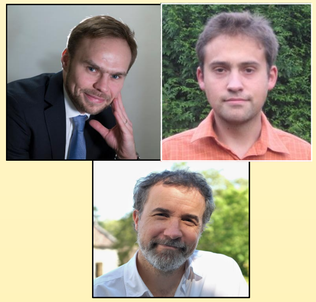

# Jet quenching and scaling properties of medium-evolved gluon cascade in expanding media

Souvik Priyam Adhya

in collaboration with

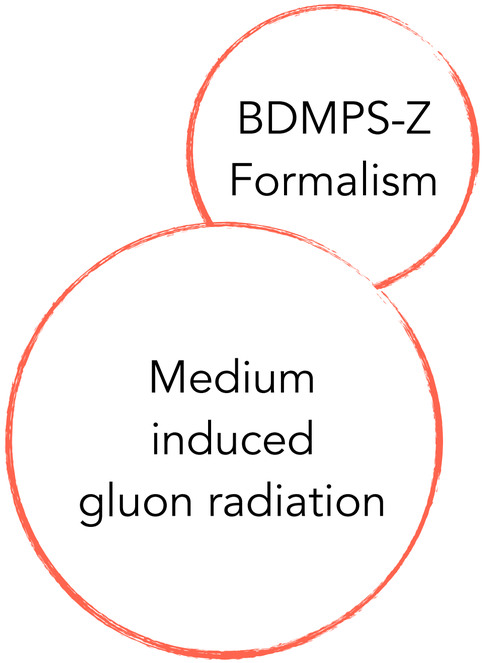
Carlos Salgado , Martin Spousta & Konrad Tywoniuk



10th International Conference on
Hard and Electromagnetic Probes of
High Energy Nuclear Collisions, 2020

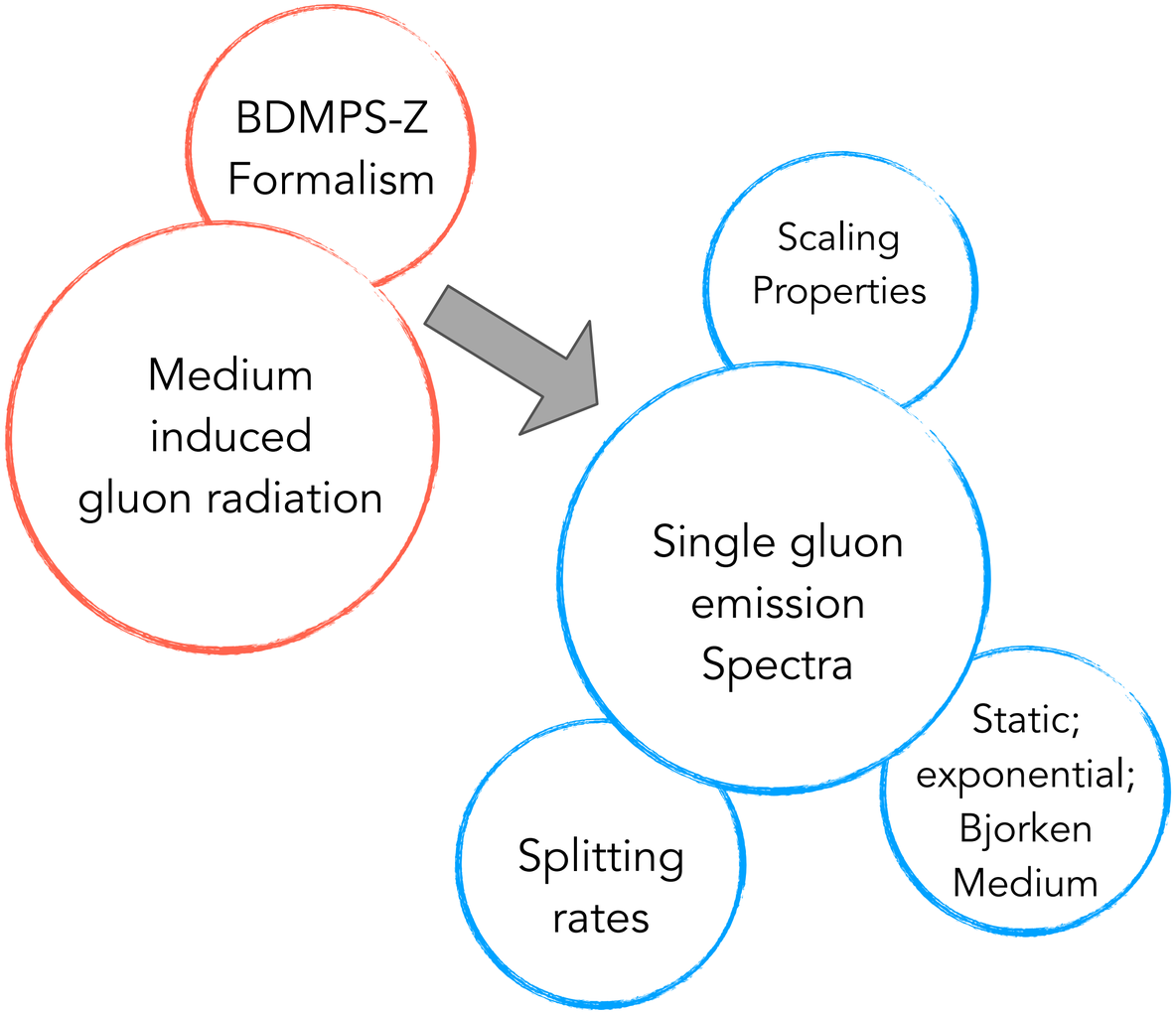
1st June, 2020

# Outline of the talk



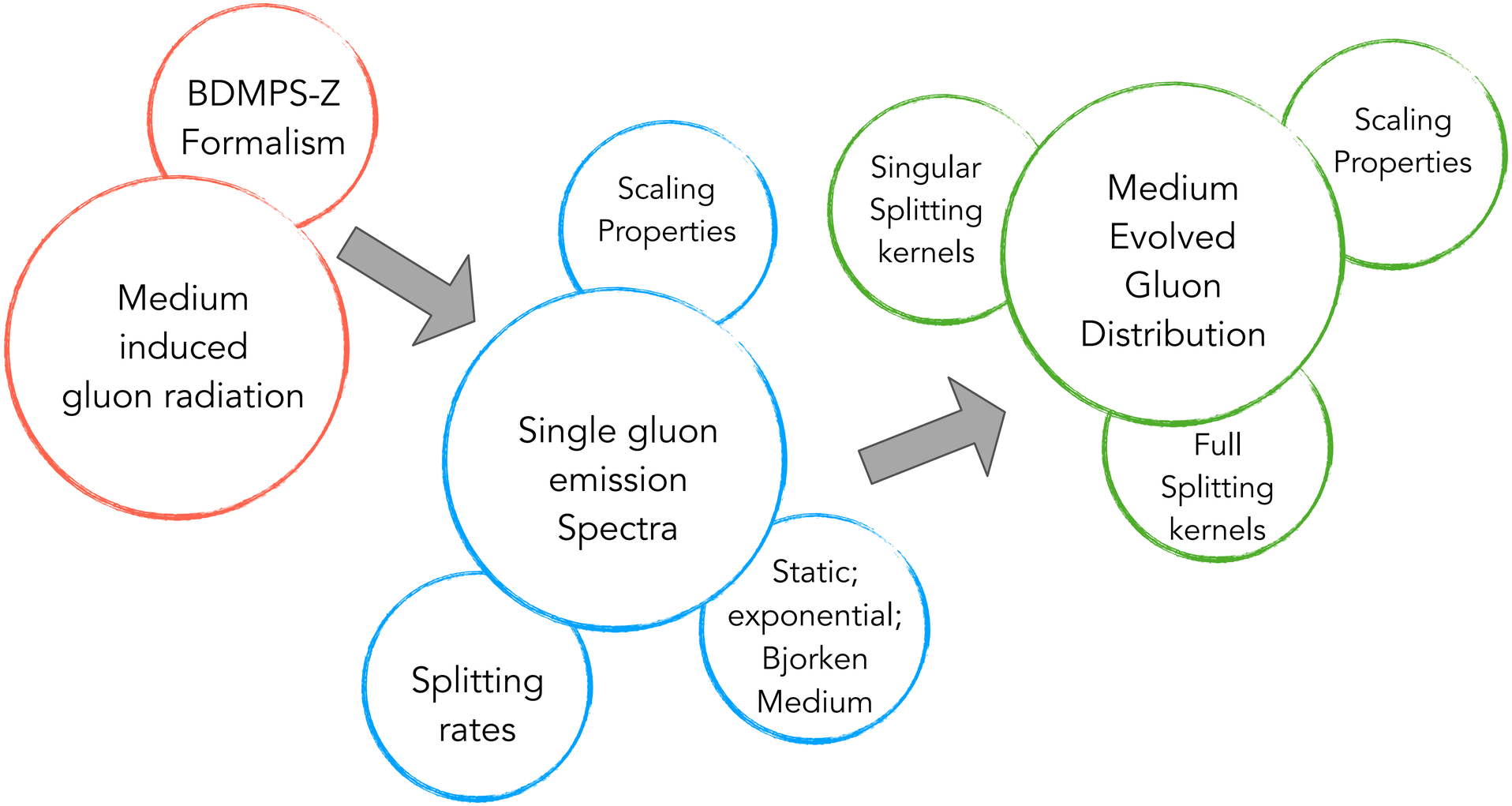

Based on the recent work : *Medium-induced cascade in expanding media;* **S. P. Adhya**, C. A. Salgado, M. Spousta, K. Tywoniuk; arXiv: 1911.12193.

# Outline of the talk



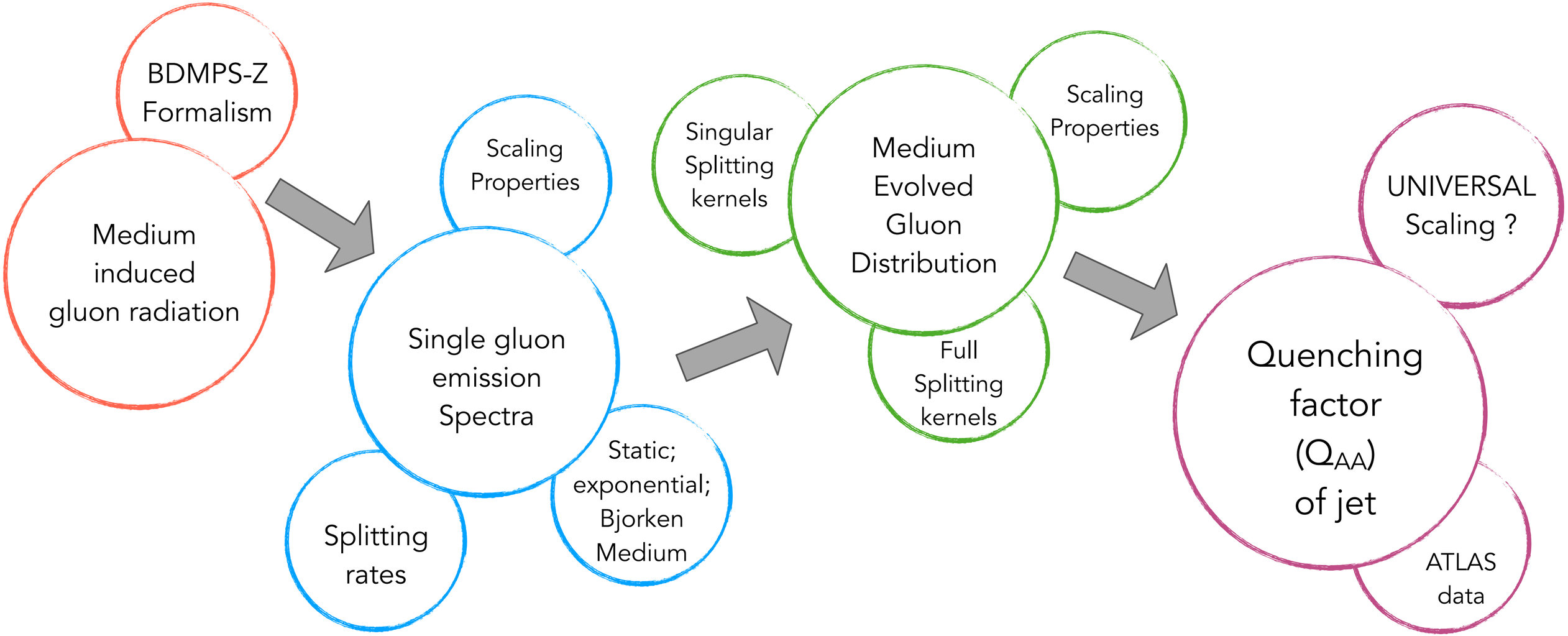

Based on the recent work : *Medium-induced cascade in expanding media;* **S. P. Adhya**, C. A. Salgado, M. Spousta, K. Tywoniuk; arXiv: 1911.12193.

# Outline of the talk



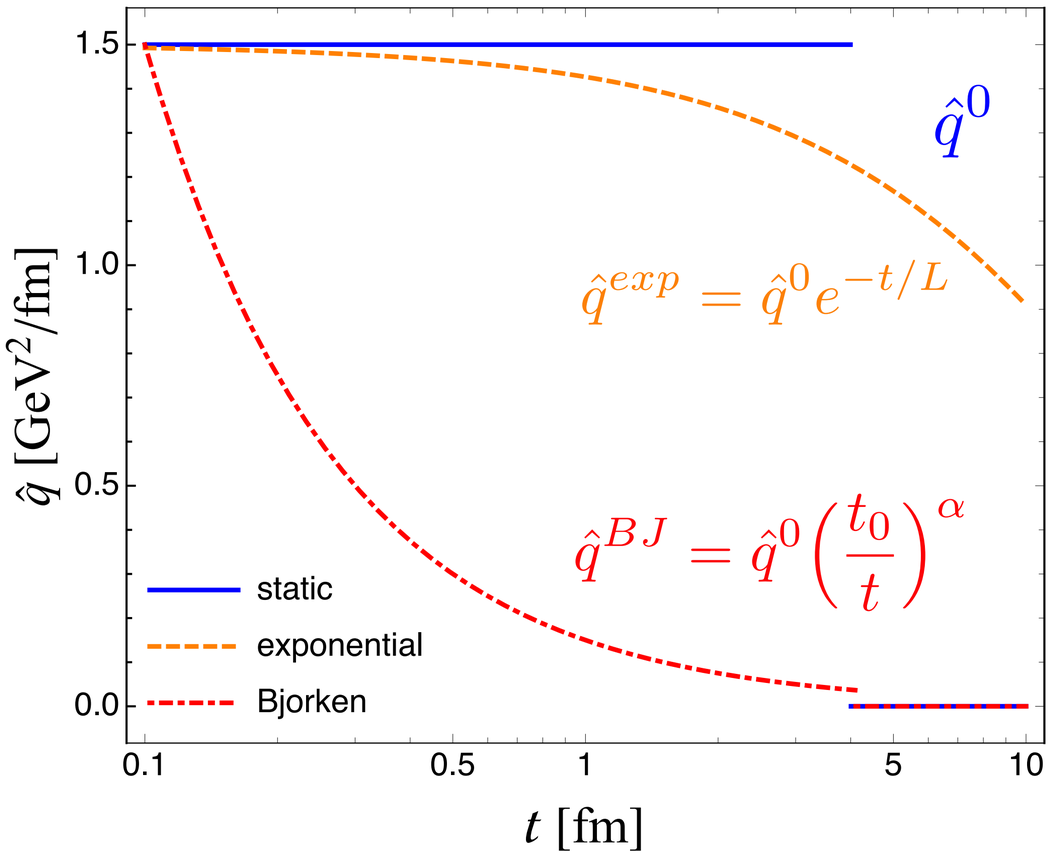

Based on the recent work : *Medium-induced cascade in expanding media;* **S. P. Adhya**, C. A. Salgado, M. Spousta, K. Tywoniuk; arXiv: 1911.12193.

# Outline of the talk




Based on the recent work : *Medium-induced cascade in expanding media;* **S. P. Adhya**, C. A. Salgado, M. Spousta, K. Tywoniuk; arXiv: 1911.12193.

# Quenching parameter for media




The Bjorken profile modelled as

$$\hat{q}(t) = \begin{cases} 0 & \text{for} \quad t < t_0\,, \\ \hat{q}_0 (t_0/t)^{\alpha} & \text{for} \quad t_0 < t < L + t_0\,, \\ 0 & \text{for} \quad L + t_0 < t\,. \end{cases}$$

- In the multiple soft scattering approximation (BDMPS) formalism, we start from harmonic oscillator (HO) with a time dependent imaginary frequency Ω(t)

$$\boxed{\frac{d^2 c(t)}{dt^2} + \Omega^2(t) c(t) = 0}$$

c (t) = information about medium and its expansion

$$\Omega^2(t) = -i \frac{\hat{q}(t)}{2z(1-z)p} \qquad \kappa(z) = \sqrt{[1 - z(1-z)]/[z(1-z)]}$$

- We only consider gluon splitting.

Average quenching parameter for static and Bjorken media

$$< \hat{q} >= \frac{2}{L^2} \int_{t_0}^{L+t_0} dt (t - t_0) \hat{q}(t)$$

Average quenching parameter for exponential medium

$$< \hat{q} >^{exp} = \frac{2}{L^2} \int_0^{\infty} dt \hat{q}(t)$$

Maximum available gluon energy in medium ==> $< \omega_c >= \frac{1}{2} < \hat{q} > L^2$

# Scaling behaviour of the spectrum

The single gluon emission spectra are given as :

$$\frac{dI^{static,soft}}{dz} \simeq \frac{\alpha_s P(z)}{\pi}\sqrt{\frac{\omega_c}{2\omega}}$$

$$\frac{dI^{static}}{dz} = \frac{\alpha_s}{\pi} P(z)\,\mathrm{Re}\ln[\cos(\Omega_0 L)]$$

$$\frac{dI^{expo}}{dz} = \frac{\alpha_s}{\pi} P(z)\,\mathrm{Re}\ln J_0(2\Omega_0 L)$$

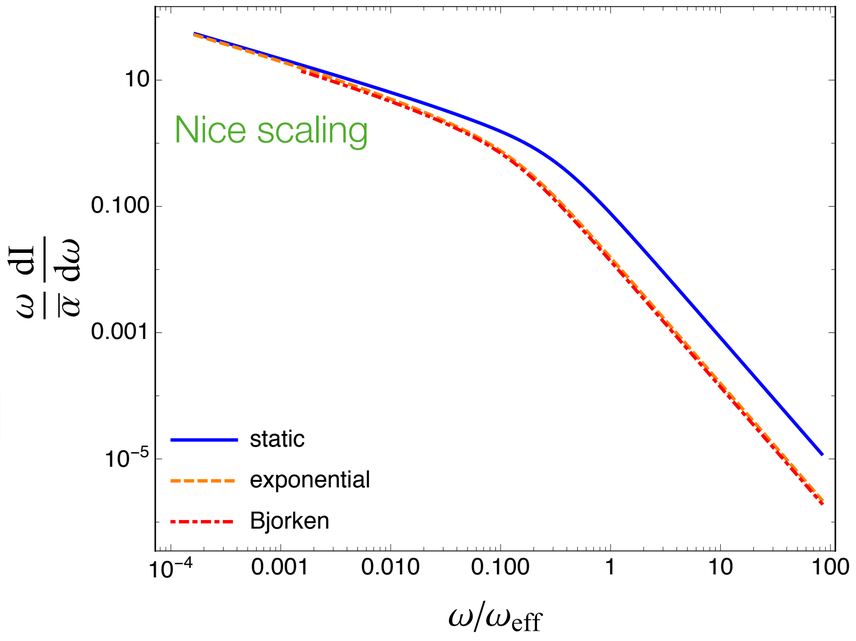
$$\frac{dI^{BJ}}{dz} = \frac{\alpha_s}{\pi} P(z)\,\mathrm{Re}\ln\left[\left(\frac{t_0}{L+t_0}\right)^{1/2}\frac{J_1(z_0)Y_0(z_L)-Y_1(z_0)J_0(z_L)}{J_1(z_L)Y_0(z_L)-Y_1(z_L)J_0(z_L)}\right]$$

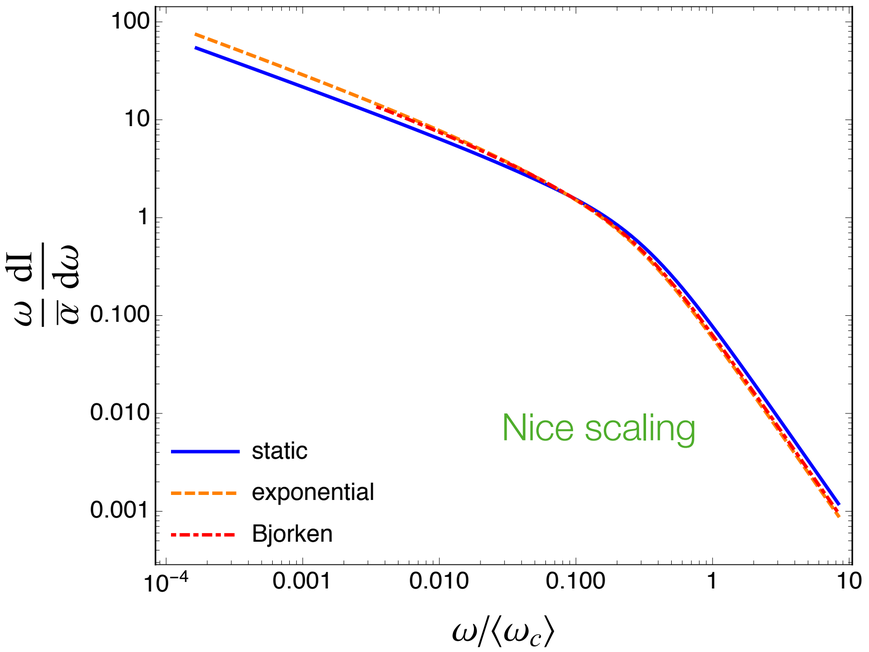
$$P_{gg} = 2C_A\frac{(1-z(1-z))^2}{z(1-z)} \qquad \tau \equiv \sqrt{\frac{\hat{q}_0}{p}}L \qquad z_0 \equiv (1-i)\kappa(z)\tau_0$$

$$z_L \equiv (1-i)\kappa(z)\sqrt{\tau_0(\tau+\tau_0)}\,,$$

P. B. Arnold, Phys. Rev. D 79 (2009) 065025.

Can we interpret the scalings in different kinematical limits ?




Effective parameter

$$\frac{dI^{static,sing}}{dz} \simeq \frac{dI^{expo,sing}}{dz} \simeq \frac{dI^{BJ,sing}}{dz}$$

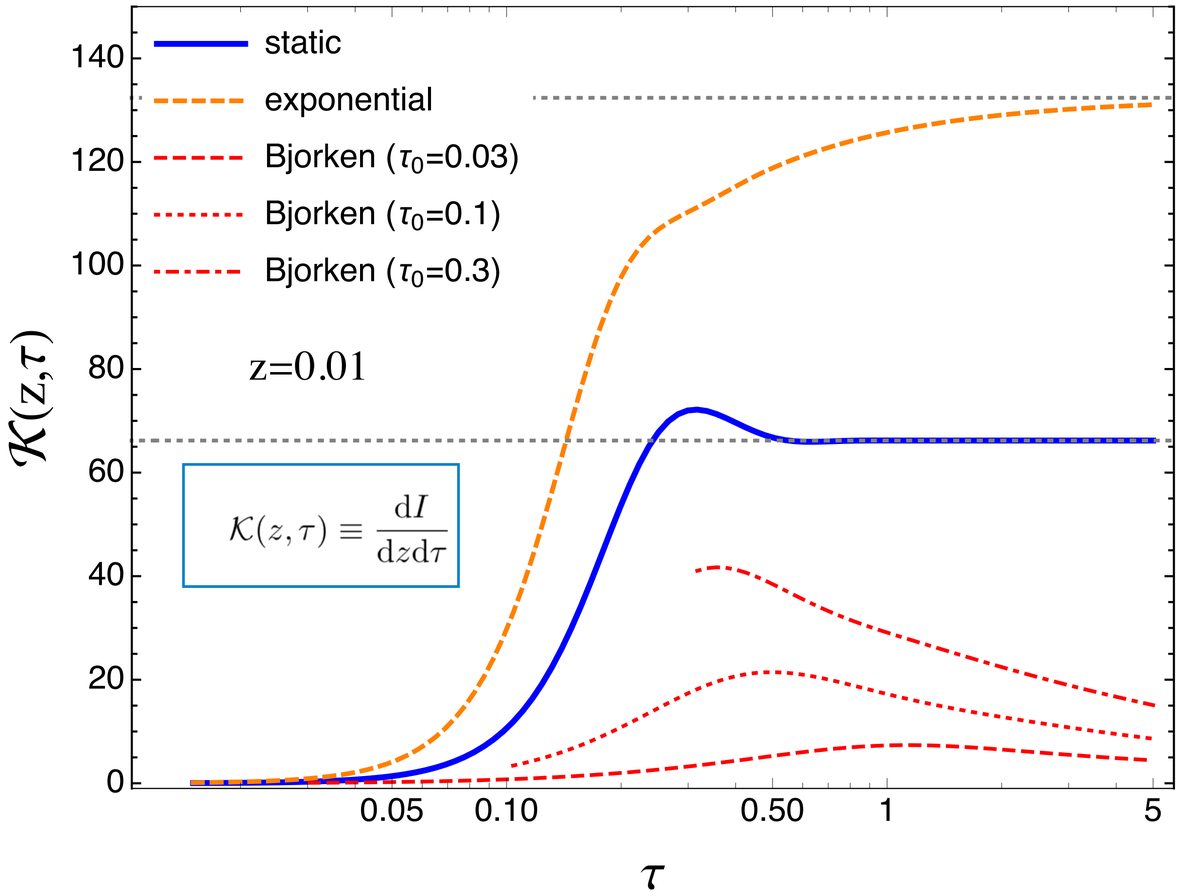
The singular spectra can be re-scaled

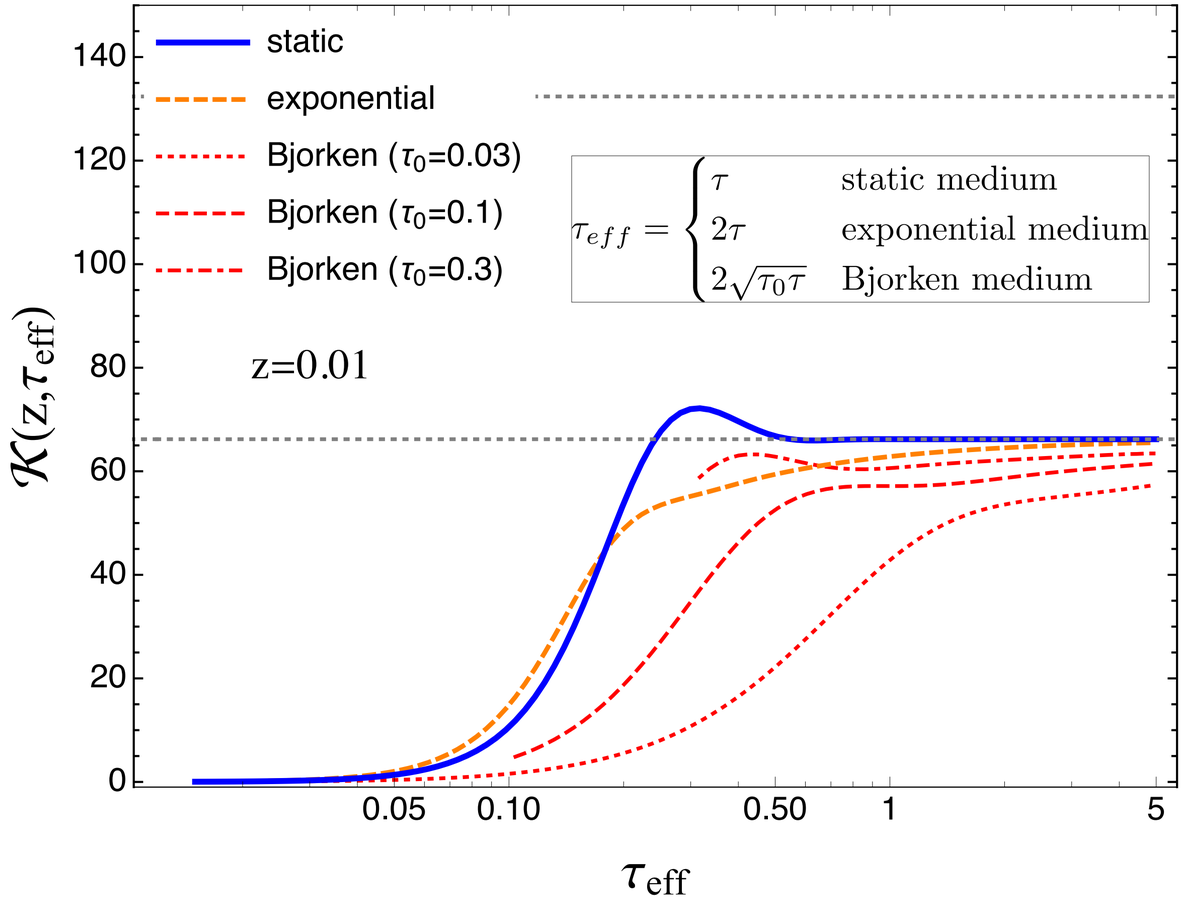
$$\omega_{\rm eff} = \begin{cases} \frac{1}{2}\hat{q}_0 L^2 & \text{static medium} \\ 2\hat{q}_0 L^2 & \text{exponentially expansion} \\ 2\hat{q}_0 t_0 L & \text{Bjorken expansion} \end{cases}.$$

$$\hat{q}^{expo}_{eff} = 4\hat{q}_0$$

$$\hat{q}^{BJ}_{eff} = 4\hat{q}_0 t_0/L$$

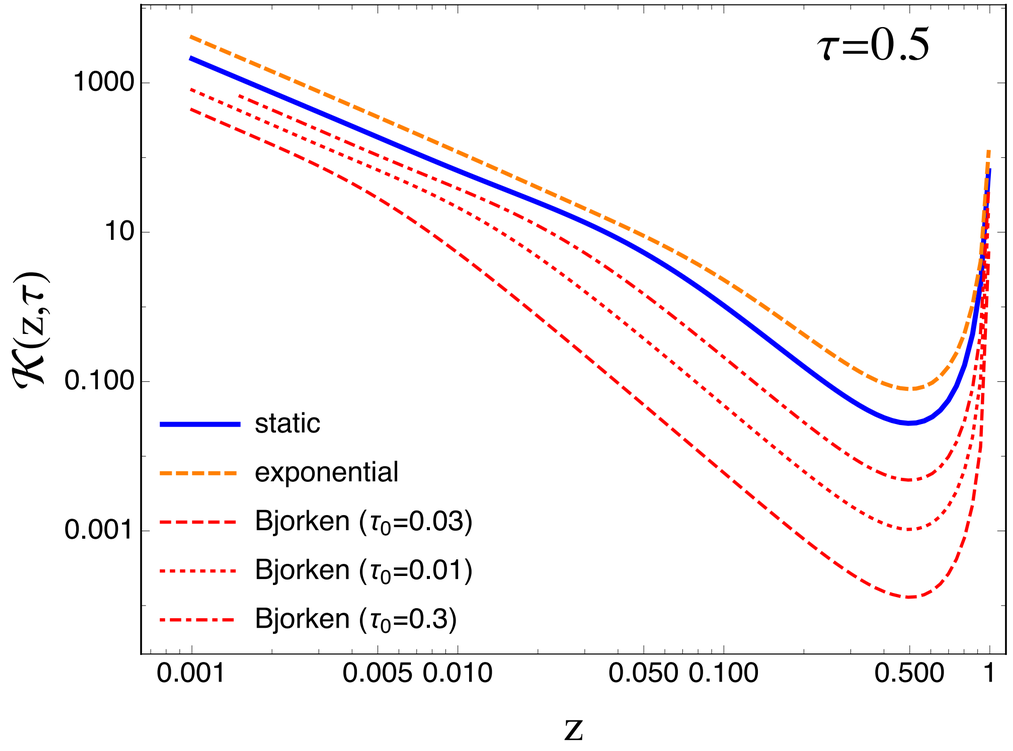
# Medium modified splitting rate ( and scaling)

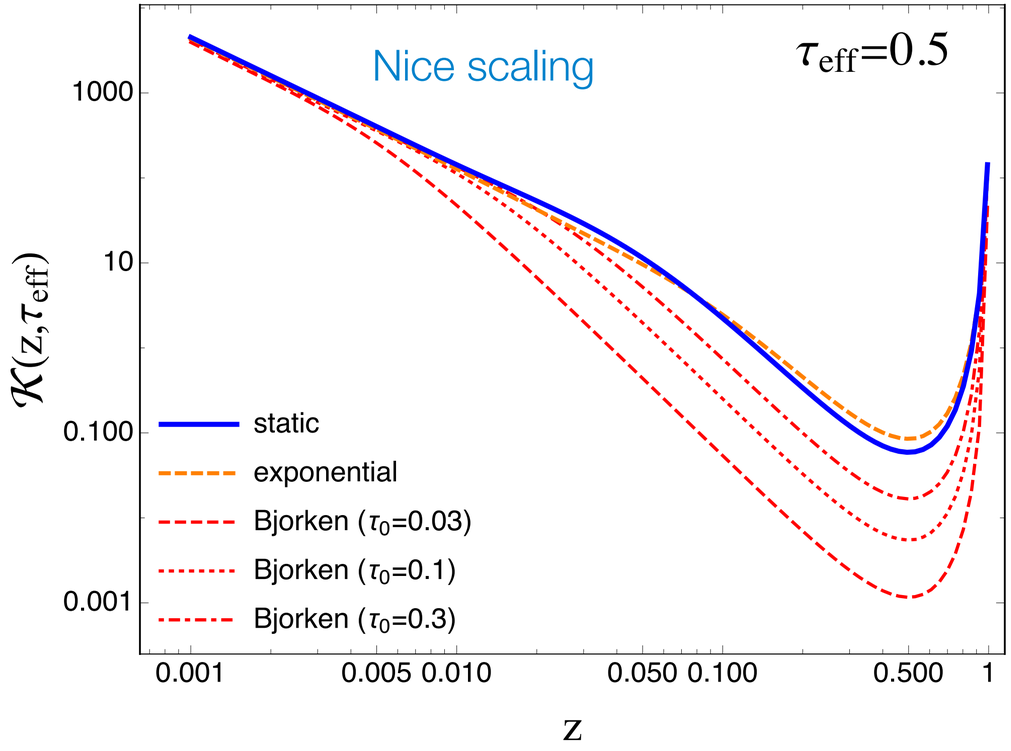



- The BDMPS soft ($w < w_c$) has a constant splitting rate independent of the time of evolution of the plasma.
- The rates for all the profiles except the BDMPS soft are similar at very low evolution time or length of the medium.
- In the Bjorken, the presence of pre- factor $\tau_0/(\tau_0 + \tau)$ leads to the dumping of the splitting rate for $\tau > \tau_0$.

# Medium modified splitting rate (and Scaling)




- At high values of z the rates for different profiles differ significantly.

- At the low-z values all profiles have universal slope due to P(z)κ(z) factor present in splitting rates of all the profiles which diverges for z → 0 as $z^{-3/2}$ .

- We recover a universal behavior of parton evolution for expanding media in the soft gluon regime with $\tau_{eff}$.

# Medium evolved gluon spectra

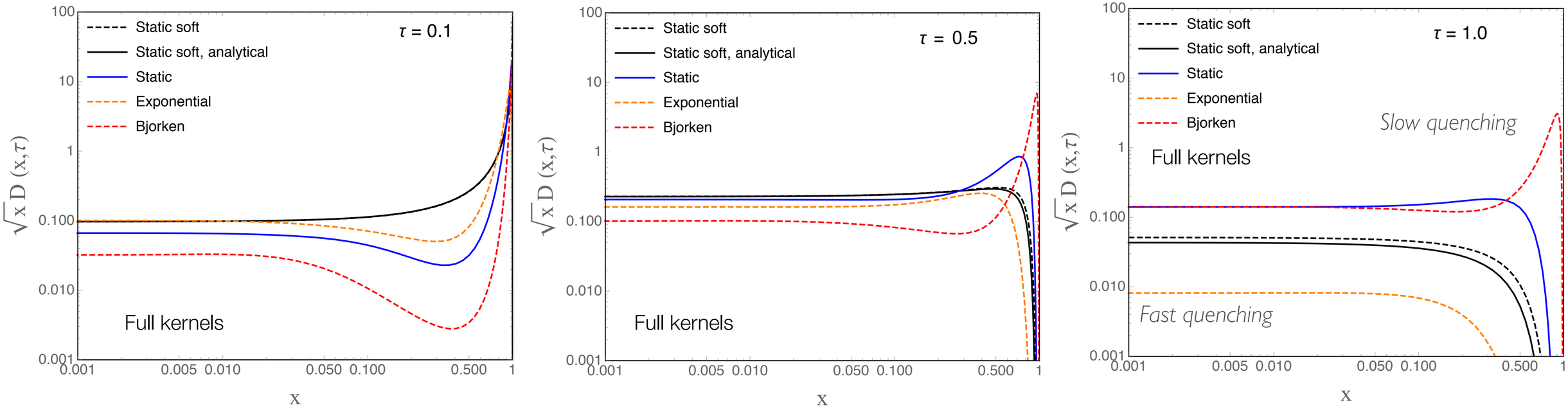
J.-P. Blaizot, E. Iancu, and Y. Mehtar-Tani, Phys.Rev.Lett. 111 (2013) 052001.

- The kinematic evolution equation (GAIN + LOSS terms) in terms of gluon spectra :

$$\frac{\partial D(x,t)}{\partial \tau} = \int dz\, \mathcal{K}(z,\tau|p) \left[ \sqrt{\frac{z}{x}} D\left(\frac{x}{z},\tau\right) - \frac{z}{\sqrt{x}} D(x,\tau) \right]$$

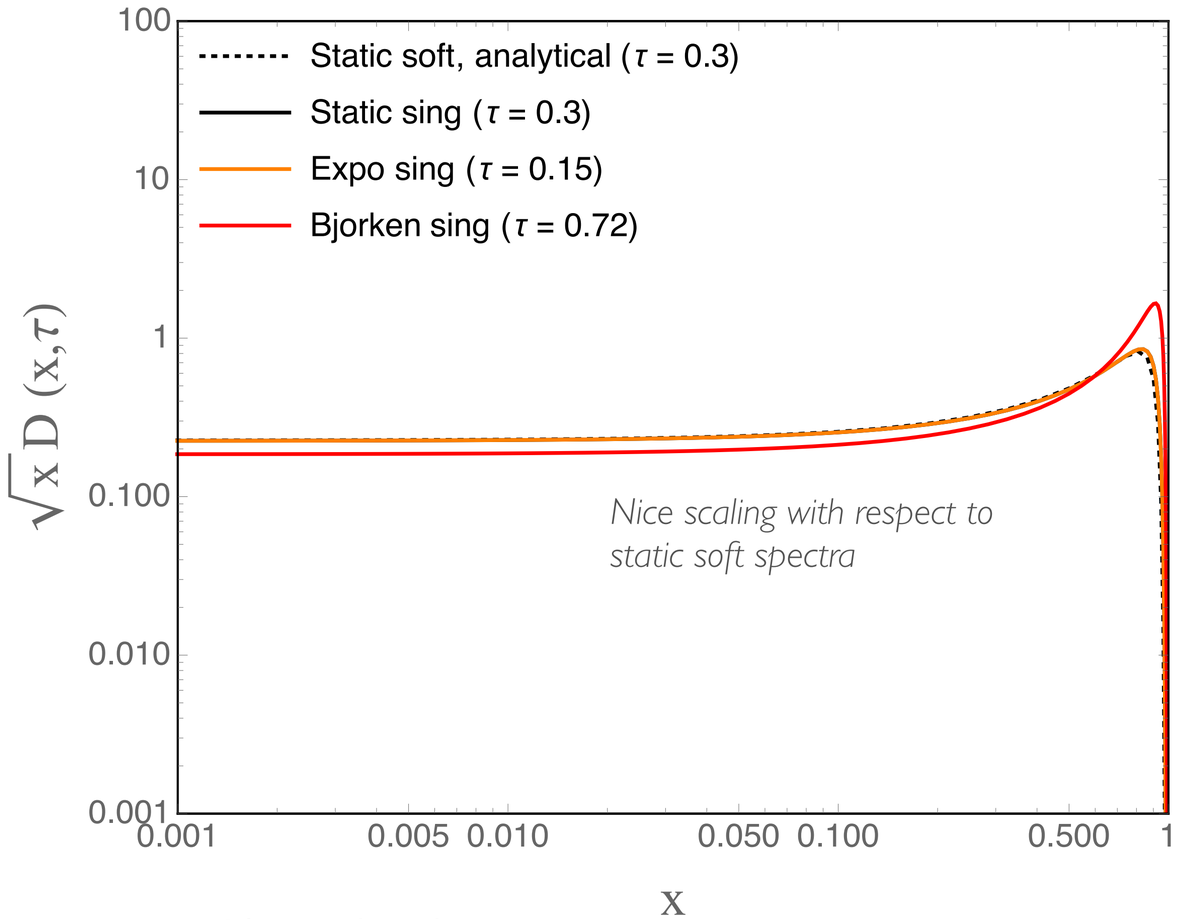
Static, soft (analytical)

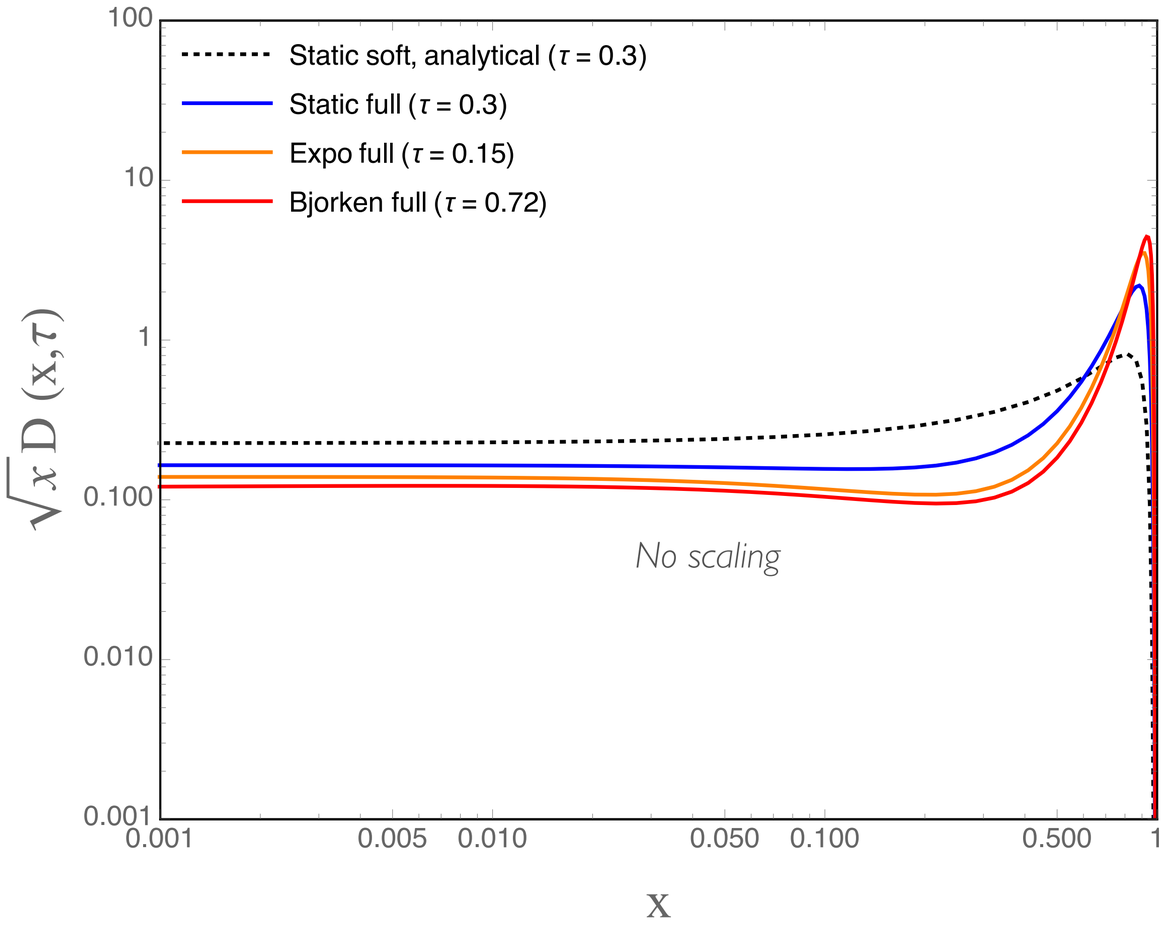
$$D(x,\tau) = \frac{\tau}{\sqrt{x}(1-x)^{3/2}} \mathrm{e}^{-\pi \frac{\tau^2}{1-x}}$$




- The numerical value of the BDMPS soft spectra agrees with the analytical result (check of the numerical routine).
- At low z, we see a 1/(√x) behaviour of all the profiles >> *recovered from the similar gluon splitting at low z.*

# Scaled gluon spectra (singular and full kernels)




- Gluon distribution:

A. Singular rates ==> Nice scaling in $\tau_{\text{eff}}$.

B. Full rates ==> No scaling in $\tau_{\text{eff}}$

$$\tau_{eff} = \begin{cases} \tau & \text{static medium} \\ 2\tau & \text{exponential medium} \\ 2\sqrt{\tau_0 \tau} & \text{Bjorken medium} \end{cases}$$

# Moments of the distribution and $Q_{AA}$

- The yield for the inclusive jet suppression can be obtained as a convolution of the D(x,τ) distribution (gluon spectra) with the initial parton spectra,

$$\frac{d\sigma_{\rm AA}}{dp_T} = \int dp'_T \int_0^1 \frac{dx}{x}\, \delta(p_T - xp'_T) D\left(x, \tau \equiv \sqrt{\hat{q}/p'_T}\right) \frac{d\sigma_0}{dp'_T}$$

Approximated by power law

$$d\sigma_0/dp_T \propto p_T^{-N}$$

We assume that we have a steeply falling hard spectrum, with n = 5.6

- The jet suppression factor :

$$Q(p_T) = \int_0^1 dx\, x^{N-1} D(x, \sqrt{x}\tau)$$

- We include only one parton species (gluons) ; thus $Q_{AA}$ is proxy for $R_{AA}$

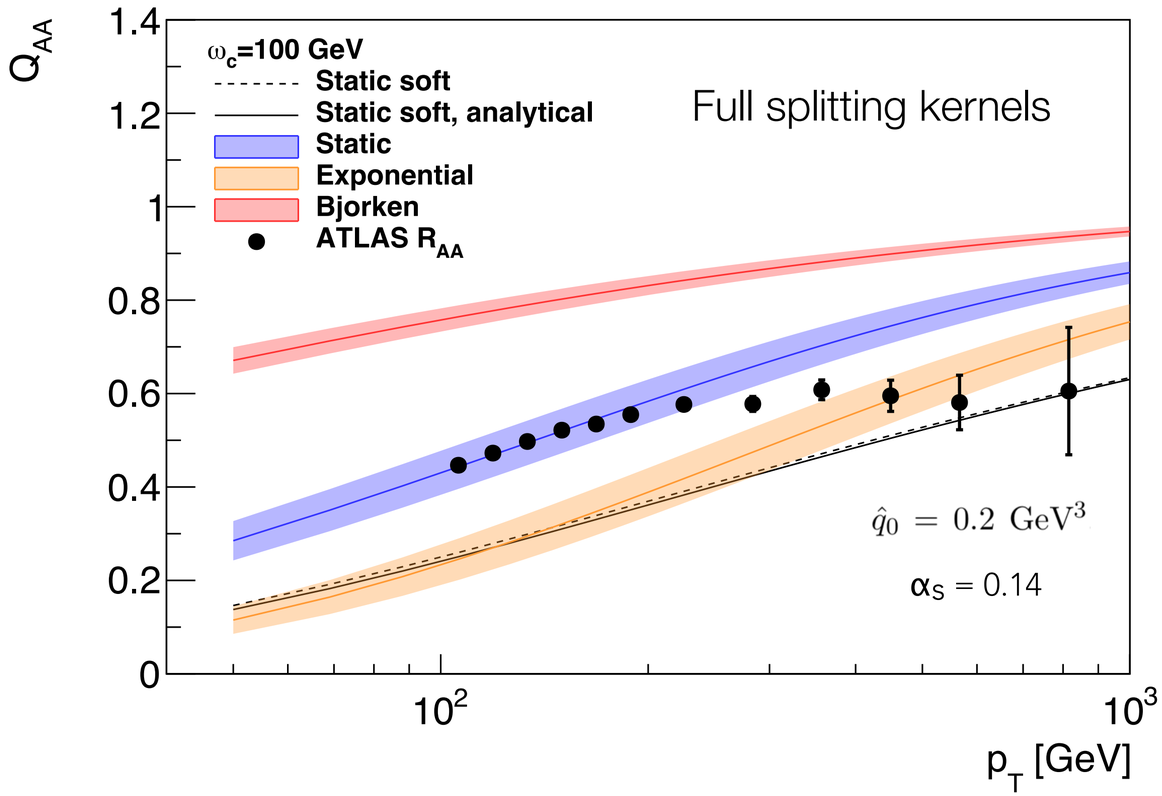
- Analytical insight : We start with the "singular" kernels and its scaling to arrive at,

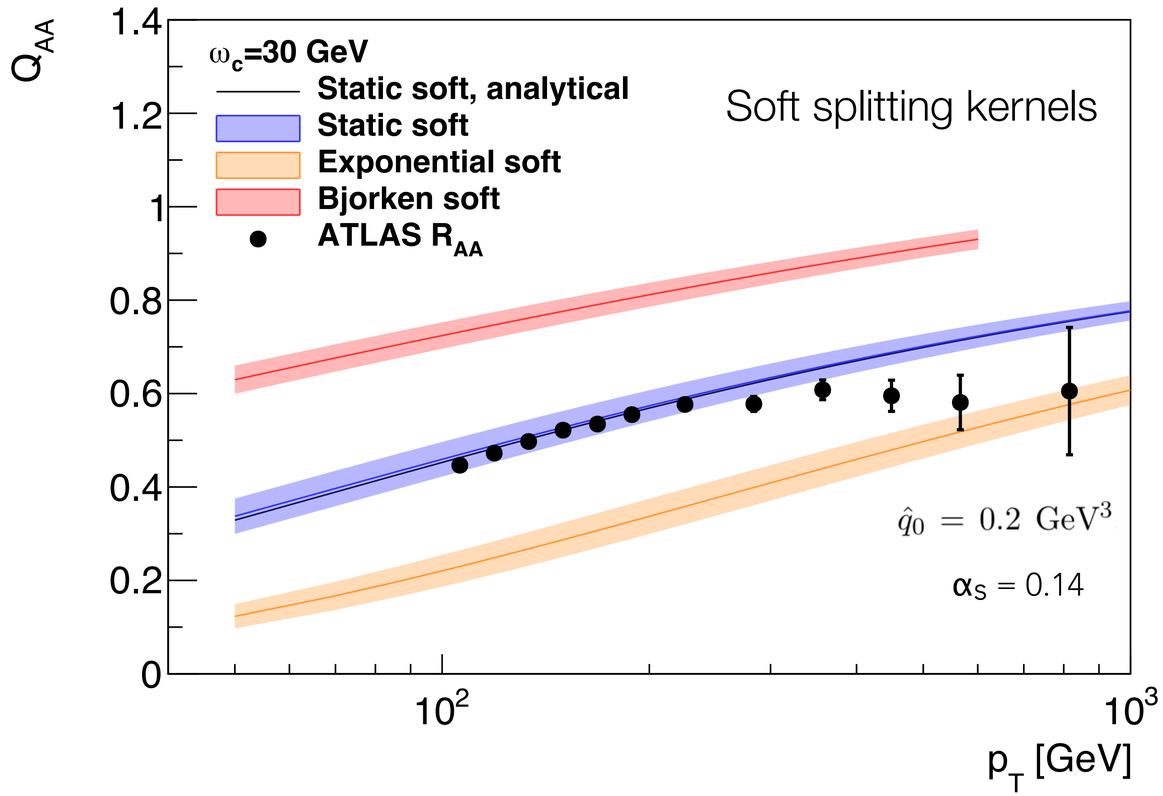
$$\frac{Q_{\rm AA}^{\rm exp}}{Q_{\rm AA}^{\rm static}} \simeq \exp\left[-2\bar{\alpha}\sqrt{\pi \hat{q}_0 L^2 (n-1)/p_T}\right]$$

$$\frac{Q_{\rm AA}^{\rm Bjork}}{Q_{\rm AA}^{\rm static}} \simeq \exp\left[-2\bar{\alpha}\sqrt{\pi \hat{q}_0 L^2 (n-1)/p_T}\left(2\sqrt{\frac{t_0}{L}} - 1\right)\right]$$

- Due to the additional, explicit dependence on the ratio ($t_0$/L), we conclude that in the case of the Bjorken expansion there is no universal way of rescaling the parameters to arrive at the results of the static medium.

# Jet $Q_{AA}$

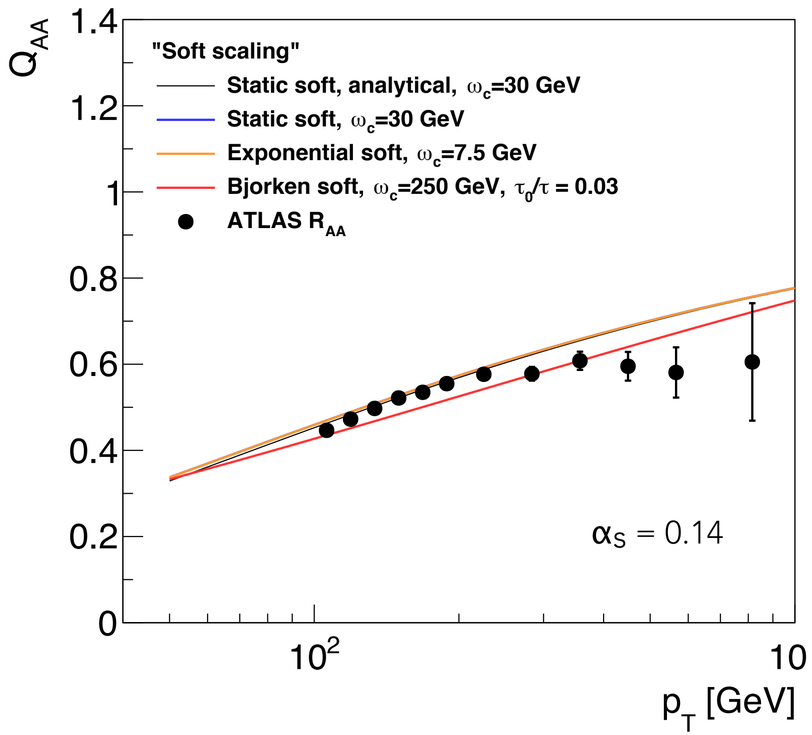


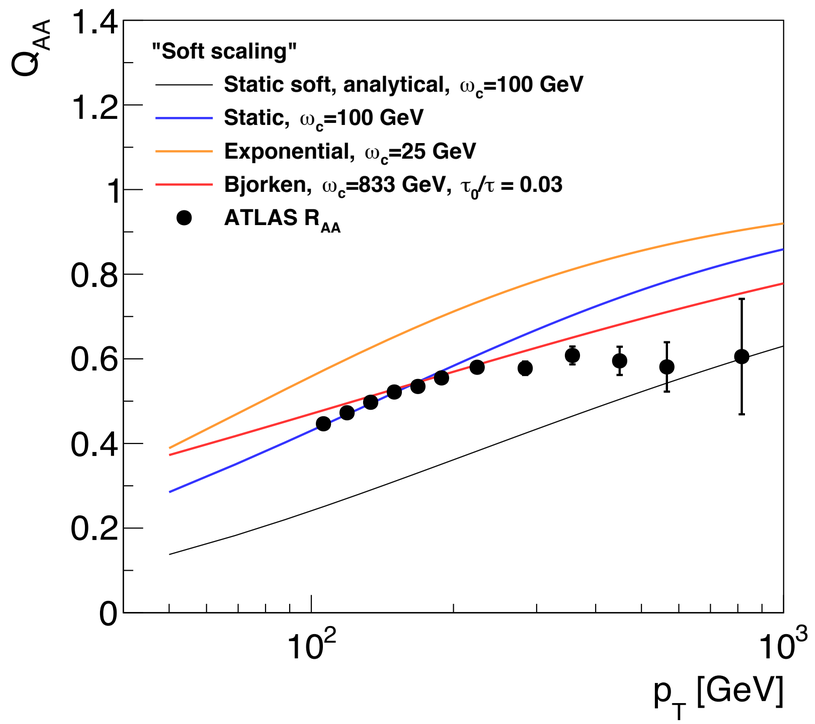



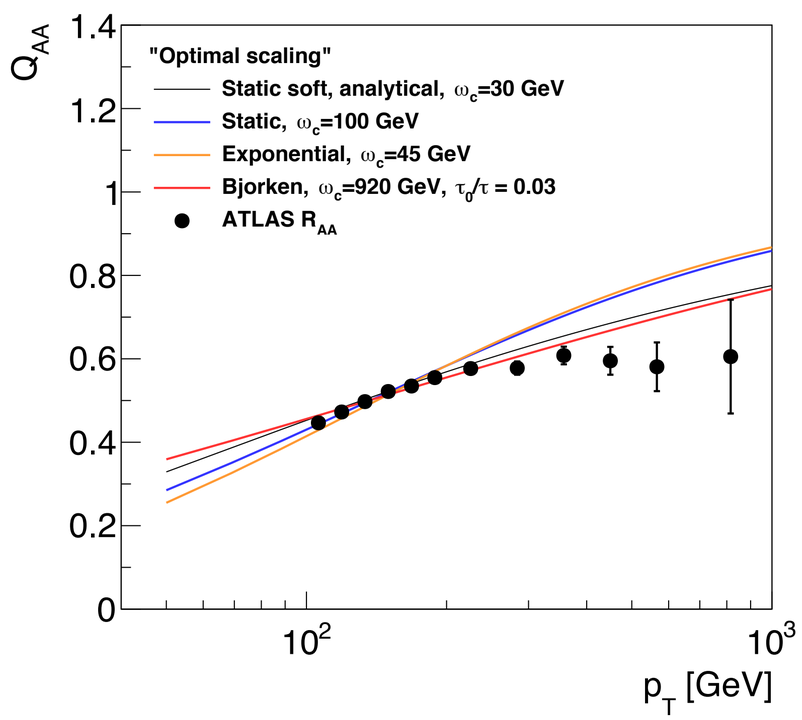

- The numerical value of the BDMPS static (soft) agrees with the analytical result.
- The uncertainty band is obtained by varying $\alpha_S$ by 10 %.
- A large difference can be seen for different media due to varying rate of expansions.

Do they respect any Scaling properties ?

# $Q_{AA}$ for re-scaled profiles




- Replace $\omega_C$ values for exponential case and Bjorken case by $\omega_{eff}$ for singular kernels.
- Recover nice scaling features as in singular rates and spectra.

- Replace $\omega_C$ for exponential case and Bjorken case by $\omega_{eff}$ for full kernels.
- Full kernels do not respect scaling laws.

- Replace $\omega_C$ values for exponential case and Bjorken case by $\omega_{opt}$ for full kernels by $\chi^2$ fit.
- Good, but not perfect scaling is achieved by minimization.
- Scaling for expo medium ~ average scaling.

The Bjorken profile depends on additional choice of $(\tau_0/\tau)$ : No universal scaling

# Summary and discussions

- We study the impact of the expansion of de-confined medium on single-gluon emission spectrum, its re-summation and the jet suppression factor ($Q_{AA}$) within the BDMPS-Z formalism.

- The distribution of medium-induced gluons is calculated using an evolution equation with splitting kernels derived from the gluon emission spectra. A universal behaviour of splitting kernels seen for soft gluon emissions for effective evolution time $\tau_{eff}$.

- For realistic spectra valid beyond the soft-gluon emission limit, these scaling features are partially replaced by a scaling expected from considering an averaged jet quenching parameter along the trajectory of propagation.

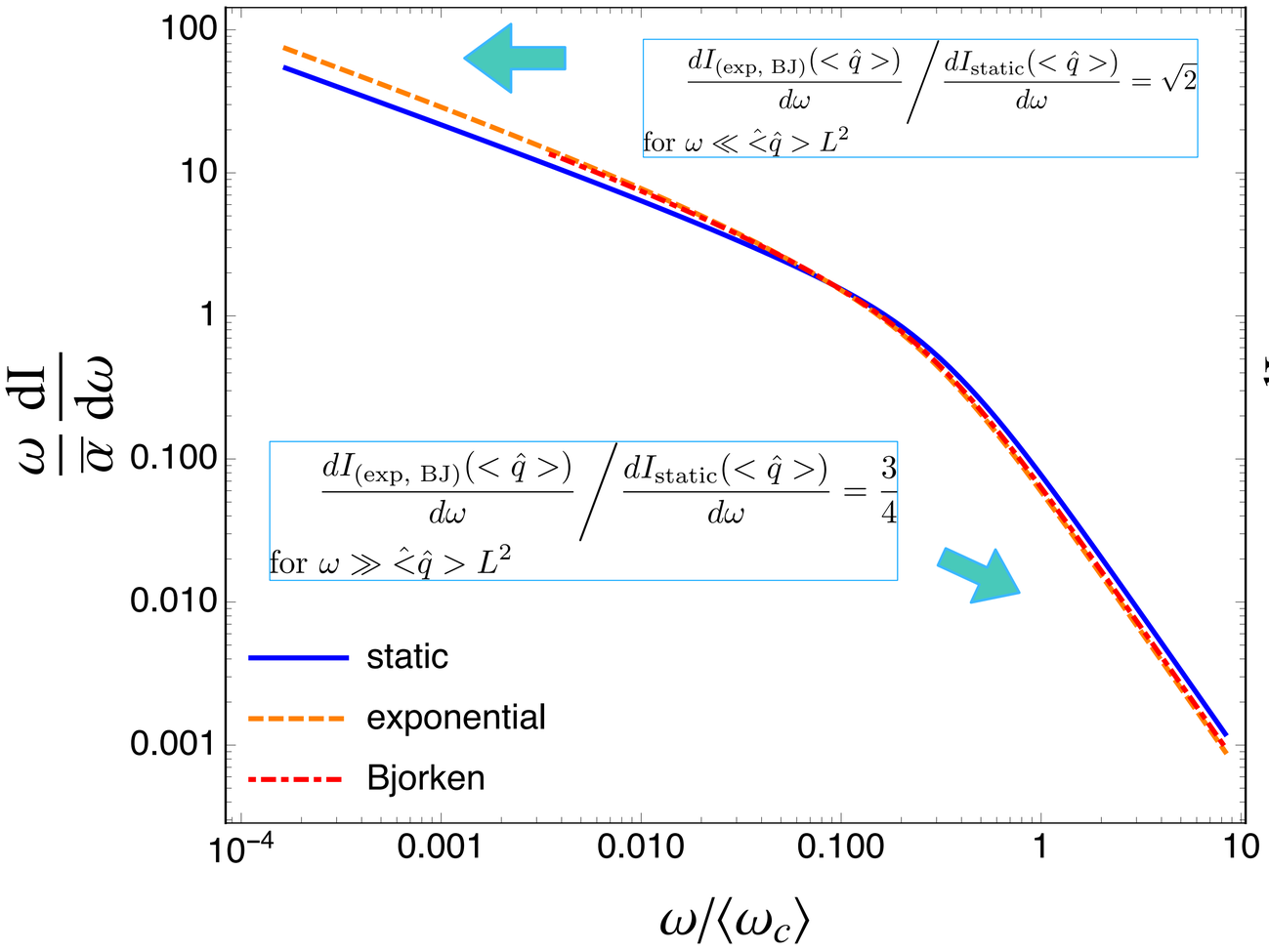
- Appropriate choice of the quenching parameter can sort out differences between different medium expansions.

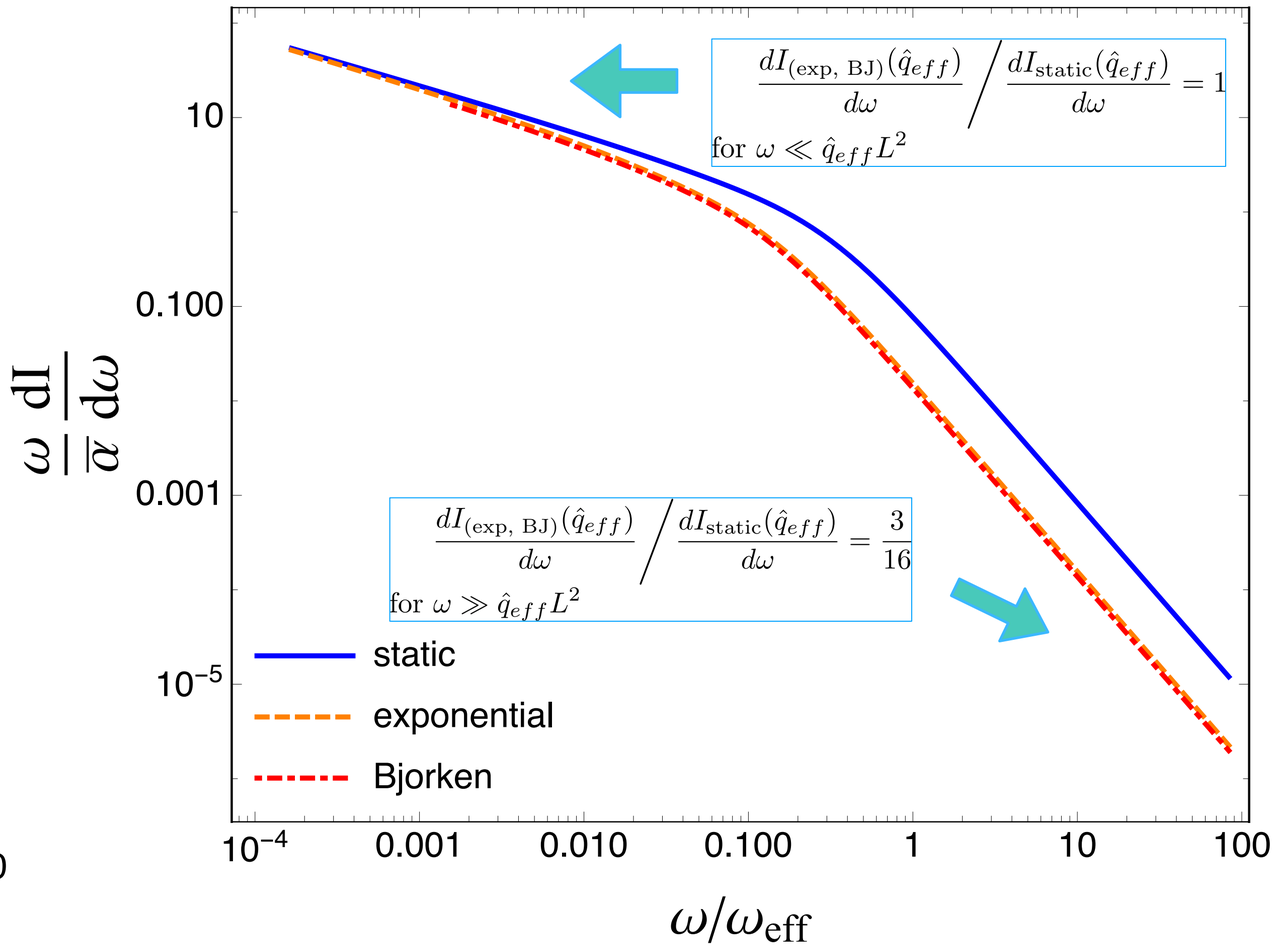
- Sizable differences among the values of the quenching parameter for different types of medium and kinematical ranges point to the importance of precise modelling of the jet quenching phenomenon.

*Thank you*

BACKUP

# Revealing scaling feature of the spectrum




Scaling properties of the full spectra:

- The insets provide analytical estimates from singular spectra only.

- Nice scaling for hard sector in left panel.
- Nice scaling for soft sector in right panel.