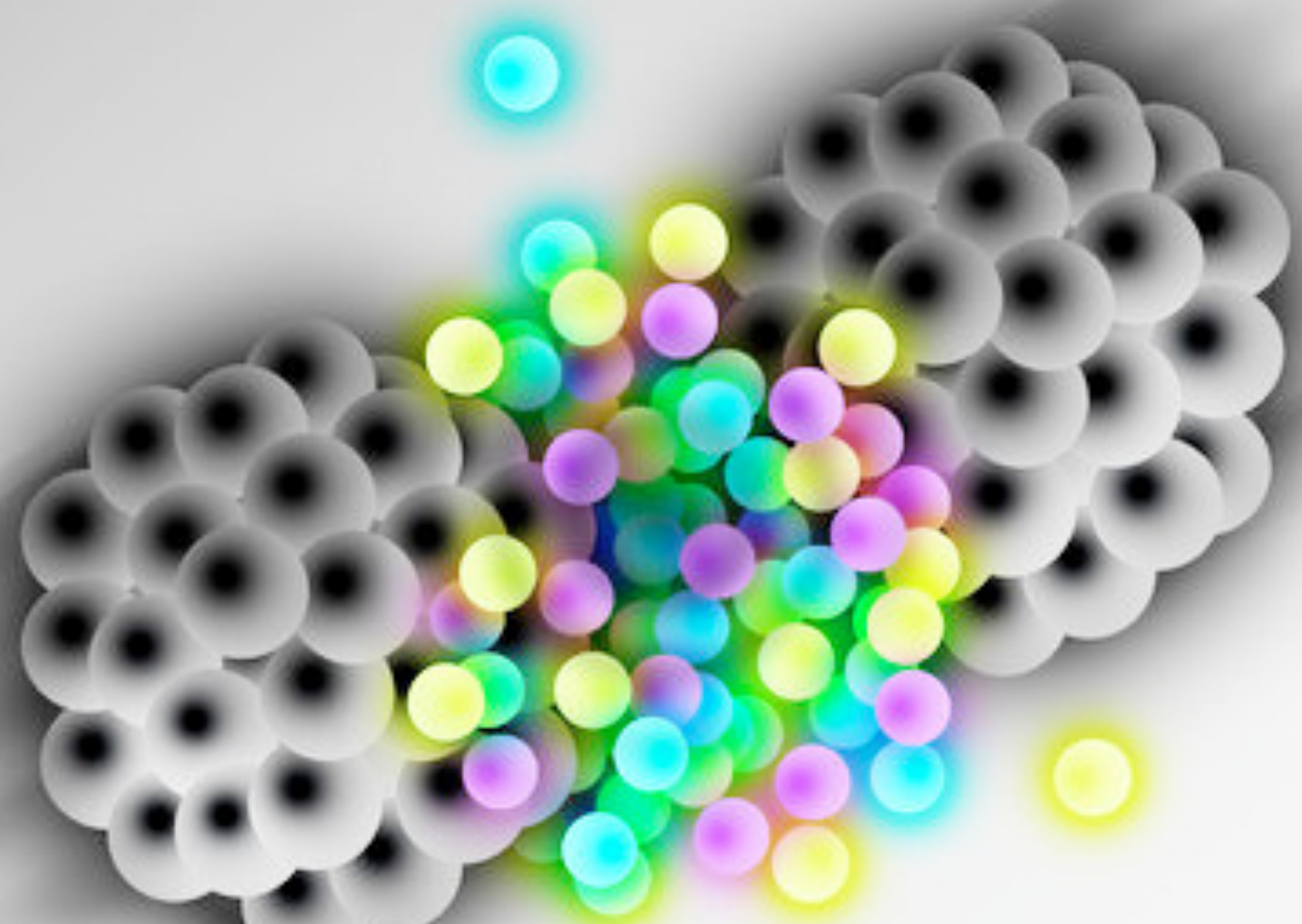
Energy loss beyond multiple soft or single hard approximations



Liliana Apolinário

LIP

based on
JHEP 07 (2020) 114

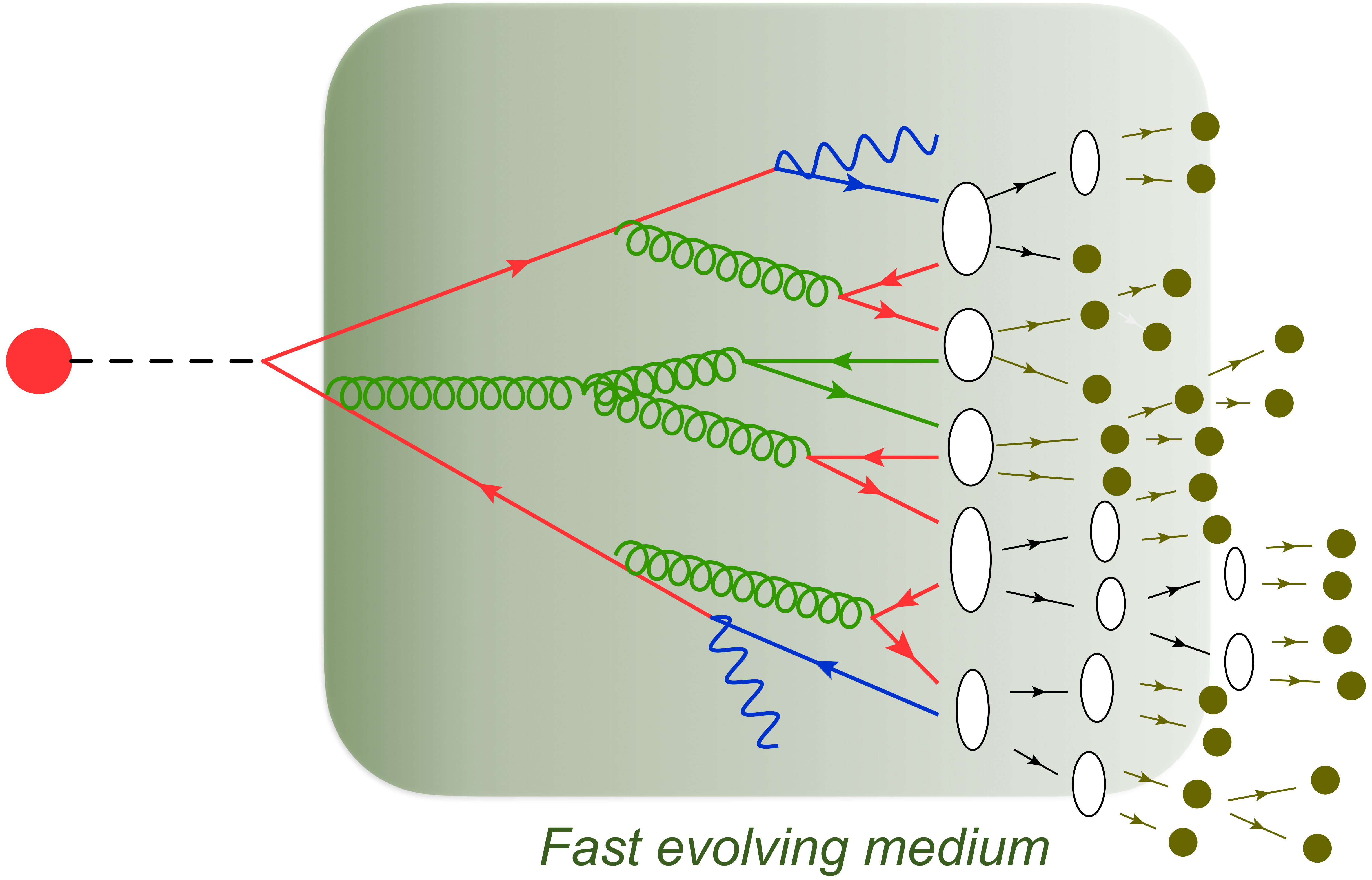
in collaboration with
C. Andrés and F. Dominguez

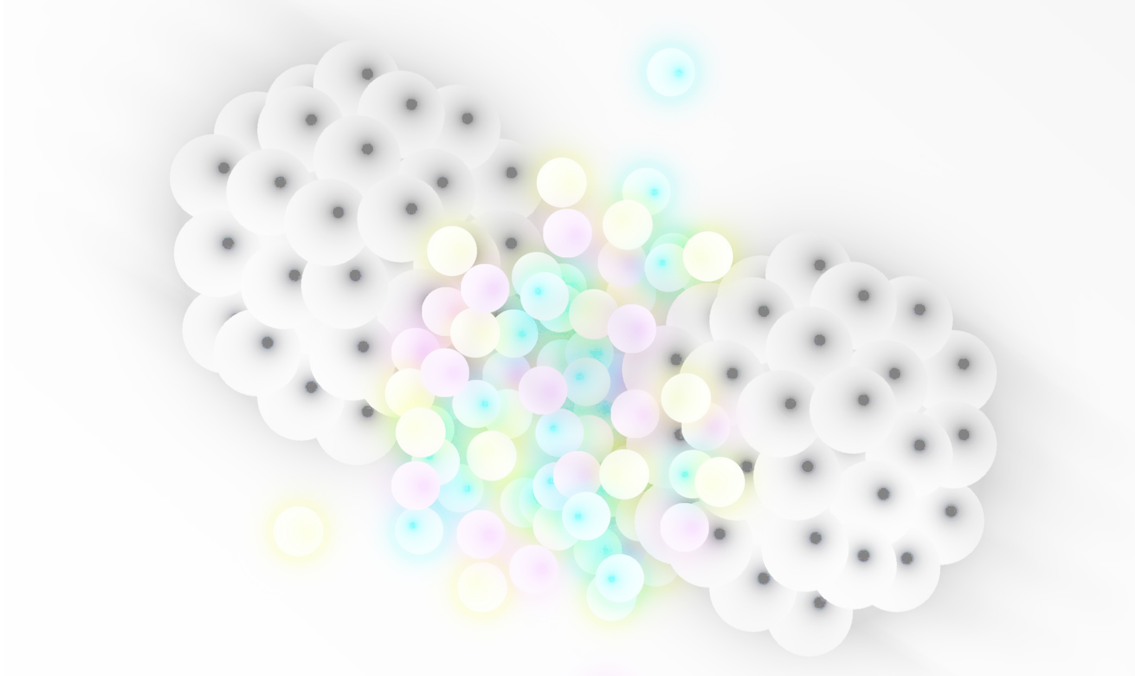
2020 RHIC/AGS Annual Users Meeting

Thursday, Oct 22nd

Jets in medium

- Several medium-induced effects will change a "pp jet" into a "PbPb jet"





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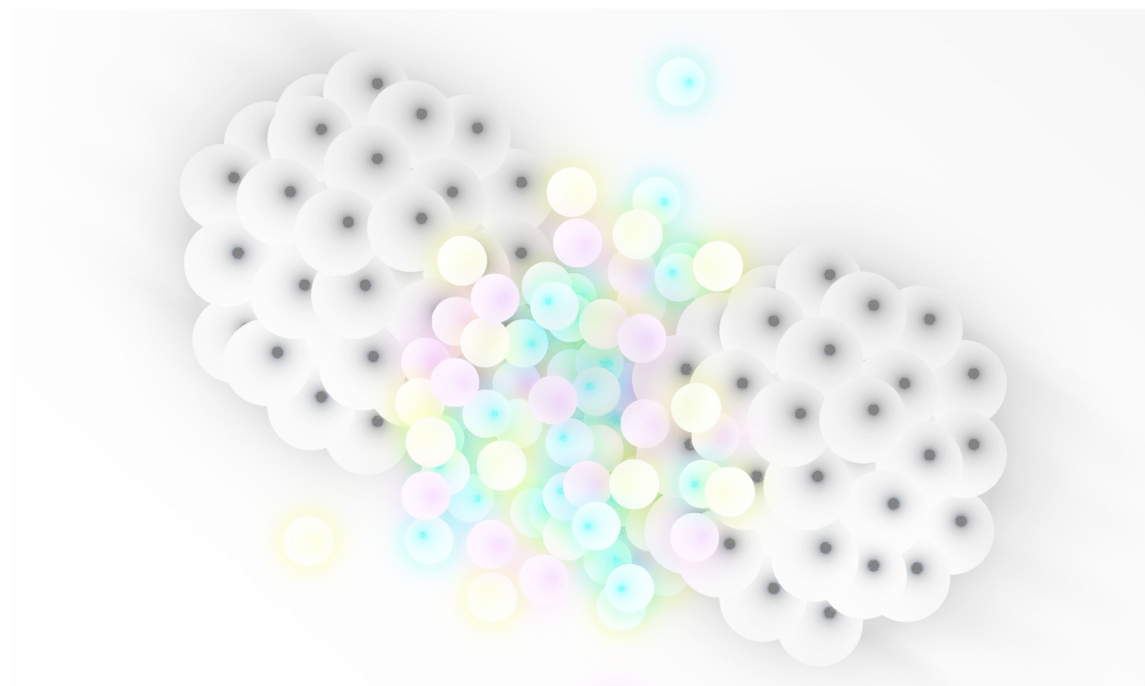

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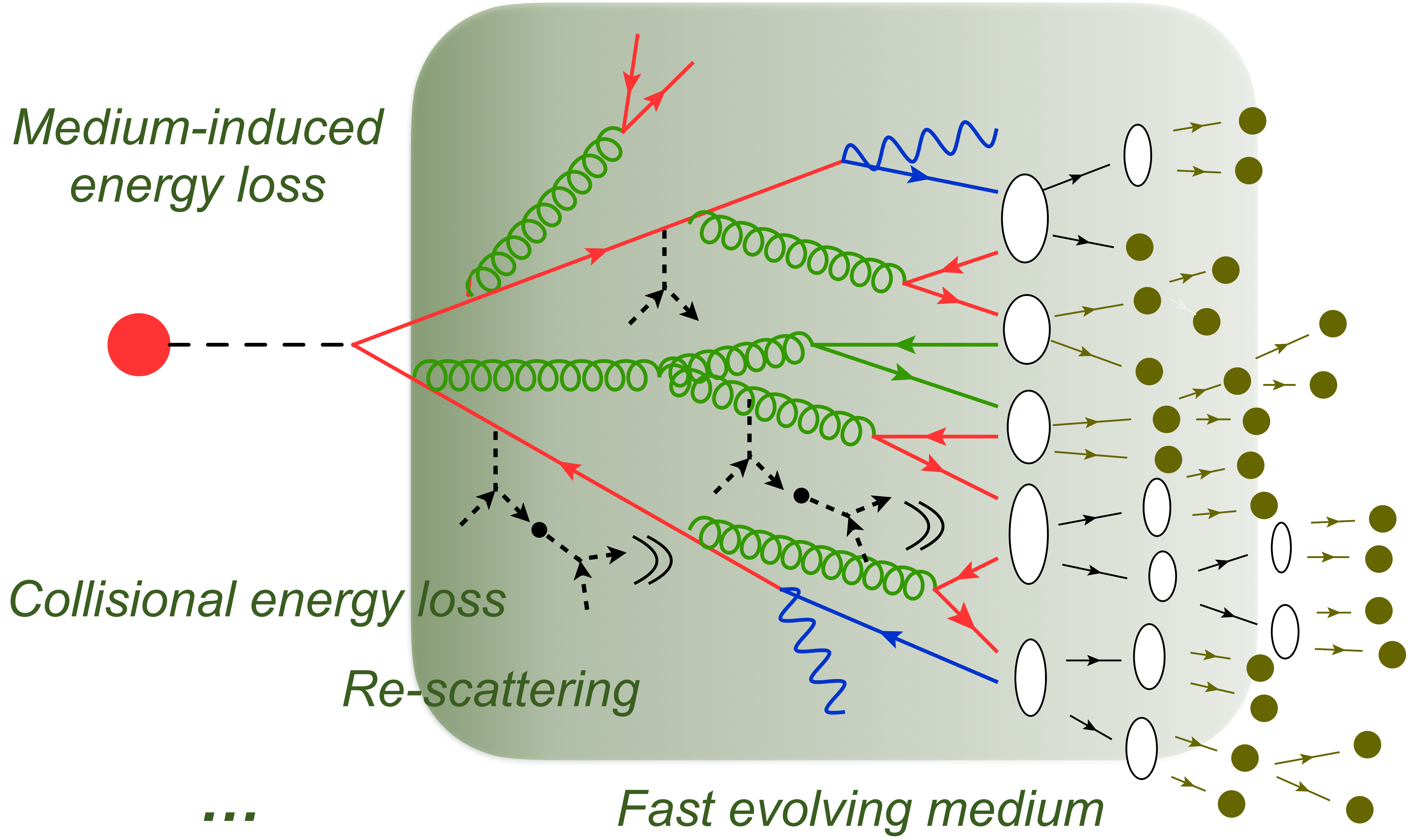

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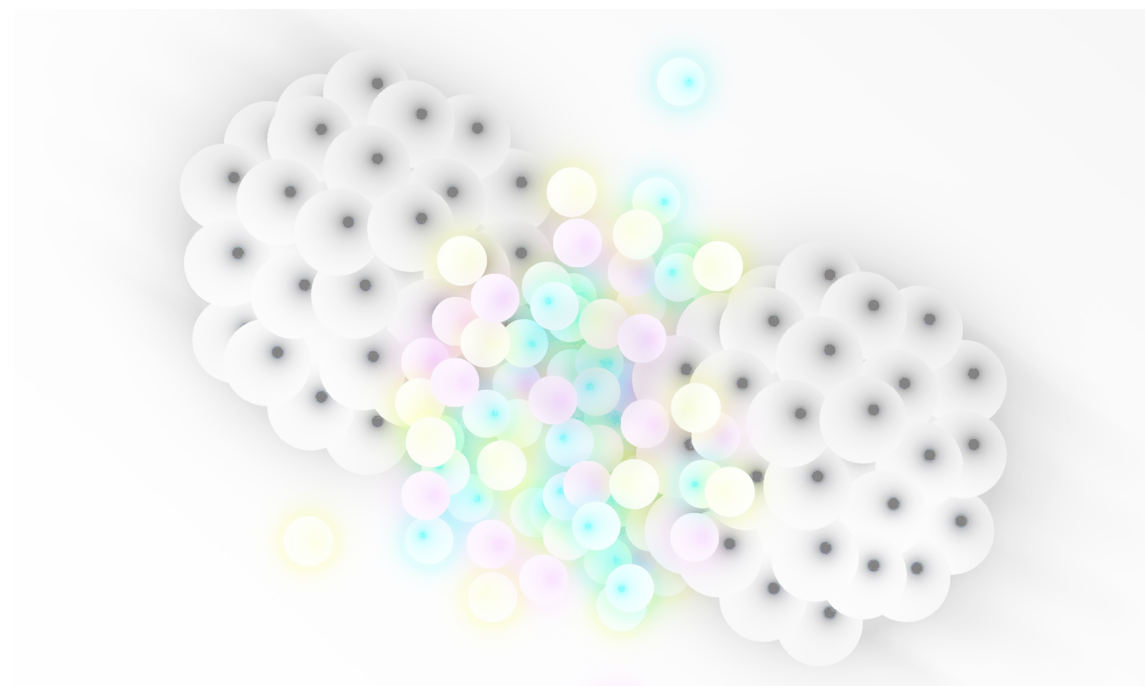

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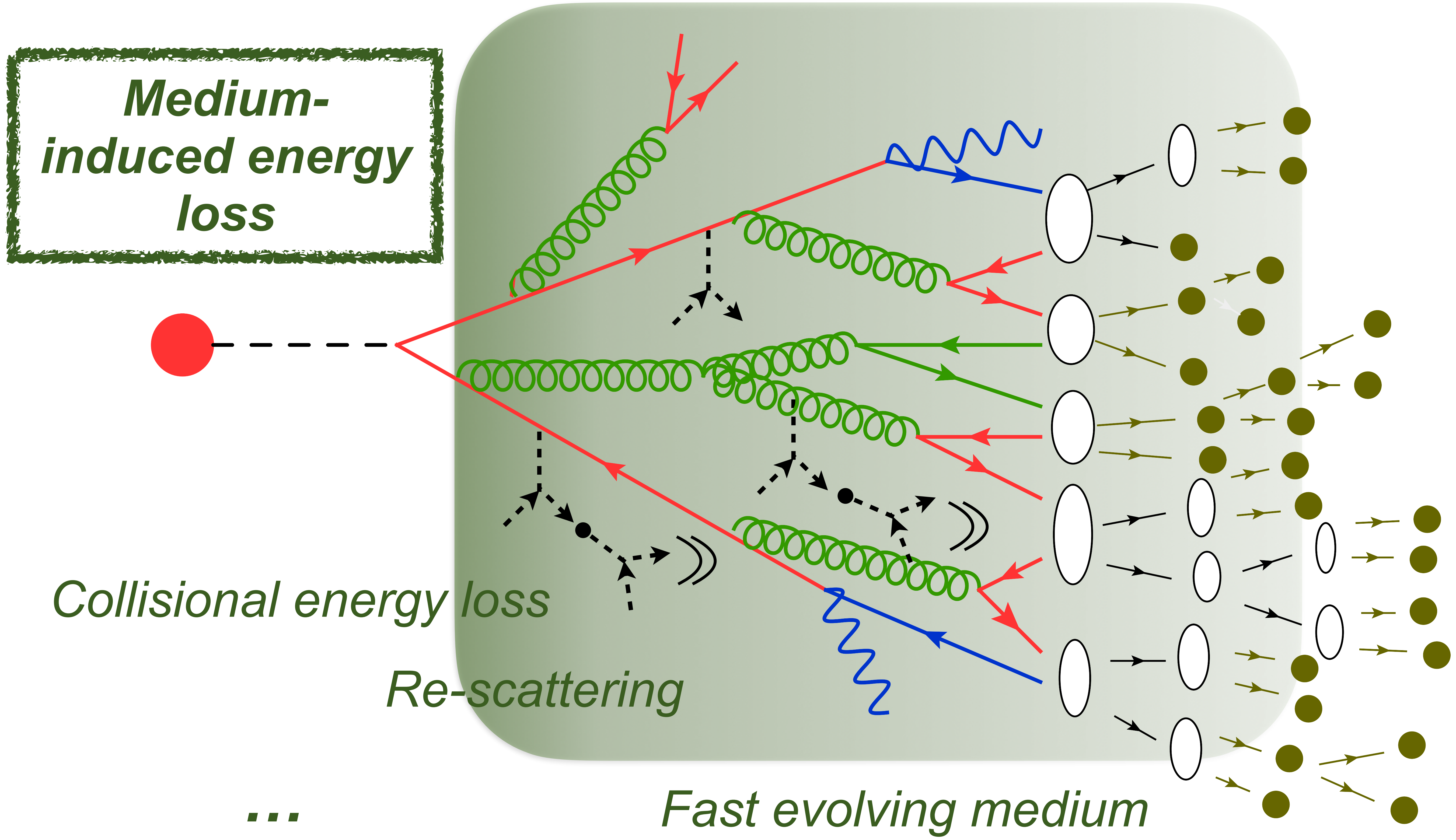

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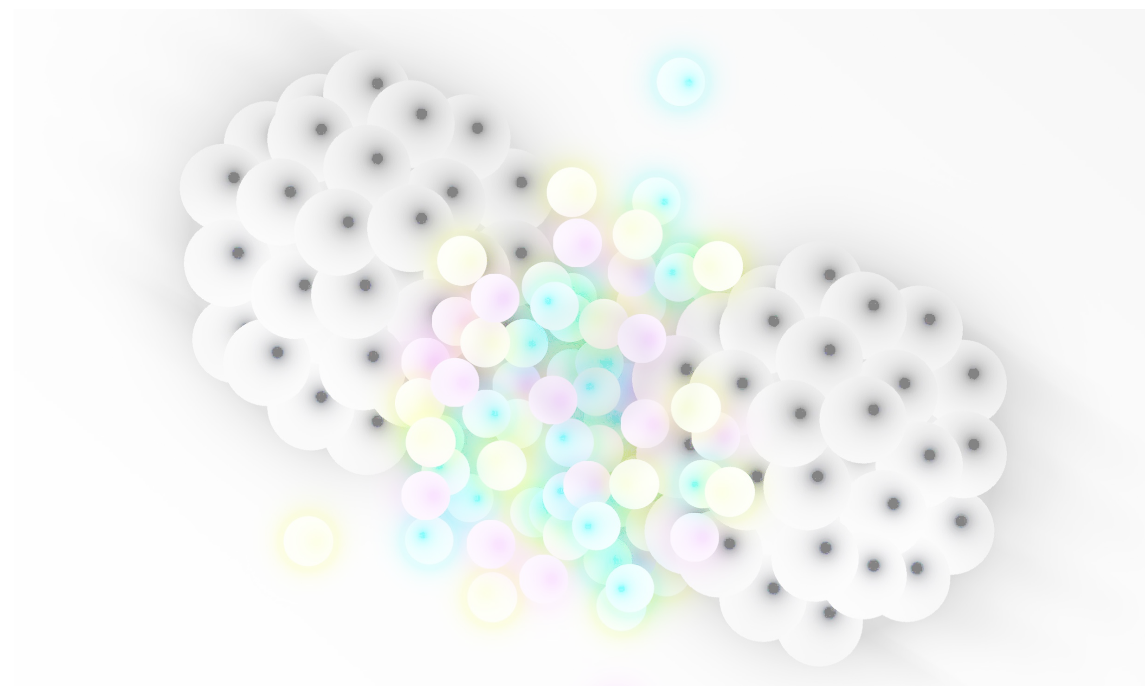

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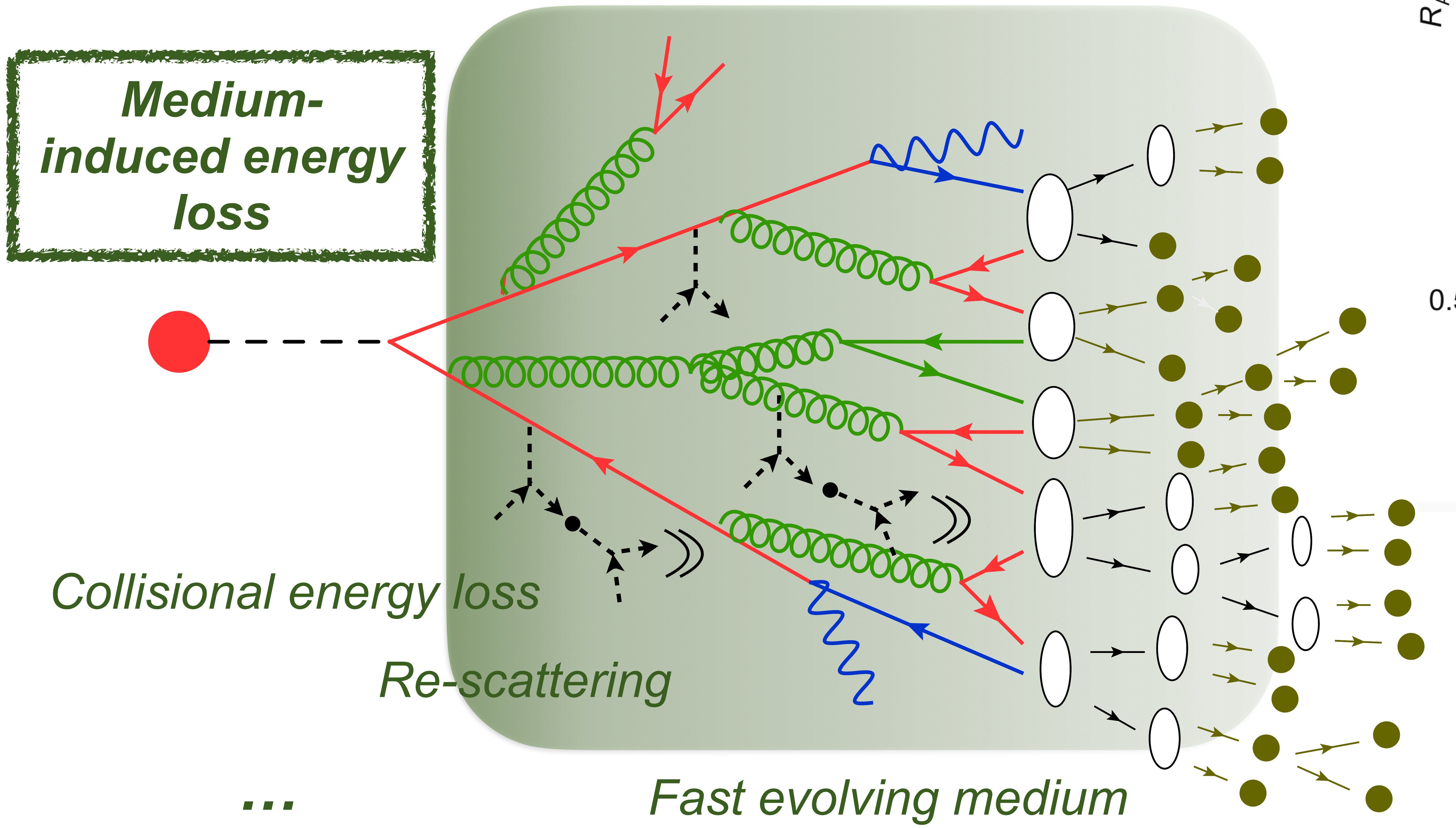
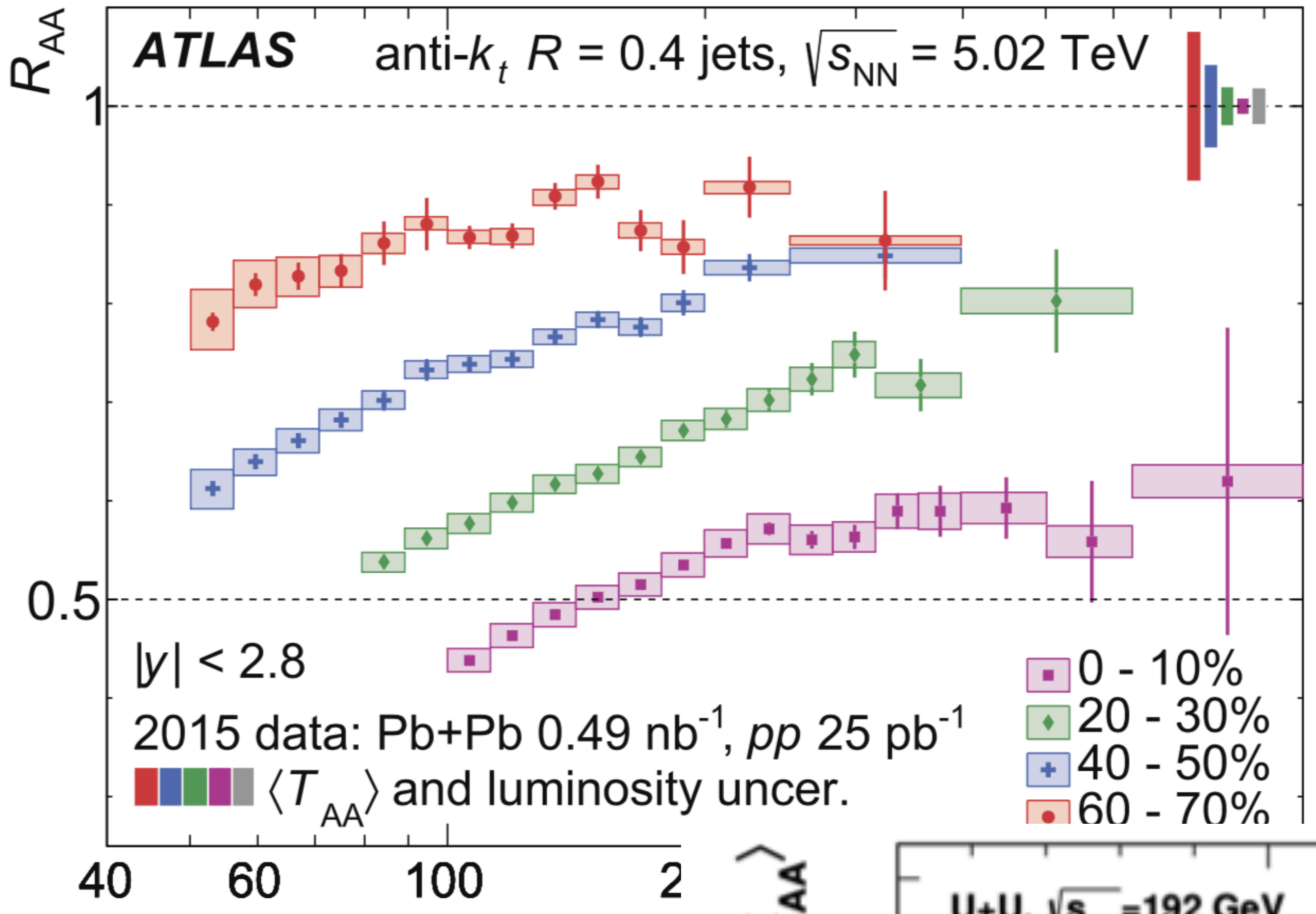


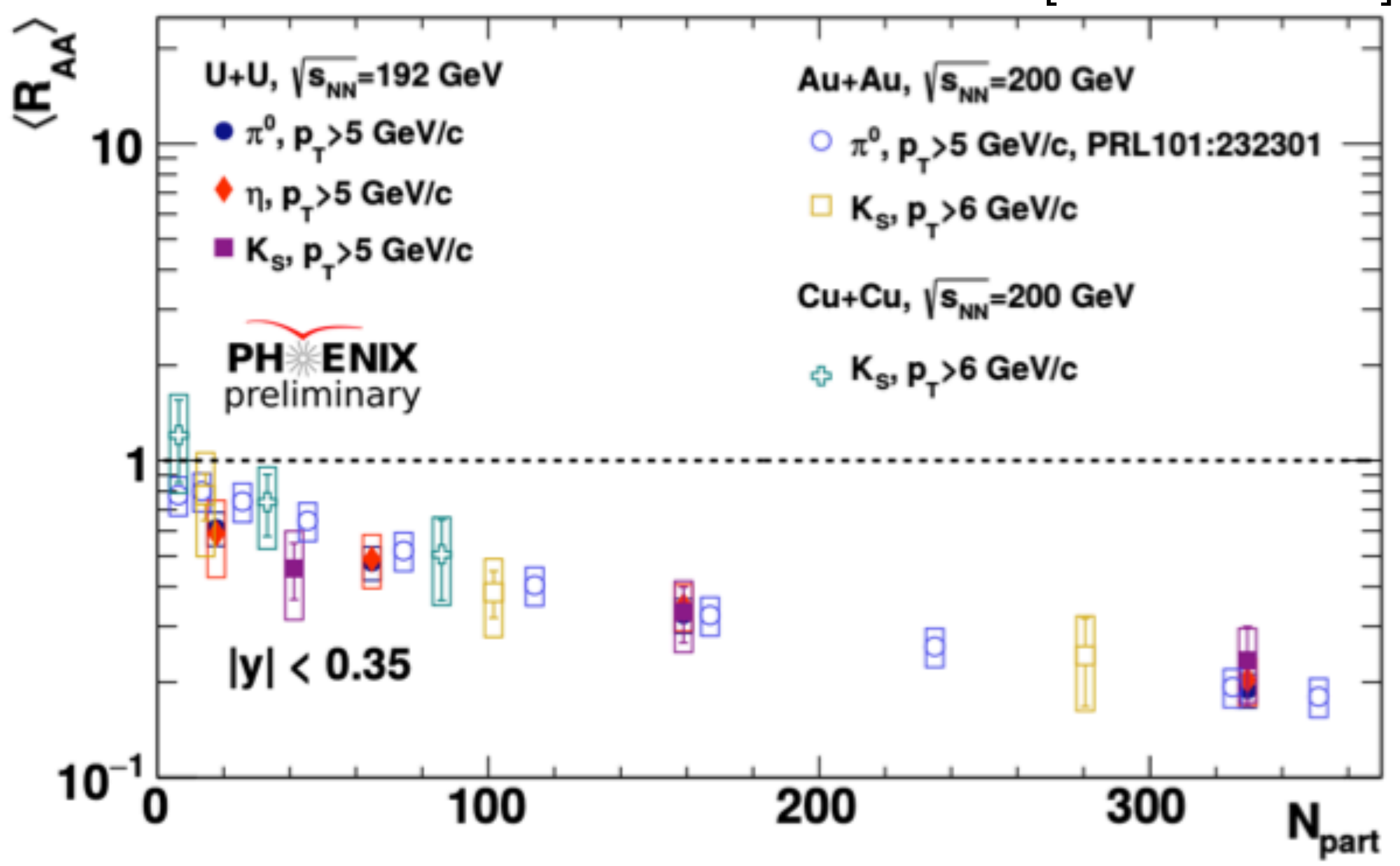
Jet Energy Loss

ATLAS [1805.05635]



Particle Energy Loss

PHENIX [2002.11156]



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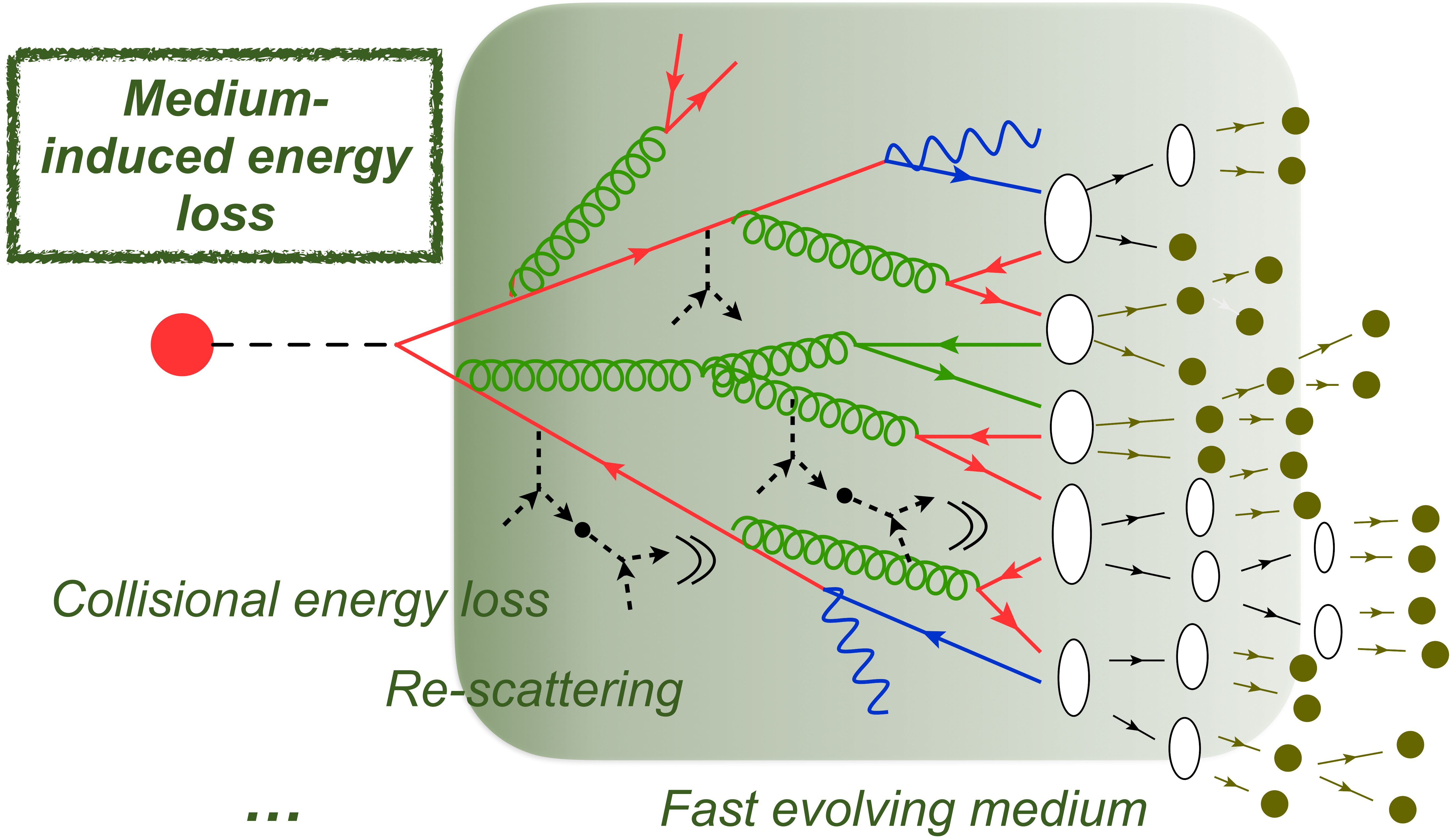
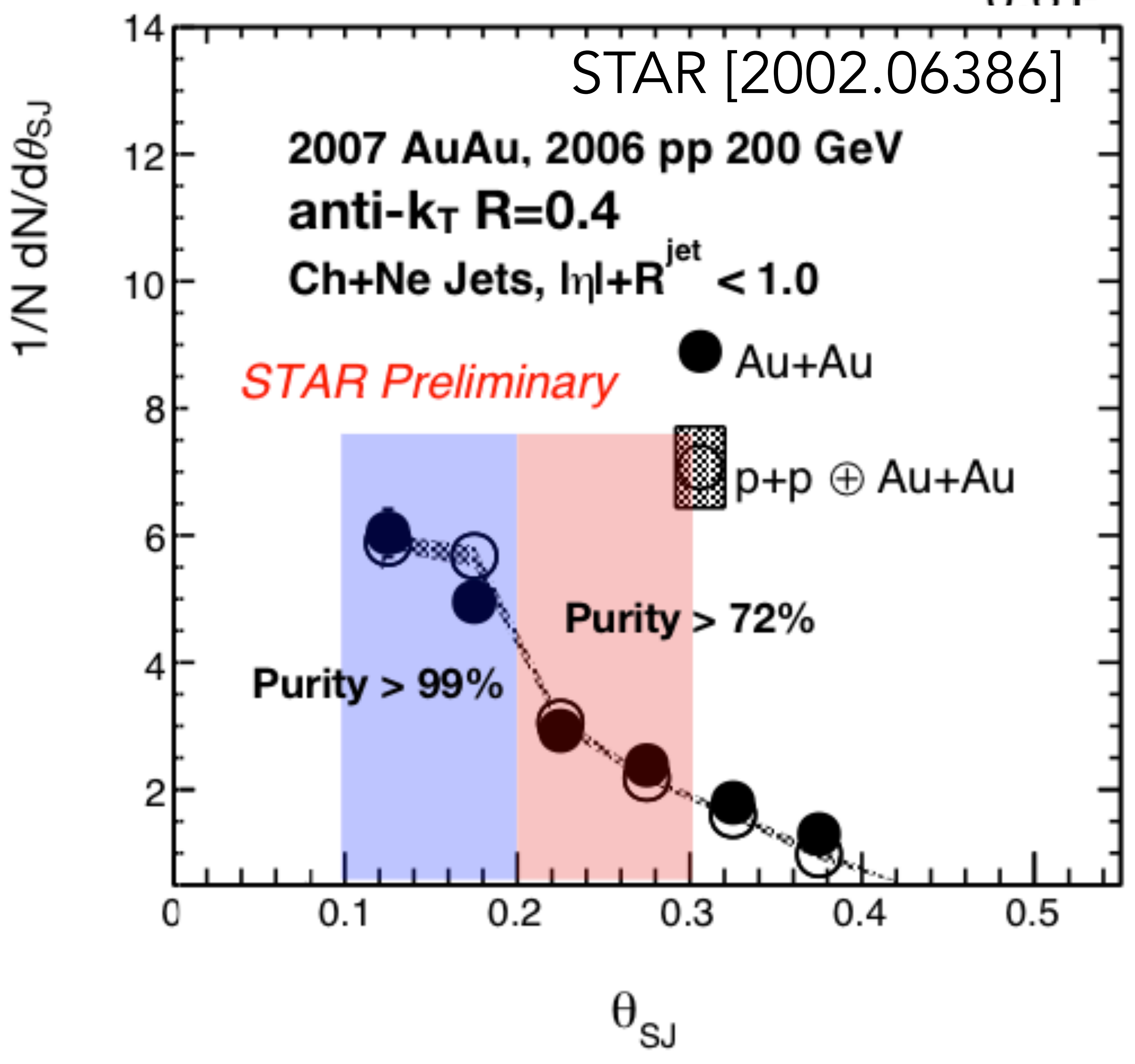
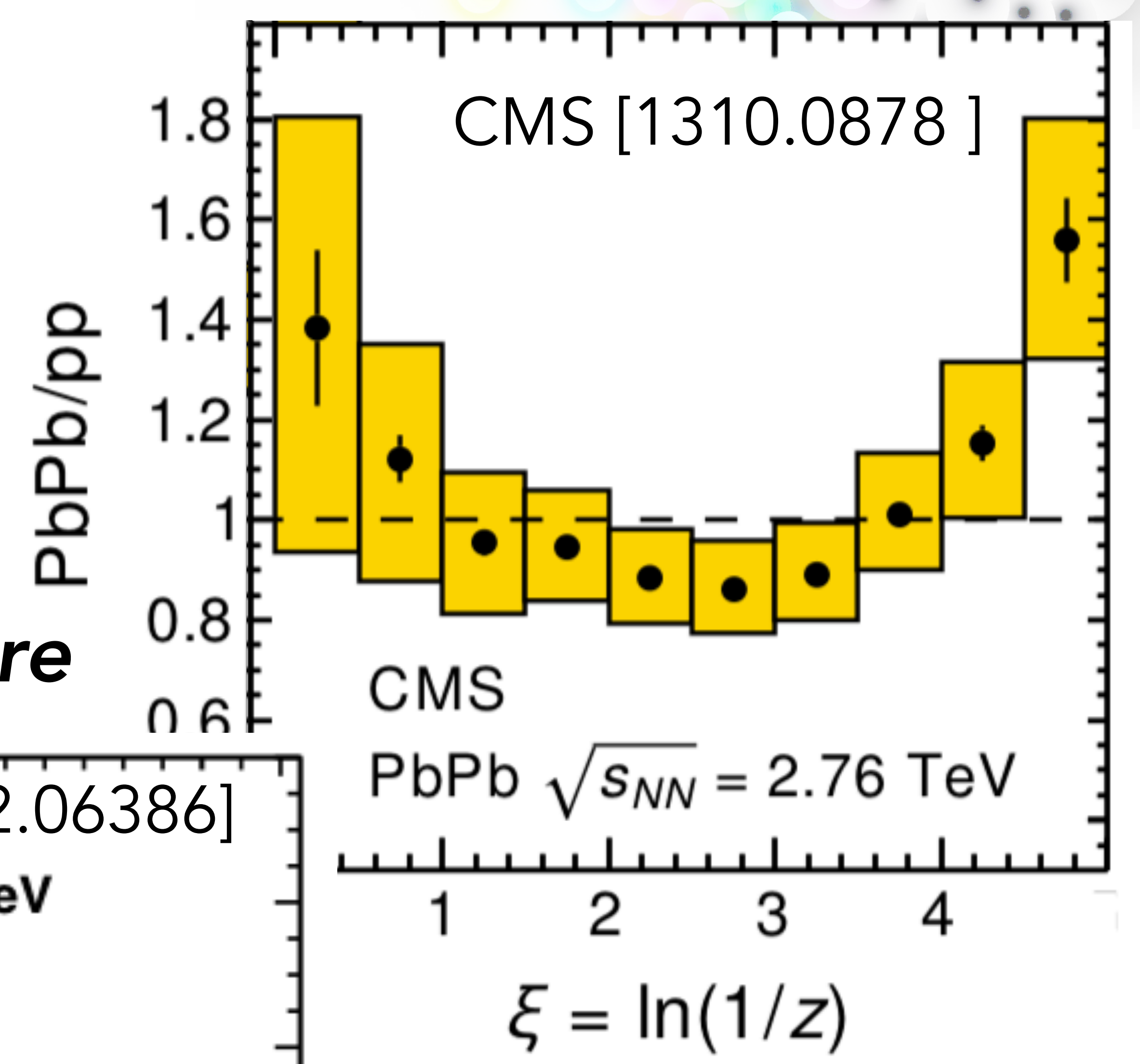


Jet Substructure



Jet Fragmentation Function



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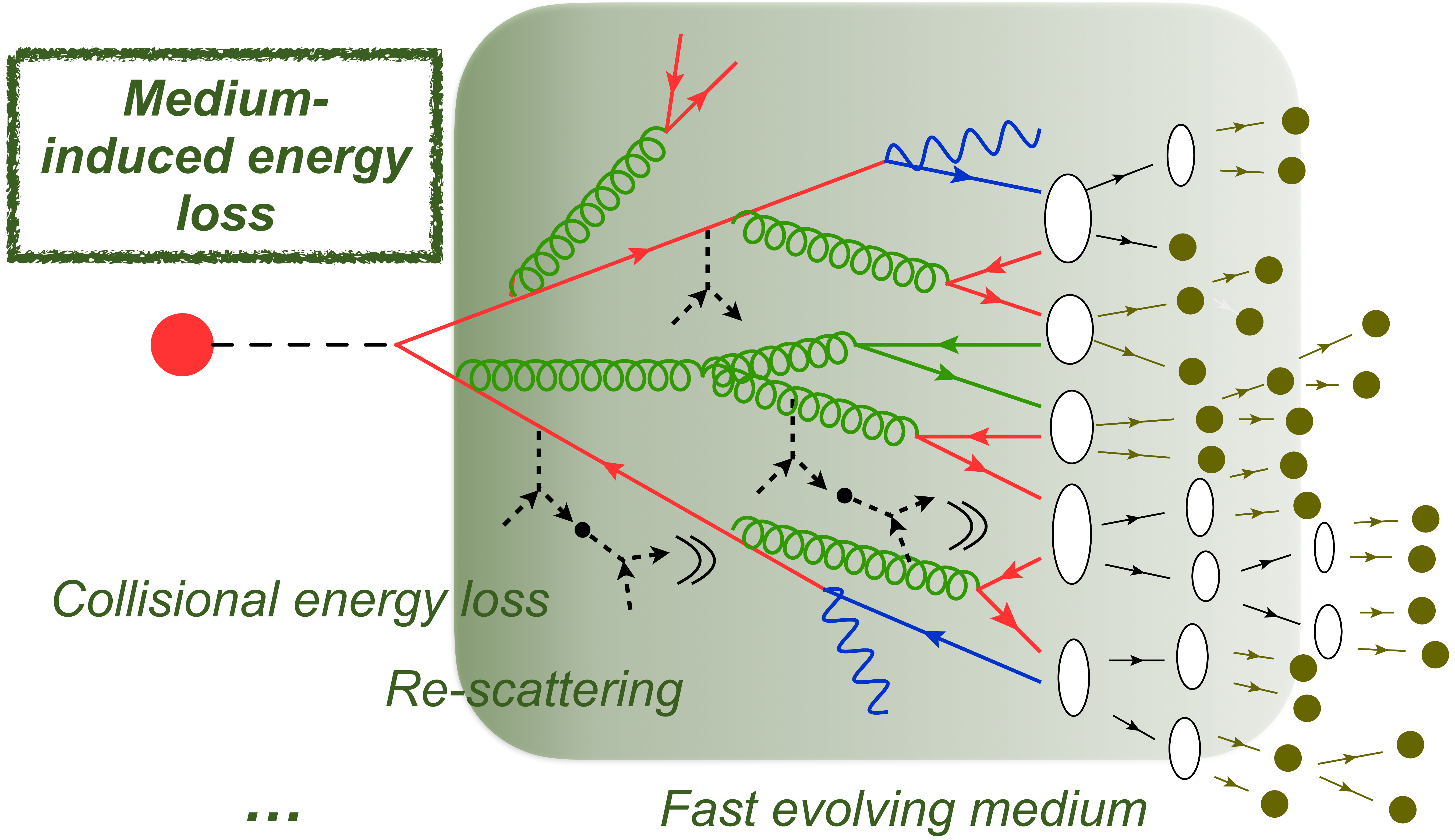
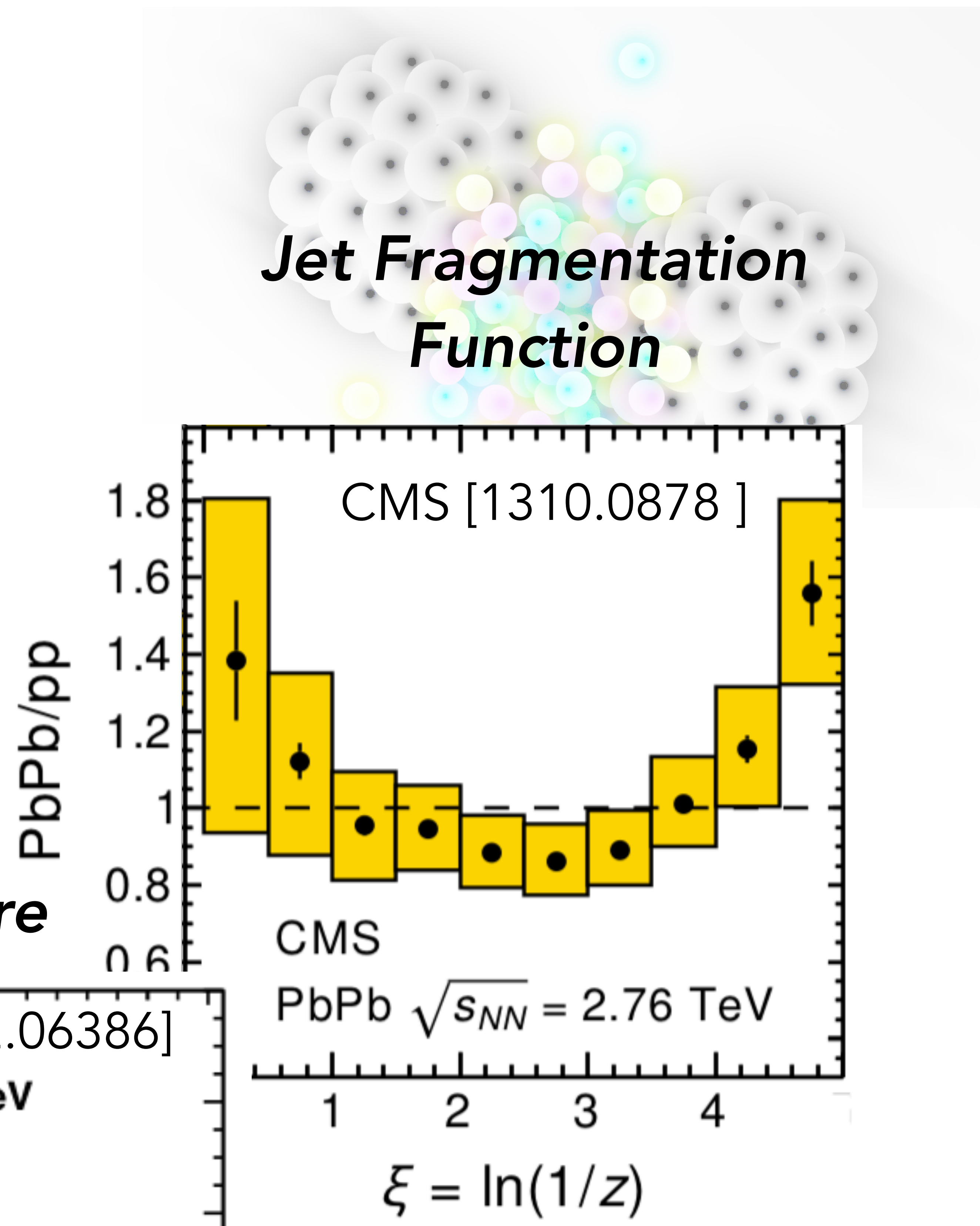
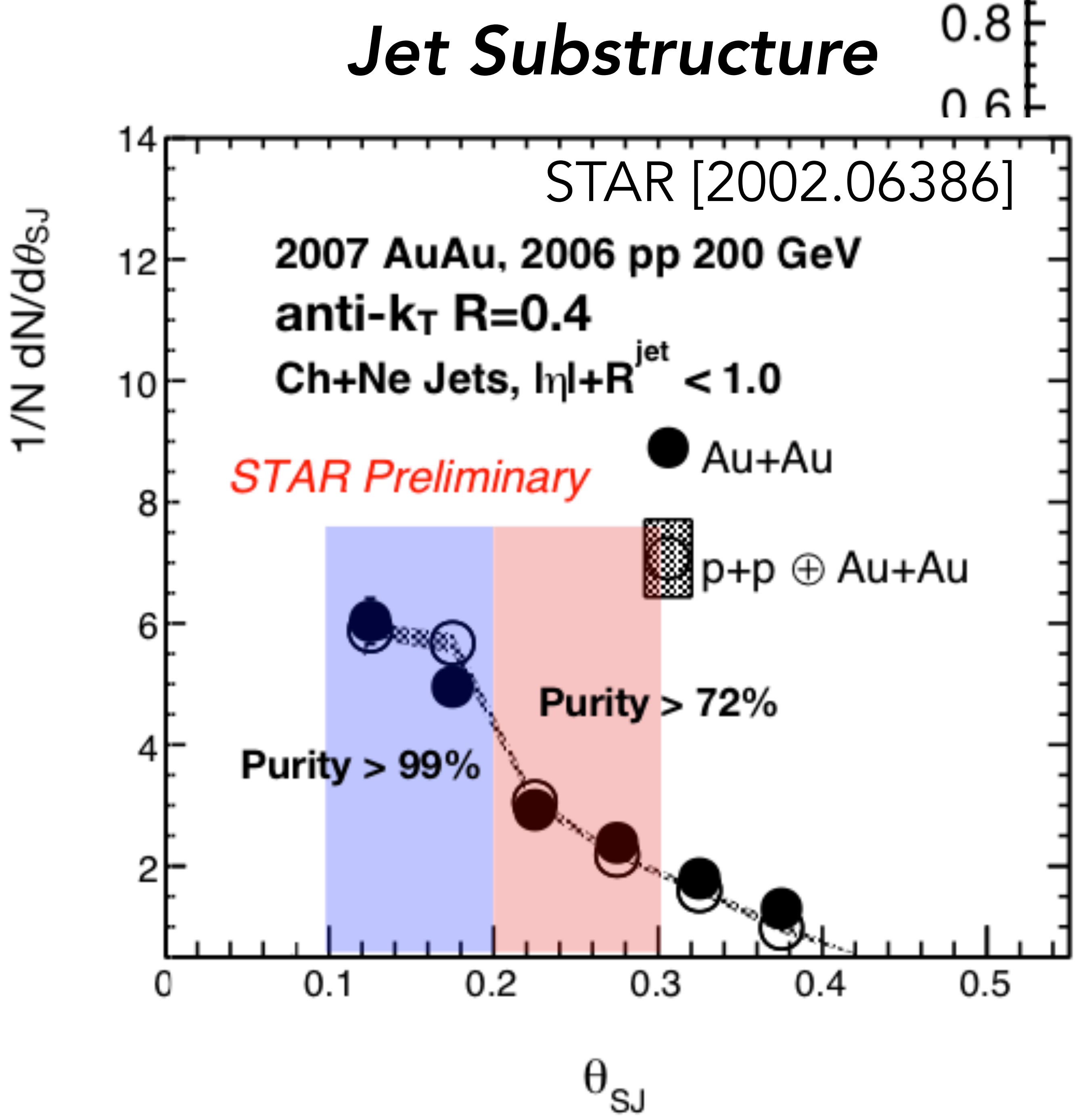


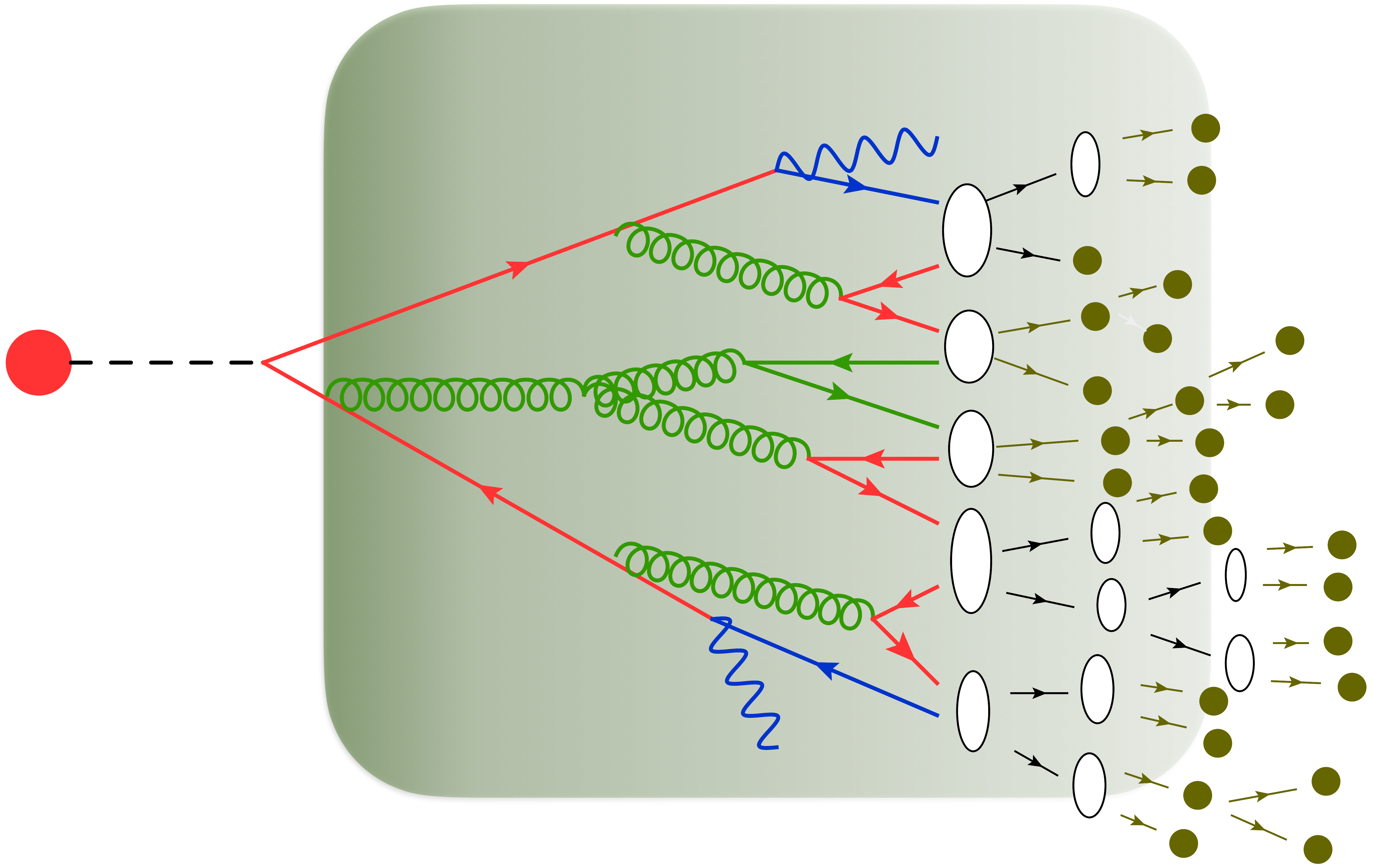




Need accurate theoretical description to withdraw QGP characteristics!

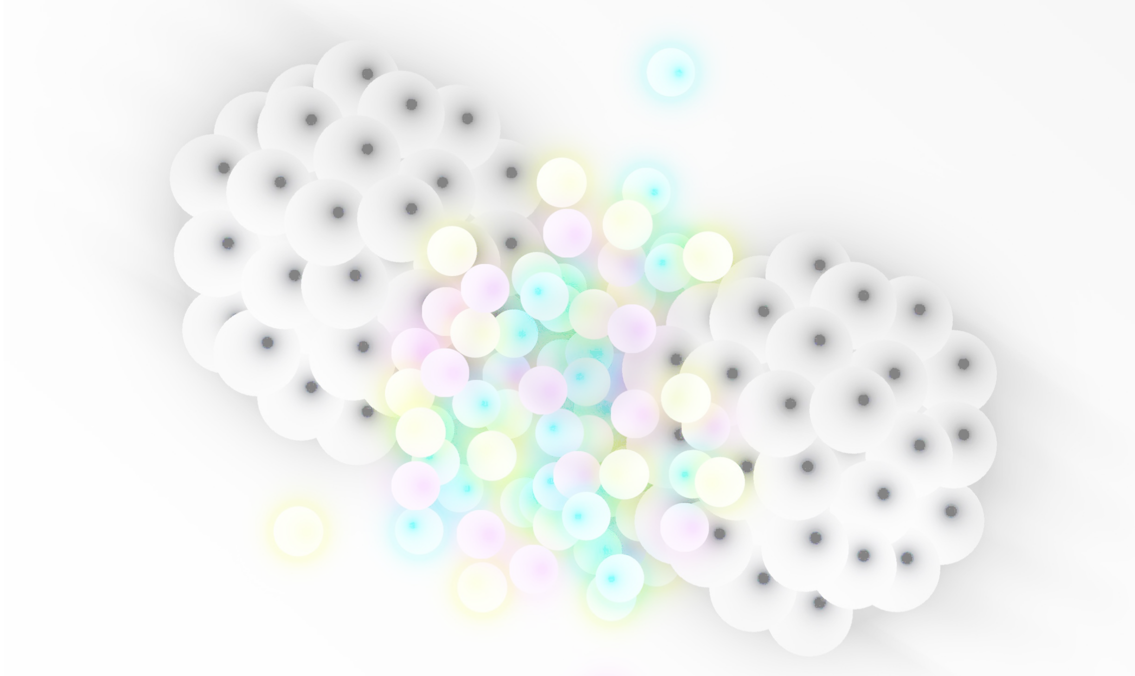
Medium-induced energy loss

- Understand the stopping power of matter for colour-charged particles



Fast evolving medium

Medium-induced energy loss



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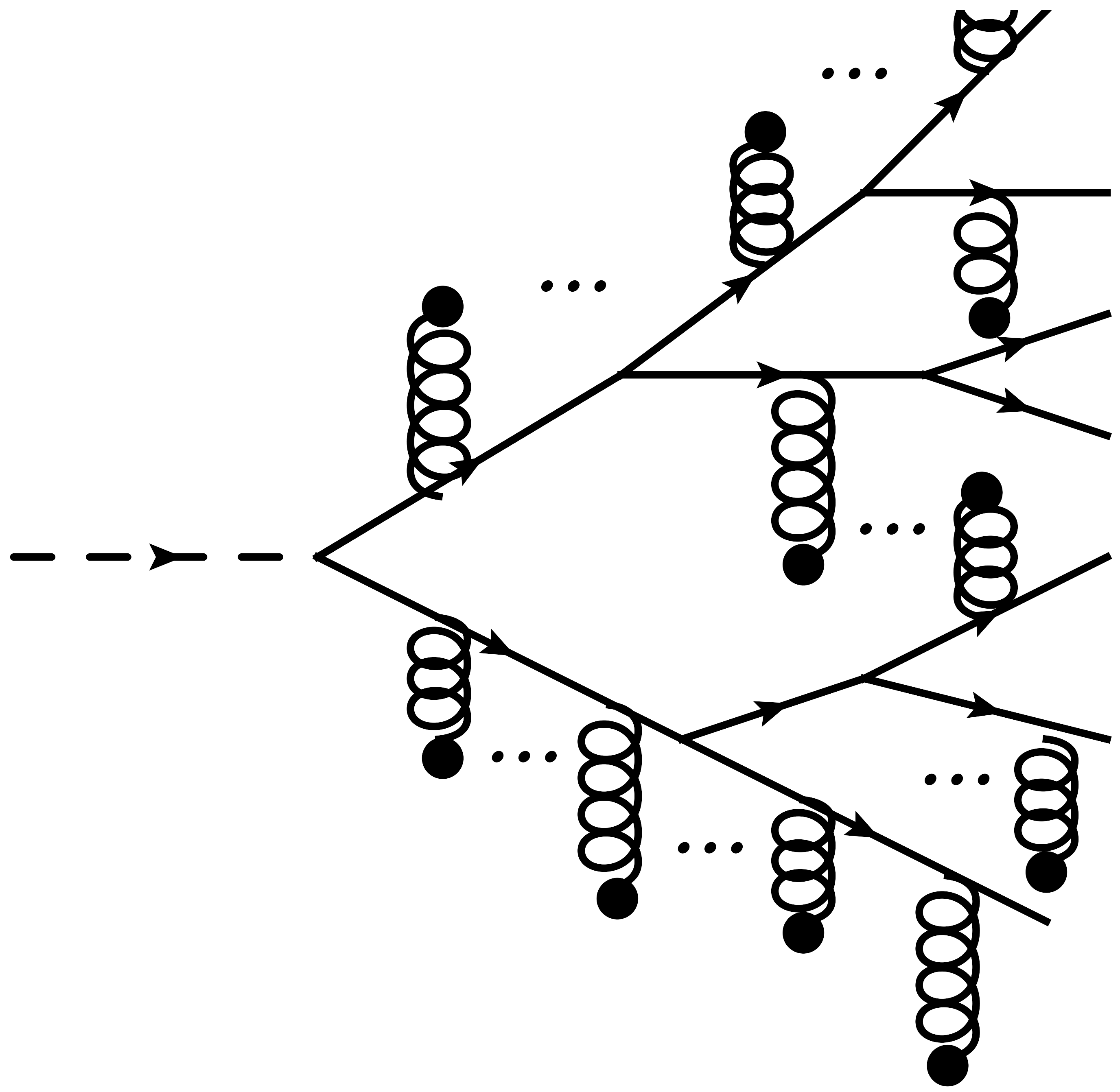
- From a pQCD view:
  - QGP is a collection of static scattering centres
  - Multiple interactions enhance gluon radiation



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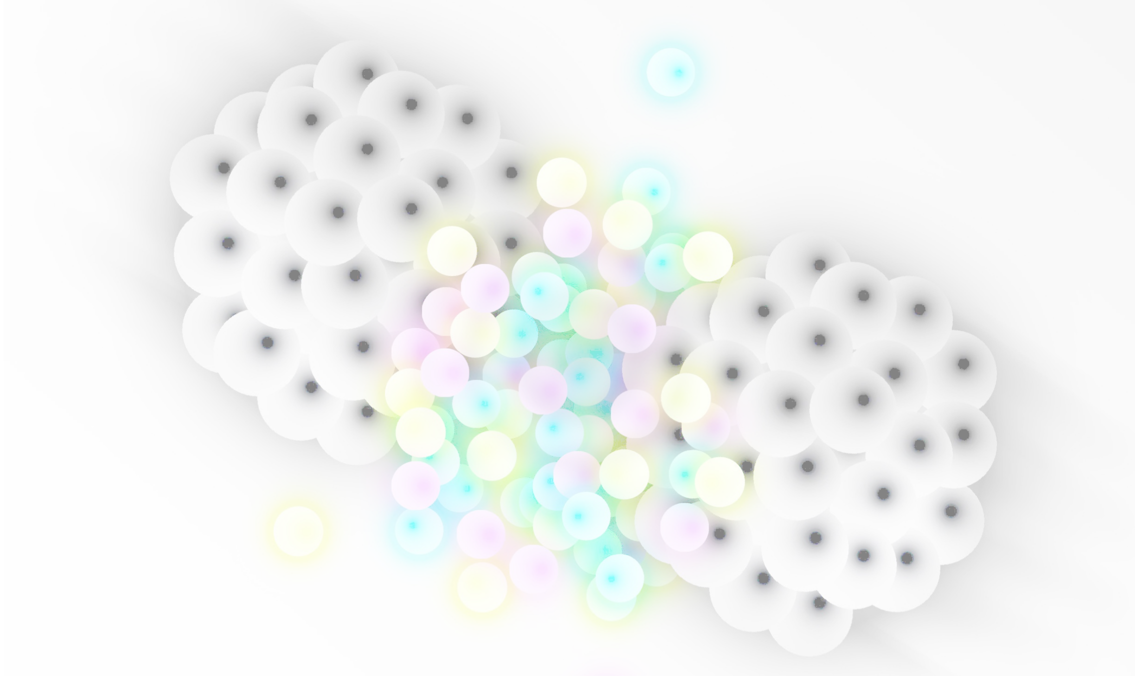

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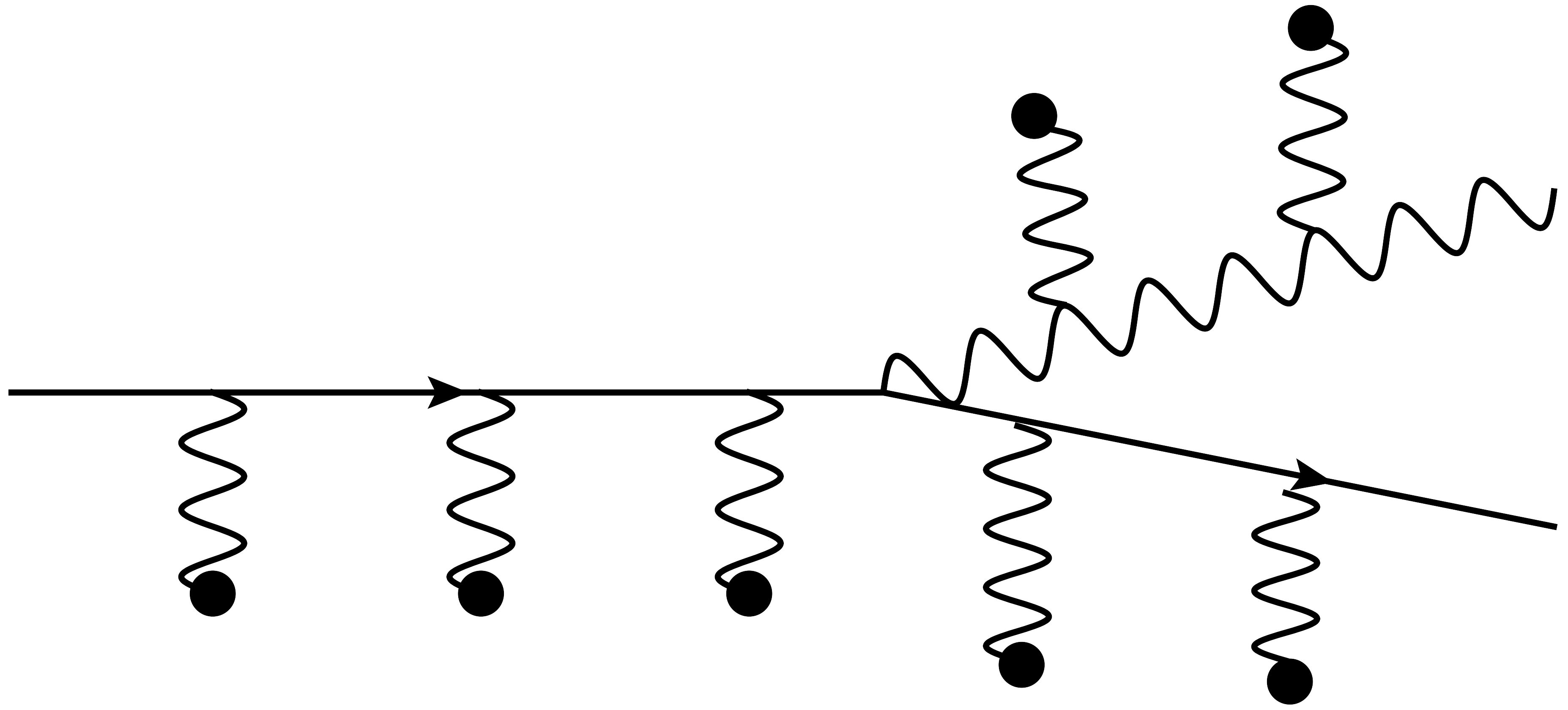

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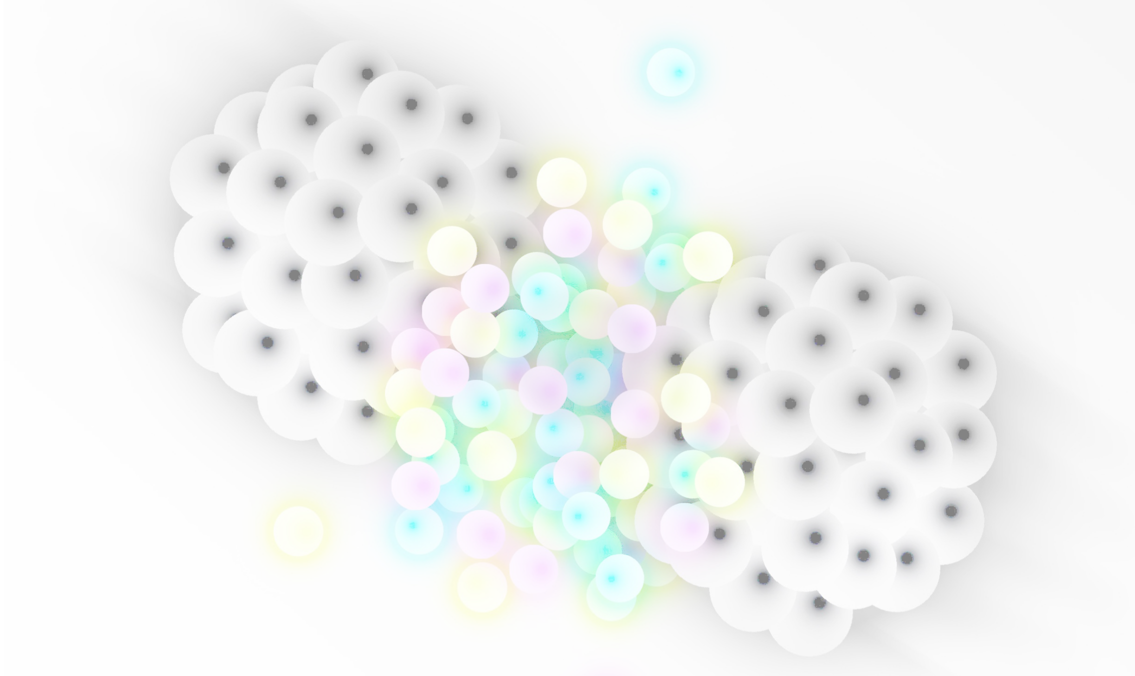

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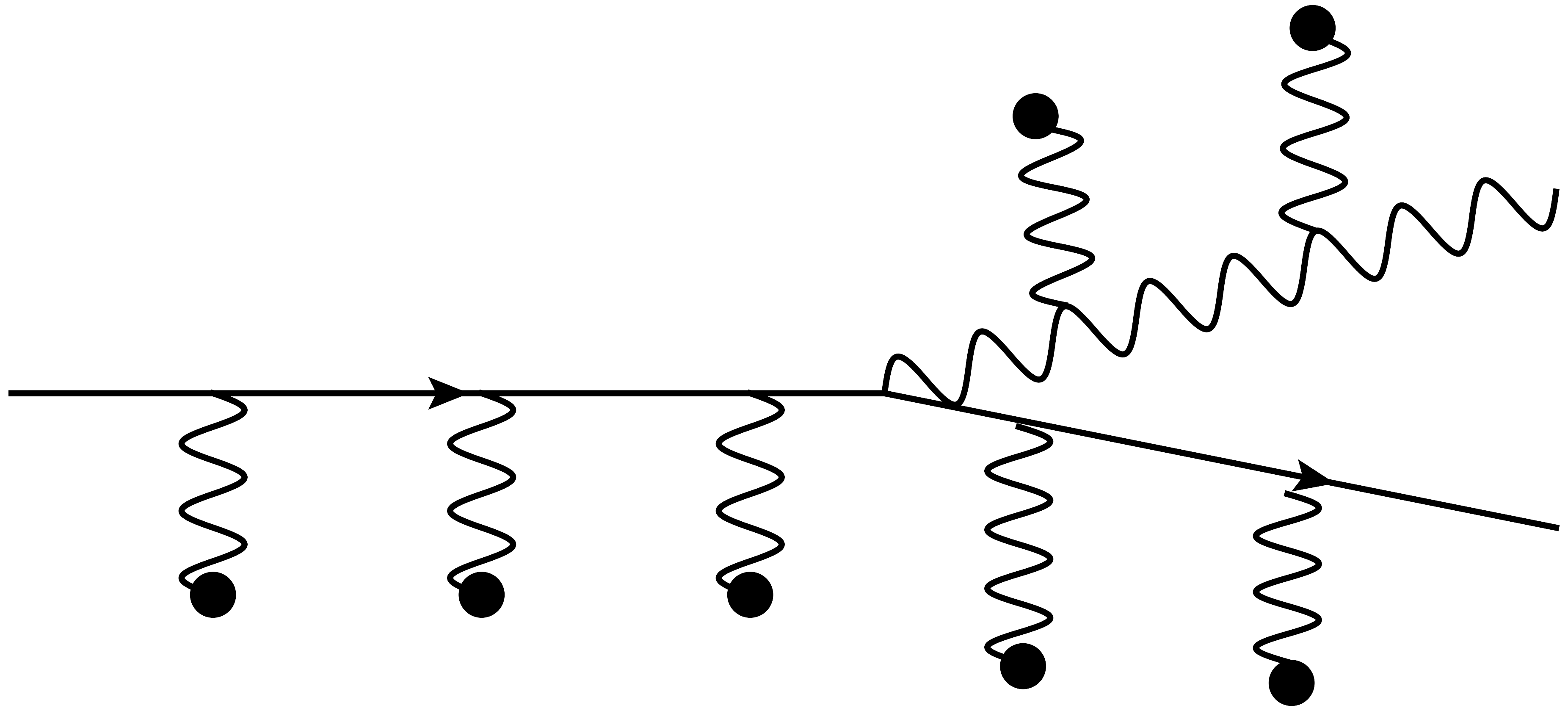
⇒ Need ressumation up to all orders

or

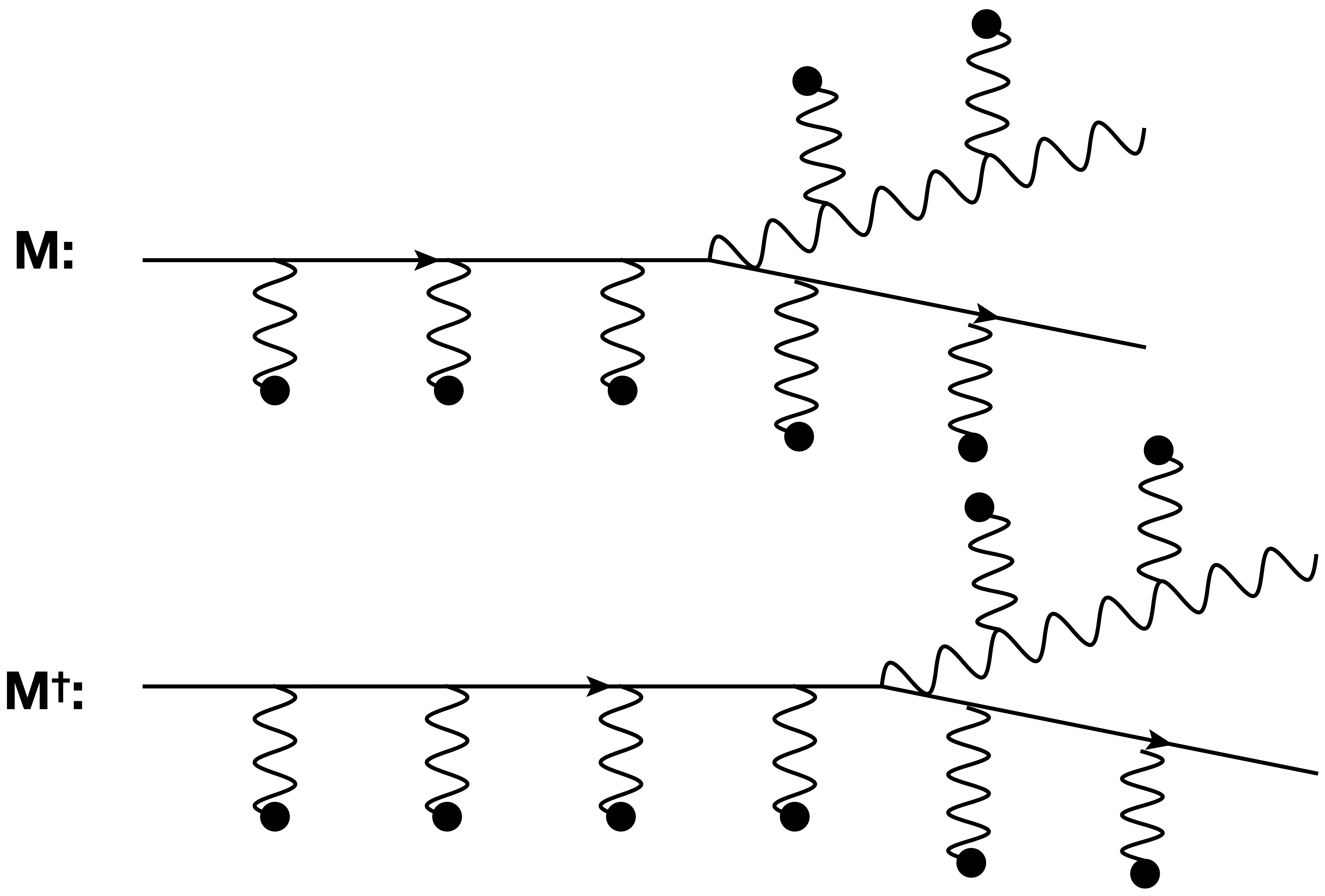
⇒ Opacity expansion (finite interactions with the medium)



Medium-induced gluon radiation

- Accumulation of momenta enhances gluon radiation:

$$\omega \frac{dI}{d\omega d^2\boldsymbol{k}} = \frac{2\alpha_s C_R}{(2\pi)^2\omega^2} \mathrm{Re} \int_0^\infty dt' \int_0^{t'} dt \int_{\boldsymbol{pq}} \boldsymbol{p}\cdot\boldsymbol{q}\, \widetilde{\mathcal{K}}(t',\boldsymbol{q};t,\boldsymbol{p})\mathcal{P}(\infty,\boldsymbol{k};t',\boldsymbol{q})$$



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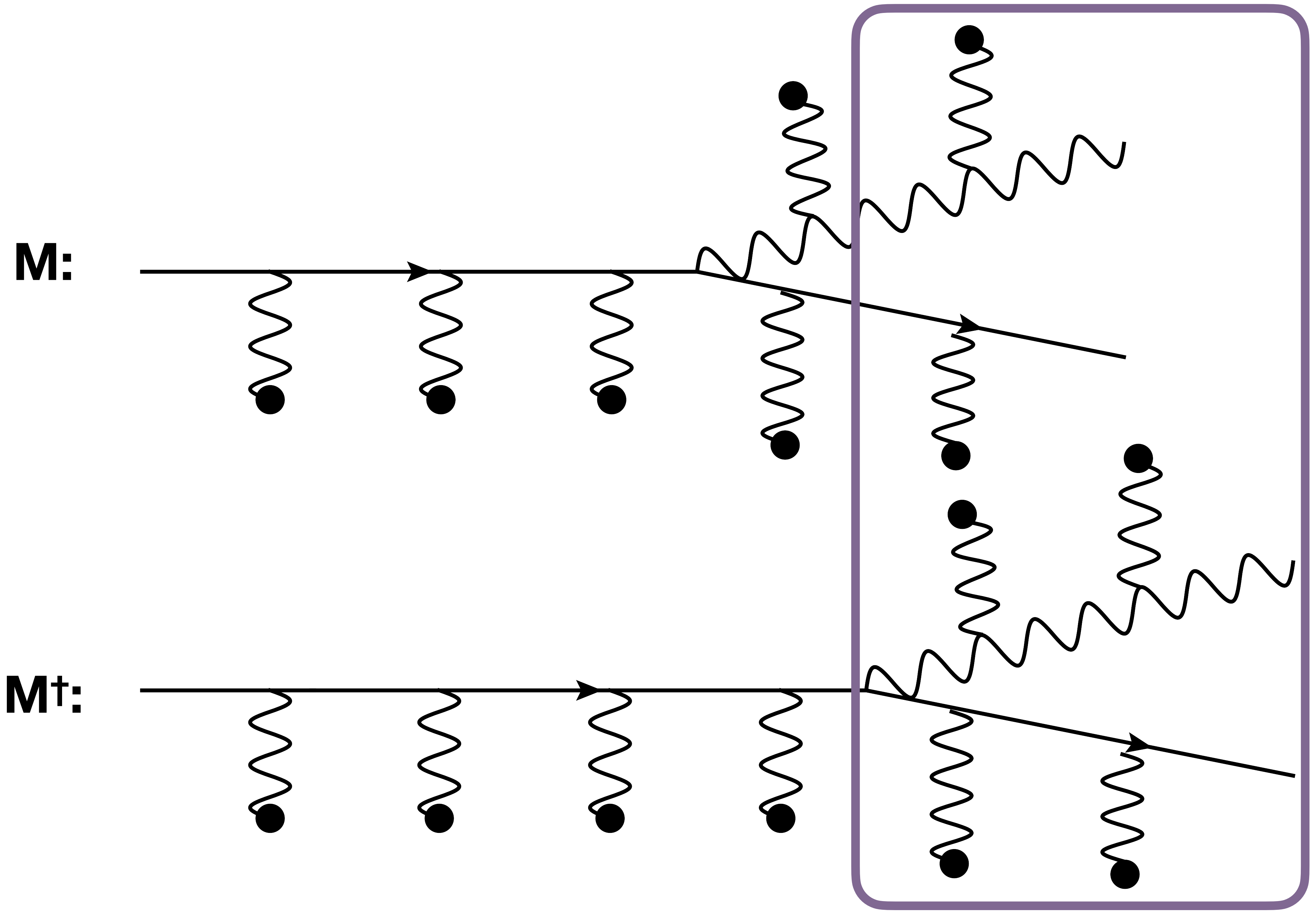

Momentum Broadening:

$$\mathcal{P}(t'',\boldsymbol{k};t',\boldsymbol{q}) \equiv \int d^2\boldsymbol{z}\, e^{-i(\boldsymbol{k}-\boldsymbol{q})\cdot\boldsymbol{z}} \exp\left\{-\frac{1}{2}\int_{t'}^{t''} ds\, n(s)\,\sigma(\boldsymbol{z})\right\}$$

Density of scattering centres:

$$n(x_+) = \int dx_{i+}\delta(x_+ - x_{i+}).$$

Dipole cross-section:

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

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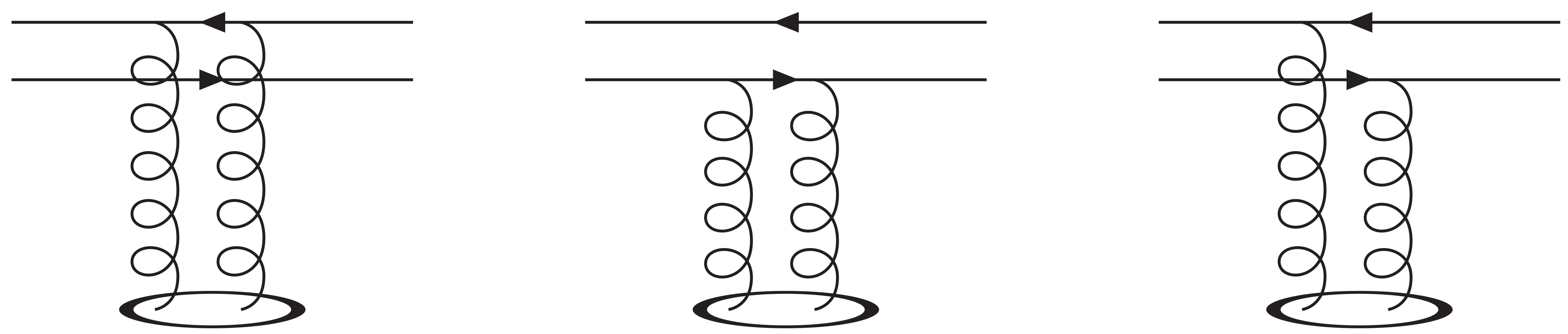

Collision rate
(parton-medium interaction)

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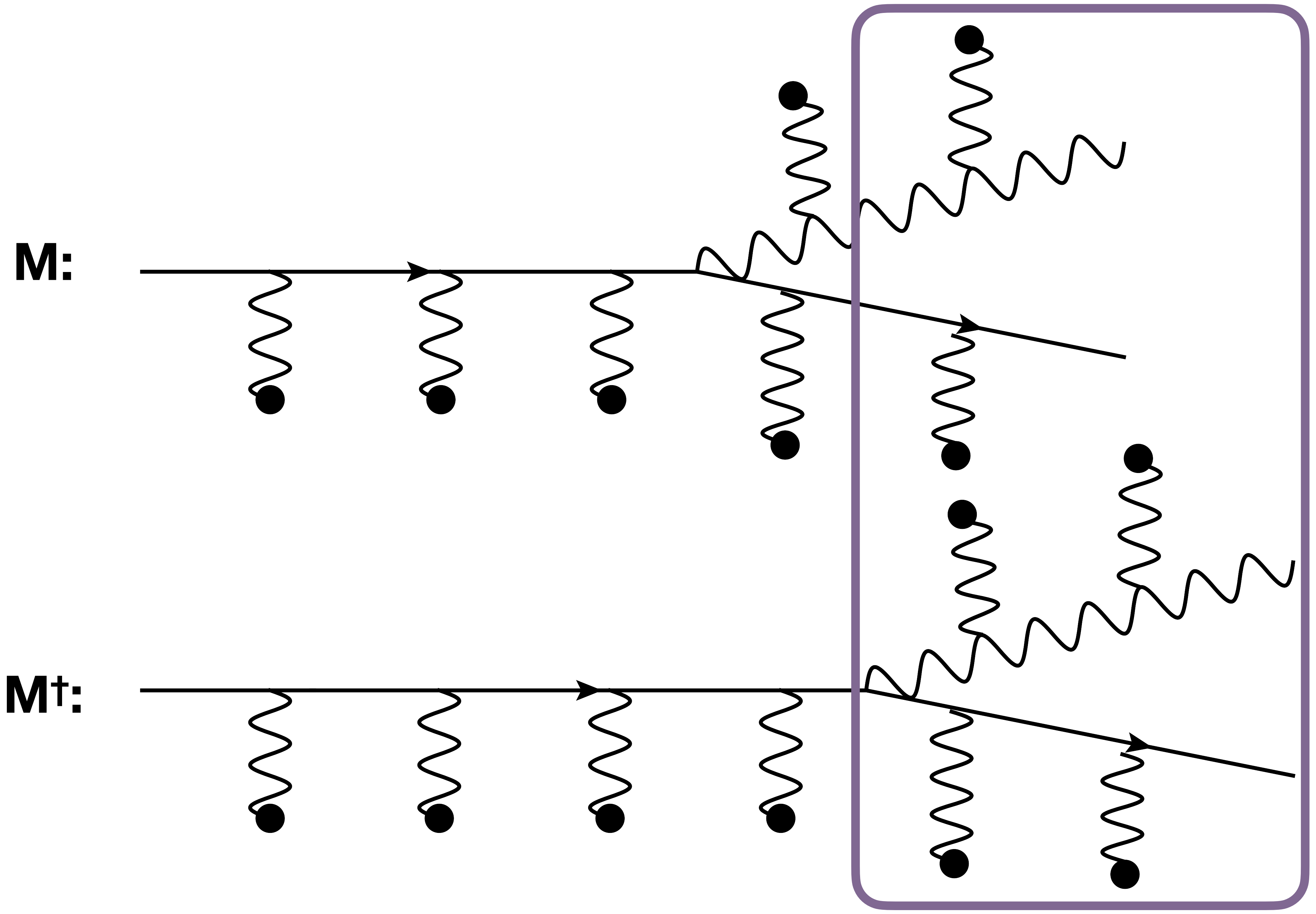

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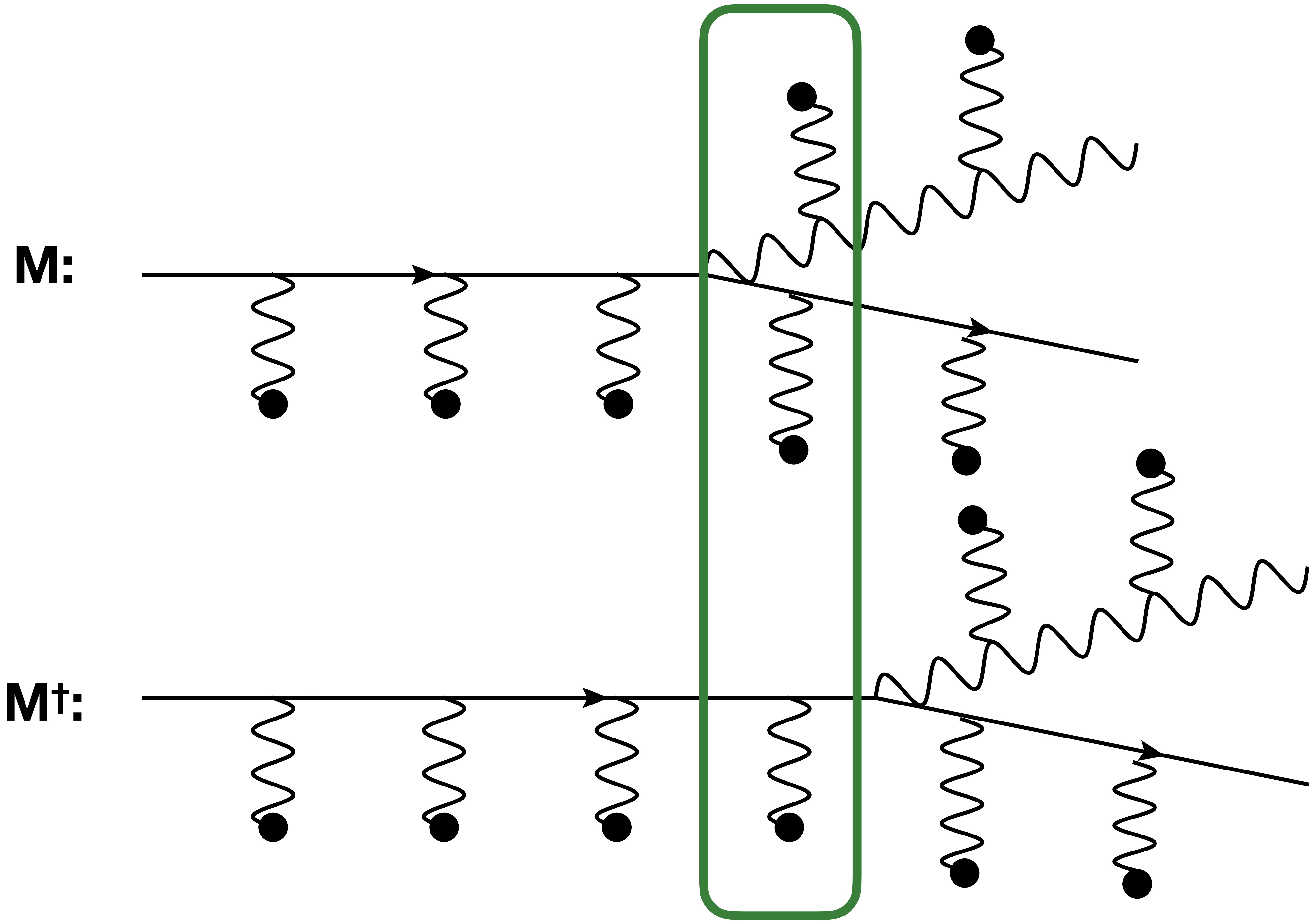

Emission Kernel:

$$\mathcal{K}(t', \boldsymbol{z}; t, \boldsymbol{y}) \equiv \int_{\boldsymbol{pq}} e^{i(\boldsymbol{q}\cdot\boldsymbol{z} - \boldsymbol{p}\cdot\boldsymbol{y})}\, \widetilde{\mathcal{K}}(t', \boldsymbol{q}; t, \boldsymbol{p})$$

$$= \int_{\boldsymbol{r}(t)=\boldsymbol{y}}^{\boldsymbol{r}(t')=\boldsymbol{z}} \mathcal{D}\boldsymbol{r} \exp\left[\int_t^{t'} ds \left(\frac{i\omega}{2}\dot{\boldsymbol{r}}^2 - \frac{1}{2}n(s)\sigma(\boldsymbol{r})\right)\right]$$

Solution to the path integral (for an arbitrary potential) poses significant technical challenges…

H. Oscillator

- Analytical solution to medium-induced gluon radiation for finite size medium
  - 2 free parameters: $\hat{q}$ and L
  - Resums scatterings over medium length

Useful to gain qualitative insight into experimental observations

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[Baier, Dokshitzer, Mueller, Peigné, Schiff (97-00), Zakharov (96)]
[Wiedemann (00), Arnold, Moore,Yaffe (01)]

[Mehtar-Tani, Salgado, Tywoniuk (2010-2011)]
[LA, Armesto, Salgado (12), Blaizot, Dominguez, Iancu, Mehtar-Tani (13-14)]
[Blaizot, Iancu, Mehtar-Tani (13), Blaizot, Mehtar-Tani, Torres (14)]
[LA, Armesto, Milhano, Salgado (15)]
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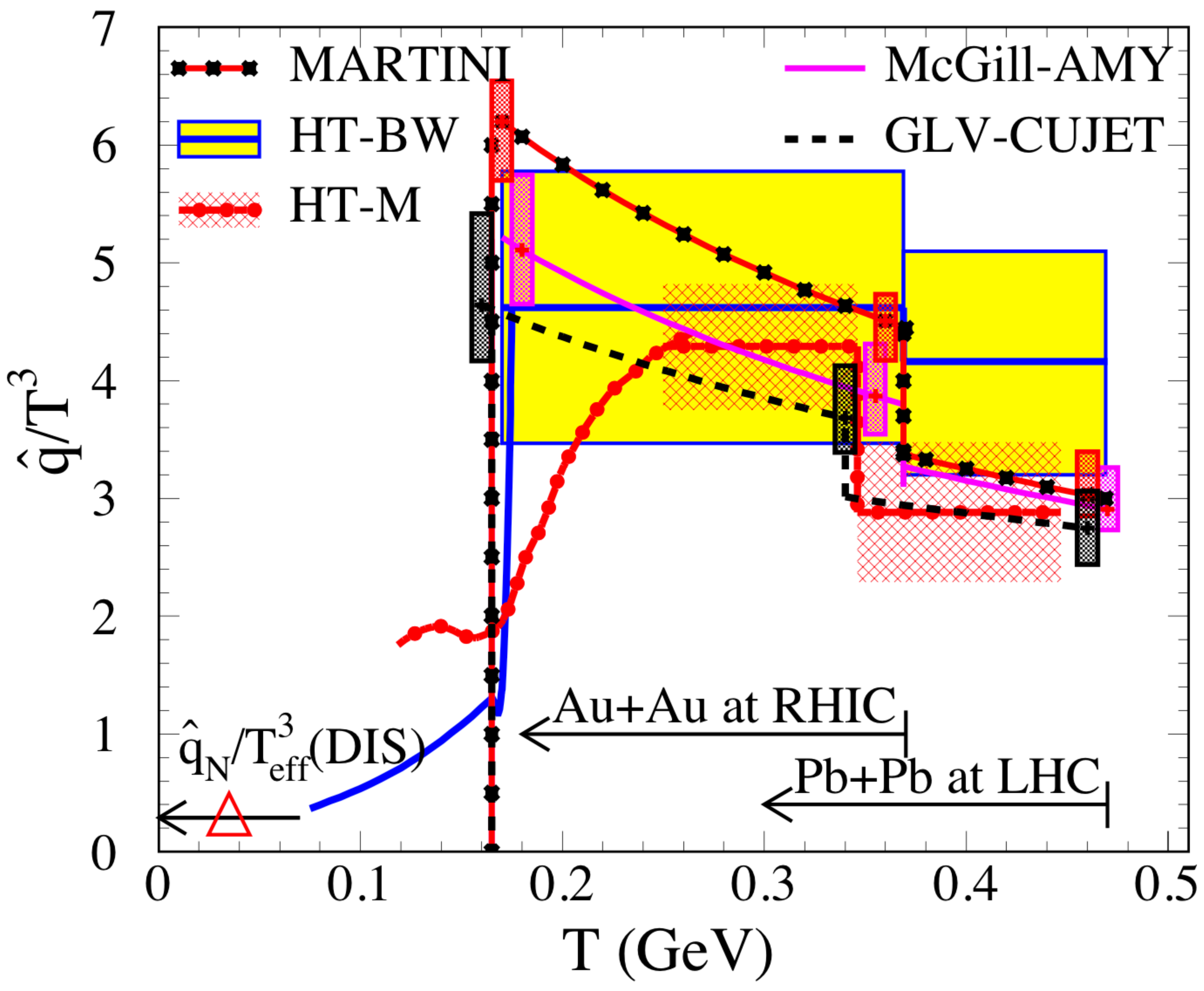
[JET Collaboration: 1312.5003]



Transport coefficient: RHIC > LHC at the same temperature ?
Center-of-mass energy dependent ?

QHat puzzle?

Opacity expansion (GLV limit)

[Gyulassy, Wang (94), Wiedemann, Gyulassy (99)]
[Gyulassy, Levai, Vitev (00, 02)]
[Wiedemann (00)]

Recent works:
[Vitev, Ovanesyan (2013)]
[Arnold, Iqbal (2015)]
[Sievert, Vitev (18)]

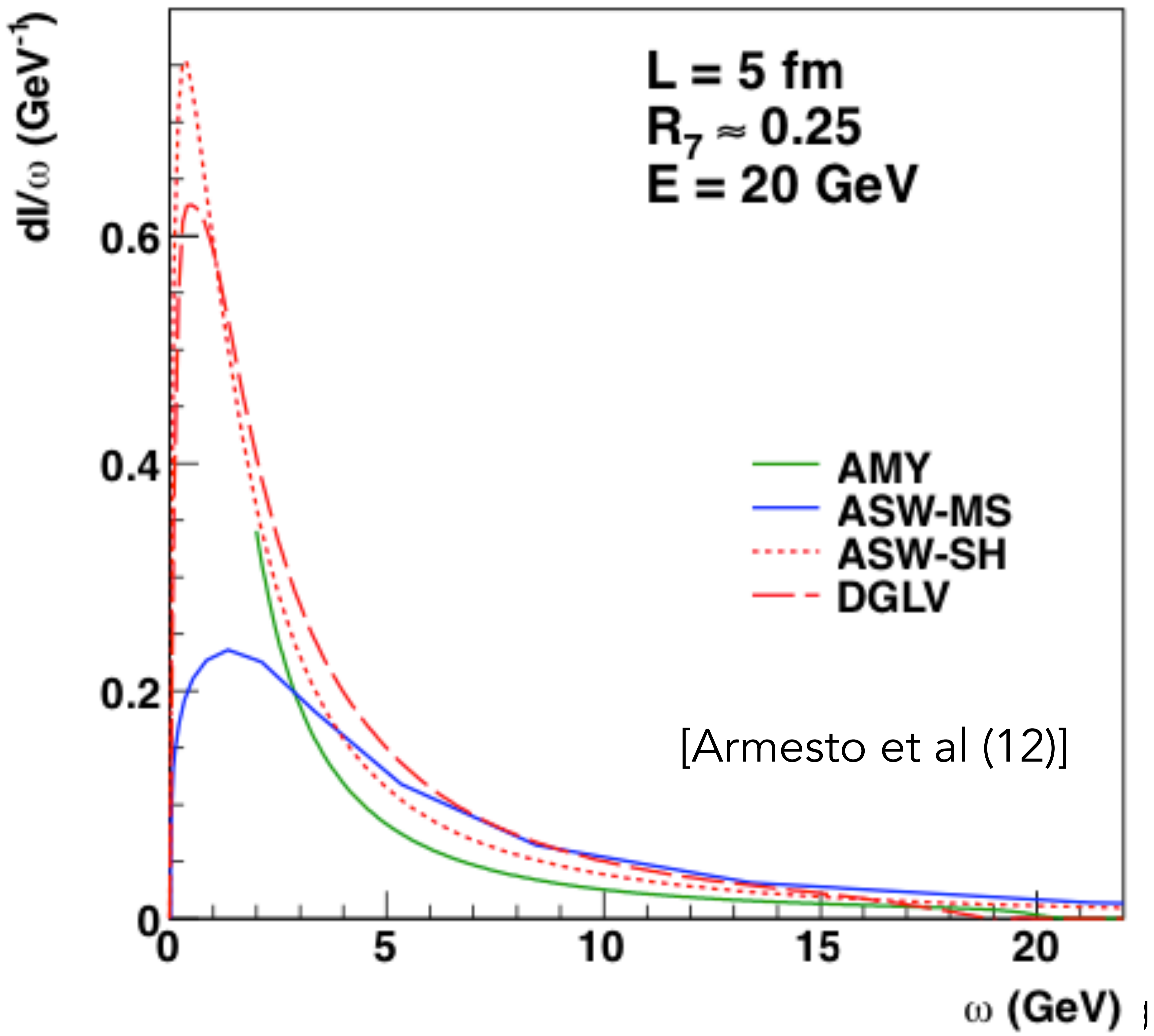
- Radiation pattern = Incoherent superposition of just a few single hard scattering processes.

$$\mathcal{P}(t'', \boldsymbol{k}; t', \boldsymbol{q}) \equiv \int d^2\boldsymbol{z}\, e^{-i(\boldsymbol{k}-\boldsymbol{q})\cdot\boldsymbol{z}} \exp\left\{-\frac{1}{2}\int_{t'}^{t''} ds\, n(s)\, \sigma(\boldsymbol{z})\right\}$$

- Expansion in terms of: $(n(s)\sigma(\boldsymbol{r}))^N$
- Exact form of potential: $V(\boldsymbol{q}) = \dfrac{8\pi\mu^2}{(\boldsymbol{q}^2+\mu^2)^2}$
- 3 parameters: n0, L, μ

Dipole cross-section:

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



[Armesto et al (12)]

An opacity expansion of the BDMPS-ASW reproduces the GLV approach

Recent works:
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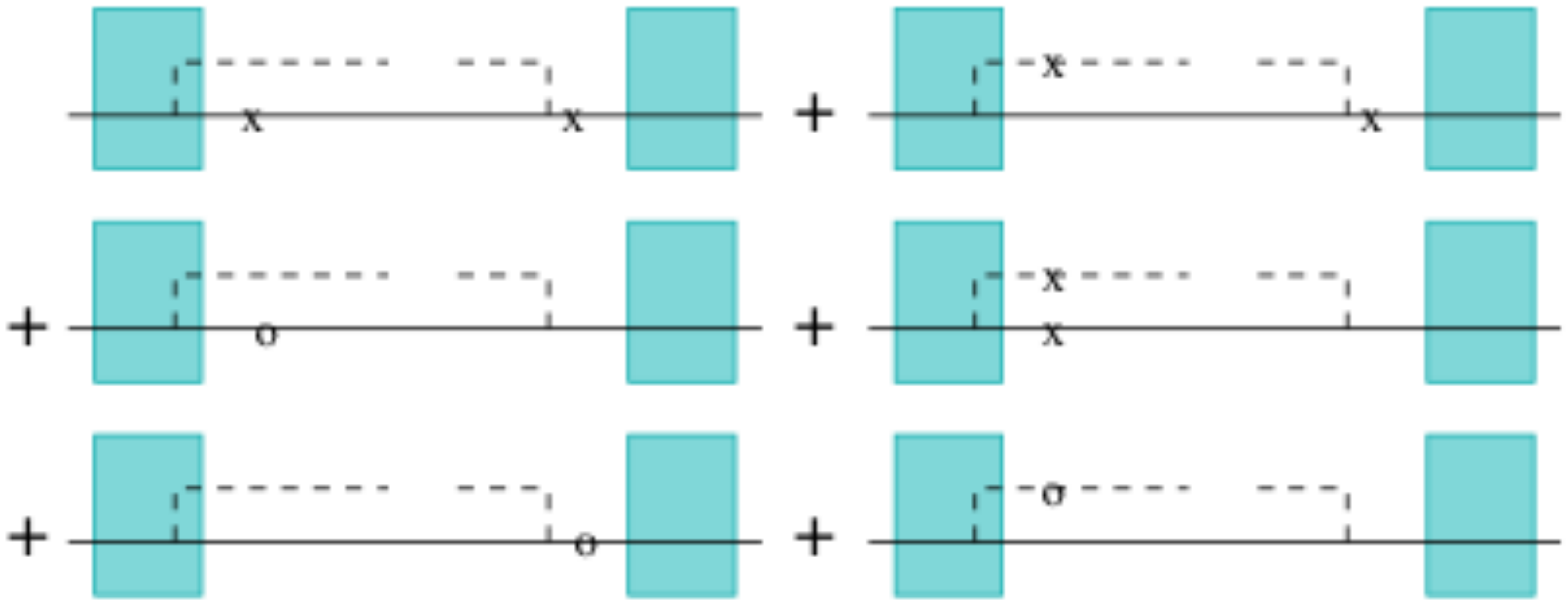
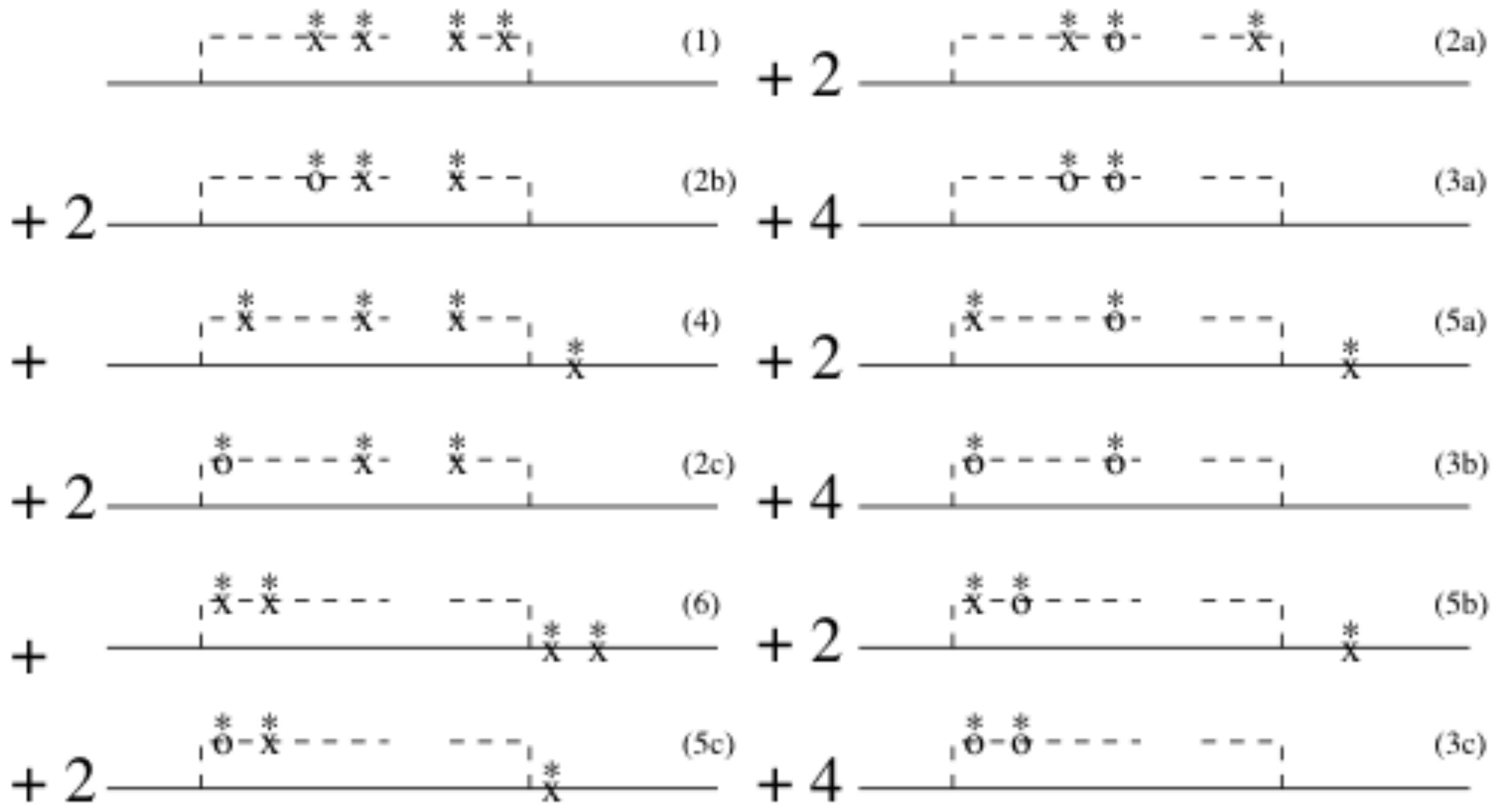
[Sievert, Vitev (18)]

Opacity expansion

- Exact limit when medium is dilute;
- For dense medium (large number of scattering centers):
  - Needs resuming the contributions from all orders (analytically and computationally demanding)



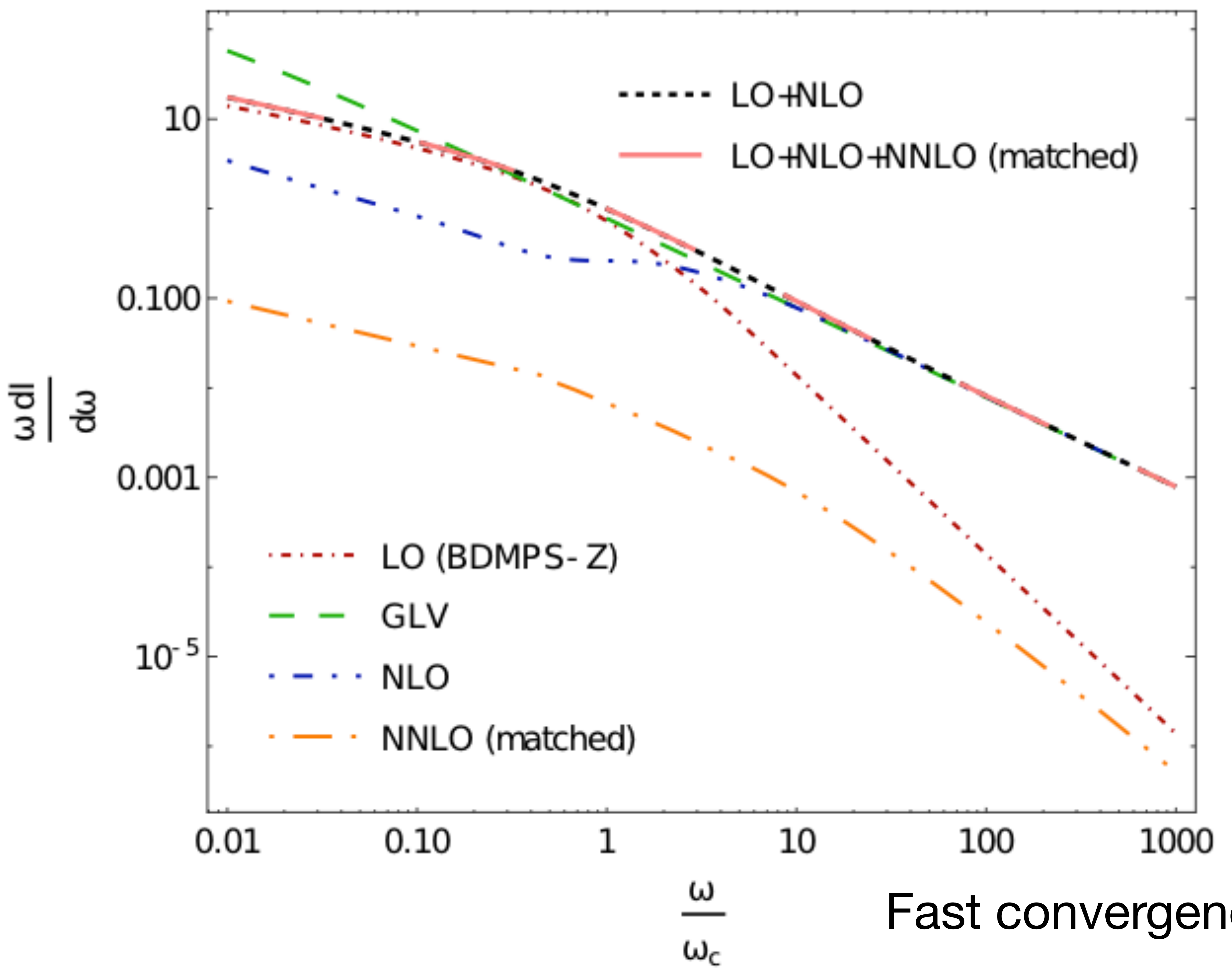


[Mehtar-Tani , Tywoniuk (20), Barata, Mehtar-Tani (20), Barata et al (20)]

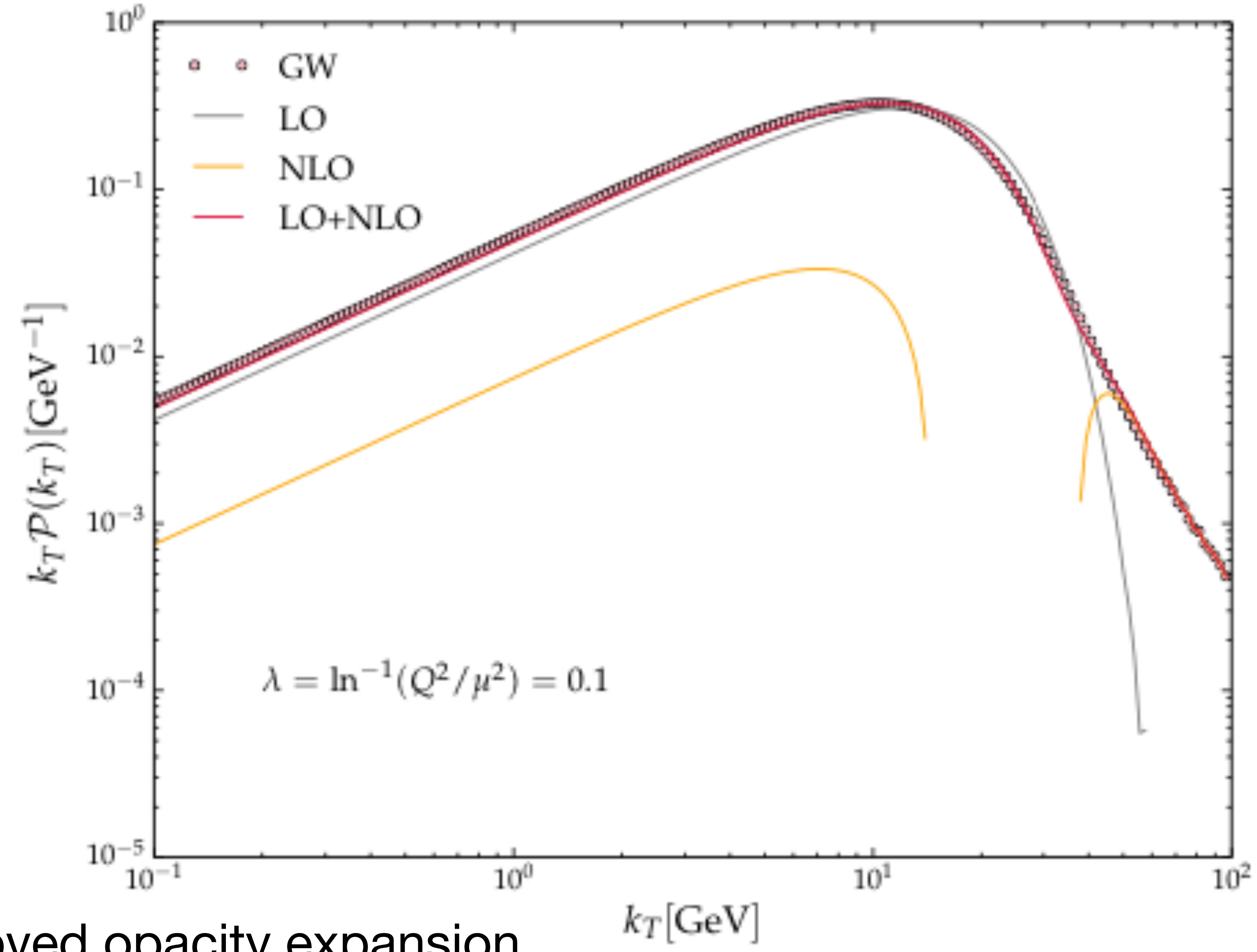
Towards resummation

- Analytical expansion around the HO: $n(s)\sigma(\boldsymbol{r}) \approx \frac{1}{2}\hat{q}(s)\boldsymbol{r}^2 + \mathcal{O}(\boldsymbol{r}^2 \ln \boldsymbol{r}^2)$

Energy Spectrum



Momentum broadening



Fast convergence of the improved opacity expansion

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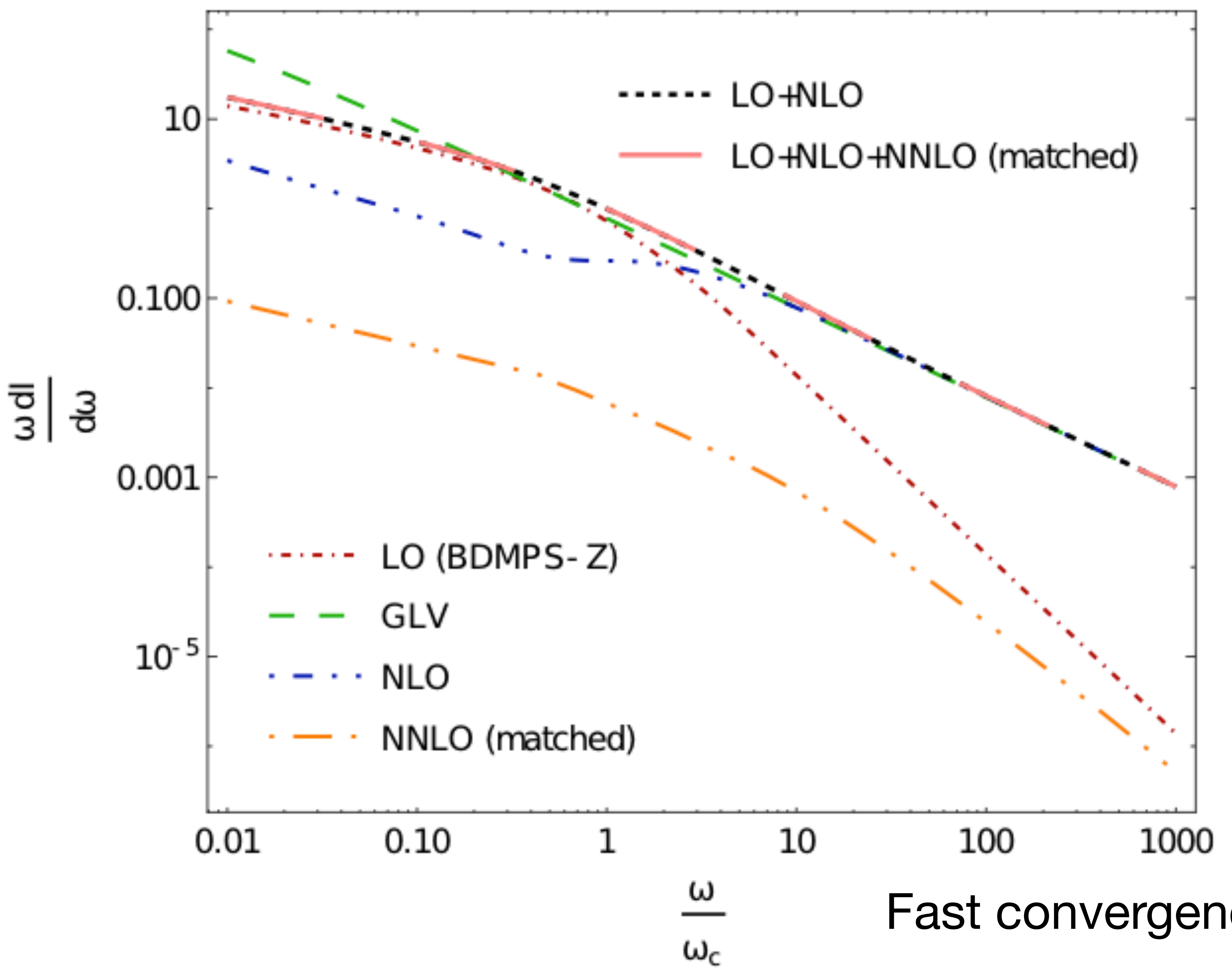

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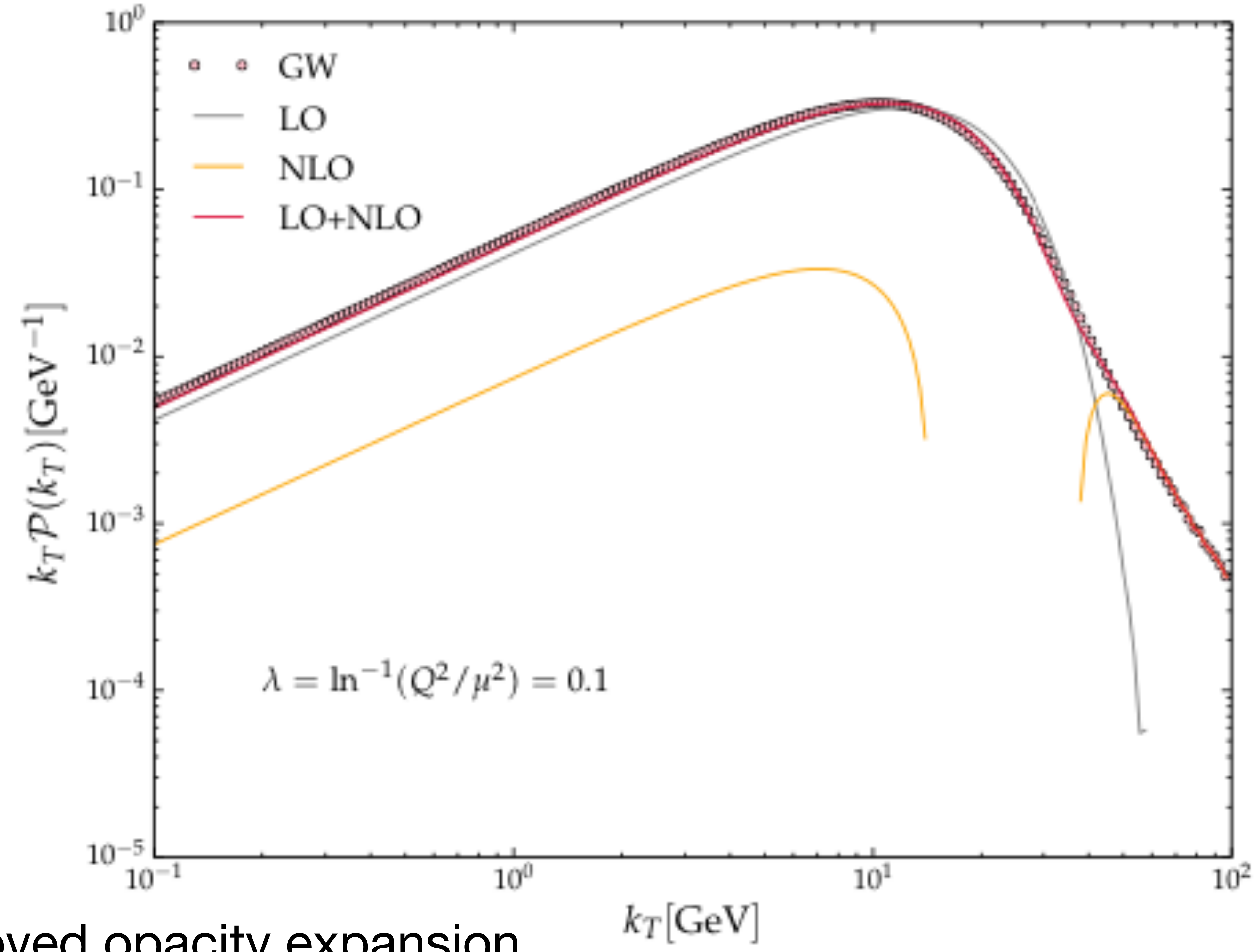


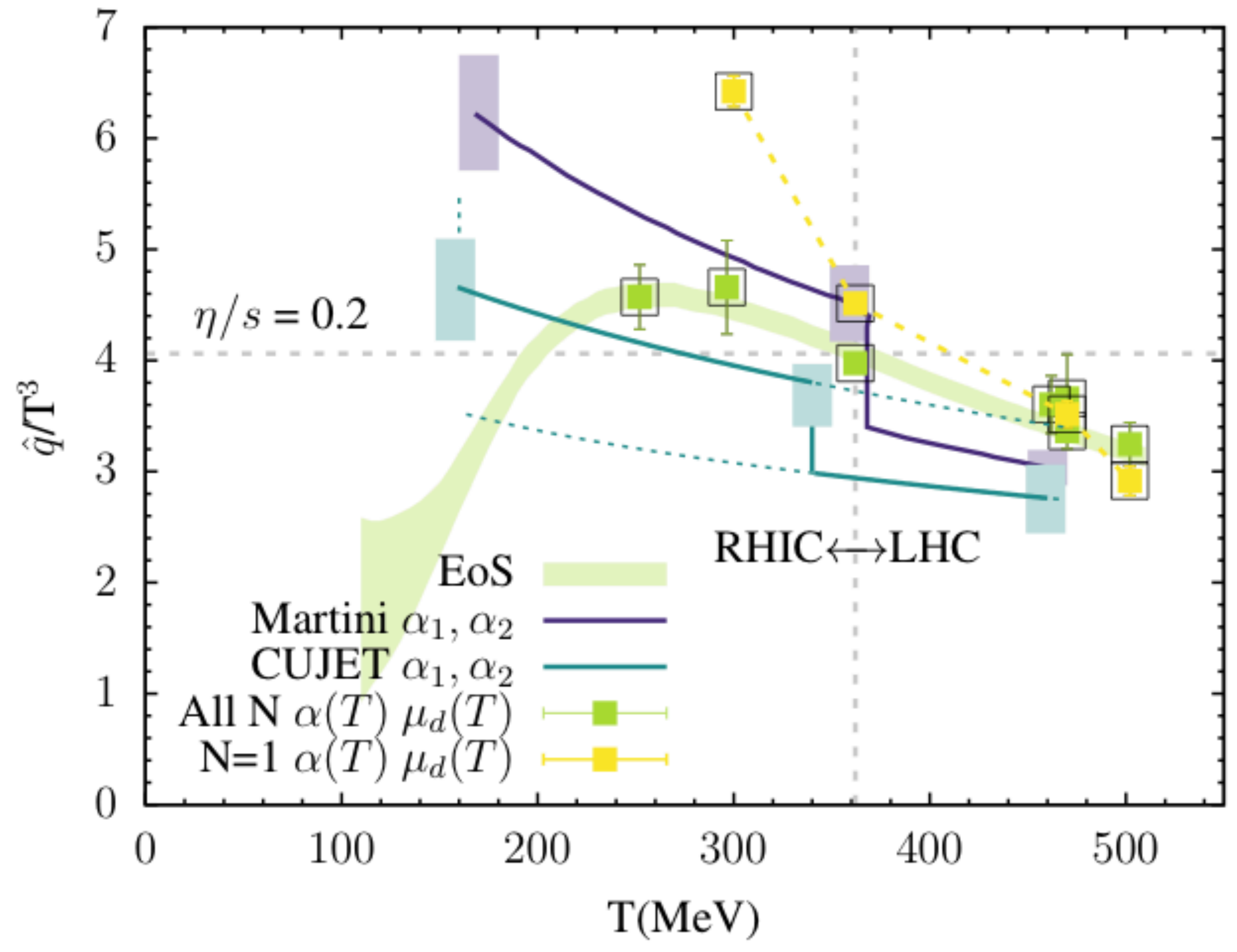
Fast convergence of the improved opacity expansion

(still limited by an order-by-order calculation)

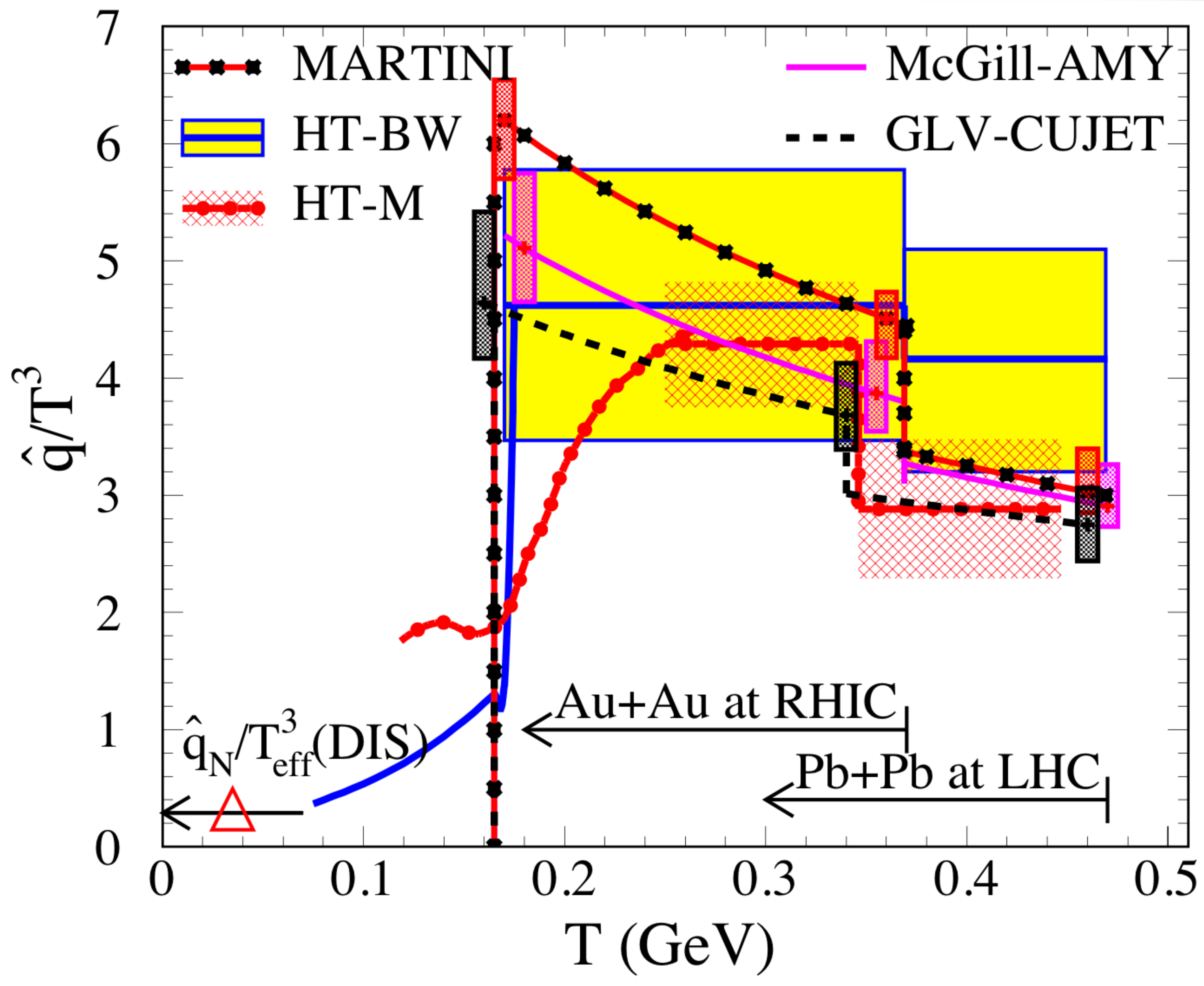
[Feal, Vazquez (18), Feal, Vazquez (20)]

Towards resummation

- Full resummation of all scatterings within a MC approach:



[JET Collaboration: 1312.5003]



Result with the full resummation of all scatterings (in the soft limit) without apparent inconsistencies in temperature

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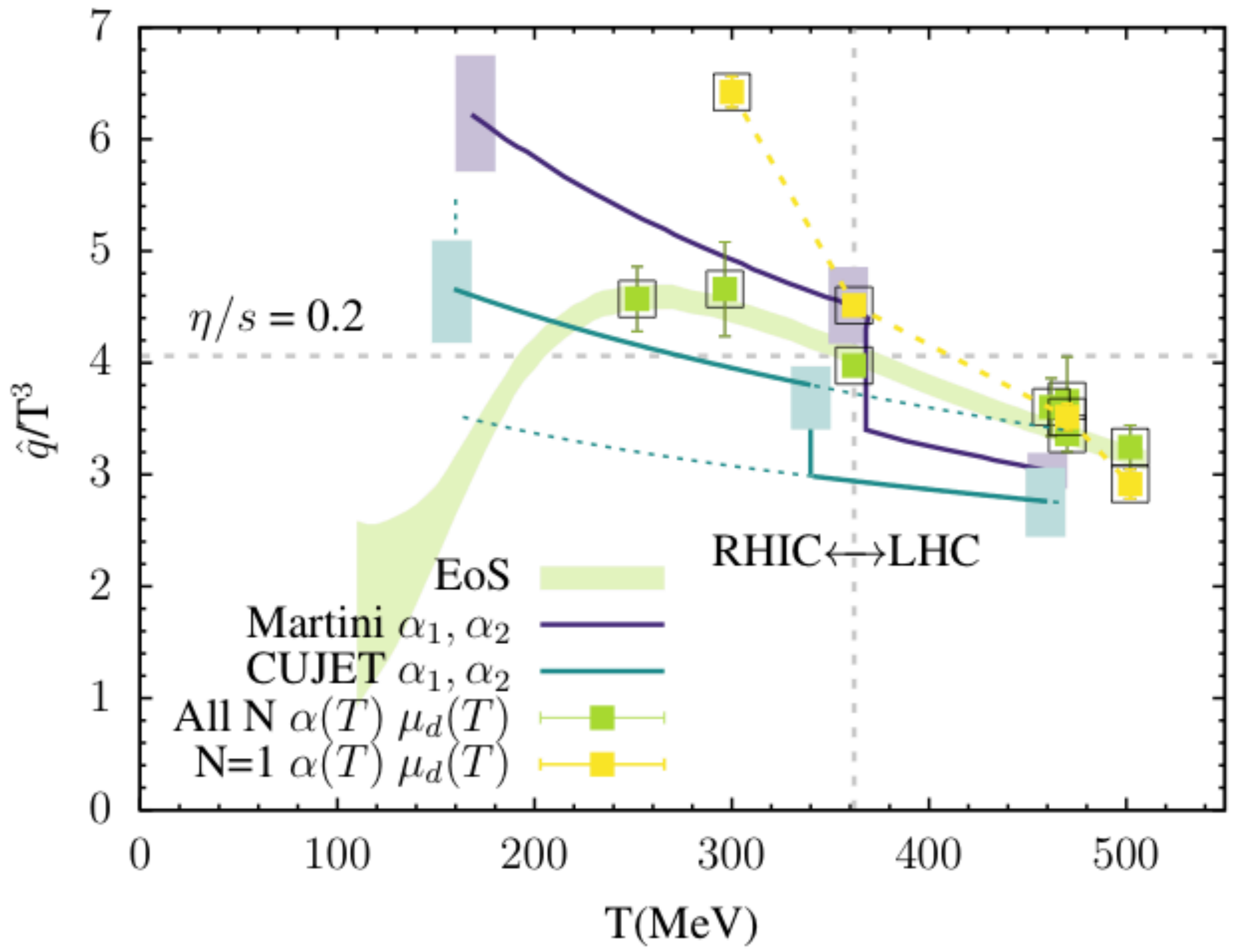

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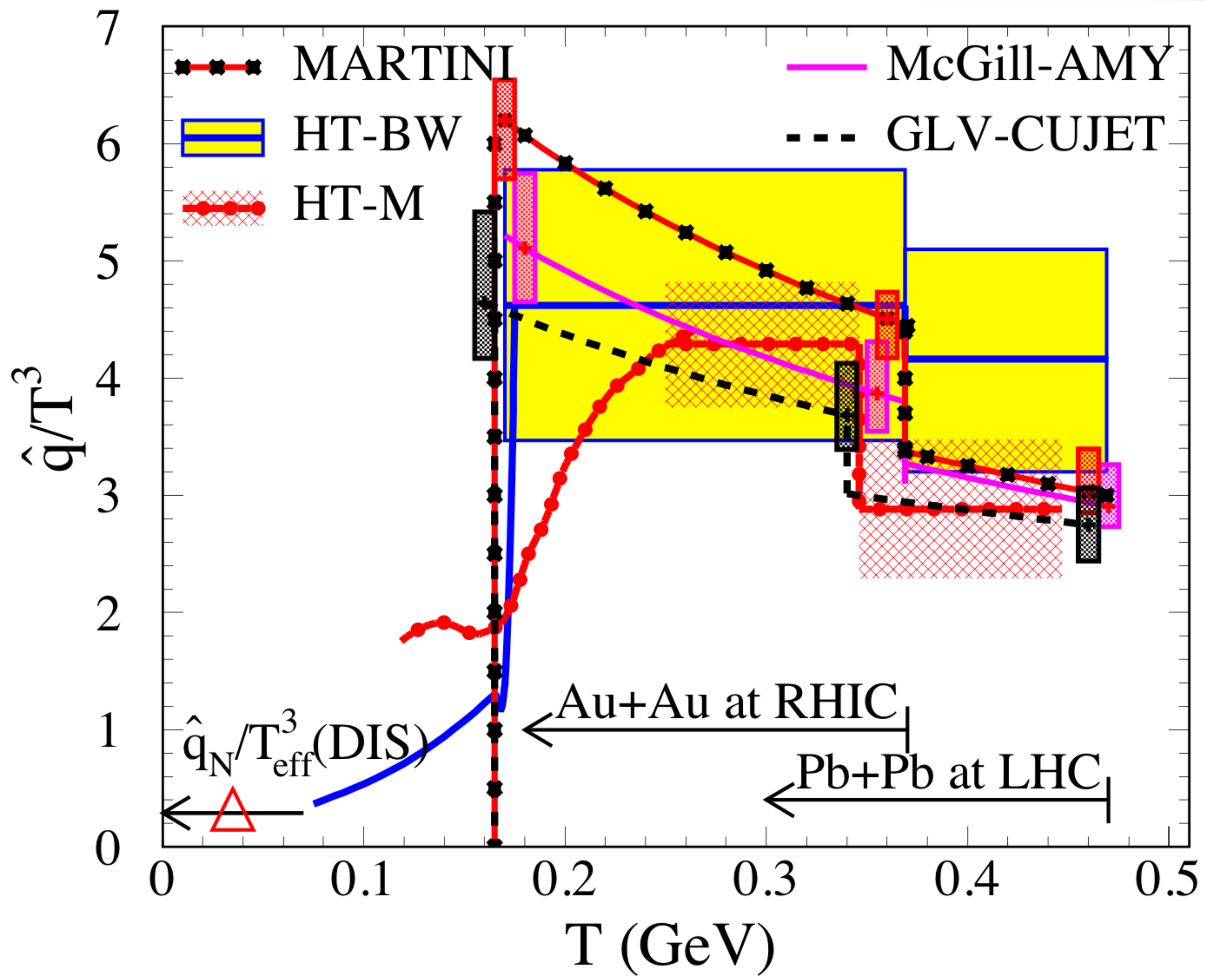

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Uses involving Monte Carlo methods
(difficult to generally apply for phenomenological studies)

[Andrés, LA, Dominguez (20)]

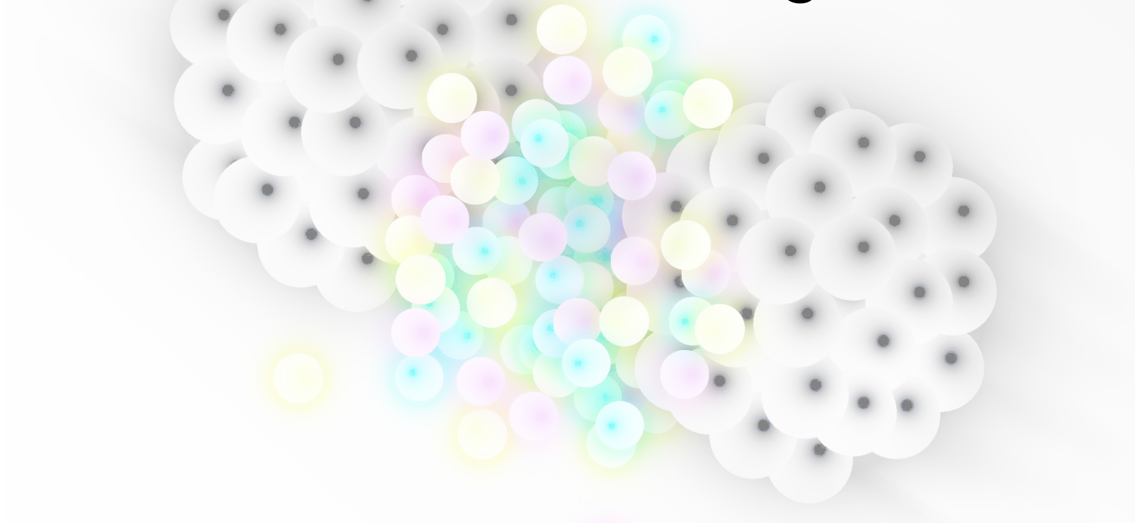
Towards resummation

- Solve the spectrum by using Schwinger-Dyson type equations (in momentum space):
  - Evolution equations for emission kernel and broadening

$$\partial_\tau \mathcal{P}(\tau, \boldsymbol{k}; s, \boldsymbol{l}) = -\frac{1}{2} n(\tau) \int_{\boldsymbol{k}'} \sigma(\boldsymbol{k} - \boldsymbol{k}') \mathcal{P}(\tau, \boldsymbol{k}'; s, \boldsymbol{l})$$

$$\partial_t \widetilde{\mathcal{K}}(s, \boldsymbol{q}; t, \boldsymbol{p}) = \frac{i\boldsymbol{p}^2}{2\omega} \widetilde{\mathcal{K}}(s, \boldsymbol{q}; t, \boldsymbol{p}) + \frac{1}{2} n(t) \int_{\boldsymbol{k}'} \sigma(\boldsymbol{k}' - \boldsymbol{p}) \widetilde{\mathcal{K}}(s, \boldsymbol{q}; t, \boldsymbol{k}')$$

[Andrés, LA, Dominguez (20)]



Towards resummation

- Solve the spectrum by using Schwinger-Dyson type equations (in momentum space):
    - Evolution equations for emission kernel and broadening

$$\partial_\tau \mathcal{P}(\tau, \boldsymbol{k}; s, \boldsymbol{l}) = -\frac{1}{2} n(\tau) \int_{\boldsymbol{k}'} \sigma(\boldsymbol{k} - \boldsymbol{k}') \mathcal{P}(\tau, \boldsymbol{k}'; s, \boldsymbol{l})$$

$$\partial_t \widetilde{\mathcal{K}}(s, \boldsymbol{q}; t, \boldsymbol{p}) = \frac{i\boldsymbol{p}^2}{2\omega} \widetilde{\mathcal{K}}(s, \boldsymbol{q}; t, \boldsymbol{p}) + \frac{1}{2} n(t) \int_{\boldsymbol{k}'} \sigma(\boldsymbol{k}' - \boldsymbol{p}) \widetilde{\mathcal{K}}(s, \boldsymbol{q}; t, \boldsymbol{k}')$$

Set of integro-partial differential equations that can be numerically solved to any (realistic) potential

Contains the resummation of all scattering scatterings, in the soft limit, without further approximations!

[Andrés, LA, Dominguez (20)]

Equations to solve numerically

- Set of integro-differential equations of that can be solve numerically:
  - Start with broadening and dipole cross-section equation:

$$\partial_\tau \boldsymbol{\phi}(\tau, \boldsymbol{k}; s, \boldsymbol{q}) = -\frac{1}{2} n(\tau) \int_{\boldsymbol{k}'} \sigma(\boldsymbol{k} - \boldsymbol{k}') \boldsymbol{\phi}(\tau, \boldsymbol{k}'; s, \boldsymbol{q})$$

Initial condition:

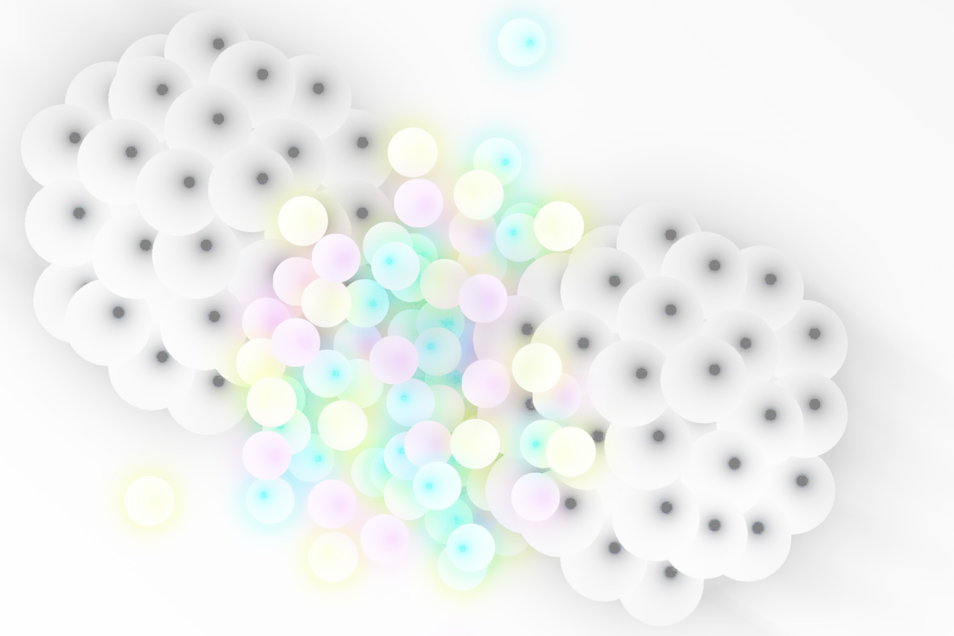
$$\boldsymbol{\phi}(s, \boldsymbol{k}; s, \boldsymbol{q}) = n(s) \left(\frac{\boldsymbol{k}}{\boldsymbol{k}^2} - \frac{\boldsymbol{q}}{\boldsymbol{q}^2} \right) \sigma(\boldsymbol{k} - \boldsymbol{q})$$

  - Use ϕ as initial condition for: $\boldsymbol{\psi}_I(s, \boldsymbol{k}; s, \boldsymbol{p}) = \boldsymbol{\phi}(L, \boldsymbol{k}; s, \boldsymbol{p})$

$$\partial_t \boldsymbol{\psi}_I(s, \boldsymbol{k}; t, \boldsymbol{p}) = \frac{1}{2} n(t) \int_{\boldsymbol{k}'} e^{\frac{i\boldsymbol{p}^2}{2\omega}(s-t)} \sigma(\boldsymbol{k}' - \boldsymbol{p}) e^{-\frac{i\boldsymbol{k}'^2}{2\omega}(s-t)} \boldsymbol{\psi}_I(s, \boldsymbol{k}; t, \boldsymbol{k}')$$

  - Finally, calculate: $\omega \frac{dI}{d\omega d^2\mathbf{k}} = \frac{2\alpha_s C_R}{(2\pi)^2 \omega} \mathrm{Re} \int_0^L ds \int_0^s dt \int_{\mathbf{p}} i\, e^{-i\frac{\mathbf{p}^2}{2\omega}(s-t)} \mathbf{p} \cdot \psi_I(s, \mathbf{k}; t, \mathbf{p})$

GLV vs Full solution



- Specifying the interaction potential: $\sigma(\boldsymbol{r}) = \int_{\boldsymbol{q}} V(\boldsymbol{q}) \left(1 - e^{i\boldsymbol{q}\boldsymbol{r}}\right)$
    - Yukawa-type interaction:

$$V(\boldsymbol{q}) = \frac{8\pi\mu^2}{(\boldsymbol{q}^2 + \mu^2)^2}$$

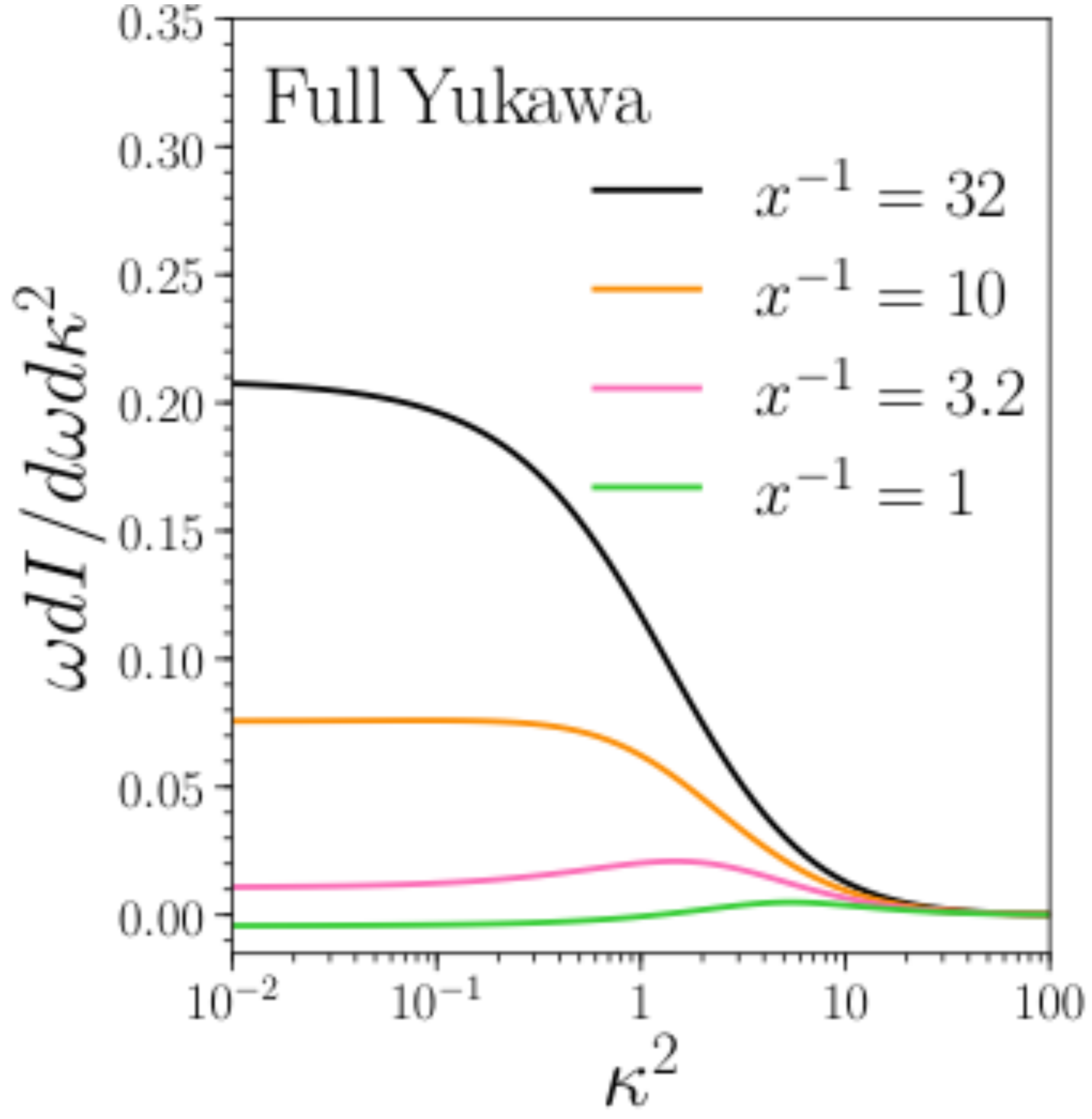
    - Parameters: n_0, L, μ

$$\kappa^2 = \frac{k^2}{\mu^2}$$

$$x^{-1} = \frac{\mu^2 L}{2\omega}$$

n_0 L = 1 (“dilute”)

k_T-spectrum



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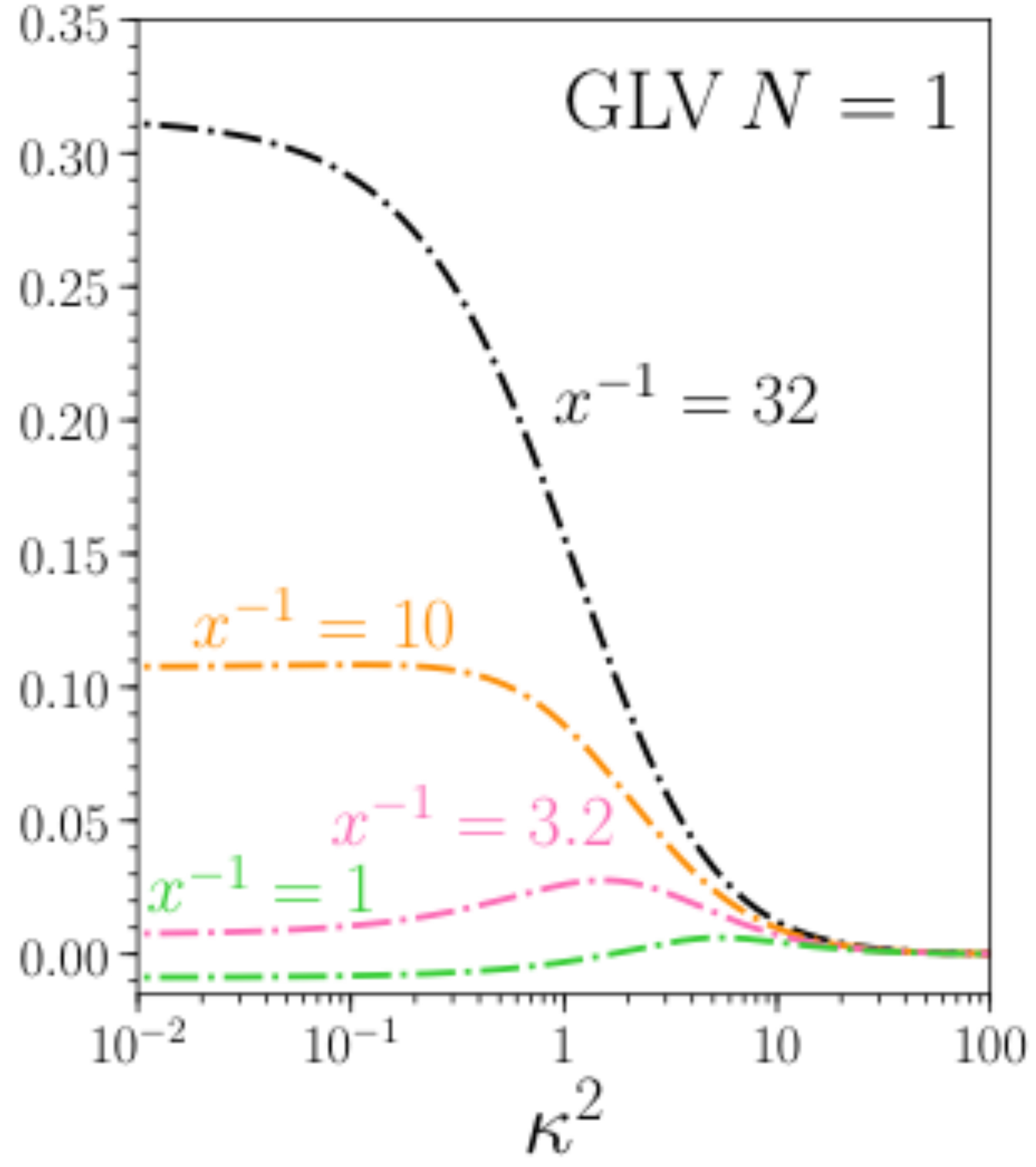
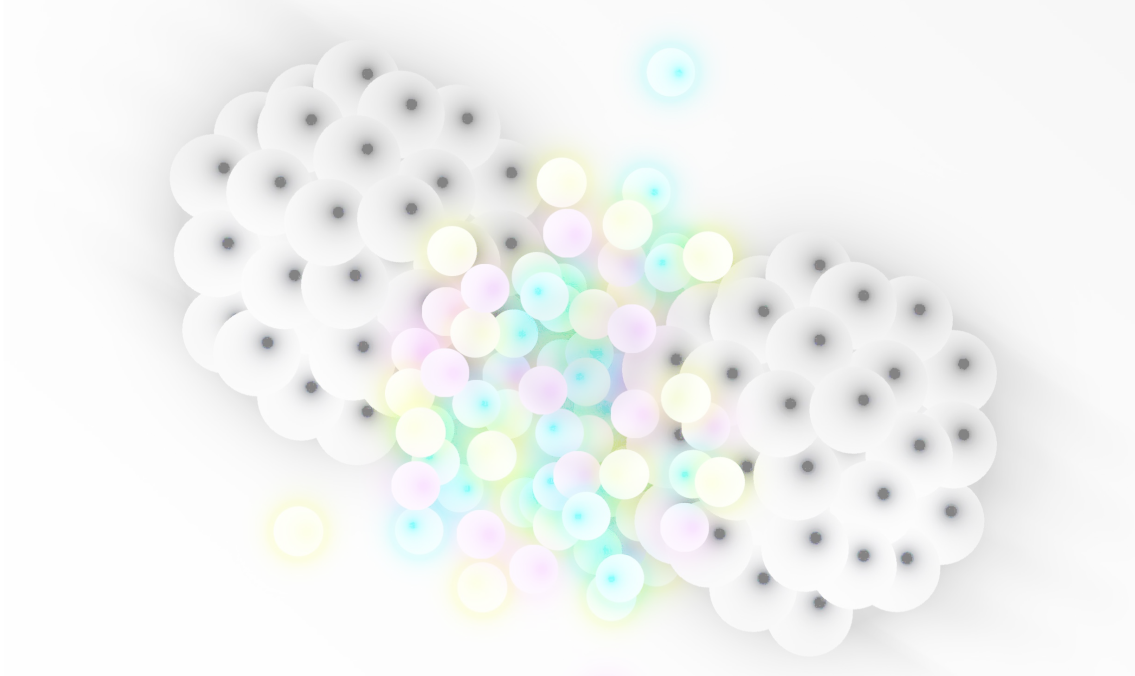


GLV vs Full solution



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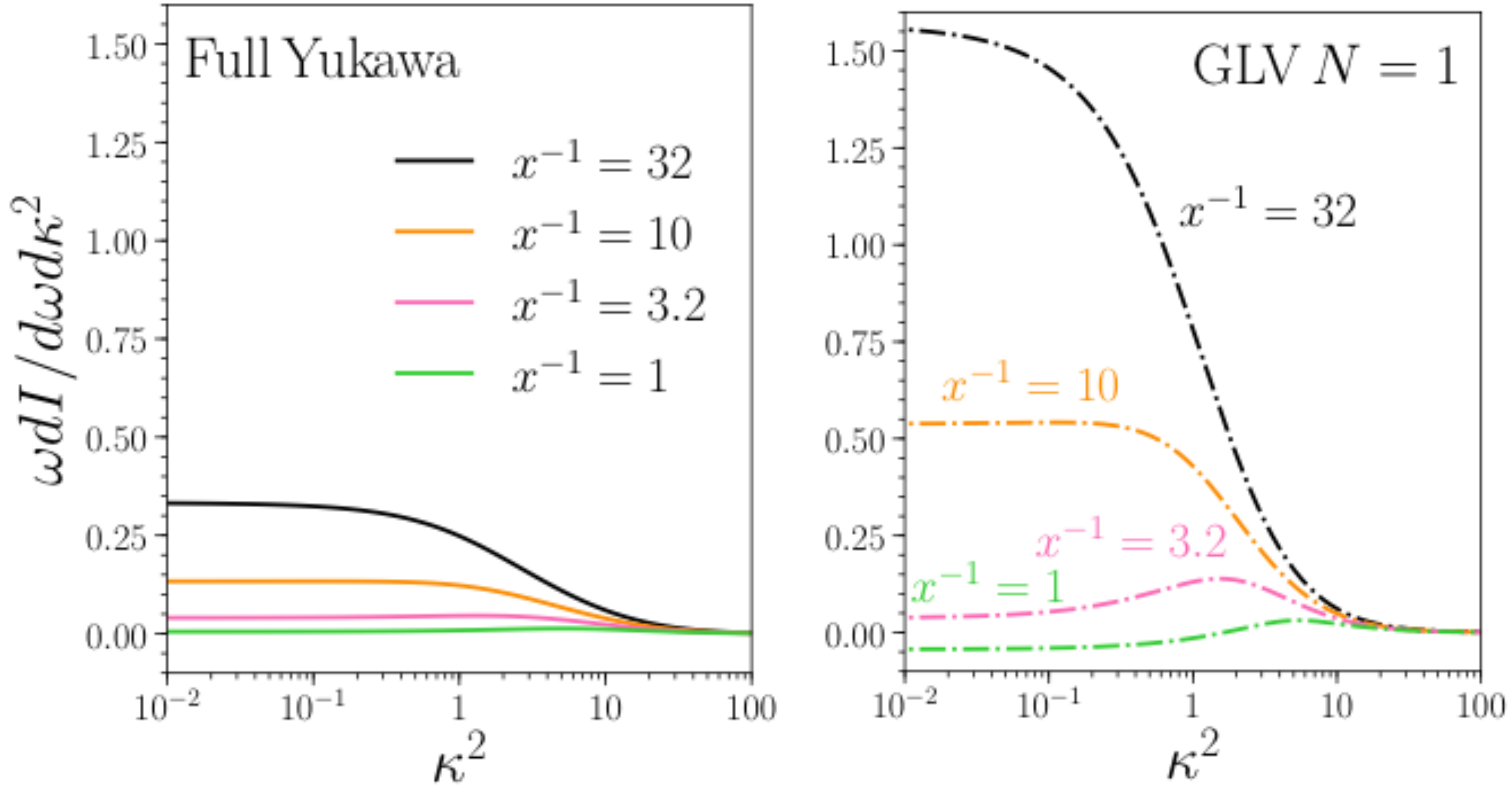
$$x^{-1} = \frac{\mu^2 L}{2\omega}$$

n_0 L = 5 (“dense”)

k_T-spectrum **k_T-spectrum**



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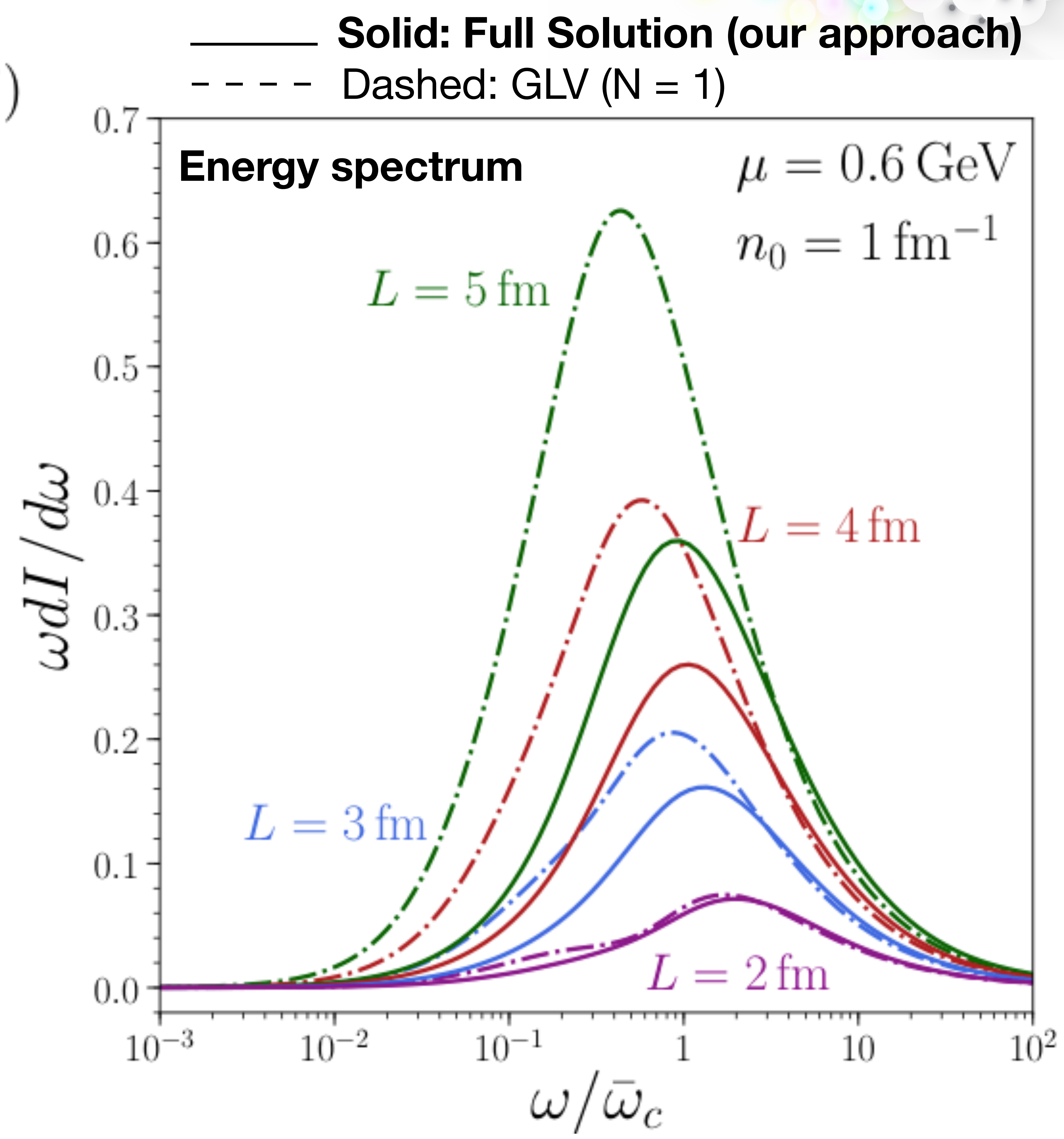

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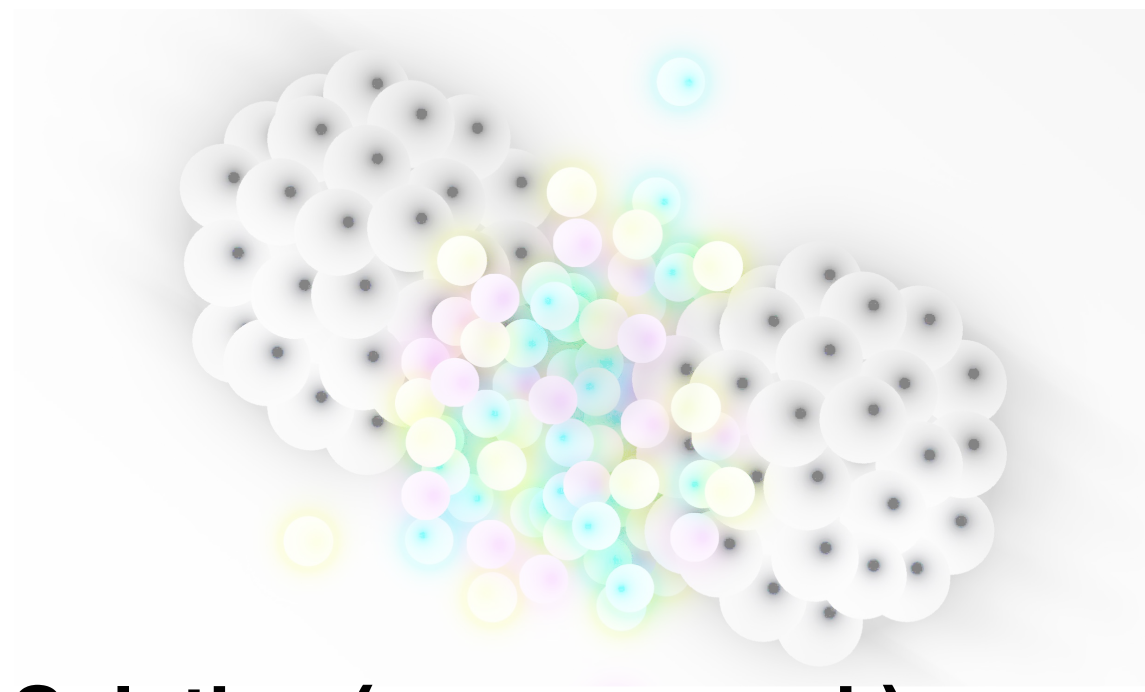

- Specifying the interaction potential: $\sigma(\boldsymbol{r}) = \int_{\boldsymbol{q}} V(\boldsymbol{q}) \left(1 - e^{i\boldsymbol{qr}}\right)$
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  - Parameters: n_0, L, μ

$$\kappa^2 = \frac{k^2}{\mu^2}$$

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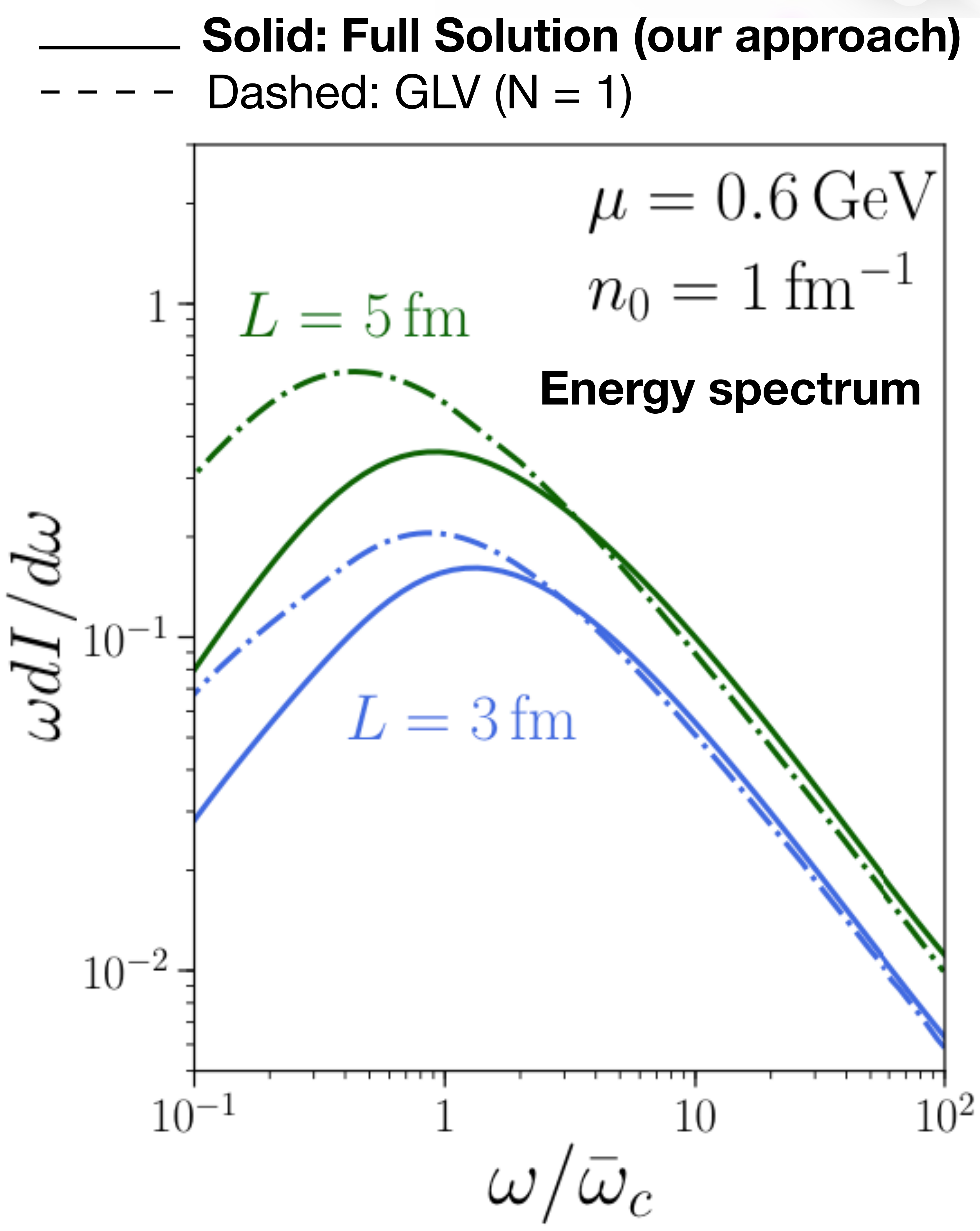

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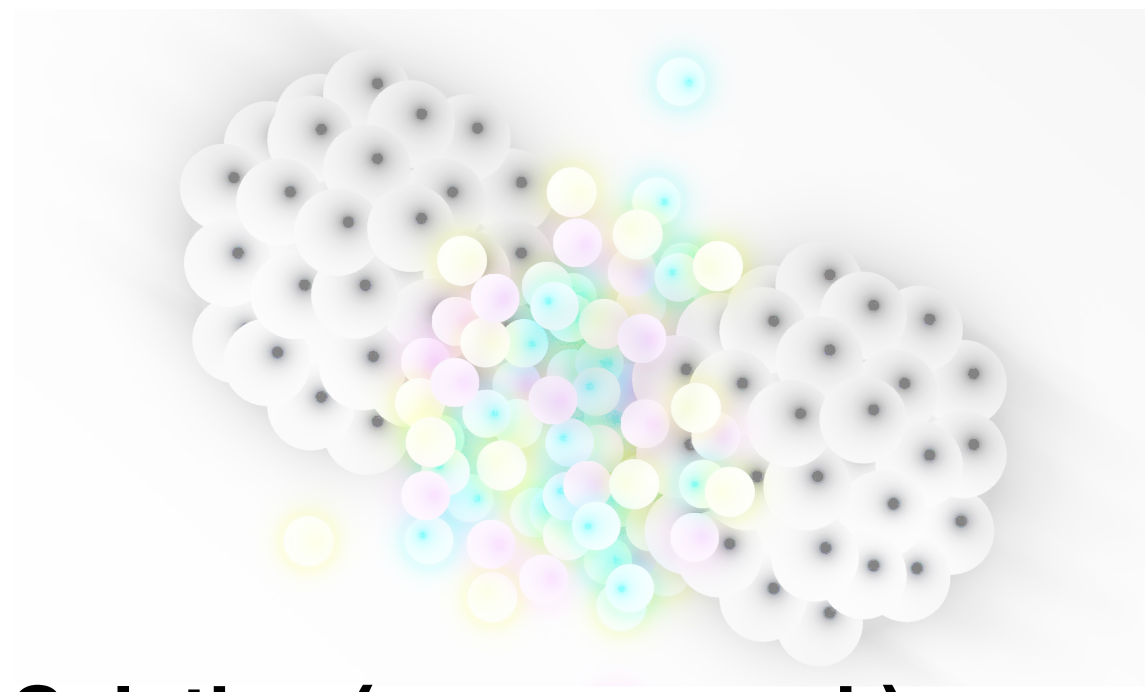

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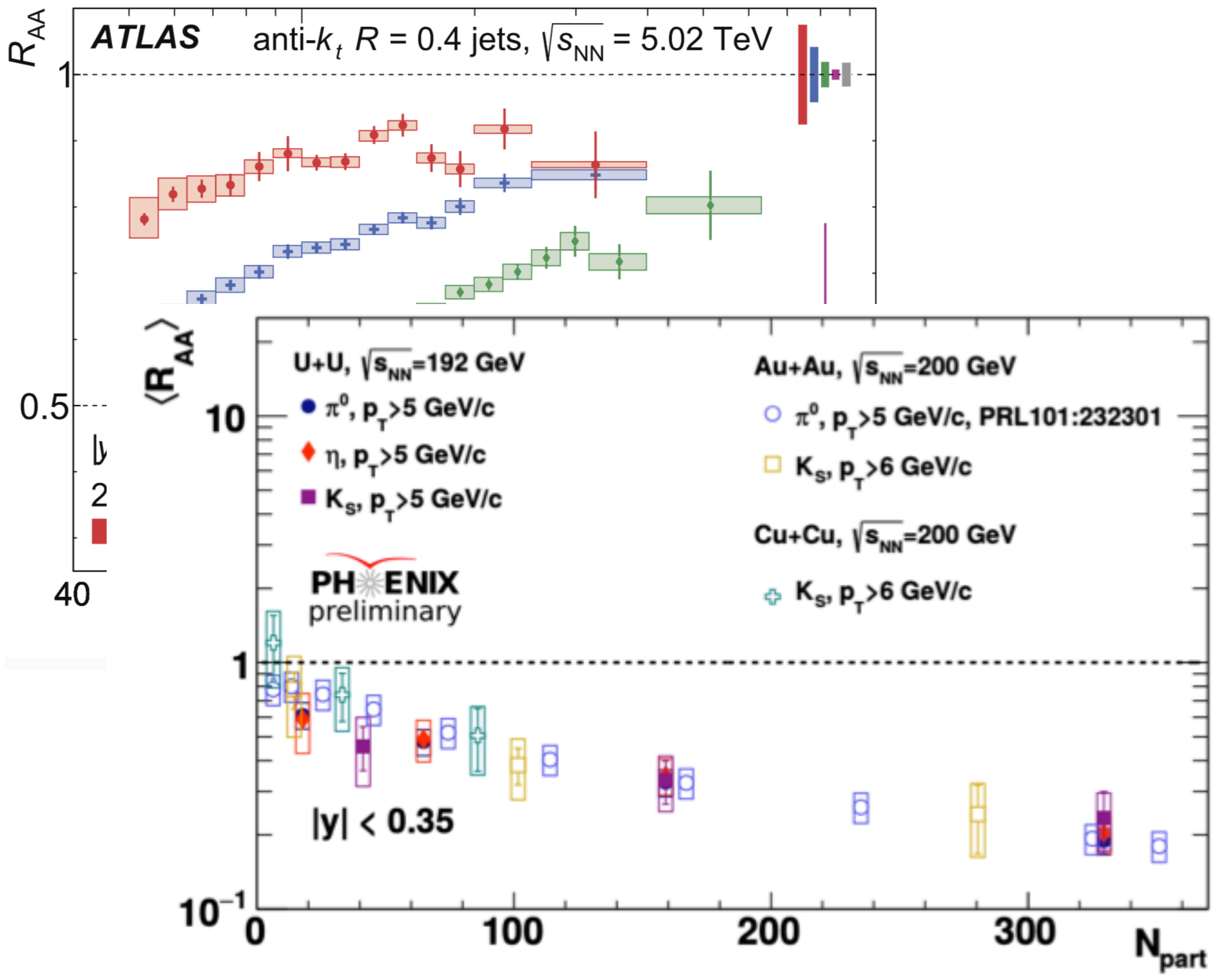

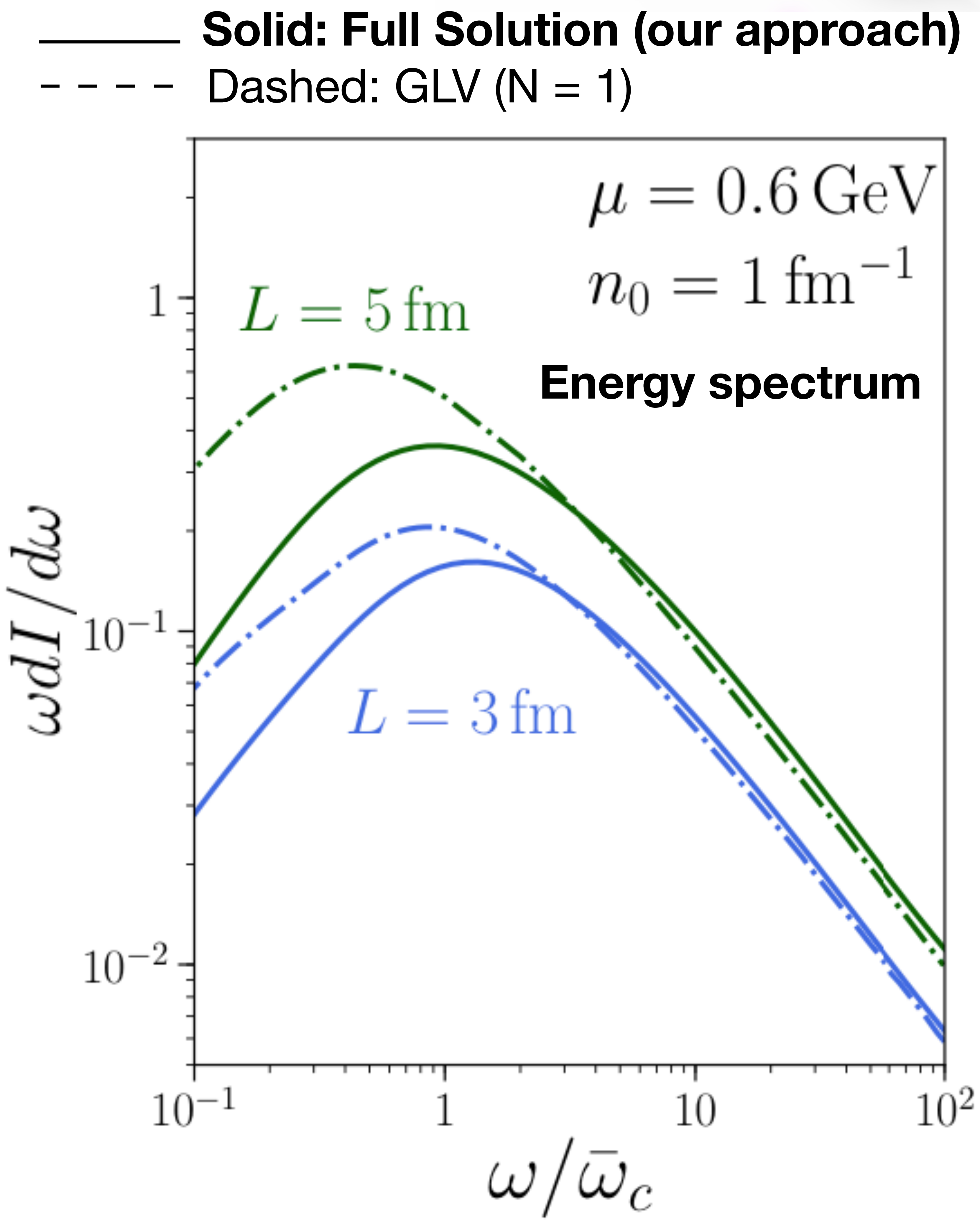

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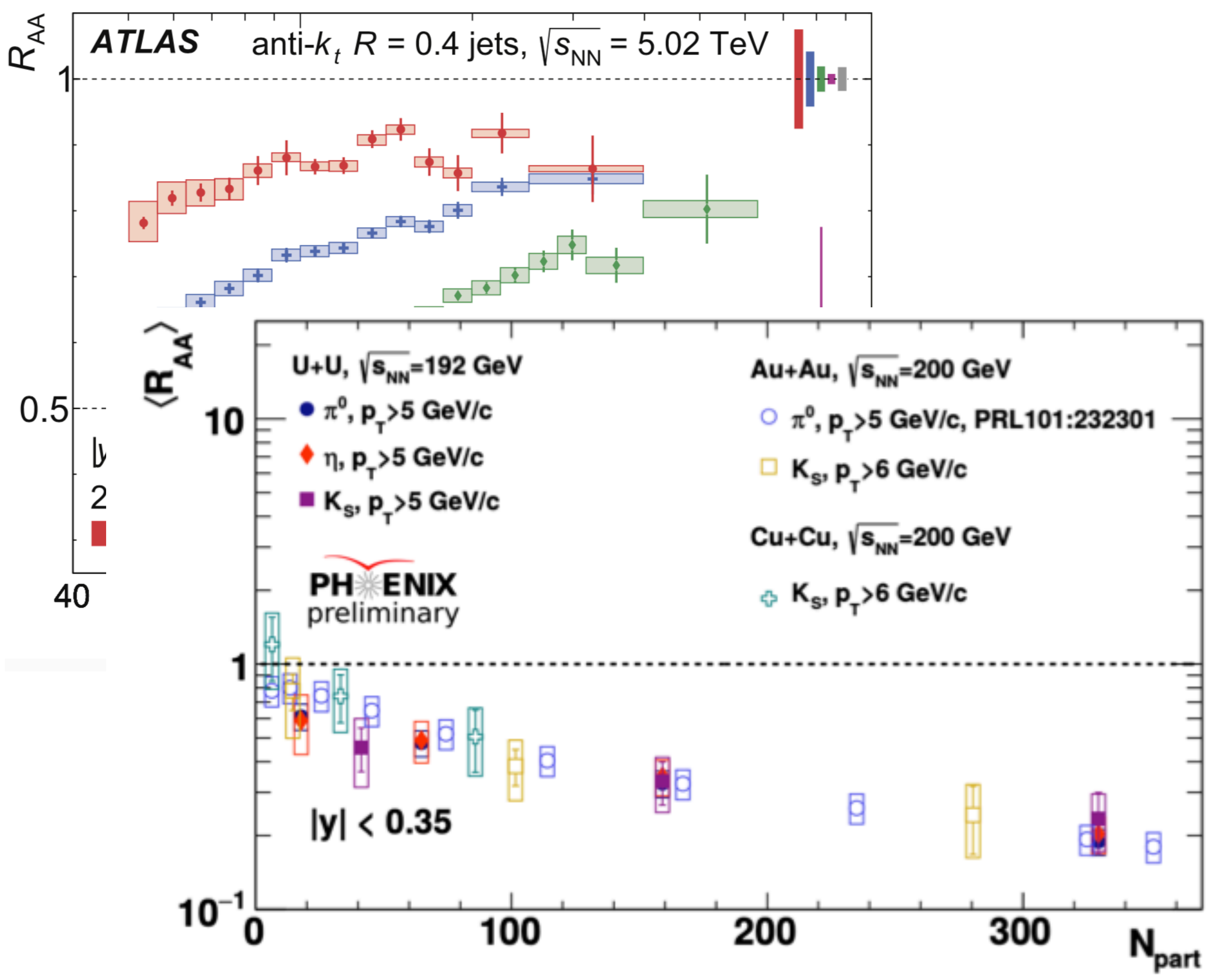
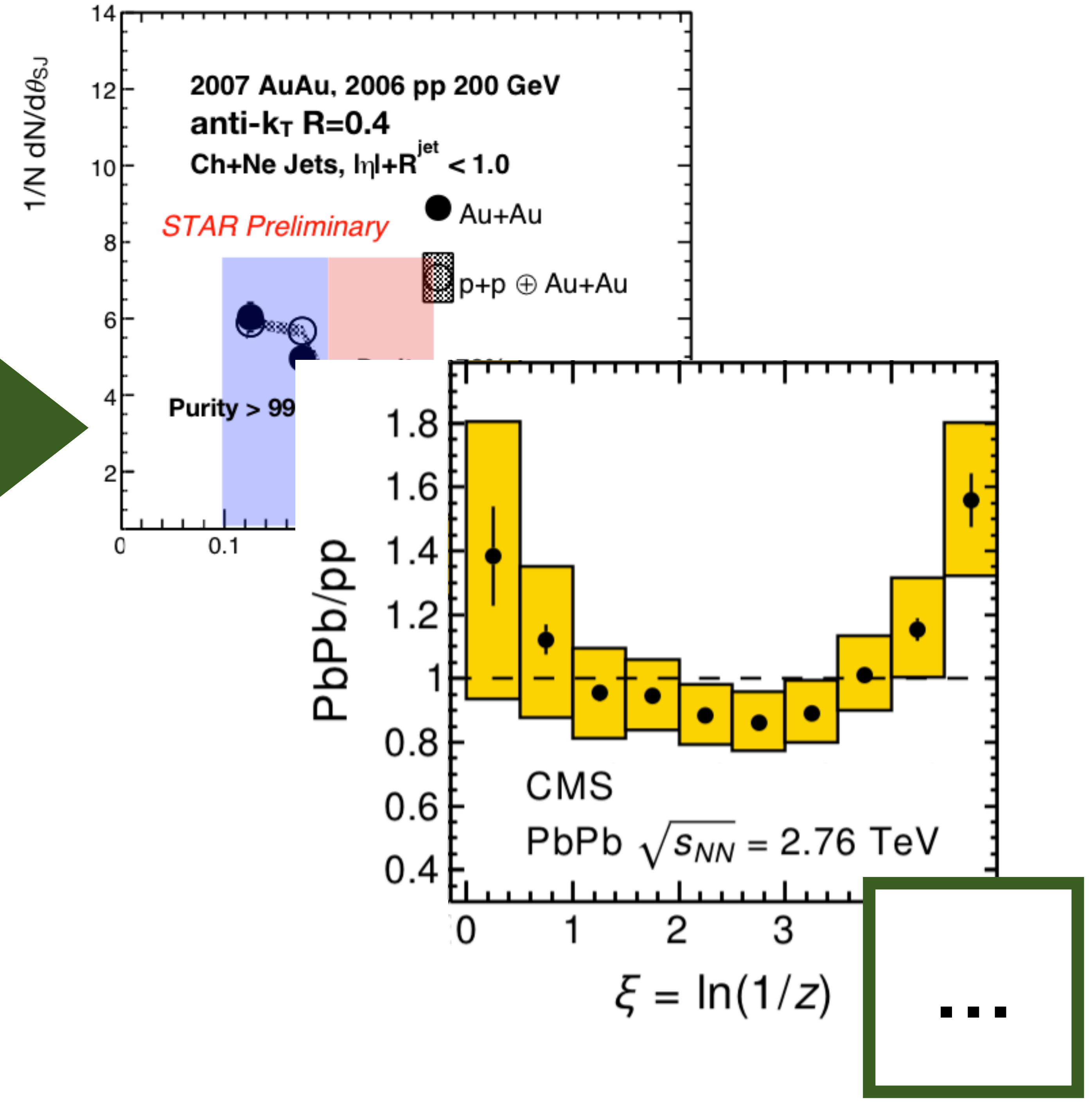
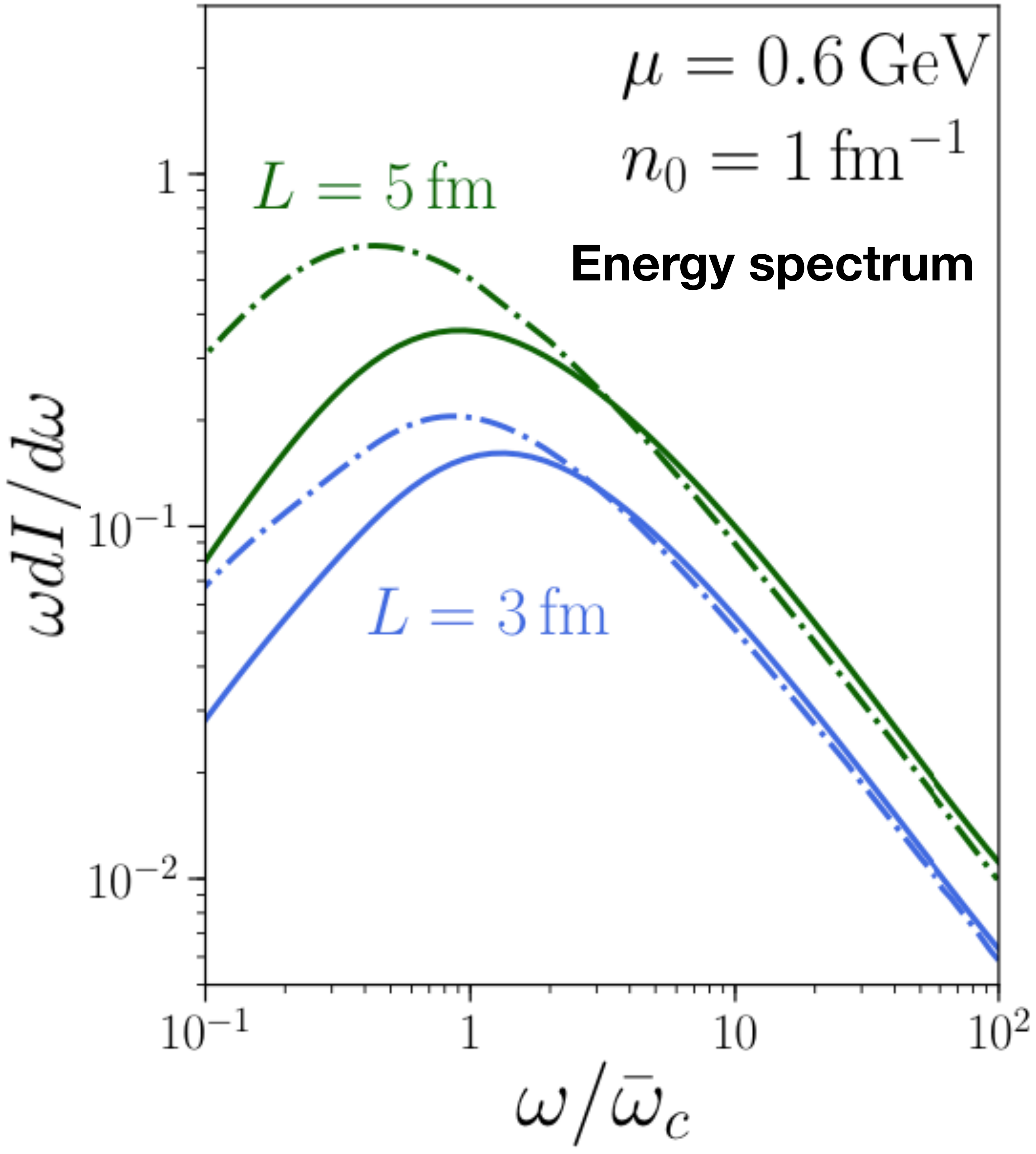
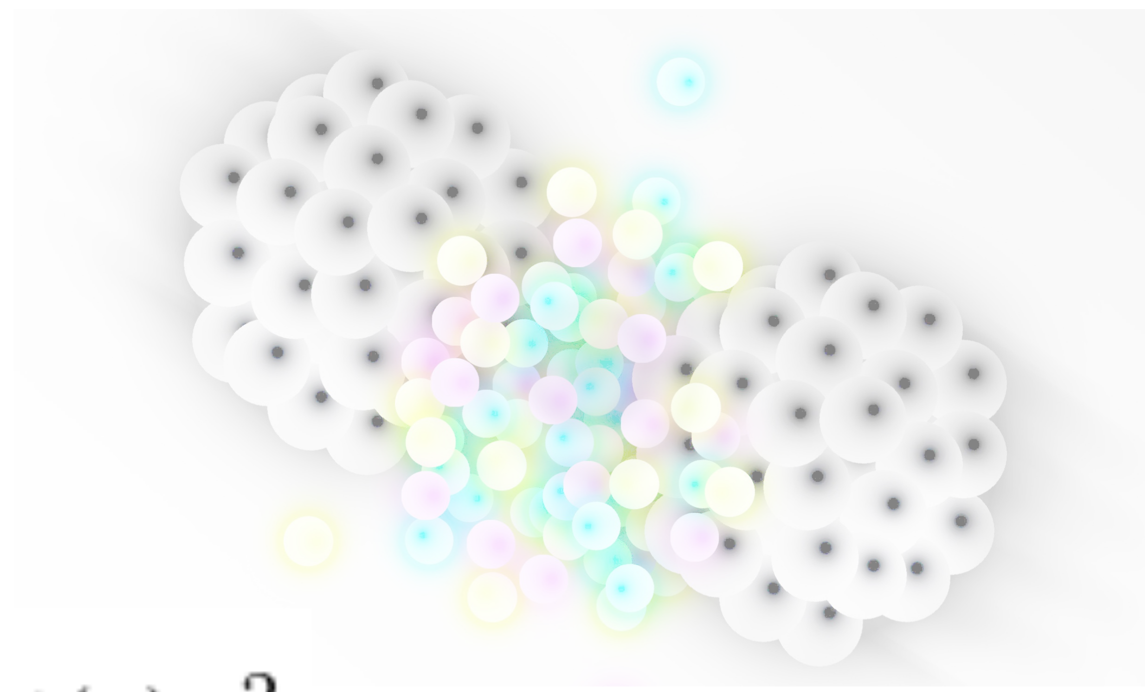




Solid: **Full Solution (our approach)**
Dashed: GLV (N = 1)



HO vs Full solution

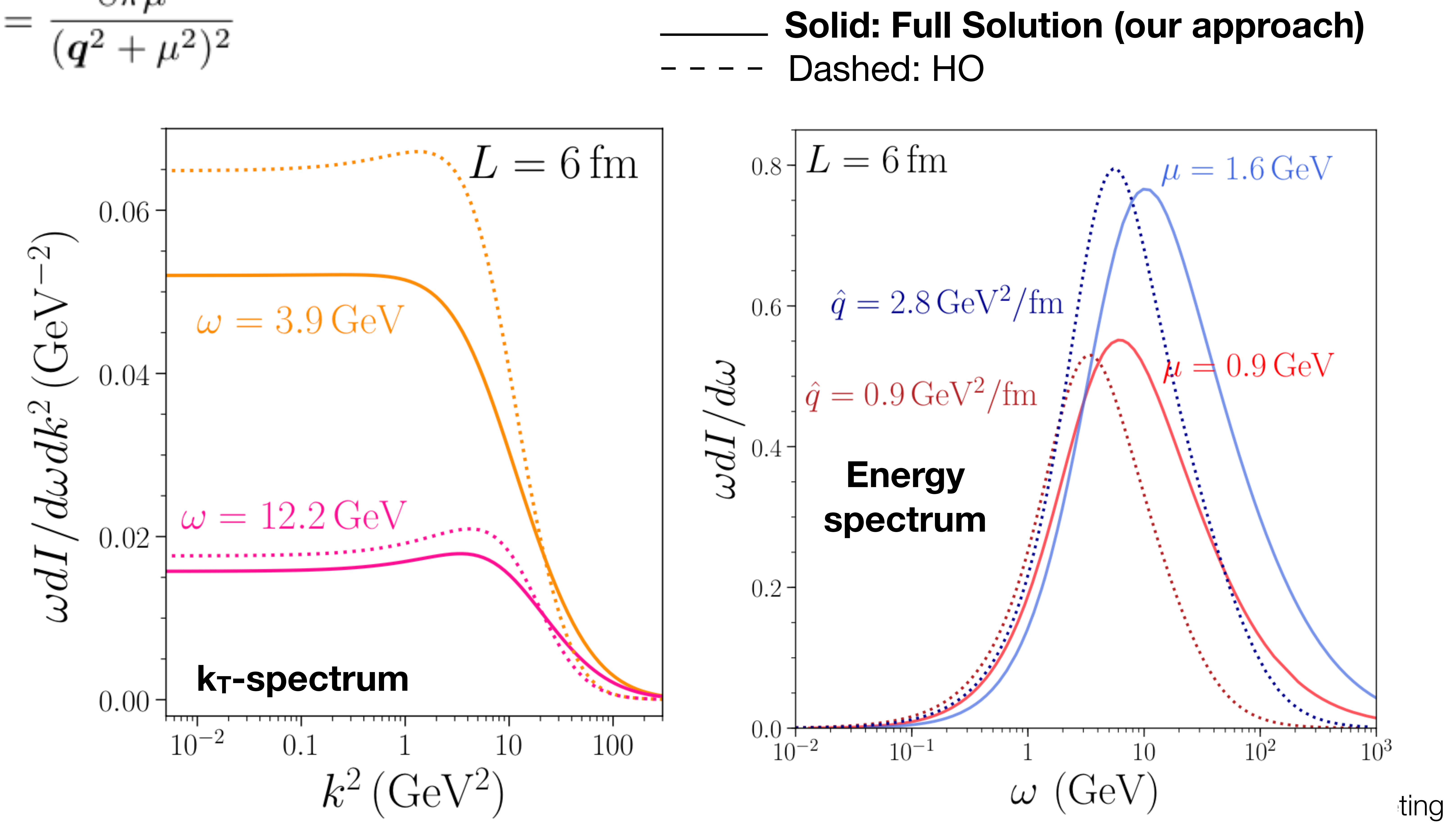


- Specifying the interaction potential: $\sigma(\boldsymbol{r}) = \int_{\boldsymbol{q}} V(\boldsymbol{q})\left(1 - e^{i\boldsymbol{q}\boldsymbol{r}}\right)$ $\qquad n(s)\sigma(\boldsymbol{r}) \approx \frac{1}{2}\hat{q}(s)\boldsymbol{r}^2$
  - Yukawa-type interaction: $V(\boldsymbol{q}) = \frac{8\pi\mu^2}{(\boldsymbol{q}^2+\mu^2)^2}$
  - Parameters (our): n_0, L, μ
  - Parameters (HO): $\hat{q}$, L

Only qualitative comparison:

$$\hat{q}L \sim (n_0 L)\mu^2 \ln\sqrt{\frac{q_{max}}{\mu}} \rightarrow 1.3(n_0 L)\mu^2$$

$$x^{-1} = \frac{\mu^2 L}{2\omega} \qquad \kappa^2 = \frac{k^2}{\mu^2}$$



Comparing QGP potential models

- Comparing two potentials:
    - Yukawa:

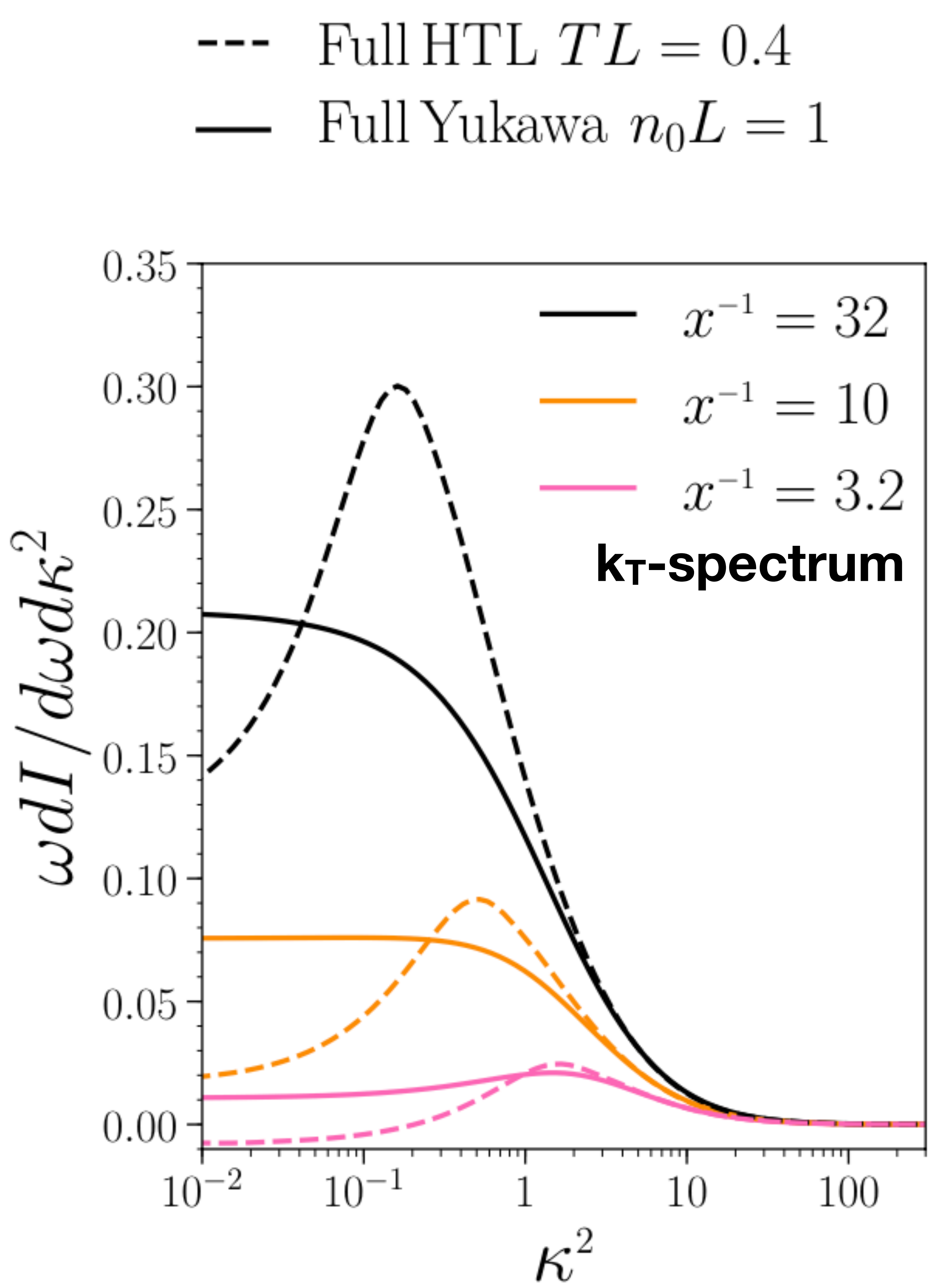
$$V(\boldsymbol{q}) = \frac{8\pi\mu^2}{(\boldsymbol{q}^2+\mu^2)^2}$$

    - Hard Thermal Loop (HTL):

$$\frac{1}{2} n\, V(\boldsymbol{q}) = \frac{g_s^2 N_c m_D^2 T}{\boldsymbol{q}^2(\boldsymbol{q}^2+m_D^2)}$$

Matching small distance behaviour:

$$n_0\mu^2 = \alpha_s N_c T m_D^2. \qquad m_D^2 = e\,\mu^2$$



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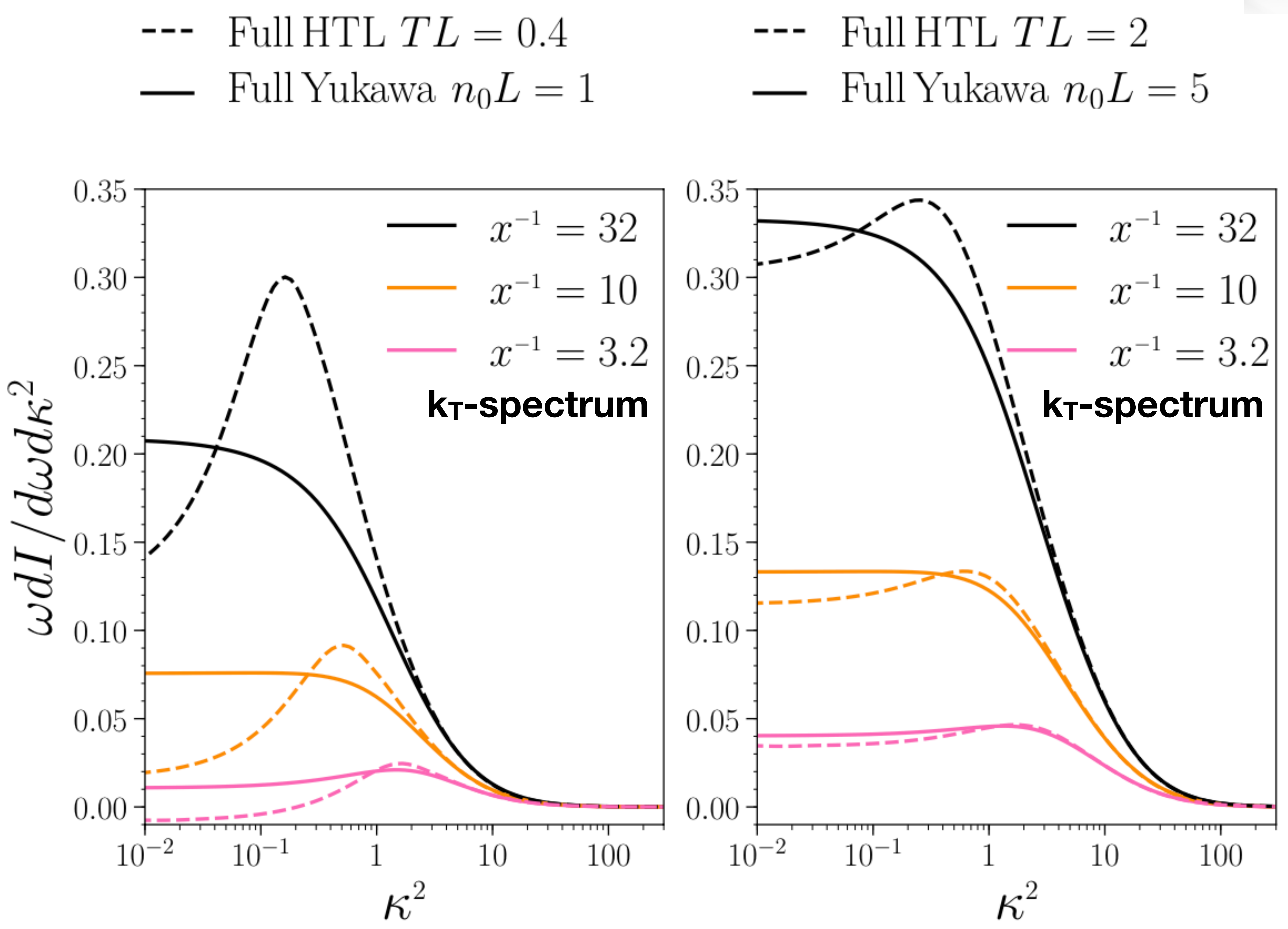

[Barata et al (20)]

Comparing QGP potential models

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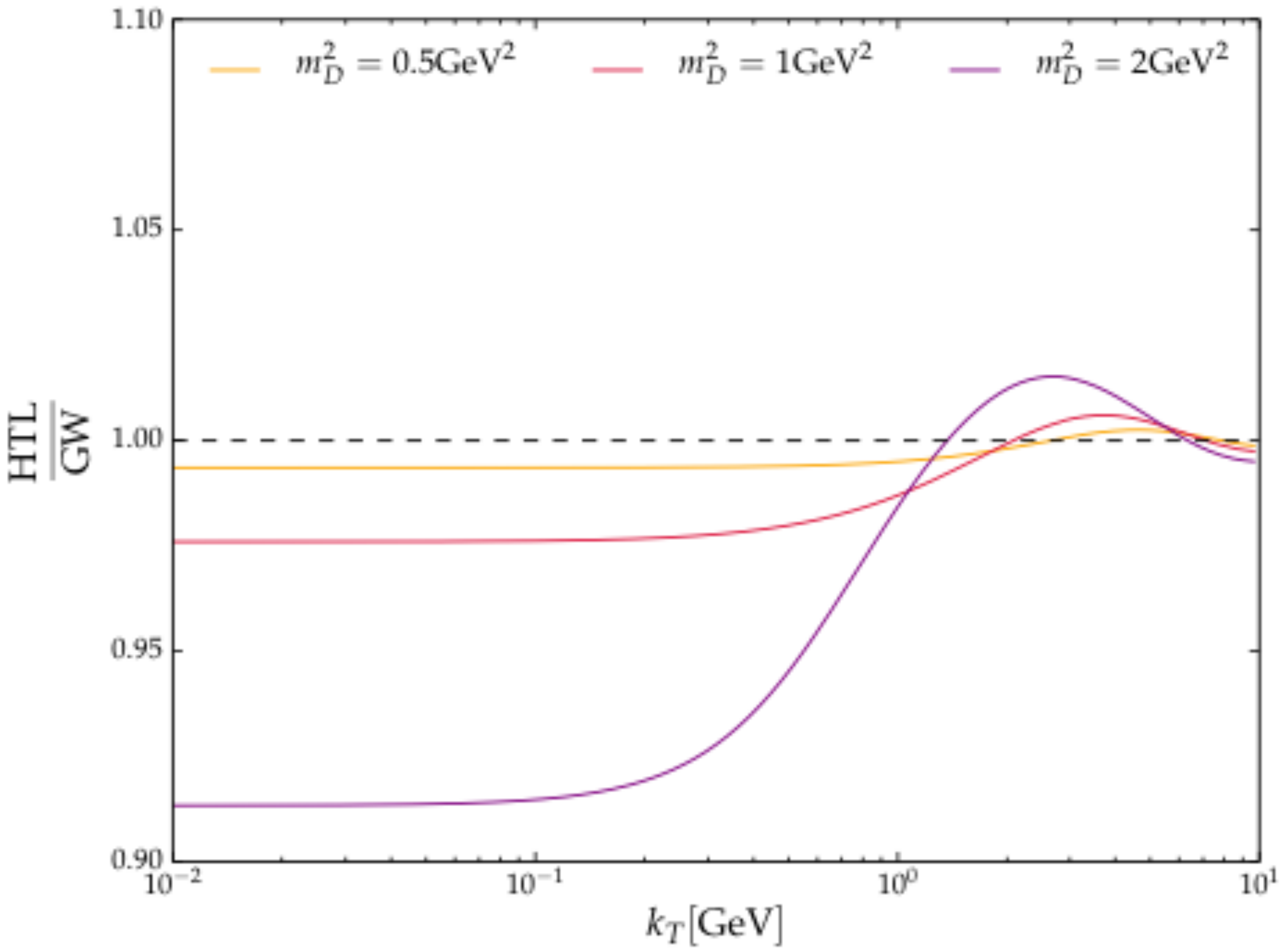
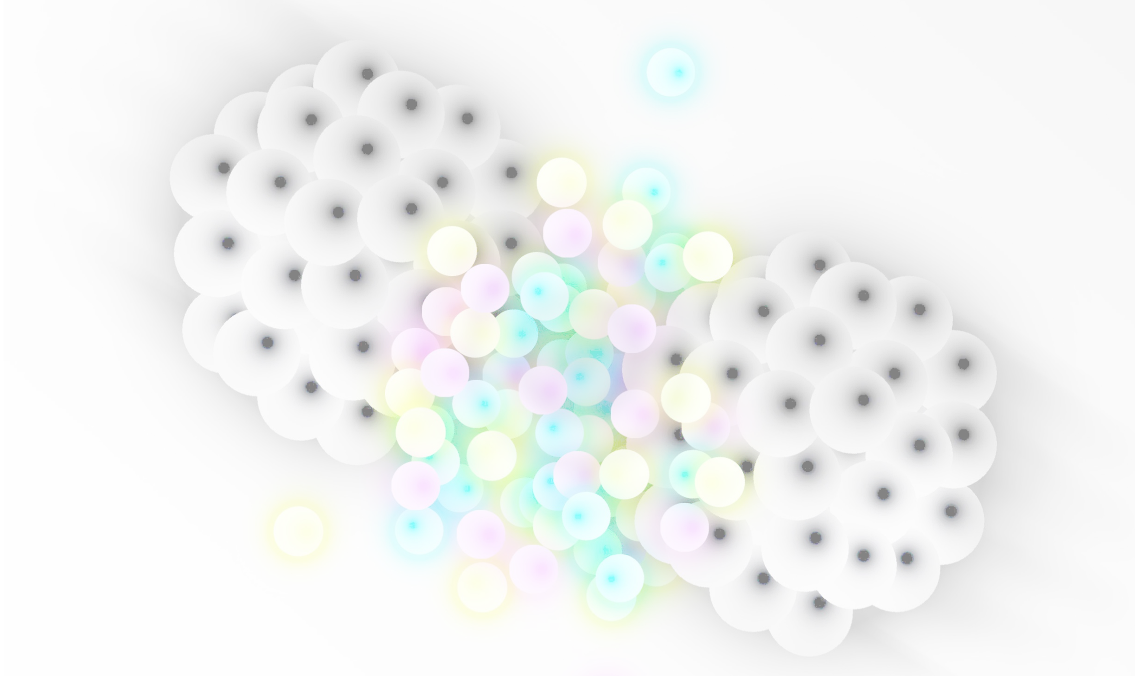
Non-universal, model dependent, contributions seem to be negligible



Summary



- Novel analytical approach: resummation of all multiple scatterings
  - Comparison with GLV limit and HO approximation:
    - GLV valid for single hard scattering; overestimate true contribution from soft and low momentum gluons
    - HO more suitable than GLV to describe low energy gluons; underestimate true contribution from hard gluons (single soft scattering)

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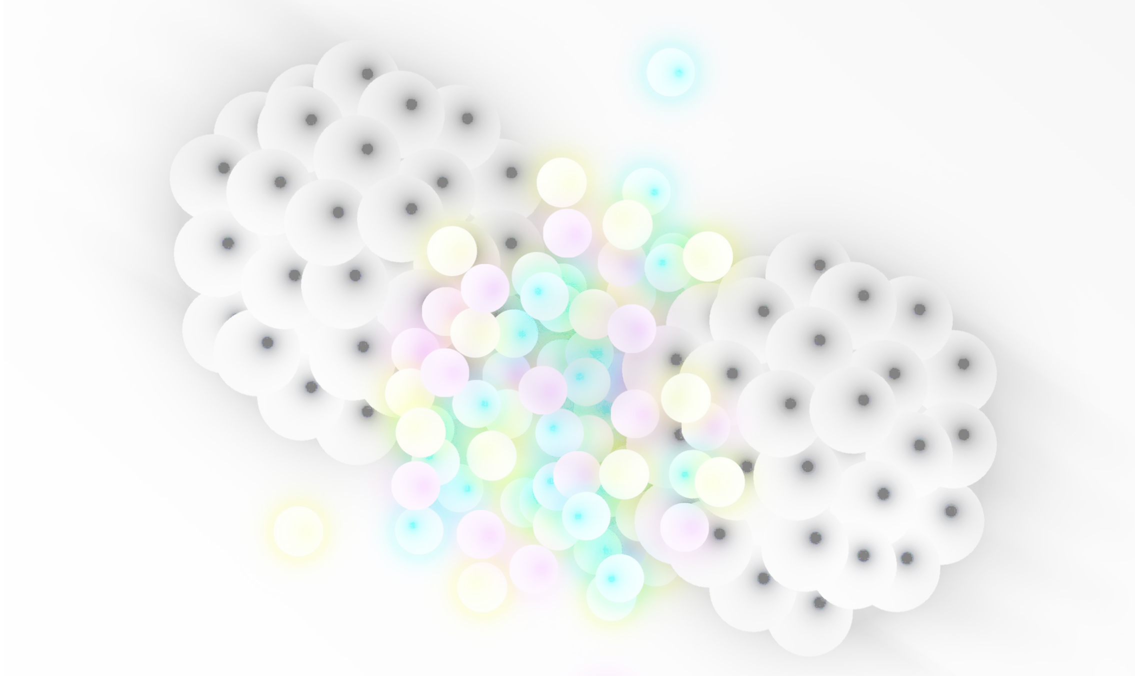

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Improves accuracy of QGP-related characteristics

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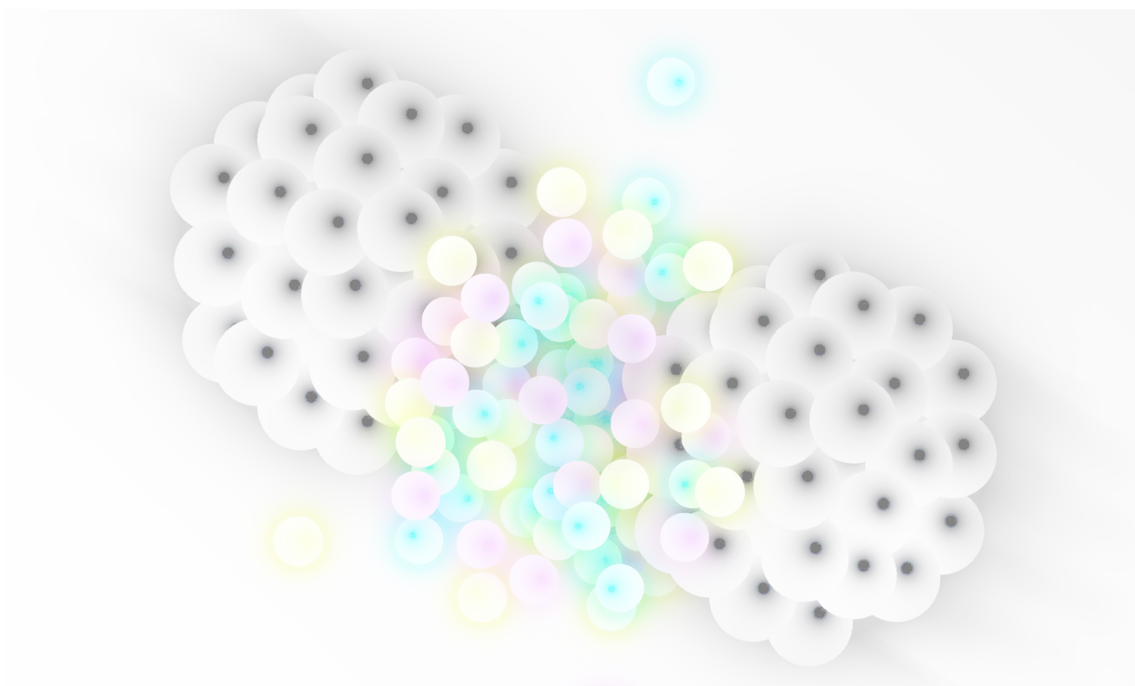

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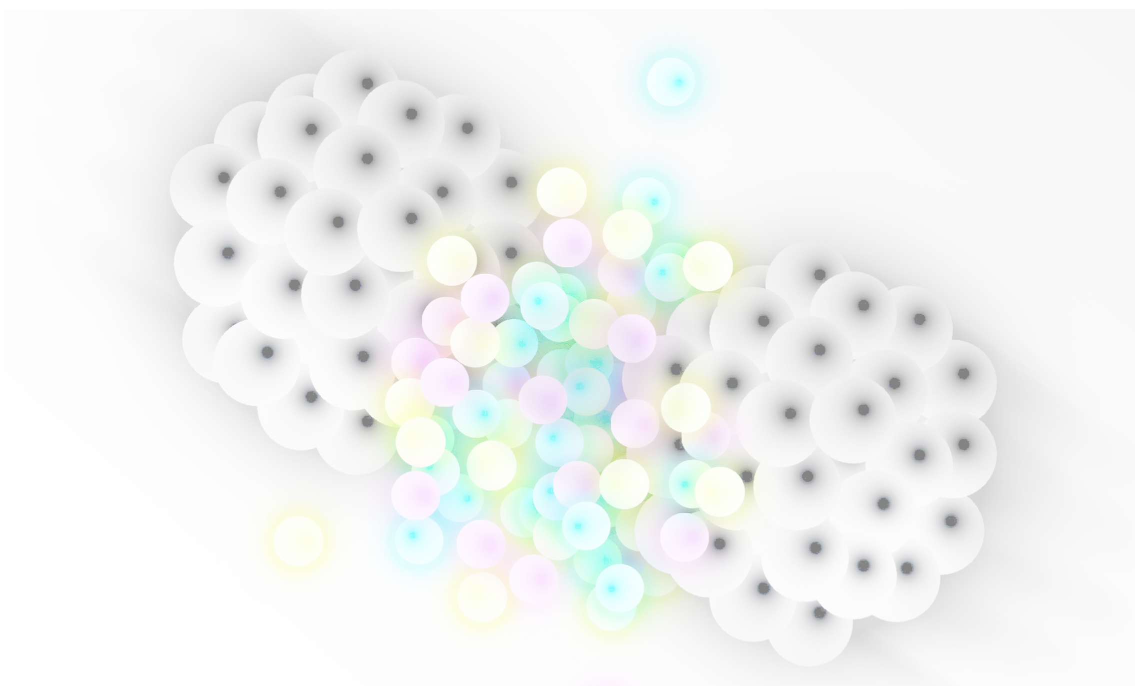

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Phase space to pin down QGP main characteristics

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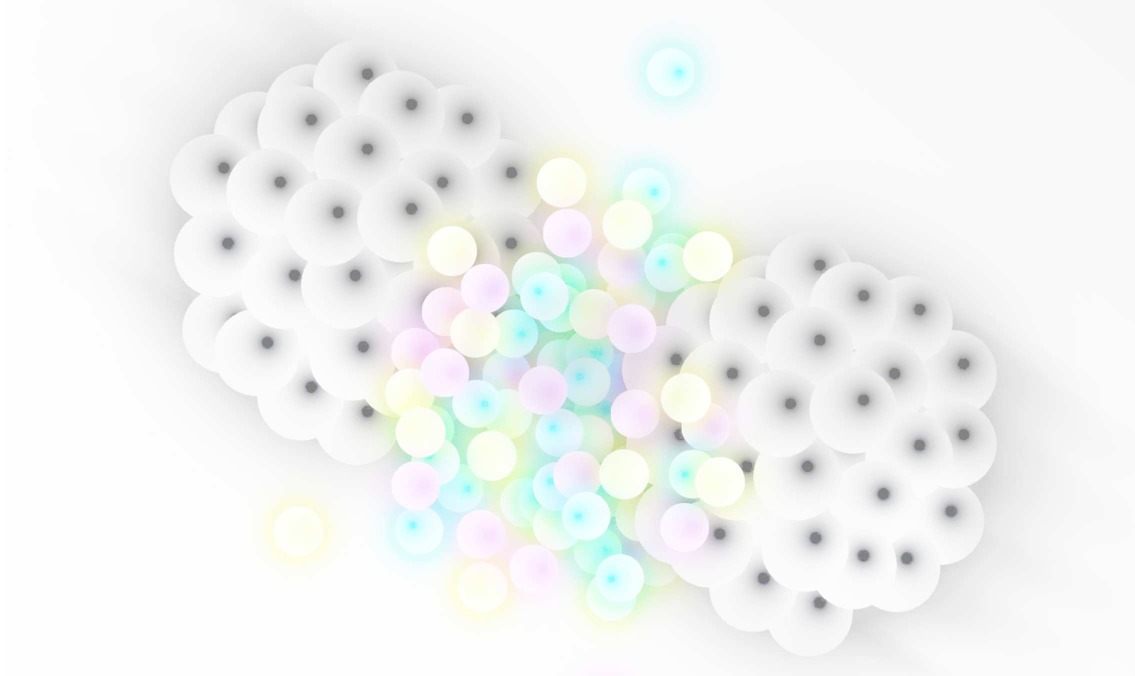

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Thank you!