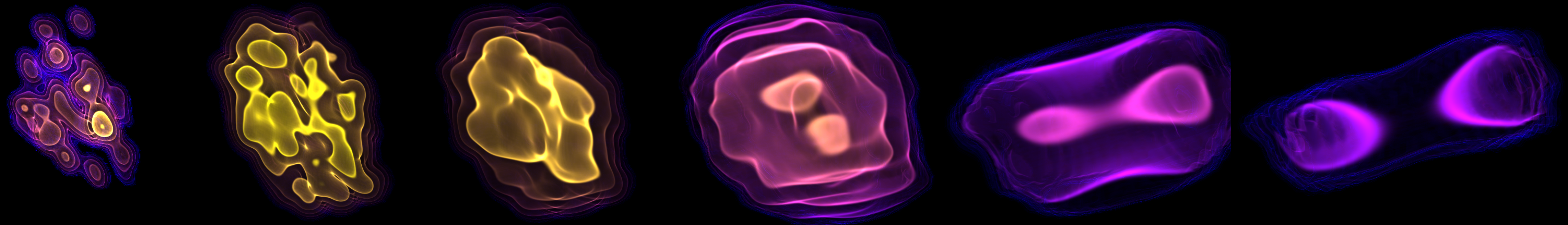
RBRC
RIKEN BNL Research Center

MULTI-MESSENGER HEAVY-ION PHYSICS WITH JETSCAPE

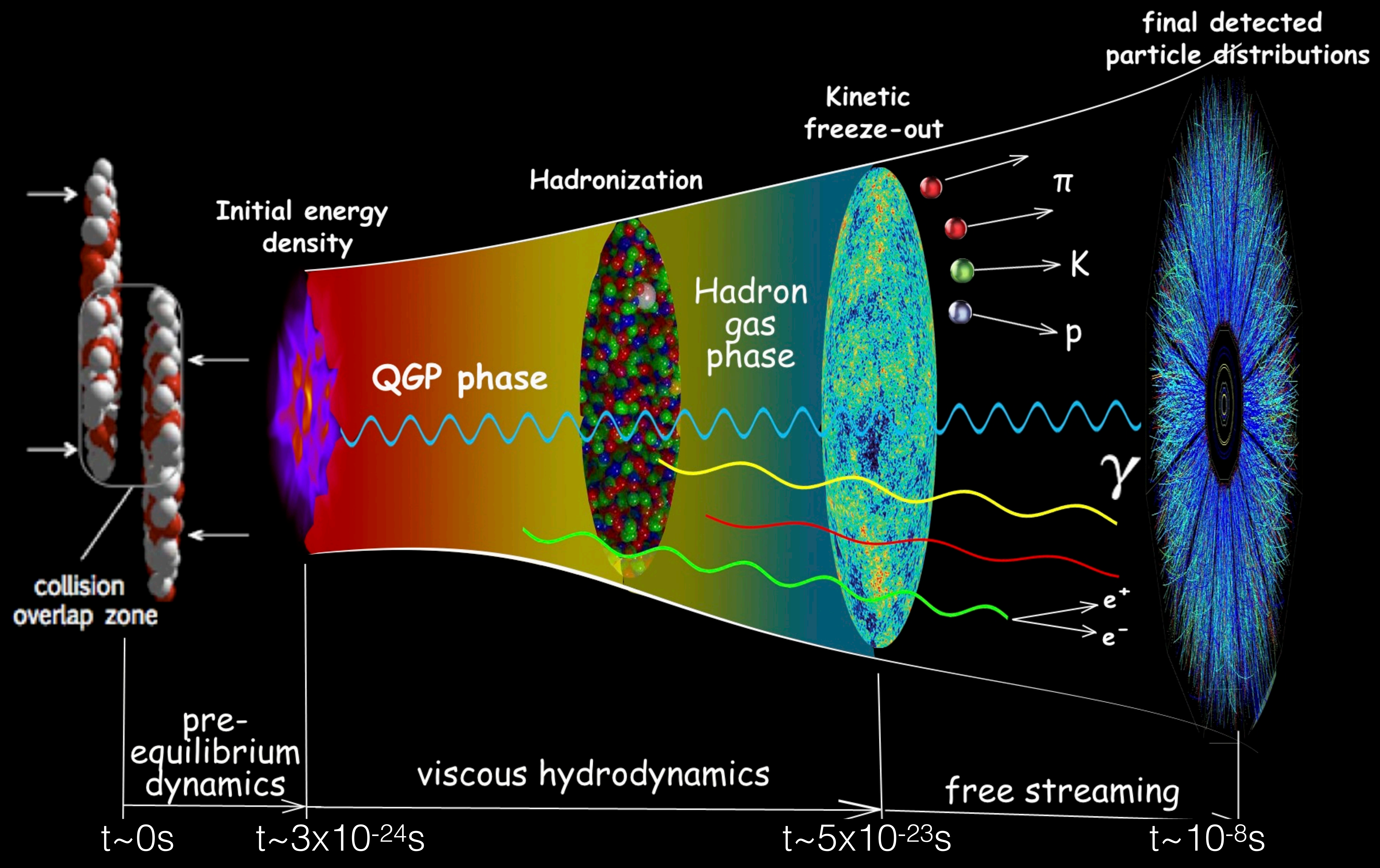
CHUN SHEN



13th International workshop on
Multiple Partonic Interactions at LHC

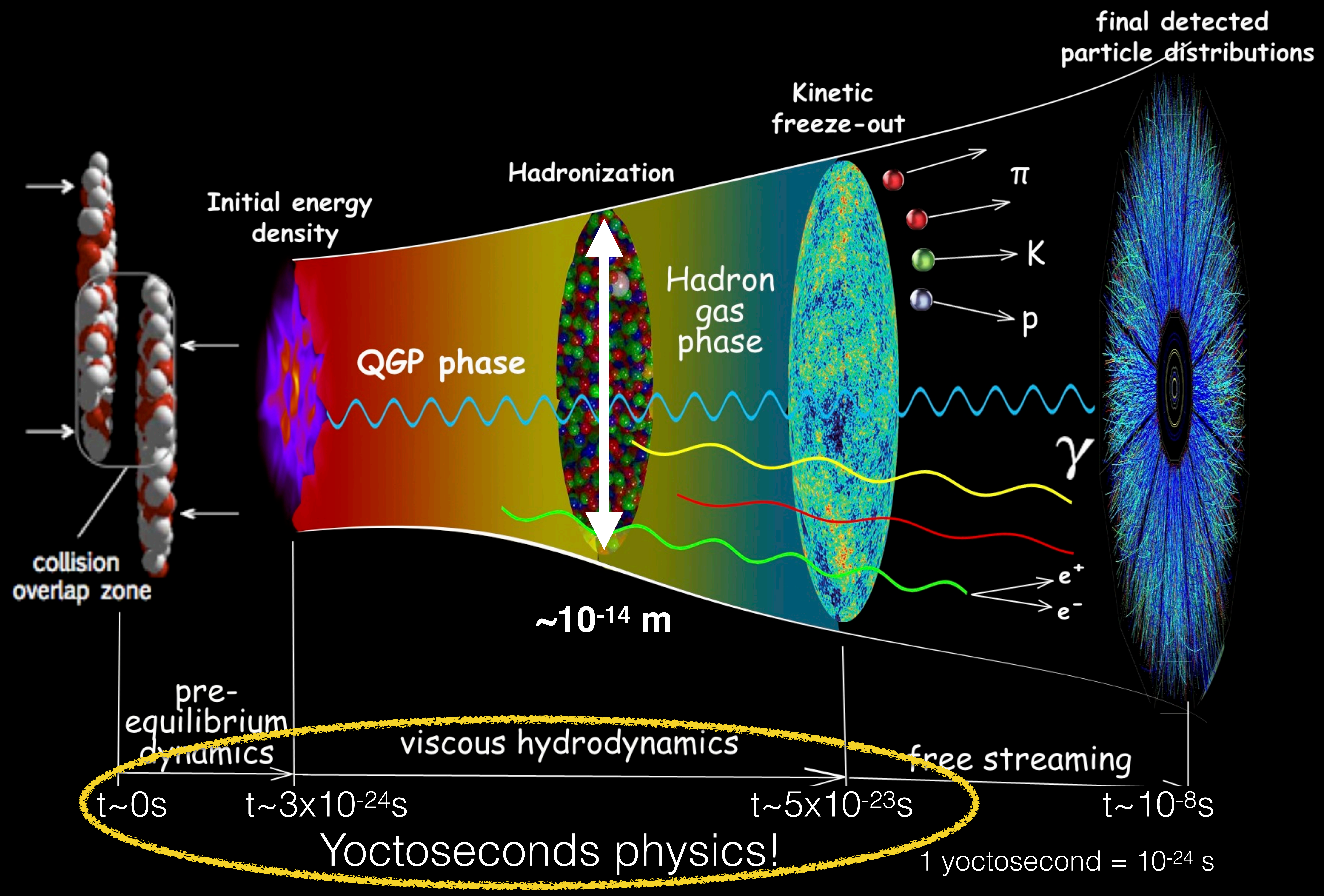
November 15, 2022

NUCLEAR MATTER UNDER EXTREME CONDITIONS



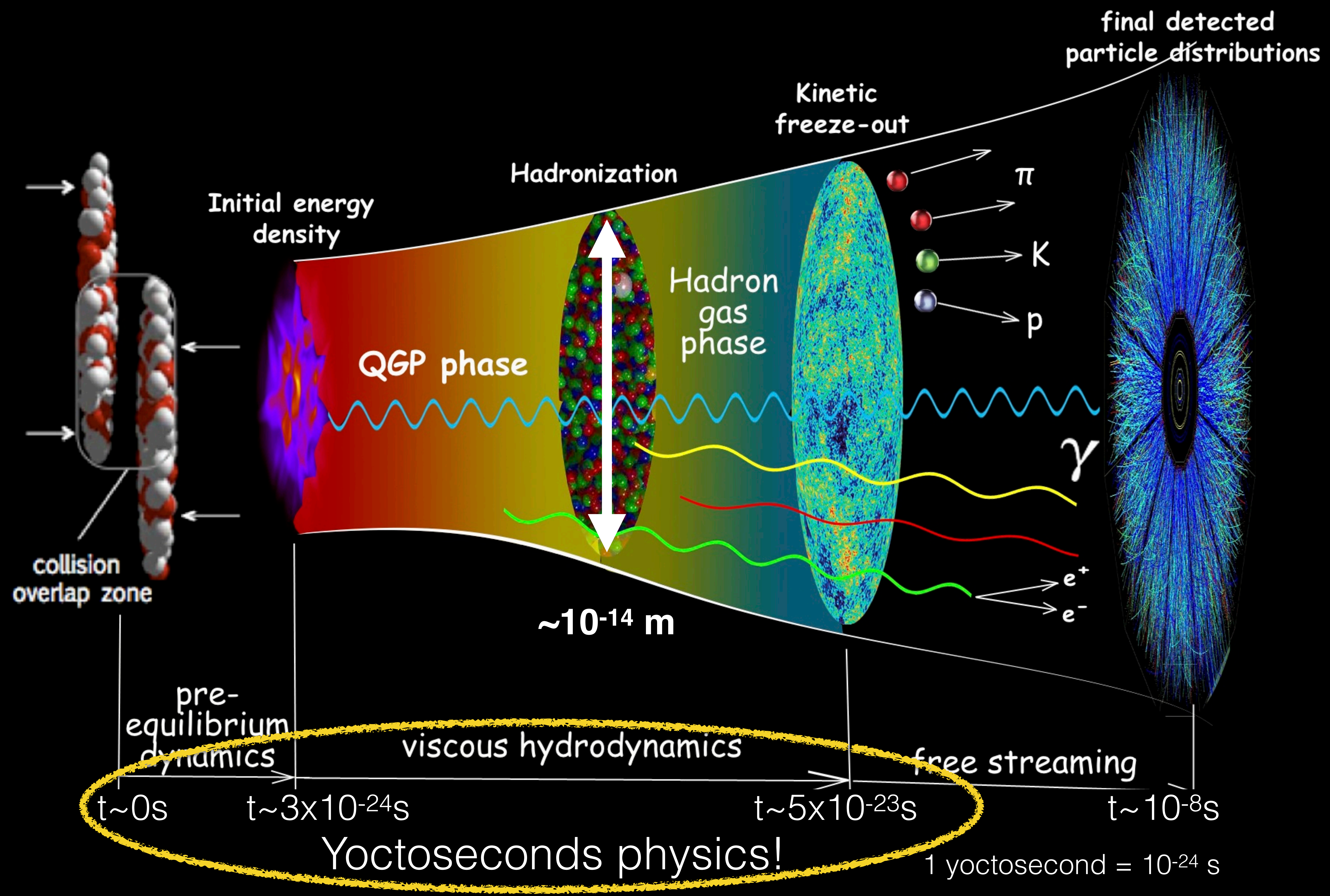
1 yoctosecond = 10^{-24} s

NUCLEAR MATTER UNDER EXTREME CONDITIONS



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

NUCLEAR MATTER UNDER EXTREME CONDITIONS



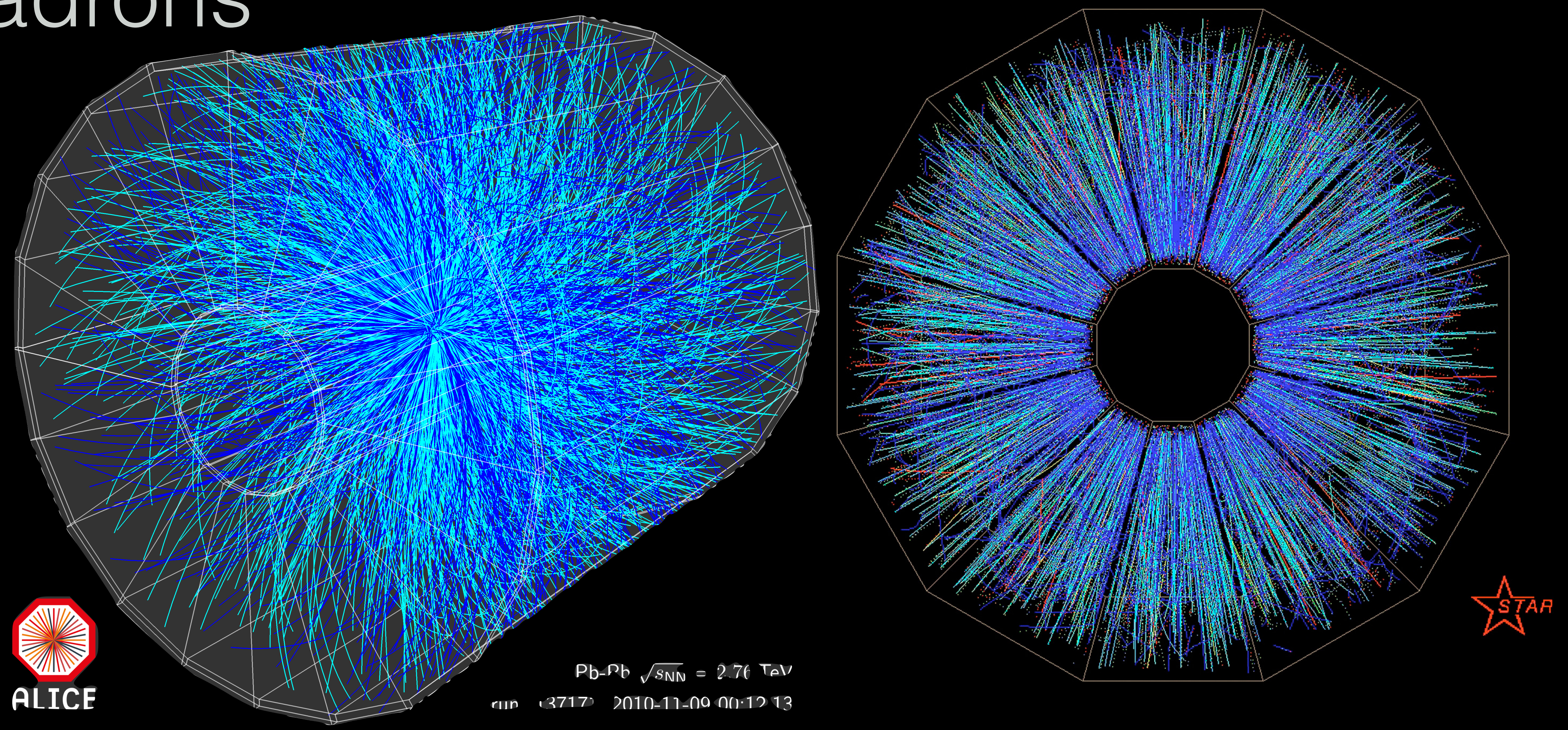
Heavy-ion collisions are tiny and have ultra-fast dynamics

A variety of particles are emitted from the collisions

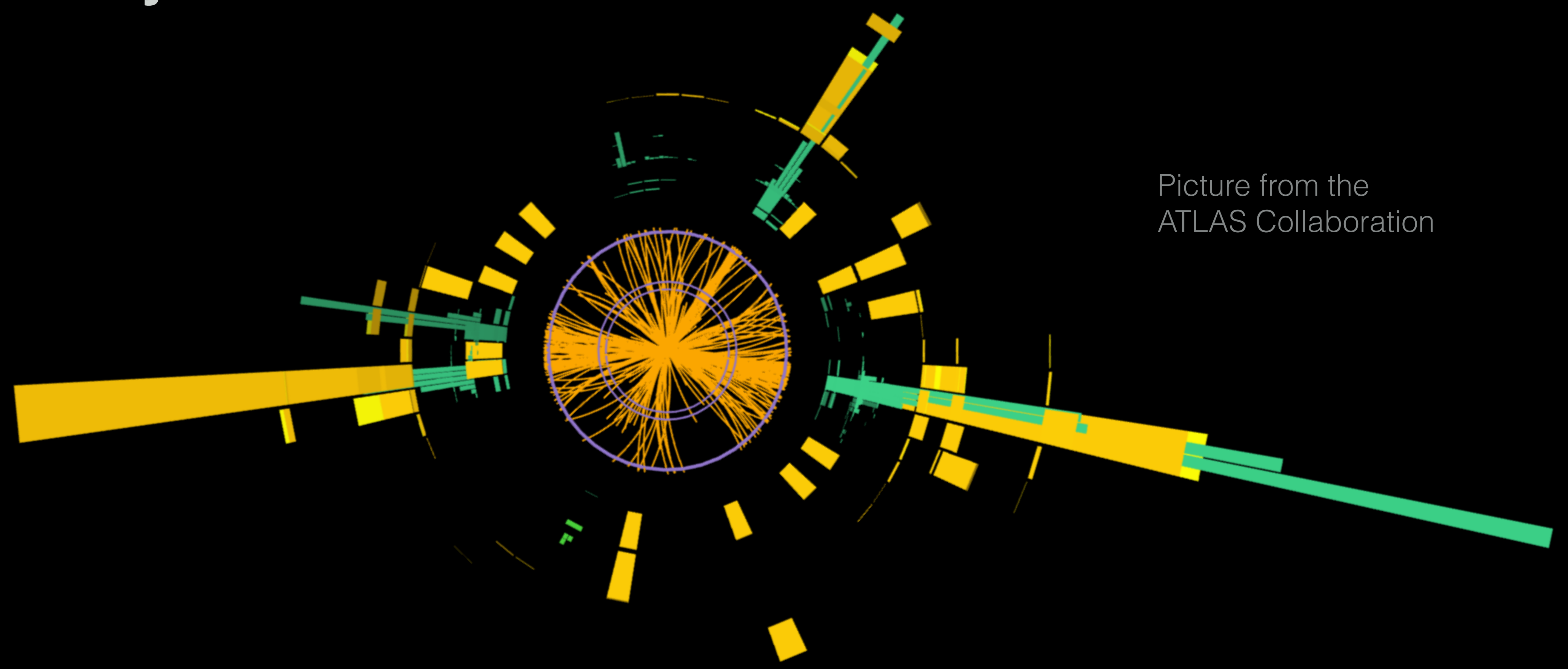
Multi-messenger nature of heavy-ion physics

MULTI-MESSENGER HEAVY-ION PHYSICS

Hadrons

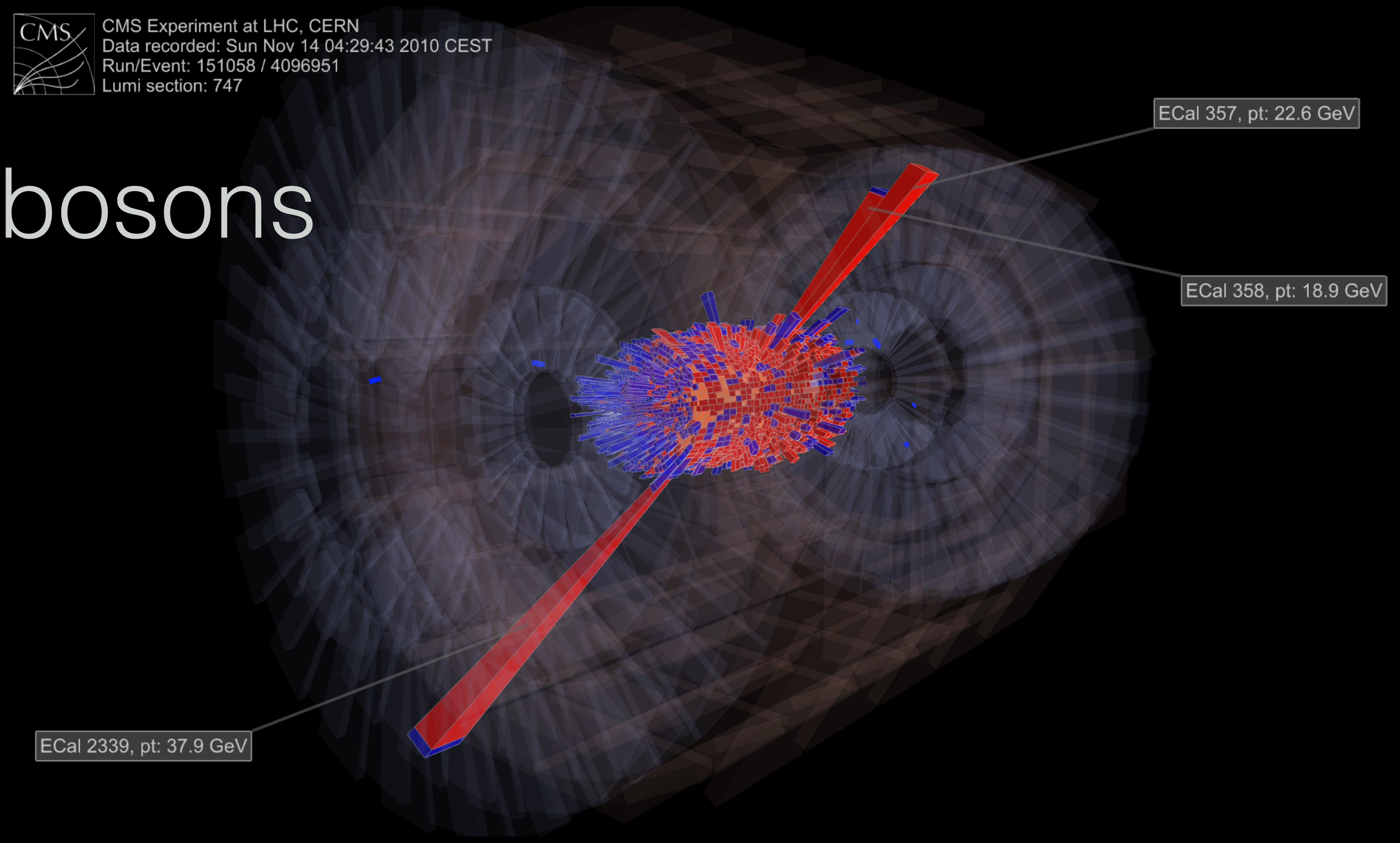


QCD jets

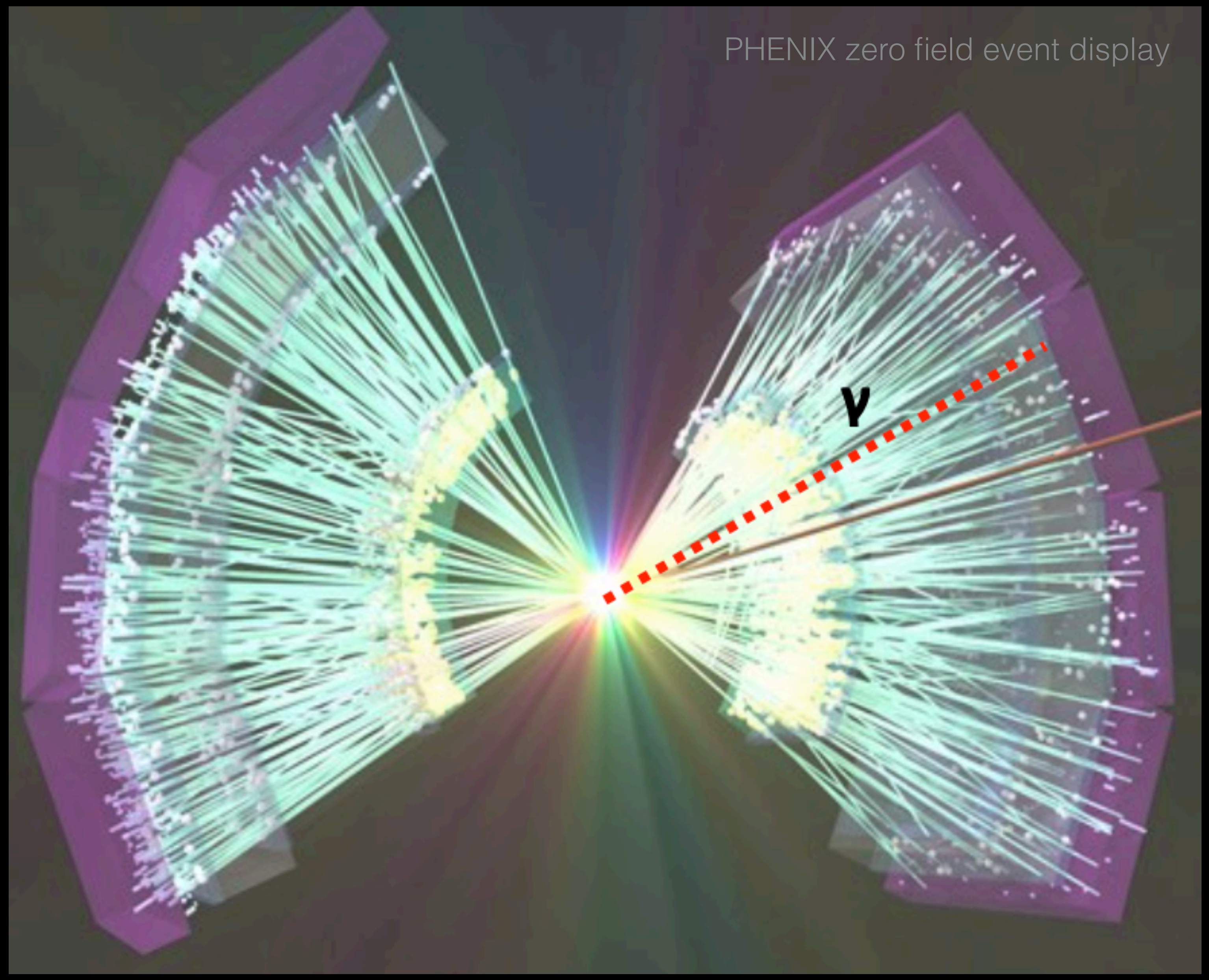


Picture from the ATLAS Collaboration

EW bosons

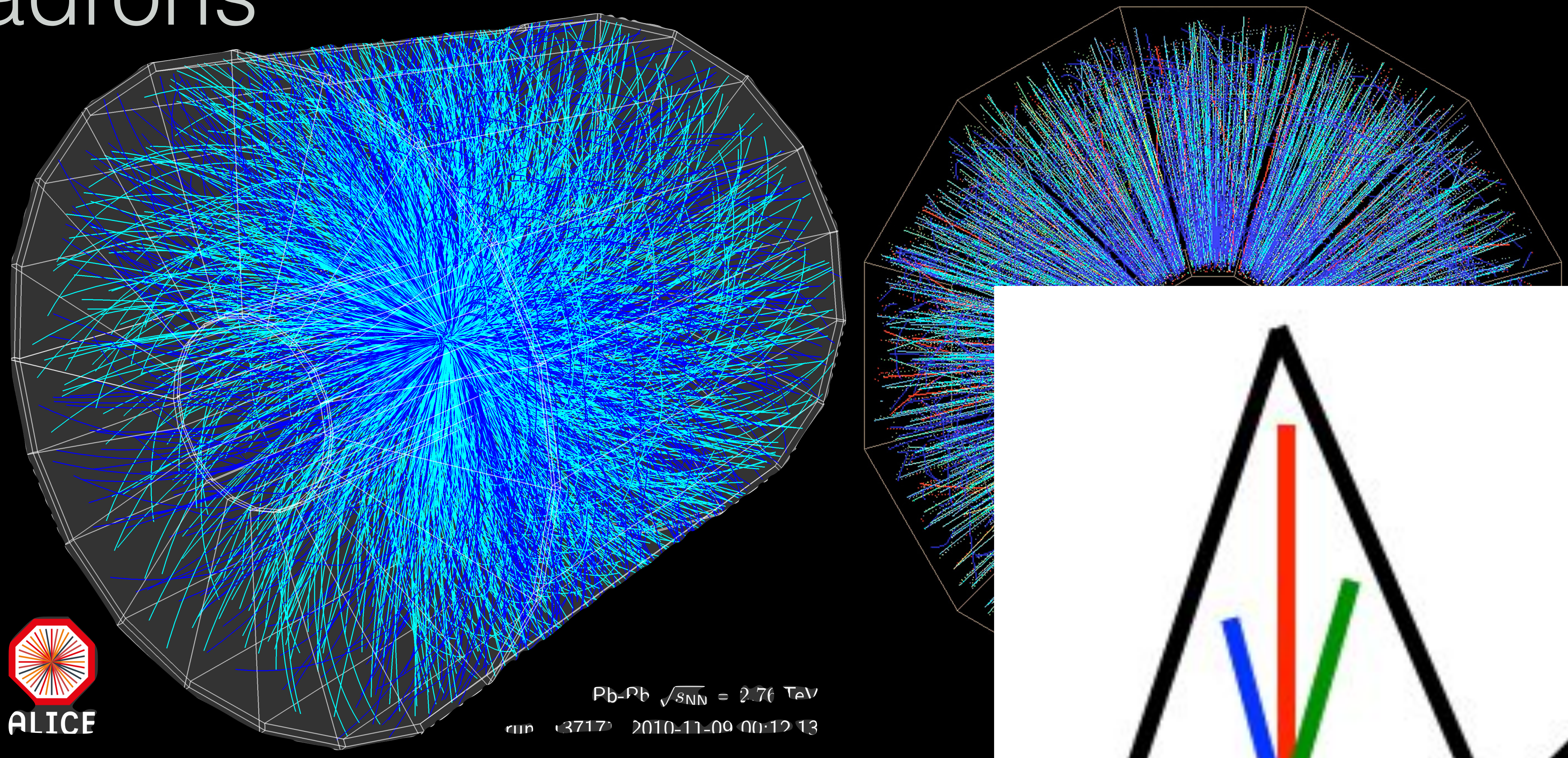


EM radiations

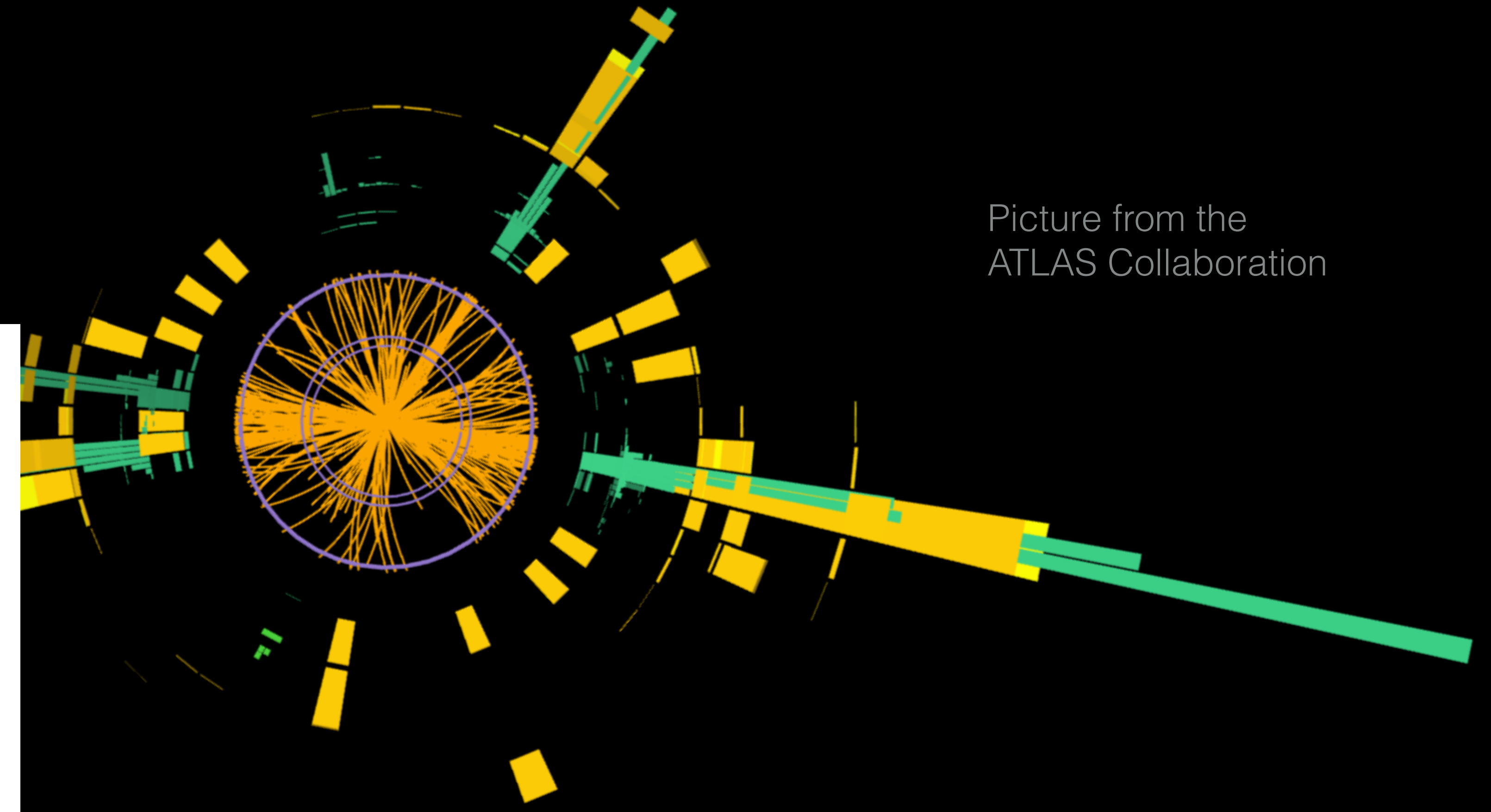


MULTI-MESSENGER HEAVY-ION PHYSICS

Hadrons



QCD jets



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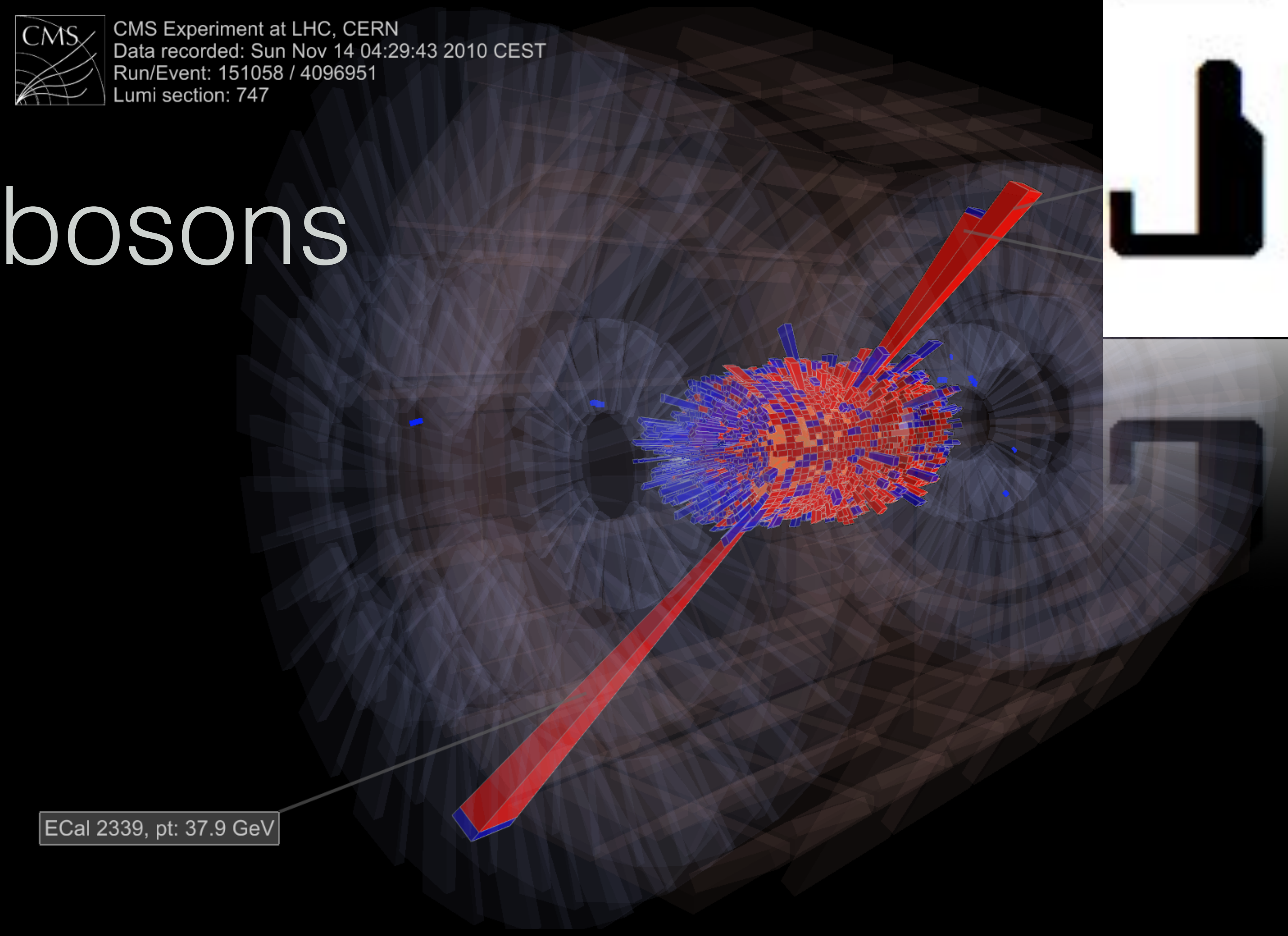
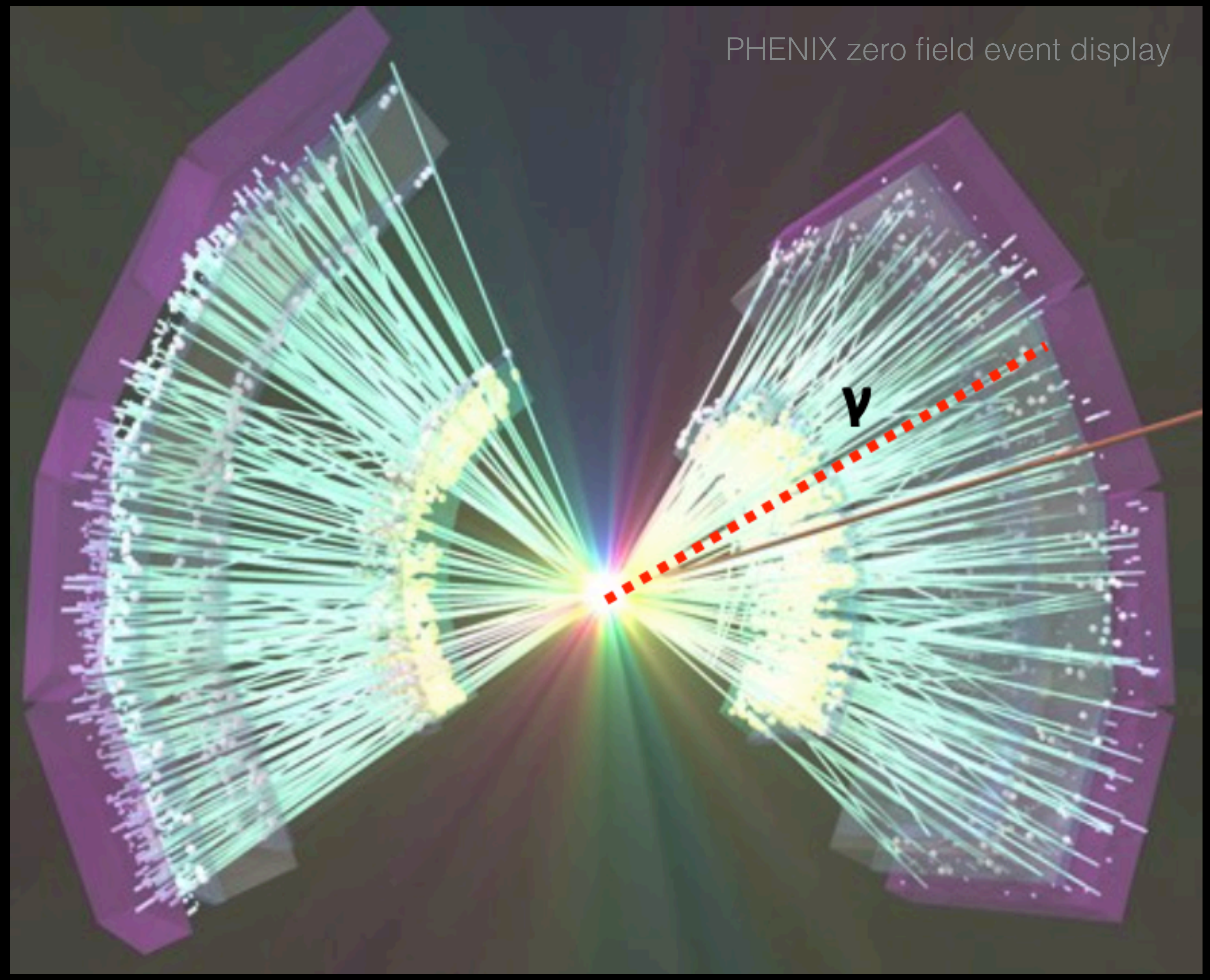
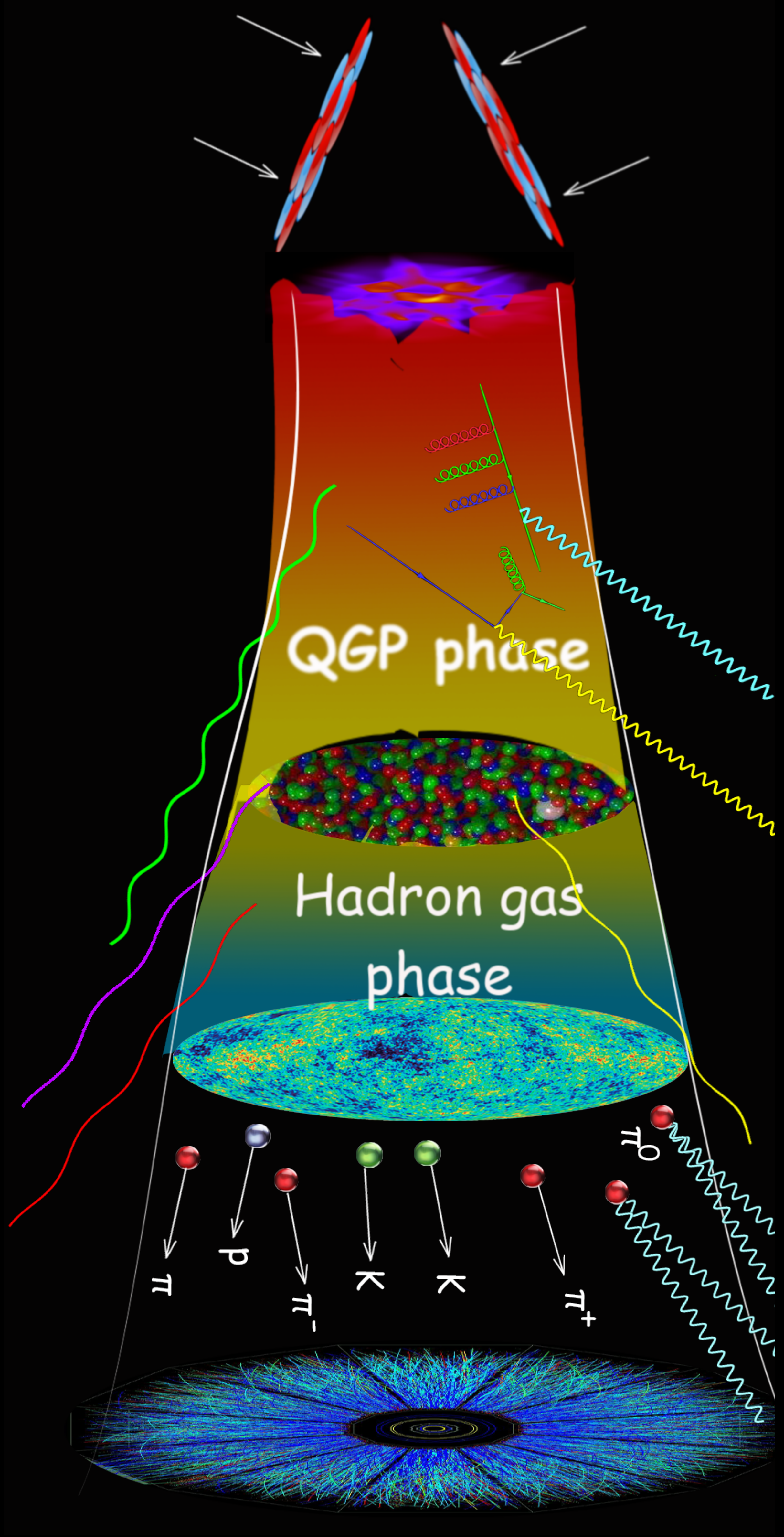




DEFINING THE QUARK-GLUON PLASMA



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

Equation of State $T^{\mu\nu} \Longleftrightarrow e, P, s$

$$c_s^2 = \partial P / \partial e|_{s/n}$$

Shear and bulk viscosities $\eta/s(T, \mu_B)$, $\zeta/s(T, \mu_B)$

Charge diffusion D_B, D_Q, D_S

Electromagnetic emissivity

Energy-momentum transport $\hat{q}, \hat{e}, \hat{e}_2, \ldots$

Spectra, collective flow, femtoscopy

Anisotropic flow v_n
Flow correlations

Balance functions

Photons and dileptons

Jets and heavy-quarks

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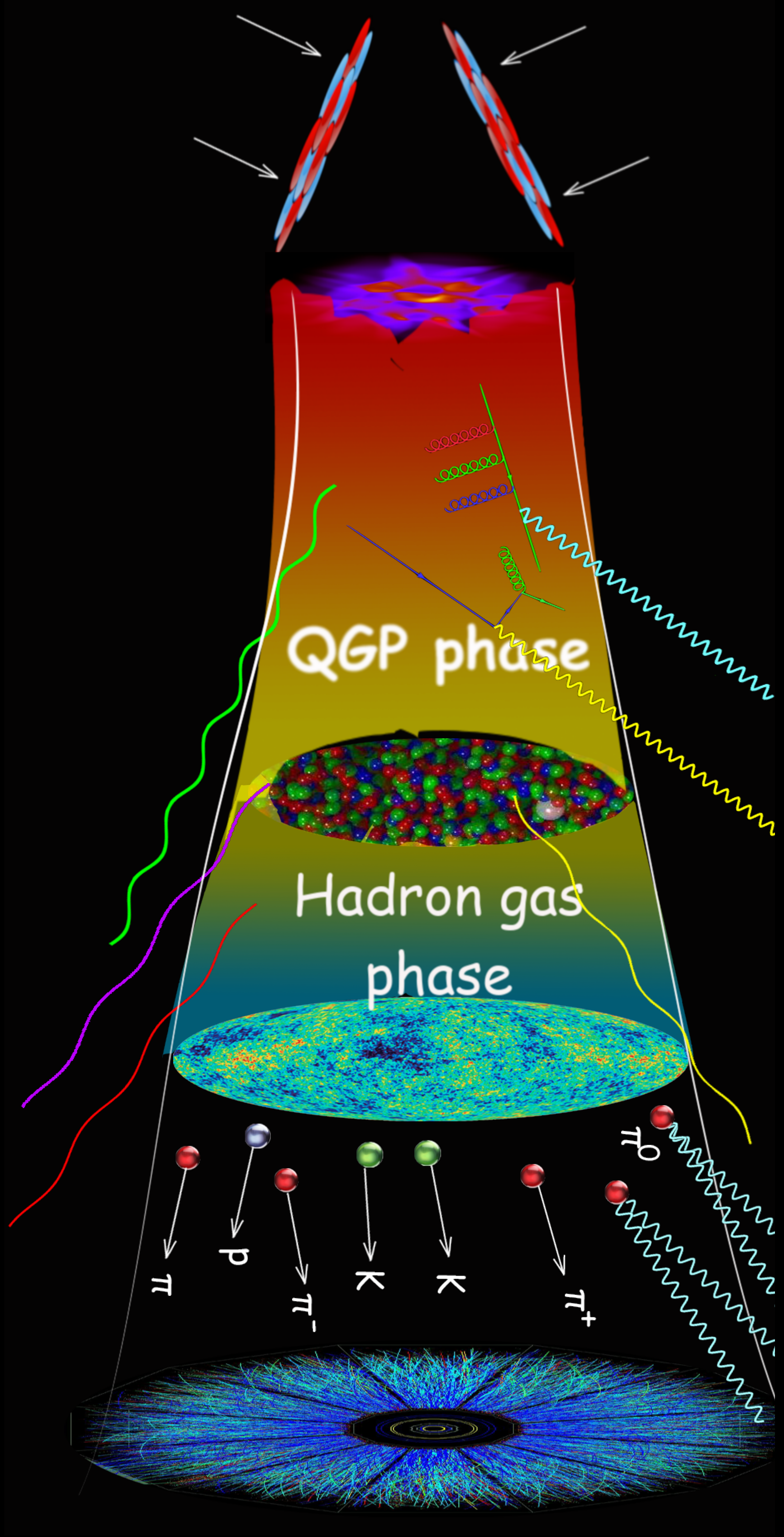

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Charge diffusion D_B, D_Q, D_S	Balance functions
Electromagnetic emissivity	Photons and dileptons
Energy-momentum transport $\hat{q}, \hat{e}, \hat{e}_2, \ldots$	Jets and heavy-quarks

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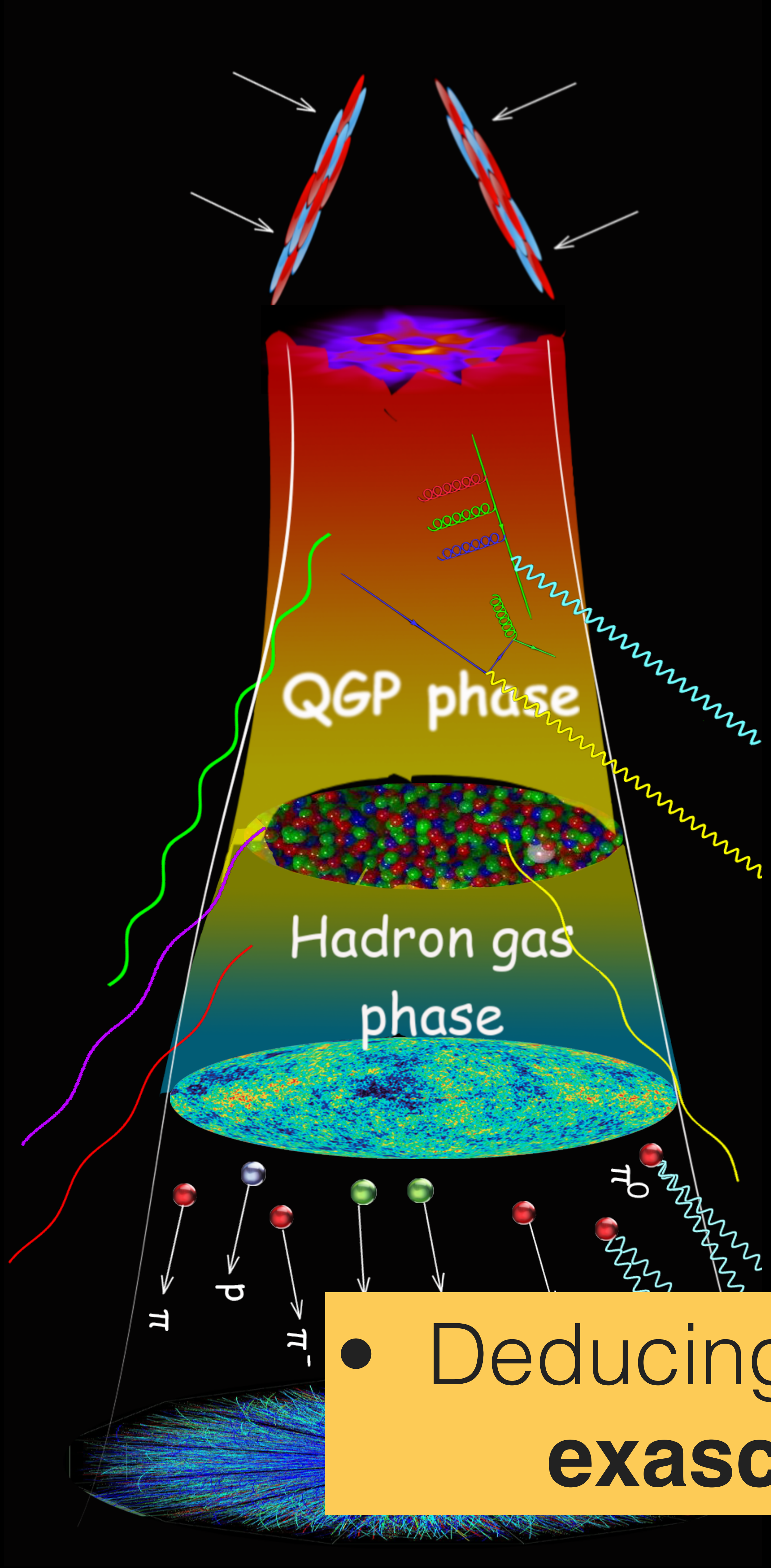

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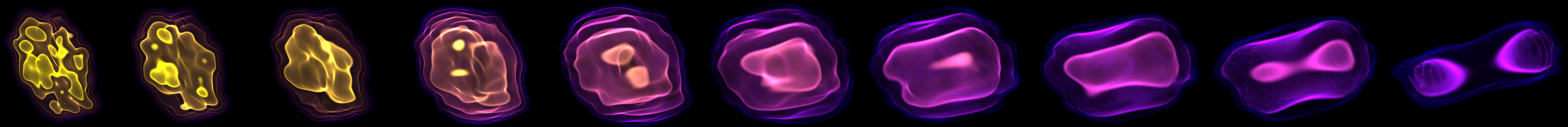
Balance functions

Photons and dileptons

quarks

- Deducing the QGP properties from experimental data requires **exascale computing** with advanced statistical methods

THE MULTI-STAGE THEORETICAL FRAMEWORK



$T^{\mu\nu}$ 0^+ 0.5-1 τ (fm)

Initial State +
Pre-equilibrium dynamics

Hydrodynamics

Hadronic Transport

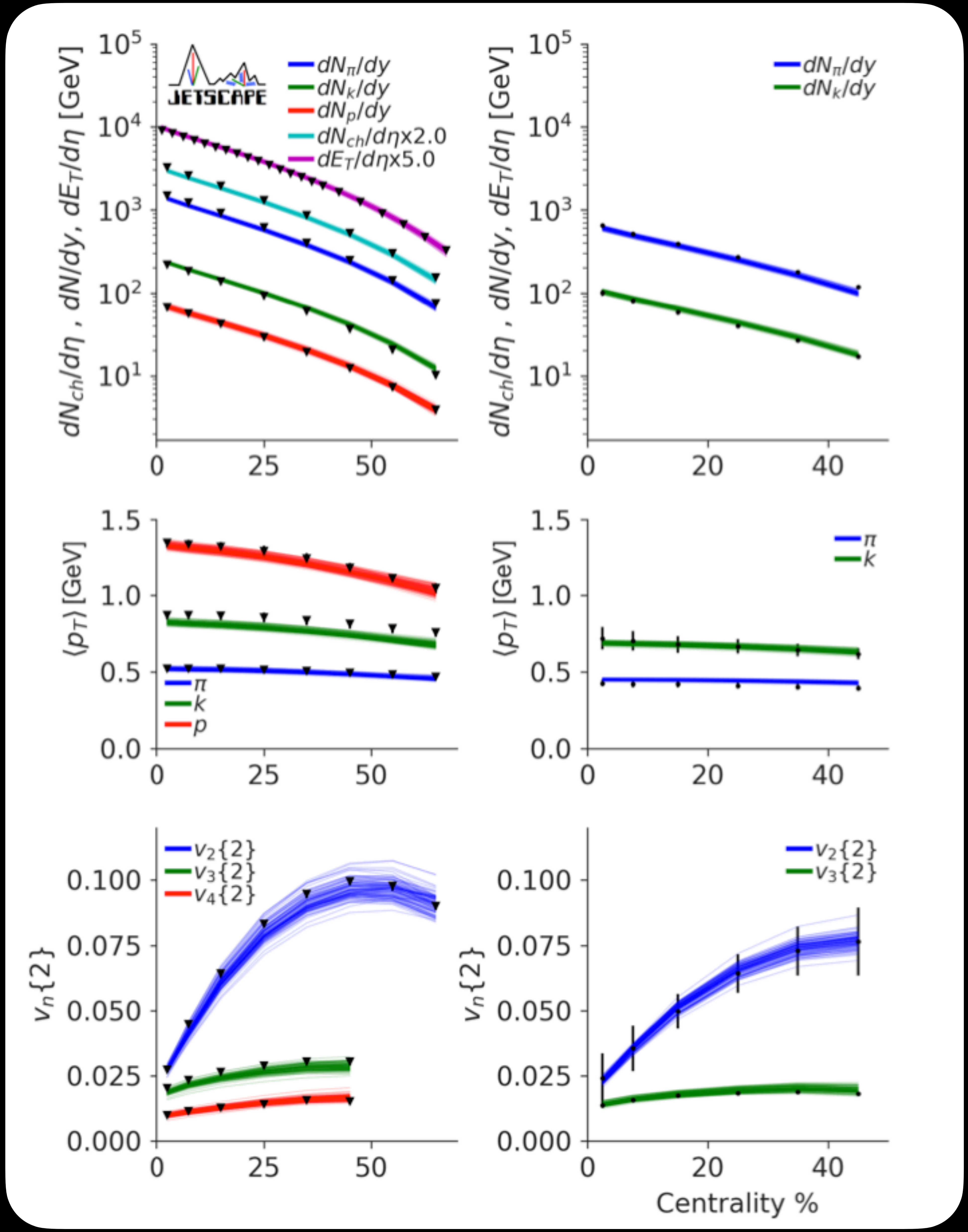
$$T^{\mu\nu}_{\rm pre.\,eq} = T^{\mu\nu}_{\rm hydro}$$

+ Landau Matching
with lattice EoS

Cooper-Frye
particlization

- Continuously connect the system's energy-momentum tensor $T^{\mu\nu}$ between different stages

GLOBAL BAYESIAN CONSTRAINTS ON QGP VISCOSITY



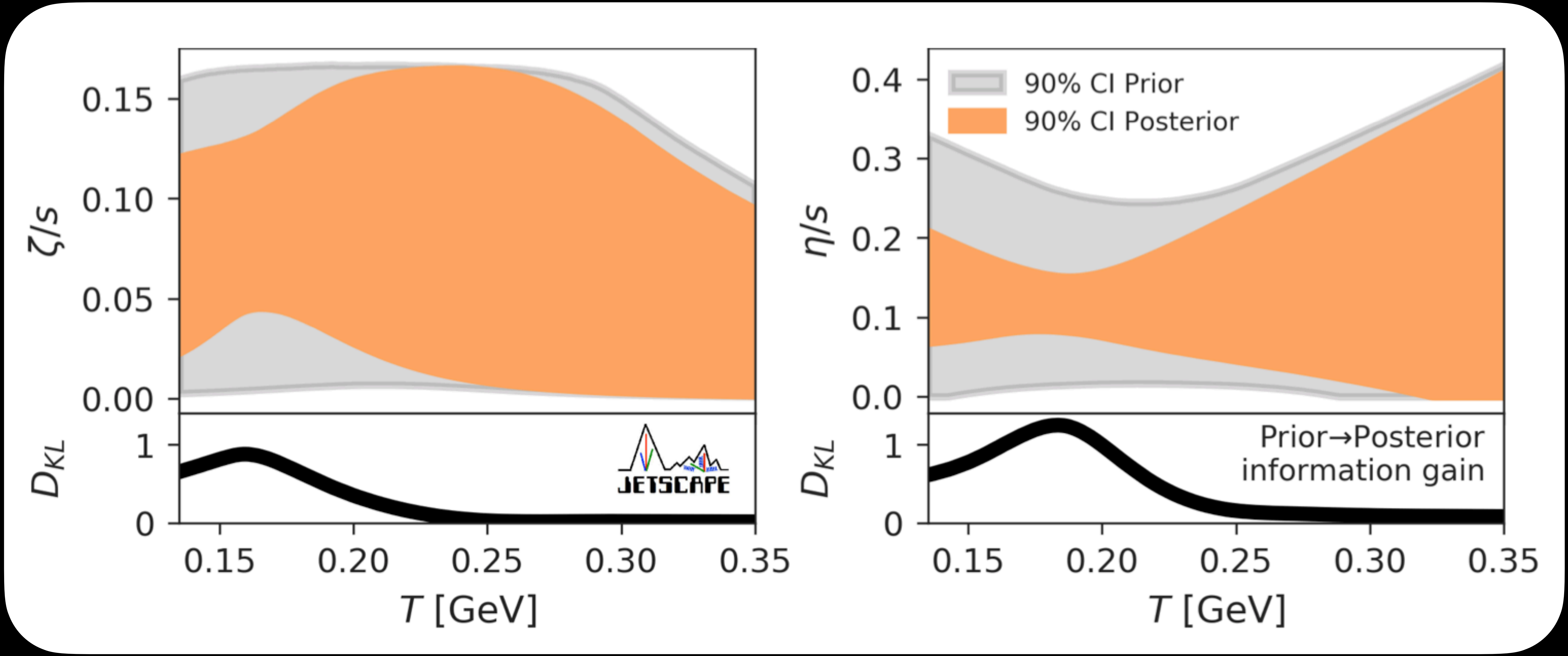
S. Pratt, E. Sangaline, P. Sorensen and H. Wang, Phys. Rev. Lett. 114, 202301 (2015)

J. E. Bernhard, J. S. Moreland, S. A. Bass, J. Liu and U. Heinz, Phys. Rev. C94, 024907 (2016)

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,
Phys. Rev. Lett. 126, 202301 (2021) & Phys. Rev. C103, 054909 (2021)

D. Everett *et al.* [JETSCAPE],
Phys. Rev. Lett.126, 242301 (2021) & Phys. Rev. C103, 054904 (2021)



- Precision hadronic measurements can systematically constrain the QGP viscosity

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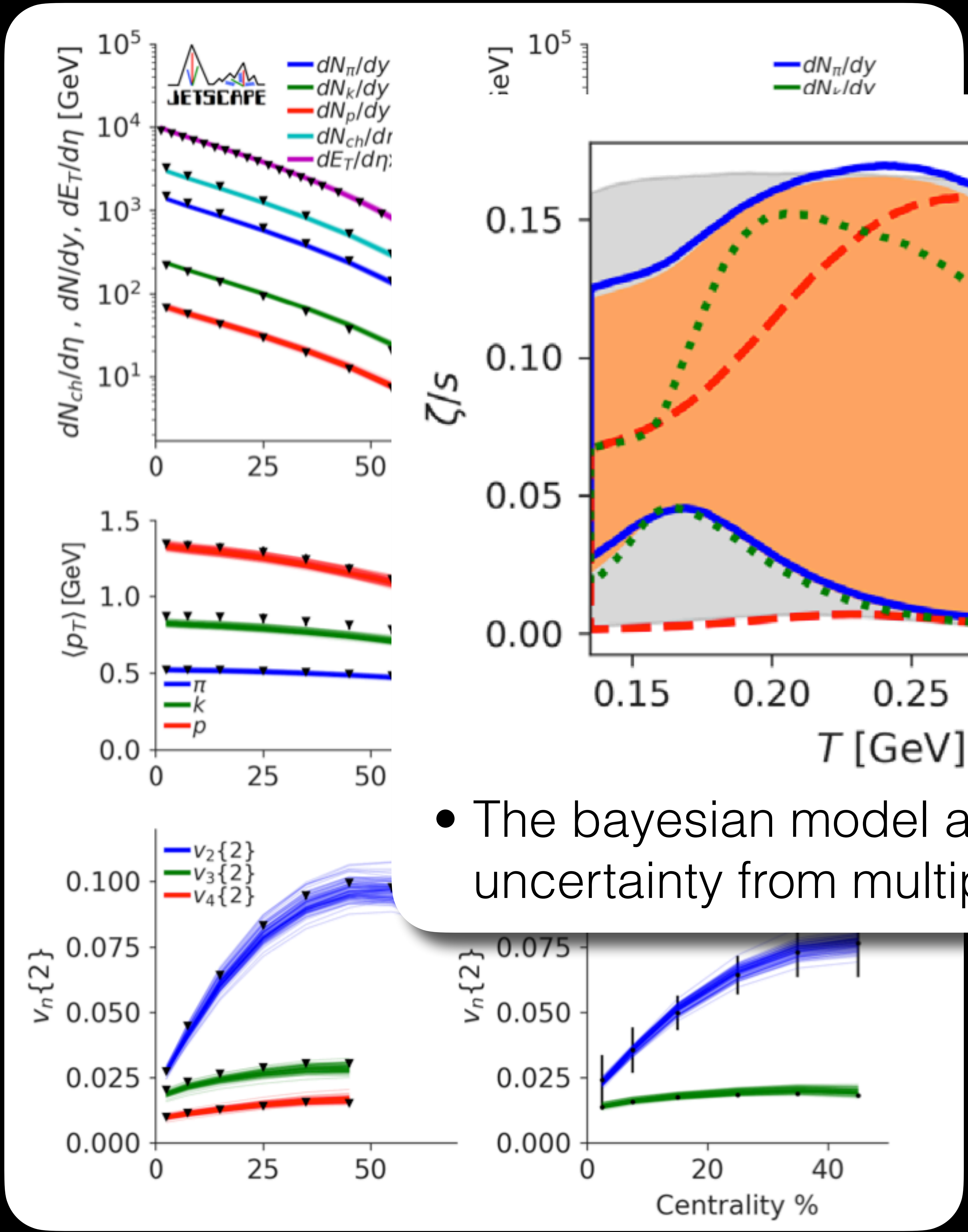
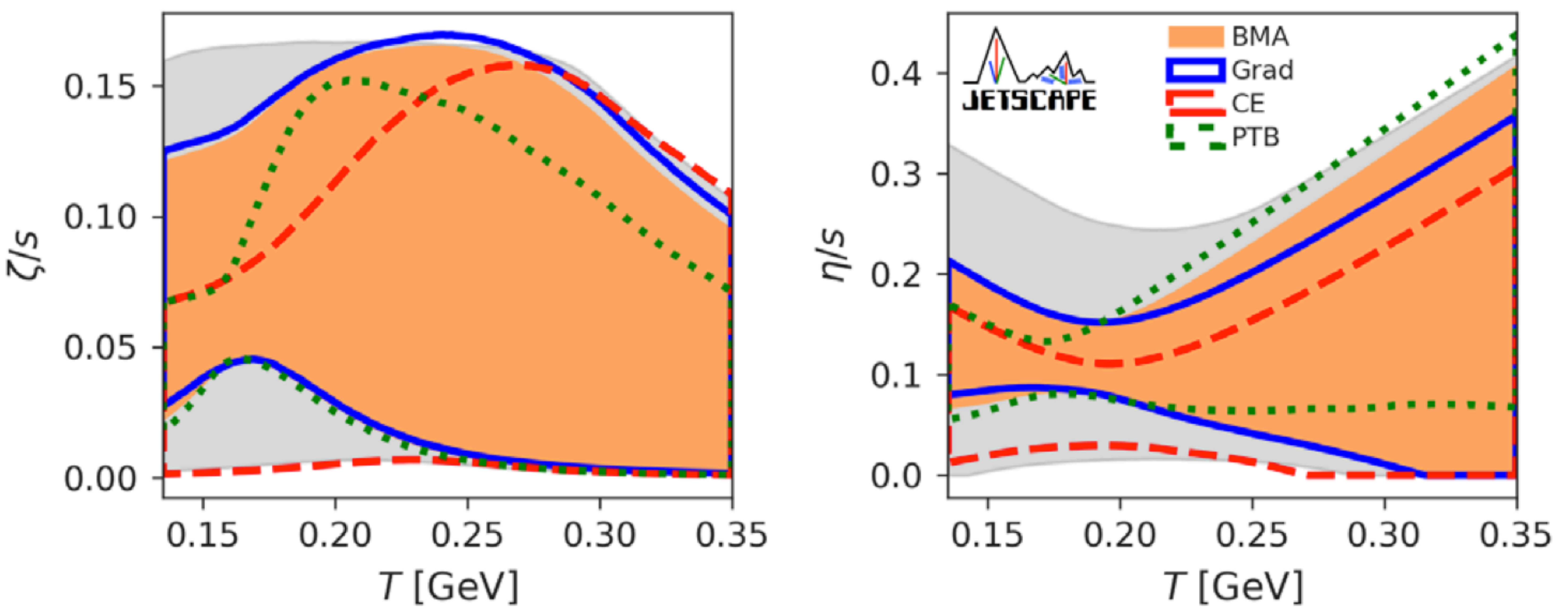
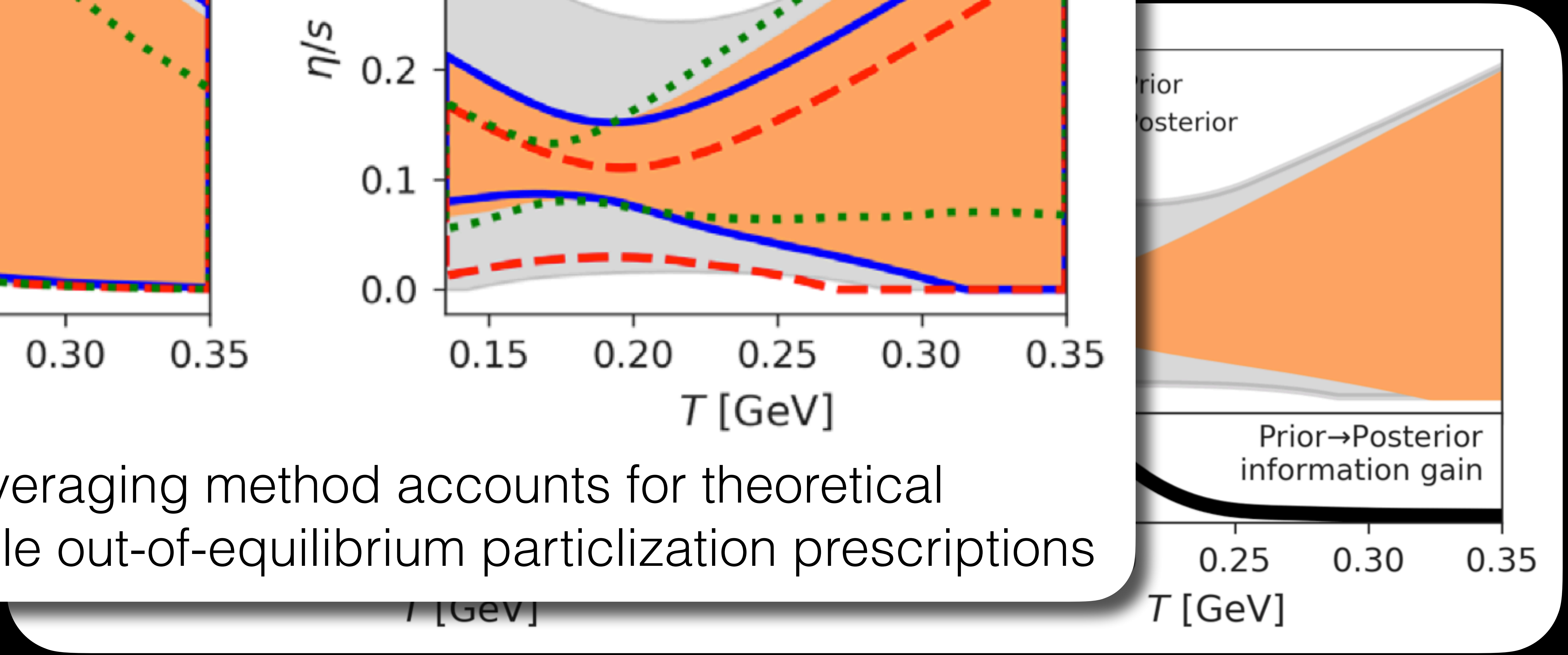




- The bayesian model averaging method accounts for theoretical uncertainty from multiple out-of-equilibrium particlization prescriptions



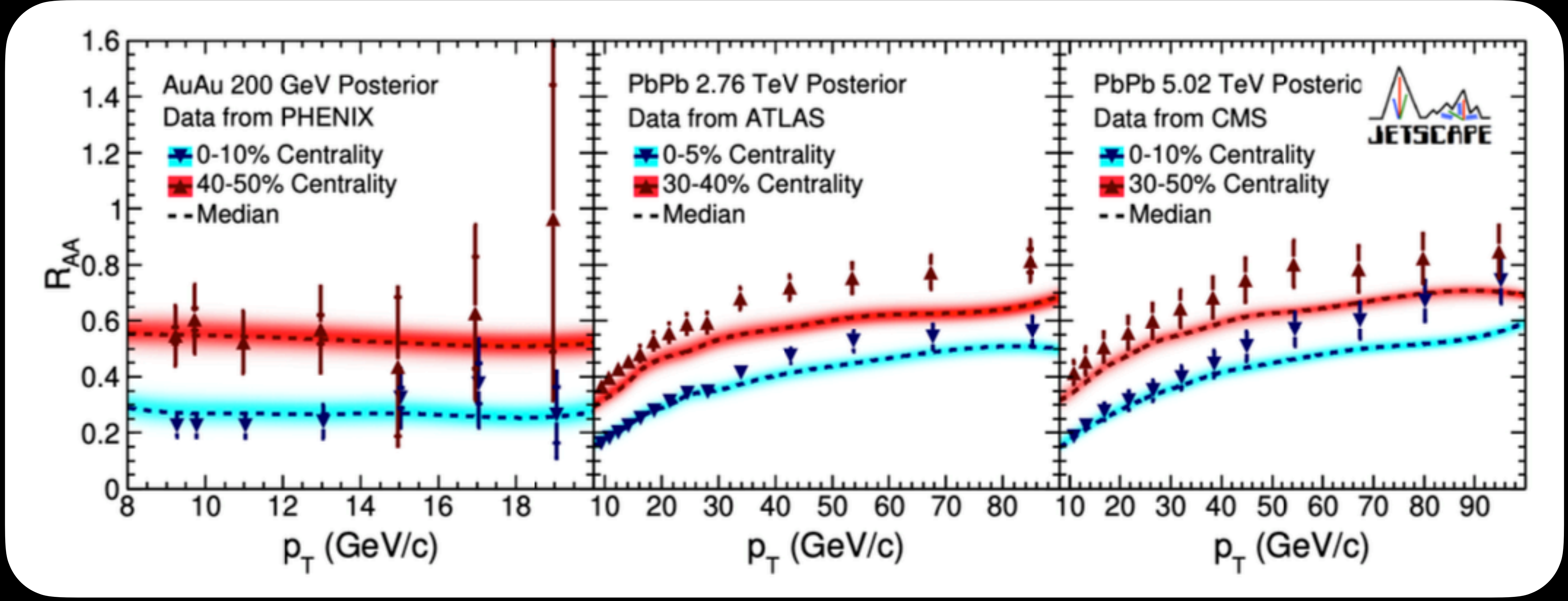
- Precision hadronic measurements can systematically constrain the QGP viscosity

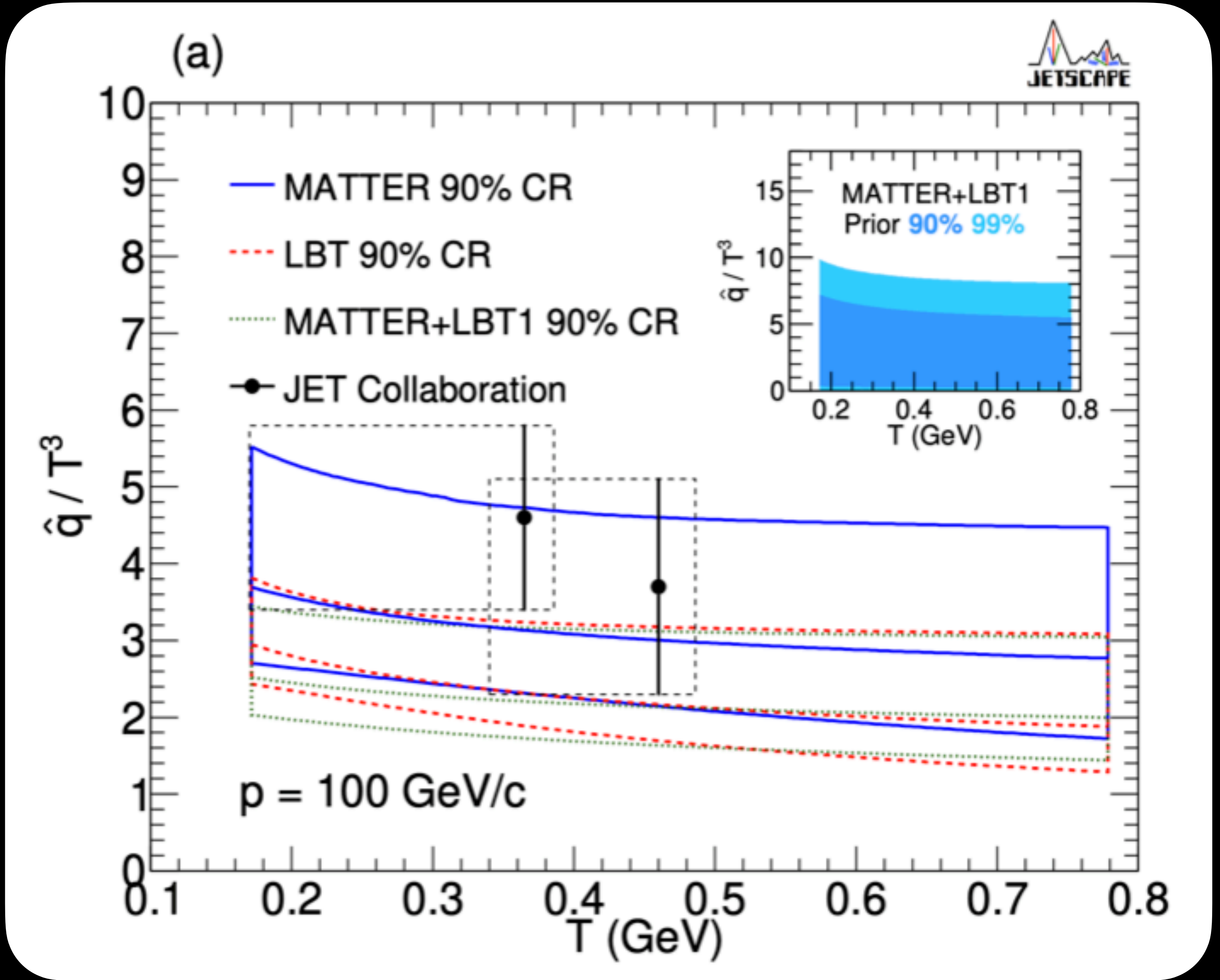
BAYESIAN CONSTRAINTS ON JET TRANSPORT

JETSCAPE, Phys.Rev.C 104 (2021) 2, 024905

- First result: focus in on inclusive charged hadron
- Partons evolve with the MATTER + LBT model through 2+1D hydrodynamic medium

$$\frac{\hat{q}(E,T)\,|_{A,B,C,D,Q_{sw}}}{T^3} = 42 C_R \frac{\zeta(3)}{\pi}\left(\frac{4\pi}{9}\right)^2 \left\{ \underbrace{\frac{A\left[\ln\left(\frac{E}{\Lambda}\right) - \ln(B)\right]}{\left[\ln\left(\frac{E}{\Lambda}\right)\right]^2}}_{\text{High virtuality, no T dep}} \underbrace{\theta(Q - Q_{sw})}_{\text{Switch models}} + \underbrace{\frac{C\left[\ln\left(\frac{E}{T}\right) - \ln(D)\right]}{\left[\ln\left(\frac{ET}{\Lambda^2}\right)\right]^2}}_{\text{HTL-like, scatter off T}} \right\}$$





WHERE WE ARE AND WHERE WE ARE GOING

- Quark-Gluon Plasma is the hottest, smallest, and the most perfect fluid ever created in the laboratory

- A fluid has "close" to the fundamental degrees of freedom

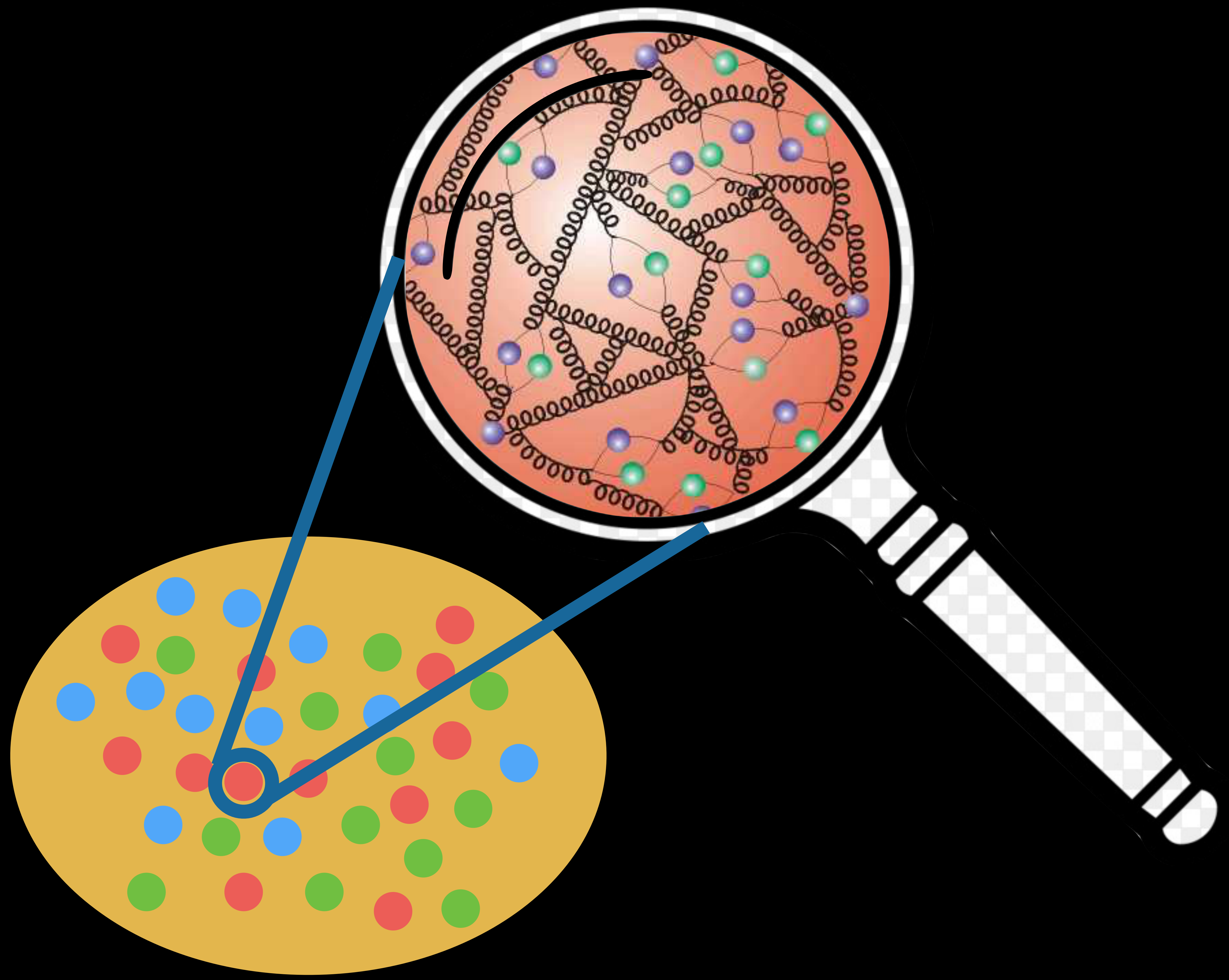
How does the strongly coupled liquid emerge from fundamental QCD interactions?

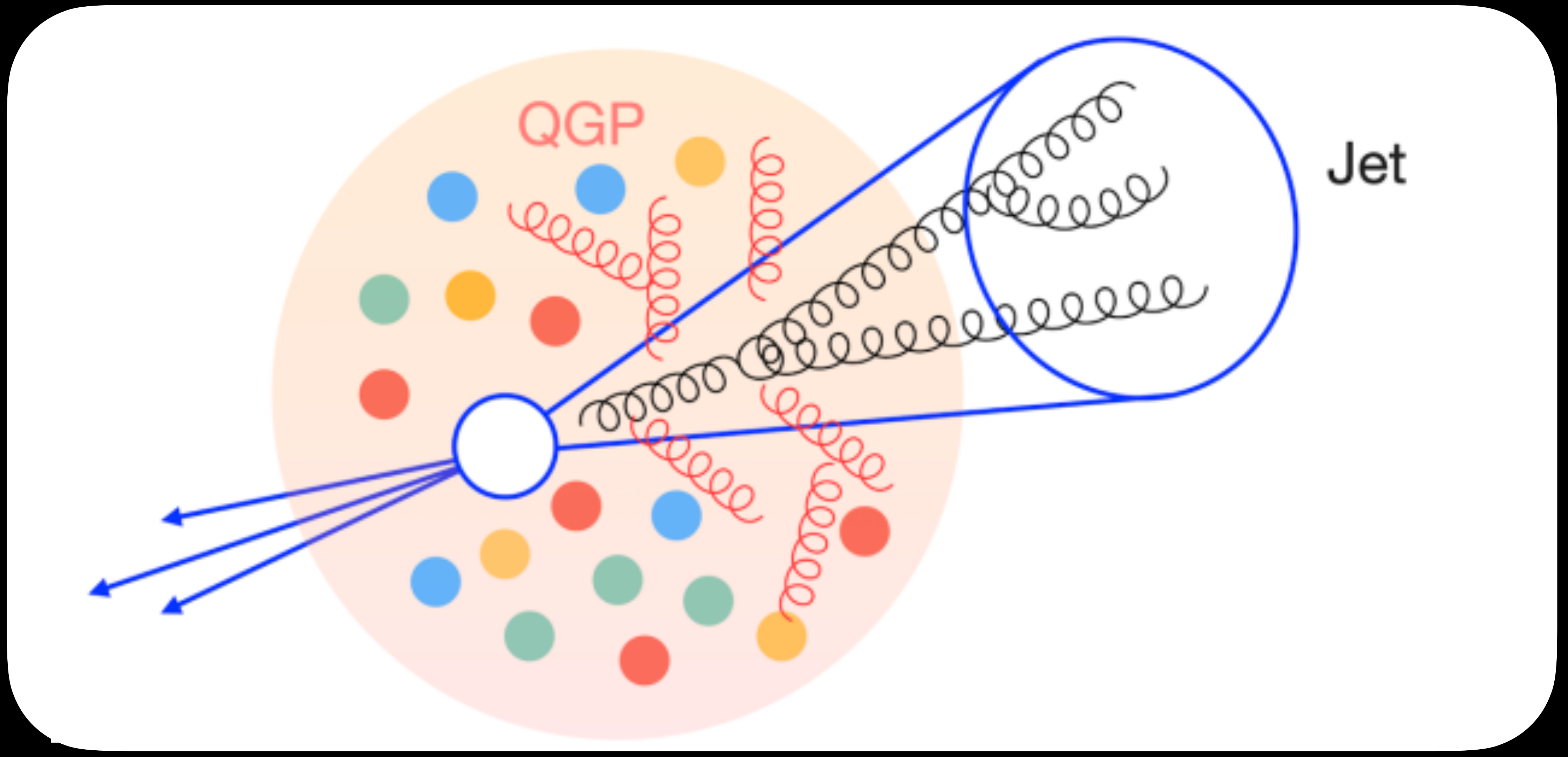
- Probes the inner working of QGP at multi-resolution scales with jets and heavy-quarks

- What is the smallest possible droplet of QGP?

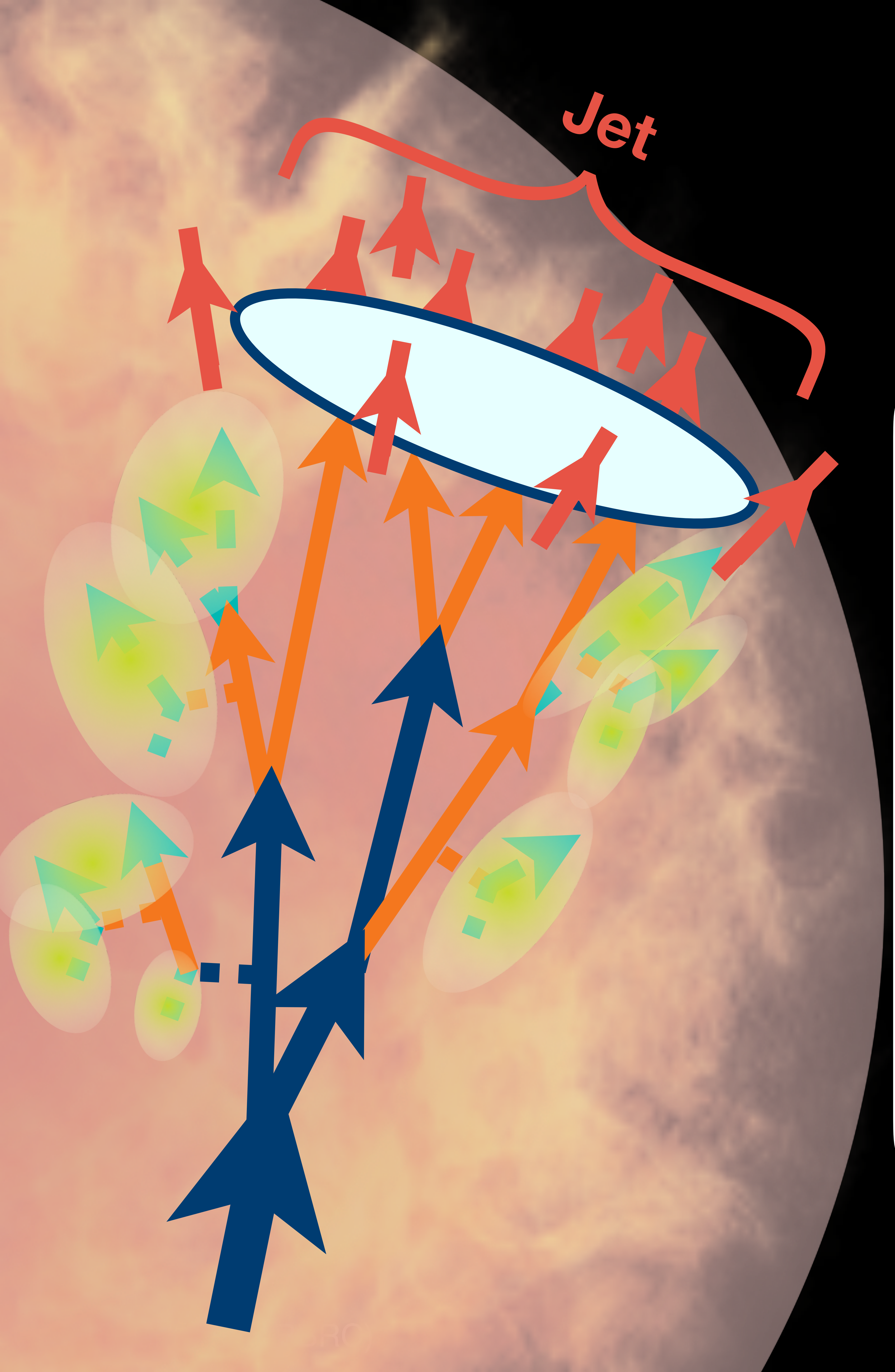
- What is the structure of QCD phase diagram?

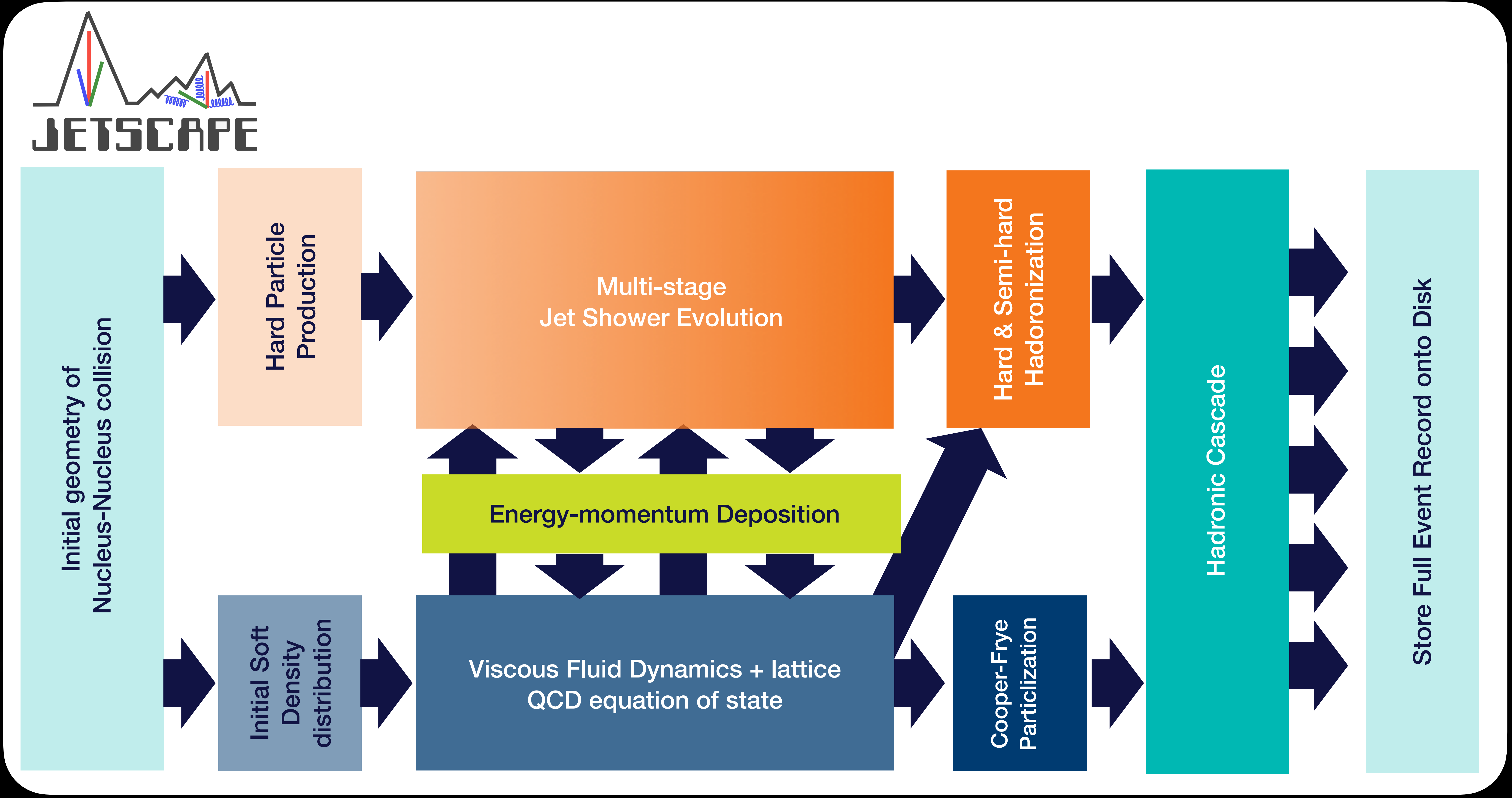
QCD JETS AS A MICROSCOPE FOR THE QCD MATTER





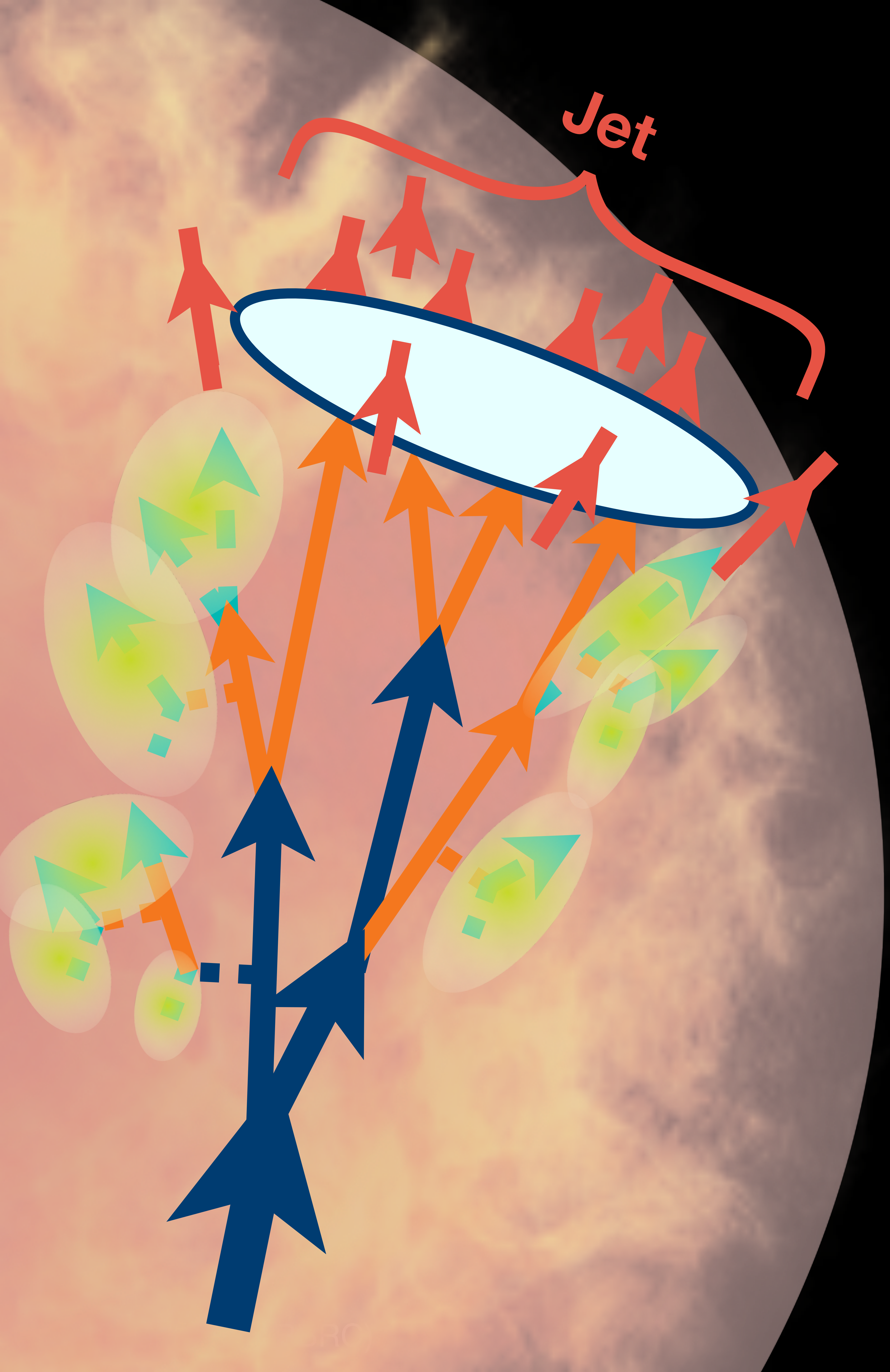
THE JETSCAPE FRAMEWORK





@ Y. Tachibana

MULTI-STAGE JET EVOLUTION



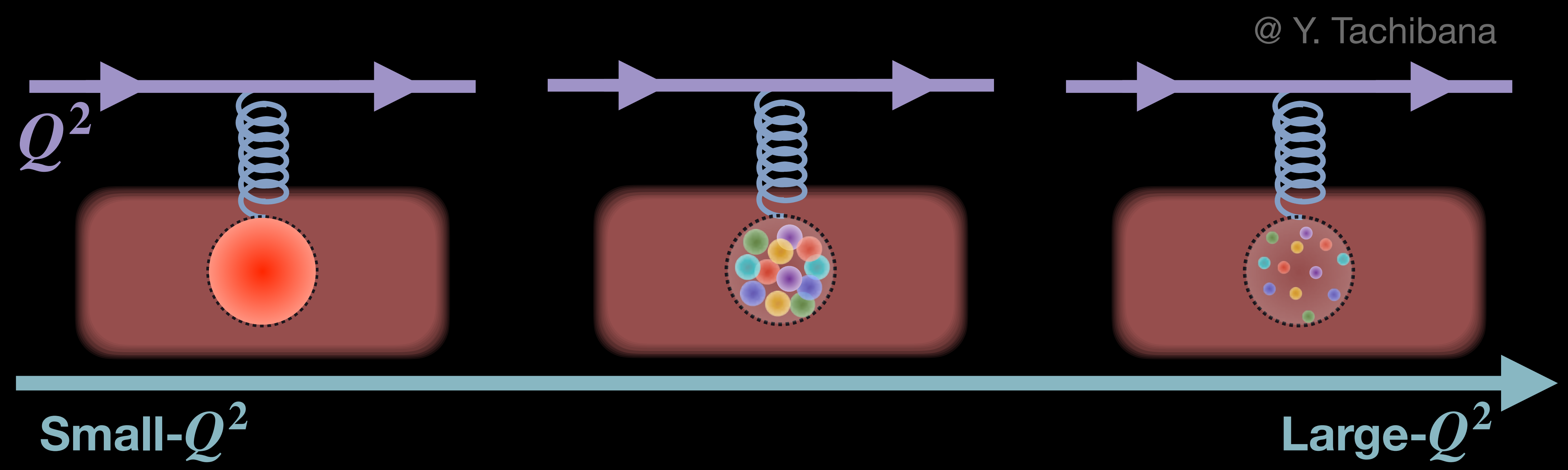
Large-Q ($> Q_0$)	Small-Q ($< Q_0$), Large-E		Small-Q ($< Q_0$), Small-E
MATTER	**LBT**	**MARTINI**	**AdS/CFT**
Majumder(13) Kordell, Majumder(17) Cao, Majumder(17)	**Wang, Zhu(13), Luo, et al.(15,18) Cao, et al.(16,17), He, et al.(18)**	Schenke, Gale, Jeon(09), Park, Jeon, Gale(17,18)	Chesler, Rajagopal(14, 15) Pablos, et al.(15,16,17)
Radiation dominated Virtuality ordered splitting	Scattering dominated On-shell parton transport		Diffusion into medium
Higher-Twist formalism	Higher-Twist formalism	AMY formalism	$\mathcal{N}$ = 4 super Yang-Mills

@ Y. Tachibana

MULTI-STAGE JET EVOLUTION

- **Coherence effects**
  Y. Mehtar-Tani, C. A. Salgado, K. Tywoniuk, PLB707, 156-159 (2012)
  J. Casalderrey-Solana, E. Iancu, JHEP08, 015 (2011)

  - Scale evolution of QGP constituent distribution
    Kumar, Majumder, Shen, PRC101, 034908 (2020)
  - Less interaction for large-Q^2 partons
    → Implemented in MATTER



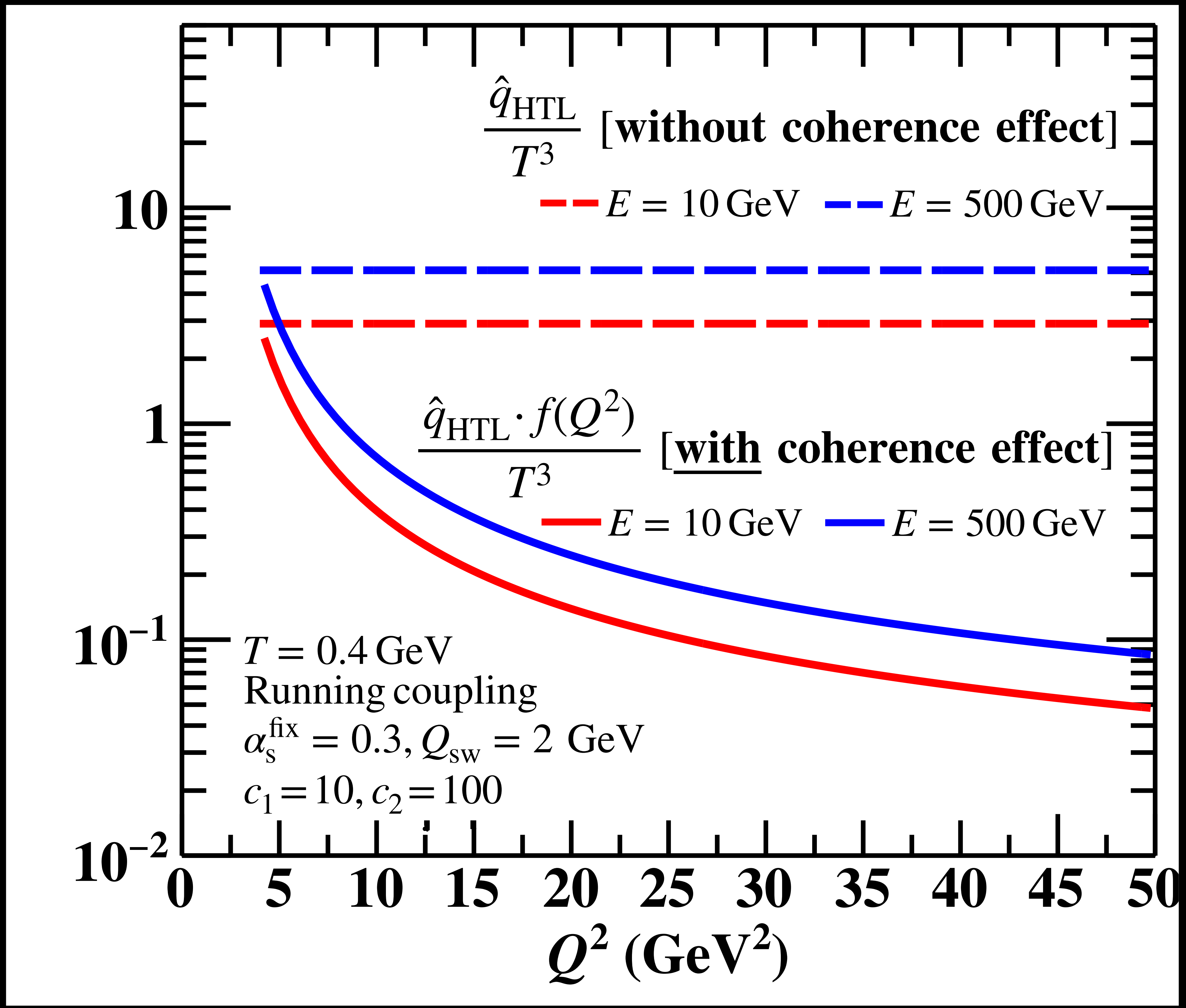
Effective jet-quenching strength

$$\hat{q}_{\rm HTL} \cdot f(Q^2)$$

JETSCAPE, arXiv:2204.01163

$$f(Q^2) = \frac{1 + c_1 \ln^2(Q^2_{\rm sw}) + c_2 \ln^4(Q^2_{\rm sw})}{1 + c_1 \ln^2(Q^2) + c_2 \ln^4(Q^2)}$$

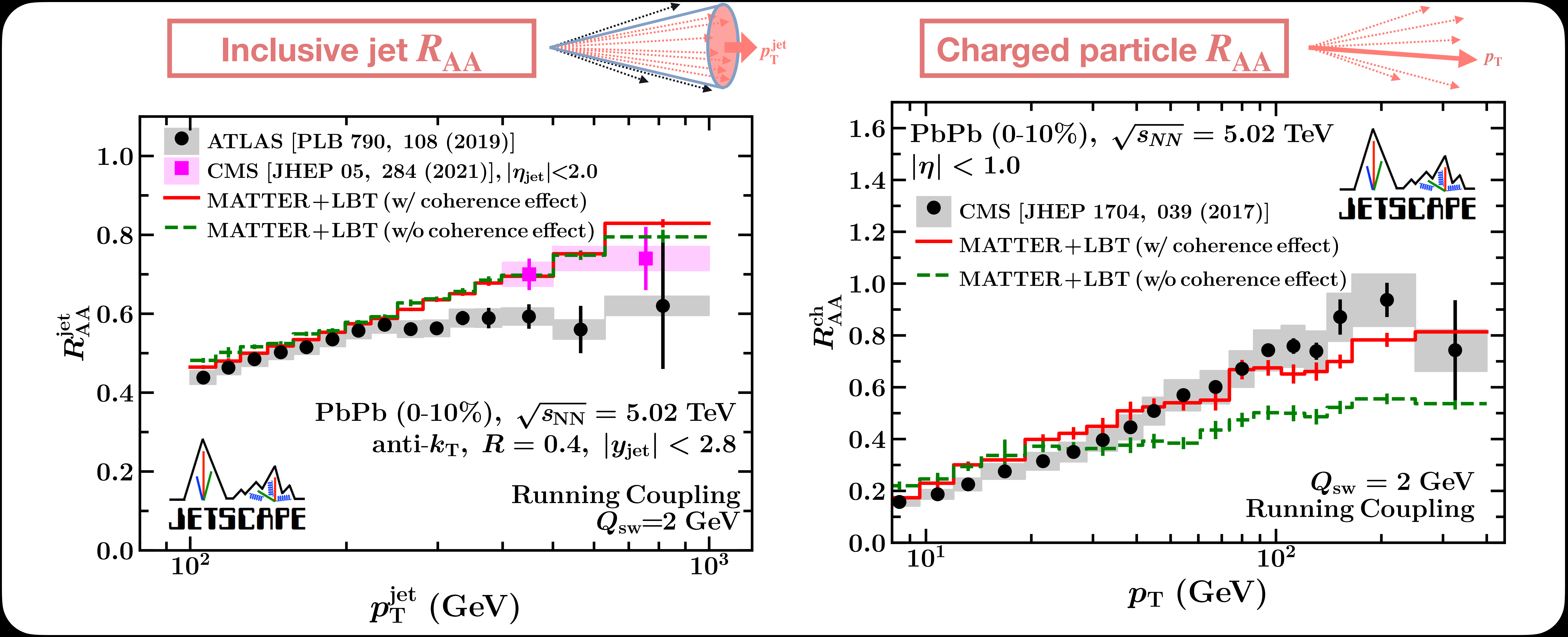
$$\hat{q}_{\rm HTL} = C_a \frac{42\zeta(3)}{\pi} \alpha_s^{\rm run} \alpha_s^{\rm fix} T^3 \ln\left[\frac{2ET}{6\pi T^2 \alpha_s^{\rm fix}}\right]$$



JET AND SINGLE PARTICLE ENERGY LOSS

Pb+Pb collisions at 5.02 TeV

JETSCAPE, arXiv:2204.01163

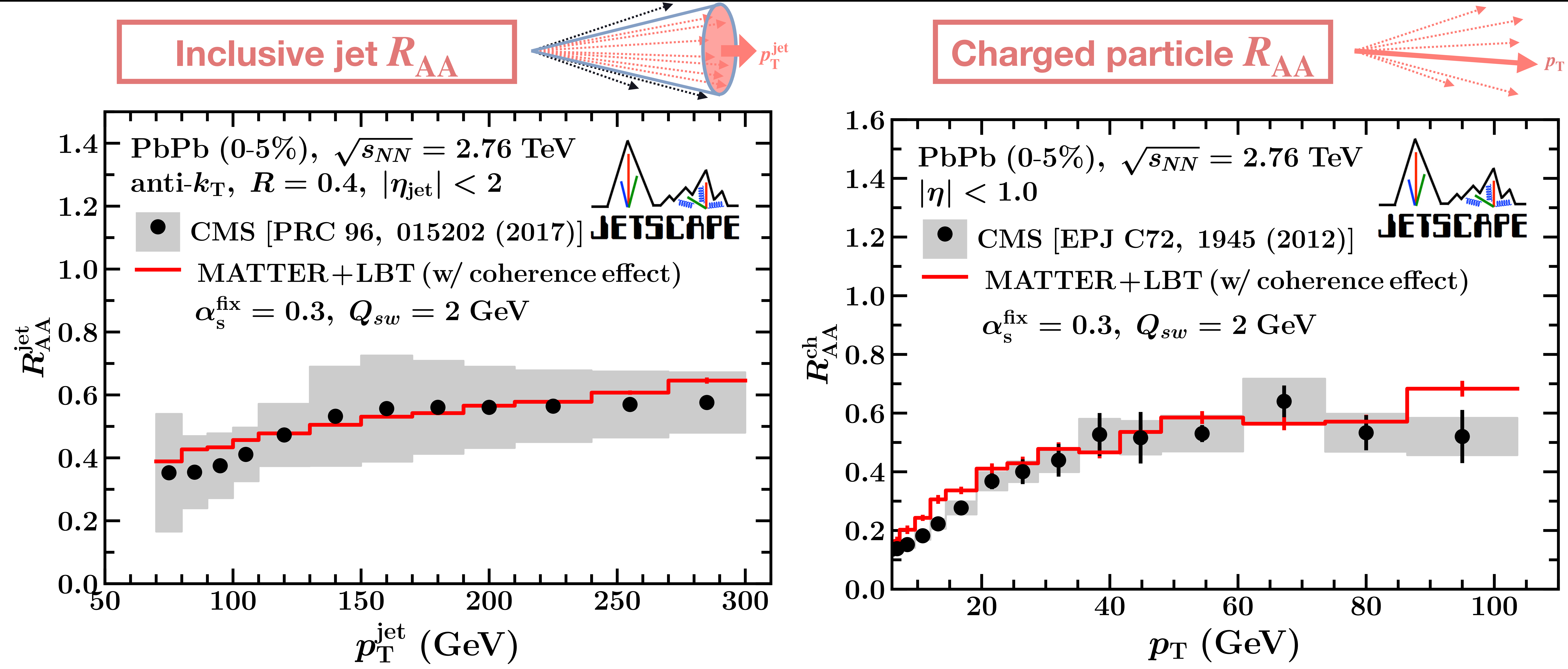


- Simultaneous description for jet and charged hadron energy loss
- Significant coherence effects on high p_T charged hadron R_{AA}

JET AND SINGLE PARTICLE ENERGY LOSS

Pb+Pb collisions at 2.76 TeV (same parameter set as 5.02 TeV)

JETSCAPE, arXiv:2204.01163

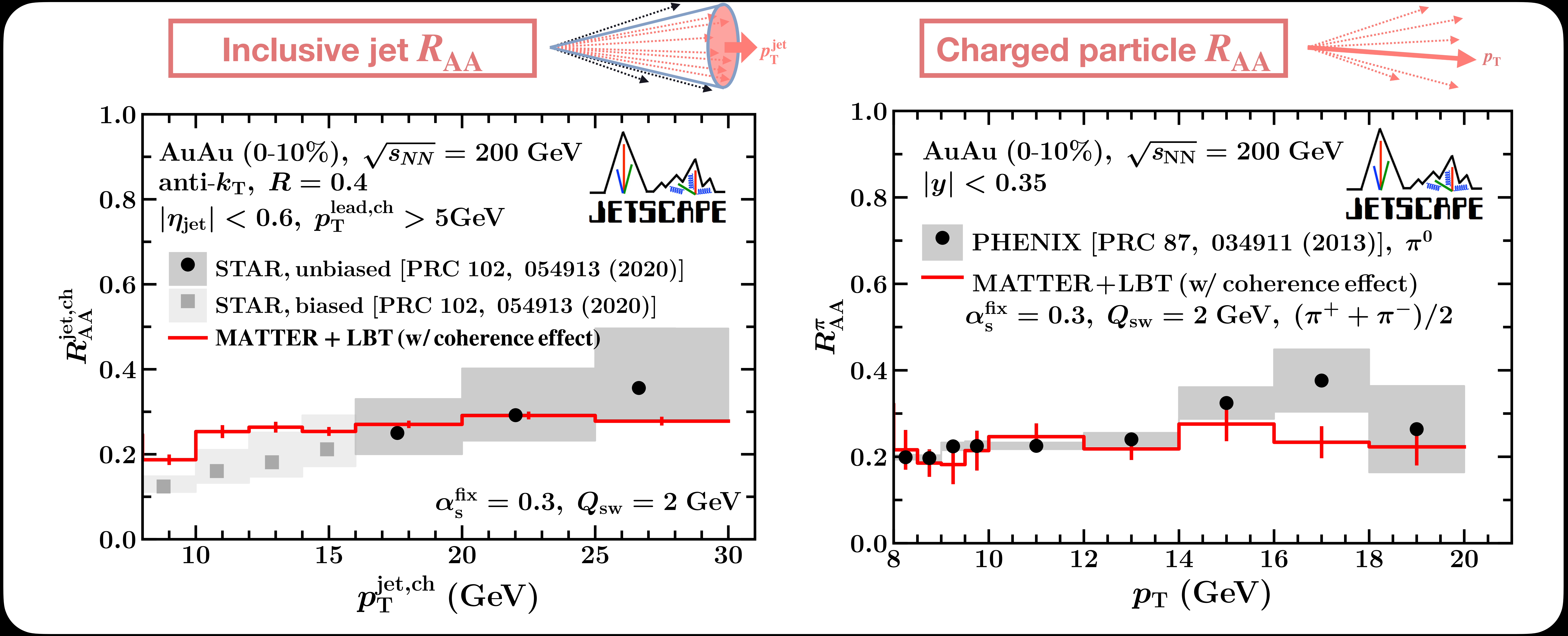


- The MATTER + LBT with coherence effects can provide a good description of parton energy loss in central Pb+Pb collisions at 2.76 TeV

JET AND SINGLE PARTICLE ENERGY LOSS

Au+Au collisions at 200 GeV (same parameter set as 5.02 TeV)

JETSCAPE, arXiv:2204.01163

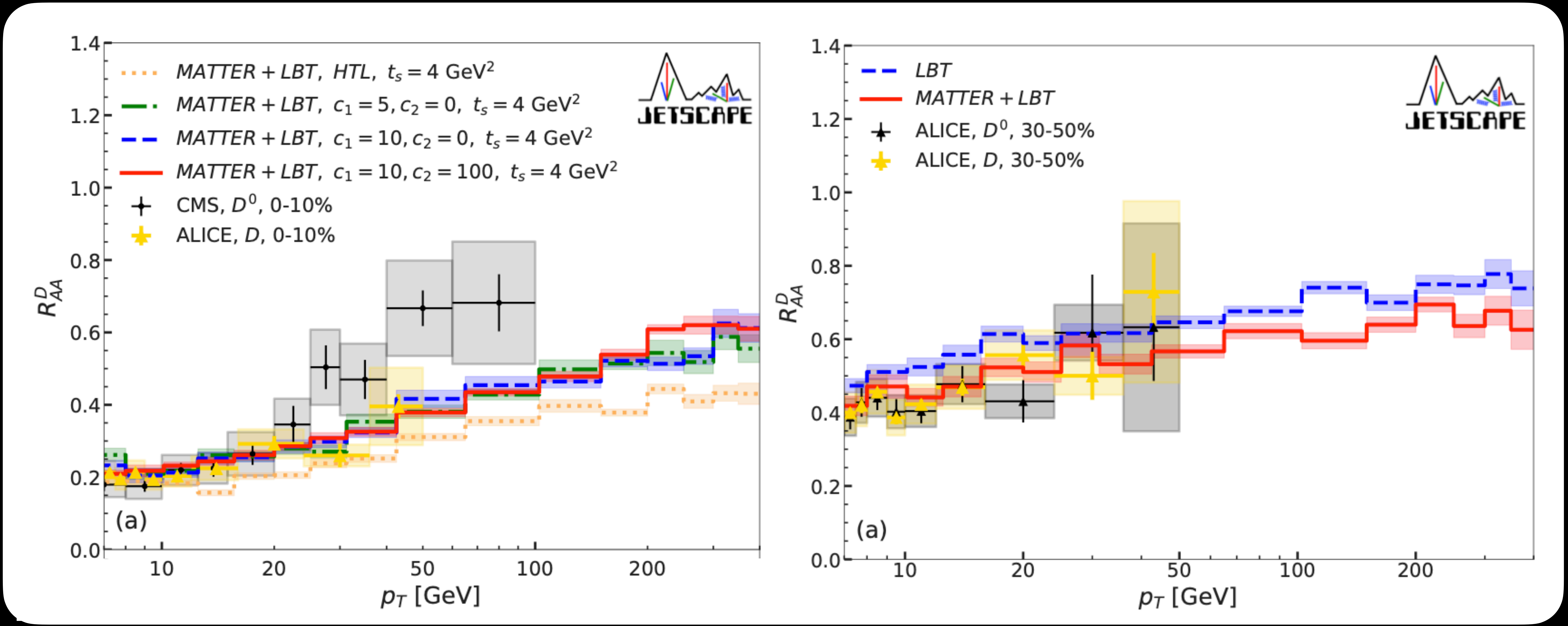


- The MATTER + LBT with coherence effects can describe the collision energy dependence of parton energy loss from 200 GeV to 5.02 TeV

HEAVY QUARK ENERGY LOSS

JETSCAPE, arXiv:2208.00983

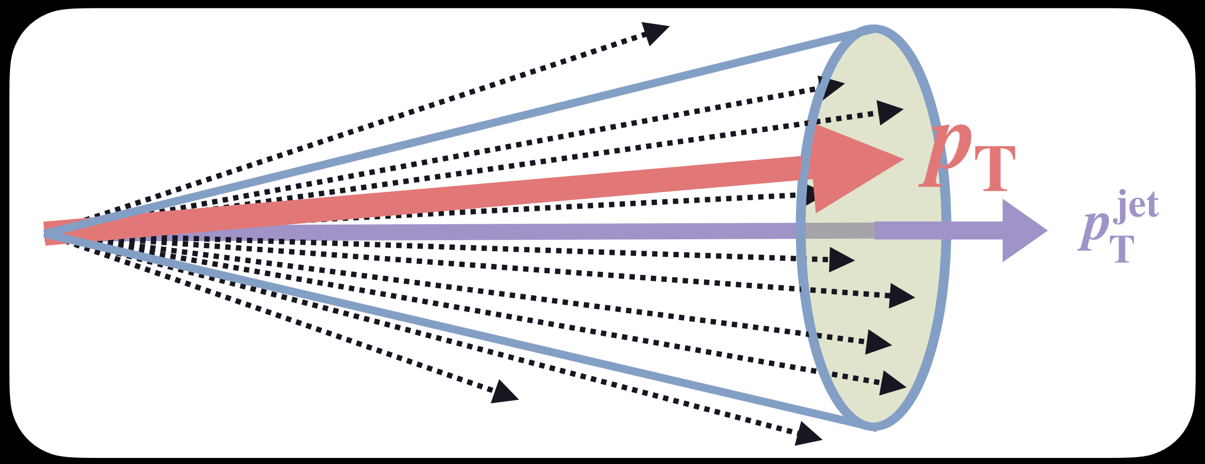
Pb+Pb collisions at 5.02 TeV (same parameter set as light hadrons)

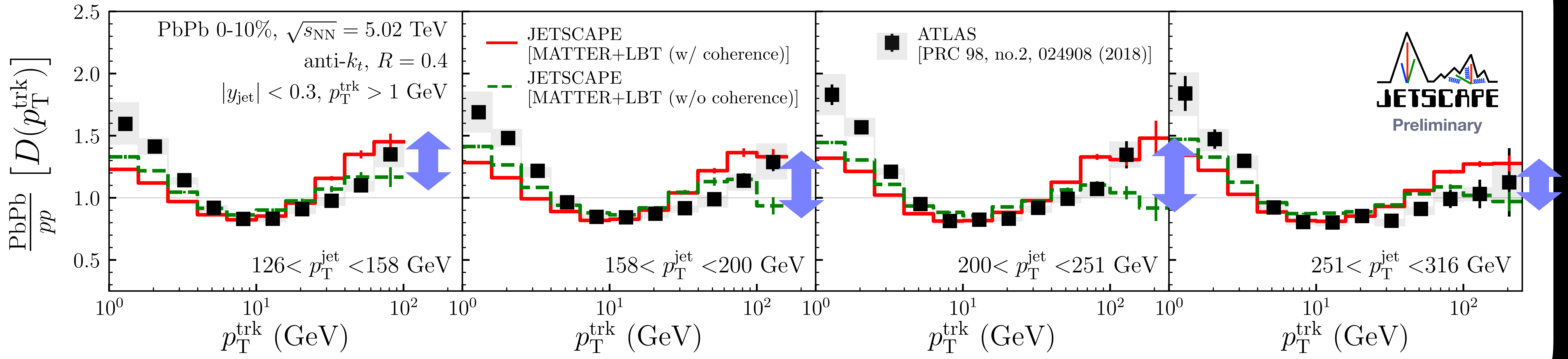


- The same MATTER + LBT with coherence effects can consistently describe the D meson energy loss in Pb+Pb collisions at 5.02 TeV

JET SUBSTRUCTURES

Jet Fragmentation function $D(p_T) = \frac{1}{N_{jet}} \sum_{jet} \frac{dN_{ch}}{dp_T}\Big|_{\text{in jet}}$

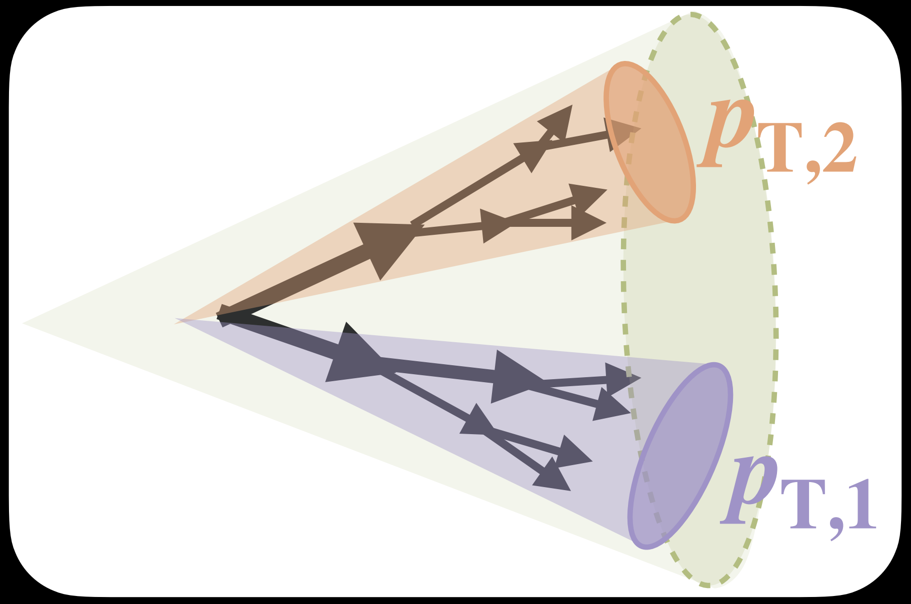


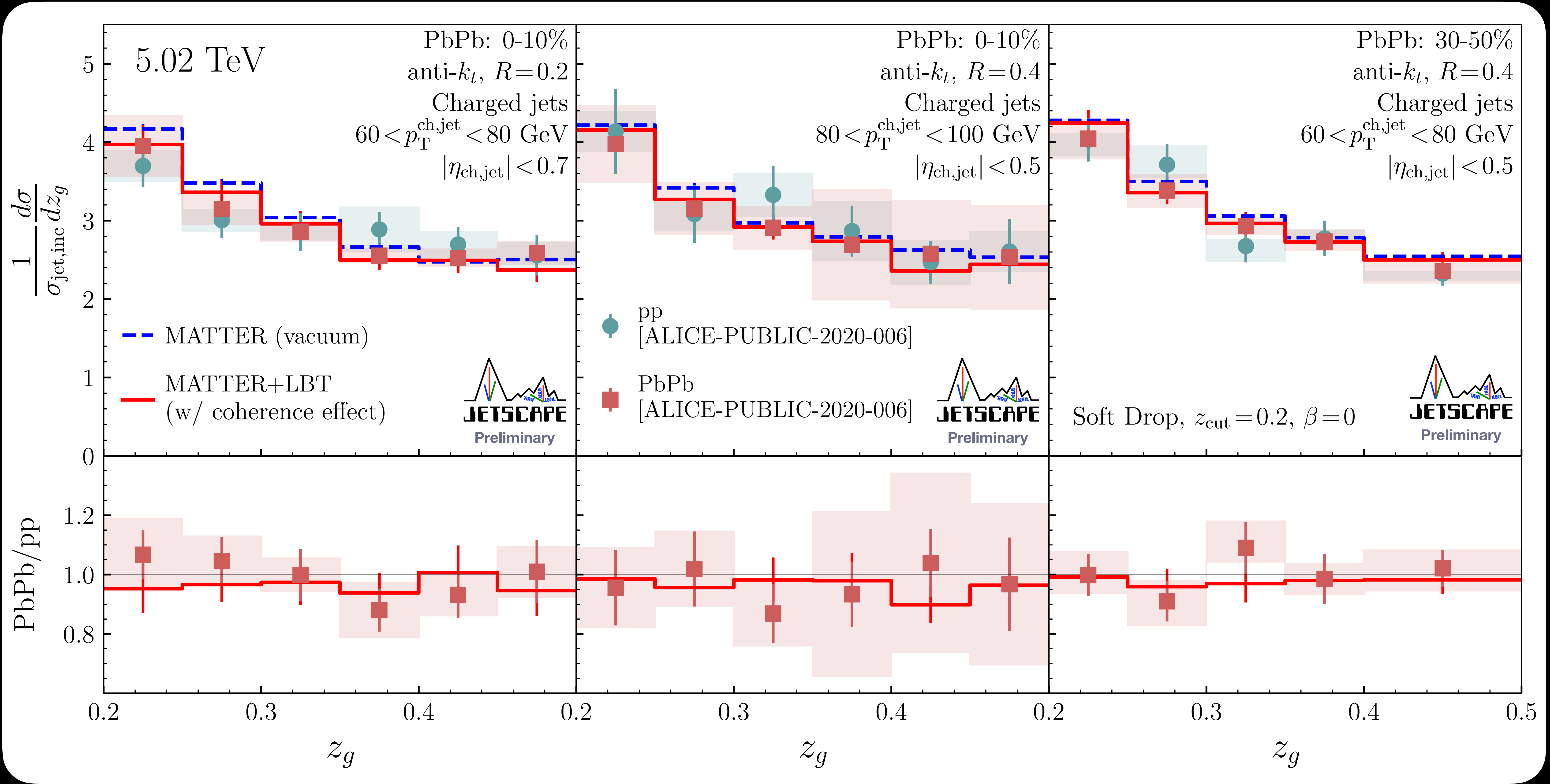


- The jet fragmentation function is sensitive to medium effects in the high virtuality phase — probing the coherence effects

JET SUBSTRUCTURES

Jet splitting function $z_g = \frac{\min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}}$





- Consistent with almost no medium modifications in the hardest splittings as in data

SYSTEMATIC CONSTRAINTS ON JET TRANSPORT

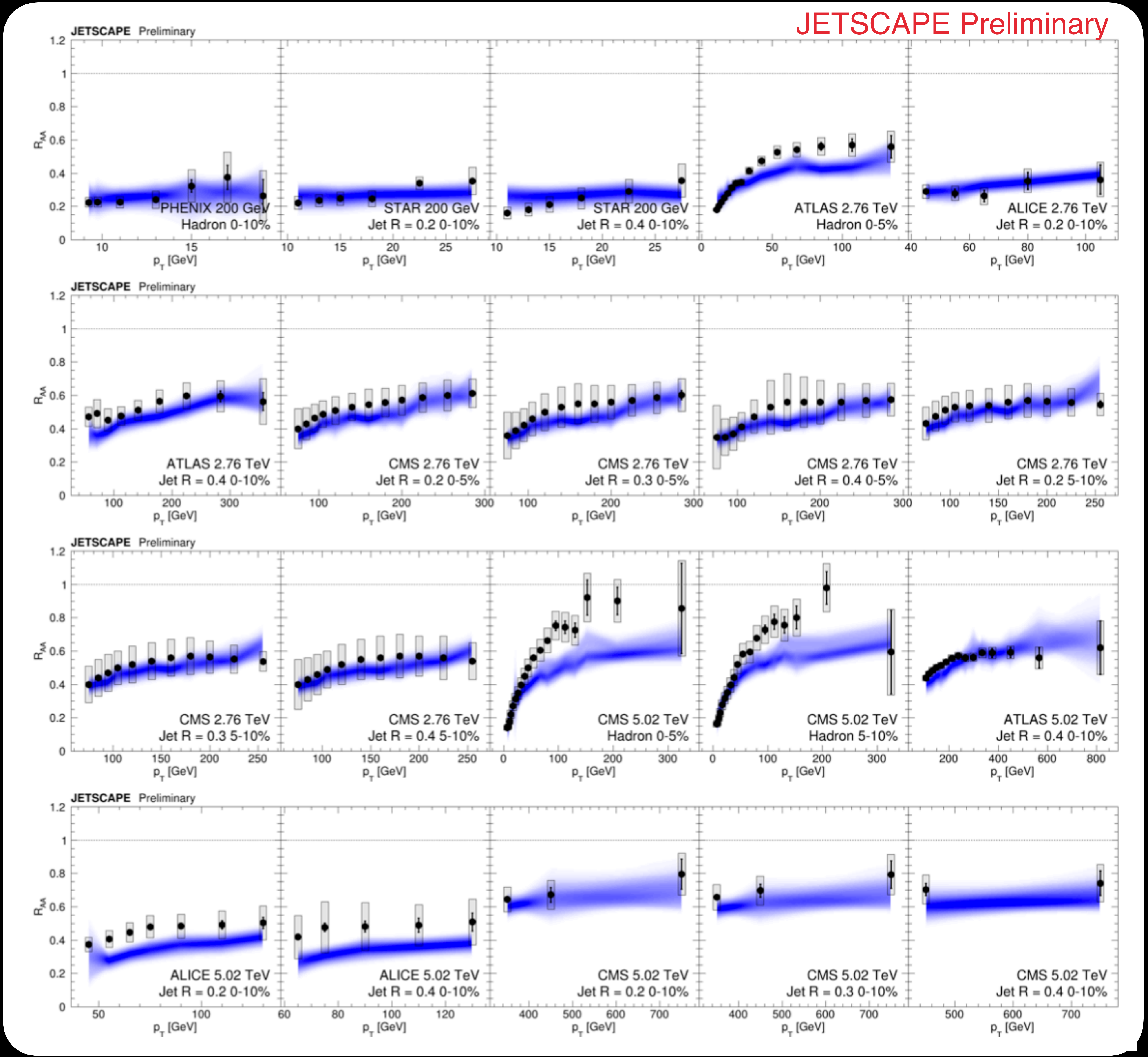
- Going beyond the first JETSCAPE Bayesian analysis of the jet transport:
  - more observables (jet R_{AA}) are included in the calibration
  - coherence effects in MATTER are parameterized
- Effective jet quenching strength:

$$\hat{q}_{\mathrm{HTL}} \cdot f(Q^2)$$

motivated by Kumar, Majumder, Shen, PRC101, 034908 (2020)

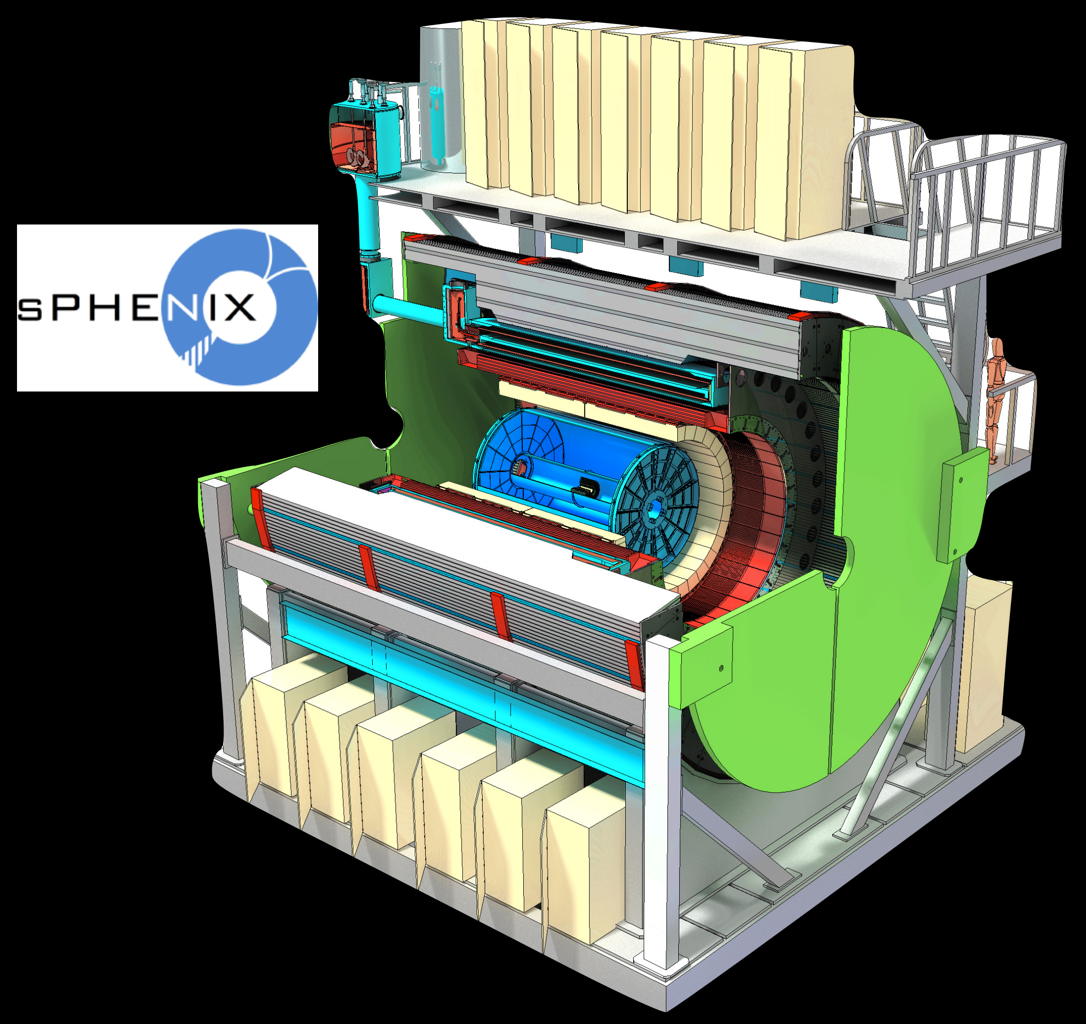
$$f(Q^2) = \frac{N \exp(c_3(1 - x_B))}{1 + c_1 \ln(Q^2/\Lambda^2_{\mathrm{QCD}}) + c_2 \ln^2(Q^2/\Lambda^2_{\mathrm{QCD}})}$$

$$f(Q^2) = 1 \text{ when } Q \leq \Lambda_{\mathrm{QCD}}$$

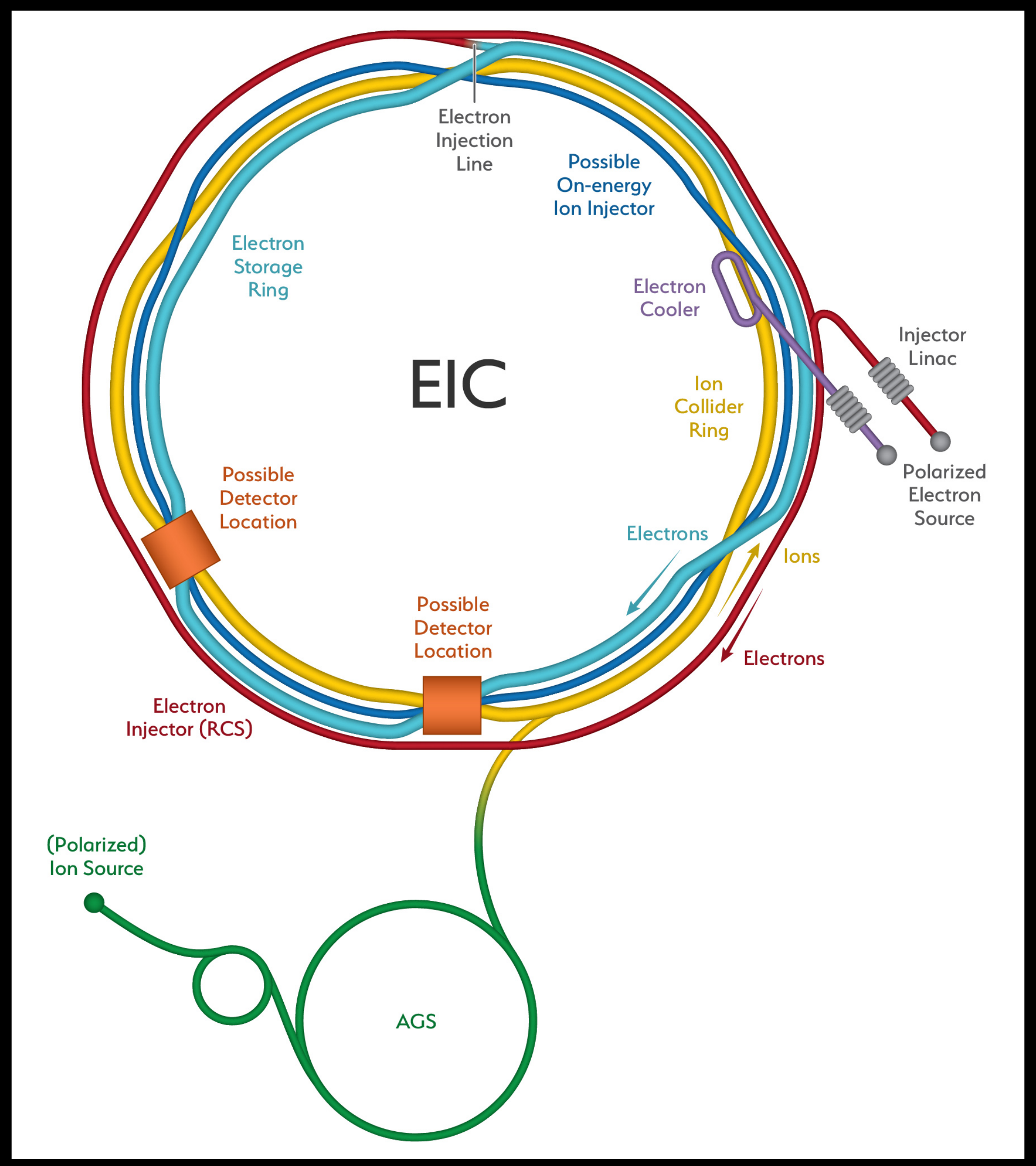


THE ERA OF MULTI-MESSENGER HEAVY-ION PHYSICS

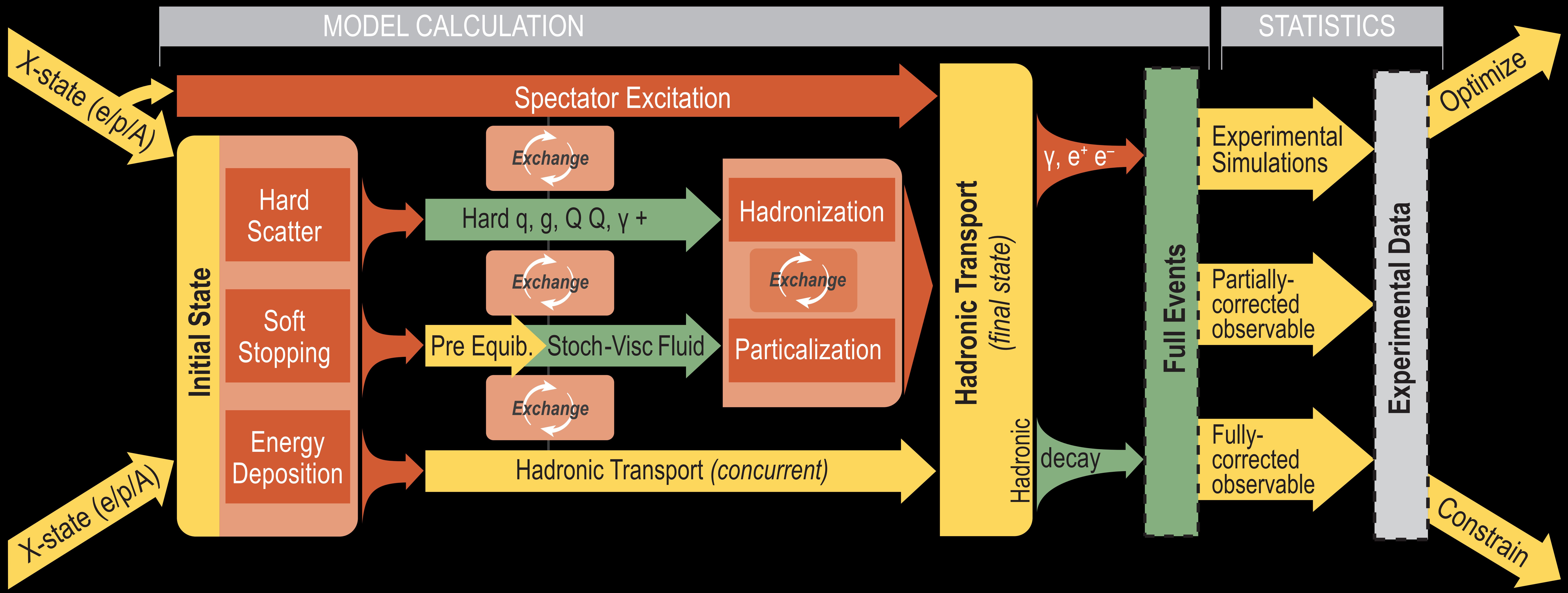
- RHIC: STAR upgrade and sPHENIX program
  - Probing QCD at high net baryon density
  - Study fully resolved jets, Upsilon states, and heavy quarks as QGP structure probes



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



THE XSCAPE PROJECT (2020 - 2024)



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

SUMMARY

- Multi-messenger heavy-ion physics has entered a precision era

    Bayesian Inference is essential to fully exploit the multi-messenger data

- The JETSCAPE framework is a unified theoretical tool to study both the soft and hard observables in a same setting

    Unravel how strongly-coupled nature of QGP is emerged at different length scales

    Interplay between collective dynamics and high energy parton shower

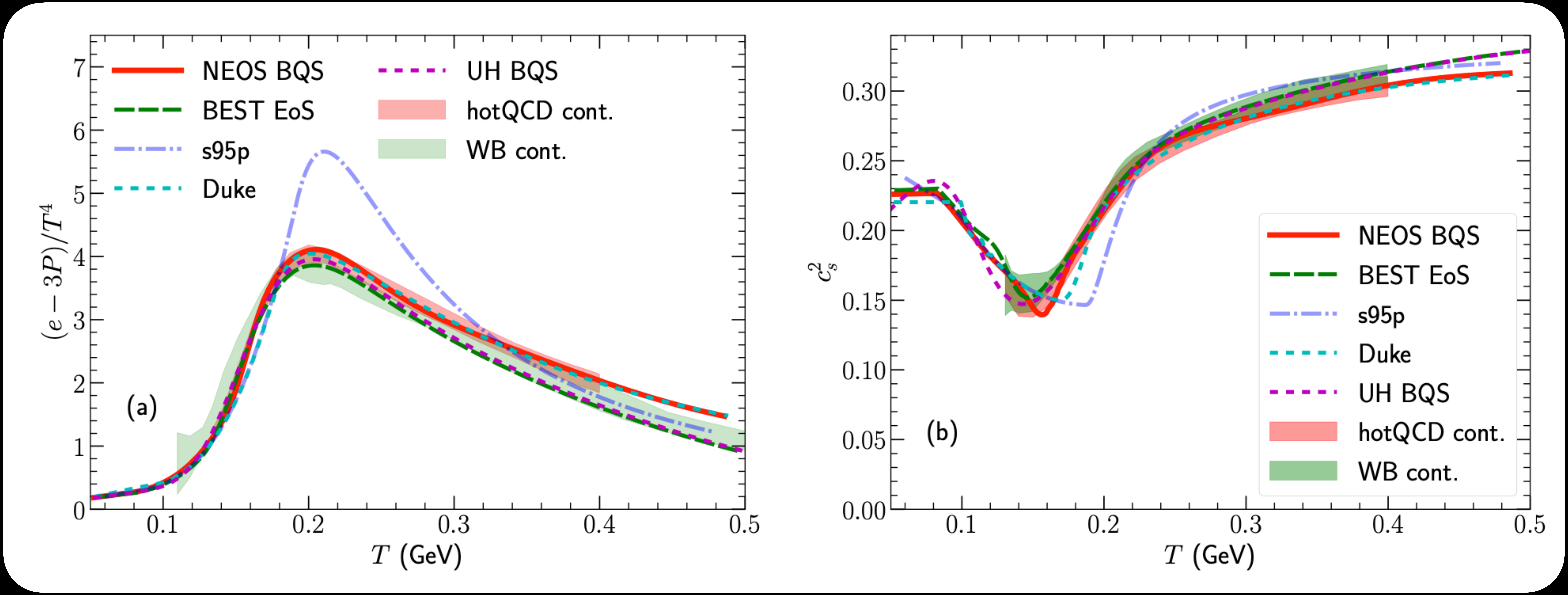
- Current JETSCAPE extensions to small systems and baryon-rich QGP with the upcoming experiments would bring a golden age to quantitatively study hot and dense QCD matter

THE JETSCAPE COLLABORATION


BACKUP

QCD EQUATION OF STATE

A. Monnai, B. Schenke and C. Shen, Int. J. Mod. Phys. A36, 2130007 (2021)



- QCD equation of state are constrained by Lattice QCD calculations