Medium response to jets in heavy ion collisions

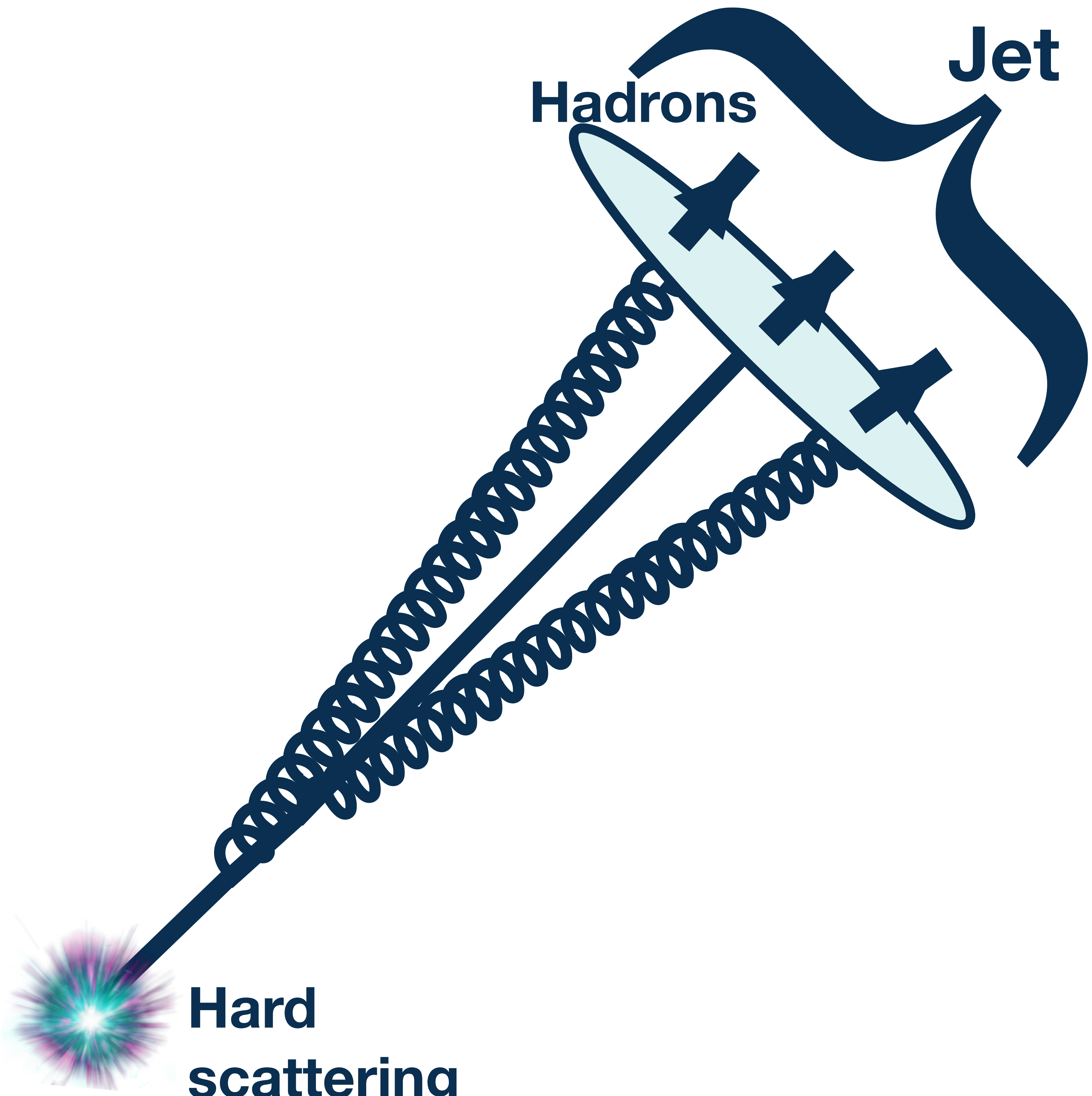
Yasuki Tachibana

Central China Normal University

ISMD 2017, Tlaxcala City, September 15th, 2017

Introduction

Medium Response to Jet Quenching in QGP



- **Jet quenching**

  J. D. Bjorken (1983), M. Gyulassy, M. Plumer (1990), M. Gyulassy, X.-N.Wang (1994), ...

  - Collisions with medium constituents
  - Induced parton radiation

- **Medium response to jet**

  H. Stöcker ('05), J. Casalderrey-Solana, E. V. Shuryak, D. Teaney ('05),…

  - Induced by energy-momentum deposition
  - Enhance the particle emission from medium

(Jet-correlated, cannot be subtracted)

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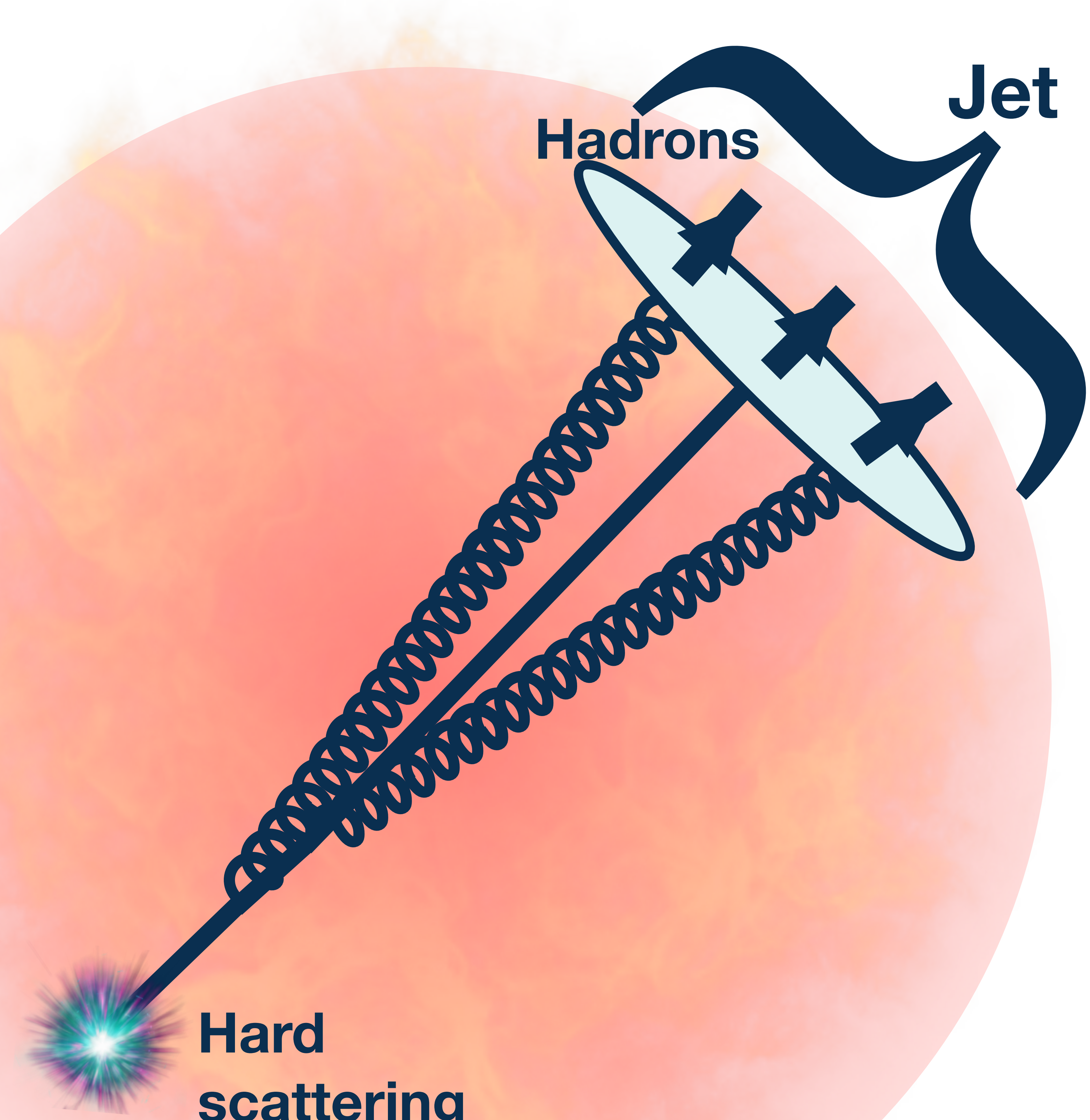

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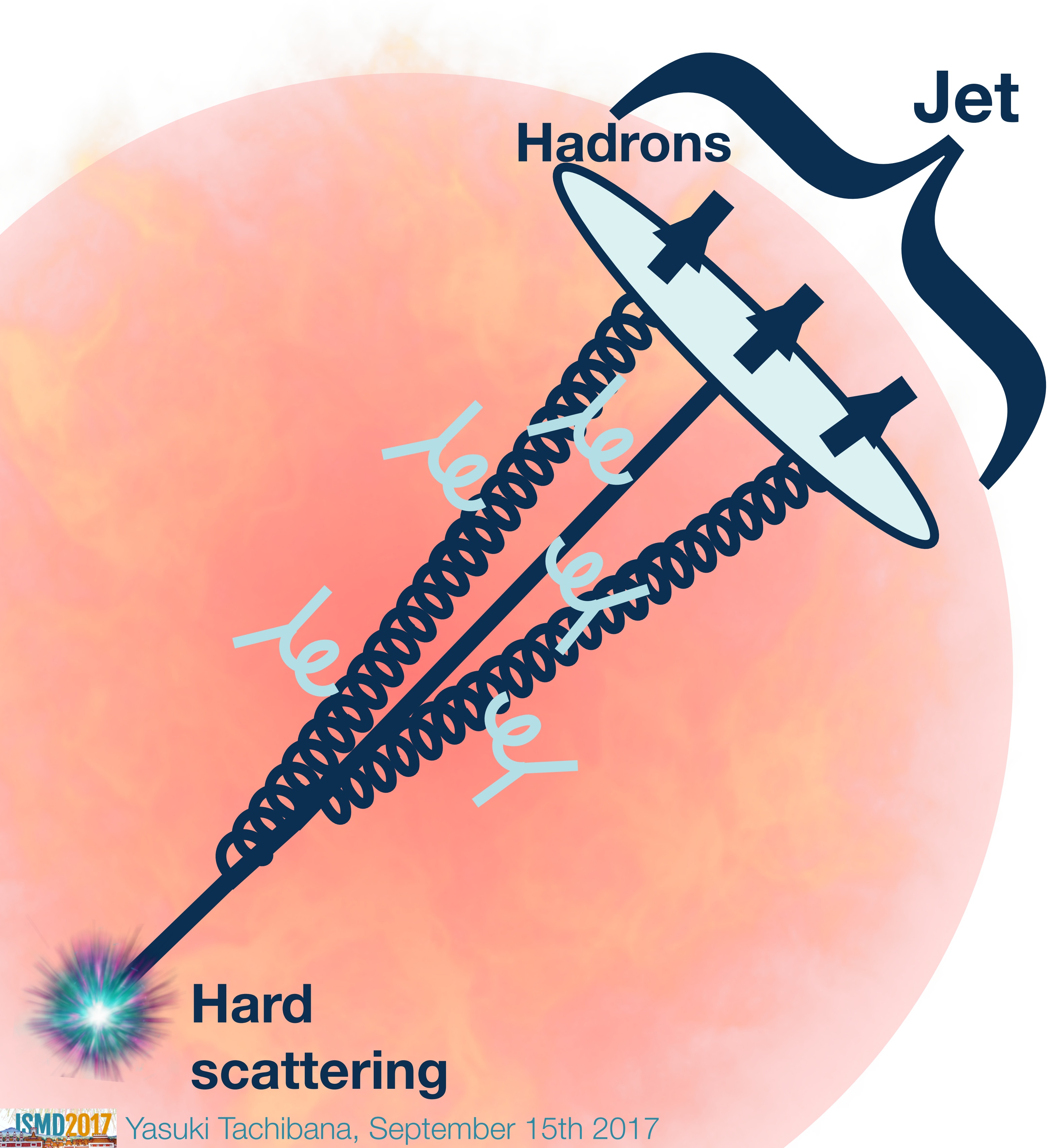

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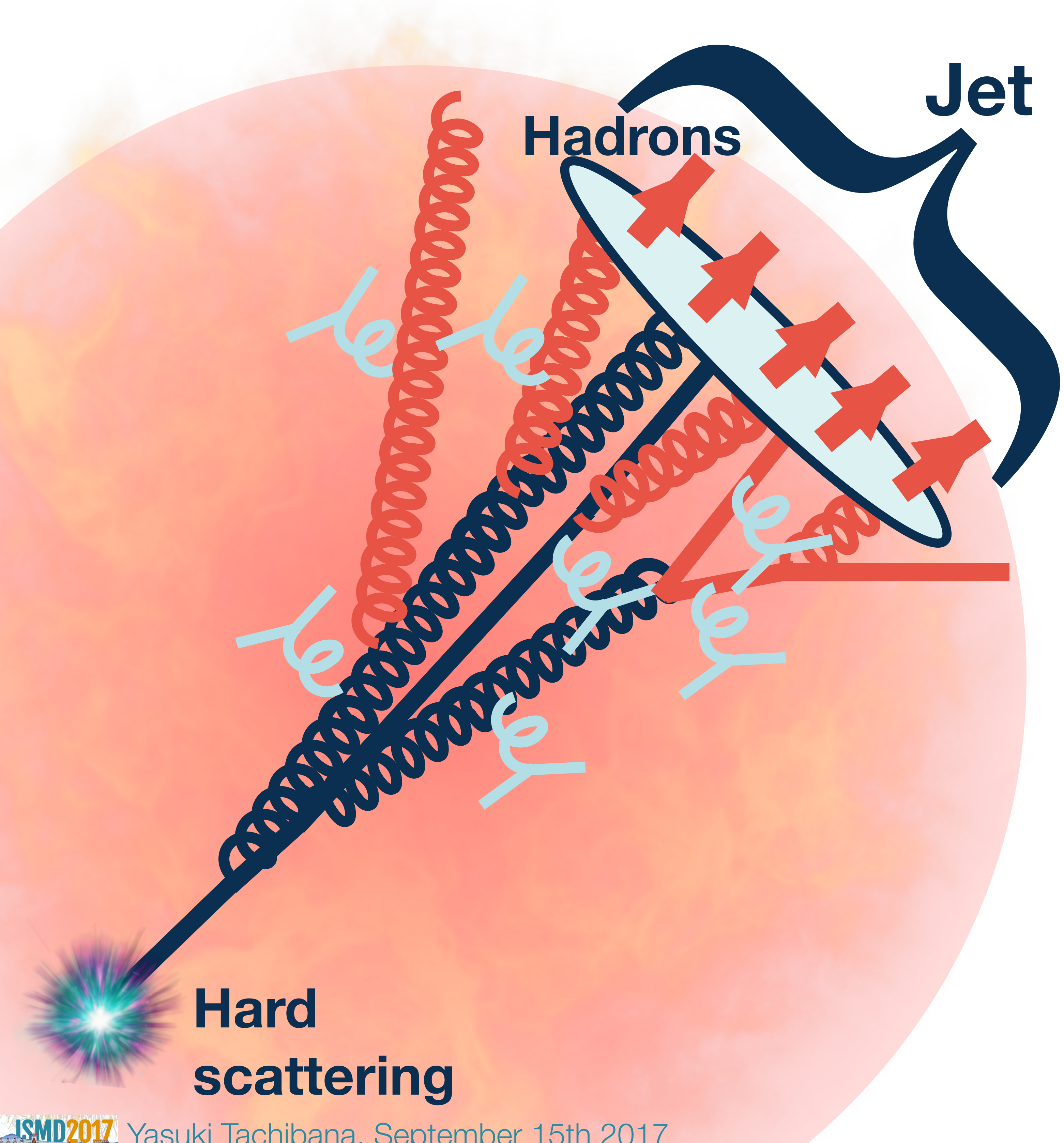

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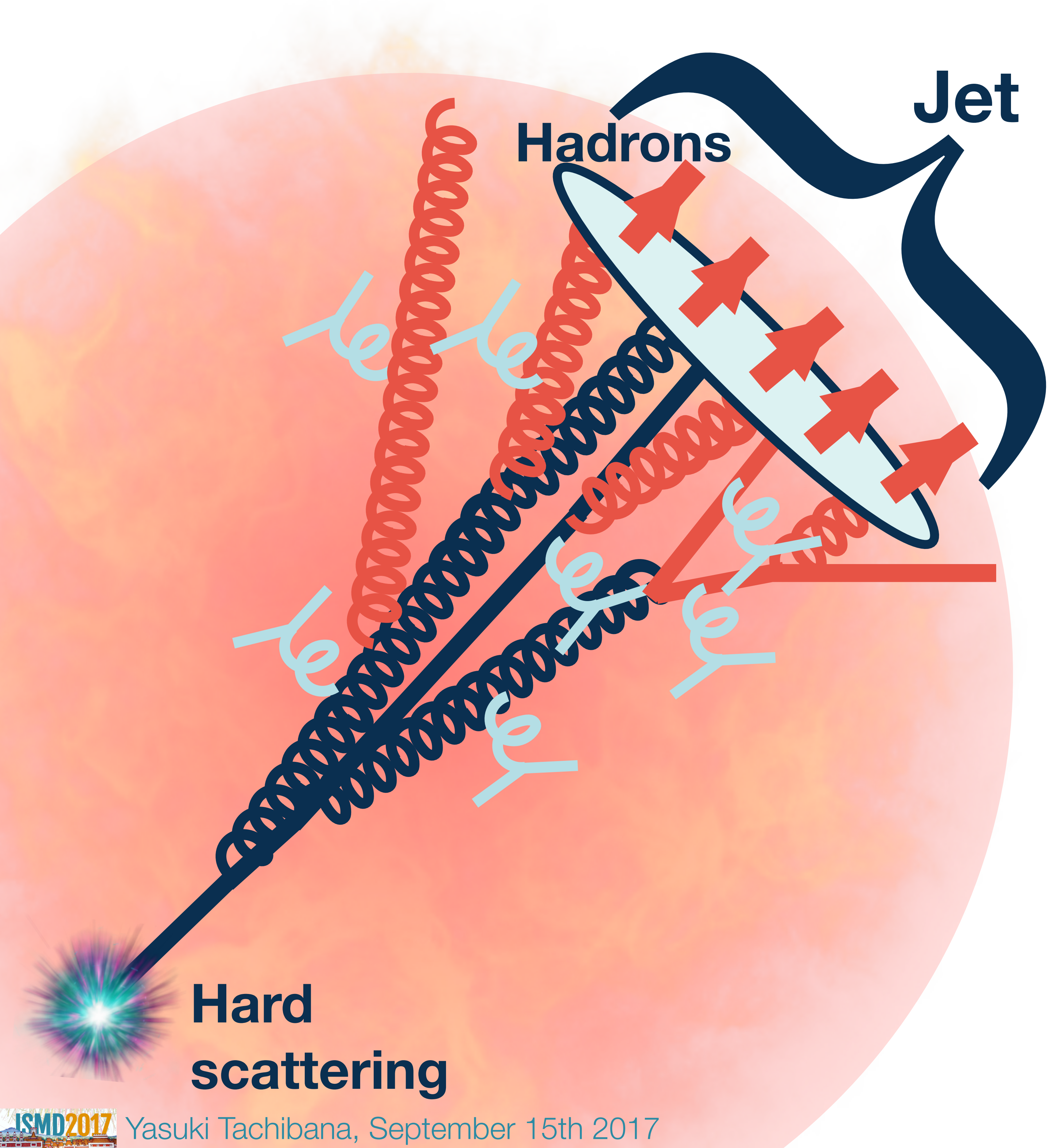

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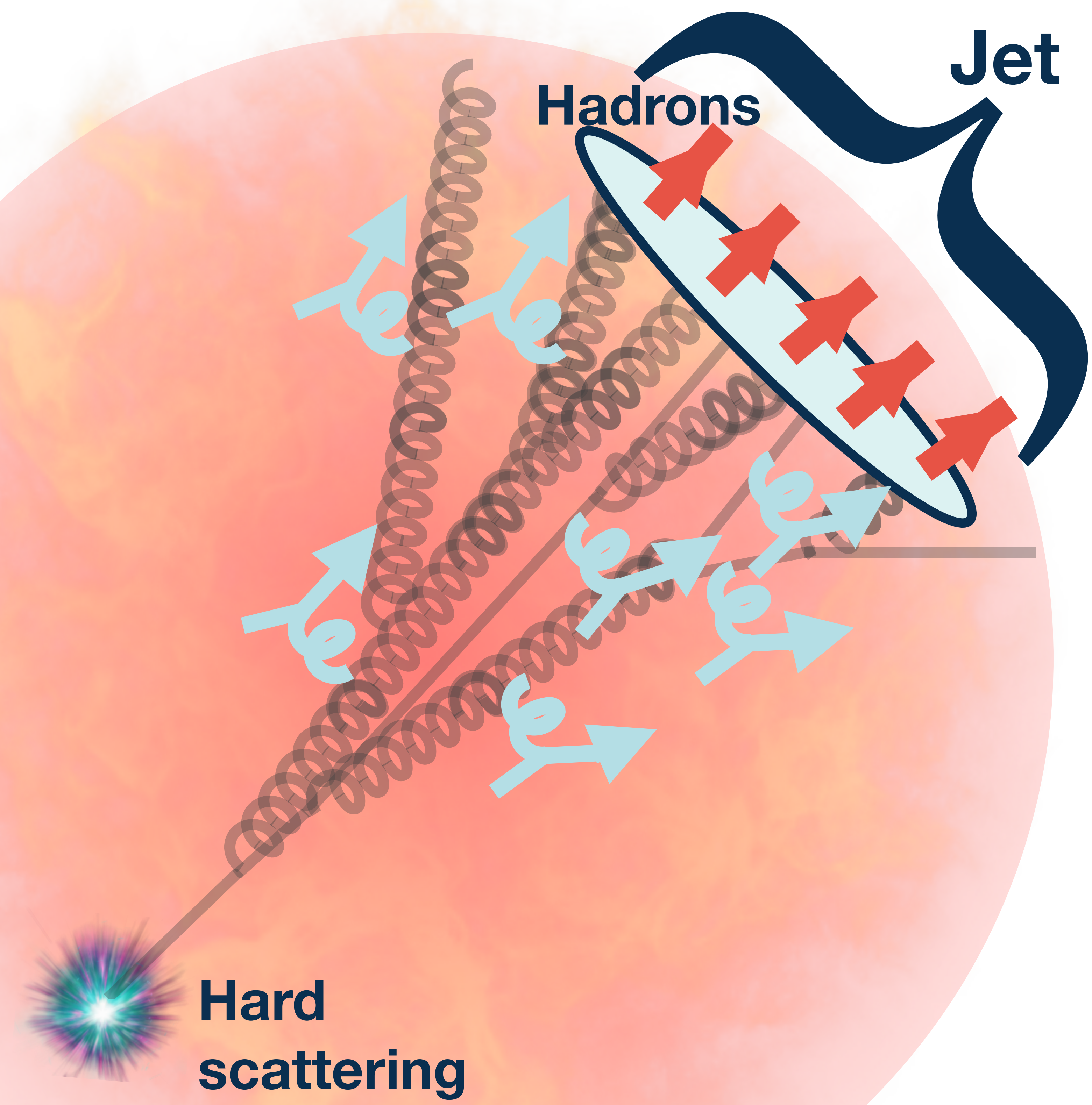

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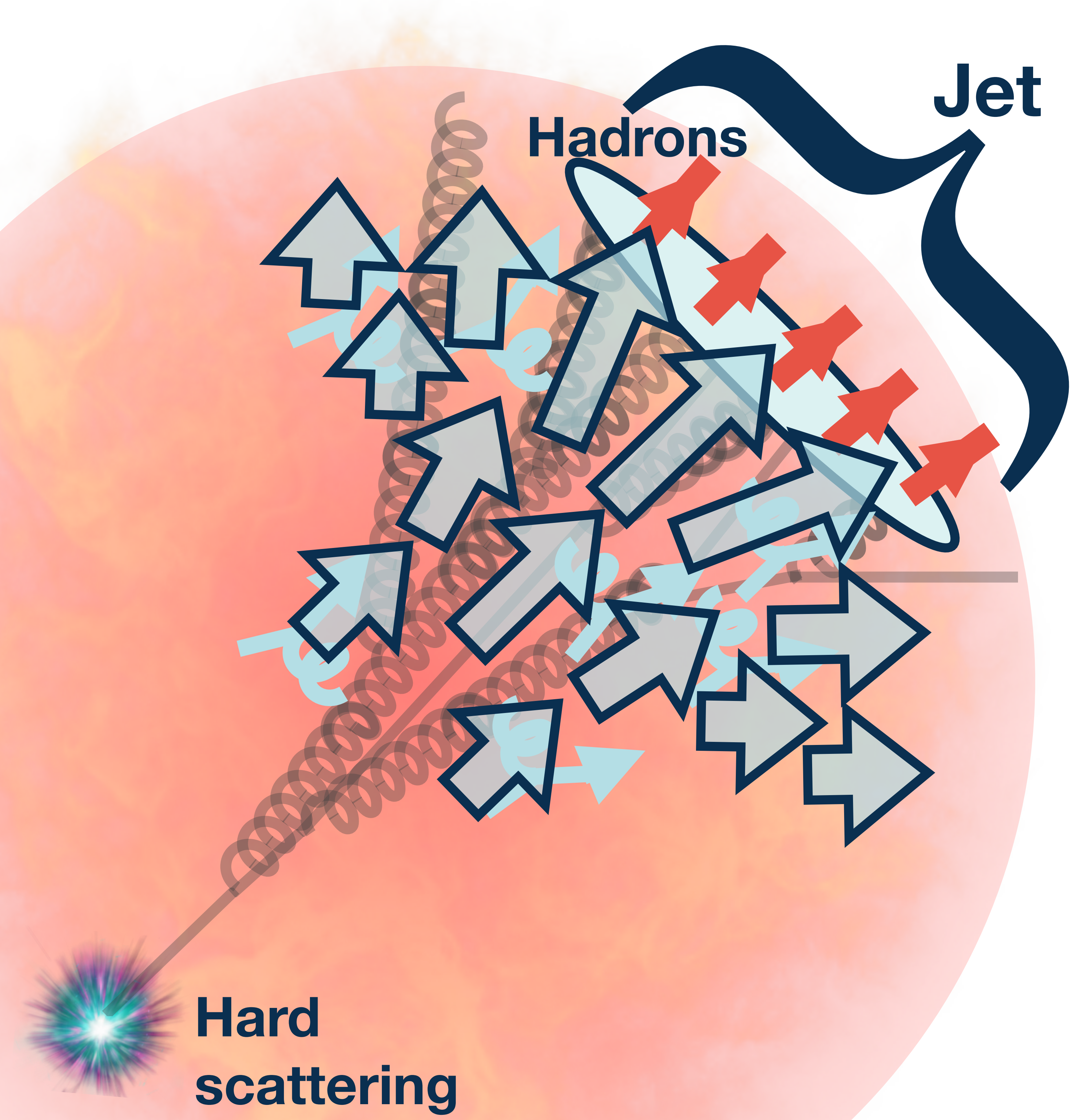

Hard scattering

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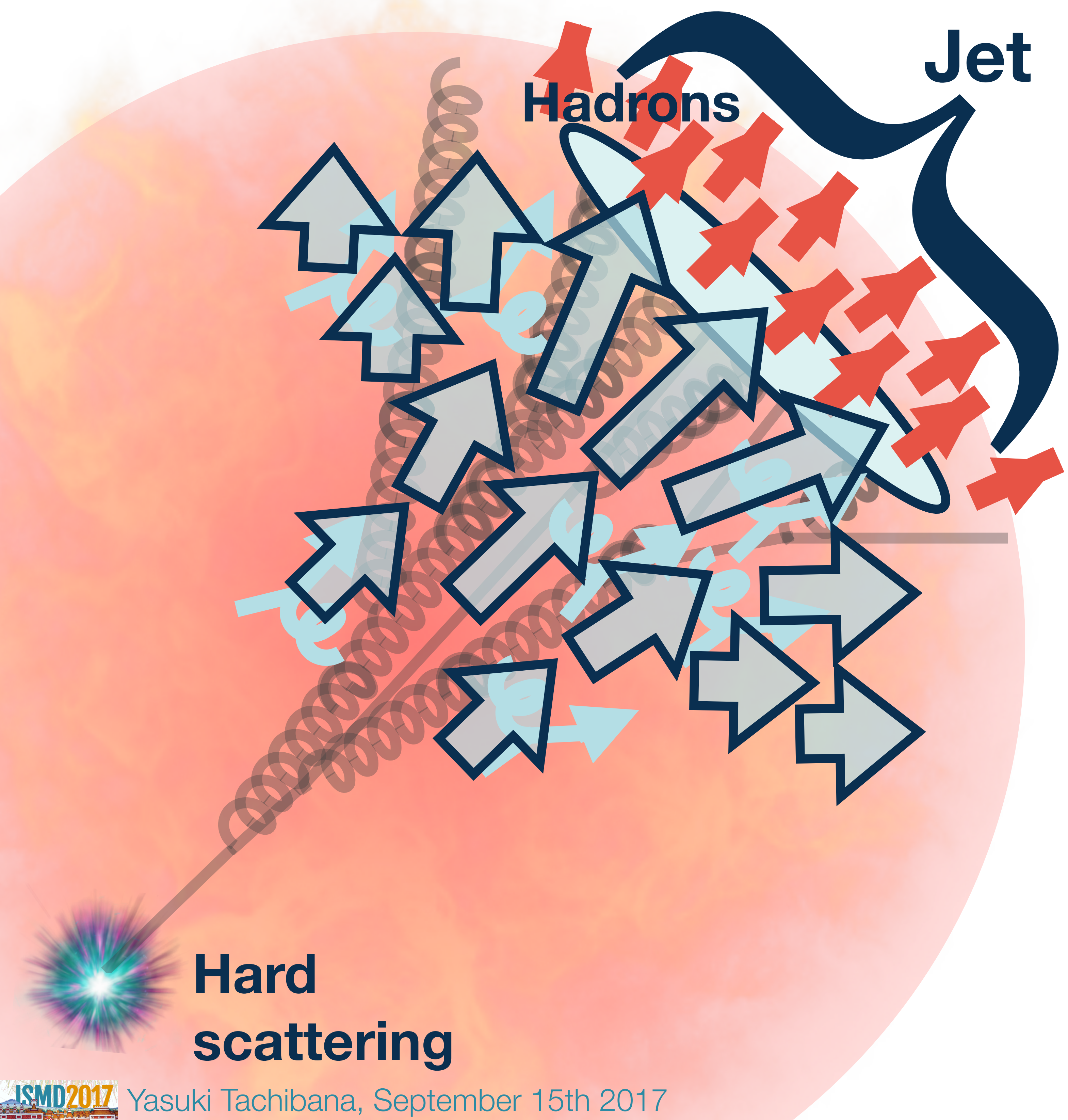

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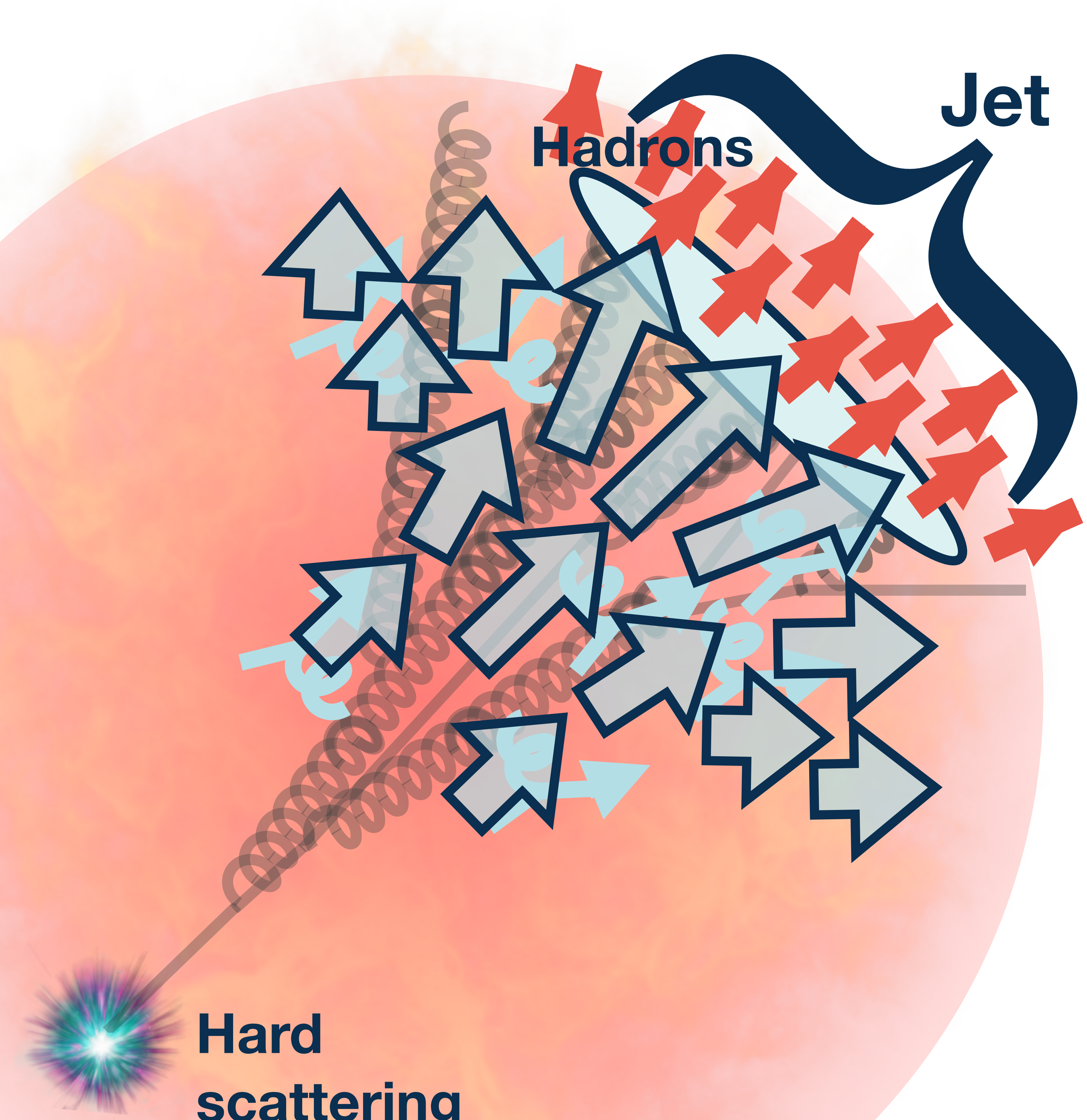

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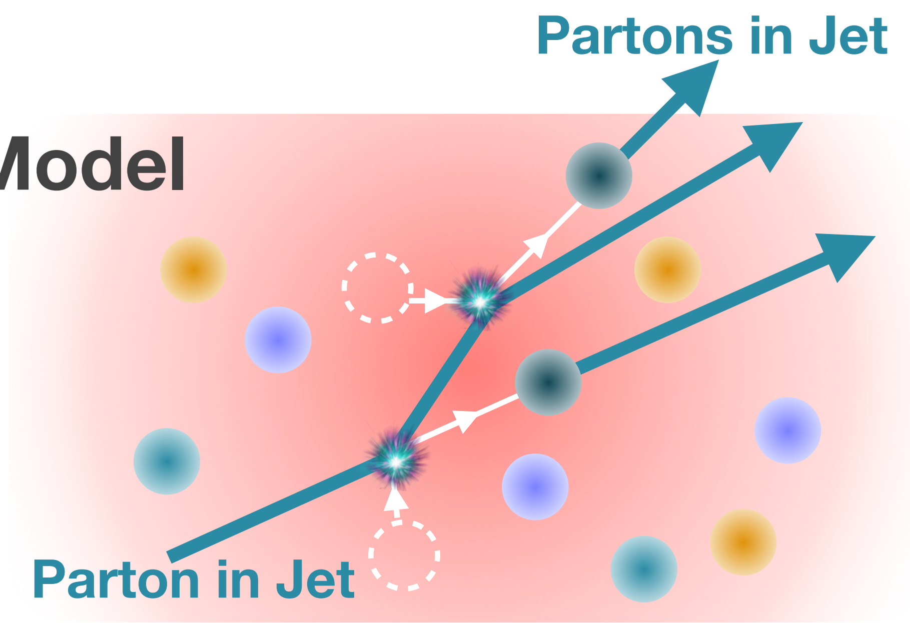
Modelings for Medium Response in Recent Studies

- **Jet evolution model with recoil partons**
  - Sampling of partons from thermalized medium for the collisions
  - Add the recoiled partons to the jet

Linearized Boltzmann Transport (LBT) Model
T. Luo, S. Cao, X.-N, Wang, G.-Y. Qin,…

JEWEL
K. C. Zapp, R. Kunnawalkam Elayavalli, J. G. Milhano, U. A. Wiedemann,…



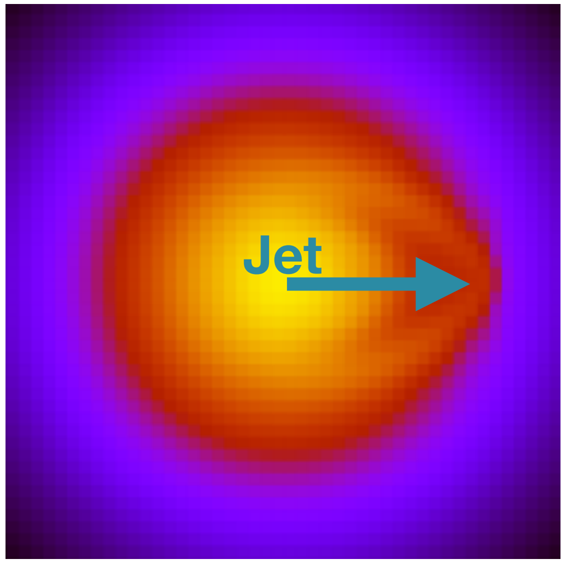
- **Jet evolution (AdS/CFT + PYTHIA) with backreaction**
  - Store the lost energy into thermalized medium as a perturbation
  - Use linear expansion of Cooper-Frye for hadrons from medium response

Hybrid Strong/Weak Coupling Model
D. Pablos, J. Casalderrey-Solana, K. Rajagopal, J. G. Milhano D. C. Gulhan,…

Modelings of Medium Response in Recent Studies

- **Jet evolution + full-hydro model with source term**
  - Solve *hydro eqs. with source term* for medium evolution

$$\underbrace{\partial_\mu T^{\mu\nu}_{\mathrm{QGP}}(x)}_{\text{Energy-momentum tensor of the QGP fluid}} = \underbrace{J^\nu(x)}_{\text{Energy and momentum deposited from the jet}}$$



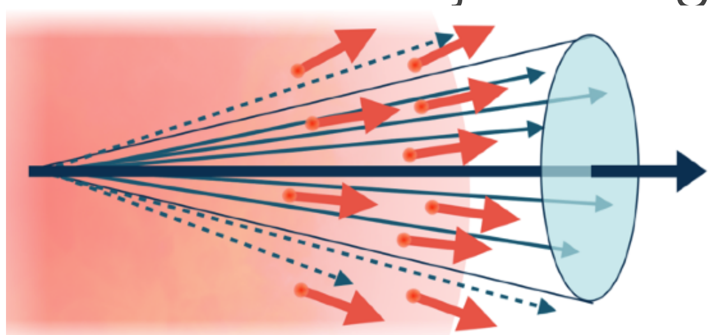
  - Source term $J^\nu(x)$ constructed by jet evolution calculation
  - Use Cooper-Frye for hadrons from medium response

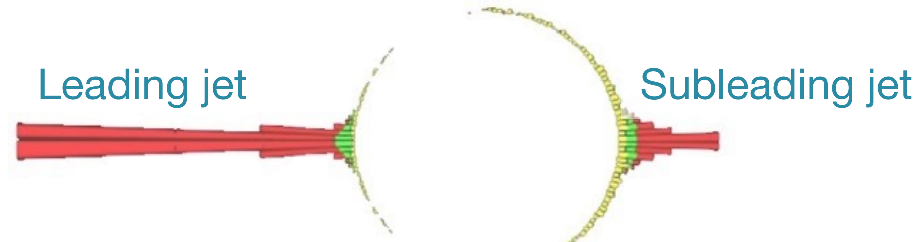
Jet Shower Transport + Hydro model
YT, N.-B. Chang, G.-Y. Qin,...

Coupled LBT Hydro Model (recoiled partons are also included)
W. Chen, T. Luo, S. Cao, L. Pang, X.-N, Wang,...

Motivation

- **Full picture of jet quenching in heavy ion collisions**
  - Redistribution of the jet energy and momentum





Adapted from C. Roland (CMS)

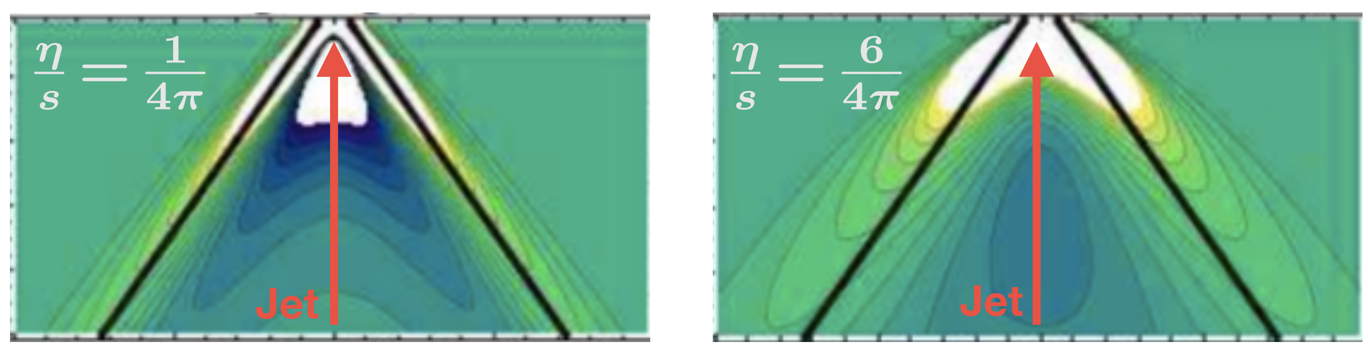
  - Precise interpretation of the experimental data
  - Hints for medium response-free observables

- **Another possible manifestation of QGP's fluidity**
  - New approach for QGP properties (viscosity, sound velocity,…) in jet events

    R. B. Neufeld ('09), R. B. Neufeld, I. Vitev ('12), Alejandro Ayala *et al*. ('16), L. Yan, S. Jeon, C. Gale ('17)

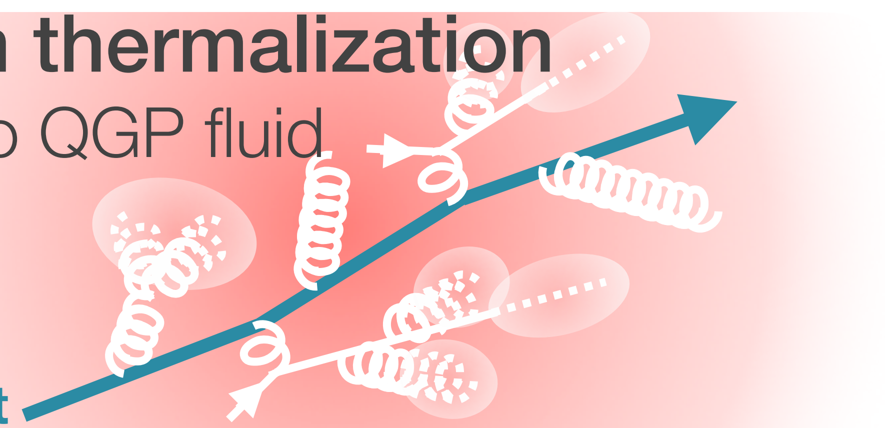
Structure of Mach cone (jet-induced shockwave)

Adapted from R. B. Neufeld ('09)



- **QGP transport properties from in-medium thermalization**
  - Mechanism of energy-momentum deposition into QGP fluid

    R. B. Neufeld ('09), E. Iancu, B. Wu ('15),…



Full Jet Study with Jet shower Transport + Hydro Model

YT, N.-B. Chang, and G.-Y. Qin, [PRC 95, 044909 (2017)]

Jet shower Transport + Hydro Model

YT, N.-B. Chang, G.-Y. Qin ('17)

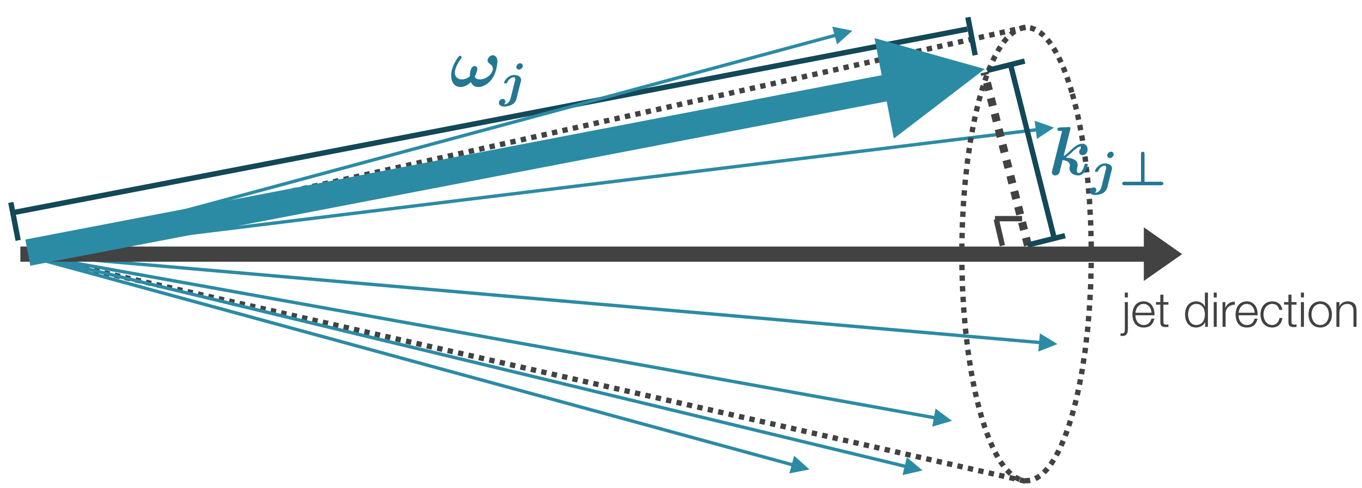
- **Transport equations for all partons in jet shower**

  N.-B. Chang, G.-Y. Qin ('16)

  - Evolution of energy and transverse momentum distributions, $f_j(\omega_j, k_{j\perp}^2, t)$

    (j: parton species)

$$\frac{df_j(\omega_j, k_{j\perp}^2, t)}{dt} = \hat{e}_j \frac{\partial}{\partial \omega_j} f_j(\omega_j, k_{j\perp}^2 t) + \frac{1}{4}\hat{q}_j \nabla_{k_\perp}^2 f_j(\omega_j, k_{j\perp}^2, t) + \sum_i \int d\omega_i dk_{i\perp}^2 \frac{d\tilde{\Gamma}_{i\to j}(\omega_j, k_{j\perp}^2|\omega_i, k_{i\perp}^2)}{d\omega_j dk_{j\perp}^2 dt} f_i(\omega_i, k_{i\perp}^2, t) - \sum_i \int d\omega_i dk_{i\perp}^2 \frac{d\tilde{\Gamma}_{j\to i}(\omega_i, k_{i\perp}^2|\omega_j, k_{j\perp}^2)}{d\omega_i dk_{i\perp}^2 dt} f_j(\omega_j, k_{j\perp}^2, t)$$



  - Initial (averaged) jet profiles are generated by PYTHIA

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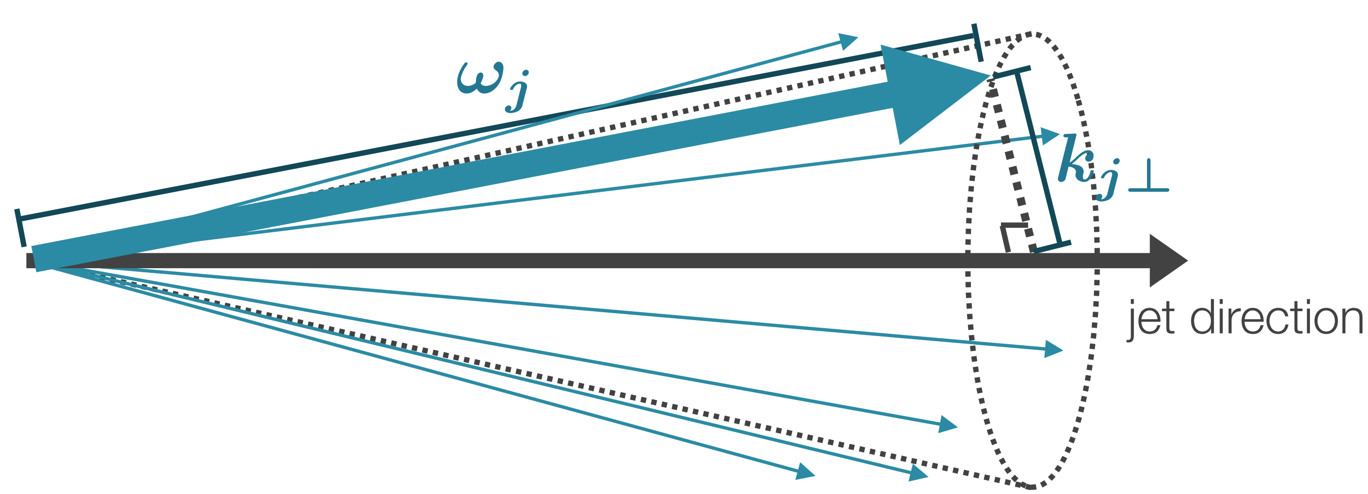
$$\frac{df_j(\omega_j, k_{j\perp}^2, t)}{dt} = \hat{e}_j \frac{\partial}{\partial \omega_j} f_j(\omega_j, k_{j\perp}^2 t) \quad \text{Collisional energy loss (longitudinal)}$$

$$+ \frac{1}{4}\hat{q}_j \nabla_{k_\perp}^2 f_j(\omega_j, k_{j\perp}^2, t) \quad \text{Momentum broadening (transverse)}$$

$$+ \sum_i \int d\omega_i dk_{i\perp}^2 \frac{d\tilde{\Gamma}_{i\to j}(\omega_j, k_{j\perp}^2 | \omega_i, k_{i\perp}^2)}{d\omega_j dk_{j\perp}^2 dt} f_i(\omega_i, k_{i\perp}^2, t) - \sum_i \int d\omega_i dk_{i\perp}^2 \frac{d\tilde{\Gamma}_{j\to i}(\omega_i, k_{i\perp}^2 | \omega_j, k_{j\perp}^2)}{d\omega_i dk_{i\perp}^2 dt} f_j(\omega_j, k_{j\perp}^2, t)$$



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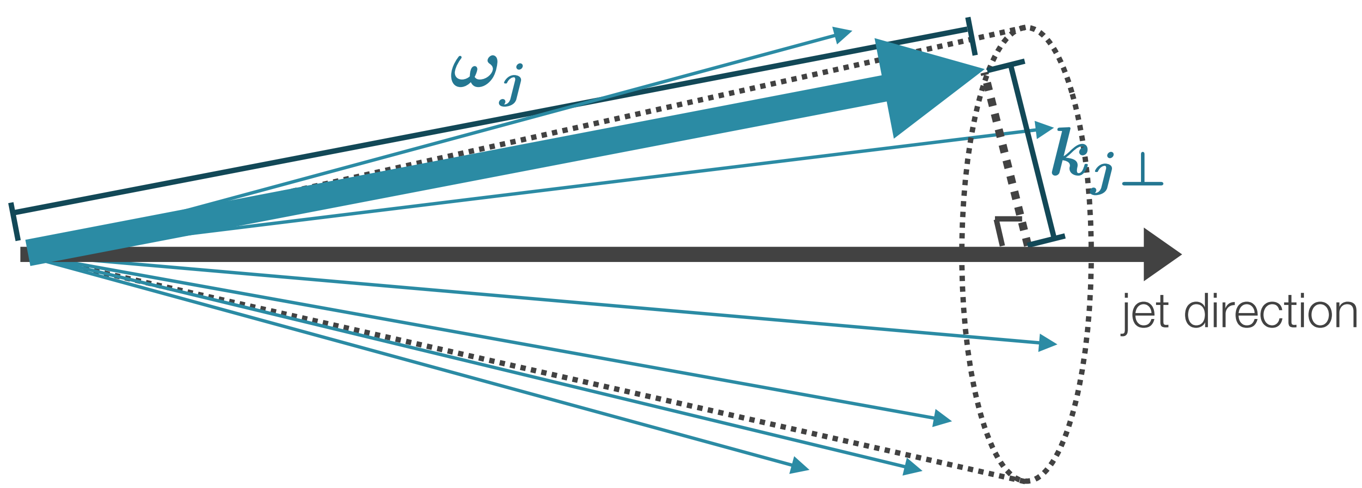
Medium-induced radiation



  - Initial (averaged) jet profiles are generated by PYTHIA

Jet shower Transport + Hydro Model

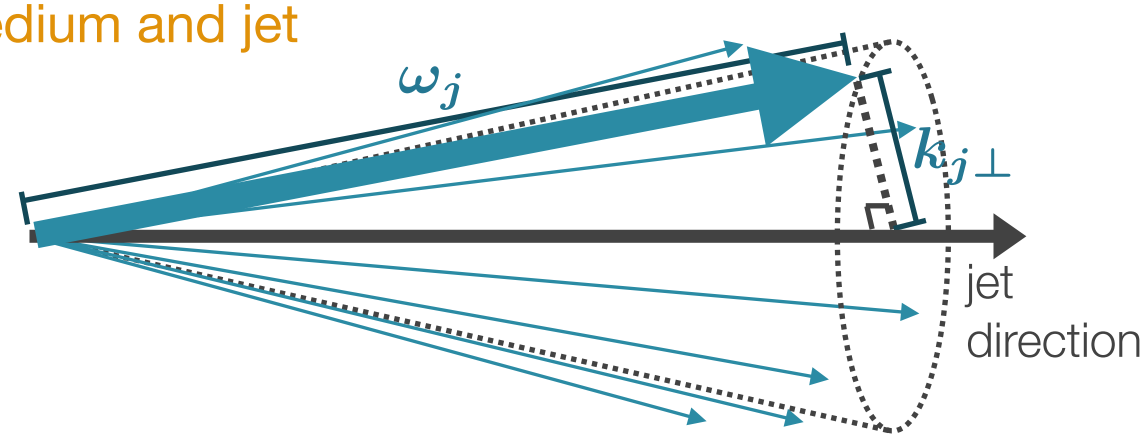
YT, N.-B. Chang, G.-Y. Qin ('17)

- **Hydrodynamic equations with source term**
  - Describe hydrodynamic response to jet and background expansion

$$\partial_\mu T^{\mu\nu}_{\mathrm{QGP}}(x) = J^\nu(x)$$

  - Source term constructed from the solution of jet-shower transport eqs.

$$J^\nu(x) = -\sum_j \int \frac{d\omega_j dk_{j\perp}^2 d\phi_j}{2\pi} \underbrace{k_j^\nu \left(\hat{e}_j \frac{\partial}{\partial \omega_j} + \frac{1}{4}\hat{q}_j \nabla^2_{k_\perp} \right)}_{\text{Momentum exchange between medium and jet}} f_j(\omega_j, k_{j\perp}^2, t)\delta^{(3)}(\boldsymbol{x} - \boldsymbol{x}^{\mathrm{jet}}(\boldsymbol{k}_j, t))$$

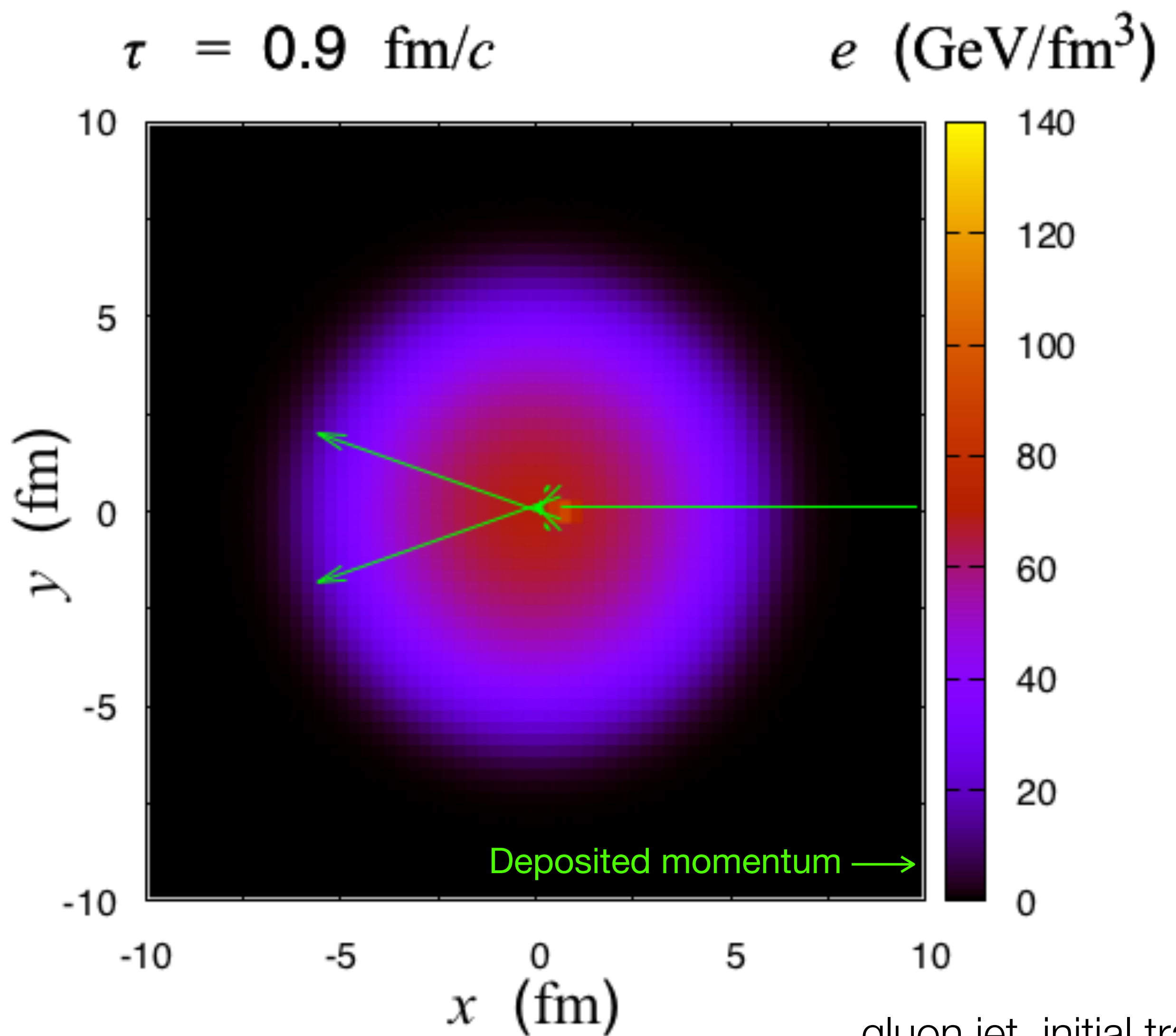


Assumption
Instantaneous local thermalization of deposited energy and momentum

Jet-induced Flow in Expanding QGP

- **(3+1)-D ideal hydro**
  - Optical Glauber model in central Pb-Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76\ \mathrm{TeV}$
  - EoS from lattice QCD
- **Evolution of medium and jet shower**

Medium energy density in transverse plane at $\eta_s = 0$



gluon jet, initial transverse momentum: 150 GeV/c

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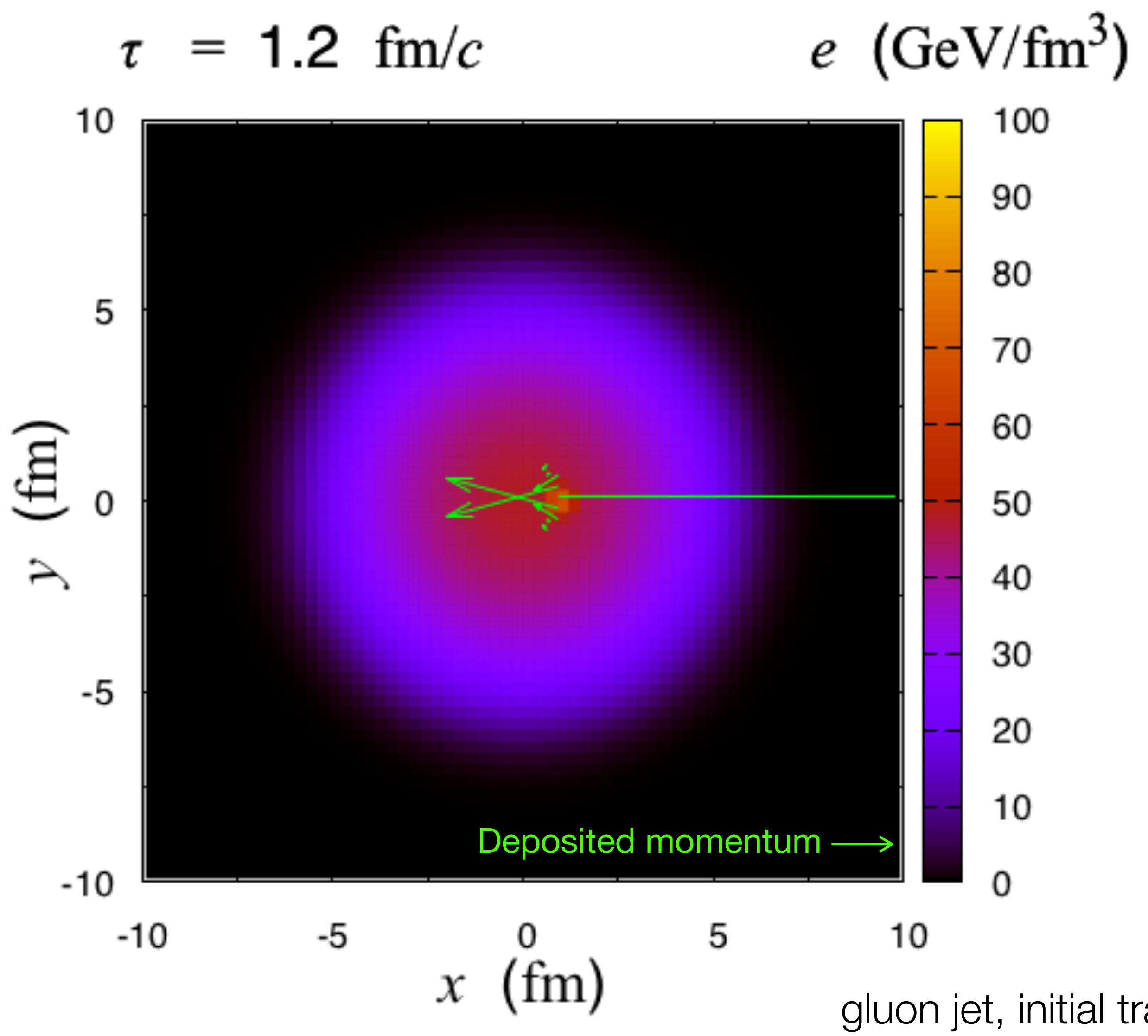

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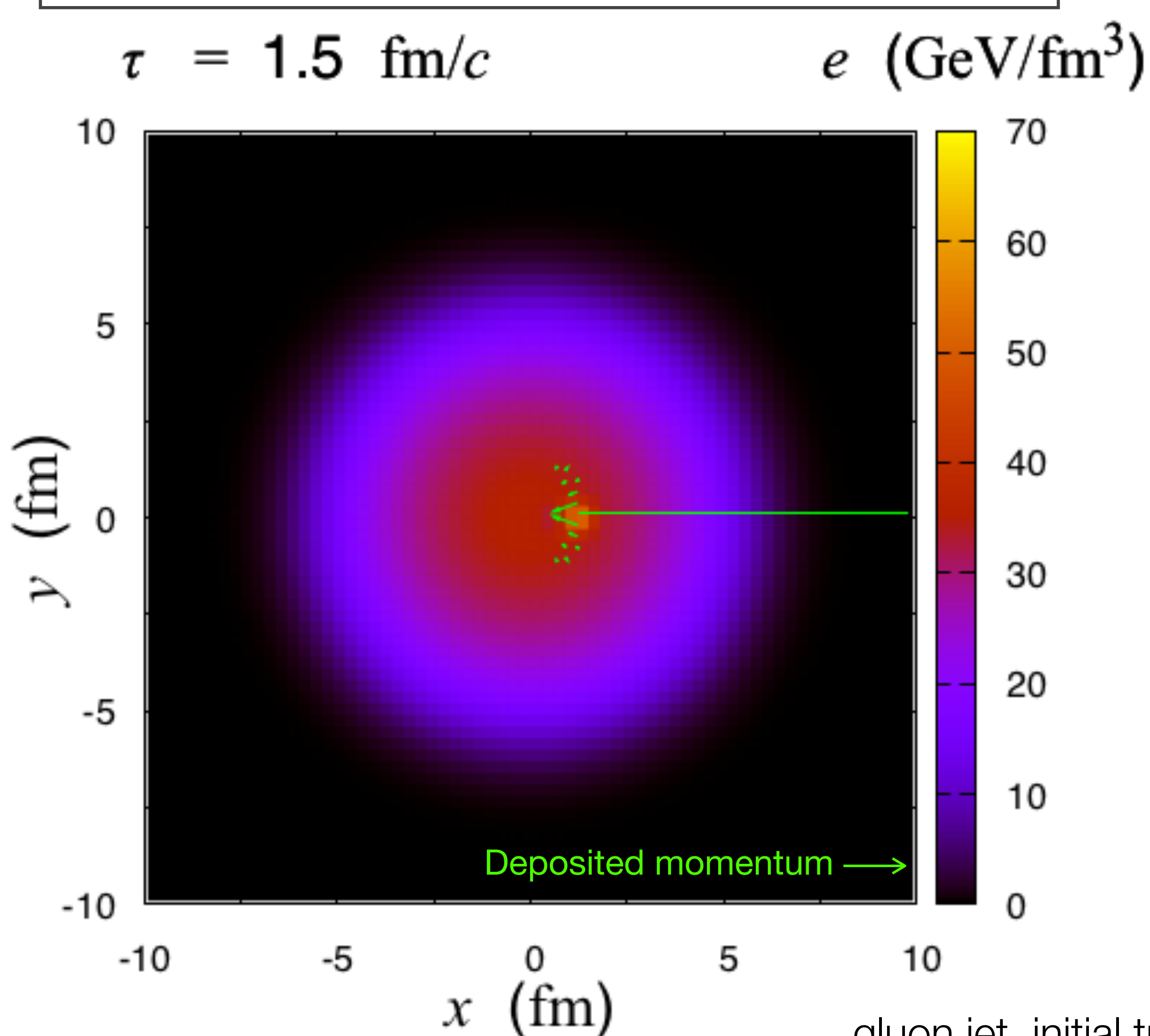

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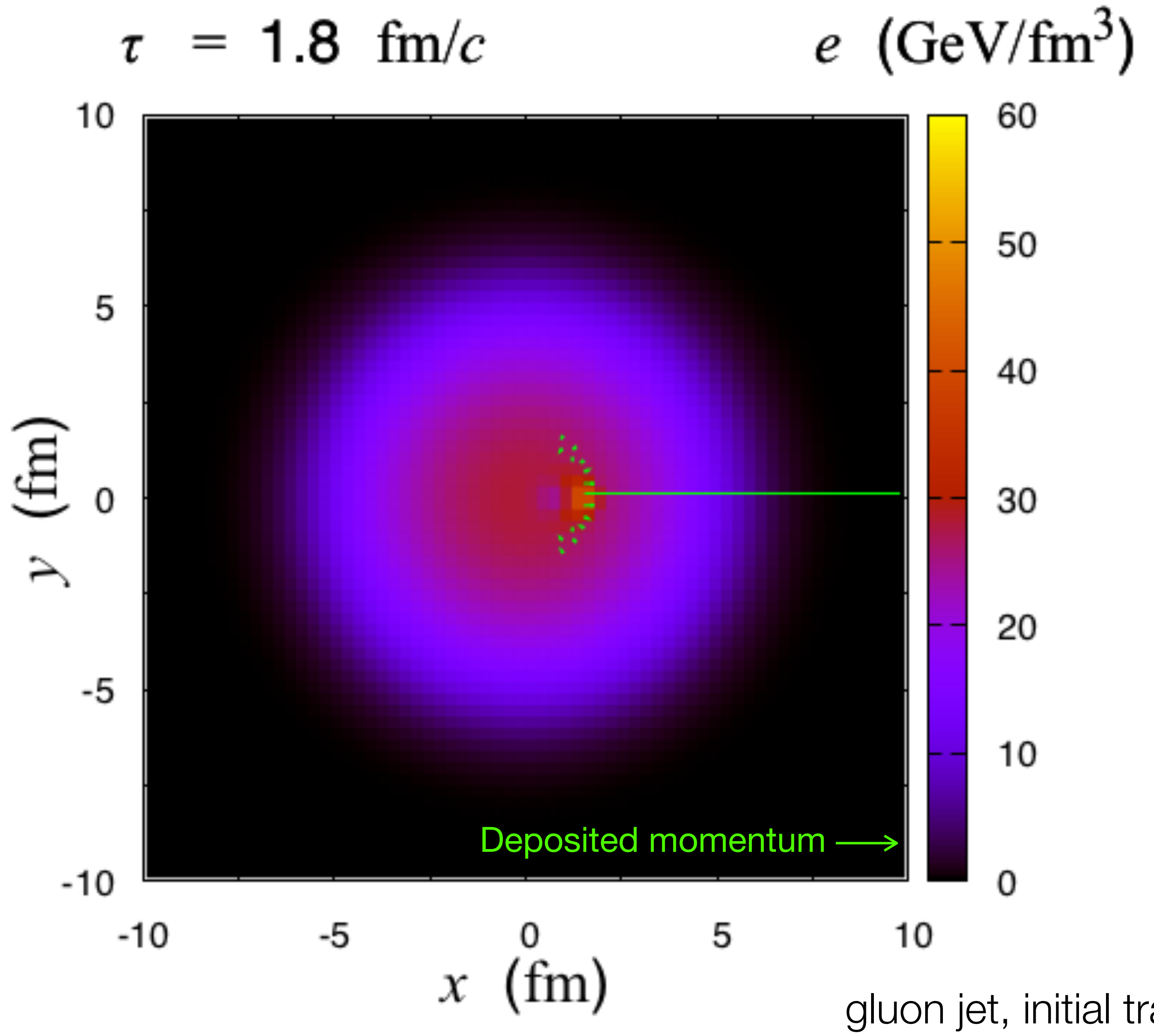

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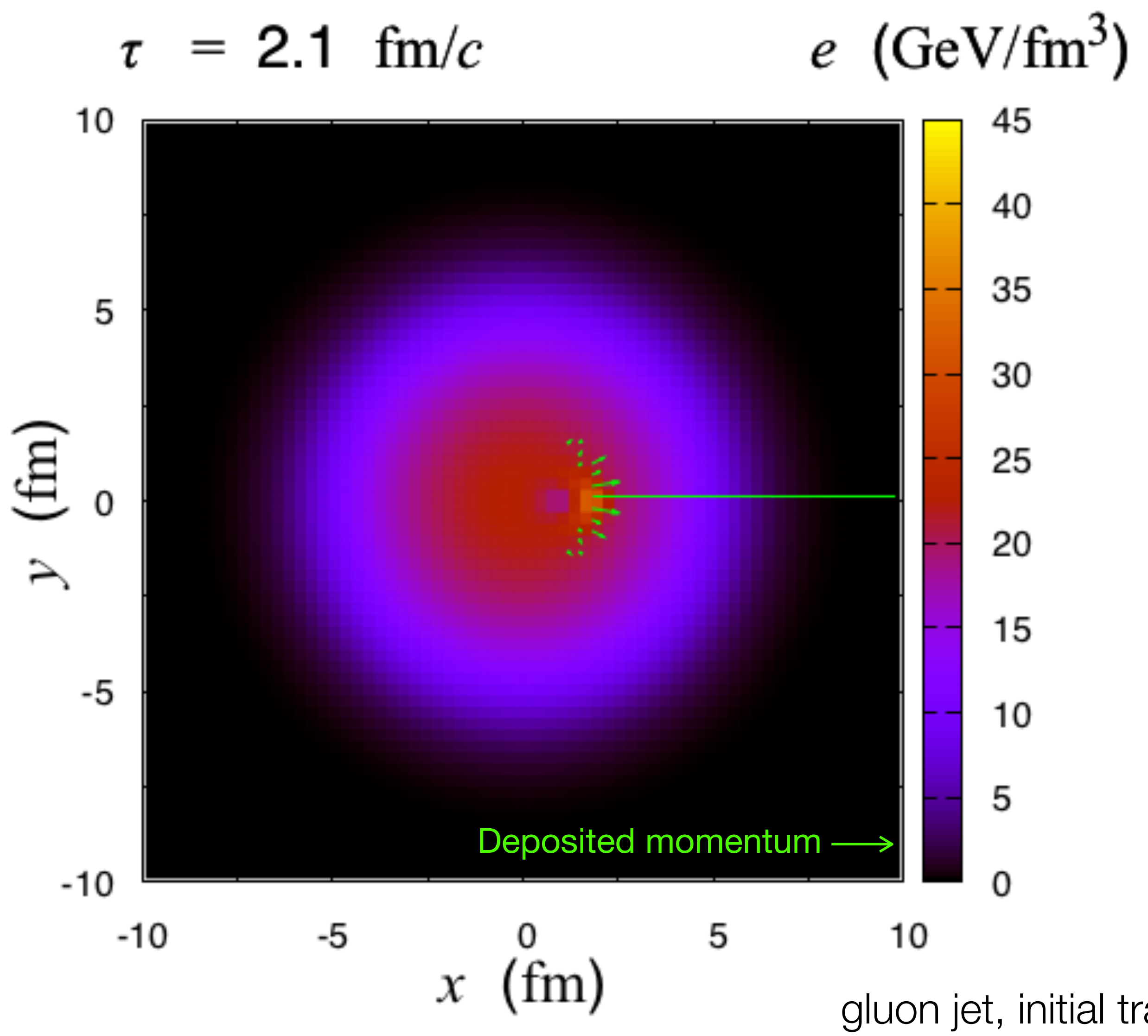

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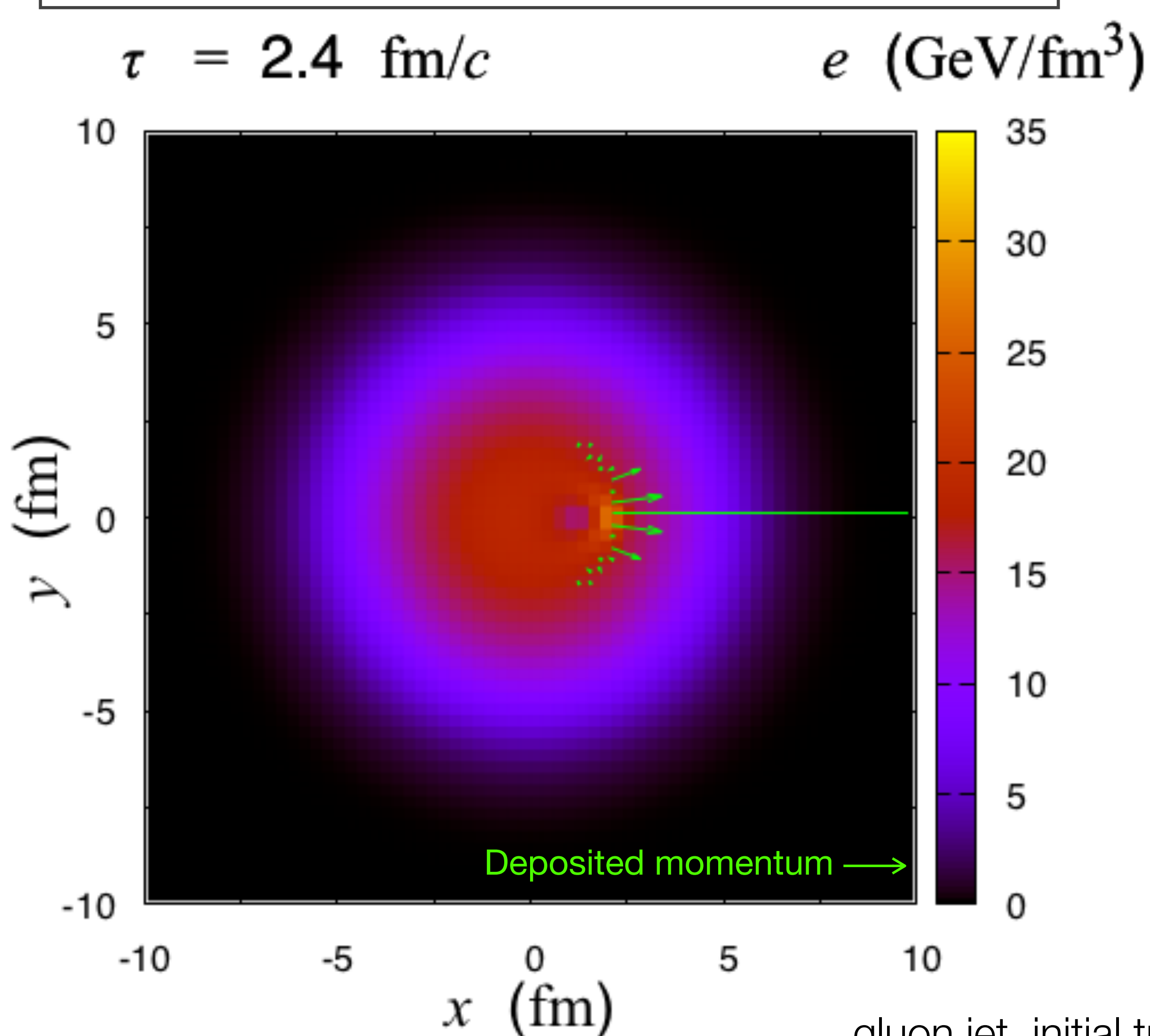

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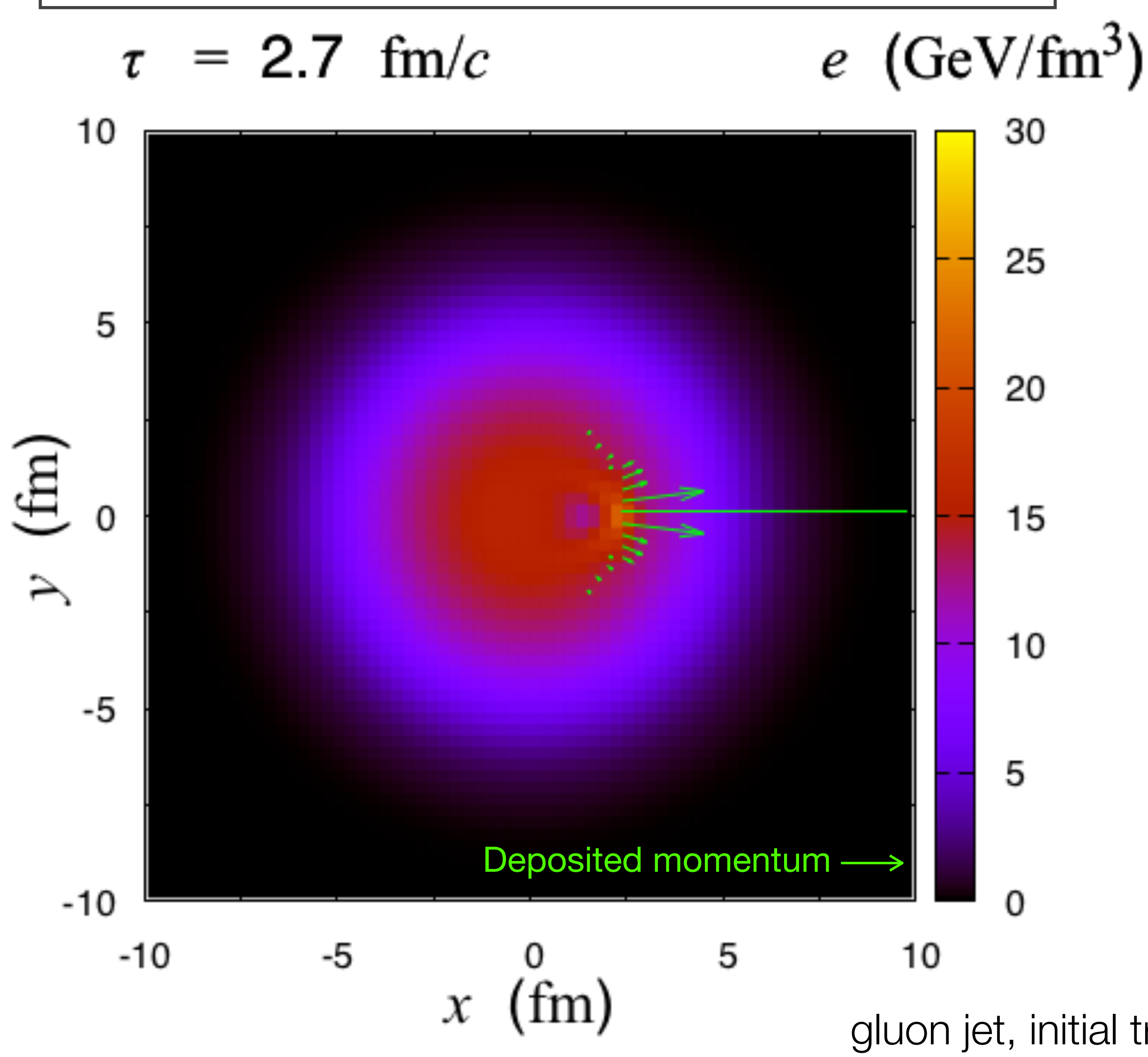

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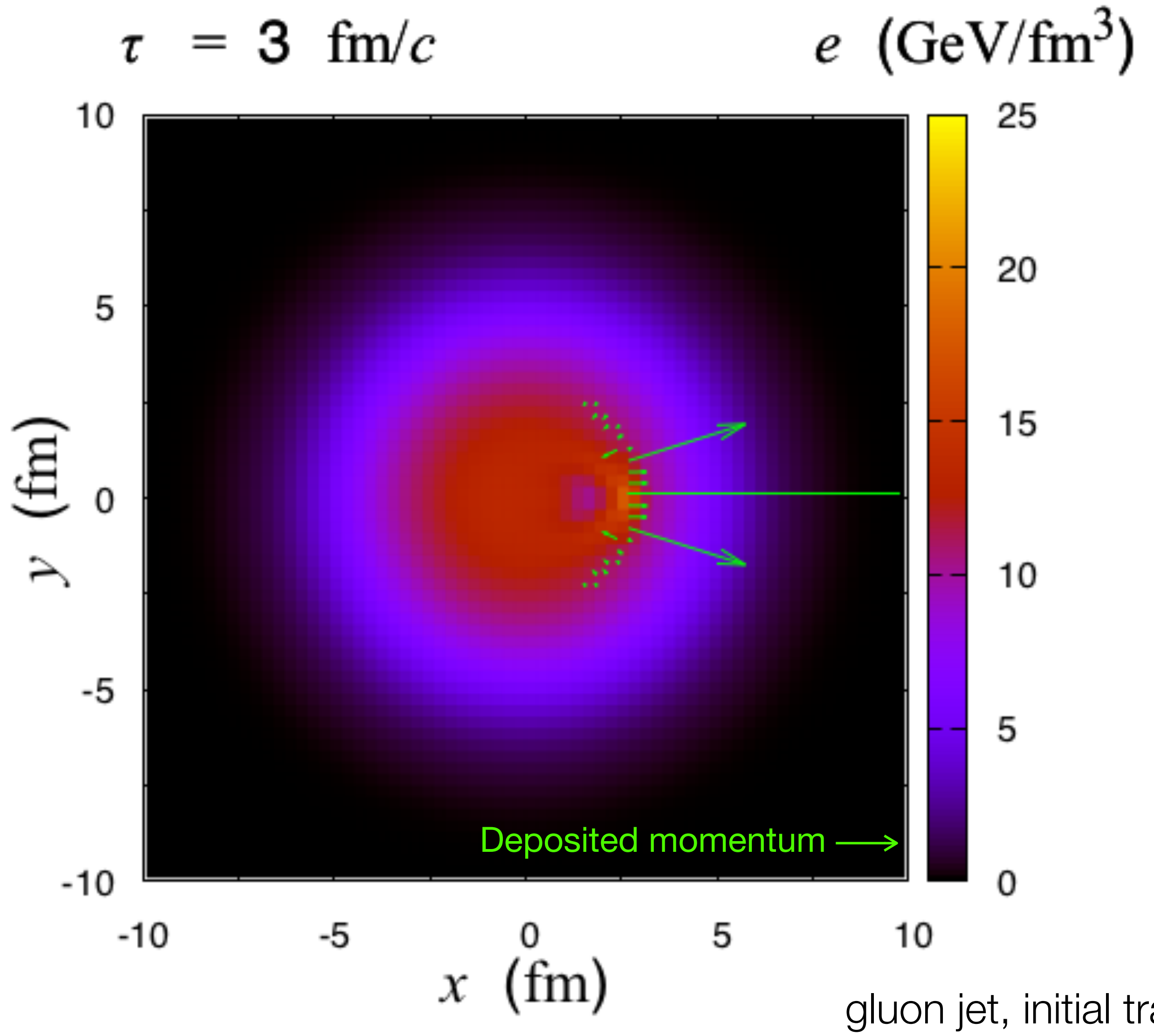

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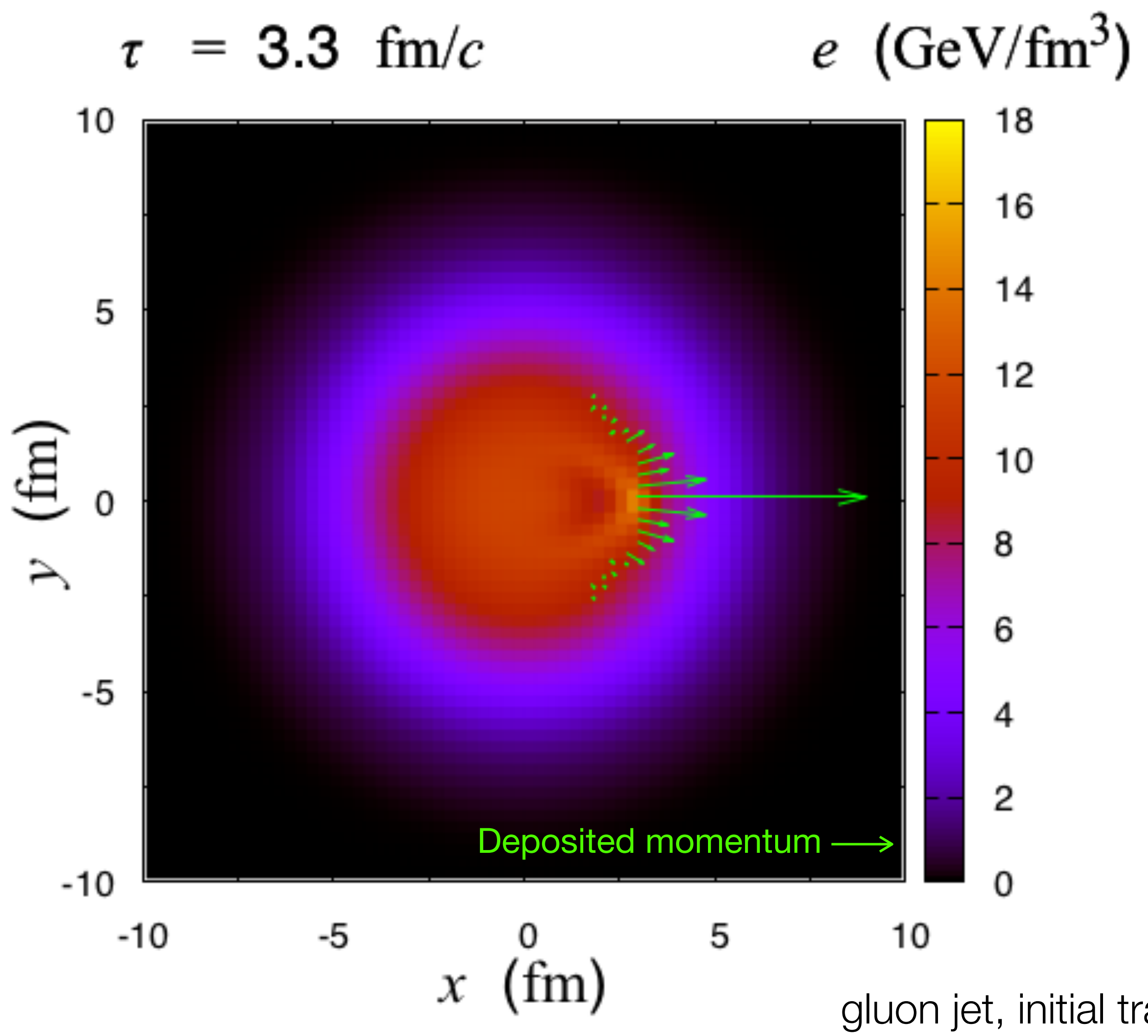

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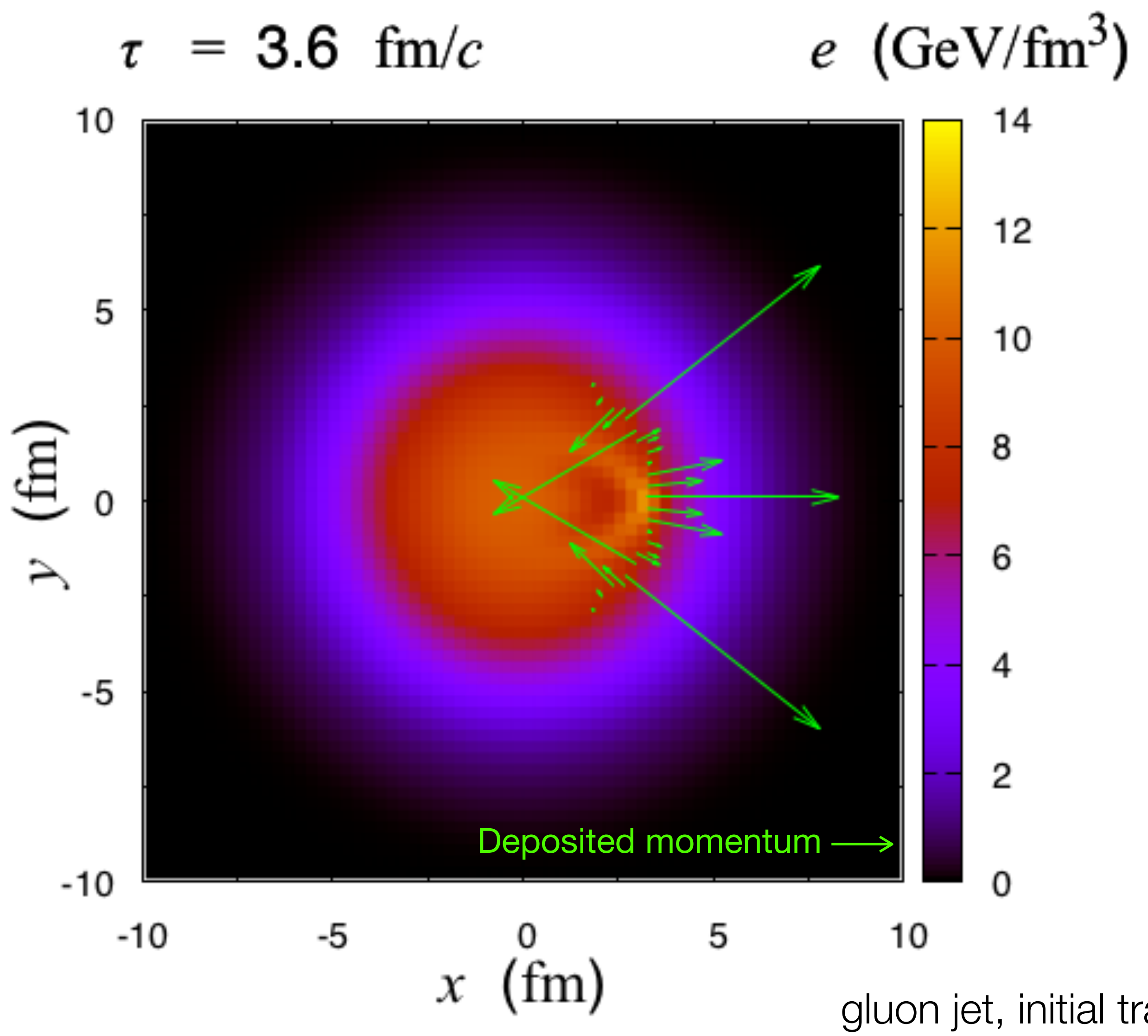

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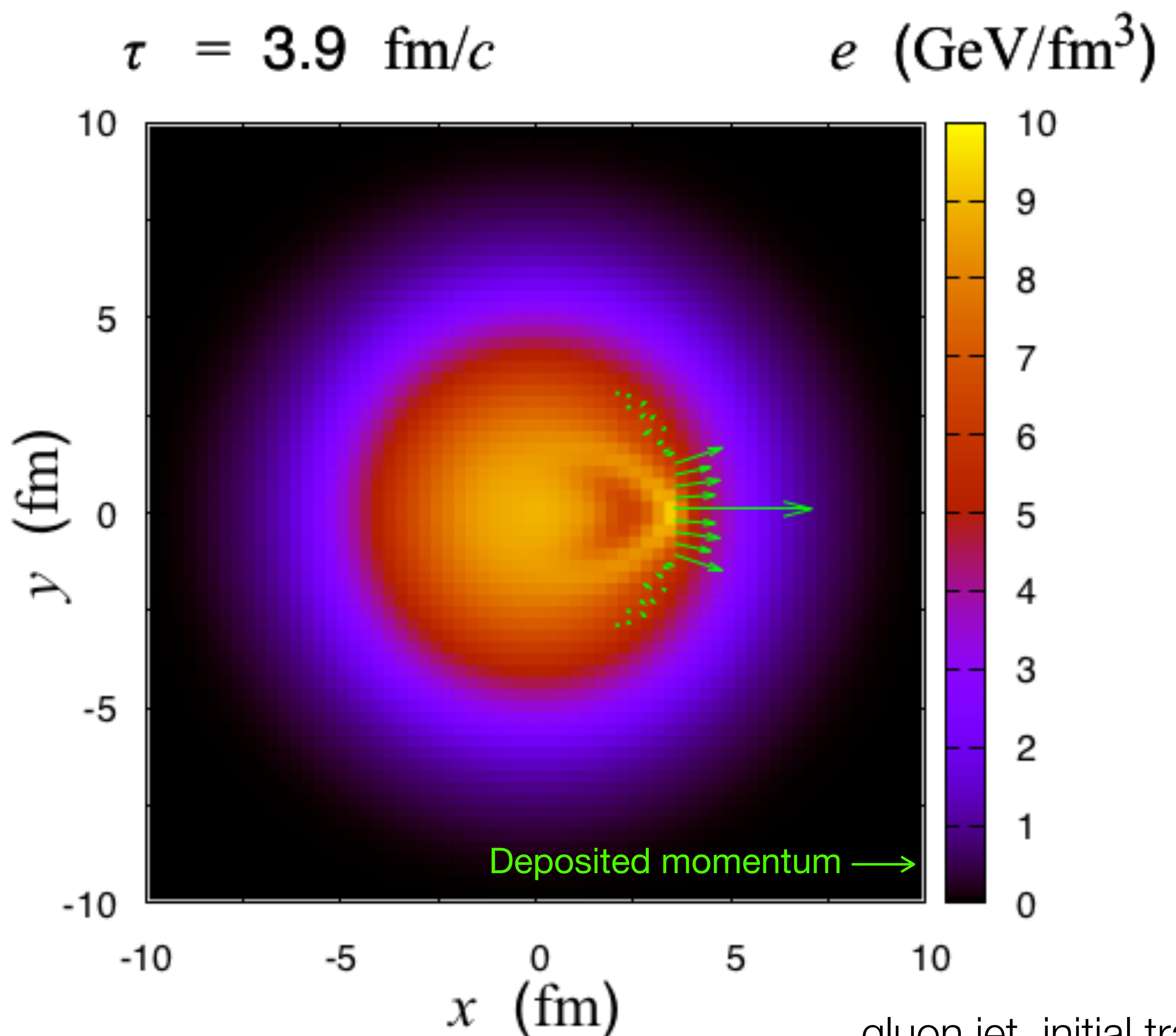

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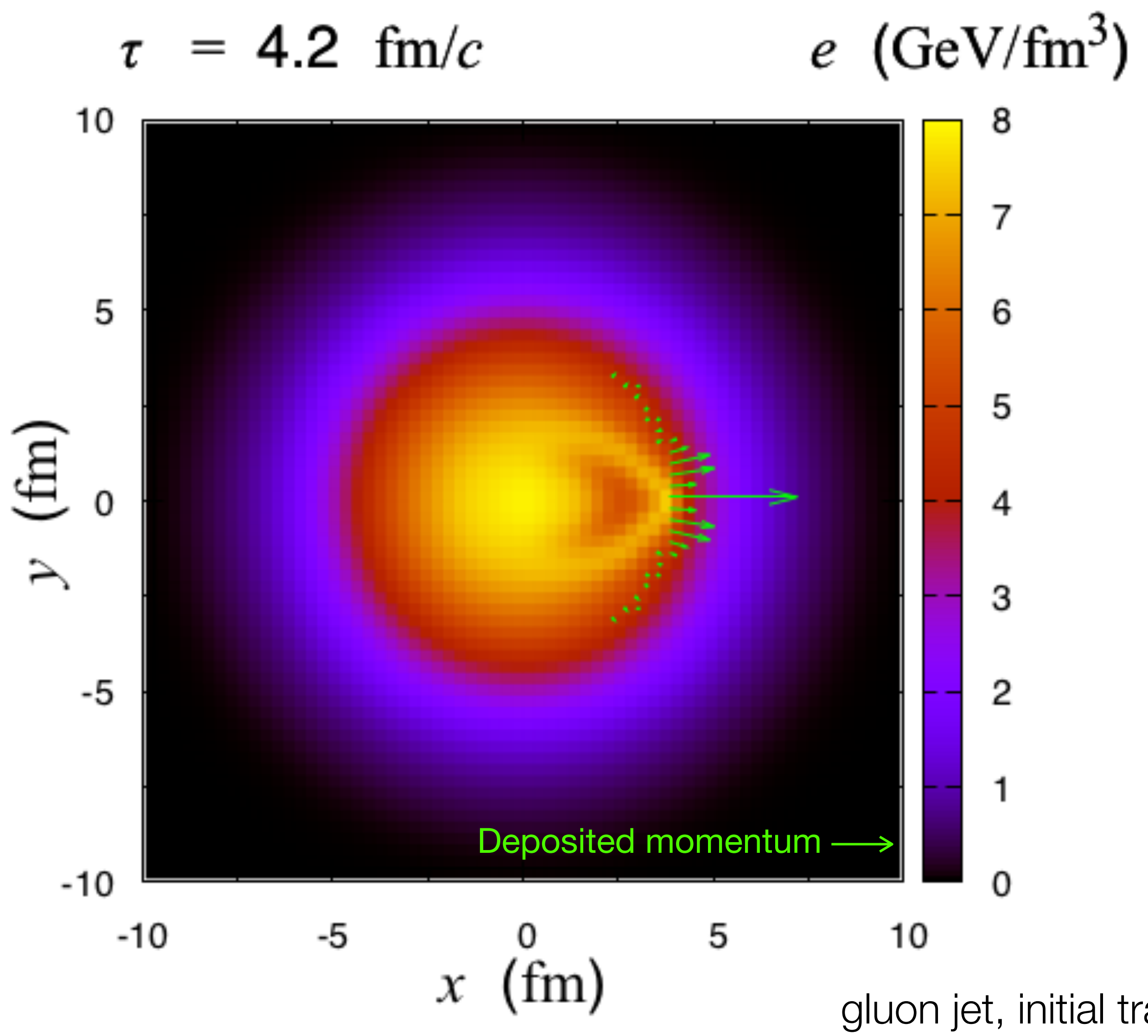
- **(3+1)-D ideal hydro**
  - Optical Glauber model in central Pb-Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76\ \mathrm{TeV}$
  - EoS from lattice QCD
- **Evolution of medium and jet shower**

Medium energy density in transverse plane at $\eta_s = 0$



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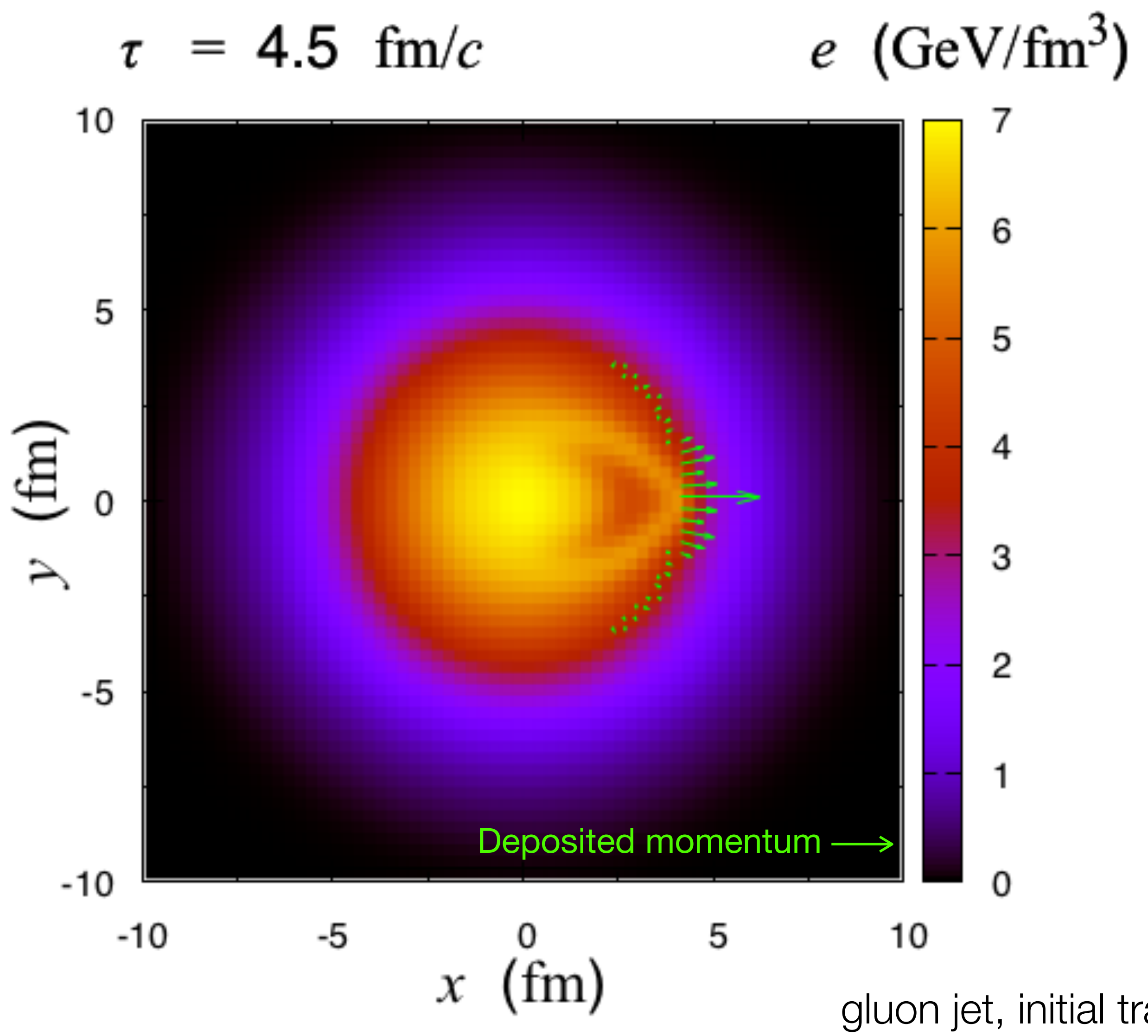

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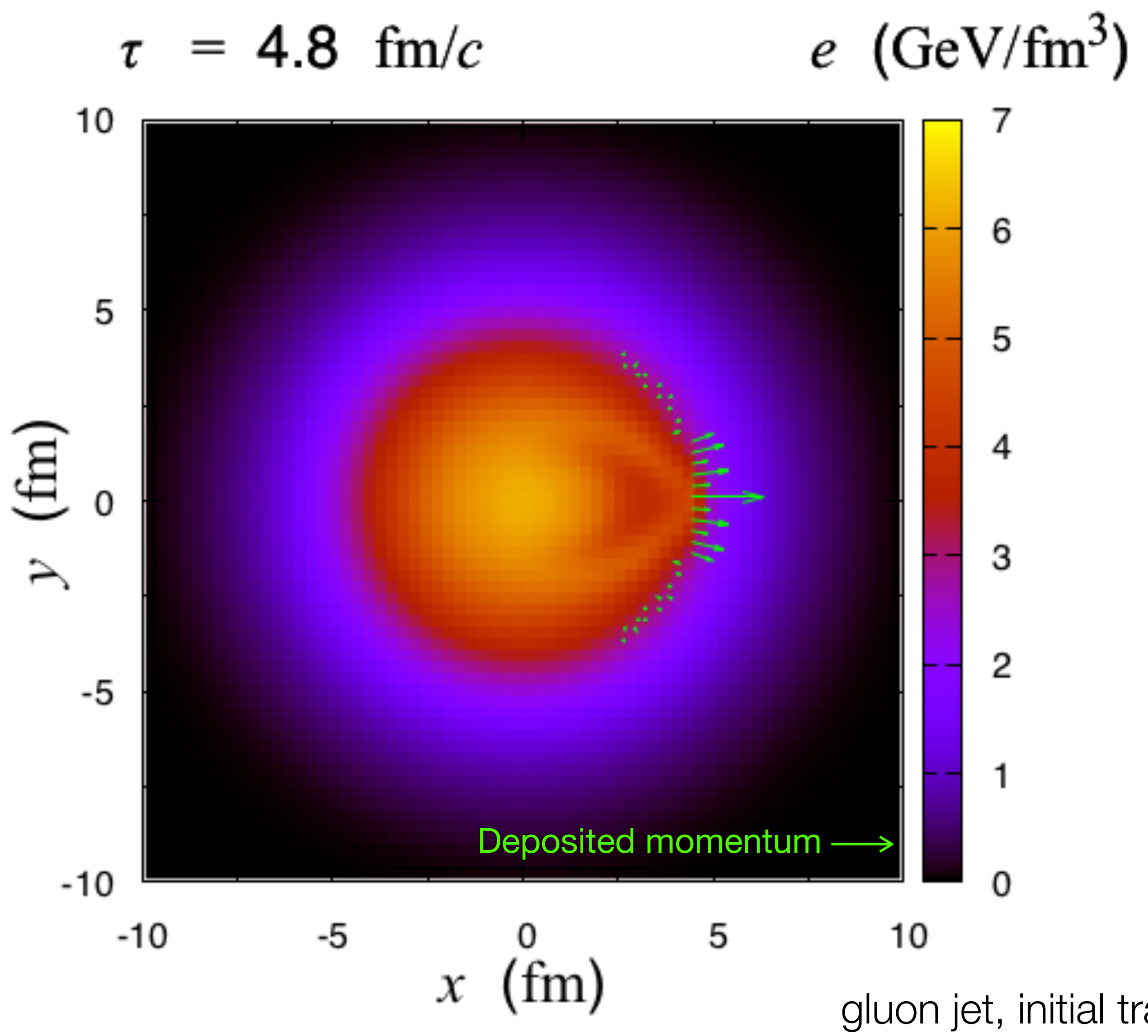

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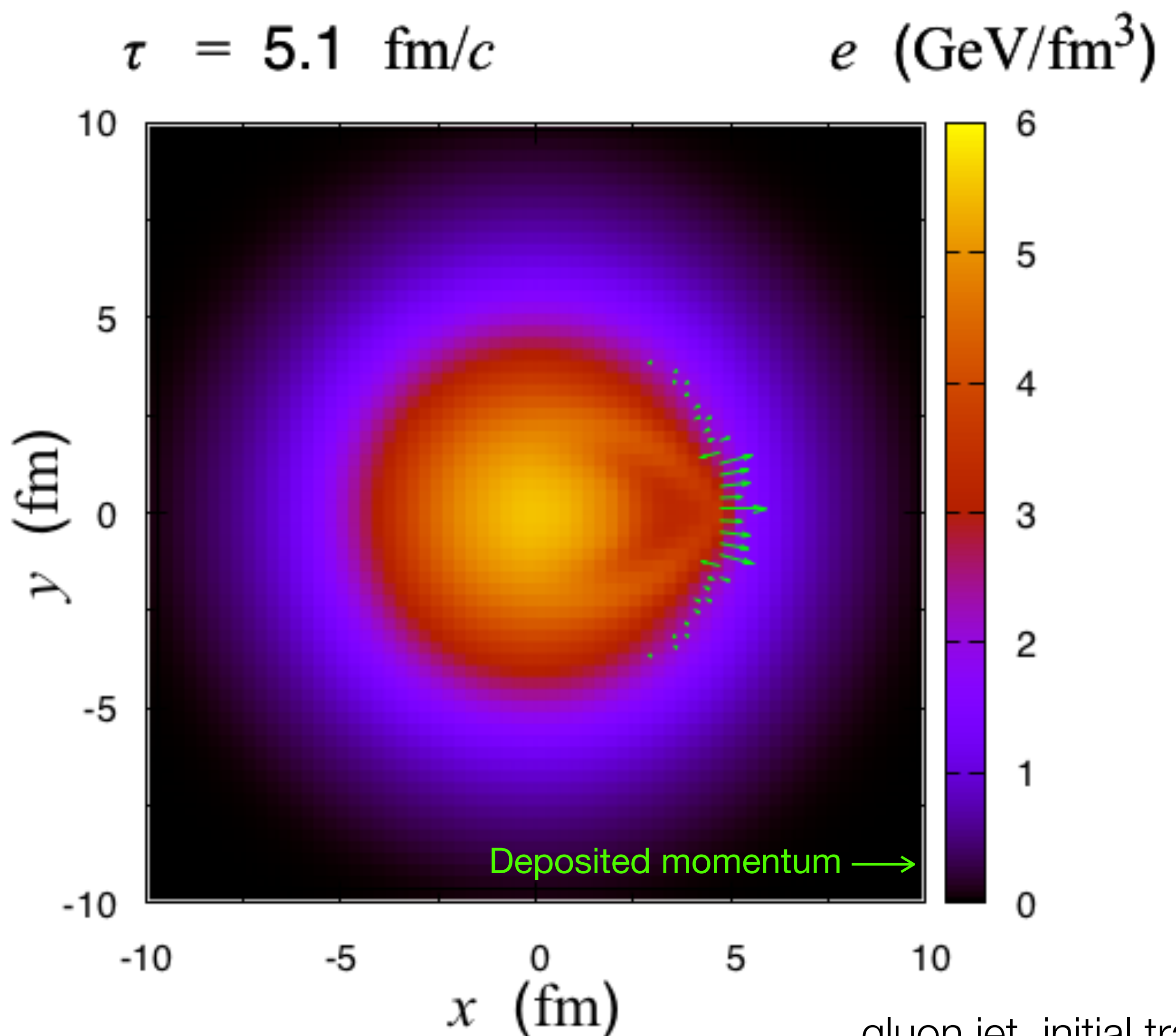

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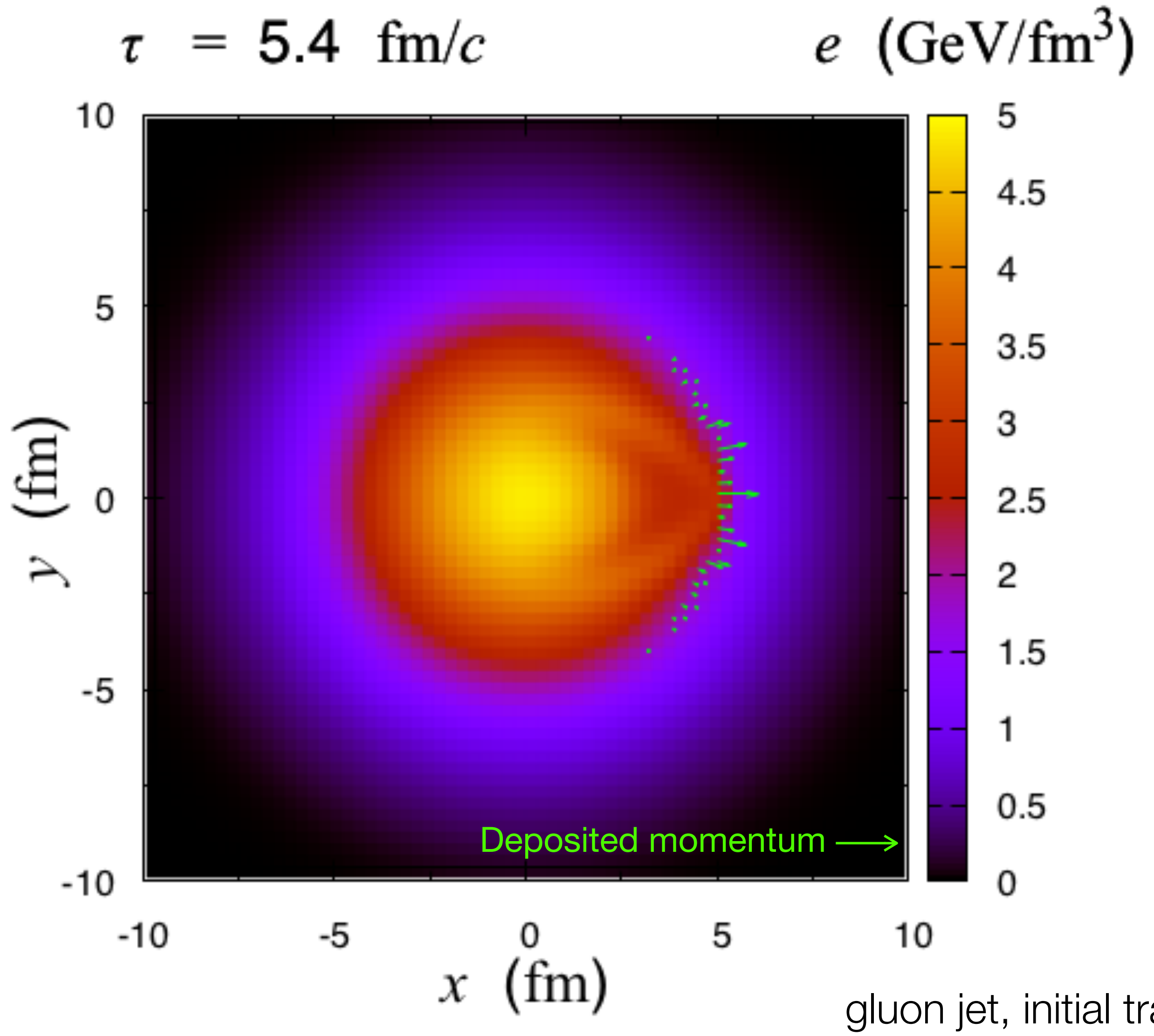

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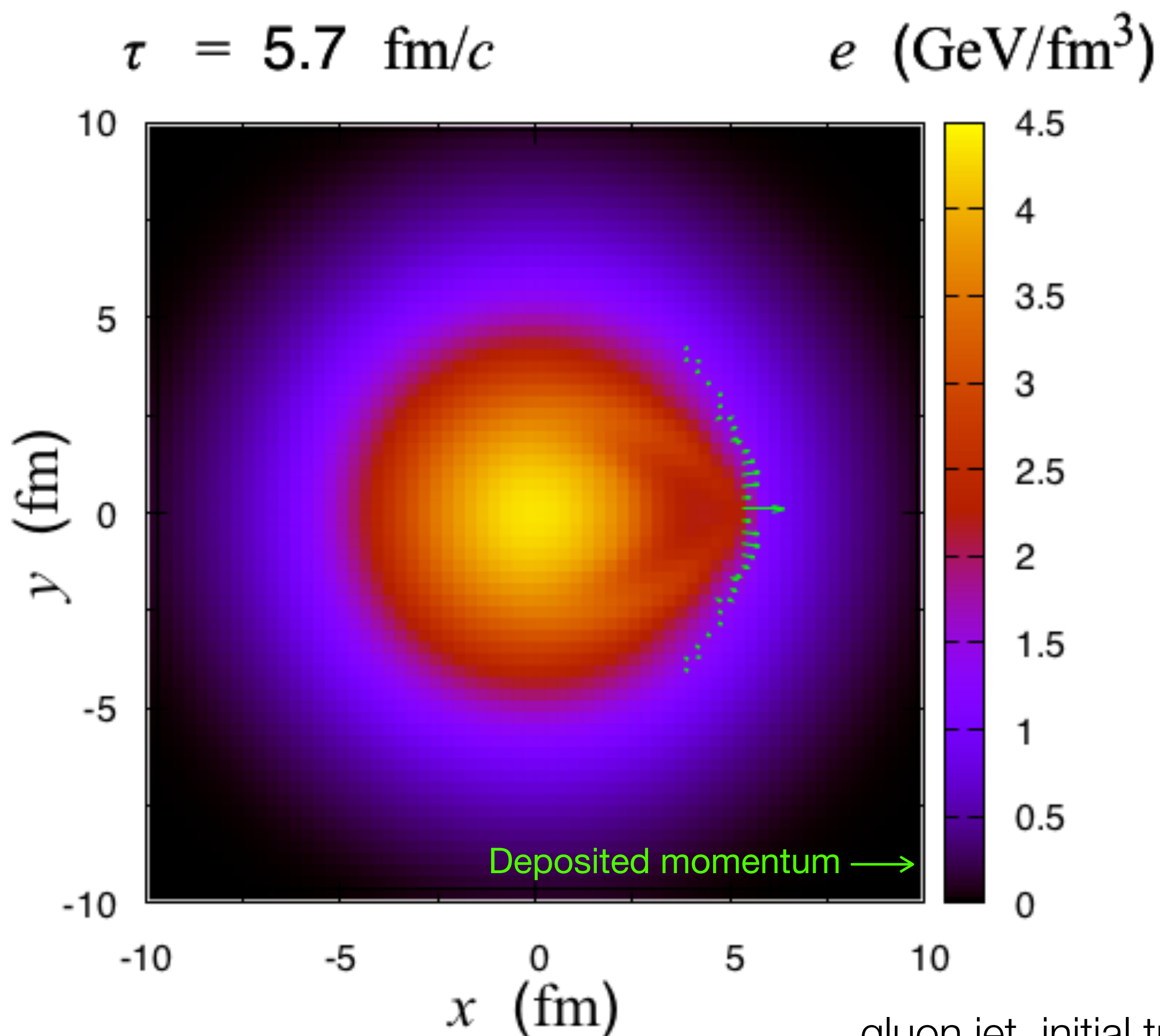

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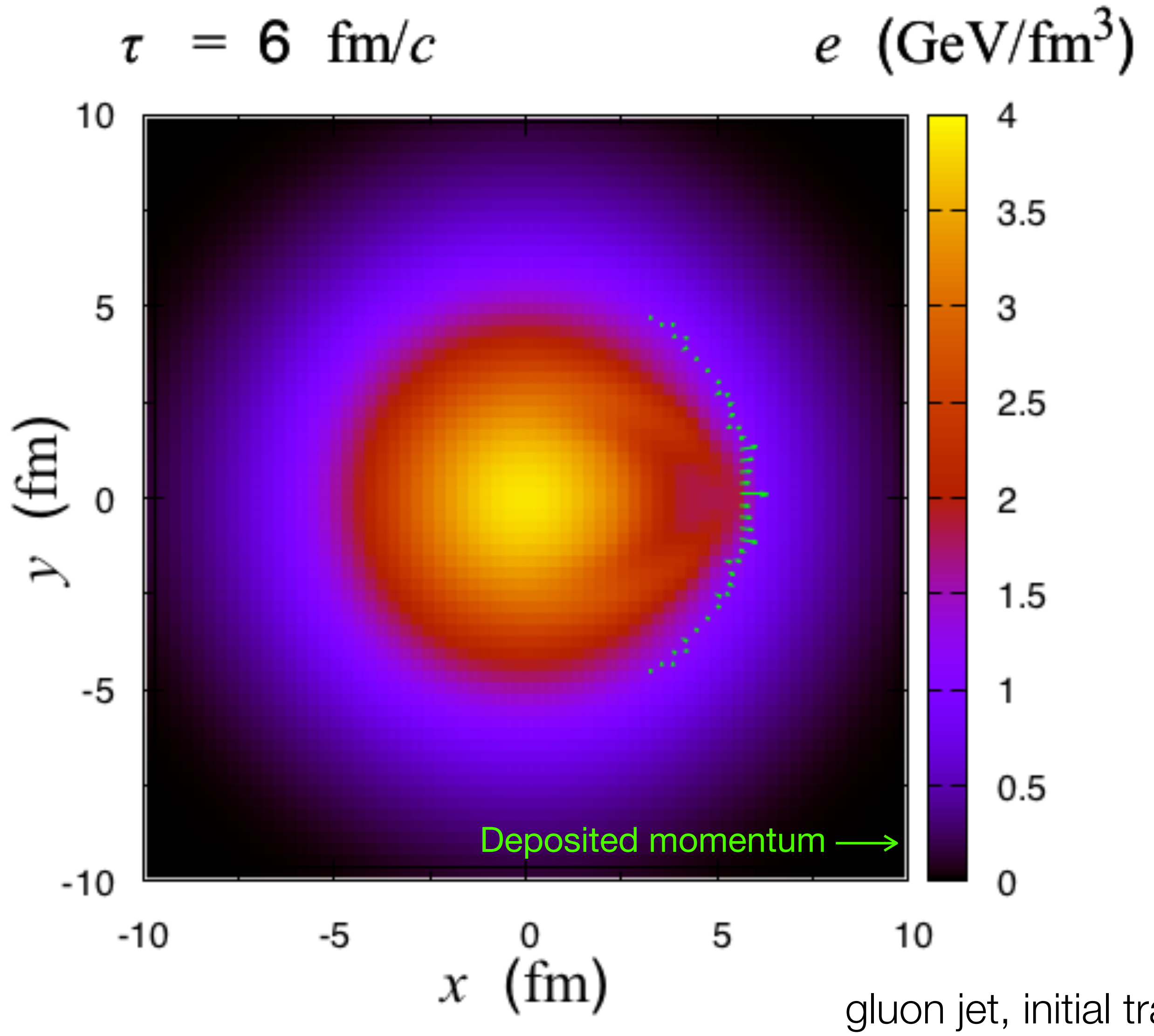

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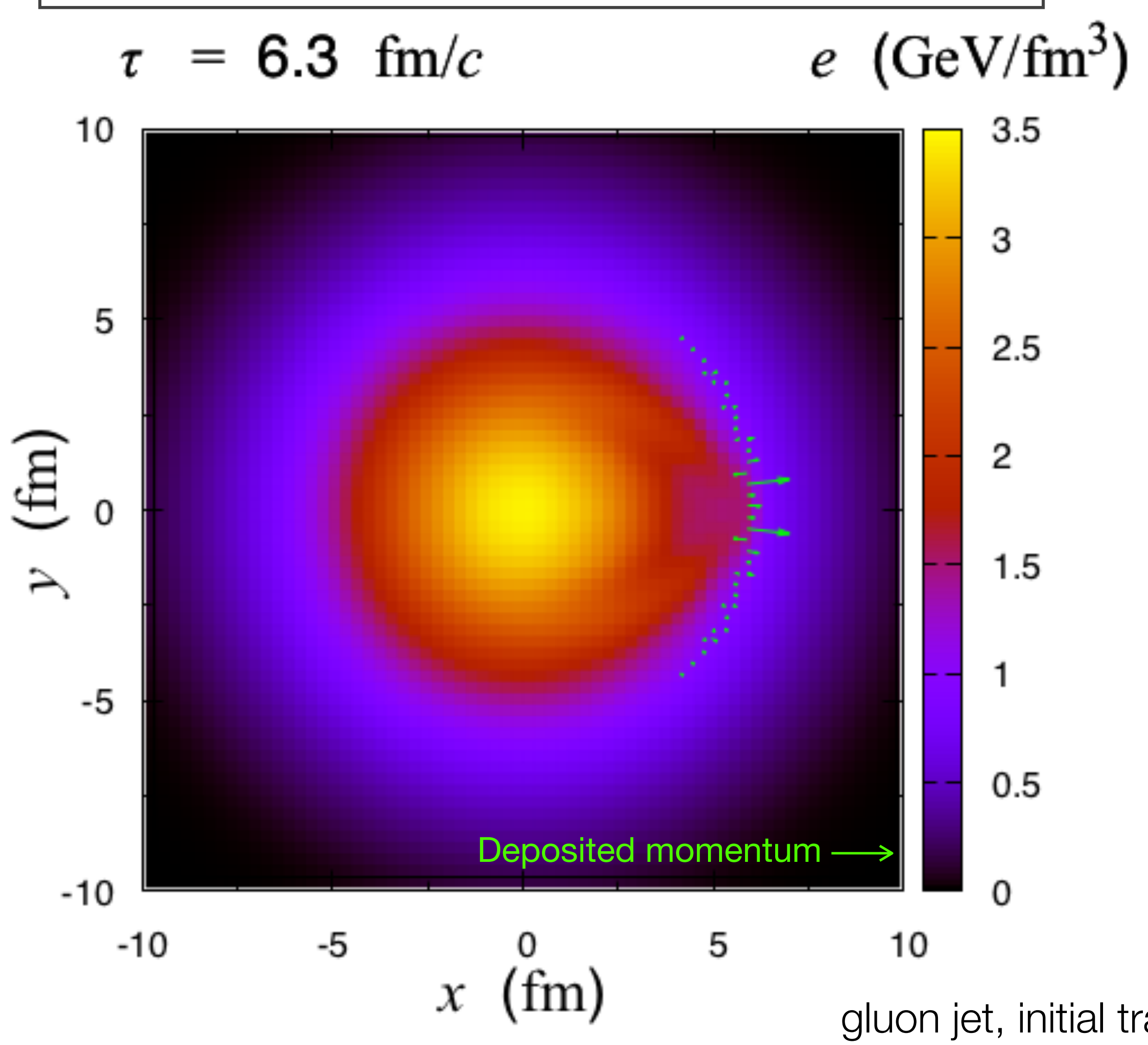

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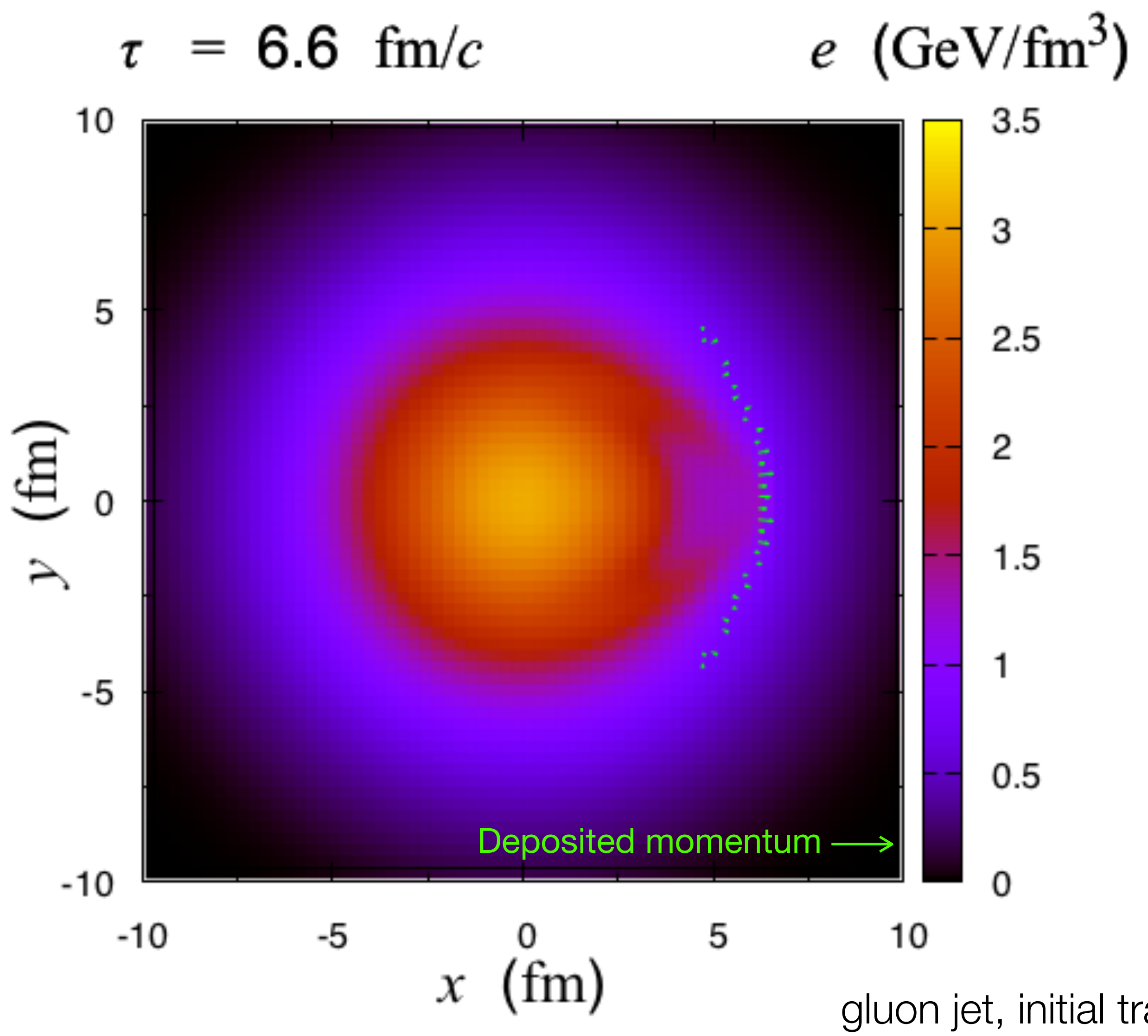

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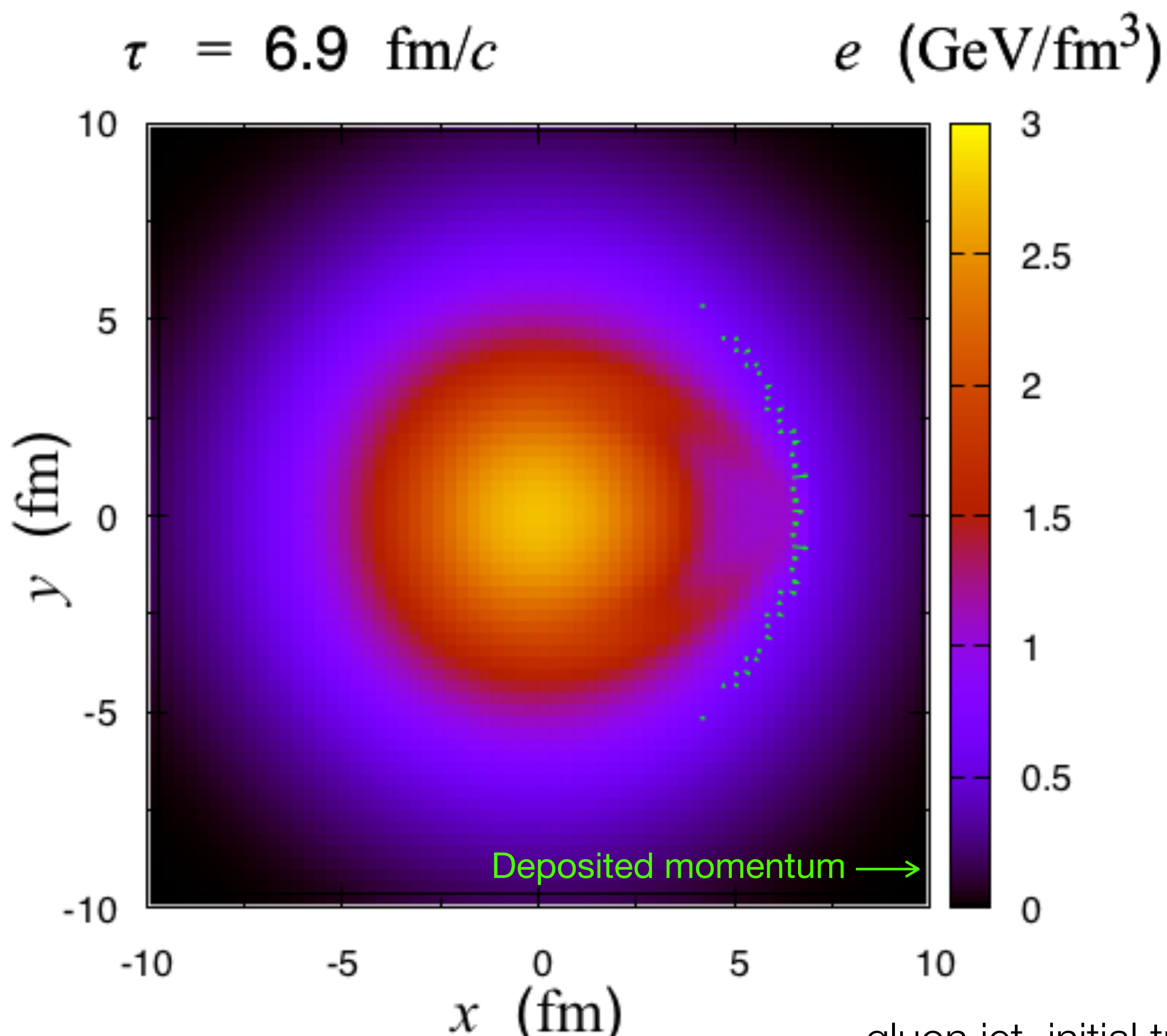

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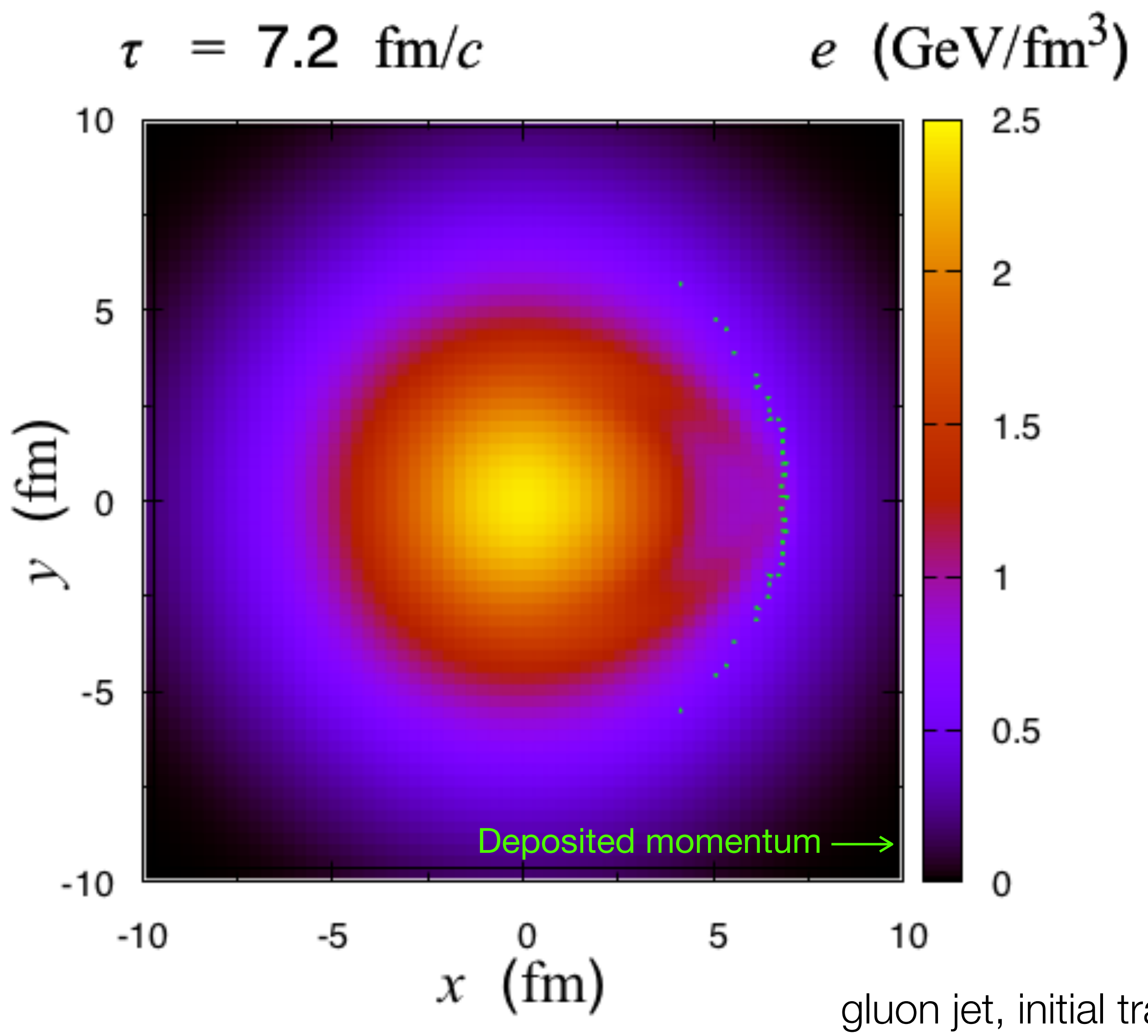
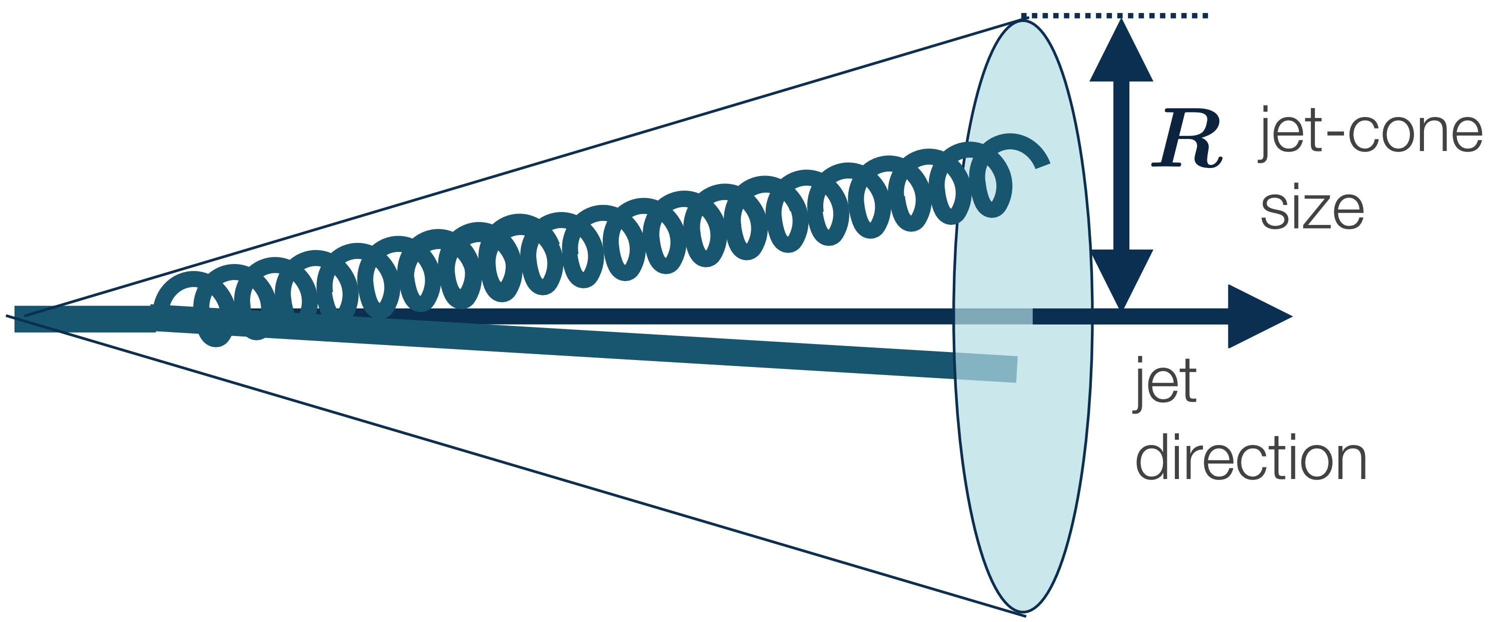


gluon jet, initial transverse momentum: $150\ \mathrm{GeV}/c$

Medium Response Contribution to Full Jet

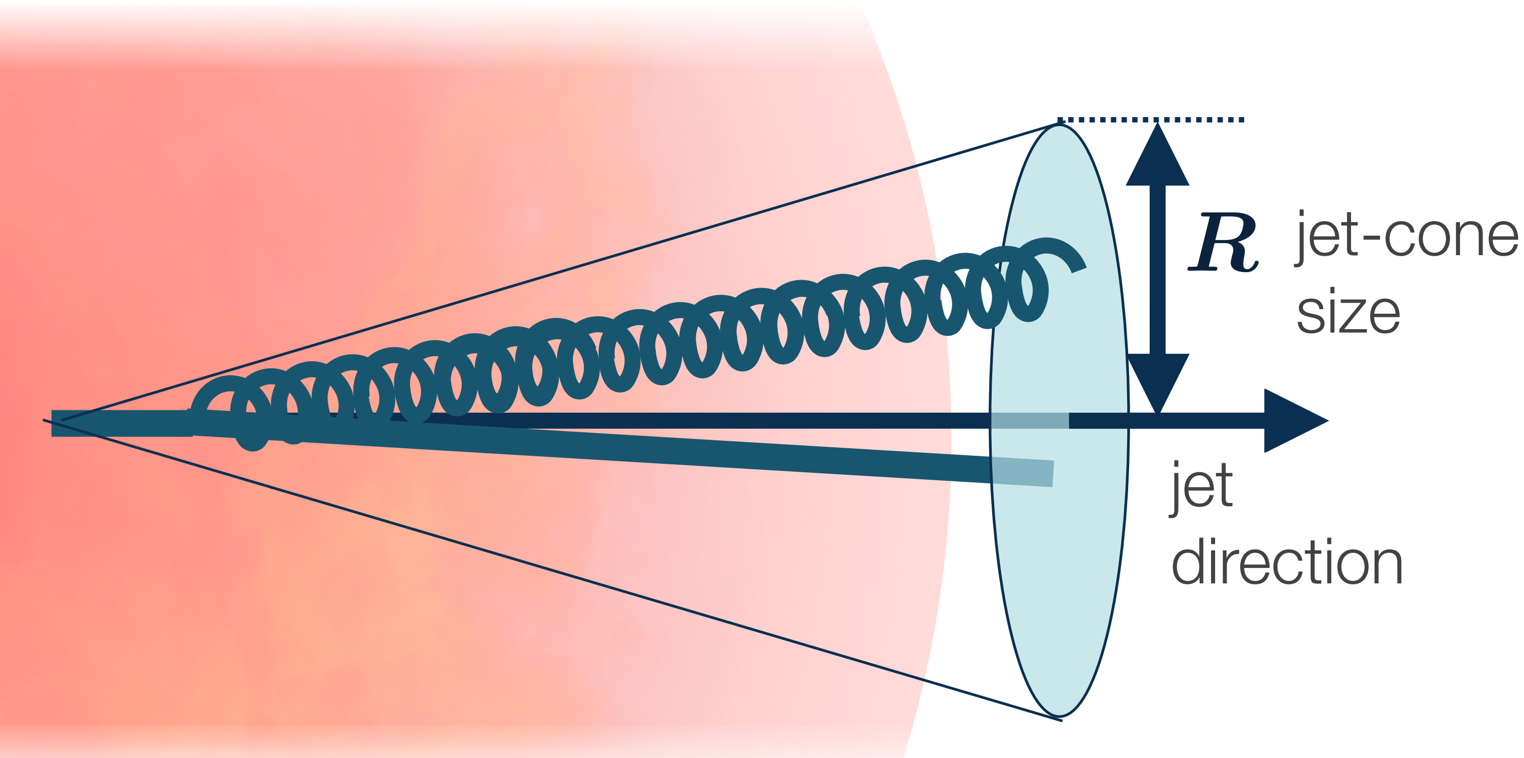


$$r = \sqrt{(\phi - \phi_{\mathrm{jet}})^2 + (\phi - \phi_{\mathrm{jet}})^2} < R$$

Counted as part of jet

- **Full jet energy loss and suppression (Jet Quenching)**

Medium Response Contribution to Full Jet



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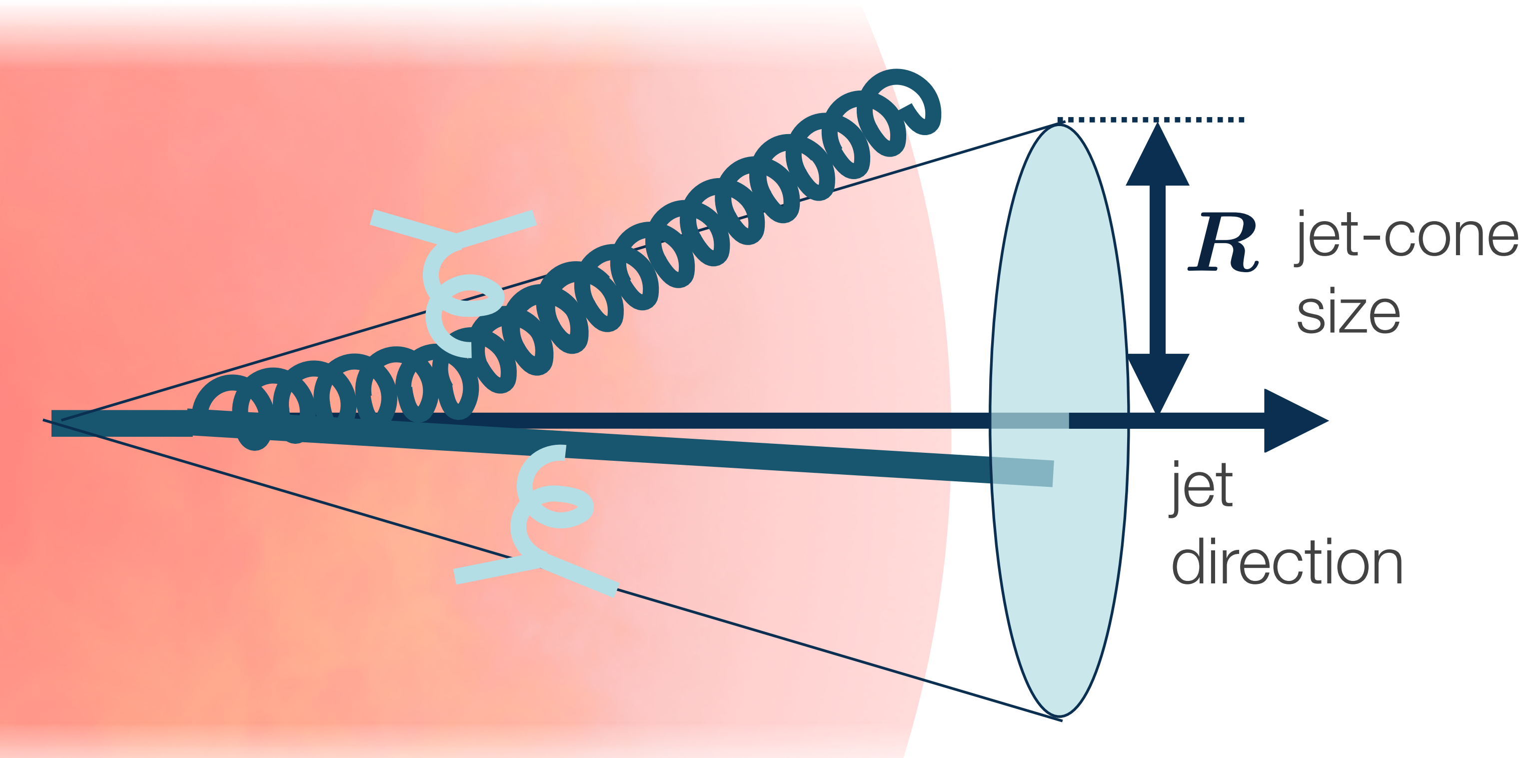

$$r = \sqrt{(\phi - \phi_{\rm jet})^2 + (\phi - \phi_{\rm jet})^2} < R$$

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- **Full jet energy loss and suppression (Jet Quenching)**
  1) Collisional energy loss (and absorption)
  2) Kick outside the jet cone (by momentum broadening)

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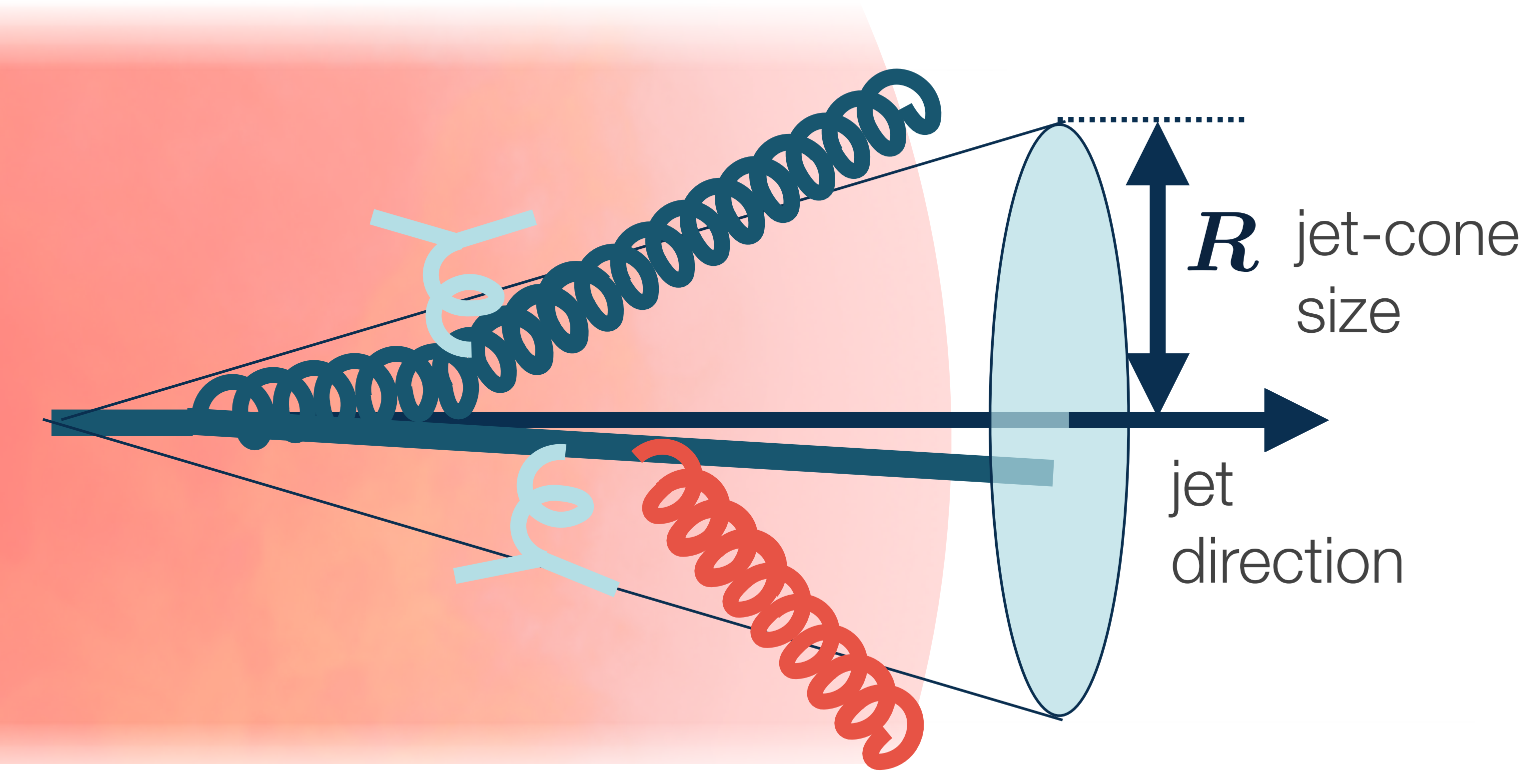

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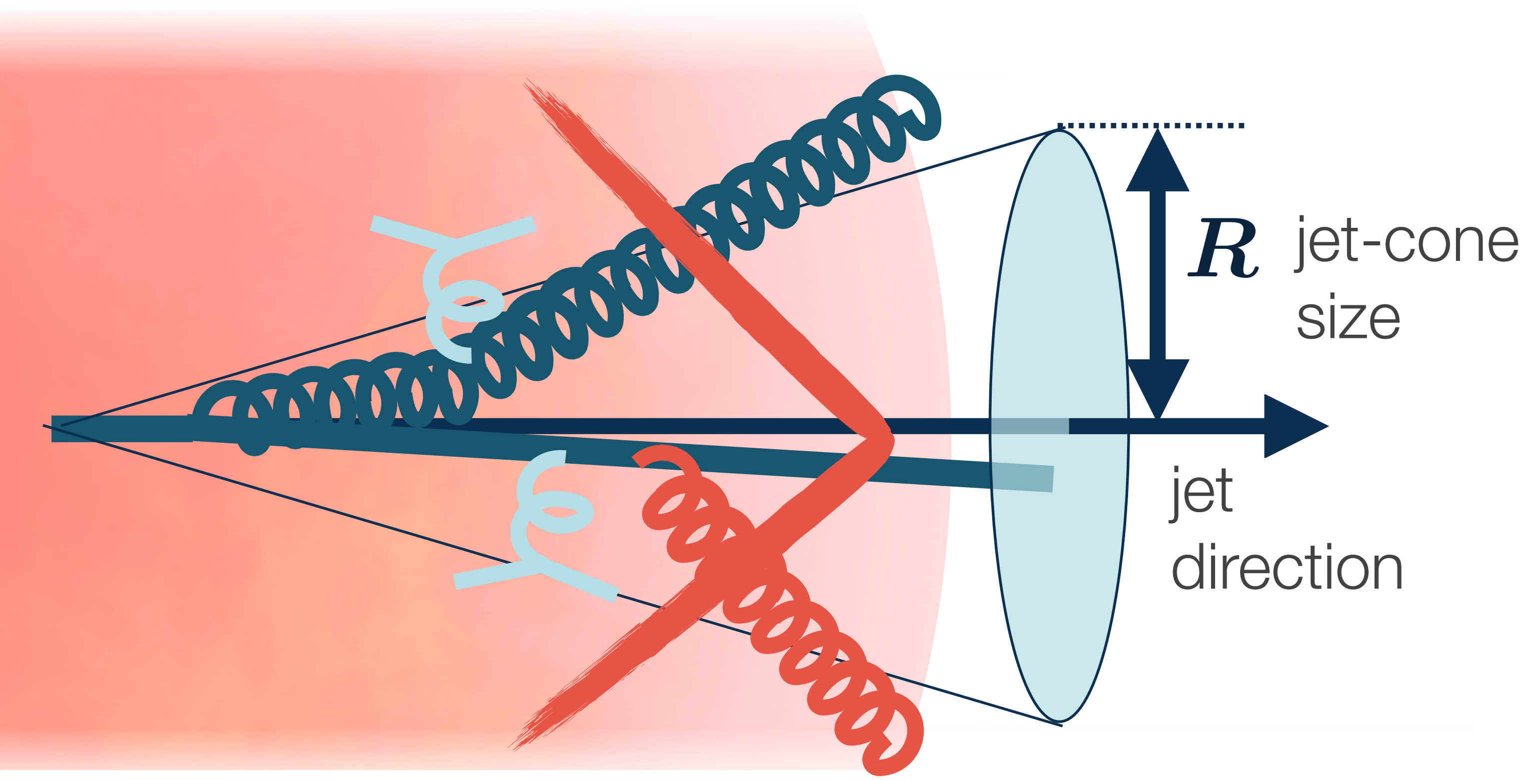

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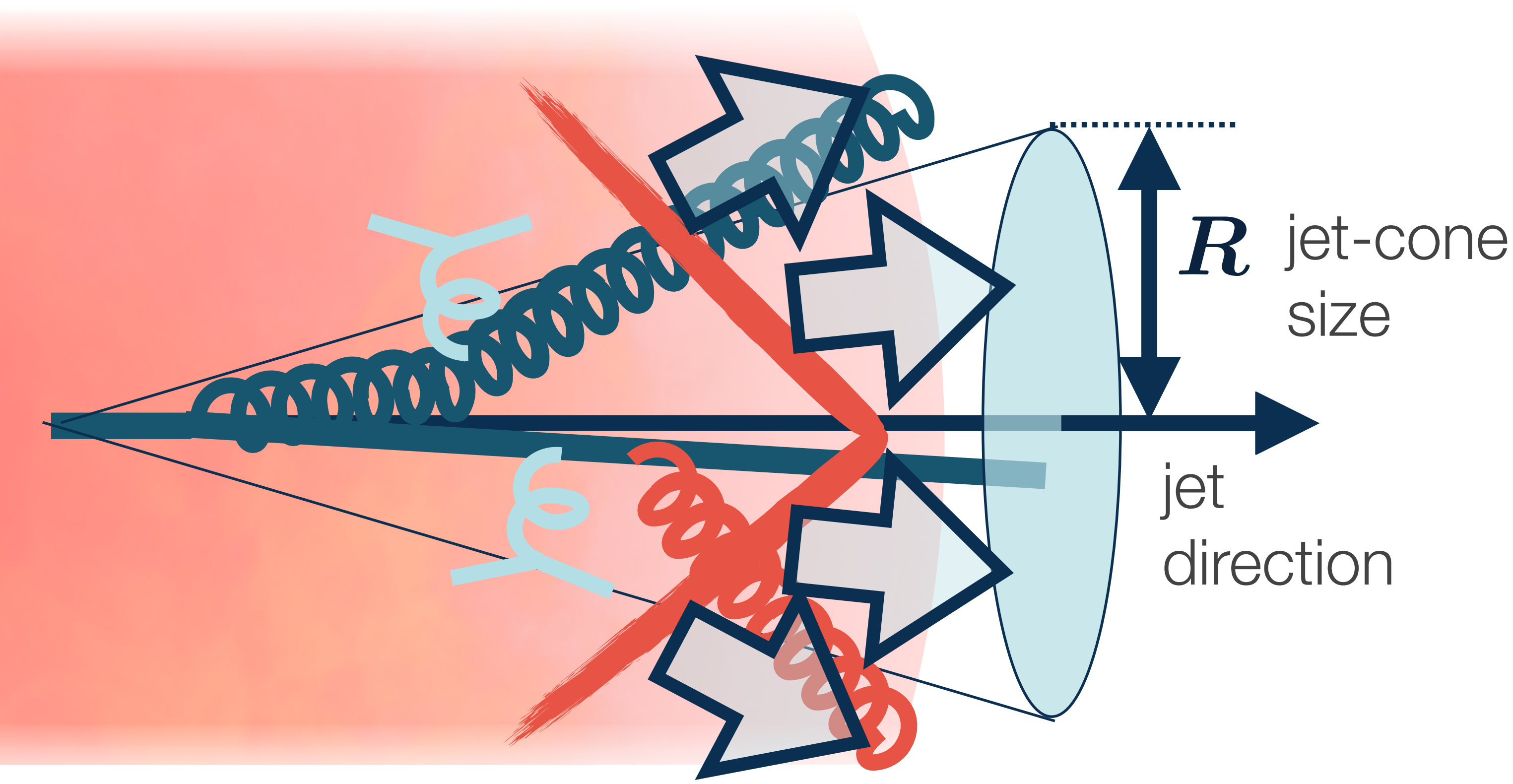

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Counted as part of jet

- **Full jet energy loss and suppression (Jet Quenching)**
  1) Collisional energy loss (and absorption)
  2) Kick outside the jet cone (by momentum broadening)
  3) Medium-induced radiation outside the jet cone
- **Particles from excited medium** **(Jet-correlated, cannot be subtracted)**
  - **Partially compensate the lost energy via 1) and 2)**

$$\Delta \frac{dN}{d^3p} = \left.\frac{dN}{d^3p}\right|_{\mathrm{w/\ jet}} - \left.\frac{dN}{d^3p}\right|_{\mathrm{w/o\ jet}} \longleftarrow$$

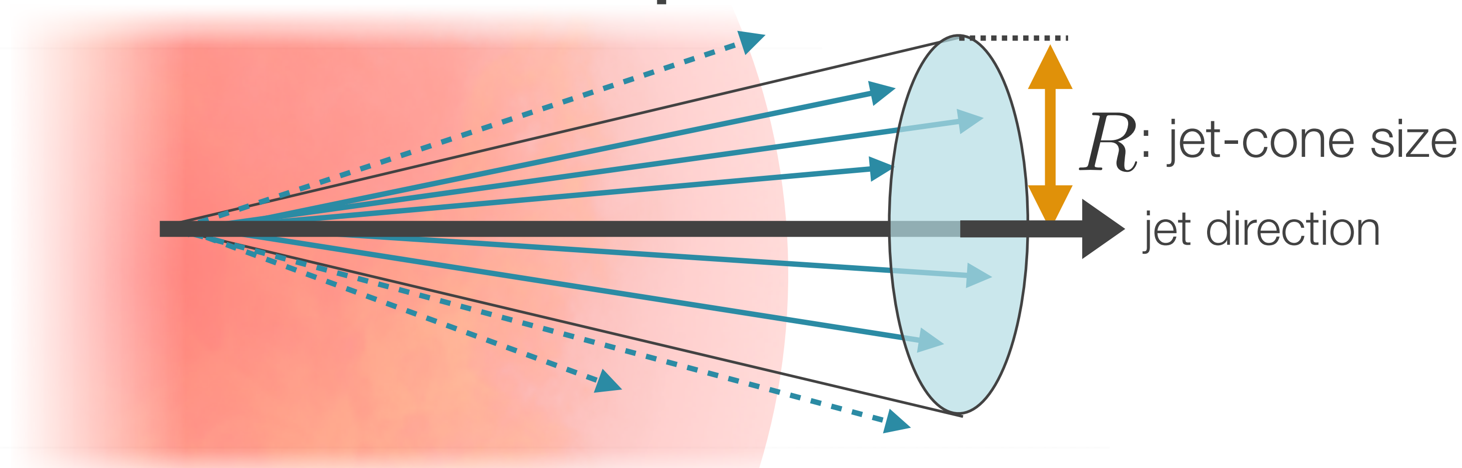
Cooper-Frye formula

$$E_i \frac{dN_i}{d^3p_i} = \frac{g_i}{(2\pi)^3} \int_\Sigma \frac{p_i^\mu d\sigma_\mu(x)}{\exp[p_i^\mu u_\mu(x)/T(x)] \mp 1}$$

Full Jet Energy Loss and Suppression

(jets are generated by PYTHIA & MC Glauber)

- **Contribution of particles emitted from excited medium**



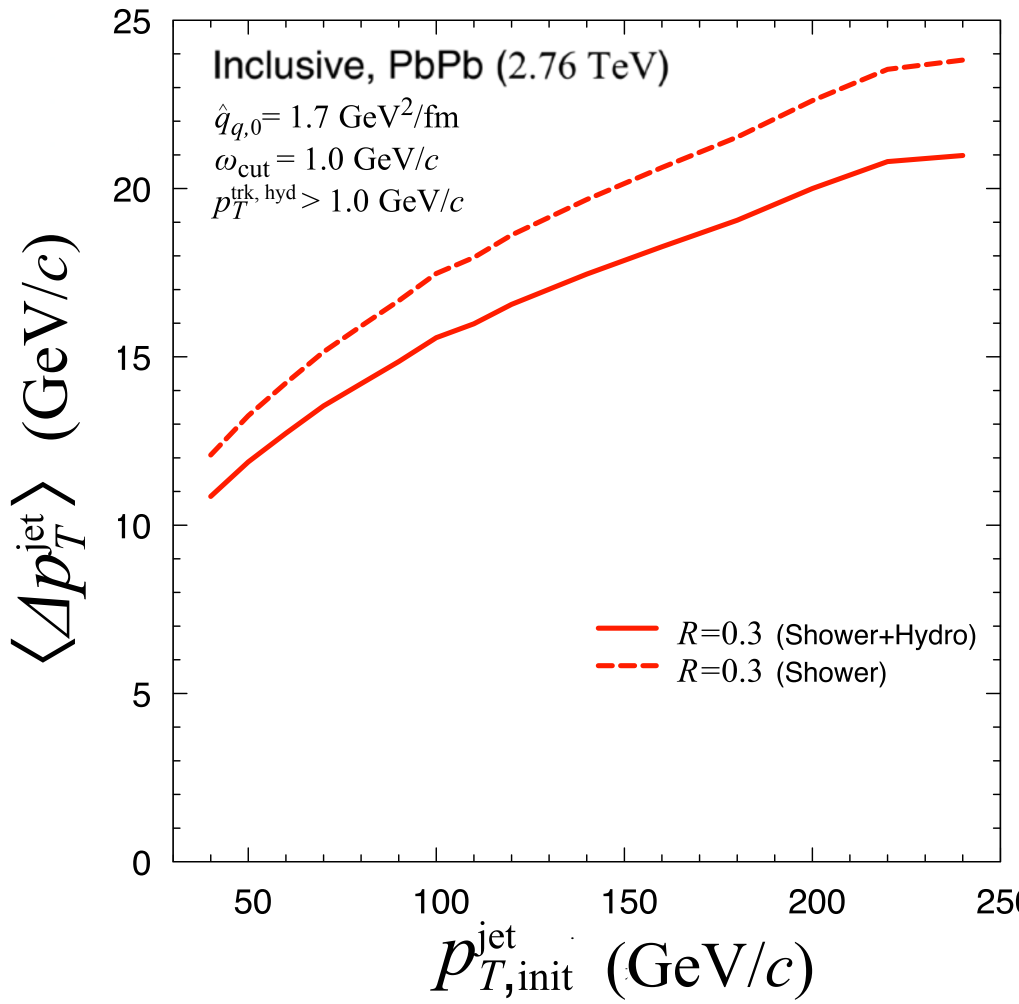
$$r = \sqrt{(\phi - \phi_{\rm jet})^2 + (\phi - \phi_{\rm jet})^2} < R$$

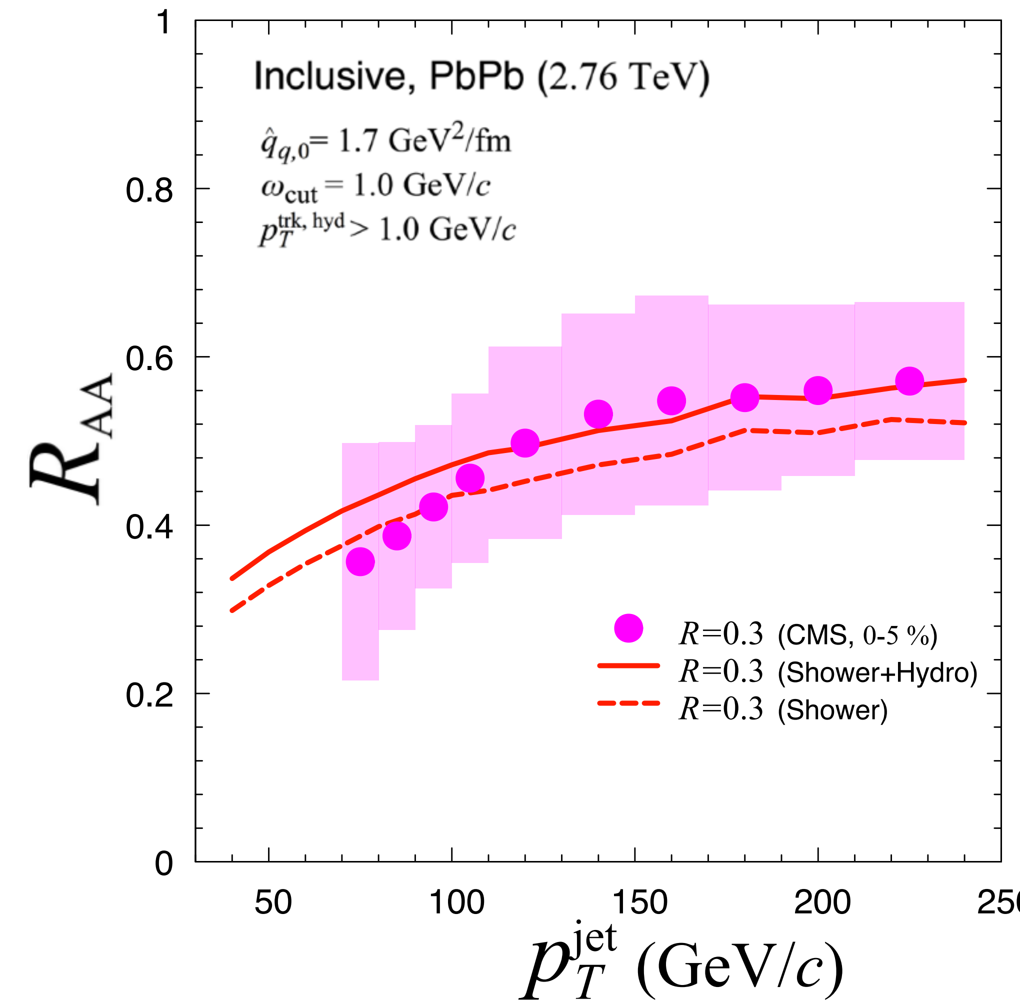
→ Counted as part of jet

Nuclear modification factor

$$R_{\rm AA} = \frac{1}{\langle N_{\rm coll}\rangle} \frac{d^2N^{\rm AA}_{\rm jet}/d\eta_p dp_T^{\rm jet}}{d^2N^{\rm pp}_{\rm jet}/d\eta_p dp_T^{\rm jet}},$$

Total transverse momentum Loss





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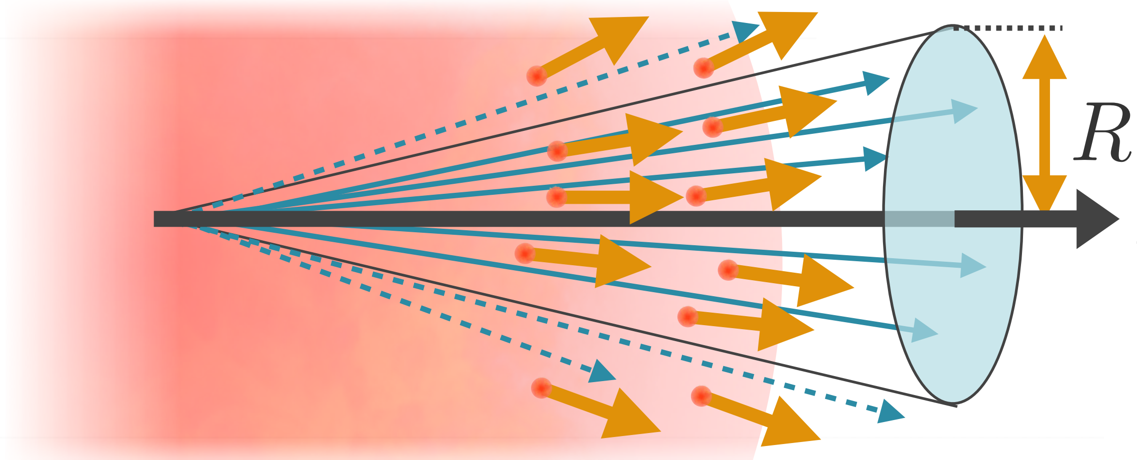

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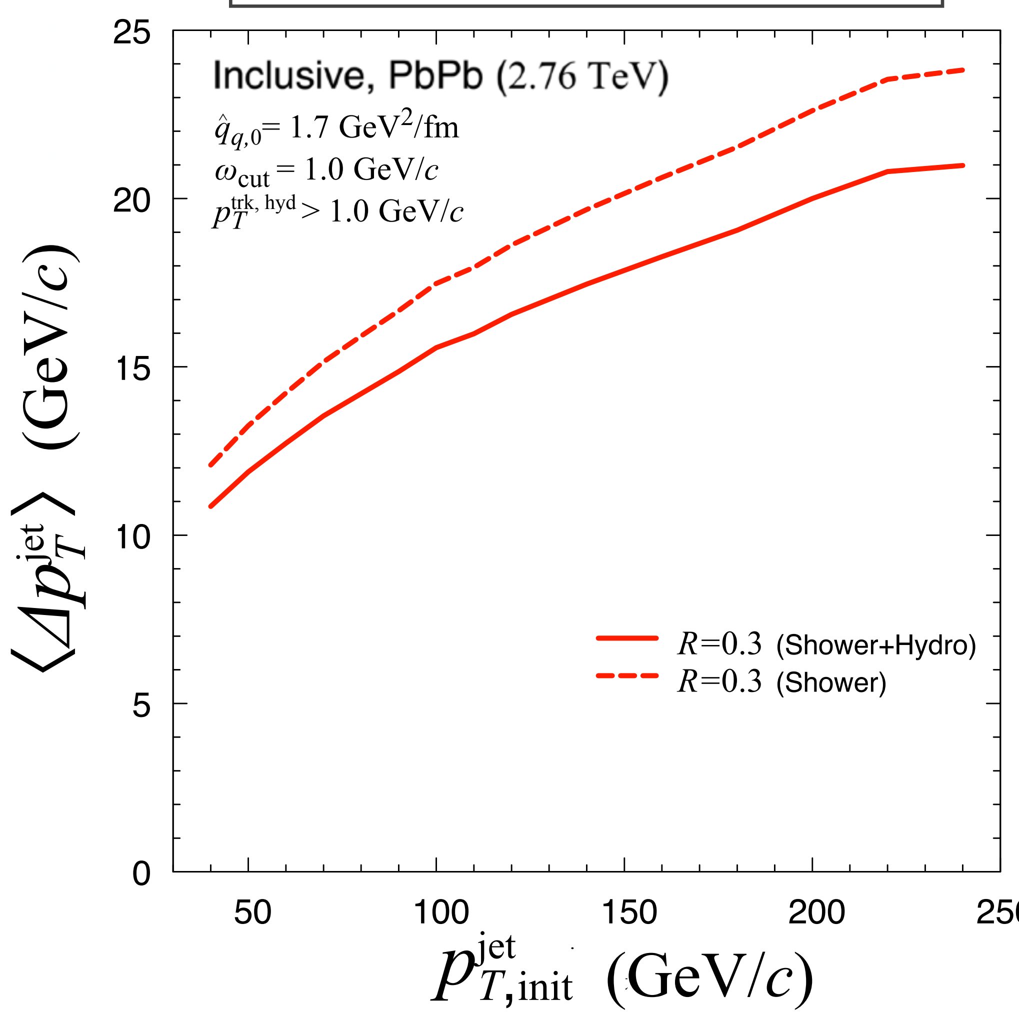
Total transverse momentum Loss



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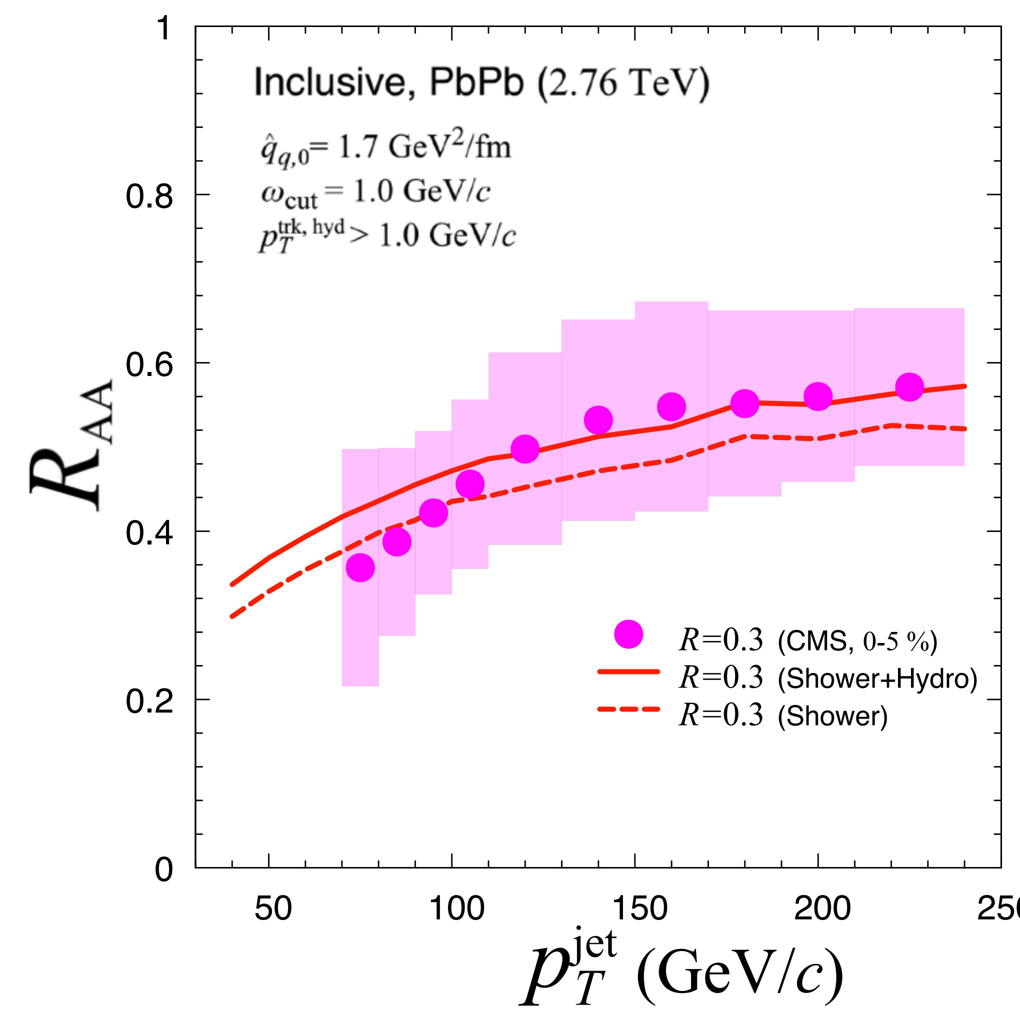

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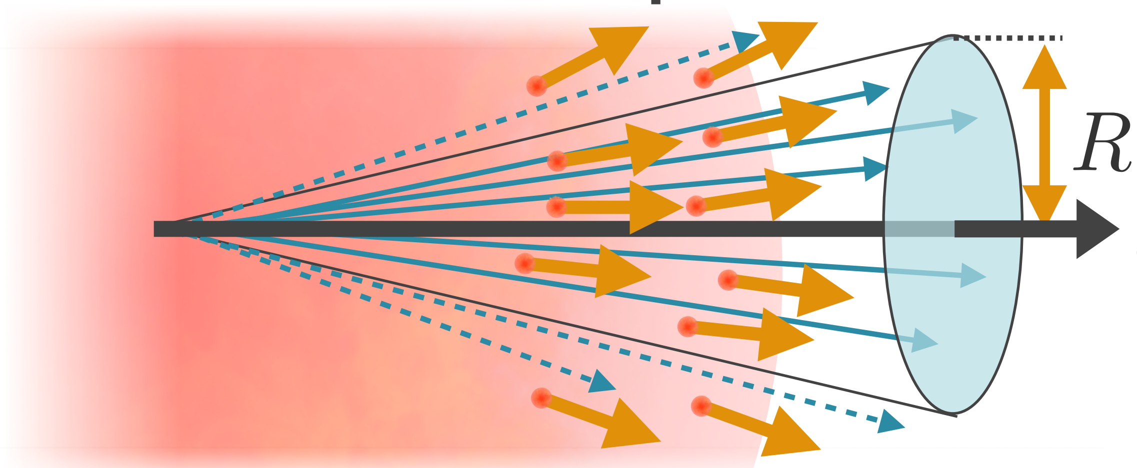

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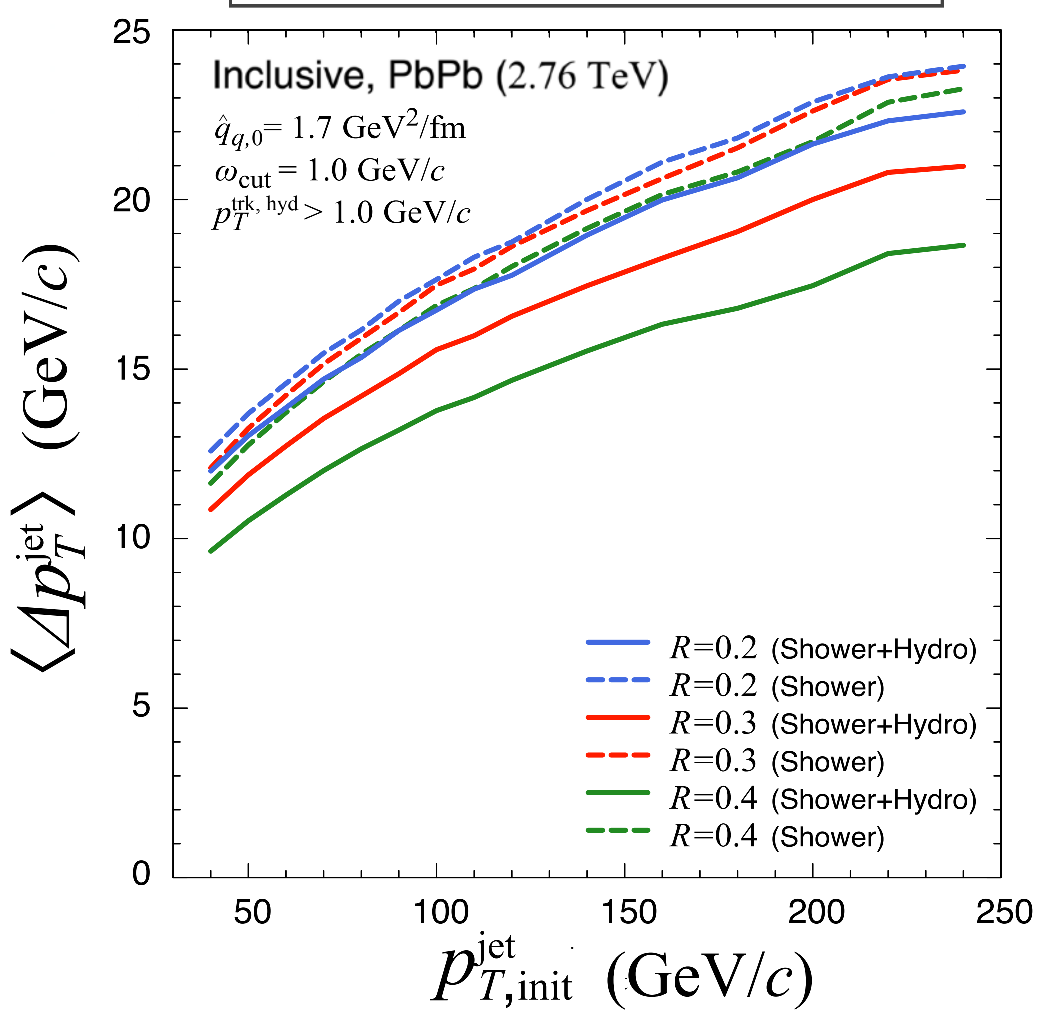

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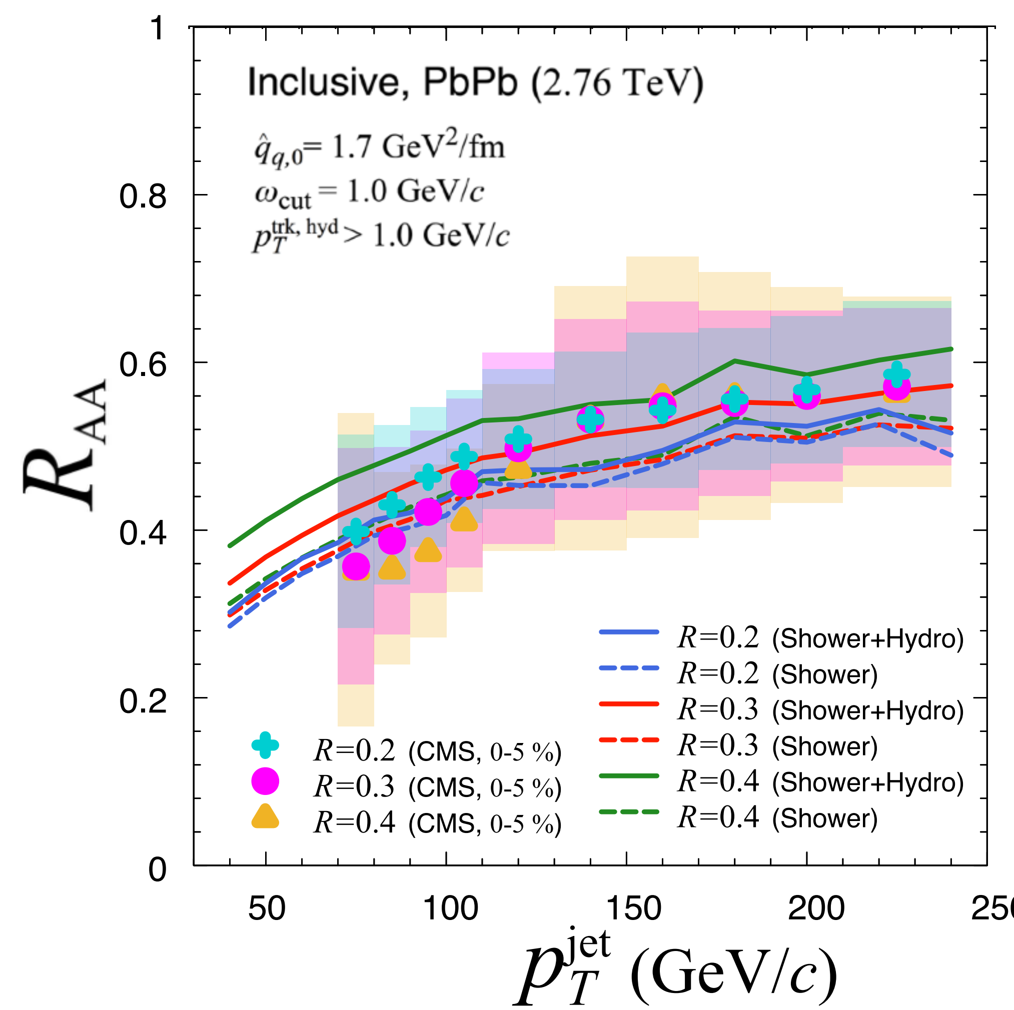

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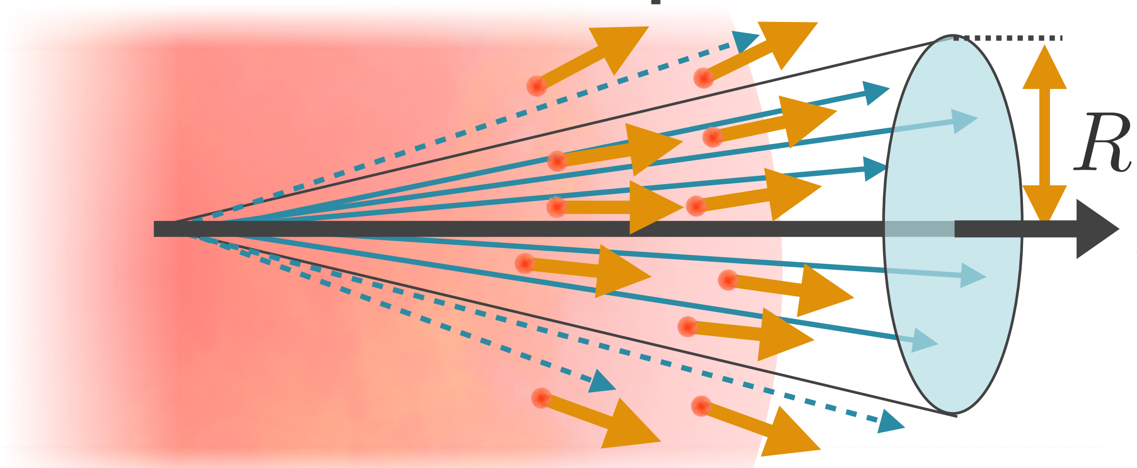

$$r = \sqrt{(\phi - \phi_{\mathrm{jet}})^2 + (\phi - \phi_{\mathrm{jet}})^2} < R$$

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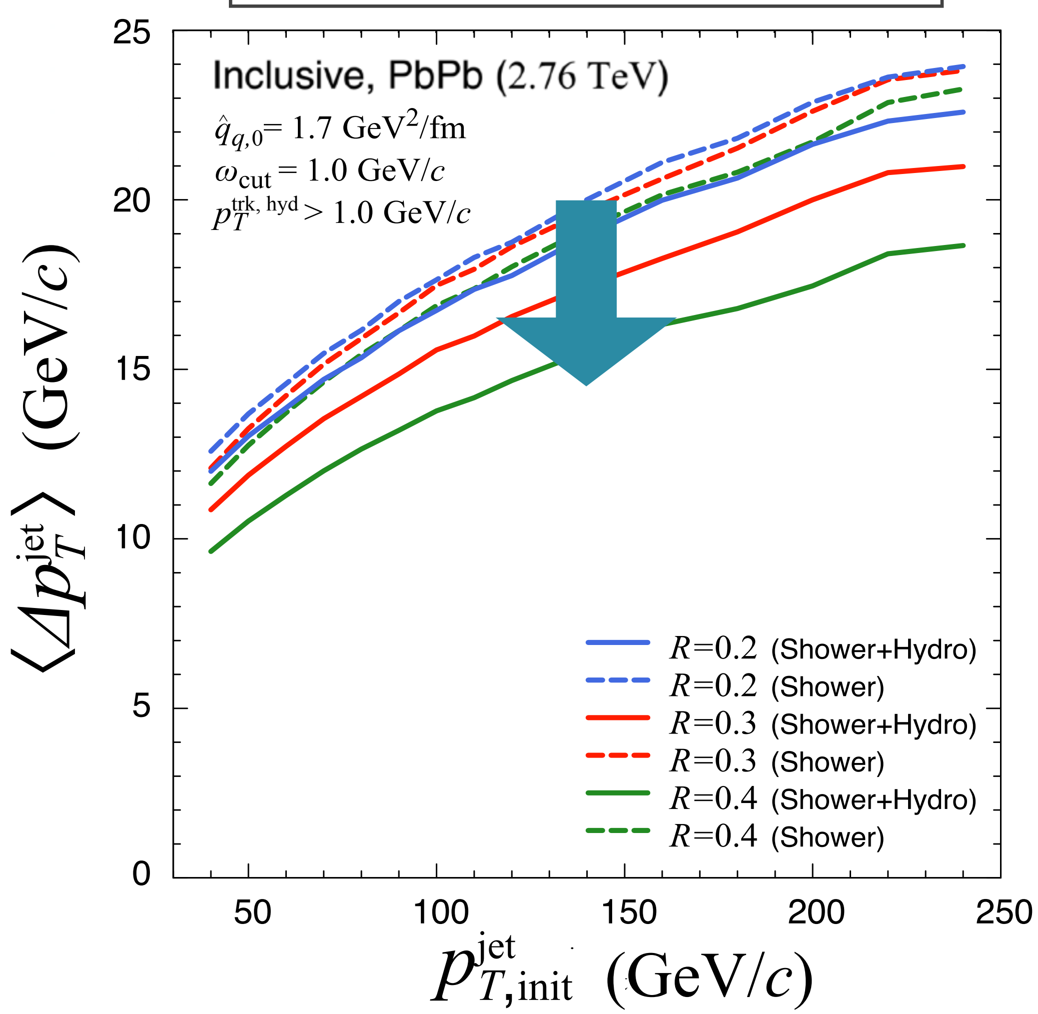
Total transverse momentum Loss



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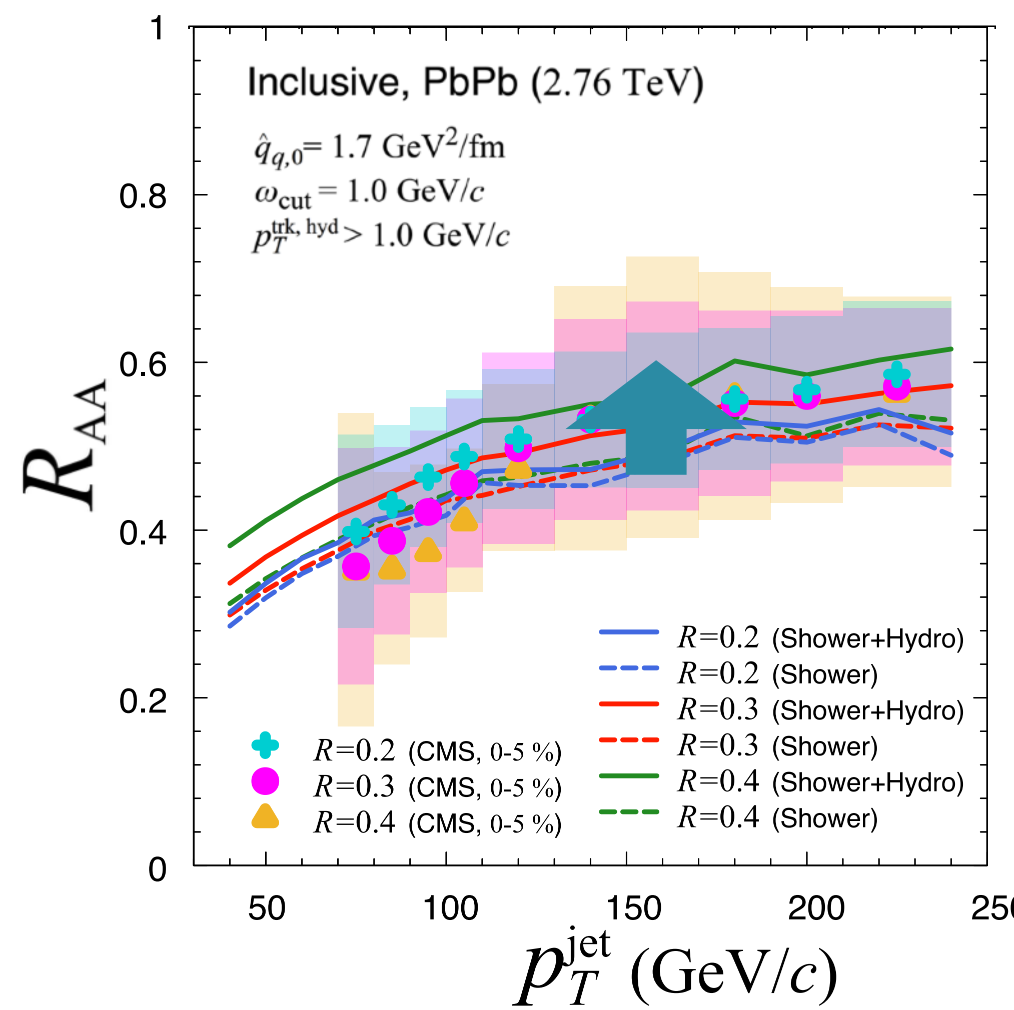

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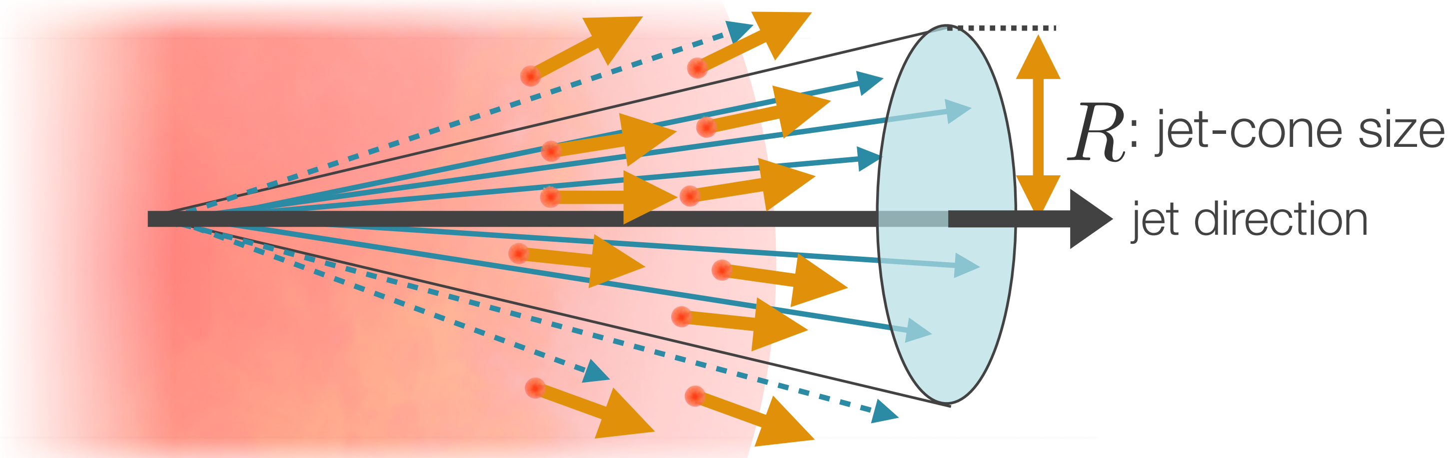

$$r = \sqrt{(\phi - \phi_{\rm jet})^2 + (\phi - \phi_{\rm jet})^2} < R$$

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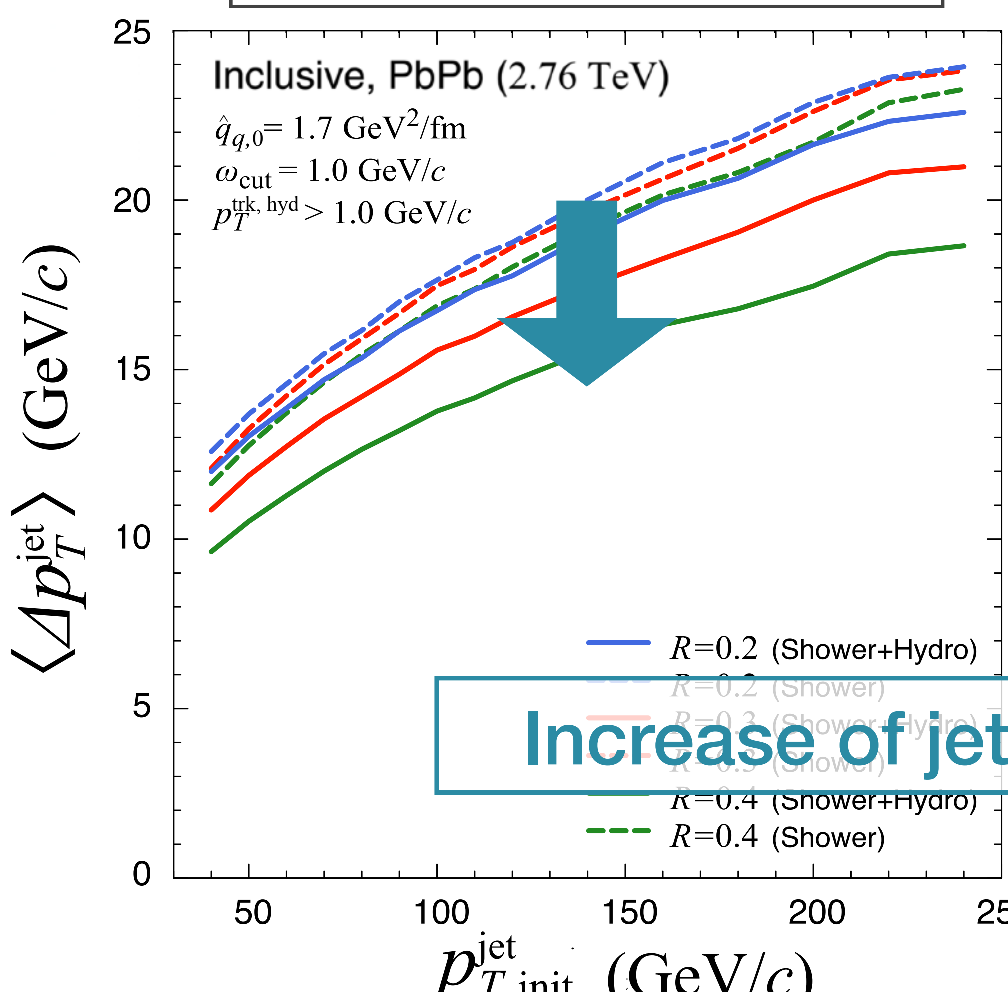
Total transverse momentum Loss



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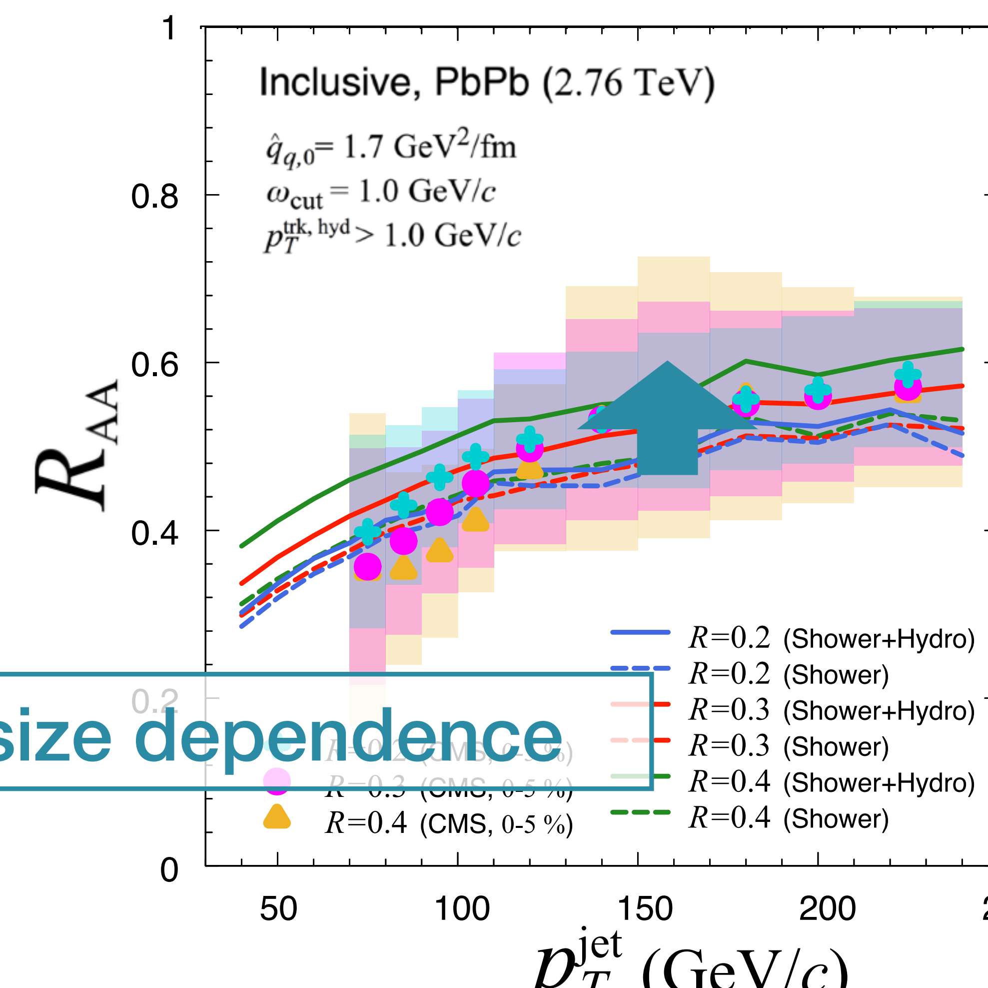


Increase of jet-cone size dependence

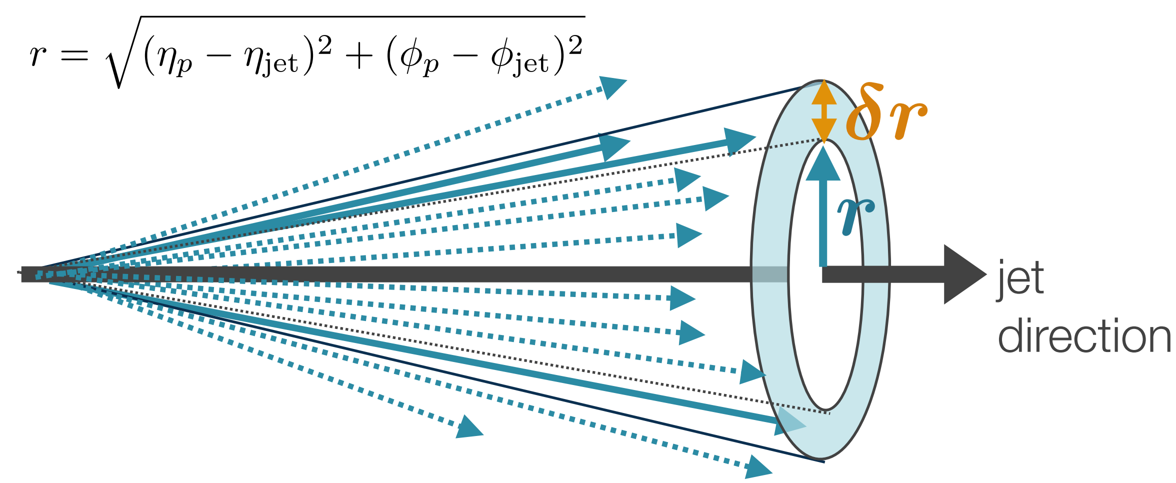
Modification of Full Jet Shape

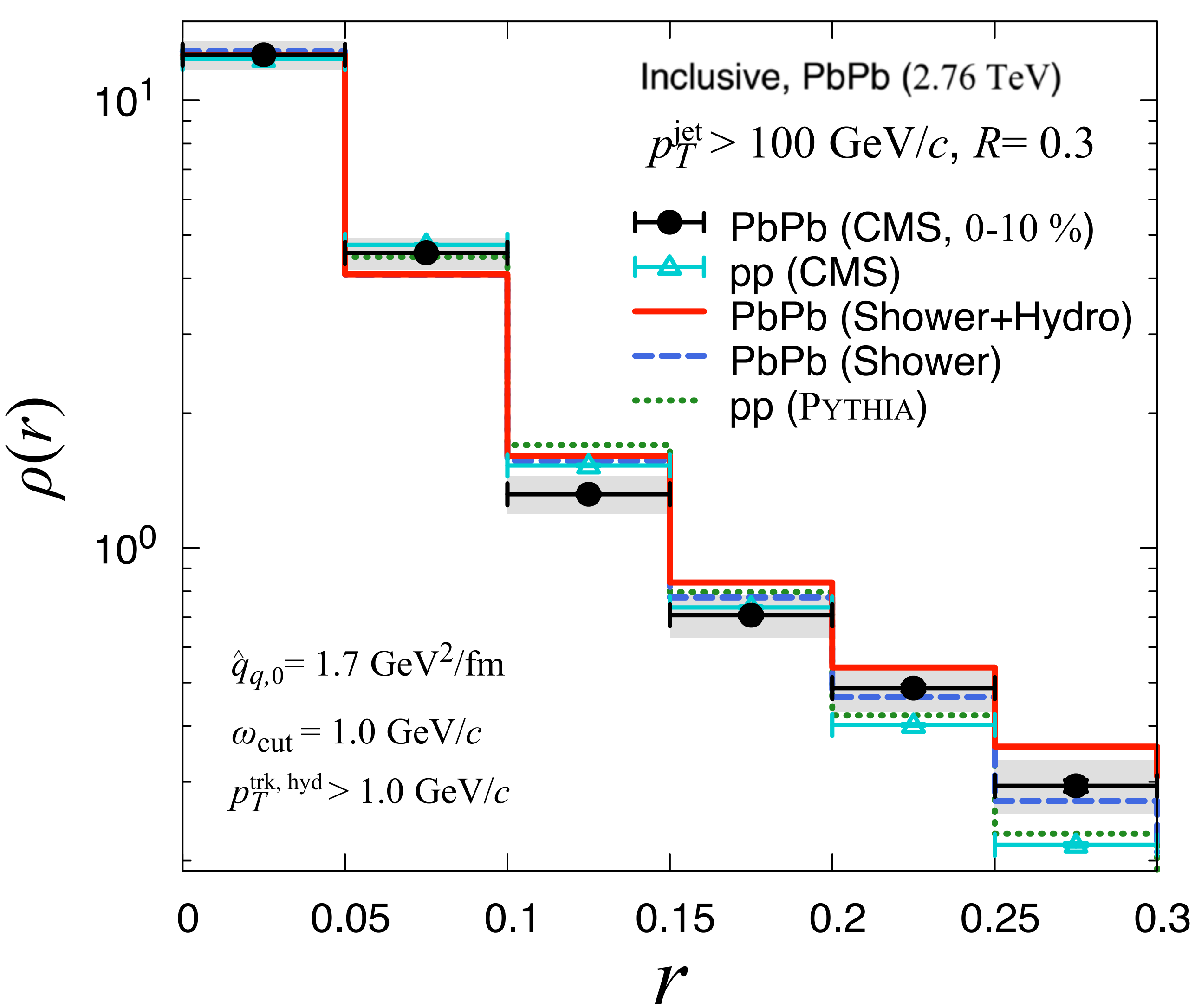
- **Jet shape function**

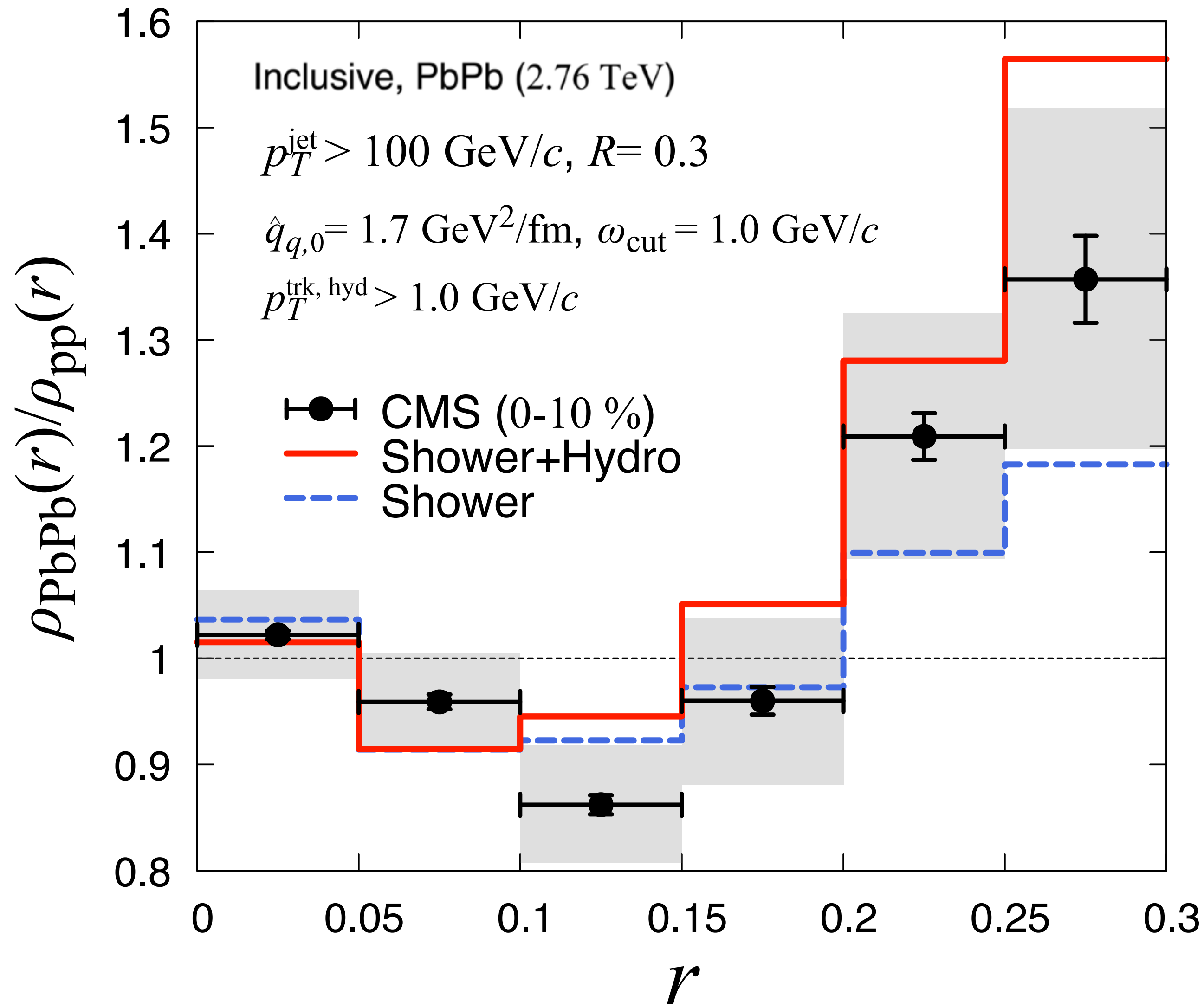
$$\rho(r) = \frac{1}{N_{\rm jet}} \sum_{\rm jet} \left[\frac{1}{p_T^{\rm jet}} \frac{\sum_{\rm trk \in (r-\delta r/2, r+\delta r/2)} p_T^{\rm trk}}{\delta r} \right]$$

  - Inclusive, $p_T > 100$ GeV/c (R=0.3)

(jets are generated by PYTHIA & MC Glauber)







Modification of Full Jet Shape

- **Jet shape function**

(jets are generated by PYTHIA & MC Glauber)

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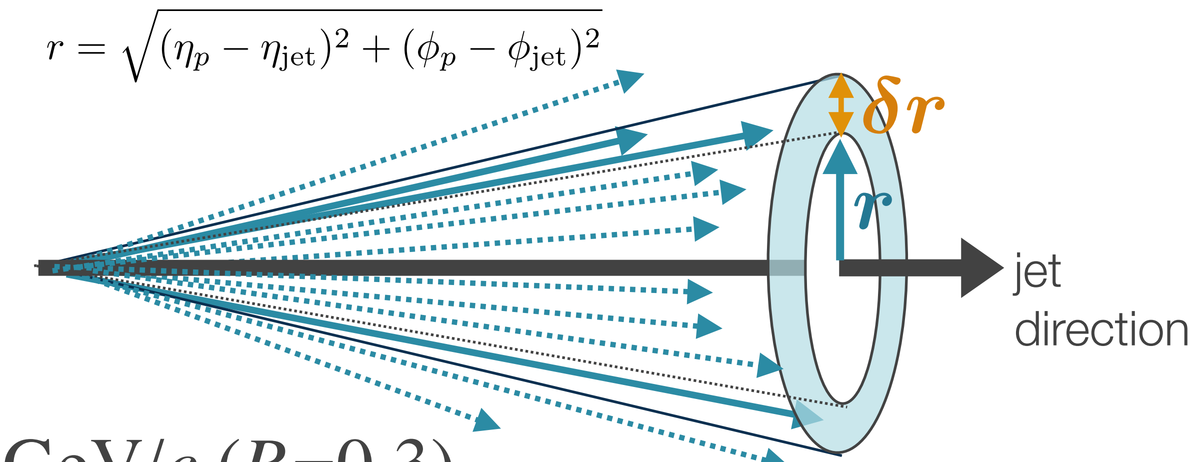
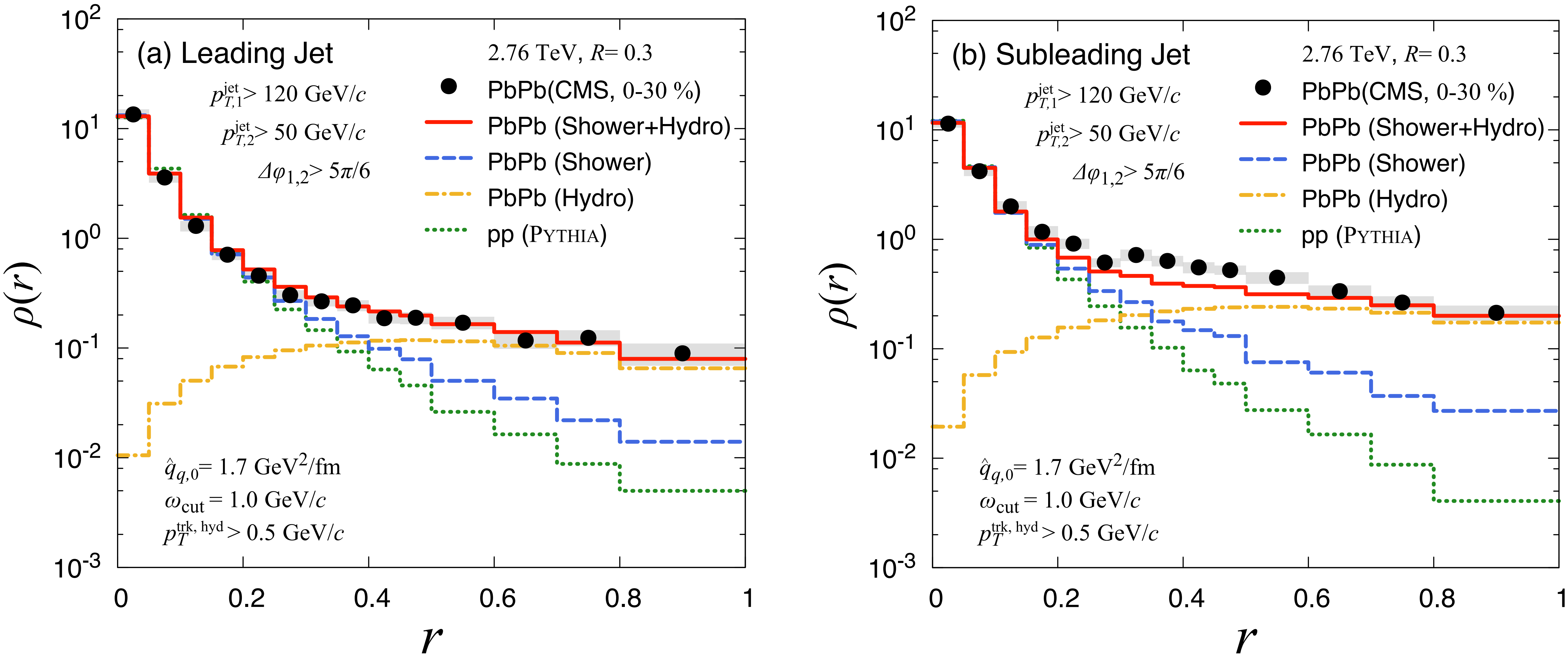


- Dijet event, $p_{T1} > 100$ GeV/c, $p_{T2} > 50$ GeV/c (R=0.3)



Modification of Full Jet Shape

- **Jet shape function**

(jets are generated by PYTHIA & MC Glauber)

$$r = \sqrt{(\eta_p - \eta_{\rm jet})^2 + (\phi_p - \phi_{\rm jet})^2}$$

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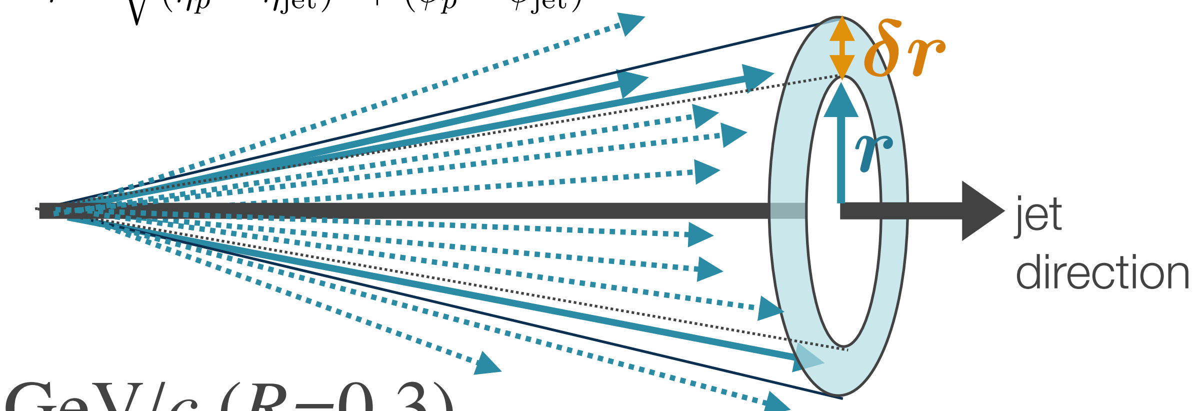

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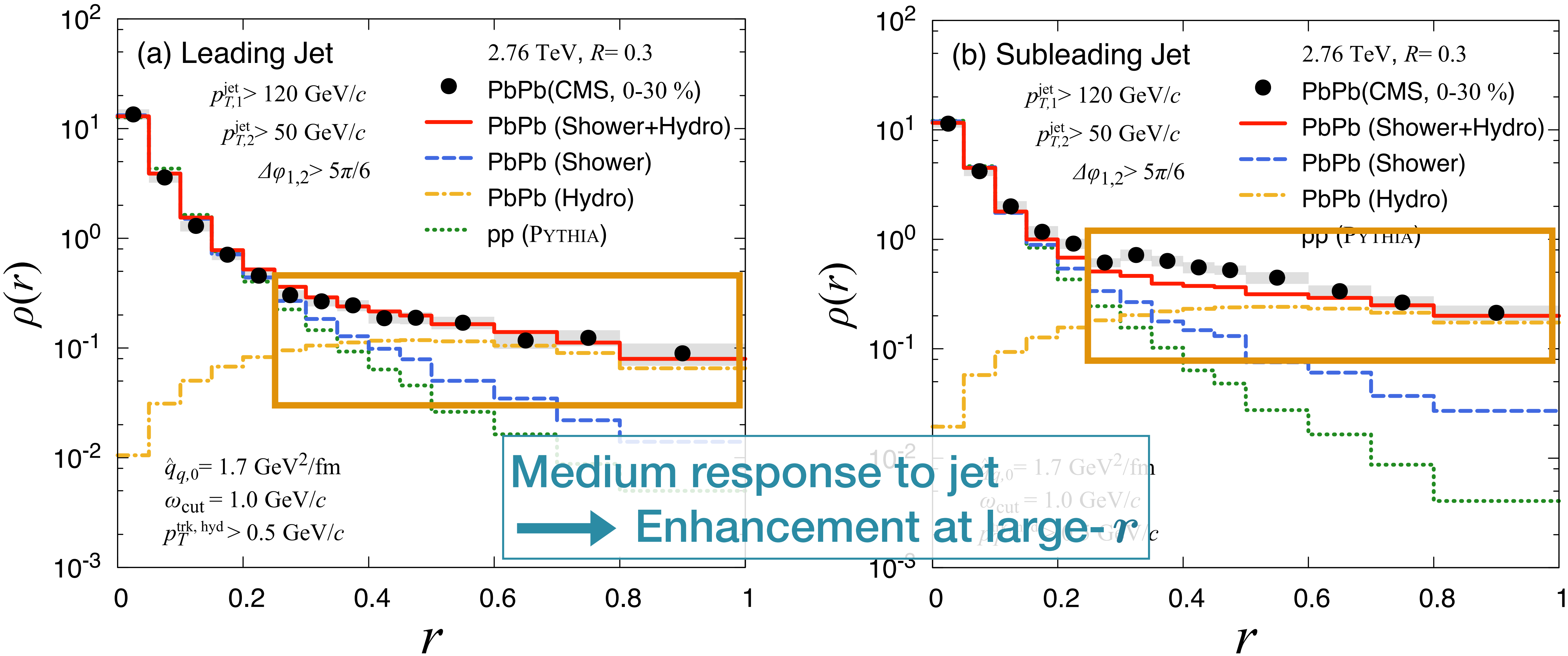


Medium response to jet
→ Enhancement at large-r

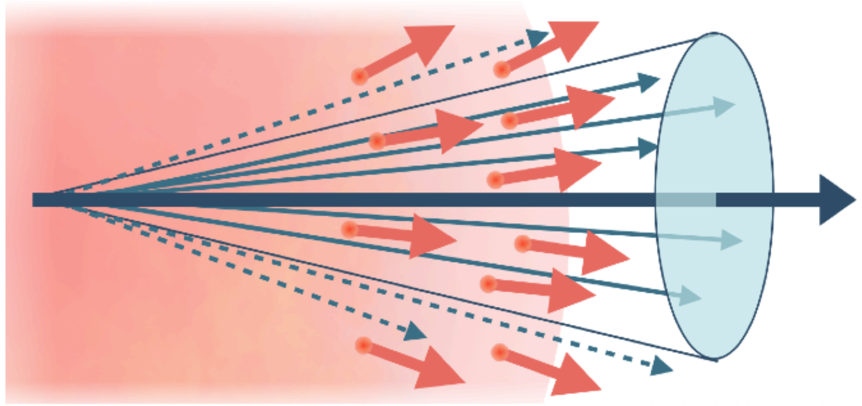
Summary, Comments, and Outlook

- **Medium response to jet quenching in QGP**
  - Excitation in QGP fluid by the deposited momentum from jet
  - Jet-correlated hadron emission from the excited medium
  - Further modification of jet structure in Heavy ion collisions

- **Full jet study with jet shower transport + hydro model**

  YT, N.-B. Chang, G.-Y. Qin ('17)

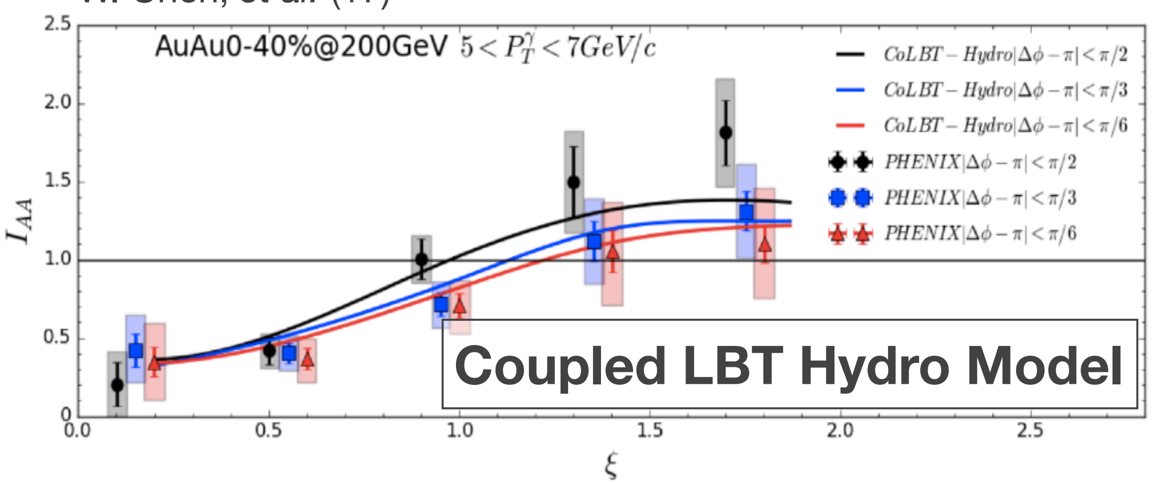
  - Jet transport equations + hydrodynamic equation with source term
  - Jet-induced shockwave (Mach cone) carrying energy to large angles
  - Increase of jet-cone size dependence
  - Medium response contribution dominates large-r region



Summary, Comments, and Outlook

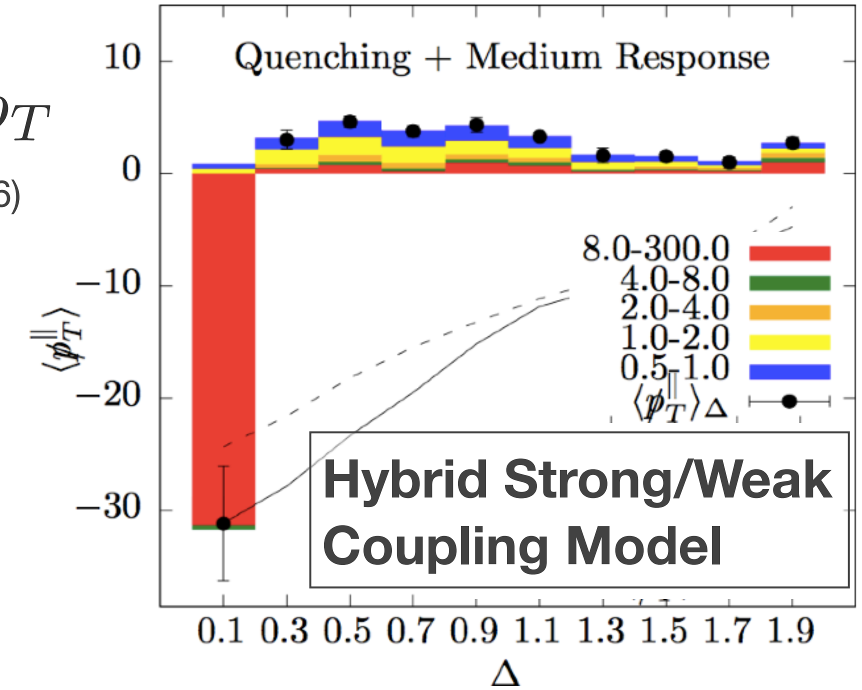
- **Medium response in other observables**
  - γ-hadron correlation

    W. Chen, *et al.* (17)



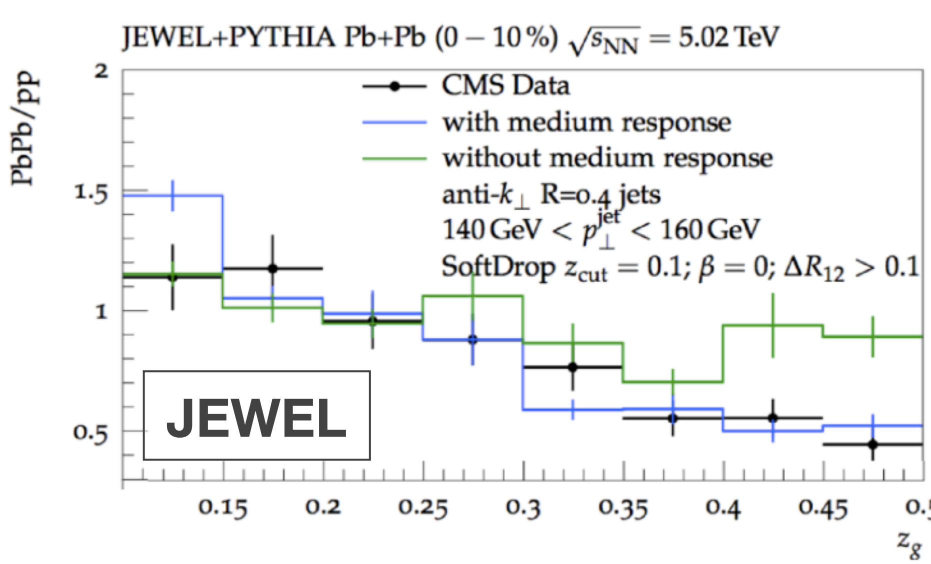
  - Missing- p_T

    D. Pablos, *et al.* (16)



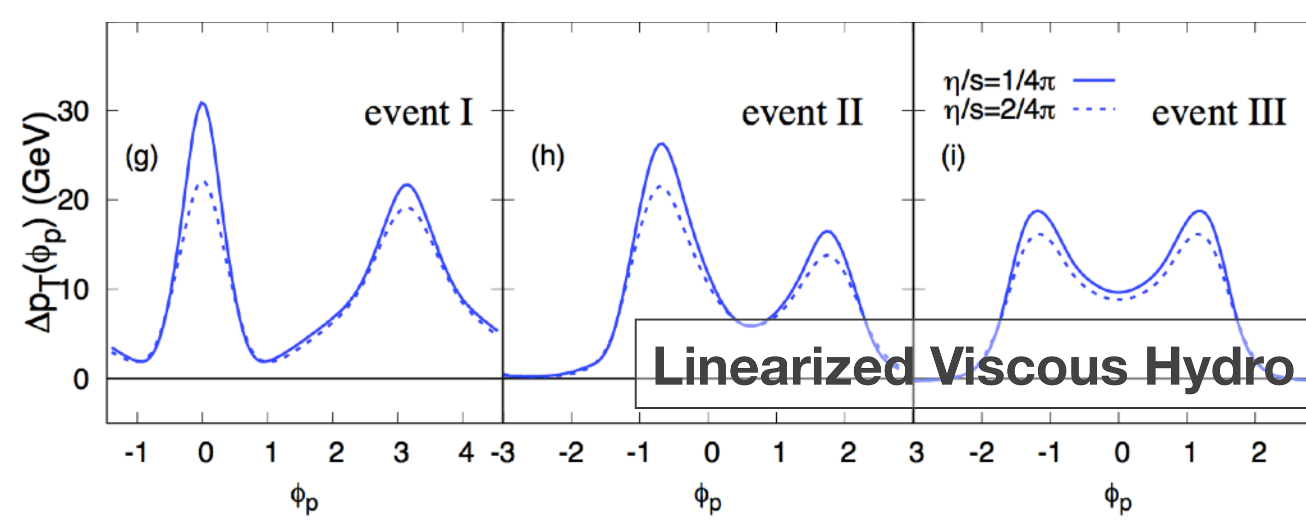
  - z_g-distribution

    J. G. Milhano, U. A. Wiedemann, K. C. Zapp (17)



  - Jet-hadron angular correlation

    L. Yan, S. Jeon, C. Gale (17)

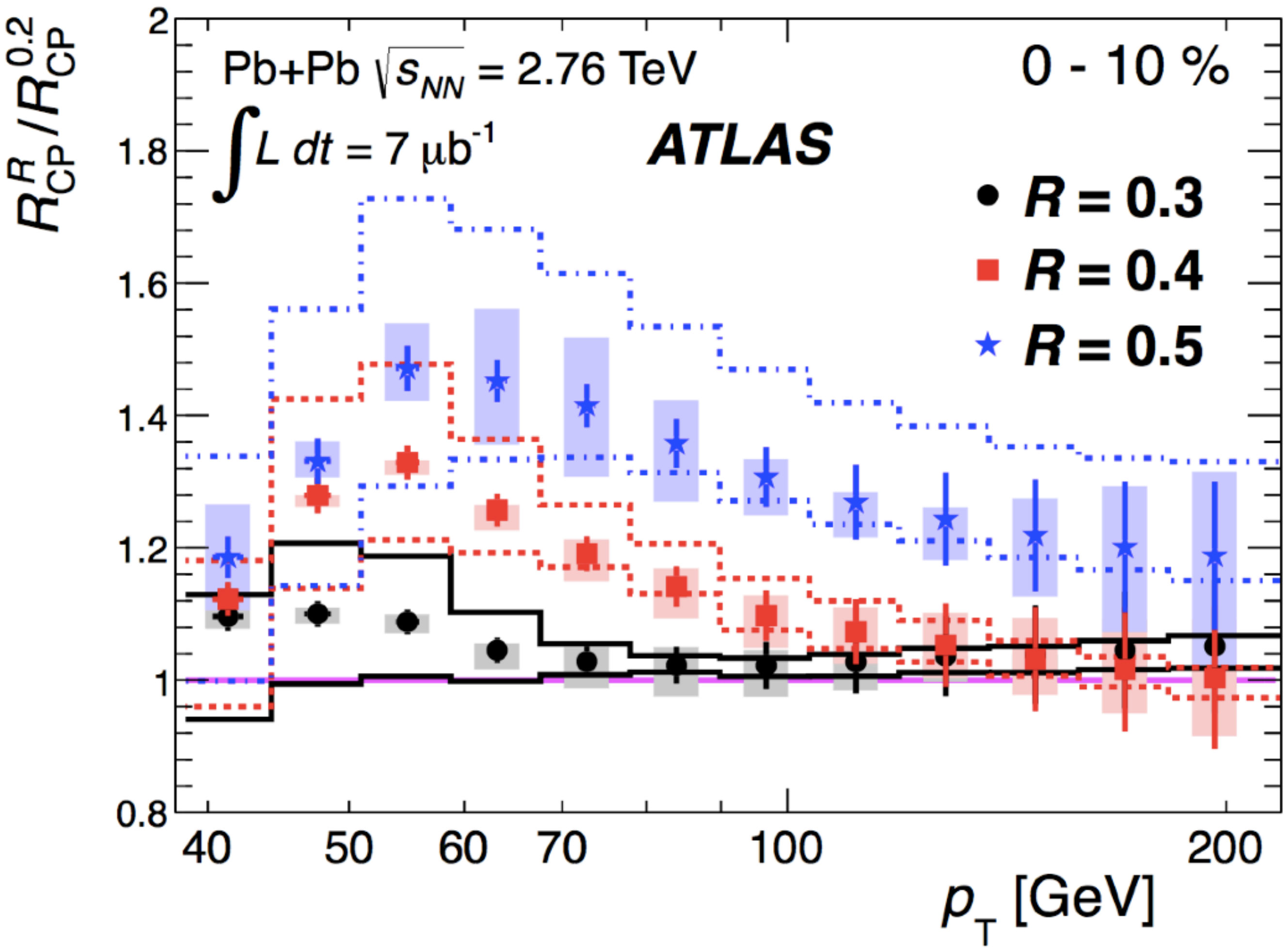


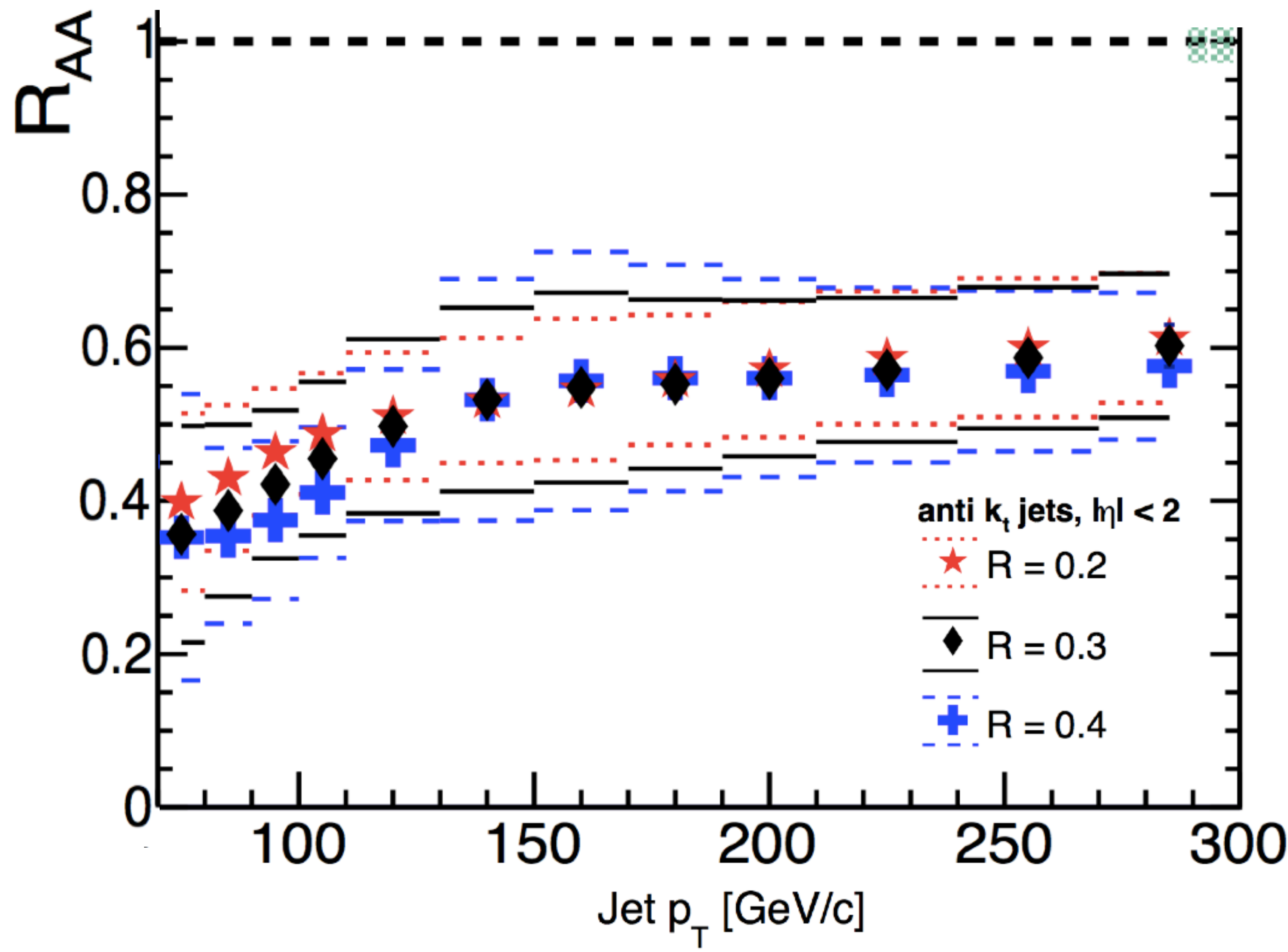
- **Outlook**
  - Full (3+1)-D event by event jet + viscous fluid calculation
  - More sophisticated source term

Backup

Cone-size dependence from experiments

- **ATLAS** Phys.Lett. B719 (2013) 220-241
- **CMS** CMS-HIN-13-005





Stronger suppression with smaller cone-size

Stronger suppression with larger cone-size
(only at small p_T)

Opposite pattern

Some details of model

- **Jet quenching parameter $\hat{q}$**

$$\hat{q}_q(x_{\rm jet}) = \hat{q}_{q,0}\frac{T^3(x_{\rm jet})}{T_0^3}\frac{p_{\rm jet}\cdot u(x_{\rm jet})}{p^0_{\rm jet}}$$

$$\hat{q}_{q,0} = 1.7\,{\rm GeV}^2/{\rm fm}$$ (chosen to fit the experimental data of $R_{\rm PbPb}$)

$$T_0 = T\left(\boldsymbol{x}=0, \tau=\tau_0\right) = 0.514\ {\rm GeV}$$

$$\hat{q}_{g,0} = \frac{C_A}{C_F}\hat{q}_{q,0}$$

- **Initial profile of medium**
  - Initial proper time $\tau_0 = 0.6\,{\rm fm}/c$
  - Optical Glauber model with $\boldsymbol{b}=0$

$$s(\tau_0, \boldsymbol{x}_\perp, \eta_{\rm s}) = s_T(\boldsymbol{x}_\perp)\,H(\eta_{\rm s})$$

$$s_T\left(\boldsymbol{x}_\perp\right) = \frac{C}{\tau_0}\left[\frac{(1-\alpha)}{2}n^{\boldsymbol{b}}_{\rm part}\left(\boldsymbol{x}_\perp\right) + \alpha n^{\boldsymbol{b}}_{\rm coll}\left(\boldsymbol{x}_\perp\right)\right],\ H(\eta_{\rm s}) = \exp\left[-\frac{(|\eta_{\rm s}|-\eta_{\rm flat}/2)^2}{2\sigma_\eta^2}\theta\left(|\eta_{\rm s}|-\frac{\eta_{\rm flat}}{2}\right)\right]$$

$C = 19.8,\ \alpha = 0.14,$
$\eta_{\rm flat} = 3.8,\ \sigma_\eta = 3.2.$

- **Generation of inclusive jet events**
  - PYTHIA + MC Glauber Model $b = 3.5\,{\rm fm}$
  - Created and traveling in transverse plane $\eta_{\rm s} = 0$

Jet Shape, hydro, and Jet energy deposition profile are 3D

Source term

- **Energy momentum conservation for QGP + jet system**

$$\partial_\mu \left[T^{\mu\nu}_{\mathrm{QGP}}(x) + T^{\mu\nu}_{\mathrm{jet}}(x) \right] = 0$$

$$\partial_\mu T^{\mu\nu}_{\mathrm{QGP}}(x) = J^\nu(x), \; J^\nu(x) \equiv -\partial_\mu T^{\mu\nu}_{\mathrm{jet}}(x)$$

$$= -\sum_j \int \frac{d^3 k_j}{\omega_j} k_j^\nu k_j^\mu \partial_\mu f_j(\boldsymbol{k}_j, \boldsymbol{x}, t)$$

$$= -\sum_j \int \frac{d^3 k_j}{\omega_j} k_j^\nu k_j^\mu \left[\partial_\mu f_j(\boldsymbol{k}_j, \boldsymbol{x}, t)|_{\hat{e},\hat{q}} \right]$$

Only col. & broad. contribution
Energy-momentum conservation during rad. processes;

$$\sum_j \int \frac{d^3 k_j}{\omega_j} k_j^\nu k_j^\mu \left[\partial_\mu f_j(\boldsymbol{k}_j, \boldsymbol{x}, t)|_{\mathrm{rad.}} \right] = 0$$

Approximation: $\boldsymbol{x}(k_j, t) = \boldsymbol{x}_0^{\mathrm{jet}} + \frac{\boldsymbol{k}_j}{\omega_j} t$

$$\rightarrow \quad J^\nu(x) = -\sum_j \int \frac{d\omega_j dk_{j\perp}^2 d\phi_j}{2\pi} k_j^\nu \left. \frac{df_j(\omega_j, k_{j\perp}^2, t)}{dt} \right|_{\mathrm{col.}} \delta^{(3)}(\boldsymbol{x} - \boldsymbol{x}^{\mathrm{jet}}(\boldsymbol{k}_j, t))$$

Jet reconstruction

- **Jet-** p_T

$$p_T^{\text{jet}} = p_{T,\text{shower}}^{\text{jet}} + p_{T,\text{medium}}^{\text{jet}}$$

$$p_{T,\text{shower}}^{\text{jet}} = \sum_j p_{T,\text{shower}}^{j} \; \theta(\Delta R - r_i)$$

$$p_{T,\text{medium}}^{\text{jet}} = \sum_i p_{T,\text{medium}}^{i} \; \theta(\Delta R - r_i)\Big|_{\text{w/ jet}} - \sum_i p_{T,\text{medium}}^{i} \; \theta(\Delta R - r_i)\Big|_{\text{w/o jet}}$$

j: partons with $p_{T,\text{shower}}^{j} > 2\ \text{GeV}/c$, i: hadrons with $p_{T,\text{medium}}^{i} > 1\ \text{GeV}/c$

- p_T **of hadrons emitted from medium (** $p_{T,\text{medium}}^{i}$ **)**
  - Cooper-Frye formula

$$E_i^0 \frac{dN_i}{d^3p_i} = \frac{g_i}{(2\pi)^3} \int \frac{p^\mu d\sigma_\mu}{\exp\left[p^\mu u_\mu(x)/T(x)\right] \mp_{\text{BF}} 1} \longrightarrow \sum_i p_{T,\text{medium}}^{i} = \sum_i \int d^3p_i \; p_{T,i} \frac{dN_i}{d^3p_i}$$

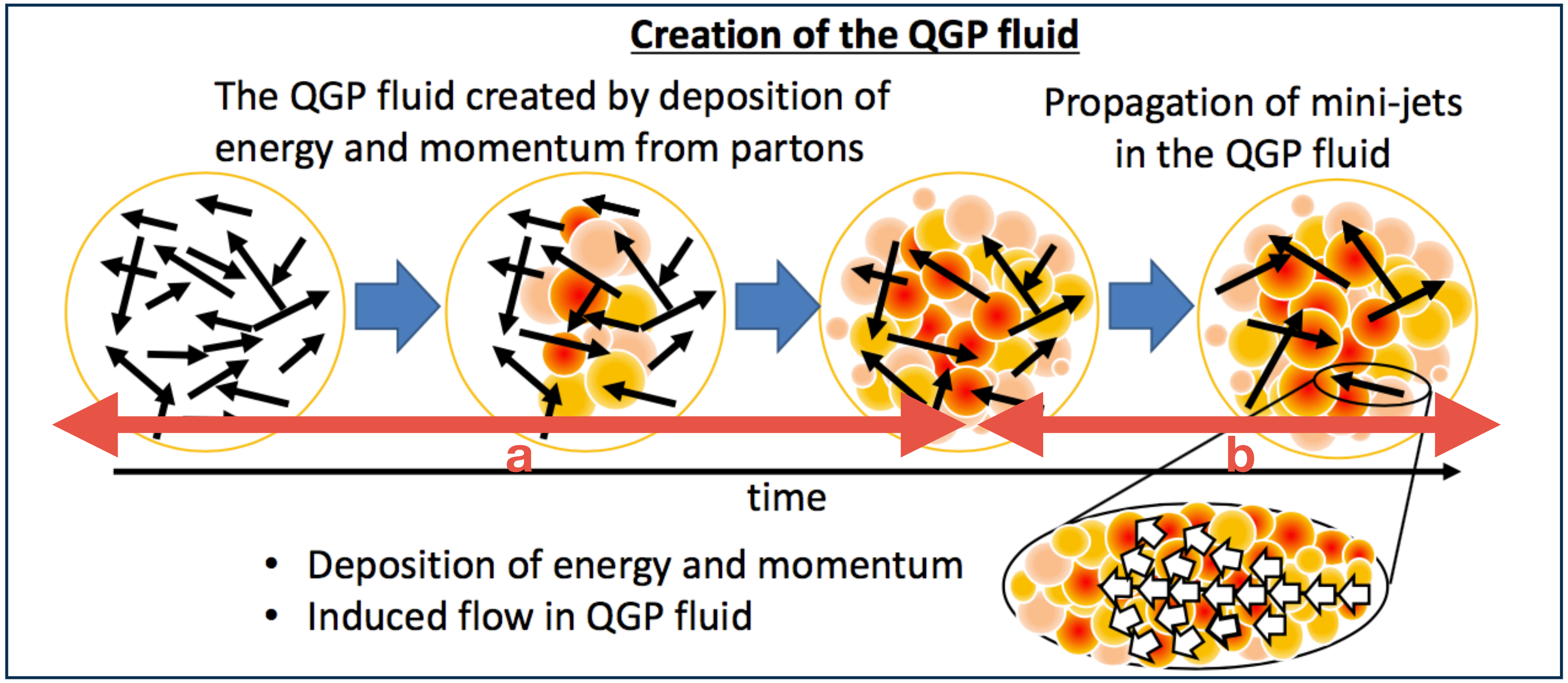
$u^\mu(x)$: flow velocity, $T(x)$: temperature, g_i: degeneracy

(No hadronic interaction after the hydrodynamic evolution)

Generation of QGP hydro via source terms

- **New approach to initialize hydrodynamic fields**

M. Okai, K. Kawaguchi, YT and T. Hirano ('17)



- Hydro eq. w/ source term

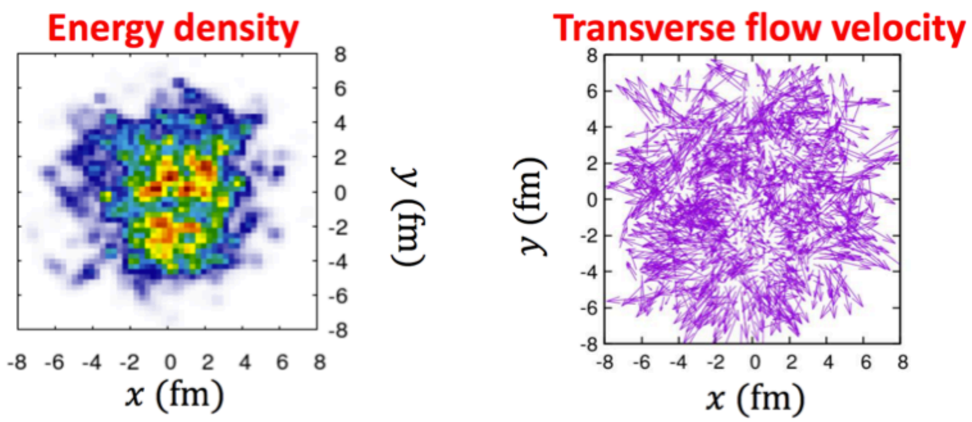
$$\partial_\mu T^{\mu\nu}_{\rm QGP}(x) = J^\nu(x)$$

a) Creation of the QGP fluid

b) Additional induced flow

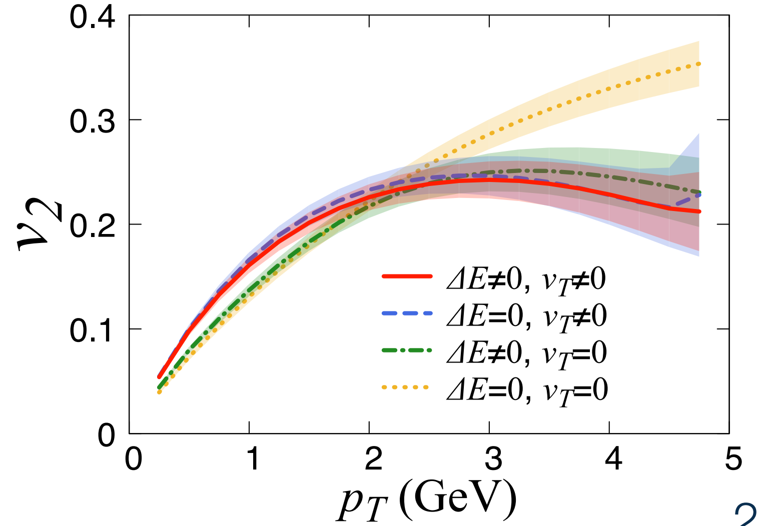
from energy-momentum deposition by partons

Generated QGP fluid



+ further parton propagation

Study harmonics



Similar approach: LEXUS model (Chun Shen *et al.*)