Deciphering the role of multiple scatterings and time delays in the in-medium emission process

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Carlota Andres, Fabio Dominguez, MGM: JHEP 03 (2021) 102
Carlota Andres, Liliana Apolinário, Fabio Dominguez, MGM, Carlos A. Salgado: work in progress

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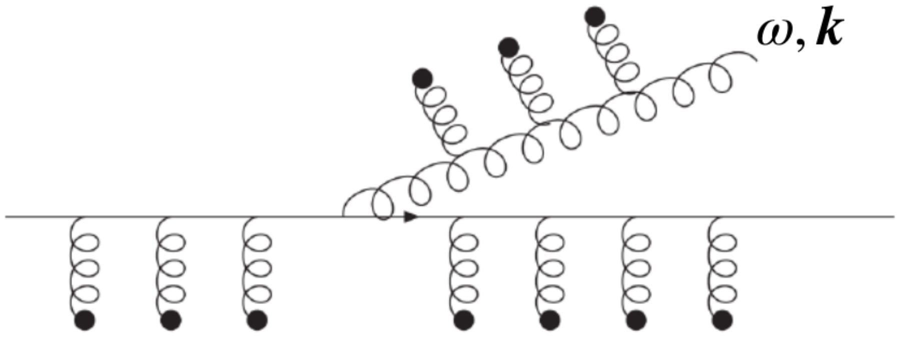
Energy loss

- Jet quenching: partons interact with QGP and lose energy



- Two available analytical approximations
  - Harmonic oscillator: multiple soft scatterings
  - First opacity or GLV approximation: one single hard scattering

Medium-induced gluon spectrum

- Emission spectrum off a parton with energy E of a soft gluon (BDMPS-Z):

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

- Recently, new method with no approximations. Full solution obtained numerically by solving two differential equations

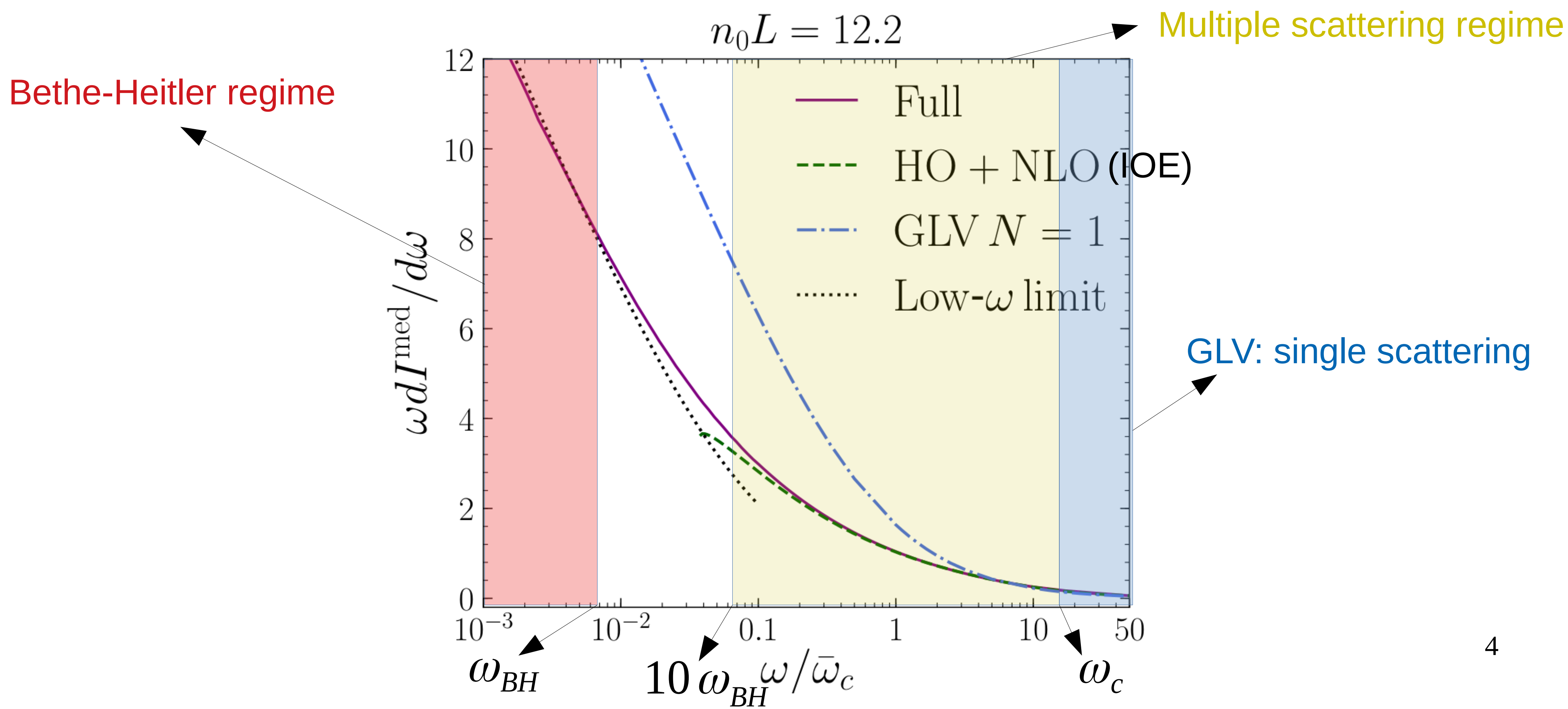
$$\partial_\tau \mathcal{P}(\tau,\boldsymbol{k};s,\boldsymbol{l}) = -\frac{1}{2}n(\tau)\int_{\boldsymbol{k}'} \sigma(\boldsymbol{k}-\boldsymbol{k}')\mathcal{P}(\tau,\boldsymbol{k}';s,\boldsymbol{l})$$

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

Carlota Andres, Liliana Apolinario, Fabio Dominguez: JHEP 07 (2020) 114

Energy regimes

$$\bar{\omega}_c = \frac{1}{2}\mu^2 L$$



Improved Opacity Expansion

- HO approximation:

$$v(\boldsymbol{r}) \equiv \frac{n_0}{2}\int_{\boldsymbol{q}} e^{-i\boldsymbol{q}\boldsymbol{r}}\,\sigma(\boldsymbol{q}) \approx \frac{1}{2}\hat{q}\,\boldsymbol{r}^2$$

- We can make the decomposition (IOE)

$$v(\boldsymbol{r}) = \frac{\hat{q}_0}{4}\boldsymbol{r}^2\left(\ln\left(\frac{Q^2}{\mu^{\star 2}}\right) - \ln(\boldsymbol{r}^2 Q^2)\right) = \underbrace{v_{HO}(\boldsymbol{r})}_{\text{LO}} + \underbrace{v_{pert}(\boldsymbol{r})}_{\text{NLO}}$$

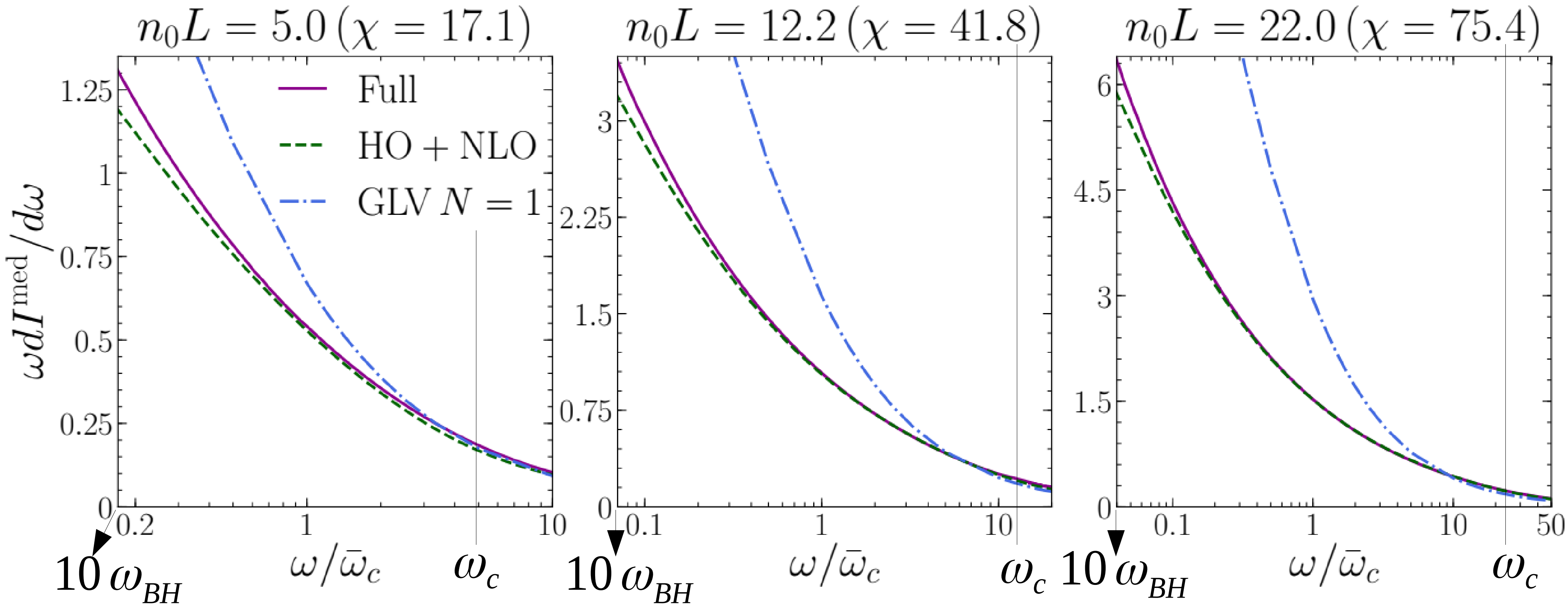
with $Q^2 = aQ_c^2$, a of order 1

Yacine Mehtar-Tani, JHEP 07 (2019) 057

Joao Barata's talk Sunday for more details

$$Q_c^2 = \sqrt{2\omega\hat{q}_0 \ln\left(\frac{Q_c^2}{\mu^{\star 2}}\right)}$$

Multiple scattering regime



IOE works well in its range of applicability

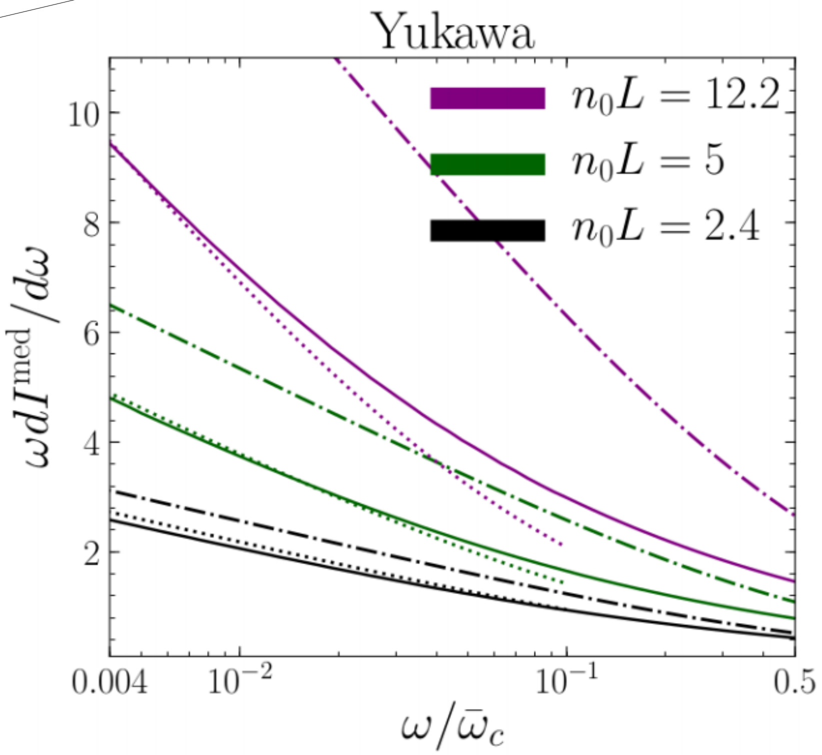
Coherence effects between multiple scatterings are essential in this region

Small energy limit (Bethe-Heitler)

$$\omega \frac{dI^{\text{med}}}{d\omega}\bigg|_{\omega\to 0} = \frac{2\alpha_s C_R}{\omega} \text{Re} \int_0^L ds\, n_0 \int_0^s dt \int_{\boldsymbol{pq}} i\, \frac{\boldsymbol{p}\cdot\boldsymbol{q}}{\boldsymbol{q}^2} \sigma(\boldsymbol{q}-\boldsymbol{p}) e^{-\left(i\frac{p^2}{2\omega}+\frac{1}{2}n_0\Sigma(p^2)\right)(s-t)}$$

GLV, one hard scattering

Probability of not experiencing any further scatterings



Full

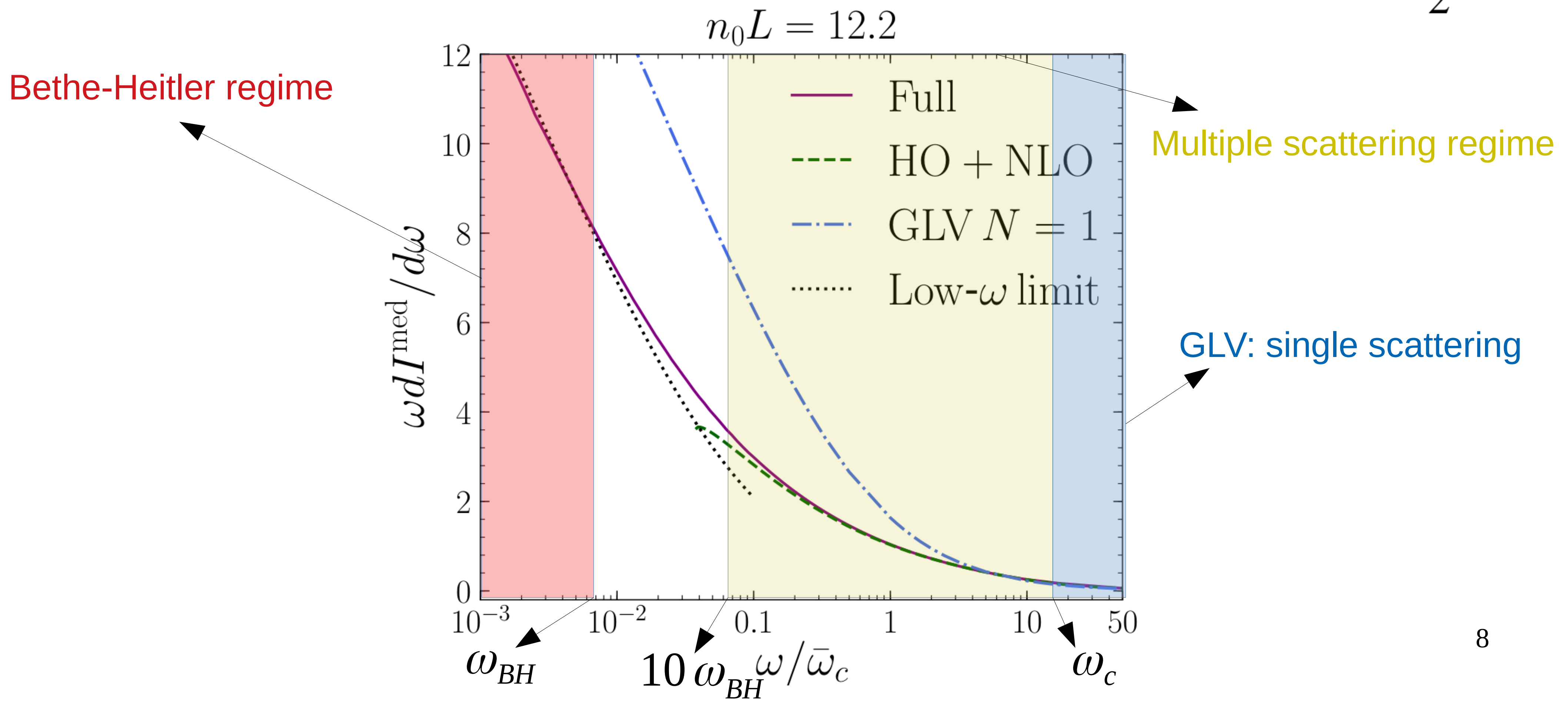
Low-ω formula

GLV N=1

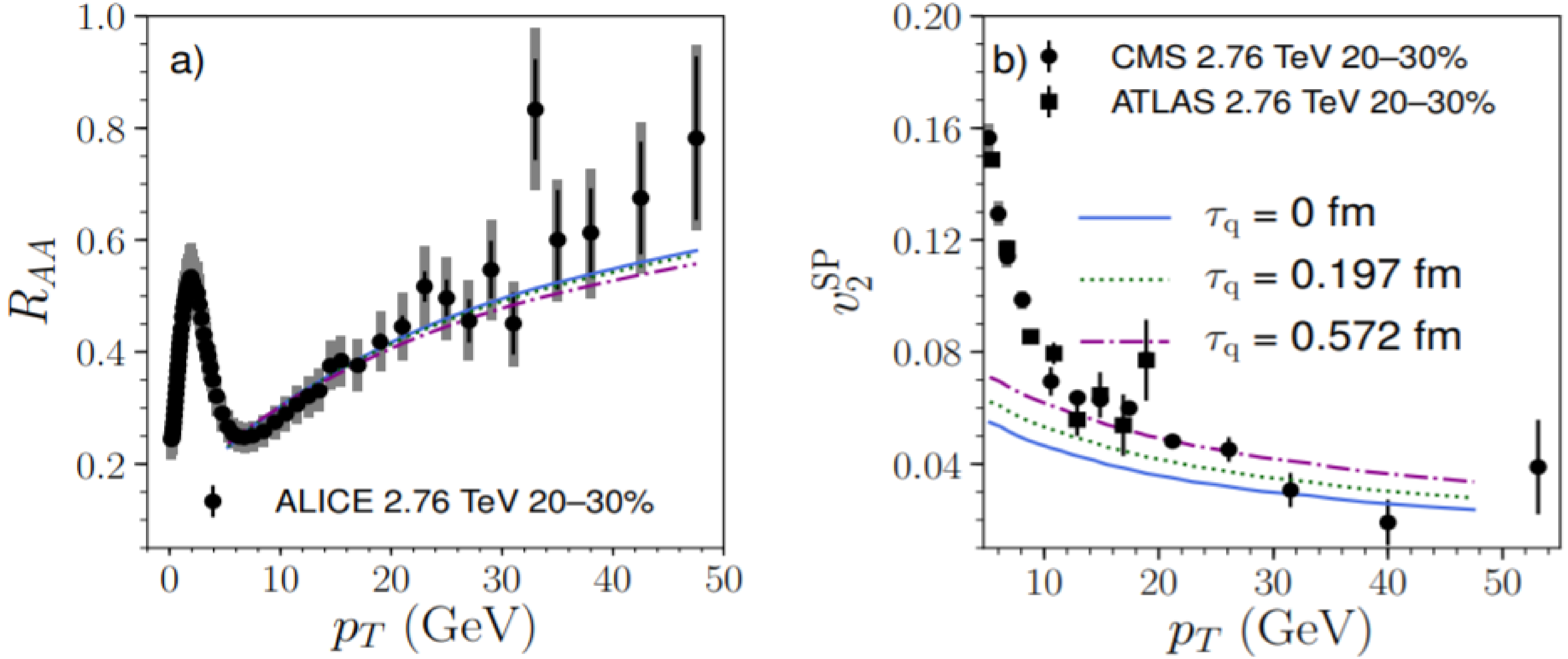
$$\bar{\omega}_c = \frac{1}{2}\mu^2 L$$

Energy regimes

$$\bar{\omega}_c = \frac{1}{2}\mu^2 L$$



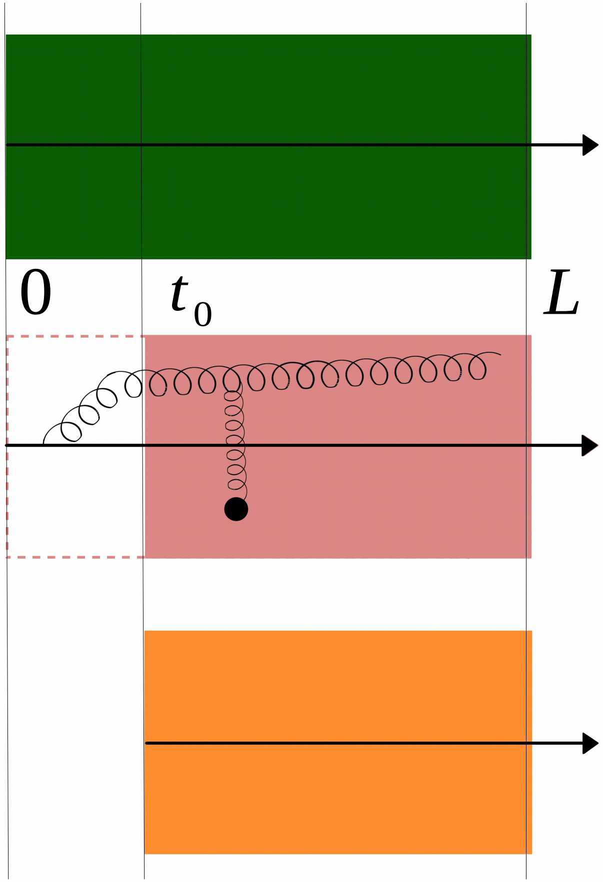
Why study initial stages?



v_2 in non central collisions: energy loss in early times modifies it a lot

Carlota Andres, Néstor Armesto, Harri Niemi, Risto Paatelainen, Carlos A. Salgado, PLB 2020 135318

Delay in medium production



No delay: medium of size L

Delay: vacuum until t_0 and medium from t_0 to L

No delay $L-t_0$: medium of size $L-t_0$
(employed in phenomenology)

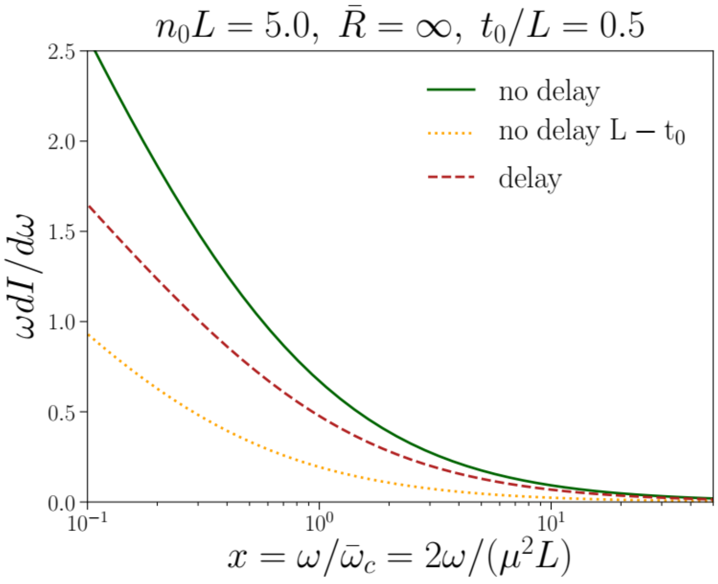
All the emissions are medium induced, pure vacuum already subtracted

The calculation

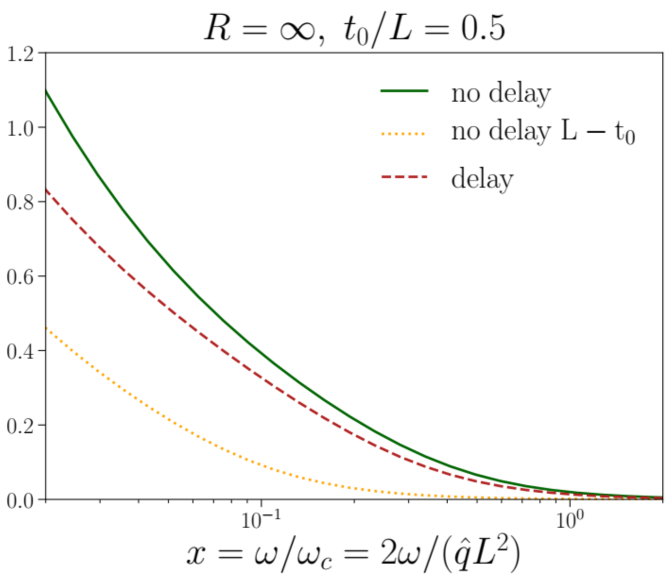
- We just need to do $\int_0^L dt = \int_0^{t_0} dt + \int_{t_0}^L dt$
- Full spectrum: easy to perform numerical evaluation
- Analytical approaches:
  - GLV: difference between no delay and delay is the spectrum of a medium of size t_0, non trivial result! New energy scale $\bar{\omega}_0 = \frac{1}{2}\mu^2 t_0 = \frac{t_0}{L}\bar{\omega}_c$
  - HO: smaller differences. New energy scale $\omega_0 = \frac{1}{2}\hat{q}\, t_0^2 = \frac{t_0^2}{L^2}\omega_c$
- Delay effects specially relevant for small energies, that is, for small gluon formation times. For big formation times initial stages are not relevant

$$\omega\frac{dI}{d\omega} = \int_0^{\infty} \omega\frac{dI}{d\omega d^2k}$$

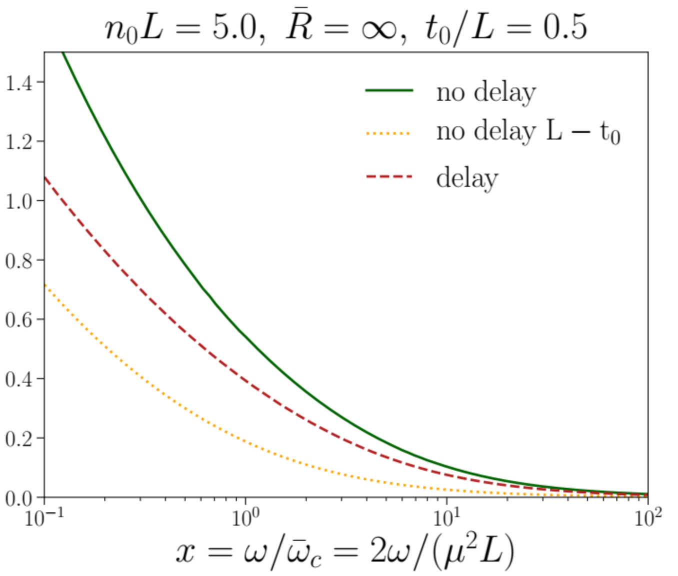
Results 1



GLV



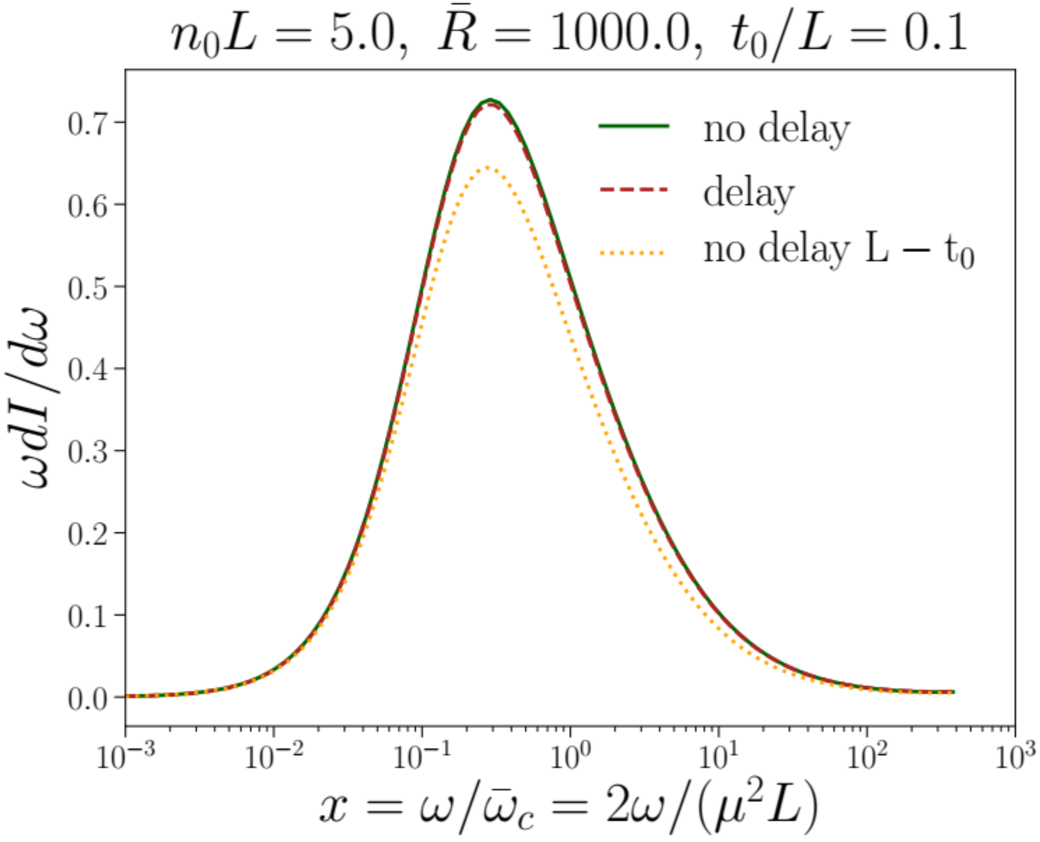
HO

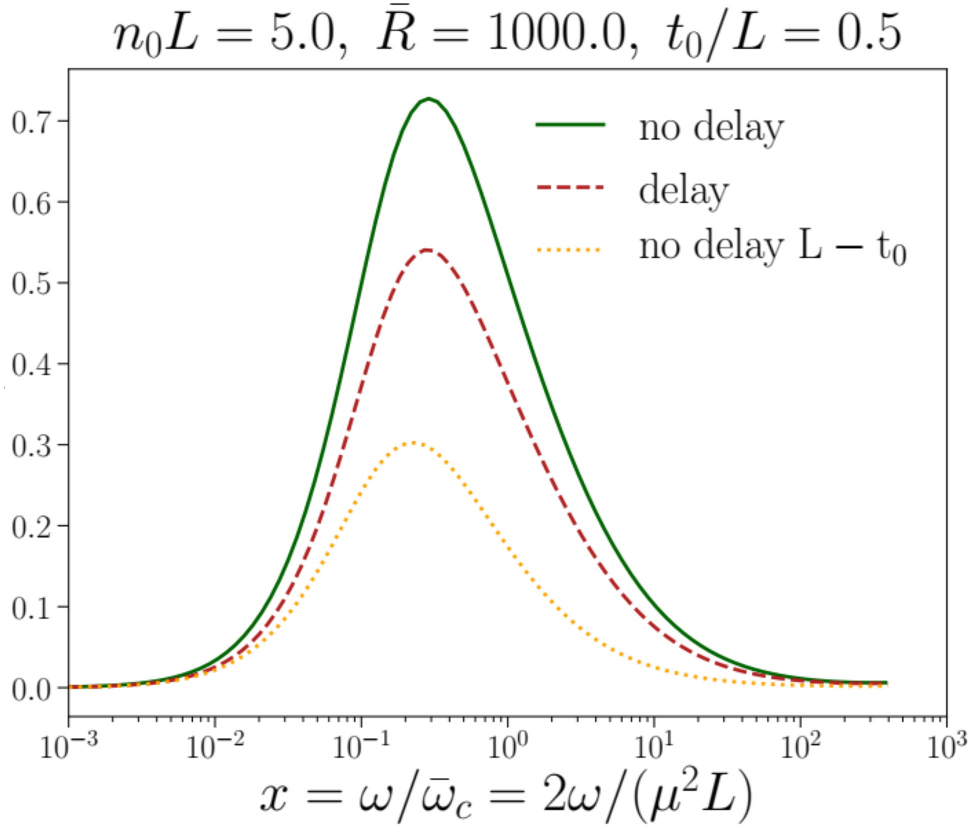


Full

$$\omega \frac{dI}{d\omega} = \int_0^{\omega} \omega \frac{dI}{d\omega d^2 k}$$

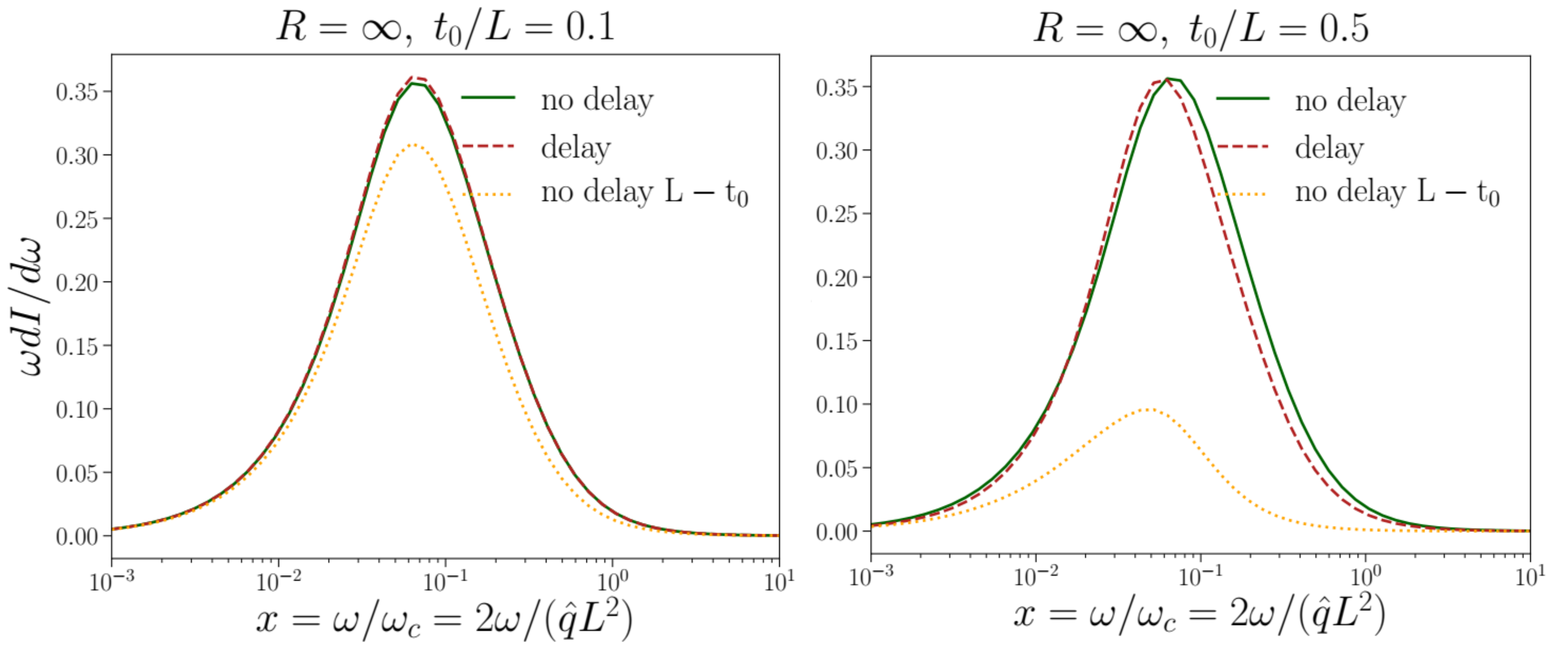
Results 2: full spectrum





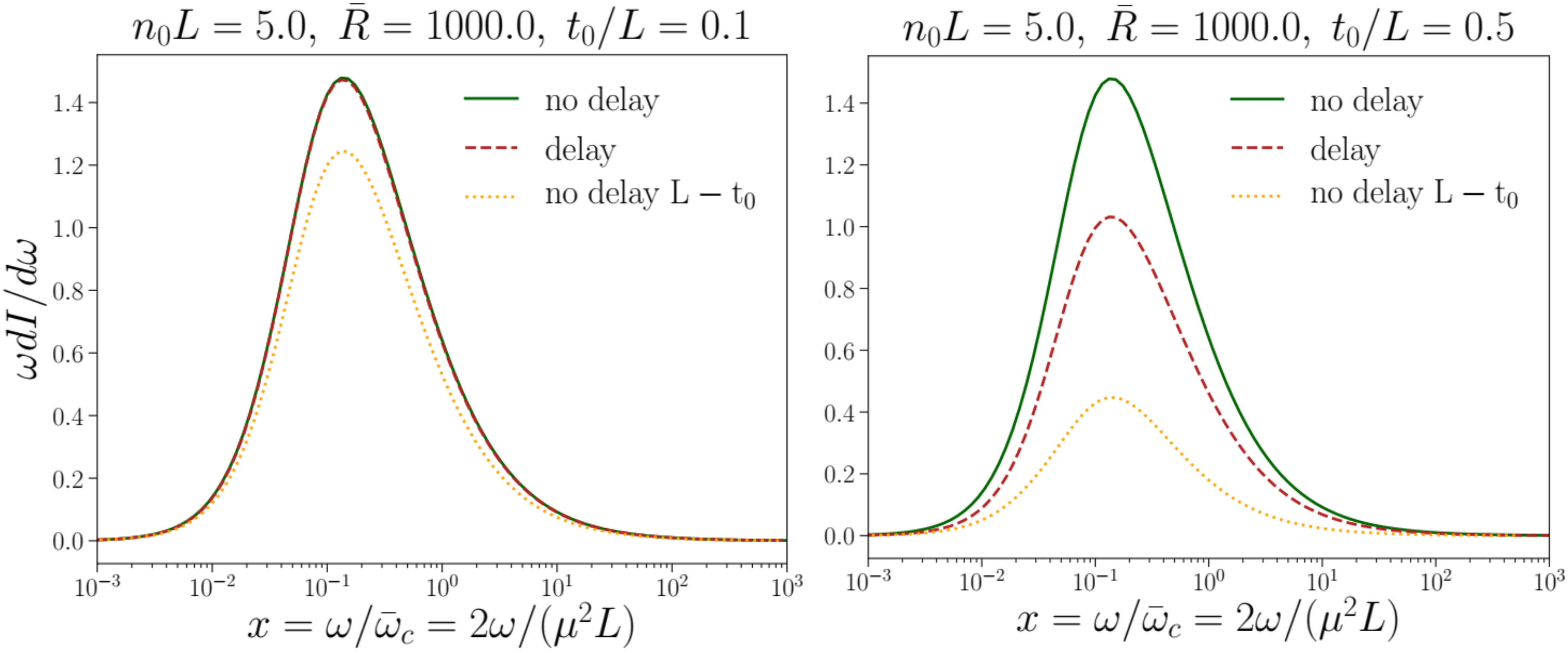
$$\omega \frac{dI}{d\omega} = \int_0^{\omega} \omega \frac{dI}{d\omega d^2 k}$$

Results 2: HO



$$\omega\frac{dI}{d\omega}=\int_0^{\omega}\omega\frac{dI}{d\omega d^2k}$$

Results 2: GLV



Summary

- We evaluated for the first time the effects of delay in medium production
- Specially relevant to understand initial stages of propagation
- Small delays: (almost) no difference between delay and medium of size L
- Large differences for big delays
- This could be important when we study propagation in very asymmetric mediums (v_2 studies for example)
- We need to perform more studies to see to what extend this is actually relevant or not in phenomenology

Thanks!