Jet modification with hydro medium response

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Central China Normal University

in collaboration with Ning-Bo Chang, Guang-You Qin [**PRC 95, 044909 (2017)**]

華中師範大學

"Precision Spectroscopy of QGP Properties with Jets and Heavy Quarks"
Institute for Nuclear Theory, University of Washington, Seattle, May 10th, 2017

Introduction

Jet quenching in QGP medium

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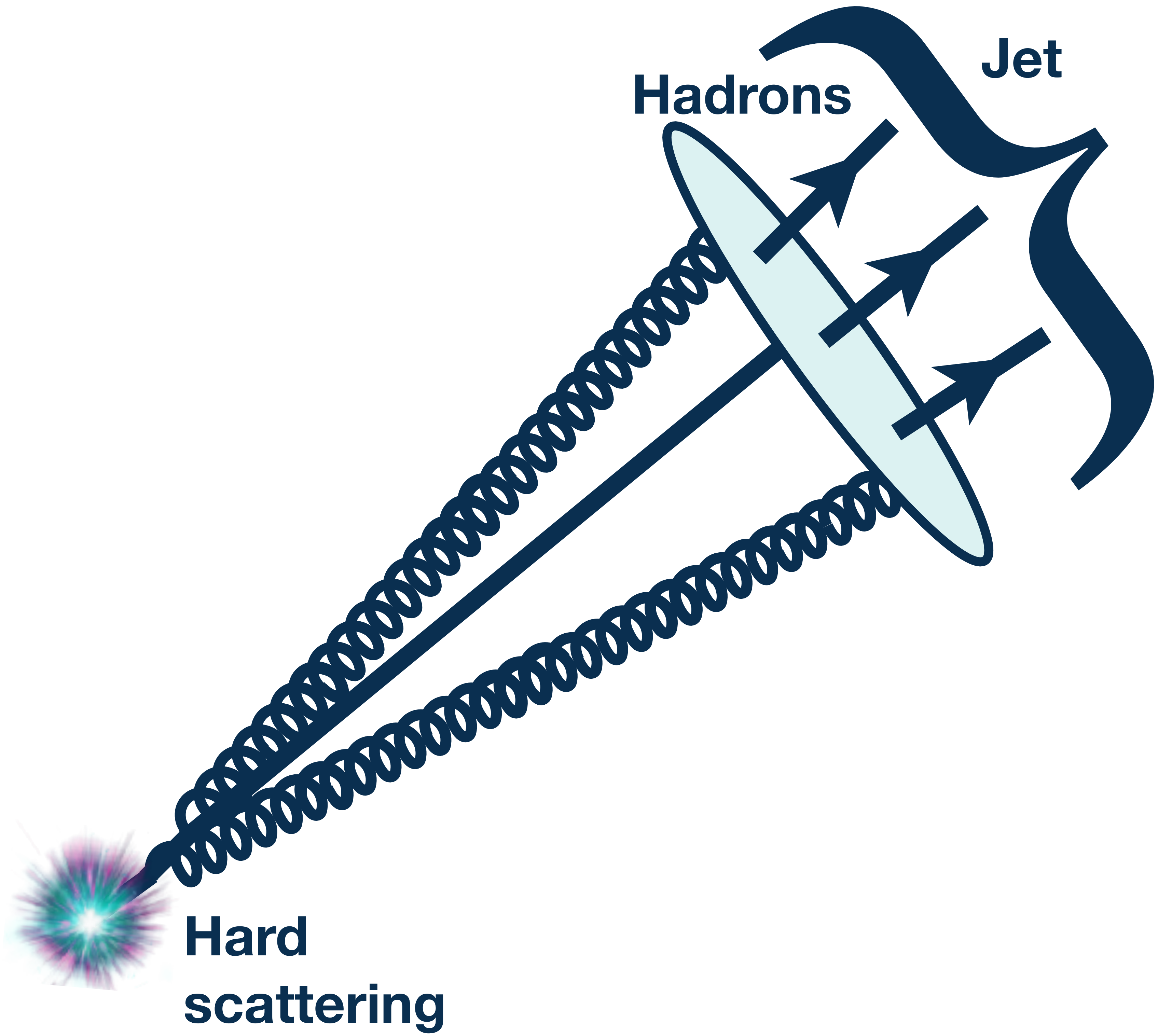

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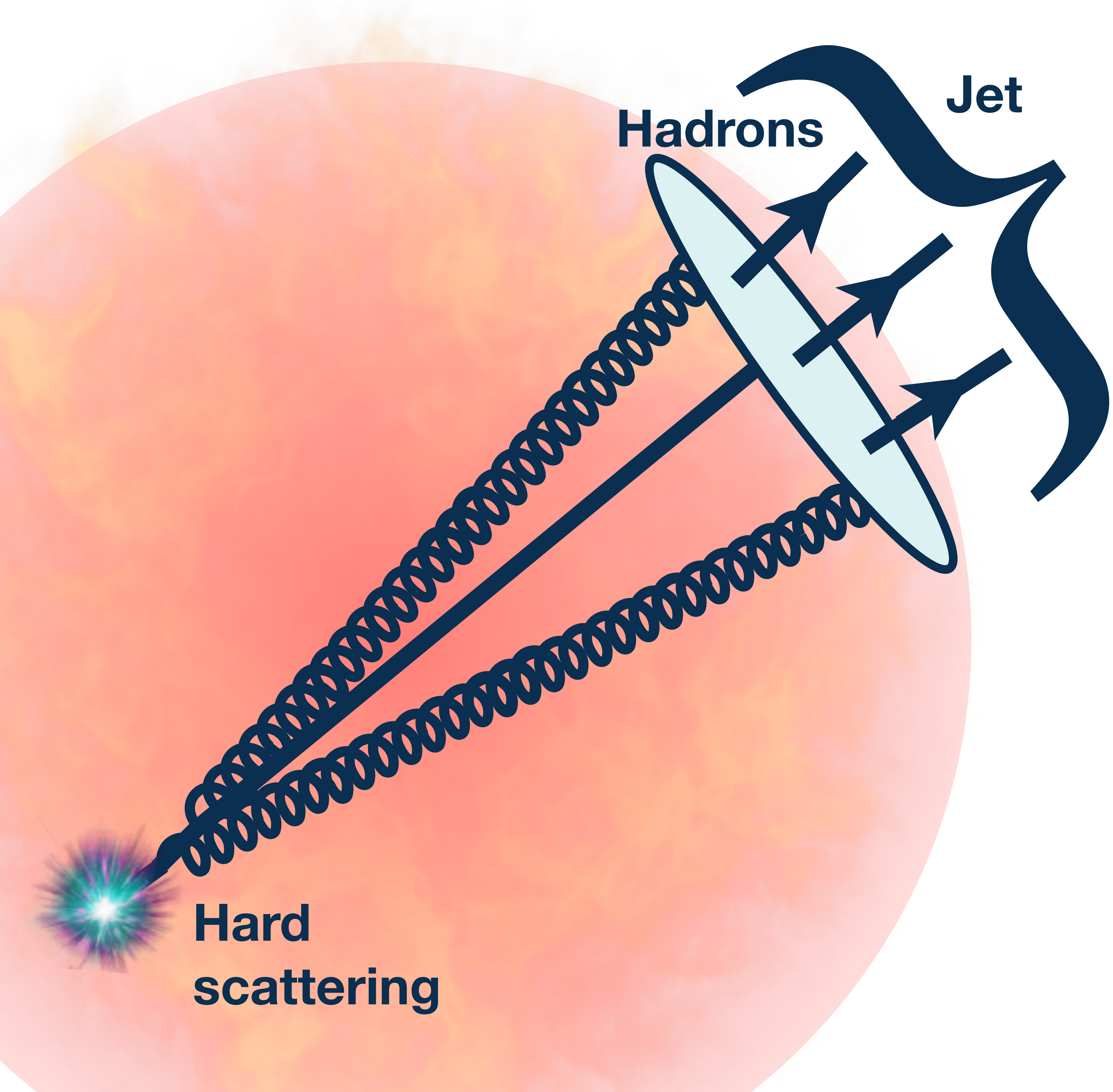

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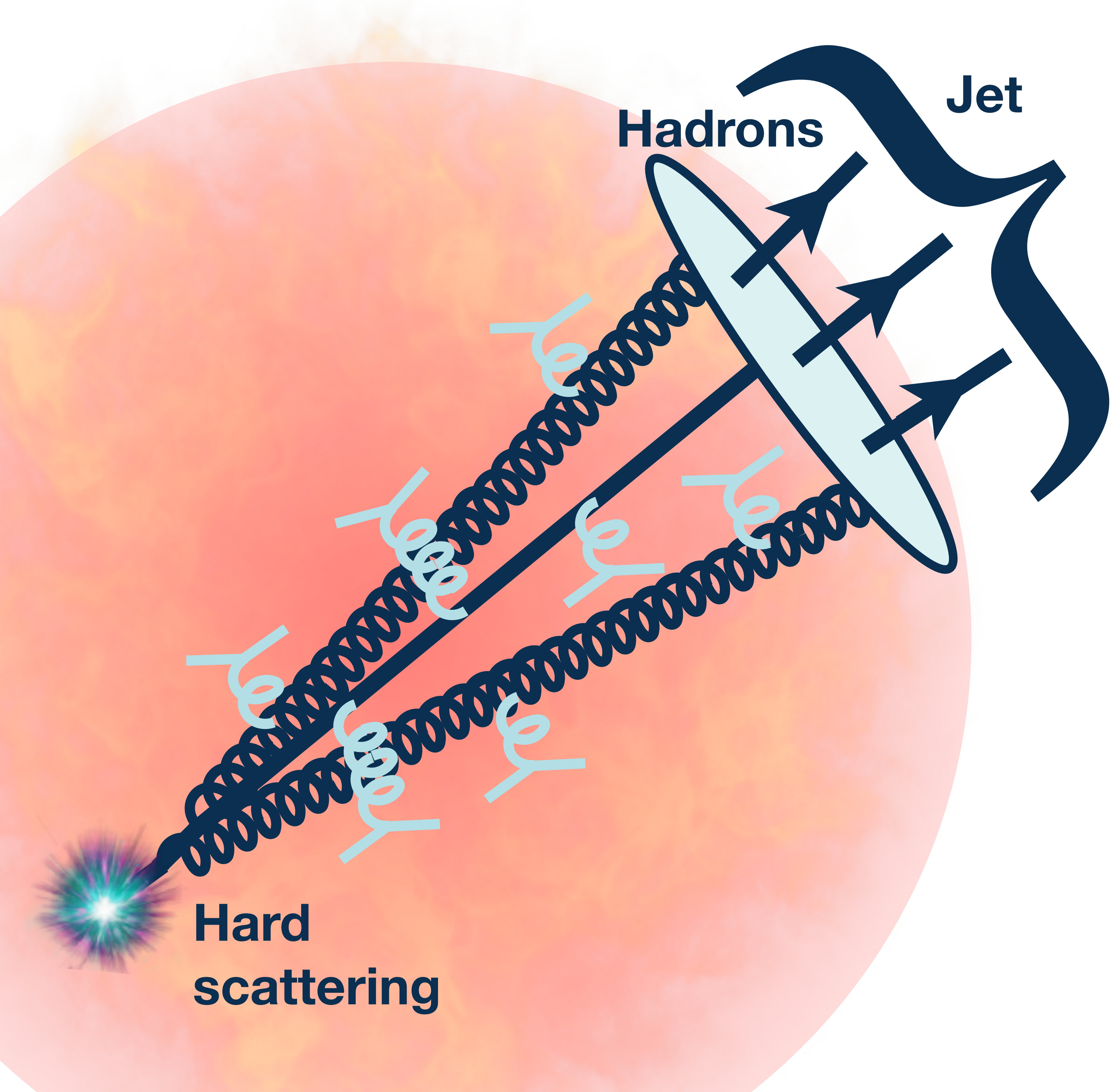

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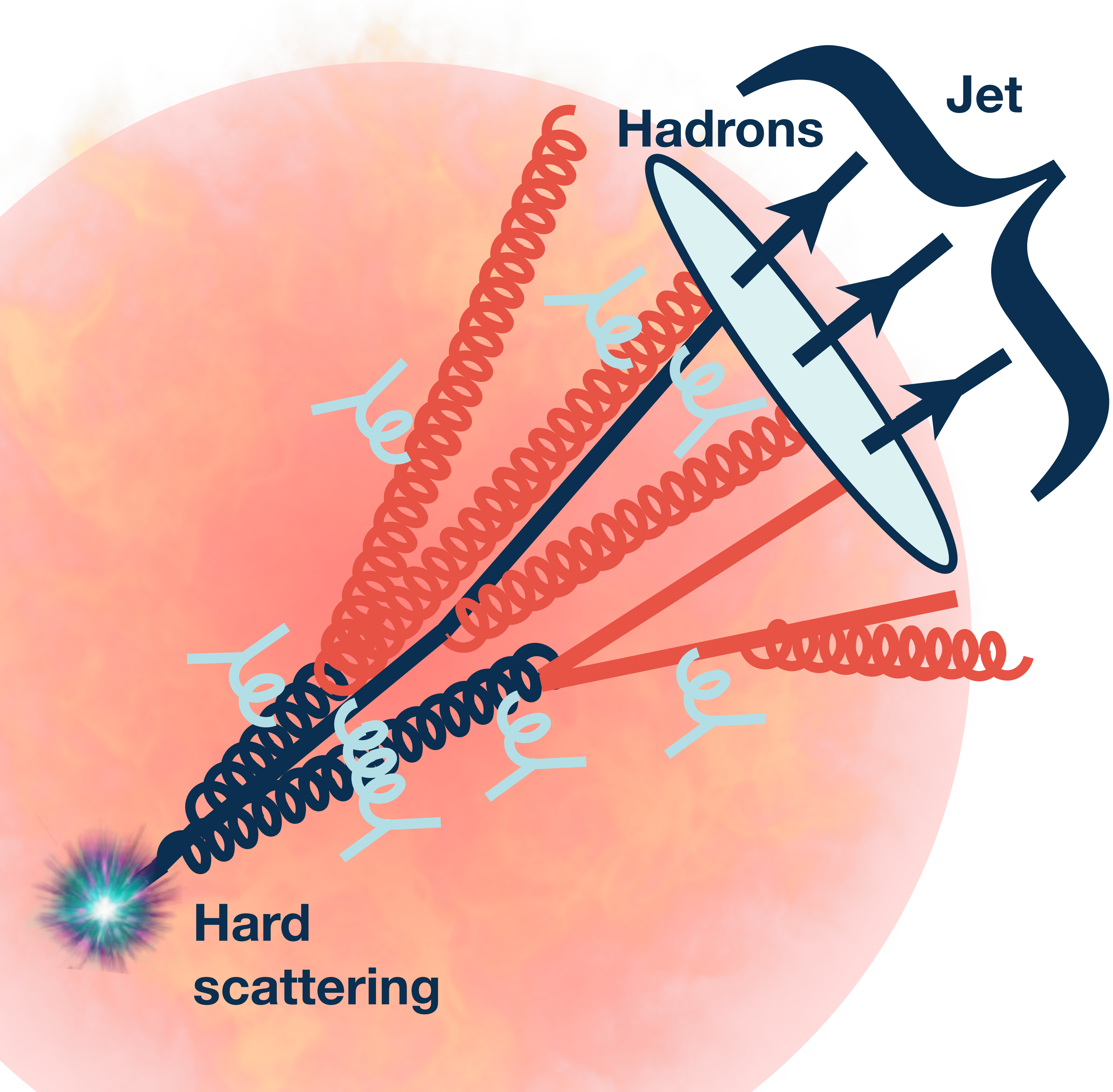

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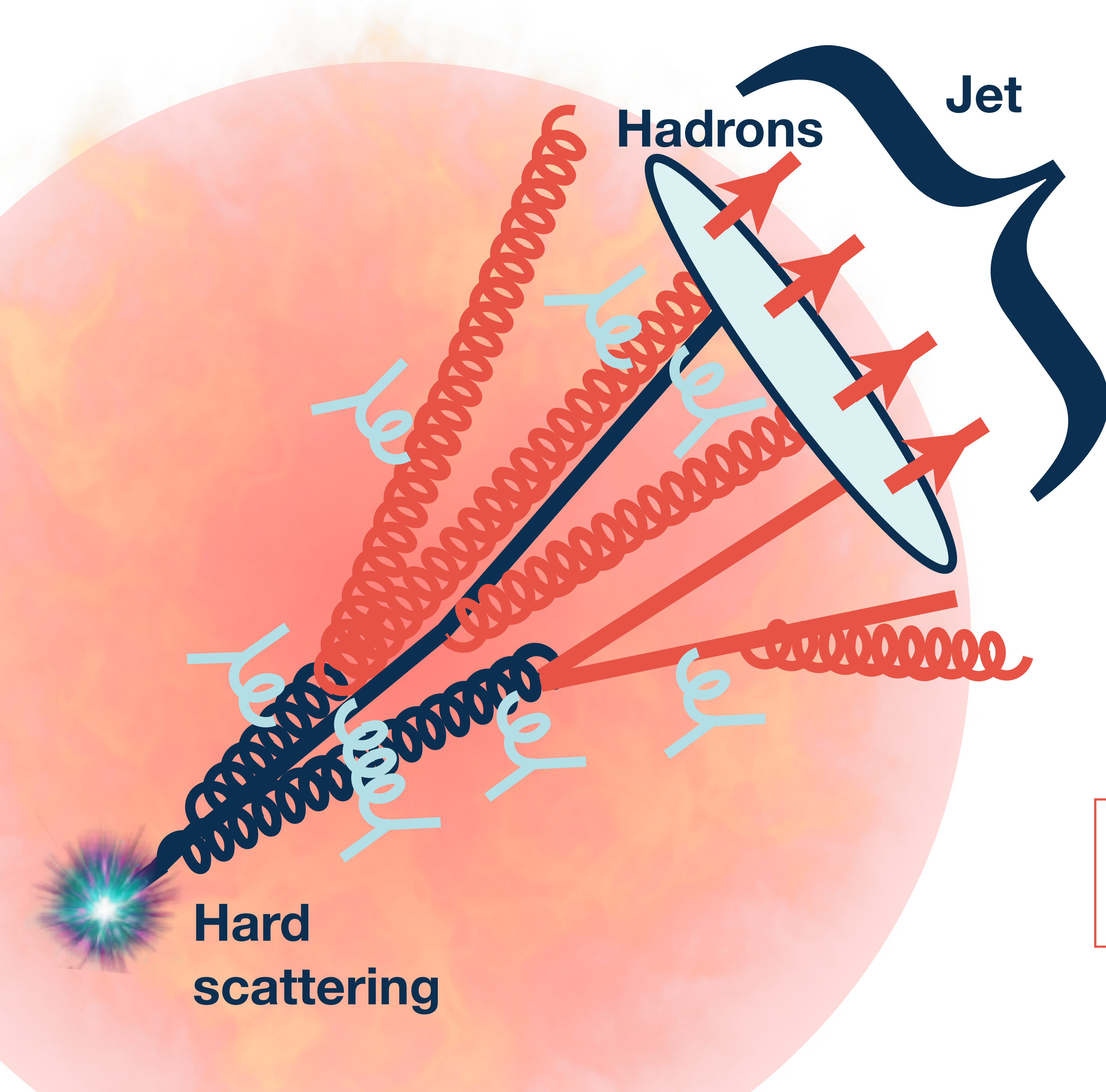

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Jet energy loss
Modification of jet structure

Medium response to jet quenching

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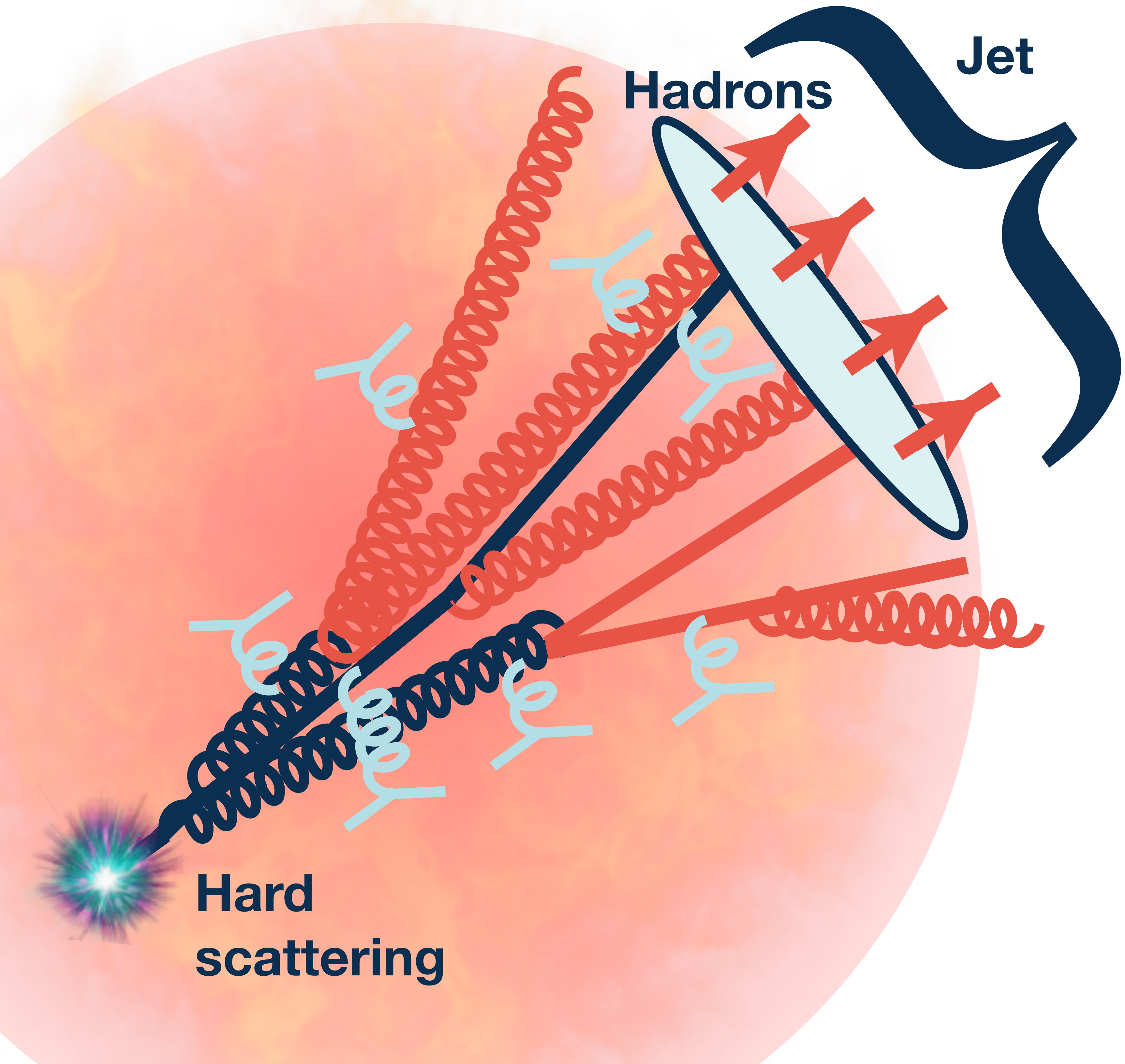

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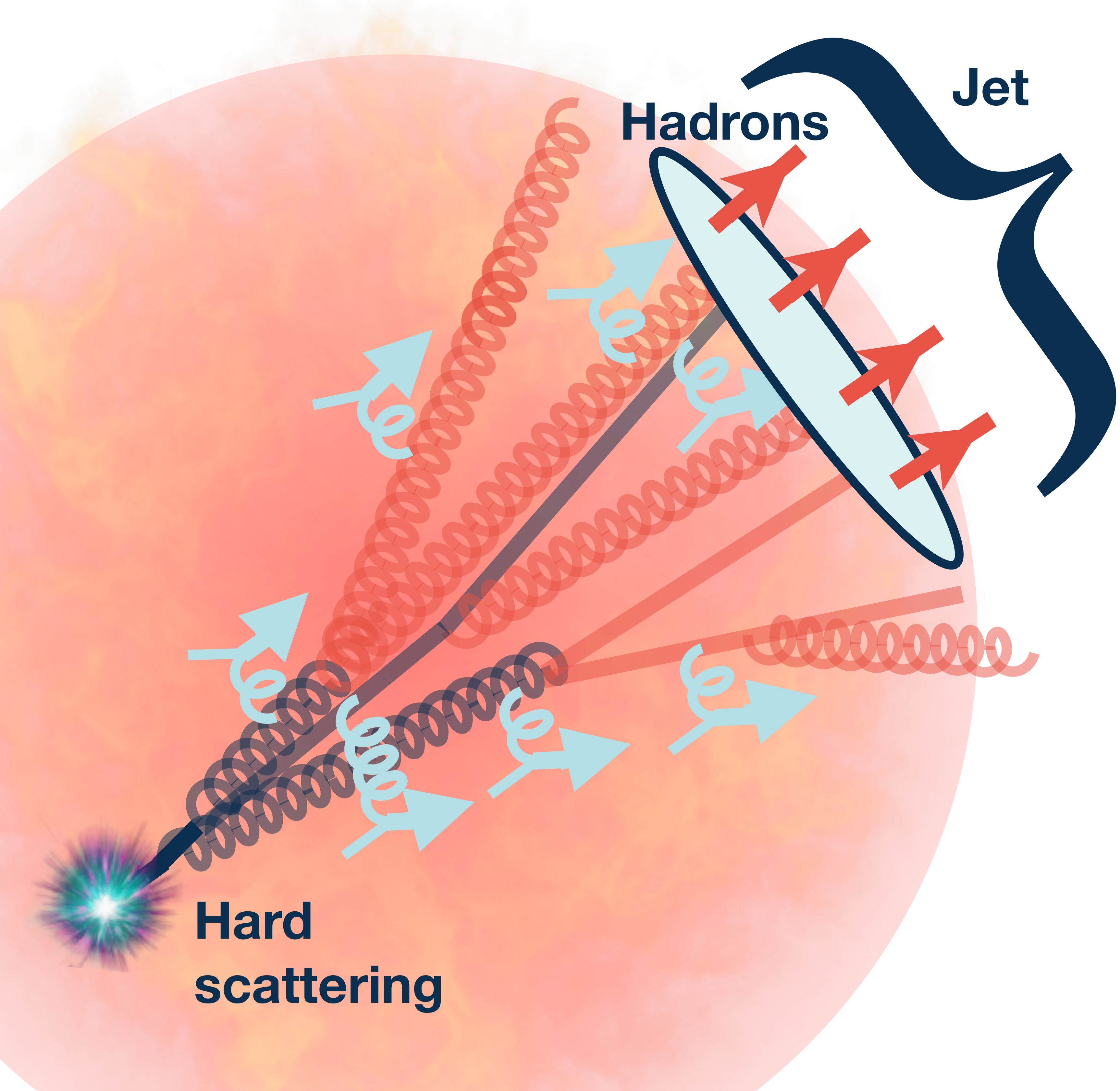

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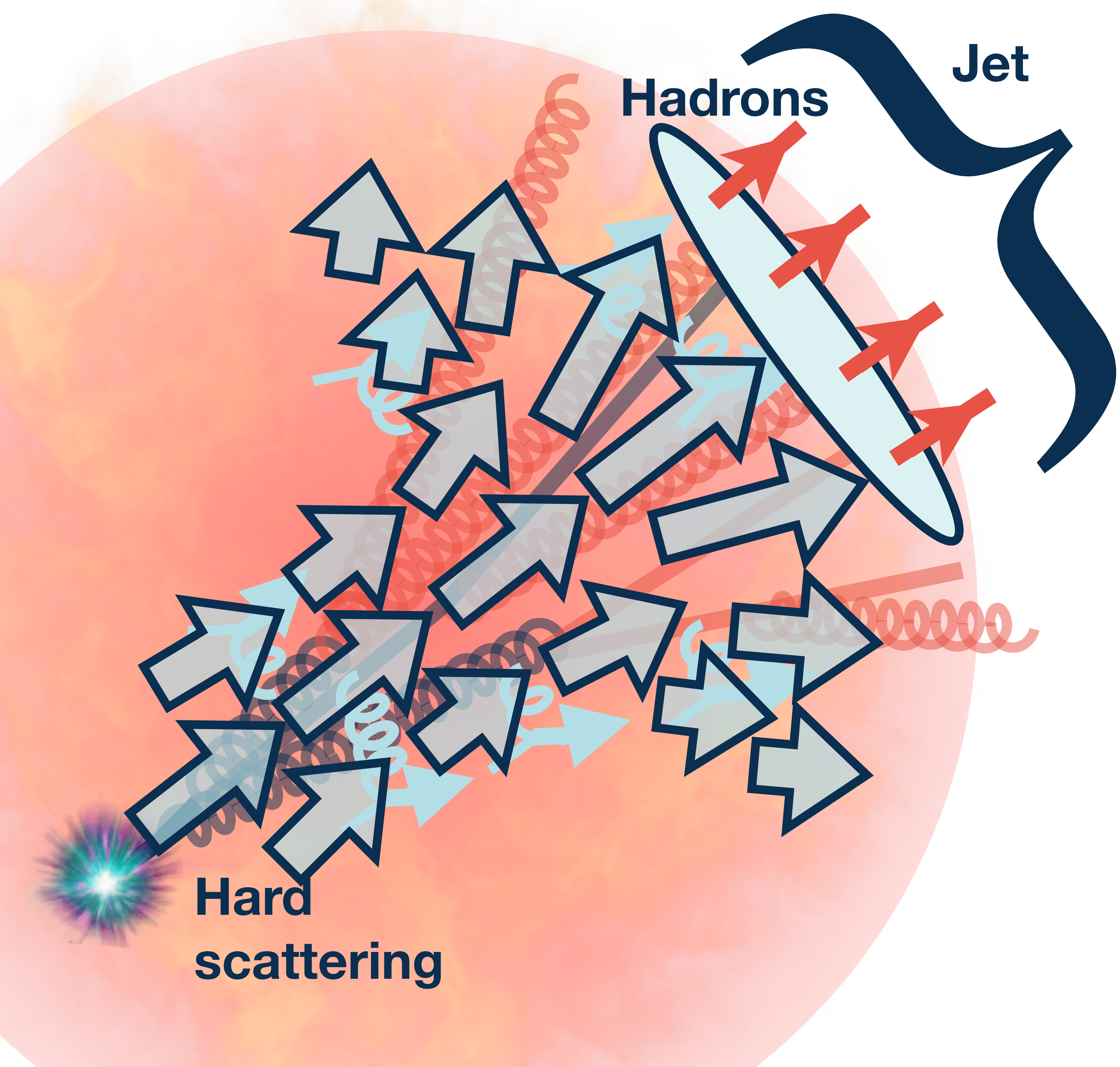

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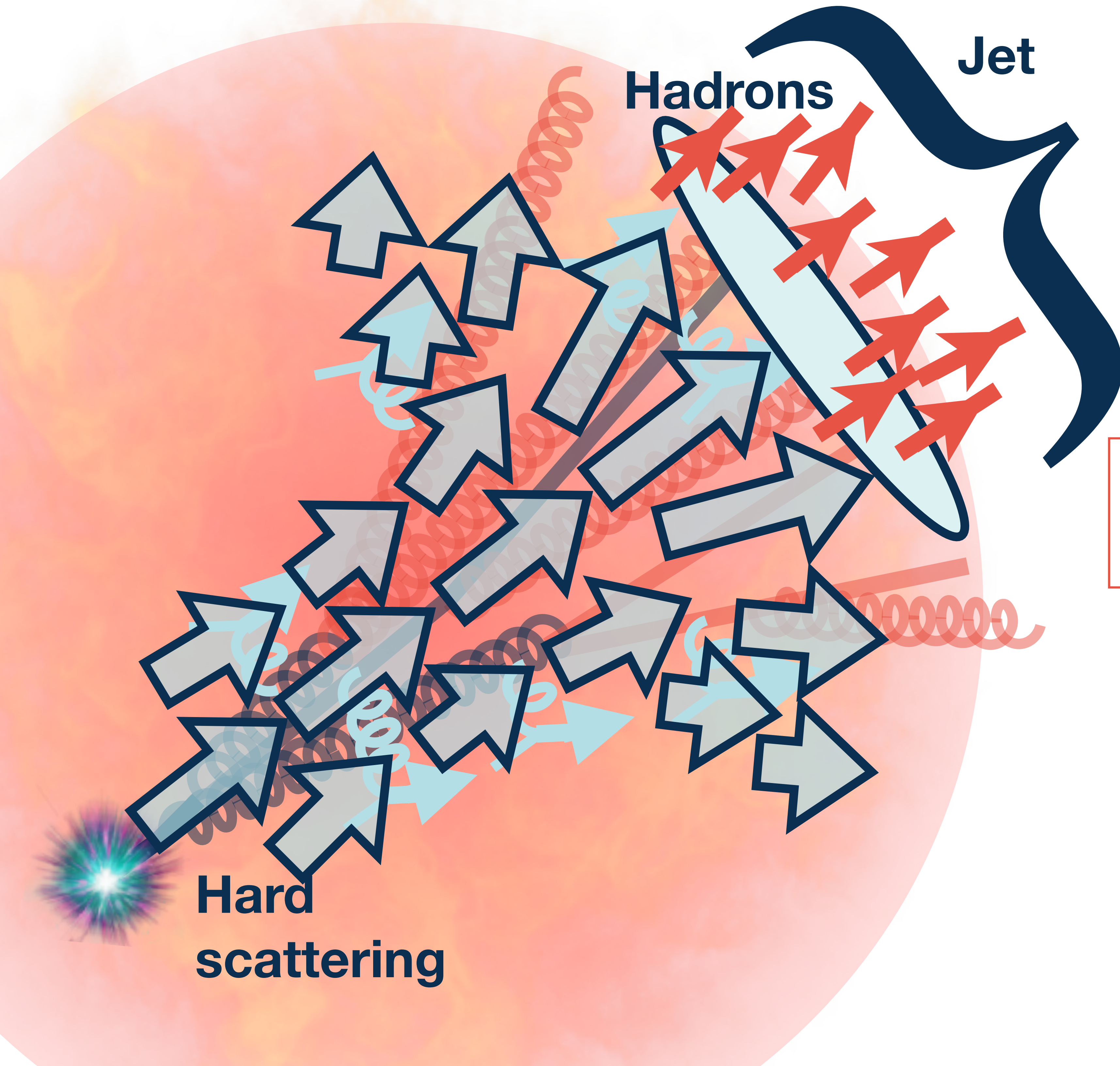

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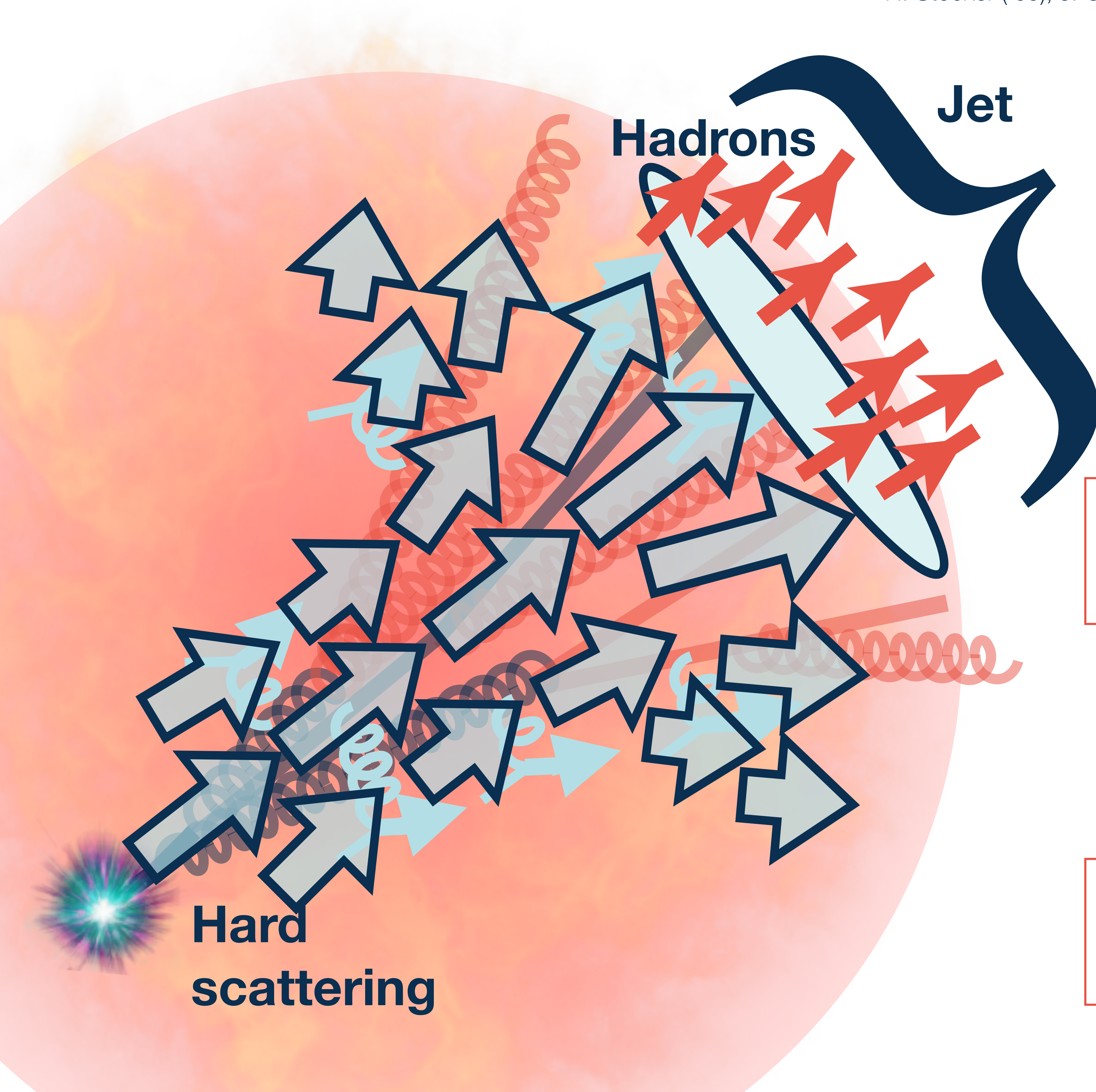

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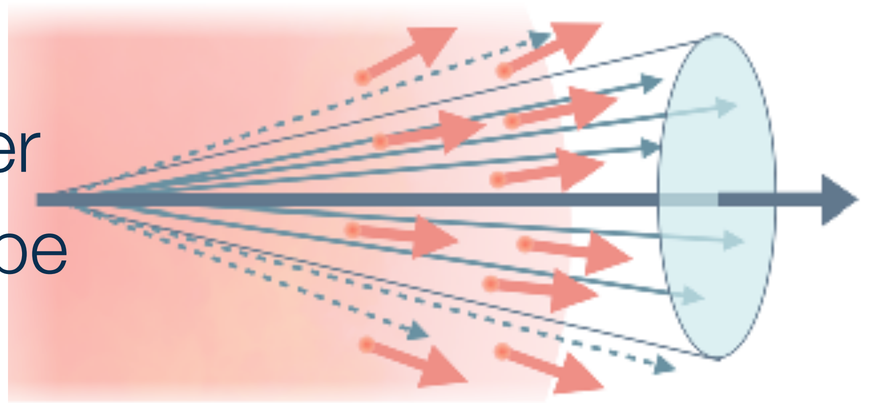
Enhancement of particle emission from medium

Further modification

Jet energy loss
Modification of jet structure

Motivation



- **Purpose**
  - Flow induced as medium response to jet shower
  - Medium contribution to jet energy loss and shape
- **Approach**
  - Describe both jet shower and medium evolution
  - Interaction between them

→ **Jet shower transport equation**
+
Hydrodynamic equation with source term

- **Other works about jet with medium response**

B. Betz, J. Noronha, G. Torrieri, M. Gyulassy, I. Mishustin, D. H. Rischke ('09), G.-Y. Qin, A. Majumder, H. Song, U. Heinz ('09), R. B. Neufeld, B. Muller ('10), R. B. Neufeld, T. Renk ('10), H. Li, F. Liu, G.-L. Ma, X.-N. Wang, Y. Zhu ('11), R. B. Neufeld, I. Vitev ('12), X.-N. Wang, Y. Zhu ('13), YT, T. Hirano ('14, '16), R. P. G. Andrade, J. Noronha, G. S. Denicol ('14), M. Schulc, B. Tomášik ('14),…

Linearized Boltzmann Transport (+ Hydro) Model (*Fully Dynamical*)

Y. He, T. Luo, X.-N. Wang, Y. Zhu ('15), S. Cao, T. Luo, G.-Y. Qin and X.-N. Wang ('16),
Y. He, H. Stoecker, L.-G. Pang, T. Luo , E. Wang, X.-N. Wang, C. Wei ('16)

Hybrid Strong/Weak Coupling Model

J. Casalderrey-Solana, D. C. Gulhan, J. G. Milhano, D. Pablos,K. Rajagopal ('16)

JEWEL

S. Floerchinger, K. C. Zapp ('14),…

The Coupled Jet-fluid Model

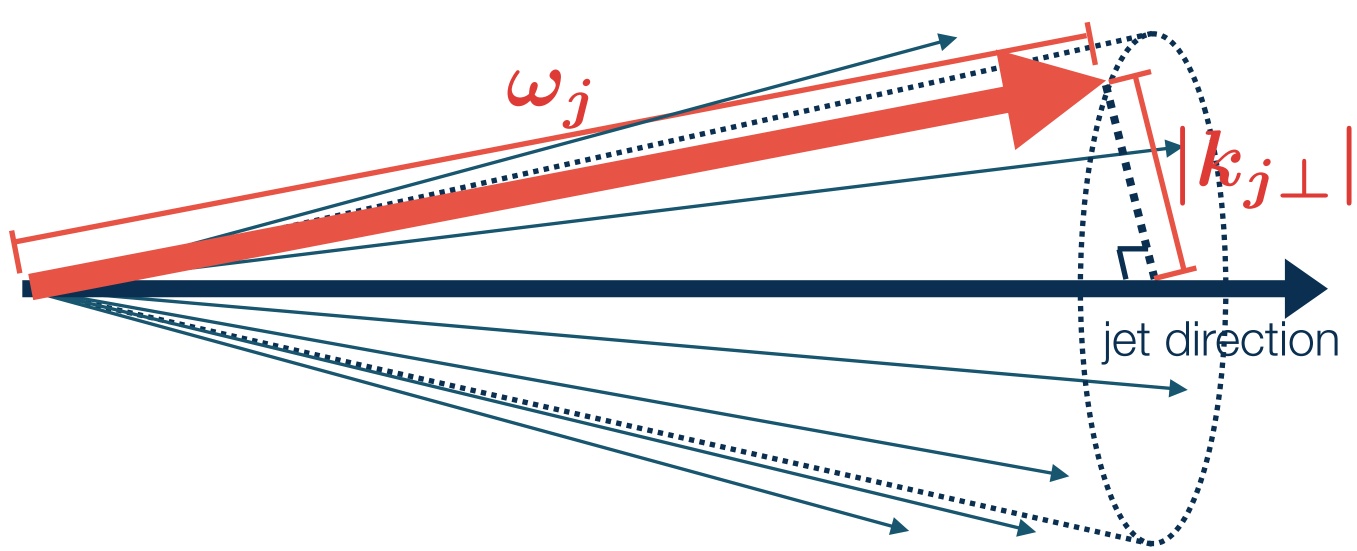
Jet shower evolution

N.-B. Chang and G.-Y. Qin, Phys. Rev. C **94**, no. 2, 024902 (2016)

- **Transport equations for *all* partons in jet shower**
  - Evolution of energy and transverse momentum distributions, $f_j\left(\omega_j, k_{j\perp}^2, t\right)$

(j: parton species)

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



Fluctuation- dissipation theorem

$$\hat{e}_j = \frac{\hat{q}_j}{4T}$$

Higher-twist

$$\frac{d\tilde{\Gamma}_{i\to j}(\omega_j, k_{j\perp}^2|\omega_i, 0)}{d\omega_j dk_{j\perp}^2 dt} = \frac{2\alpha_s}{\pi}\hat{q}_g \frac{xP_{i\to j}(x)}{\omega_j k_{j\perp}^4} \sin^2\left(\frac{t-t_i}{2\tau_f}\right)$$

($P_{i\to j}(x=\omega_j/\omega_i)$: vacuum splitting function)

Initial jet profiles are generated by PYTHIA

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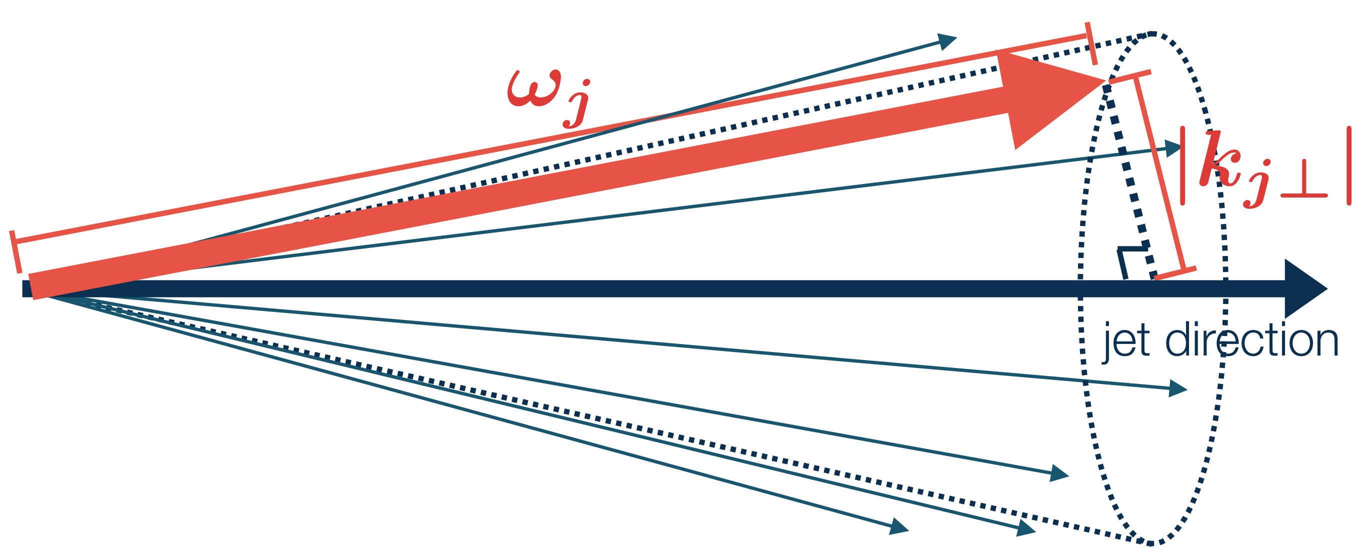
Collisional energy loss (longitudinal)

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

Momentum broadening (transverse)

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



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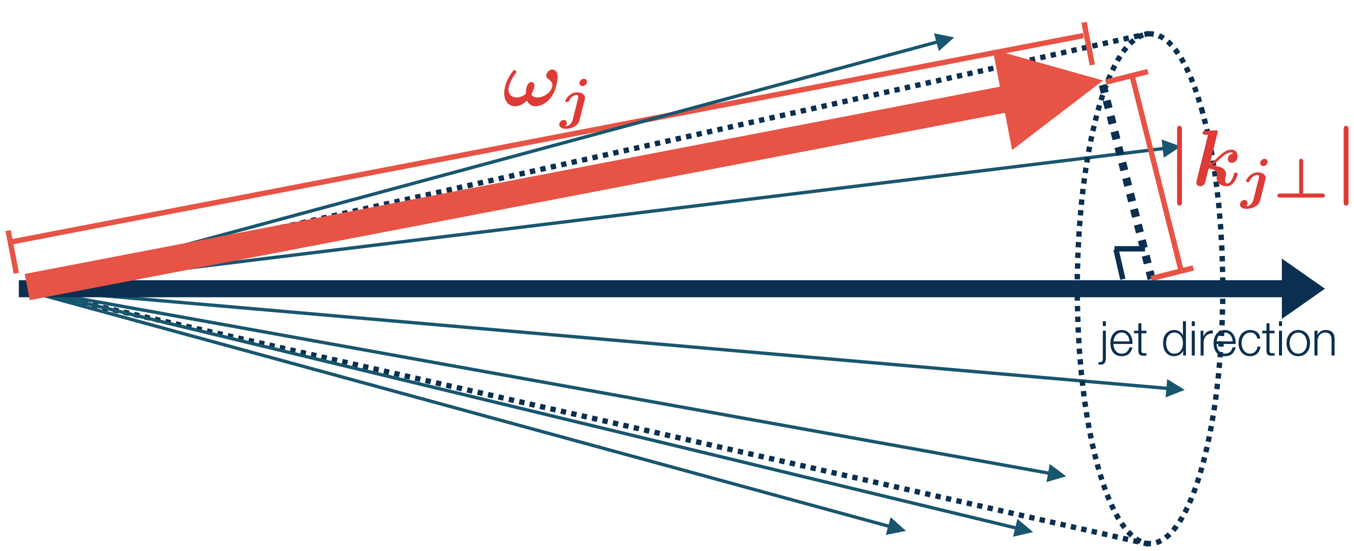
Medium-induced radiation



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Initial jet profiles are generated by PYTHIA

Space-time evolution of QGP medium

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

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

Energy-momentum tensor of the QGP fluid

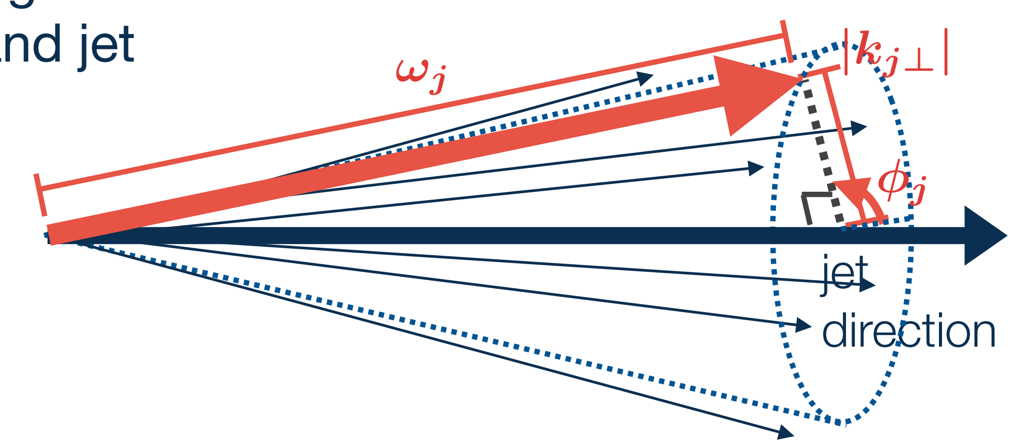
Energy and momentum deposited from the jet

- **Source term**

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

$$\left.\frac{df_j(\omega_j, k_{j\perp}^2, t)}{dt}\right|_{\mathrm{col.}} = \left(\hat{e}_j \frac{\partial}{\partial \omega_j} + \frac{1}{4}\hat{q}_j \nabla^2_{k_\perp}\right) f_j(\omega_j, k_{j\perp}^2, t)$$

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

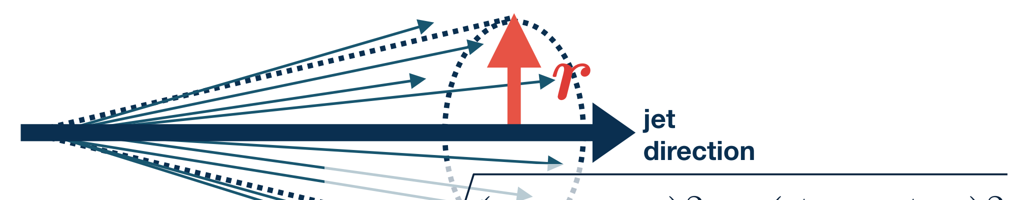


Assumption
Instantaneous local thermalization of deposited energy and momentum

Simulations and Results

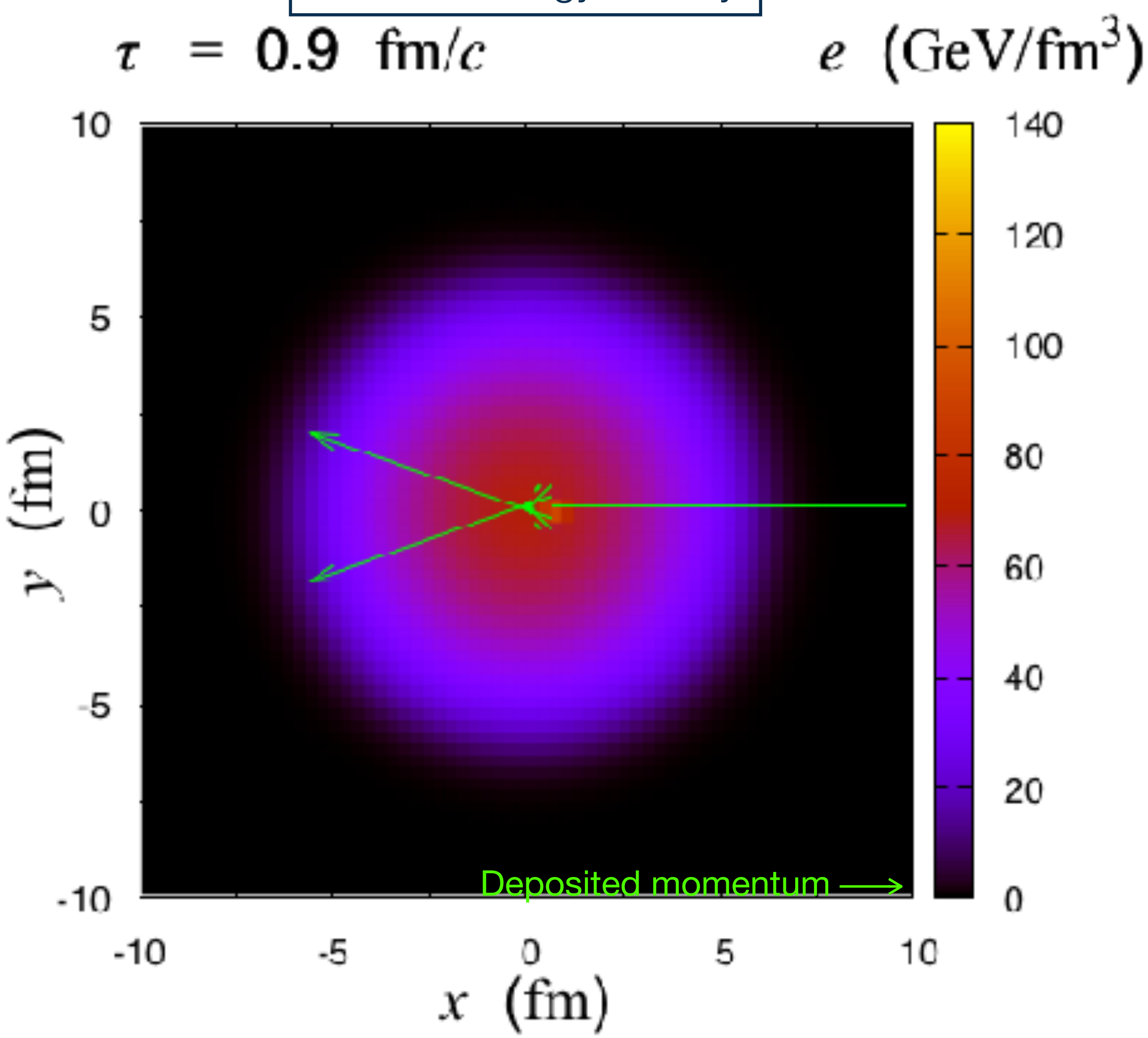
Flow in QGP fluid induced by jet shower

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

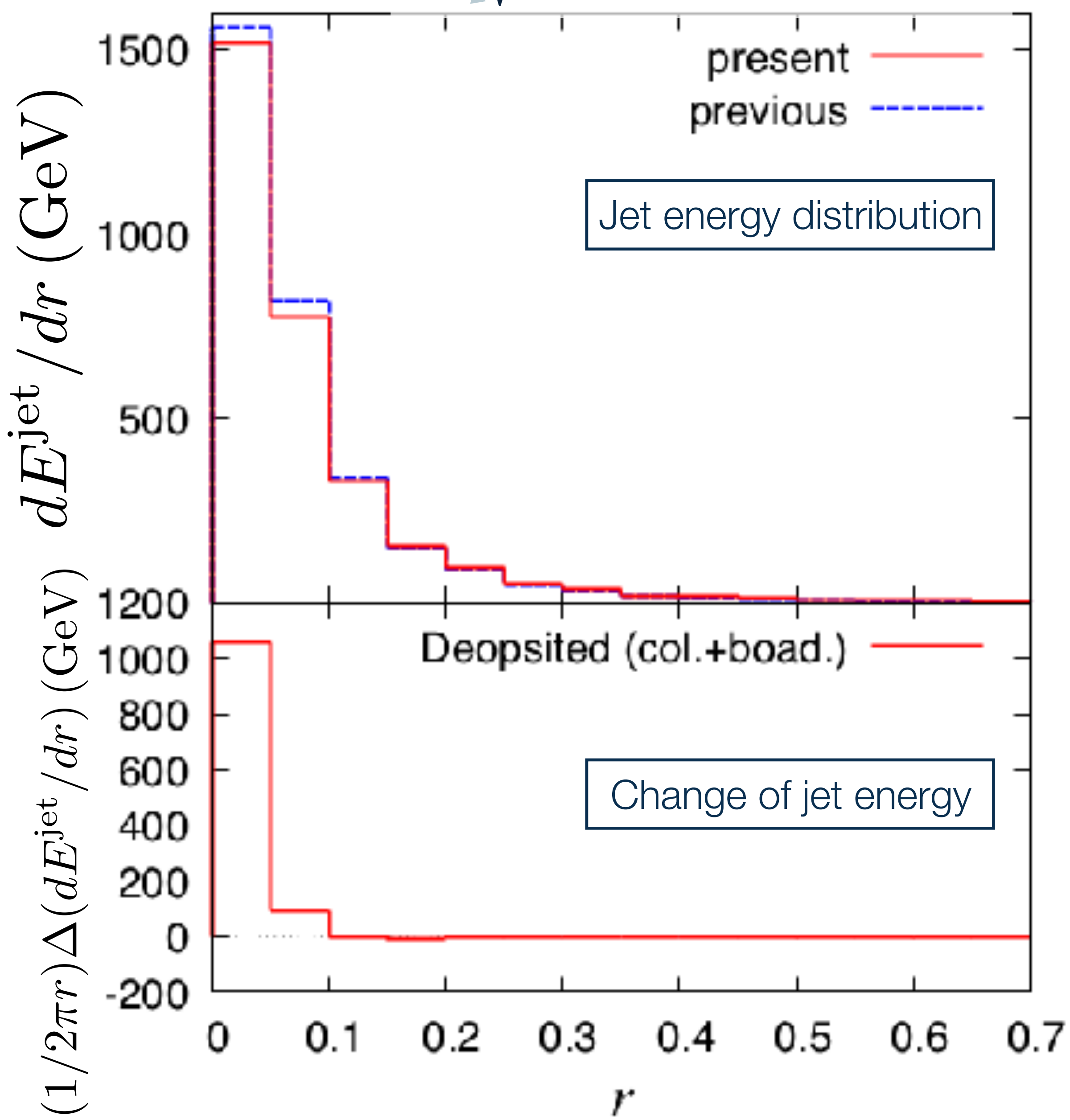


$$r = \sqrt{(\eta_p - \eta_{\rm jet})^2 + (\phi_p - \phi_{\rm jet})^2}$$

Medium energy density



Inital jet energy: 150 GeV



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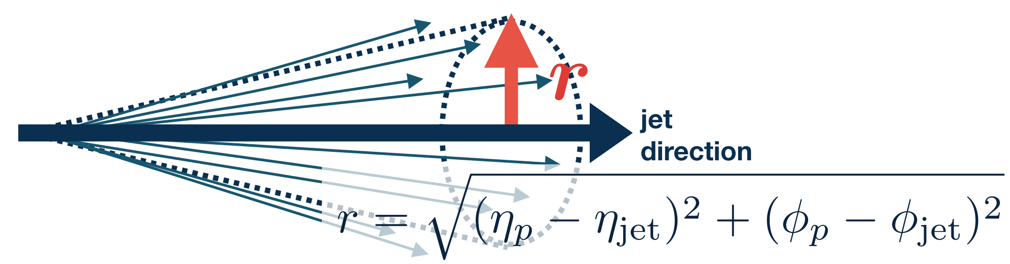

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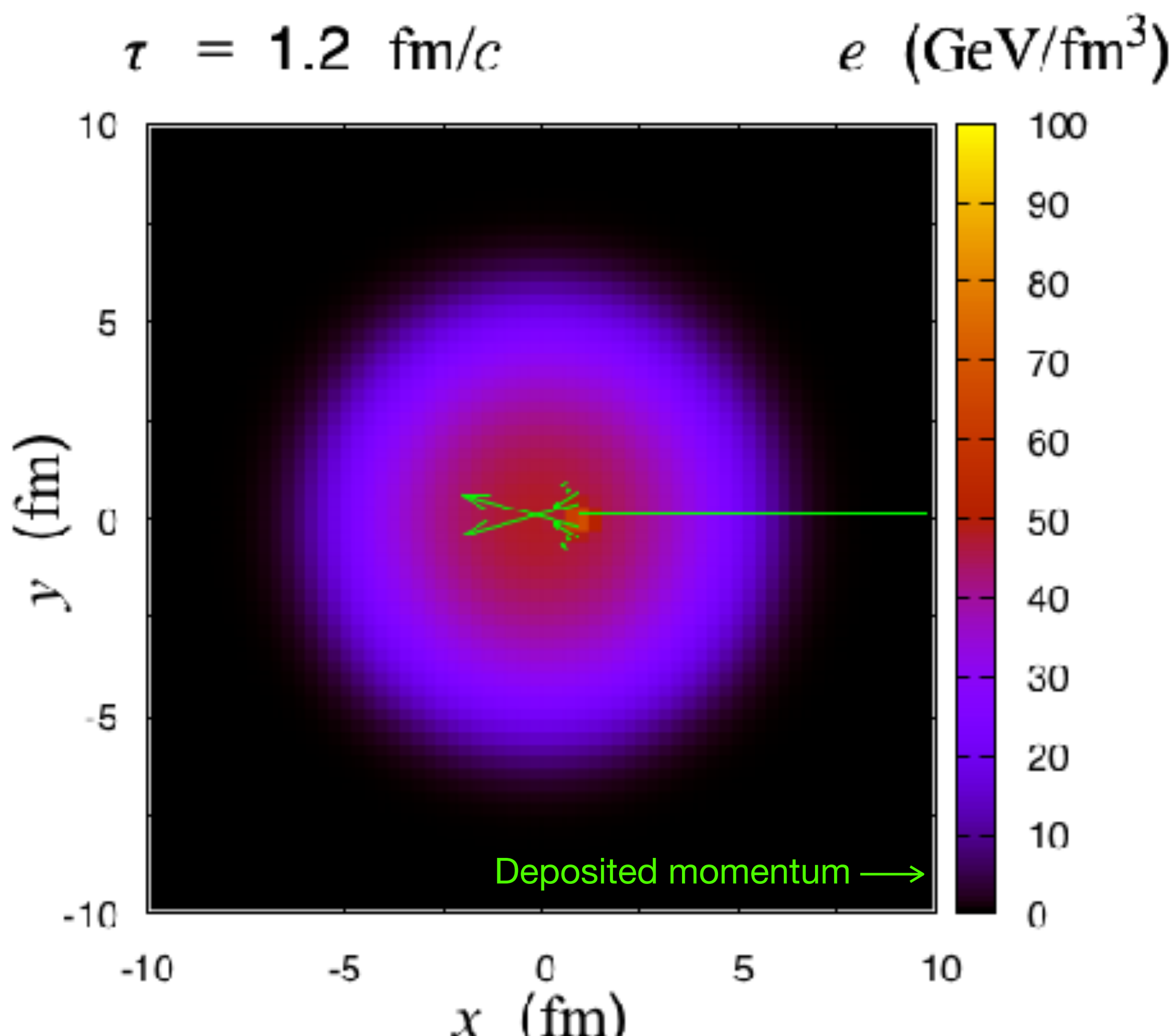

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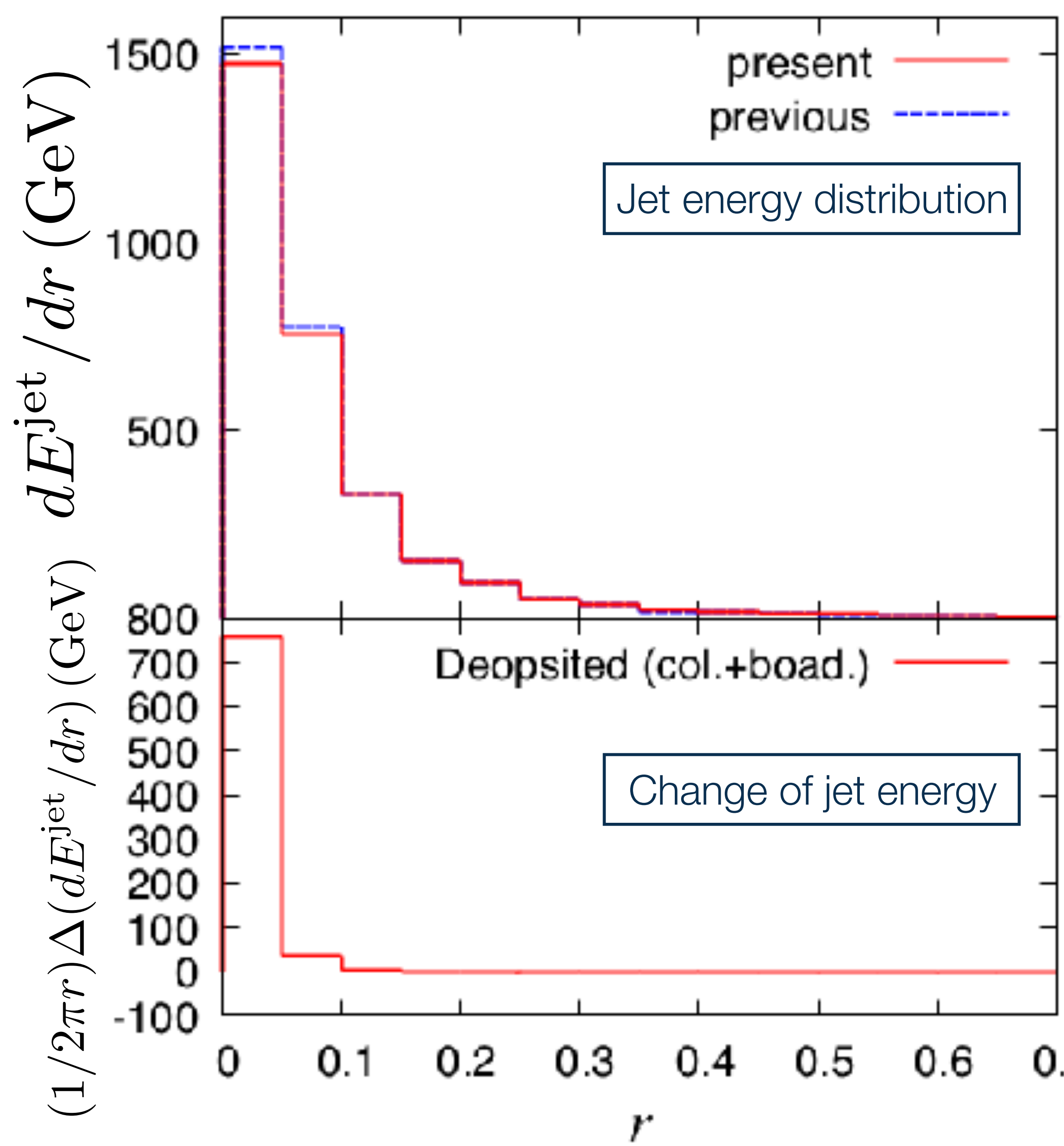

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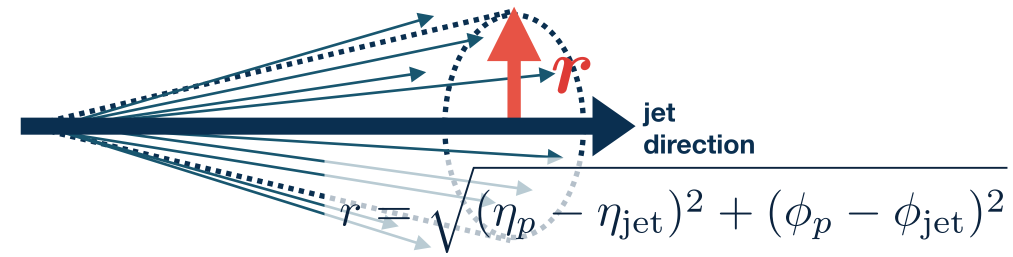

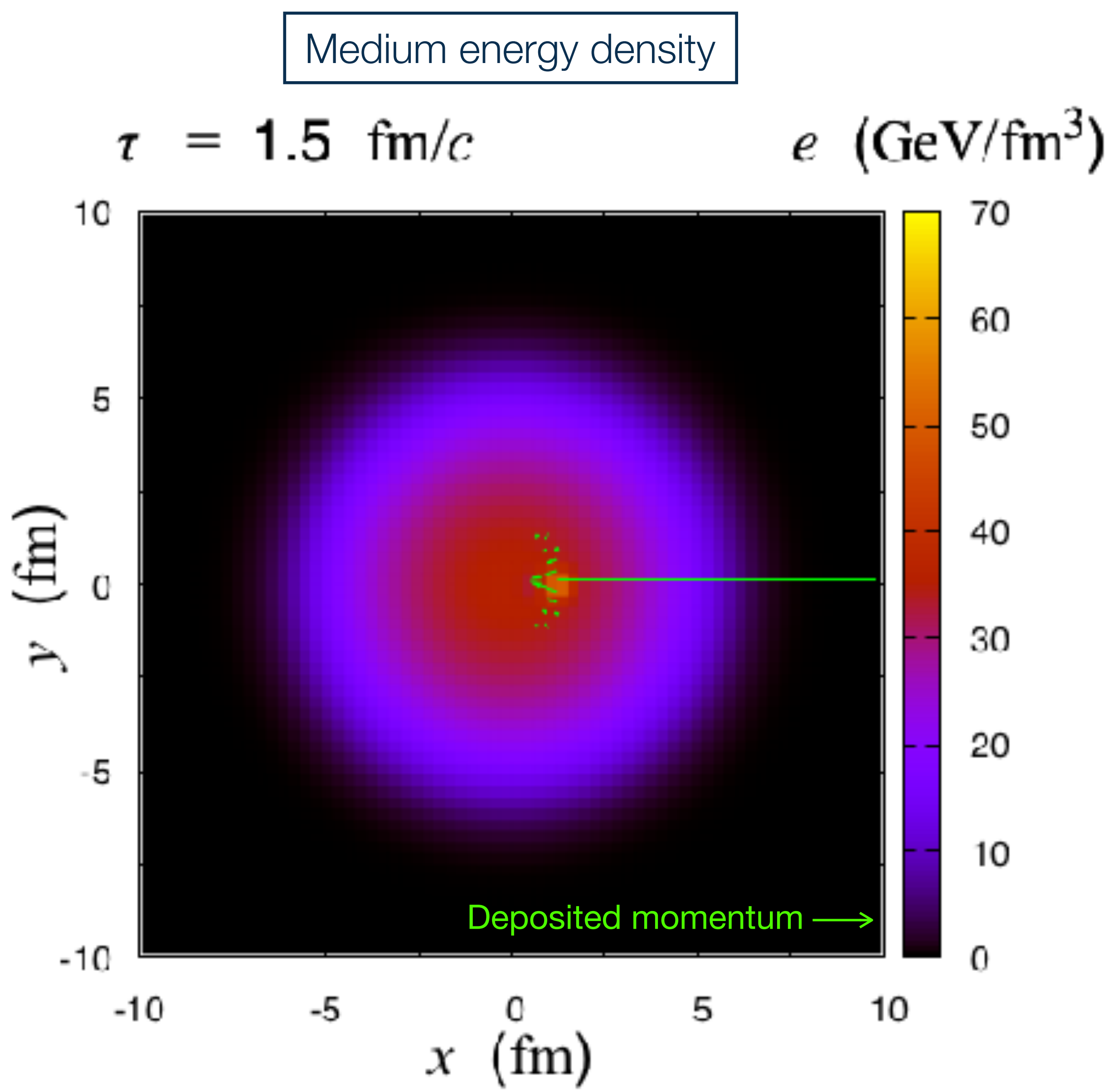

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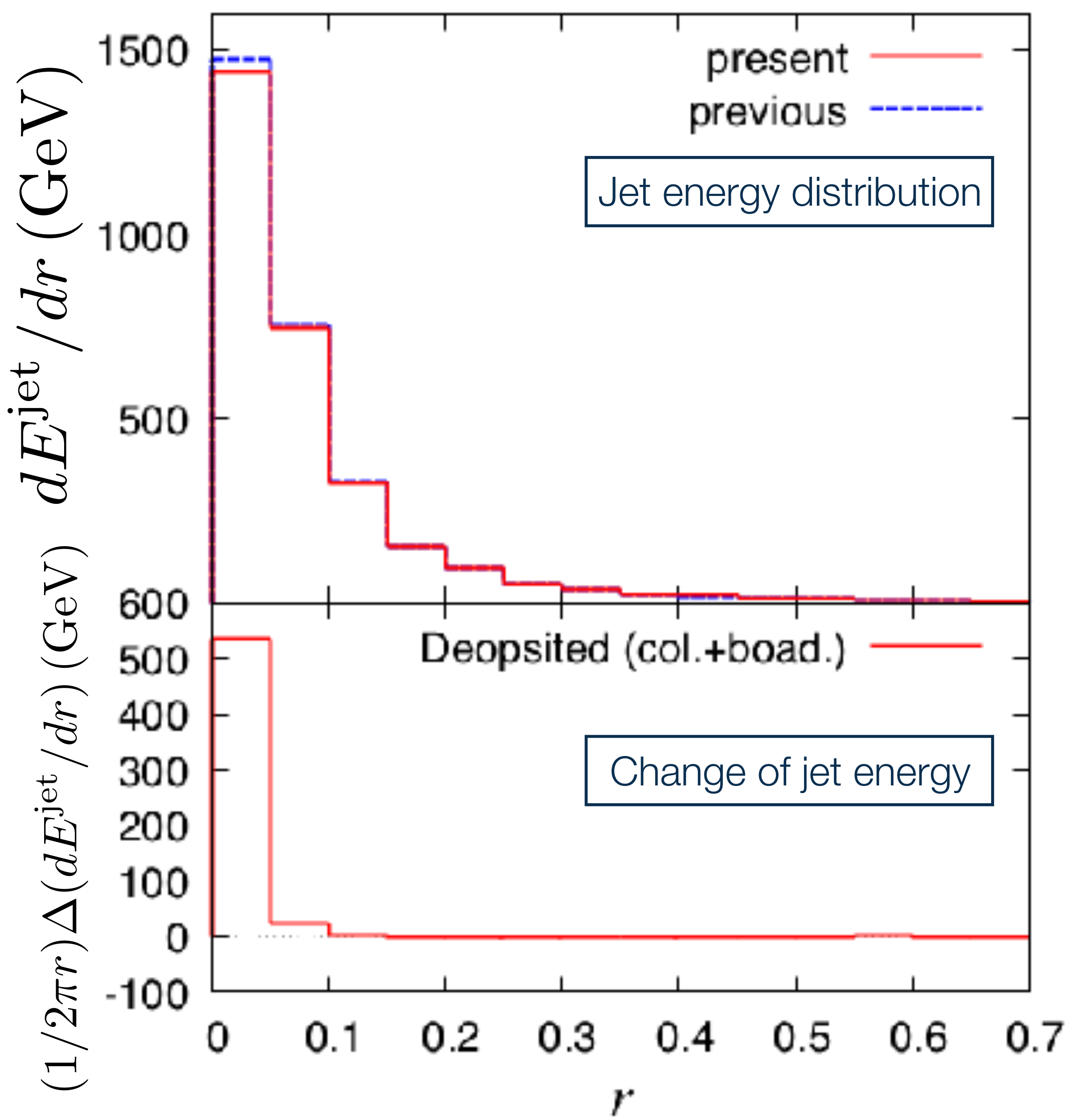

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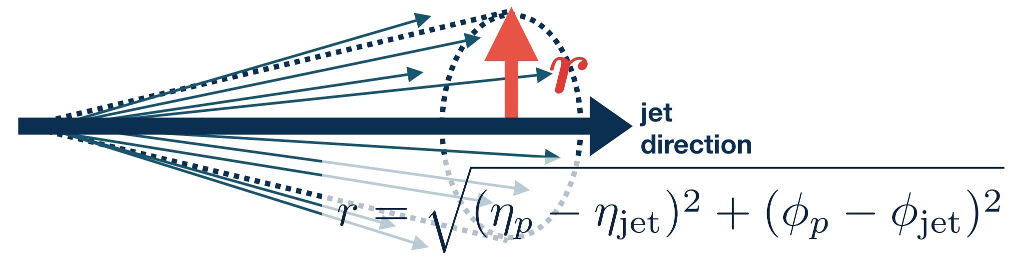

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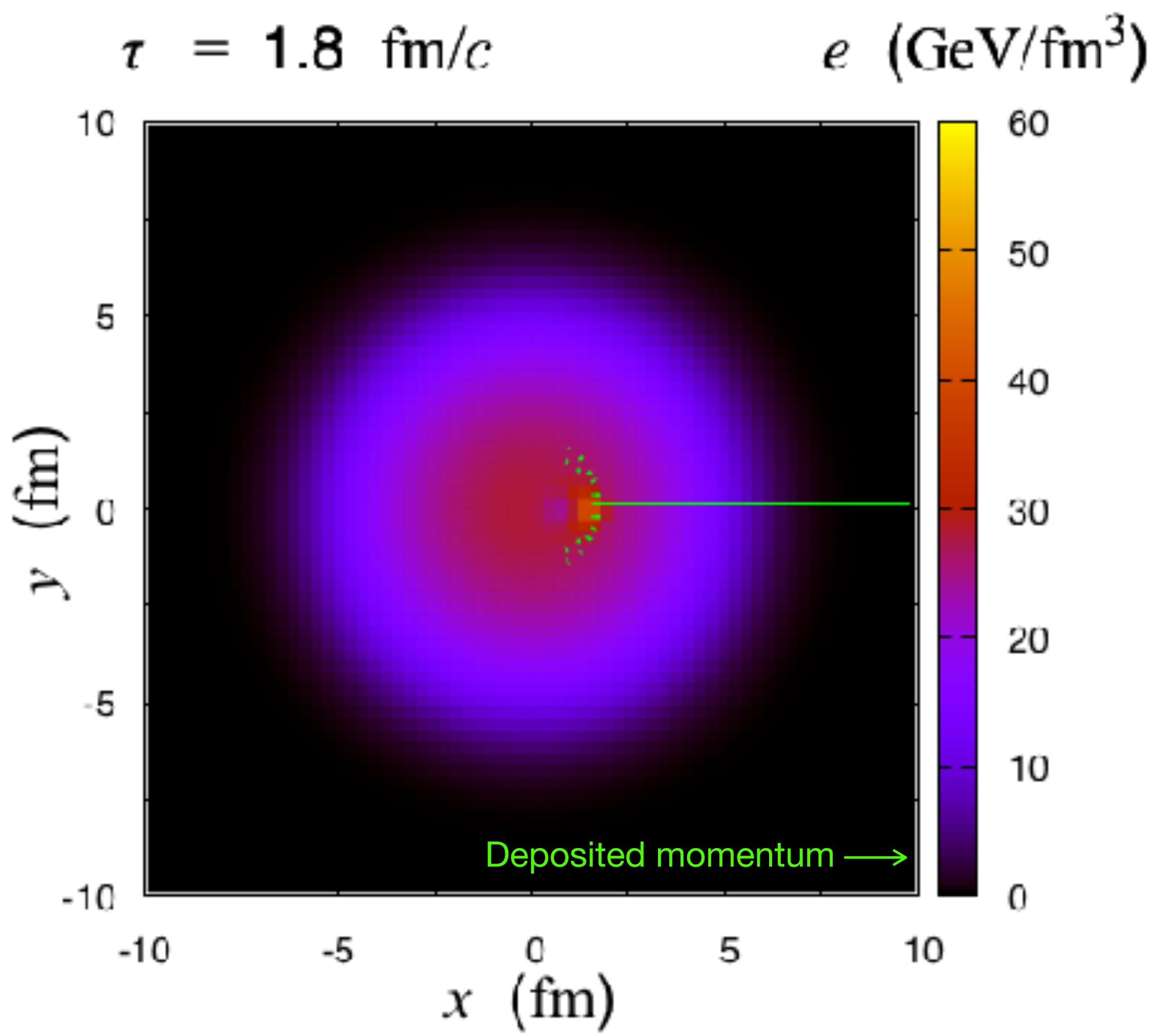

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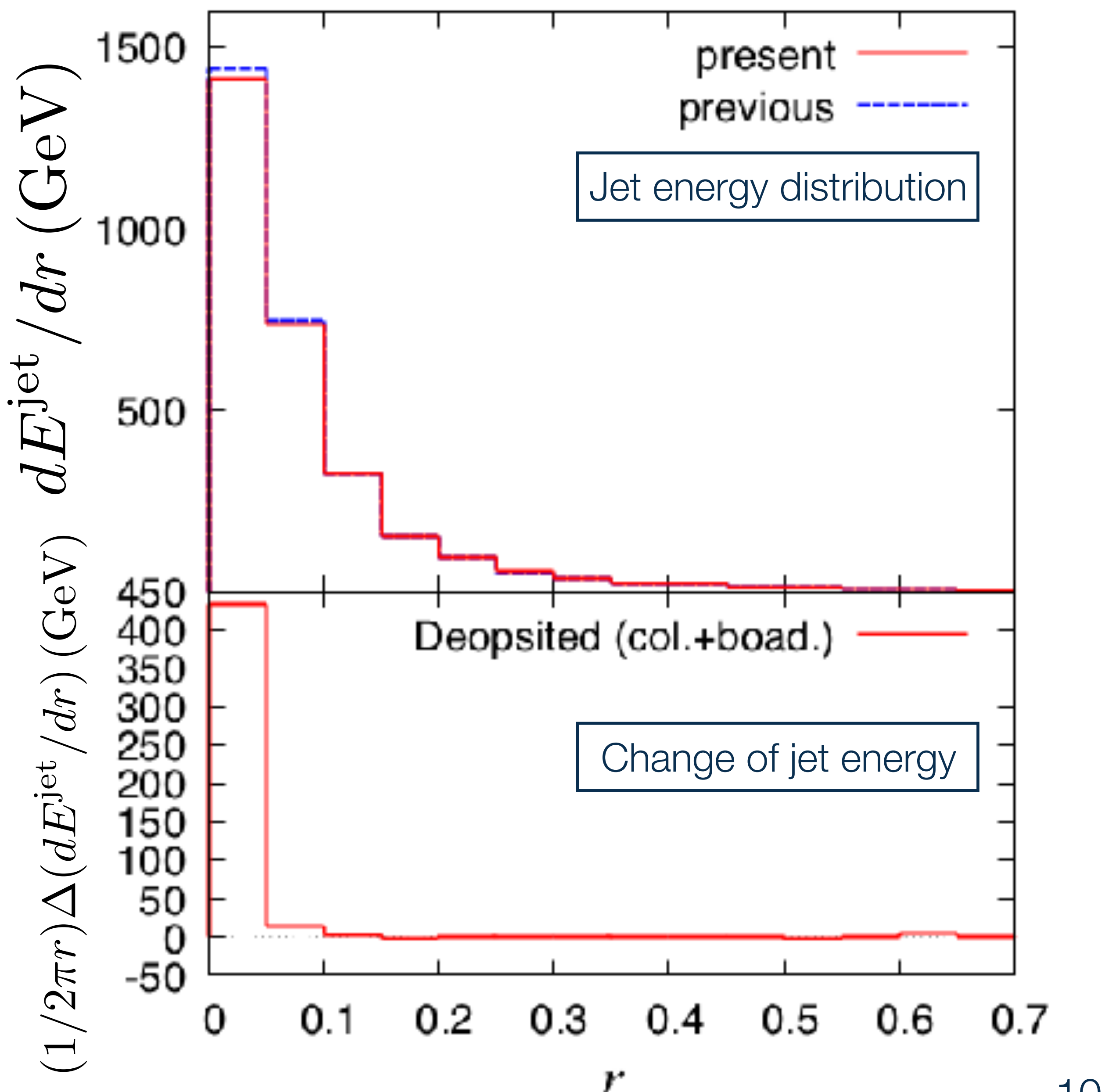

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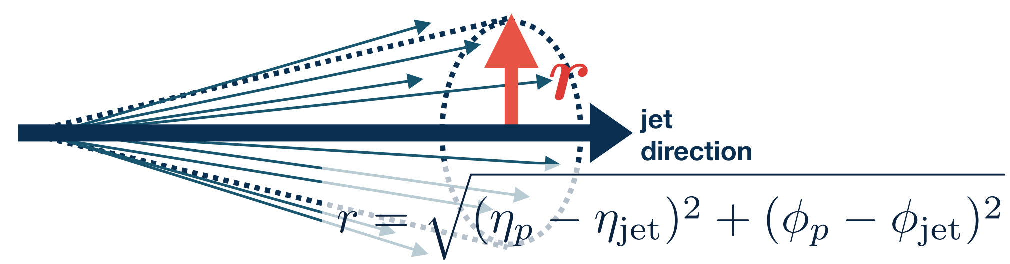

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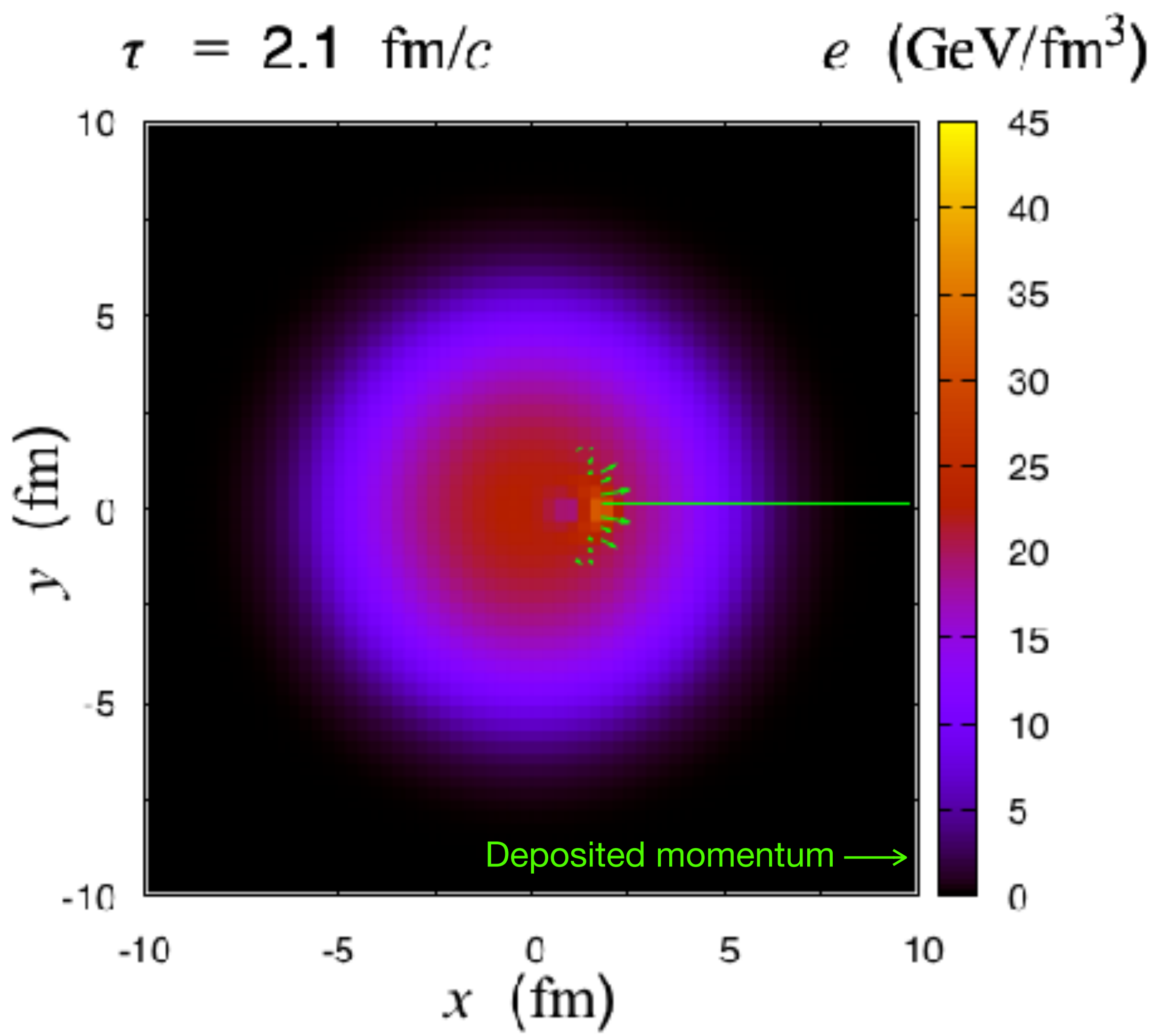

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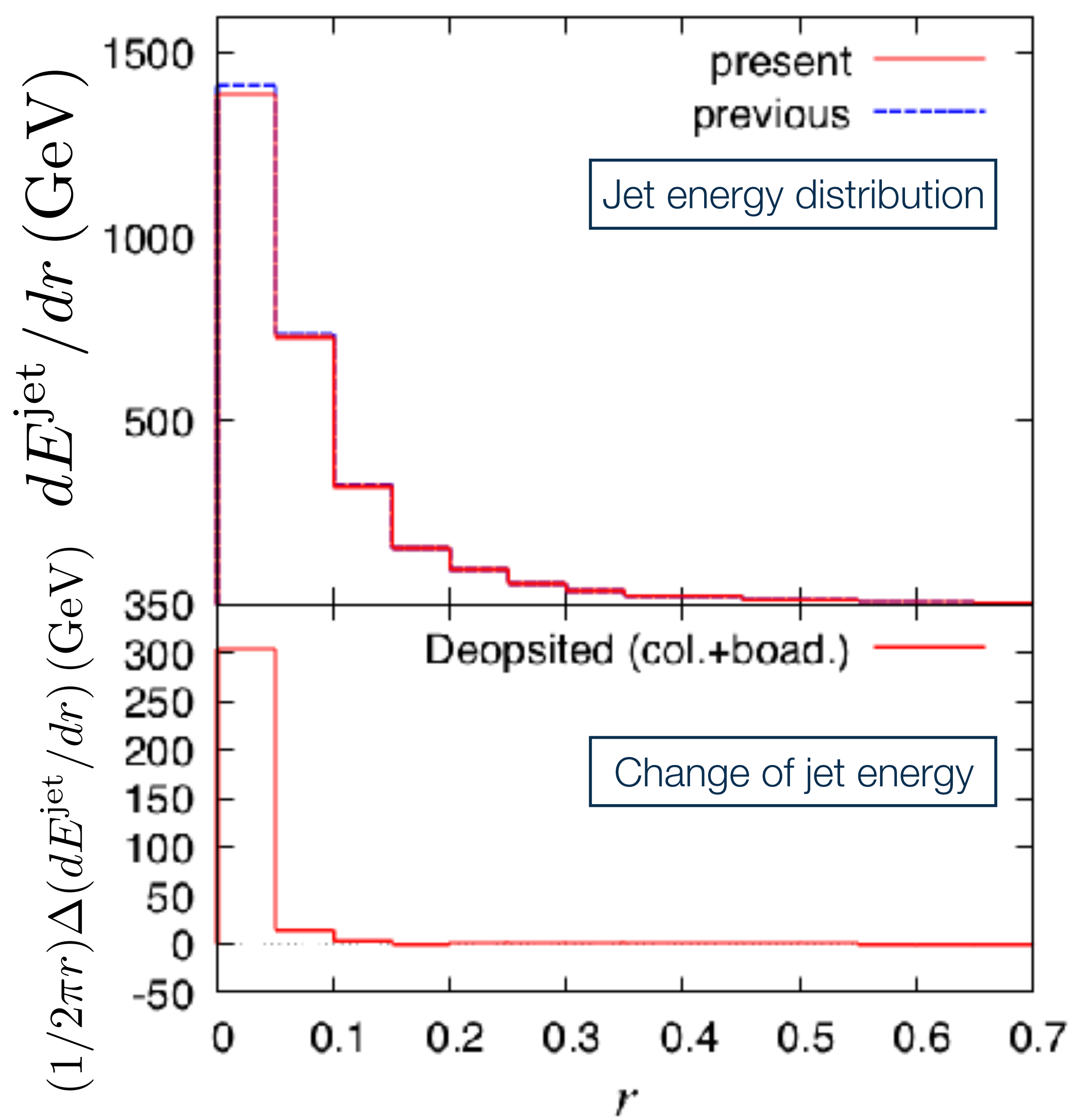

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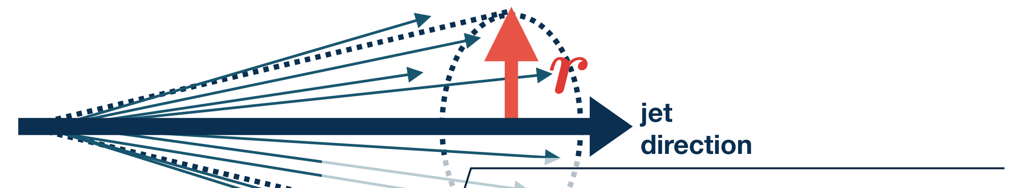

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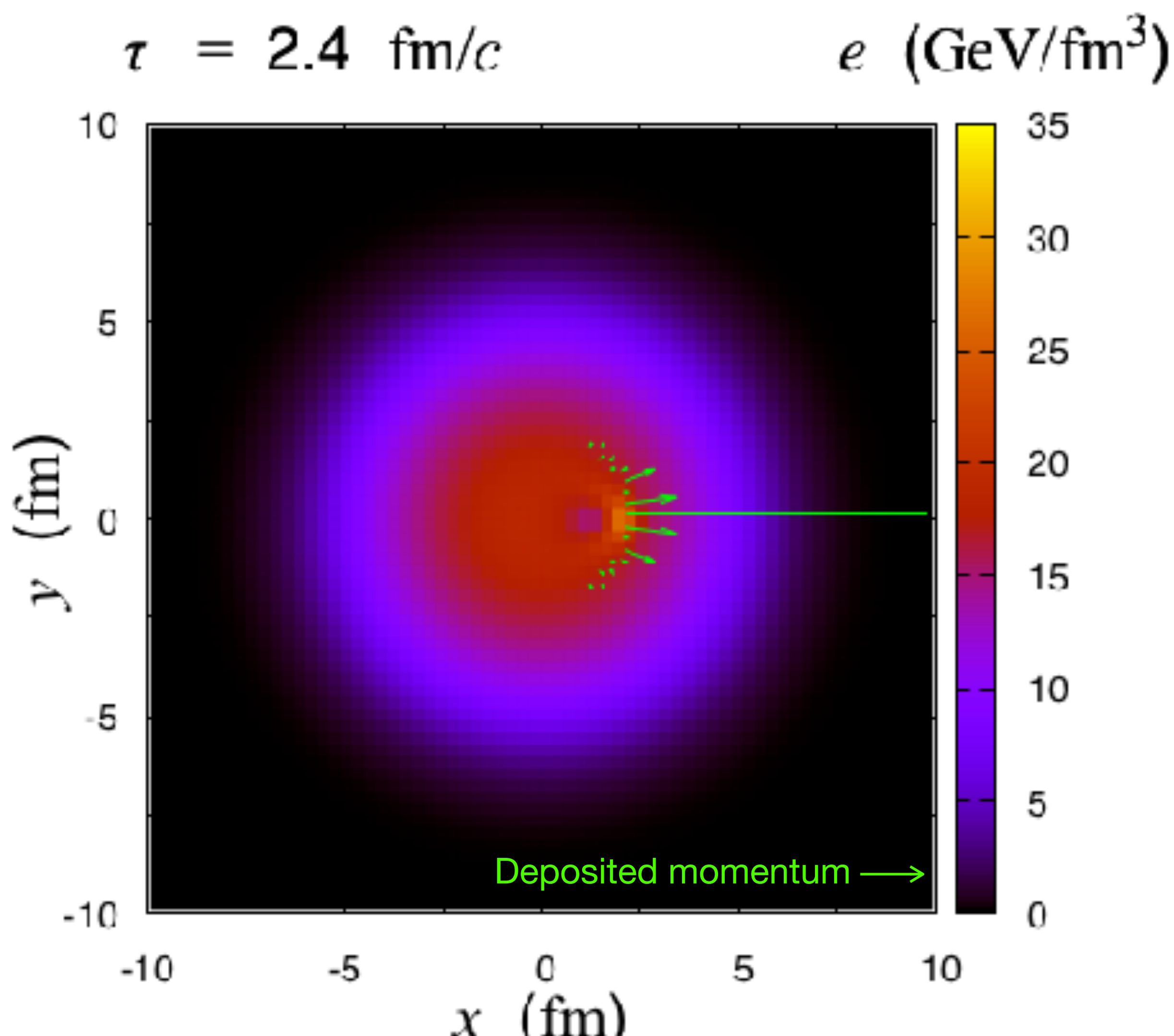

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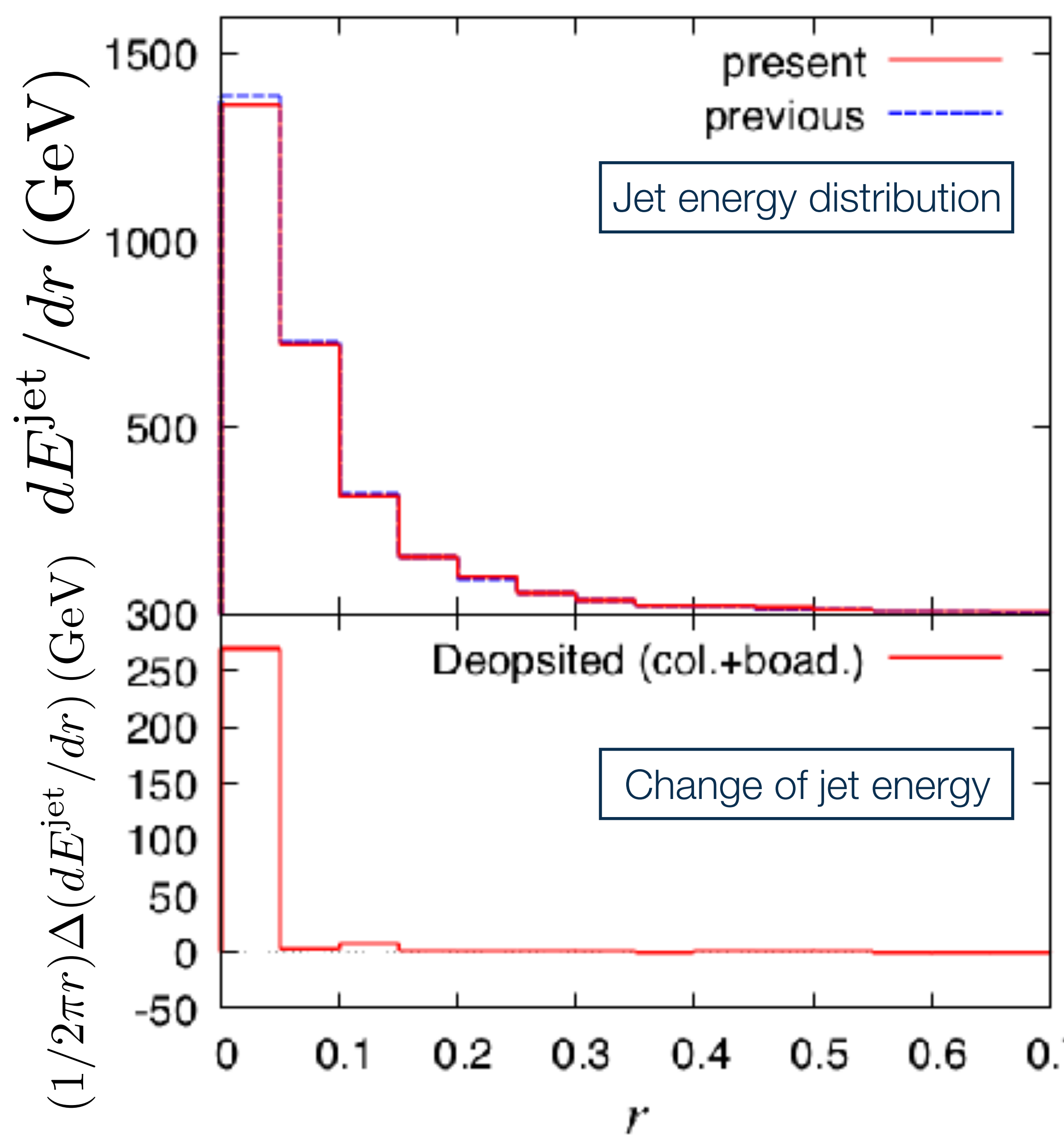

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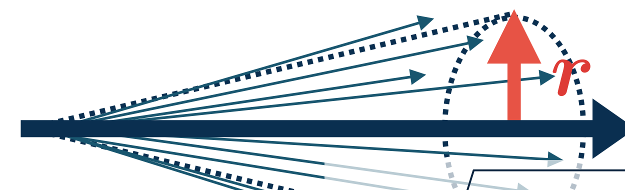

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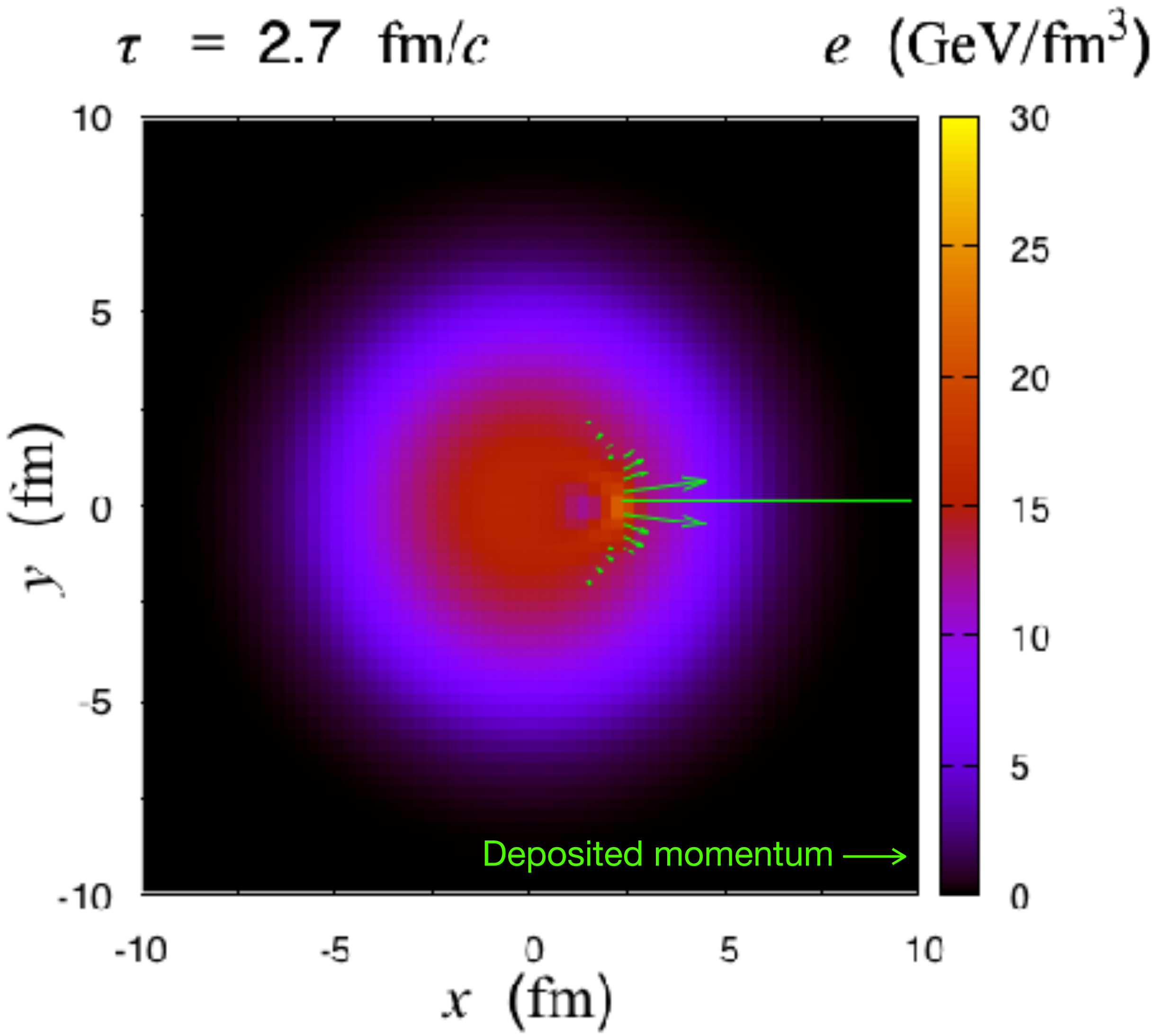

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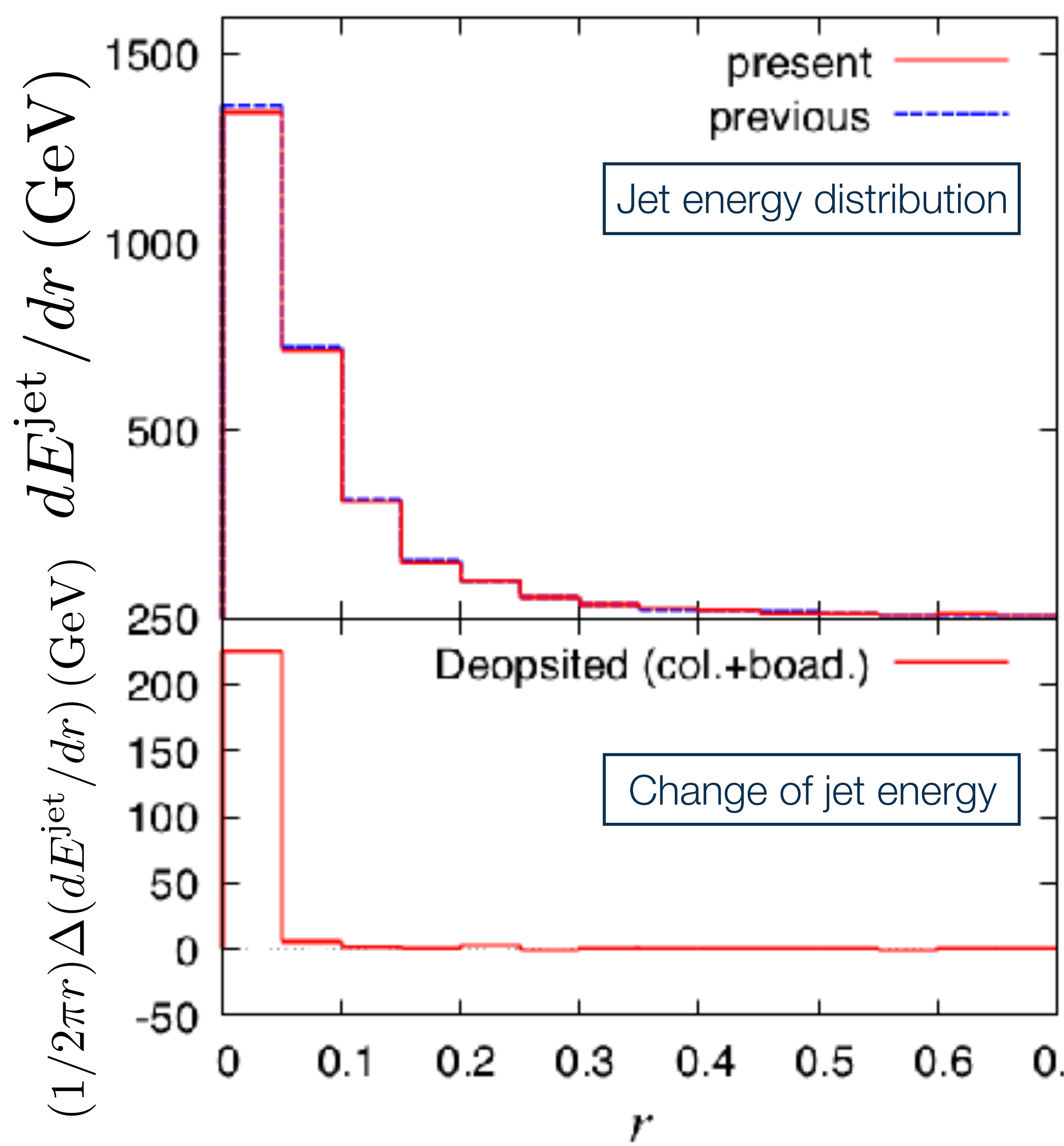

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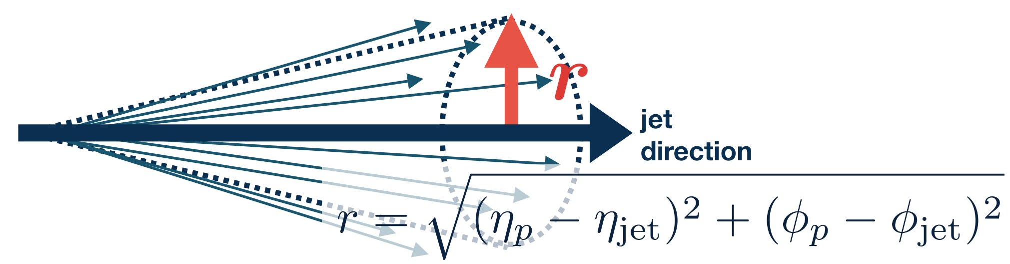

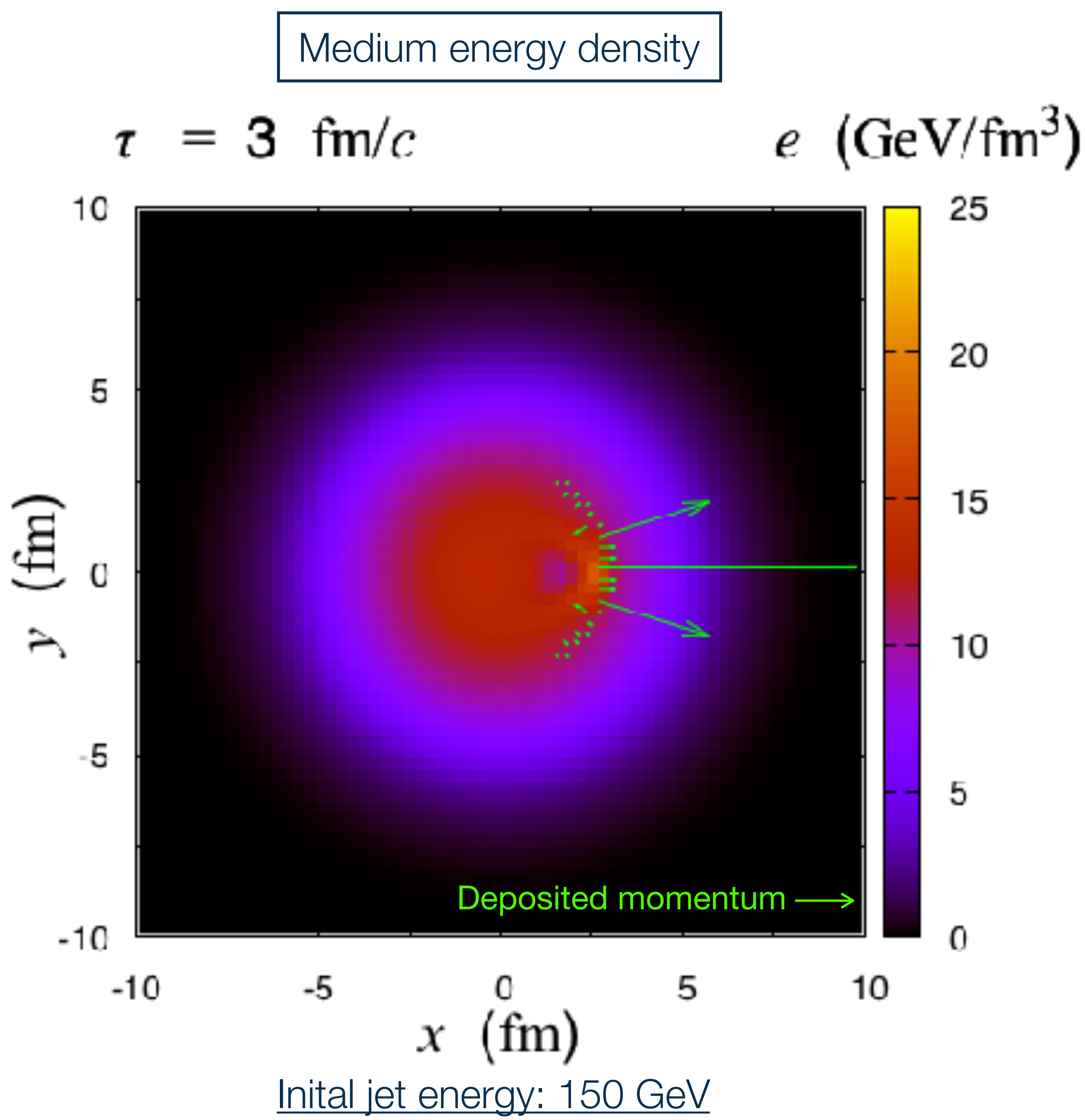

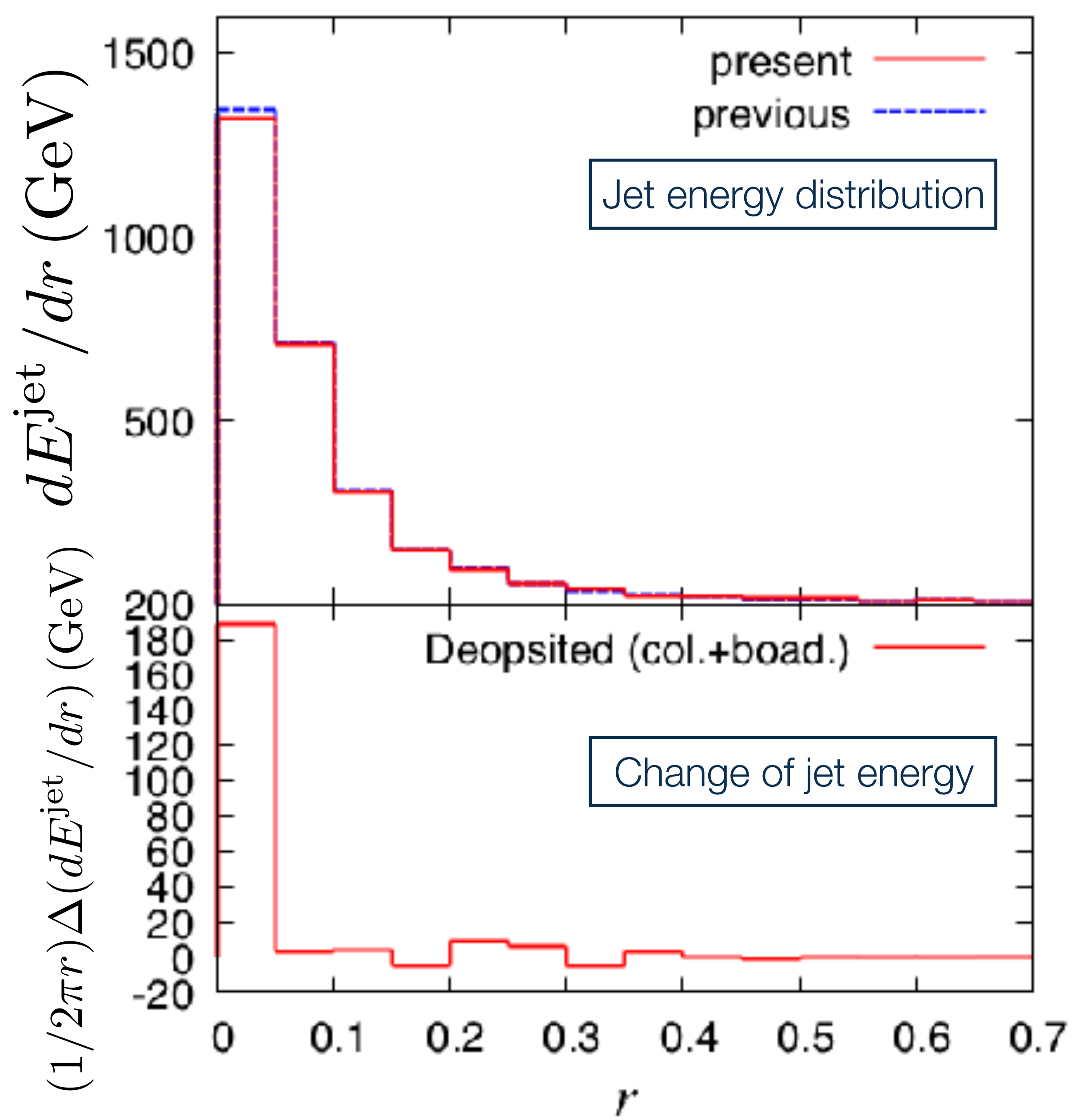

Flow in QGP fluid induced by jet shower

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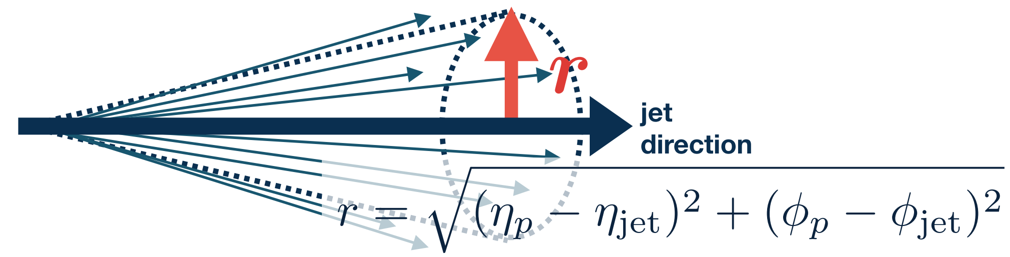
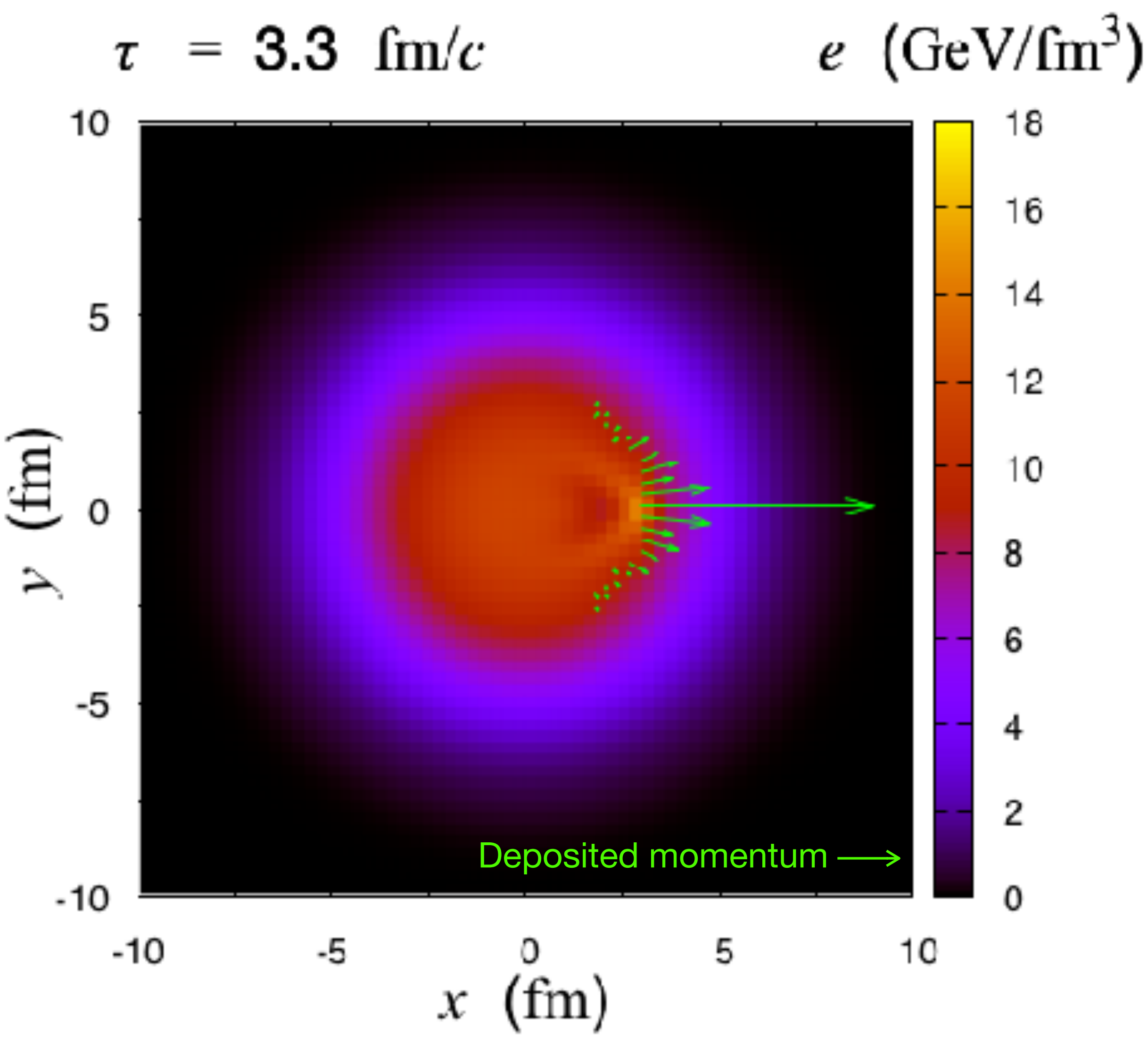
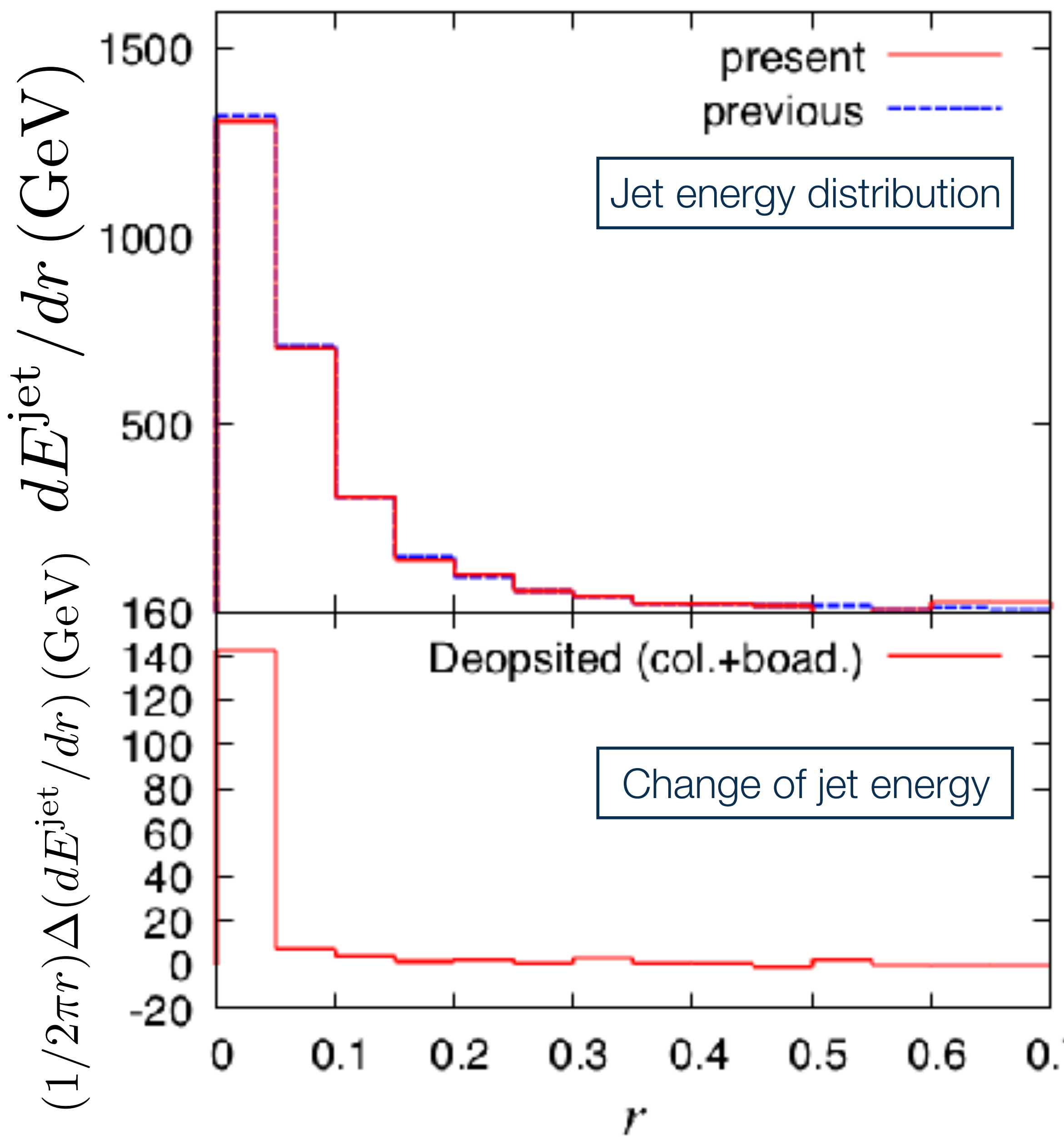


- **Evolution of medium and jet shower**

Medium energy density



Inital jet energy: 150 GeV



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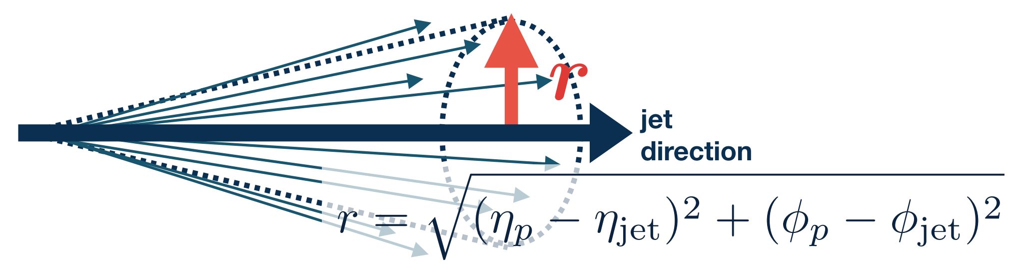

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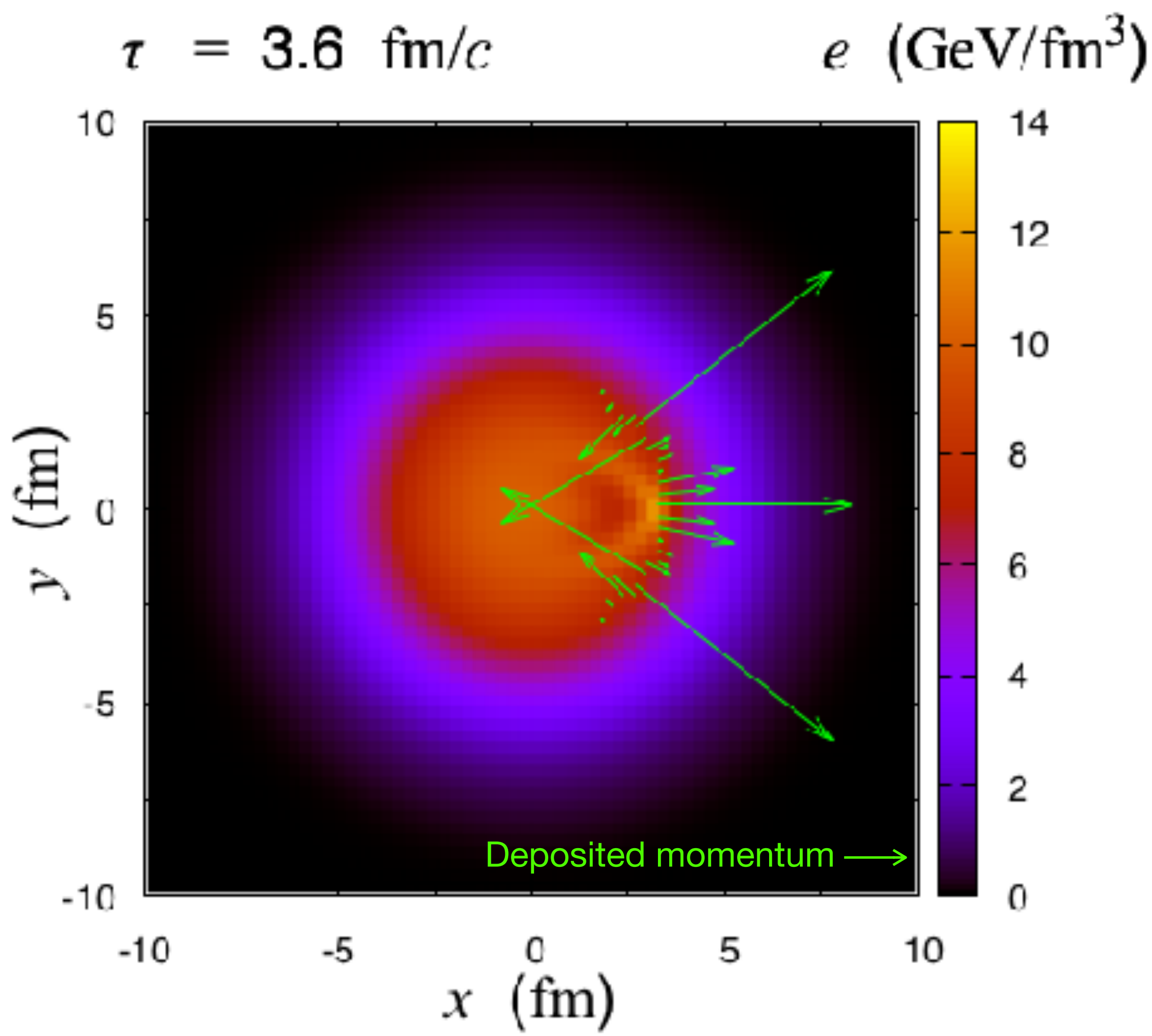

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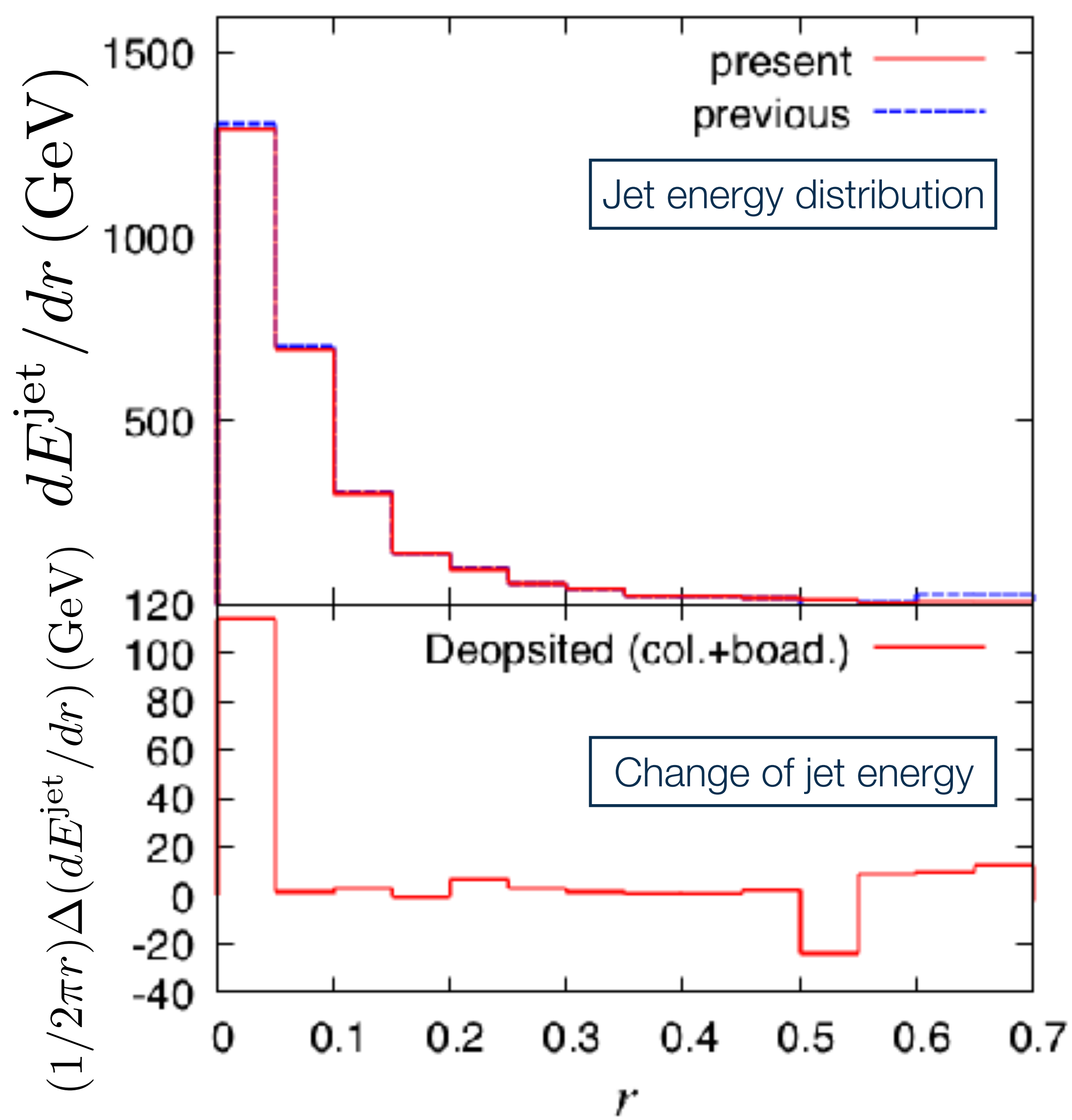

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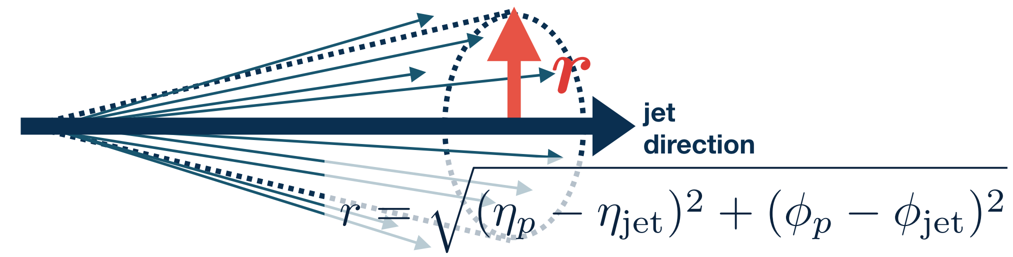
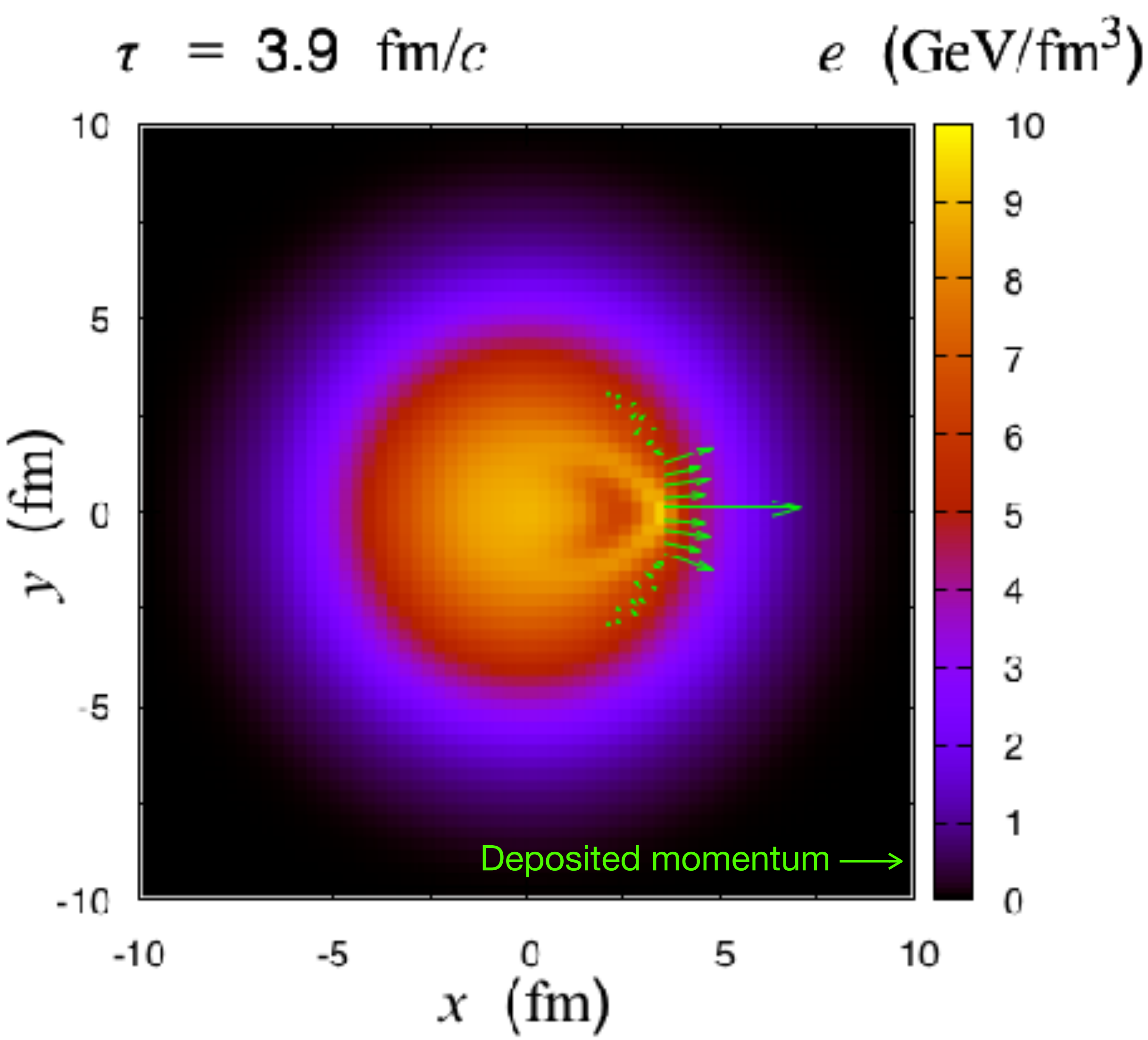


$$r = \sqrt{(\eta_p - \eta_{\rm jet})^2 + (\phi_p - \phi_{\rm jet})^2}$$

Medium energy density



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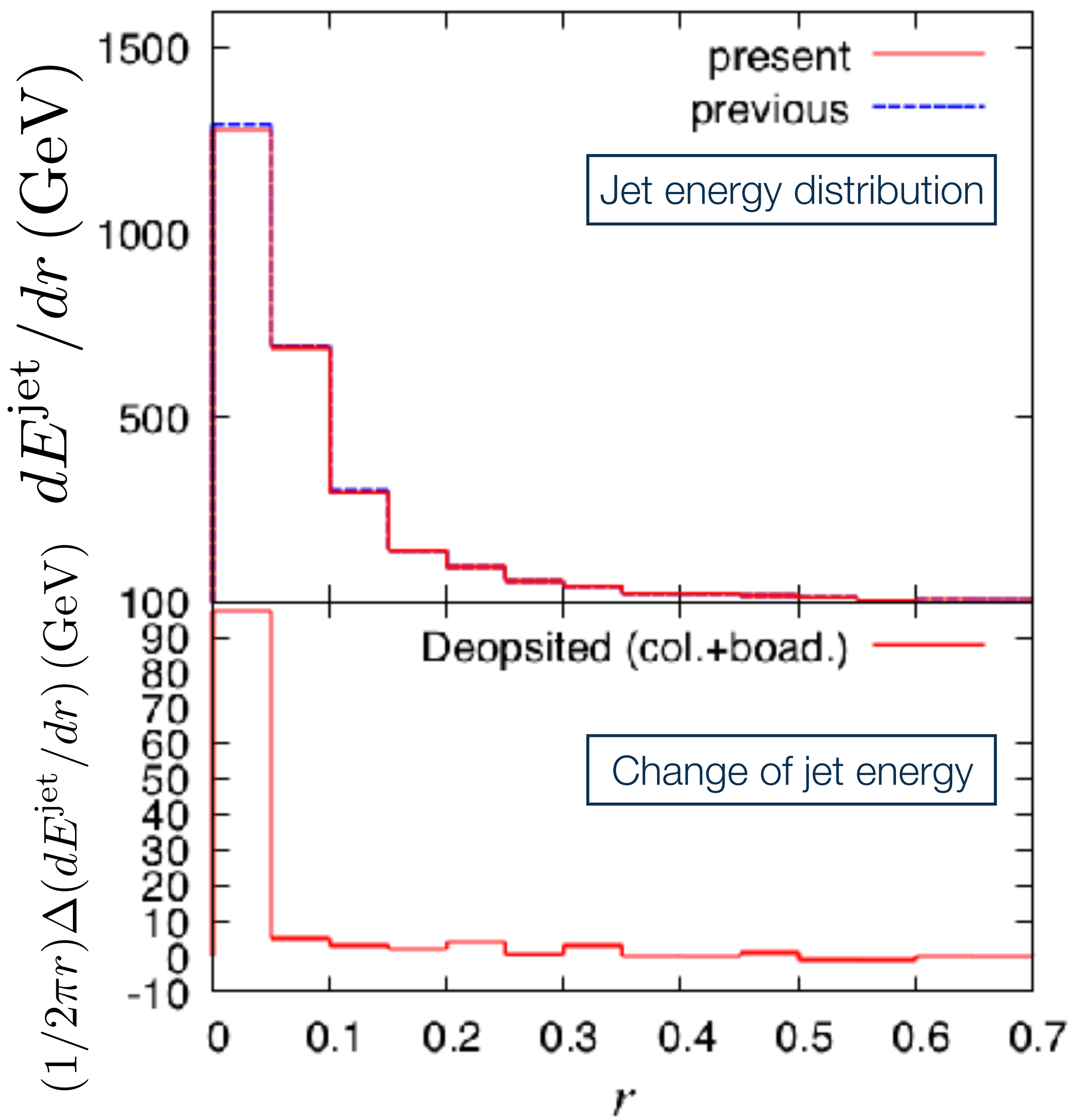

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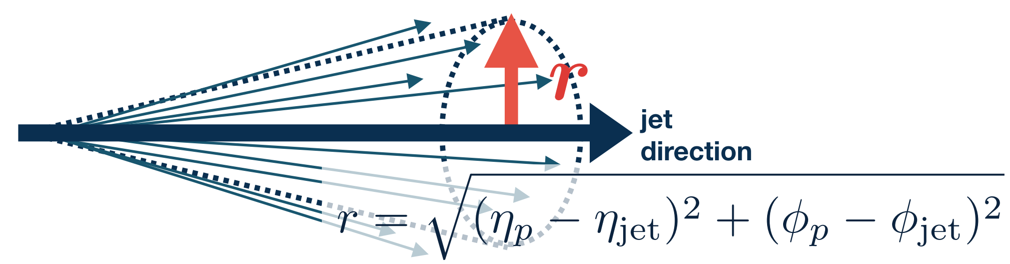

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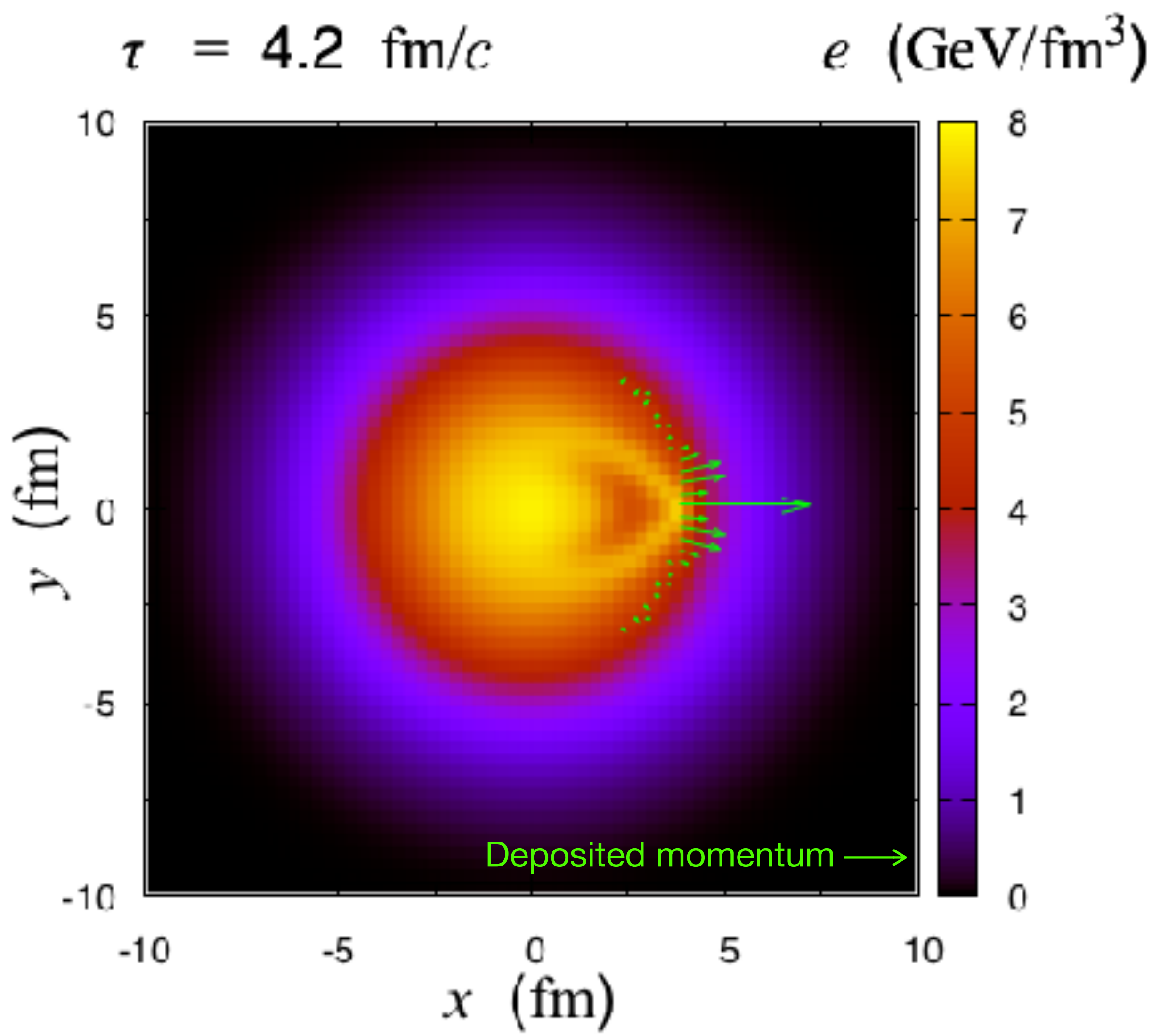

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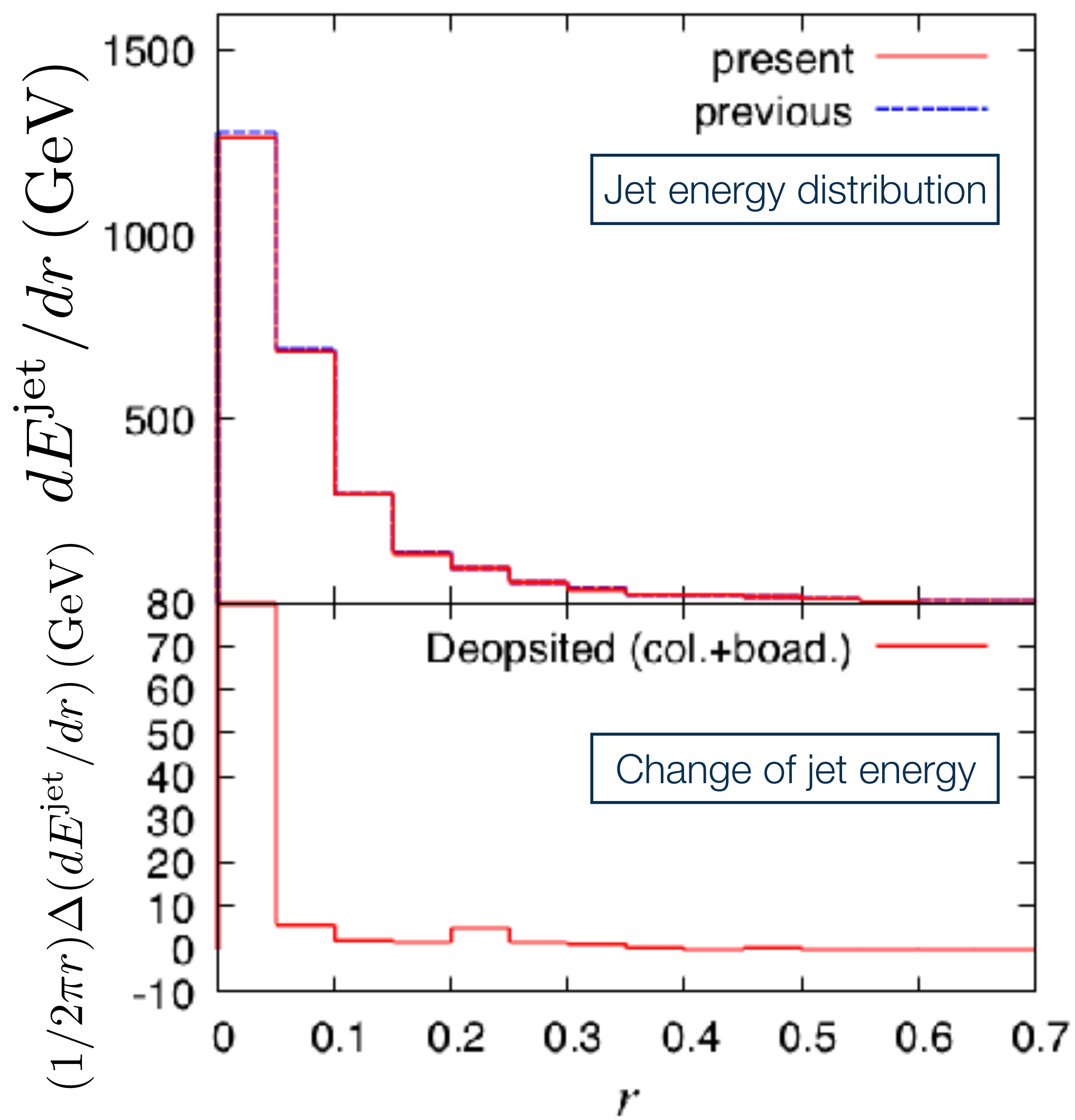

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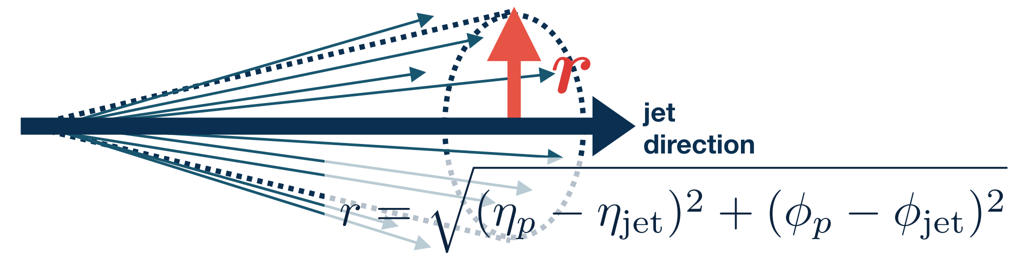

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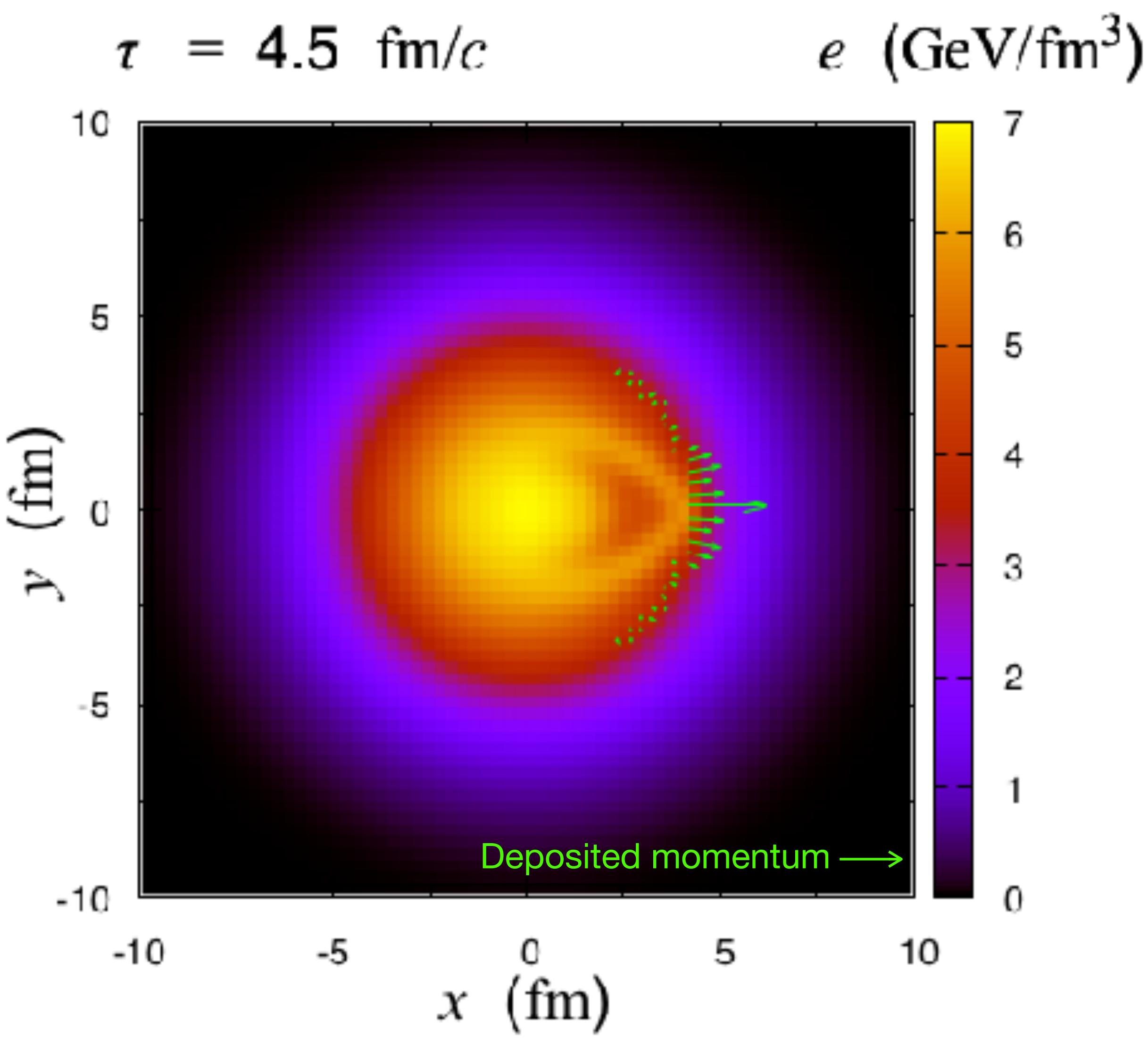
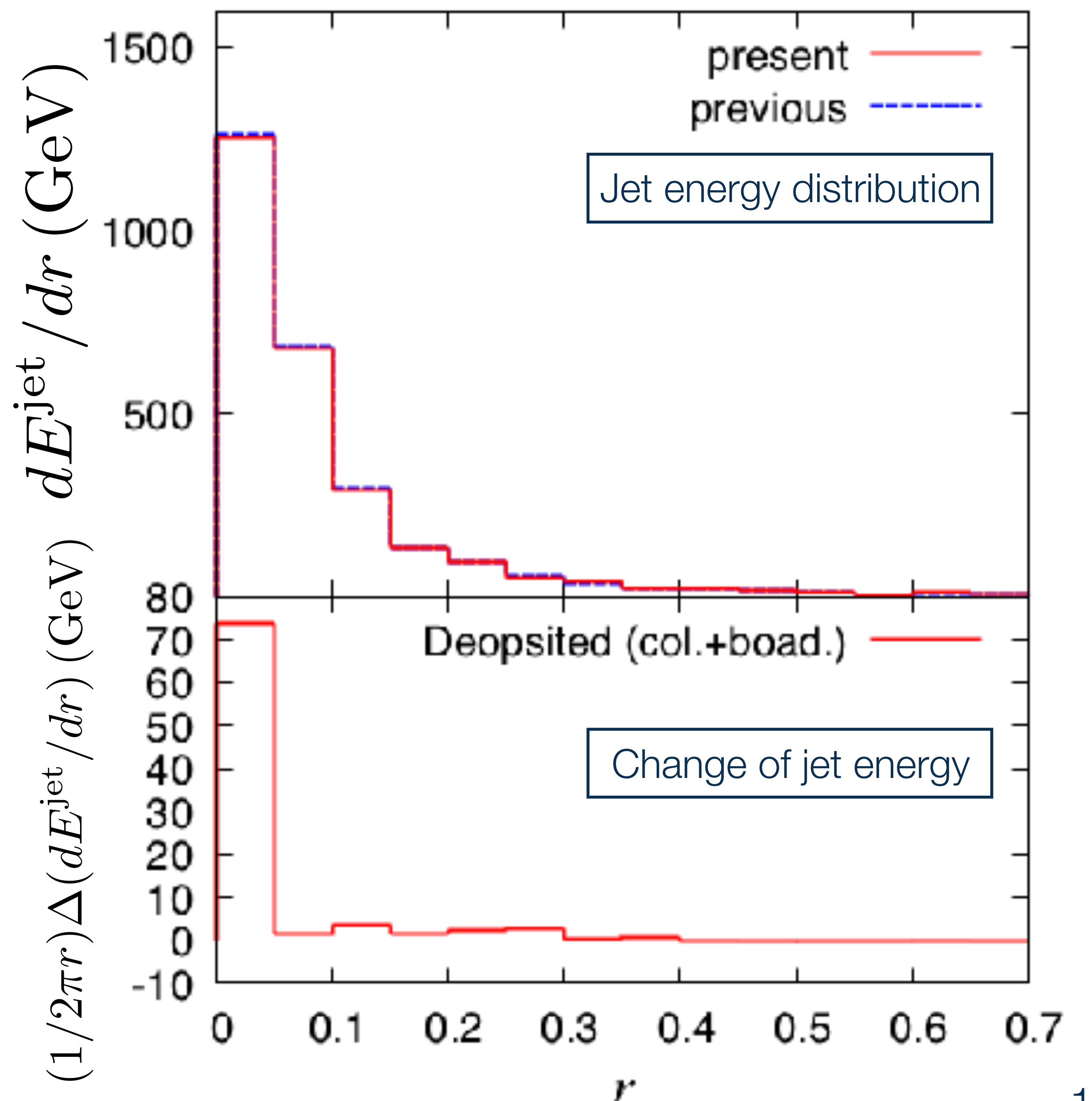


Inital jet energy: 150 GeV



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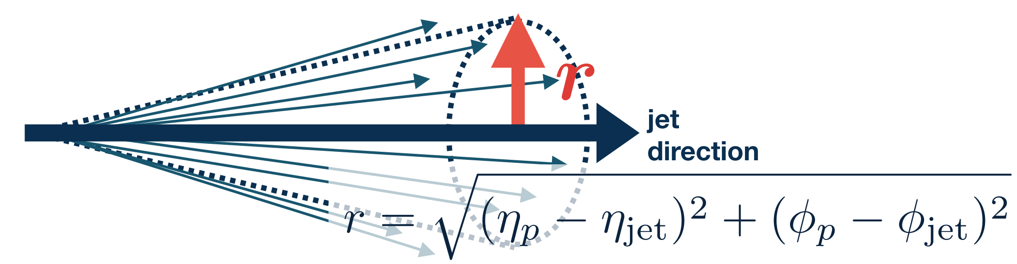

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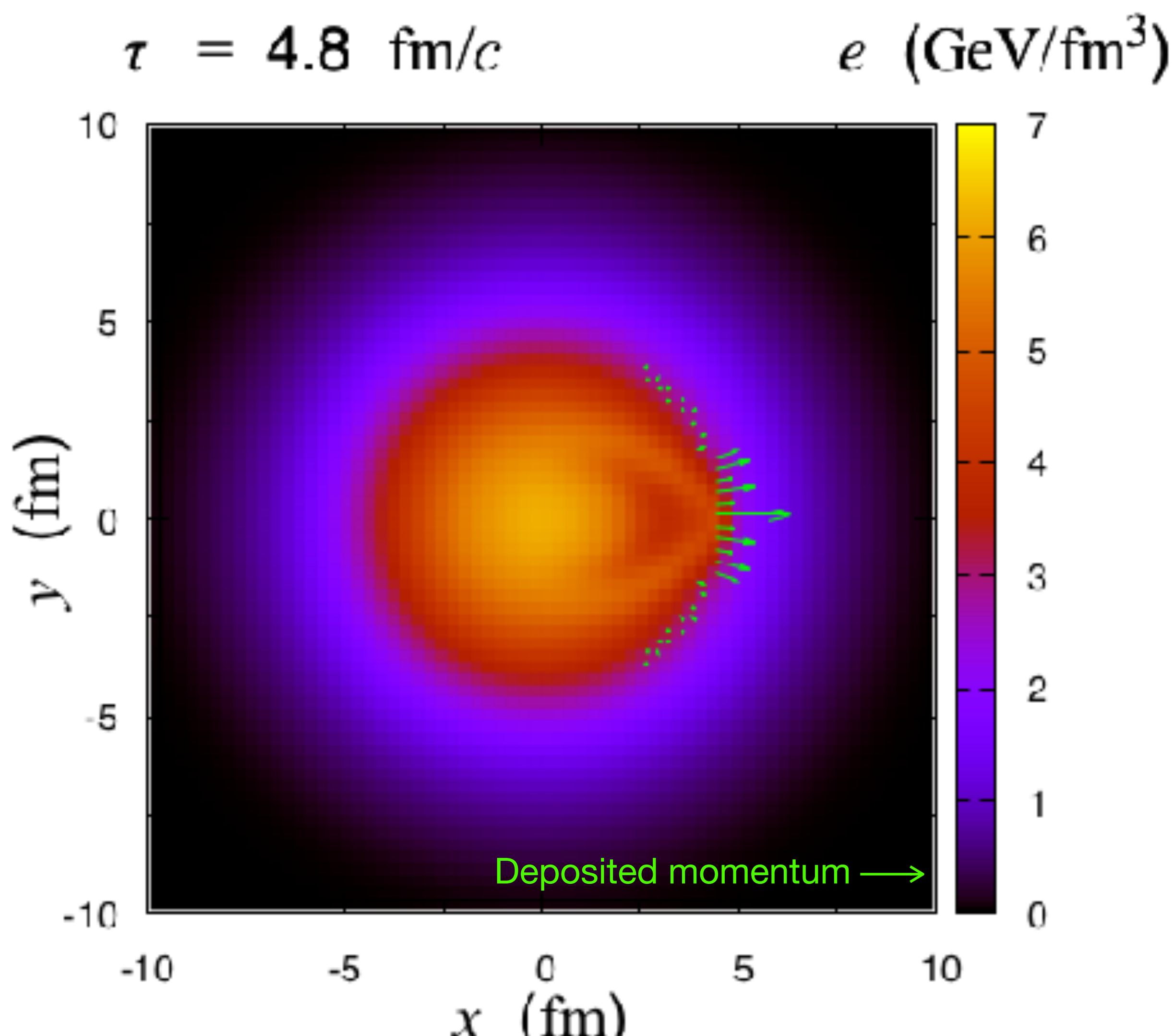

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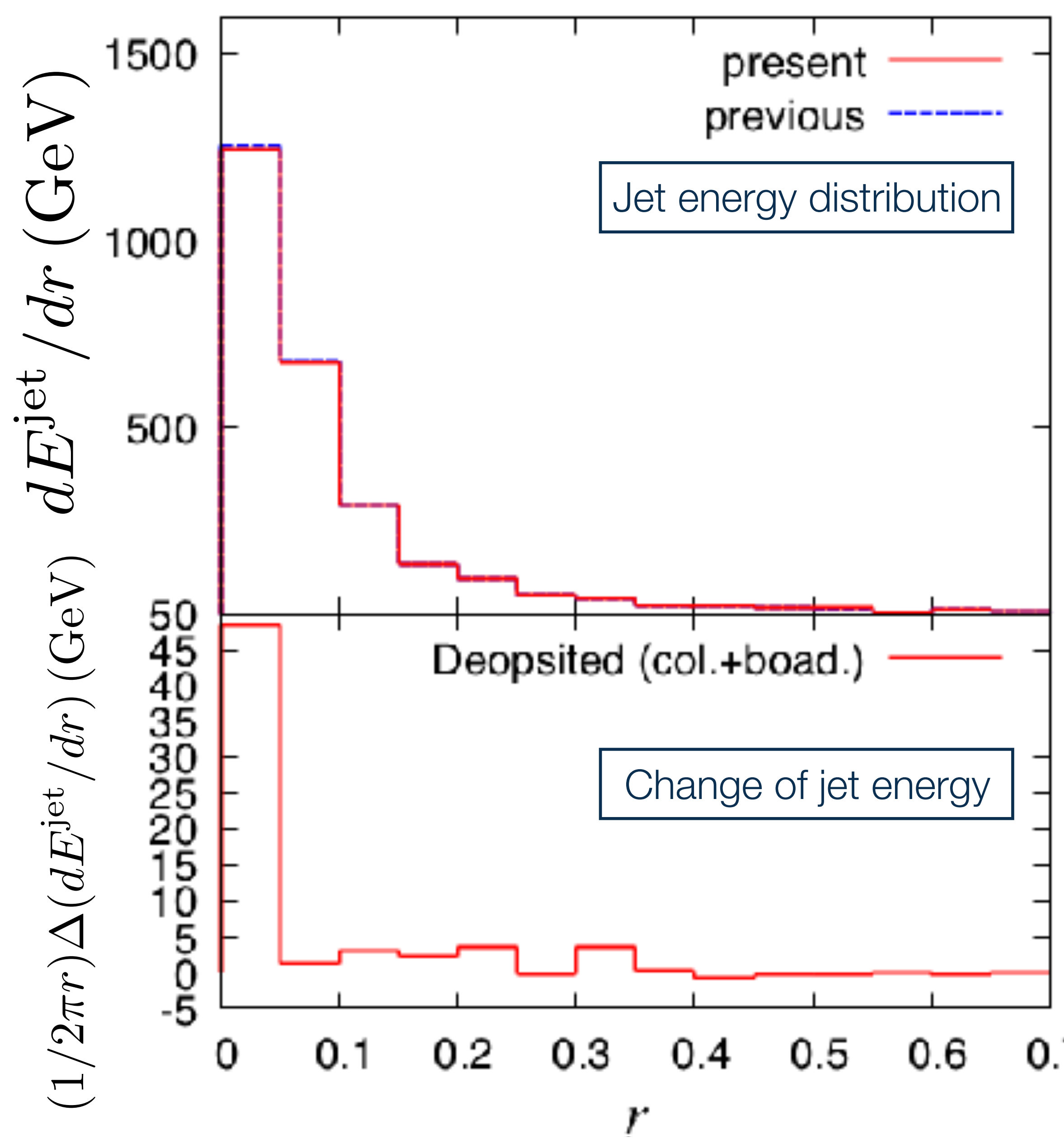

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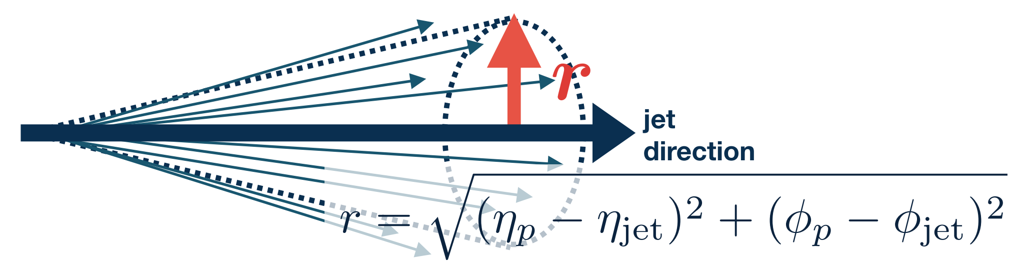

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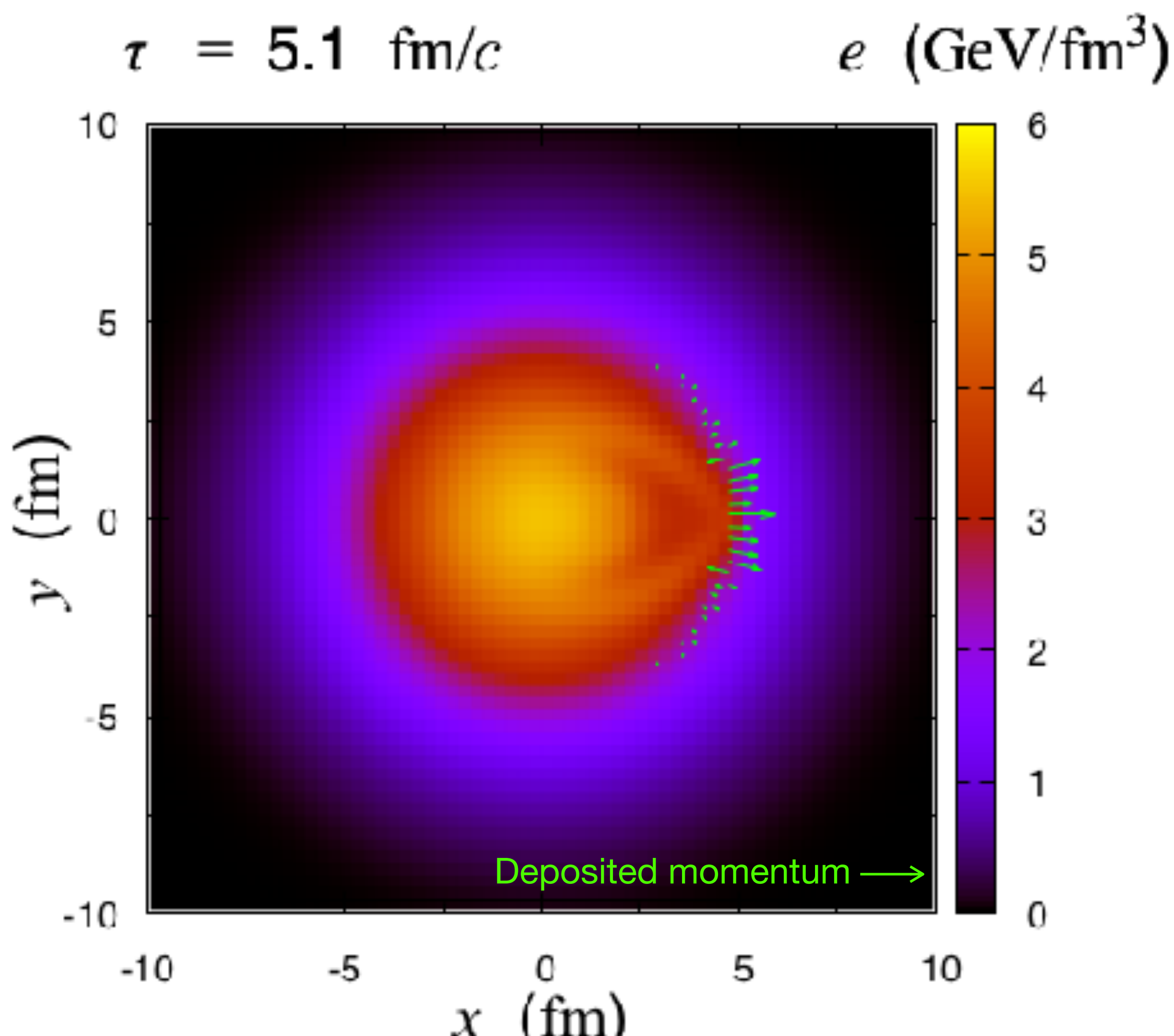

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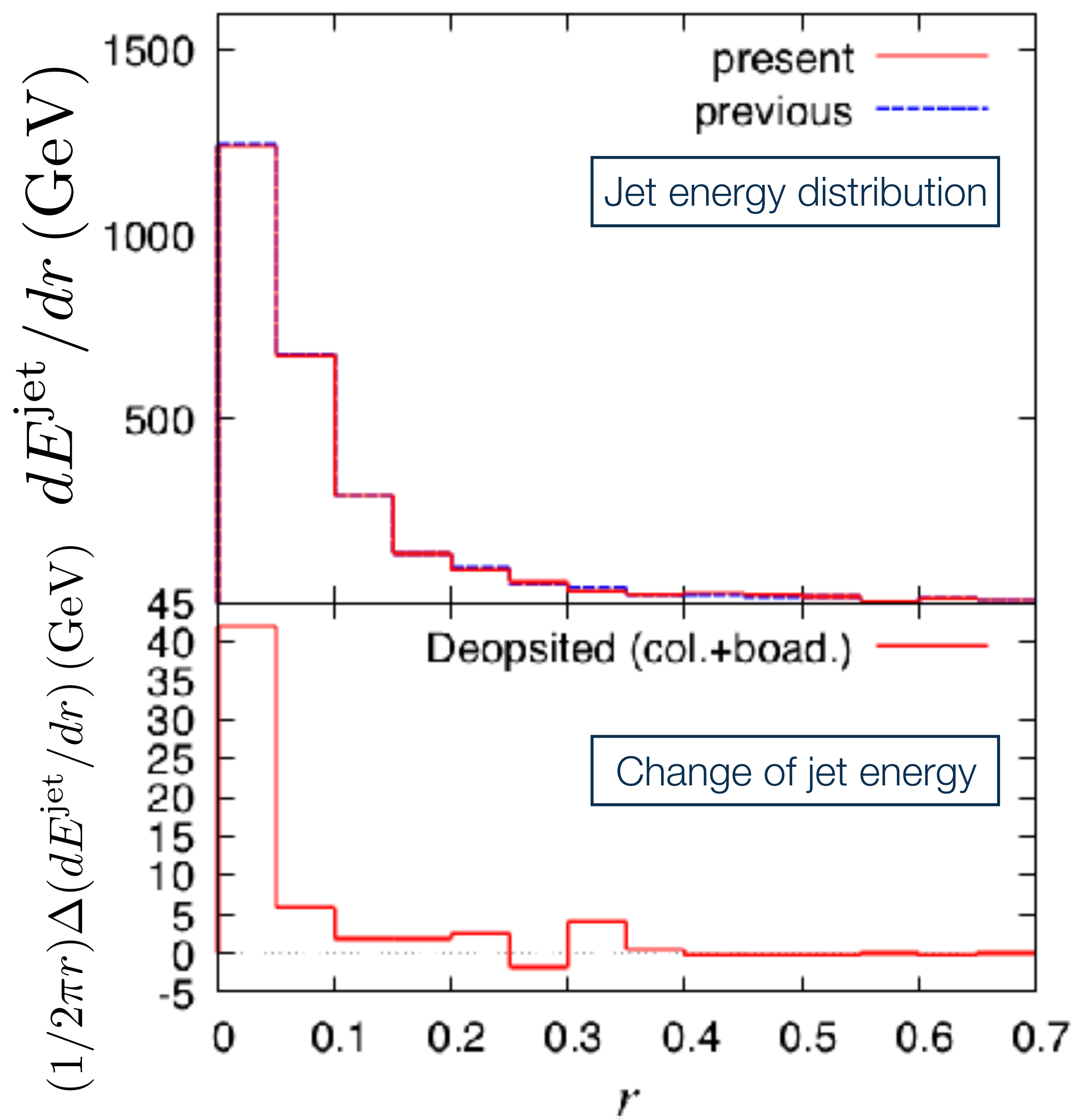

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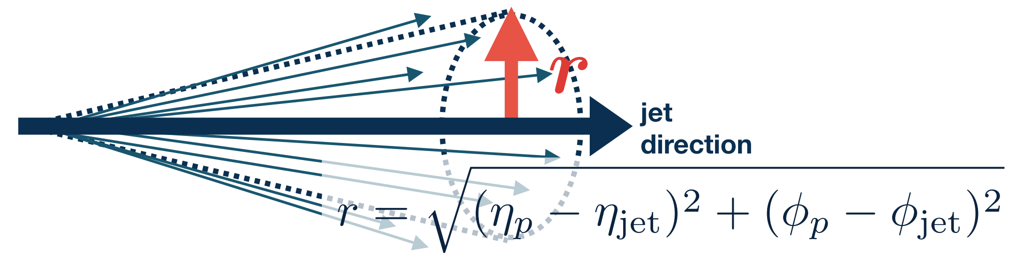

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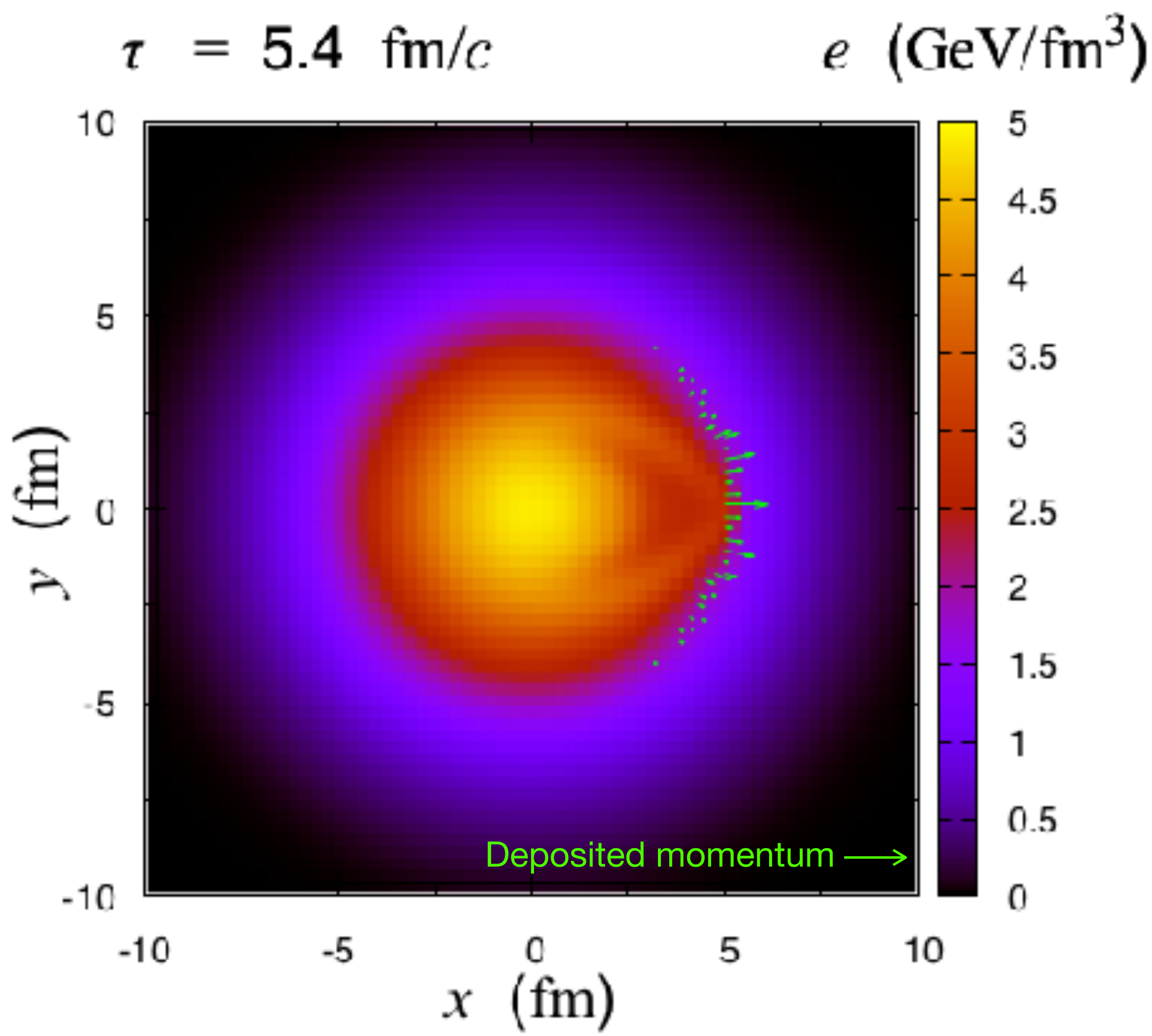

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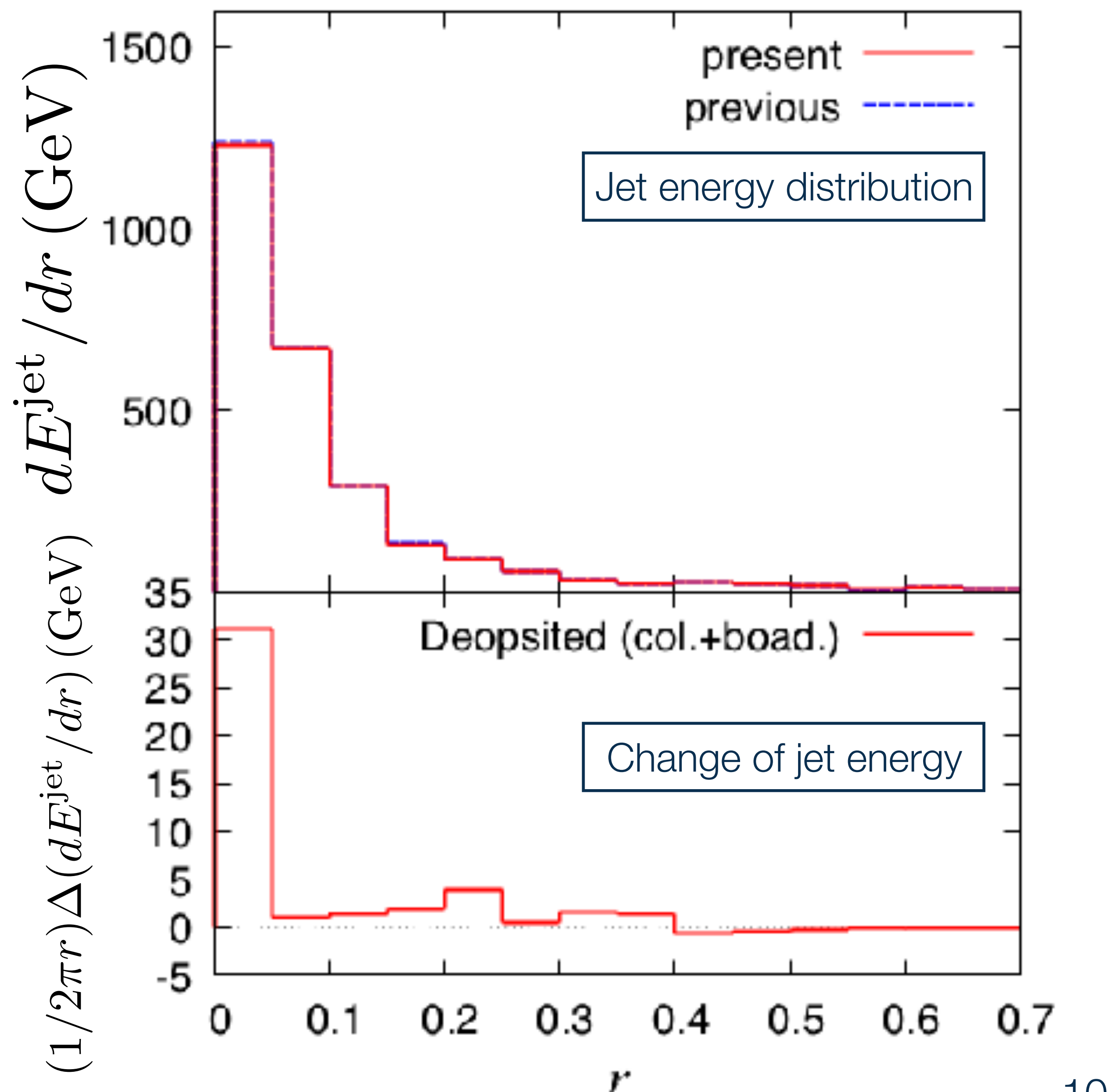

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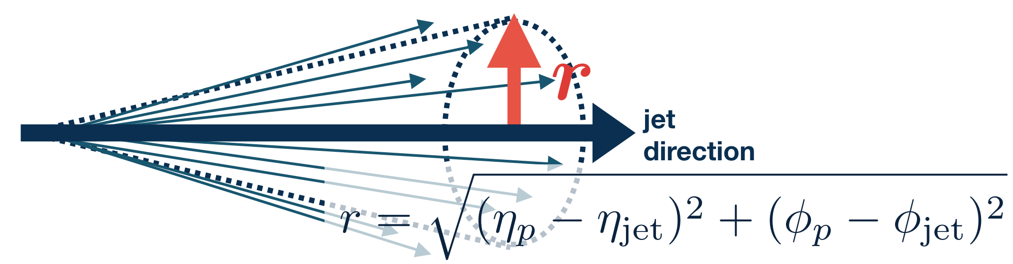

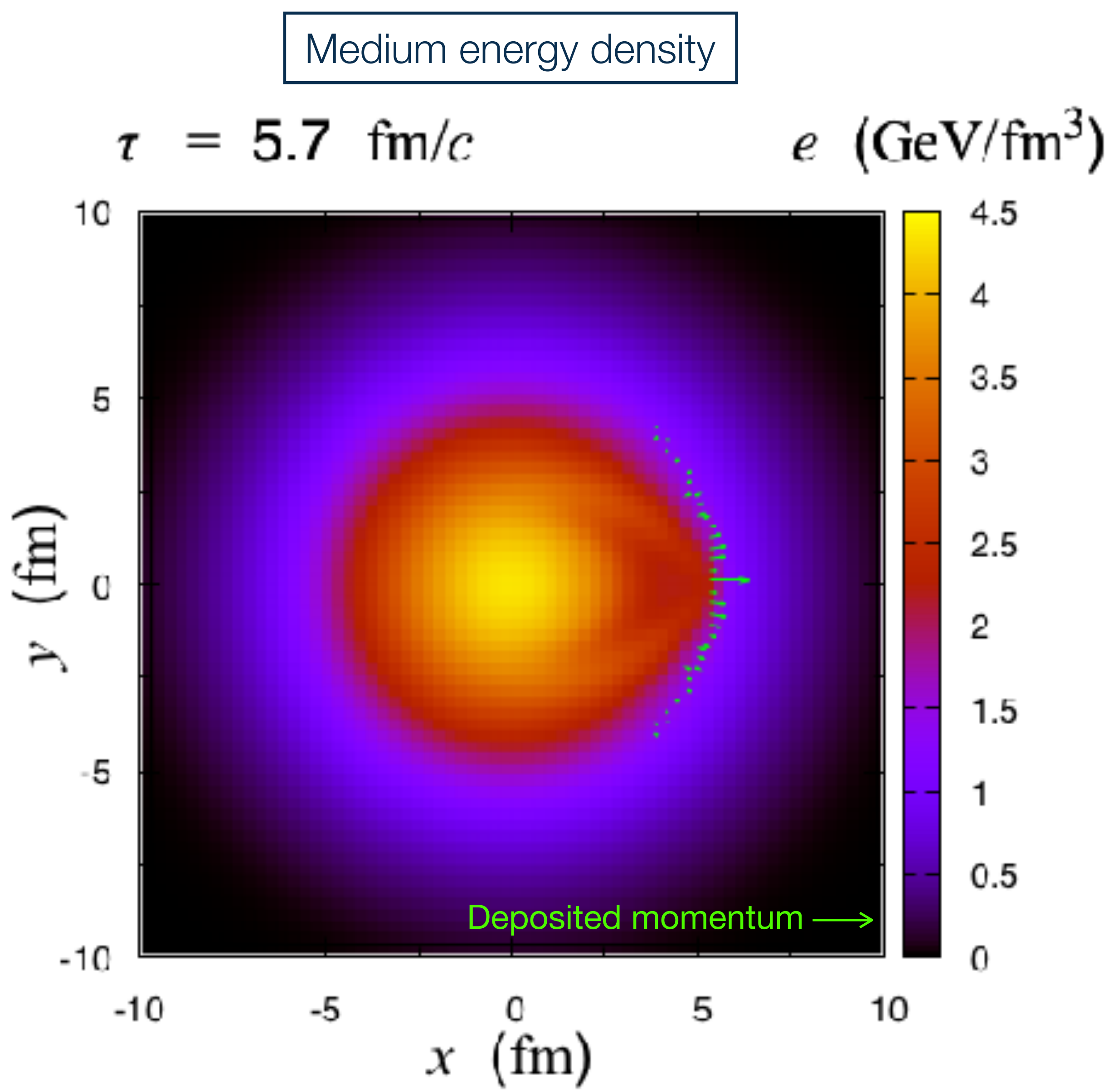

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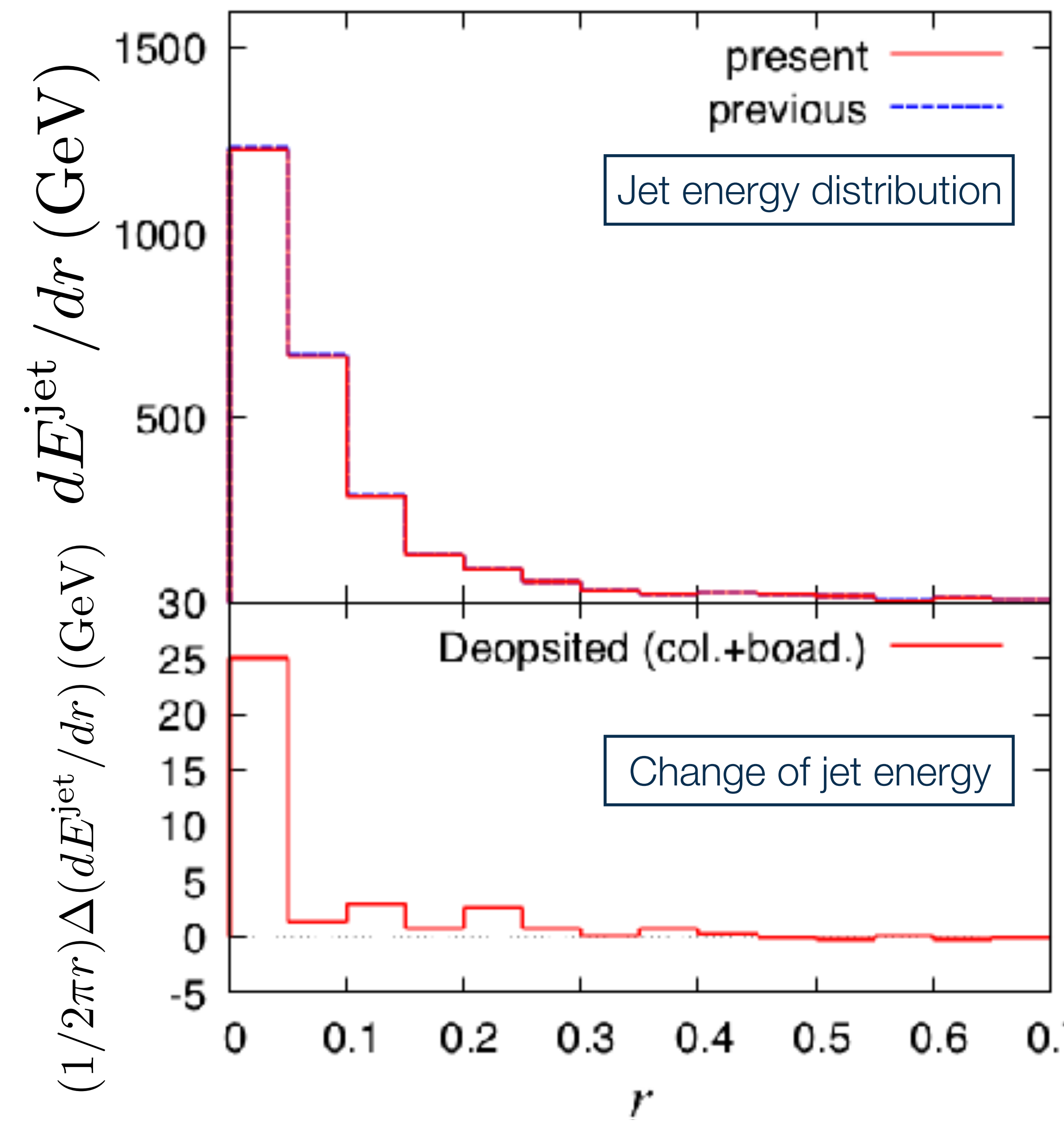

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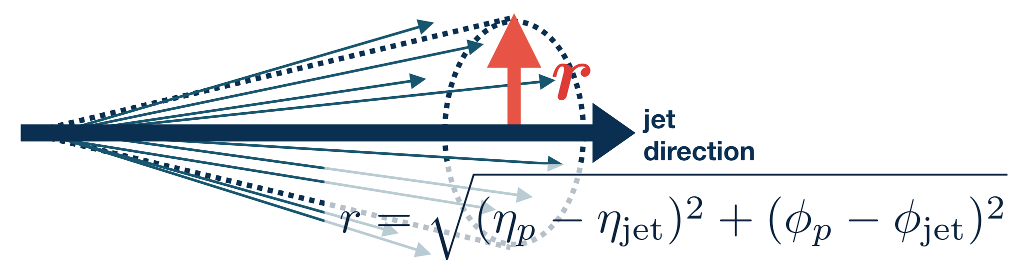

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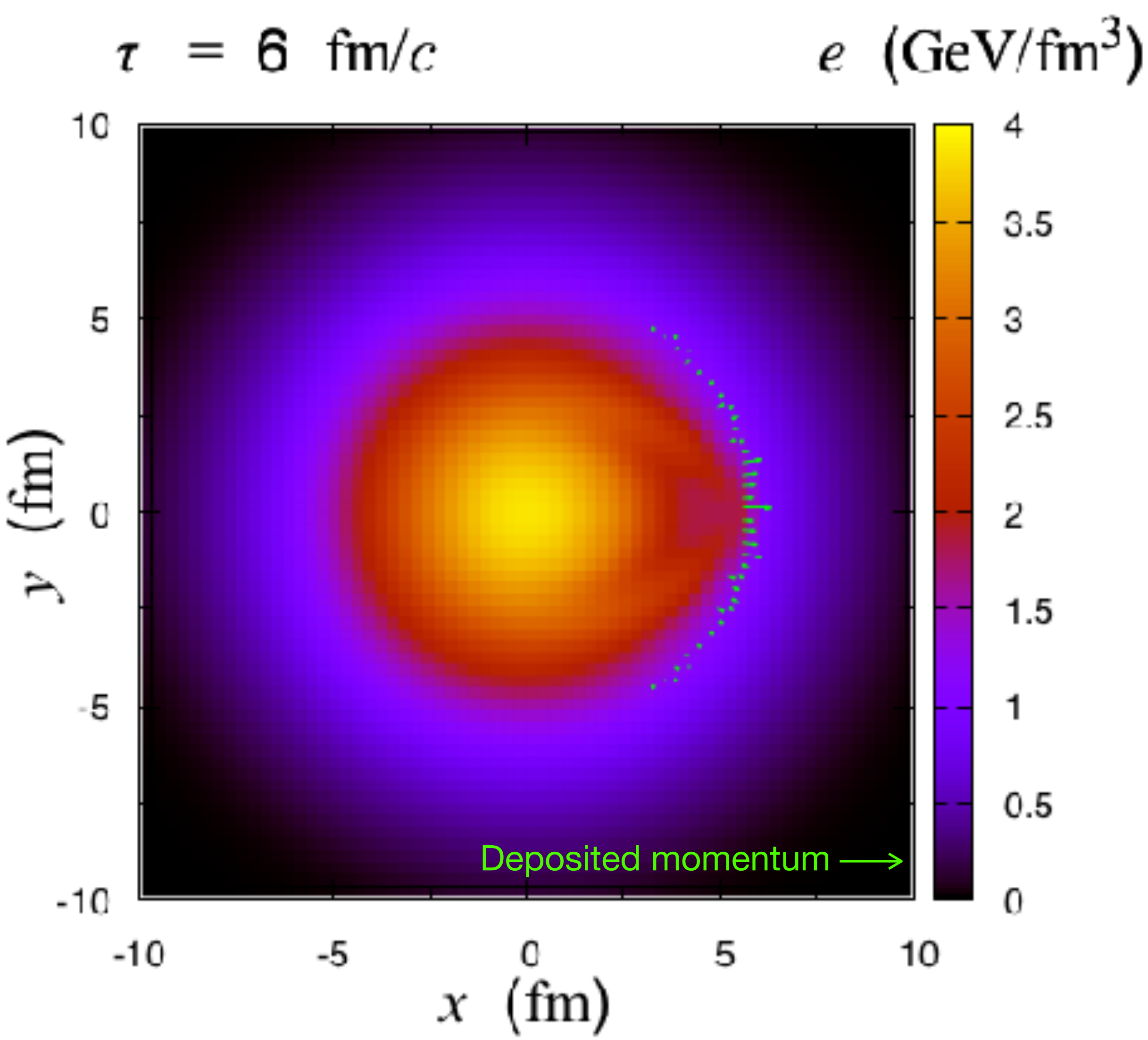

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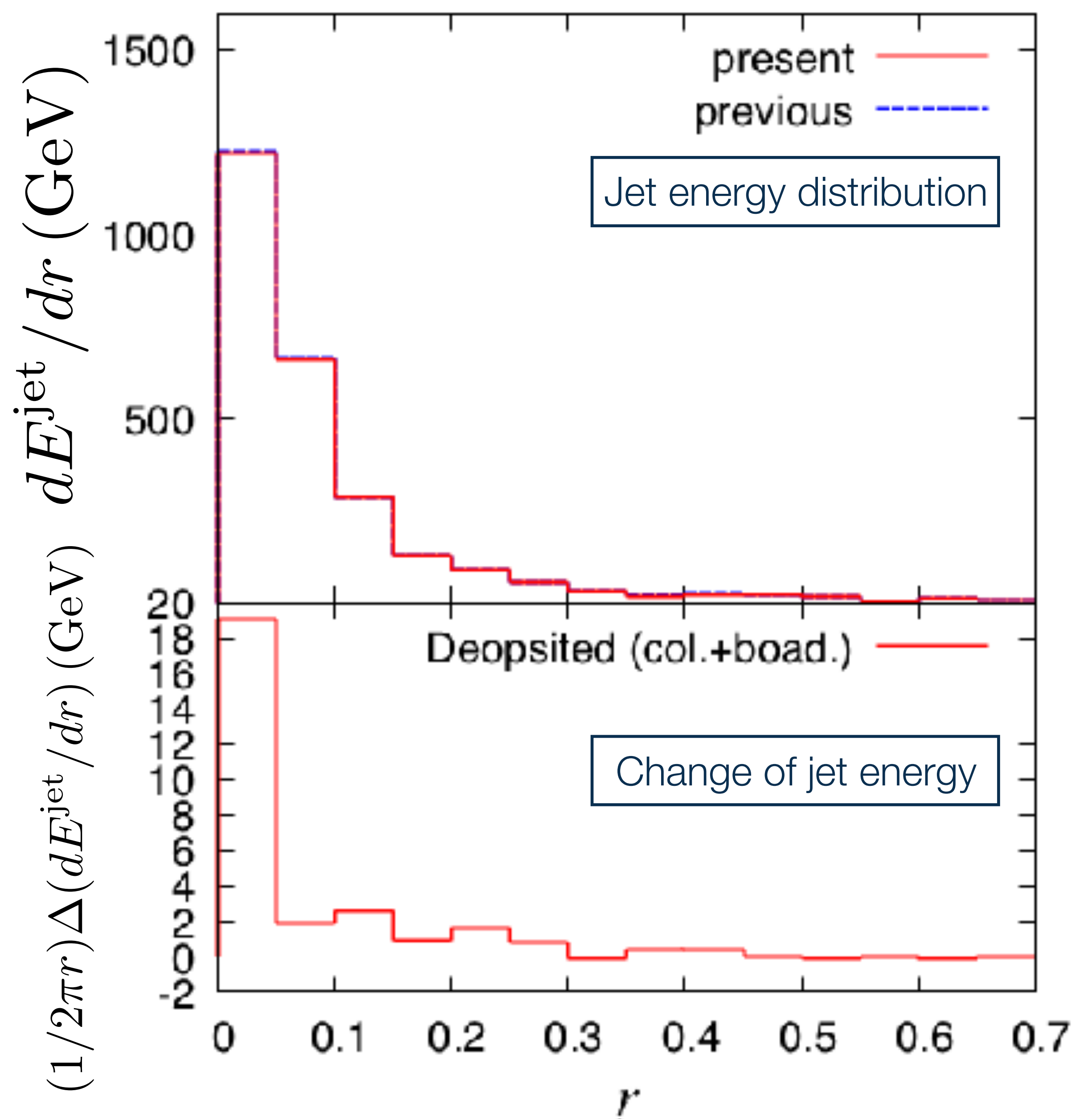

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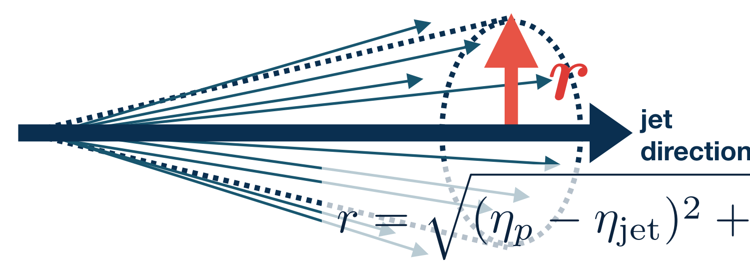
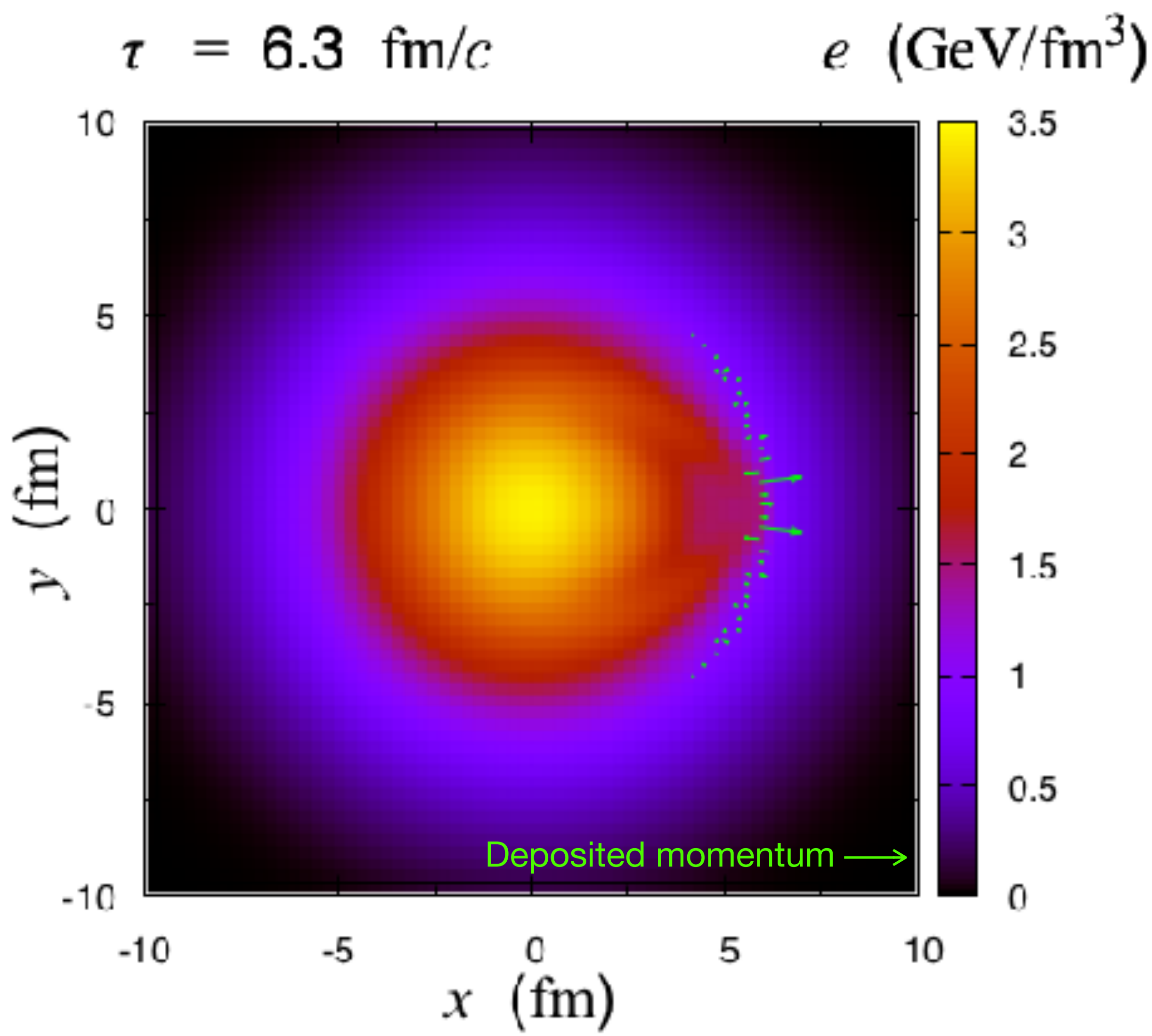


$$r = \sqrt{(\eta_p - \eta_{\mathrm{jet}})^2 + (\phi_p - \phi_{\mathrm{jet}})^2}$$

Medium energy density



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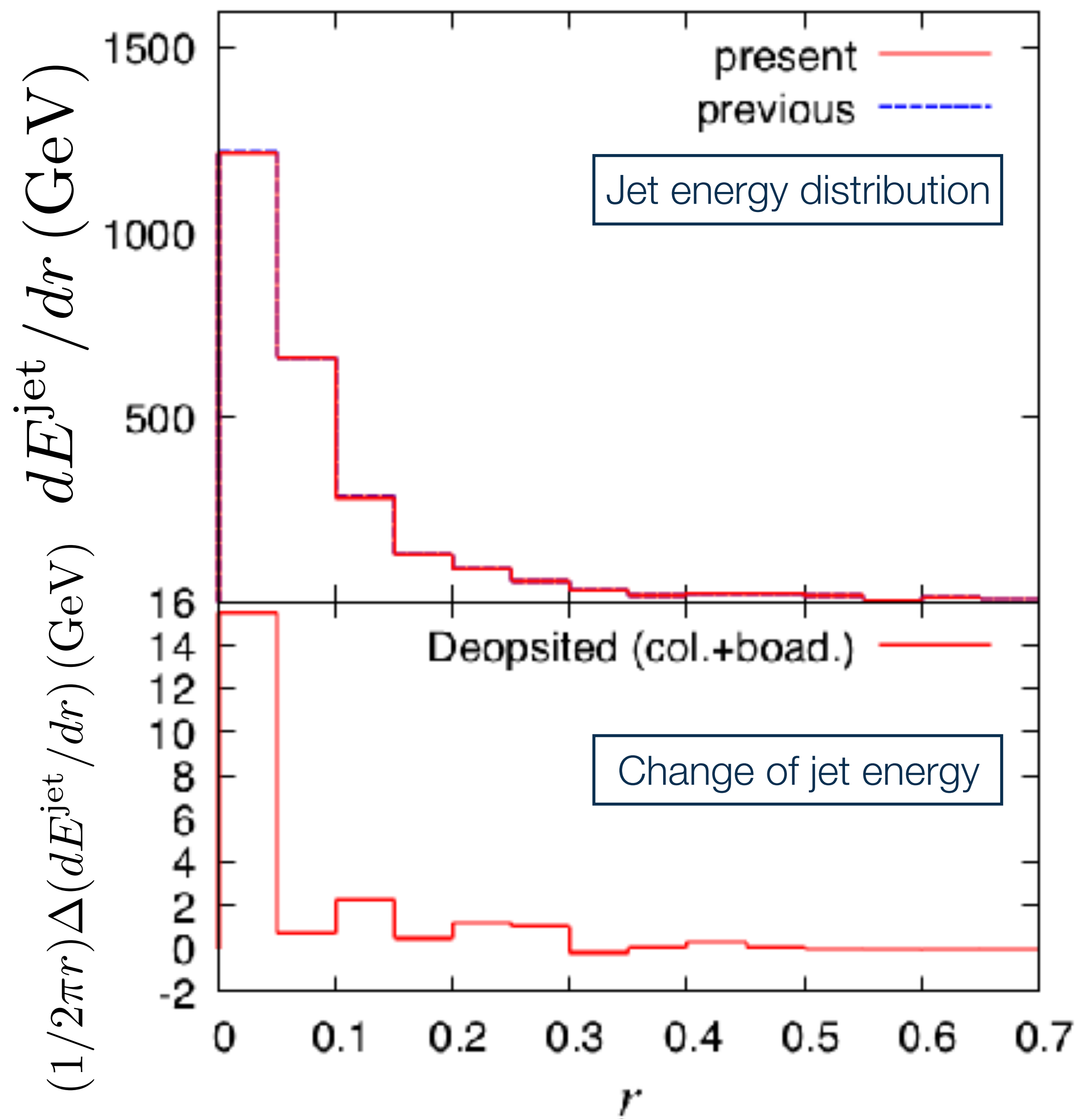

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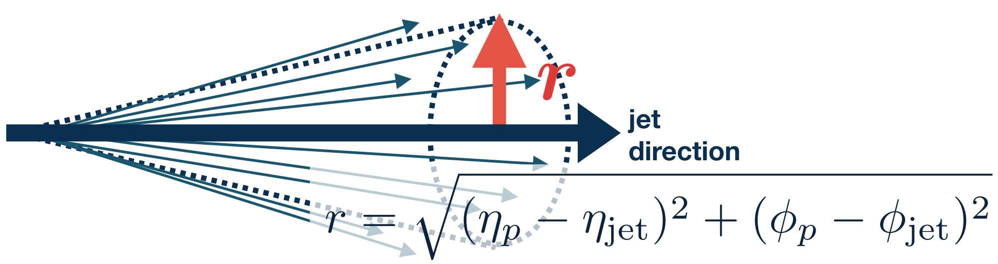

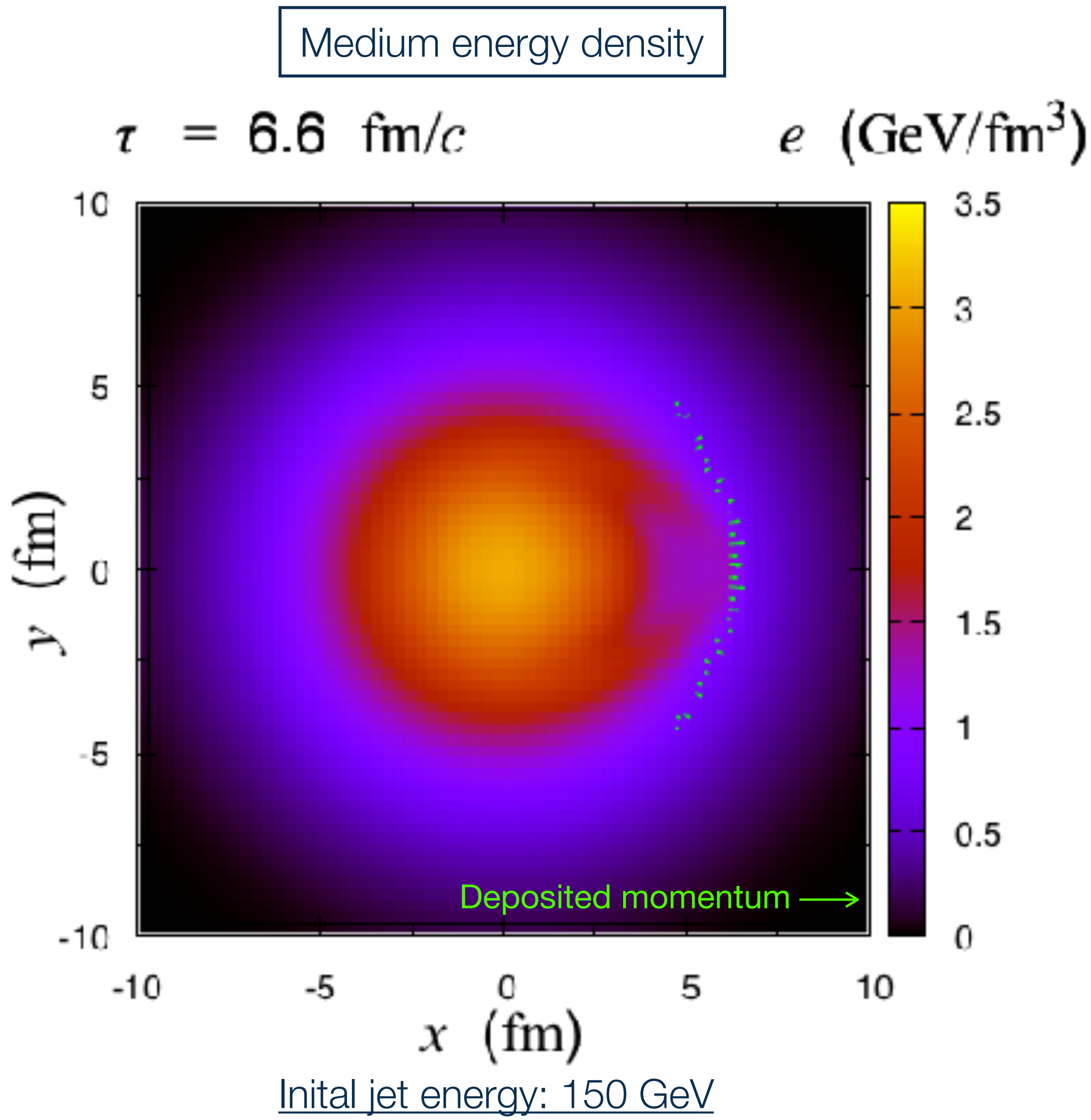

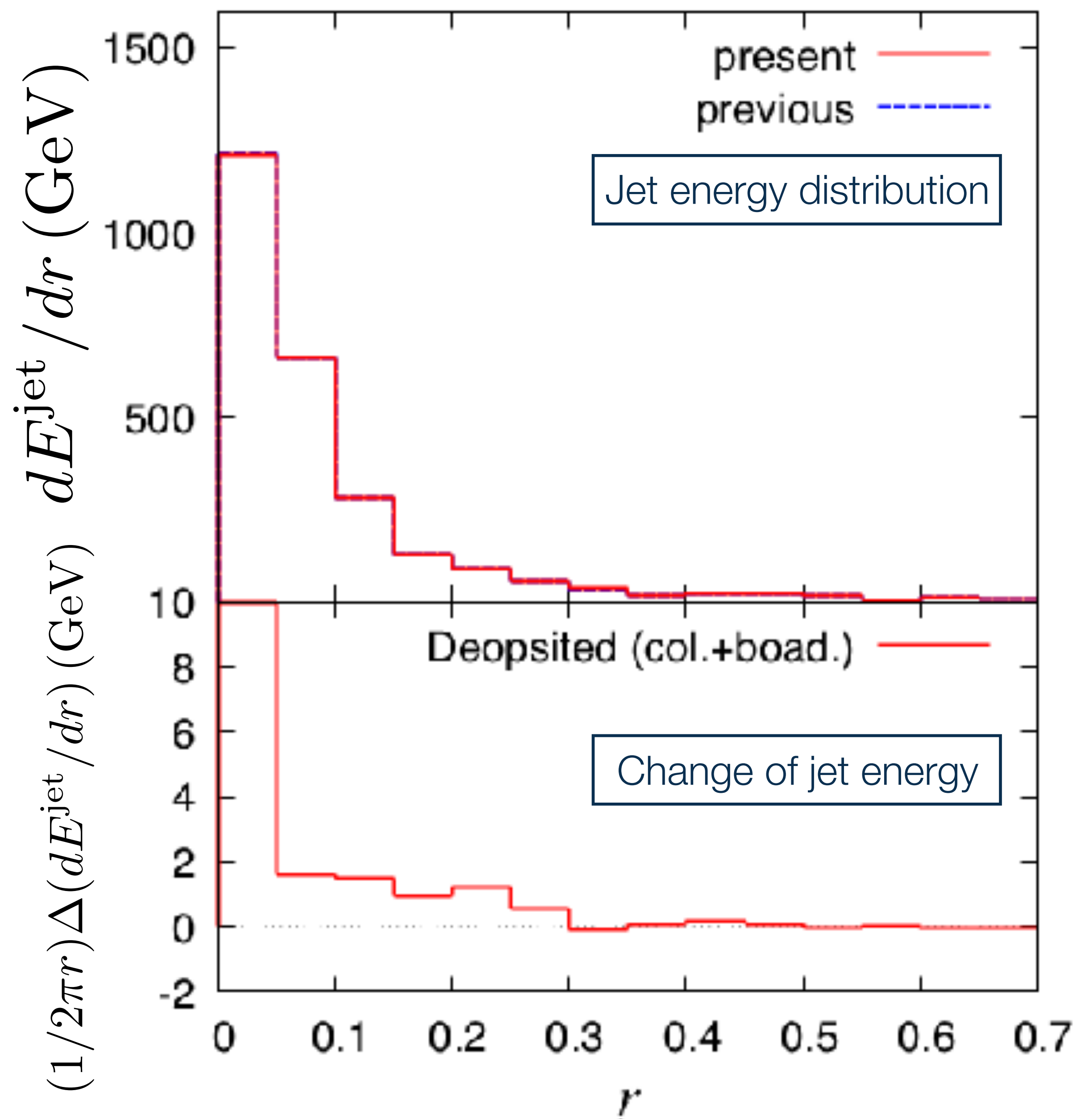

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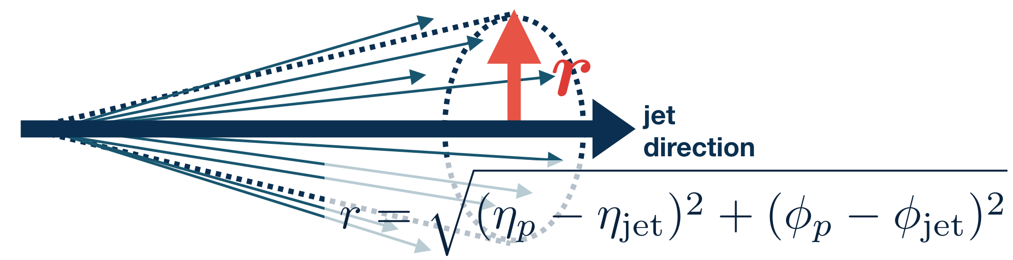

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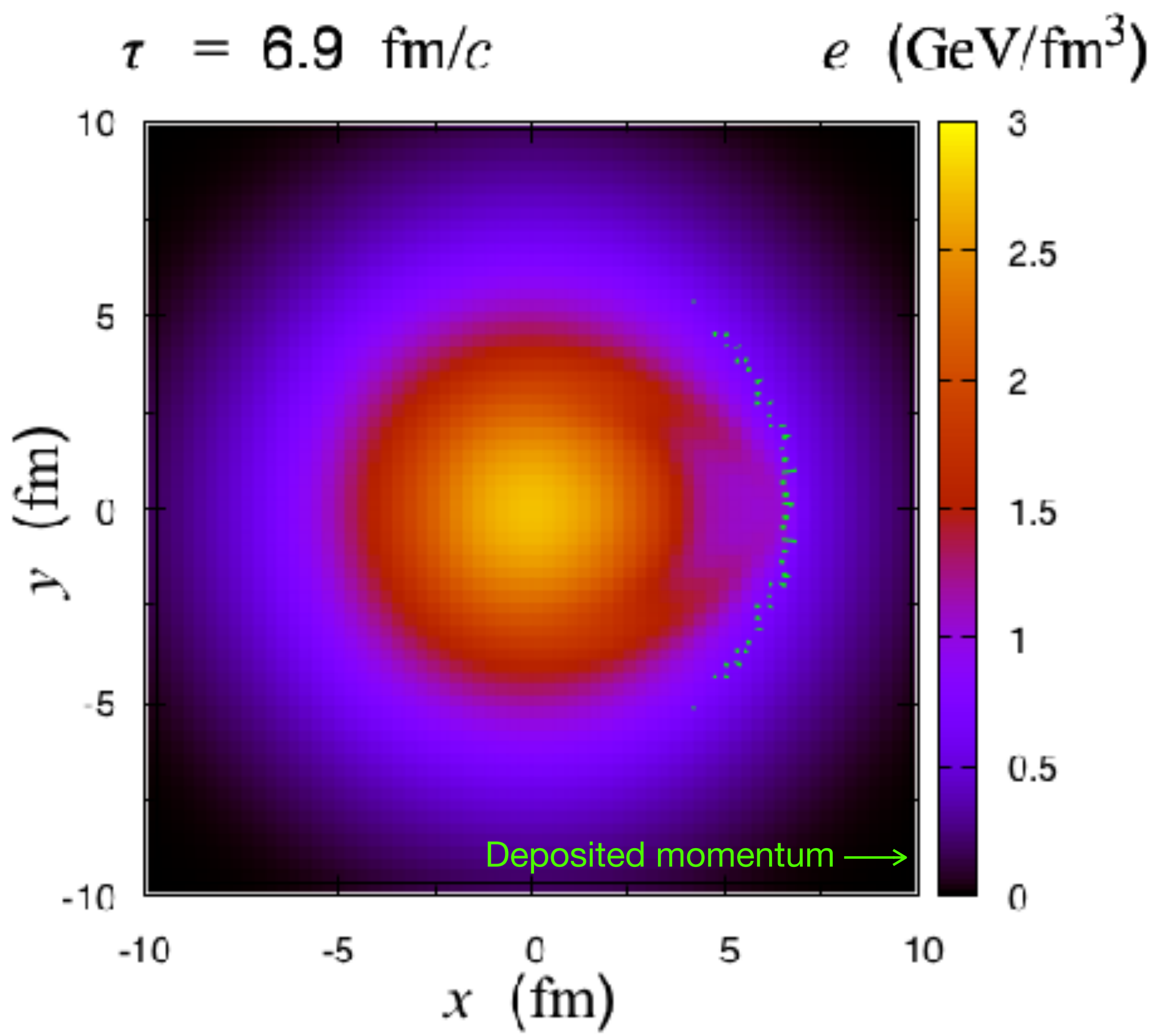

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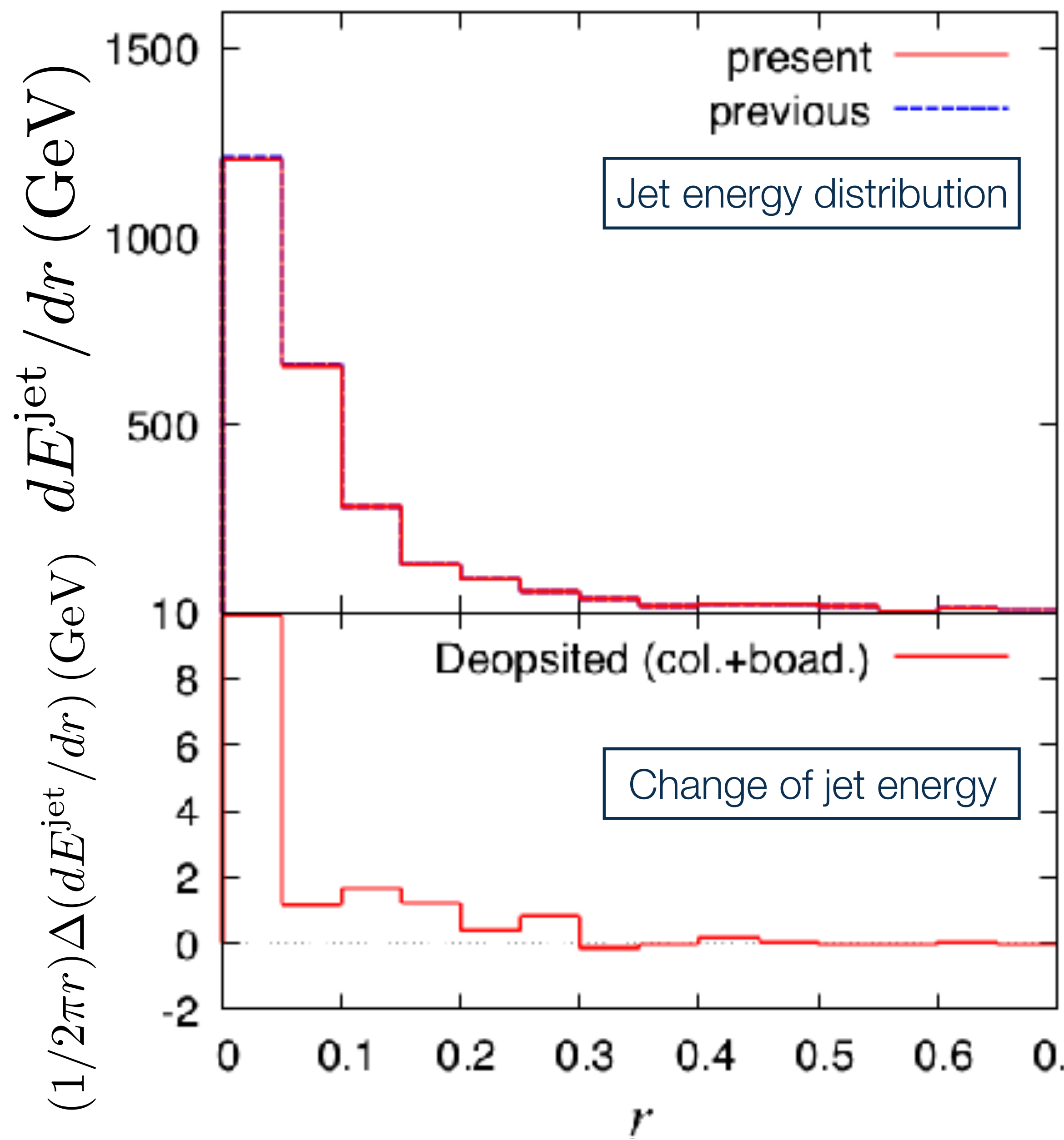

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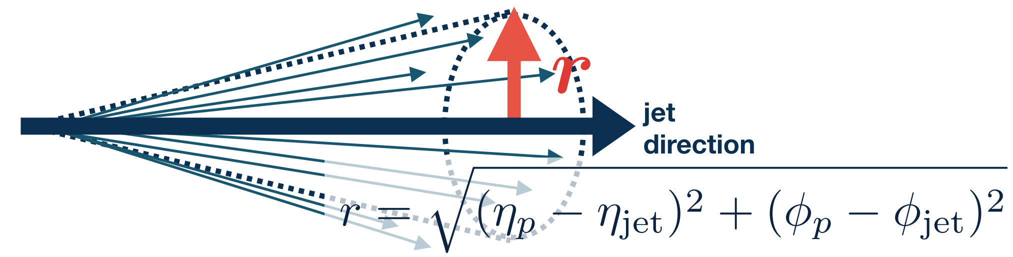

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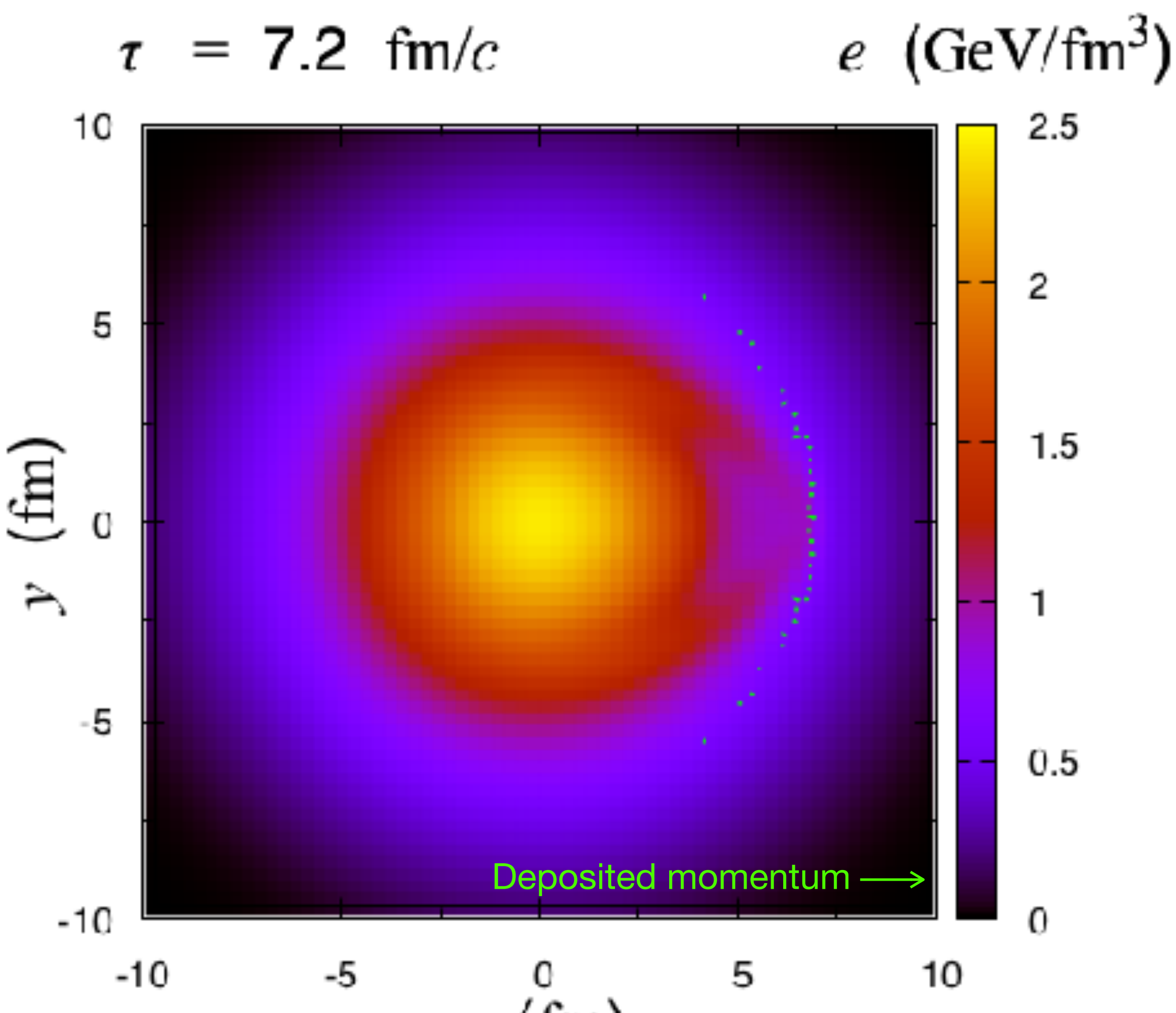

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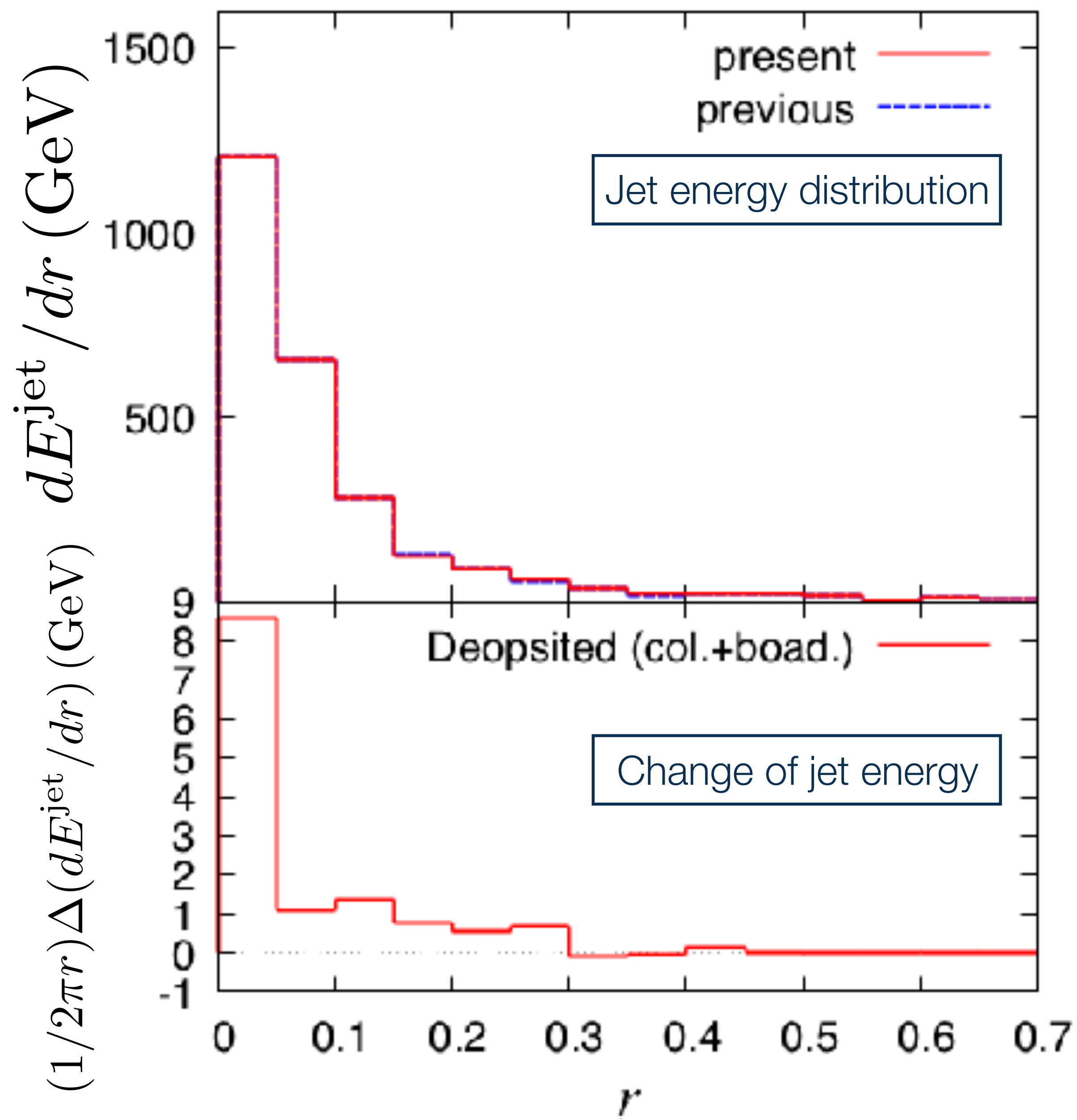
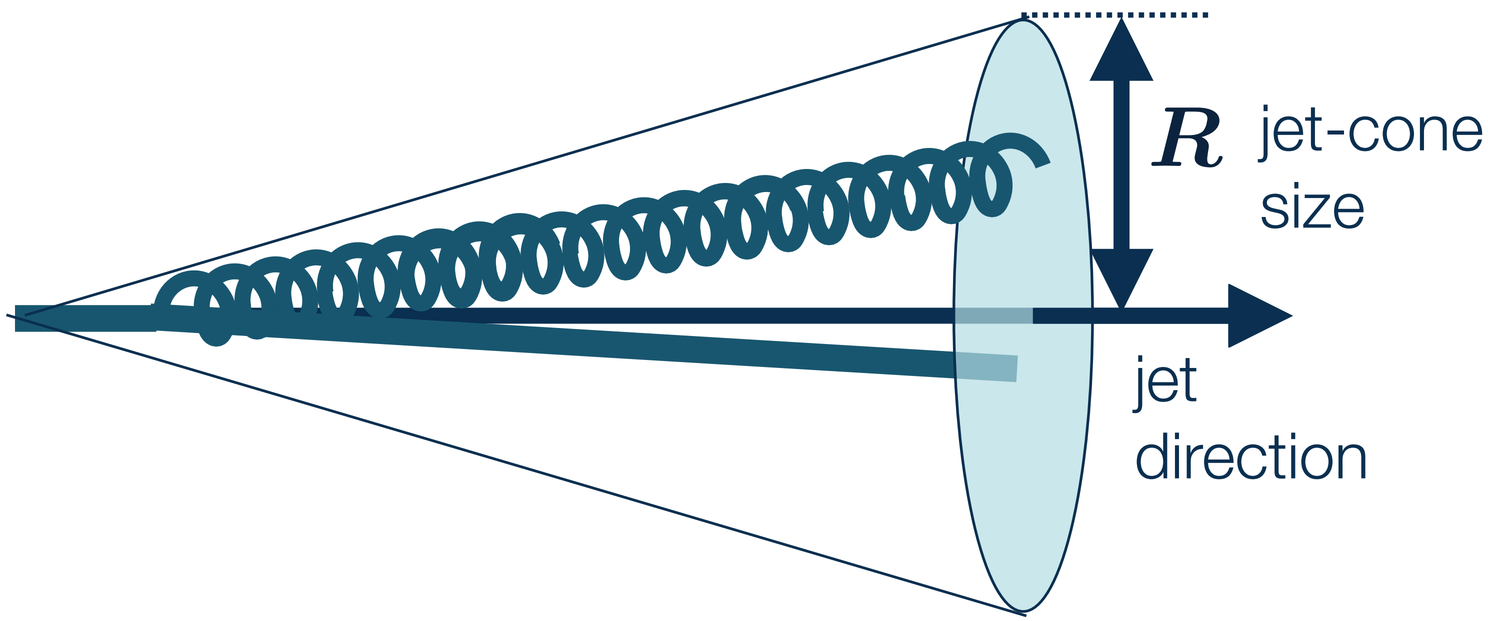


Medium response contribution to full jet

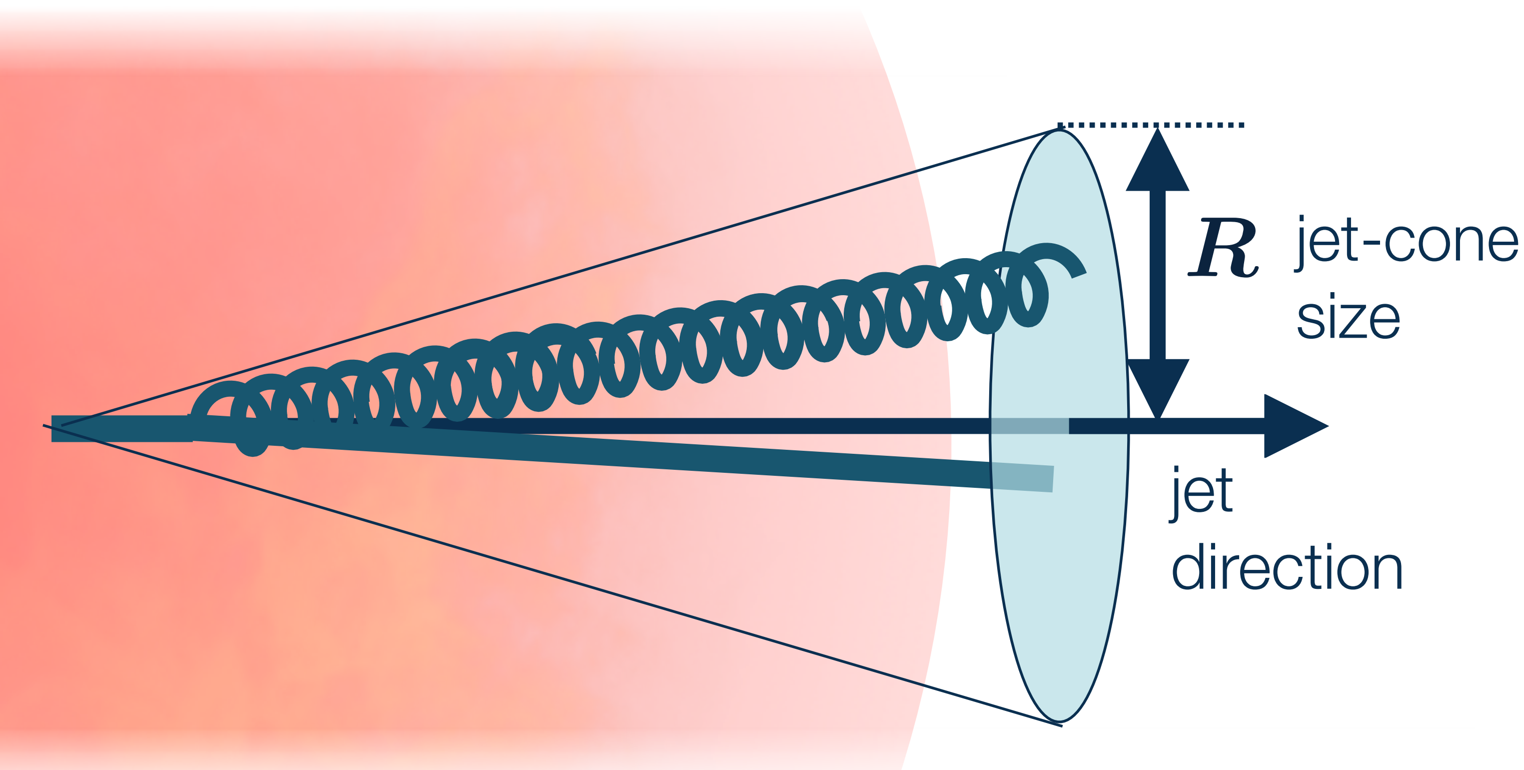


$$r = \sqrt{(\eta_p - \eta_{\rm jet})^2 + (\phi_p - \phi_{\rm jet})^2} < R$$

Counted as part of jet

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

Medium response contribution to full jet



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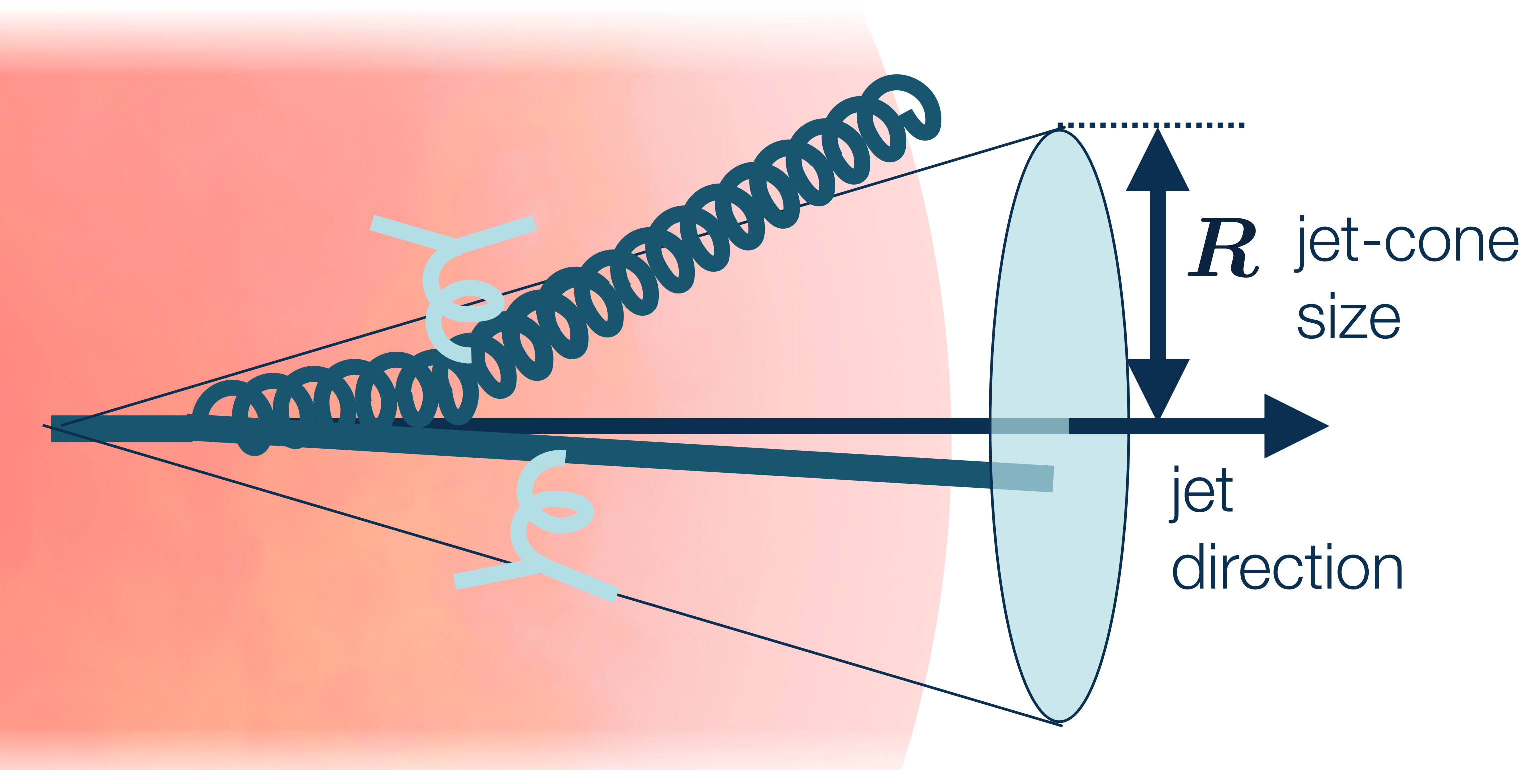

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- **Full jet energy loss and suppression (Jet Quenching)**
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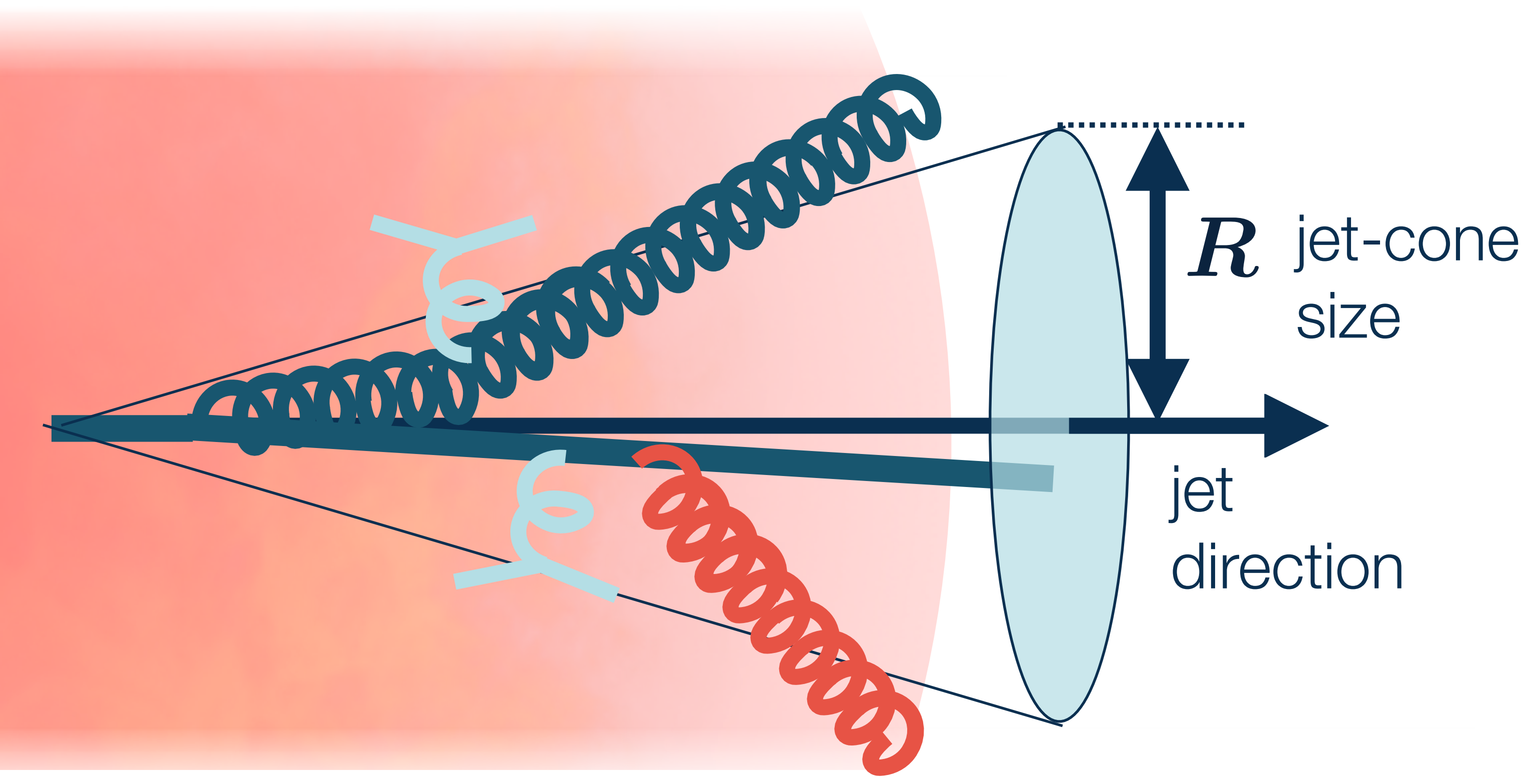
  2) Kick outside the jet cone (by momentum broadening)

Medium response contribution to full jet



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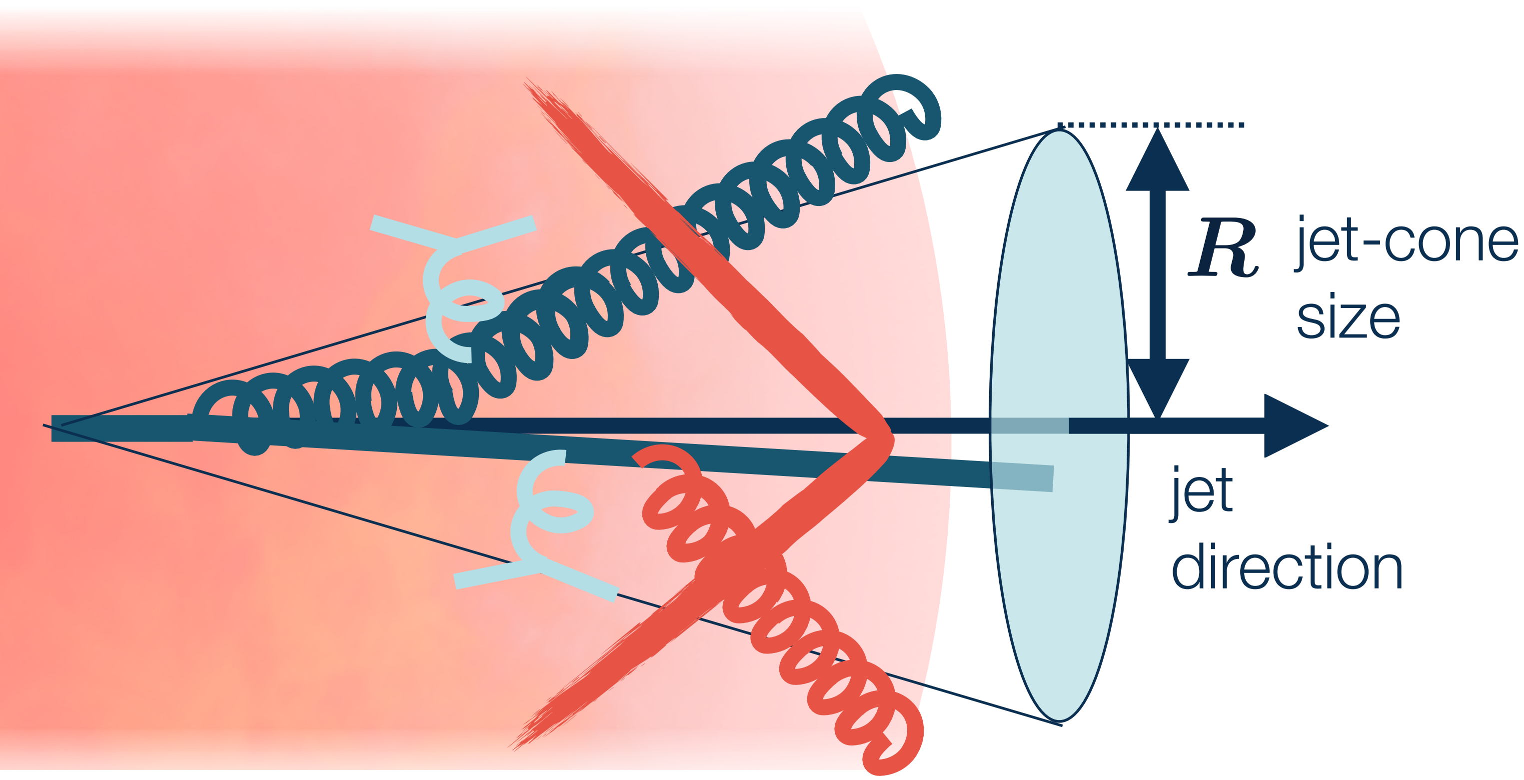

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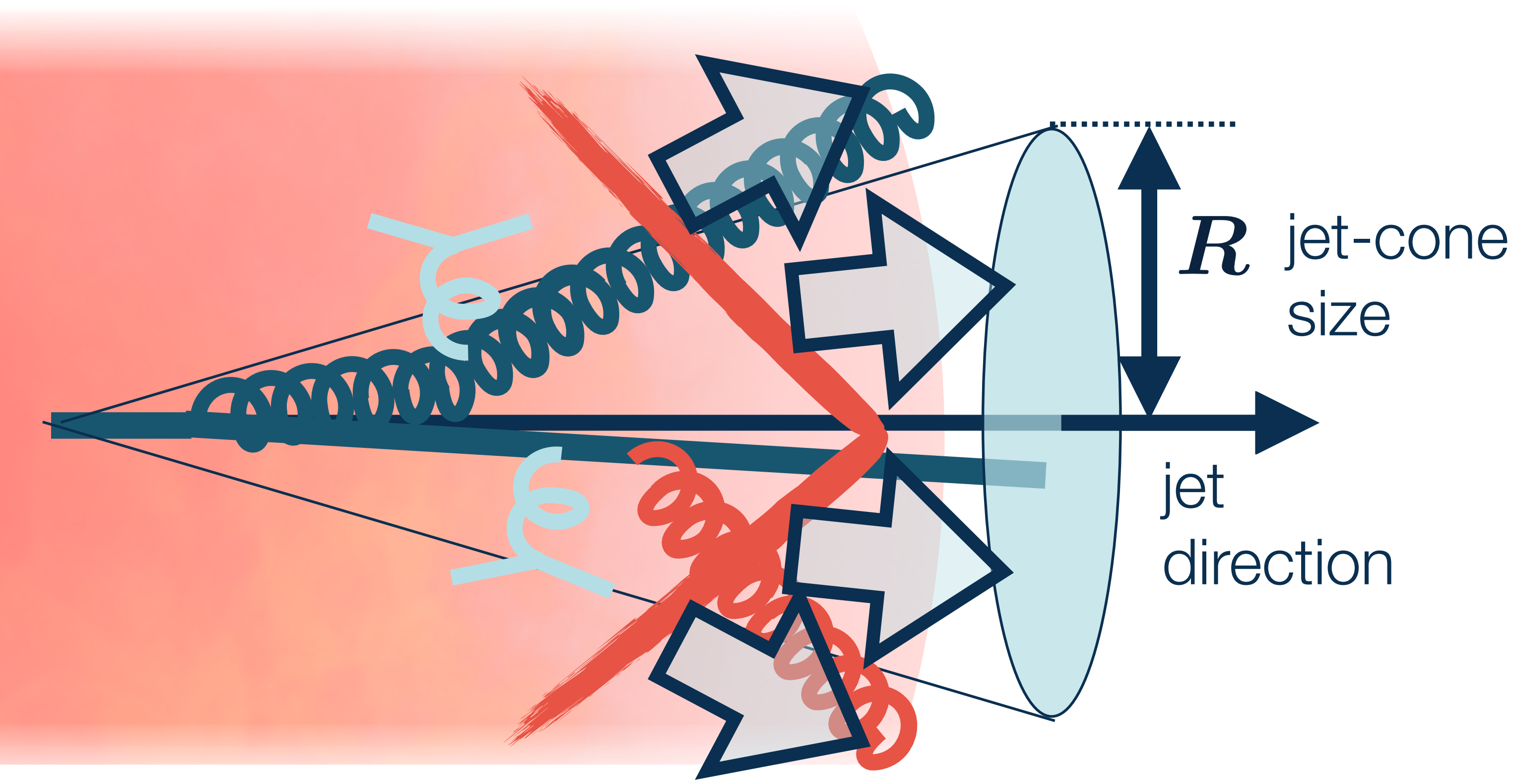

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Counted as part of jet

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  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)**

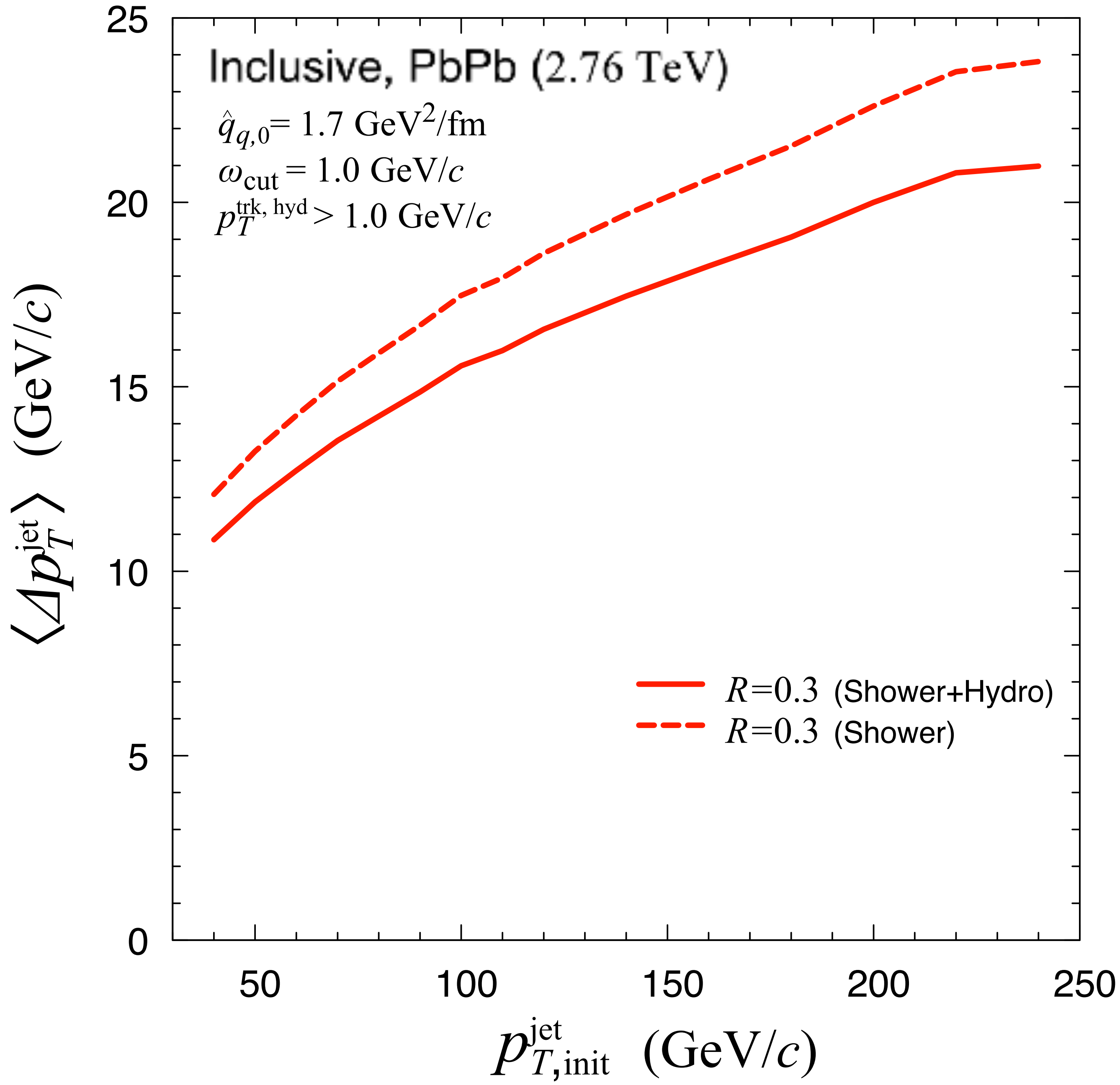
$$\Delta \frac{dN}{d^3p} = \left.\frac{dN}{d^3p}\right|_{\rm w/\ jet} - \left.\frac{dN}{d^3p}\right|_{\rm w/o\ jet} \longleftarrow$$

Cooper-Frye formula

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

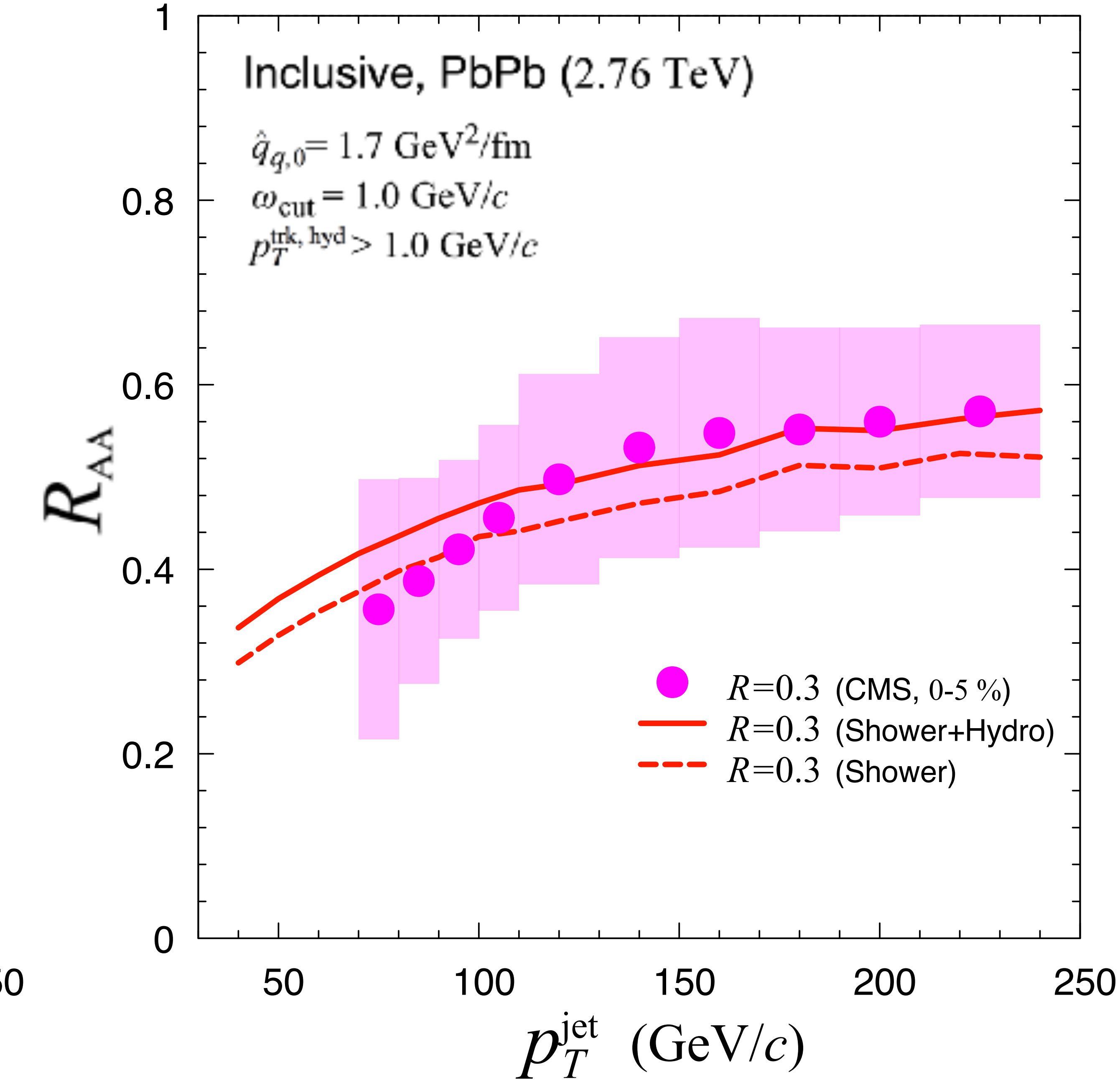
Full jet energy loss and suppression

Total transverse momentum Loss



Nuclear modification factor

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



(jets are generated by PYTHIA & MC Glauber)

YT, Chang, Qin, PRC

Full jet energy loss and suppression

Total transverse momentum Loss

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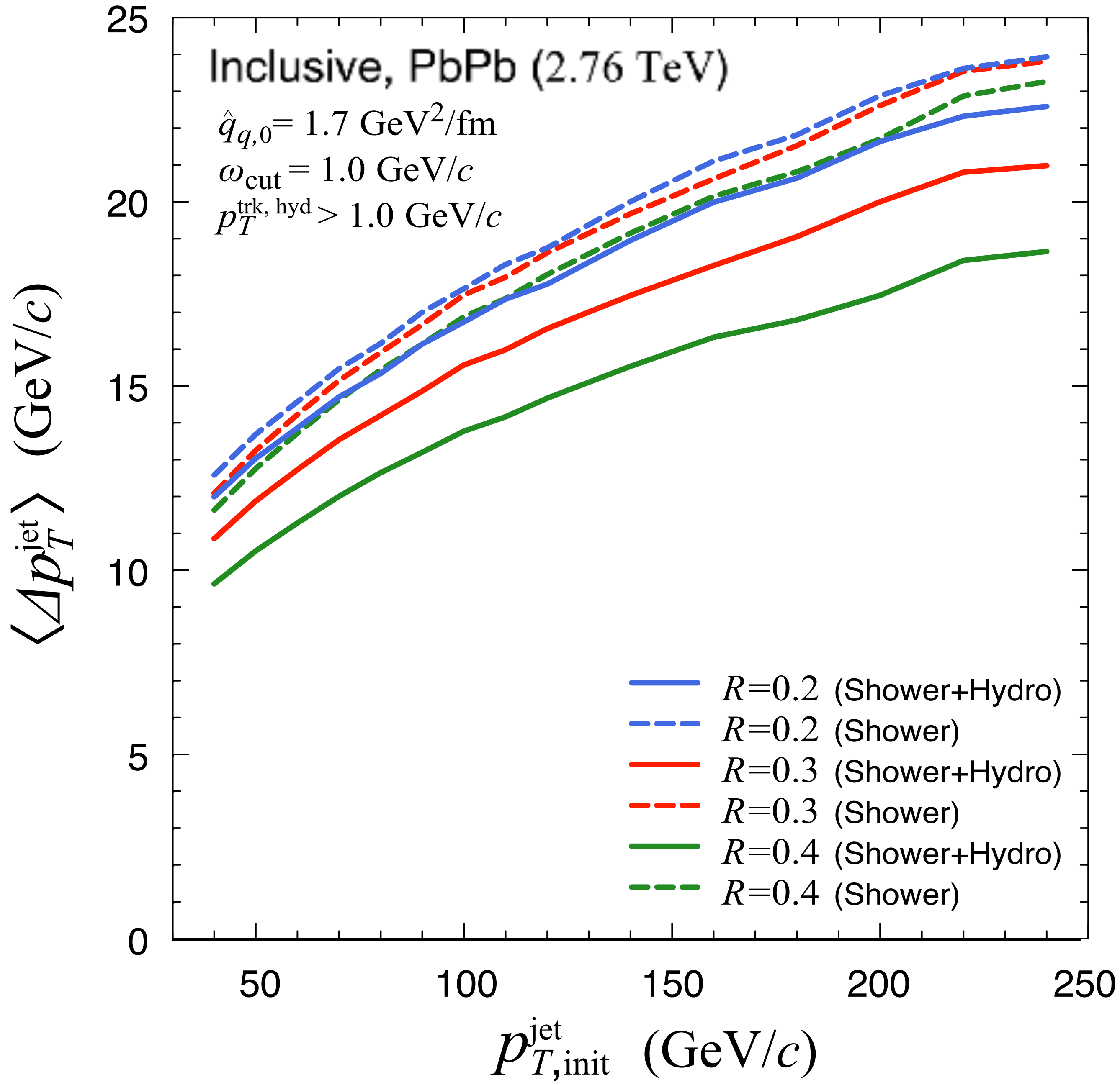

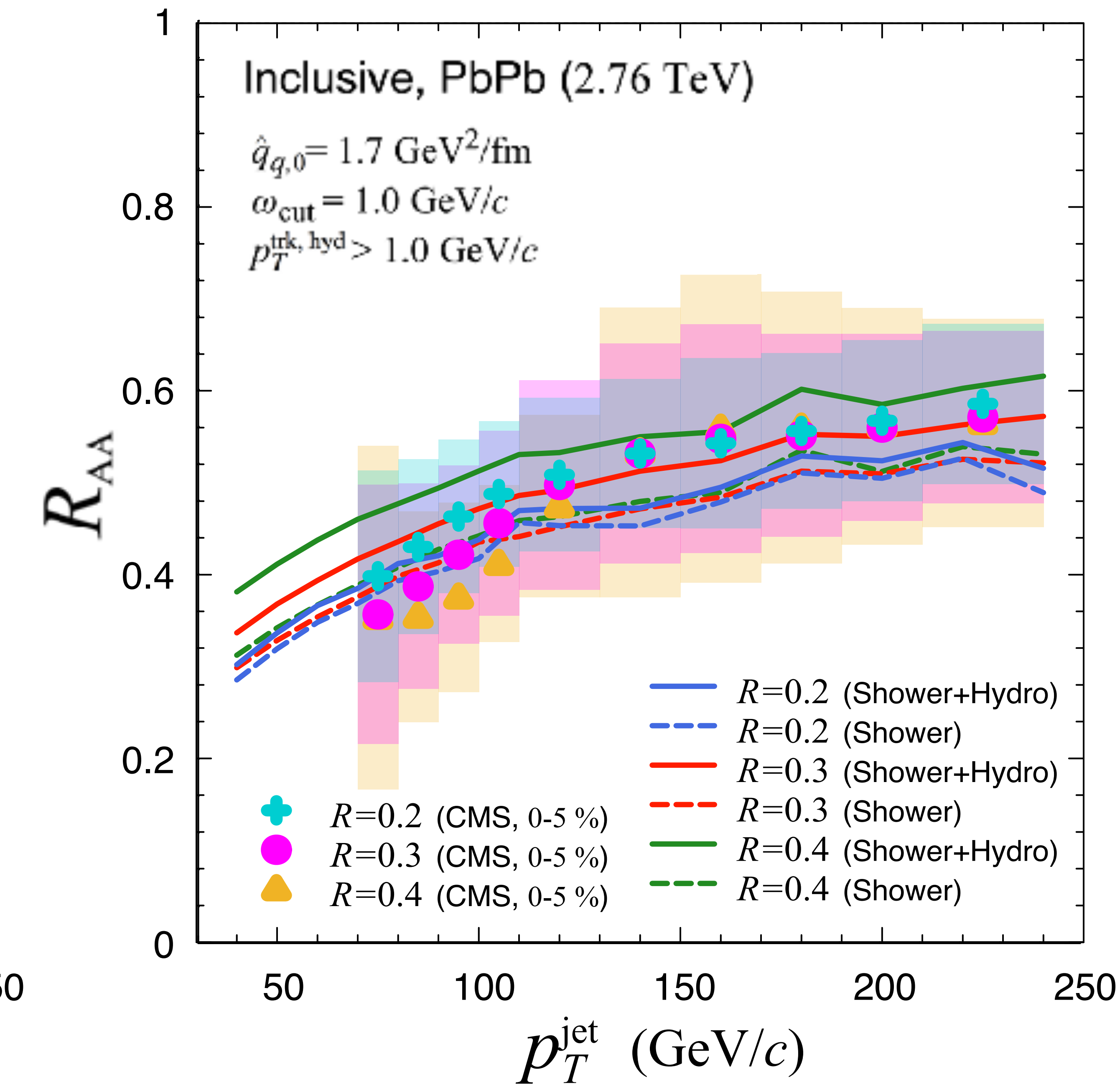

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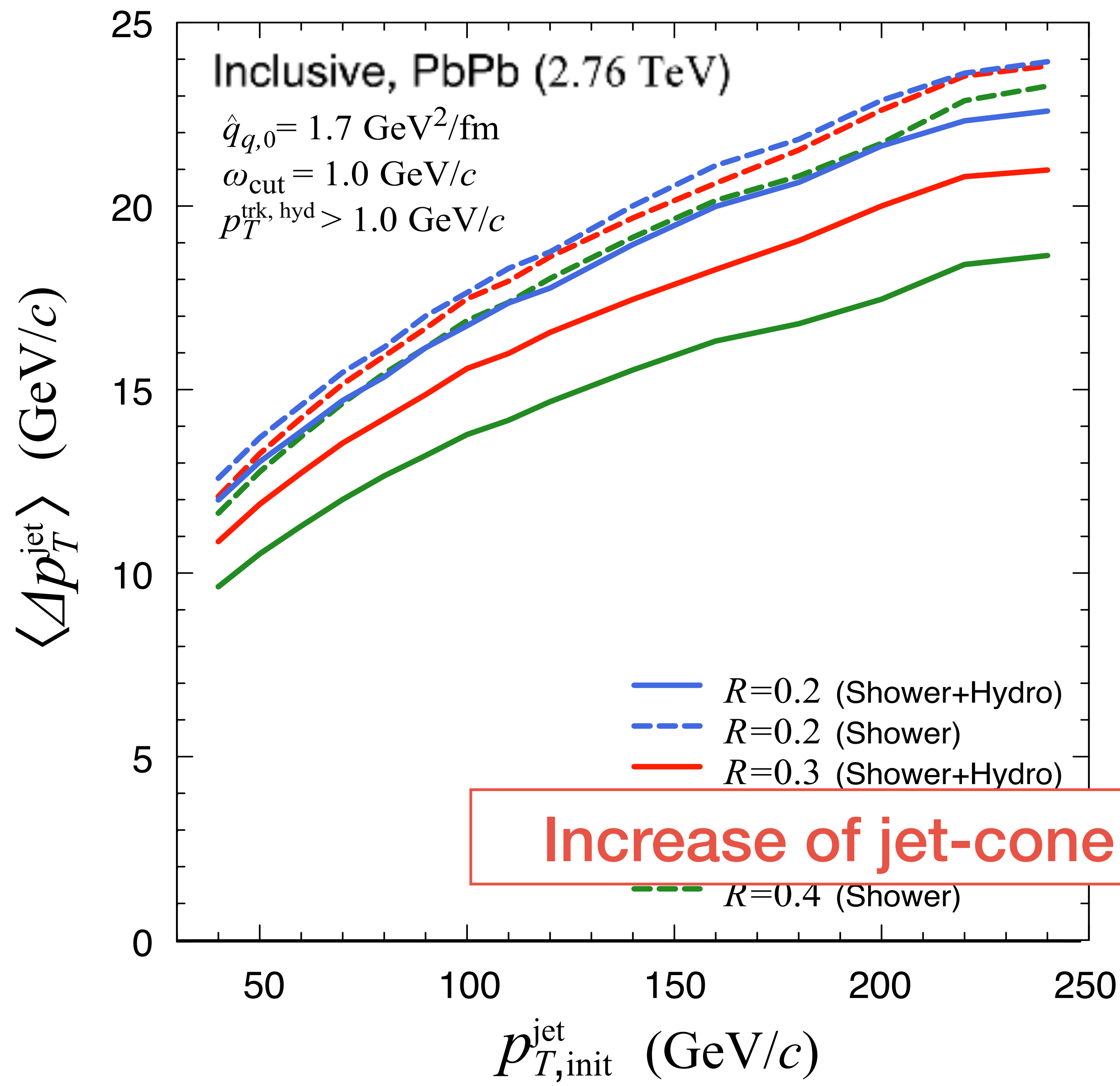
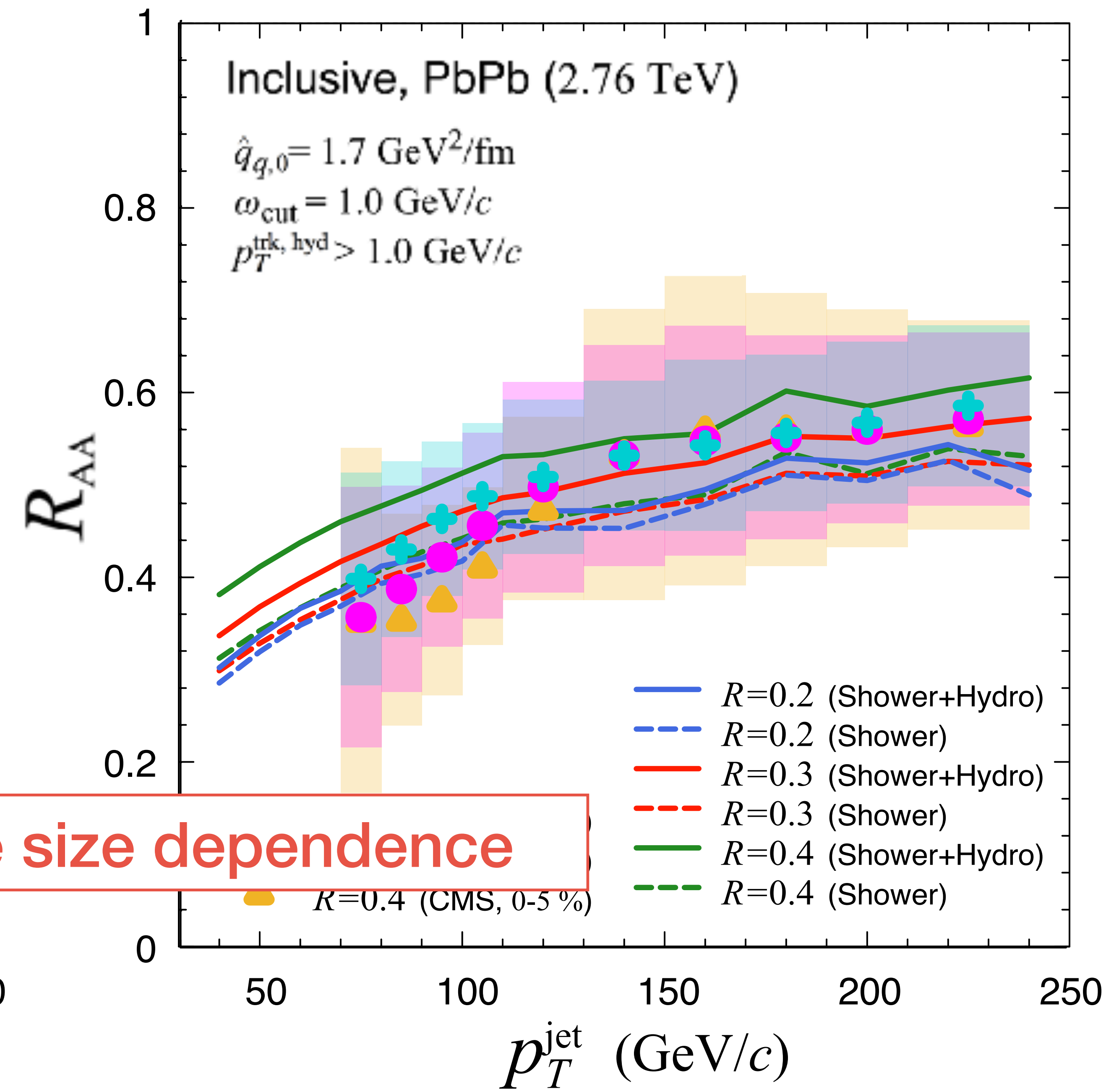


Nuclear modification factor

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



Increase of jet-cone size dependence

(jets are generated by PYTHIA & MC Glauber)

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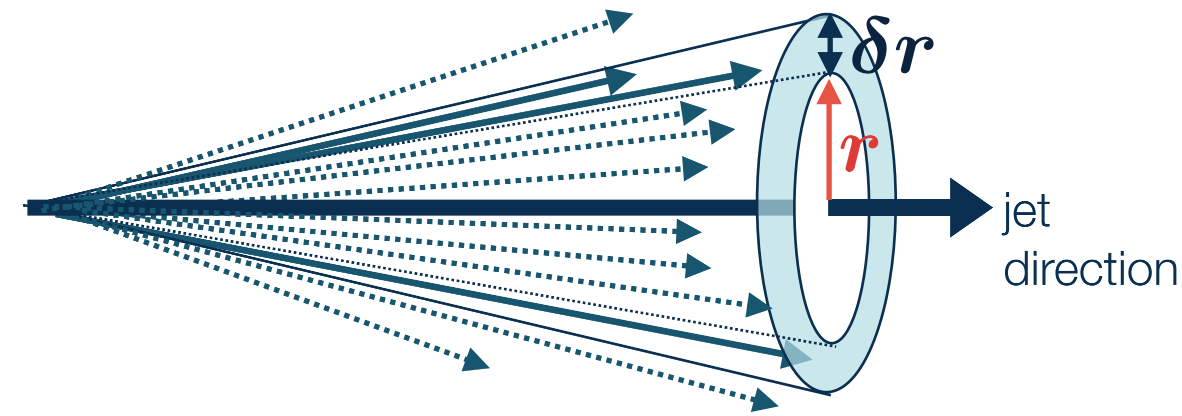
Modification of full jet shape

- **Jet shape function**

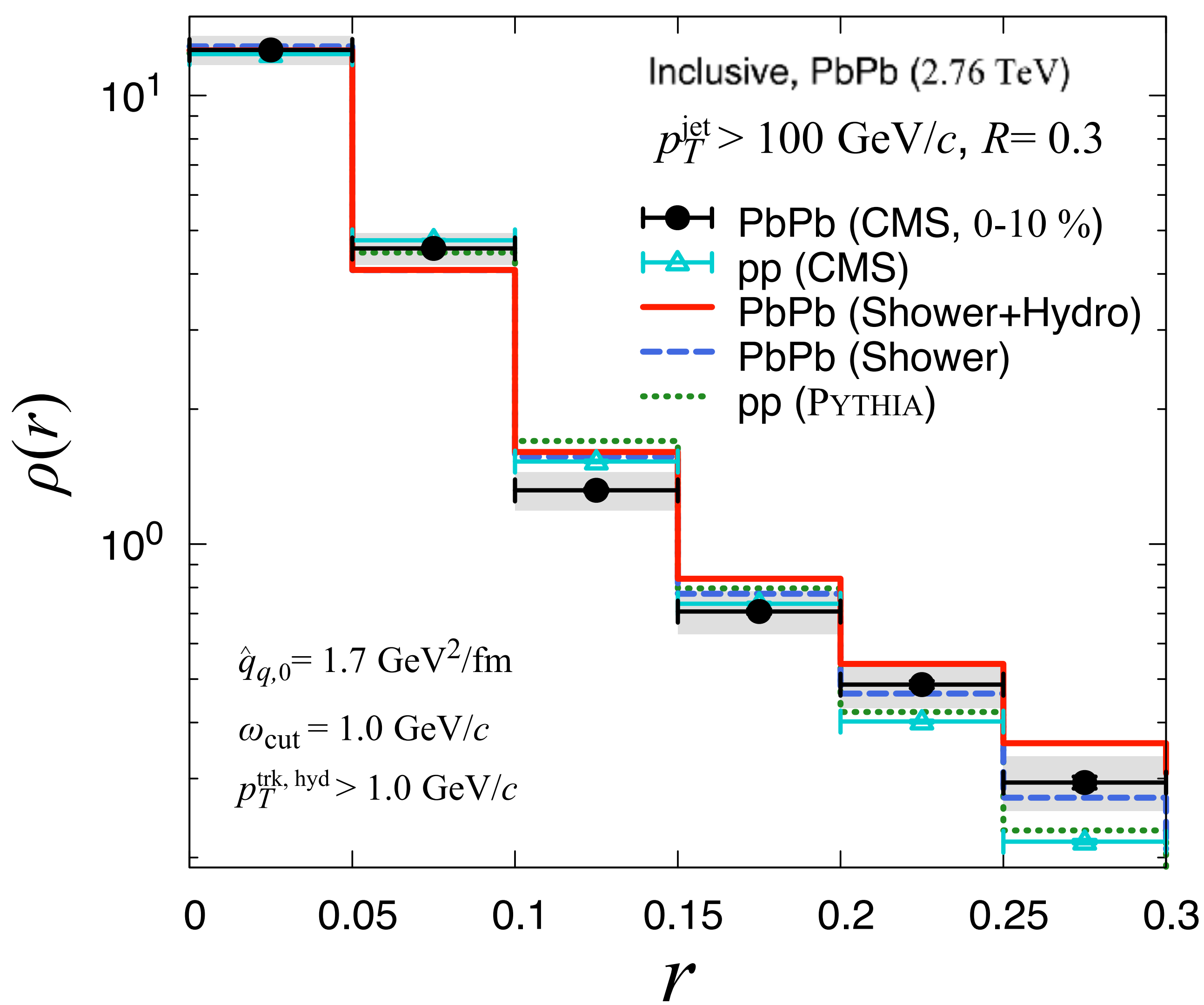
(jets are generated by Pythia & MC Glauber)

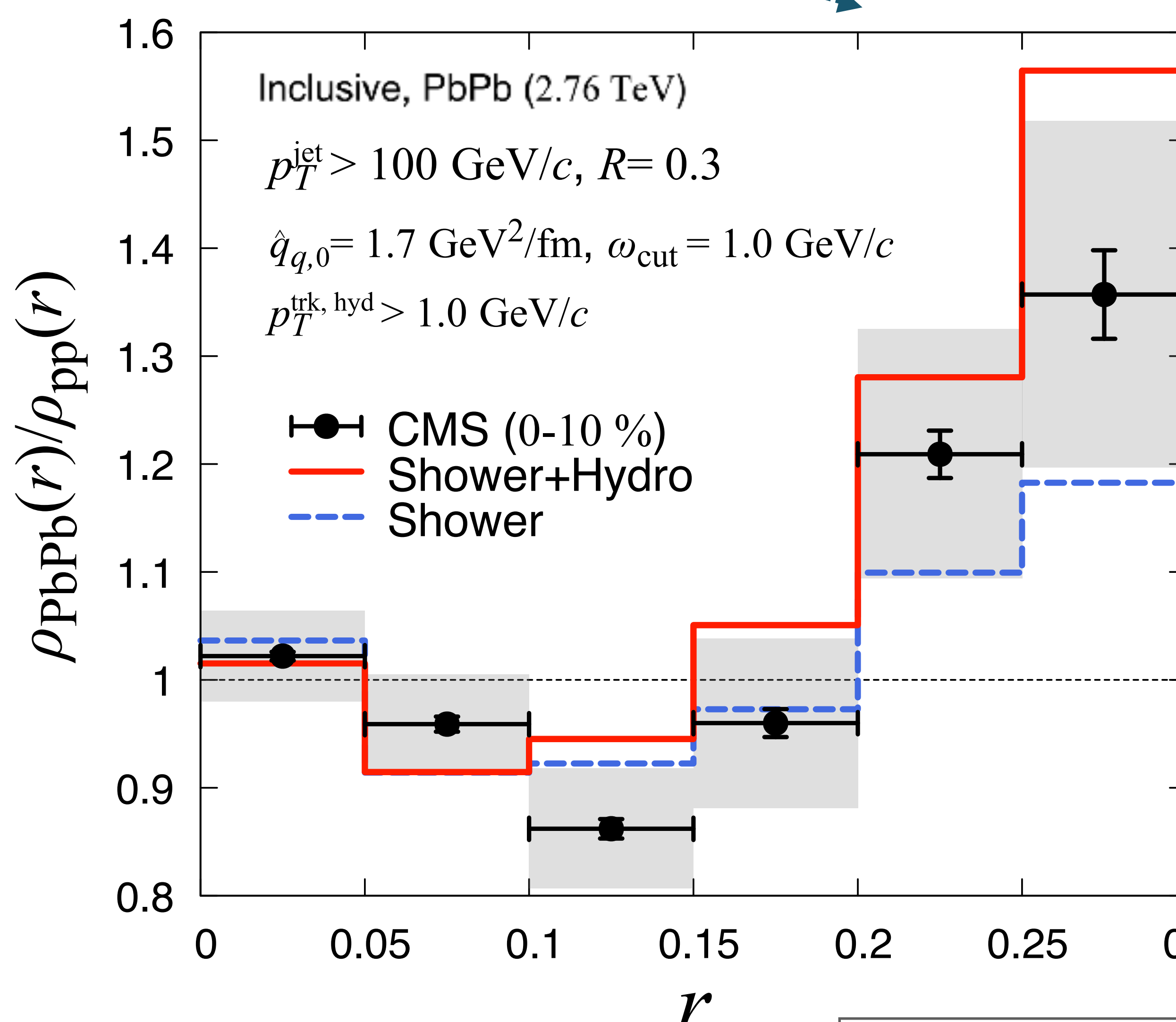
$$r = \sqrt{(\eta_p - \eta_{\rm jet})^2 + (\phi_p - \phi_{\rm jet})^2}$$



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

- Inclusive, $p_T^{\rm jet} \geq 100\,{\rm GeV}/c\,(R = 0.3)$





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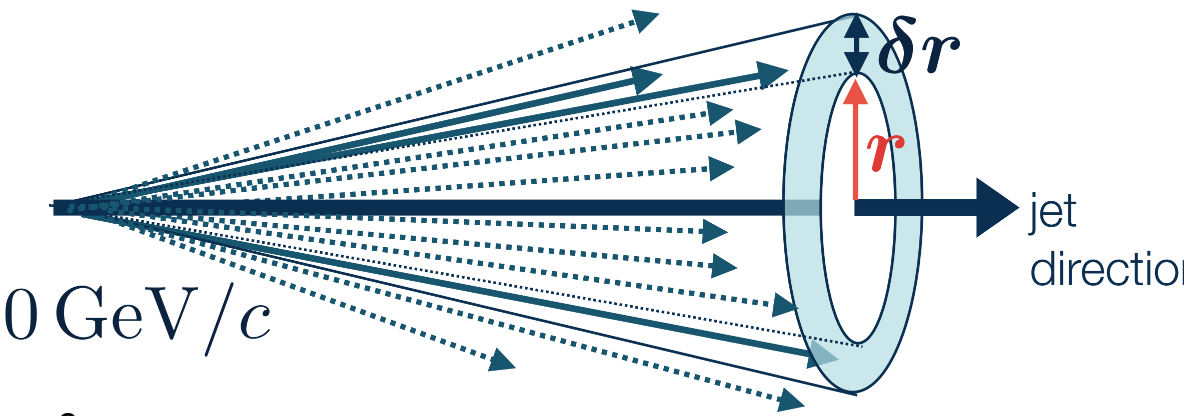
Modification of full jet shape

- **Jet shape function**

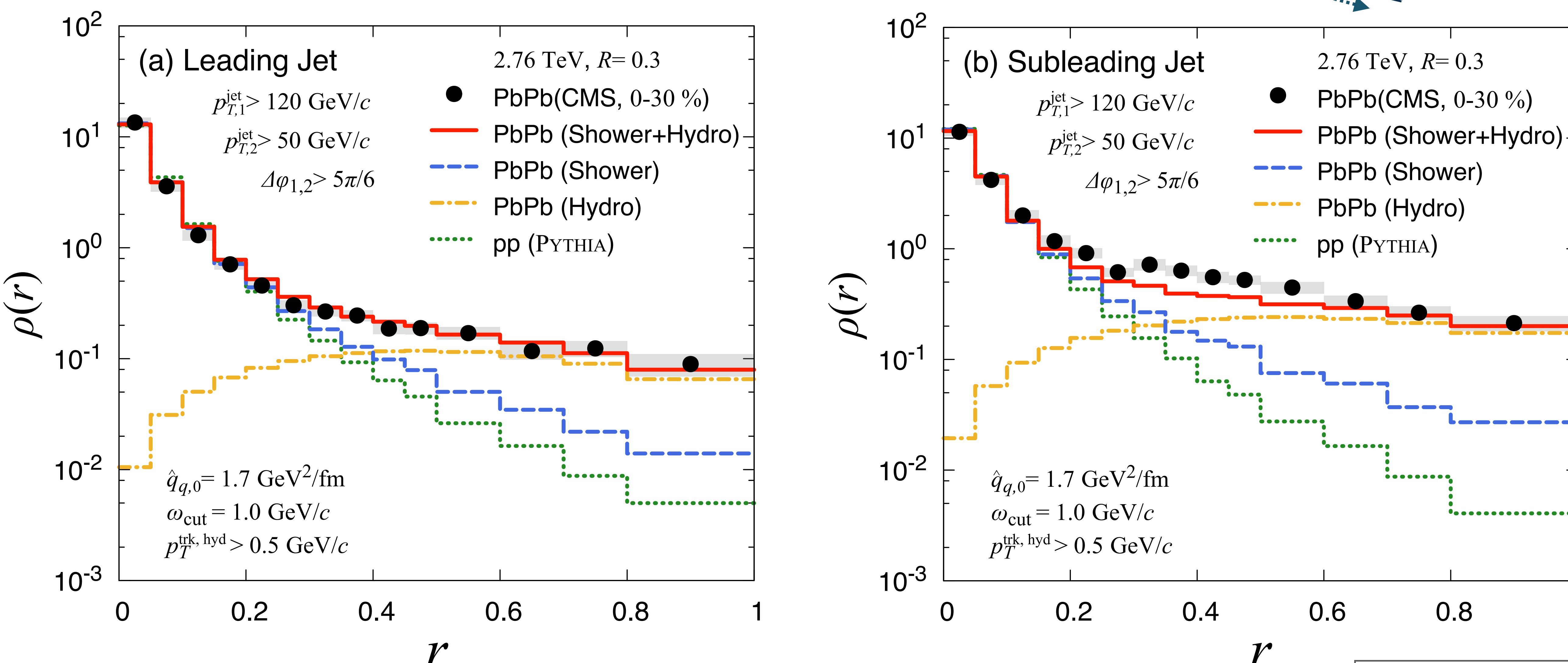
(jets are generated by PYTHIA & MC Glauber)

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

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



- Dijet event, $p_{T,1}^{\rm jet} \geq 120\,{\rm GeV}/c$, $p_{T,2}^{\rm jet} \geq 50\,{\rm GeV}/c$



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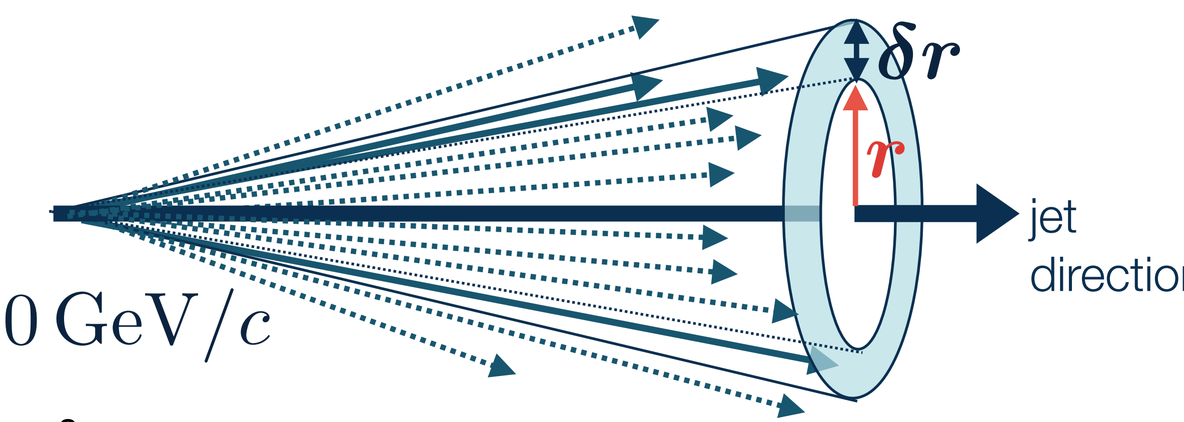
Modification of full jet shape

- **Jet shape function**

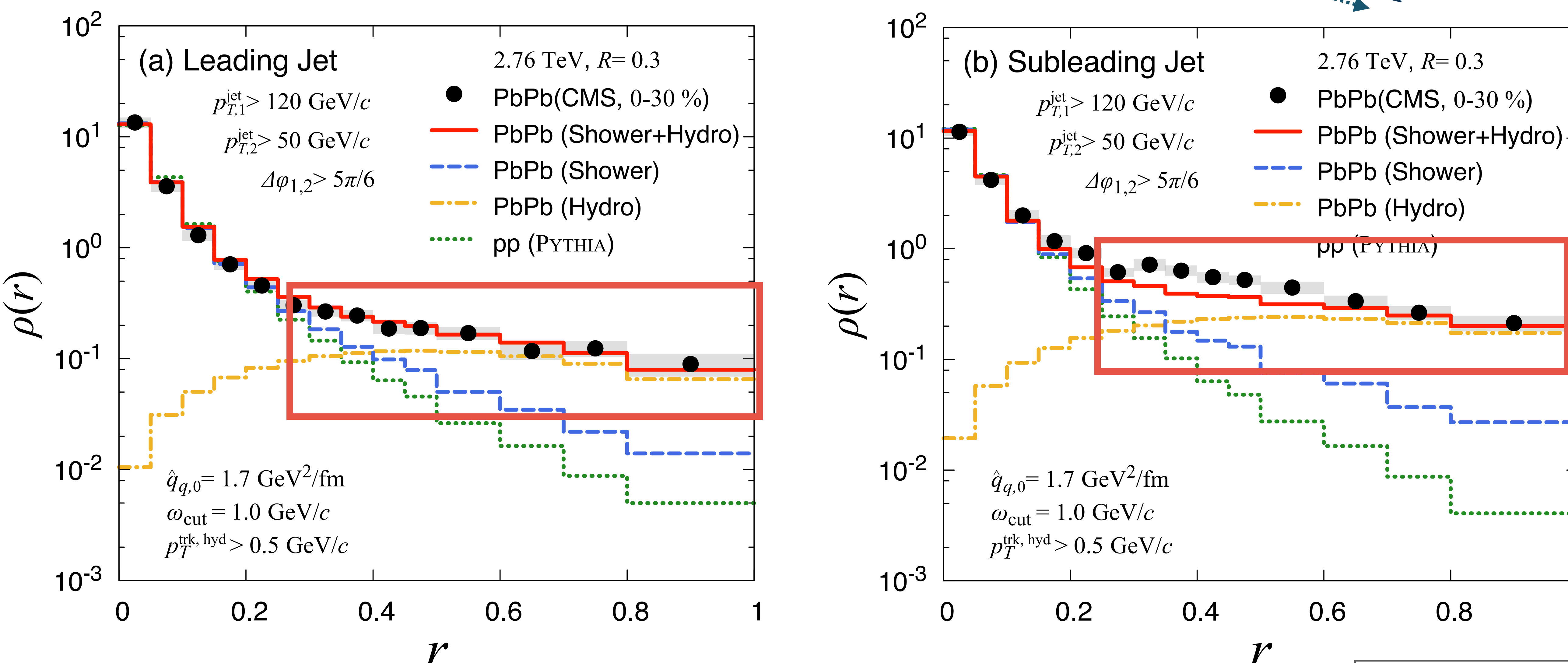
(jets are generated by PYTHIA & MC Glauber)

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

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



- Dijet event, $p_{T,1}^{\rm jet} \geq 120\,{\rm GeV}/c$, $p_{T,2}^{\rm jet} \geq 50\,{\rm GeV}/c$



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Modification of full jet shape

- **Jet shape function**

(jets are generated by PYTHIA & MC Glauber)

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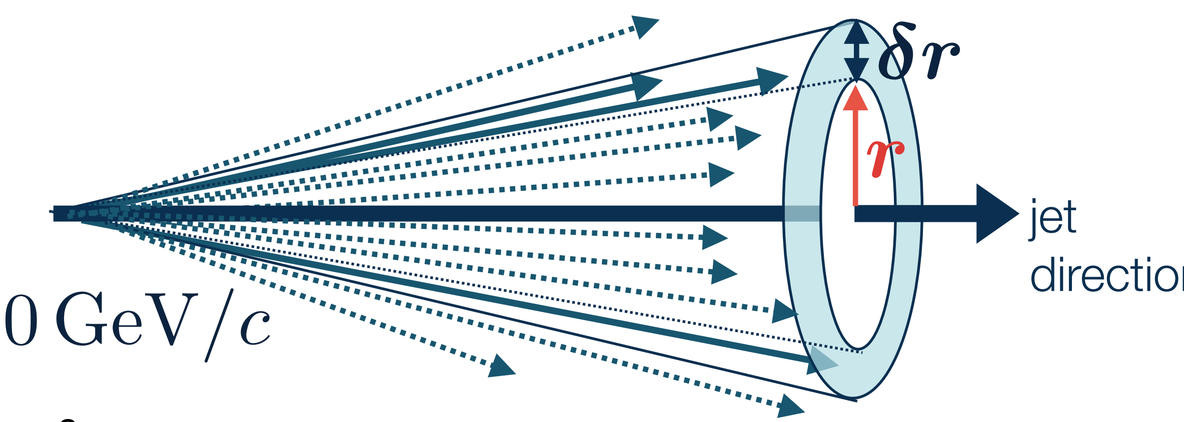
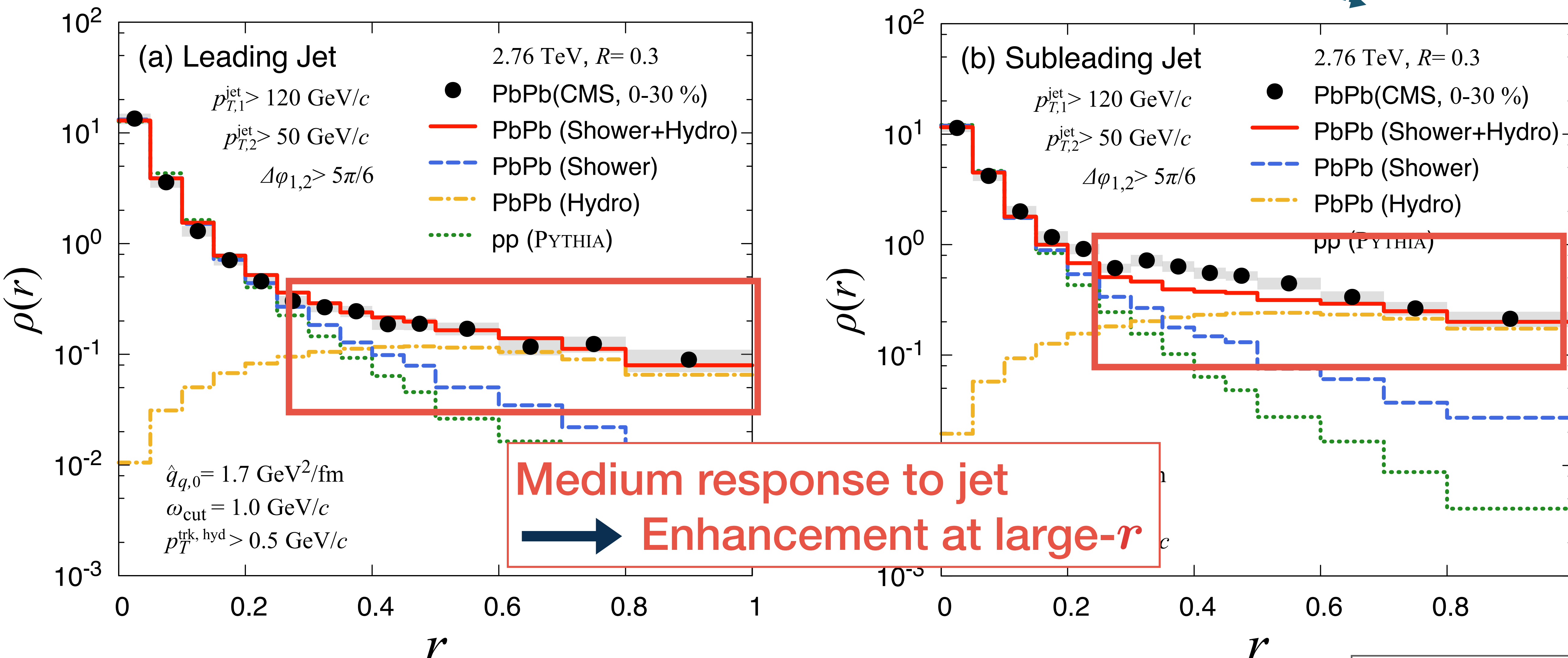


\- Dijet event, $p_{T,1}^{\rm jet} \geq 120\,{\rm GeV}/c$, $p_{T,2}^{\rm jet} \geq 50\,{\rm GeV}/c$



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Summary

Summary

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- **Full jet shower + hydro model**
  - Jet shower evolution: transport equations for partons in jet
  - Medium evolution: hydrodynamic equation with source term

Constructed from jet transport equation

- **Medium response contribution to jet energy loss**
  - Increase of jet cone size dependence
- **Medium response contribution to jet shape modification**
  - Further broadening of jet shape
  - Significantly modification except for very small-r
  - Medium contribution dominates large-r region