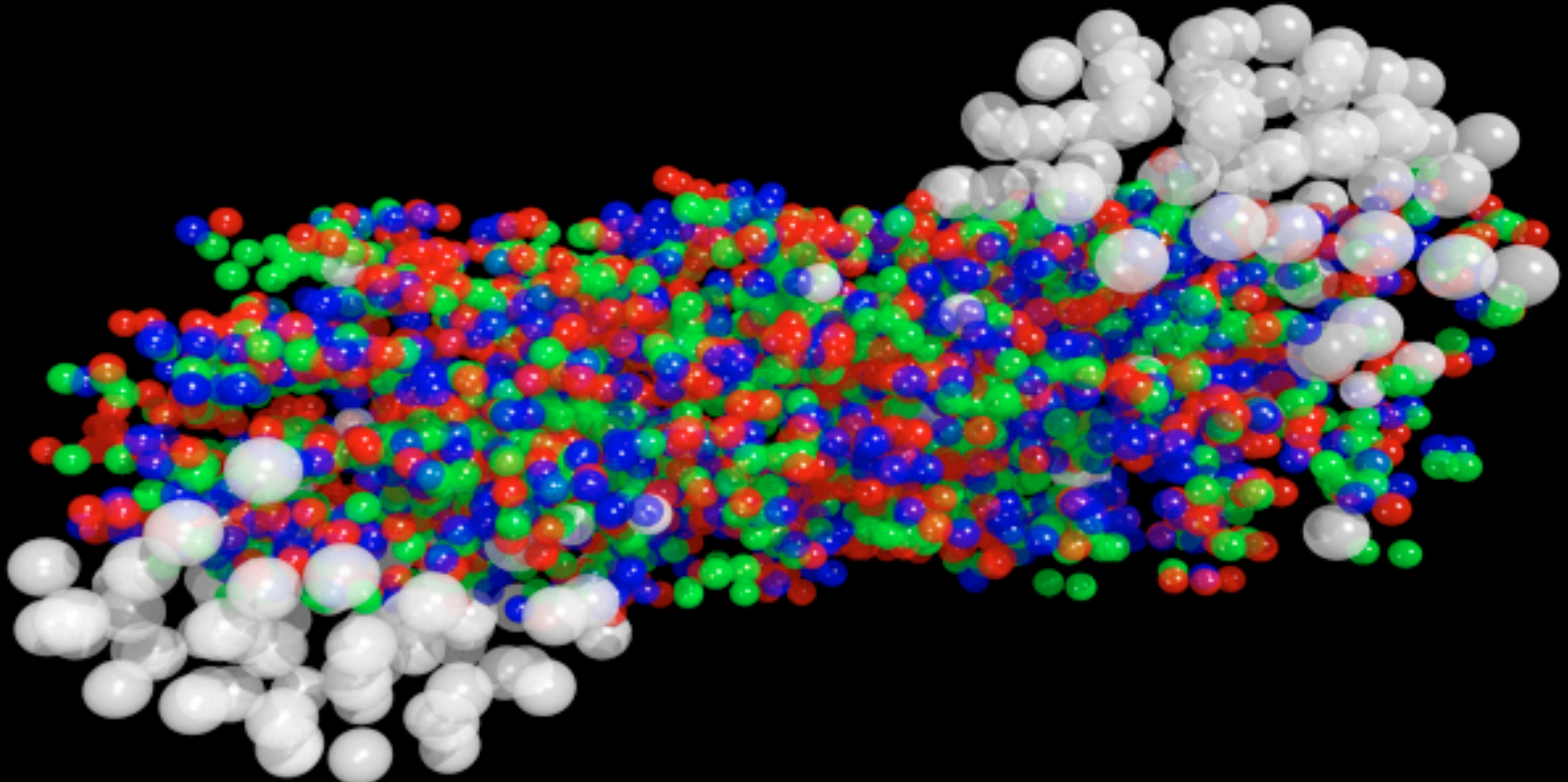
RBRC
RIKEN BNL Research Center

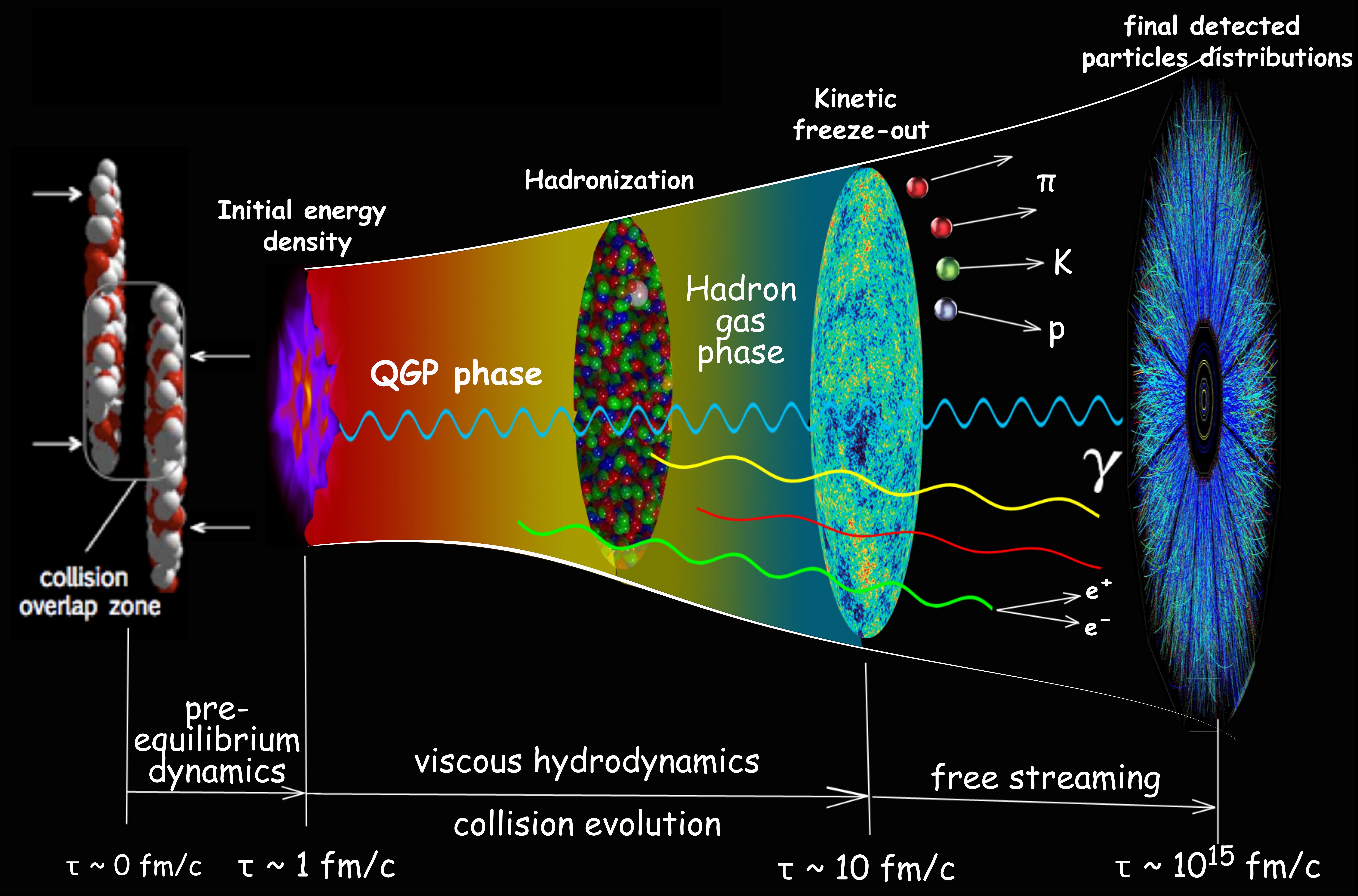
DYNAMICAL MODELING OF RELATIVISTIC HEAVY-ION COLLISIONS AT BEAM ENERGY SCAN ENERGIES

CHUN SHEN



The 4th RHIC-BES Theory and Experiment Online Seminar
Aug. 25, 2020

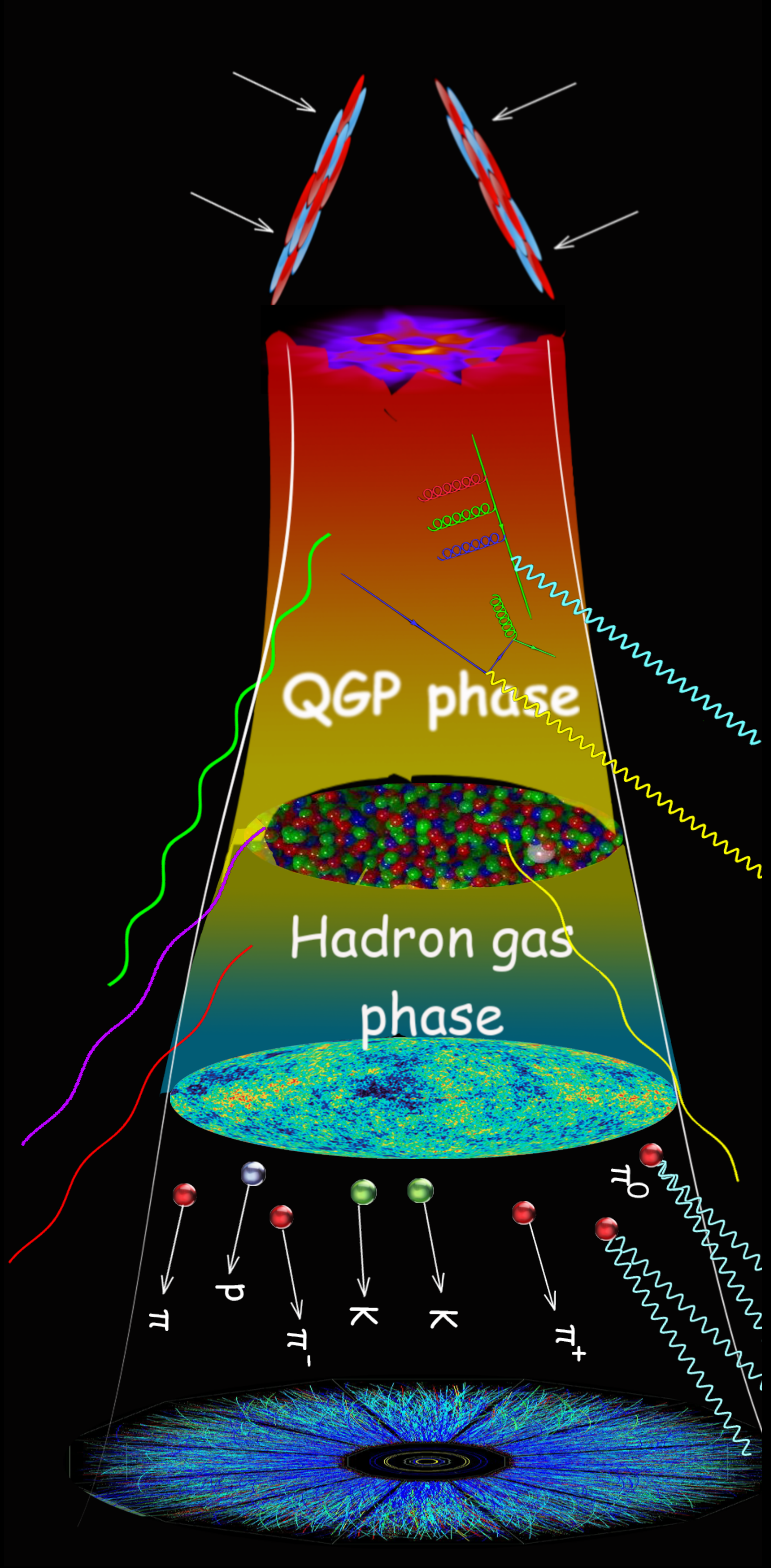
RELATIVISTIC HEAVY-ION COLLISIONS



Complex dynamics driven by multiple length scales

Hybrid multi-stage modeling with event-by-event fluctuations

DEFINING THE QUARK-GLUON PLASMA



Which **properties of hot QCD matter** can we determine from relativistic heavy ion data (LHC, RHIC, and future FAIR/NICA/JPAC)?

Equation of State $e(T, \{\mu_q\}), P(T, \{\mu_q\}), c_s^2(T, \{\mu_q\})$ Critical point & 1st order PT	Spectra, collective flow, femtoscopy, light-nuclei production, net-proton fluctuations
Initial Fluctuation spectrum & baryon stoping $T^{\mu\nu}(\tau, \mathbf{r}), J^\mu(\tau, \mathbf{r})$	Net particle distributions
Shear and bulk viscosities $(\eta/s)(T, \{\mu_q\}), (\zeta/s)(T, \{\mu_q\})$ Charge diffusion D_B, D_Q, D_S	Anisotropic flow v_n Flow correlations Balance functions
Electromagnetic emissivity	Photons and dileptons

COLLECTIVITY & HYDRODYNAMICS

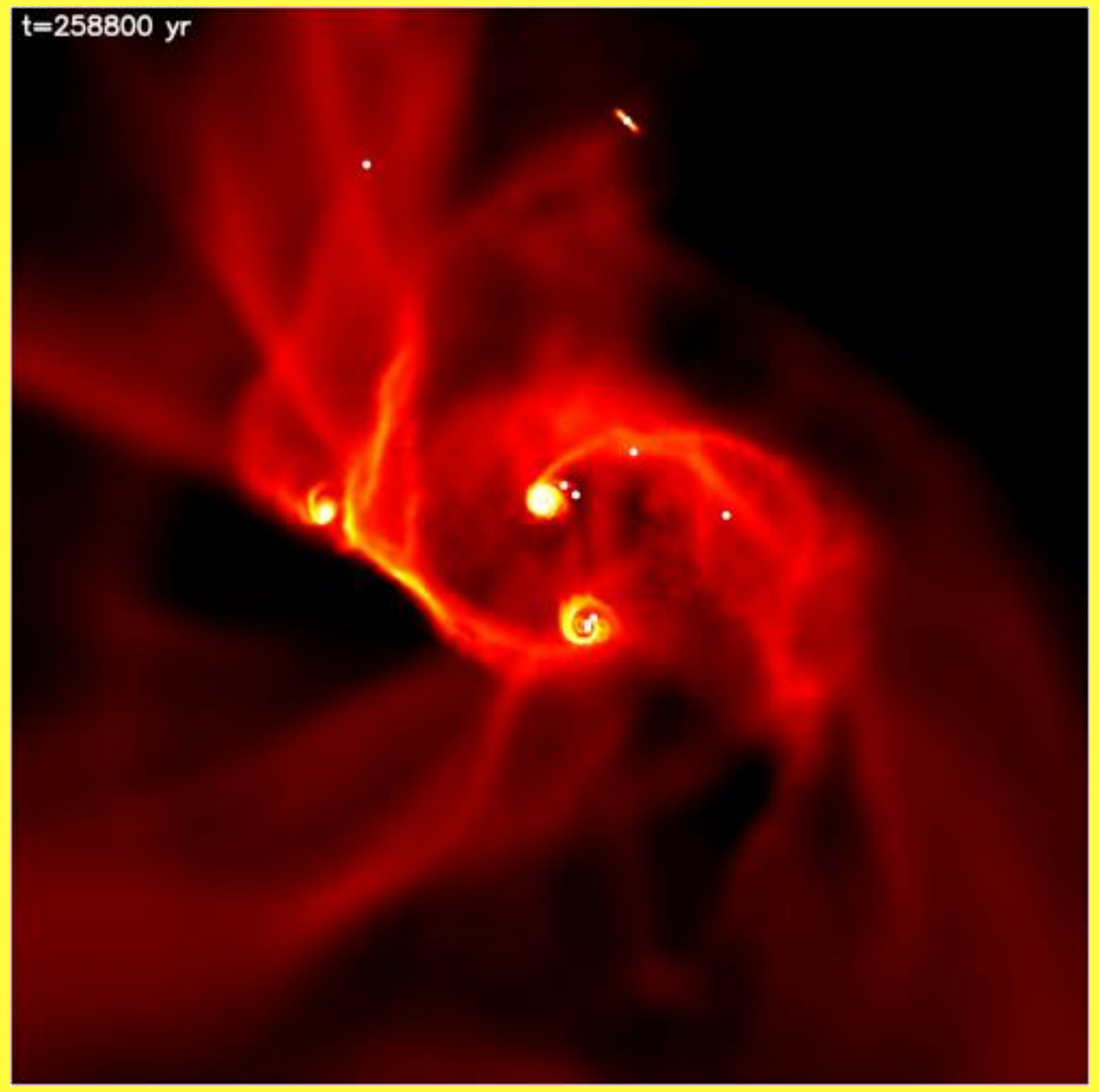
A long wavelength effective description of interacting systems

Conservation laws

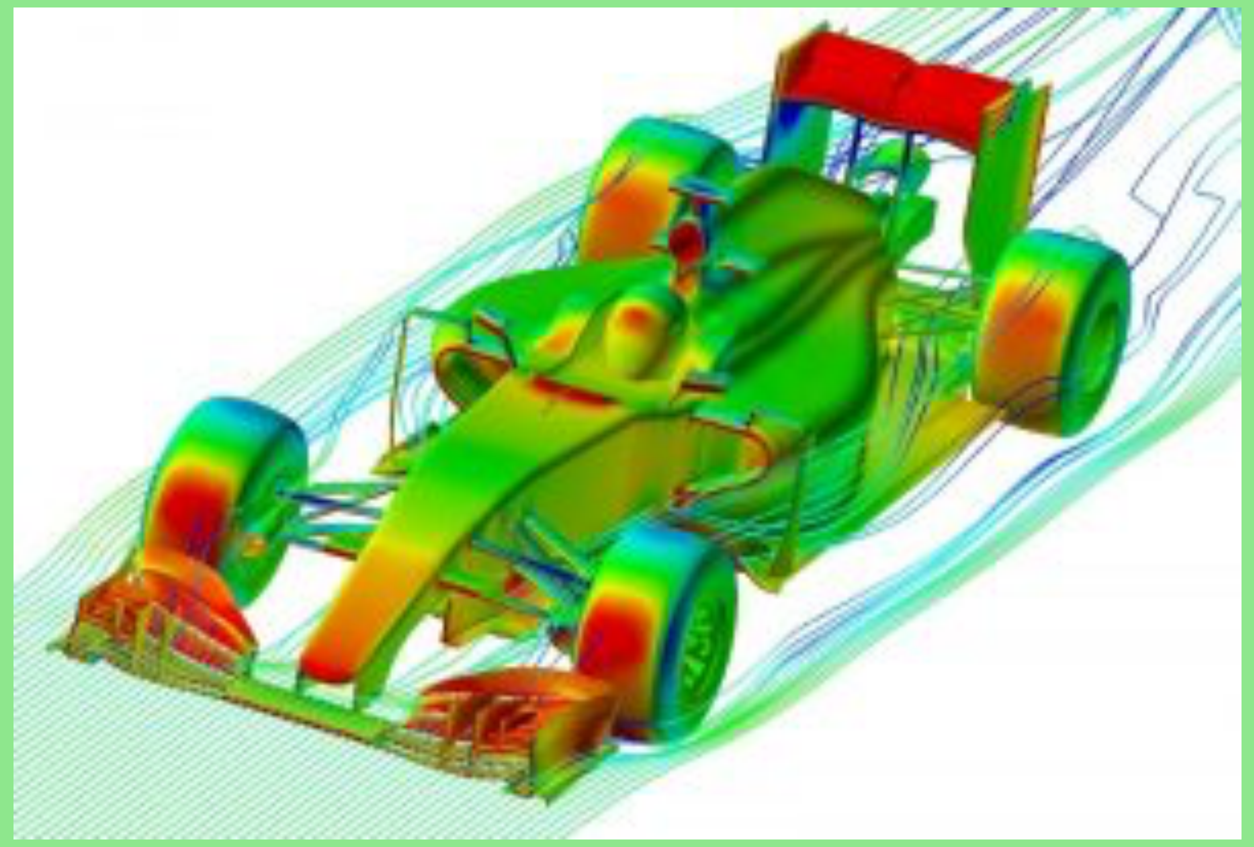
+

Equation of State

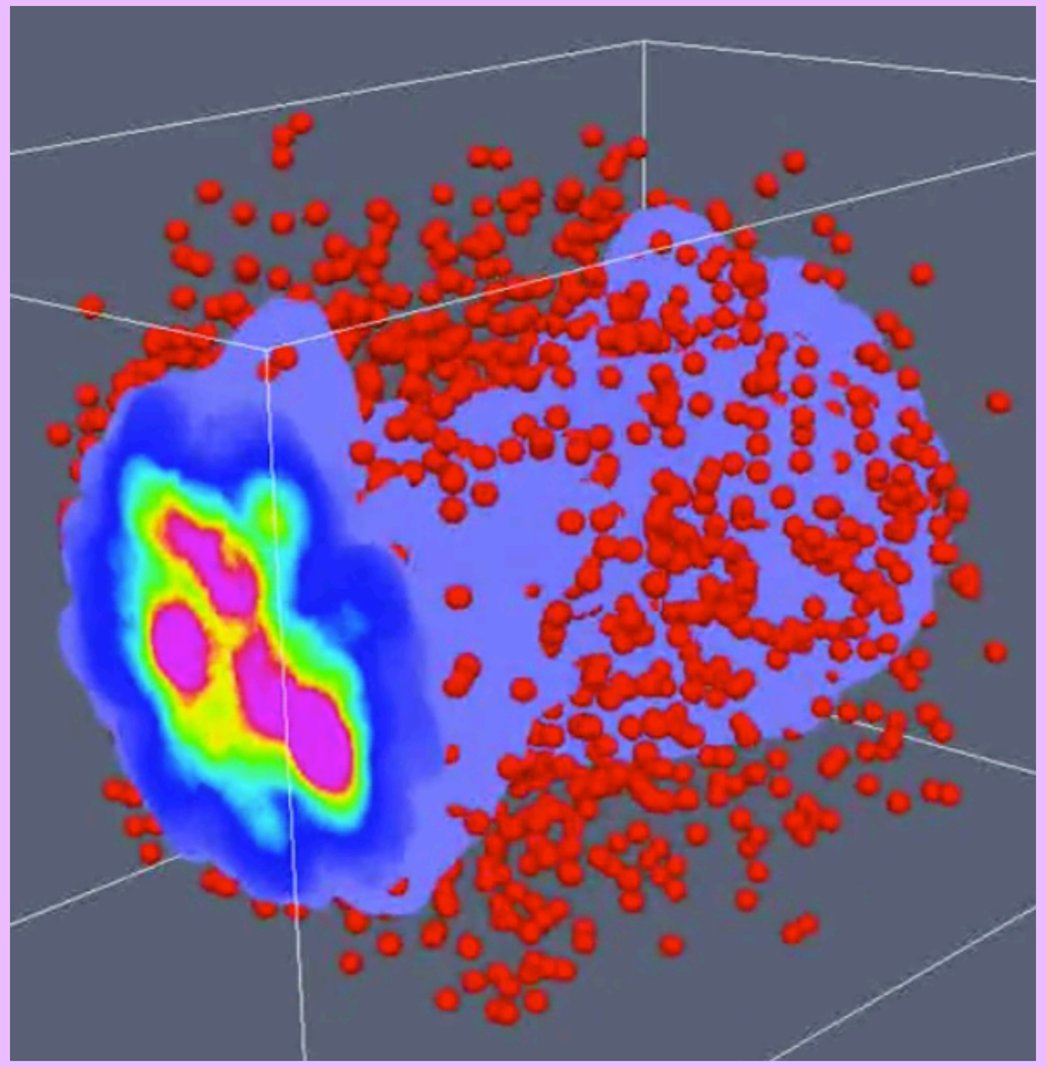
Star formation



Air dynamics of race car

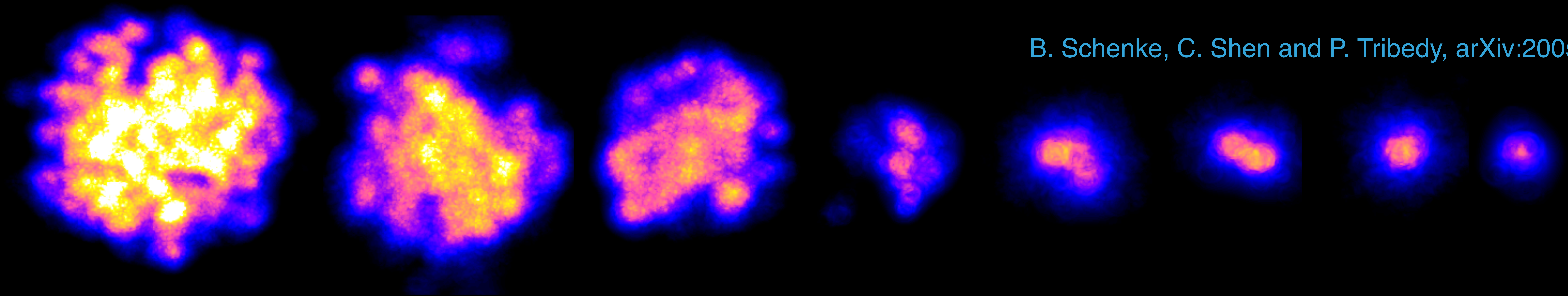


Quark-Gluon Plasma



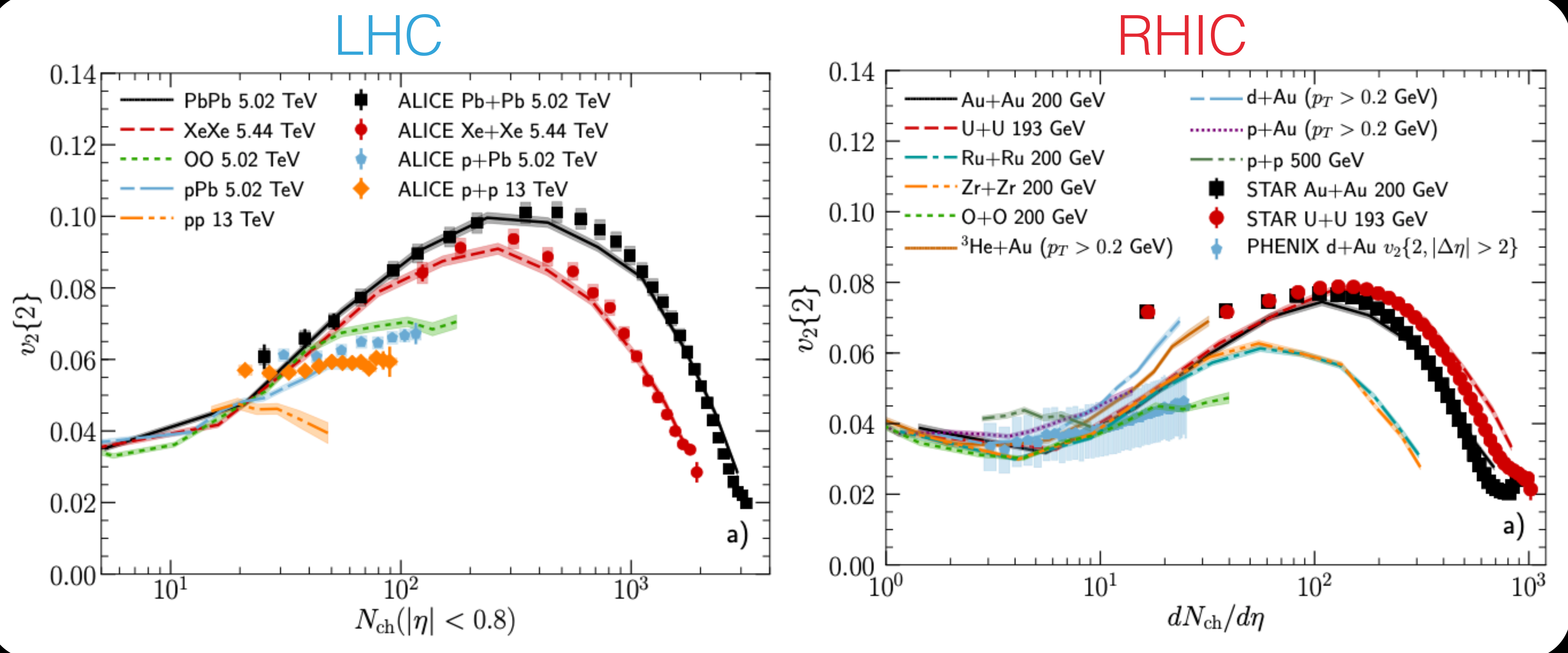
Studying collective phenomena in heavy-ion collisions has been leading the theory frontier of developing causal viscous relativistic hydrodynamics

RUNNING THE GAMUT OF HIGH ENERGY NUCLEAR COLLISIONS



B. Schenke, C. Shen and P. Tribedy, arXiv:2005.14682 [nucl-th]

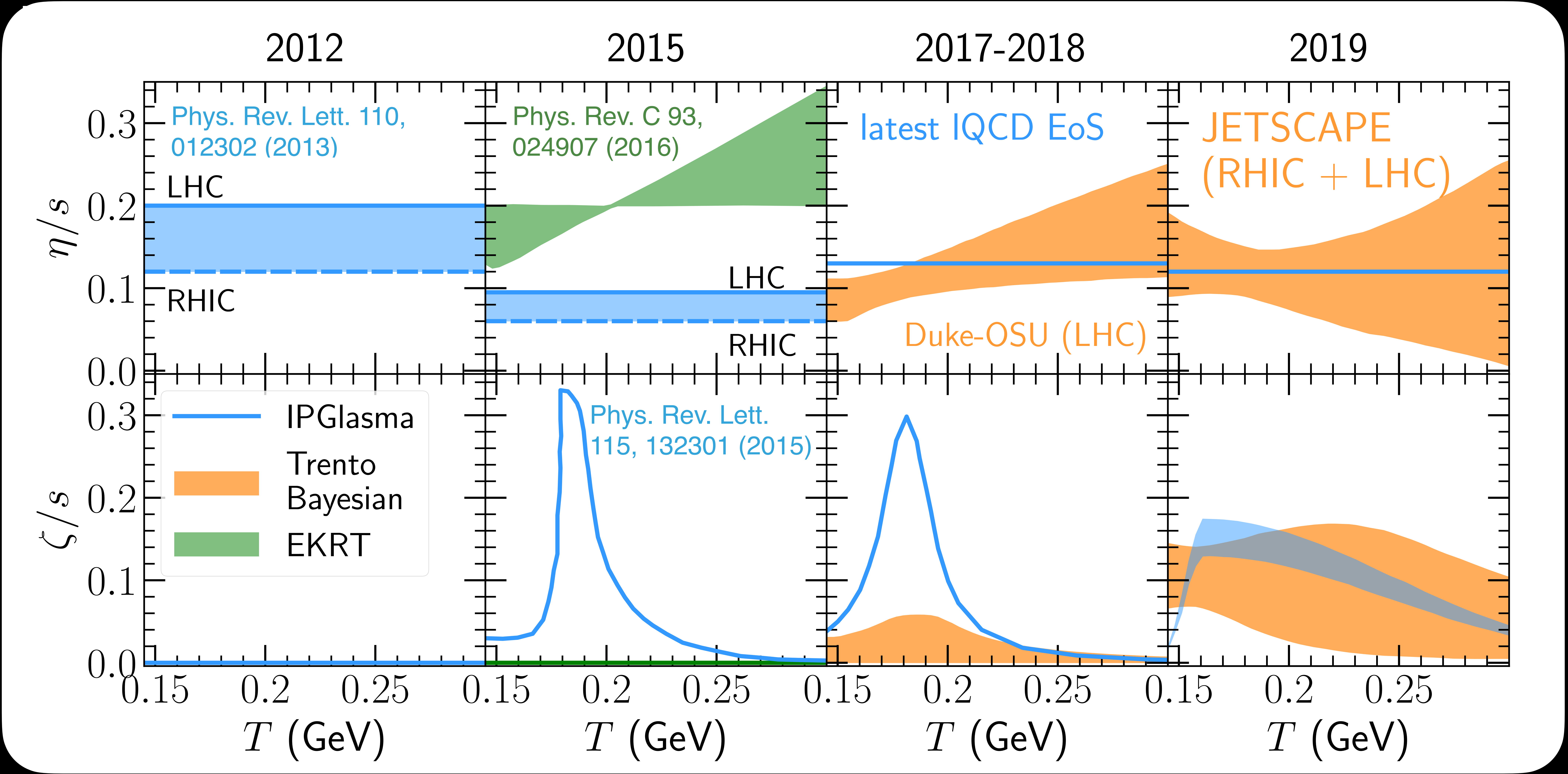
- One single set of model parameters for all types of collisions at the top RHIC and LHC energies



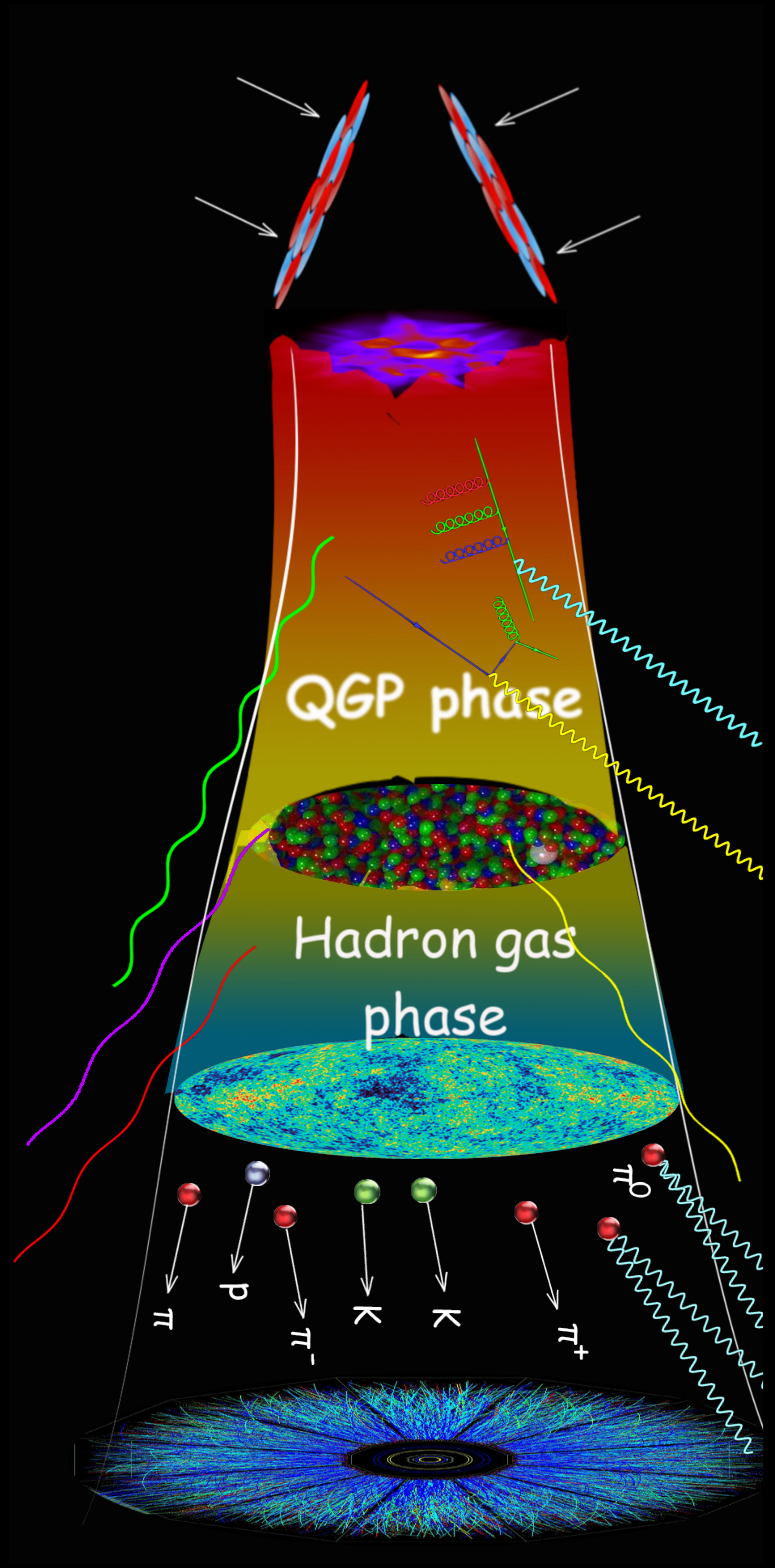
QUANTITATIVE CHARACTERIZATION OF QGP

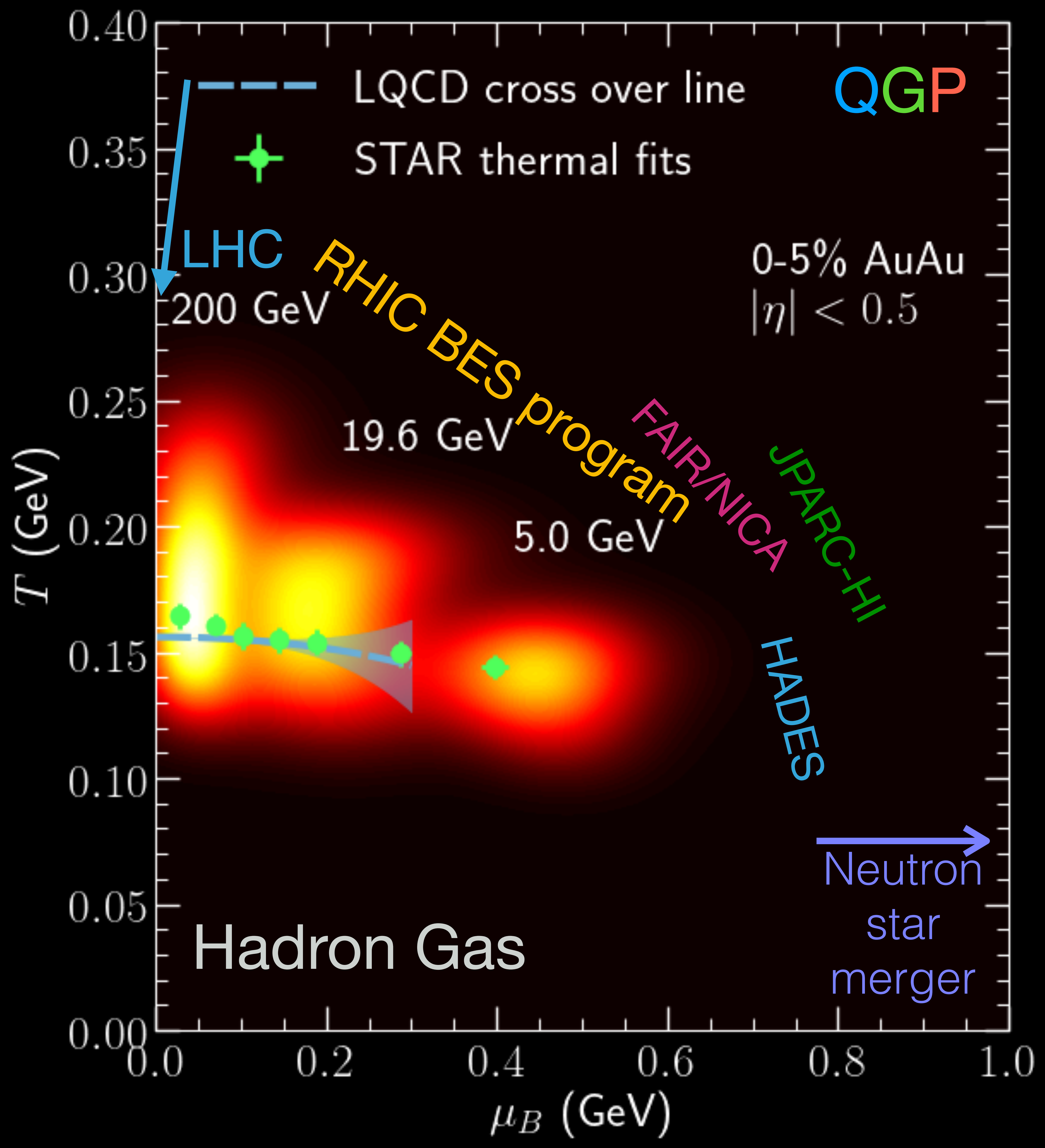
C. Shen, arXiv:2001.11858 [nucl-th]

Phenomenological constraints from top RHIC and LHC data



PROBING THE NUCLEAR MATTER PHASE DIAGRAM





- Search for a critical point & 1st order phase transition
- How does the QGP transport property change with baryon doping?

  $(\eta/s)(T, \{\mu_q\})$, $(\zeta/s)(T, \{\mu_q\})$

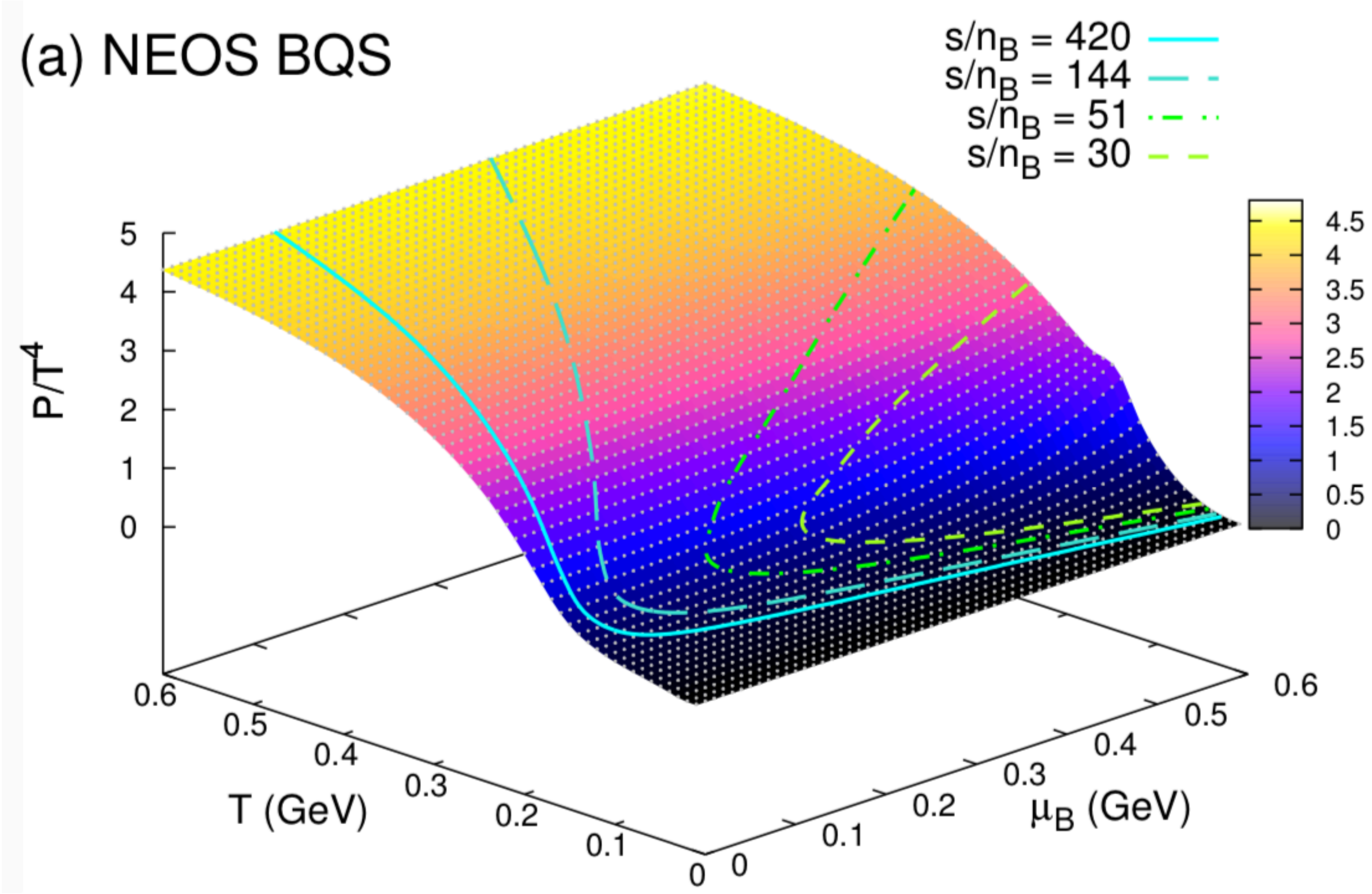
- Access to new transport phenomena

  Charge diffusion

QCD EQUATION OF STATE AT FINITE DENSITIES

M. Albright, J. Kapusta and C. Young, Phys. Rev. C90, 024915 (2014)
A. Monnai, B. Schenke and C. Shen, Phys. Rev. C100, 024907 (2019)
J. Noronha-Hostler, P. Parotto, C. Ratti and J. M. Stafford, Phys. Rev. C100, 064910 (2019)

$n_s = 0 \quad n_Q = 0.4 n_B$



Lattice QCD: Taylor expansion up to the 4th order

$$\frac{P}{T^4} = \frac{P_0}{T^4} + \sum_{l,m,n} \frac{\chi_{l,m,n}^{B,Q,S}}{l!m!n!} \left(\frac{\mu_B}{T}\right)^l \left(\frac{\mu_Q}{T}\right)^m \left(\frac{\mu_S}{T}\right)^n$$

Match to Hadron Resonance Gas model at low T

$$\frac{P}{T^4} = \frac{1}{2}[1 - f(T, \mu_J)] \frac{P_{\rm had}(T, \mu_J)}{T^4} + \frac{1}{2}[1 + f(T, \mu_J)] \frac{P_{\rm lat}(T, \mu_J)}{T^4}$$

$$f(T, \mu_B) = \tanh[(T - T_c(\mu_B)/\Delta T_c]$$

$$T_c(\mu_B) = 0.16\,\mathrm{GeV} - 0.4(0.139\,\mathrm{GeV}^{-1}\mu_B^2 + 0.053\,\mathrm{GeV}^{-3}\mu_B^4)$$

$$\Delta T_c = 0.1 T_c(\mu_B = 0)$$

QCD EQUATION OF STATE AT FINITE DENSITIES

A. Monnai, B. Schenke and C. Shen, Phys. Rev. C100, 024907 (2019)
https://sites.google.com/view/qcdneos/

- Strangeness neutrality improves the hadronic chemistry in the hybrid dynamic framework

Enabled hydrodynamic simulations at finite μ

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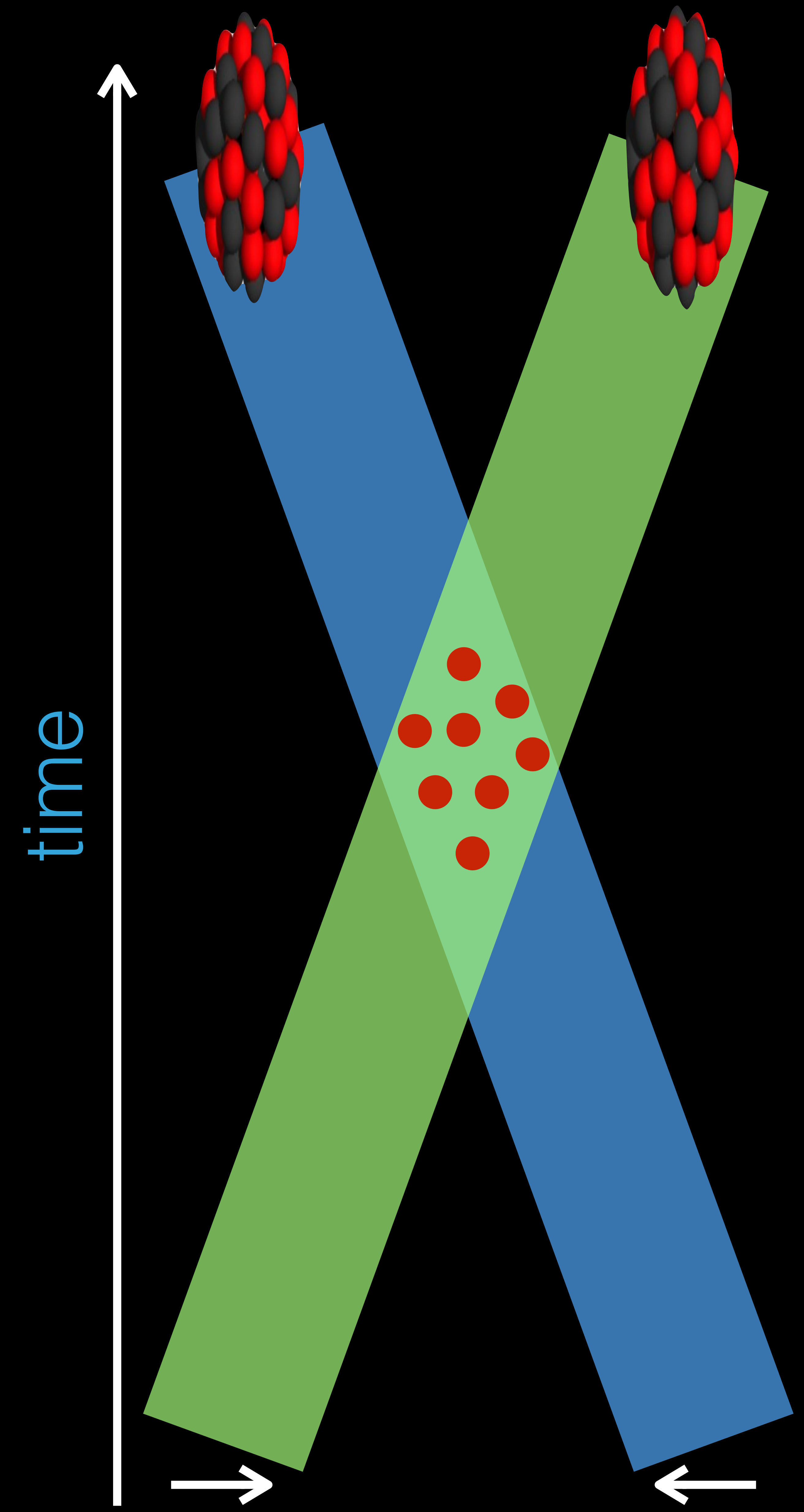
3D DYNAMICS BEYOND THE BJORKEN PARADIGM



- Geometry-Based initial conditions

  C. Shen and S. Alzhrani, Phys. Rev. C 102, 014909 (2020)

- Classical string-based initial conditions

  A. Bialas, A. Bzdak and V. Koch, Acta Phys. Polon. B49 (2018)

  C. Shen and B. Schenke, Phys.Rev. C97 (2018) 024907

- Transport model based initial conditions

  I. A. Karpenko, P. Huovinen, H. Petersen and M. Bleicher, Phys. Rev. C91 (2015) 064901

  L. Du, U. Heinz and G. Vujanovic, Nucl. Phys. A982 (2019) 407-410

- Color Glass Condensate based models

  M. Li and J. Kapusta, Phys. Rev. C 99, 014906 (2019)

  L. D. McLerran, S. Schlichting and S. Sen, Phys. Rev. D 99, 074009 (2019)

  M. Martinez, M. D. Sievert, D. E. Wertepny and J. Noronha-Hostler, arXiv:1911.10272 + arXiv:1911.12454 [nucl-th]

- Holographic approach at intermediate coupling

  M. Attems, et al., Phys.Rev.Lett. 121 (2018), 261601

A MINIMUM EXTENSION TO 3D INITIAL CONDITIONS

C. Shen and S. Alzhrani, Phys. Rev. C 102, 014909 (2020)

- Impose energy and momentum conservation on the Glauber geometry
  Assumption: All of the energy and momentum is deposited into the medium

$$\begin{aligned} E(x,y) &= [T_A(x,y) + T_B(x,y)] m_N \cosh(y_{\rm beam}) \\ &\equiv M(x,y)\cosh(y_{\rm CM}(x,y)) \\ P_z(x,y) &= [T_A(x,y) - T_B(x,y)] m_N \sinh(y_{\rm beam}) \\ &\equiv M(x,y)\sinh(y_{\rm CM}(x,y)). \end{aligned}$$

$$y_{\rm CM}(x,y) = \mathrm{arctanh}\left[\frac{T_A - T_B}{T_A + T_B}\tanh(y_{\rm beam})\right]$$

$$M(x,y) = m_N\sqrt{T_A^2 + T_B^2 + 2T_A T_B \cosh(2y_{\rm beam})}$$

- Assume Bjorken flow for the velocity profile $u^\mu_{\rm init} = (\cosh(\eta_s), 0, 0, \sinh(\eta_s))$
- Energy density given by a longitudinal flux-tube profile

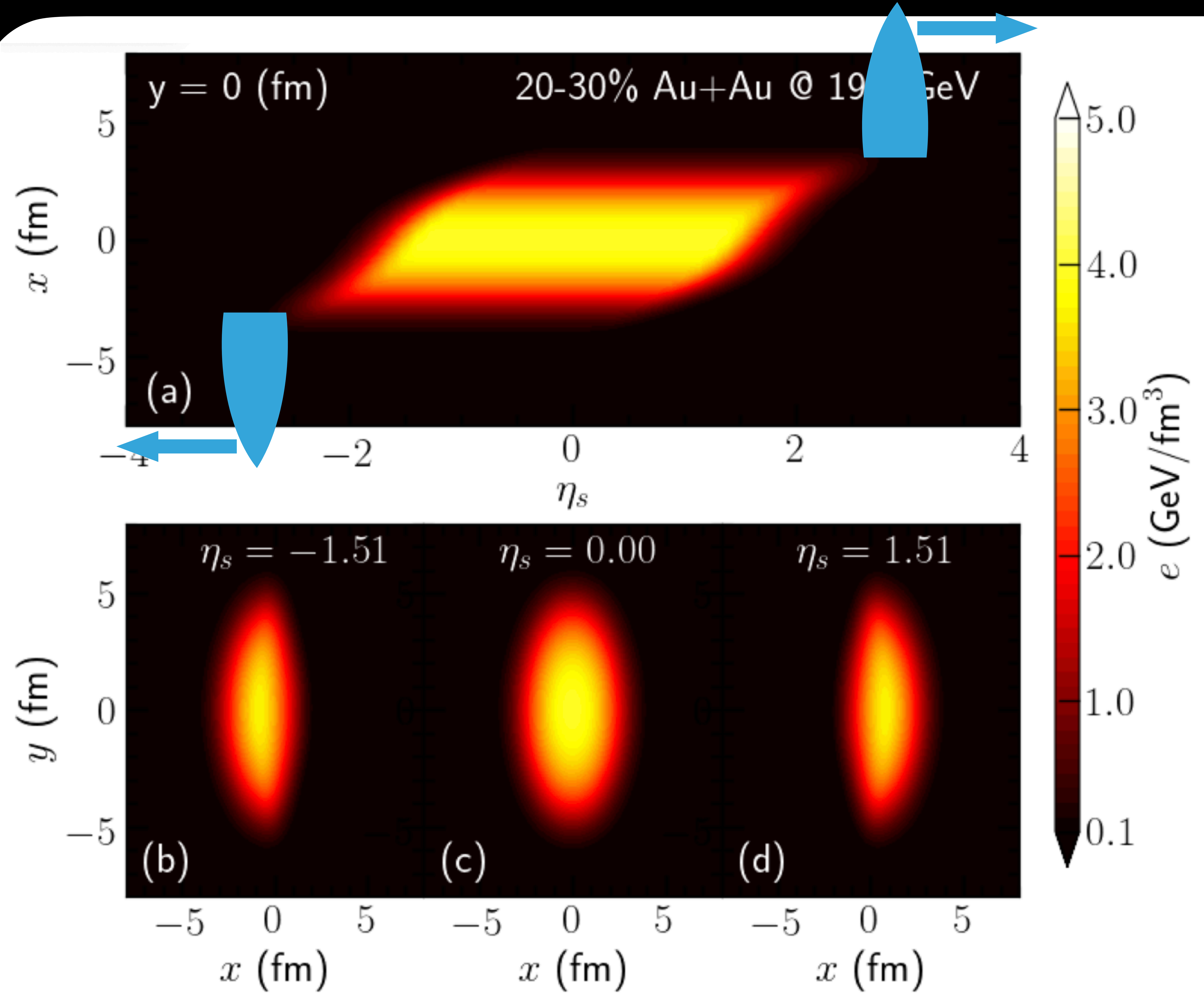
$$\begin{aligned} e(x,y,\eta_s;y_{\rm CM}) &= \mathcal{N}_e(x,y) \\ &\times \exp\left[-\frac{(|\eta_s - y_{\rm CM}| - \eta_0)^2}{2\sigma_\eta^2}\theta(|\eta_s - y_{\rm CM}| - \eta_0)\right] \end{aligned}$$

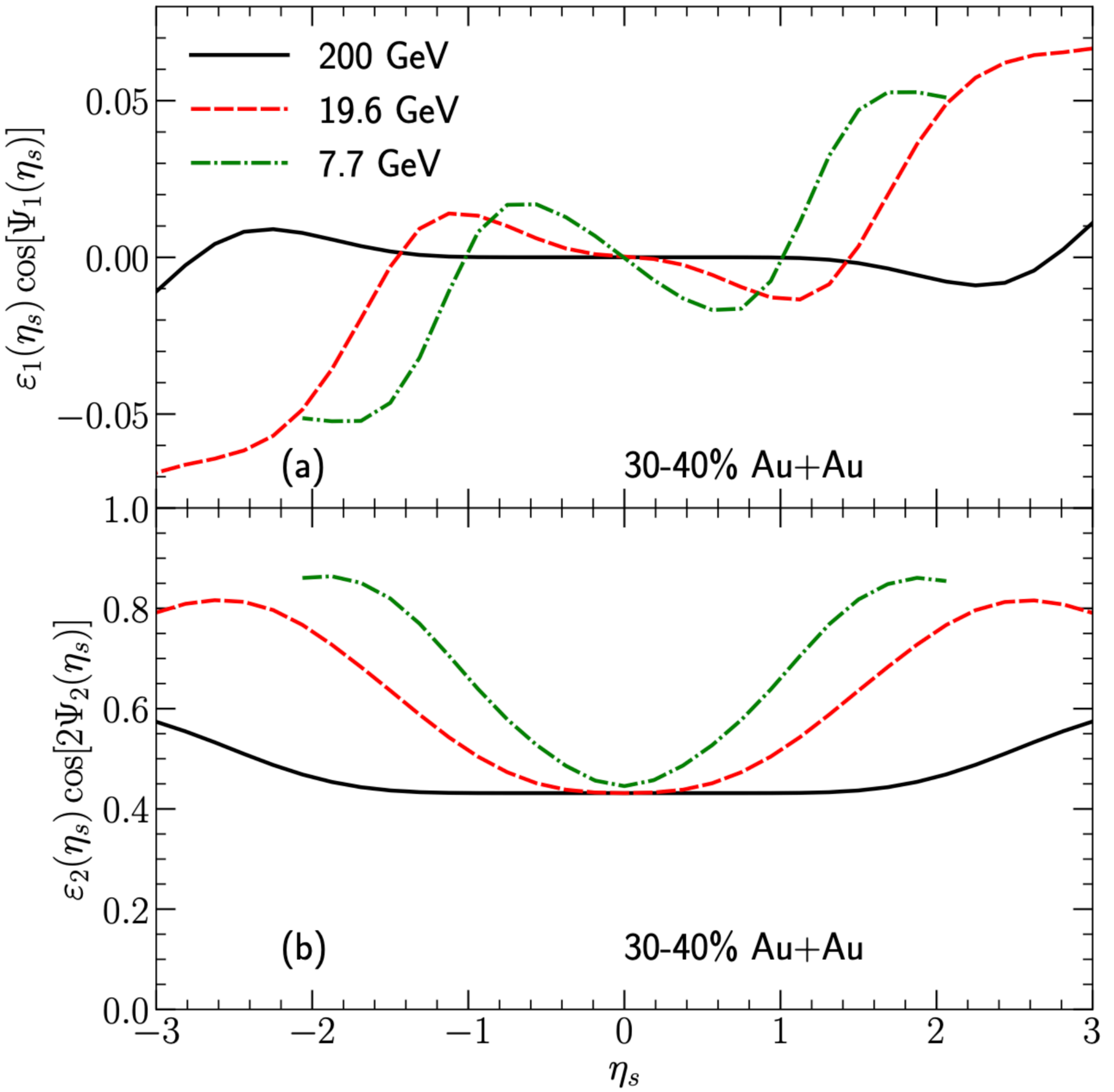
where $\mathcal{N}_e(x,y) \propto M(x,y)$

- For $\sqrt{s} \geq 5\,\mathrm{GeV}$, the local energy density $e(x,y) \propto \sqrt{T_A T_B}$

A MINIMUM EXTENSION TO 3D INITIAL CONDITIONS

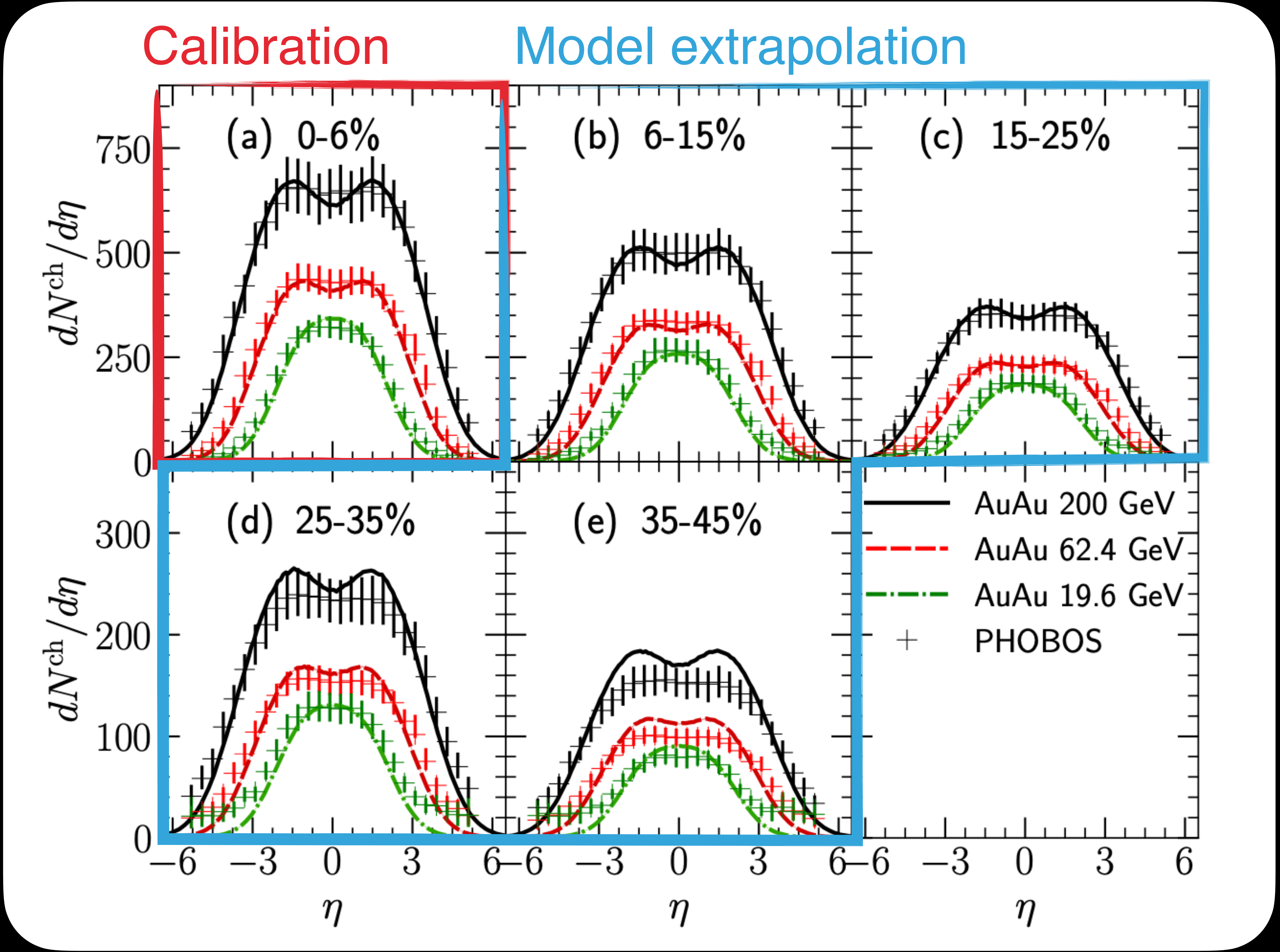
C. Shen and S. Alzhrani, Phys. Rev. C 102, 014909 (2020)

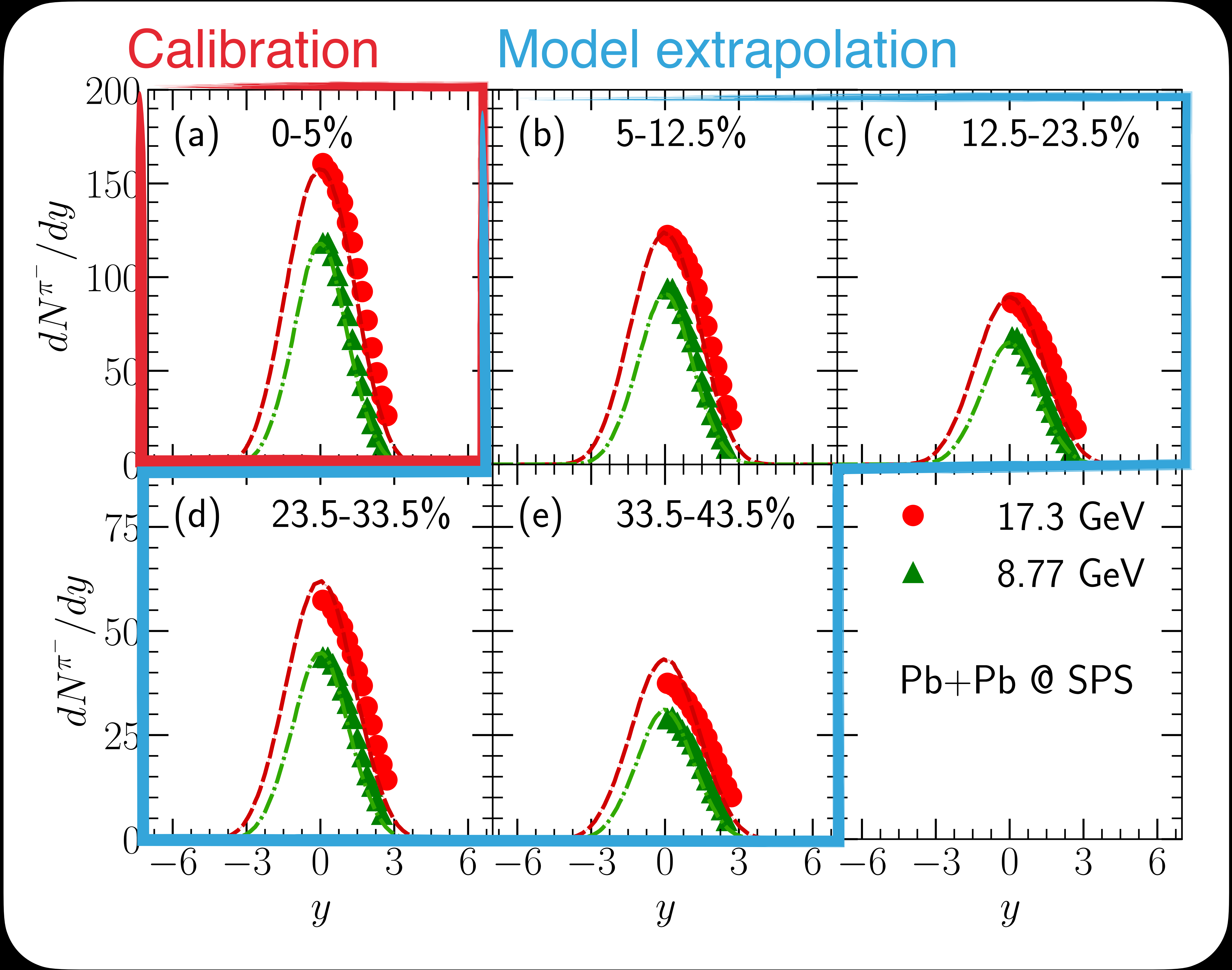




PARTICLE PRODUCTIONS AT RHIC BES AND SPS

C. Shen and S. Alzhrani, Phys. Rev. C 102, 014909 (2020)

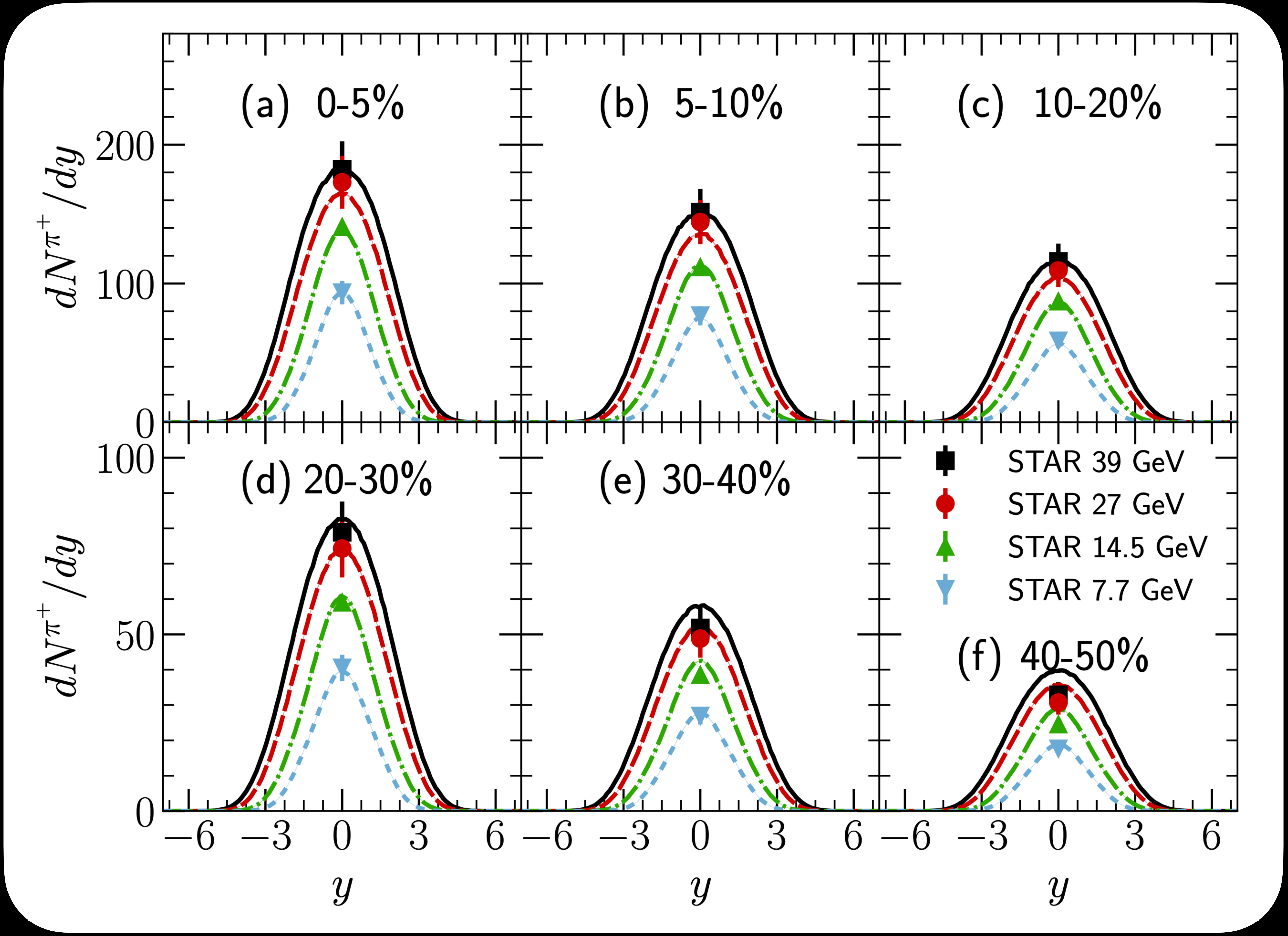




- Centrality dependence of particle production can be well reproduced

PARTICLE RAPIDITY DISTRIBUTION AT RHIC BES

C. Shen and S. Alzhrani, Phys. Rev. C 102, 014909 (2020)



- With limited data from RHIC BES I, we make predictions for the rapidity dependence of particle productions

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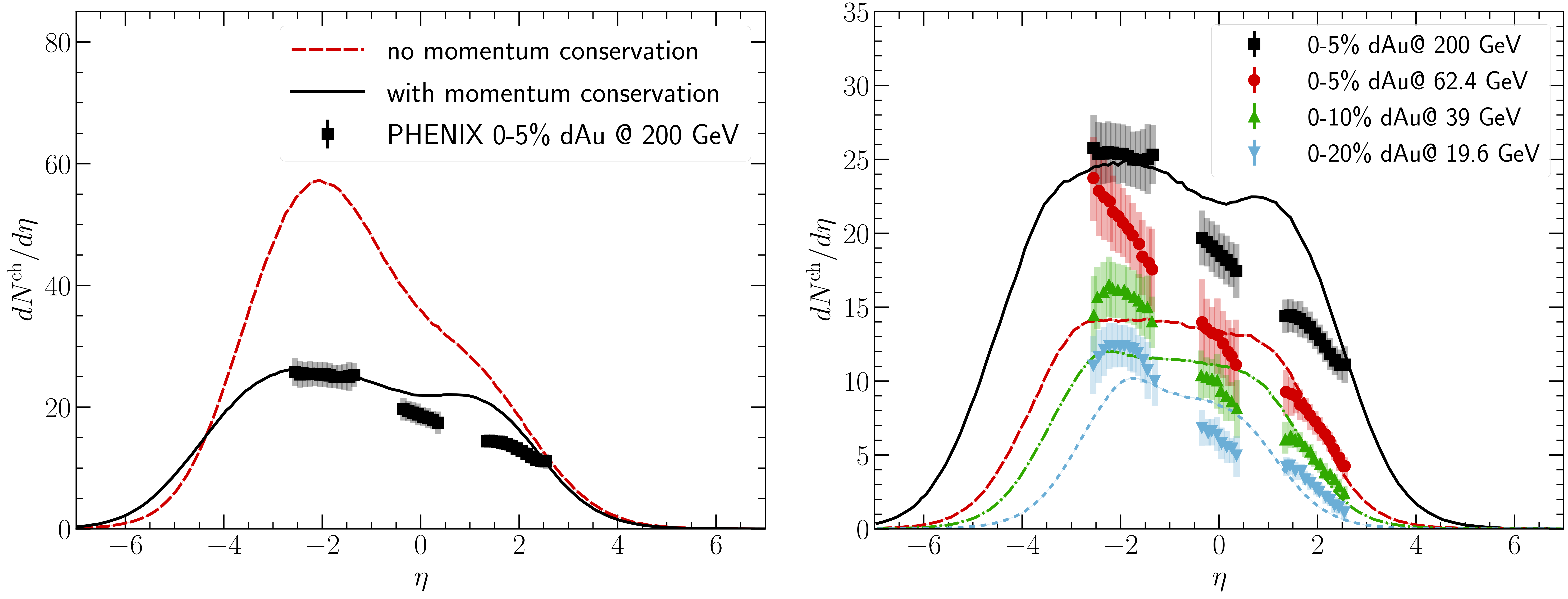
C. Shen and S. Alzhrani, Phys. Rev. C 102, 014909 (2020)



- Imposing energy-momentum conservation is extremely important for making predictions for asymmetric d+Au collisions

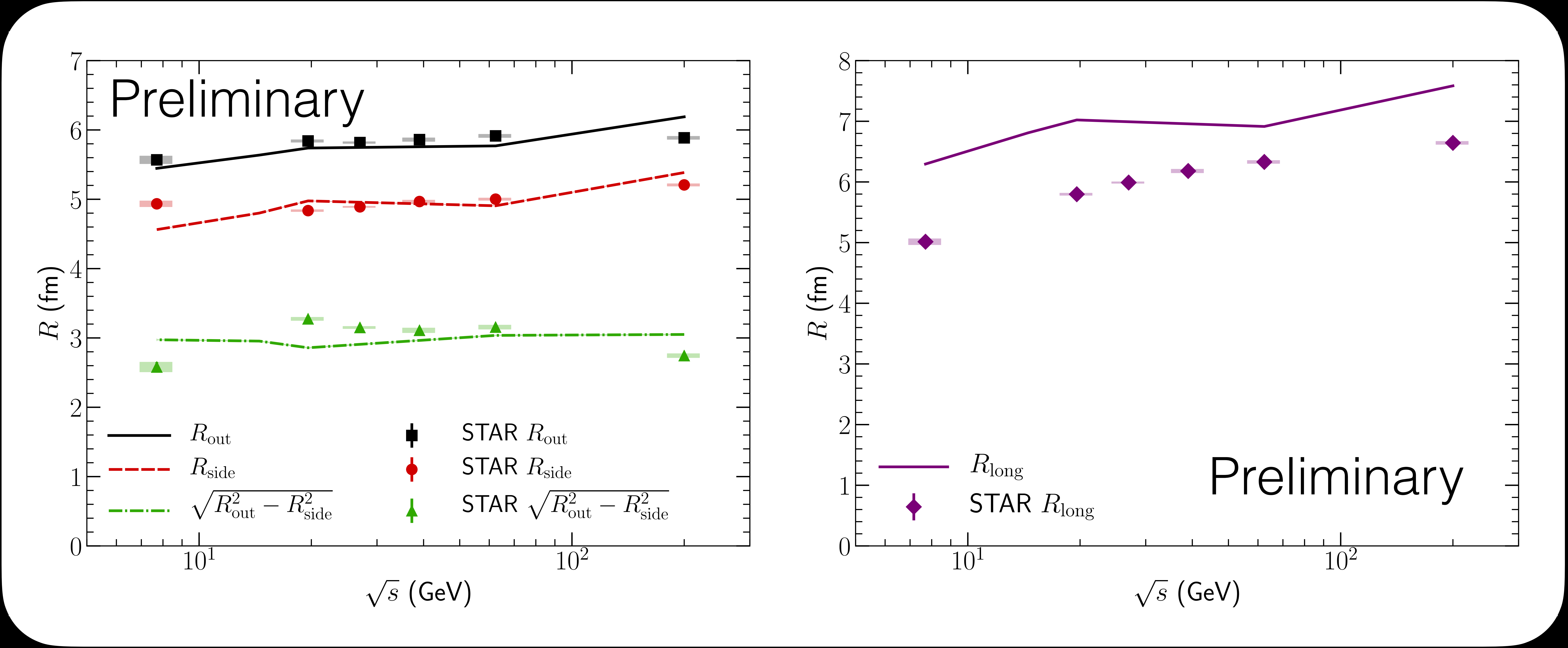
ELLIPTIC FLOW AT RHIC BES AND SHEAR VISCOSITY

I. A. Karpenko, P. Huovinen, H. Petersen and M. Bleicher, Phys. Rev. C91 (2015) 064901
C. Shen and S. Alzhrani, Phys. Rev. C 102, 014909 (2020)

- The rapidity and centrality dependence of v_2 can set strong constraints on the $(\eta/s)(T, \mu_B)$

HBT RADII AT THE RHIC BES

Based on C. Shen and S. Alzhrani, Phys. Rev. C 102, 014909 (2020)

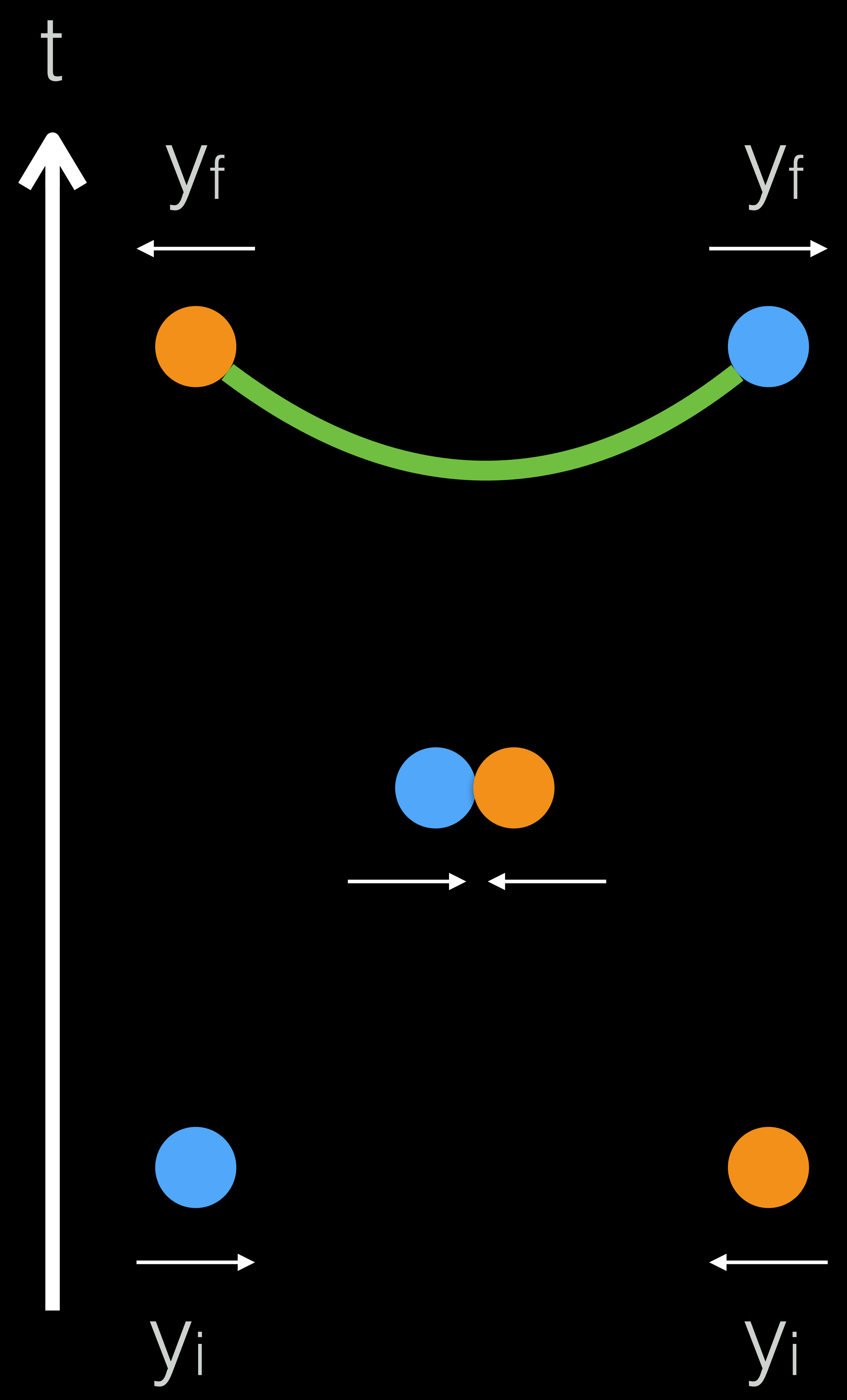


- The model reasonably describe the collision energy dependence of R_{out} and R_{side}; R_{long} is overestimated and need further investigation
- $\sqrt{R_{out}^2 - R_{side}^2}$ is flat vs. $\sqrt{s}$

THE 3D MC-GLAUBER + STRING MODEL

C. Shen and B. Schenke, Phys.Rev. C97 (2018) 024907

Pair rest frame



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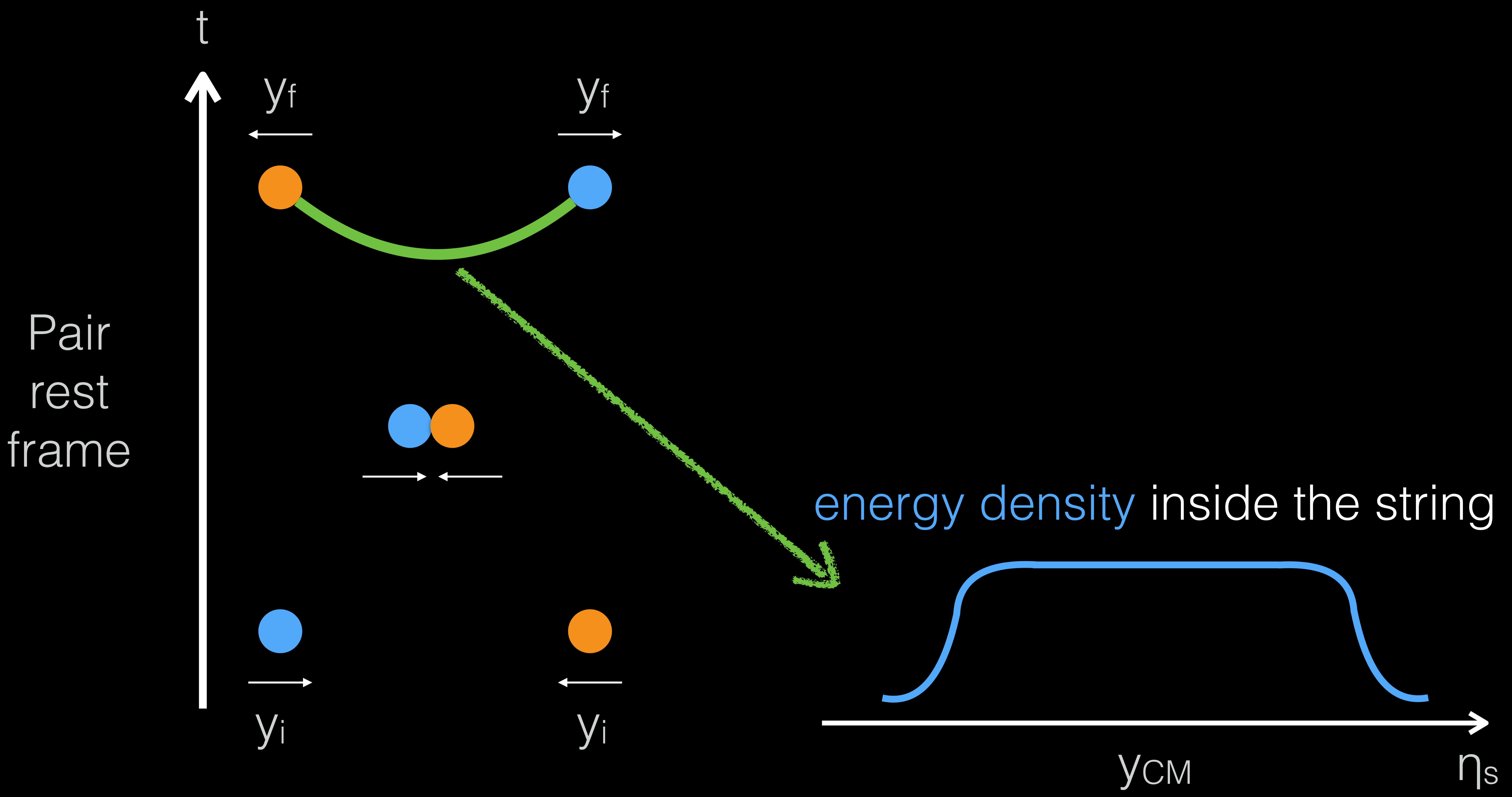

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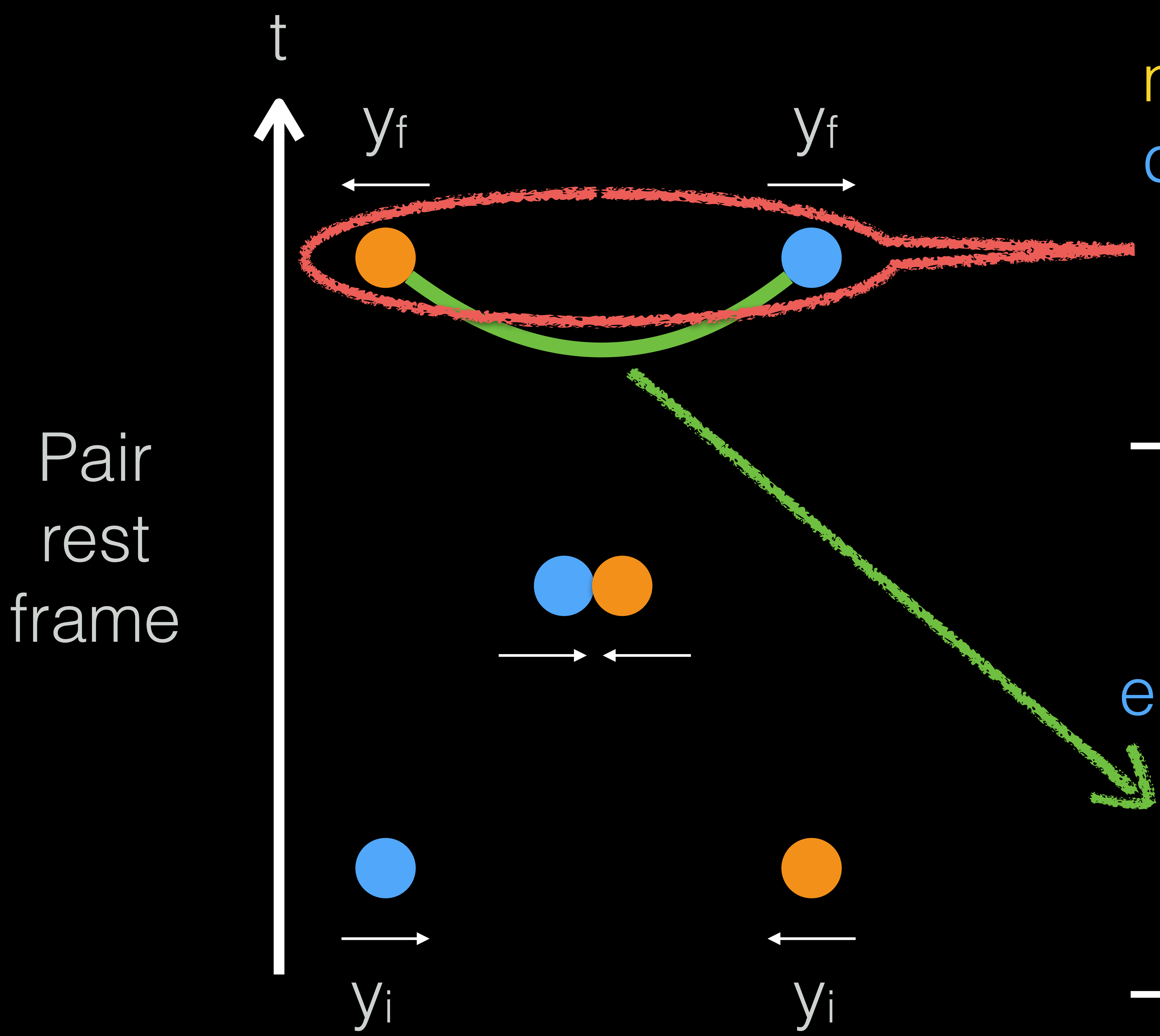
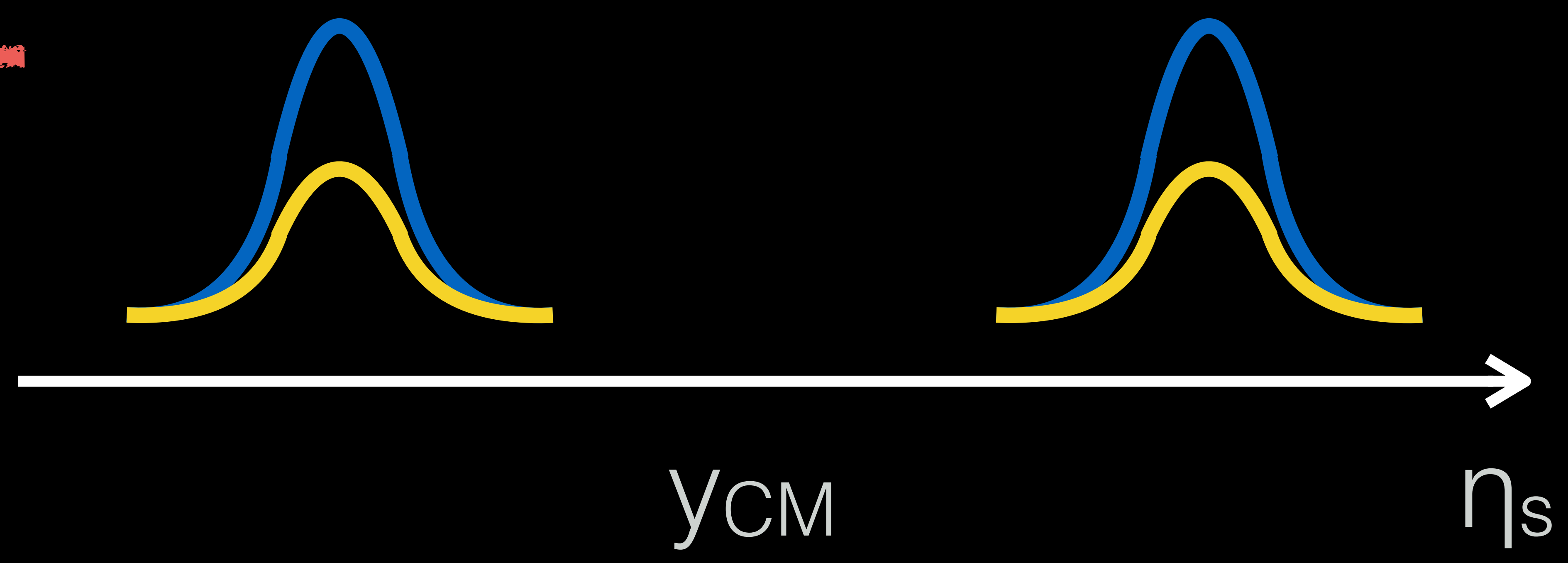
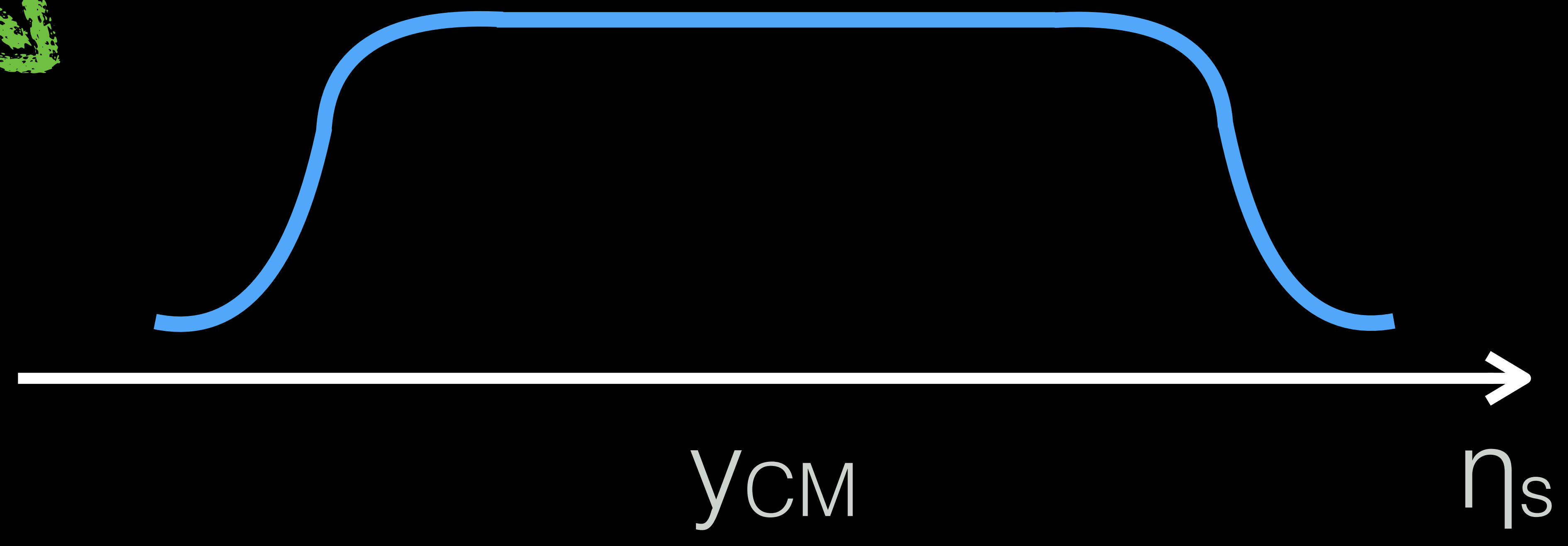


net baryon density and energy density at the string ends



energy density inside the string



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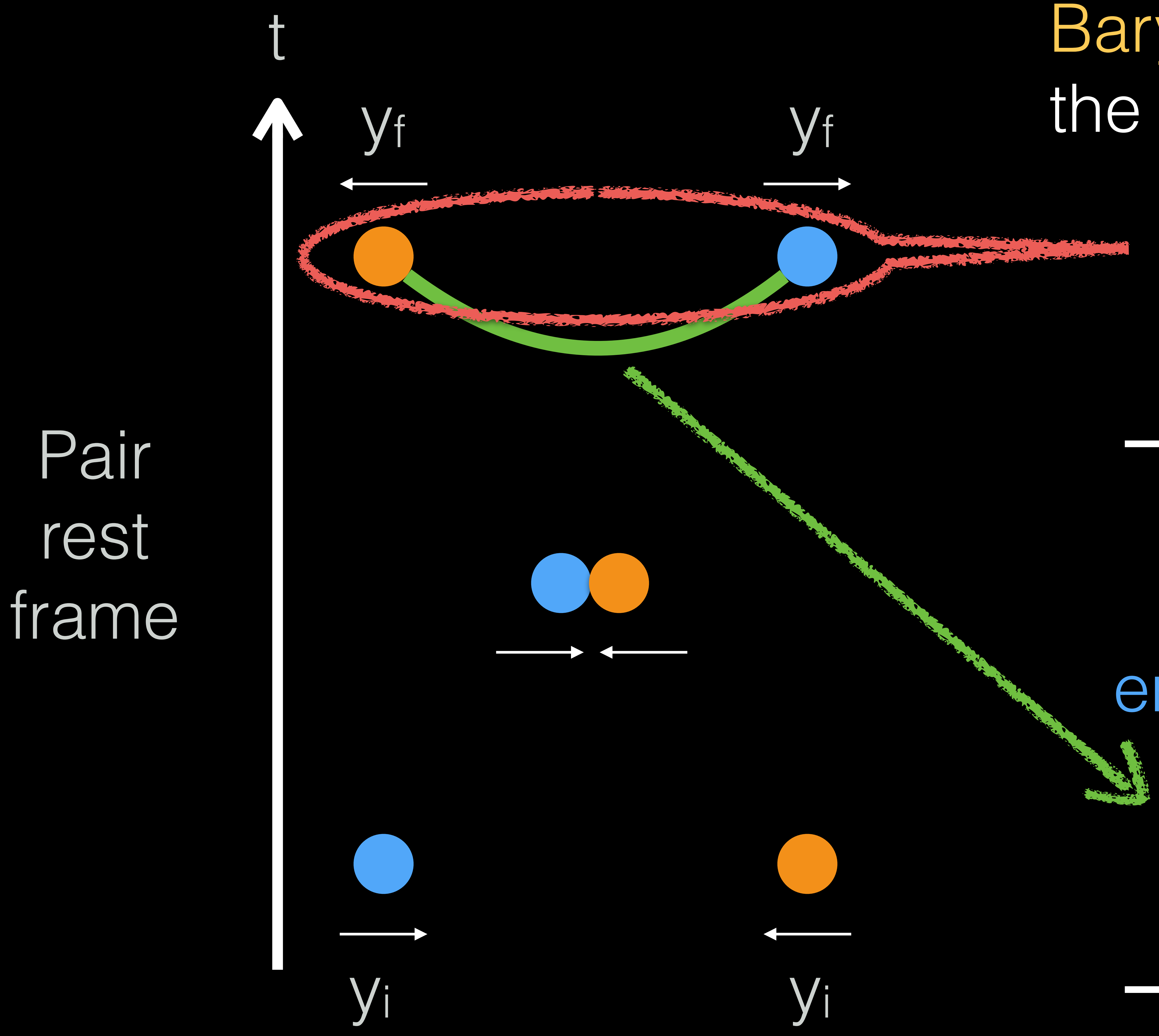
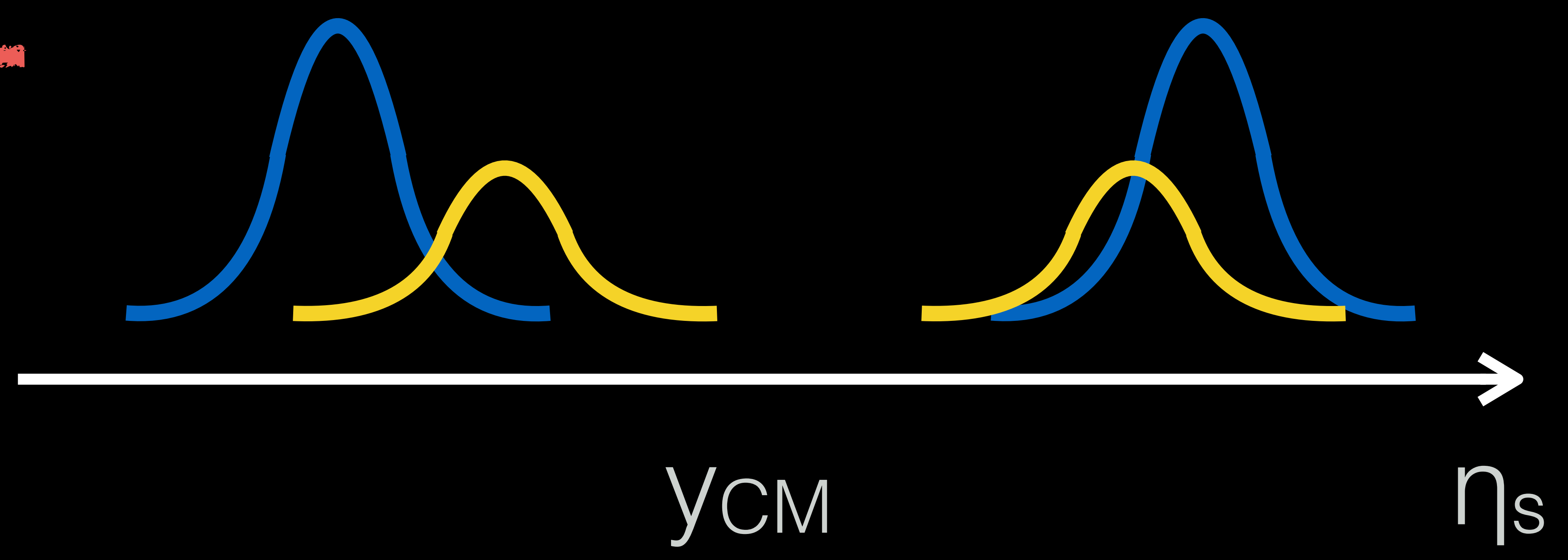
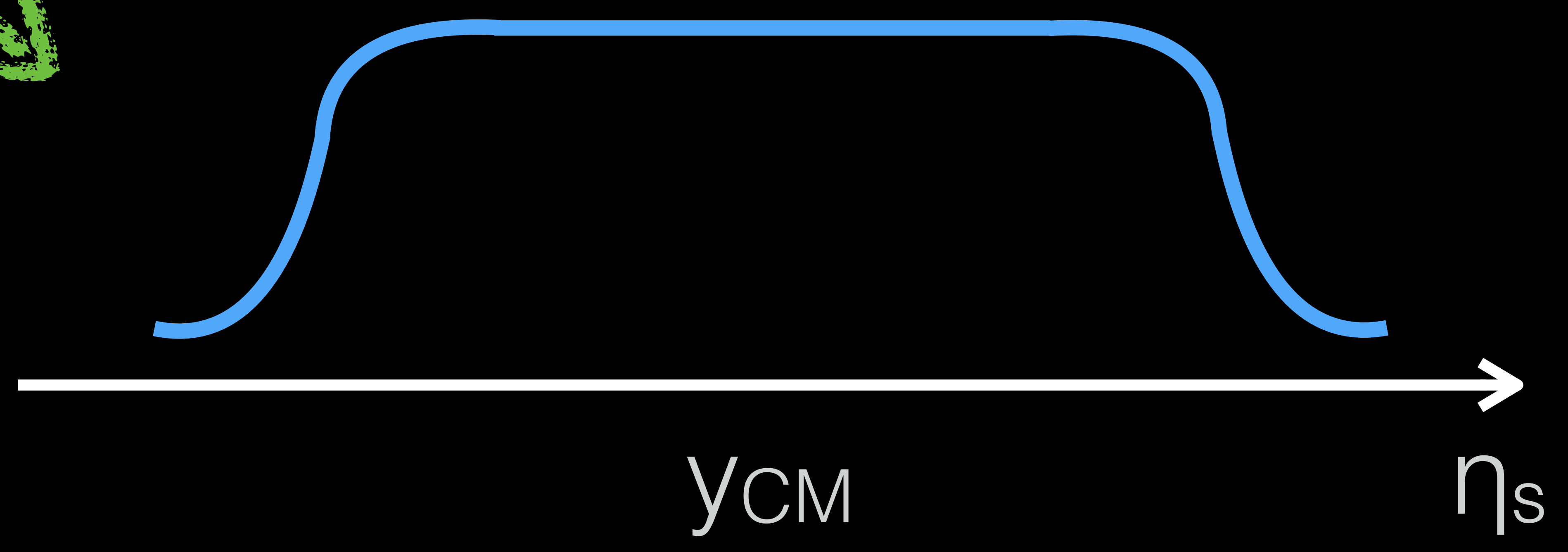


Baryon density are deposited at the string ends or string junctions

D. Kharzeev, Phys. Lett. B 378, 238 (1996)



energy density inside the string



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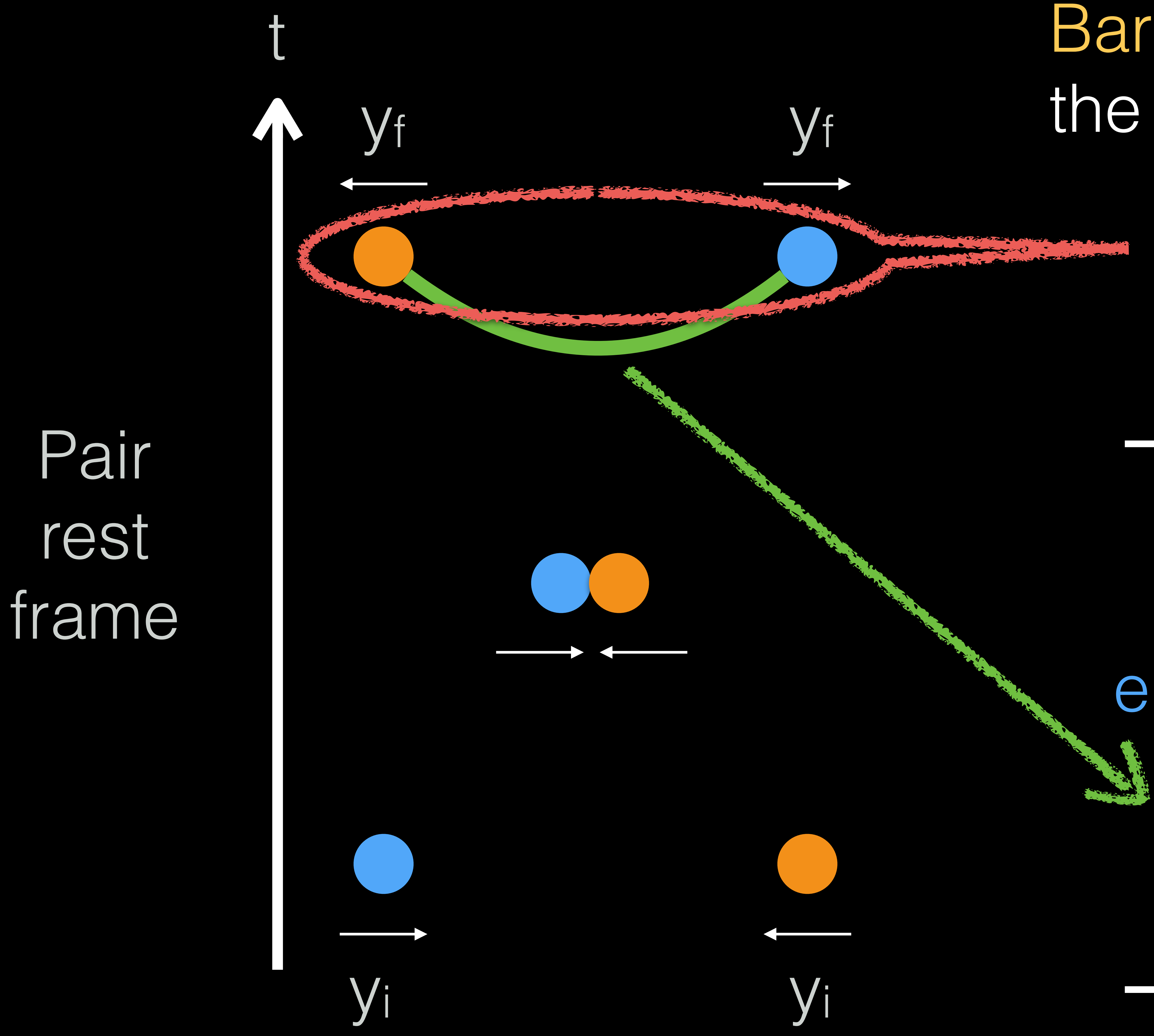

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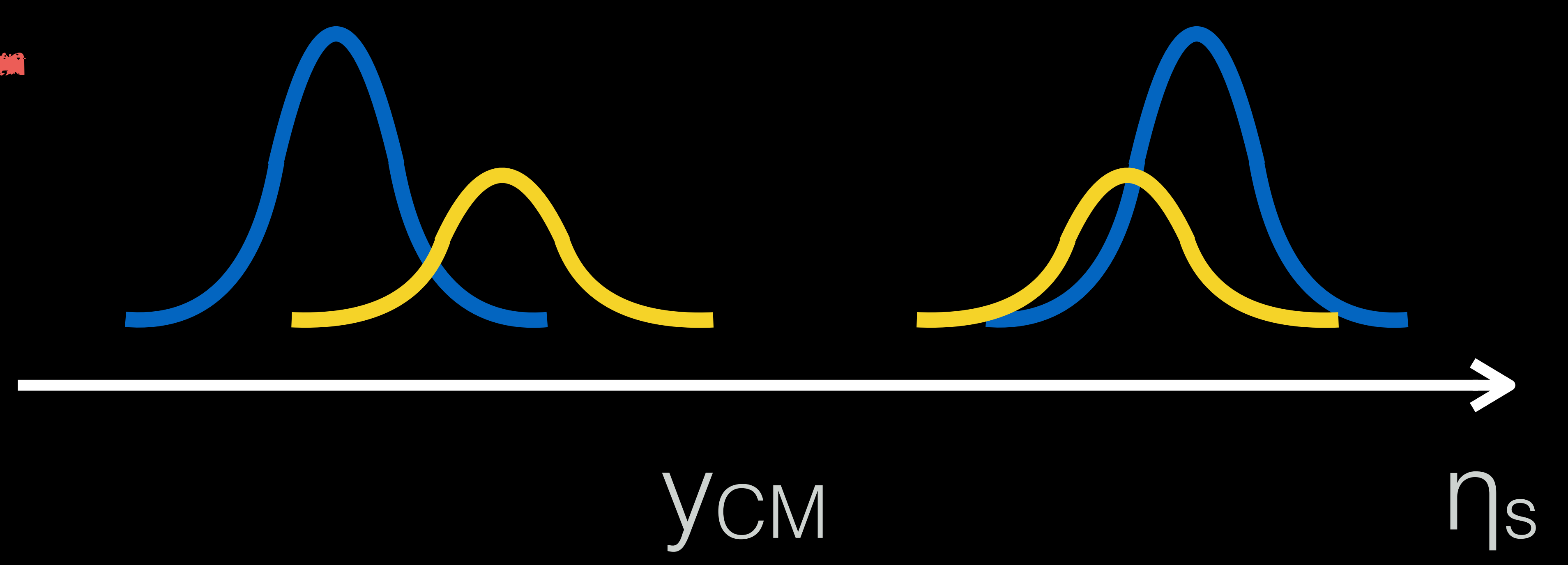
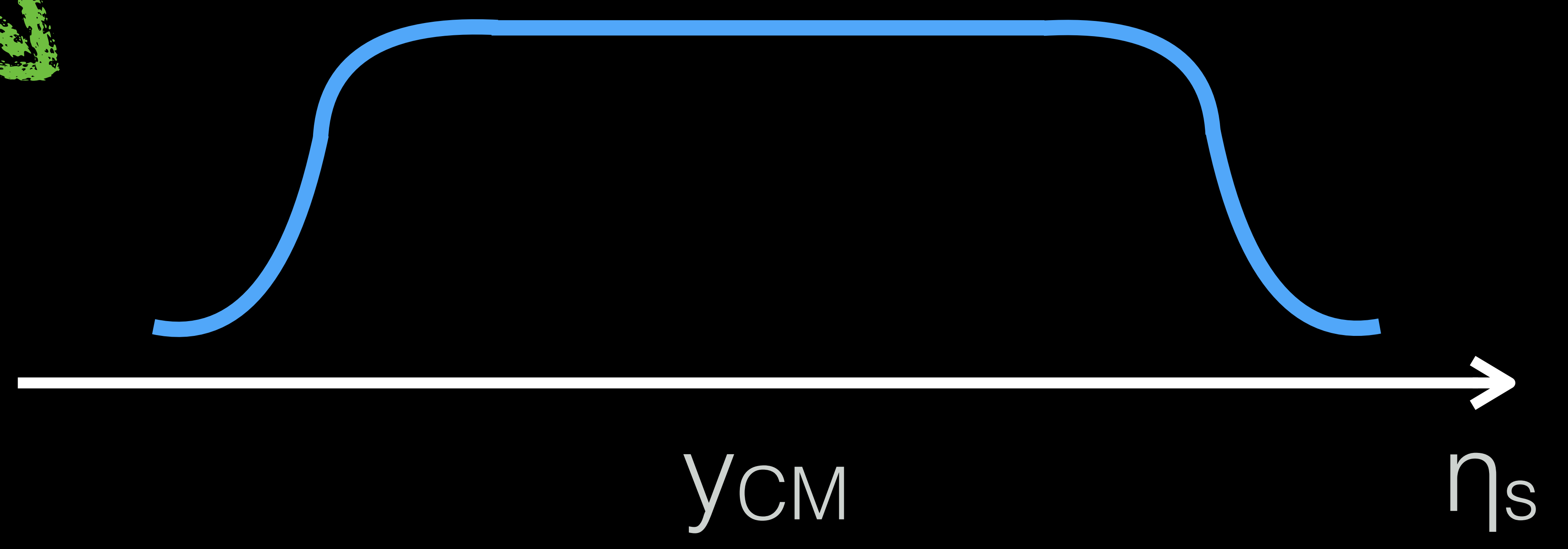
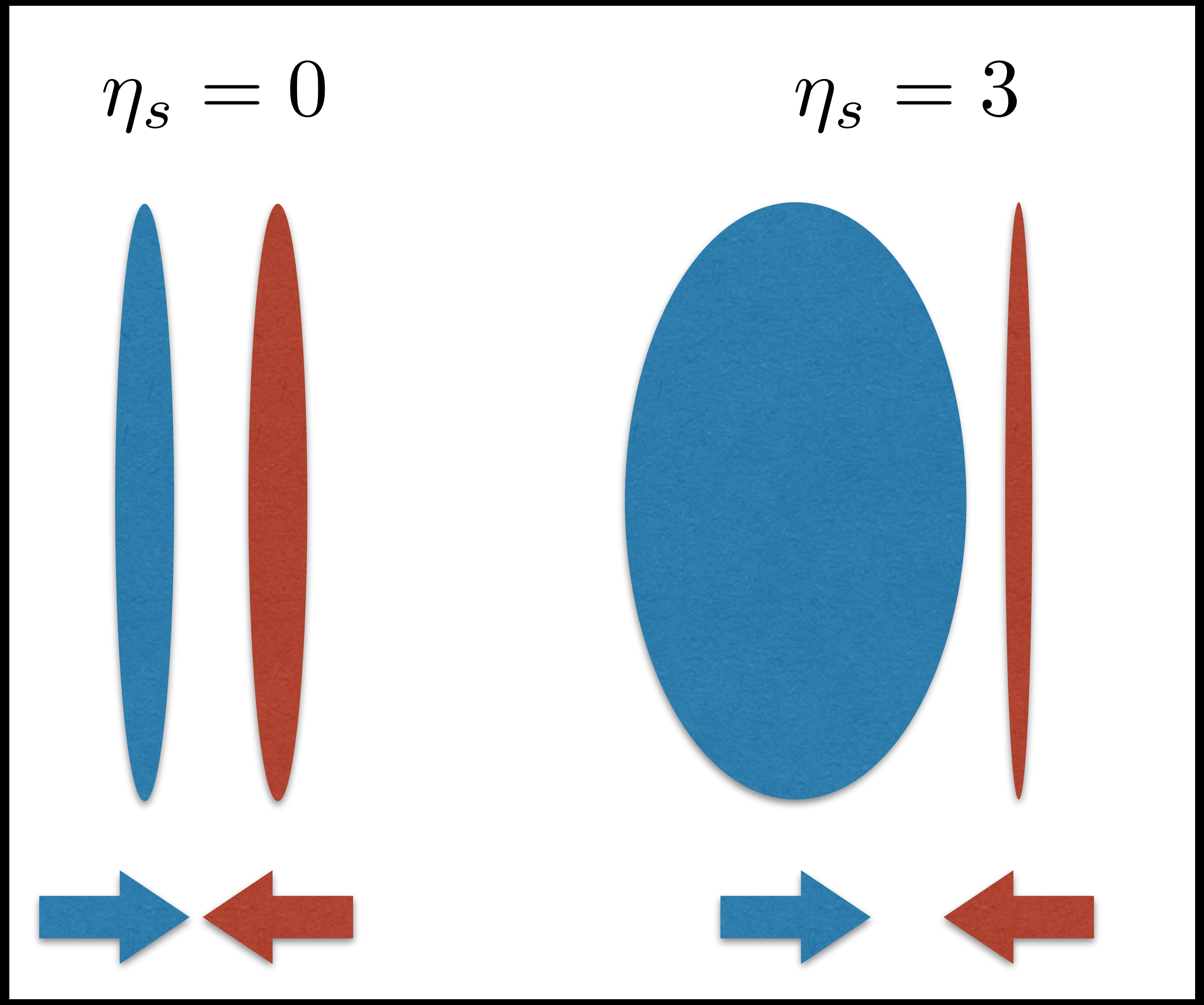


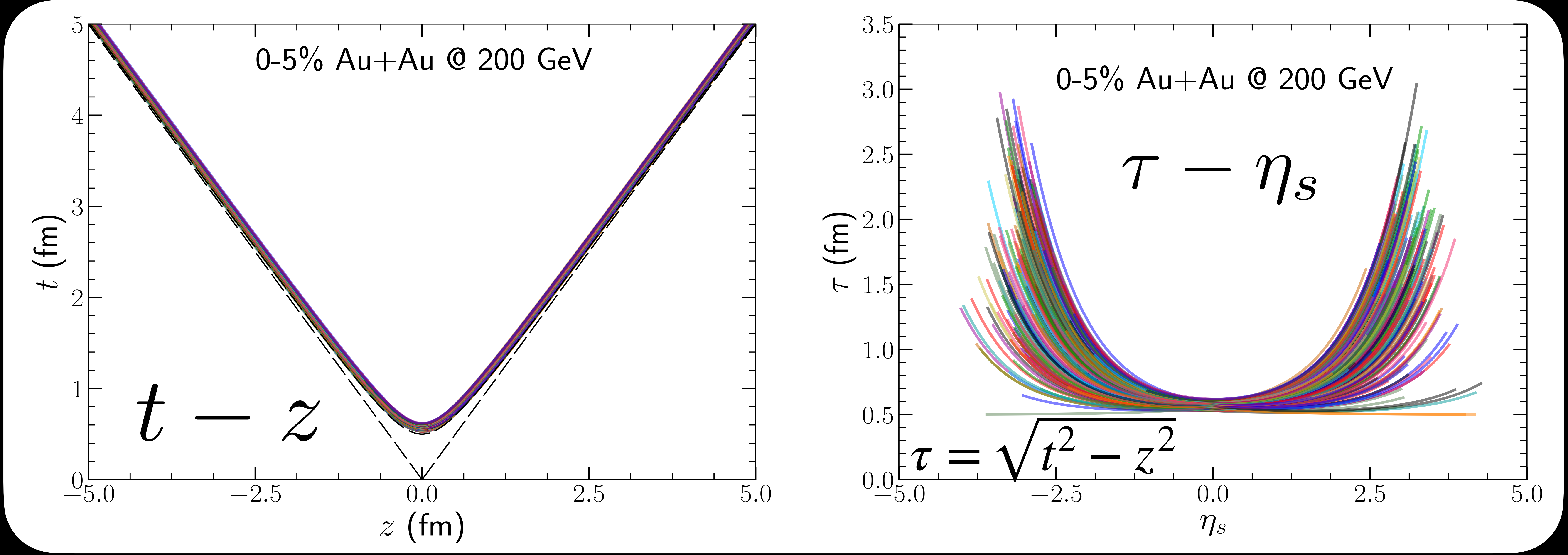
energy density inside the string

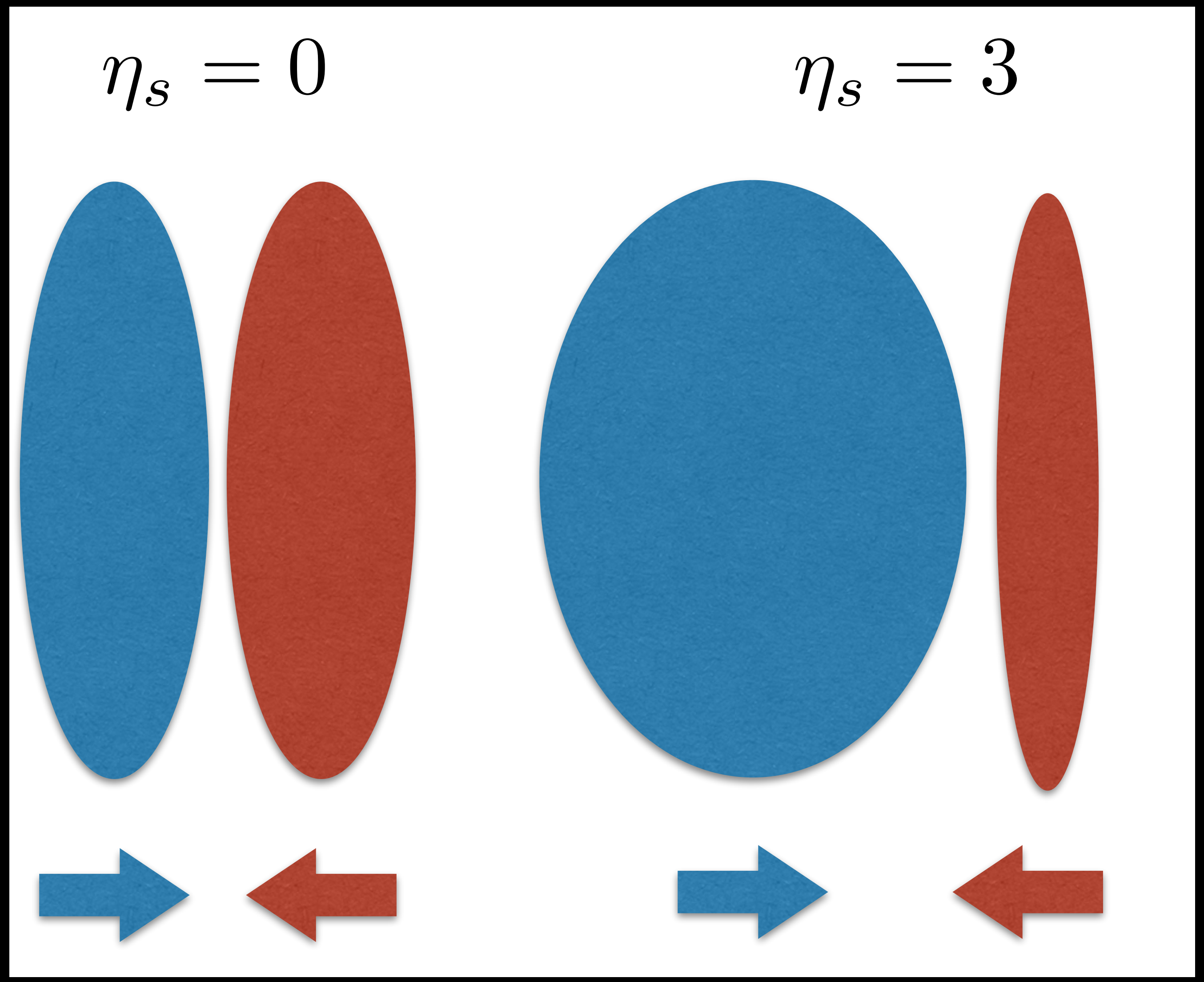


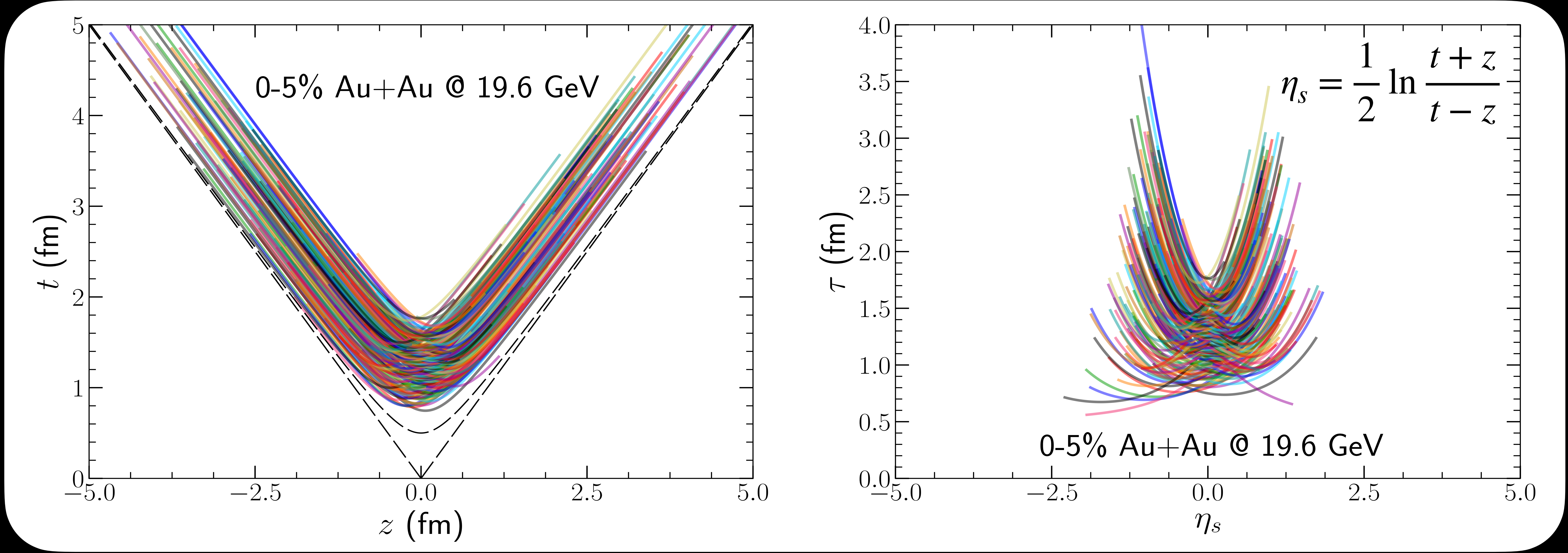
Imposed conservation for energy, momentum, and net baryon density

STRINGS' SPACE-TIME DISTRIBUTION



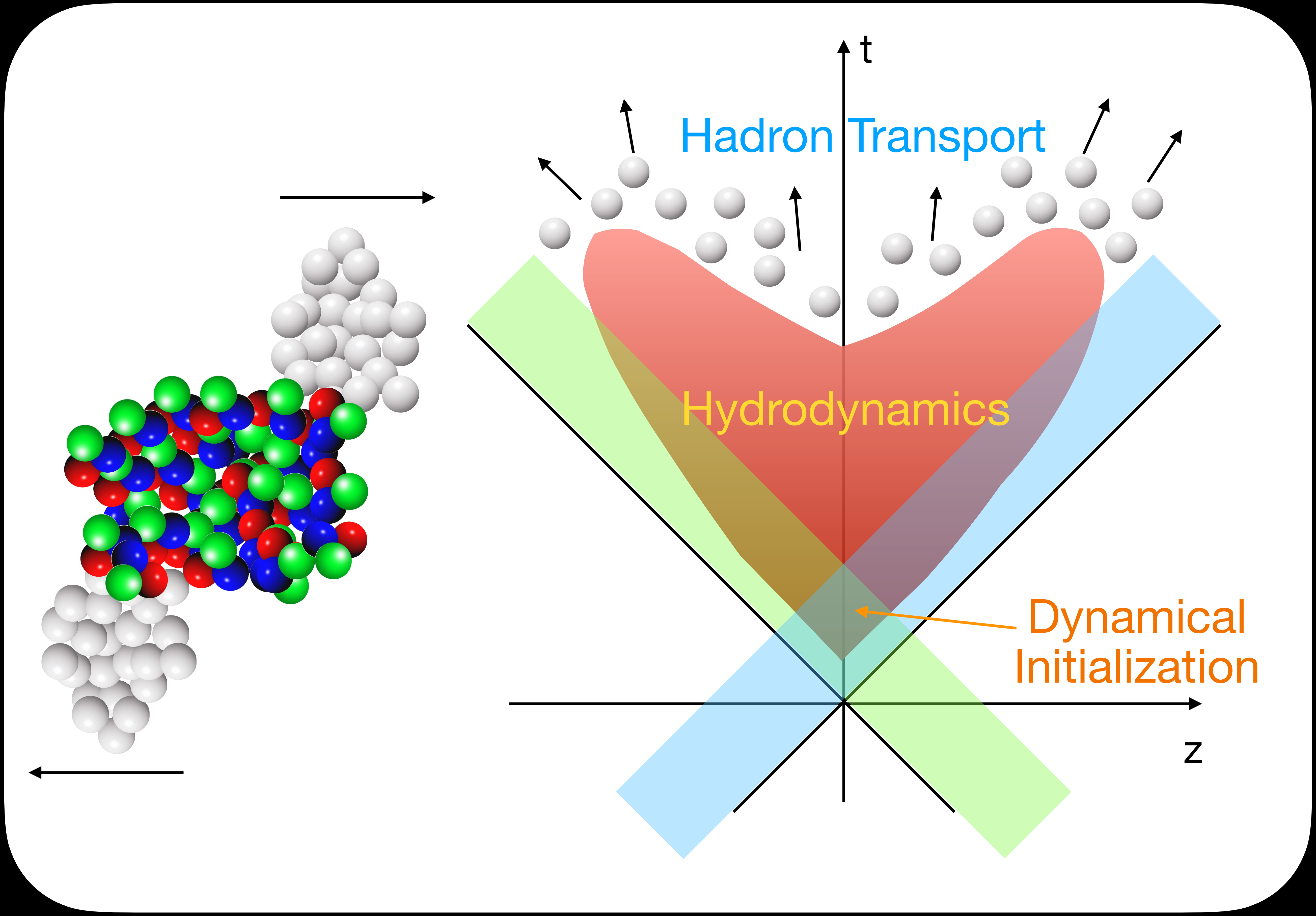






HYDRODYNAMICS WITH SOURCES

Energy-momentum current and net baryon density are fed into hydrodynamic simulation as source terms



$$\partial_\mu T^{\mu\nu} = J^\nu_{\mathrm{source}}$$

$$\partial_\mu J^\mu = \rho_{\mathrm{source}}$$

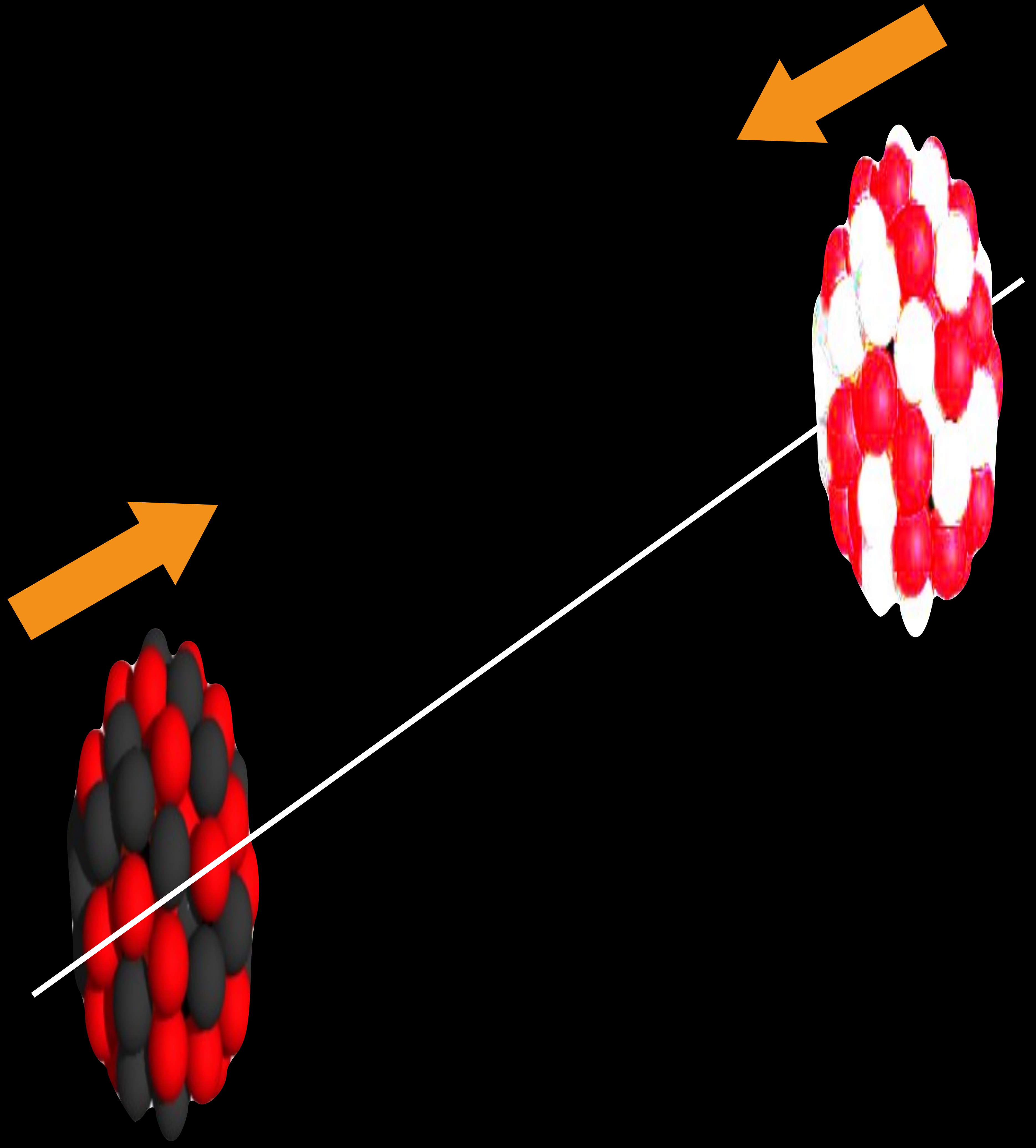
M. Okai, K. Kawaguchi, Y. Tachibana, and T. Hirano, Phys. Rev. C95, 054914 (2017)

C. Shen and B. Schenke, Phys. Rev. C97 (2018) 024907

L. Du, U. Heinz and G. Vujanovic, Nucl. Phys. A982 (2019) 407-410

HYDRODYNAMICAL EVOLUTION WITH SOURCES

C. Shen and B. Schenke, Phys. Rev. C97 (2018) 024907



$$\sqrt{s_{\mathrm{NN}}} = 19.6\,\mathrm{GeV}$$

HYDRODYNAMICAL EVOLUTION WITH SOURCES

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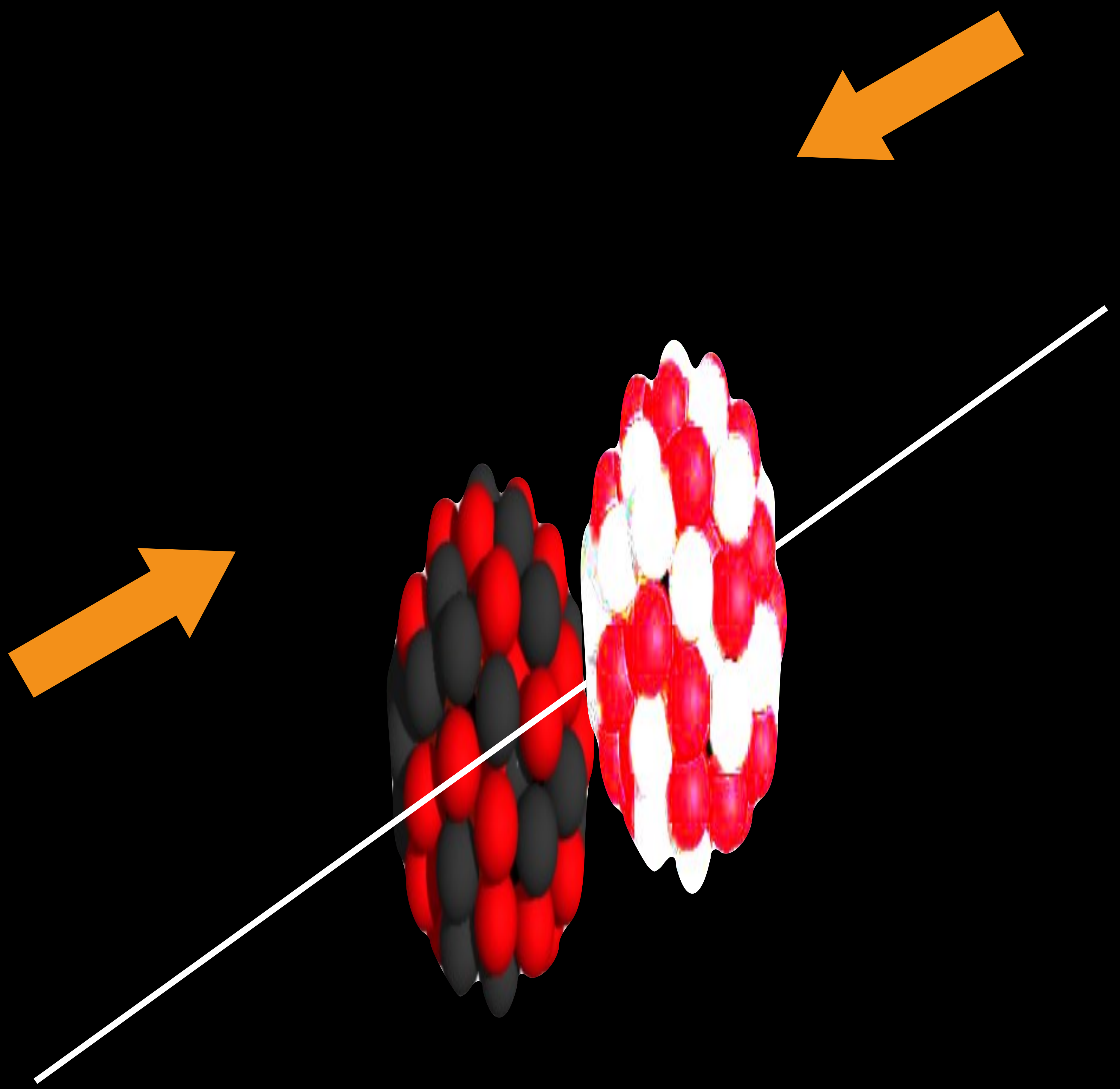

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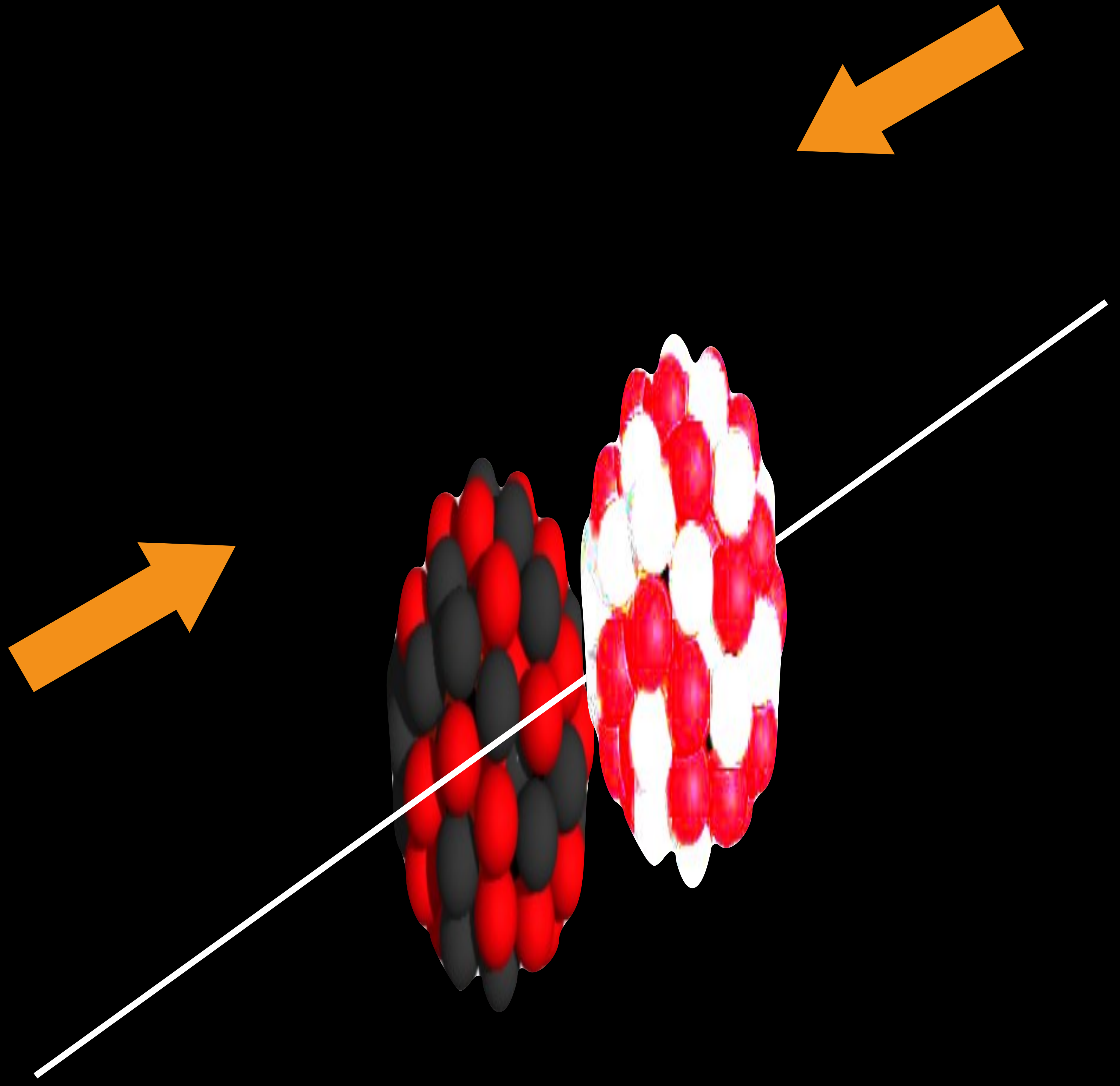

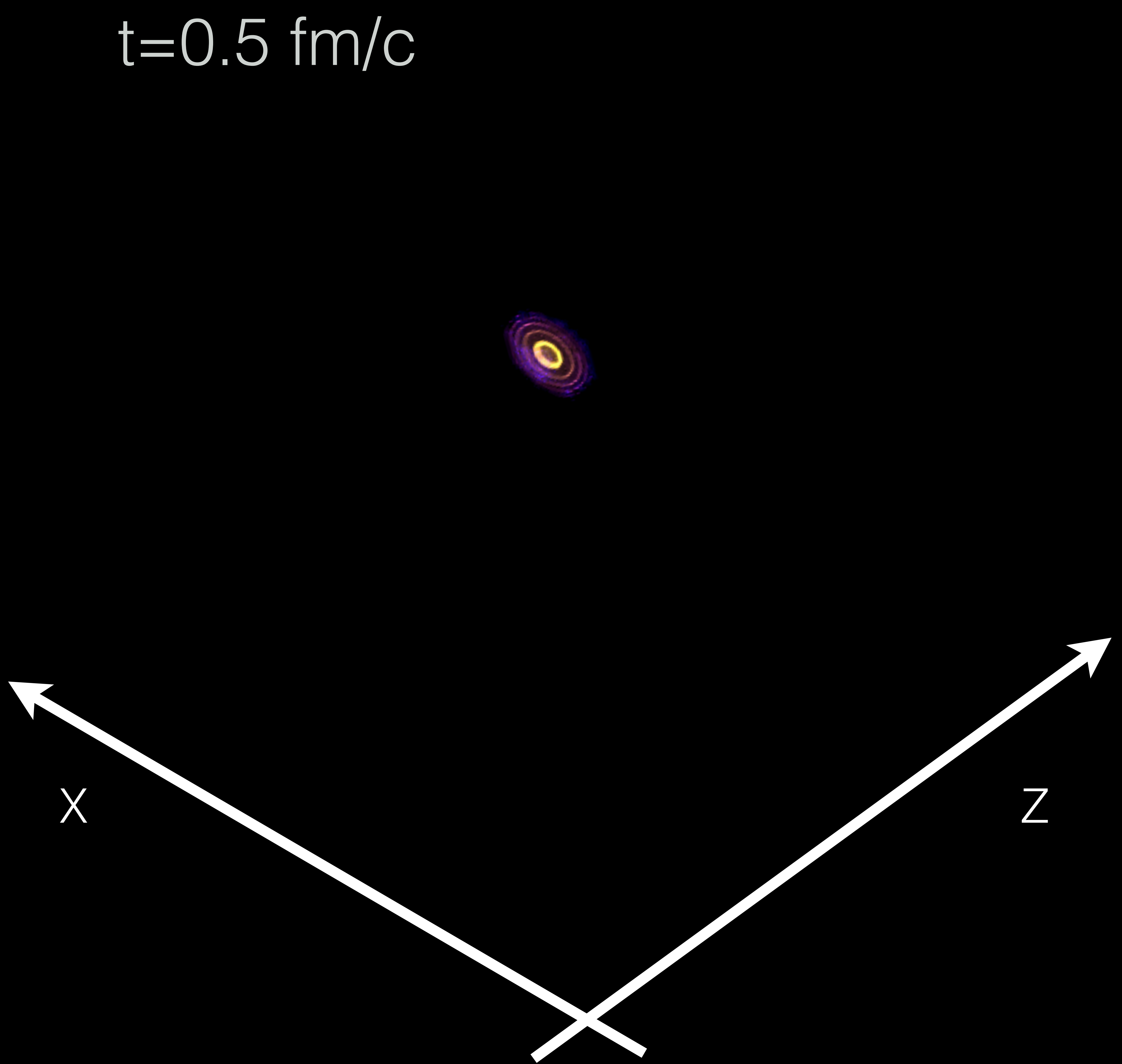

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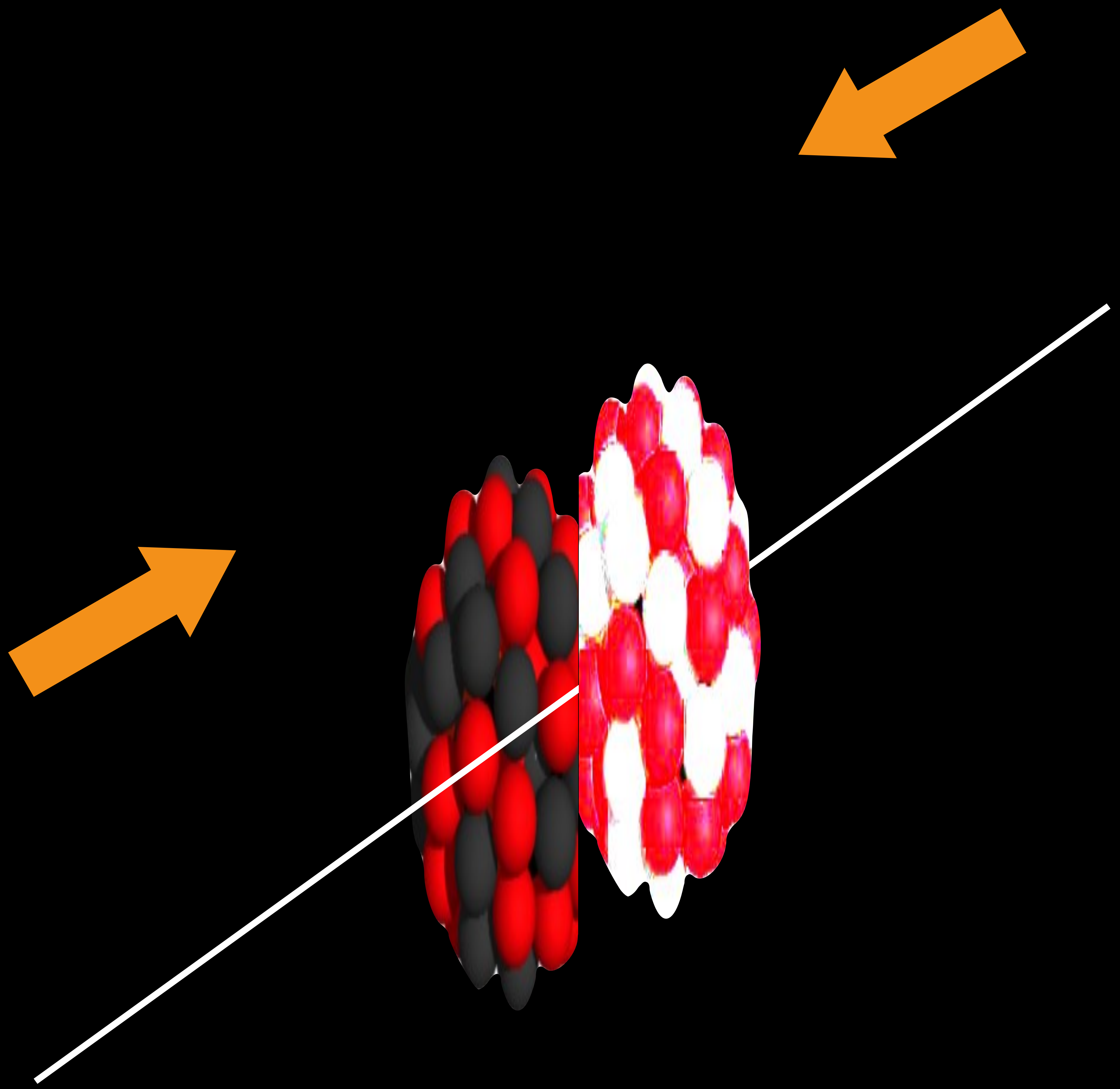
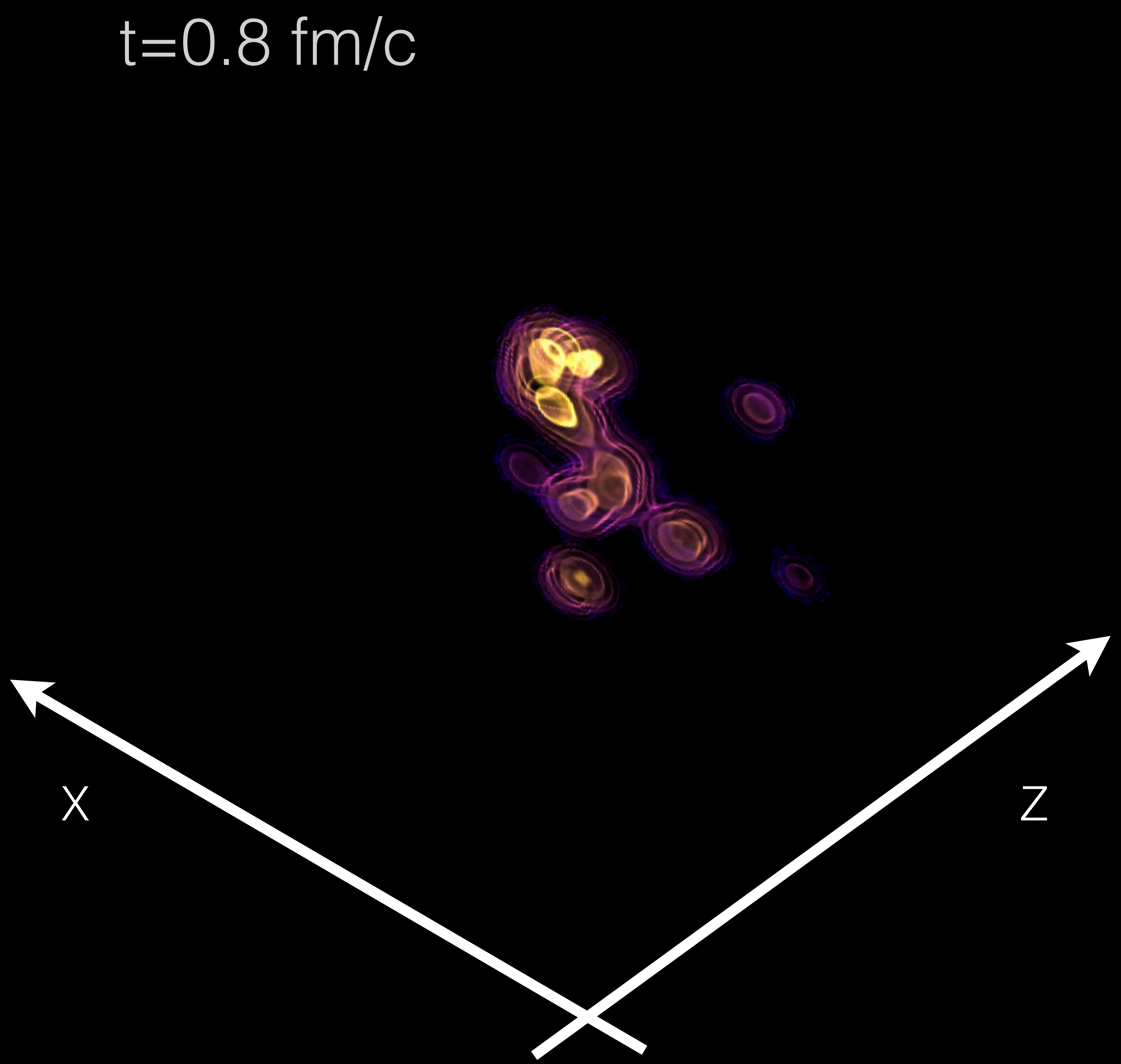
C. Shen and B. Schenke, Phys. Rev. C97 (2018) 024907





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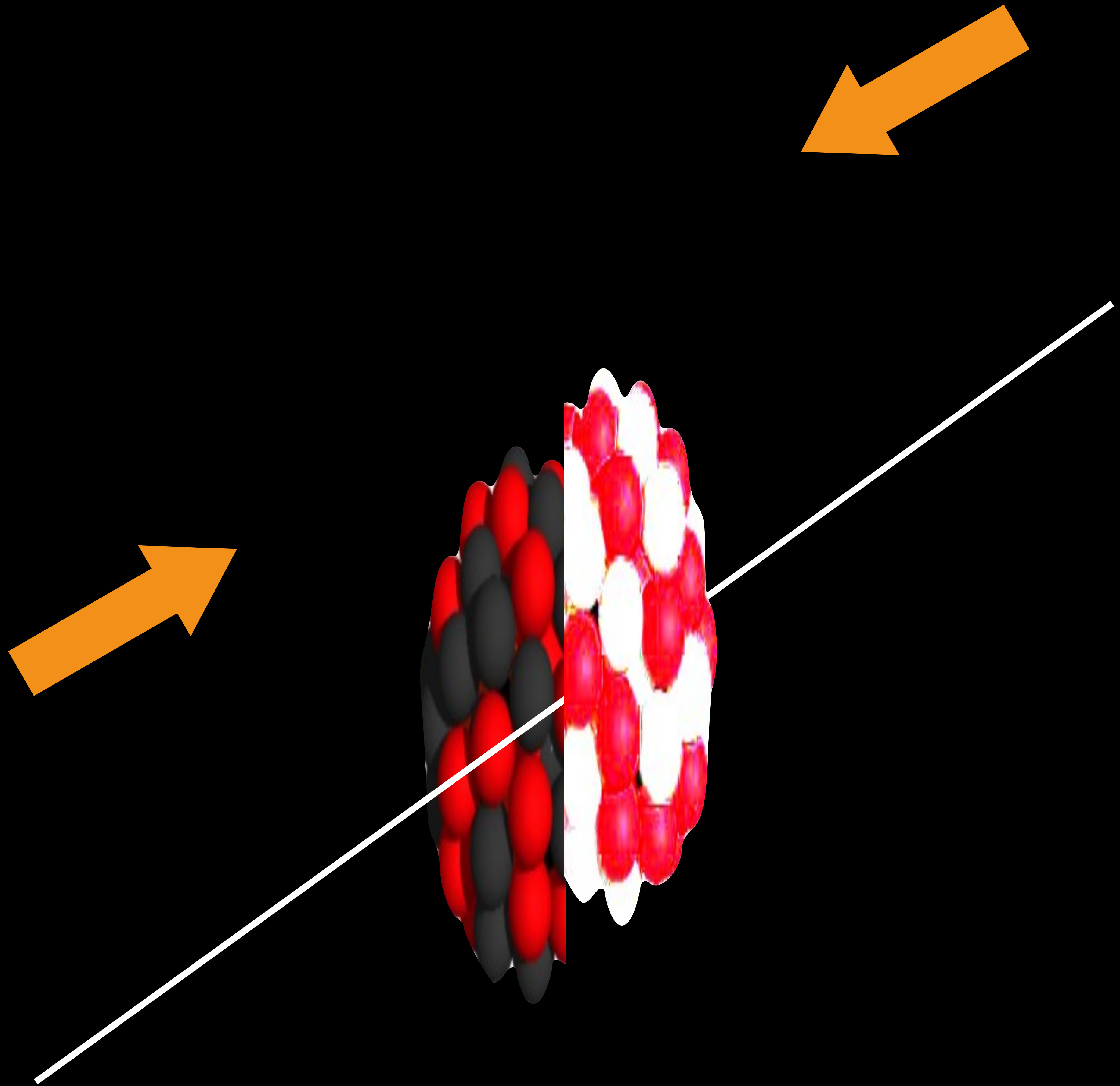

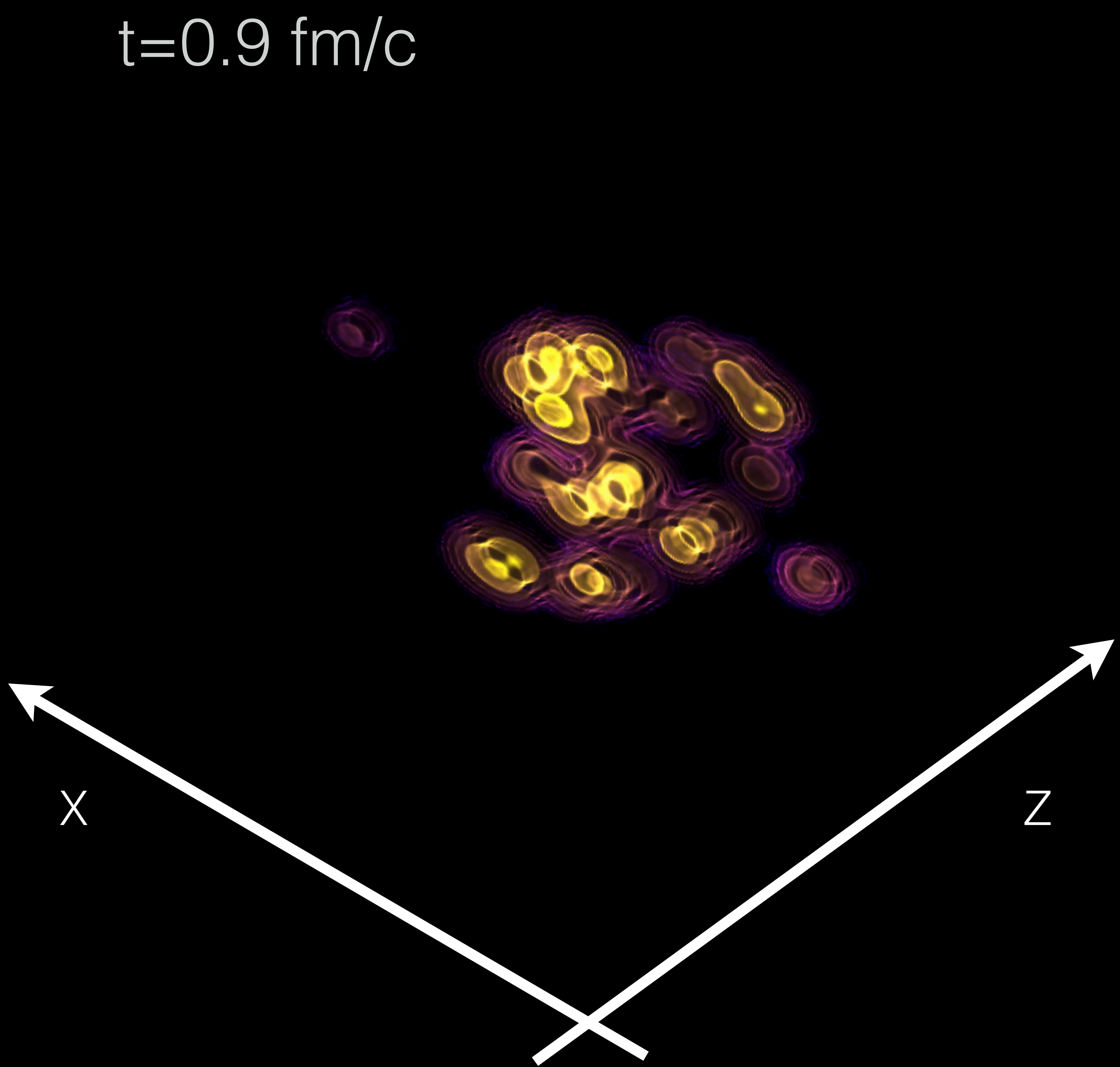

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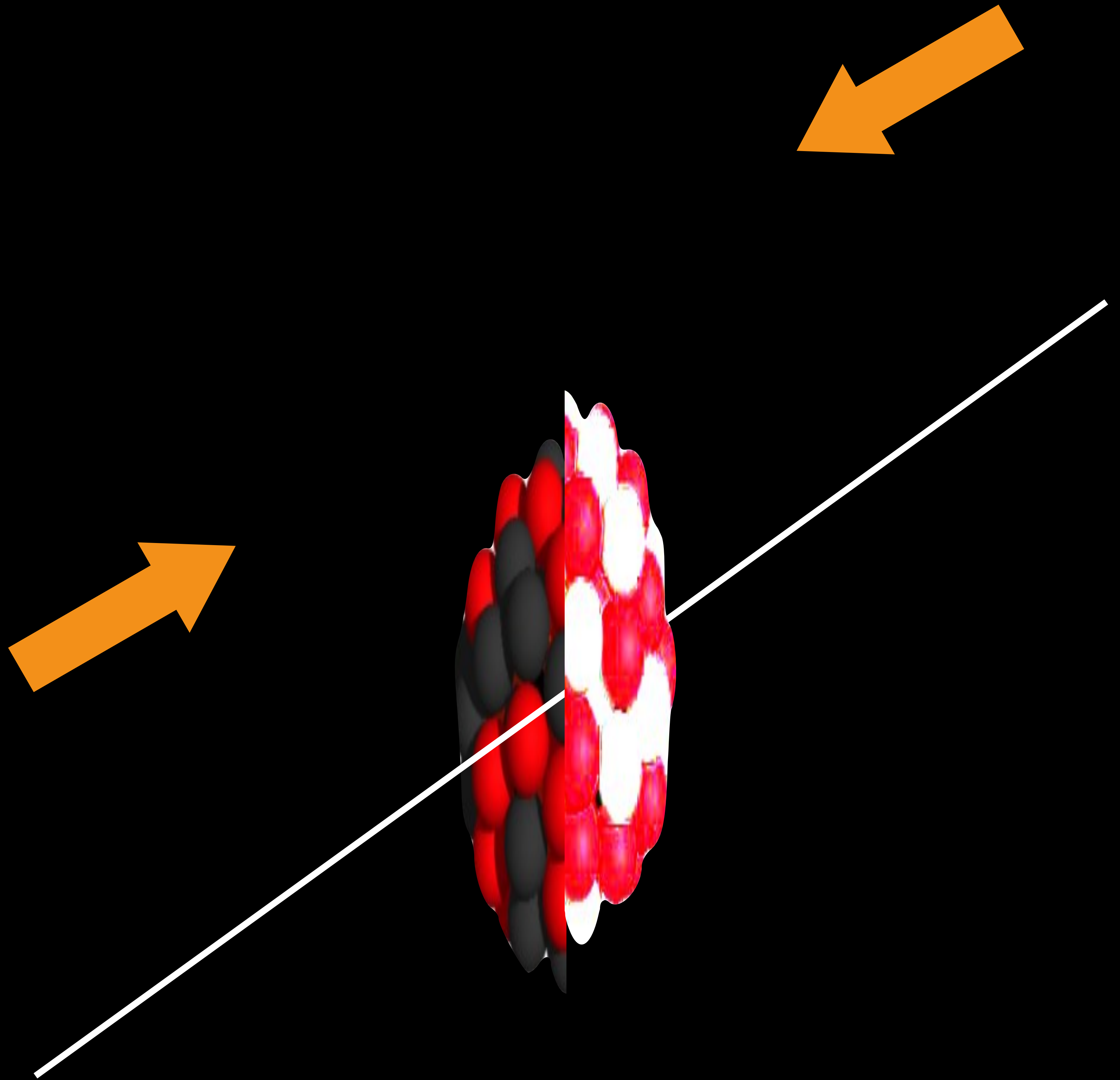

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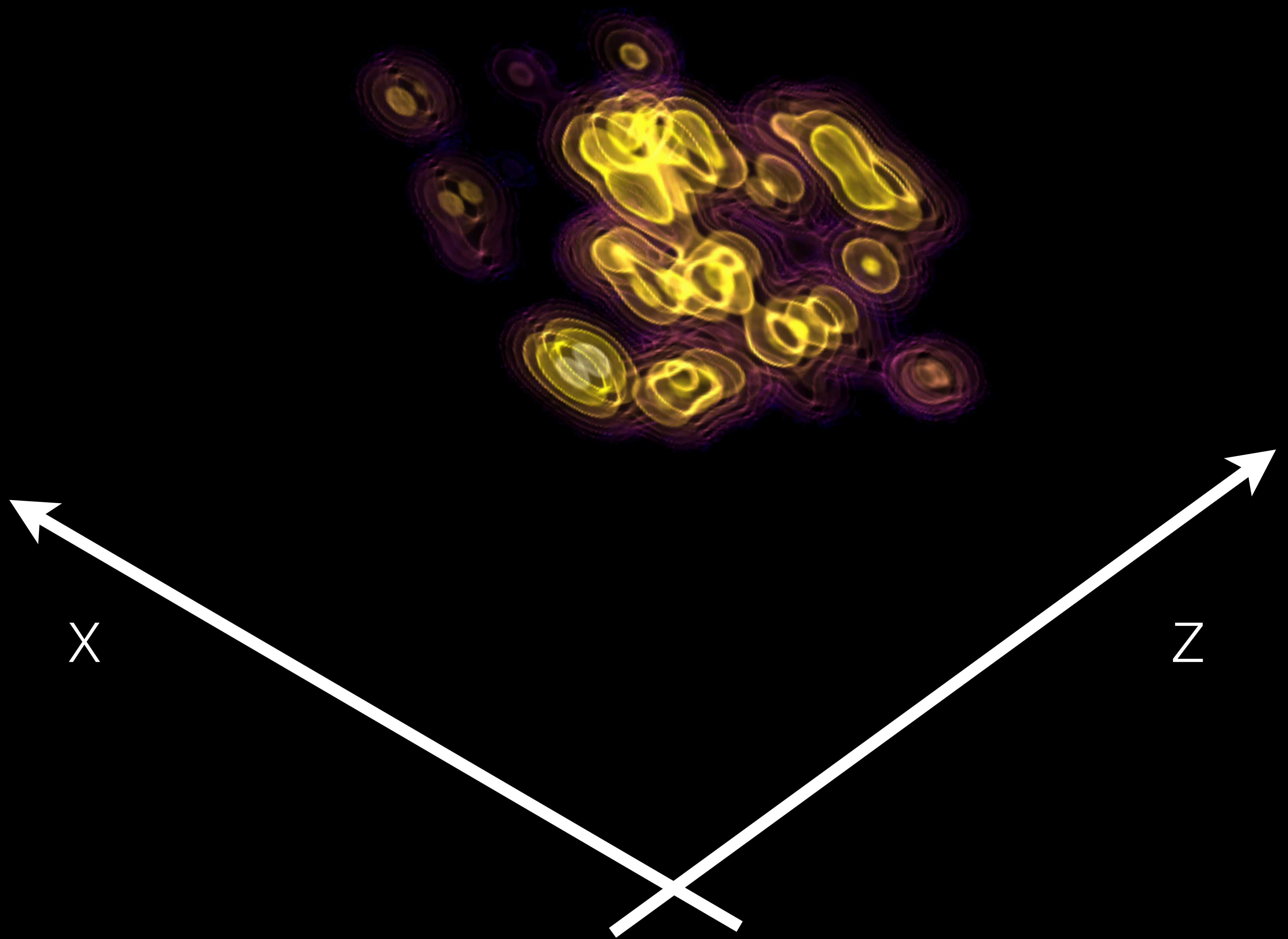
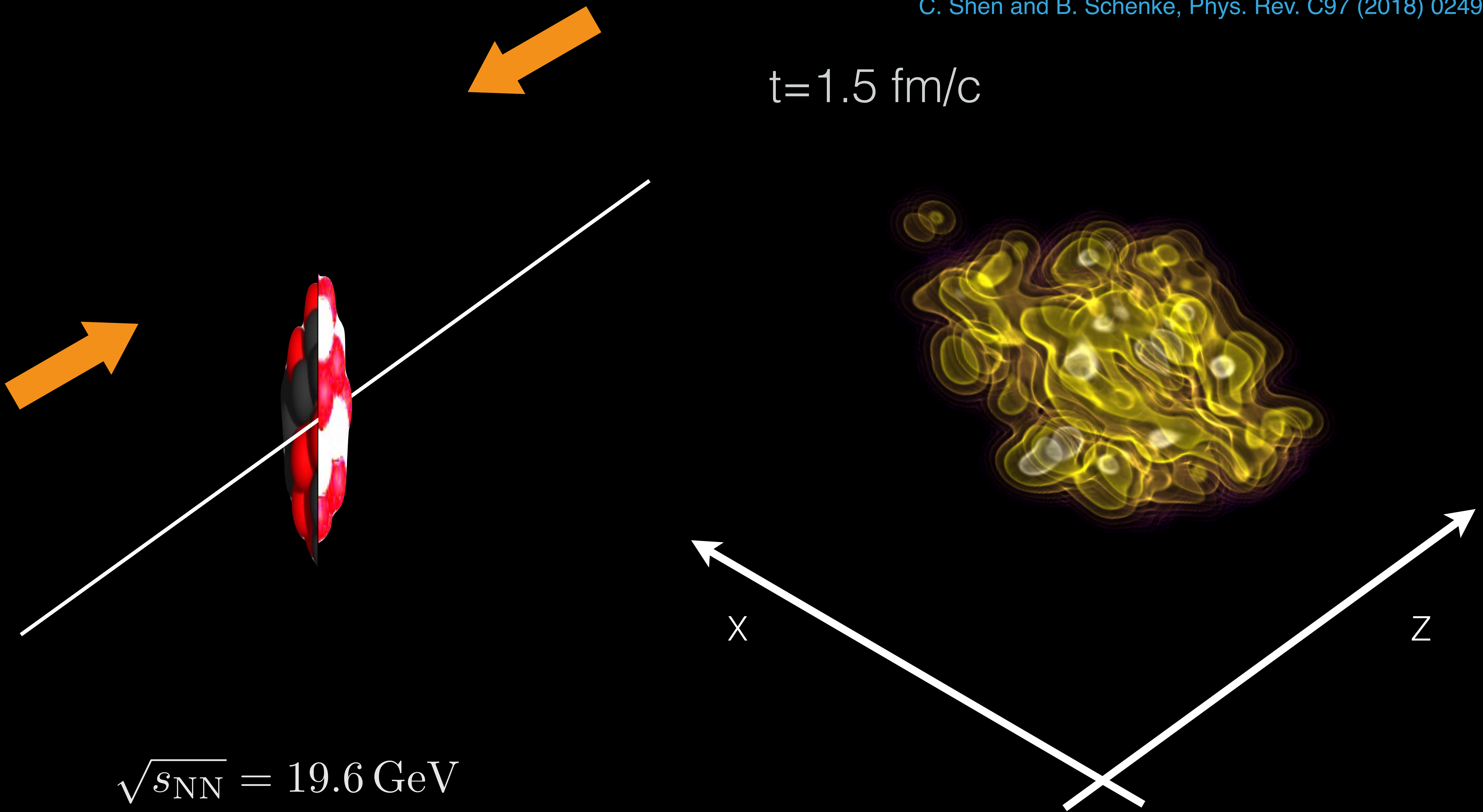


$$\sqrt{s_{\rm NN}} = 19.6\,{\rm GeV}$$

HYDRODYNAMICAL EVOLUTION WITH SOURCES

C. Shen and B. Schenke, Phys. Rev. C97 (2018) 024907



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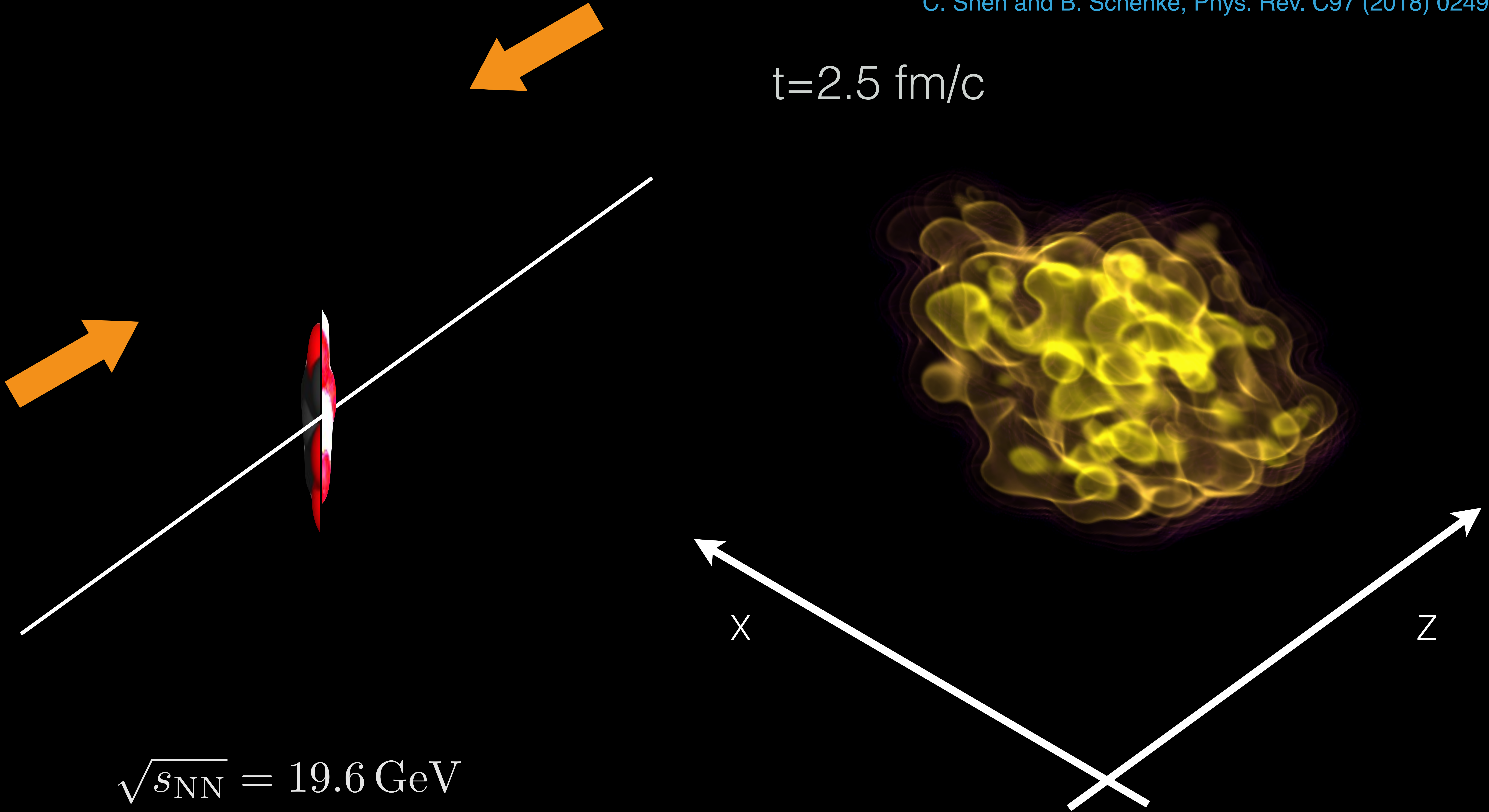
C. Shen and B. Schenke, Phys. Rev. C97 (2018) 024907



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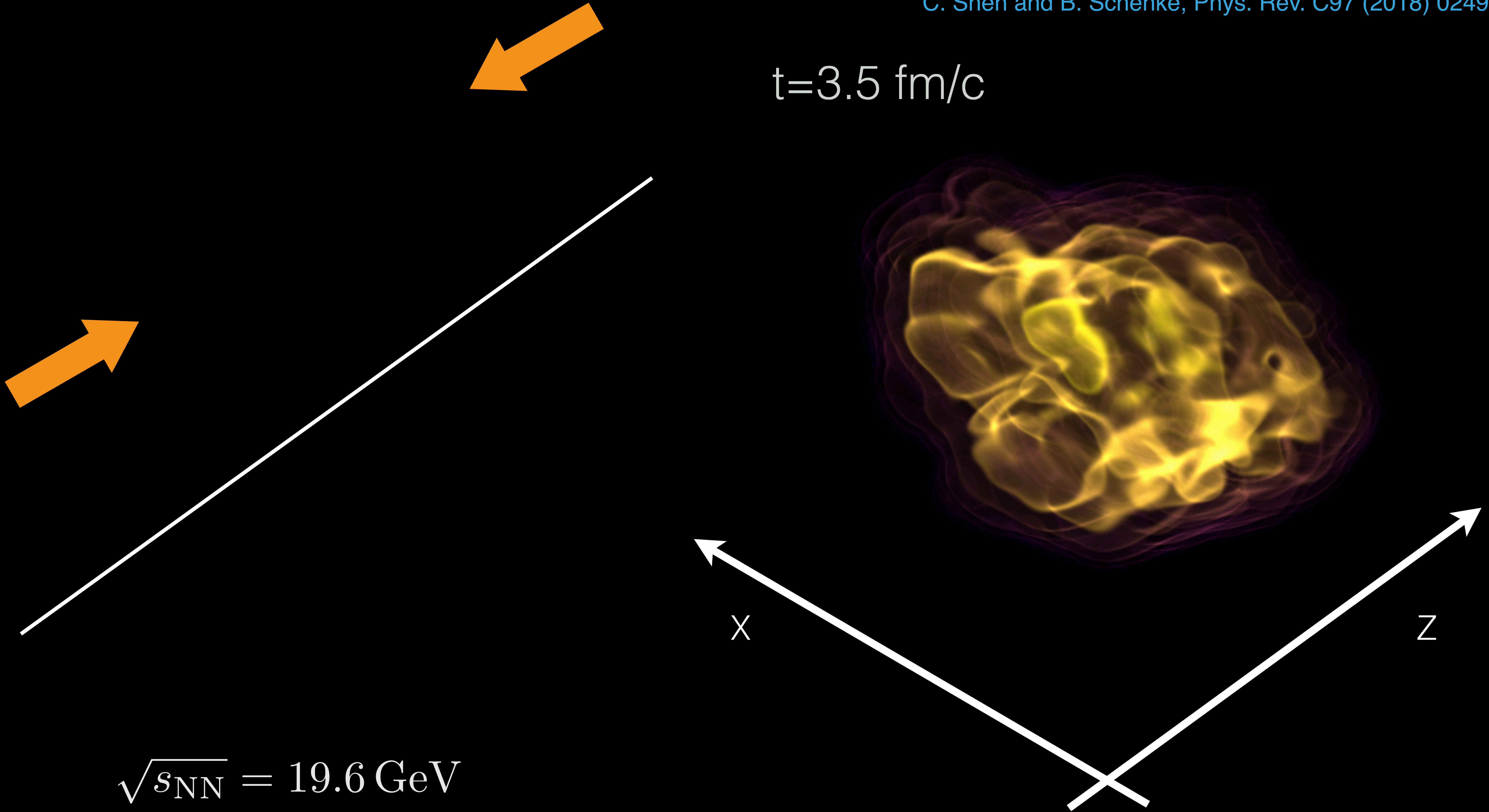

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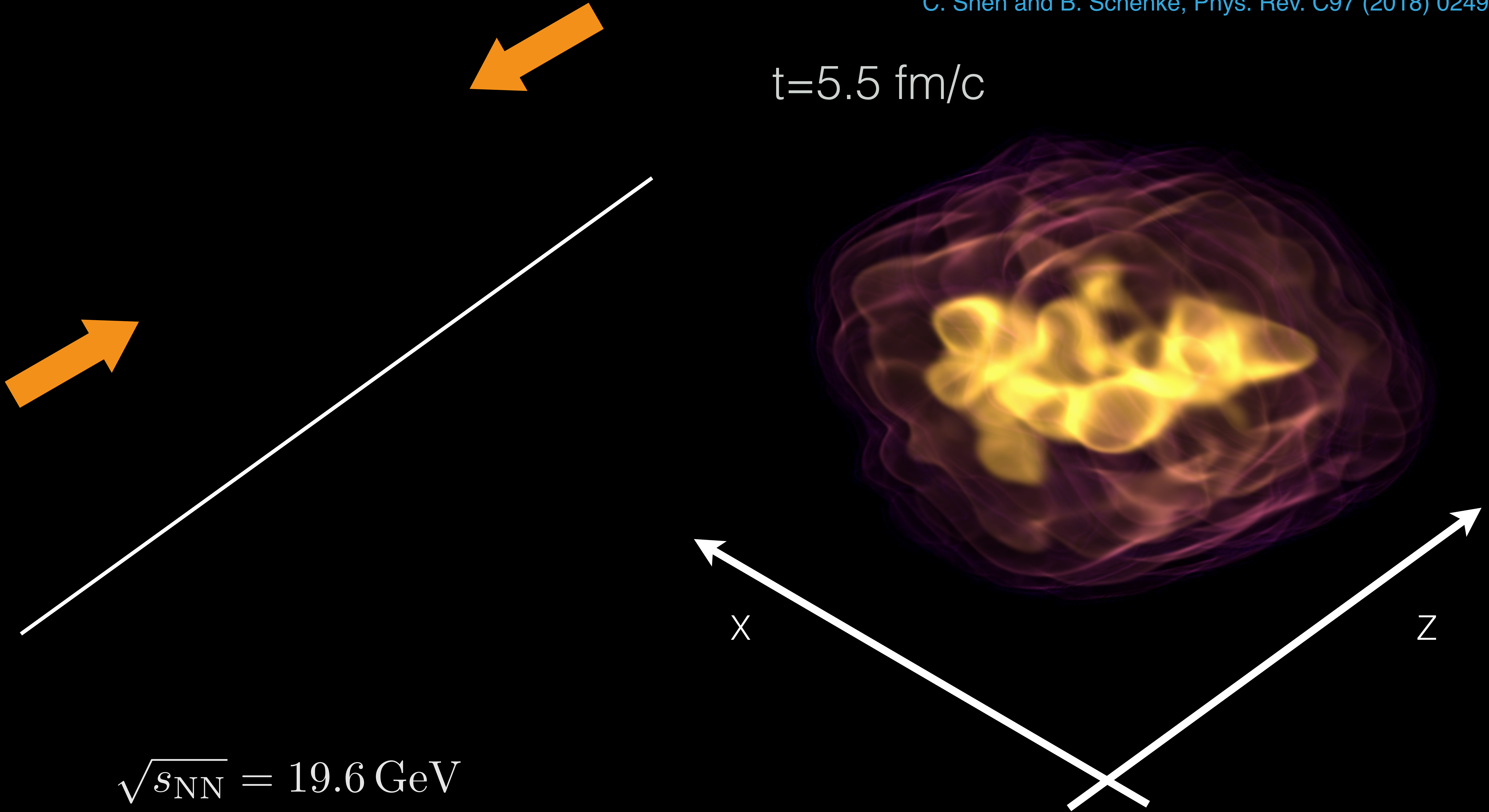

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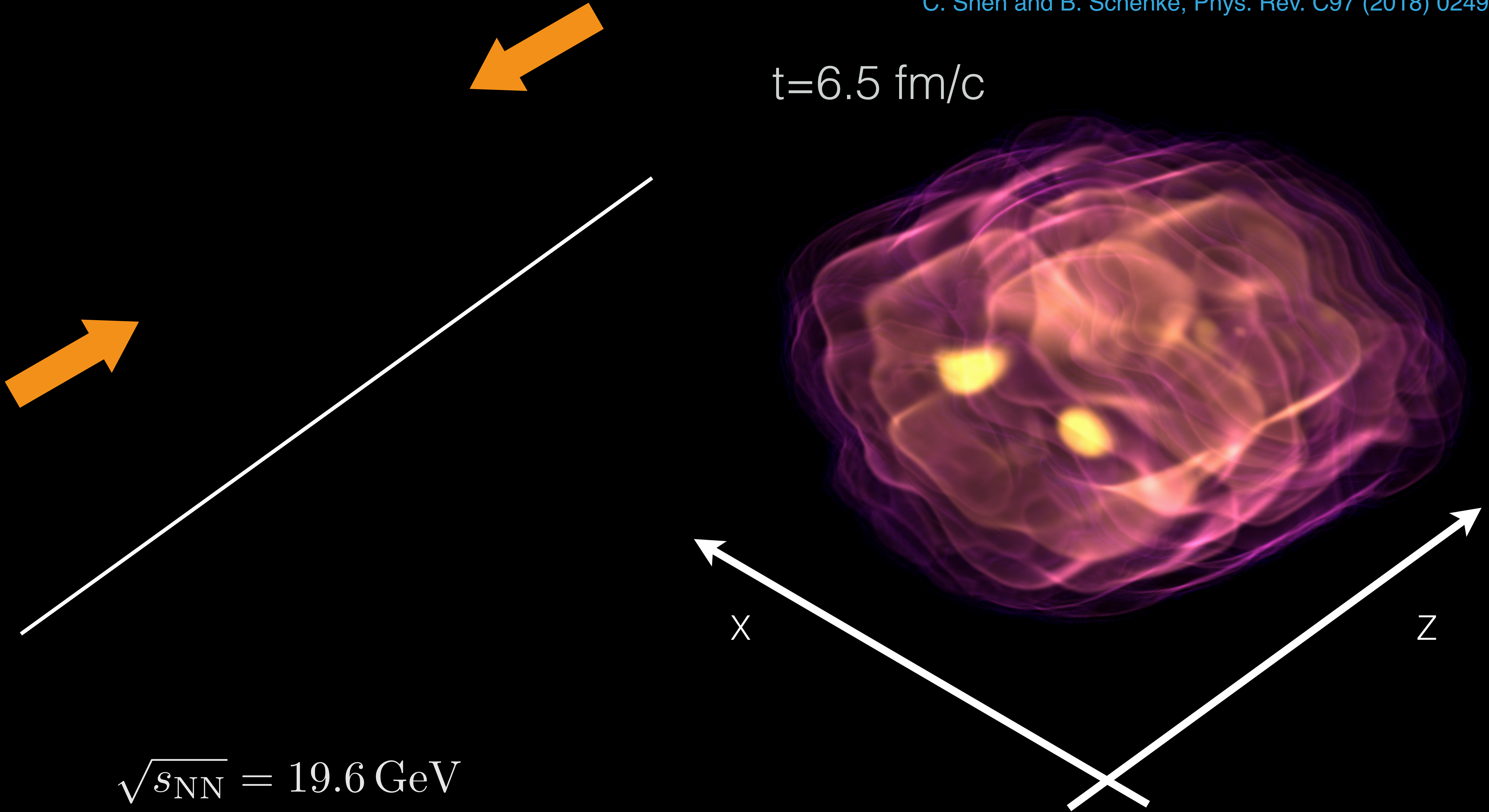

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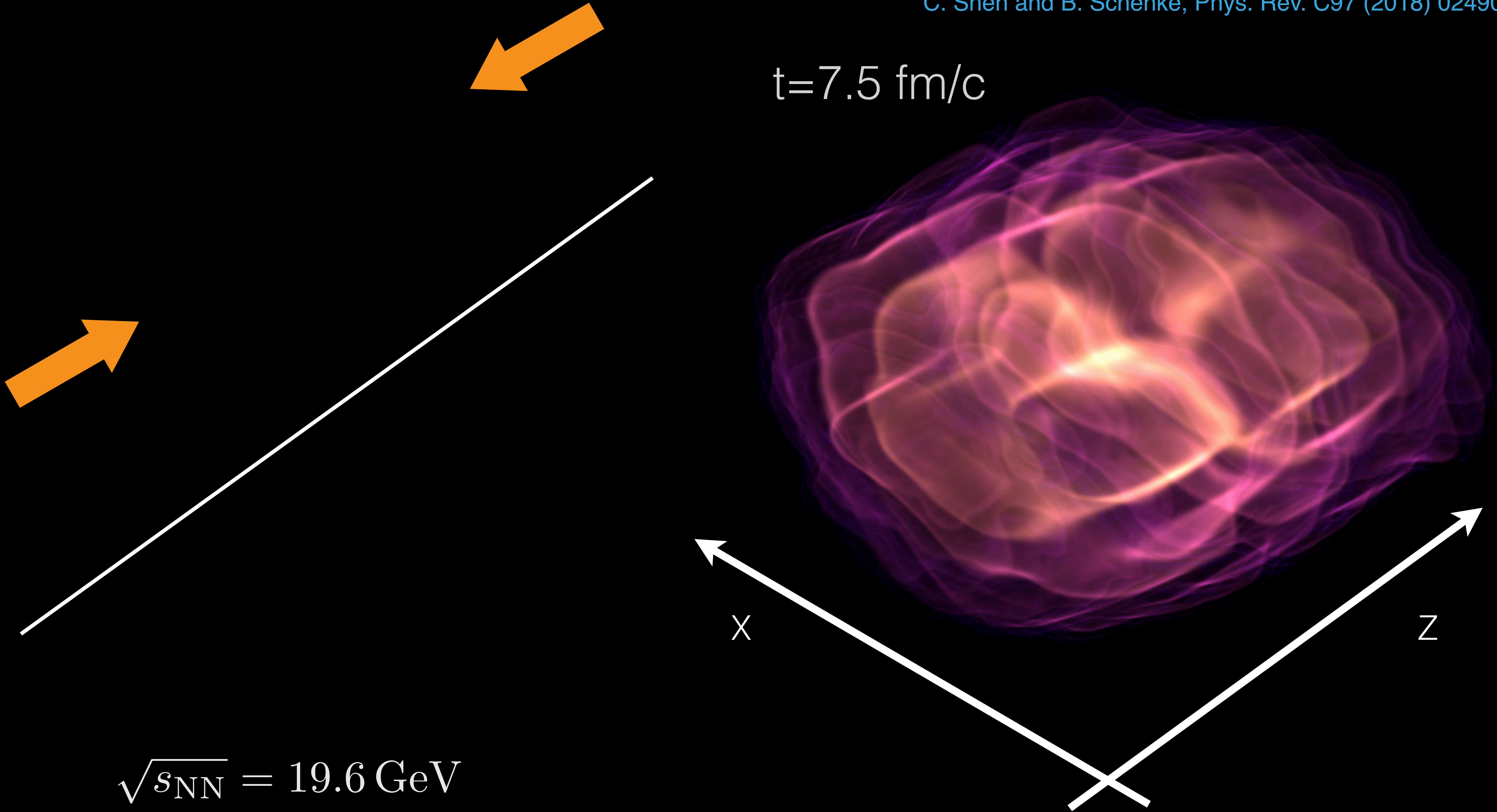

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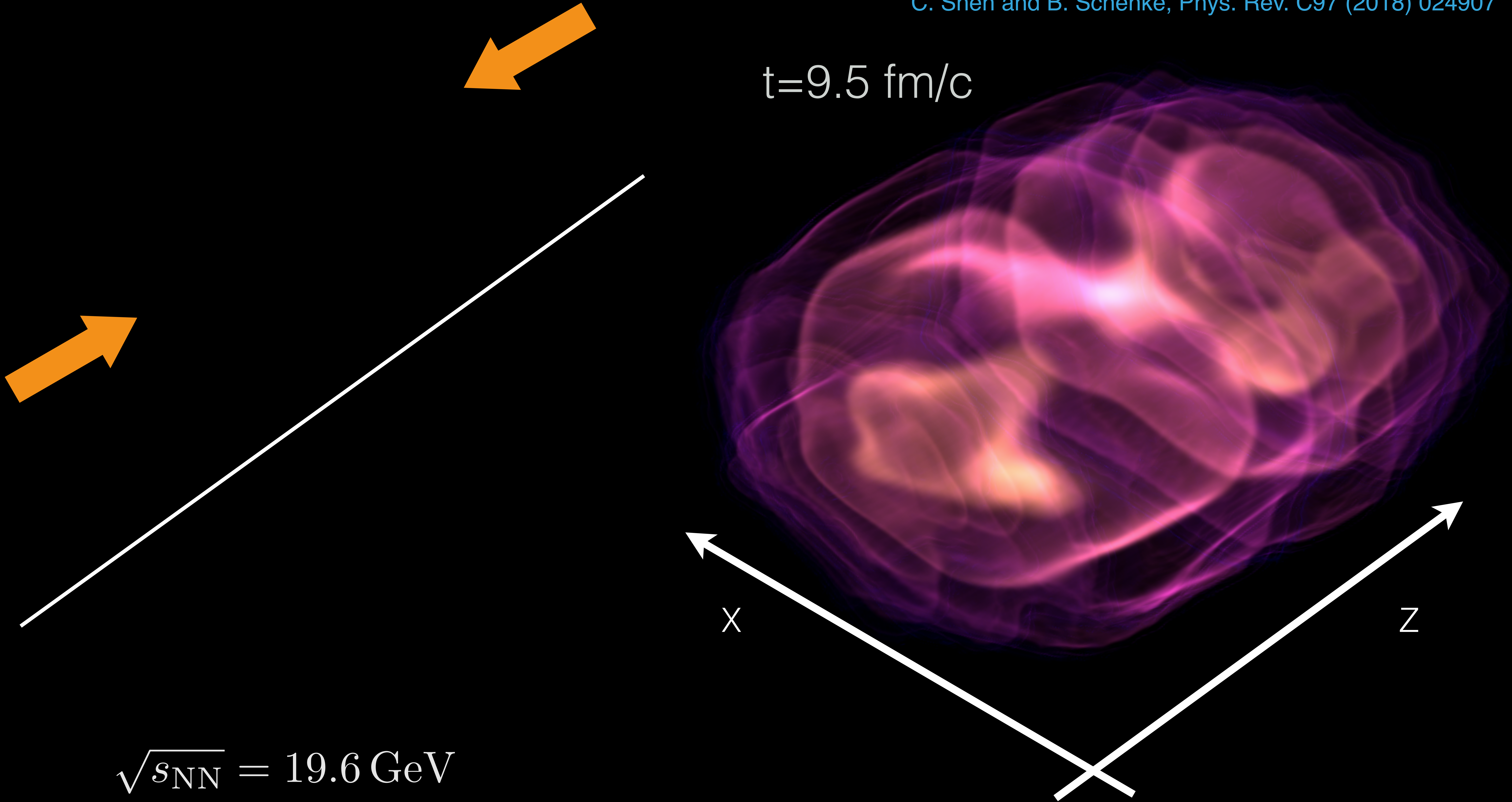

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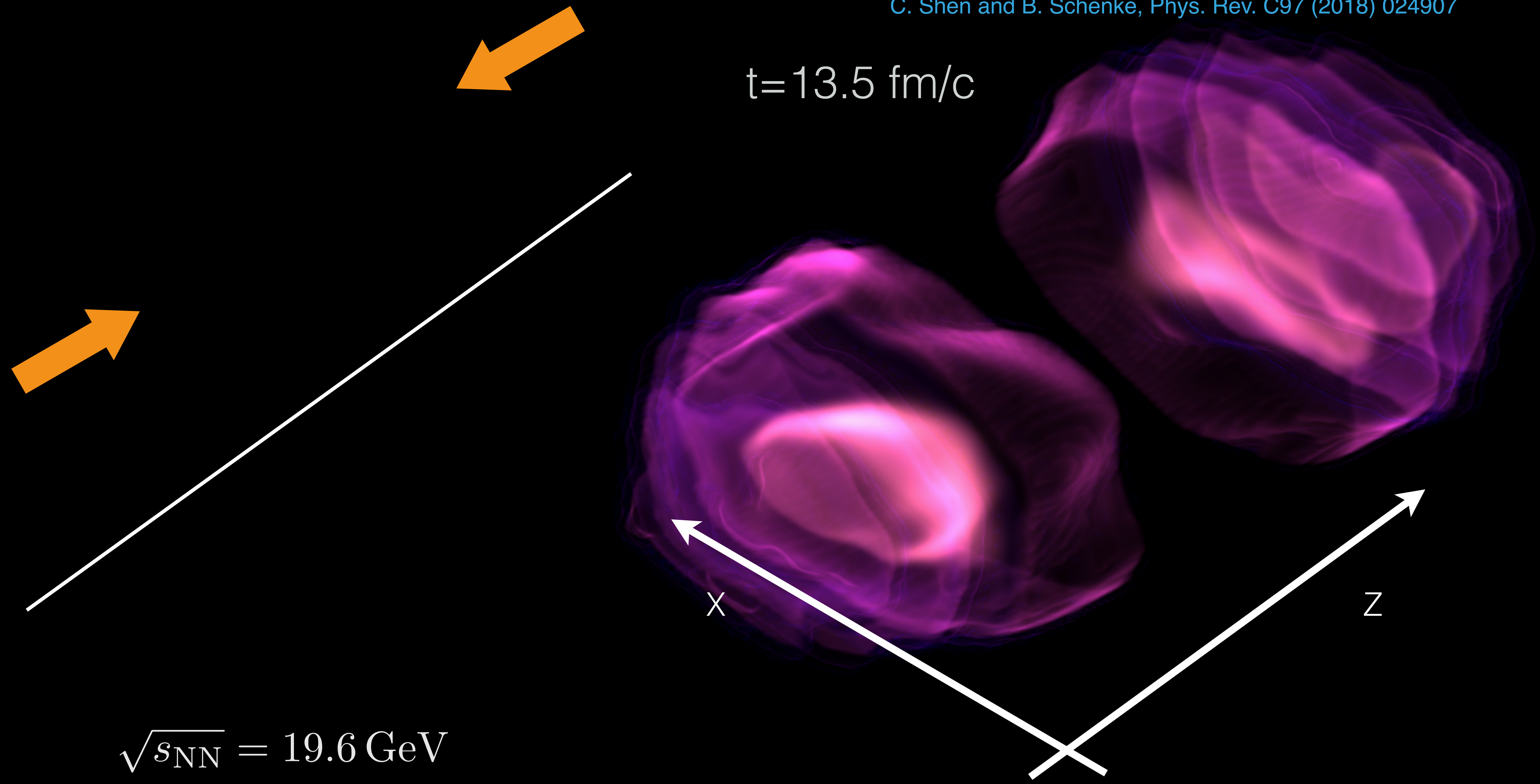
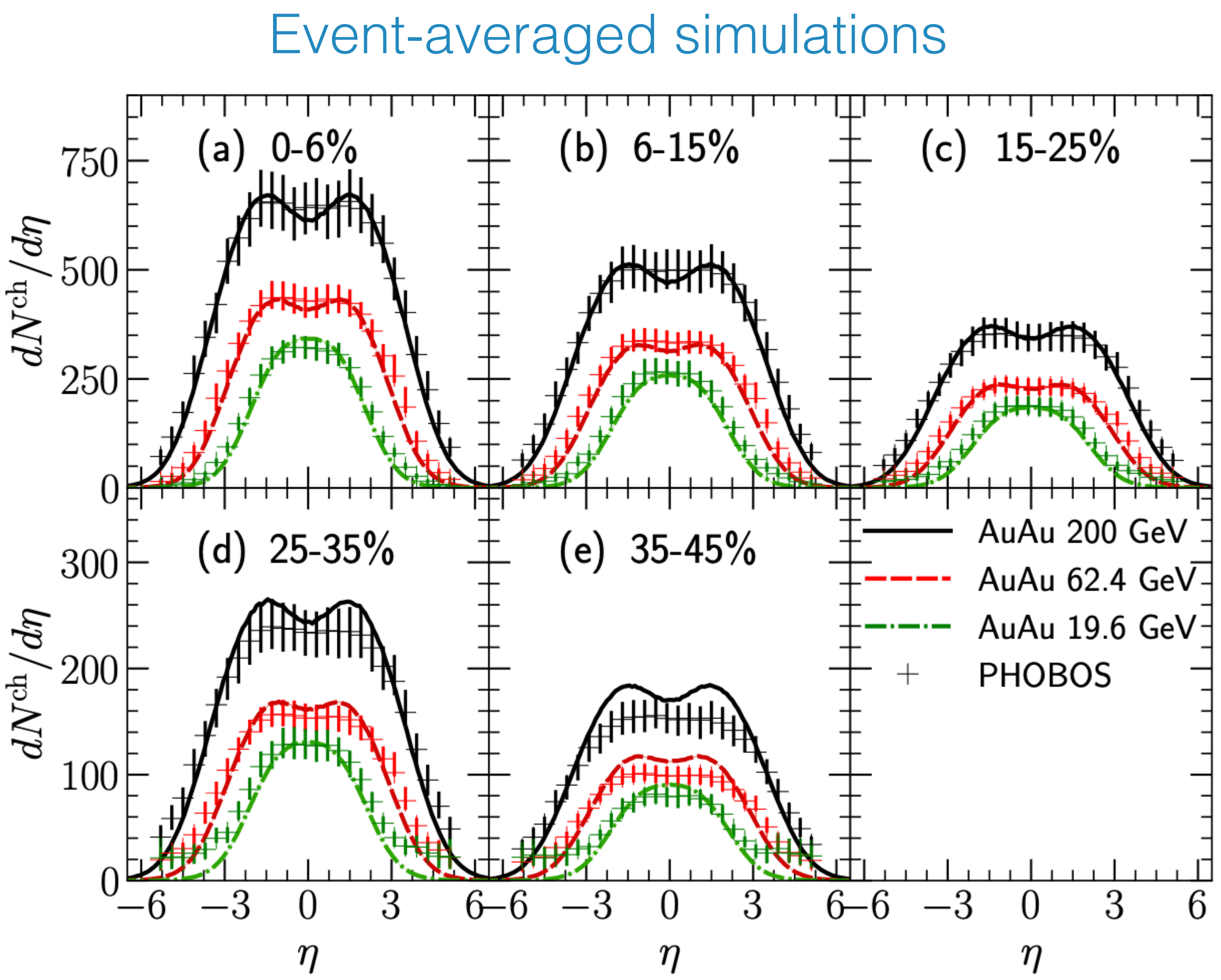
C. Shen and B. Schenke, Phys. Rev. C97 (2018) 024907

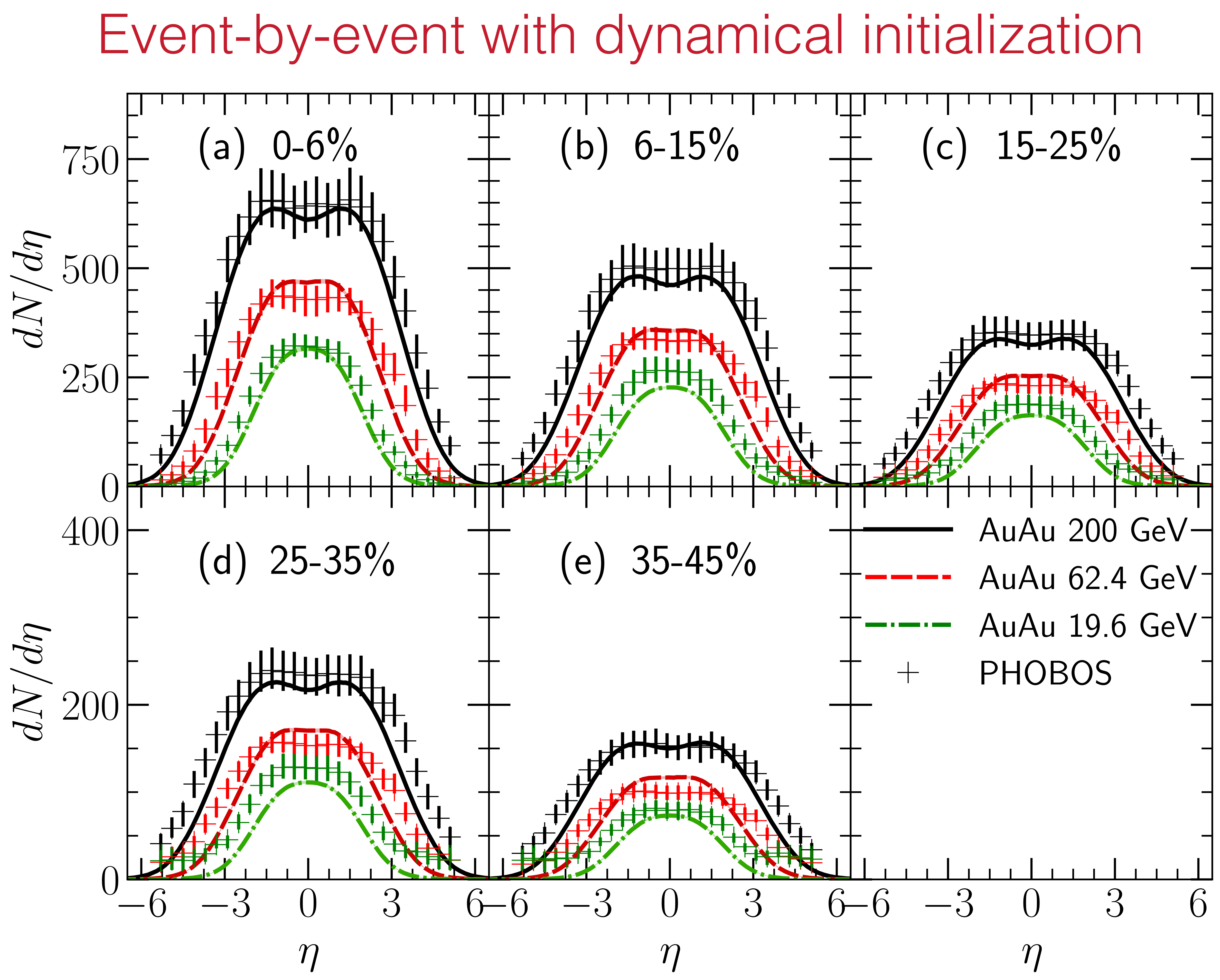


$$\sqrt{s_{\rm NN}} = 19.6\,{\rm GeV}$$

EVENT-BY-EVENT FLUCTUATIONS AT THE RHIC BES

B. Schenke and C. Shen, in preparation





- A good description of particle productions in AuAu collisions

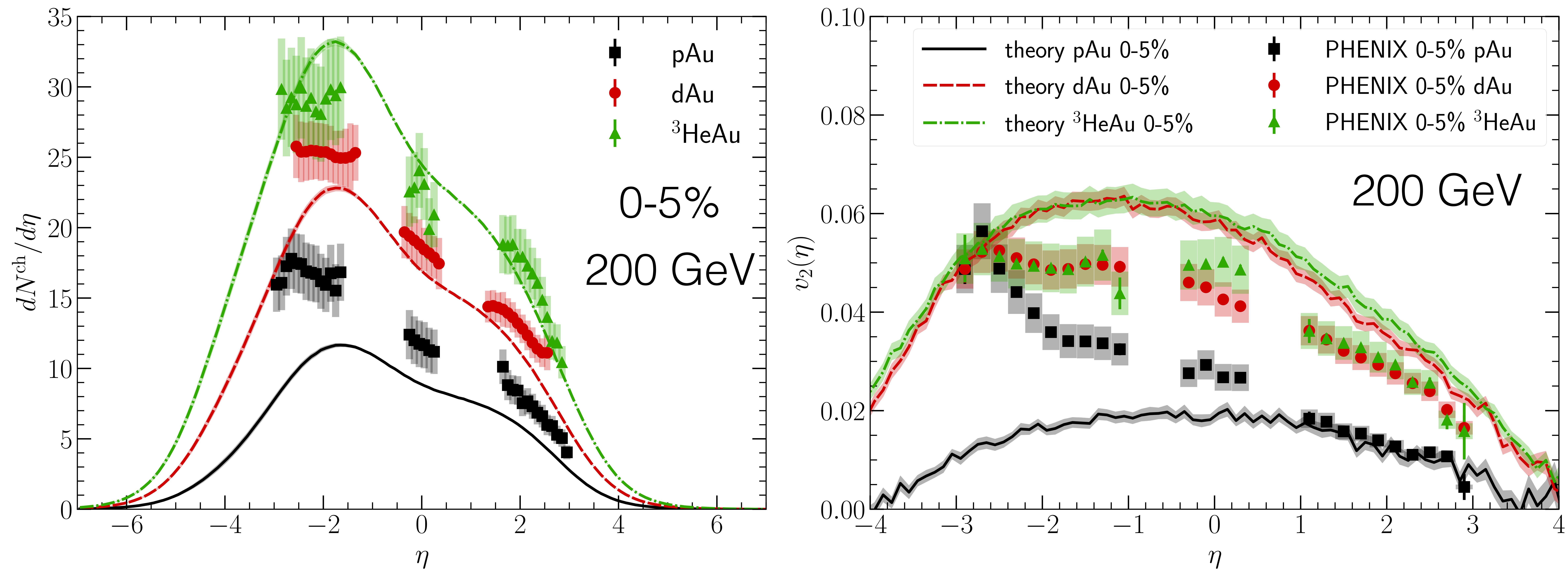
3D DESCRIPTION OF SMALL SYSTEMS AT THE RHIC BES

B. Schenke and C. Shen, in preparation

- The event-by-event simulations give a better prediction for particle productions in d+Au collisions at RHIC BES

3D DESCRIPTION OF SMALL SYSTEMS AT THE RHIC BES

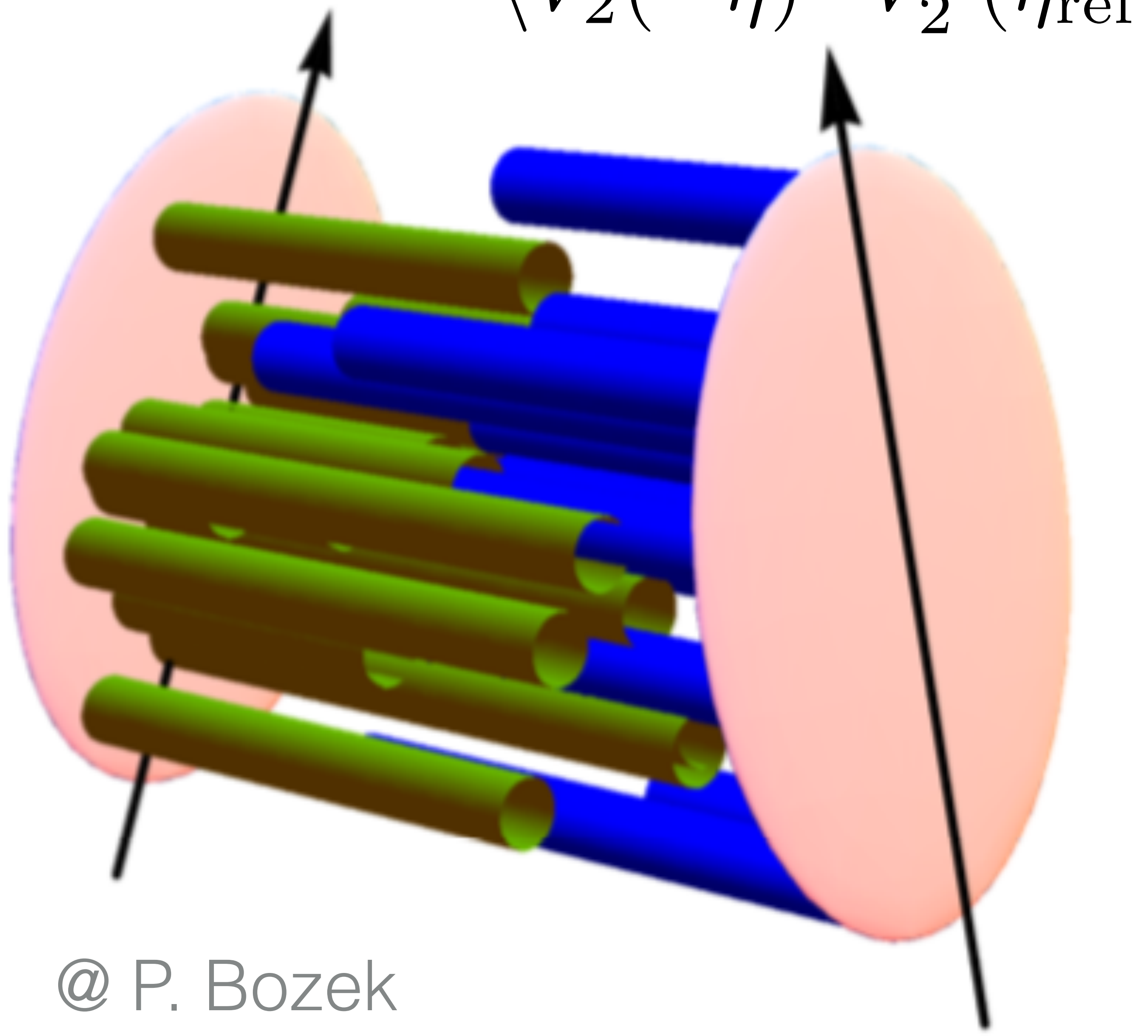
B. Schenke and C. Shen, in preparation



- A good starting point to study longitudinal fluctuations in asymmetric systems at RHIC

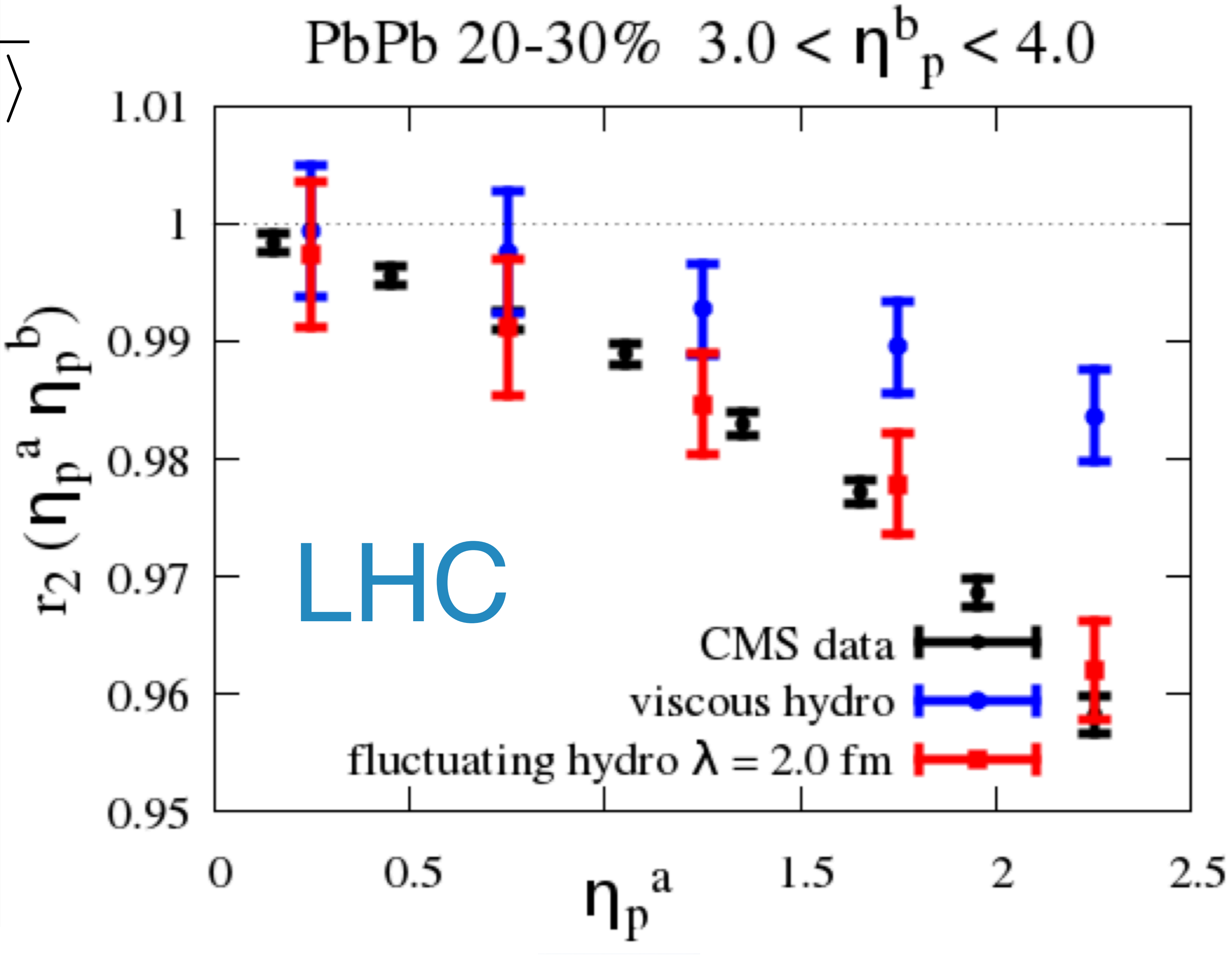
CONSTRAINING LONGITUDINAL FLUCTUATIONS

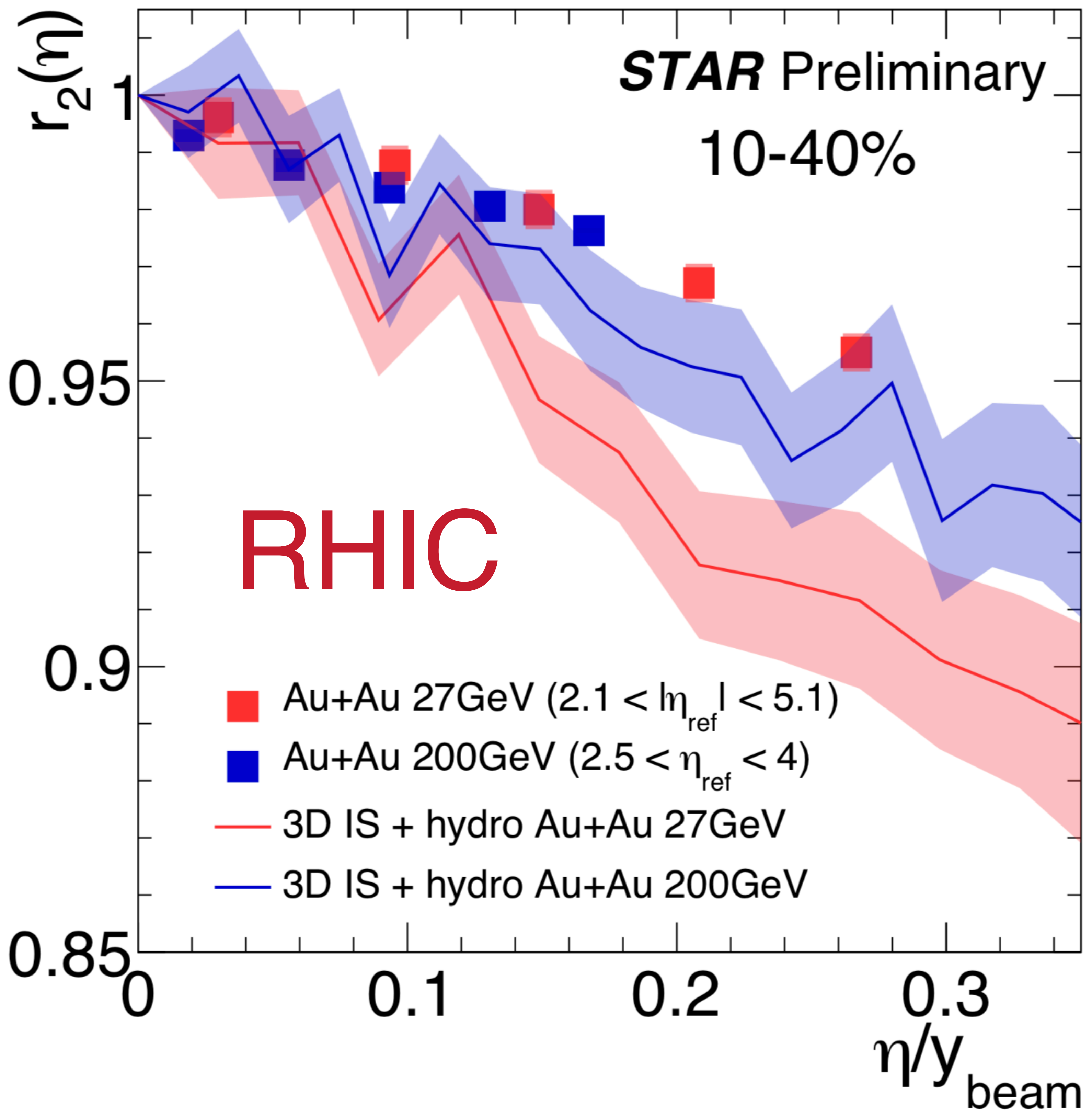
$$r_2(\eta, \eta_{\rm ref}) = \frac{\langle V_2(\eta) \cdot V_2^*(\eta_{\rm ref}) \rangle}{\langle V_2(-\eta) \cdot V_2^*(\eta_{\rm ref}) \rangle}$$



@ P. Bozek

A. Sakai, K. Murase and T. Hirano, arXiv:2003.13496 [nucl-th]

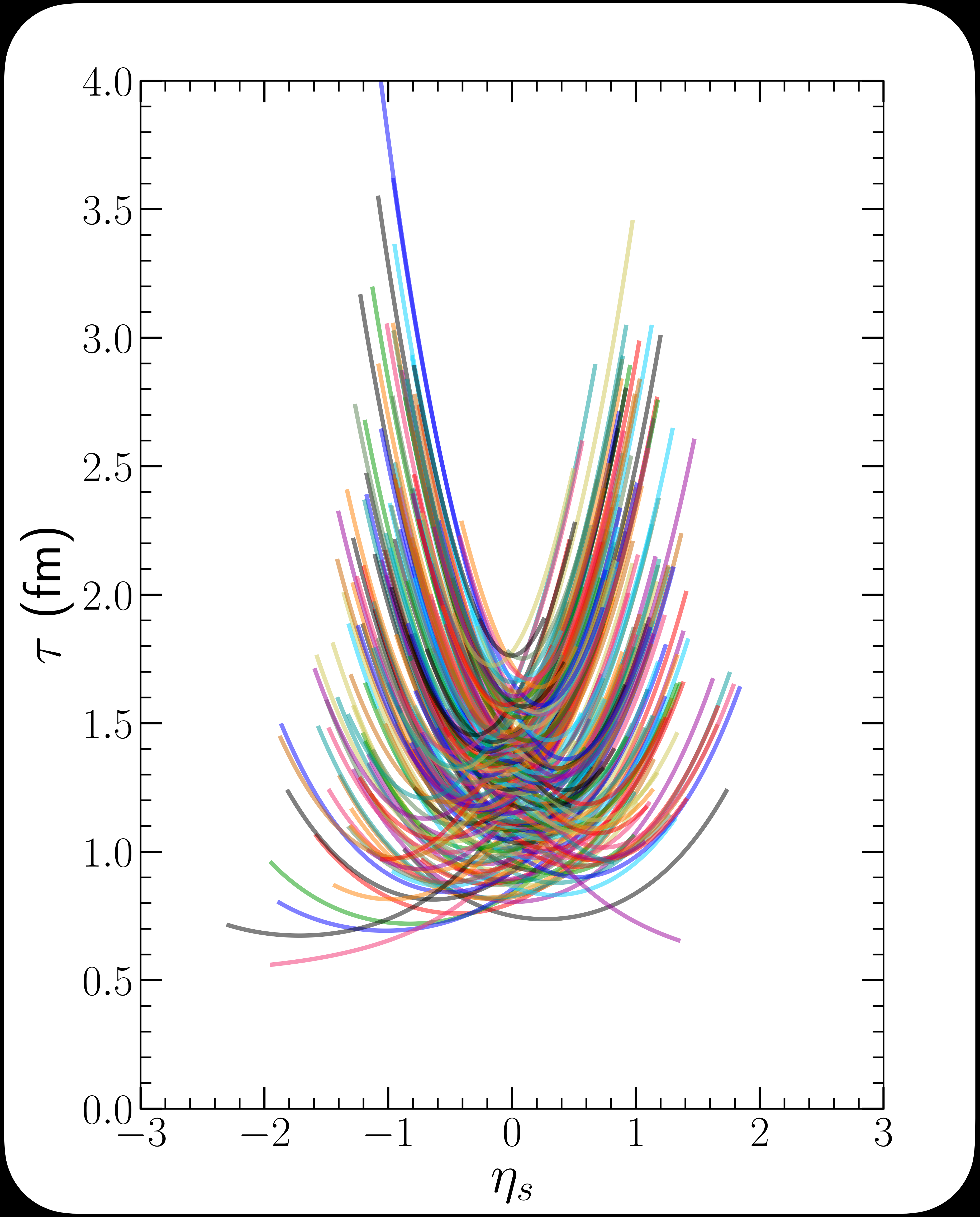




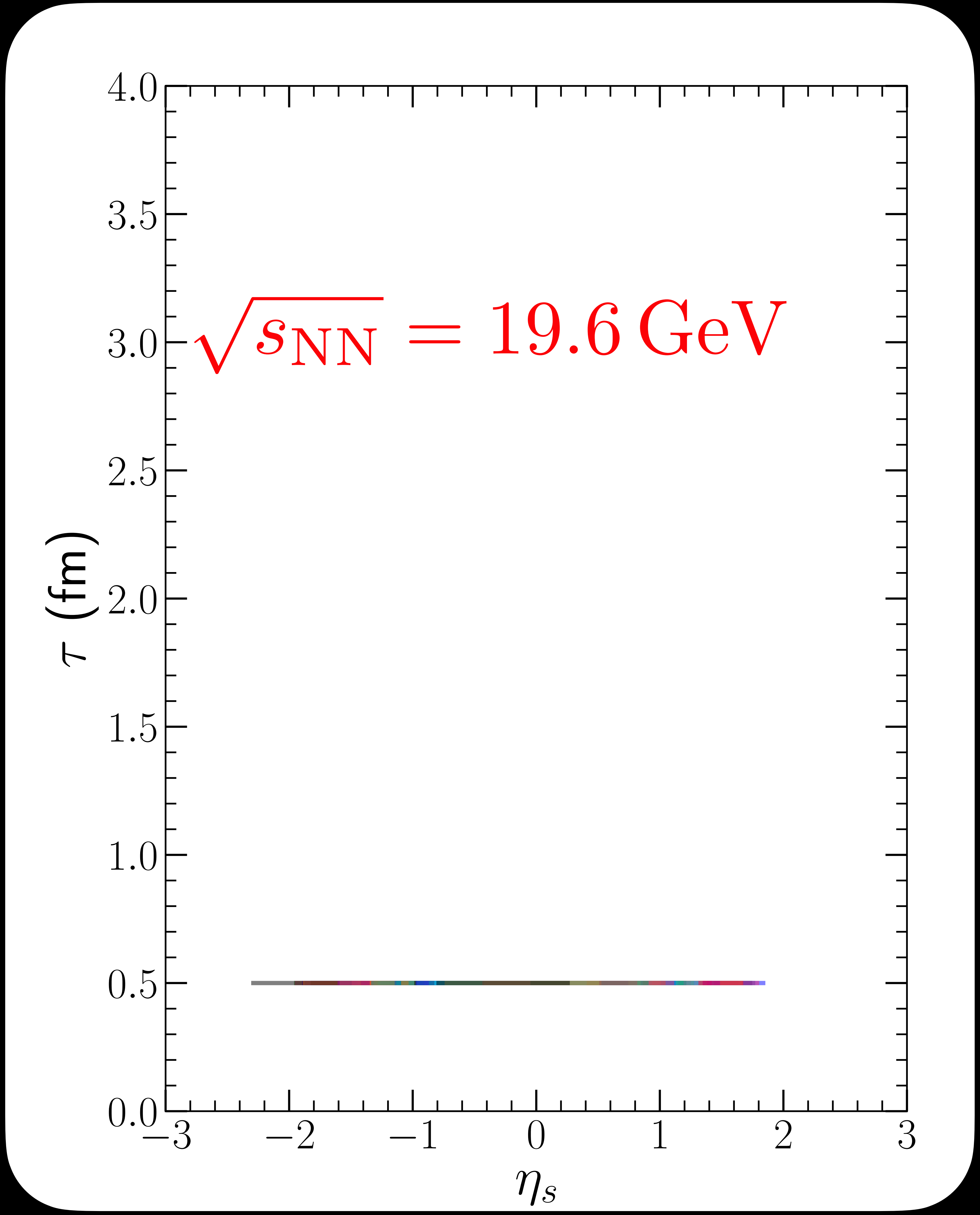
- Longitudinal flow decorrelation encodes the dynamical evolution of rapidity and thermal fluctuations

Strong constraining power on longitudinal dynamics

EARLY TIME DYNAMICS AT THE RHIC BES

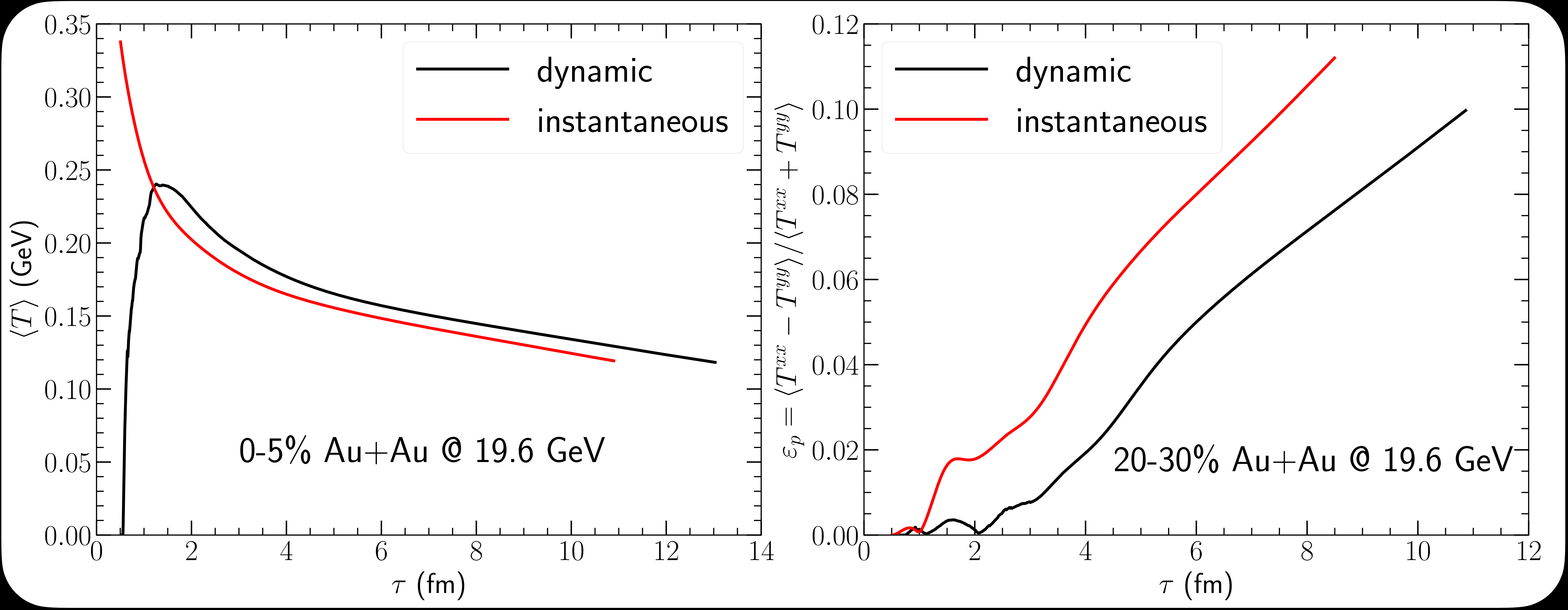


vs.



TRANSVERSE DYNAMICS WITH SOURCES

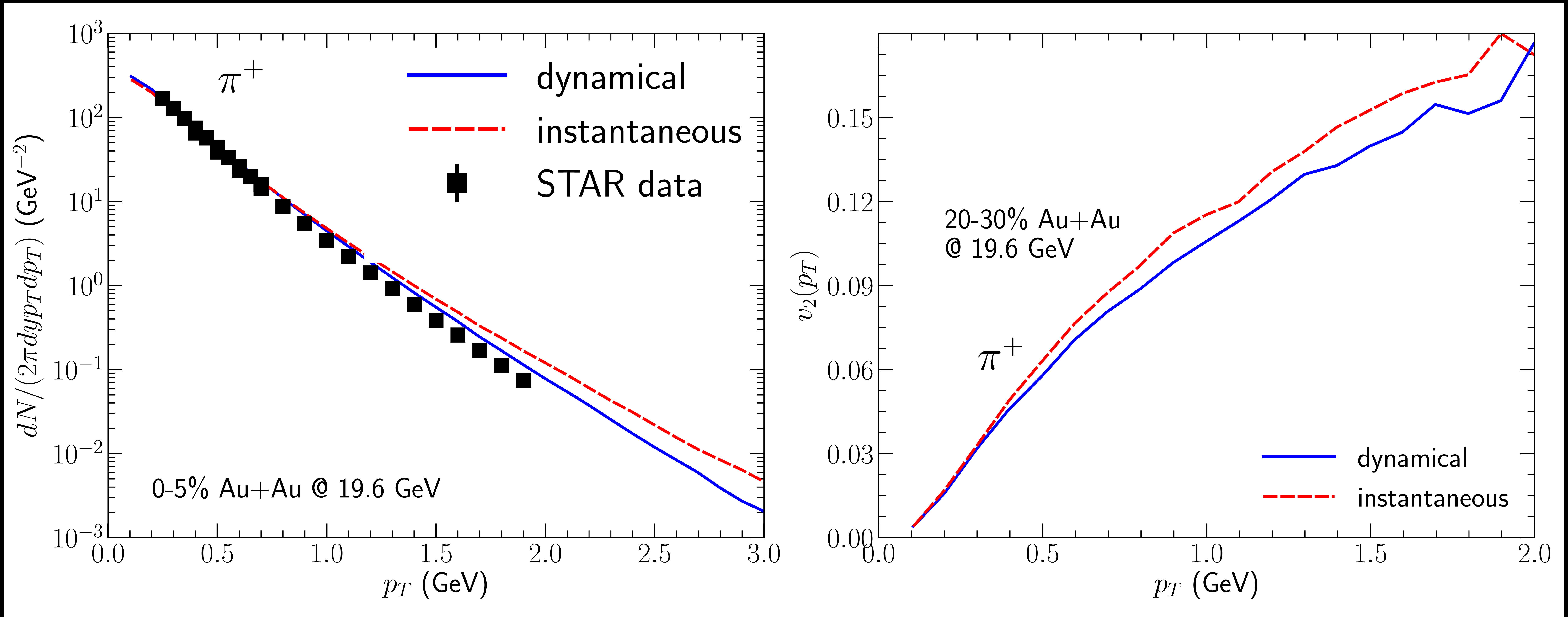
C. Shen and B. Schenke, Nucl. Phys. A 982, 411-414 (2019)



- Fireball lives ~2 fm longer with dynamical initialization compared to the instantaneous setup
- Hydrodynamic flow and its anisotropy develop slower with dynamical sources

DYNAMICAL VS INSTANTANEOUS INITIALIZATION

C. Shen and B. Schenke, Nucl. Phys. A 982, 411-414 (2019)



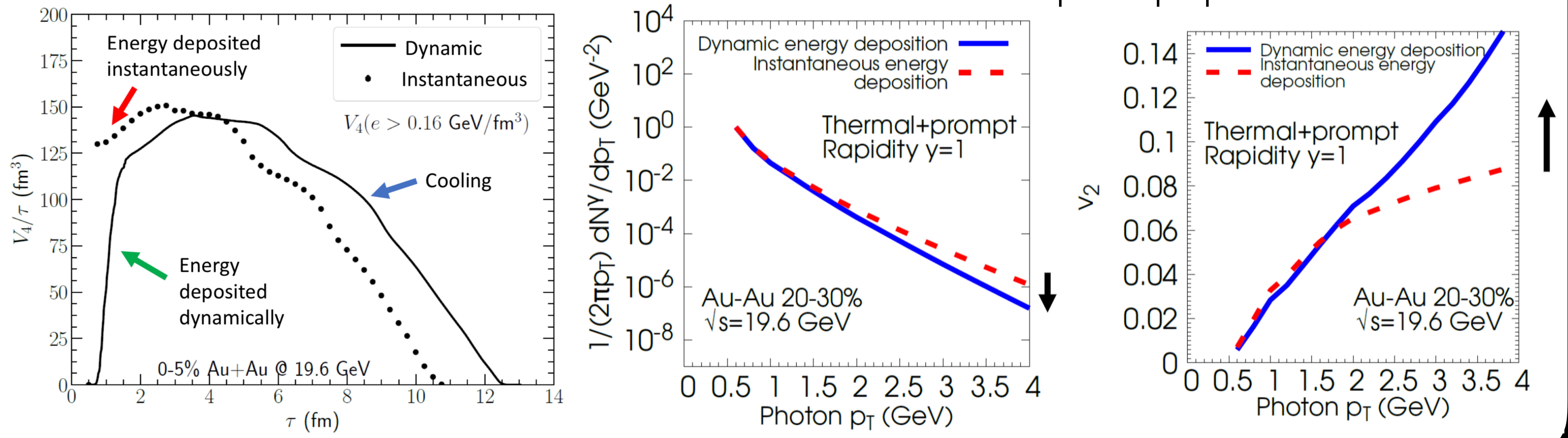
- Dynamical initialization results steeper particle spectra and smaller $v_2(p_T)$

5-10% less radial and elliptic flow

DYNAMICAL INITIALIZATION EFFECT ON EM PROBES

C. Gale, S. Jeon, S. McDonald, J.F. Paquet and C. Shen, Nucl. Phys. A982 (2019) 767-770

Thermal + prompt photons

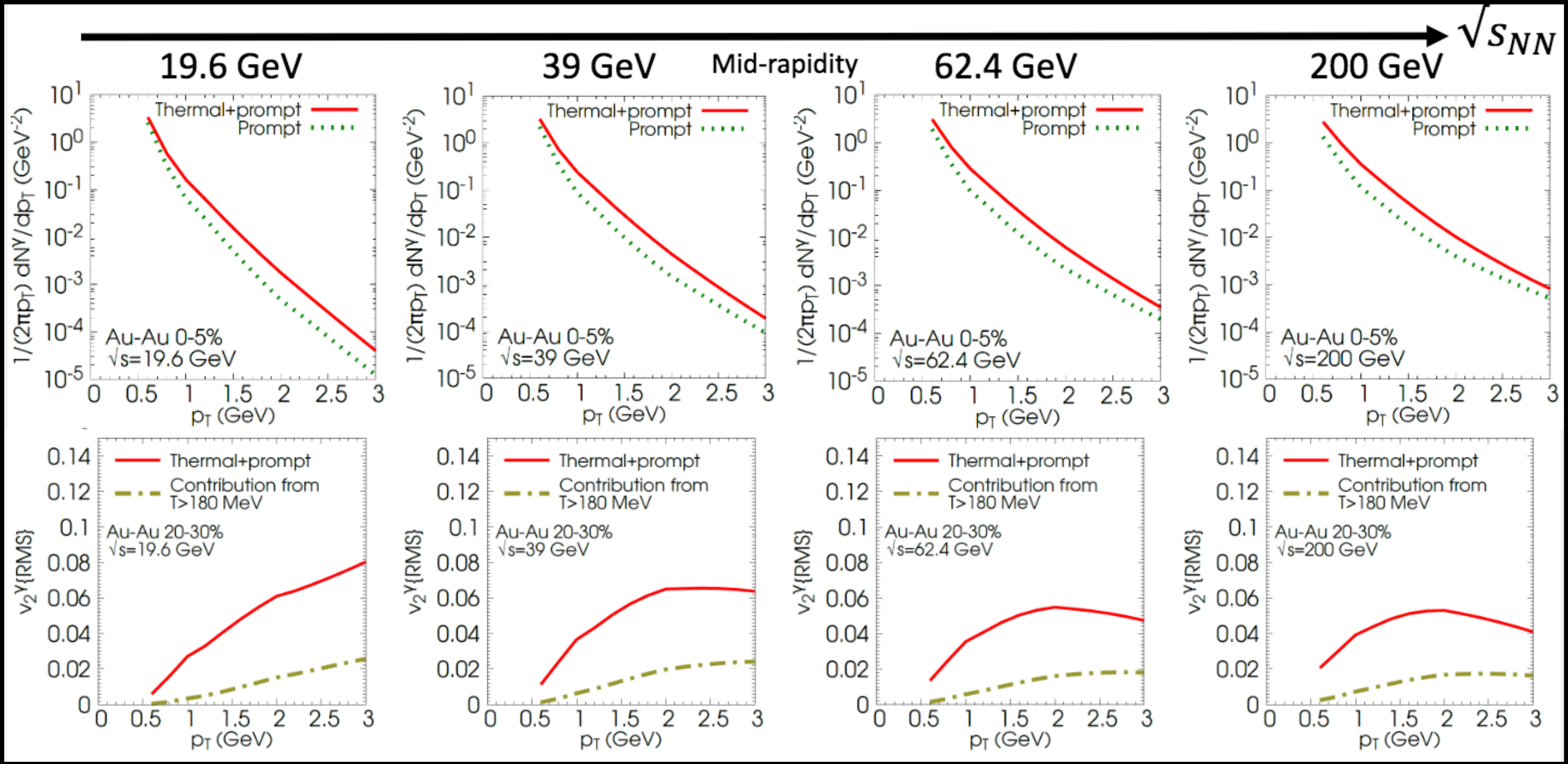


- Dynamical initialization results in large direct photon v_2 at high p_T

EM probes show a large sensitivity to the early time dynamics

EM TOMOGRAPHY AT RHIC BES ENERGIES

C. Gale, S. Jeon, S. McDonald, J.F. Paquet and C. Shen, Nucl. Phys. A982 (2019) 767-770



Photons are *unique* soft penetrating probes to early time dynamics

ACCESSING NEW QGP TRANSPORT PROPERTY

G. Denicol, C. Gale, S. Jeon, A. Monnai, B. Schenke and C. Shen, Phys. Rev. C98, 034916 (2018)
L. Du and U. Heinz, arXiv:1906.11181 [nucl-th]
M. Li and C. Shen, Phys. Rev. C 98, 064908 (2018)

$$T^{\mu\nu} = e u^\mu u^\nu - (P + \Pi)\Delta^{\mu\nu} + \pi^{\mu\nu}$$

$$J^\mu = n u^\mu + q^\mu$$

$$\partial_\mu T^{\mu\nu} = 0 \quad \partial_\mu J^\mu = 0 \quad + \quad P(e, n)$$

$$\pi^{\mu\nu} \sim 2\eta \nabla^{\langle\mu} u^{\nu\rangle} \quad \Pi \sim -\zeta \partial_\mu u^\mu \quad q^\mu \sim \kappa \nabla^\mu \frac{\mu}{T}$$

- The charge diffusion current q^μ characterizes how conserved charges diffuse in and out of fluid cells
- The κ is the QGP charge diffusion coefficient [matrix]

ACCESSING NEW QGP TRANSPORT PROPERTY

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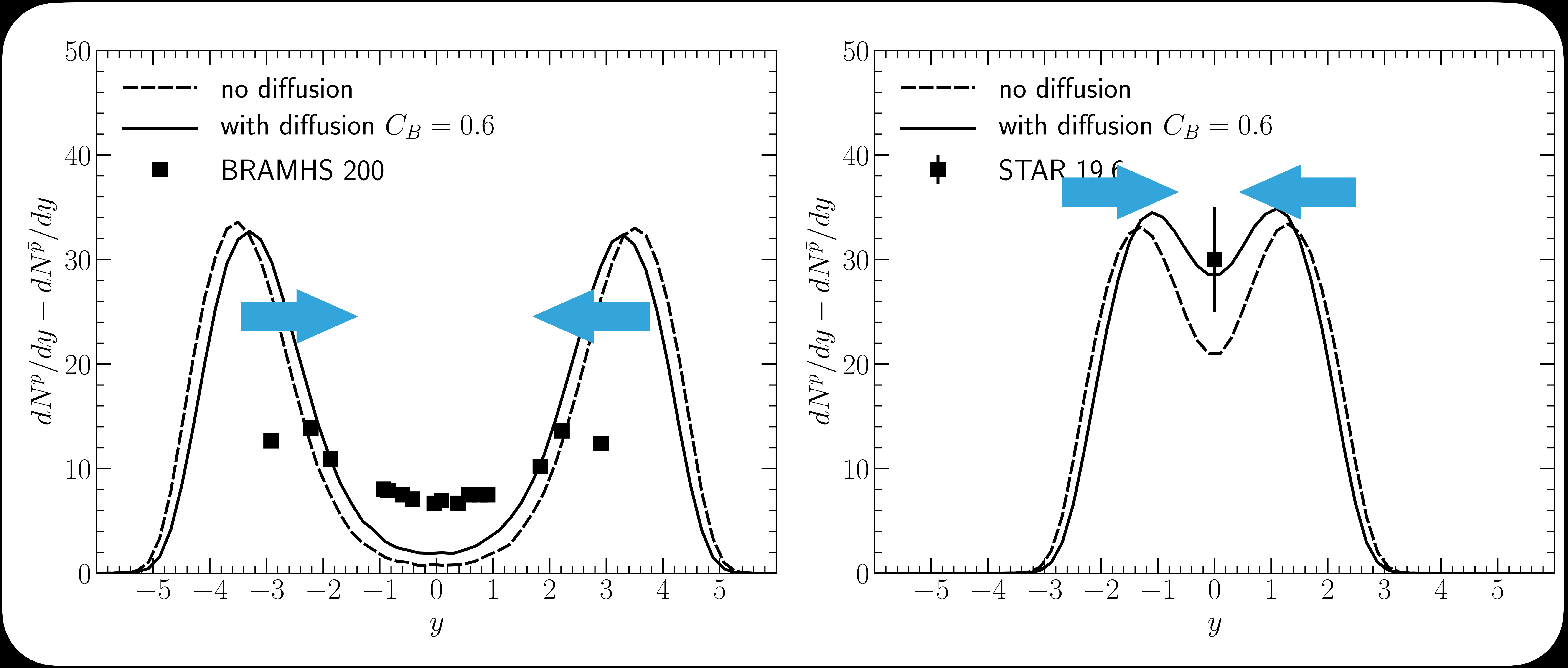
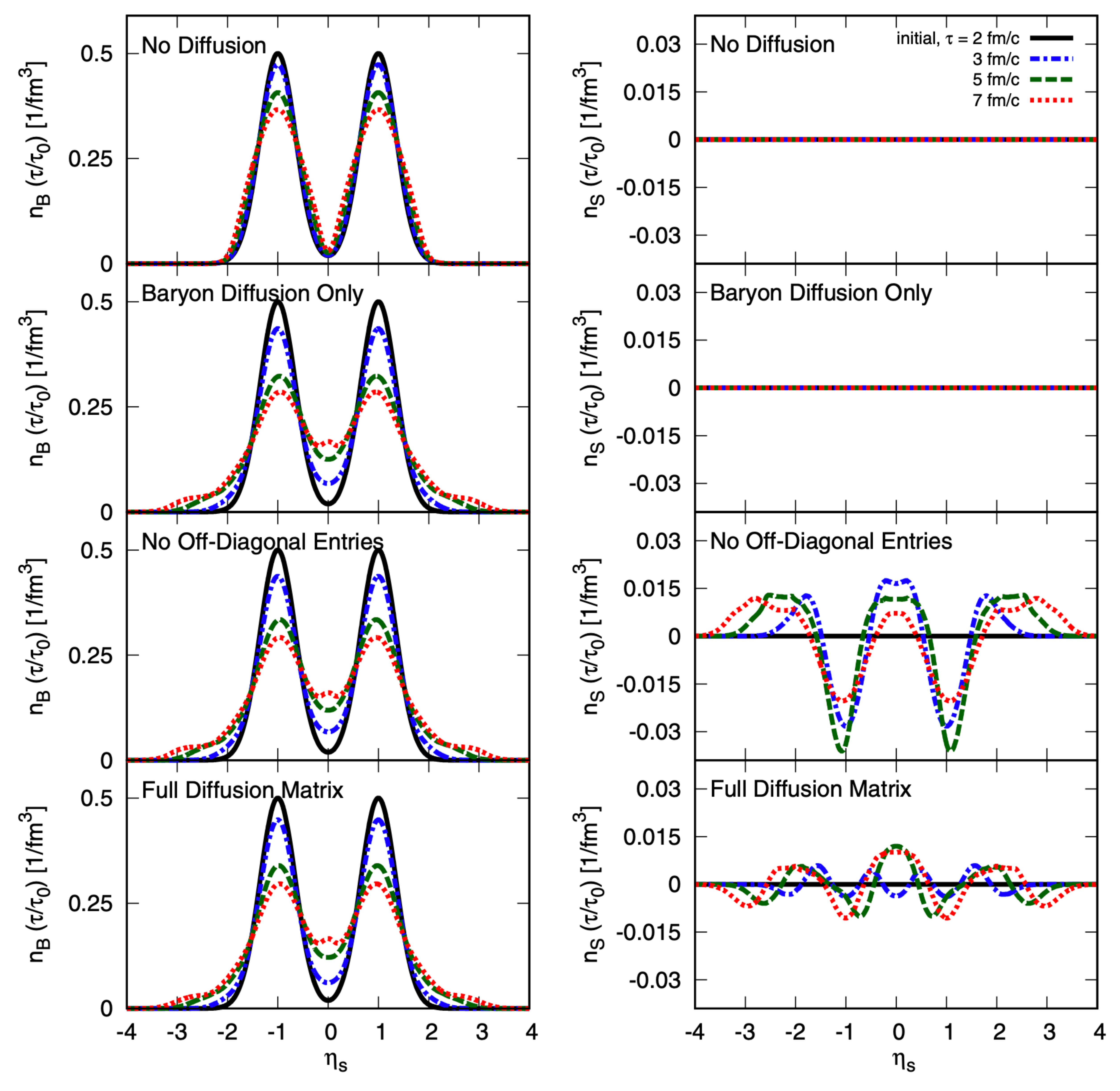


- The net baryon diffusion current is driven by $\nabla^\mu \frac{\mu_B}{T}$; It transports more baryon charges to the mid-rapidity region

ACCESSING NEW QGP TRANSPORT PROPERTY

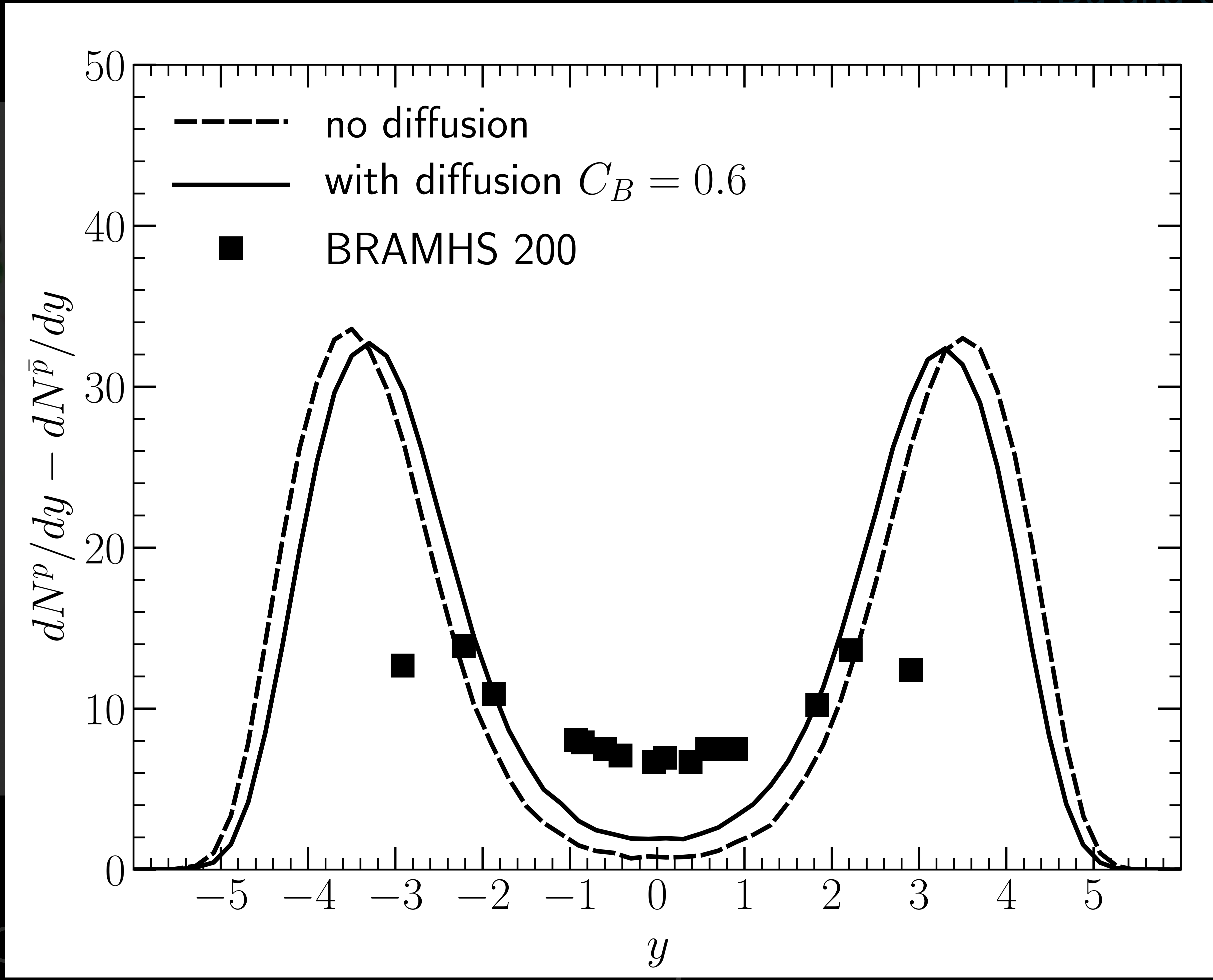


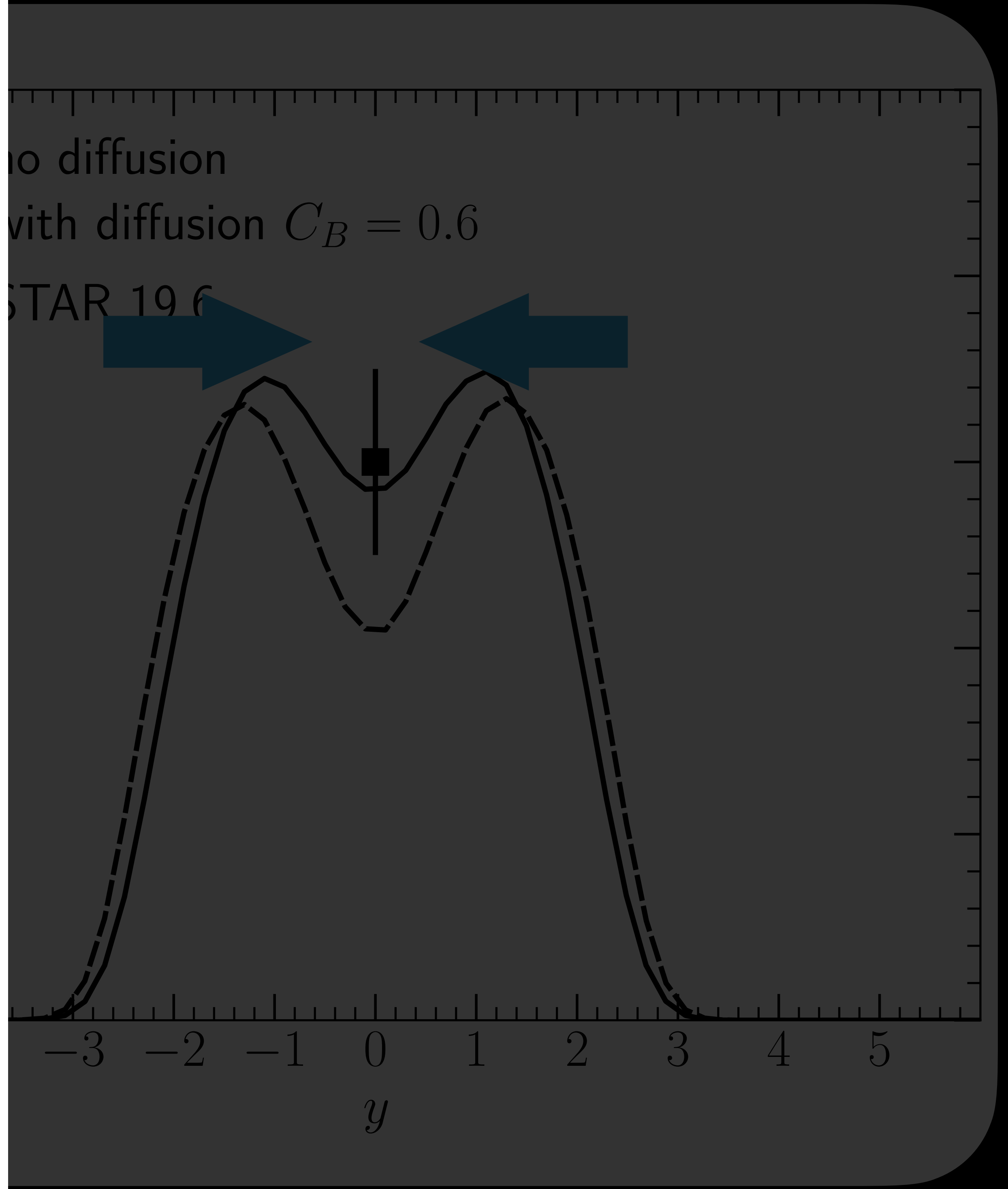
J. A. Fotakis, M. Greif, C. Greiner, G. S. Denicol, and H. Niemi, Phys. Rev. D 101, 076007 (2020)

- Heavy-ion collisions have at least three types conserved charges (B, Q, S)
- Their diffusion processes are mixed with each others
- For $n_S = 0$, the baryon diffusion dominates the evolution of the net baryon current
- The baryon diffusion can cross feed to the evolution of the net strangeness current

ACCESSING NEW QGP TRANSPORT PROPERTY

G. Denicol, C. Gale, S. Jeon, A. Monnai, B. Schenke and C. Shen, Phys. Rev. C98, 034916 (2018)
L. Du and U. Heinz, arXiv:1906.11181 [nucl-th]
...n, Phys. Rev. C 98, 064908 (2018)



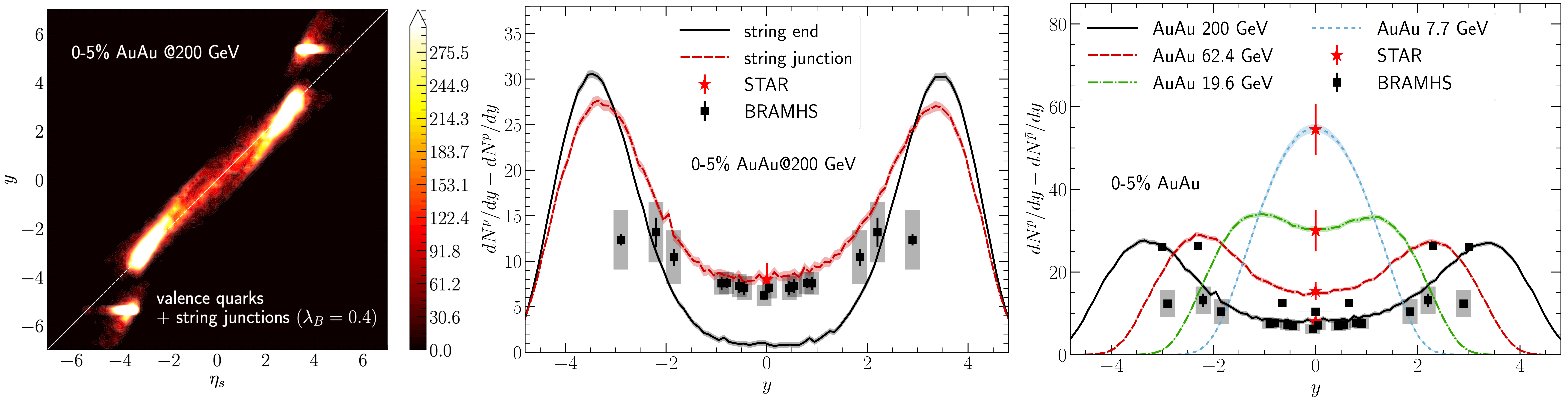


- Net charge diffusi... es to the mid-rapidity region

Not enough in high energy collisions

INITIAL STATE BARYON STOPPING

C. Shen and B. Schenke, in preparation



- Allowing the initial baryon charges to fluctuate to string junctions improves description at high collision energies

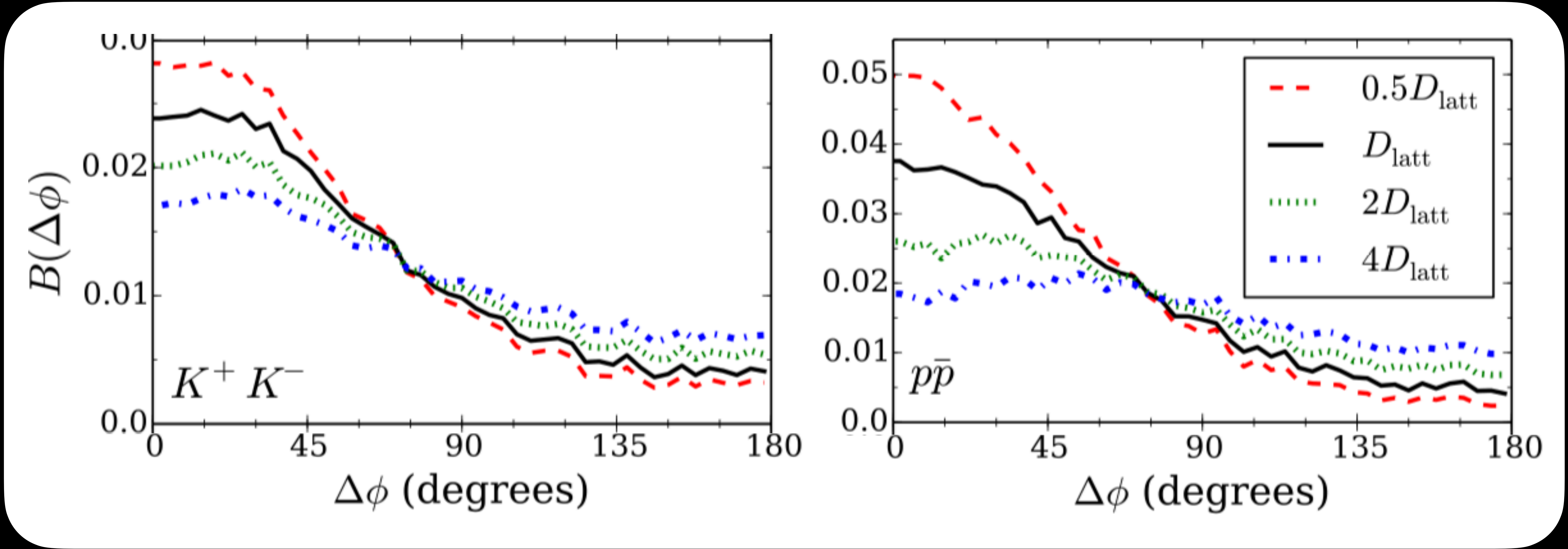
D. Kharzeev, Phys. Lett. B 378, 238 (1996)

Interplay between baryon diffusion and initial fluctuations

ACCESSING NEW QGP TRANSPORT PROPERTY

J. Kapusta and C. Plumberg, Phys. Rev. C97, 014906 (2018)

S. Pratt and C. Plumberg, arXiv:1904.11459 [nucl-th]



- A larger diffusion constant diffuse the charge pair more away from each other — widened the charge balance function in the azimuthal direction

An independent observable to constrain charge diffusion

SUMMARY

- Relativistic heavy-ion collisions over 3 orders of magnitude in collision energy map out the phase structure of hot QCD matter

    Search for a critical point and the first-order phase transition

    Build connections with neutron star/black hole mergers

- Full 3D hybrid framework starts to quantitatively describe bulk observables at the RHIC BES program

    First principle inputs from lattice QCD

    Elucidating the initial baryon stopping, charge diffusion, and collectivity of QGP in a baryon rich environment

    Consistent 3D dynamical descriptions of pp, pA, and AA collisions