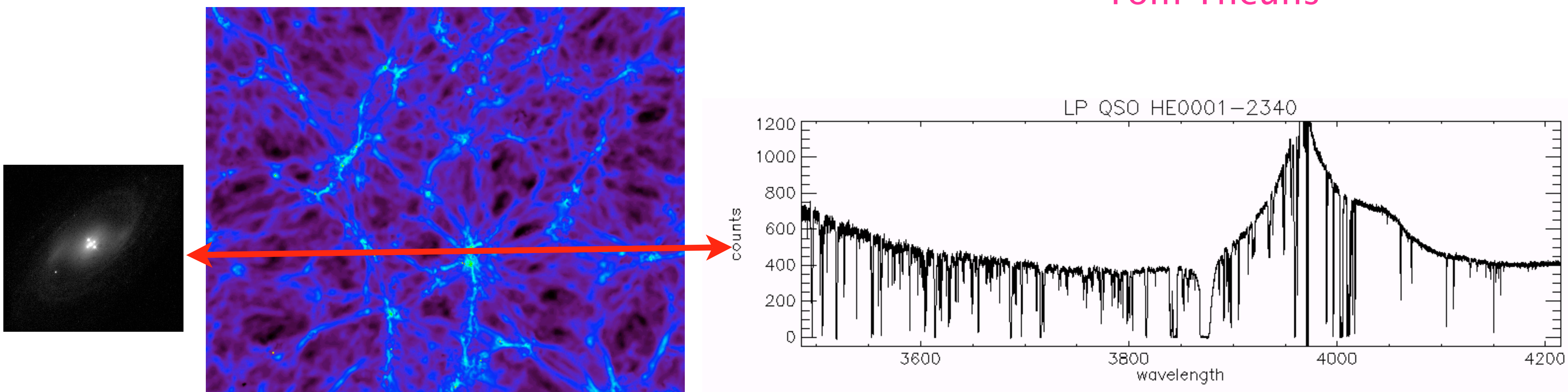
Durham University

Observing and simulating the Lyman-alpha forest

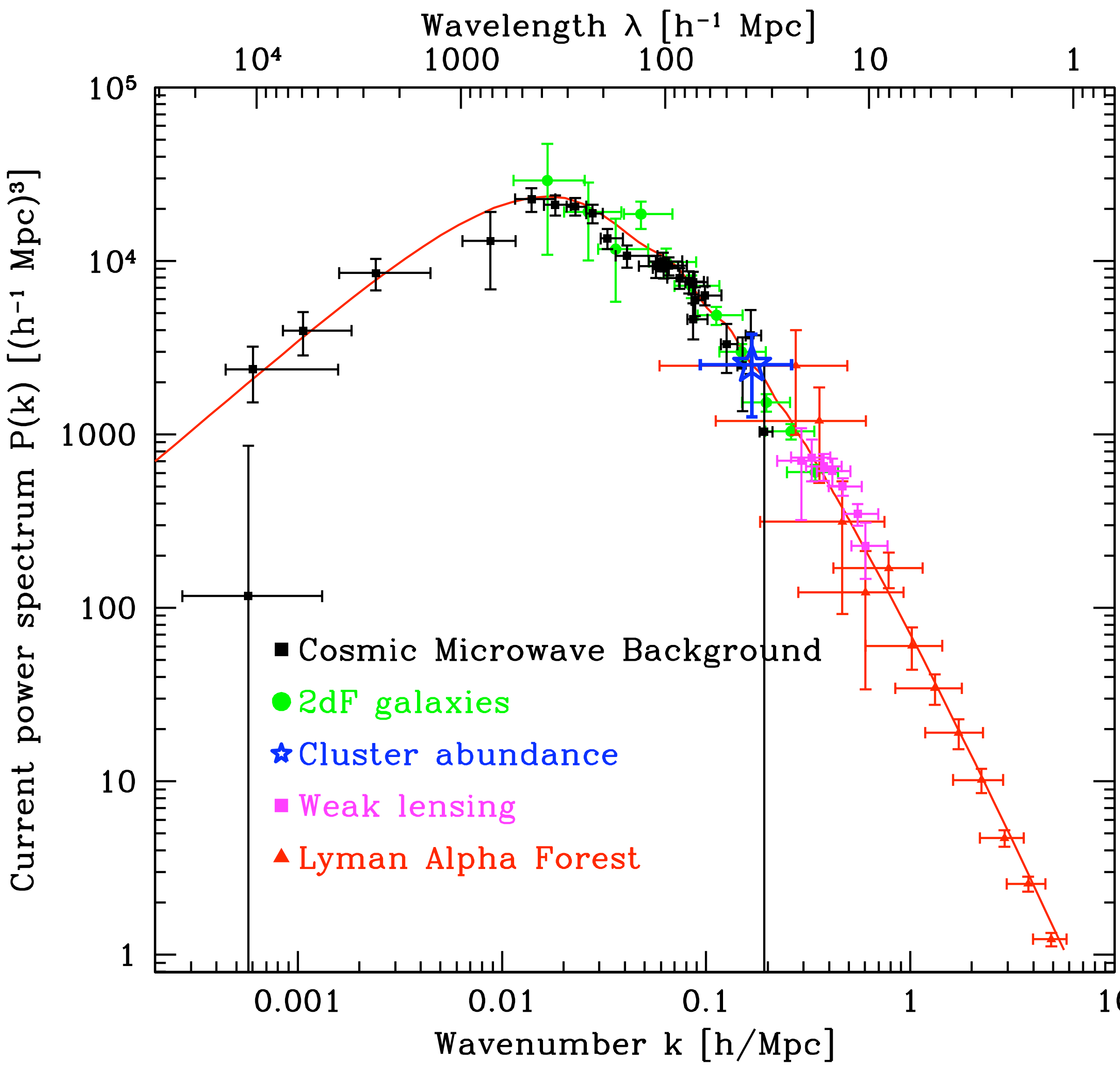
Tom Theuns

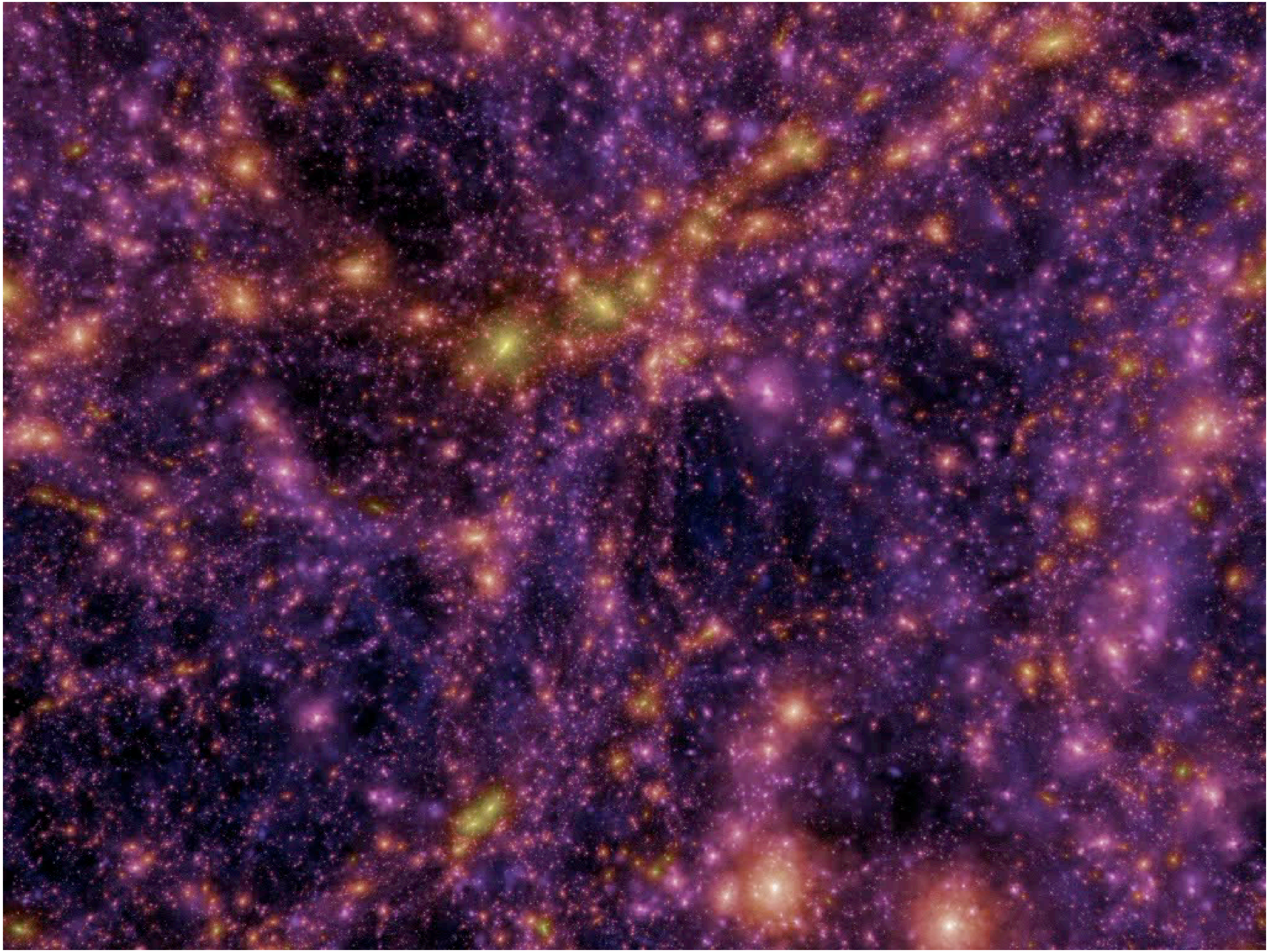


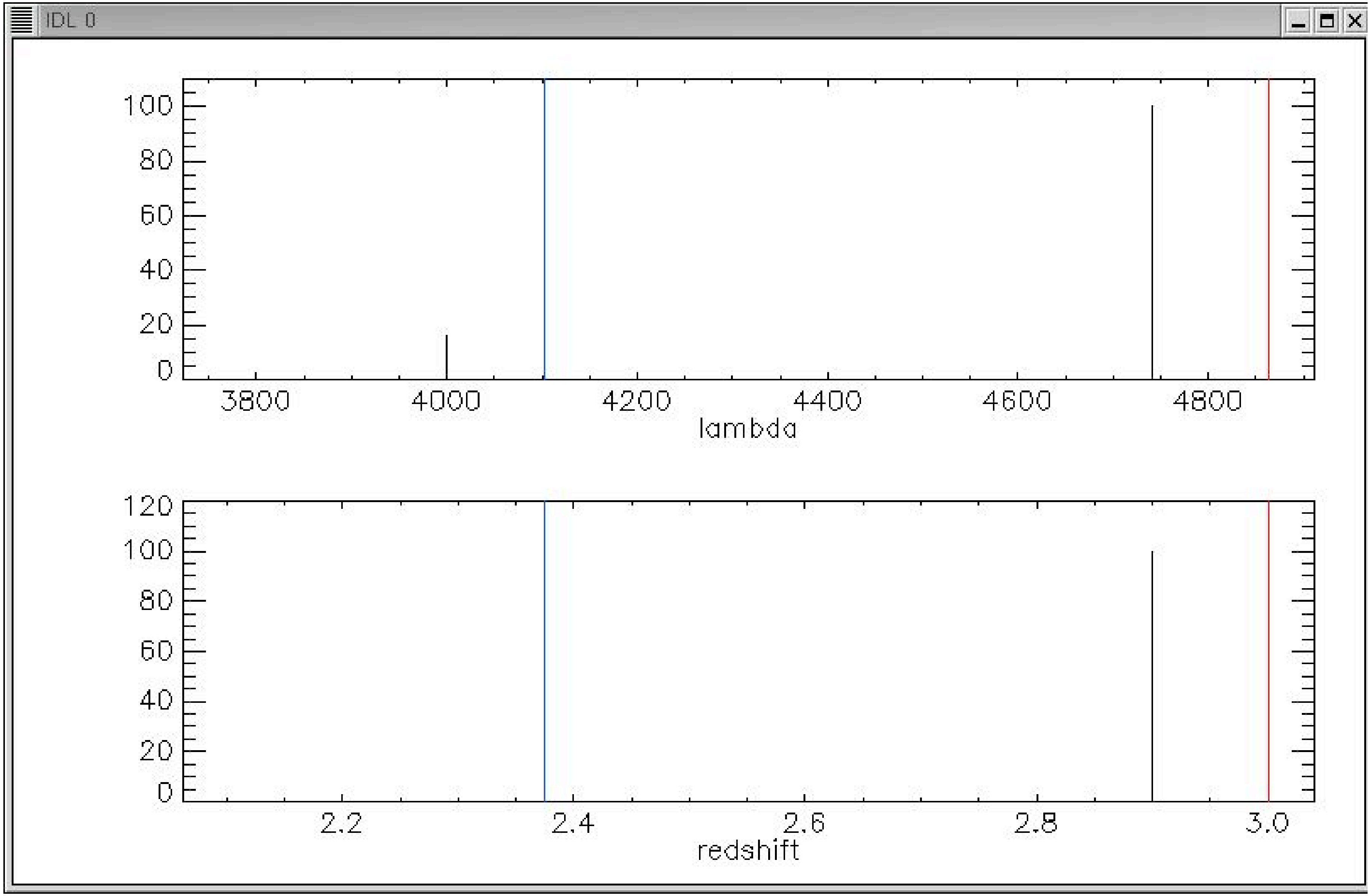
- Introduction
- Current observations
- Simulating the forest

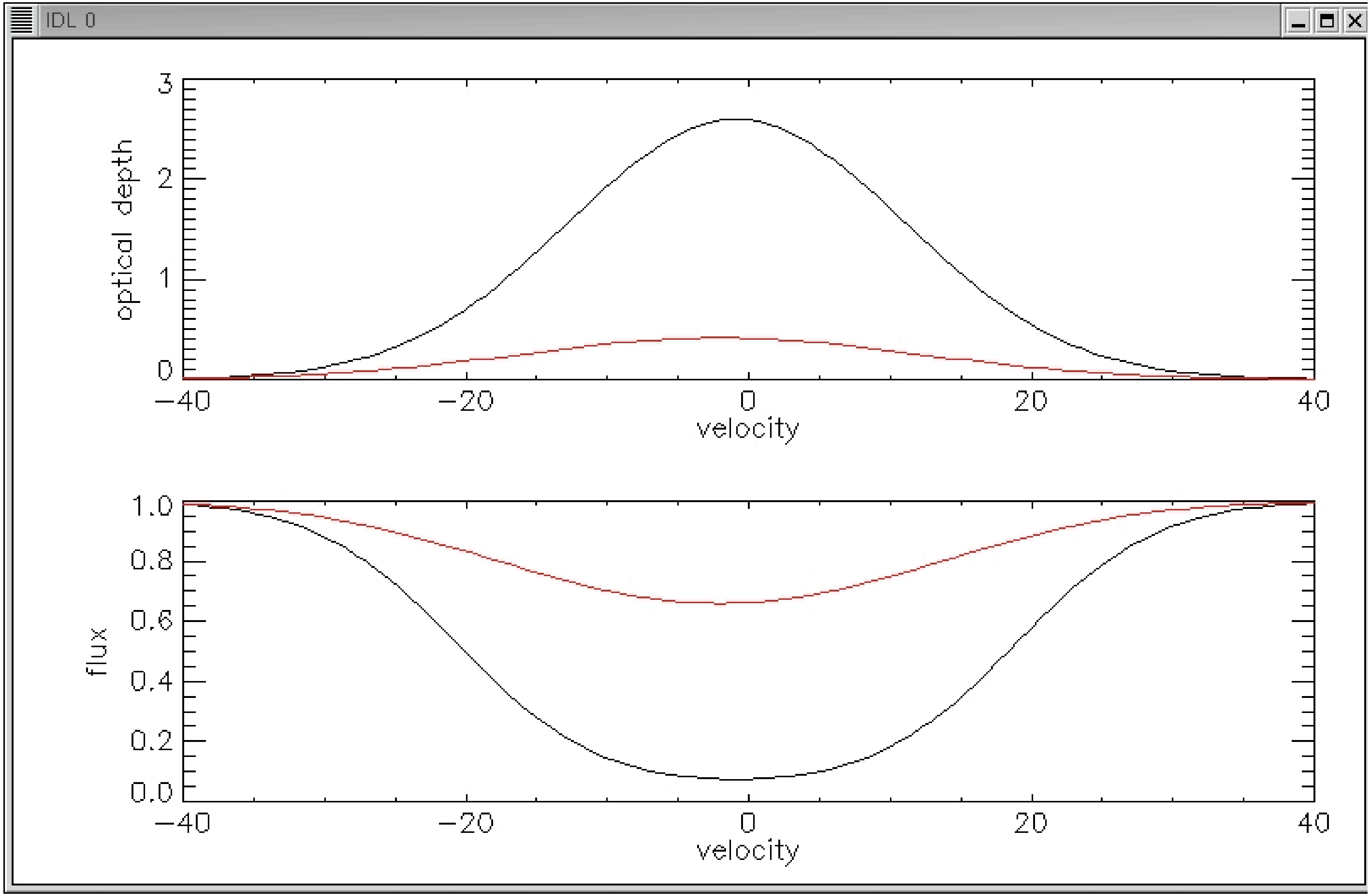
Separating the Early Universe from the Late Universe: cosmological parameter estimation beyond the black box

Max Tegmark[1] & Matias Zaldarriaga[2,3]

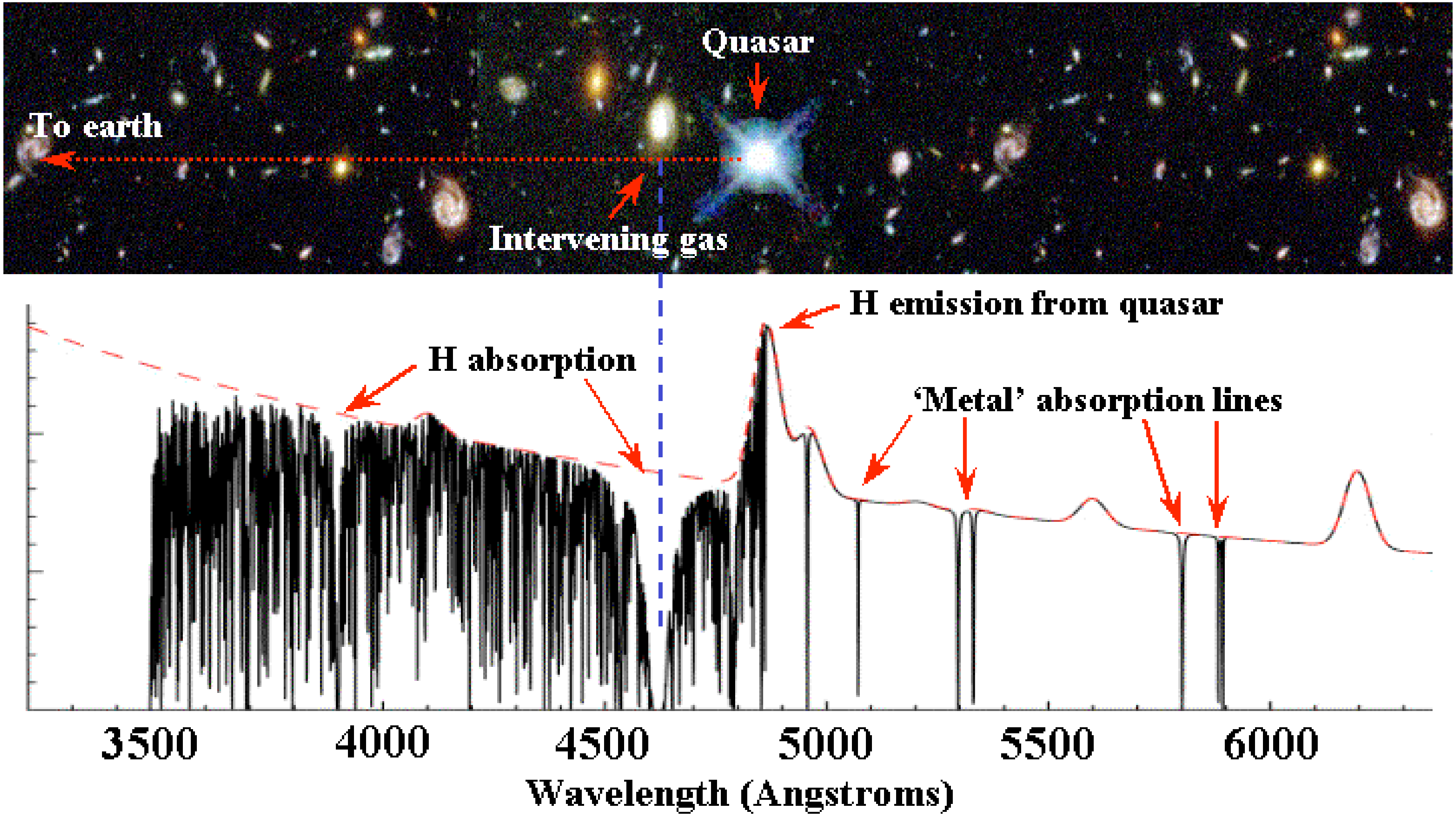


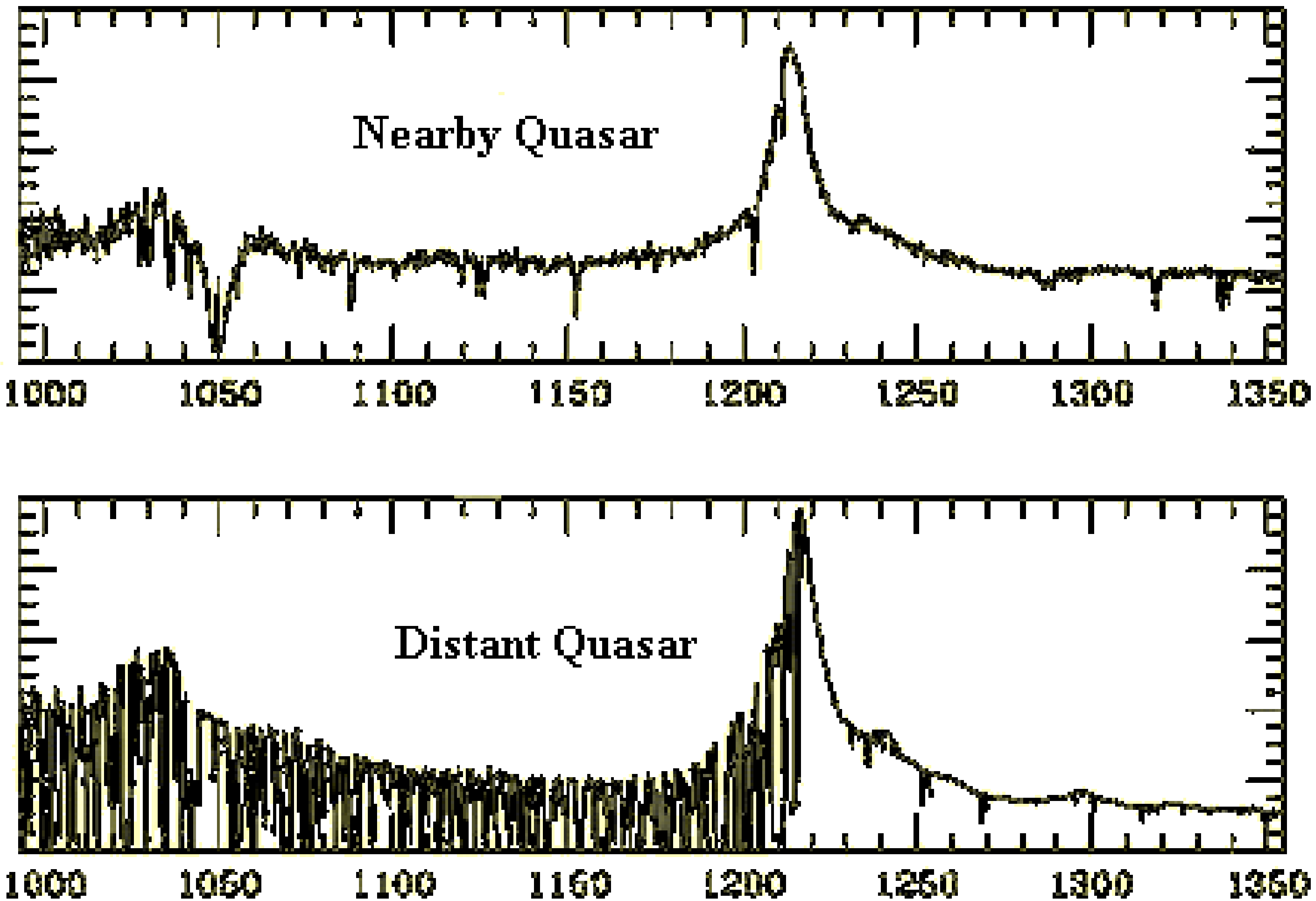



IDL 0
100
80
60
40
20
0
3800
4000
4200
4400
4600
4800
lambda
120
100
80
60
40
20
0
2.2
2.4
2.6
2.8
3.0
redshift

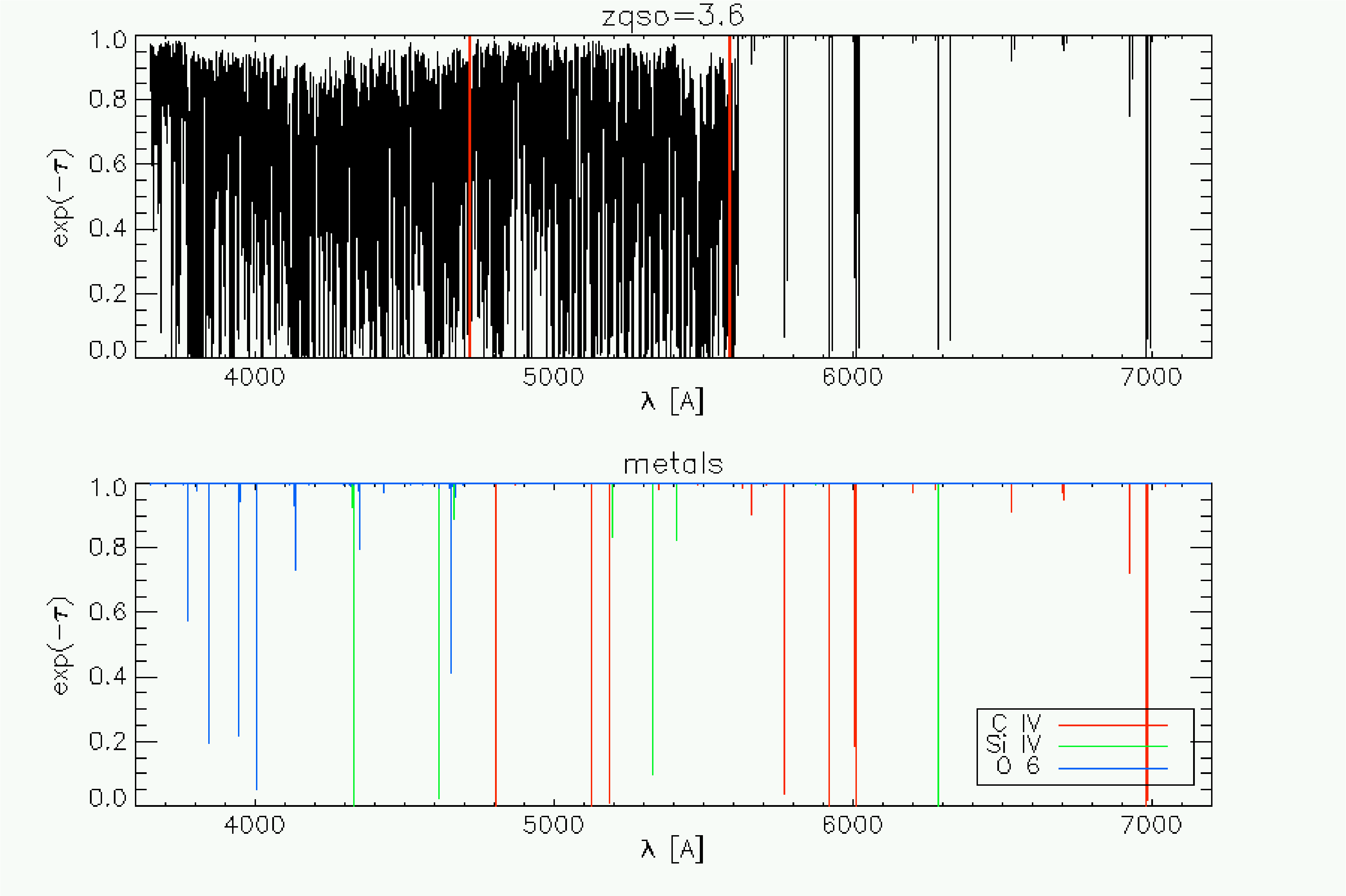


IDL 0
optical depth
3
2
1
0
−40
−20
0
20
40
velocity
flux
1.0
0.8
0.6
0.4
0.2
0.0
−40
−20
0
20
40
velocity

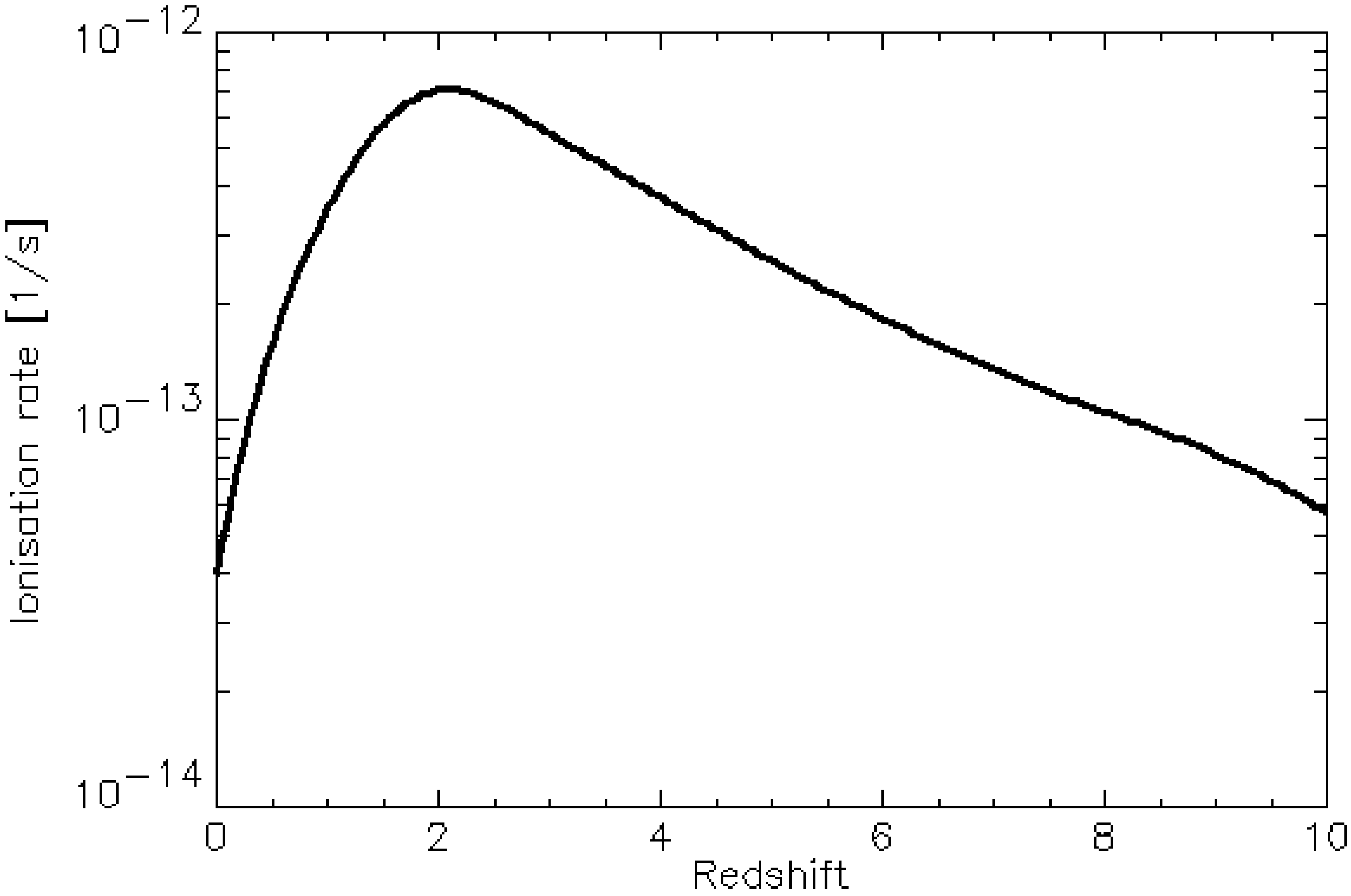

Quasar
To earth
Intervening gas
H emission from quasar
H absorption
'Metal' absorption lines
3500
4000
4500
5000
5500
6000
Wavelength (Angstroms)


Nearby Quasar
1000
1050
1100
1150
1200
1250
1300
1350
Distant Quasar
1000
1050
1100
1150
1200
1250
1300
1350

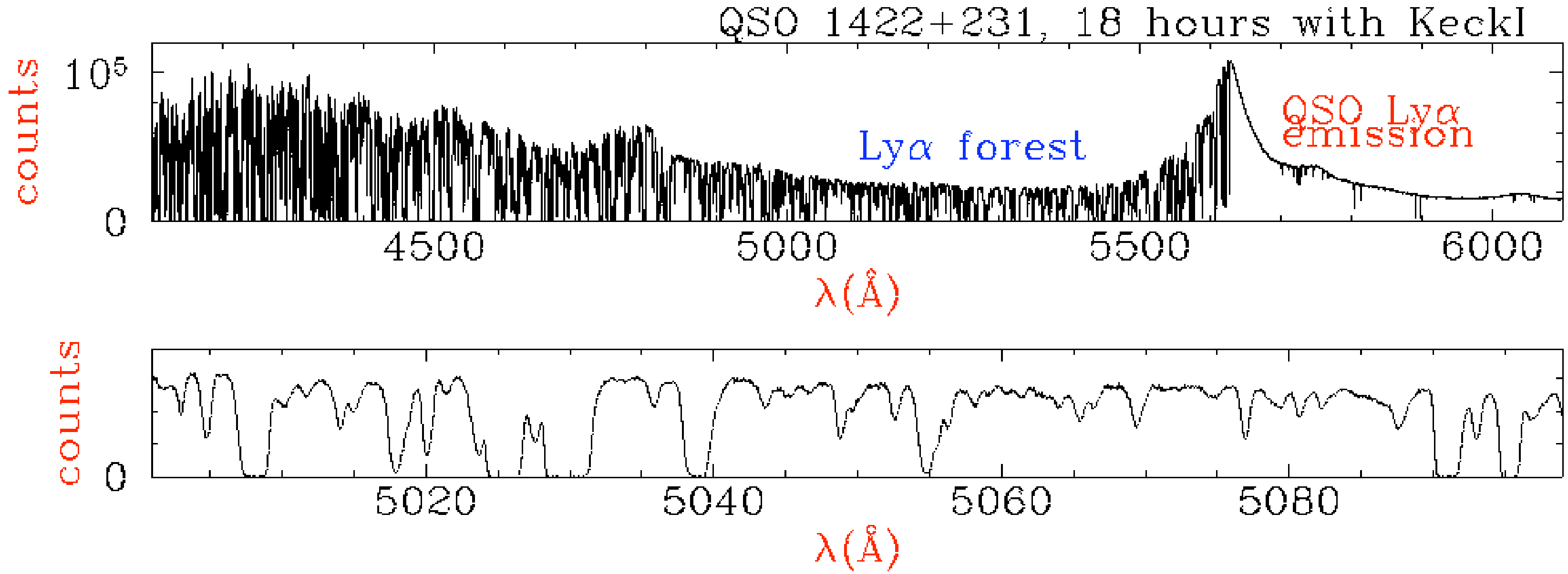
Simulated absorption spectrum

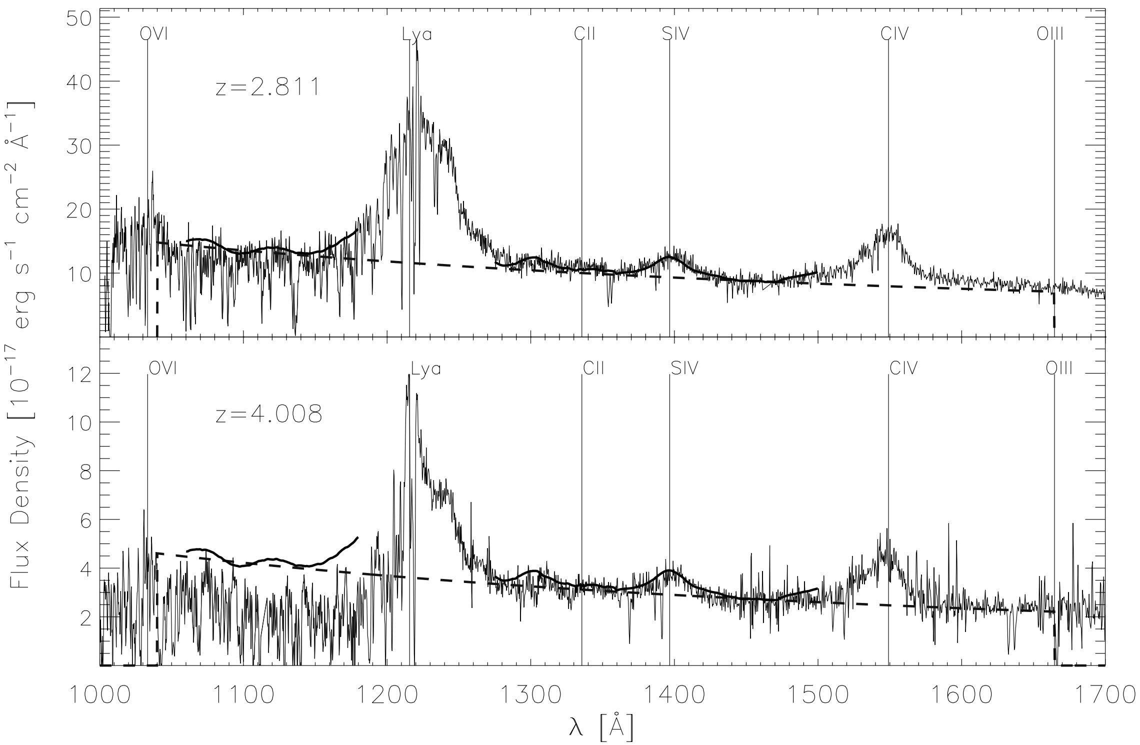


The IGM is highly ionized



Ionization rate from galaxies & QSOs as computed by Haardt & Madau 2001





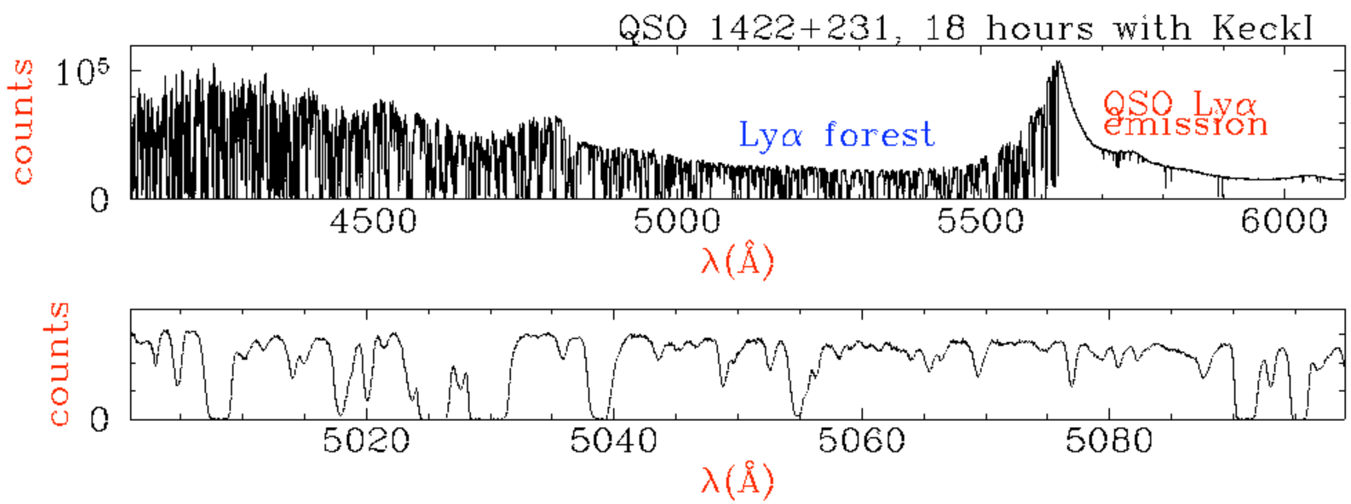
High-resolution (Keck, VLT)

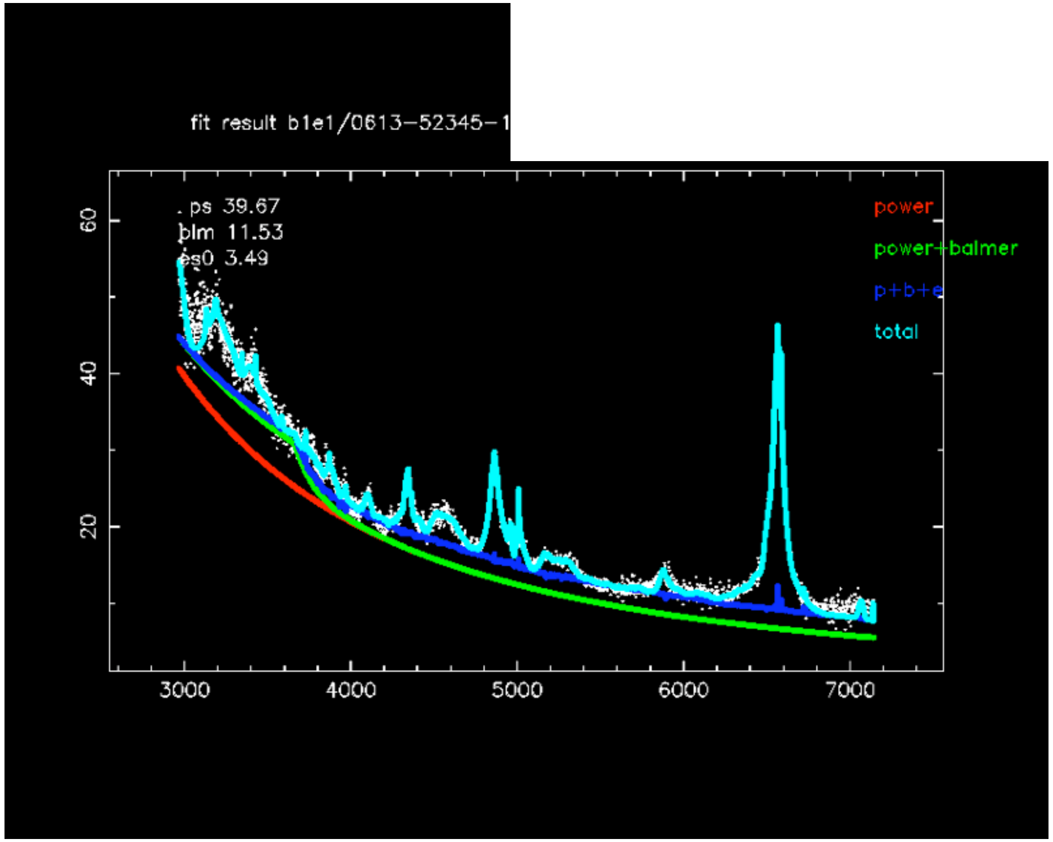
Low-resolution (SDSS)

Some Issues:

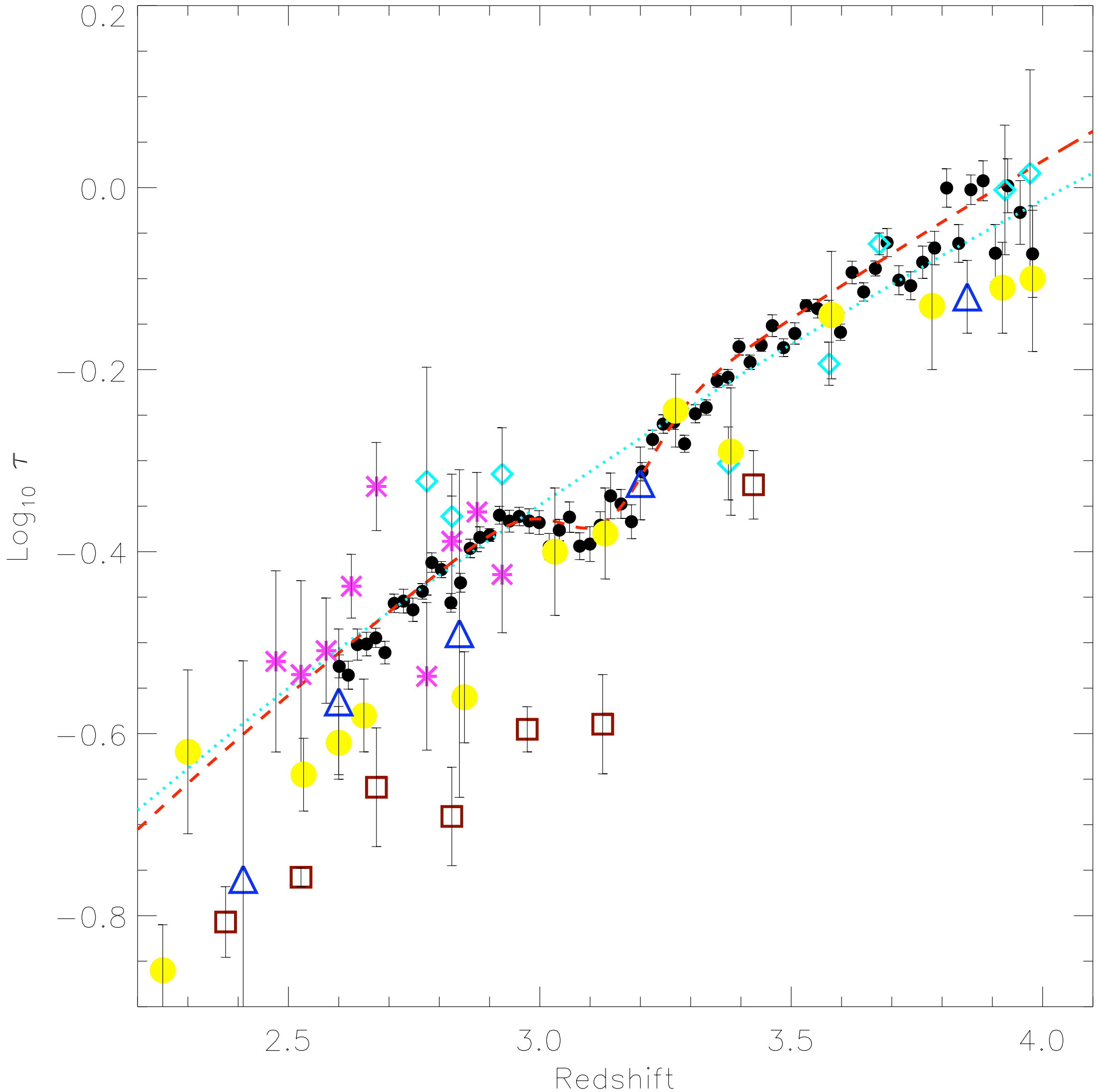
- Continuum fitting
- Noise properties
- Are all lines Hydrogen?
- Are all lines cosmological?

Continuum fit





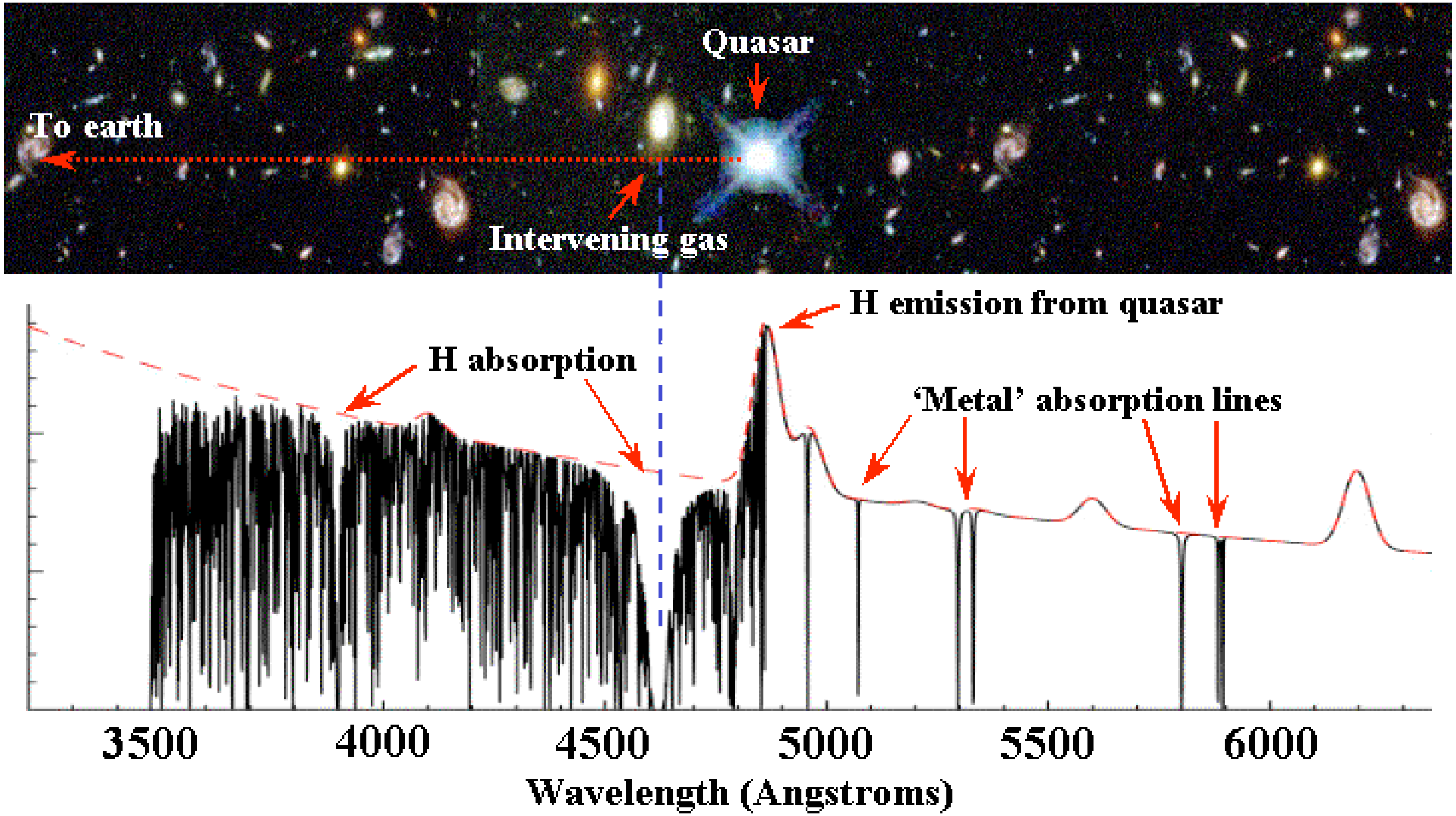
Mean amount of absorption?



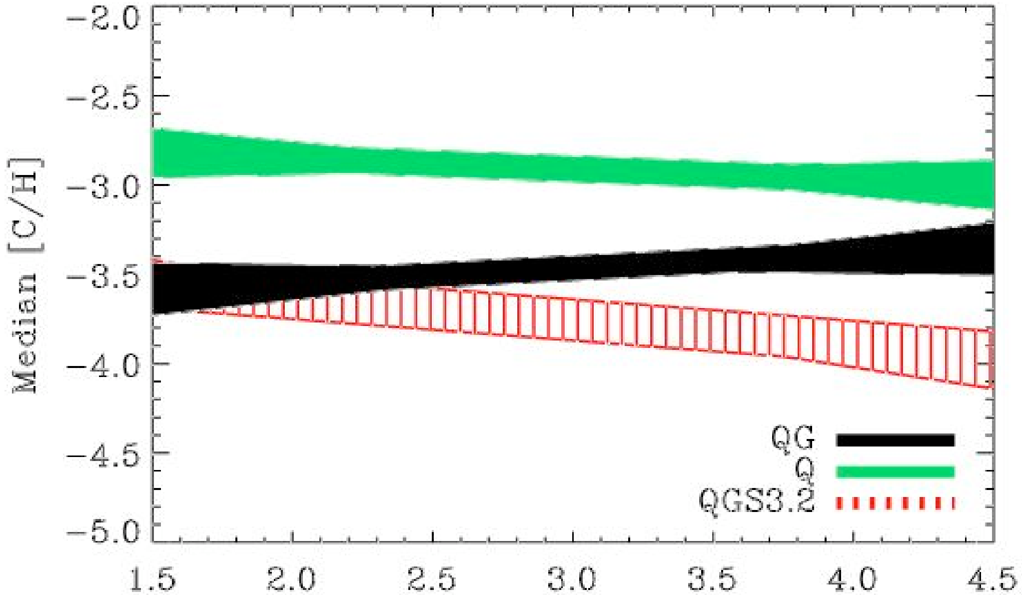
Bernardi et al 02

Fig. 13.— Comparison of measurements of the evolution of the effective optical depth in the Lyα forest. Stars, diamonds, squares and small filled circles show measurements from 42 low resolution spectra by Sargent, Steidel & Bocksenberg (1989), 33 from Schneider, Schmidt & Gunn (1991), 42 from Zuo & Lu (1993), and the subset of 796 QSOs in the SDSS sample which had $S/N > 4$ and were studied in this paper. Triangles and large filled circles show measurements in ~ 10 higher resolution spectra by McDonald et al. (2000) and Schaye et al. (2000). Dotted line shows the evolution reported by Press, Rybicki & Schneider (1993), and dashed line shows the evolution given in Table 1.

Are all lines Hydrogen lines? Are they cosmological?

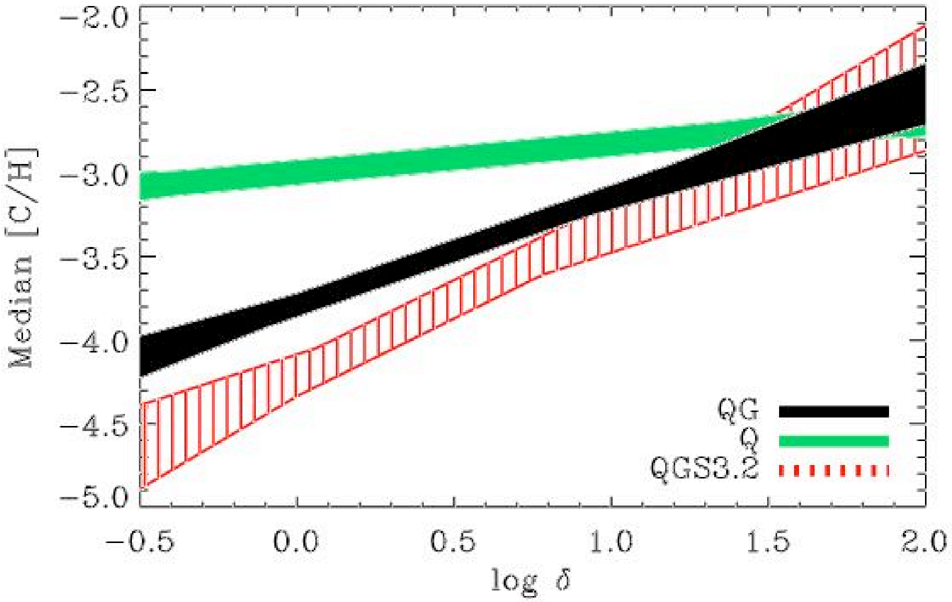


Delta =3



Redshift

z=3



Schaye et al 03

Density

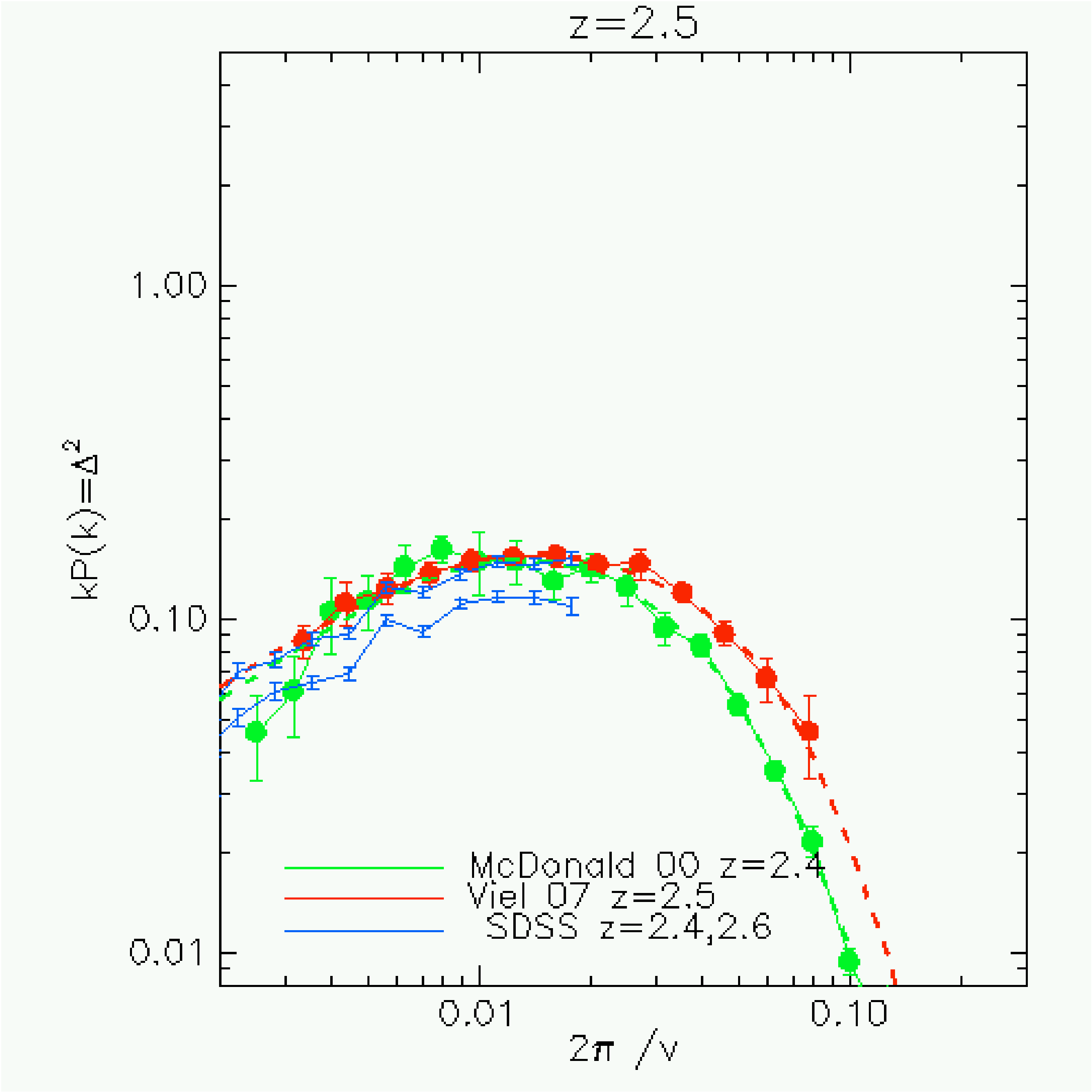
•Current observations

Measurements of the flux power-spectrum

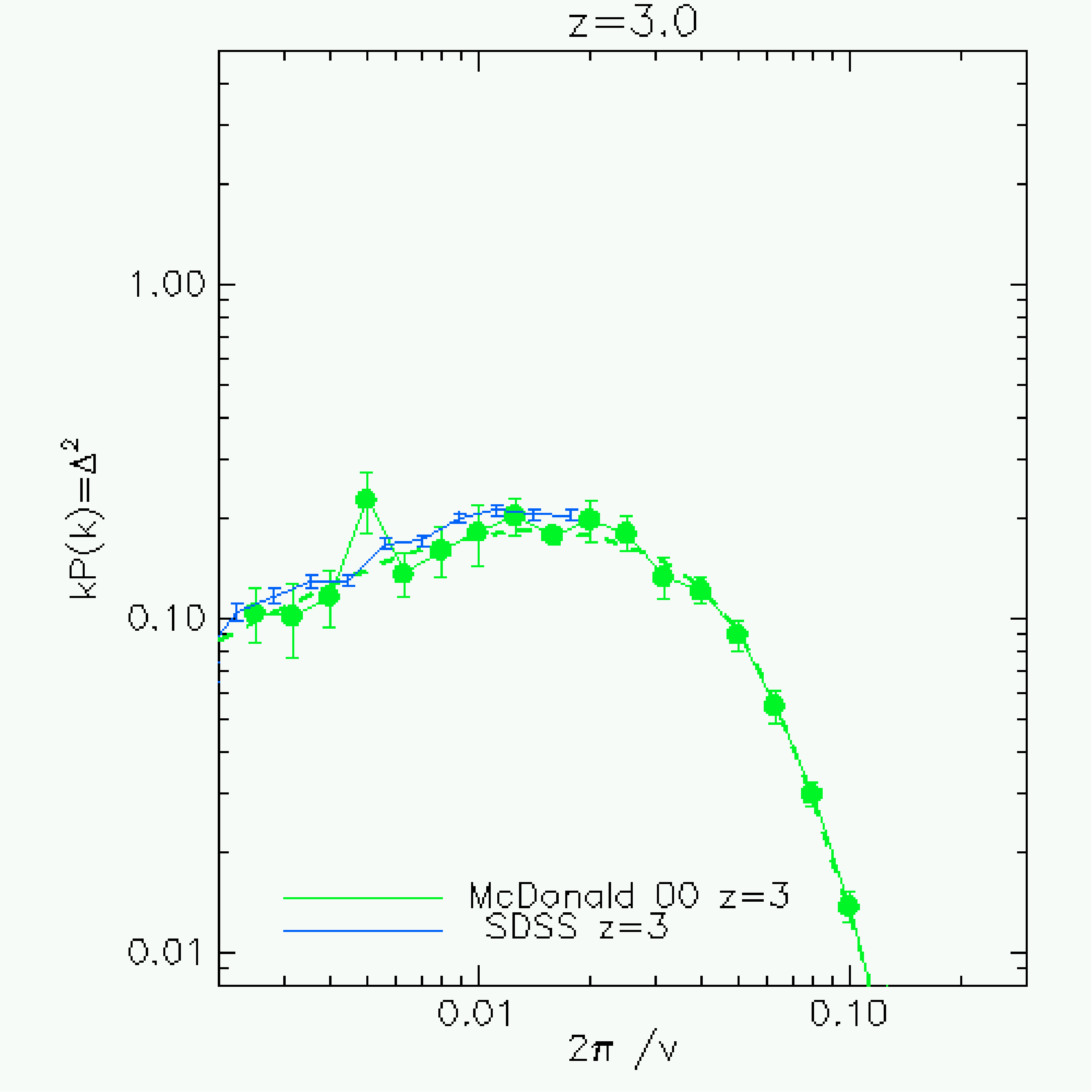
$$\exp(-\tau) \equiv \frac{\text{Observed counts}}{\text{Emitted counts}}$$

$$\begin{aligned}
\frac{d\lambda}{\lambda} &= \frac{dv}{c} \\
\log(\frac{\lambda}{\lambda 0}) &= \exp(v/c) \\
k &= \frac{2\pi}{v} \quad \text{has dimensions of s km}^{-1} \\
P(k) &= \text{power spectrum of } \exp(-\tau) \\
kP(k) &= \Delta^2(k) \quad \text{is dimensionless}
\end{aligned}$$

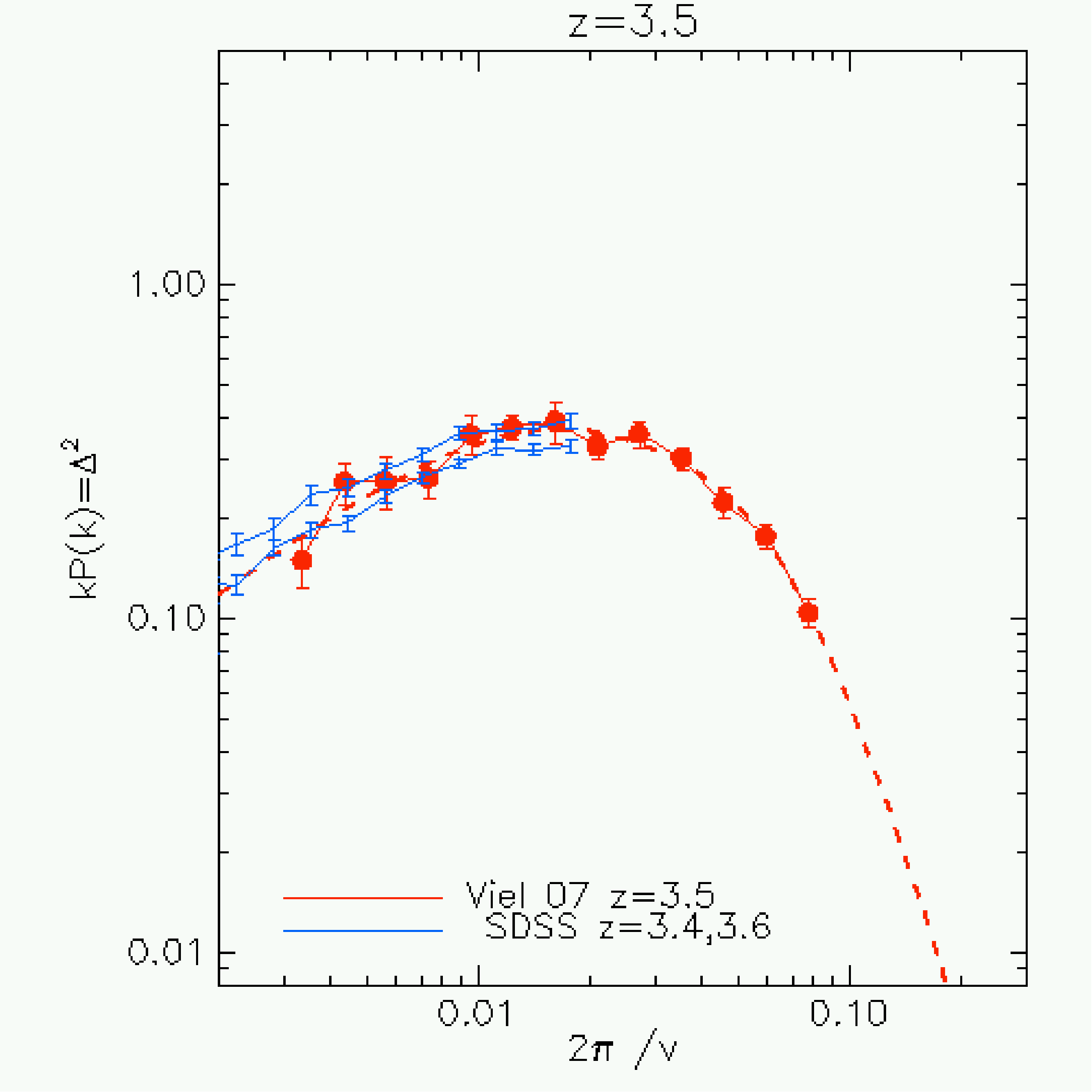
Observations: Mcdonald HiRes / Viel / McDonald SDSS



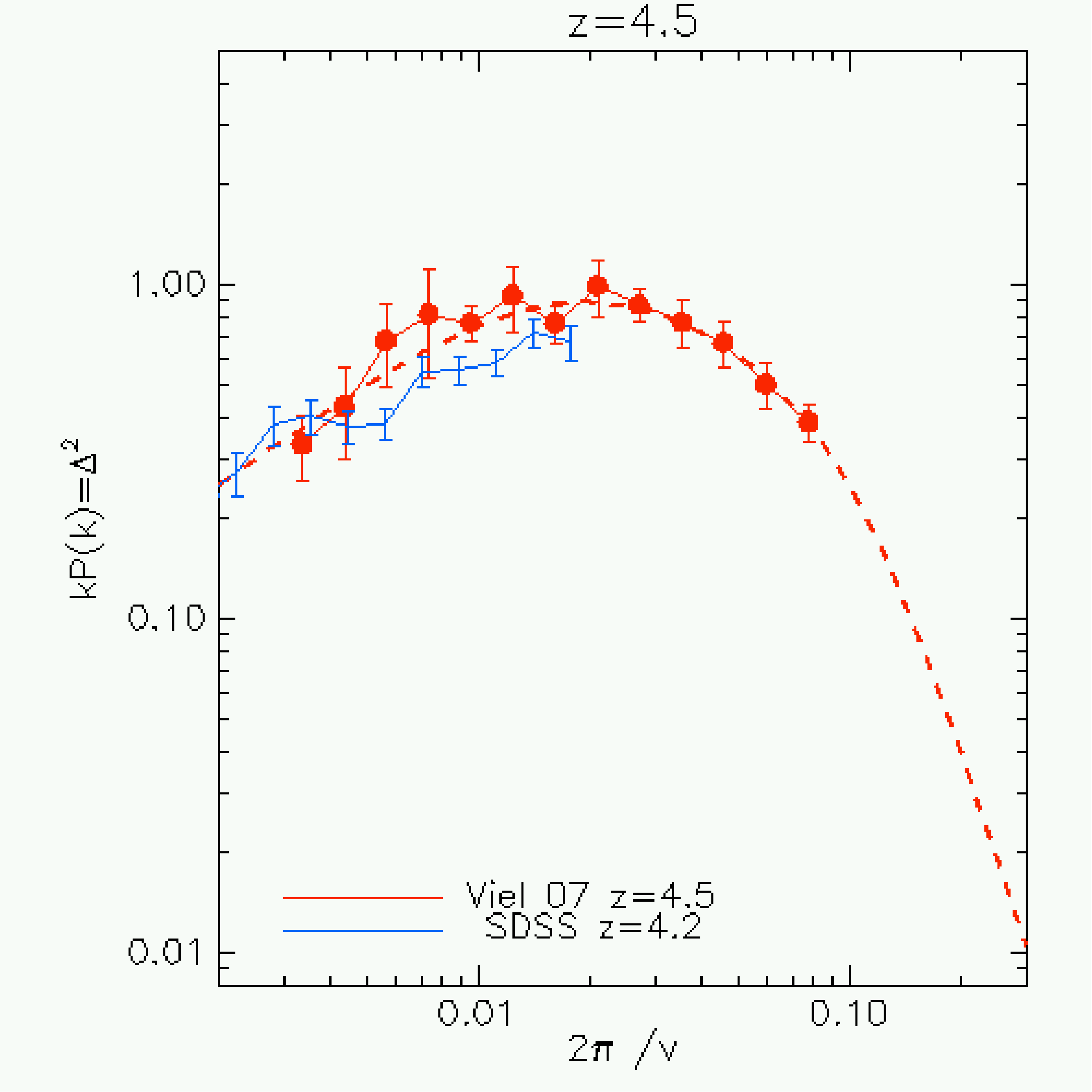
Observations: Mcdonald HiRes / Viel / McDonald SDSS



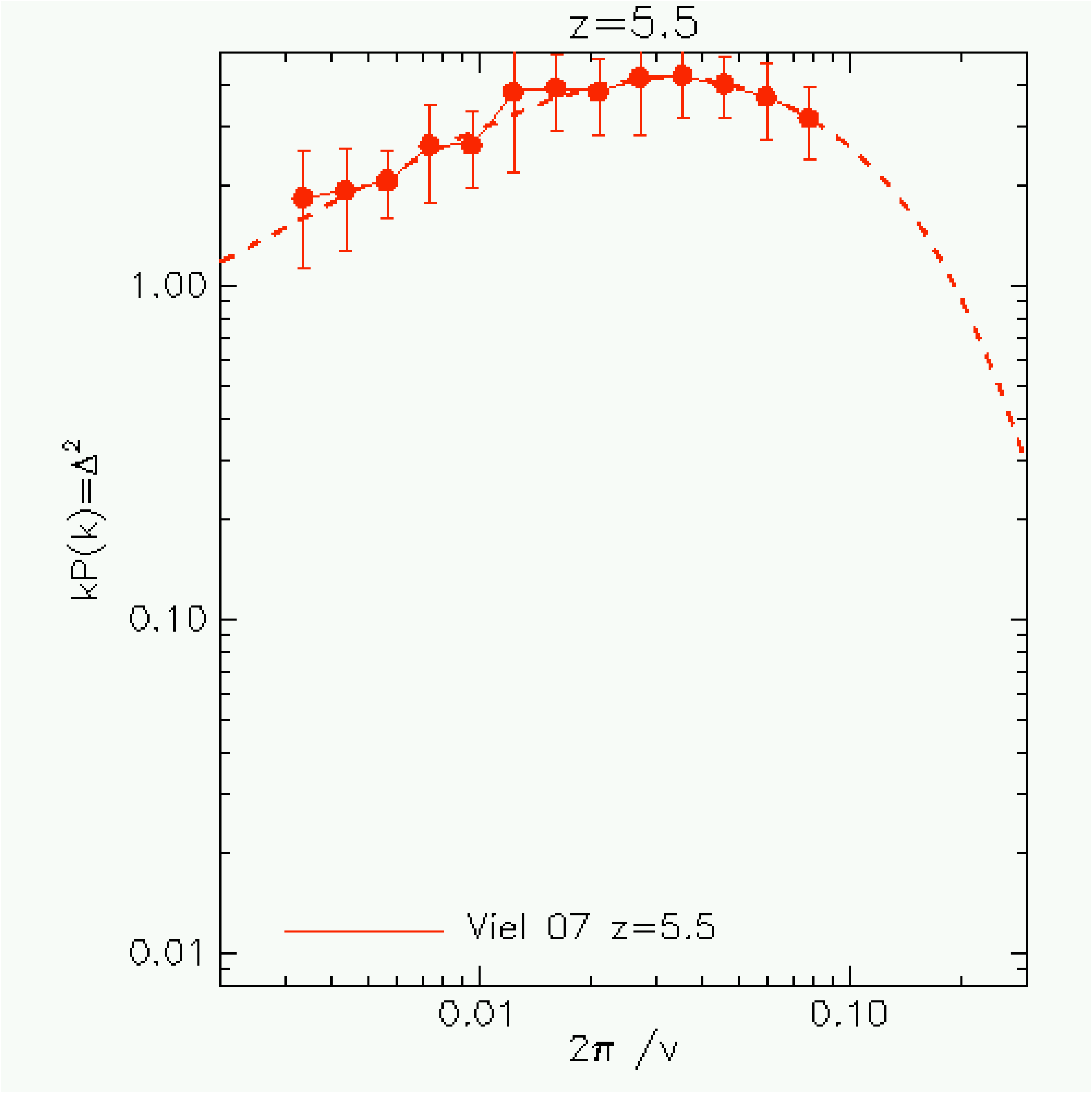
Observations: Mcdonald HiRes / Viel / McDonald SDSS



Observations: Mcdonald HiRes / Viel / McDonald SDSS

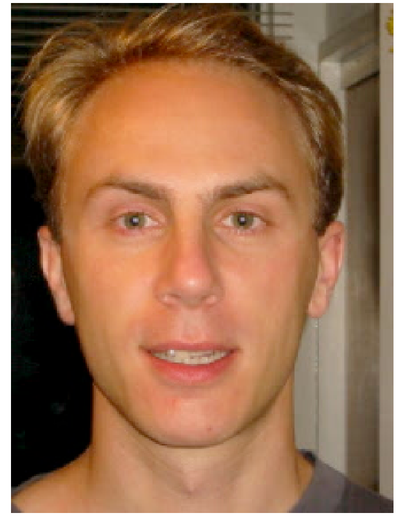


Observations: Mcdonald HiRes / Viel / McDonald SDSS

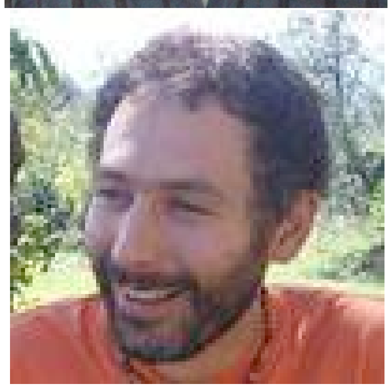


•Simulating the forest

Leiden:
Claudio Dalla Vecchia
Joop Schaye



Trieste:
Luca Tornatore



Aims:
- simulate IGM and galaxies together
- investigate numerical/physical uncertainties

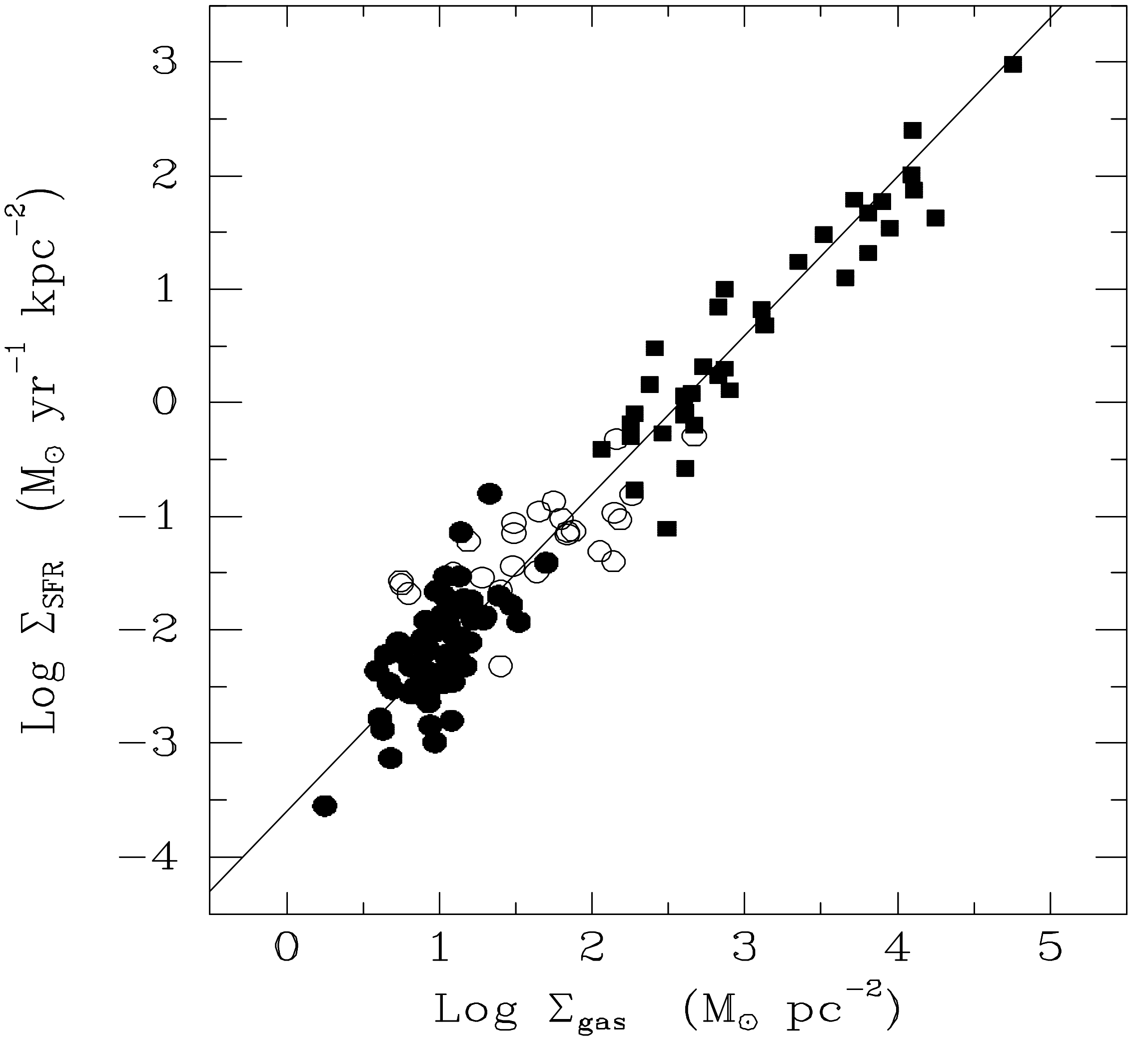
MPA:
Volker Springel

- Gadget 3
- Star formation guarantees Schmidt law
- Stellar evolution
- Winds
- Metal-dependent cooling

Observed star formation:

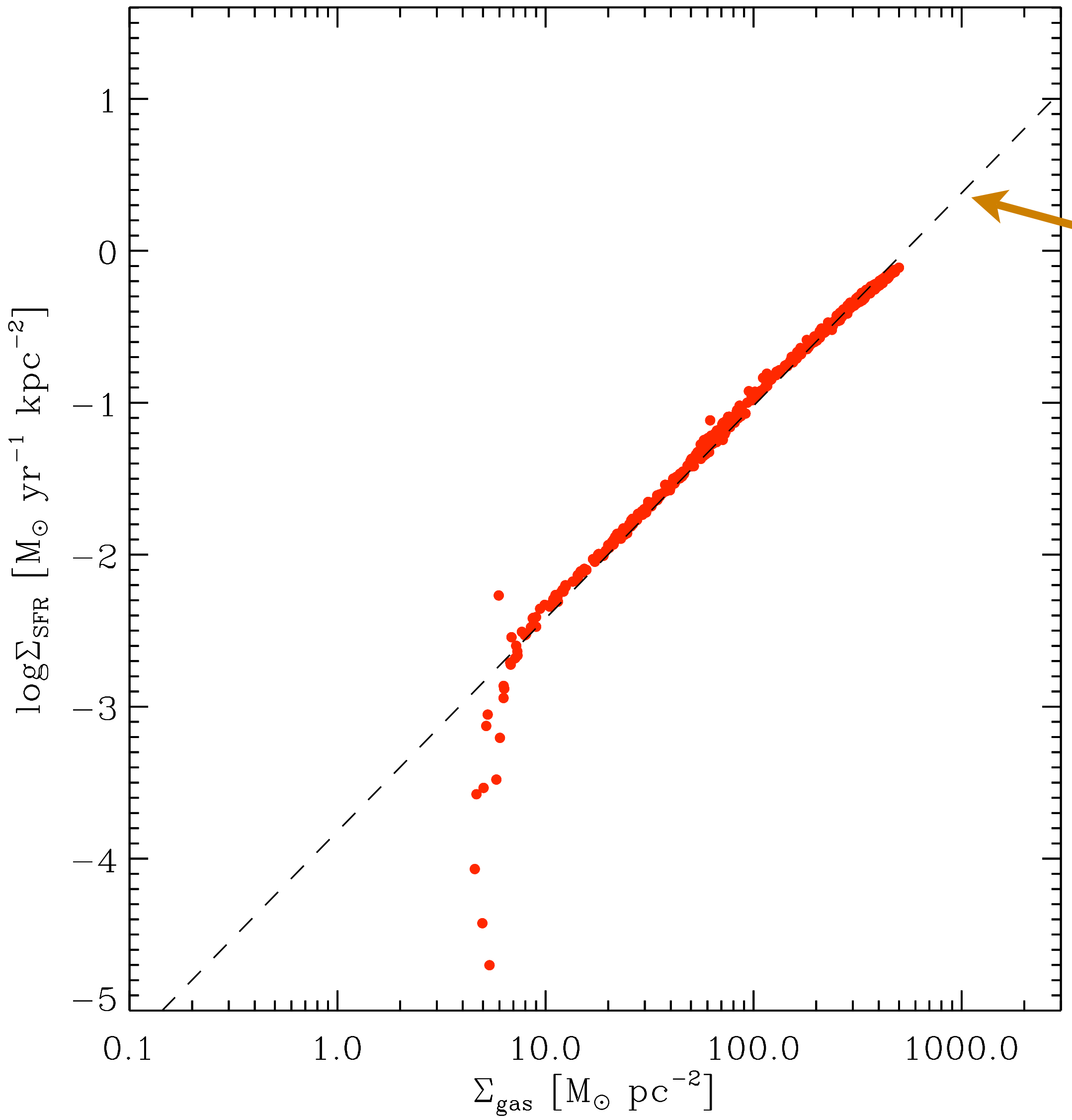
Schmidt law

$$\Sigma_{SFR} \propto \Sigma_{gas}^{n} \quad (n = 1.4 \pm 0.15)$$



(Kennicutt 1989)

Simulated star formation:

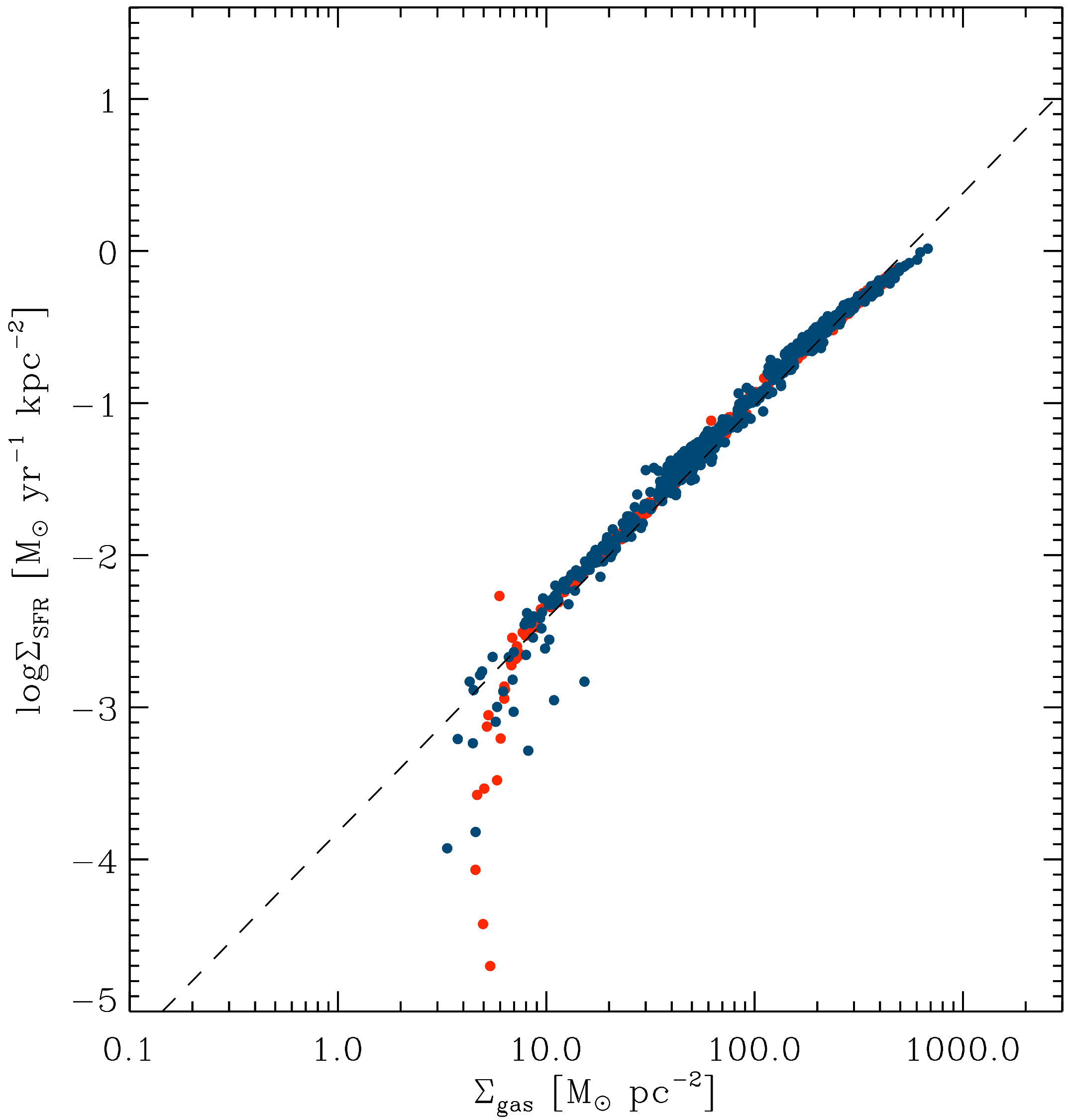


this is not a fit

● $N_{\text{part}} = 100$

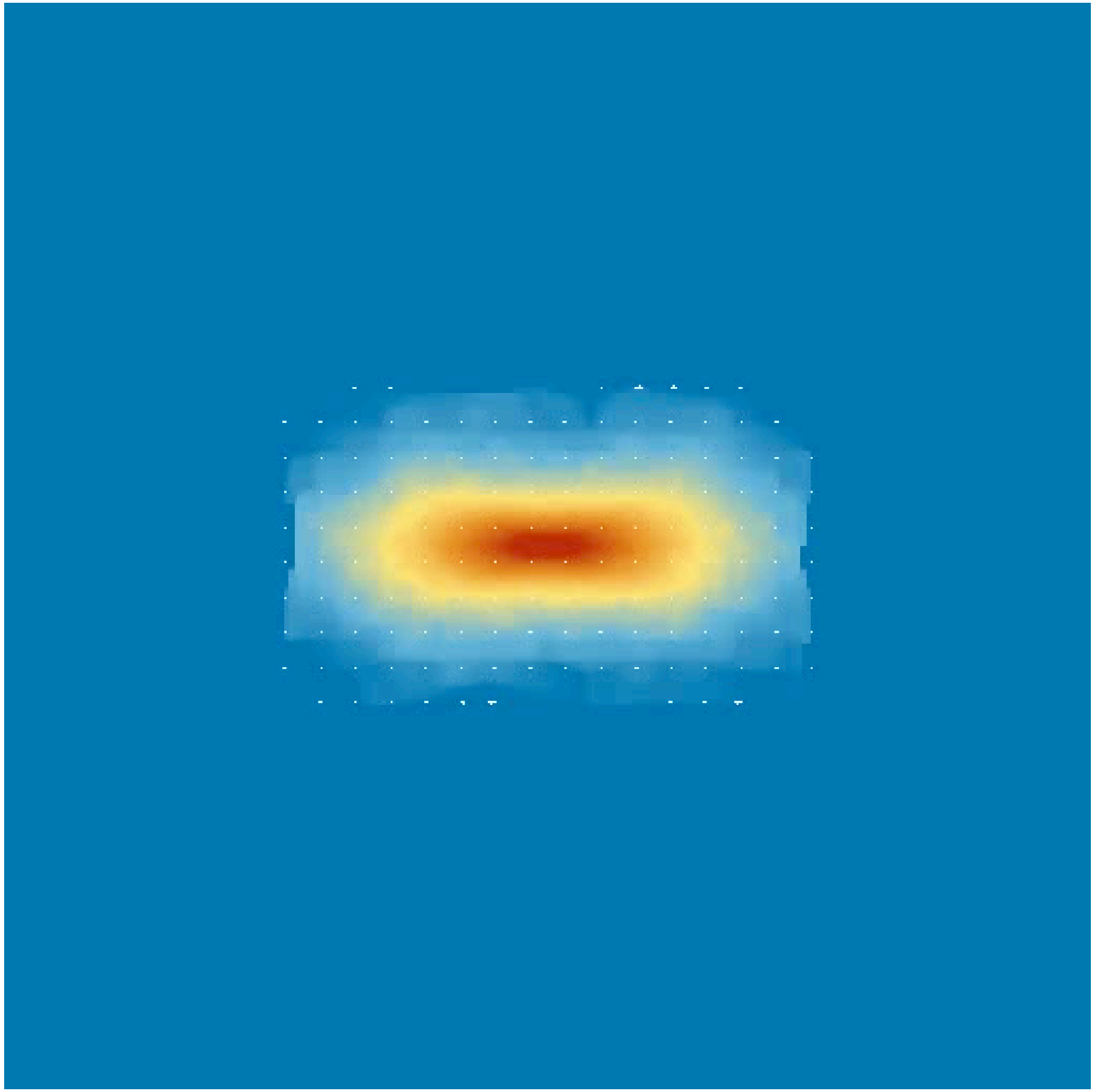
Simulated star formation:

"resolution independent"



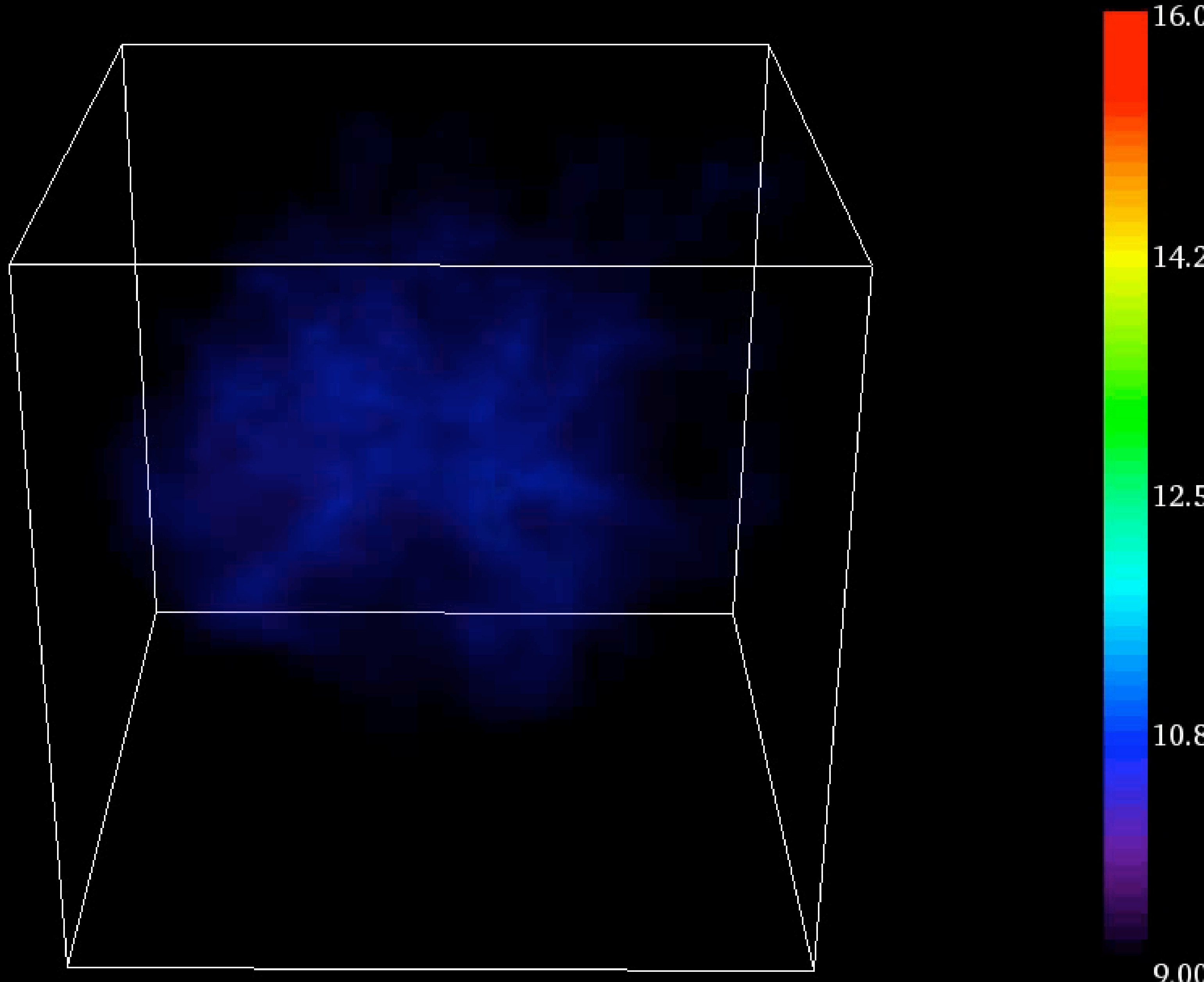
$N_{part} = 100$

$N_{part} = 12$



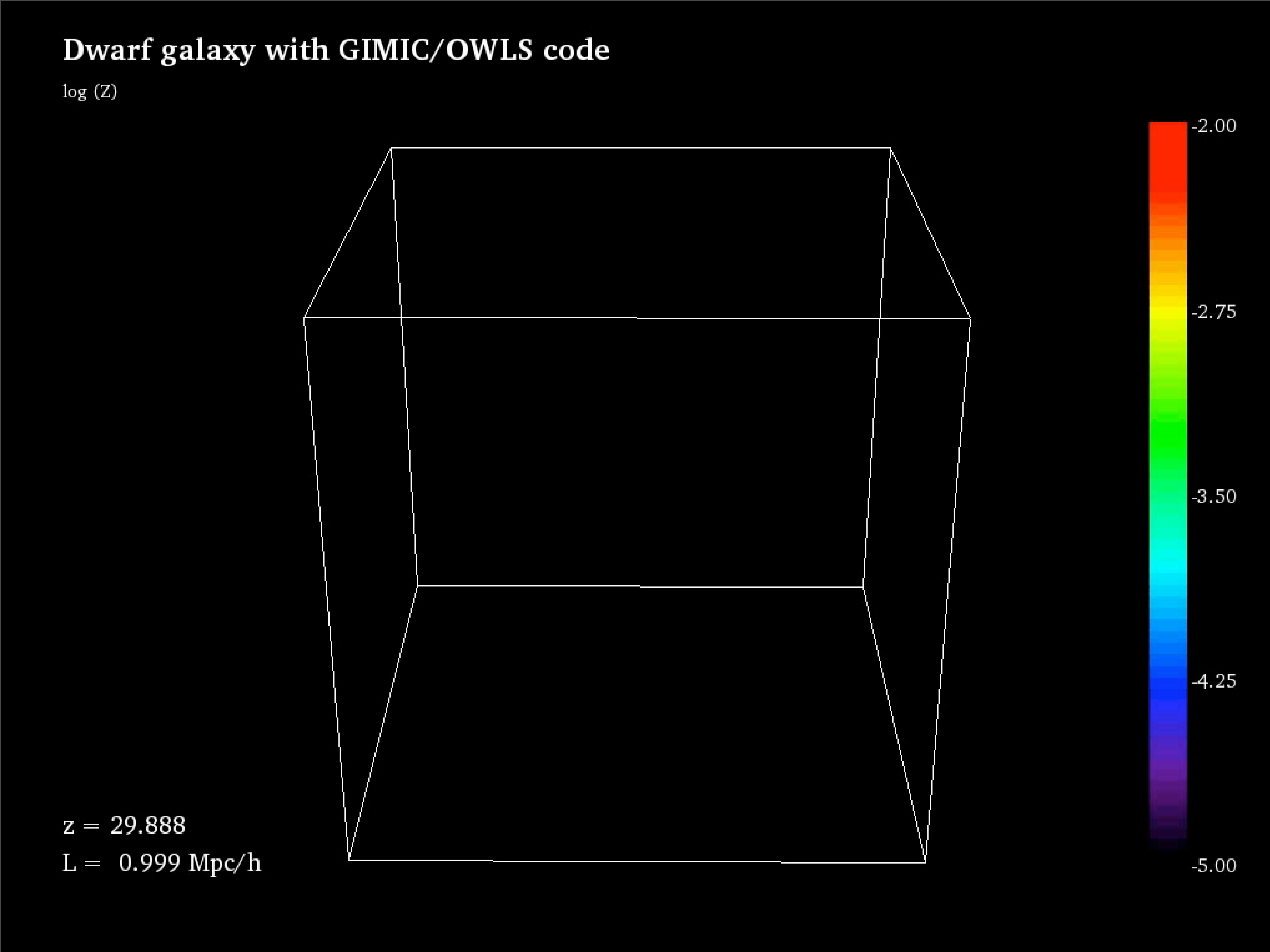
Dwarf galaxy with GIMIC/OWLS code

log (Gas density) in [Msun/h / (Mpc/h) ^ 3]



z = 29.888

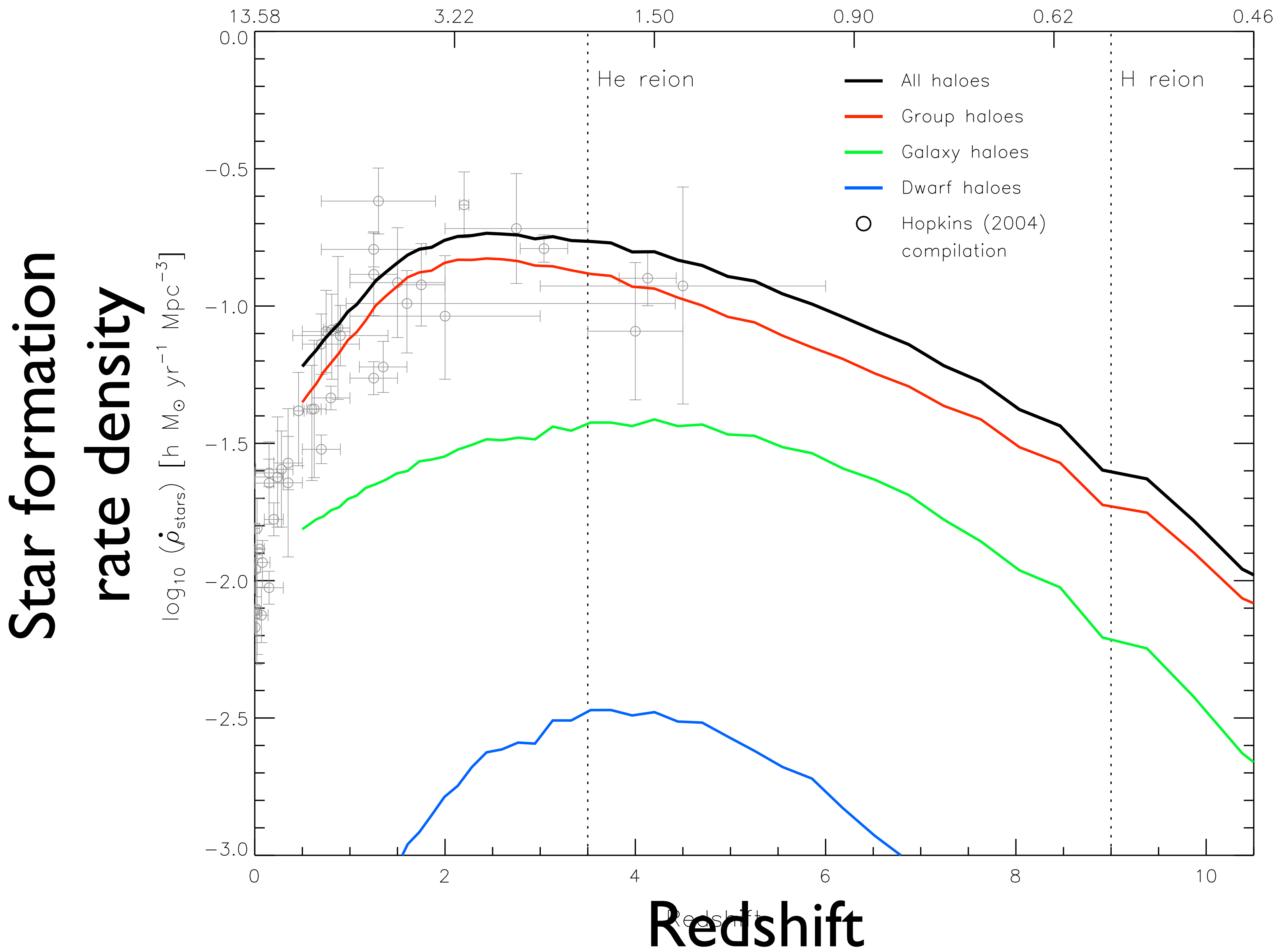
L = 0.999 Mpc/h


Dwarf galaxy with GIMIC/OWLS code
log (Z)
-2.00
-2.75
-3.50
-4.25
-5.00
z = 29.888
L = 0.999 Mpc/h

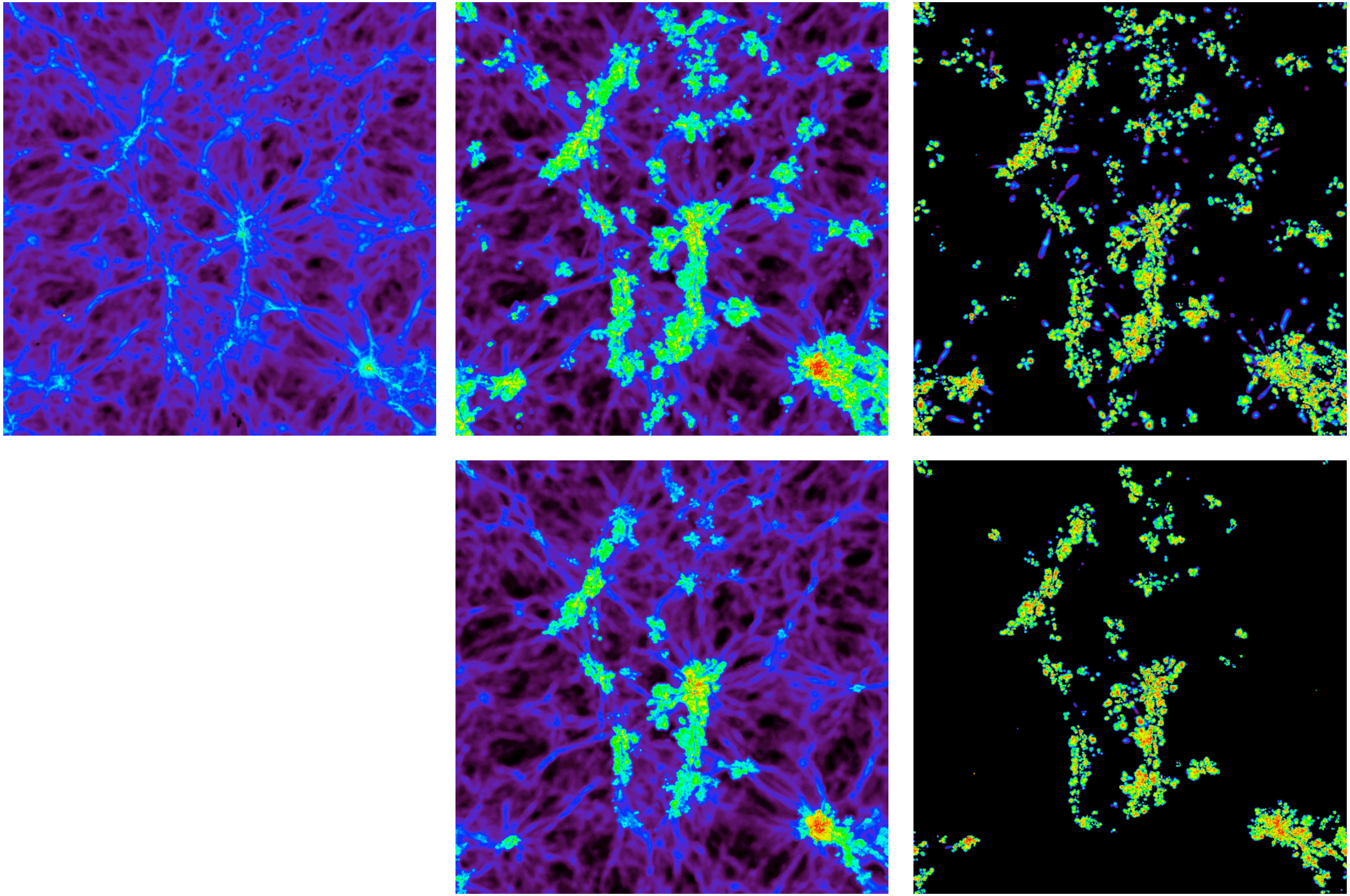
Suite of simulations varying:

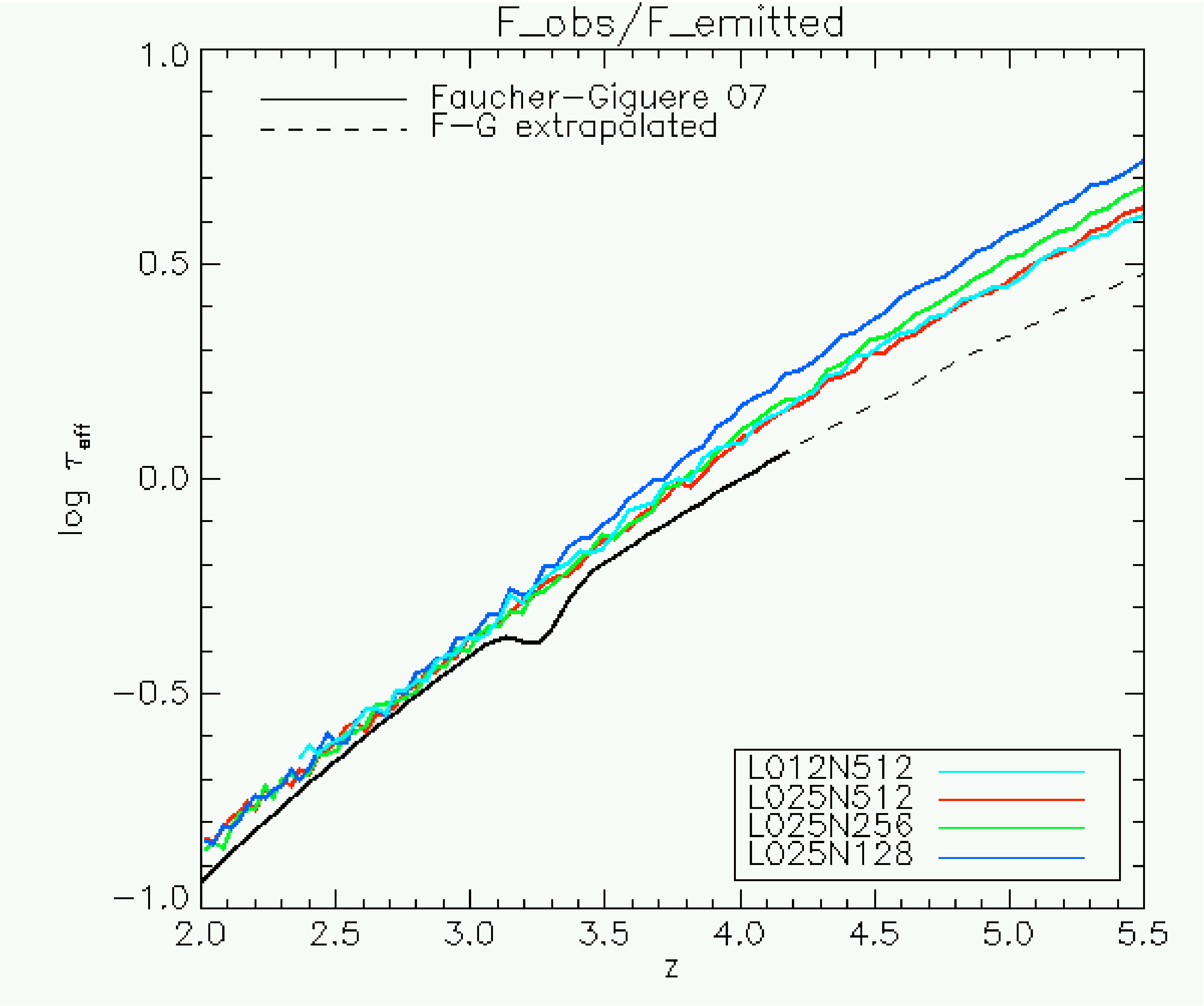
- Star formation parameters
- Wind implementation
- Resolution
- Box size
- Cosmology
- Reionization history

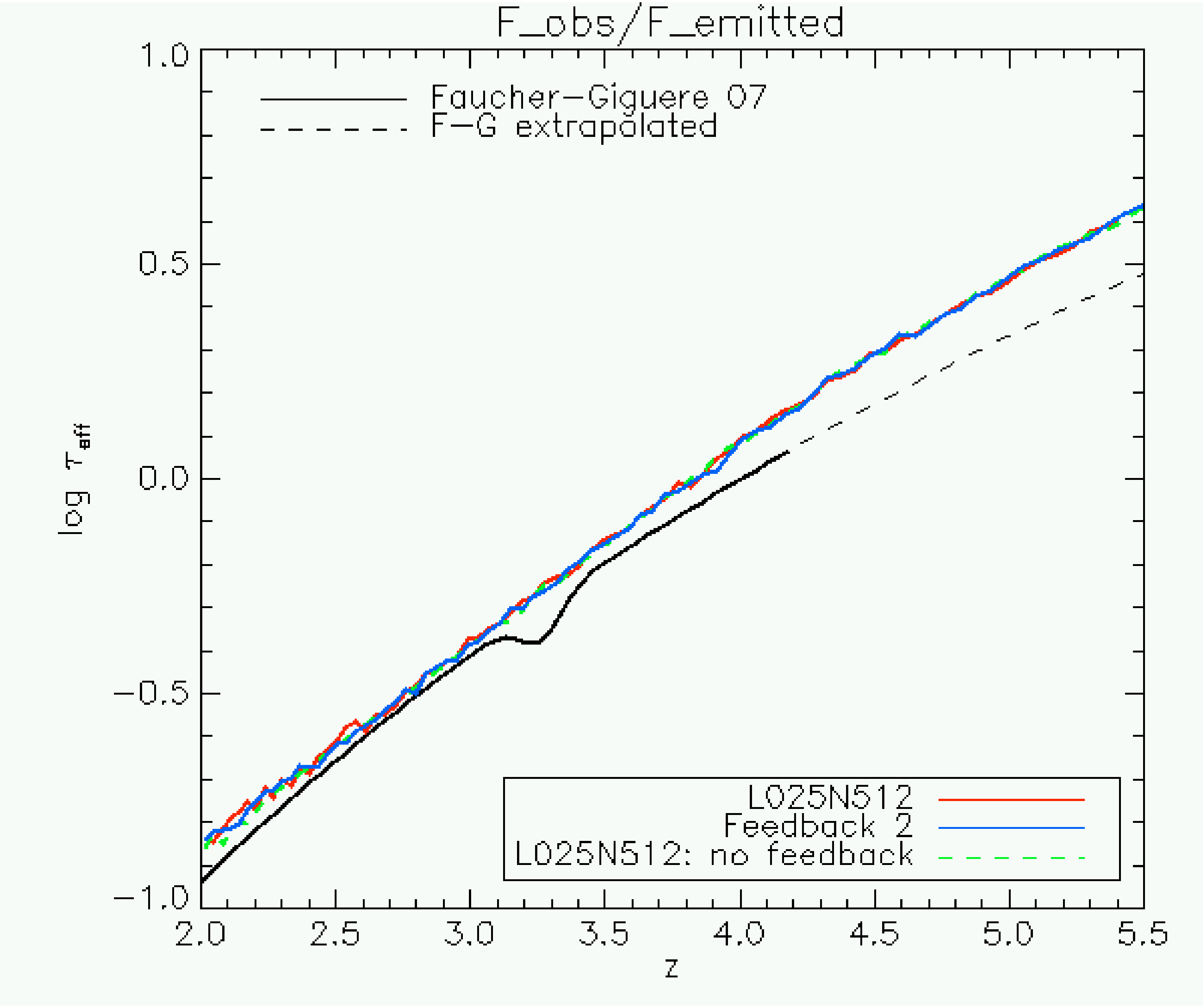
Star formation history

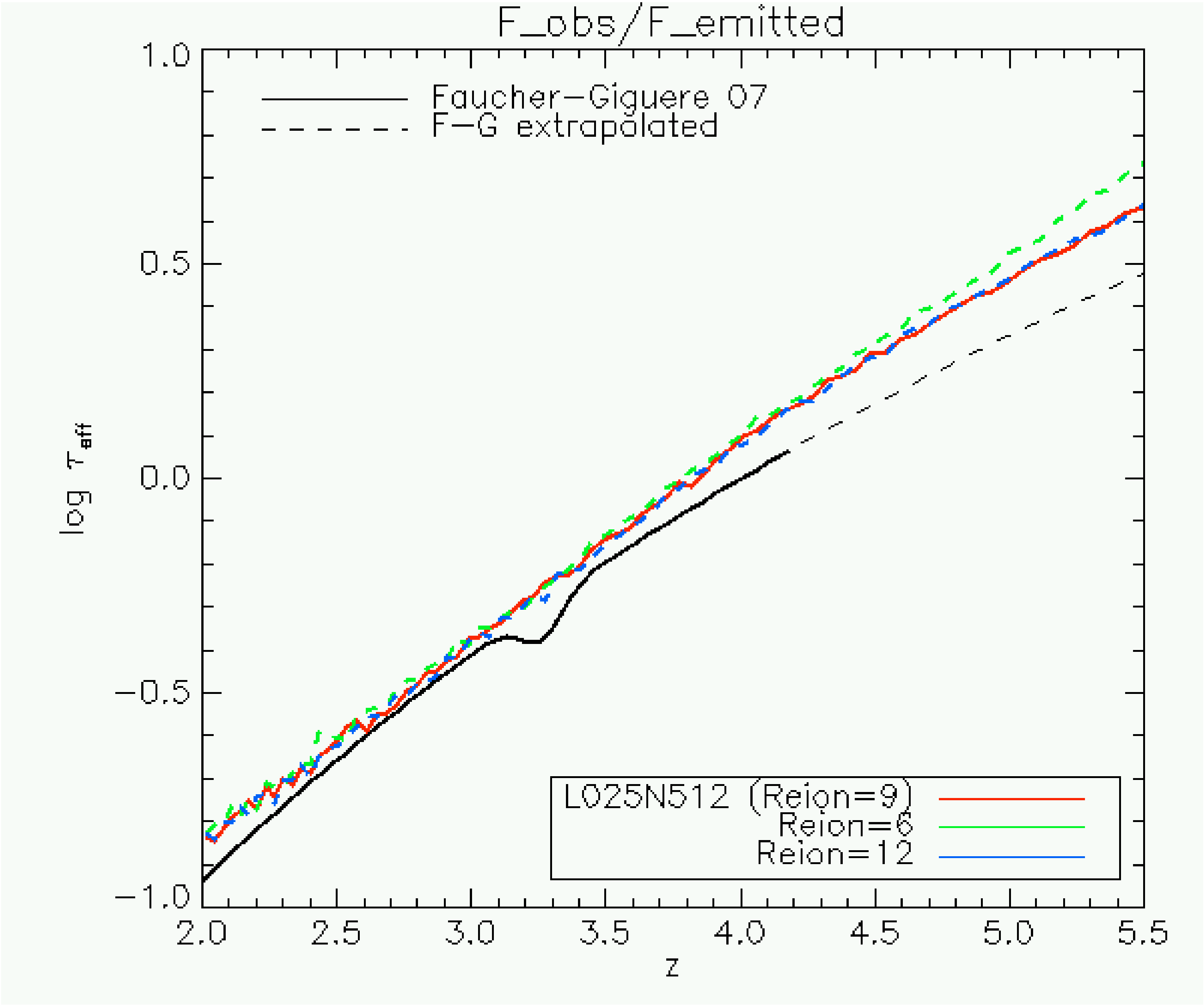


Density | Temperature | Metallicity

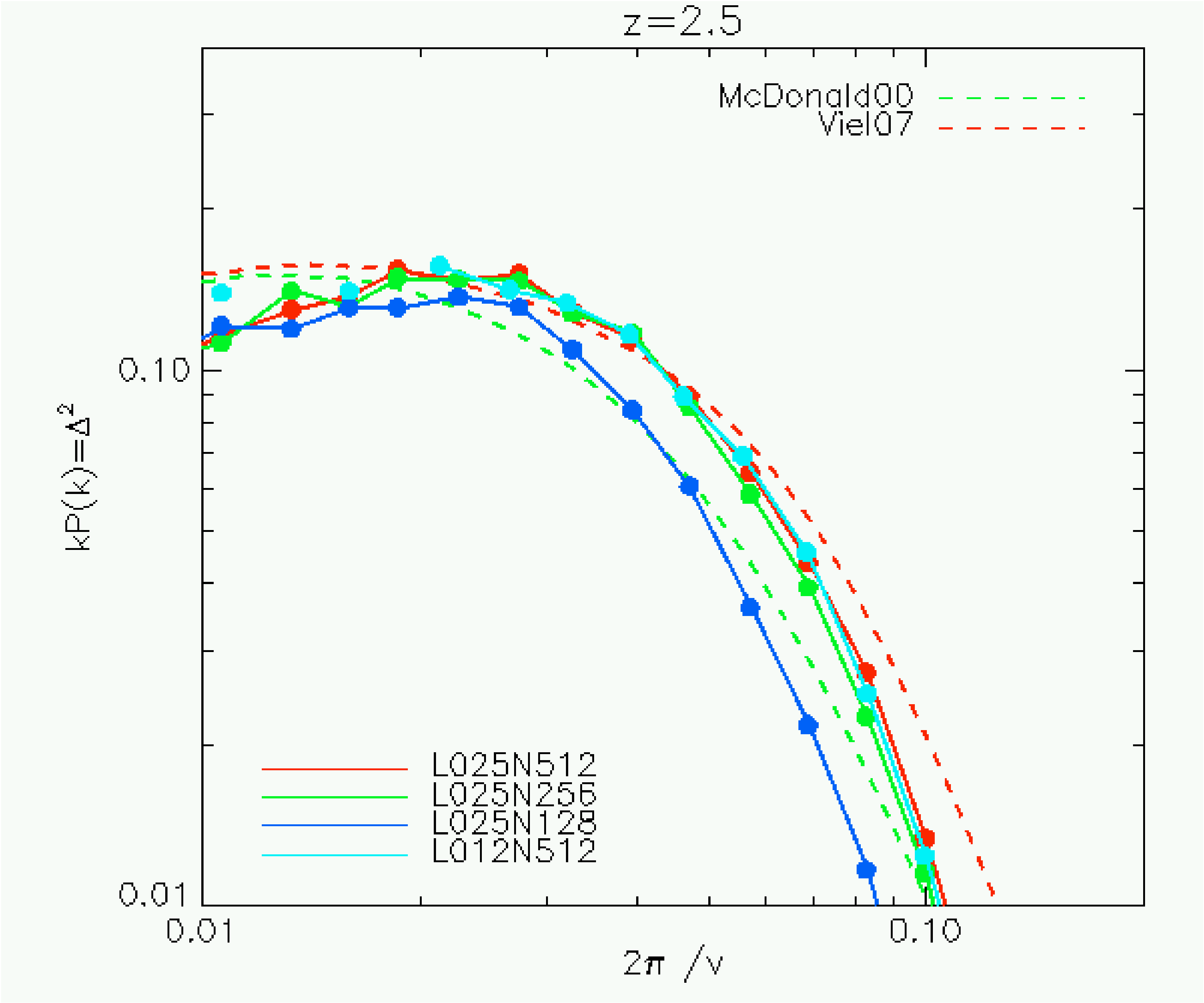



F_obs/F_emitted
Faucher-Giguere 07
F-G extrapolated
L012N512
L025N512
L025N256
L025N128
log τ_eff
z
1.0
0.5
0.0
−0.5
−1.0
2.0
2.5
3.0
3.5
4.0
4.5
5.0
5.5

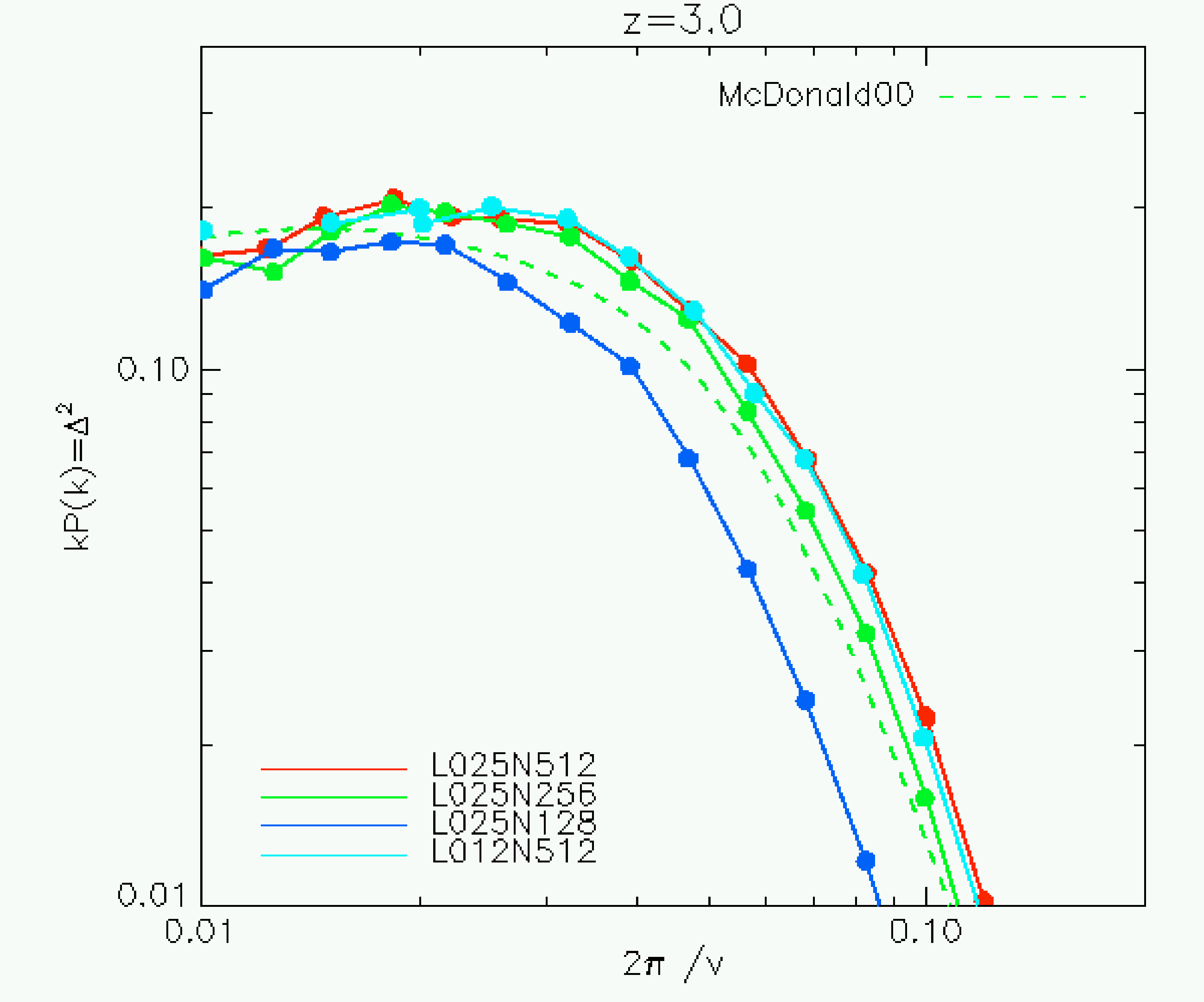

F_obs/F_emitted
Faucher-Giguere 07
F-G extrapolated
L025N512
Feedback 2
L025N512: no feedback
log τ_{eff}
z
1.0
0.5
0.0
−0.5
−1.0
2.0
2.5
3.0
3.5
4.0
4.5
5.0
5.5


F_obs/F_emitted
Faucher-Giguere 07
F-G extrapolated
L025N512 (Reion=9)
Reion=6
Reion=12
log τ_{eff}
z
1.0
0.5
0.0
−0.5
−1.0
2.0
2.5
3.0
3.5
4.0
4.5
5.0
5.5

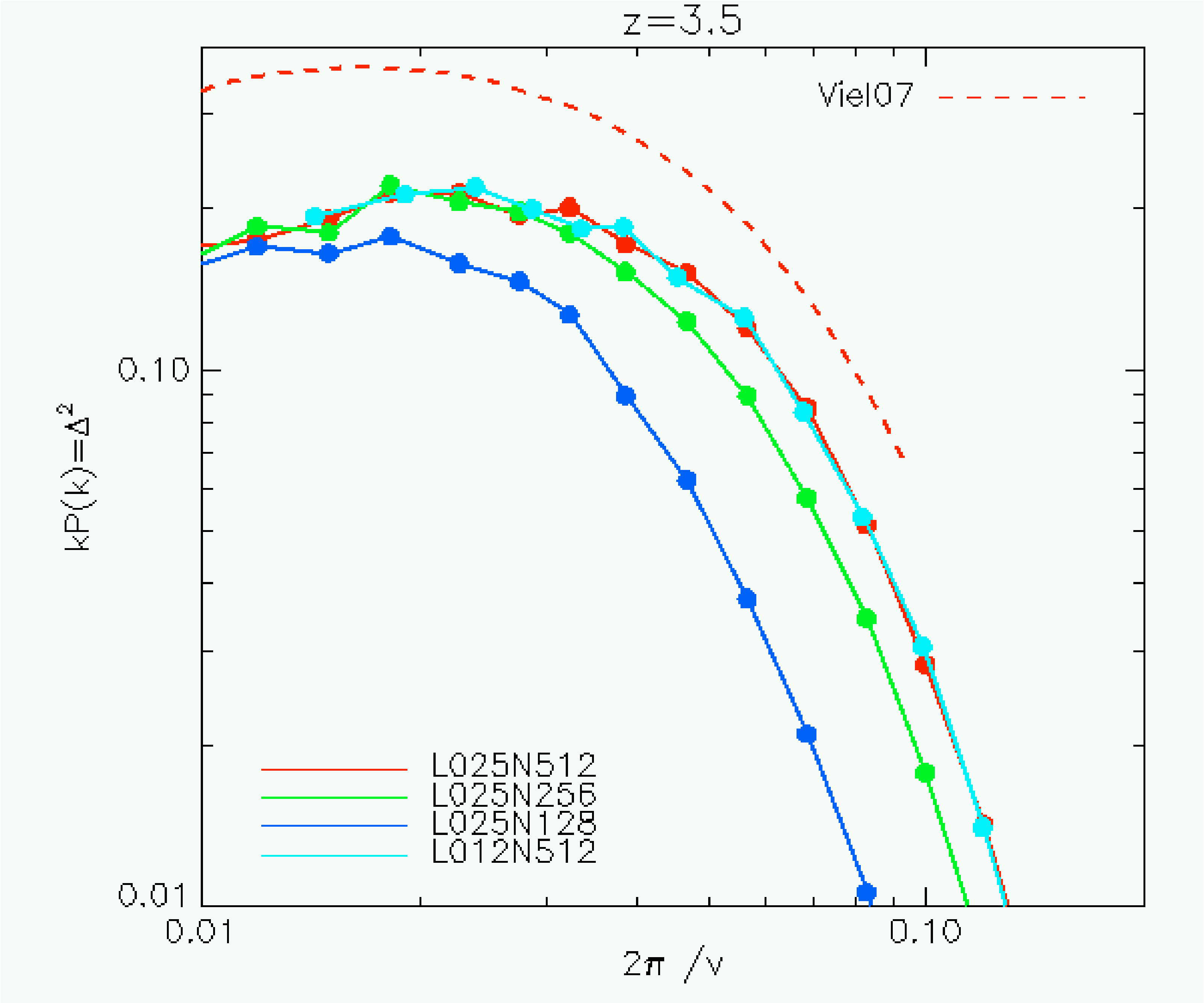
Resolution: low / medium / high / very high



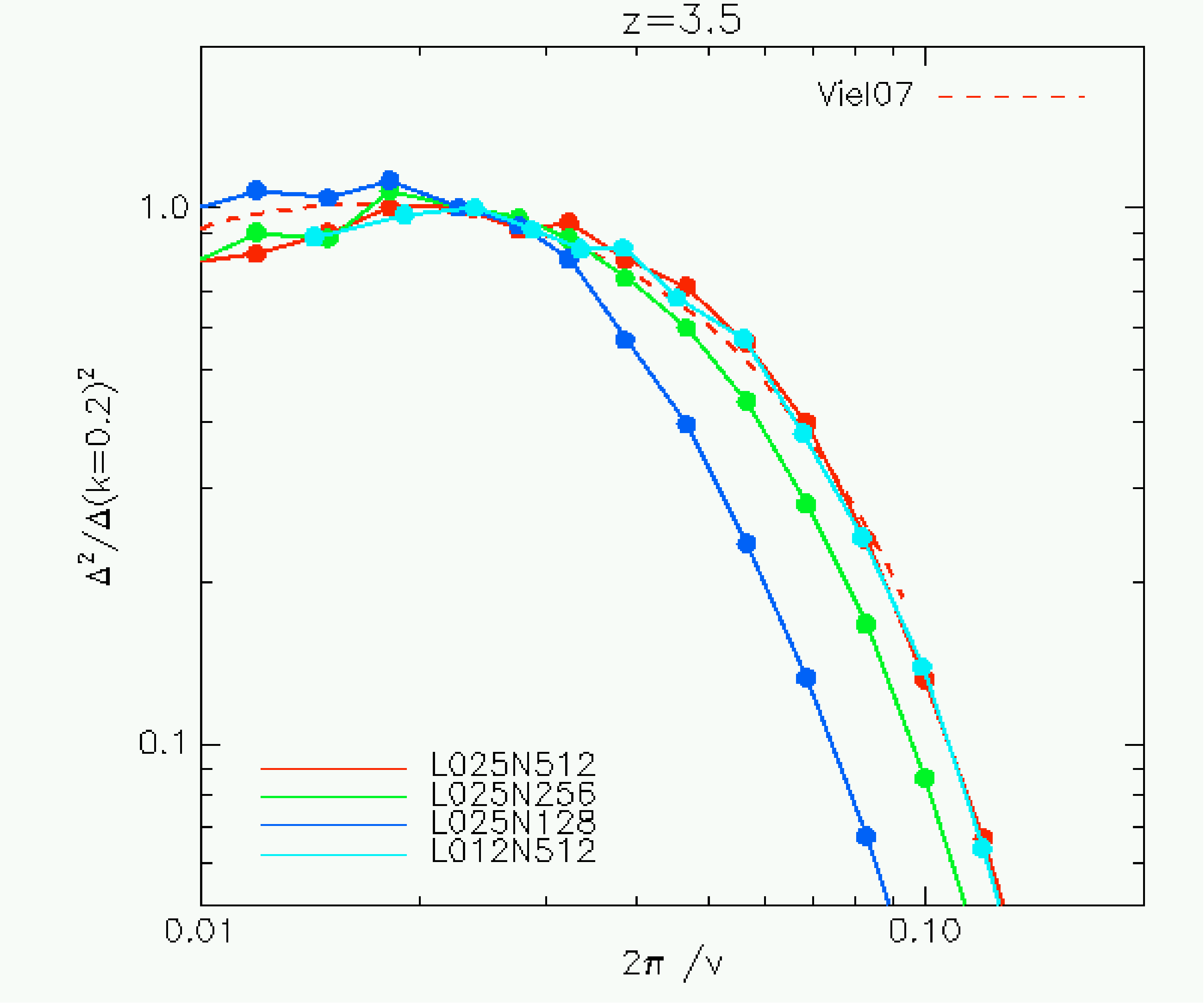
Resolution: low / medium / high / very high



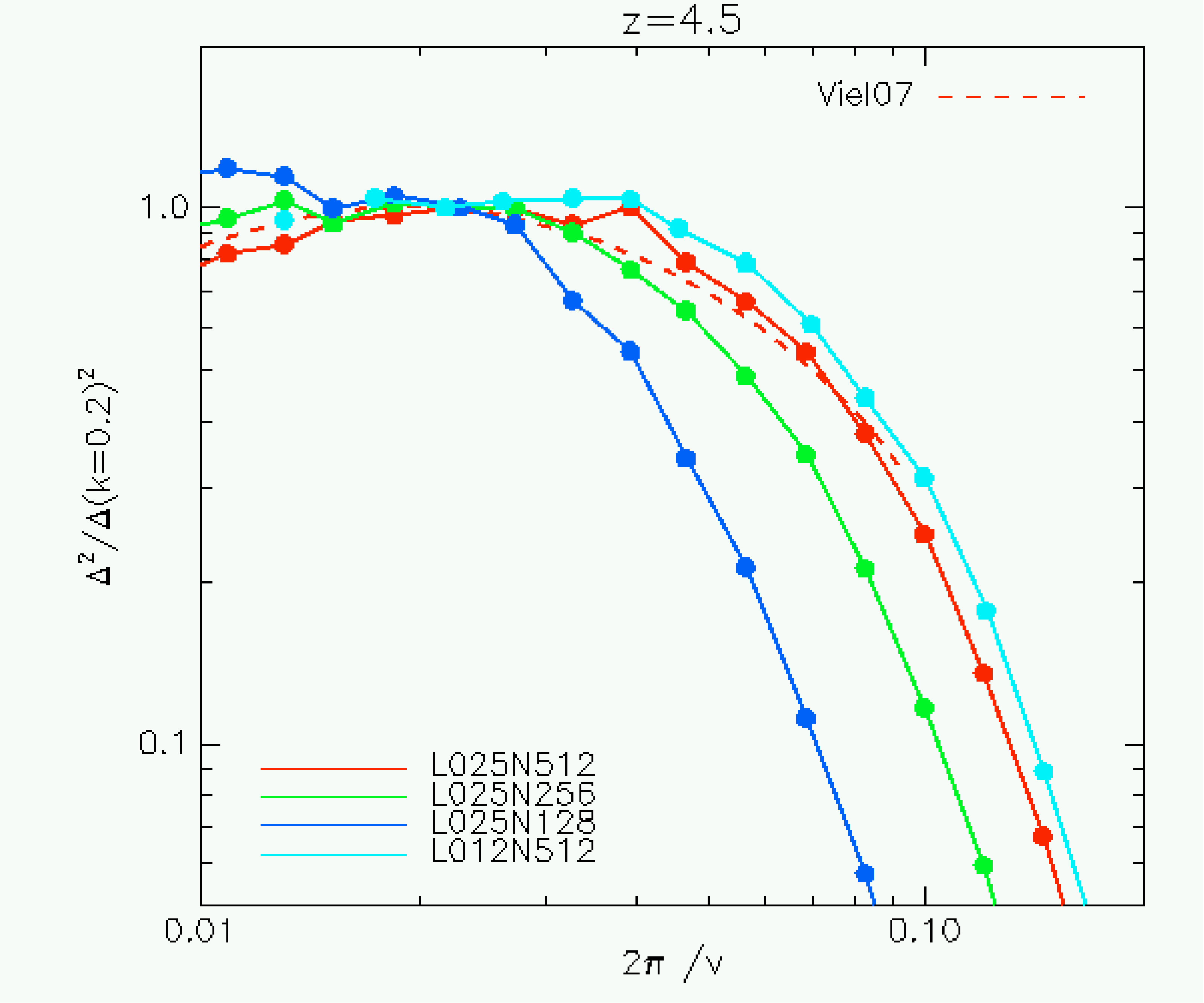
Resolution: low / medium / high / very high



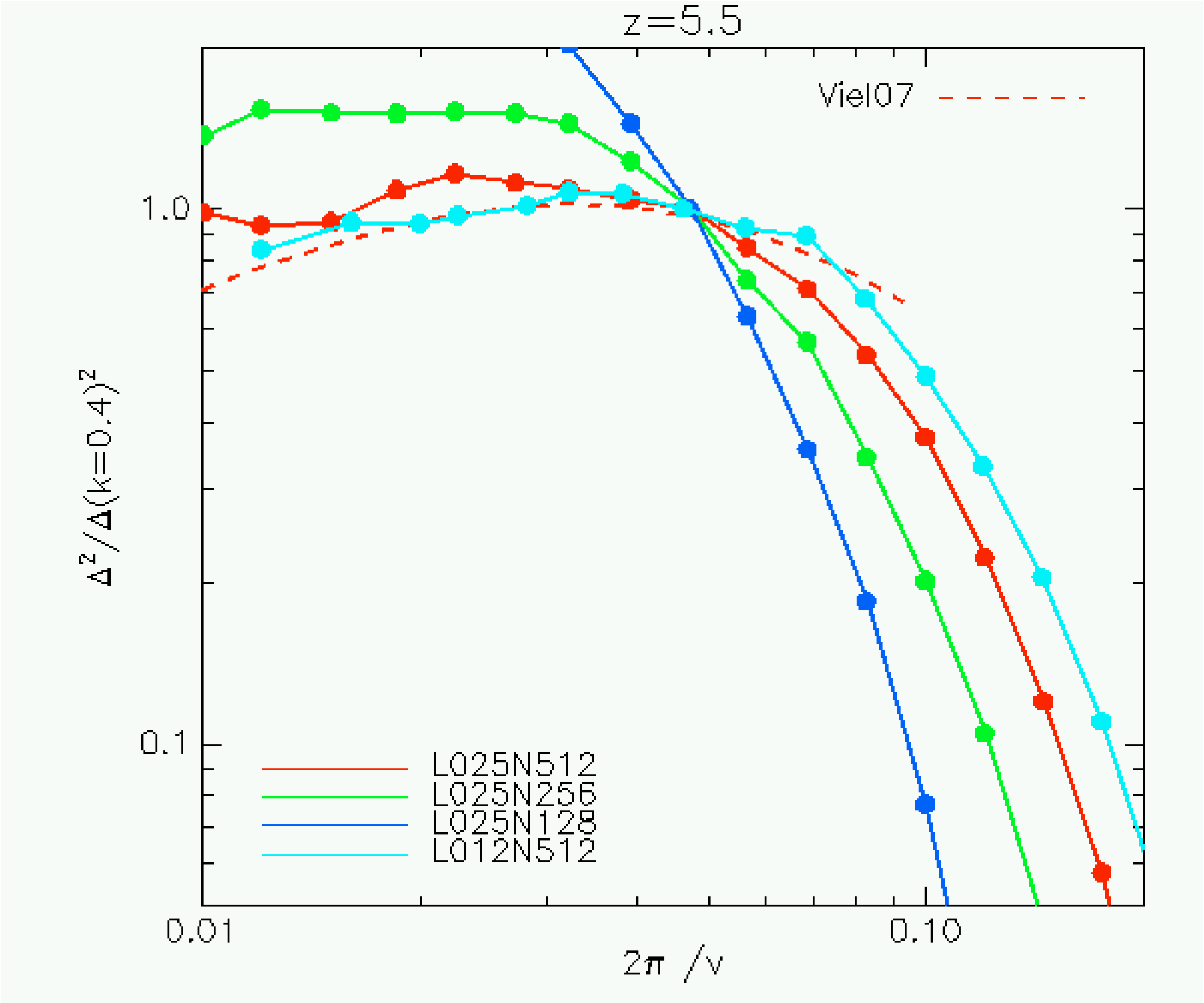
Resolution: low / medium / high / very high



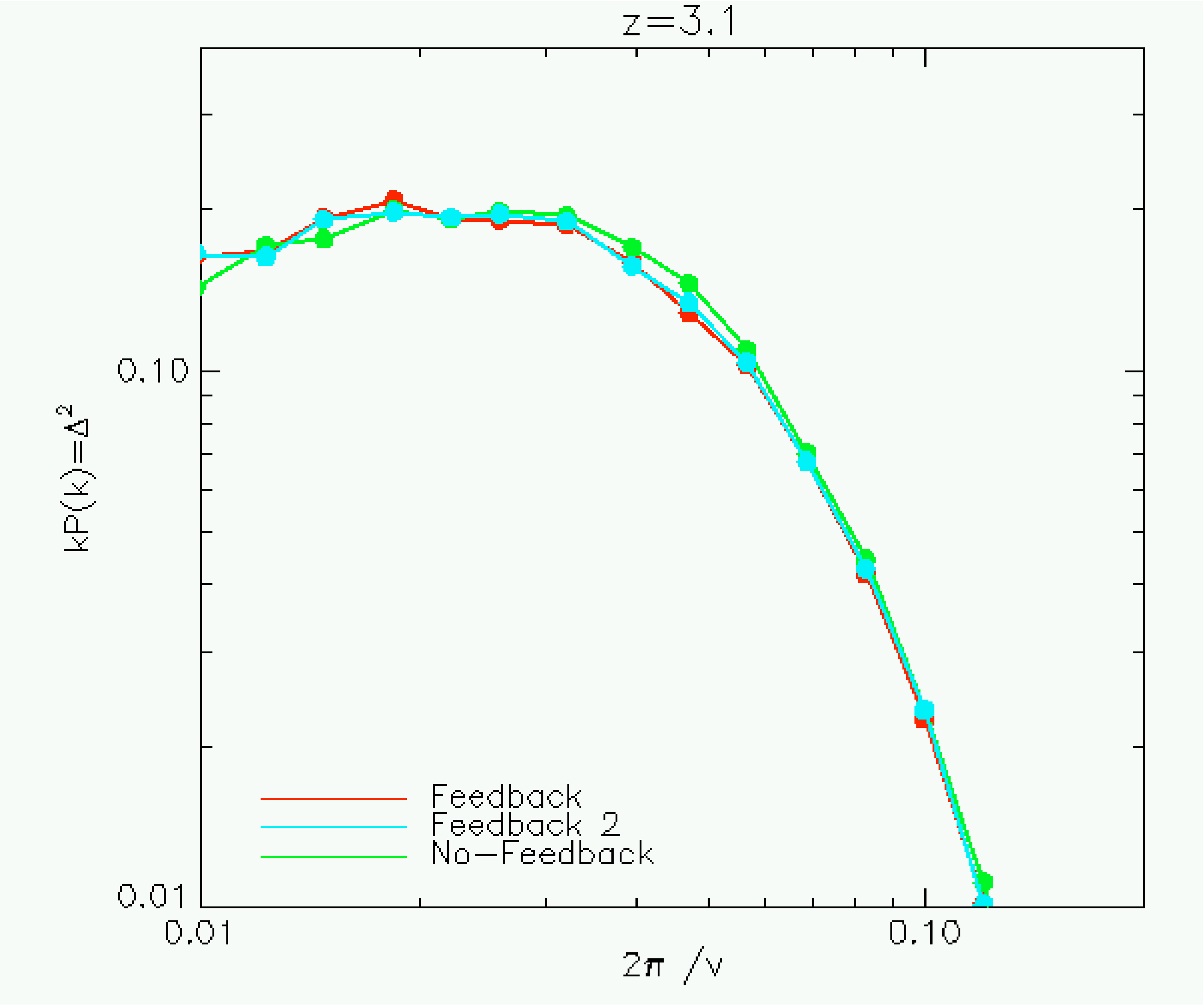
Resolution: low / medium / high / very high



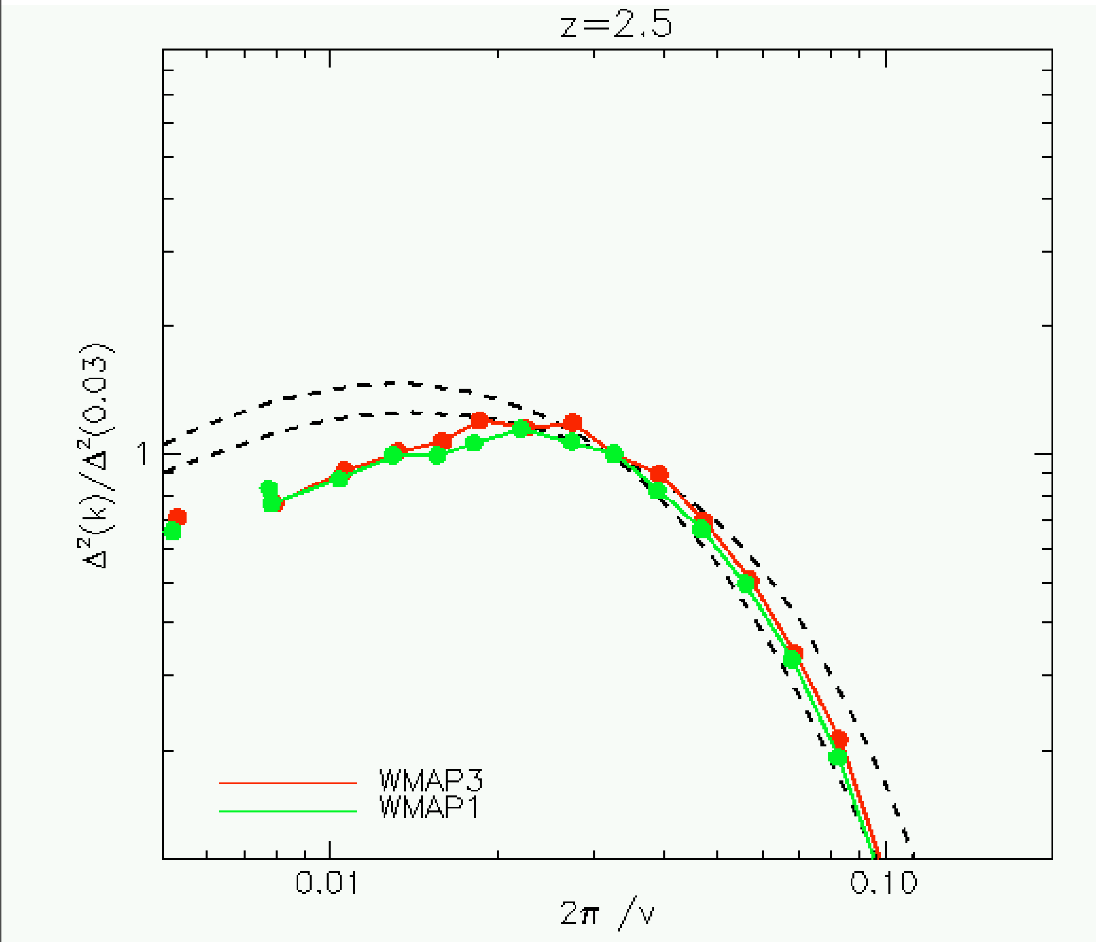
Resolution: low / medium / high / very high

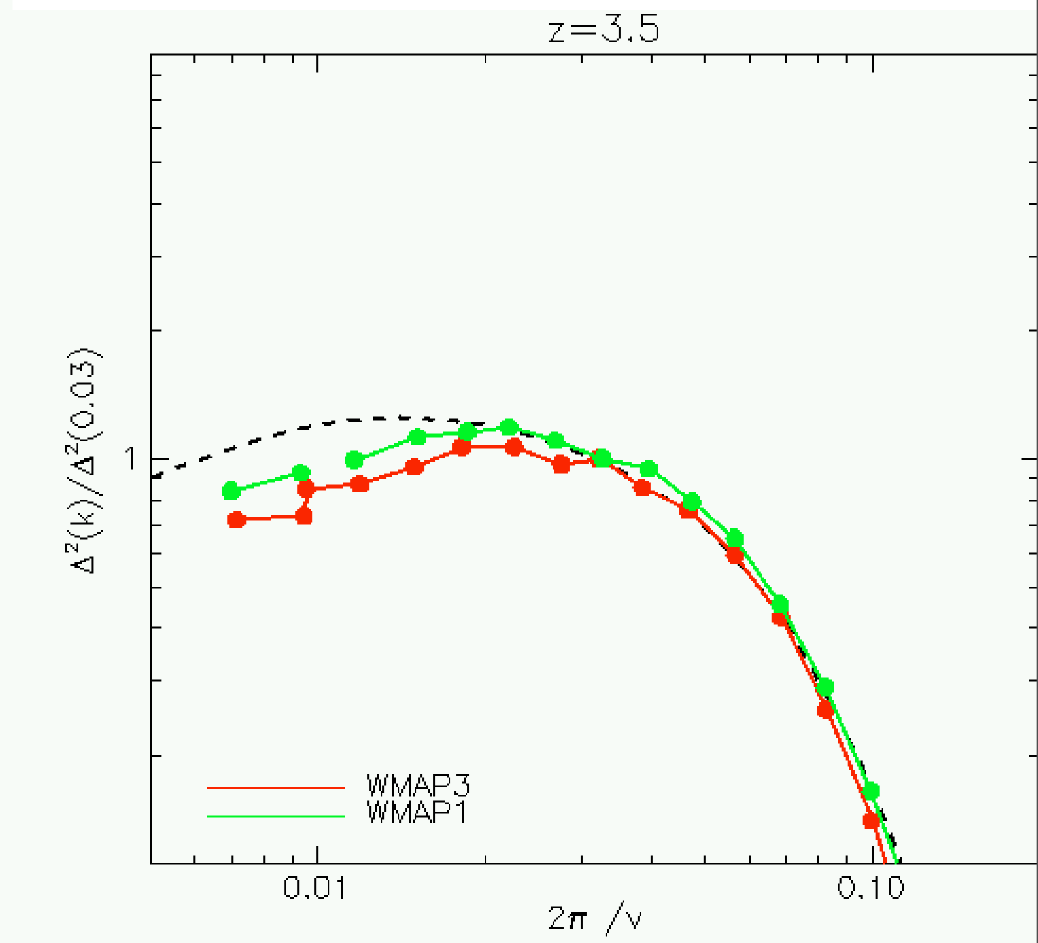


Feedback / Feedback2 / No-Feedback



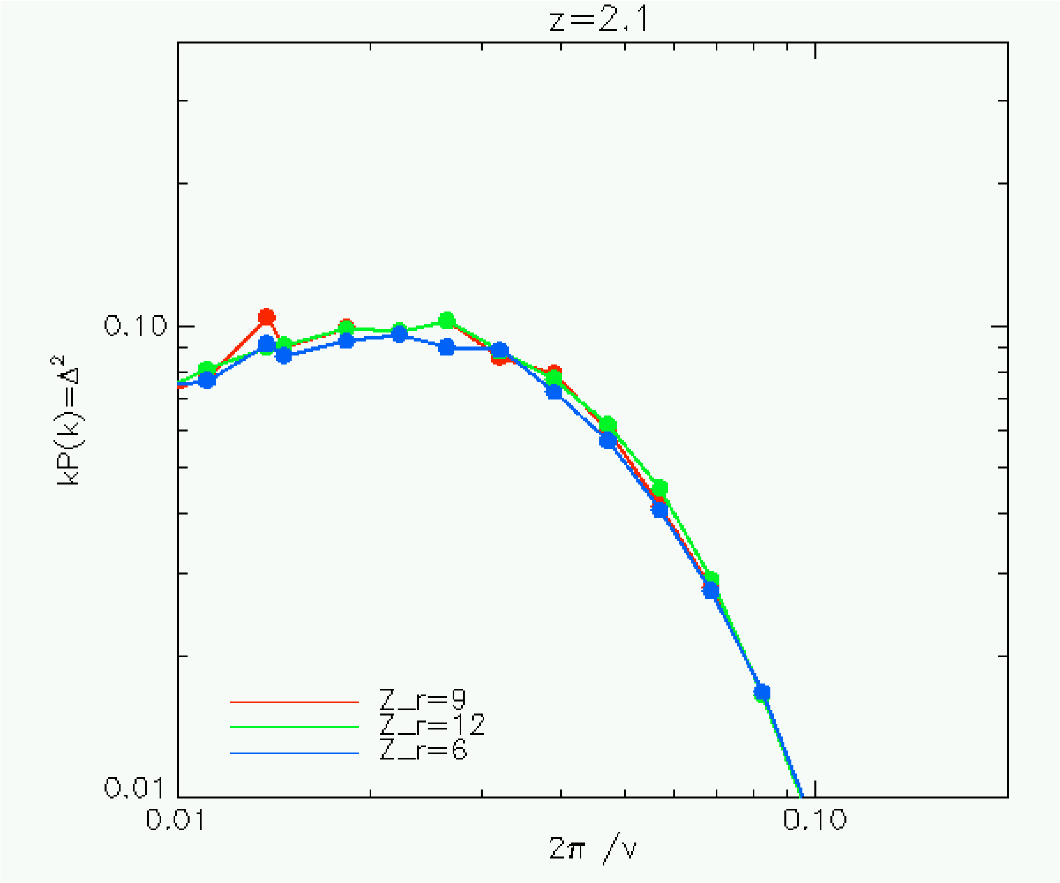
cosmology: WMAP3/WMAP1

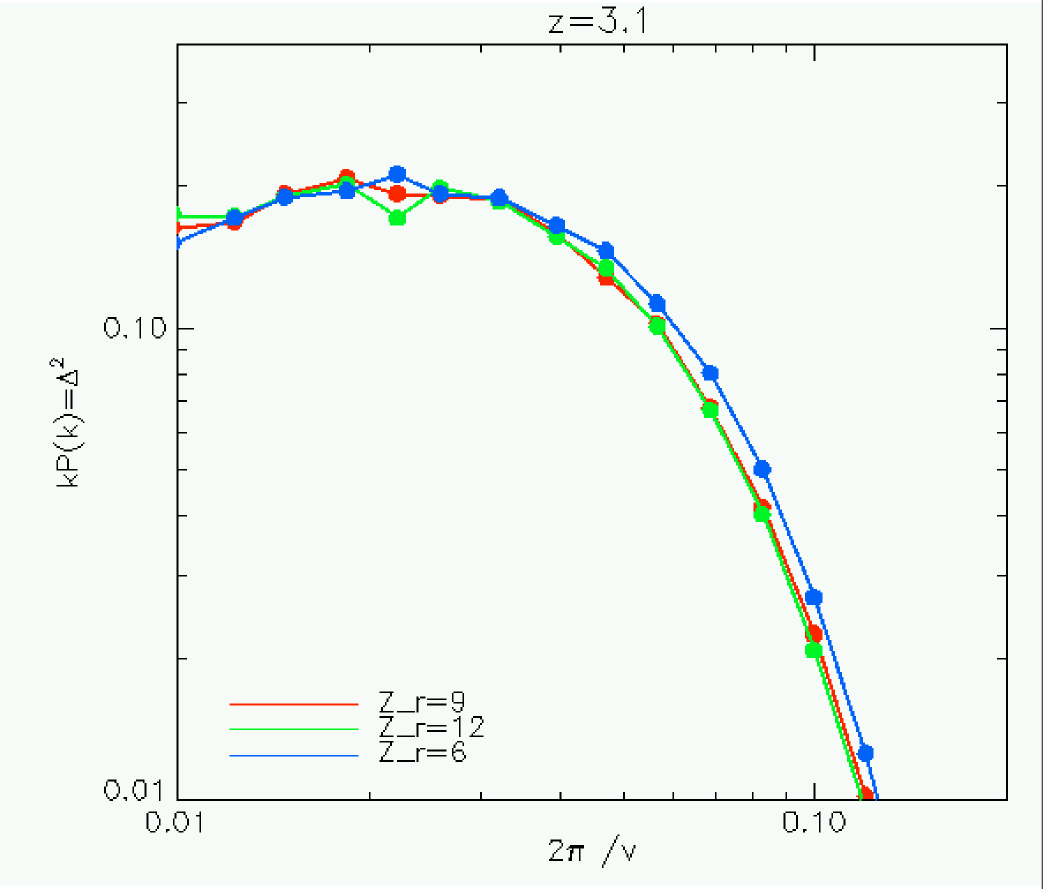




Epoch of HI reionization:

Z_reion=6/
Z_reion=9/
Z_reion=12

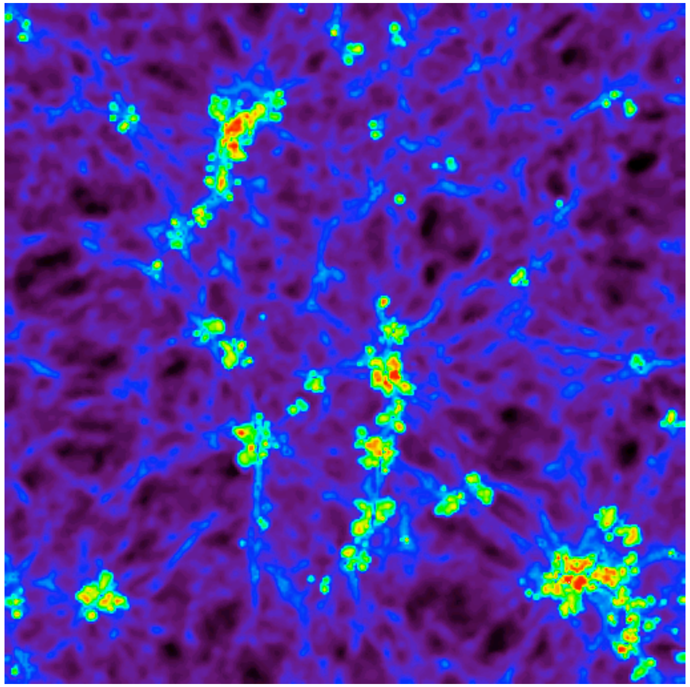


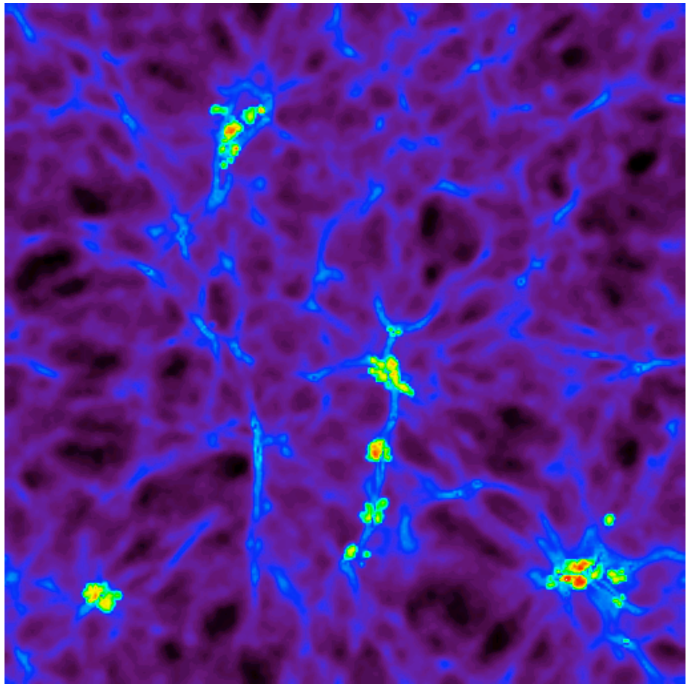


WDM

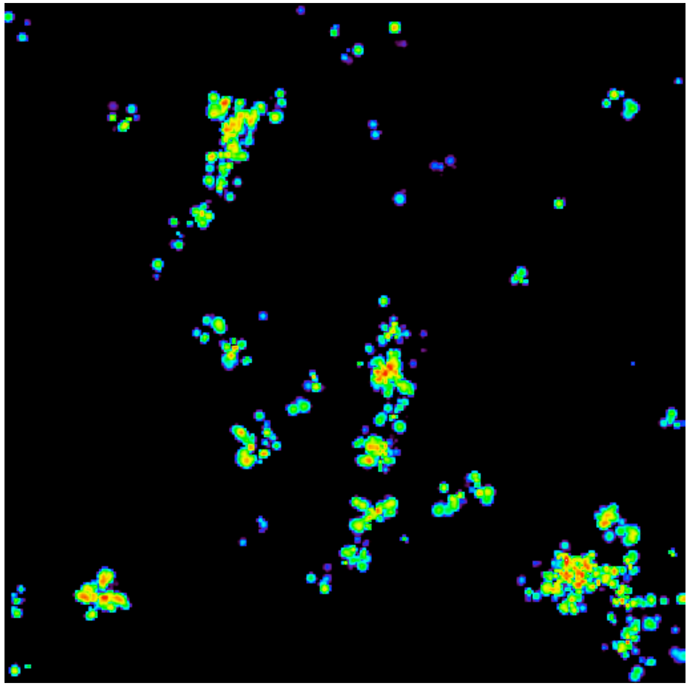
7 keV

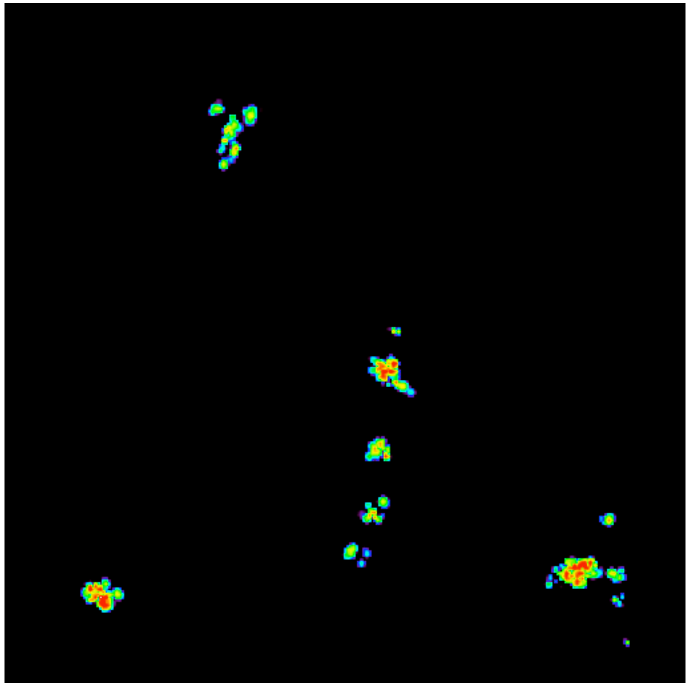
1 keV





temperature

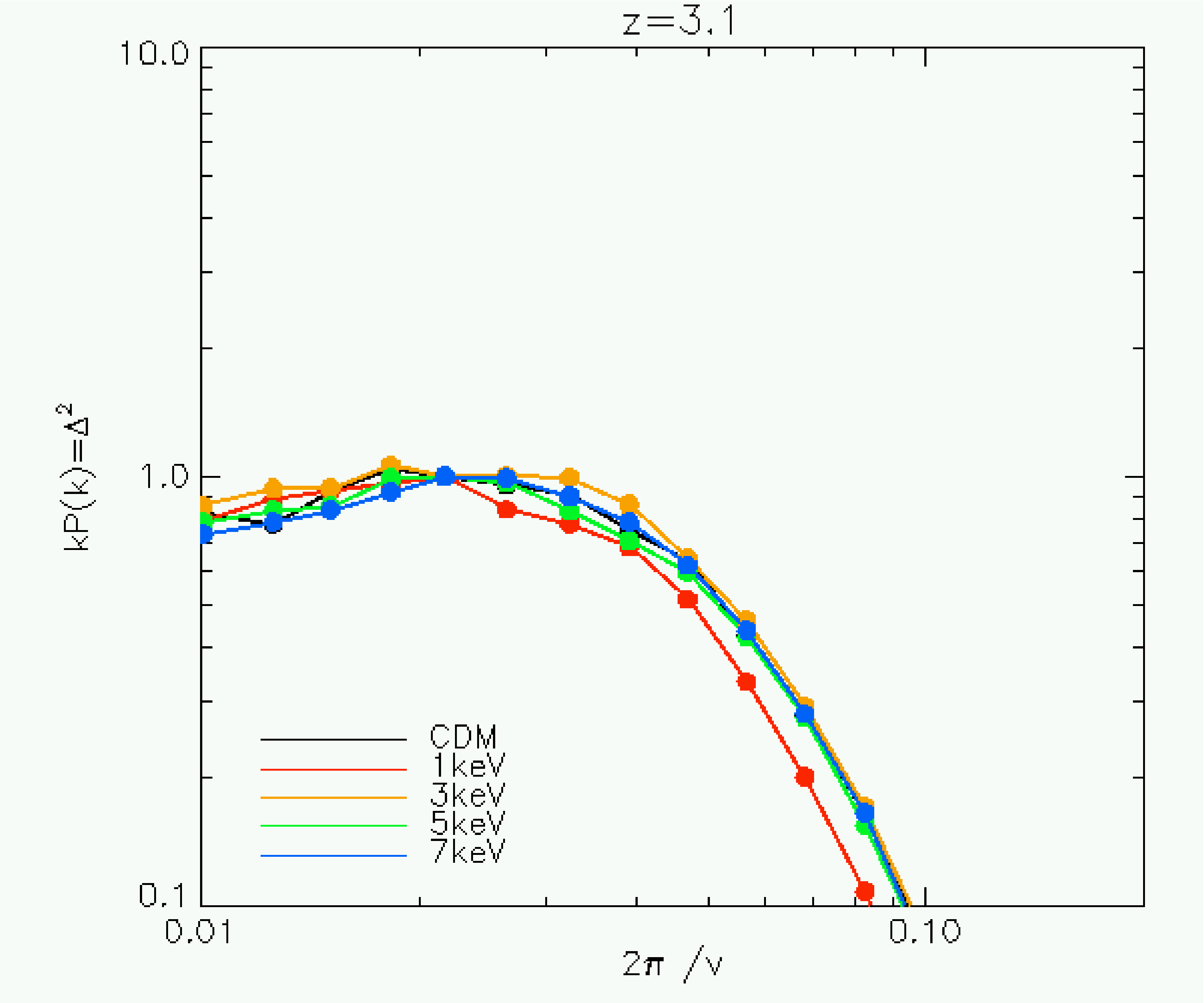




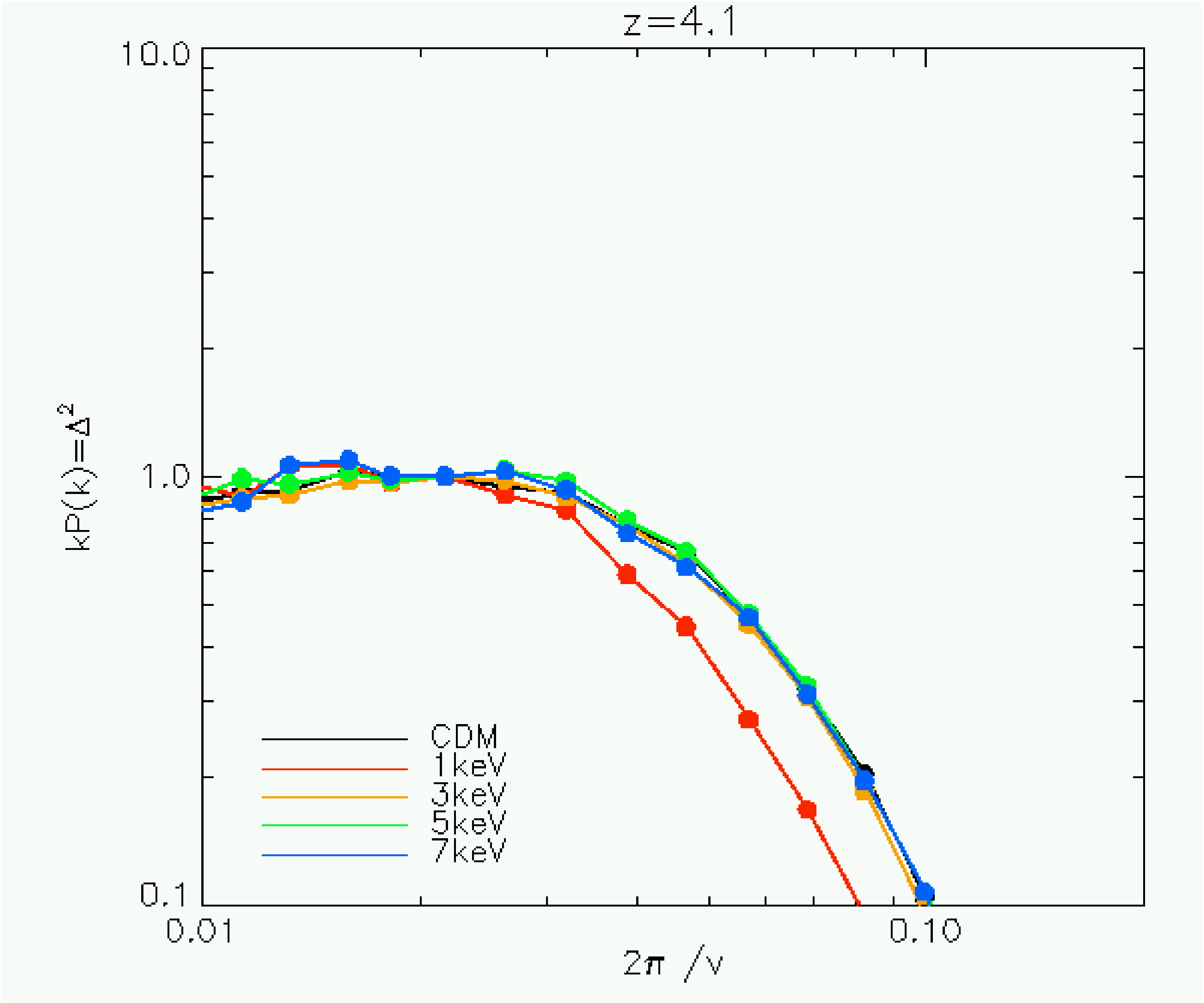
metallicity

Redshift = 4

dark matter: 1keV / 3 keV / 5keV / 7keV / CDM



dark matter: 1keV / 3 keV / 5keV / 7keV / CDM



dark matter: 1keV / 1keV including WDM velocities