Characterising turbulence in clusters with X-rays

Edouard LECOQ

WHIM and Cluster Outskirts:
Lost and Found Baryons in the Local Universe

WHICH PROCESSES AND WHICH SCALES (1) ?

Injection of turbulent motions

Observation of cluster merger

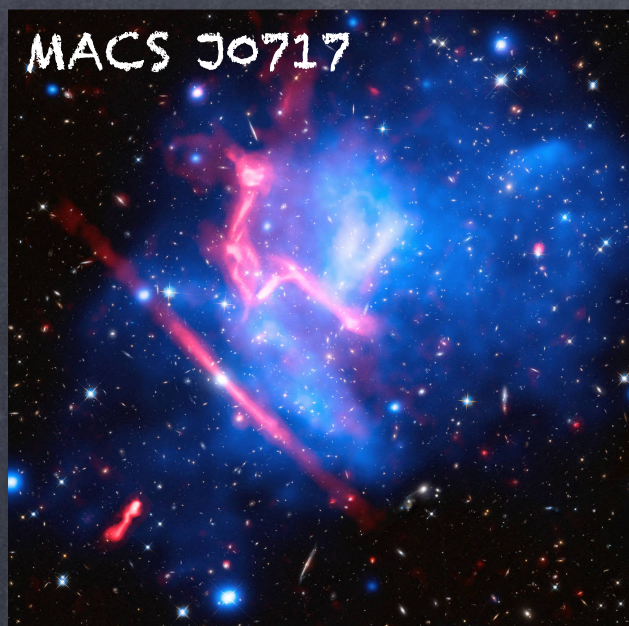
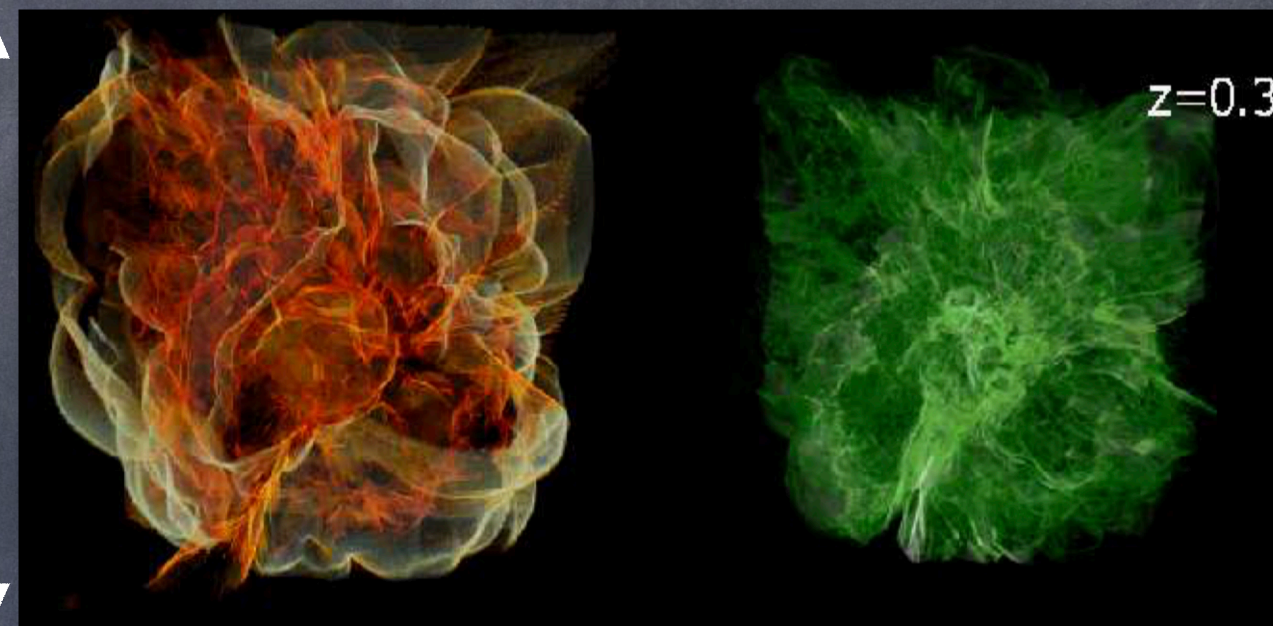


Image credit: X-ray: NASA/CXC/SAO/van
Optical: NASA/STScI; Radio: NSF/NRAO/VLA

Simulation of cluster merger

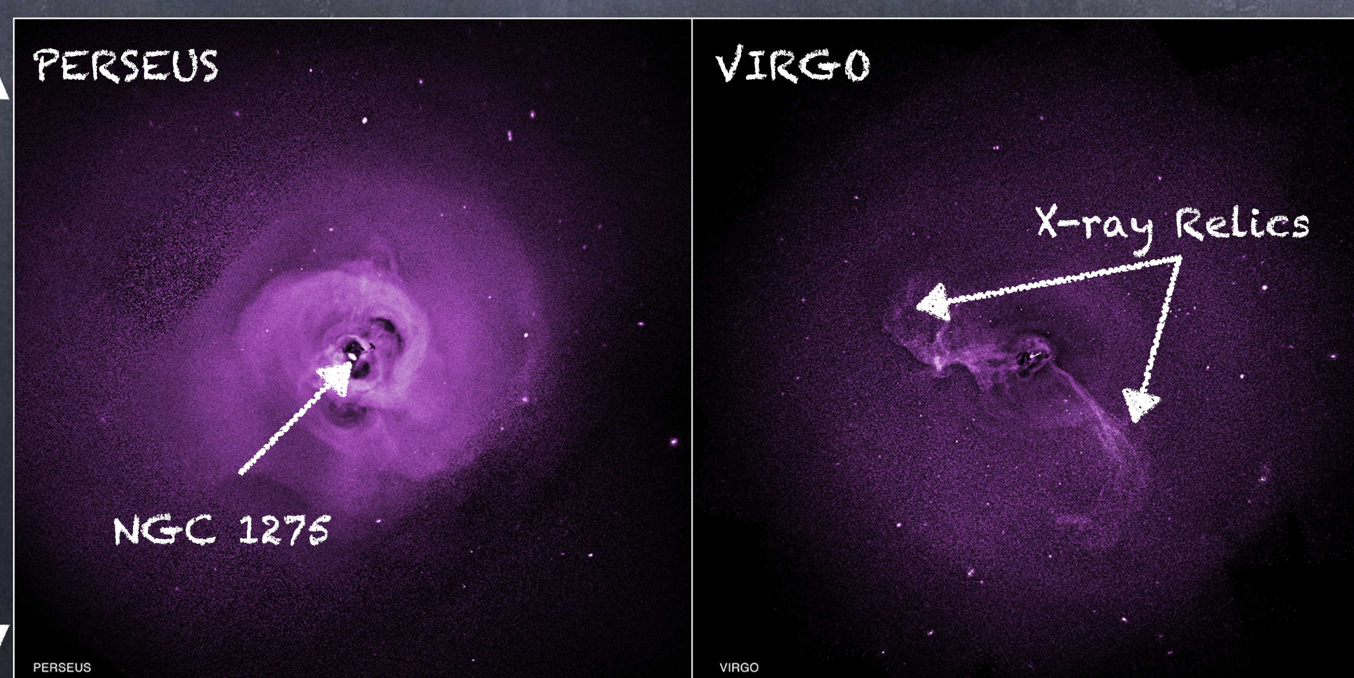
6.3 Mpc



6.3 Mpc

Vazza et al. - 2016

≈ 500 kpc



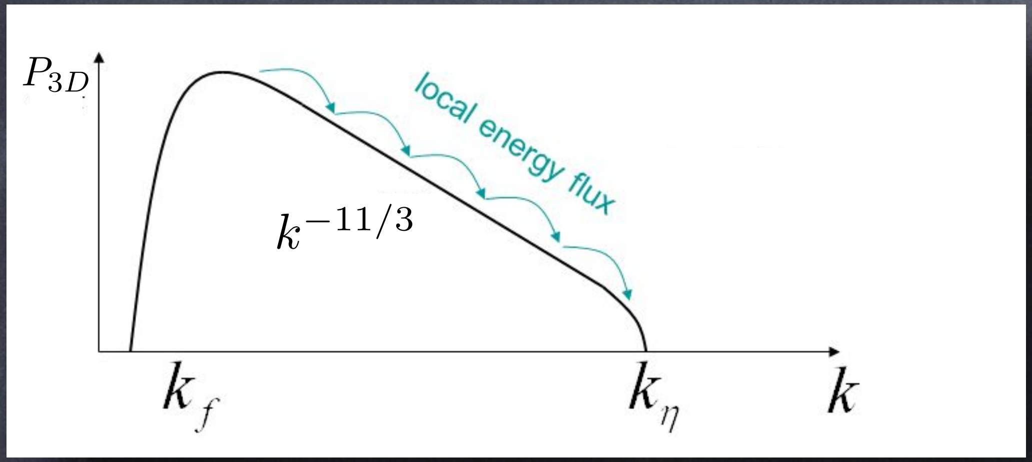
≈ 500 kpc

Image credit: X-ray: Chandra X-ray observatory

ByoPiC

WHICH PROCESSES AND WHICH SCALES (2) ?

Quantify + characterise Turbulence



Kolmogorov Spectrum

k_f Injection wavenumber

k_η Dissipation wavenumber

Detect

XARM (X-Ray Astronomy Recovery Mission)

Athena Observatory

X-Ray Facilities

WHICH PROCESSES AND WHICH SCALES (3) ?

Dissipation of turbulent motions

Simplest case

Isotropic Spitzer viscosity
+
Unmagnetised cluster plasma

→

Range of dissipation scales
$k_d \approx [10 - 50]$ kpc

(ZuHone et. al 2016)

But ICM is weakly magnetised

Since $l_{\mathrm{free,ion}} \ll r_{\mathrm{Larmor}}$ → Viscosity becomes anisotropic
(Braginskii 1965)

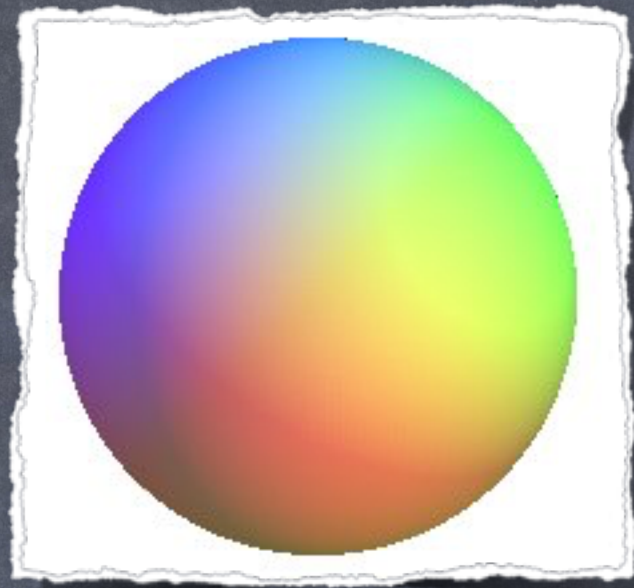
And

Given an isotropically tangled magnetic field → Viscosity reduced by a factor 5
(Nulsen and McNamara 2013)

ByoPiC

Cosmological Context

Nowadays →



A cluster is a sphere
at
Hydrostatic Equilibrium

$$\frac{dP_{th}}{dr} = -\frac{GM(r)\rho(r)}{r^2}$$

In the scope of this approximation

$$\boxed{M_X = -\frac{k_B T(r) r}{\mu m_p G}\left(\frac{\mathrm{d}ln(\rho(r))}{\mathrm{d}ln(r)} + \frac{\mathrm{d}ln(T(r))}{\mathrm{d}ln(r)}\right)}$$

However : The measure mass due to lensing

$$\boxed{M_{lens} = M_{true} = (1-b)M_X}$$

b : mass bias

ByoPiC

Add non-thermal processes $\longrightarrow$ $\frac{d(P_{th}+P_{n-th})}{dr} = -\frac{GM(r)\rho(r)}{r^2}$

$$\boxed{M_X = -\frac{k_B T(r) r}{\mu m_p G}\left(\frac{\mathrm{d}ln(\rho(r))}{\mathrm{d}ln(r)} + \frac{\mathrm{d}ln(T(r))}{\mathrm{d}ln(r)} + \frac{P_{n-th}}{P_{th}}\frac{\mathrm{d}ln(P_{th}(r))}{\mathrm{d}ln(r)}\right)}$$

$$M_X + \underbrace{\frac{k_B T(r) r}{\mu m_p G}\frac{P_{n-th}}{P_{th}}\frac{\mathrm{d}ln(P_{th}(r))}{\mathrm{d}ln(r)}}_{\propto -b} = \underline{-\frac{k_B T(r) r}{\mu m_p G}\left(\frac{\mathrm{d}ln(\rho(r))}{\mathrm{d}ln(r)} + \frac{\mathrm{d}ln(T(r))}{\mathrm{d}ln(r)}\right)}$$

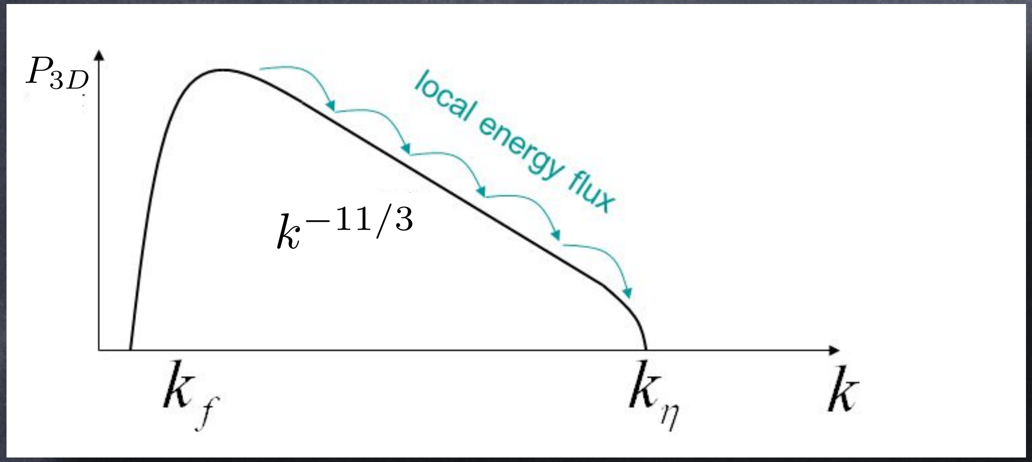
Candidate for (part of) the mass bias

Overestimate of the "true mass"

ByoPiC

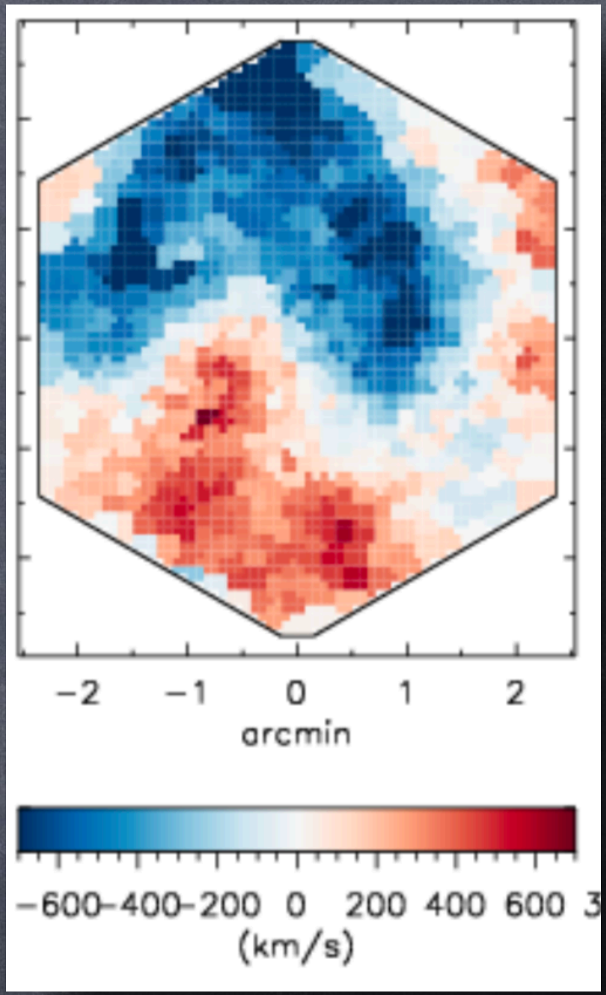
STUDY THE DETECTABILITY OF TURBULENCE TROUGH THOSE NEW GENERATION X-RAY SATELLITES

Theory



Kolmogorov Spectrum $P_{3D} = |\tilde{v}_{3d}|^2(\vec{k})$

Observable



Roncarelli et al. 2018

Centroid velocities

$$\bar{v}_z(r_\perp) = \int v_{3d}(r_\perp, r_z)\omega(r_\perp, r_z)\mathrm{d}r_z$$

Where $\omega(r_\perp, r_z)$ is the normalised emissivity

How do I retrieve k_{inj} and k_{diss} from the observable?

What is the relation from $P_{3D}(k_{3d})$ to $P_{2D}(k_\perp)$? (1)

Due to the sensitivity of the current X-ray telescopes

Observation limited to the central regions

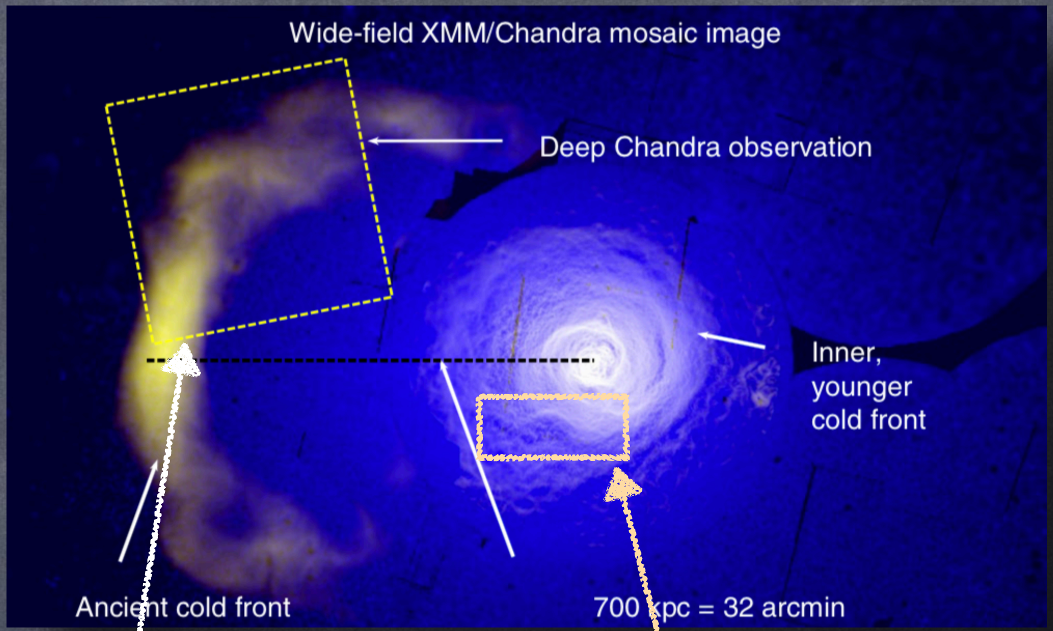
$$P_{2D}(k_\perp; x, y) = P_{3D}(k_\perp) \int P_\omega(k_z; x, y)\, dk_z$$

(Churazov et al. 2012)

(Zhuravleva et al. 2012)

(ZuHone et al. 2016)

BUT



(Walker et al. 2018)

Old Cold Front consequent of passing by cluster that agitated the ICM

(ZuHone et al. 2011)

Potential Kelvin Helmholtz instability in the sloshing cold front

(Walker et al. 2017)

What is the relation from $P_{3D}(k_{3d})$ to $P_{2D}(k_\perp)$? (2)

With new X-Ray satellite → Better sensitivity

From $\bar{v}_z(r_\perp) = \int v_{3d}(r_\perp, r_z)\omega(r_\perp, r_z)\mathrm{d}r_z$

Full 3D Fourier transform

$$\langle P_{2D}(\vec{k}_\perp)\rangle_S = \int d^2\vec{k}_{\perp_1} dk_{z_1} P_{3D}\left(\sqrt{k_{\perp_1}^2 + k_{z_1}^2}\right) P_\omega(\vec{k}_\perp - \vec{k}_{\perp_1}, k_{z_1})$$

Emissivity weighted line of sight velocity power spectrum
=
Centroid velocity power spectrum

Velocity power spectrum (described by a Kolmogorov spectrum)

Emissivity power spectrum

Computation of the emissivity power spectrum

Taking $$n_e = \left(1 + \left(\frac{r}{r_c}\right)^2\right)^{-3\beta/2}$$

r_c the cluster core radius

$\beta = 2/3$

We can define $$\omega(r_\perp, r_z) = \frac{n_e^2(r_\perp, r_z)}{\int n_e^2(r_\perp, r_z)\ dz}$$

In the coordinate system

$$(r_\perp = \sqrt{x^2+y^2}, \theta, z)$$

We got $$\omega(r_\perp, z) = \frac{2}{\pi} \frac{(r_c^2 + r_\perp^2)^{3/2}}{(r_c^2 + r_\perp^2 + z^2)^2}$$

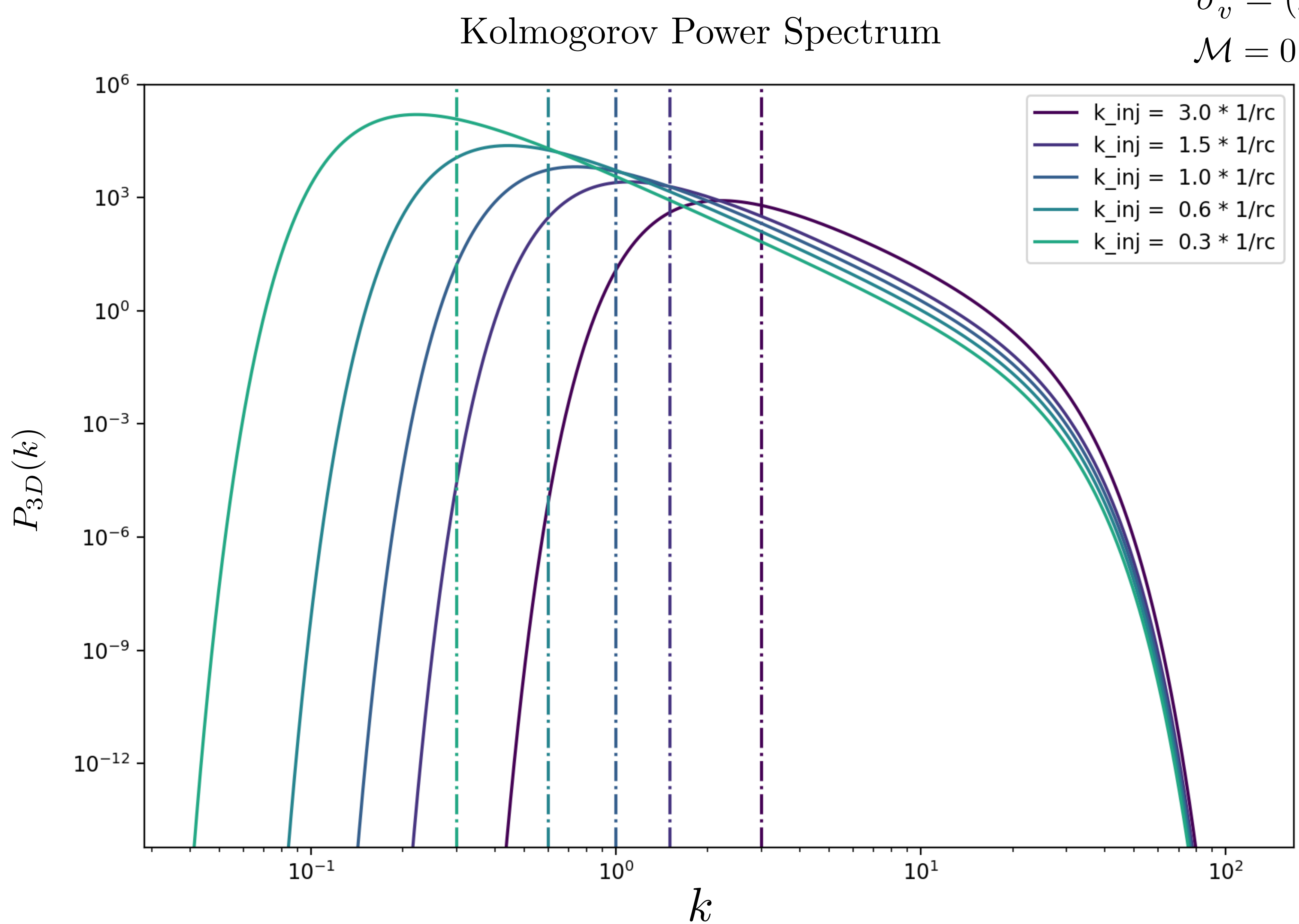
Taking the squared amplitude of its Fourier transform

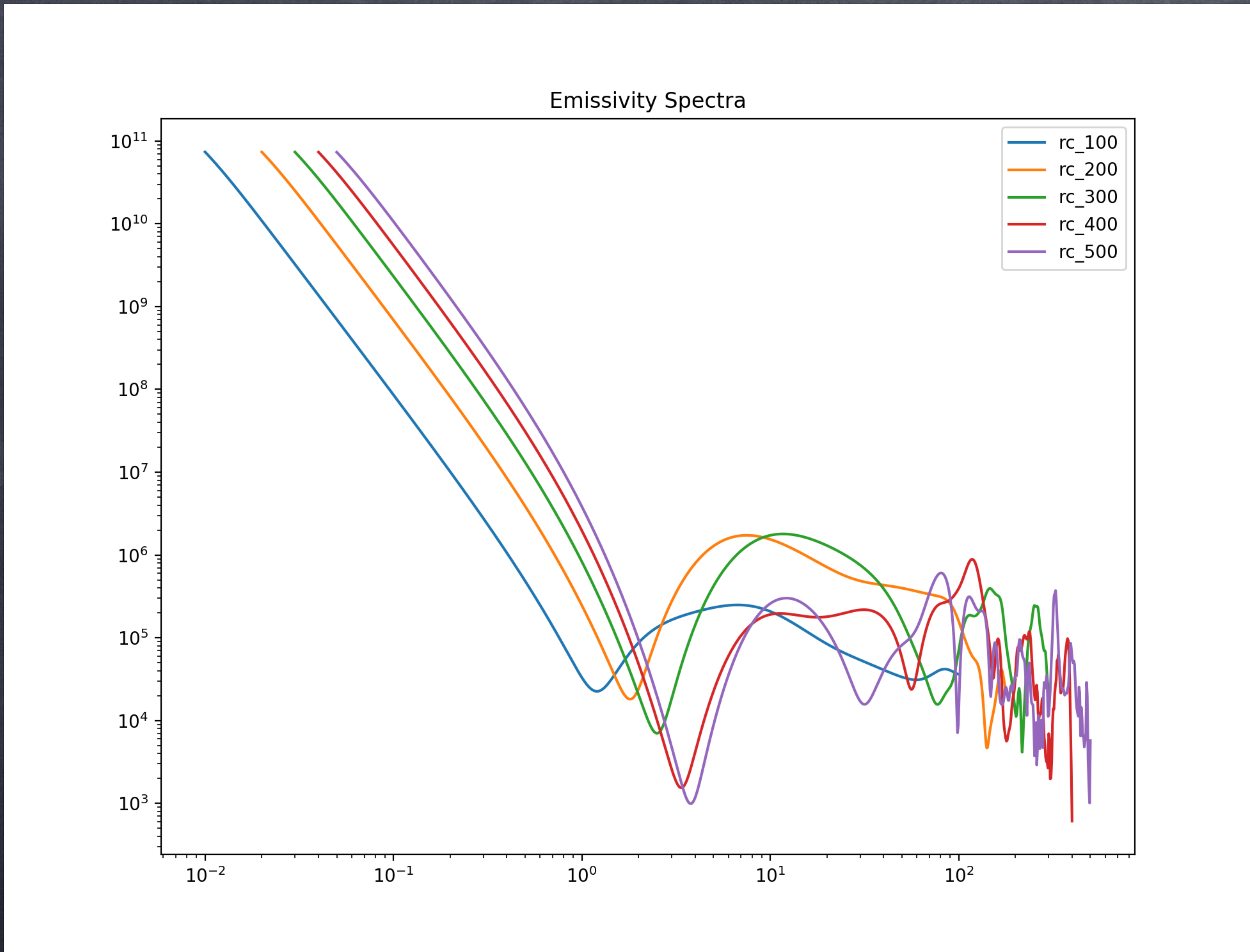
$$P_\omega(k_\perp, k_z) = |\tilde{\omega}(k_\perp, k_z)|^2 = \frac{1}{2\pi}\left(\int_{r_c}^{+\infty} (|c^2 k_z| + c)\ J_0\left(k_\perp (c^2 - r_c^2)^{1/2}\right) e^{-|ck_z|} dc\right)^2$$

ByoPiC

$\sigma_v^2 = (\mathcal{M}\ c_s)^2$

$\mathcal{M} = 0.3$



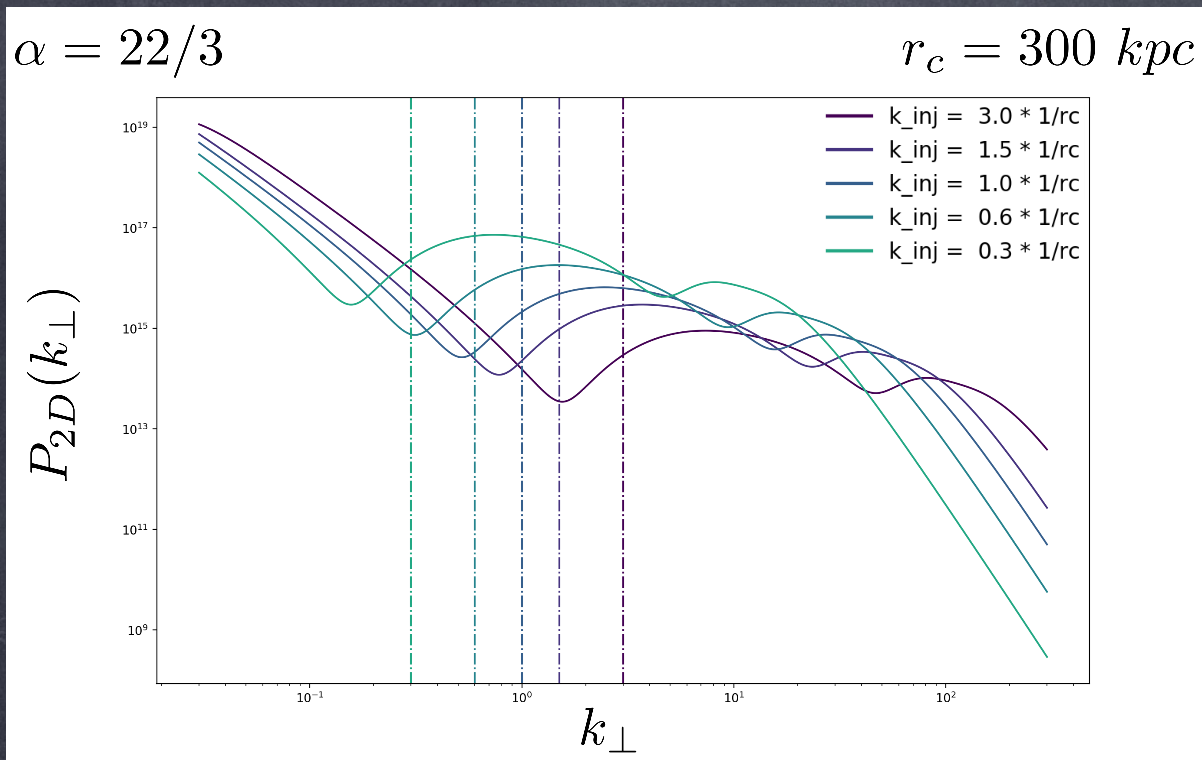


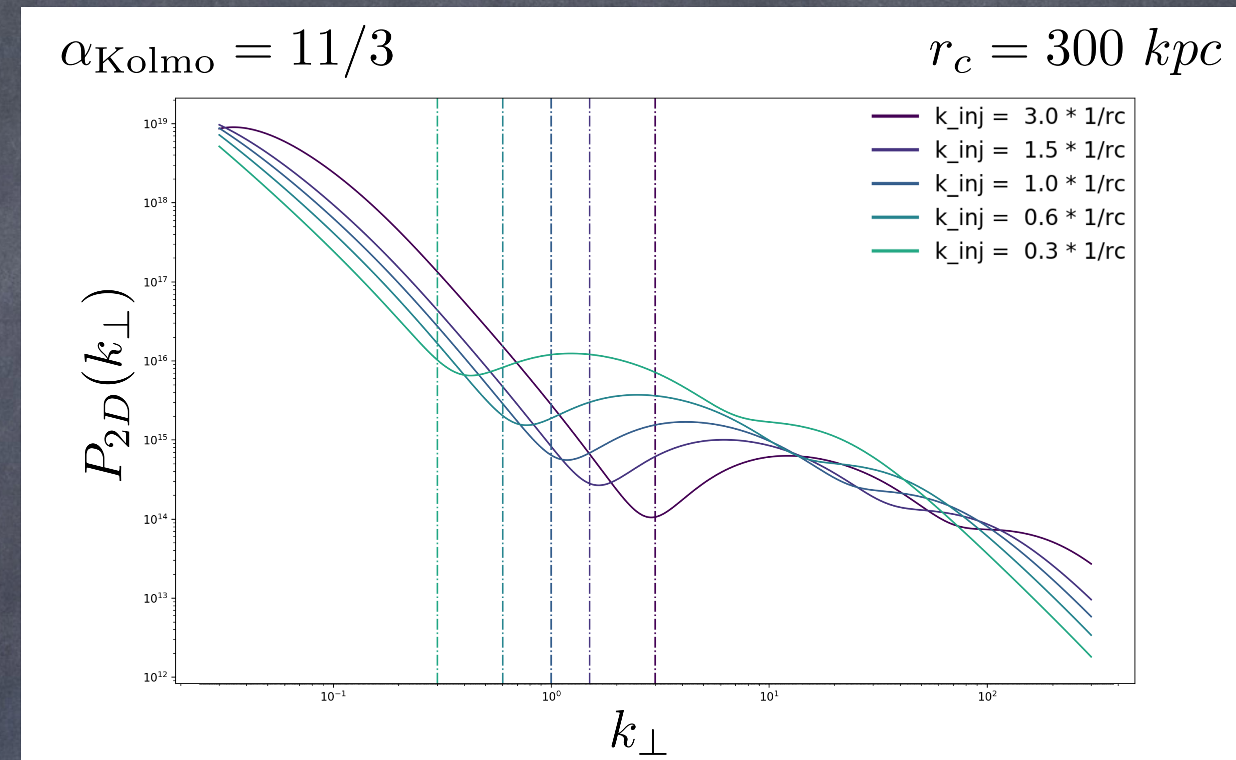
Preliminary

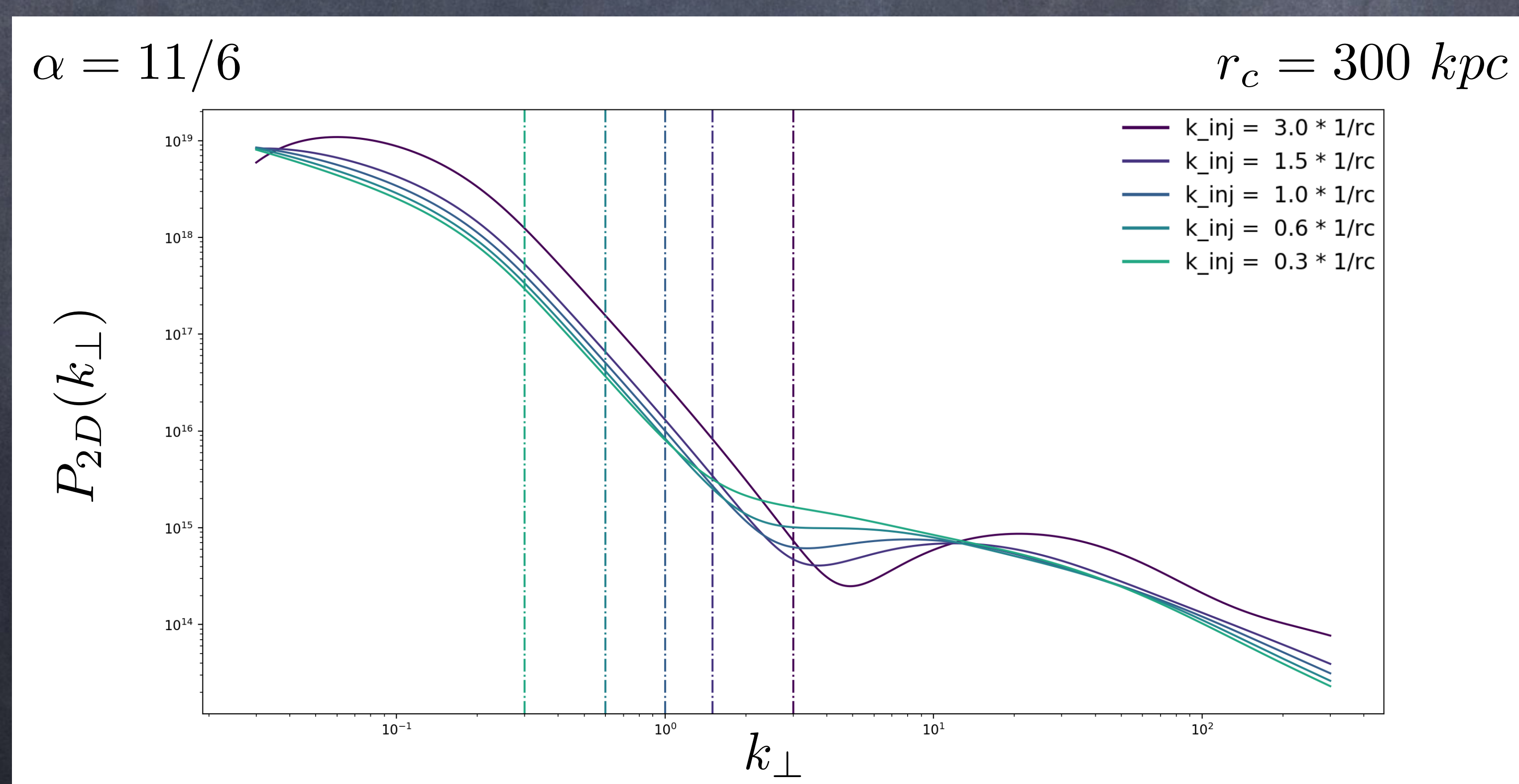
$$\int_0^\infty P_\omega(k_\perp, k_z)\, dk_z = \int_0^\infty |\tilde{\omega}(k_\perp, k_z)|^2\, dk_z = \int_0^\infty \frac{1}{2\pi} \left(\int_{r_c}^\infty (|c^2 k_z| + c)\ J_0 \left(k_\perp (c^2 - r_c^2)^{1/2} \right) e^{-|ck_z|} dc \right)^2 dk_z$$

ByoPiC

Variations with the spectral index

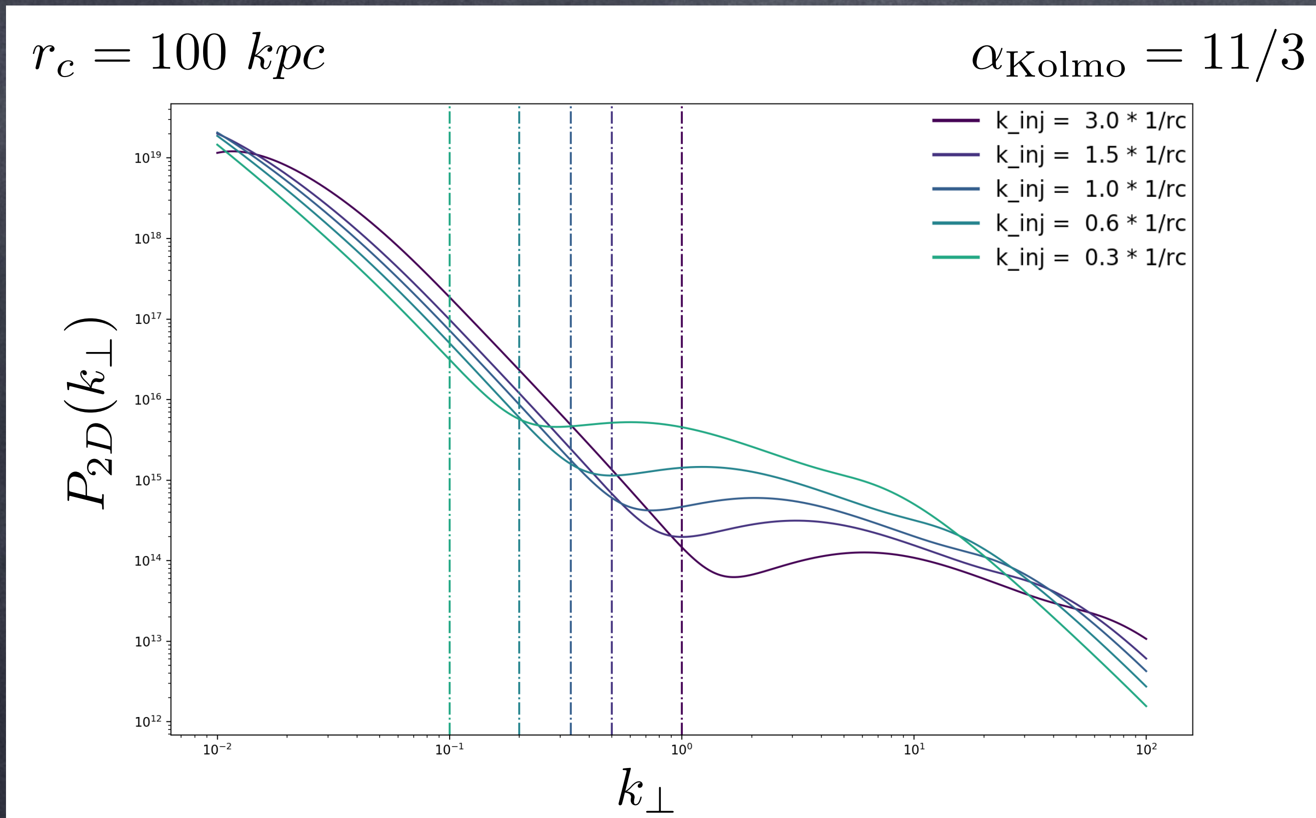


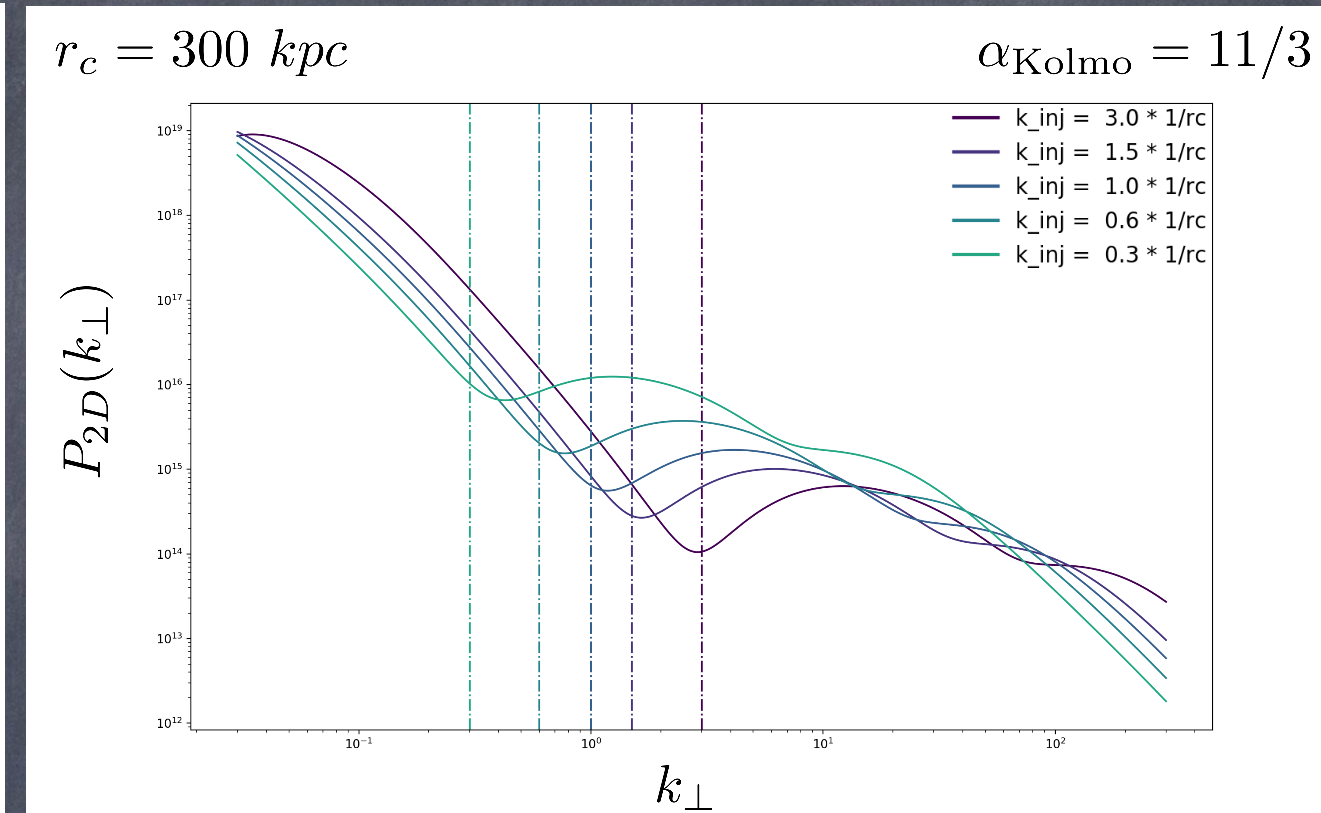


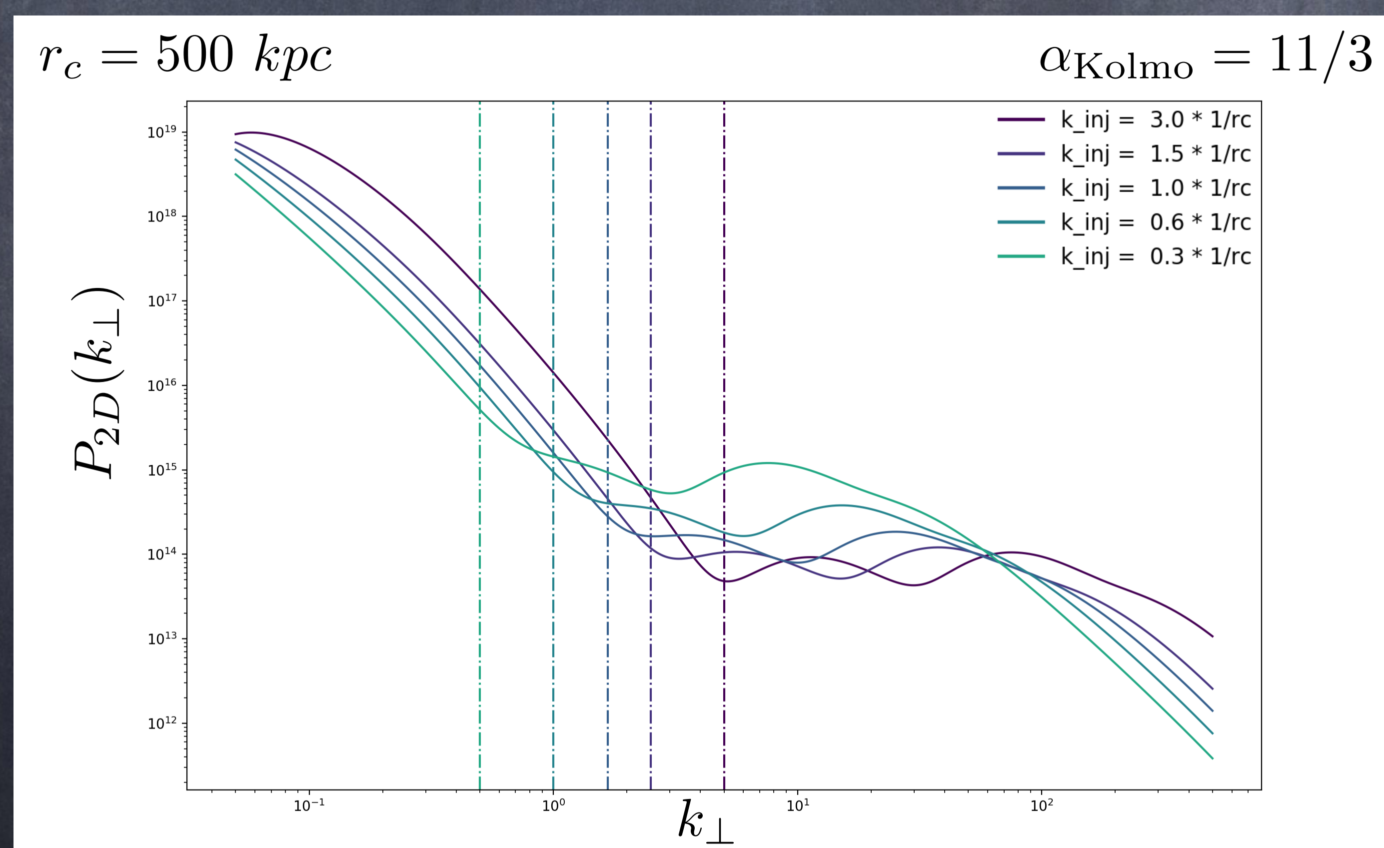


Preliminary

Variations with the core radius

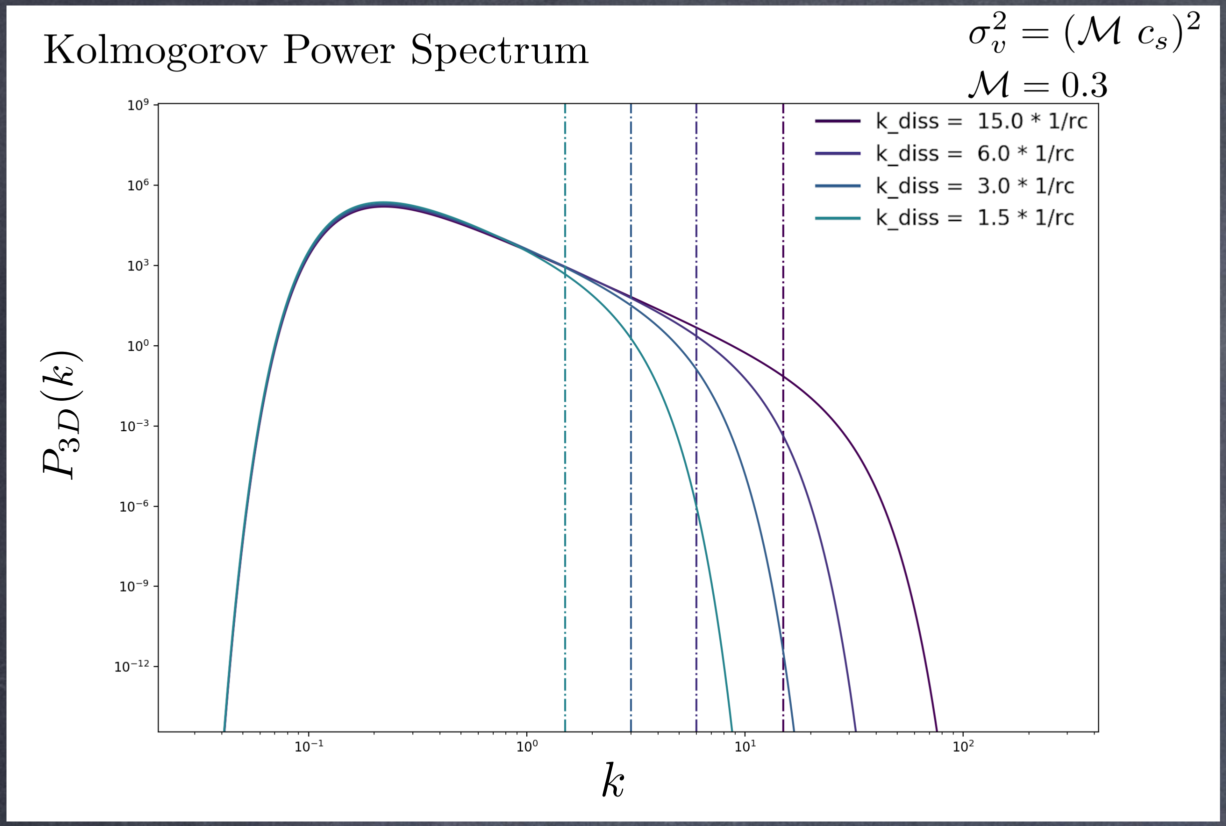




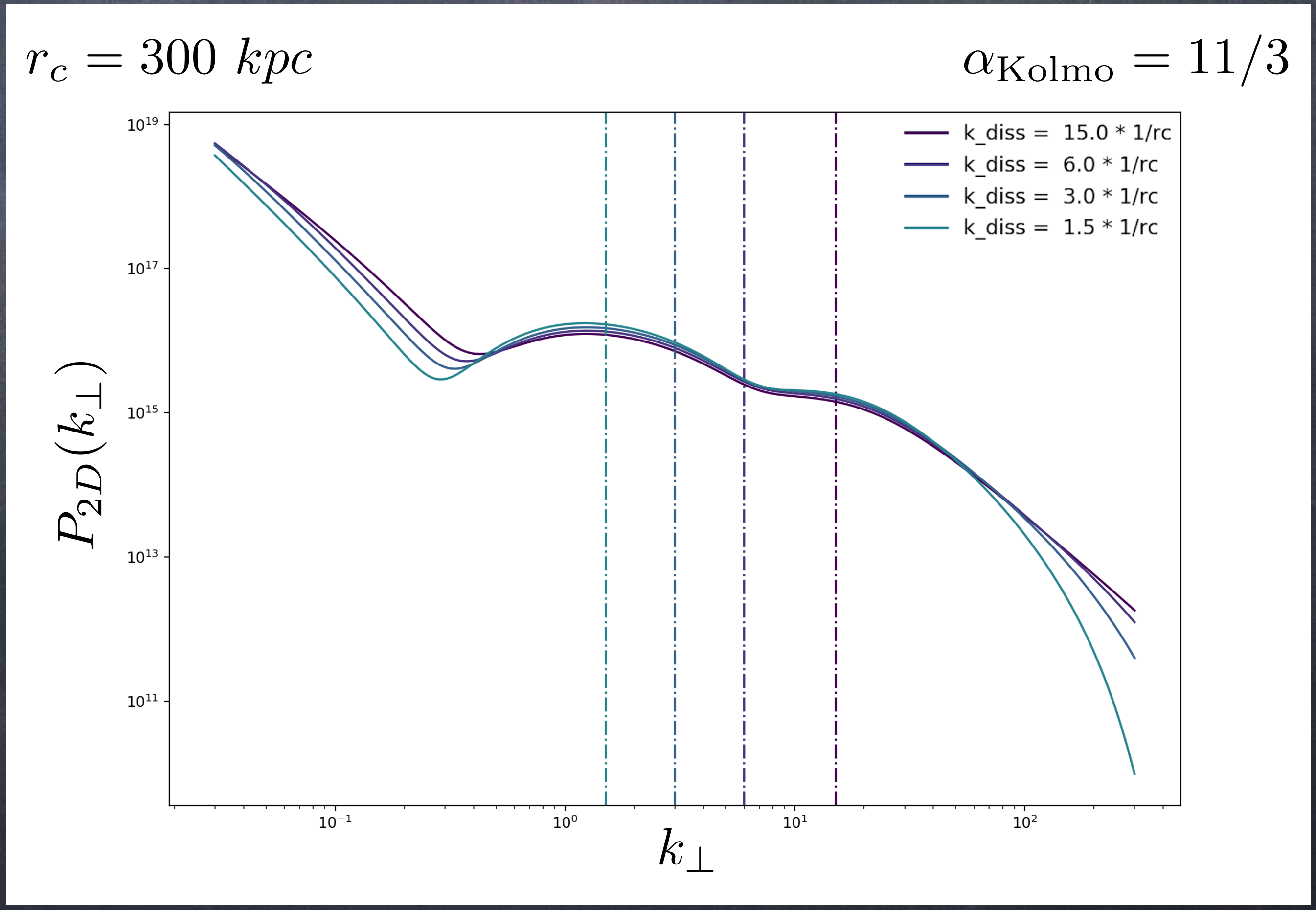


Preliminary

What about dissipation scales ?



Preliminary



Unlikely to probe the dissipation scales

ByoPiC

The Structure Function

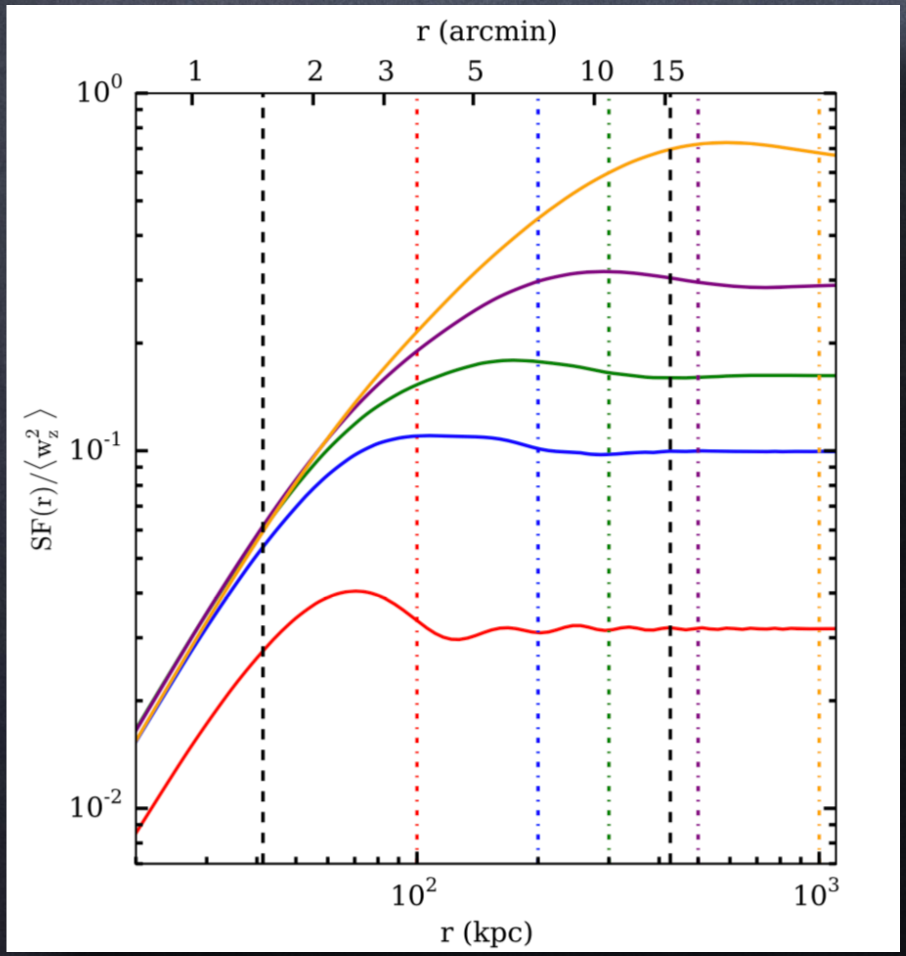
$$SF(r_\perp) = \left\langle \left|\bar{v}_z(\chi_\perp + r_\perp) - \bar{v}_z(\chi_\perp)\right|^2 \right\rangle_{r_\perp}$$

Prediction

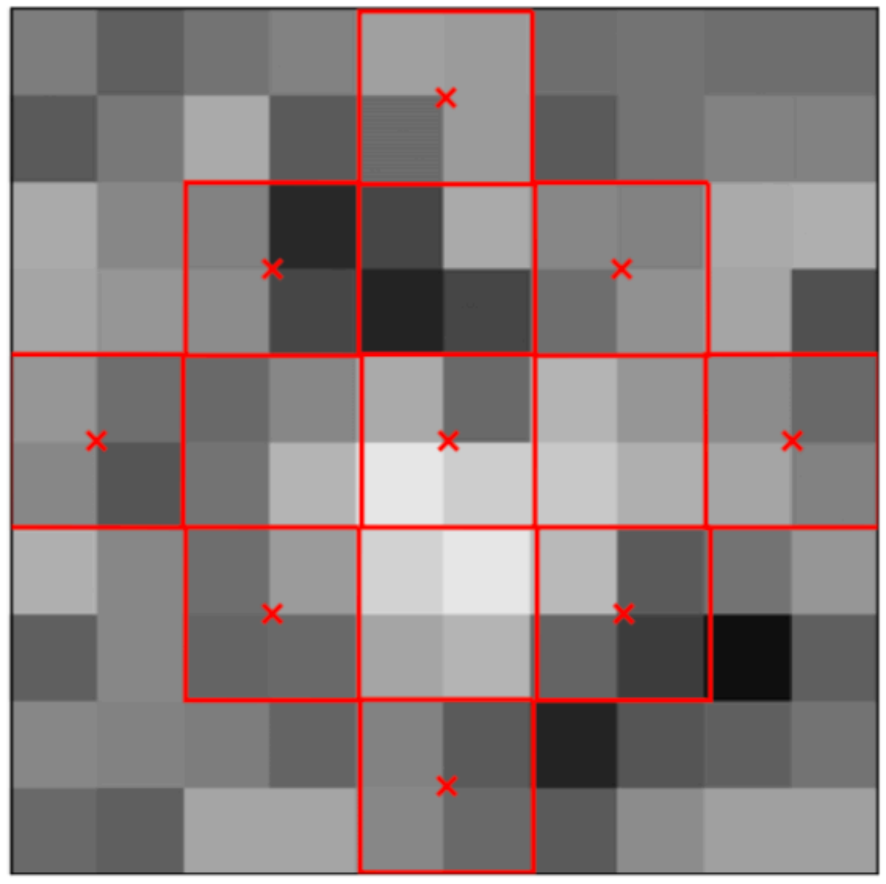
$$SF(r) = 4\pi \int_0^\infty (1 - J_0(2\pi k_\perp r)) P_{2\mathrm{D}}(k_\perp) k_\perp dk_\perp$$

$$P_{2\mathrm{D}}(k_\perp) = |\tilde{\bar{v}}_z(k_\perp)|^2$$

(ZuHone et. al 2016)



Reconstruction



(ZuHone et. al 2016)

Mock observation of the velocity centroid for Astro-H satellite resolution

ByoPiC

Conclusion and Prospects

We have shown that:

Dinstiguishe between various dissipation scale ✗

Dinstiguishe between various injection scale ✓ For Kolmogorov spectrum

BUT

Maybe not the best statistics → Look at the Structure Function

Cluster density is irregular → Add density fluctuation to the model

Take into account the instruments response → Statistical and systematics errors

ByoPiC

THANKS !