# Radiative-transfer effects: a new scale in the bias expansion

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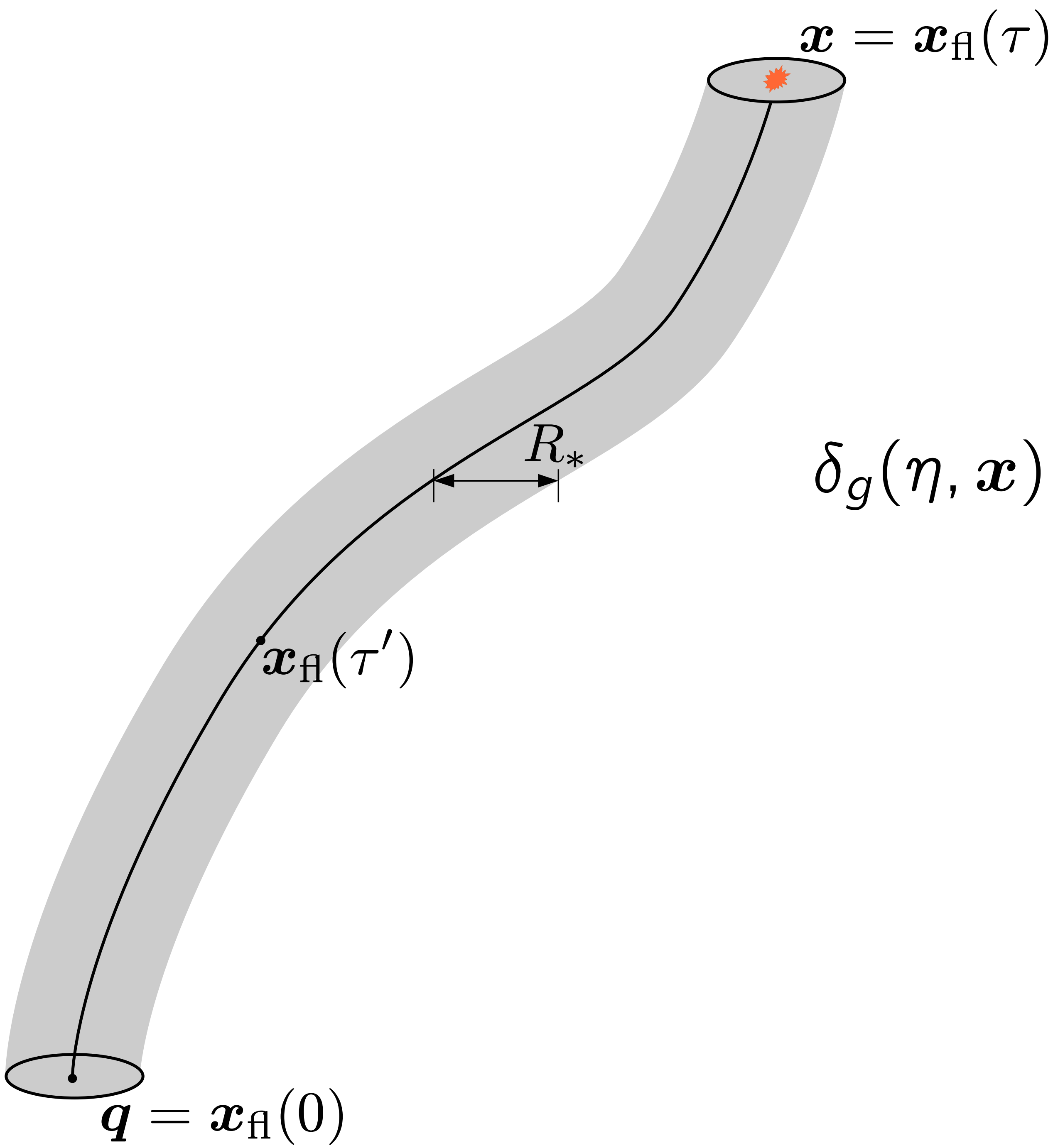
# Locality and the bias expansion

e.g.: Desjacques, Jeong, Schmidt (2016)

Bias expansion -> describe clustering of DM tracers

Rooted in the hypothesis of locality of galaxy formation




$$\delta_g(\eta, \boldsymbol{x}) = \int \mathrm{d}\eta' \mathrm{d}^3 y \, F_g(\eta, \eta', |\boldsymbol{y}|) \, \delta(\eta', \boldsymbol{x} + \boldsymbol{y})$$

with

$$F_g = 0 \text{ for } |\boldsymbol{y}| \gtrsim R(M_h)$$

# The derivative expansion

The assumption of locality allows a derivative expansion ~>

$$\delta_g(\eta, \boldsymbol{x}) = \int \mathrm{d}\eta' \mathrm{d}^3 y\, F_h(\eta, \eta', |\boldsymbol{y}|)\, \delta(\eta', \boldsymbol{x}) + \frac{1}{6} \int \mathrm{d}\eta' \mathrm{d}^3 y\, F_h(\eta, \eta', |\boldsymbol{y}|)\, |\boldsymbol{y}|^2\, \nabla^2 \delta(\eta', \boldsymbol{x}) + \ldots$$

If the growth rate is scale-independent, we can get rid of NL in time ~>

$$\delta_g(\eta, \boldsymbol{k}) = b_1(\eta)\delta(\eta, \boldsymbol{k}) - b_{\nabla^2\delta}(\eta) k^2 \delta(\eta, \boldsymbol{k}) + \ldots$$

where we expect $b_{\nabla^{2n}\delta} \sim R^{2n}(M_h)$

# The derivative expansion

The higher-derivative terms can be treated perturbatively if the nonlocality scale is short. *The shorter the scale, the better!*

**Radiative-transfer effects** ~> during reionization, UV photons can affect formation of protogalaxies (e.g., photoionize gas accreting onto halo => change relation between halo mass and stellar mass).

e.g.: Efstathiou (1992), Barkana, Loeb (1999), Schmidt, Beutler (2017)

**NL scale** ~> m.f.p. of radiation. Can be of order 100 Mpc/h!

can we resum these terms?

$$\delta_g(\eta,\boldsymbol{k}) \supset \sum_{n=0}^{+\infty} r_{2n}(\eta)(-1)^n(\lambda_{\rm eff}k)^{2n}\delta(\eta,\boldsymbol{k}) \xrightarrow{?} \sum_{n=0}^{+\infty} \#_n(\eta) f_n(k^2\lambda_{\rm eff}^2)\delta(\eta,\boldsymbol{k})$$

with $\#_{n+1} \ll \#_n$, so that we can stop at a finite n?

# Galaxy response to ionizing radiation

Encoded in "Green's function" $G_g$ ~>

$$\delta_g(\eta, \boldsymbol{x}) = \int_0^\eta \mathrm{d}\eta' \int \mathrm{d}\hat{\boldsymbol{n}}\, G_g(\eta, \eta')\, \delta\mathcal{I}(\eta', \boldsymbol{x}, \hat{\boldsymbol{n}})$$

For simplicity: assume monochromatic radiation and neglect redshift. Also, assume homogeneous optical depth for now…

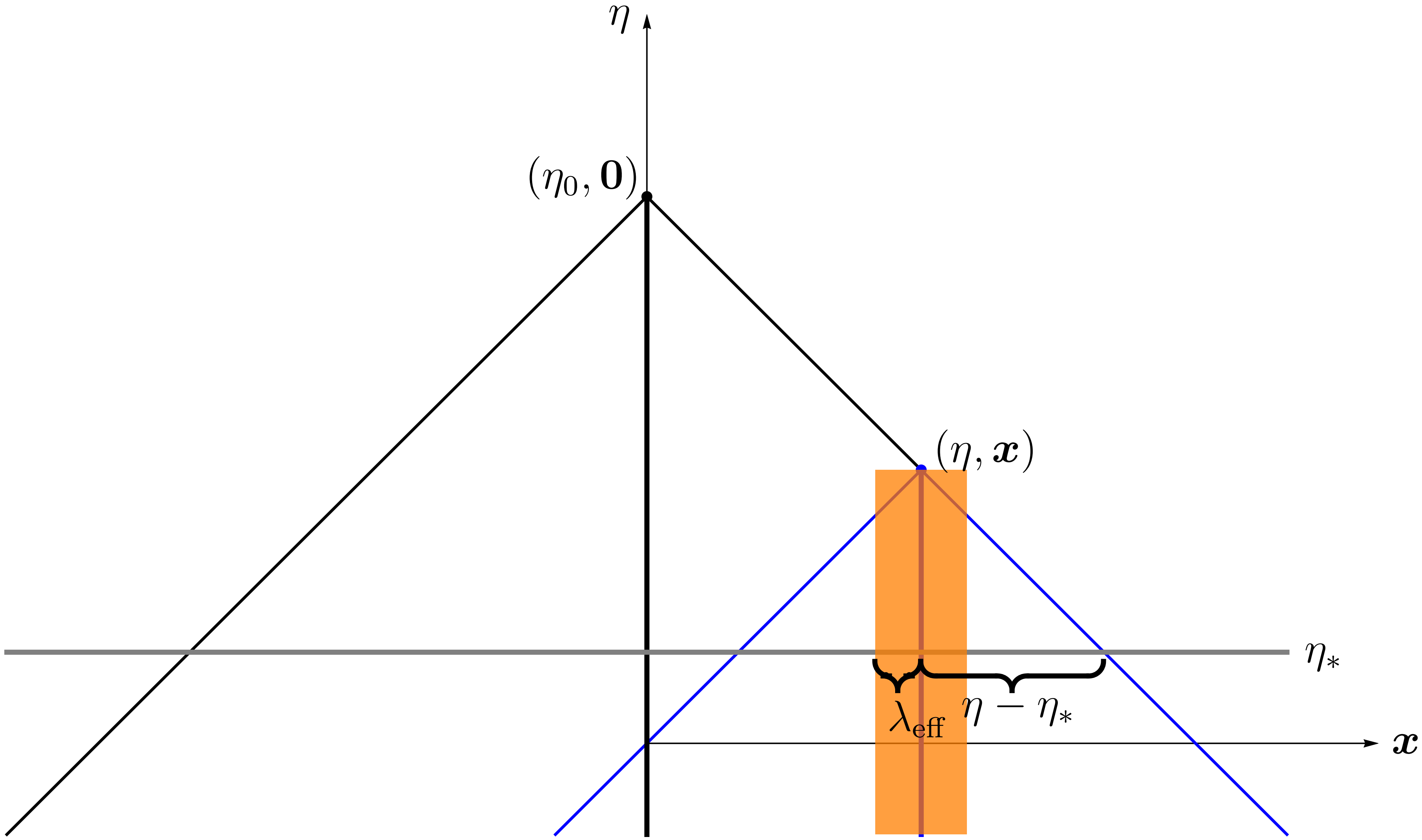
Inhomogeneities in incoming radiation field: $\delta\mathcal{I} \sim \delta_{\rm em} \sim \delta$ (assume linearly-biased density of emitters)

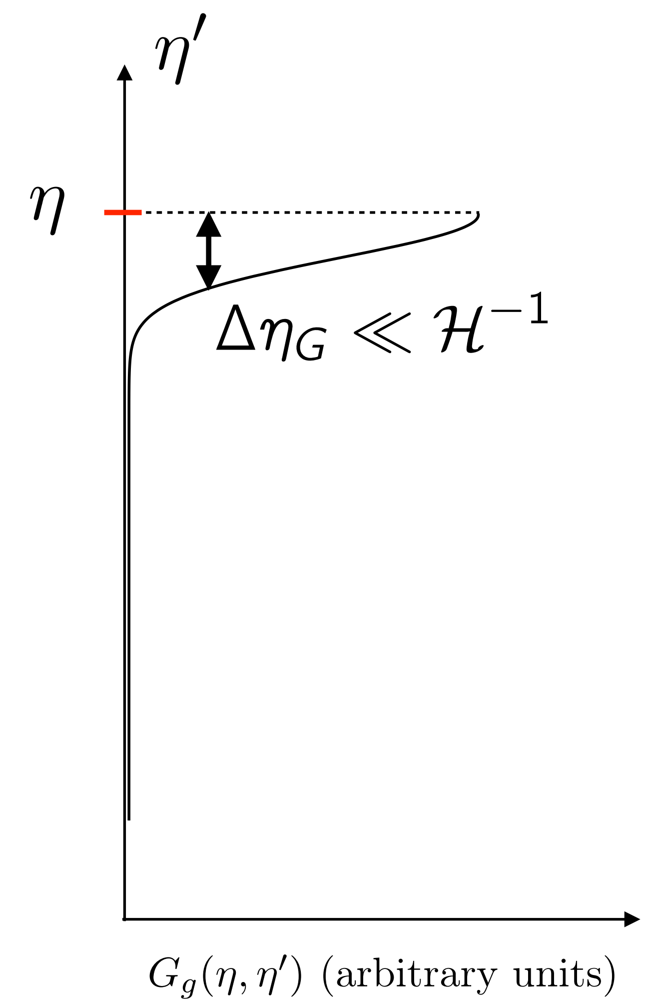
whether we can resum or not depends on the properties of the response

# Resummation - 1

First, assume that all radiation is emitted in short burst $\Delta\eta_{\rm em} \ll \mathcal{H}^{-1}$

If response is instantaneous…

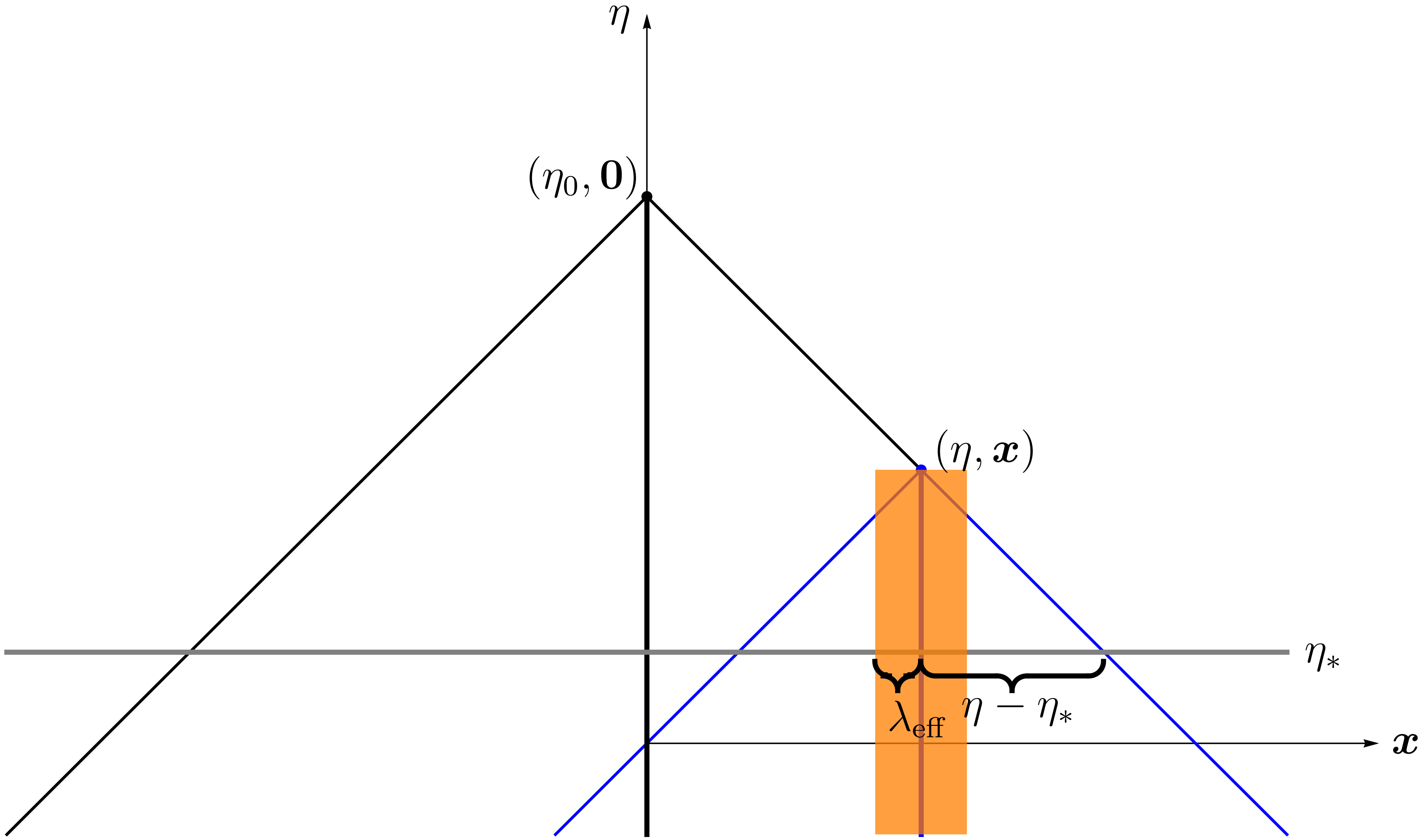


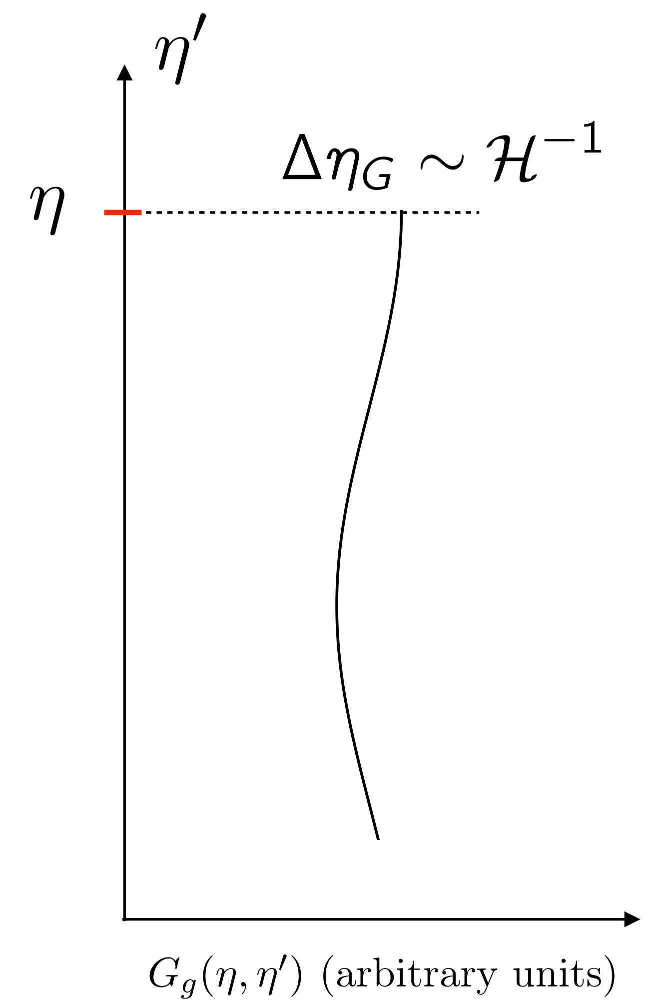




… radiation is absorbed before reaching $(\eta, \boldsymbol{x})$ and we don't have to worry!

# Resummation - 2

If response is slow ~> $G_g(\eta,\eta') = \sum_{n=0}^{+\infty} g_n \mathcal{H}^n (\eta' - \eta_*)^n$

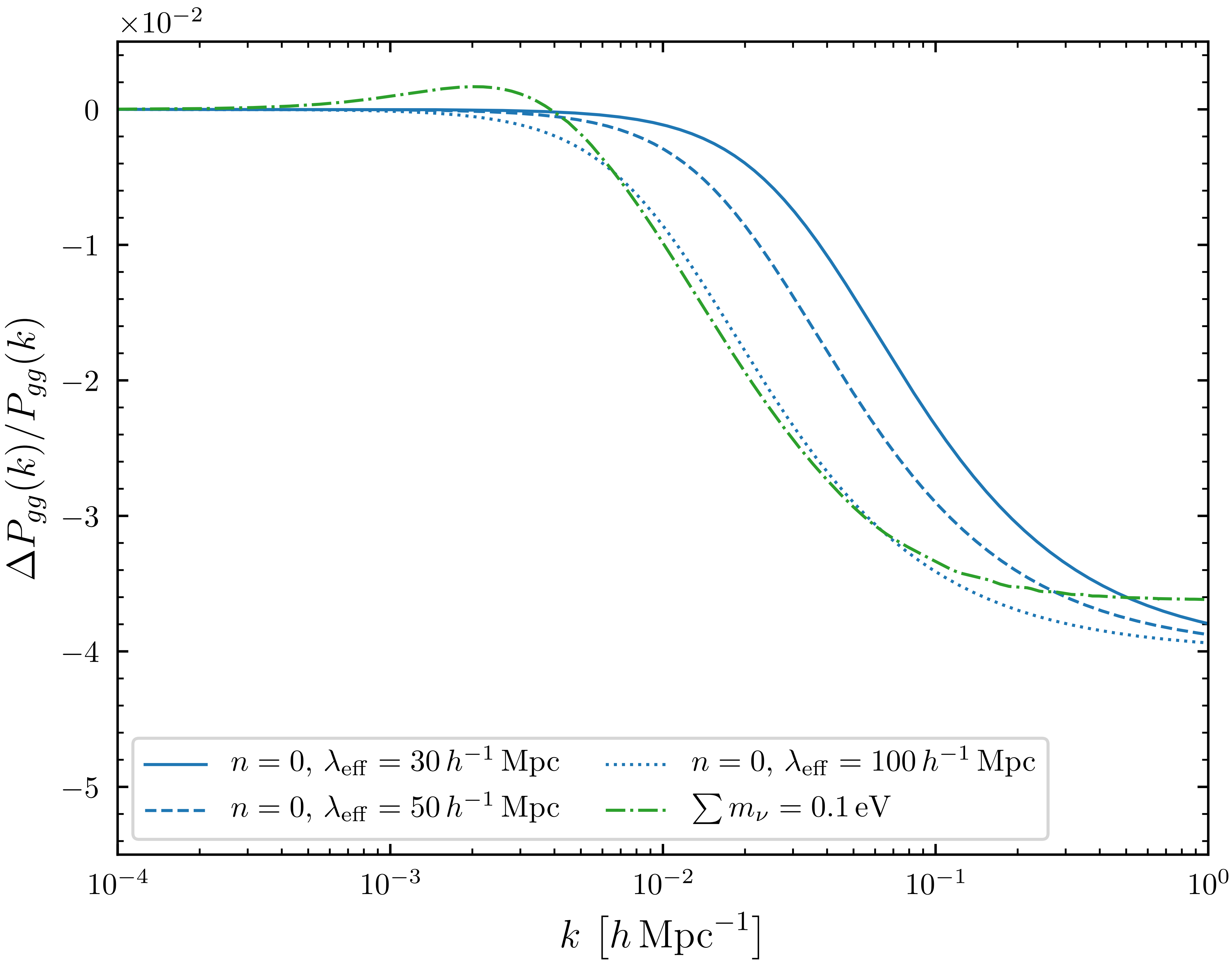



=> the coefficients of the resummation are $\#_n \sim g_n \times (\mathcal{H}\lambda_{\rm eff})^n$

# Effect on galaxy power spectrum

Plot zeroth order in $\mathcal{H}\lambda_{\rm eff}$ for $g_0 \sim 10^{-2}$ ~>




Things like energy dependence of response will change quantitatively the shape

but there is always a feature at the m.f.p. scale

# Multiple emissions and inhomogeneities in the optical depth

If emission is not fast, even if we stop at zeroth order in $\mathcal{H}\lambda_{\rm eff}$ we need an infinite number of bias coefficients ~> we cannot resum the RT effects!

| $\delta\tau = 0$ | $\Delta\eta_G \ll \mathcal{H}^{-1}$ | $\Delta\eta_G \sim \mathcal{H}^{-1}$ |
|---|---|---|
| $\Delta\eta_{\rm em} \ll \mathcal{H}^{-1}$ | ✓ | ✓ |
| $\Delta\eta_{\rm em} \sim \mathcal{H}^{-1}$ | ✓ | ✗ |

Inhomogeneities in the optical depth act as “sinks” of radiation, evolving on Hubble time scales!

| $\delta\tau \neq 0$ | $\Delta\eta_G \ll \mathcal{H}^{-1}$ | $\Delta\eta_G \sim \mathcal{H}^{-1}$ |
|---|---|---|
| $\Delta\eta_{\rm em} \ll \mathcal{H}^{-1}$ | ✓ | ✗ |
| $\Delta\eta_{\rm em} \sim \mathcal{H}^{-1}$ | ✓ | ✗ |

# Conclusions

- we can treat these effects non-perturbatively if tracer response is fast…
- … or we can hope that the response is small
- the response is probably large for diffuse gas emission, e.g. Ly-$\alpha$ forest
- if the momentum transfer is small, then tracer velocities are unaffected -> the higher-derivative terms in the bias expansion of the velocity are small, and RSDs are unaffected

**Thanks!**