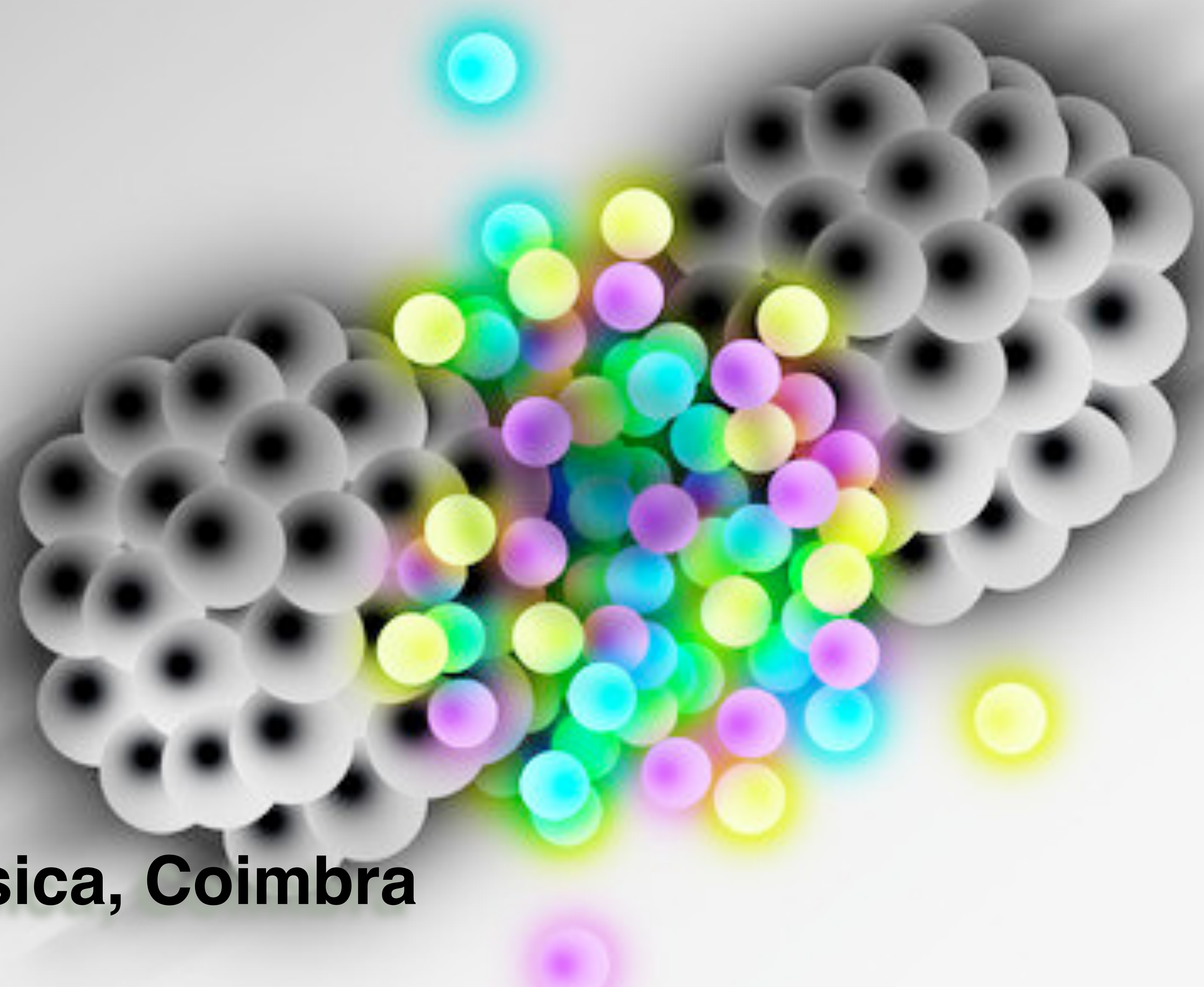
# What do we know about the Quark-Gluon Plasma?

Liliana Apolinário

LIP

TÉCNICO LISBOA



Café com Física, Coimbra

Wednesday, May 18th

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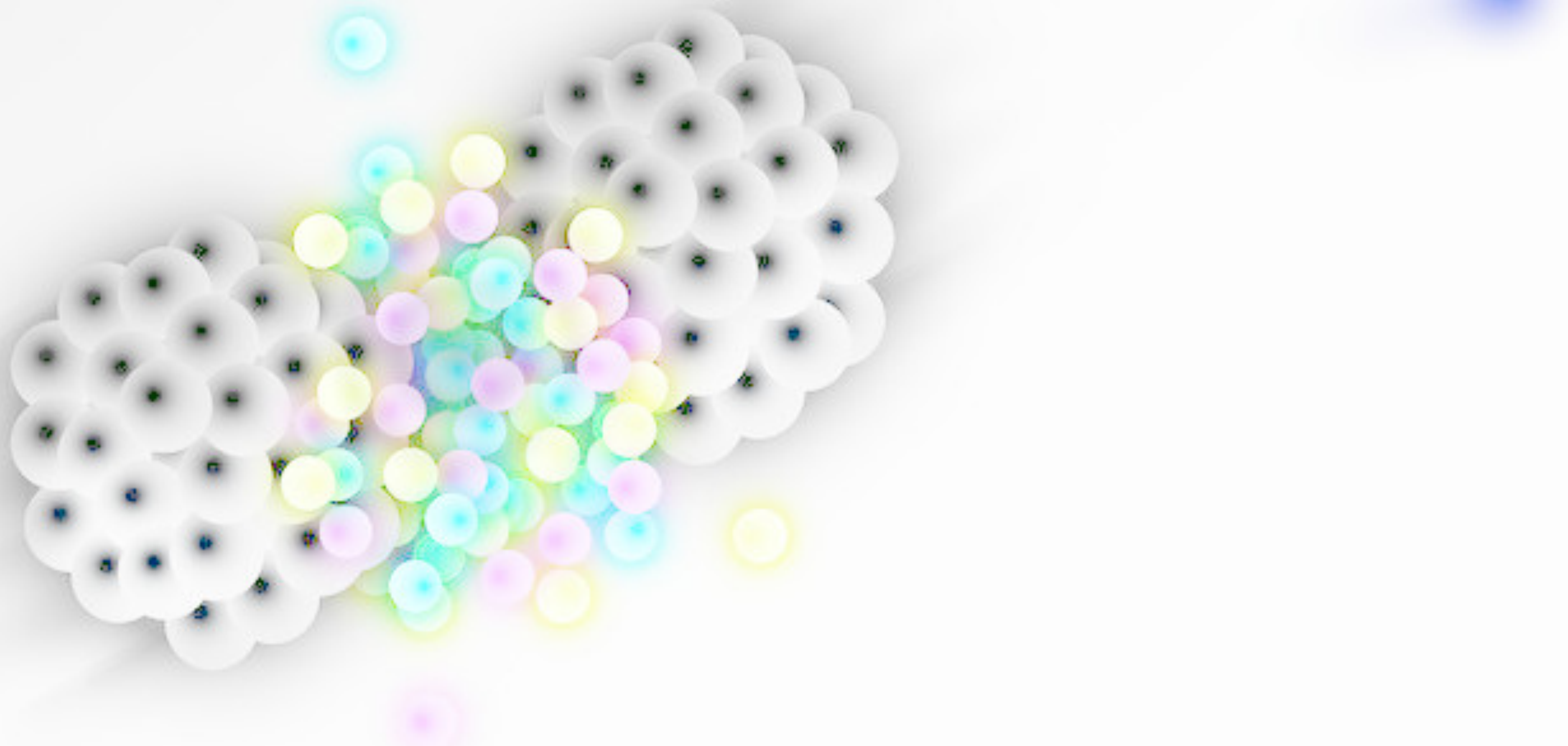
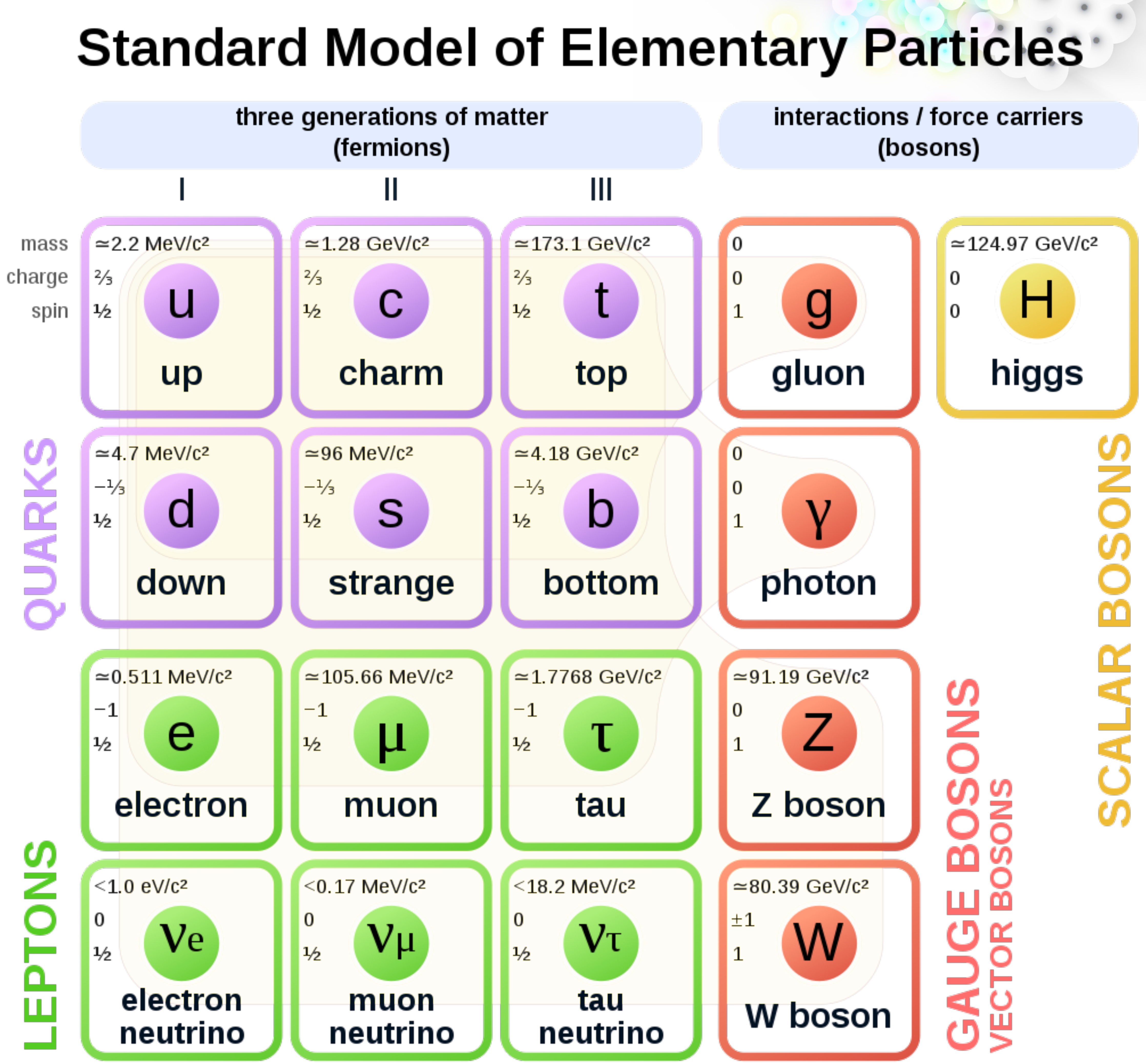
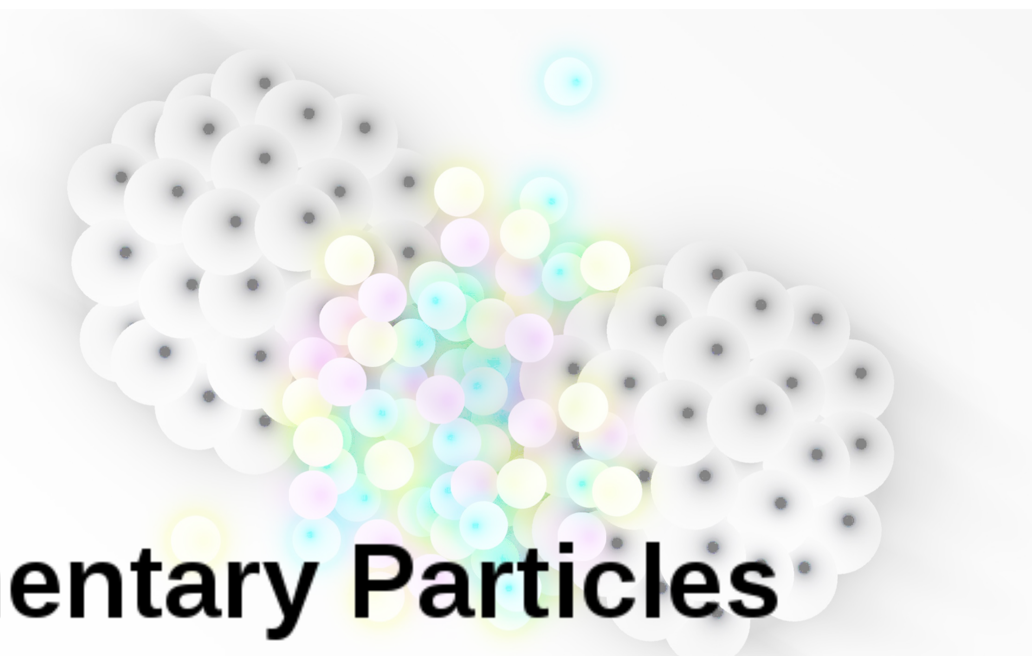


# SM and QCD

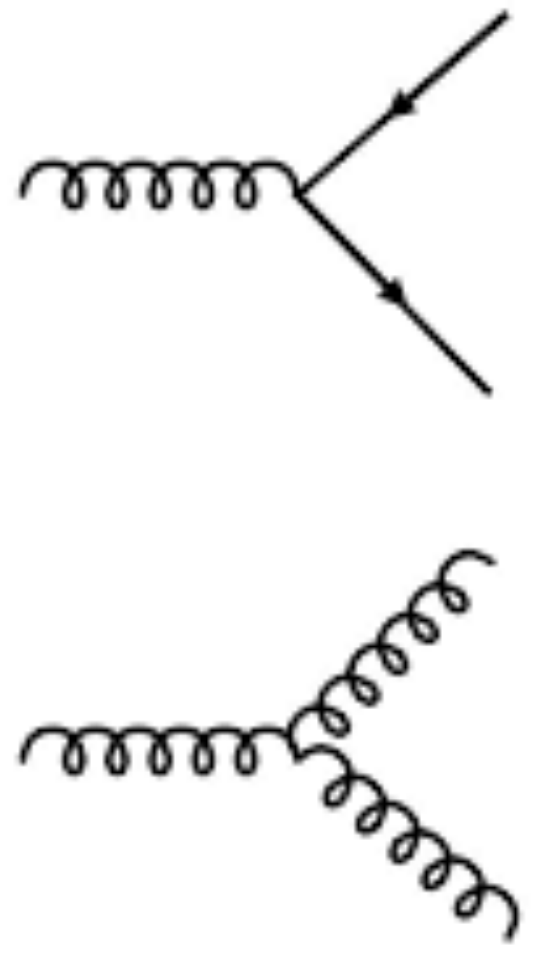
- Standard Model (SM);
  - Strong and Electro-weak interactions



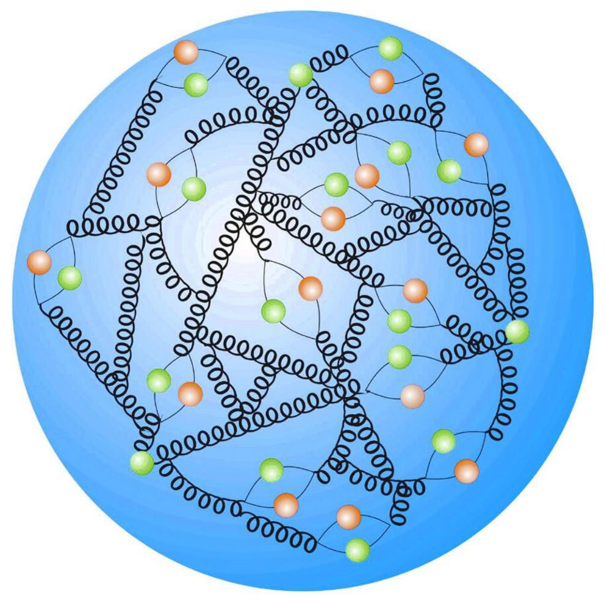
# SM and QCD



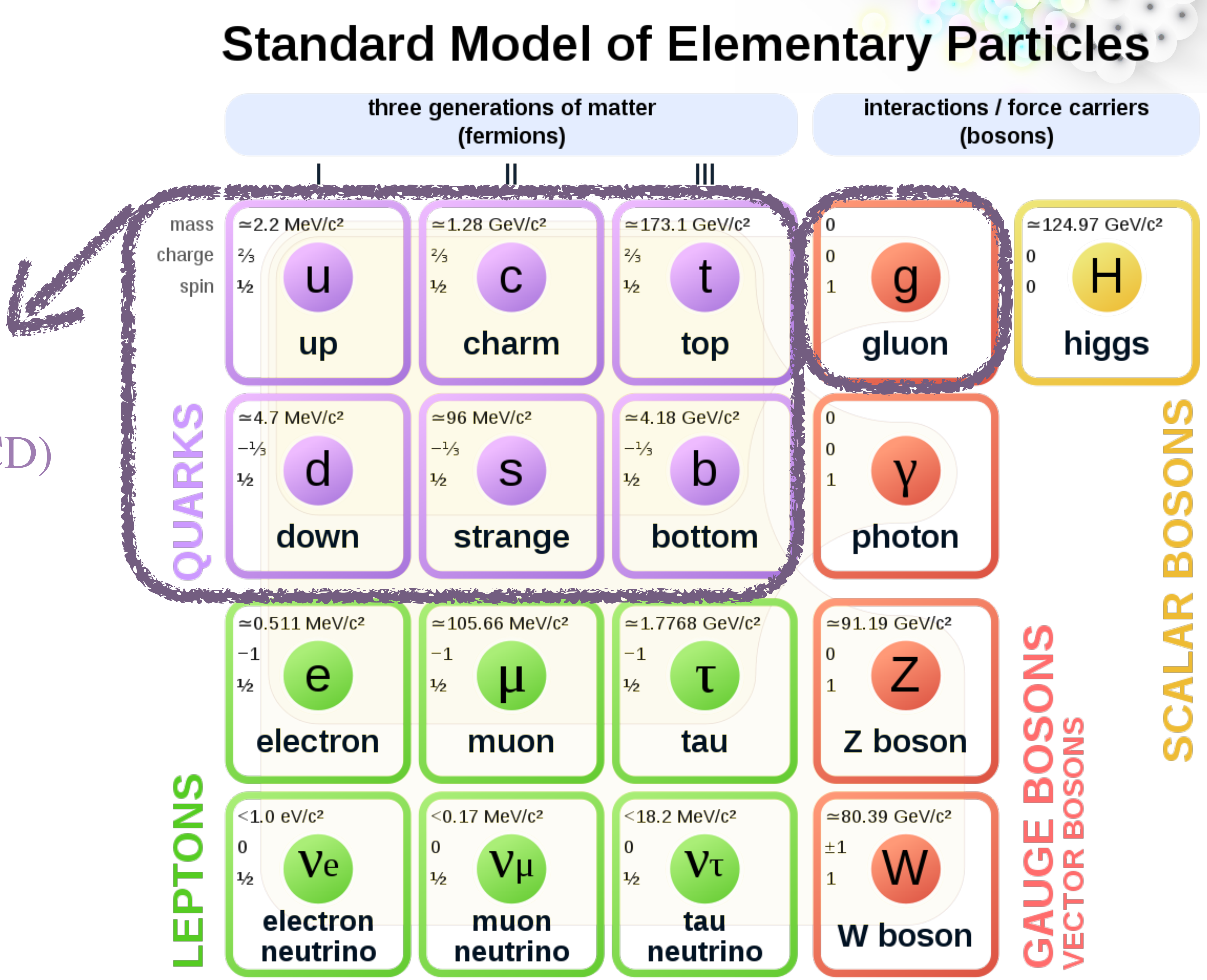
- Standard Model (SM);
  - Strong and Electro-weak interactions
- Color sector of SM:
  - Described by Quantum Chromodynamics (QCD)



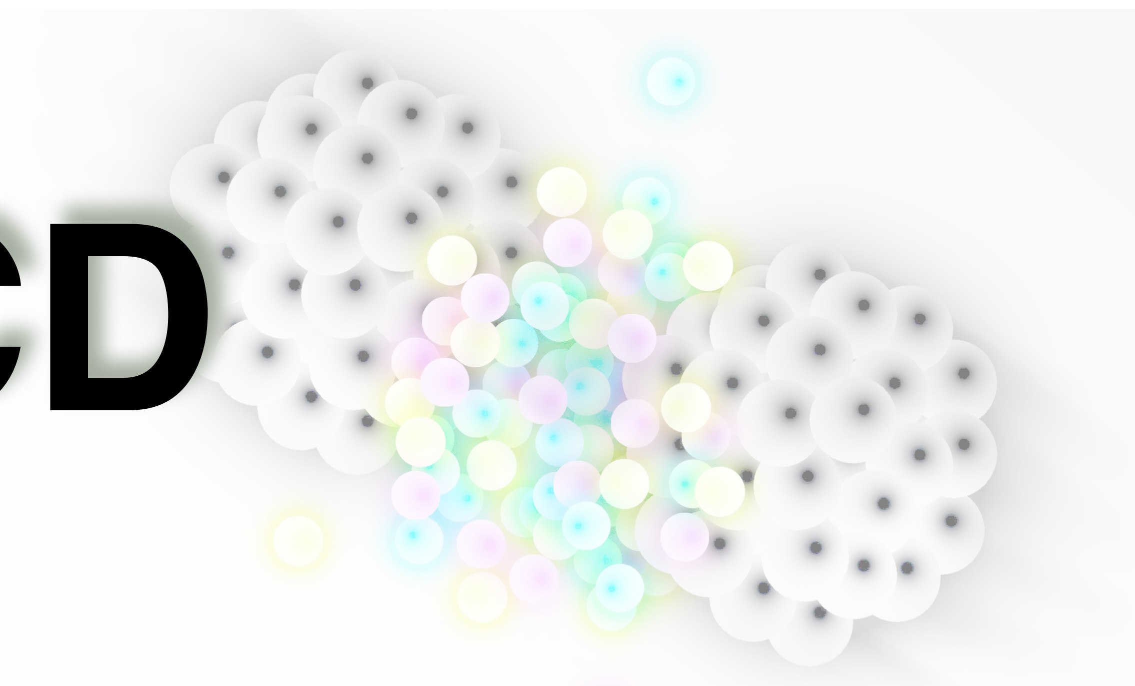
proton structure



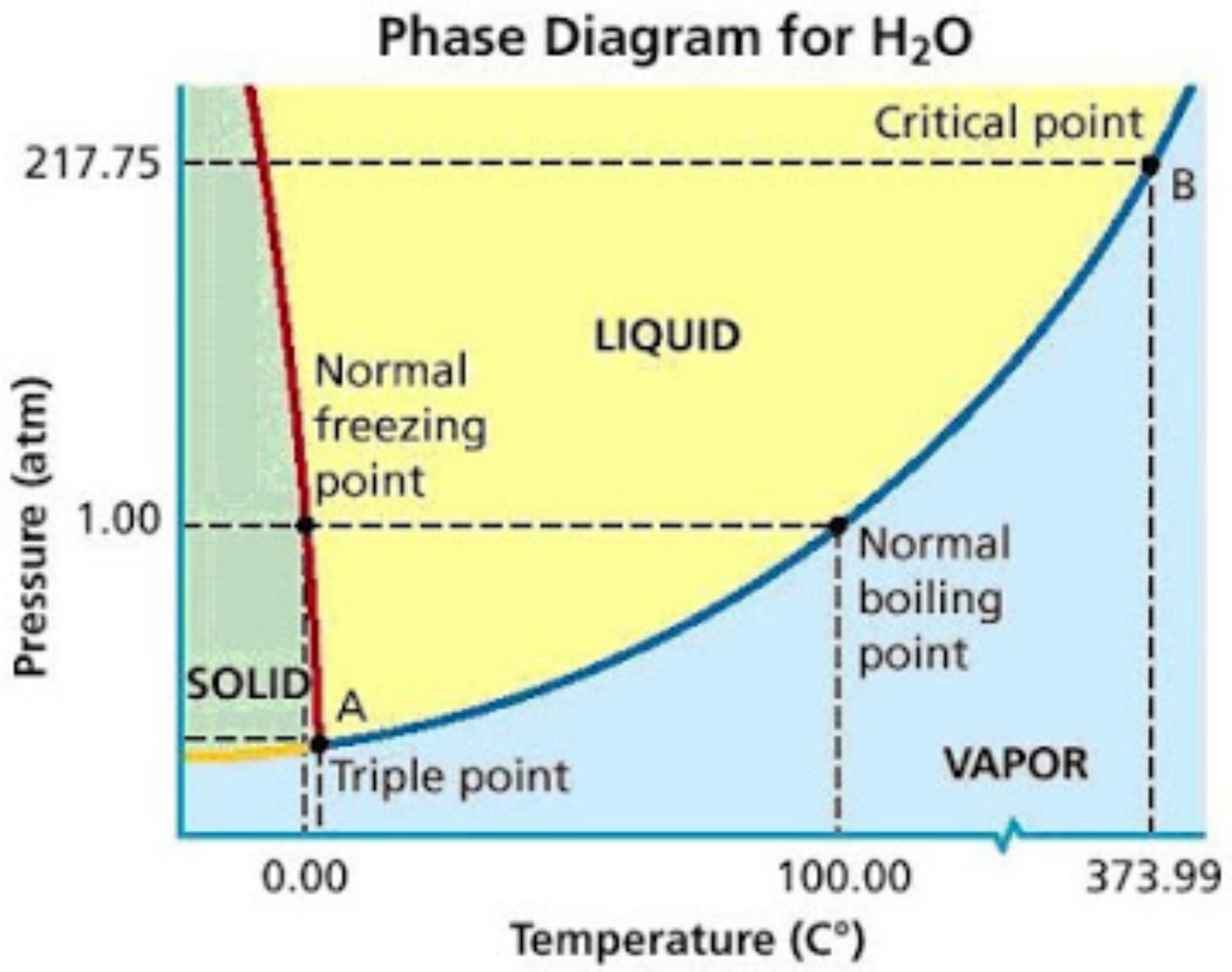
valence + sea
(quarks and gluons)

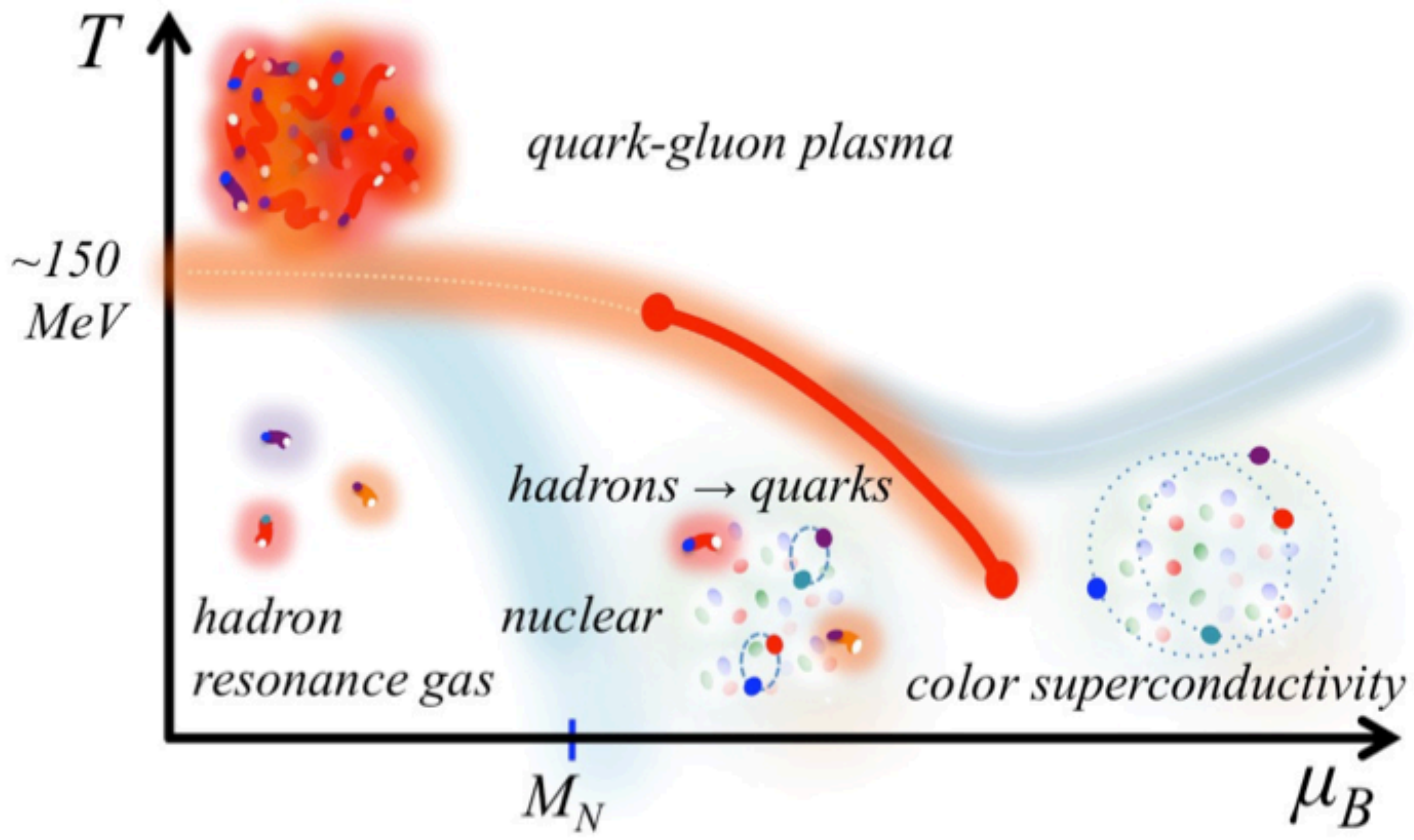


# From dilute QCD to dense QCD



- QCD is not limited to a collection of small particles…
- QCD matter has a rich and vast phase diagram



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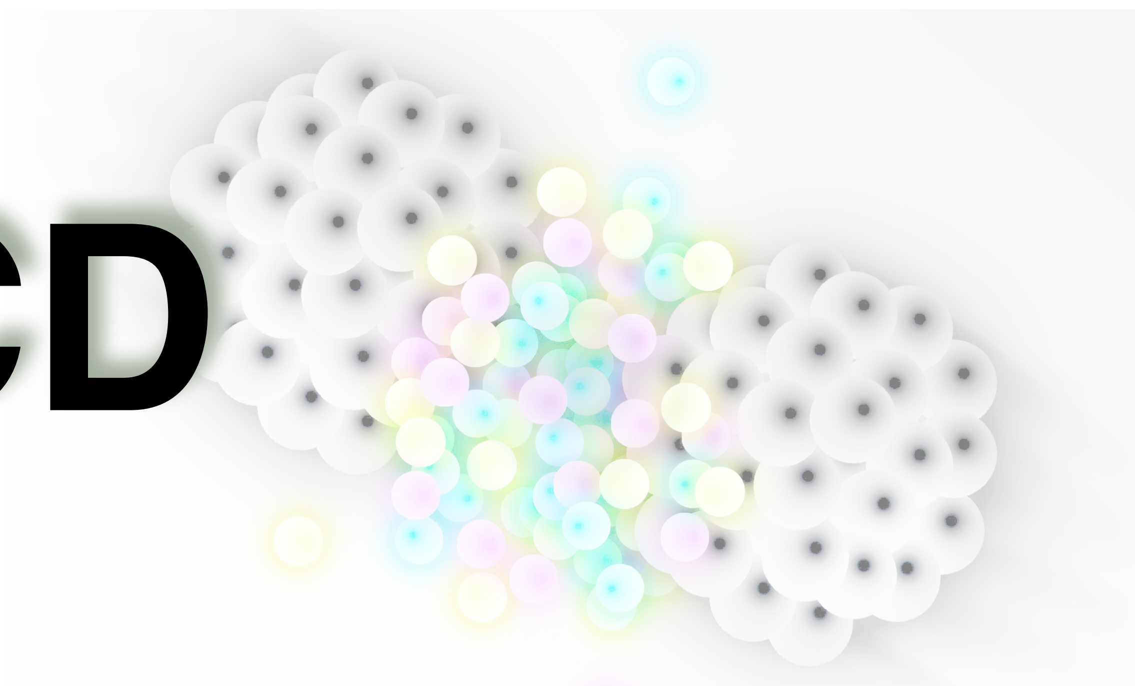
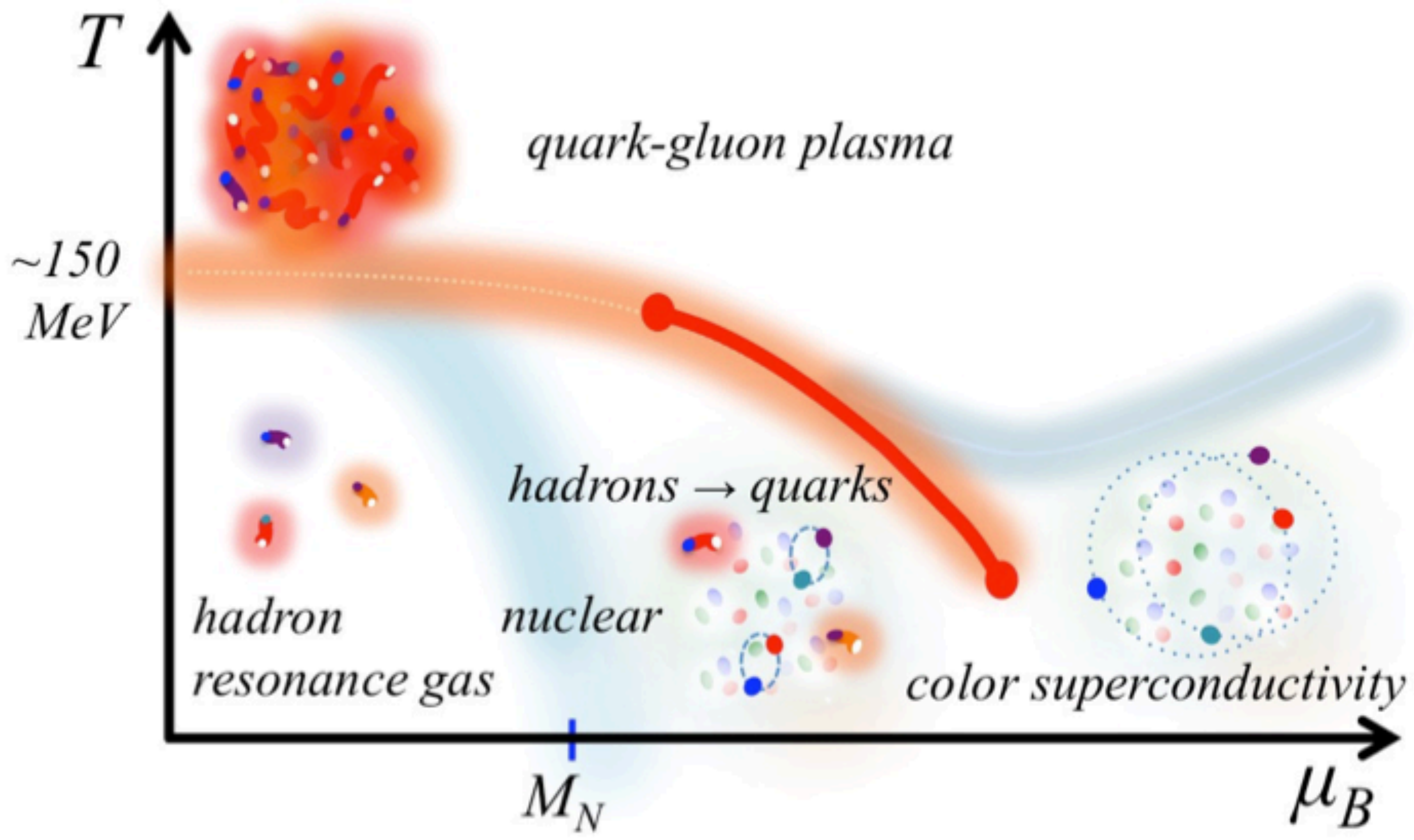


- QCD is not limited to a collection of small particles…
- QCD matter has a rich and vast phase diagram

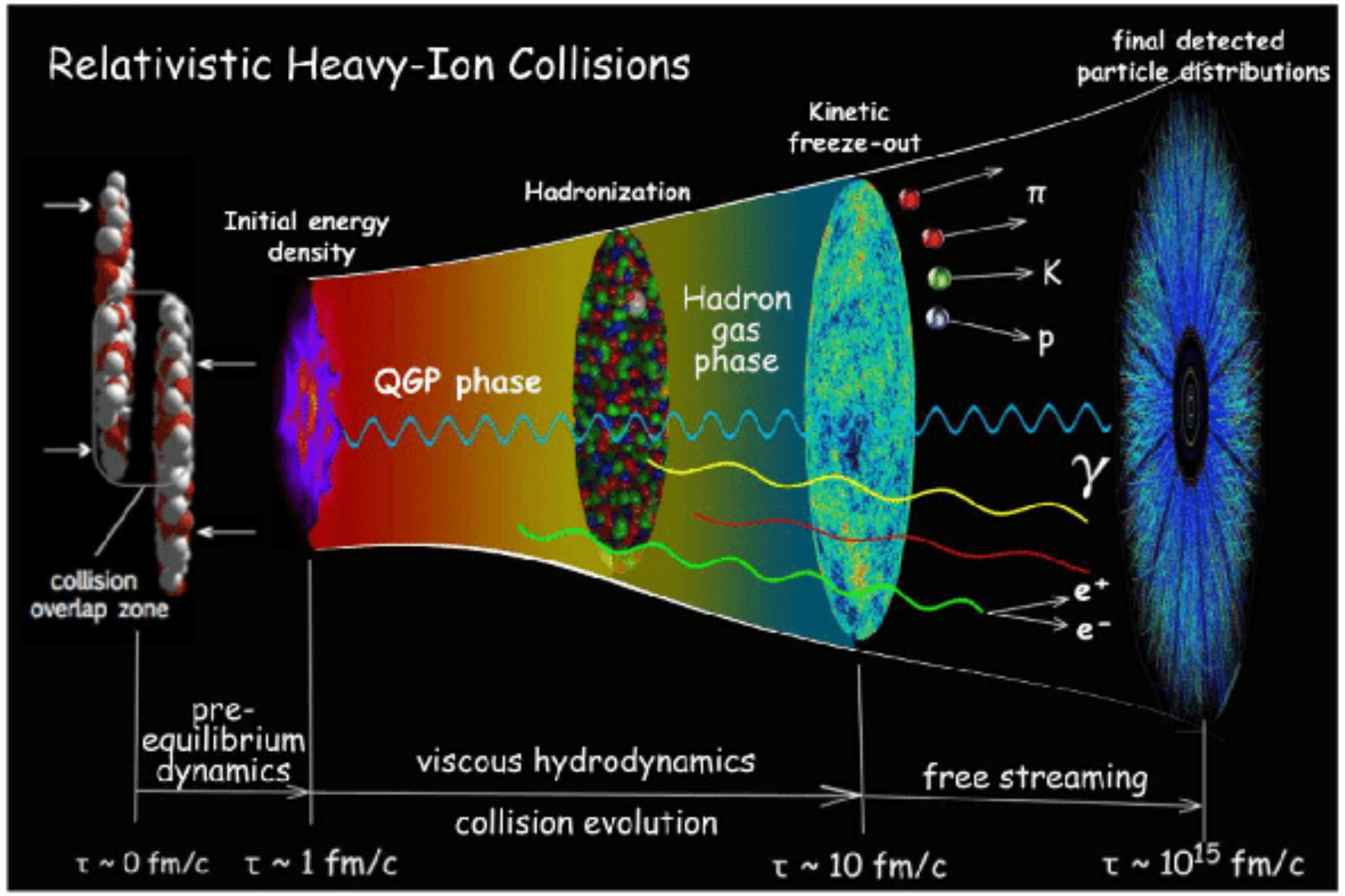
**QCD theory (1973)**
**SU(3) Color symmetry; confinement; asymptotic freedom, …**

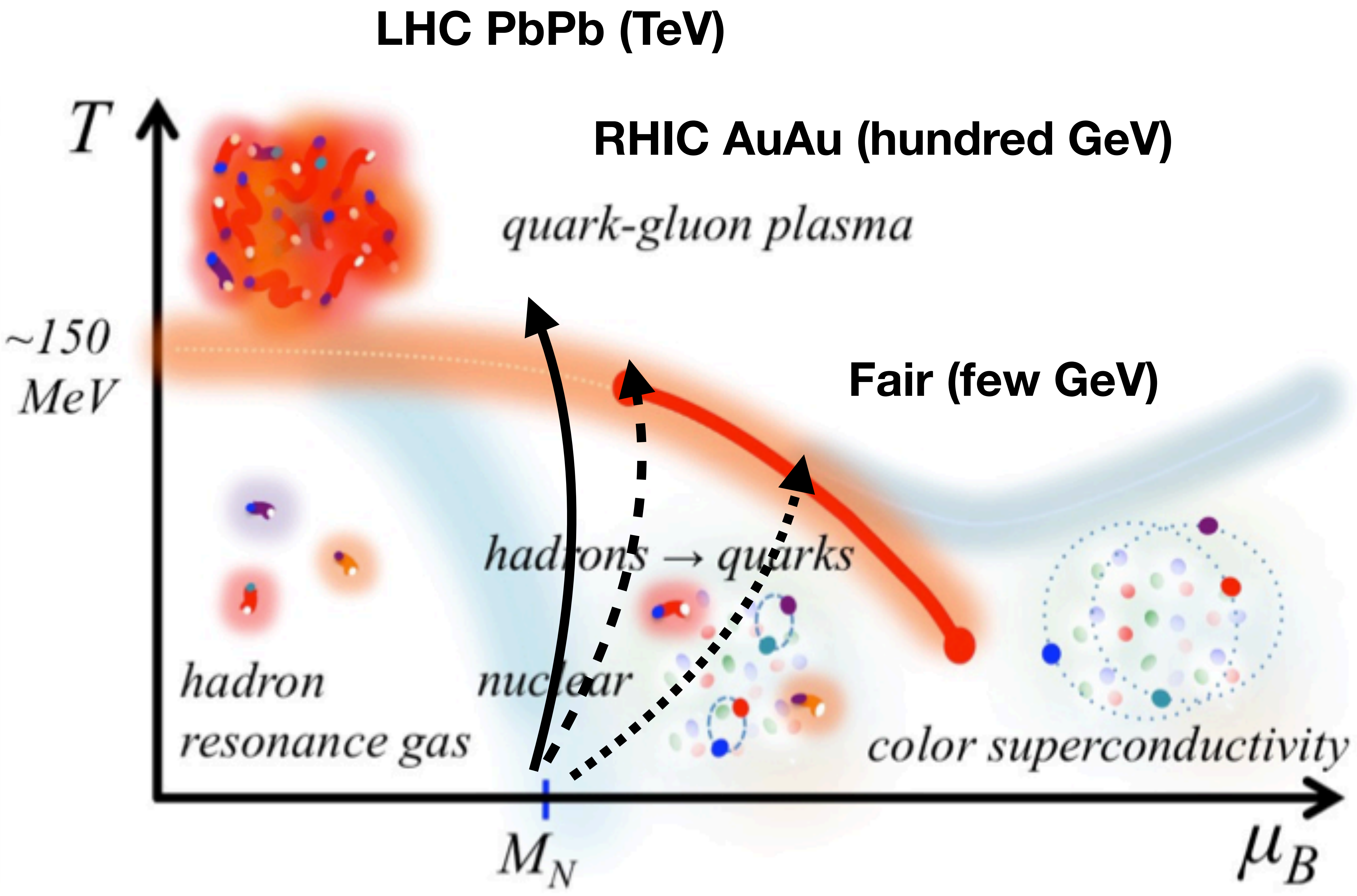
**QGP initial idea (1975)**
**"Weakly coupling quark soup"**
**State of matter where quarks and gluons are asymptotically free**



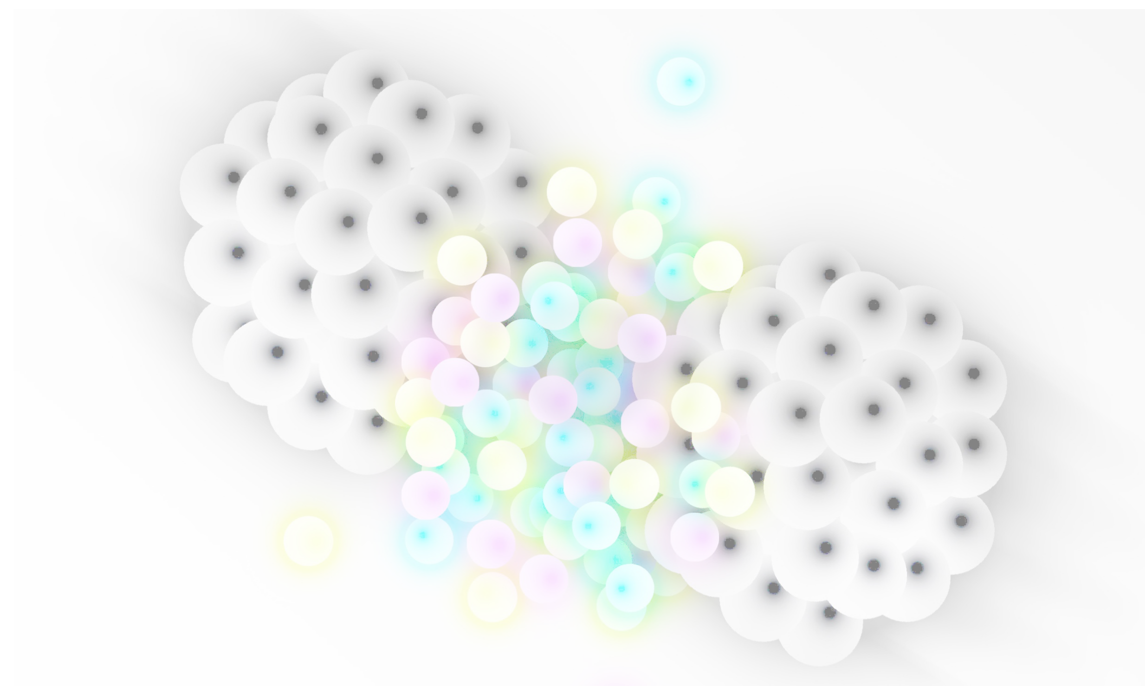
# Discovering QCD phase diagram

- How to unveil the unknown corners of the QCD phase diagram?
  - Through heavy-ion collisions:

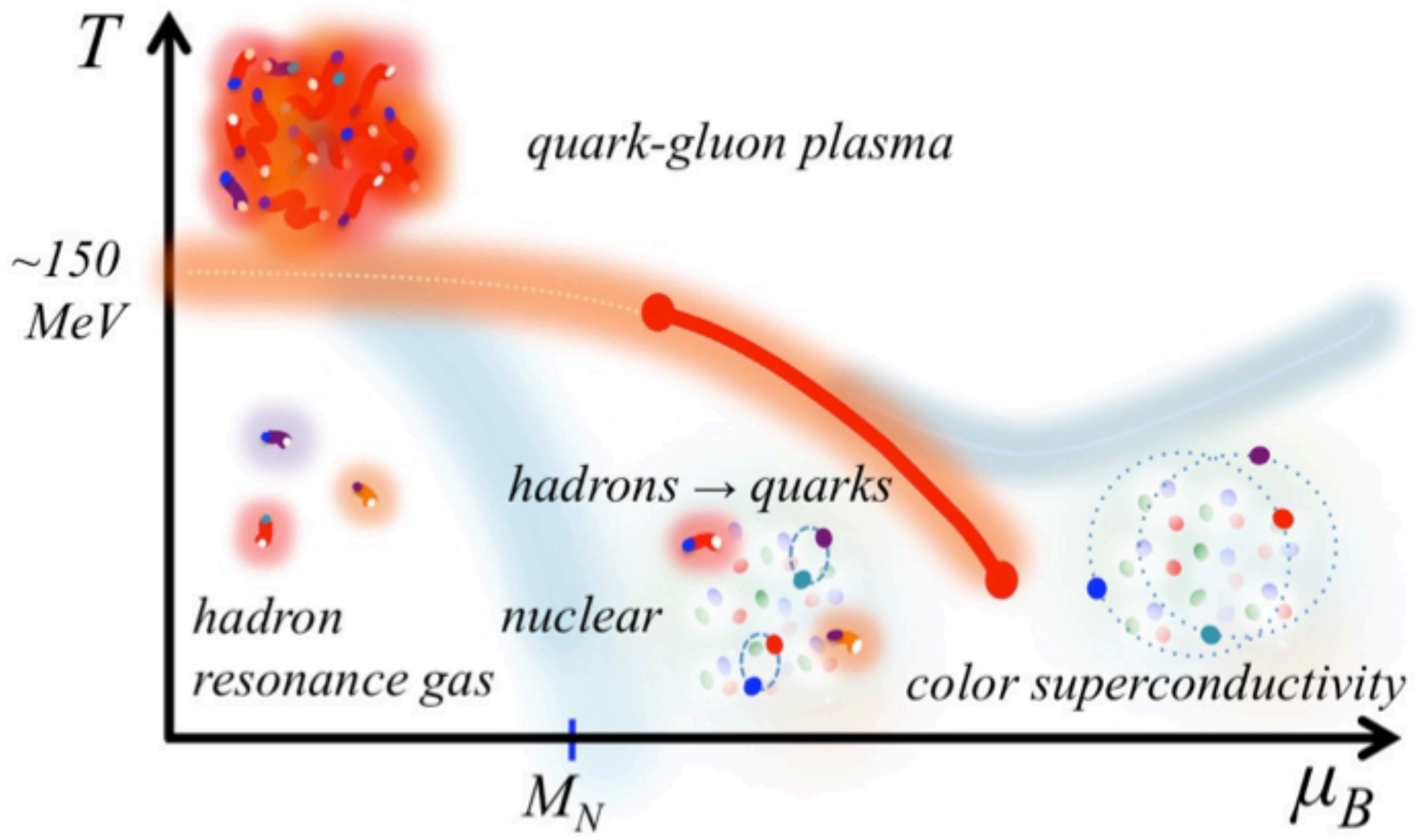


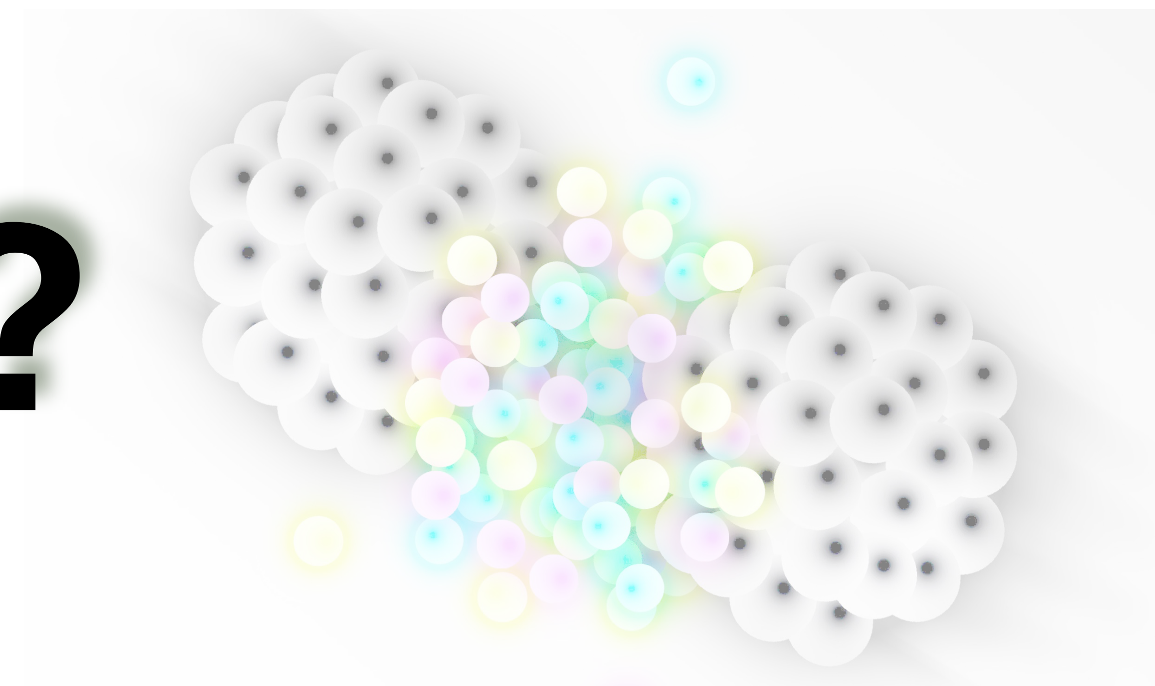
# Heavy-Ion collisions



- Why heavy-ions?
  - Probe the QCD phase diagram
  - Understand the QCD fundamental interactions
    - Collectivity from a gauge-field theory?
  - Tools used to study created matter shared with nearby physics fields research
    - QGP vs colliding nuclei?

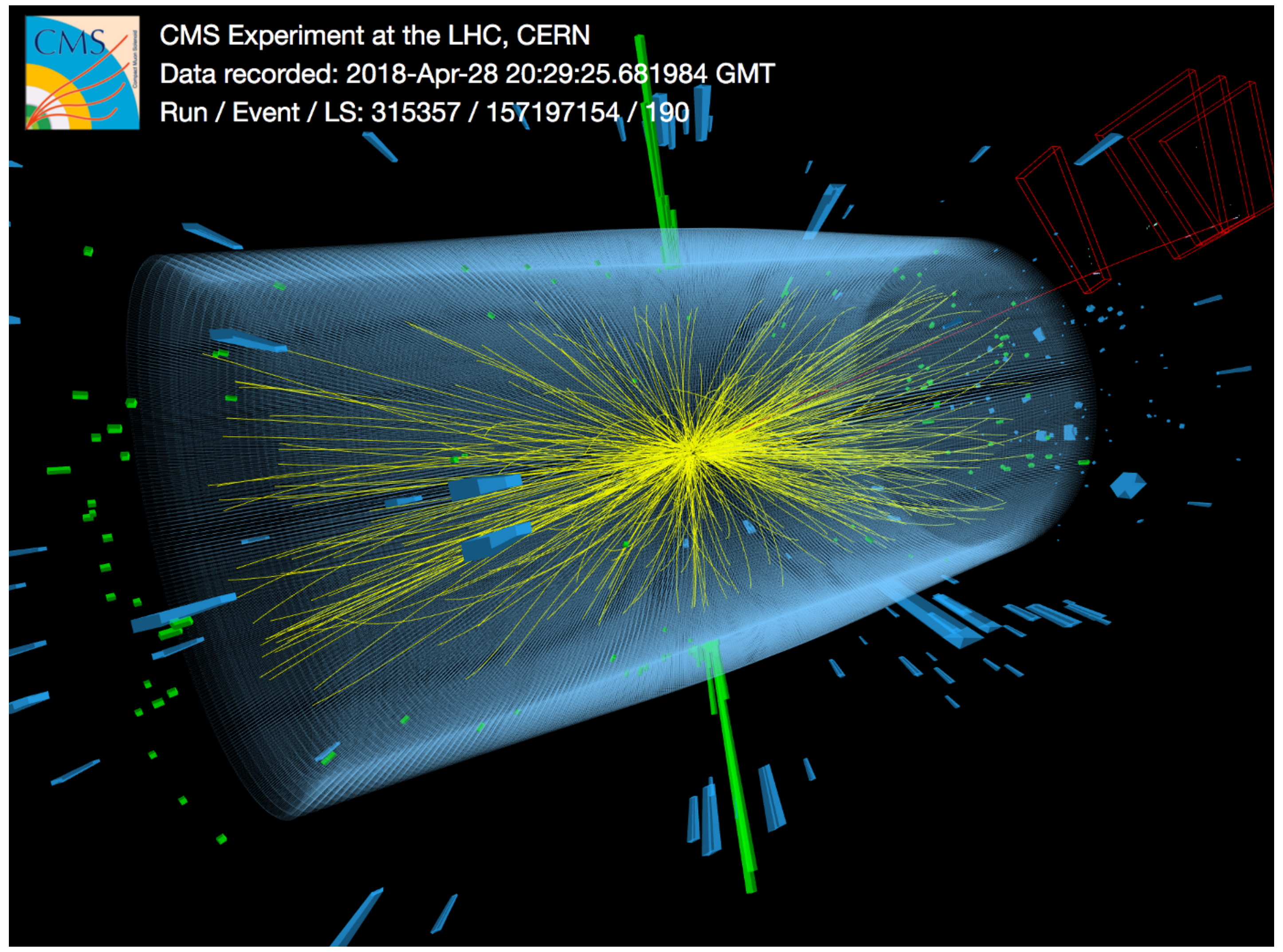


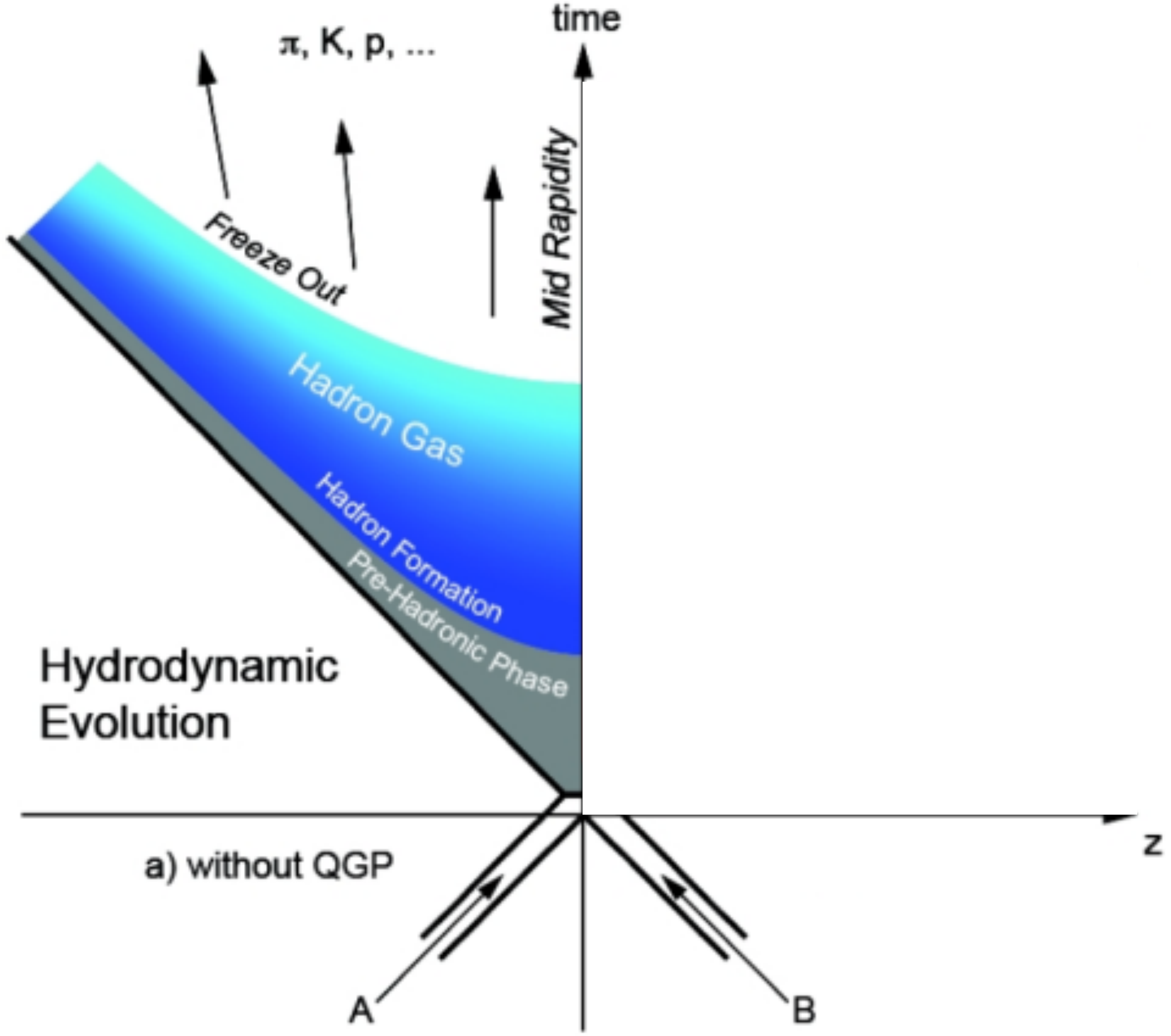
# What is a heavy-ion collision?



- Proton-proton vs heavy-ion collisions:

**Proton-proton collisions**
**Low multiplicity event**



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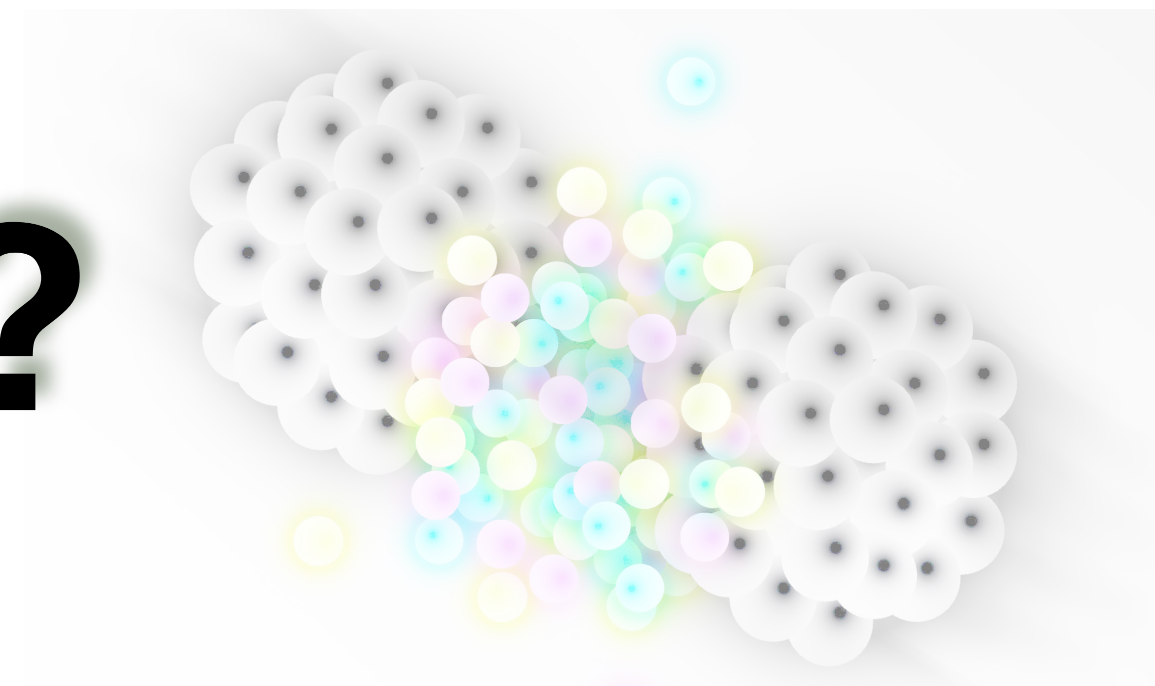

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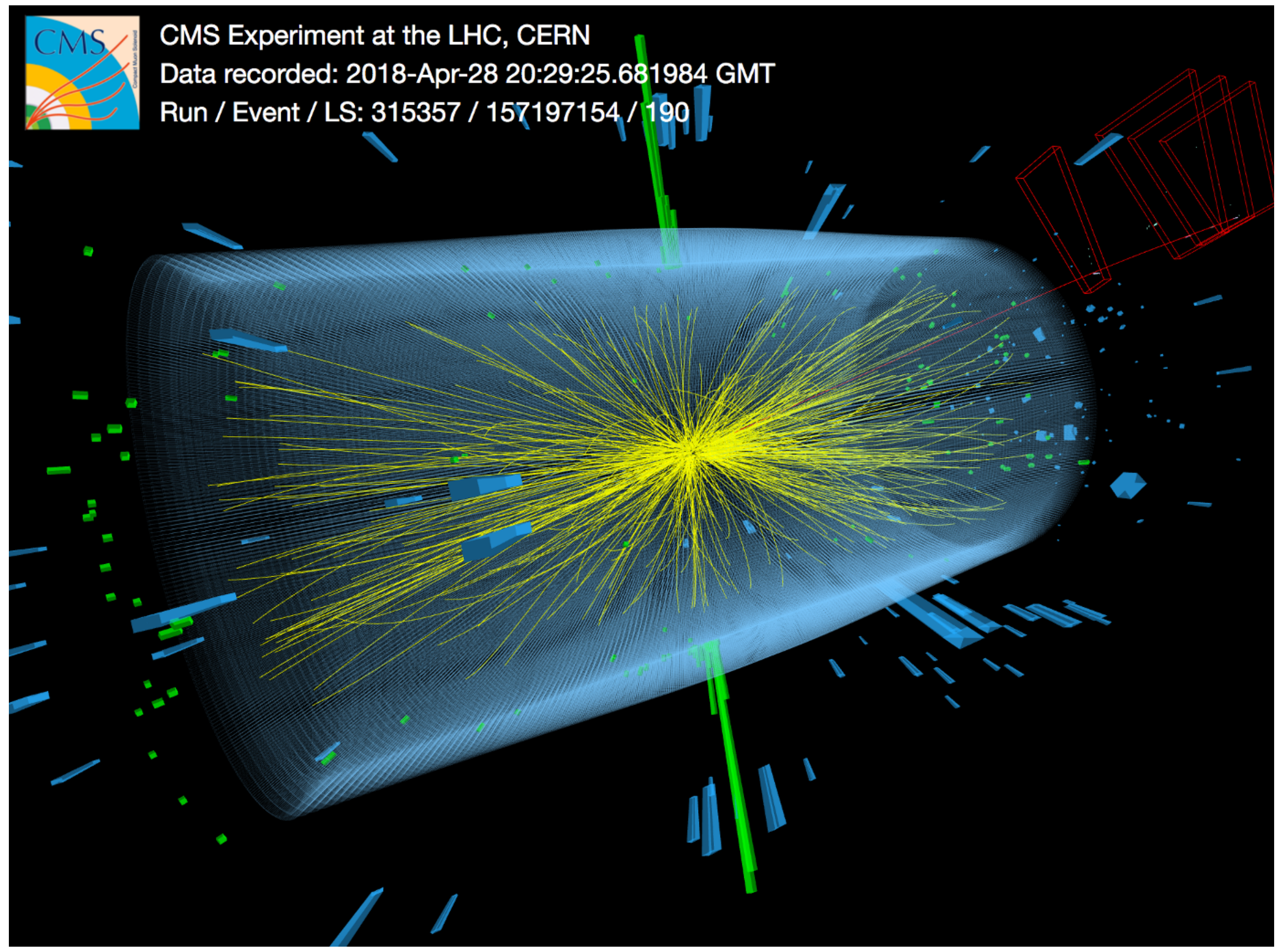
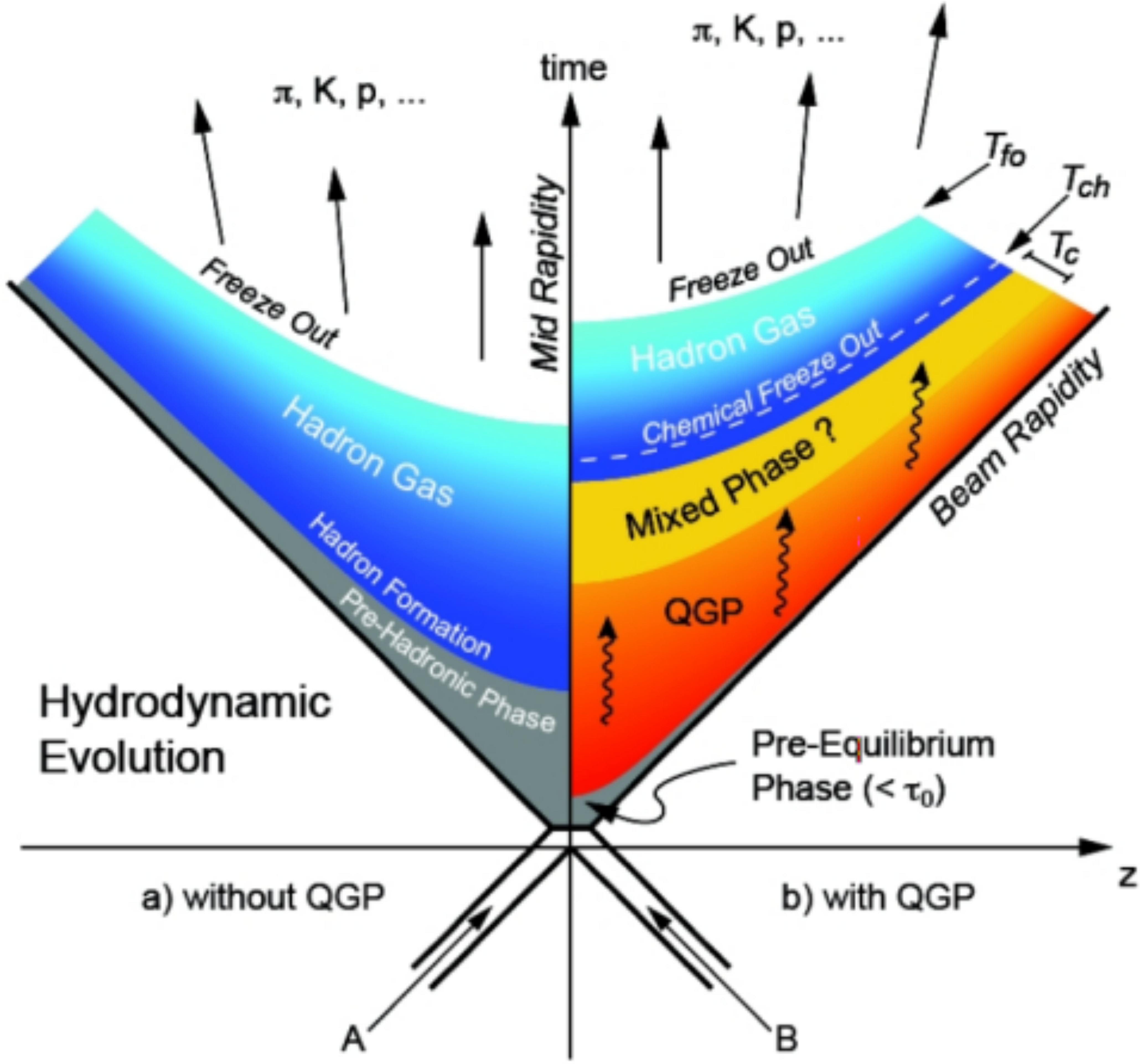
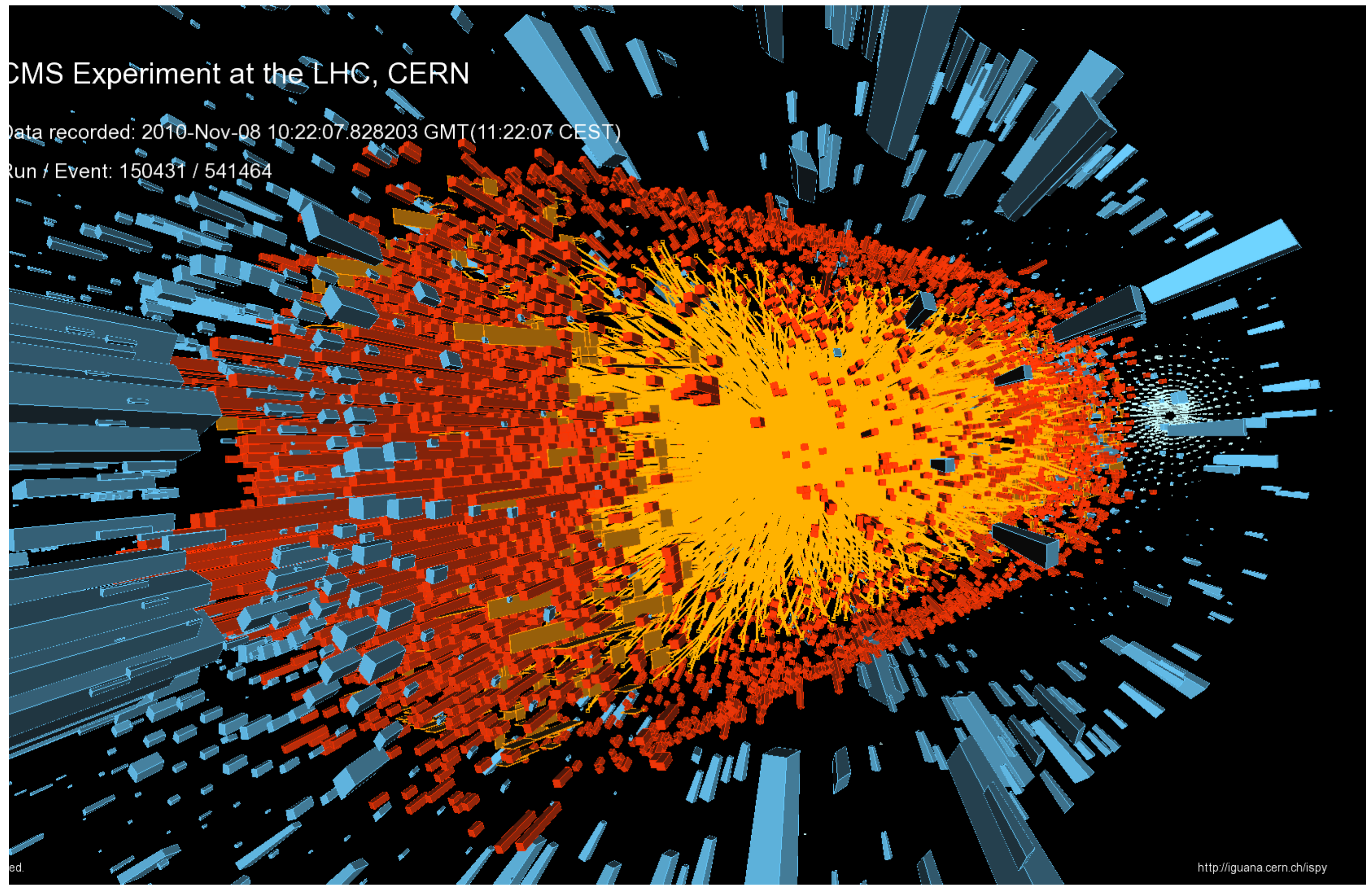
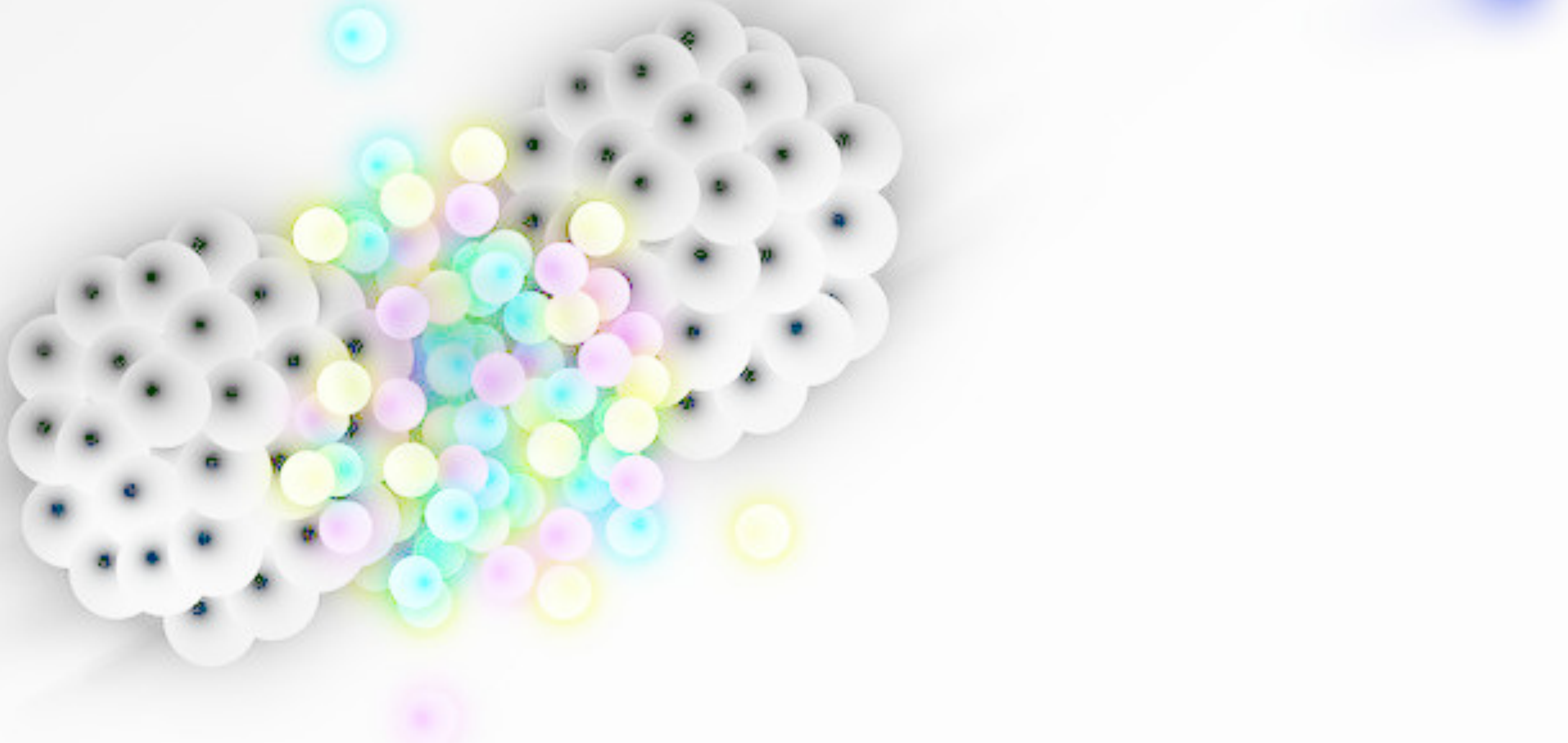



**Lead-Lead collisions**
**High multiplicity event**
**(result of QGP formation)**



# How to study the Quark-Gluon Plasma?



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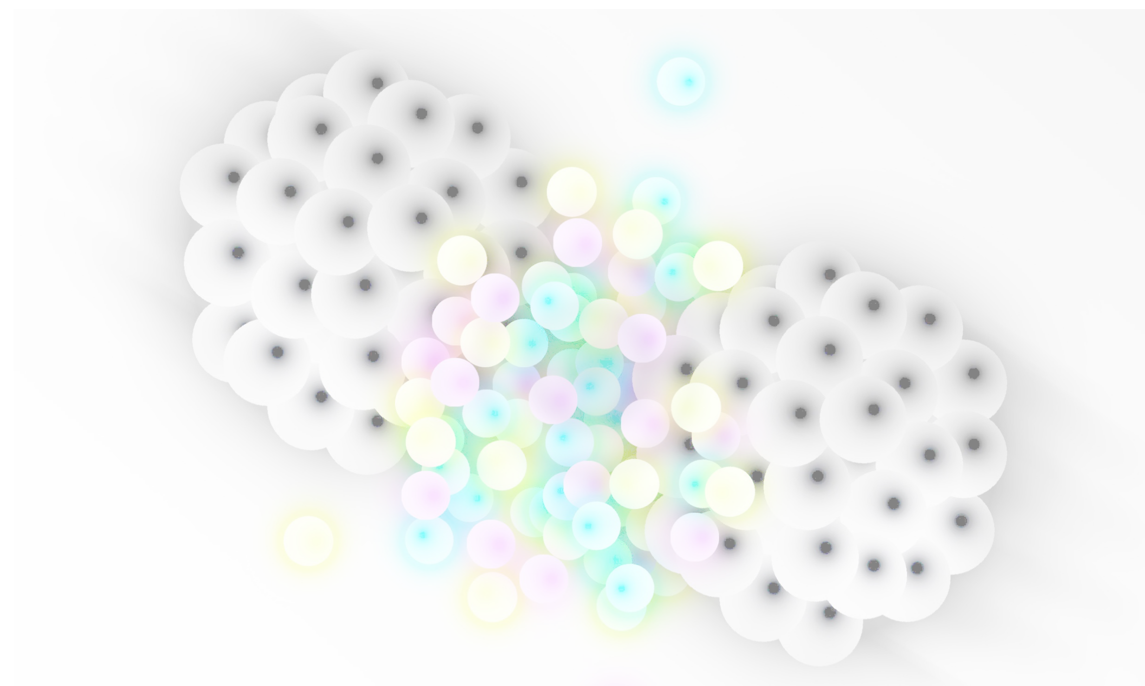
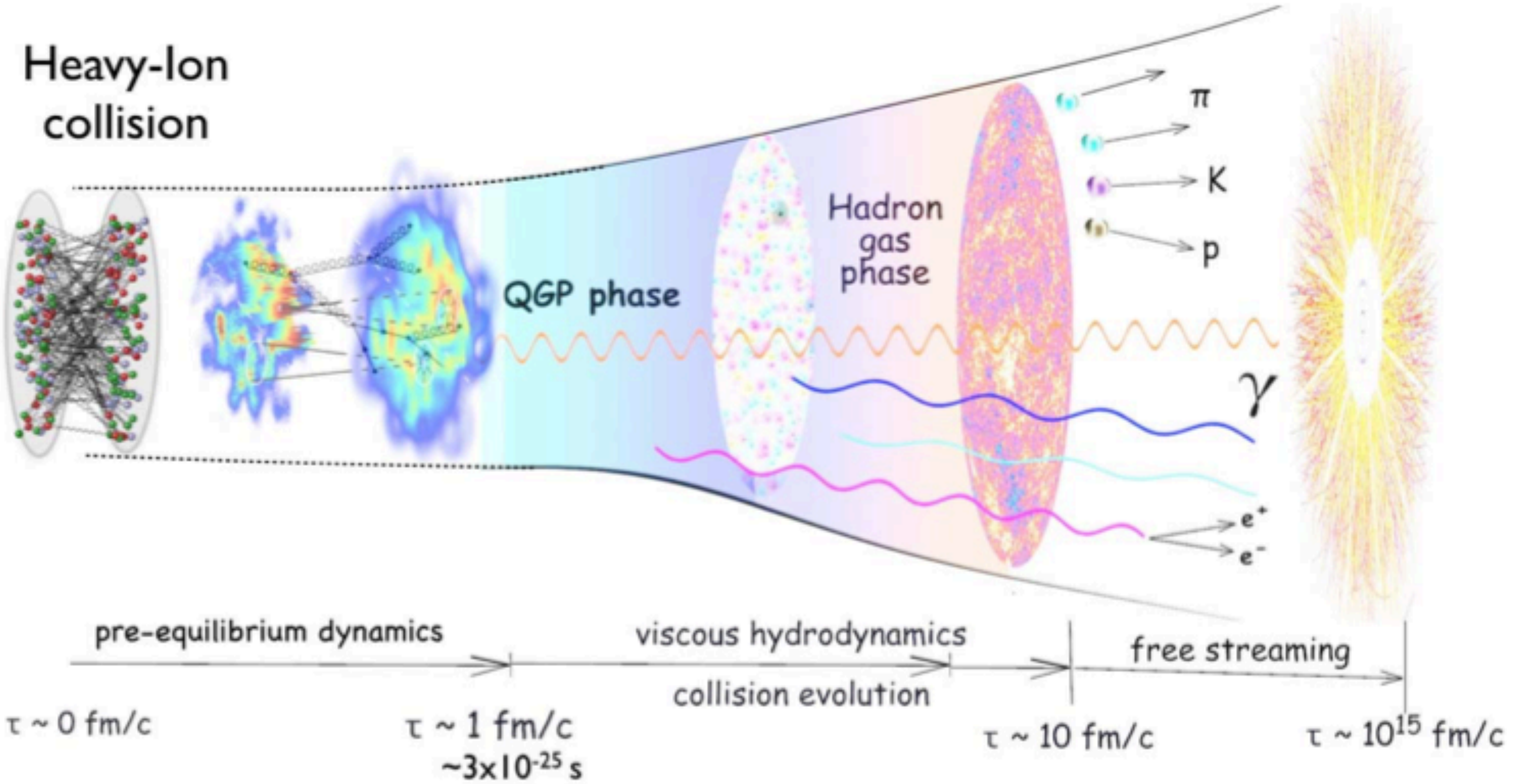


- Different QGP probes will access different wavelengths:



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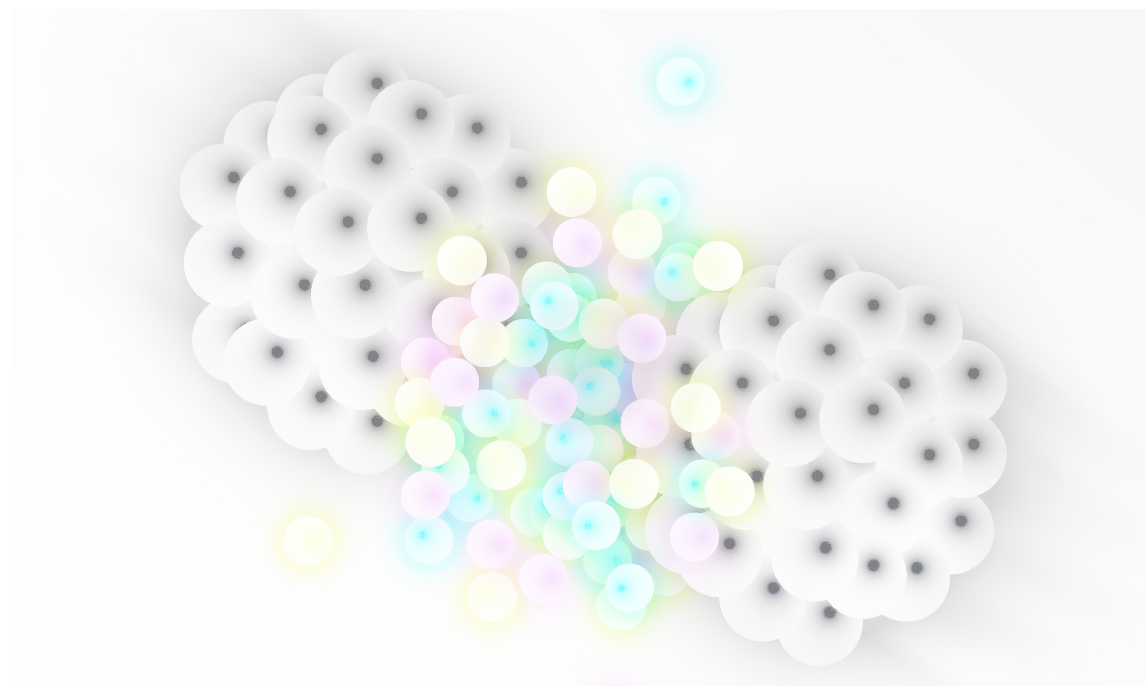

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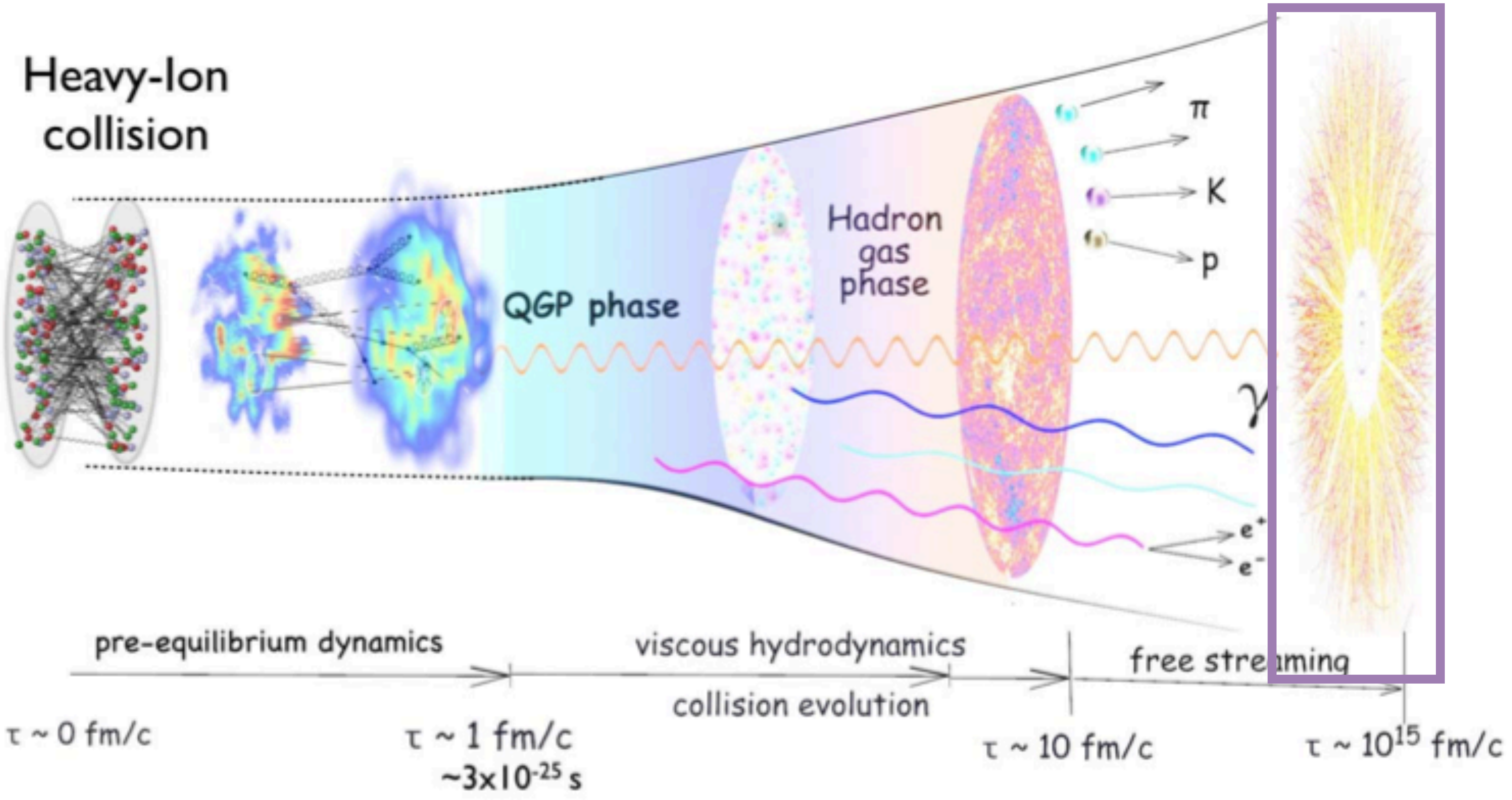

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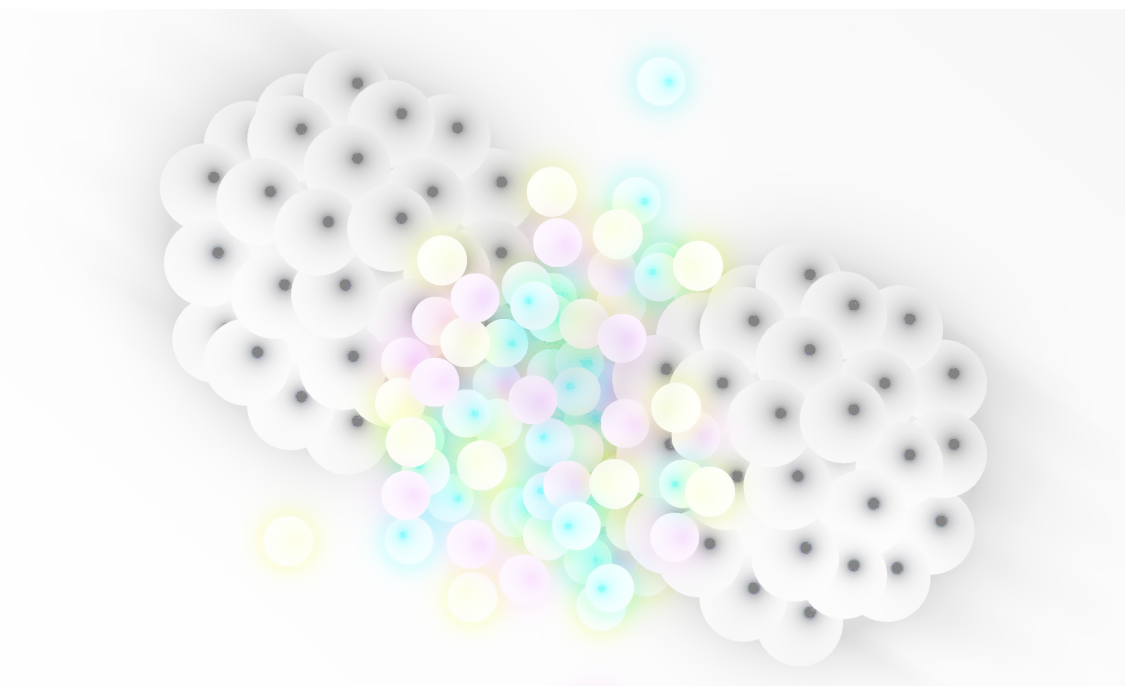

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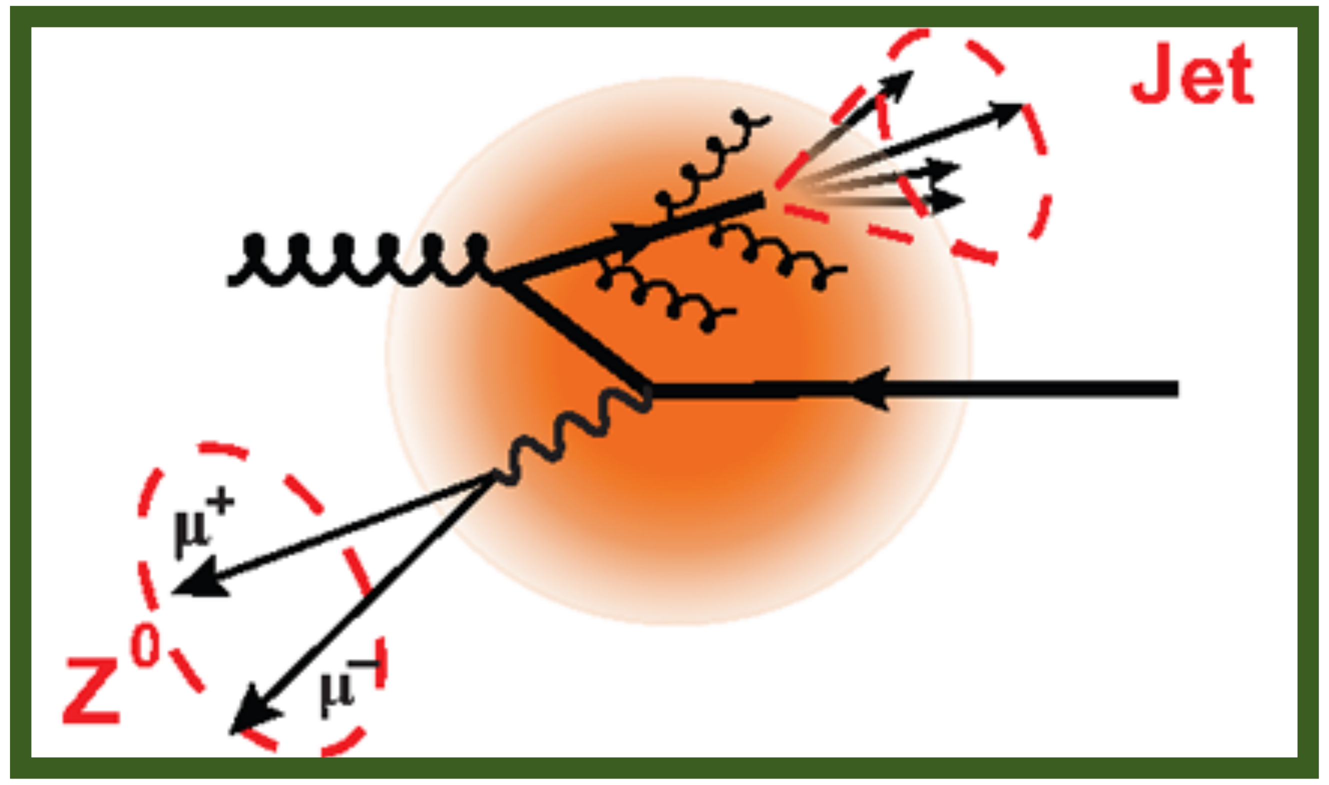


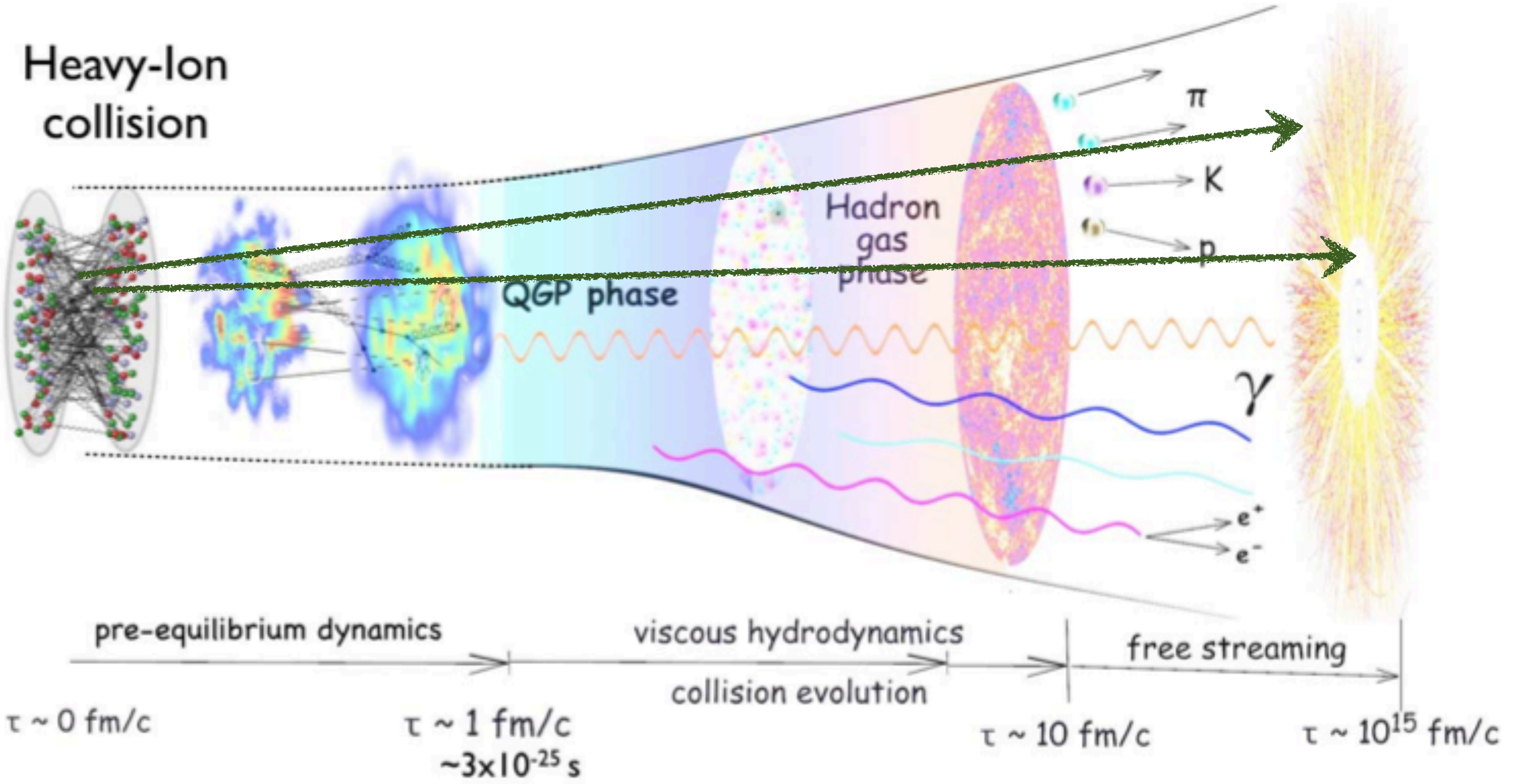

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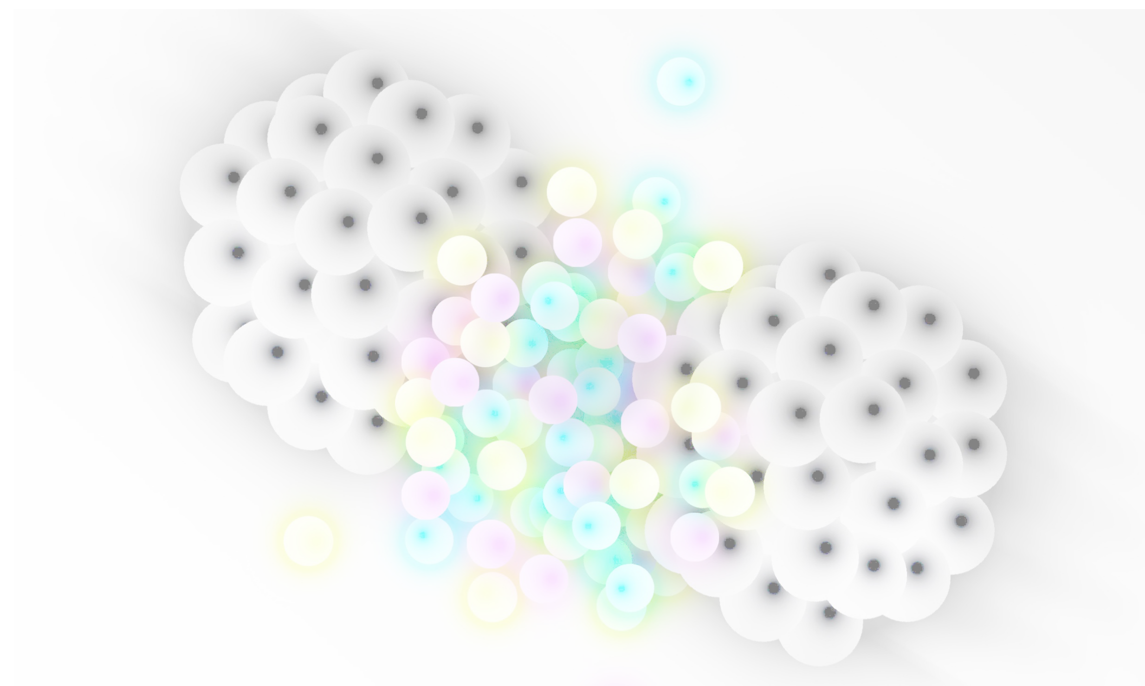

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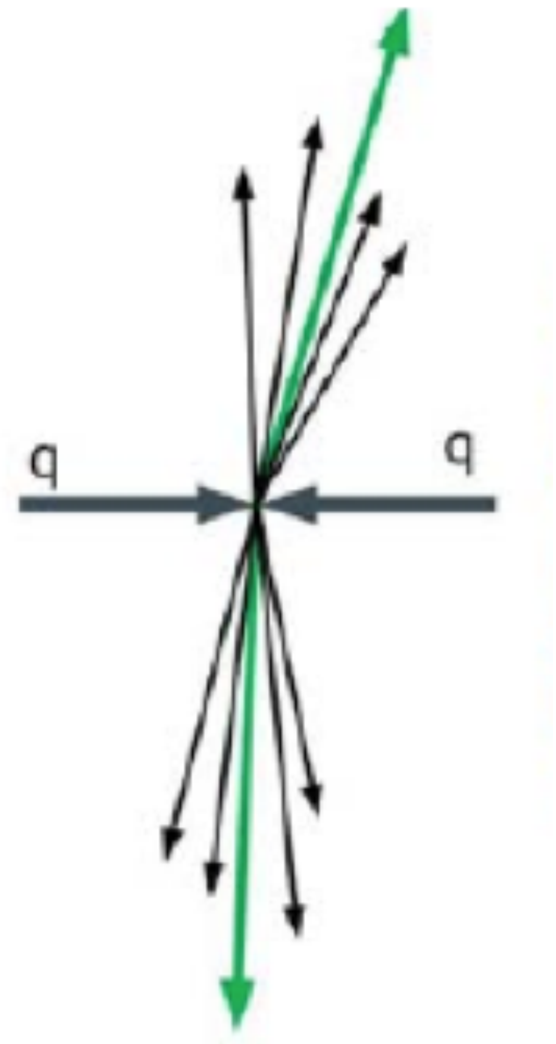
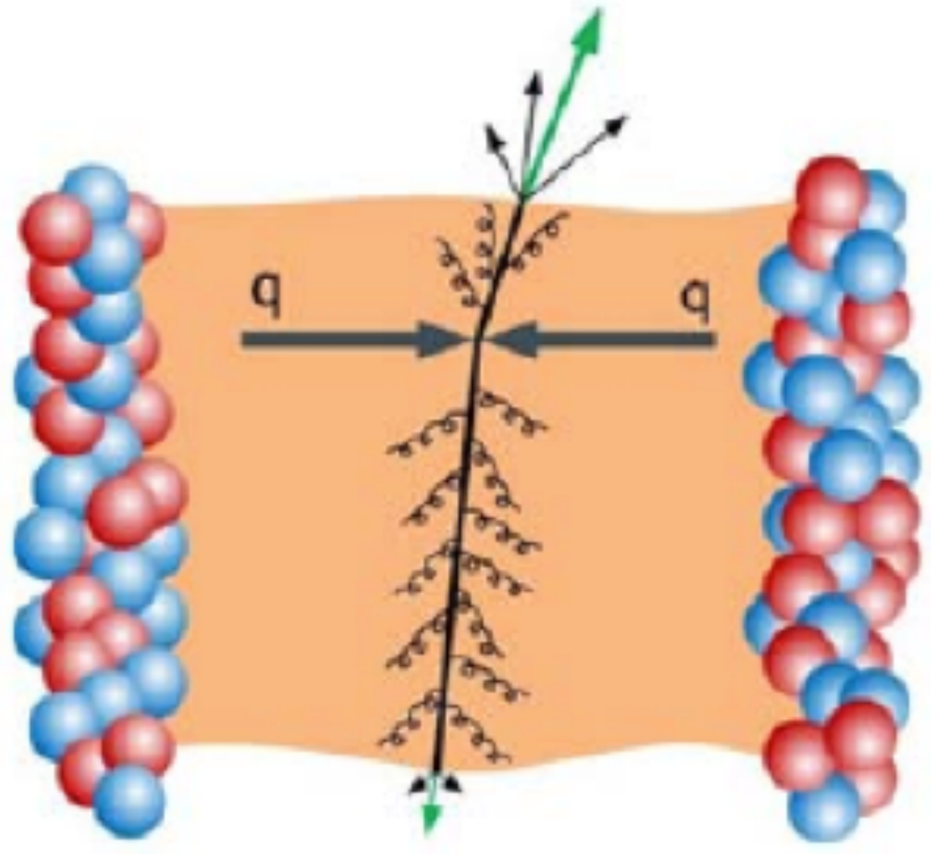
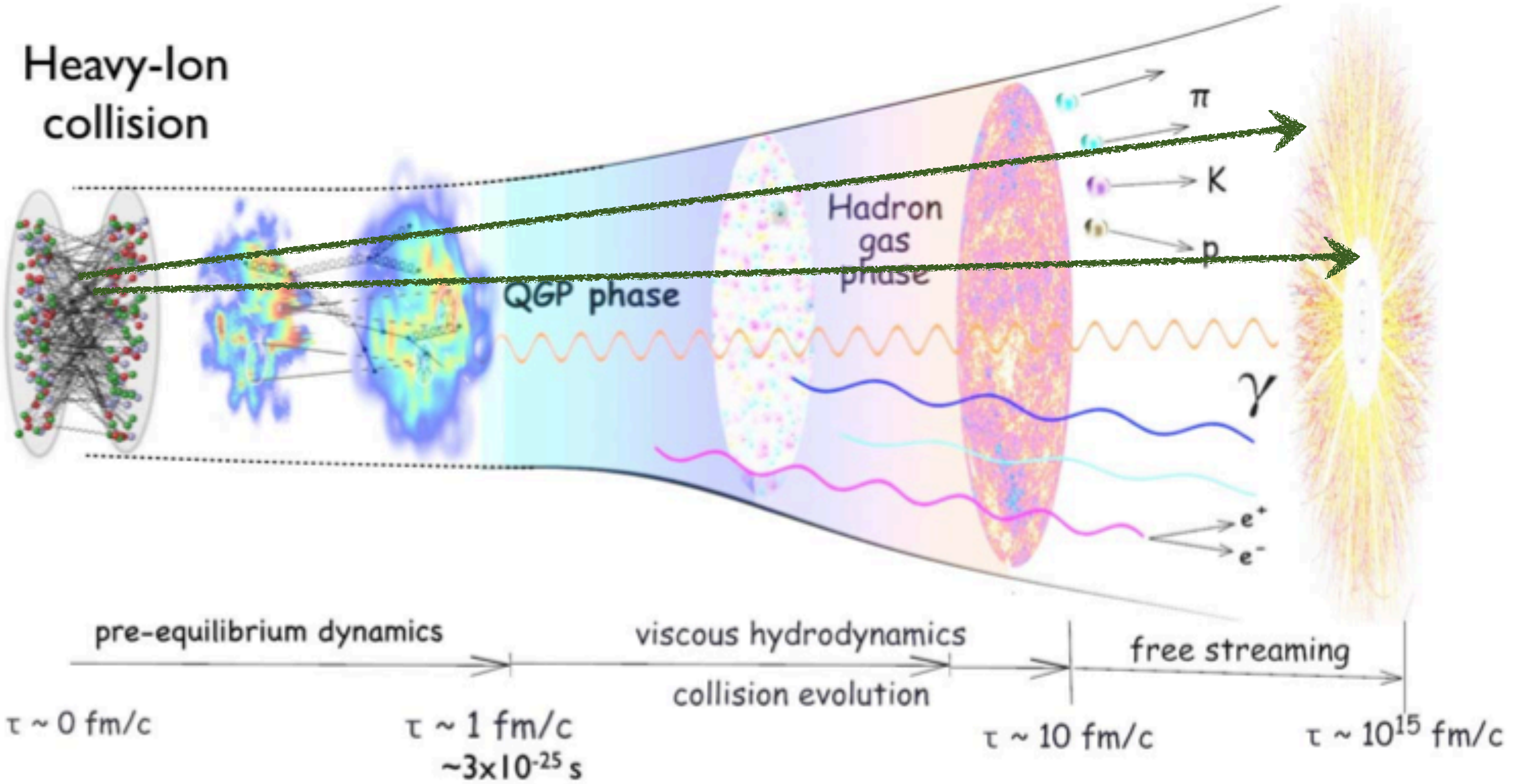



p+p




A+A



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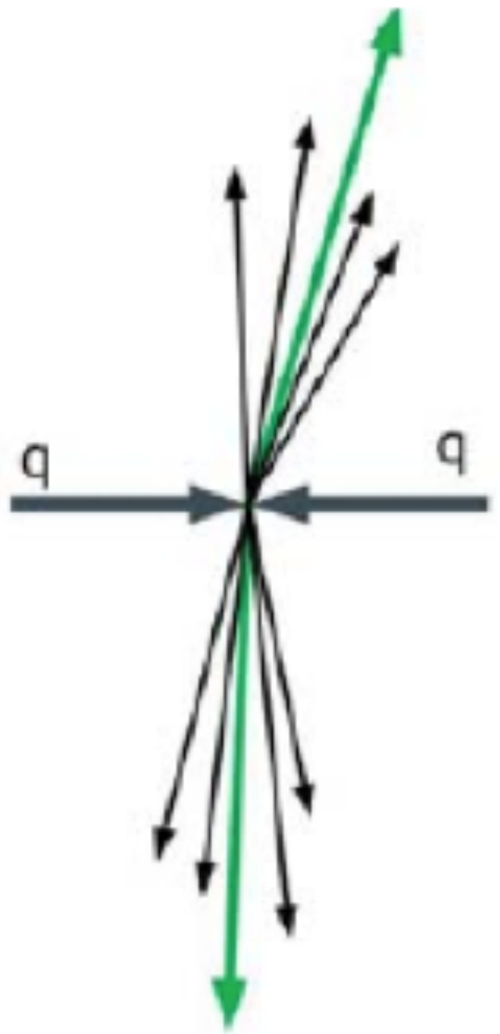


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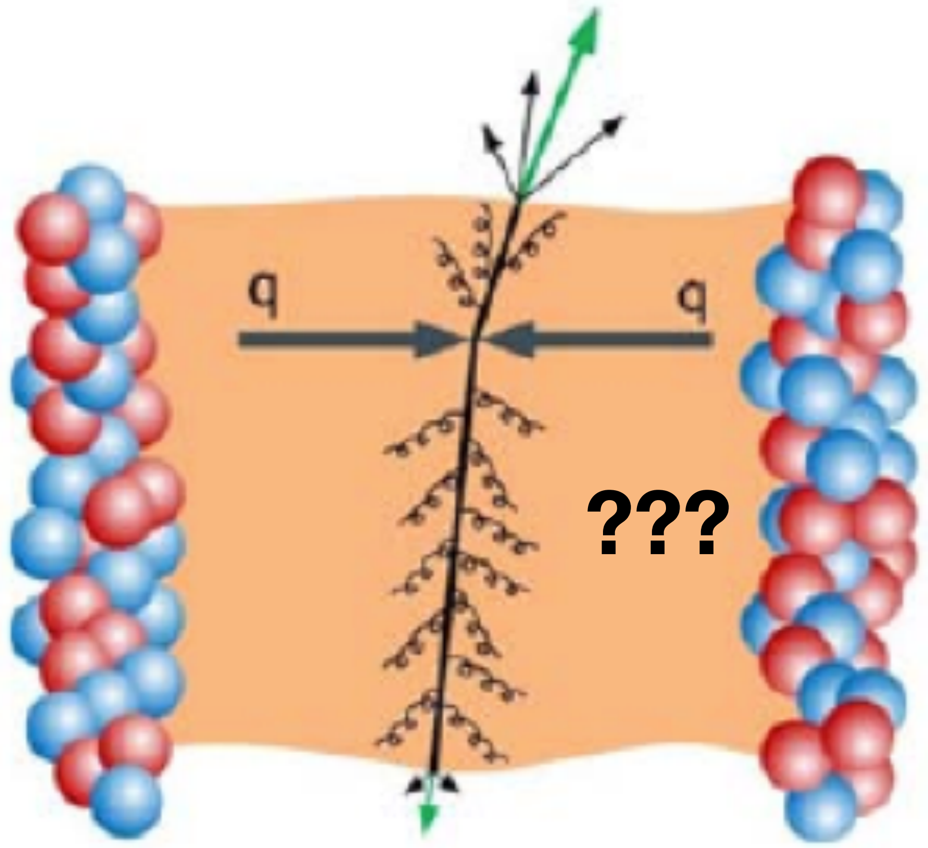


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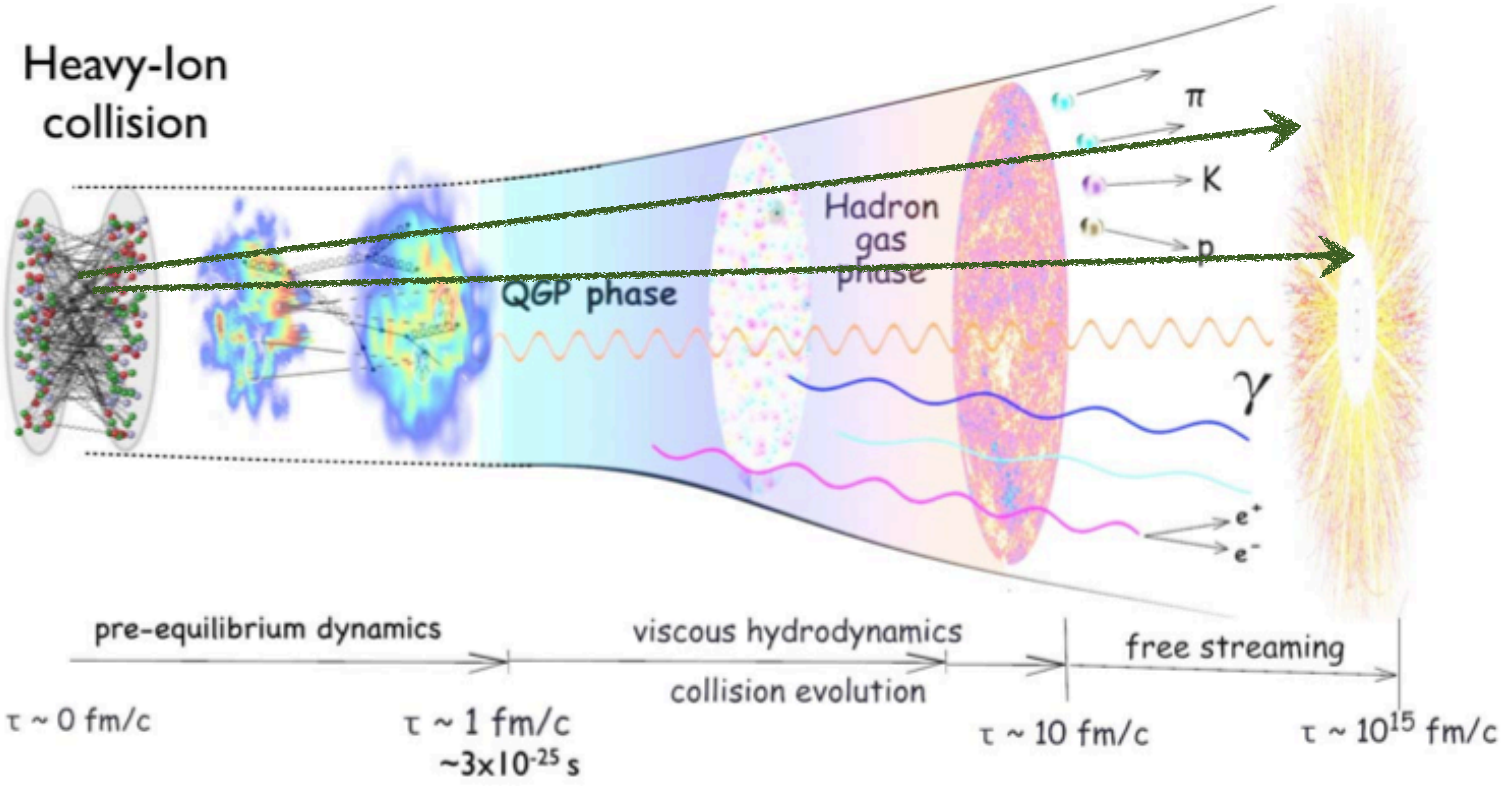

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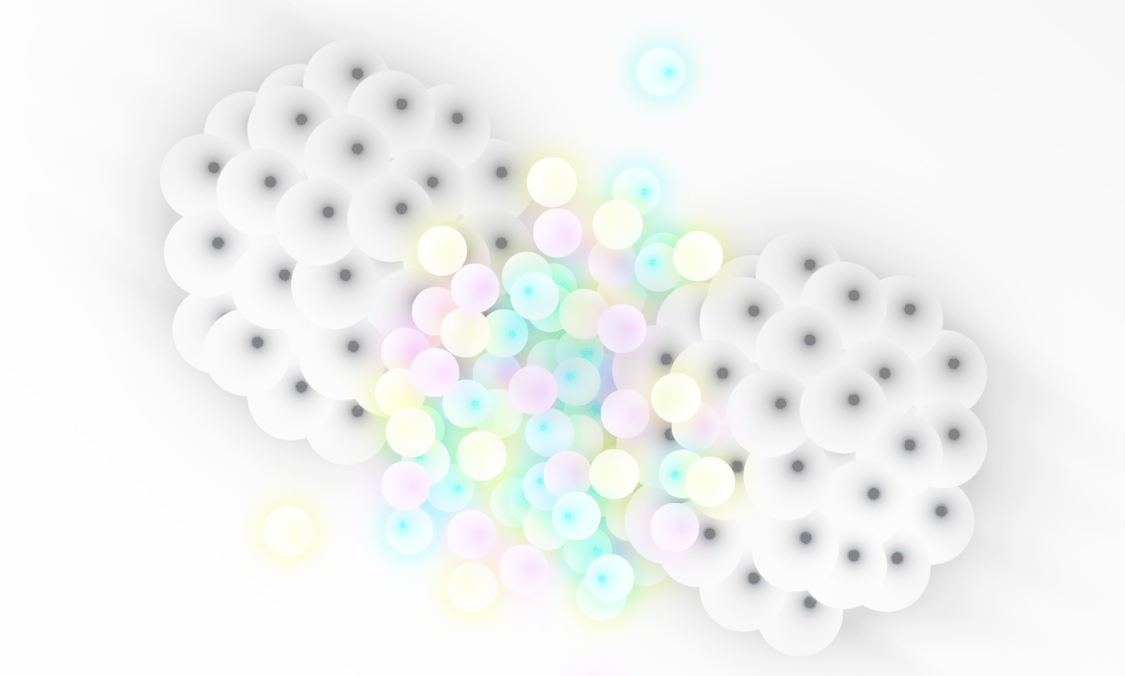

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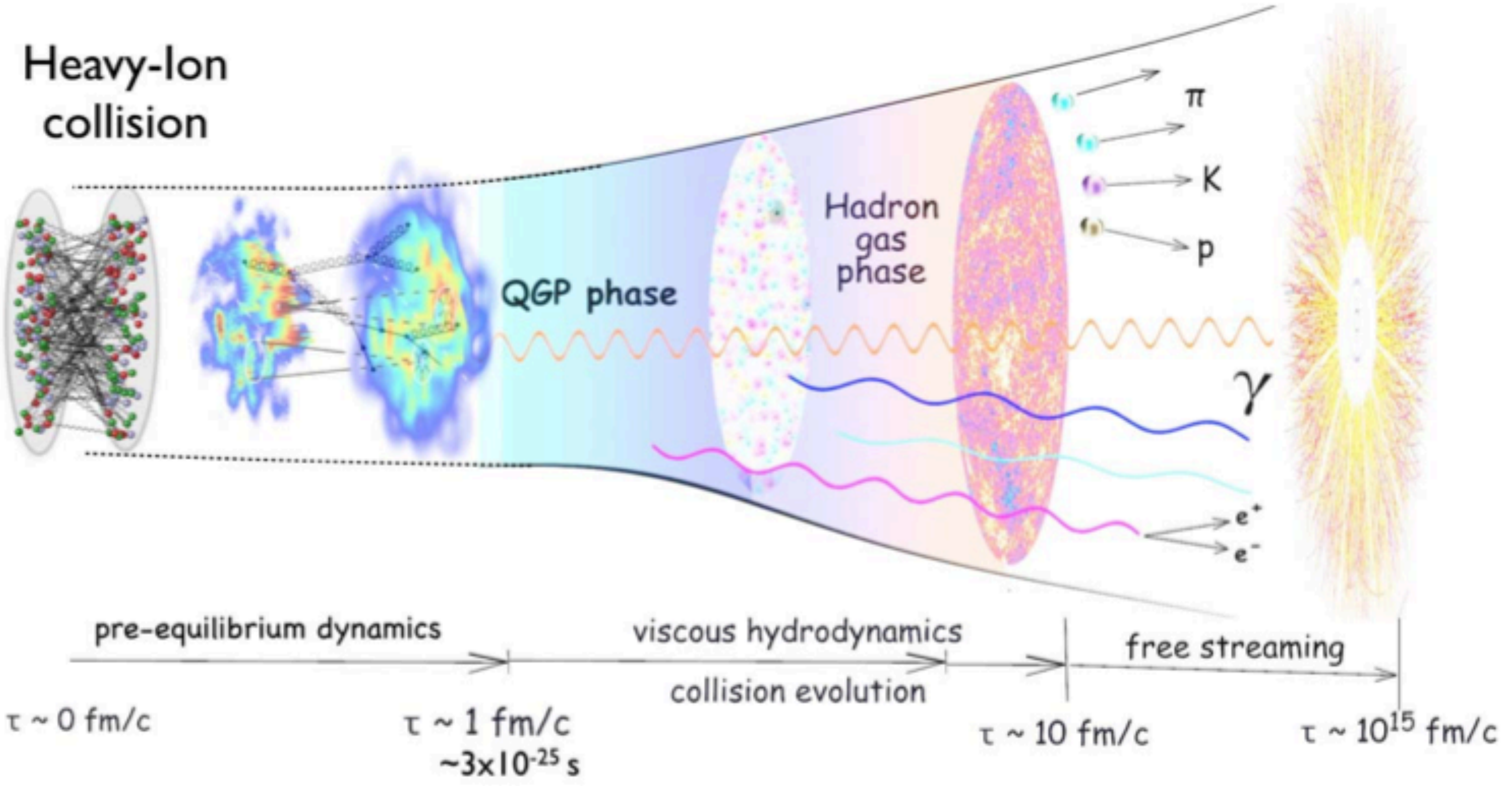
Common difficulty: QGP is dynamically evolving system

All observables require interpretation in the framework of transport models



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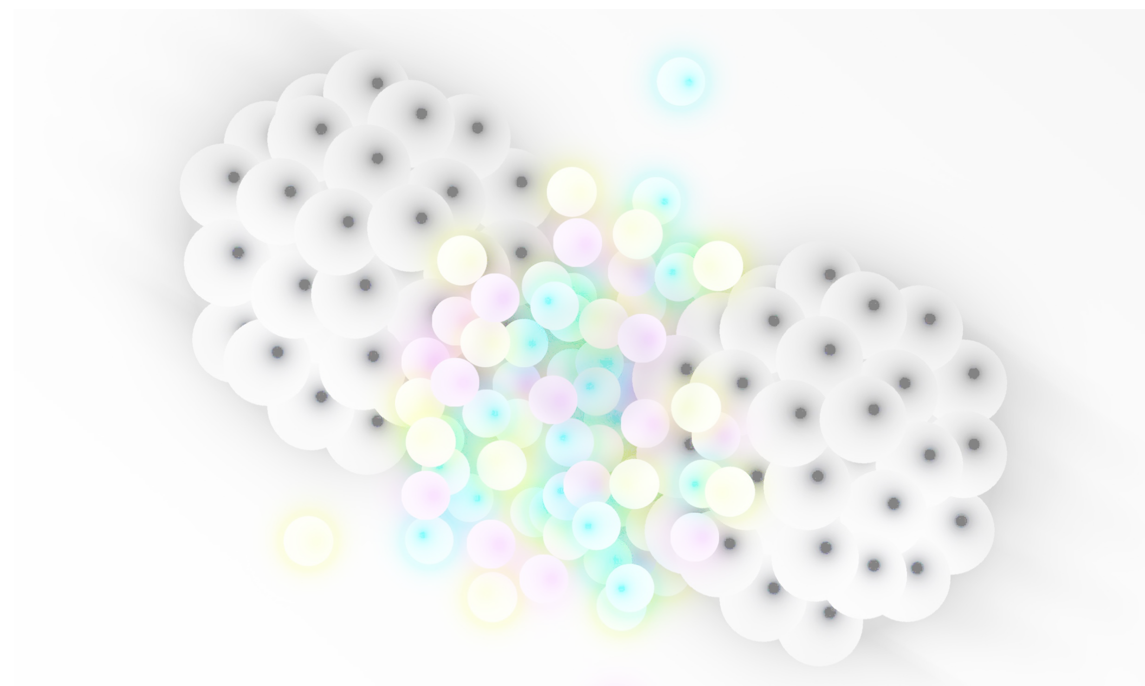

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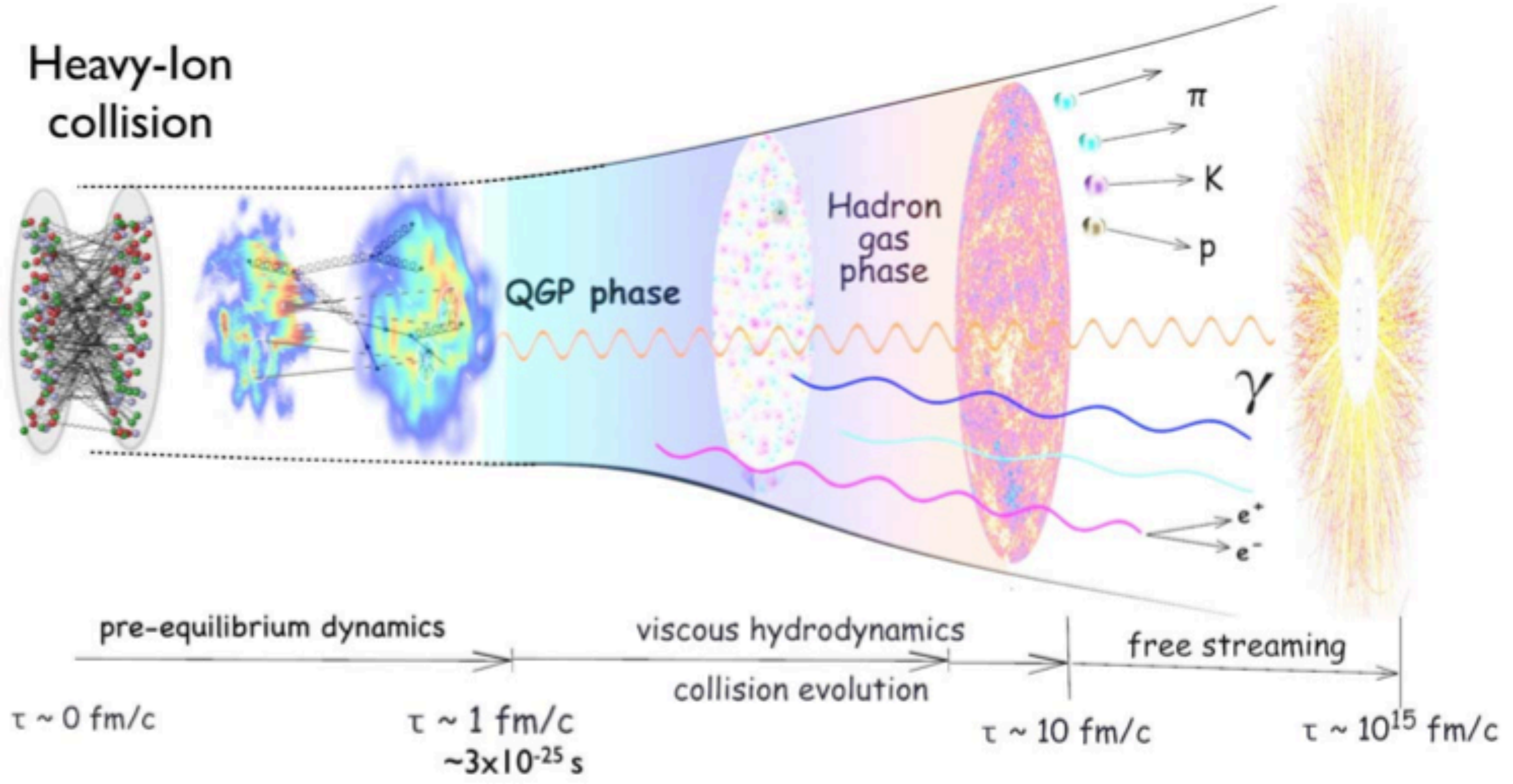
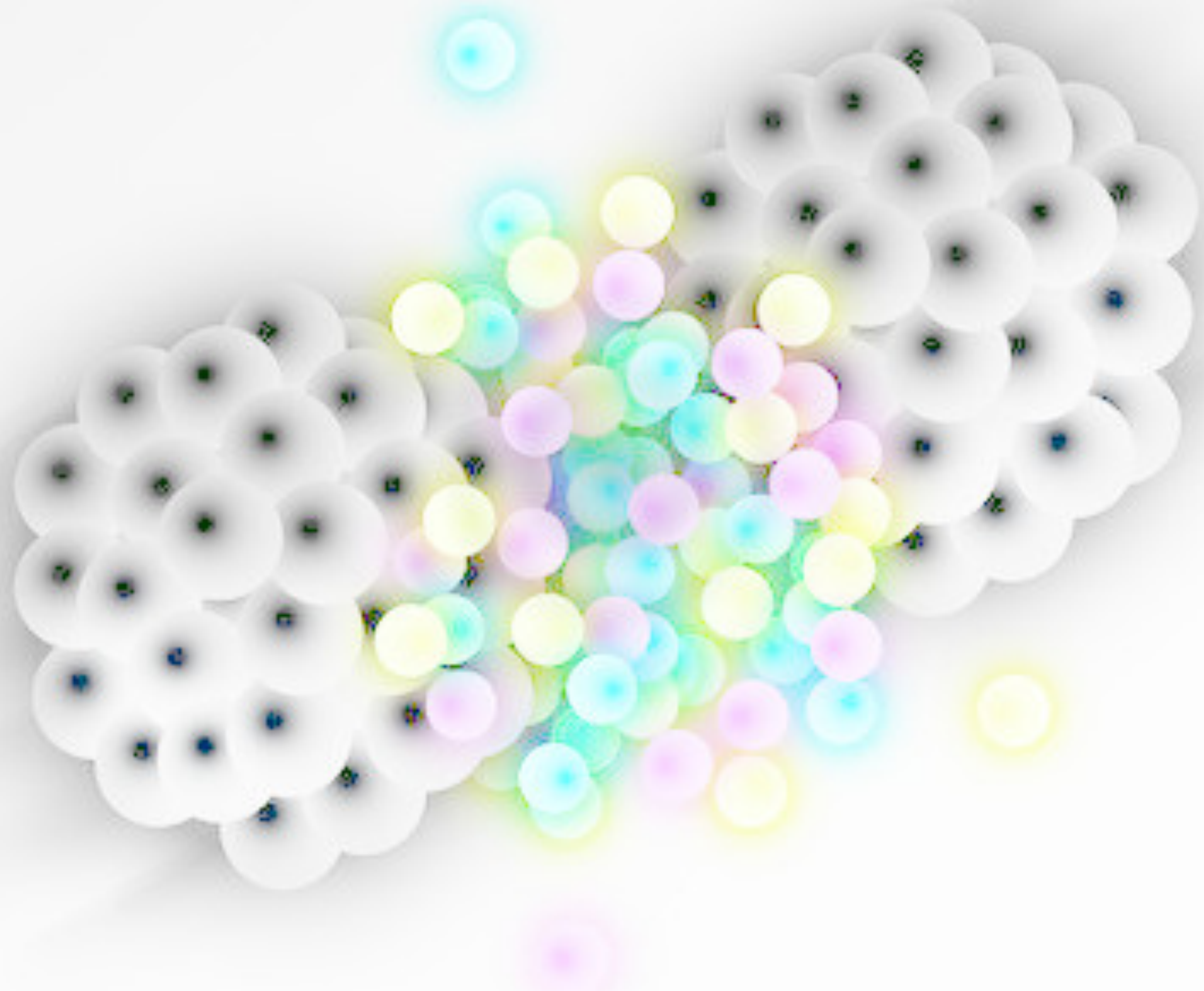
Heavy-ion collision characterisation:

**A multi-scale problem!**

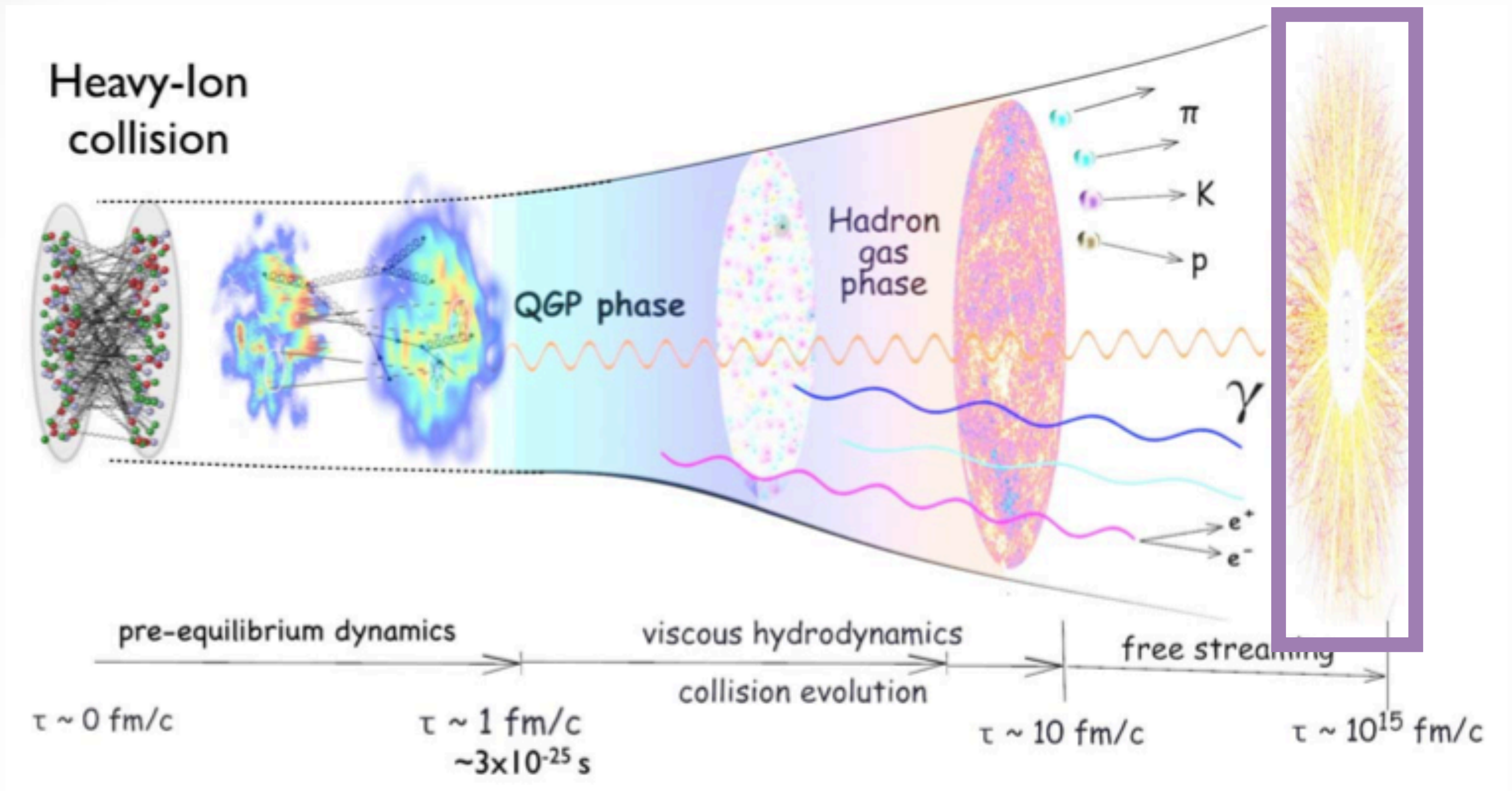


# What to we know about the Quark-Gluon Plasma?



**Soft probes**

**(Bulk of the collision
Low momentum particles)**



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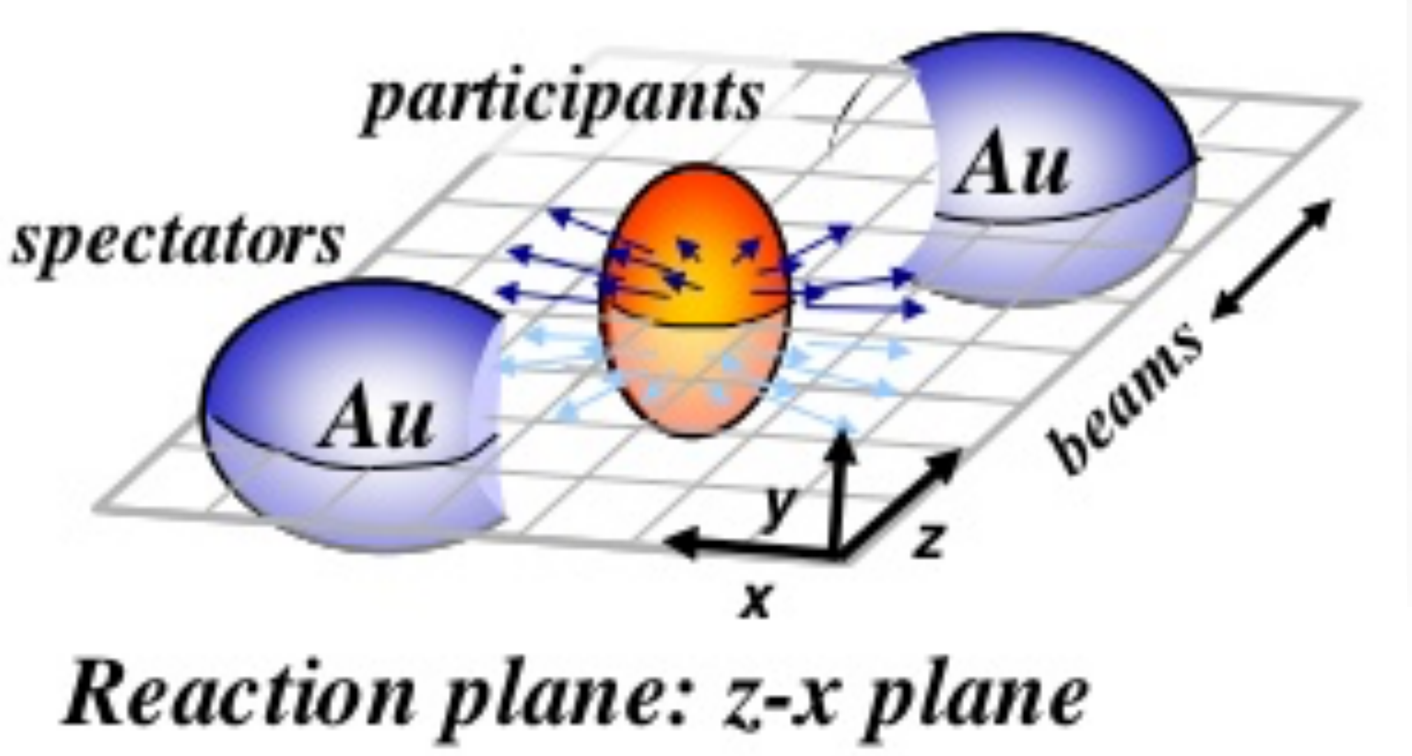
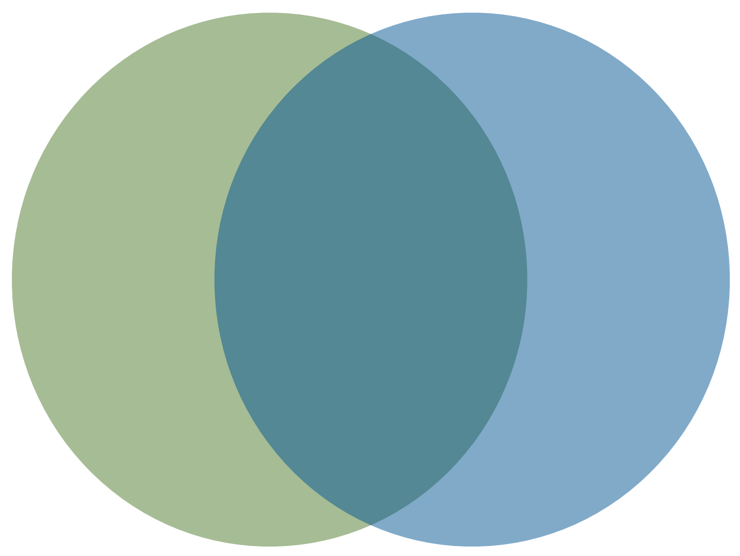



- Try different centralities and check response of the system to initial spatial anisotropy:



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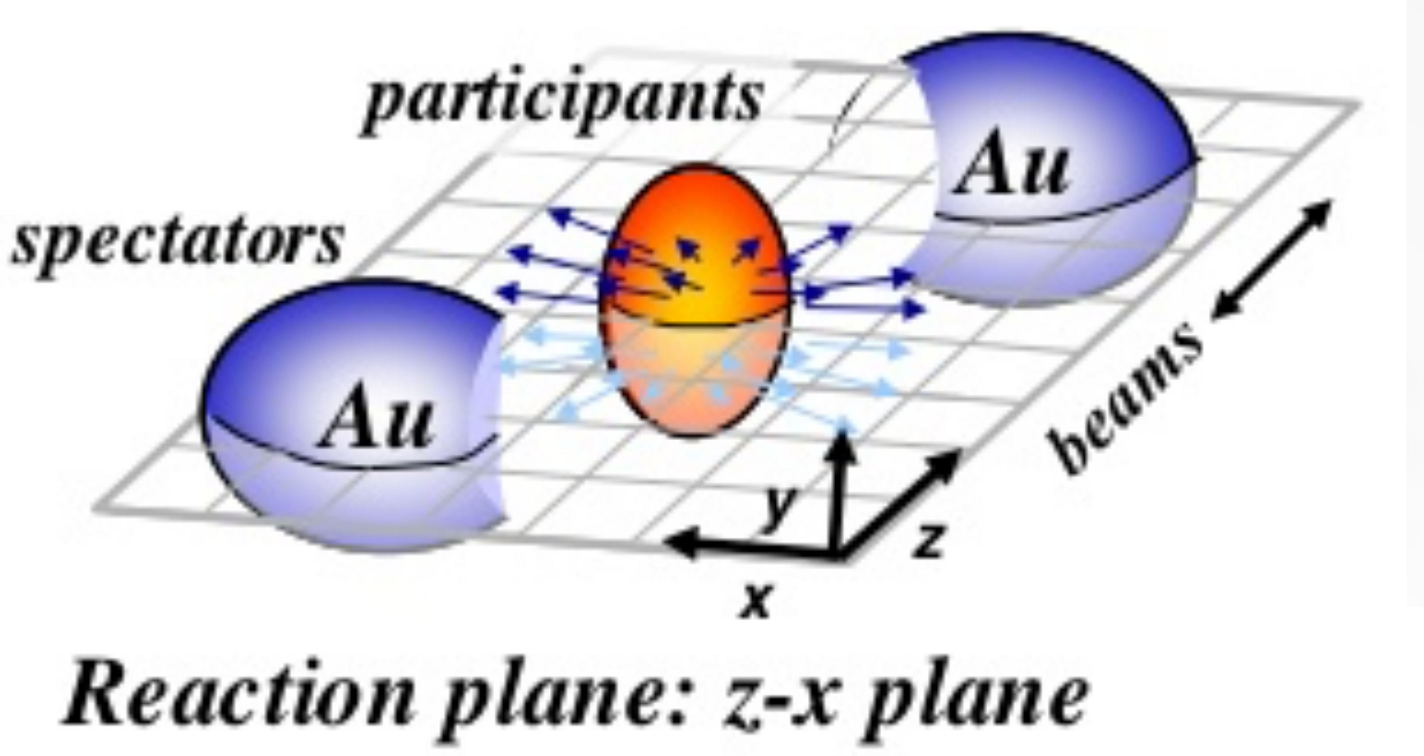


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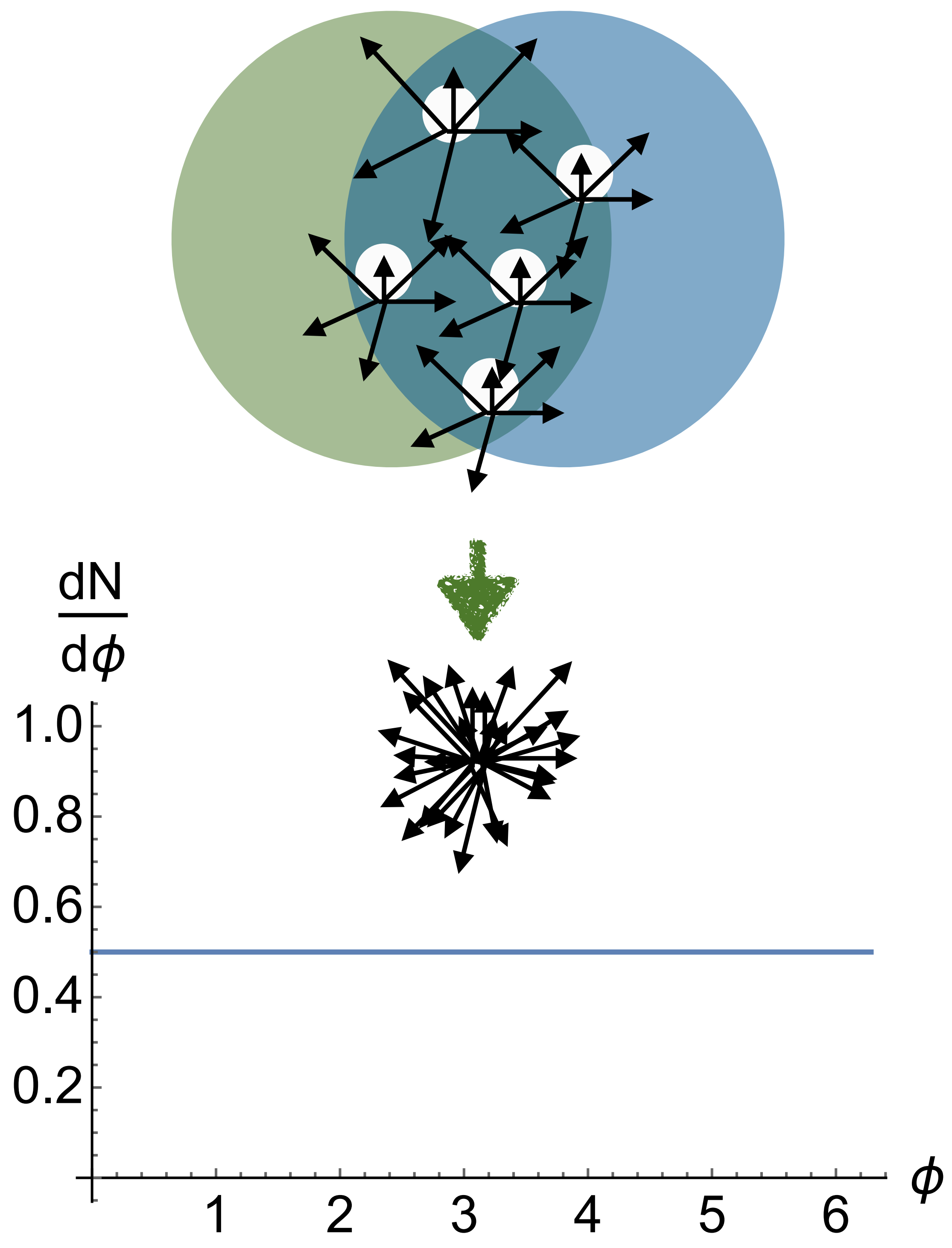
**Superposition of multiple pp collisions**



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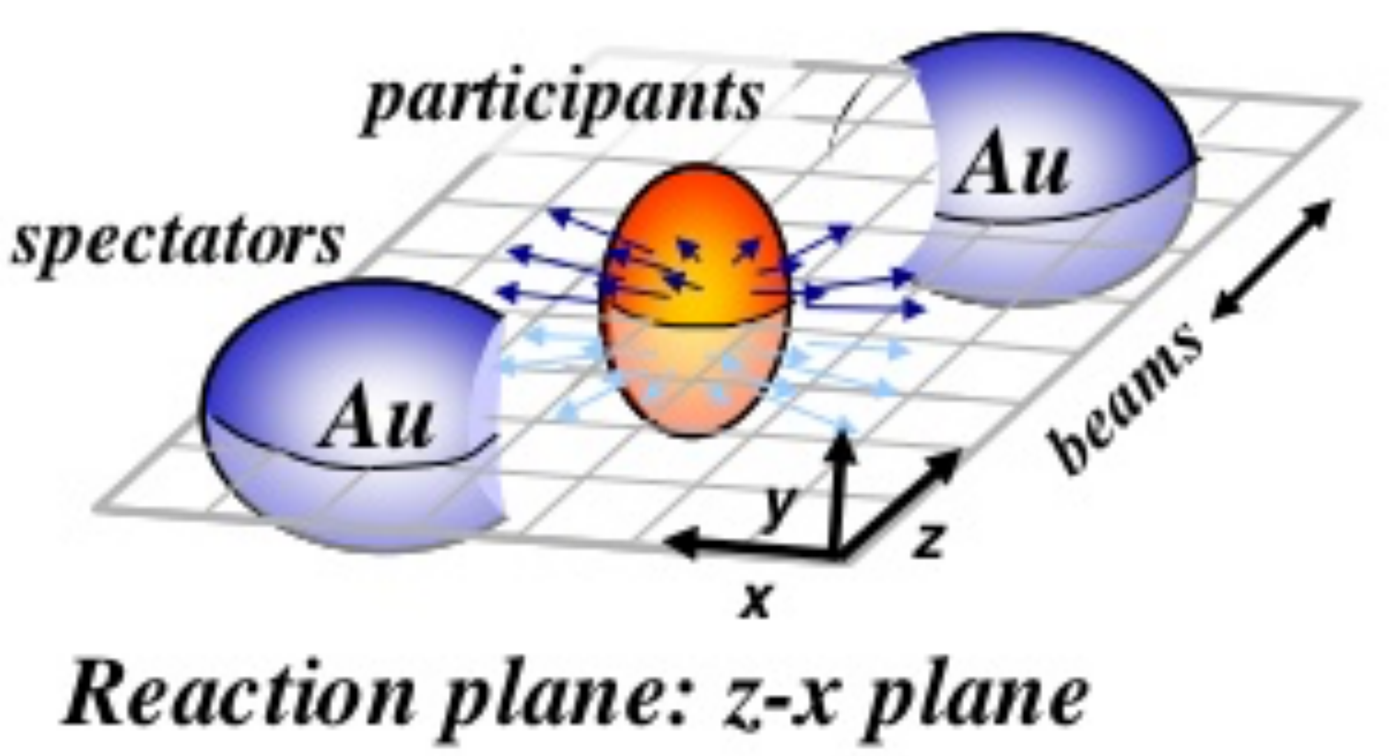


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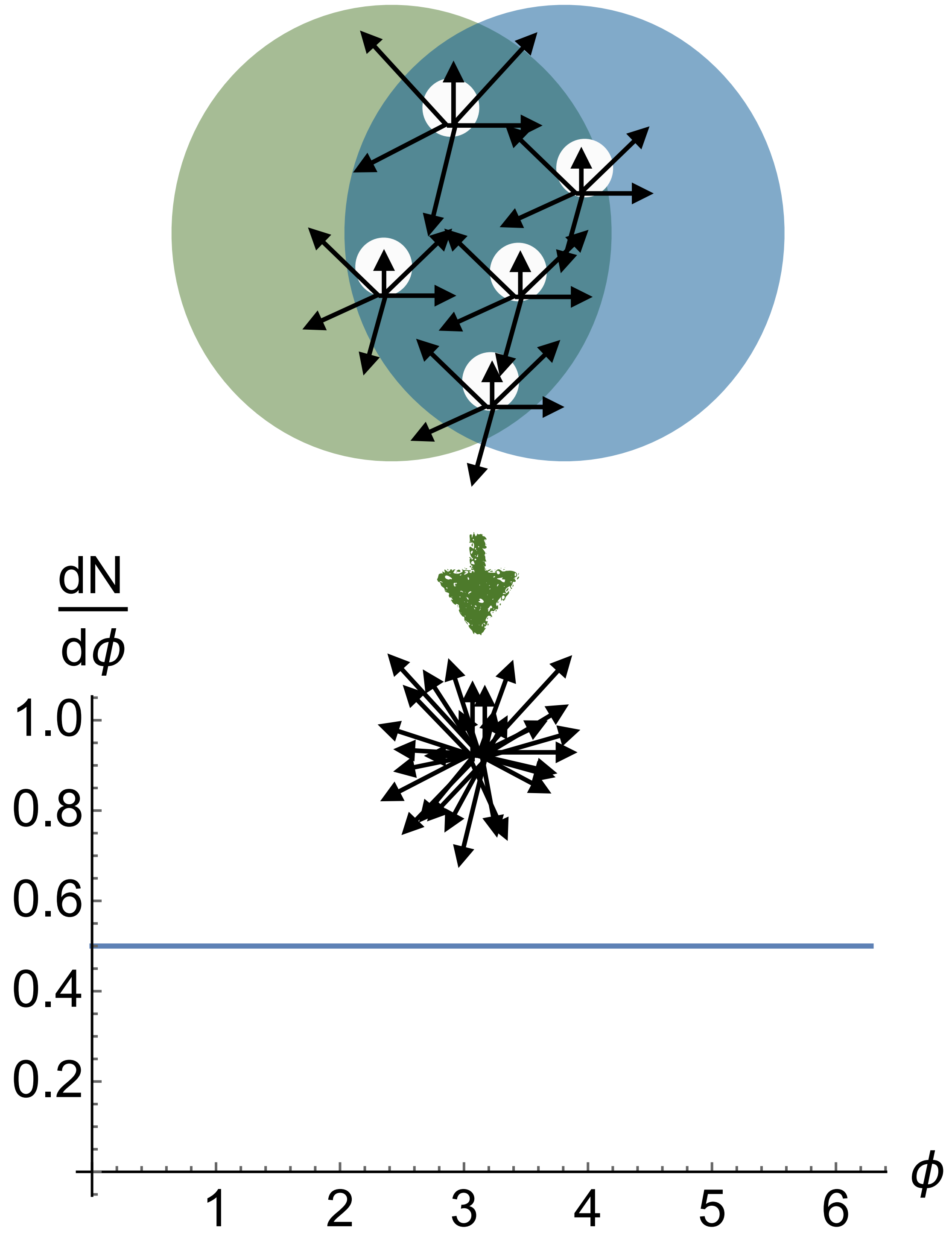
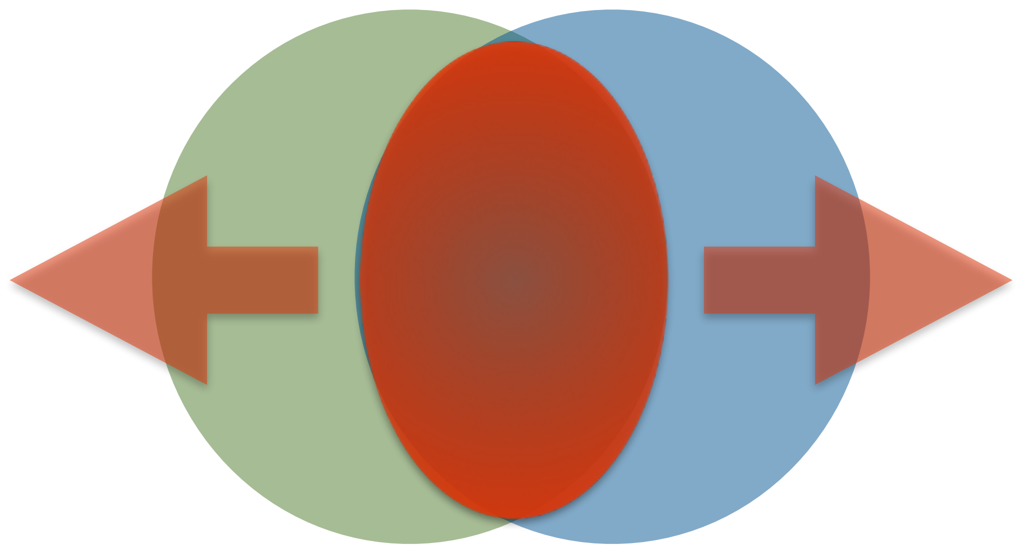
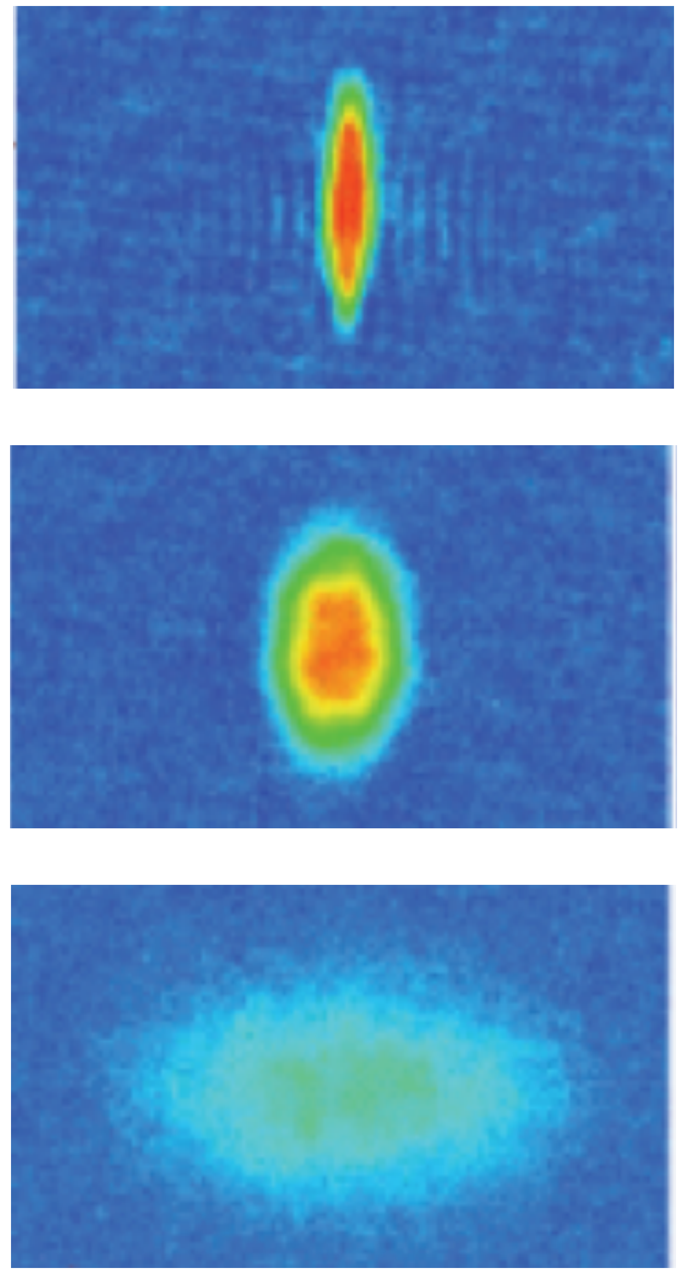



**Collective bulk behaviour**



**Pressure driven expansion:**



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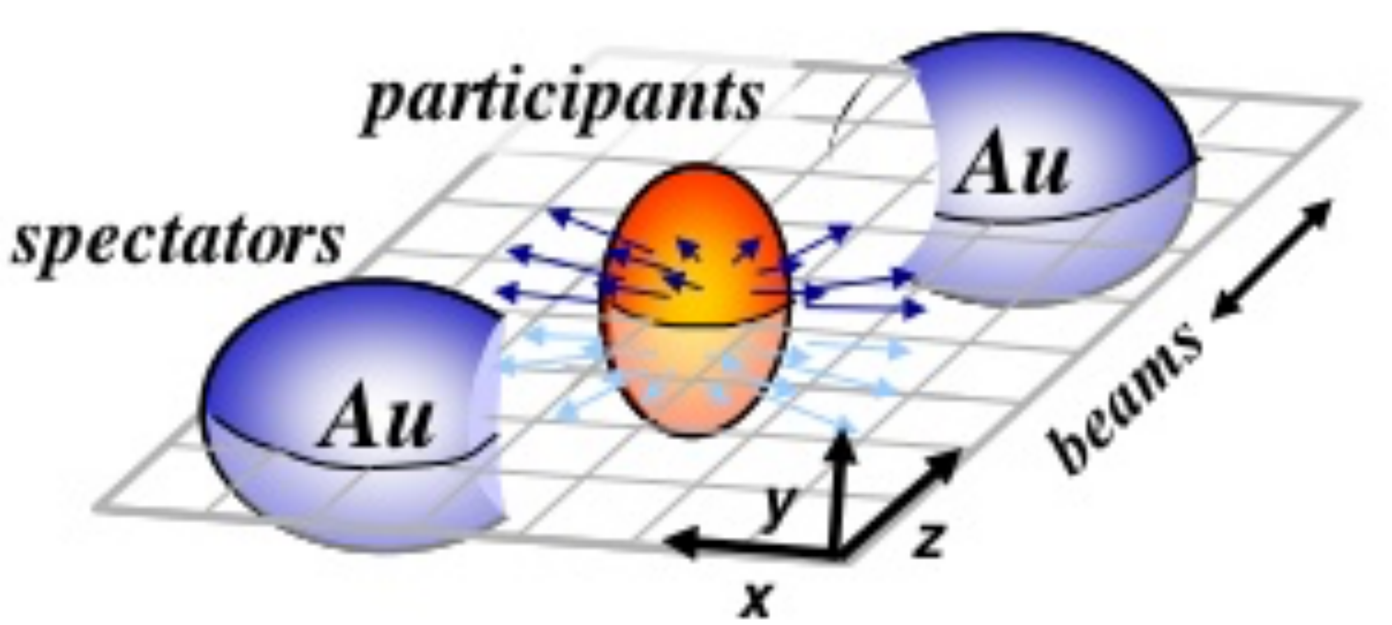


Reaction plane: z-x plane

- Try different centralities and check response of the system to initial spatial anisotropy:

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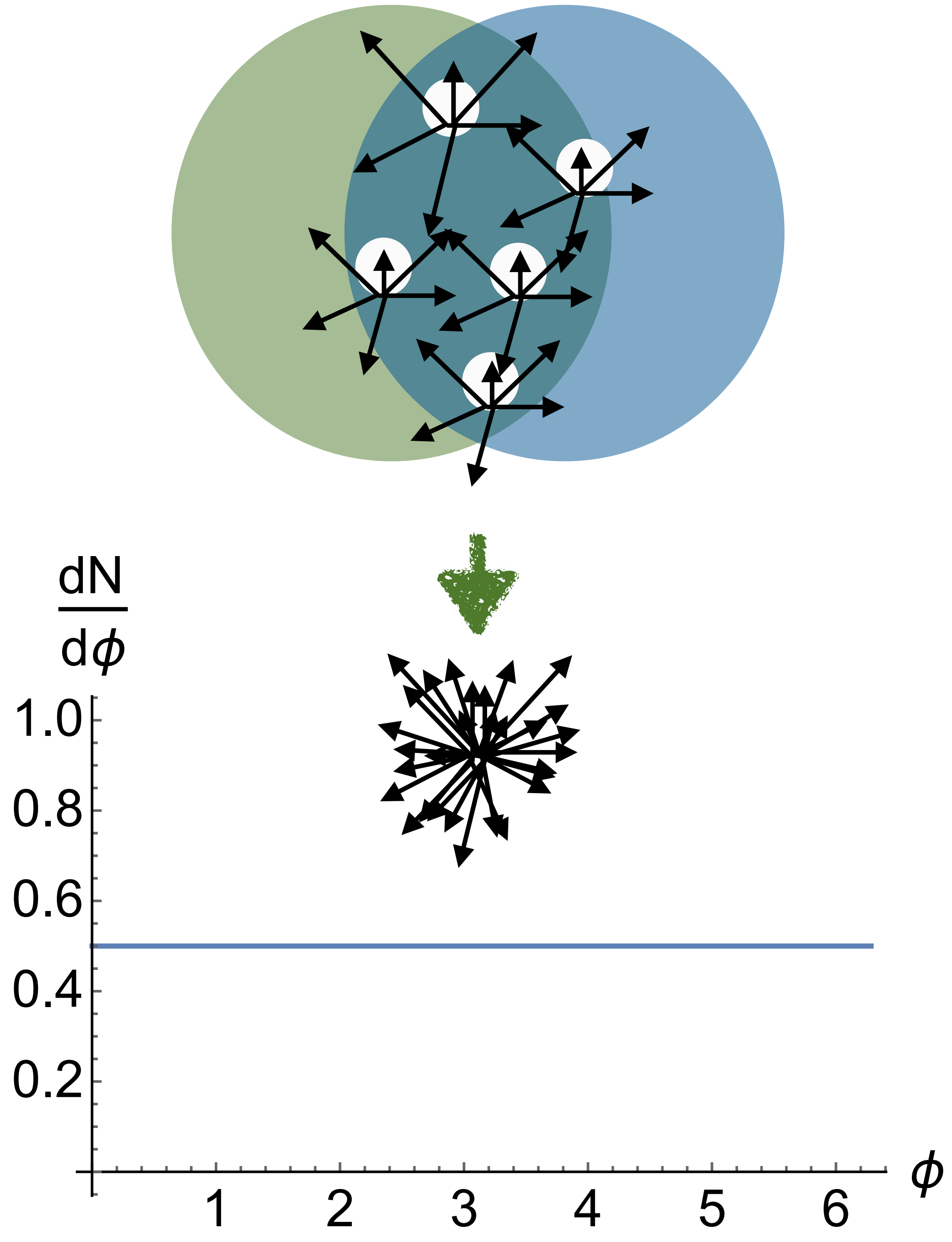


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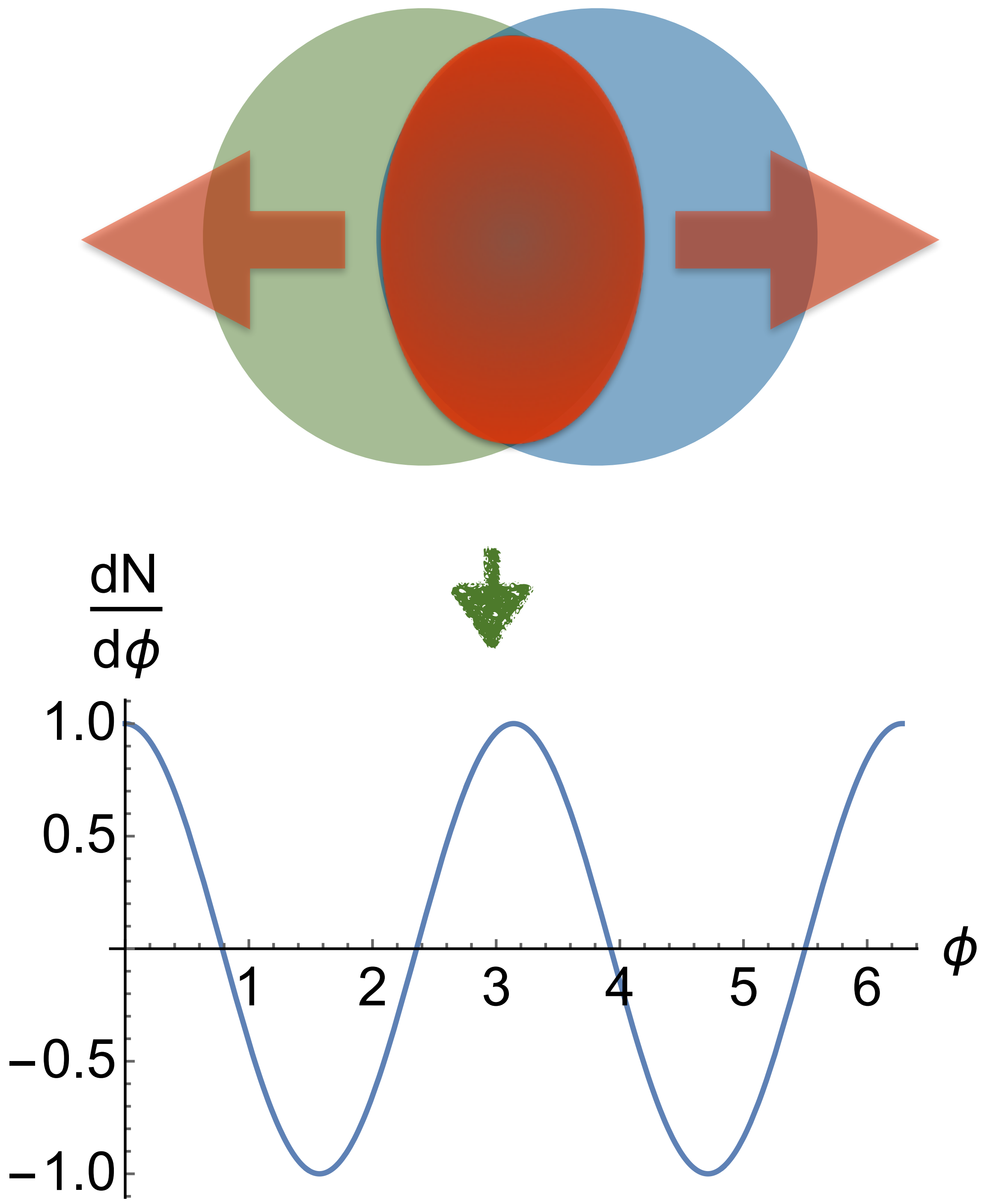


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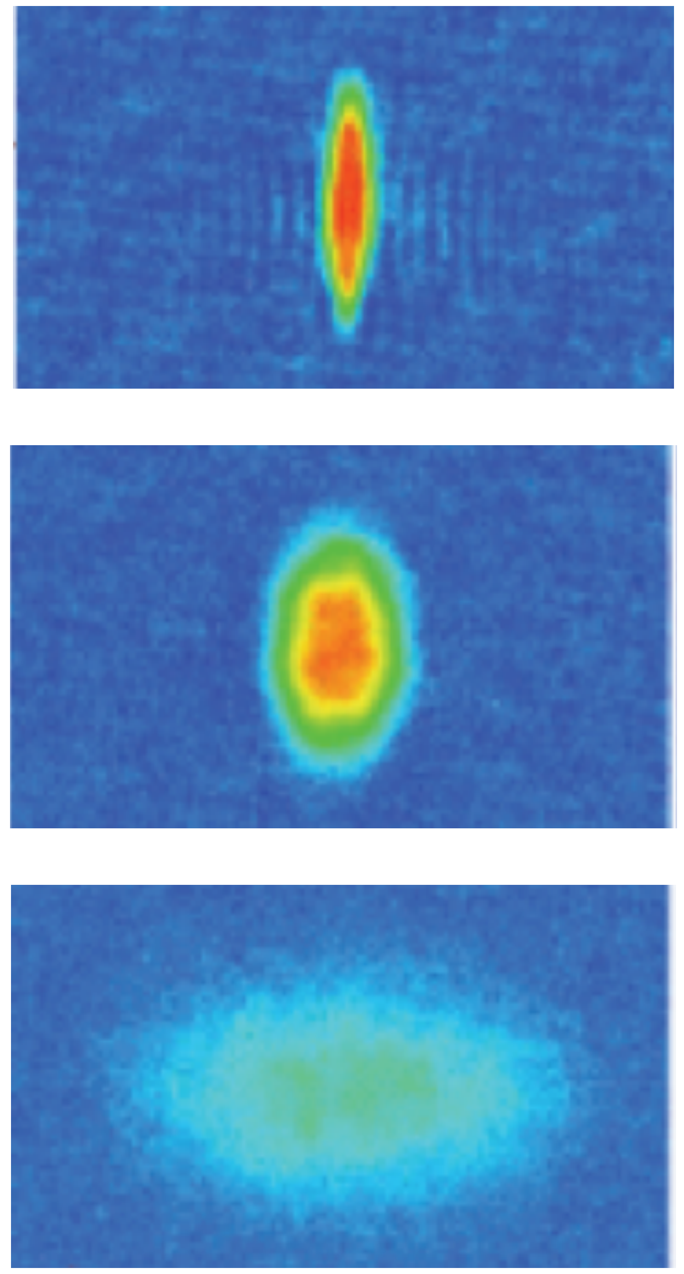

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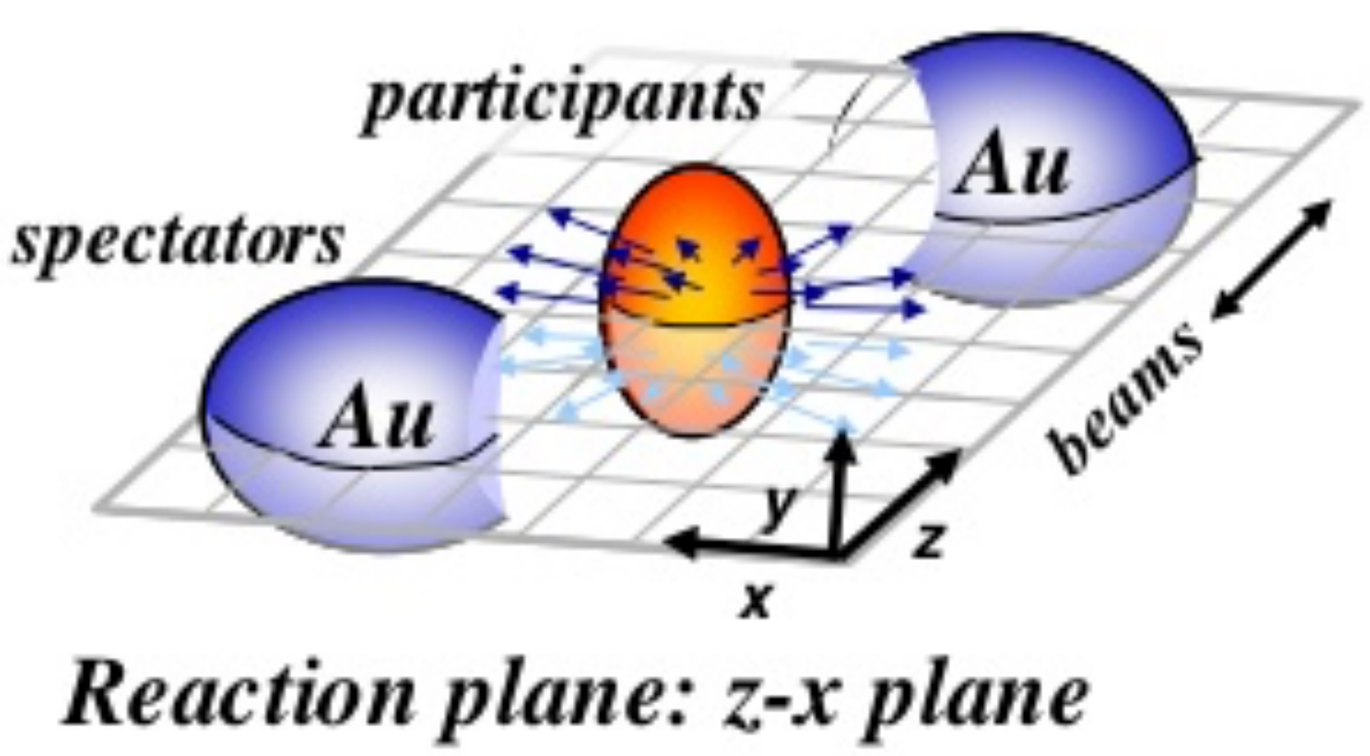


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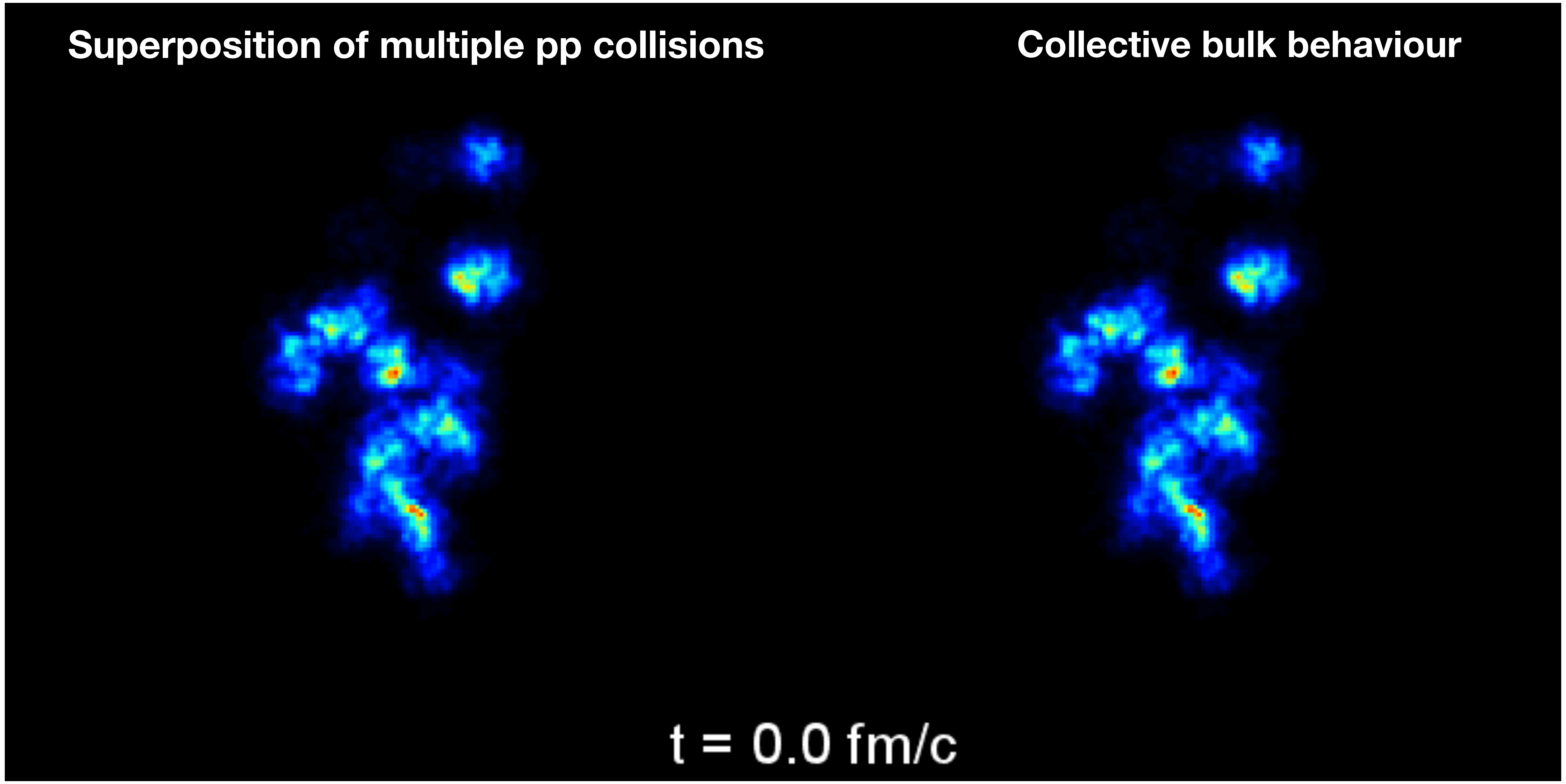

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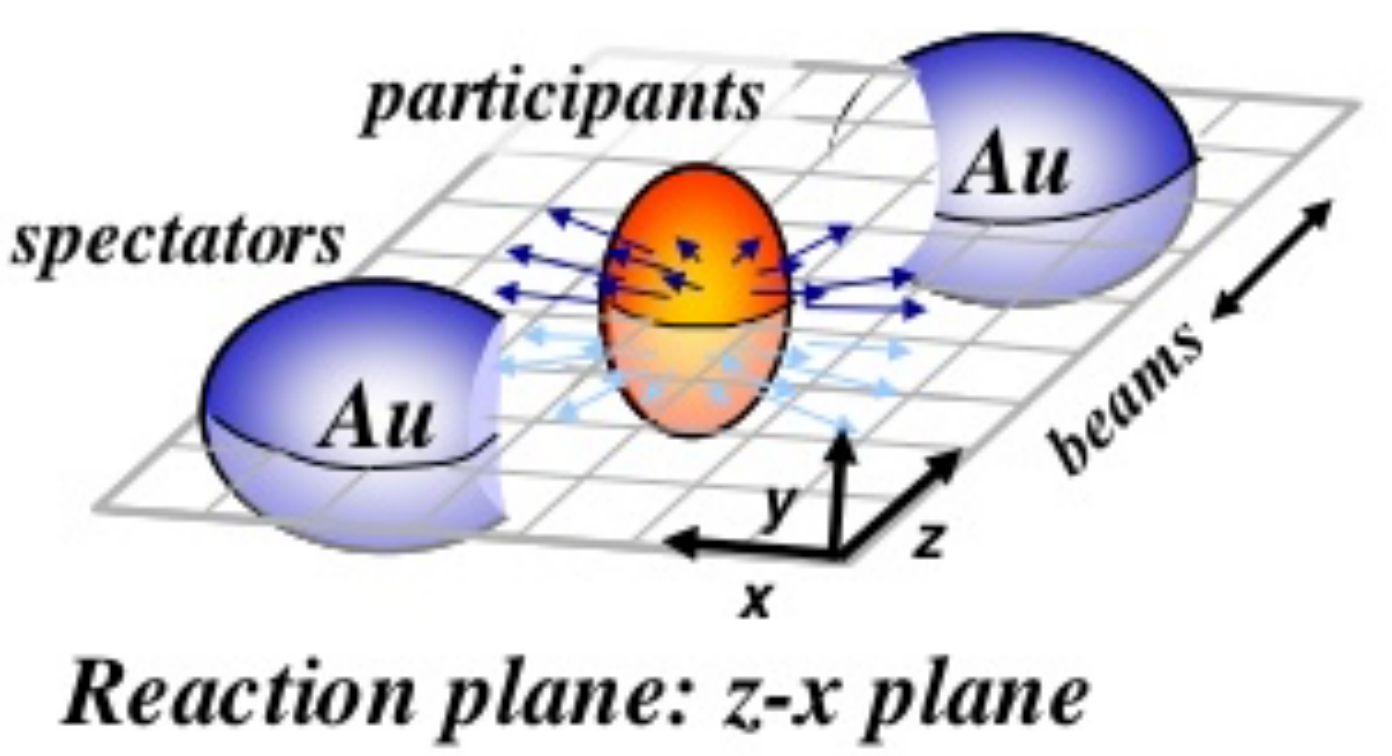


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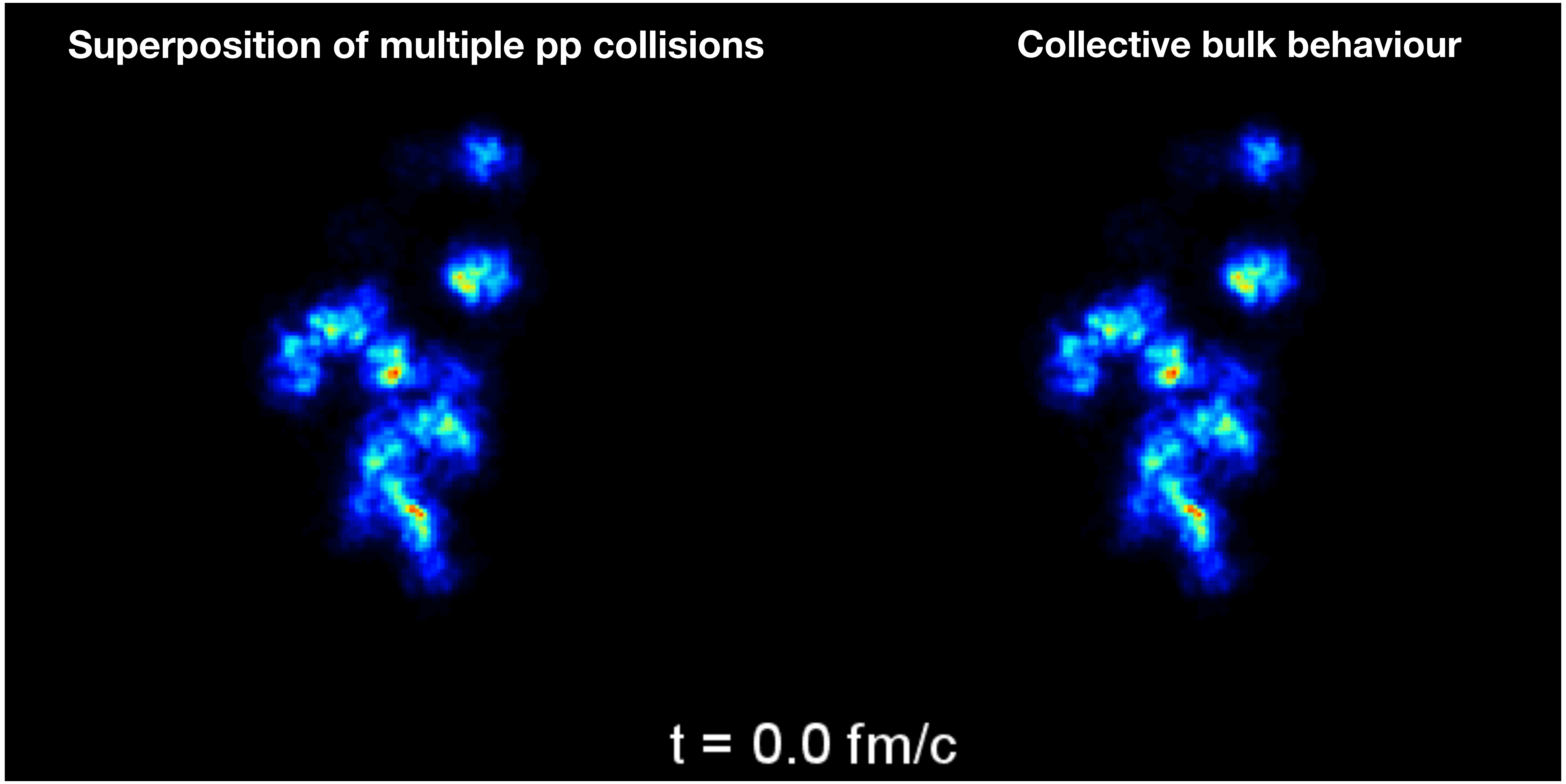
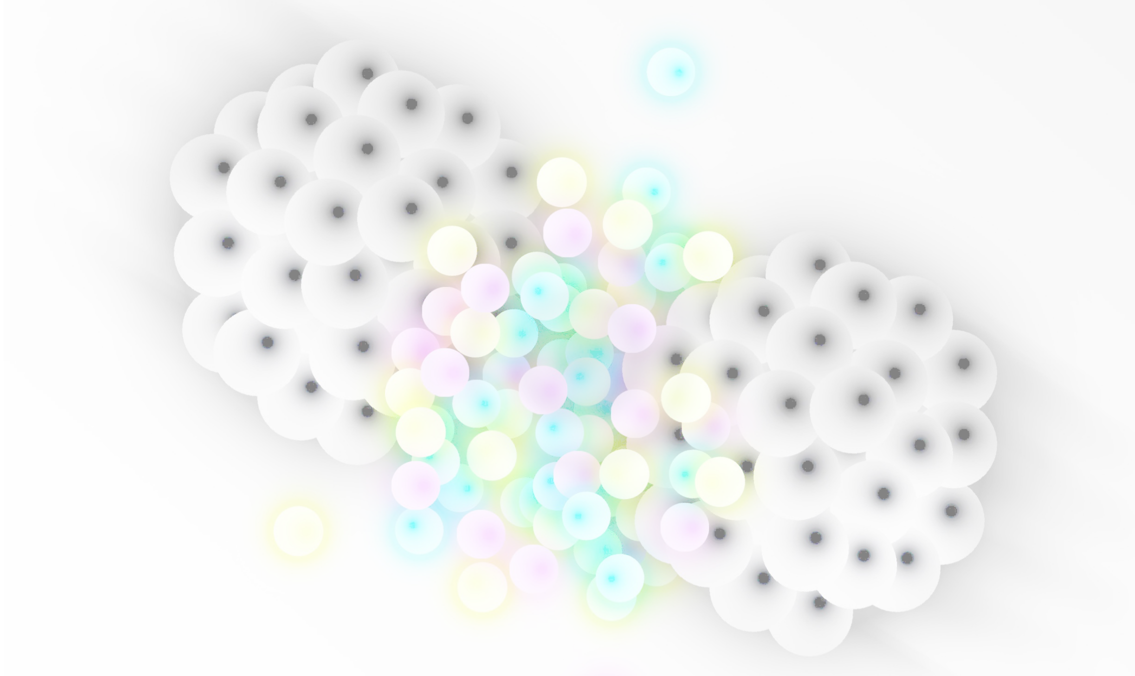


# Spatial anisotropies



- Quantification through Fourier transformation of the particles angular distribution:

$$\frac{dN}{d\phi} = \frac{N}{2\pi}\left(1 + 2\sum_{n=1}^{\infty} \nu_n \cos\left(n(\phi - \Psi_n)\right)\right)$$

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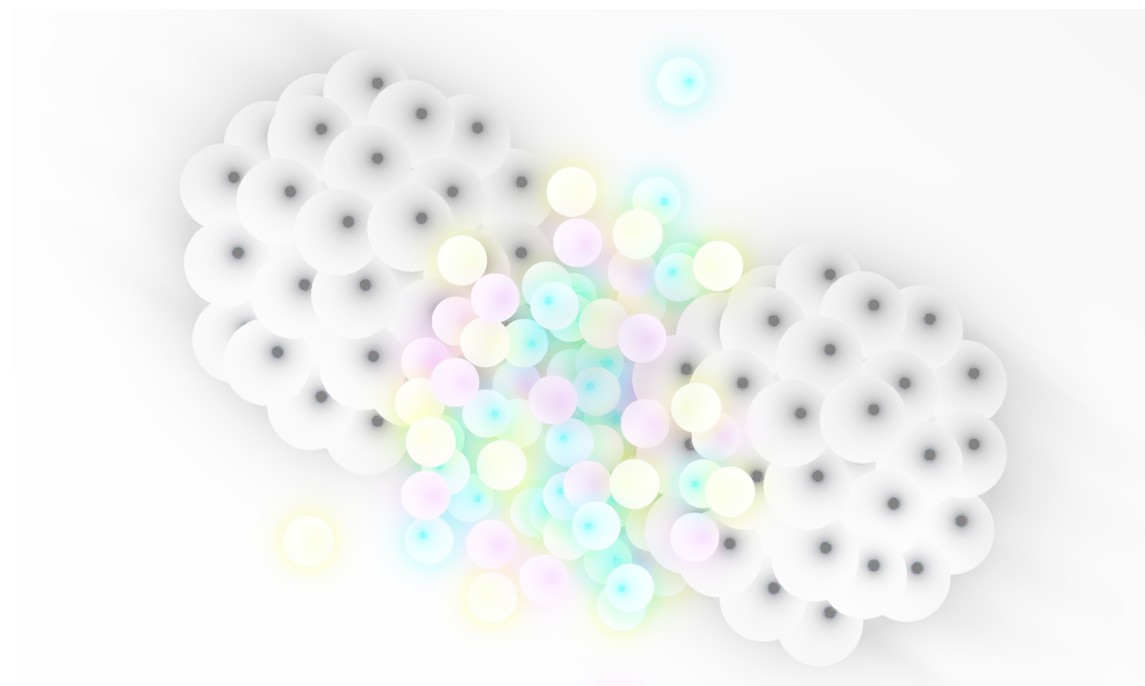

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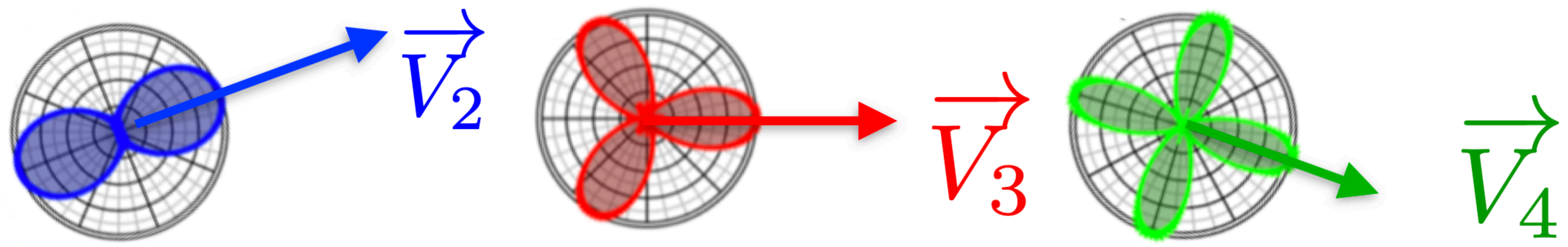
**Reaction plane angle**
**(where the nth harmonic component has its maximum multiplicity)**



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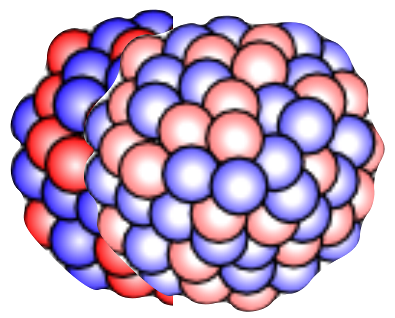
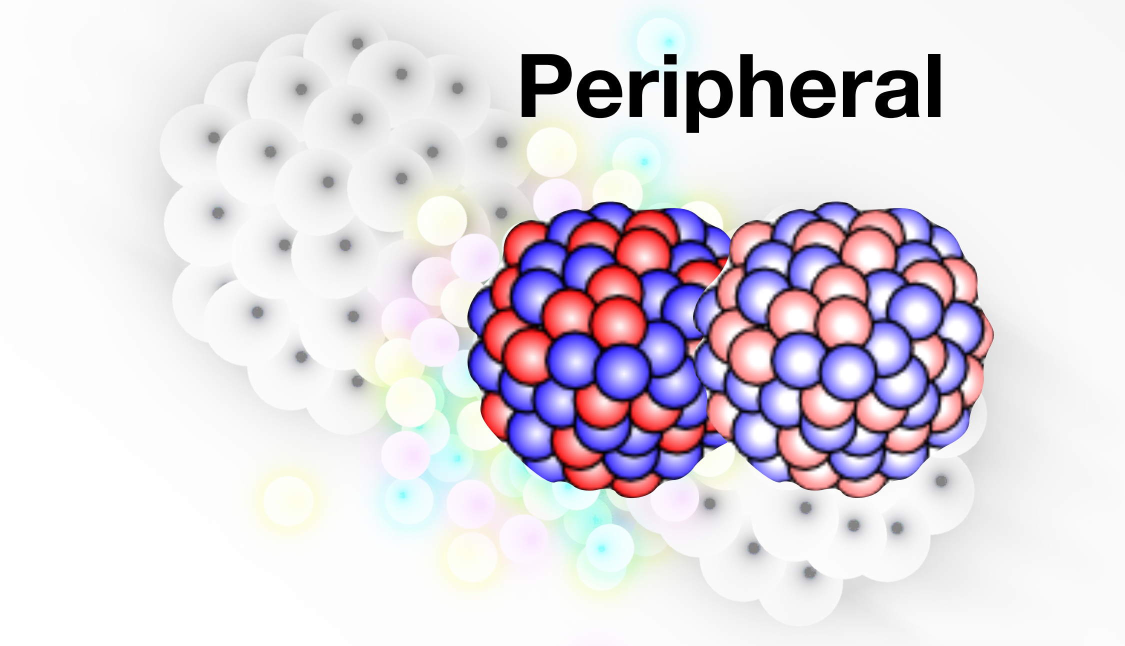
Central



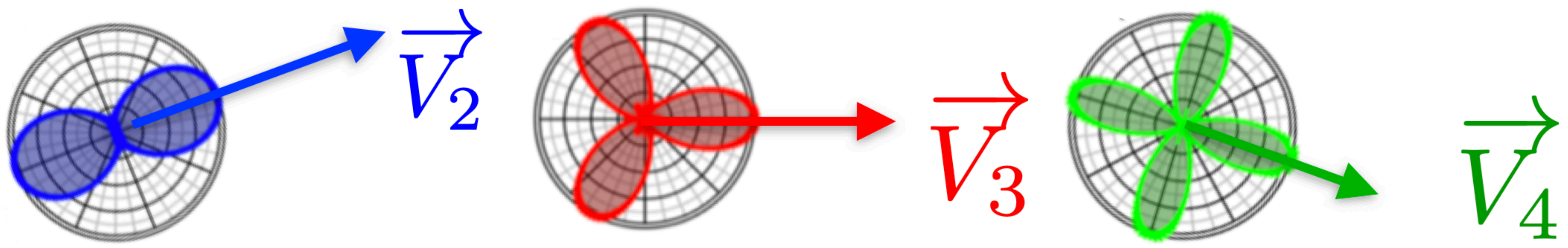
Peripheral



- Quantification through Fourier transformation of the particles angular distribution:

$$\frac{dN}{d\phi} = \frac{N}{2\pi}\left(1 + 2\sum_{n=1}^{\infty} \nu_n \cos\left(n(\phi - \Psi_n)\right)\right)$$

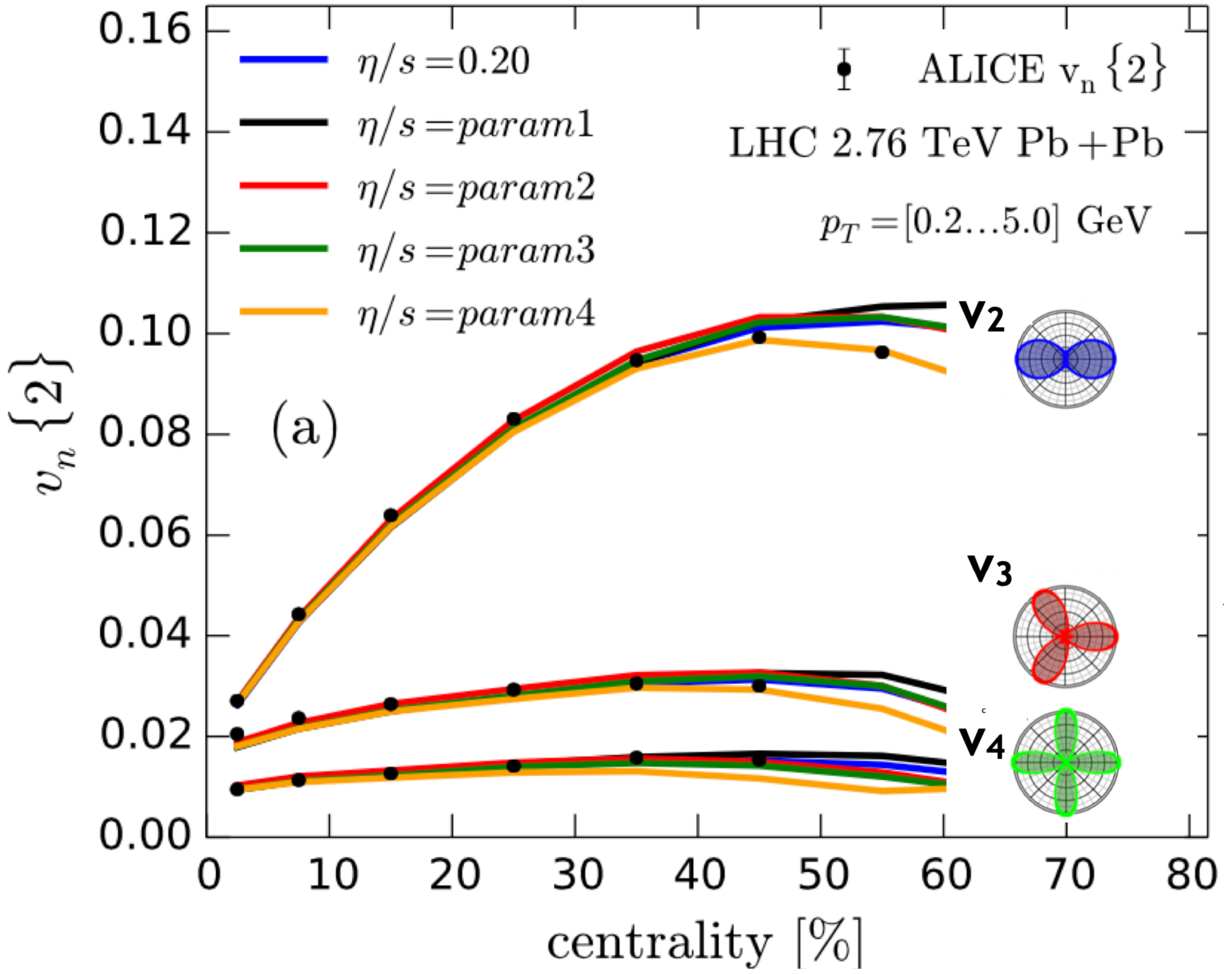
**Reaction plane angle (where the nth harmonic component has its maximum multiplicity)**



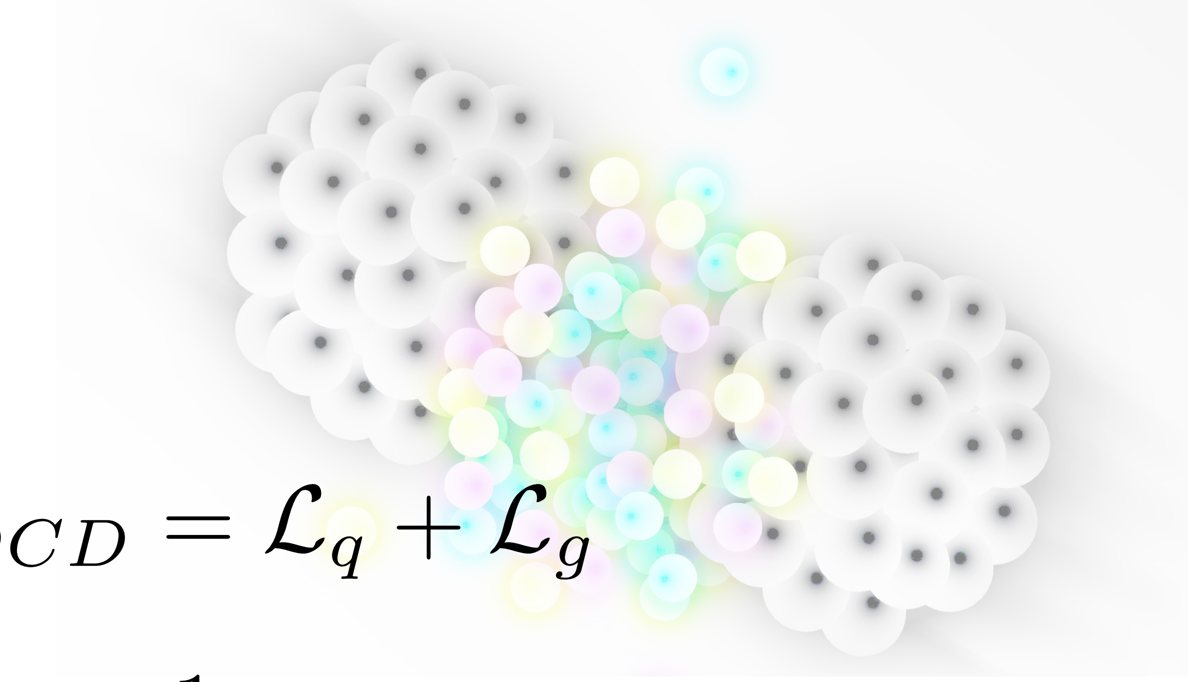

**From charged multiplicity, extract elliptic ($v_2$), triangular ($v_3$),… flow coefficients**

$$\nu_2 = \langle \cos 2(\phi - \Psi_2) \rangle$$

…



# Hydrodynamics



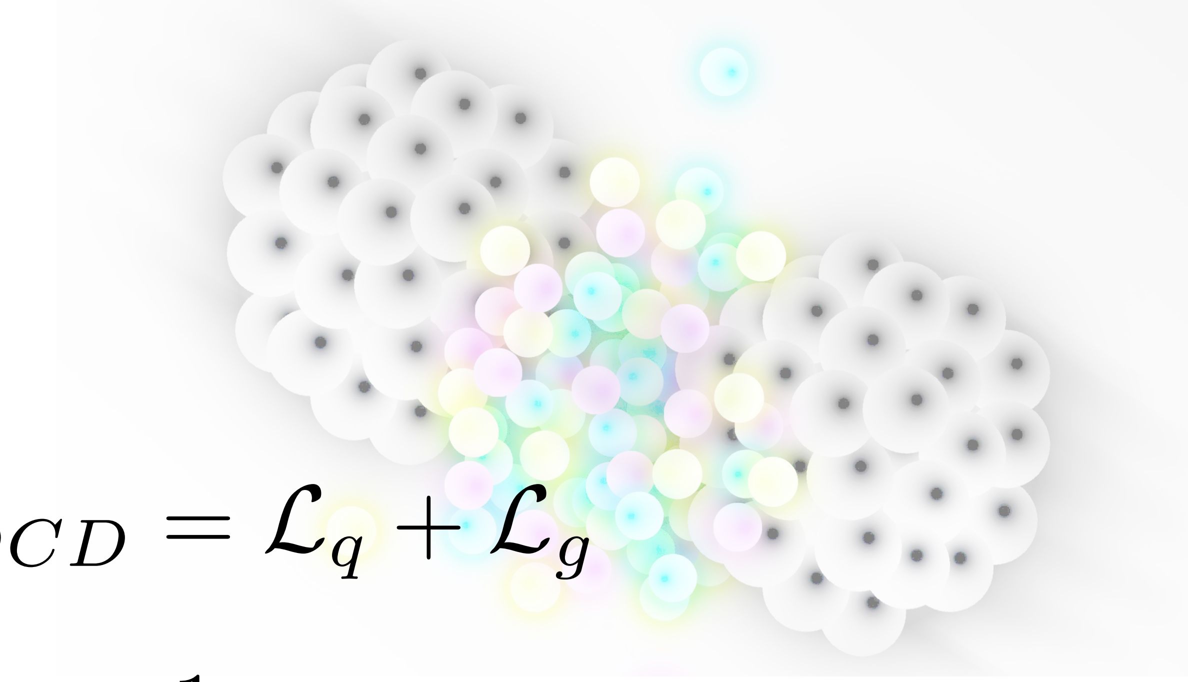
$$\mathcal{L}_{QCD} = \mathcal{L}_q + \mathcal{L}_g$$

- Why hydrodynamics?
  - Complicated to withdraw information from QCD Lagrangian…

$$\mathcal{L}_g = -\frac{1}{4}F_A^{\mu\nu}F^{A\mu\nu}$$

$$\mathcal{L}_q = \bar{\psi}_a(i\gamma^\mu\partial_\mu\delta_{ab} - g_s\gamma^\mu t_{ab}^C A_\mu^C - m)\psi_b$$

# Hydrodynamics



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  - Input includes the Equation-of-State (EoS)
    - Provided by, e.g., Lattice QCD

$$P = P(e, n)$$

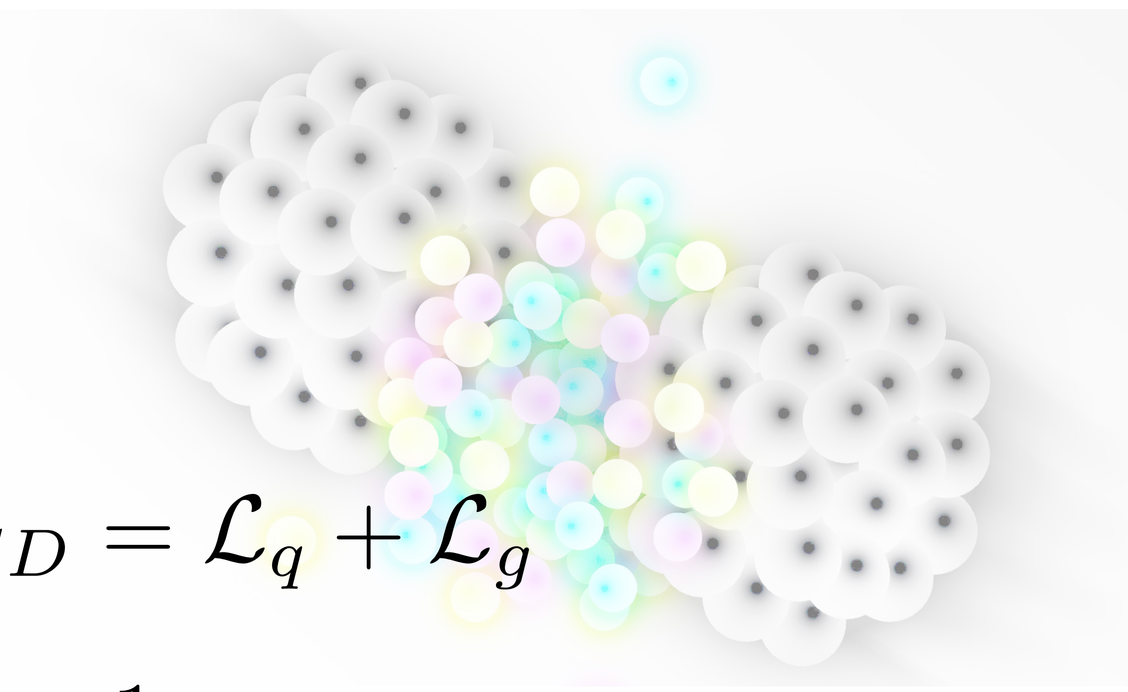
**Energy-momentum conservation:**

$$\partial_\mu T^{\mu\nu} = 0$$

**Current conservation:**

$$\partial_\mu N^\mu = 0$$

# Hydrodynamics



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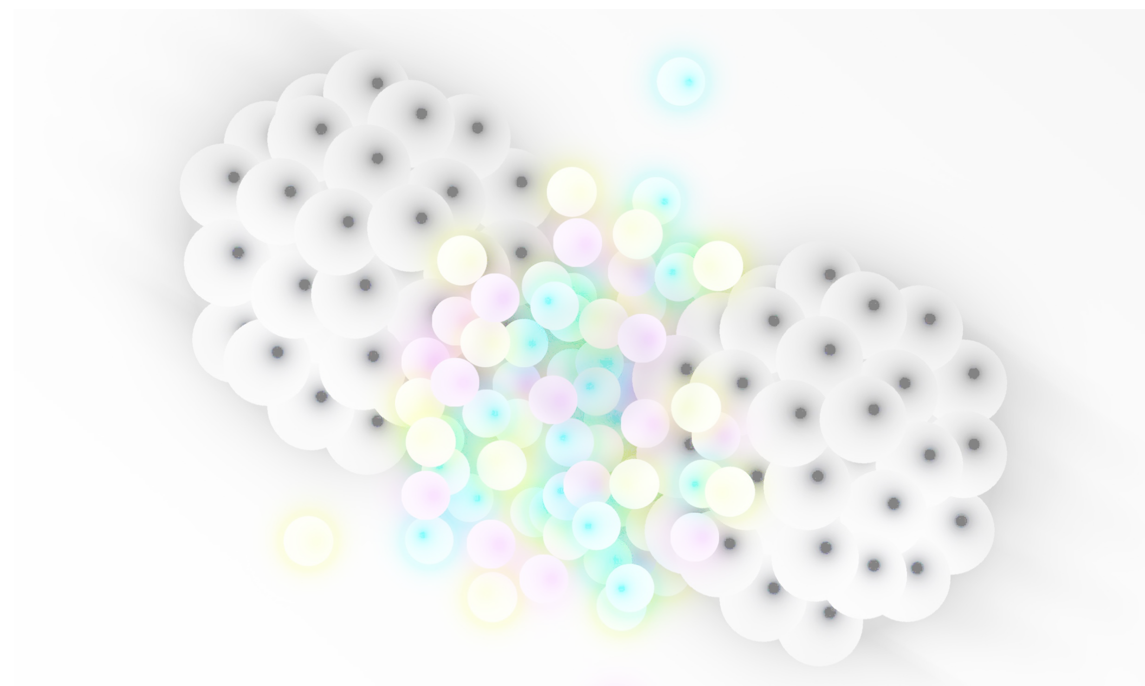
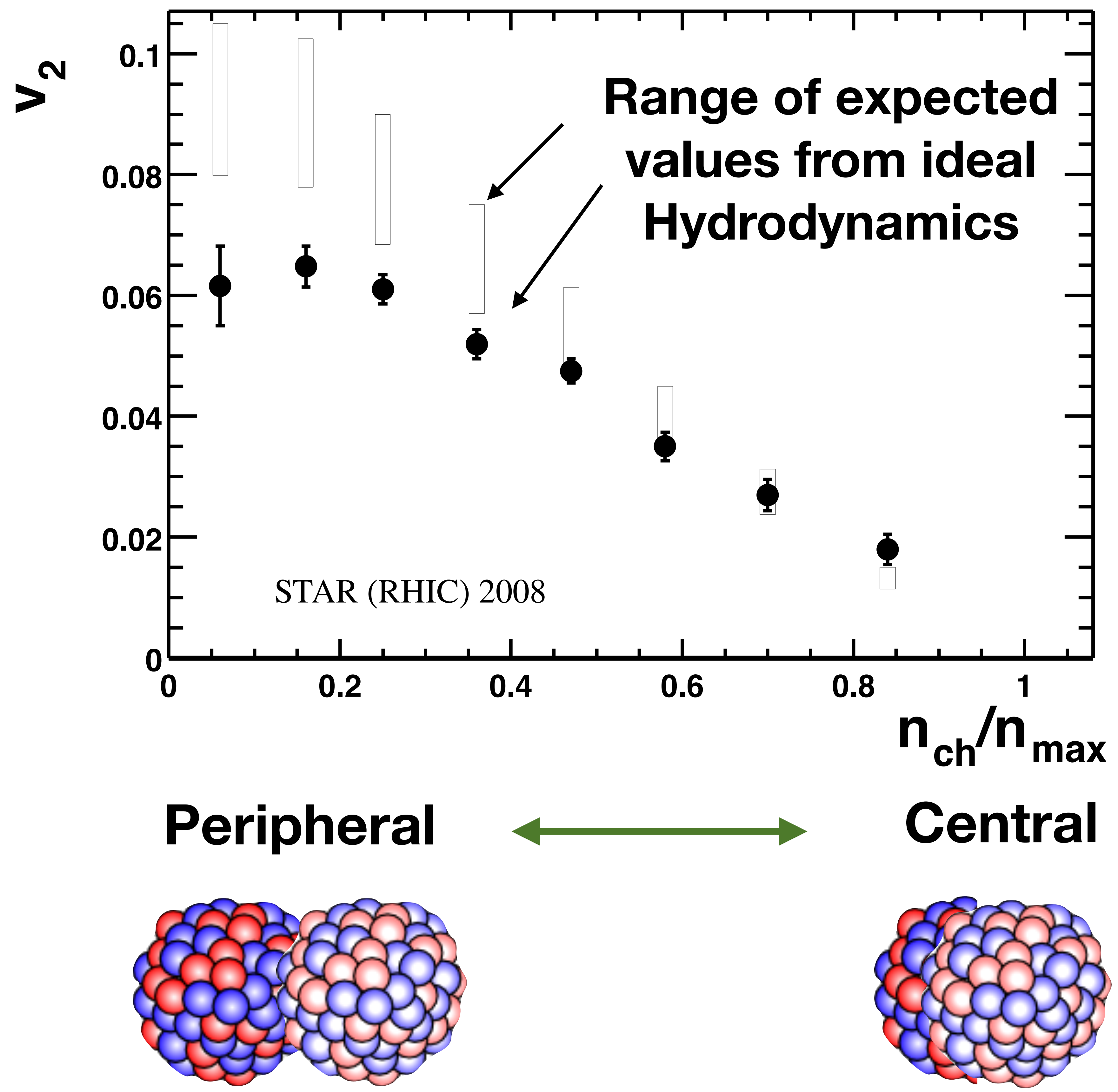
**Deviations from ideal hydro (viscous hydro) include additional coefficients:**
**Shear viscosity $\eta$, bulk viscosity $\zeta$, …**

# QGP is a fluid



- QGP is an (almost) ideal fluid:



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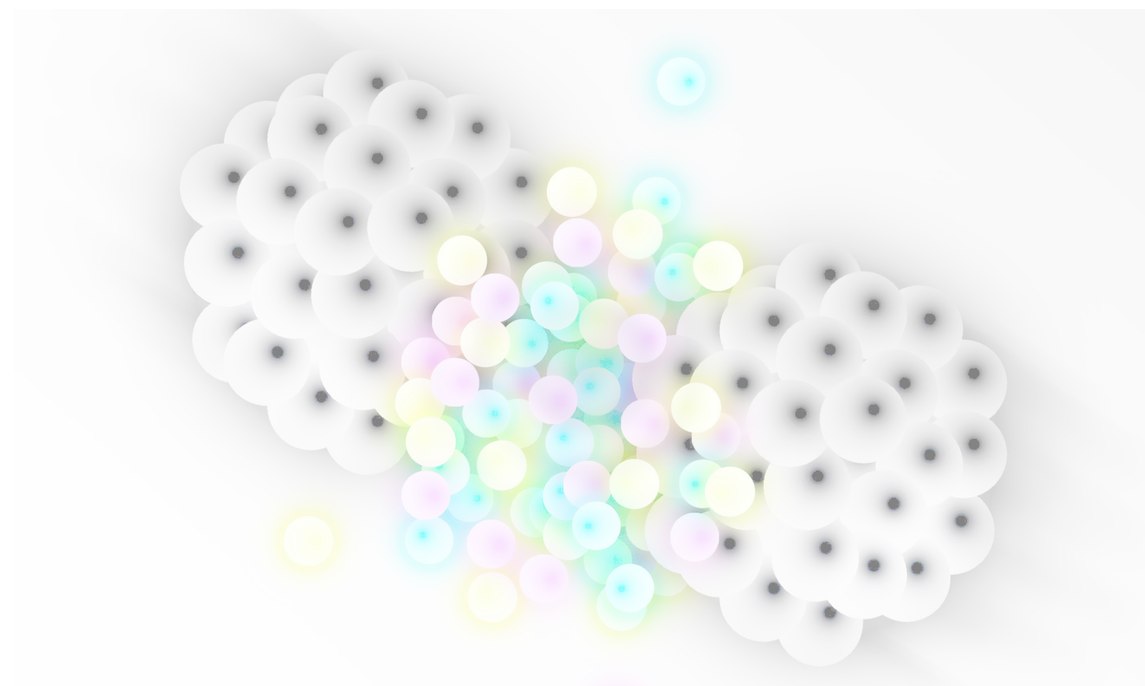
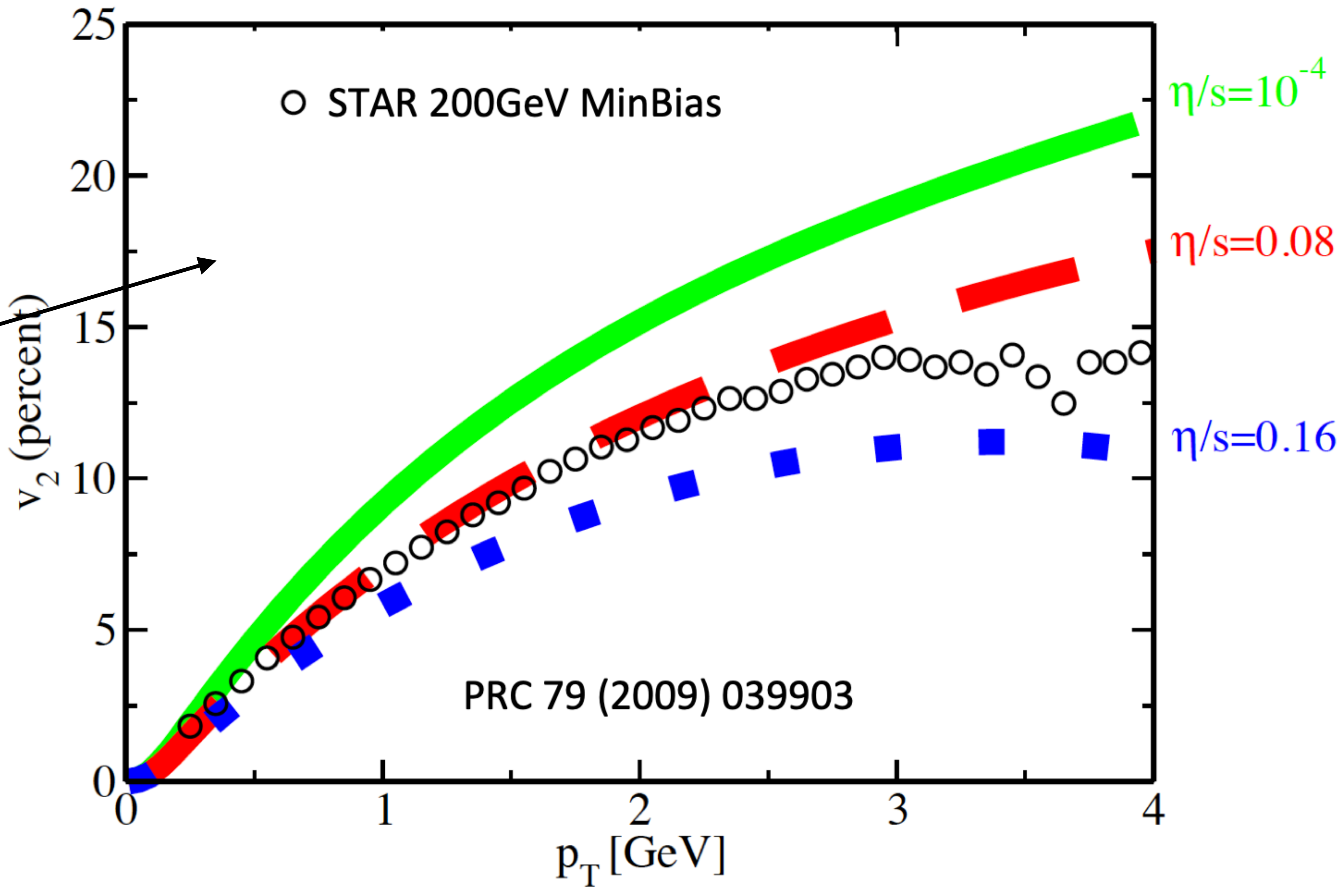
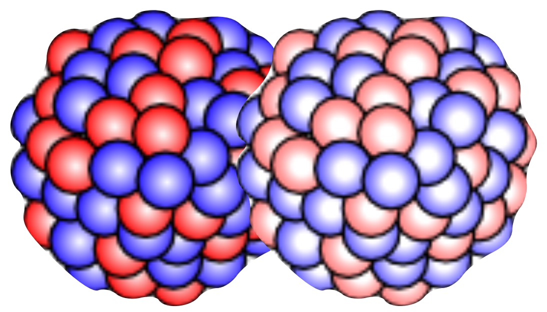


- QGP is an (almost) ideal fluid:

**Highly sensible to $\eta/s$**




**Peripheral**



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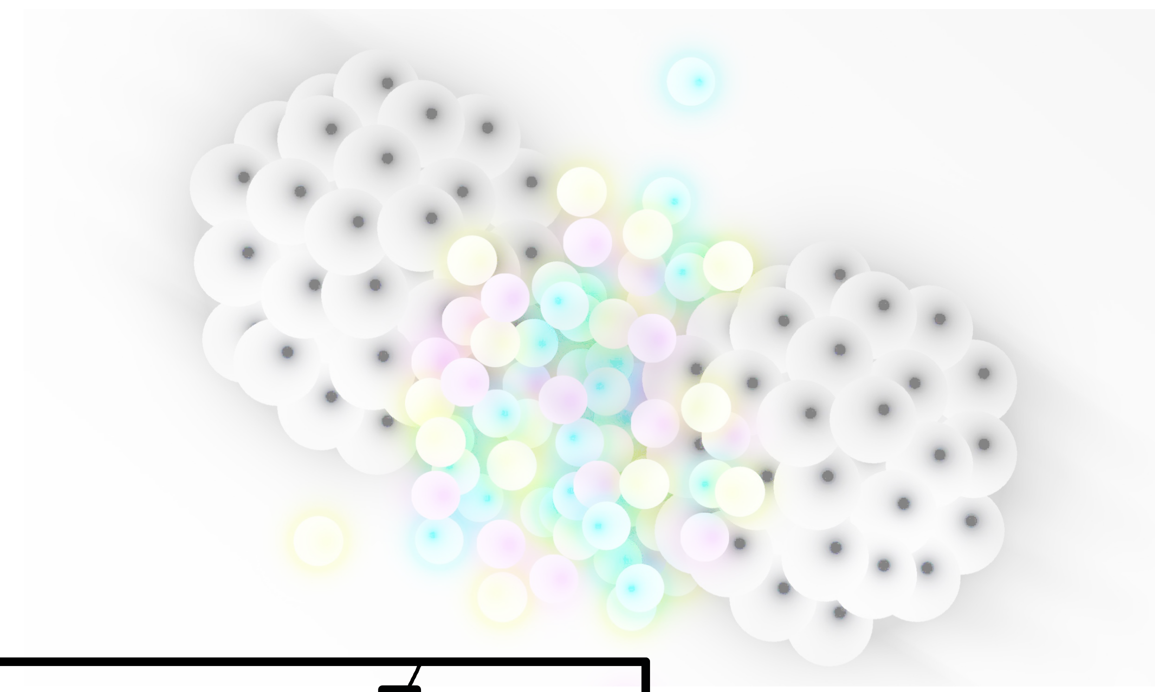

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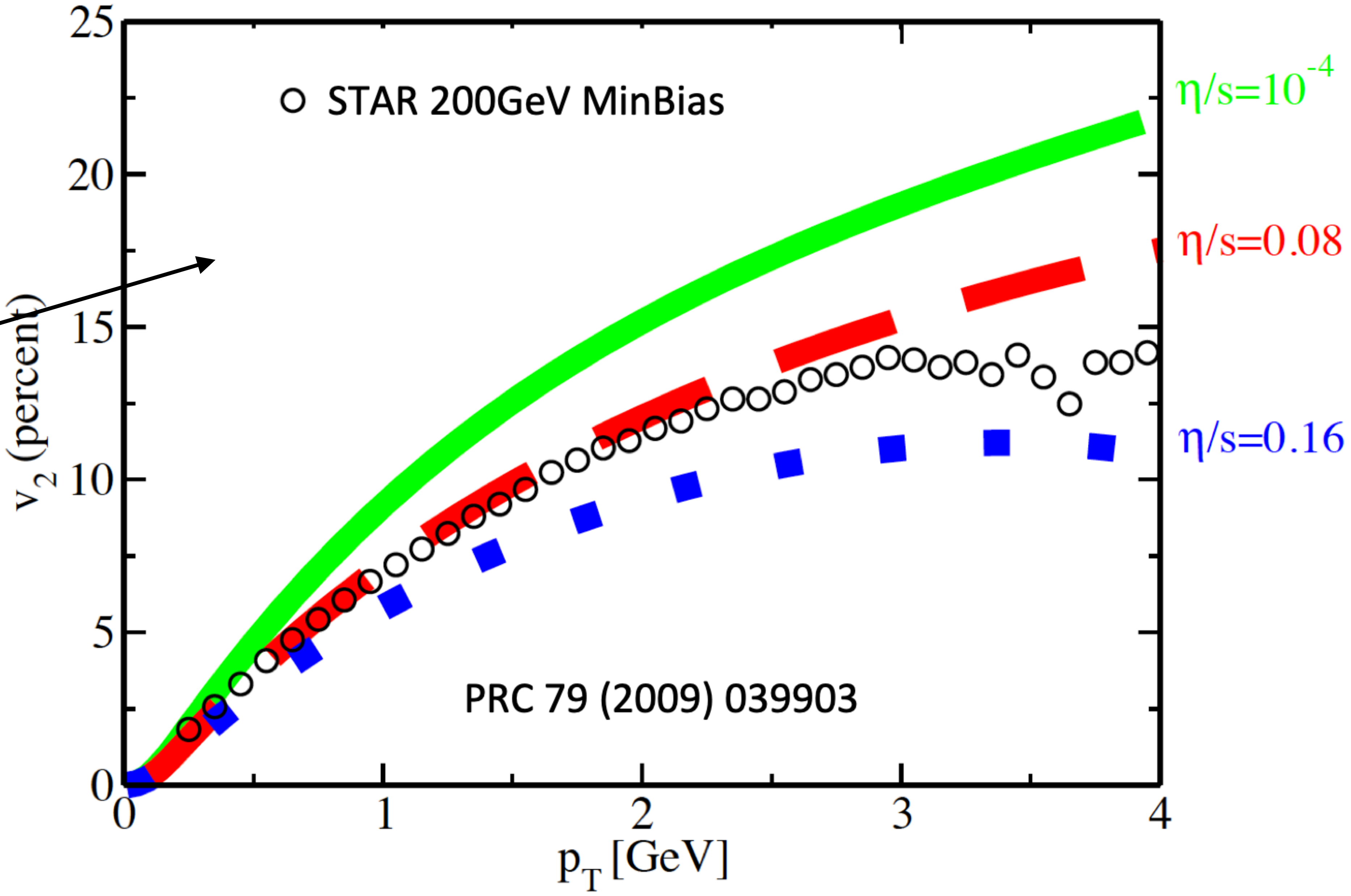


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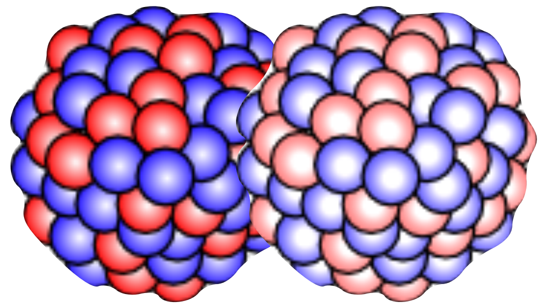
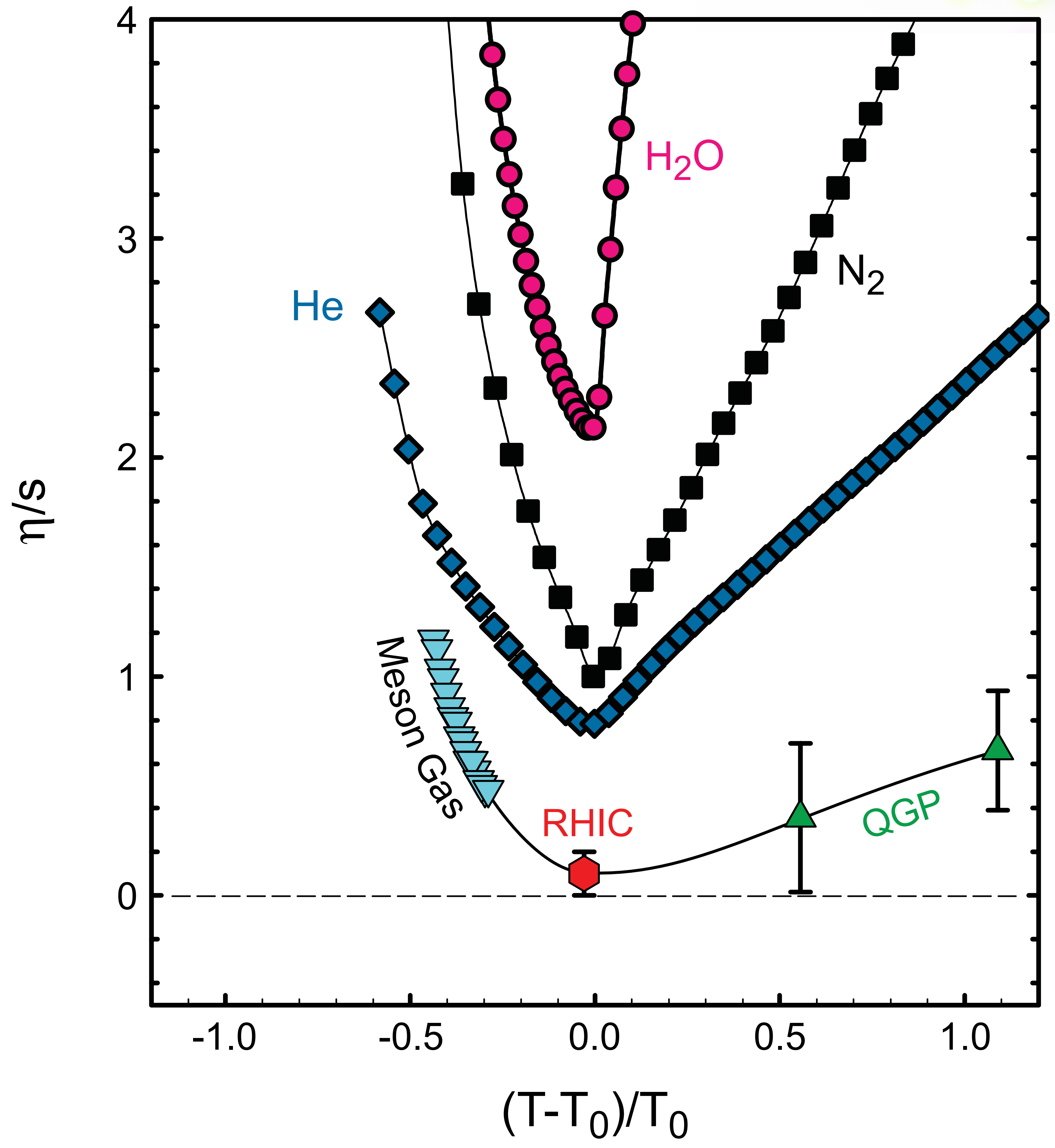
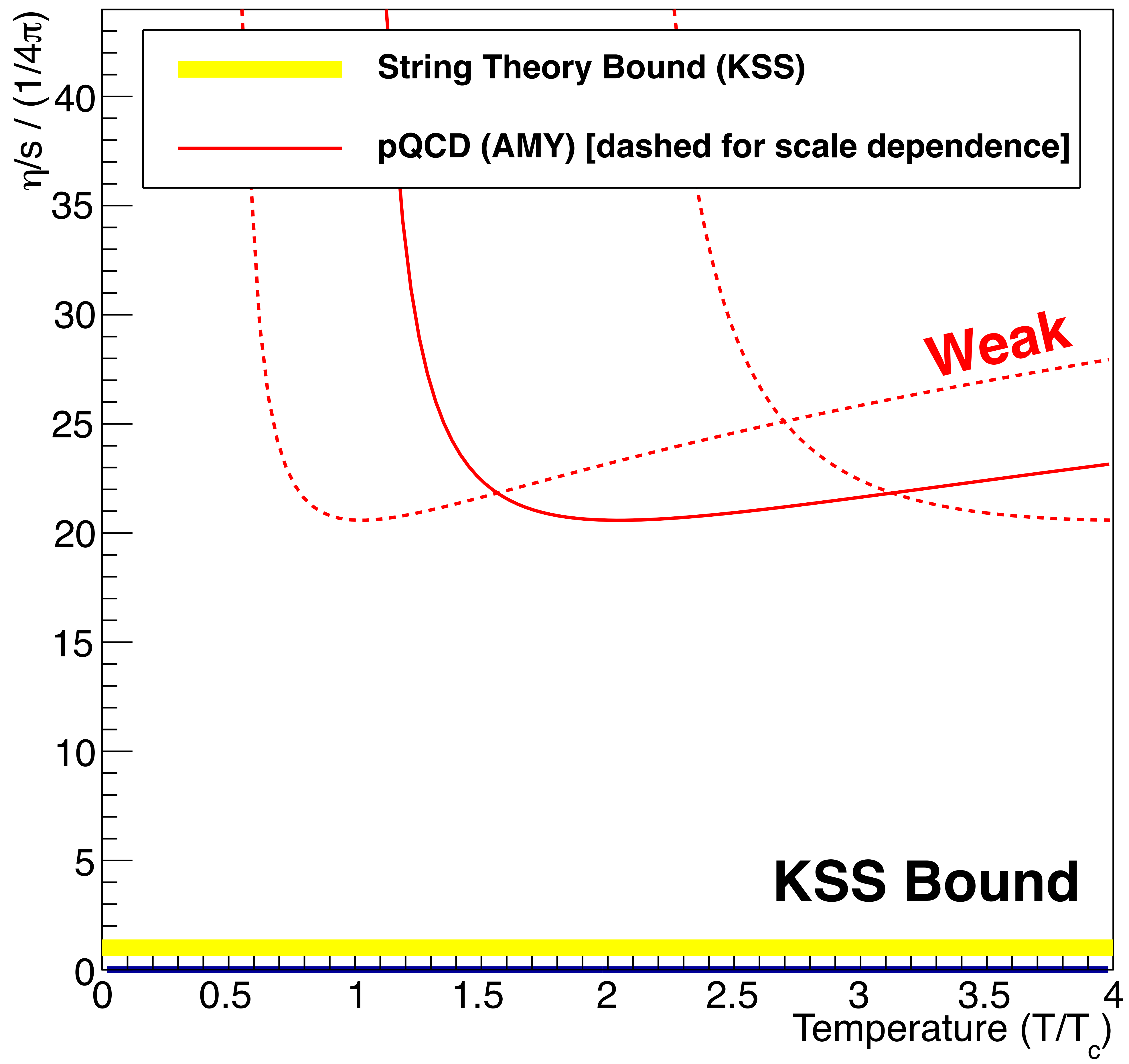
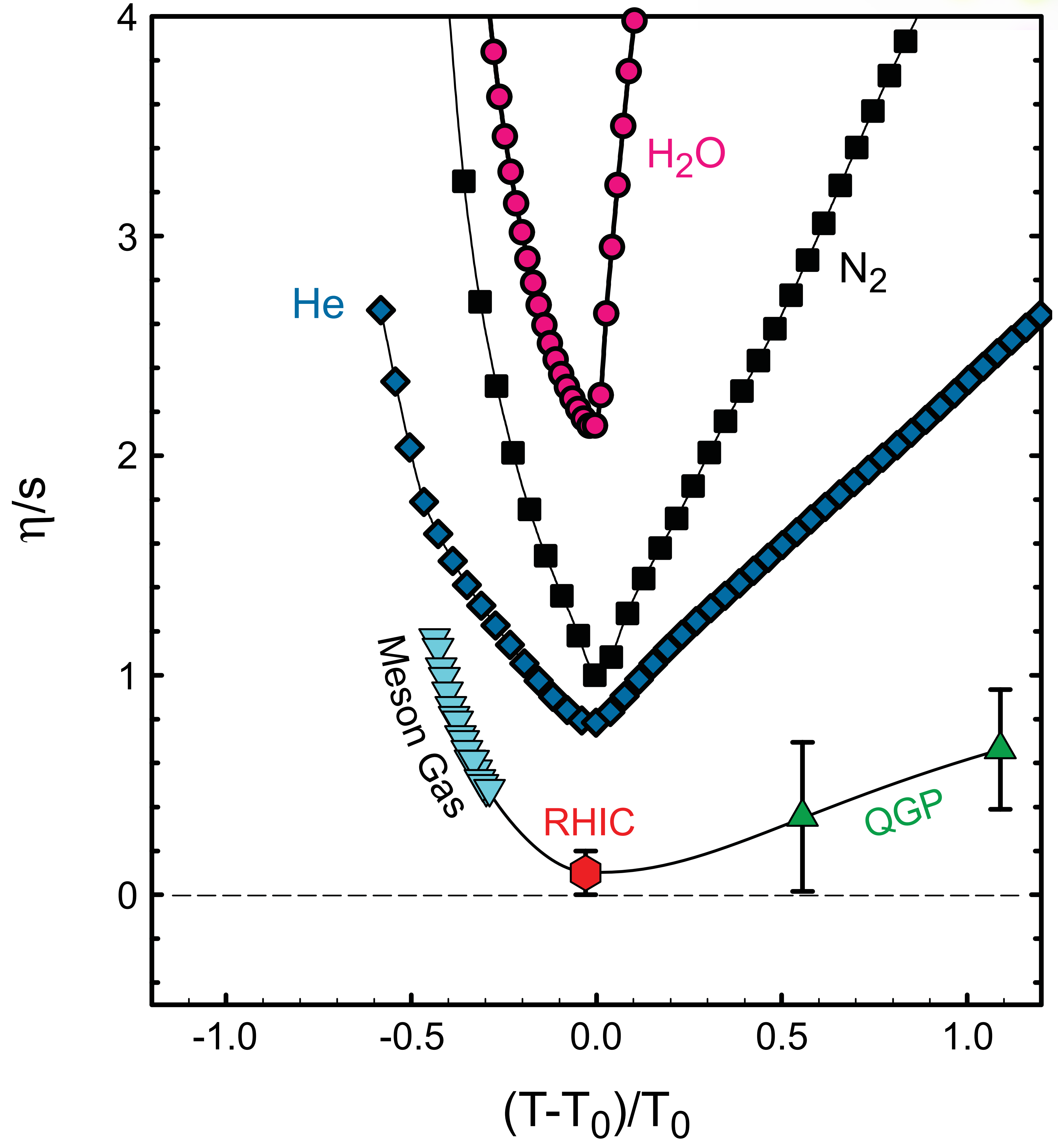




# QGP is a fluid

- QGP is an (almost) ideal **strongly-coupled** fluid:



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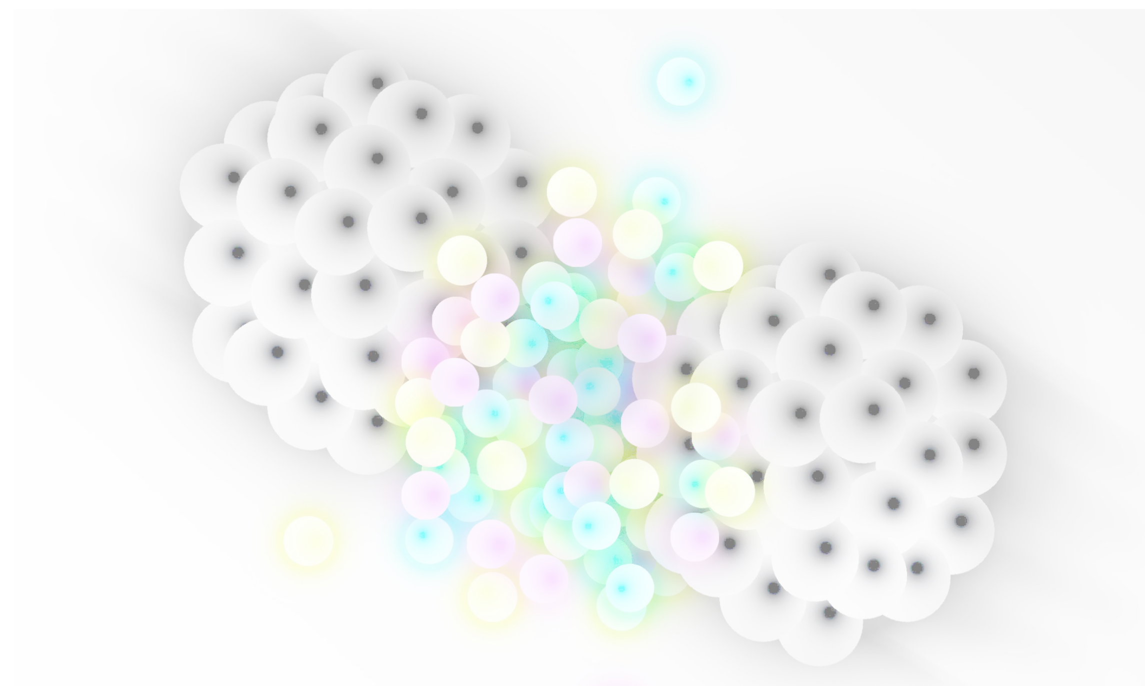

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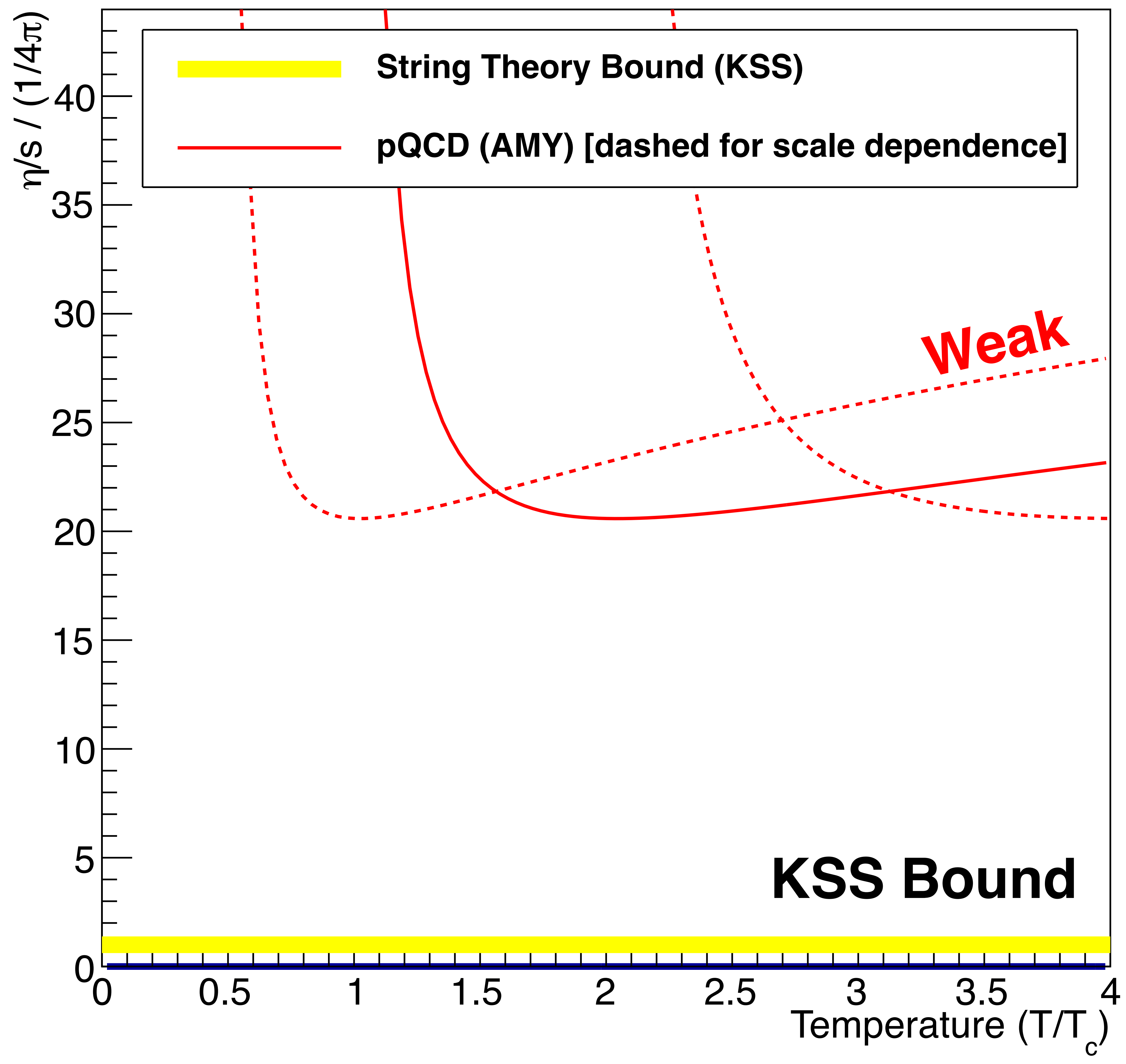
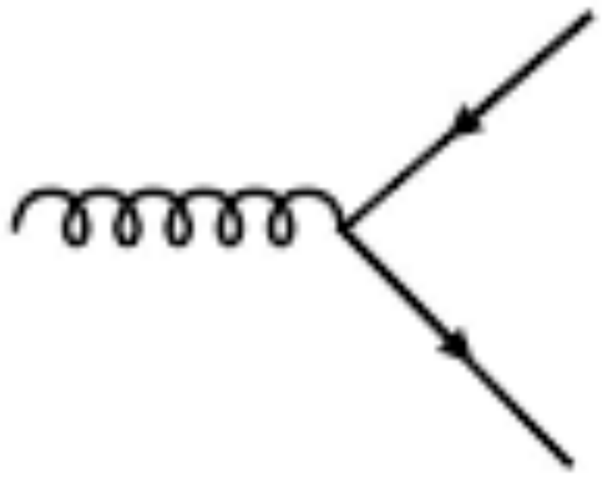



**Weak coupling**

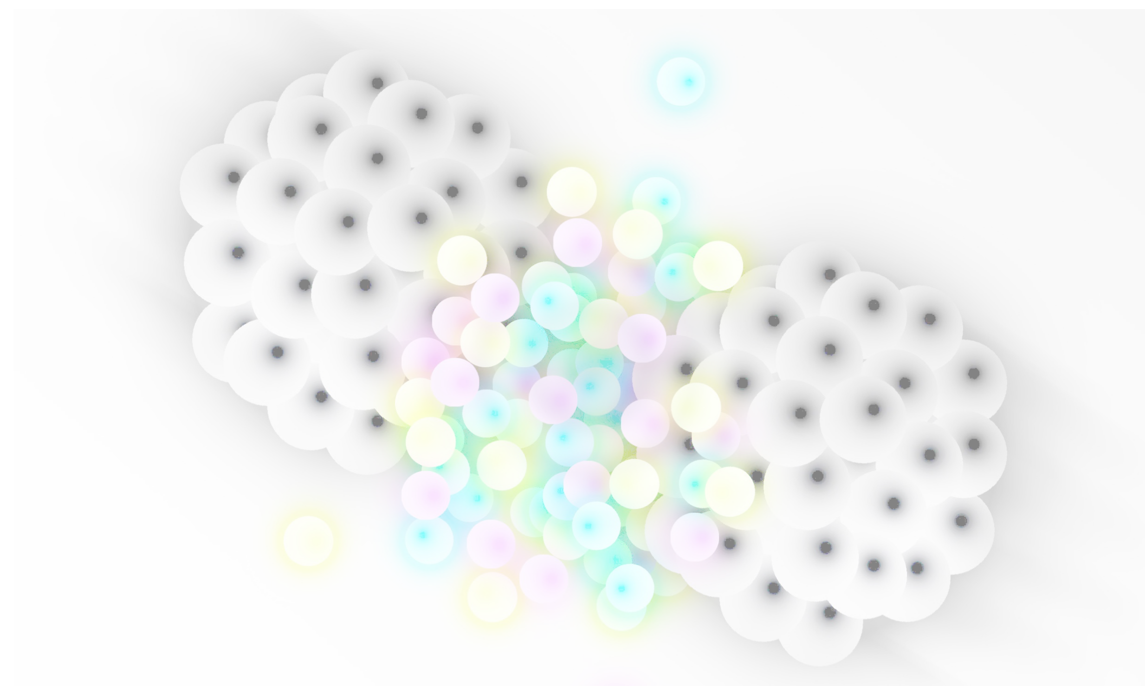
$$\alpha_s = \frac{g_s^2}{4\pi} \ll 1$$



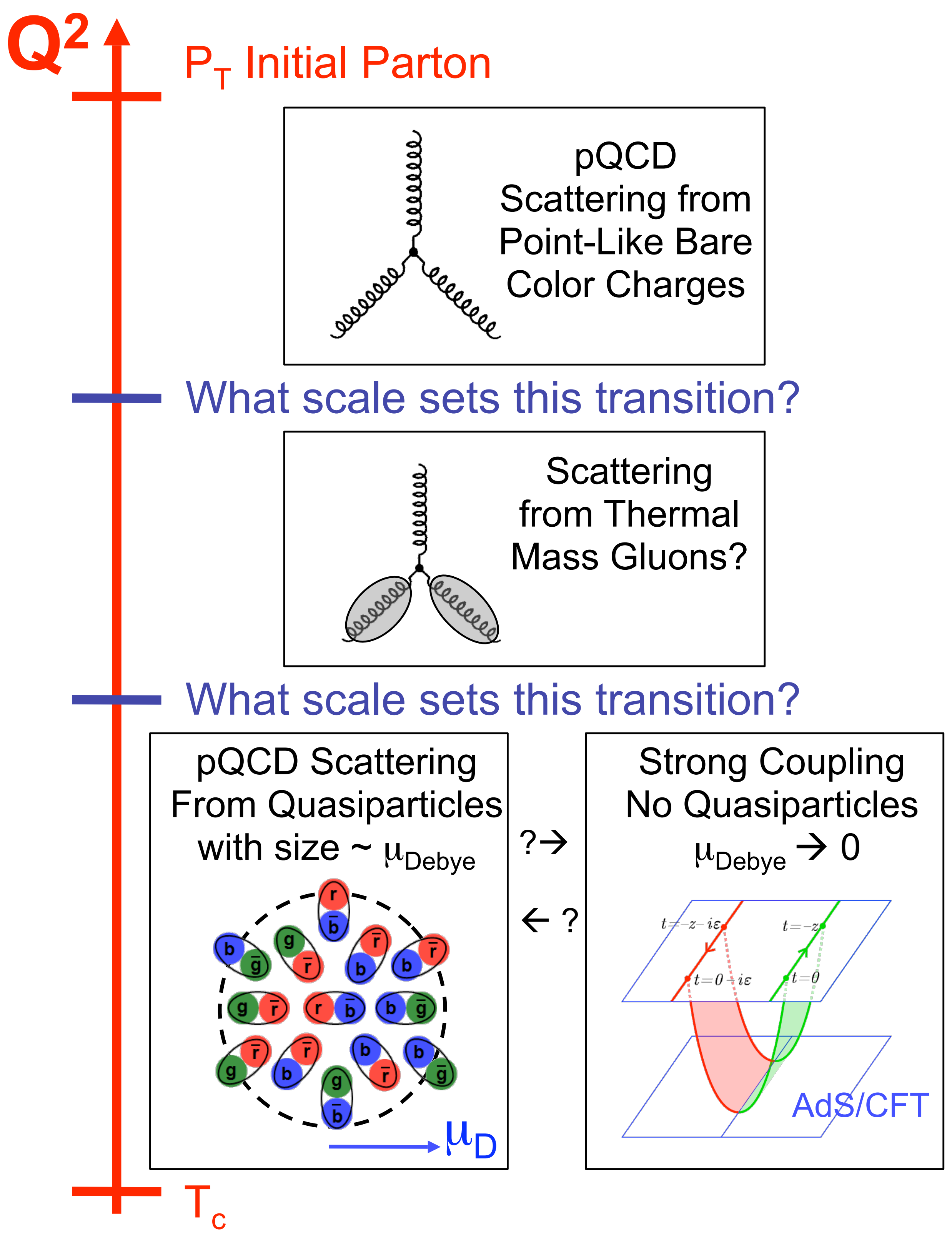
**Strong coupling**

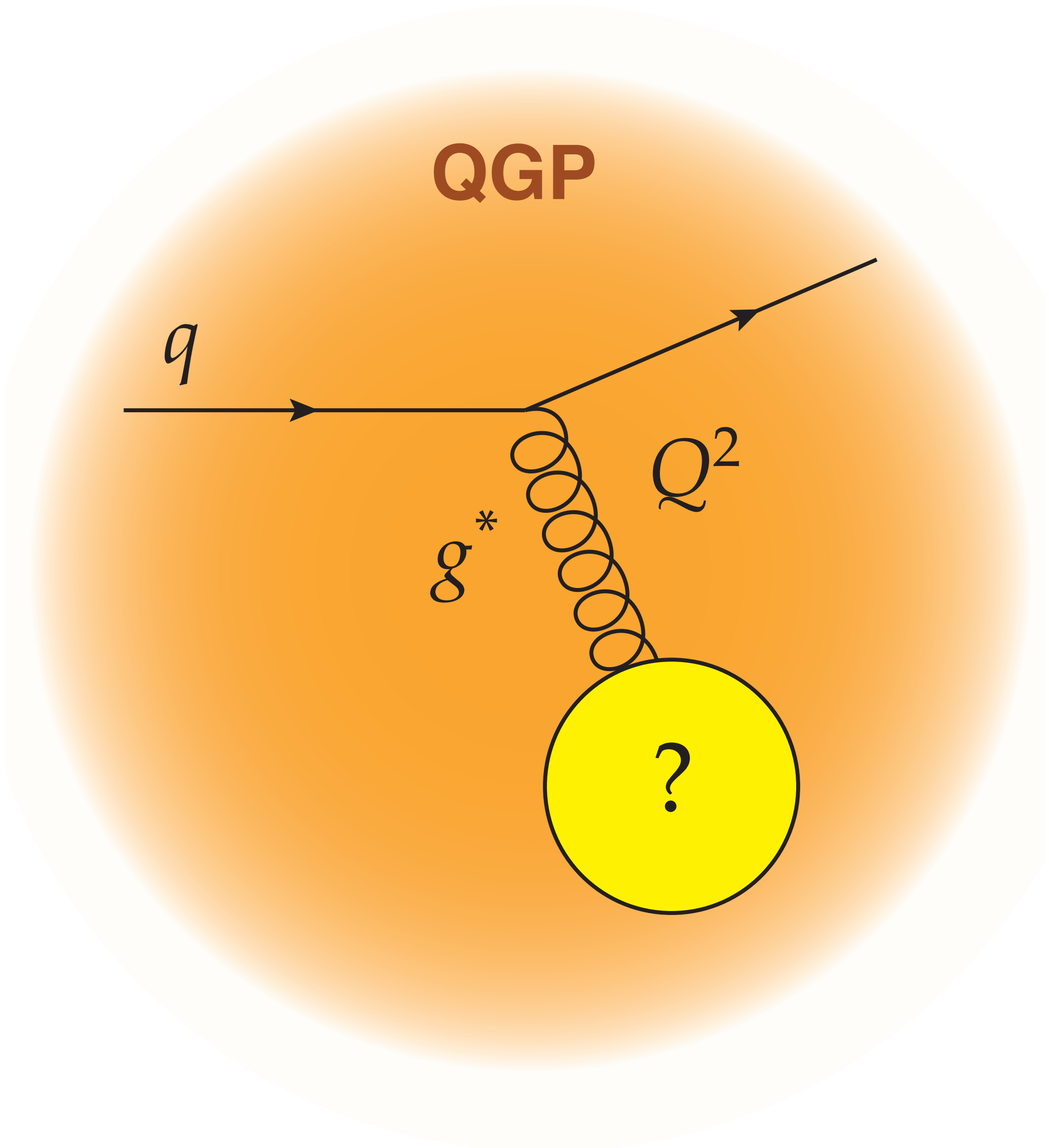
$$\alpha_s \simeq 1$$

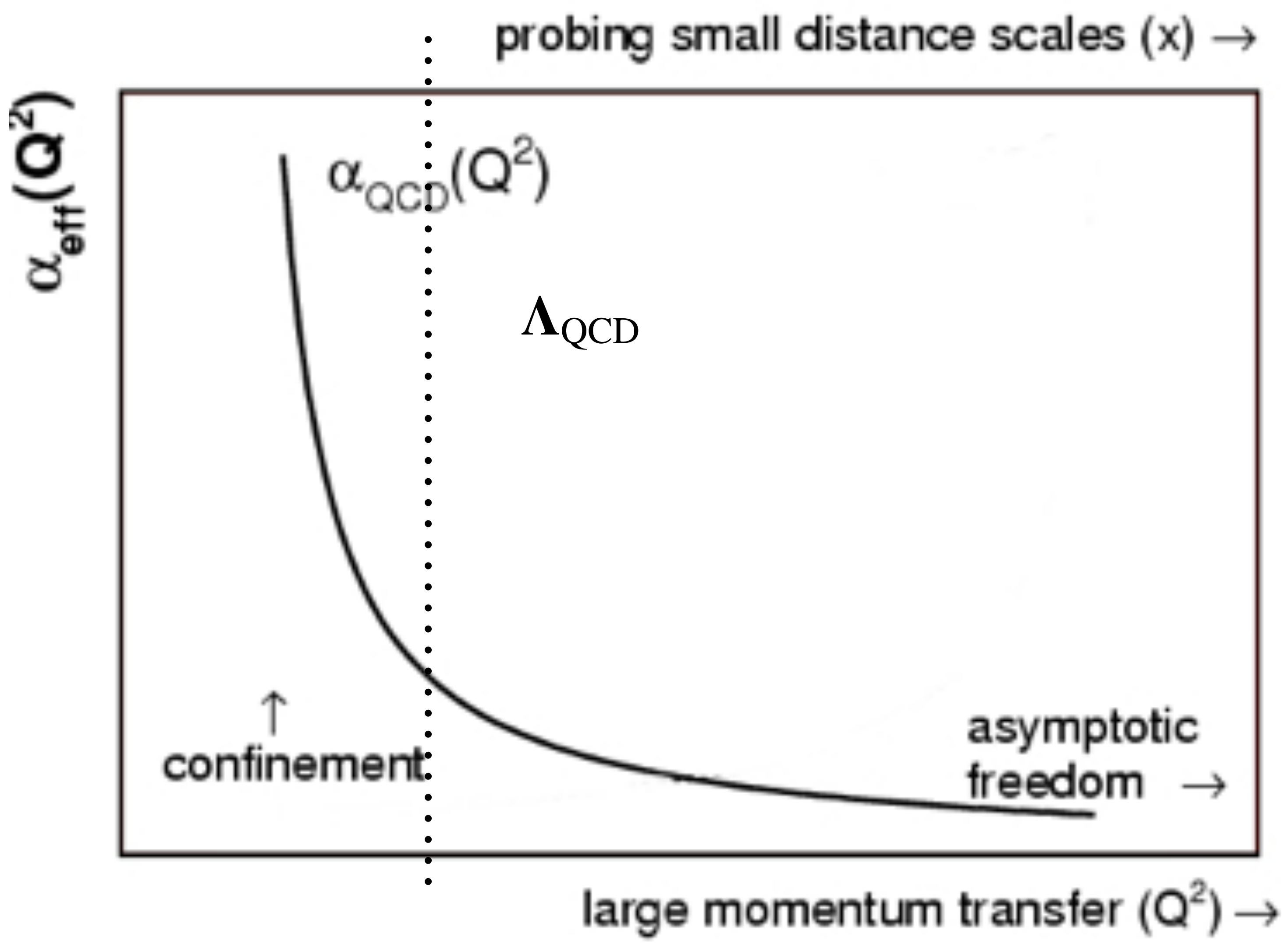
# QGP constitution?



- Is the QGP a collection of point-like quasi-particles?

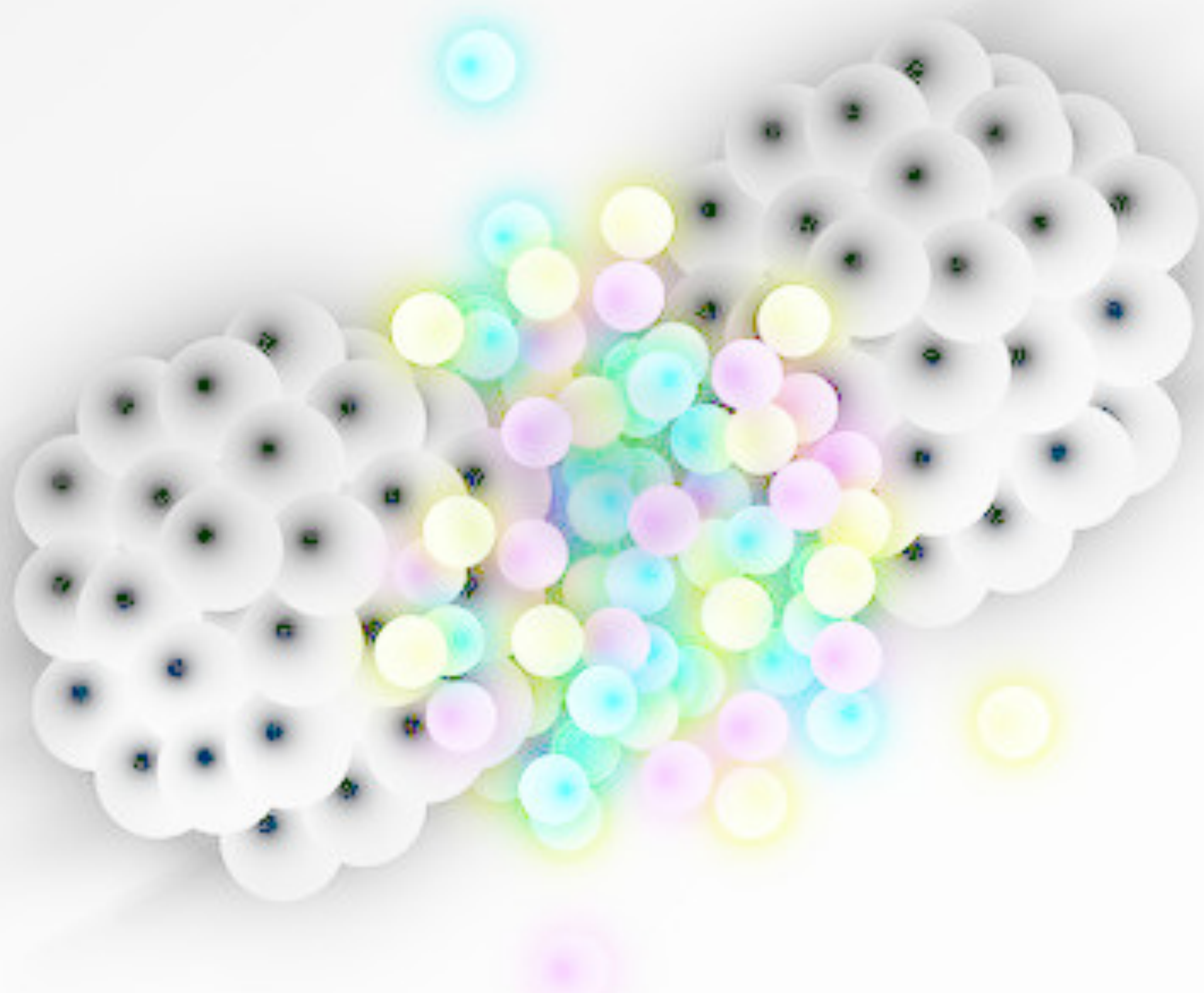


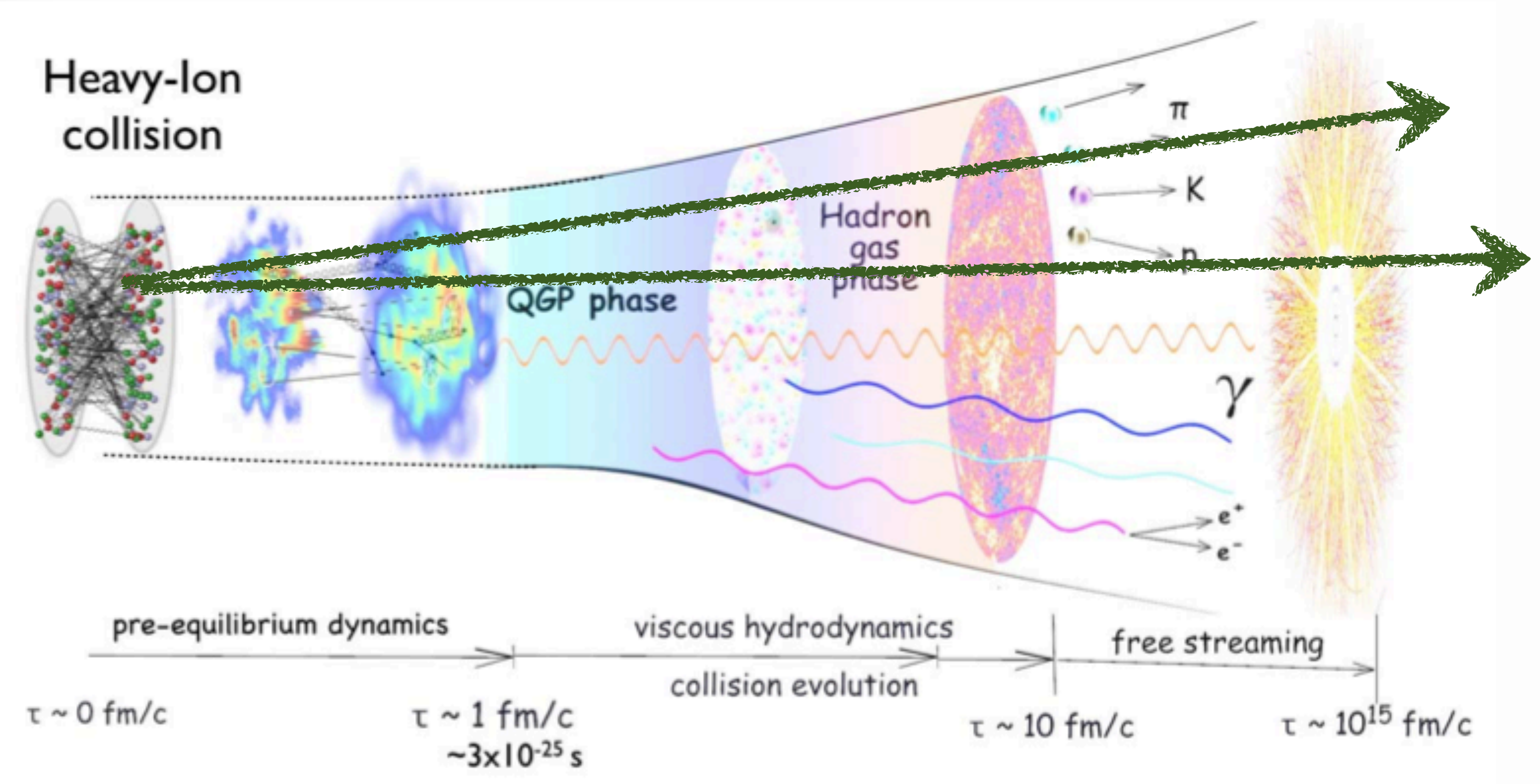

**Pushing boundaries of pQCD**

# How is "vacuum QCD" modified by the QGP?

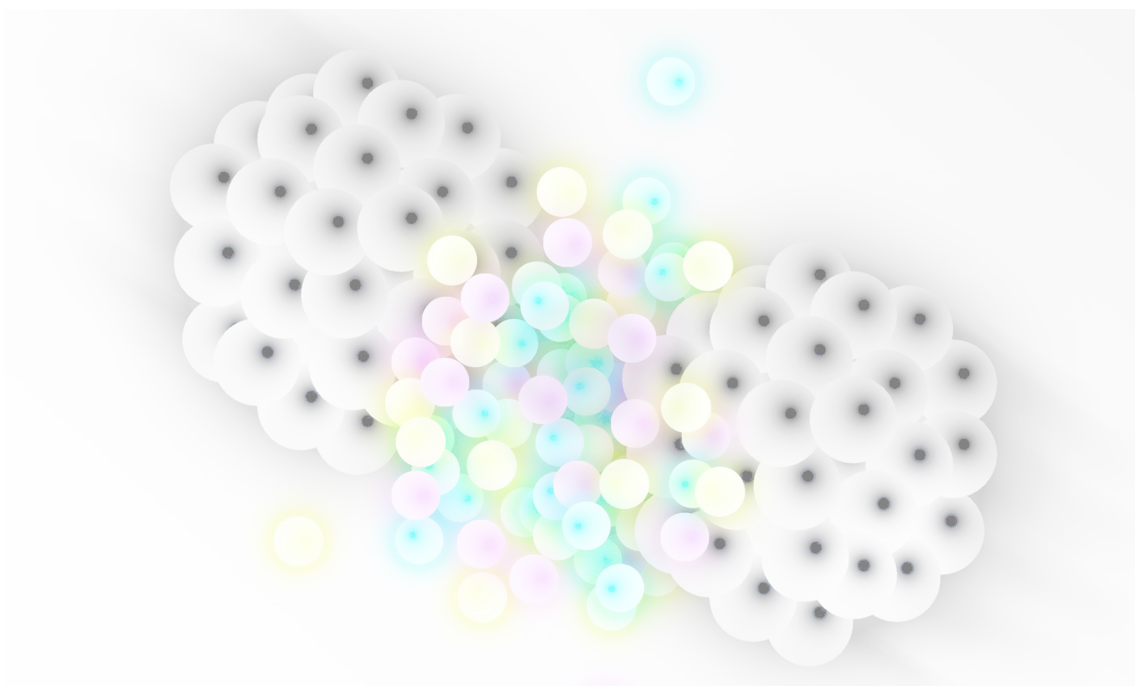


**Hard Probes**

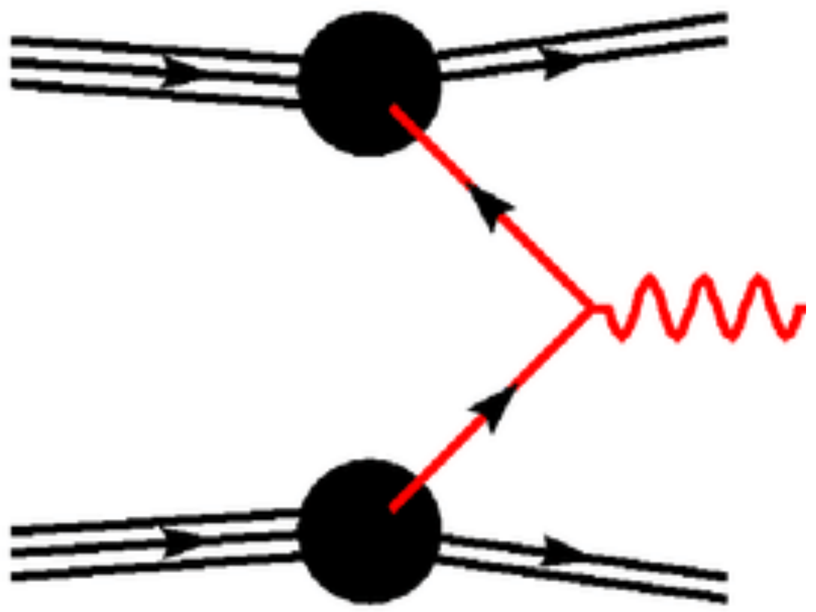
**(Hard scattering
High momentum particles)**



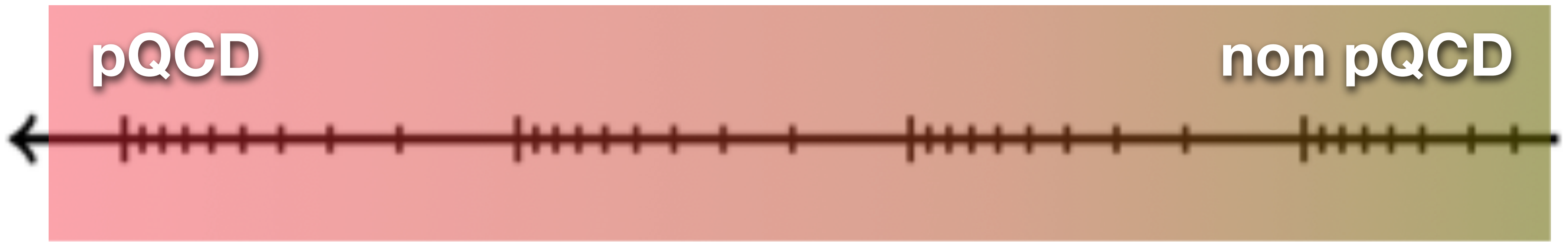
# Jets in heavy-ions



- Also a multi-scale problem:



$Q^2 \equiv \mathcal{O}(100^2\mathrm{GeV}^2 \sim 1\mathrm{TeV}^2)$

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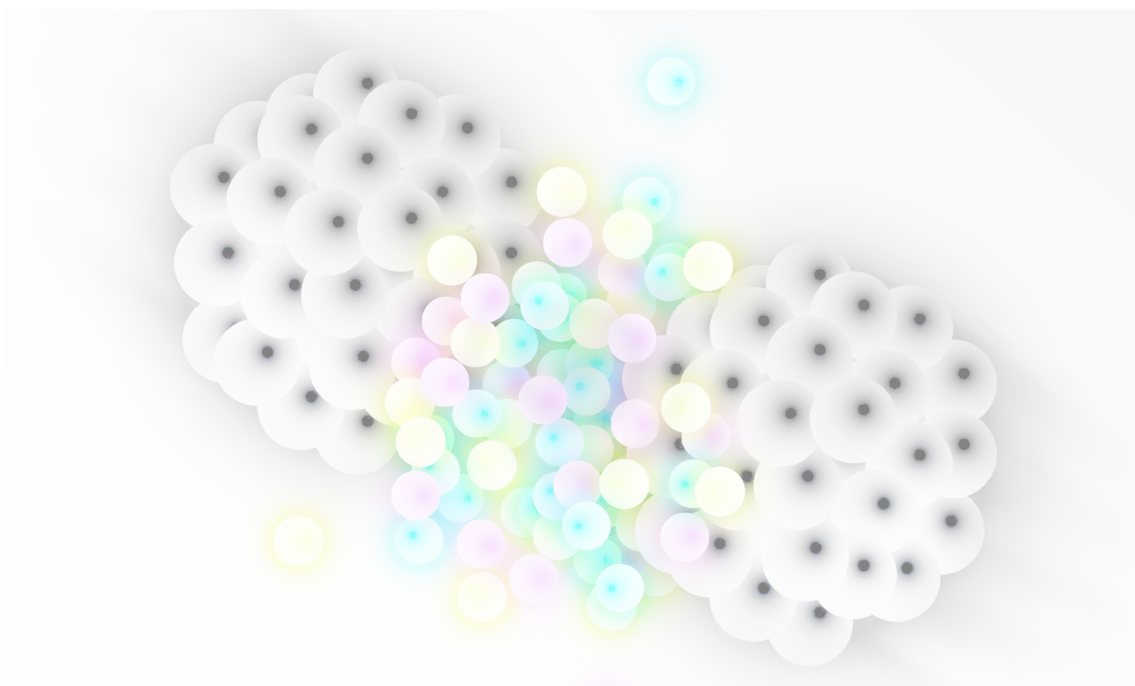

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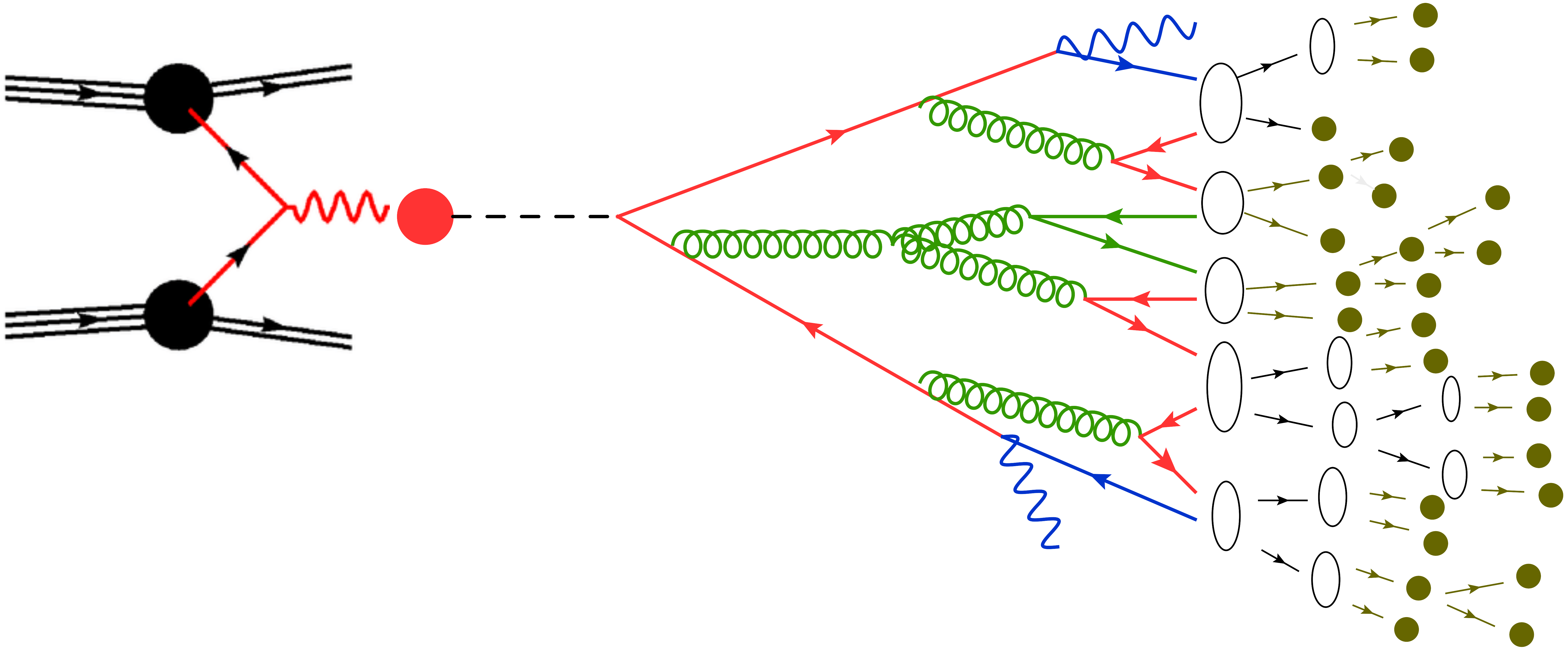

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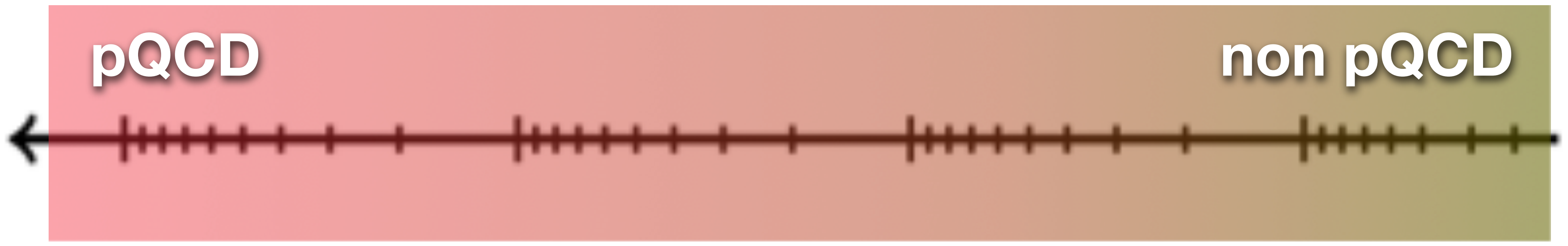


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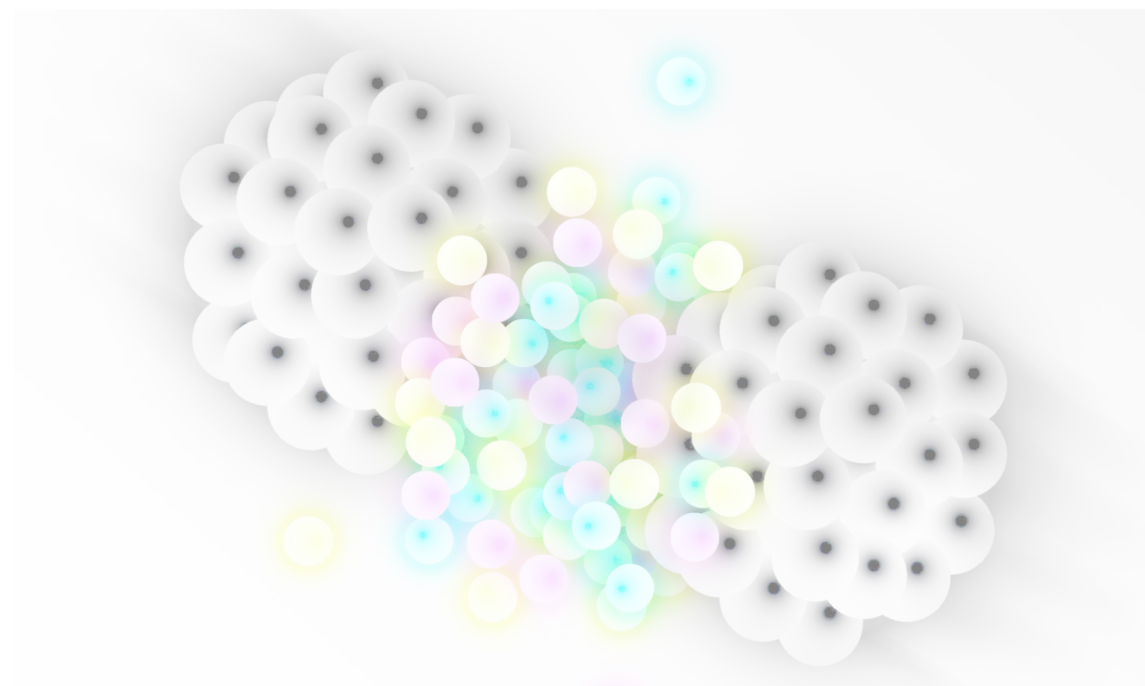

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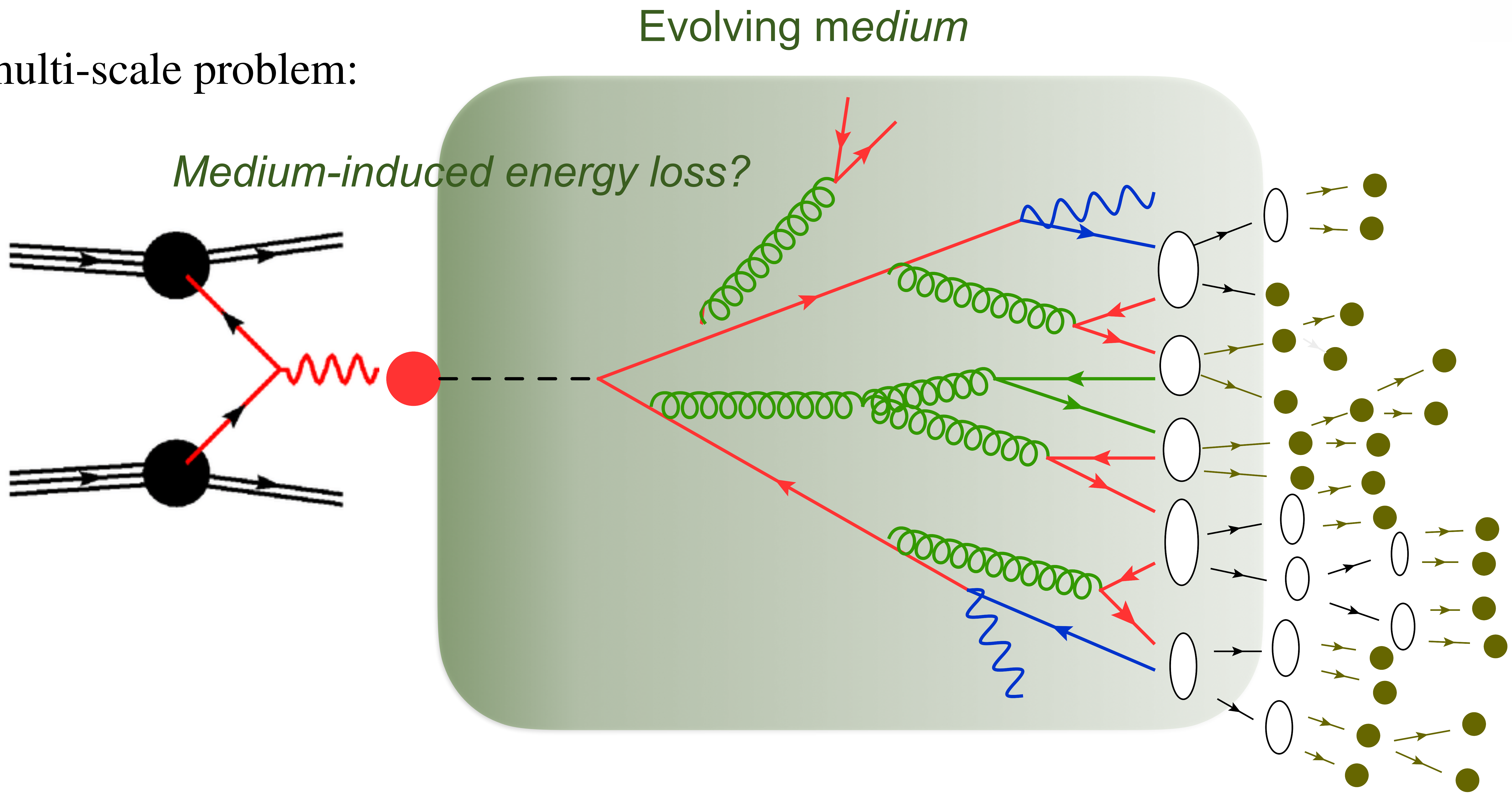


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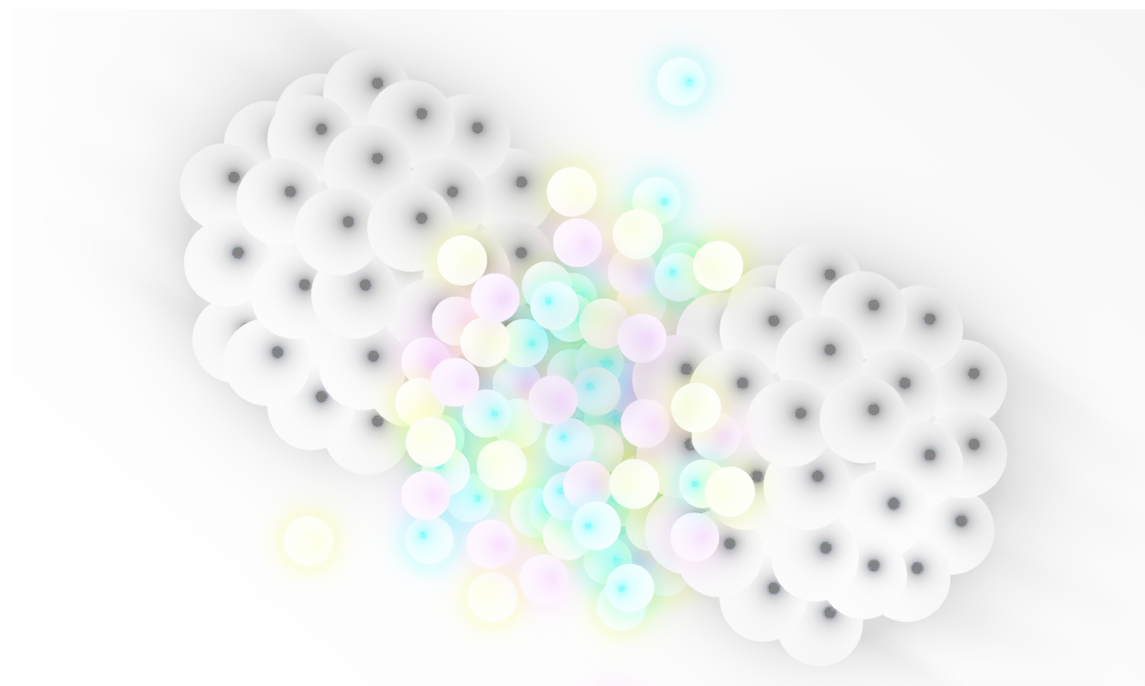

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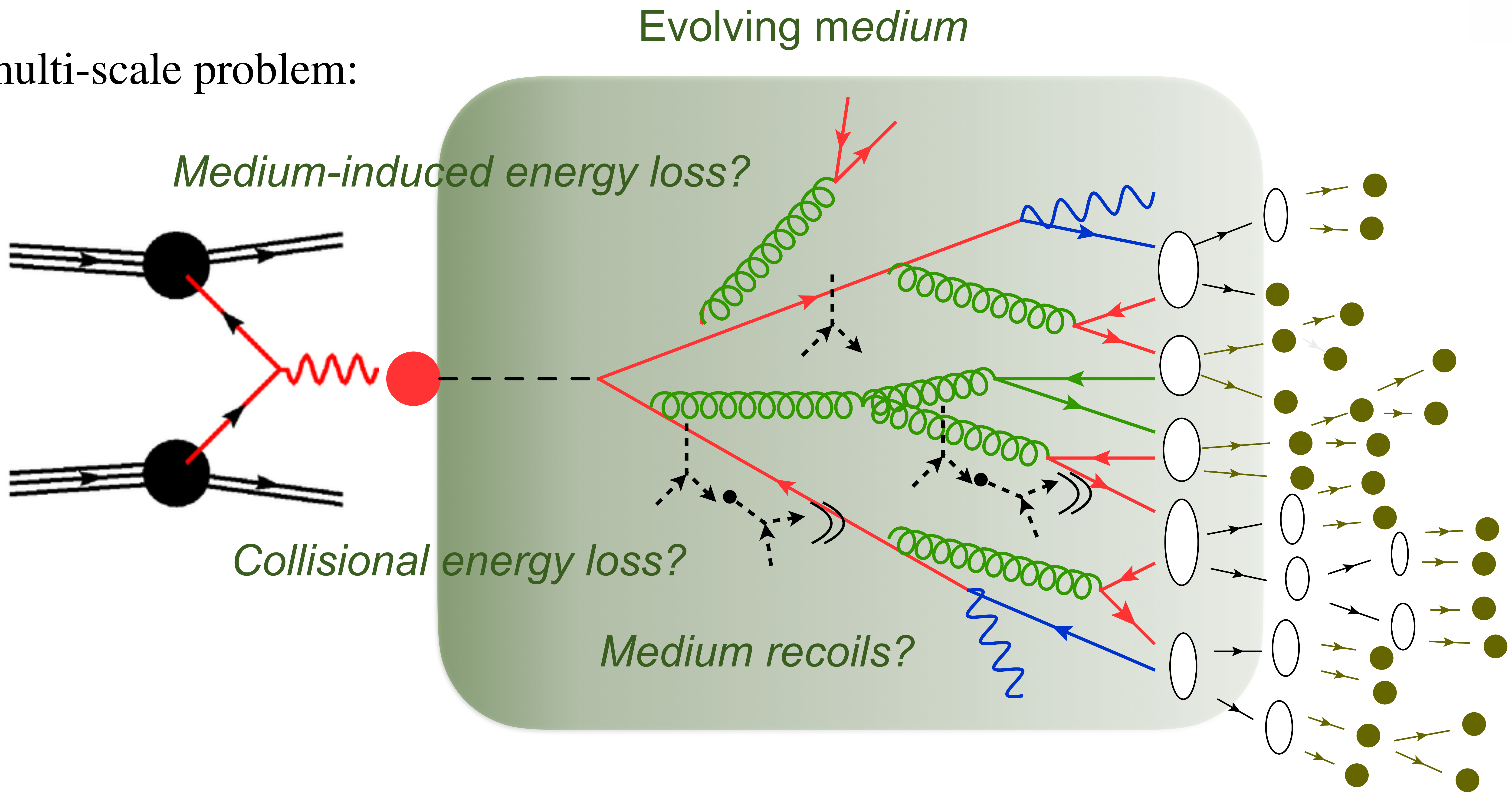


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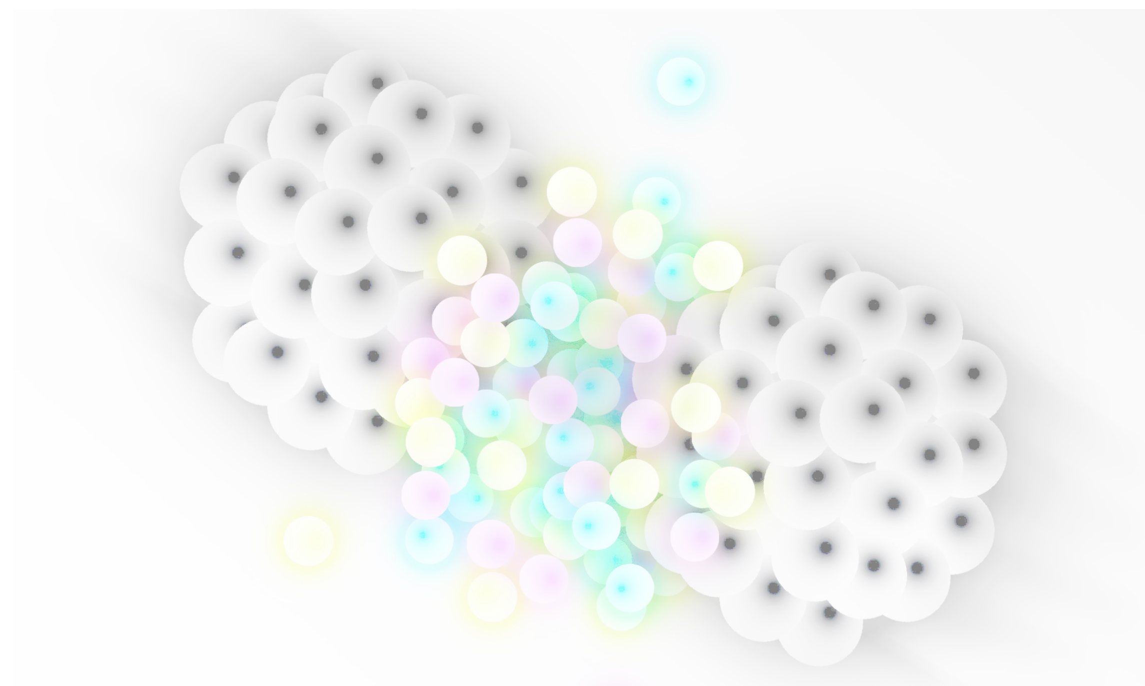

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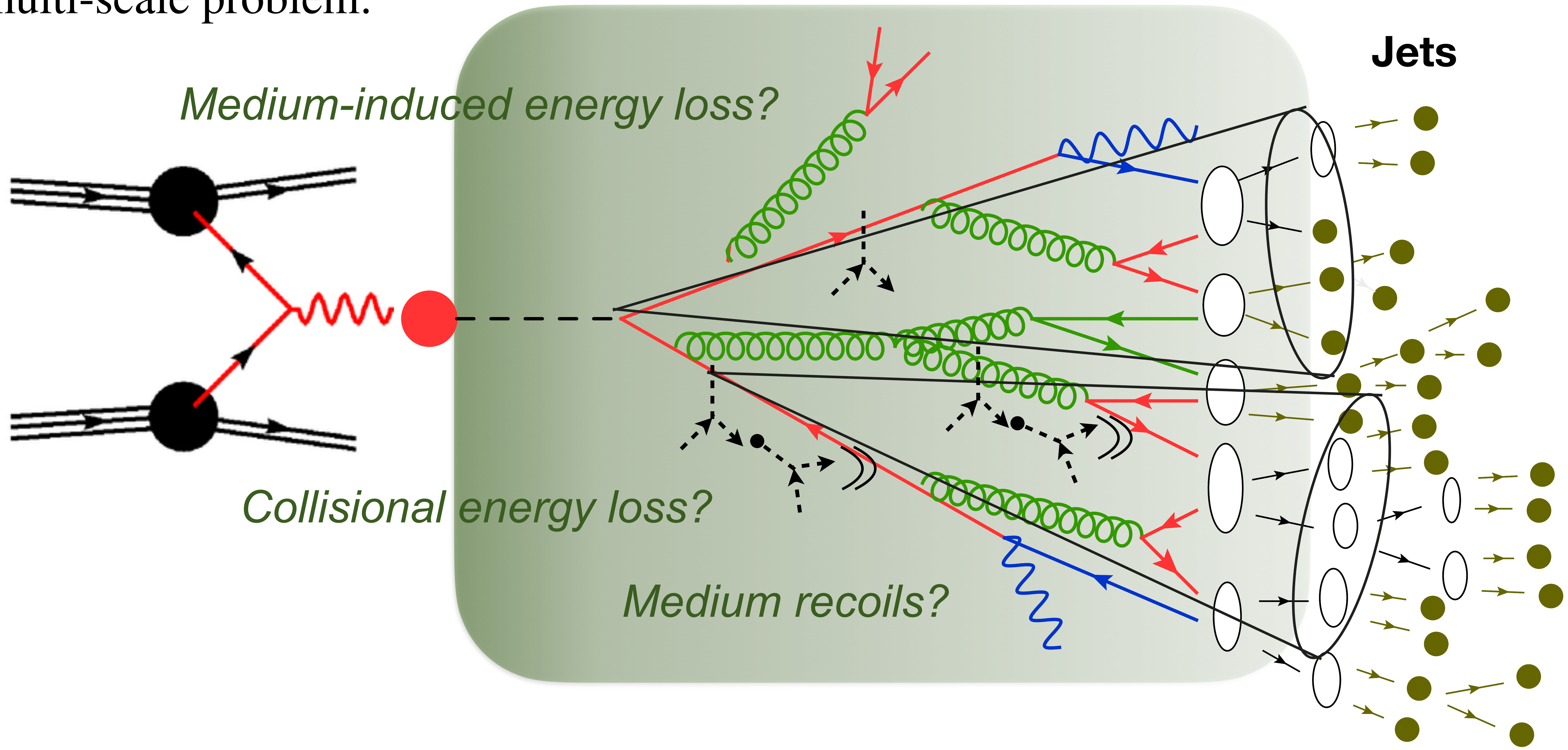


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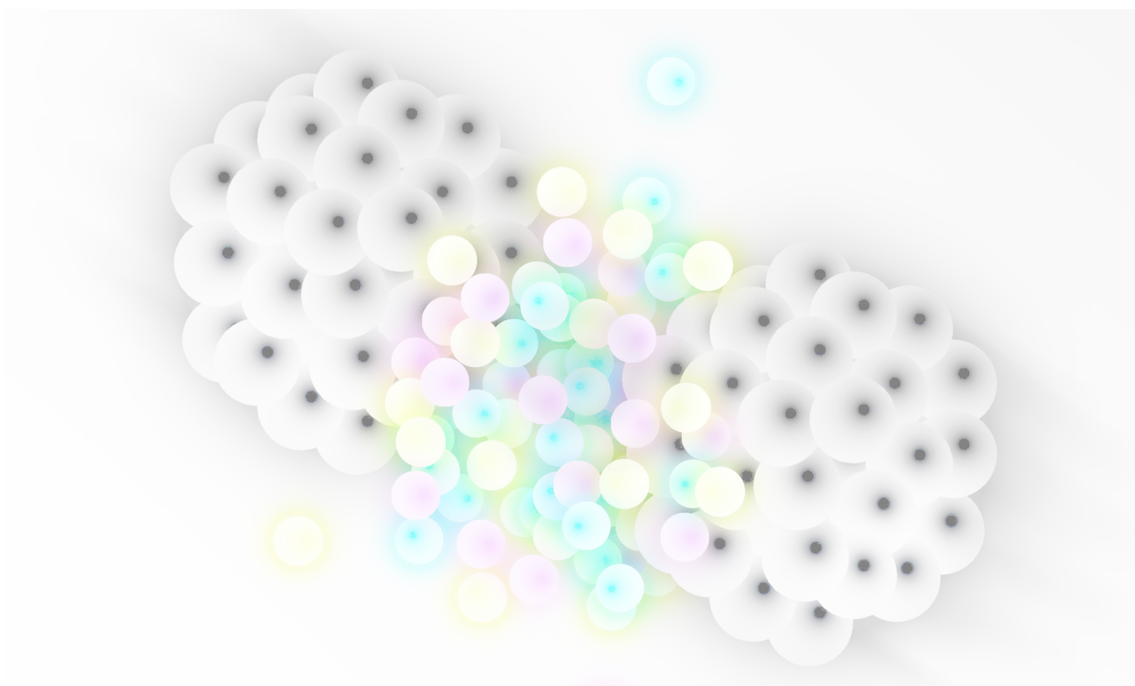
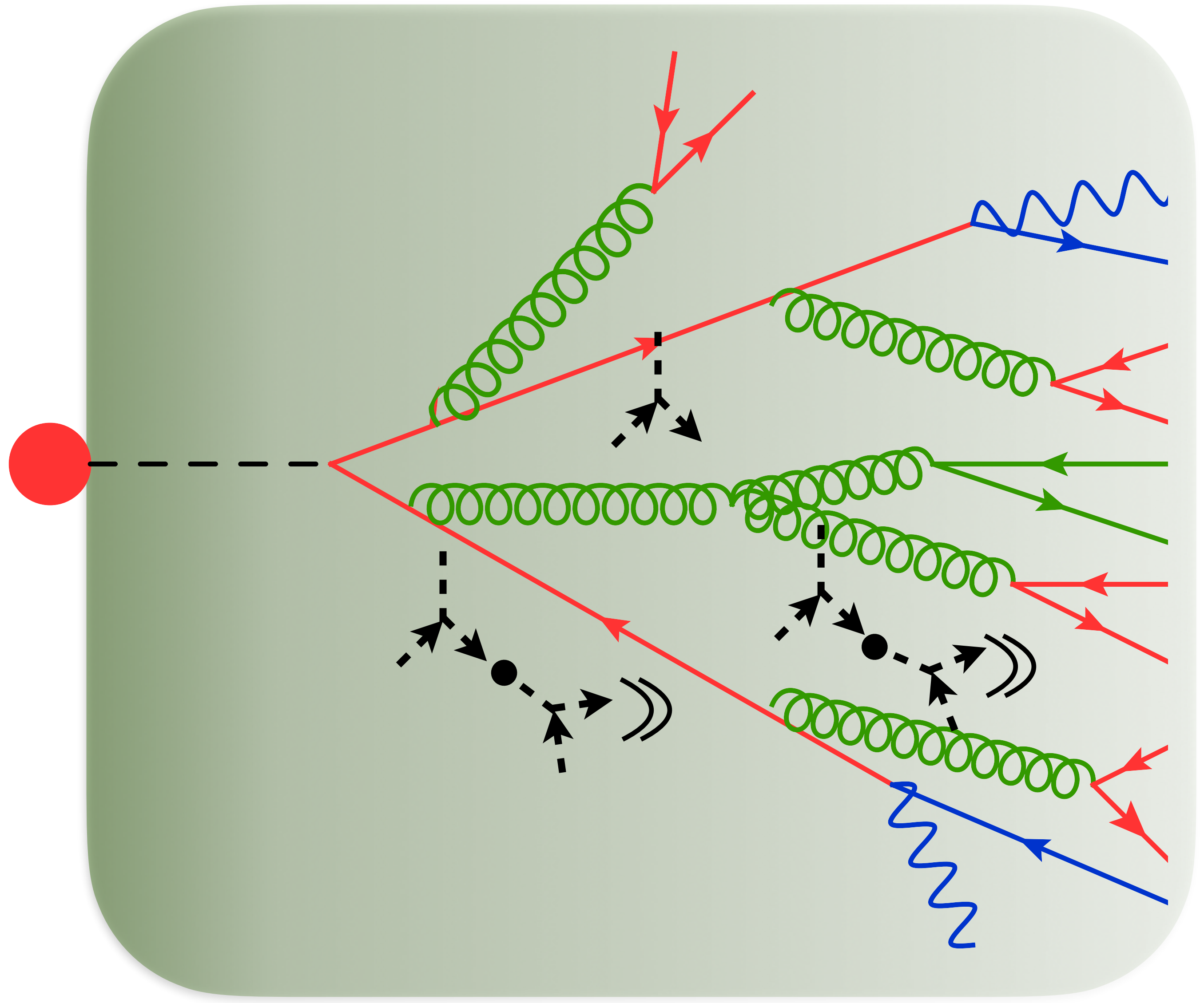
# In-medium processes



- Amount of energy loss measures transparency to the passage of a high momentum particle:
    - Towards higher accuracy in elementary building blocks of the parton shower



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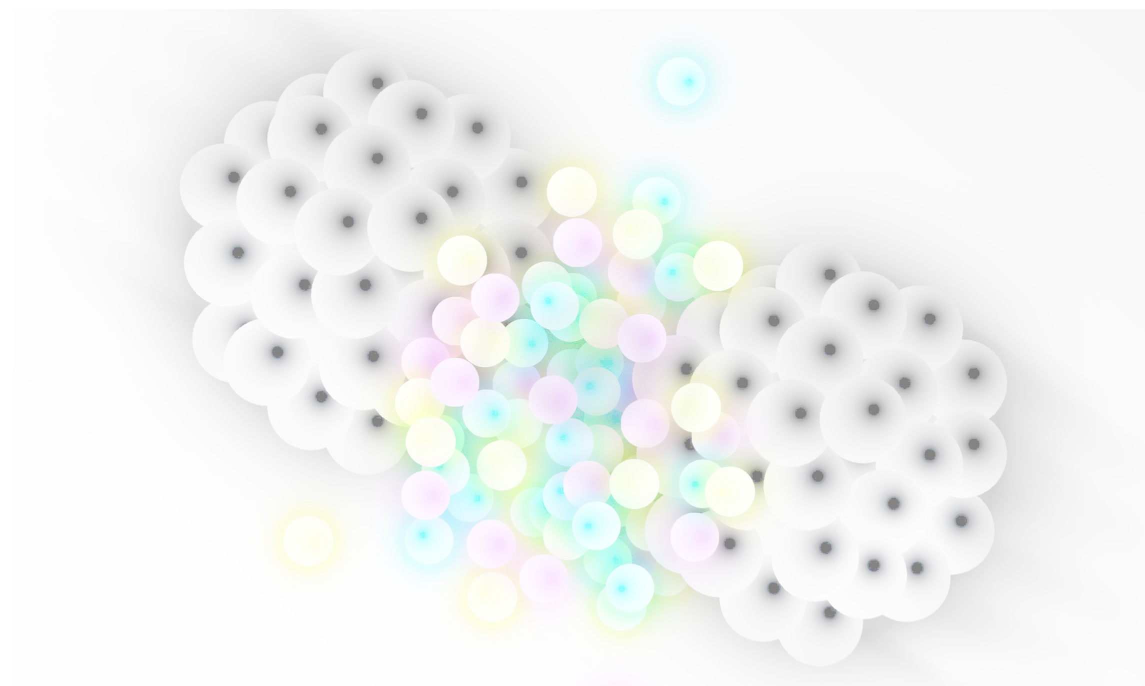

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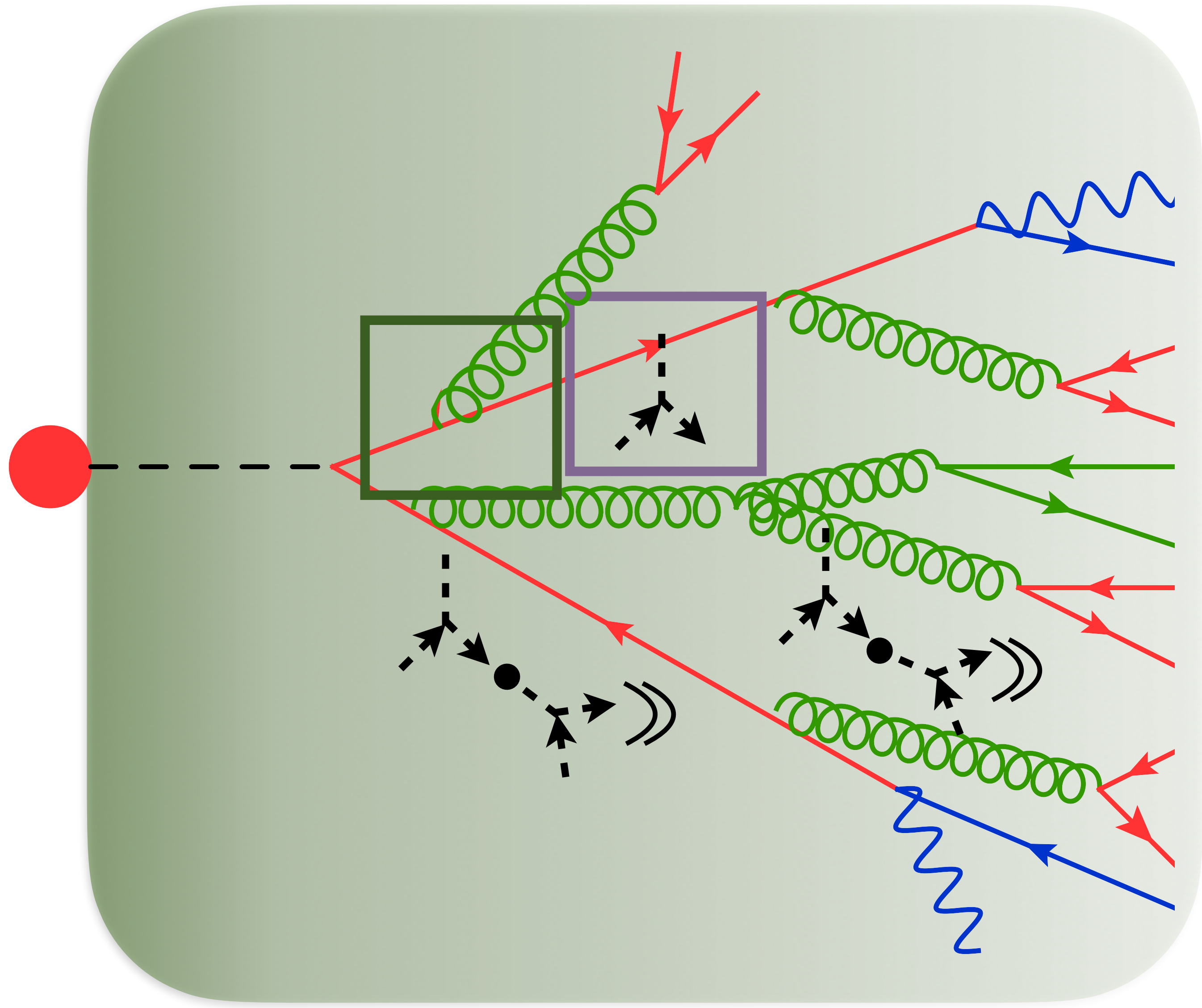
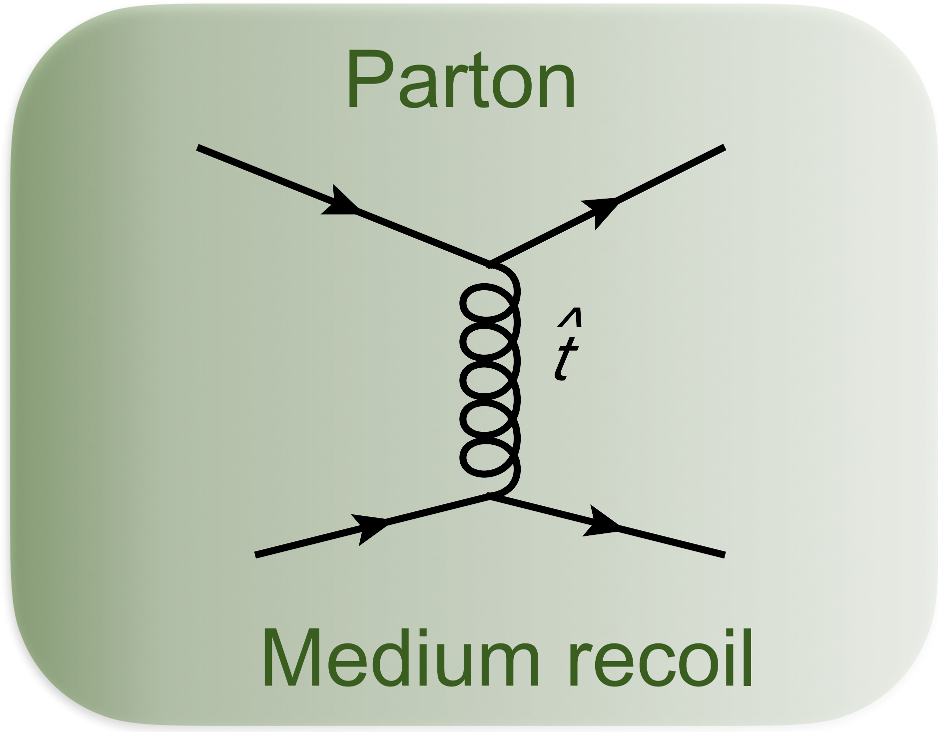


Dominant for light (high-energy) partons

Elastic scattering processes:

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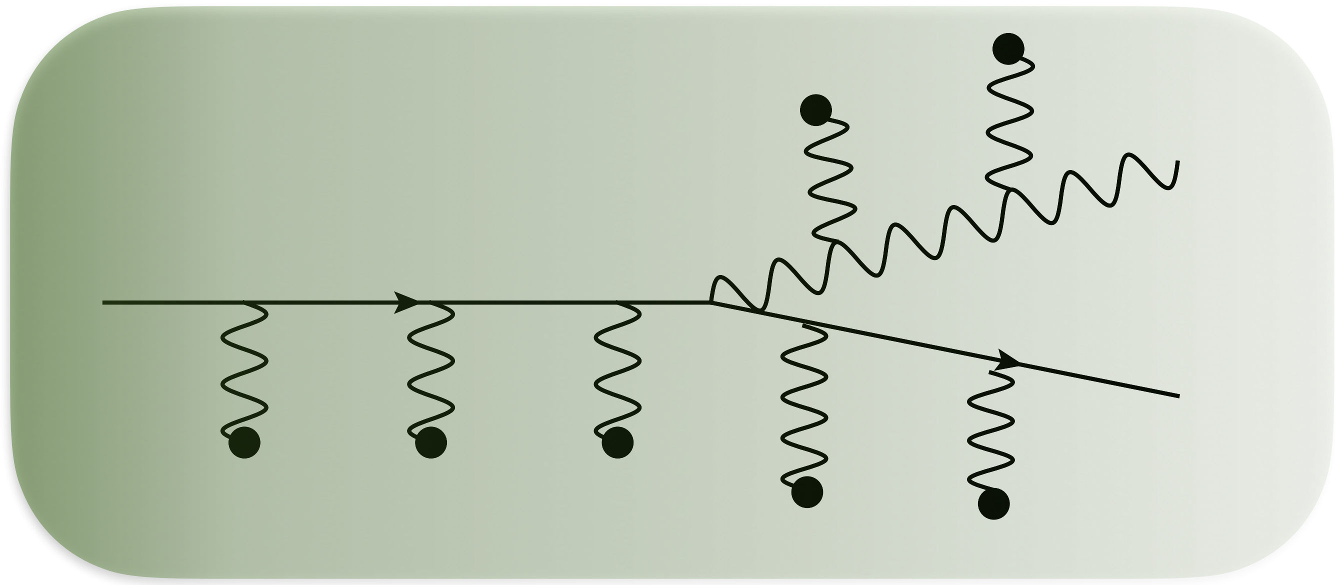
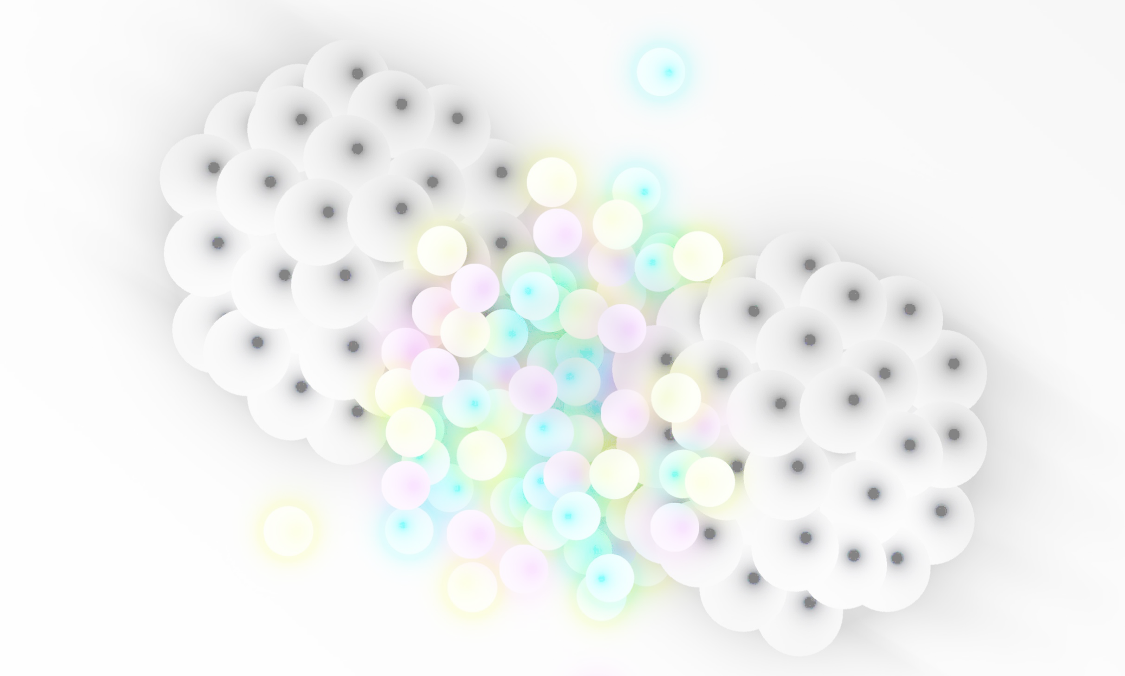
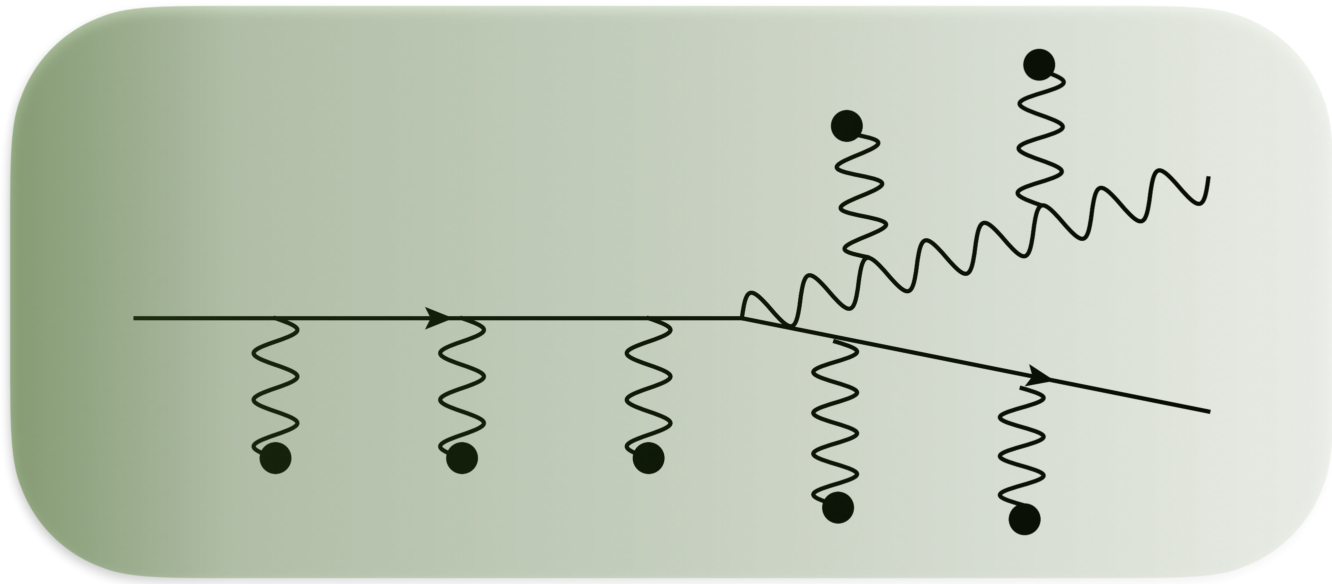


Relevant for heavy (low-energy) partons

# Medium-induced radiation



- Accumulation of momenta enhances gluon radiation:



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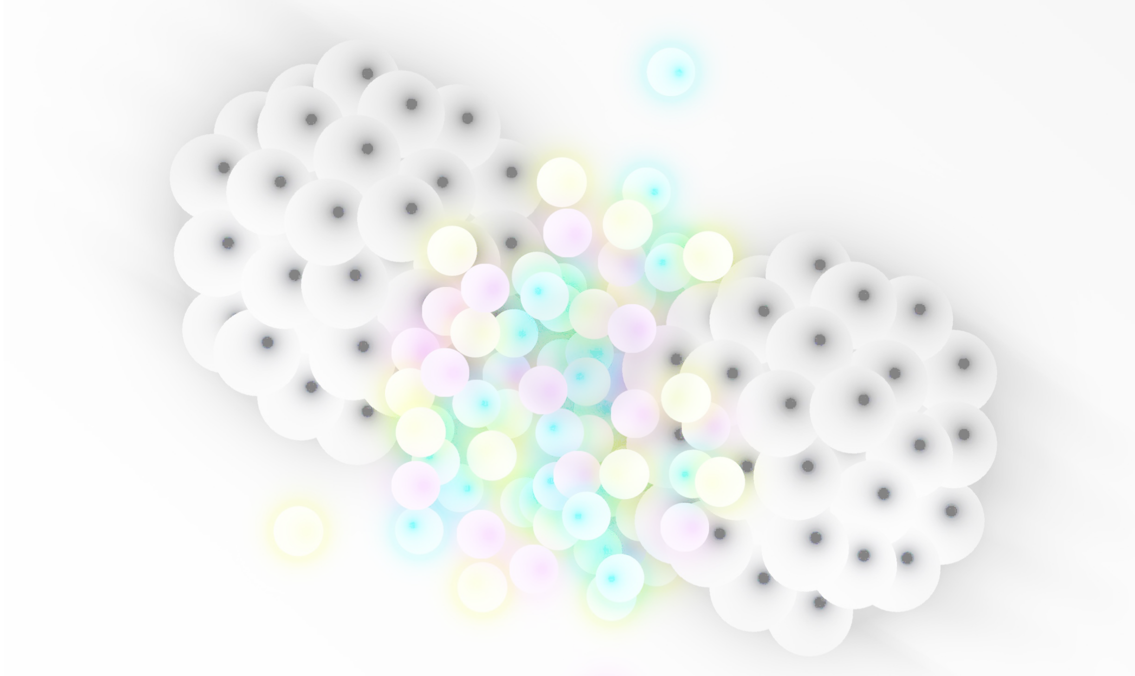
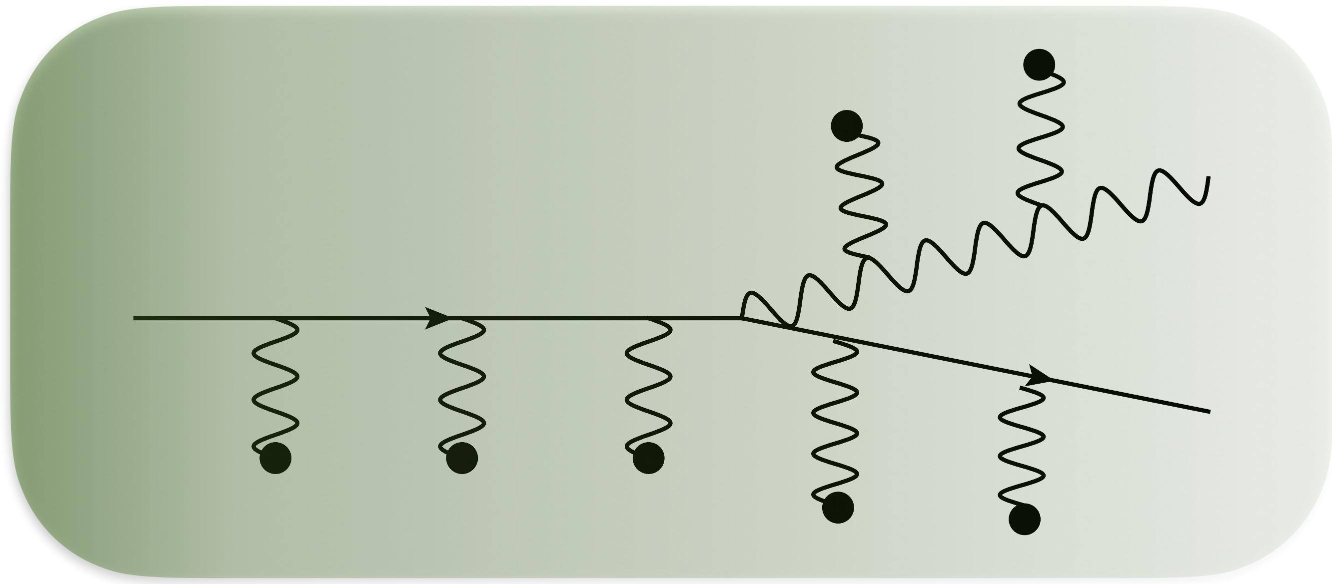
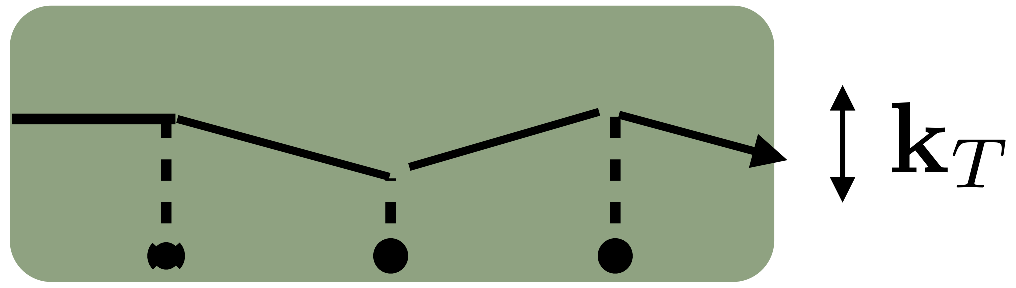


- Accumulation of momenta enhances gluon radiation:
  - In addition to energy loss, parton also undergoes transverse momentum diffusion
    - Medium-induced transverse momentum broadening

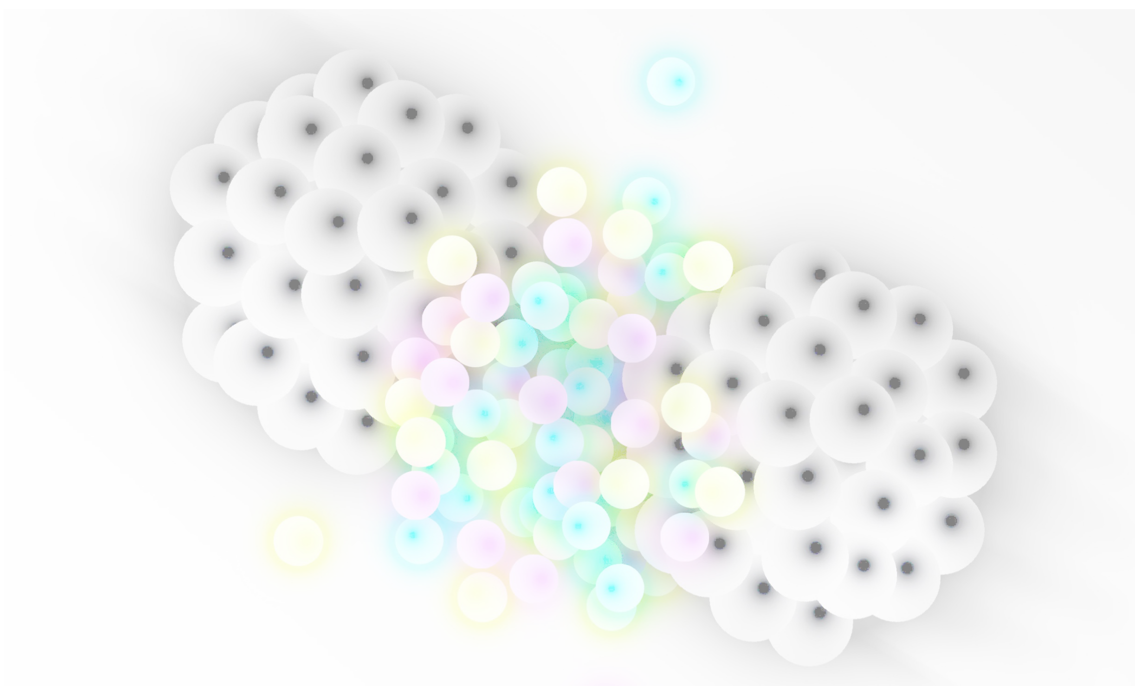





**Transport coefficient:**

$$\hat{q} = \frac{\langle k_T \rangle}{\lambda}$$

$$\hat{q} \propto \int d^2\mathbf{q}^2 q^2 \frac{d\sigma(\mathbf{q})}{d^2\mathbf{q}}$$



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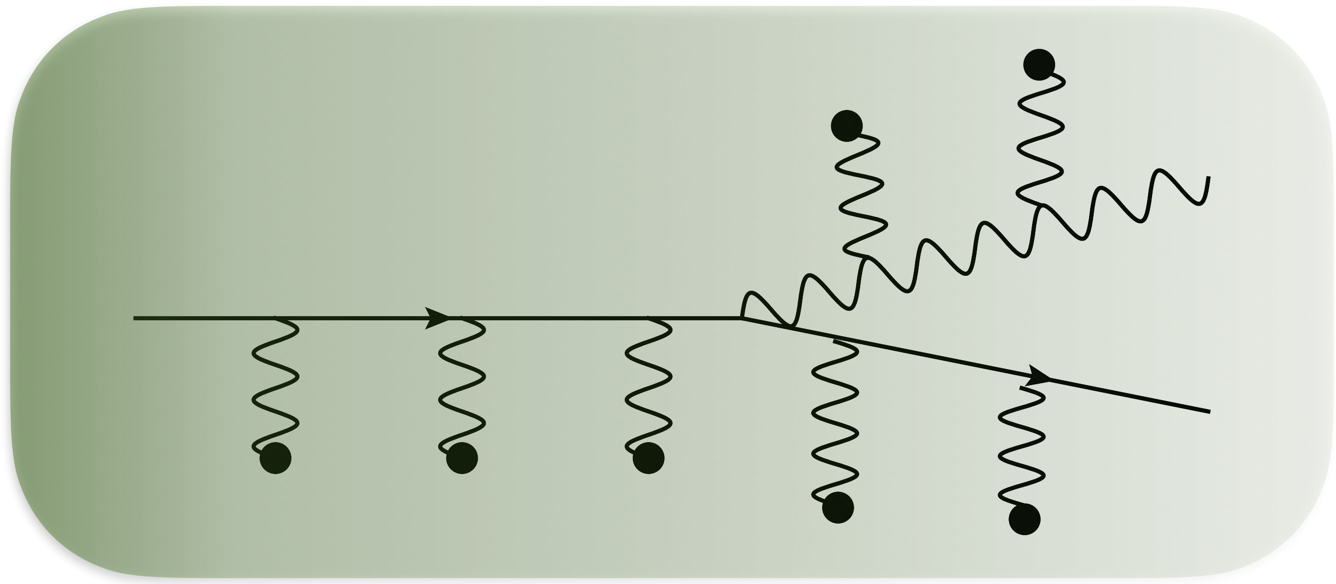

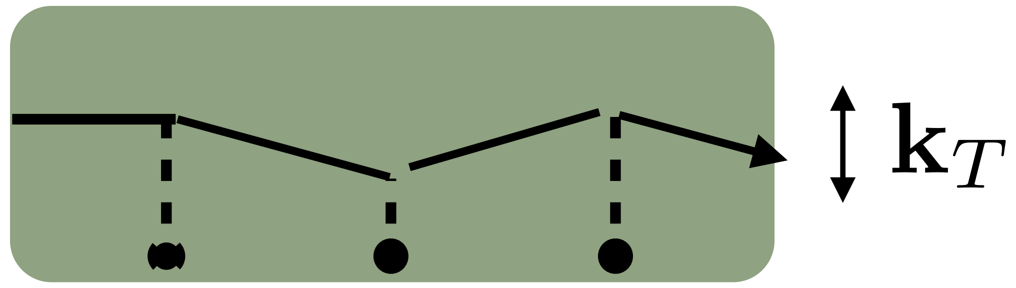


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**Dipole cross-section (collision rate):**

$$\sigma(\boldsymbol{r}) = \int_{\boldsymbol{q}} V(\boldsymbol{q}) \left(1 - e^{i\boldsymbol{q}\boldsymbol{r}}\right)$$

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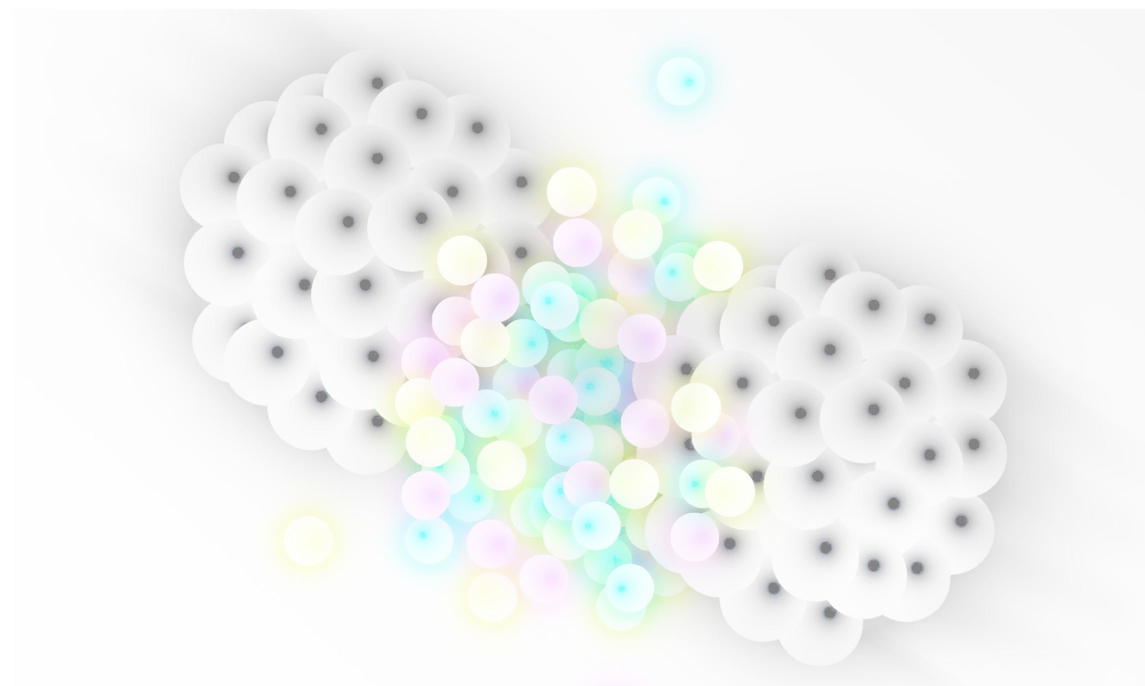

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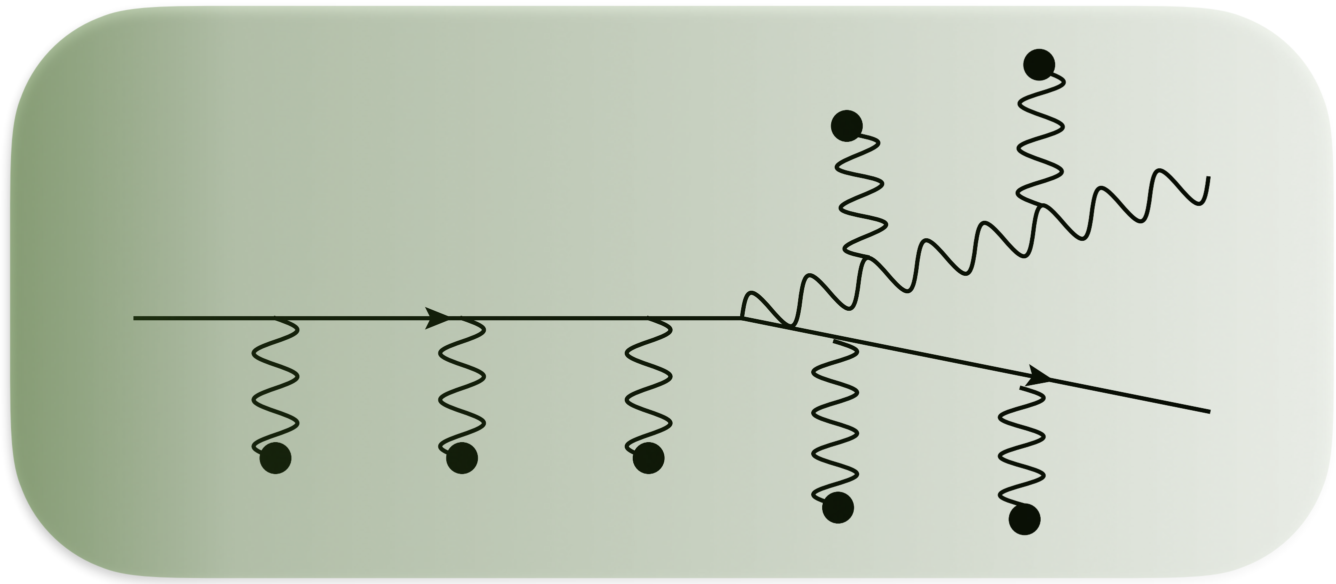

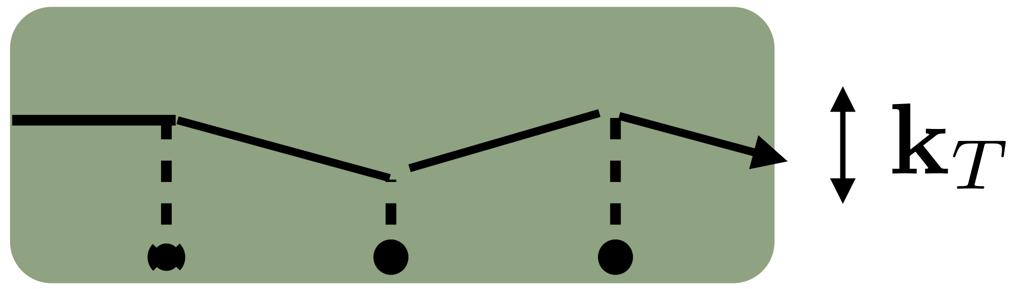


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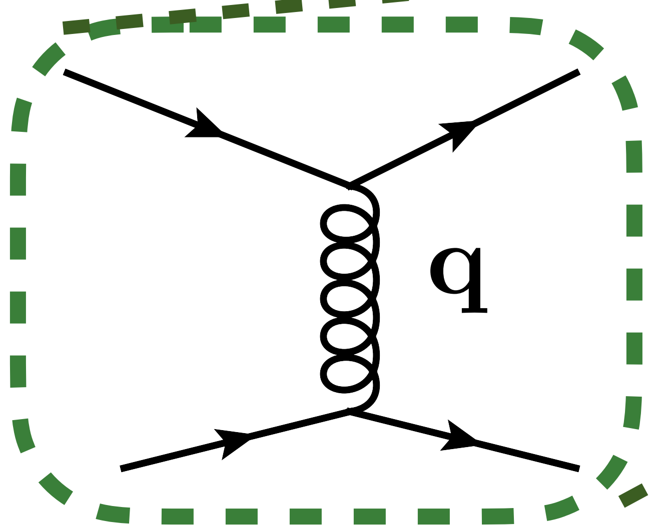
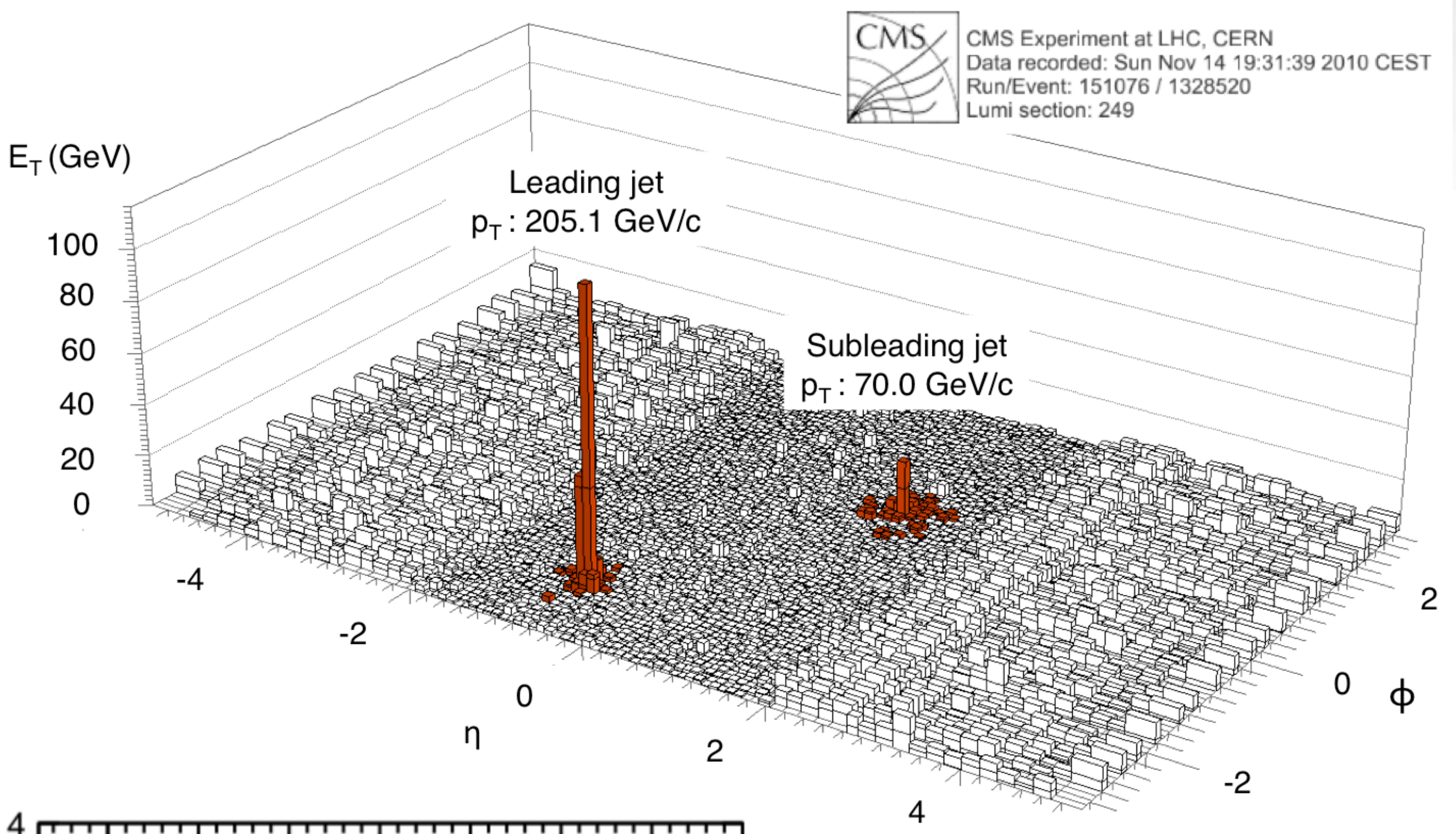


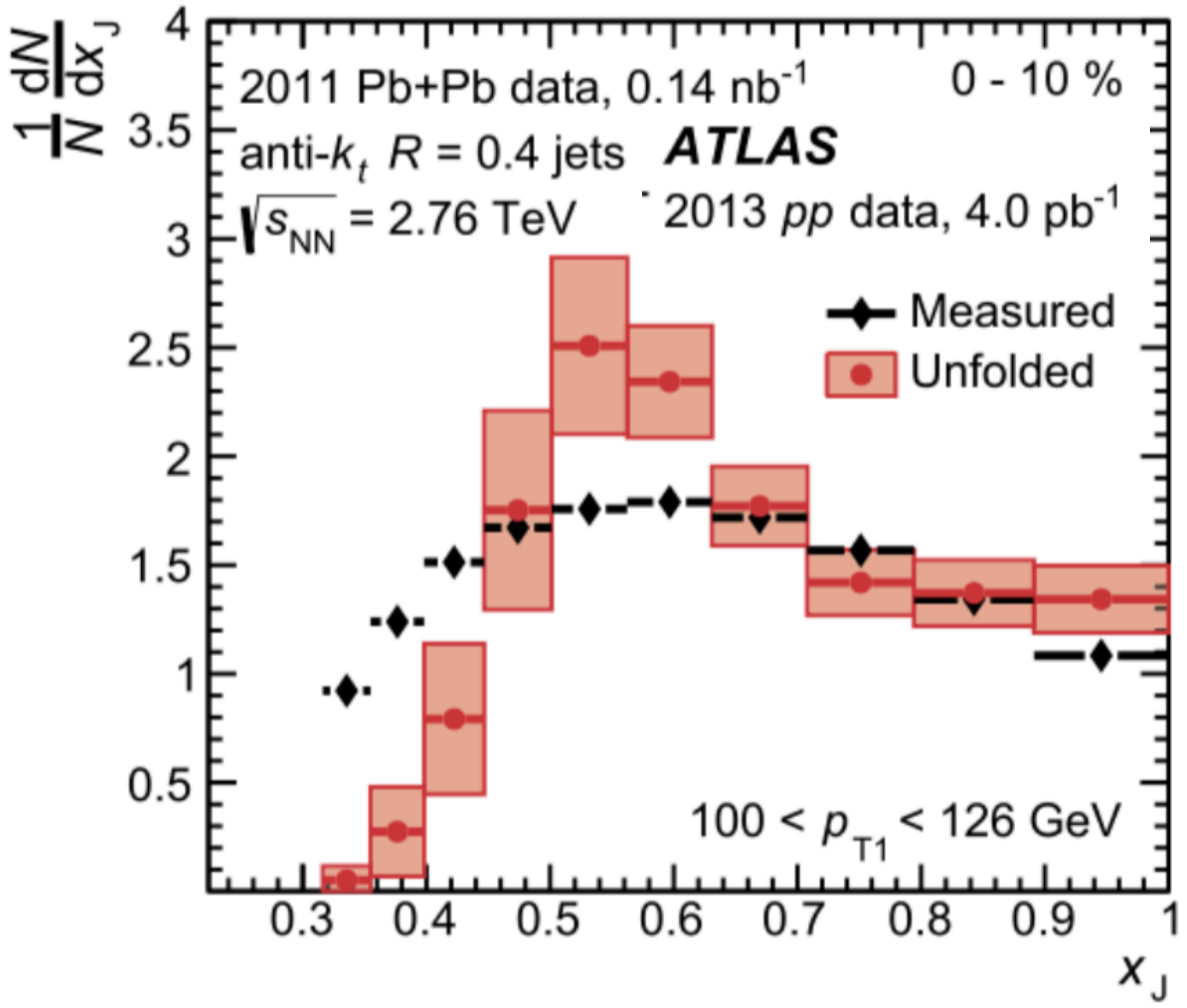

Parton-medium interaction

**Medium-induced energy loss and momentum broadening closely connected!**

# Energy Loss

- Jet quenching was a major step in establishing the QGP
  - It was needed:
    - Theoretical developments to accurately address QGP-jet interactions
    - Experimental control to reconstruct jets in a large and fluctuating background

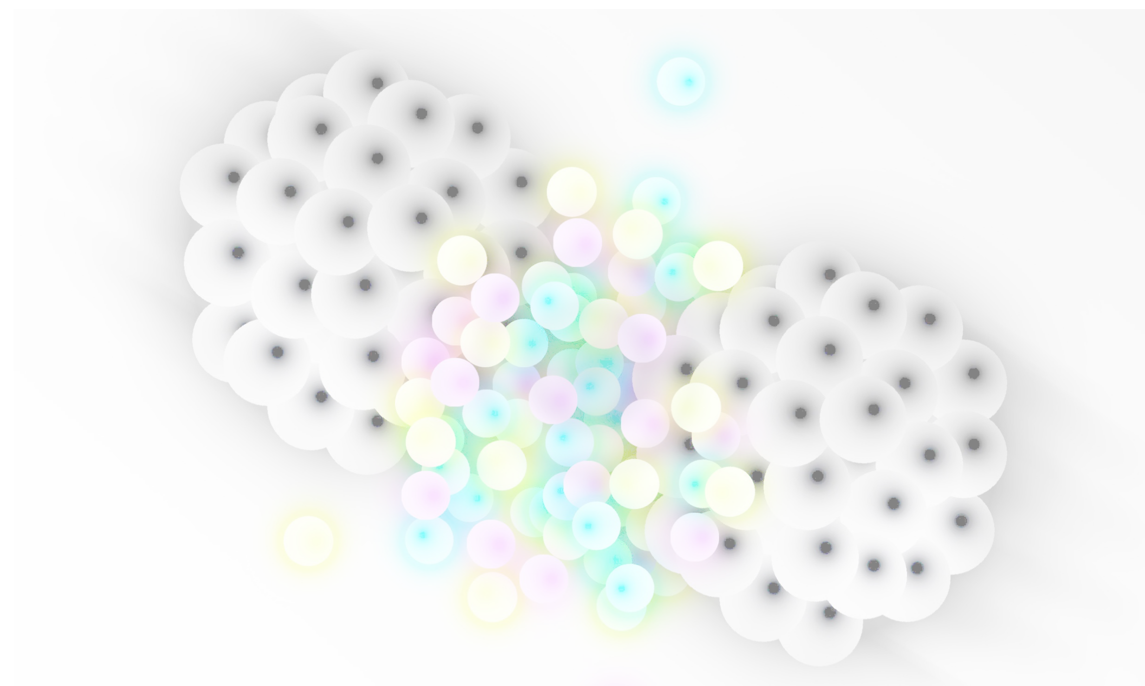


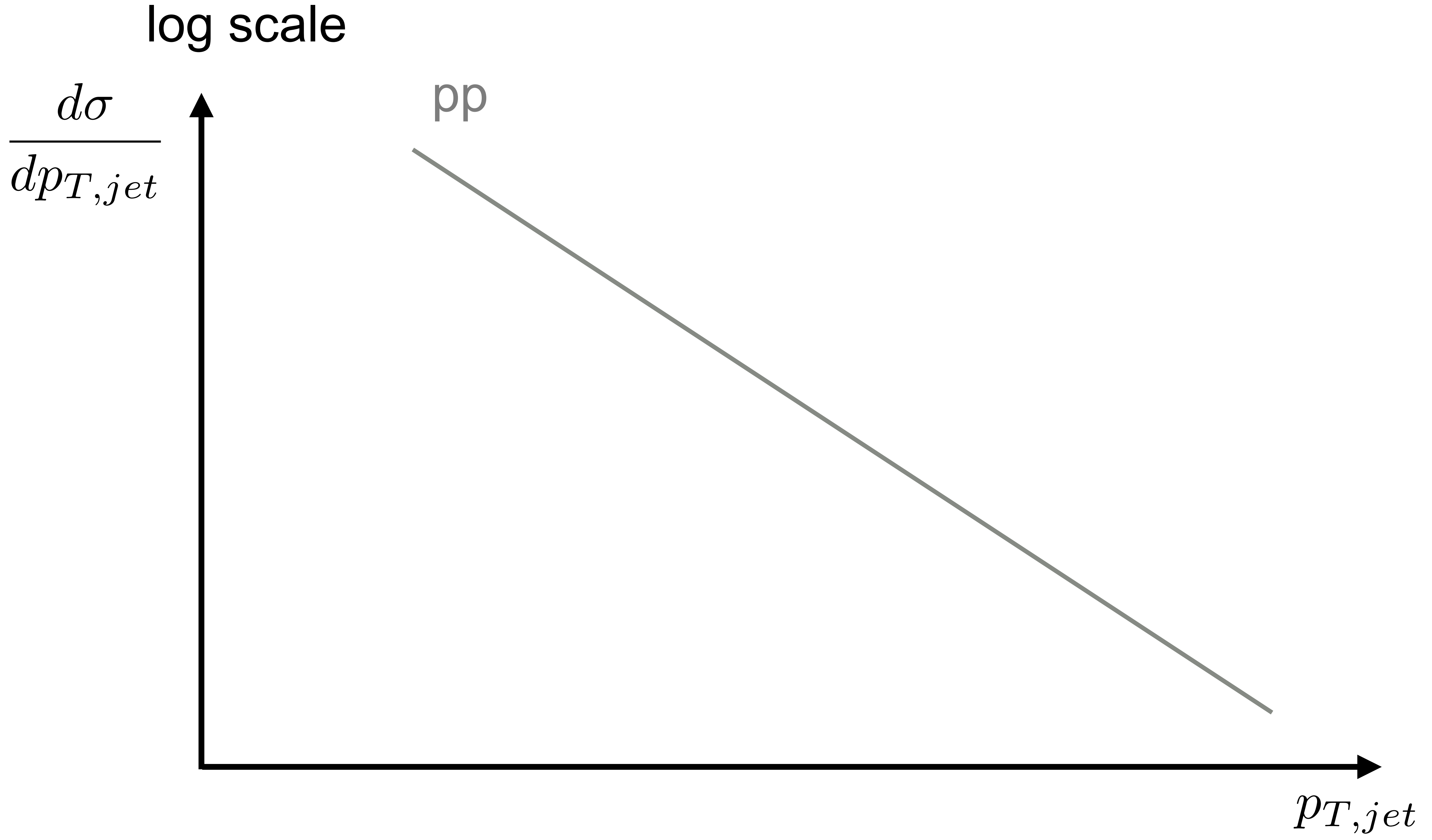

$x_J = p_{T_2}/p_{T_1},$

Initial efforts towards global jet properties

# Average in-medium jets



- Jet spectrum affected by jet-QGP interactions:
  - Energy loss will shift population towards smaller $p_T$



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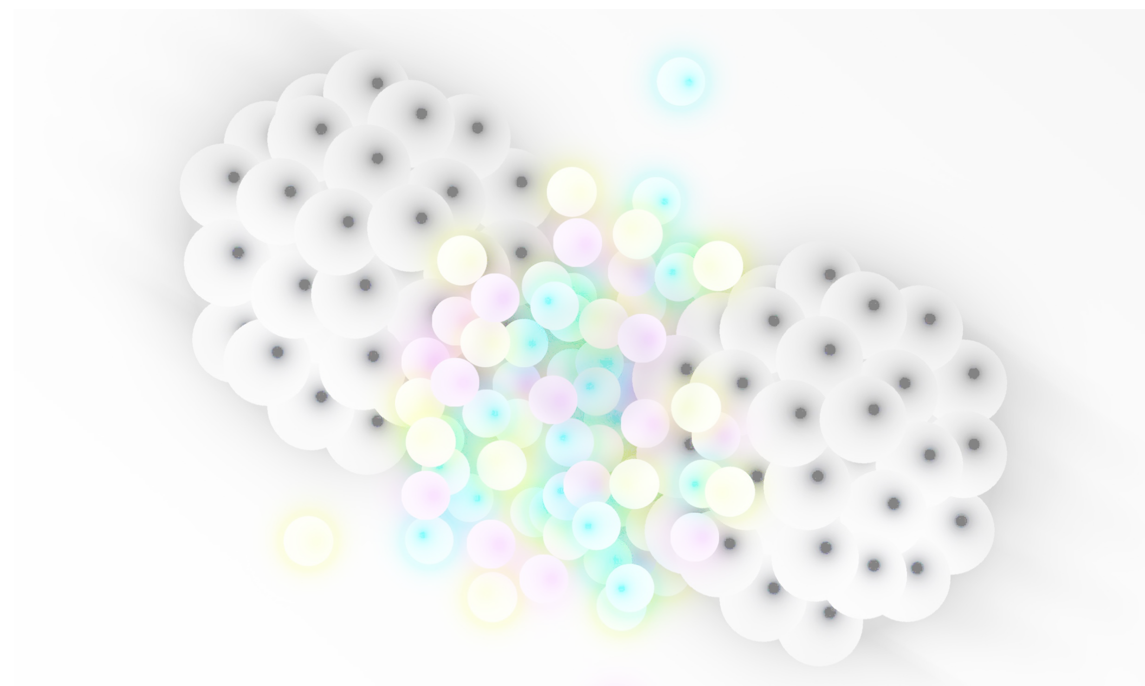

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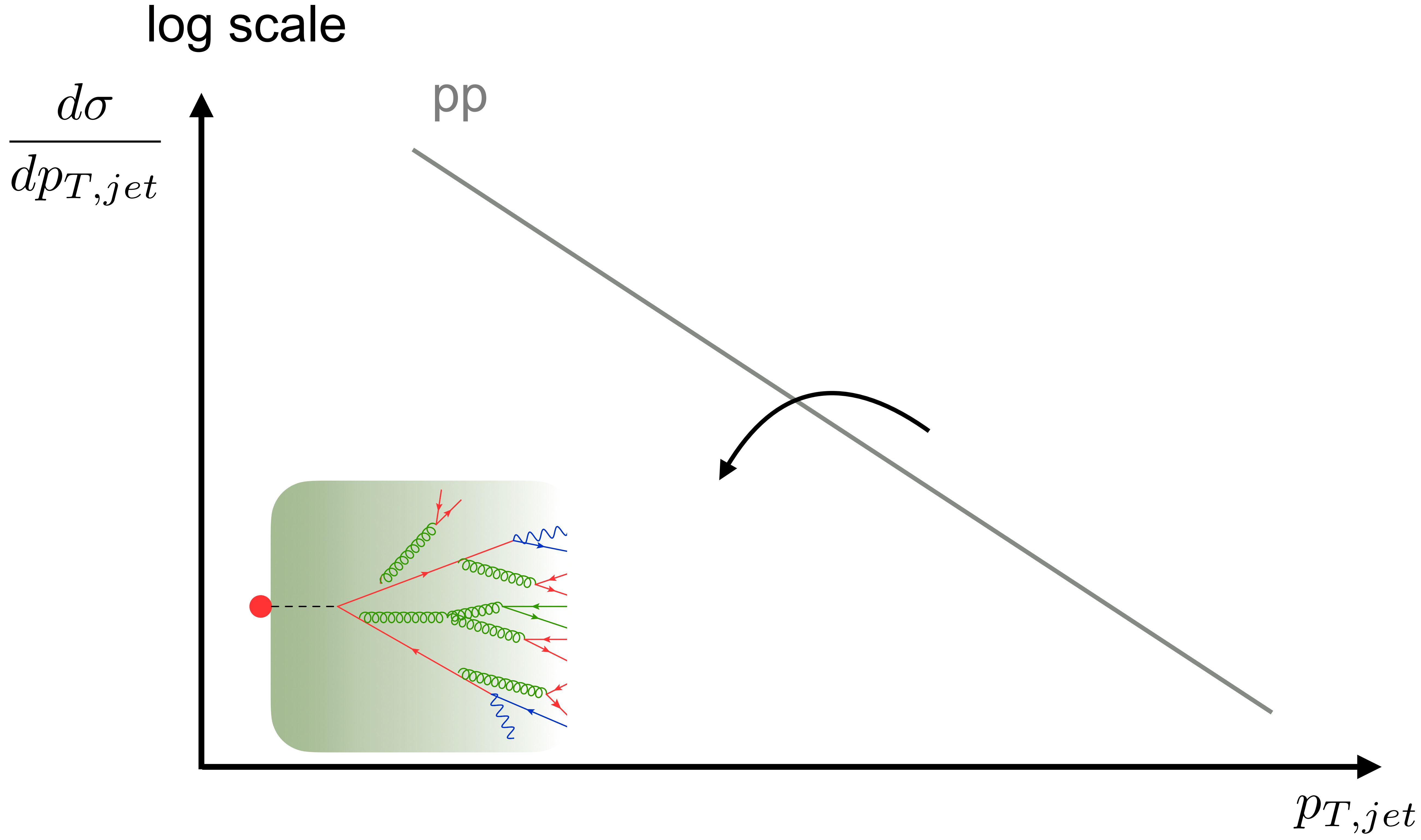

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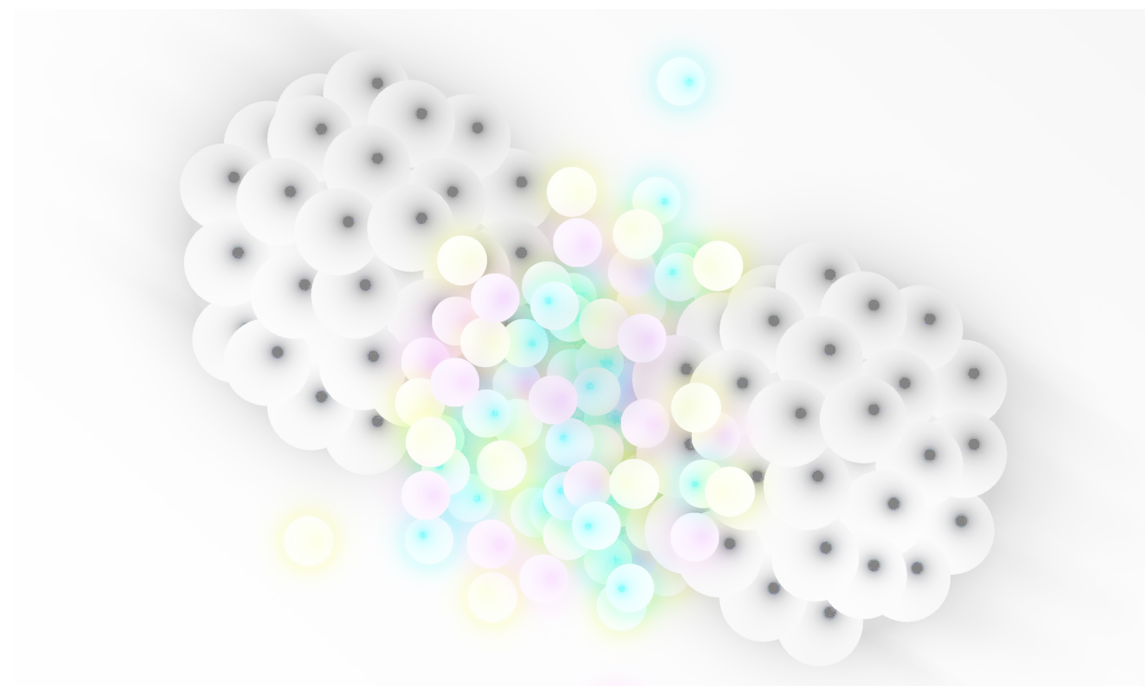

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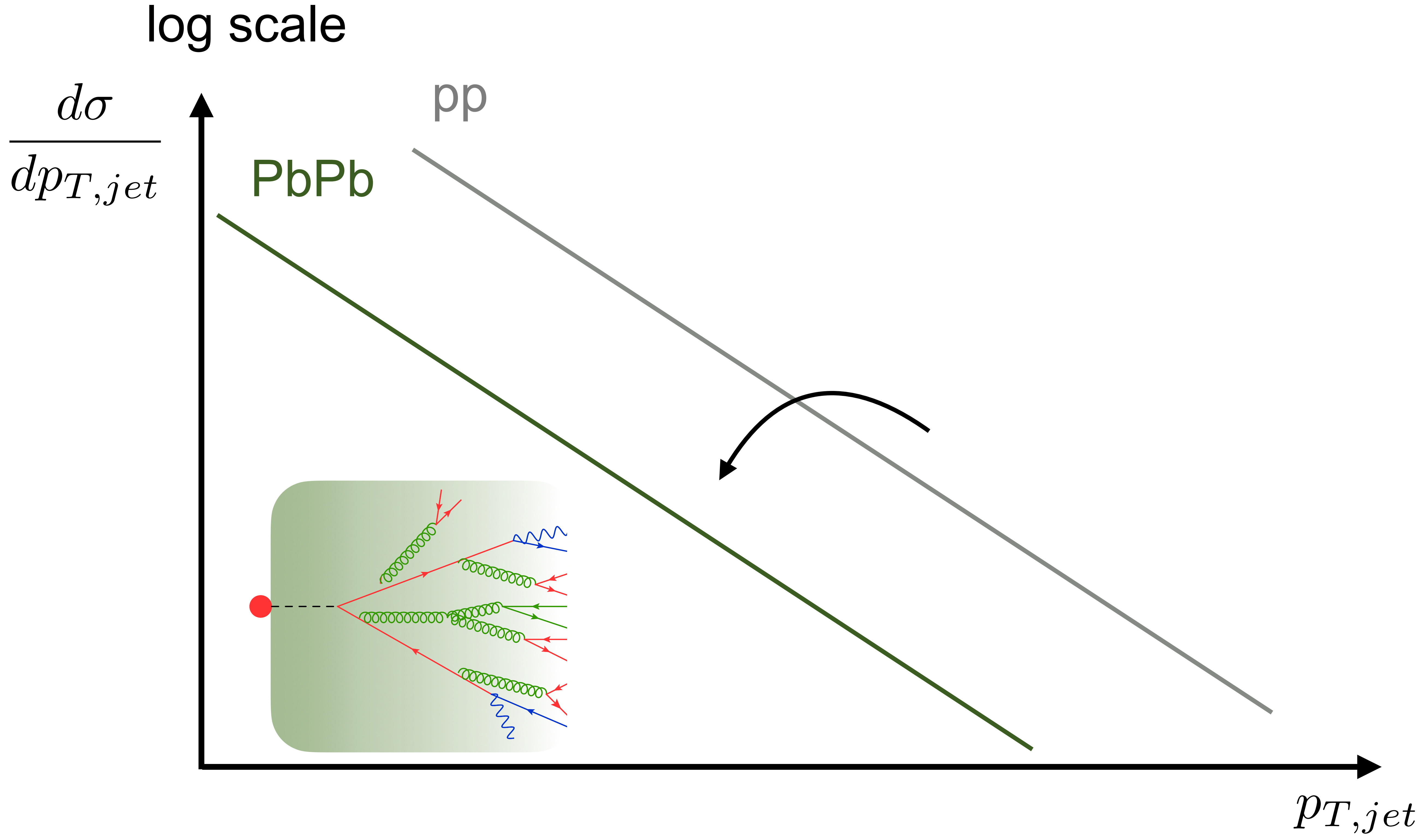

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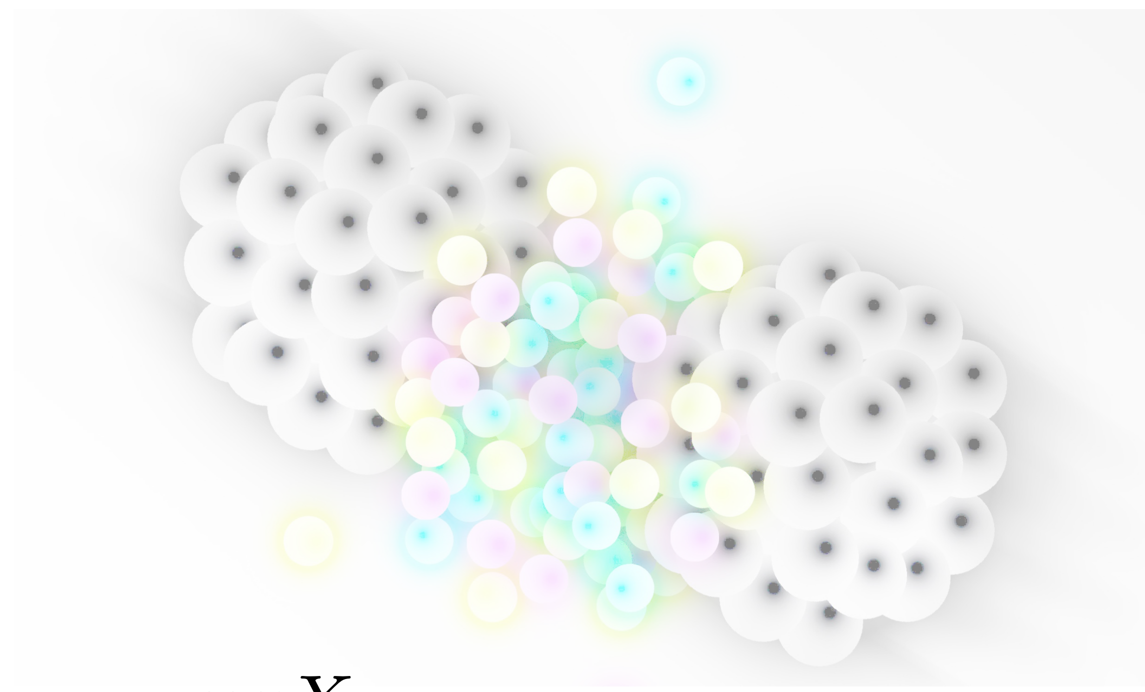

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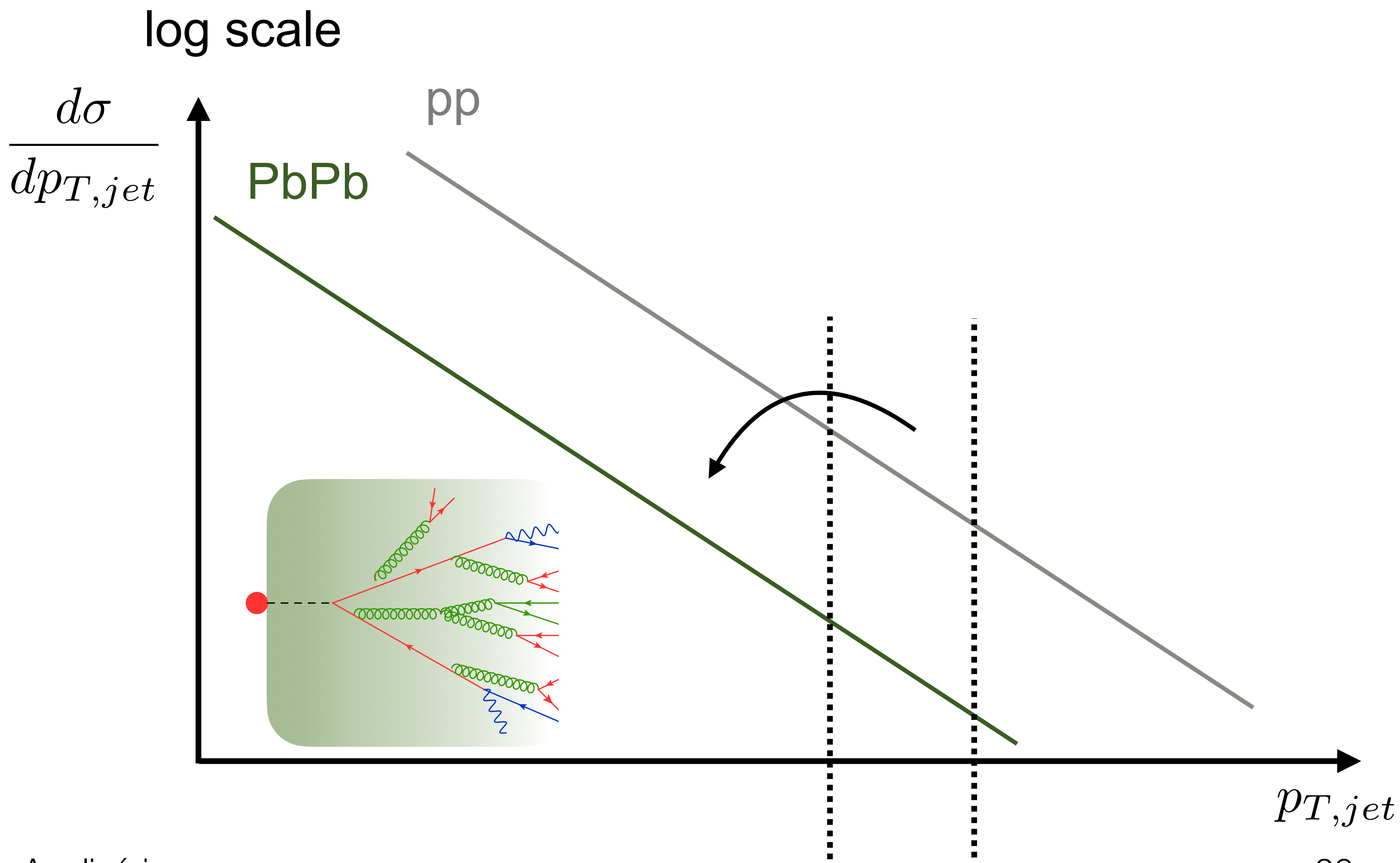
$$R_{AA} = \frac{Y_{AA}^X}{\langle T_{AA} \rangle \cdot \sigma_{pp}^X}$$



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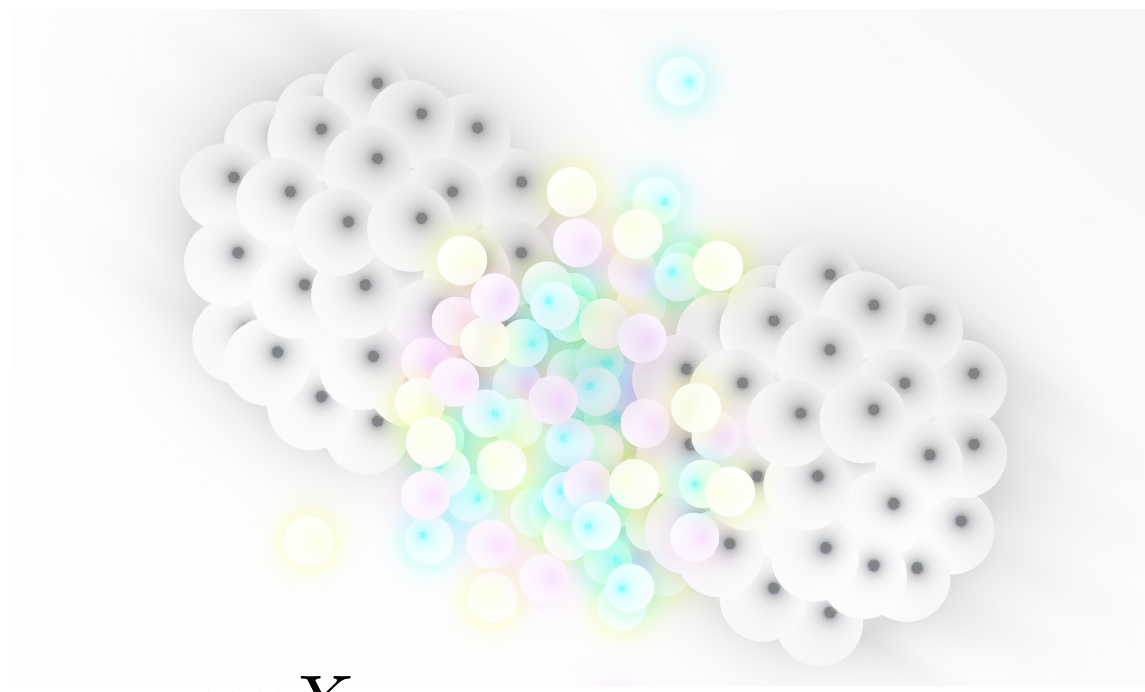

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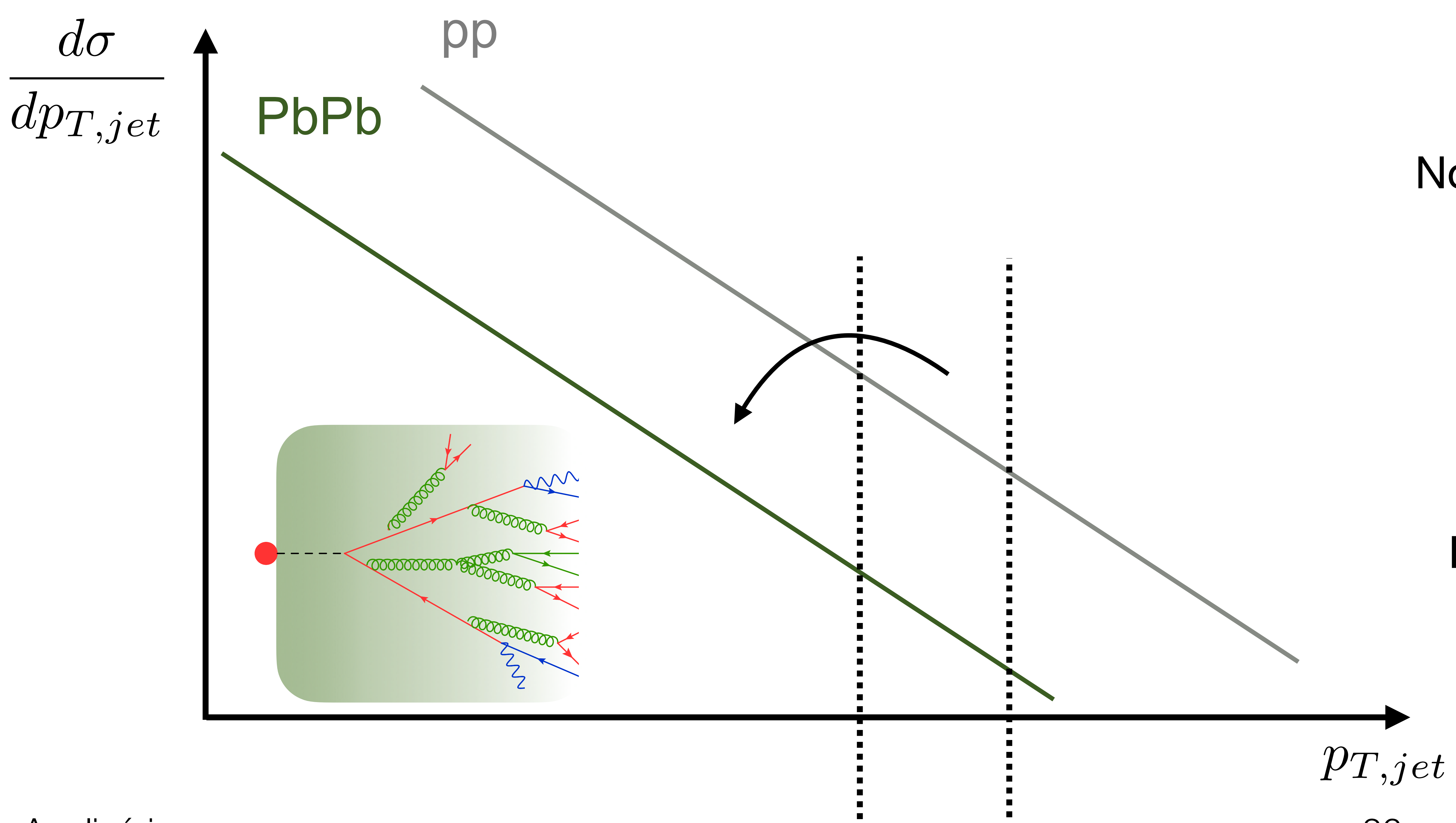
$$R_{AA} = \frac{Y^X_{AA}}{\langle T_{AA} \rangle \cdot \sigma^X_{pp}}$$

log scale



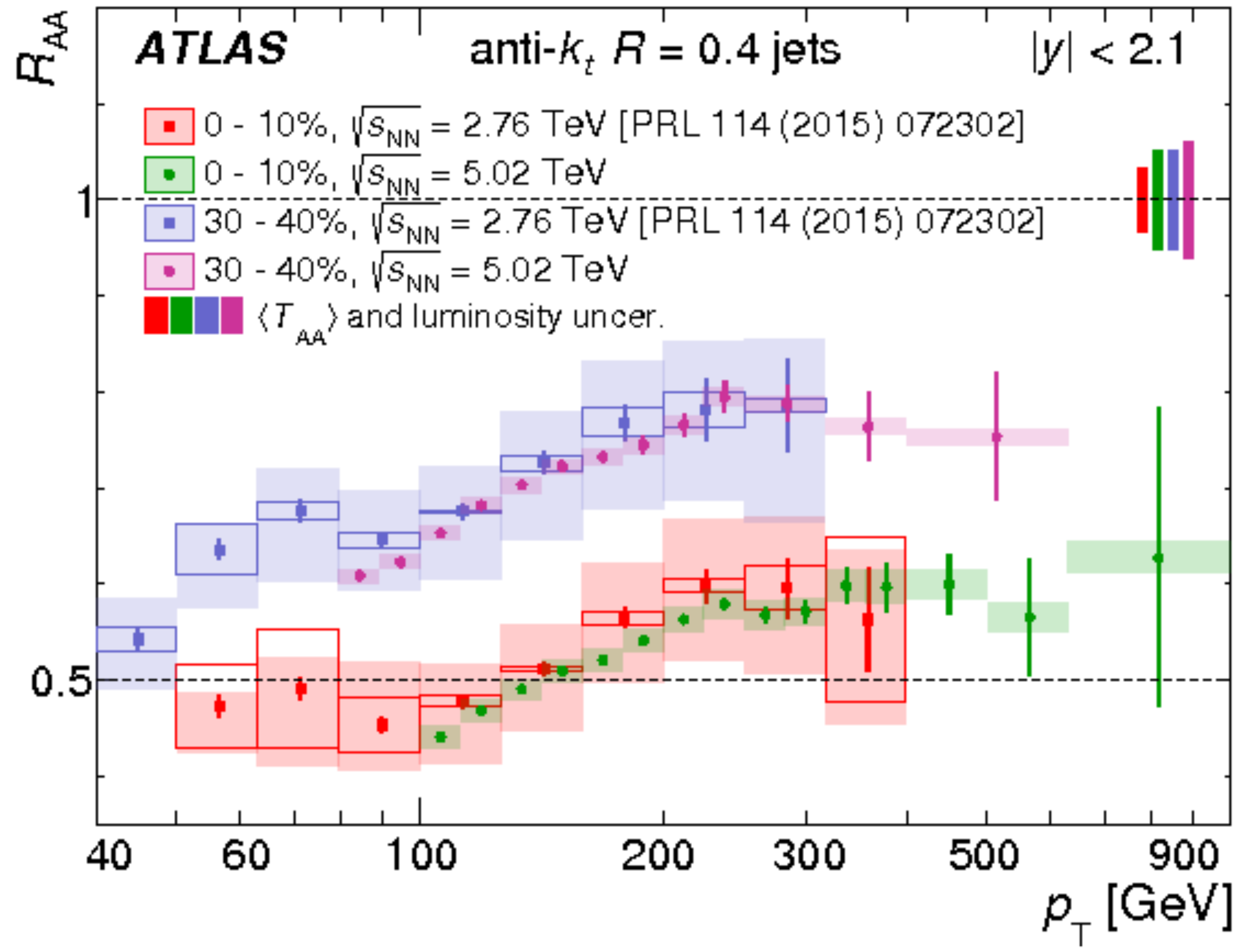

$R_{AA} = 1$

No energy loss

$R_{AA} < 1$

Energy loss

[ATLAS (19)]



# Current landscape

- From single-particle or jet suppression, recover transport coefficient $\hat{q}$

$R_{AA} = 1$

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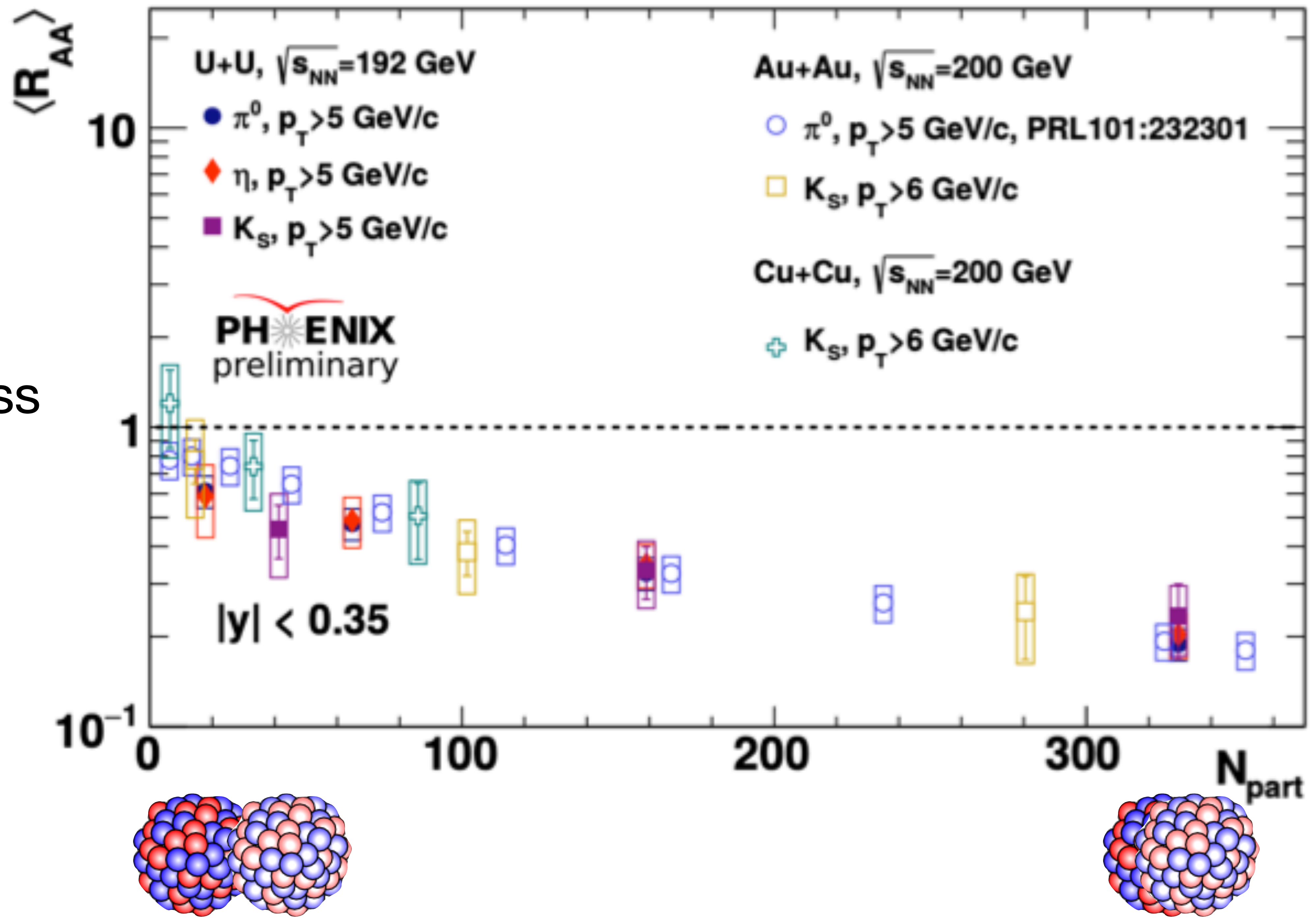
$R_{AA} < 1$

Energy loss

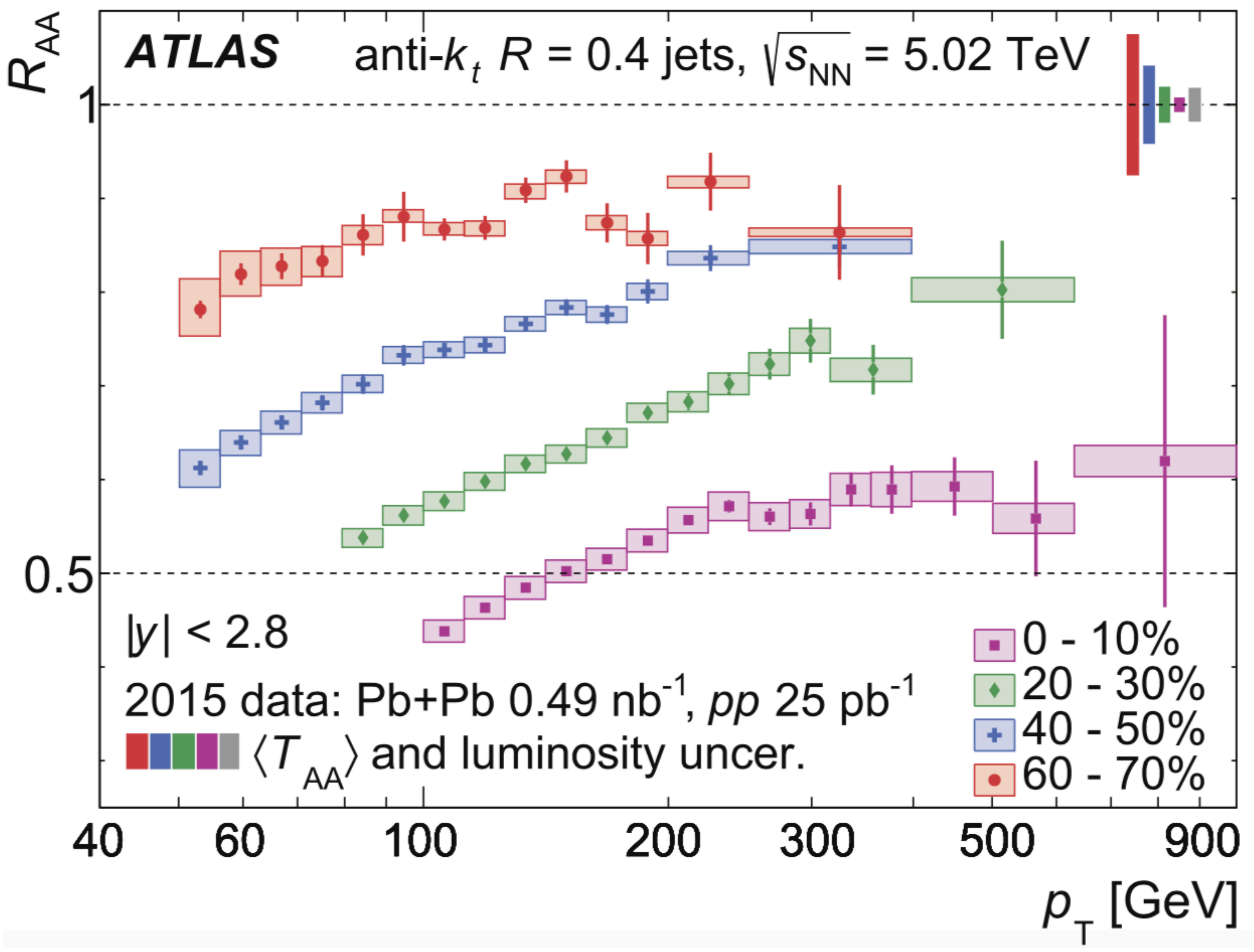
***Particle Energy Loss***

PHENIX [2002.11156]




***Jet Energy Loss***

ATLAS [1805.05635]



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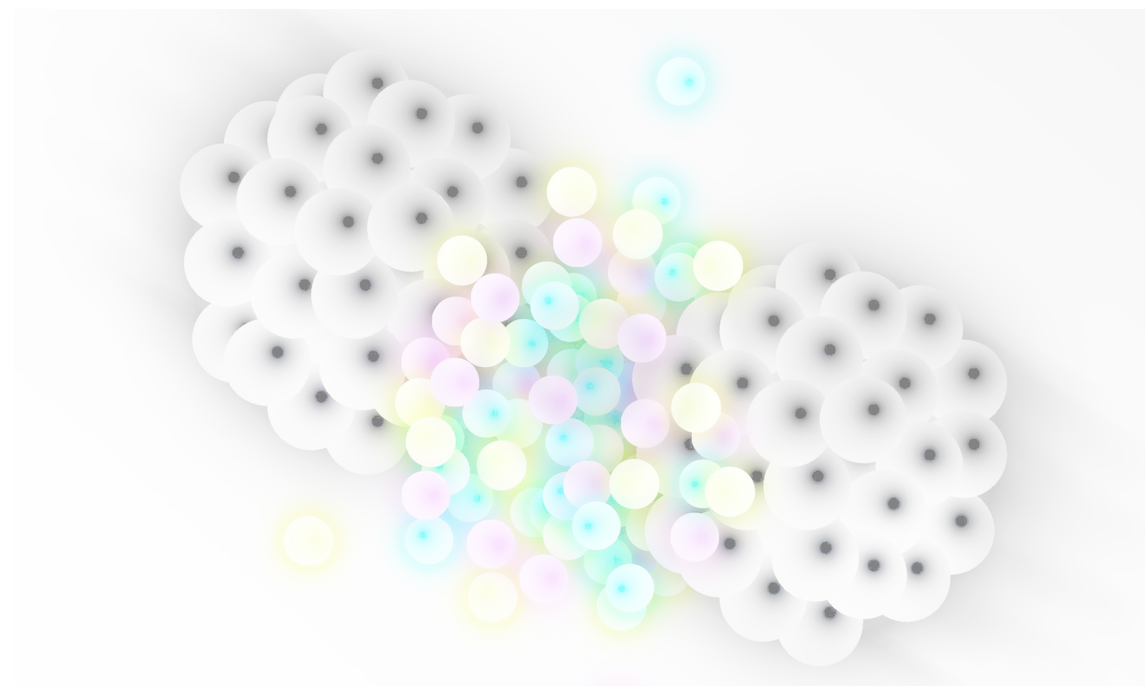

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**RHIC (AuAu 200 GeV)**

*Particle Energy Loss*

PHENIX [2002.11156]

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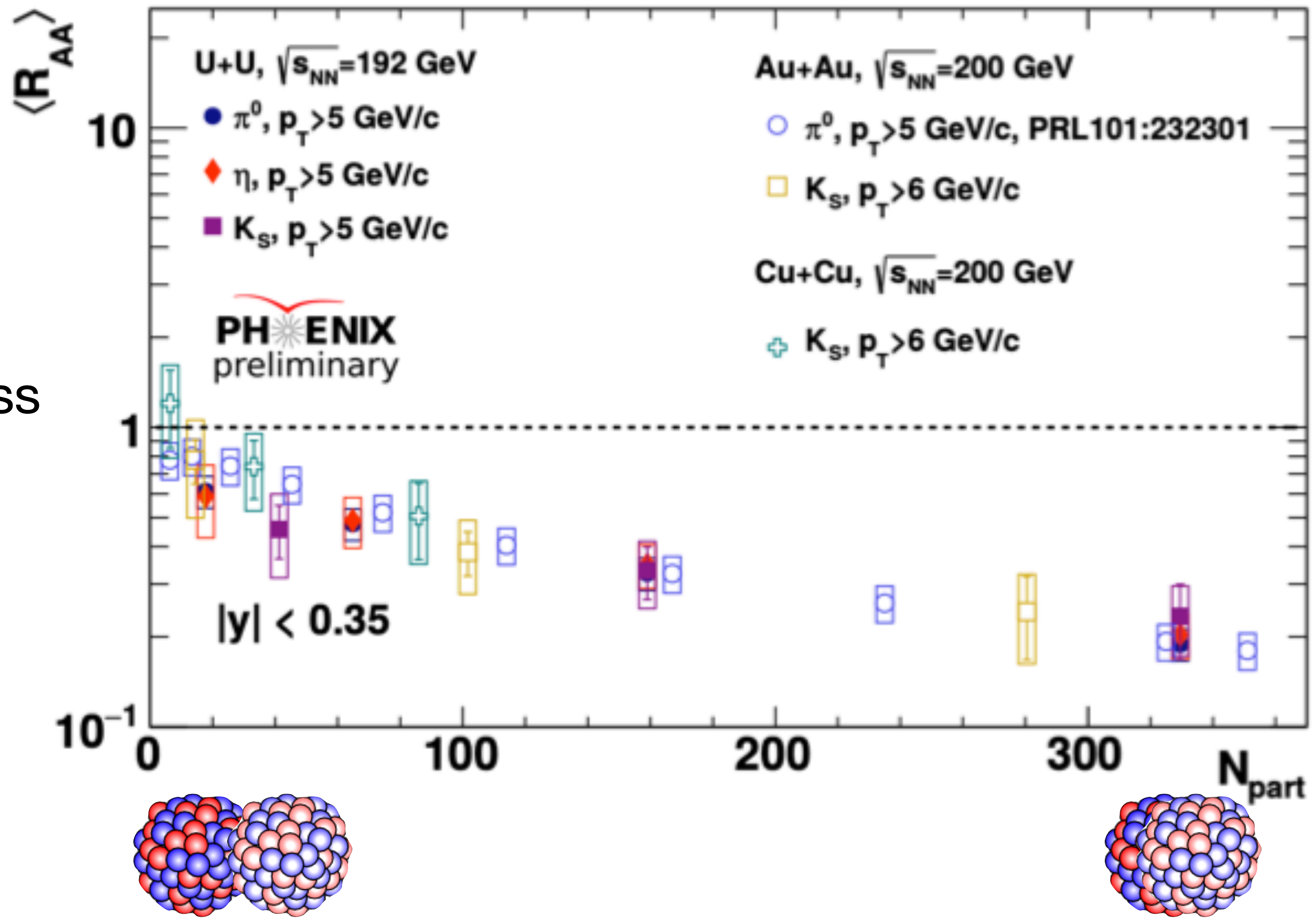
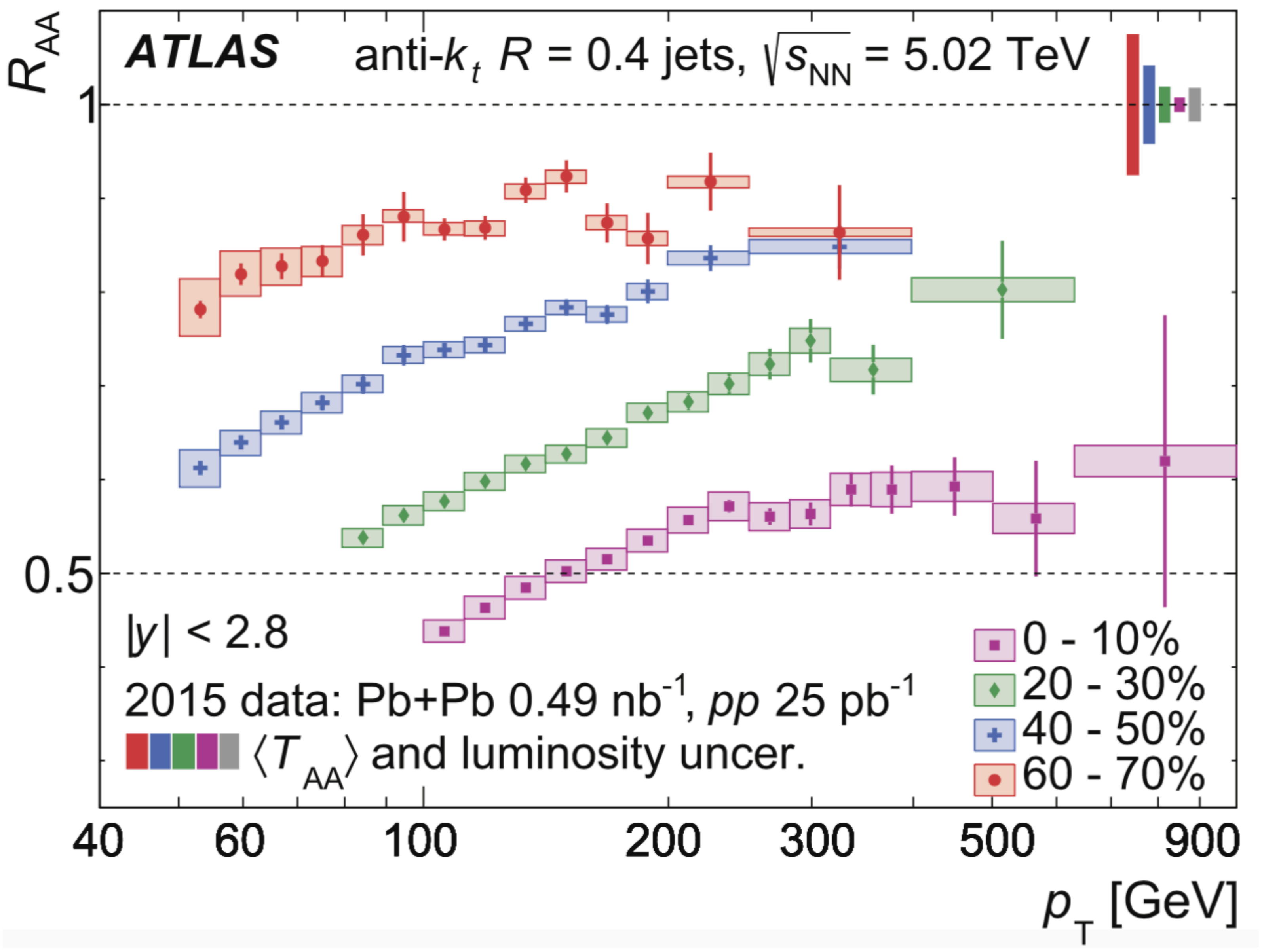
Energy loss




**LHC (PbPB 5.02 TeV)**

*Jet Energy Loss*

ATLAS [1805.05635]



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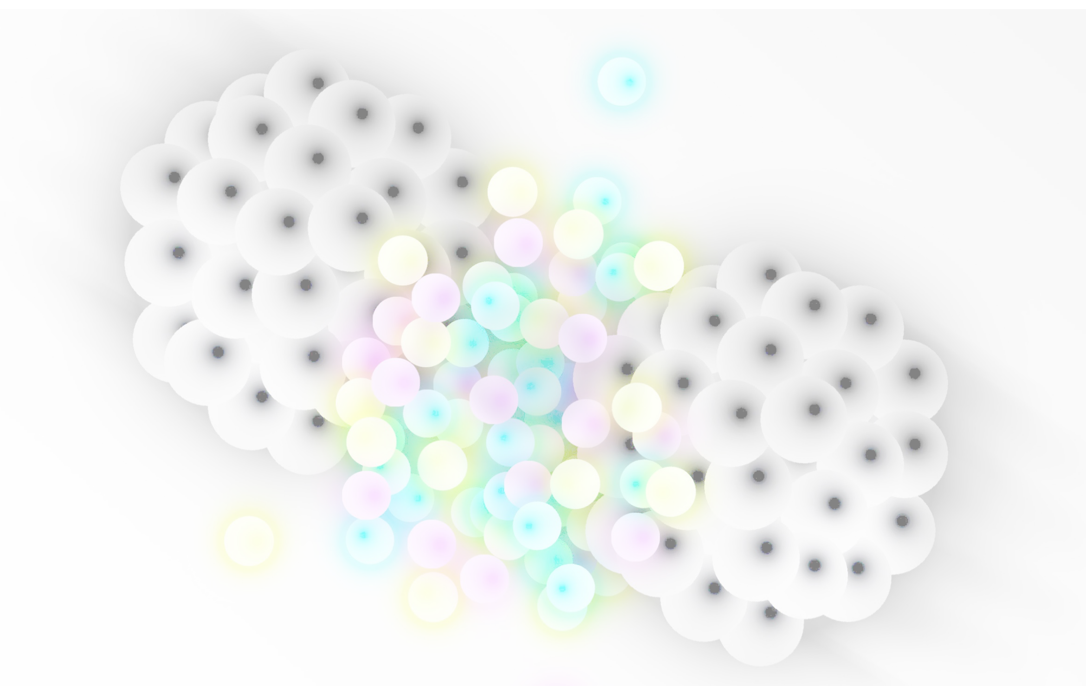

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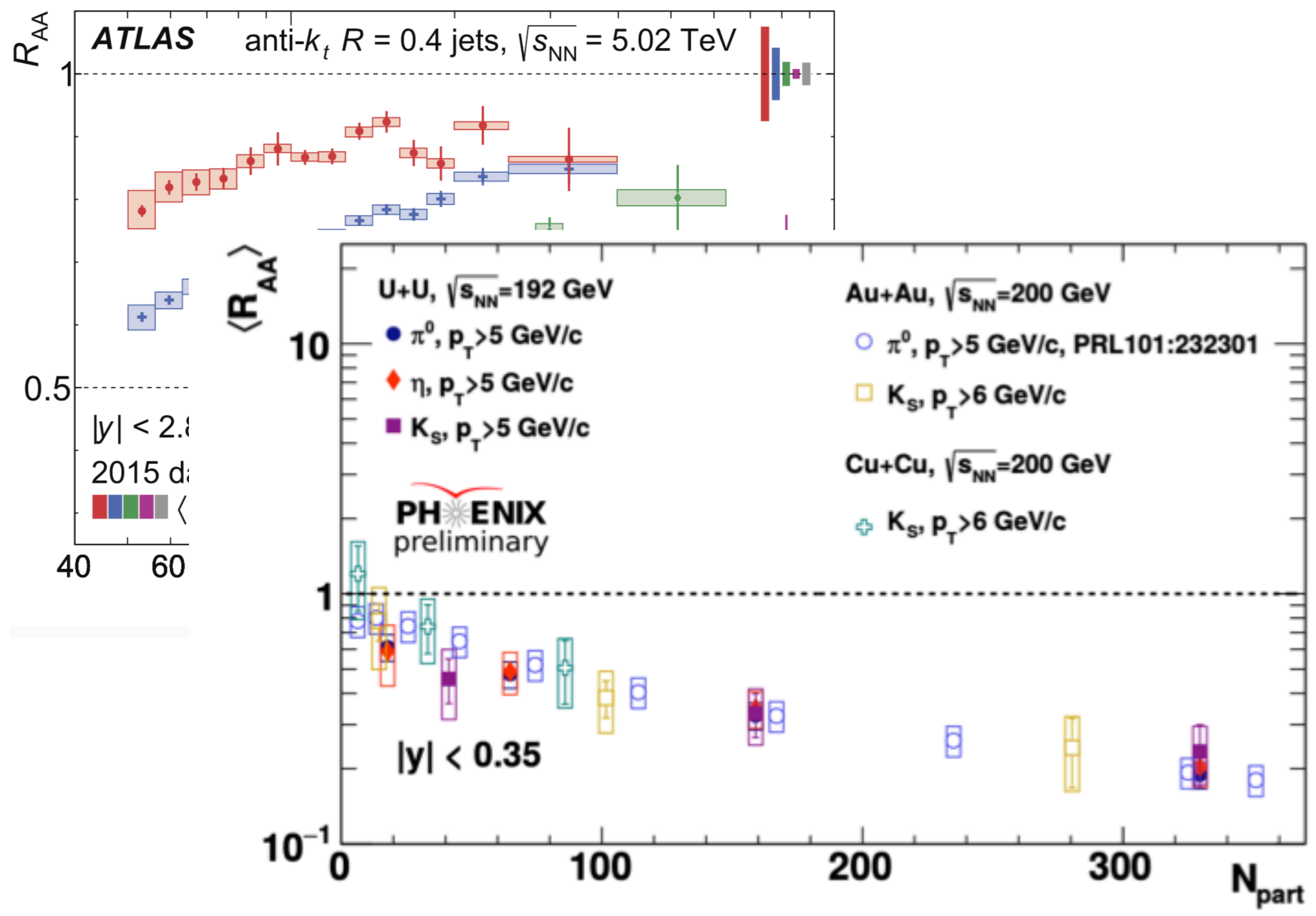
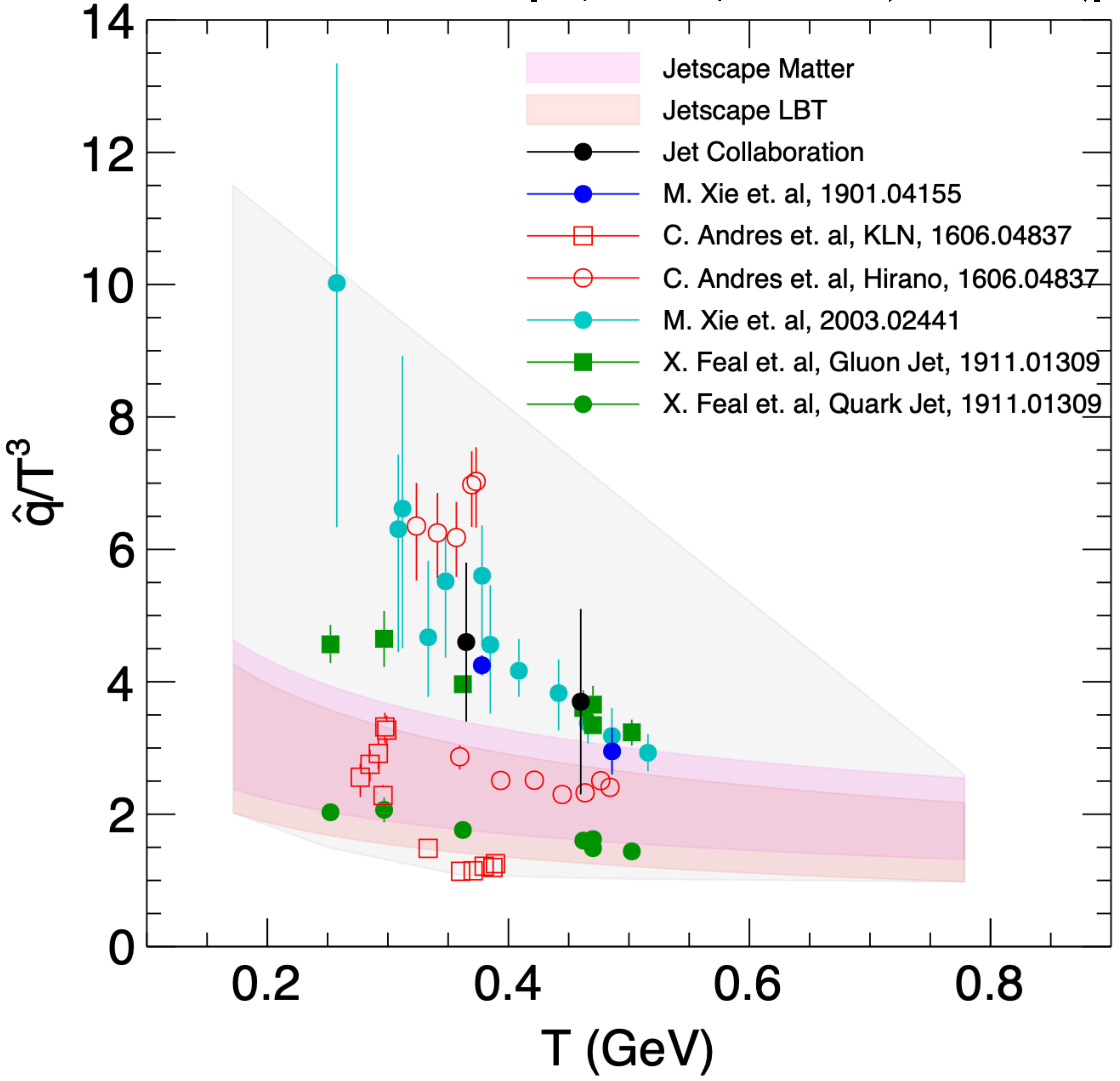



[LA, Y-J Lee, M. Winn (2203.16352)]



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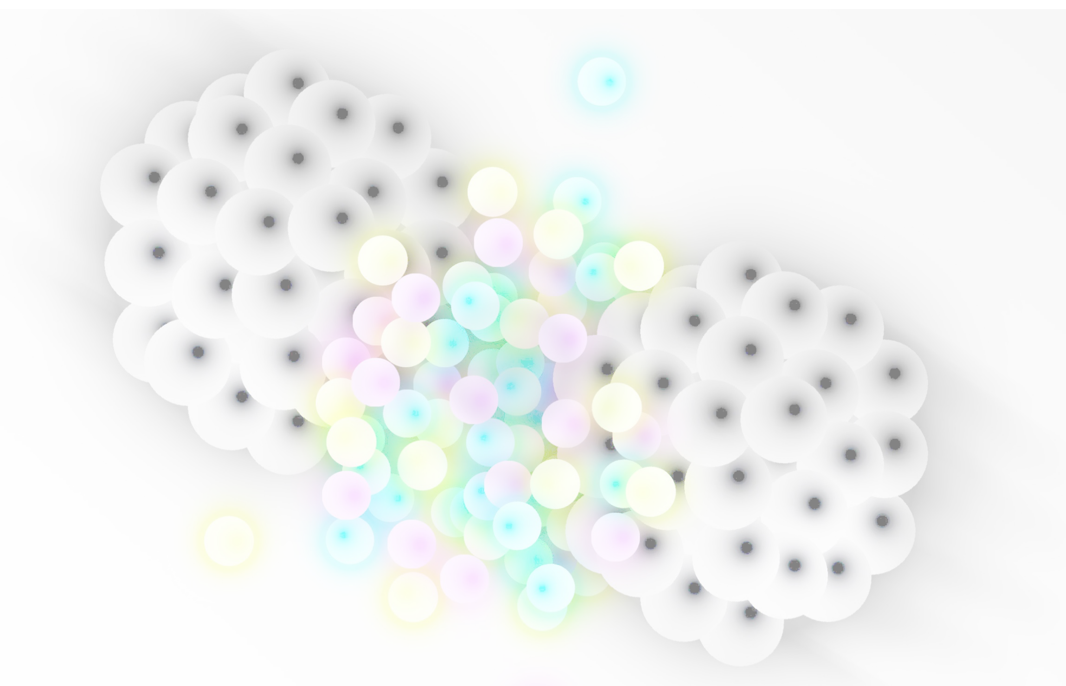

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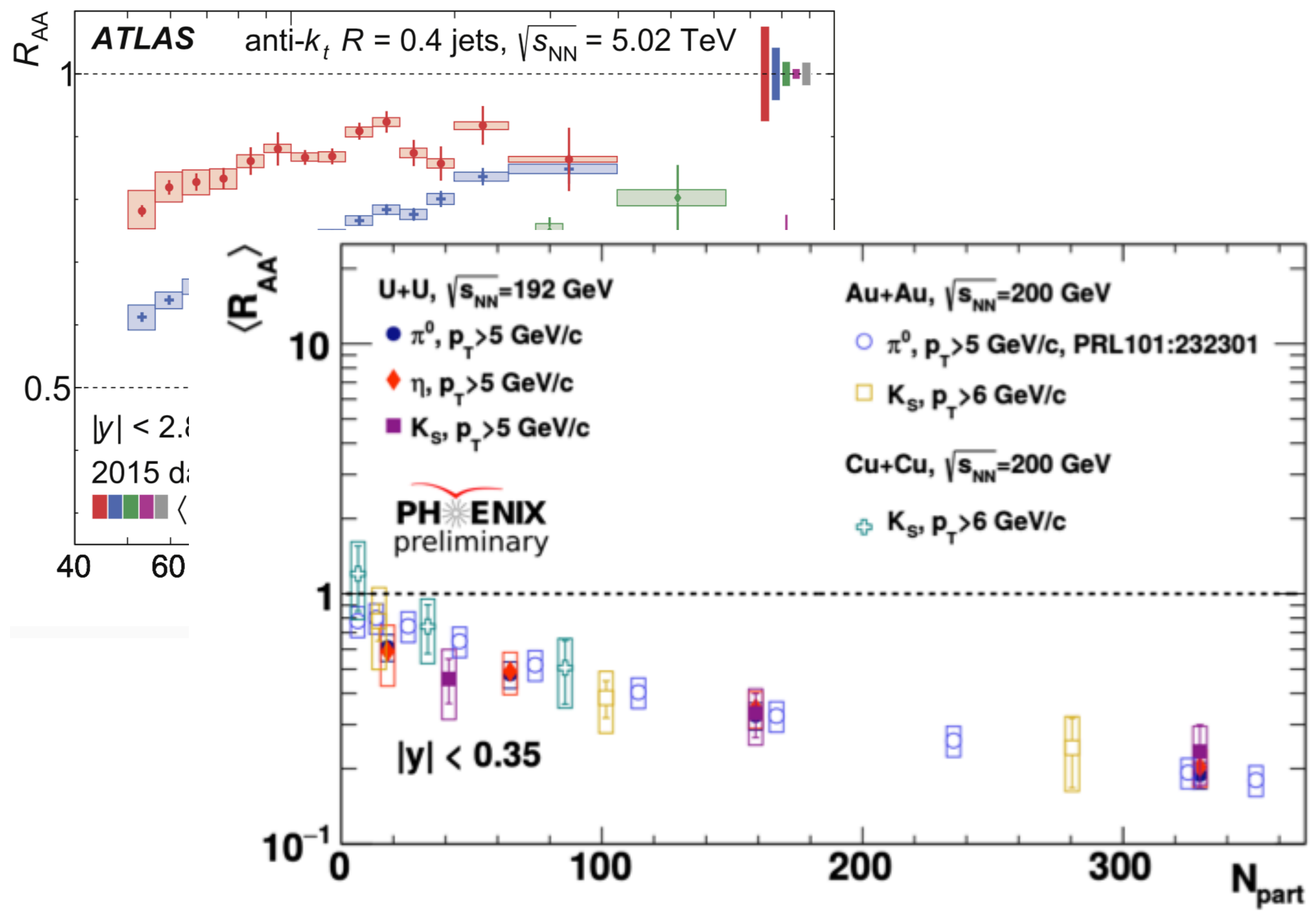
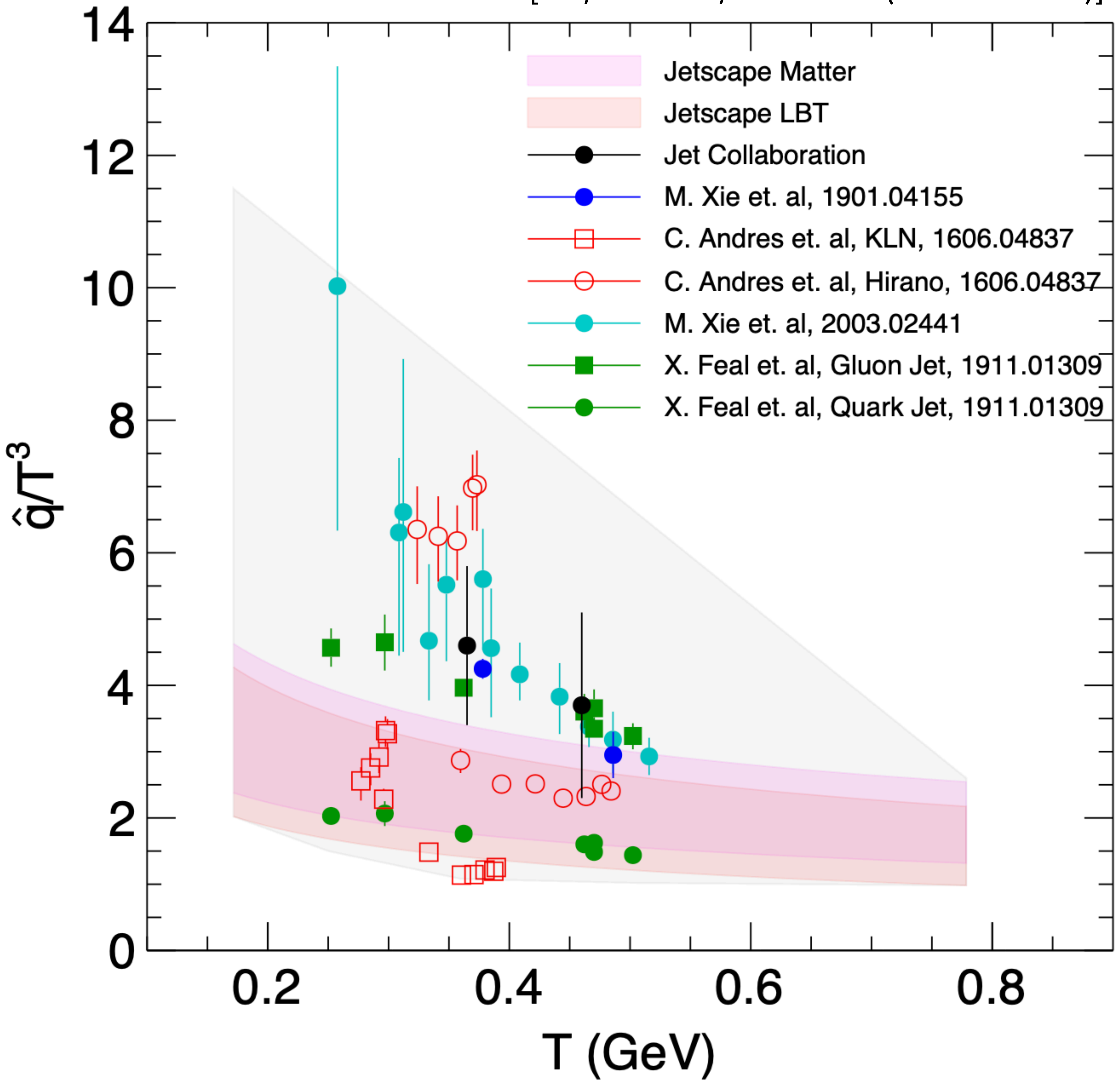



**Several ansatz:**

- Initial state (factorisation to final-state effects)?
- Medium temperature and energy-density time-evolution profiles?
- QGP phase initialisation time?
- Energy loss during partonic and hadronic phases?
- QGP EoS and degrees of freedom?
- …

[LA, Y-J Lee, M. Winn (2203.16352)]



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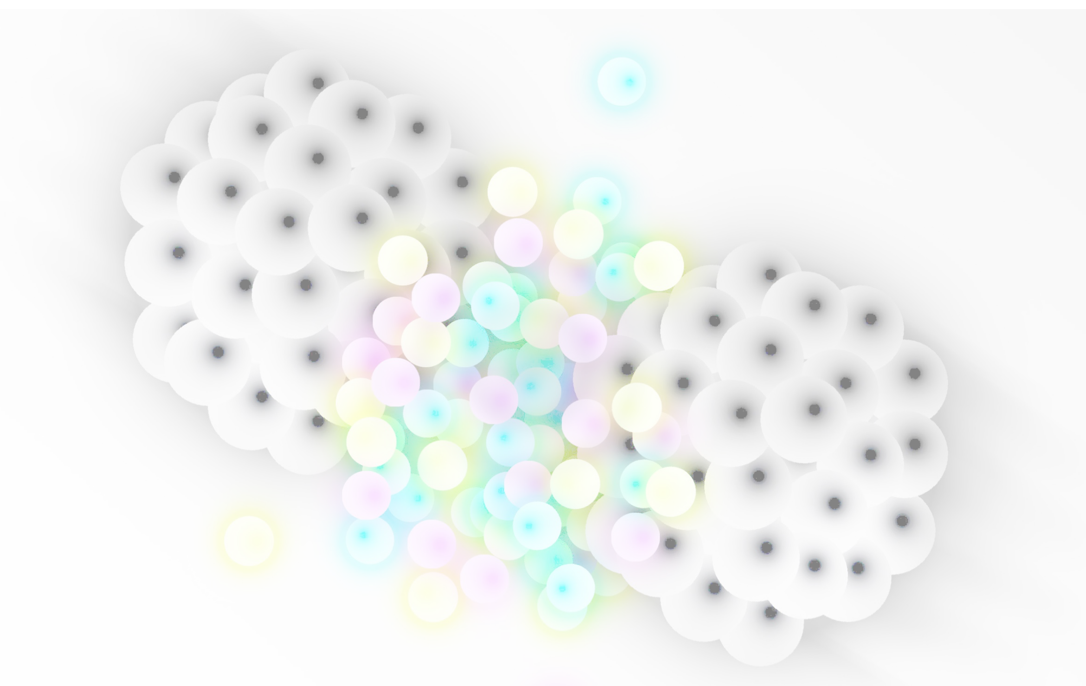

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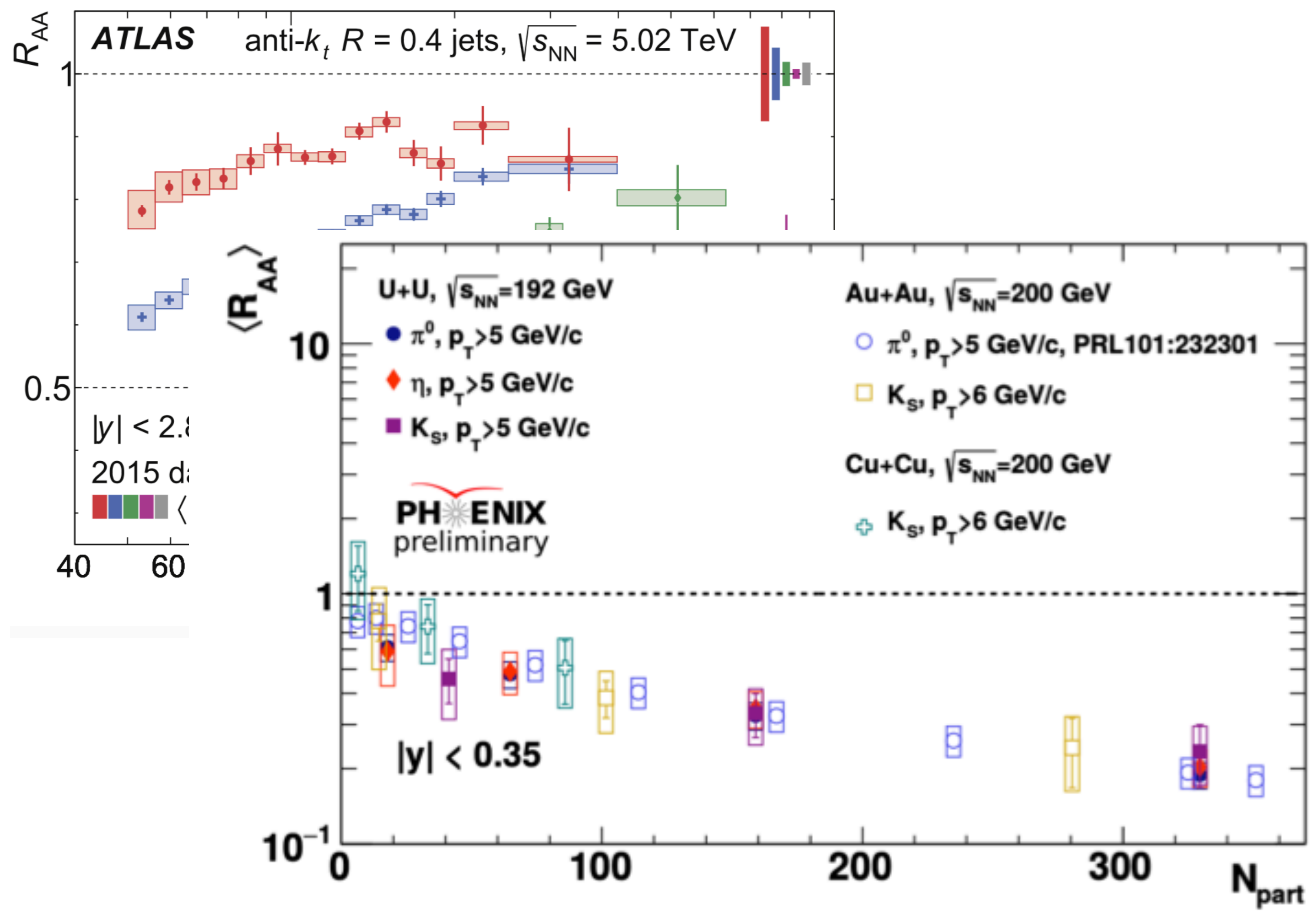


**How can we improve it?**

**Several ansatz:**

- Initial state (factorisation to final-state effects)?
- Medium temperature and energy-density time-evolution profiles?
- QGP phase initialisation time?
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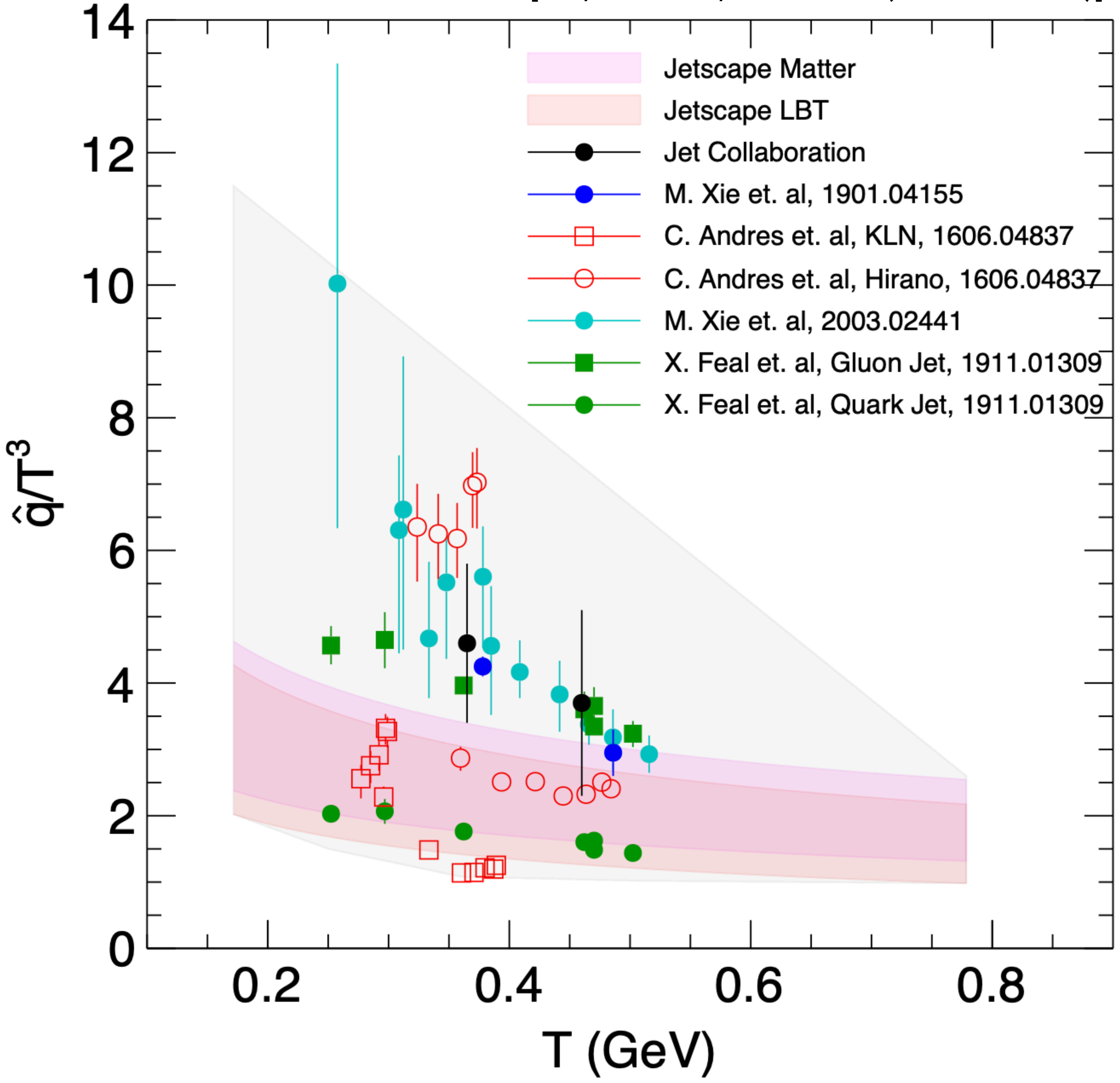


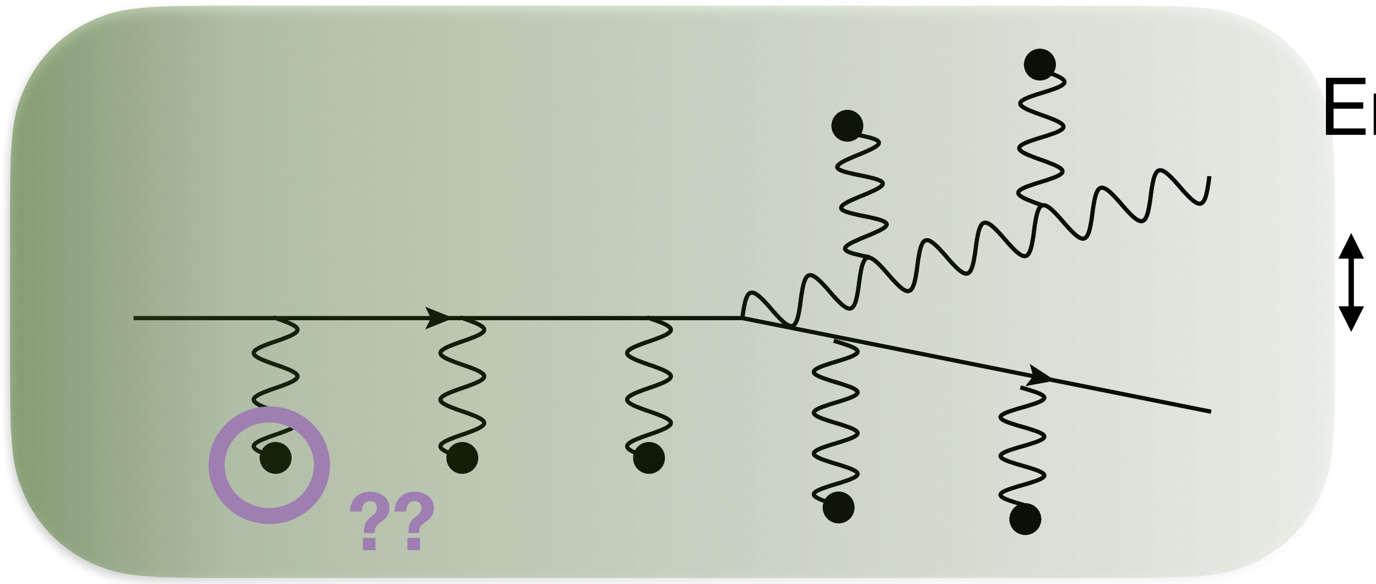
# Improving medium-induced radiation

[Andrés, LA, Dominguez, (2002.01517)]

- **Accuracy** of radiation spectrum:
  - Relaxing previous kinematic constrains allows more sensitivity to different realistic parton-medium potentials:

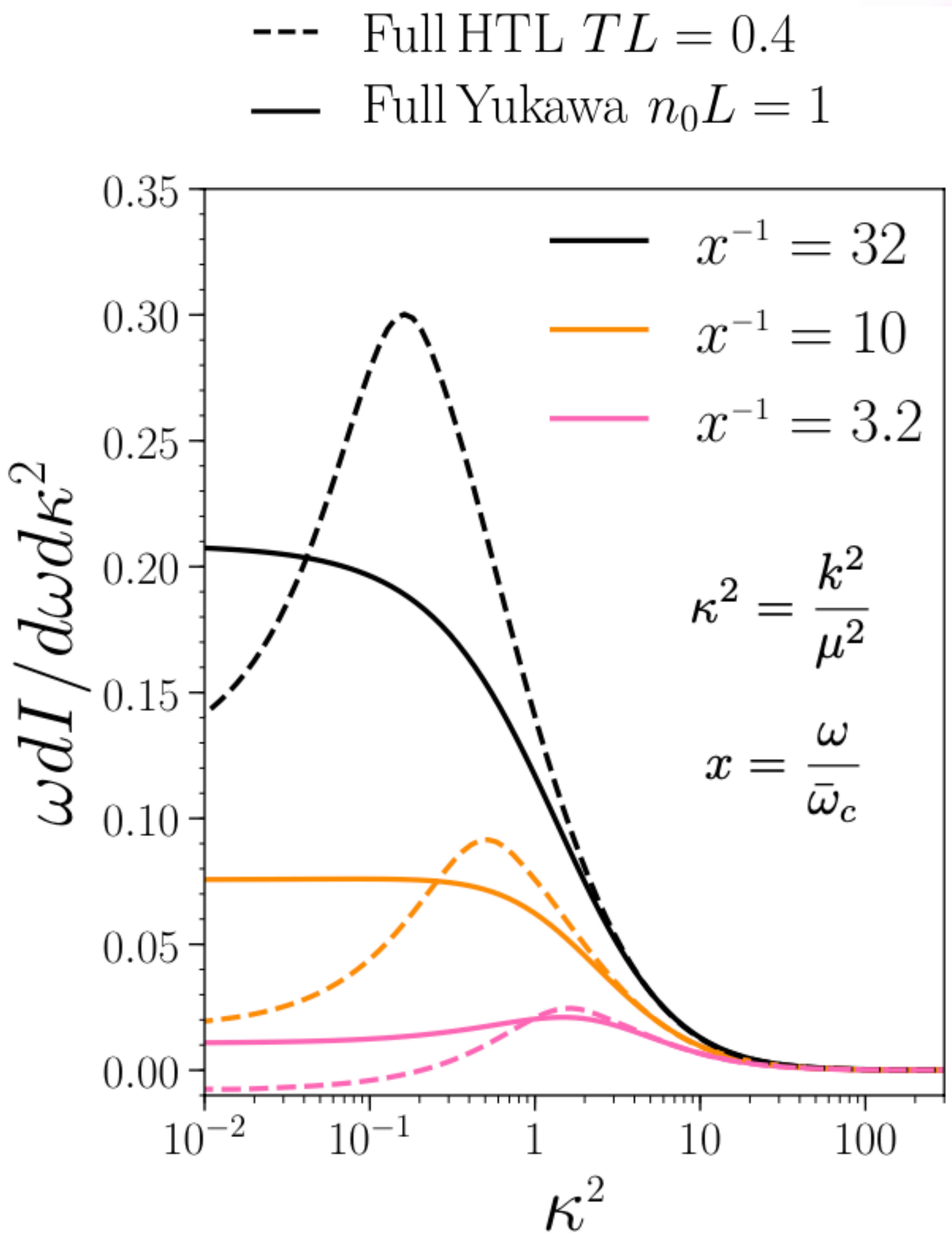
**Yukawa potential:** $V(\boldsymbol{q}) = \dfrac{8\pi\mu^2}{(\boldsymbol{q}^2+\mu^2)^2}$

**HTL potential:** $\dfrac{1}{2} n\, V(\boldsymbol{q}) = \dfrac{g_s^2 N_c m_D^2 T}{\boldsymbol{q}^2(\boldsymbol{q}^2+m_D^2)}$

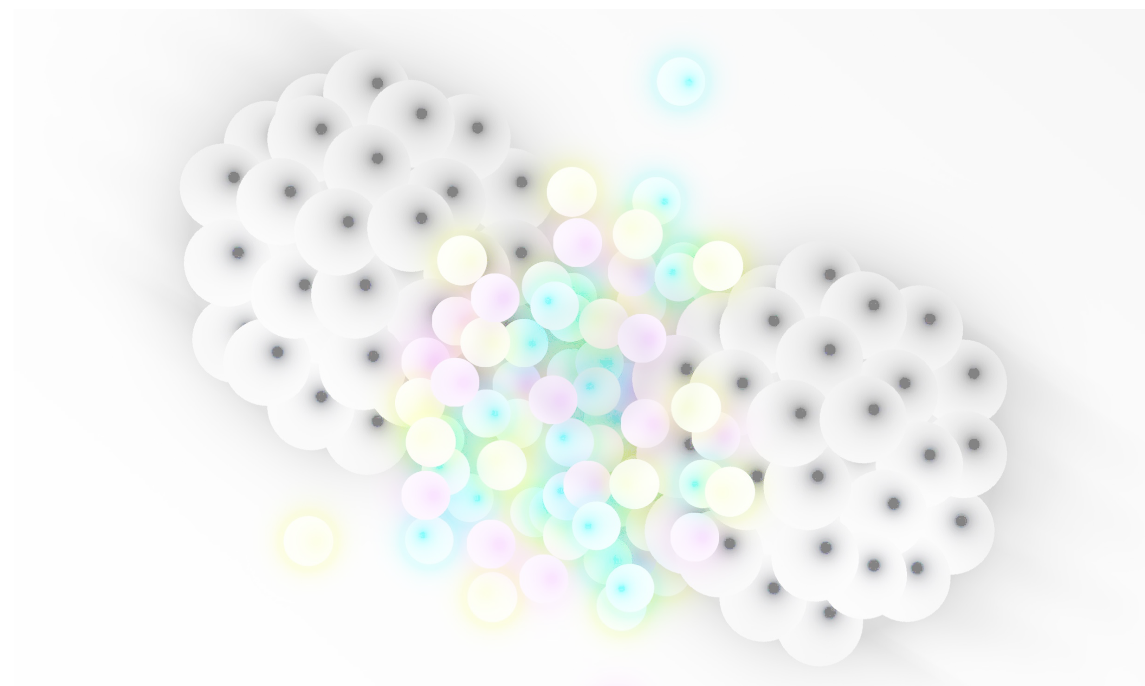



Energy: $\omega$

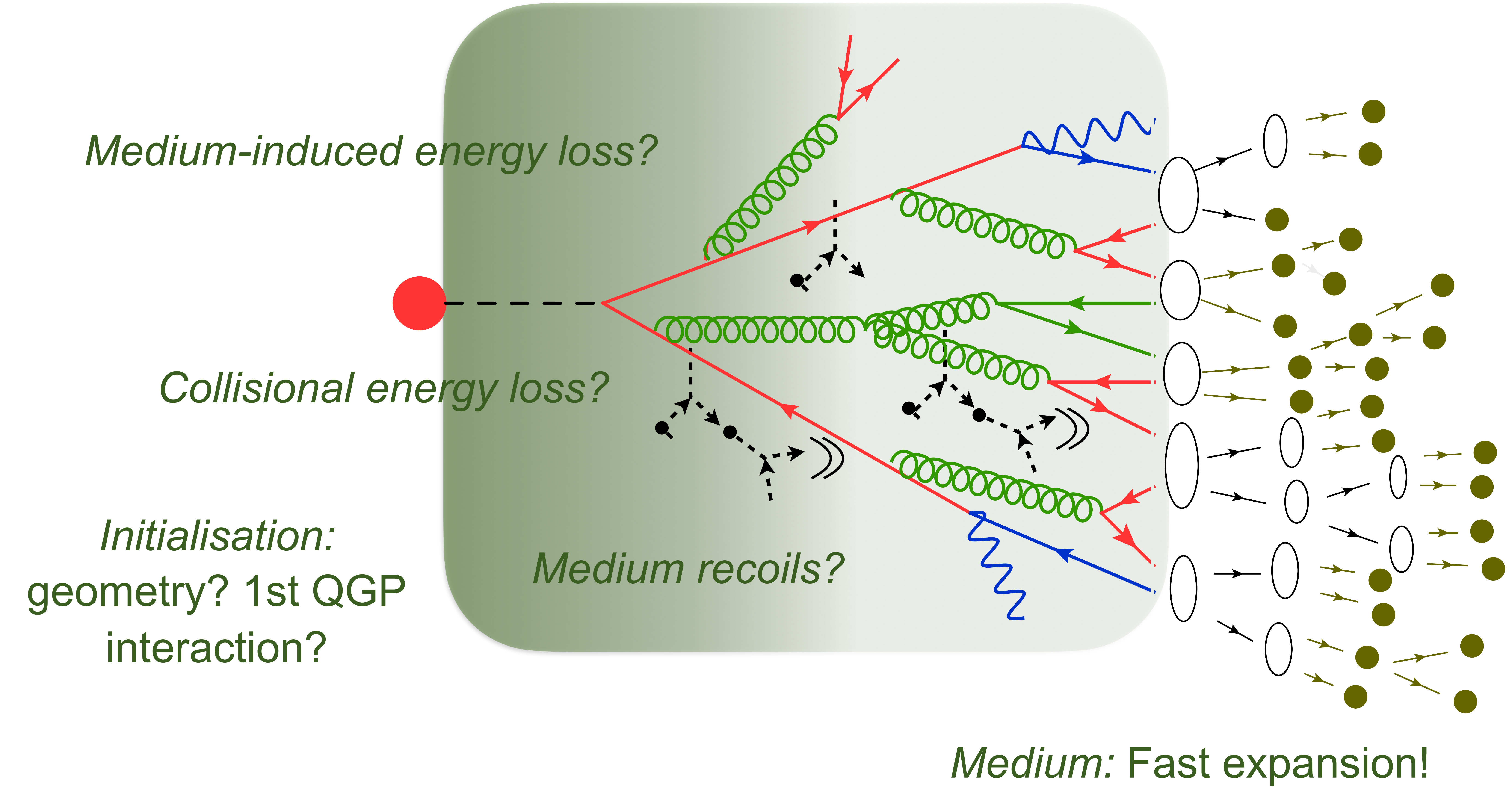
Transverse momentum: $k^2$



# Elastic energy loss



- Jets in heavy-ions: going to lower energy scales



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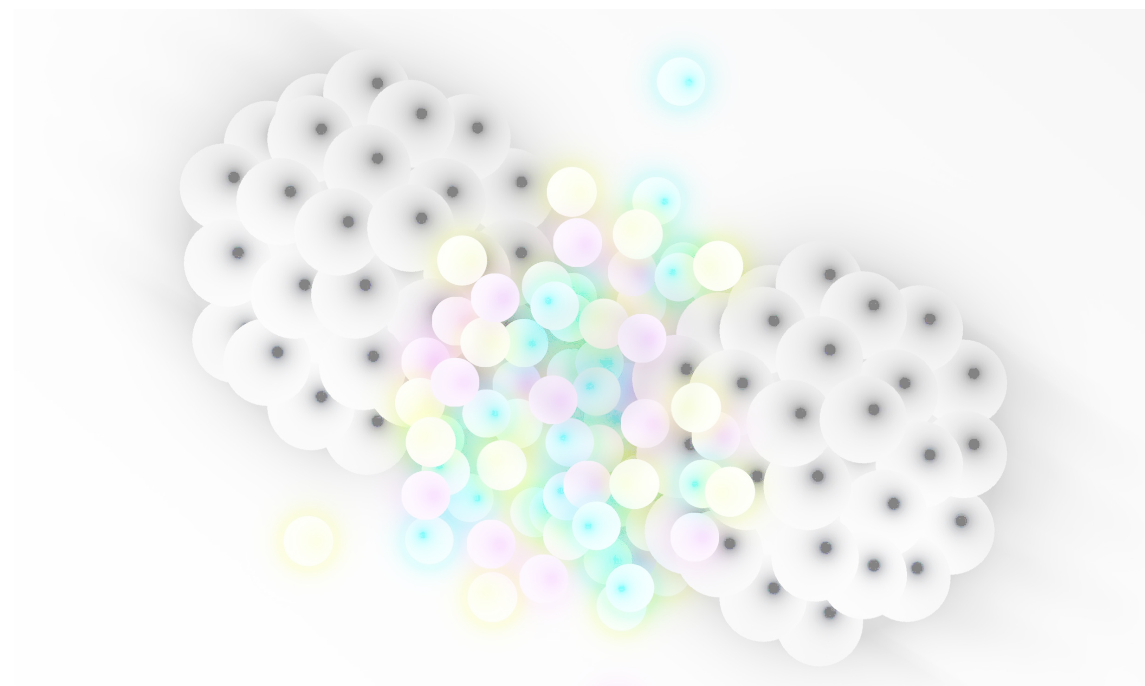

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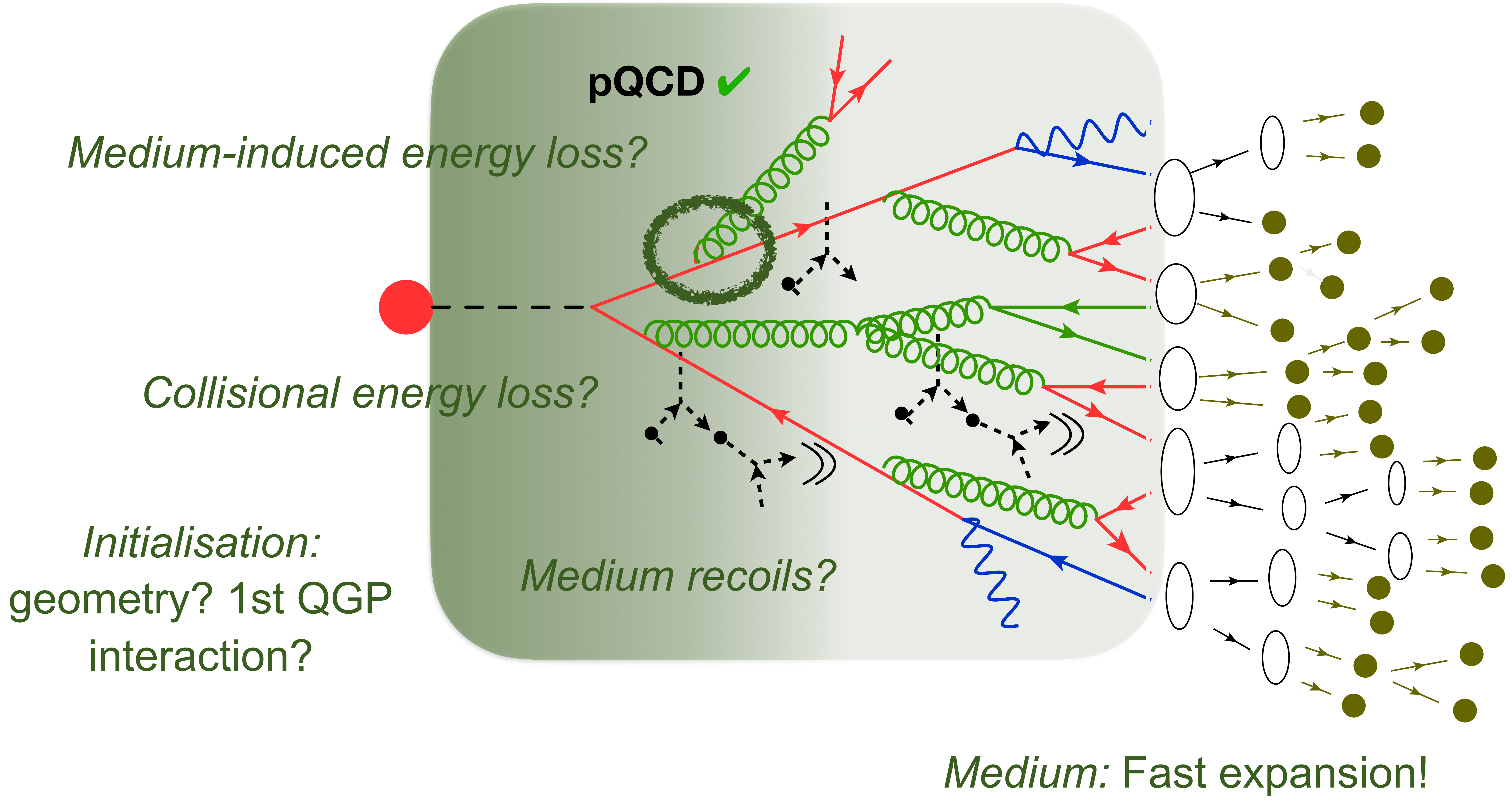

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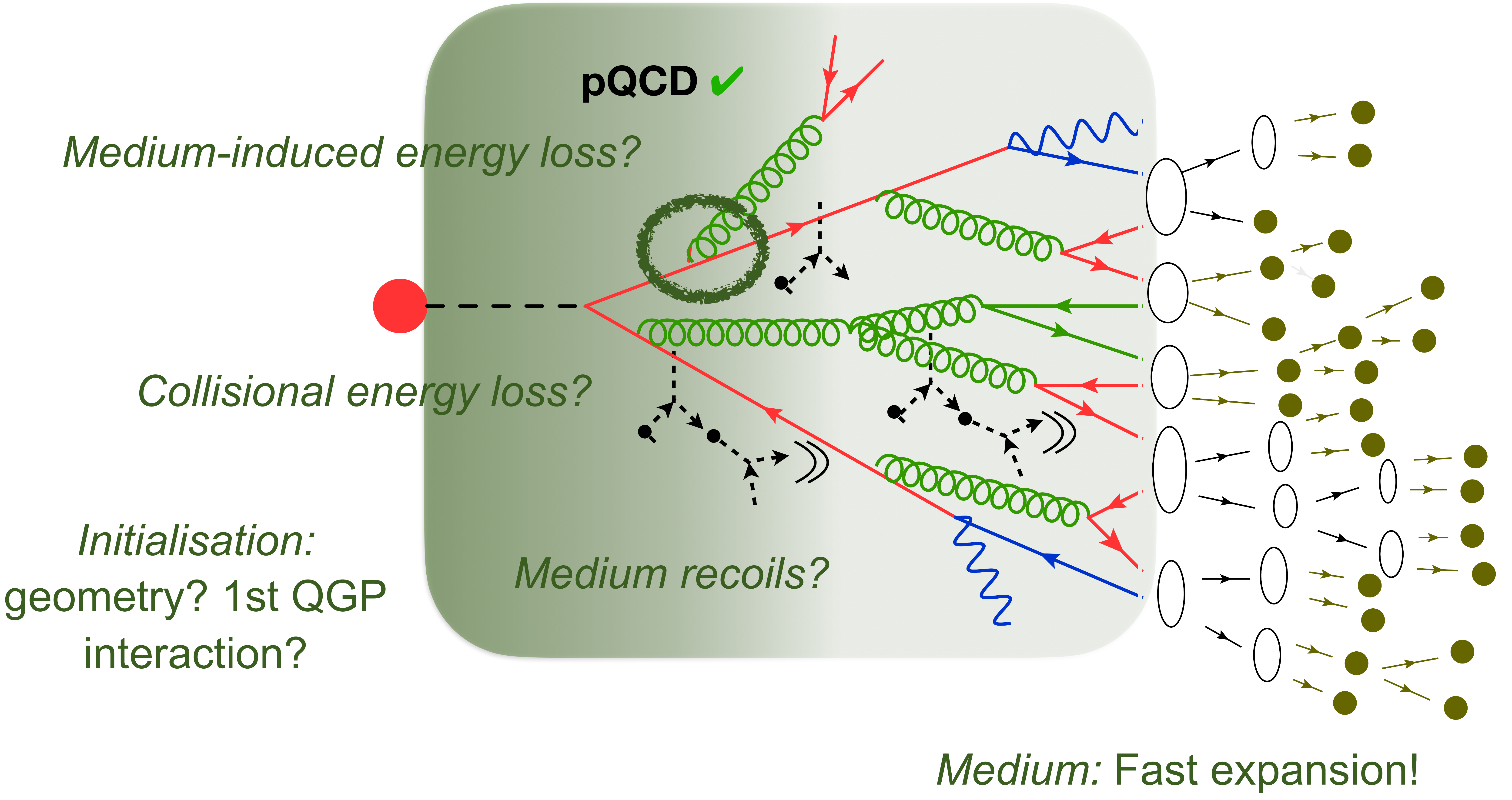


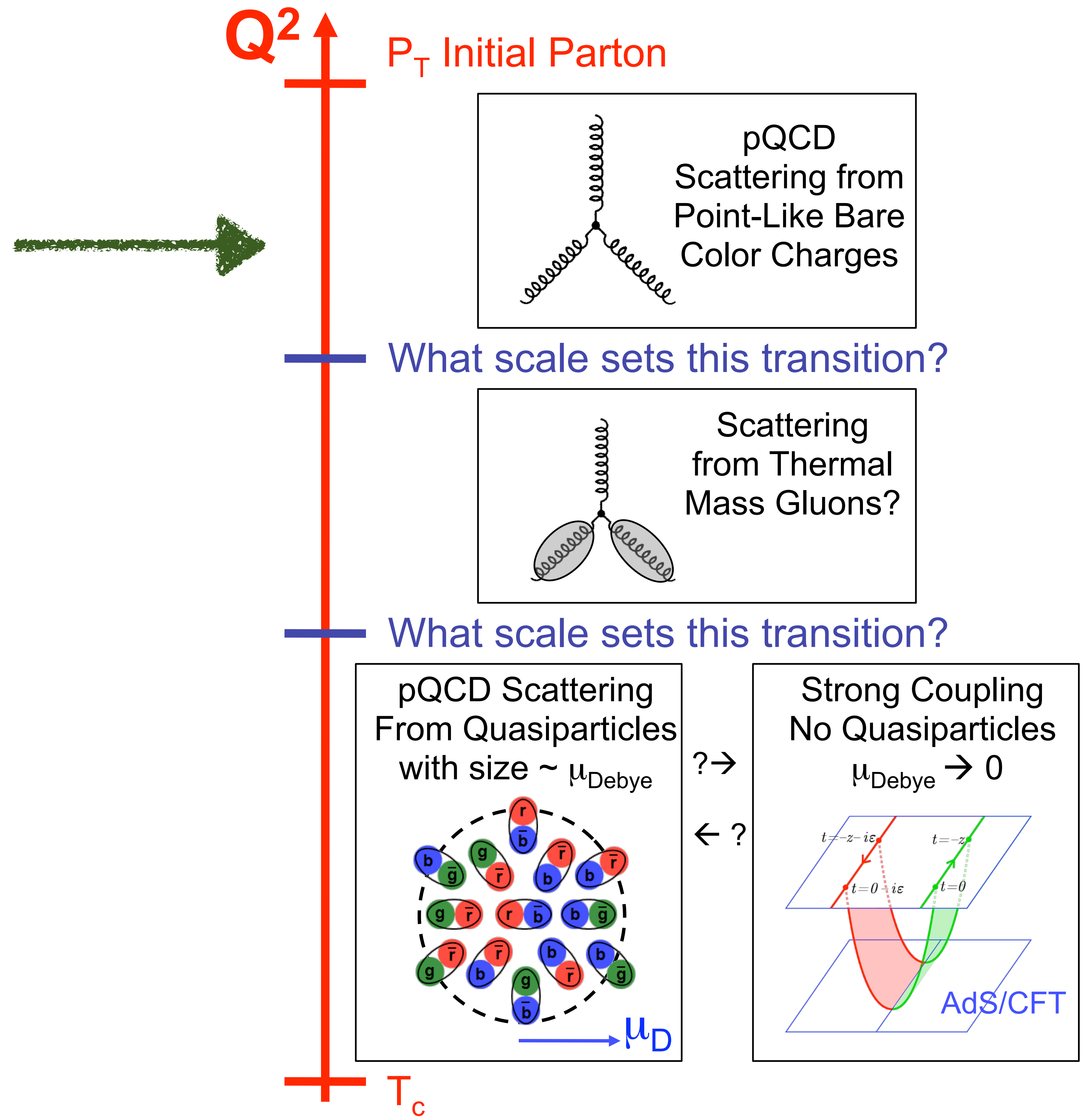


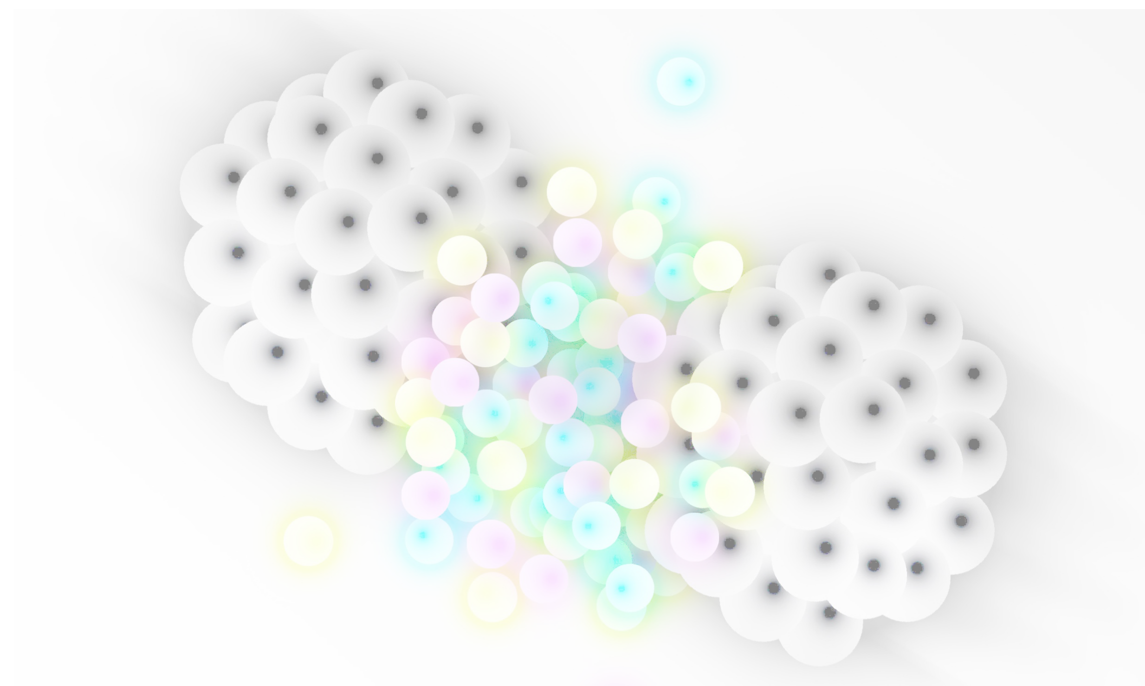

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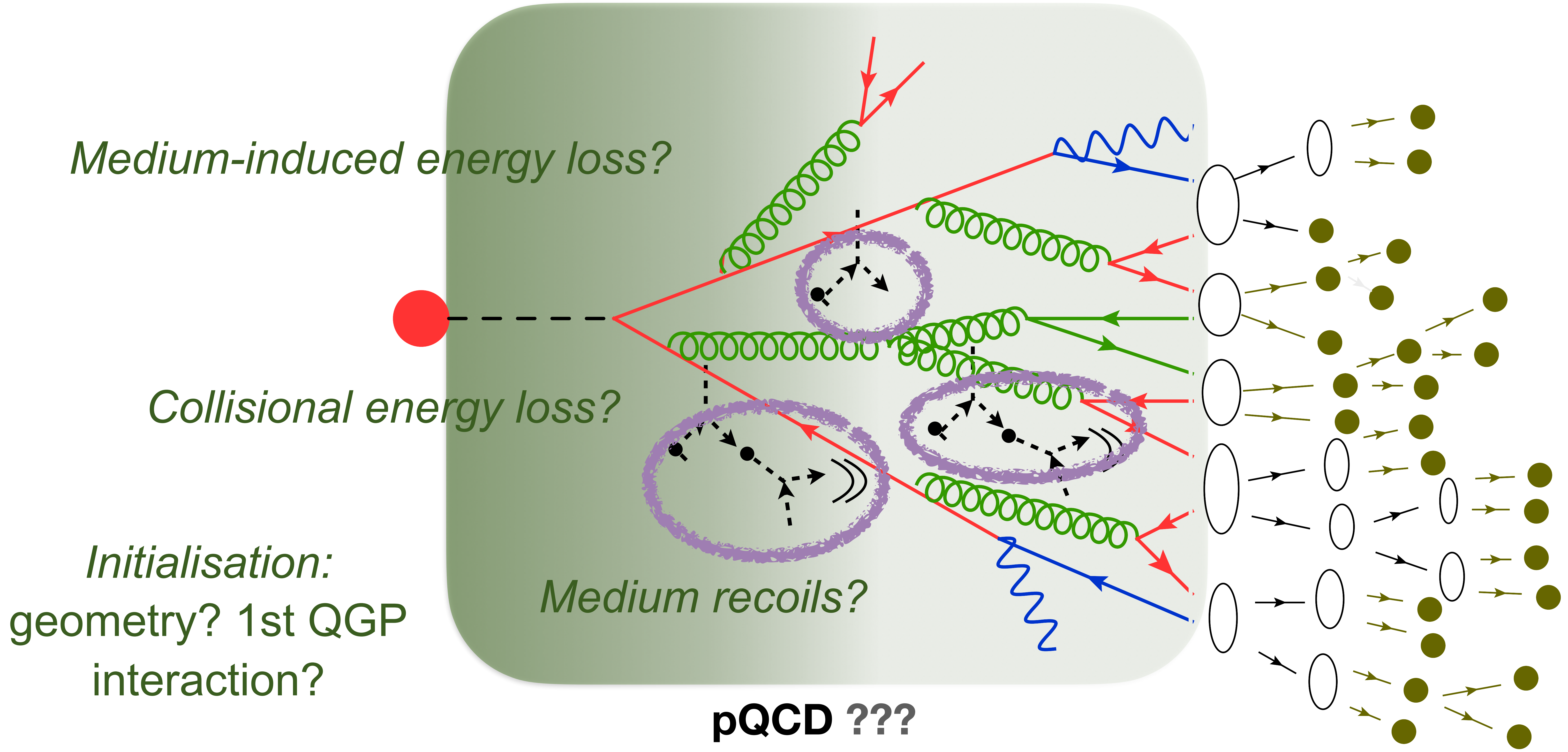
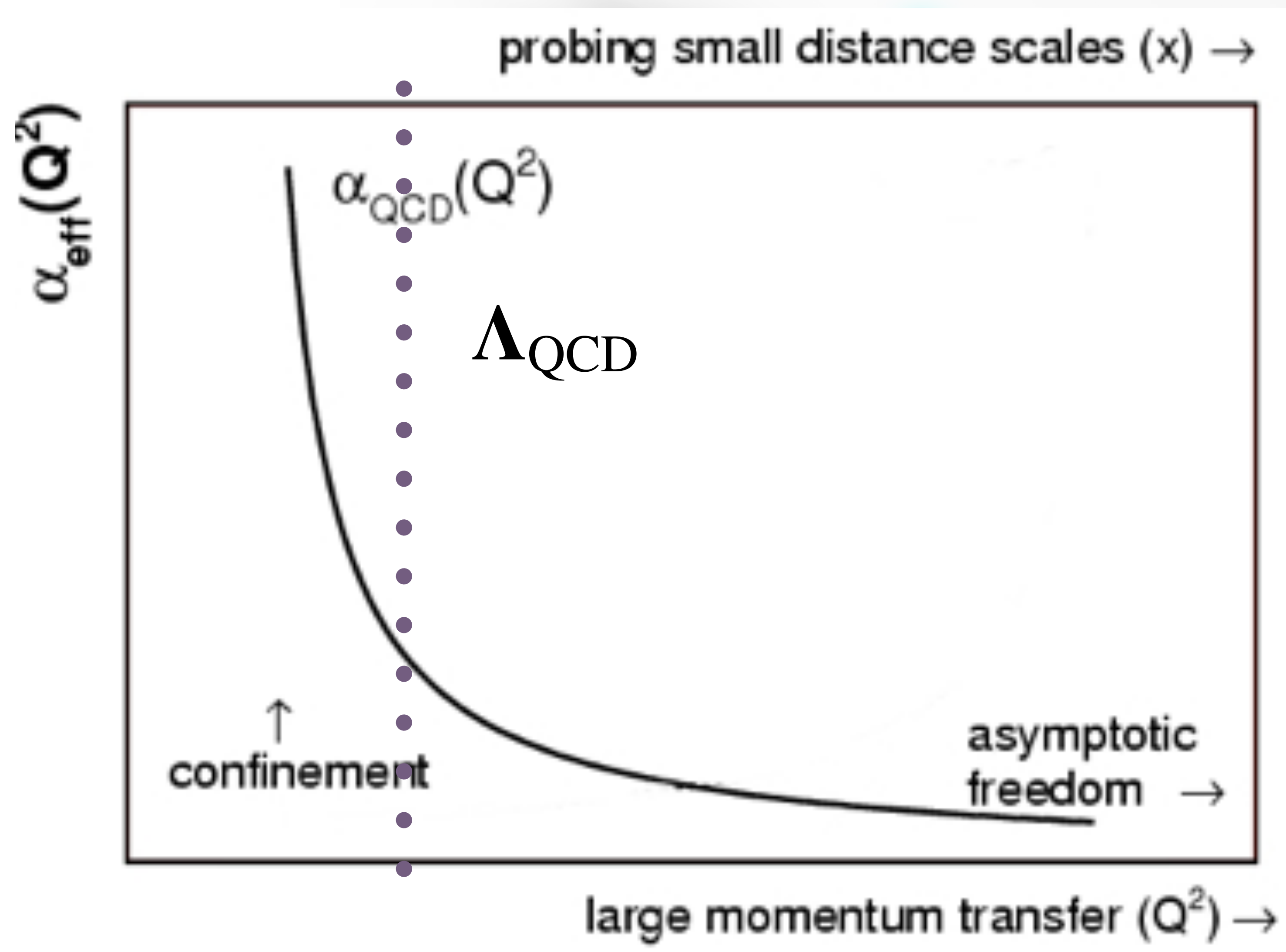
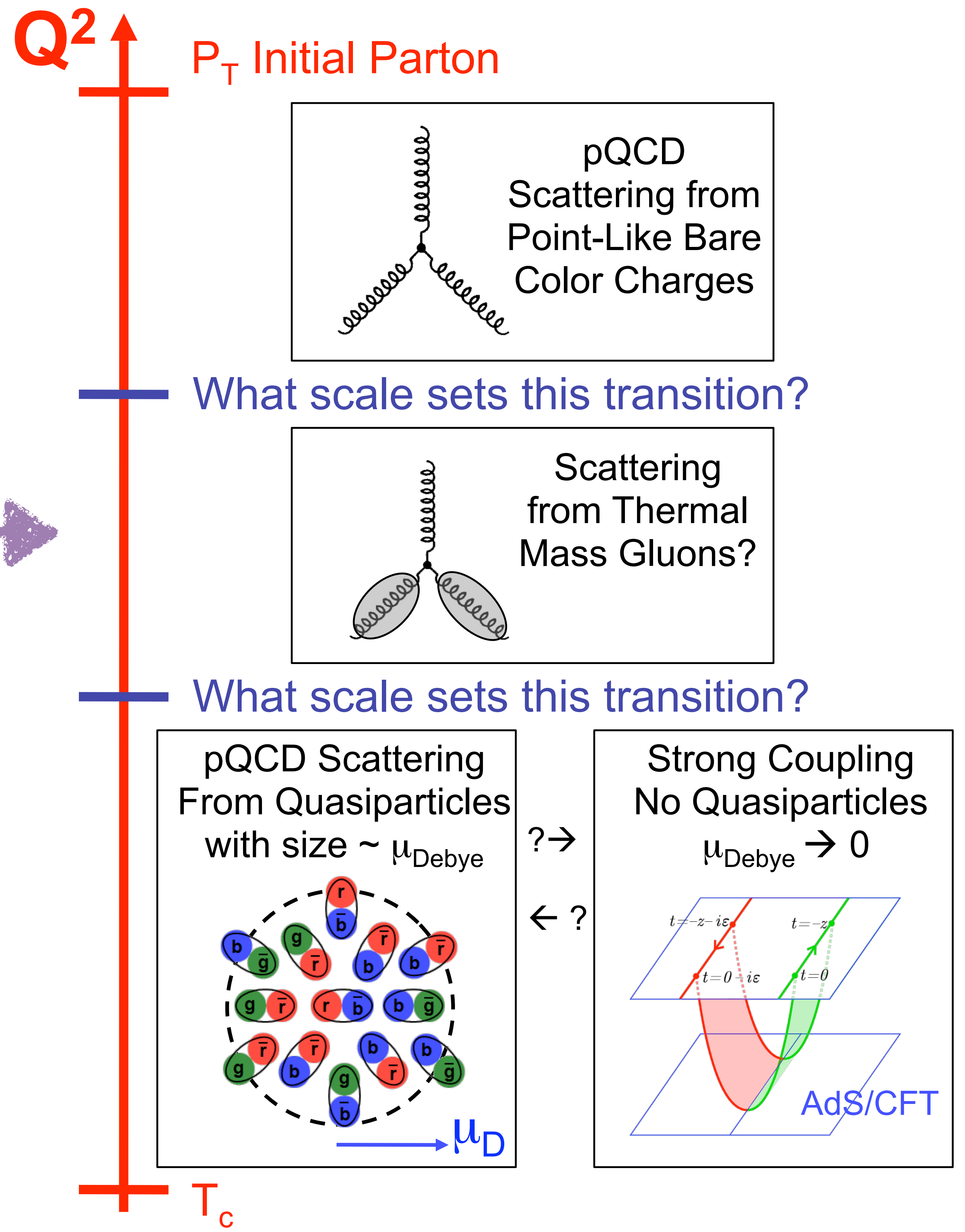
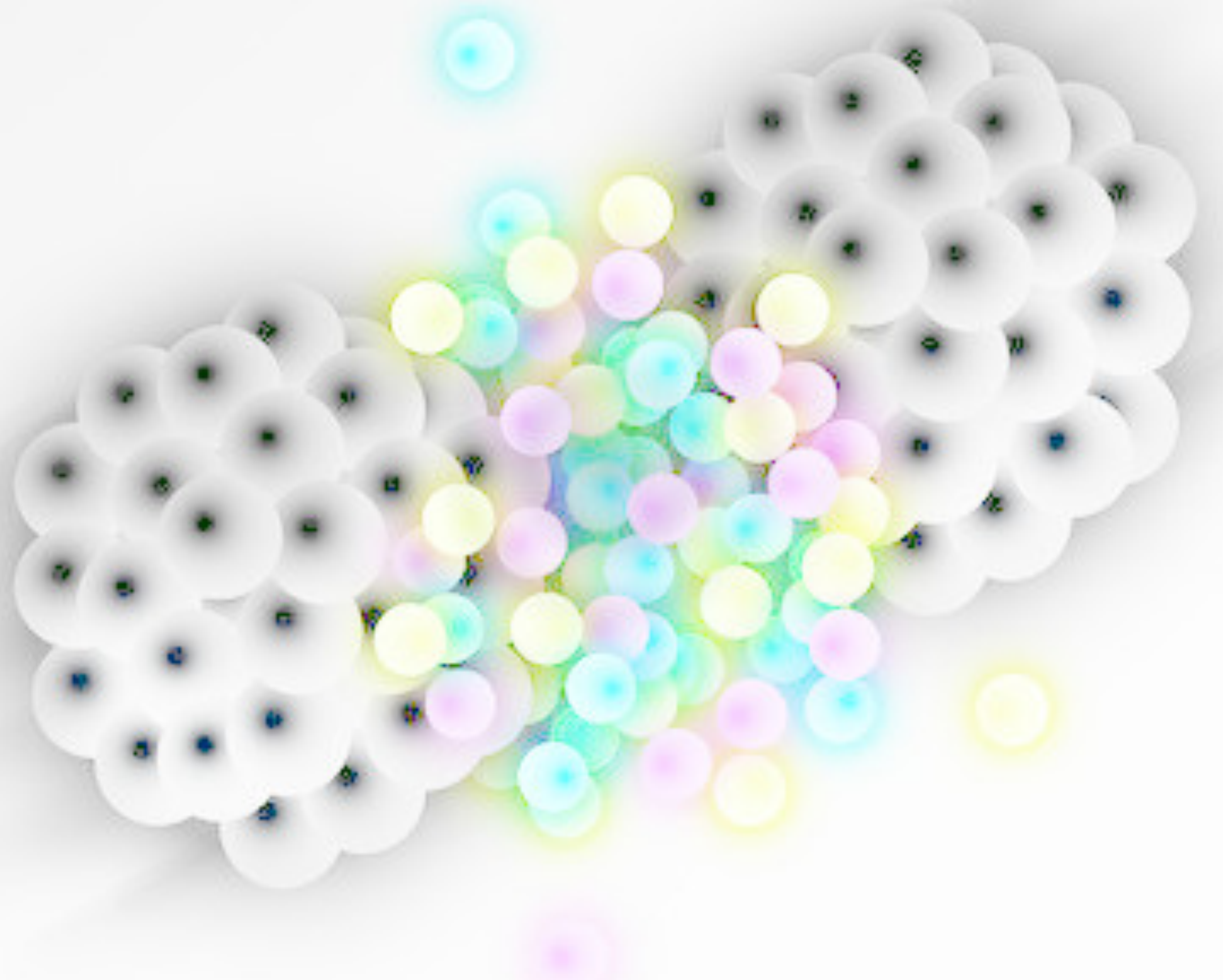


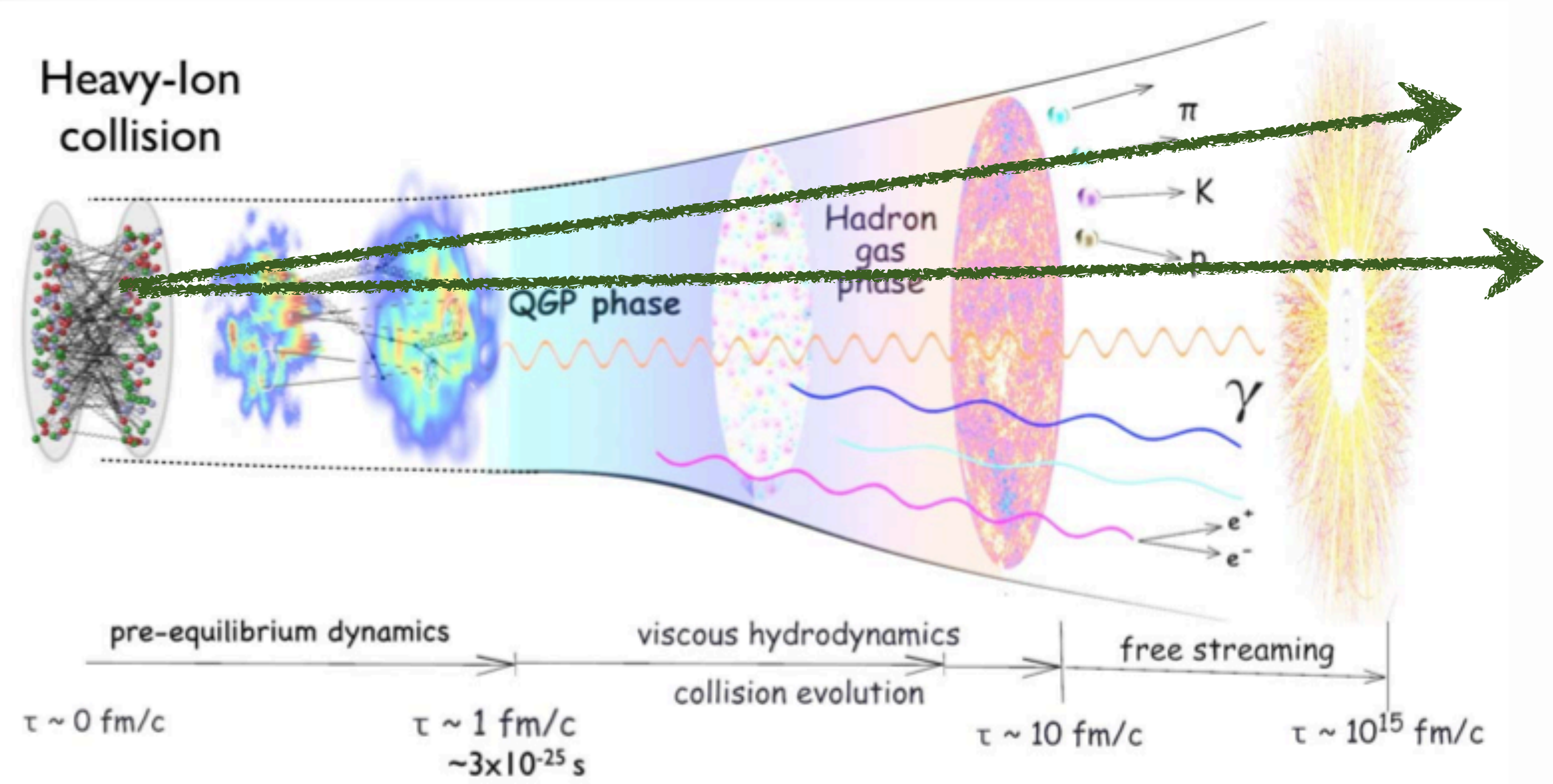

*Medium:* Fast expansion!



# How fast is the energy thermalised within the QGP?



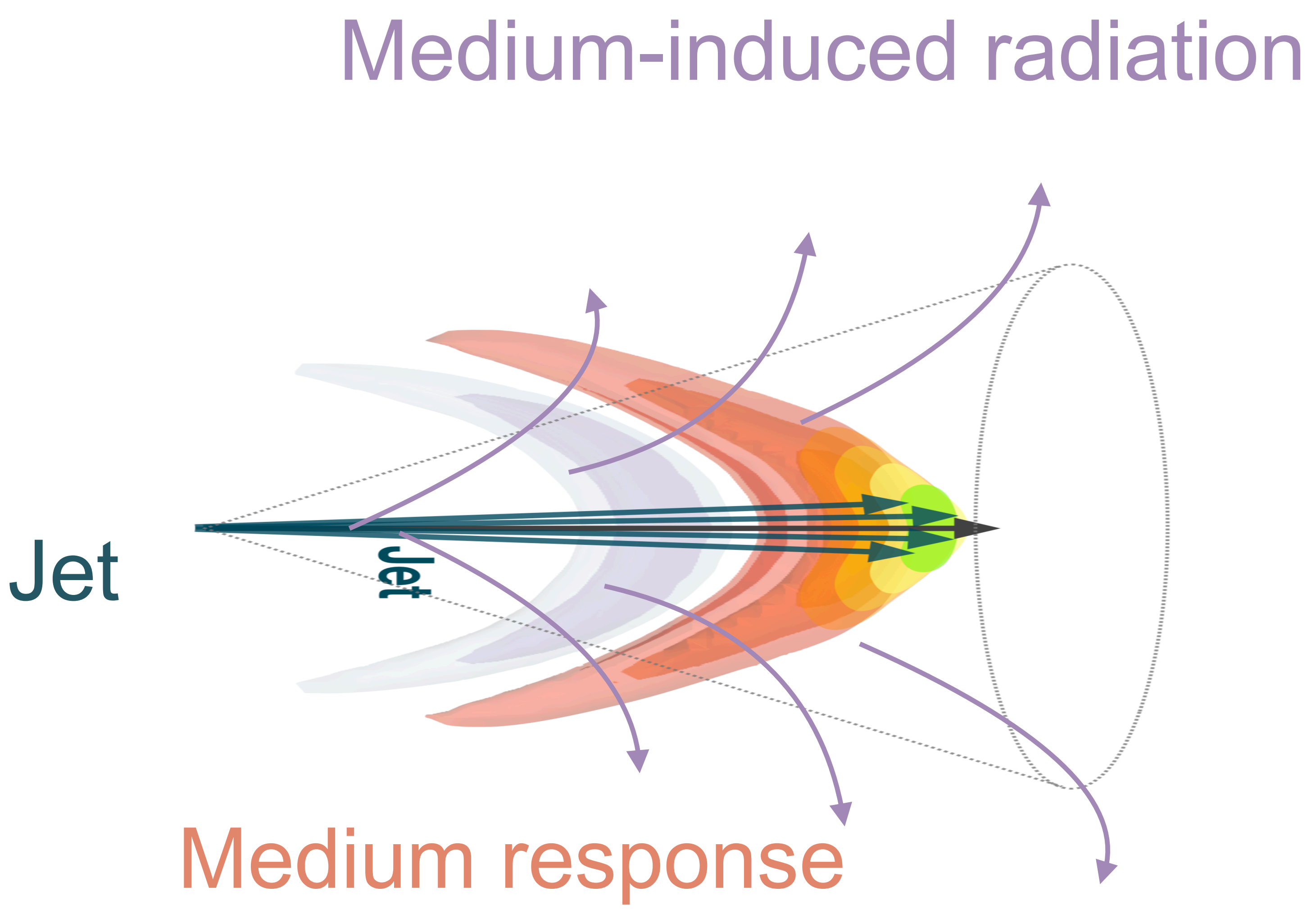


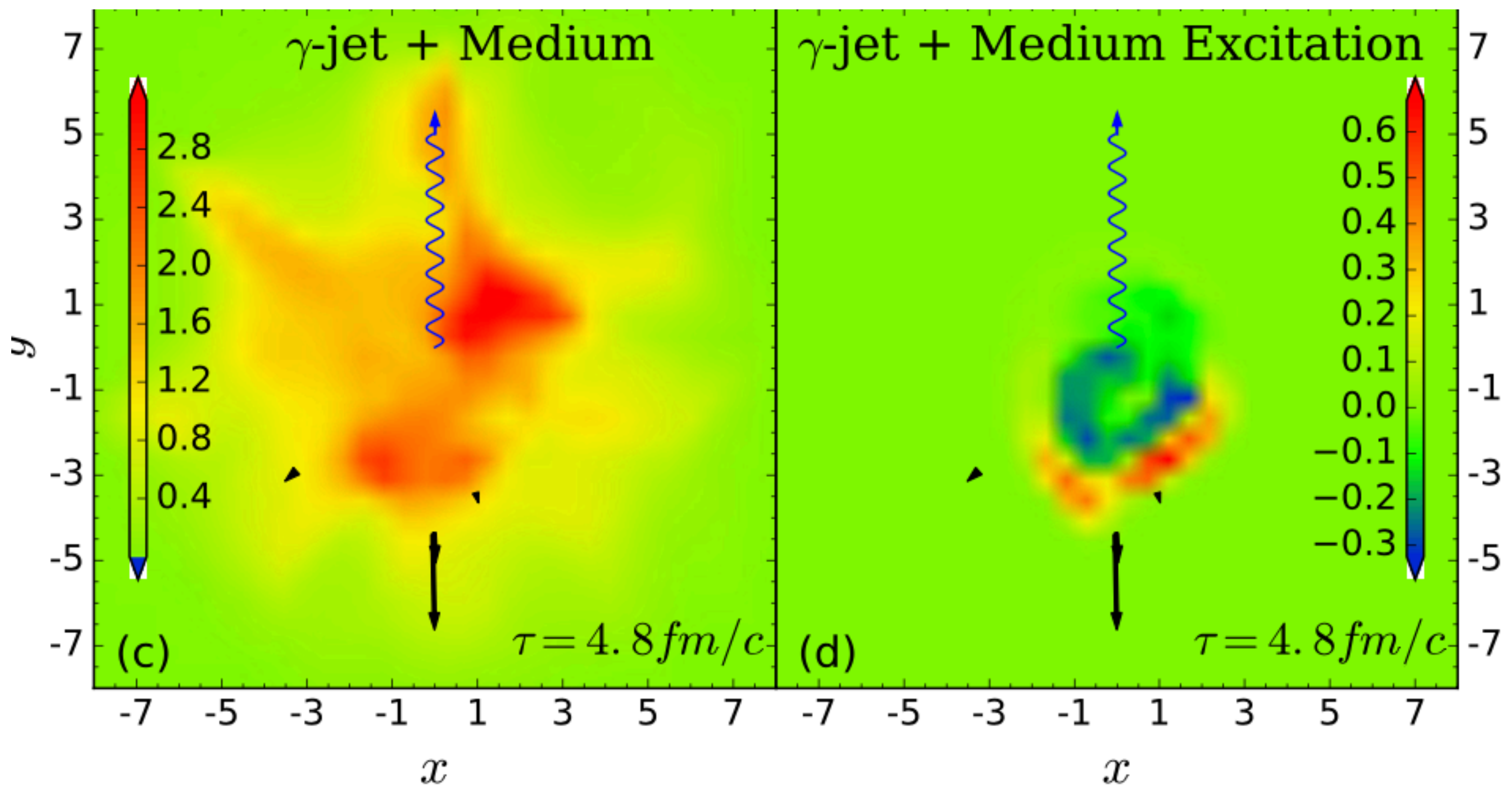
# Thermalisation

[W. Chen, S. Cao, T. Luo, L-G. Pang, X-N. Wang (18)]

- Transparency to the passage of a high momentum particle:
  - Thermalisation/Equilibration
    - How fast is the jet energy propagated and thermalised with the rest of the QGP?

[Co-LBT: arXiv: 1704.03648 ]



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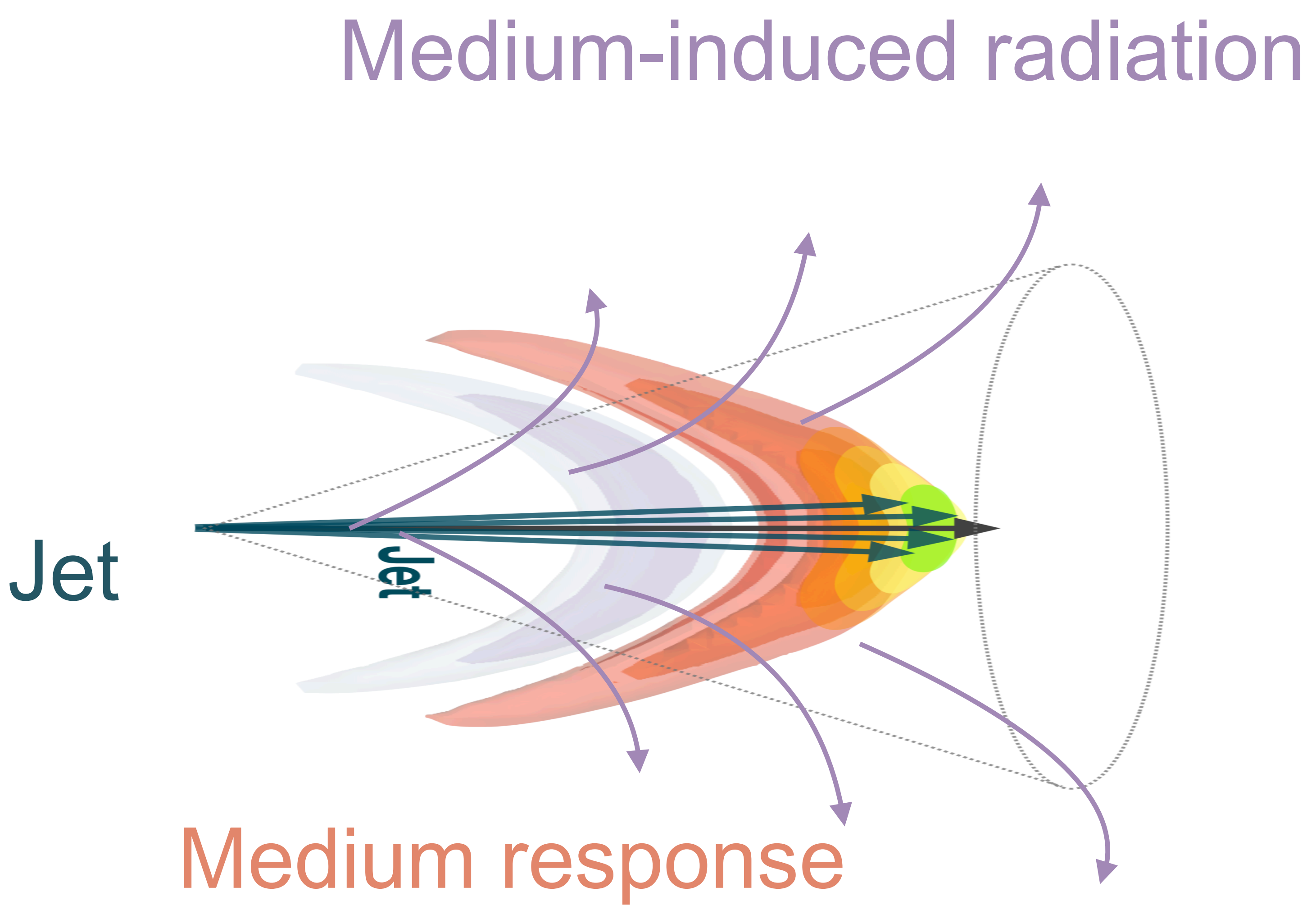
How much do they contribute to jet observables?
Where can we find it?

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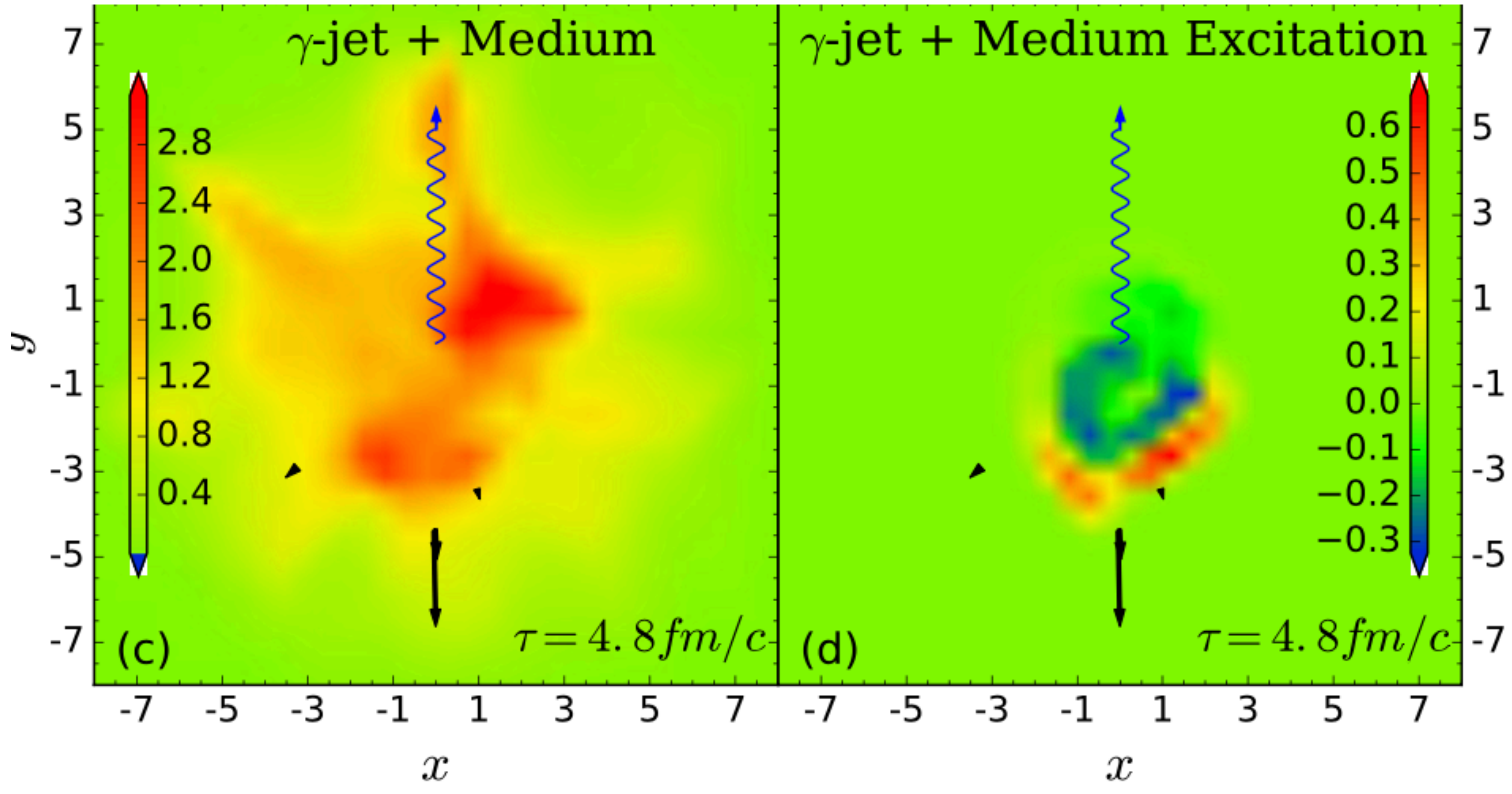
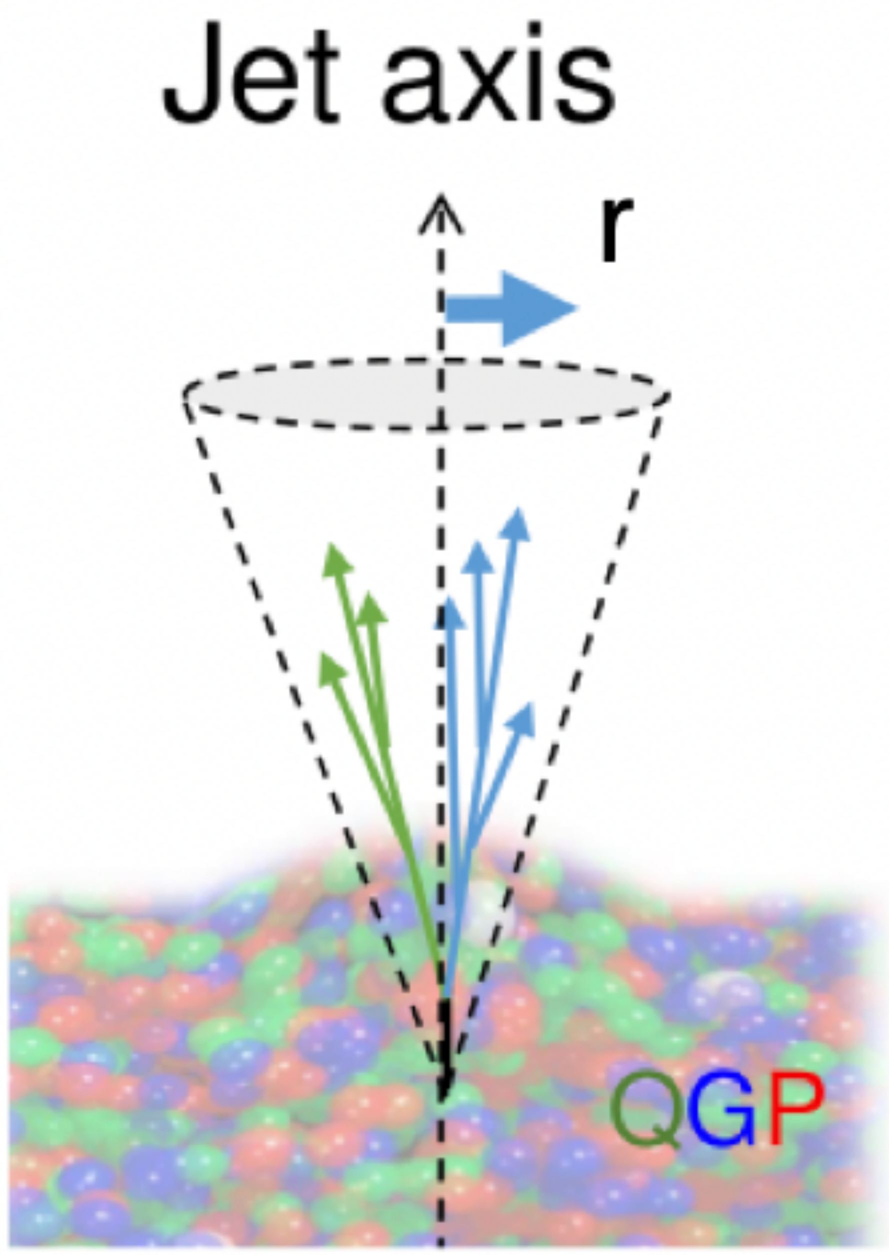
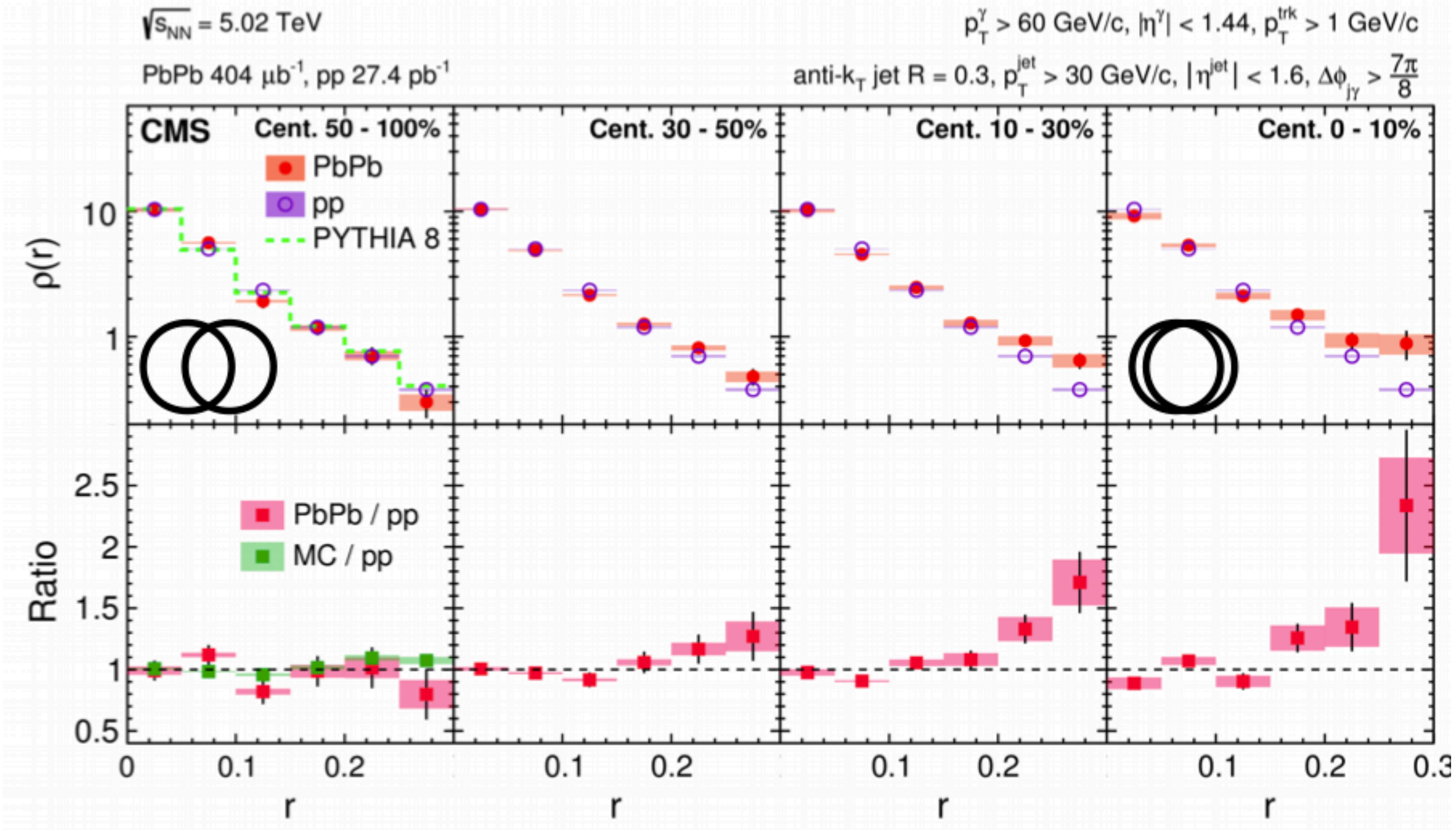


# Jet substructure

- Looking inside jets and looking to its constituents distribution and transverse momentum spectrum:



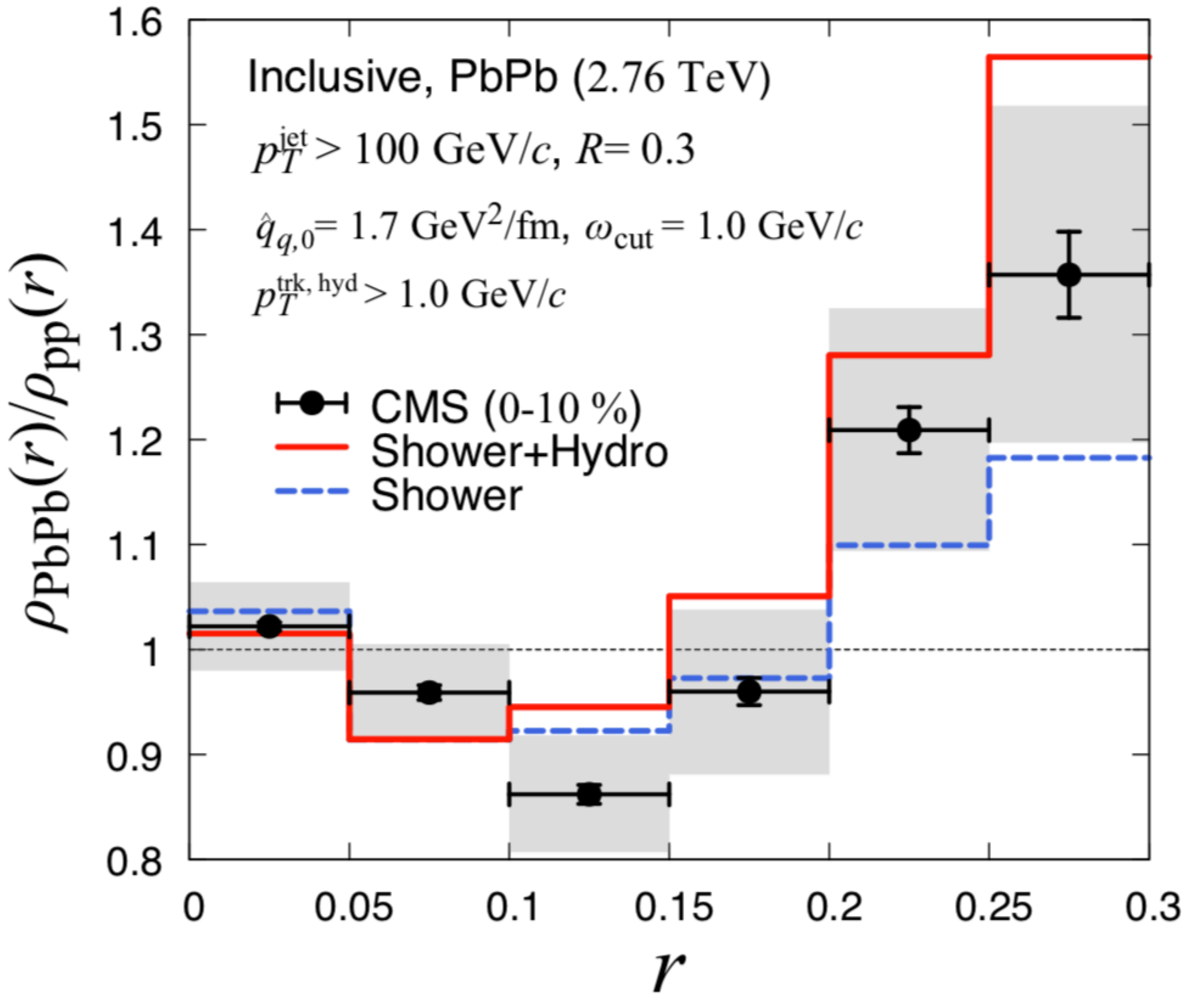



# Medium response

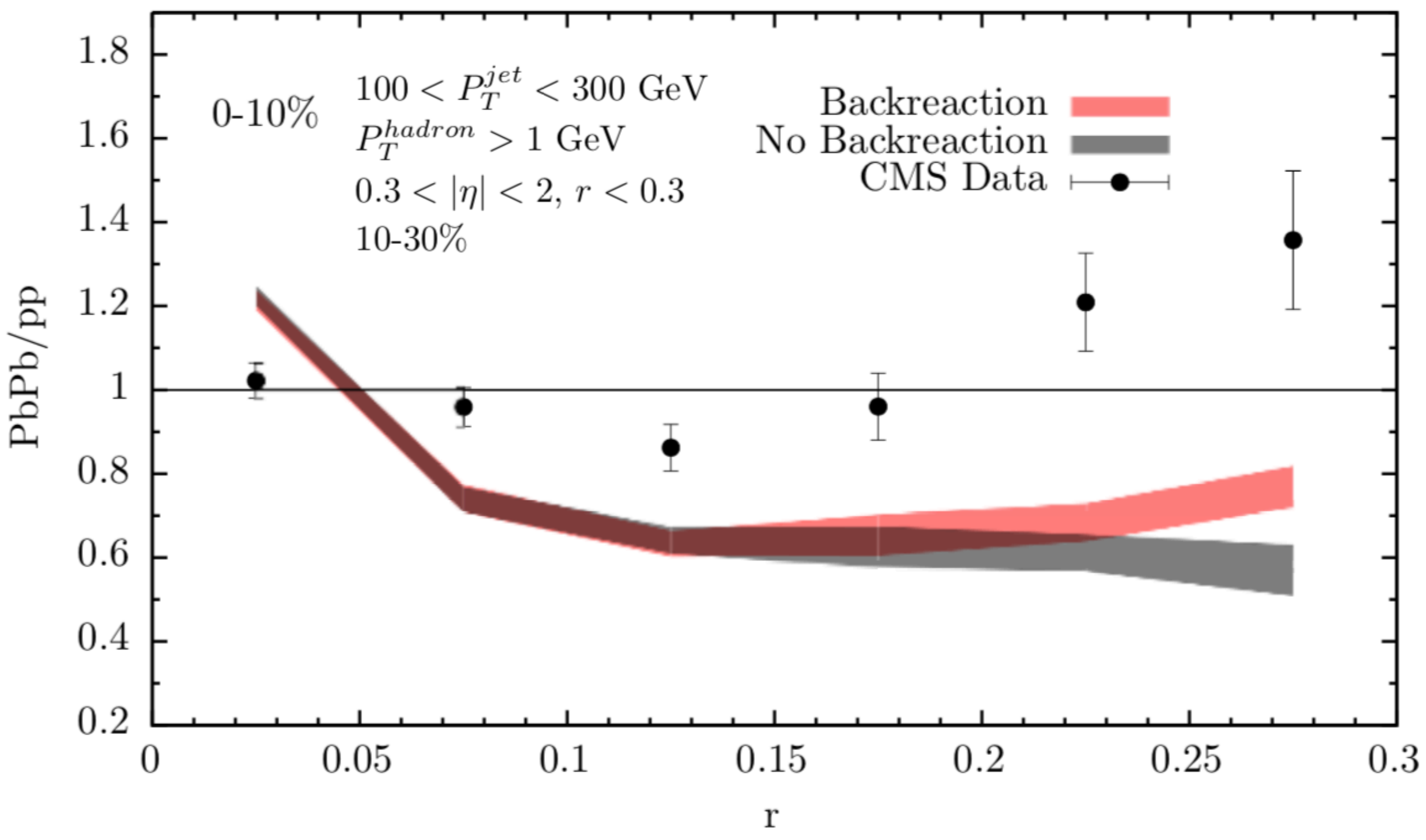
[Tachibana, Chang, Qin (17)]
[Casalderrey-Solana, Gulhan, Milhano, Pablos, Rajagopal (14;17)]
[Park, Jeon, Gale (18)]

- Mostly seen in jet radial profile but signatures of each approach is very different:

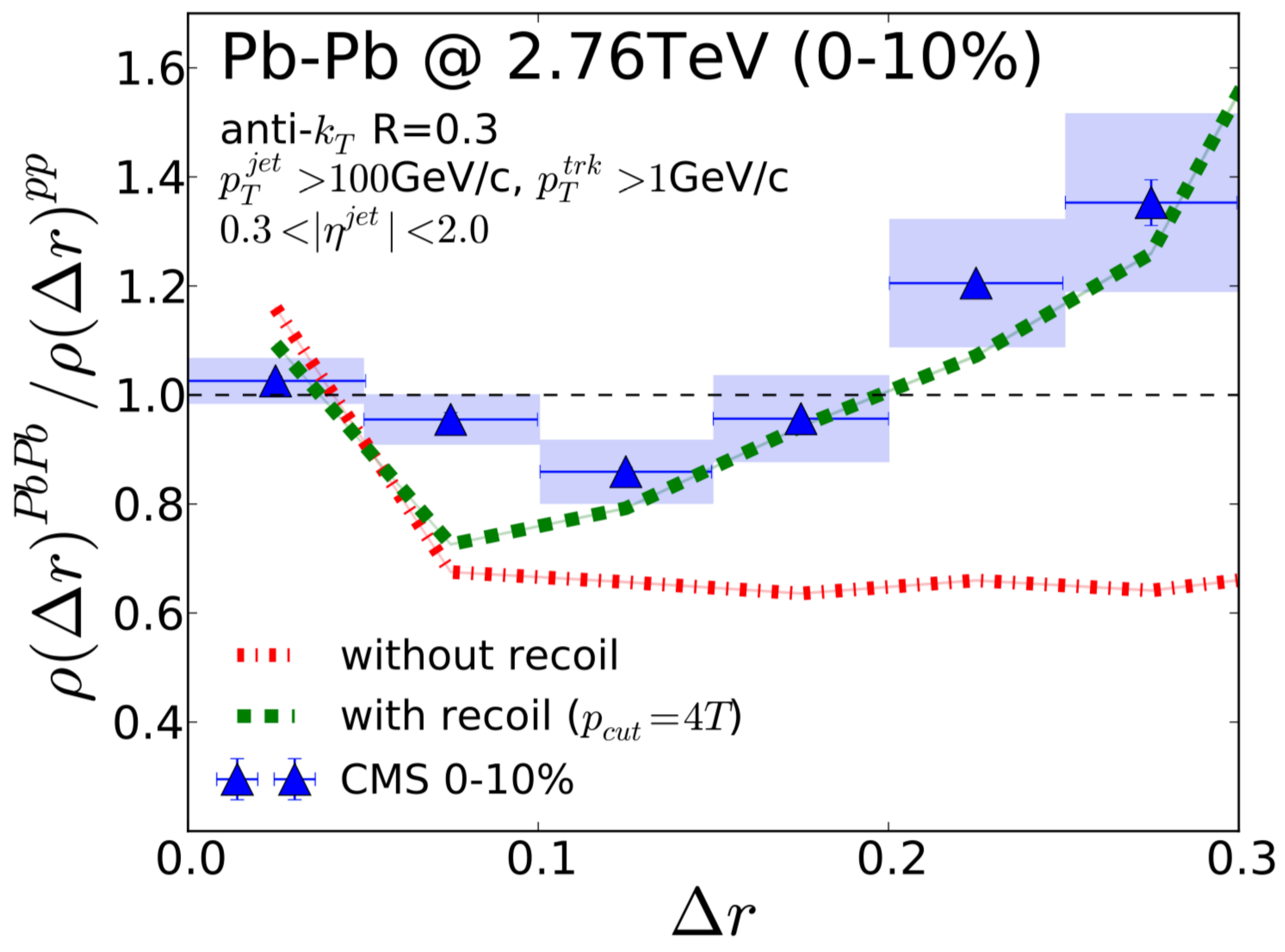
[Coupled Jet-Fluid: 1701.07951]




[Hybrid: 1609.05842]




[MARTINI:1807.06550]



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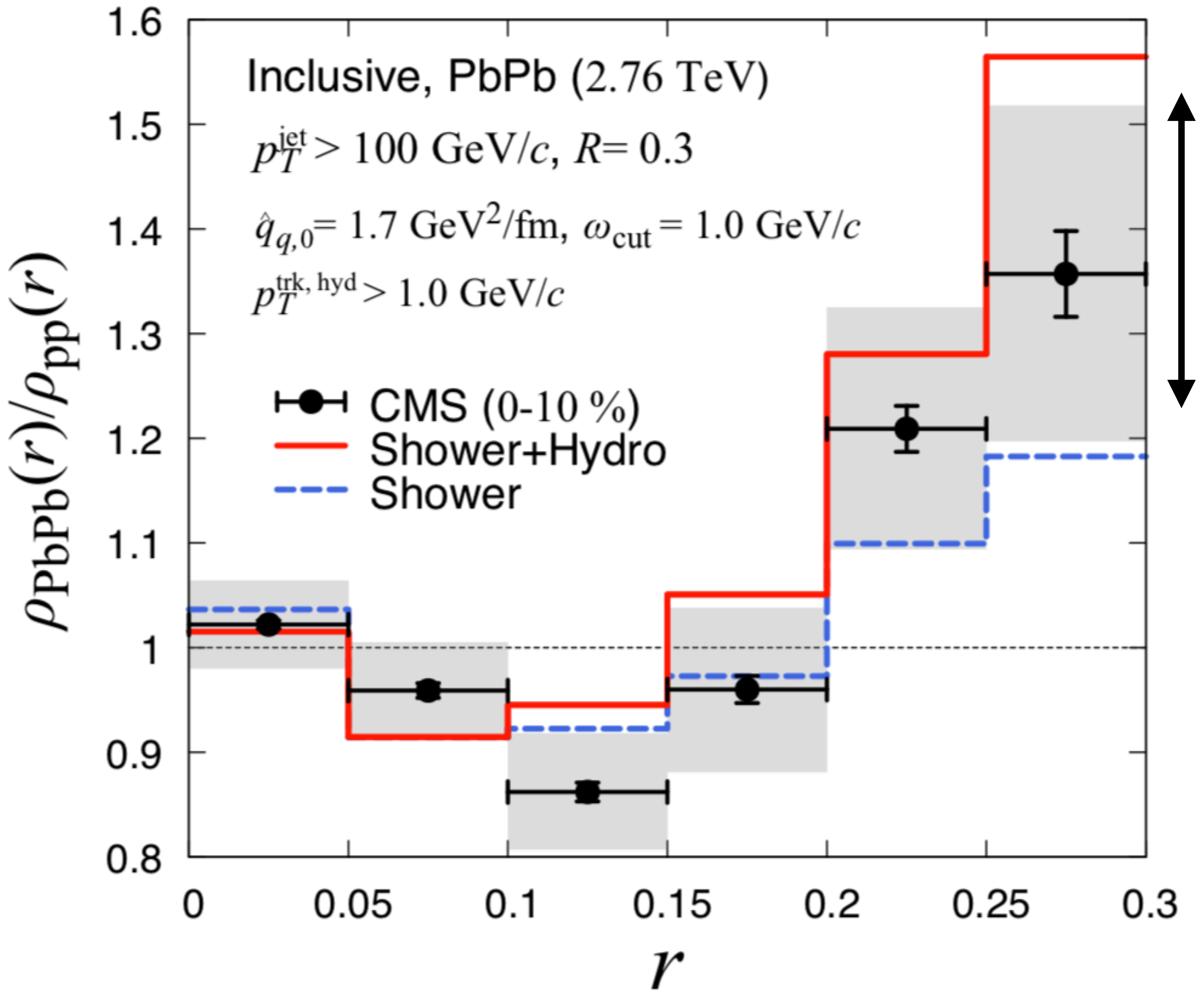


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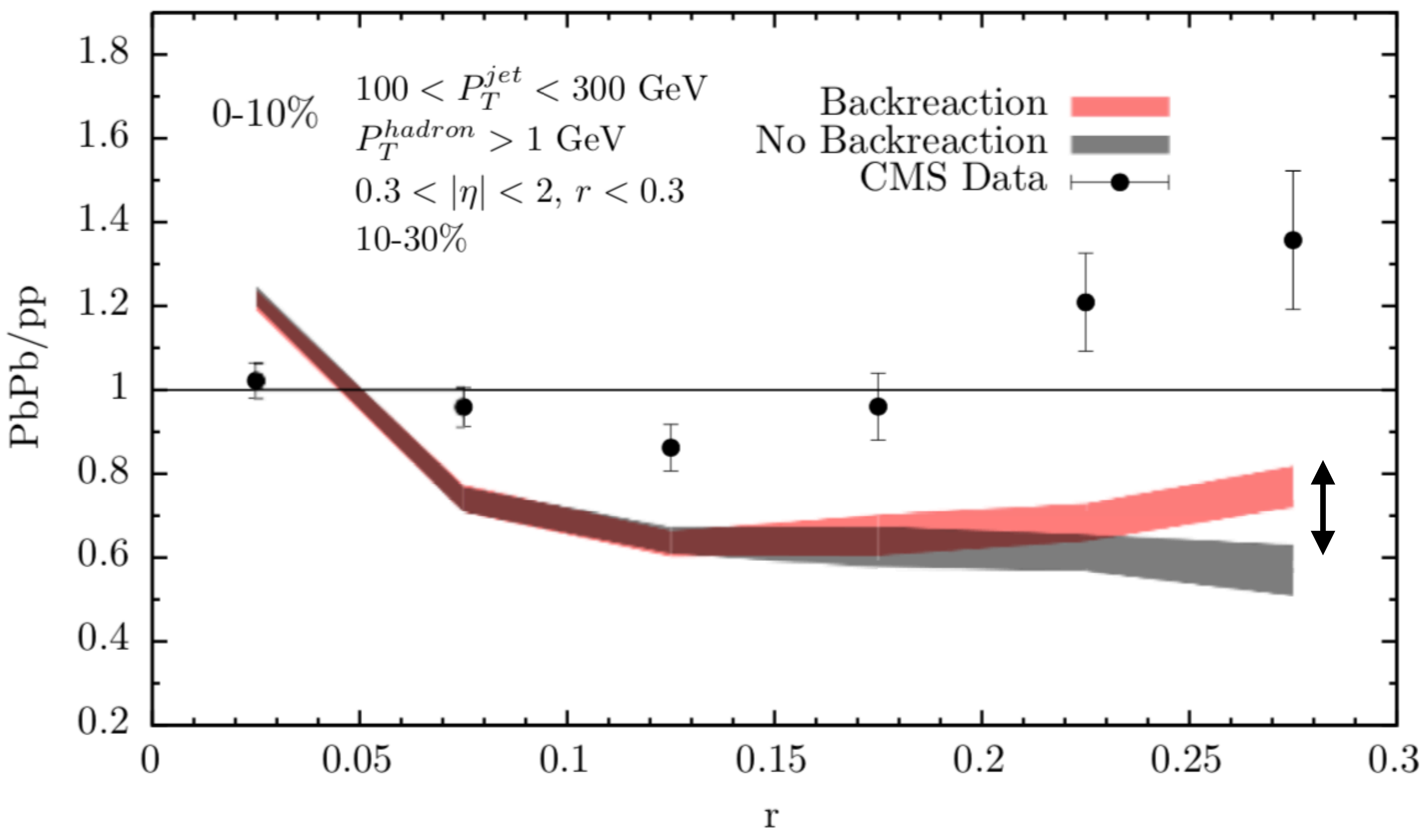


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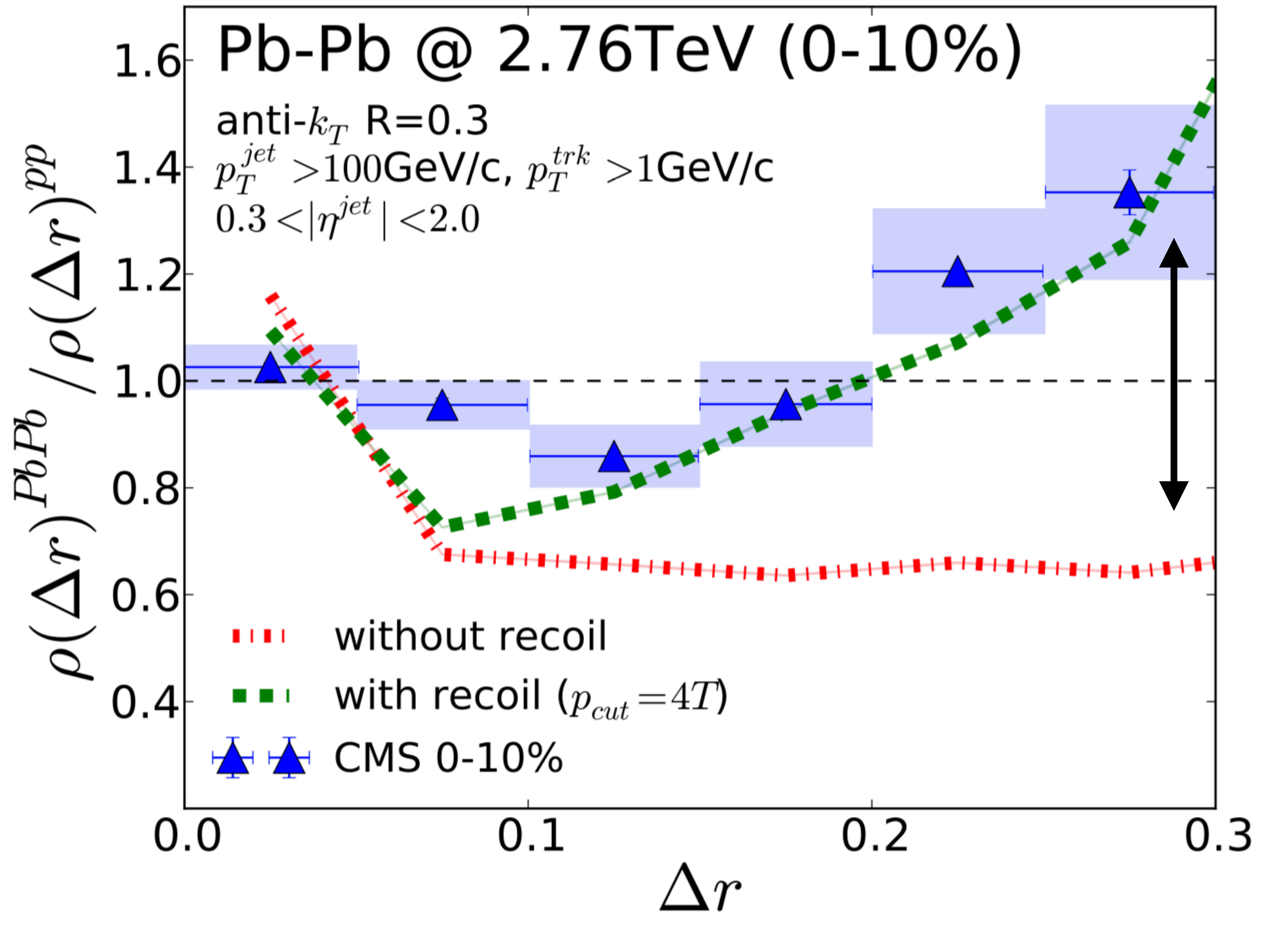
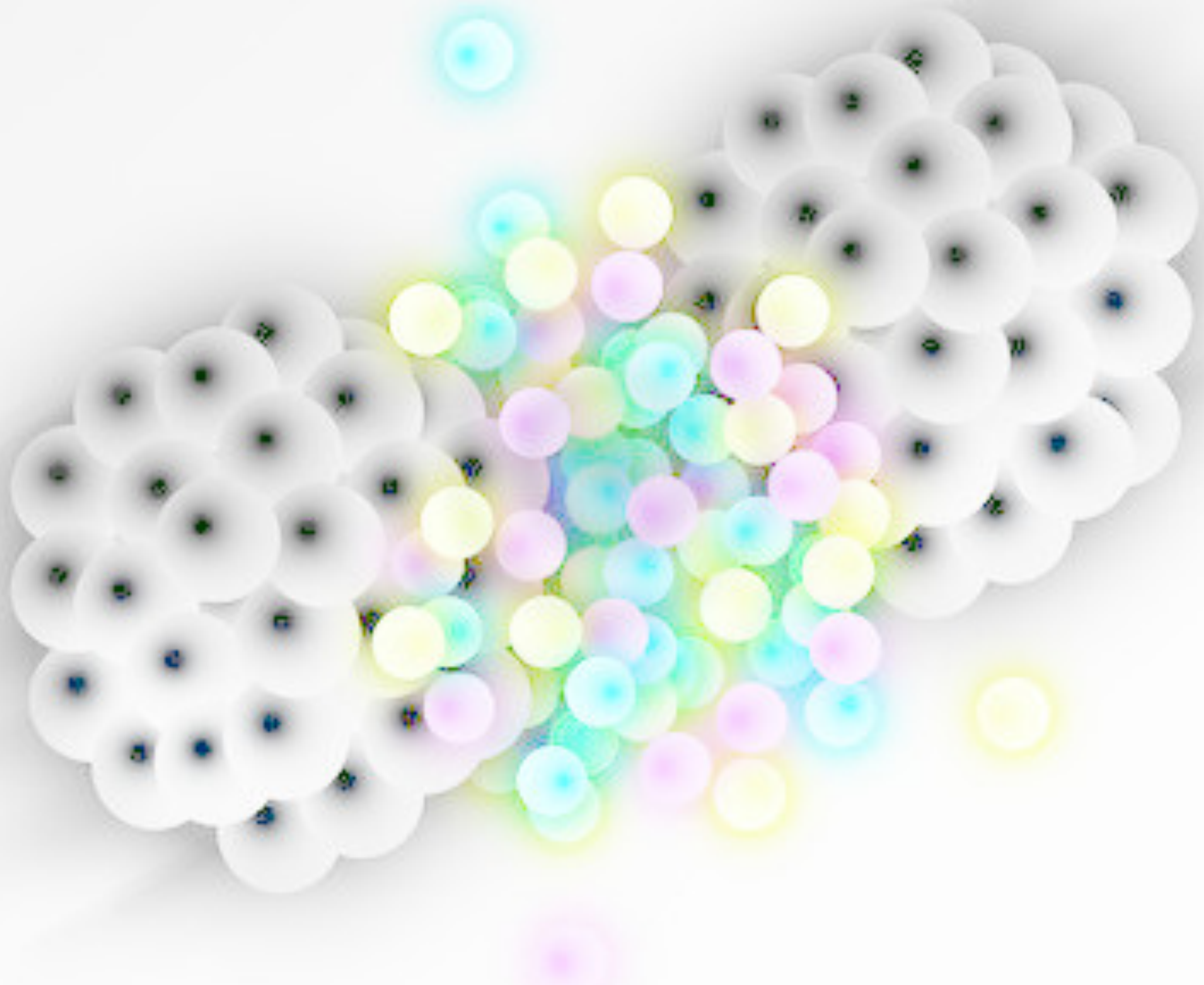


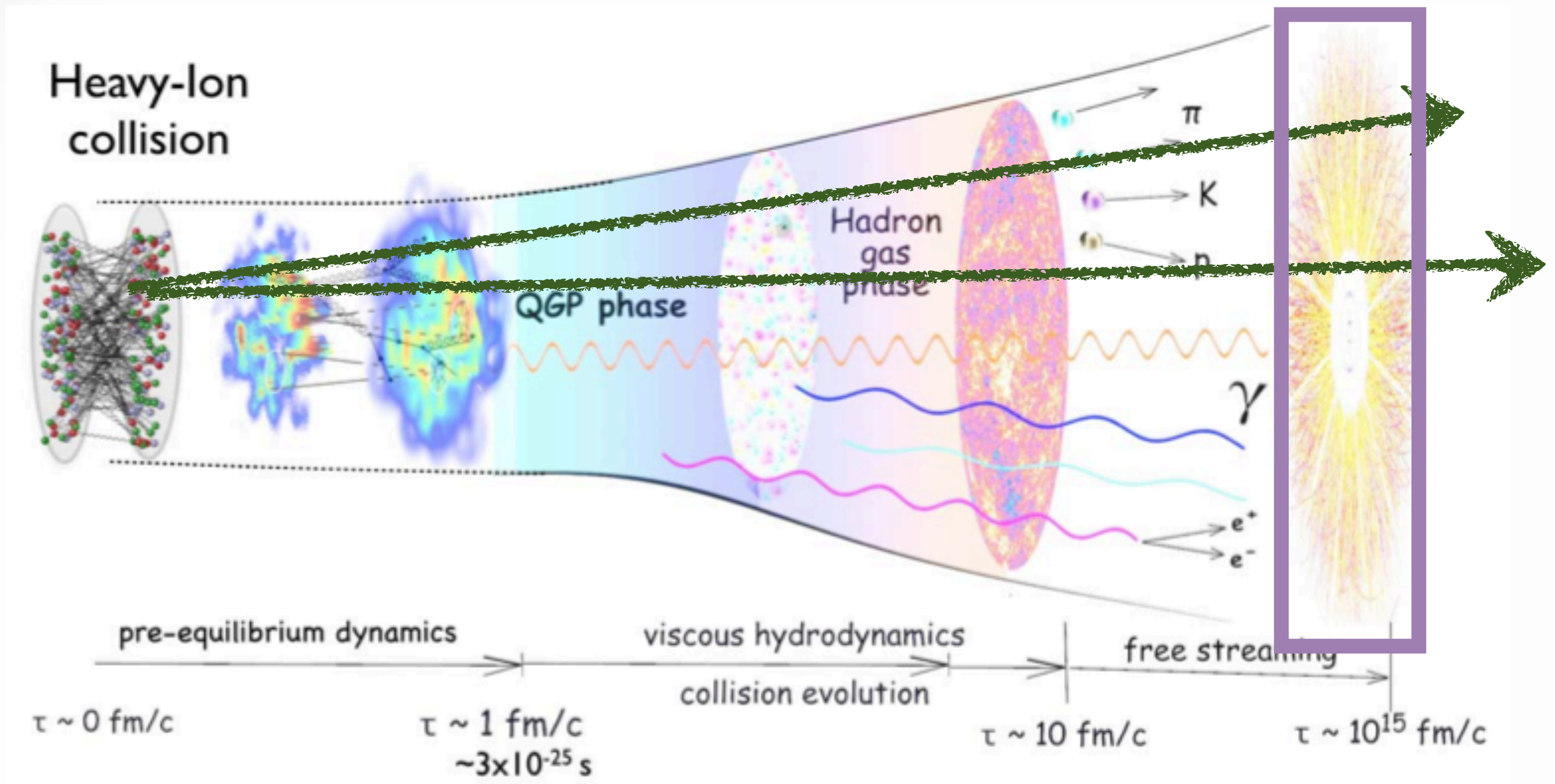

Several uncertainties… But seems to be necessary to describe excess of particles at large angles…

# Overall picture from hard and soft sector?



**Soft Probes + Hard Probes**

**(Full Collision)**



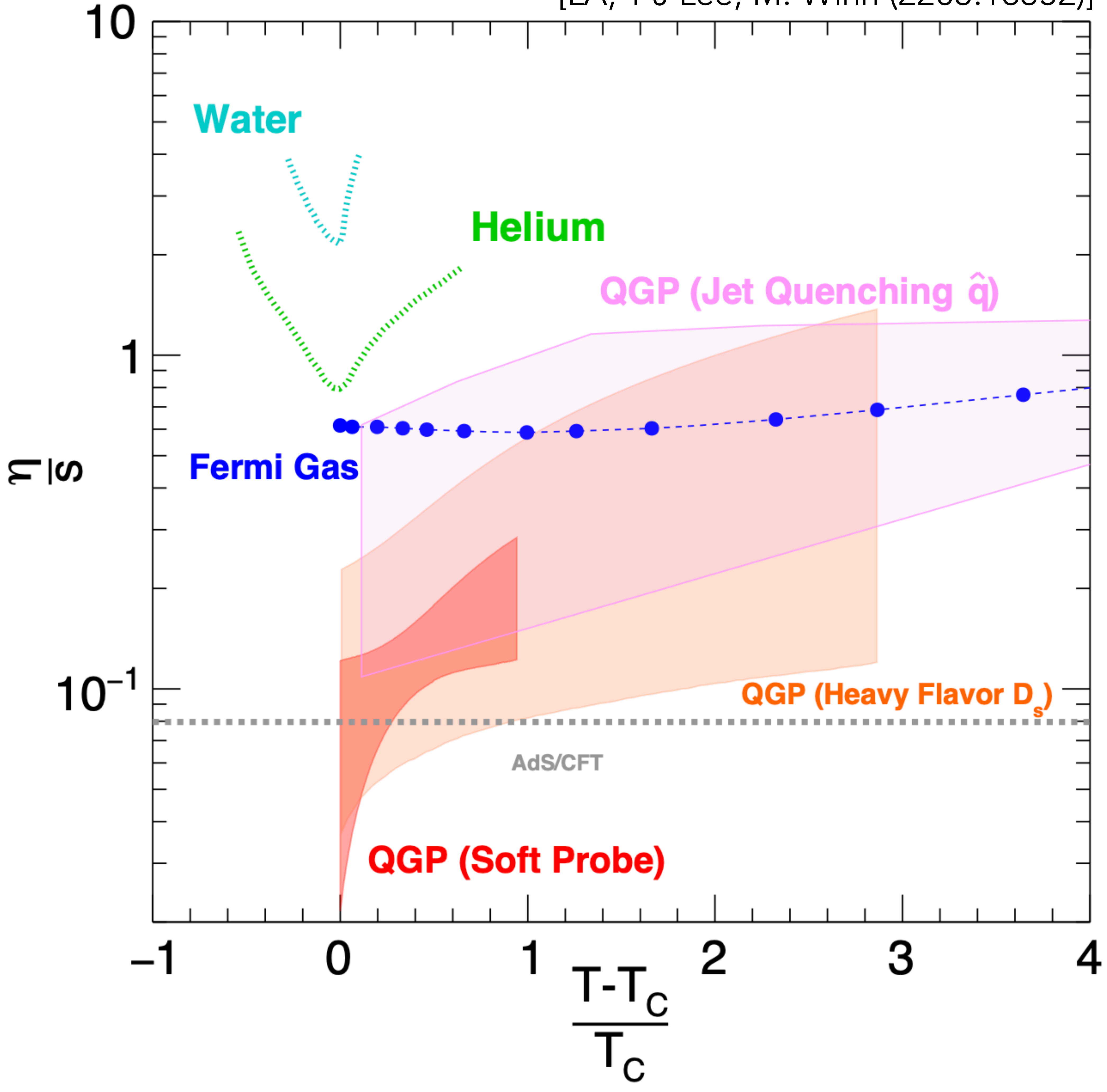
# Soft vs Hard

- Shear viscosity can also be related to transport coefficients:
  - But still model dependent…

**Light Flavour/Jets:** $\frac{\eta}{s} \approx 1.25 \frac{T^3}{\hat{q}}$

**Heavy Flavour:** $\frac{\eta}{s} = \frac{Ds(2\pi T)}{4\pi k}$

[LA, Y-J Lee, M. Winn (2203.16352)]



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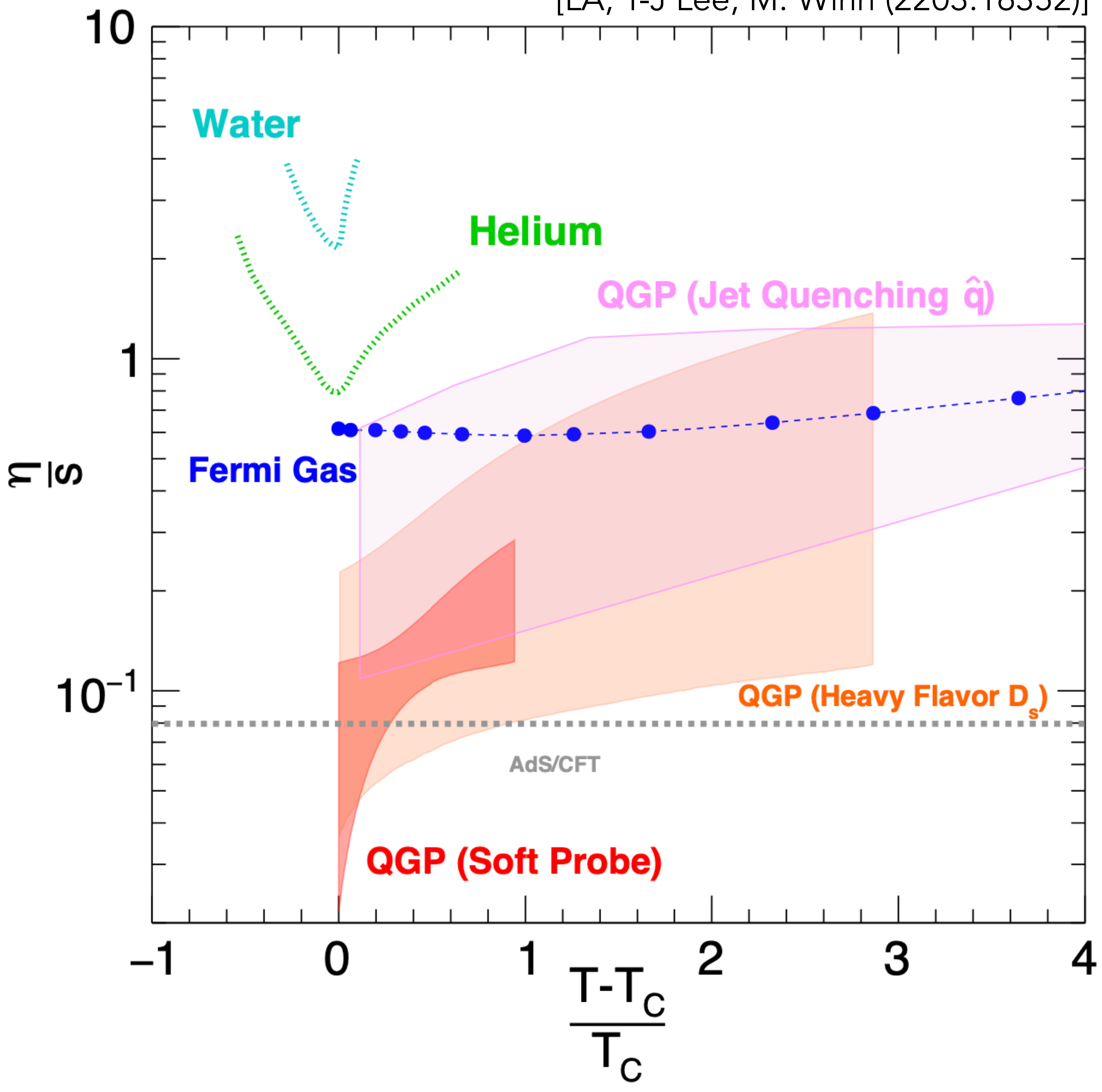
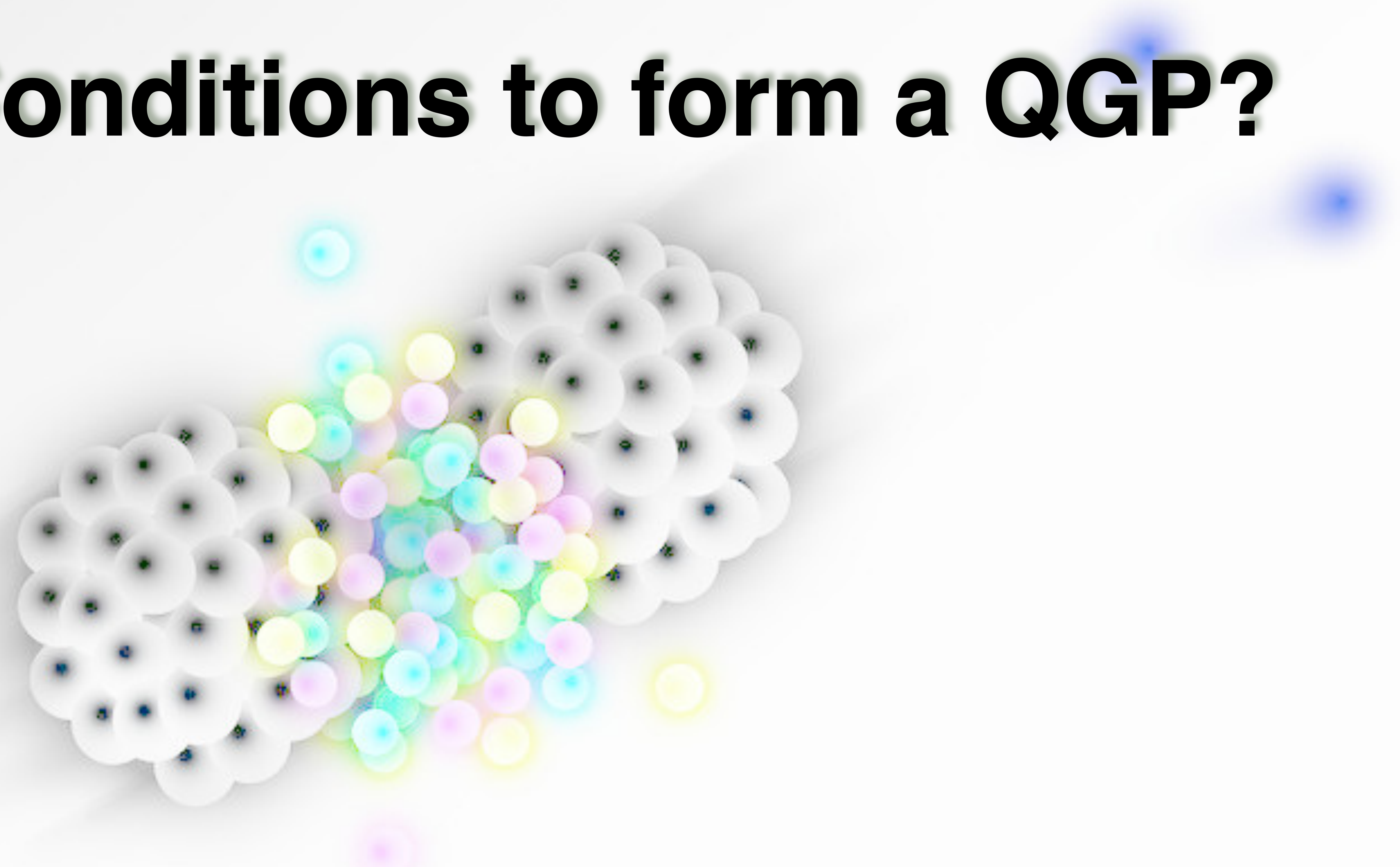
**But QGP is a fast expanding medium…**

**What is the time-dependence of the medium properties?**

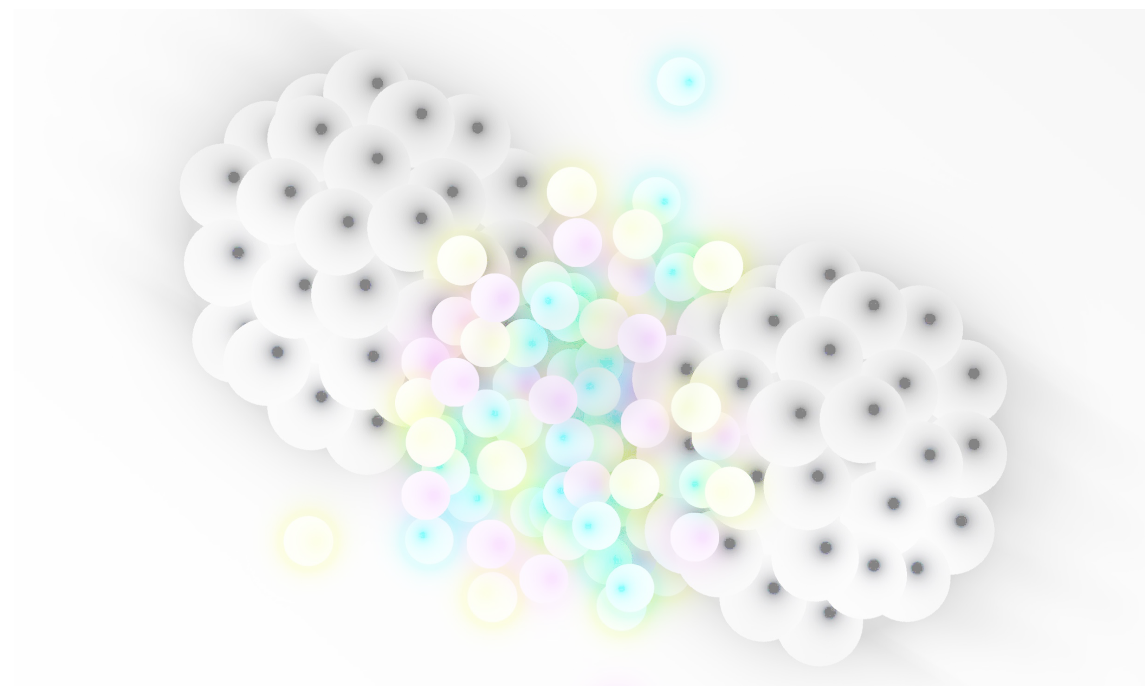
[LA, Y-J Lee, M. Winn (2203.16352)]



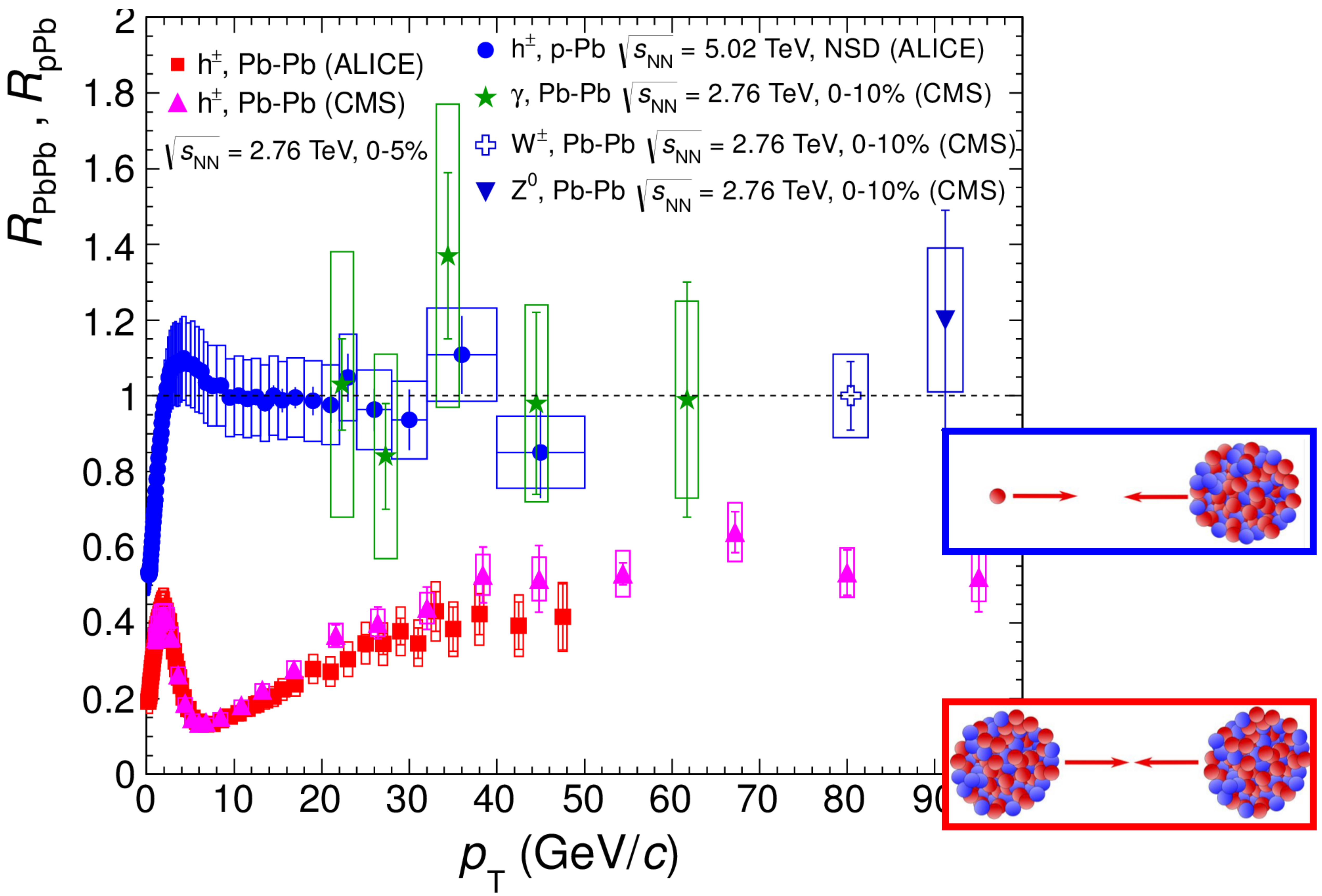
# Conditions to form a QGP?



# QGP onset



- No energy loss in pA…



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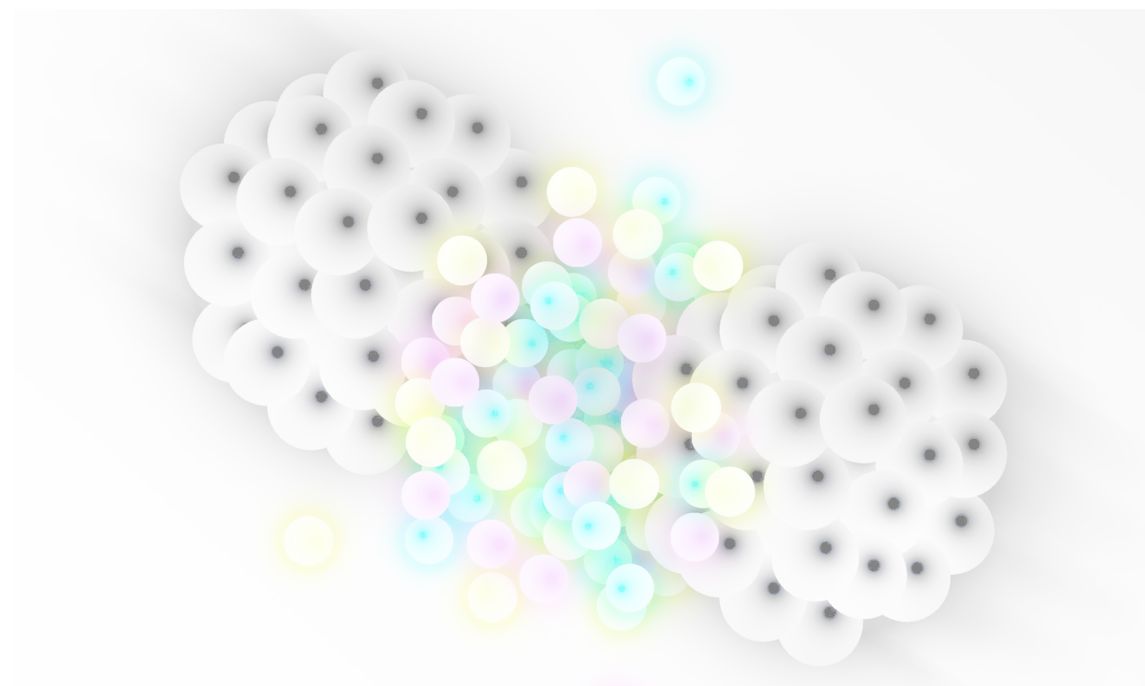
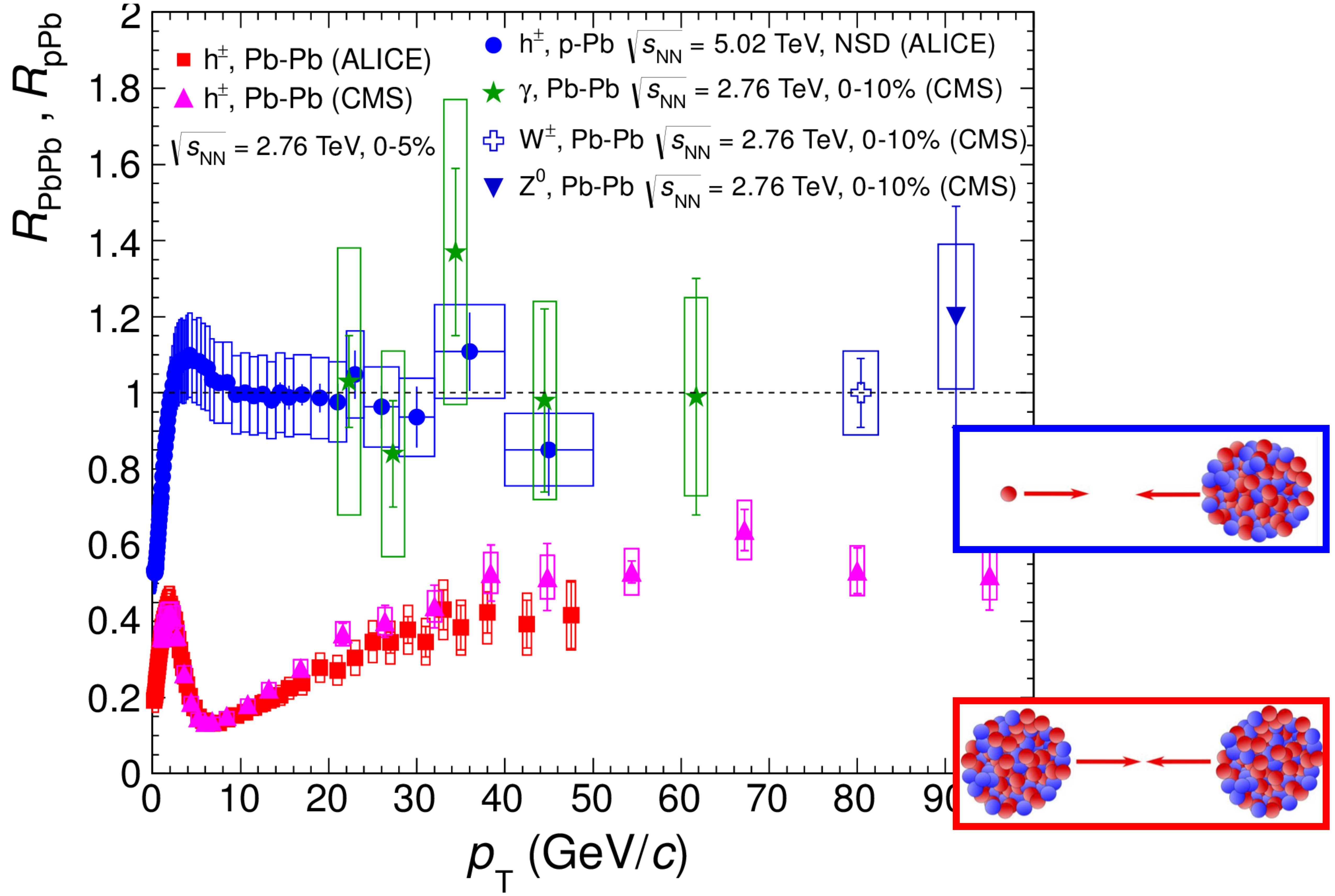
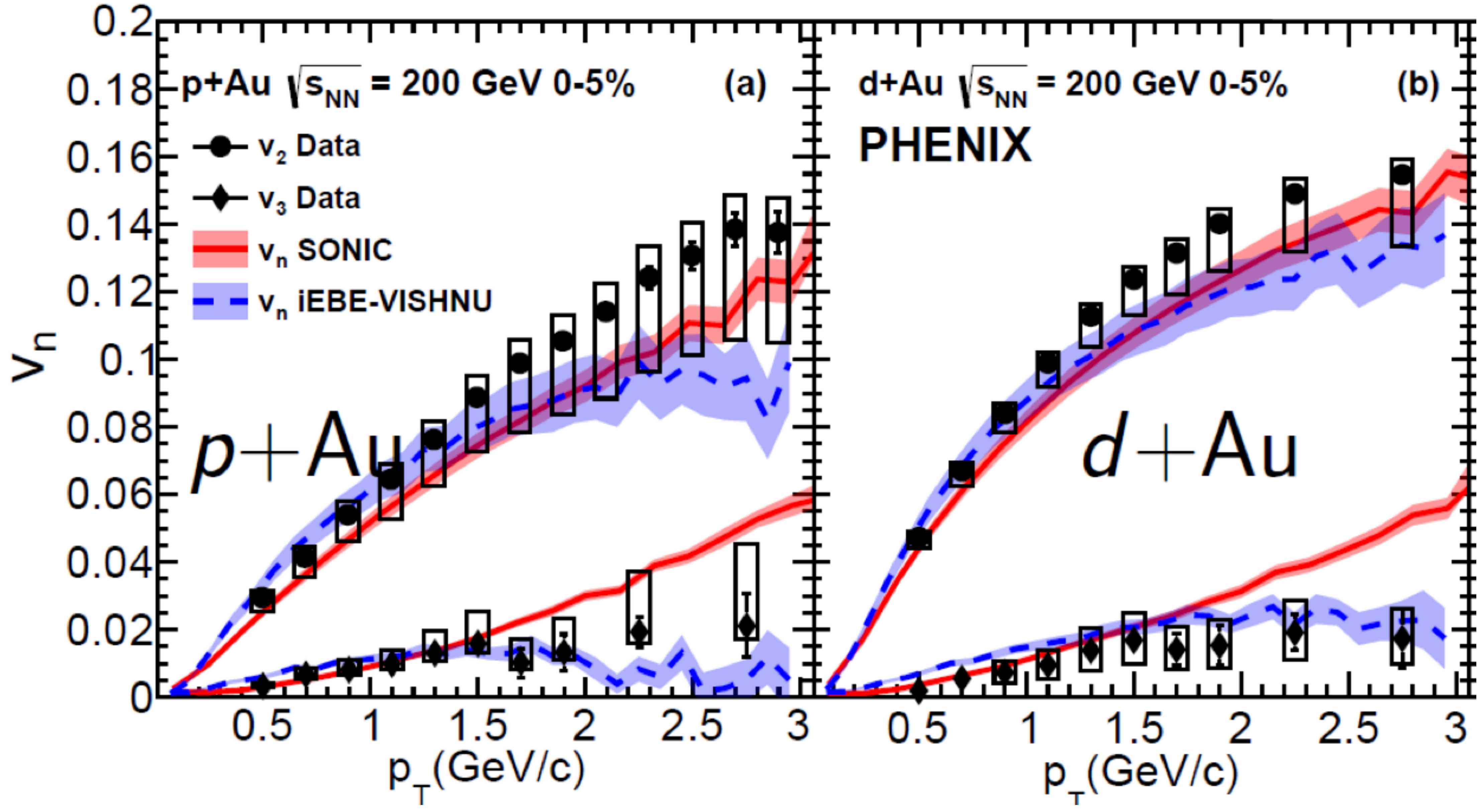


- No energy loss in pA… but strong evidence in support of hydrodynamic behavior

[PHENIX (PRL 123, 039901)]




Flow coefficients well reproduced by hydro predictions, but not by initial state effects only

# Light Systems

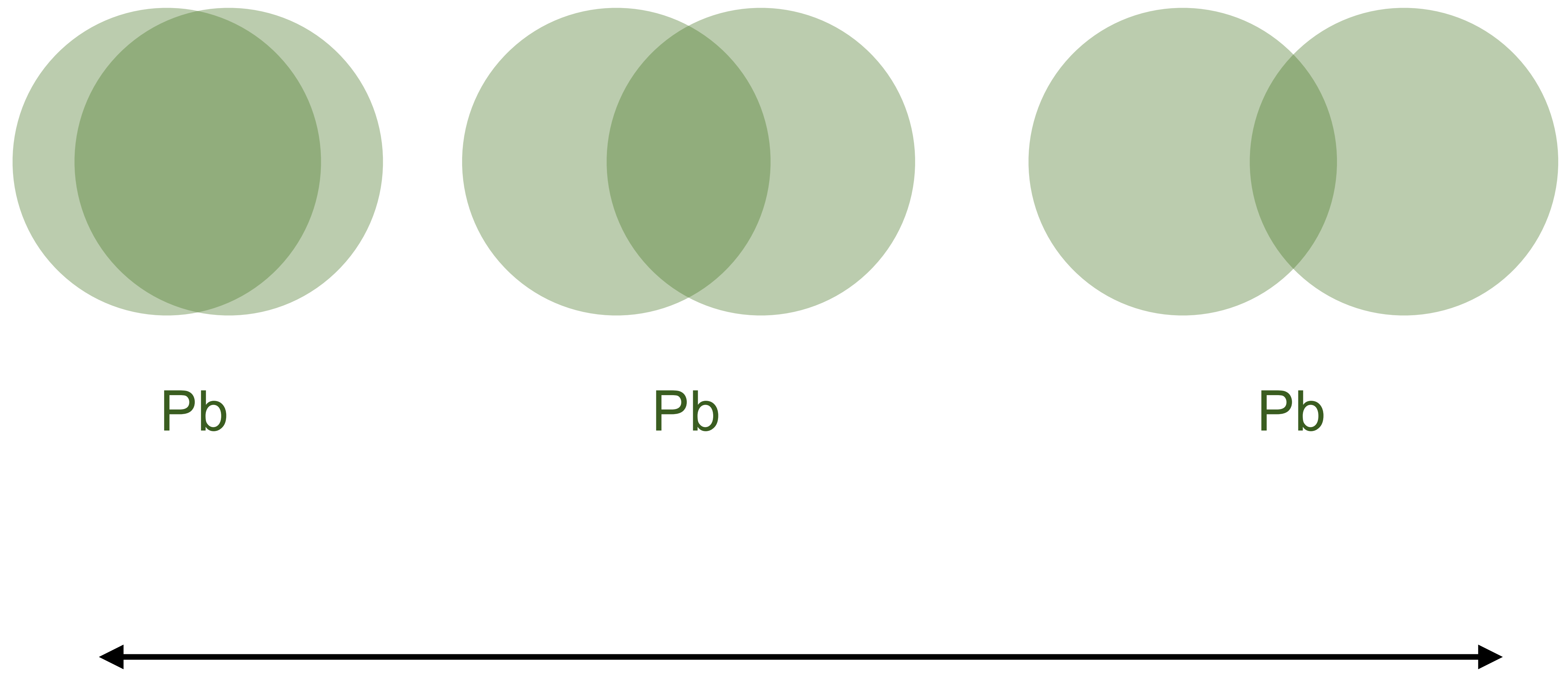
[JEWEL: Zapp (14)]

[Citron, Dainese et al (19)]

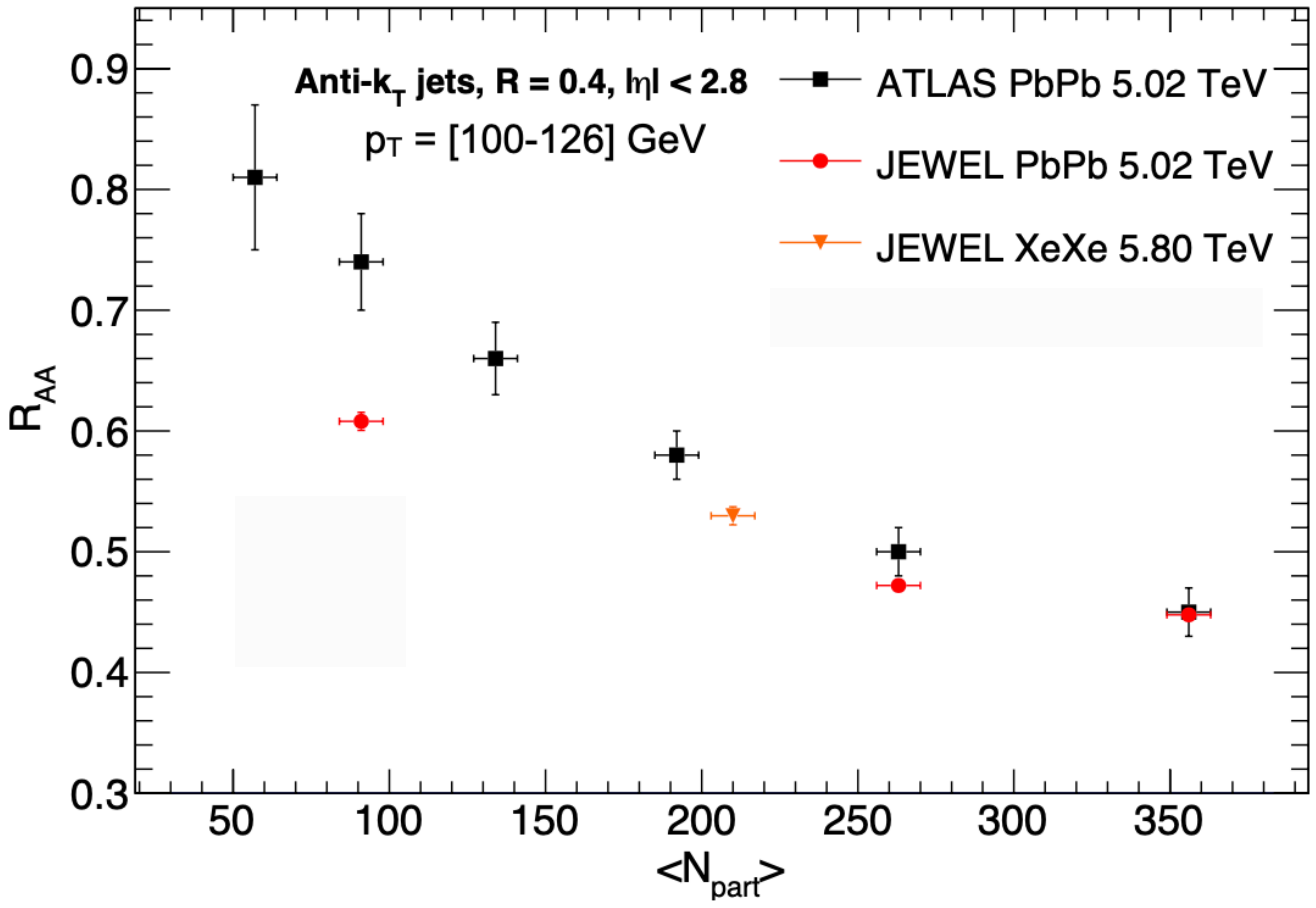
Several changes at the same time: energy loss, nuclear overlap,…

(too many variables)

- Magnitude of Jet quenching depends on system size:
  - Peripheral collisions: expected some energy loss




[arXiv: 1812.06772]

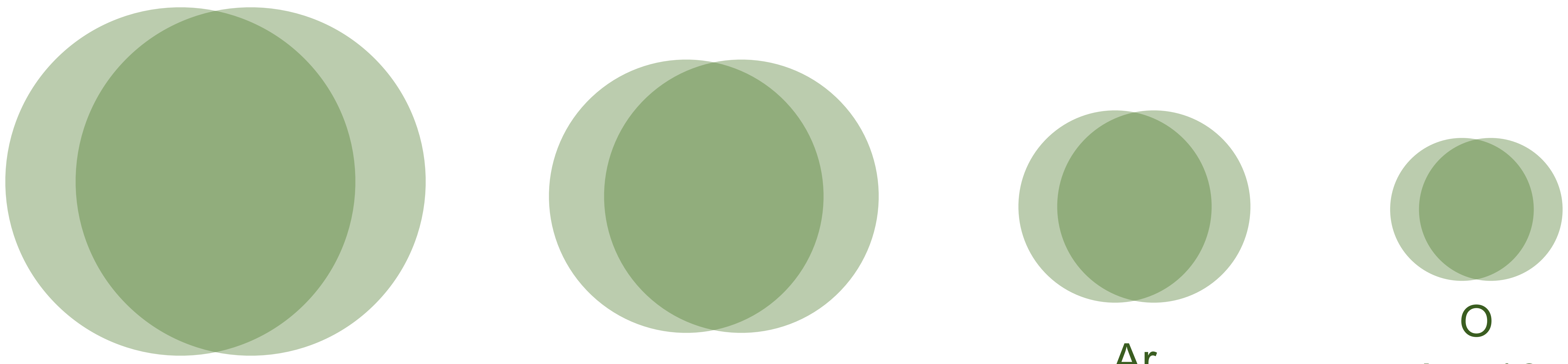


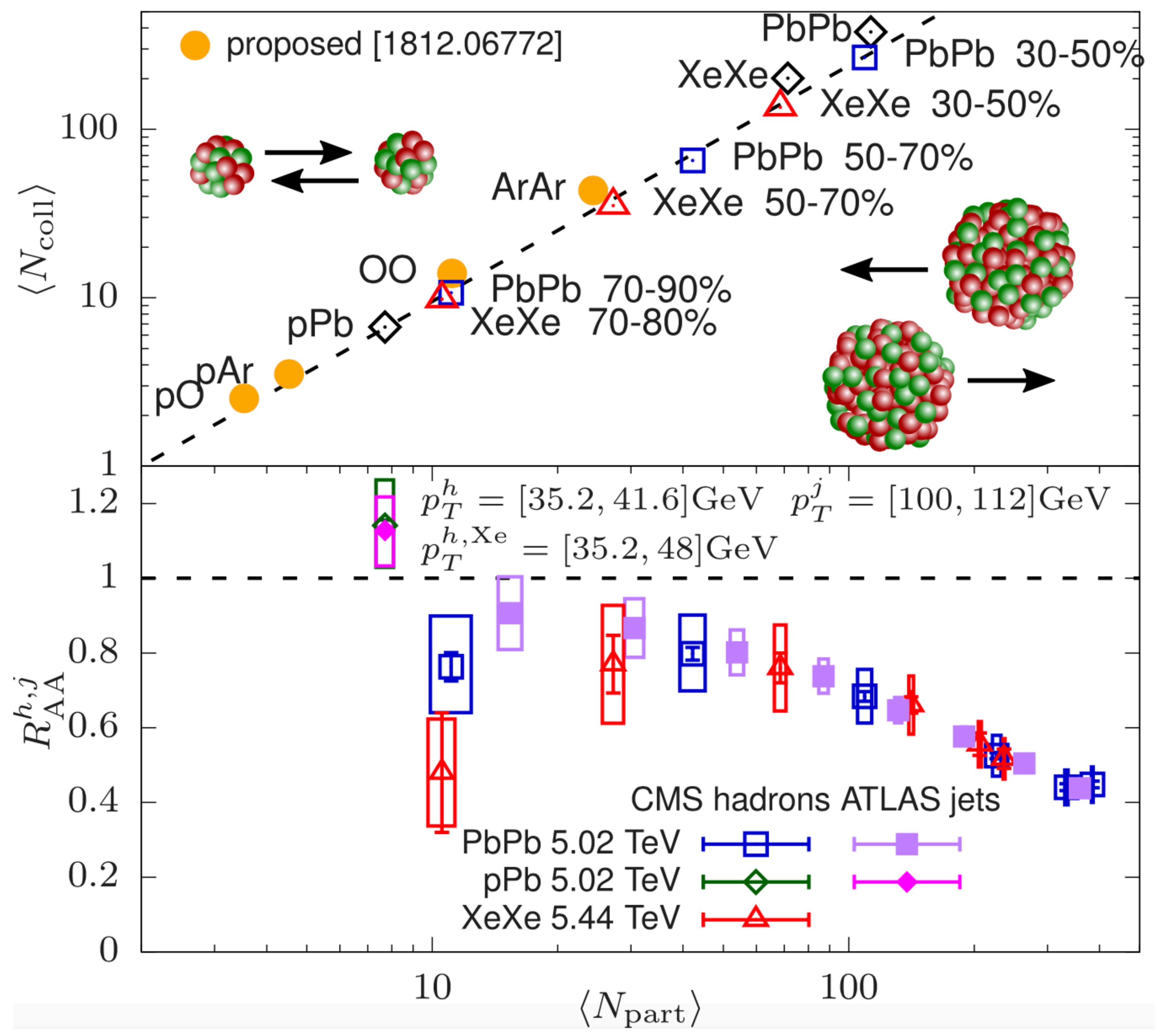
# Light Systems

[Huss, Kurkela, Mazeliauskas, Paatelainen, Van der Schee, Widemann (20)]

[arXiv:2007.13754]

- Magnitude of Jet quenching depends on system size:
  - Lighter nuclei allow to fix geometry




**Studies of System Size dependence**
(always fixing geometry - [0-10]%)

**Better control on initial condition to collectivity studies**

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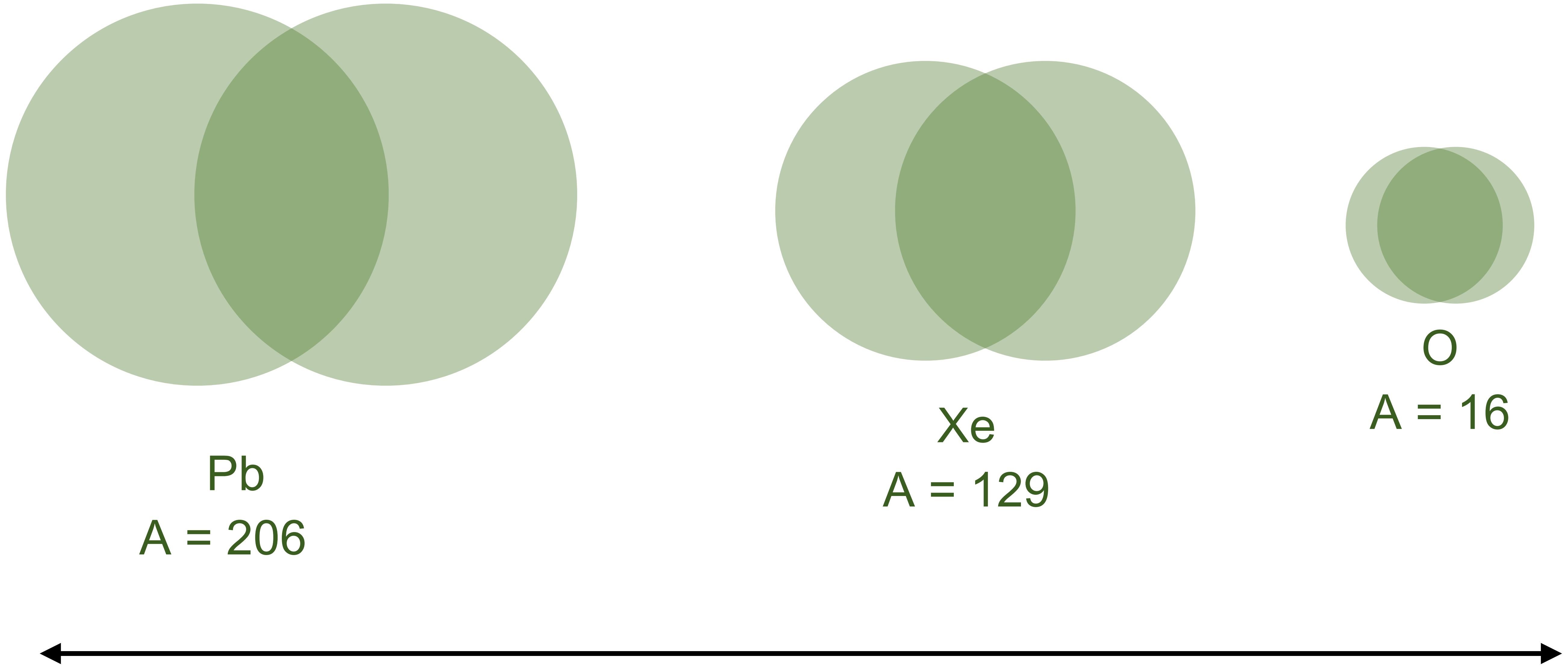
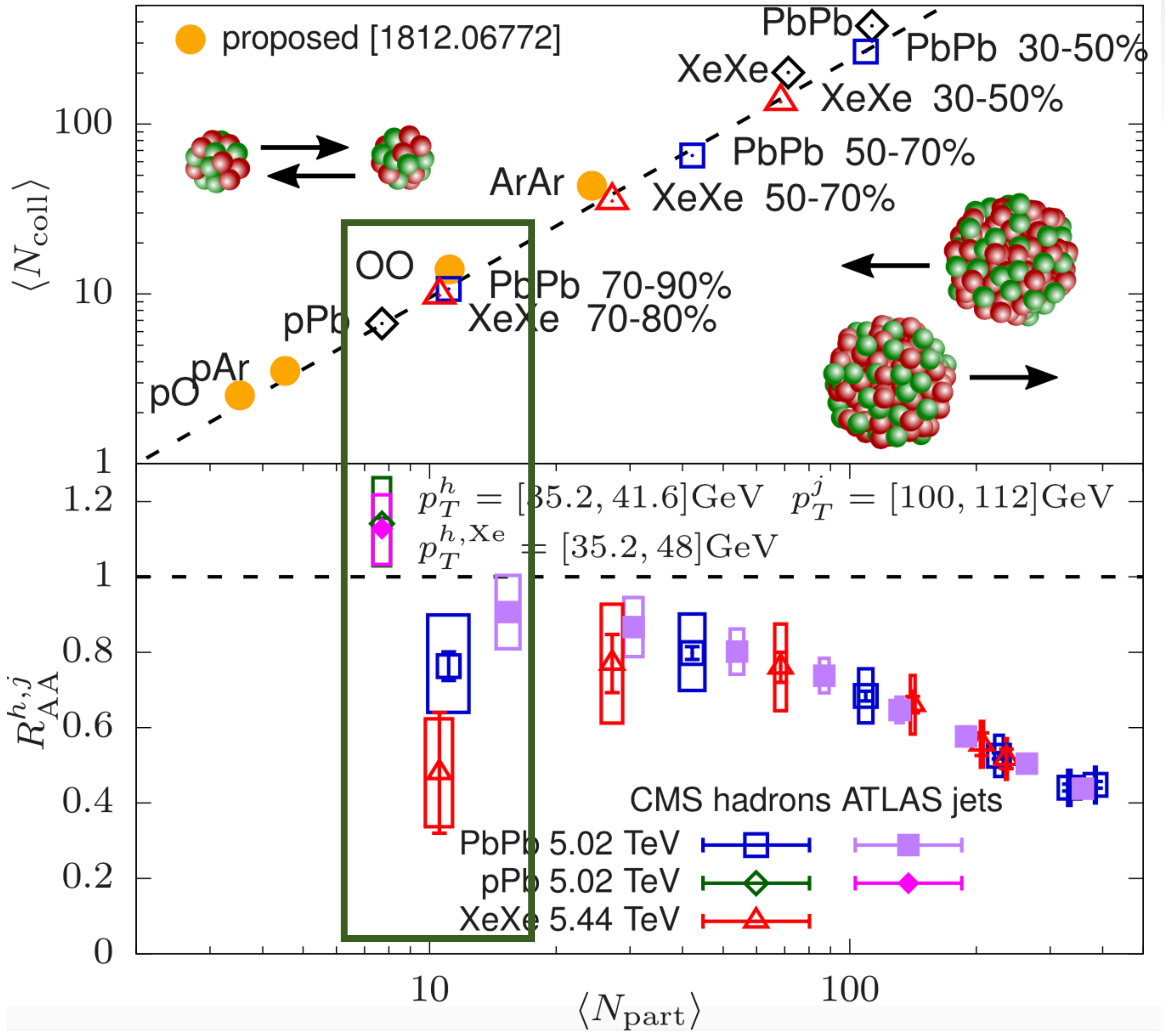


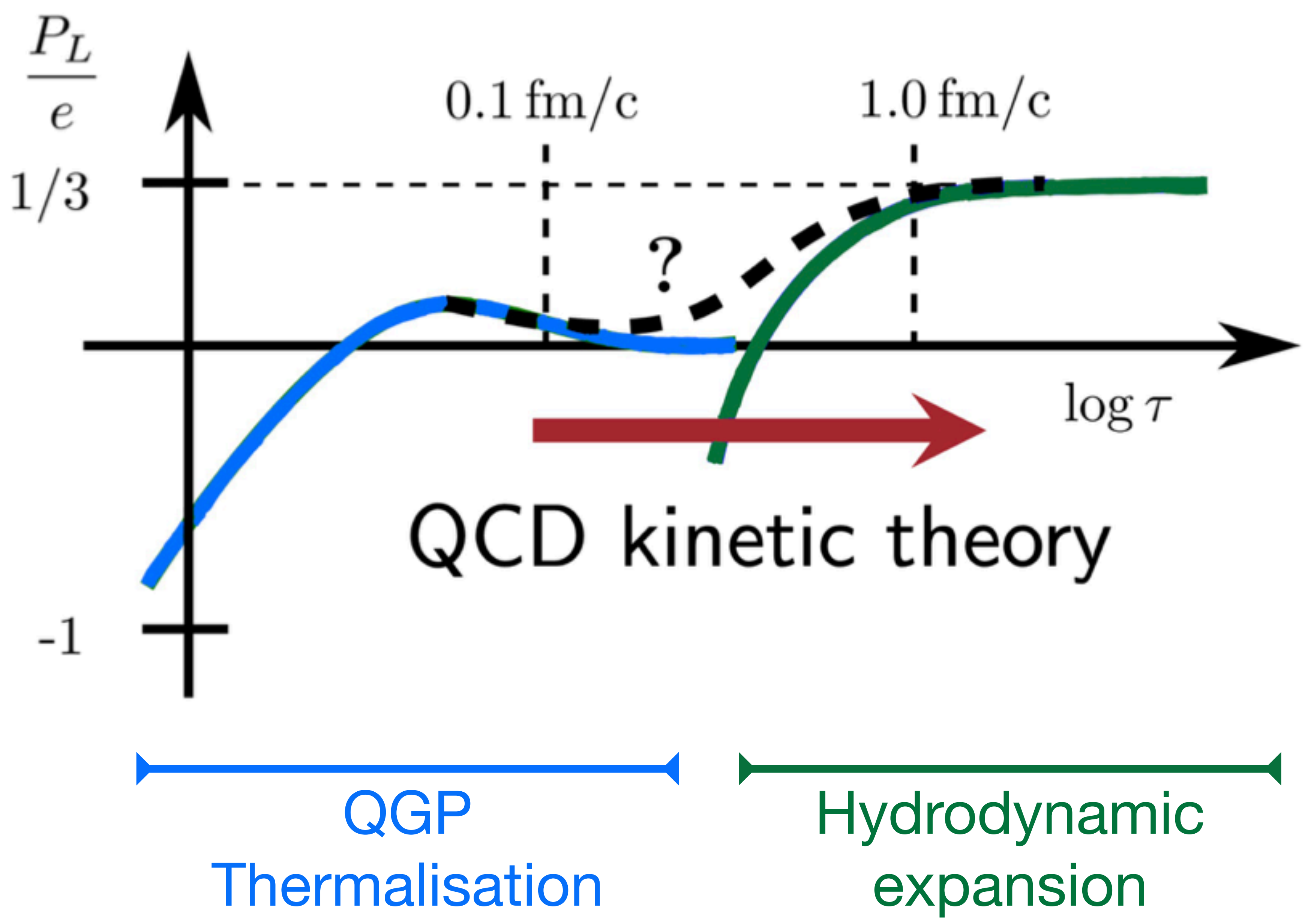




**Better control on initial condition to collectivity studies**

# From dense to light systems

[Kurkela, Mazeliauskas, Paquet, Schlichting, Teaney (1601.03283, 1805.00961)]
[Schlichting, Soudi (2008.04928)]

- Extrapolation from dense to light needs further understanding…



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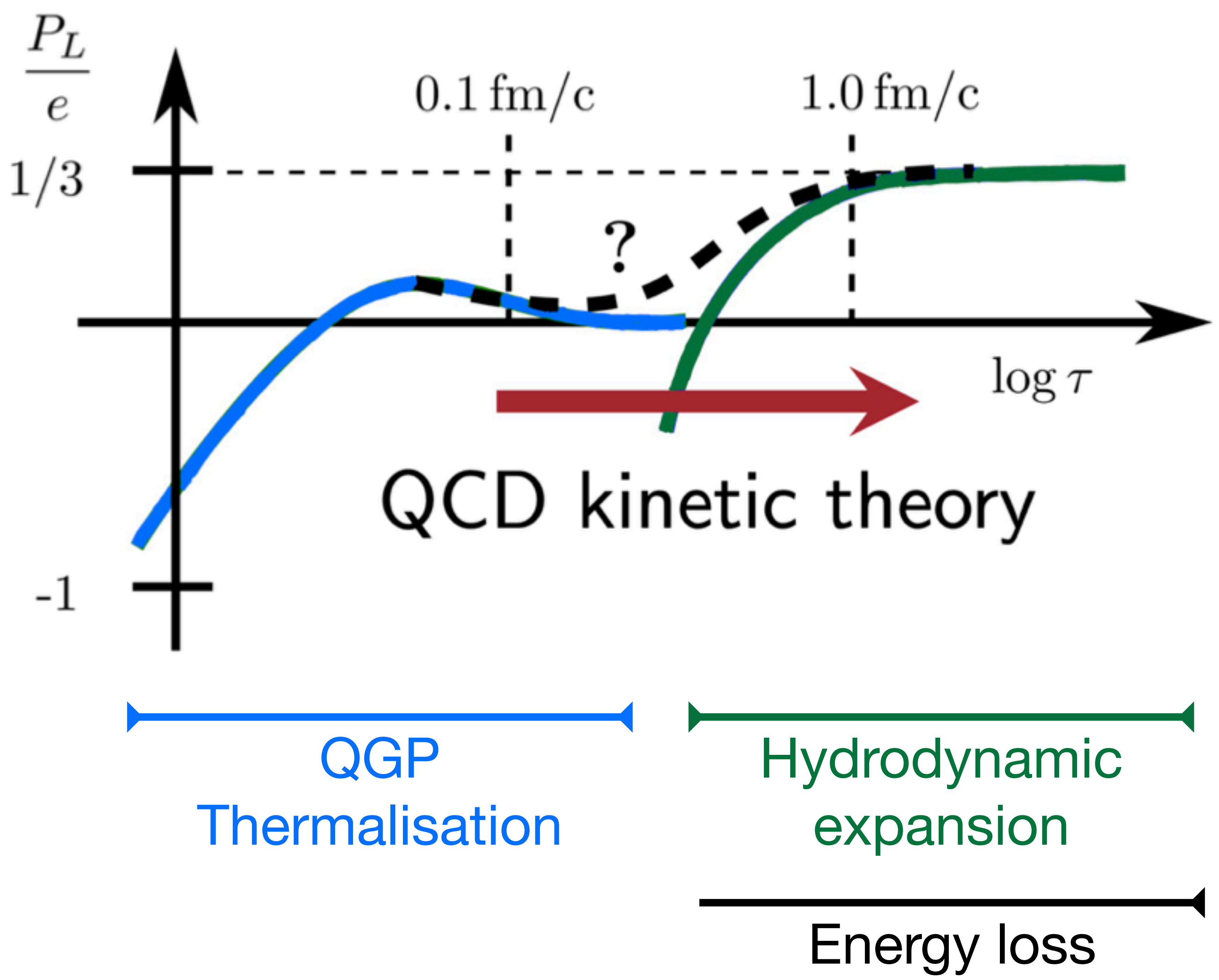

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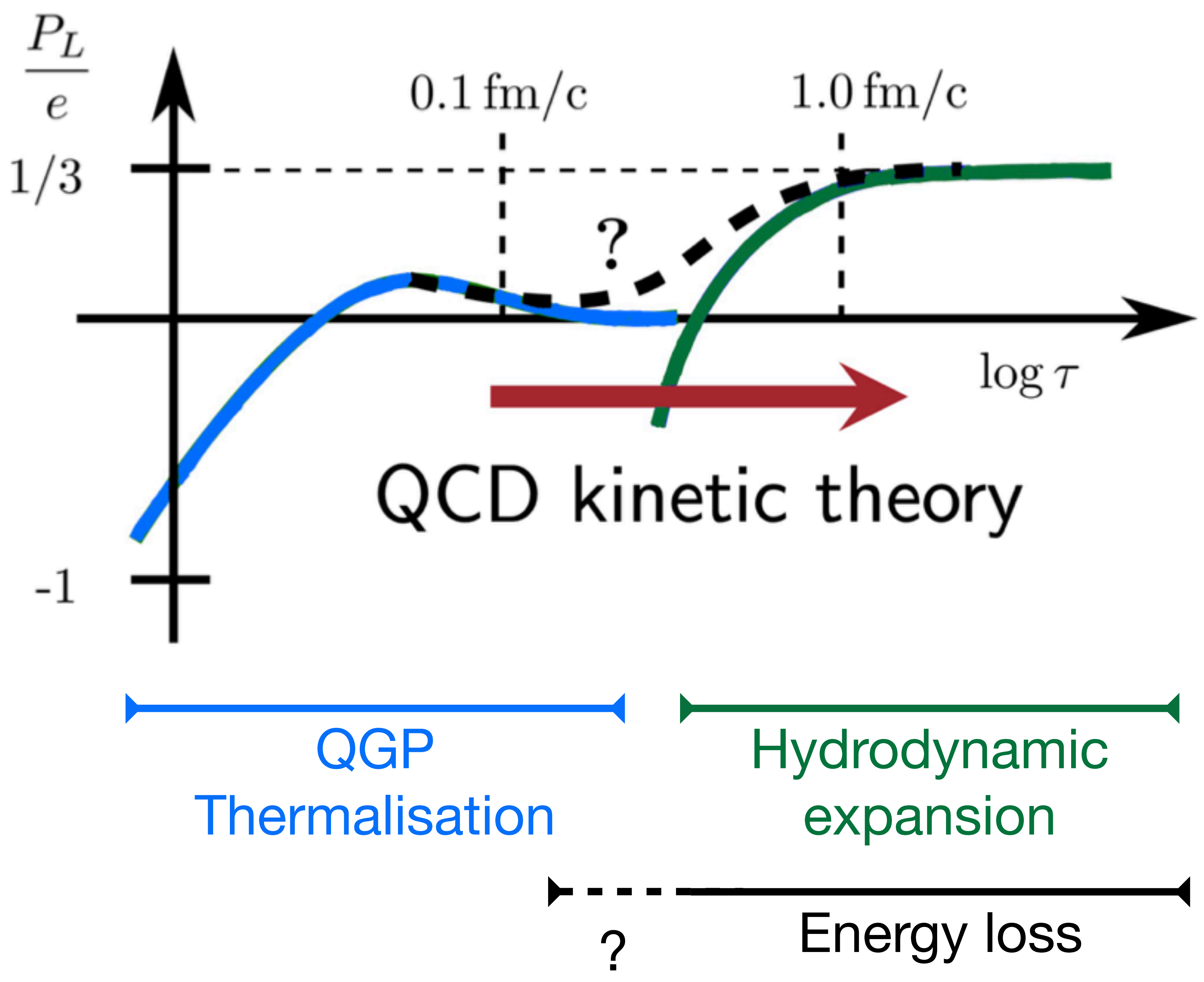

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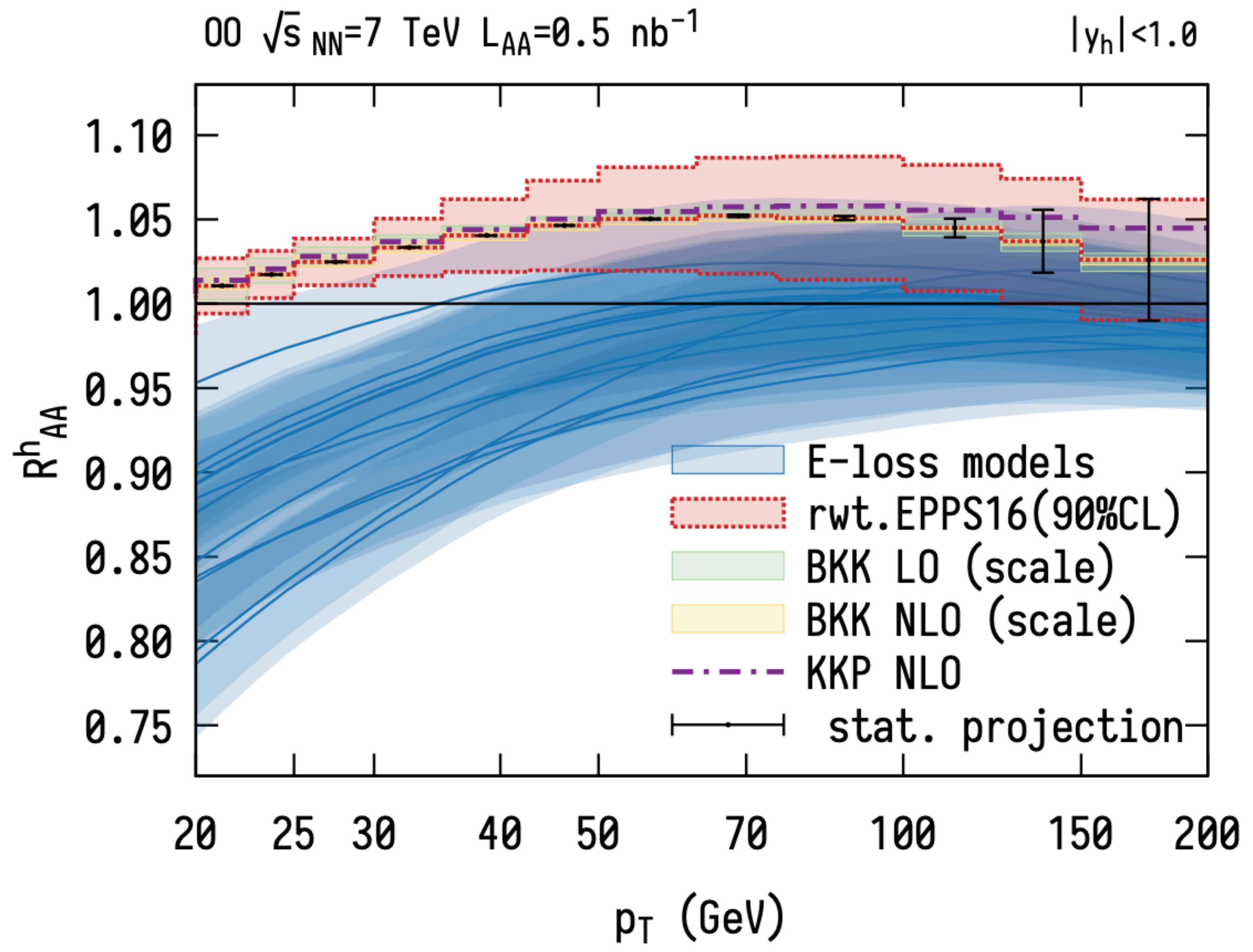
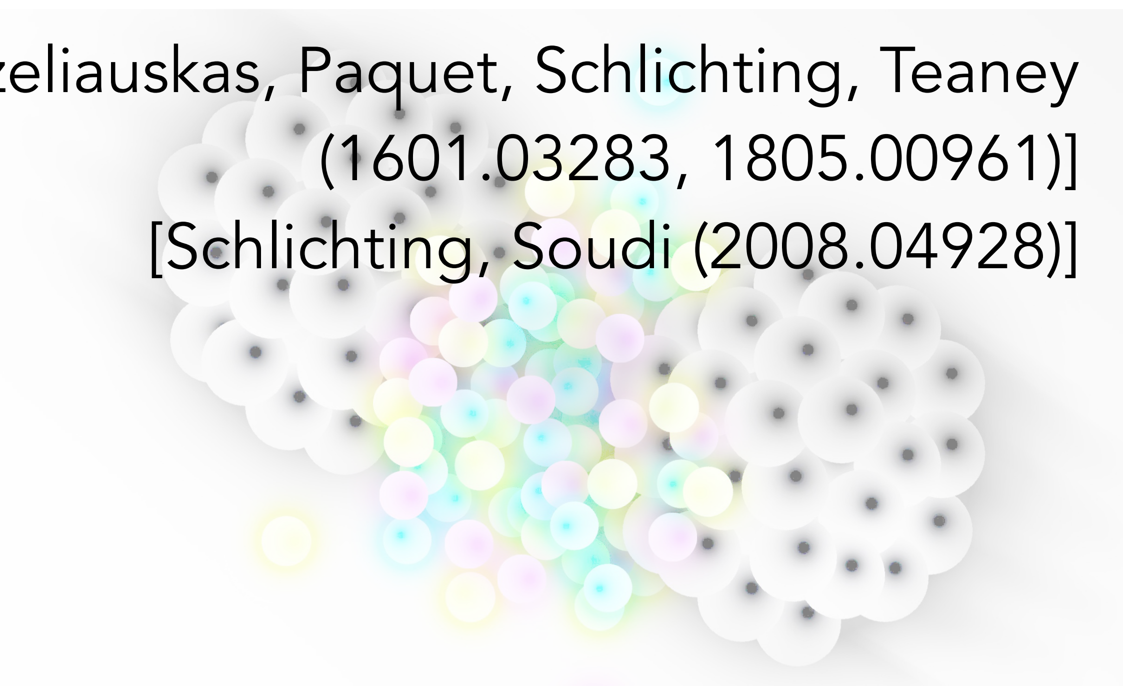
- Future oxygen runs can help us to determine the smallest amount of energy loss, provided that we control the initial state

Future OO run similar to PbPb peripheral (better suited to system-size dependence)

Future pO run crucial do reduce nPDF uncertainties

[Huss, et al (2007.13754)]





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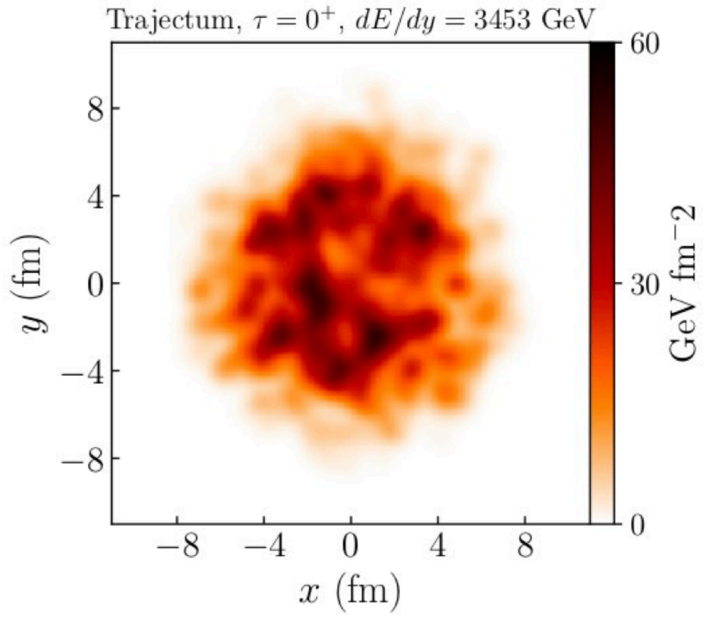
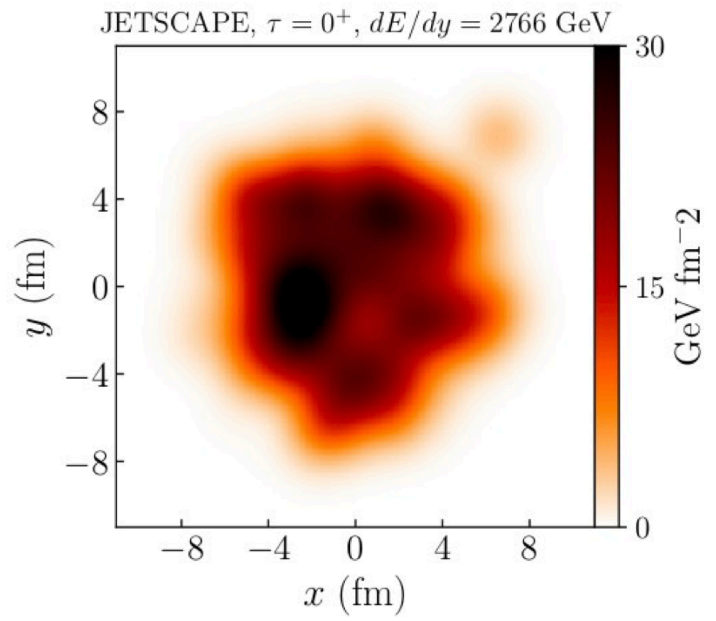
**Cold or Hot nuclear matter effects?**

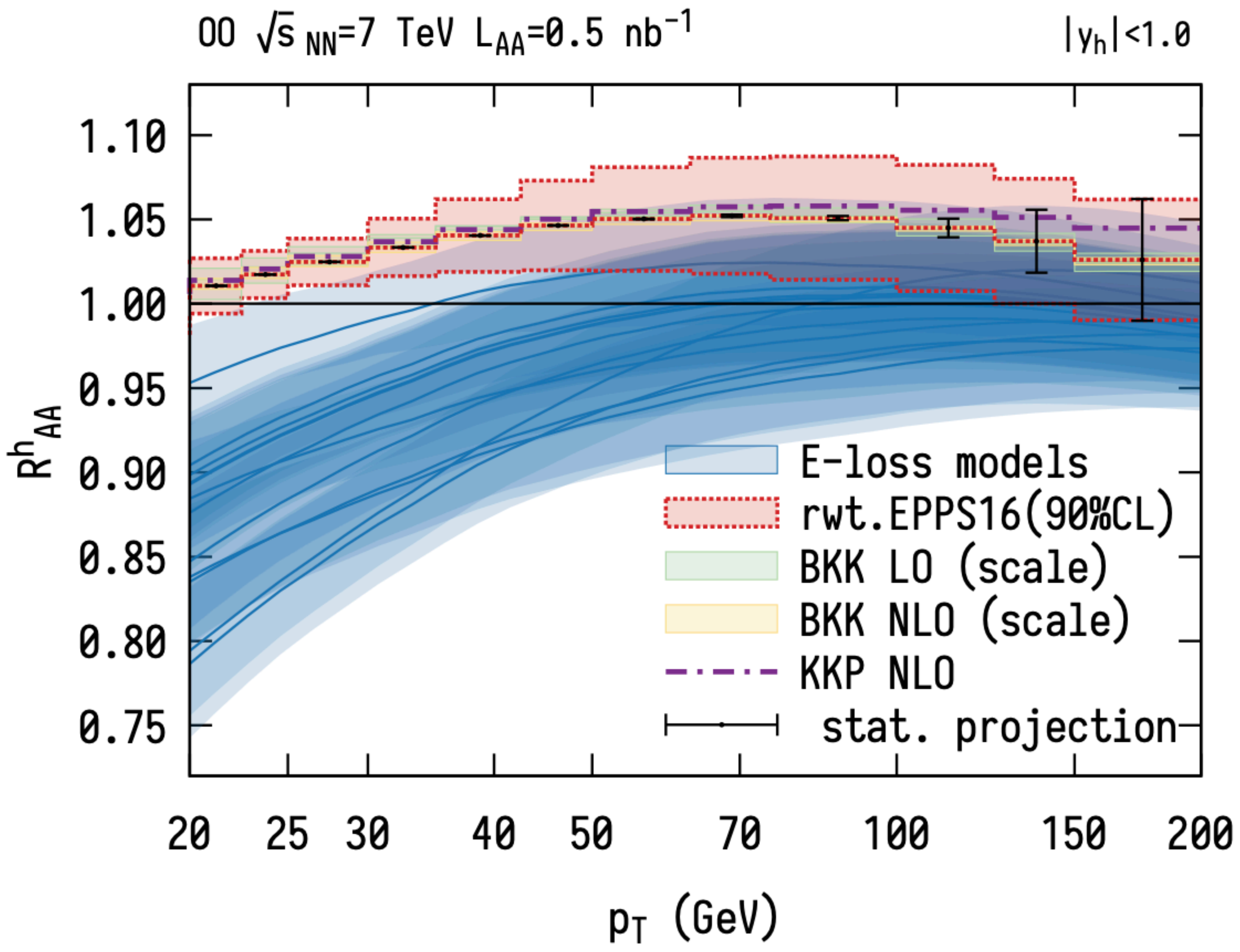
Nucleon structure at high energy:



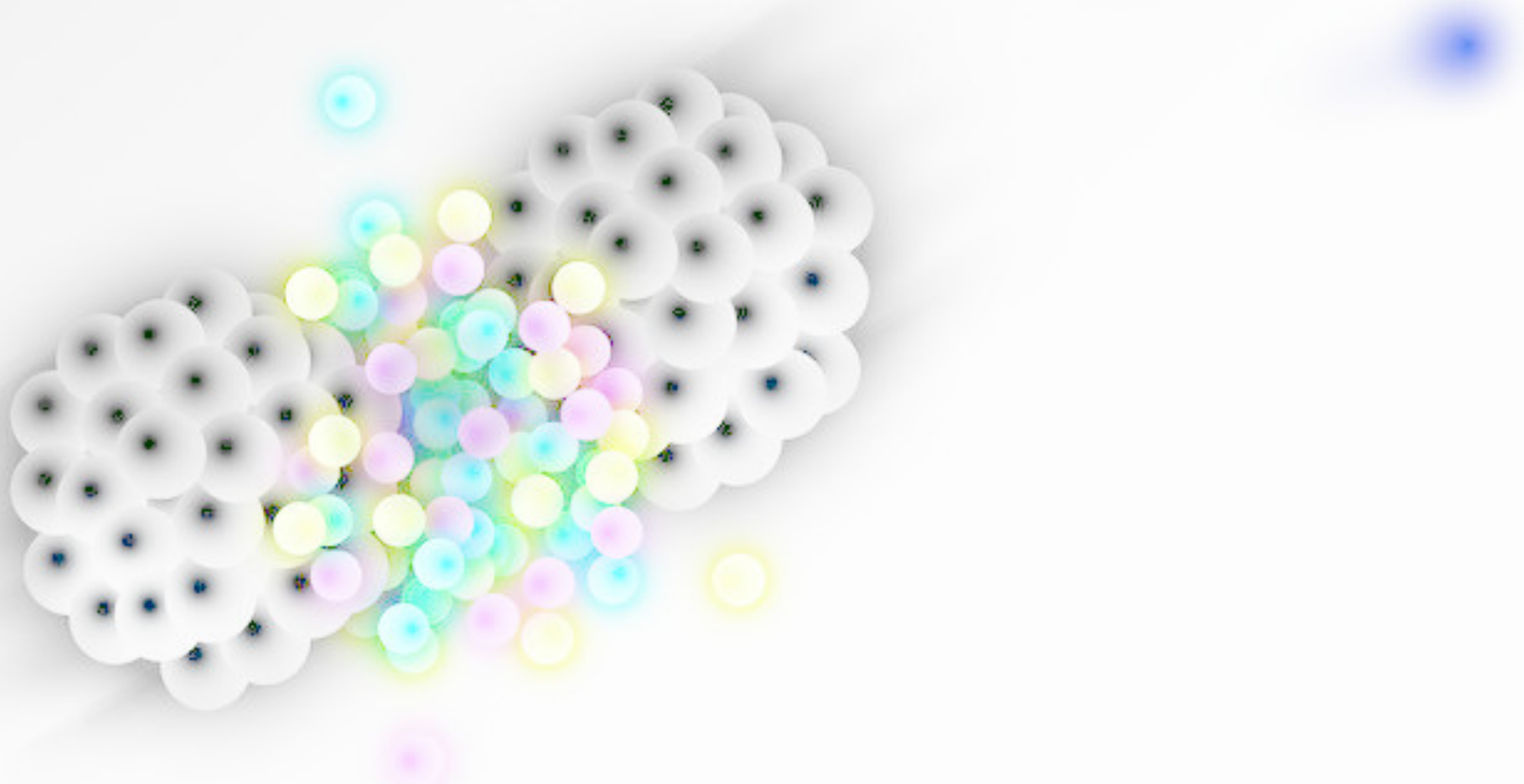

or



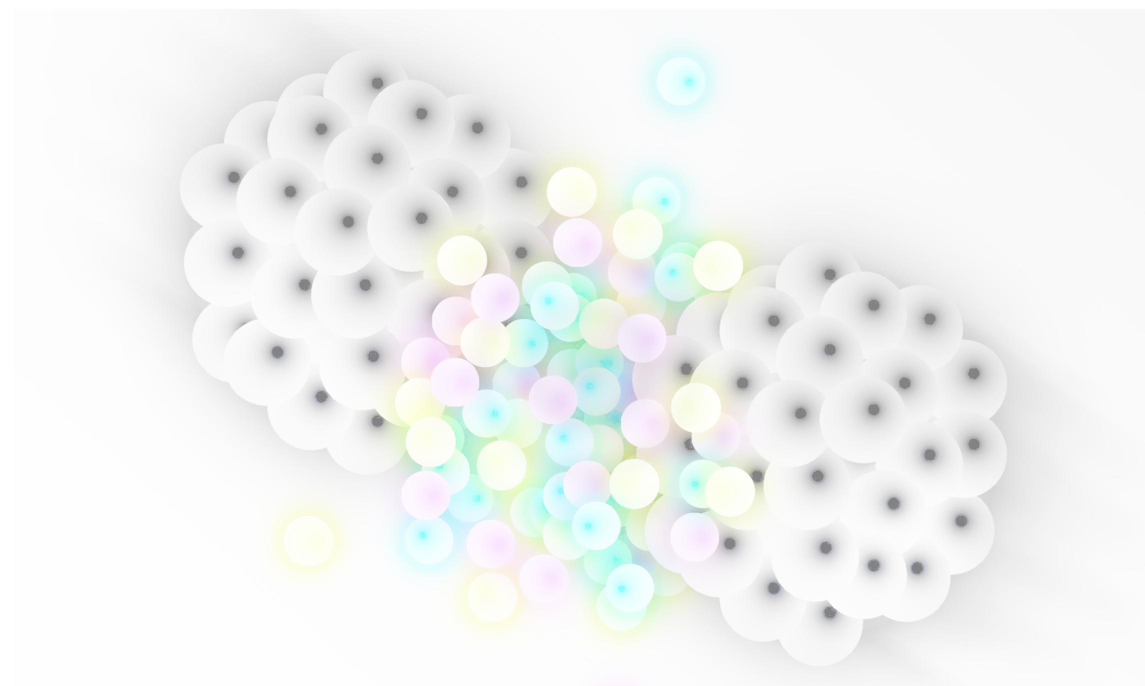

?



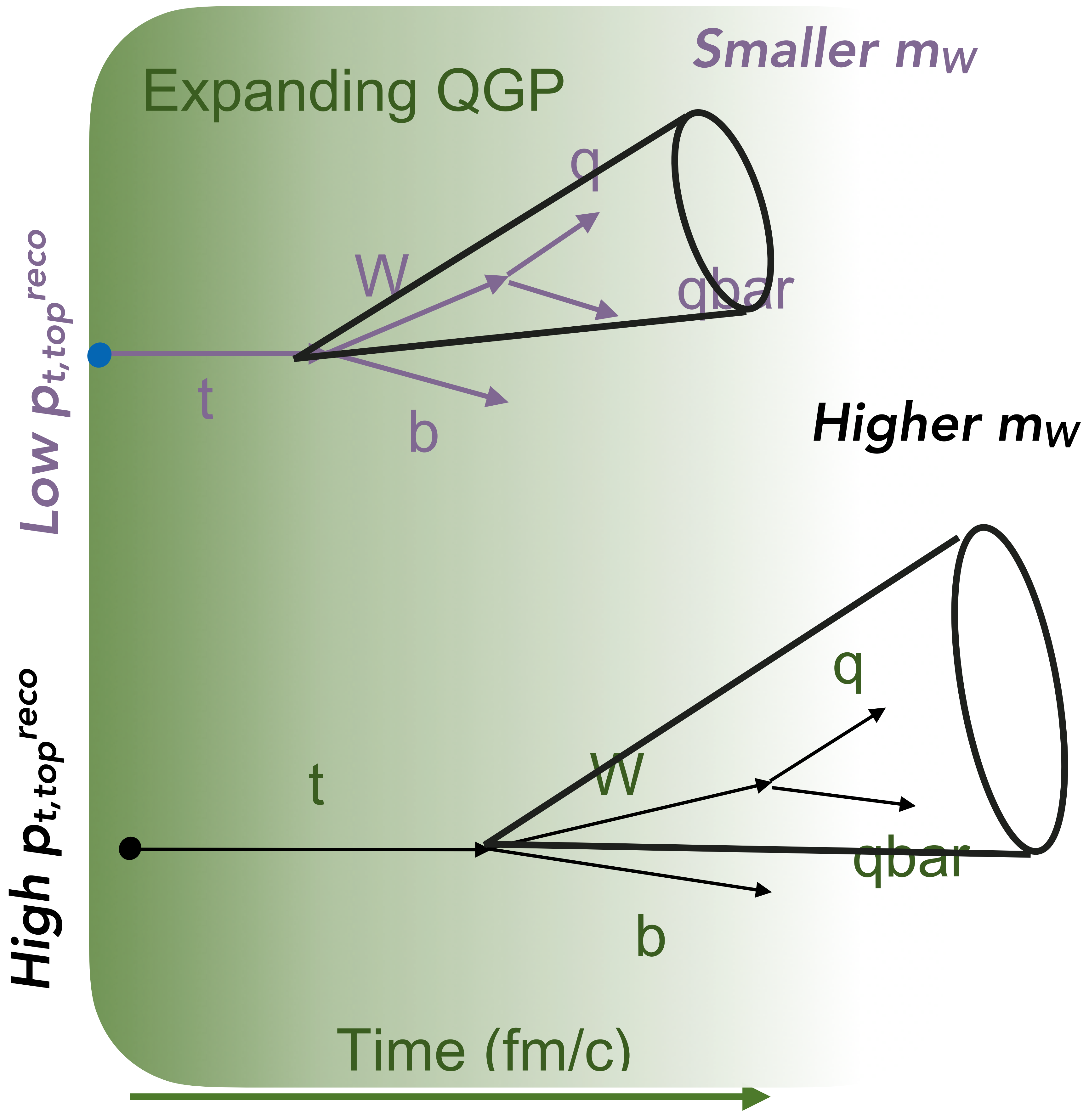
# QGP evolution?



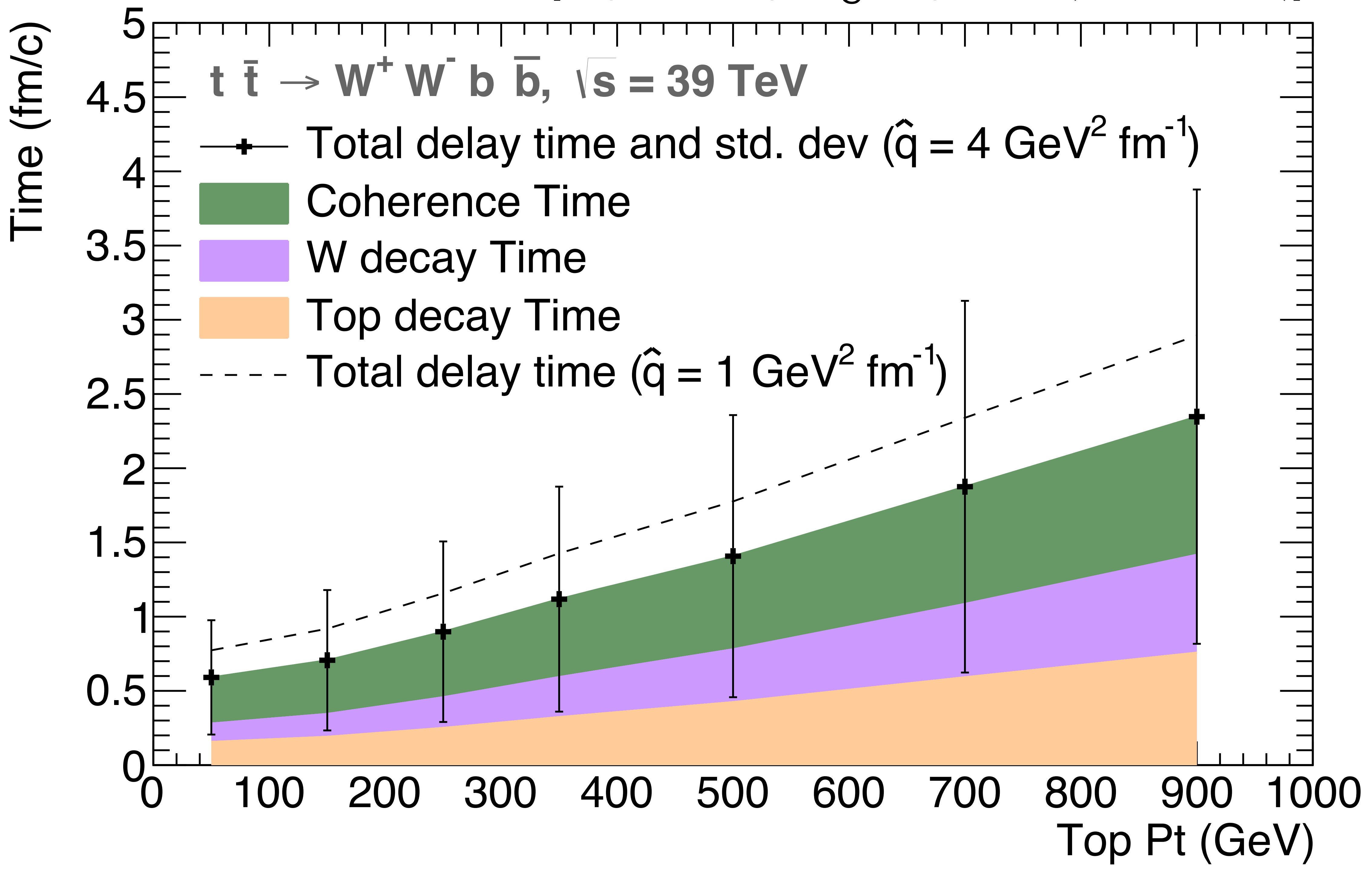
# Top-initiated jets



- Reconstructed hadronic W boson jet mass:



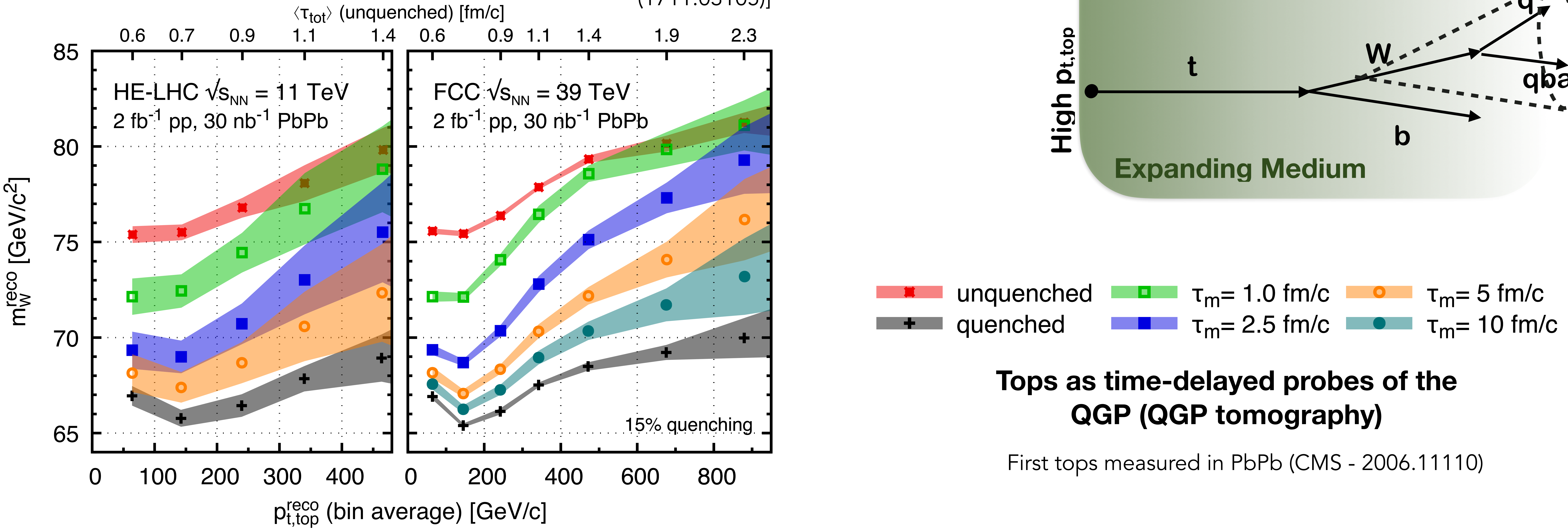

[LA, Milhano, Salgado, Salam (1711.03105)]

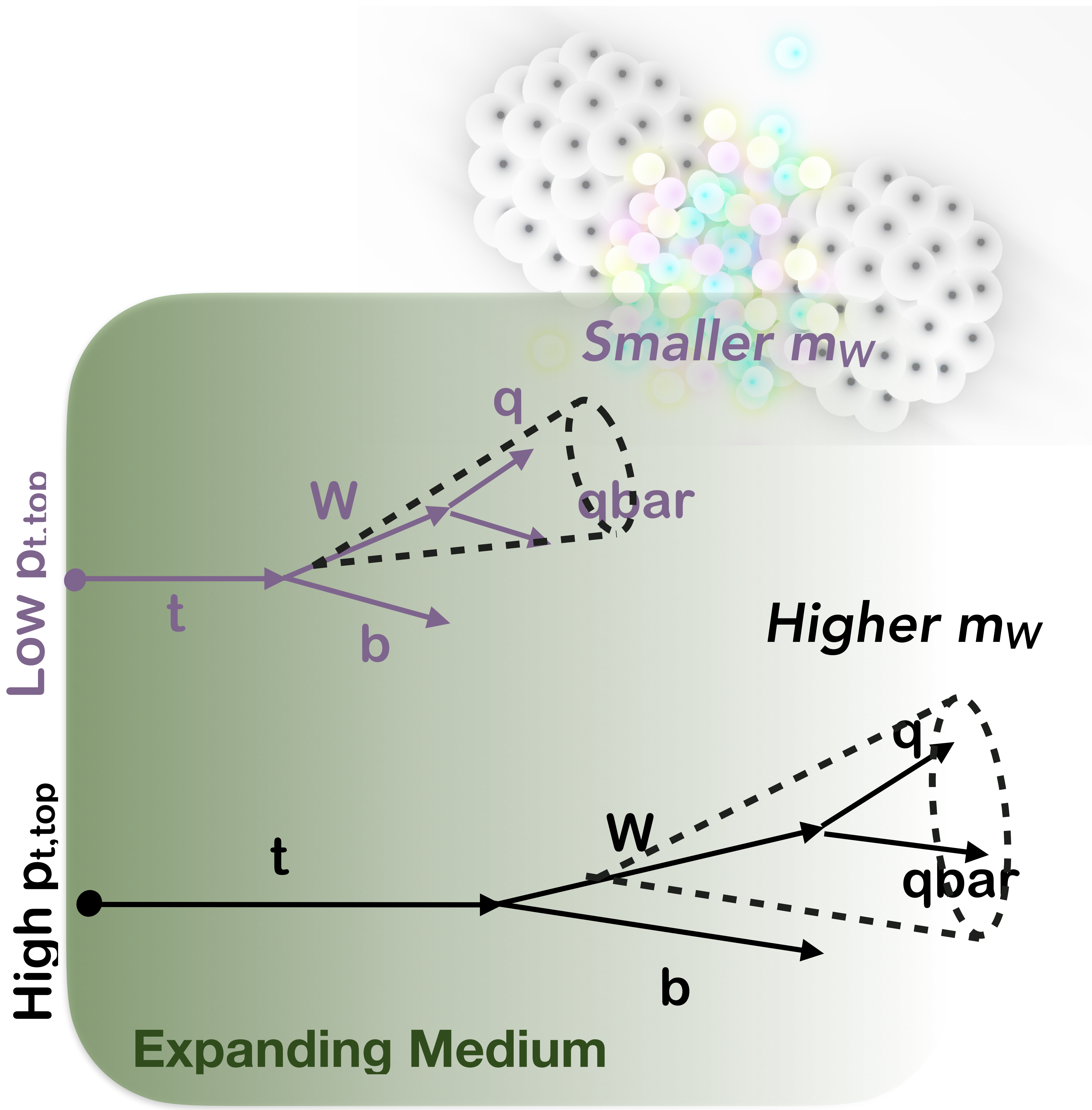


# Top-initiated jets @ FCC

- Time-differential measurements might be possible with tops

[LA, Milhano, Salgado, Salam (1711.03105)]

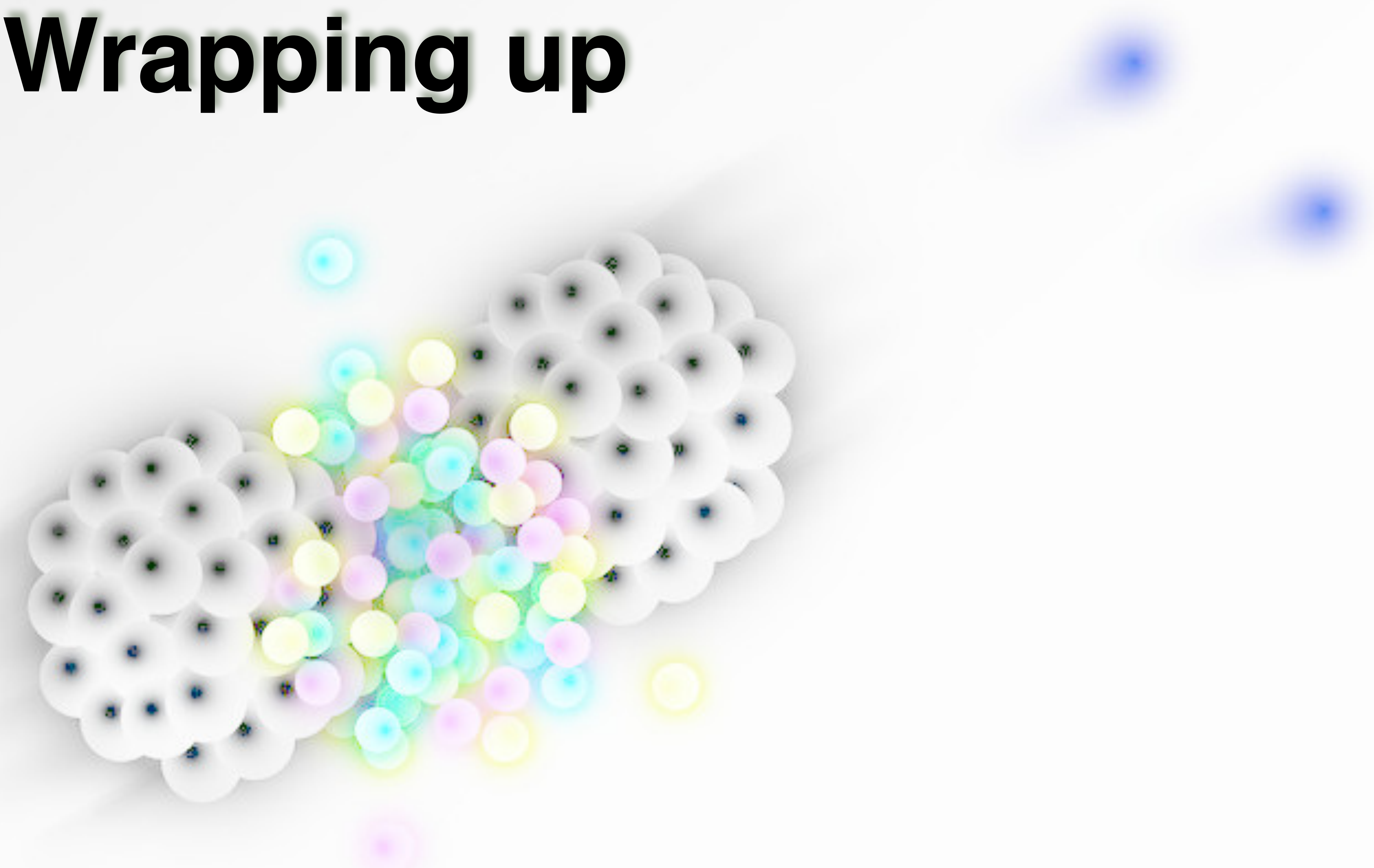


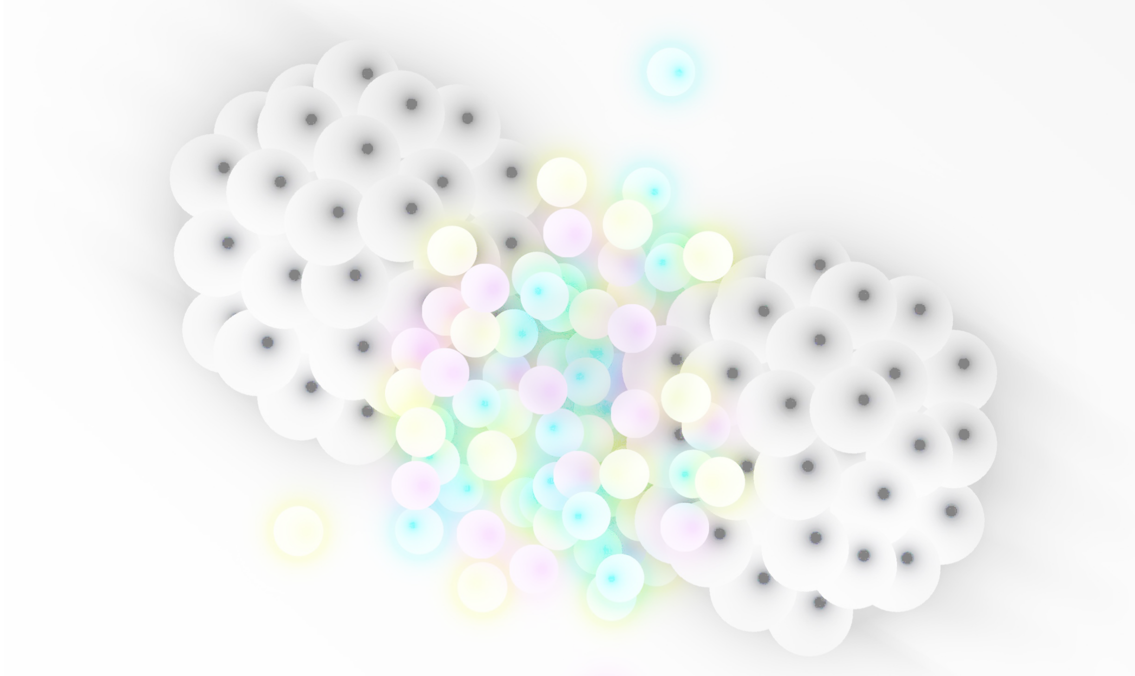

**Tops as time-delayed probes of the QGP (QGP tomography)**

First tops measured in PbPb (CMS - 2006.11110)

# Wrapping up



# Summary



- **Heavy-ions** are a vibrant field full of **activity**
  - From far-from-equillibrium QCD to a fully thermalised medium
- **Quark-Gluon Plasma** studies have entered **precision** physics era
  - Determination of energy loss, momentum broadening and structure of a medium-modified parton showers
- **Future runs / Future colliders** will provide crucial input to many of our current **unsolved questions**
  - HL-LHC, FCC…

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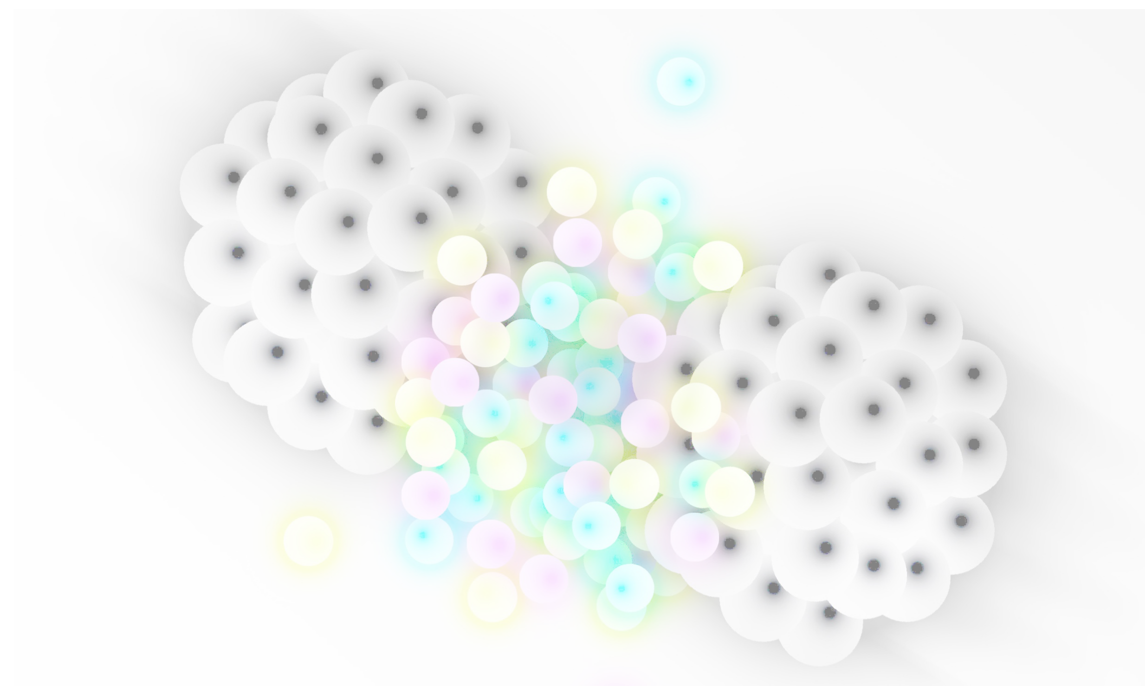

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**Thank you!**

# Acknowledgments

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LIP

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