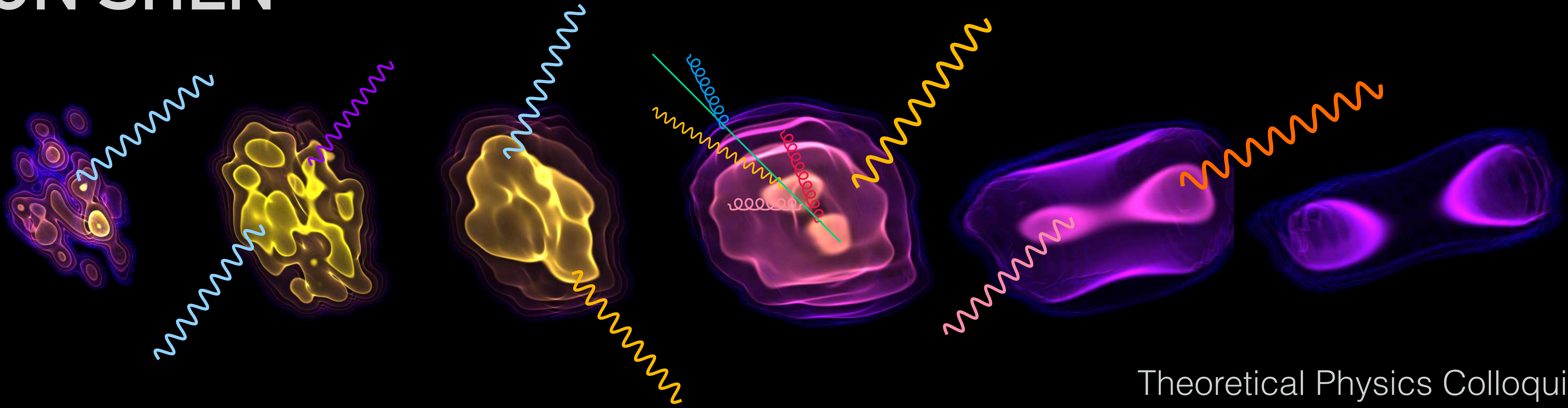
RBRC
RIKEN BNL Research Center

BEST COLLABORATION

JETSCAPE

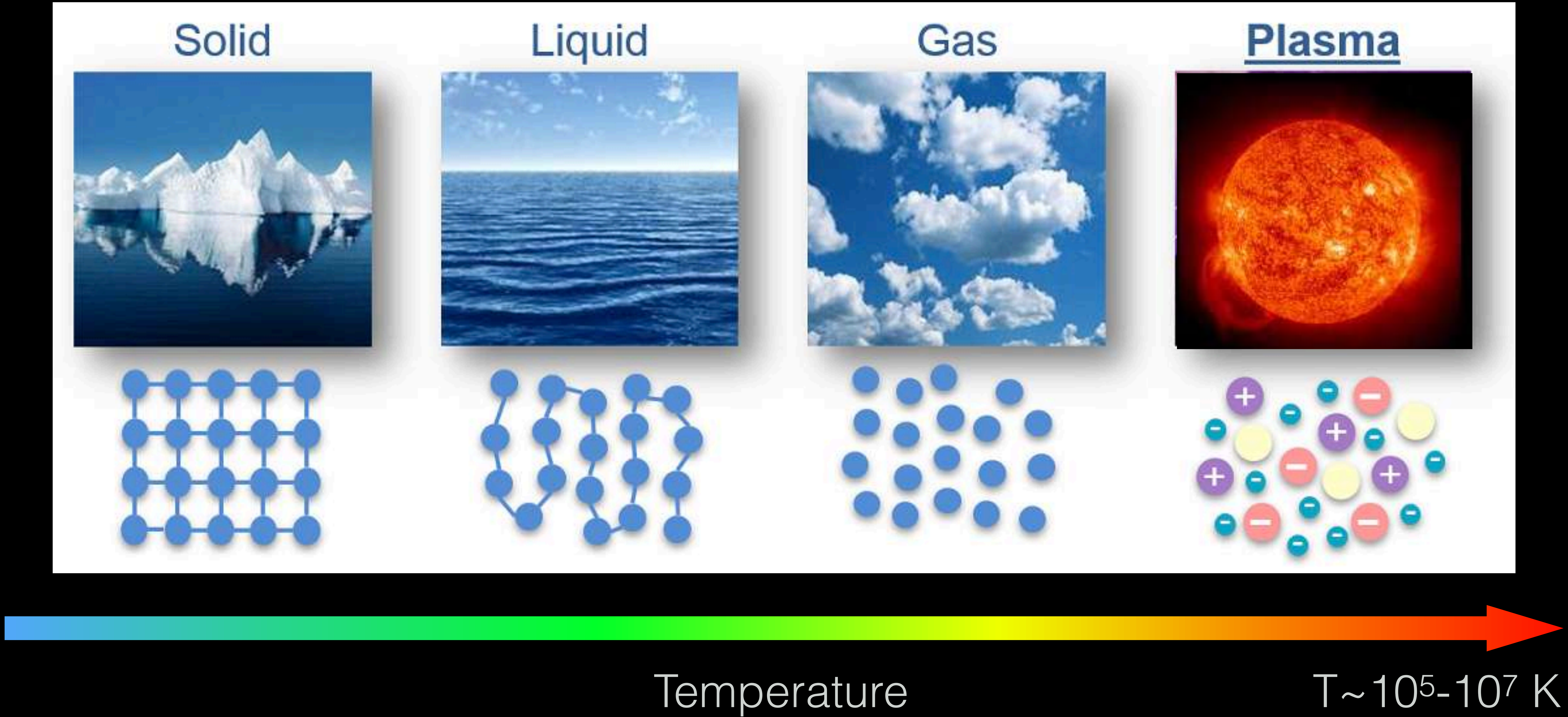
MULTI-MESSENGER HEAVY-ION PHYSICS

CHUN SHEN



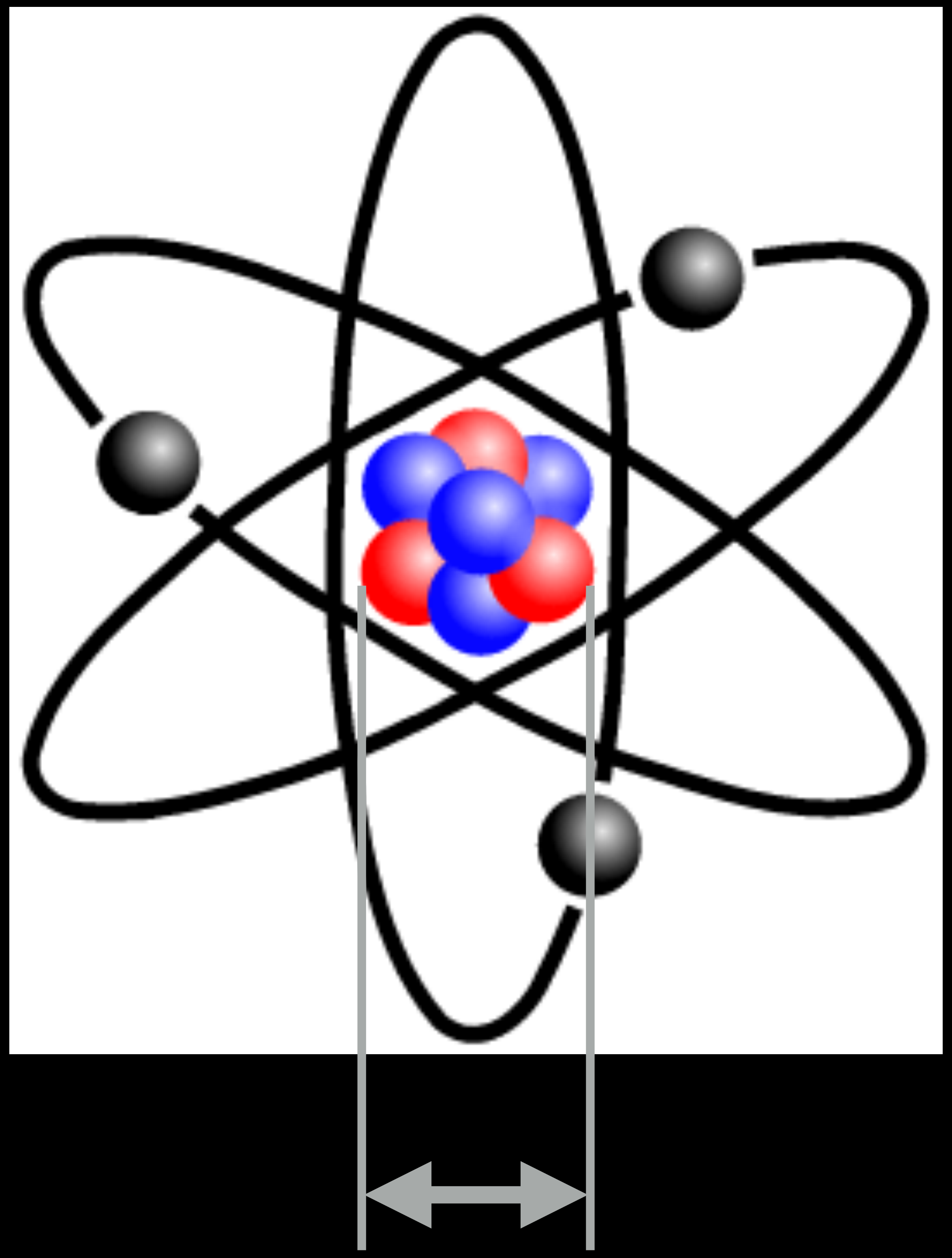
Theoretical Physics Colloquium
March 31, 2021

EXPLORING THE PHASE OF MATTER



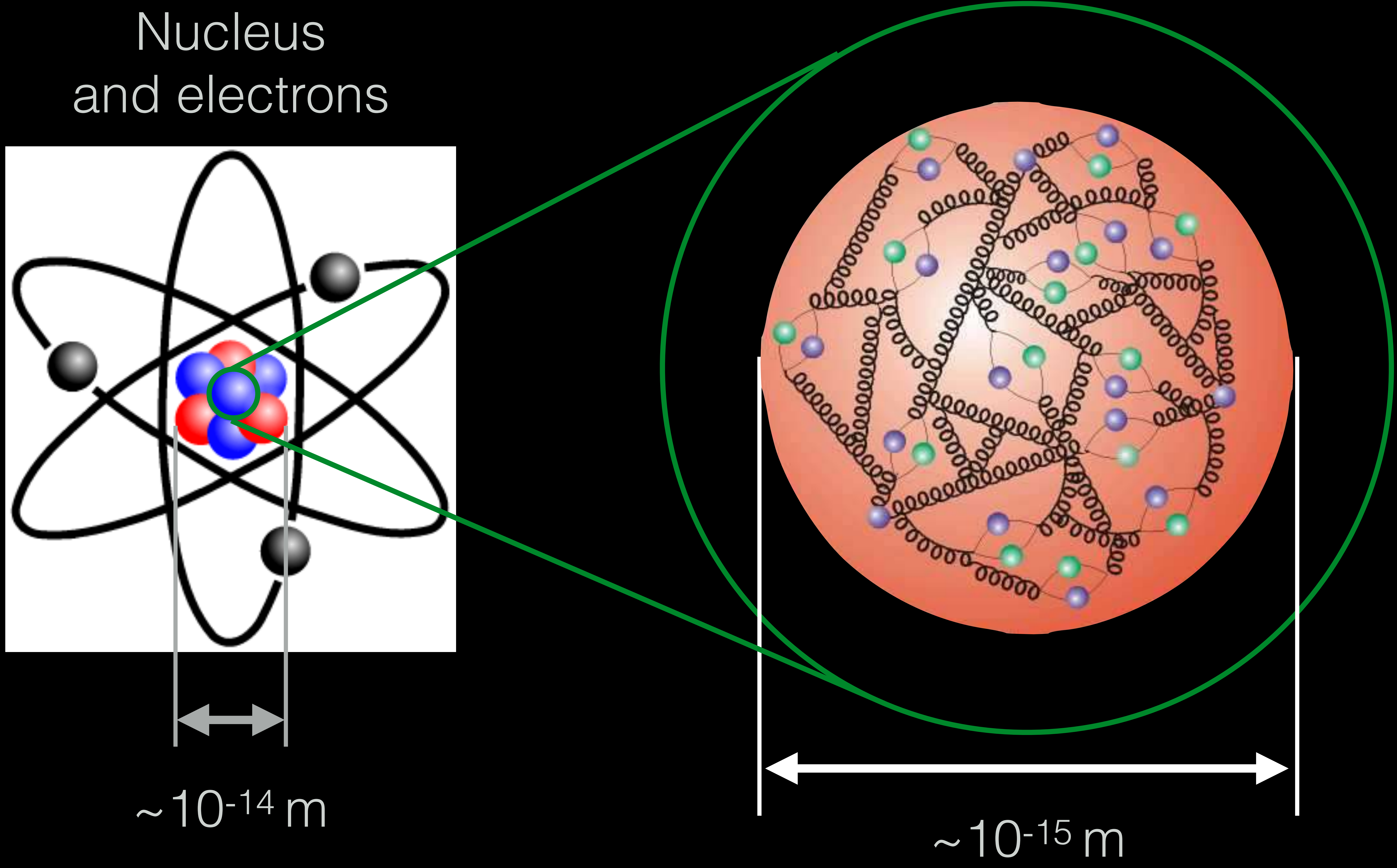
EXPLORING THE PHASE OF MATTER

Nucleus
and electrons

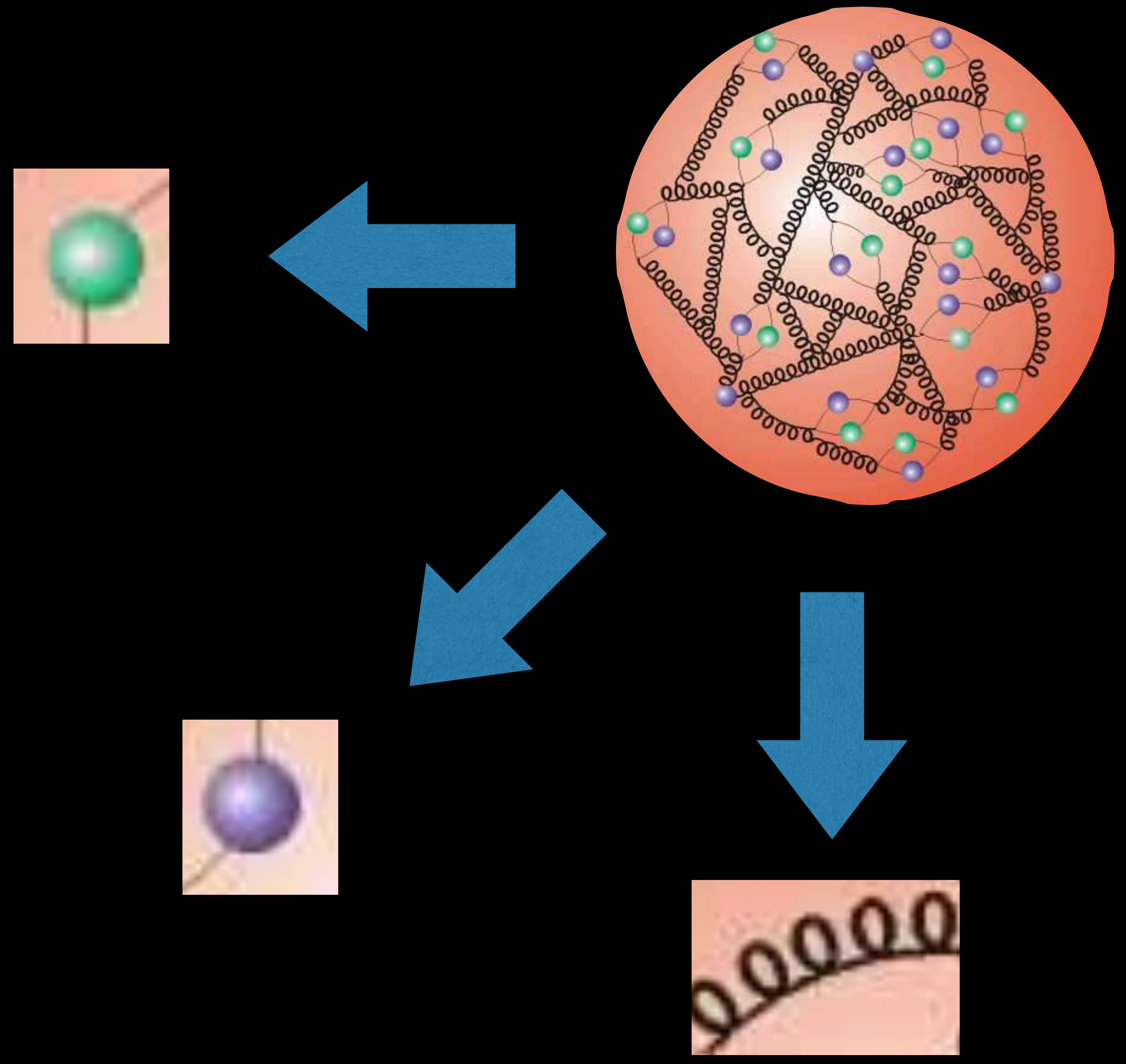


$\sim 10^{-14}$ m

EXPLORING THE PHASE OF MATTER

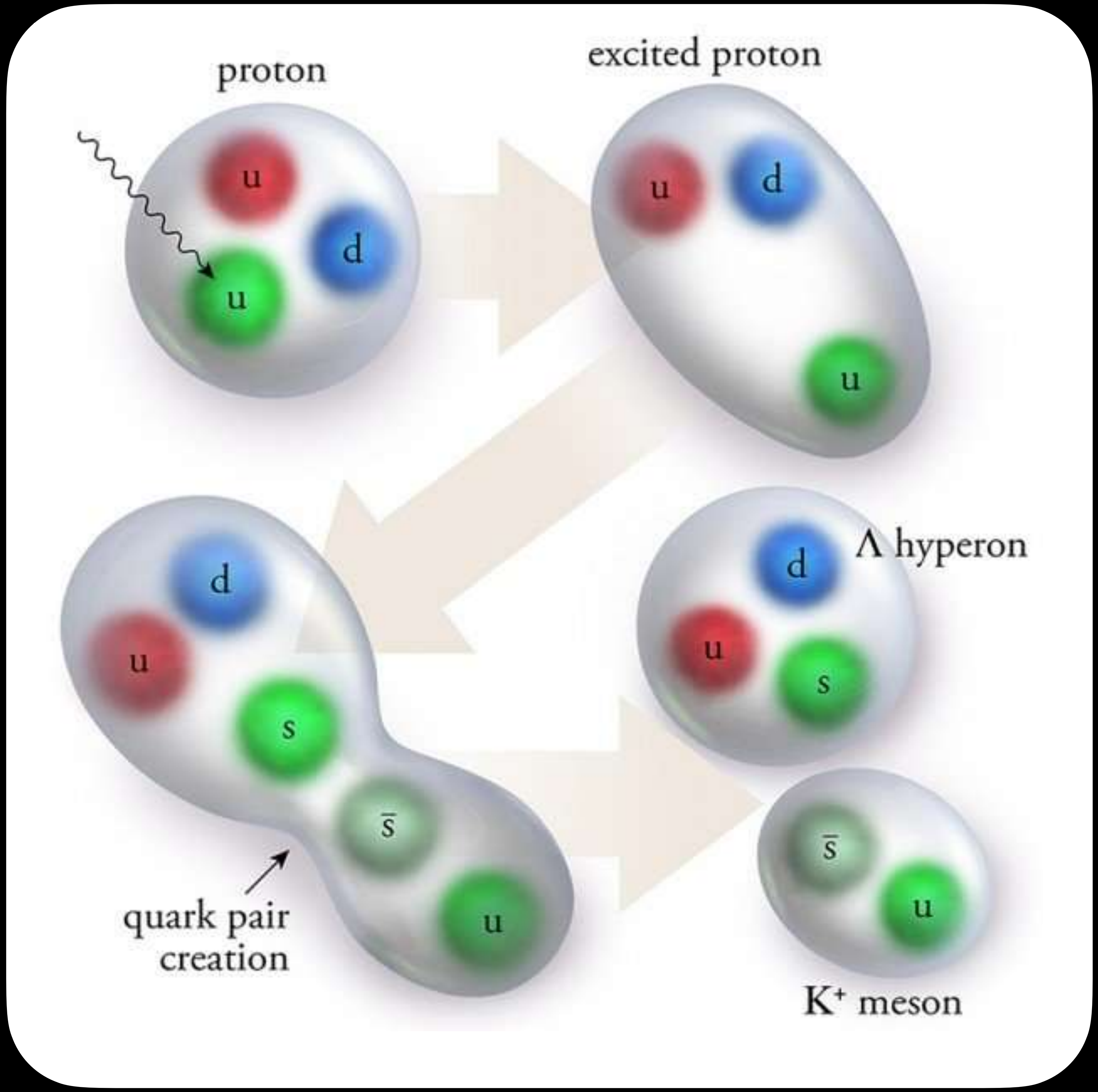


EXPLORING THE PHASE OF MATTER



Strip off individual quarks and gluons?

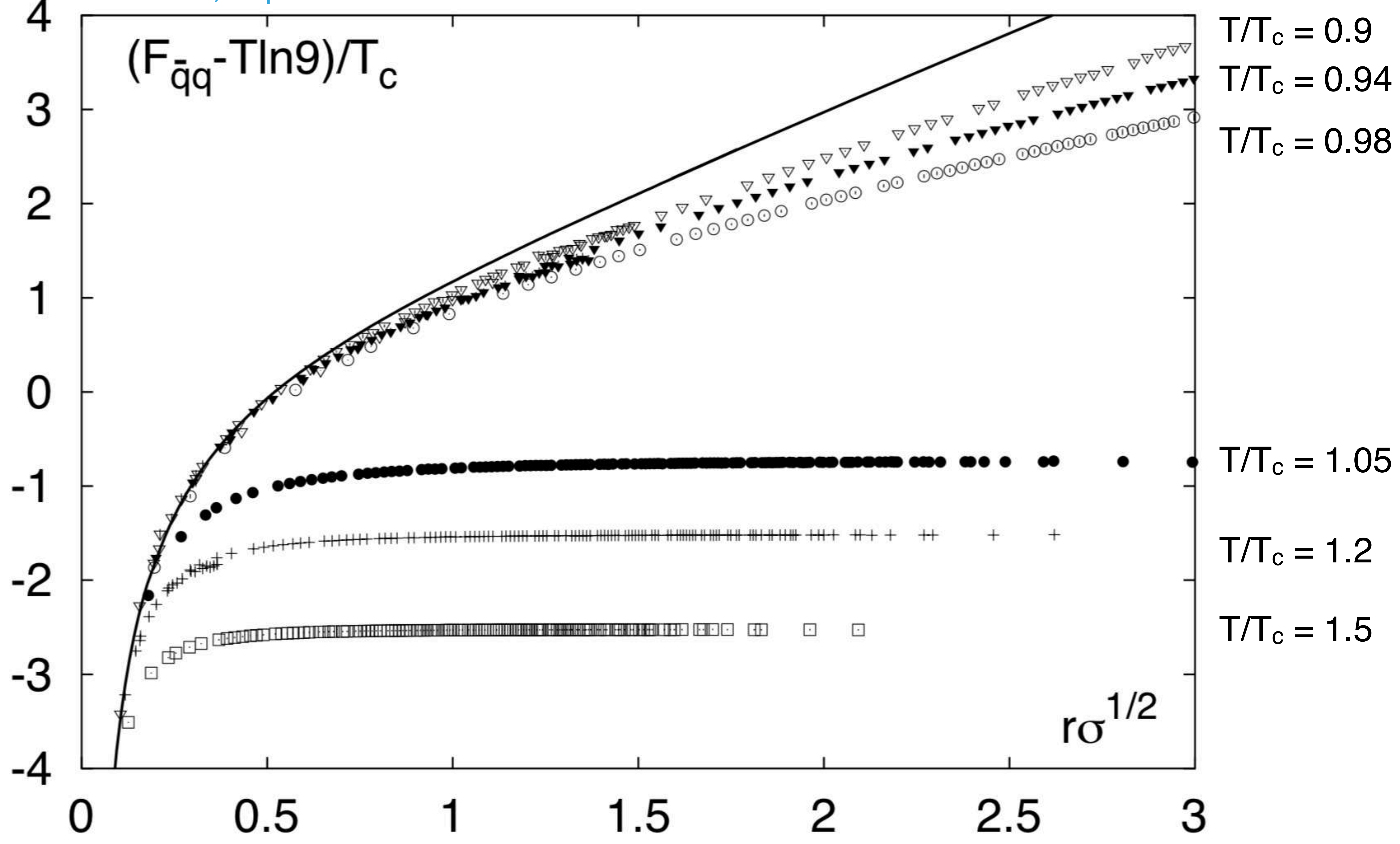
EXPLORING THE PHASE OF MATTER



Impossible because of linearly increasing separation energy

COLOR SCREENING AT HIGH TEMPERATURE

F. Karsch, hep-lat/0403016



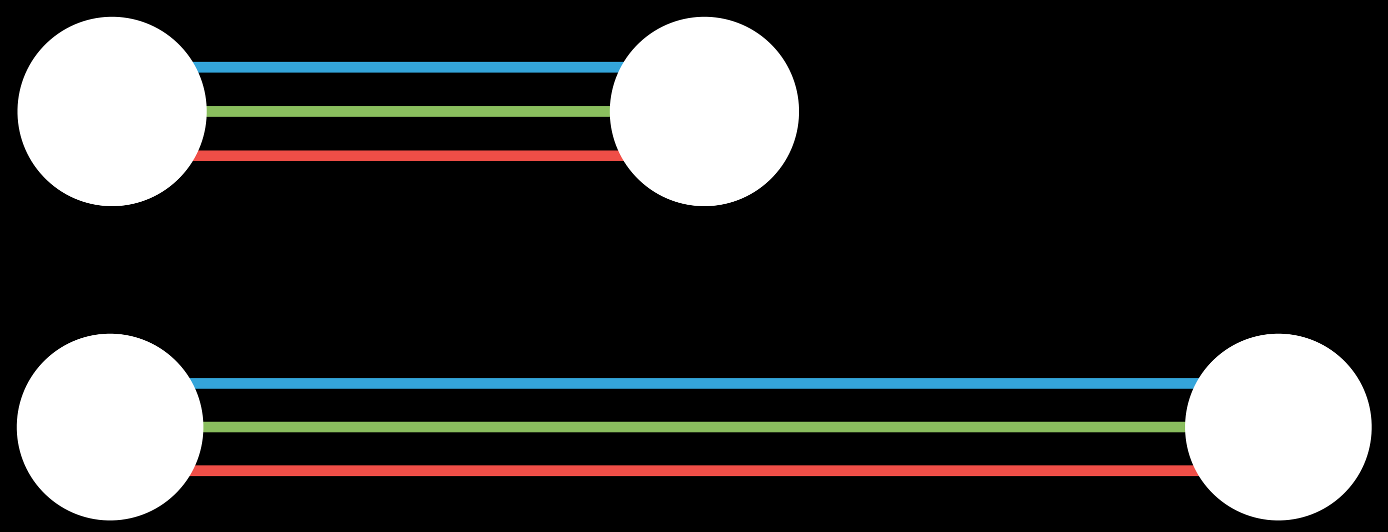
- The color averaged heavy quark free energy

$$\phi^a = t^a \frac{\alpha_s}{r} e^{-\mu r}$$

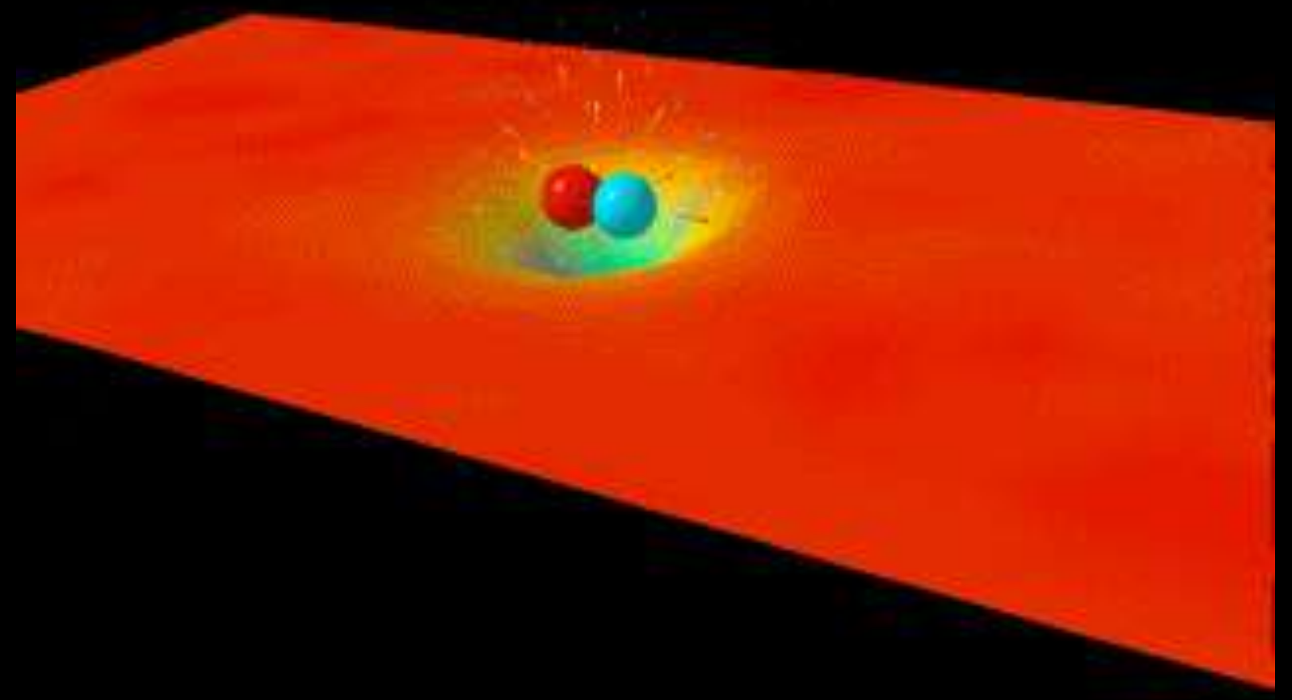
Full (2+1) flavor results in Phys. Rev. D 98, 054511 (2018)

WHAT DOES IT MEAN?

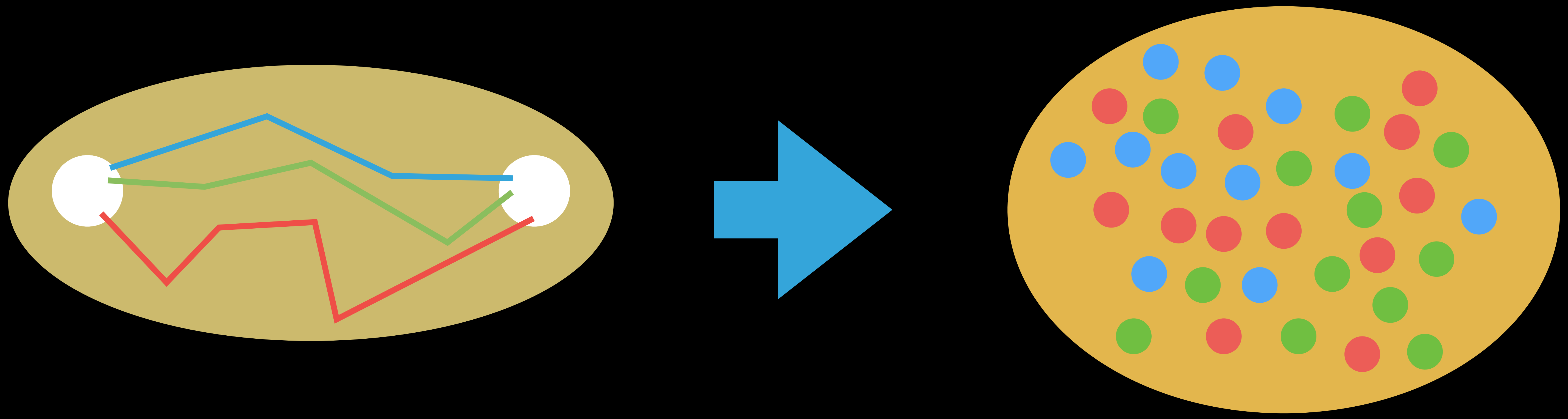
Low temperature: color flux tube extends



http://www.physics.adelaide.edu.au/theory/staff/leinweber/VisualQCD/Nobel/



At high temperature

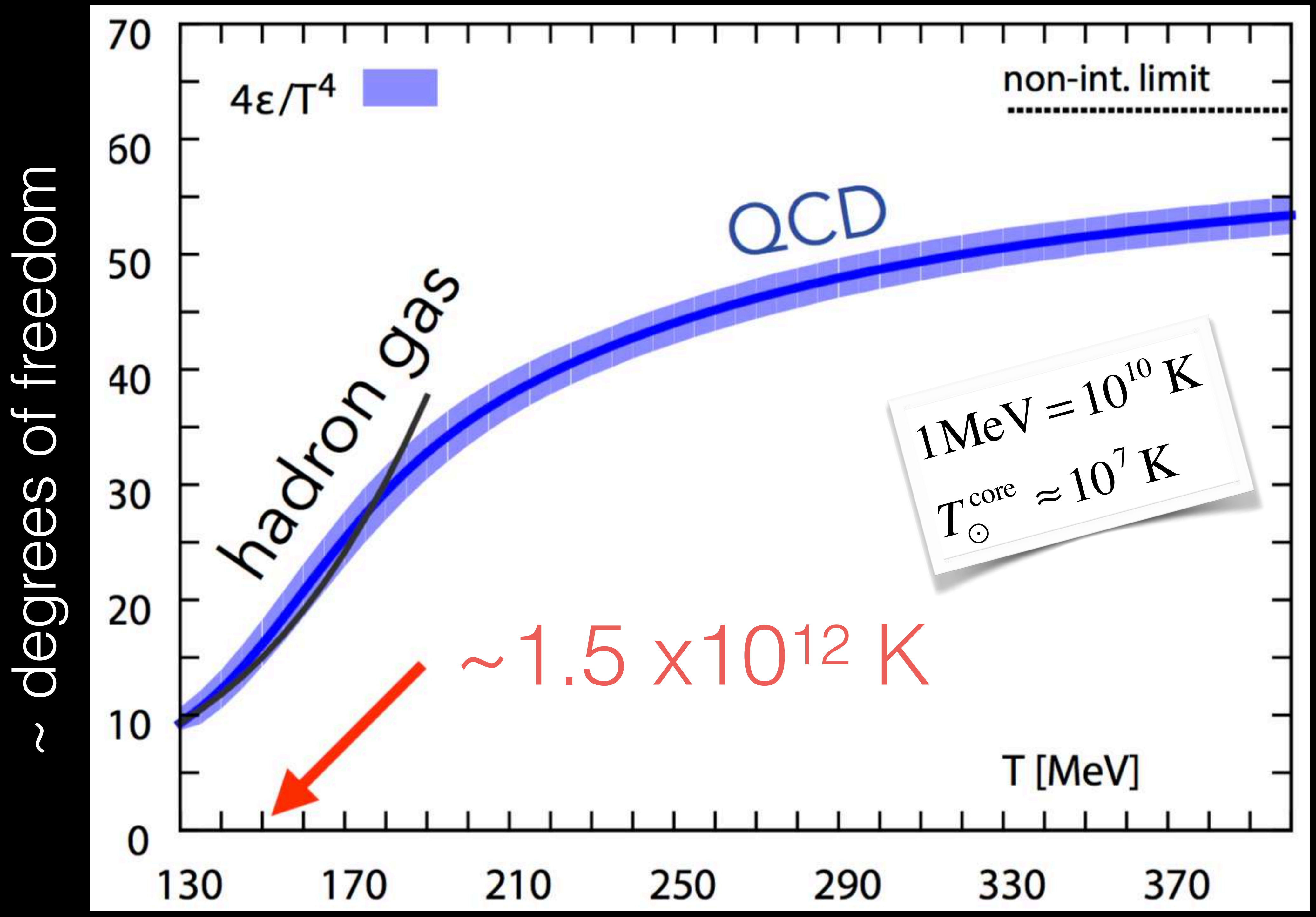


The color fields are screened;
Randomly kicked by thermal particles

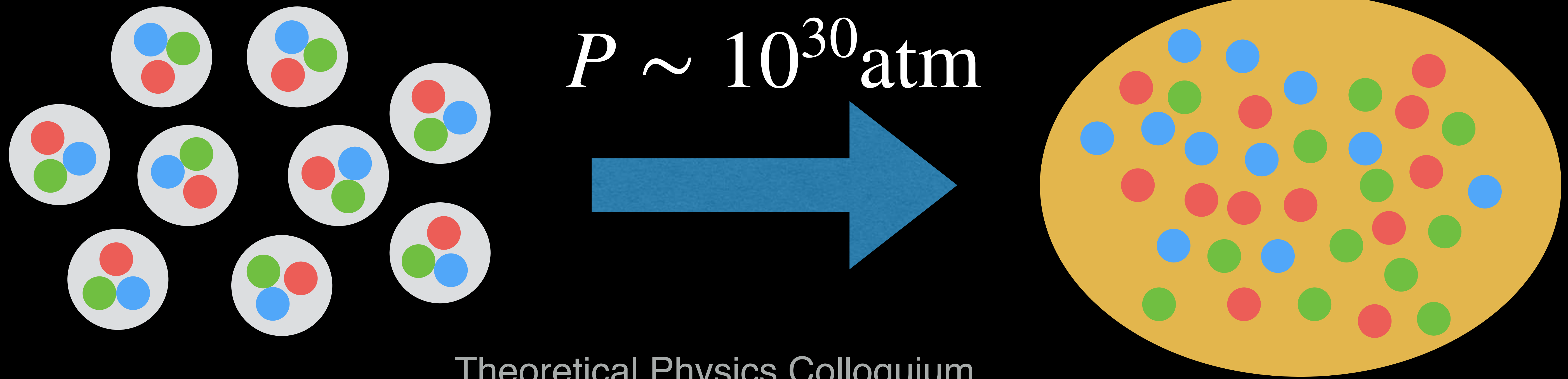
MATTER IN EXTREME CONDITIONS

Quantum Chromo-Dynamics (QCD) predicts crossover to a system of liberated quarks and gluons above a temperature of ~ 2 trillion degrees

HotQCD Collaboration, Phys.Rev. D90 (2014) 094503



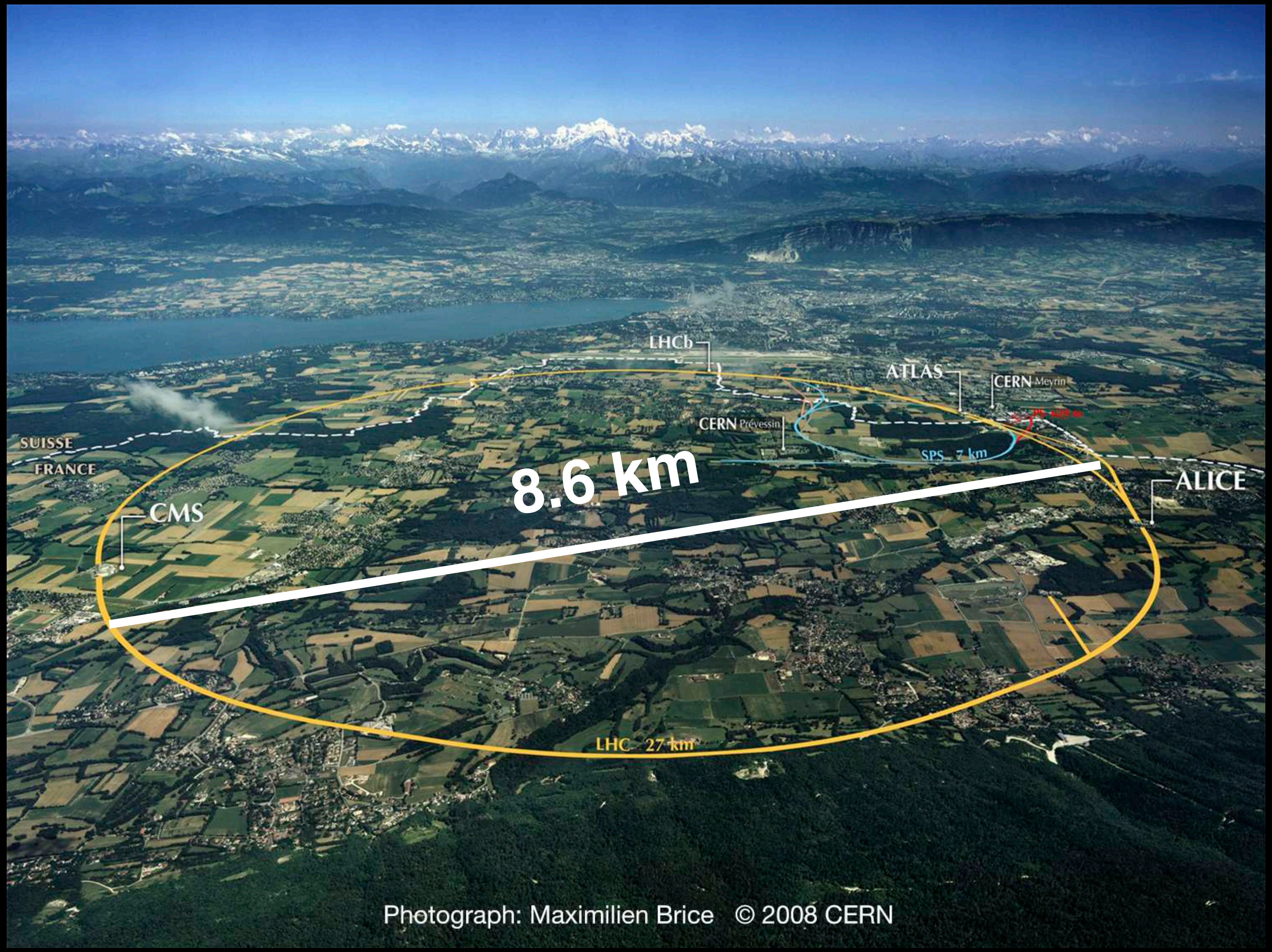
Quark-Gluon Plasma



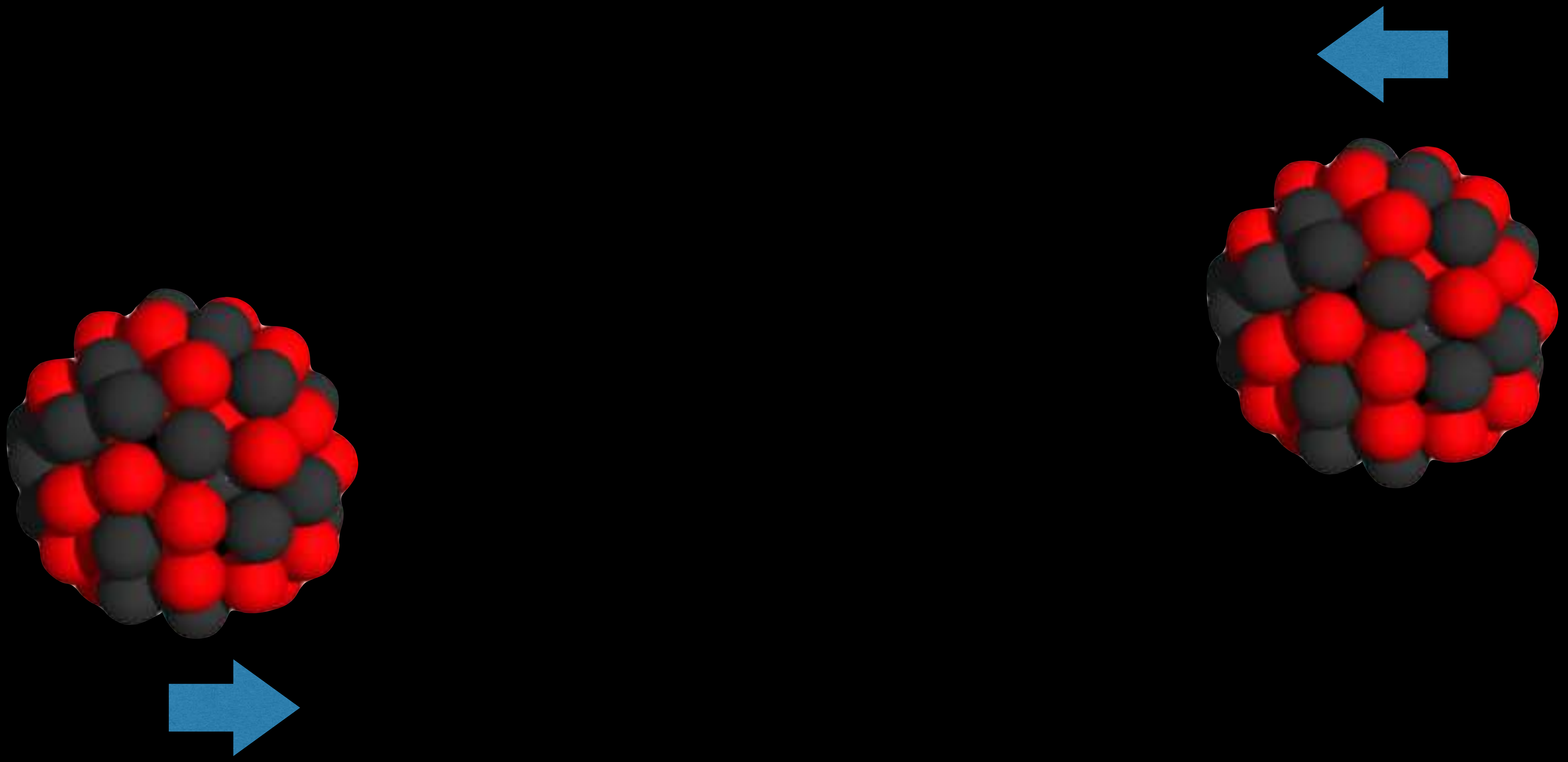
HOW TO ACHIEVE TRILLION DEGREE TEMPERATURE?

Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Lab

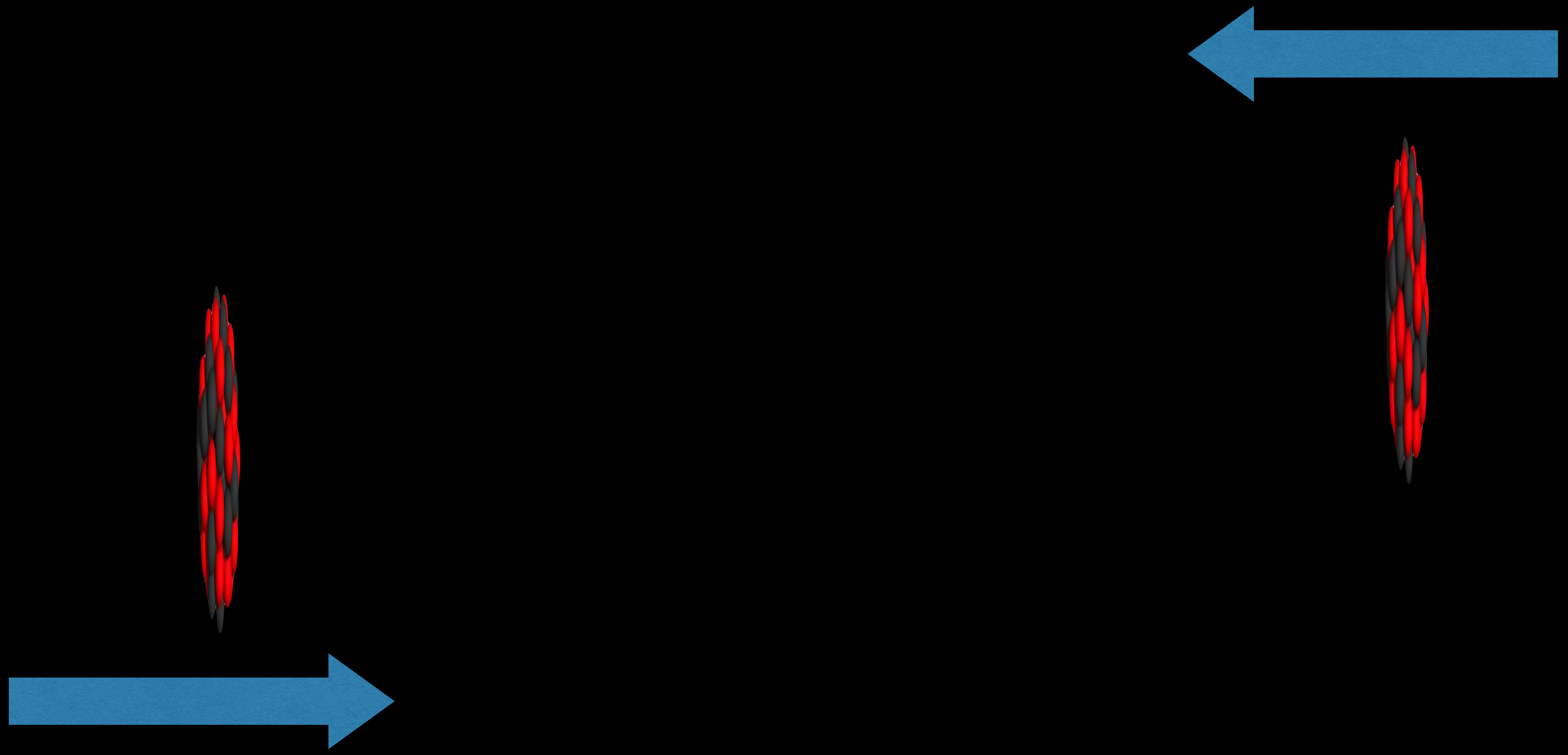
Large Hadron Collider (LHC) at CERN



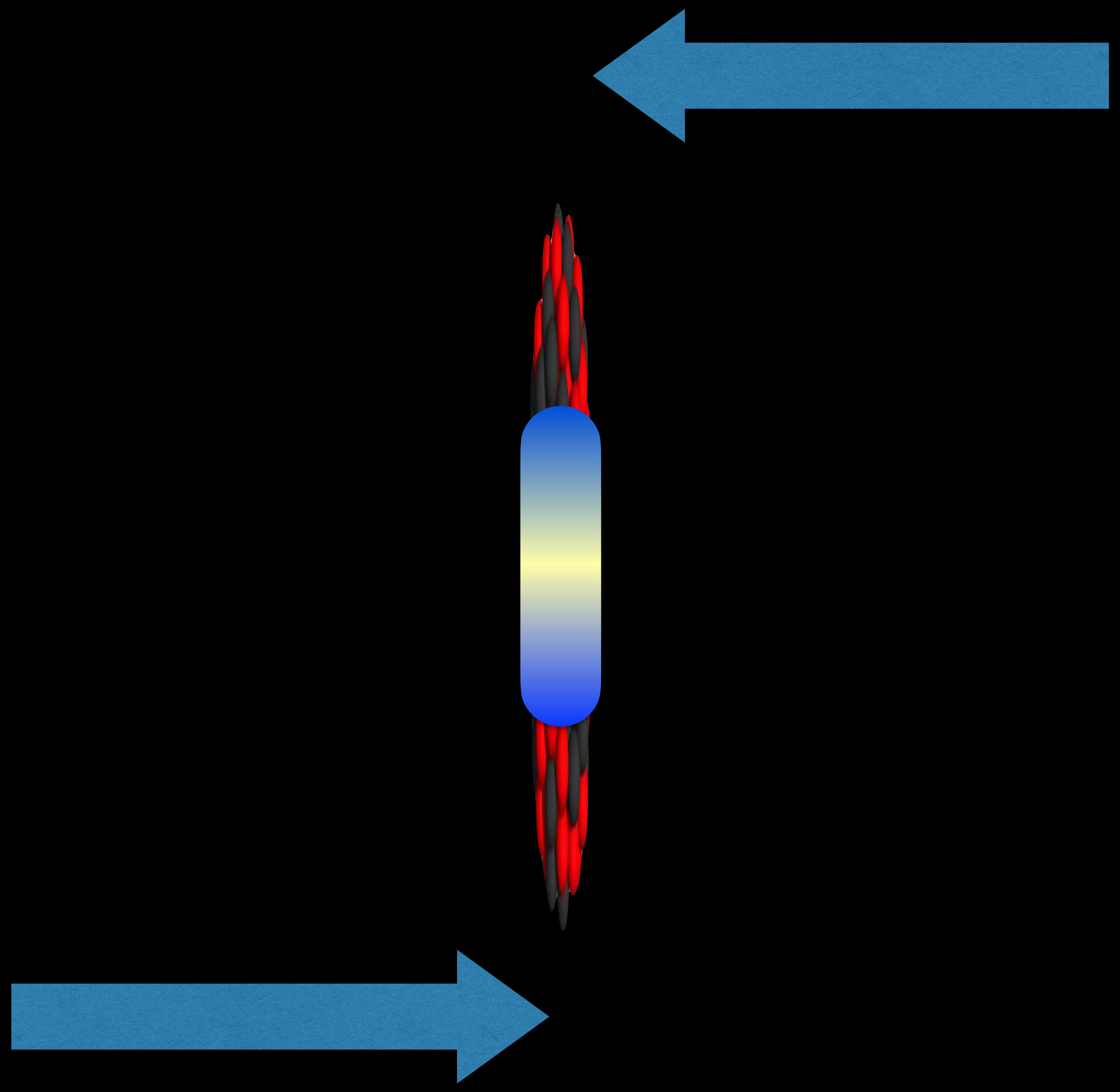
RELATIVISTIC HEAVY-ION COLLISIONS



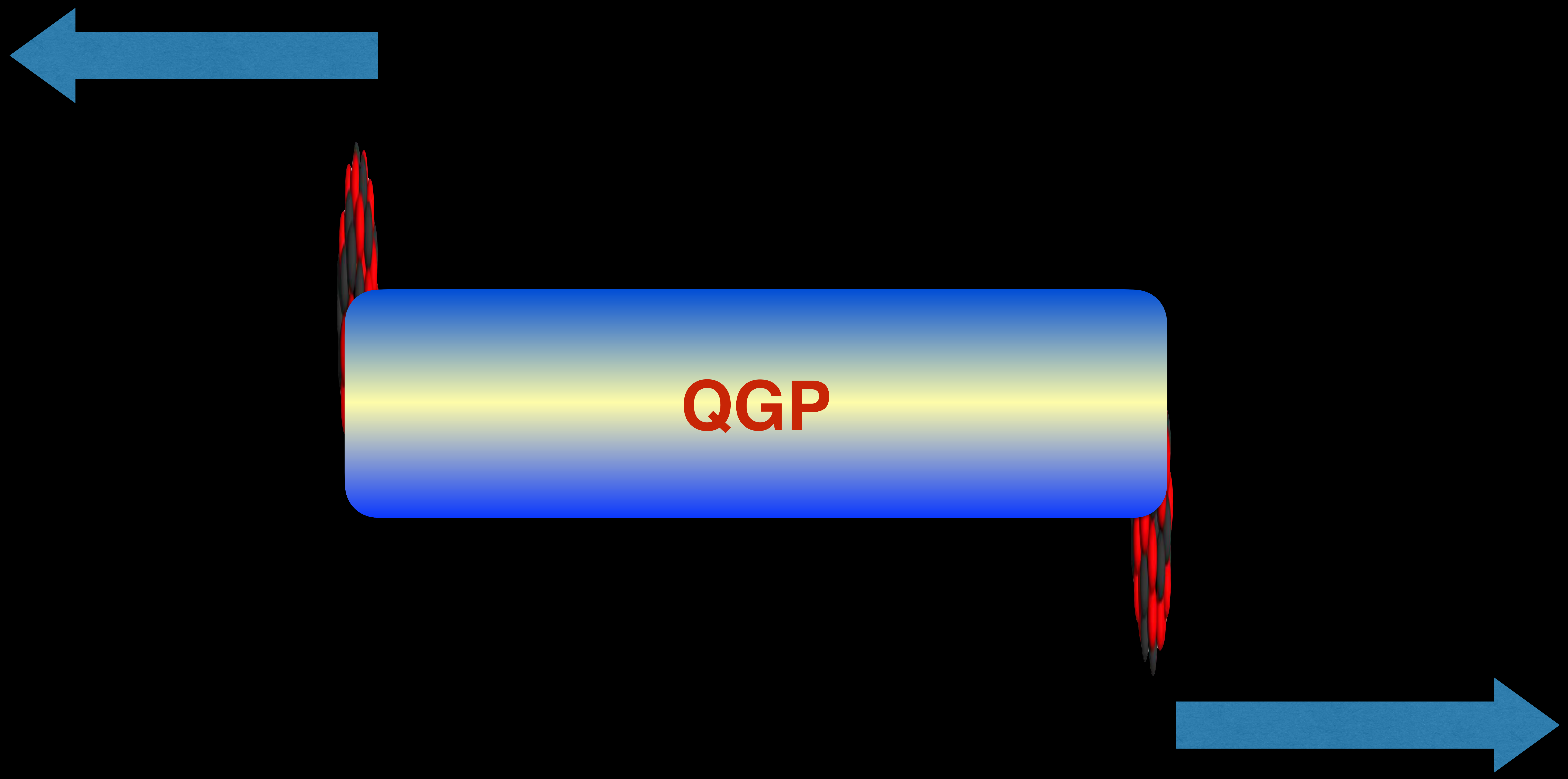
RELATIVISTIC HEAVY-ION COLLISIONS



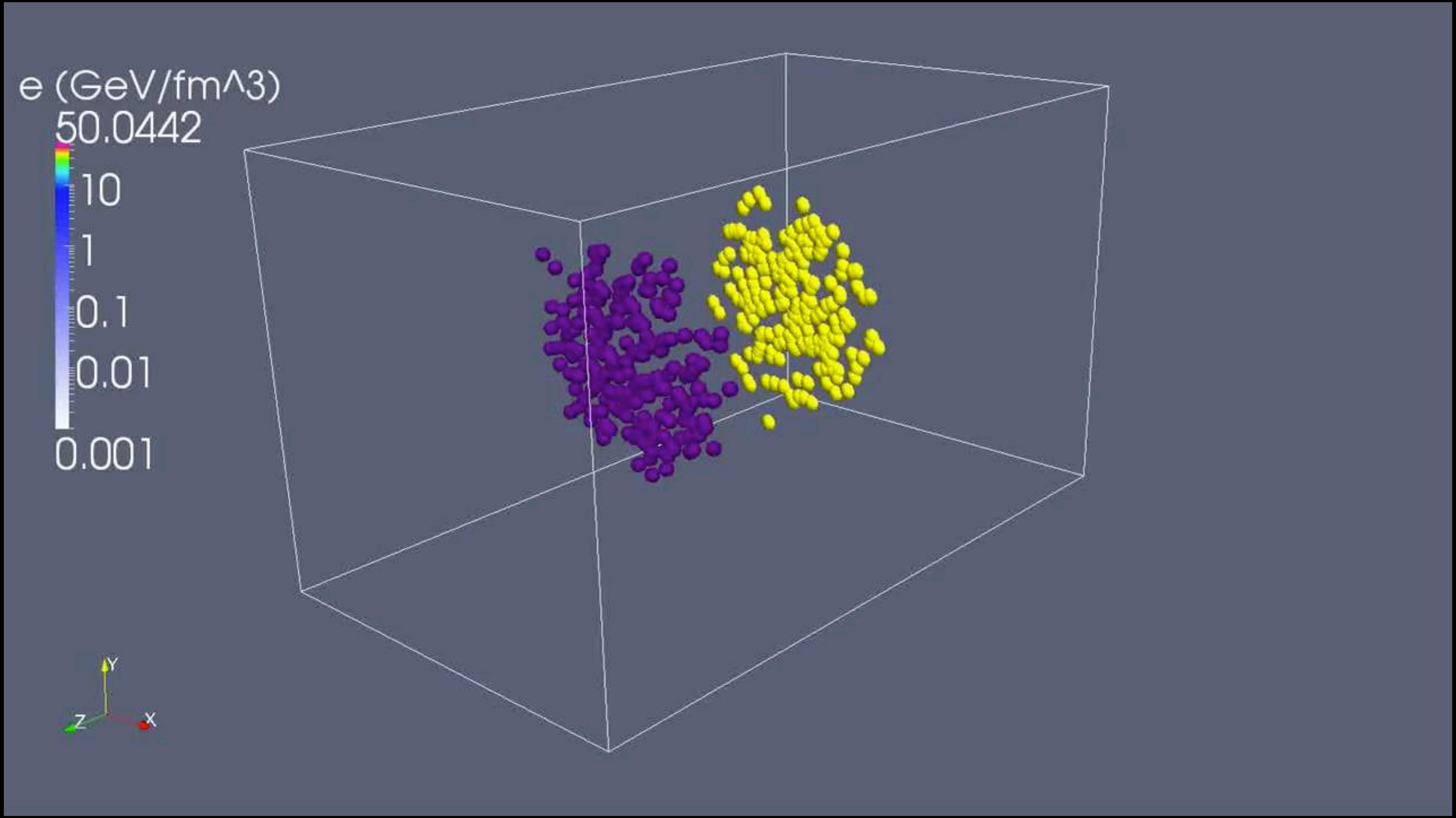
RELATIVISTIC HEAVY-ION COLLISIONS



RELATIVISTIC HEAVY-ION COLLISIONS

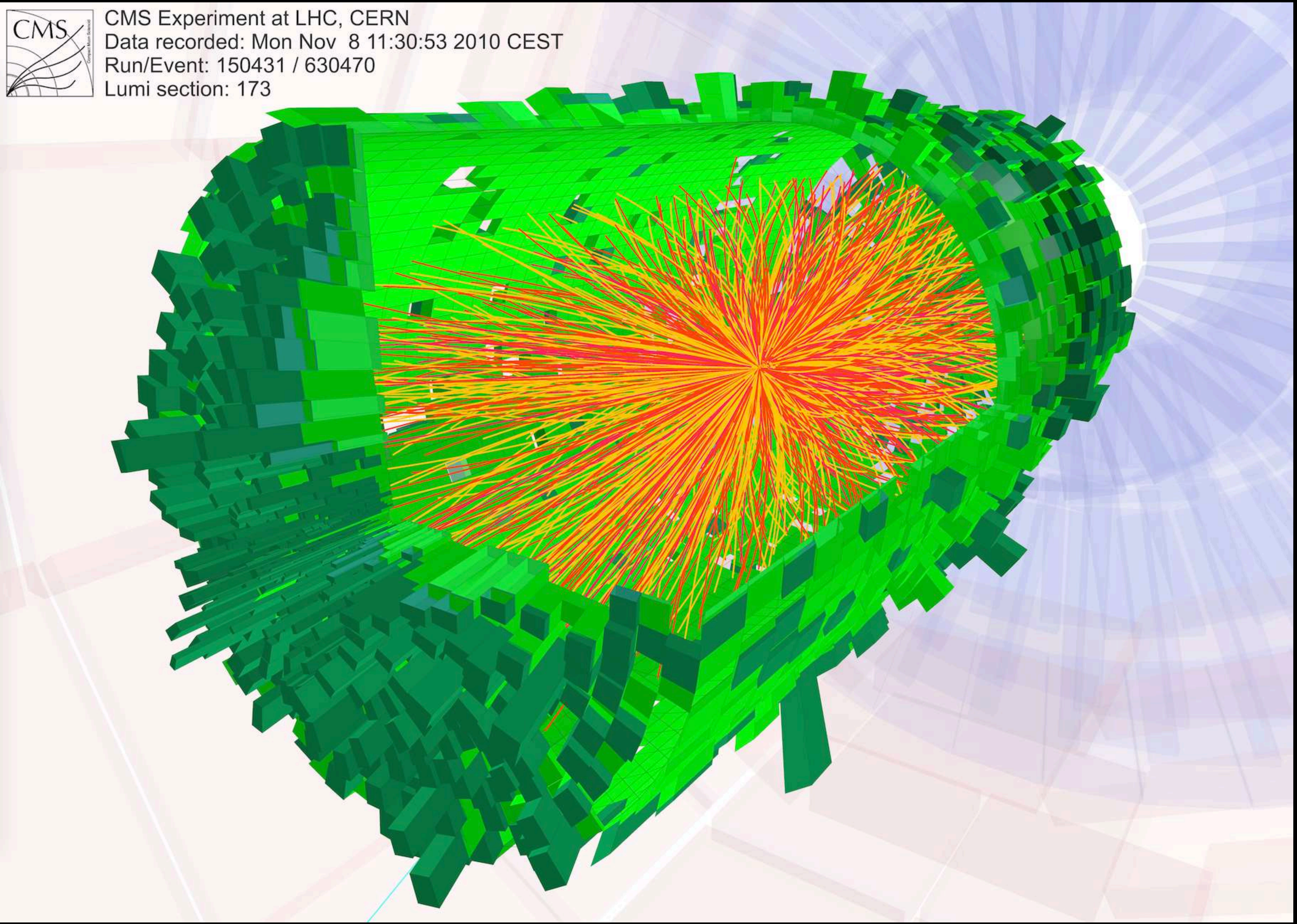


A "LITTLE BANG"

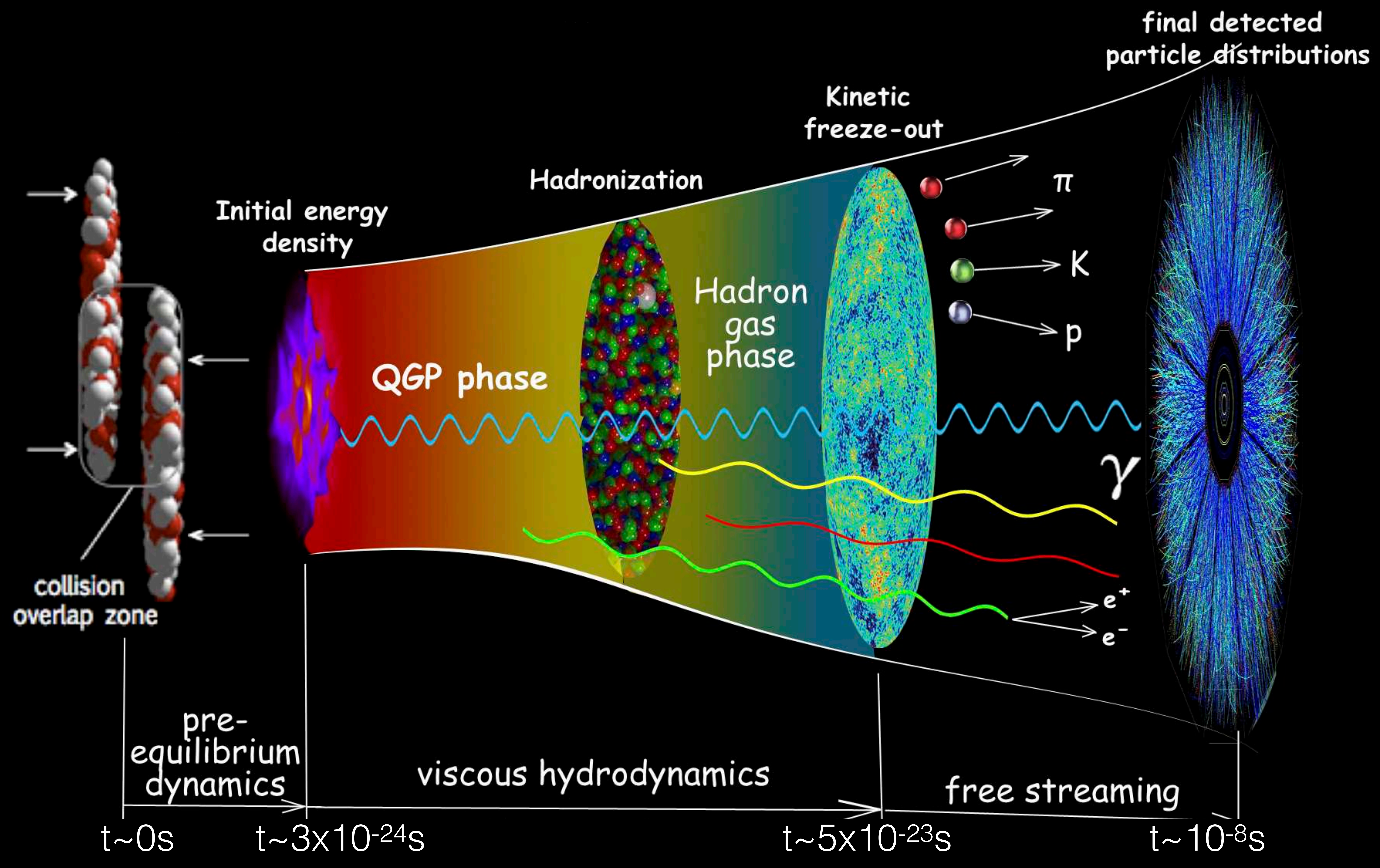


http://youtu.be/W3h5vQOUJTg

A PB+PB COLLISION AT THE LARGE HADRON COLLIDER

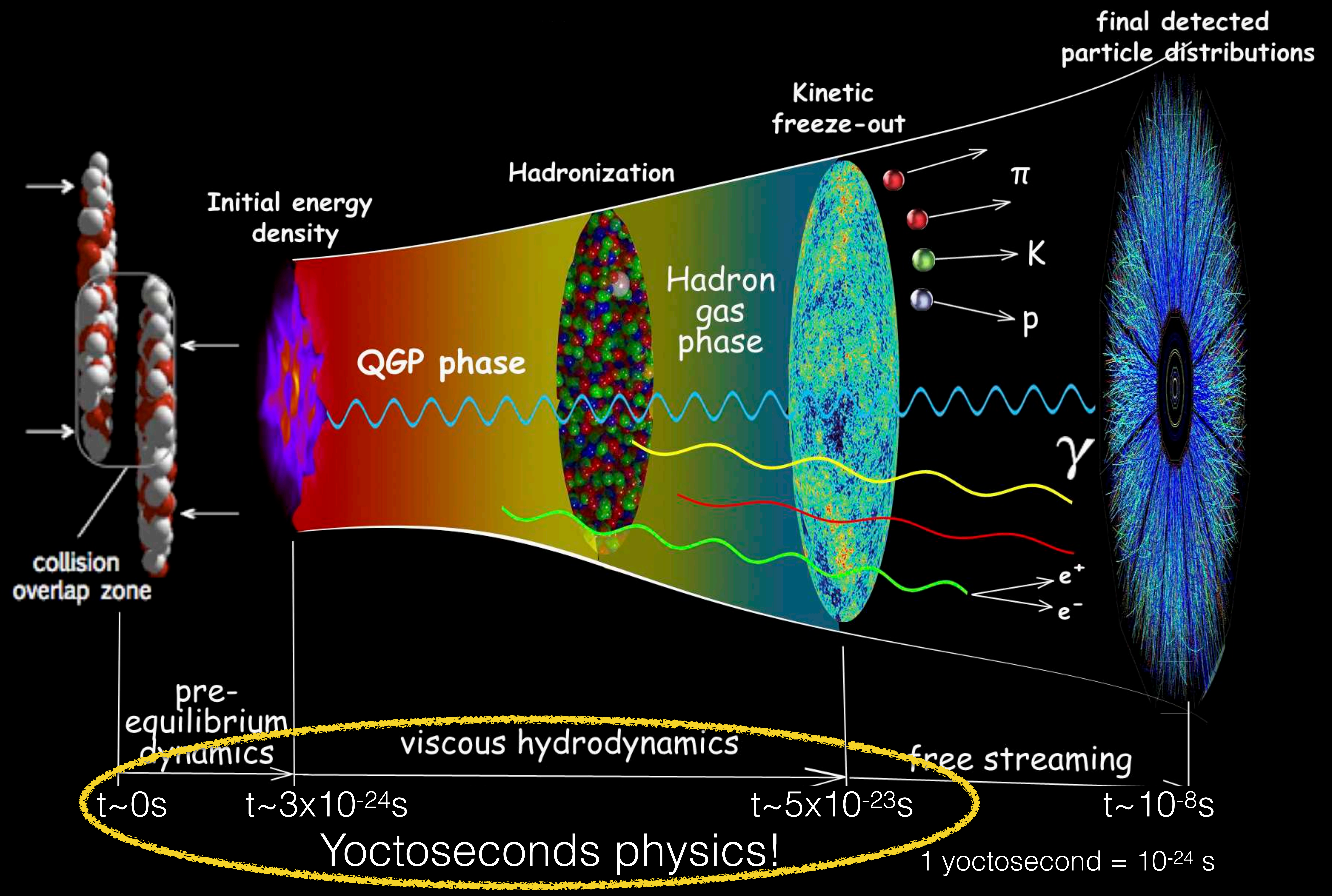


RELATIVISTIC HEAVY-ION COLLISIONS



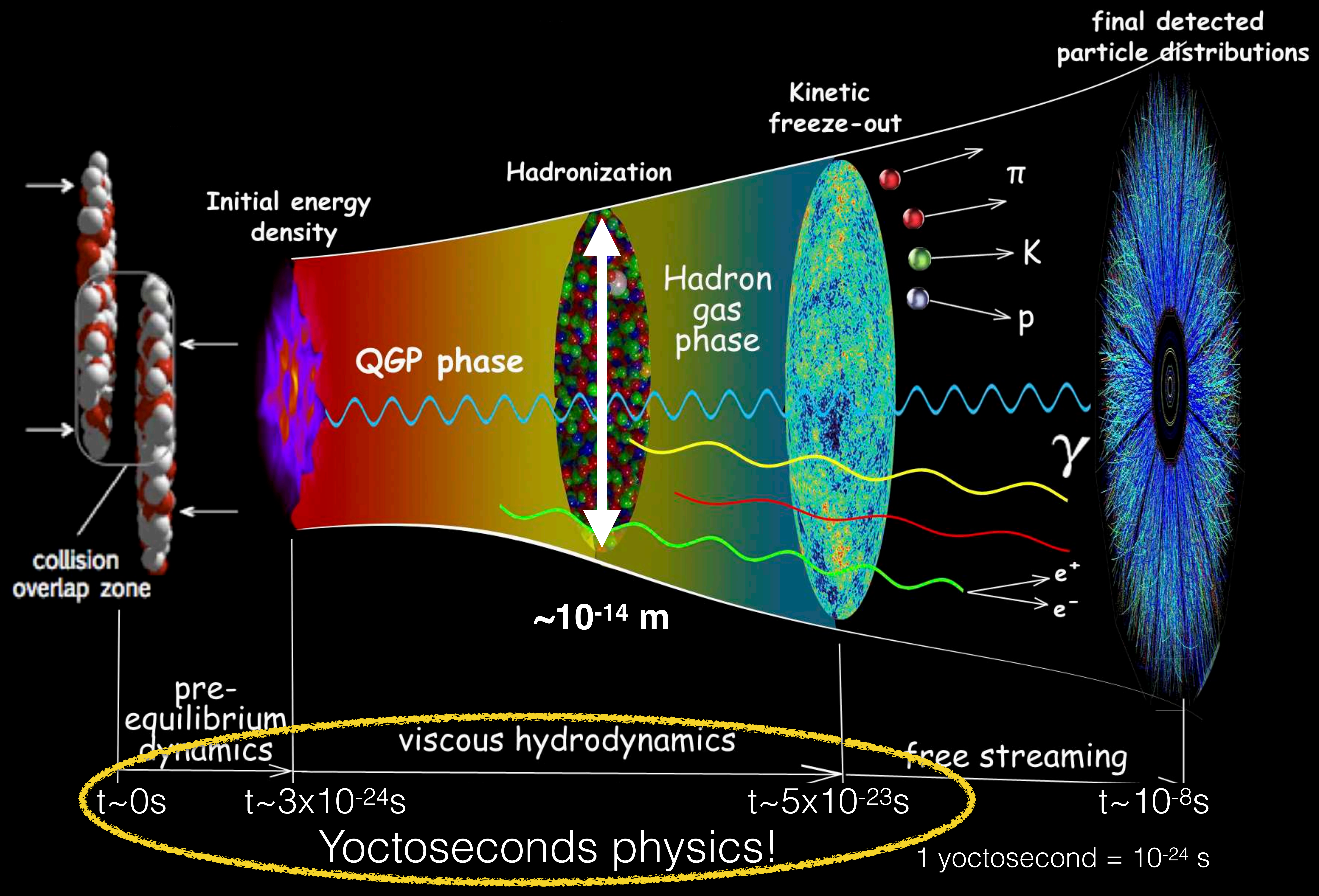
1 yoctosecond = 10^{-24} s

RELATIVISTIC HEAVY-ION COLLISIONS



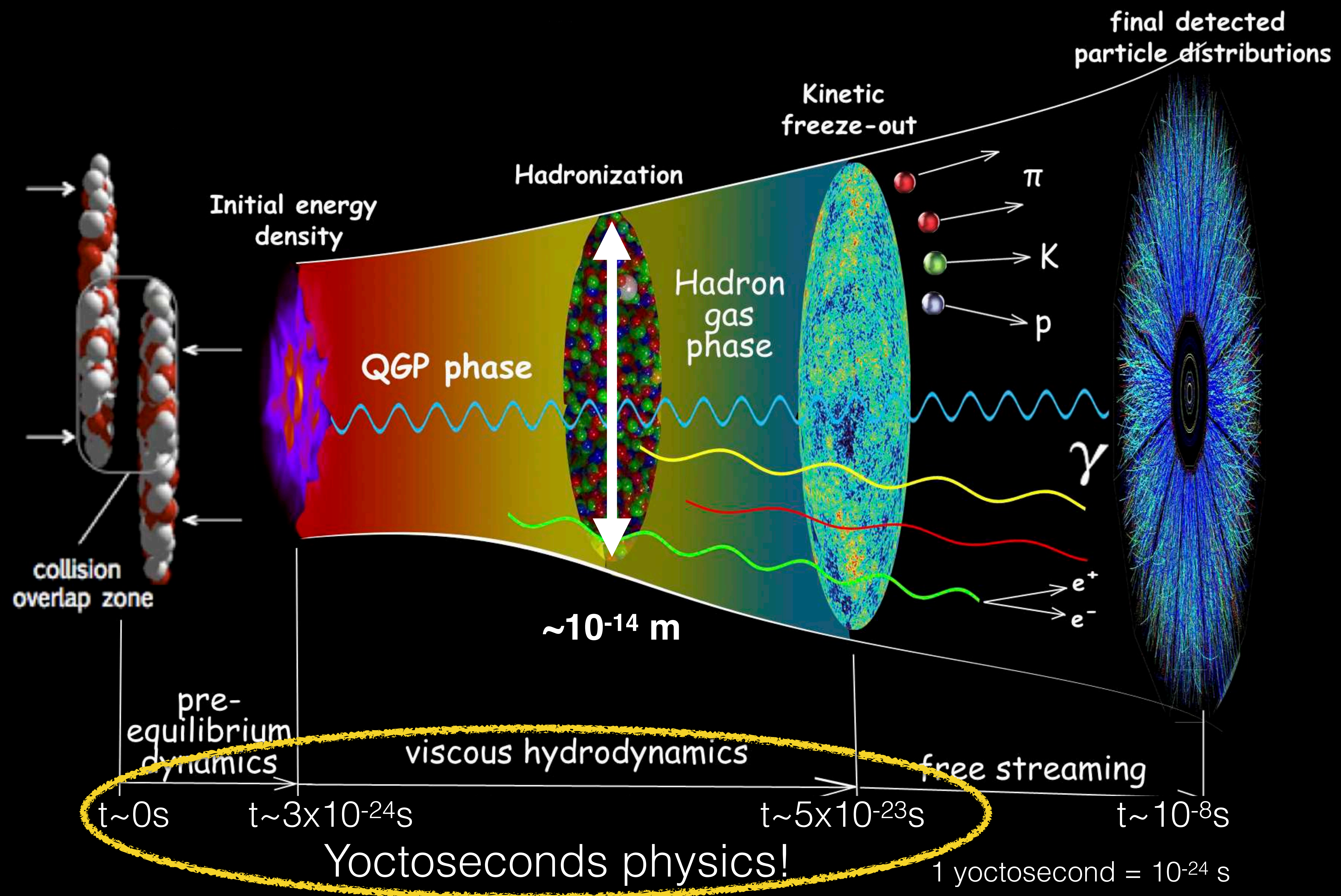
Heavy-ion collisions are tiny and have ultra-fast dynamics

RELATIVISTIC HEAVY-ION COLLISIONS



Heavy-ion collisions are tiny and have ultra-fast dynamics

RELATIVISTIC HEAVY-ION COLLISIONS



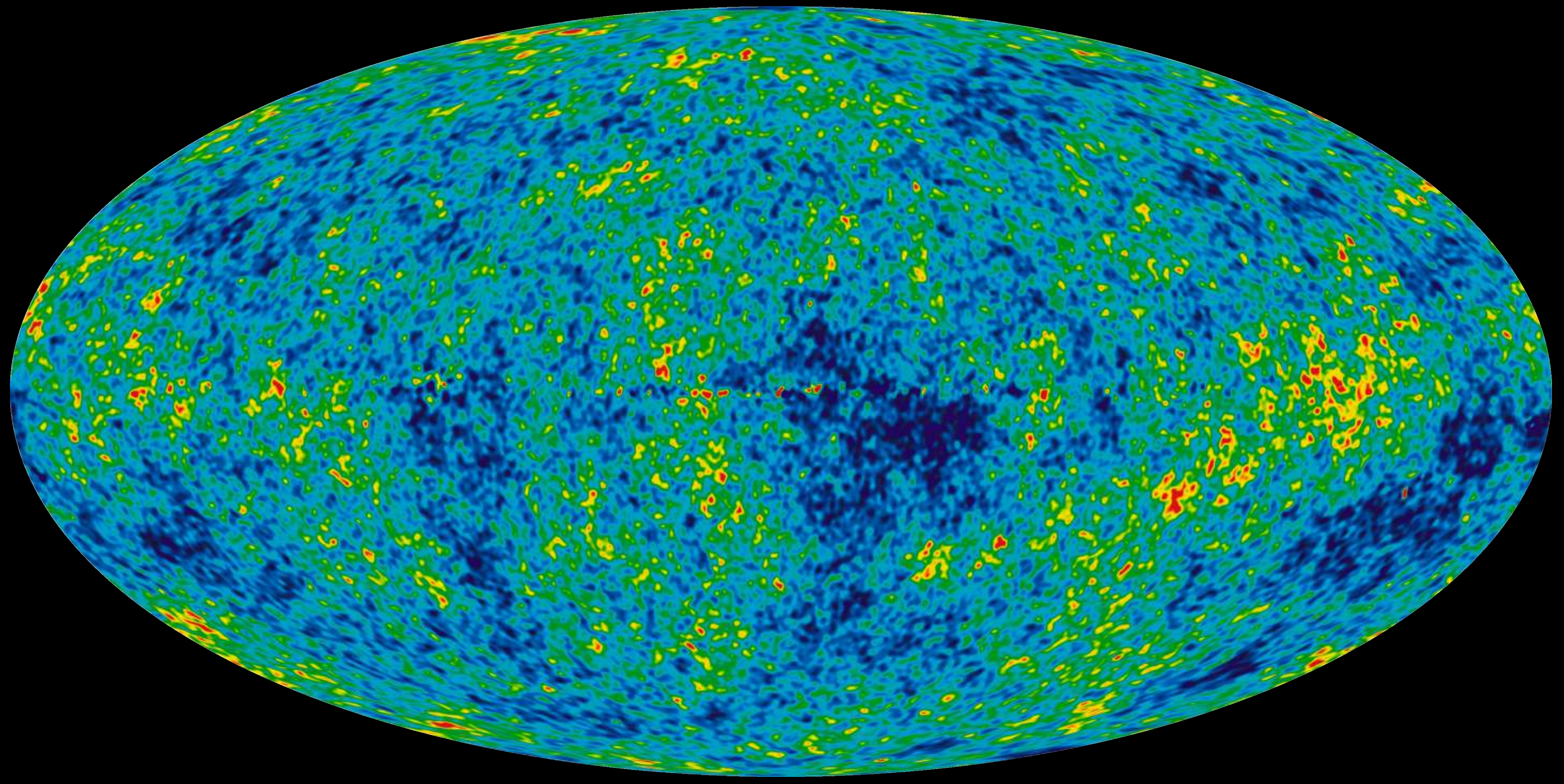
Heavy-ion collisions are tiny and have ultra-fast dynamics

A variety of particles are emitted from the collisions

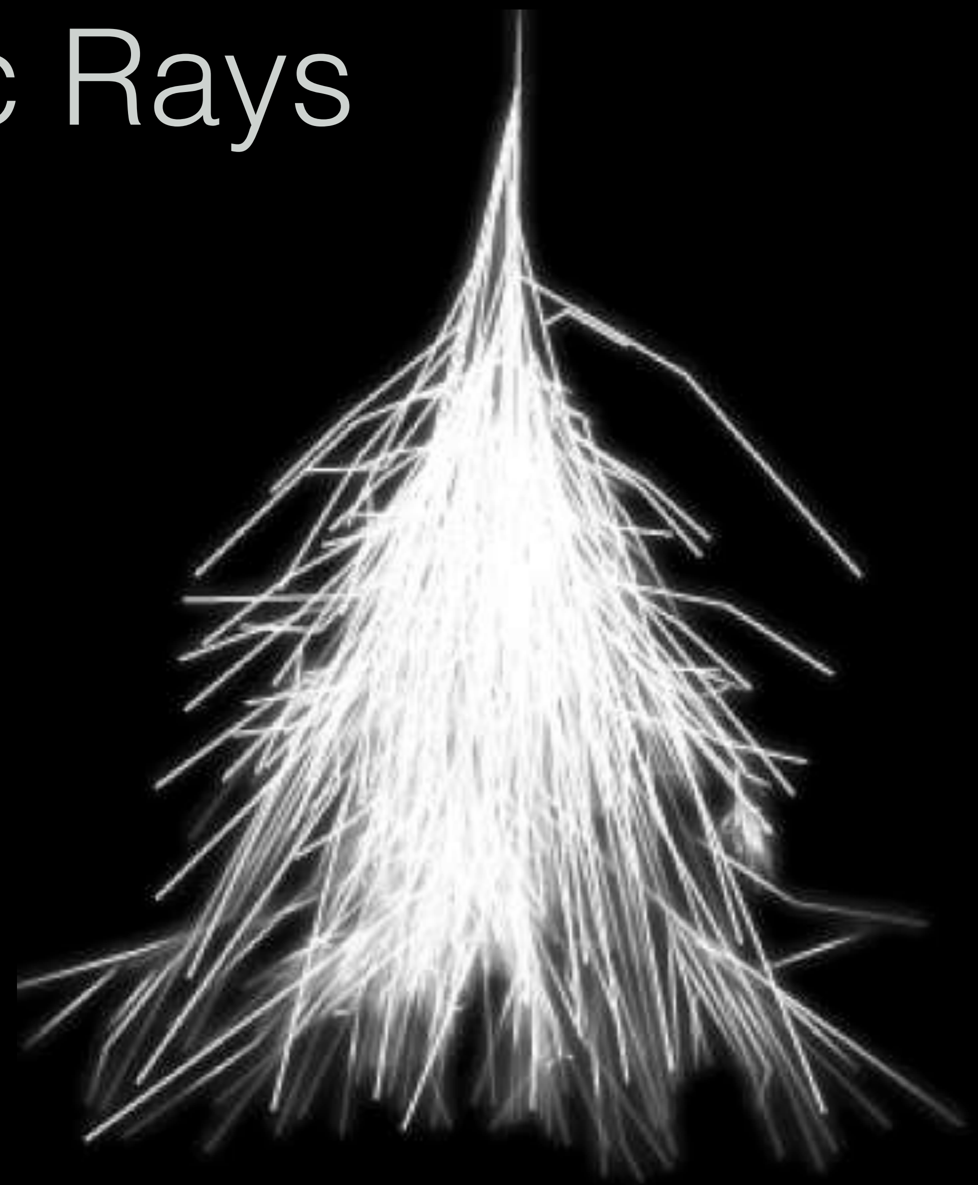
Multi-messenger nature of heavy-ion physics

MULTI-MESSENGER ASTRONOMY

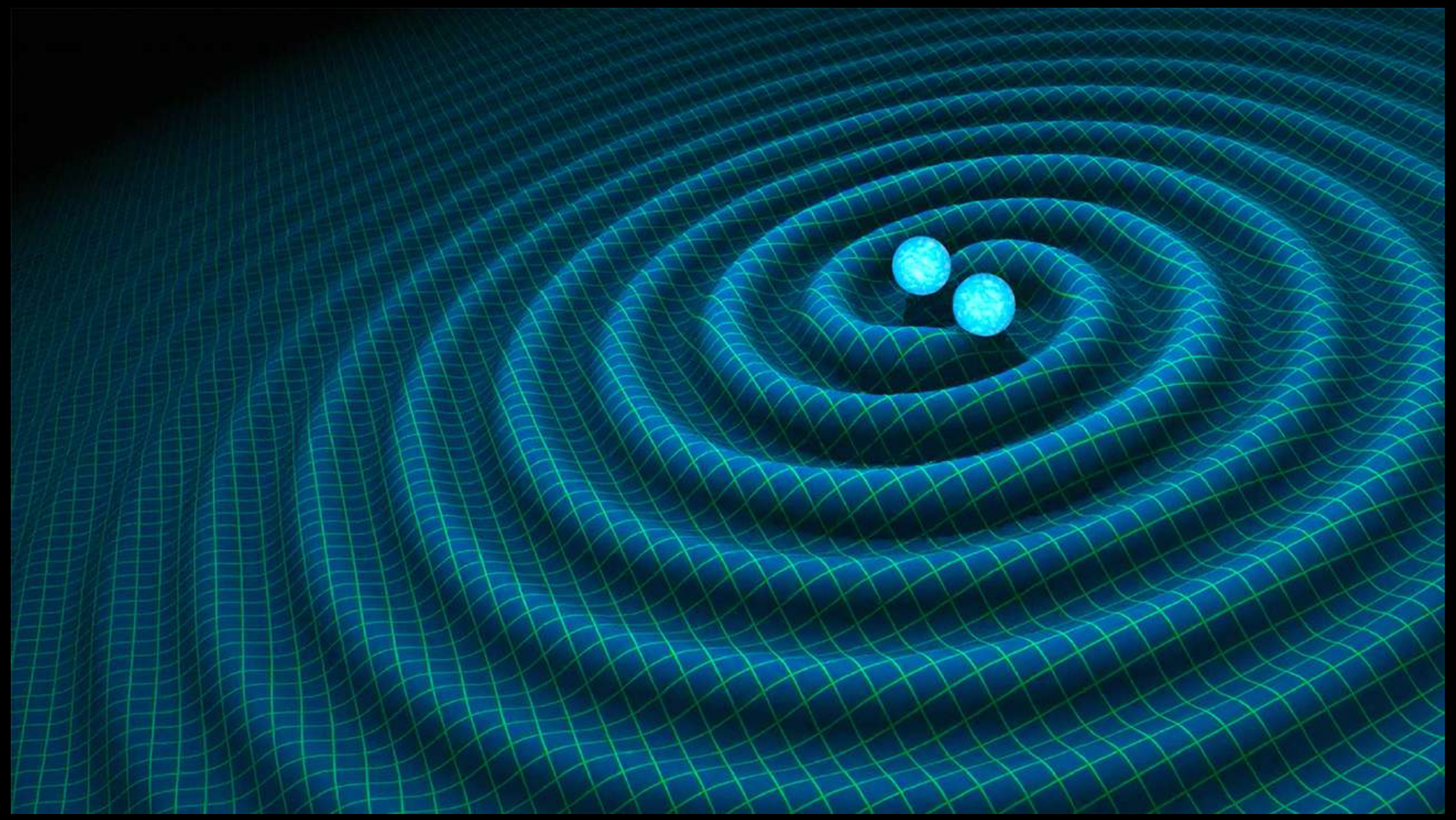
EM Radiation



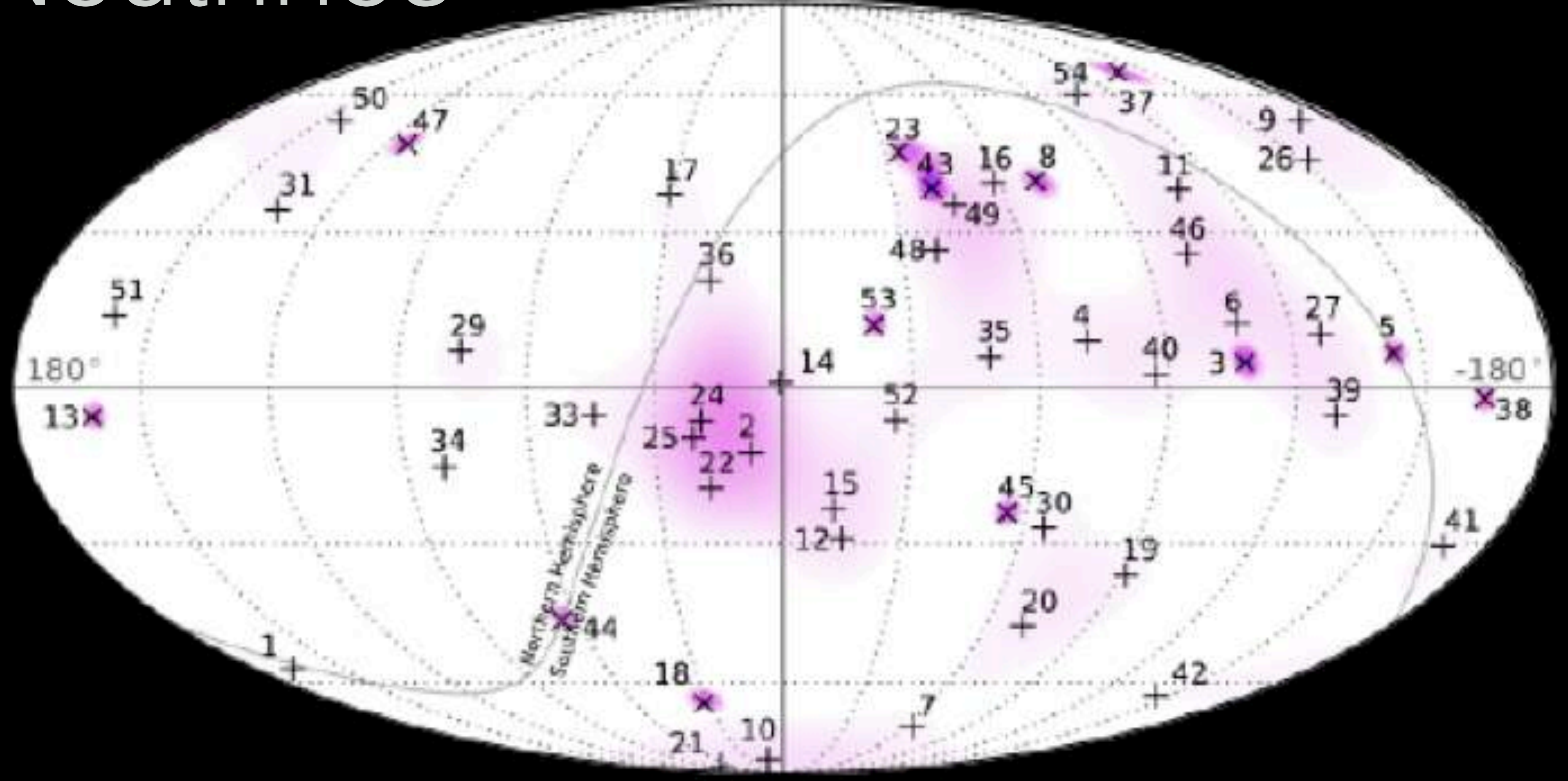
Cosmic Rays



Gravitational Waves

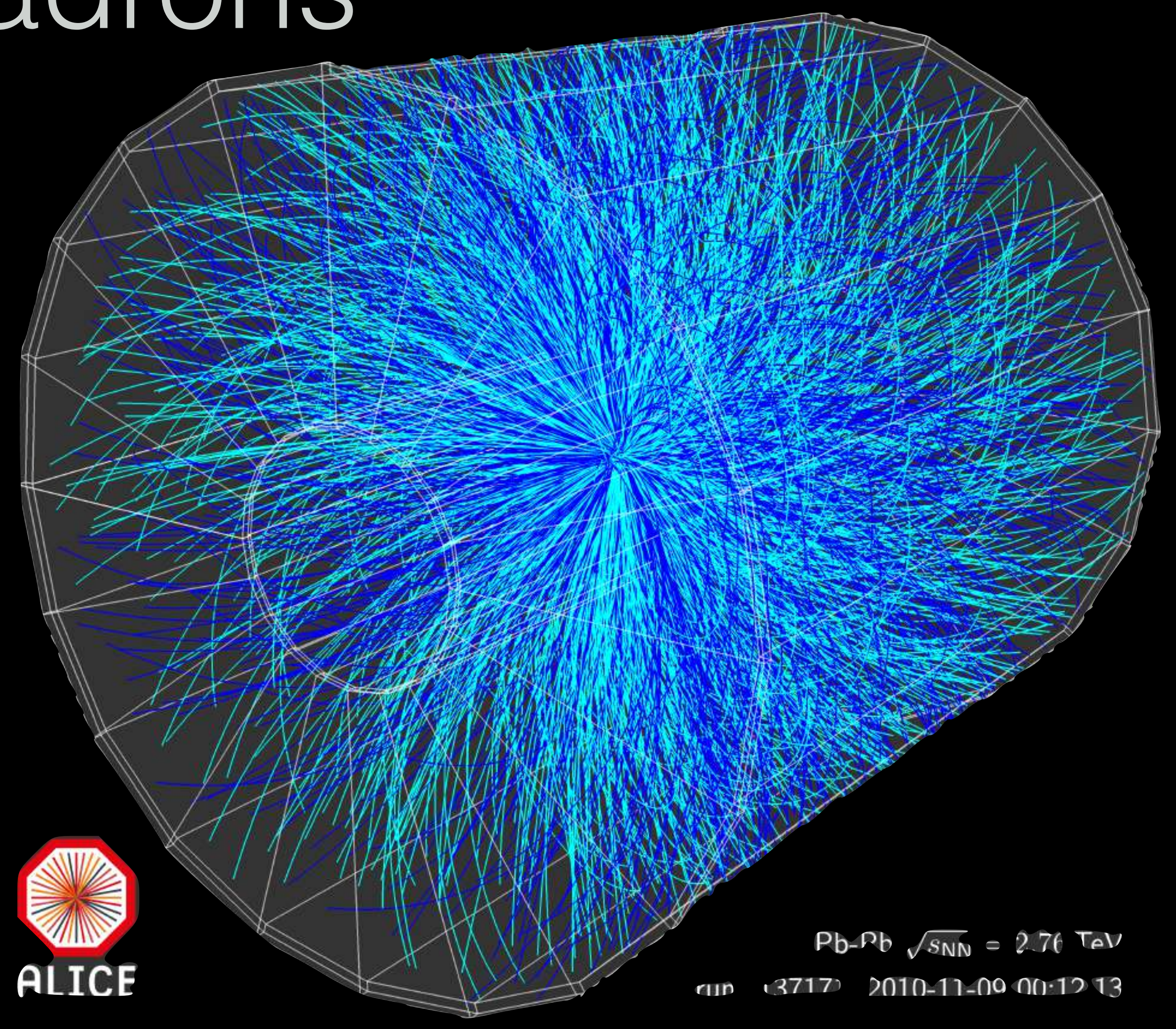


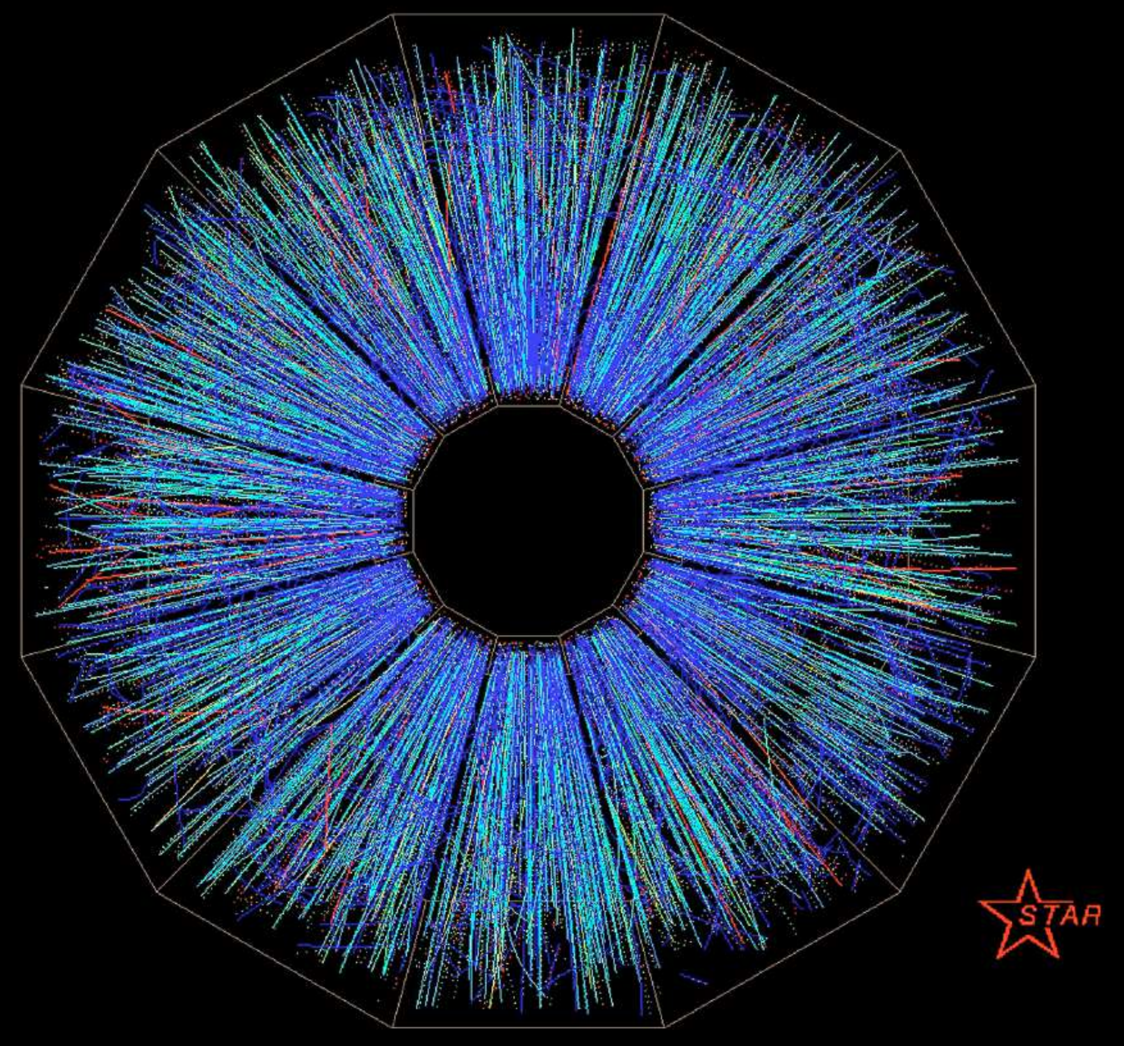
Neutrinos



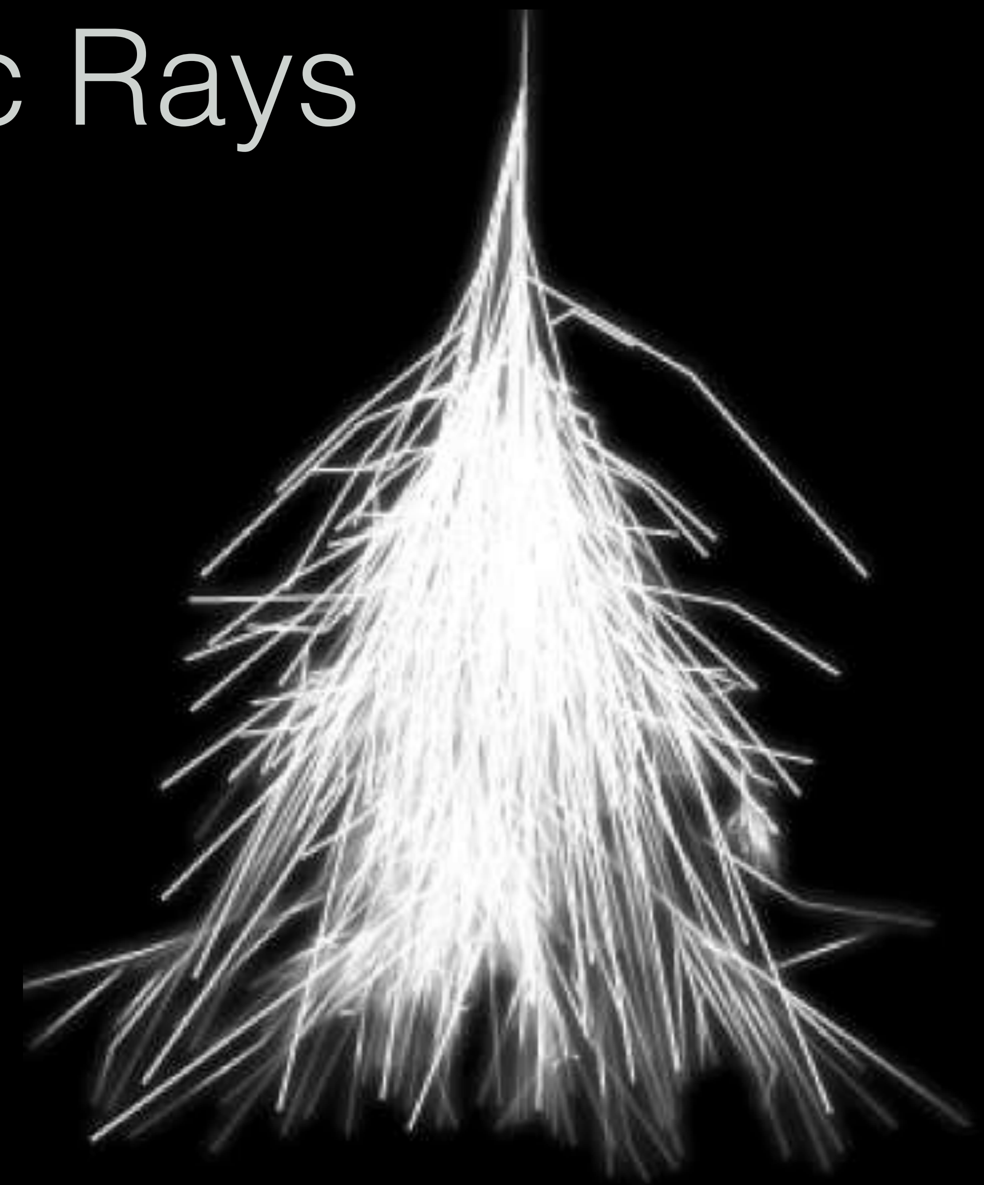
MULTI-MESSENGER HEAVY-ION PHYSICS

Hadrons

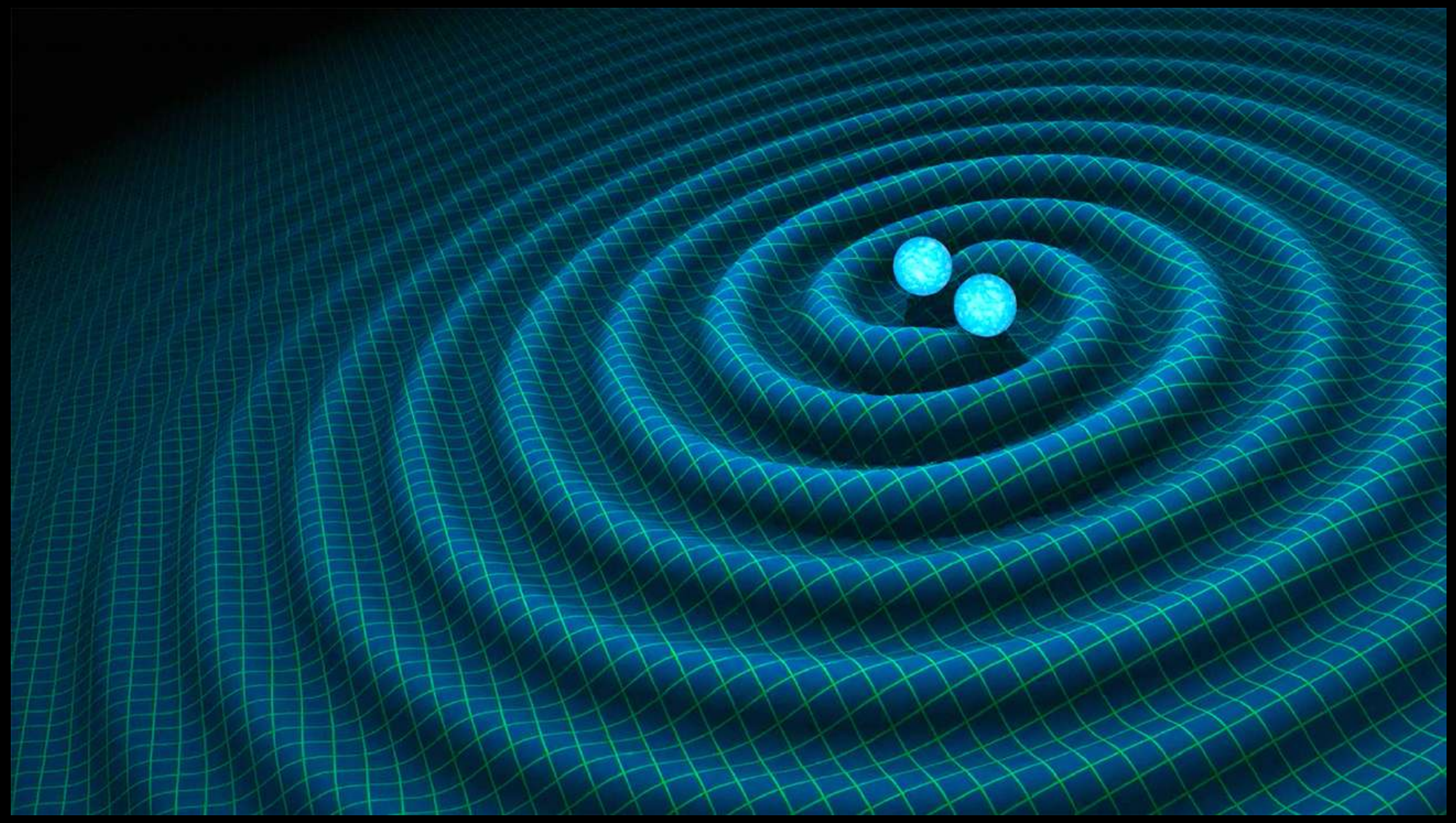




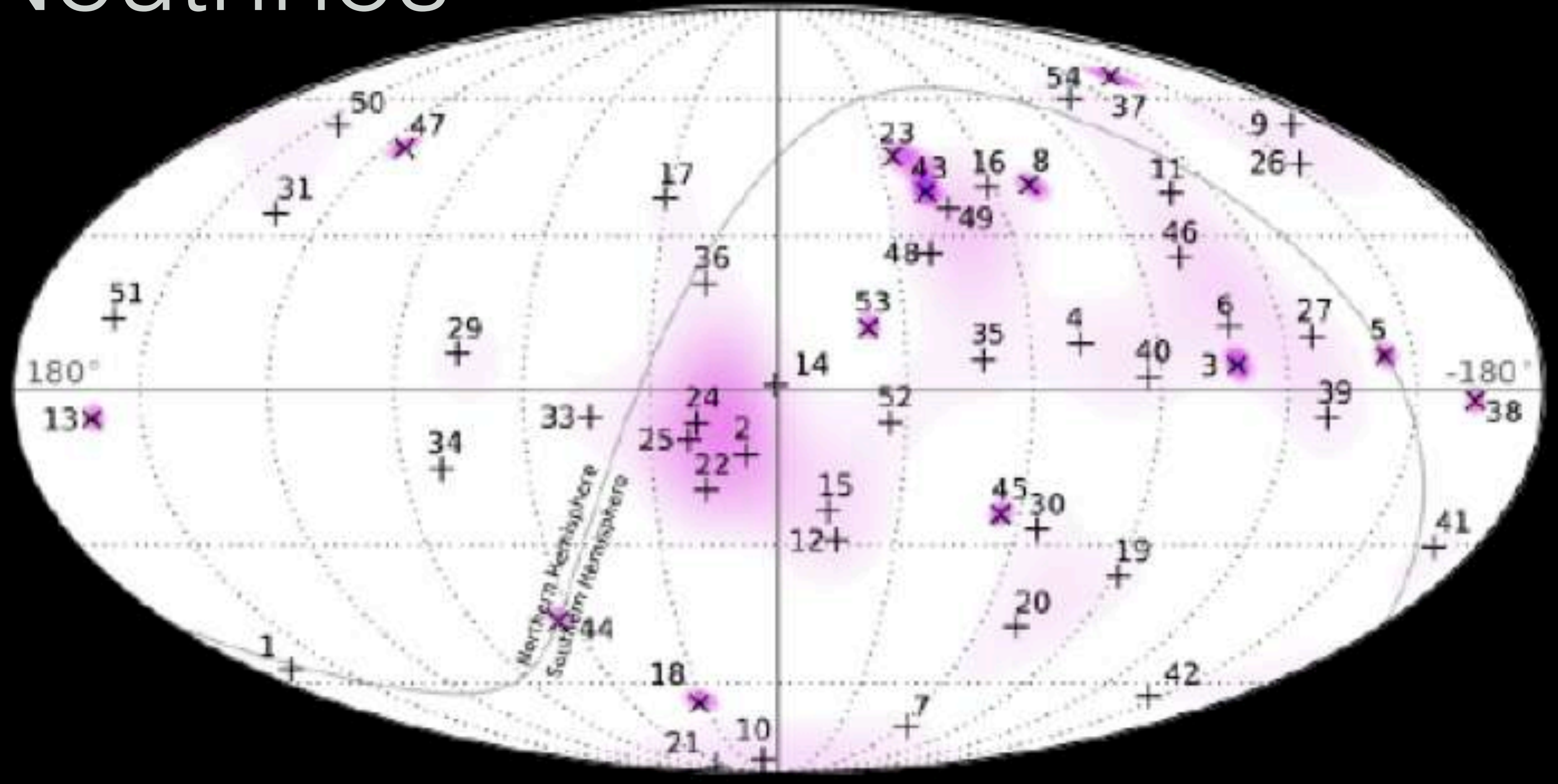
Cosmic Rays



Gravitational Waves

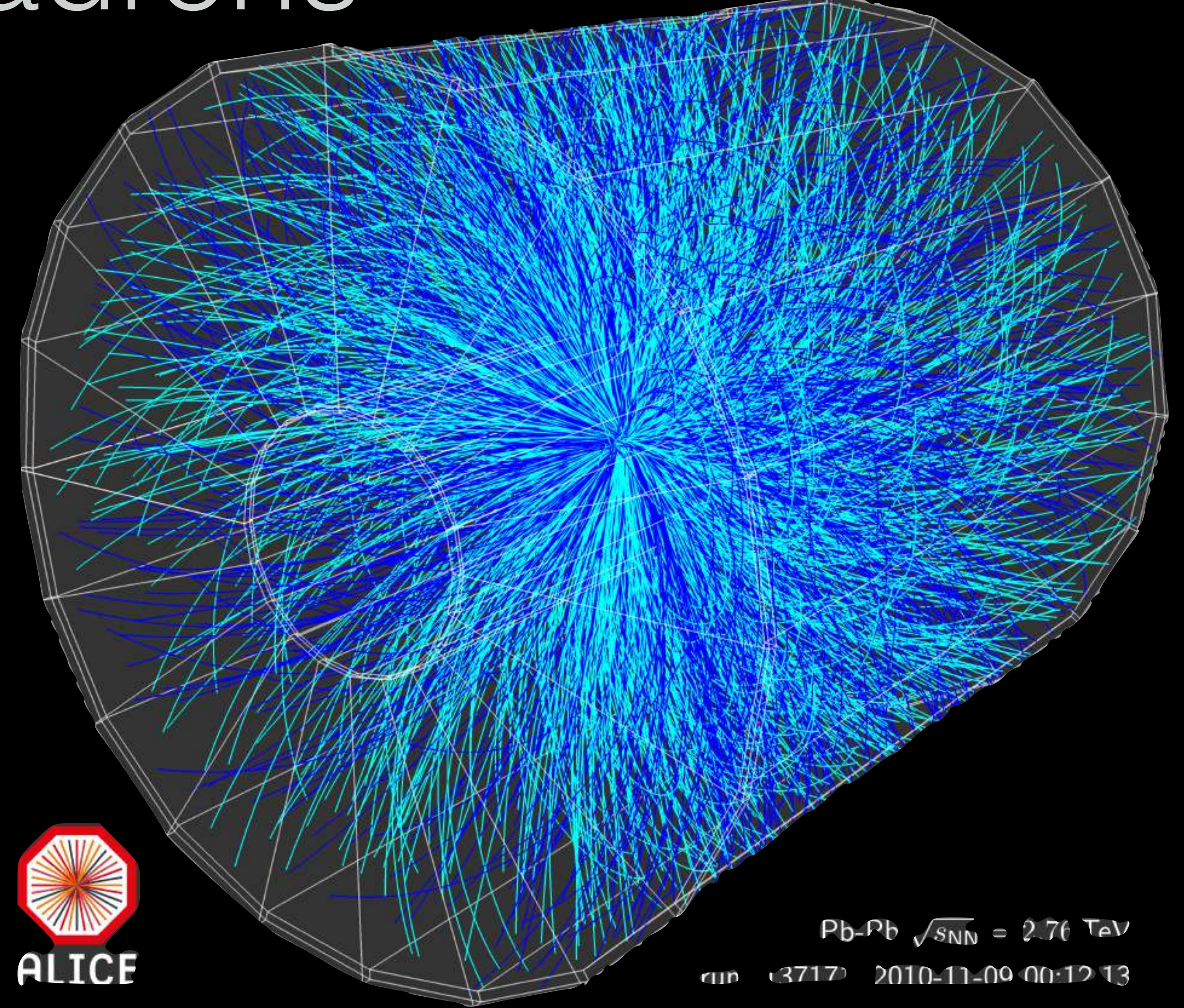


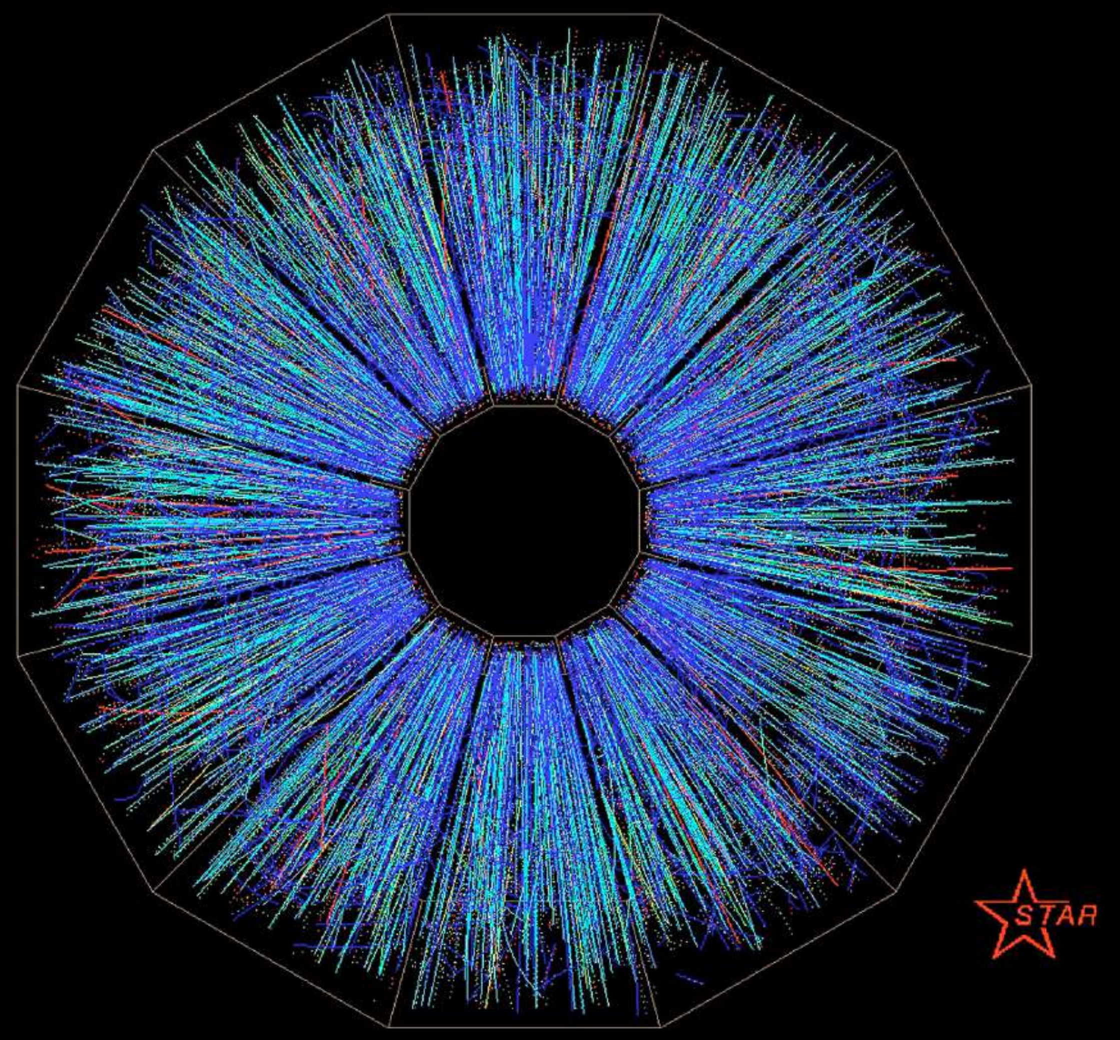
Neutrinos



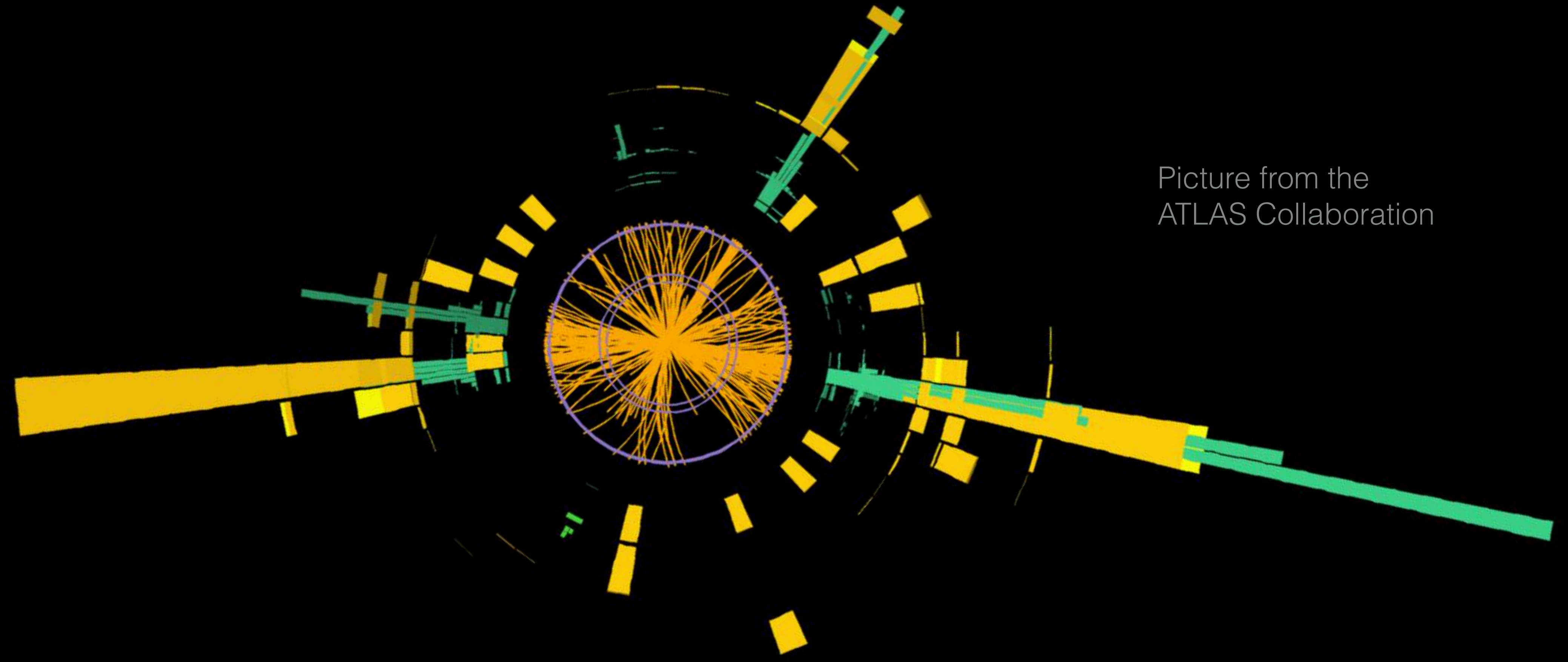
MULTI-MESSENGER HEAVY-ION PHYSICS

Hadrons



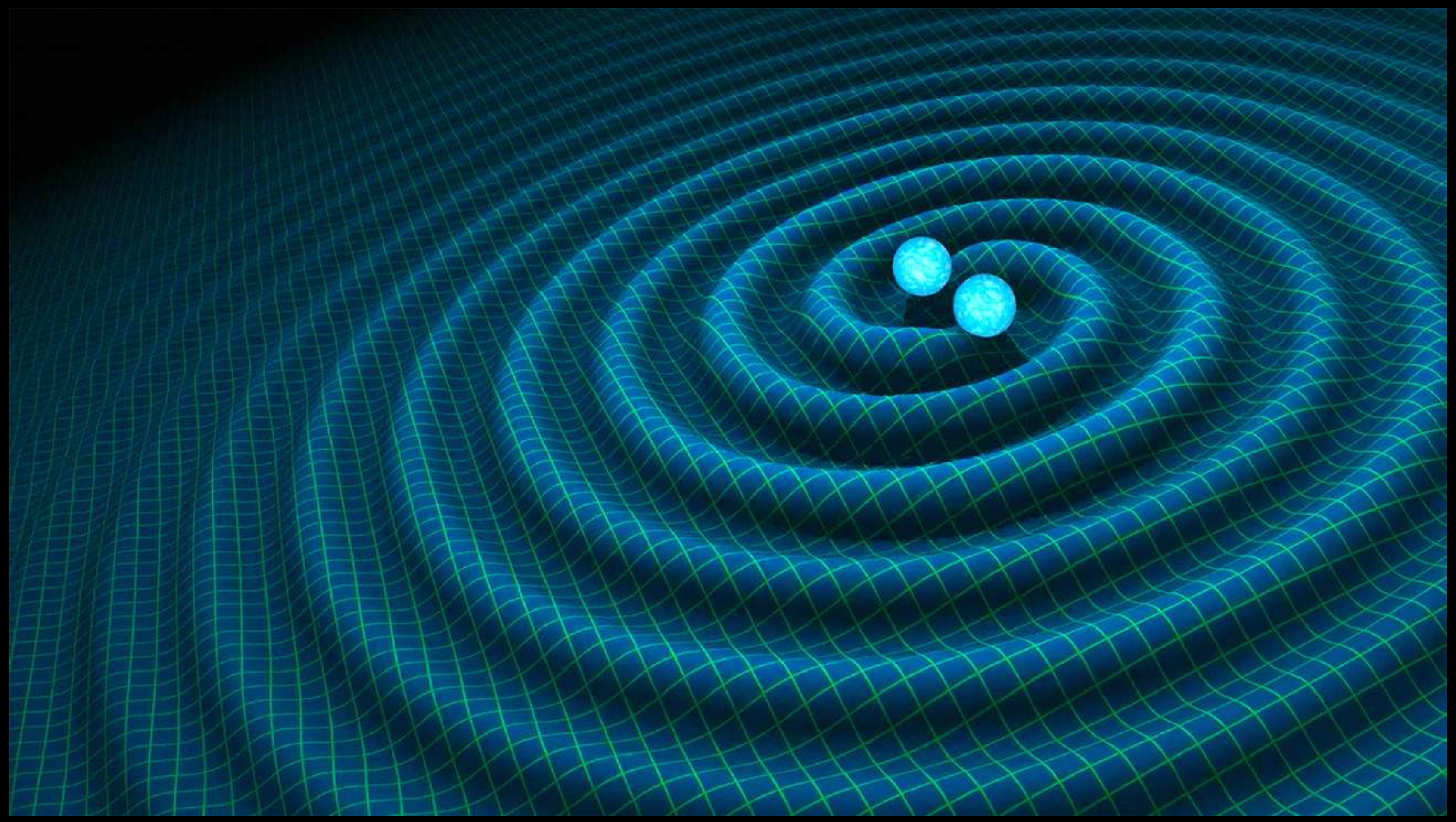


QCD jets

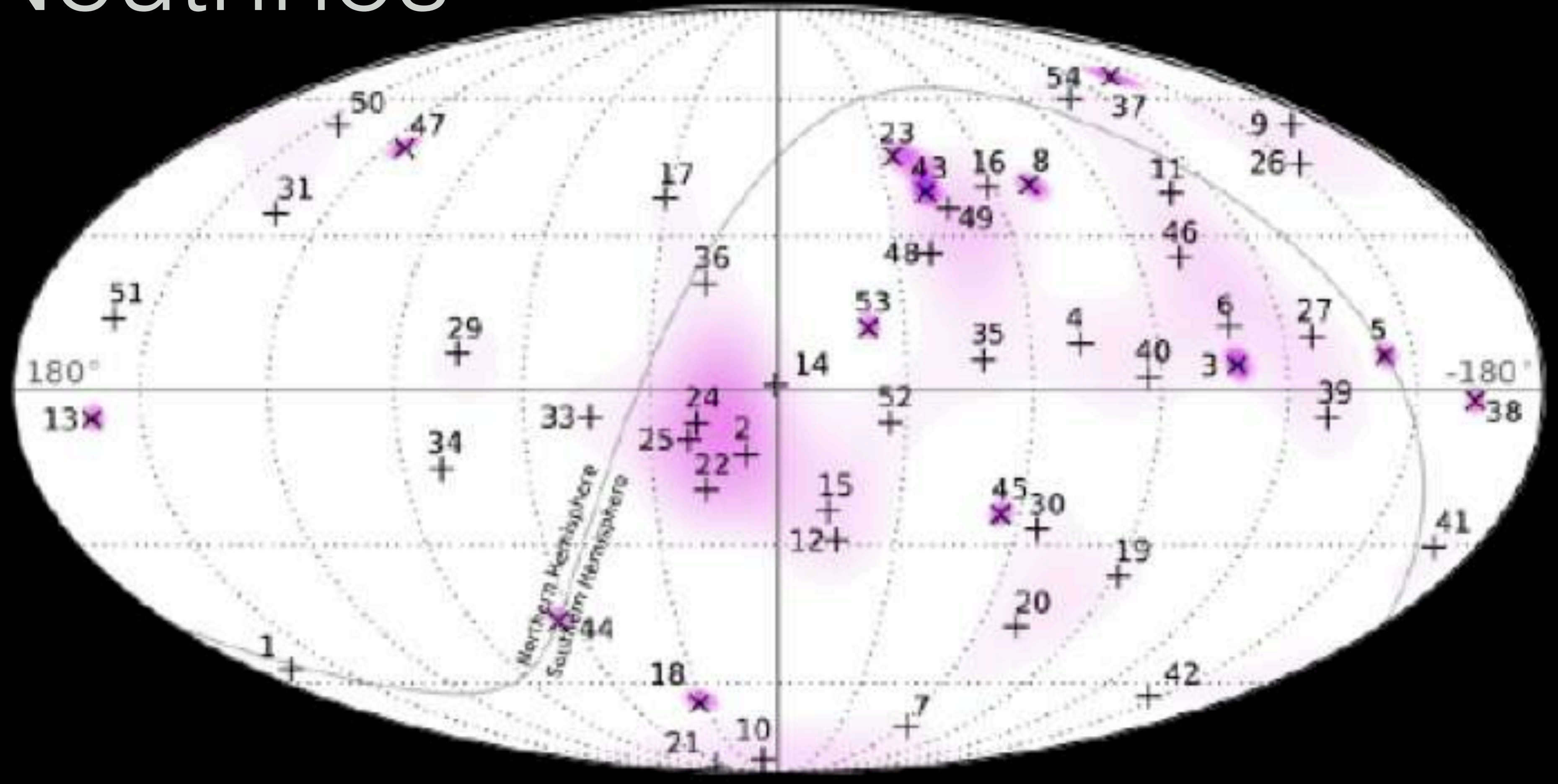


Picture from the ATLAS Collaboration

Gravitational Waves

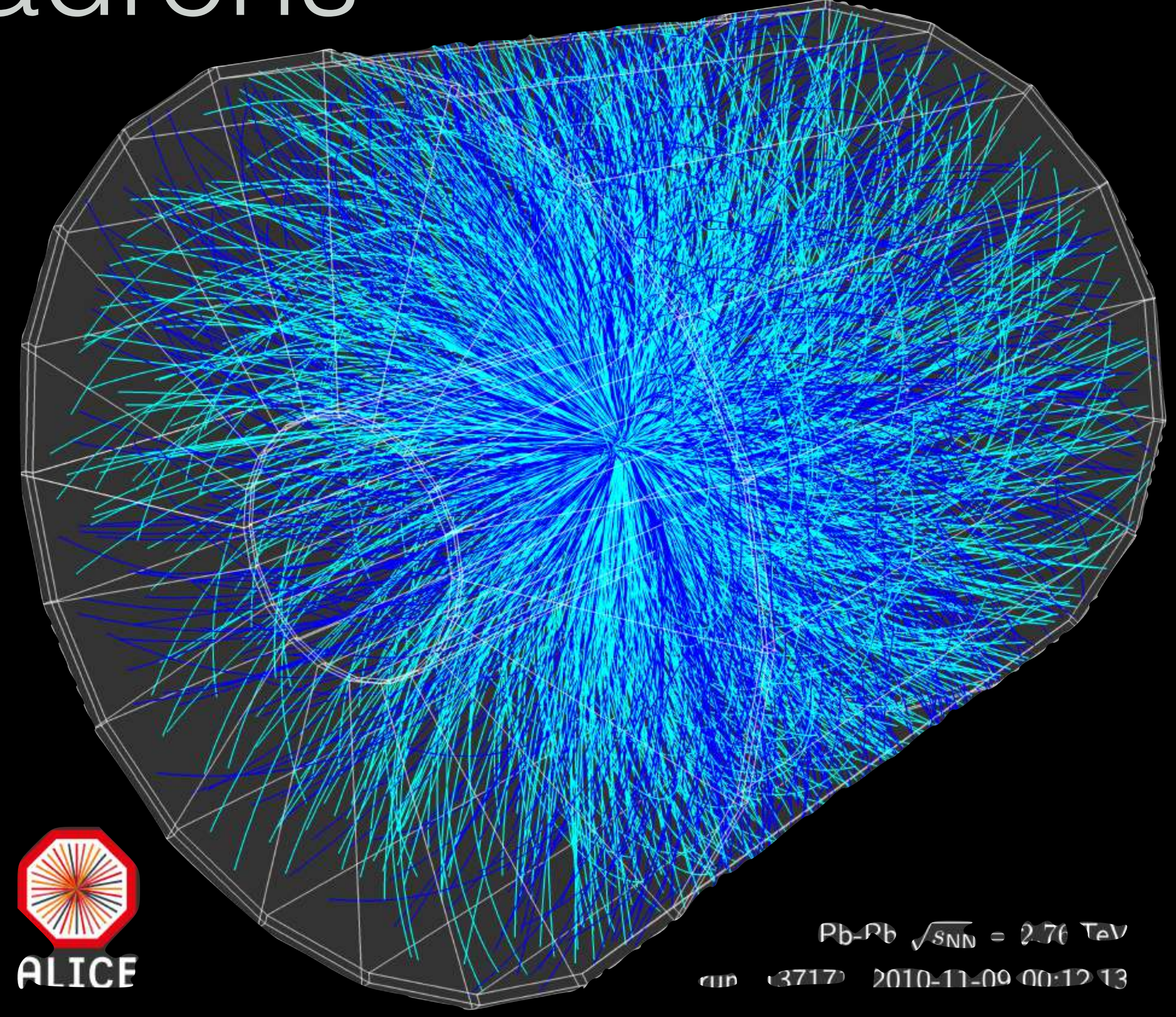


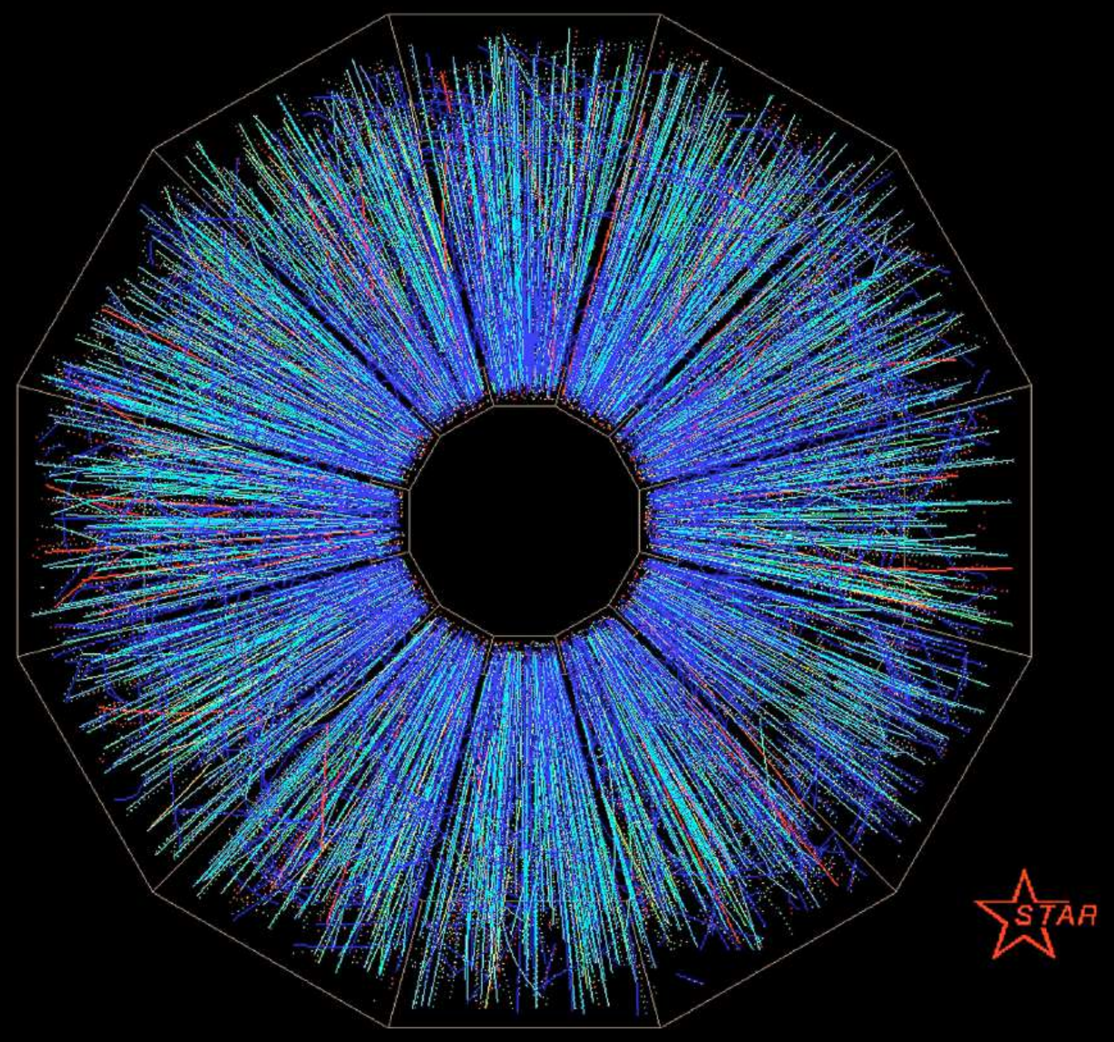
Neutrinos



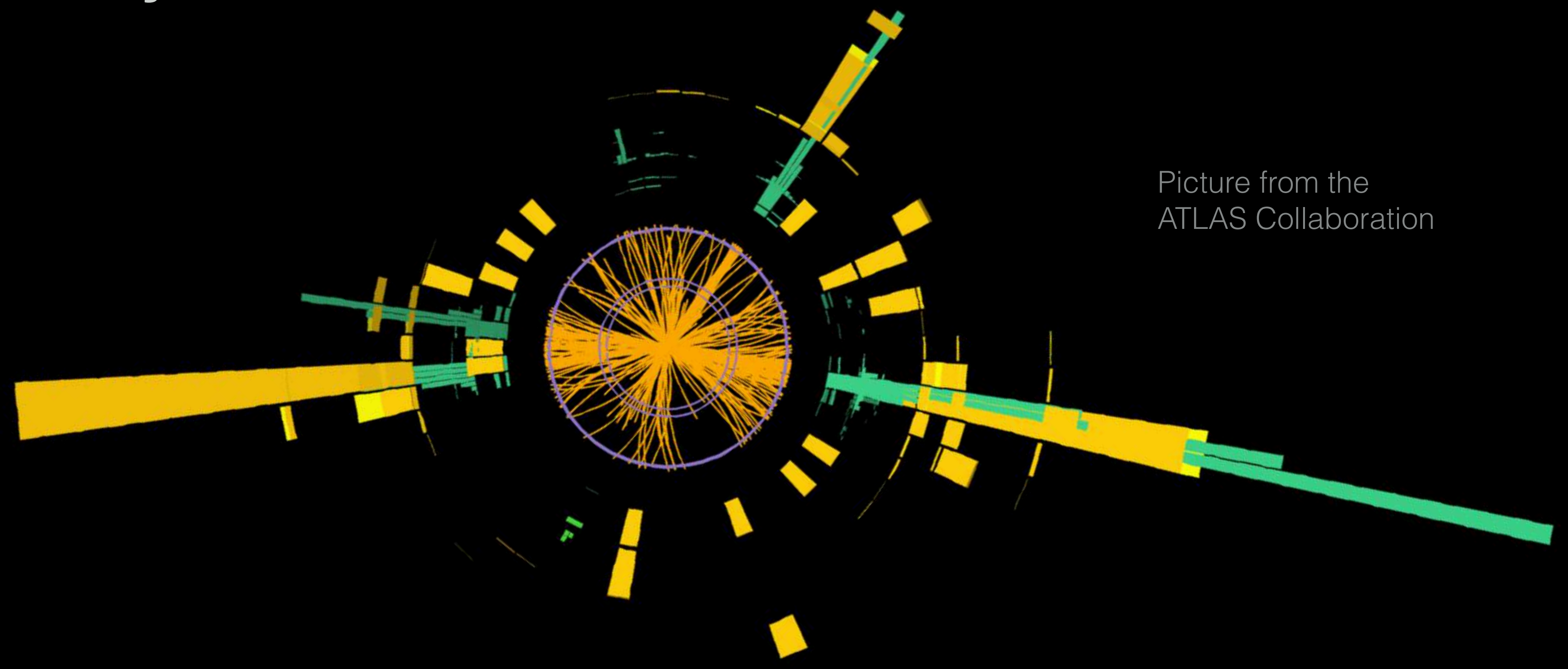
MULTI-MESSENGER HEAVY-ION PHYSICS

Hadrons



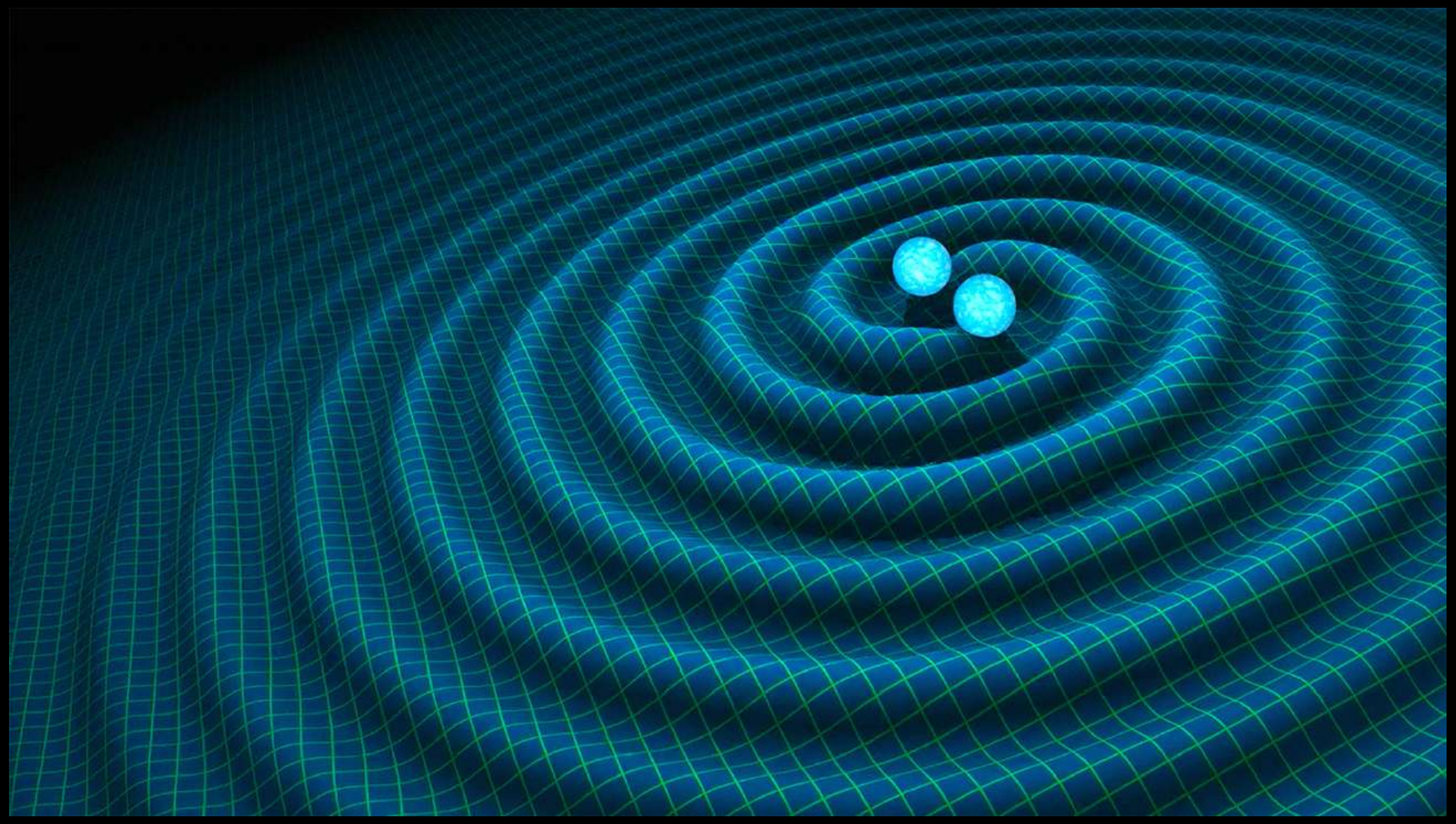


QCD jets

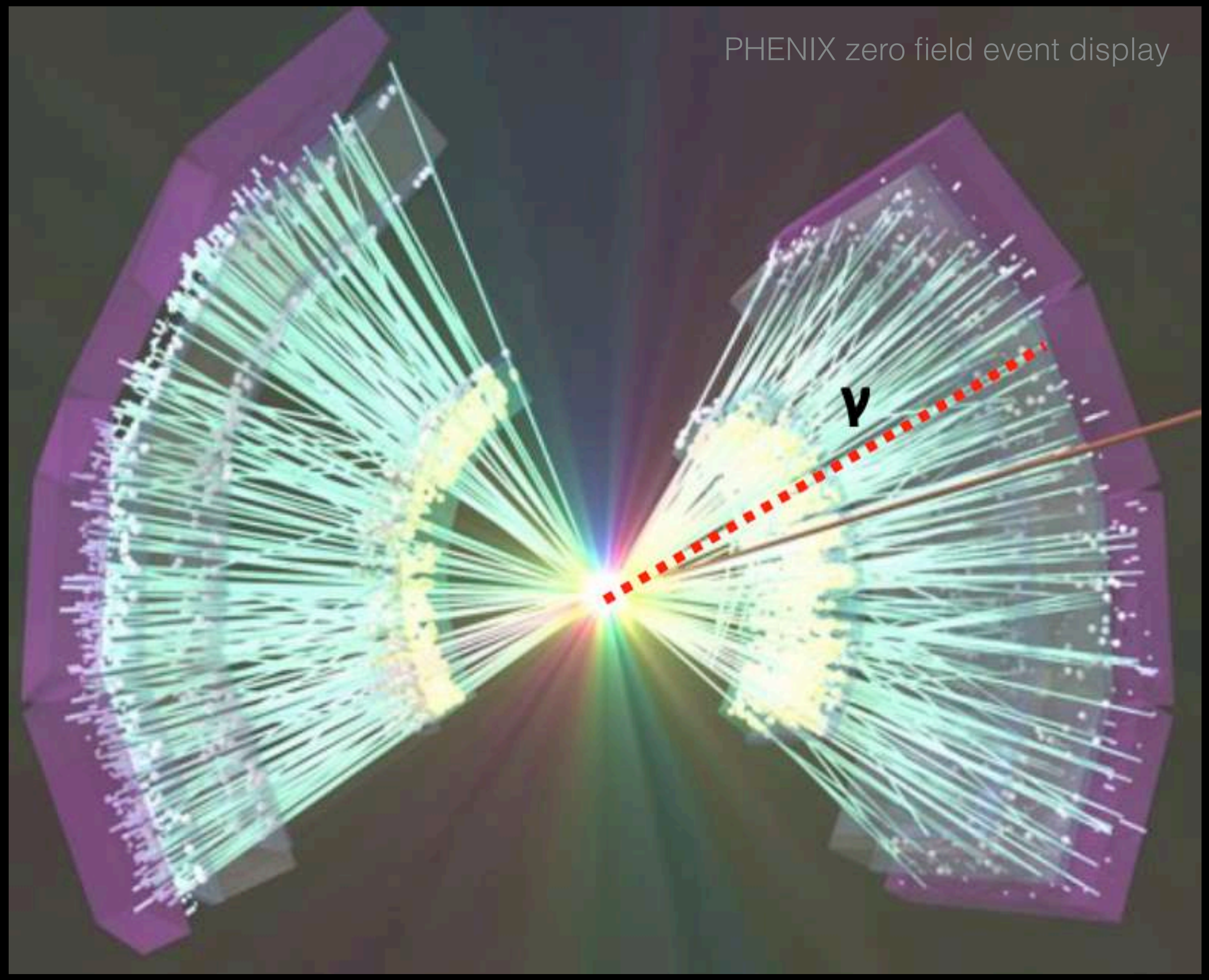


Picture from the
ATLAS Collaboration

Gravitational Waves

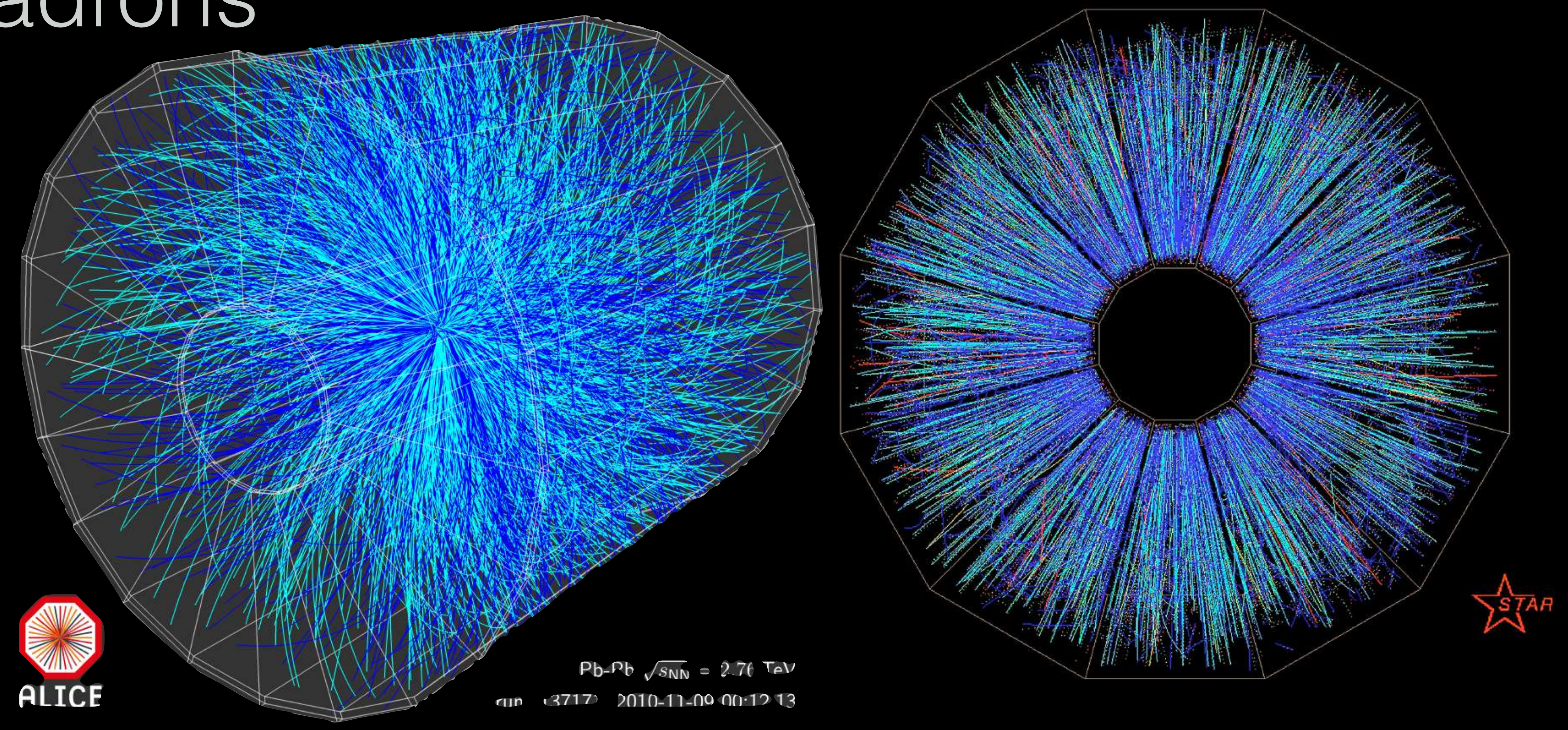


EM radiations

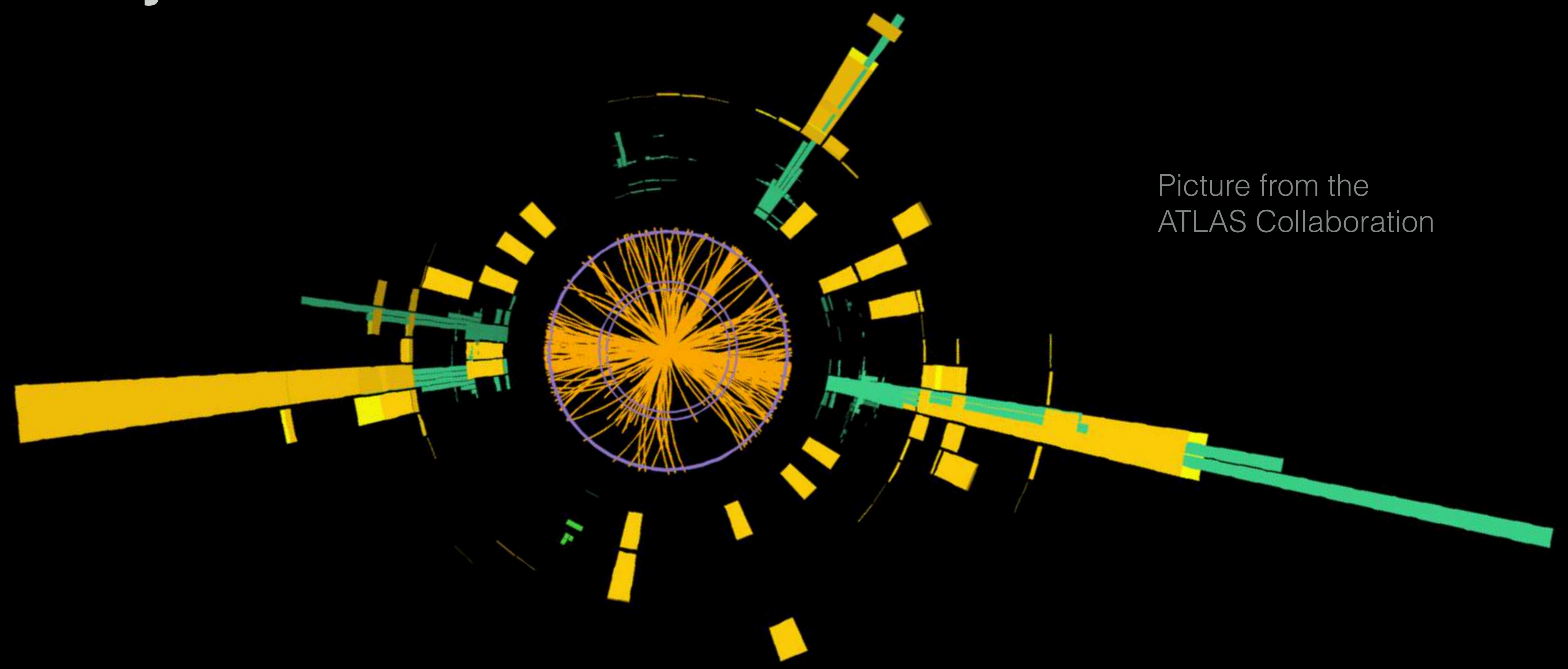


MULTI-MESSENGER HEAVY-ION PHYSICS

Hadrons

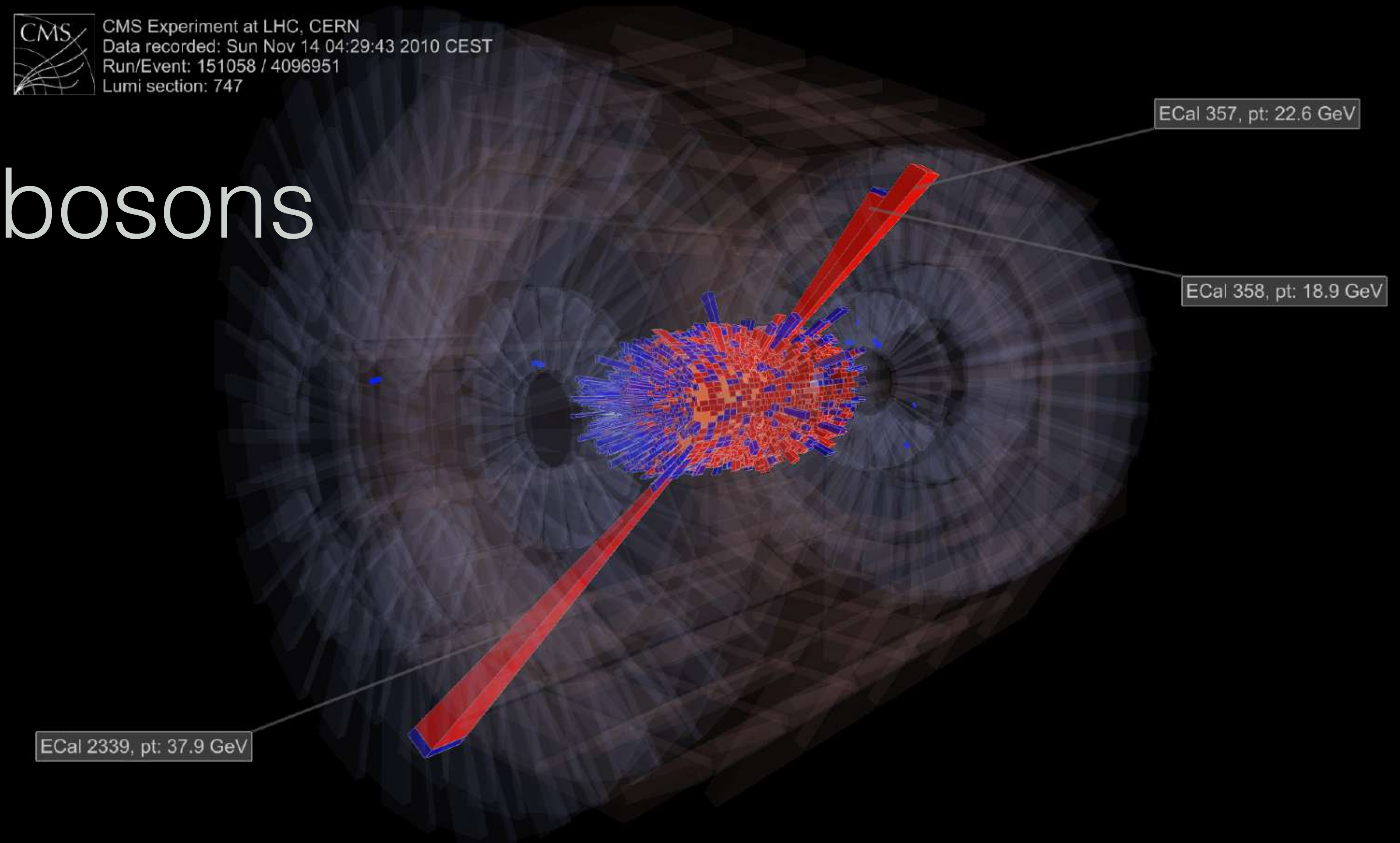


QCD jets

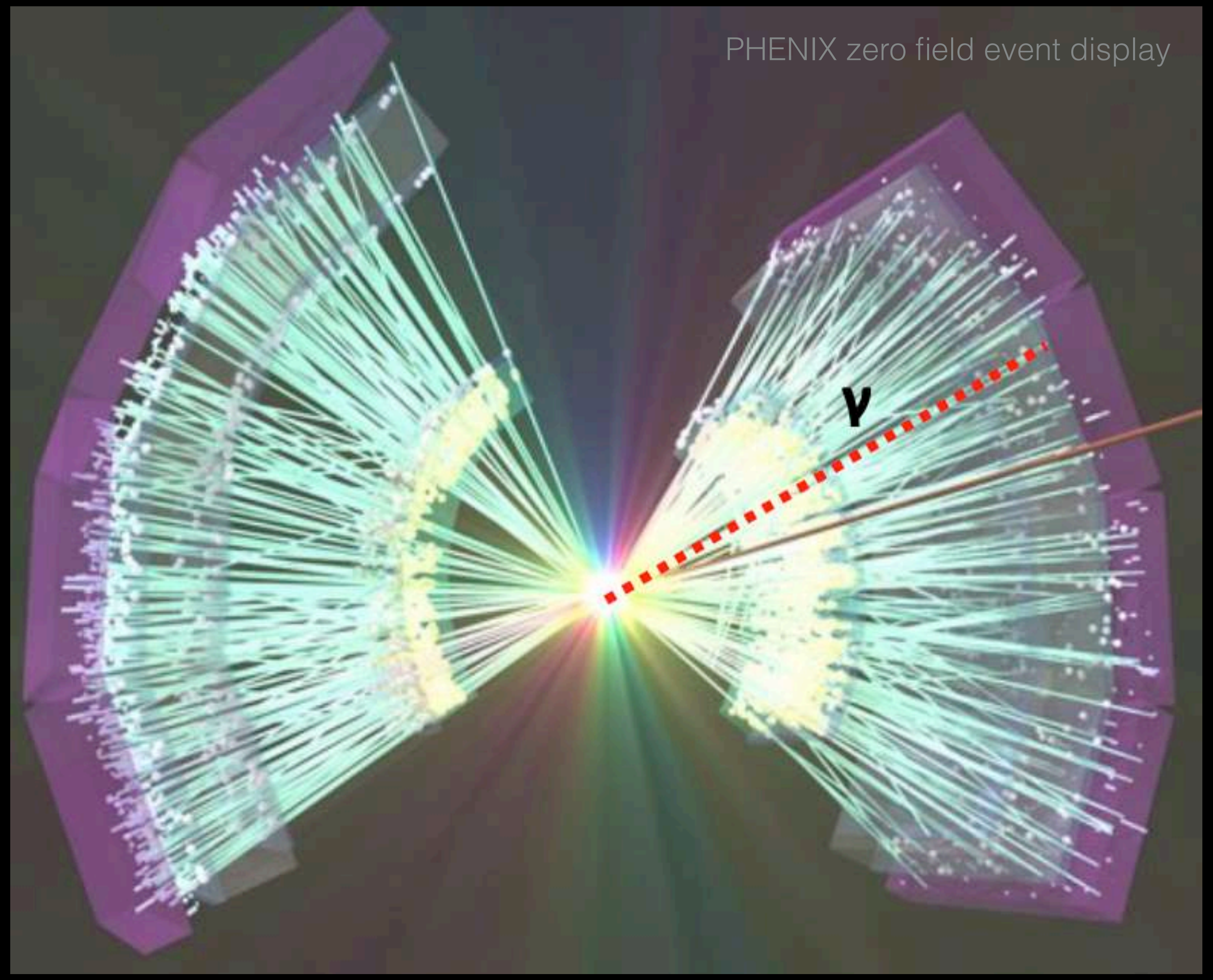


Picture from the
ATLAS Collaboration

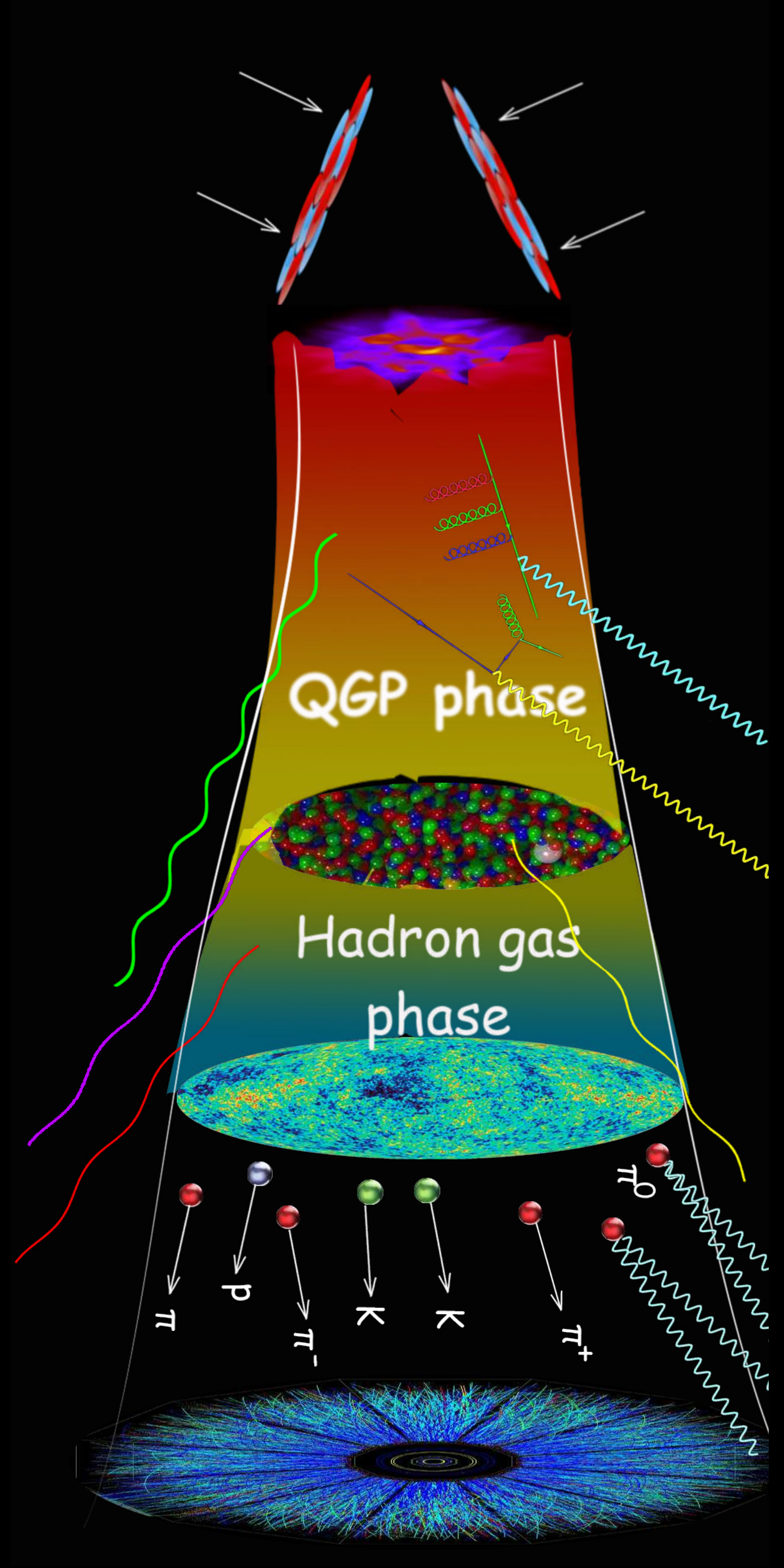
EW bosons



EM radiations



DEFINING THE QUARK-GLUON PLASMA



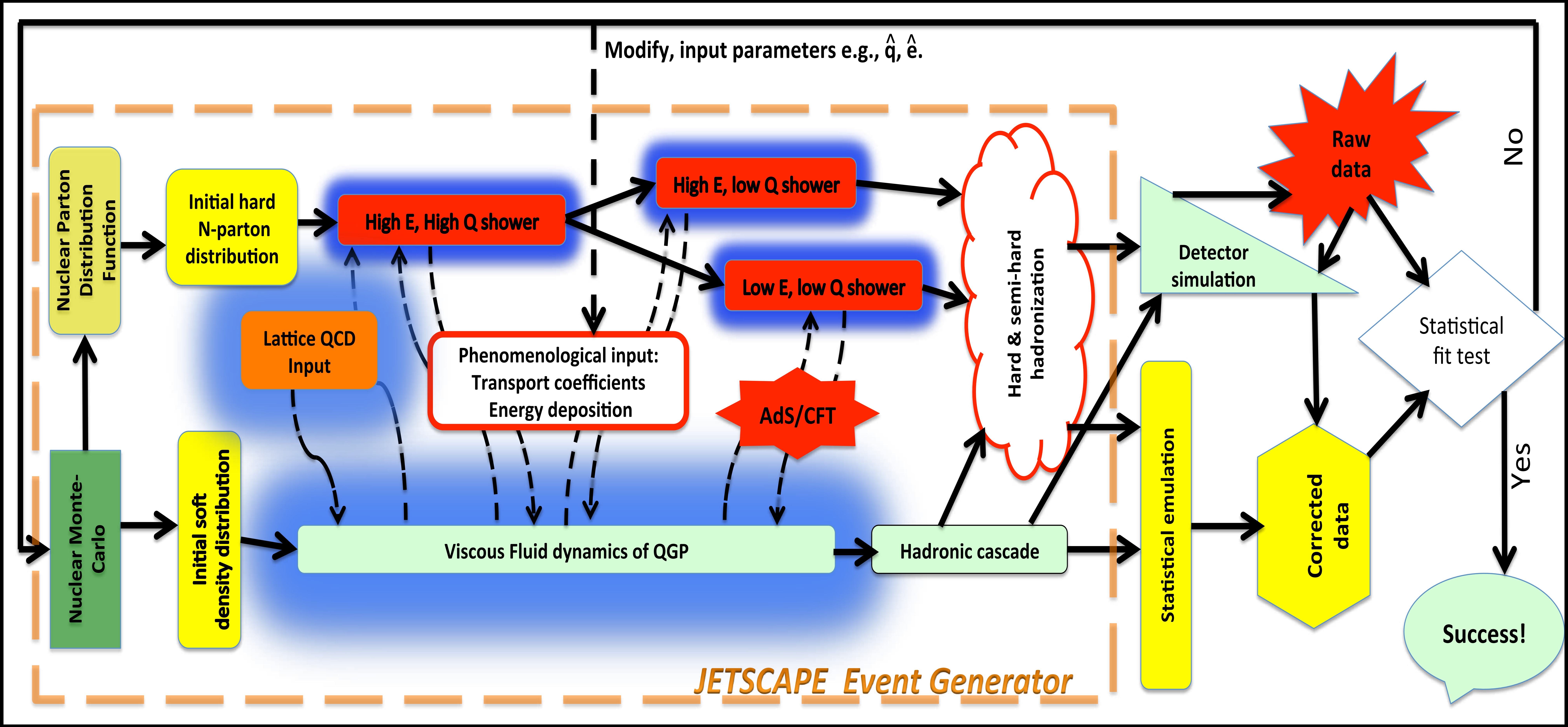
Which **properties of hot QCD matter** can we determine from relativistic heavy ion data (LHC, RHIC, and future FAIR/NICA/JPAC)?

Equation of State $T^{\mu\nu} \Longleftrightarrow e, P, s$ $c_s^2 = \partial P / \partial e\|_{s/n}$	Spectra, collective flow, femtoscopy
Shear and bulk viscosities $\eta/s(T, \mu_B), \zeta/s(T, \mu_B)$	Anisotropic flow v_n Flow correlations
Charge diffusion D_B, D_Q, D_S	Balance functions
Electromagnetic emissivity	Photons and dileptons
Energy-momentum transport $\hat{q}, \hat{e}, \hat{e}_2, \ldots$	Jets and heavy-quarks

THE JETSCAPE FRAMEWORK

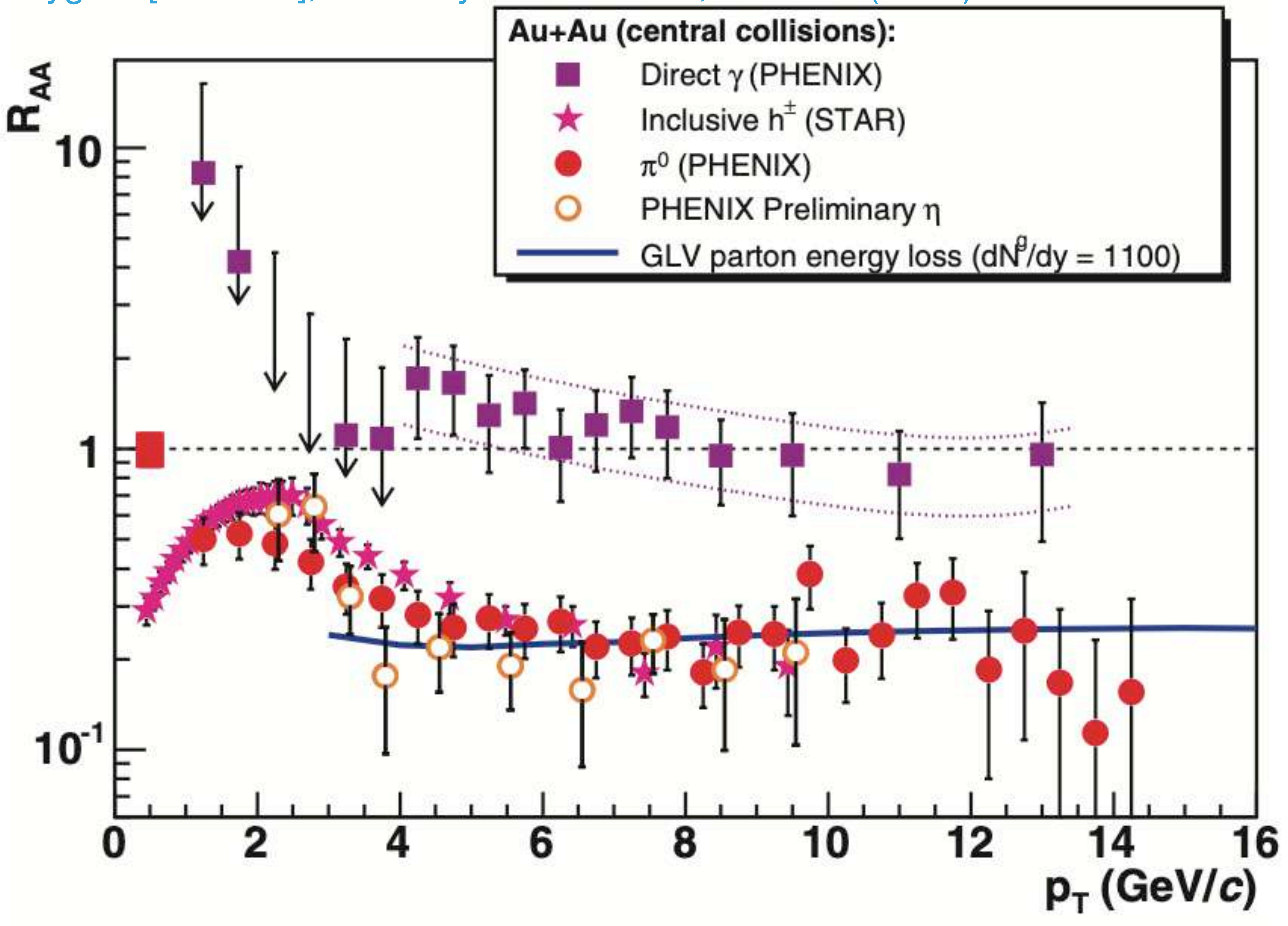
"The JETSCAPE framework," arXiv:1903.07706 [nucl-th]

- A unified event-generator for the high energy nuclear physics community

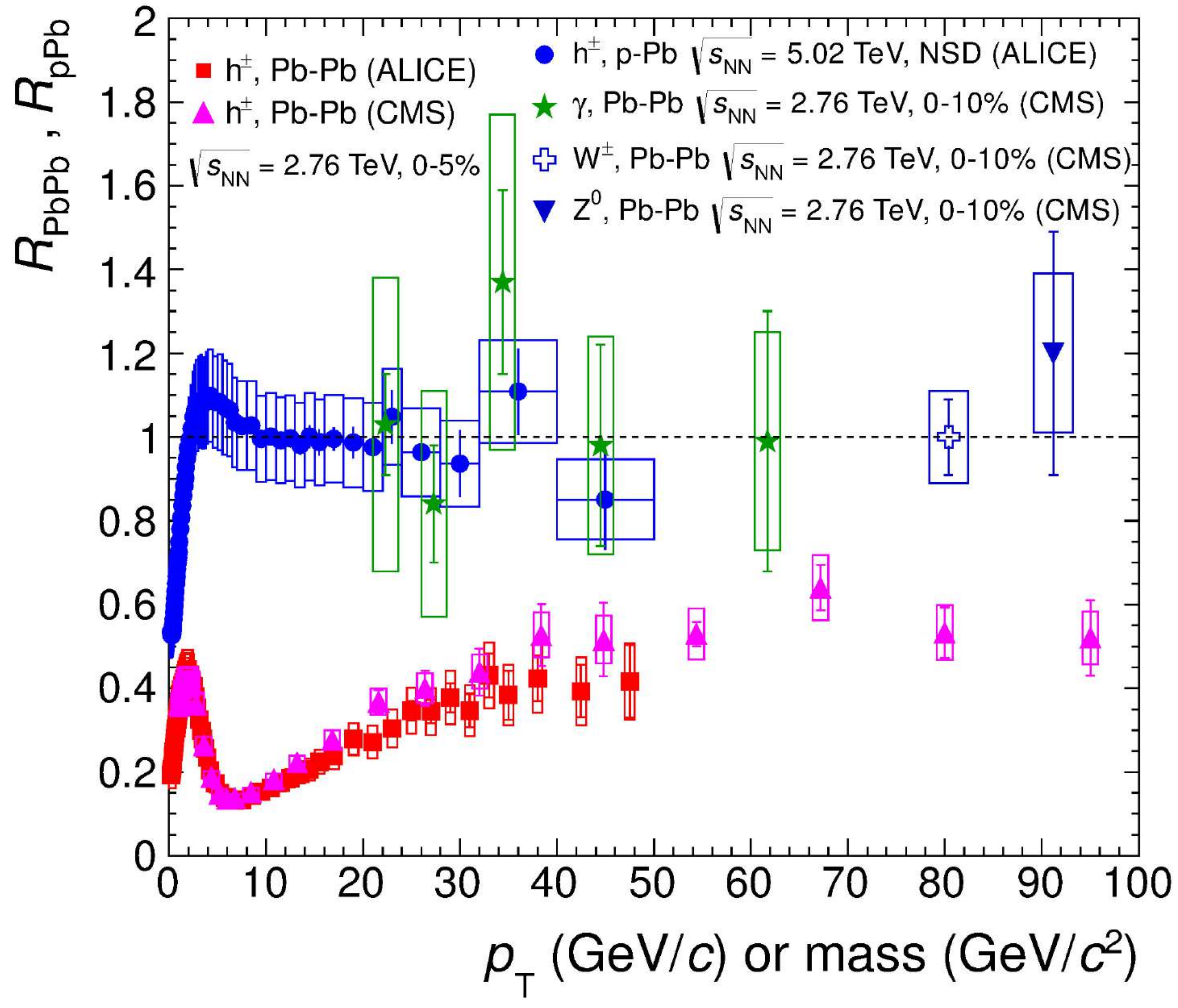


MULTI-MESSENGER HEAVY-ION PHYSICS

K. Reygers [PHENIX], Acta Phys. Polon. B37, 727-732 (2006)



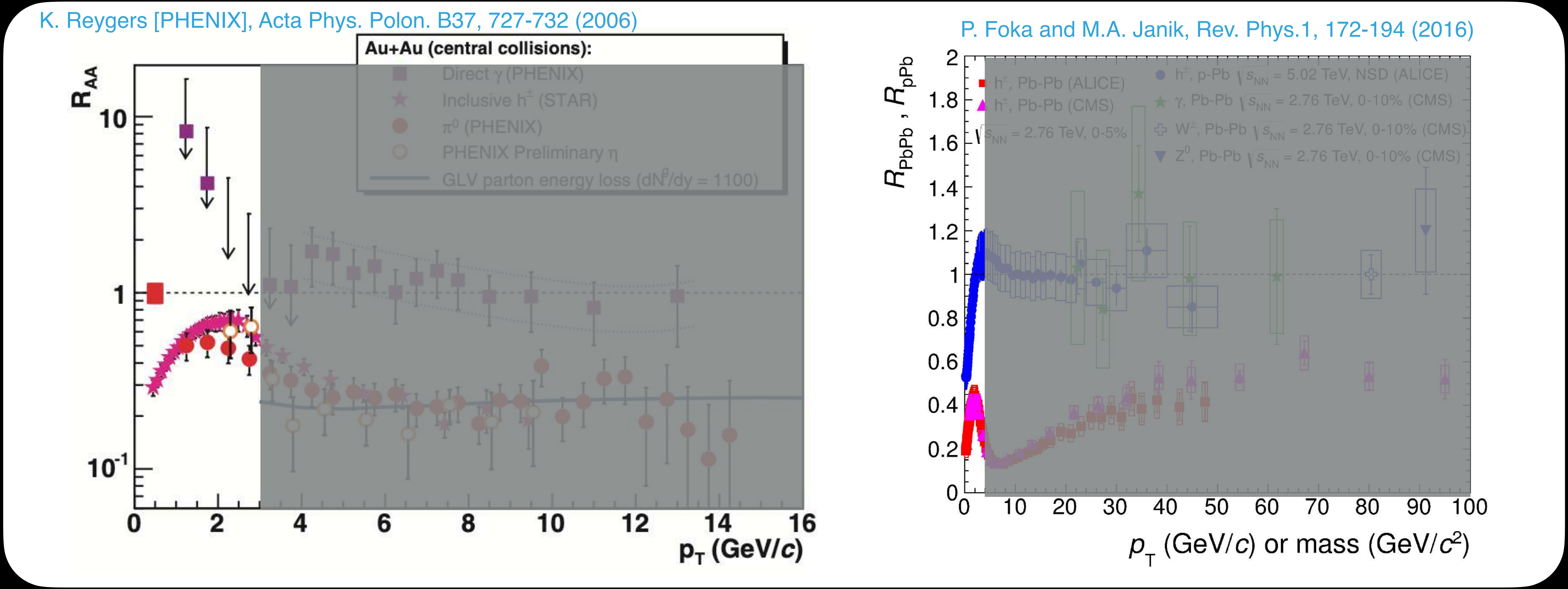
P. Foka and M.A. Janik, Rev. Phys.1, 172-194 (2016)



- Different specifies of particles carry their unique information about the hot QGP medium

$$R_{AA} = \frac{dN^{AA}/d^3p}{\langle T_{AA}\rangle dN^{pp}/d^3p}$$

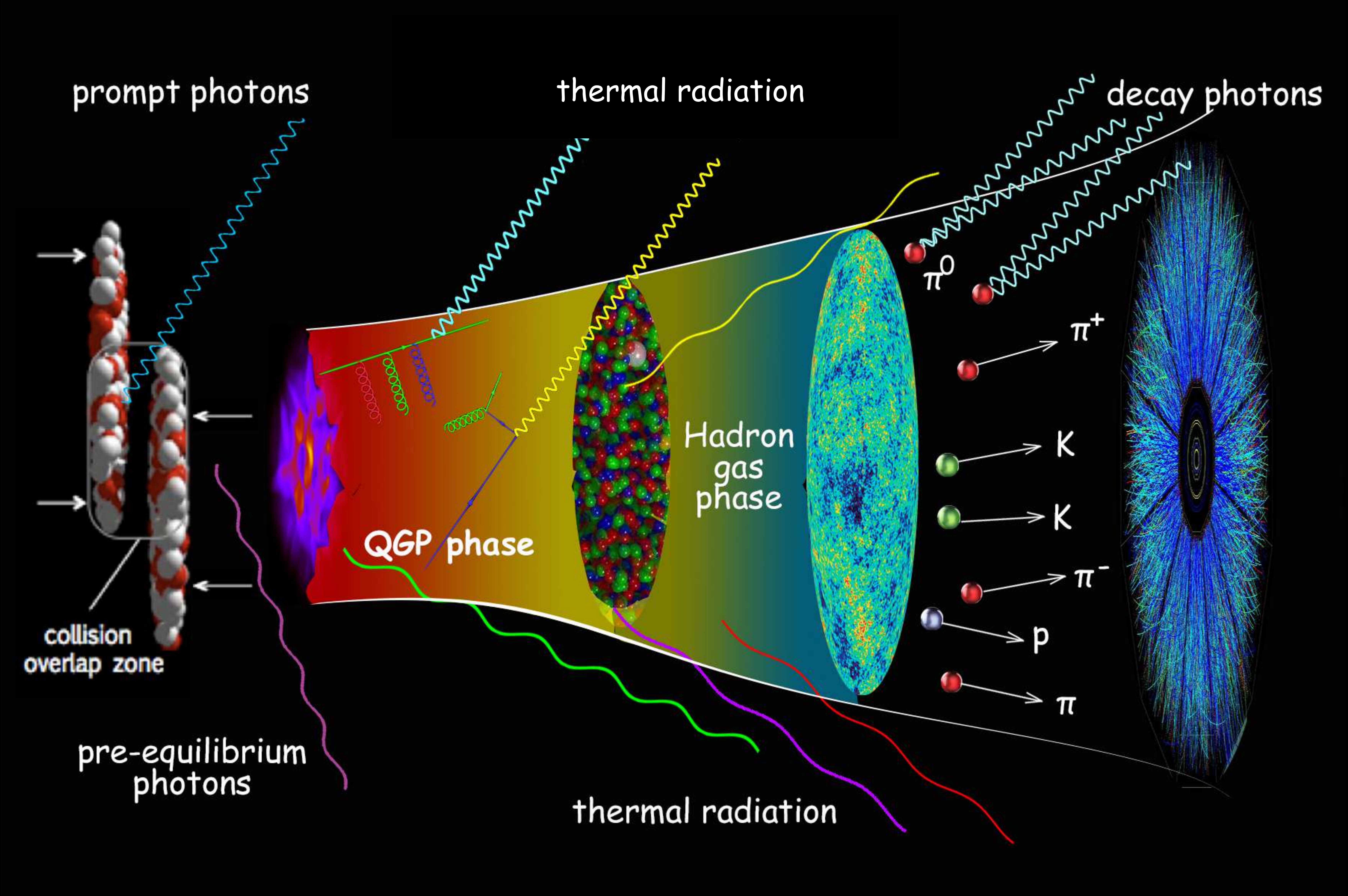
MULTI-MESSENGER HEAVY-ION PHYSICS



- Let's focus on soft particles with momentum below 3 GeV (99% of all particles)
- Their momentum information carries the system's thermodynamic and dissipative properties

$$R_{AA} = \frac{dN^{AA}/d^3p}{\langle T_{AA}\rangle dN^{pp}/d^3p}$$

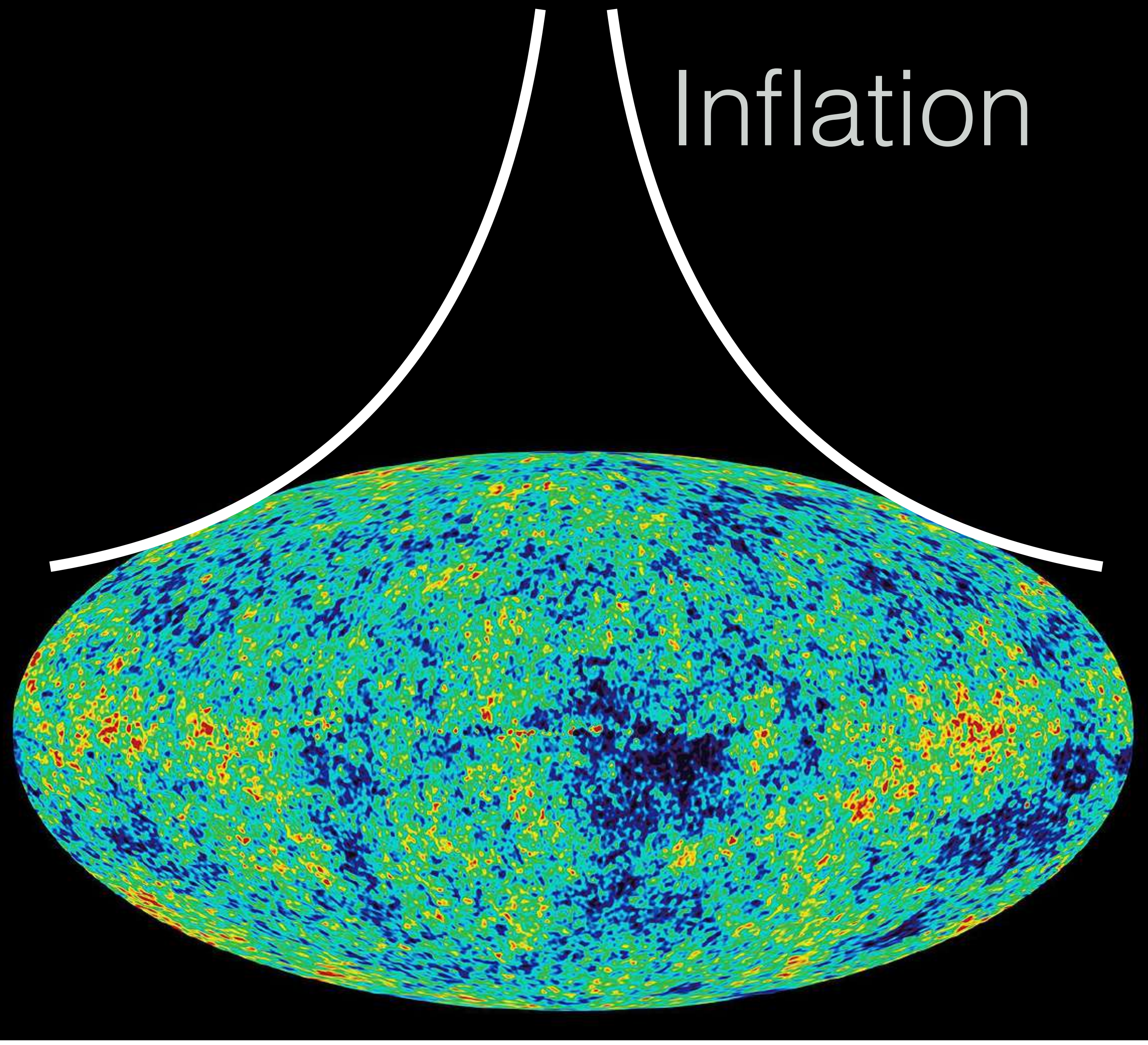
SOFT PROBES OF HEAVY-ION COLLISIONS

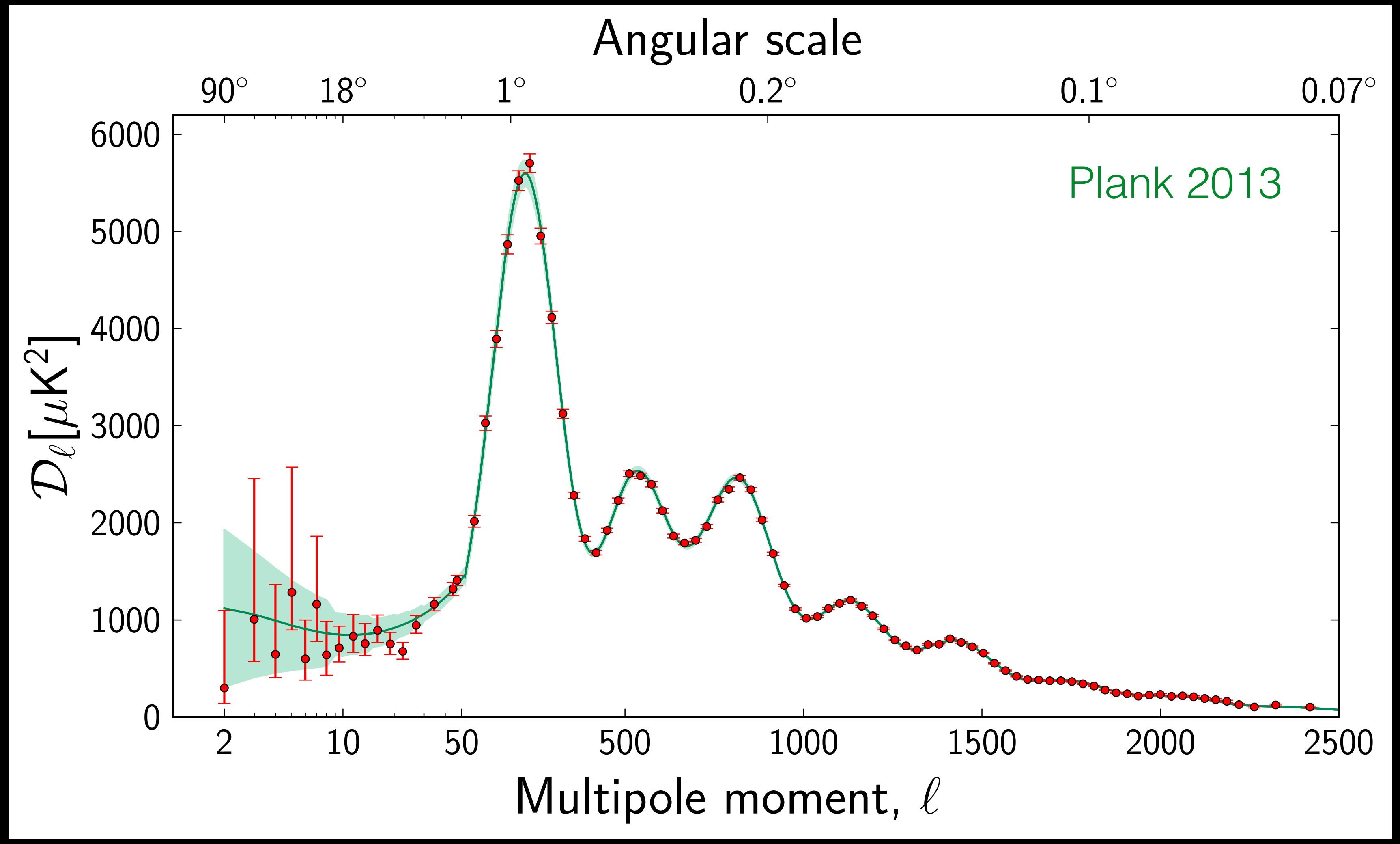


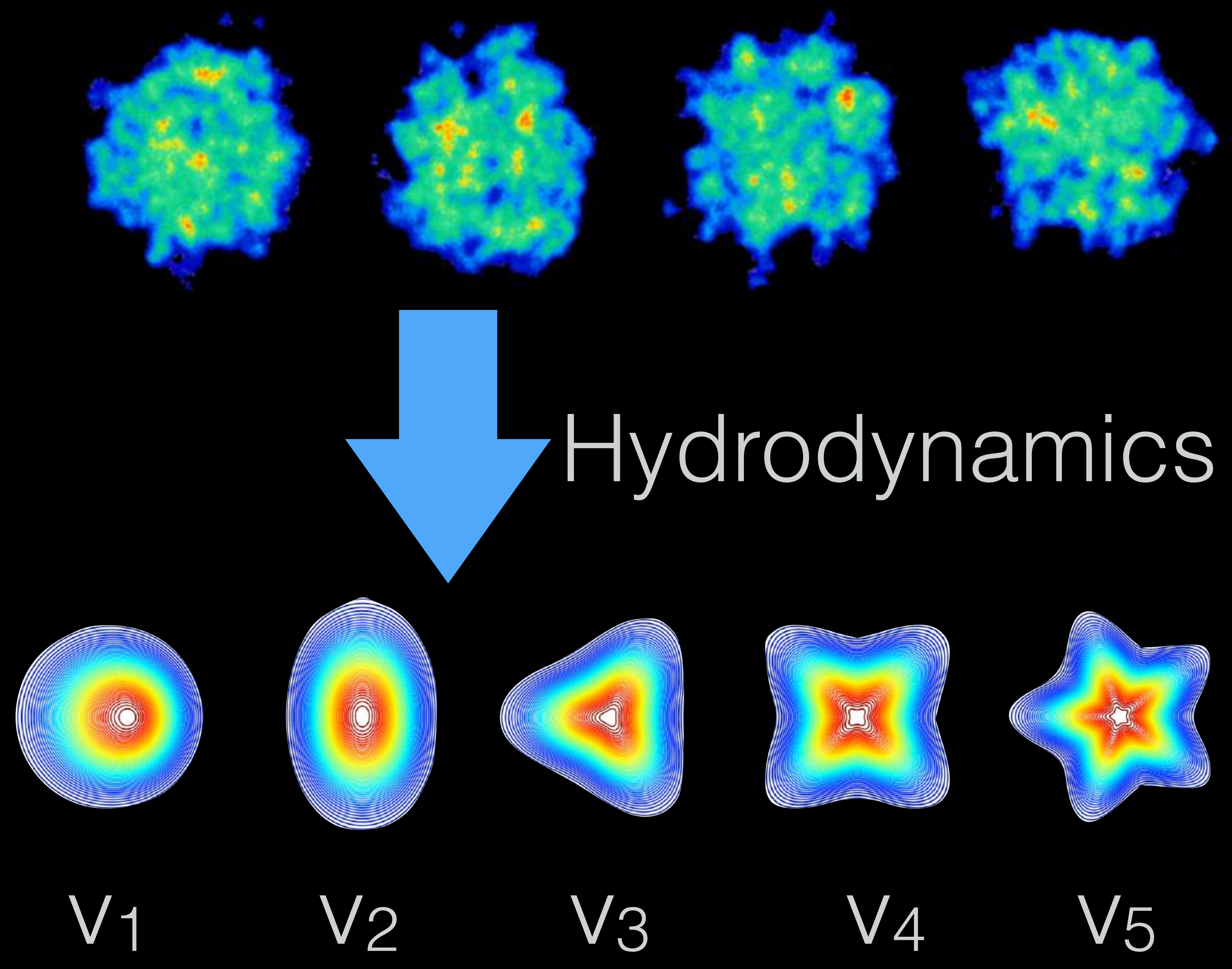
Electromagnetic radiation is the unique *soft* and *penetrating* probe of heavy-ion collisions over the full space-time volume

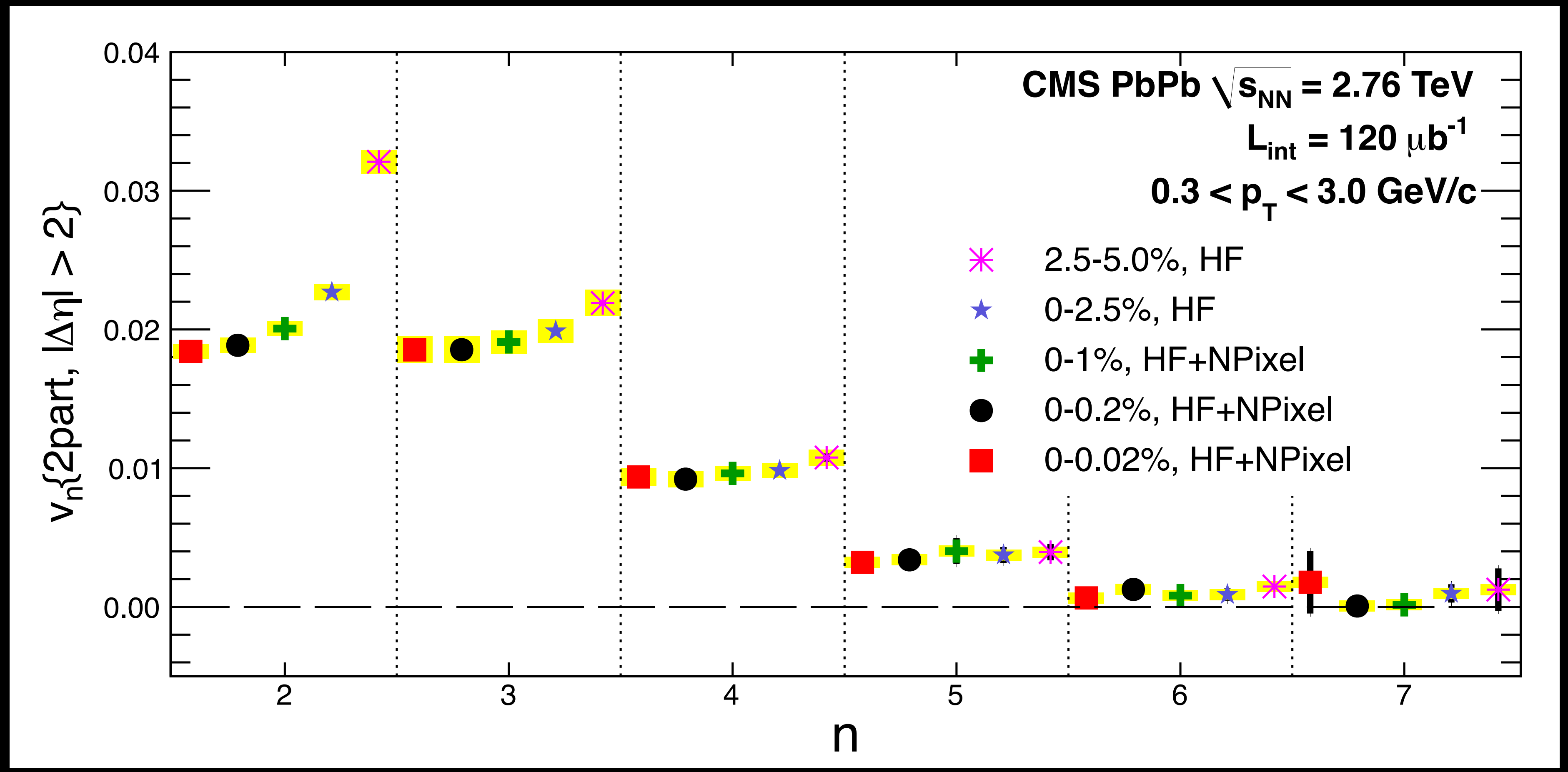
Hadrons are free at the late stage of evolution; they lose (part of) their memory along the way

HADRON FLUCTUATION POWER SPECTRUM

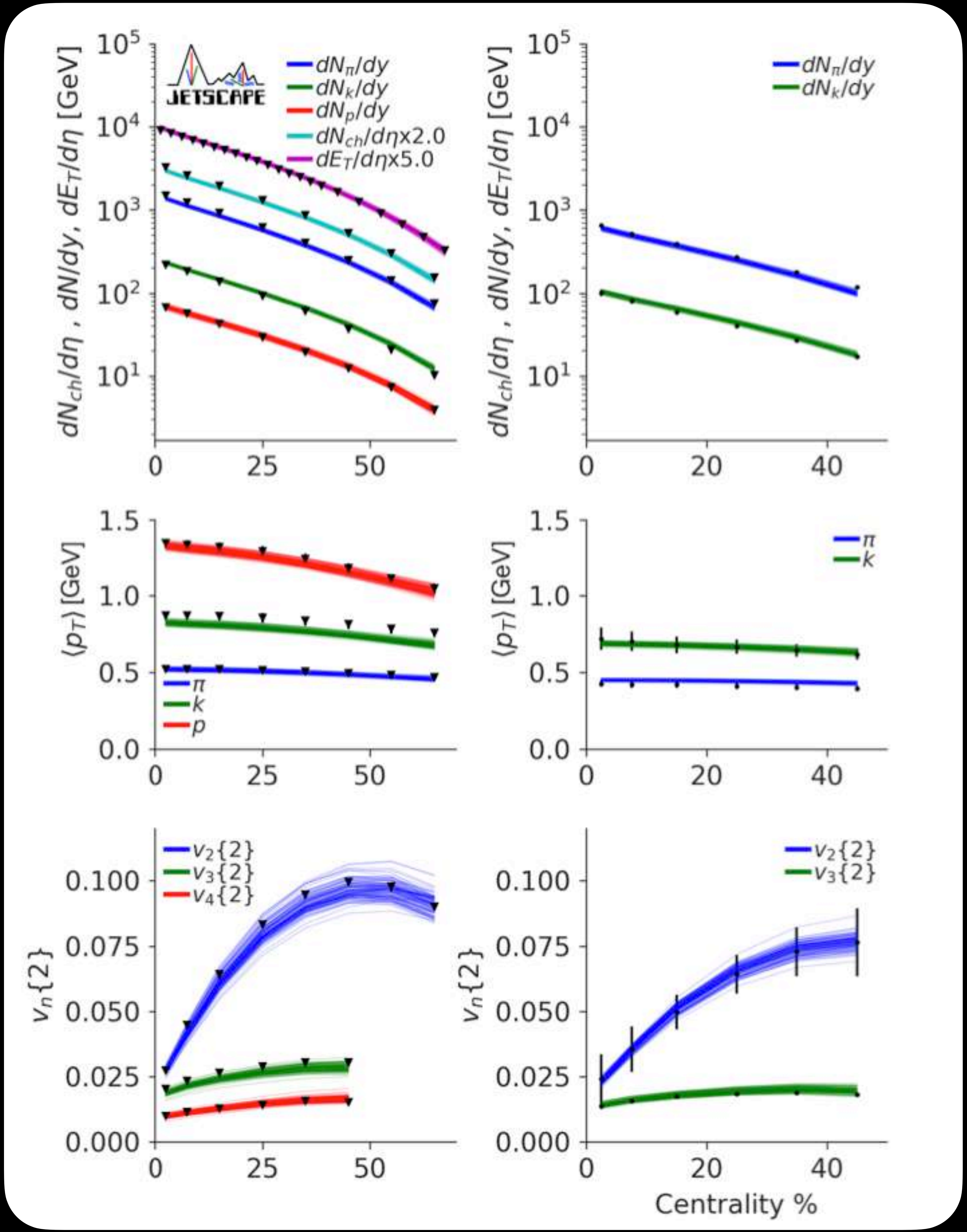




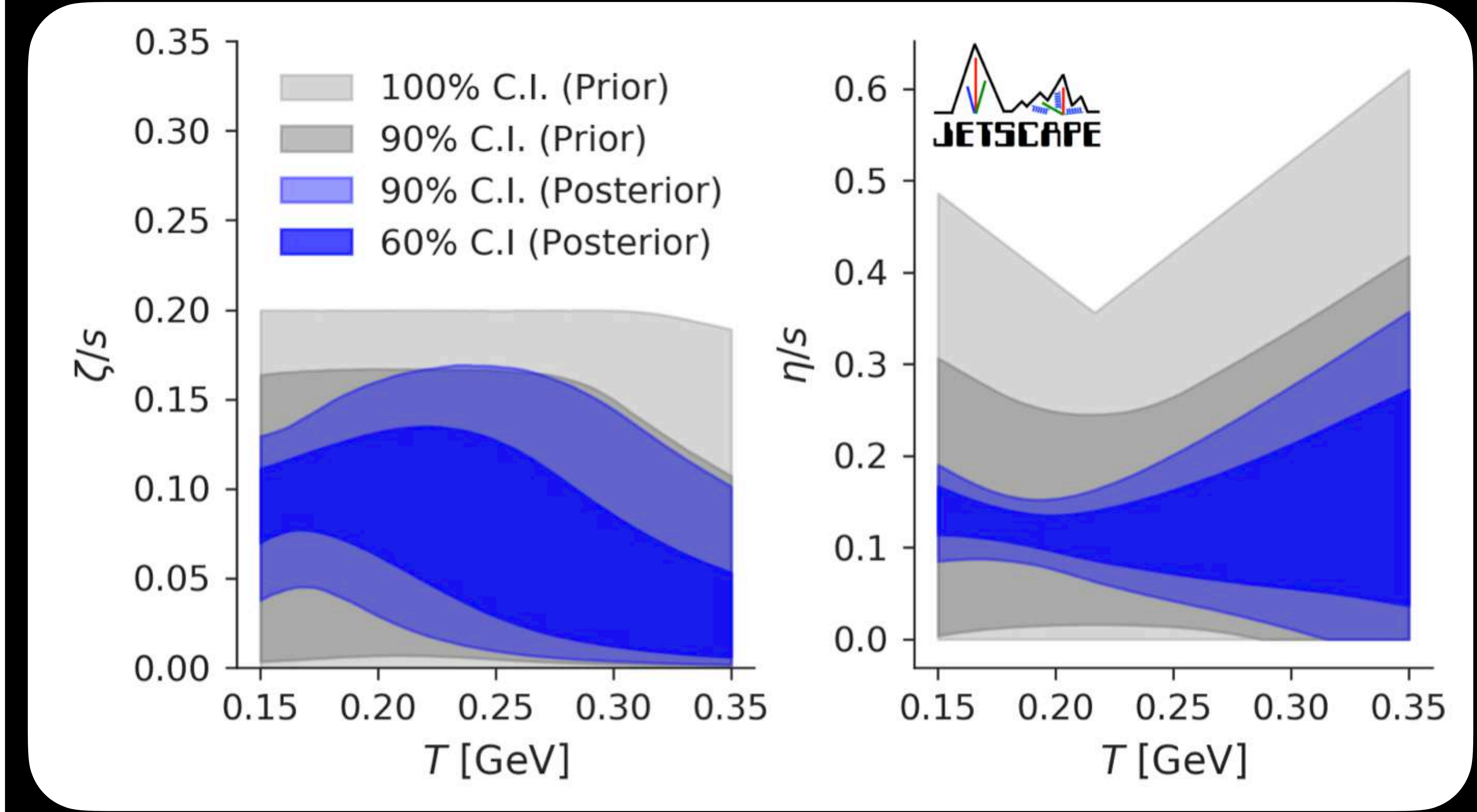




GLOBAL BAYESIAN CONSTRAINTS ON QGP VISCOSITY

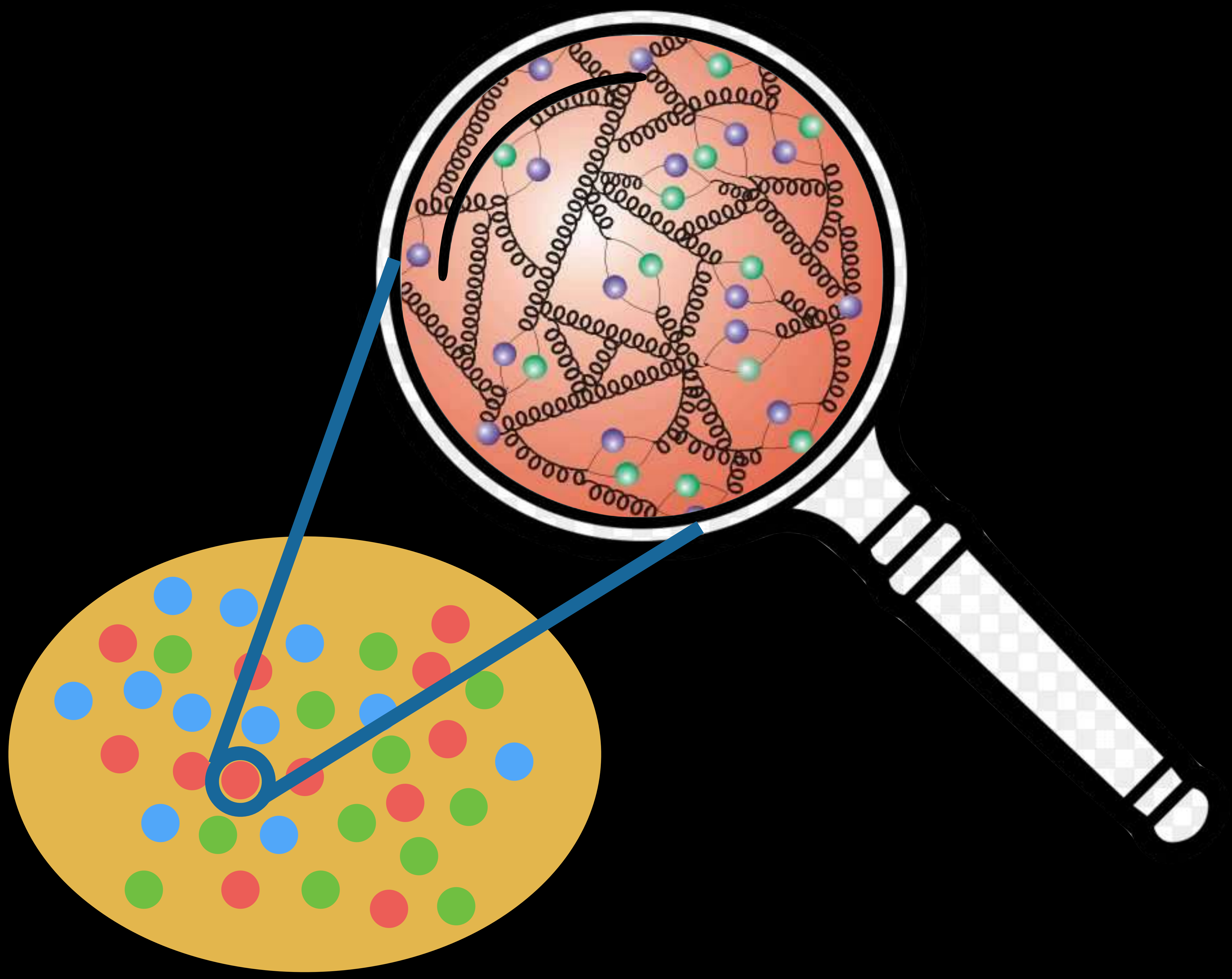


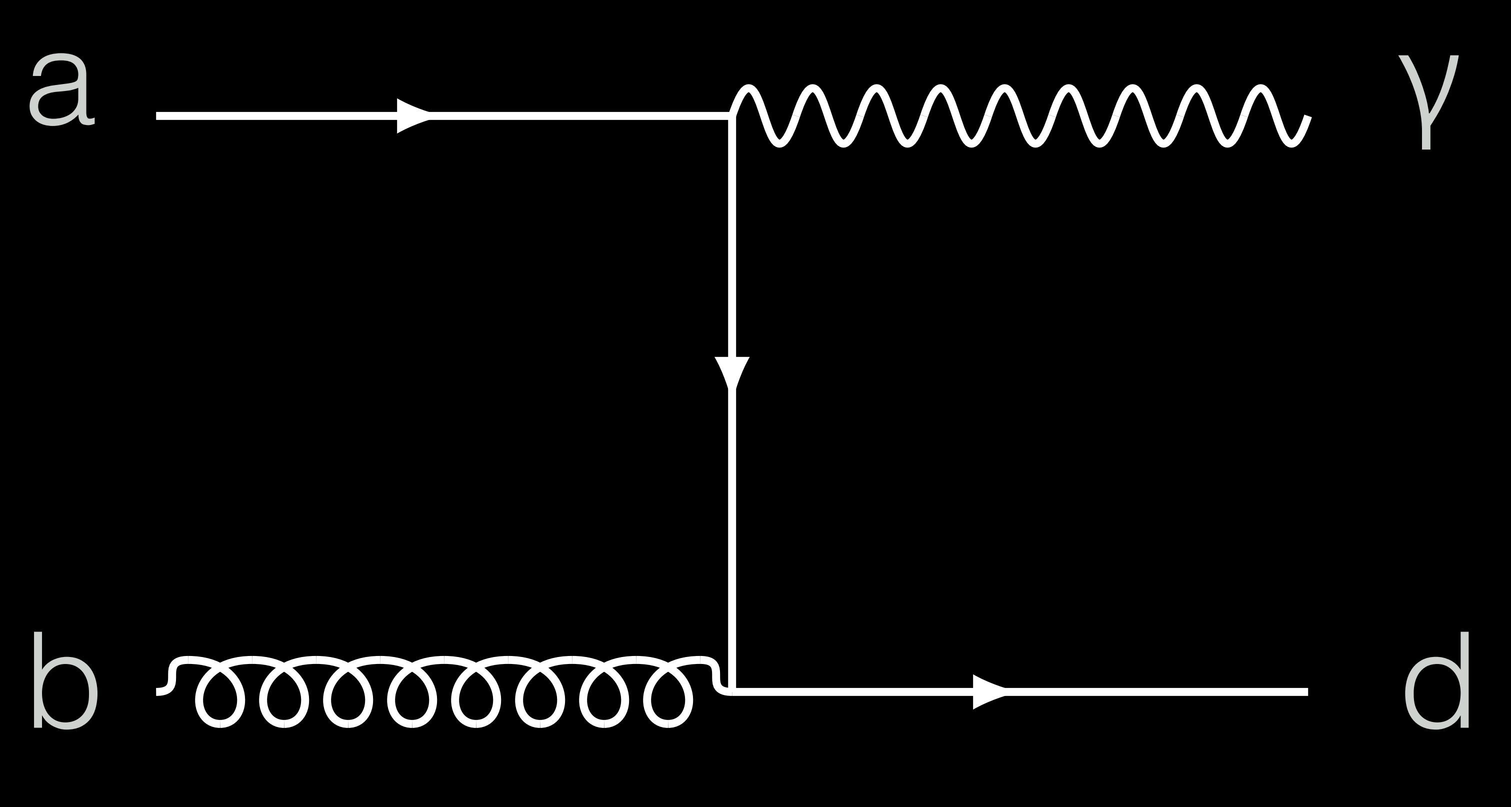
J. E. Bernhard, J. S. Moreland and S. A. Bass, Nature Phys. 15, 1113-1117 (2019)
G. Nijs, W. Van Der Schee, U. Gursoy and R. Snellings, arXiv:2010.15134 [nucl-th]
D. Everett *et al.* [JETSCAPE], arXiv:2011.01430 [hep-ph]



- Precision hadronic measurements systematically constrain the QGP viscosity

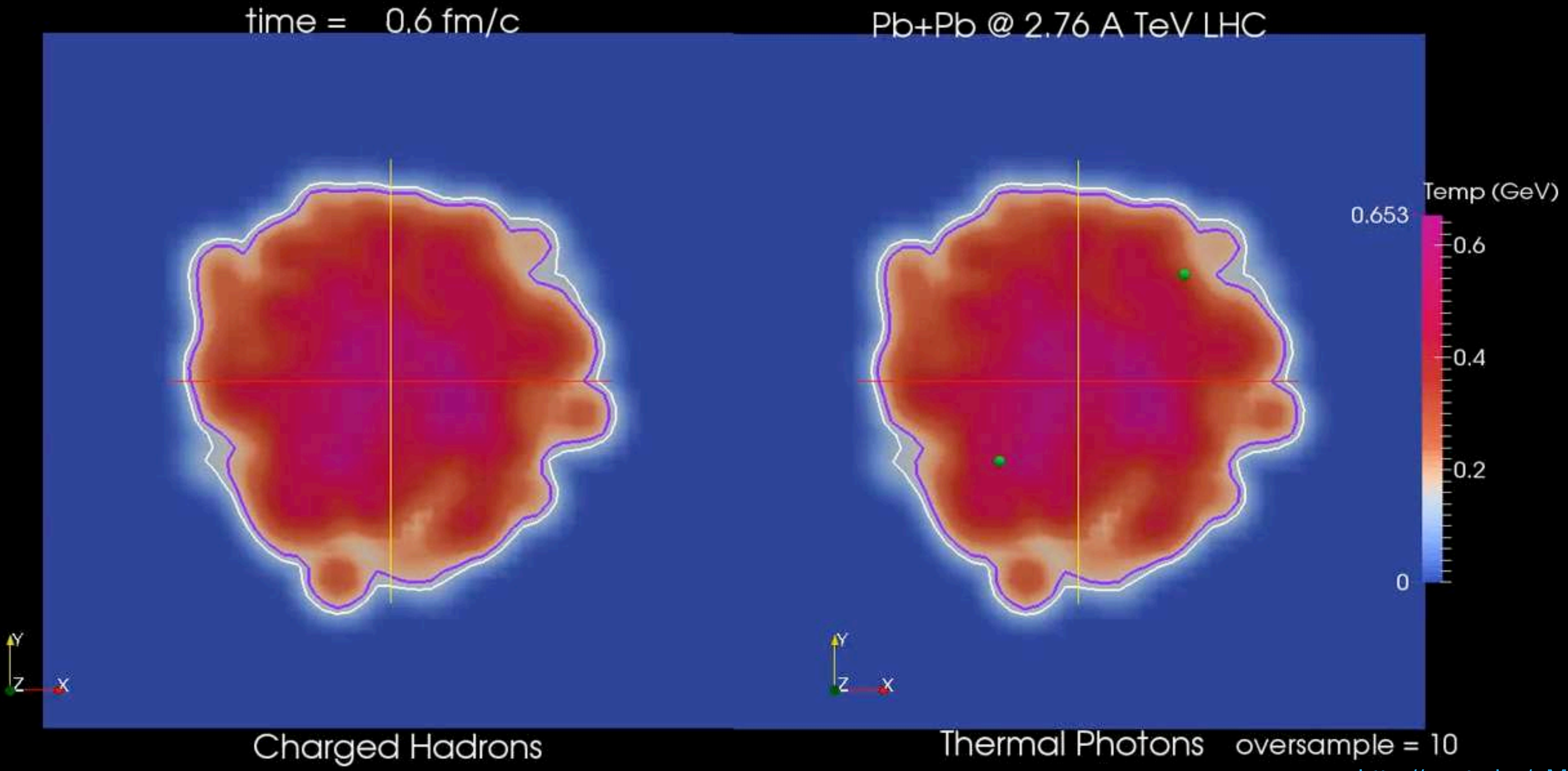
PHOTON AS A MICROSCOPE FOR THE QCD MATTER





$$E_p \frac{dN^\gamma}{d^3p} \propto f_a(p)$$

PHOTONS ARE TOMOGRAPHIC PROBES OF THE QGP



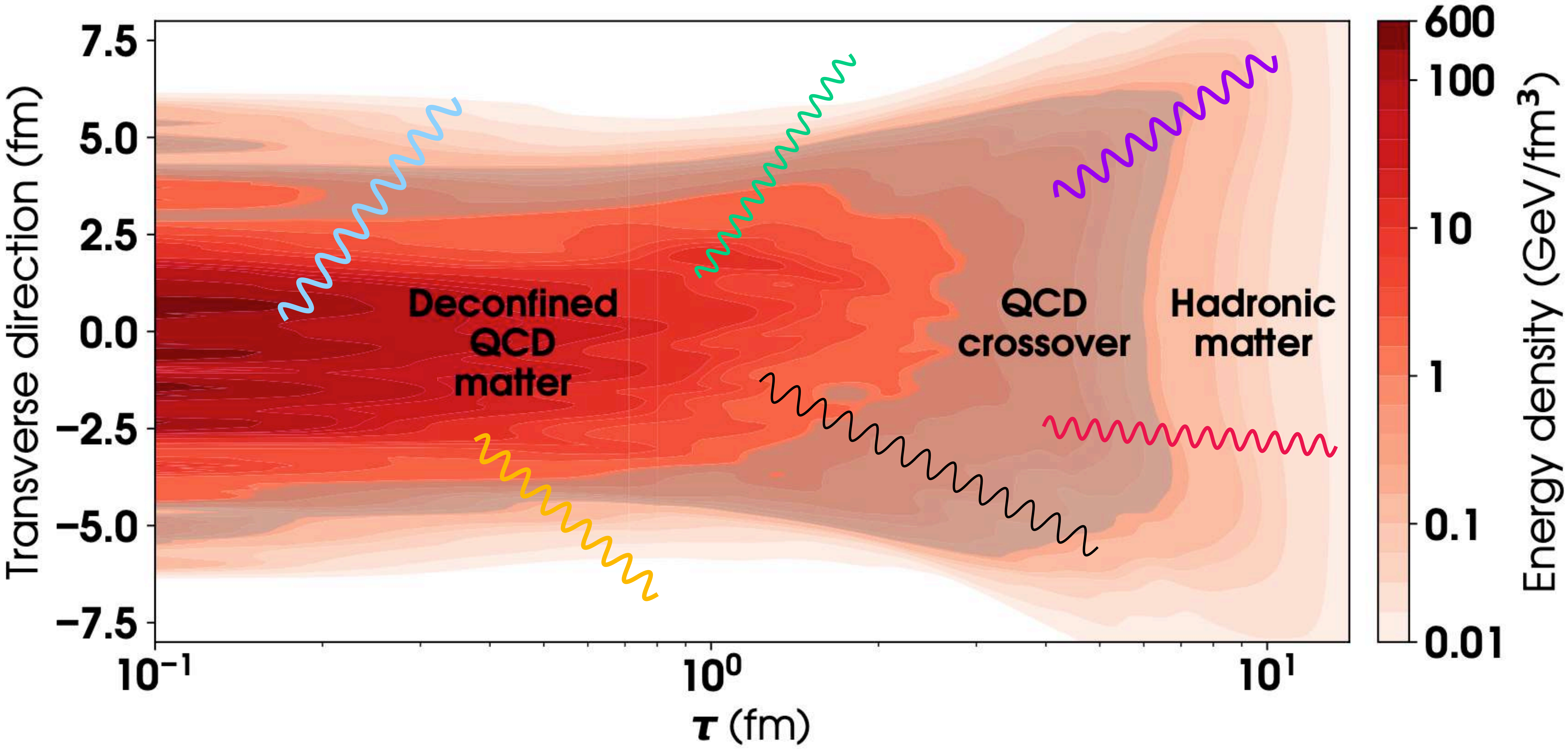
http://youtu.be/oMFboC7O1DU

Electromagnetic probes emerge from *entire space time volume*

Hadrons emerge from the freeze-out surface

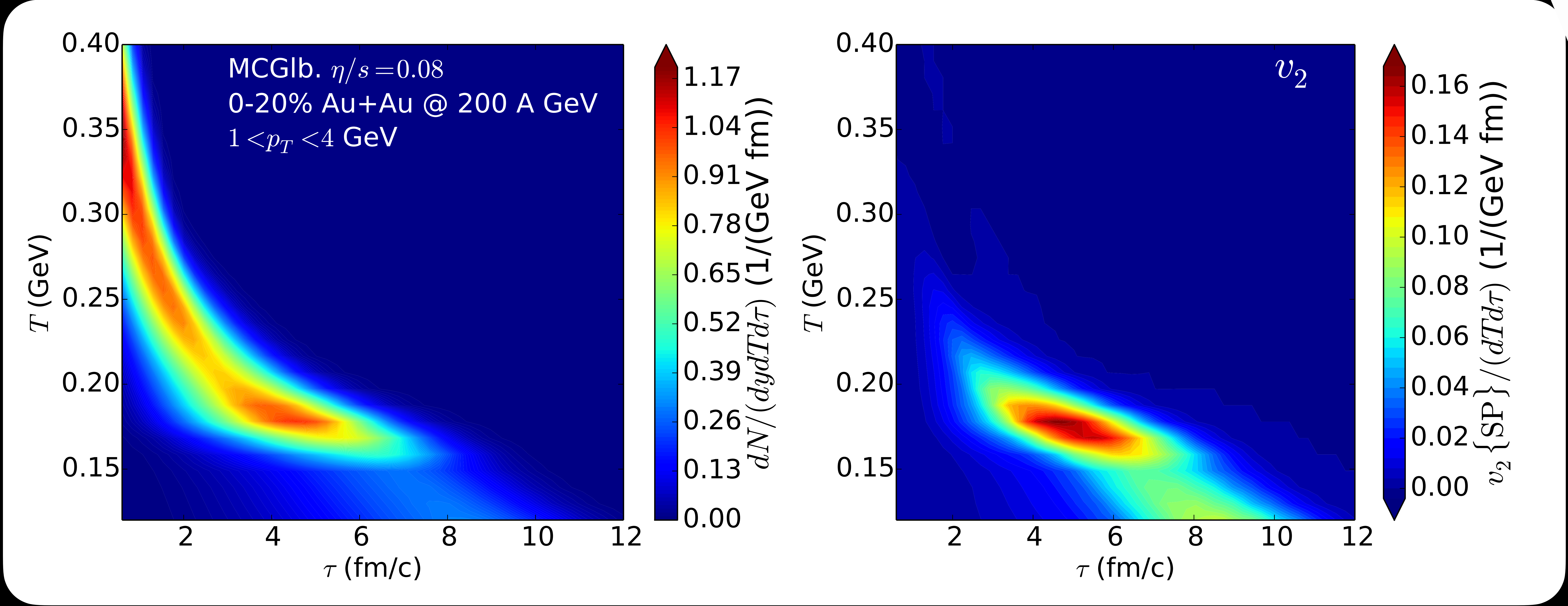
PHOTONS PROBES OF THE INNER WORKING OF QGP

C. Gale, J. F. Paquet, B. Schenke and C. Shen, arXiv:2009.07841 [nucl-th]



THERMAL PHOTON TOMOGRAPHY

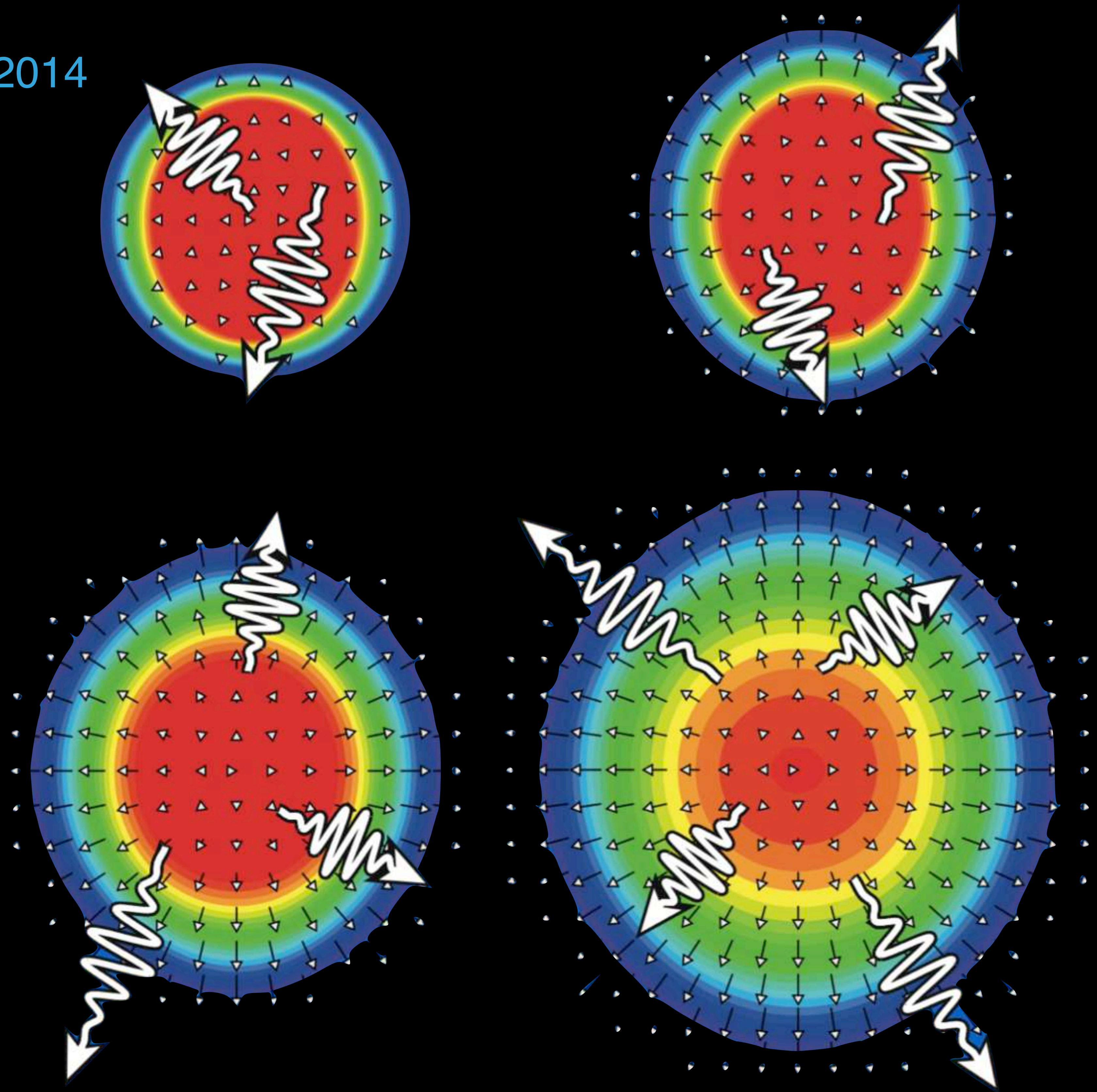
C. Shen, U. Heinz, J. F. Paquet, I. Kozlov, and C. Gale, Phys. Rev. C 91, 024908 (2015)



- We observe a two-wave structure in thermal photon emission
- Thermal photon v_2 is mostly coming from the transition region, T = 150~200 MeV, τ = 3 ~ 8 fm @ RHIC

DOPPLER EFFECT IN HEAVY-ION COLLISIONS

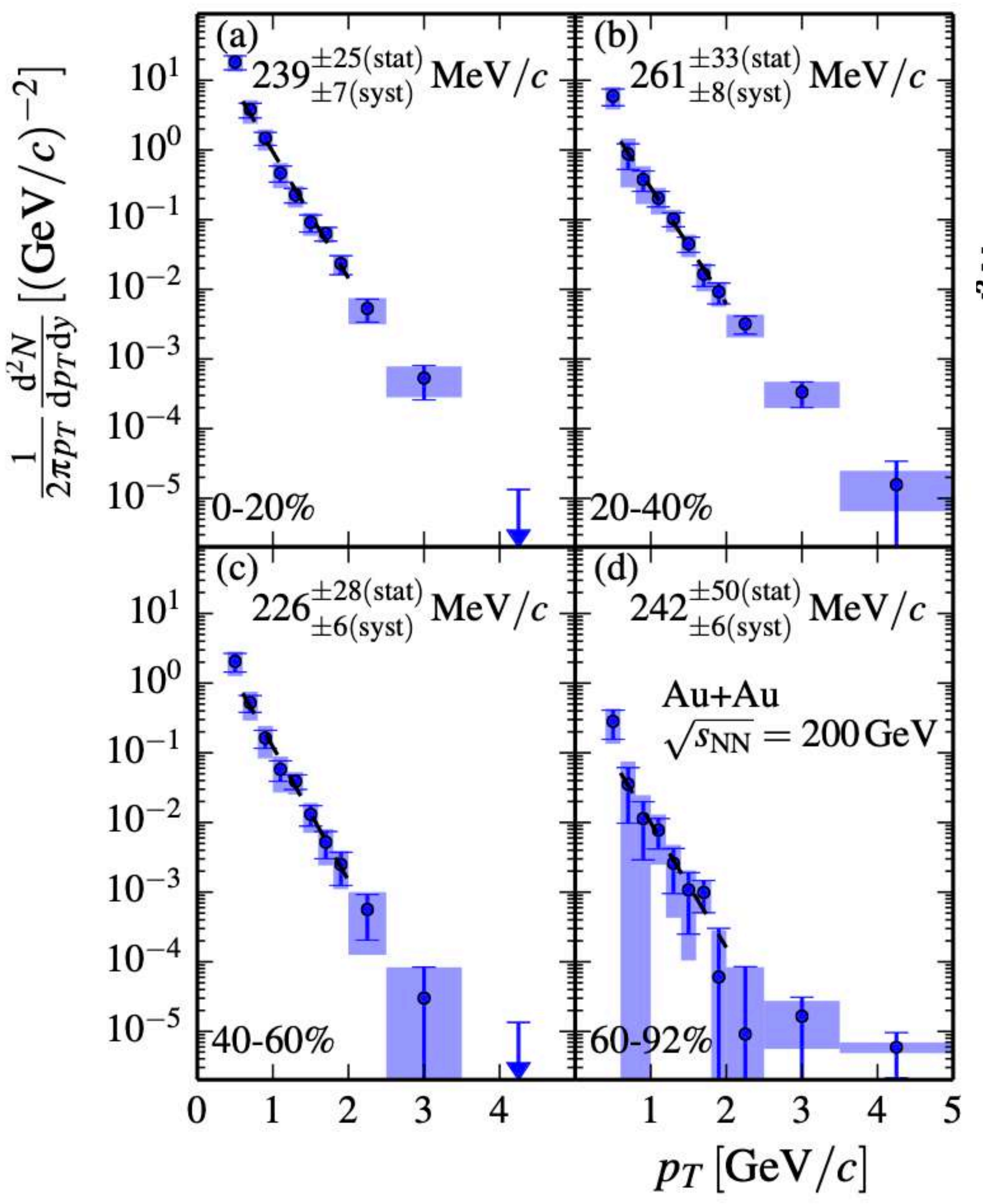
EMMI RRTF 2014



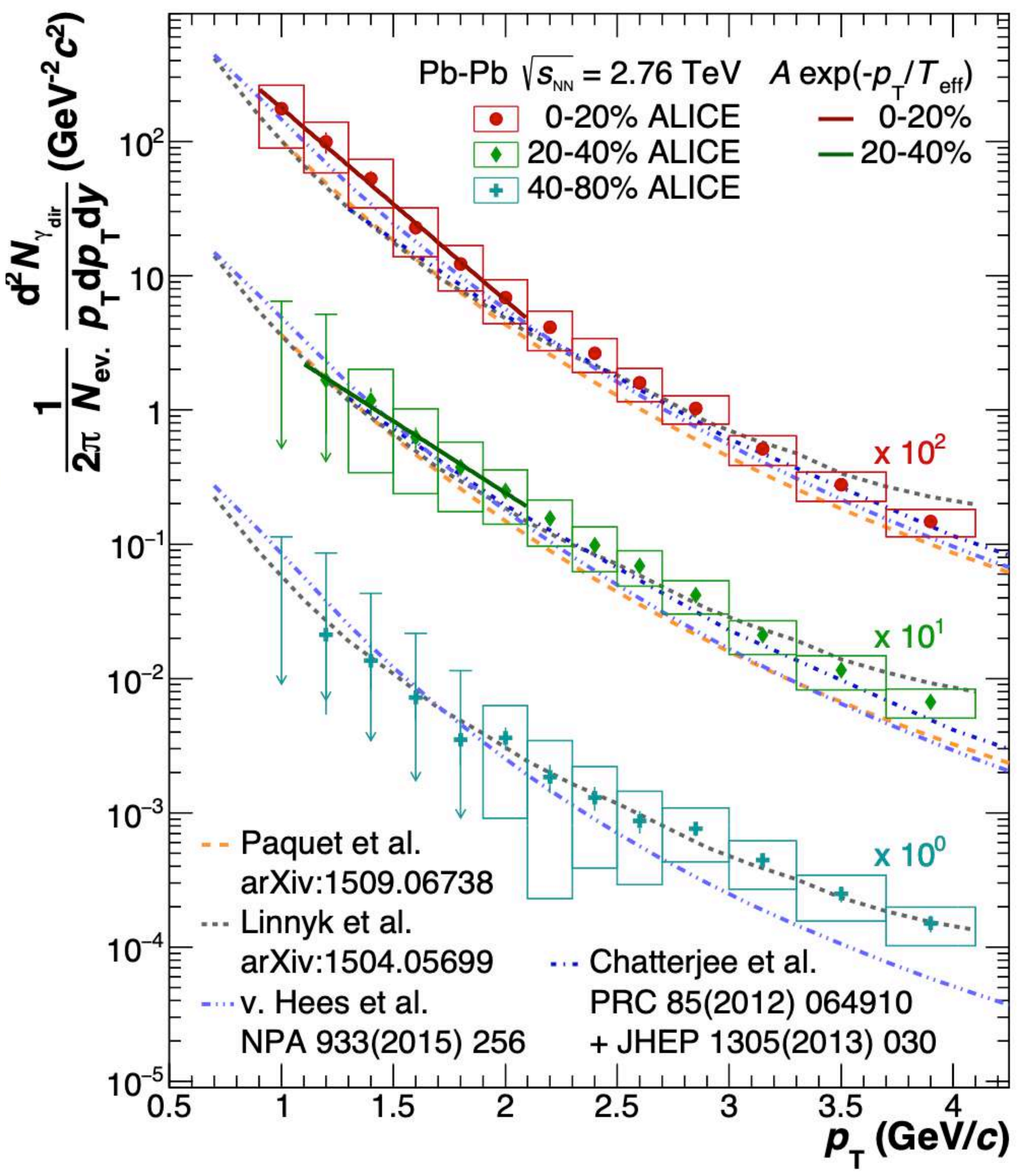
$$E\frac{dN}{d^3p} \sim \int d^4x \frac{p^\mu u_\mu}{\exp[p^\mu u_\mu/T] \pm 1} \qquad T_{\mathrm{slope}} \sim T\sqrt{\frac{1+v}{1-v}}$$

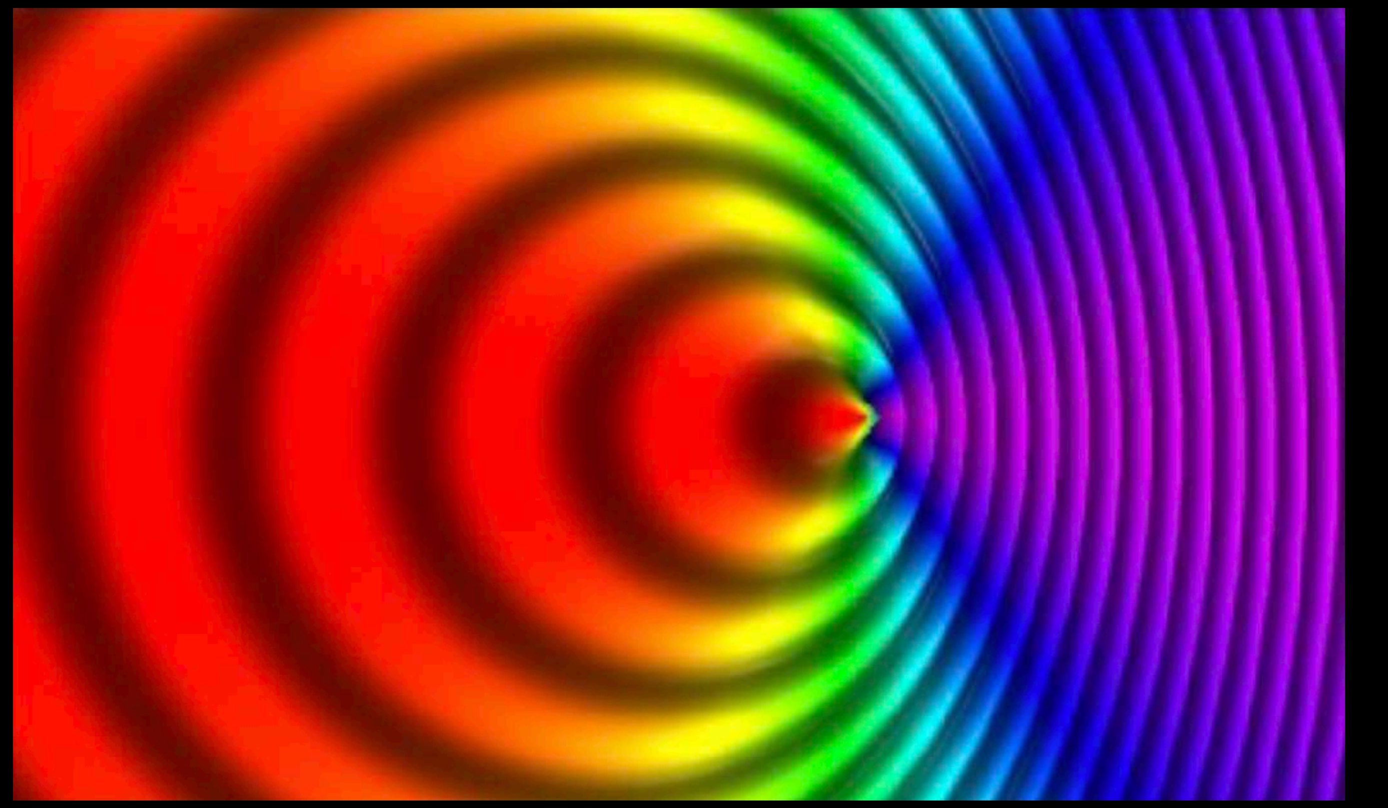
BLUE-SHIFTED BLACK BODY RADIATION

A. Adare *et al.* [PHENIX], Phys. Rev. C91, 064904 (2015)



J. Adam *et al.* [ALICE], Phys. Lett. B 754, 235-248 (2016)

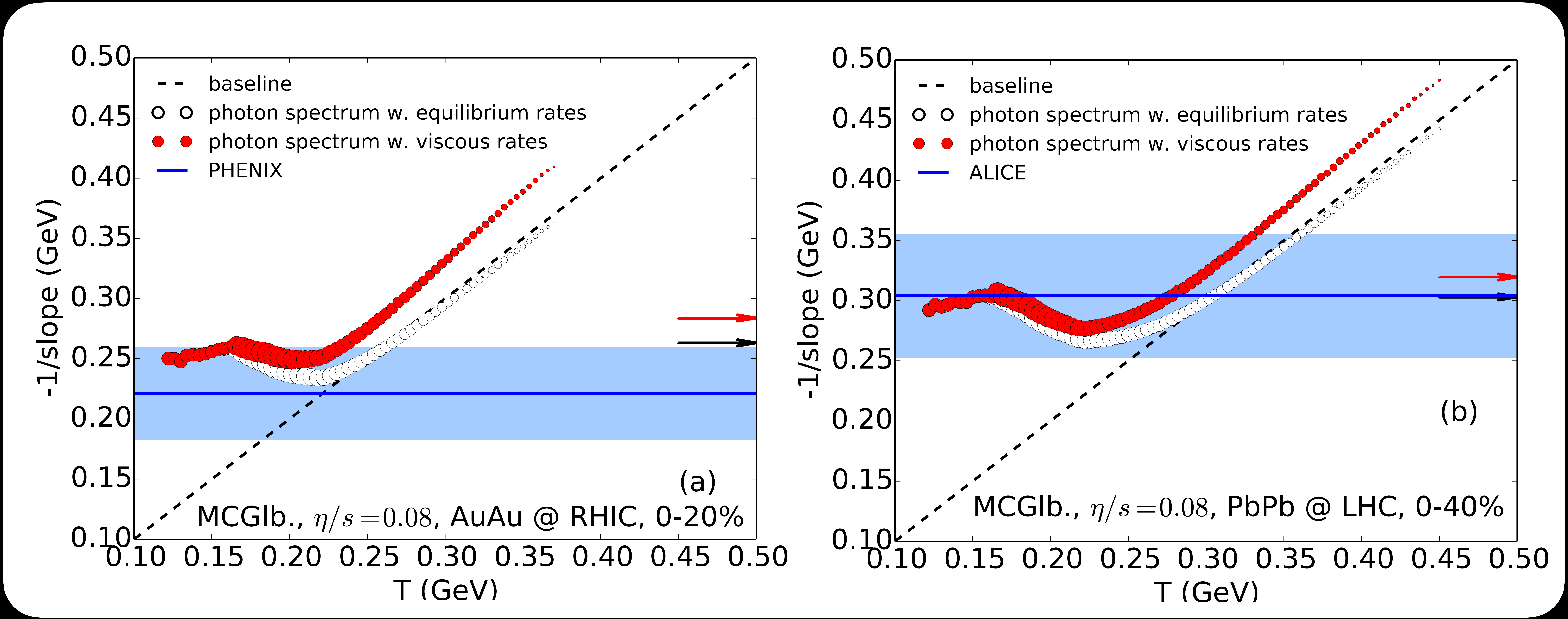




- How to extract physical information from the inverse slope of direct photon spectra?

DECODING THE INVERSE SLOPE

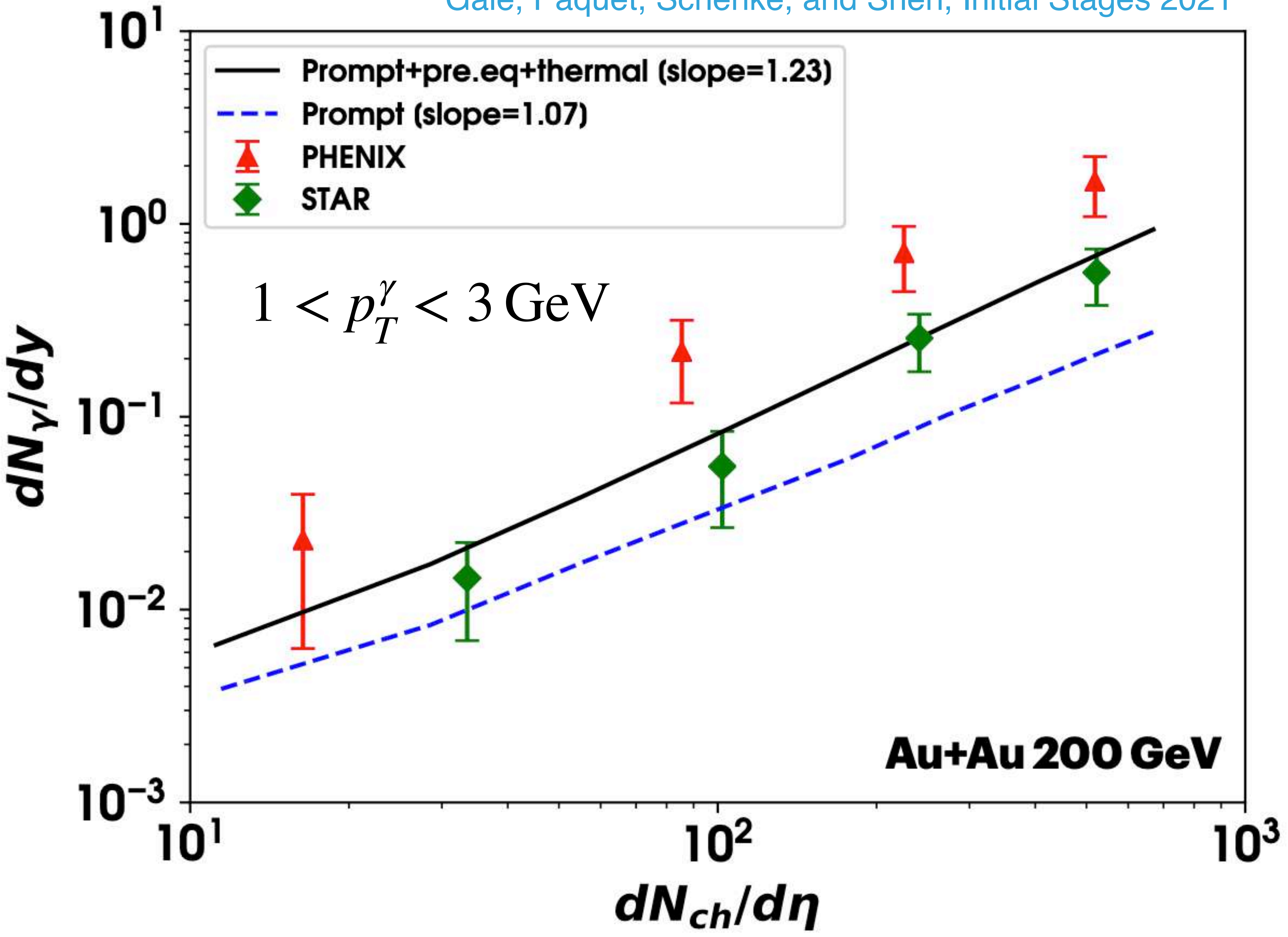
C. Shen, U. Heinz, J.-F. Paquet and C. Gale, Phys. Rev. C 89, 044910 (2014)



- **All** photons with T < 250 MeV at RHIC and < 300 MeV at LHC carries T_{eff} within the experimental fitted region
- About **50-60%** of photons are emitted from T = 165~250 MeV, they are strongly blue shifted by radial flow

CENTRALITY SCALING OF DIRECT PHOTON YIELD

Gale, Paquet, Schenke, and Shen, Initial Stages 2021



PHENIX Collaboration, Phys.Rev.C91 (2015) 6, 064904
STAR Collaboration, Phys.Lett.B770 (2017) 451-458; Phys.Rev.C79 (2009) 034909

- The direct photon yield shows a stronger centrality dependence than charged hadrons

Thermal photons:

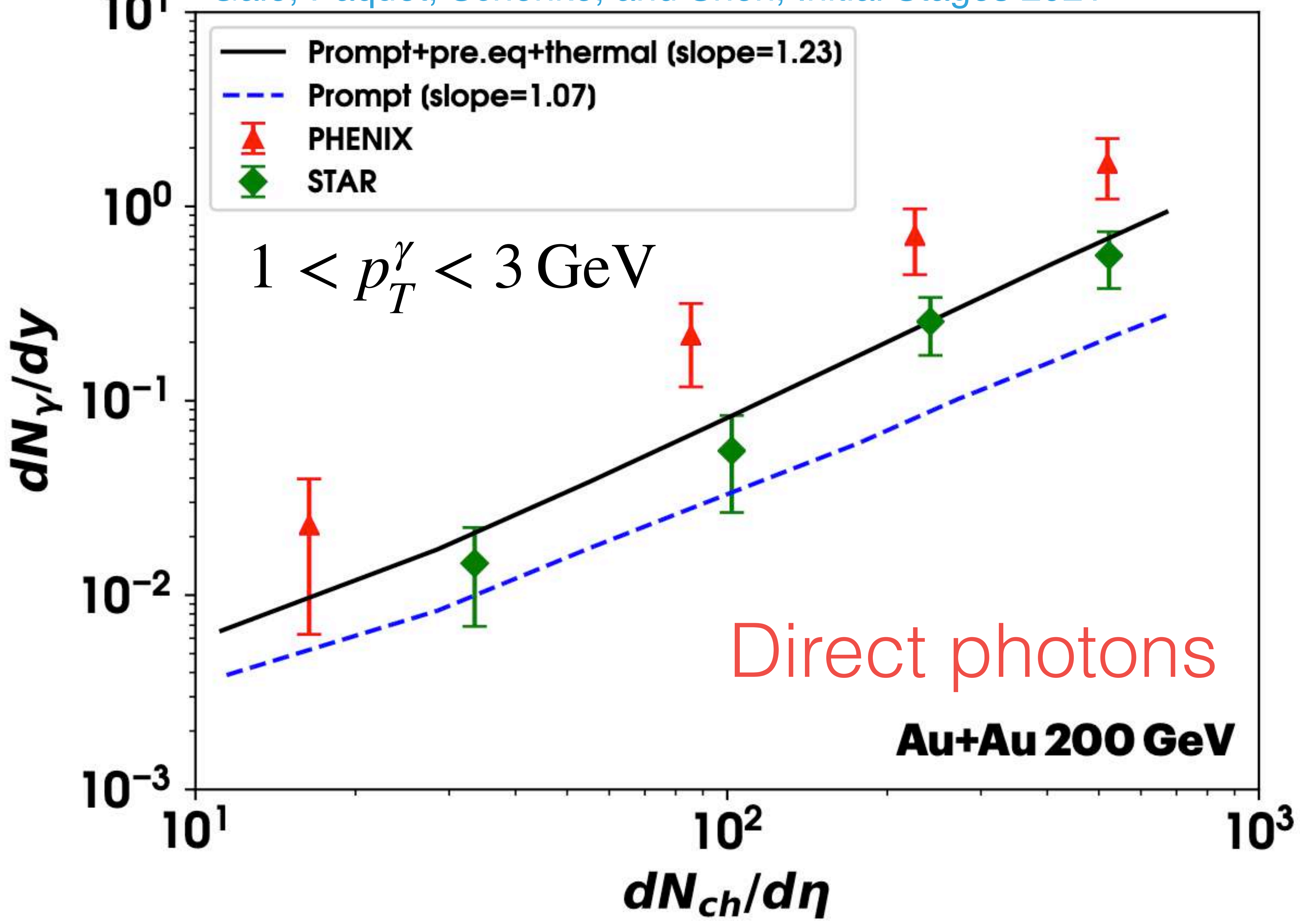
$$\frac{dN^\gamma_{\mathrm{thermal}}/dy}{dN^{\mathrm{ch}}/dy} \propto \frac{\langle T^4 V_4 \rangle}{\langle s V_3 \rangle} \propto \langle T \rangle \tau_f$$

Prompt photons:

$$\frac{dN^\gamma_{\mathrm{prompt}}/dy}{dN^{\mathrm{ch}}/dy} \propto \frac{N_{\mathrm{coll}}}{N_{\mathrm{part}}}$$

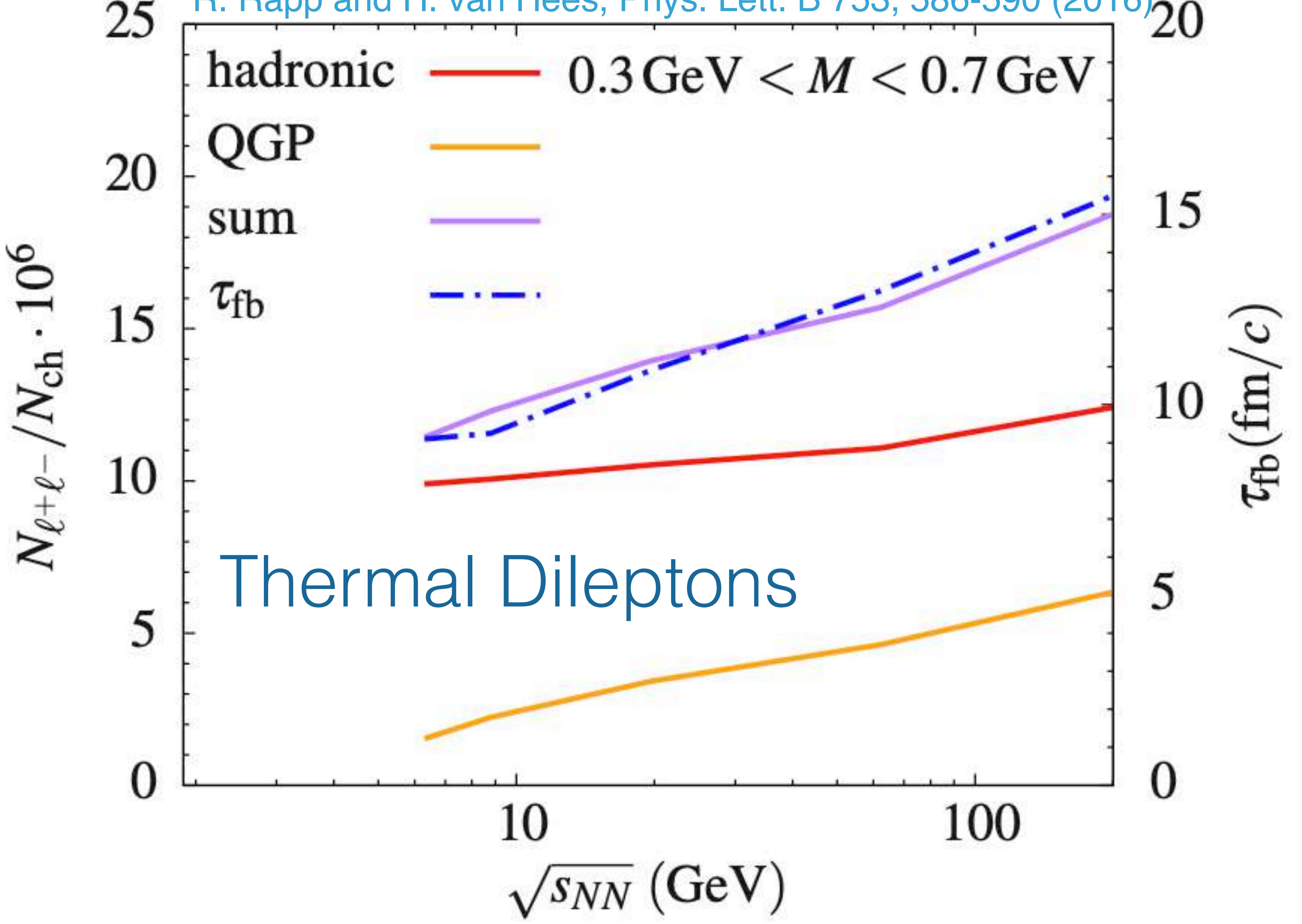
CENTRALITY SCALING OF EM PROBES

Gale, Paquet, Schenke, and Shen, Initial Stages 2021



PHENIX Collaboration, Phys.Rev.C91 (2015) 6, 064904
STAR Collaboration, Phys.Lett.B770 (2017) 451-458; Phys.Rev.C79 (2009) 034909

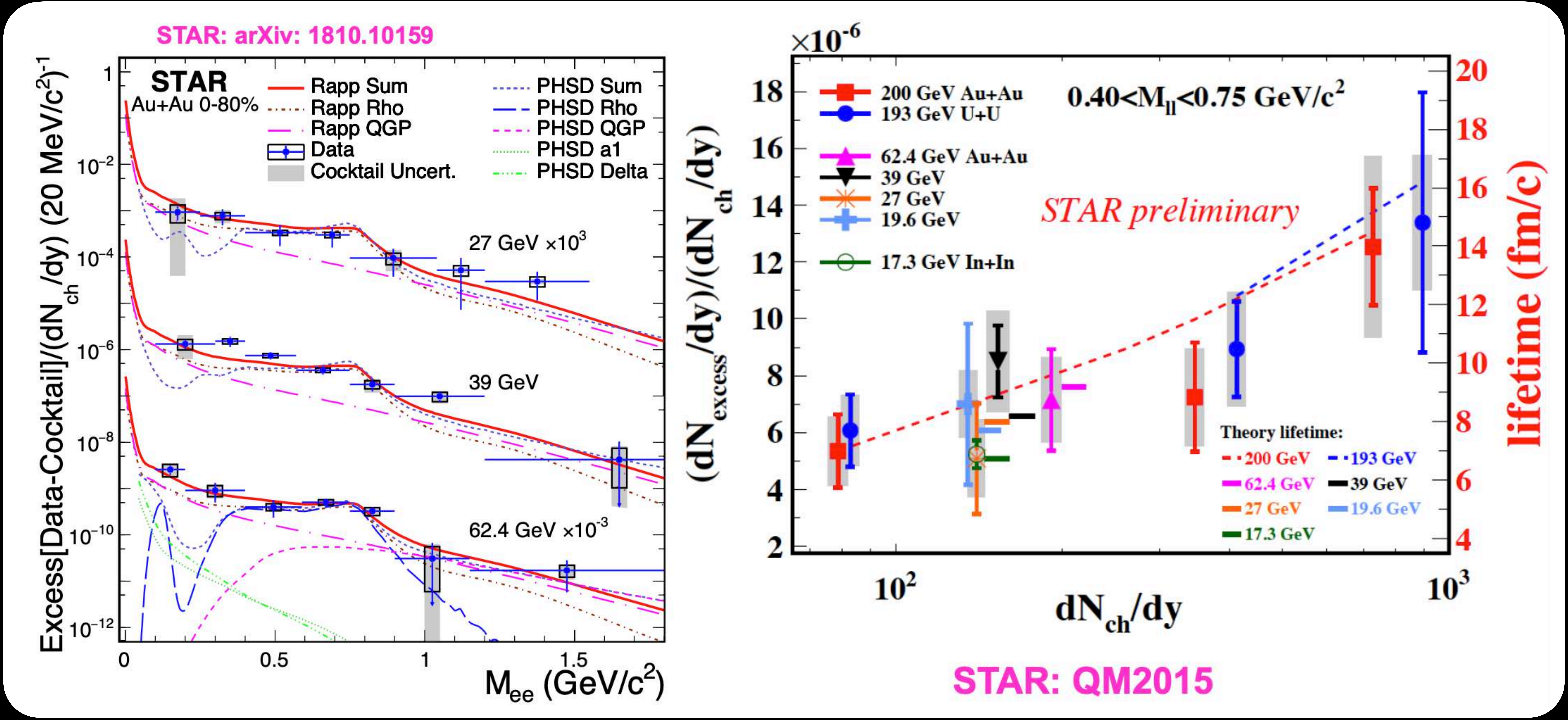
R. Rapp and H. van Hees, Phys. Lett. B 753, 586-590 (2016)



- Low mass thermal dileptons showed a similar excitation function, which has strong correlation with fireball lifetime

$$\frac{dN^\gamma_{\mathrm{thermal}}/dy}{dN^{\mathrm{ch}}/dy} \propto \langle T \rangle \tau_f$$

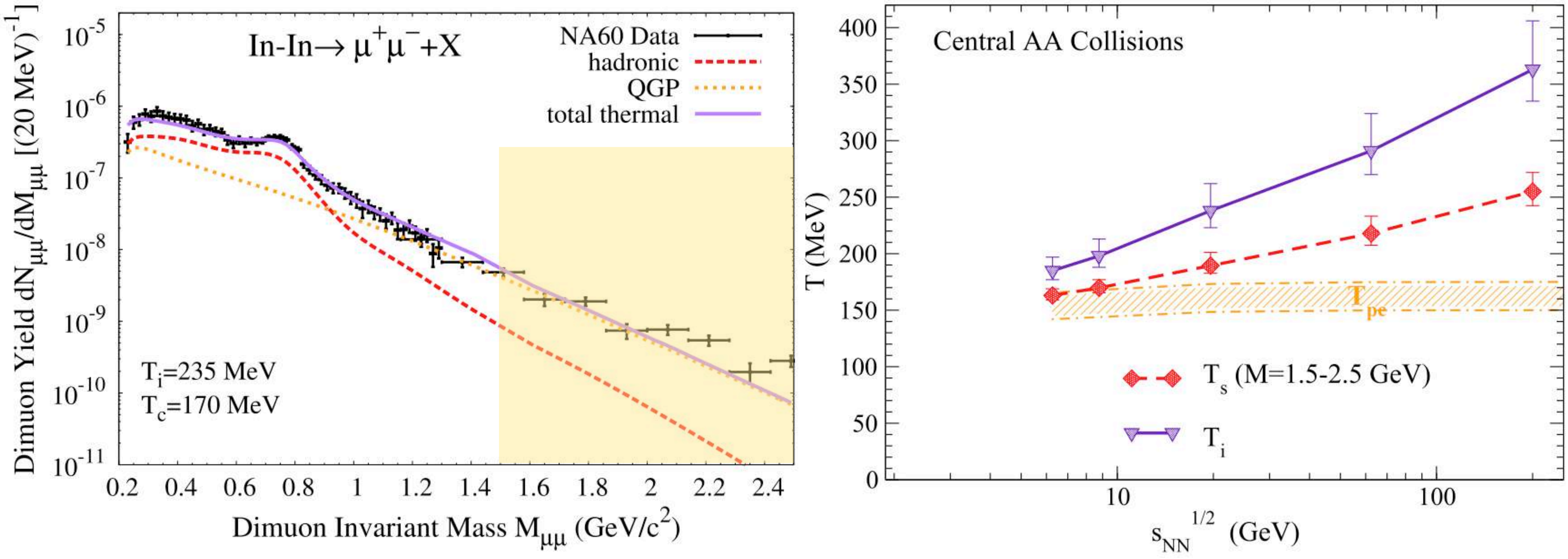
THE DIELECTRON EXCESS SPECTRUM: LIFETIME INDICATOR



A broadened ρ-spectral function consistently describes the low mass dielectron excess for different collisions energies, which is correlated with fireball lifetime

THERMAL DILEPTON AS A QGP THERMOMETER

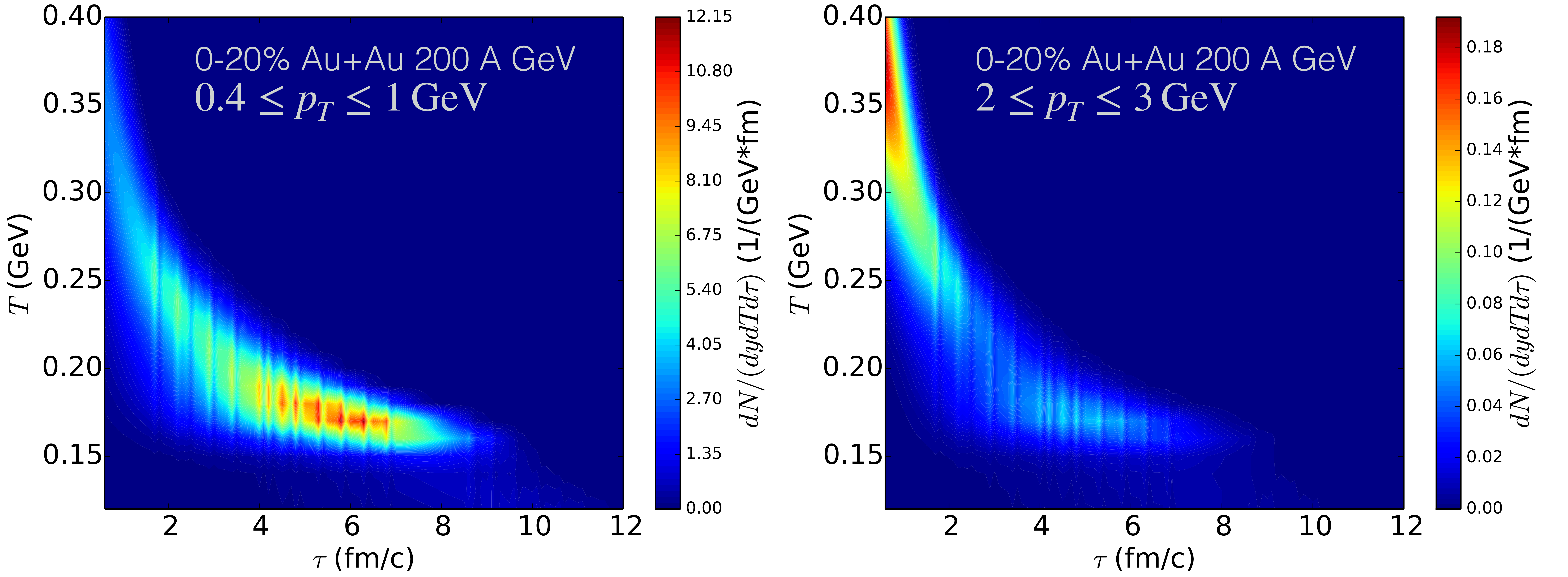
R. Rapp and H. van Hees, Phys. Lett. B 753, 586-590 (2016)



$$\frac{dR_{ll}}{dM} \propto (MT)^{3/2} \exp(-M/T)$$

- Thermal dilepton invariant mass spectrum is <u>independent</u> of blue-shift effects and can reveal true medium temperature

PROBING EARLY STAGES OF COLLISIONS



- High p_T thermal photons are emitted from high temperature fluid cells at early time

EFFECTS OF PRE-EQUILIBRIUM STAGE ON HADRONS

Gale, Paquet, Schenke, and Shen, in preparation

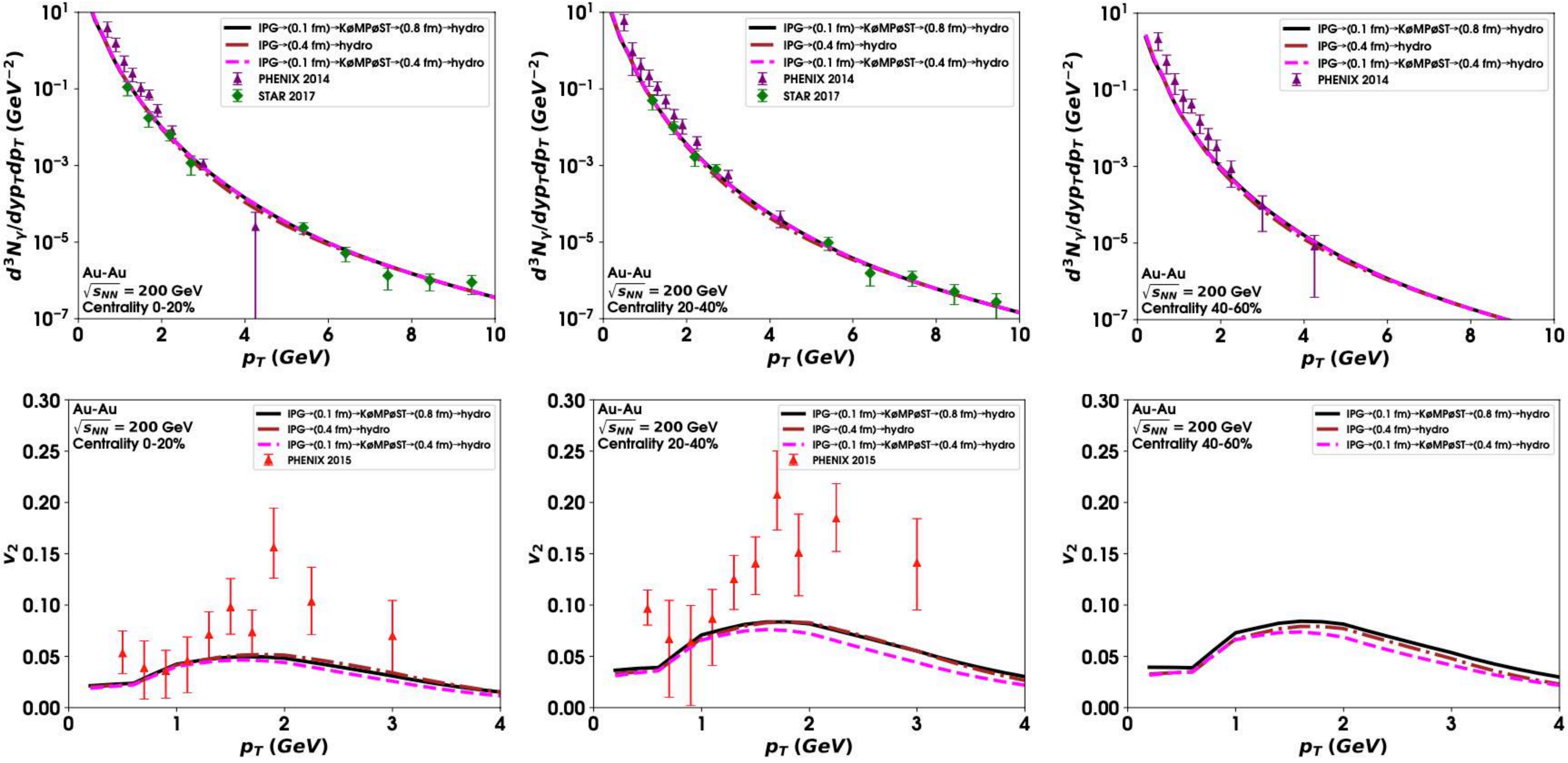
0^+ 0.1 0.4 0.8 τ (fm)

IP-Glasma Hydrodynamics Transport

IP-Glasma KoMPoST Hydrodynamics Transport

DIRECT PHOTON OBSERVABLES AT RHIC

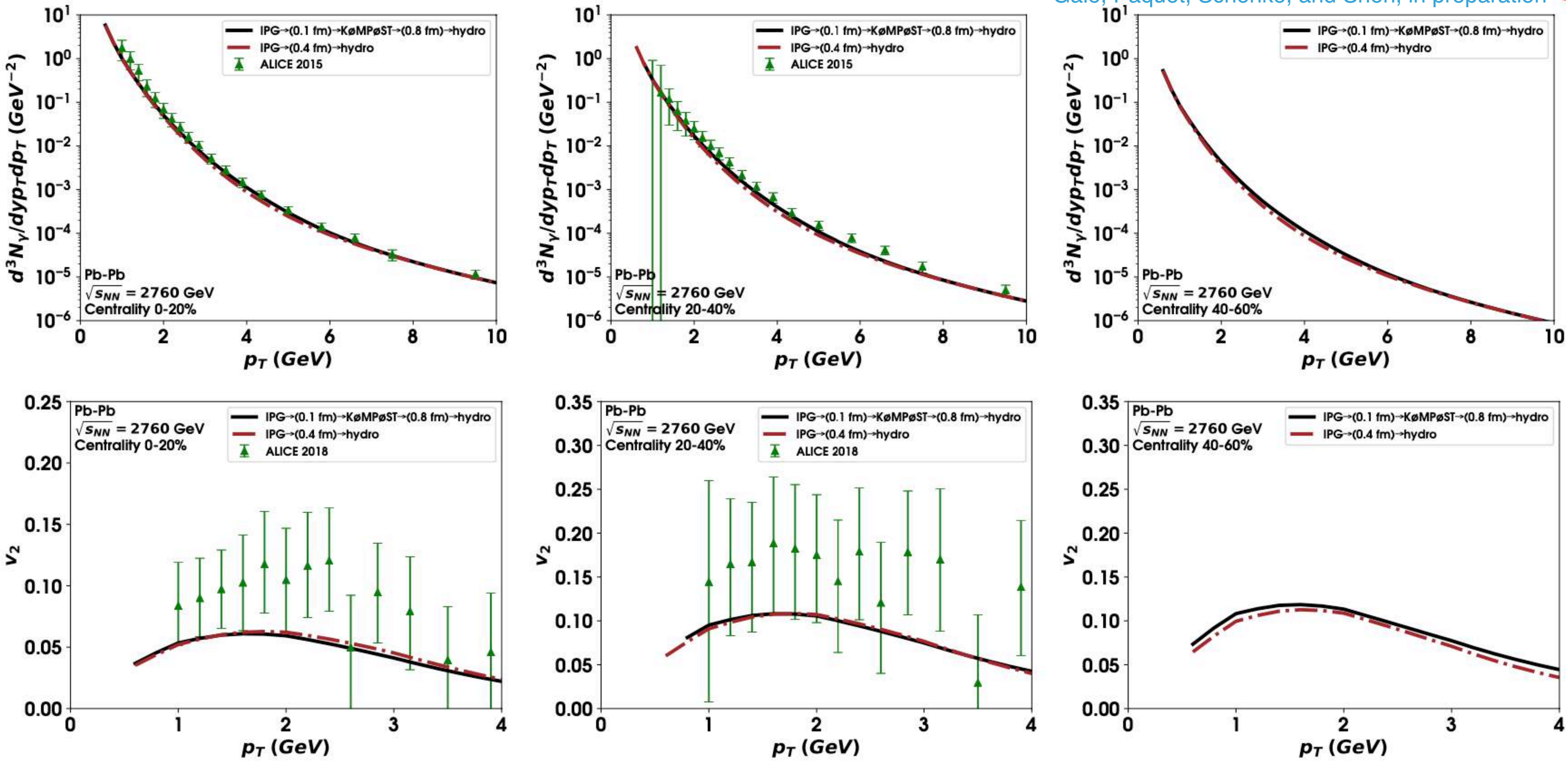
Gale, Paquet, Schenke, and Shen, in preparation



PHENIX Collaboration, Phys.Rev.C91 (2015) 6, 064904; Phys. Rev. C 94, 064901 (2016); STAR Collaboration, Phys.Lett.B770 (2017) 451-458

DIRECT PHOTON OBSERVABLES AT LHC

Gale, Paquet, Schenke, and Shen, in preparation

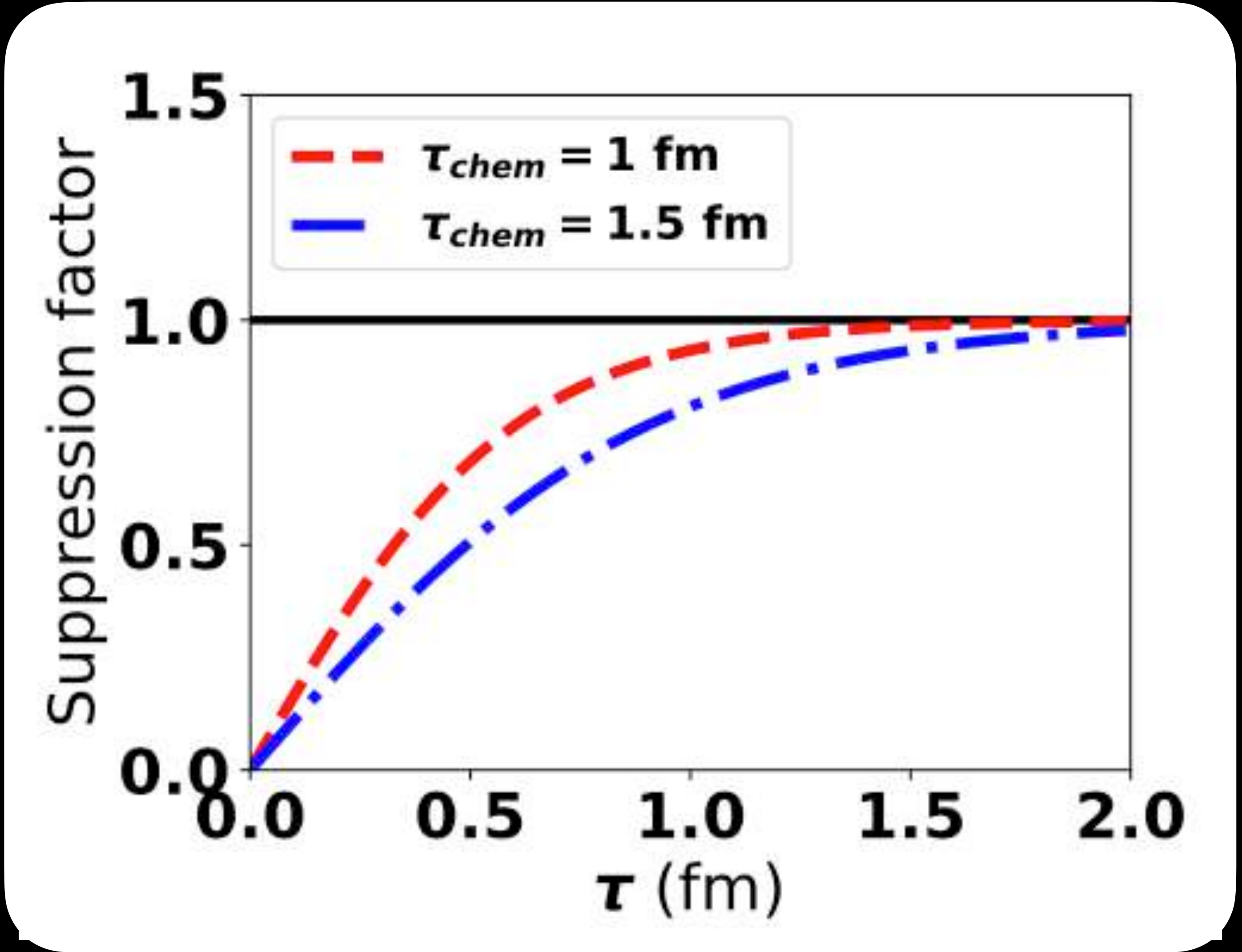


ALICE Collaboration, Phys. Lett. B 754, 235-248 (2016); Phys.Lett.B 789 (2019) 308-322

PROBING THE EARLY-STAGE CHEMICAL EQUILIBRATION

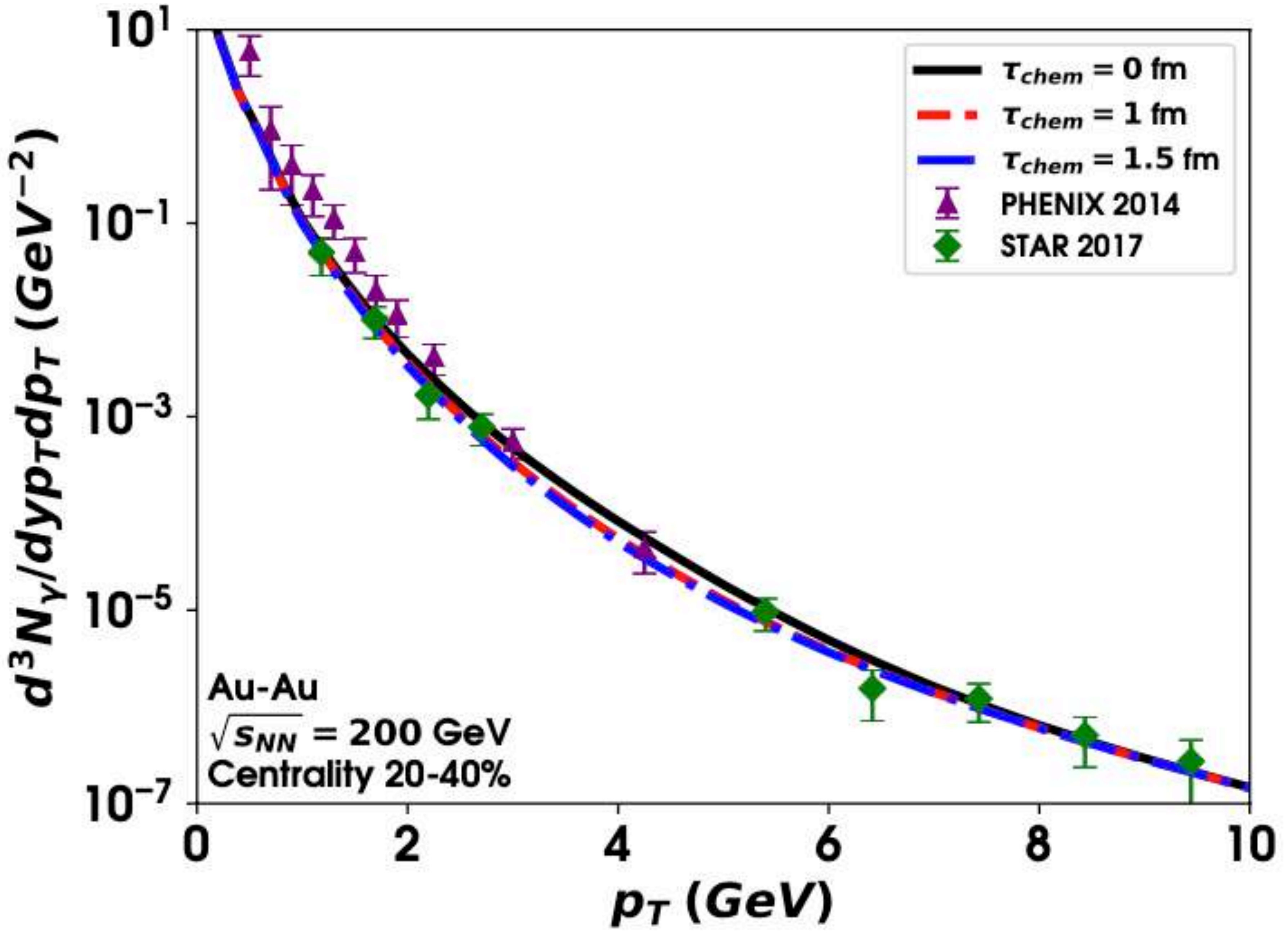
Account for chemical non-equilibration in the pre-equilibrium phase by suppressing the photon rate

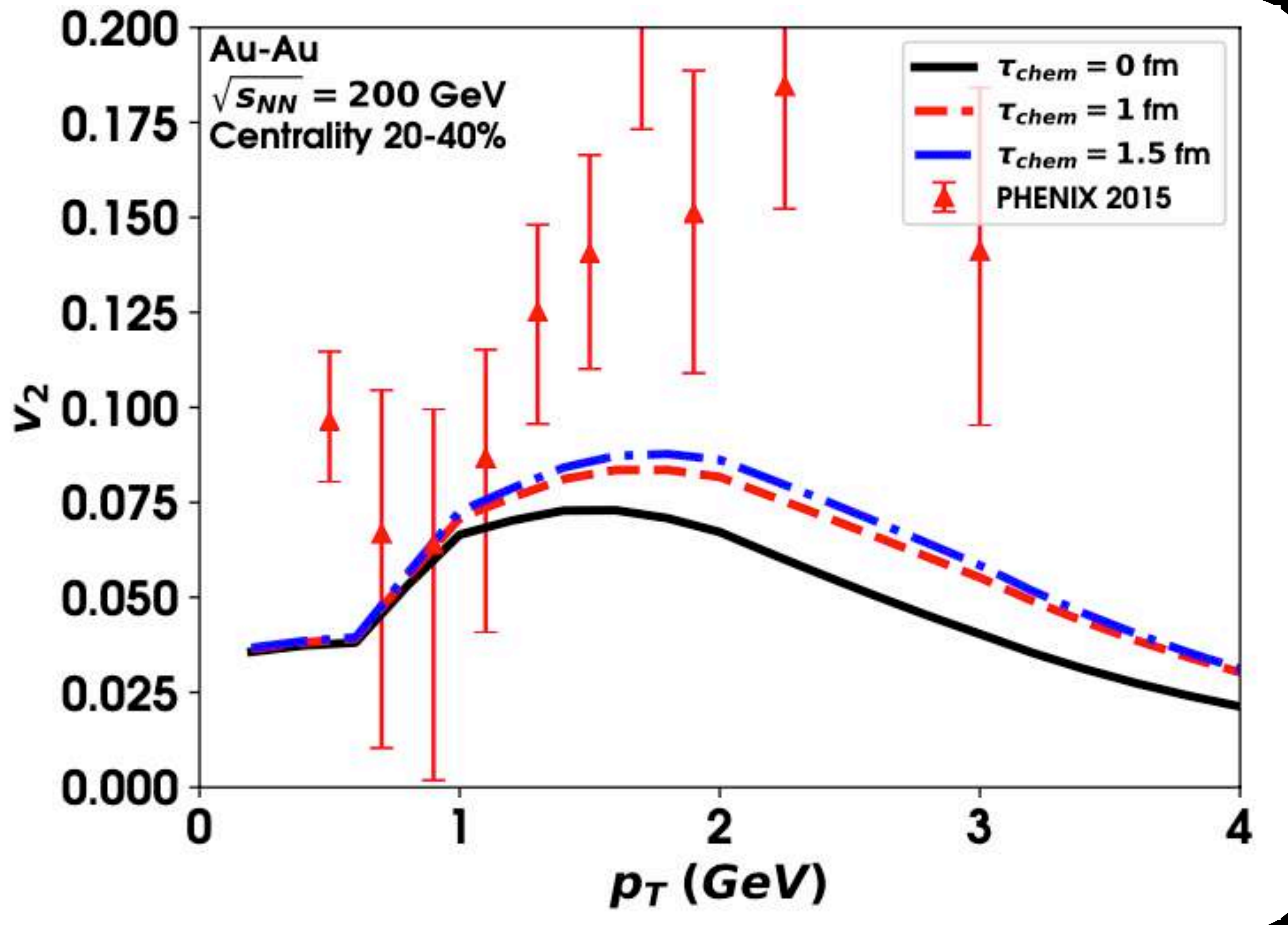
$$\frac{dN_\gamma}{d^3p} = \text{Suppression}(\tau) \int d^4x \frac{dR_\gamma}{d^3p}$$



Estimated from Phys.Rev.Lett. 122 (2019) 142301

Gale, Paquet, Schenke, and Shen, Initial Stages 2021



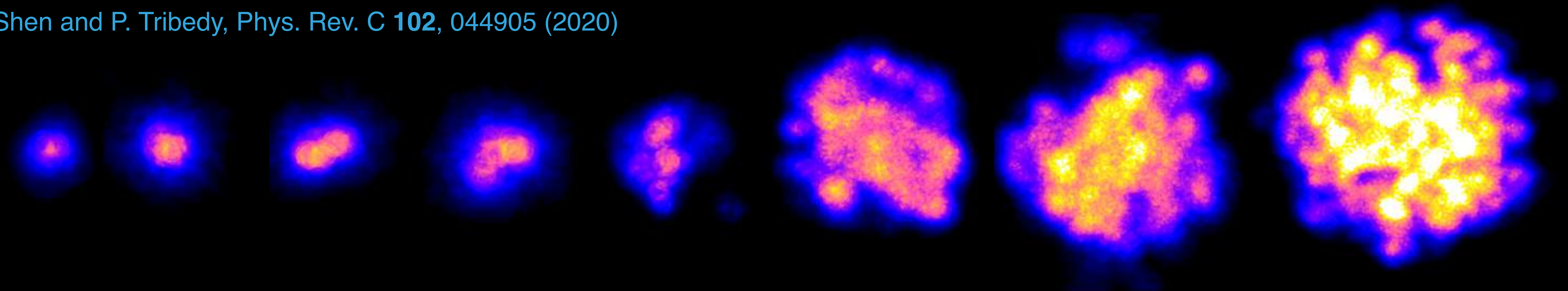


Direct photon v_2 is sensitive to the early-stage chemistry

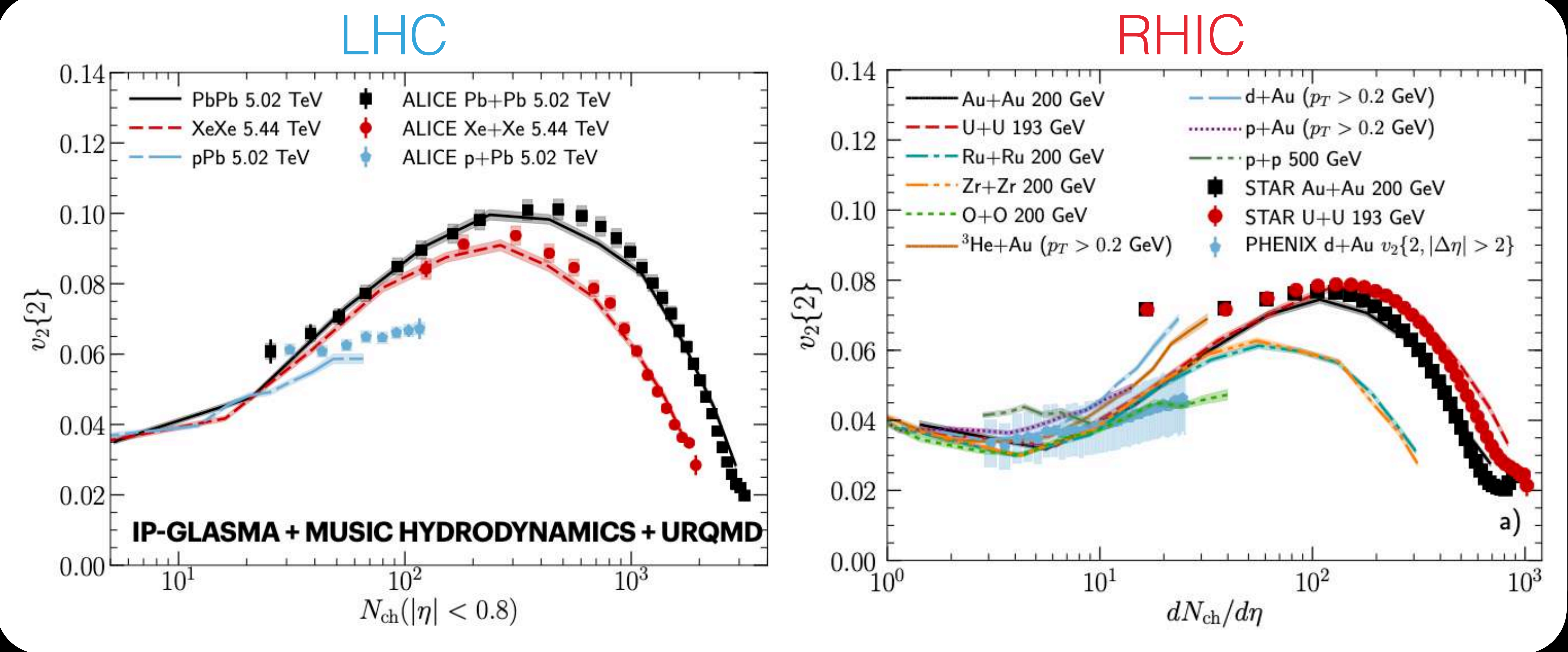
Data are from:
Phys.Rev.C91 (2015) 6, 064904
Phys.Lett.B770 (2017) 451-458
Phys. Rev. C 94, 064901 (2016)

SHRINKING QGP DROPLETS

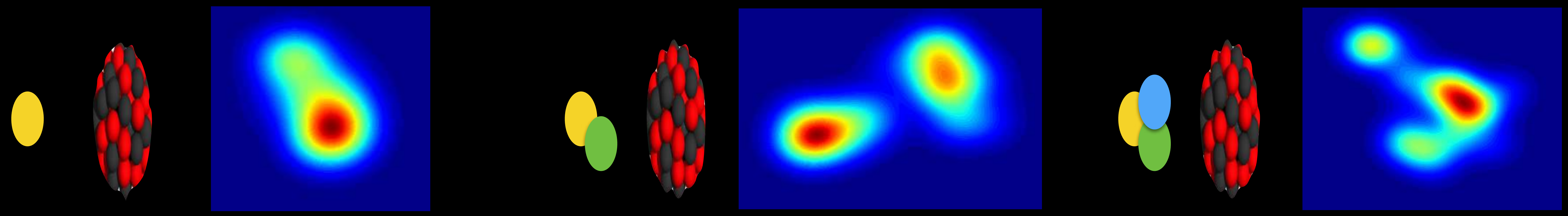
B. Schenke, C. Shen and P. Tribedy, Phys. Rev. C **102**, 044905 (2020)

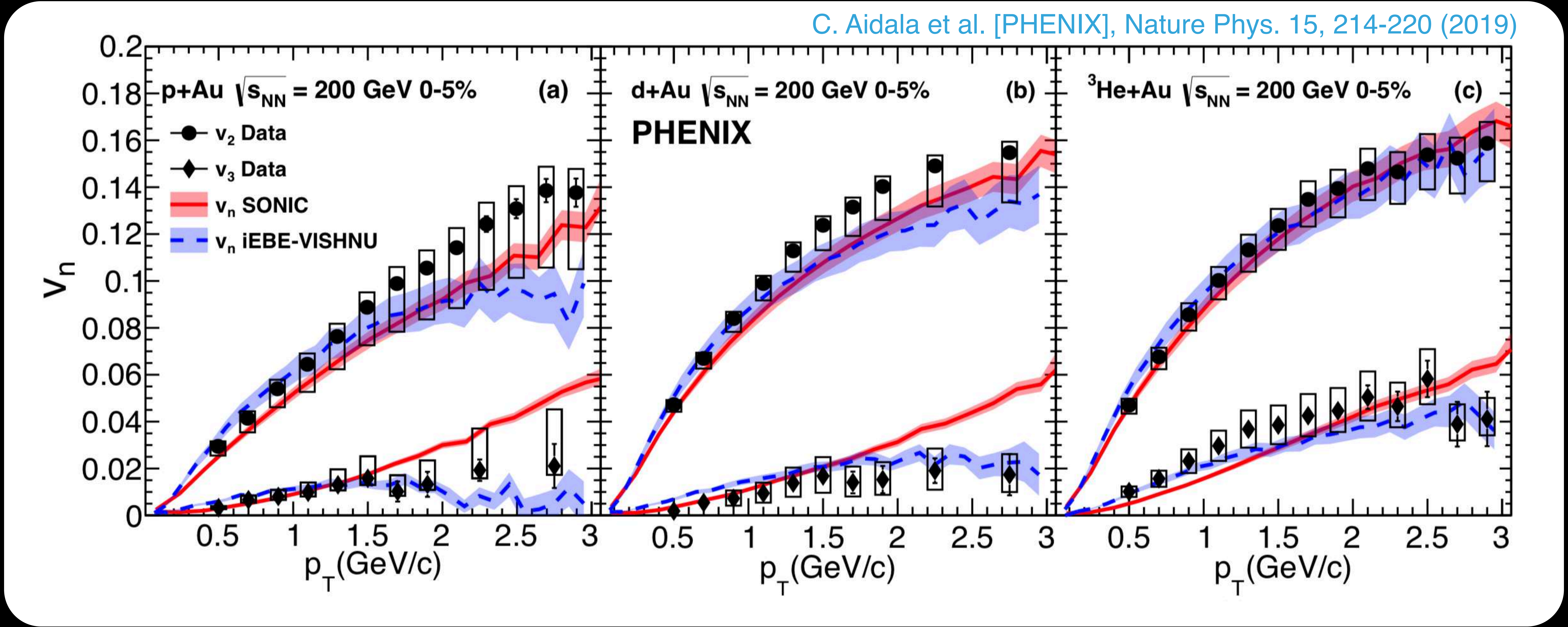


- Collective behavior persists in small collision systems
- Hot small QGP droplets?



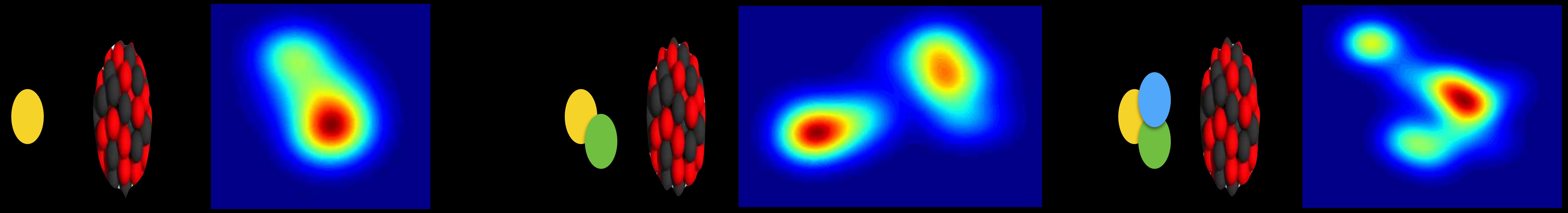
SMALL SYSTEMS WITH DIFFERENT GEOMETRY

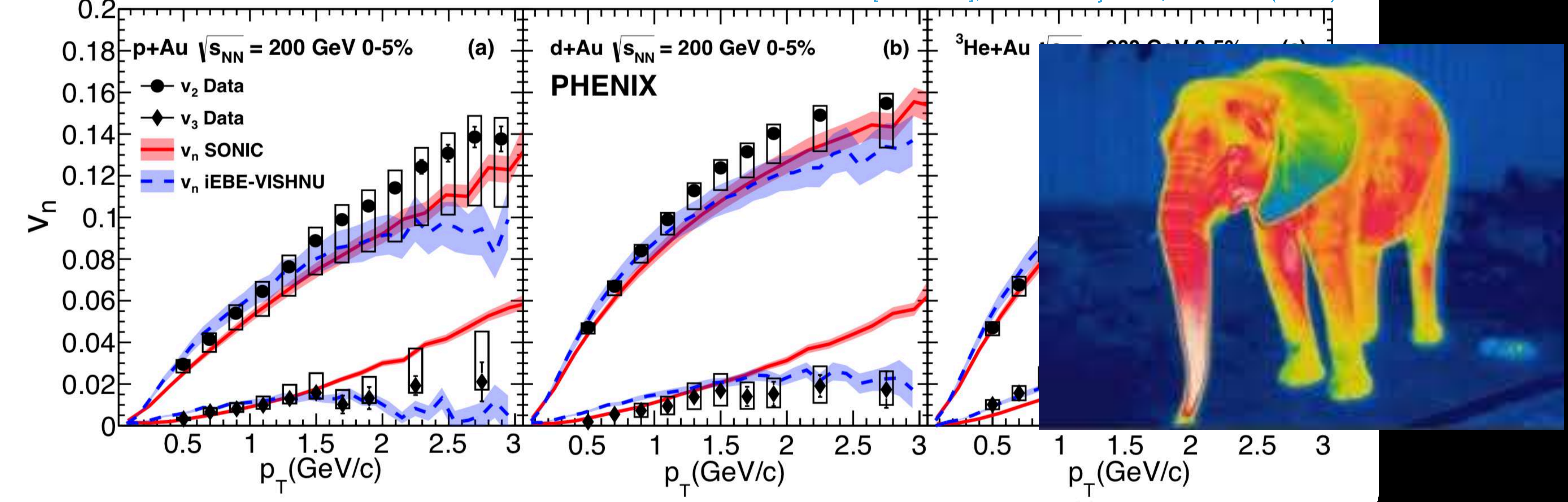




- Hydrodynamic response converts spatial gradients into measured momentum anisotropy

SMALL SYSTEMS WITH DIFFERENT GEOMETRY



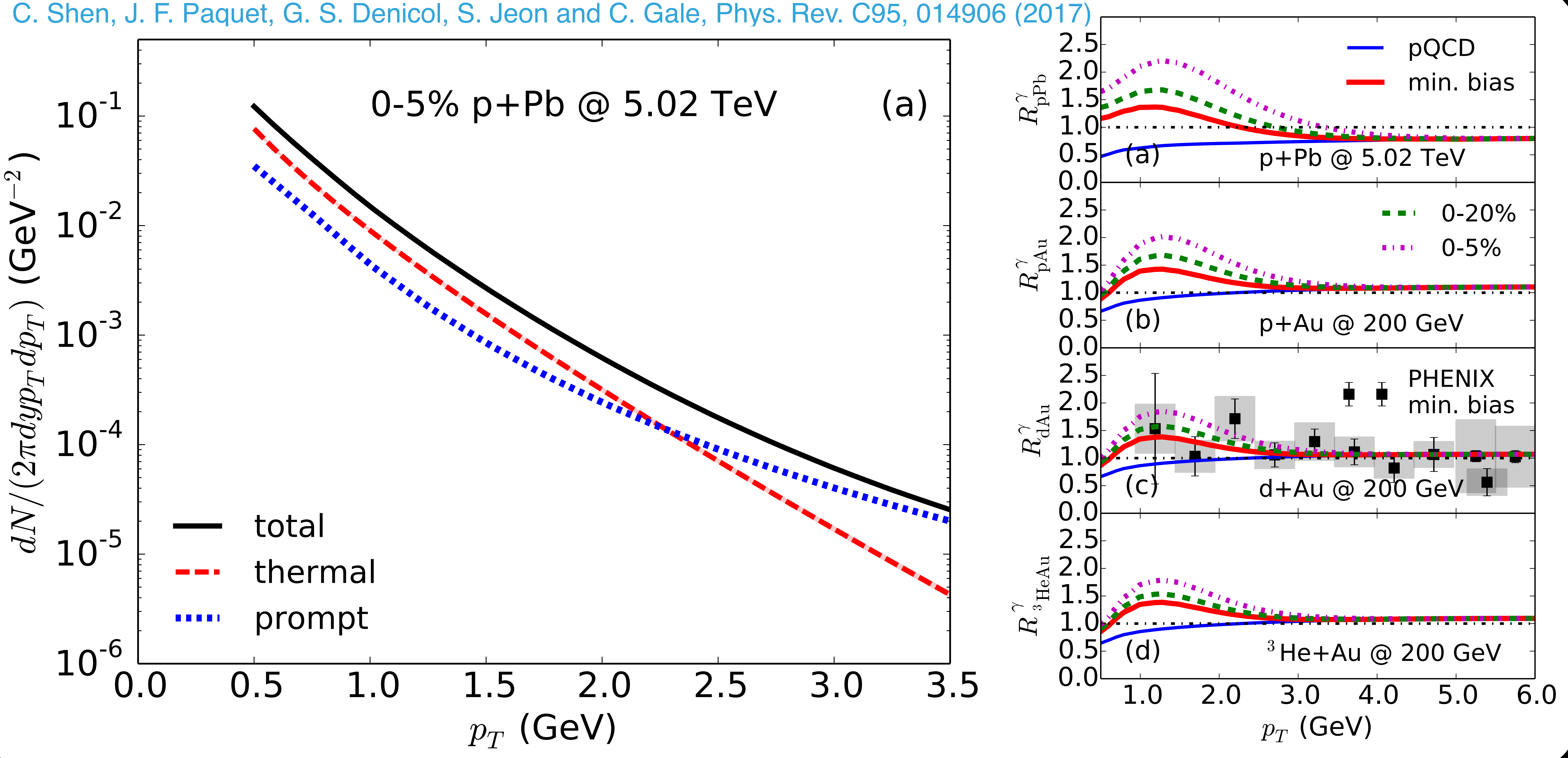


C. Aidala et al. [PHENIX], Nature Phys. 15, 214-220 (2019)

- How about thermal radiation from these small collisions?

PREDICTION OF THERMAL RADIATION IN SMALL SYSTEMS

C. Shen, J. F. Paquet, G. S. Denicol, S. Jeon and C. Gale, Phys. Rev. C95, 014906 (2017)

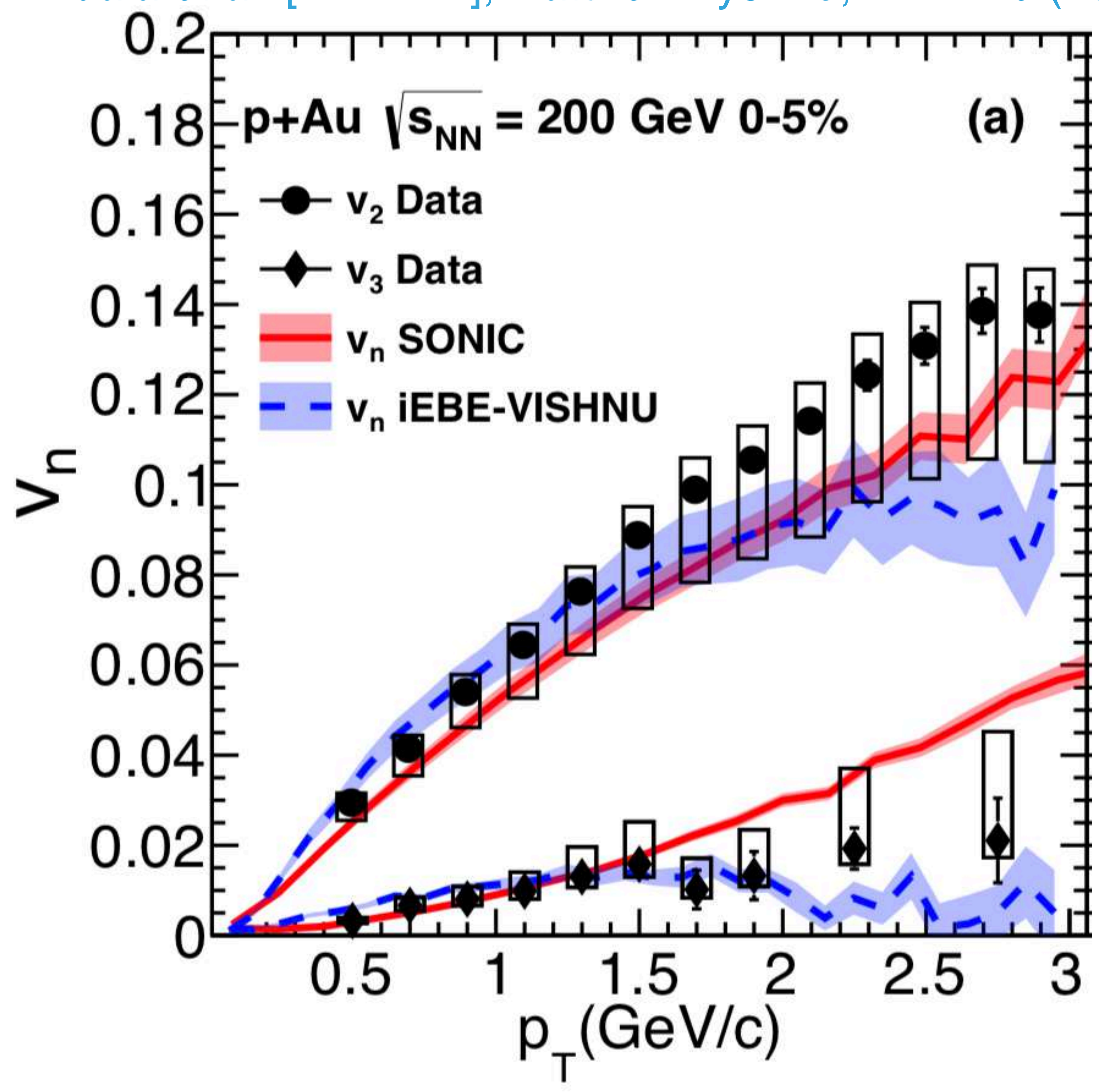


- Thermal photon radiation can leave visible imprint at low p_T R^{γ}_{pA}

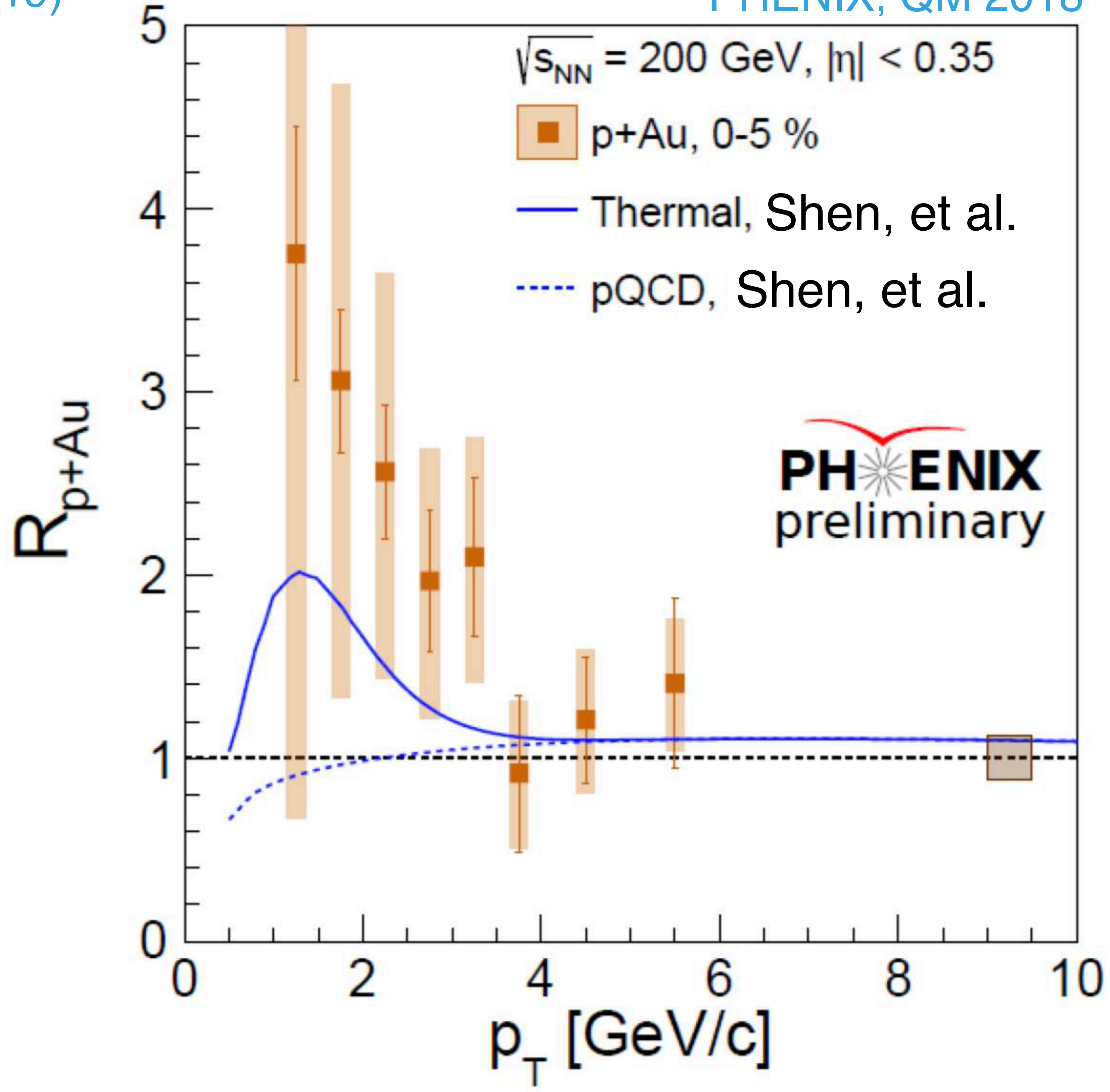
a **signature** of hot QGP medium

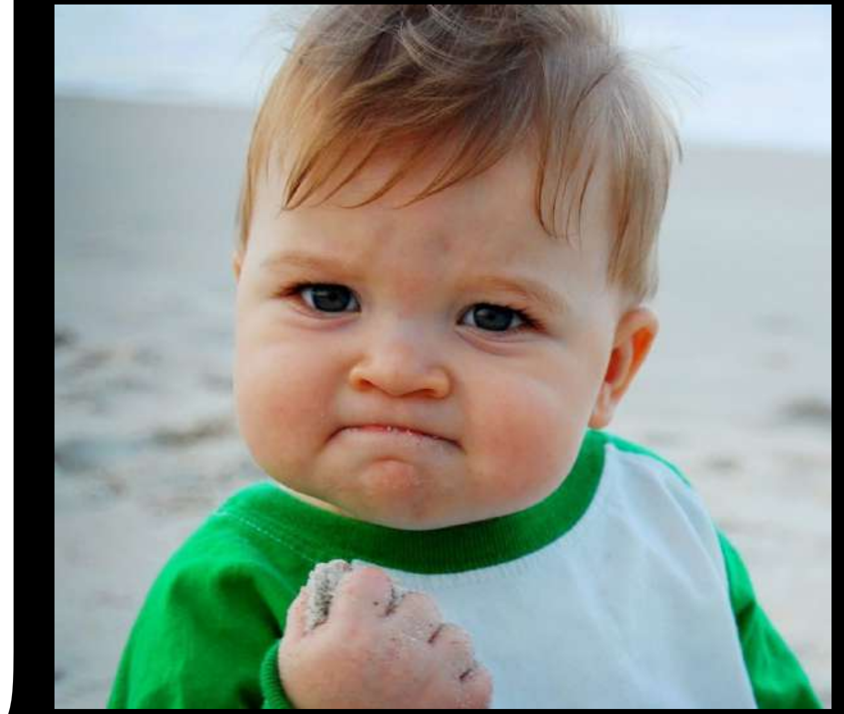
WHAT DOES THE MEASUREMENT SAY?

C. Aidala et al. [PHENIX], Nature Phys. 15, 214-220 (2019)



PHENIX, QM 2018





- The preliminary PHENIX data shows a promising sign of thermal photon enhancement in central pAu collisions
- Precise hadron and photon measurements together could provide **strong** evidence of hot QGP in central pAu collisions

OTHER INTERESTING TOPICS ABOUT EM PROBES

- EM emission rates from first-principles lattice QCD calculations

  precision calculations of EM spectral functions

  G. Jackson et al., JHEP 1911, 144 (2019)]

- Probing the effect of chiral symmetry restoration

  in-medium ρ spectral function

  R. Rapp and J. Wambach, Adv. Nucl. Phys. 25, 1 (2000)

  P. M. Hohler and R. Rapp, Phys. Lett. B 731, 103-109 (2014)

- Quantifying out-of-equilibrium dynamics with photons and dileptons

  QGP transport properties

  C. Shen *et al.*, Phys. Rev. C91, 024908 (2015)

  G. Vujanovic *et al.*, Phys. Rev. C 101, 044904 (2020)

  B. S. Kasmaei and M. Strickland, Phys. Rev. D102, 014037 (2020)

- UPC Breit-Wheeler process and vacuum birefringence

  probing extreme electromagnetic fields

  J. Adam *et al.* [STAR], arXiv:1910.12400 [nucl-ex]

  S. Klein *et al.*, Phys. Rev. D102, 094013 (2020)

- Effects from early strong magnetic field

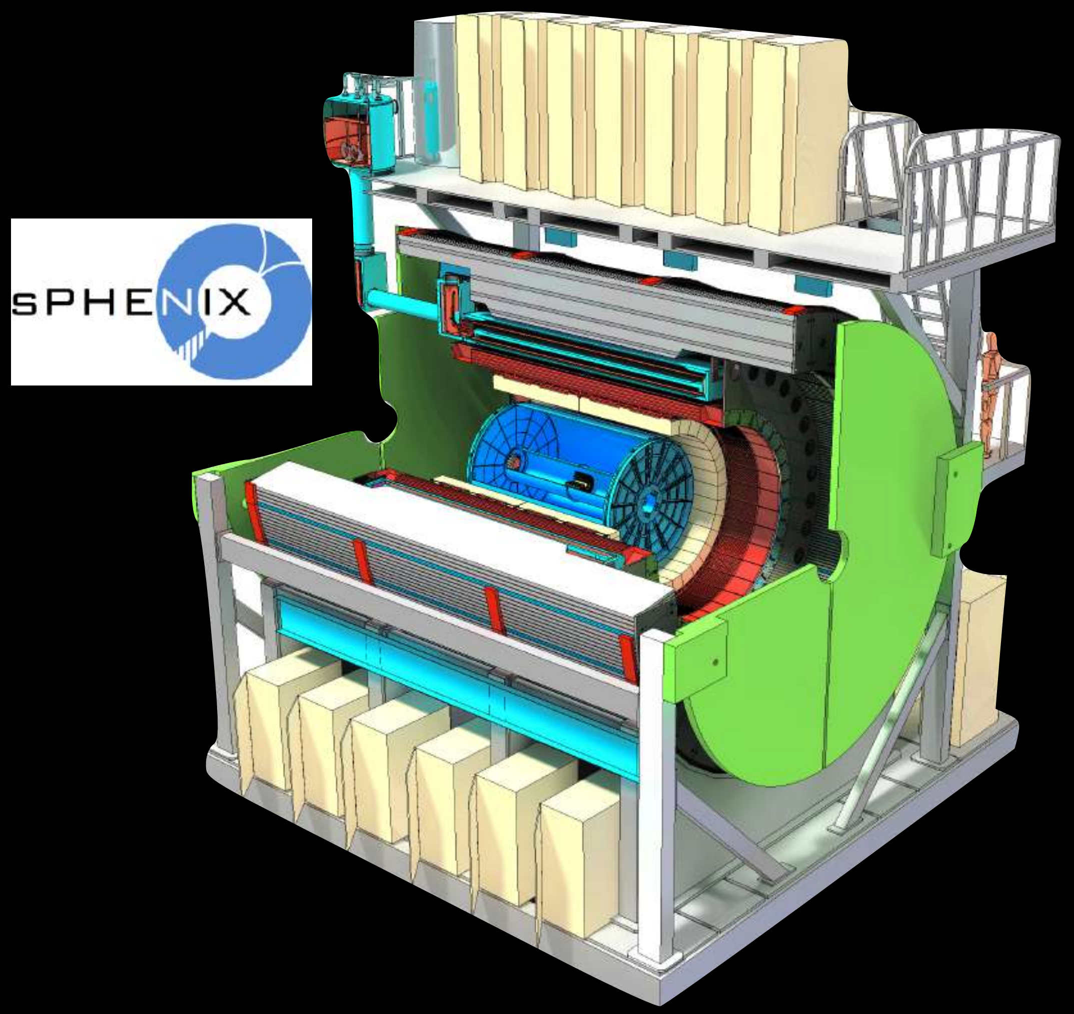
  potentially enhance photon elliptic flow

  G. Basar *et al.*, Phys. Rev. Lett. 109, 202303 (2012)

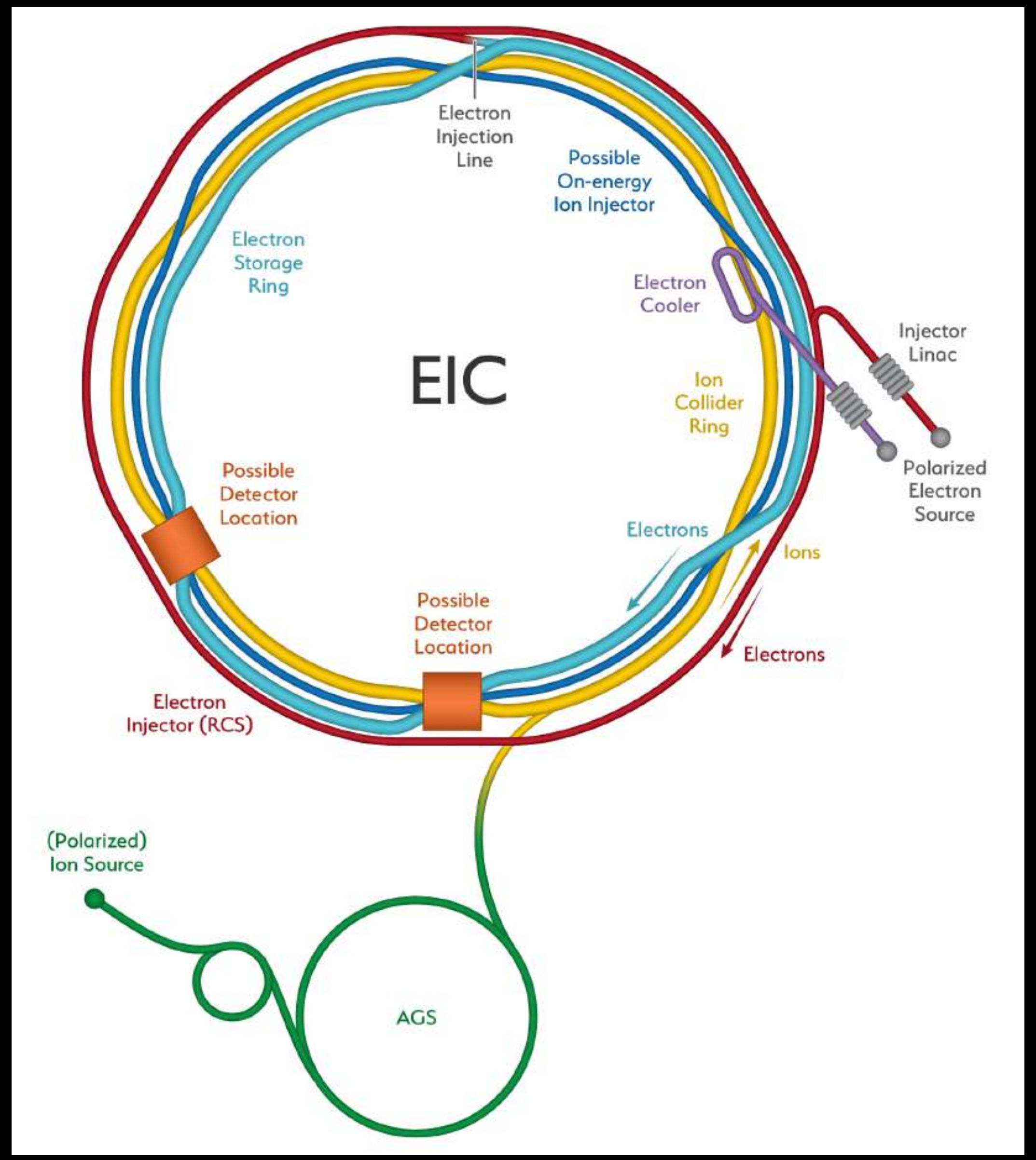
  X. Wang *et al.*, Phys. Rev. D102, 076010 (2020)

THE ERA OF MULTI-MESSENGER HEAVY-ION PHYSICS

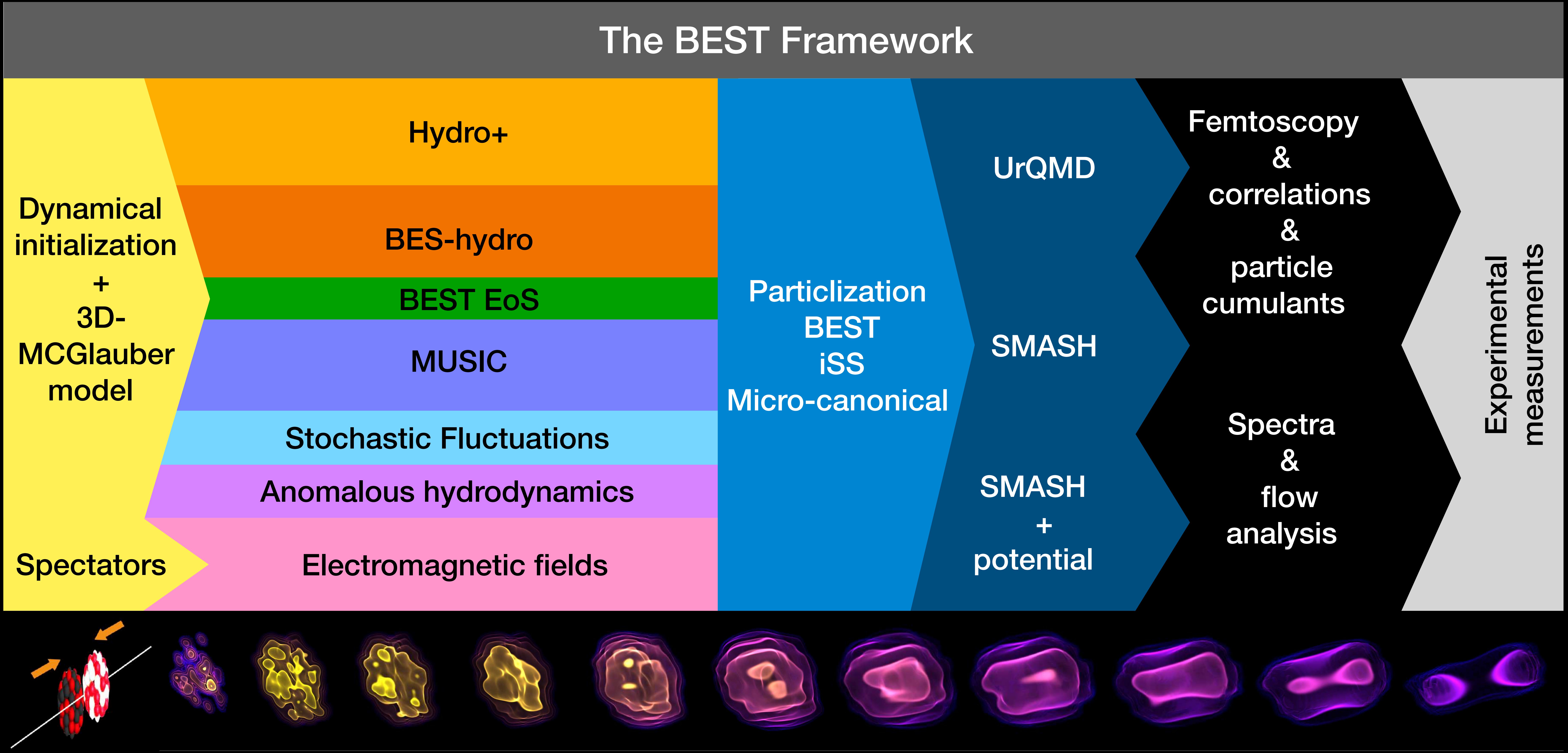
- RHIC: STAR upgrade and sPHENIX program
  - Probing QCD at high net baryon density
  - Study fully resolved jets, Upsilon states, and heavy quarks as QGP structure probes



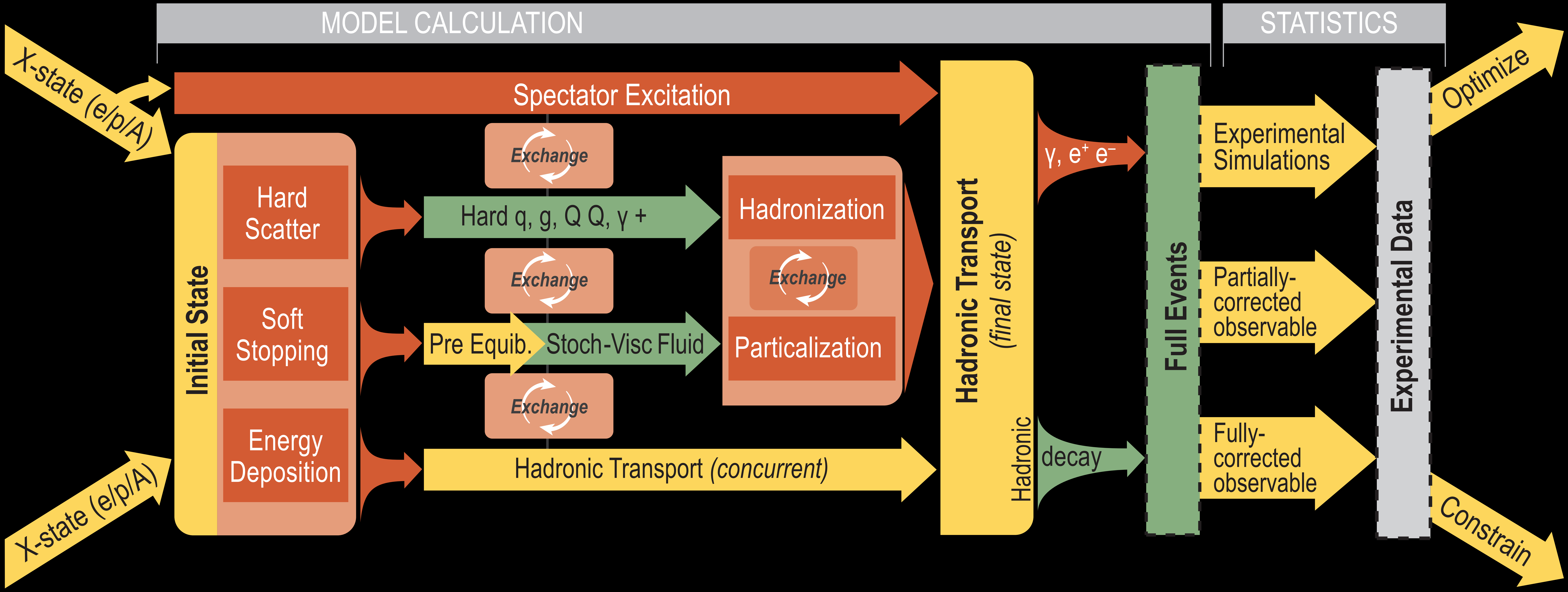
- LHC: ALICE, CMS, ATLAS upgrades
  - High energy and high luminosity frontier
  - Precision measurements for rare probes
- HADES, FAIR, NICA, J-PAC-HI
  - Phase structure of hot QCD matter
- Future Electron-Ion Collider
  - Tomography of nucleon and nucleus



THE BEST FRAMEWORK



THE NEXT GENERATION XSCAPE FRAMEWORK



- A unified event-generator for high energy nuclear physics community

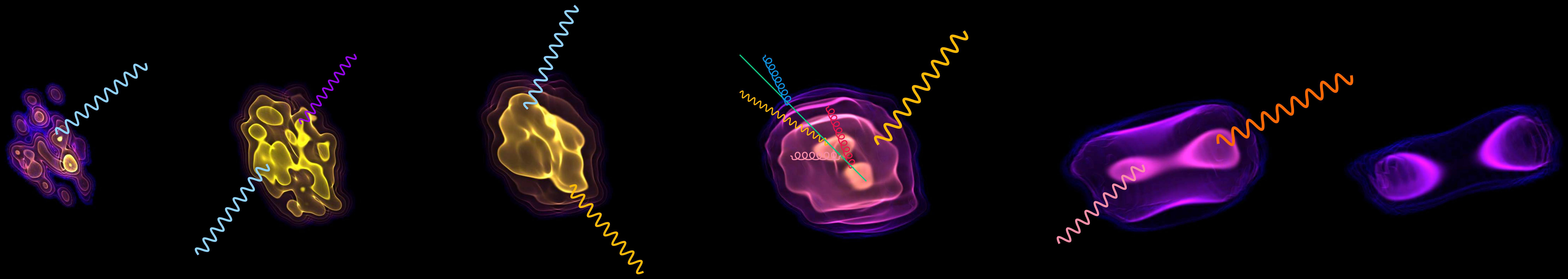
SUMMARY

- The vibrant experimental programs with precision measurements have been driving heavy-ion physics to the multi-messenger era

  Unified theoretical + statistical frameworks are *essential* to unravel physics

- The combined hadronic + EM probes analysis is a powerful tool to elucidate soft dynamics of hot QCD matter

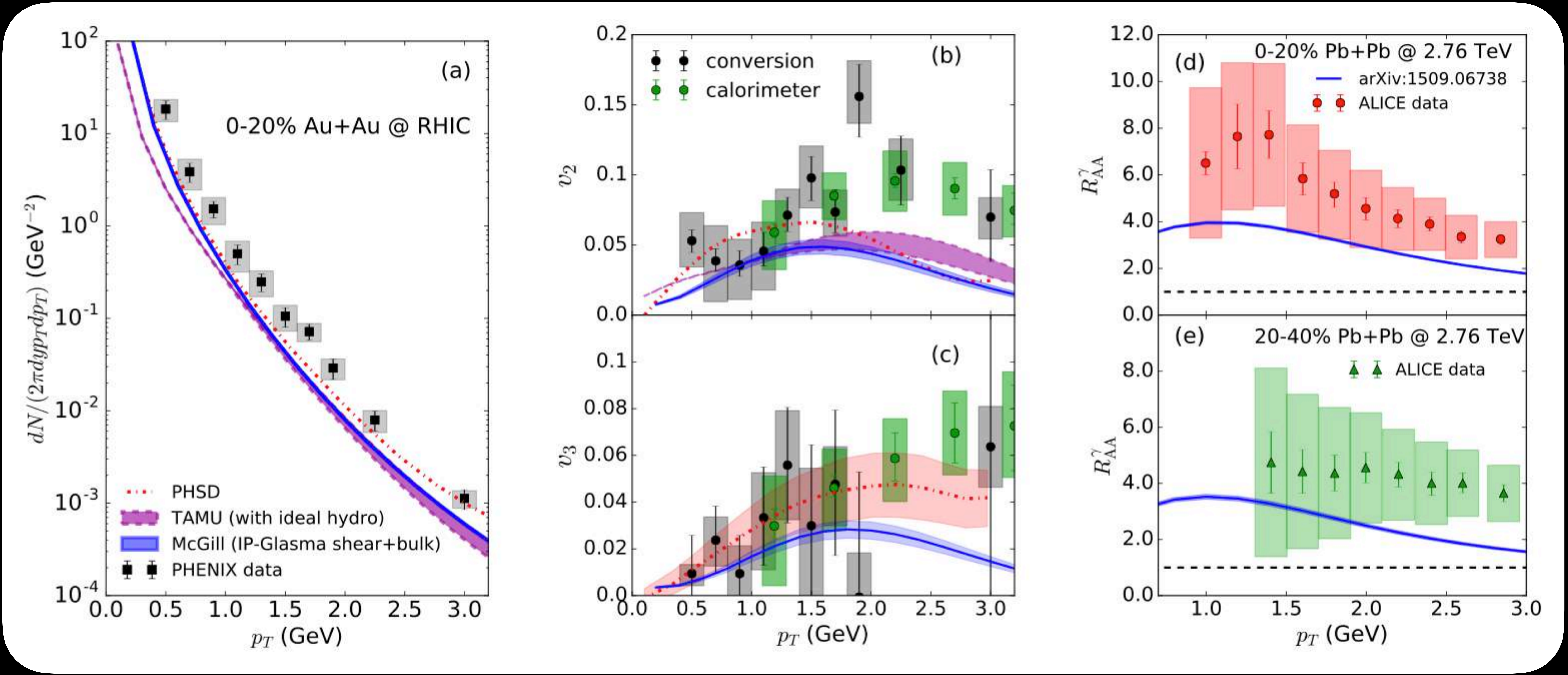
- Further embracing high p_T observables can fully characterize the properties of QGP




BACKUP

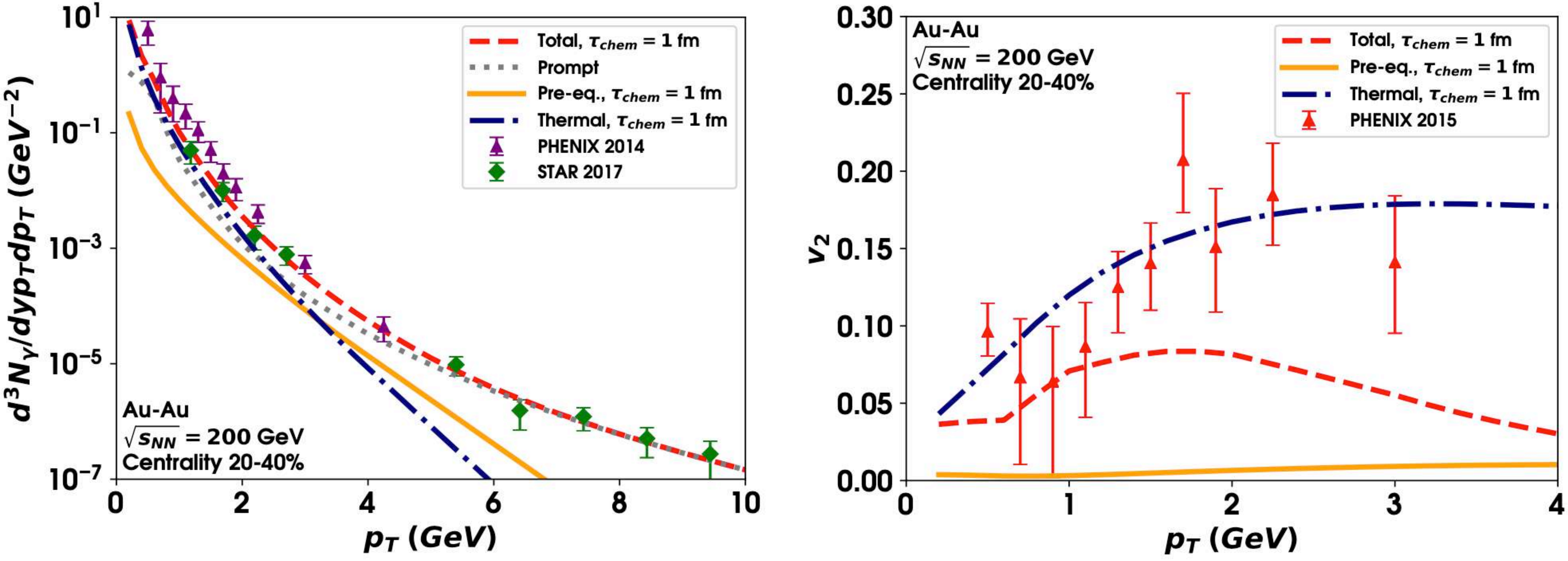
STATUS OF THE DIRECT PHOTON FLOW PUZZLE

C. Shen, Nucl. Phys. A 956, 184-191 (2016)



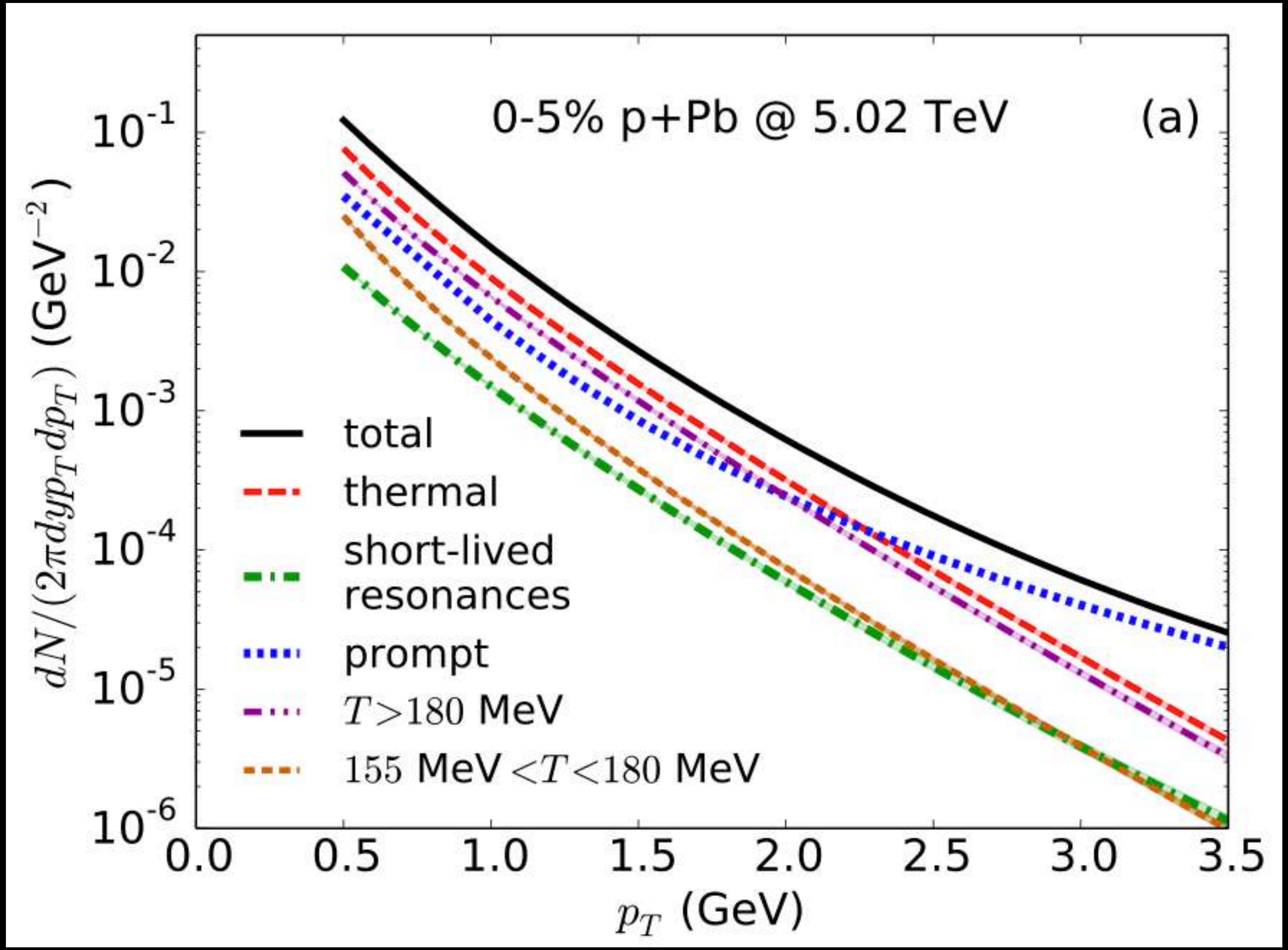
PHOTON SPECTRUM AND ELLIPTIC FLOW

Gale, Paquet, Schenke, and Shen, Initial Stages 2021



PHOTON SPECTRA IN SMALL SYSTEMS

C. Shen, J. F. Paquet, G. S. Denicol, S. Jeon and C. Gale, Phys. Rev. C95, 014906 (2017)



THERMAL RADIATION IN PP COLLISIONS?

C. Shen, J. F. Paquet, G. S. Denicol, S. Jeon and C. Gale, Phys. Rev. C95, 014906 (2017)