Medium Excitation by Jets

[#jet-tachibana]

Yasuki Tachibana for the JETSCAPE Collaboration

JETSCAPE

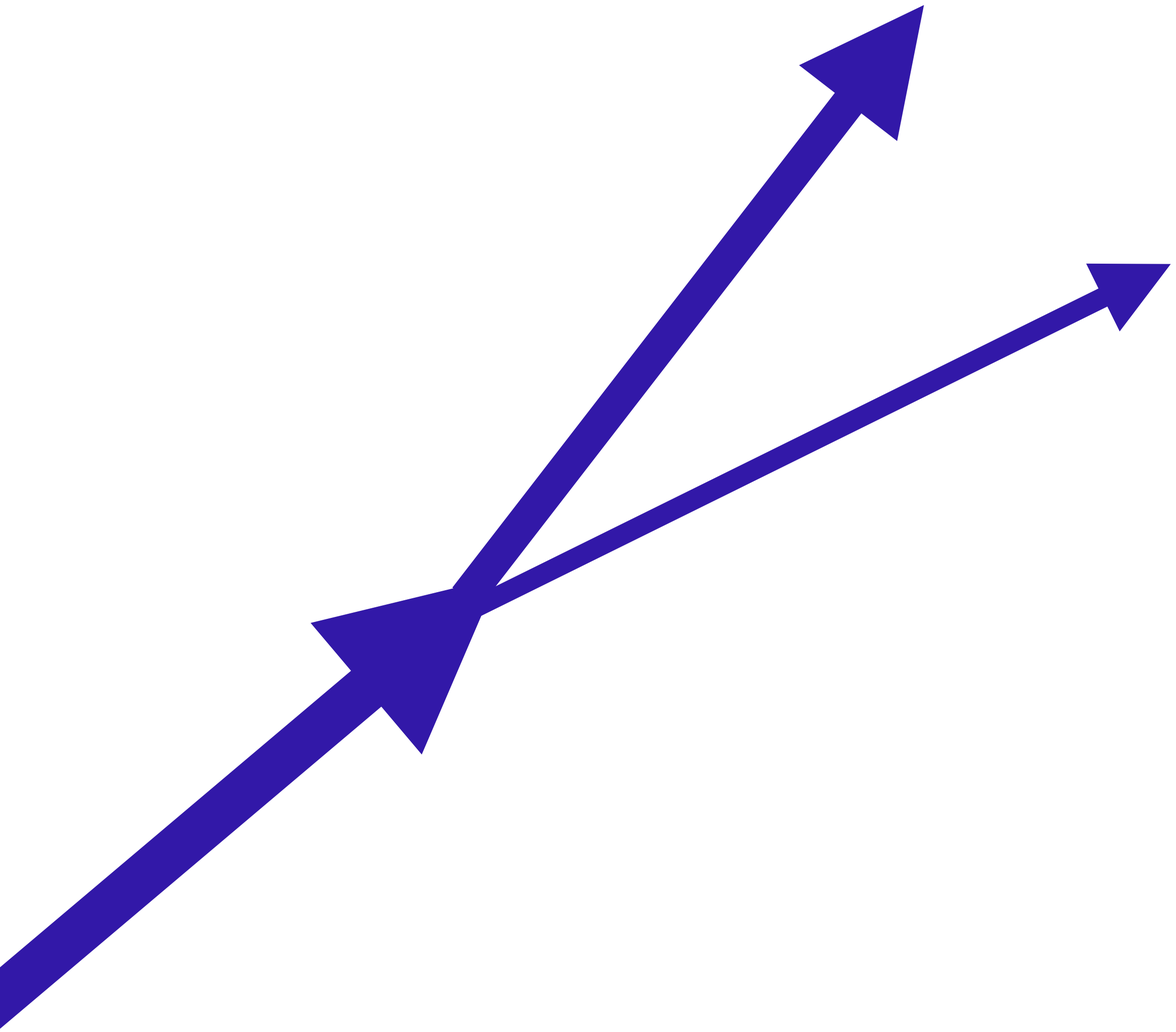
Online, July 17th, 2020

#jet-tachibana

JETSCAPE School 2020

Introduction

Modification of jet shower by a medium



- **Medium effect on jets**
  - Collisional energy loss
  - Medium modified/induced splittings

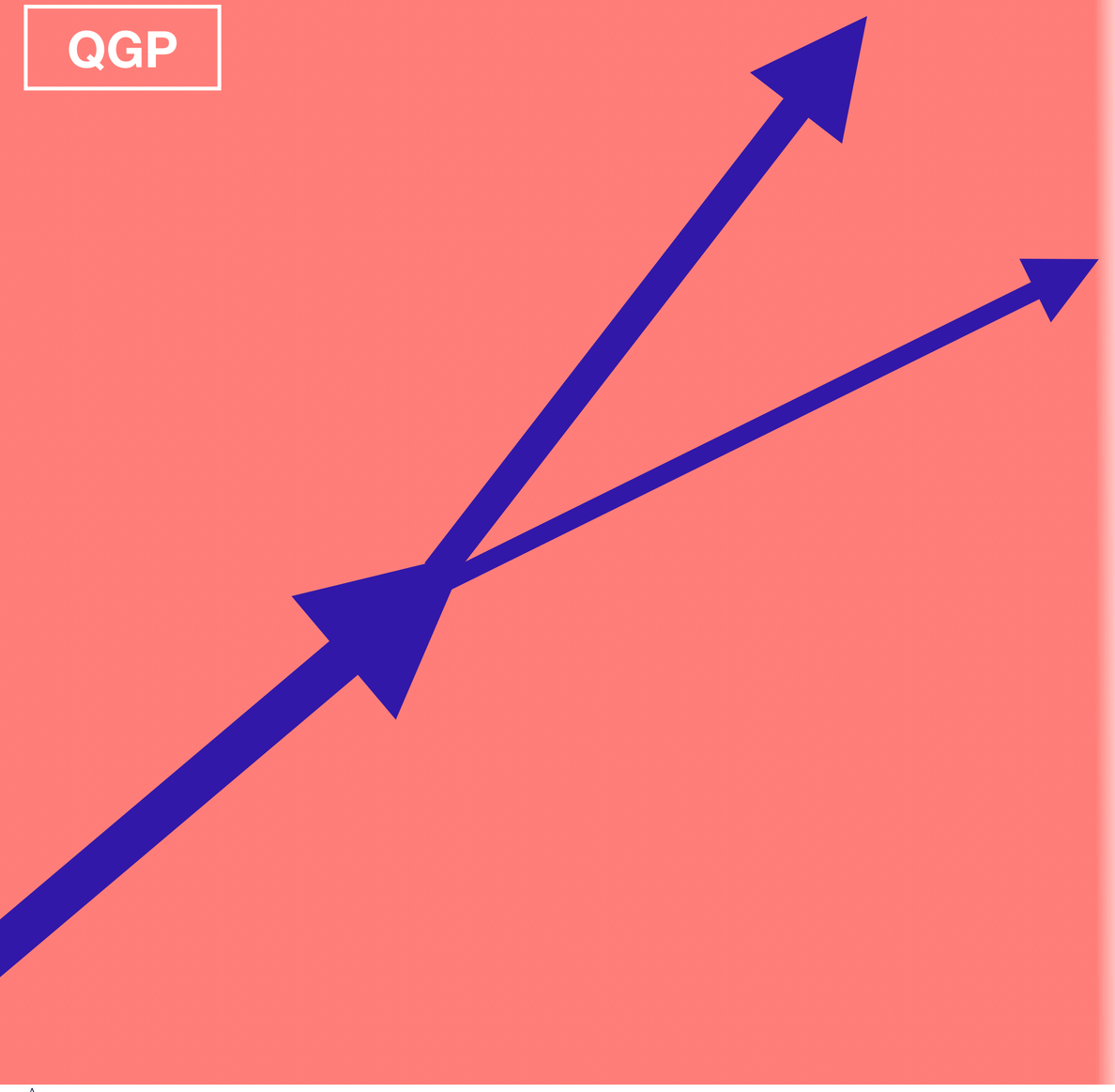
  See Gojko's Lecture

- **Momentum transfer with medium**
  - The source for the modifications of

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    { medium constituents

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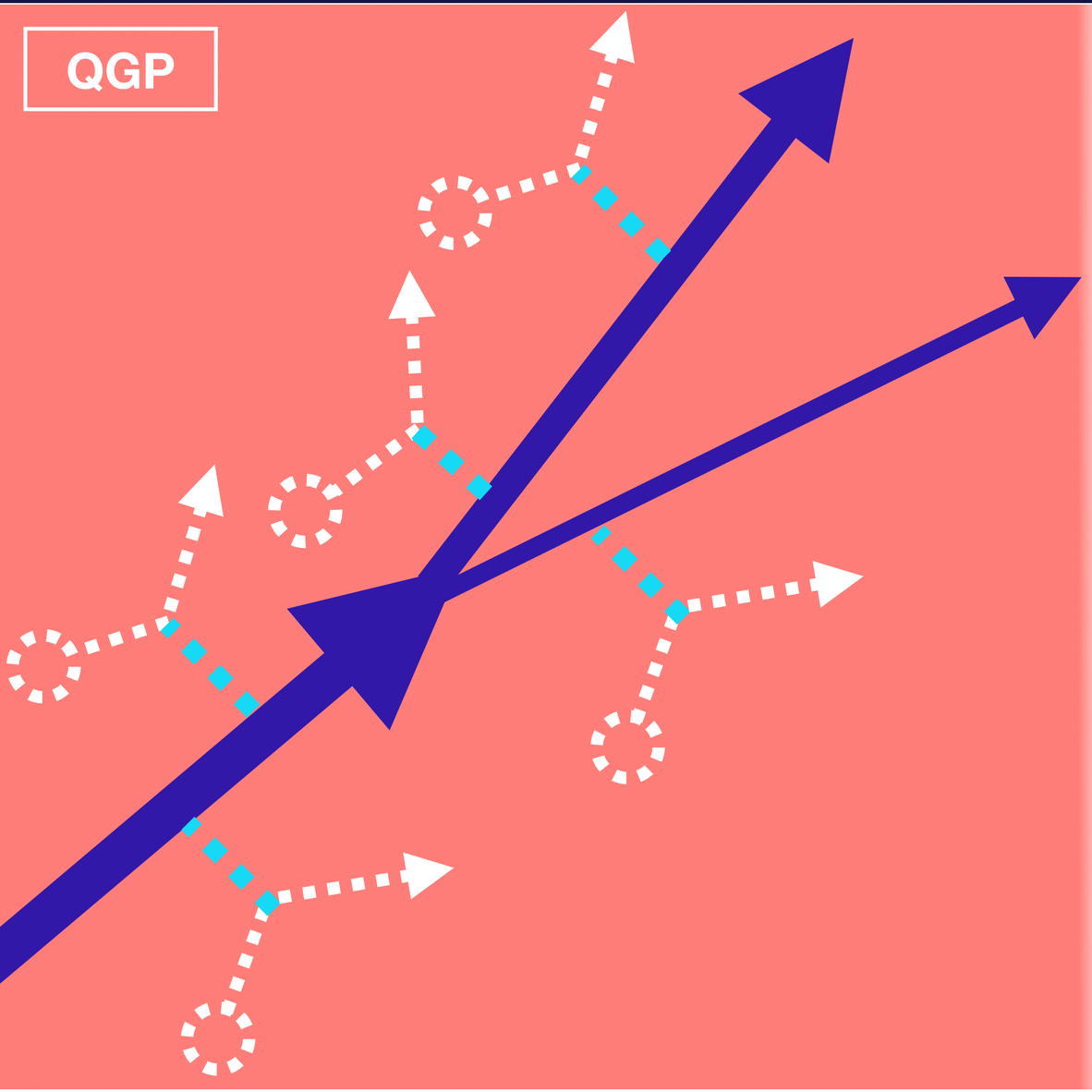
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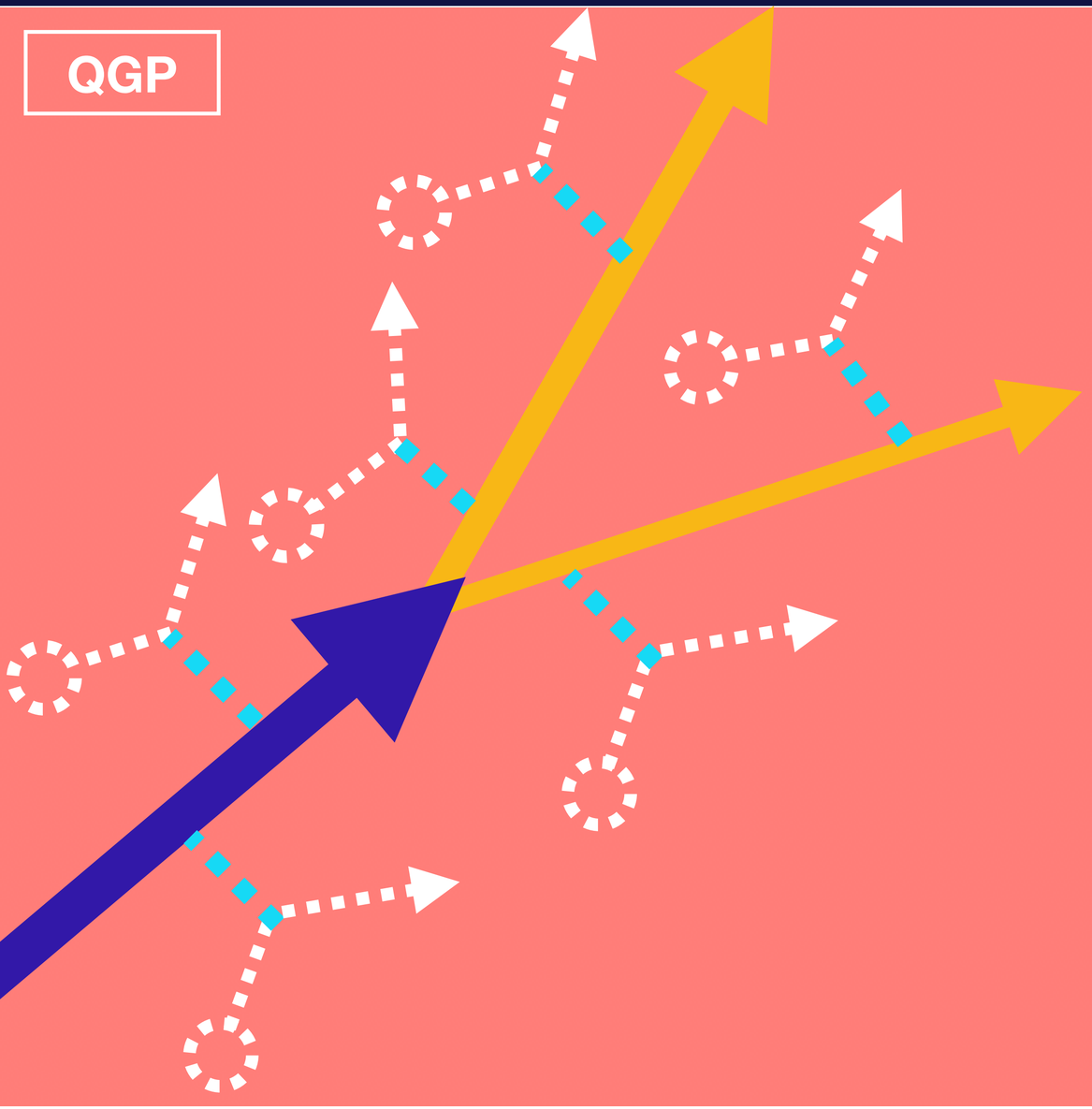
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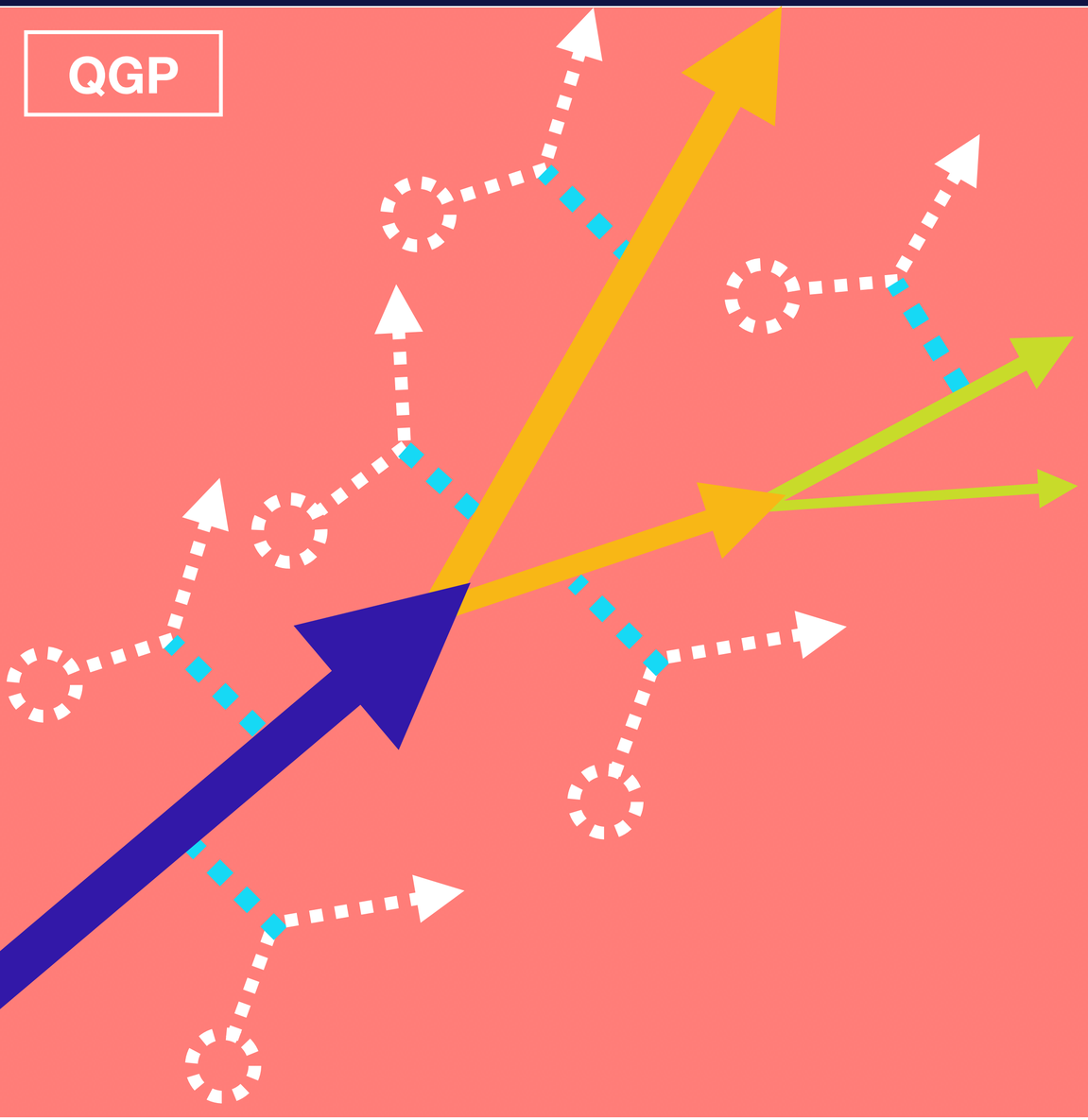
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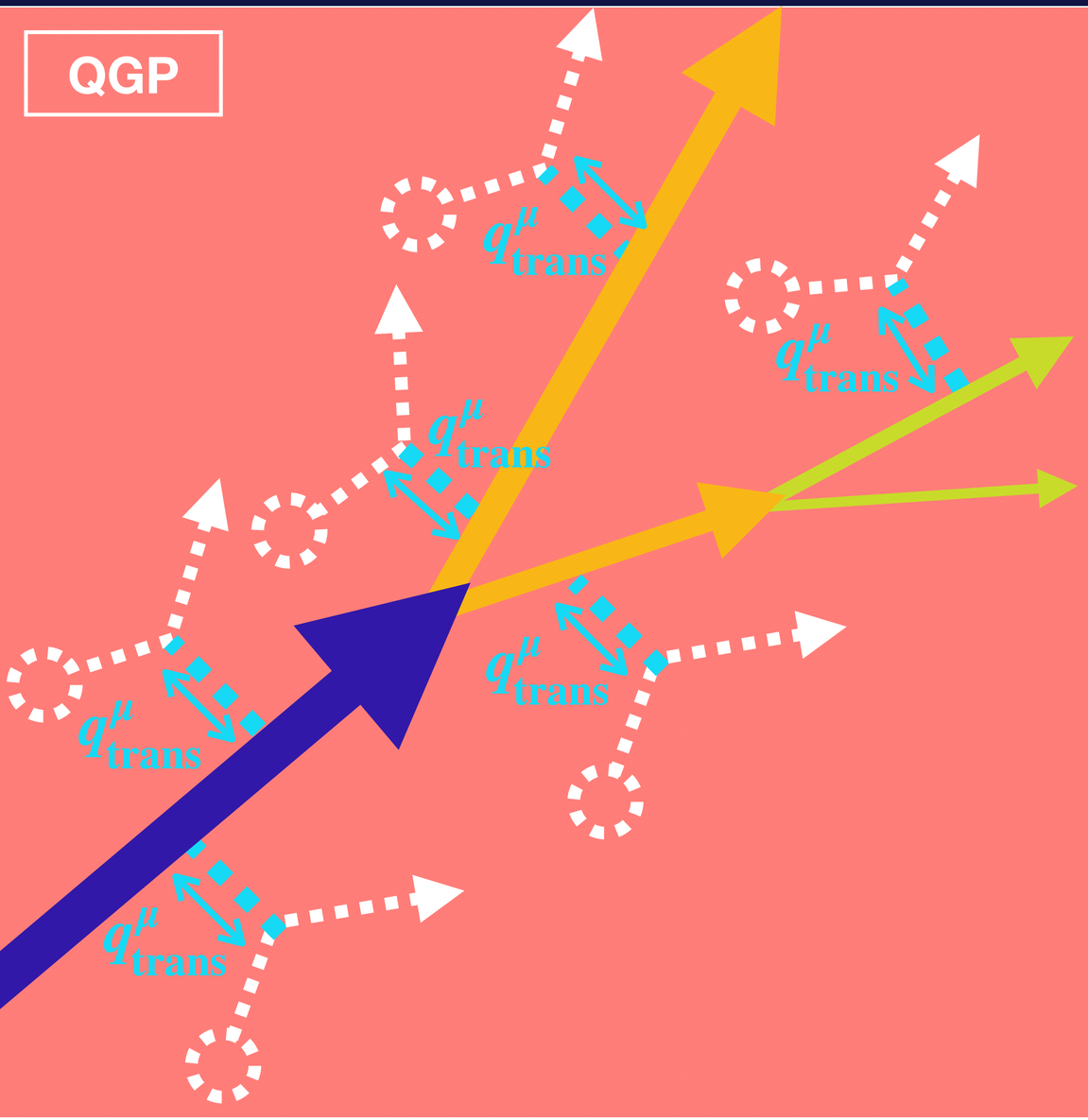
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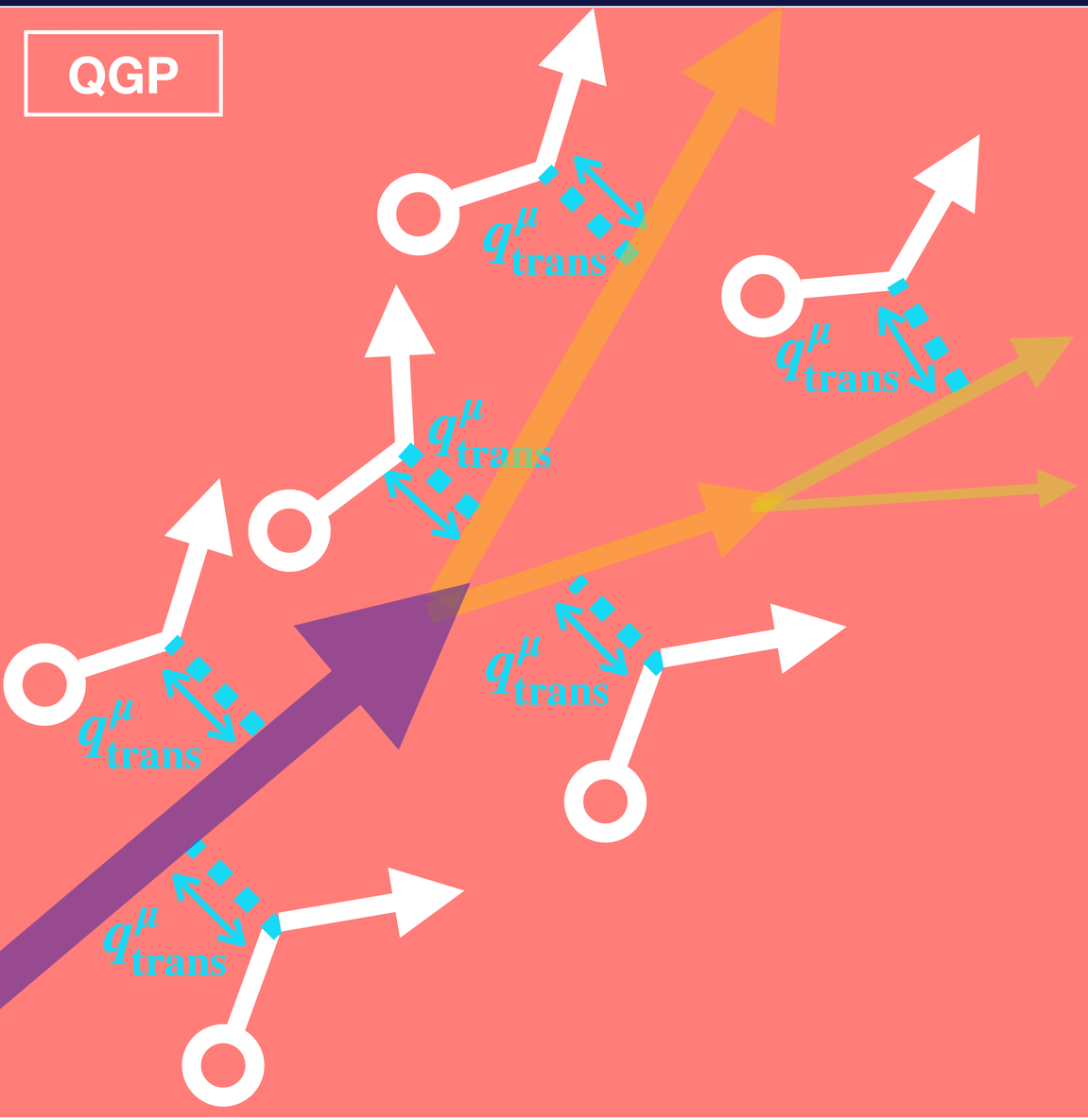


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Modification of jet shower by a medium

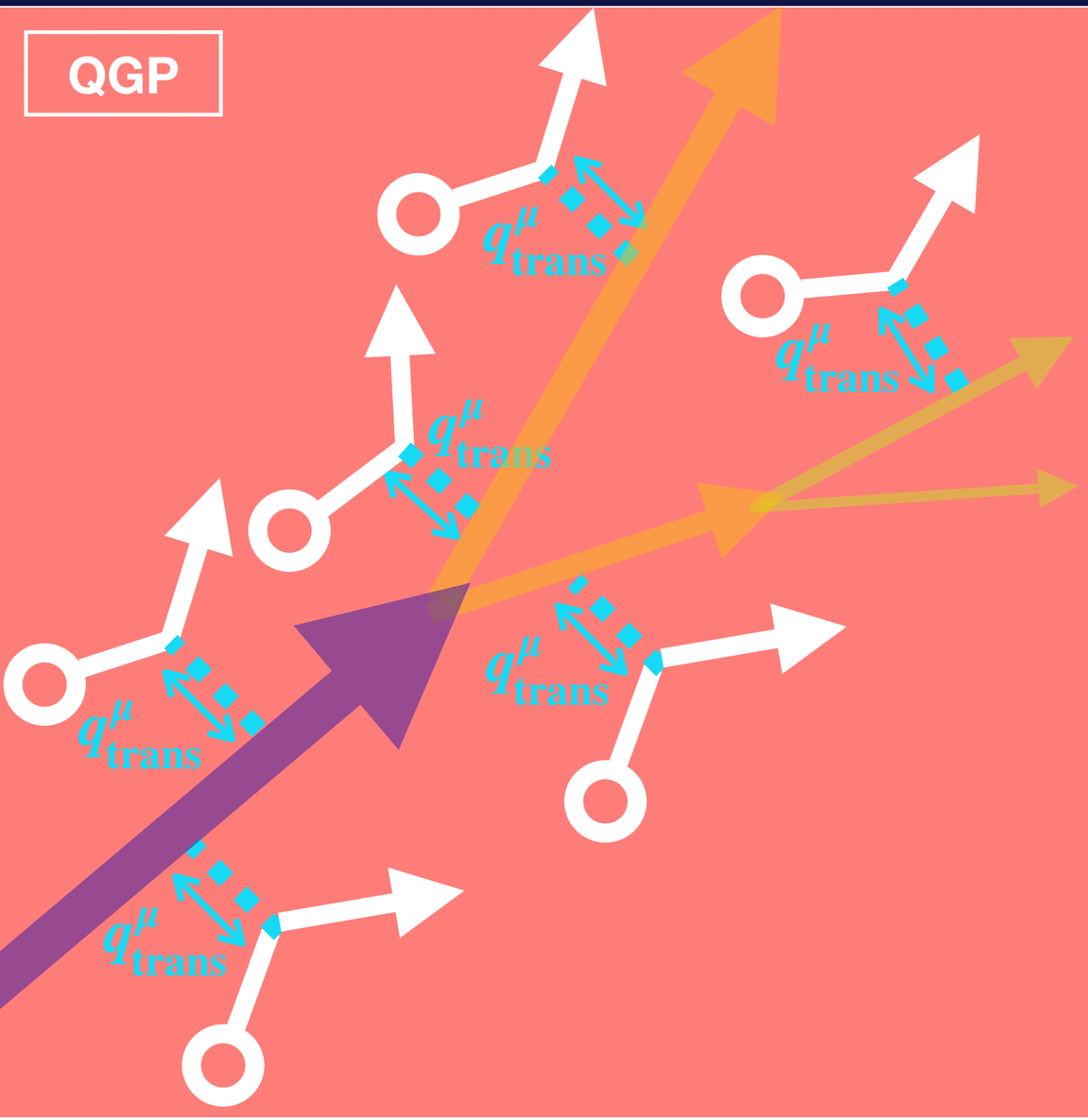


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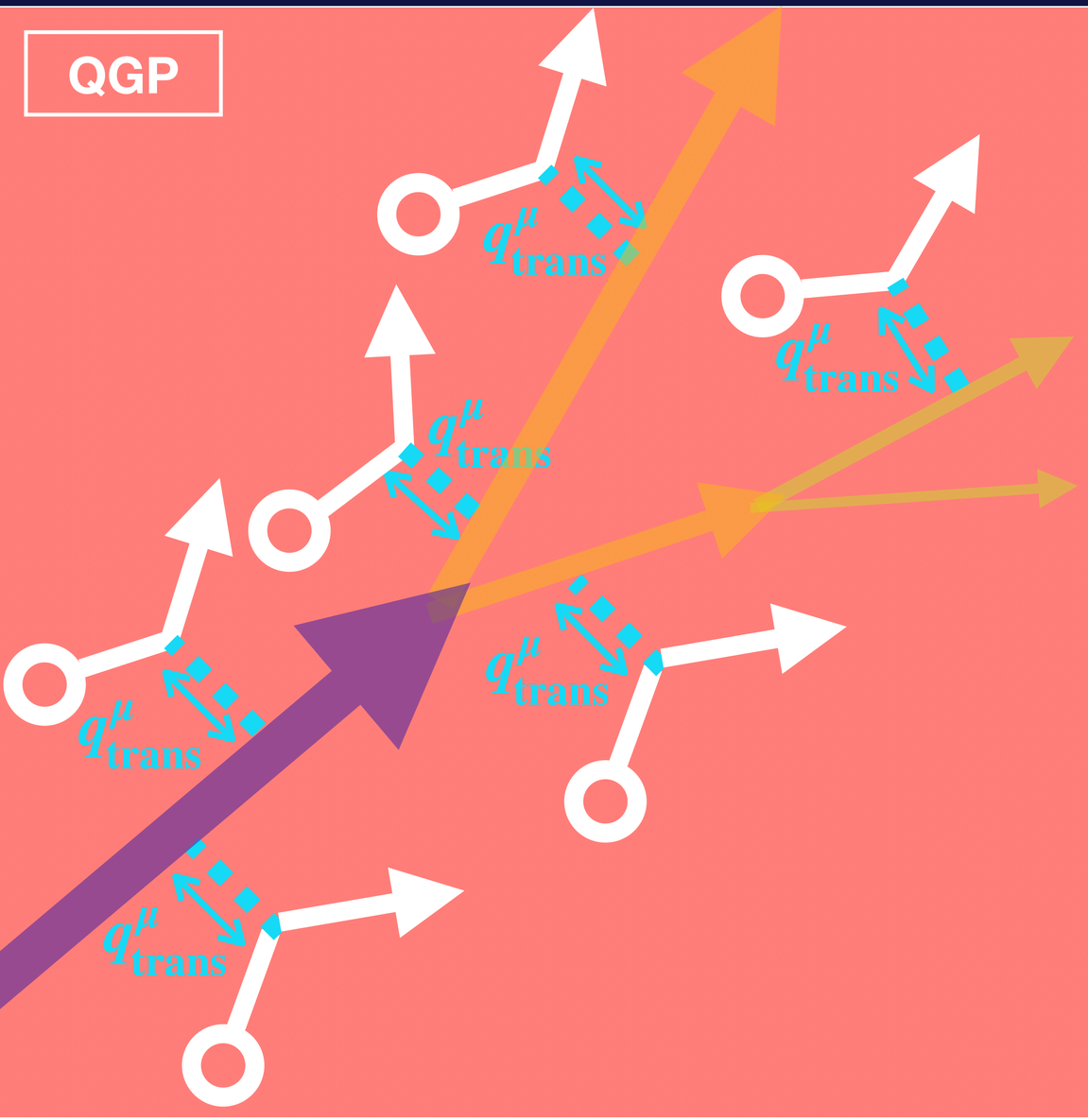
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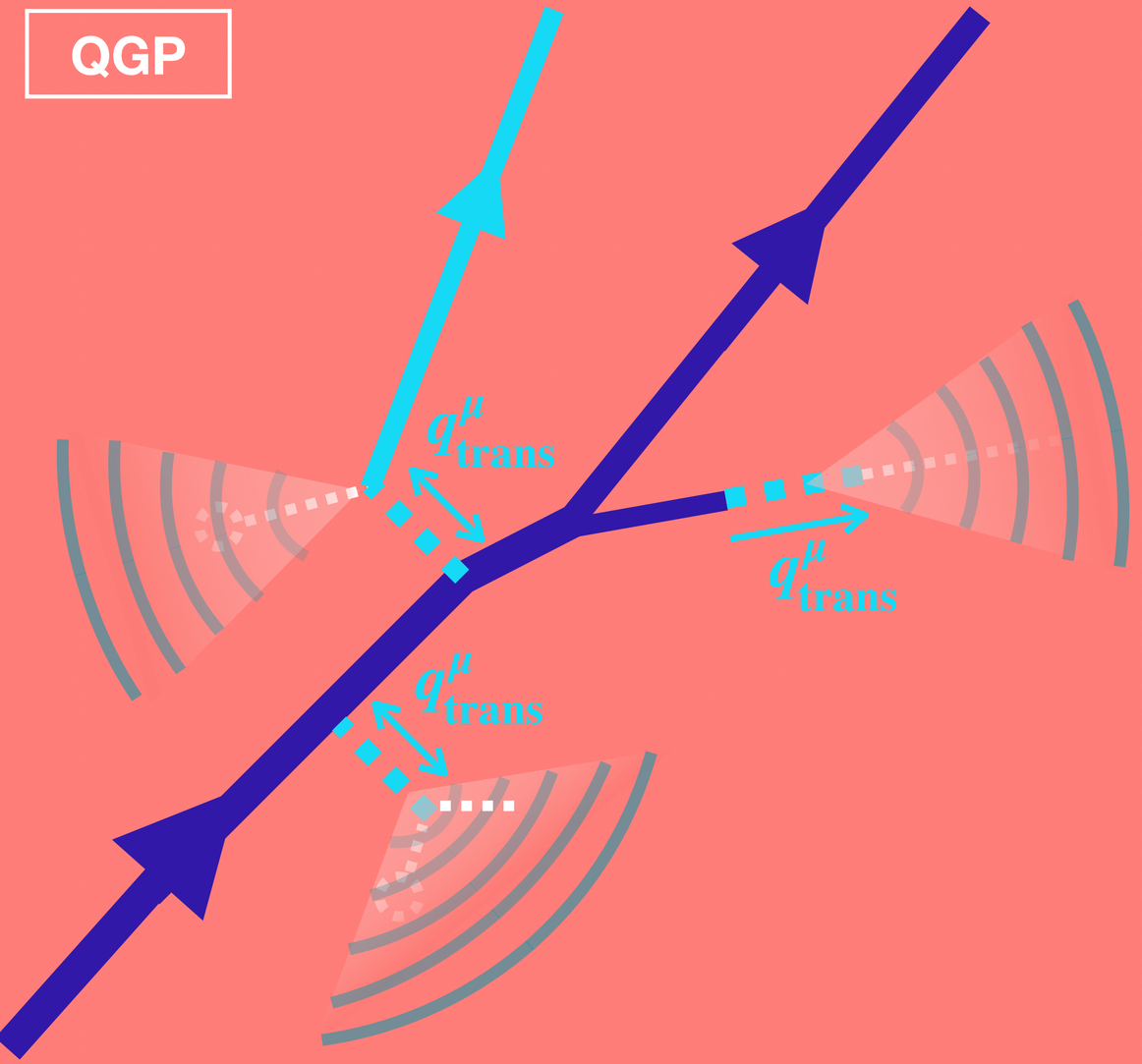
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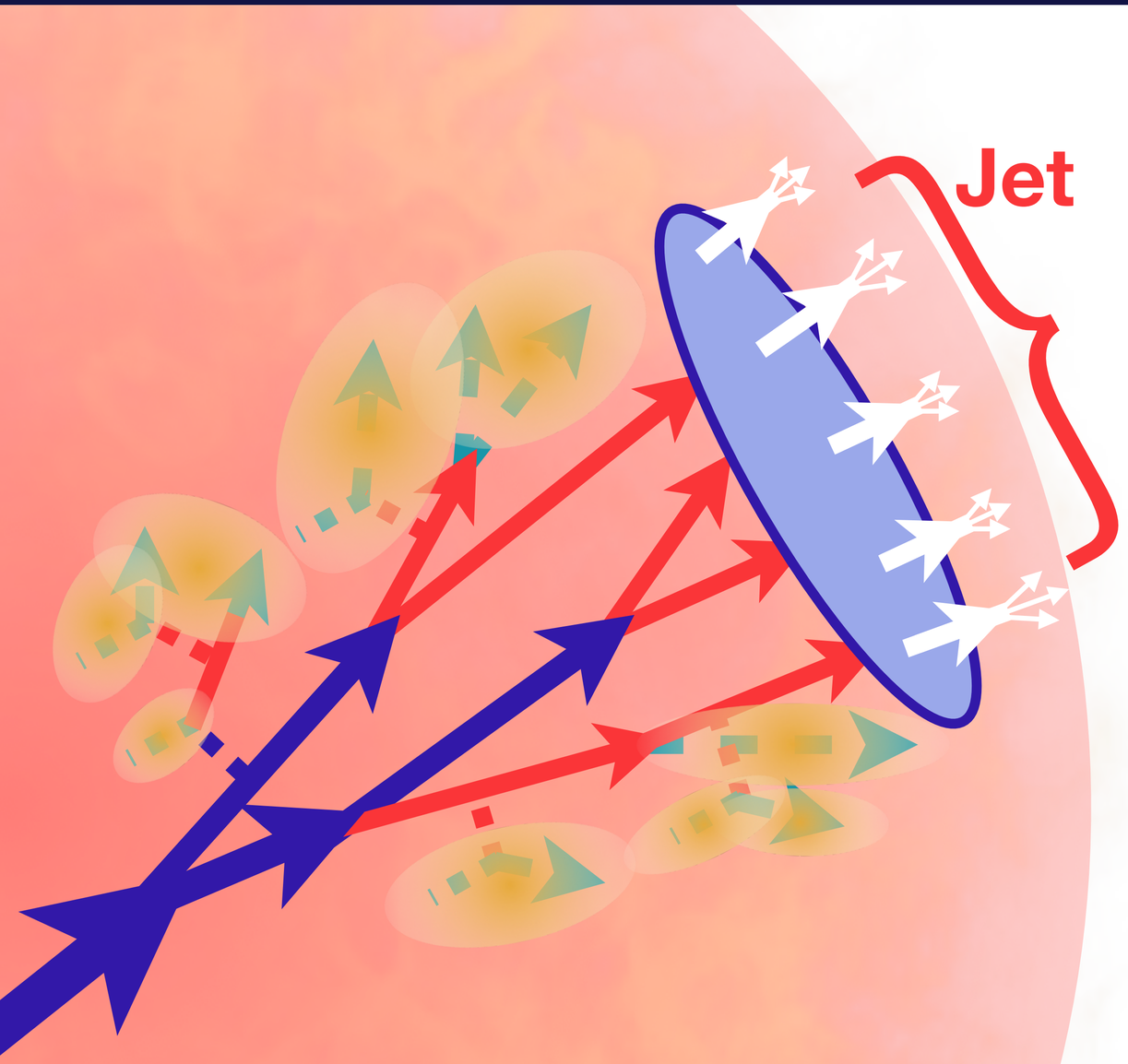
    medium constituents ← **This talk**

Medium response to jet partons



- **Momentum transfer from jet partons**
  - Medium constituents' reactions
  - Lead nonequilibrium processes involving medium constituents
- **In-medium thermalization**
  - Transferred momentum carried by (locally) thermalized medium
  - Transition to hydrodynamic transport

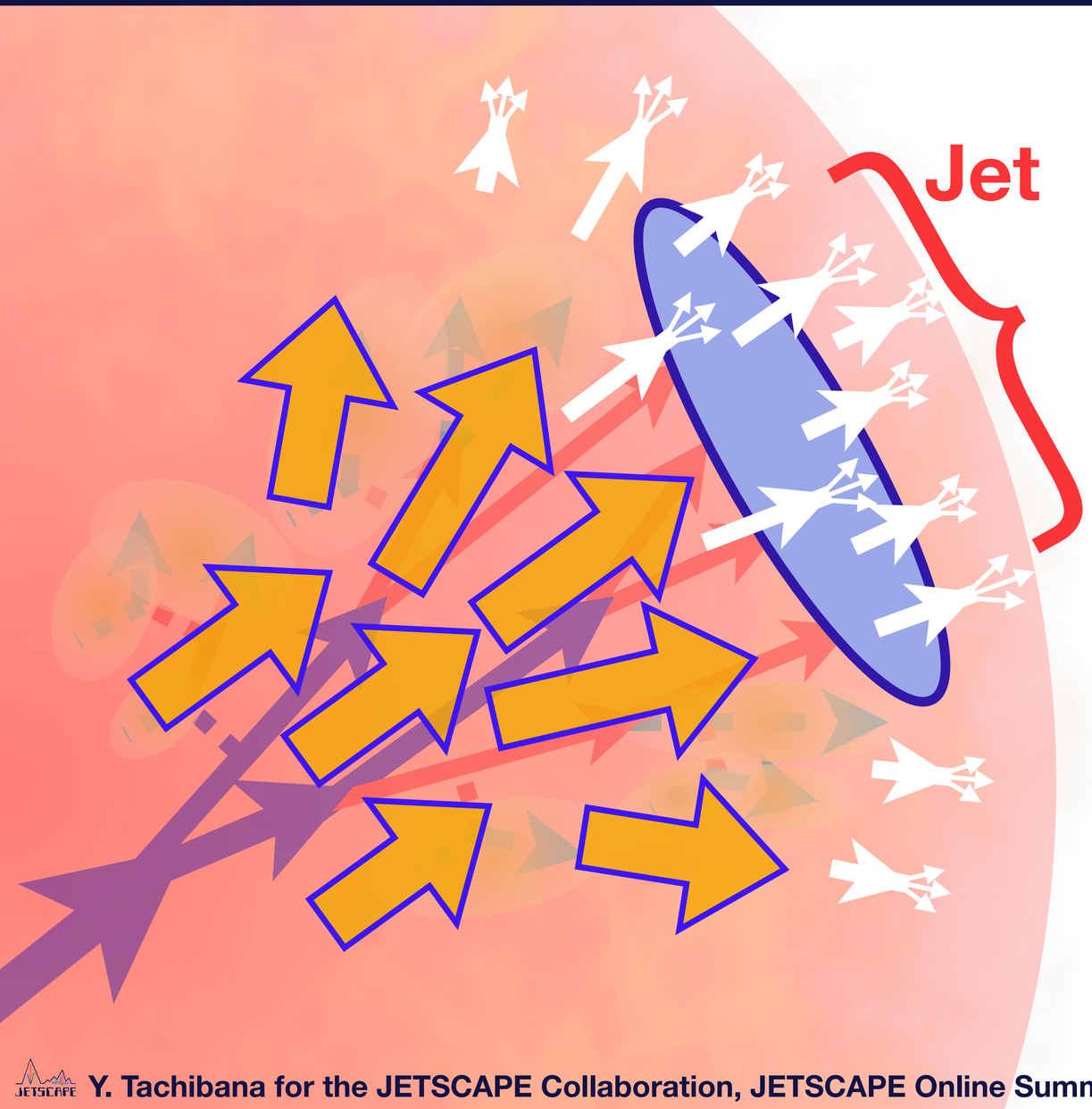
Medium Response Effect in Heavy Ion Collisions



- **Jet-induced excitation of medium**
  - Transport momentum transferred from jet
  - Modify particle emission around jet

- **Particles from medium repsonse**
  - Soft, spread out from jet
  - Jet-correlated, cannot/should not be subtracted
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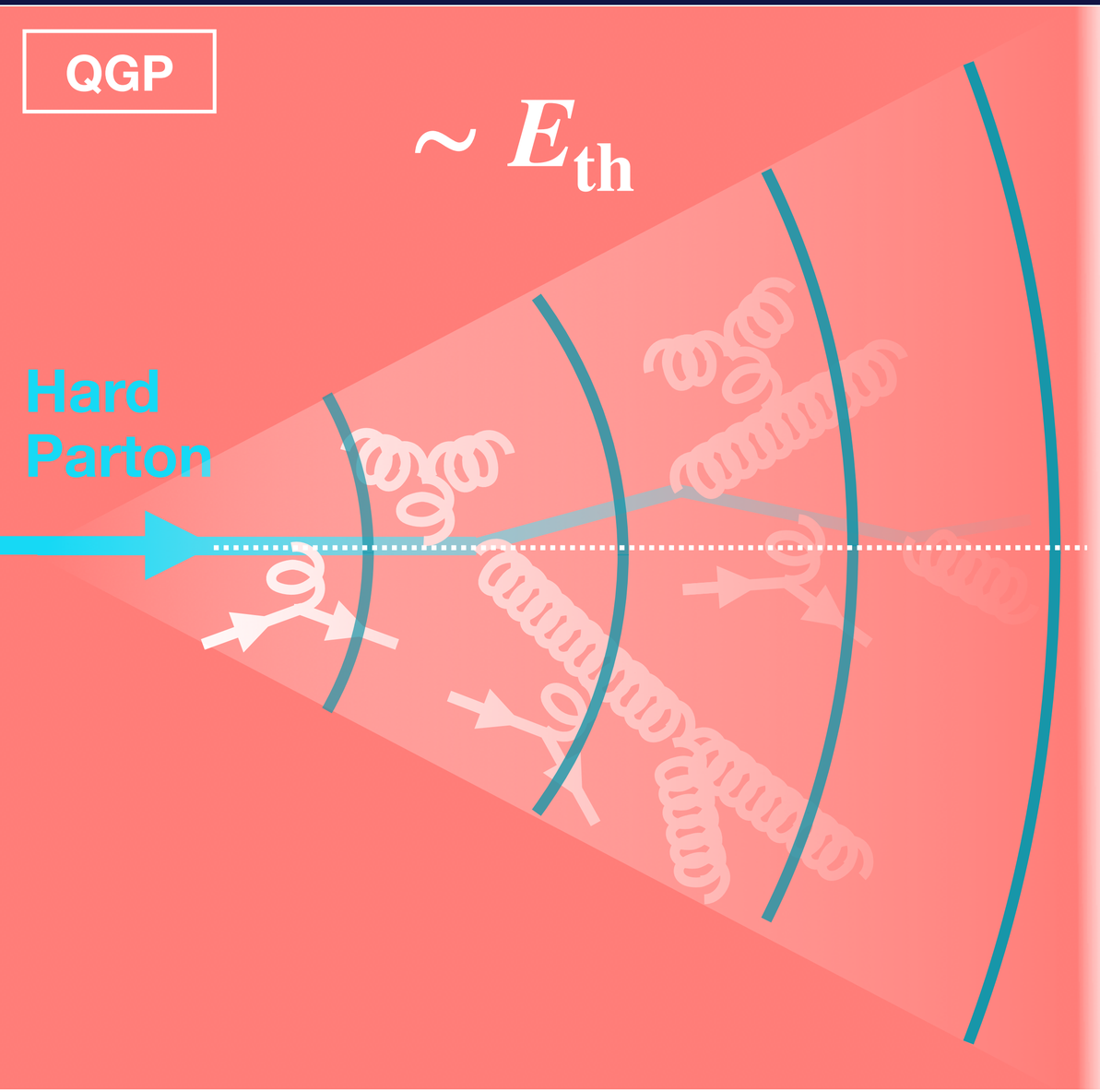
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Motivations



- **QGP properties involved with in-medium thermalization**

  E. Iancu, B. Wu ('15), YT, C. Shen, A. Majumder ('19), JETSCAPE ('19)…

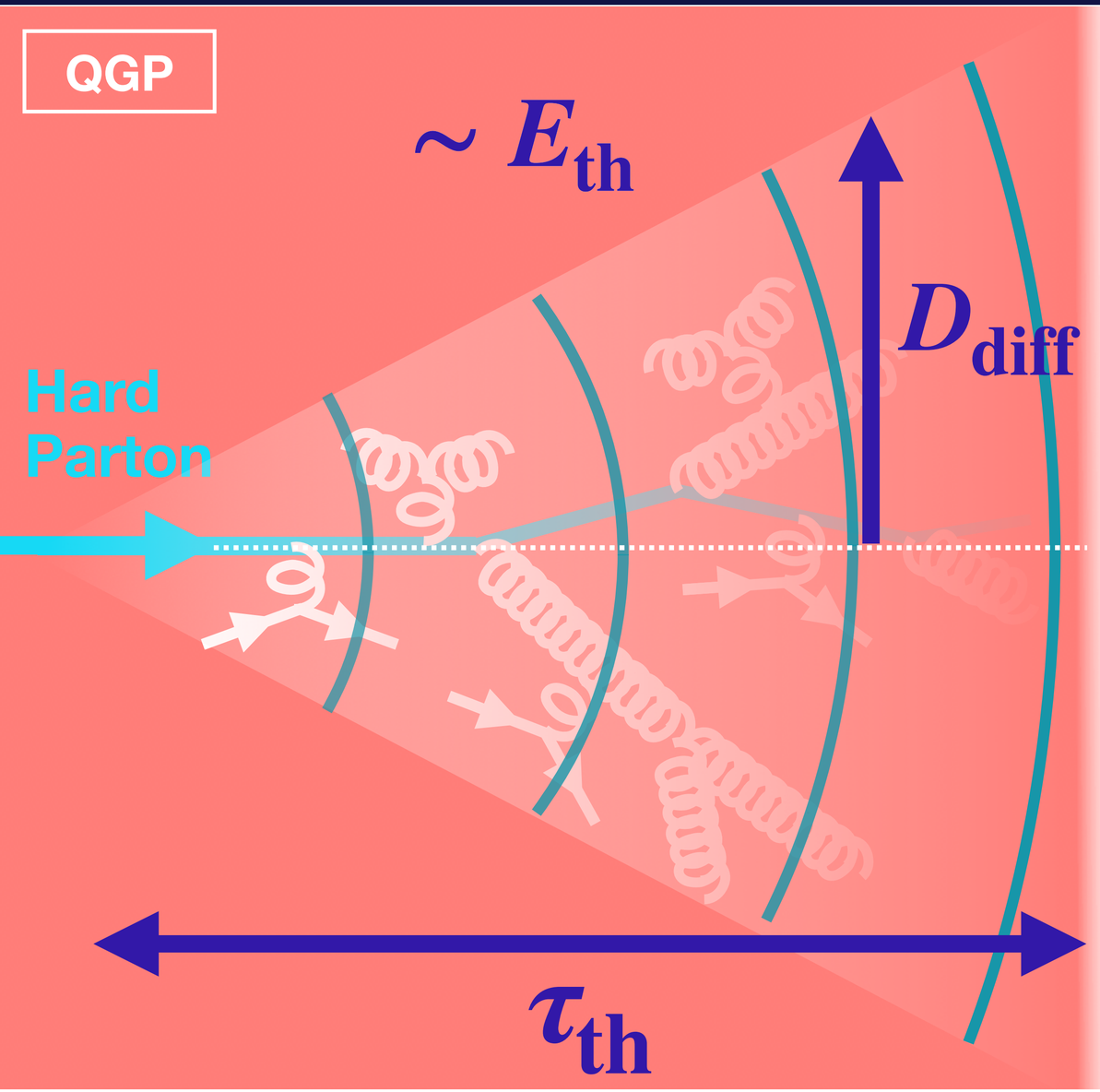
  - Partial thermalization of jet energy and momentum
  - Propagation as jet-induced hydrodynamic flow in medium

Thermalized part contribution in jet

Information of in-medium thermalization

Thermalization time τ_{th},
Diffusion coefficient D_{diff},
Typical energy scale E_{th}, etc.

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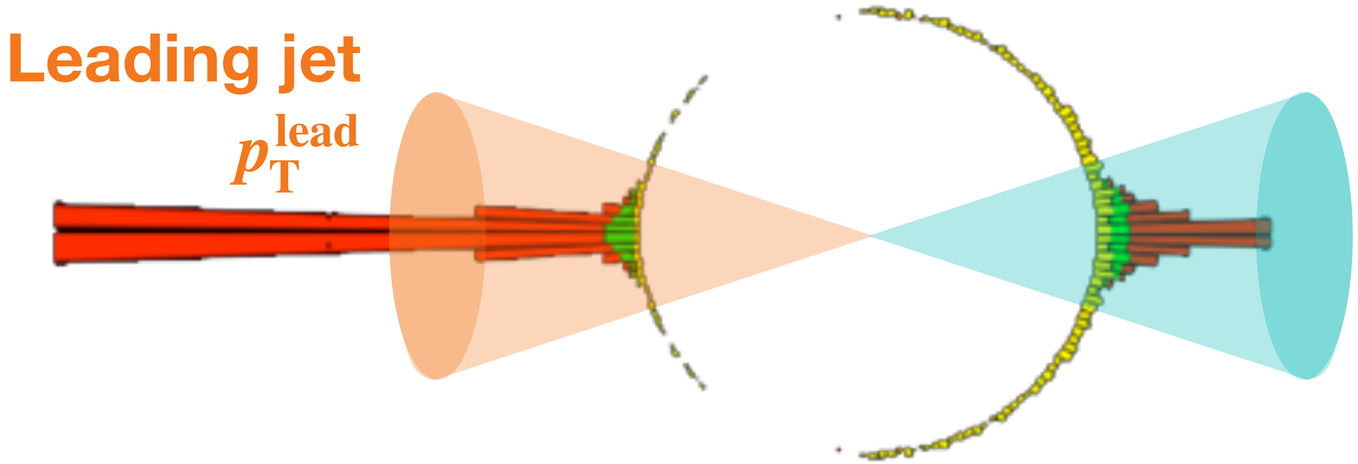
Re-distribution of the jet energy and momentum

CMS ('11)

>8 GeV

4-8 GeV

1-4 GeV



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Re-distribution of the jet energy and momentum

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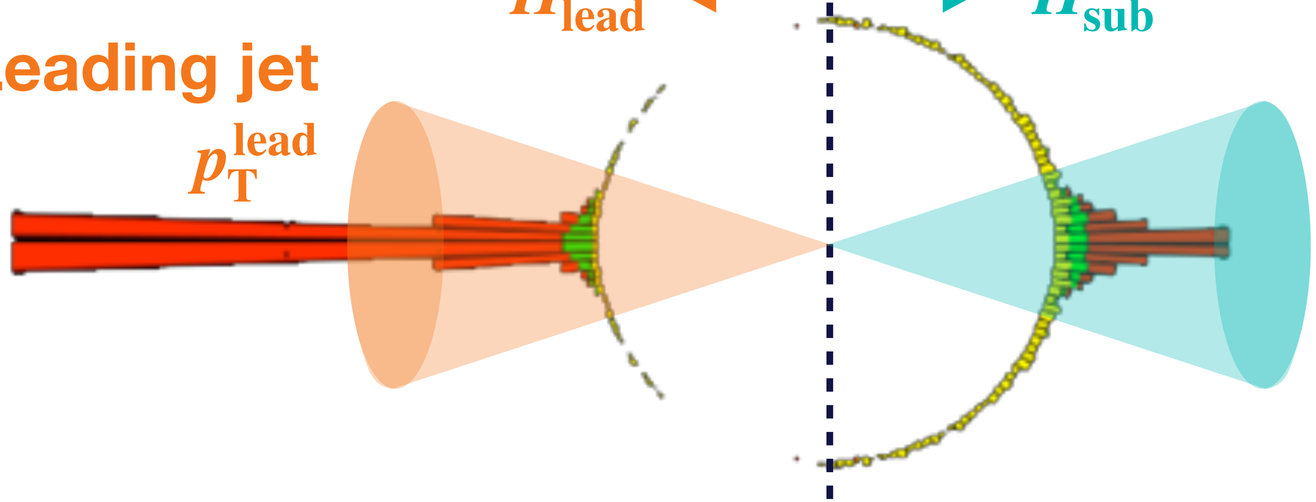
Balance

$$\sum_{i \in H_{\mathrm{lead}}} \vec{p}_i \simeq -\sum_{i \in H_{\mathrm{sub}}} \vec{p}_i$$

H_{lead} H_{sub}

Leading jet

$p_{\mathrm{T}}^{\mathrm{lead}}$



Subleading jet

$p_{\mathrm{T}}^{\mathrm{sub}} \; (< p_{\mathrm{T}}^{\mathrm{lead}})$

Motivations

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Re-distribution of the jet energy and momentum

CMS ('11)

>8 GeV
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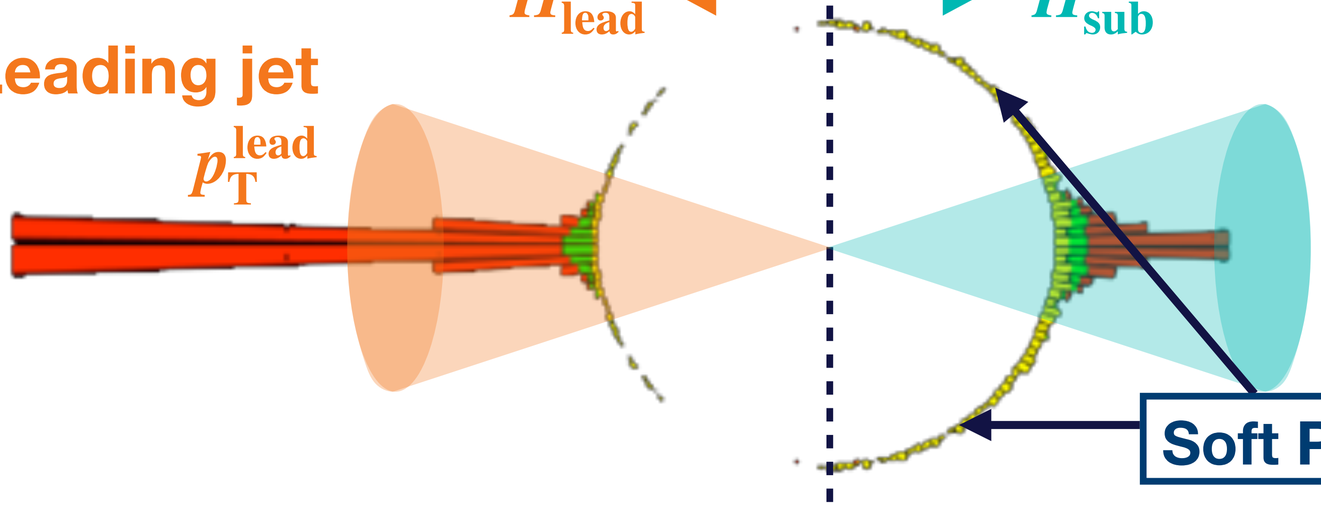
$H_{\rm lead}$ $H_{\rm sub}$

Leading jet

$p_{\rm T}^{\rm lead}$

Subleading jet

$p_{\rm T}^{\rm sub}$ $(< p_{\rm T}^{\rm lead})$



Soft Particles

Involve entire process in jet quenching

FAQ

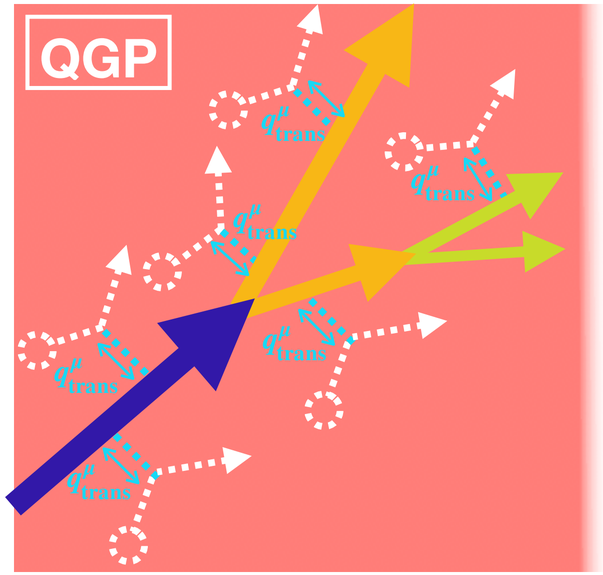
Q. Does medium response exist?

A. Medium response must always exist whenever jets interact with the medium. There are momentum transfers between jets and medium. Momentum is conserved for the whole system (jets+medium) in every single event.

Large modification of jet shower

Large momentum transfer

Large effect of medium response



FAQ

Q. Is medium response necessary?

A. It depends on the size of its contribution in the jet observable you are interested in. At least the size must be estimated for each observable.

Size of medium response contribution (Naive expectation)



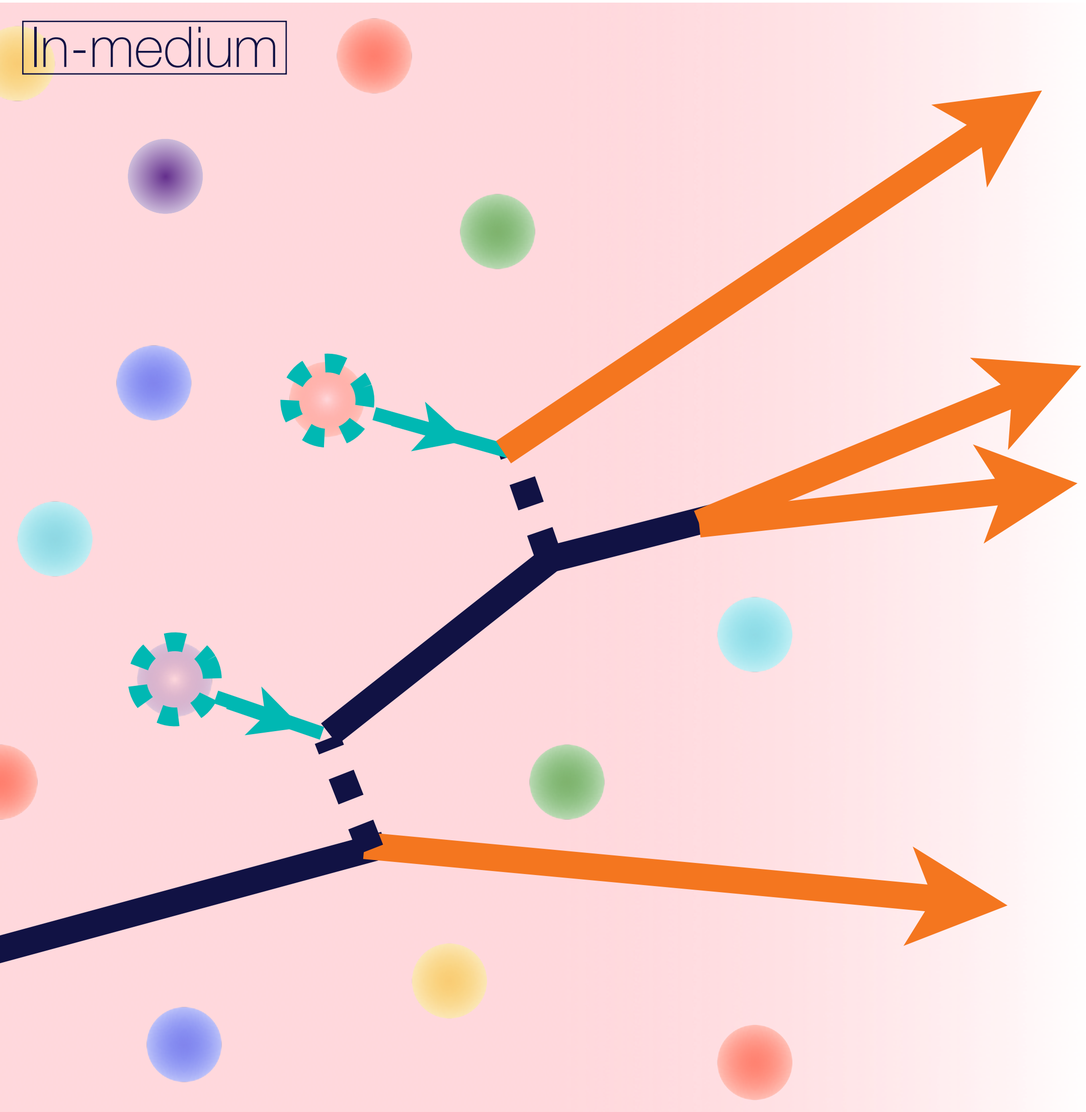
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Description of medium response in JETSCAE

Weakly-coupled Description: Recoils

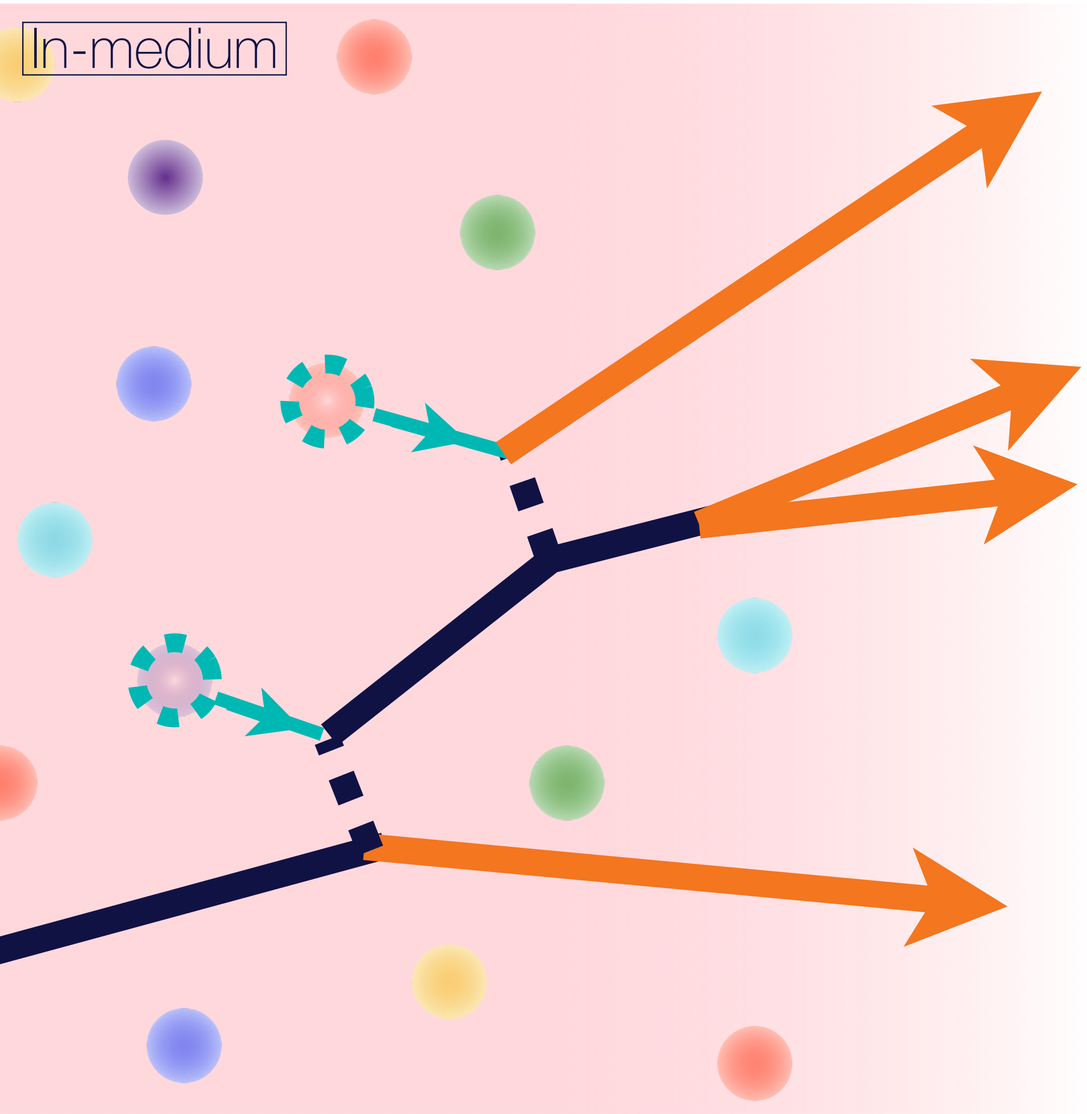
K. C. Zapp, F. Krauss, U. A. Wiedemann ('13), X.-N. Wang, Y. Zhu(13), T. Luo, et al.(15,18), C. Park, S. Jeon, C. Gale(18), S. Cao, A. Majumder (18)



Implemented in MATTER, LBT and MARTINI

- **Partons scattered off from medium**
  - Sample a parton from thermal QGP medium for each scattering
  - Add the recoiled partons to the jet shower
  - Reasonable for partons with $E > E_{\mathrm{med}}$
    (E_{med}: typical energy of medium constituents)

Weakly-coupled Description: Recoils



- **Picked up momentum from medium (a.k.a negative partons or holes)**
  - Original momenta of sampled thermal partons
  - Assumed to freestream
  - Subtracted from final signal

$$\left.\frac{dp^\mu}{d\eta d\phi}\right|_{\text{signal}} = \left.\frac{dp^\mu}{d\eta d\phi}\right|_{\text{jet shower}} - \left.\frac{dp^\mu}{d\eta d\phi}\right|_{\text{picked-up}}$$

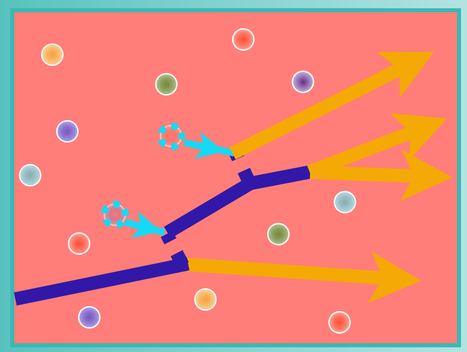
Description of medium response in JETSCAE

Recoil

MATTER

LBT

MARTINI



Weakly-coupled ($> E_{\mathrm{med}}$) $\sim E_{\mathrm{th}}$ ($\sim \sup E_{\mathrm{med}}$) Strongly-coupled ($\sim E_{\mathrm{med}}$)

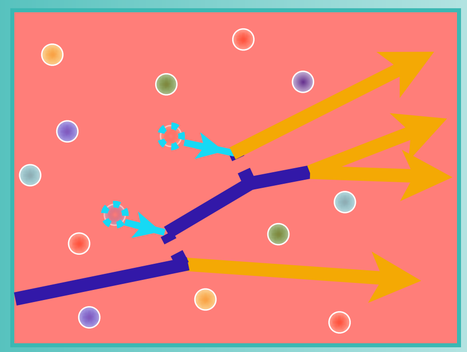
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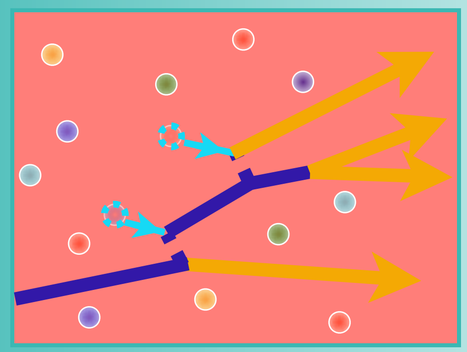
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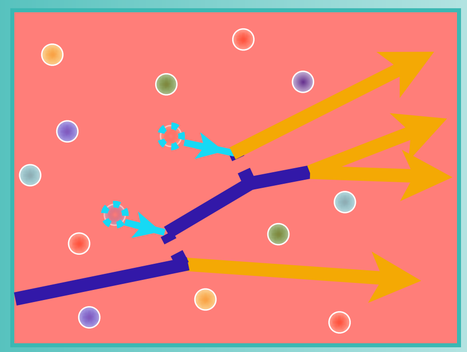
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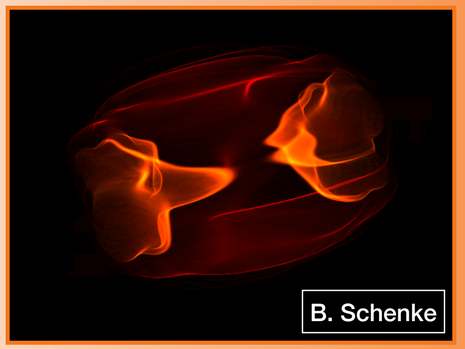


See Chun's Lecture

Hydrodynamics

MUSIC

CLVisc

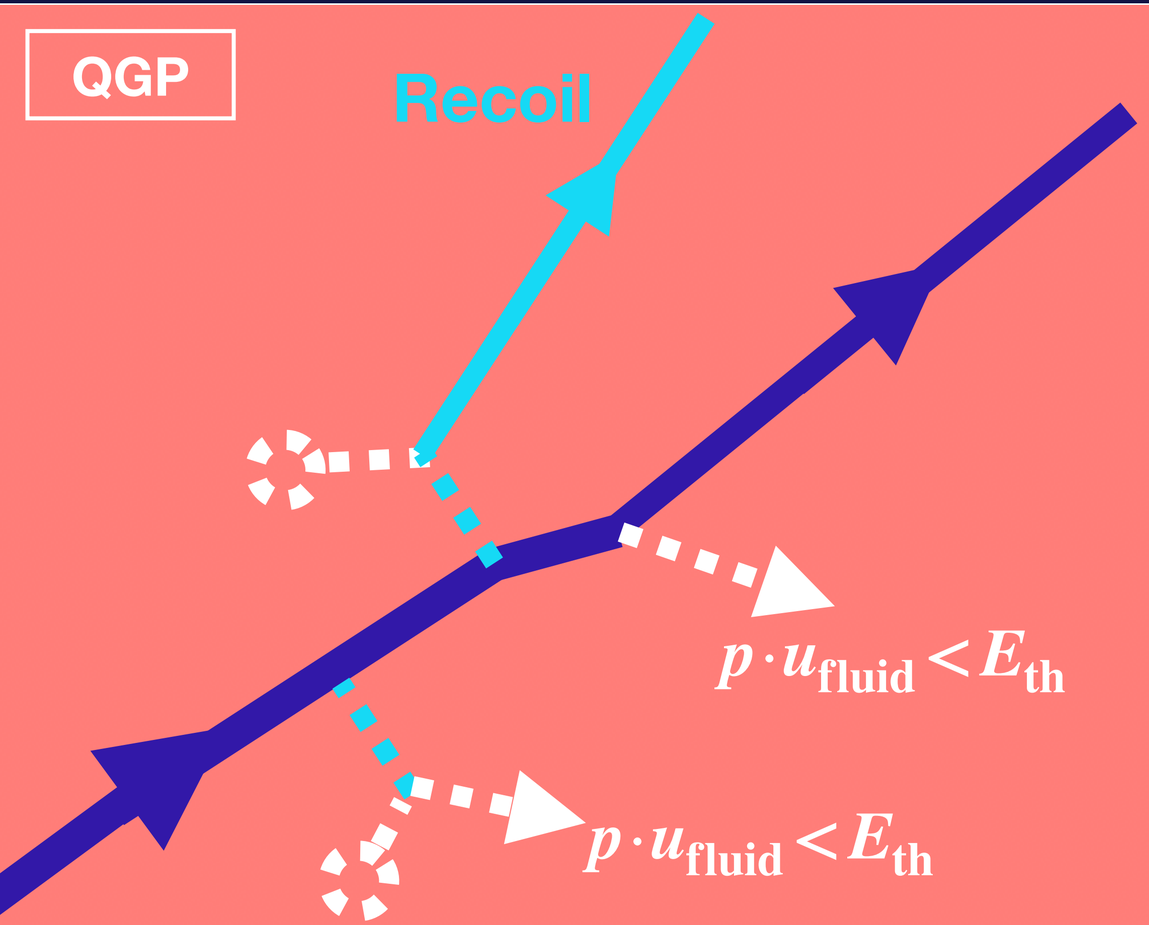


Weakly-coupled ($> E_{\mathrm{med}}$)

$\sim E_{\mathrm{th}}$ ($\sim \sup E_{\mathrm{med}}$)

Strongly-coupled ($\sim E_{\mathrm{med}}$)

Access to the Strongly-coupled Description (Hydro)



E_{th} : energy cut for in-medium thermalization

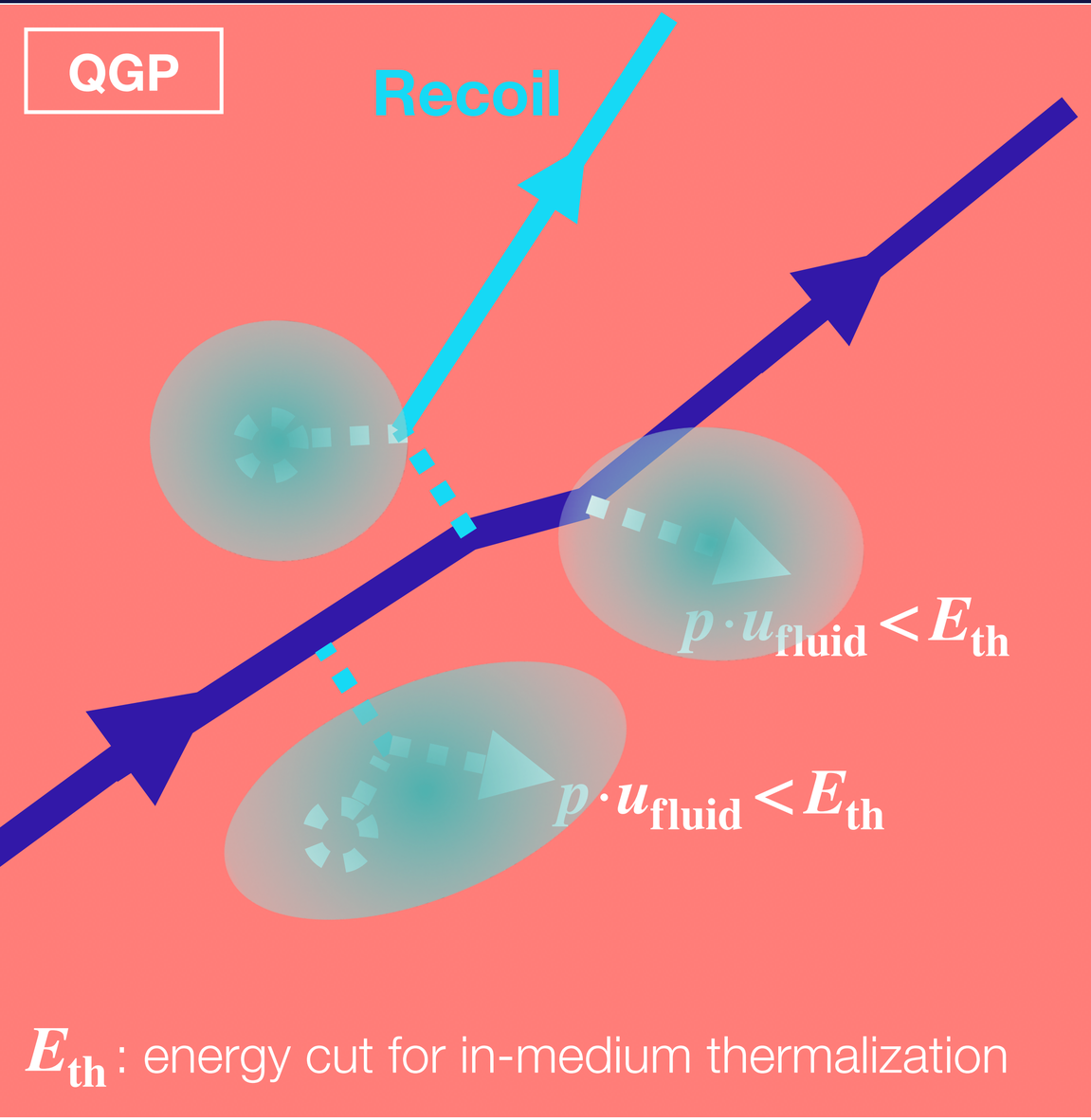
- **Diffusion into the medium**
  - Absorption of soft partons ($E < E_{\mathrm{th}} \sim \sup E_{\mathrm{med}}$)
  - Picked up energy and momentum

  Model: **Causal Diffusion**

- **Evolution as part of bulk medium**
  - Flow excited by diffused jet momentum
  - Jet-correlated particle emission from medium

  Model: **Hydrodynamics (e.g. MUSIC)**

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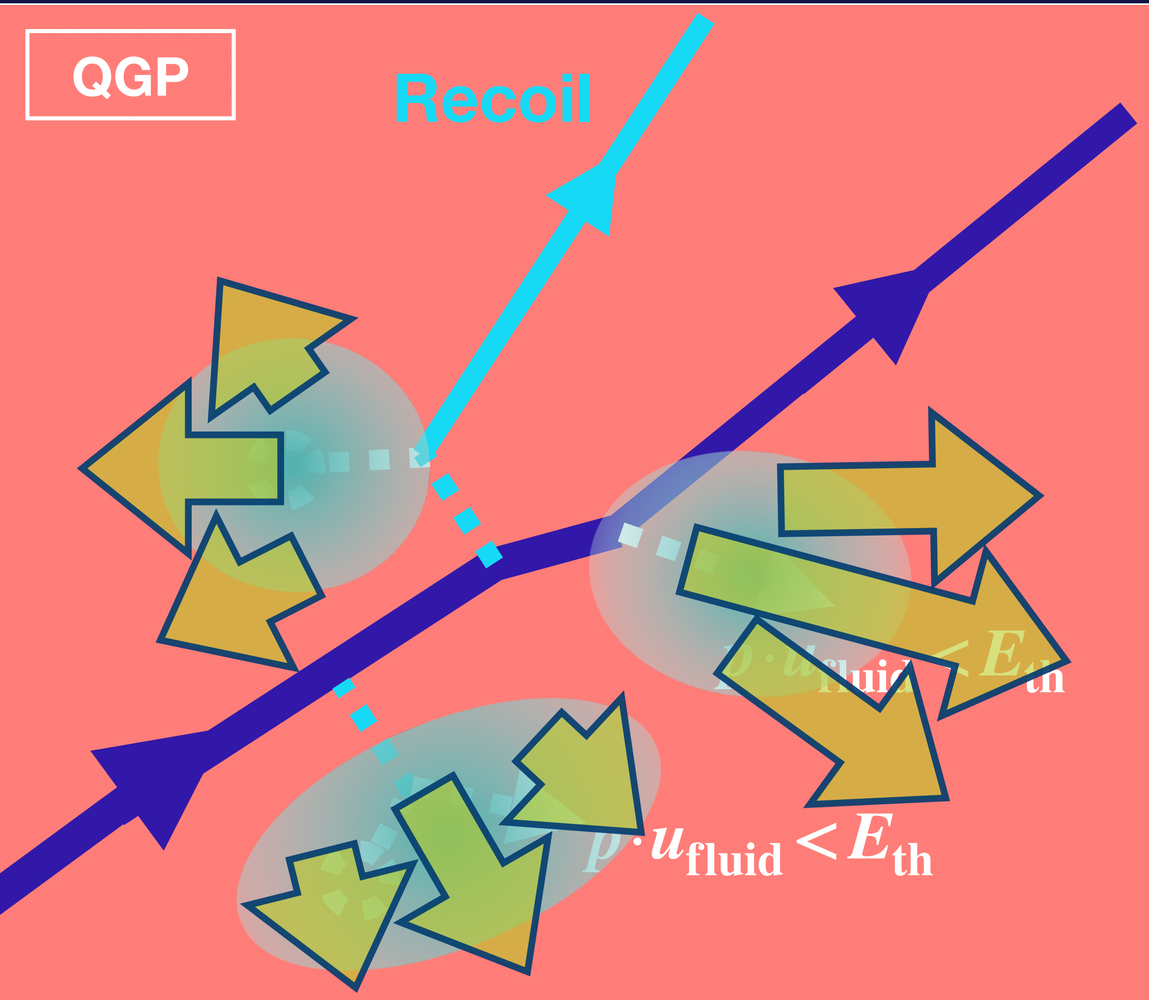
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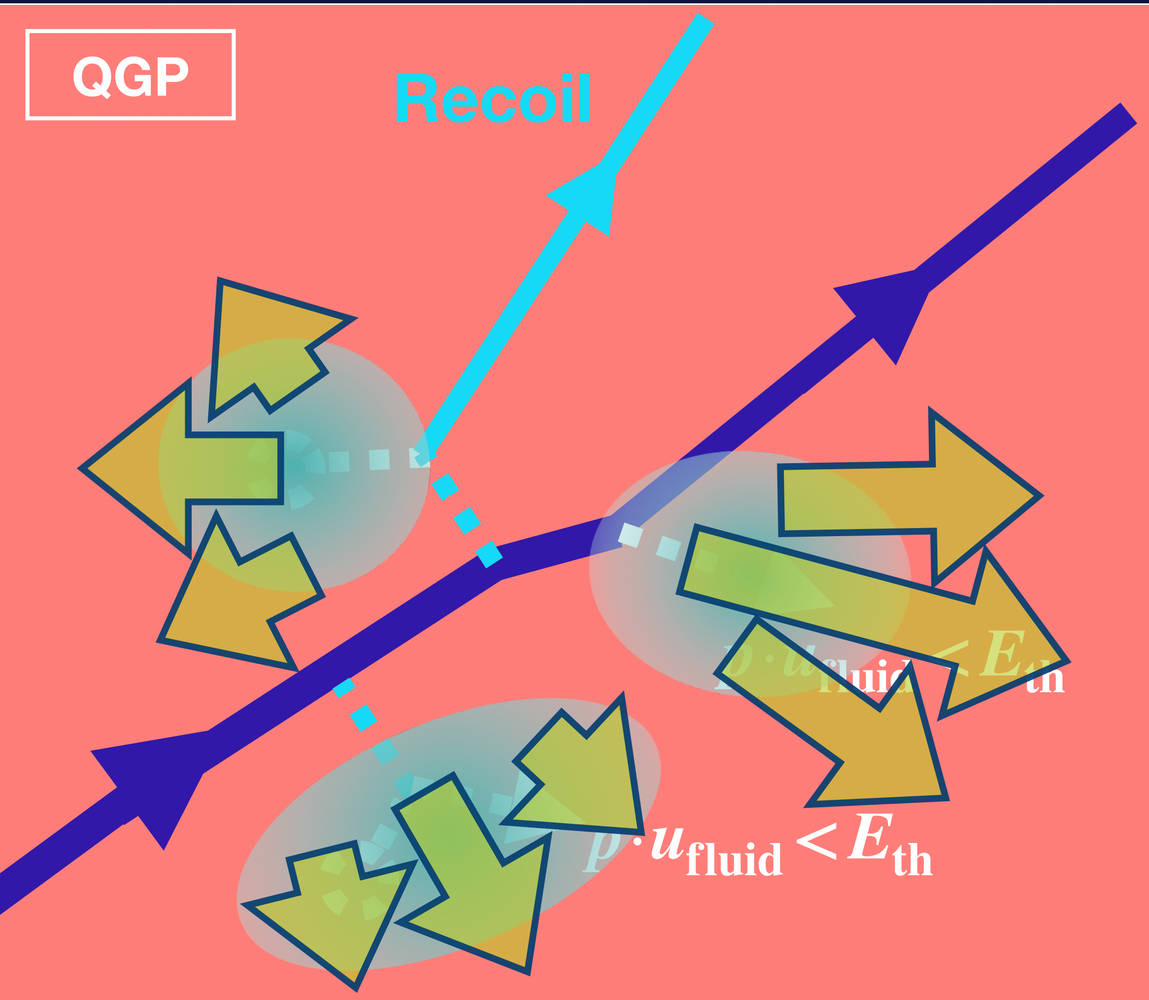
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  ➡ **Source Profile for Fluid**

- **Evolution as part of bulk medium**
  - Flow excited by diffused jet momentum
  - Jet-correlated particle emission from medium

  Model: **Hydrodynamics (e.g. MUSIC)**

  ➡ **Hydrodynamic Response**

Strongly-coupled Description: Hydrodynamics

- **Conventional hydrodynamic equation**

$$\nabla_\mu T^{\mu\nu}_{\mathrm{med}}(x) = 0$$

$T^{\mu\nu}_{\mathrm{med}}$: energy-momentum tensor of medium fluid

- Energy momentum conservation in medium fluid

- **Hydrodynamic equation with source term**

e.g.) YT, N.-B. Chang, G.-Y. Qin (17,19), W. Chen, T. Luo, S. Cao, L. Pang, X.-N, Wang (18), YT, C. Shen, A. Majumder (20)

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

J^ν_{jet}: Incoming four-momentum density due to jet propagation (source term)

- Medium fluid evolution with energy-momentum deposition
- Bulk part particle with hydro response obtained via Cooper-Frye

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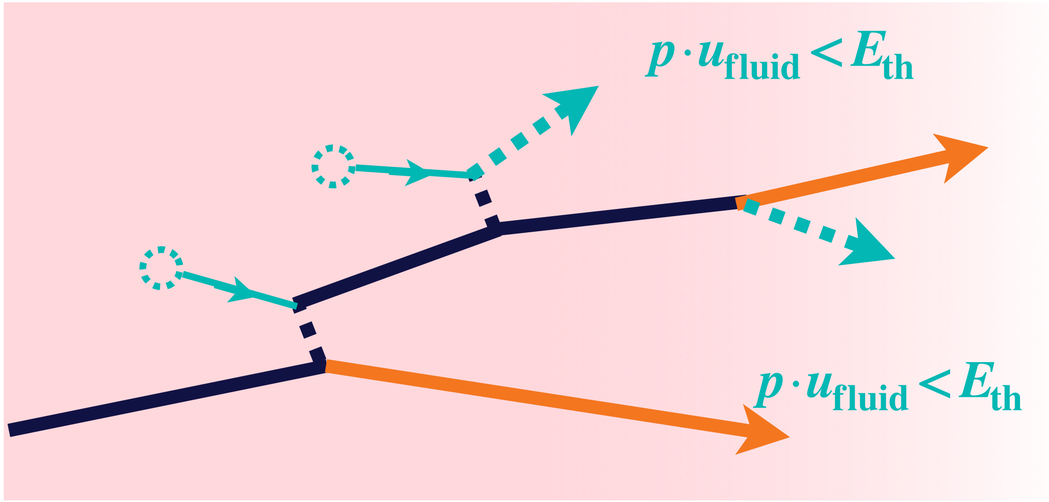
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Modeled with Causal Diffusion (Liquefier) in JETSCAPE

Causal Diffusion ans Source Profile

- **Energy-momentum deposition**
  - Soft parton absorption
  - Picked-up energy and momentum

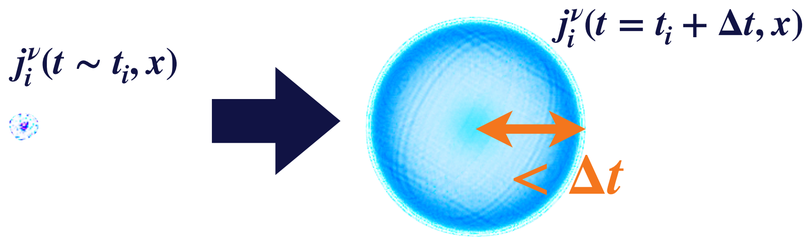


- **Causal source profile**
  - Relativistic diffusion equation

$$\left[\frac{\partial}{\partial t} + \tau_{\mathrm{diff}}\frac{\partial^2}{\partial t^2} - D_{\mathrm{diff}}\nabla^2\right] j^{\nu}(x) = 0$$

with initial condition

$$j^{\nu}(t = t_{\mathrm{dep}}, \vec{x}) = p^{\nu}_{\mathrm{dep.}}\delta^{(3)}(\vec{x} - \vec{x}_{\mathrm{dep}})$$



Parameters

E_{th}: Momentum scale for in-medium thermalization

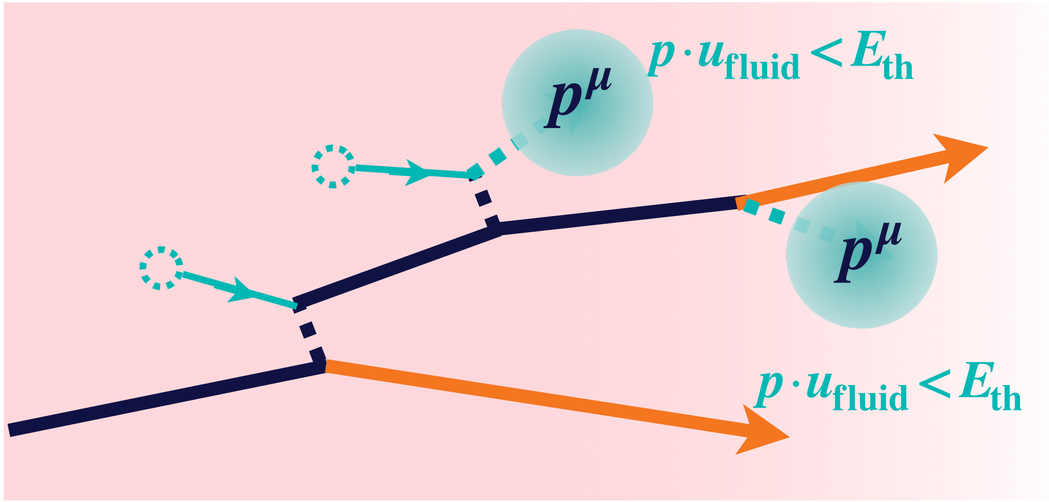
Δt: Timescale for in-medium thermalization

D_{diff}: Diffusion coefficient

τ_{diff}: Relaxation time in diffusion

Causal Diffusion ans Source Profile

- **Energy-momentum deposition**
  - Soft parton absorption
  - Picked-up energy and momentum

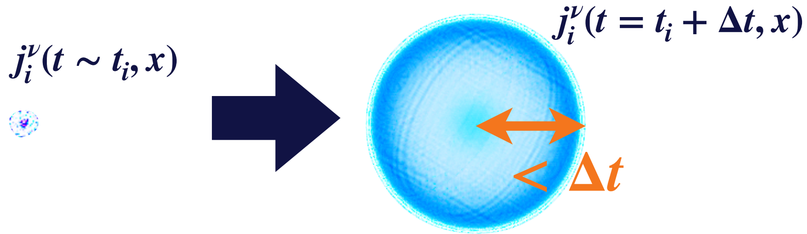


- **Causal source profile**
  - Relativistic diffusion equation

$$\left[\frac{\partial}{\partial t} + \tau_{\rm diff}\frac{\partial^2}{\partial t^2} - D_{\rm diff}\nabla^2\right] j^\nu(x) = 0$$

with initial condition

$$j^\nu(t = t_{\rm dep}, \vec{x}) = p^\nu_{\rm dep.}\delta^{(3)}(\vec{x} - \vec{x}_{\rm dep})$$



Parameters

$E_{\rm th}$: Momentum scale for in-medium thermalization

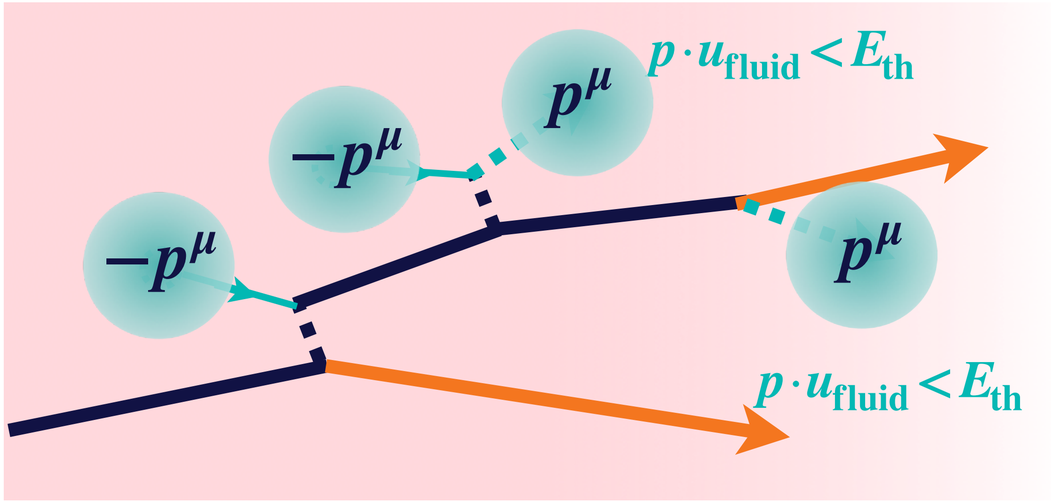
Δt: Timescale for in-medium thermalization

$D_{\rm diff}$: Diffusion coefficient

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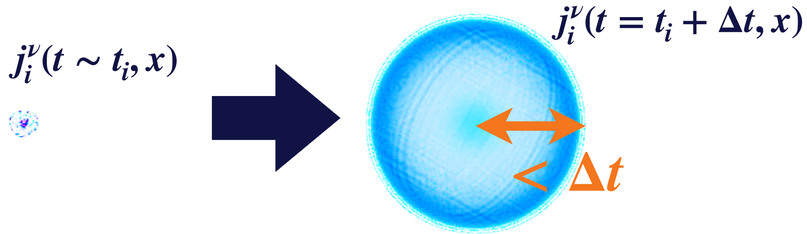


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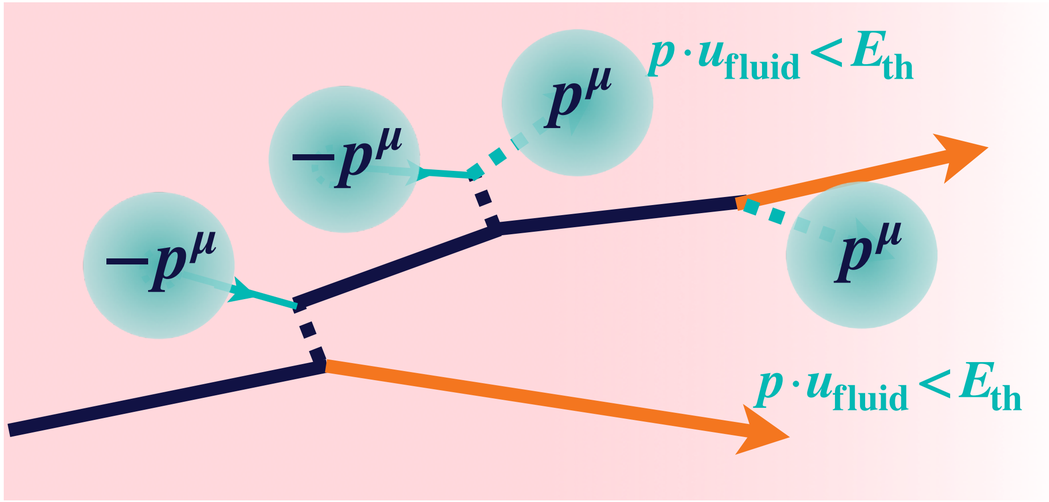
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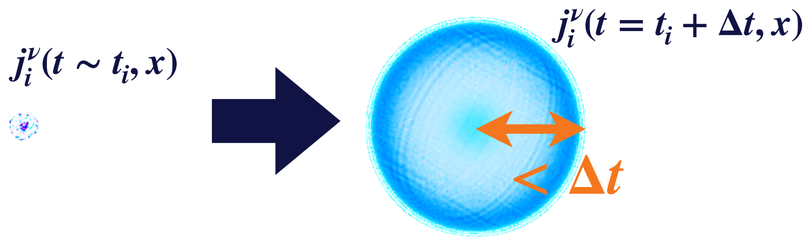


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Para **Characterize dynamics during in-medium thermalization process**

$E_{\rm th}$: Momentum scale for in-medium thermalization

$D_{\rm diff}$: Diffusion coefficient

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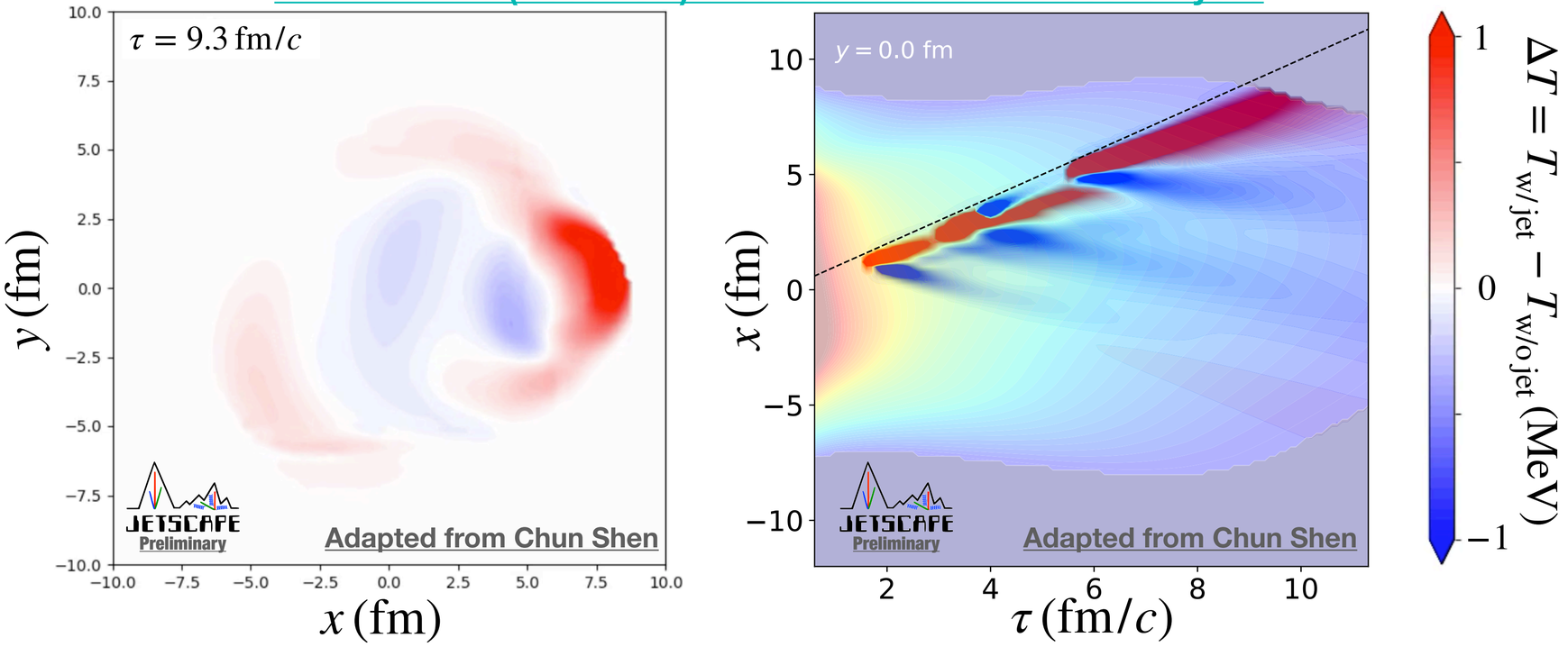
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Evolution of Medium Response by Strongly Coupled Description

- **Hydrodynamic flow induced by jet momentum deposition**
  - Jet following flow by positive energy deposition
  - Diffusion wakes and flow by momentum picked-up from medium

Temperature field modification in medium by jet propagation

MATTER+LBT (Recoil ON) + Causal Diffusion + Viscous Hydro

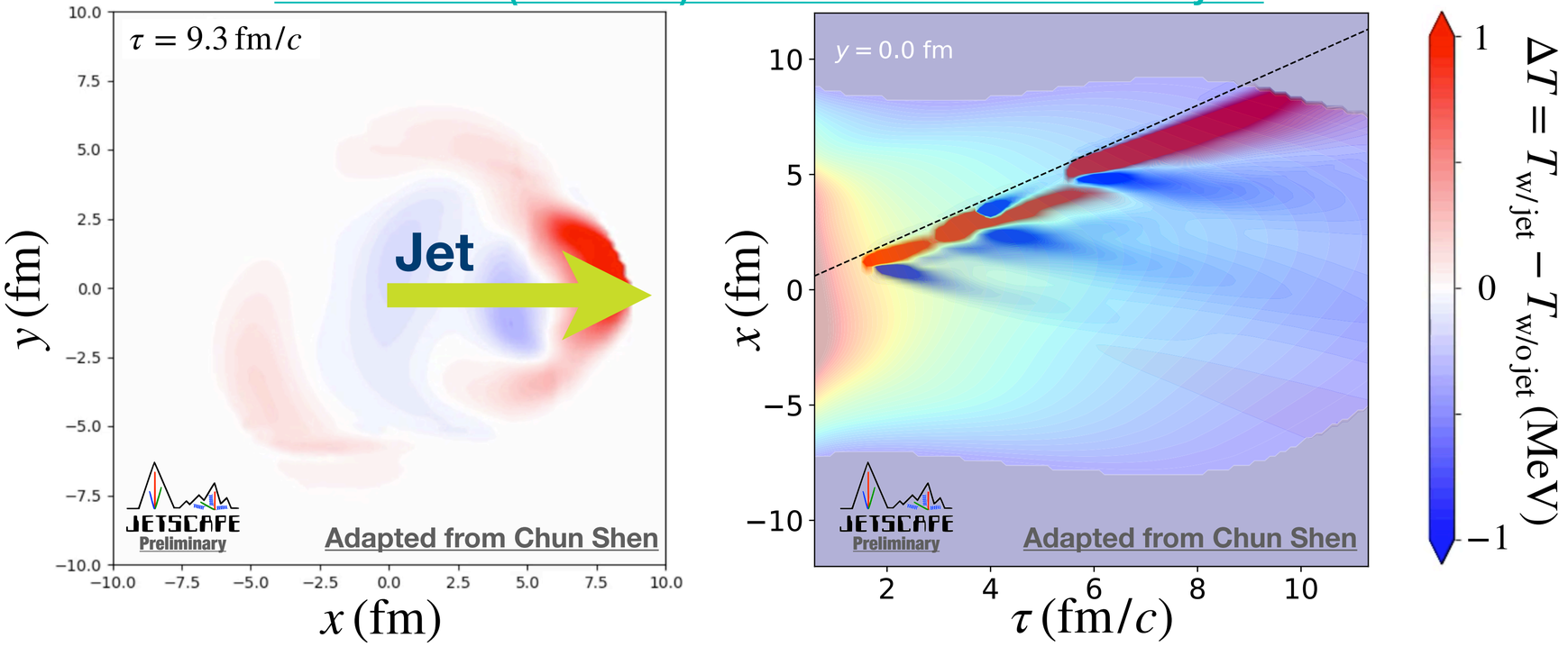


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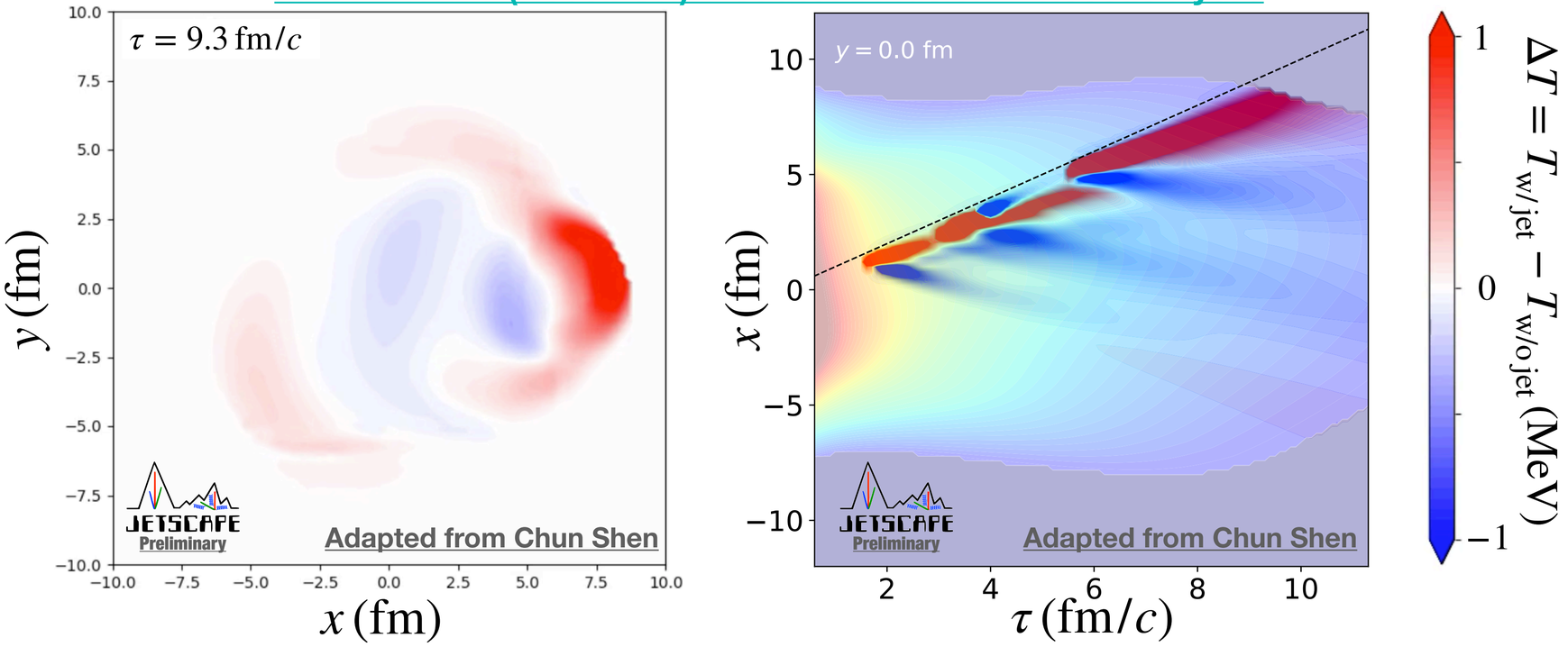


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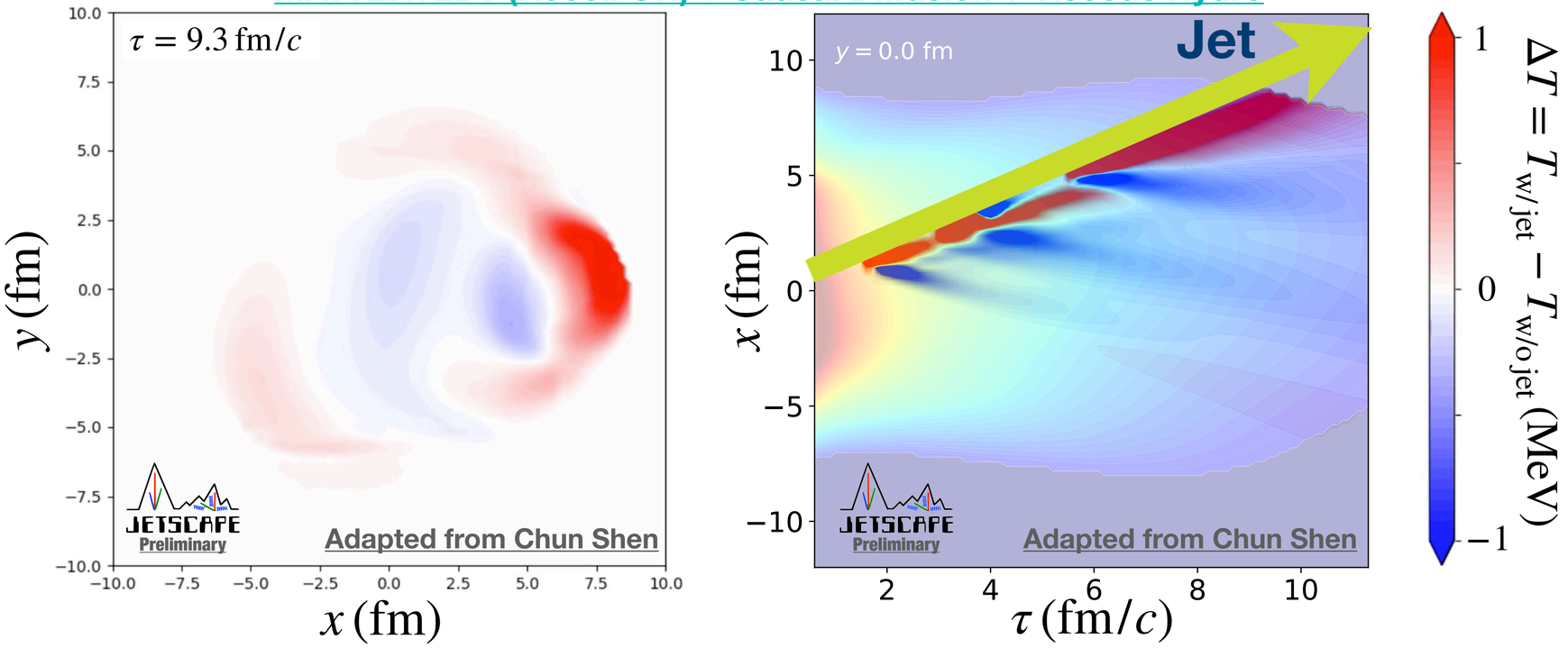


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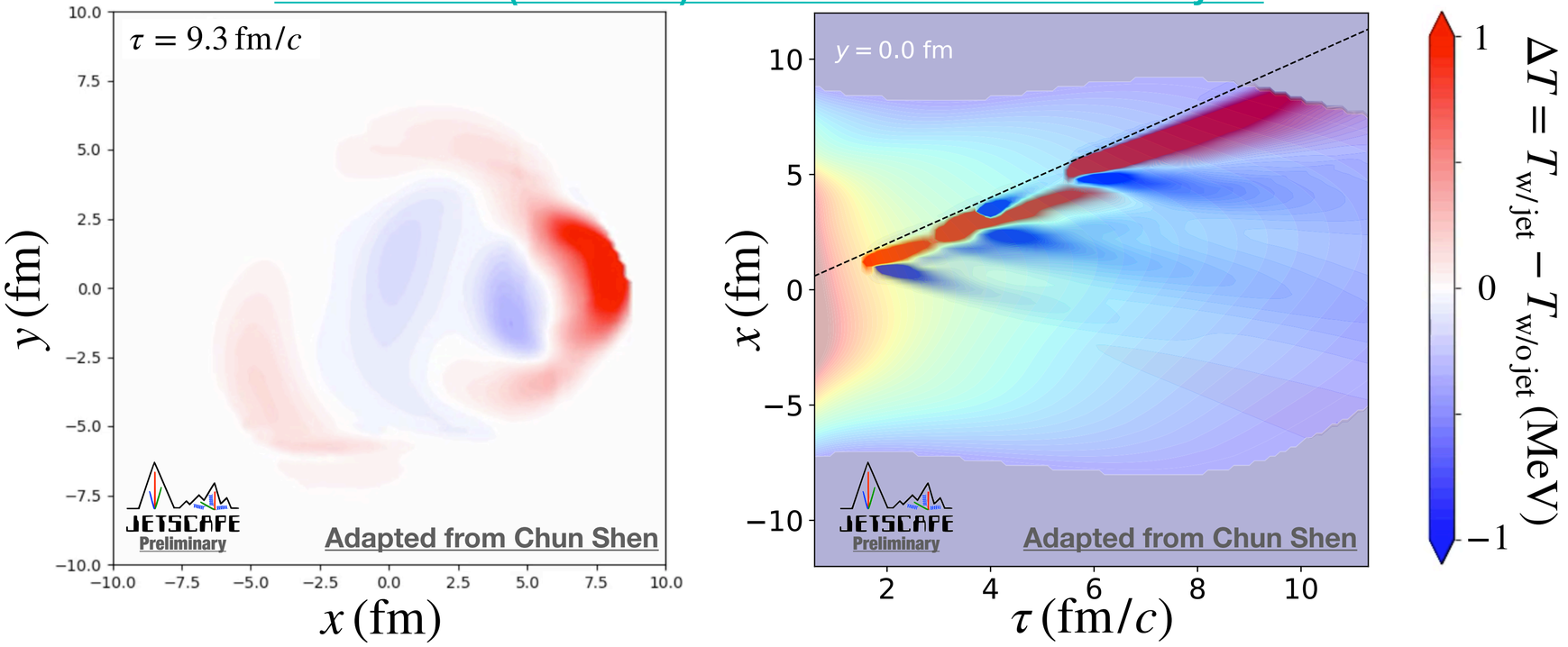


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Description of medium response in JETSCAE

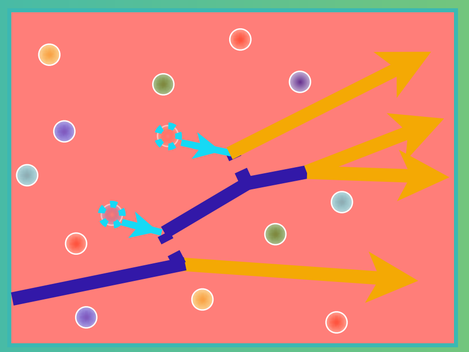
Recoil

MATTER
LBT
MARTINI

Causal Diffusion
(Causal Liquefier Module)

Hydrodynamics

MUSIC
CLVisc





Adapted from Chun Shen

Weakly-coupled ($> E_{\mathrm{med}}$) $\sim E_{\mathrm{th}}$ ($\sim \sup E_{\mathrm{med}}$) Strongly-coupled ($\sim E_{\mathrm{med}}$)

#jet-tachibana

JETSCAPE School 2020

Results From JETSCAPE

- With Weakly-coupled Description by Recoils
- With Strongly-coupled Description by hydrodynamics

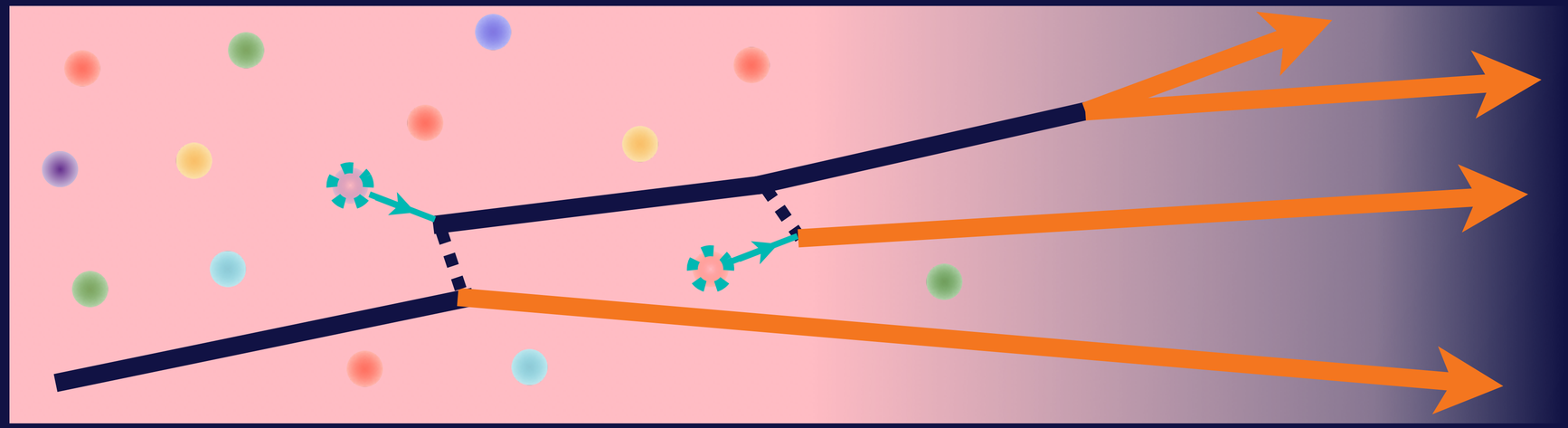
#jet-tachibana

JETSCAPE School 2020

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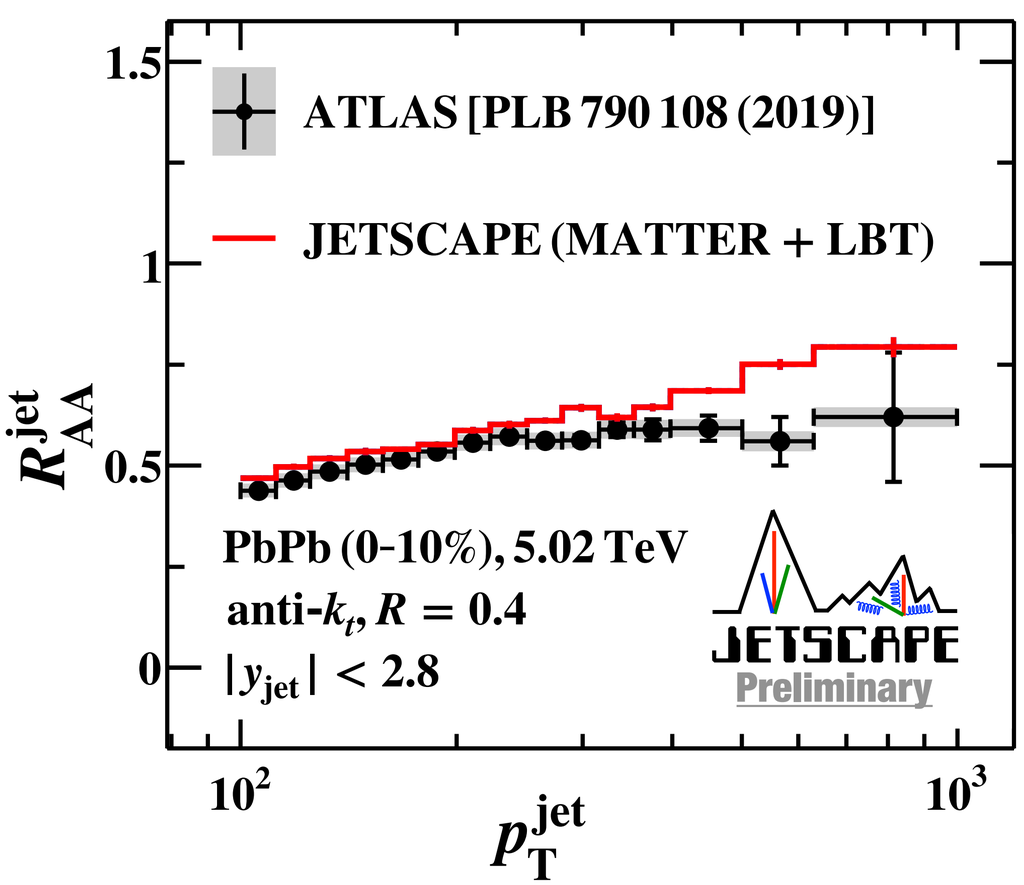
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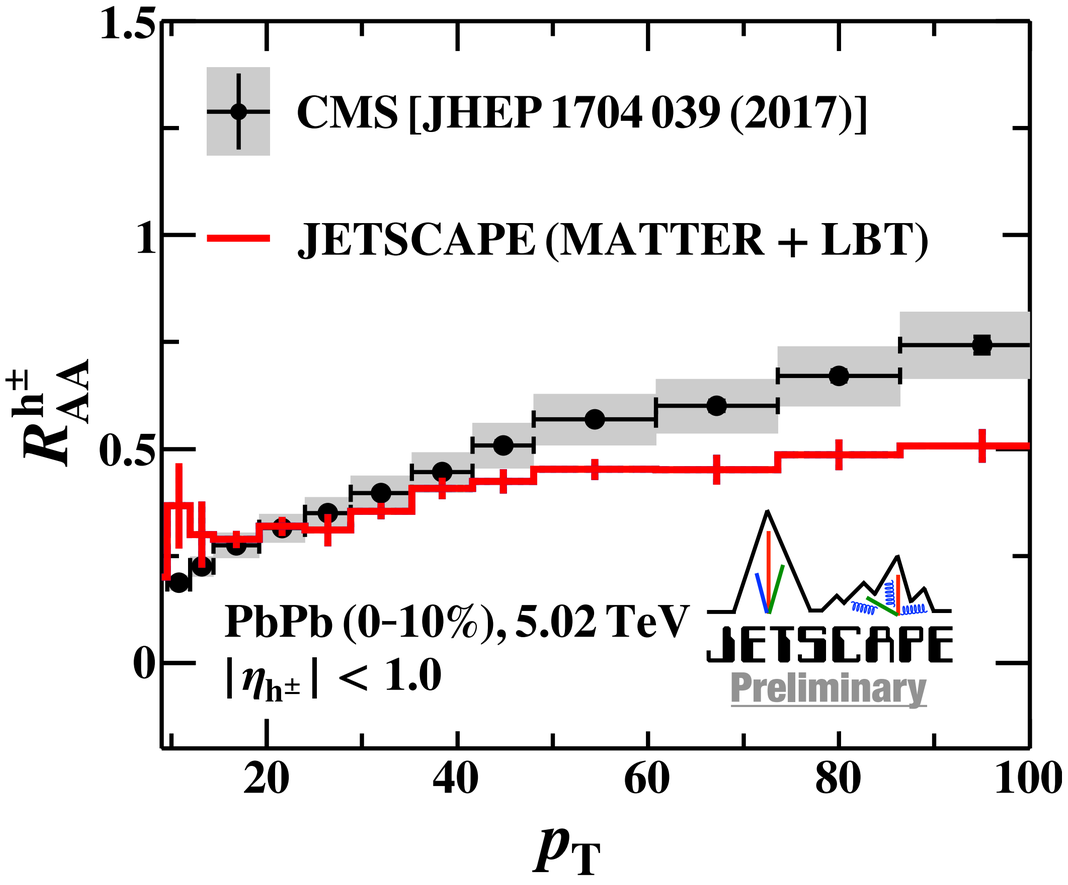


Results with Weakly-coupled Description of Med. Res.

- **Jet-R_{AA} and charged hadron-R_{AA}**
  - Tuned for PbPb (0-10%) collisions at 5.02 TeV and 2.76 TeV
  - Jet Shower by MATTER+LBT (with Recoil)

A. Kumar QM19

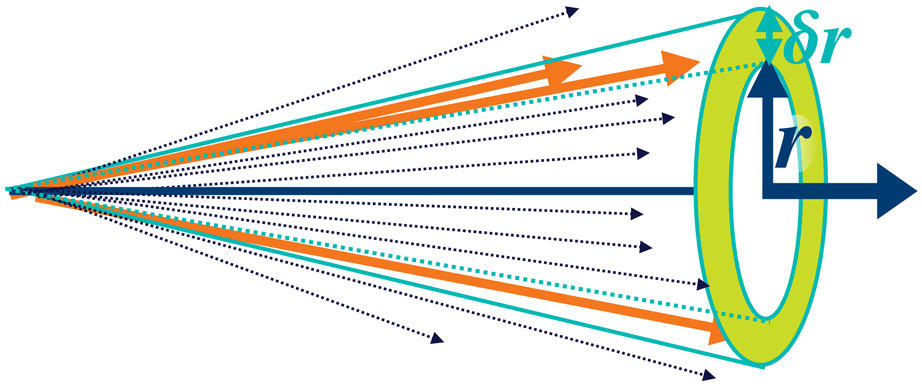




Results with Weakly-coupled Description of Med. Res.

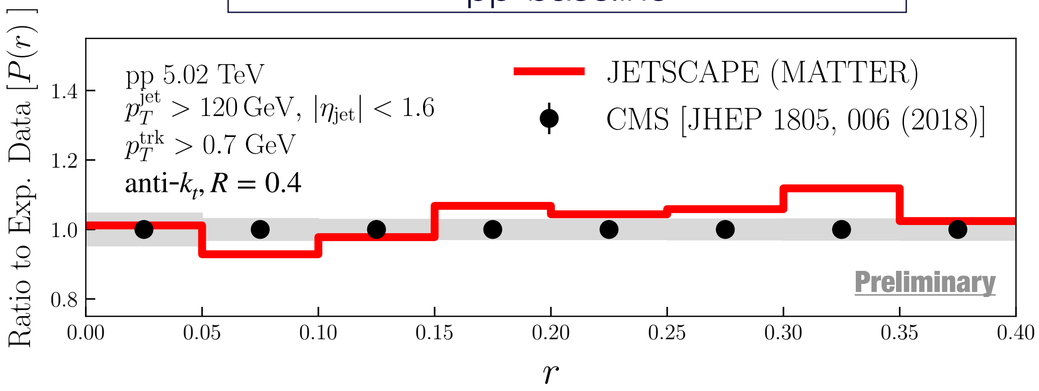
- **Jet shape function**
  - Angular structure of jet

$$P(r) = \frac{1}{N_{\text{jet}}} \sum_{\text{jet}} \frac{\sum_{\text{trk}\in(r\pm\delta r/2)} p_{\text{T}}^{\text{trk}}}{\delta r}$$

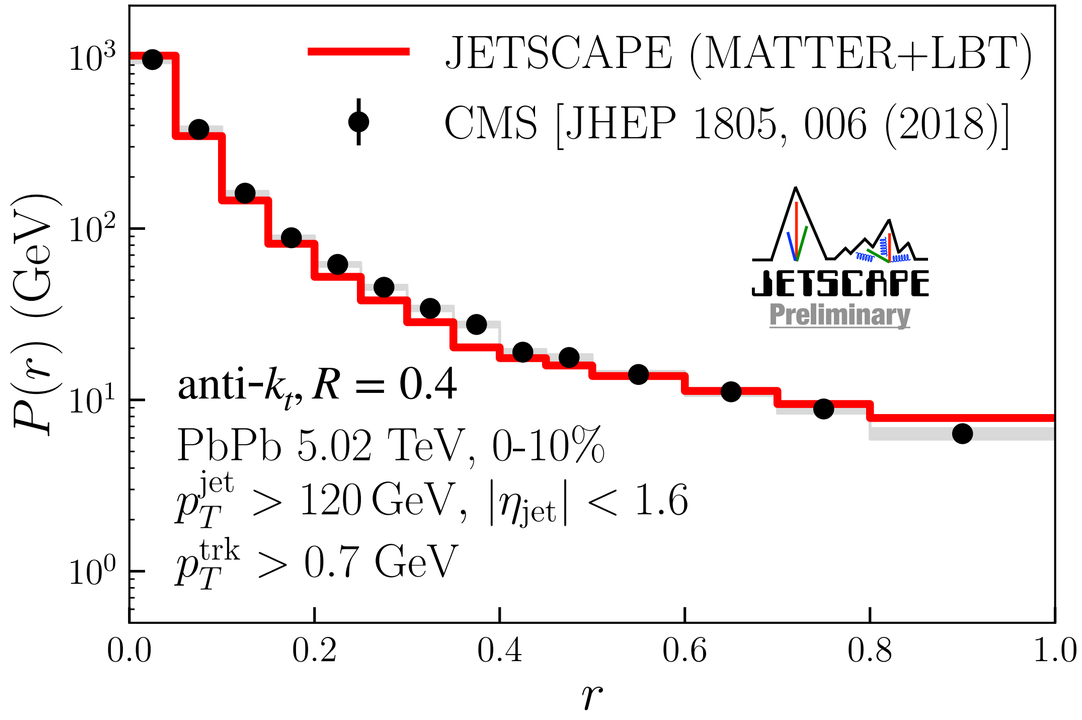


$$r = \sqrt{(\eta_{\text{trk}} - \eta_{\text{jet}})^2 + (\phi_{\text{trk}} - \phi_{\text{jet}})^2}$$

pp-baseline



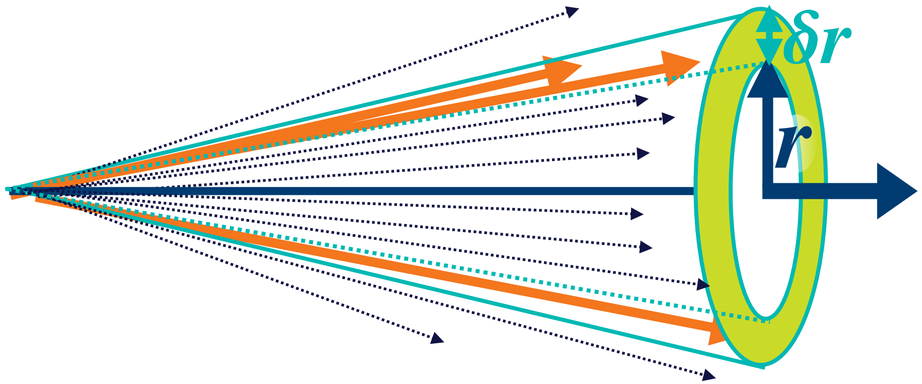
PbPb @ 5.02 TeV

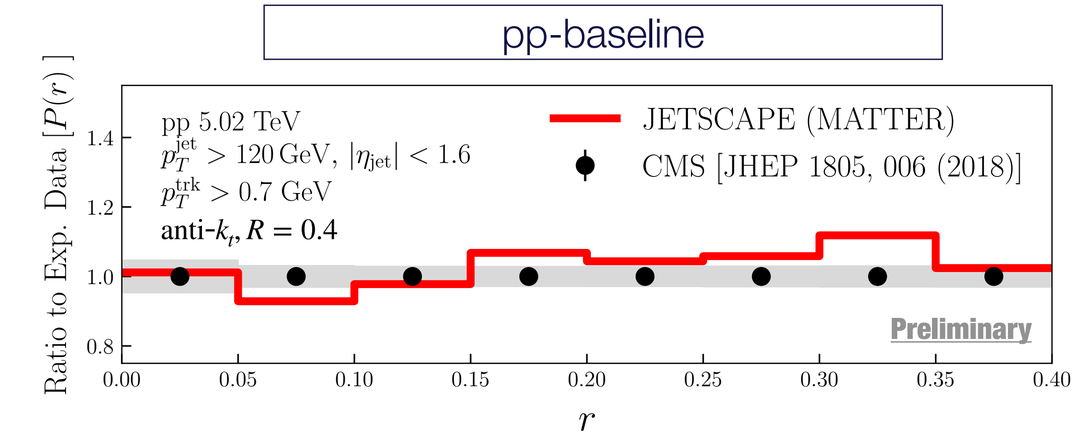


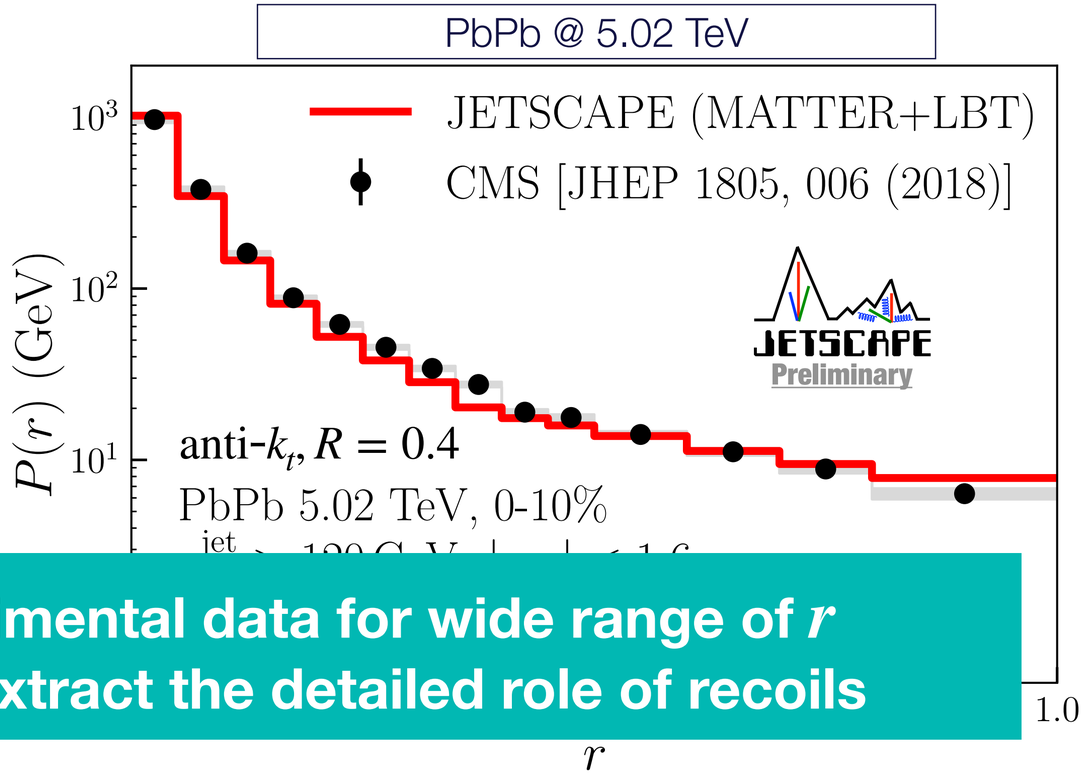
Results with Weakly-coupled Description of Med. Res.

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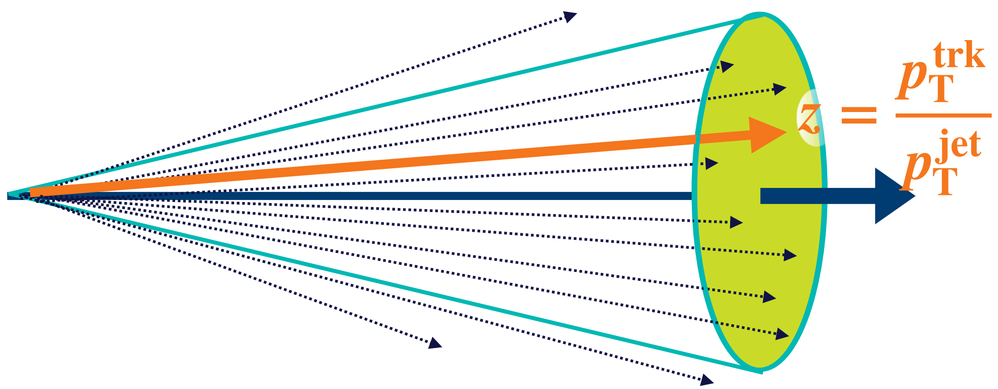


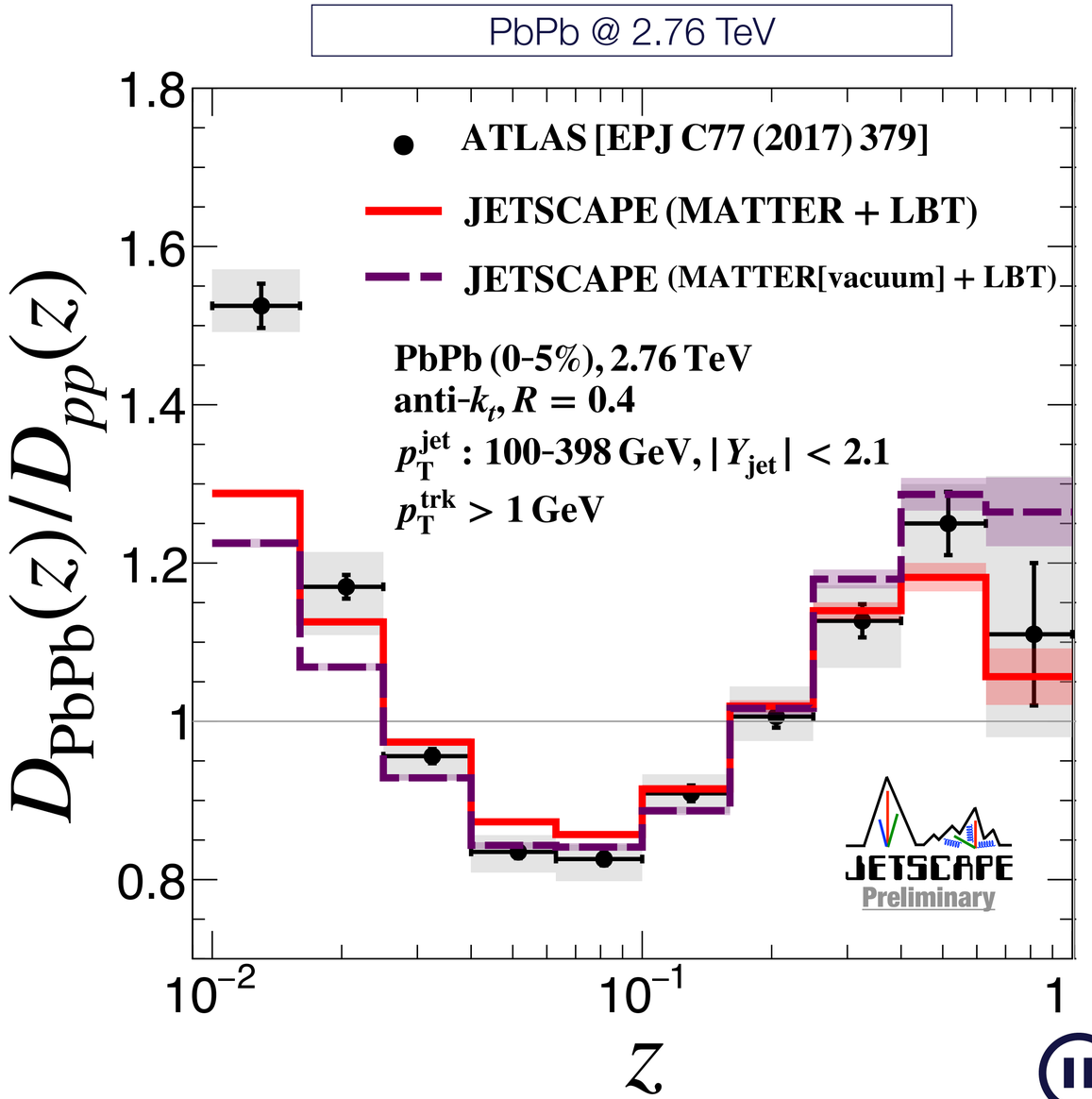
- Reasonable agreement with experimental data for wide range of *r*
- Need further systematic study to extract the detailed role of recoils

Results with Weakly-coupled Description of Med. Res.

- **Jet fragmentation**
  - Momentum structure of jet

$$D(z) = \frac{1}{N_{\text{jet}}} \sum_{\text{jet}} \frac{dN_{\text{trk}}}{dz}\bigg|_{\text{in jet}}$$

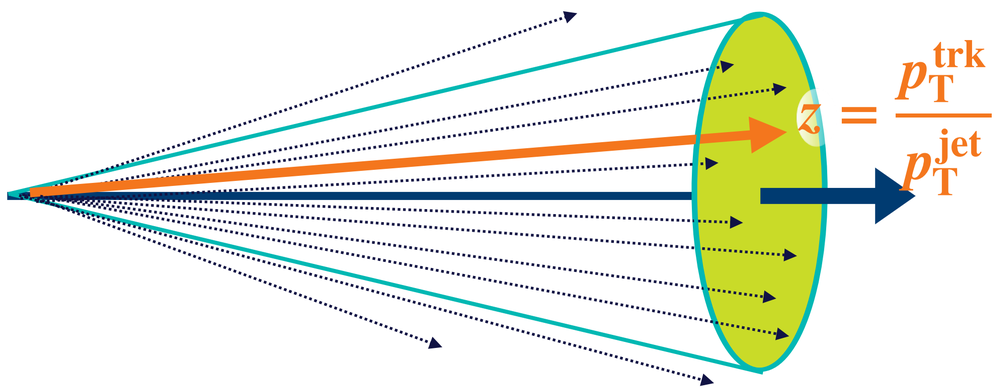


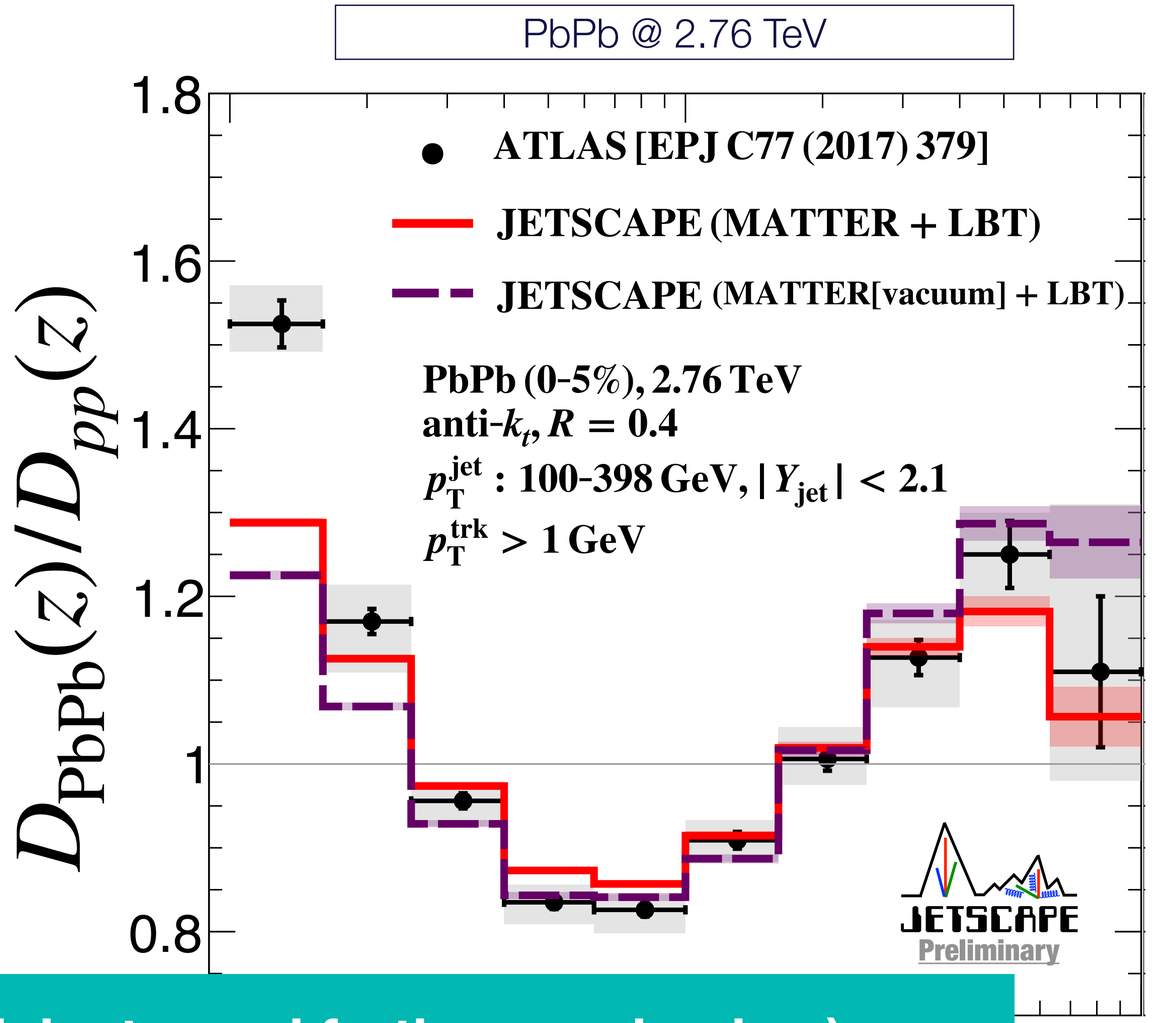


Results with Weakly-coupled Description of Med. Res.

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- Enhancement at small-z (but insufficient, need further mechanism)
- Sizable medium effect during virtuality ordered splitting

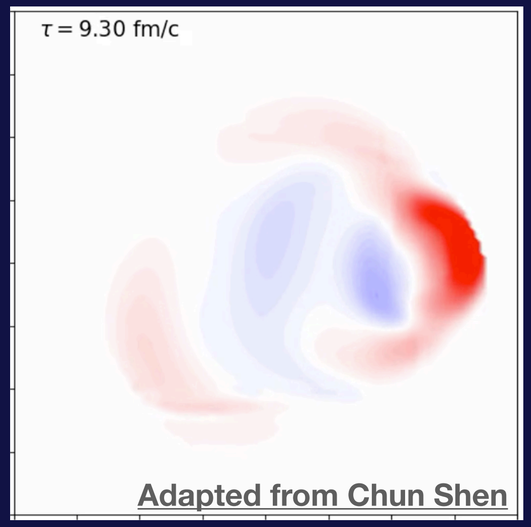
#jet-tachibana

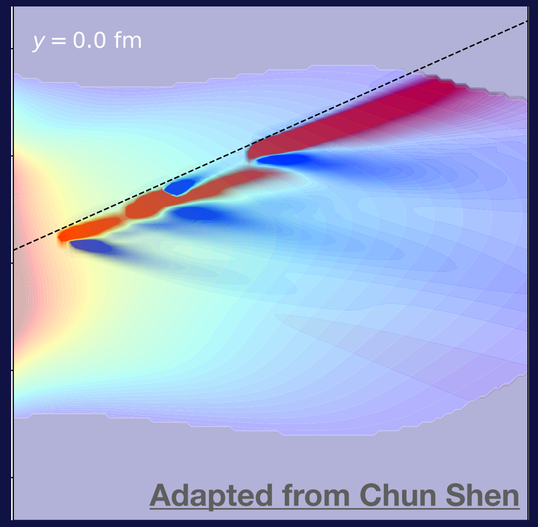
JETSCAPE School 2020

Results From JETSCAPE

- With Weakly-coupled Description by Recoils

- With Strongly-coupled Description by hydrodynamics

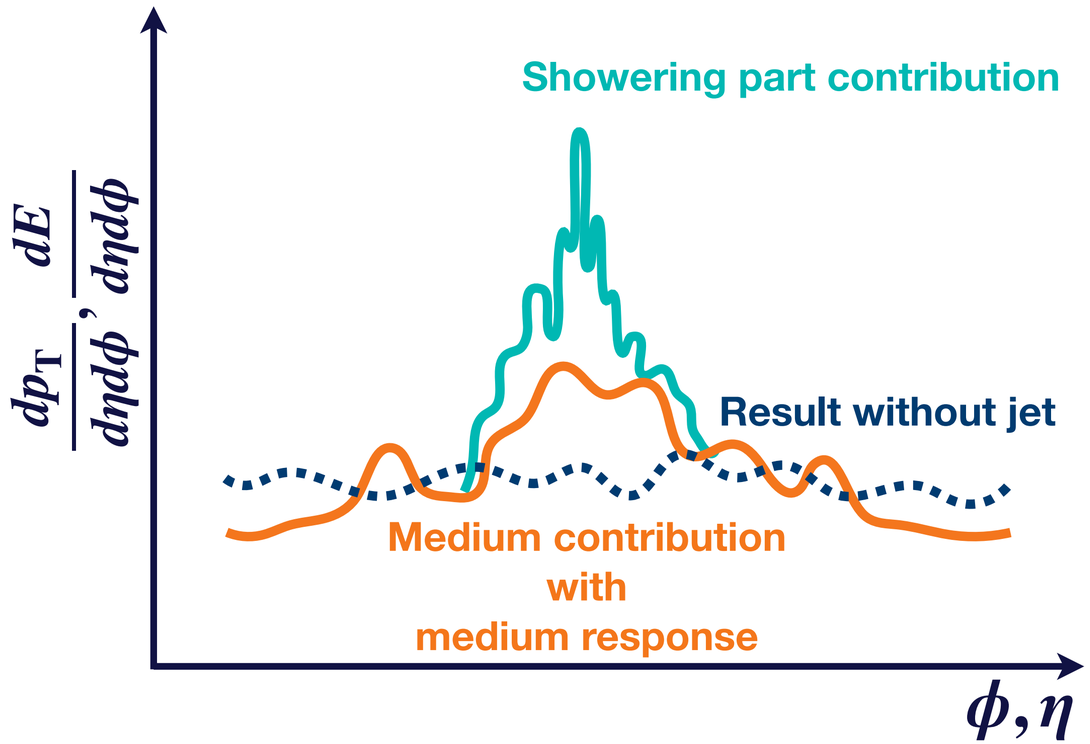




Background Subtraction for Strongly-coupled Description of Med. Res.

Theoretically defined background subtraction

$$\left.\frac{dp^\mu}{d\eta d\phi}\right|_{\text{signal}} = \left.\frac{dp^\mu}{d\eta d\phi}\right|_{\text{shower}} + \left.\frac{dp^\mu}{d\eta d\phi}\right|_{\substack{\text{med.}\\ \text{w/ jet}}} - \left.\frac{dp^\mu}{d\eta d\phi}\right|_{\substack{\text{med.}\\ \text{w/o jet}}}$$



- Designed for theoretical interpretation of jet momentum transport
- Negative $dp^0/d\eta d\phi$ is possible
- Well-defined only for conserved quantities
  - ✓ energy, momentum, charges,…
  - ? particle number

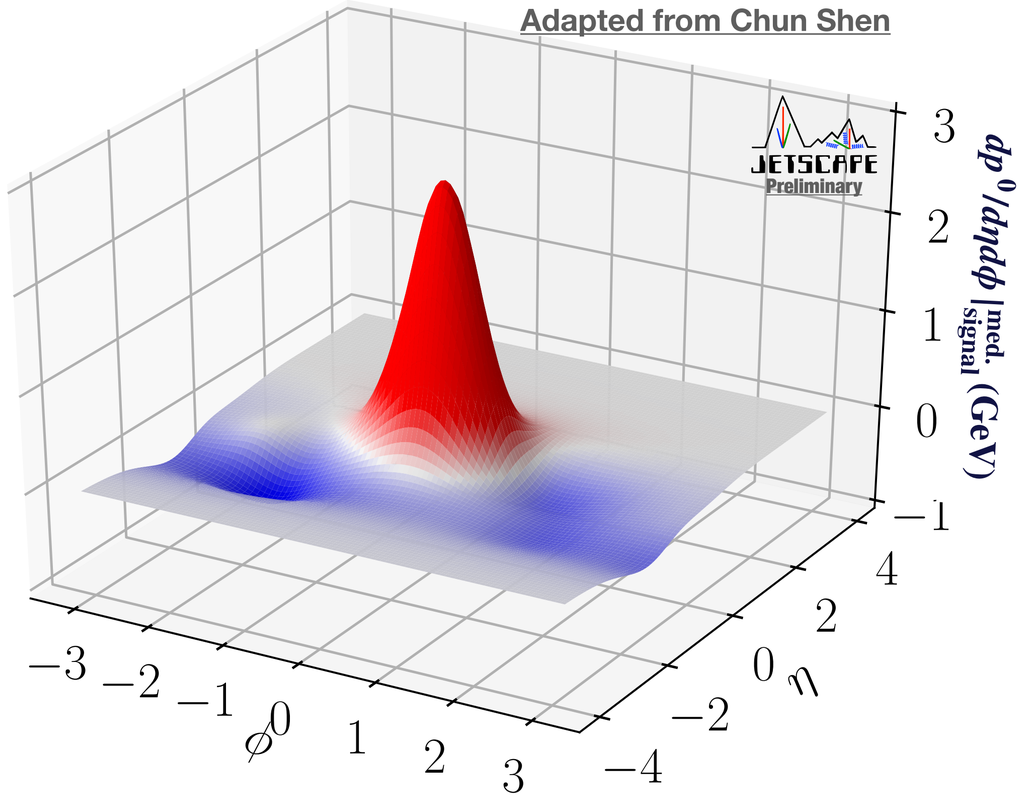
Signal from Strongly-coupled Description of Med. Res.

- Jet-modified spectrum of bulk medium (single event example)

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MATTER+LBT (Recoil ON) + Causal Diffusion + Viscous Hydro

Adapted from Chun Shen



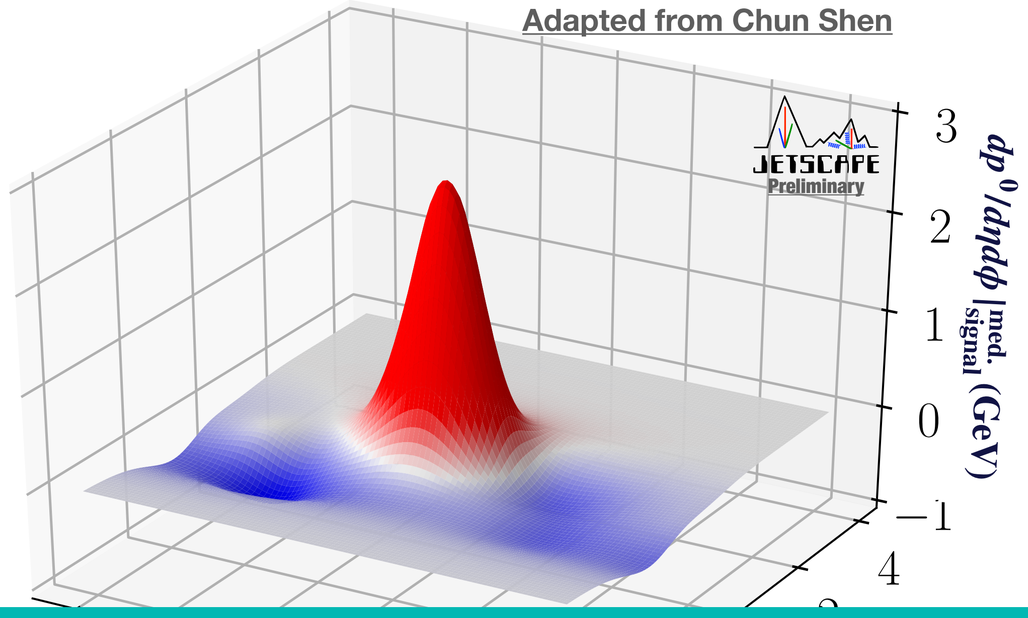
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MATTER+LBT (Recoil ON) + Causal Diffusion + Viscous Hydro

Adapted from Chun Shen



- Jet-correlated structure in hadron emission from the bulk medium
- Negative contribution by medium response

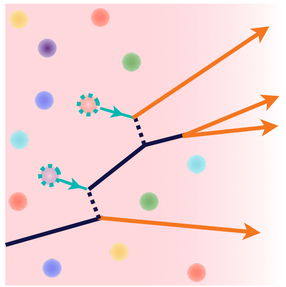
Summary

- **Medium response to jet quenching**
  - Medium constituents' reactions to interactions with jet
  - Contribute to jets observed in heavy ion collisions
  - Carry information of the in-medium thermalization process
  - Essential for comprehensive understanding of the jet quenching

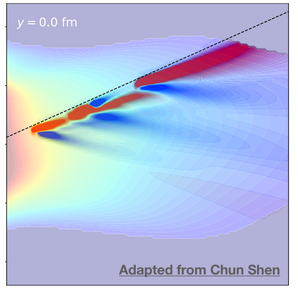
- **Implementation of medium response in JETSCAPE**
  - Weakly-coupled description → **Recoil (in MATTER, LBT and MARTINI)**
  - Strongly-coupled description → **Hydrodynamics (MUSIC, CLVisc)**
  - Intermediate stage. → **Causal Diffusion (Causal Liquefier)**

Summary and Outlook

- **Weakly-coupled description of medium response**
  - Large broadening, soft particle enhancement
  - Good description of jet substructure observables



- **Strongly-coupled description of medium response**
  - No clear distinction of background → Need background subtraction
  - Jet-correlated structure in hadron emission from the bulk medium



- **Outlook**
  - Systematic studies to extract the detailed role of medium response
  - Further test of simulations and study of background subtraction
  - Full simulation with Strongly-coupled description of medium response

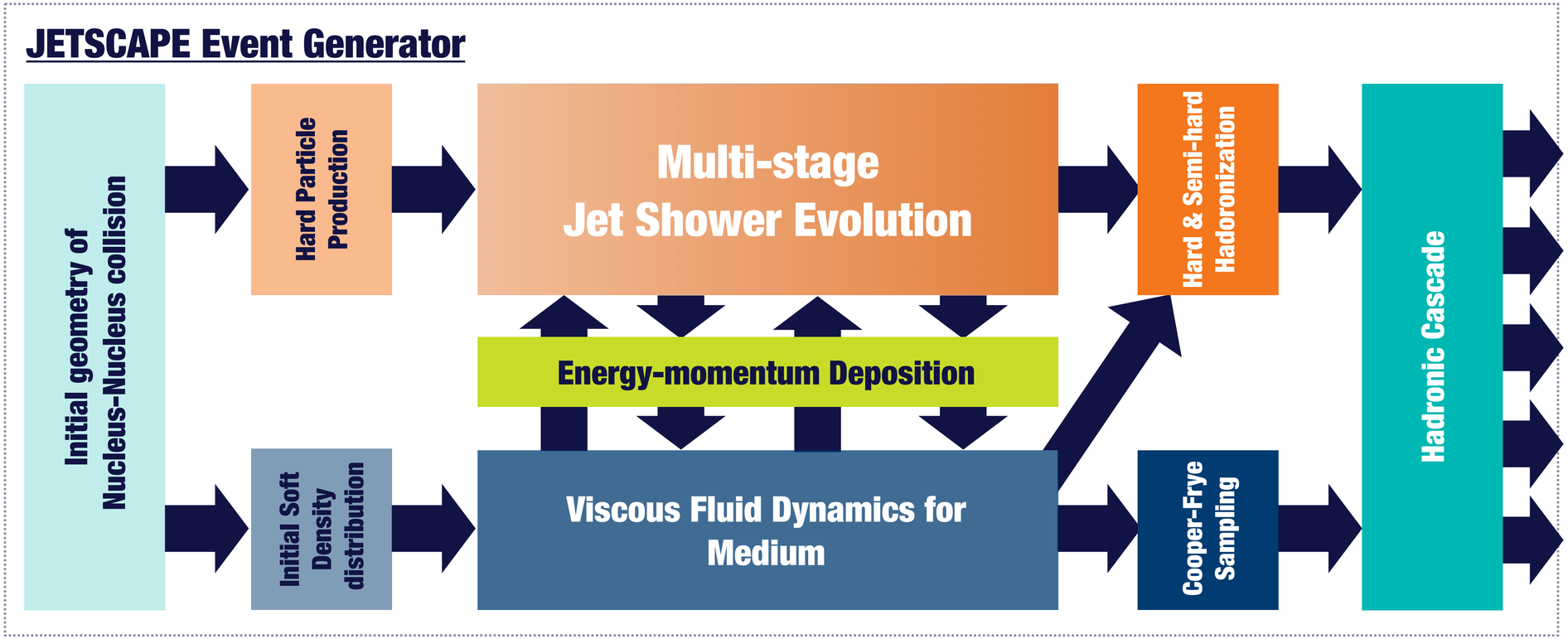
#jet-tachibana

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Backup

JETSCAPE

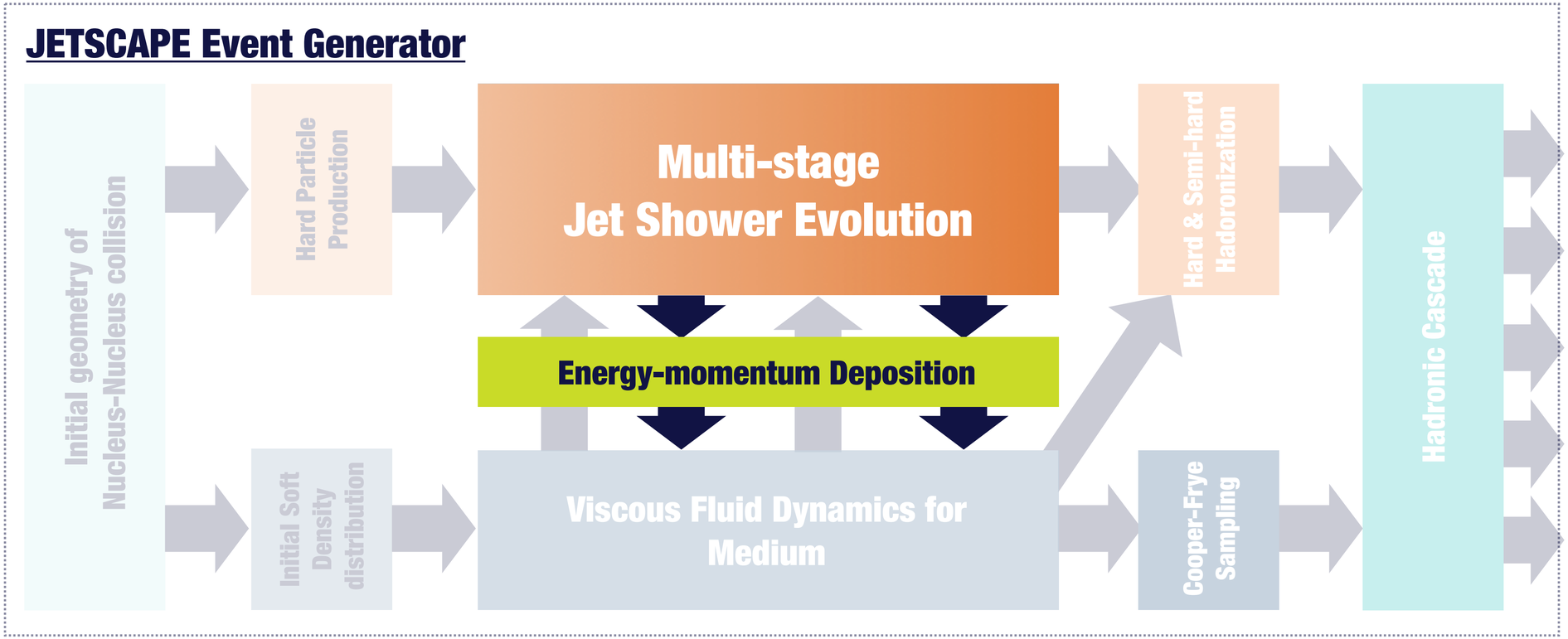
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  - JETSCAPE 2.0 available on GitH github.com/JETSCAPE
  - General, modular and highly extensible — Lecture by J. Mulligan



Soft Part → Lecture by C. Shen

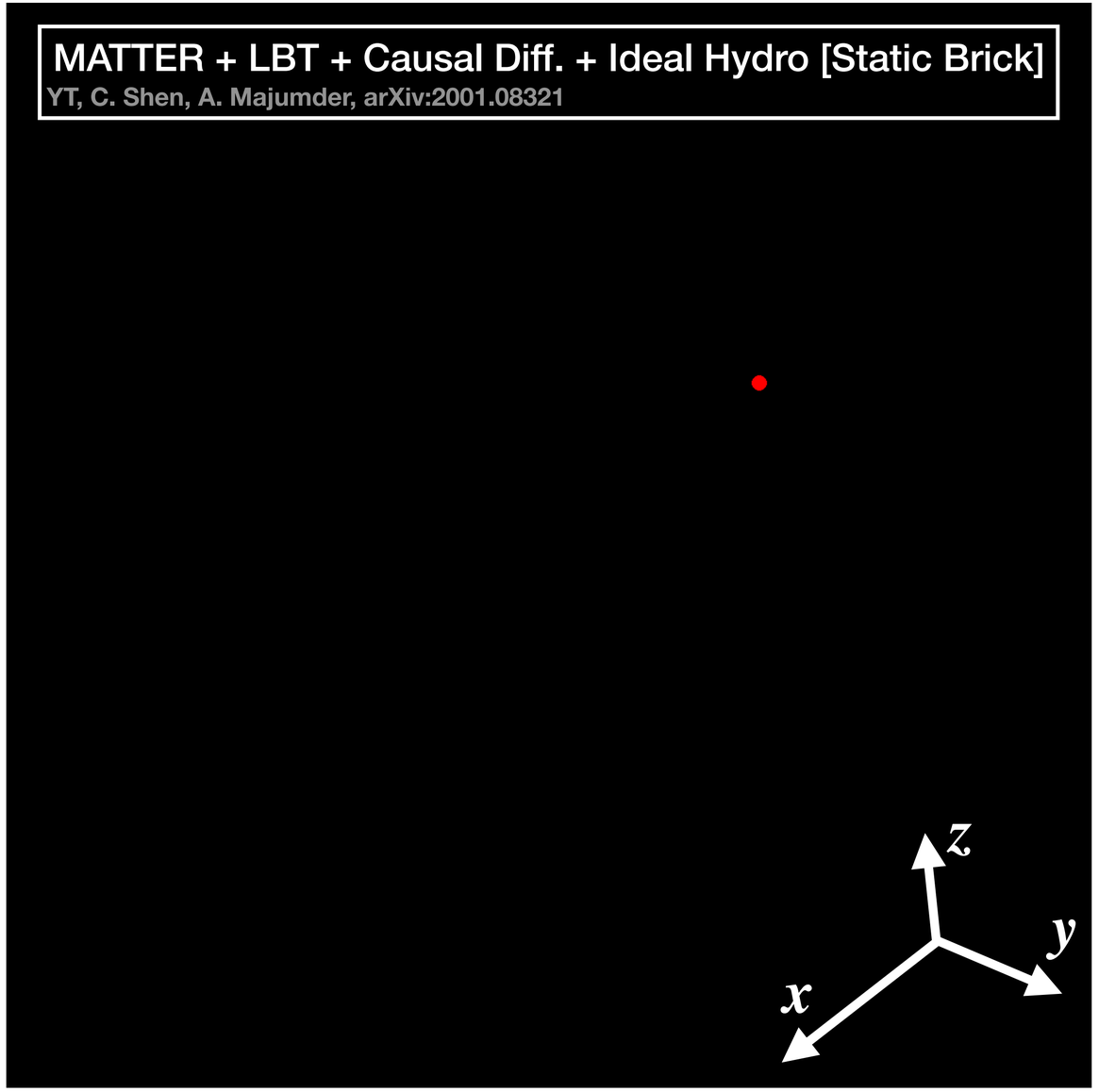
JETSCAPE

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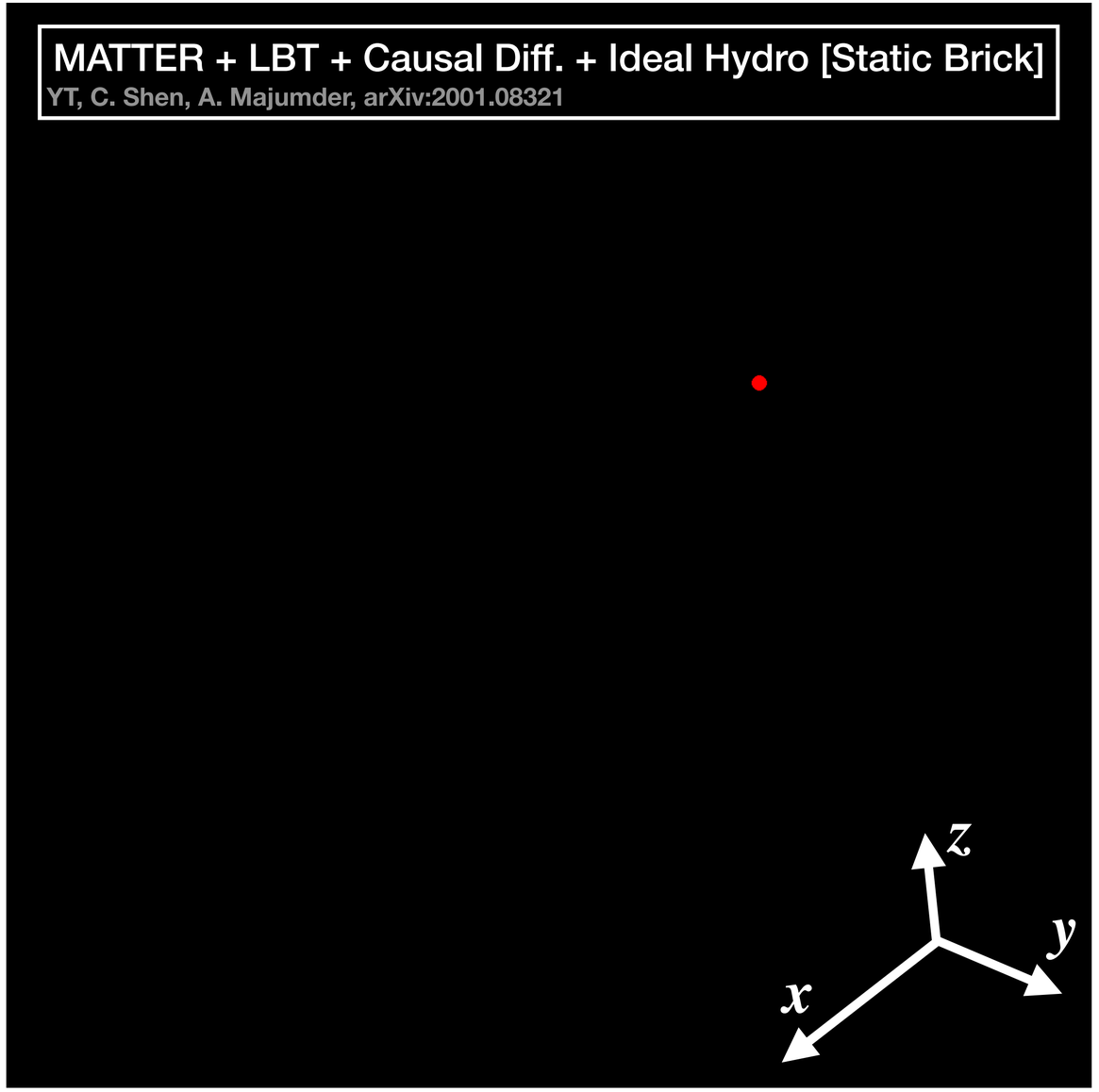


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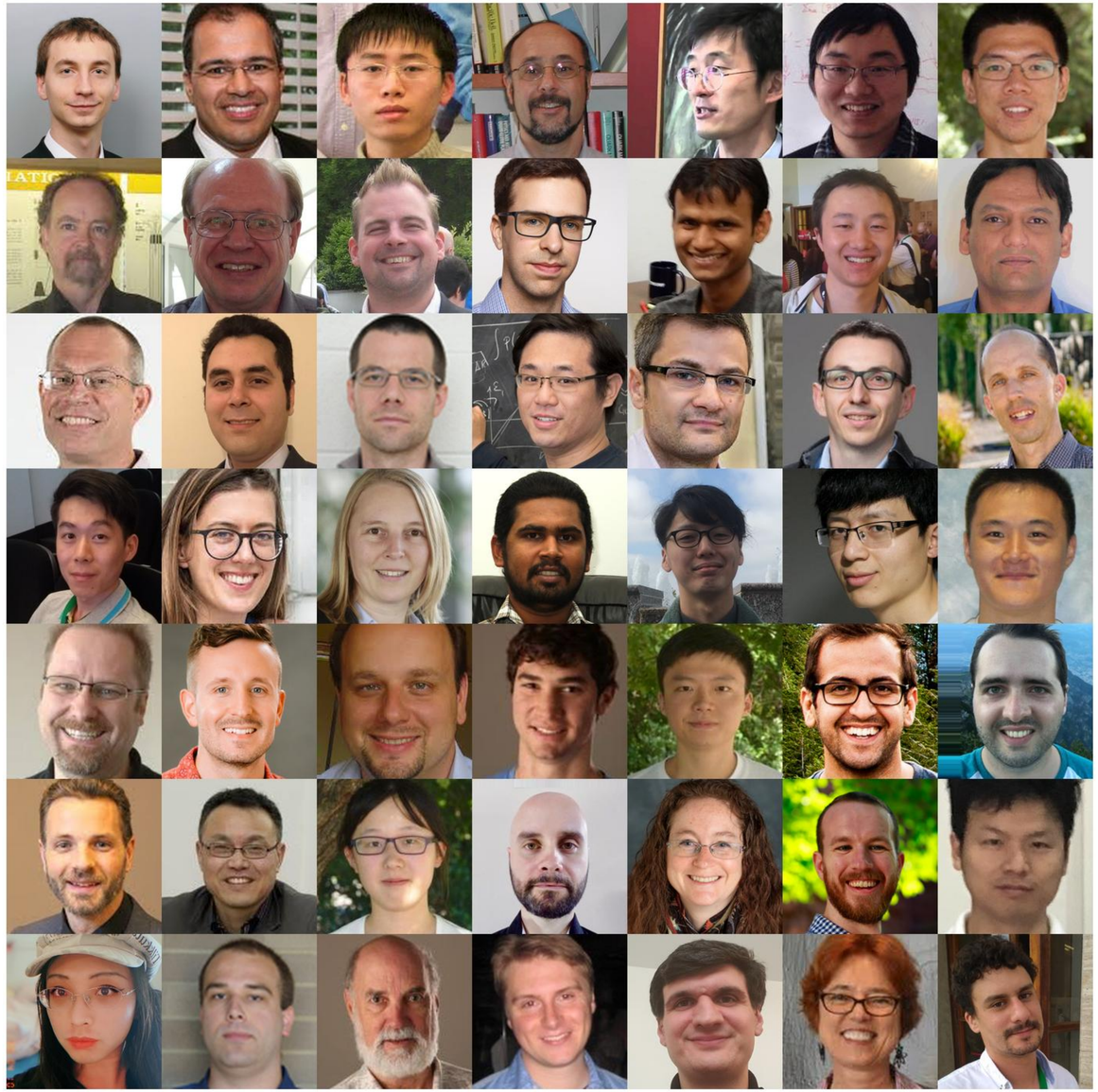
Hydrodynamic medium response to jet propagation



Hydrodynamic medium response to jet propagation



JETSCAPE Collaboration

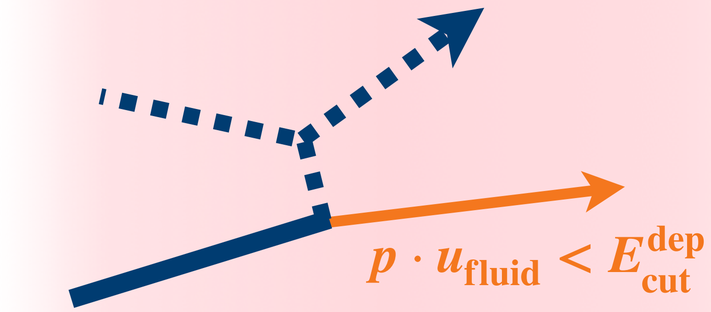


JETSCAPE

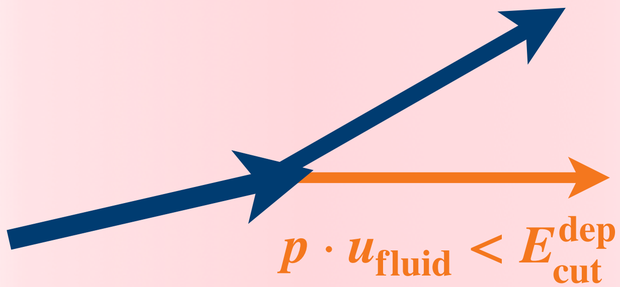
Strongly-coupled Description: Energy-momentum Depositions

- Positive deposition for partons with energy at medium's local rest frame $p \cdot u_{\rm fluid} < E^{\rm dep}_{\rm cut}$
- Negative deposition due to energy picked up from medium

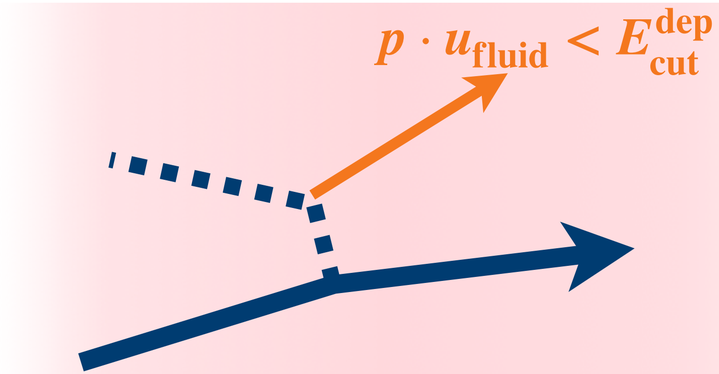
Shower parton soften by collision



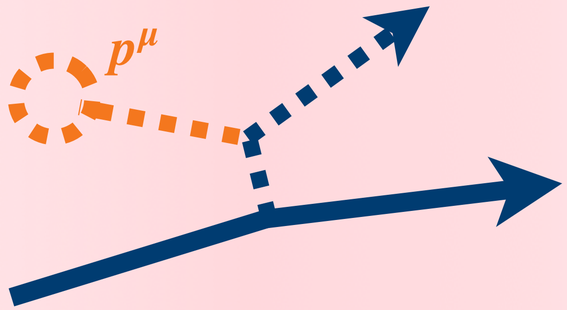
Soft radiated partons



Soft recoils in collisions



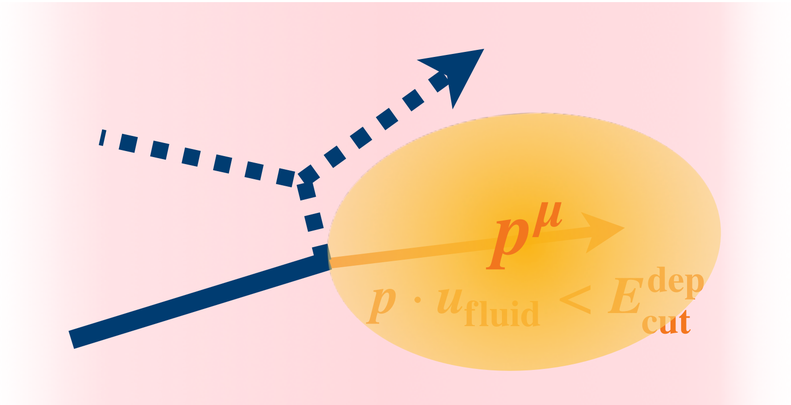
Medium parton kicked out by collision



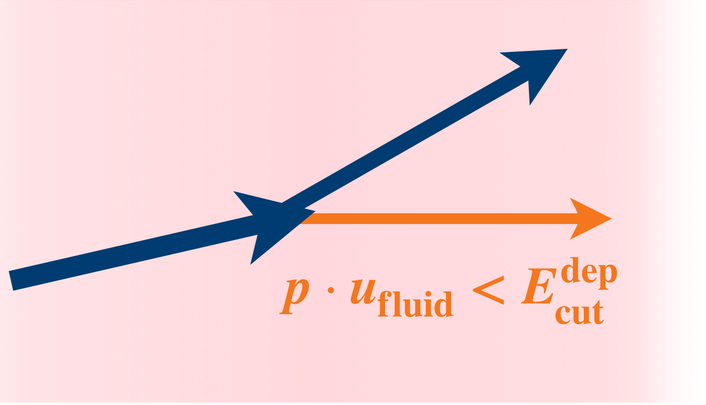
Strongly-coupled Description: Energy-momentum Depositions

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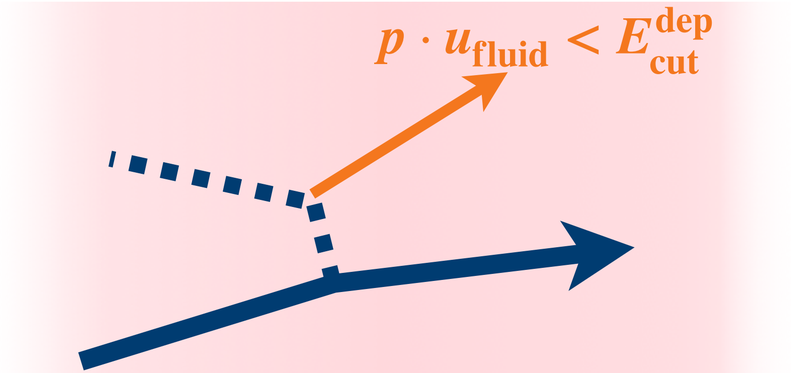
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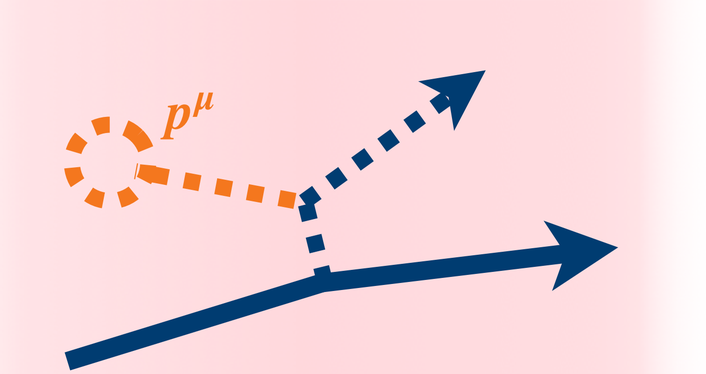
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Soft recoils in collisions



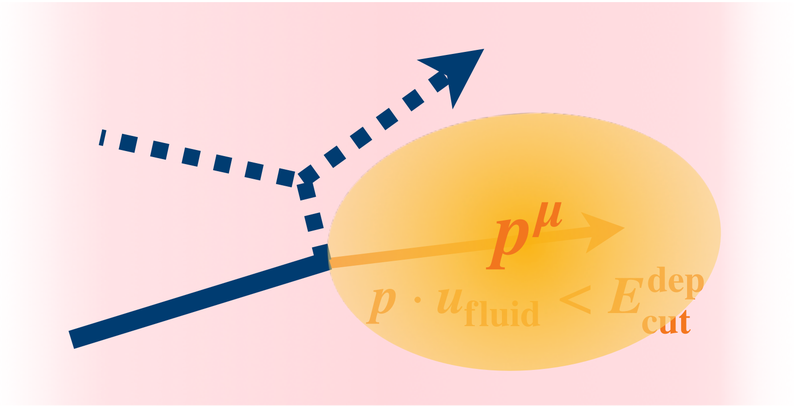
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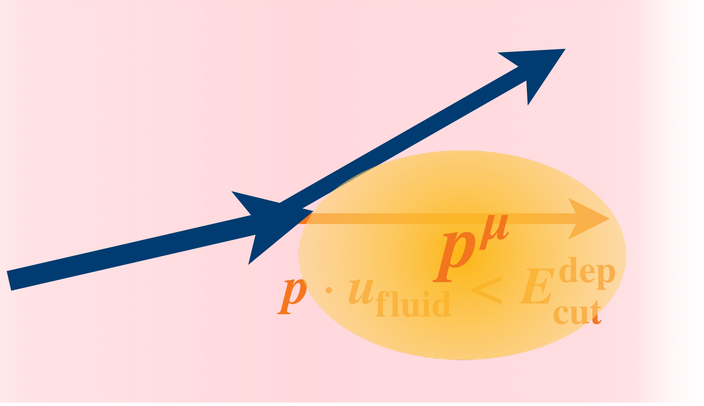
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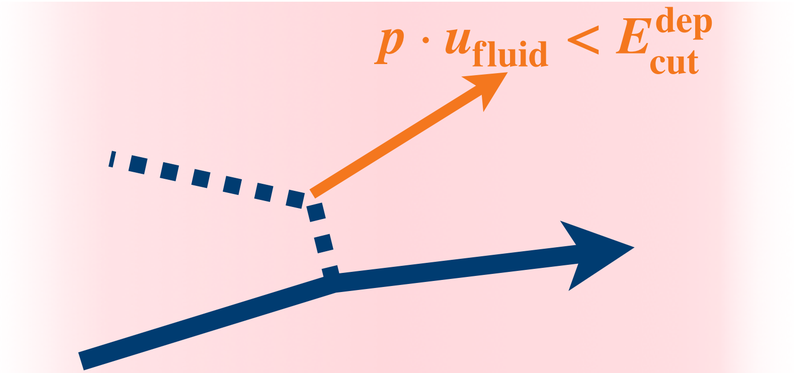
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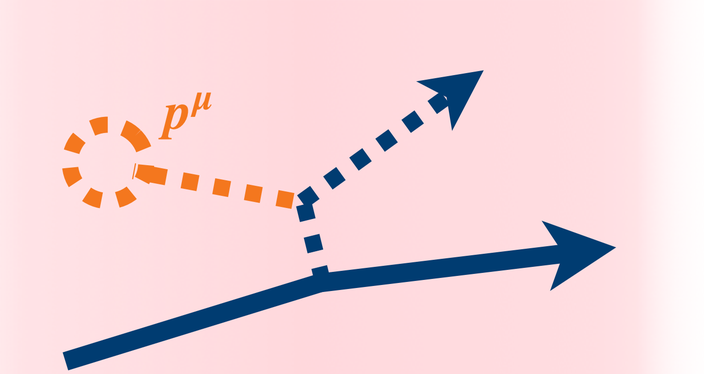
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Soft recoils in collisions



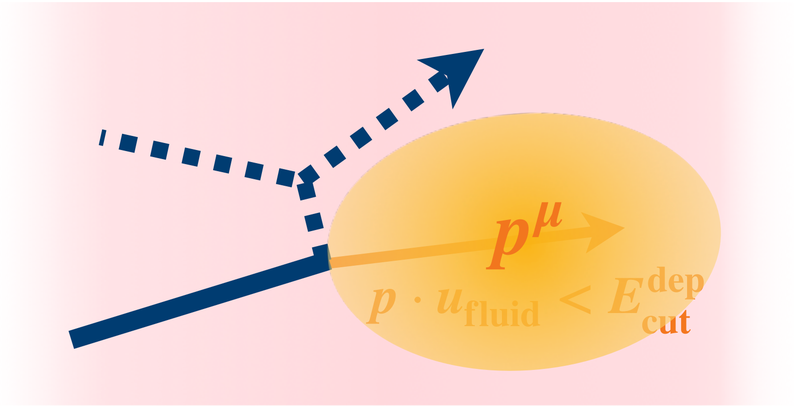
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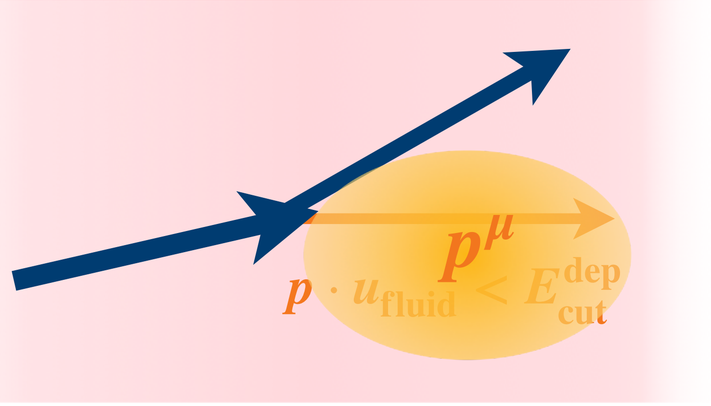
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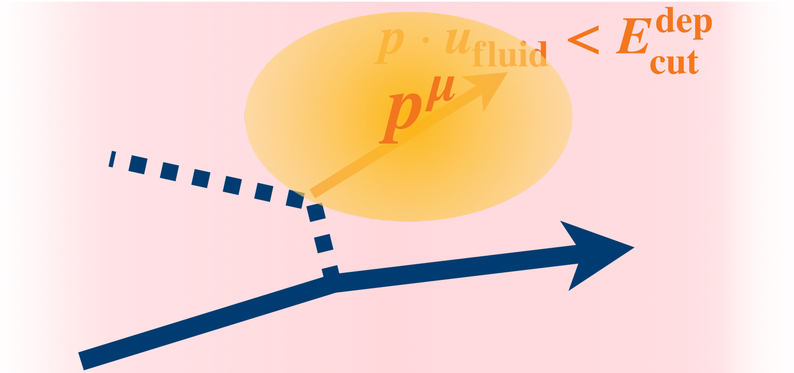
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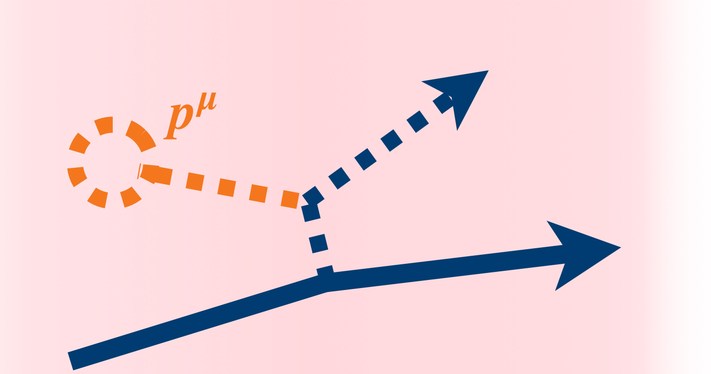
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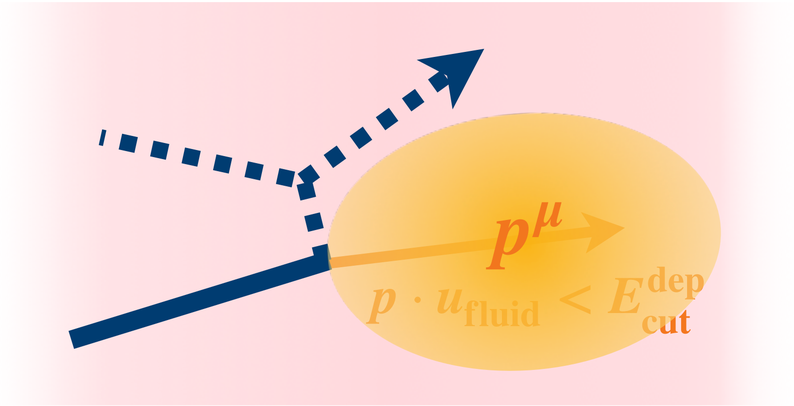
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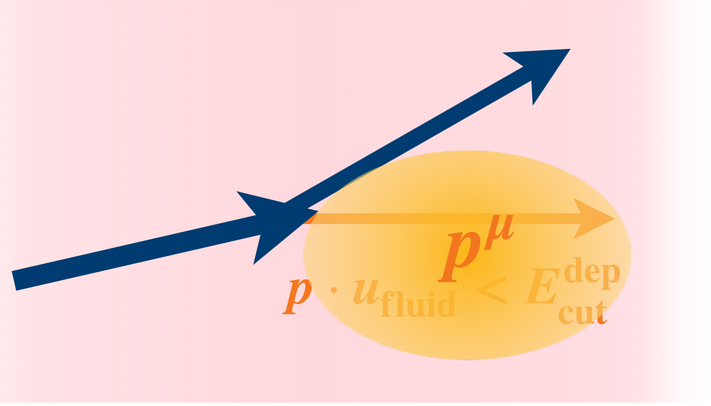
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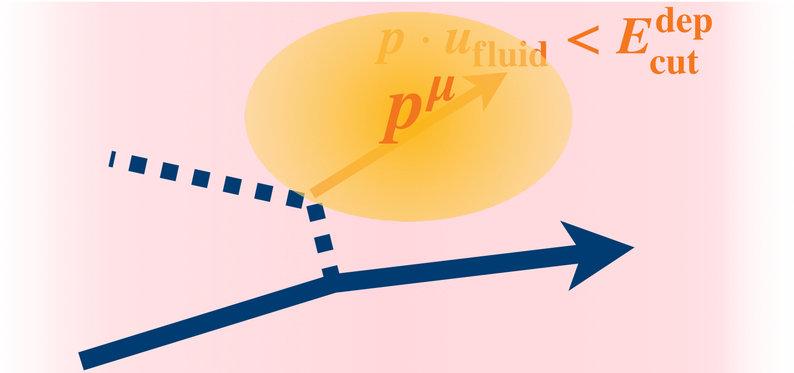
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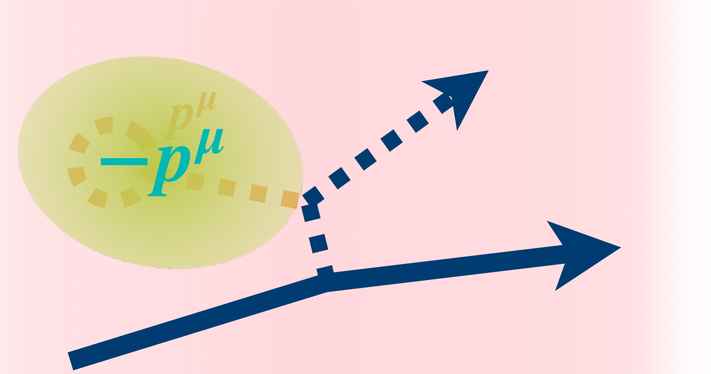
Soft radiated partons



Soft recoils in collisions



Medium parton kicked out by collision



Strongly-coupled Description: Causal Formulation for Source Term

Source profile based on causal diffusion

YT, C. Shen, A. Majumder, in preparation

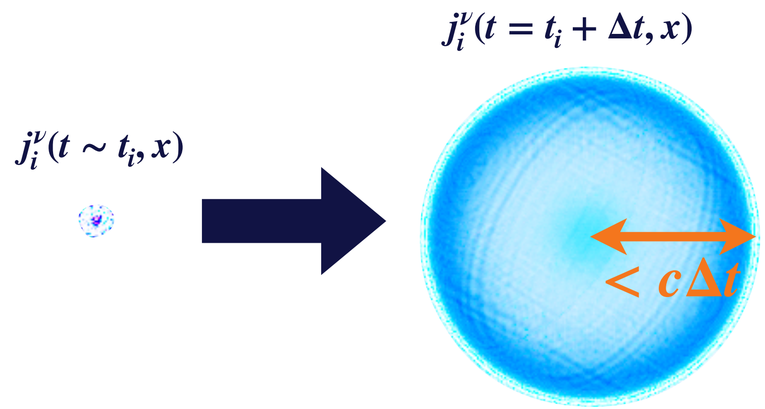
$$J^{\nu}_{\rm jet}(x) = \sum_i j^{\nu}_i(x)\,\delta\big(t - [t_i + \Delta t]\big)$$

- Underlying equation of motion: Relativistic diffusion equation

$$\left[\frac{\partial}{\partial t} + \tau_{\rm diff}\frac{\partial^2}{\partial t^2} - D_{\rm diff}\nabla^2\right] j^{\nu}_i(x) = 0$$

with initial condition $j^{\nu}_i(t = t_i, \vec{x}) = (\pm)_i p^{\nu}_i \delta^{(3)}(\vec{x} - \vec{x}_i)$ and $\dfrac{\partial j^{\nu}_i}{\partial t}(t = t_i, \vec{x}) = 0$

(i: deposited parton, $(\pm)_i$ for positive/negative deposition)



$D_{\rm diff}$: Diffusion coefficient

$\tau_{\rm diff}$: Relaxation time

Δt: Timescale for in-medium thermalization

Simulations with JETSCAPE 2.0

- **Settings for PbPb collisions at 5.02 TeV**

Jet Shower

- MATTER+LBT (Recoil ON, Virtuality separation $Q_0 = 2\,\mathrm{GeV}$)
- Initial condition from TRENTo+Pythia (MPI&ISR ON, $\hat{p}_\mathrm{T} = 100\text{-}150\,\mathrm{GeV}$)

Moreland, Bernhard, Bass

- Lund hadronization

Source Term

- Causal profile generated via relativistic diffusion equation
- Absorption of partons with energy at LRF of medium $p \cdot u_\mathrm{fluid} < 2\,\mathrm{GeV}$

Medium Fluid

- TRENTo initial profile
- (3+1)-D viscous hydro calculation with source term by MUSIC

Denicol, Gale, Jeon, Luzum, Paquet, Schenke, Shen

- Particle emission at freezeout via Cooper-Frye sampling

Energy-momentum Depositions from Jet Shower

- **Standard source profile and diffusion equation**
  - Gaussian smearing

$$J^{\nu}_{\rm jet}(x) = \sum_i \frac{(\pm)_i p_i^{\mu}}{(\sqrt{2\pi}\sigma)^3} \exp\left[-\frac{|\vec{x} - \vec{x}_i|^2}{2\sigma^2}\right] \delta\left(t - [t_i + \Delta t]\right)$$

i: deposited parton, $(\pm)_i$ for positive/negative deposition

Infinite tail → acausal

  - Underlying equation of motion: *Non-relativistic* diffusion equation

$$\left[\frac{\partial}{\partial t} - D_{\rm diff}\nabla^2\right] f(x) = 0$$

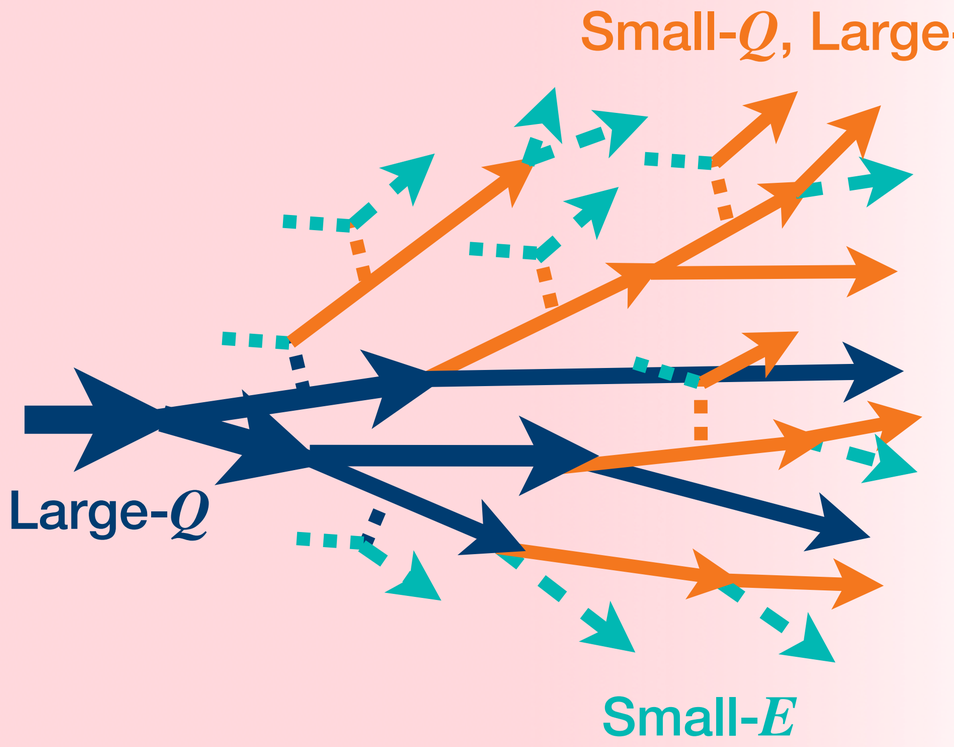
with initial condition $f(t = t_i, \vec{x}) = p_i^{\nu}\delta^{(3)}(\vec{x} - \vec{x}_i)$

and diffusion coefficient $D_{\rm diff} = \frac{\sigma^2}{2\Delta t}$

Weak

Majumder, Putschke (16), JETSCAPE (17)

In-medium



Q^2: virtuality (off-shellness)

Large-Q

Virtuality ordered splittings with small medium effect

Model: **MATTER**

Small-Q, Large-E

Splittings driven by in-medium scatterings

Models: **LBT, MARTINI**

Small-E

Energy-momentum diffusion into medium

Model: **AdS/CFT**

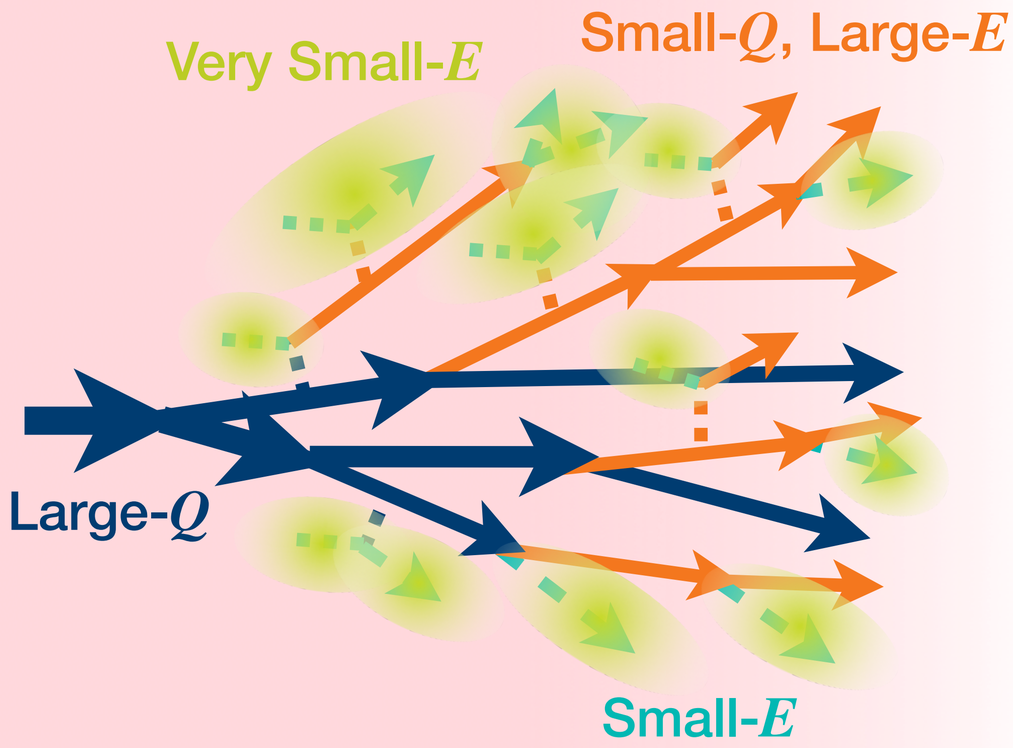
Event-by-event Jet Simulation → Talk by A. Kumar (Wed)

Heavy Quarks → Talk by G. Vujanovic (Tue)

Weak

Majumder, Putschke (16), JETSCAPE (17)

In-medium



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Very Small-E

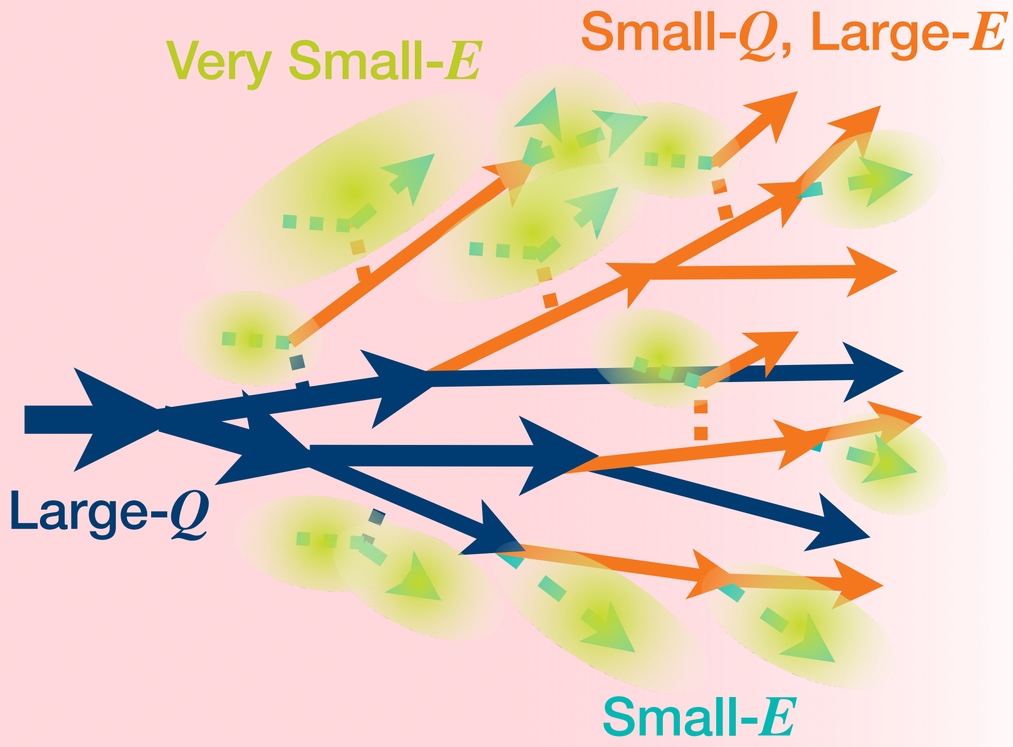
Hydrodynamical evolution with bulk medium

Model: **Hydrodynamics (e.g. MUSIC)**

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Majumder, Putschke (16), JETSCAPE (17)

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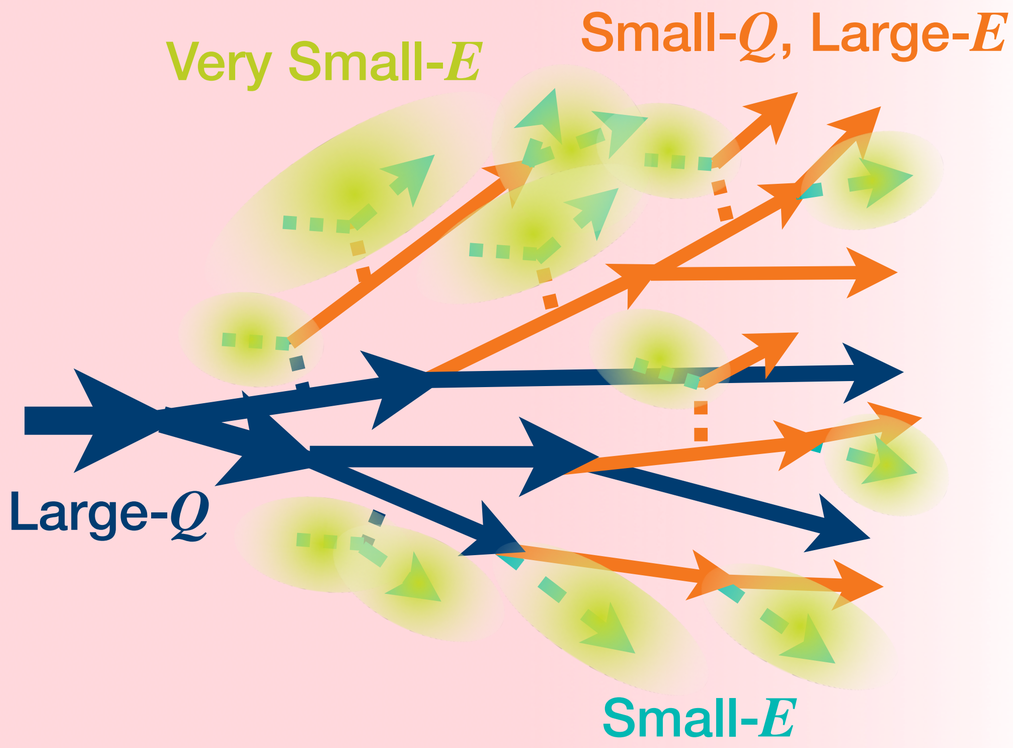
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Energy-momentum diffusion into medium

Model: **Causal Diffusion**

➡ **Source Profile for Fluid**

Very Small-E

Hydrodynamical evolution with bulk medium

Model: **Hydrodynamics (e.g. MUSIC)**

➡ **Hydrodynamic Response**

