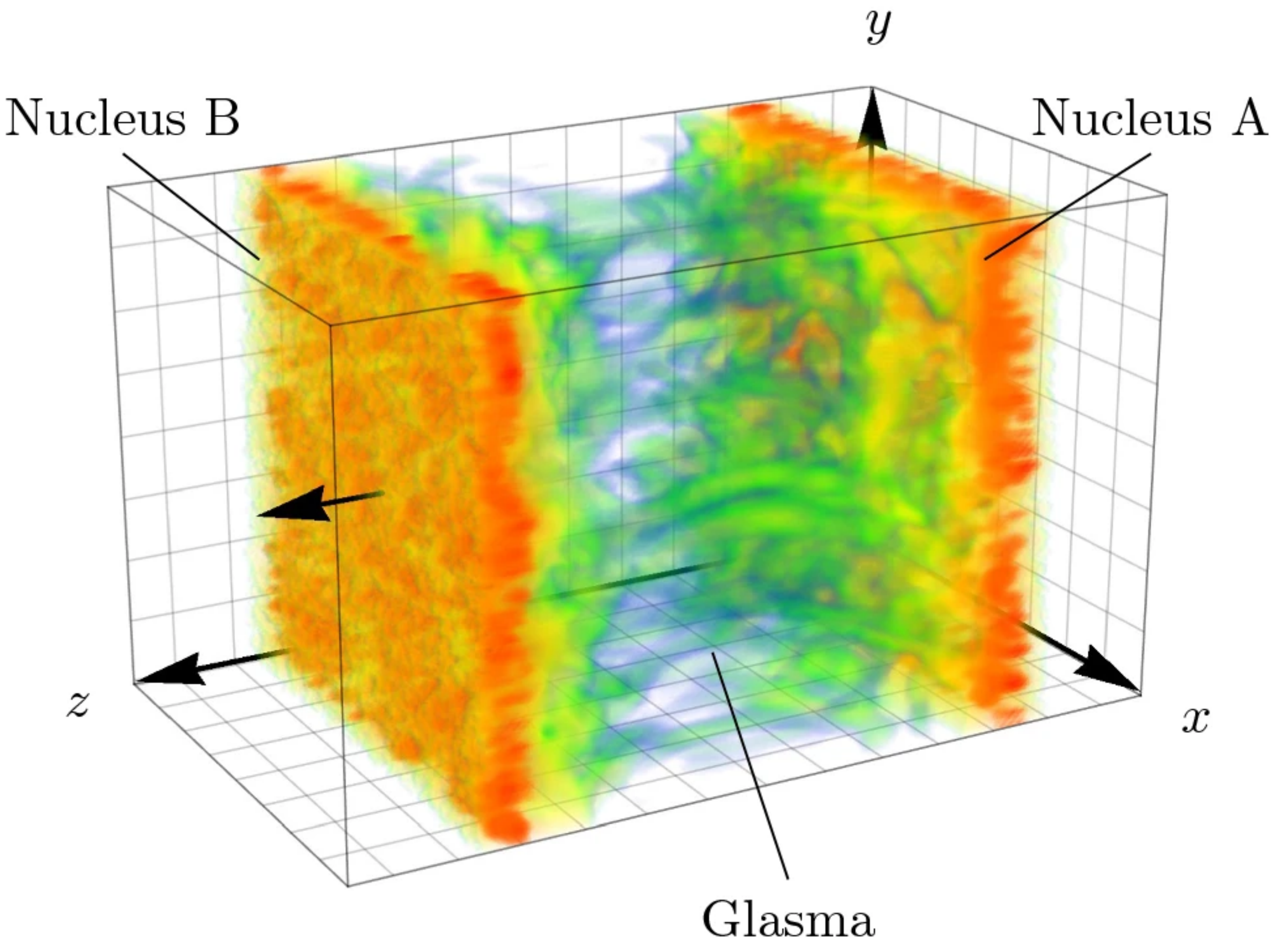
- **What we can do**
  - SURGE collaboration: precision saturation theory and global analysis framework
  - NLO CGC calculations for small-x observables
  - Better connections between CGC, TMD, high-twist, and nuclear-PDF approaches
  - Event-by-event HIC initial state tied to small-x dynamics, including constrained JIMWLK evolution
  - Inclusion of ab-initio nuclear structure calculations



H. Mäntysaari, B. Schenke, C. Shen, W. Zhao, Phys.Rev.Lett. 135 (2025) 2, 022302 and Phys.Rev.C 113 (2026) 3, 034914

COLD QCD AND INITIAL STATE

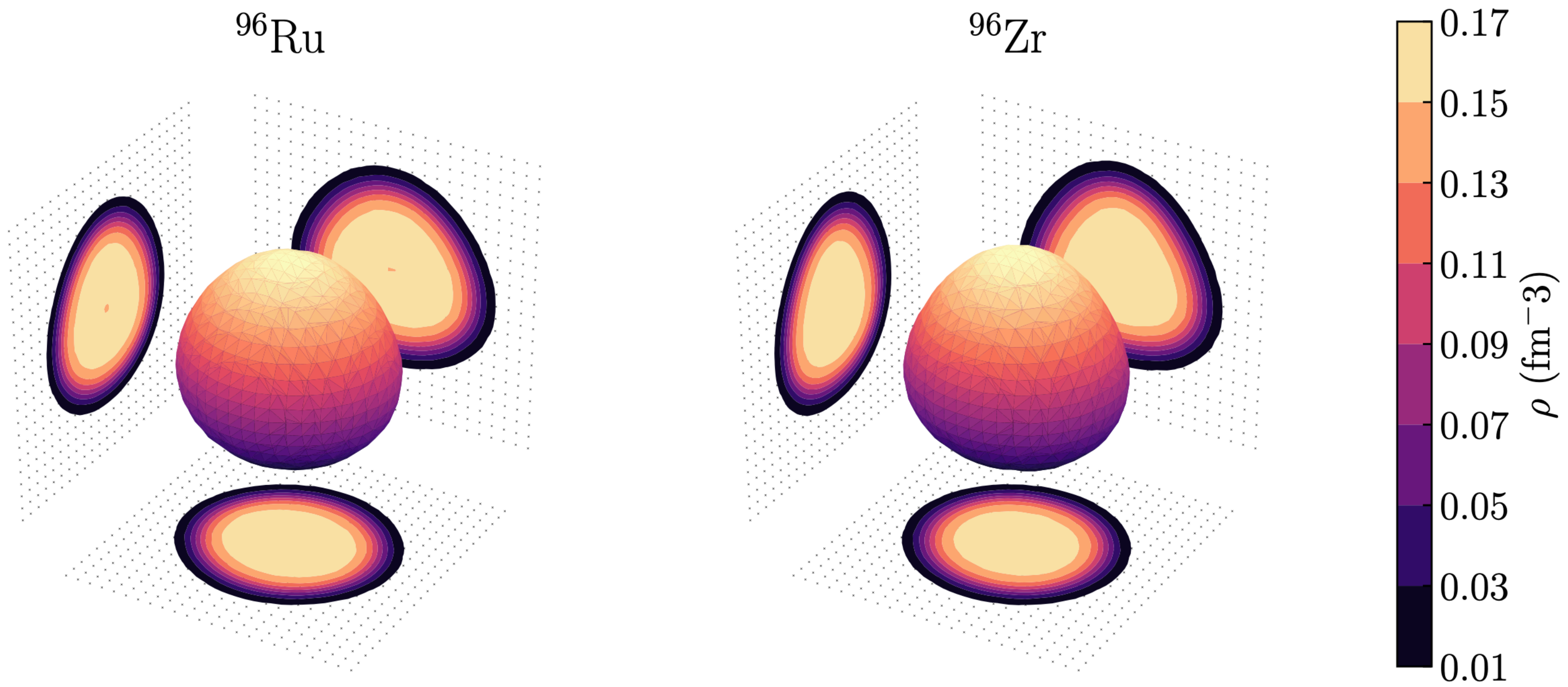
- **What needs improvement**
  - Include quarks in CGC framework
  - Full 3+1D description including dynamic hydrodynamization - thermalization? Quantum computing could tackle this problem
  - Determine what is the smallest droplet of QGP
  - Global saturation fits including RHIC, LHC, HERA, and eventually EIC
- **What it will unlock**
  - Enable precision extraction of QGP properties
  - Discover and explore saturation regime



A. Ipp, D.I. Mueller, Eur.Phys.J.A 56 (2020) 9, 243

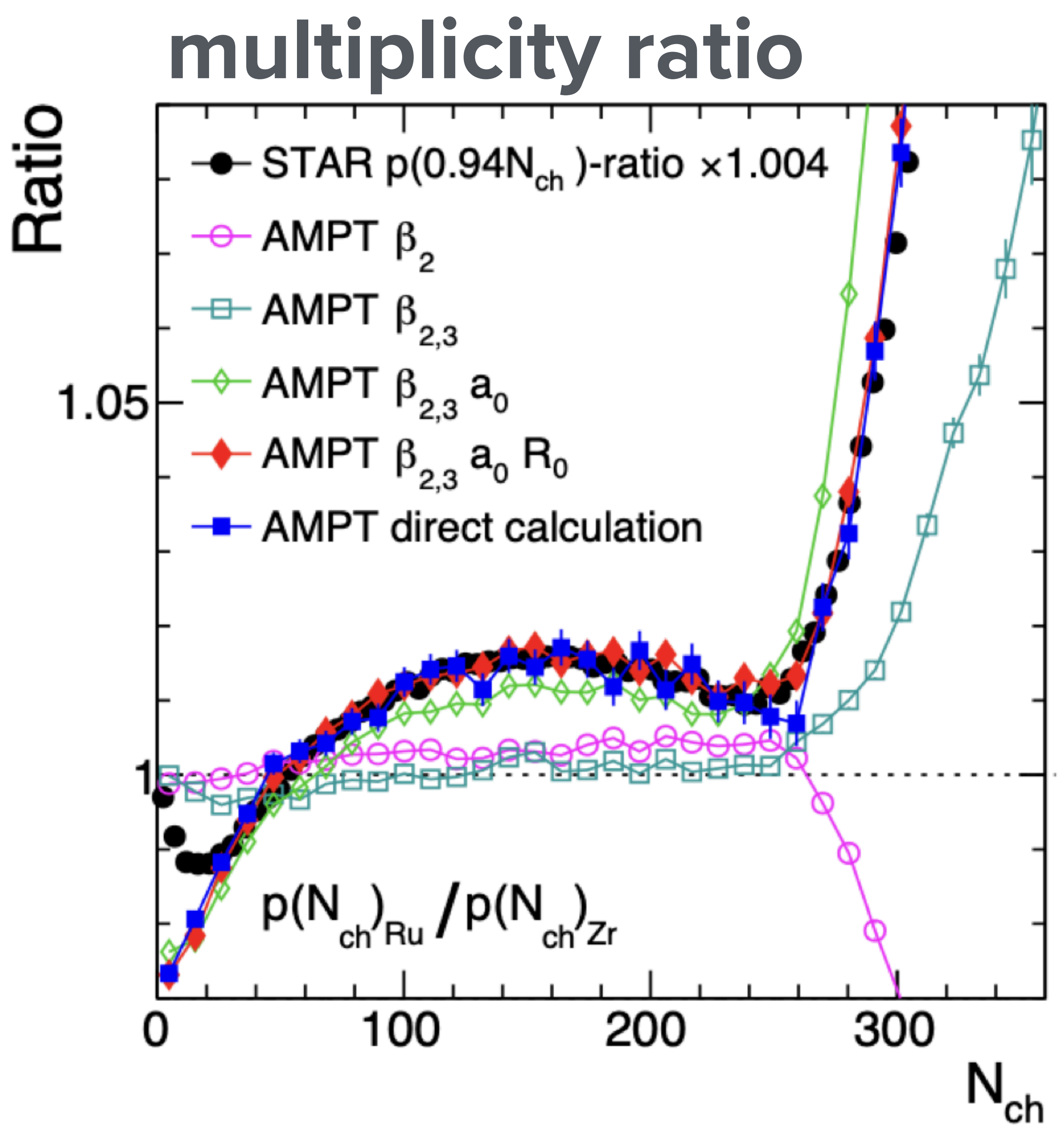
SYNERGY: NUCLEAR STRUCTURE

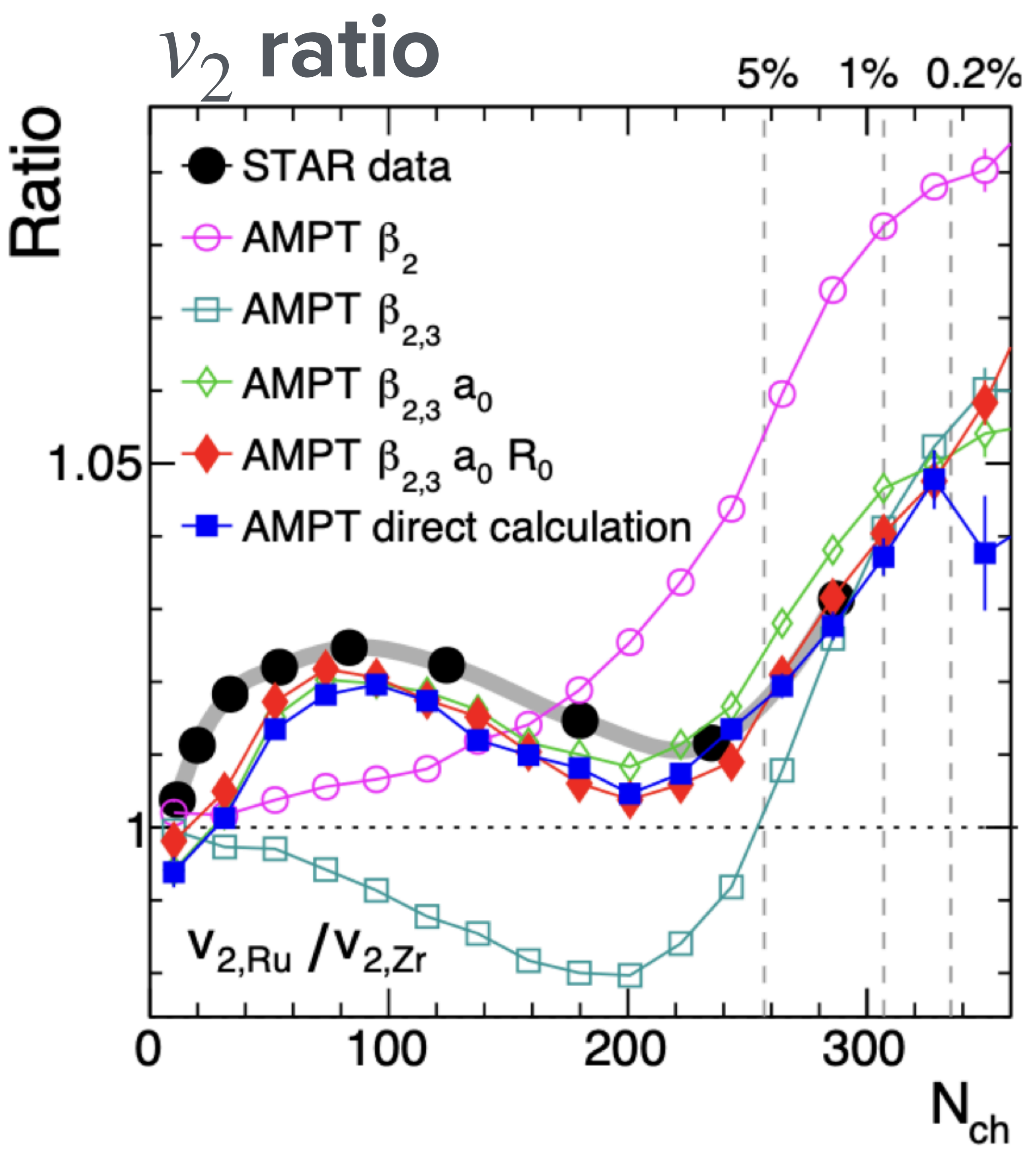
- **Heavy ion observables are highly sensitive to details of the nuclear structure of colliding nuclei**
- Important for proper initial state modeling
- New way to extract nuclear structure properties



- Use input from ab-initio nuclear structure calculations
- Collaboration between subfields
  - hopefully will grow
- Relevant also for certain observables at the EIC
- **Stunning new insight into quantum nature of nuclei**

G. Giacalone, arXiv:2507.01454

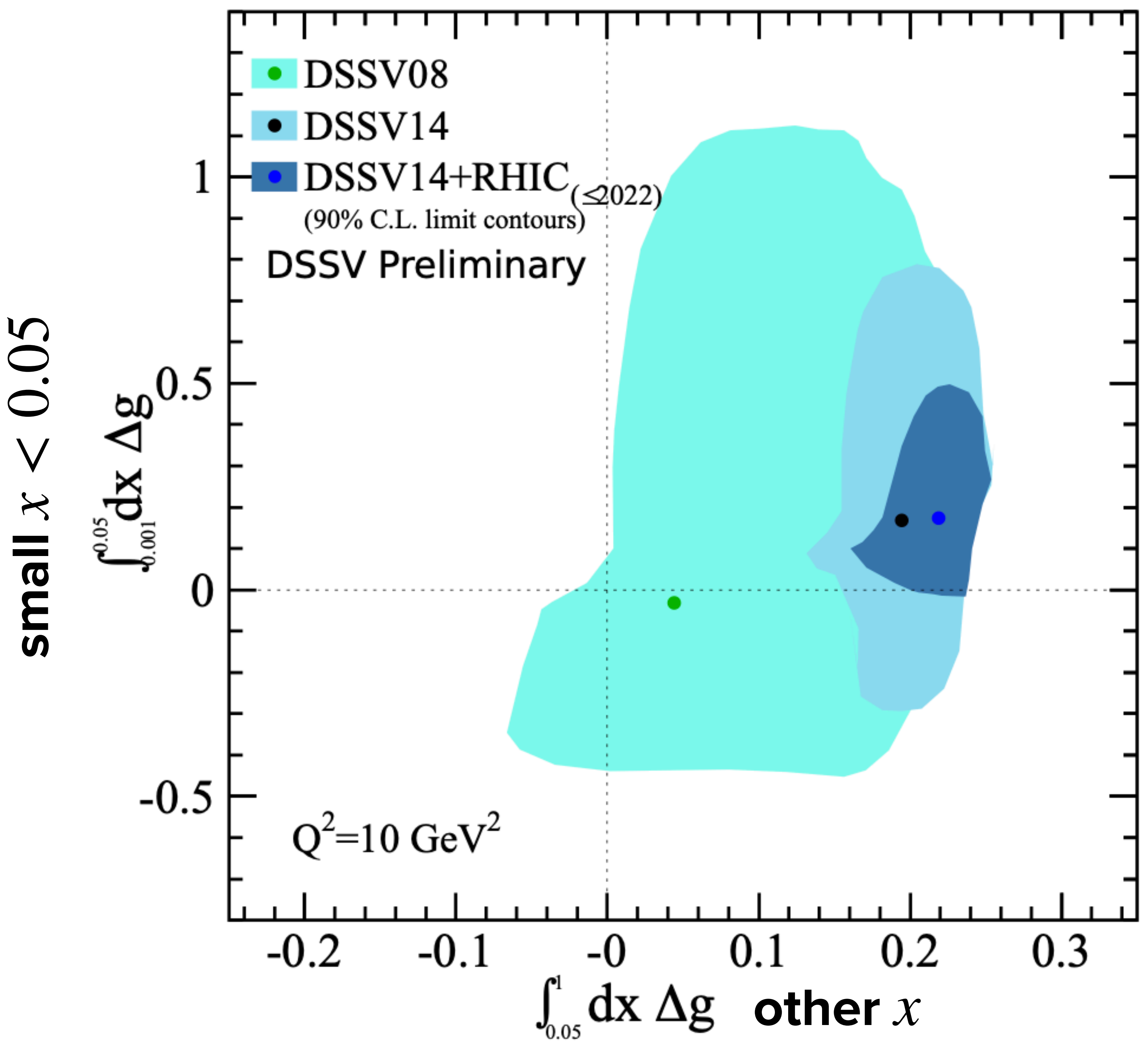




PROTON SPIN AND HADRON STRUCTURE

- **What we can do**
  - RHIC data strongly constrain gluon polarization at moderate x
  - Global analyses: DIS, SIDIS, and p+p spin asymmetry data, some at NNLO
  - NLO TMD/twist-3 descriptions now available for key transverse-spin observables
- **What needs improvement**
  - Global analysis with all RHIC spin data included
  - Implement small-x helicity evolution
  - Better treatment of fragmentation functions and correlated uncertainties in global analysis
  - Higher order calculations, e.g. NNLO for dijets at RHIC
  - Orbital angular momentum constraints

allowed gluon spin contribution in different x ranges



PHENIX Collaboration, Phys. Rev. Lett. 130, 251901
RHIC SPIN Collaboration, White Paper, arXiv:2302.00605
D. de Florian et al, Phys. Rev. Lett. 113, 012001 (2014)
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I. Borsa et al, Phys.Rev.Lett. 133 (2024) 151901
D. Rein et al, Phys.Rev.Lett. 135 (2025) 25, 251901
JAM Collaboration, Phys.Rev.D 112 (2025) 11, 114017
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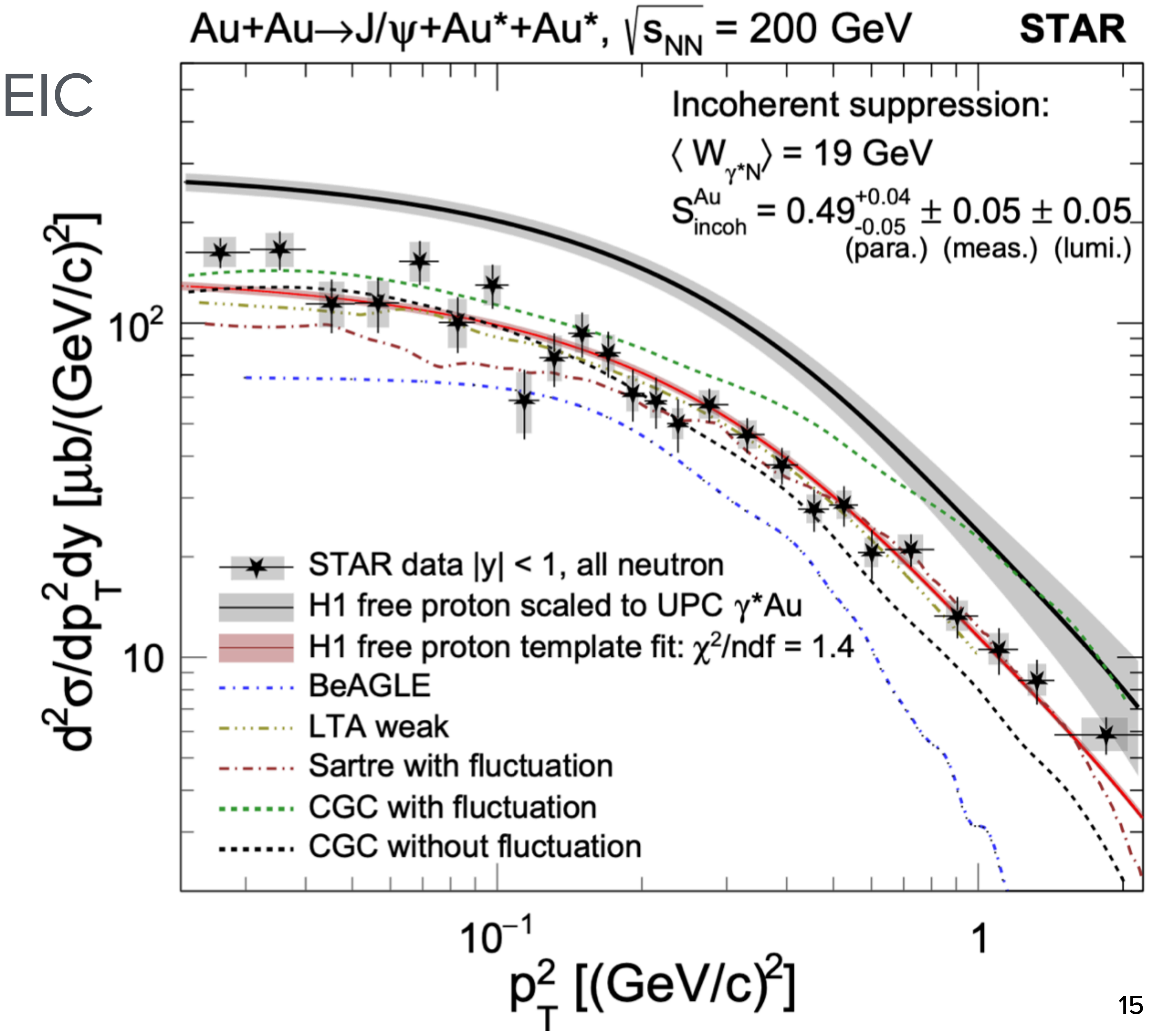
R. Ikarashi, Y. Koike, S. Yoshida, Phys.Rev.D 113 (2026) 7, 074033
J. Borden, Y.V. Kovchegov, Phys.Rev.D 108 (2023) 1, 014001

SYNERGY: EIC - HEAVY-ION COLLISIONS

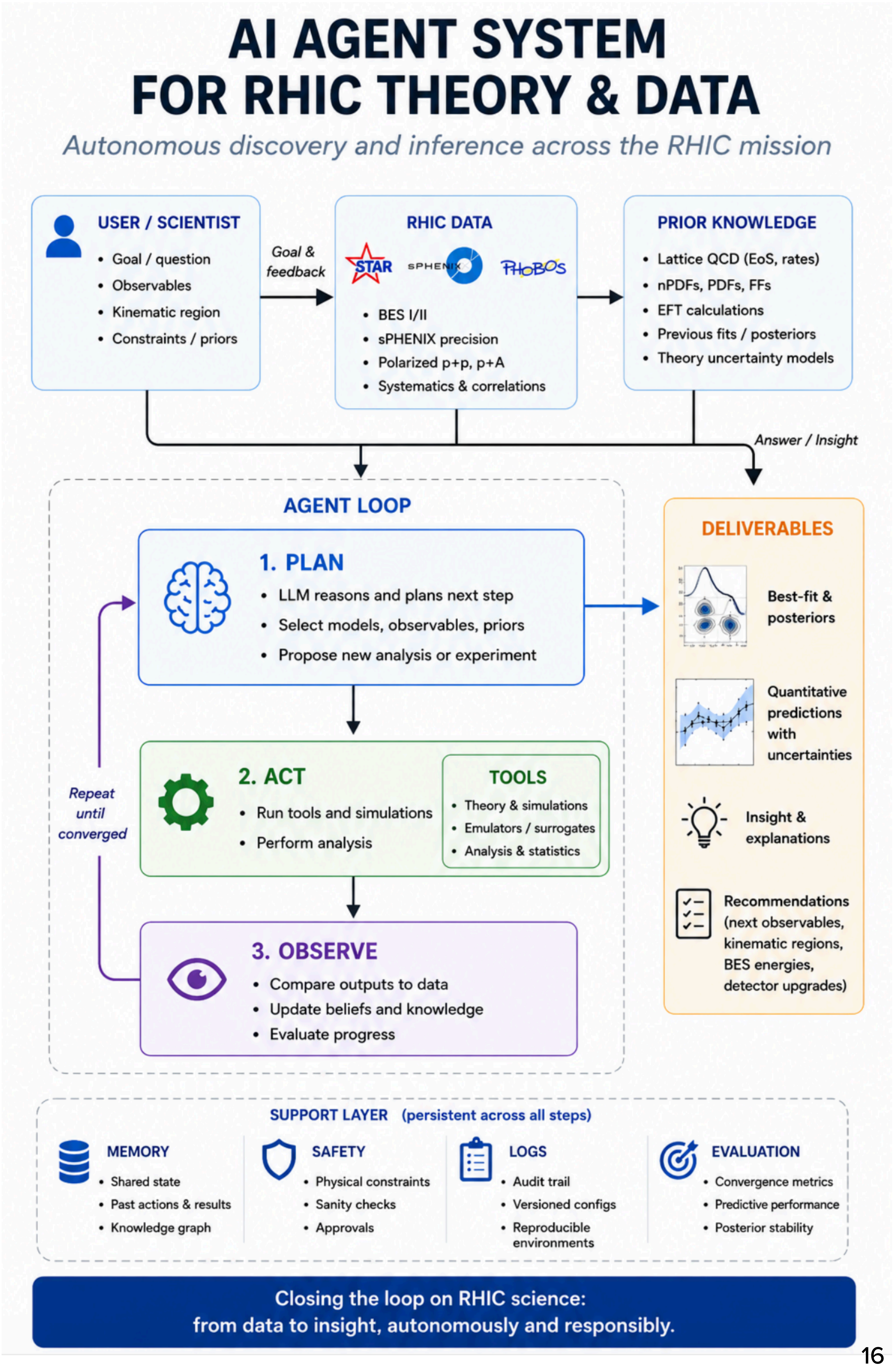
- **RHIC completion and EIC readiness are deeply connected**
- Example: Significant advances in initial state description including substructure fluctuation and JIMWLK evolution, all born out of studies in e+p and e+A scattering
- Example: Ultra-peripheral collisions at RHIC and LHC prepare us for and complement e+A collisions at the EIC
- Example: Incoherent J/ψ production
  - Suppressed in Au+Au UPC vs. scaled free proton
  - More suppressed than coherent
  - Can constrain fluctuations at different length scales
- Example: Collectivity in $\gamma + A$



STAR Collaboration, Phys. Rev. C 110 (2024) 014911
W. Chang, E.-C. Aschenauer, M. D. Baker, A. Jentsch, J.-H. Lee, Z. Tu, Z. Yin, and L. Zheng, Phys. Rev. D 106, 012007 (2022)
V. Guzey, M. Strikman, and M. Zhalov, Eur. Phys. J. C 74, 2942 (2014)
H. Mäntysaari, F. Salazar, B. Schenke, Phys.Rev.D 106 (2022) 7, 074019
H. Mäntysaari, H. Roch, F. Salazar, B. Schenke, C. Shen, W. Zhao, Phys.Rev.D 113 (2026) 1, 014038

AI/ML

- **What we can do**
  - Bayesian inference is now standard
  - Gaussian-process emulators and surrogate models
  - Symbolic regression emerging
- **What needs improvement**
  - Agentic AI for Nuclear Physics
  - Theory assistance: Symbolic manipulation, generating surrogate models, deriving effective parameterizations, code generation for hydrodynamics or transport calculations, automated literature synthesis…
  - Autonomous scientific loops: propose observables, run Monte Carlo studies, evaluate objective functions, revise hypotheses, and repeat



CONCLUSION

Sustained theory effort is essential to complete the RHIC science mission

RHIC's "theory completion criterion" should be a set of reproducible, uncertainty-quantified legacy statements: the temperature dependence of QGP transport coefficients; the microscopic mechanism of jet and heavy-flavor energy loss; the status of the QCD critical point in the BES-covered region; controlled cold-QCD and saturation baselines; and final global constraints on proton spin structure.

Continued RHIC theory development will deepen our microscopic understanding of QCD matter far from equilibrium, strongly interacting quantum systems, and emergent collective phenomena. RHIC theory developments in spin, saturation, small-x, and global-analysis frameworks are direct inputs to EIC physics. All these advances will directly inform future studies at the EIC, LHC and beyond, and provide broadly applicable theoretical and computational tools.

Sustained theory effort is also needed to keep a trained workforce engaged through the RHIC-to-EIC transition