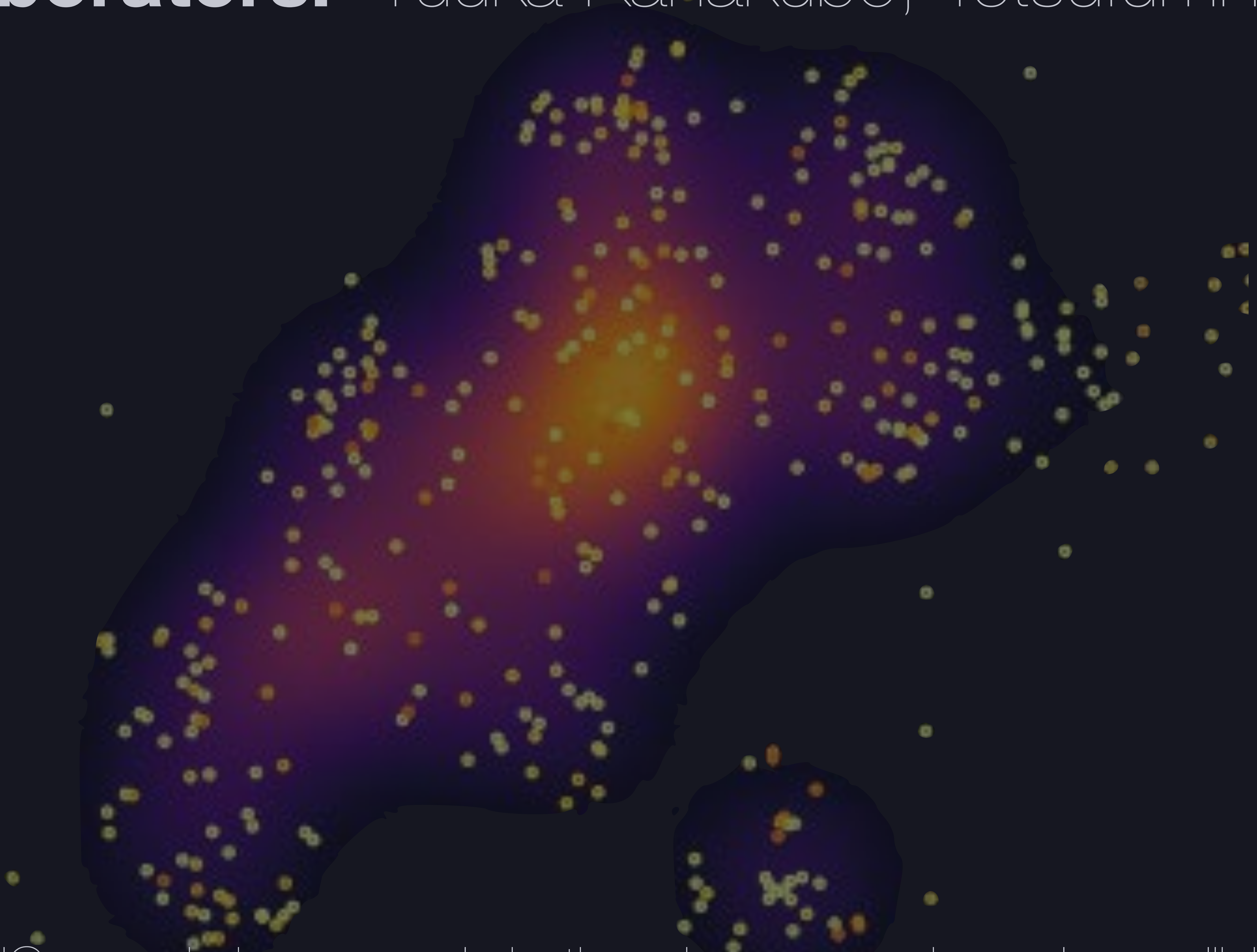
Dynamical core-corona initialization model

for high-energy nuclear collisions

Yasuki Tachibana

Collaborators: Yuuka Kanakubo, Tetsufumi Hirano

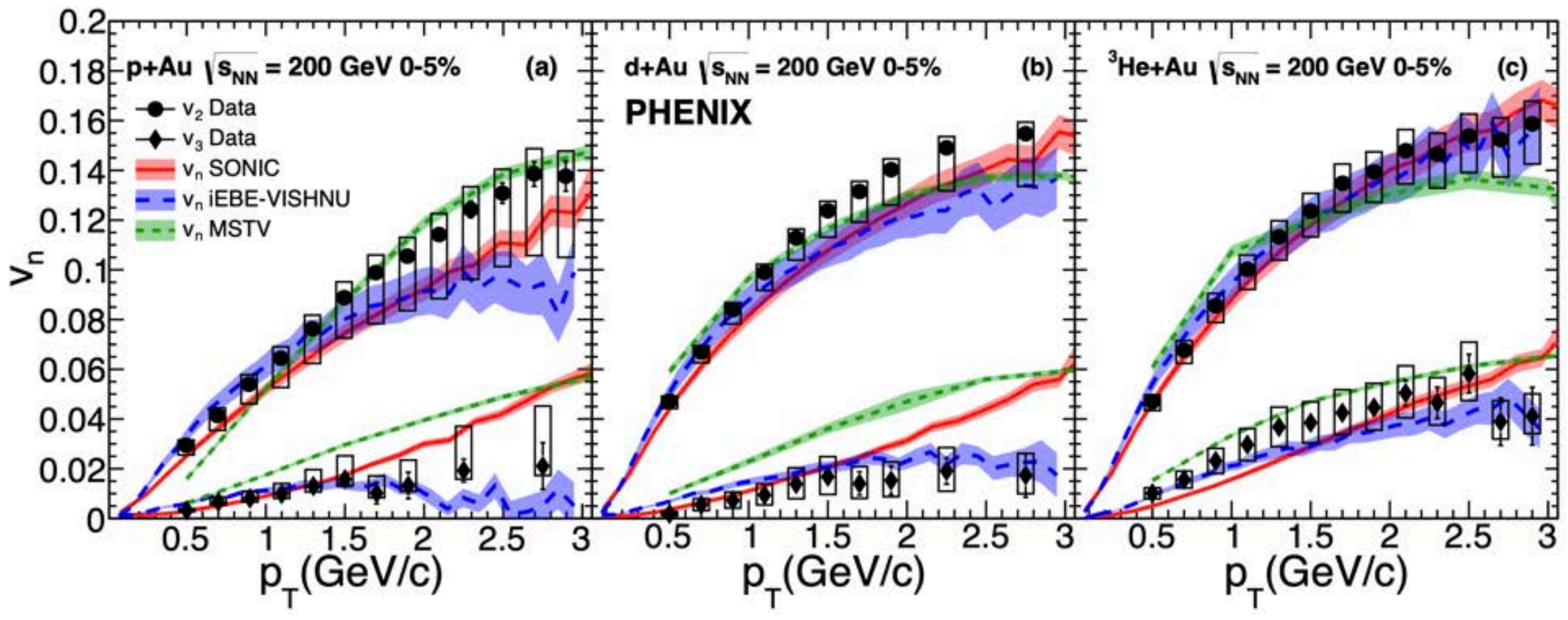


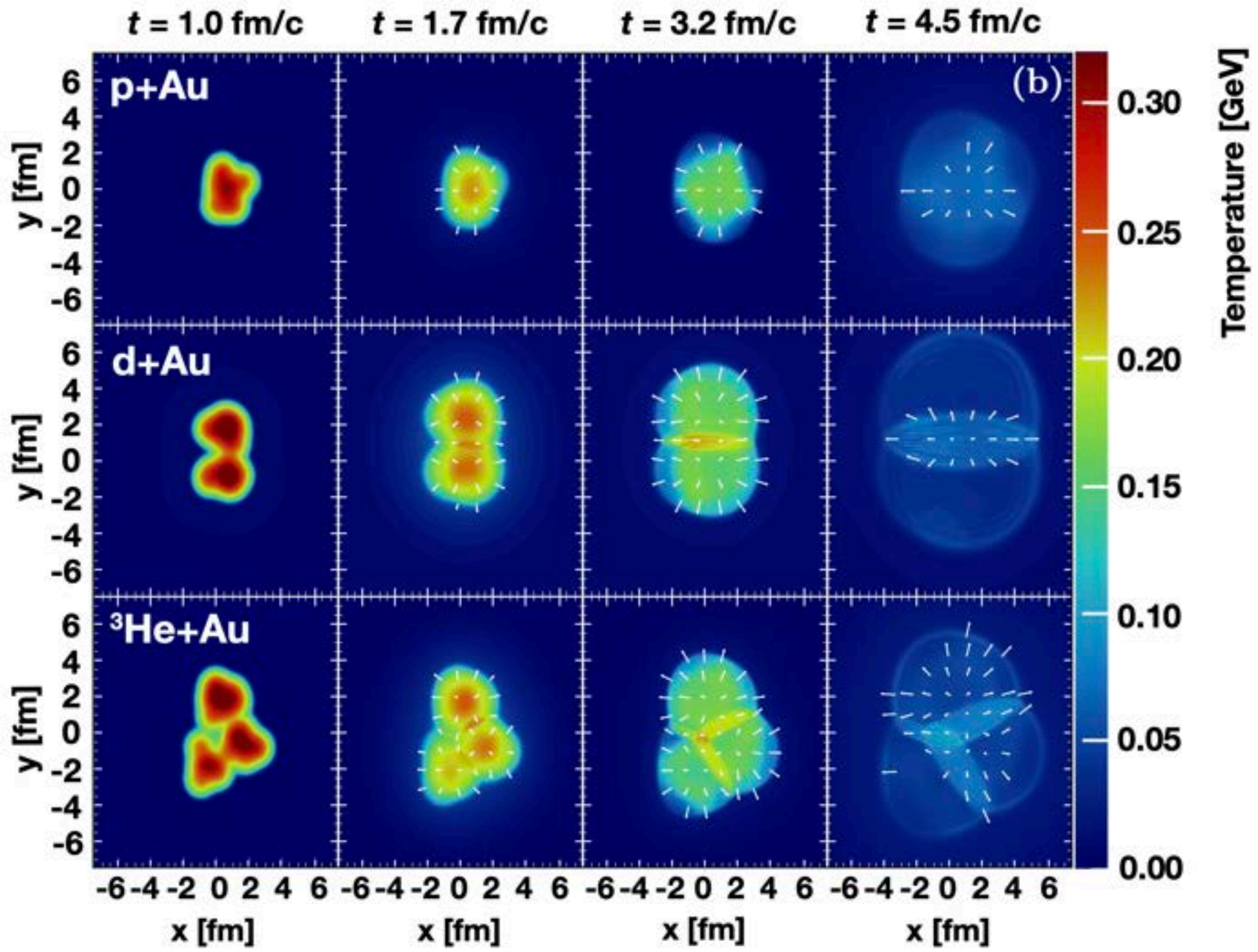
ExHIC-p workshop on polarization phenomena in nuclear collisions
Institute of Physics, Academia Sinica, Taipei, March 15th, 2024

Introduction

QGP fluid signal even in small systems

- **Collectivity seen in high multiplicity small systems**
  - Hydrodynamic response to initial collision geometry (v_n)

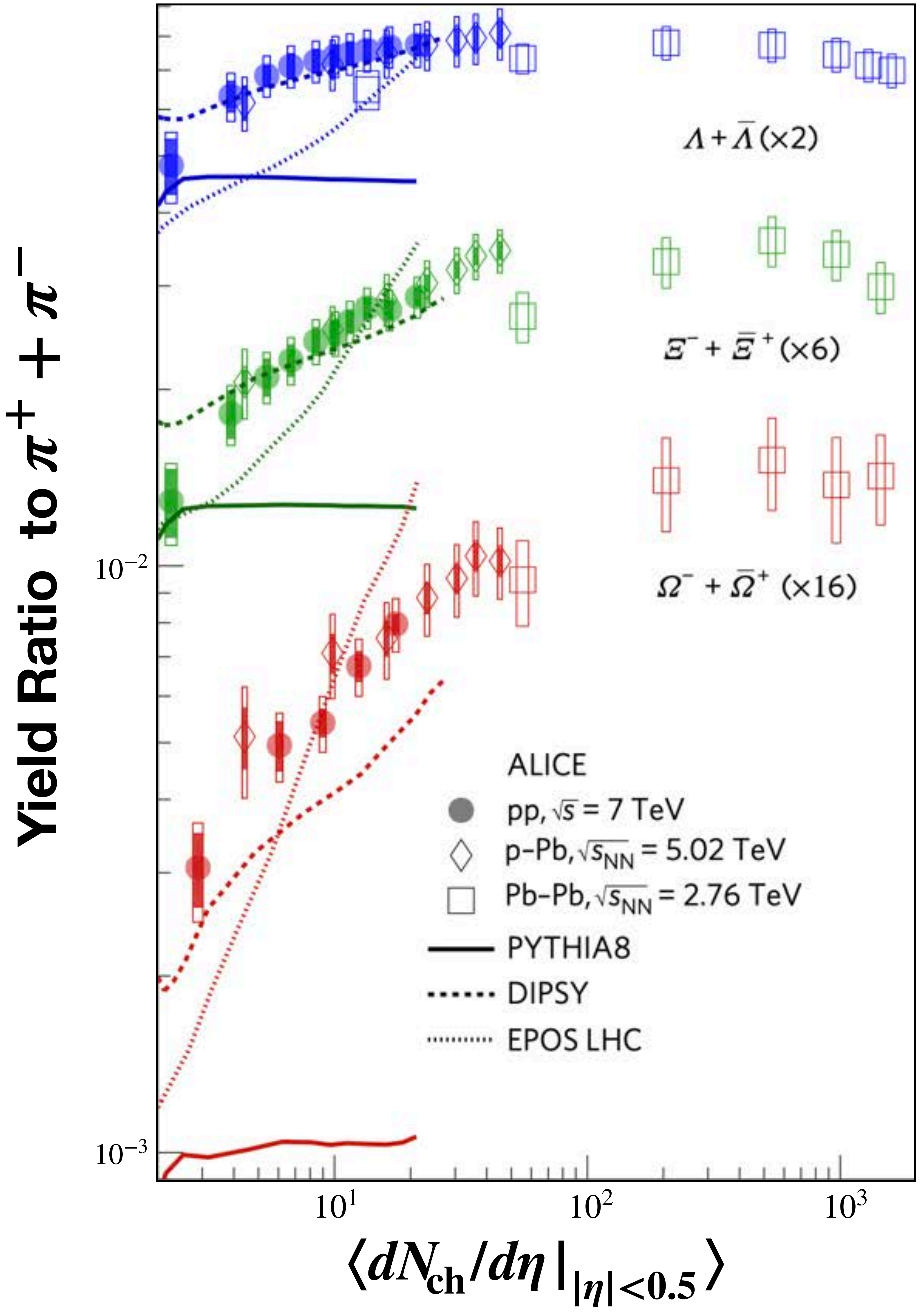




PHENIX, Nat. Phys. 15, 214–220 (2019)

Hadron production from small to large systems

ALICE, Nature Phys. 13, 535-539 (2017)



- **Strange baryon production ratio**
  - Smooth increase scaled to multiplicity
  - No system size dependence
  - No collision energy dependence

Hadron production from small to large systems

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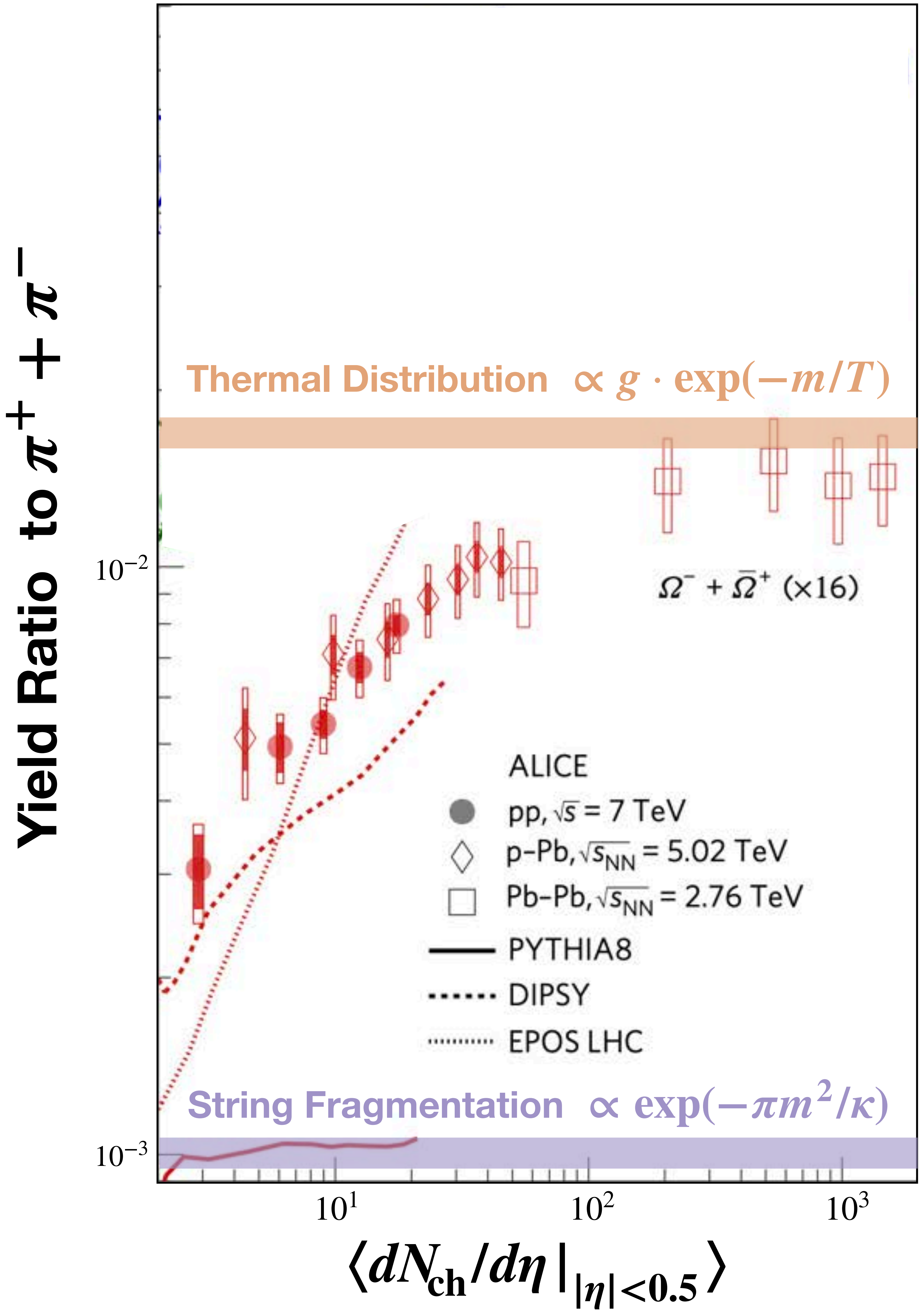

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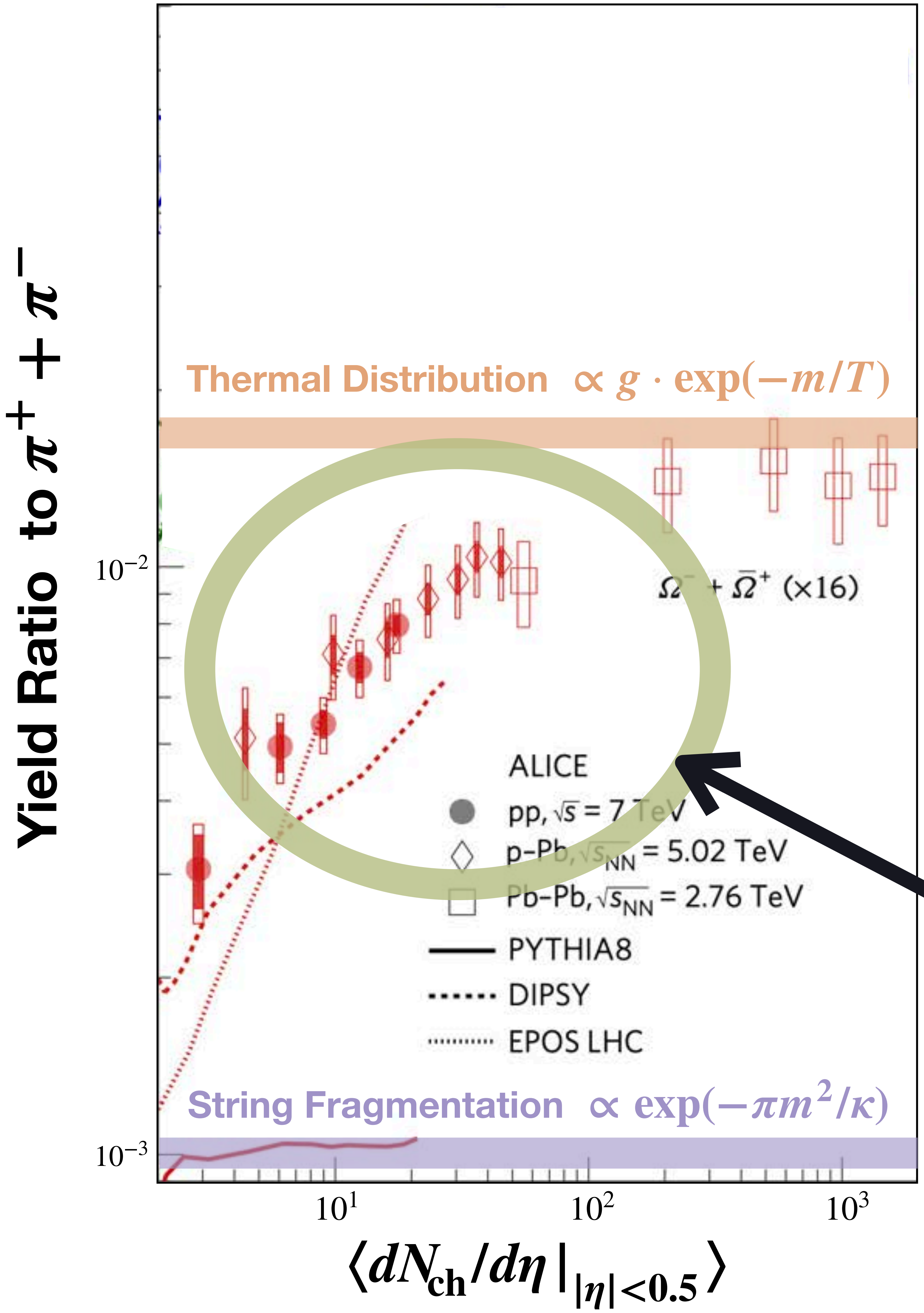
Transition from vacuum to thermal

Hadron production from small to large systems

ALICE, Nature Phys. 13, 535-539 (2017)



- **Strange baryon production ratio**
  - Smooth increase scaled to multiplicity
  - No system size dependence
  - No collision energy dependence

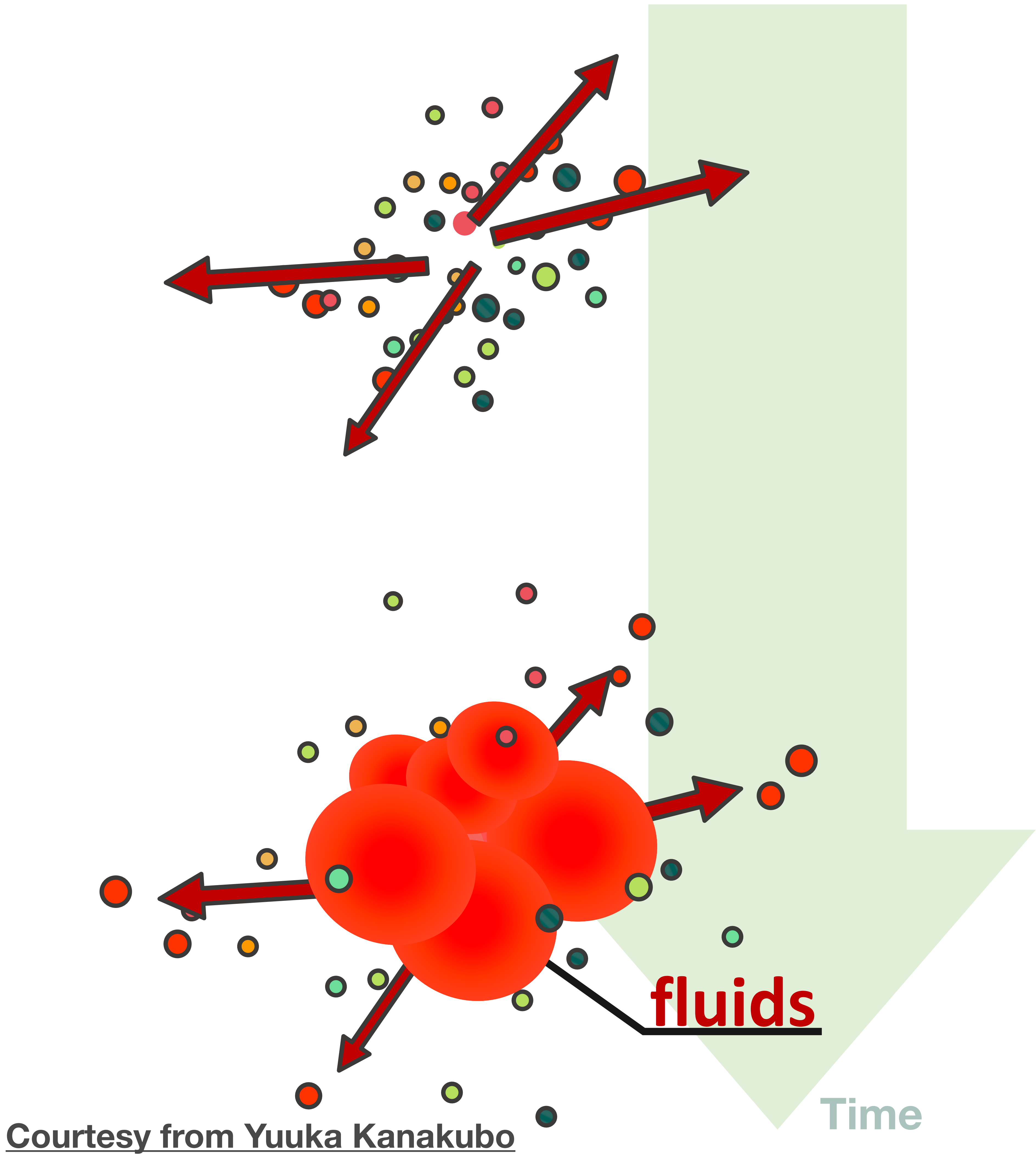
Transition from vacuum to thermal

Partial thermalization?

Dynamical core-corona initialization

Dynamical initialization framework

M. Okai, et al., PRC 95, 054914 (2017), C. Shen, B. Schenke, PRC 97, 024907 (2018), Y. Akamatsu, et al., PRC98, 024909 (2018)



- **Dynamical initialization via source terms**
  - Initial parton creation via an MC event generator
  - Fluid formation by hydrodynamic eq. with source term

$$\nabla_\mu T^{\mu\nu}_{\mathrm{fluid}}(x) = J^\nu(x)$$

with initial condition $T^{\mu\nu}_{\mathrm{fluid}}(t=0,\vec{x}) = 0$

  - Source term J^ν accounting for the thermalized energy-momentum of initial partons
  - Energy-momentum conservation in the whole system (No overall normalization factor)
  - Natural introduction of initial velocity distribution → Source of vorticity locally distributed in QGP fluid?

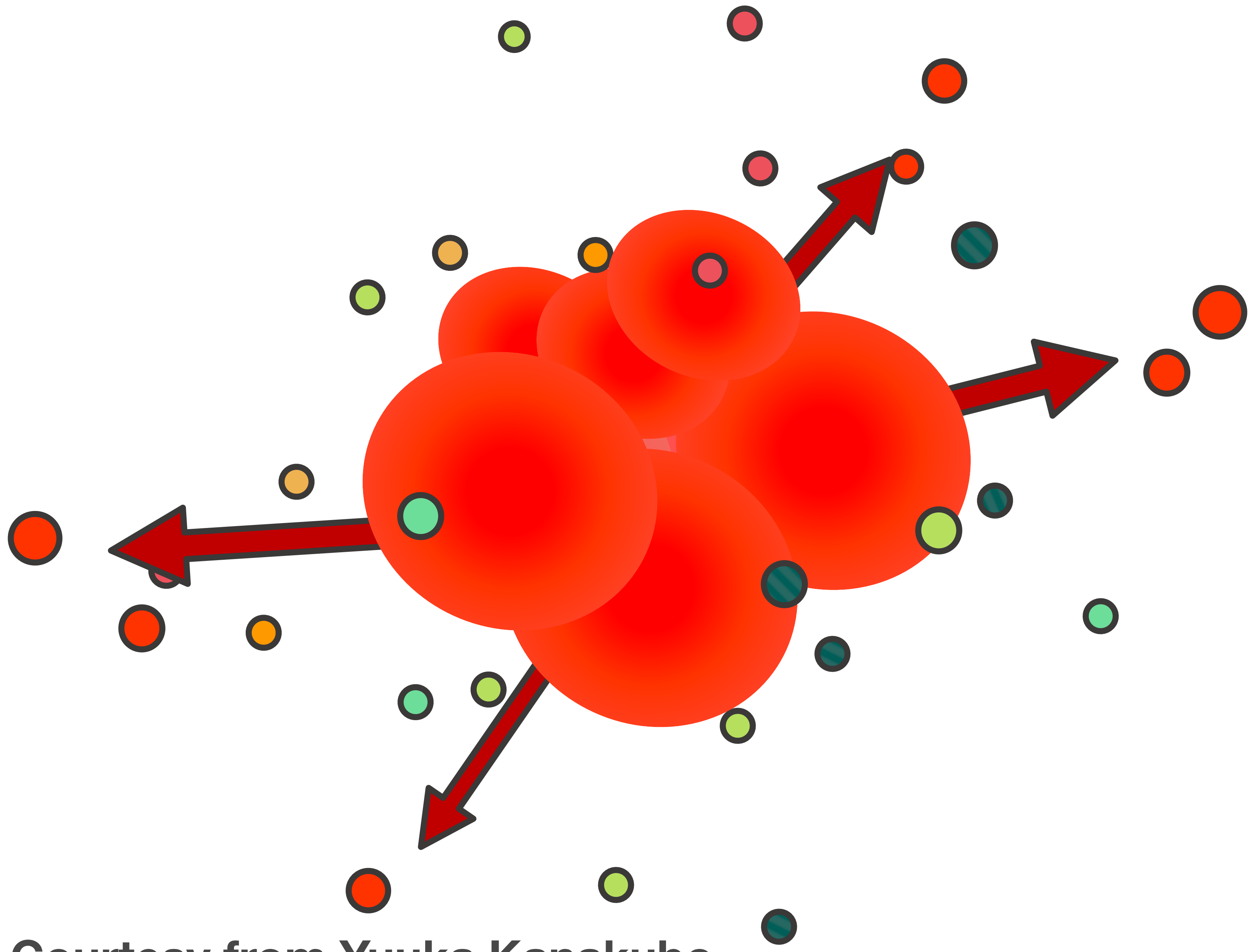
Dynamical core-corona initialization (DCCI)

Y. Kanakubo, *et al.*, PTEP 2018, no.12, 121D01 (2018), PRC 101, no.2, 024912 (2020), PRC 105, no.2, 024905 (2022)

- **Source term from interaction rates among partons**

$$J^{\nu}(x) = \sum_{i \in \text{non-eq. partons}} \left[-\frac{dp_i^{\nu}}{dt} \right] \rho\left(\vec{x} - \vec{x}_i(t)\right), \quad \frac{dp_i^{\nu}}{dt} = \sum_{\substack{j \in \text{partons} \\ j \neq i}} \sigma_{ij} \,|\vec{v}_{ij}^{\,\text{rel}}|\, p_i^{\nu} \rho\left(\vec{x}_j(t) - \vec{x}_i(t)\right),$$

ρ: Gaussian profile



Courtesy from Yuuka Kanakubo

- Smooth separation of components

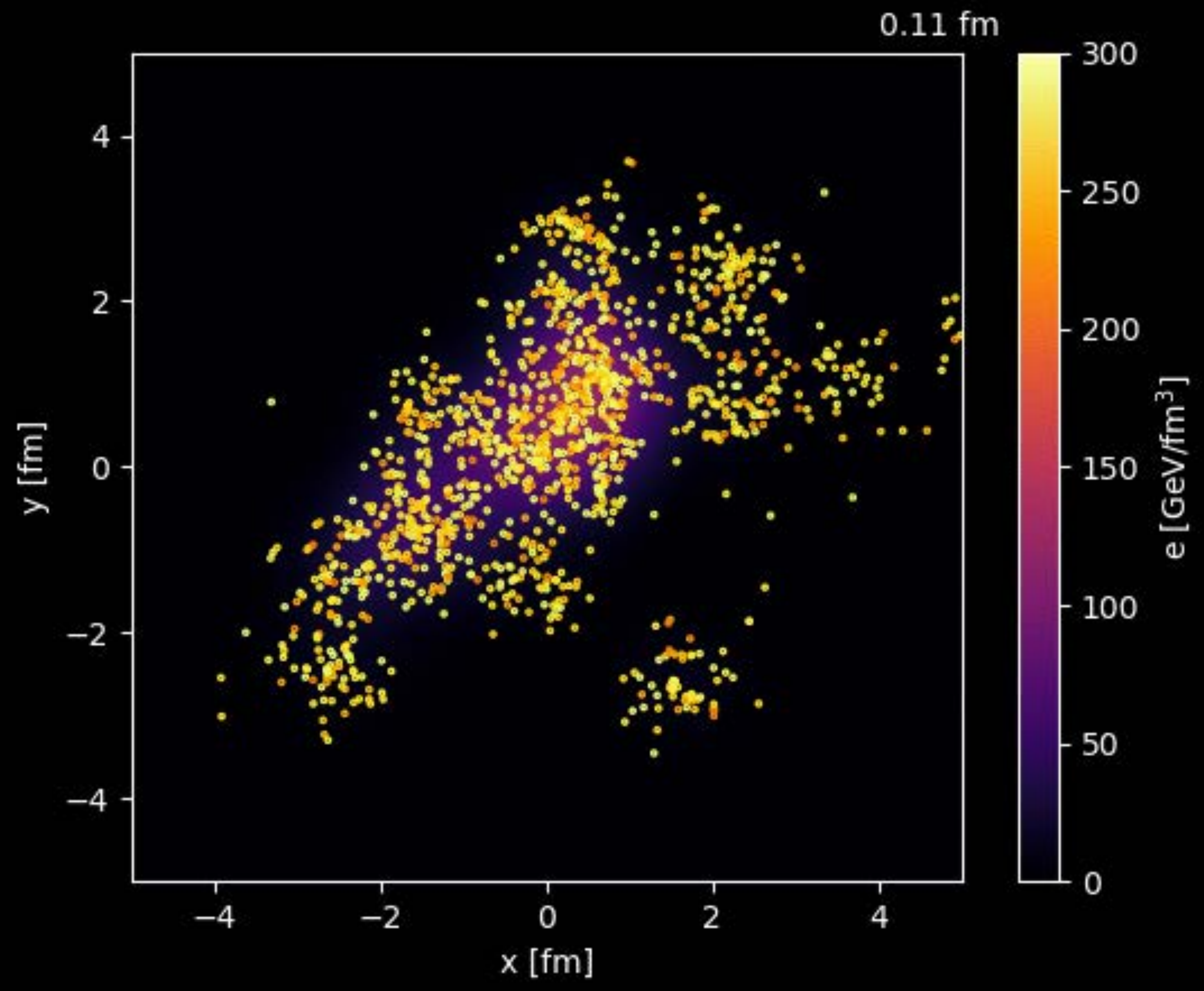
Dense/low-p_T → Core (fluid)

Dilute/high-p_T → Corona (non-eq. partons)

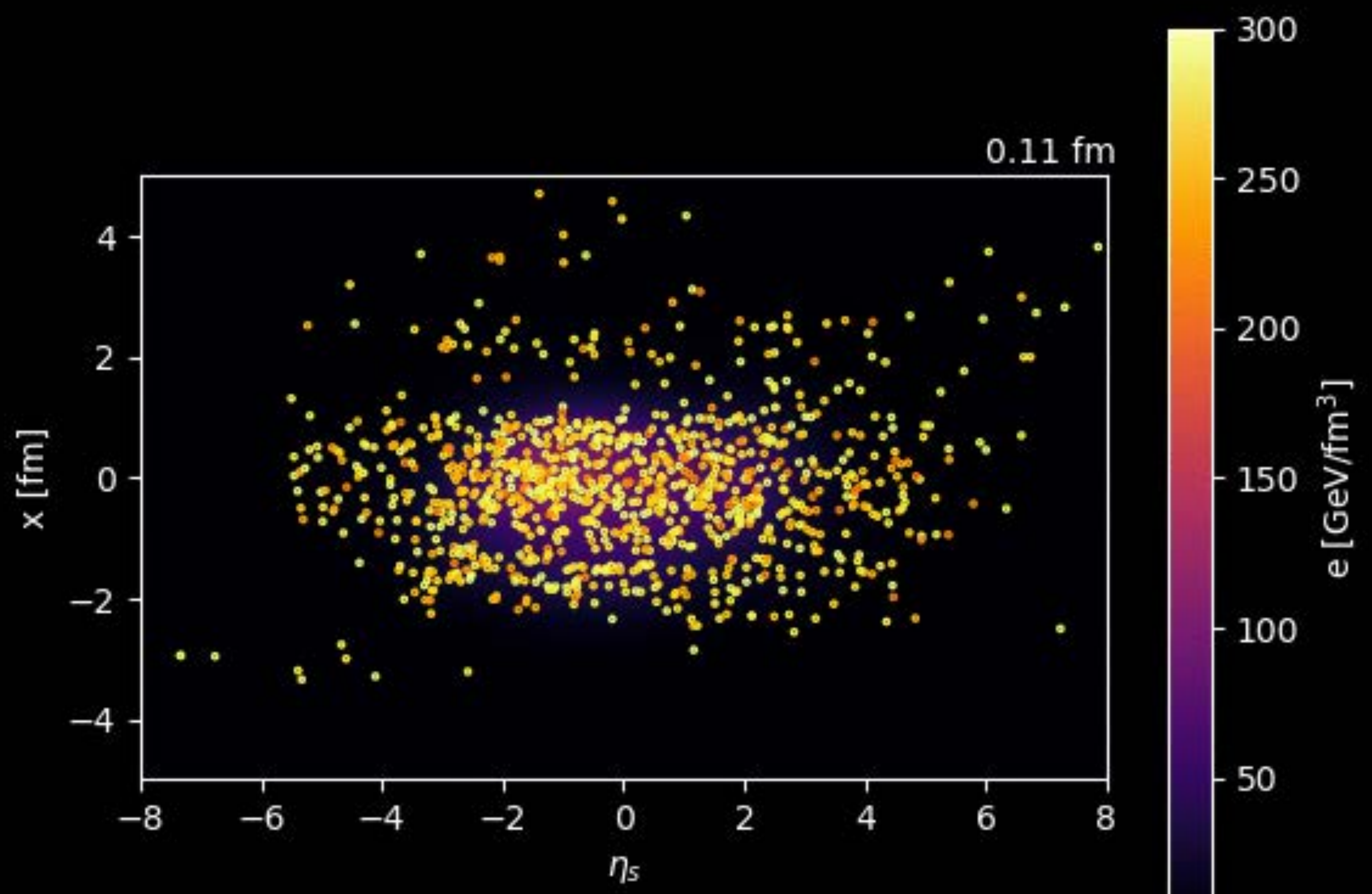
Dynamical core-corona initialization (DCCI)

PbPb, $\sqrt{s_{NN}} = 2.76$ TeV

Transverse ($|\eta_s| < 0.5$)



Longitudinal ($|y| < 0.5$)



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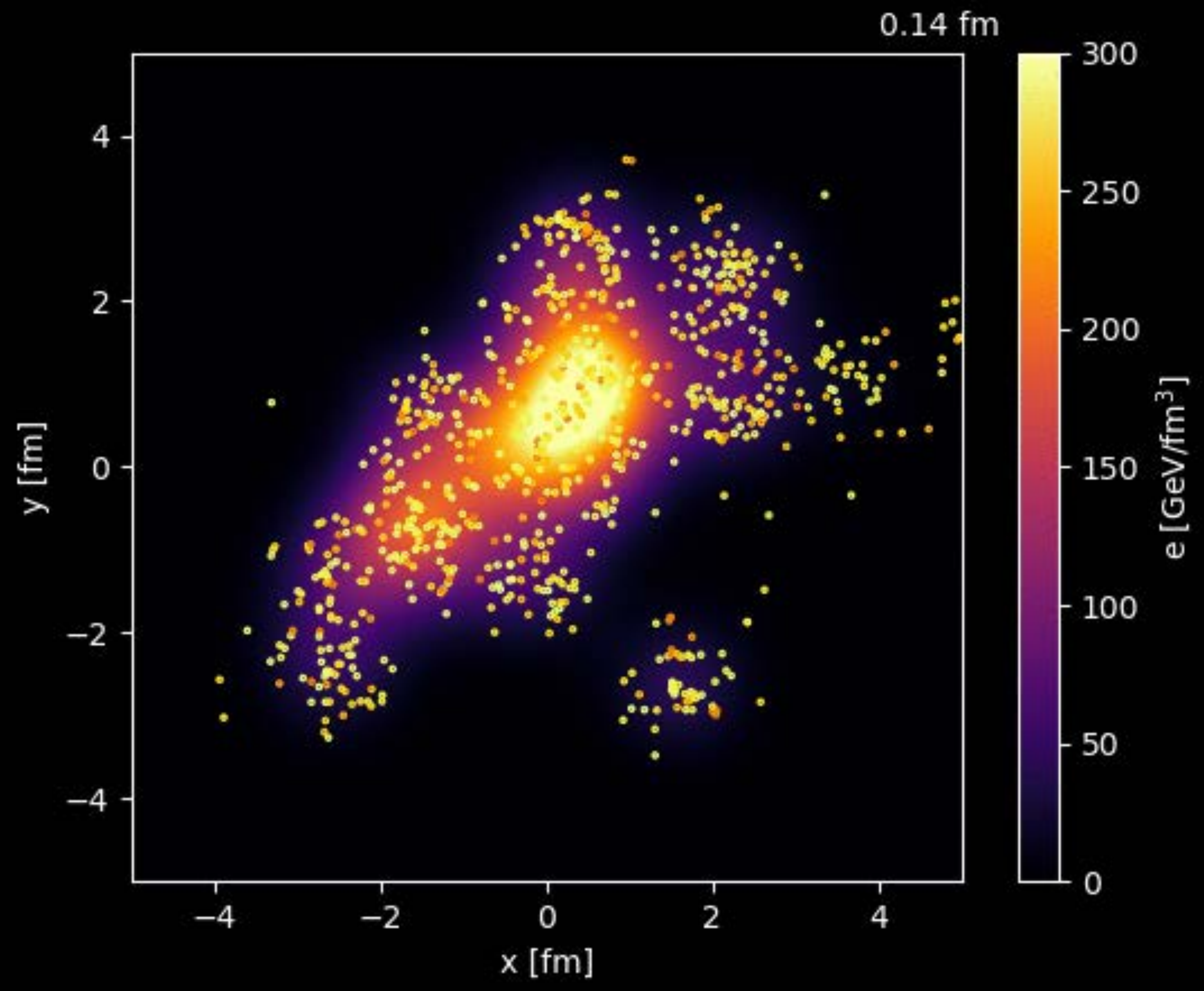

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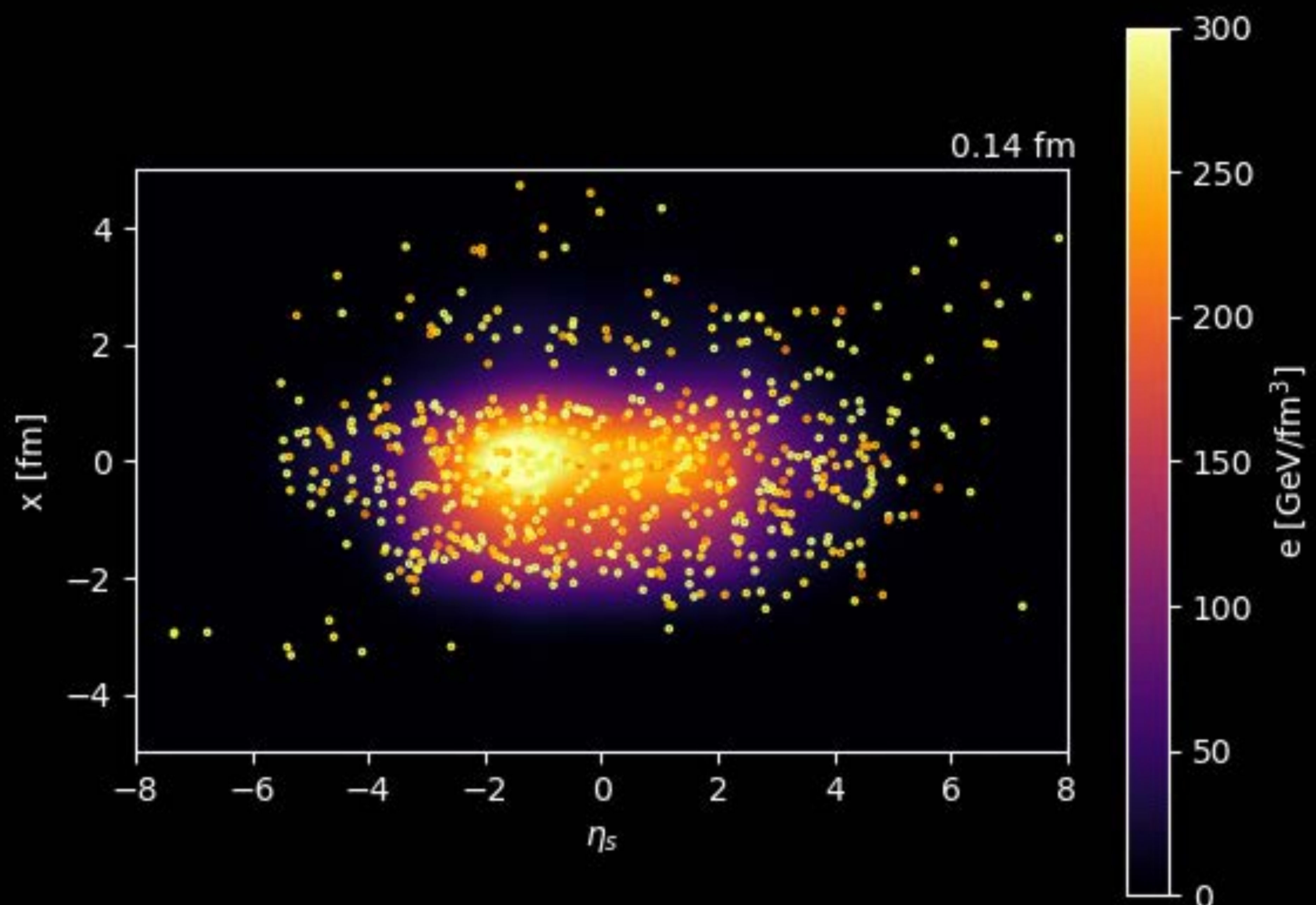

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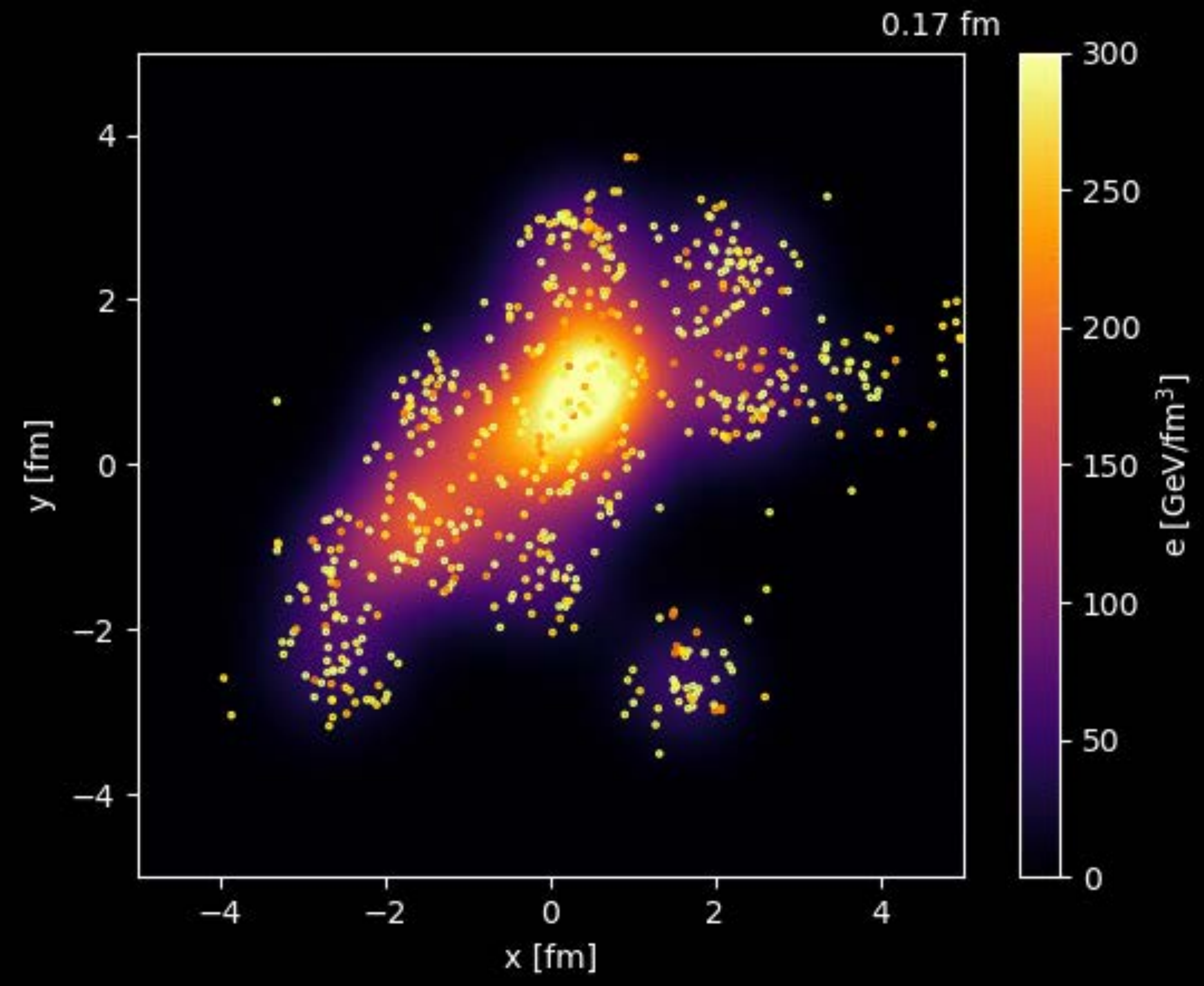

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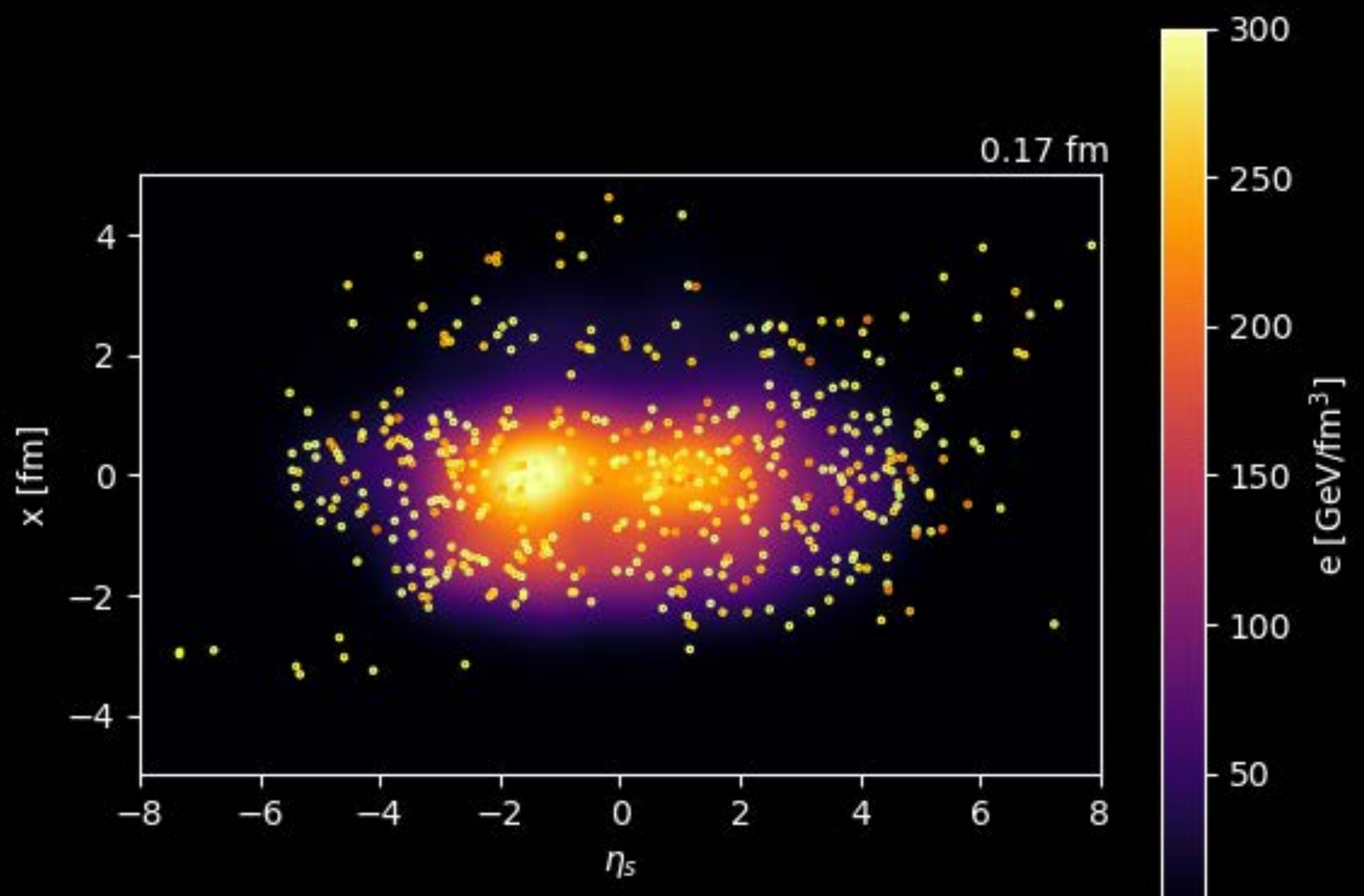

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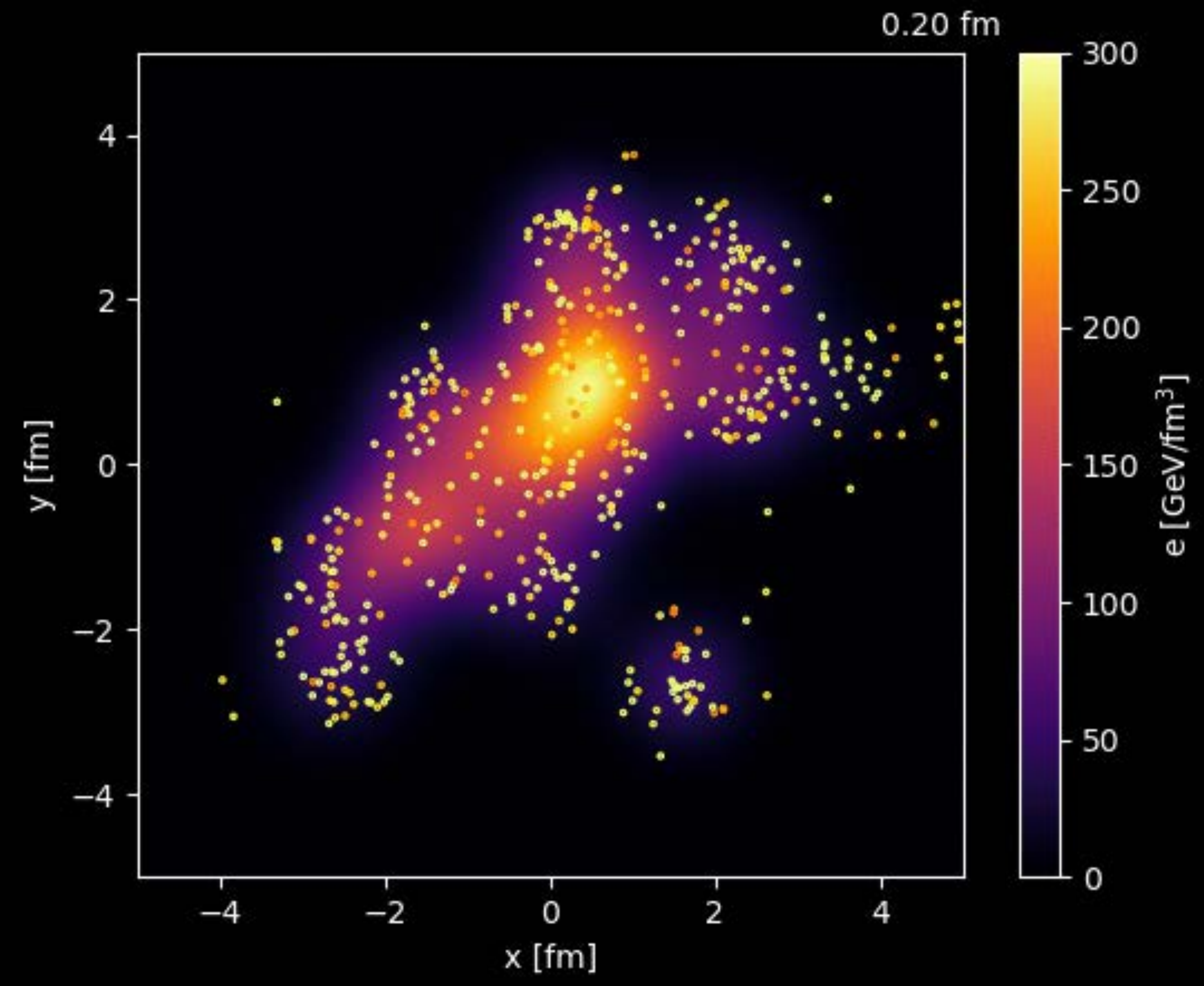

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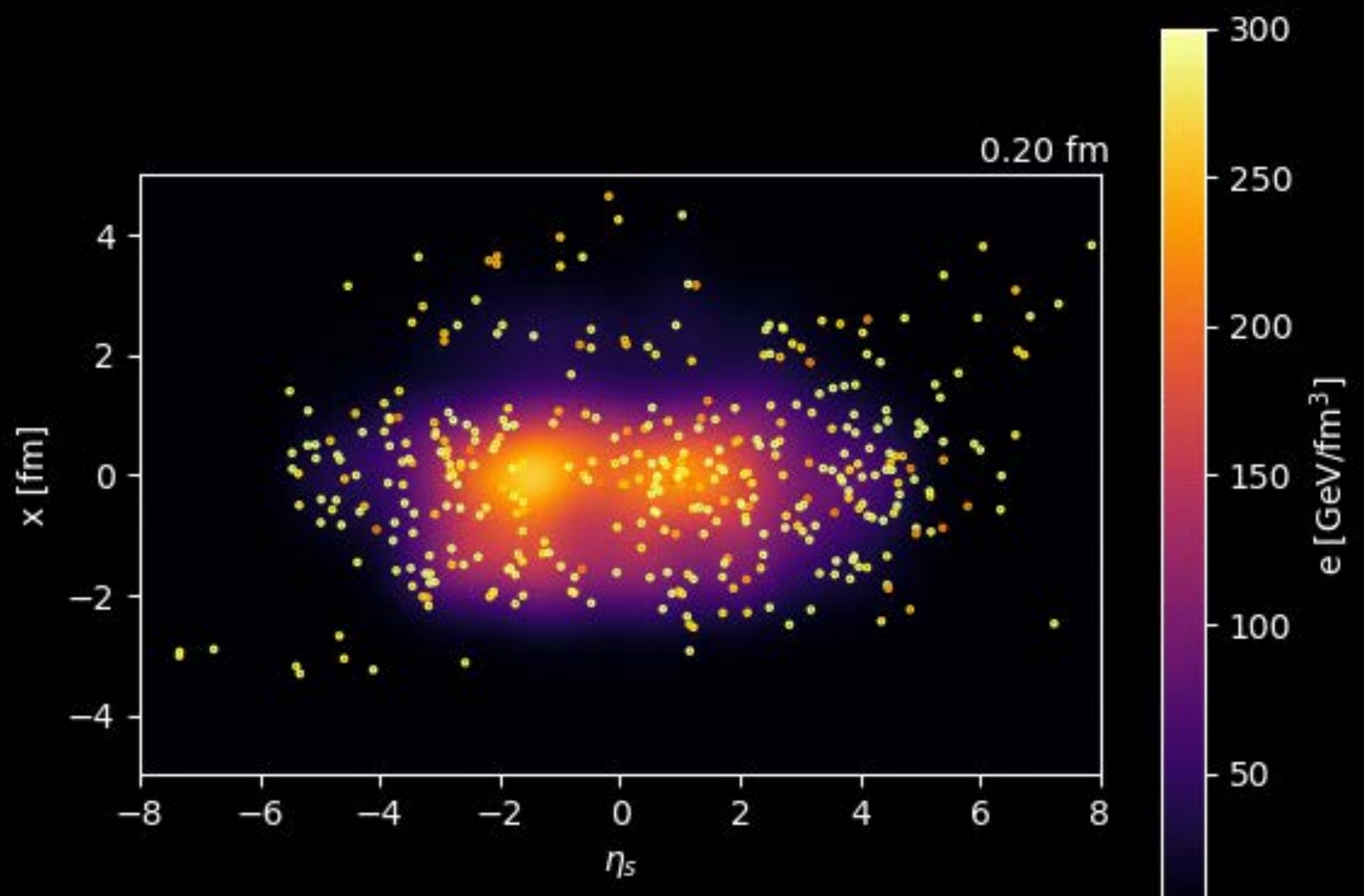

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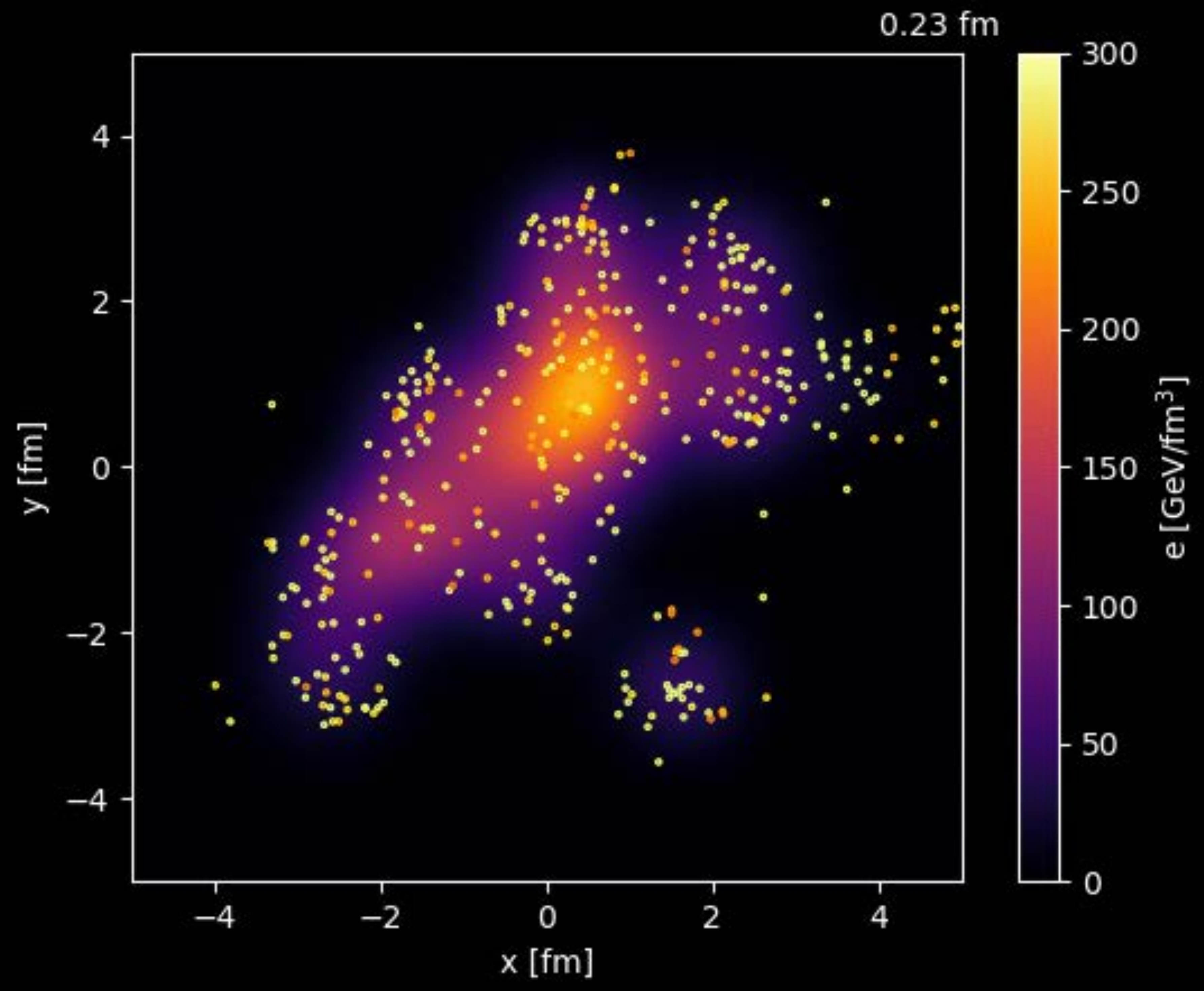

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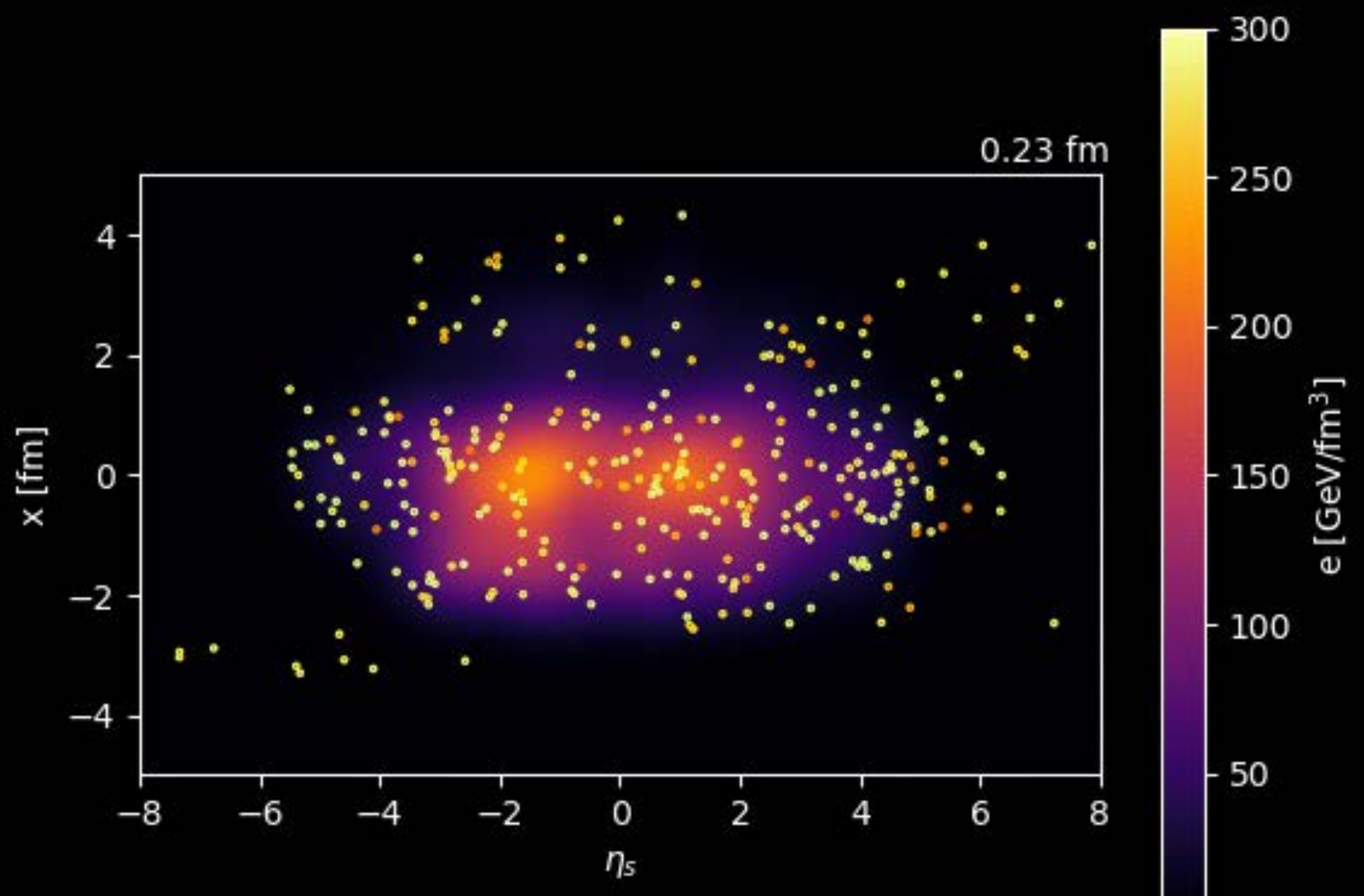

Courtesy from Yuuka Kanakubo

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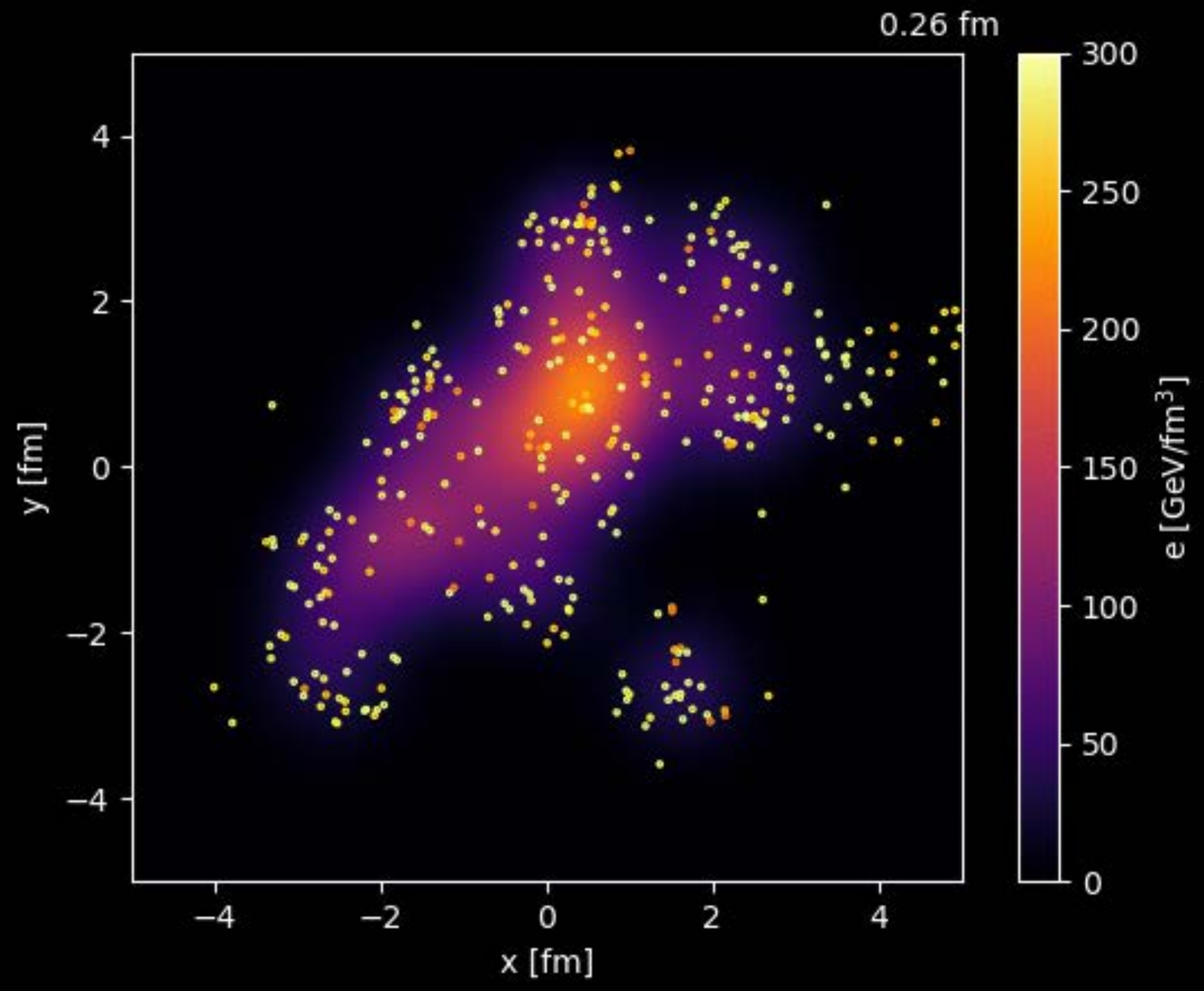

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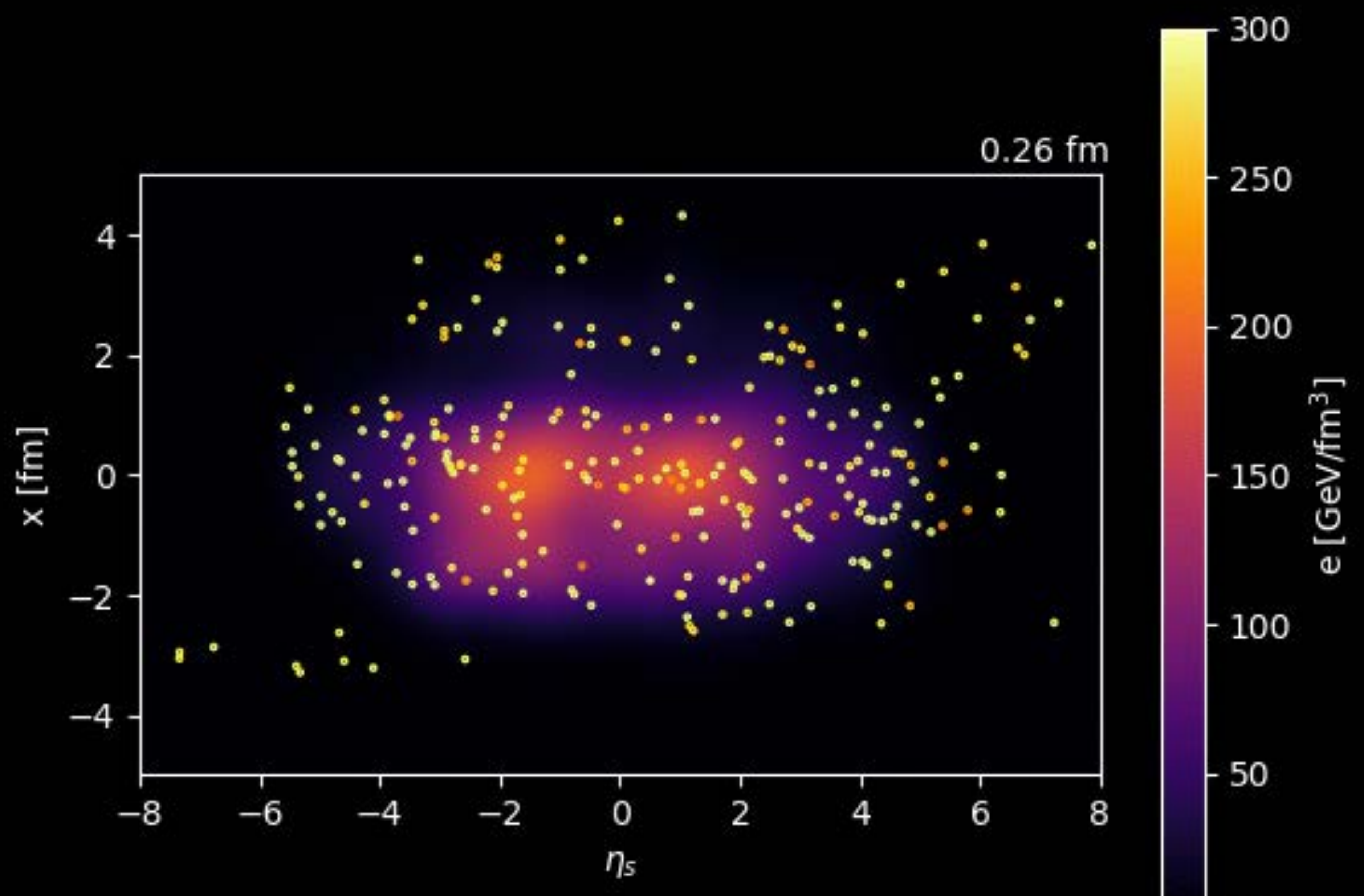

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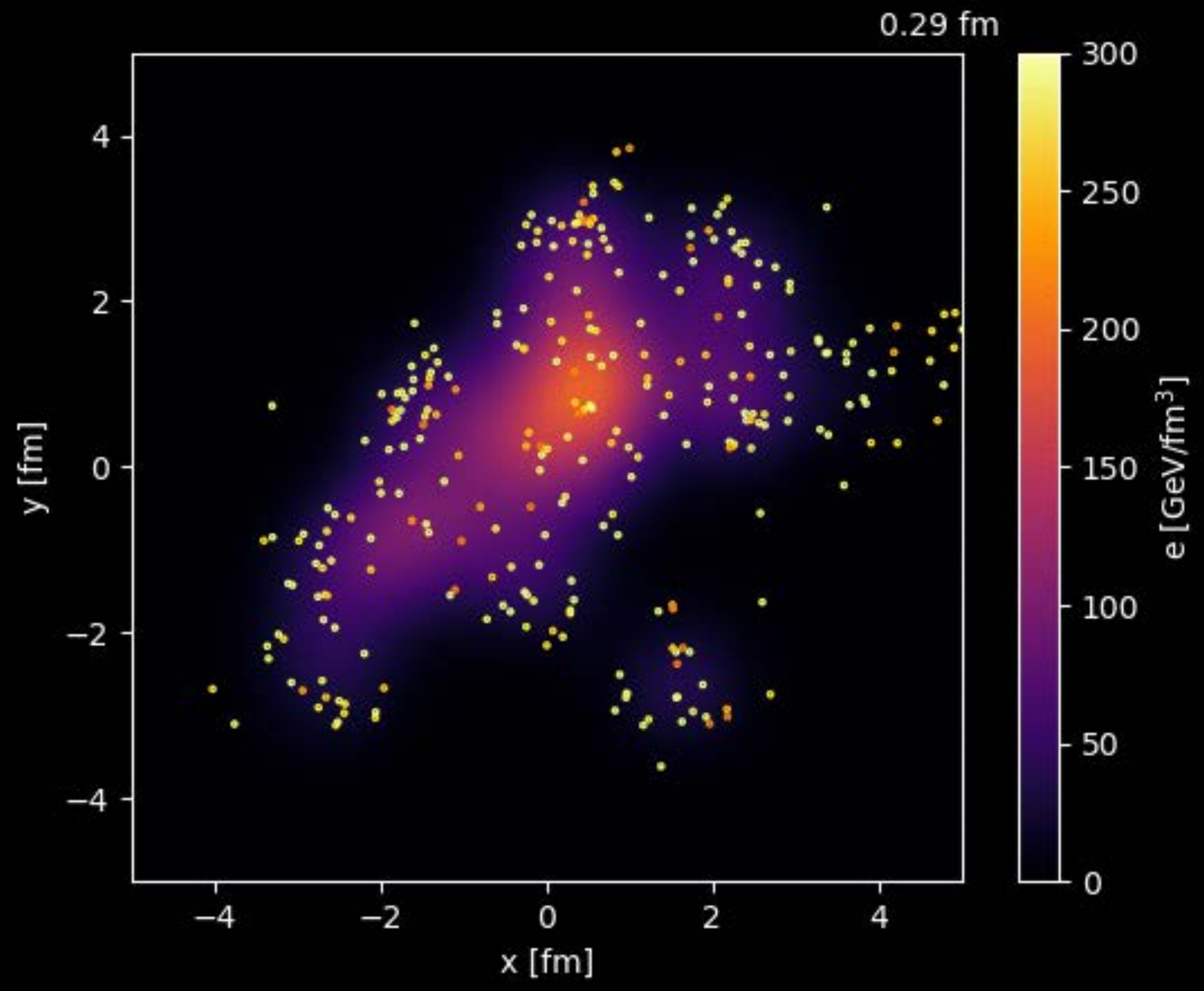

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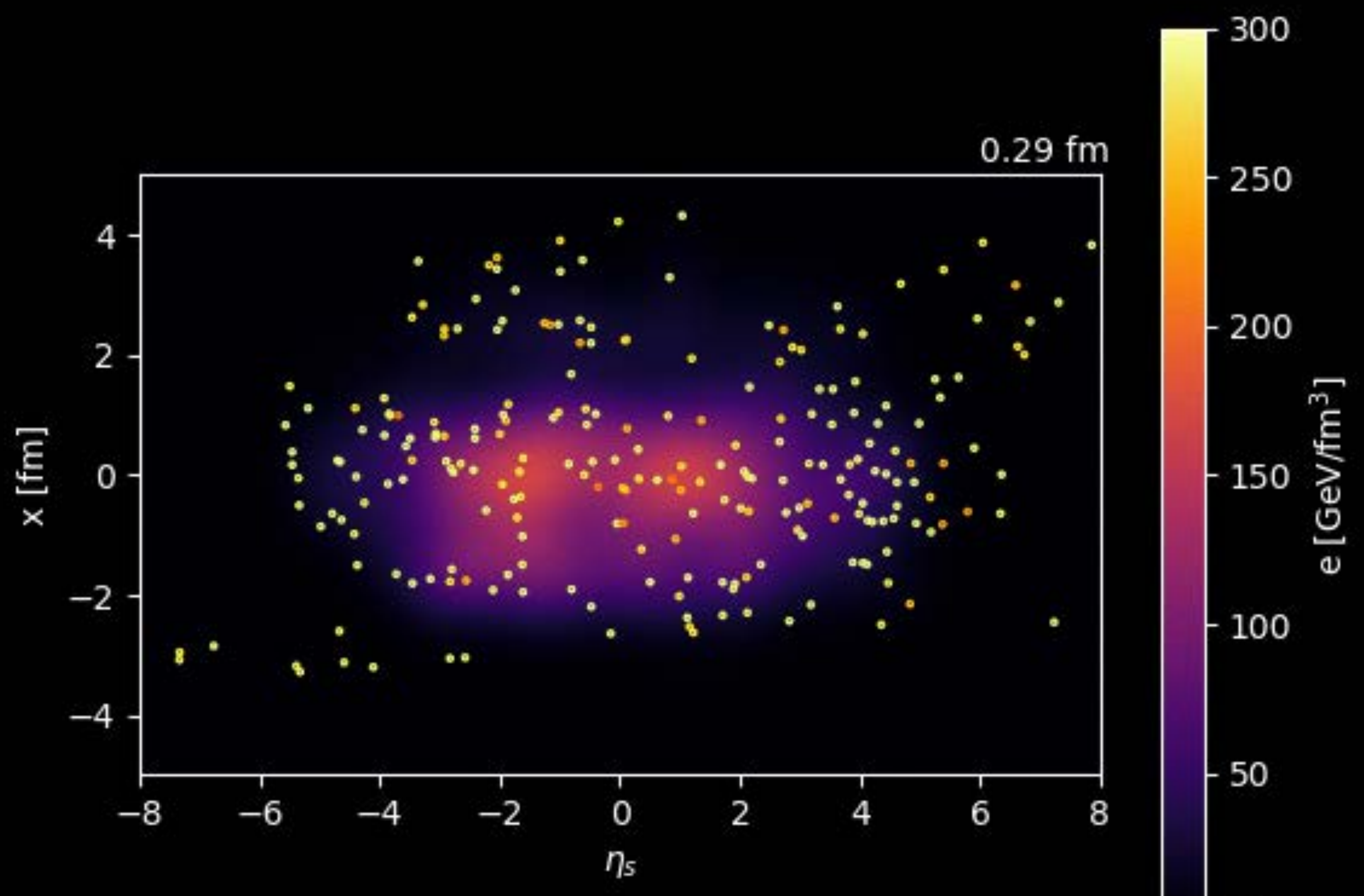

Courtesy from Yuuka Kanakubo

Dynamical core-corona initialization (DCCI)

pp, $\sqrt{s_{\mathrm{NN}}} = 7\ \mathrm{TeV}$

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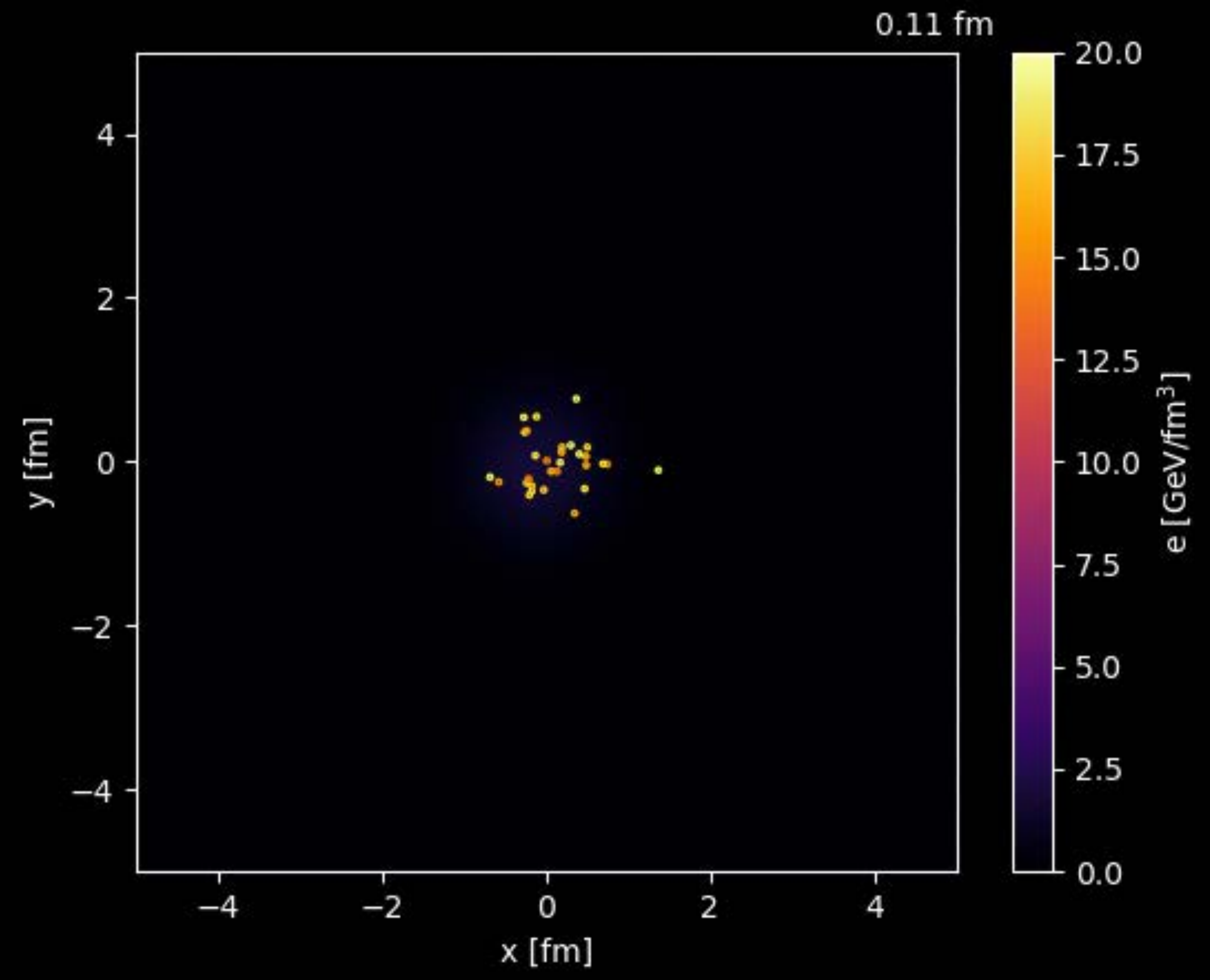

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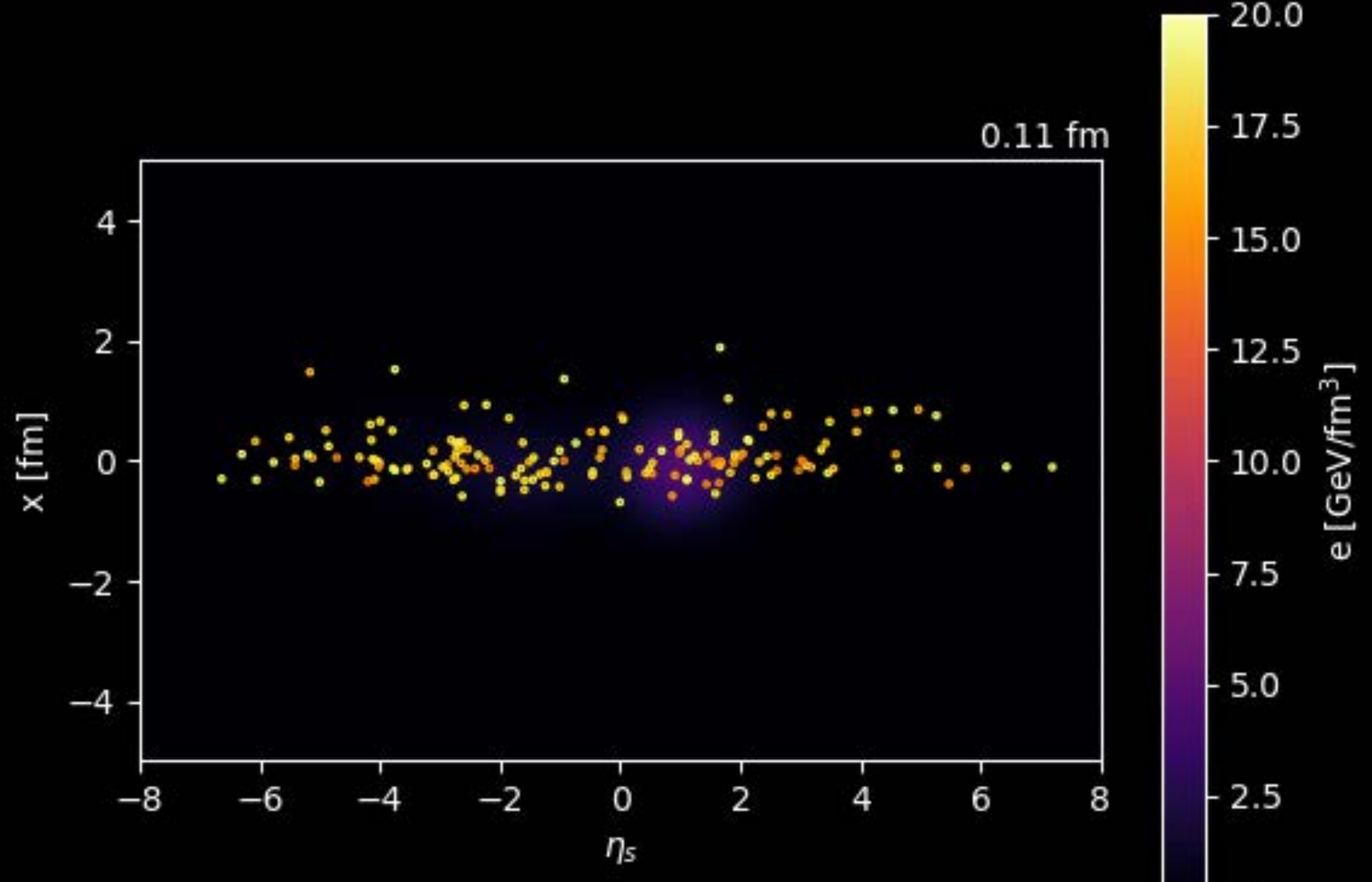

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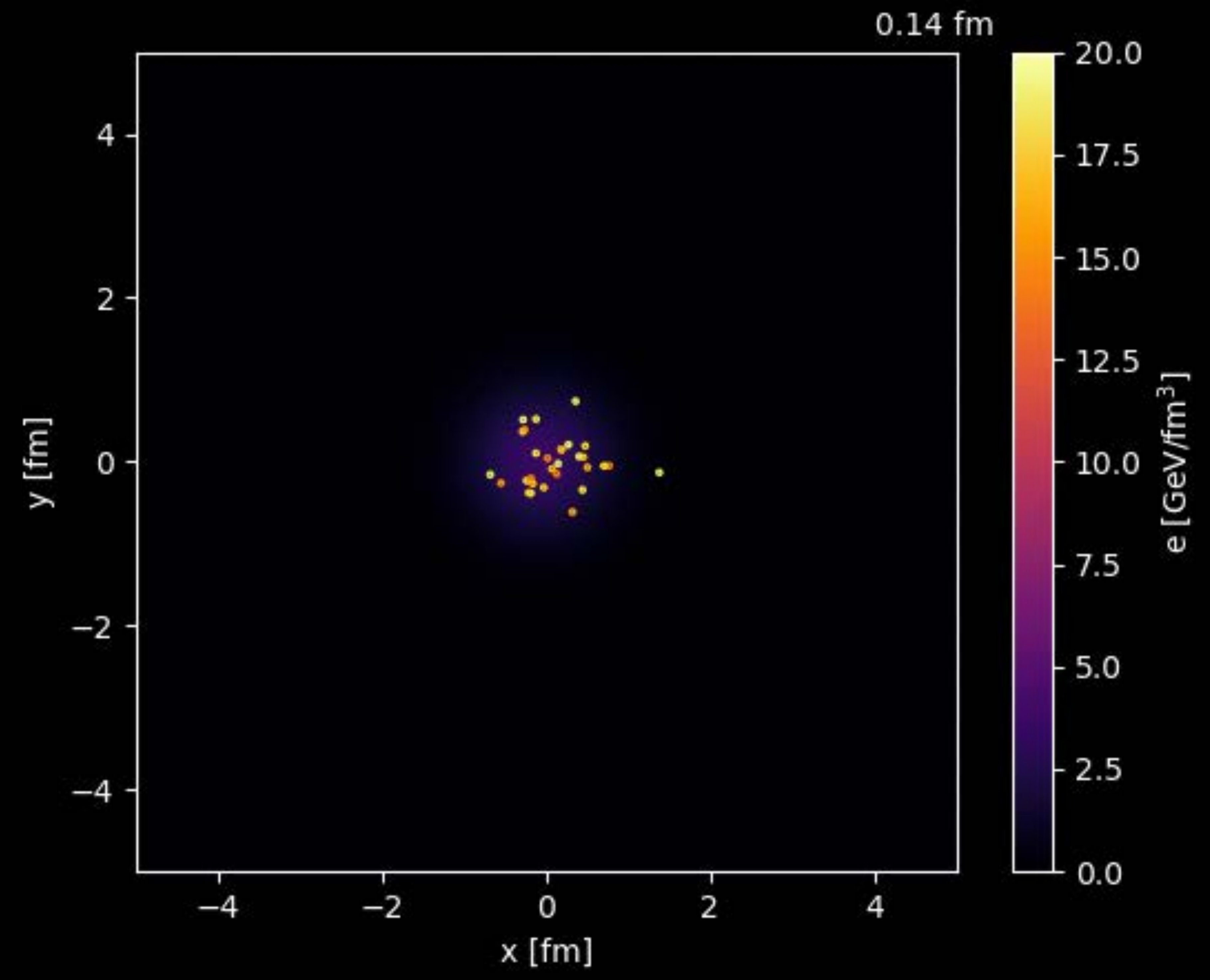

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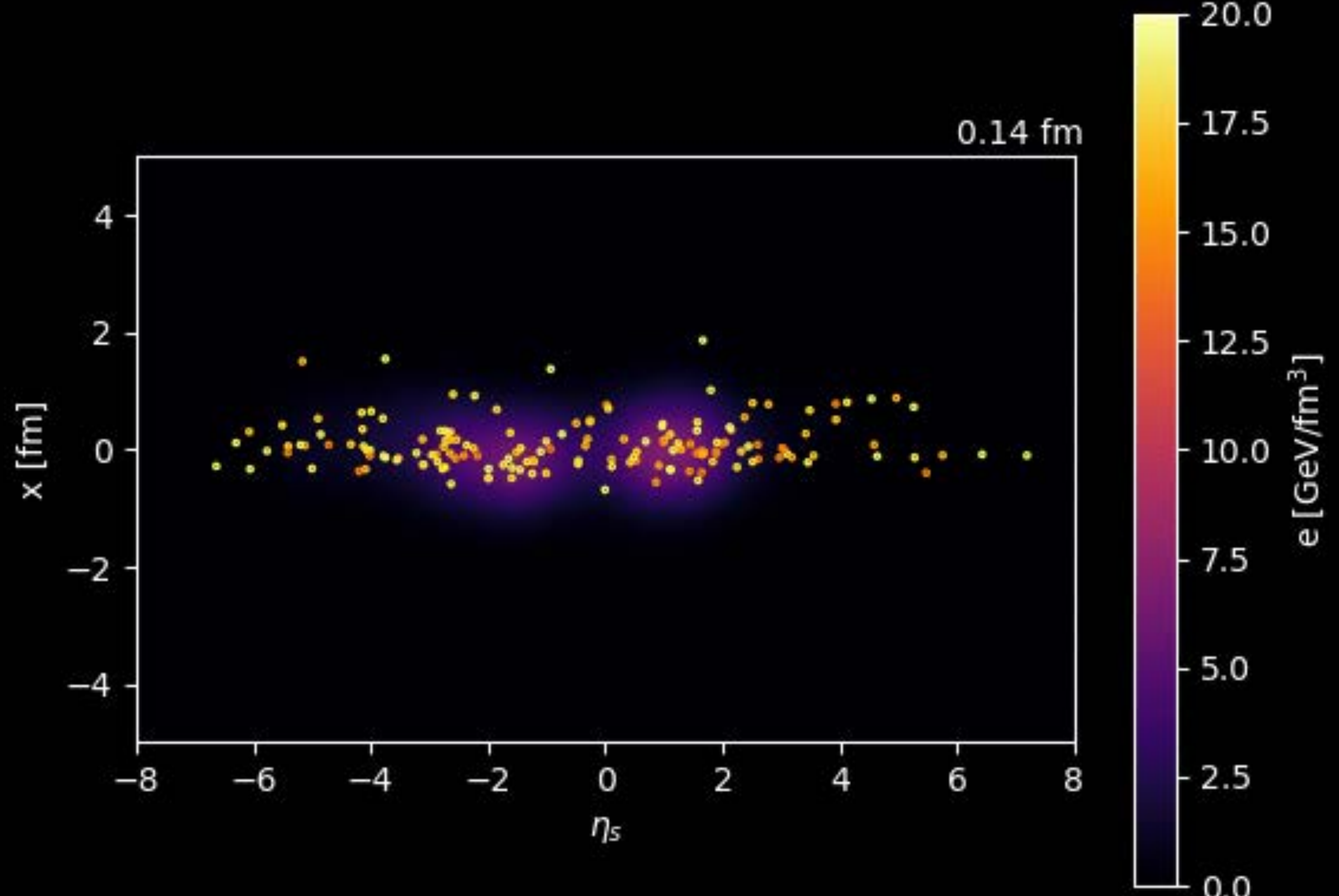

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Dynamical core-corona initialization (DCCI)

pp, $\sqrt{s_{\mathrm{NN}}} = 7$ TeV

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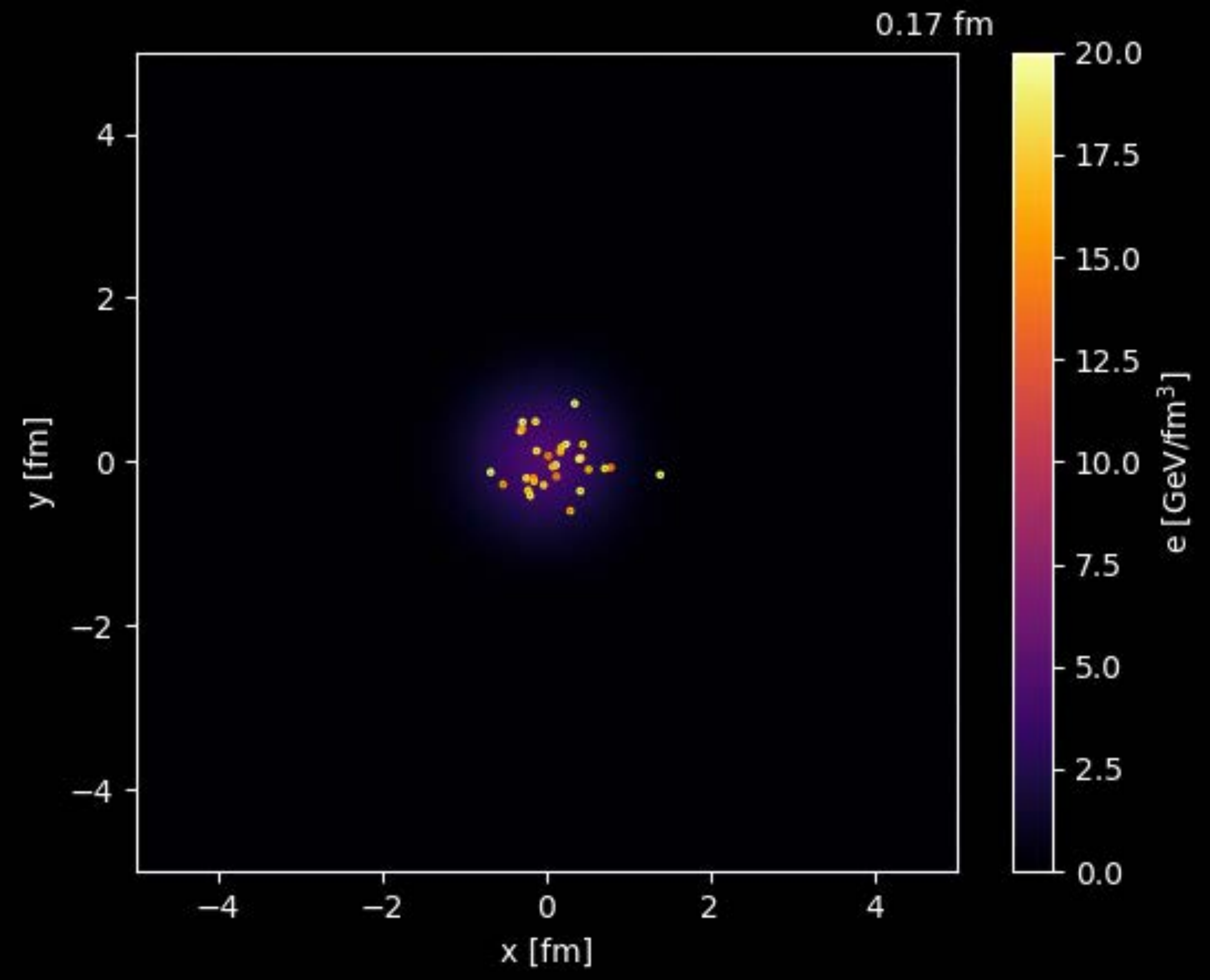

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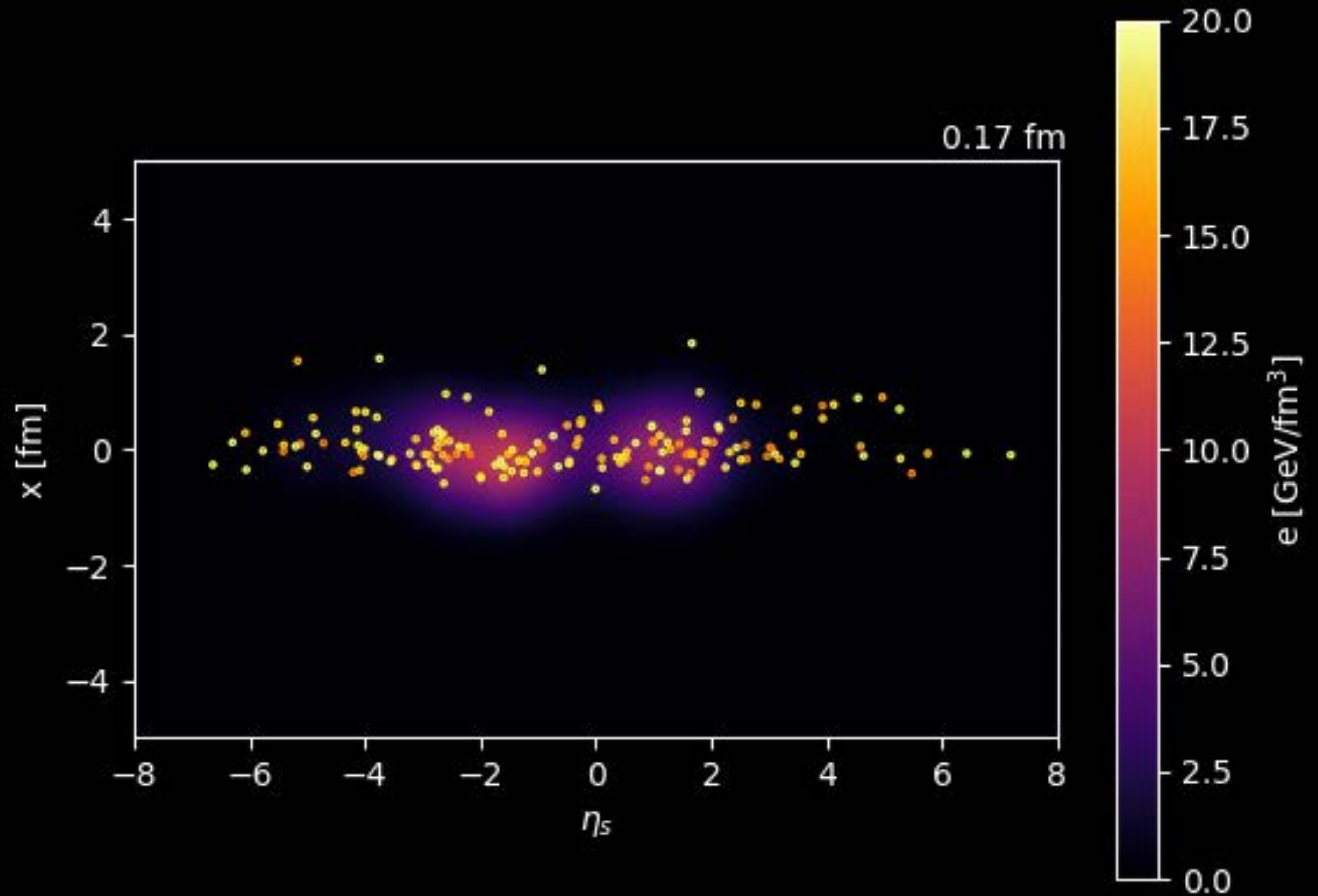

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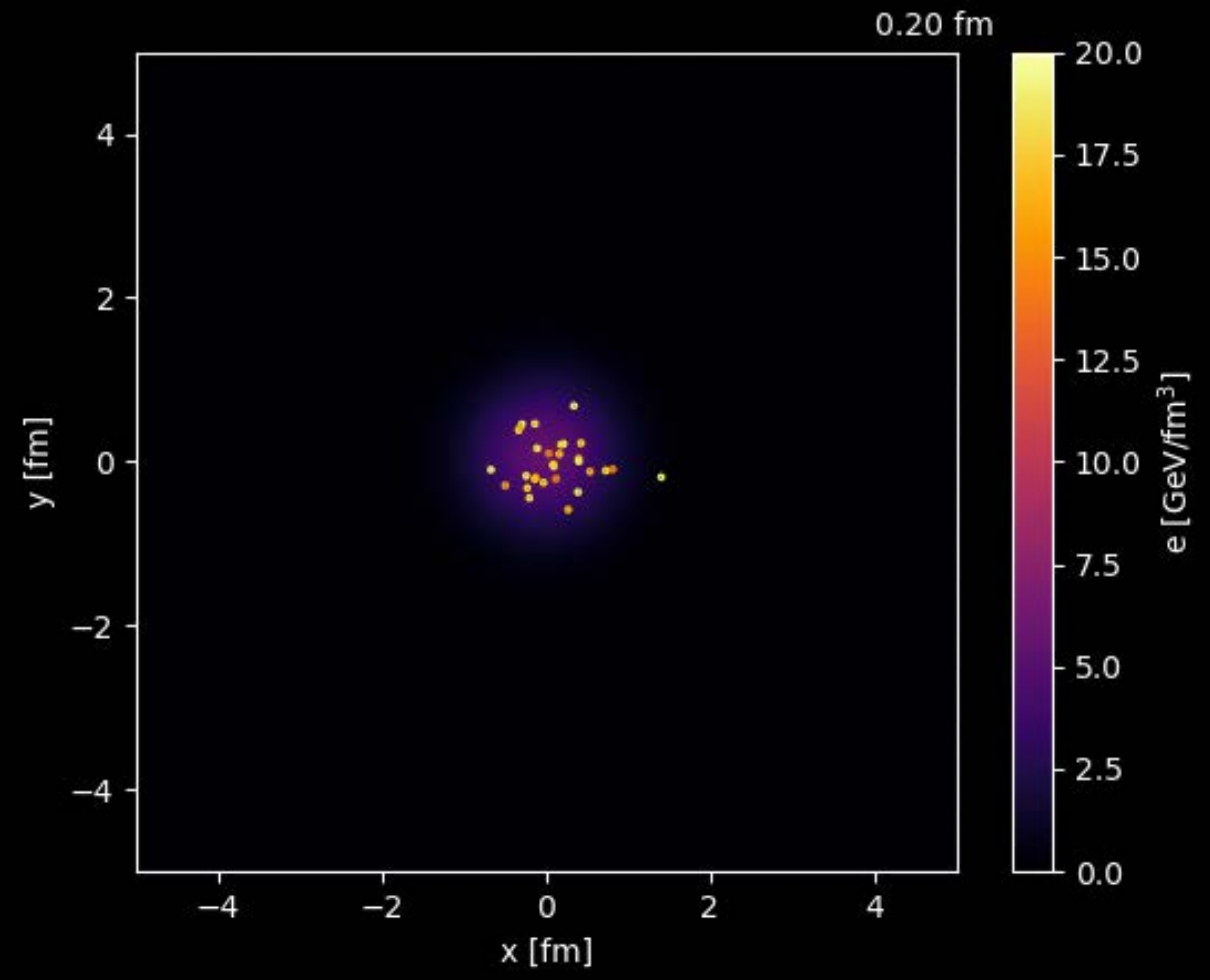

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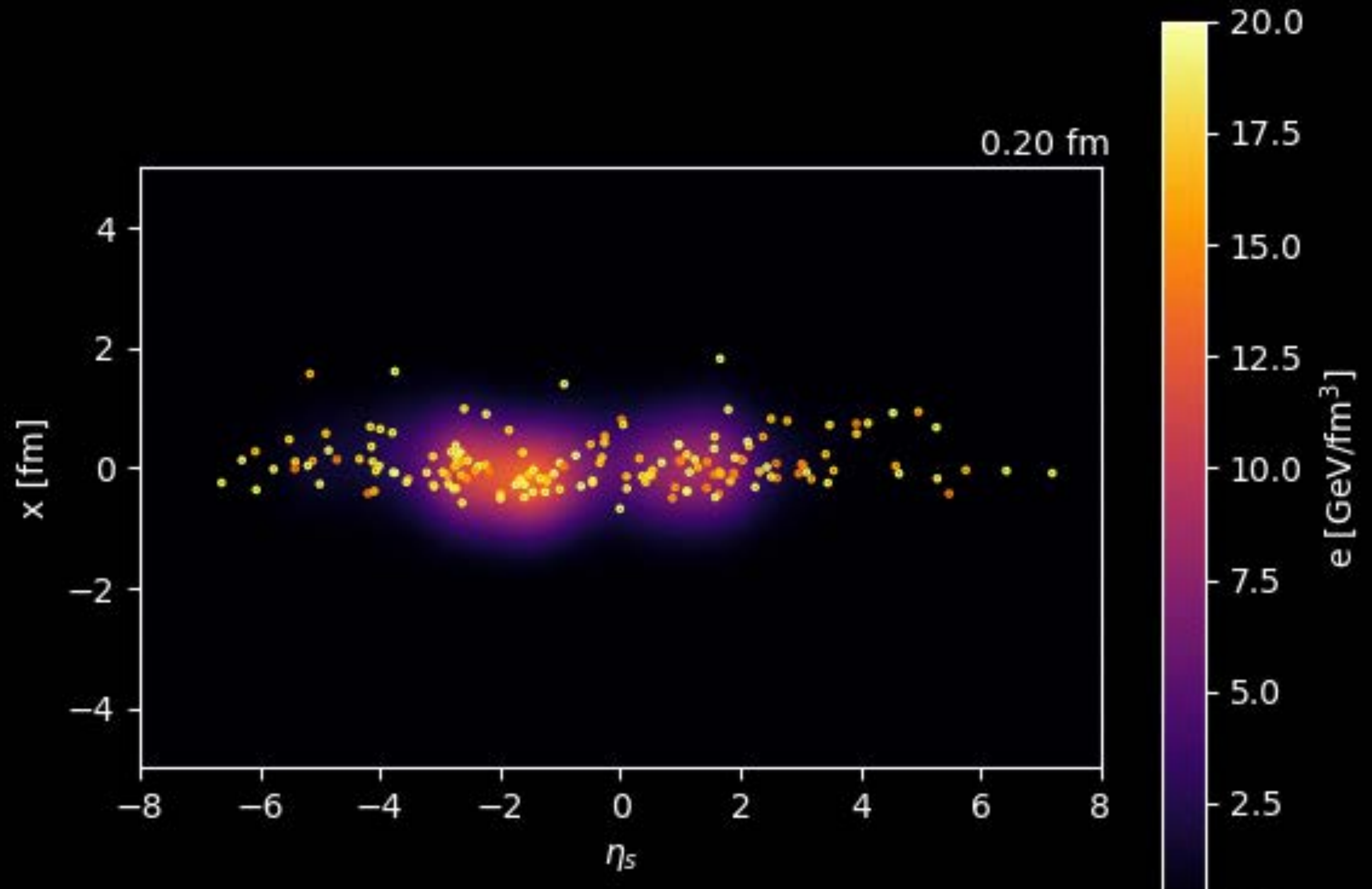

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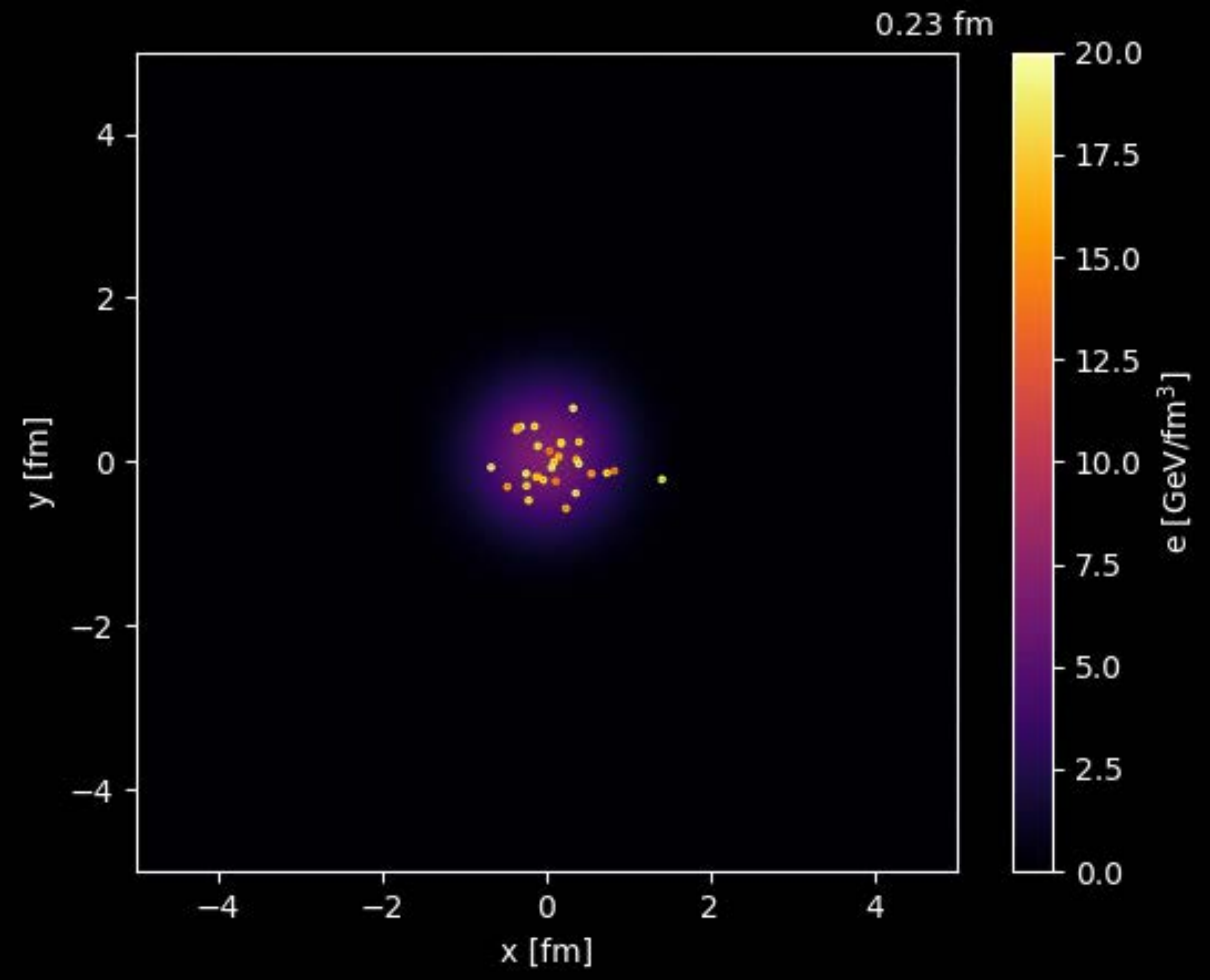

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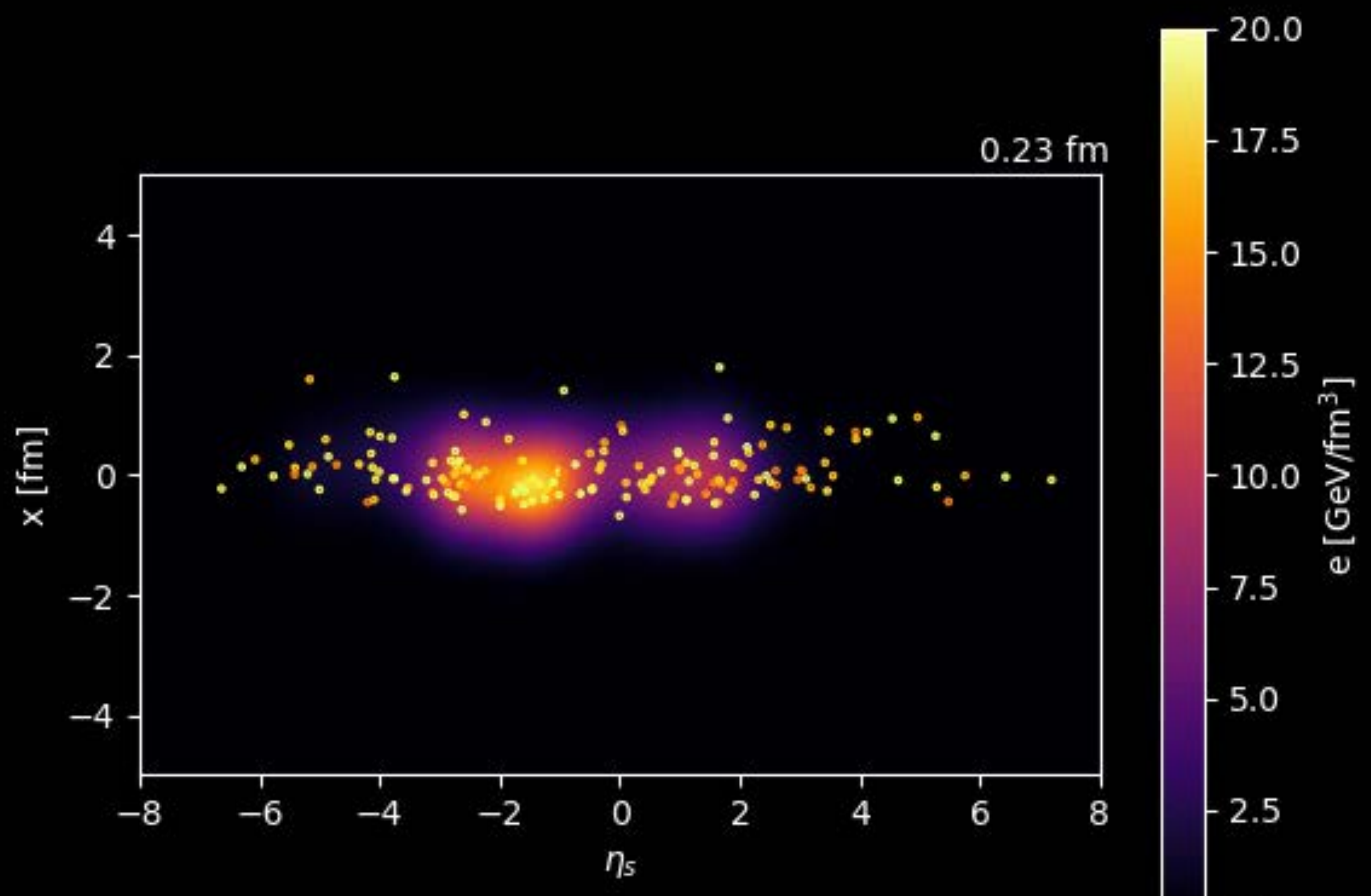

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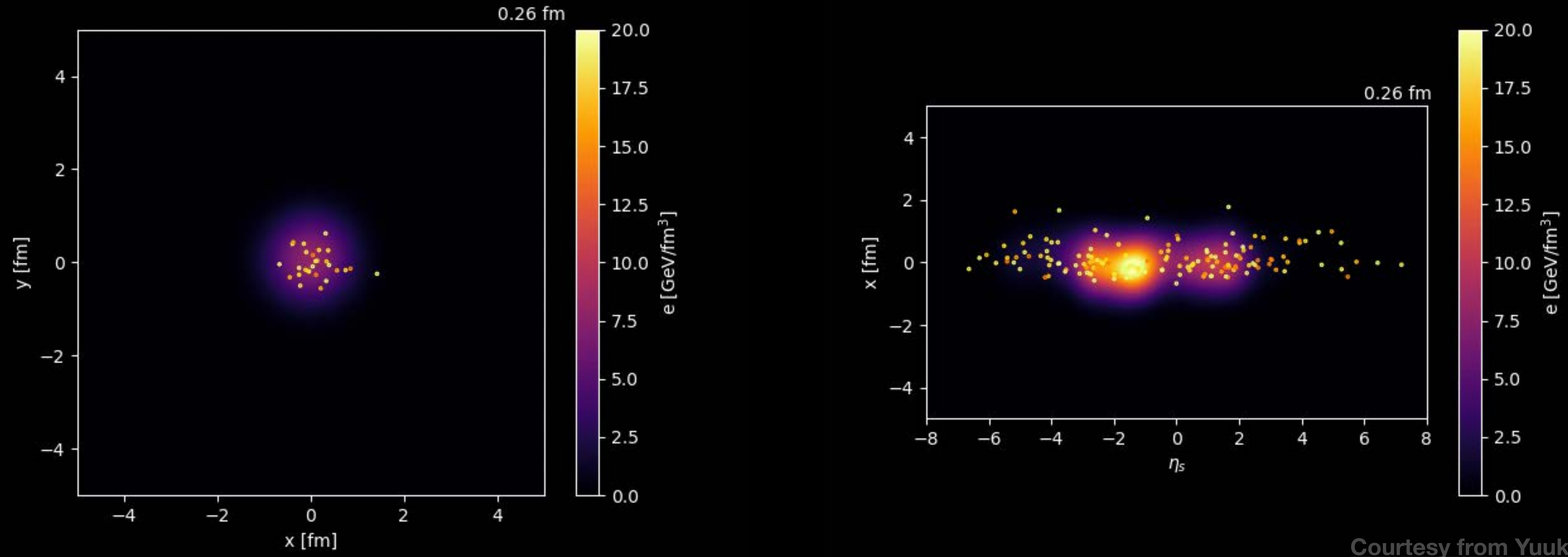

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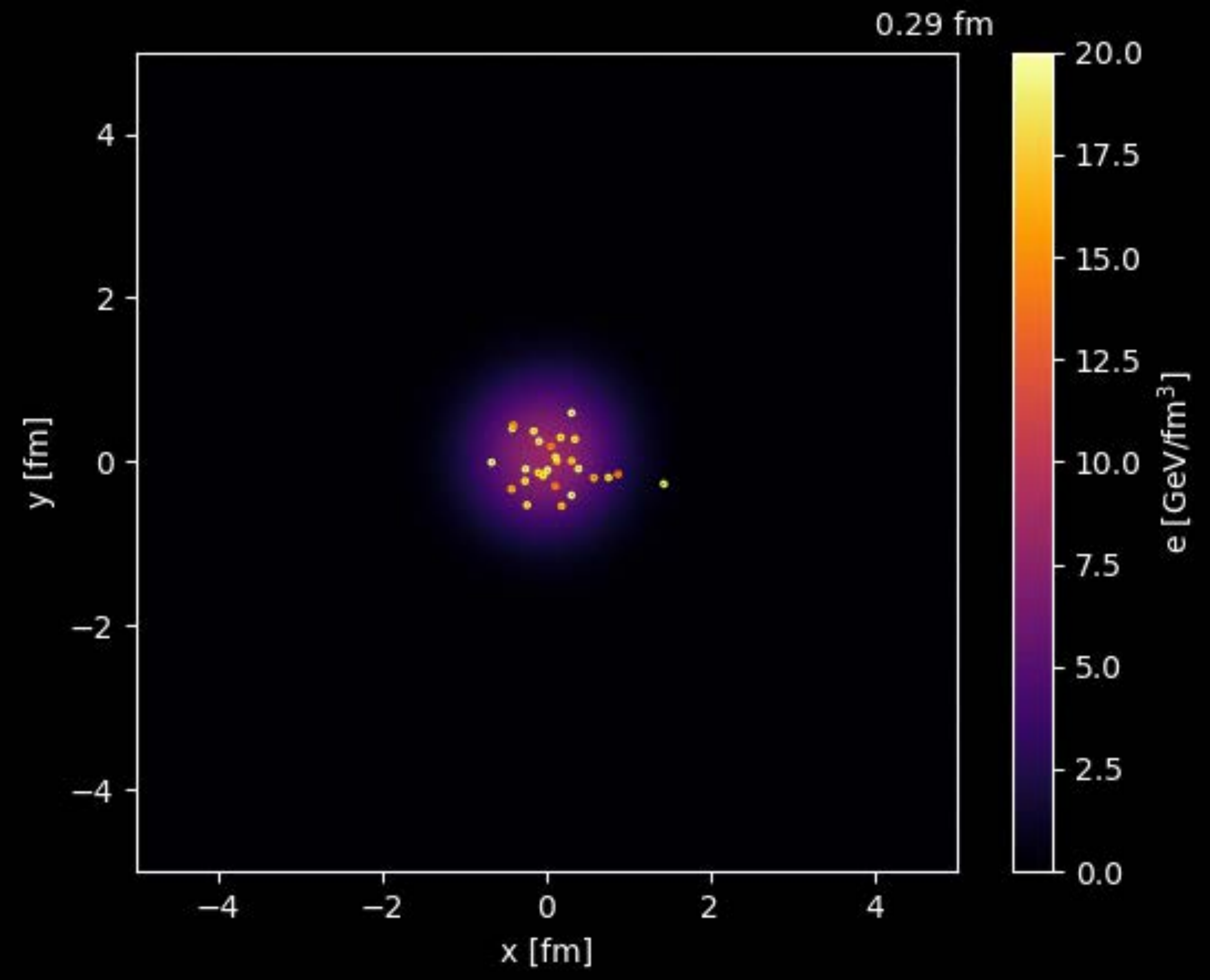

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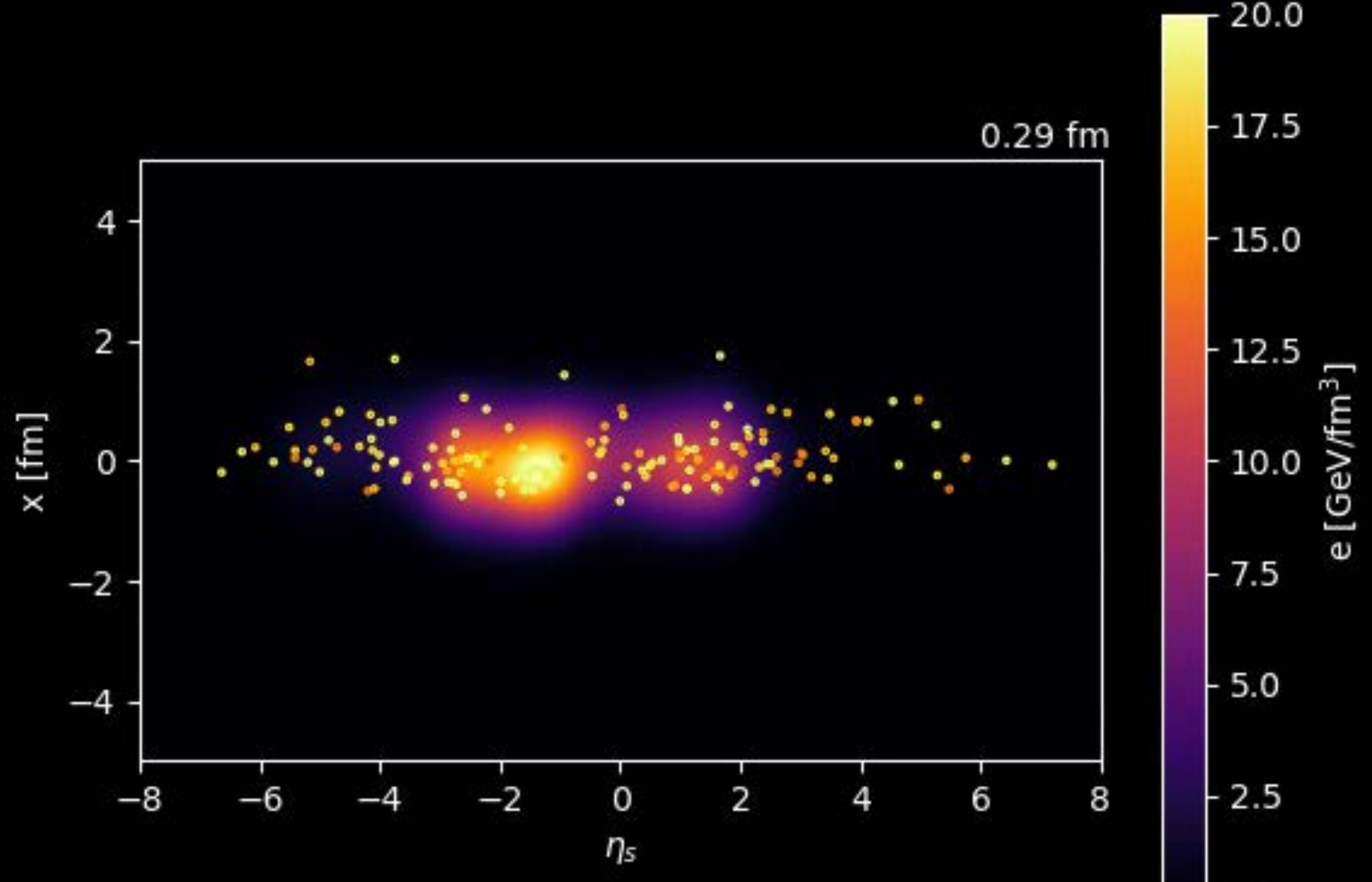
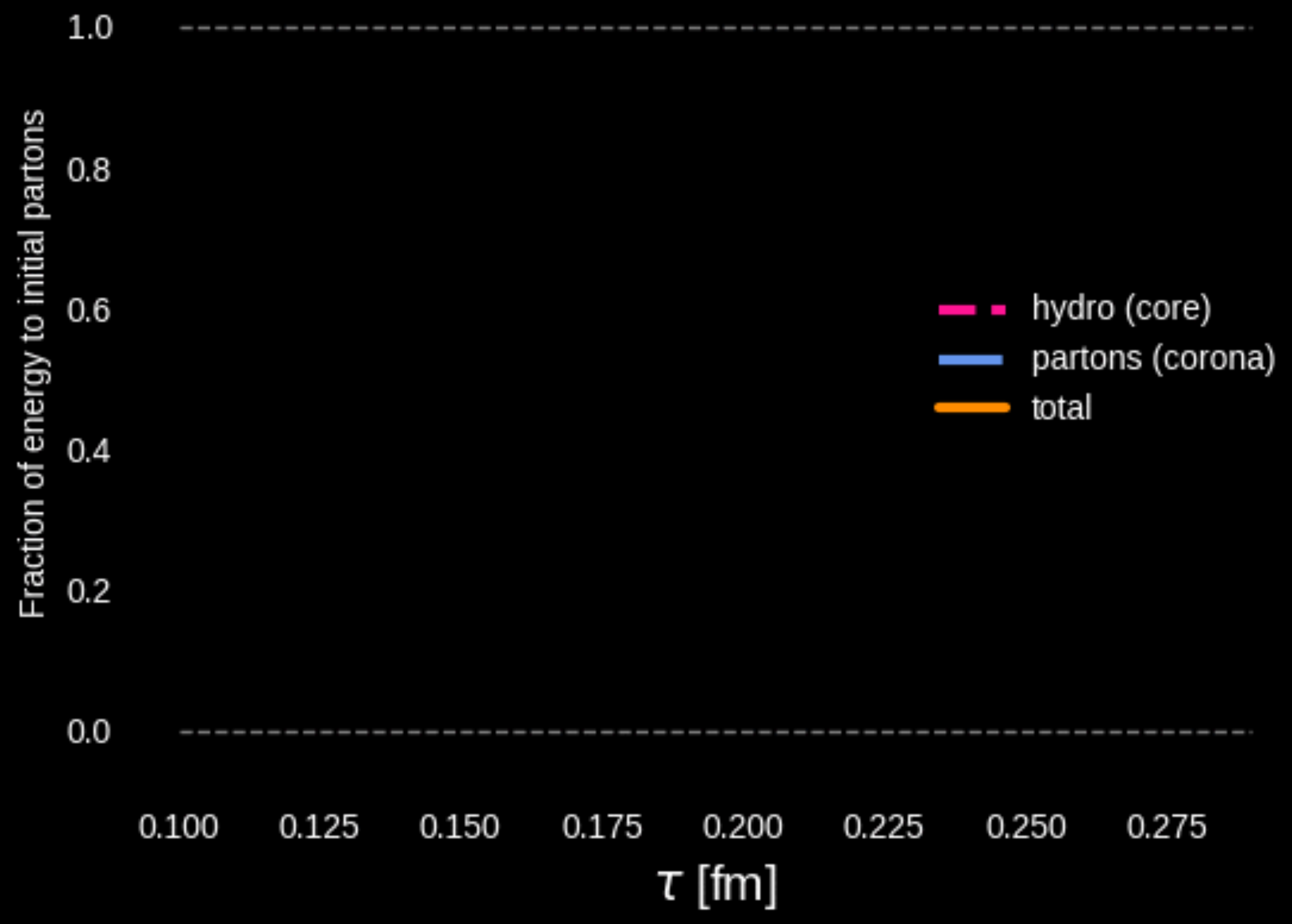


Courtesy from Yuuka Kanakubo

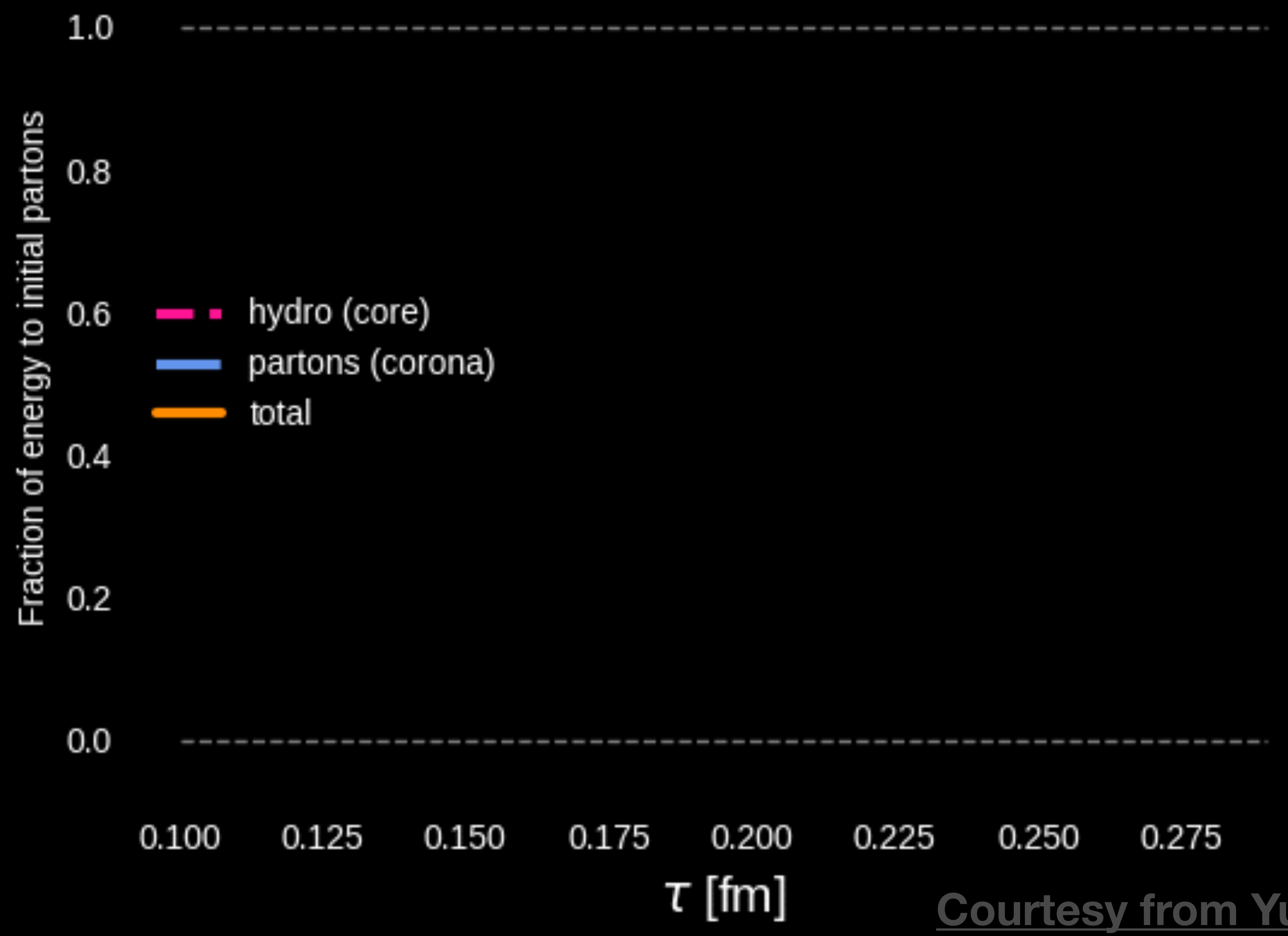
Dynamical core-corona initialization (DCCI)

<u>Dynamical conversion of energy into fluid</u>

pp, $\sqrt{s_{NN}} = 7$ TeV



PbPb, $\sqrt{s_{NN}} = 2.76$ TeV



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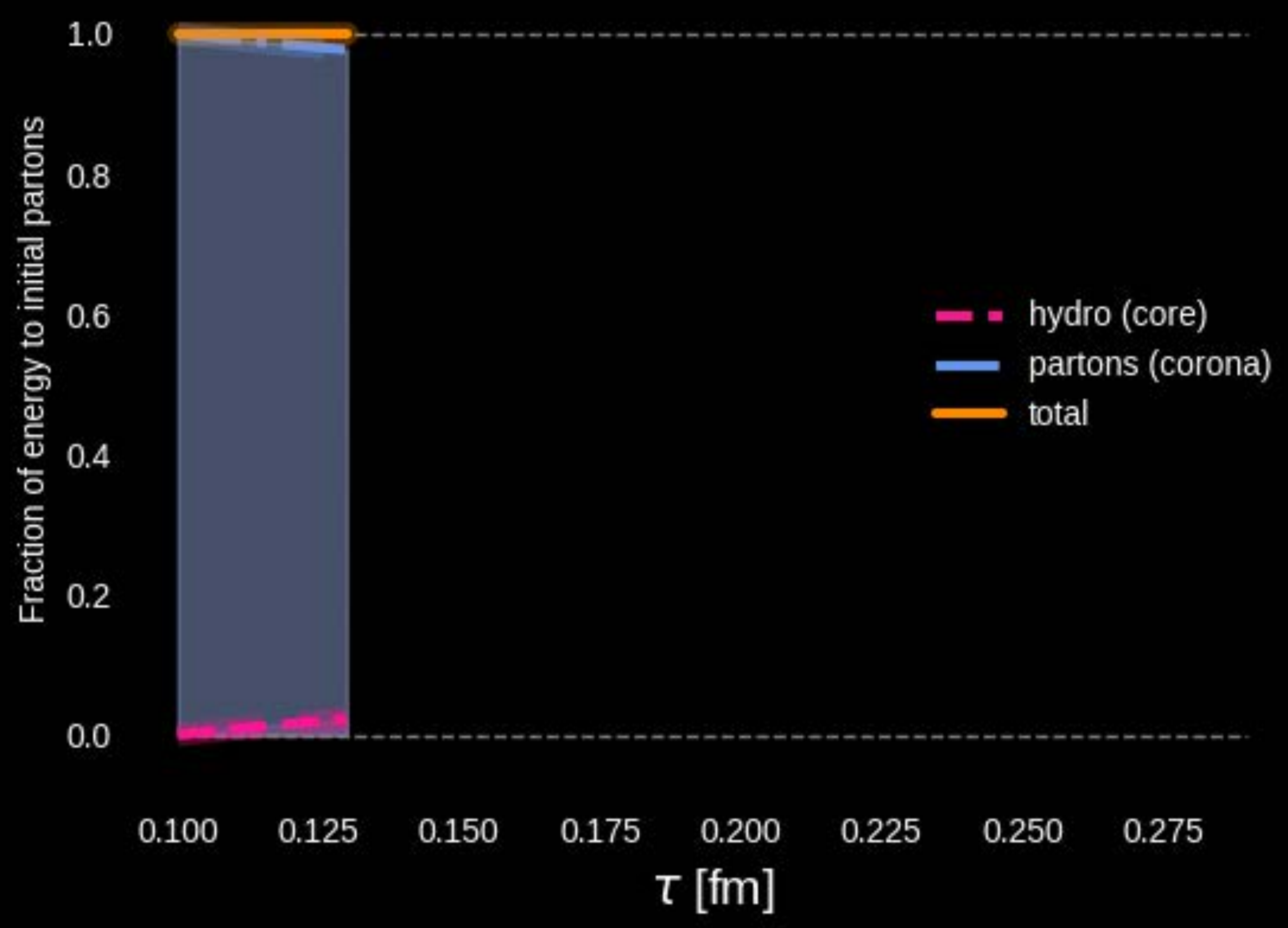

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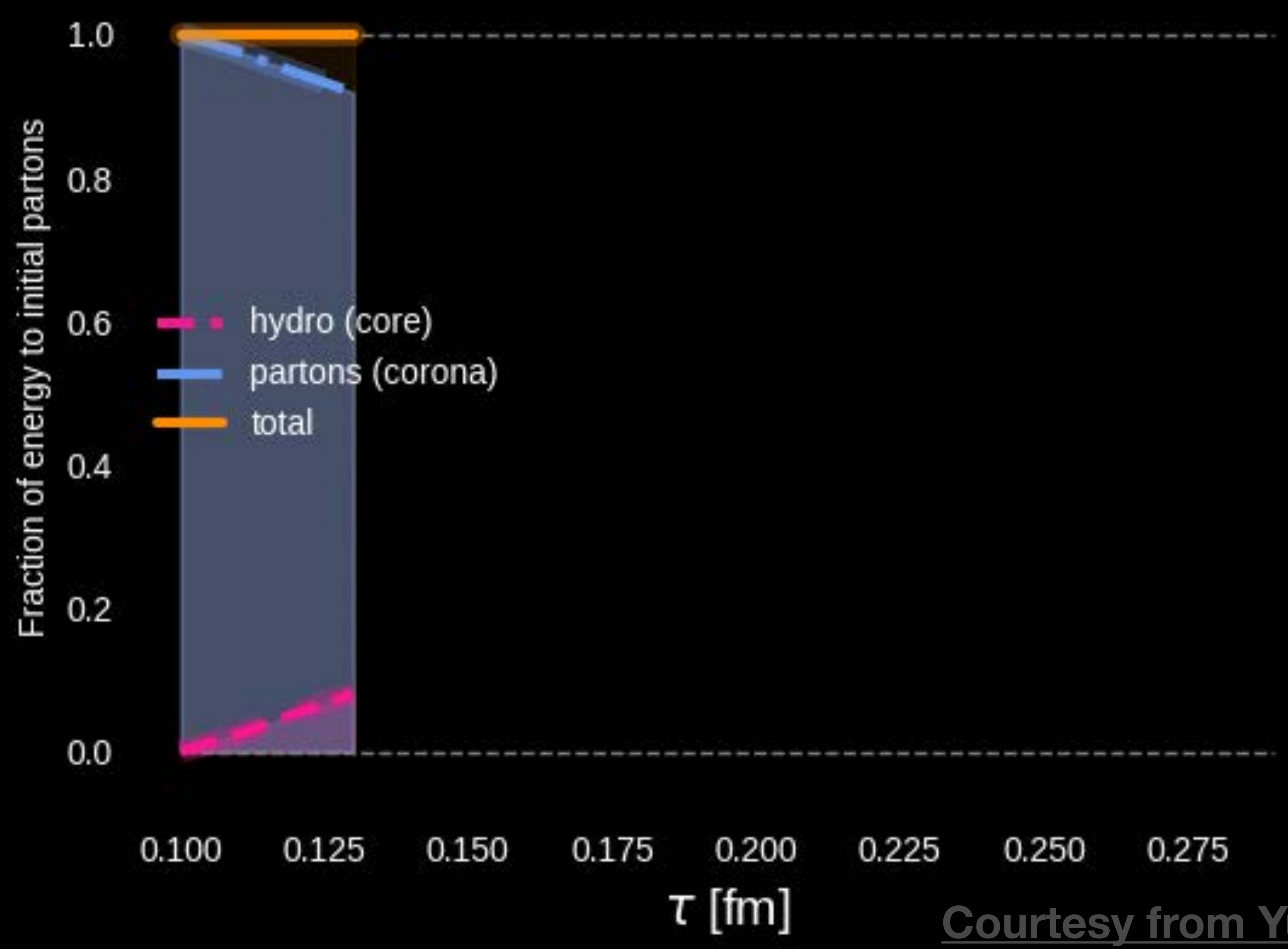

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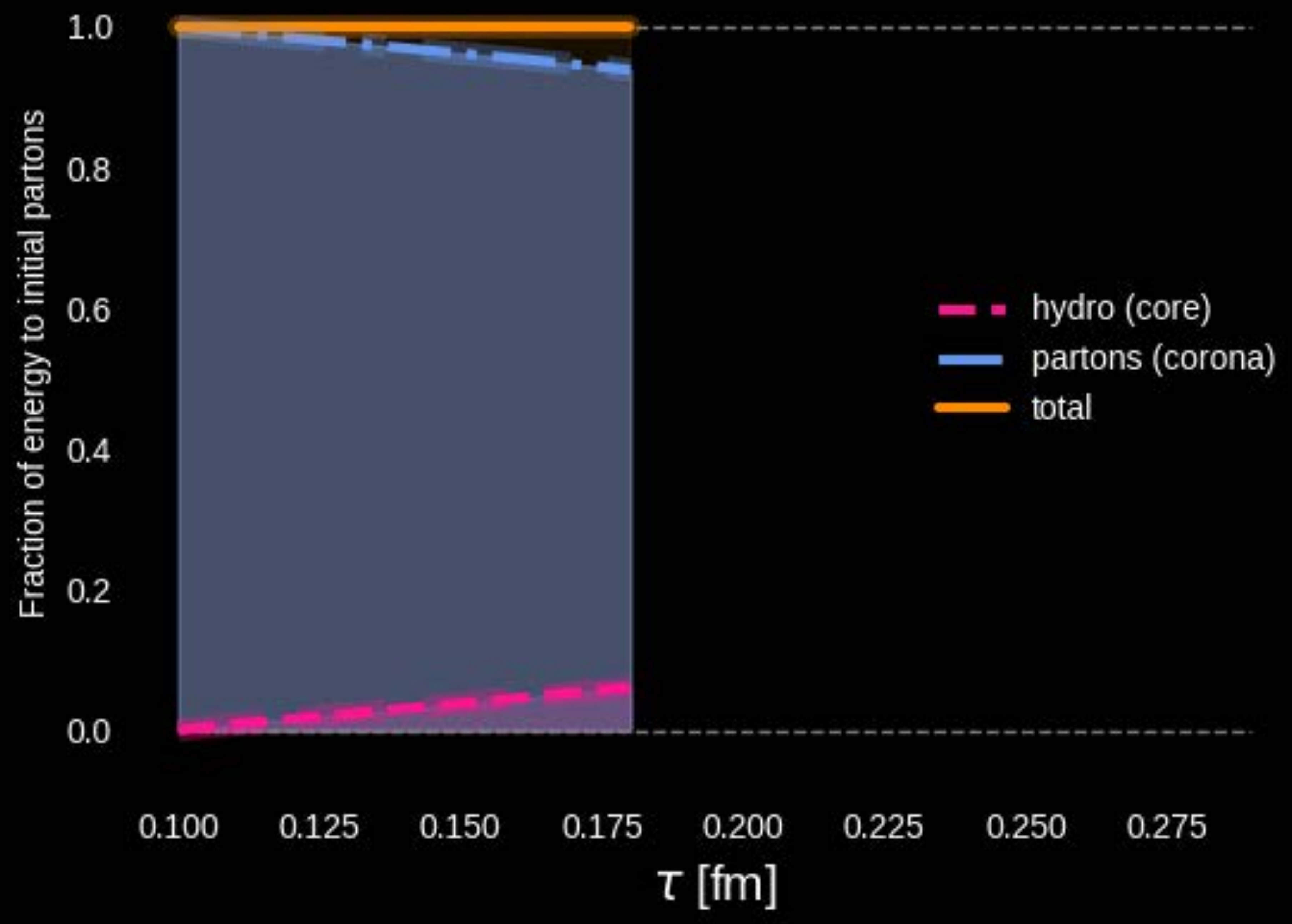

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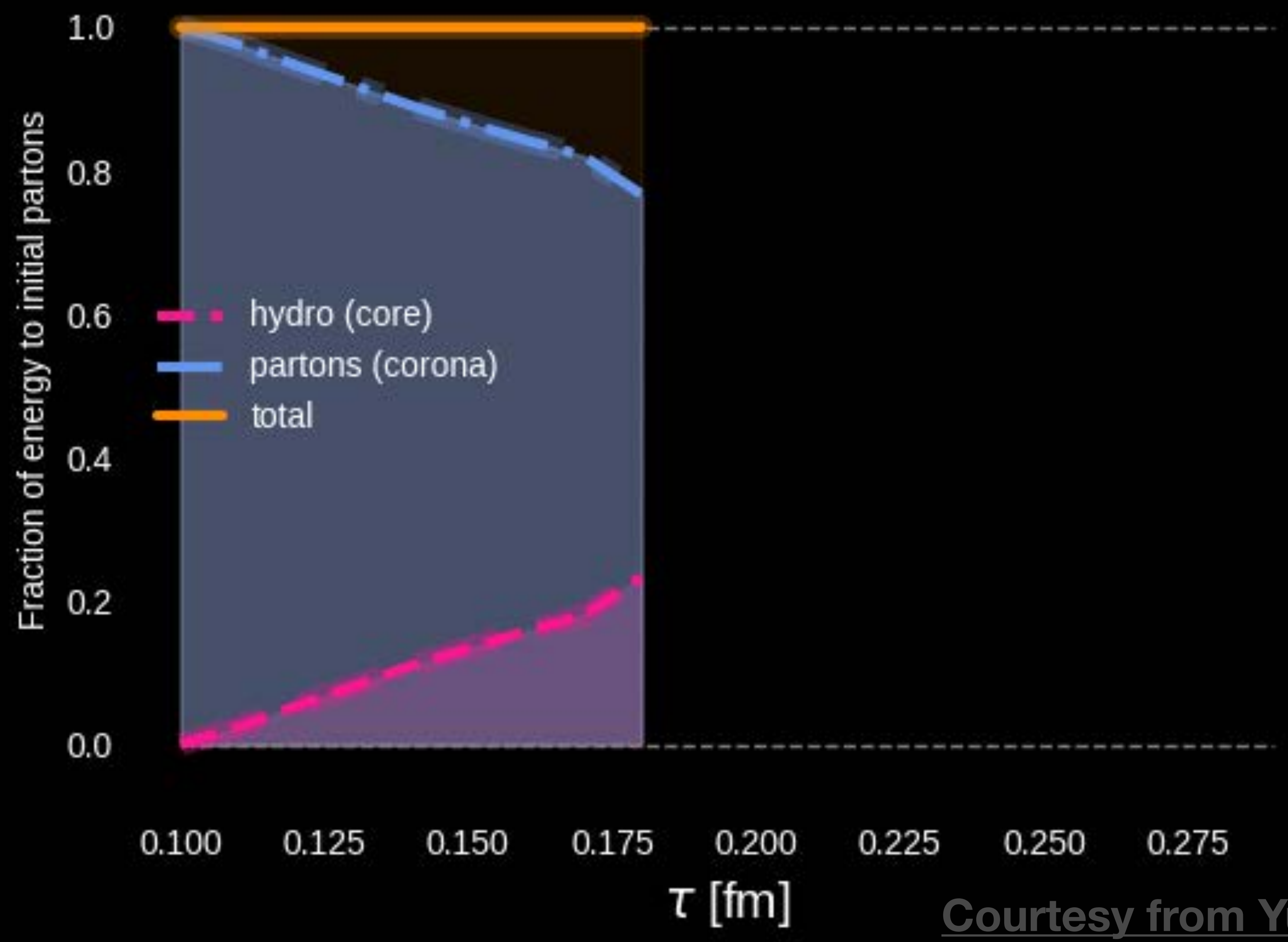

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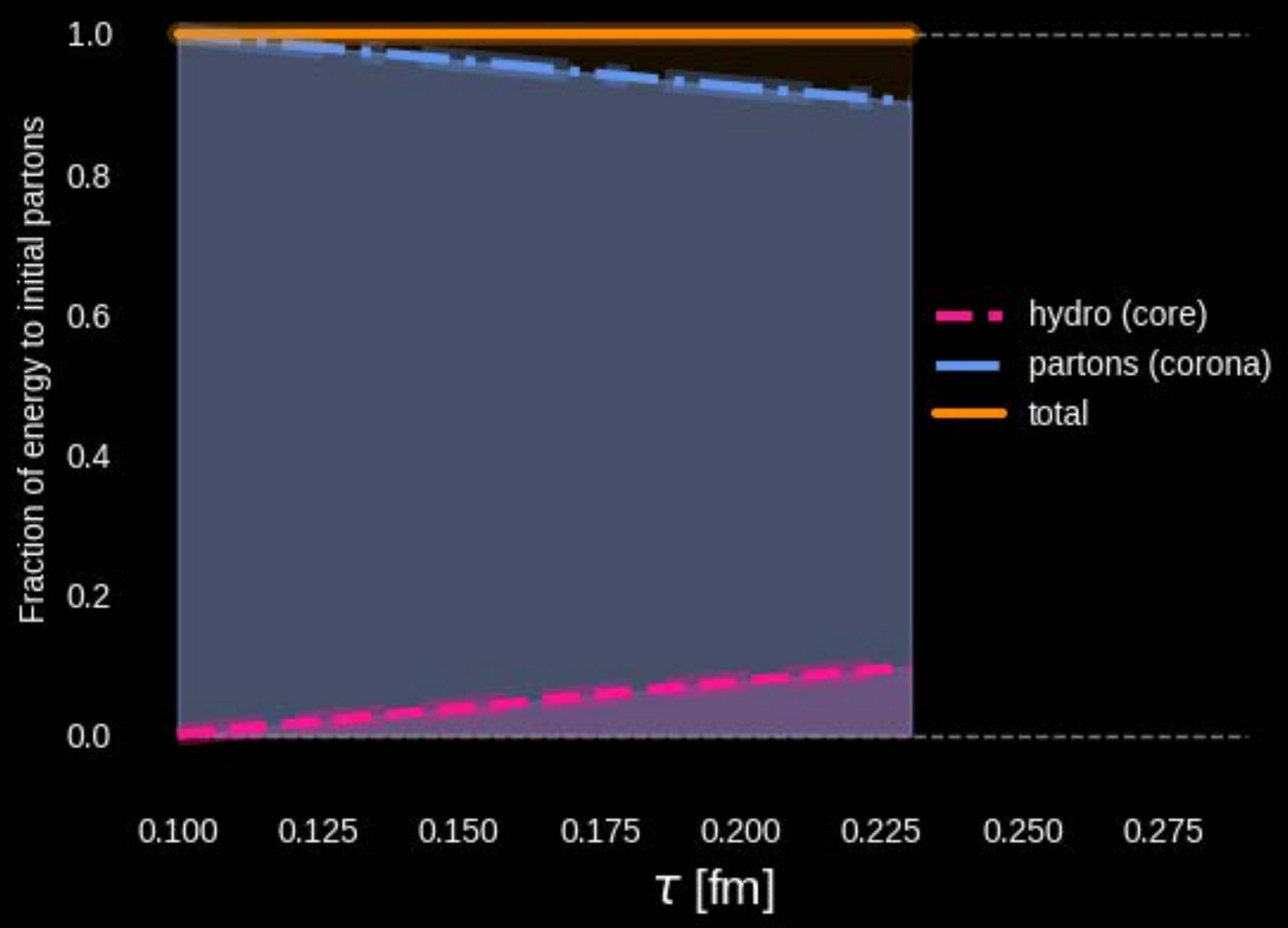

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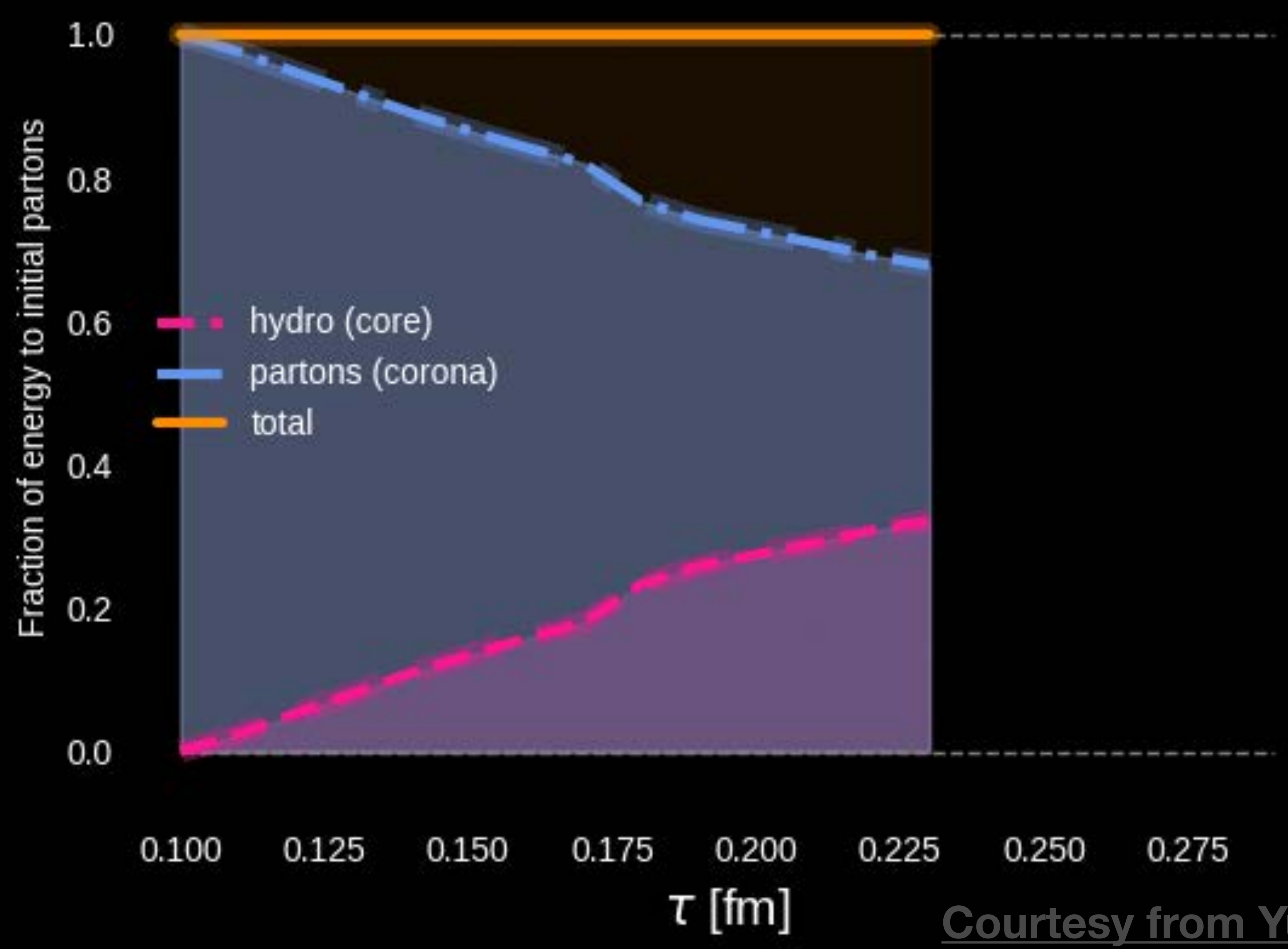

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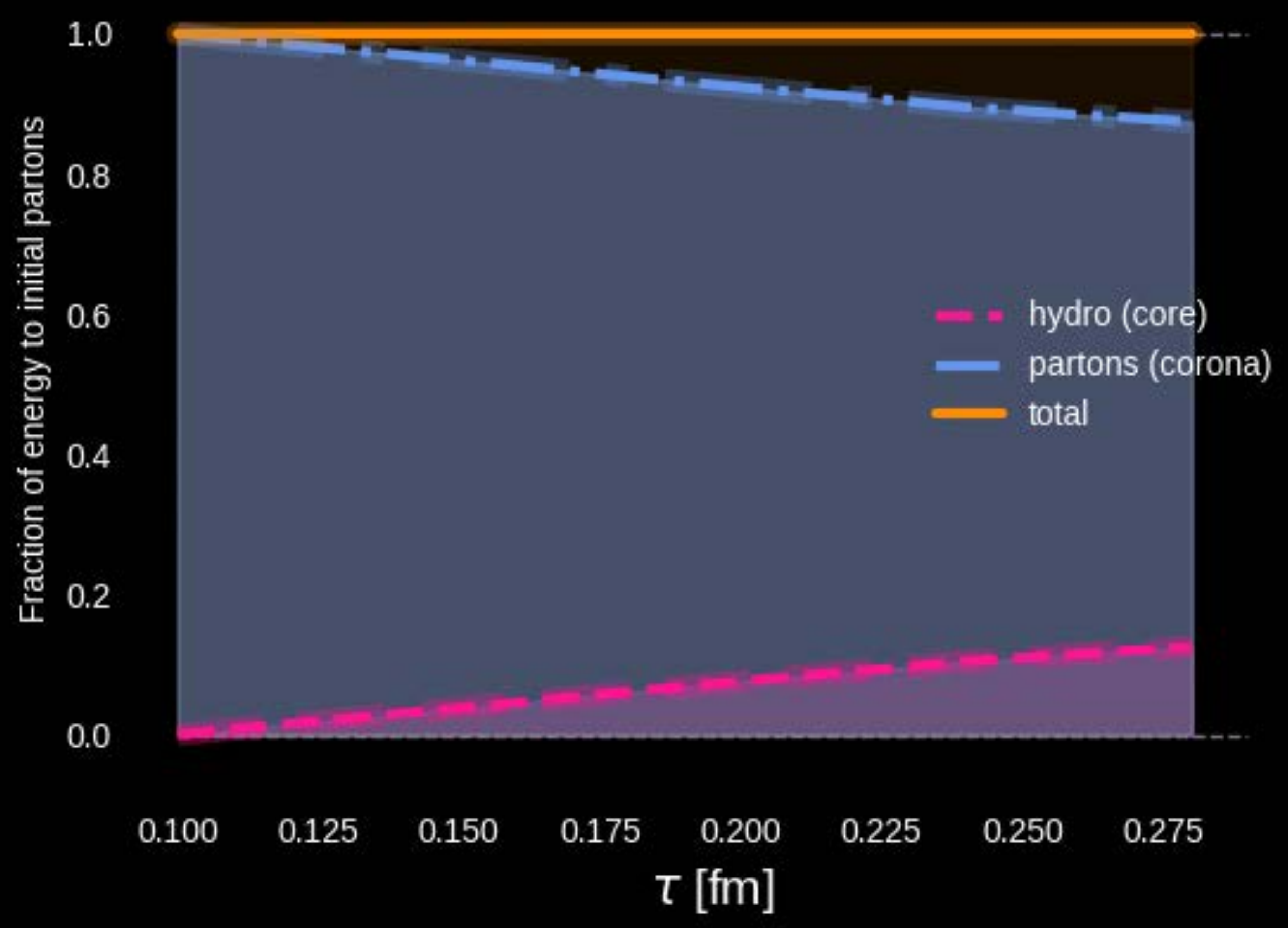

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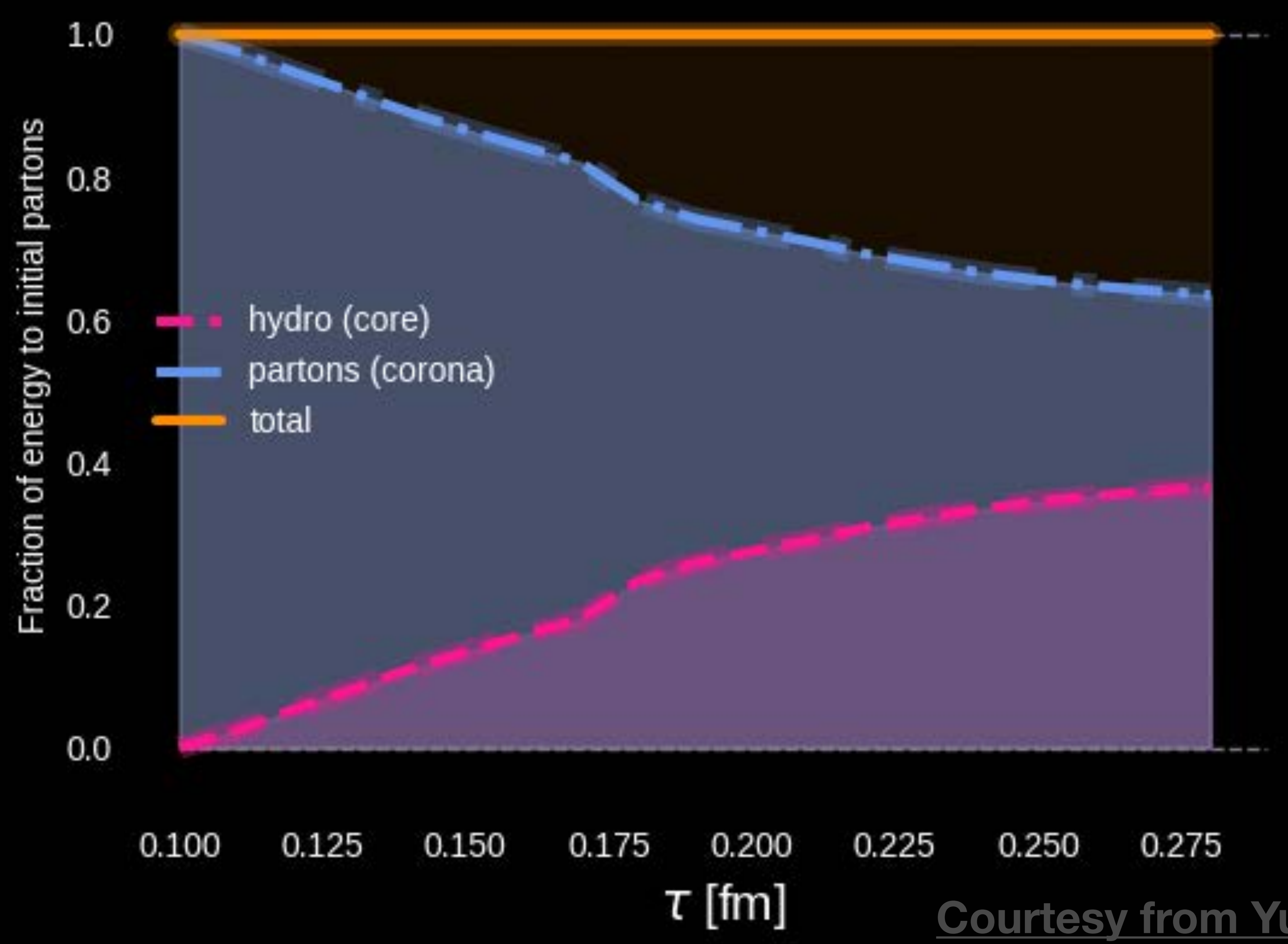


Courtesy from Yuuka Kanakubo

Results from DCCI2

Integrated model: DCCI2

Y. Kanakubo, YT, Hirano, PRC 105, no.2, 024905 (2022)

DCCI2 framework

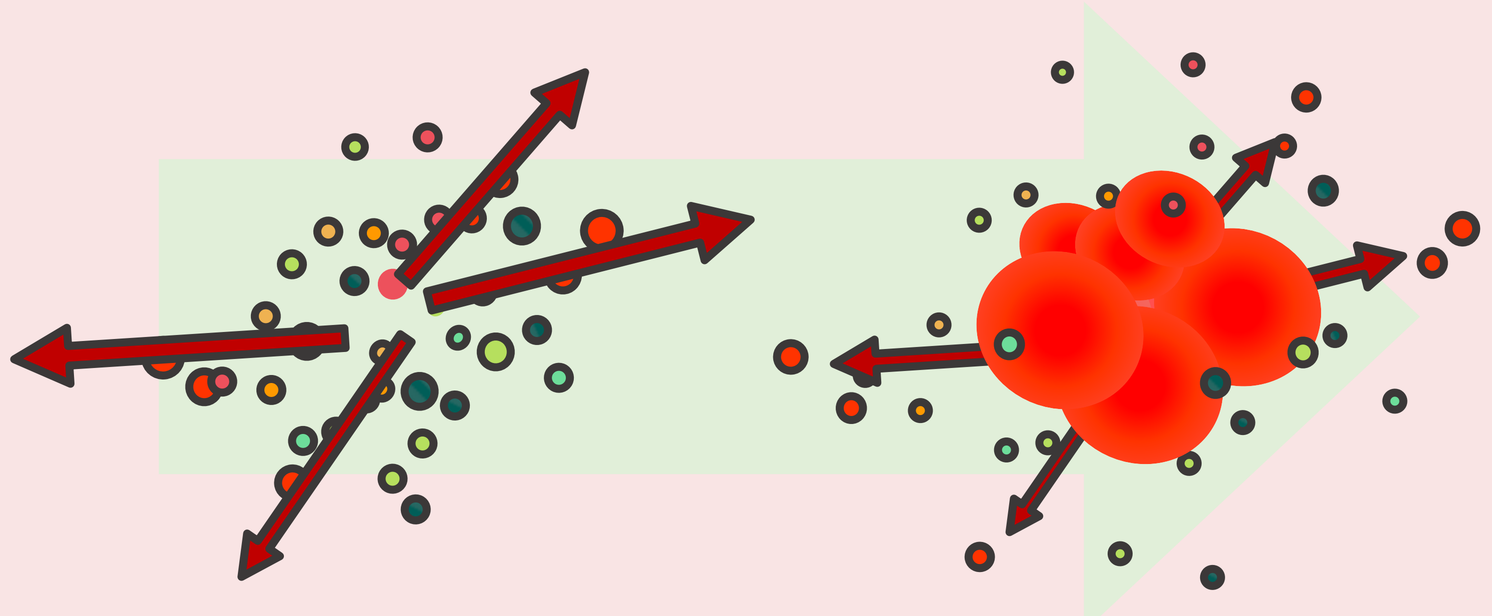
Initial Parton

PYTHIA8/
PYTHIA8 Angantyr

T. Sjöstrand et al., Comput. Phys. Commun. 191, 159 (2015);
C. Bierlich et al., JHEP 1610 139 (2016)

Fluid production and evolution

$$\nabla_\mu T^{\mu\nu}_{\mathrm{fluid}}(x) = J^\nu(x)$$



Courtesy from Yuuka Kanakubo

Thermal Hadron Sampling

iS3D

M. McNelis et al., Comput. Phys.Commun. 258, 107604 (2021)

Fragmentation

PYTHIA 8
(Lund String)

Hadron Cascade

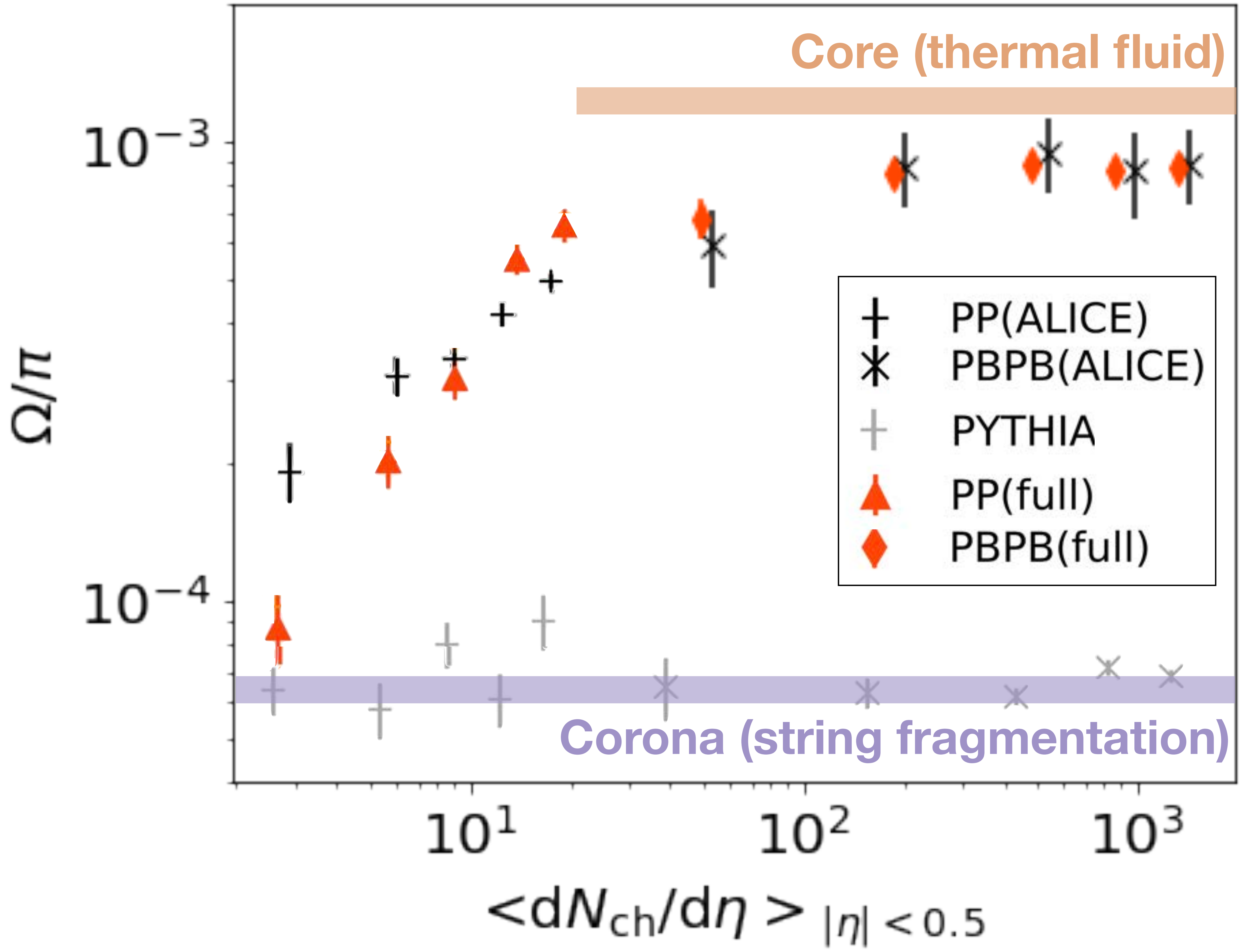
JAM

Y. Nara et al.,Phys. Rev. C61, 024901 (2000)

Fluidization rate in DCCI2

Y. Kanakubo, YT, Hirano, PRC 105, no.2, 024905 (2022)

Exp. Data: ALICE, Nature Phys. 13, 535-539 (2017); PLB728, 216-227 (2014)

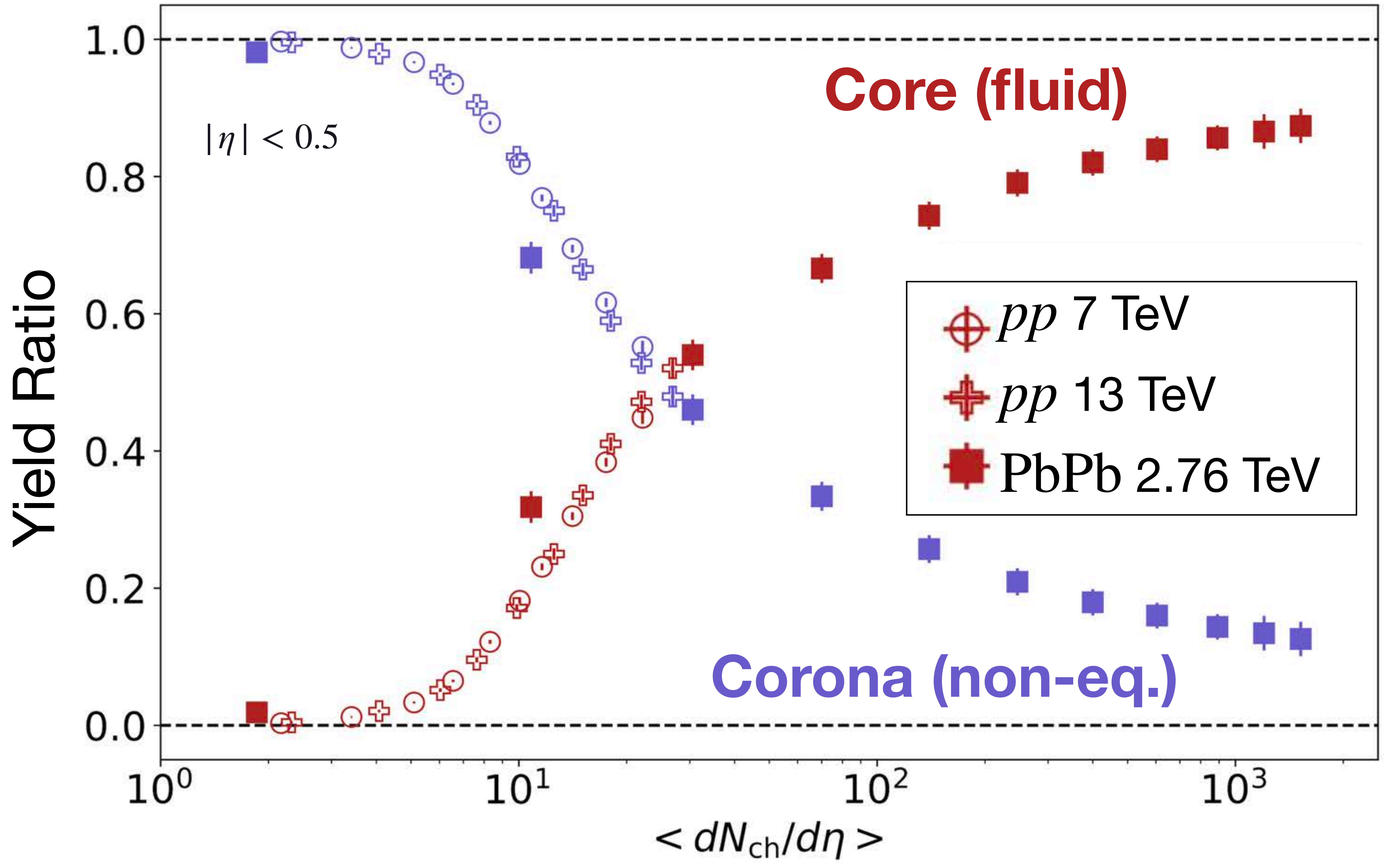


- **Multiplicity dependence of Ω/π**
  - Smooth transition from vacuum to thermal
  - good measure of fluidization rate
  - Fixing parameters in DCCI process

*Deviation from data at low multiplicity can be attributed to PYTHIA default tuning

Fluidization rate in DCCI2

Y. Kanakubo, YT, Hirano, PRC 105, no.2, 024905 (2022)



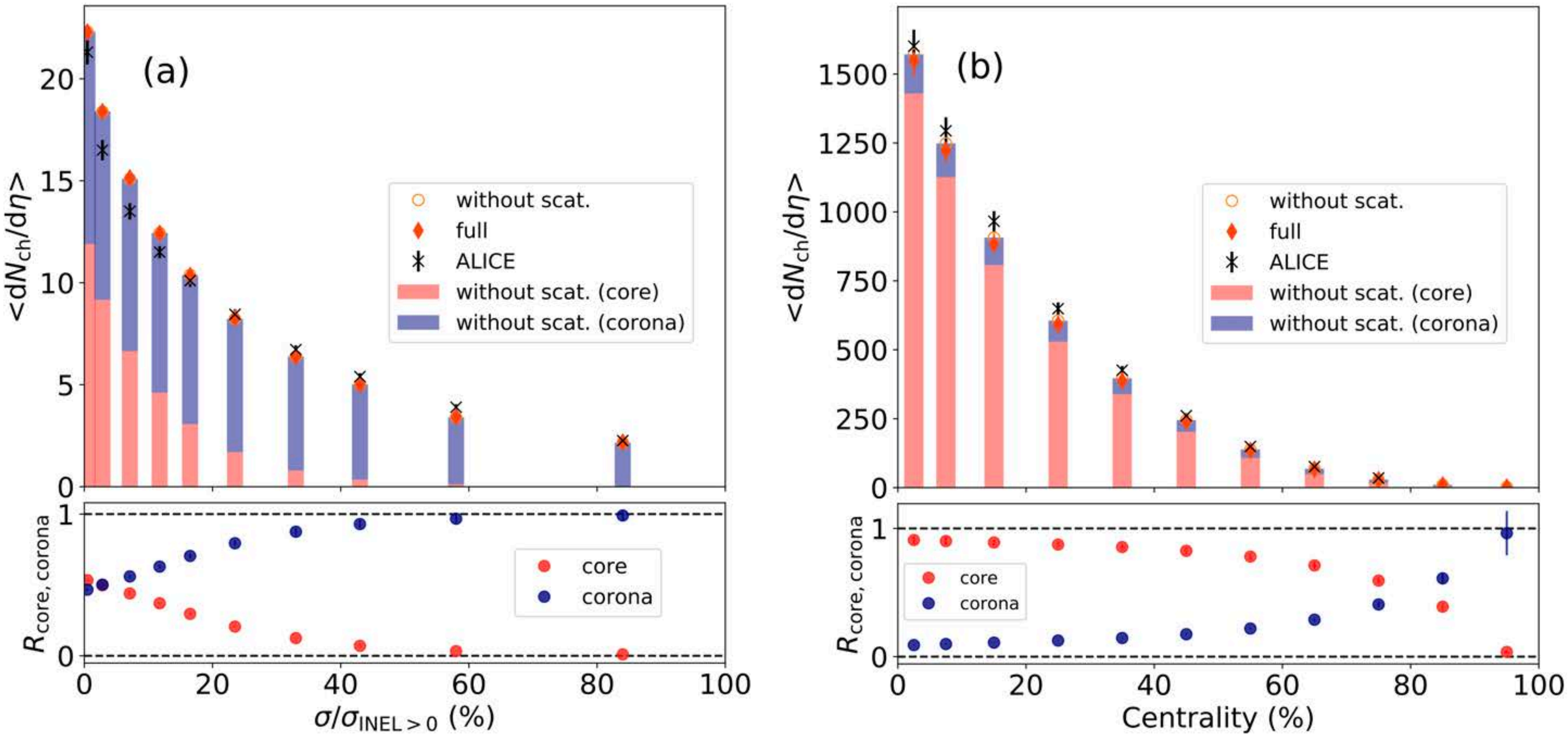
- **Core-corona composition rate**
  - Smooth multiplicity Scaling
  - Core dominance at $dN_{\rm ch}/d\eta \gtrsim 20$ (even in pp!)

Fluidization rate in DCCI2

Y. Kanakubo, YT, Hirano, PRC 105, no.2, 024905 (2022)

pp, $\sqrt{s_{\mathrm{NN}}} = 7$ TeV

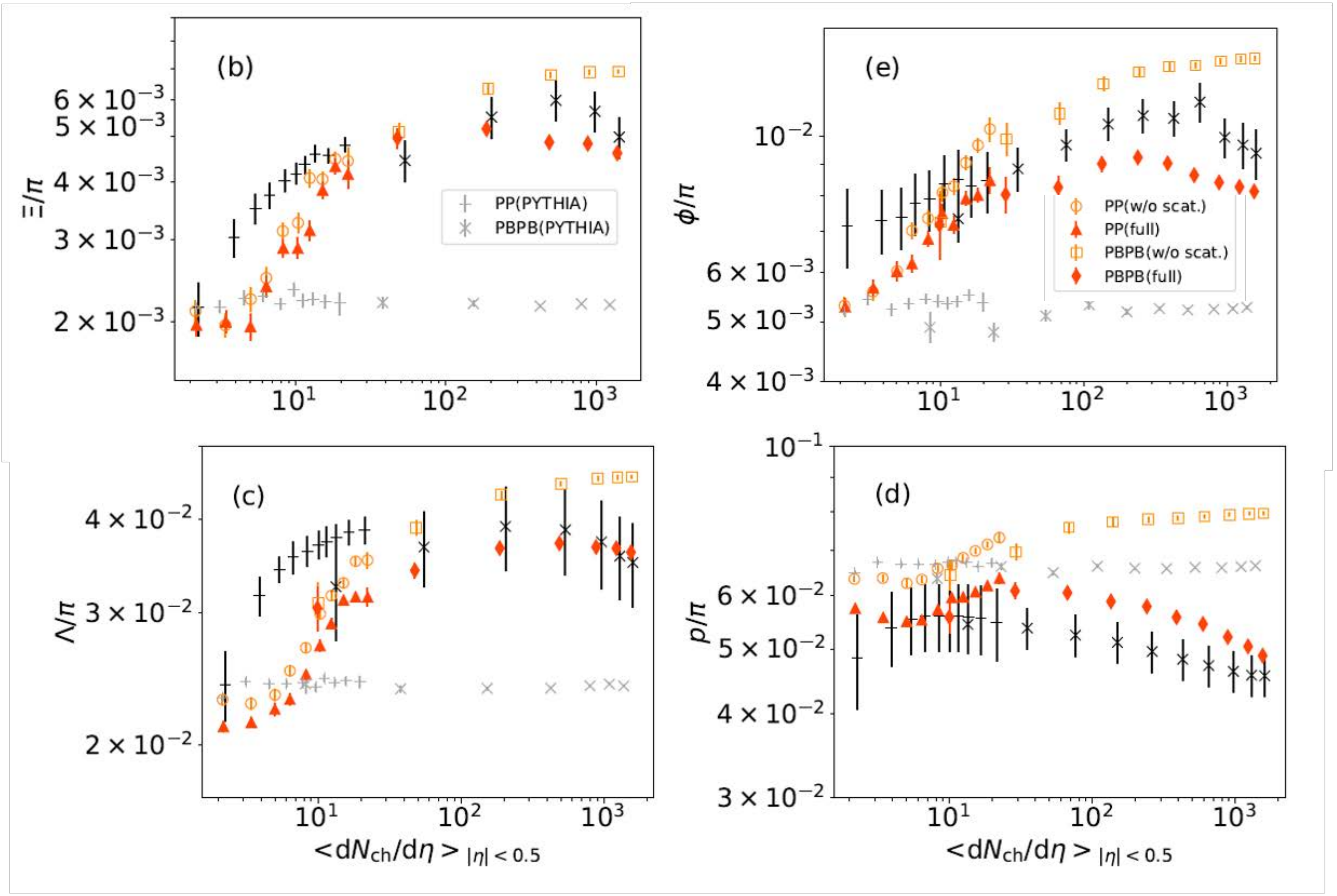
PbPb, $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV



Significant contribution from both core and corona in wide ranges

Hadron composition from DCCI2

Y. Kanakubo, YT, Hirano, PRC 105, no.2, 024905 (2022)



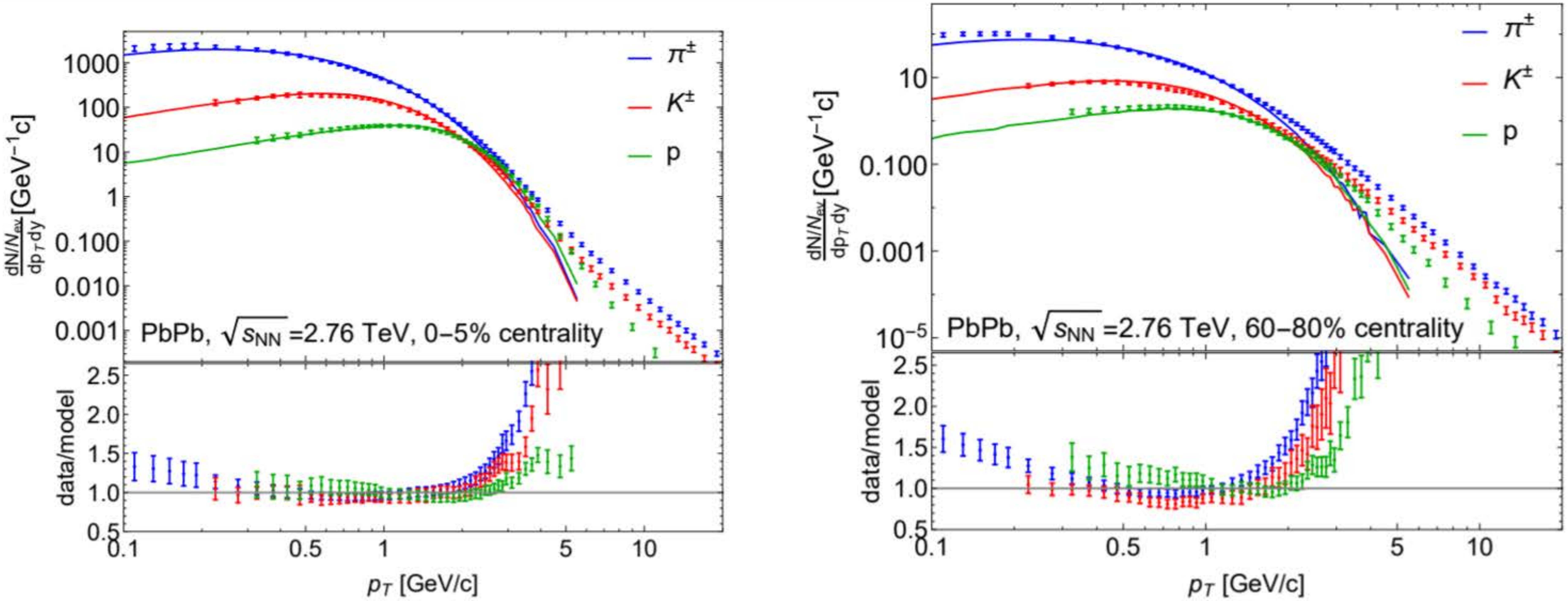
- **Multiplicity dep. of yeild ratios**
  - No further parameter tuning
  - Capture the trends
  - Dissociation/annihilation in hadronic scattering even in low-multiplicity

Puzzle: Very soft particles from hydro models

- Naive expectation: Soft particle spectra ←fluid (core) component dominant

Example) Trajectum (conventional hydro-based model)

G. Nijs et al., Phys. Rev. C 103, 054909 (2021)



Puzzle: Very soft particles from hydro models

- Naive expectation: Soft particle spectra ←fluid (core) component dominant

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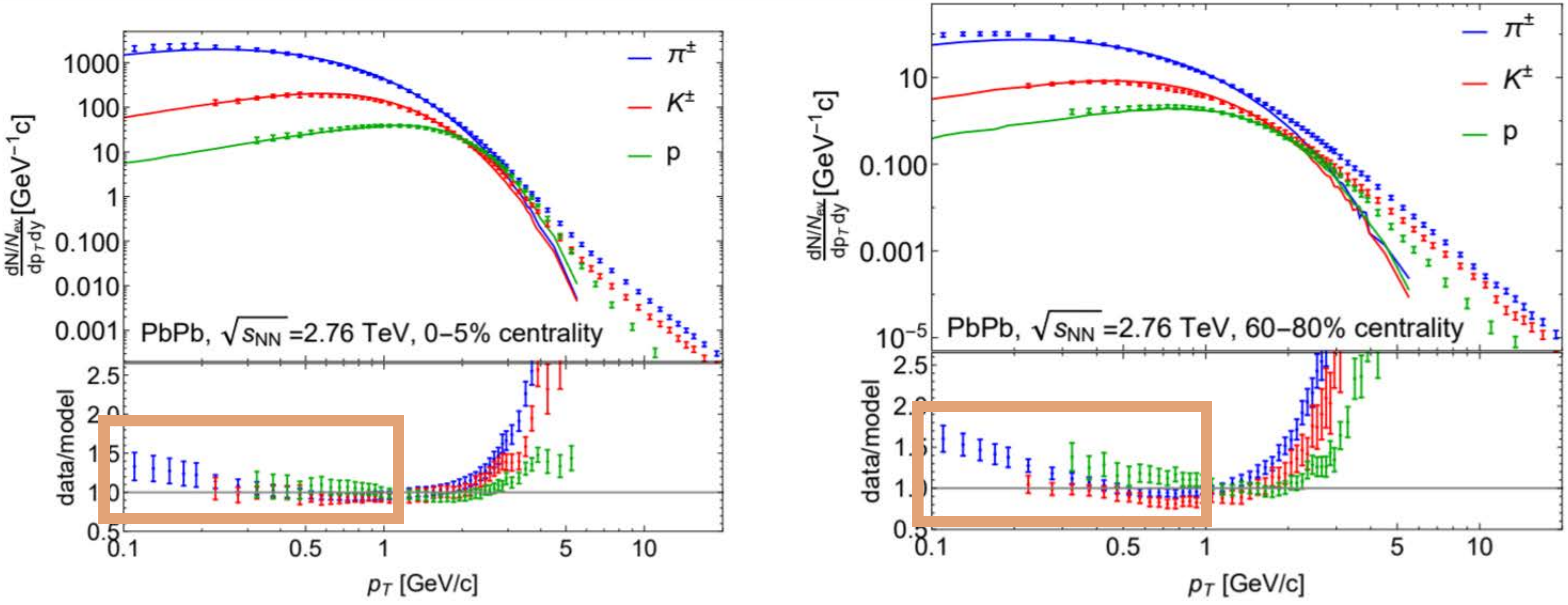
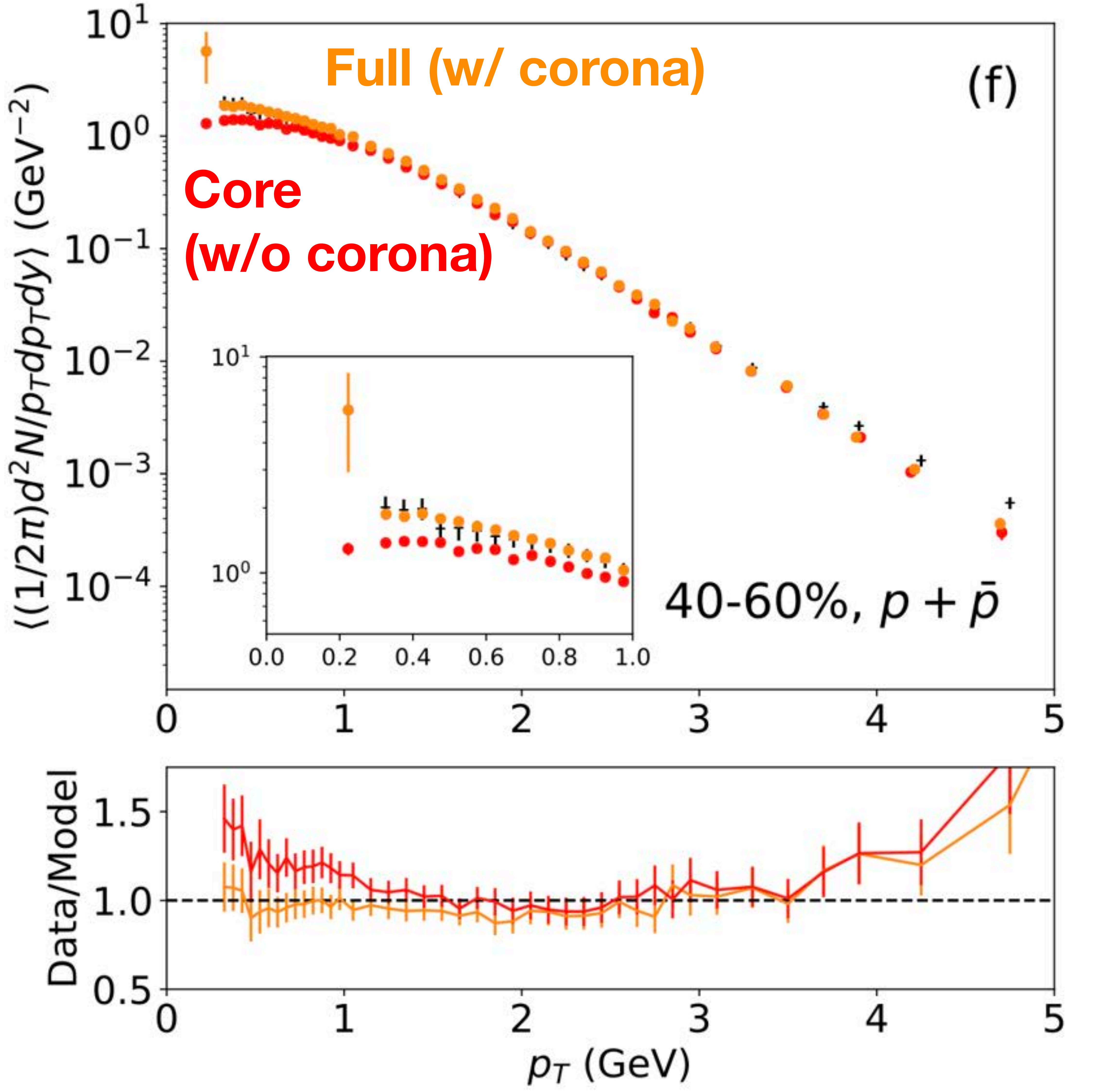


Lack of soft particles ($p_T \lesssim 0.5$ GeV)

Soft particles from DCCI2

Y. Kanakubo, YT, Hirano, PRC 105, no.2, 024905 (2022)



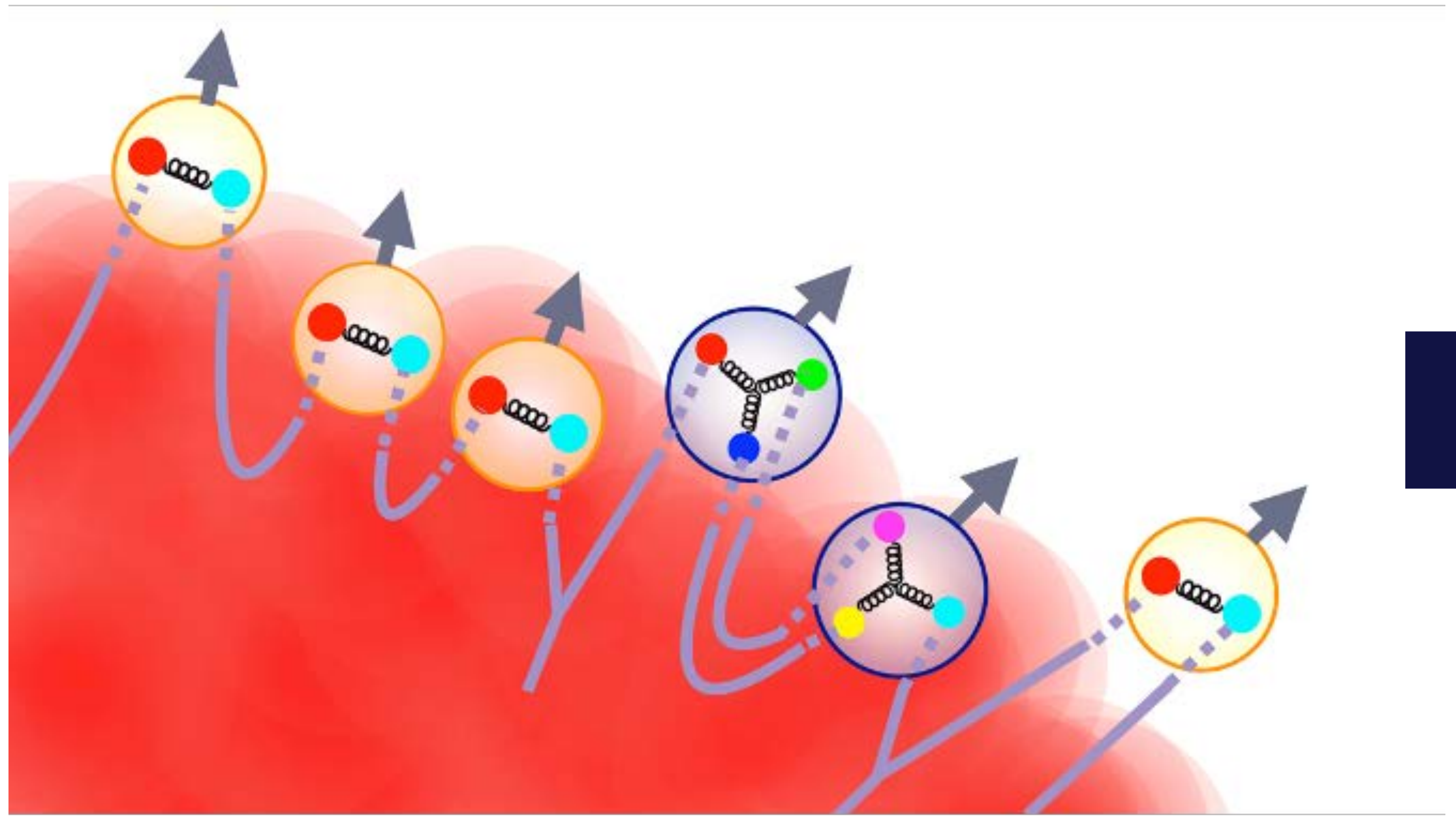
- **Non-eq. corona component**
  - Dominant at very low-p_T

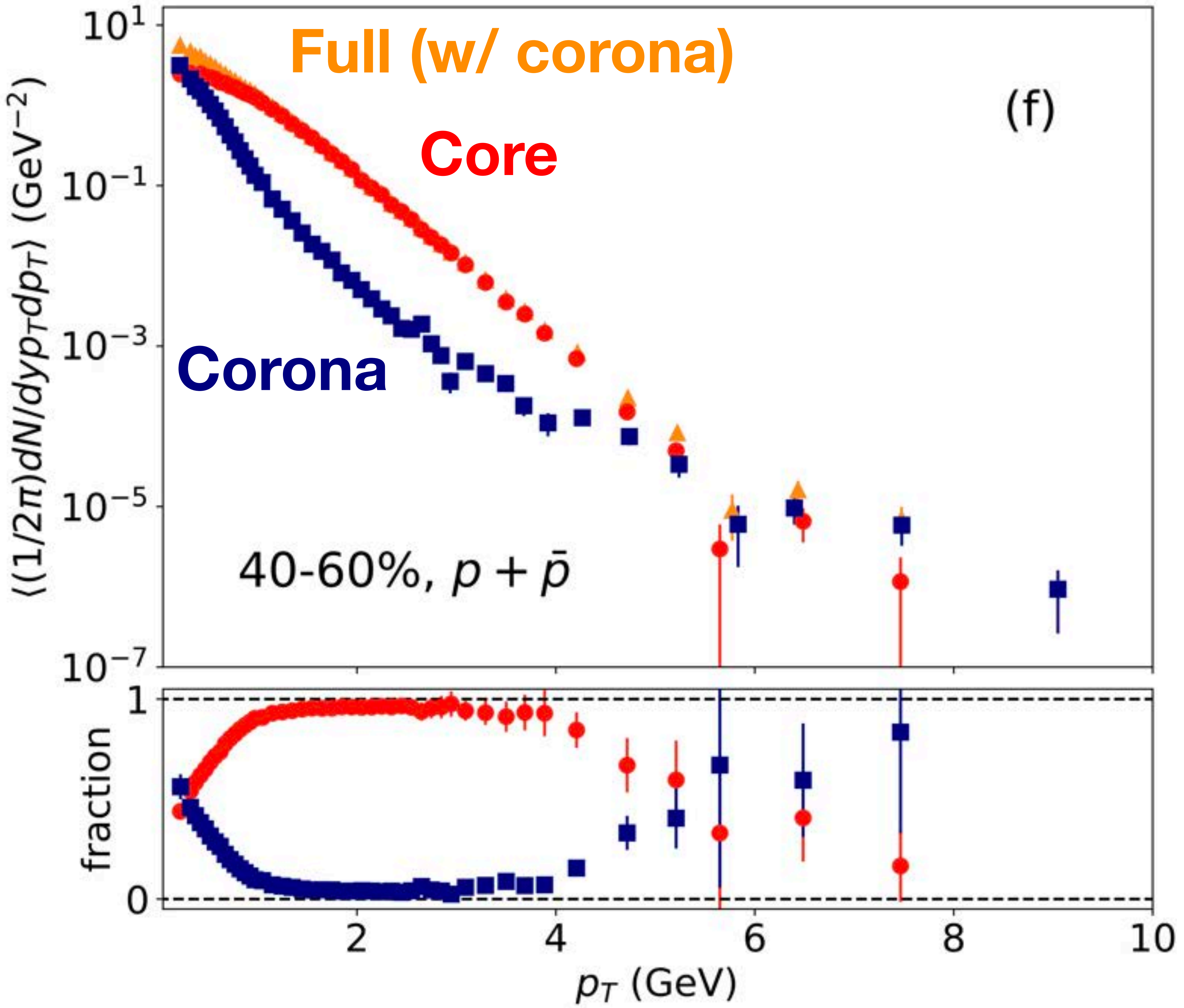
Compensate the yield shortage from hydro

Soft particles from corona

Y. Kanakubo, YT, Hirano, PRC 105, no.2, 024905 (2022)

- **Partons in corona component**
  - Produced according to power law
  - Soften via hydrodynamization but hard enough to survive as non-eq. partons
  - Fragmented into soft hadrons





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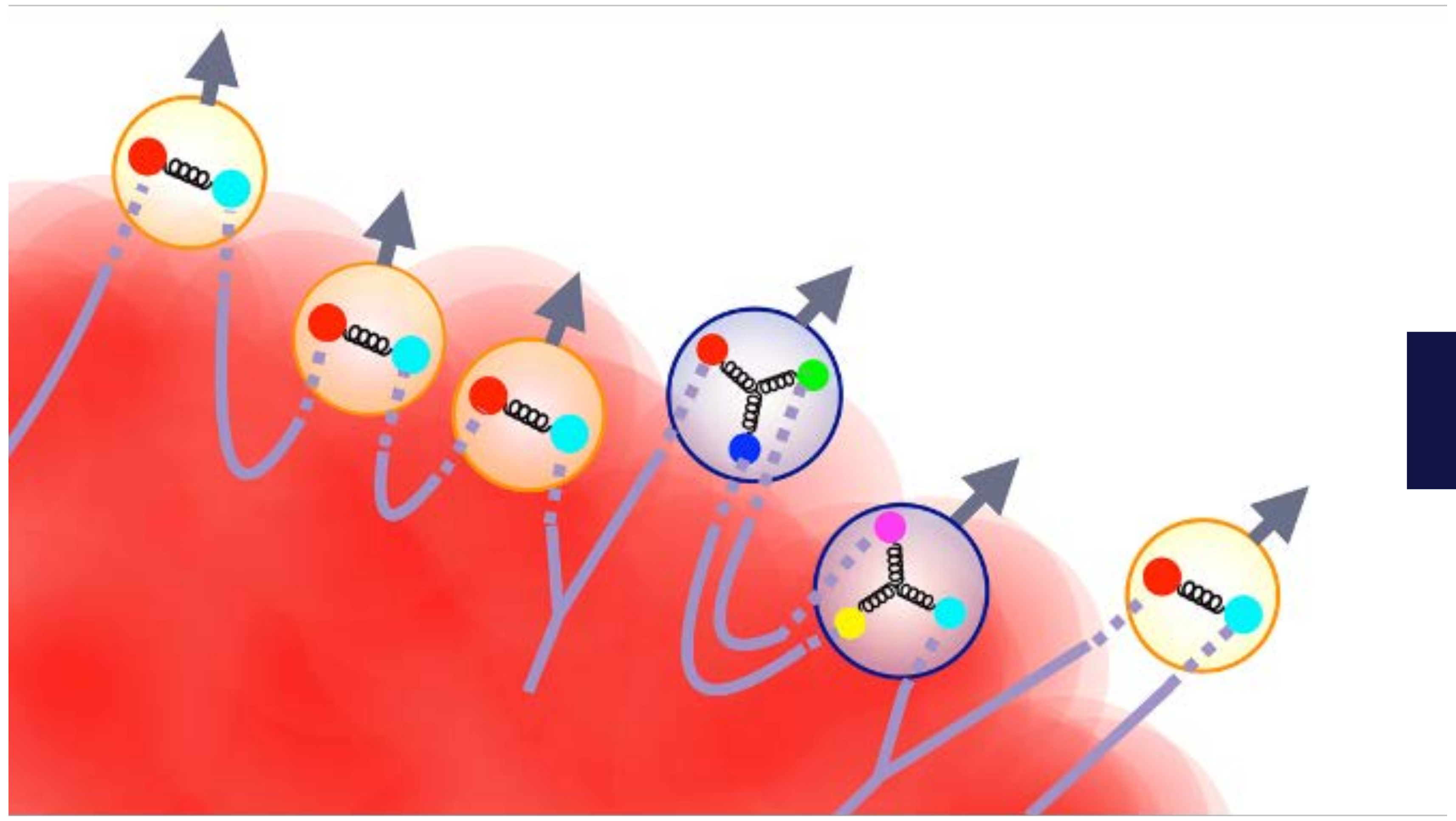
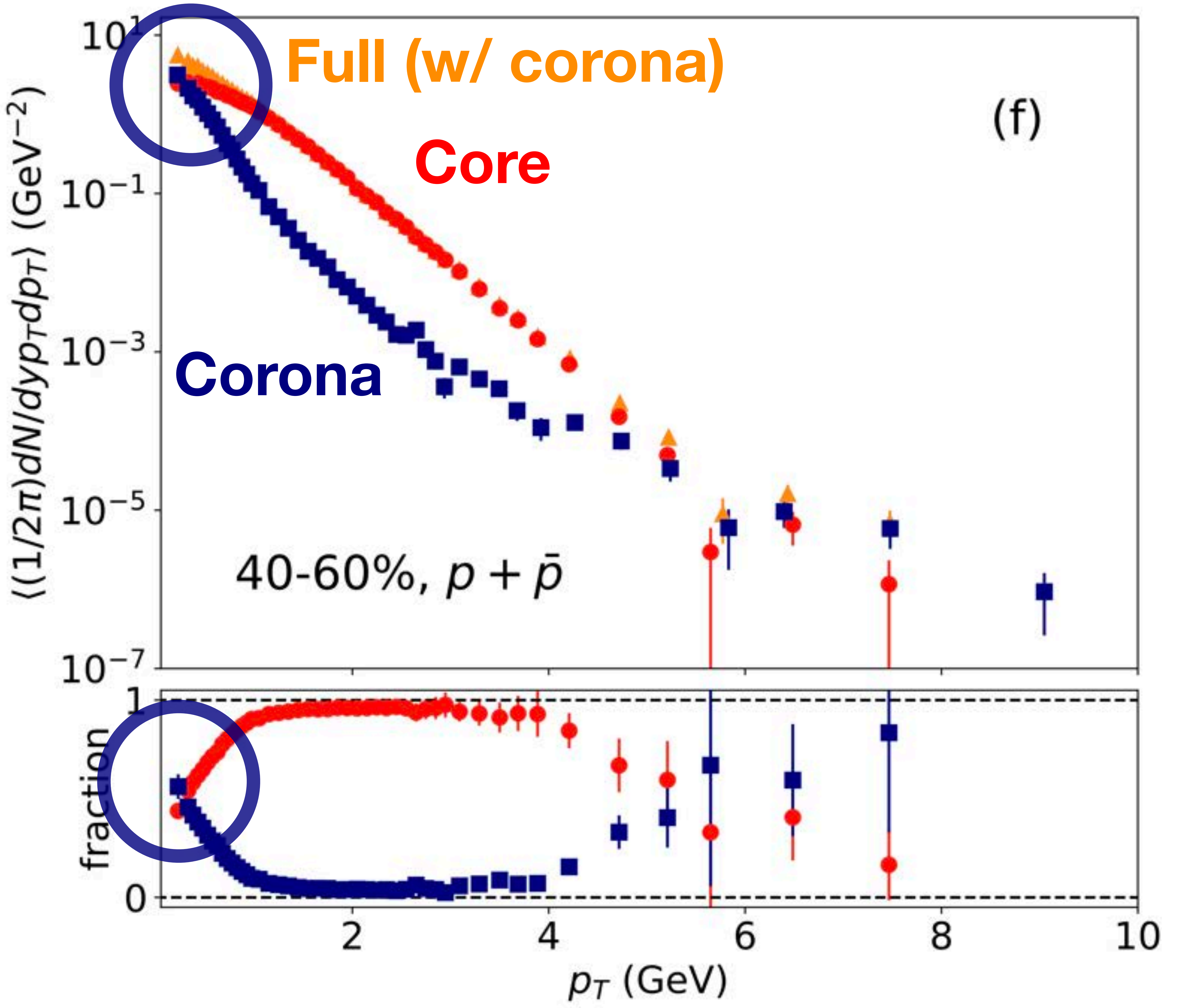
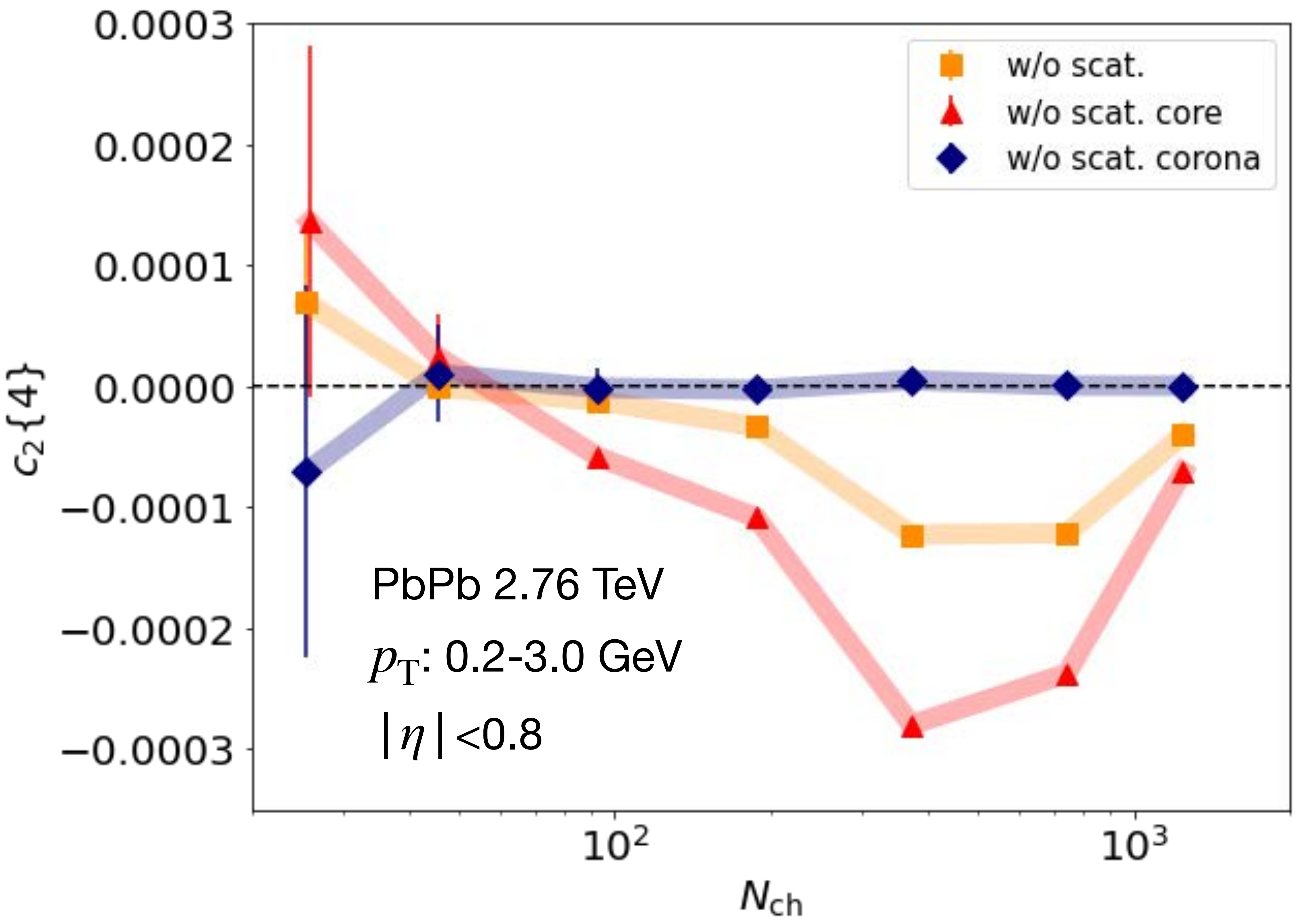




Effect on studies of QGP transport properties

Y. Kanakubo, YT, Hirano, PRC 105, no.2, 024905 (2022)



- **Corona contributions to flow observables**
  - Weaker collectivity manifestation than pure fluid (core) contribution
  - Simulations without corona → miss-extraction of transport coefficients
  - Contribution from corona to polarized hadrons measured in HIC?

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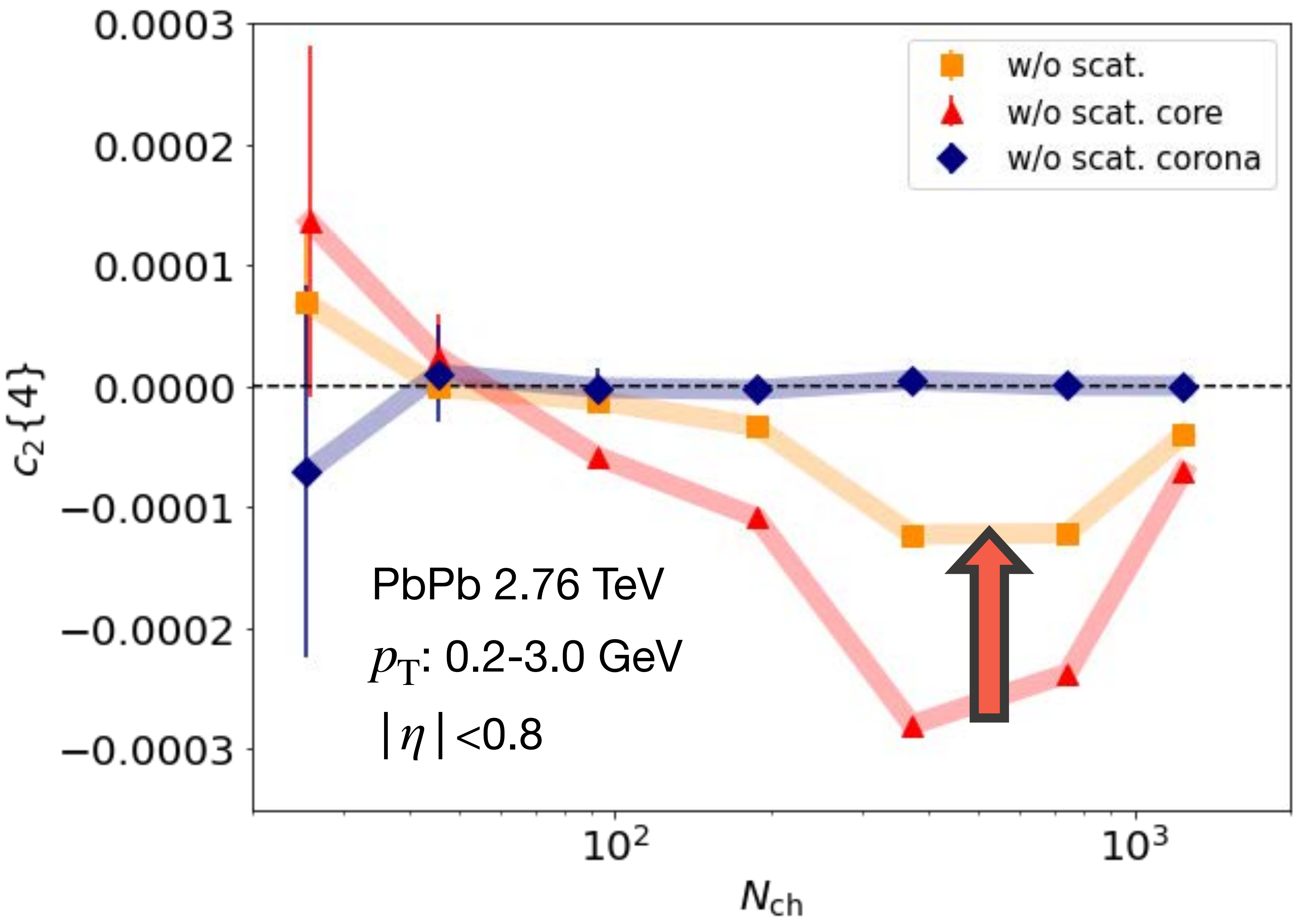

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    → miss-extraction of transport coefficients
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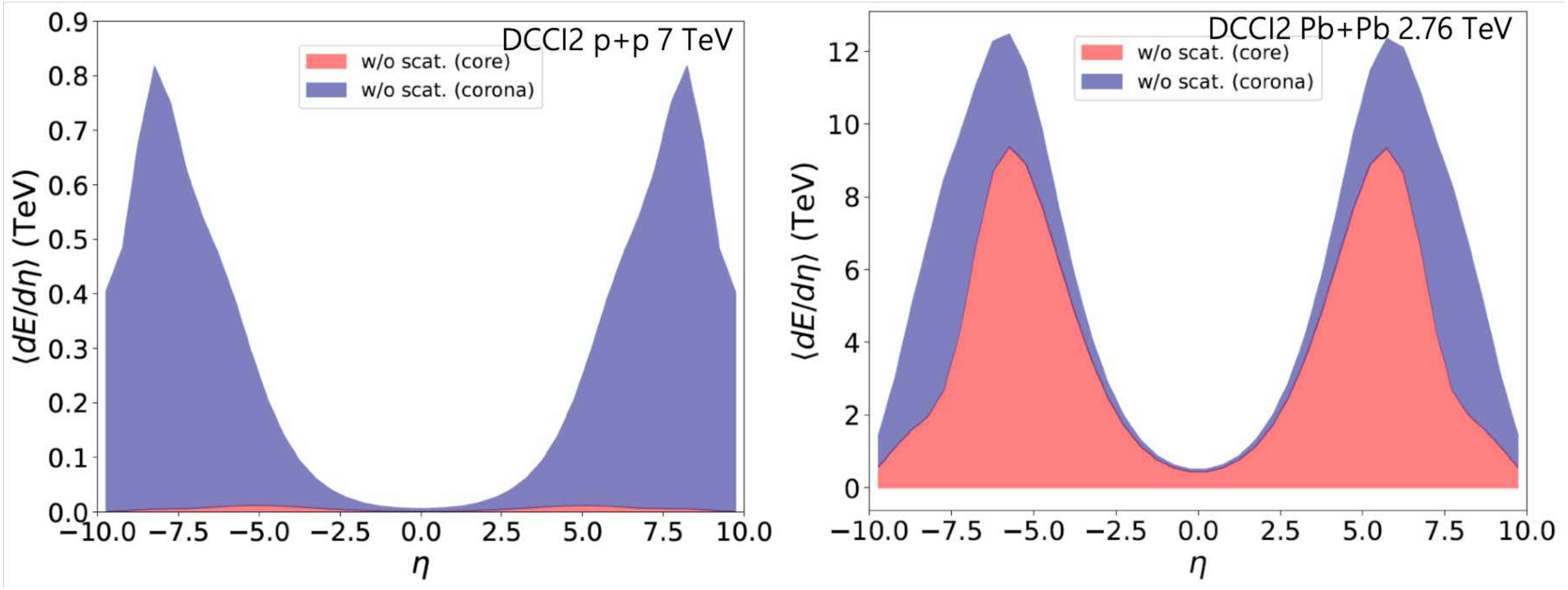
Summary and overlook

- **Dynamical core-corona initialization (DCCI)**
  - Provide appropriate space-time dependence for QGP fluid production
  - Smooth separation between equilibrated fluids (core) and nonequilibrated partons (corona)
  - Unified description applicable from small to large systems
  - Initial flow with geometrical fluctuation → **Vorticity in QGP fluid produced in HIC?**

- **Fluidization rate extracted from hadron composition with DCCI**
  - Switches to core (fluid) dominance at $dN_{\mathrm{ch}}/d\eta \gtrsim 20$ even in pp
  - $\gtrsim 15\ \%$ of hadrons from corona even in central PbPb

- **Corona dominance at very low-p_{T} in large systems**
  - Resolve the issue of insufficient particle production in hydro models
  - Significantly impact QGP transport coefficients estimation from bulk observables
  - **Corona contribution to polarized hadron measured in HIC?**

Longitudinal profile of core-corona composition



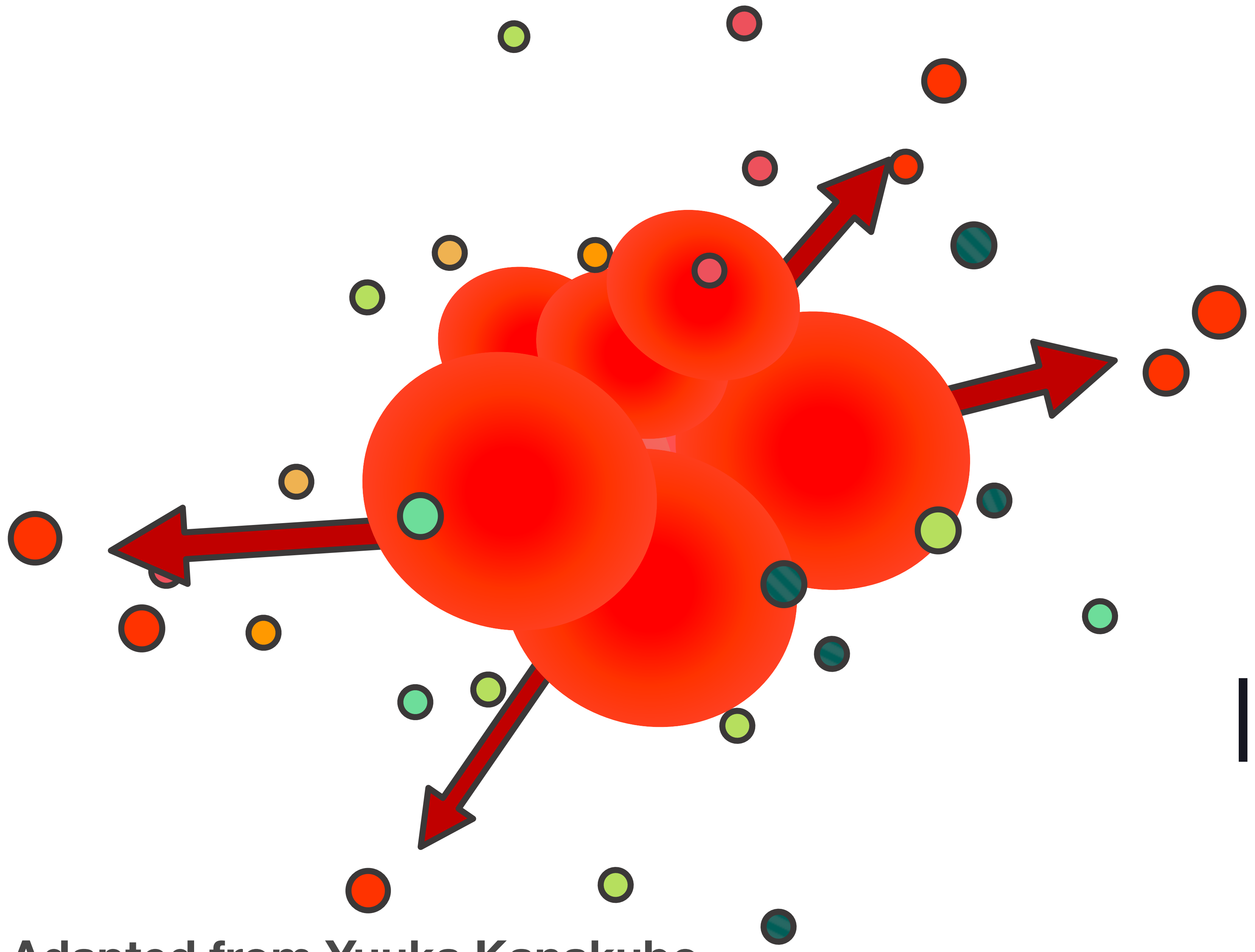
- More corona in baryon-rich forward region in HIC → Effects on transported quarks?

Dynamical Core-corona Picture

Y. Kanakubo, *et al.*, PTEP 2018, no.12, 121D01 (2018), PRC 101, no.2, 024912 (2020), PRC 105, no.2, 024905 (2022)

- **Source term from interaction rates among partons**

$$J^\nu(x) = \sum_{i \in \text{non-eq. partons}} \left[-\frac{dp_i^\nu}{dt} \right] \rho\left(\vec{x} - \vec{x}_i(t)\right), \quad \frac{dp_i^\nu}{dt} = \sum_{\substack{j \in \text{partons} \\ j \neq i}} \sigma_{ij} |\vec{v}_{ij}^{\text{rel}}| p_i^\nu \rho\left(\vec{x}_j(t) - \vec{x}_i(t)\right),$$



Adapted from Yuuka Kanakubo

$$\sigma_{ij} = \min\left\{ \frac{\sigma_0}{s_{ij}/[1\ (\text{GeV}^2)]}, \pi b_{\text{cut}}^2 \right\}$$

$s_{ij} = (p_i^\mu + p_j^\mu)^2$

b_{cut}: infra-cut

$$|\vec{v}_{ij}^{\text{rel}}| = \left| \frac{\vec{p}_j}{p_j^0} - \frac{\vec{p}_i}{p_i^0} \right|$$

→ suppress interactions between partons in the same shower

Corona components from string modification

String modification caused by ..

- Spatial overlap of strings and medium
- Completely fluidized partons

1. Discard dead partons
2. Find hypersurface boundaries T_{sw}
3. Sample partons & boost with v_{fluid} at the boundary (recreation of color singlet)

Courtesy from Yuuka Kanakubo

Corona components from string modification (cont'd)

4. Surviving partons traverse medium
5. Make a pair for a parton coming out from medium

*$p_{T,\,\mathrm{cut}}$: threshold to/not to modify a string

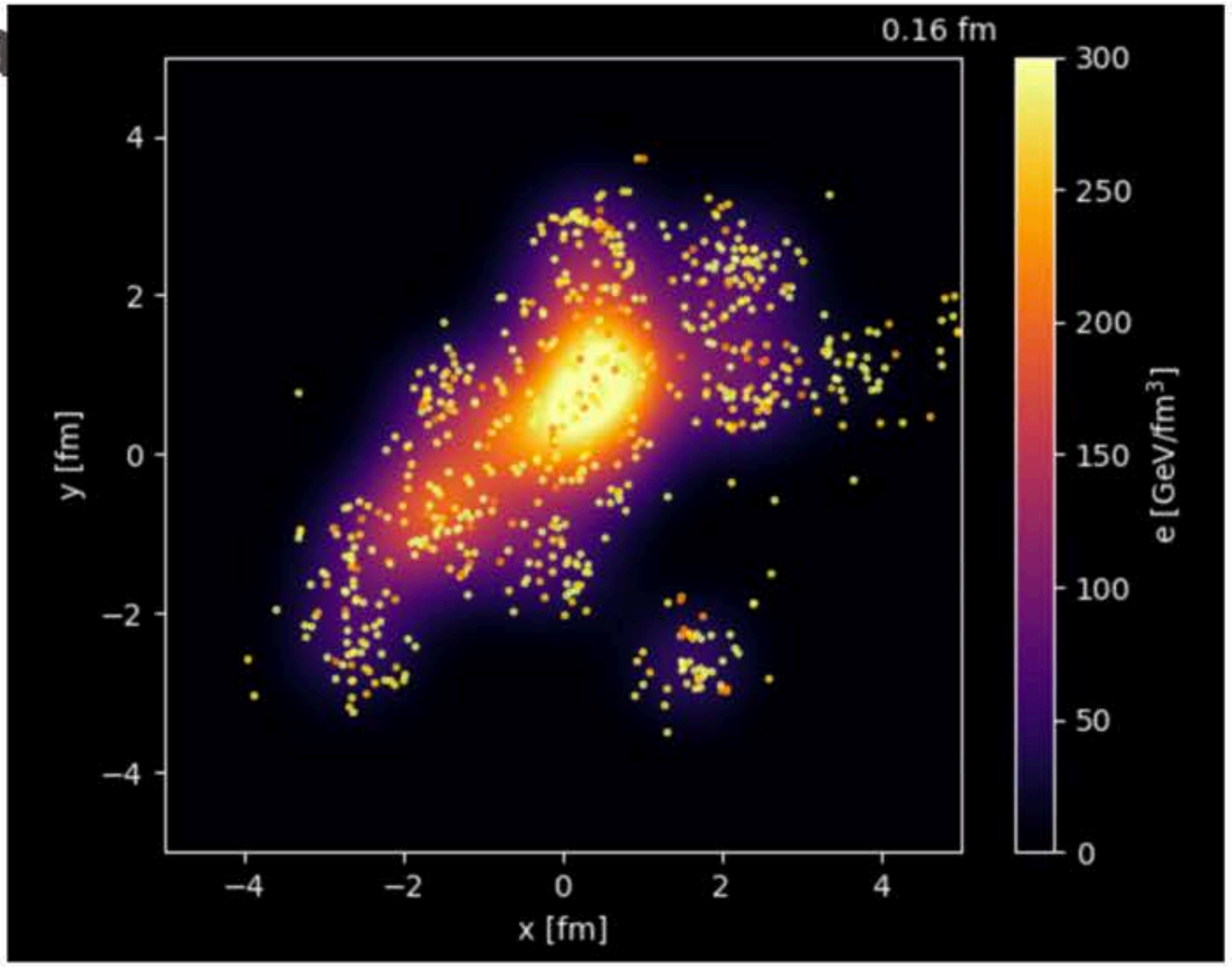
Non-thermal & thermal
→ Contributes as corona components

Courtesy from Yuuka Kanakubo

Collision with constituent partons of QGP fluids

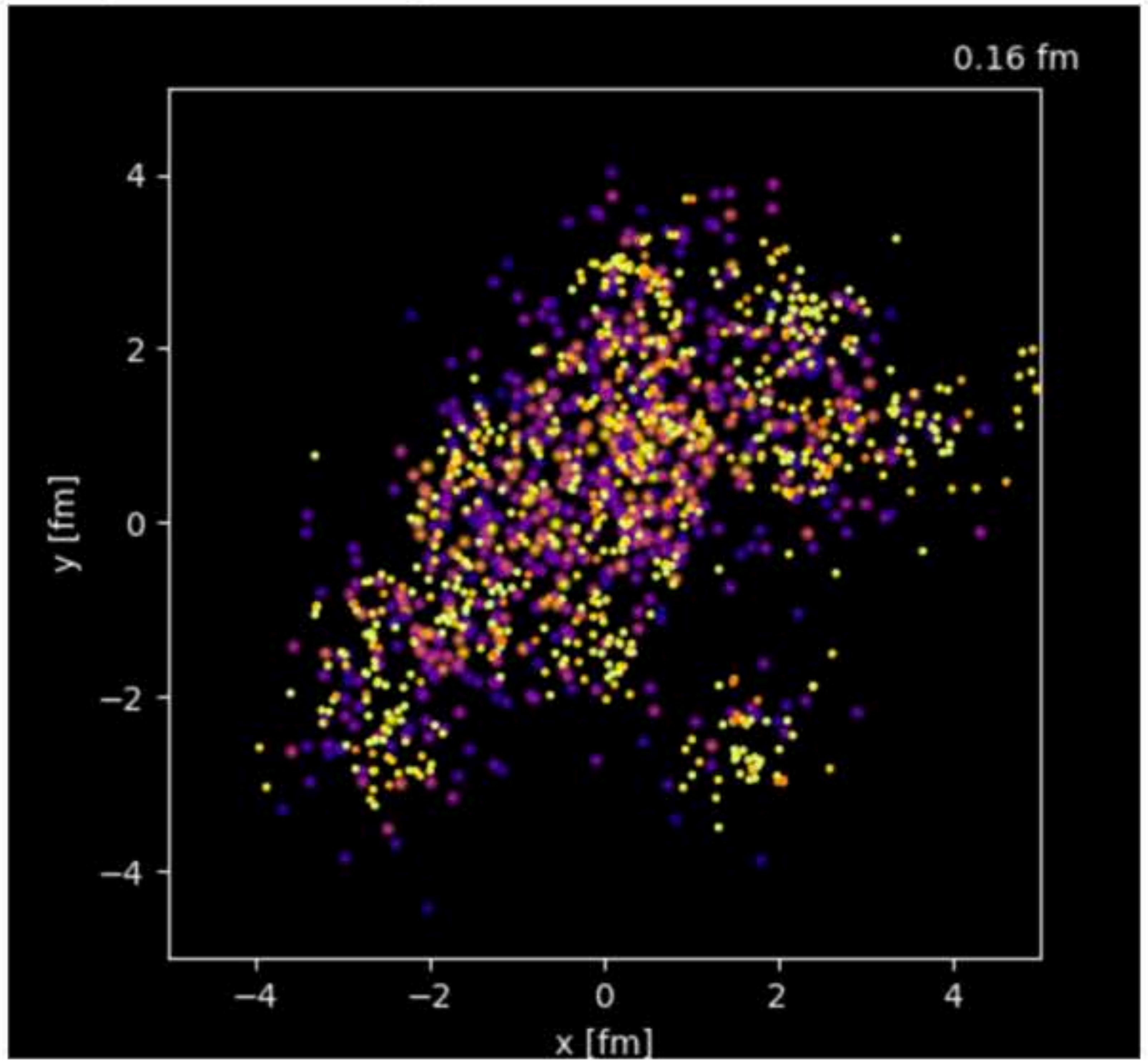
$$\frac{dp_i^{\mu}}{d\tau} = -\sum_{j}^{N_{\rm scat}} \rho_{i,j}\sigma_{i,j}\left|v_{{\rm rel},\,i,j}\right| p_i^{\mu}$$

➔ **Applied to both core (QGP fluids) and corona (non-equilibrated pa**



Sampling of equilibrated partons at each time step

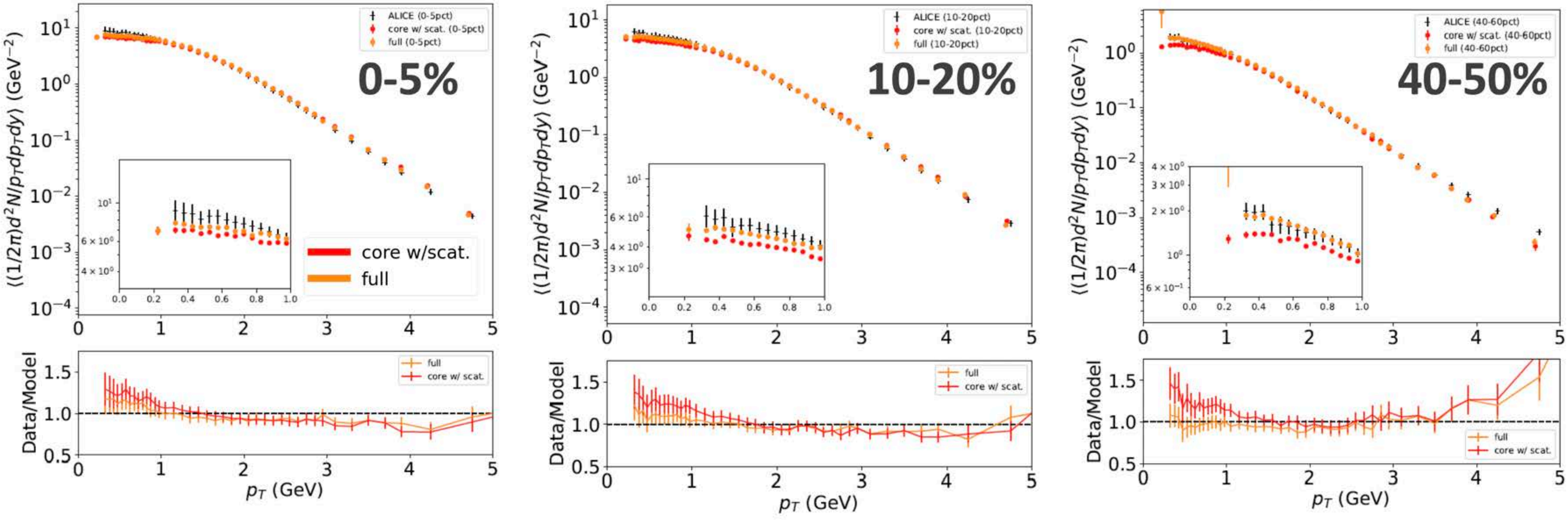
*with mass-less ideal gas approximation



Courtesy from Yuuka Kanakubo

Comparison with exp. data

PbPb 2.76 TeV, $p + \bar{p}$



ALICE Collaboration, Phys. Rev. C 93 (2016) 3, 034913

Corona at very low p_T: possible compensation of yield

Courtesy from Yuuka Kanakubo

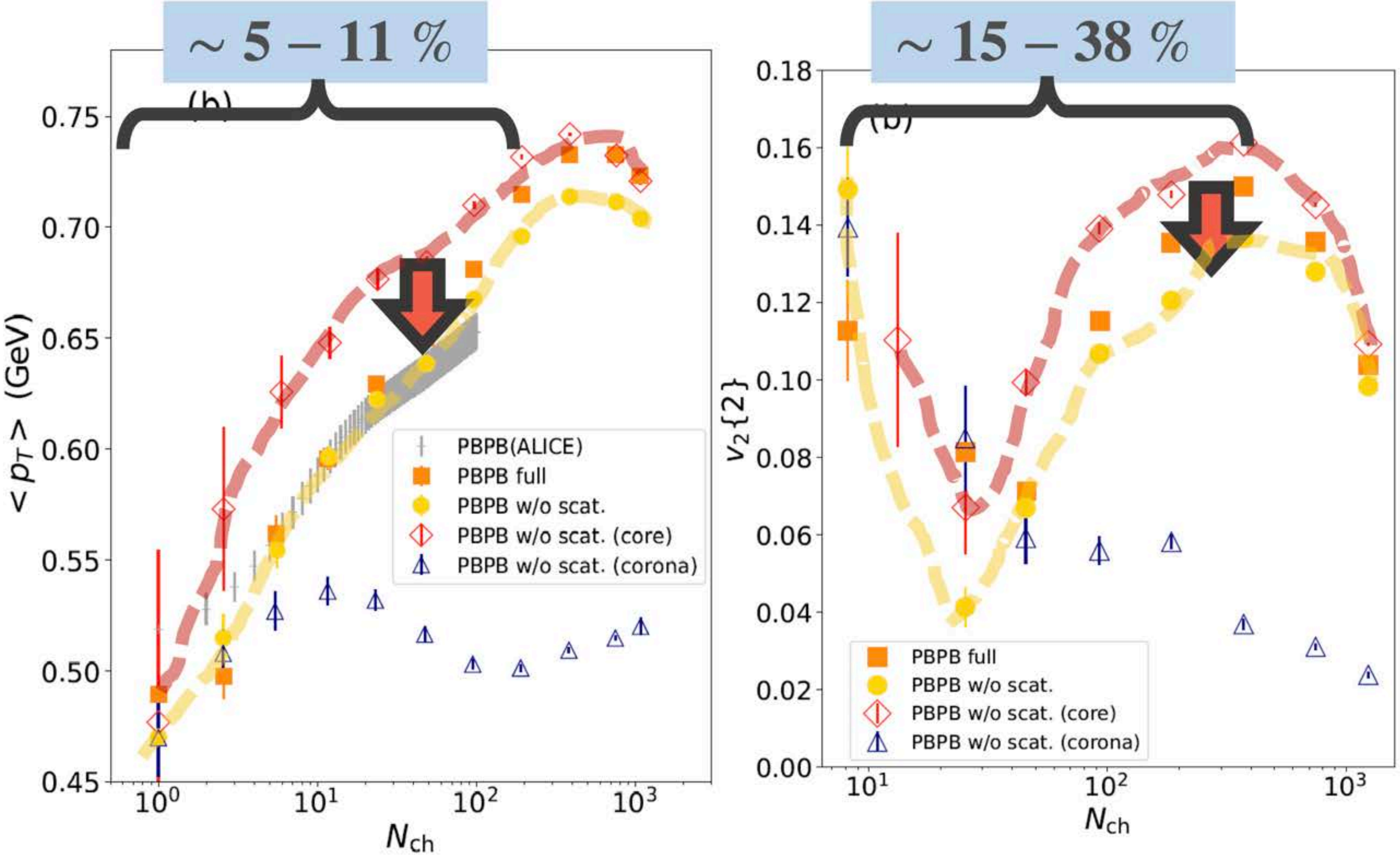
Comparison with exp. data

PbPb 2.76 TeV, $\pi^{\pm}$

Corona at very low p_T: possible compensation of yield

Courtesy from Yuuka Kanakubo

Corona correction in PbPb



- Mean p_T and momentum anisotropy → non-negligible effect of corona

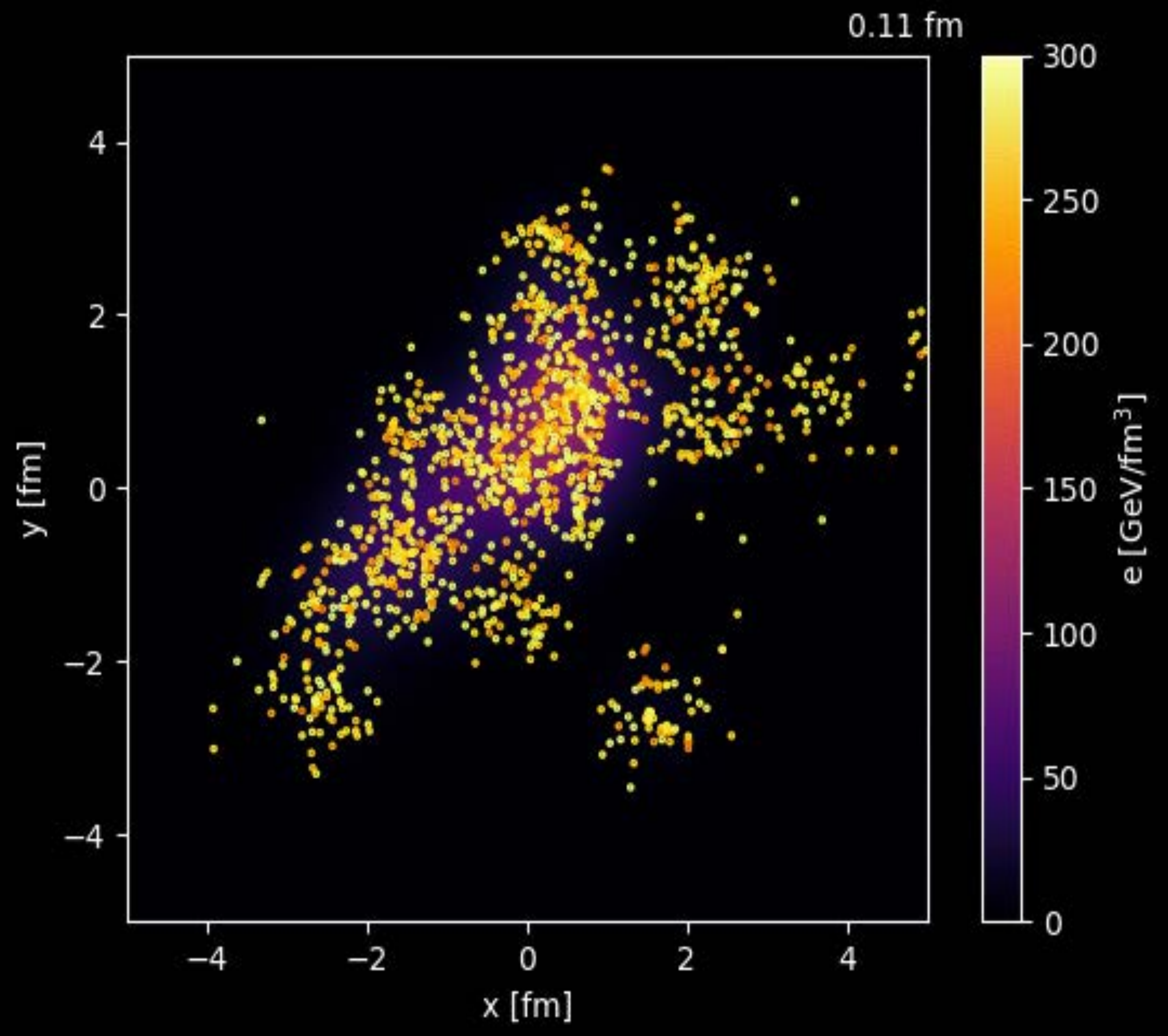
- Pure hydro calculation can bring misinterpretation of exp. data even in PBPB

Courtesy from Yuuka Kanakubo

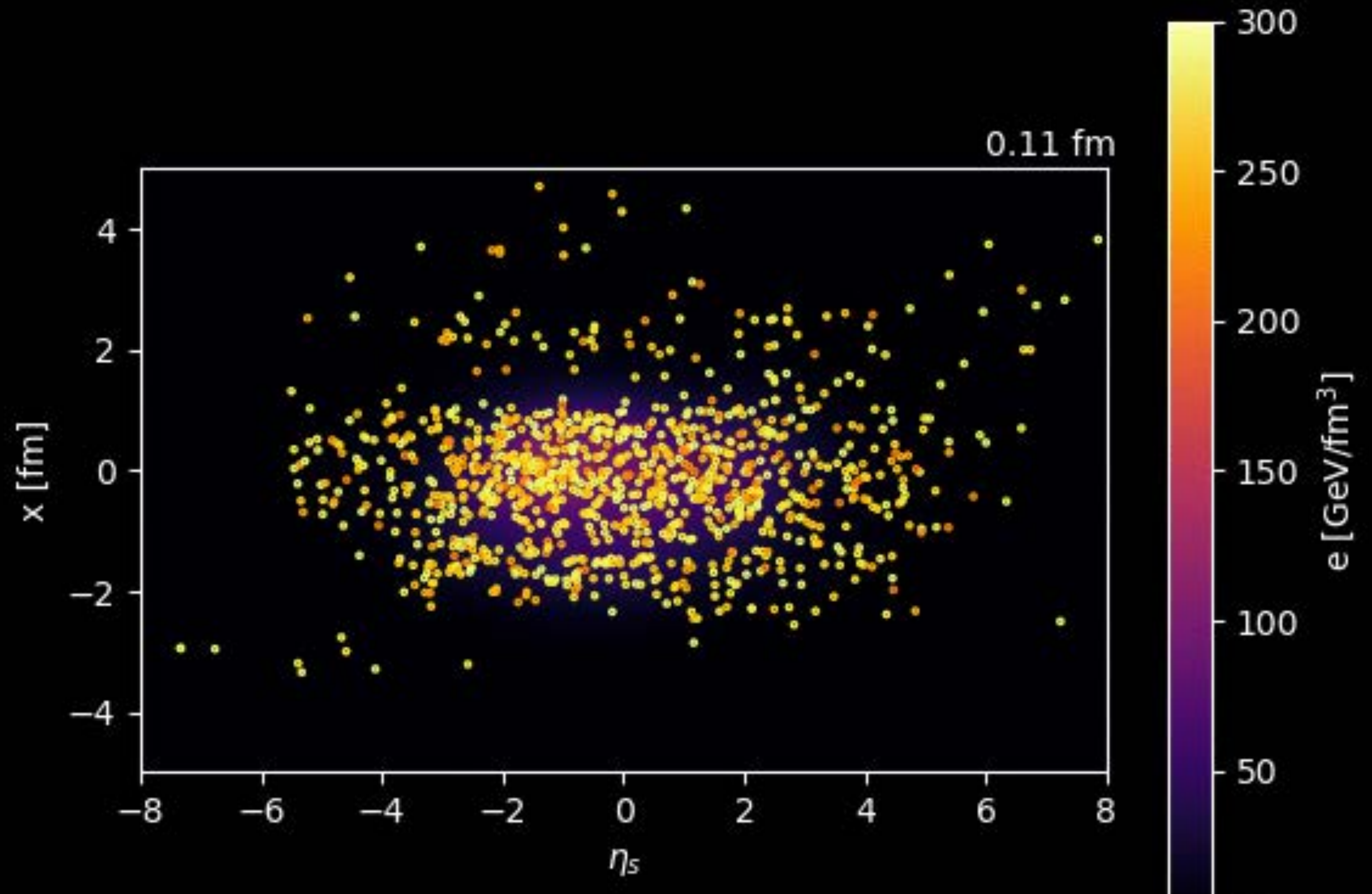
Dynamical core-corona initialization (DCCI)

PbPb, $\sqrt{s_{NN}} = 2.76$ TeV

Transverse ($|\eta_s| < 0.5$)



Longitudinal ($|y| < 0.5$)



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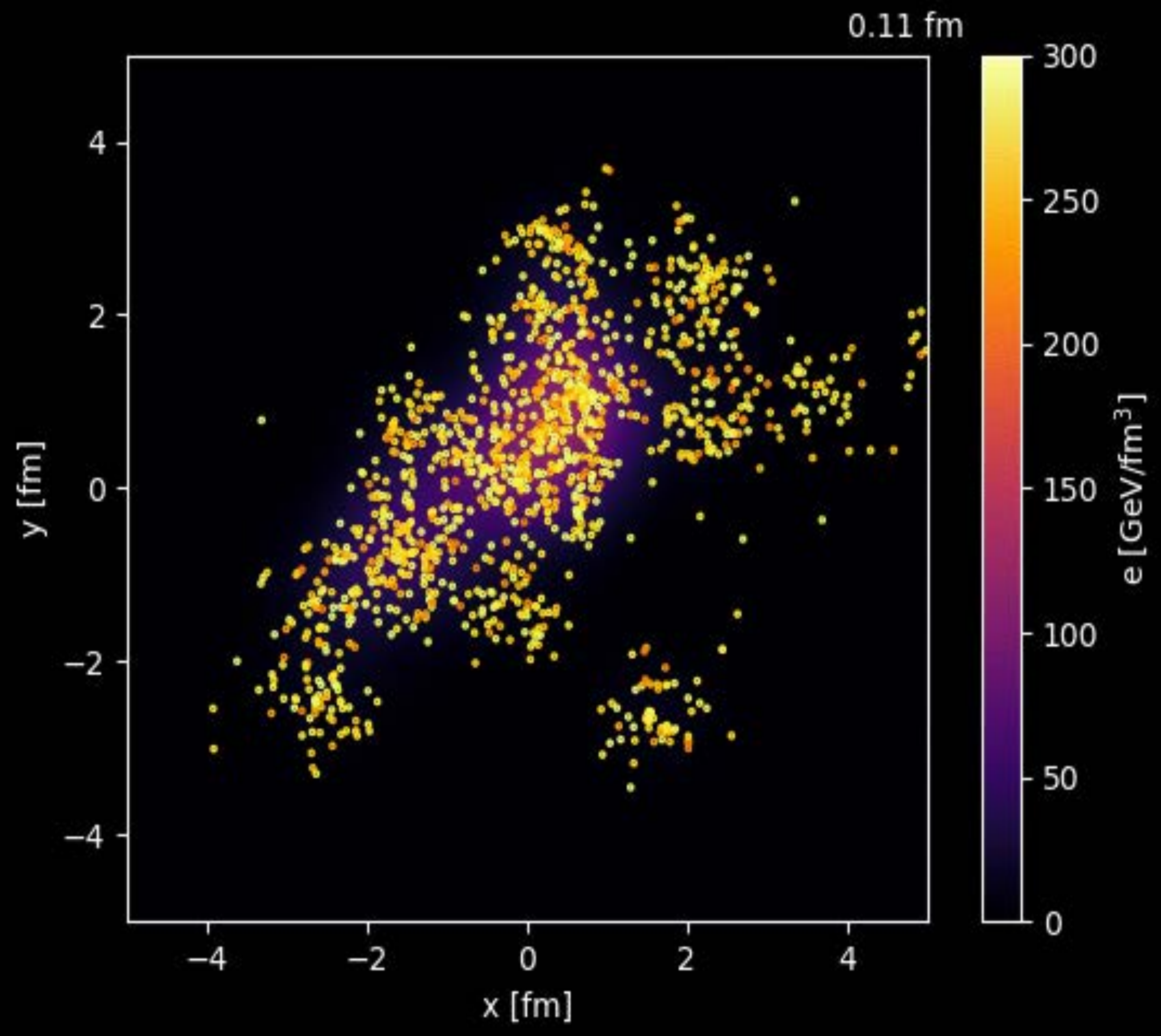

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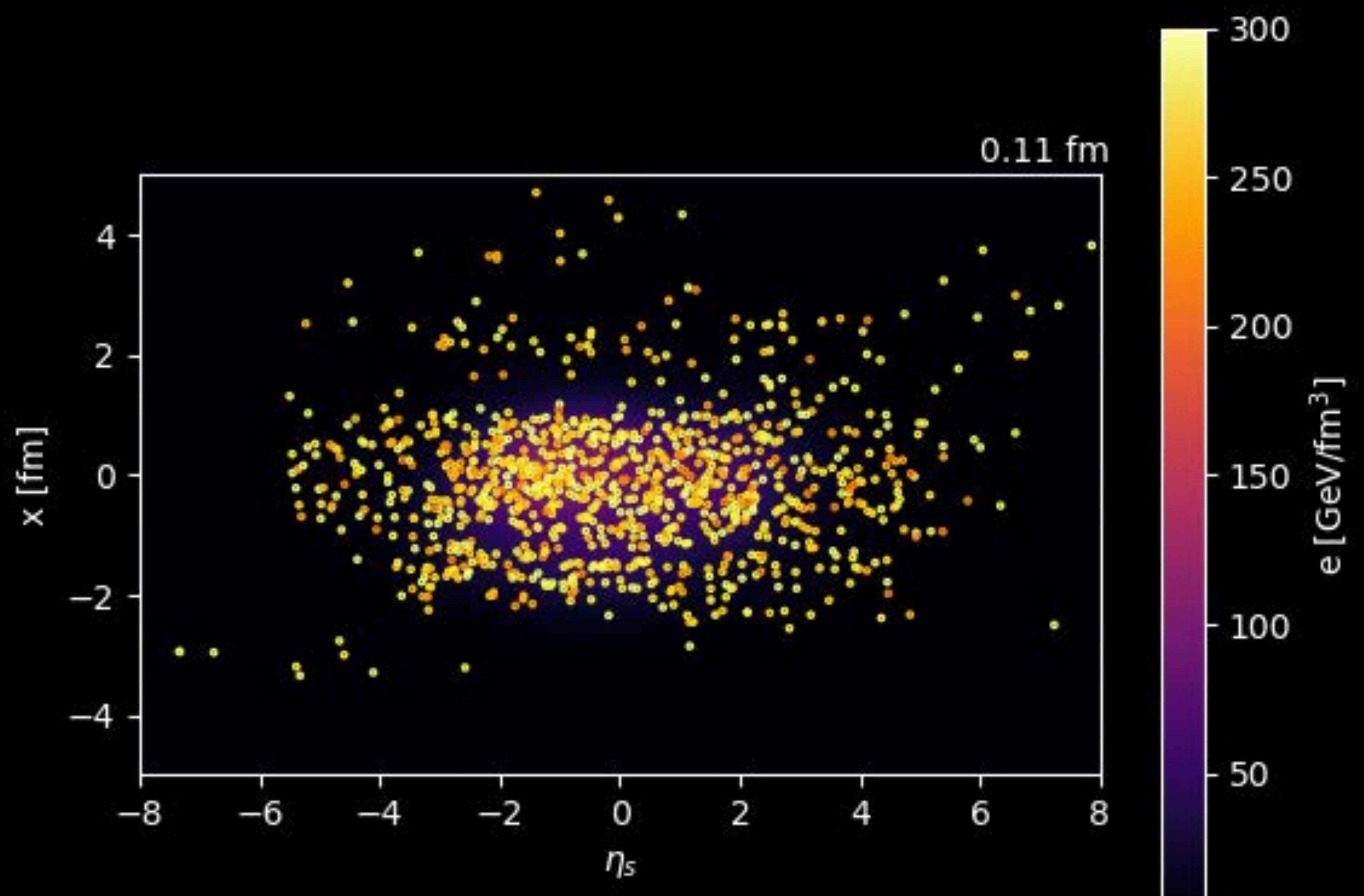

Courtesy from Yuuka Kanakubo

Dynamical core-corona initialization (DCCI)

pp, $\sqrt{s_{\mathrm{NN}}} = 7$ TeV

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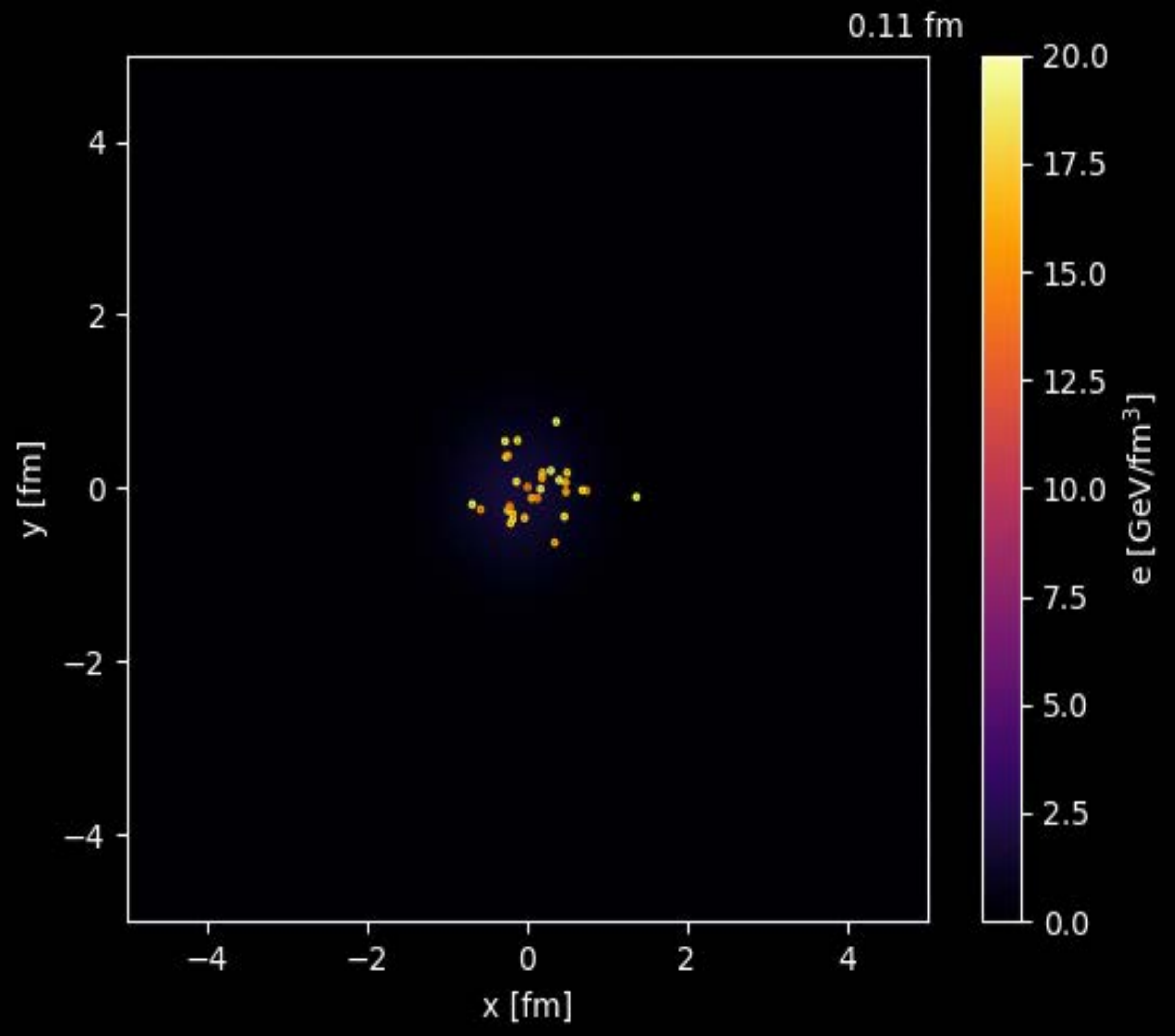

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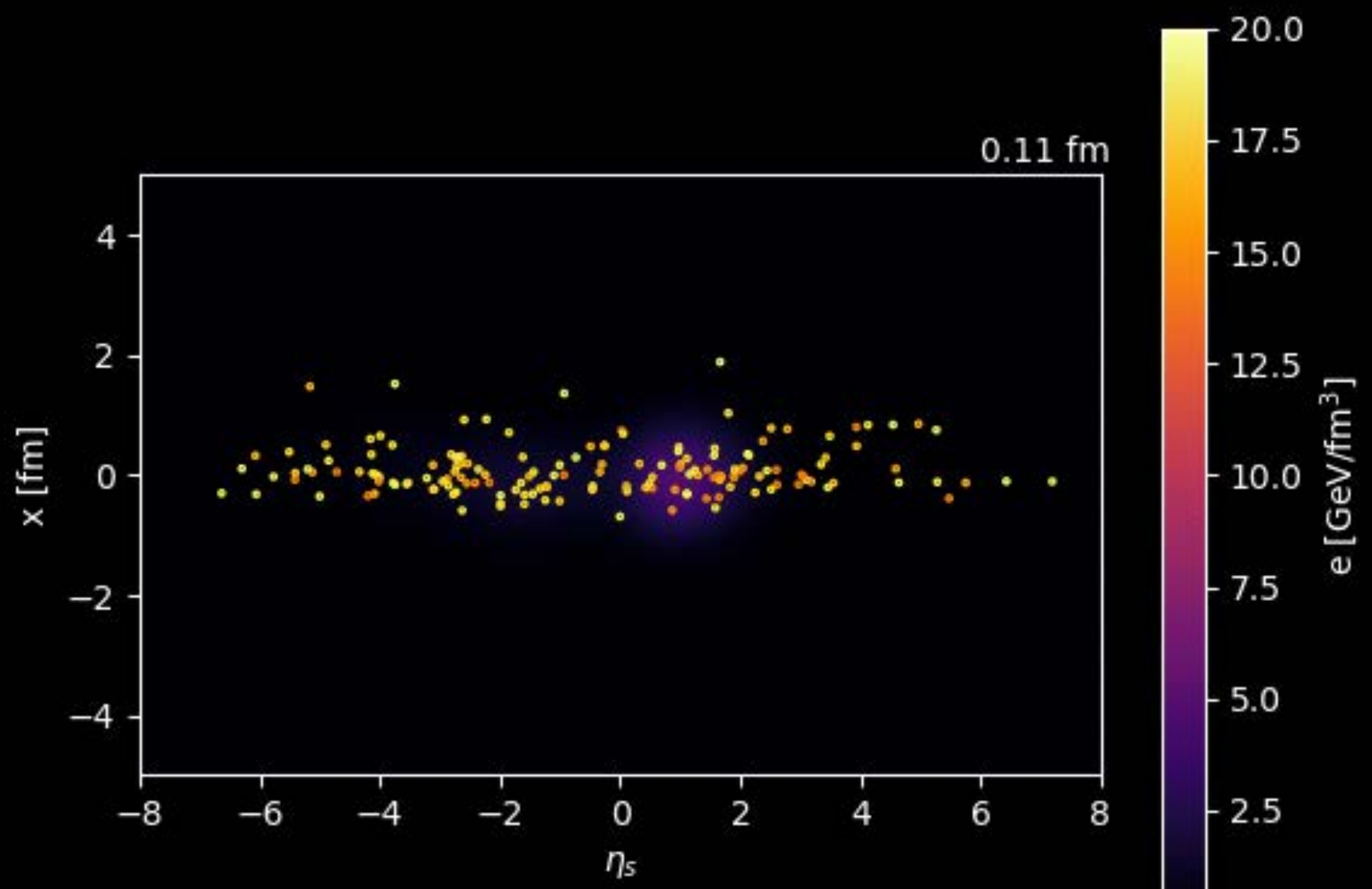

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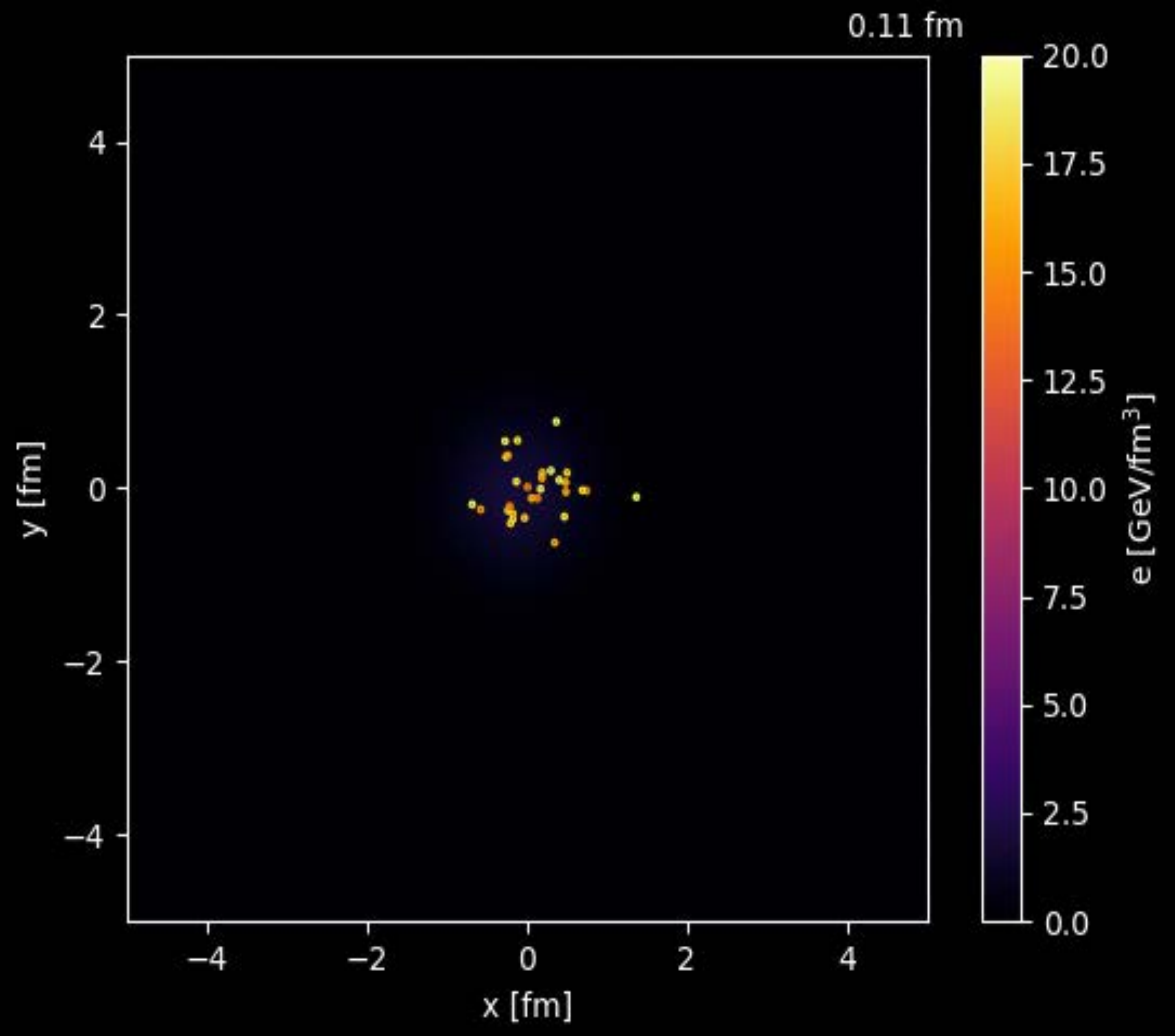

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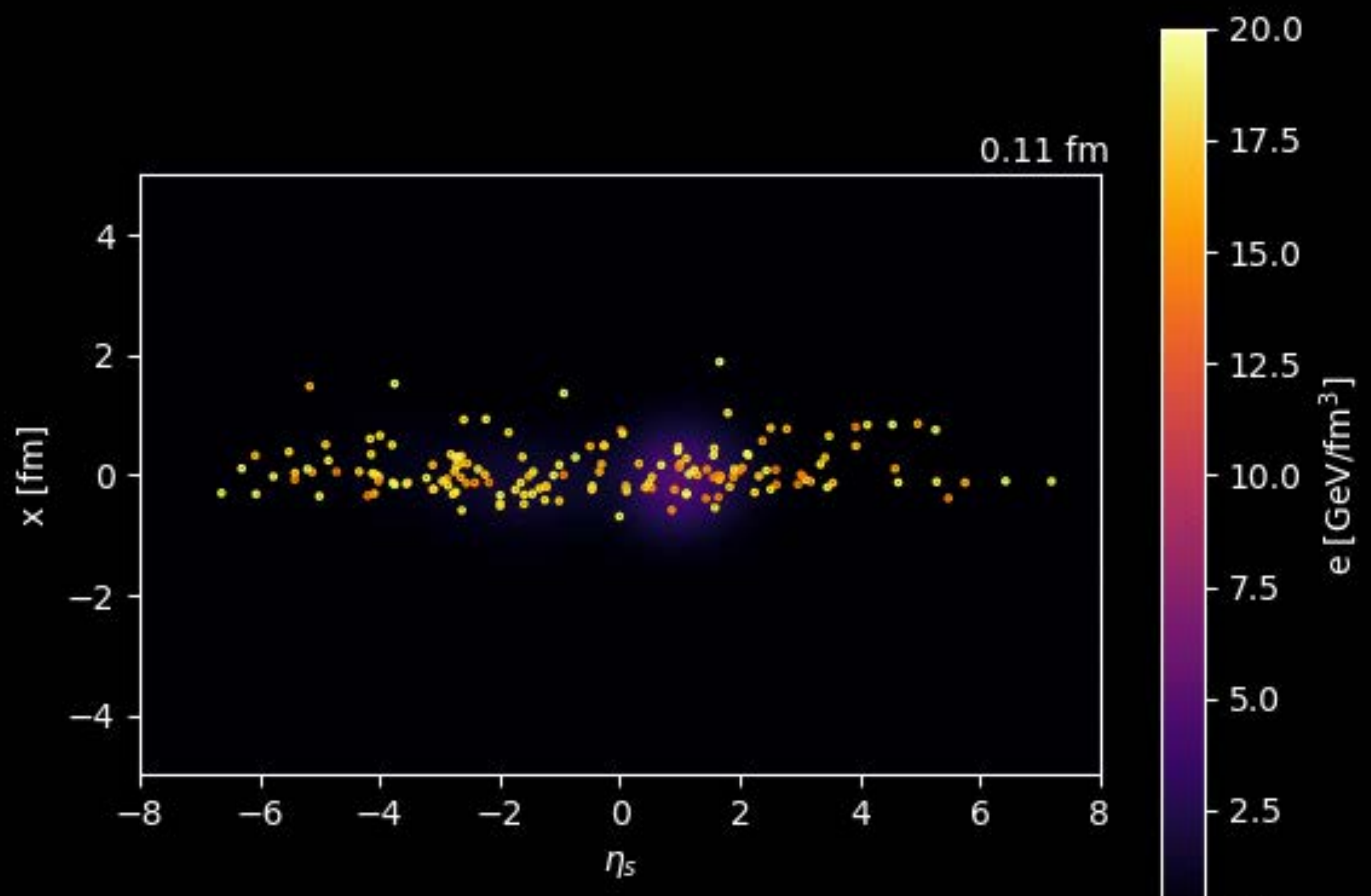
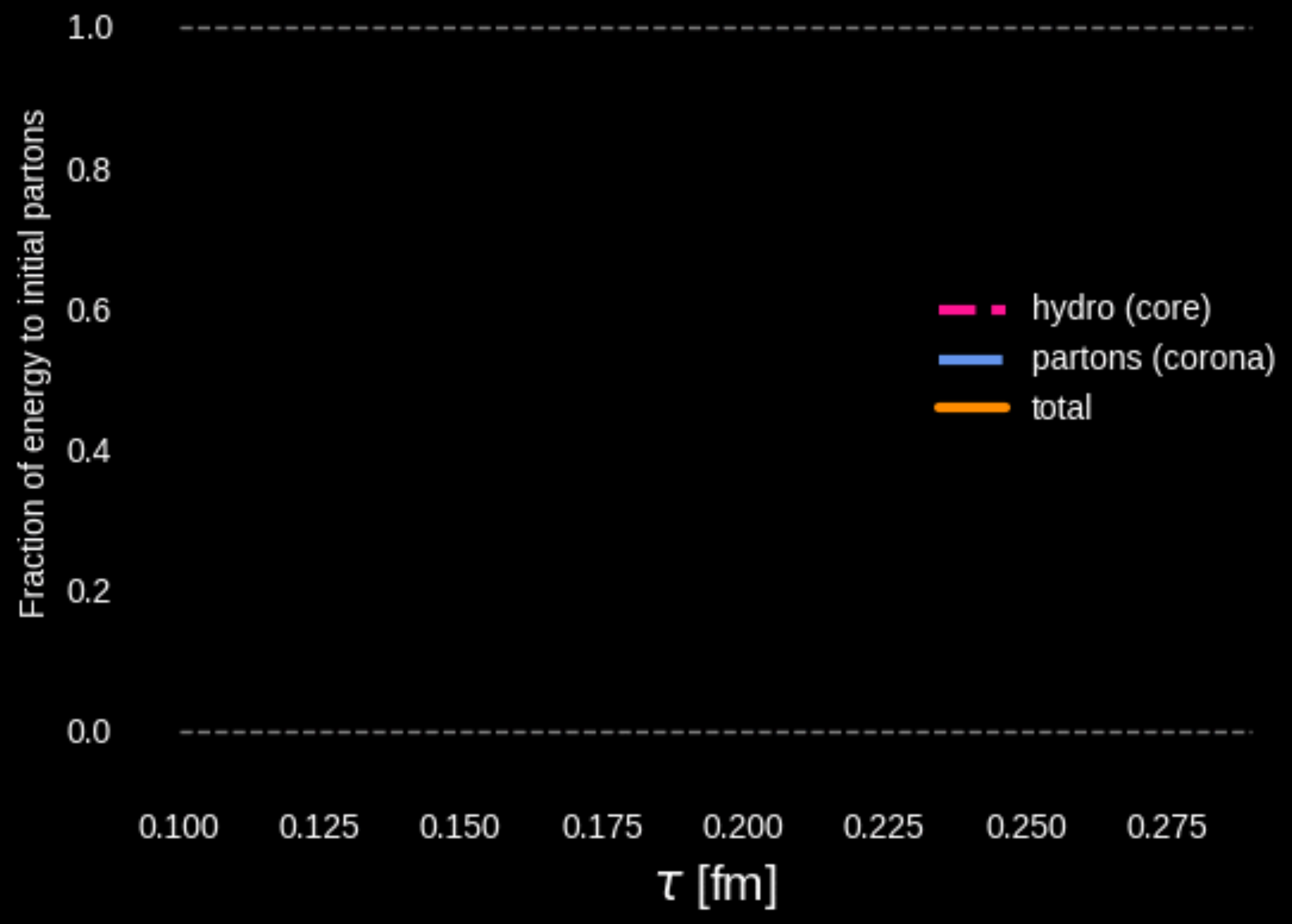


Courtesy from Yuuka Kanakubo

Dynamical core-corona initialization (DCCI)

Dynamical conversion of energy into fluid

pp, $\sqrt{s_{\mathrm{NN}}} = 7\ \mathrm{TeV}$



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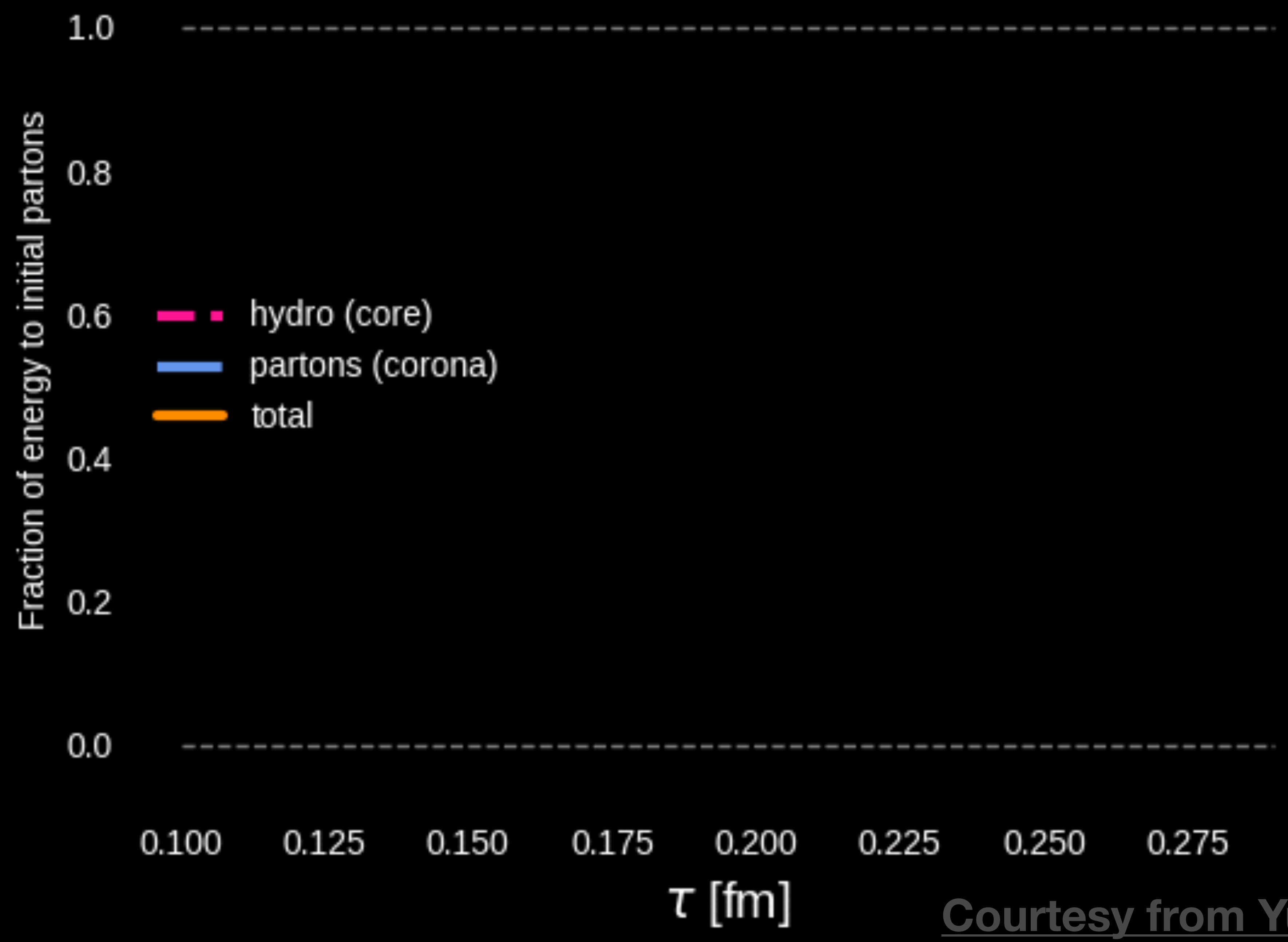

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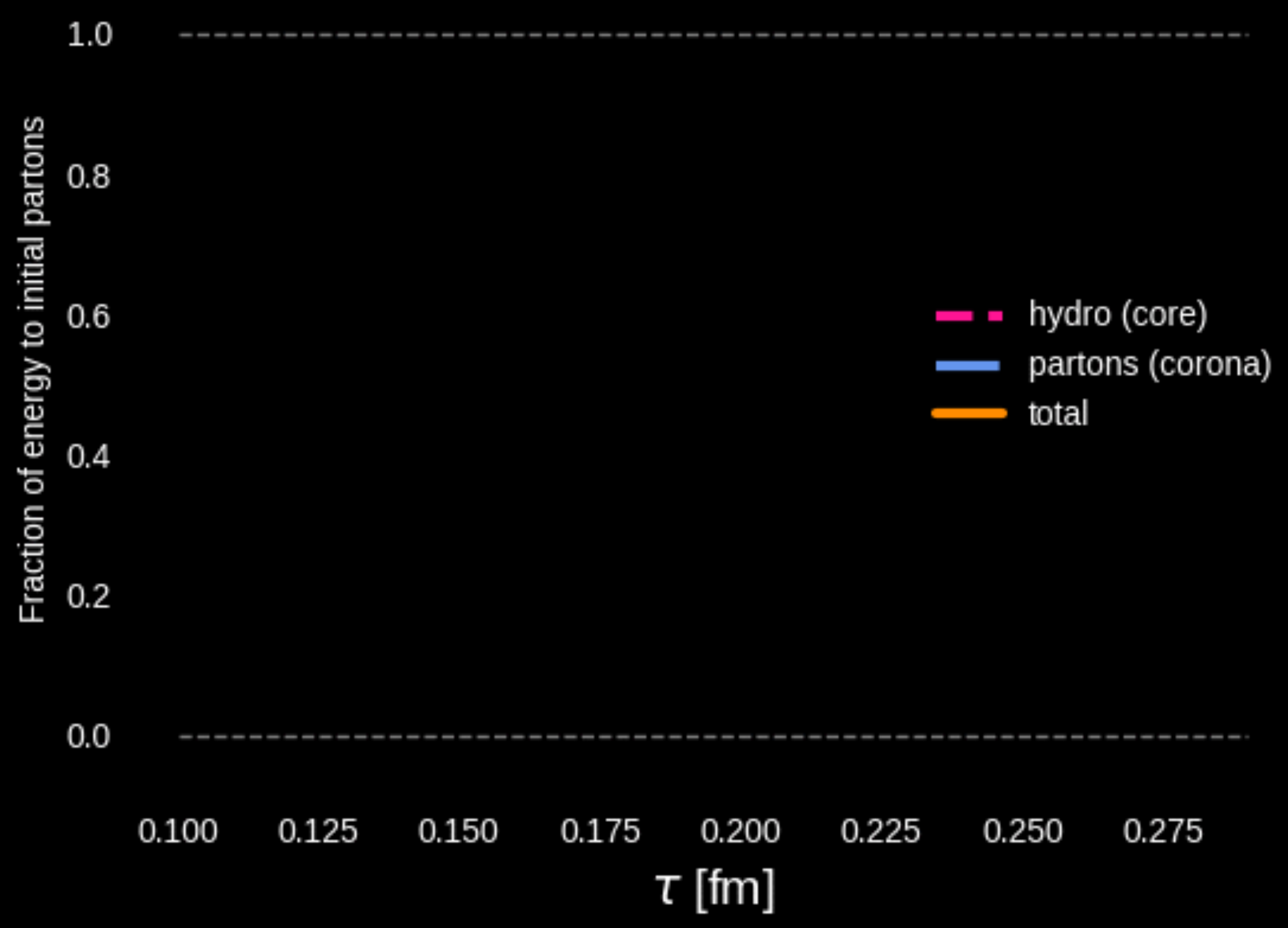

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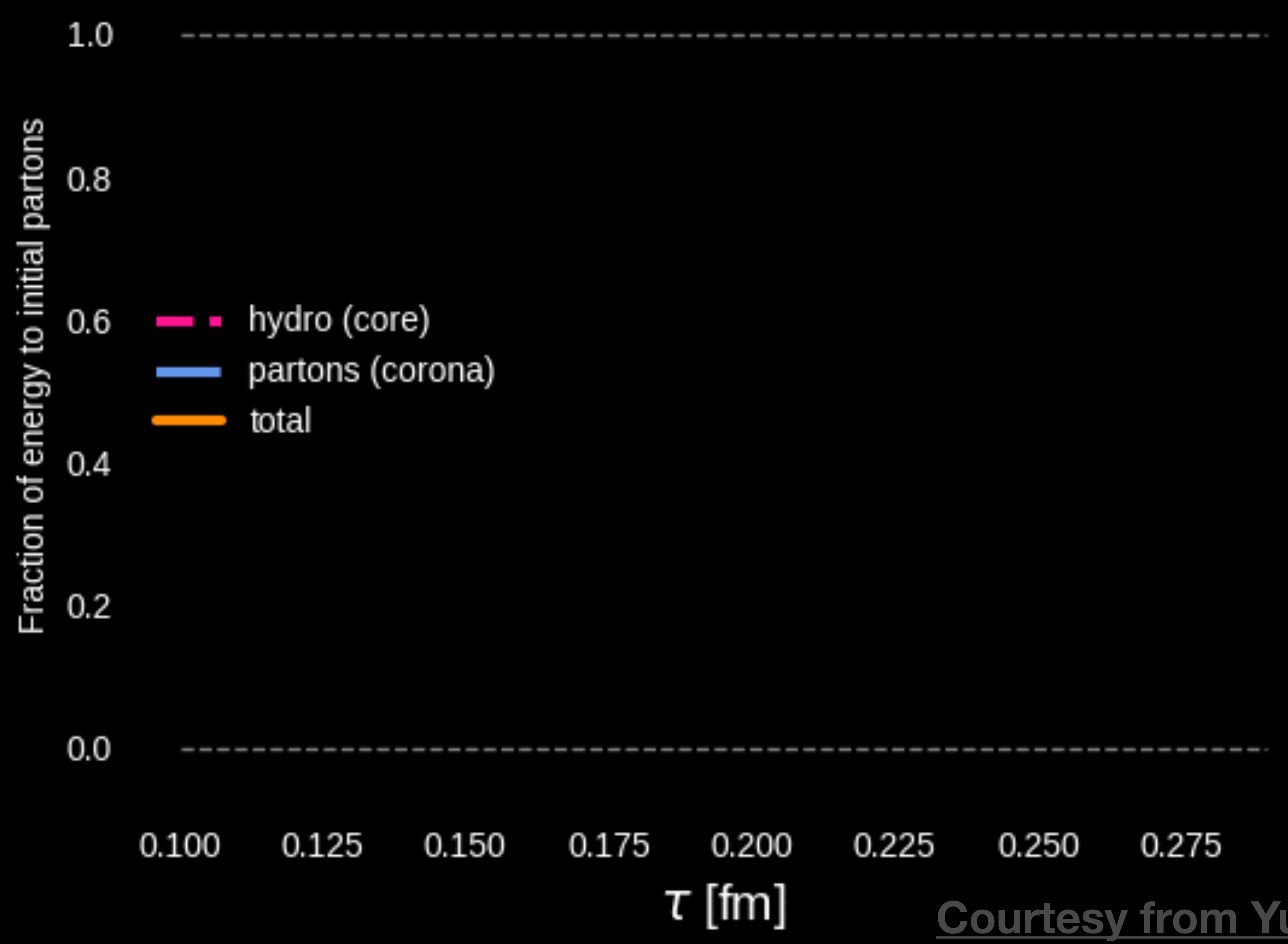

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