Medium response and bulk fluid velocity effect in jet quenching

Yasuki Tachibana

in collaboration with Chun Shen and Abhijit Majumder [arXiv:2001.08321]

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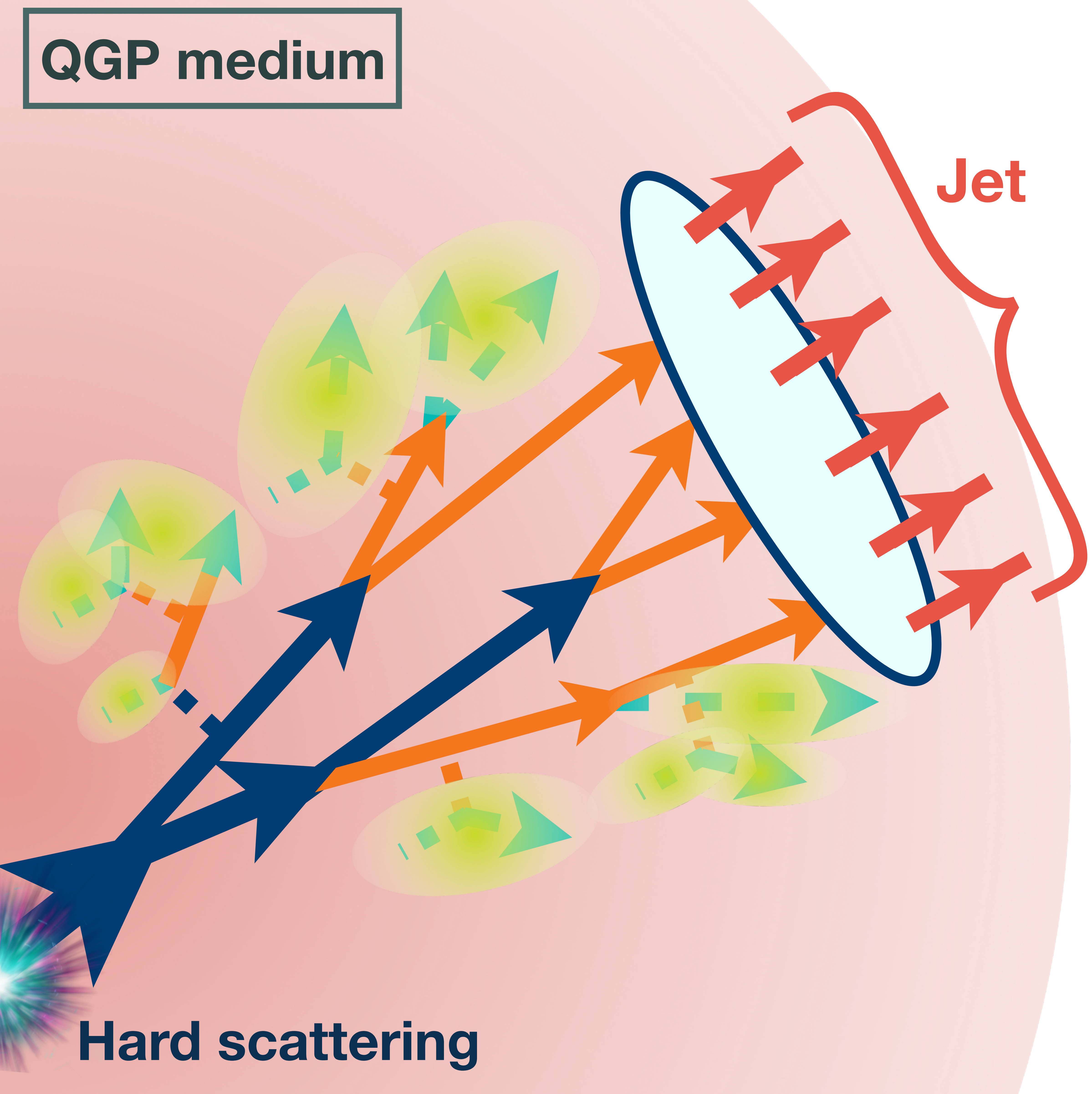
Medium Response Effects on Jets



- **Jet-induced excitation of medium**
  - Transport energy and momentum received from jet as wakes
  - Modify particle emission around jet
- **Particles from wakes**
  - Jet correlated, cannot/should not be subtracted
  - Affect structures inside/around jet
    - Angular Structure
    - Momentum Structure
    - Hadron Species

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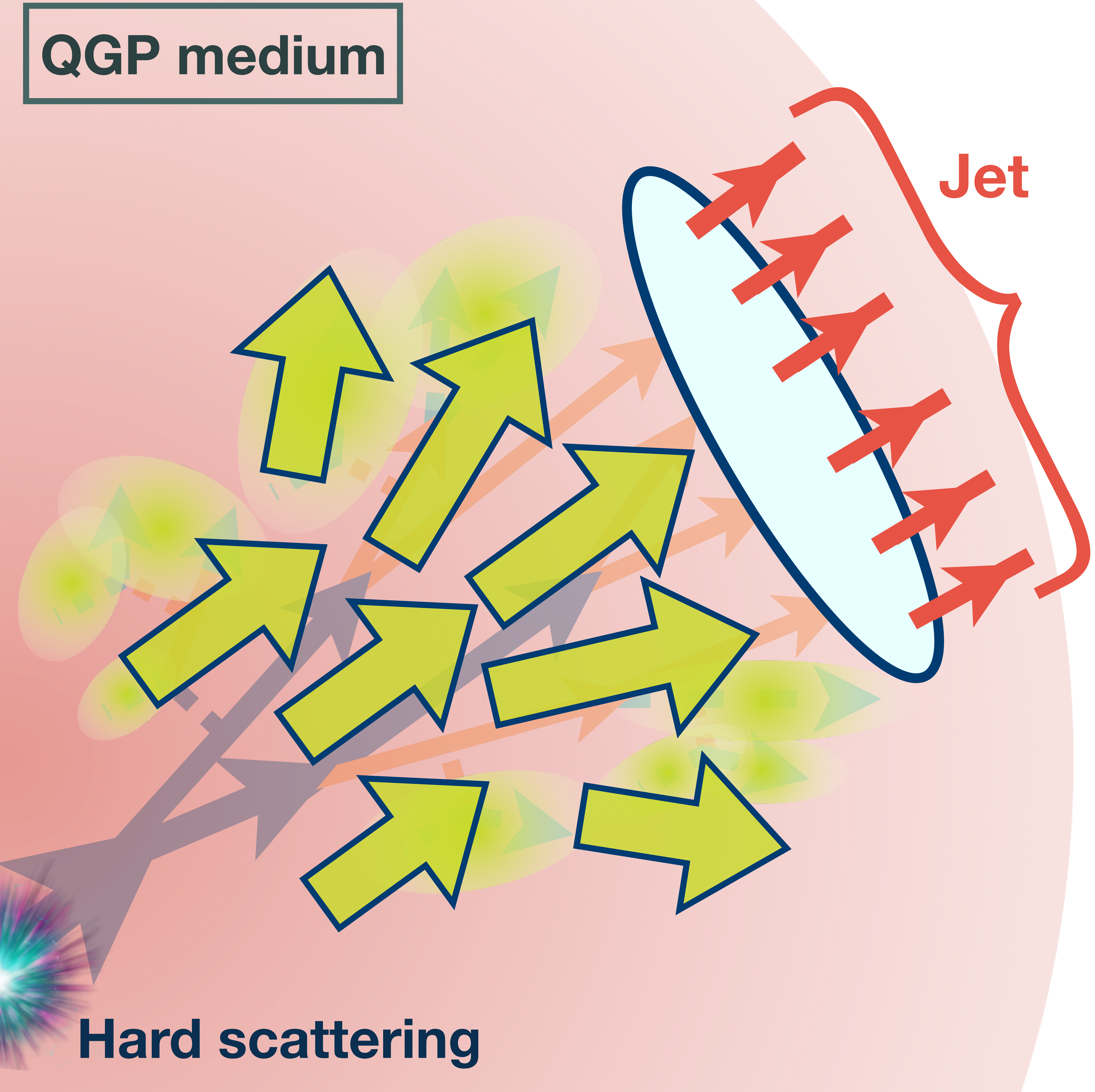

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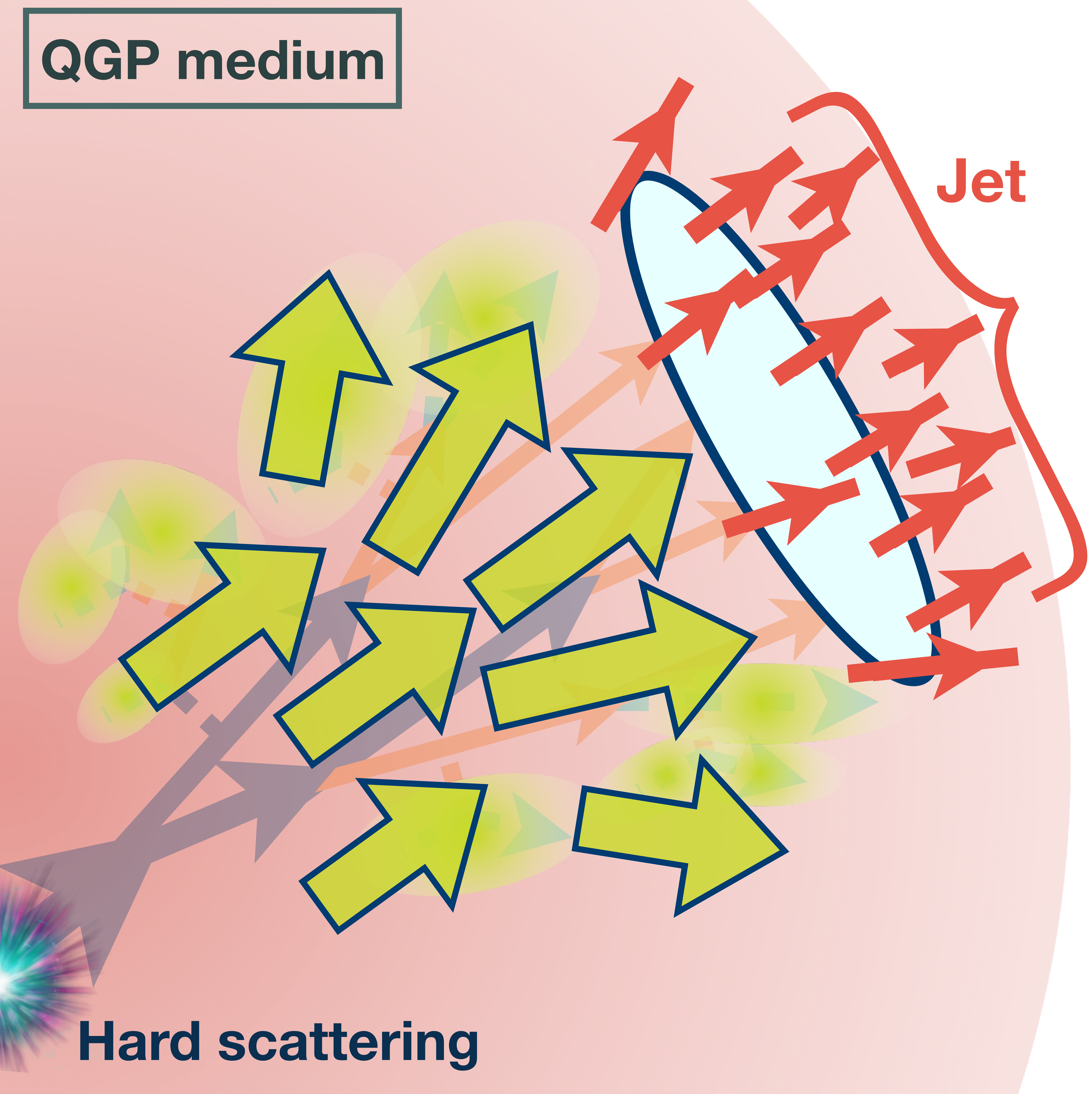

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Motivations

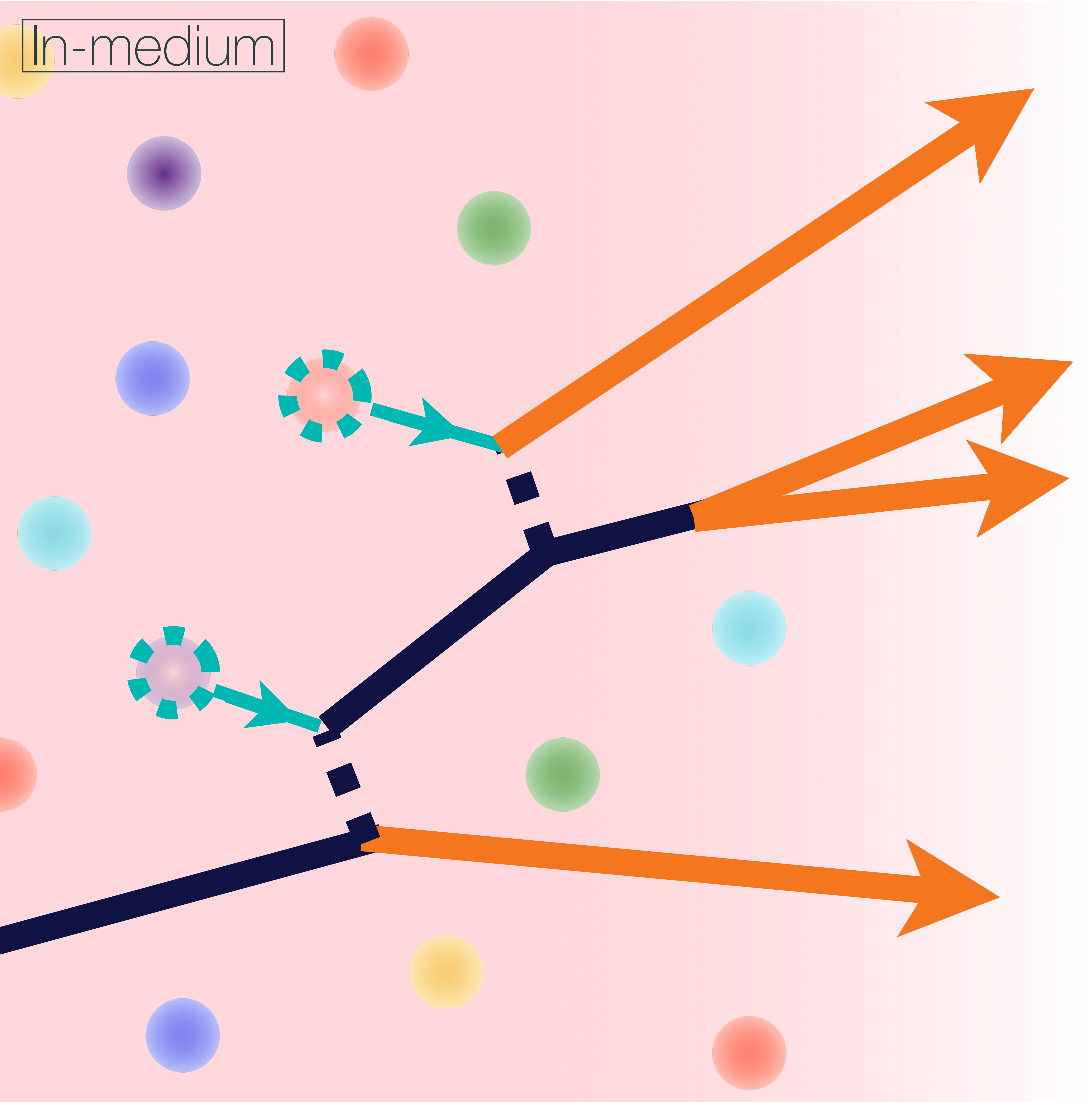
- **Models to describe jet-induced excitation of medium**
  - Extension from jet side: weak coupling, scatterings based on pQCD
  - Extension from medium side: strong coupling, hydrodynamics

- **Background medium flow effect**
  - Wakes induced as medium response evolve in an expanding fluid
  - How can wakes' contribution in jet be affected?
  - Different effects in different models for medium response?

Models

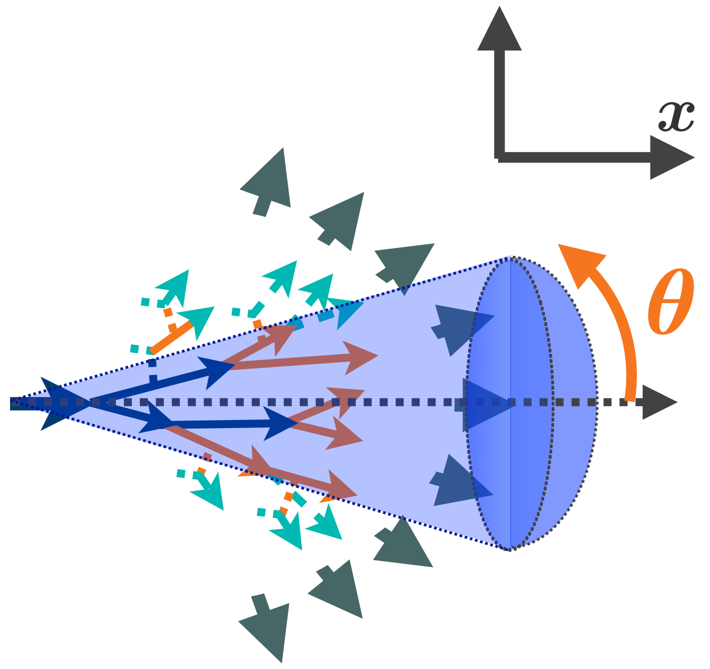
1. Weakly-coupled Description: Recoils

Zapp, Krauss, Wiedemann ('13), Wang, Zhu(13), Luo, et al.(15,18), Park, Jeon, Gale(18), Cao, Majumder (18)

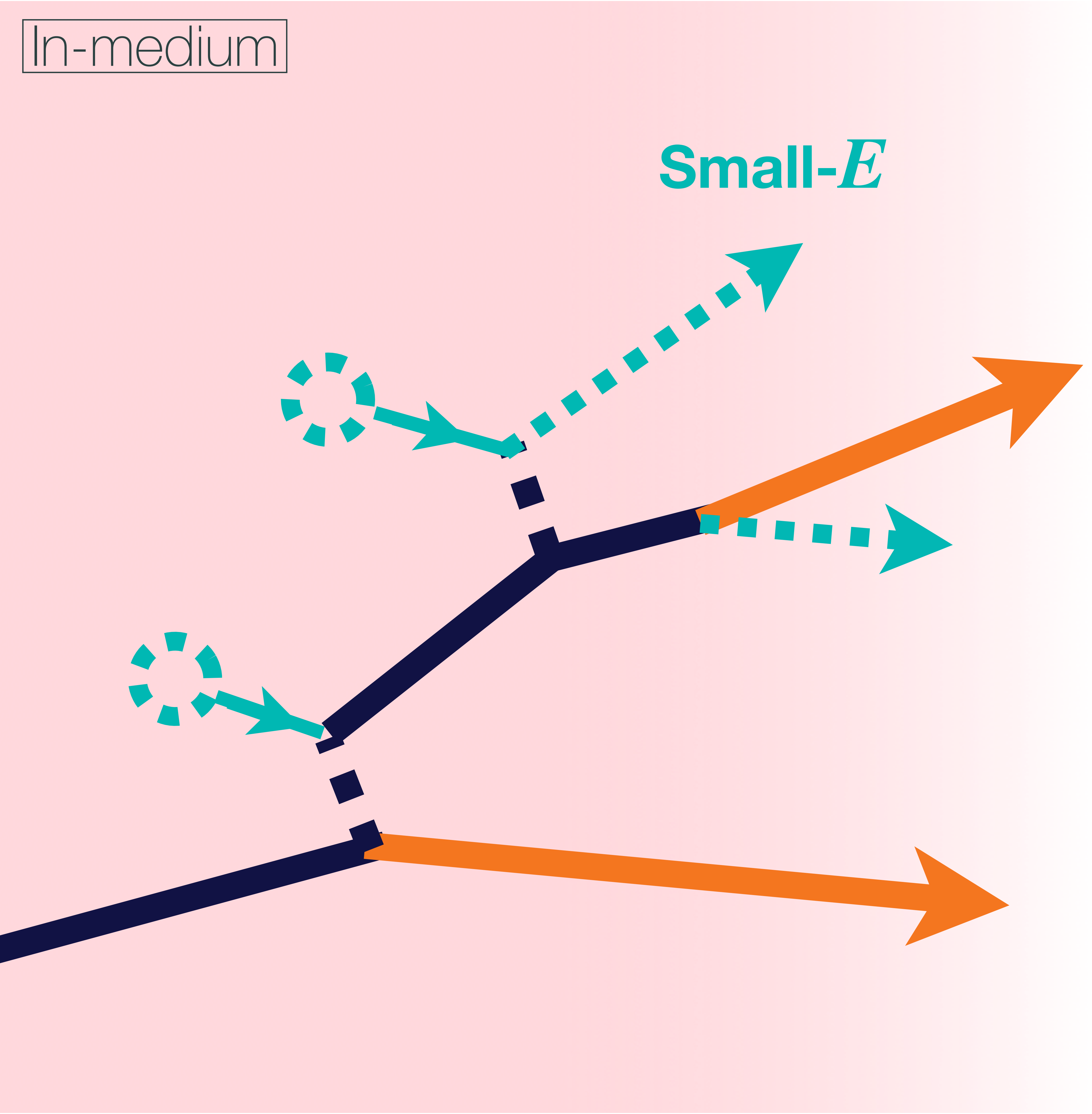


- **Recoils**
  - Medium partons kicked out by jet parton
  - Propagate as a parton in jet shower
  - Wakes induced by successive scatterings
- **Hole: Picked up energy and momentum**
  - Sampled from thermal medium
  - Freestreaming
  - Subtracted from final signal

$$\left.\frac{dp^\mu}{d\theta}\right|_{\text{signal}} = \left.\frac{dp^\mu}{d\theta}\right|_{\text{jet shower}} - \left.\frac{dp^\mu}{d\theta}\right|_{\text{hole}}$$



2. Strongly-coupled Description: Hydro Response



- **Diffusion into the medium**
  - Soft partons
    ($E_{\mathrm{parton}} \sim$ typical energy scale in thermal medium)
  - Holes' energy and momentum

  Model: **Causal Diffusion Equation**

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

  Model: **Hydrodynamics with Source**

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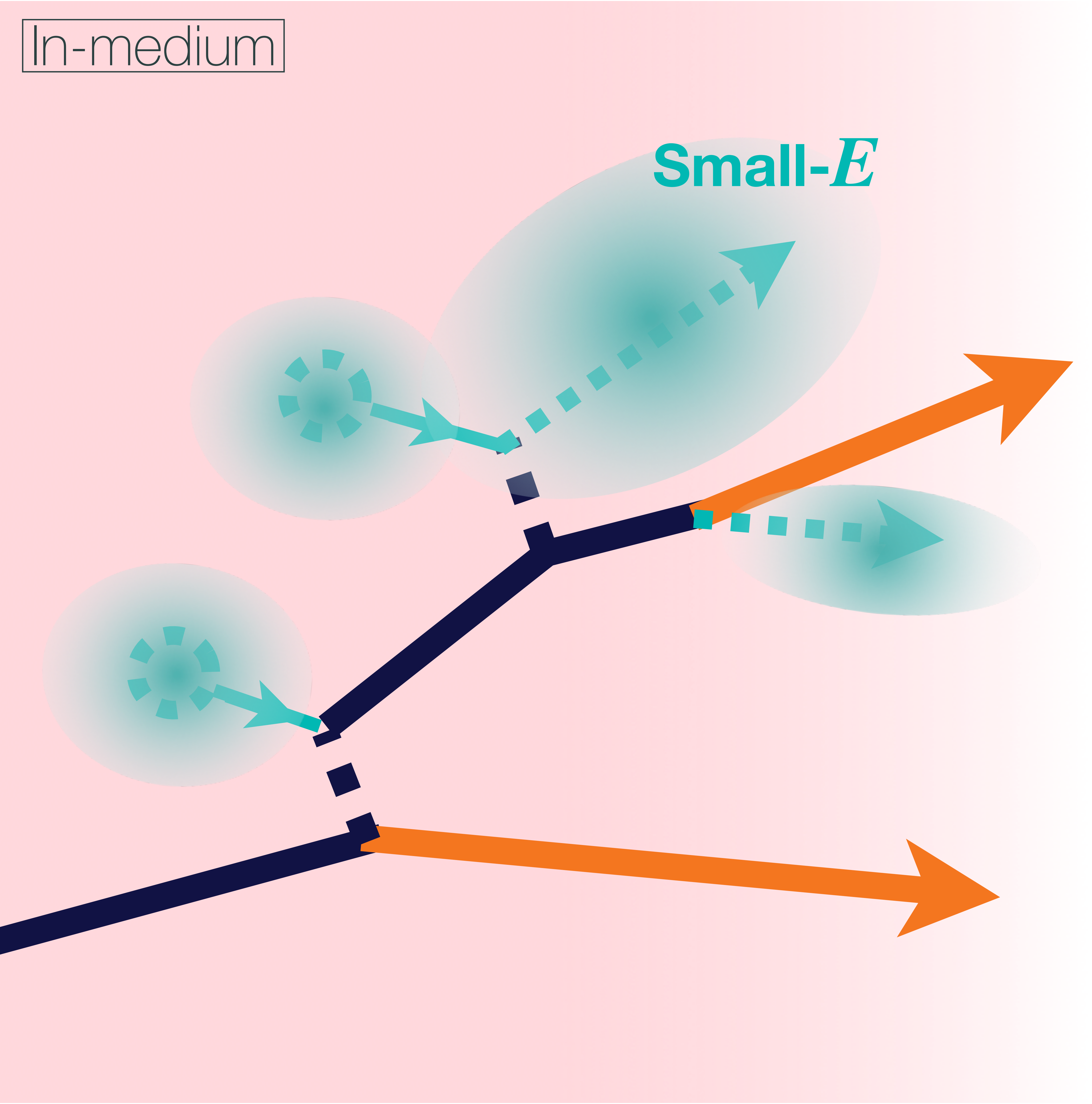

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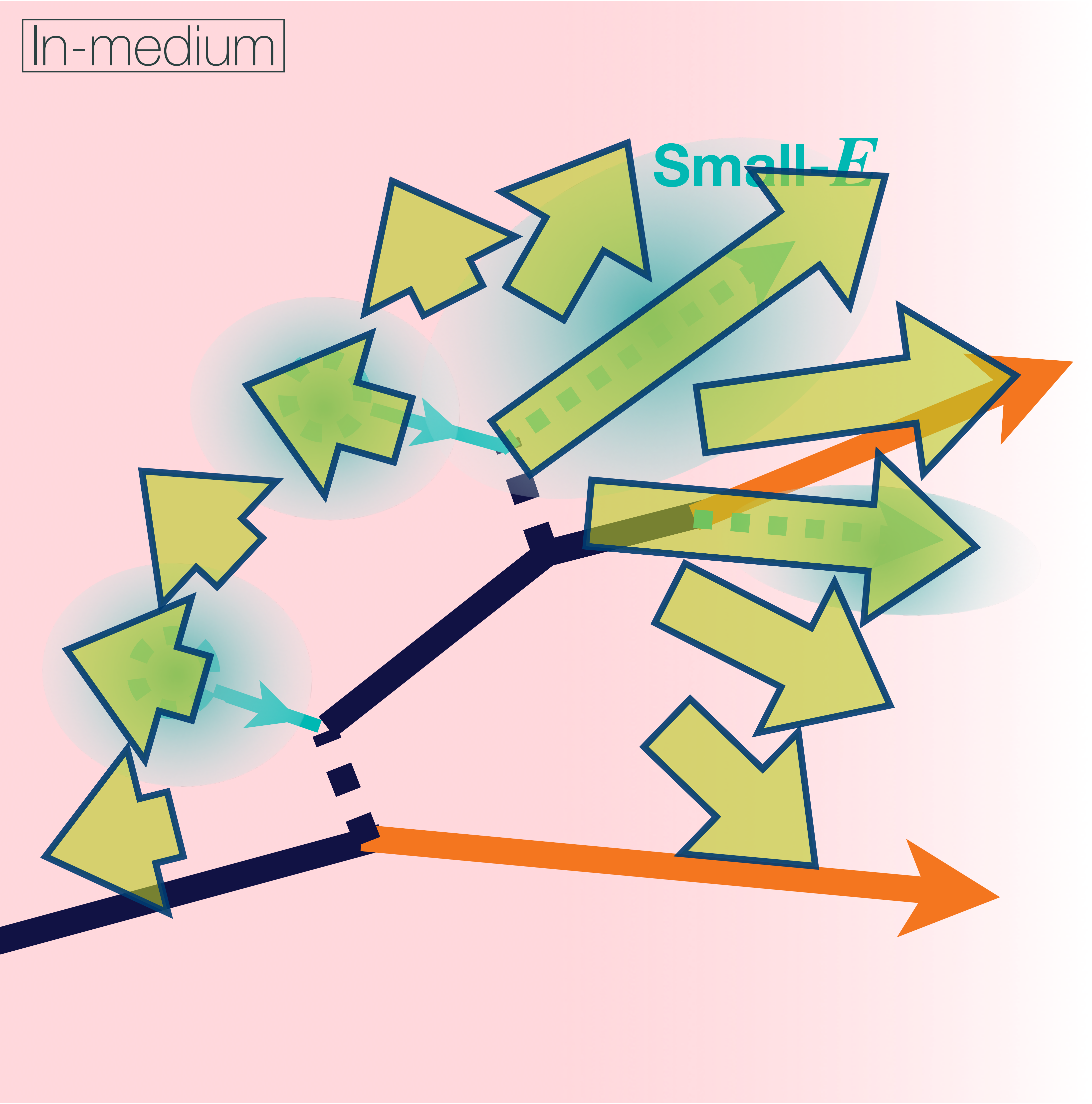

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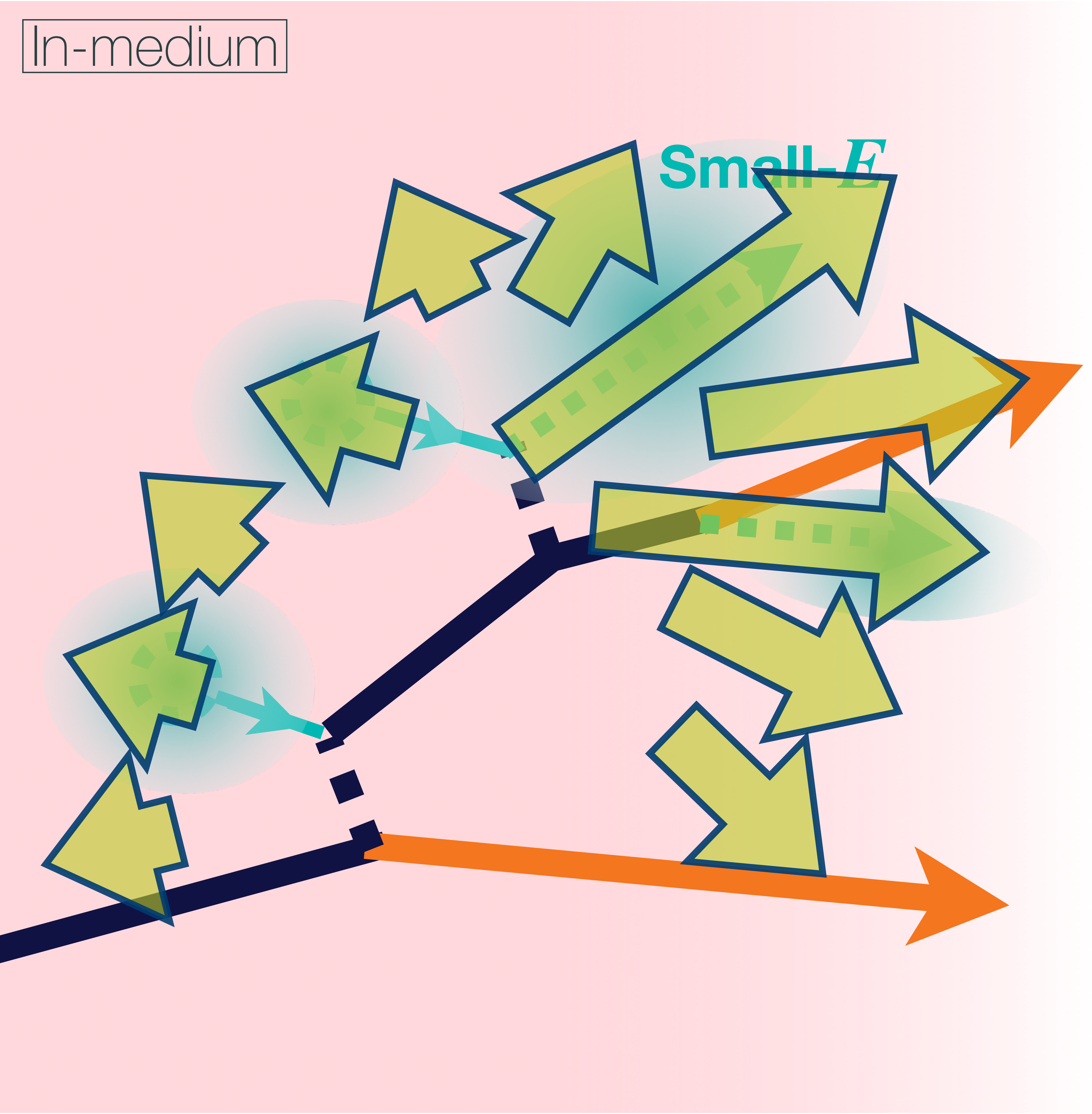

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  - Soft partons
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  → **Source Profile for Fluid**

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

  Model: **Hydrodynamics with Source**

  → **Hydrodynamic Response**

2. Strongly-coupled Description: Hydro Response

- **Conventional hydrodynamic equation**

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

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

  - Energy momentum conservation in medium fluid

- **Hydrodynamic equation with source term**

e.g.) YT, Chang, Qin (17,19), Chen, Luo, Cao, Pang, Wang (18)

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

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

  - Medium fluid evolution with energy-momentum deposition
  - No distinction between soft part of jets and the bulk medium

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Medium fluid evolution with energy-momentum deposition

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Modeled with Causal Diffusion Equation

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- **Energy-momentum deposition**
  - Soft partons
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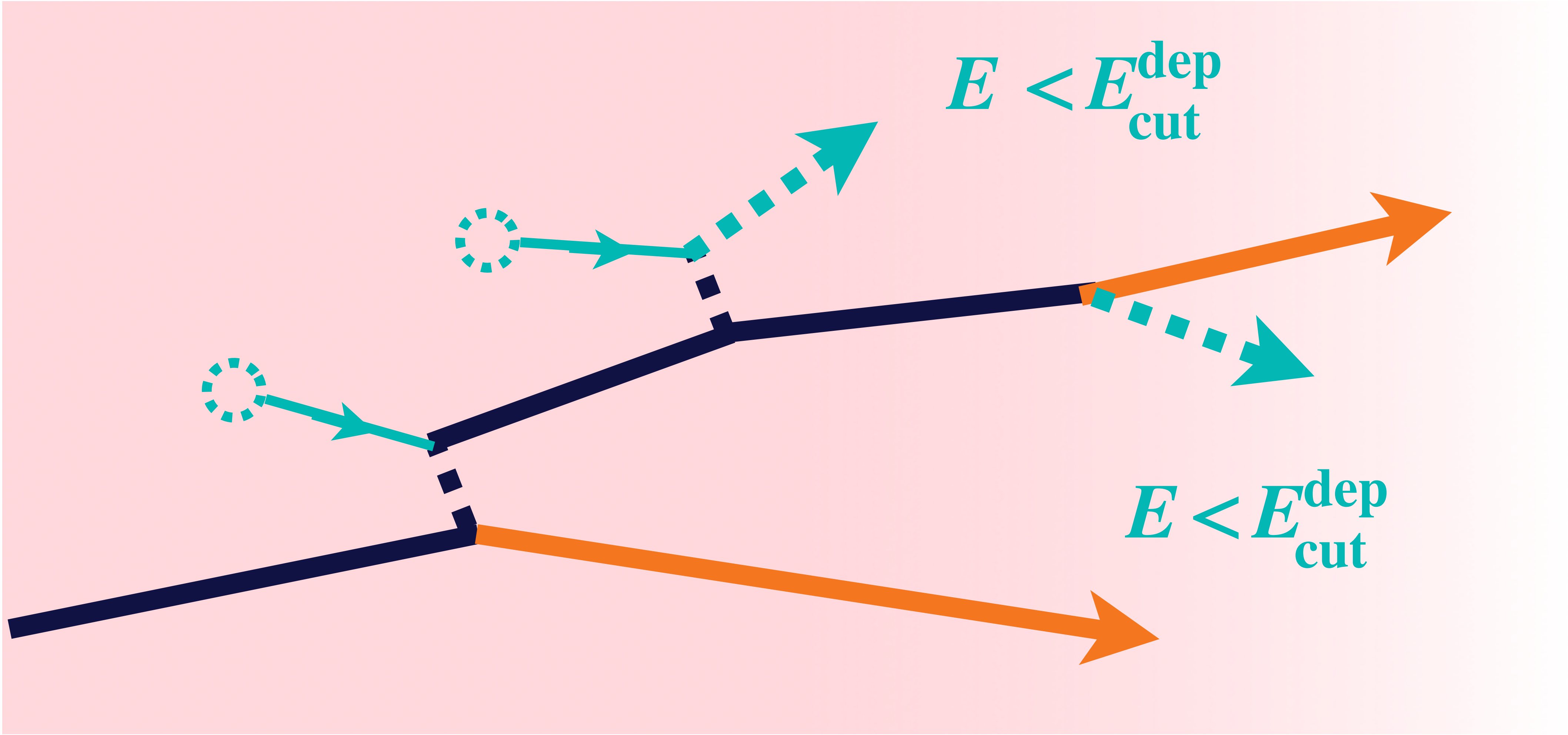
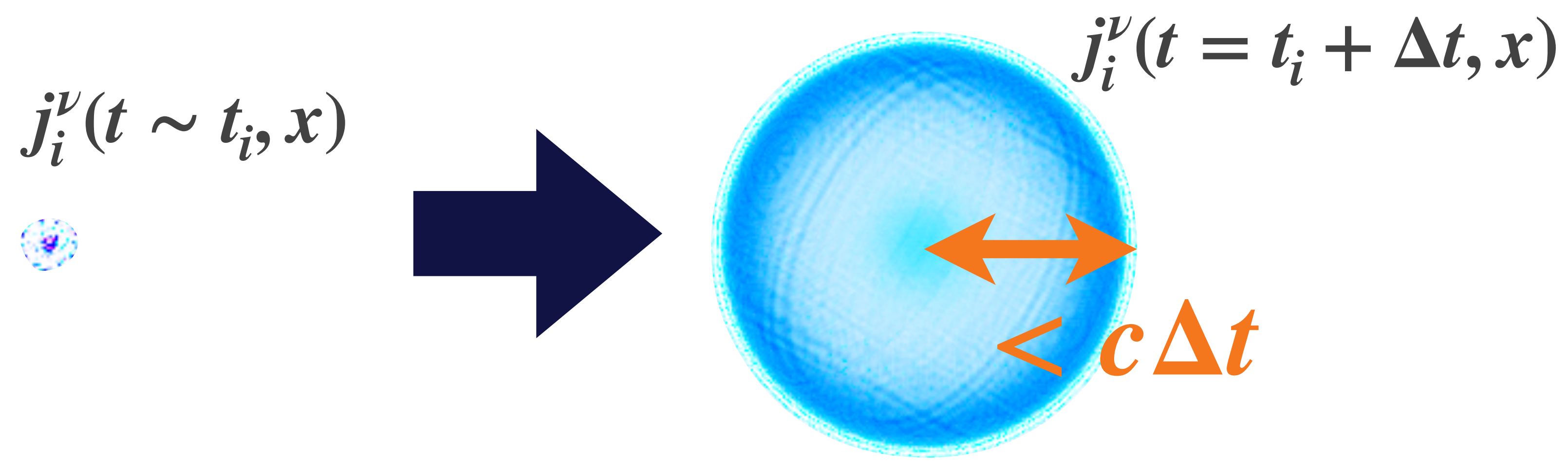


- **Causal source profile**
  - Relativistic diffusion equation

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

with initial condition

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



Parameters

$E_{\mathrm{cut}}^{\mathrm{dep}}$: Energy scale for in-medium thermalization

Δt: Timescale for in-medium thermalization

D_{diff}: Diffusion coefficient

τ_{diff}: Relaxation time in diffusion

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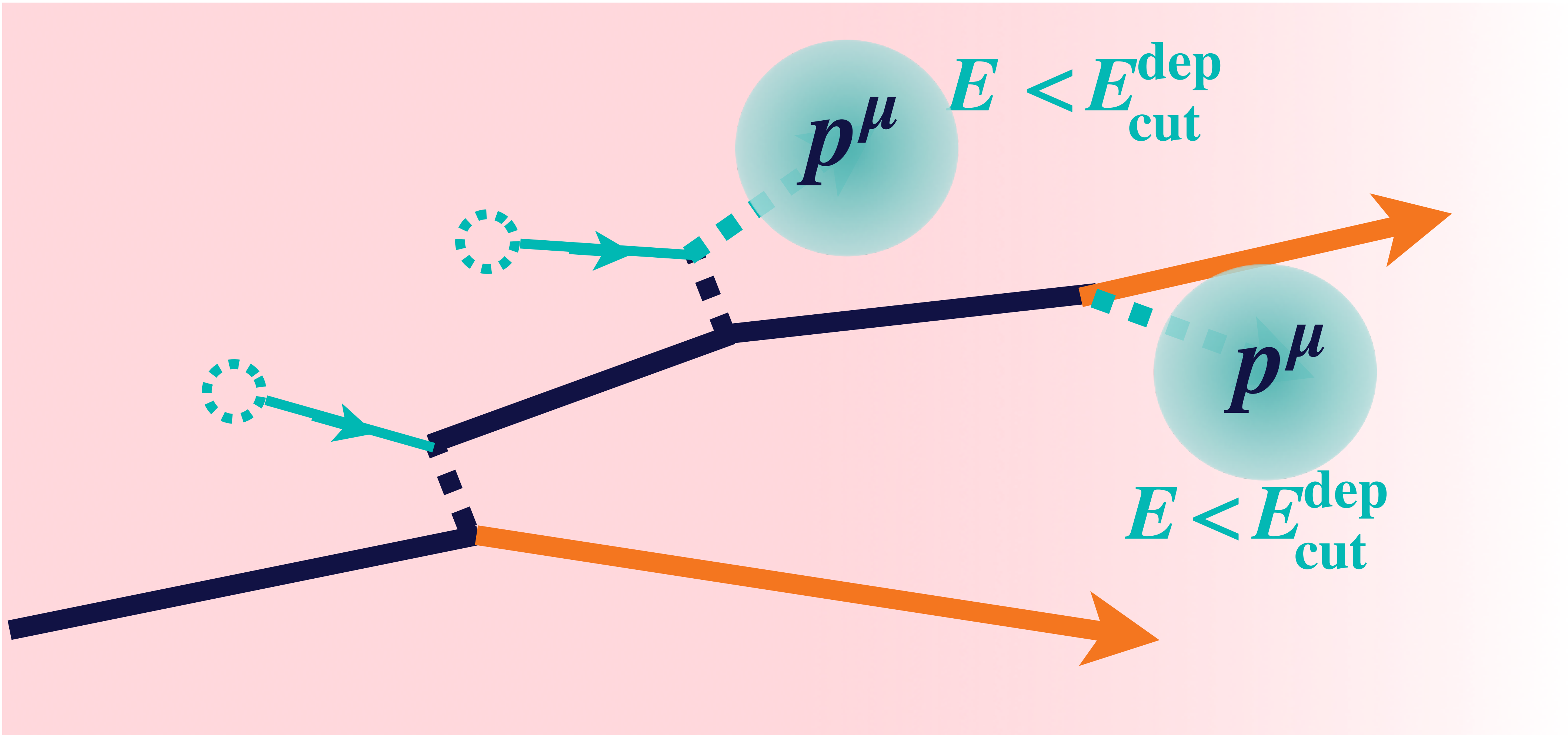

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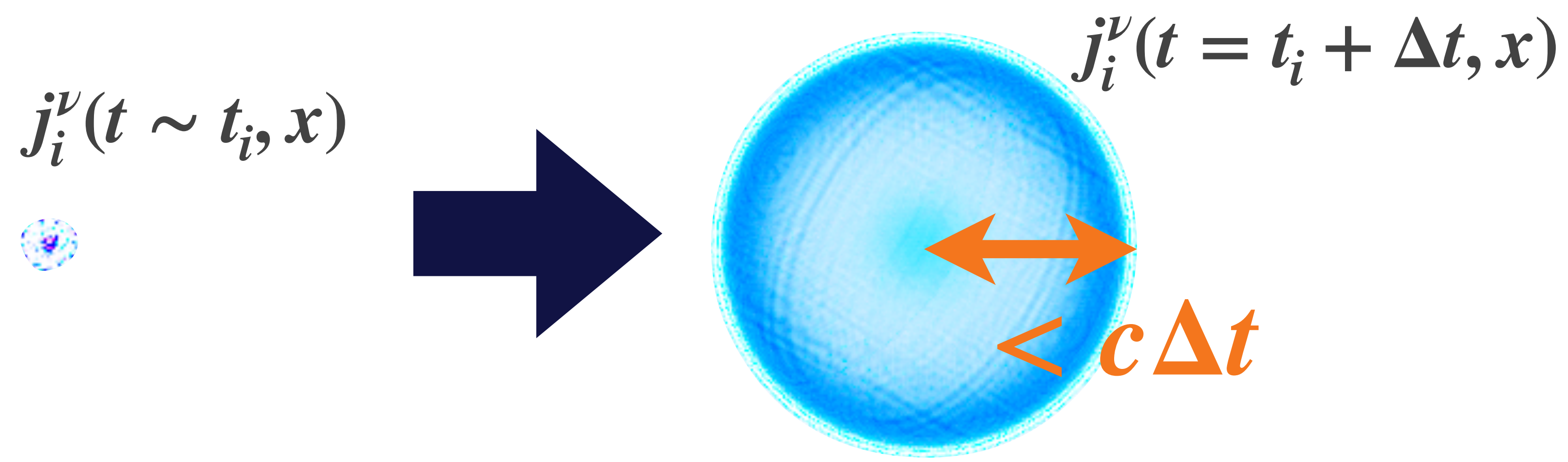

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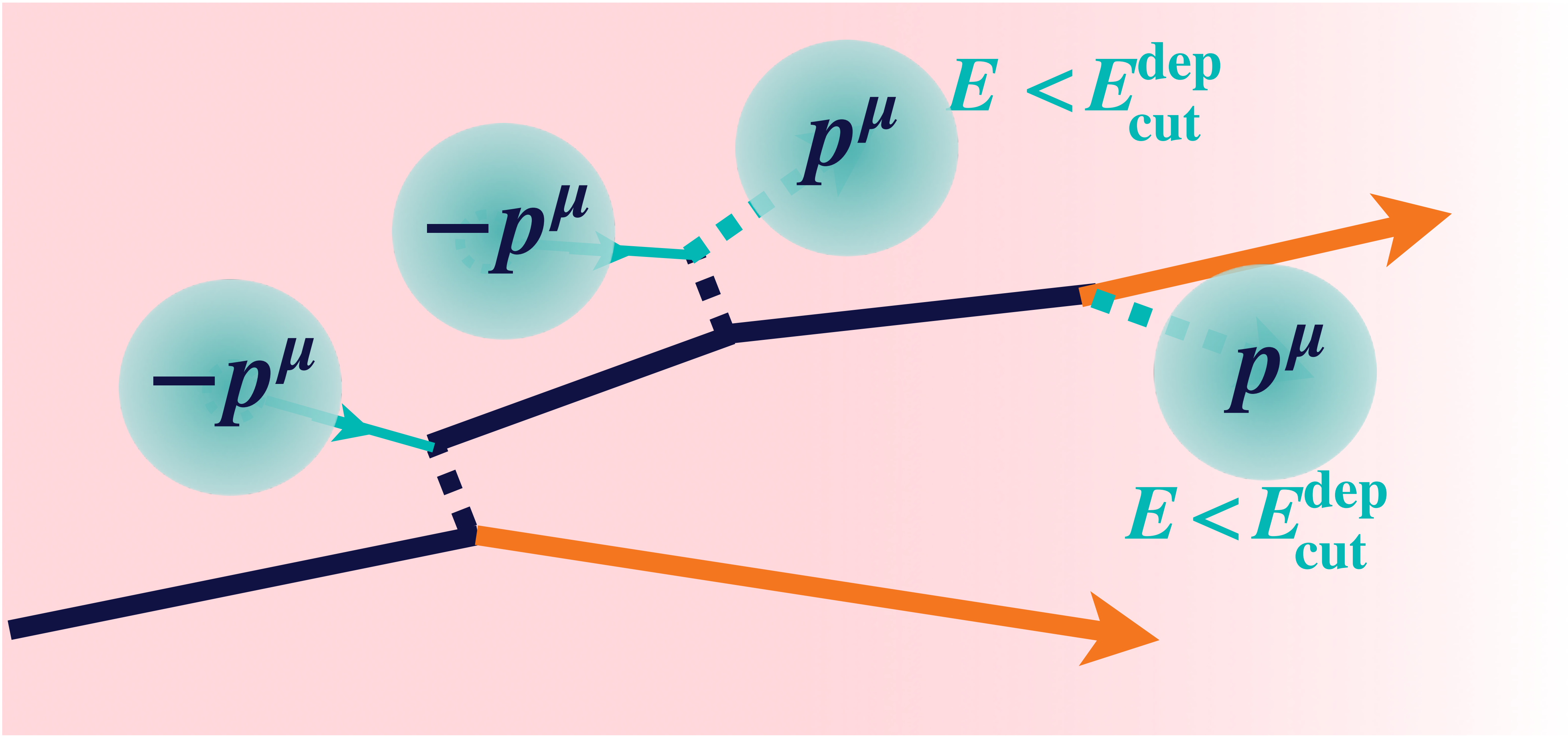

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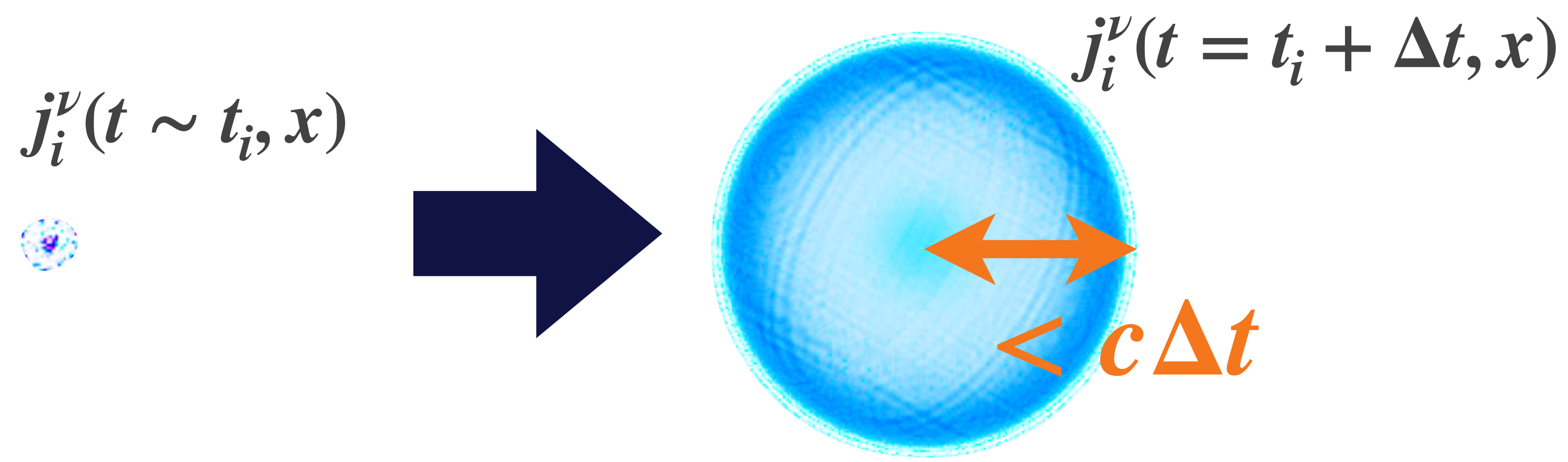

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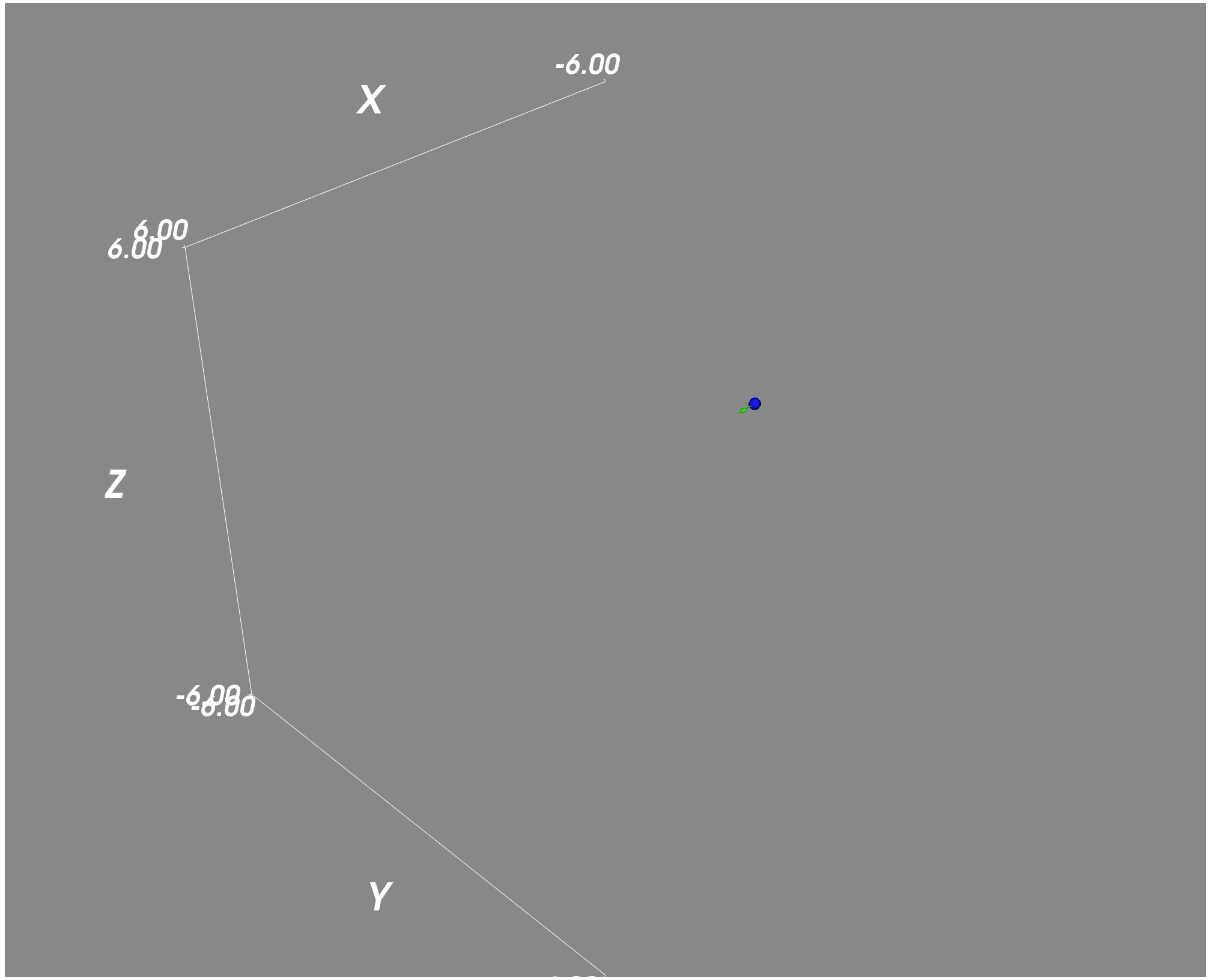
- Jet propagation in a medium fluid with static uniform initial profile



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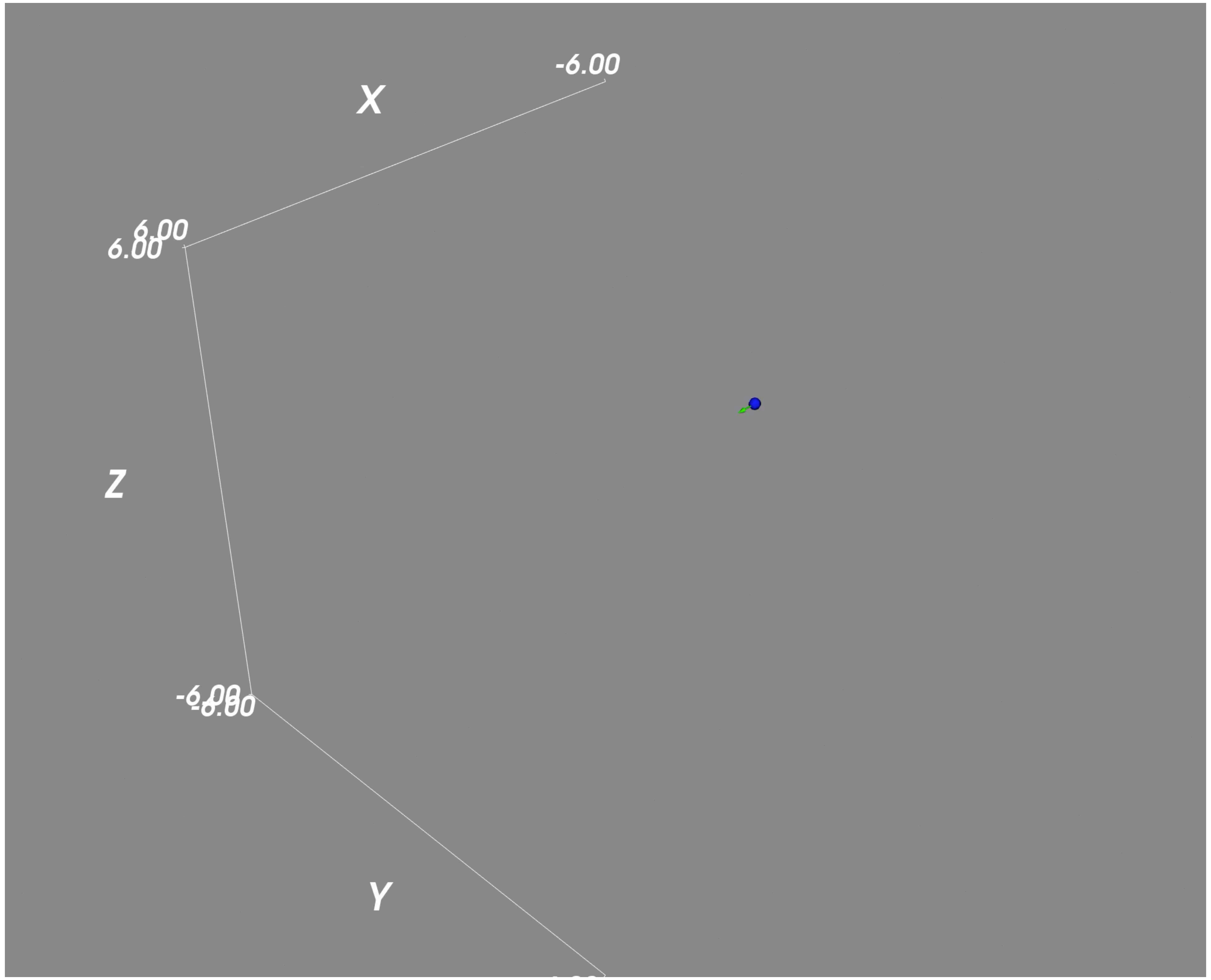


Simulations and Results

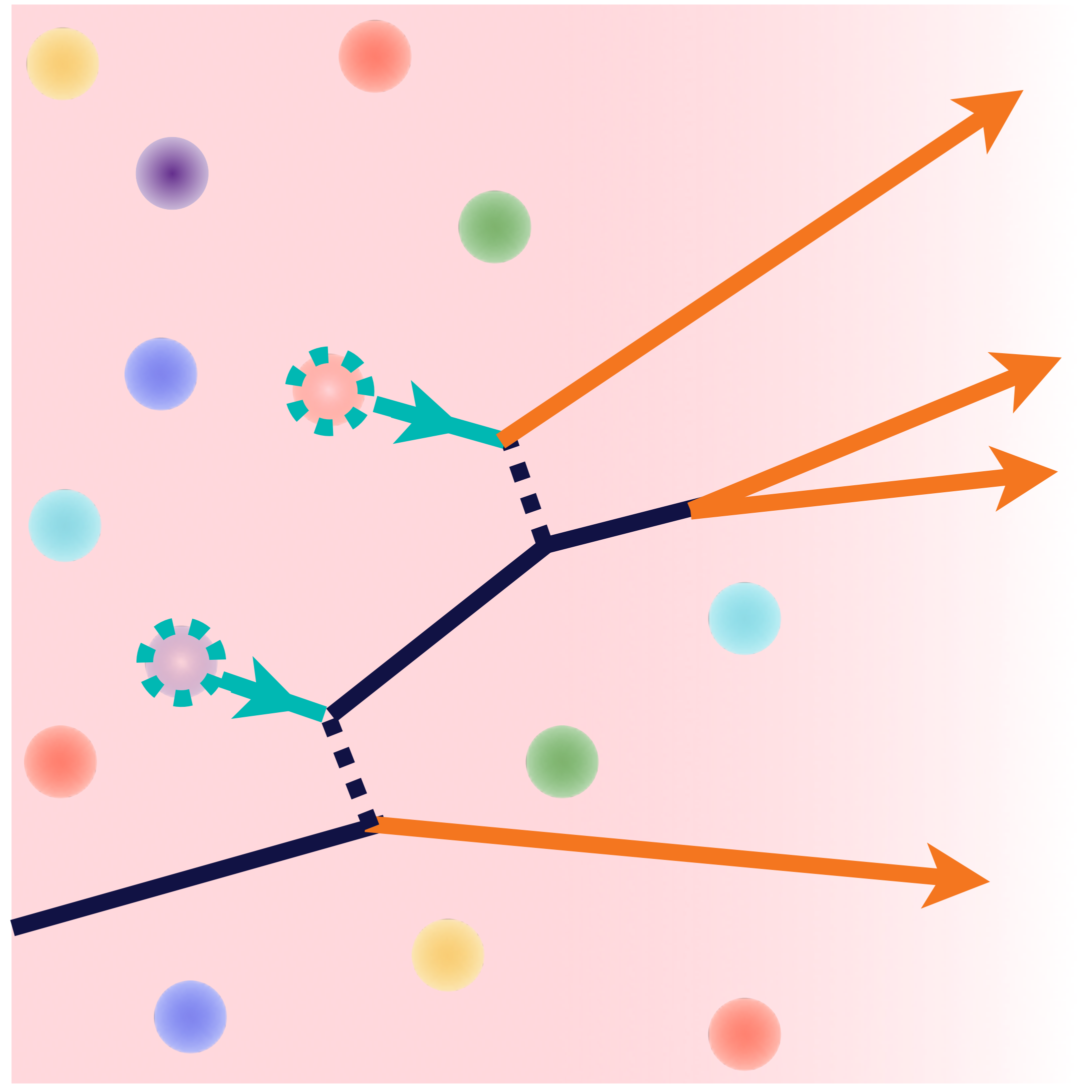
Simulation setup: Jet

* Majumder(13), Kordell, Majumder(17), Cao, Majumder(17)

† Wang, Zhu(13), Luo, et al.(15,18) Cao, et al.(16,17), He, et al.(18)

- **Single jet shower propagation in a medium**
  - Start with a single parton with a fixed energy $E_{\mathrm{init}} = 140\ \mathrm{GeV}$
  - Shower evolution by *MATTER** +*LBT*† in *JETSCAPE* JETSCAPE Collaboration (18)
  - 2 different models for medium response for comparison
  - Jet interacts with QGP medium with $T > 160\,\mathrm{MeV}$ upto $t = 8\,\mathrm{cm}$

Weakly-coupled: Recoils



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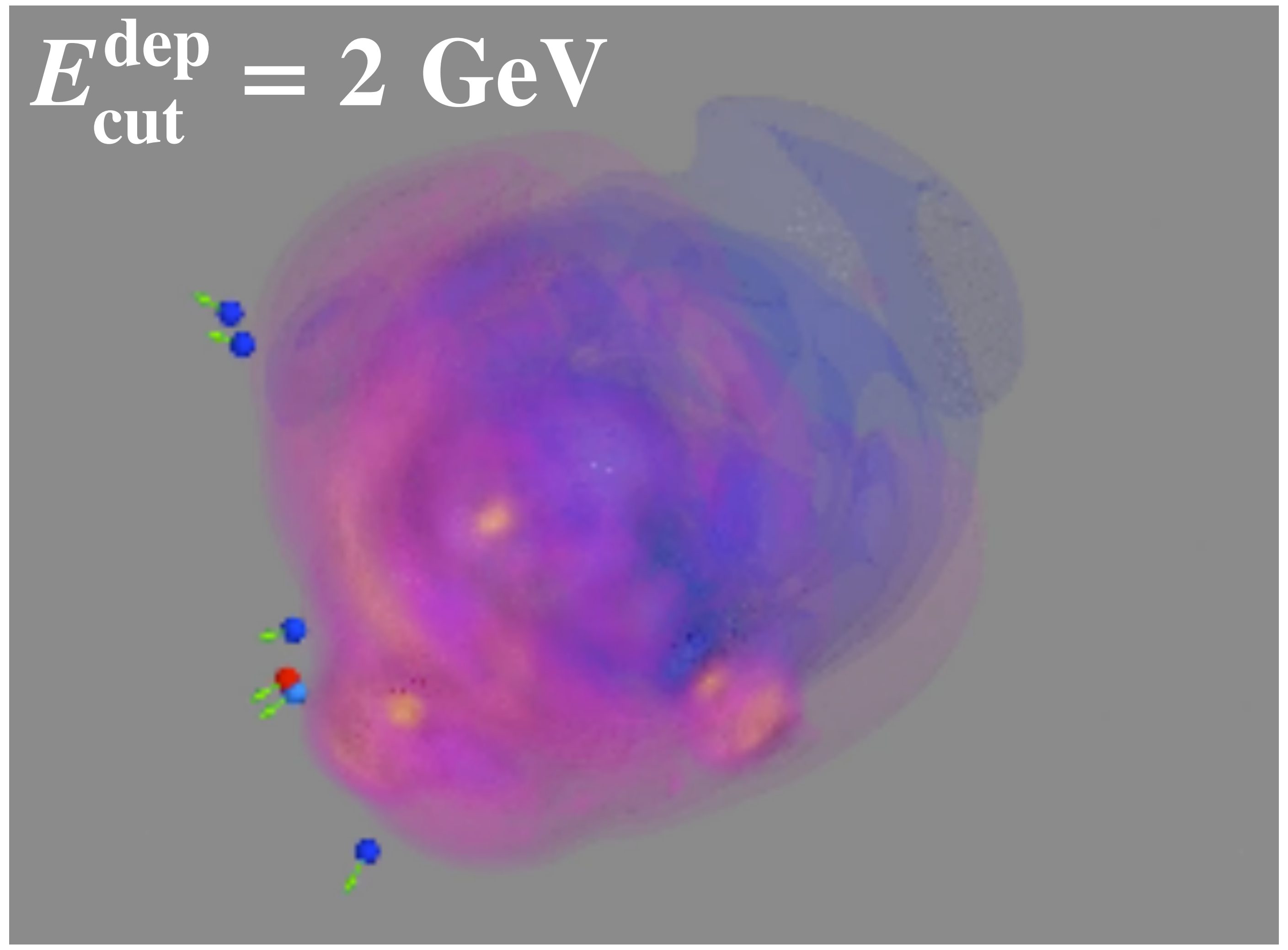
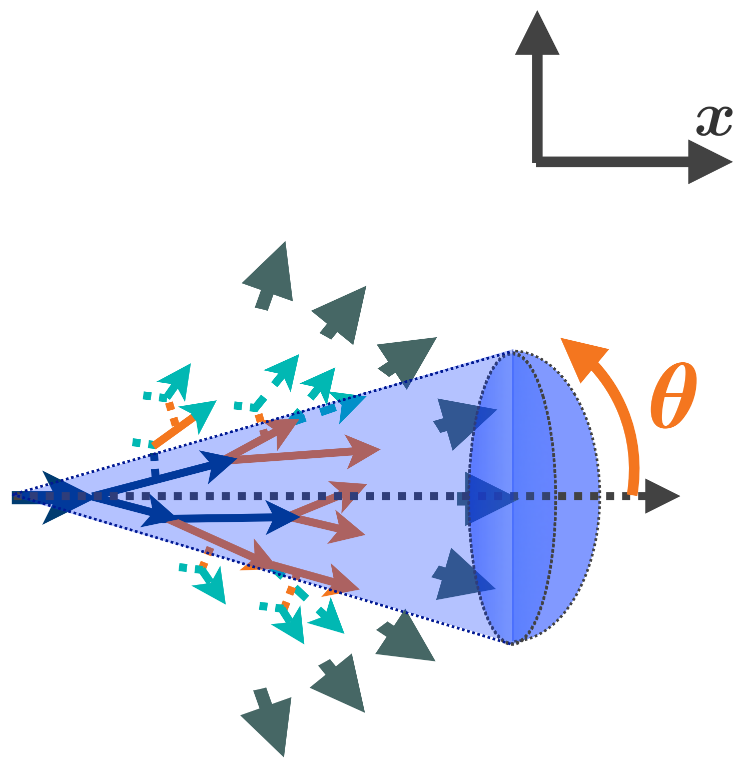


$\tau_{\mathrm{relax}} = 1\ \mathrm{fm},\ D_{\mathrm{diff}} = 0.6\ \mathrm{fm},\ t_{\mathrm{th}} = 1.5\ \mathrm{fm}$ for diffusion

Simulation setup: Hydro Part Contribution

- **Estimation of hydro response contribution**
  - Ideal (theoretically defined) background subtraction

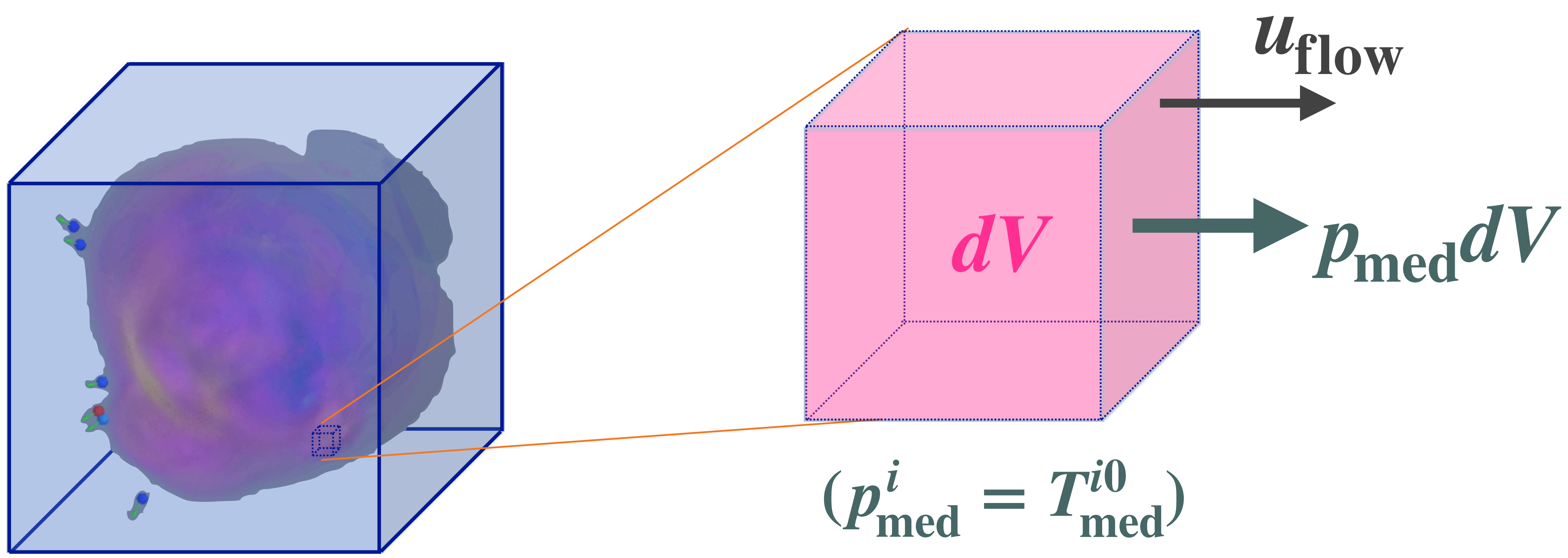
$$\left.\frac{dp^\mu}{d\theta}\right|_{\text{signal}} = \left.\frac{dp^\mu}{d\theta}\right|_{\text{shower}} + \left.\frac{dp^\mu}{d\theta}\right|_{\text{med. w/ jet}} - \left.\frac{dp^\mu}{d\theta}\right|_{\text{med. w/o jet}}$$



  - 2 different ways to calculate hydro contribution

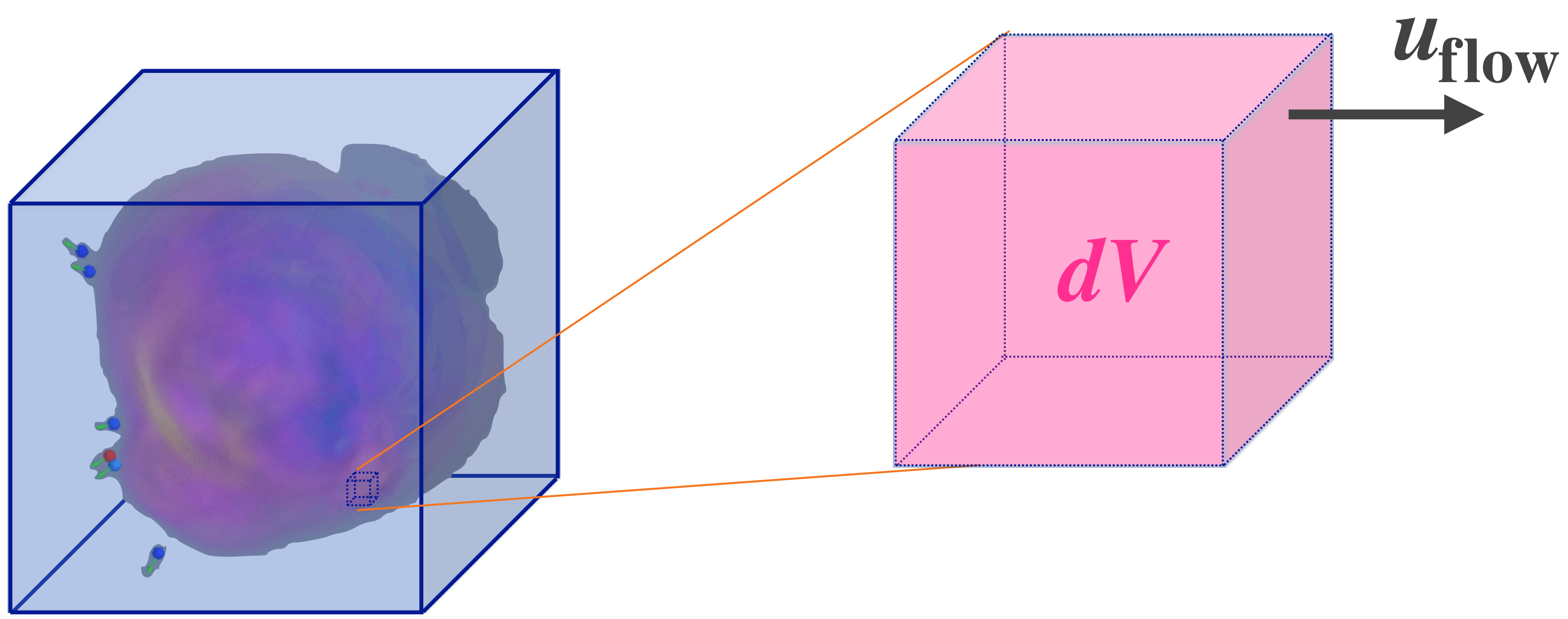
w/o Particlization

- Treat fluid elements as particles



w/ Particlization (Cooper-Frye)

- Consider thermal distribution in fluid elements



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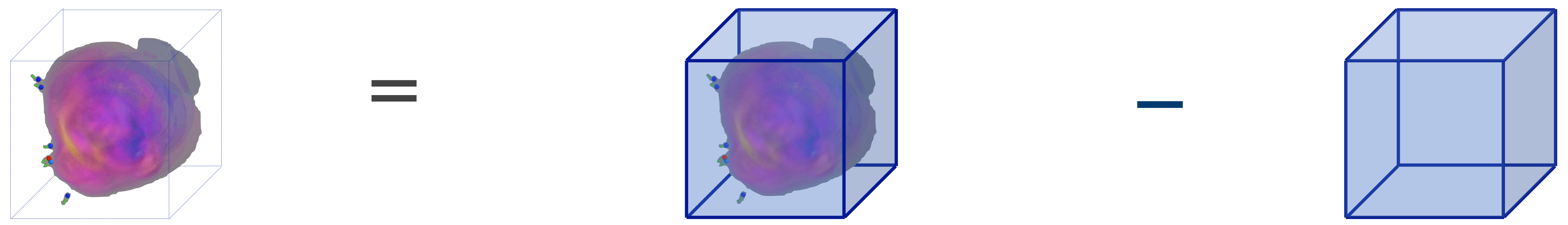

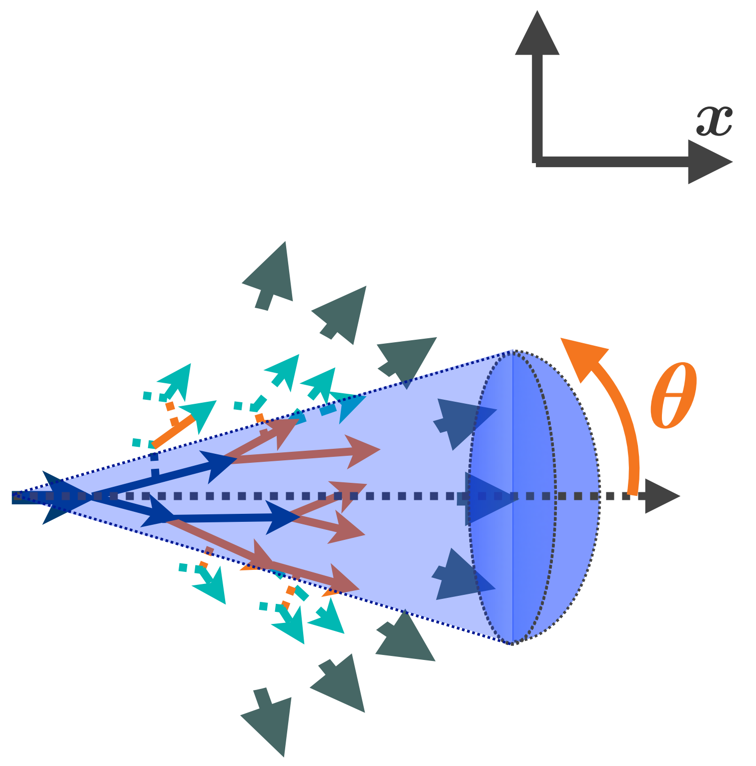

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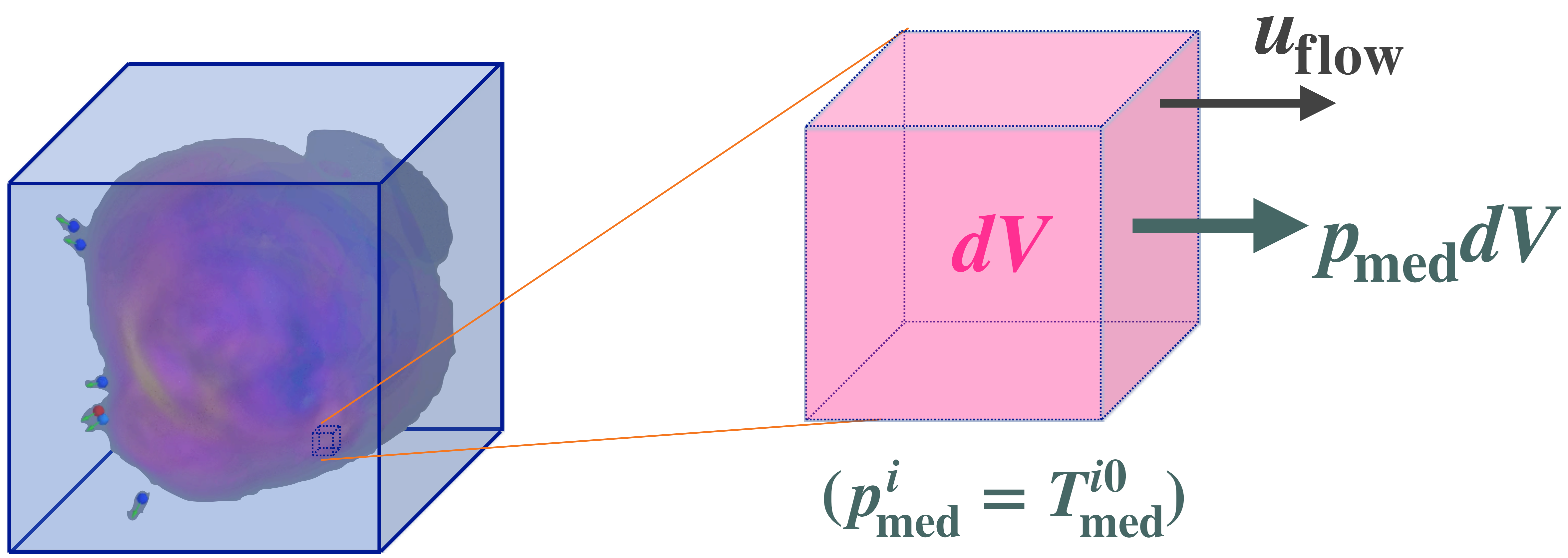

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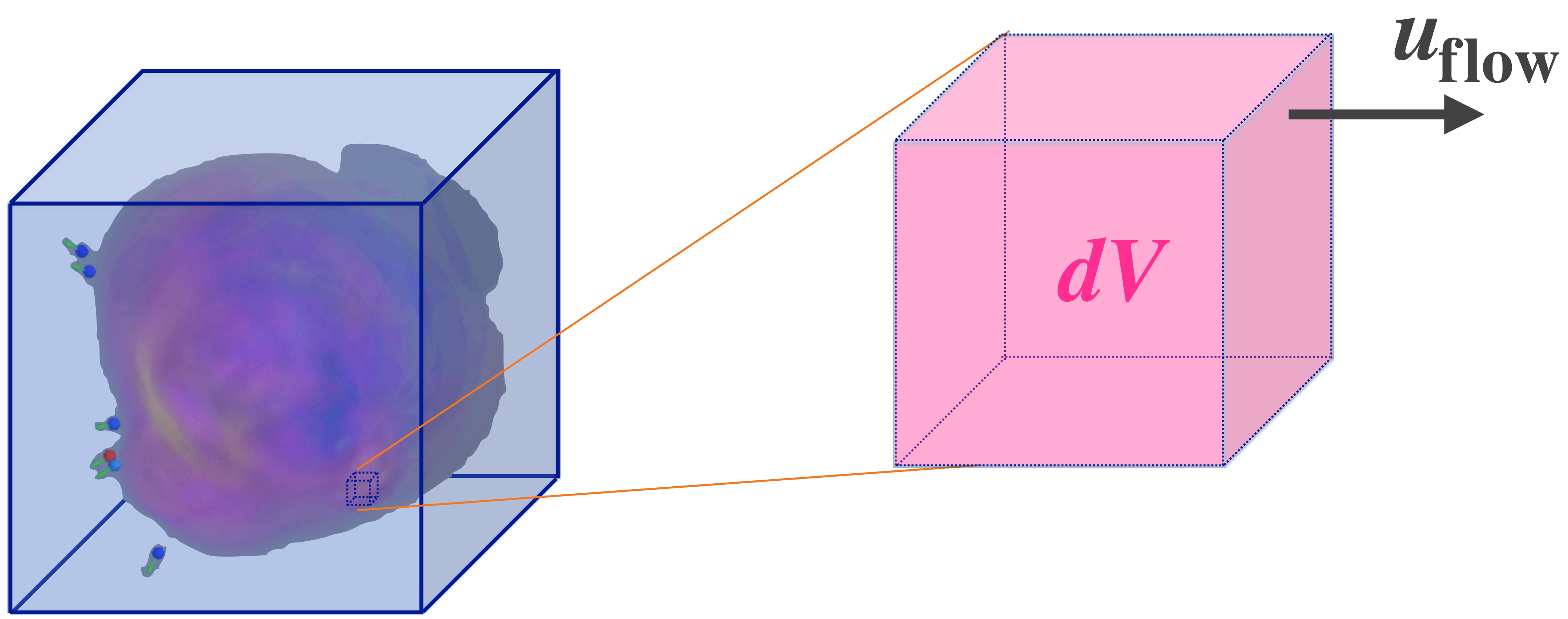

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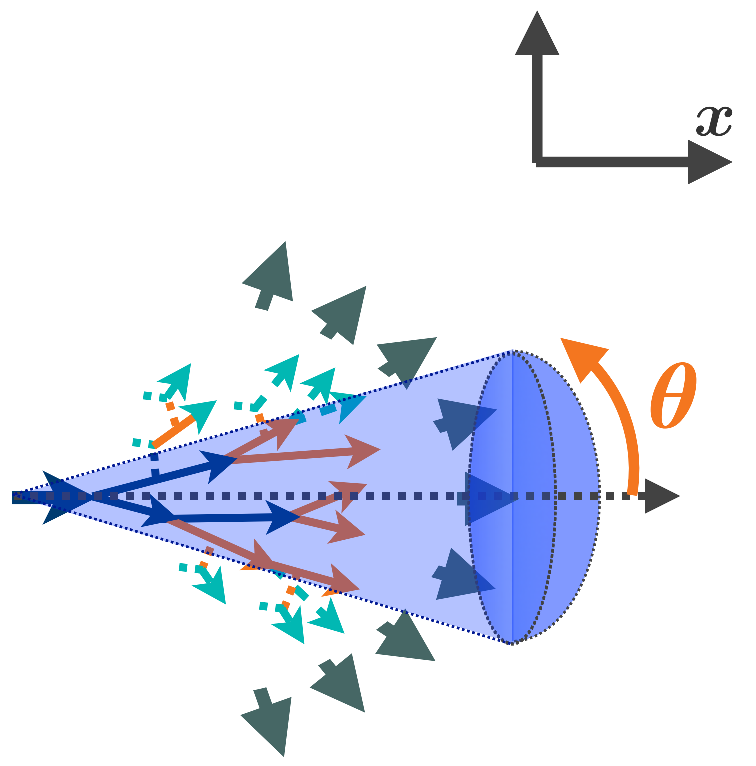

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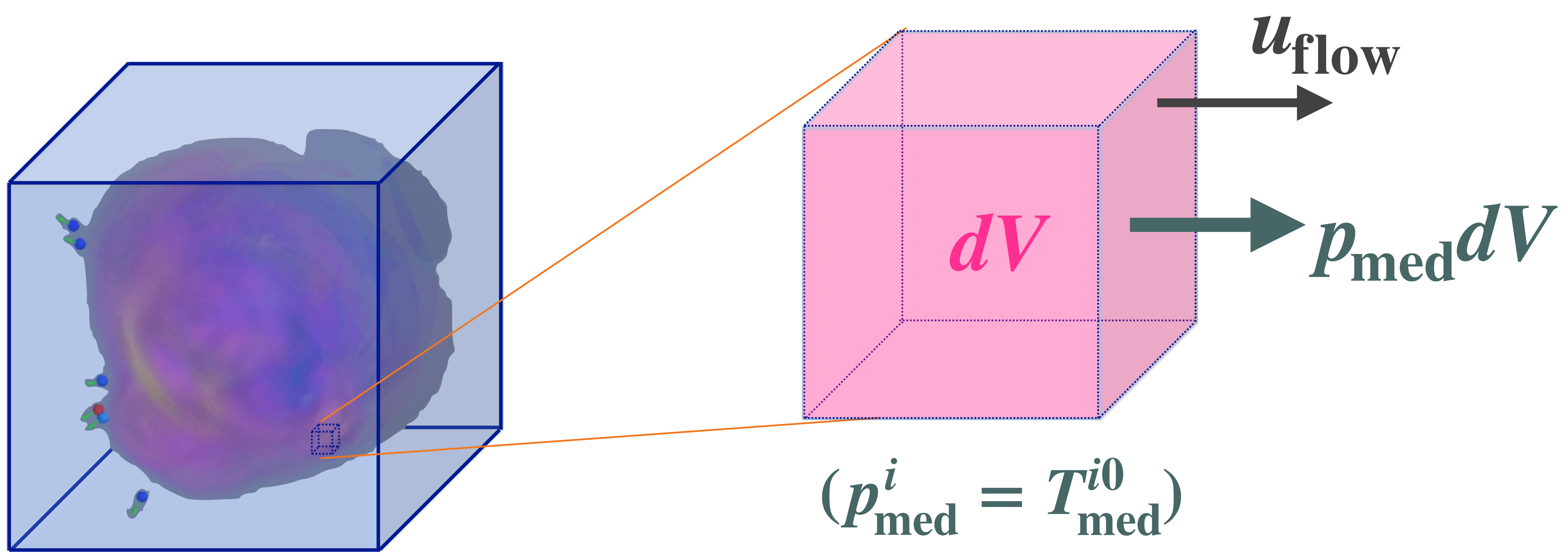

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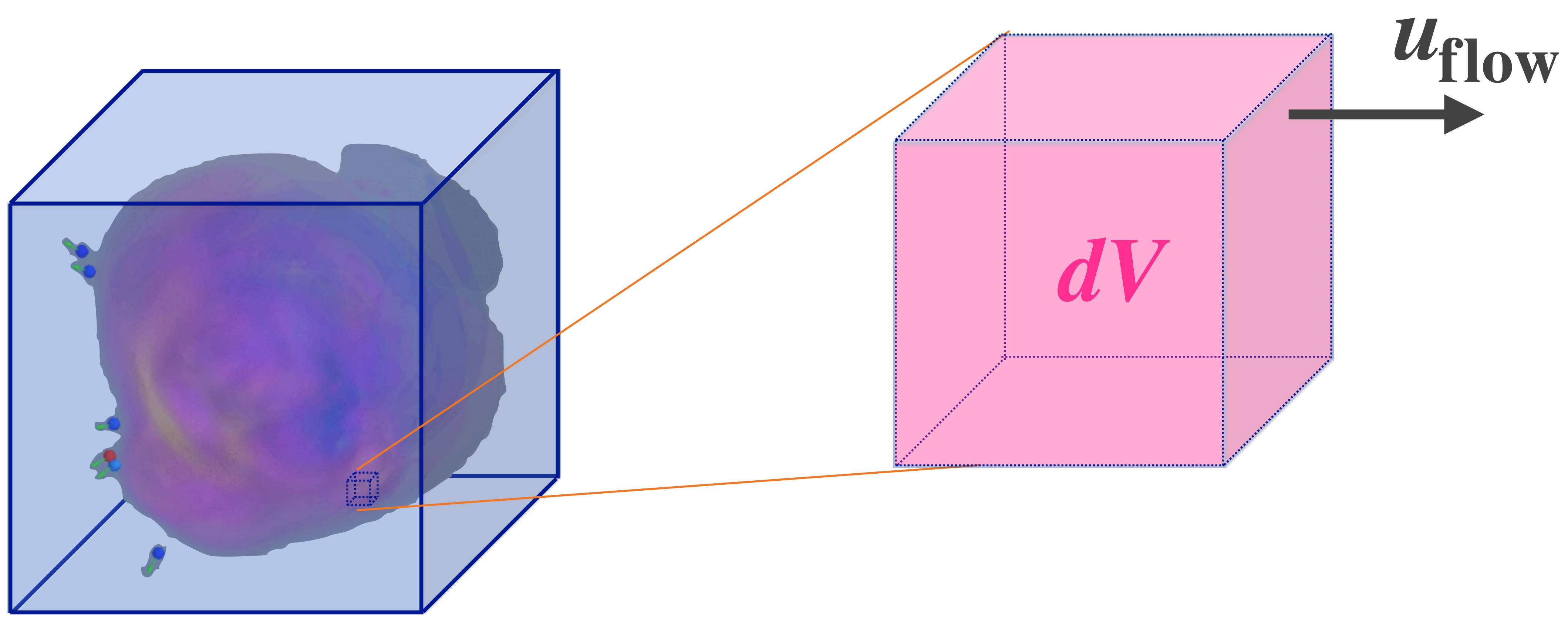

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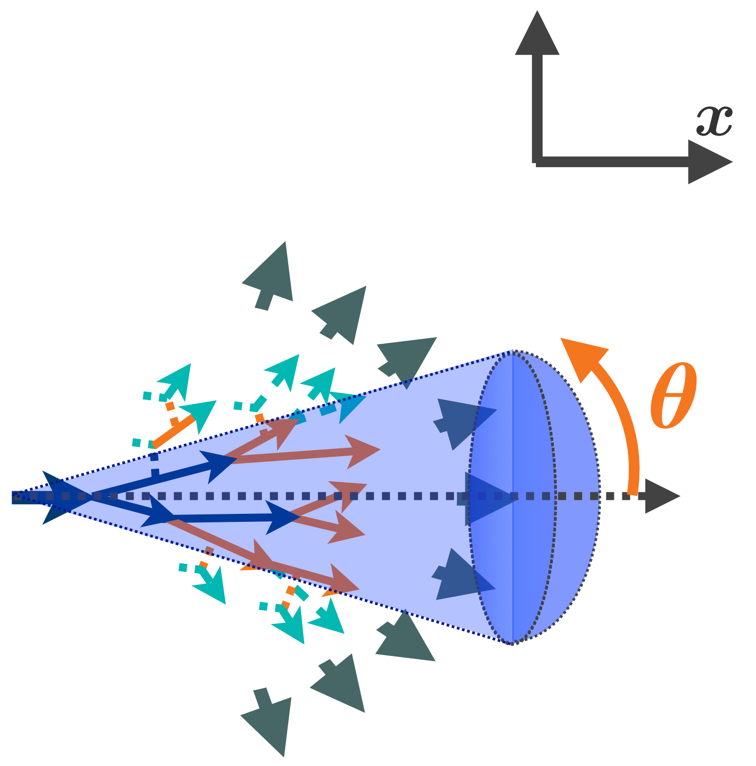

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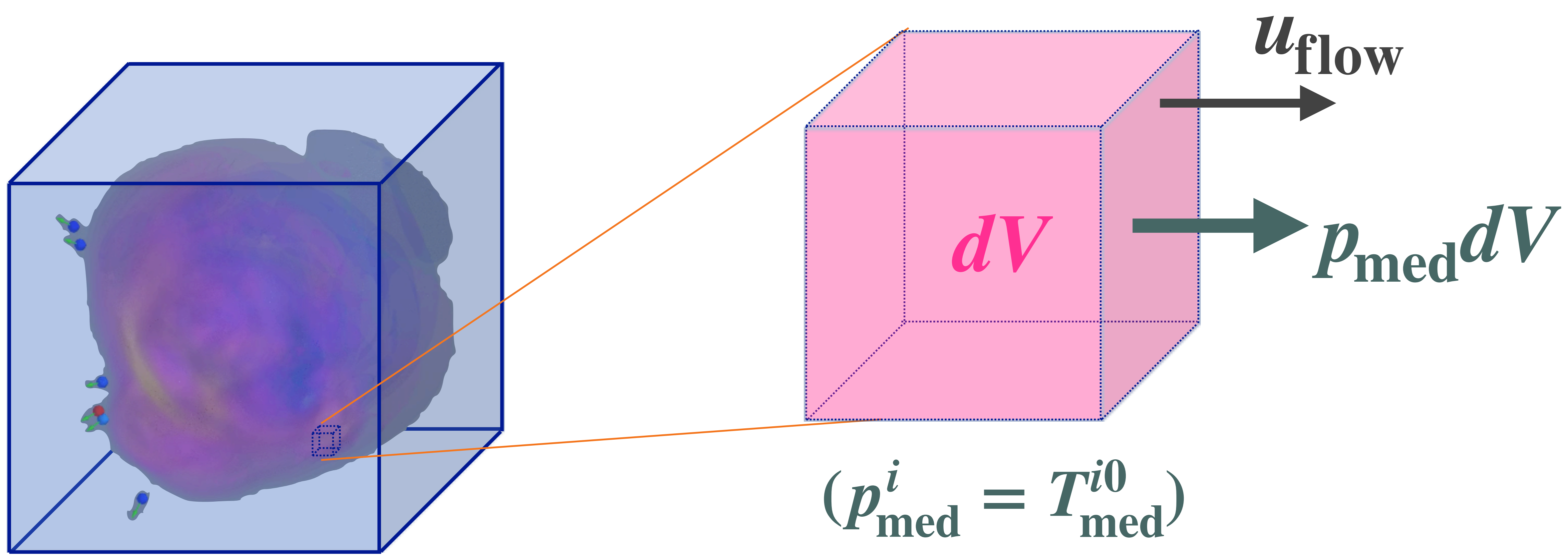

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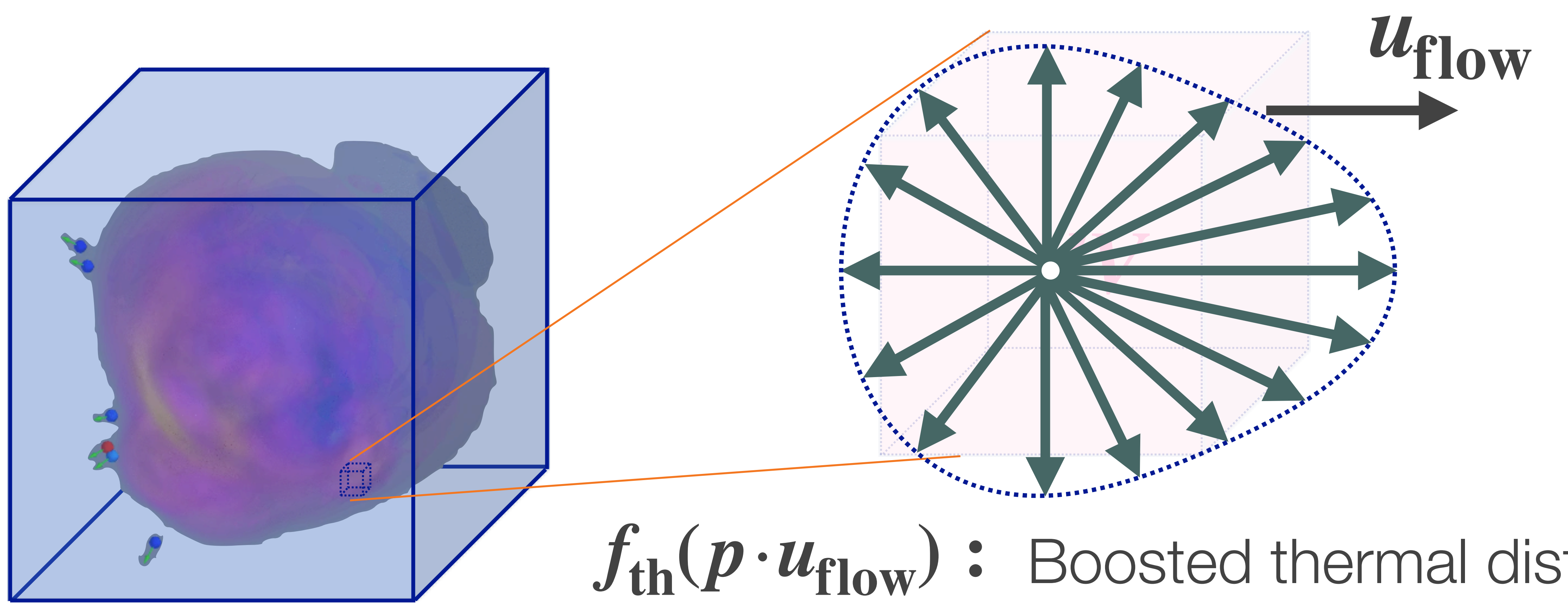

$f_{\text{th}}(p \cdot u_{\text{flow}})$: Boosted thermal distribution

Simulation setup: Hydro Part Contribution

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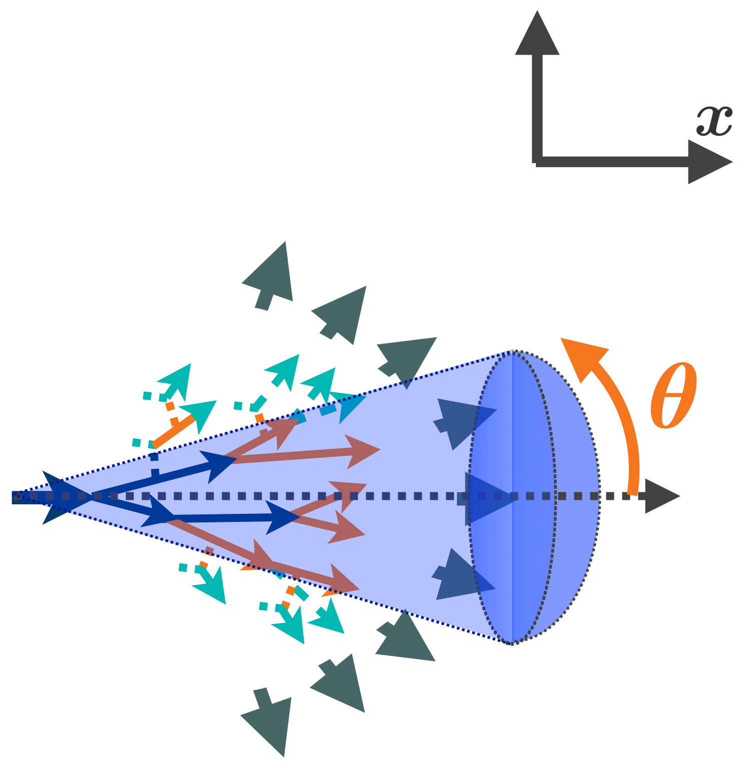

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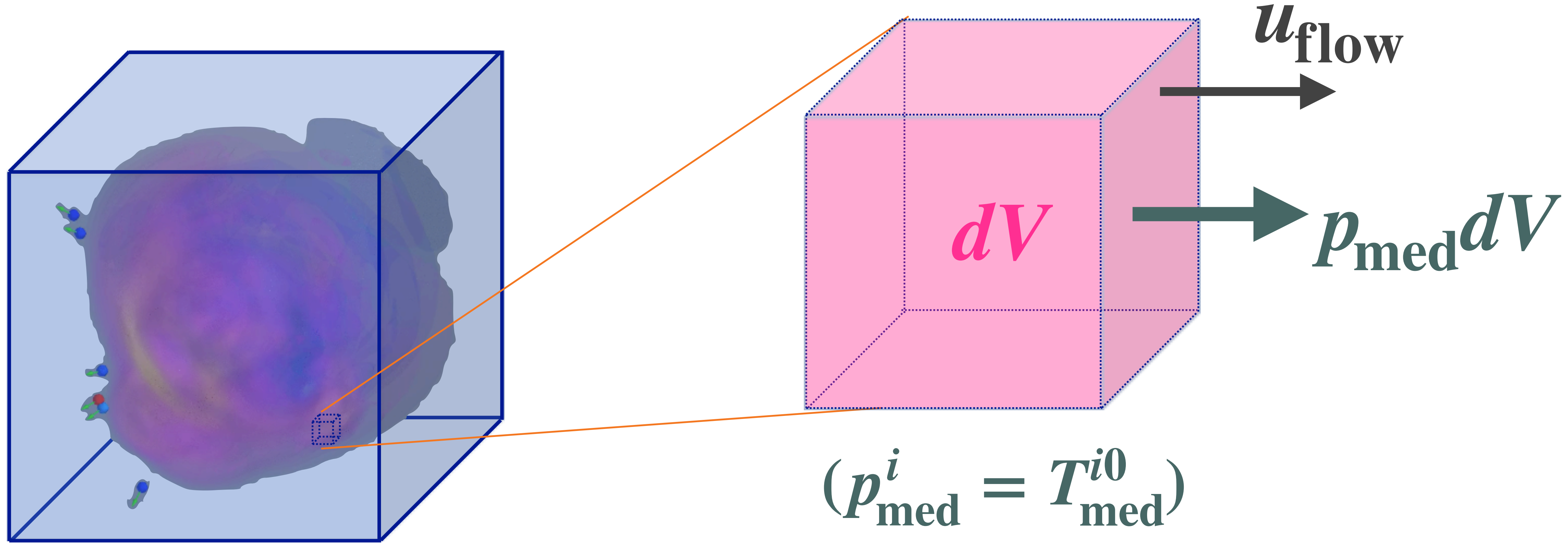

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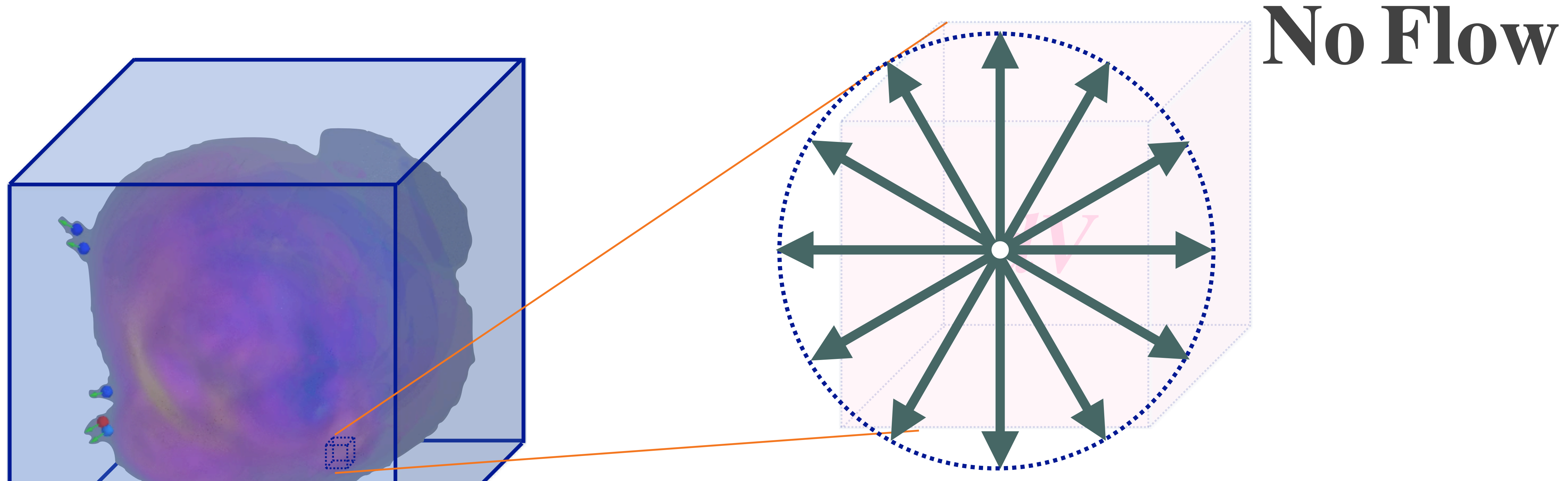

$f_{\text{th}}(p^0)$: (Isotropic) thermal distribution

Simulation setup: Hydro Part Contribution

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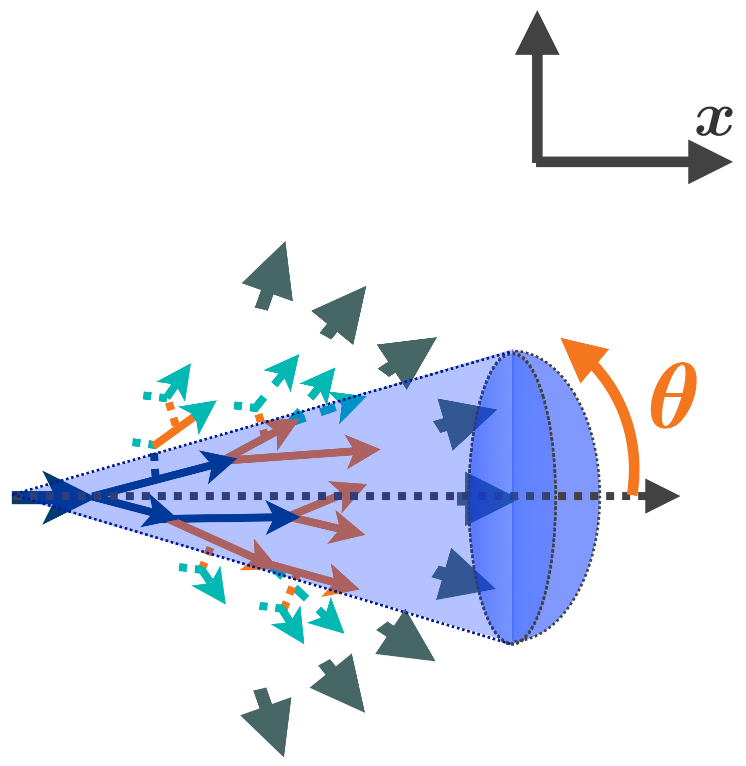

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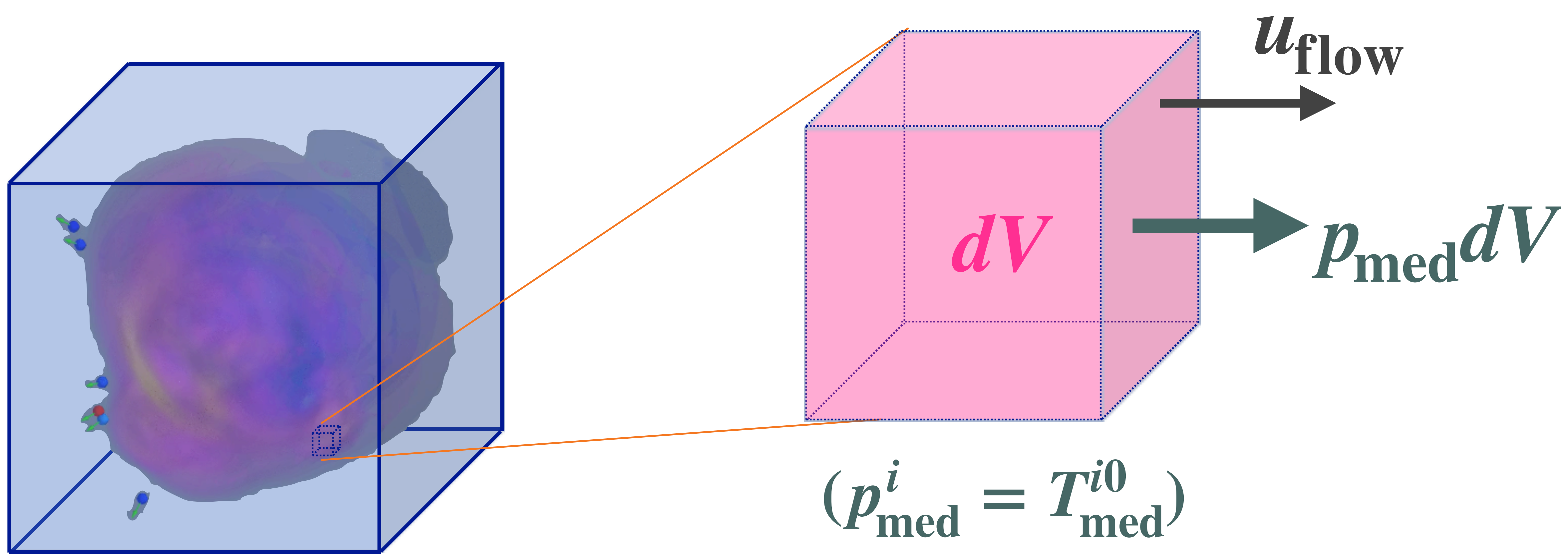

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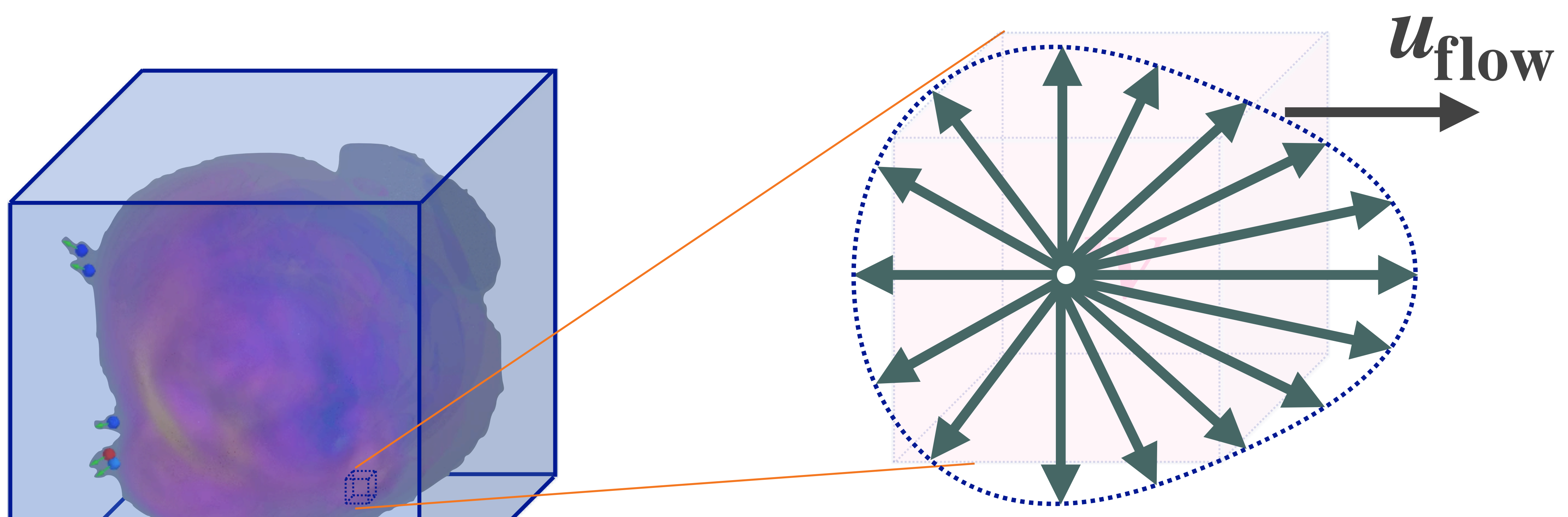


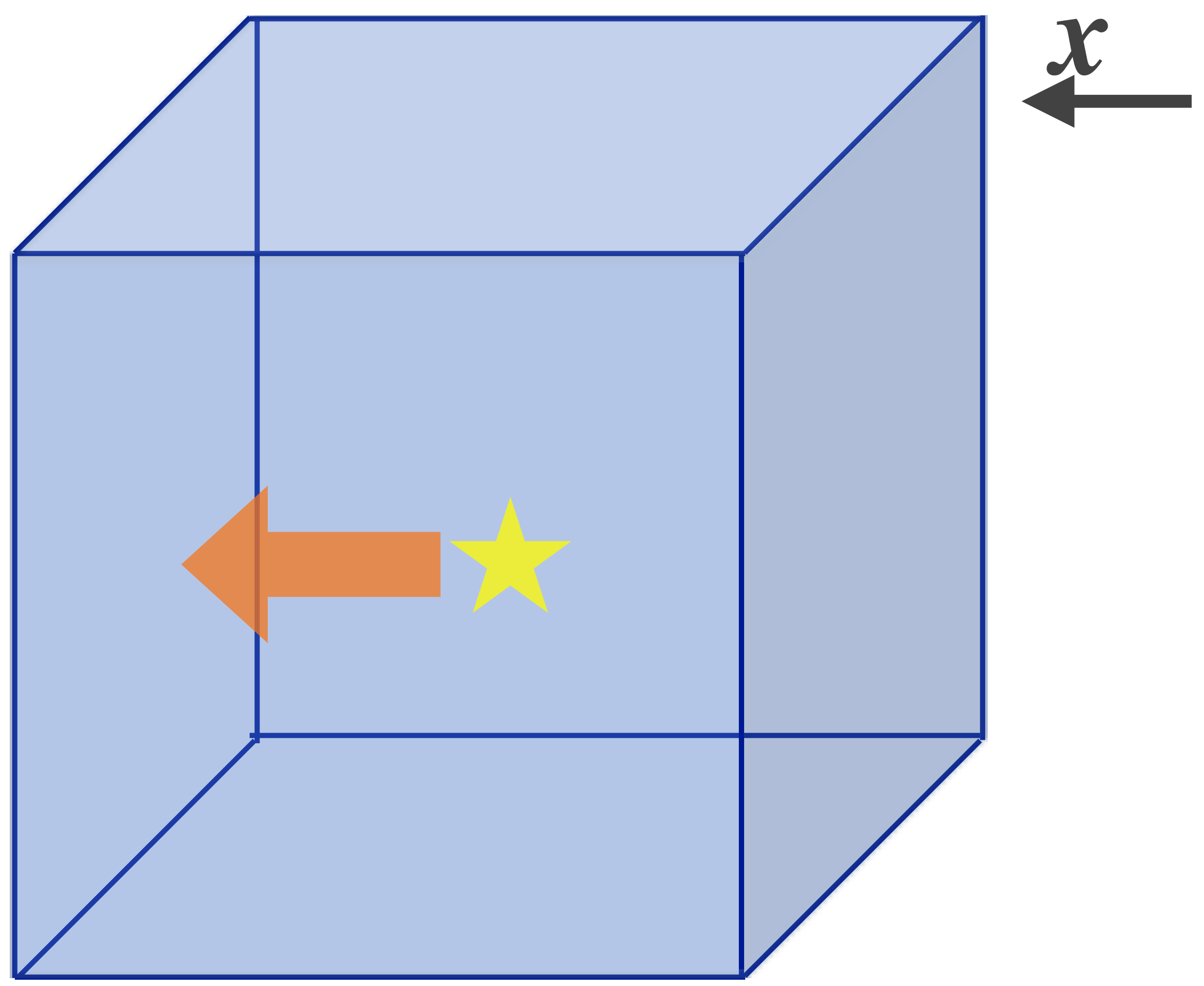
$f_{\text{th}}(p \cdot u_{\text{flow}})$: Boosted thermal distribution

Simulation setup: Flow in the medium

- **3 different configurations for an ideal fluid medium**
  - Brick, medium with uniform static initial condition
  - Expanding fluid with initial 3-D Gaussian energy density profile
  - Medium evolves upto $t = 10\,\mathrm{fm}$

(a) Brick

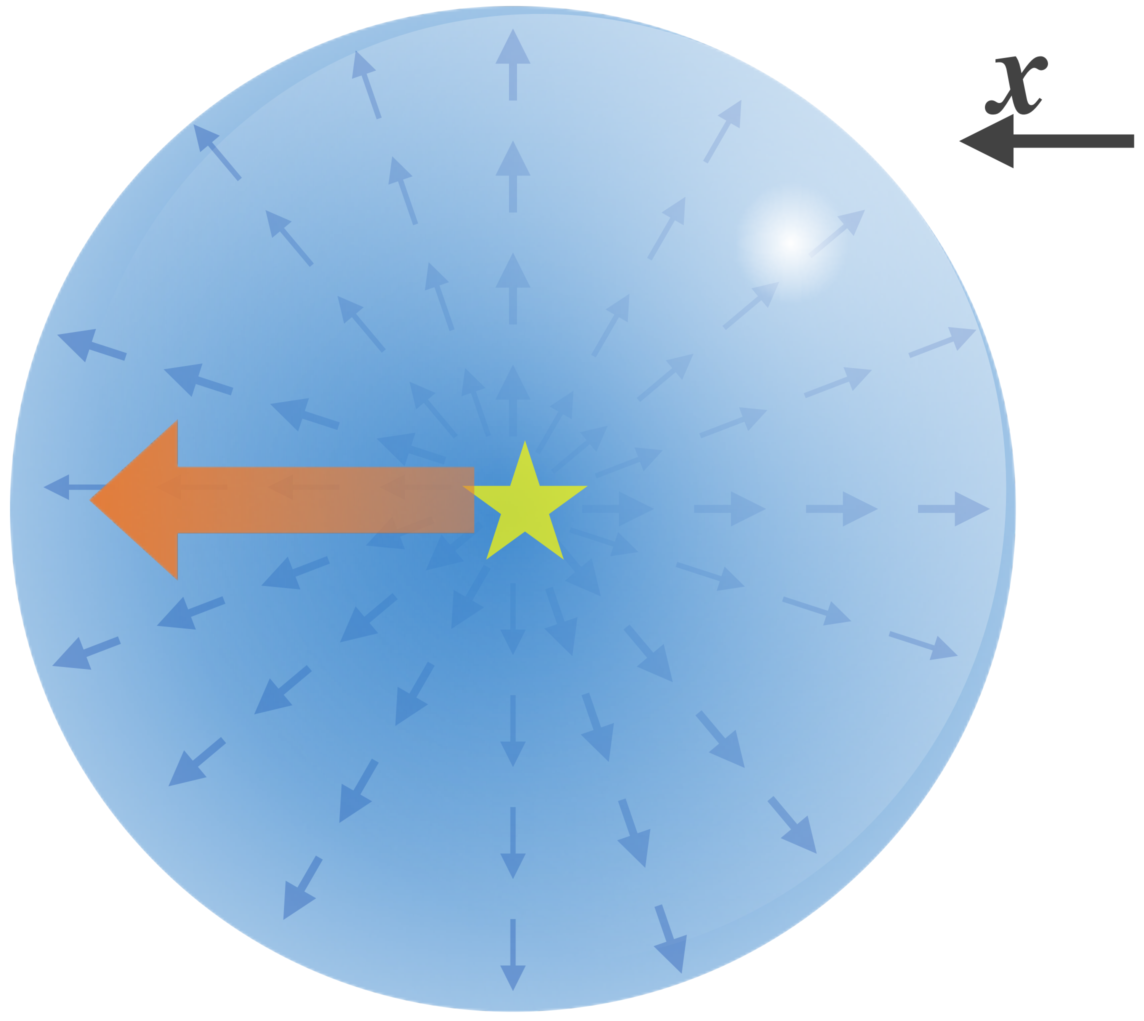
- No Flow



$T = 0.25$ GeV

(b) Expanding, Outward

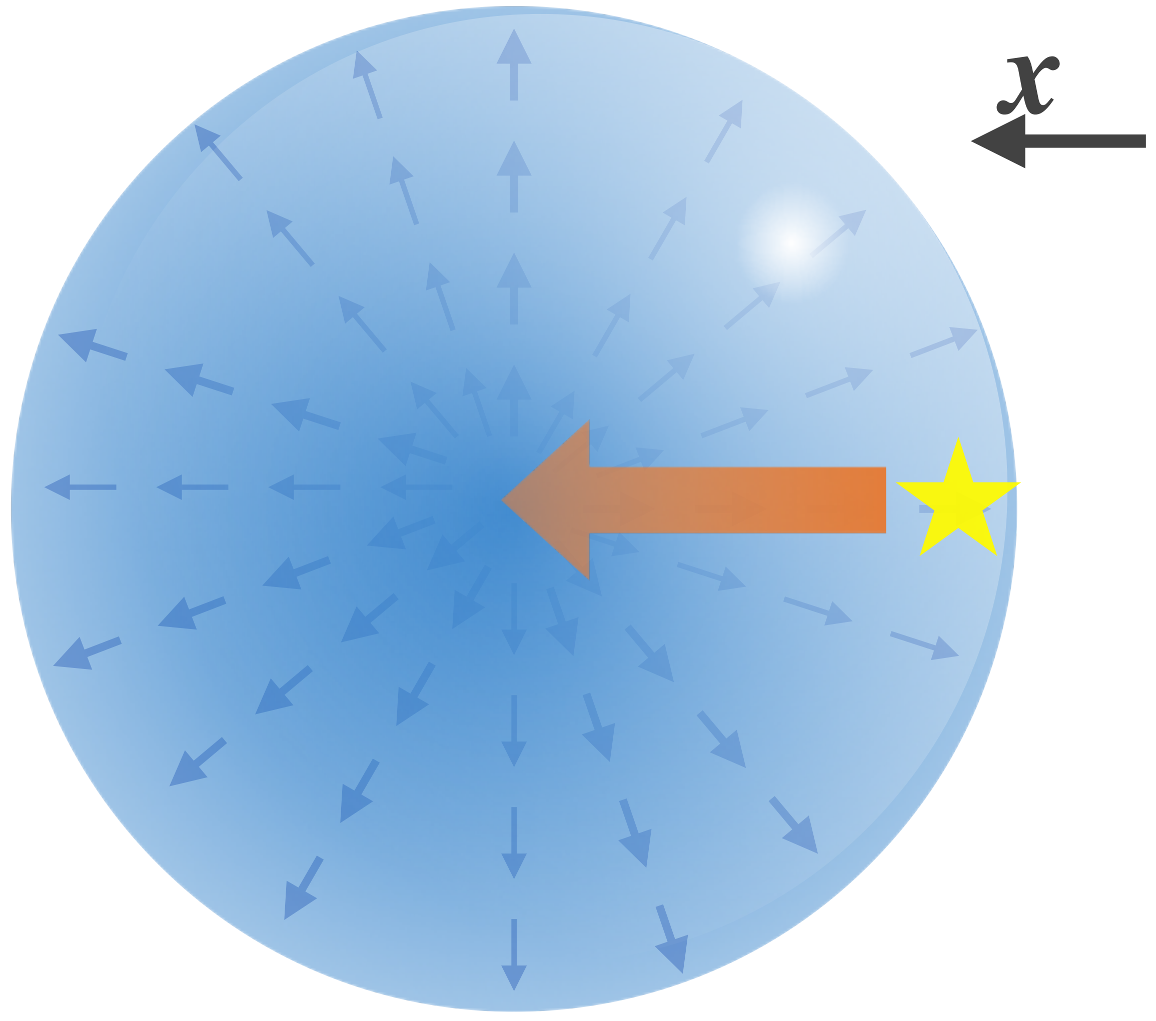
- Following Flow



$T_{\mathrm{center}} = 0.5$ GeV

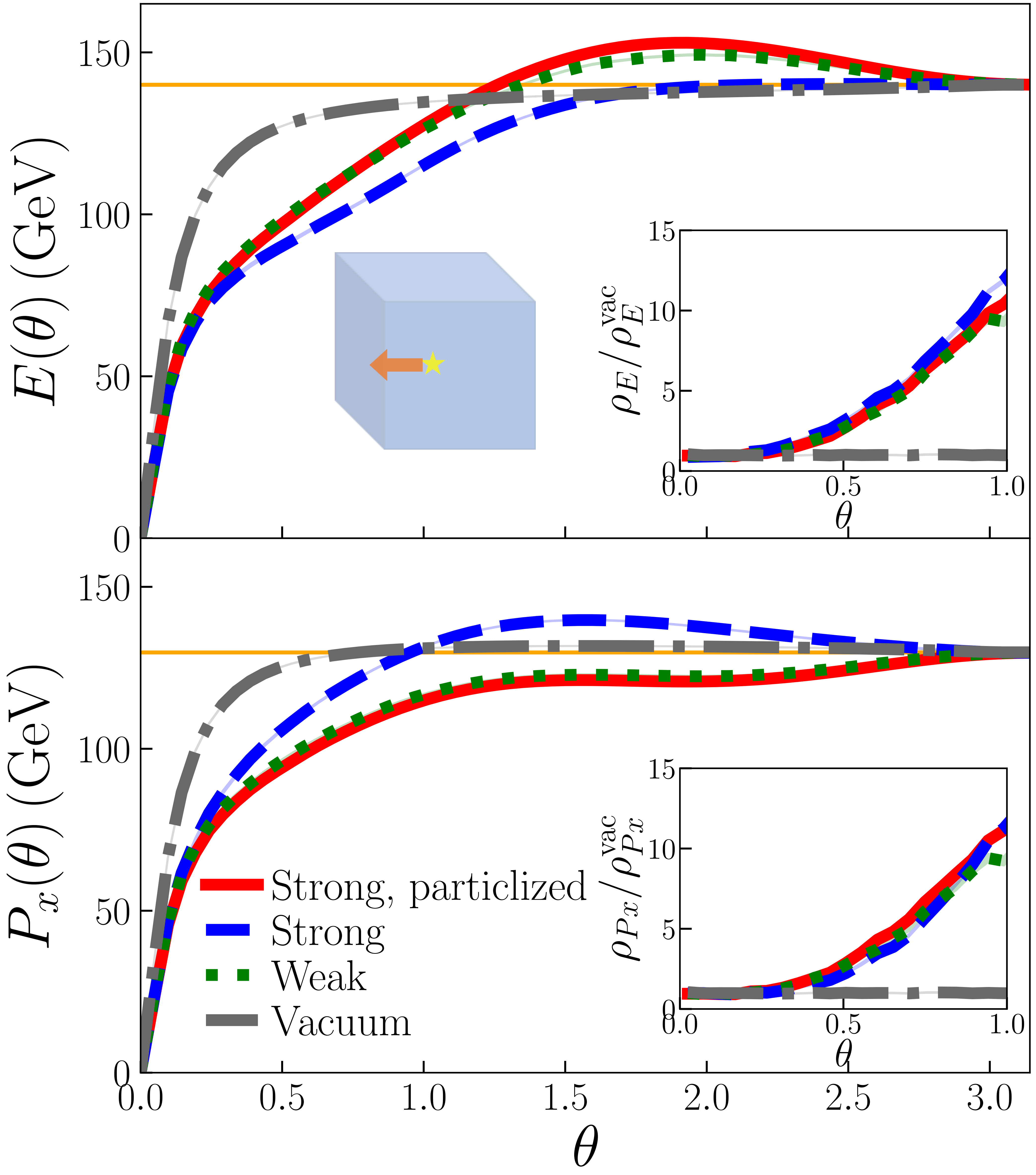
(c) Expanding, Inward

- Opposing Flow



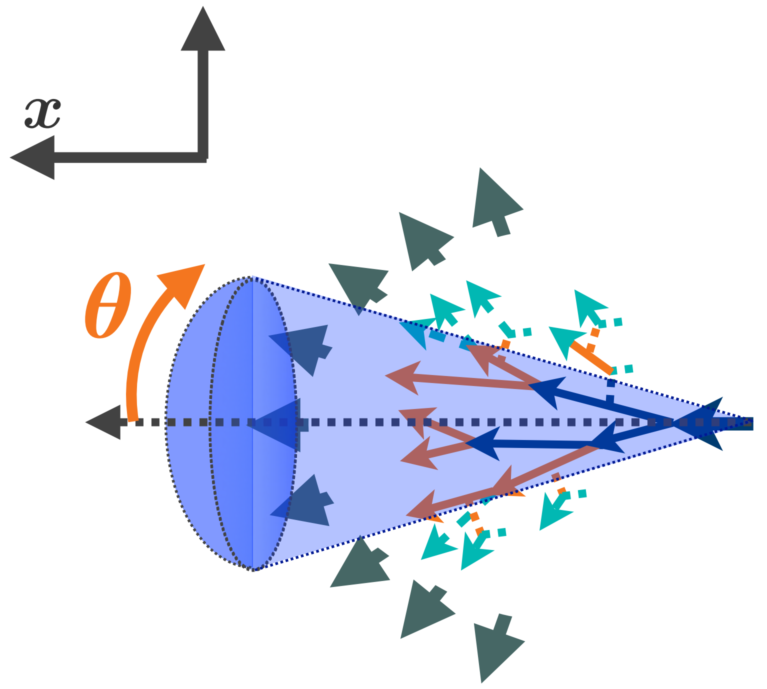
$T_{\mathrm{center}} = 0.5$ GeV

Results: (a) Brick



- **Angular Structure of Jet**
  - Jet energy and momentum

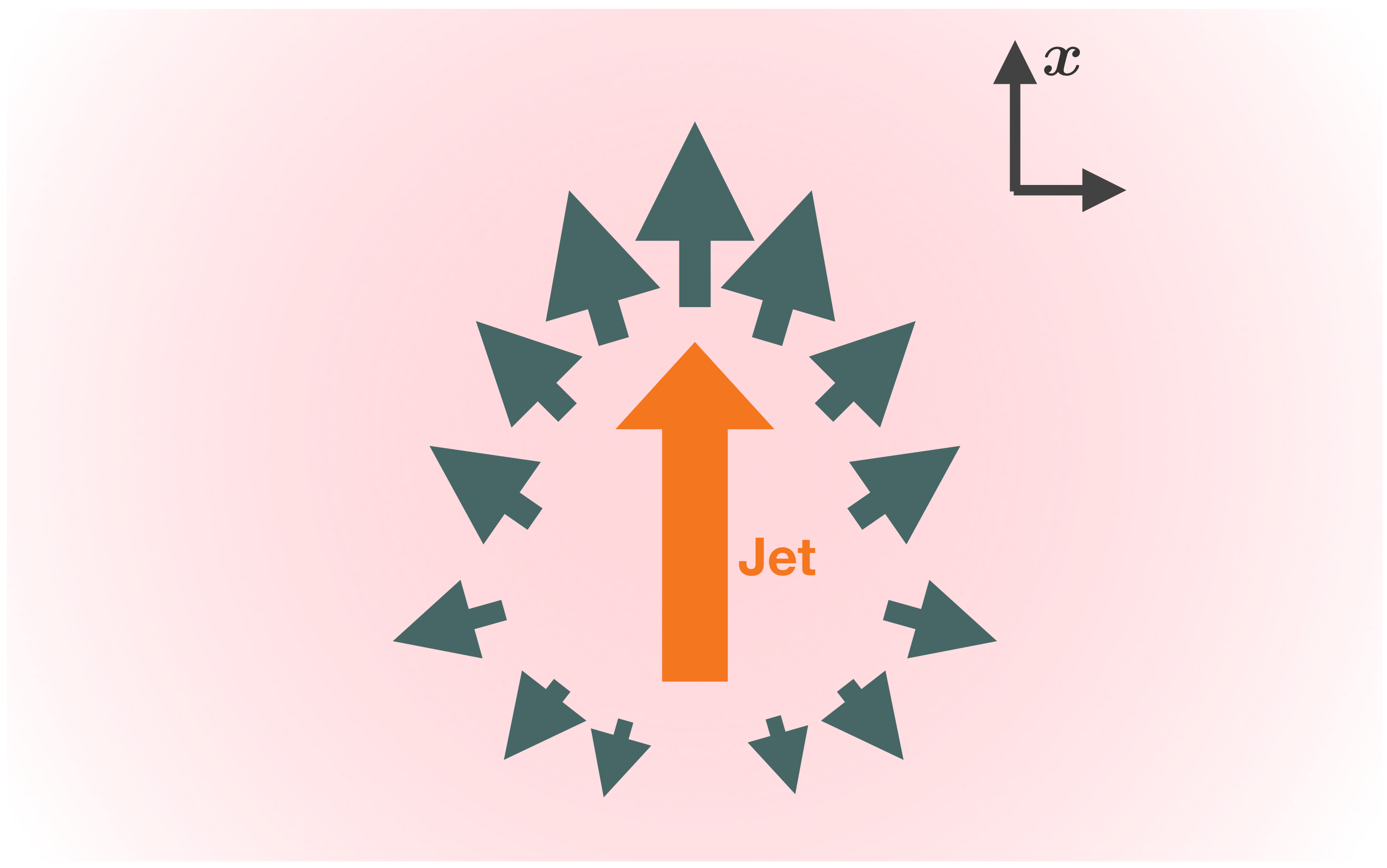
$$E(\theta) = \int_0^\theta d\theta' \frac{dE}{d\theta'}\bigg|_{\text{signal}}, \quad P_x(\theta) = \int_0^\theta d\theta' \frac{dp_x}{d\theta'}\bigg|_{\text{signal}}$$



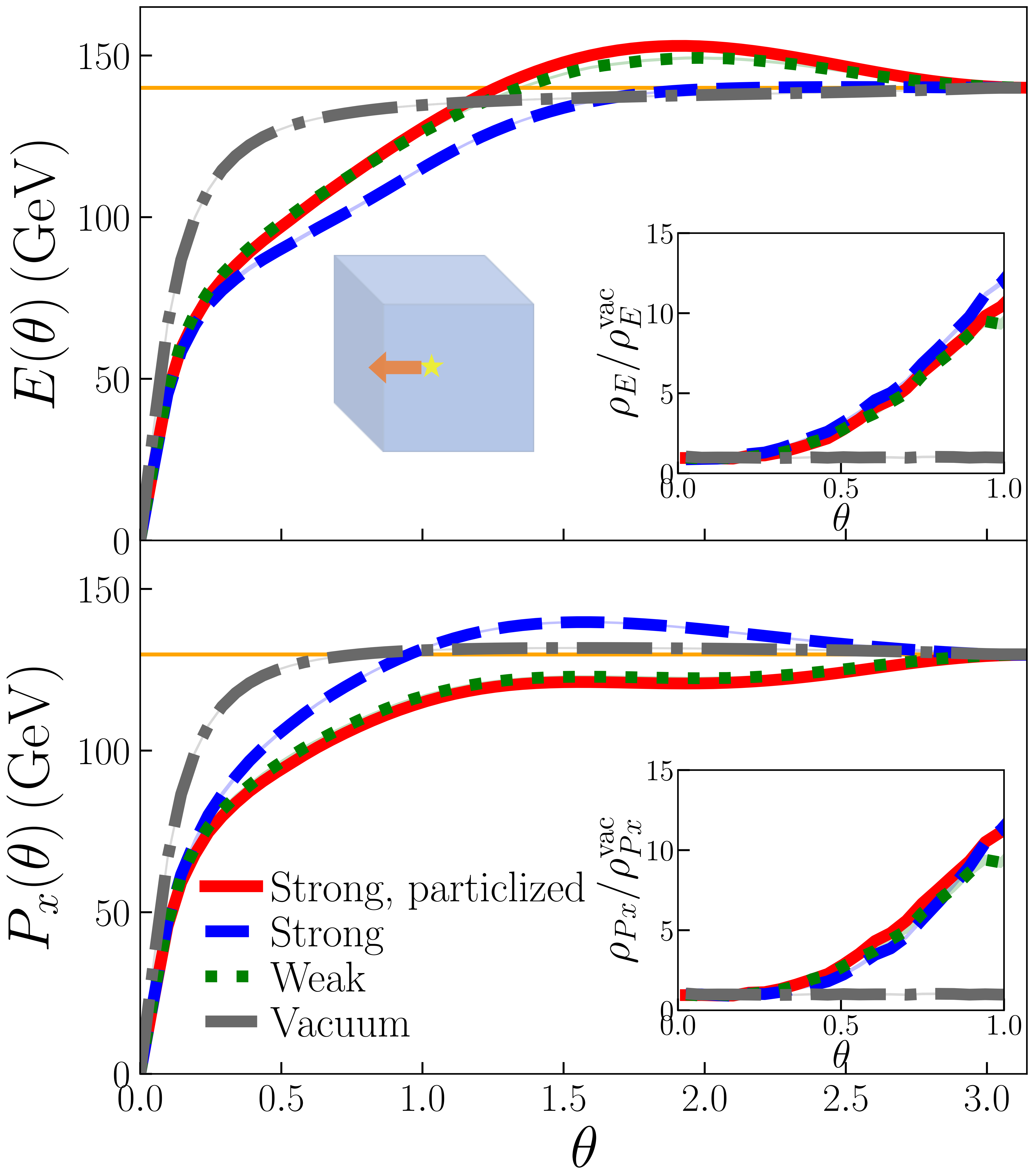
  - Detailed substructure

$$\rho_E(\theta) = \frac{1}{E(\theta=0.4)}\frac{dE}{d\theta}\bigg|_{\text{signal}}, \quad \rho_{P_x}(\theta) = \frac{1}{P_x(\theta=0.4)}\frac{dP_x}{d\theta}\bigg|_{\text{signal}}$$

  - Widely spreading flow as hydro response (strong)



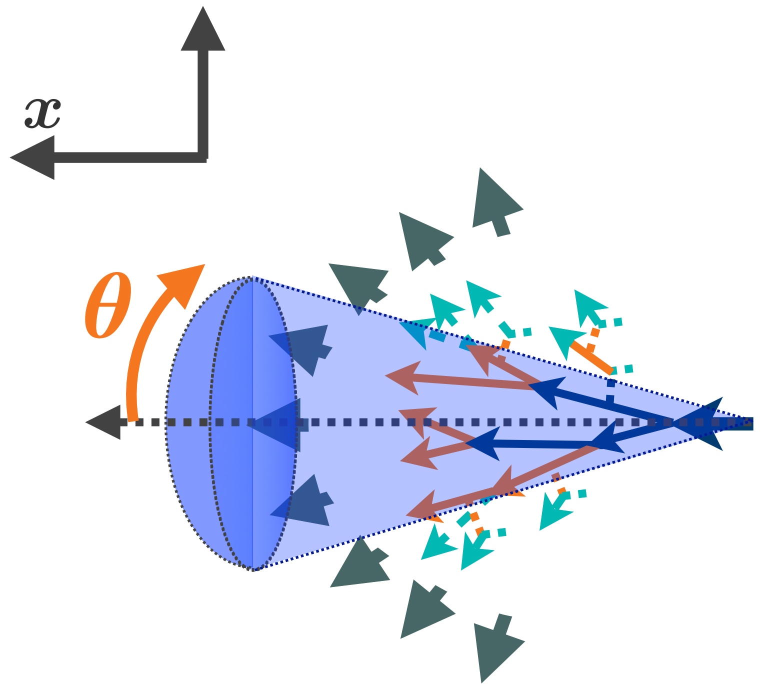
Results: (a) Brick



Angular Structure of Jet

- Jet energy and momentum

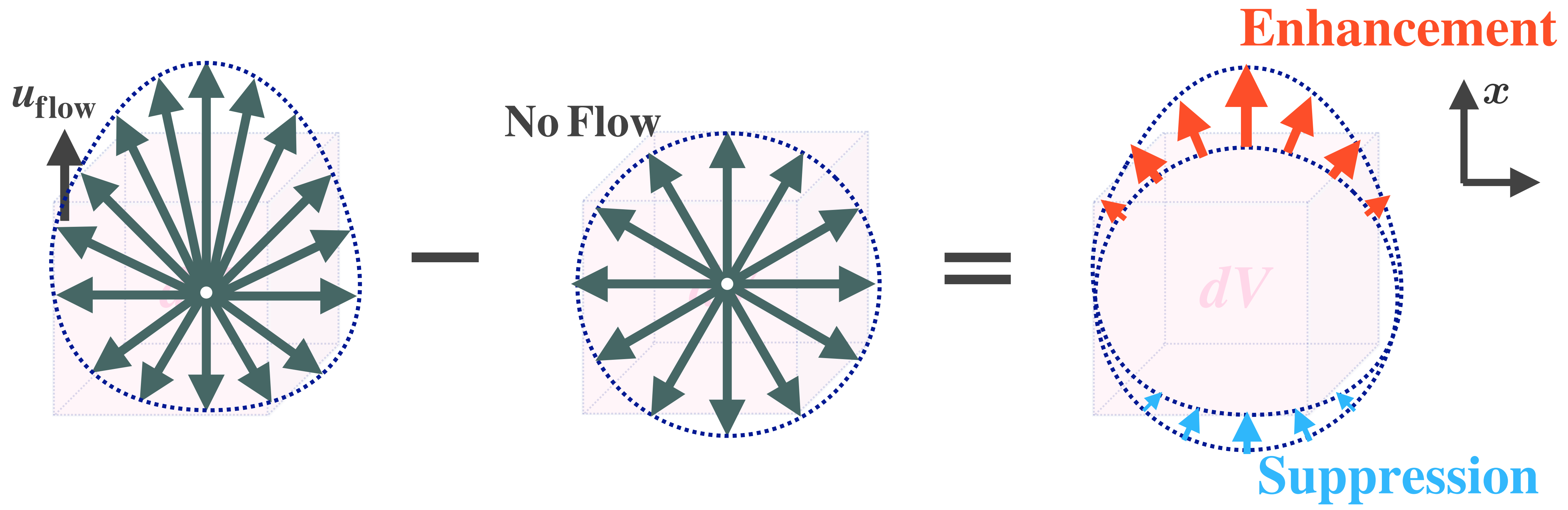
$$E(\theta) = \int_0^{\theta} d\theta' \frac{dE}{d\theta'}\bigg|_{\rm signal}, \quad P_x(\theta) = \int_0^{\theta} d\theta' \frac{dp_x}{d\theta'}\bigg|_{\rm signal}$$



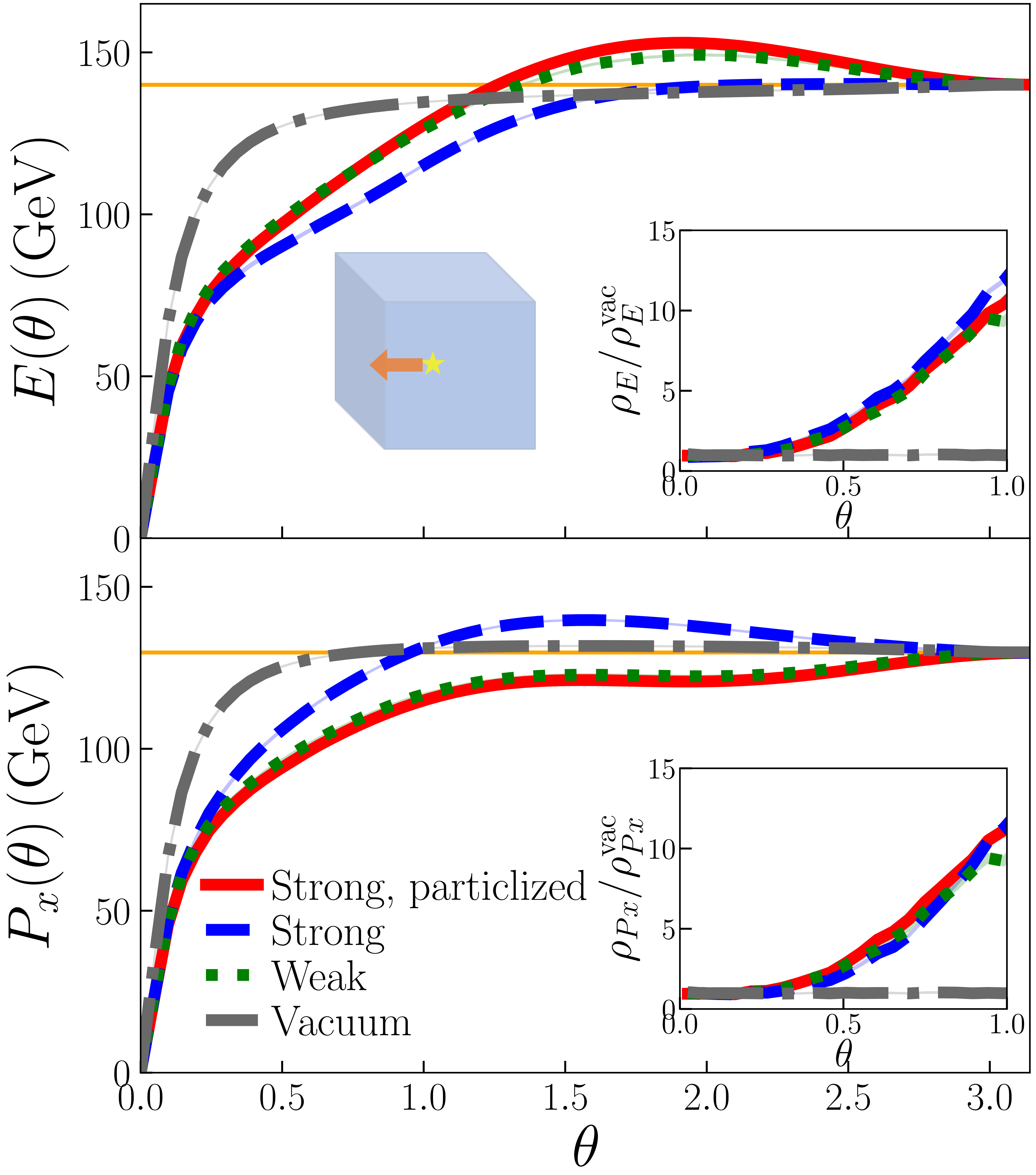
- Detailed substructure

$$\rho_E(\theta) = \frac{1}{E(\theta=0.4)}\frac{dE}{d\theta}\bigg|_{\rm signal}, \quad \rho_{P_x}(\theta) = \frac{1}{P_x(\theta=0.4)}\frac{dP_x}{d\theta}\bigg|_{\rm signal}$$

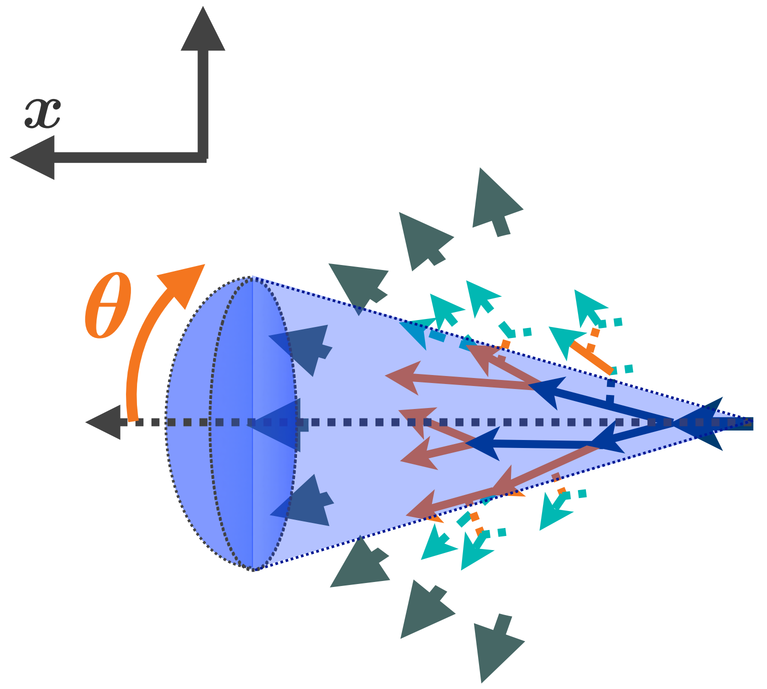
- Widely spreading flow as hydro response (strong)
- Backward suppression due to particlization (strong)



Results: (a) Brick



Angular Structure of Jet



- Jet energy and momentum

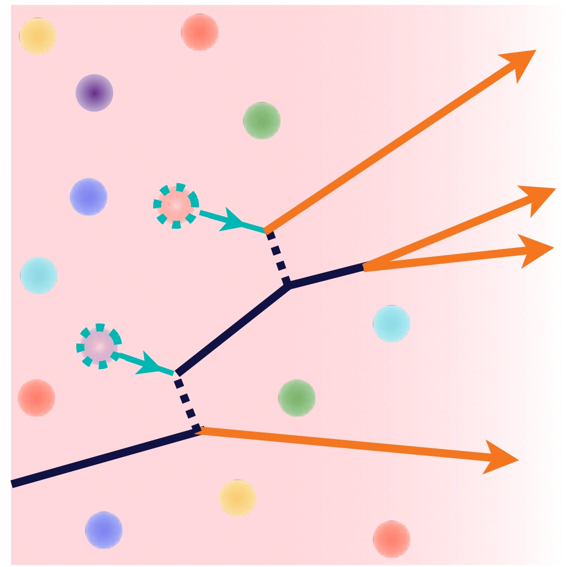
$$E(\theta) = \int_0^{\theta} d\theta' \left.\frac{dE}{d\theta'}\right|_{\mathrm{signal}}, \quad P_x(\theta) = \int_0^{\theta} d\theta' \left.\frac{dp_x}{d\theta'}\right|_{\mathrm{signal}}$$

- Detailed substructure

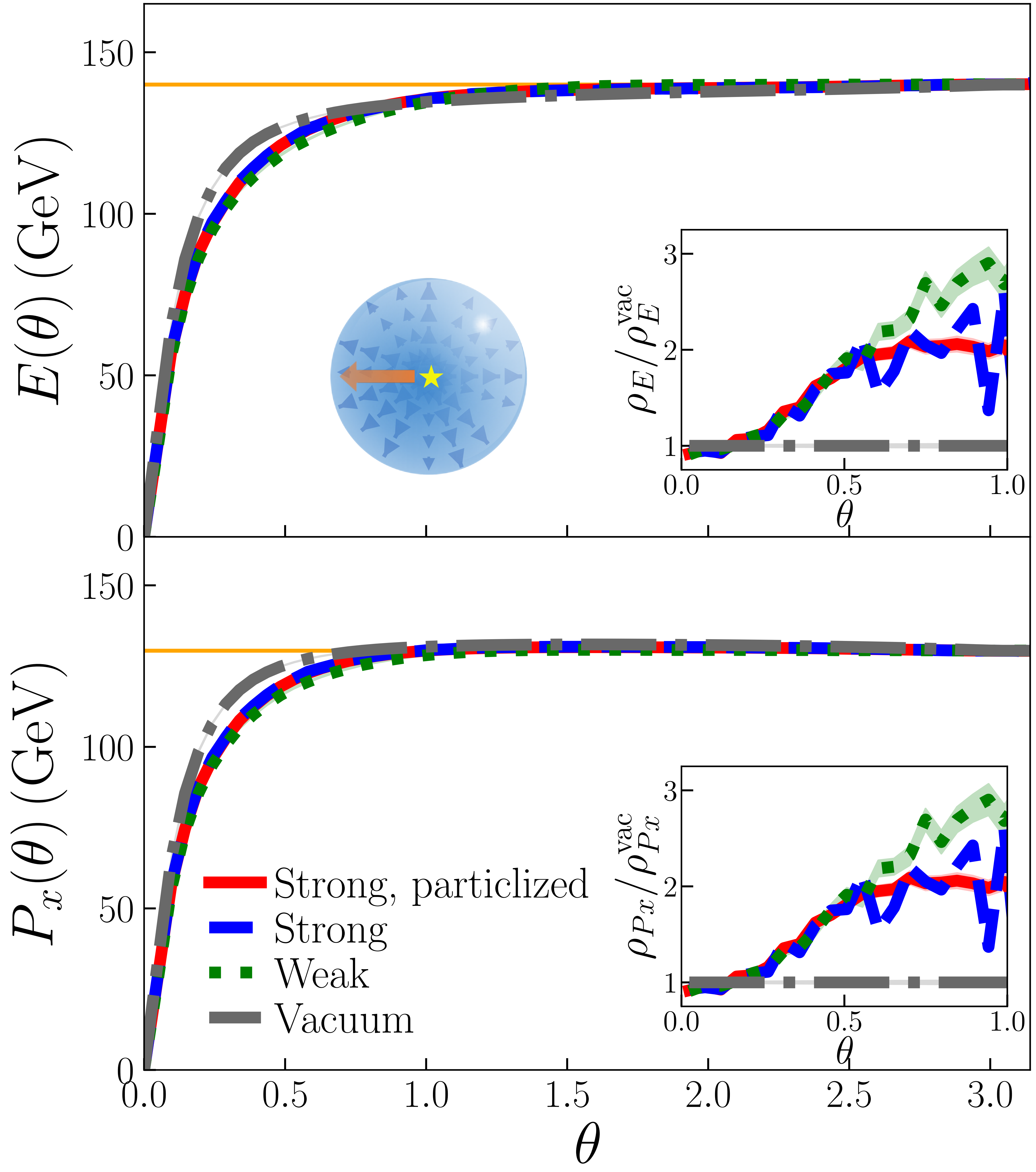
$$\rho_E(\theta) = \frac{1}{E(\theta=0.4)} \left.\frac{dE}{d\theta}\right|_{\mathrm{signal}}, \quad \rho_{P_x}(\theta) = \frac{1}{P_x(\theta=0.4)} \left.\frac{dP_x}{d\theta}\right|_{\mathrm{signal}}$$

- Widely spreading flow as hydro response (strong)
- Backward suppression due to particlization (strong)
- Backward suppression due to holes (weak)

$$\left.\frac{dp^\mu}{d\theta}\right|_{\mathrm{signal}} = \left.\frac{dp^\mu}{d\theta}\right|_{\mathrm{jet\ shower}} - \left.\frac{dp^\mu}{d\theta}\right|_{\mathrm{hole}}$$



Results: (b) Expanding, Outward



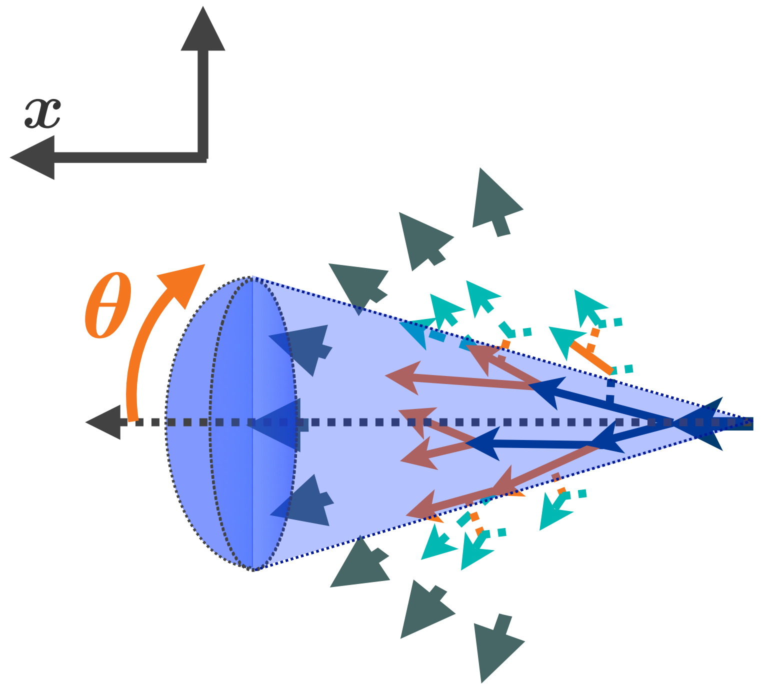
- **Angular Structure of Jet**
  - Jet energy and momentum

$$E(\theta) = \int_0^{\theta} d\theta' \frac{dE}{d\theta'}\bigg|_{\rm signal},\quad P_x(\theta) = \int_0^{\theta} d\theta' \frac{dp_x}{d\theta'}\bigg|_{\rm signal}$$

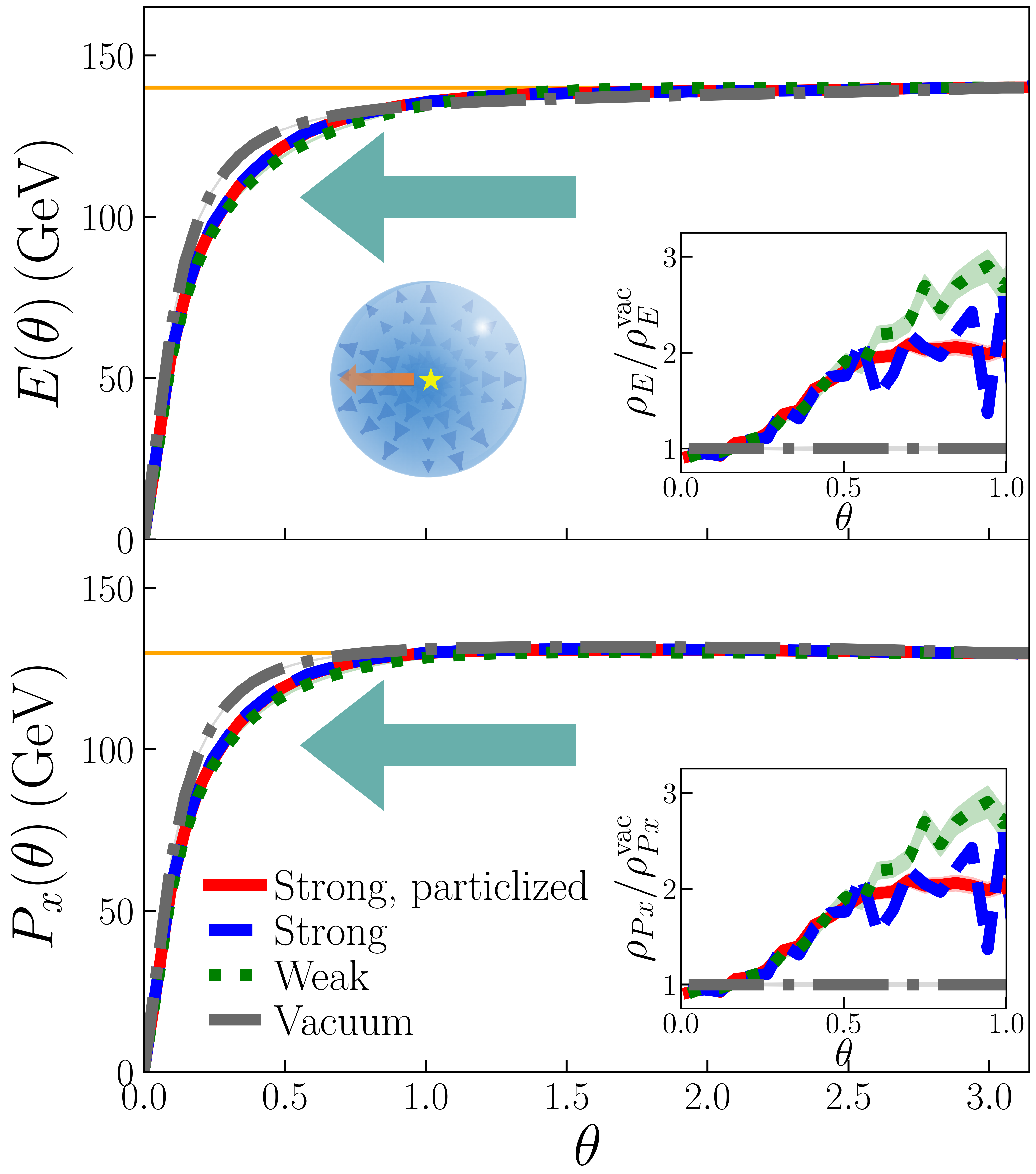
  - Detailed substructure

$$\rho_E(\theta) = \frac{1}{E(\theta=0.4)}\frac{dE}{d\theta}\bigg|_{\rm signal},\quad \rho_{P_x}(\theta) = \frac{1}{P_x(\theta=0.4)}\frac{dP_x}{d\theta}\bigg|_{\rm signal}$$

  - Collimation due to push by the flow



Results: (b) Expanding, Outward



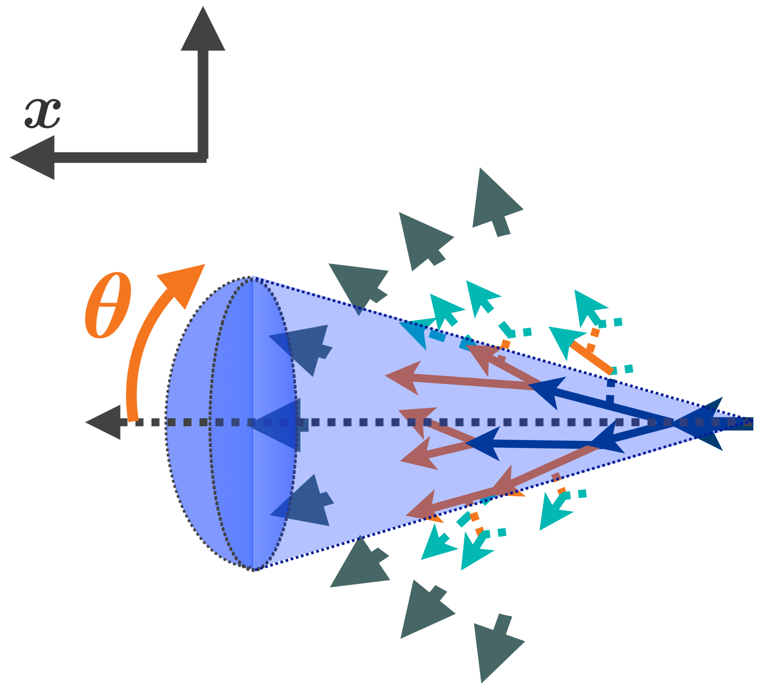
- **Angular Structure of Jet**
  - Jet energy and momentum

$$E(\theta) = \int_0^{\theta} d\theta' \frac{dE}{d\theta'}\bigg|_{\rm signal}, \quad P_x(\theta) = \int_0^{\theta} d\theta' \frac{dp_x}{d\theta'}\bigg|_{\rm signal}$$

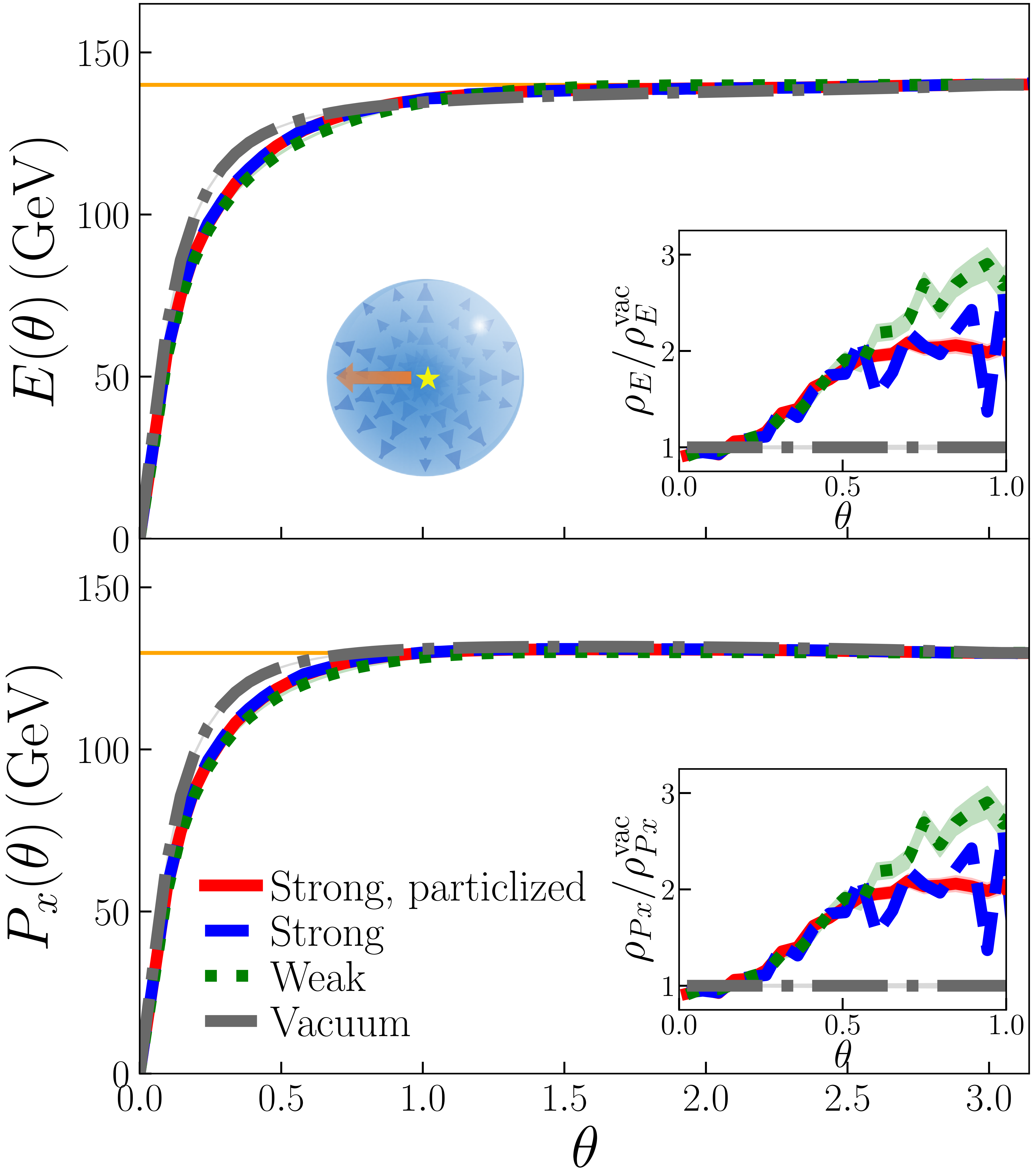
  - Detailed substructure

$$\rho_E(\theta) = \frac{1}{E(\theta=0.4)}\frac{dE}{d\theta}\bigg|_{\rm signal}, \quad \rho_{P_x}(\theta) = \frac{1}{P_x(\theta=0.4)}\frac{dP_x}{d\theta}\bigg|_{\rm signal}$$

  - Collimation due to push by the flow



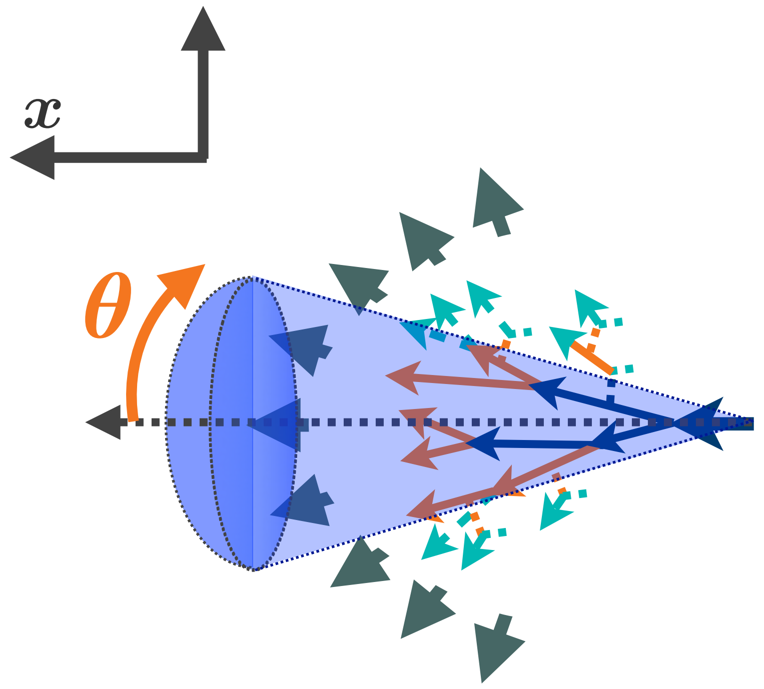
Results: (b) Expanding, Outward



Angular Structure of Jet

- Jet energy and momentum

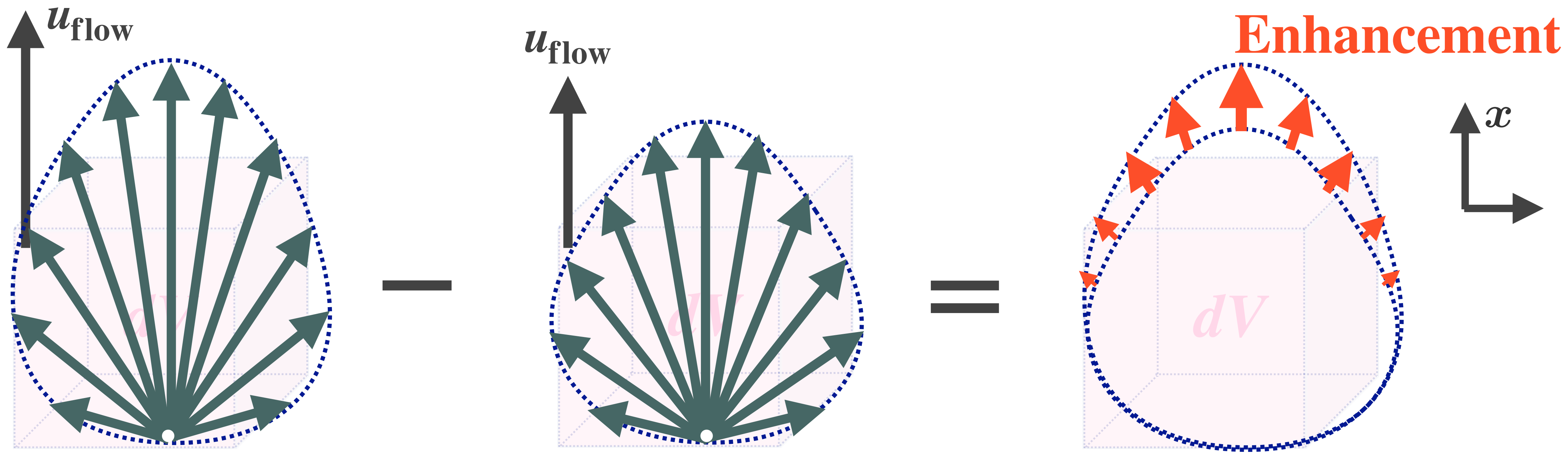
$$E(\theta) = \int_0^{\theta} d\theta' \frac{dE}{d\theta'}\bigg|_{\rm signal}, \quad P_x(\theta) = \int_0^{\theta} d\theta' \frac{dp_x}{d\theta'}\bigg|_{\rm signal}$$



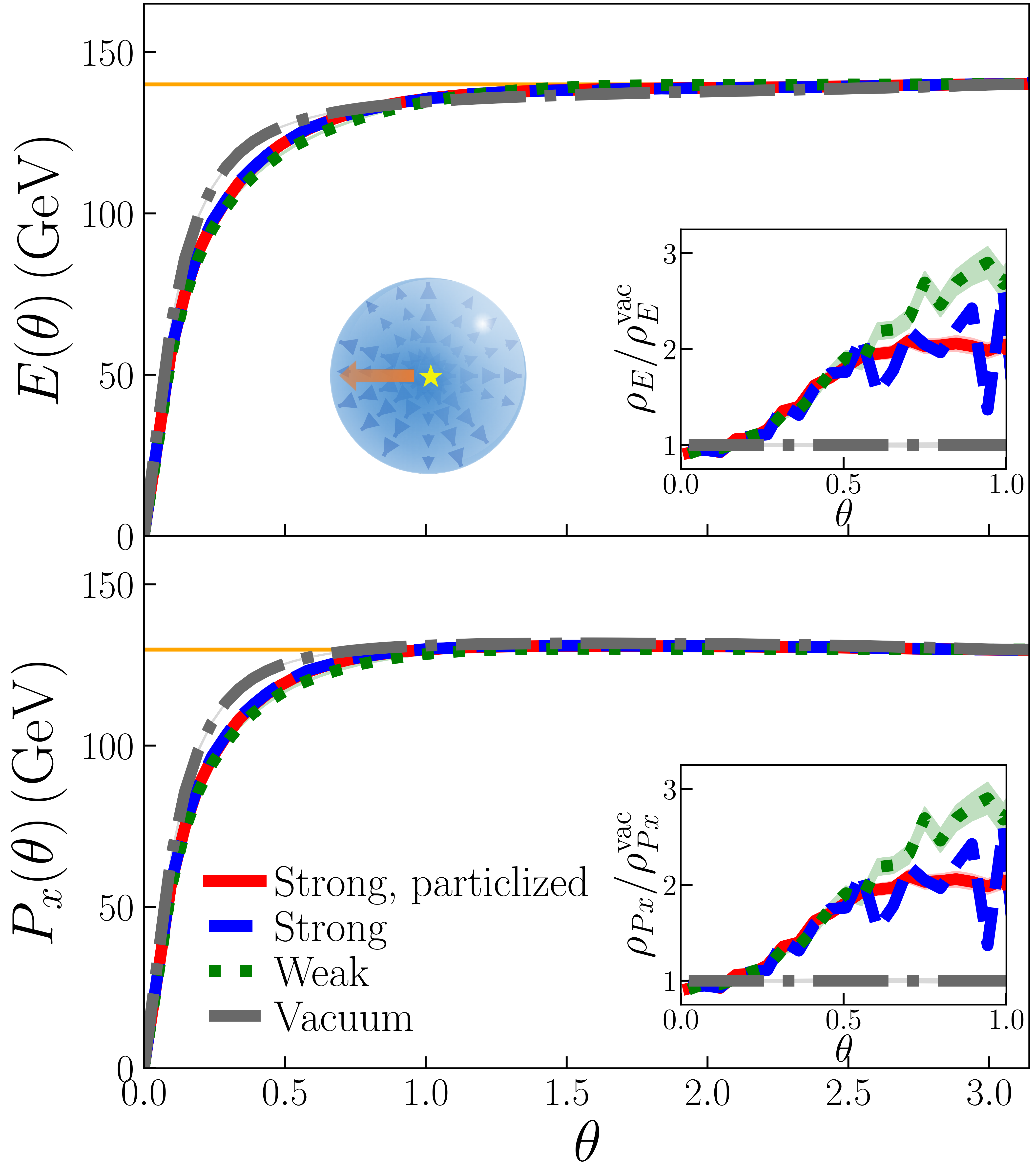
- Detailed substructure

$$\rho_E(\theta) = \frac{1}{E(\theta=0.4)} \frac{dE}{d\theta}\bigg|_{\rm signal}, \quad \rho_{P_x}(\theta) = \frac{1}{P_x(\theta=0.4)} \frac{dP_x}{d\theta}\bigg|_{\rm signal}$$

- Collimation due to push by the flow
- No backward suppression by particlization (strong)

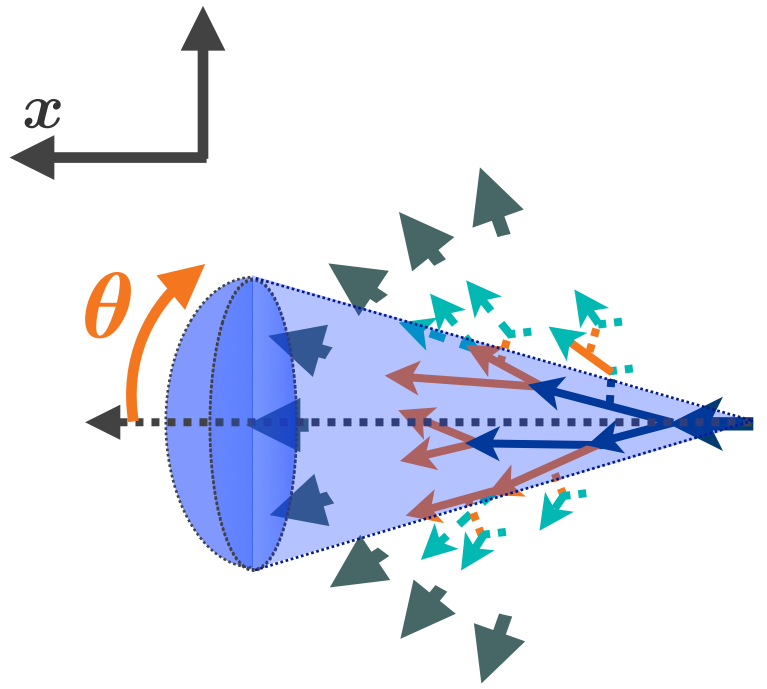


Results: (b) Expanding, Outward



- **Angular Structure of Jet**
  - Jet energy and momentum

$$E(\theta) = \int_0^\theta d\theta' \frac{dE}{d\theta'}\Big|_{\text{signal}}, \quad P_x(\theta) = \int_0^\theta d\theta' \frac{dp_x}{d\theta'}\Big|_{\text{signal}}$$

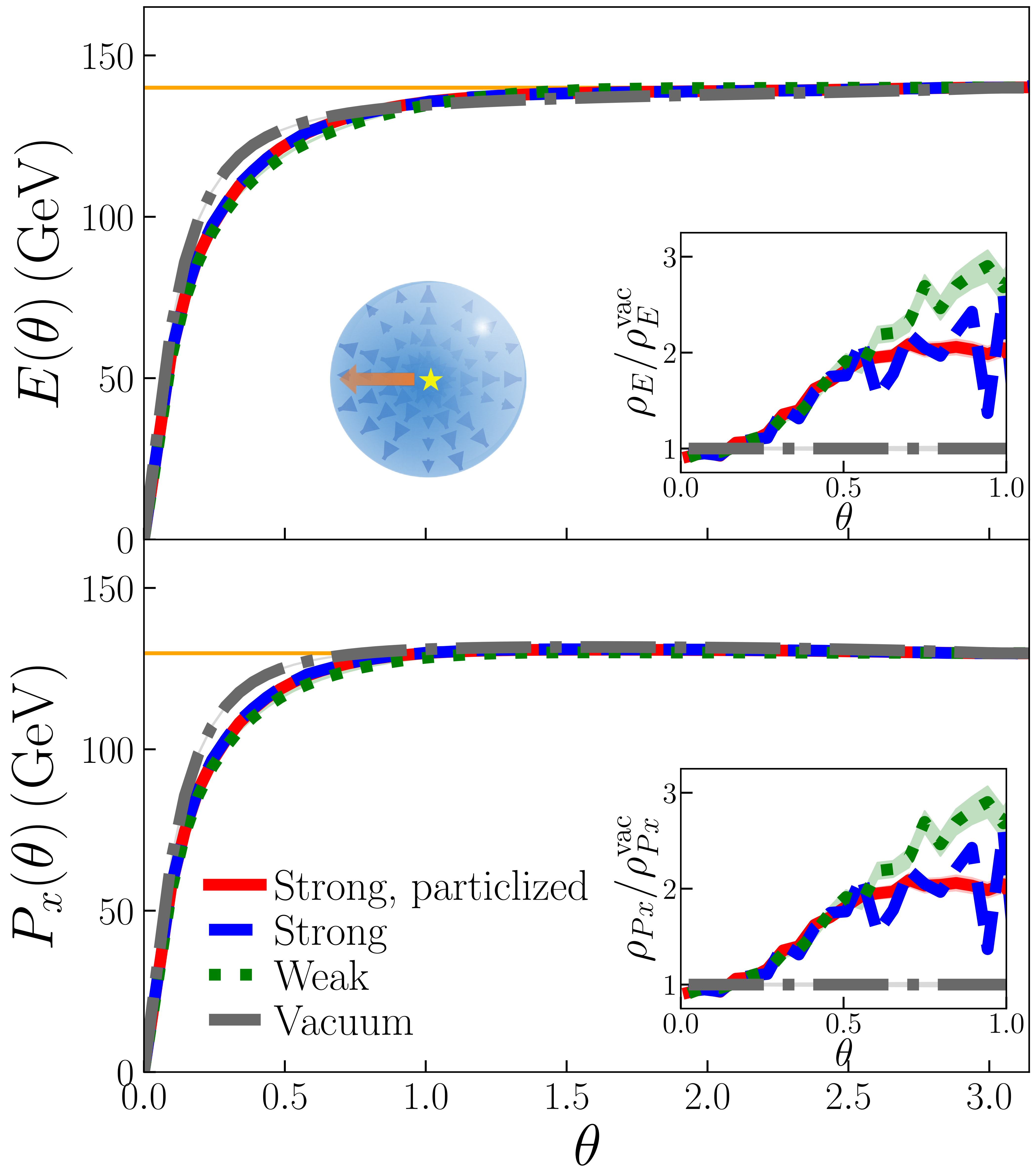


  - Detailed substructure

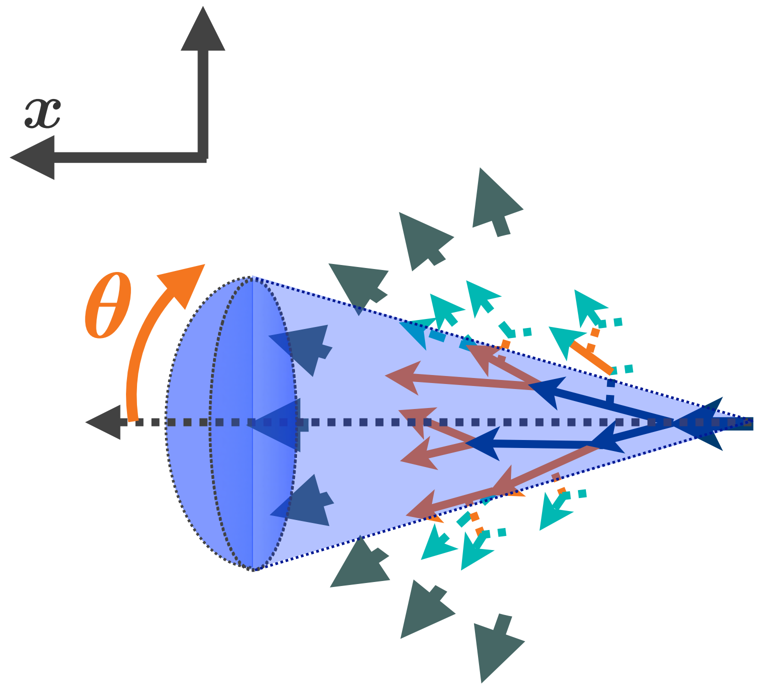
$$\rho_E(\theta) = \frac{1}{E(\theta=0.4)} \frac{dE}{d\theta}\Big|_{\text{signal}}, \quad \rho_{P_x}(\theta) = \frac{1}{P_x(\theta=0.4)} \frac{dP_x}{d\theta}\Big|_{\text{signal}}$$

  - Collimation due to push by the flow
  - No backward suppression by particlization (strong)
  - No backward suppression due to holes (weak)

Results: (b) Expanding, Outward



Angular Structure of Jet



- Jet energy and momentum

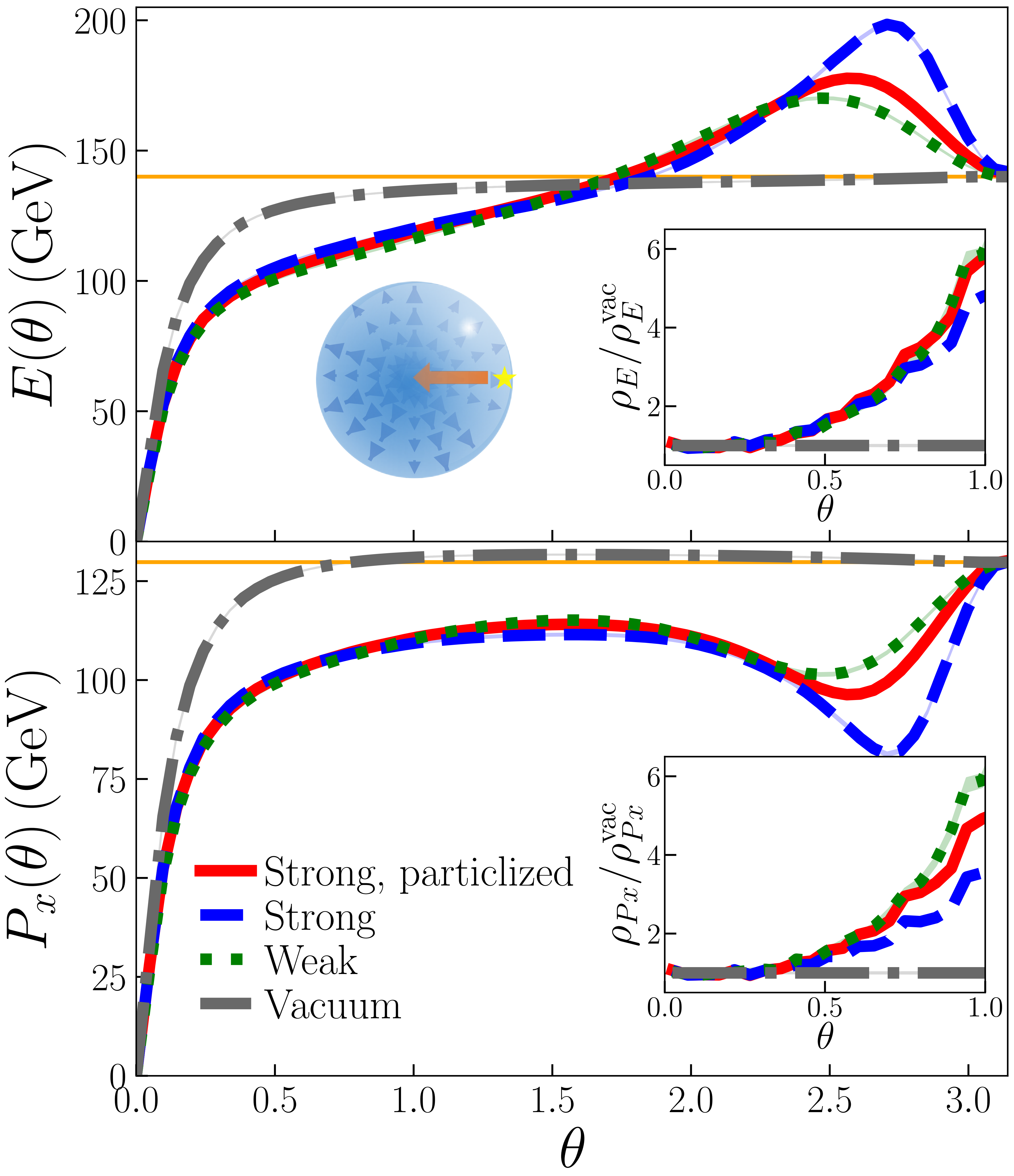
$$E(\theta) = \int_0^\theta d\theta' \frac{dE}{d\theta'}\bigg|_{\text{signal}}, \quad P_x(\theta) = \int_0^\theta d\theta' \frac{dp_x}{d\theta'}\bigg|_{\text{signal}}$$

- Detailed substructure

$$\rho_E(\theta) = \frac{1}{E(\theta=0.4)}\frac{dE}{d\theta}\bigg|_{\text{signal}}, \quad \rho_{P_x}(\theta) = \frac{1}{P_x(\theta=0.4)}\frac{dP_x}{d\theta}\bigg|_{\text{signal}}$$

- Collimation due to push by the flow
- No backward suppression by particlization (strong)
- No backward suppression due to holes (weak)
- Difference between strong and weak

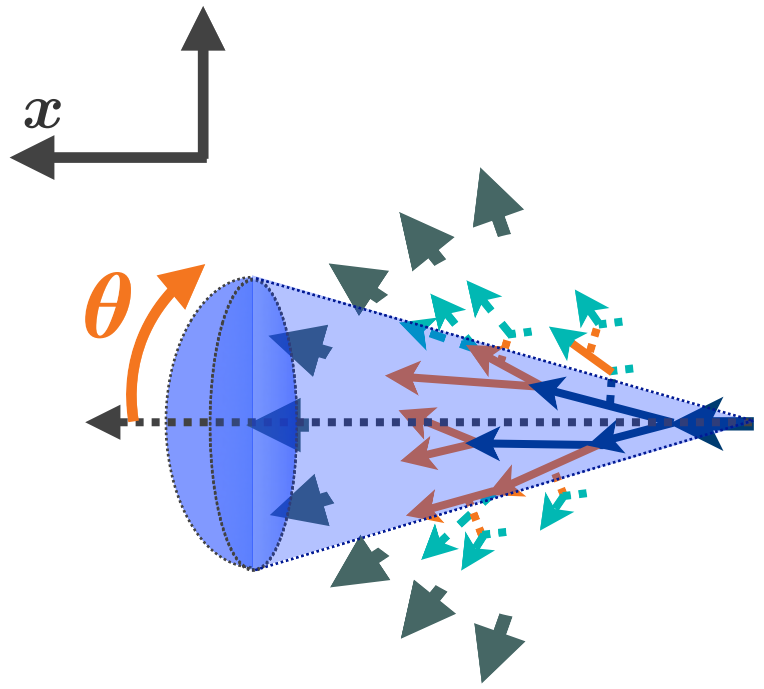
Results: (c) Expanding, Inward



Angular Structure of Jet

- Jet energy and momentum

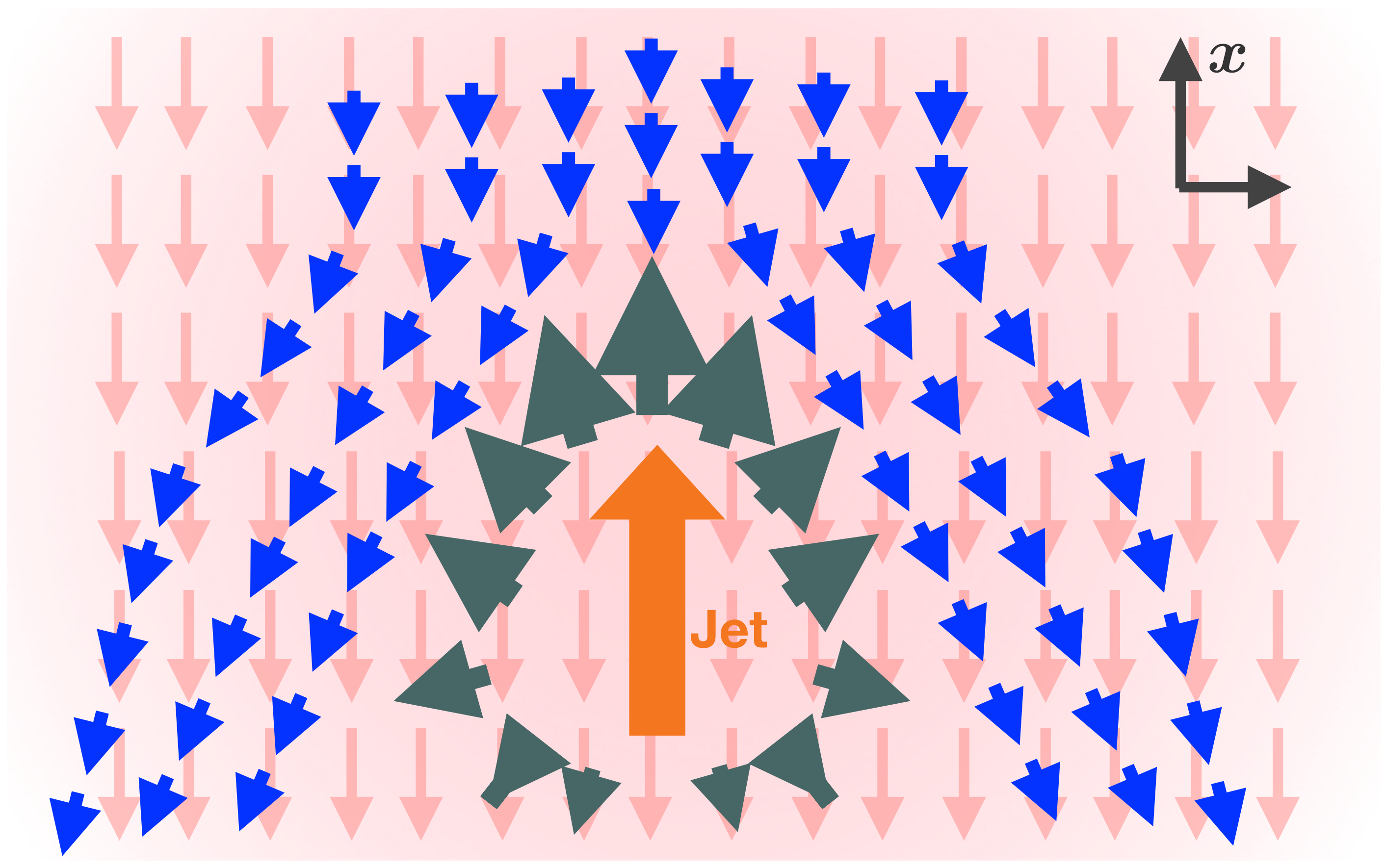
$$E(\theta) = \int_0^\theta d\theta' \frac{dE}{d\theta'}\bigg|_{\rm signal}, \quad P_x(\theta) = \int_0^\theta d\theta' \frac{dp_x}{d\theta'}\bigg|_{\rm signal}$$



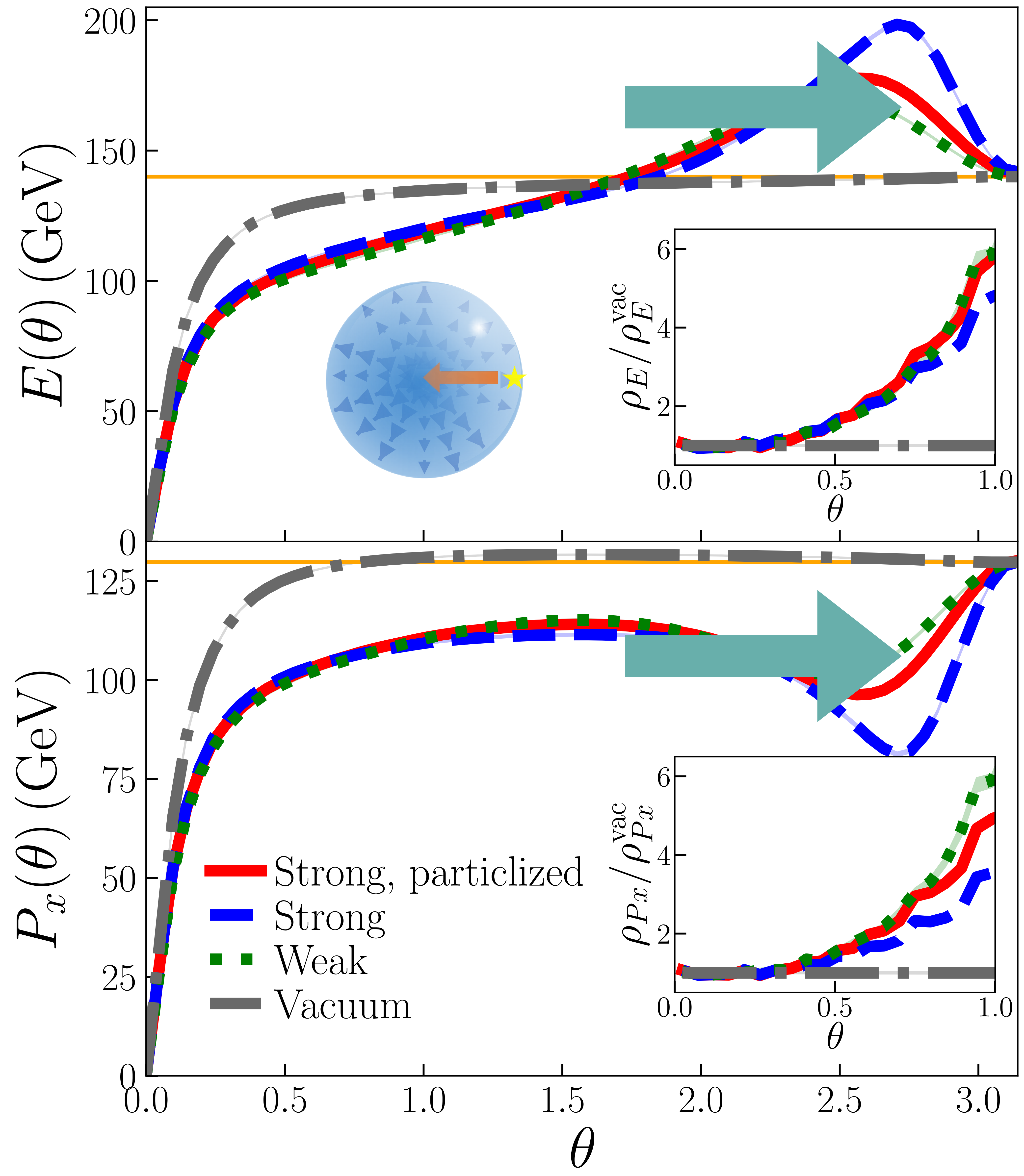
- Detailed substructure

$$\rho_E(\theta) = \frac{1}{E(\theta=0.4)}\frac{dE}{d\theta}\bigg|_{\rm signal}, \quad \rho_{P_x}(\theta) = \frac{1}{P_x(\theta=0.4)}\frac{dP_x}{d\theta}\bigg|_{\rm signal}$$

- Accumulation in backward

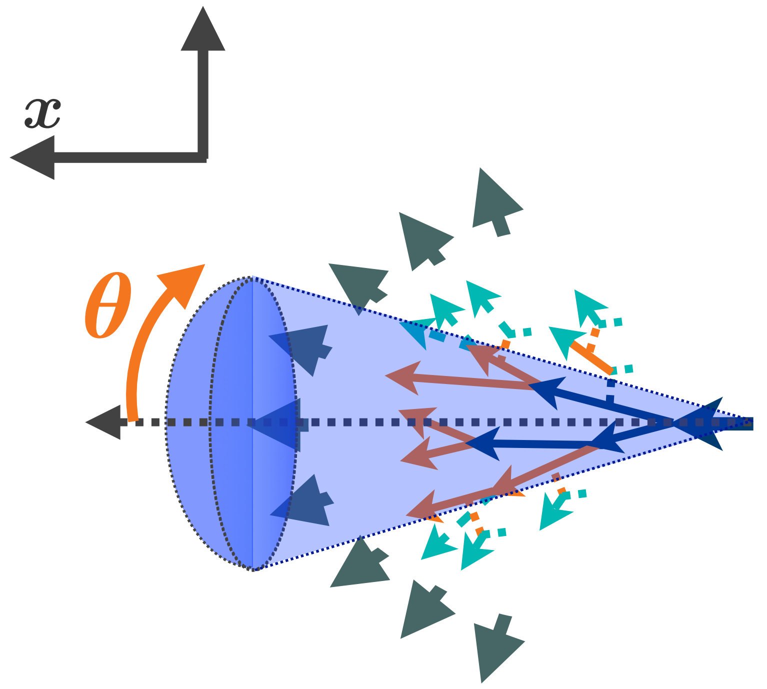


Results: (c) Expanding, Inward



- **Angular Structure of Jet**
  - Jet energy and momentum

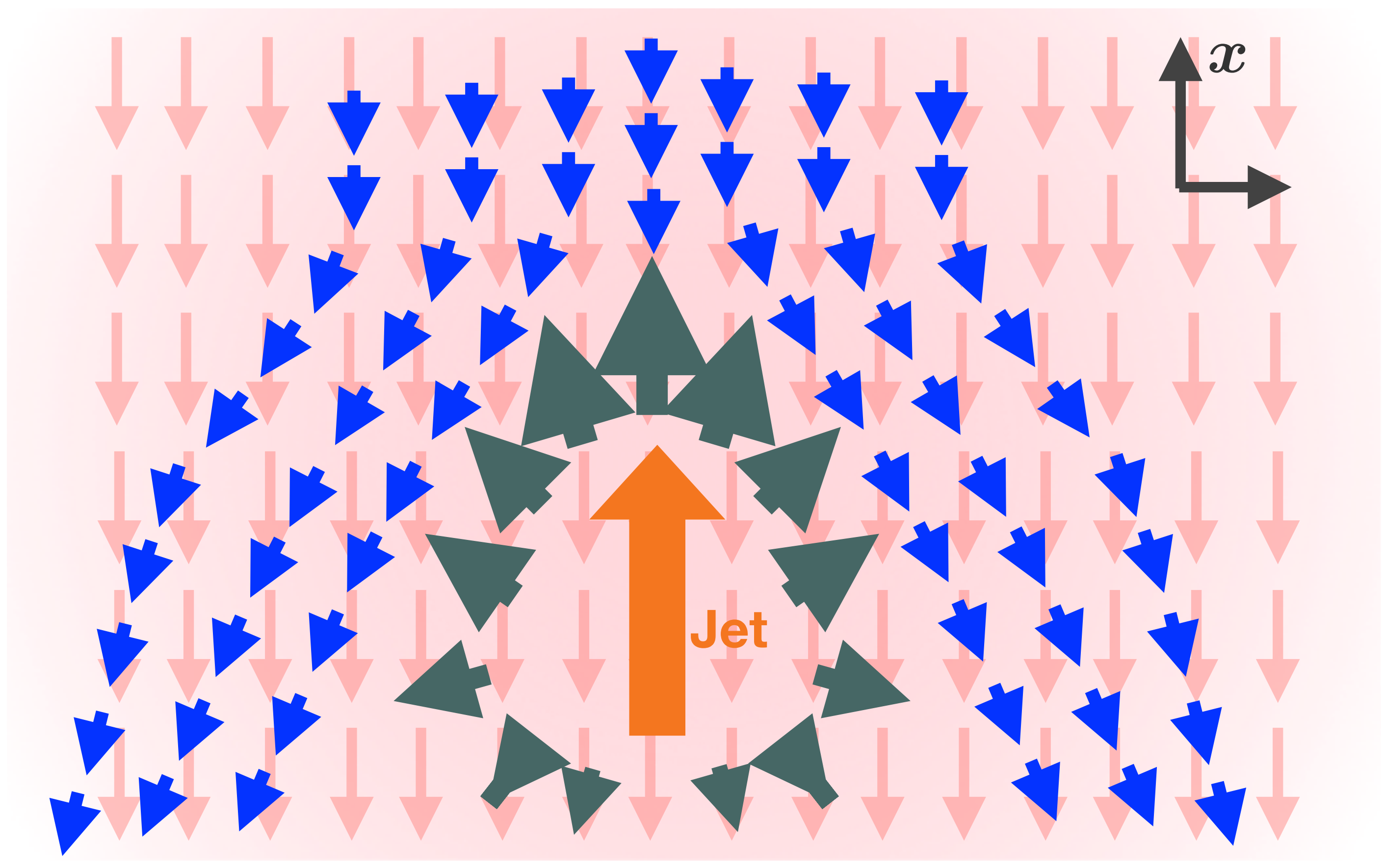
$$E(\theta) = \int_0^\theta d\theta' \frac{dE}{d\theta'}\bigg|_{\rm signal}, \quad P_x(\theta) = \int_0^\theta d\theta' \frac{dp_x}{d\theta'}\bigg|_{\rm signal}$$



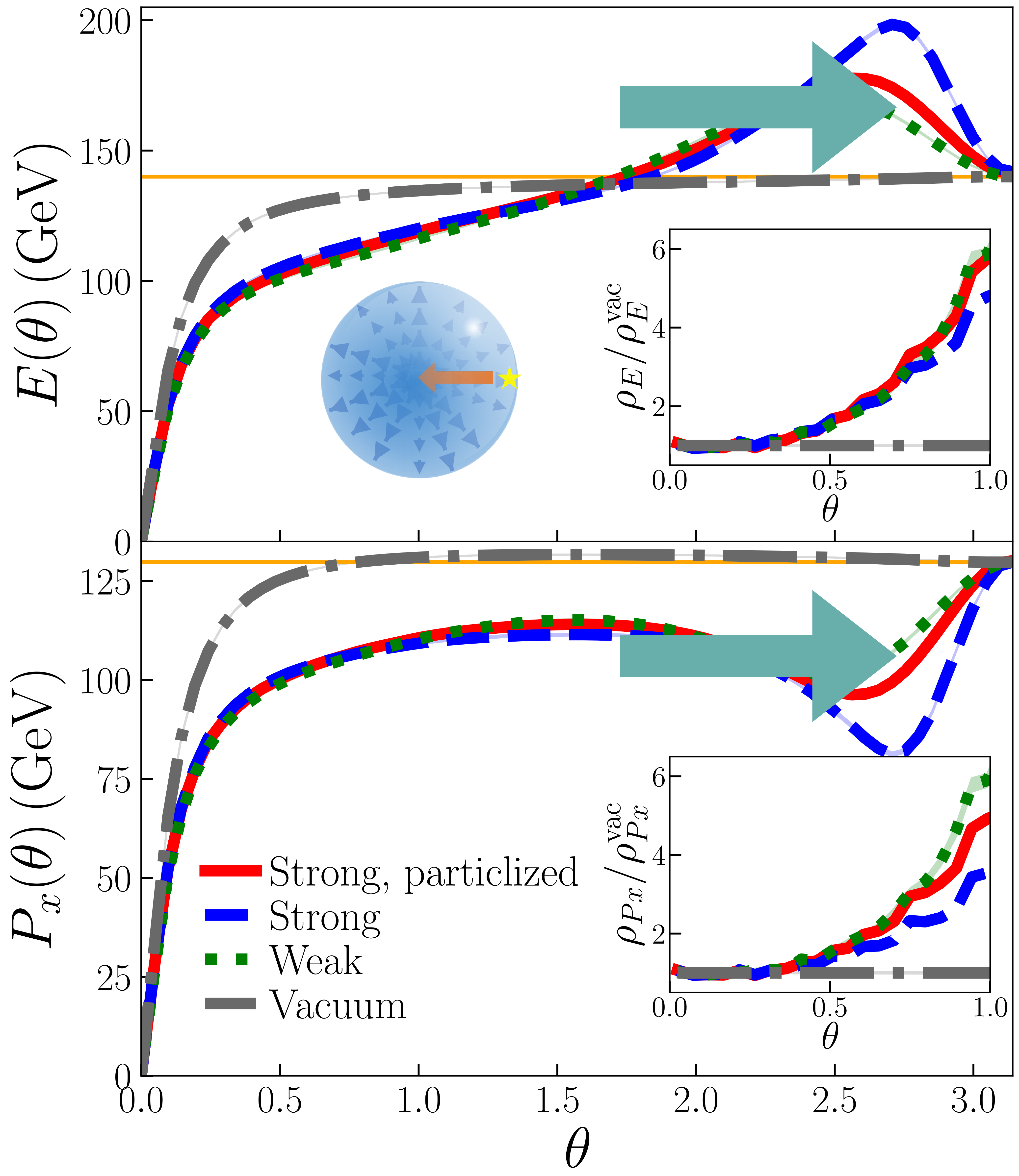
  - Detailed substructure

$$\rho_E(\theta) = \frac{1}{E(\theta=0.4)}\frac{dE}{d\theta}\bigg|_{\rm signal}, \quad \rho_{P_x}(\theta) = \frac{1}{P_x(\theta=0.4)}\frac{dP_x}{d\theta}\bigg|_{\rm signal}$$

  - Accumulation in backward

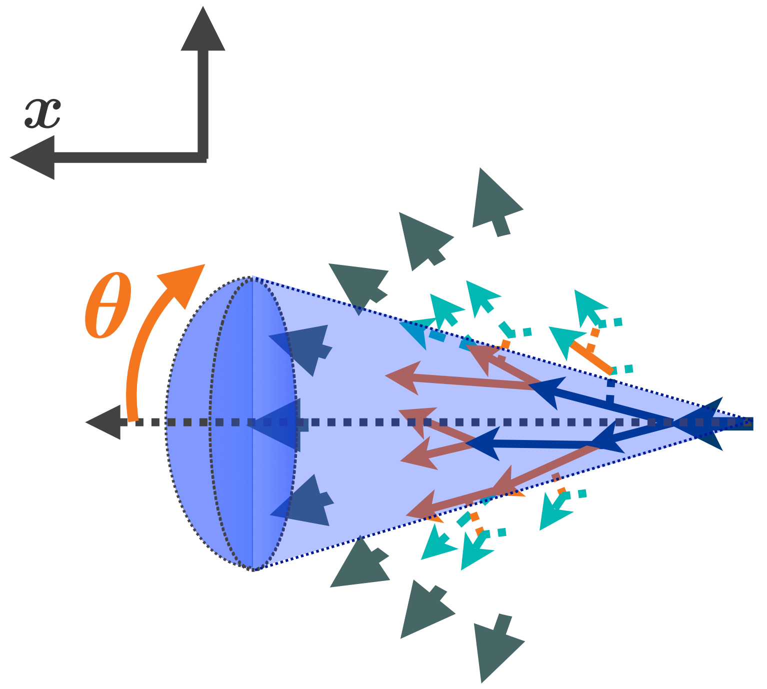


Results: (c) Expanding, Inward



- **Angular Structure of Jet**
  - Jet energy and momentum

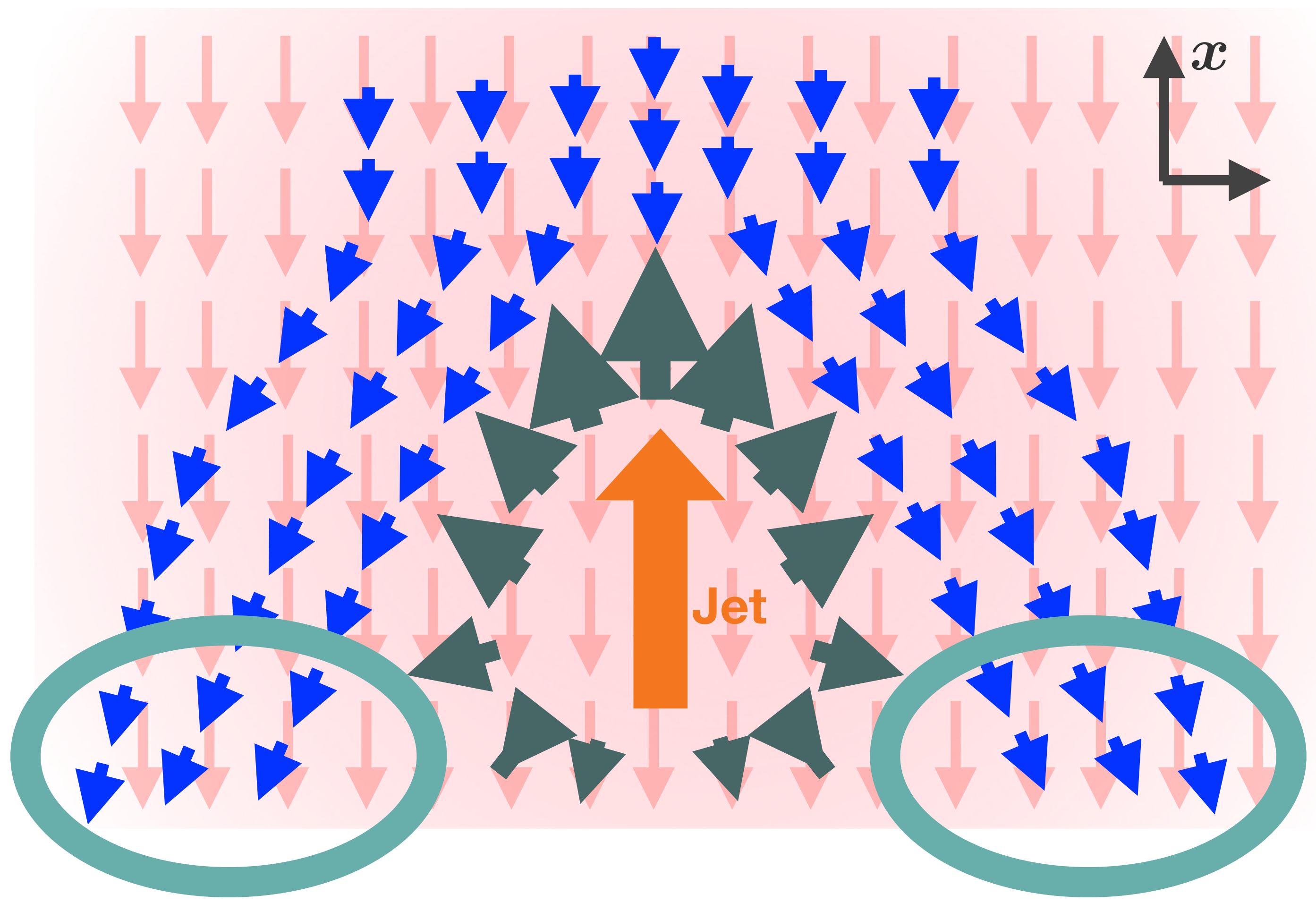
$$E(\theta) = \int_0^\theta d\theta' \frac{dE}{d\theta'}\bigg|_{\text{signal}}, \quad P_x(\theta) = \int_0^\theta d\theta' \frac{dp_x}{d\theta'}\bigg|_{\text{signal}}$$



  - Detailed substructure

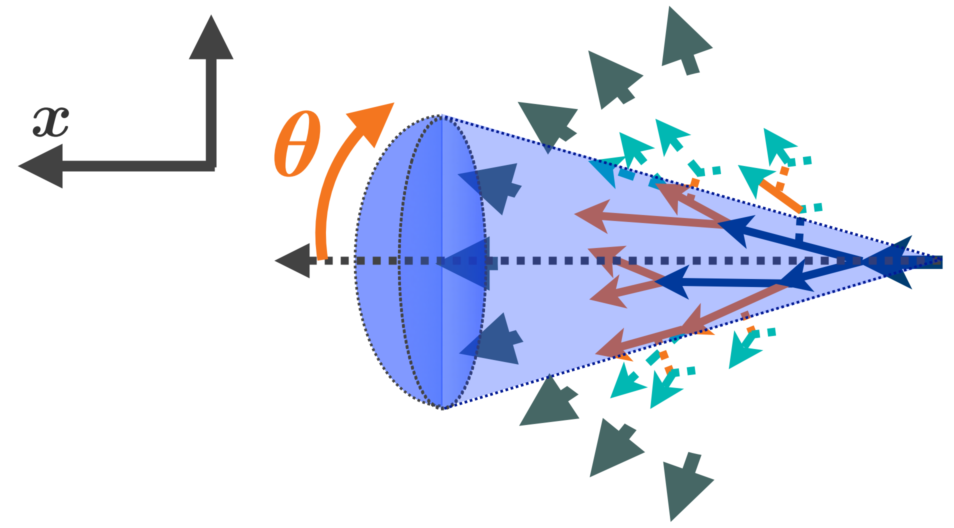
$$\rho_E(\theta) = \frac{1}{E(\theta=0.4)} \frac{dE}{d\theta}\bigg|_{\text{signal}}, \quad \rho_{P_x}(\theta) = \frac{1}{P_x(\theta=0.4)} \frac{dP_x}{d\theta}\bigg|_{\text{signal}}$$

  - Accumulation in backward

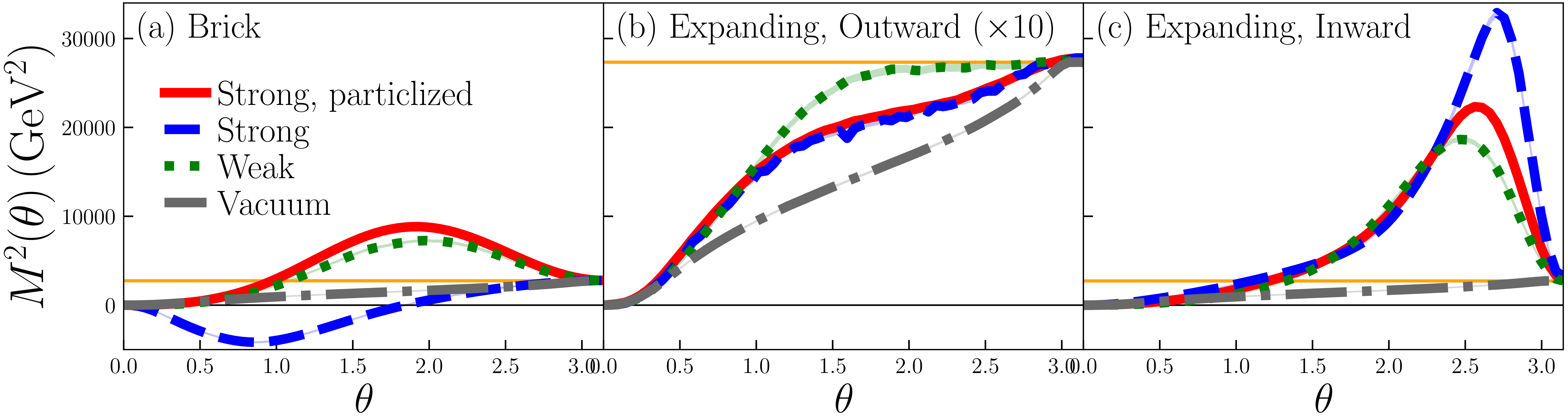


Results: Jet Mass

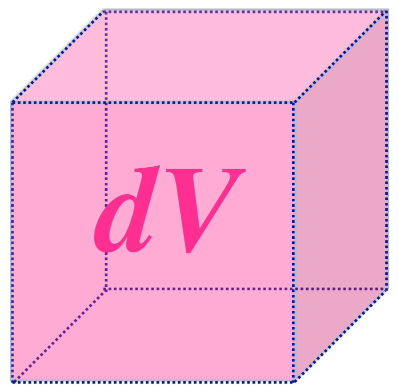
- **Angular Structure of Jet Mass**



$$M^2(\theta) = P^\mu(\theta)P_\mu(\theta), \quad P^\mu(\theta) = \int_0^\theta d\theta' \frac{dp^\mu}{d\theta'}\bigg|_{\text{signal}}$$



- More prominent bump structures for the cases with the brick and the opposing flow
- Negative mass in the Brick before the particlization (space-like momentum transfer)



$E_{\text{fluid}} = E_{\text{original}} + E_{\text{induced}}$

$\vec{p}_{\text{fluid}} = \vec{p}_{\text{induced}}$

$|\vec{p}_{\text{induced}}| > E_{\text{induced}}$ is allowed if $E_{\text{fluid}} > |\vec{p}_{\text{fluid}}|$

Summary

- **Medium response to jet propagation in QGP fluid**
  - Transport energy and momentum as wakes by medium constituents
  - Treated as part of jets observed in heavy ion collisions
  - Weakly coupled description: Recoil
  - Strongly coupled description: Hydro response (hydro+causal source)
- **Background flow effect with medium response**
  - Significant effect for both recoil evolution and hydro response
  - Clarify the difference between strongly and weakly coupled description (Stronger effect for hydro response)
- **Future outlook**
  - Full simulations with realistic configurations for heavy ion collisions