Structure formation and the nature of the dark matter

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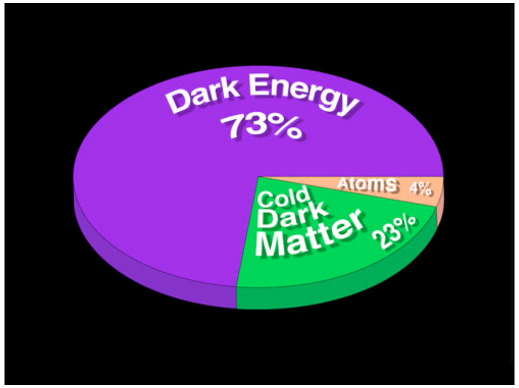
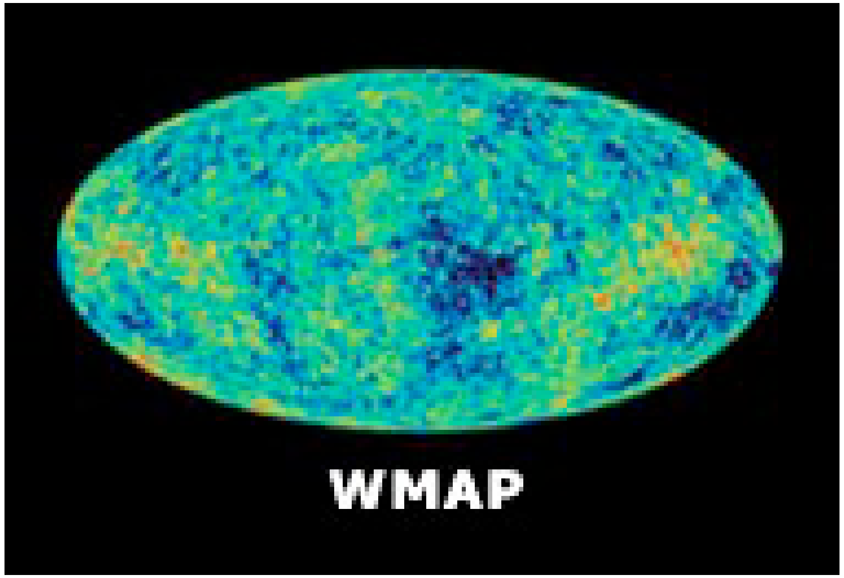
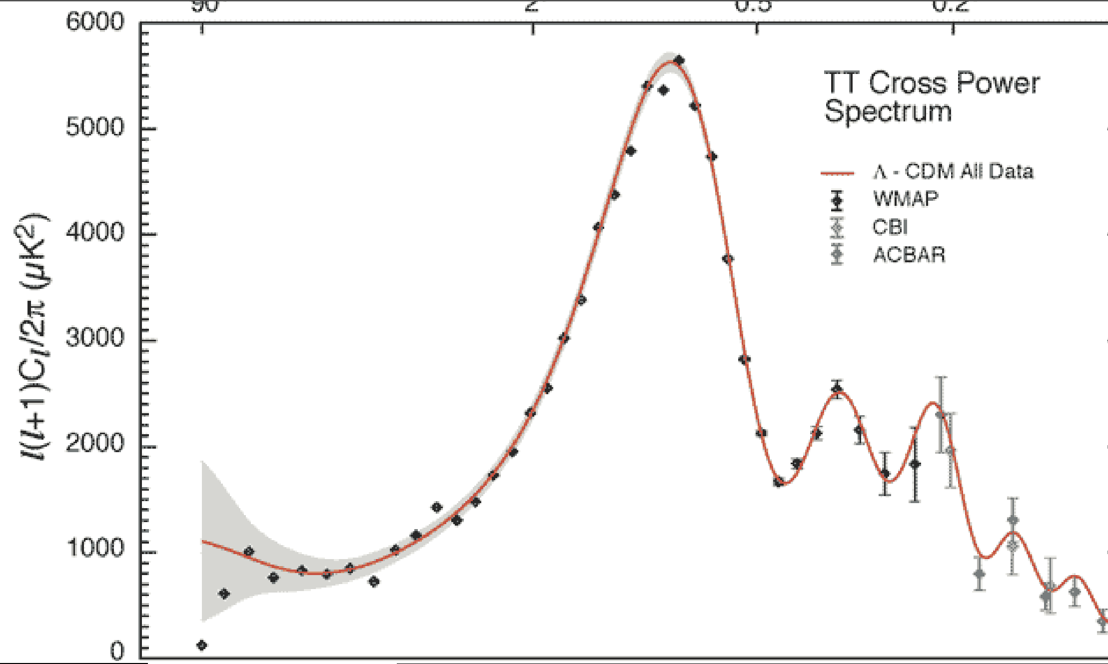
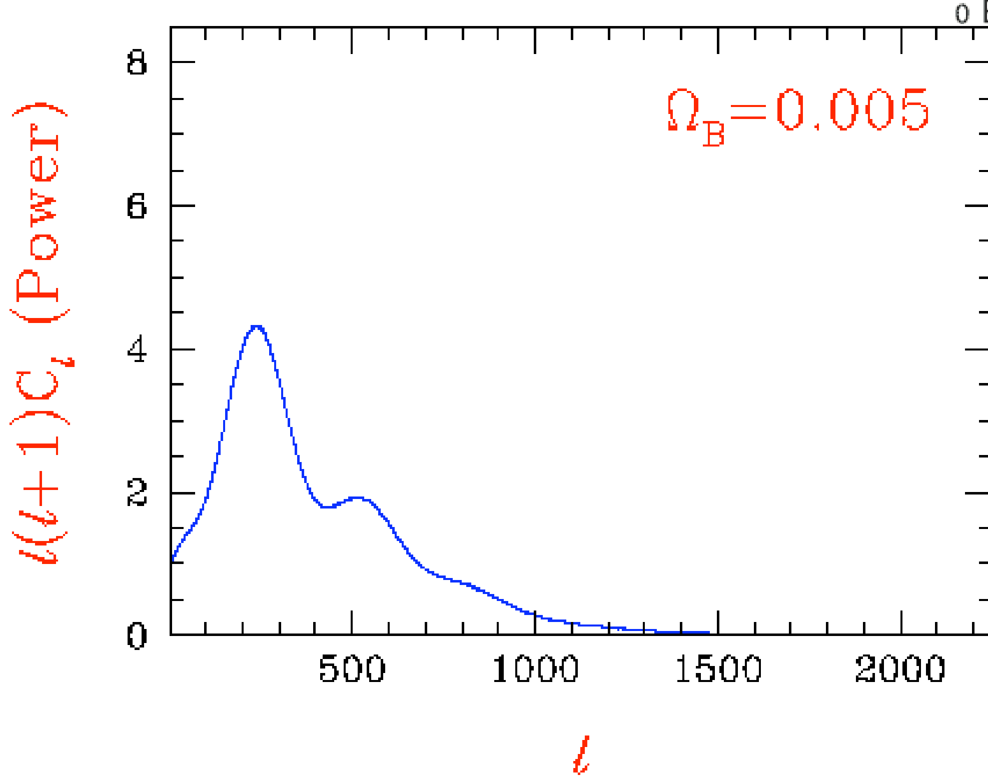
Contents of the Universe

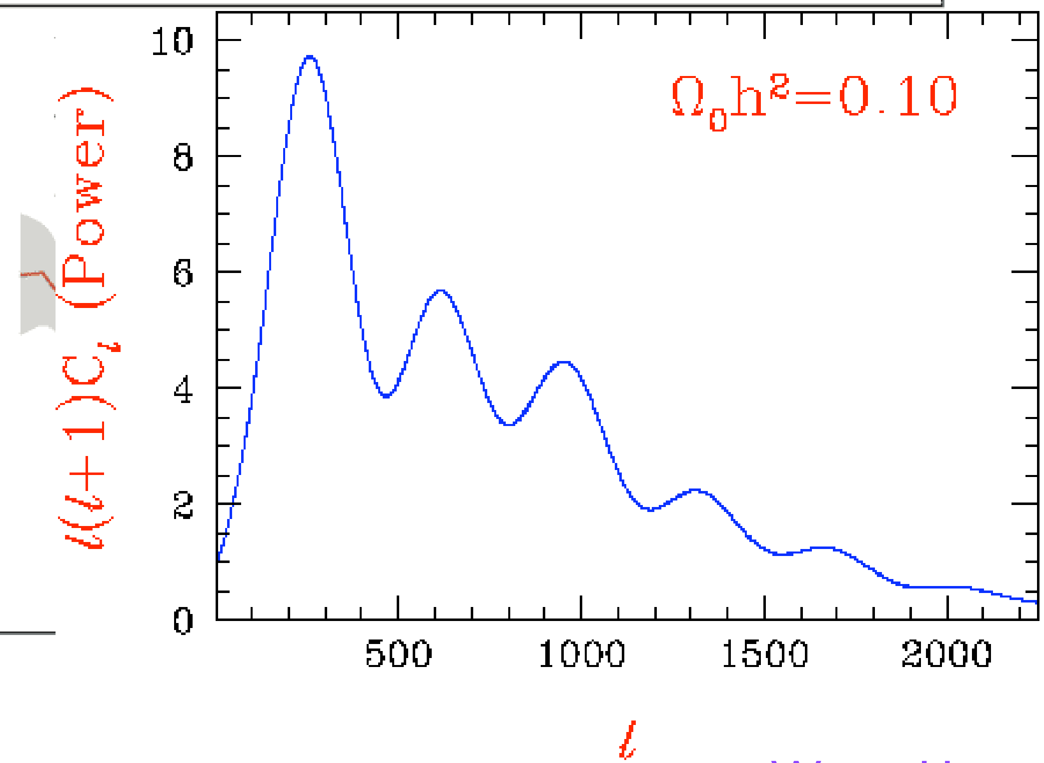


- Introduction
- Success of dark matter models
- Possible issues with Cold Dark Matter
- Dark matter candidates
- Constraints on the nature of the dark matter
  - Lyman-alpha forest
  - First stars


WMAP

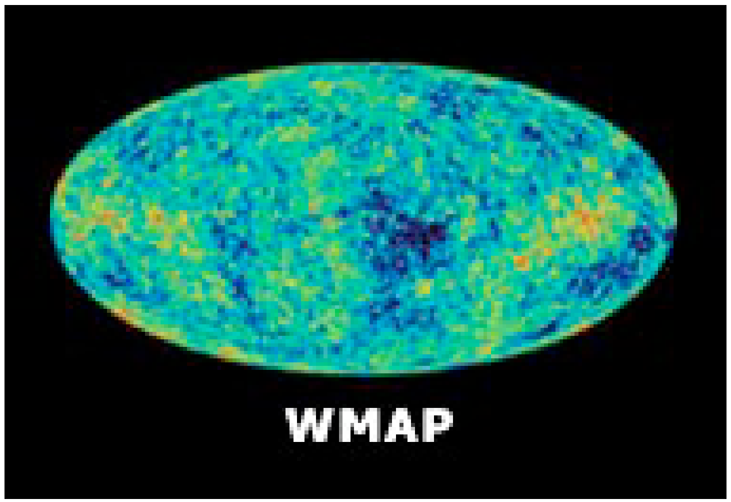

TT Cross Power Spectrum
Λ - CDM All Data
WMAP
CBI
ACBAR
$l(l+1)C_l/2\pi\ (\mu K^2)$
0
1000
2000
3000
4000
5000
6000
2
0.5
0.2


$\Omega_B=0.005$
$l(l+1)C_l$ (Power)
l
0
2
4
6
8
500
1000
1500
2000

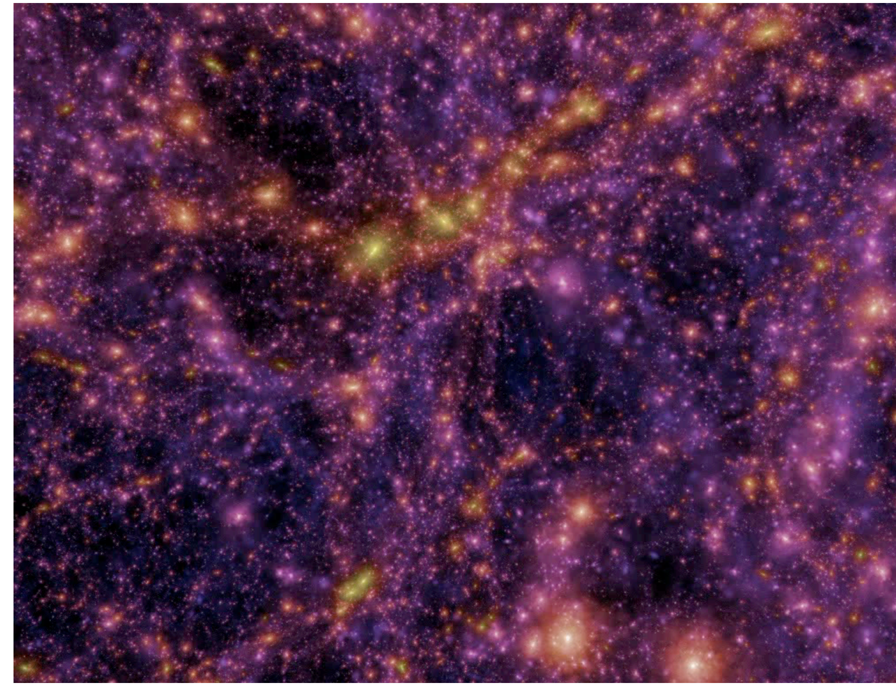

$\Omega_0 h^2=0.10$
$l(l+1)C_l$ (Power)
l
0
2
4
6
8
10
500
1000
1500
2000

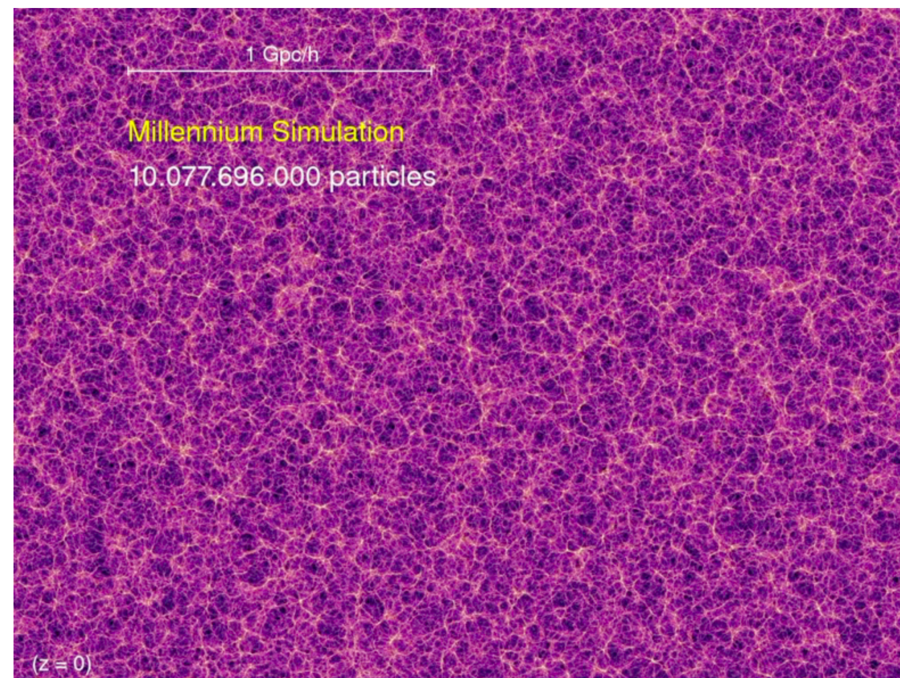
Wayne Hu

Durham University



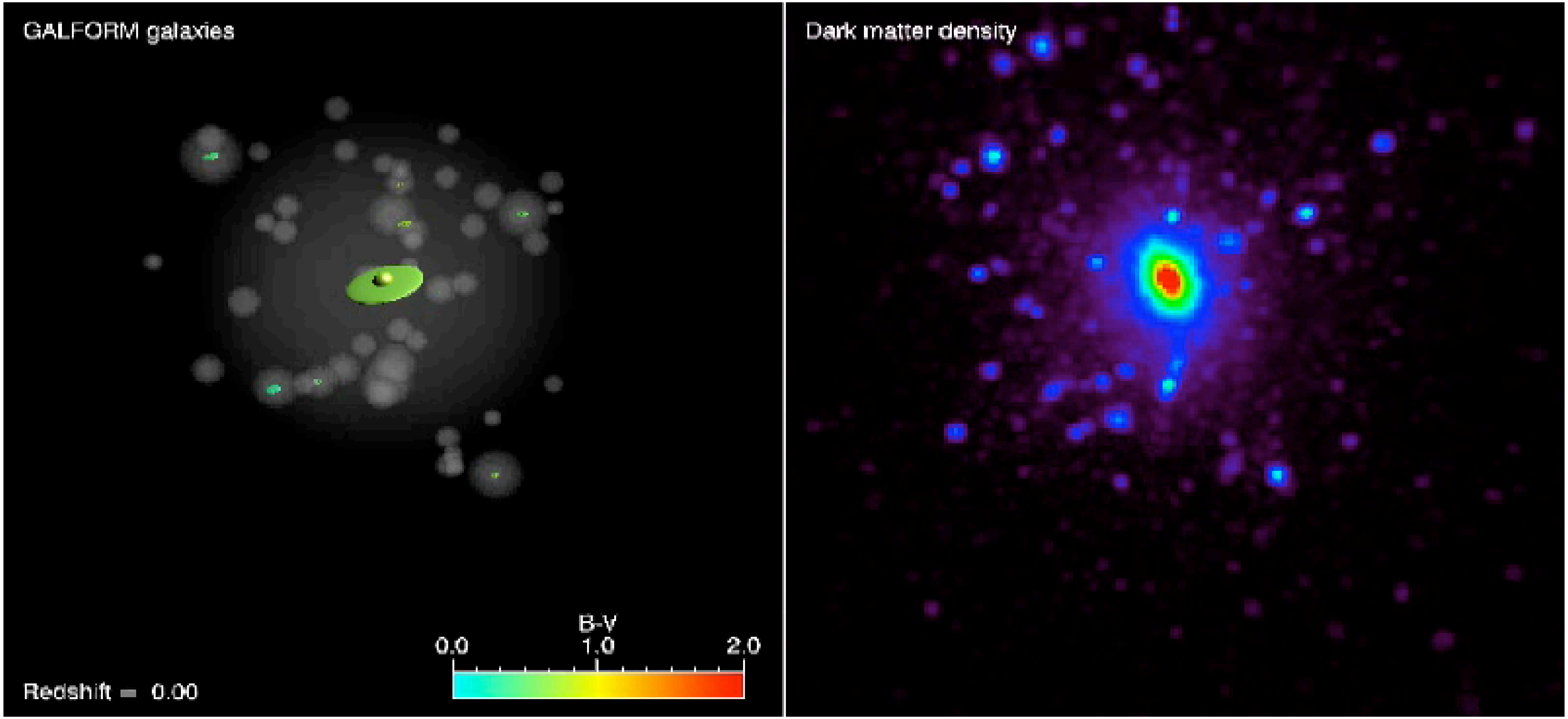
+ Gravity





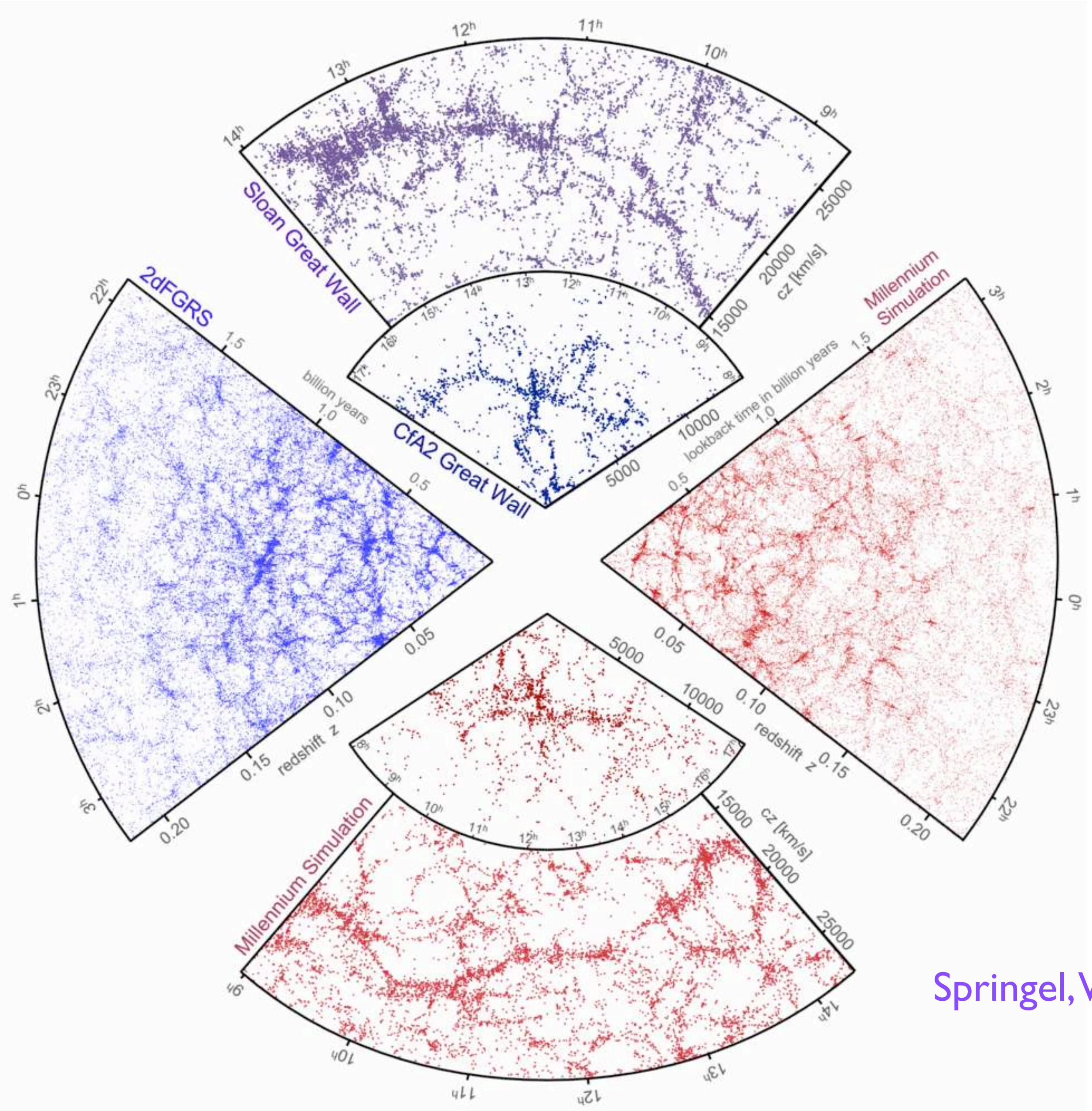

1 Gpc/h
Millennium Simulation
10.077.696.000 particles
(z = 0)

Semi-analytic modelling



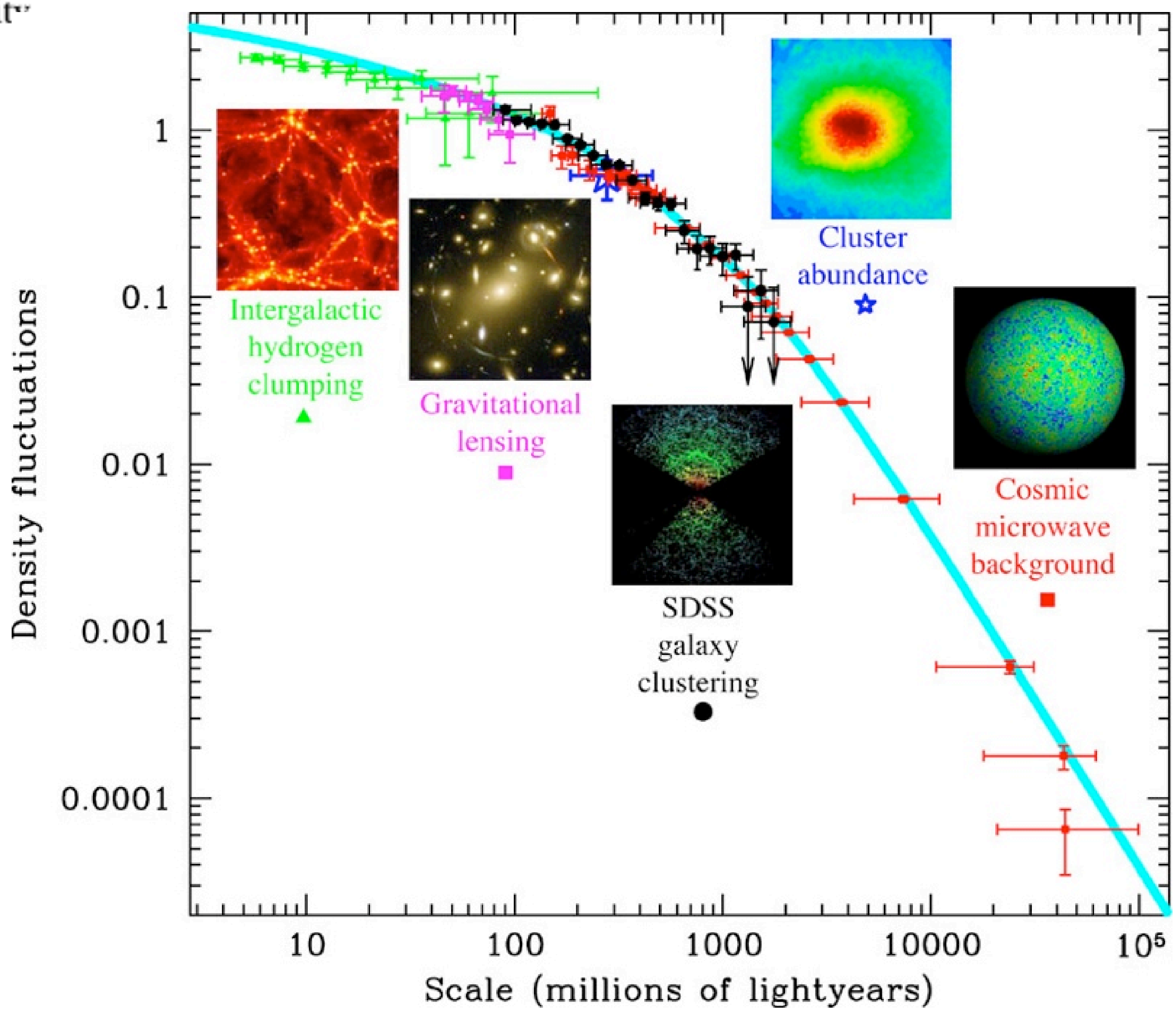
J Helly

Simulated versus real galaxies



Springel, White & Frenk

Durham University



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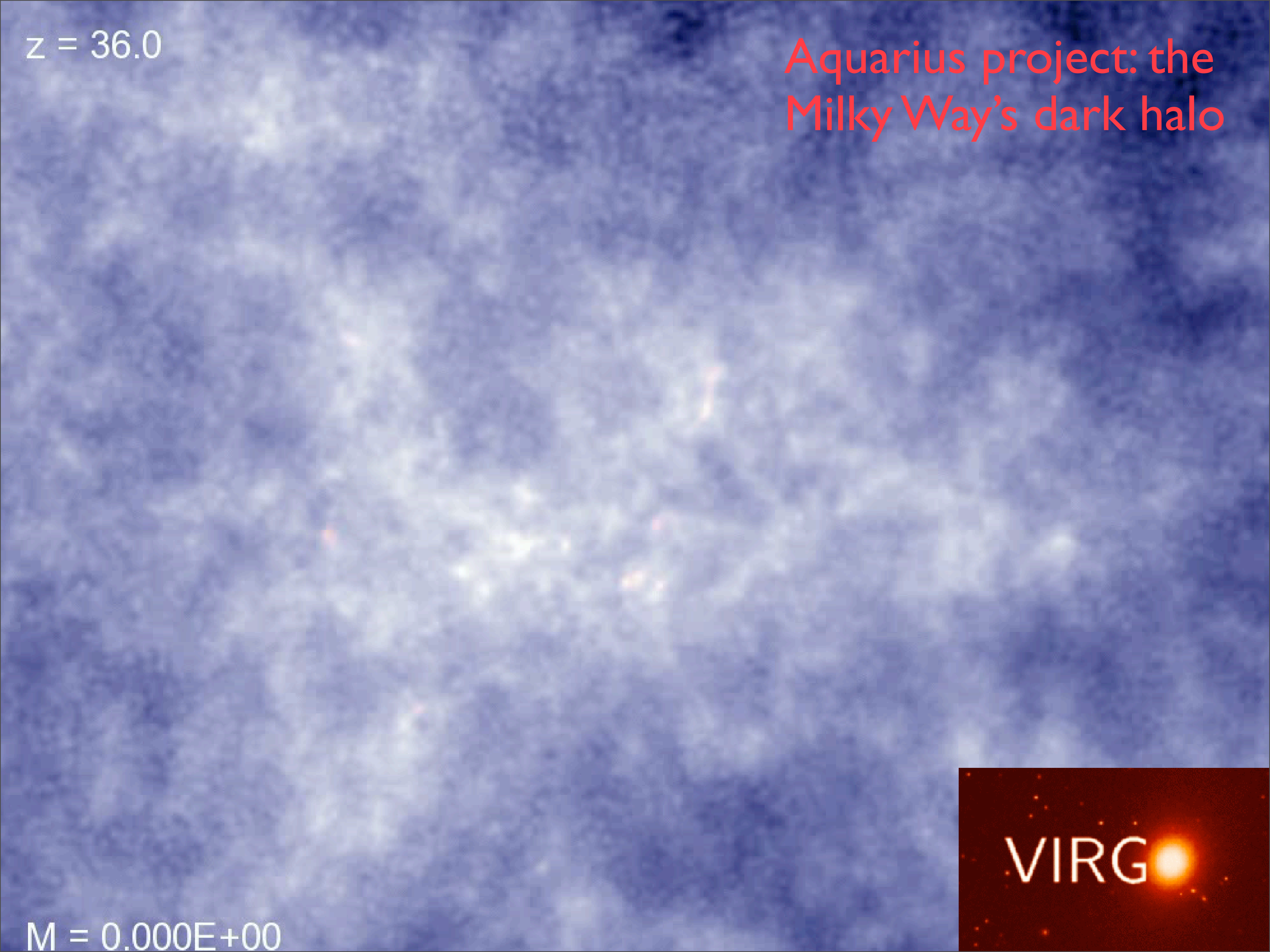
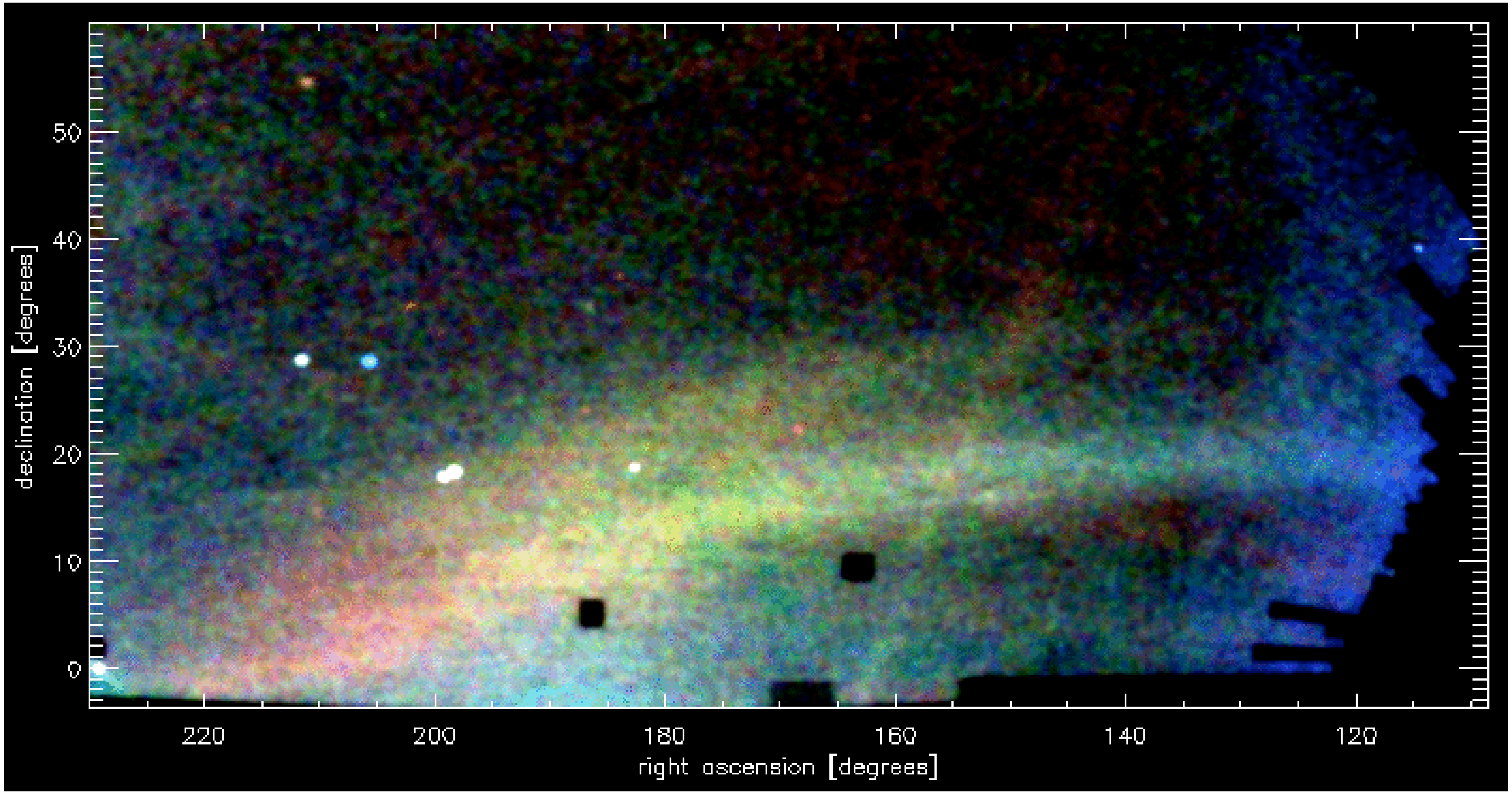
Models with Cold Dark Matter produce model Universes that look very much like the real world on large scales

How well do they do on small scales?

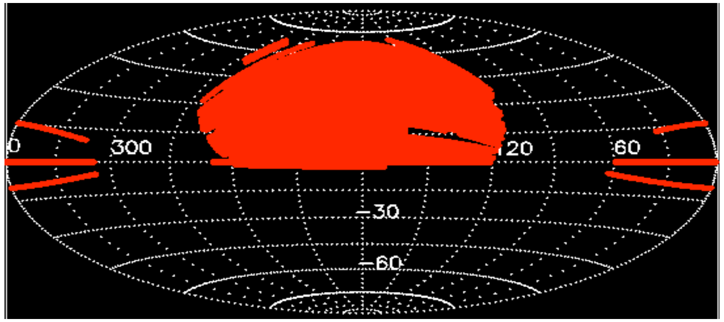
Aquarius project: the Milky Way's dark halo



The Field of Streams



Evans, Belokurov, Zucker, Fellhauer



SDSS

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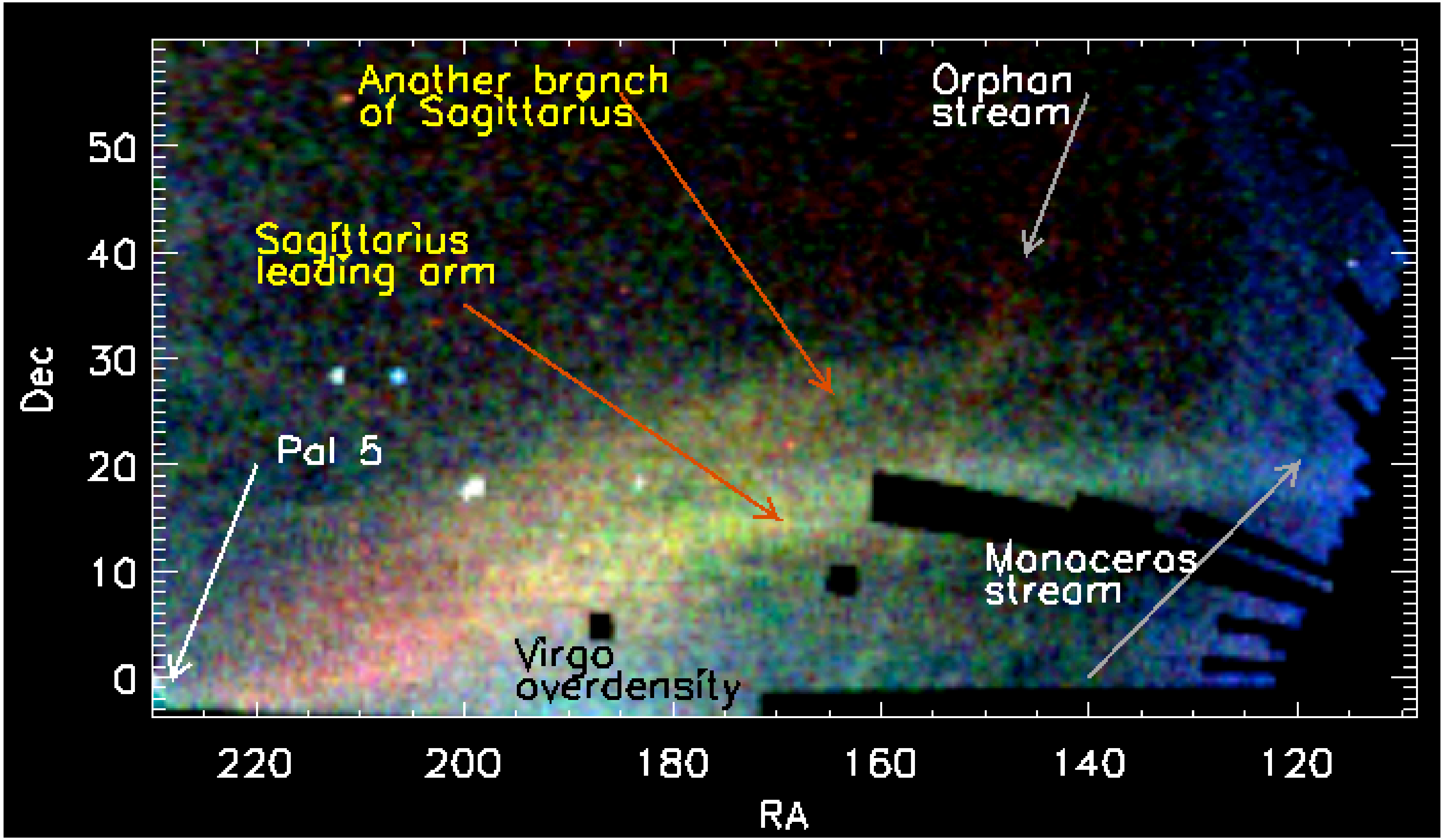
The Sagittarius Stream and the Orphan Stream



Evans, Belokurov, Zucker, Fellhauer

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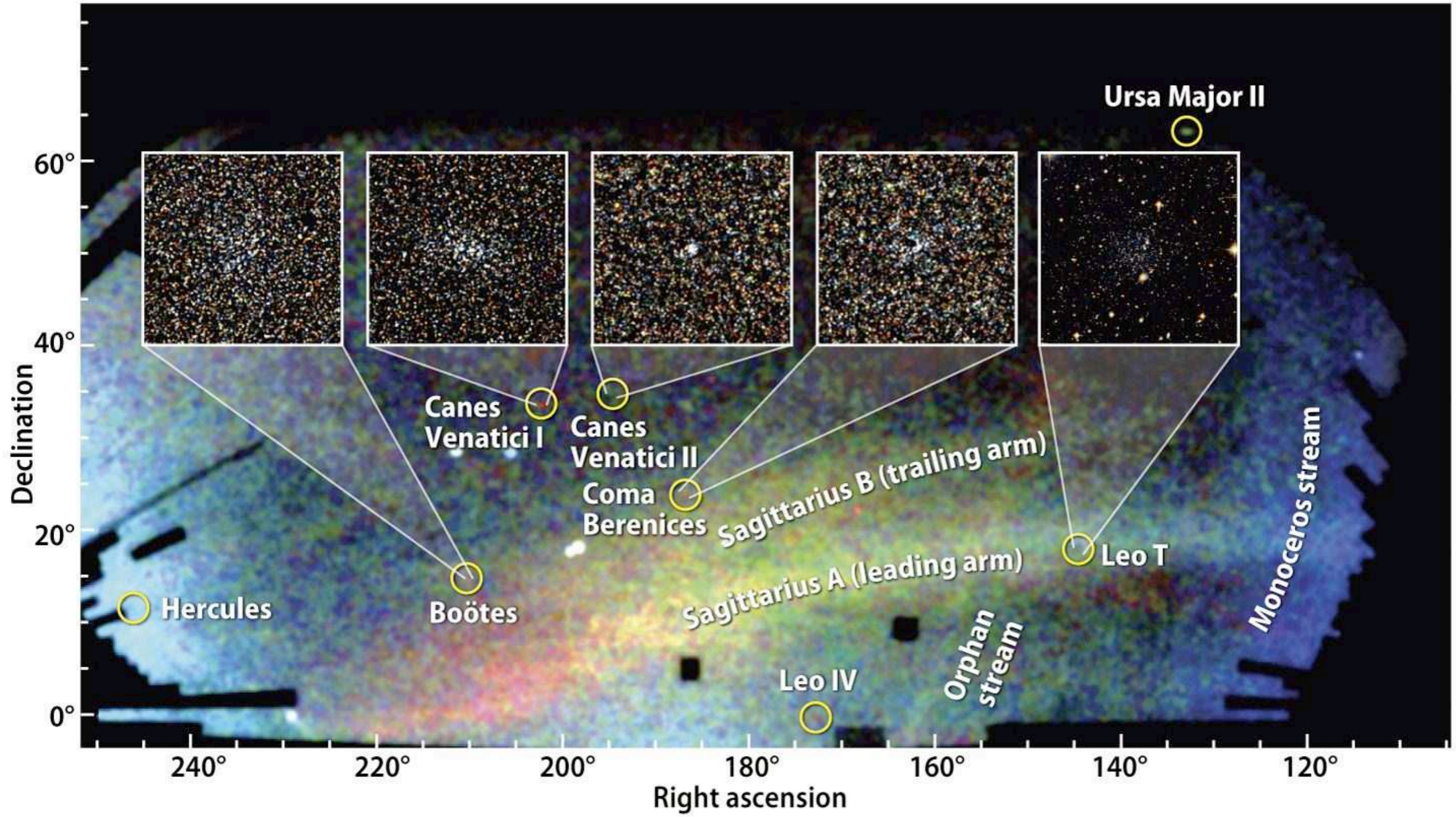
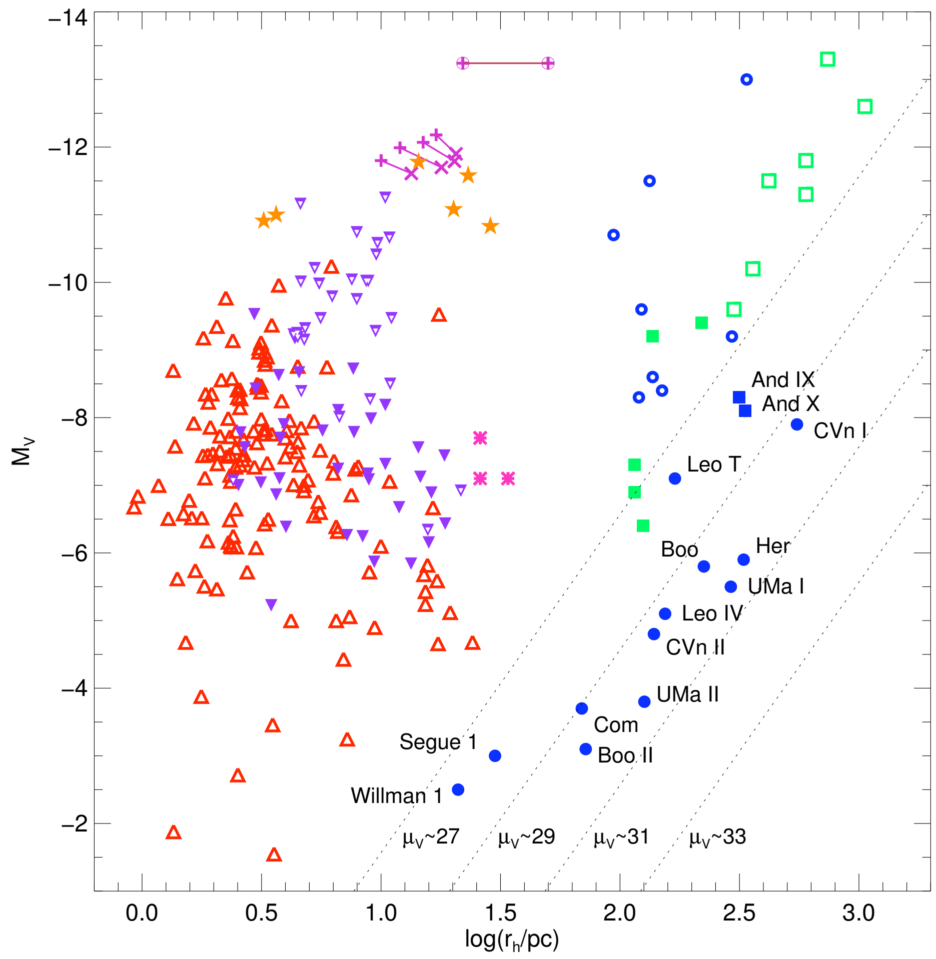
The Milky Way Dwarfs



Evans, Belokurov, Zucker, Fellhauer

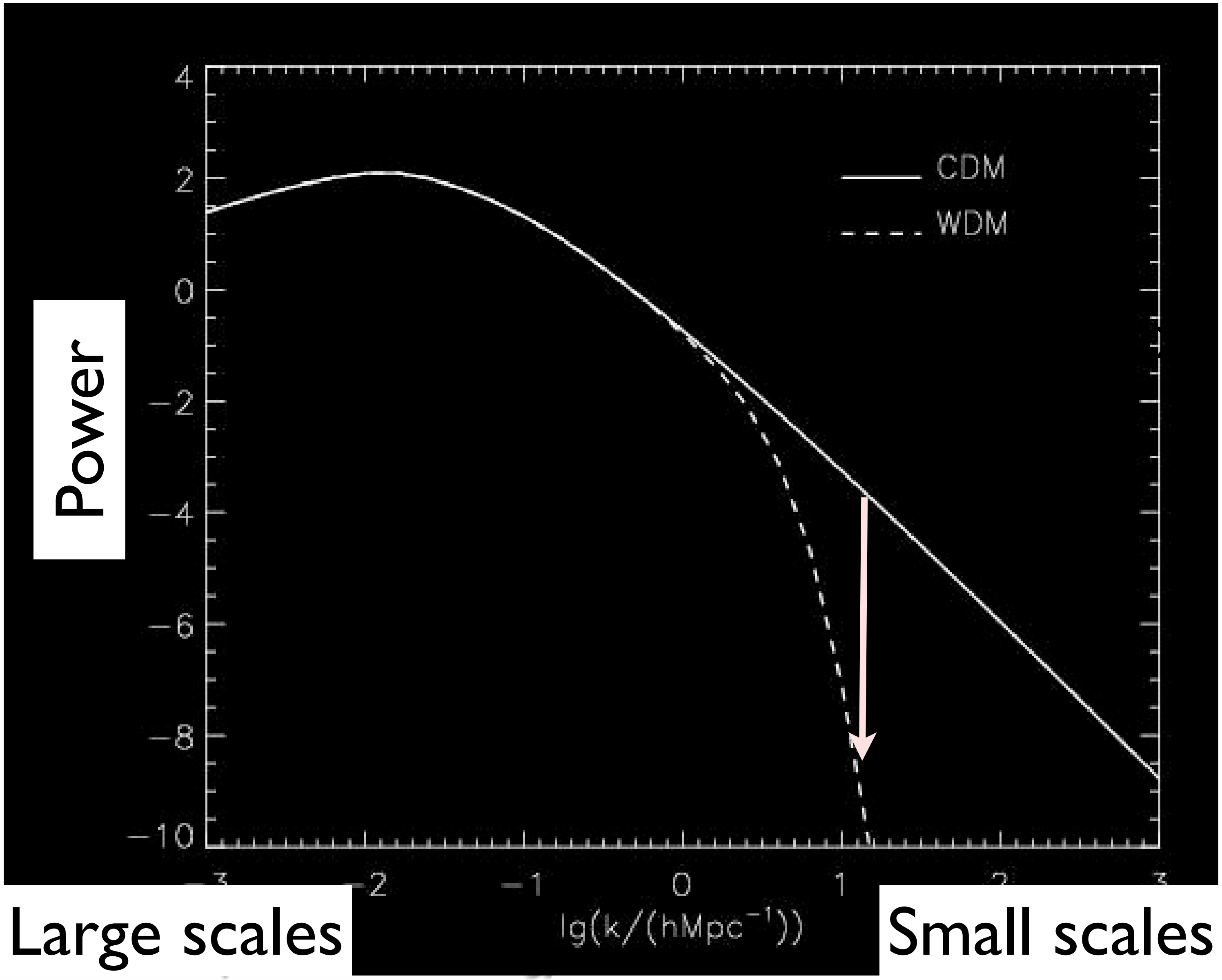
The Milky Way Dwarfs

Luminosity



Size

How does nature of the dark matter affect structure formation?



Dark Matter and Particle Physics:
no lack of candidates!

- neutrino
- sterile neutrino (pulsar kicks?)
- gravitino
- axion
- .....

These decouple at different times, depending on whether they are relativistic or not when entering the horizon when radiation dominates: Hot vs Warm vs Cold Dark Matter

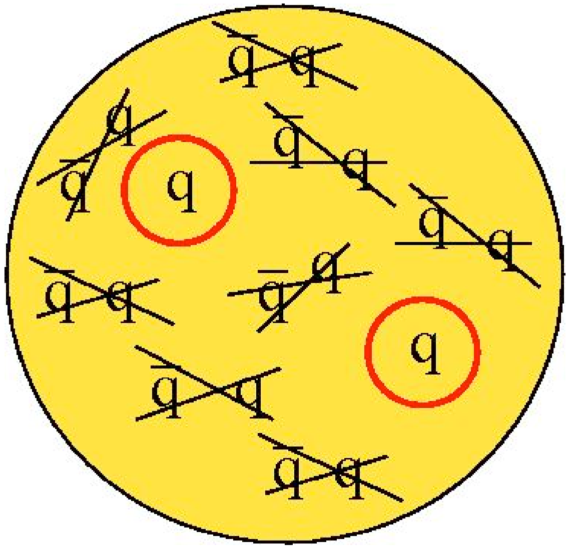
Particle physics motivation for new physics:

Leptogenesis and the Baryon Asymmetry

10000000001 quarks

In the Early Universe

10000000000 antiquarks



As the temperature drops, only quarks are left:

The excess of quarks can be explained by **Leptogenesis**: the heavy N responsible for neutrino masses generate a **baryon asymmetry**.

Plausible DM candidates

* Neutrino
  - Hot dark matter!

* Sterile neutrino
  - No interactions within standard model
    - except with SM neutrinos
    - except gravitationally
  - keV masses
  - Decays in other neutrinos with emission of photon
  - Could explain pulsar kicks
  - Three families: heavy one explains baryogenesis, light one is dark matter
  - Heavier sterile neutrinos could explain masses of ordinary neutrinos through 'see-saw' mechanism

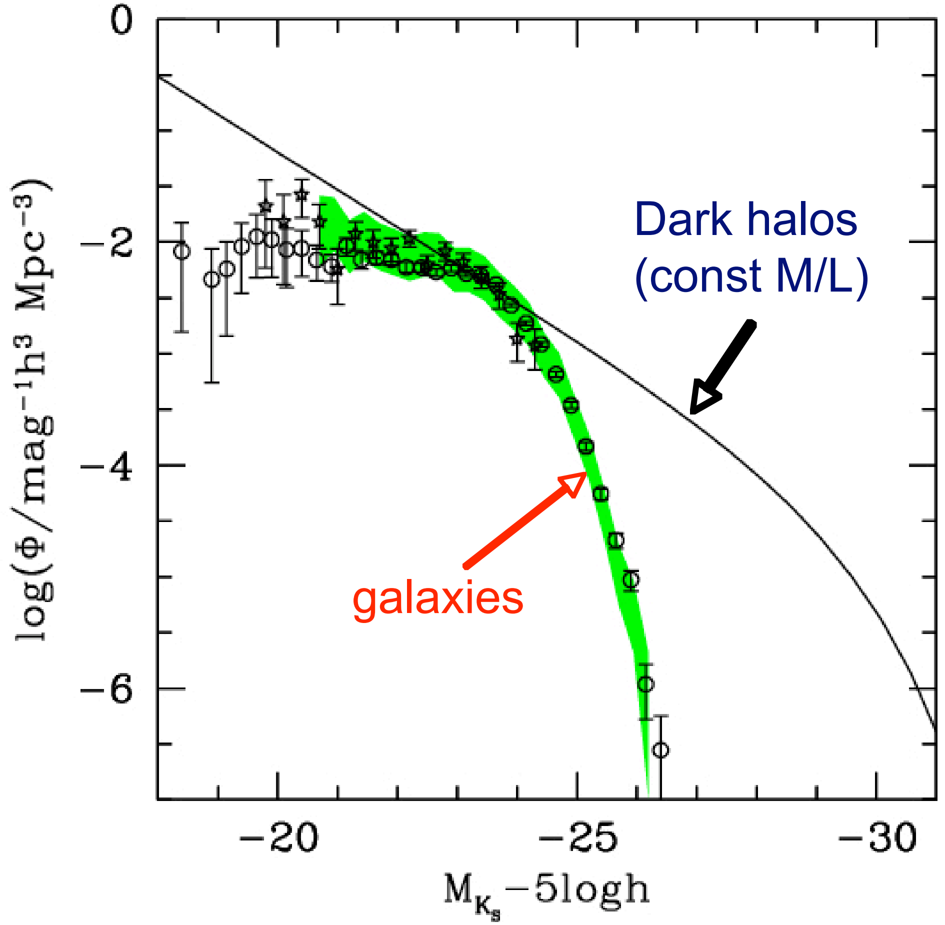
* WIMPS
  - GeV-TeV masses
  - SUSY particle
    - neutralino (a neutral fermion)
    - gravitino

* Axion
  - Light CDM relic

Possible issues with Cold Dark Matter:

- Satellite problem:
  why is DM substructure so dark?
- Cusp problem:
  observed dwarf galaxies are cored, DM haloes are cusped

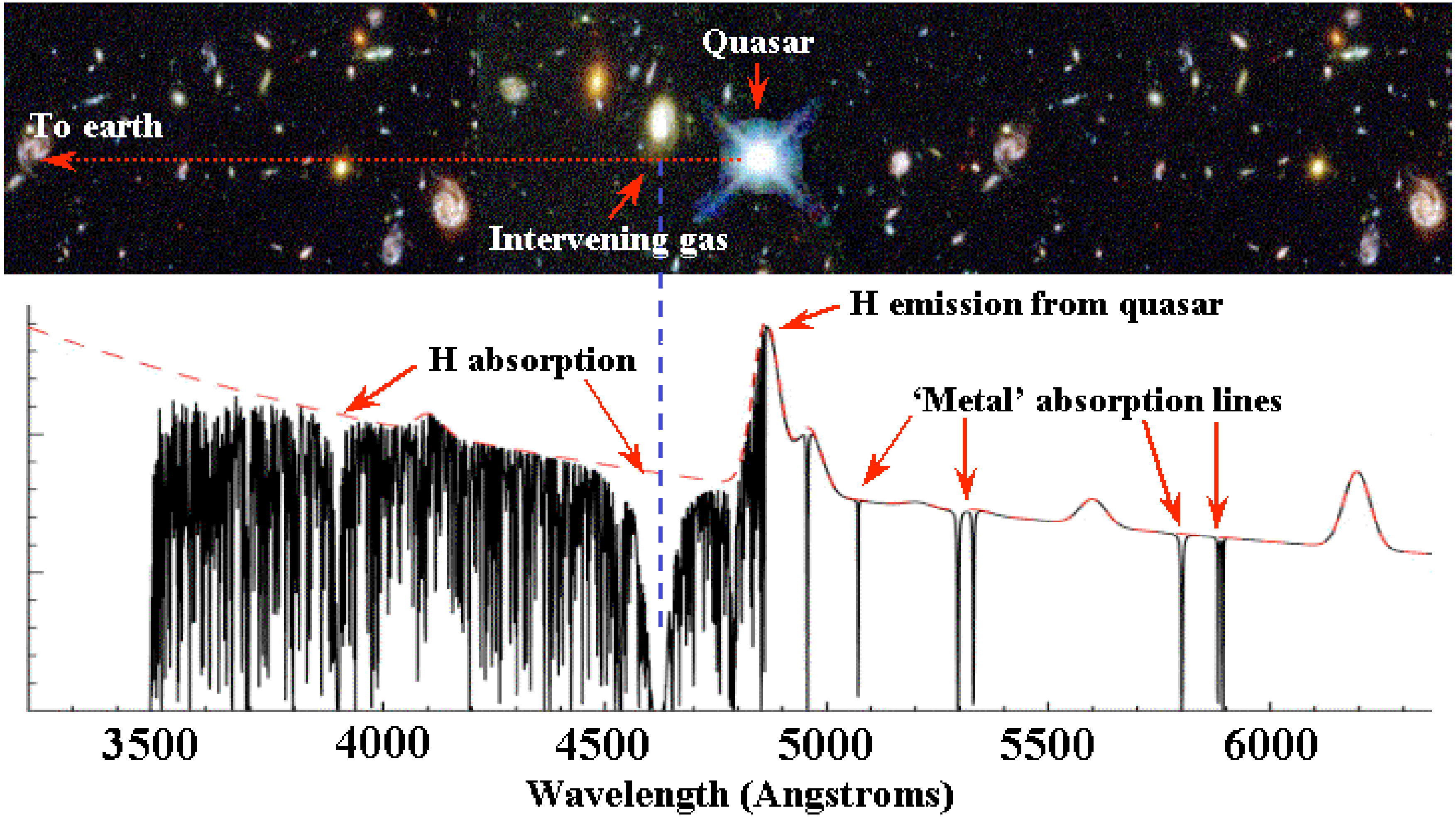
"Gastrophysics?"



Cosmological constrains on the nature of the dark matter

- Lyman-alpha forest
- First stars

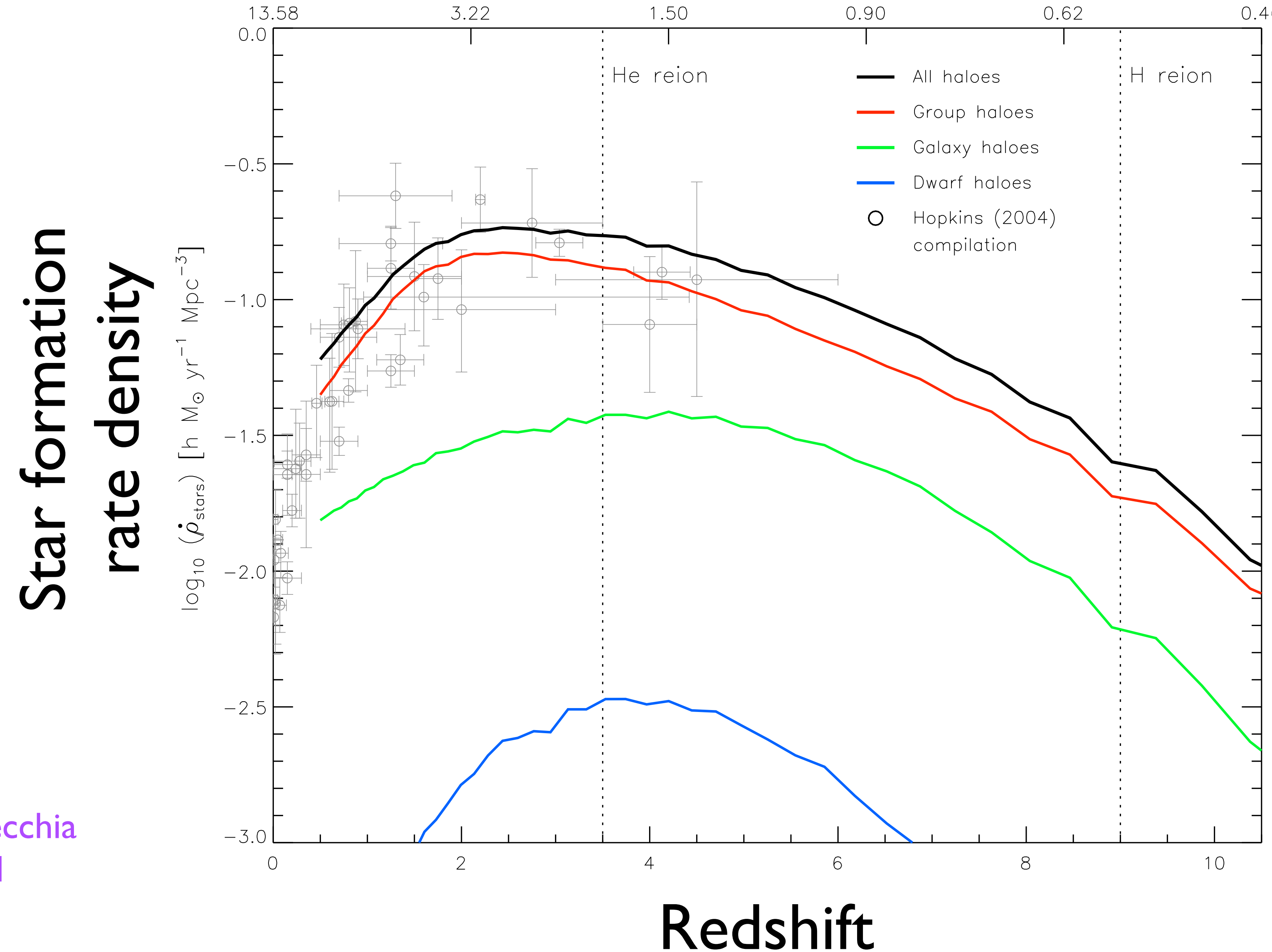
Lyman-alpha forest:



Quasar spectra sample the matter distribution along the line of sight

Simulating galaxies and the intergalactic medium

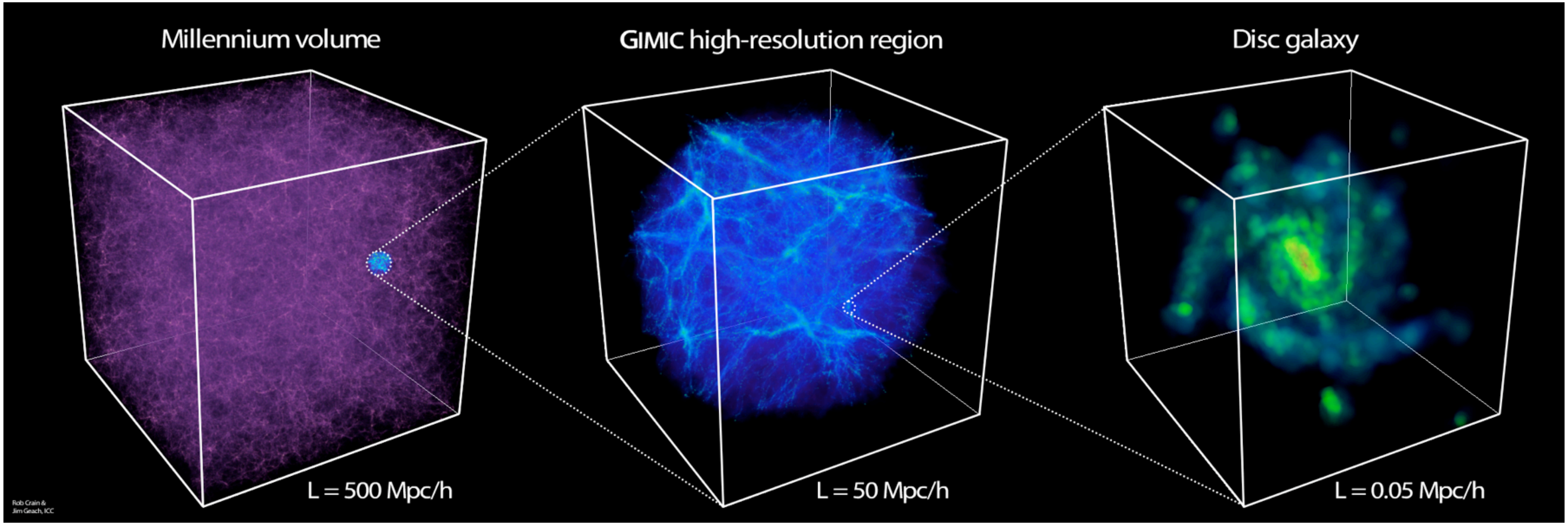
Cosmic star formation history



Schaye
Dalla Vecchia
Springel
TT

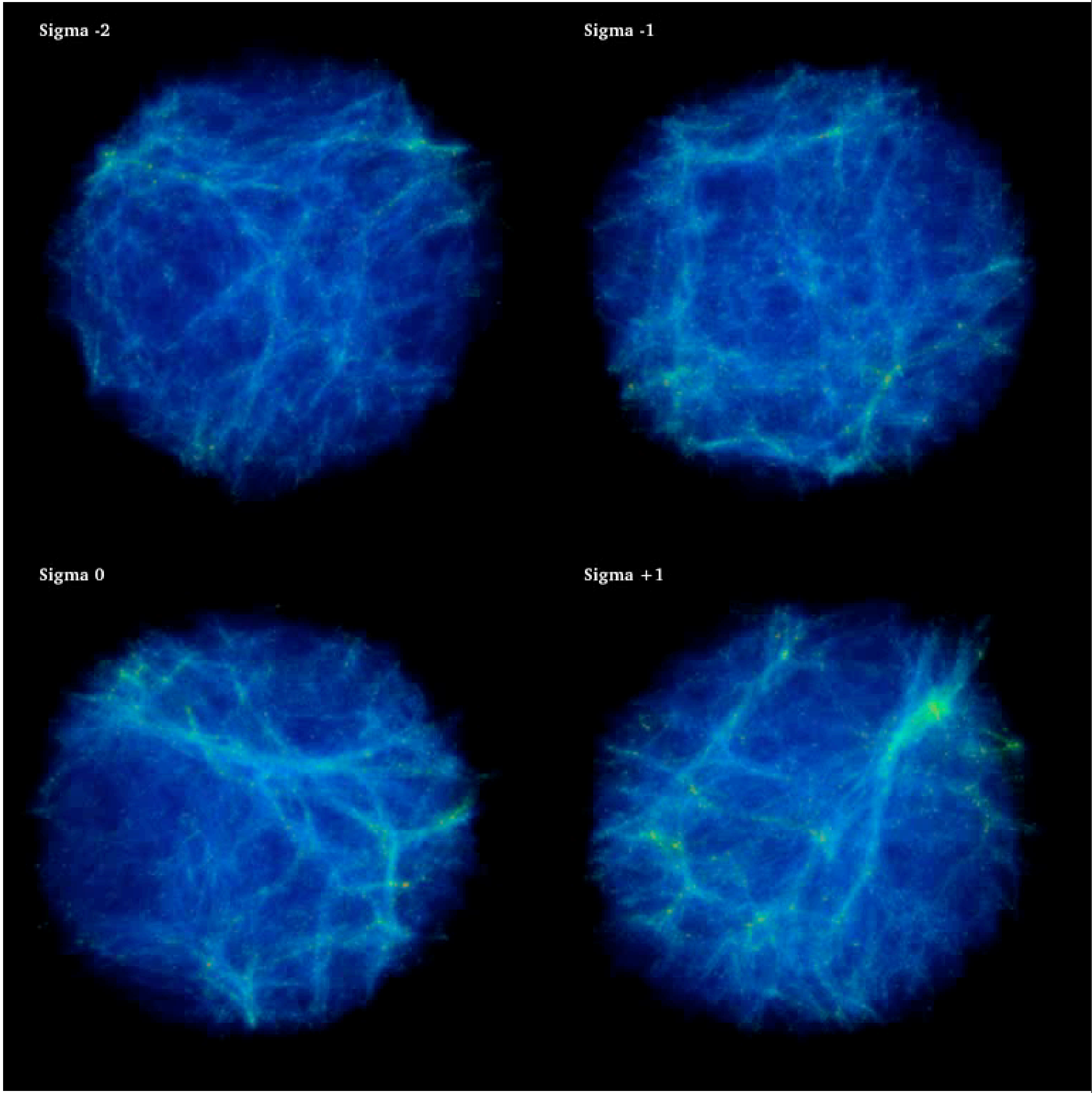
Suite of simulations: GIMIC/OWLS

Galaxy-Intergalactic Medium Interaction Calculation



Zoomed simulations of 5 spheres picked from the Millennium Simulation

Combine LSS with high numerical resolution



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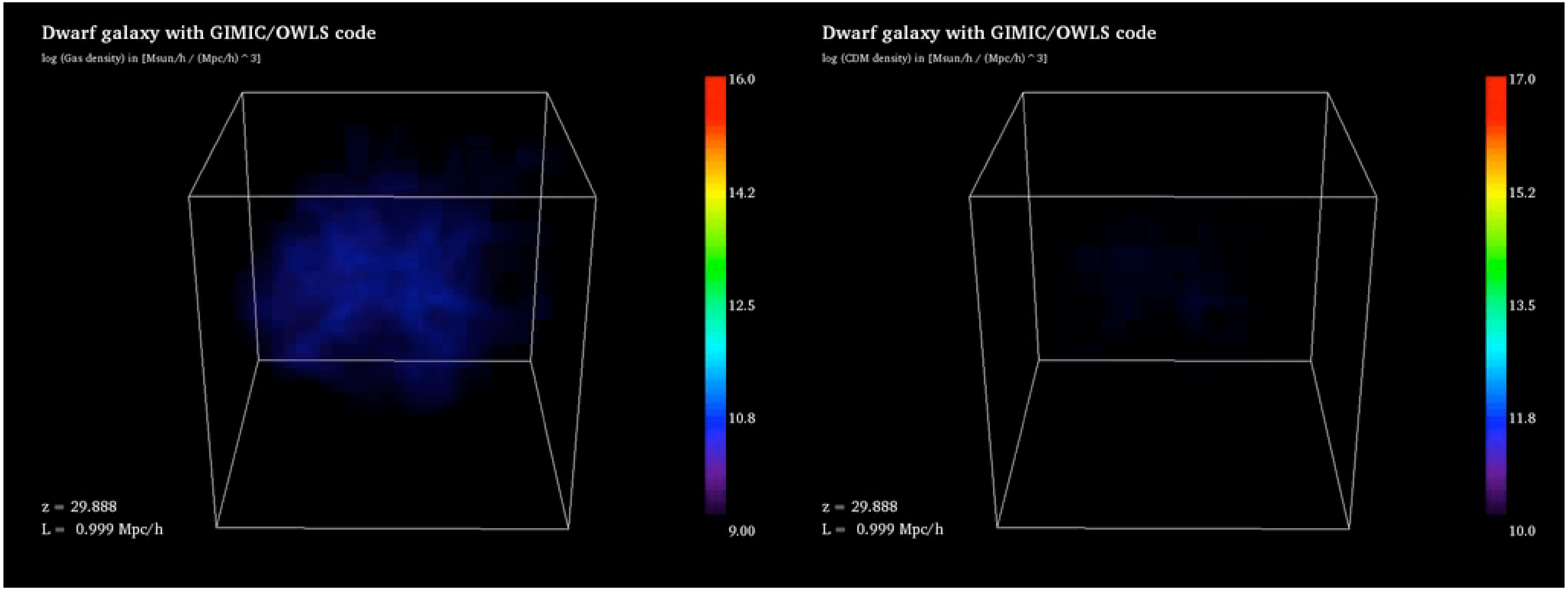
Galactic winds enrich surroundings with metals



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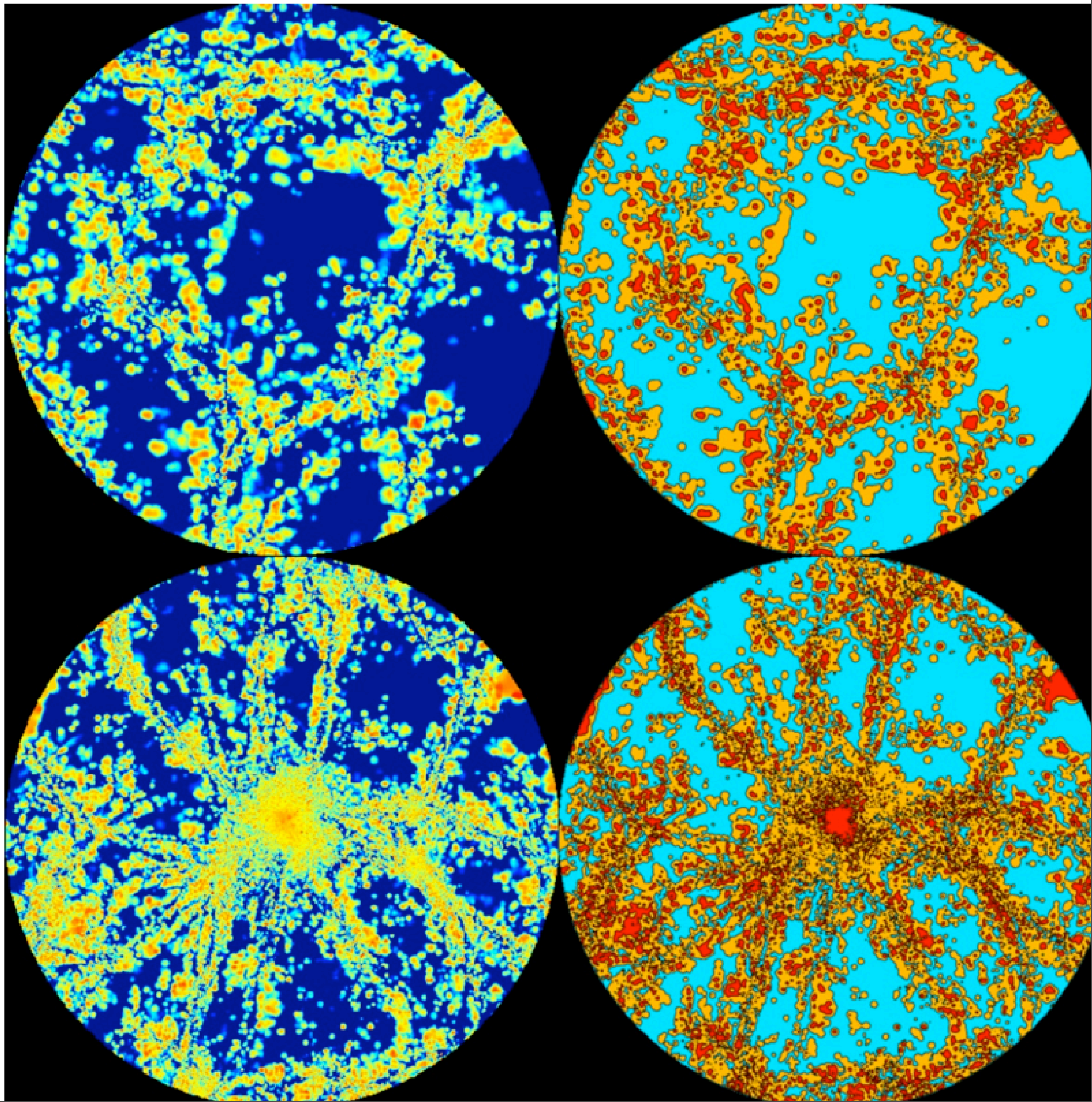
Metal enrichement



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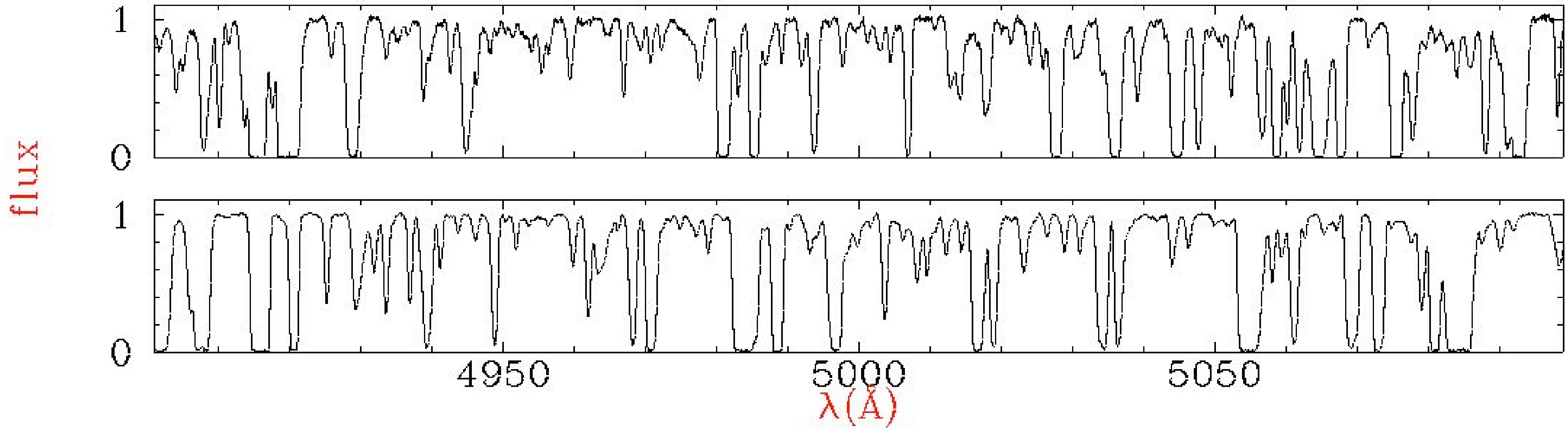


Simulated versus observed Ly-a spectrum

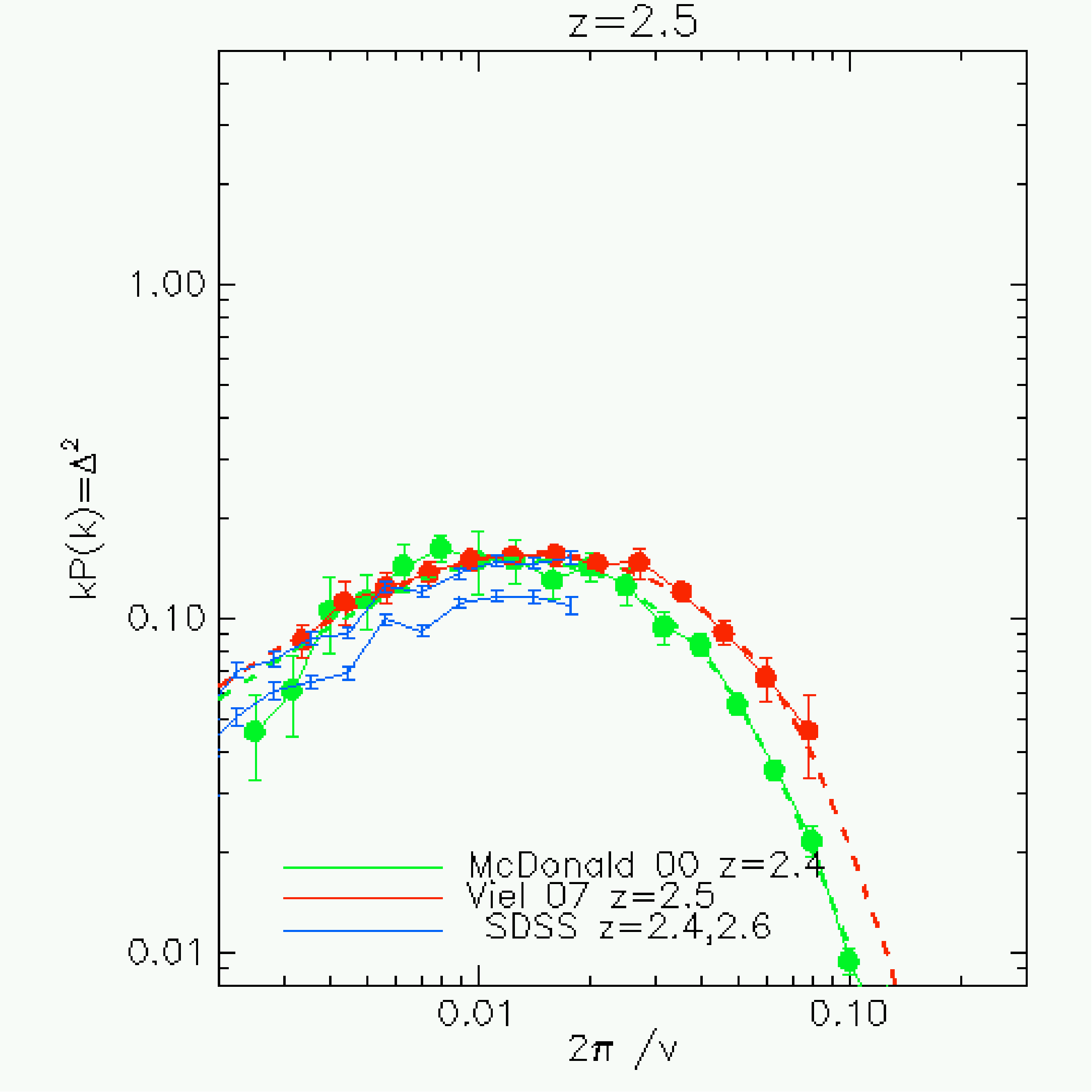
•Current observations

Measurements of the flux power-spectrum

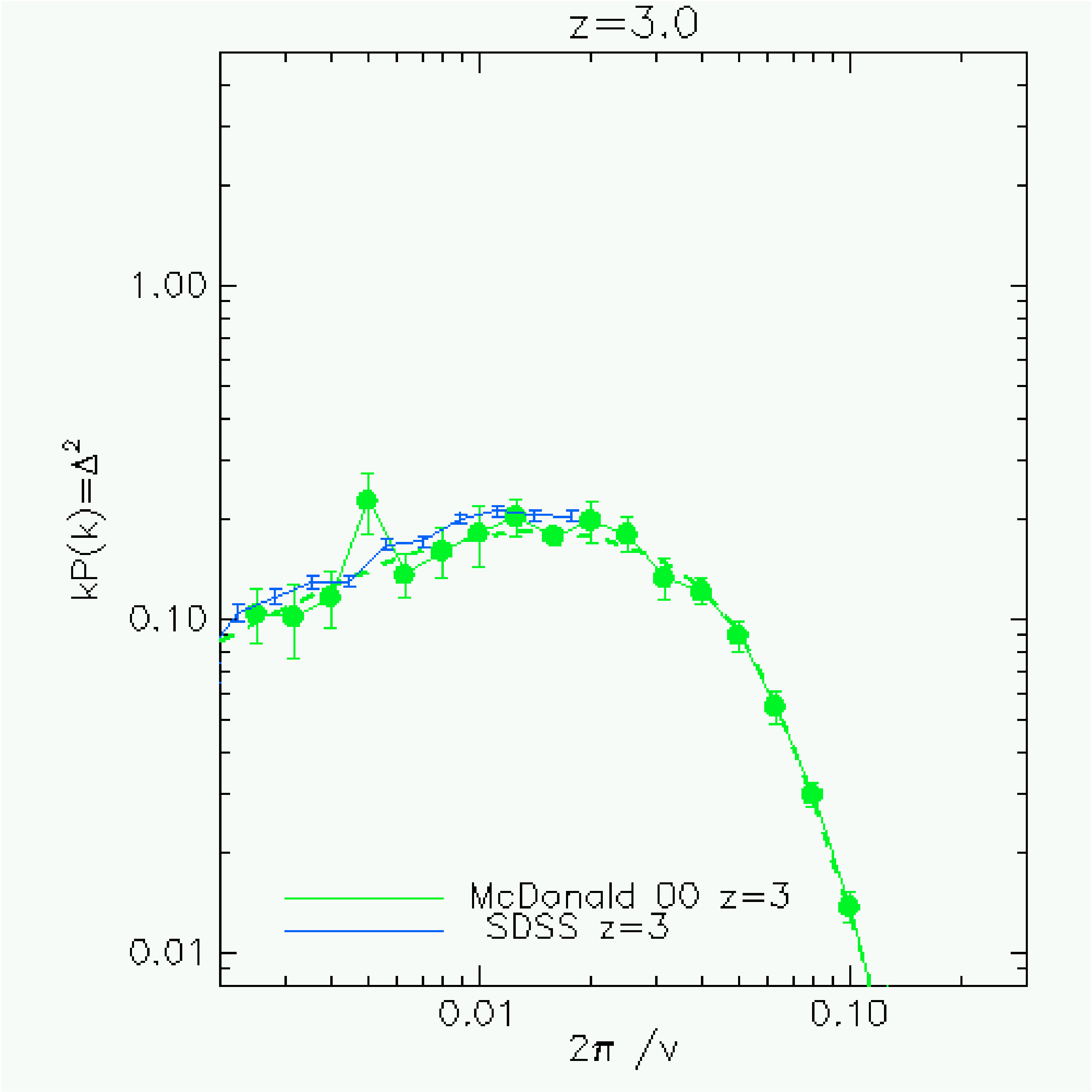
$$\exp(-\tau) \equiv \frac{\text{Observed counts}}{\text{Emitted counts}}$$

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

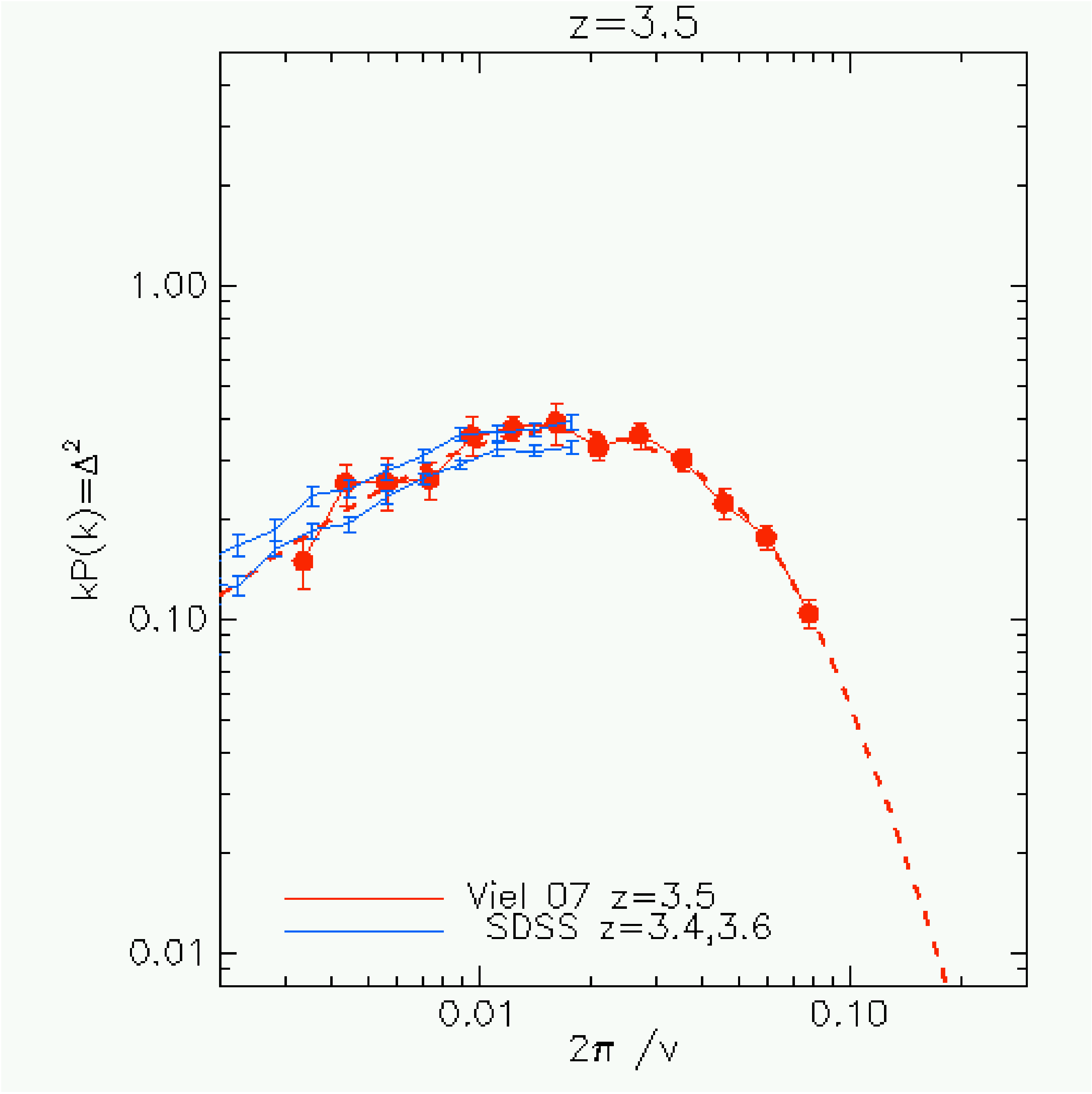
Observations: Mcdonald HiRes / Viel / McDonald SDSS



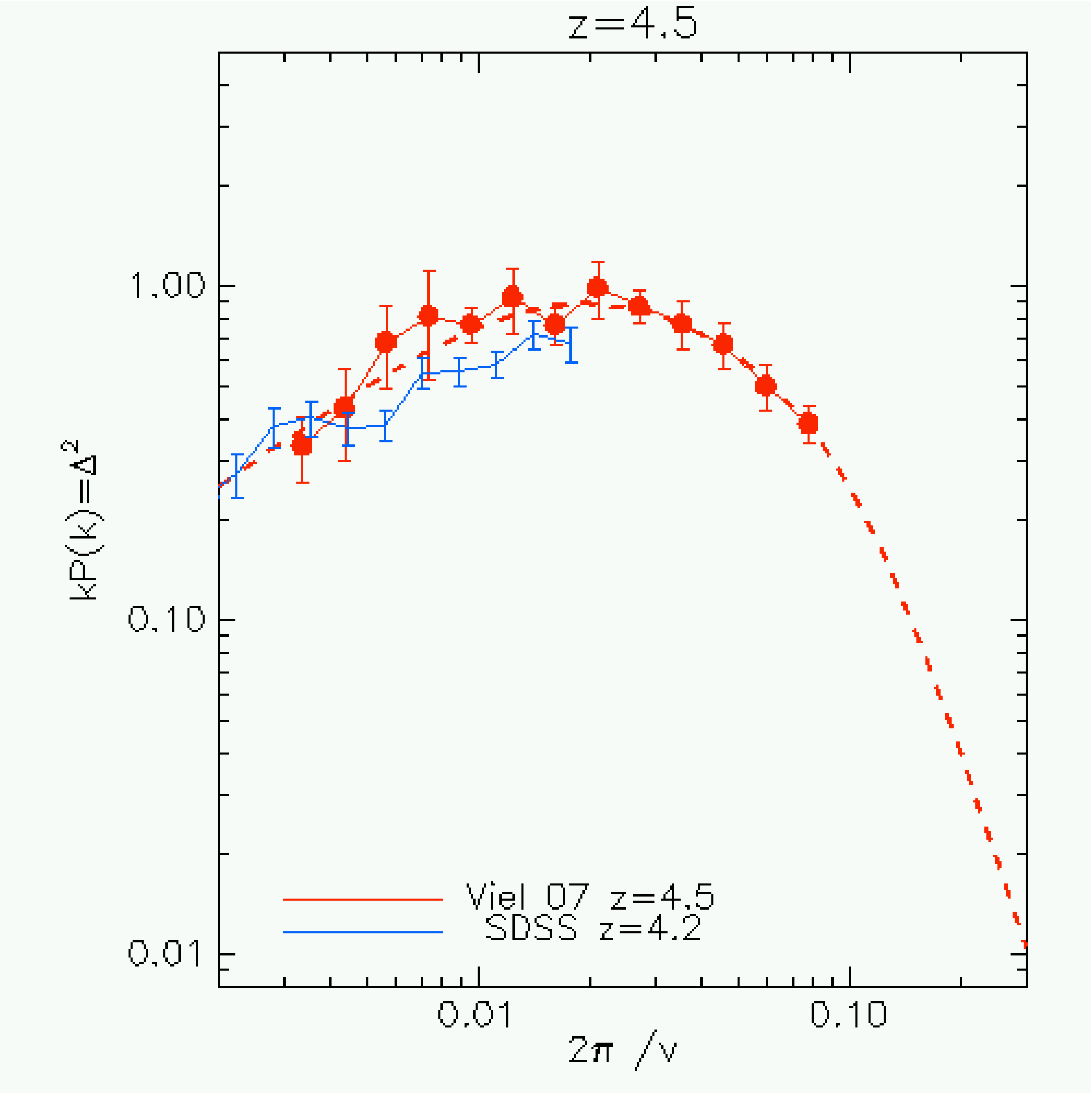
Observations: Mcdonald HiRes / Viel / McDonald SDSS



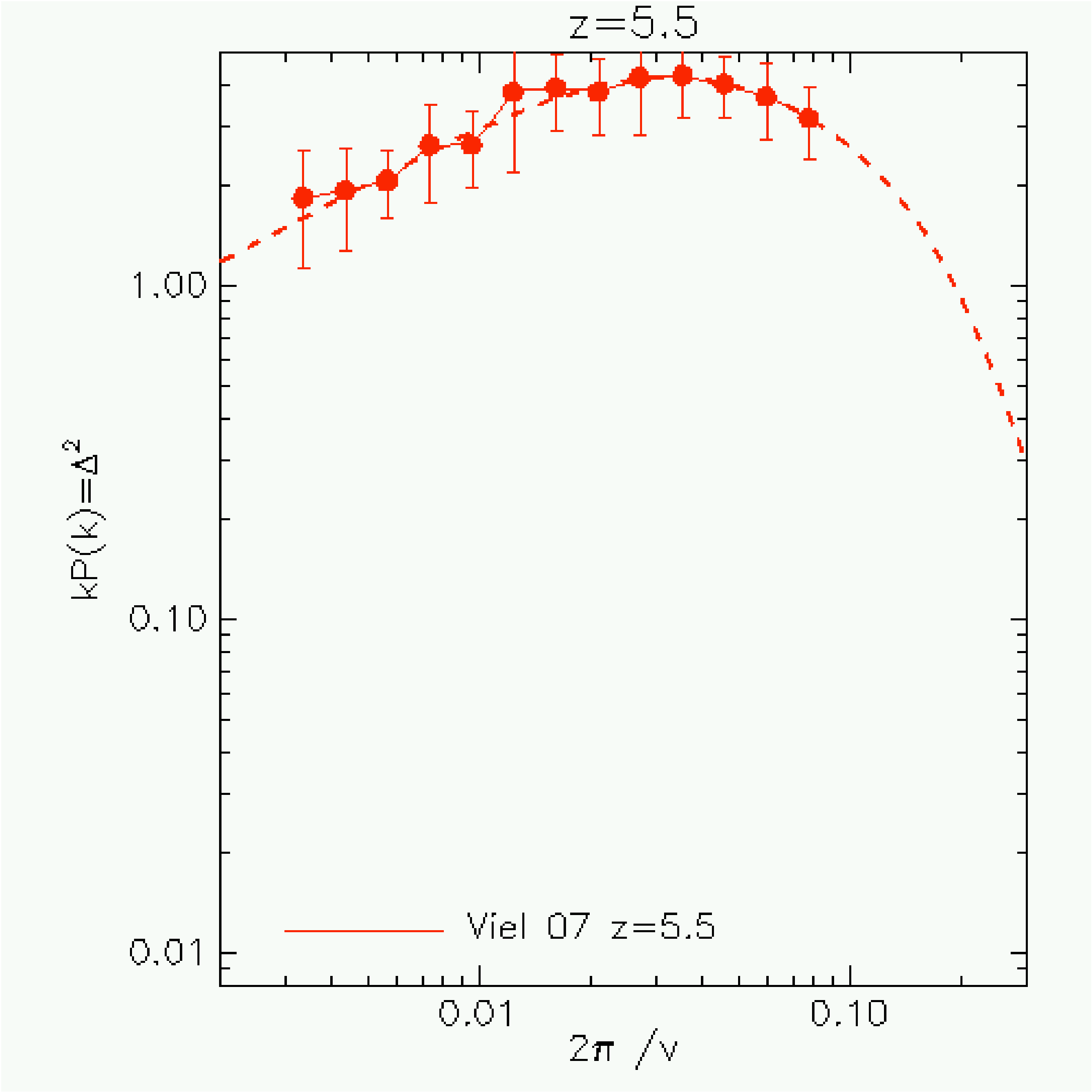
Observations: Mcdonald HiRes / Viel / McDonald SDSS



Observations: Mcdonald HiRes / Viel / McDonald SDSS

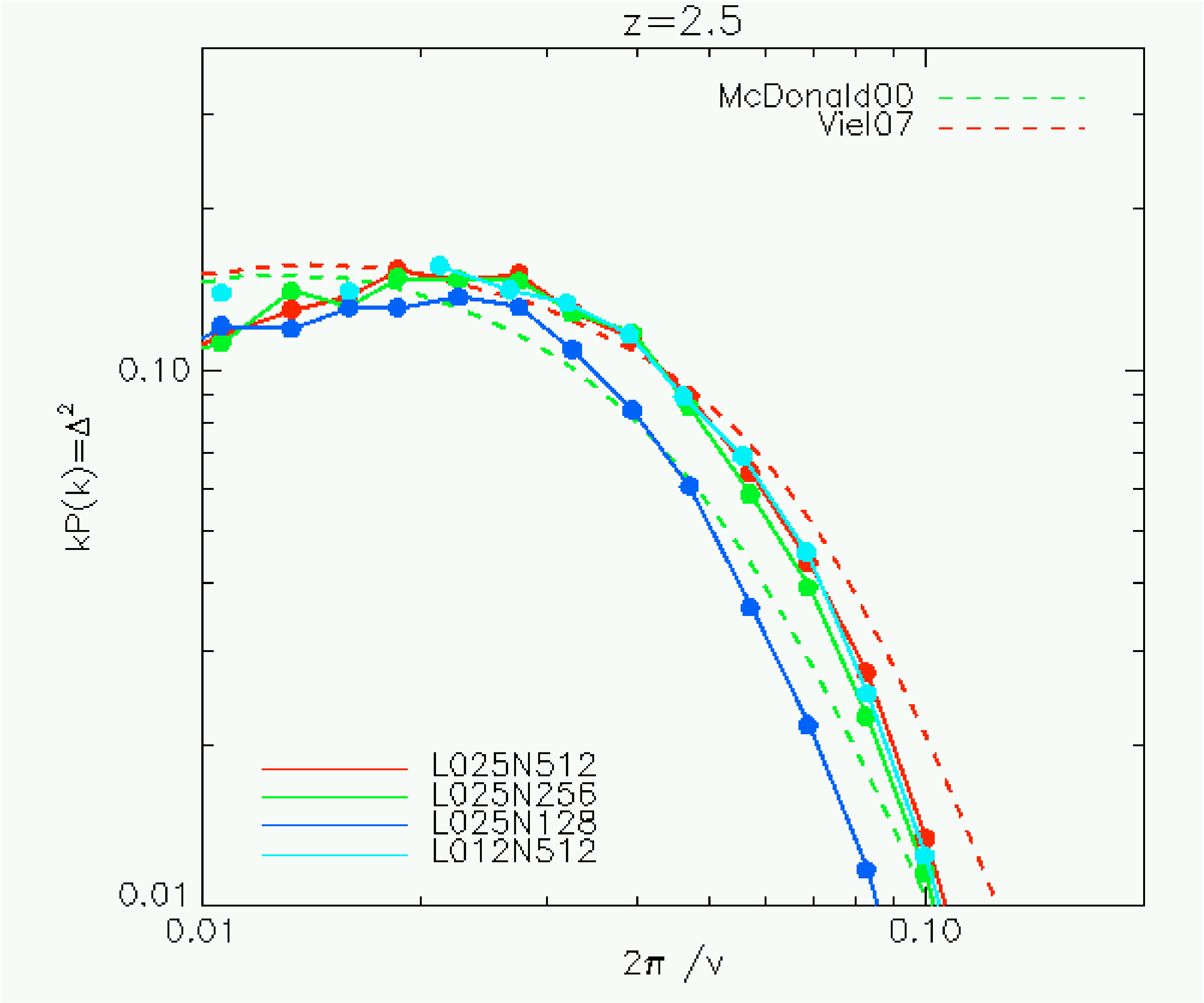


Observations: Mcdonald HiRes / Viel / McDonald SDSS

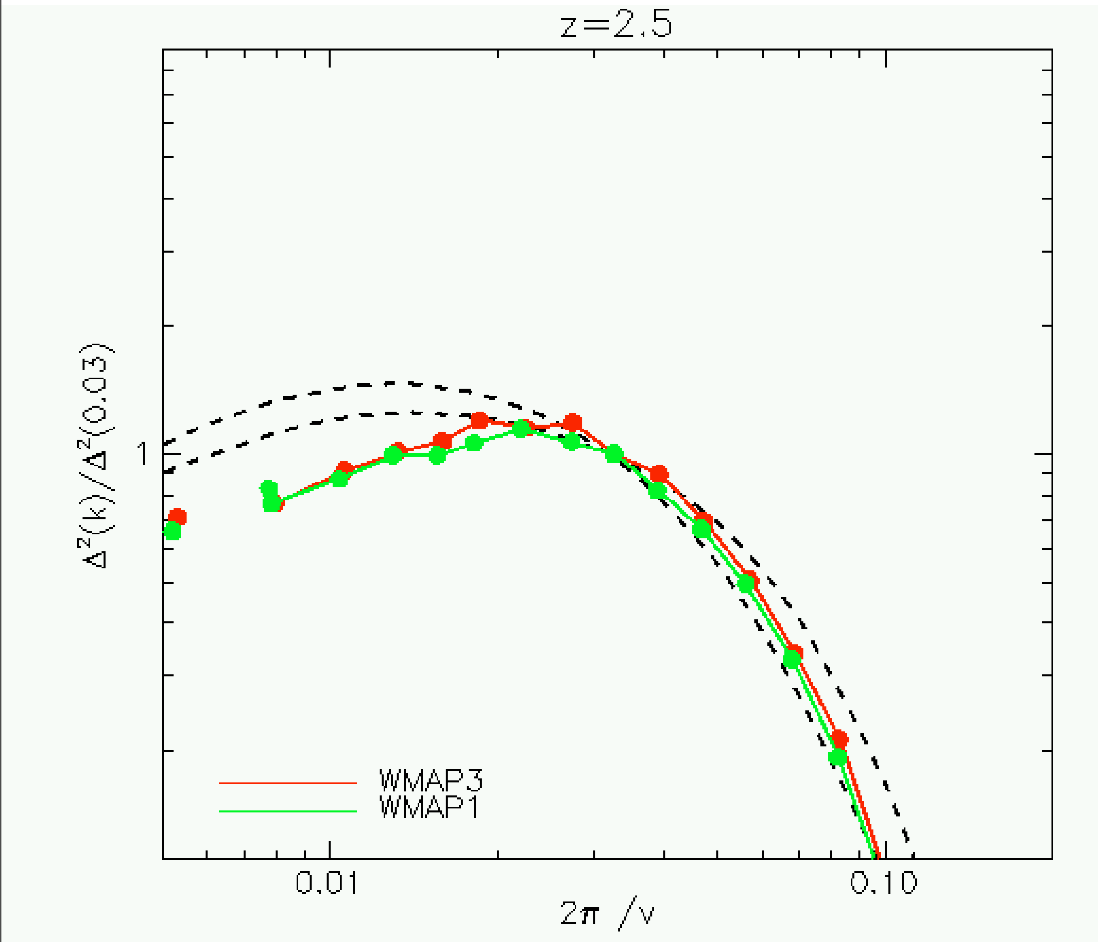


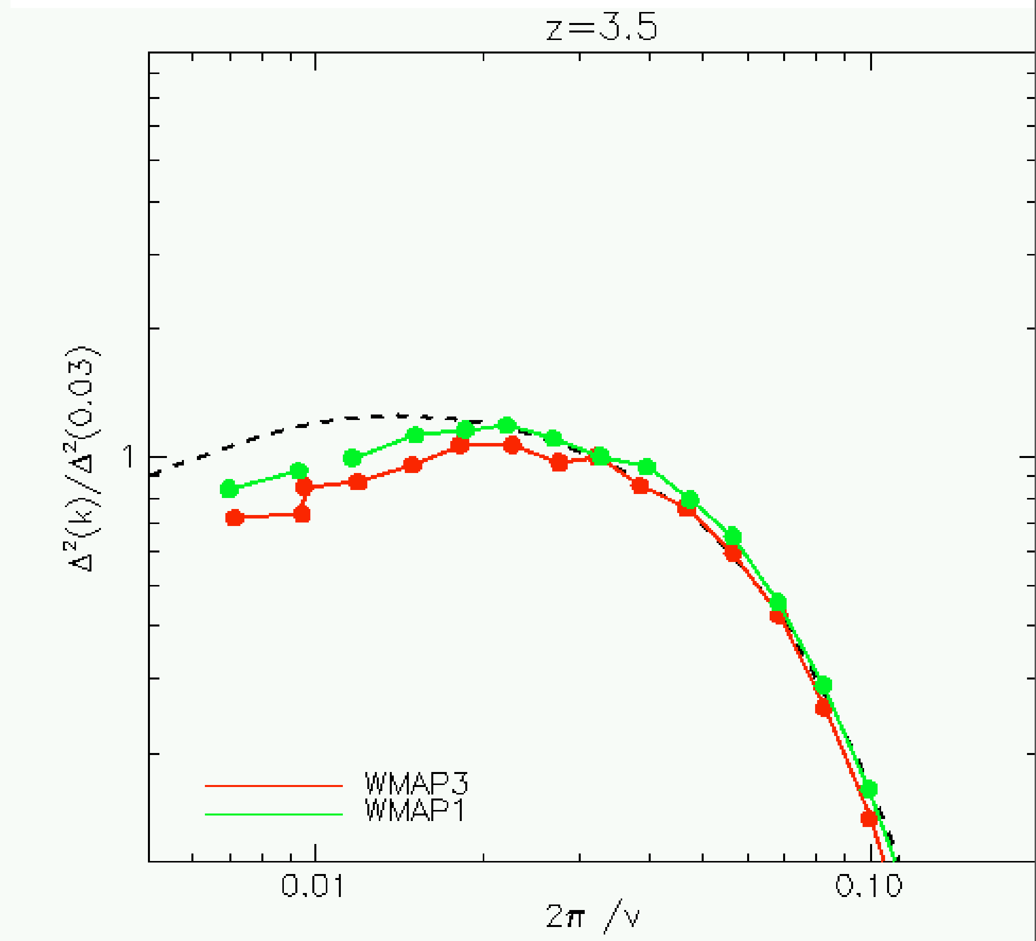
How well do simulated observations reproduce the measure powerspectrum?

Resolution: low / medium / high / very high



Effect of cosmology: WMAP3/WMAP1

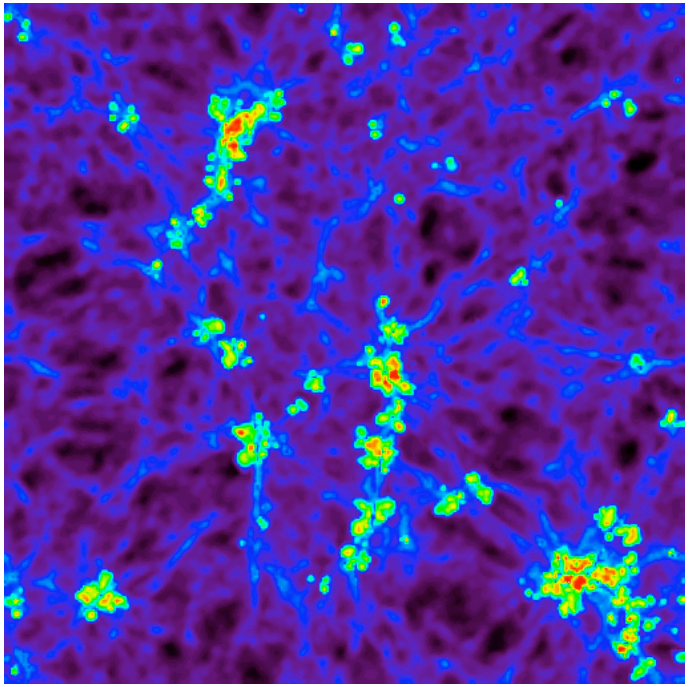


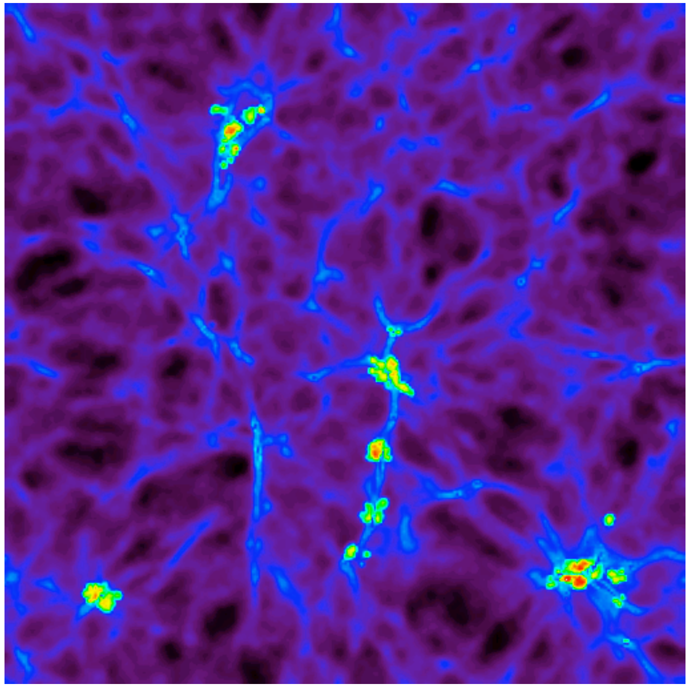


Effect of dark matter type

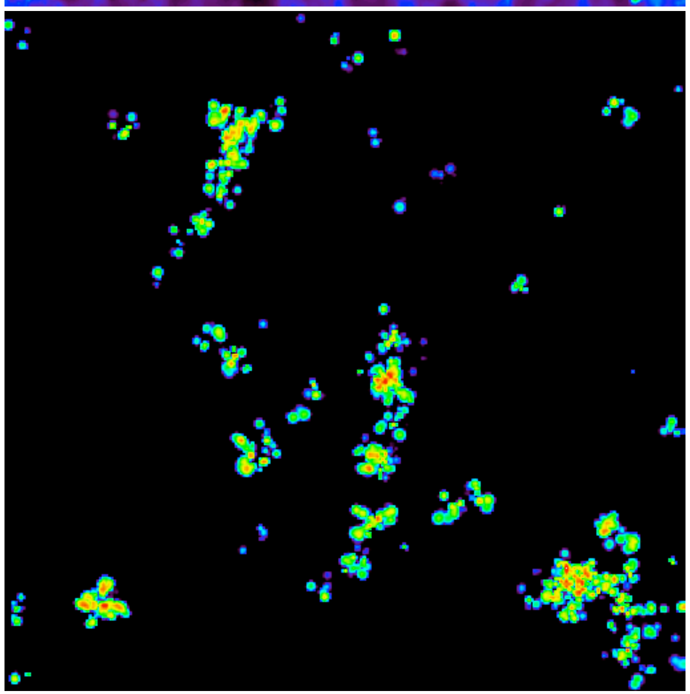
7 keV

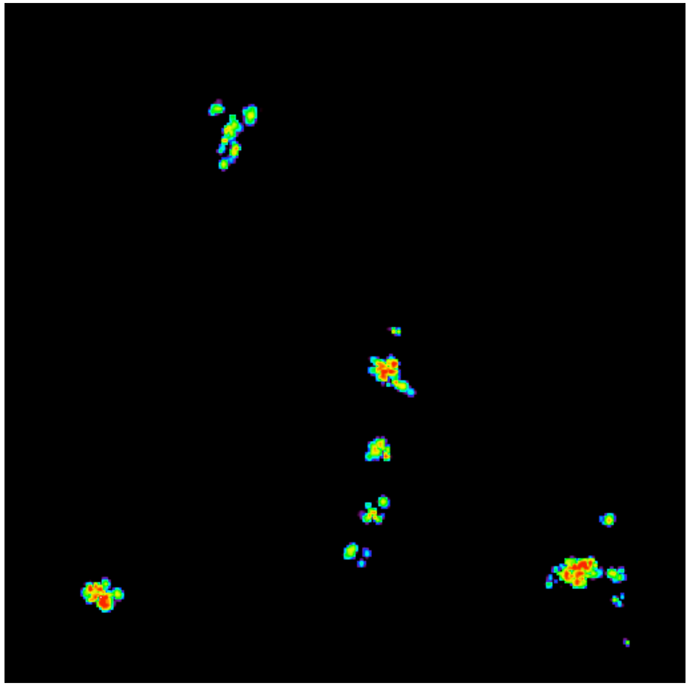
1 keV





temperature

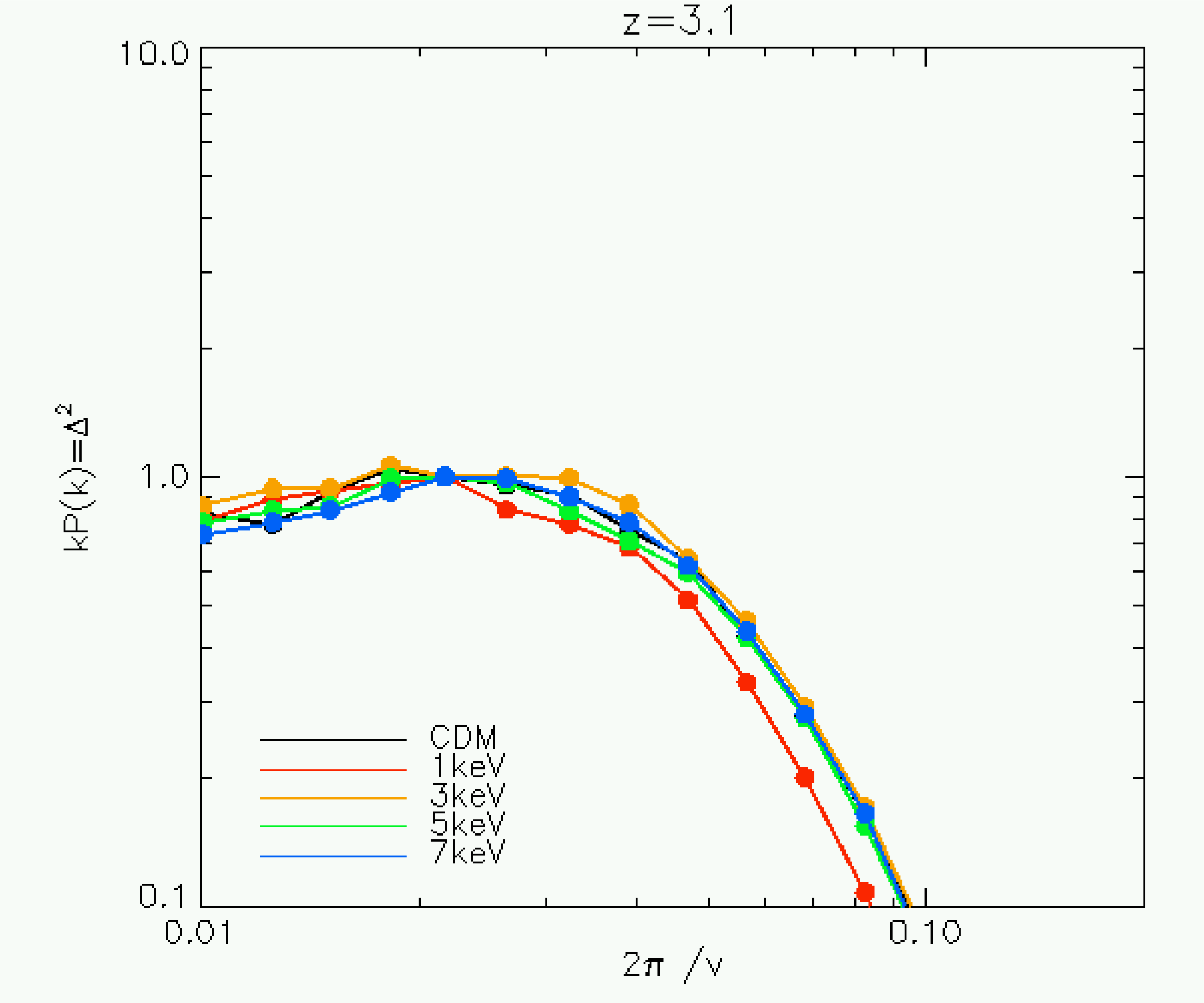




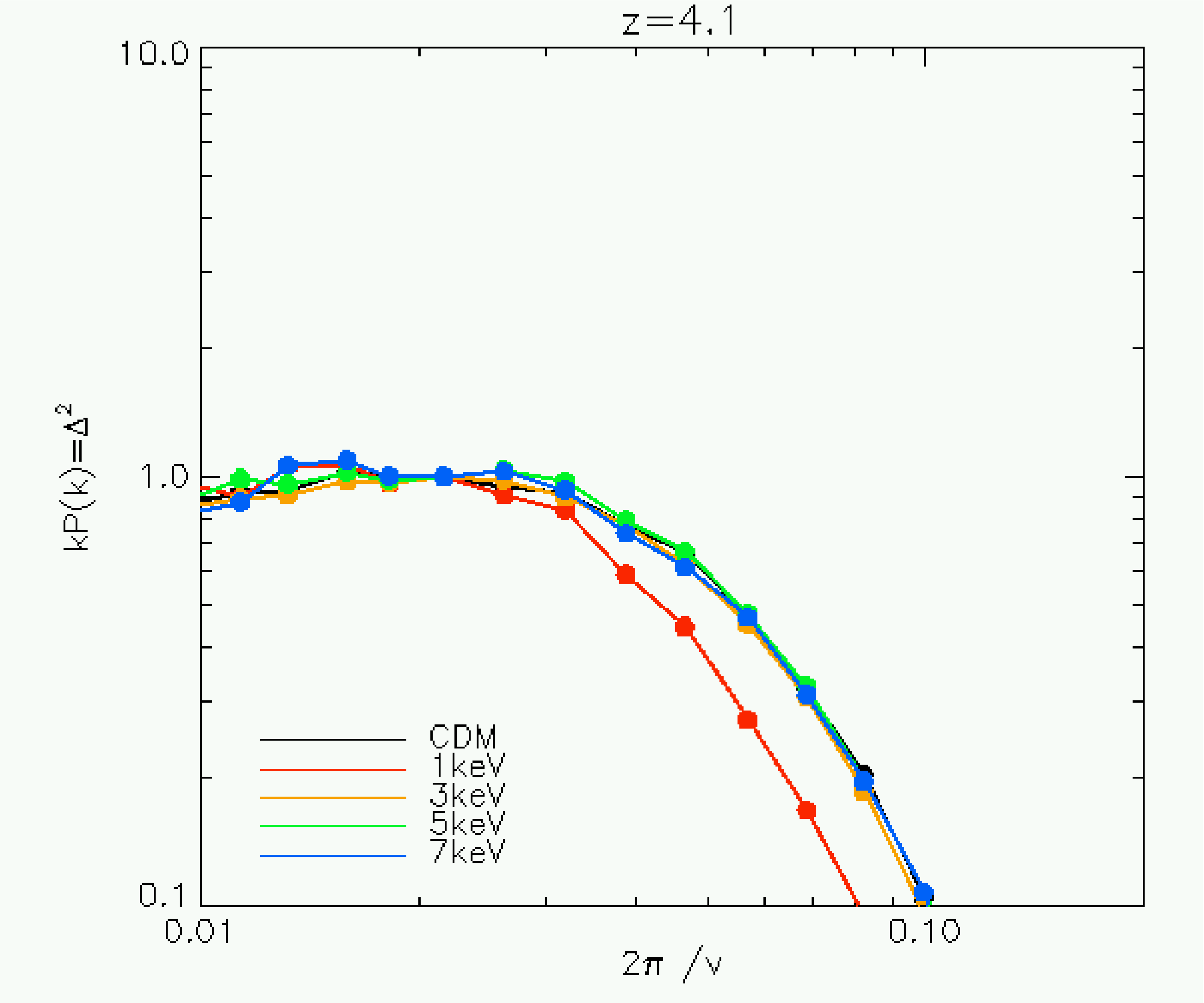
metallicity

Redshift = 4

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

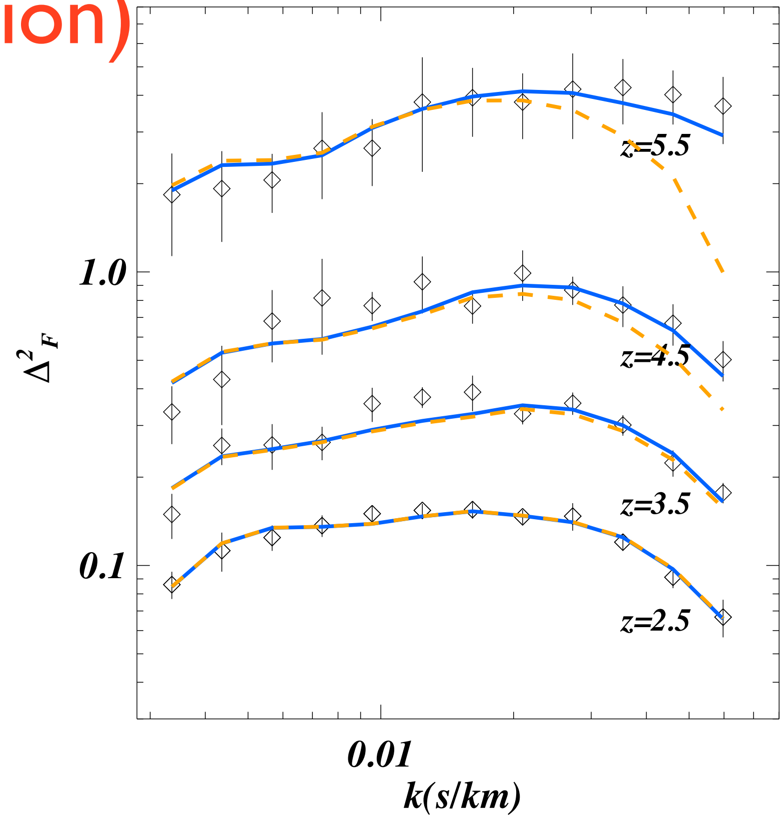


dark matter: 1keV / 3 keV / 5keV / 7keV / CDM



Conclusion from Lyman-alpha forest:

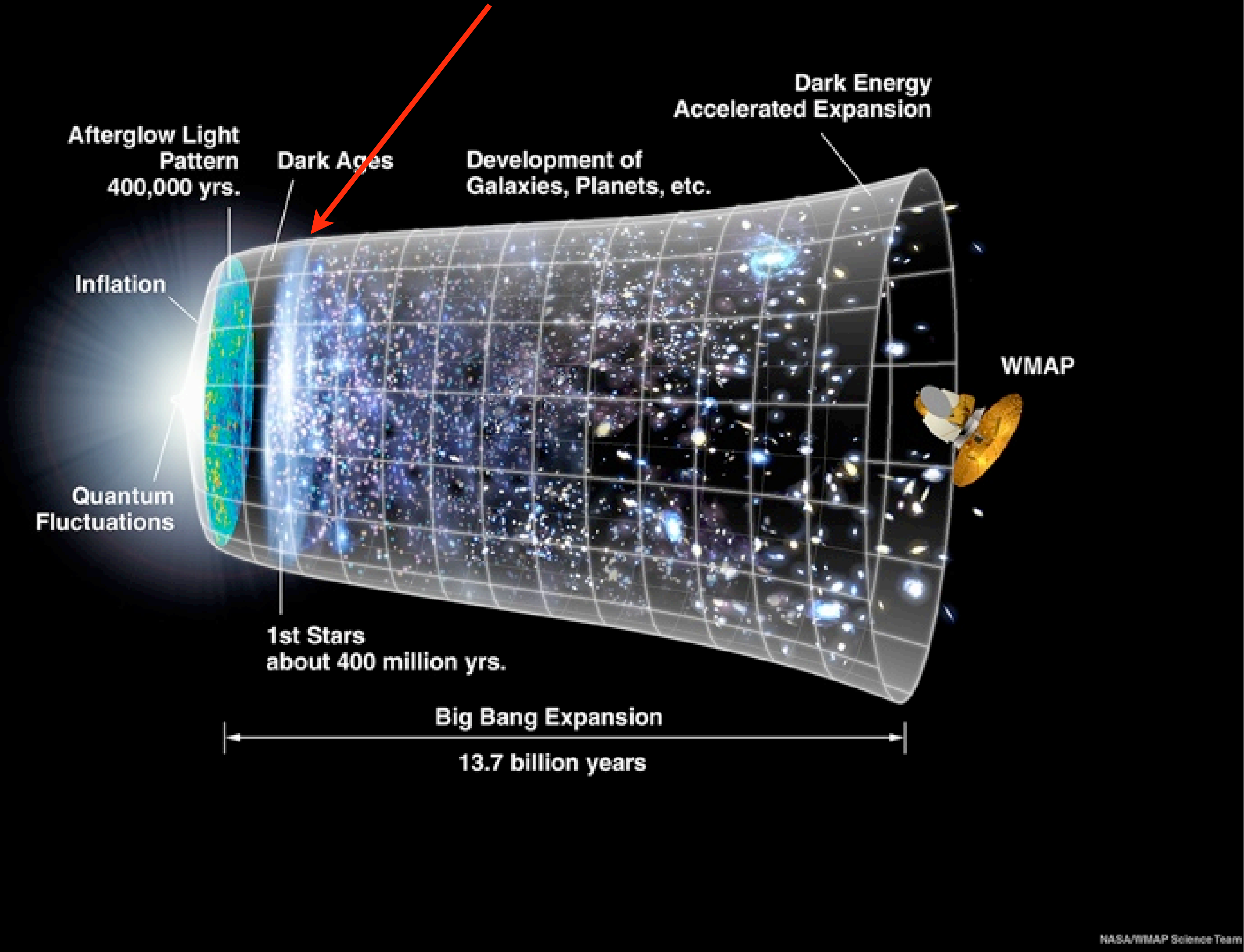
- dark matter cannot be too warm
- most constraints from high-z where simulations are hard to perform (resolution)



Viel et al 07

FIG. 1: Flux power spectrum of the HIRES data set at different redshifts and best fit models (solid curve) with $m_{\rm WDM} = 8$ keV and a model with $m_{\rm WDM} = 2.5$ keV (dashed curve).

Formation of first stars:

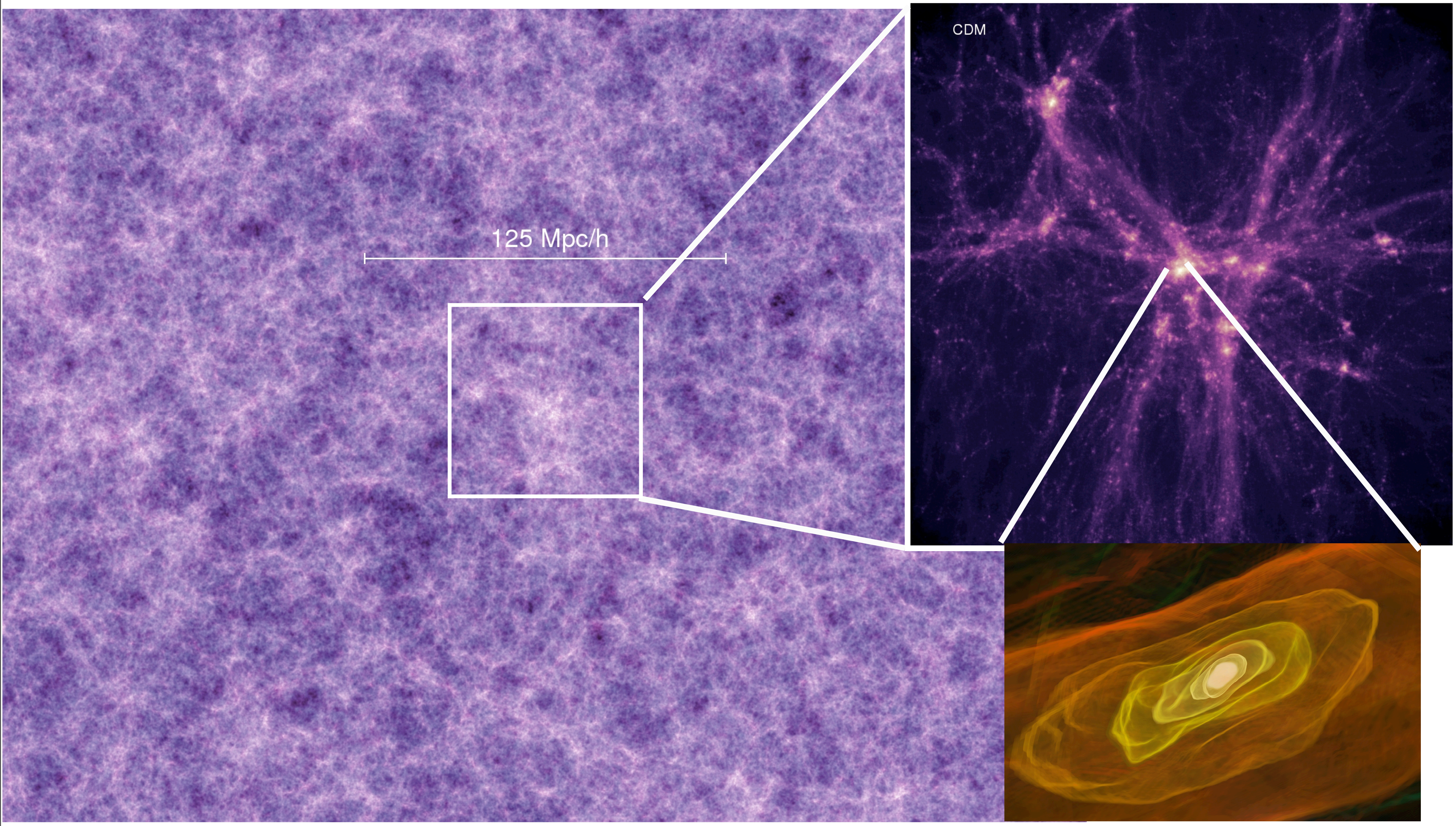


Formation of first stars:

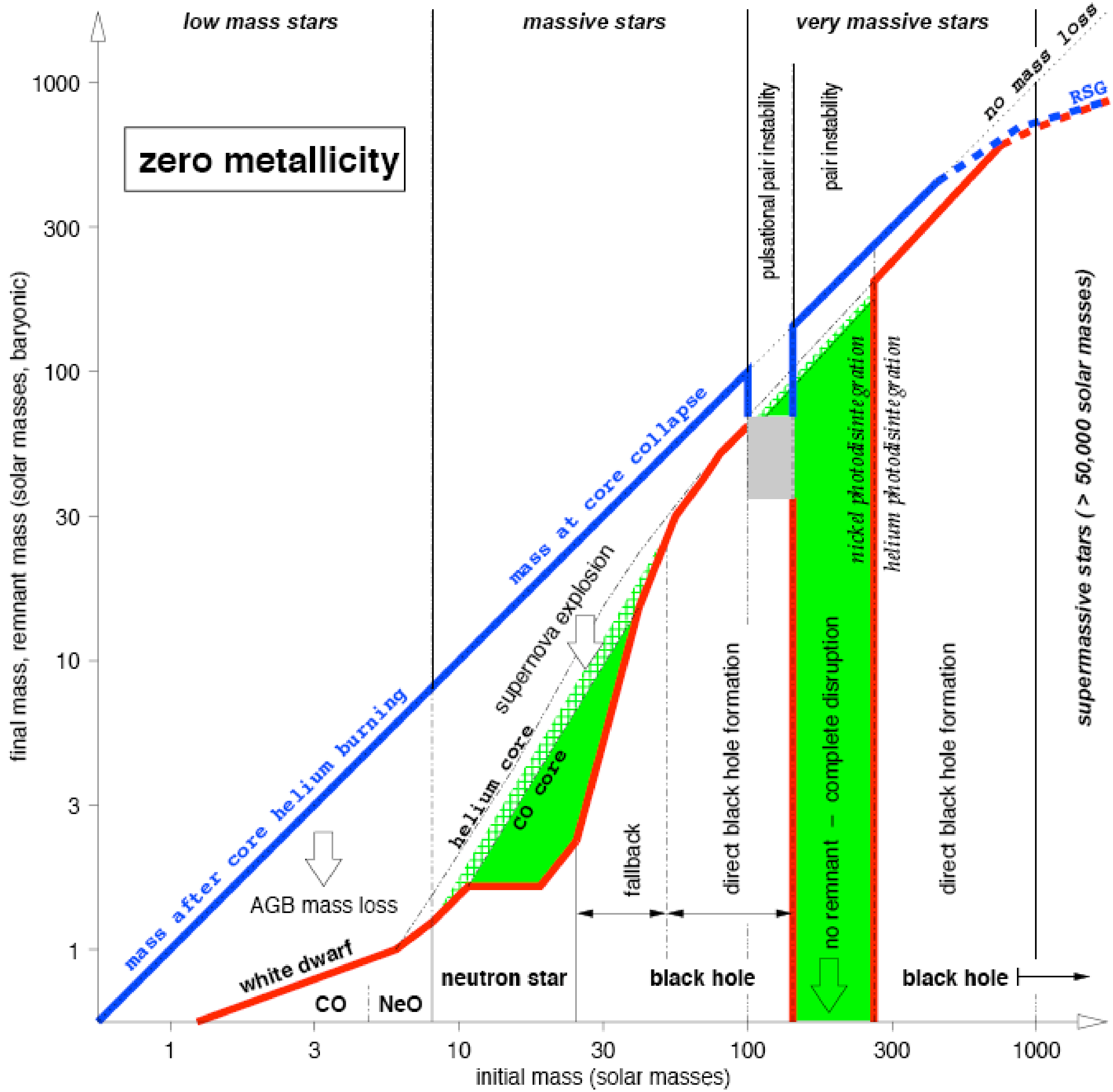
- haloes too cold for HI cooling ($T<10^4$K)
- cooling by molecular Hydrogen, H_2
- H_2 formation requires high temperature (T>8000K)
- Cold dark matter halos at z>15

- Abel et al
- Yoshida et al
- Bromm et al
- Gao et al

Formation of first stars in CDM

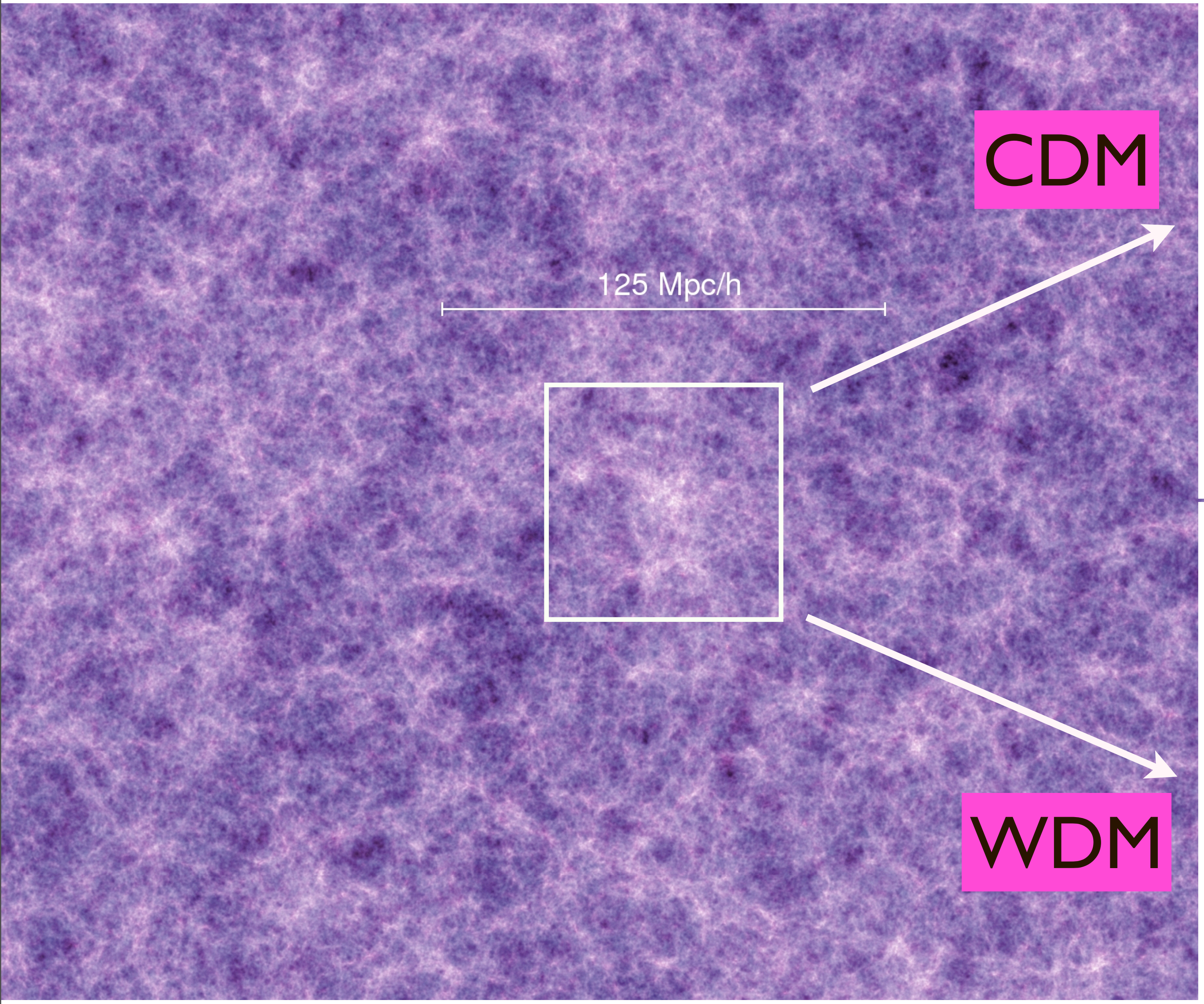


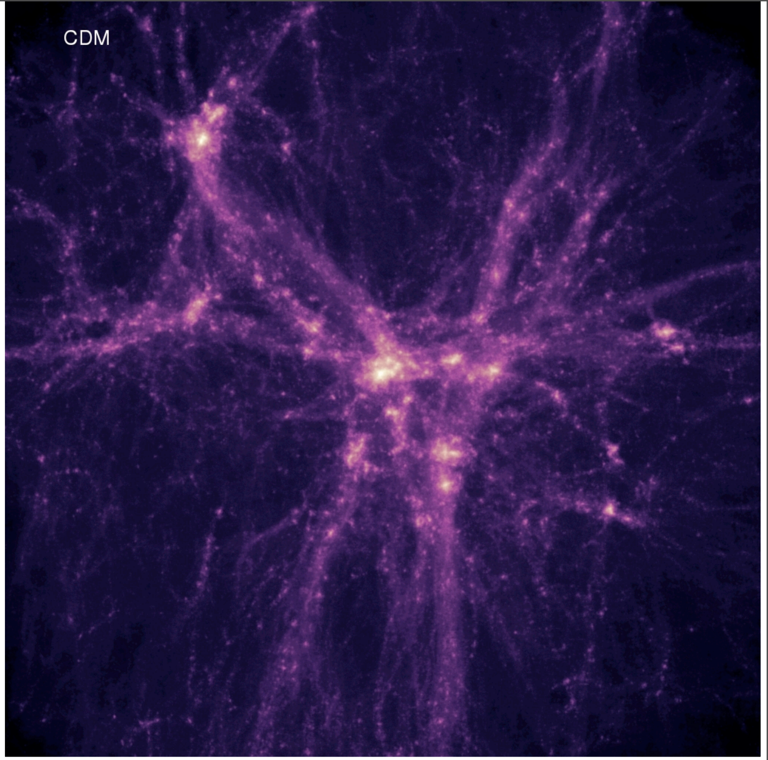
Gao et al
Abel et al

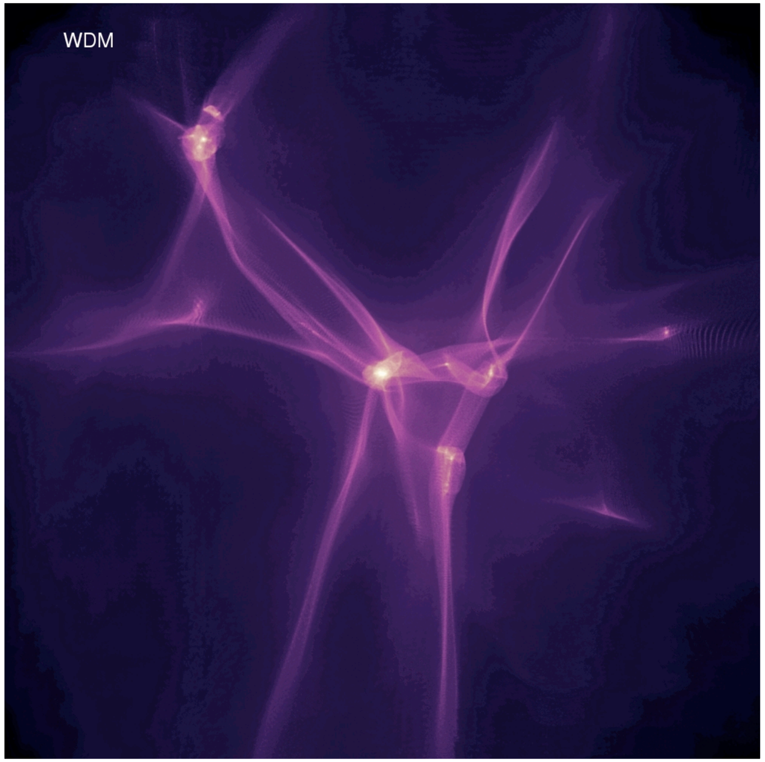


Woosley et al

CDM: some haloes massive enough for star formation







WDM: **filaments** massive enough for star formation

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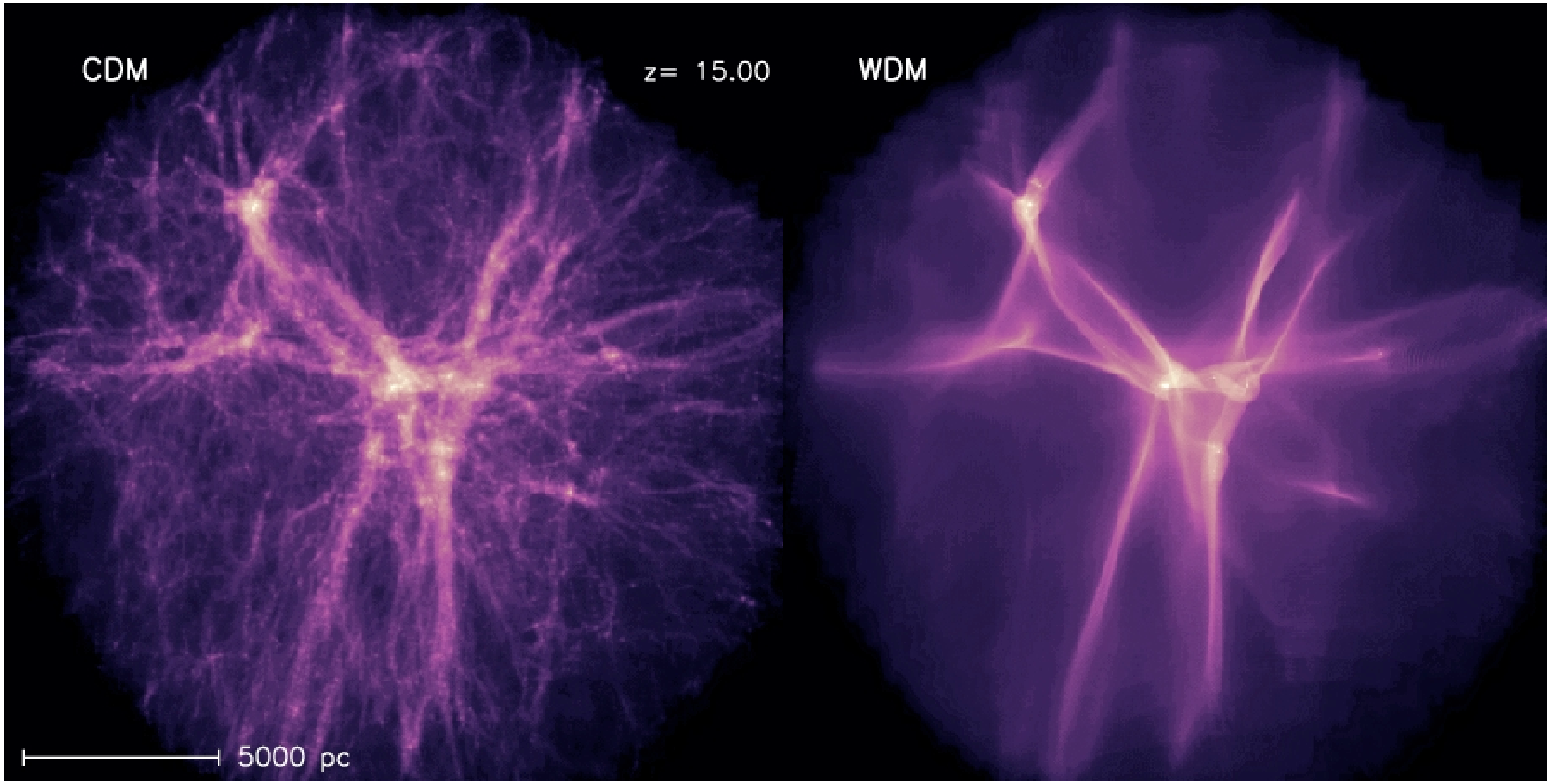
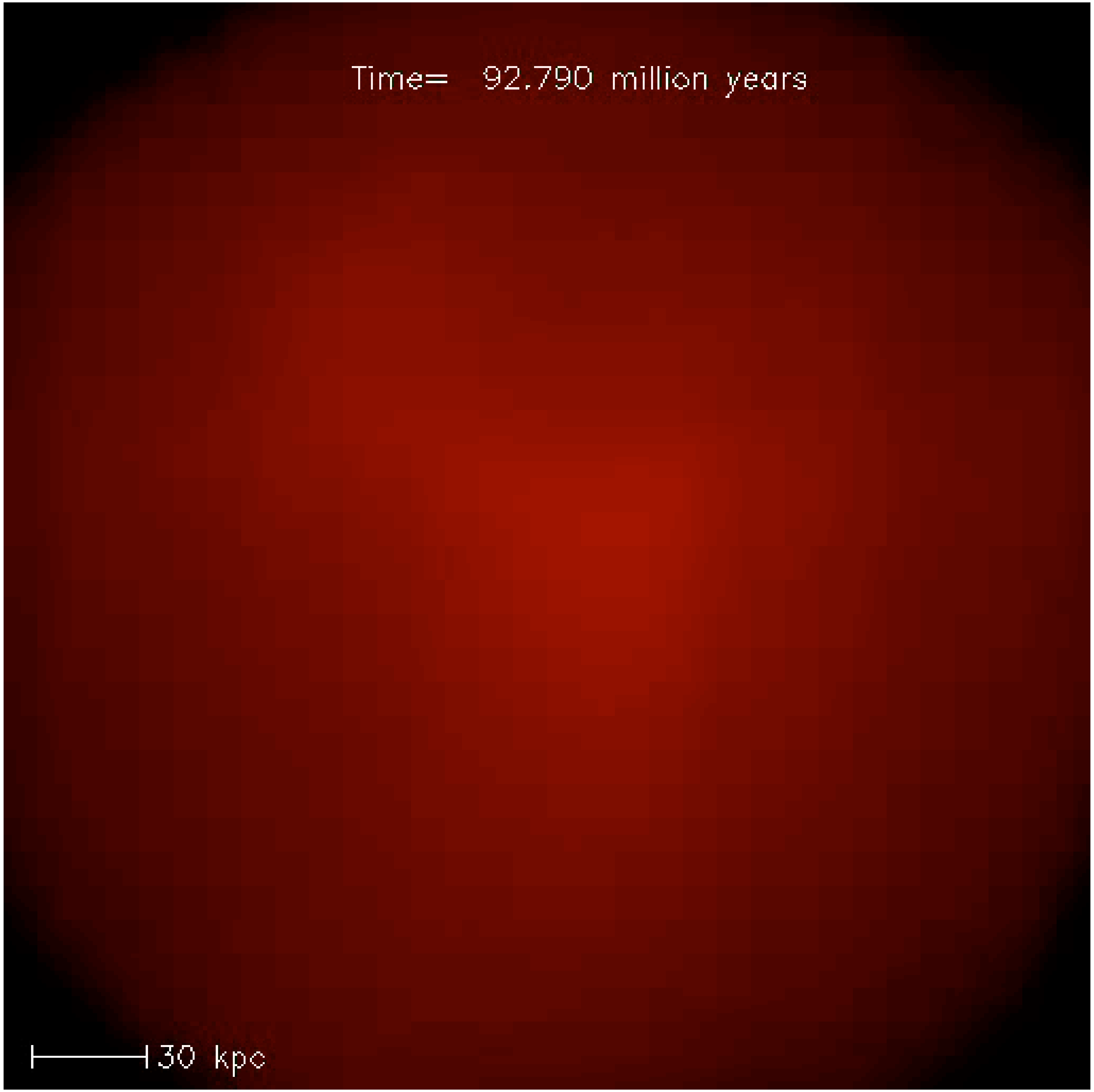
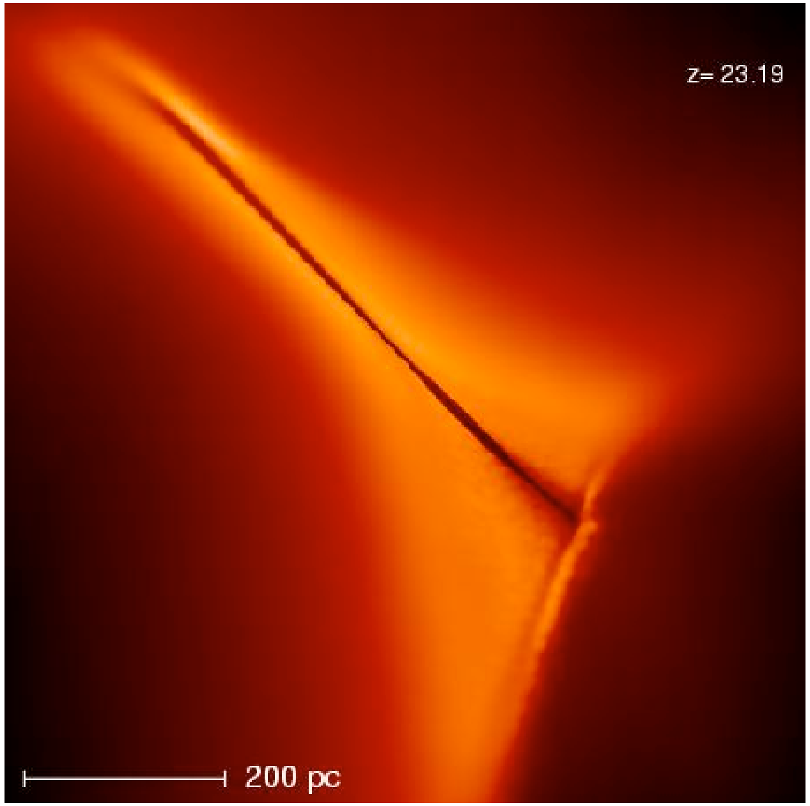
Structure formation is suppressed below warm dark matter free streaming scale



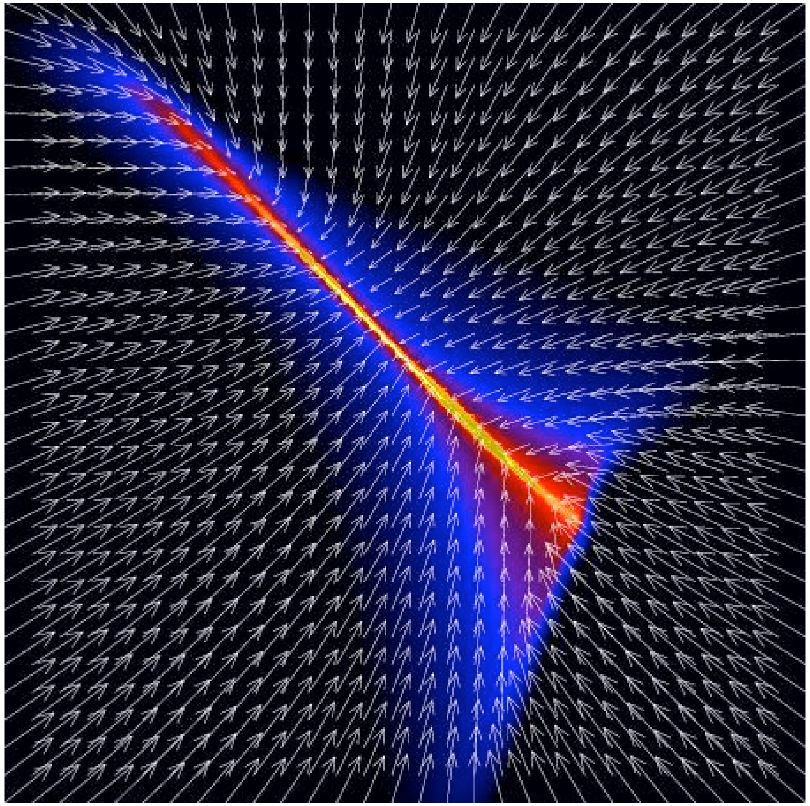
M_{dm} = 3 keV, M_{fs} ~ 3 x 10^8 solar masses


Time= 92.790 million years
30 kpc

First structure in WDM



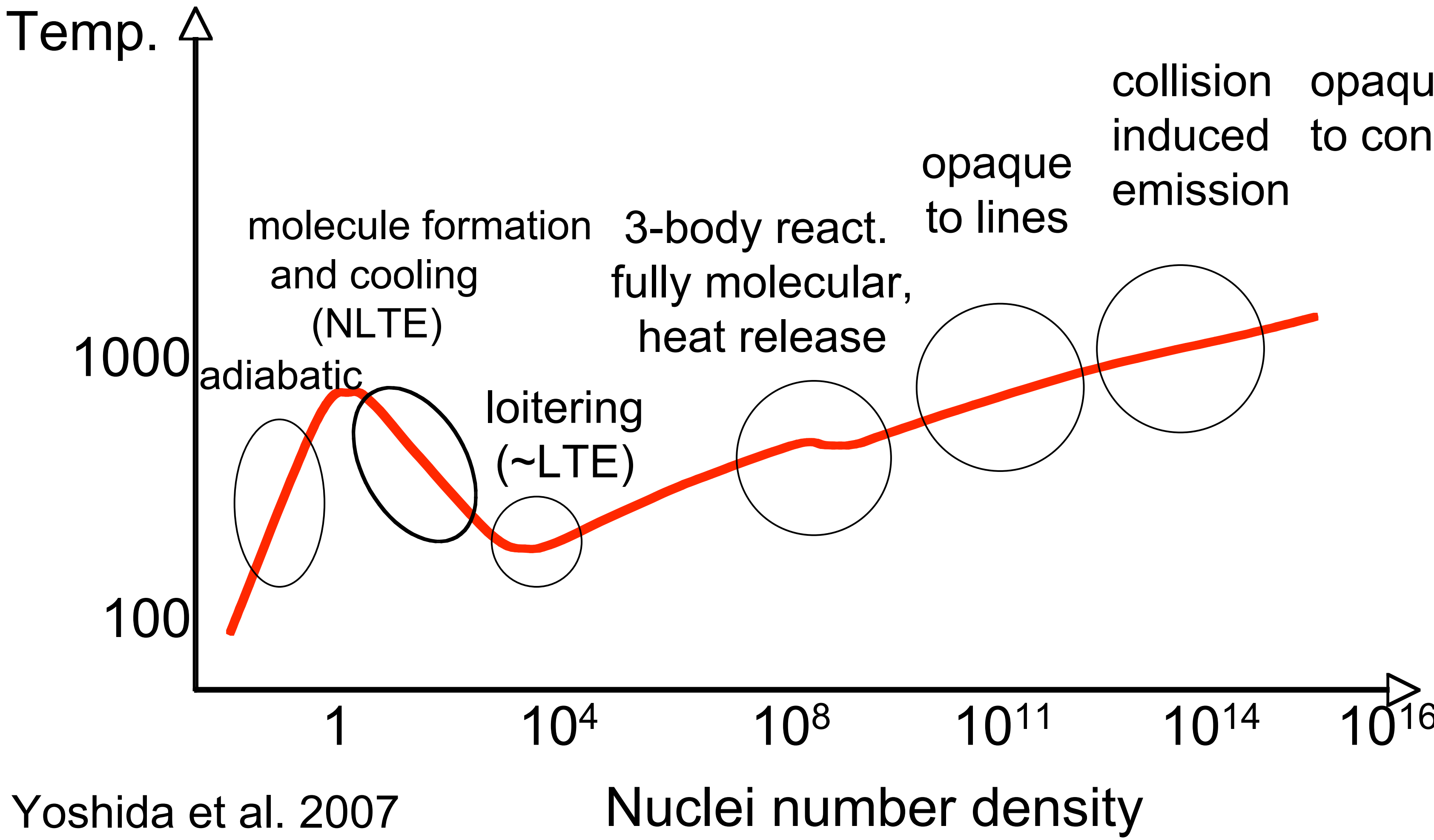
Temperature



Density

M_{dm} = 3 keV, M_{fs} ~ 3 x 10^8 solar masses

Stability of filament is determined by H2 physics



Yoshida et al. 2007

Application to a primordial filament: I

When does filament fragment?

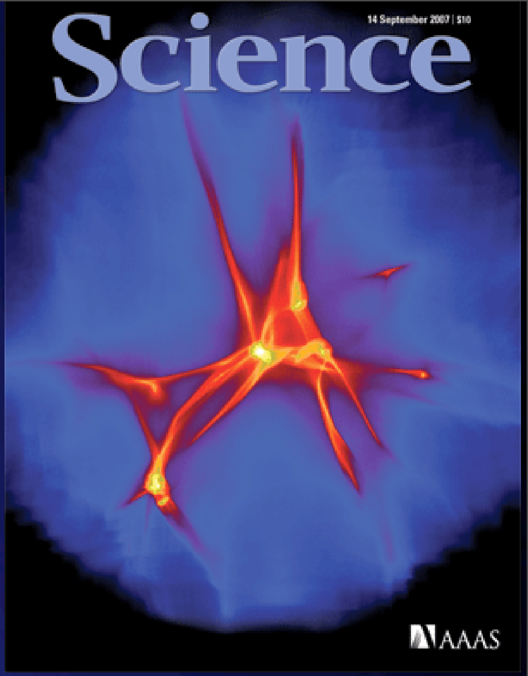
Two density scales where collapse of filament slows and fragmentation can occur:

1) $n_h \sim 10^4$ cc where LTE level populations are achieved.
   Fragments ~100 solar masses
2) $n_h > 10^{12}$ cc where gas become optical to H_2 lines.
   Fragments ~1 solar mass

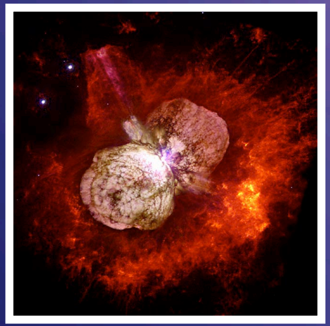
Application to a primordial filament: II

What induces fragmentation?

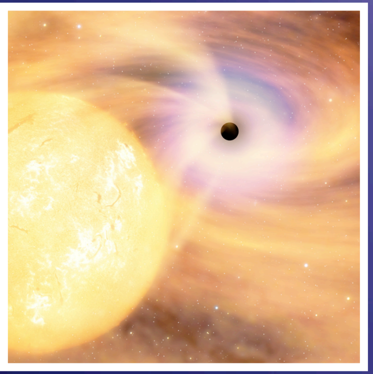
- No small-scale power!
- Tidal field induces fragmentation
- Huge star burst, stars with range of mass <1 to > 100 solar masses



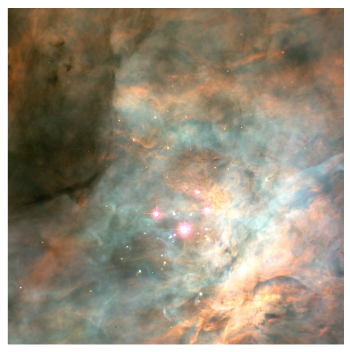
Gao & Theuns
Science 2007



Massive stars



Seed for super-massive BH



Low-mass stars

Conclusion: first stars in CDM vs WDM

CDM:

- massive, short-lived stars
- hyper metal poor stars should reflect abundance pattern characteristic of massive SNe

WDM:

- both low and high-mass stars
- low-mass stars may exist today
- origin of peculiar abundances in MW stars (This indeed explains existing two HMP stars better !).
- collapsing filament seeds super-massive black hole

Conclusion

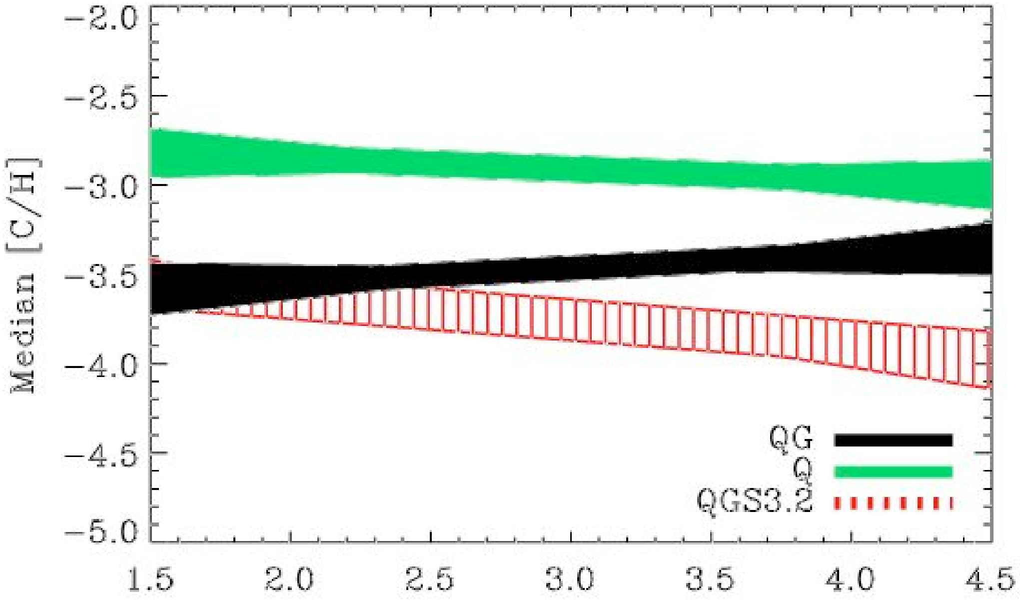
- Nature of dark matter unknown
- Lyman-alpha forest limits mass of WDM particle
- First stars may be best probe of DM particle

Thoughts:
Could be more than one type of DM
Annihilating DM may affect first stars

Freese et al

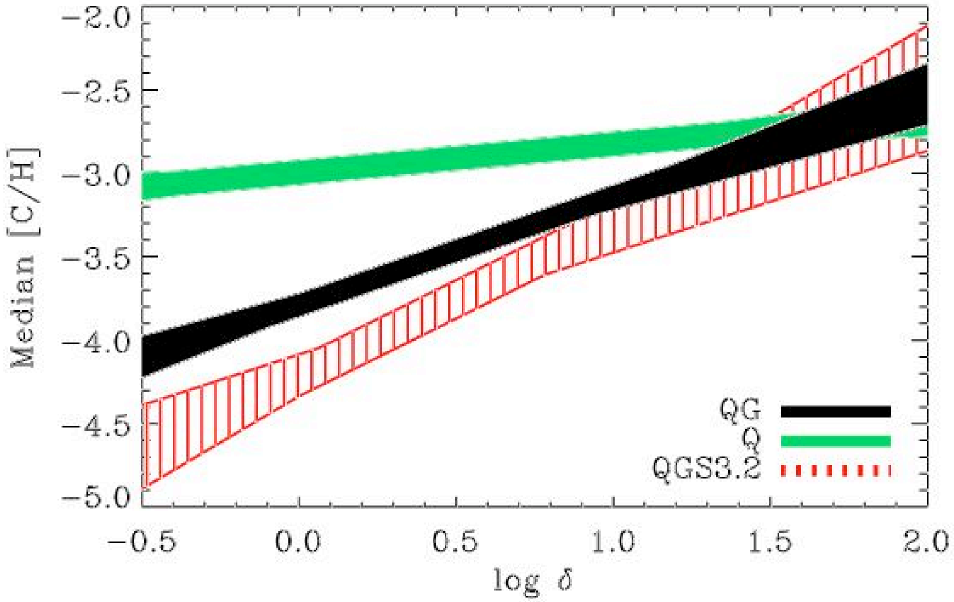
Thank you!

Delta =3



Redshift

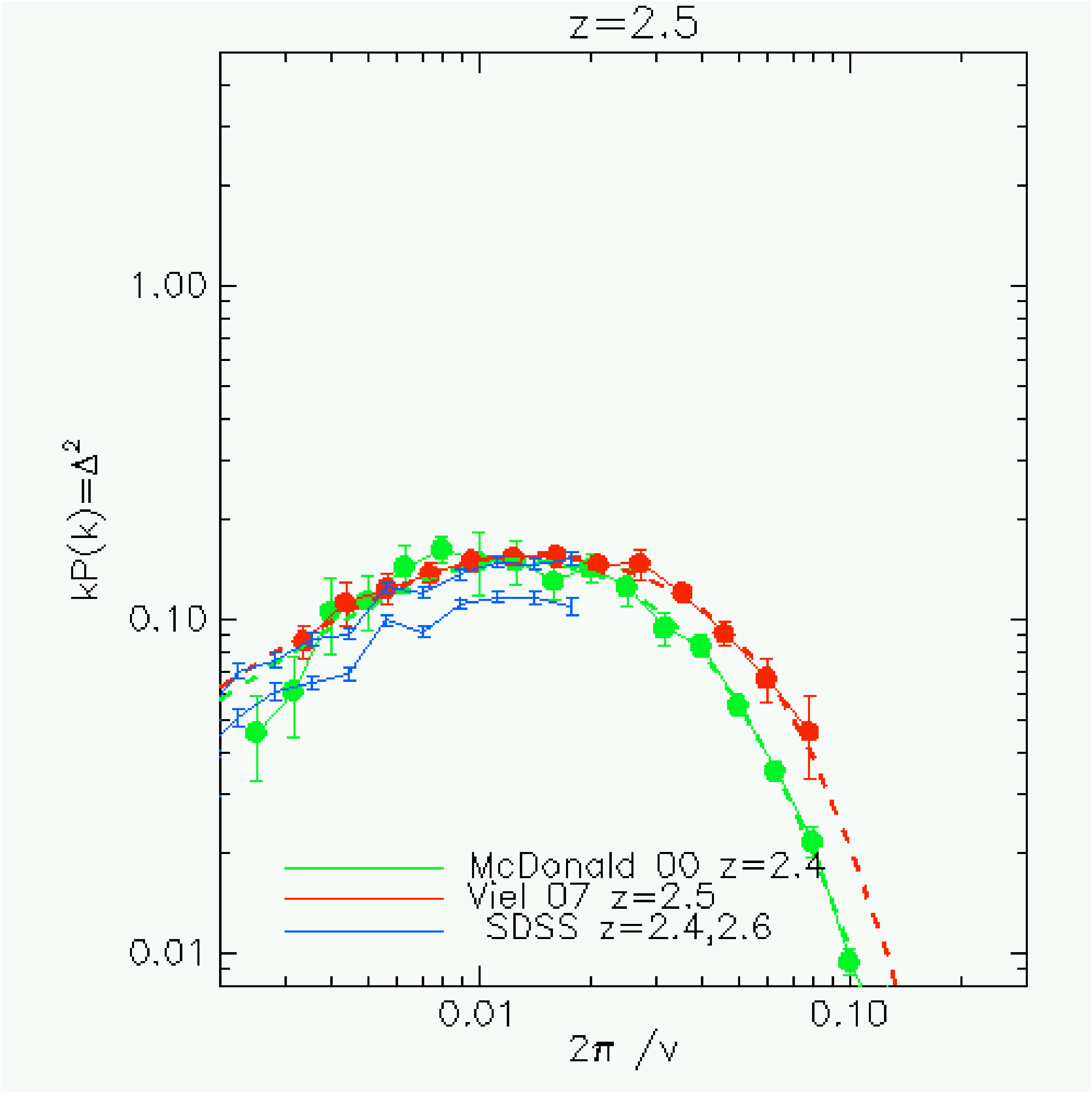
z=3



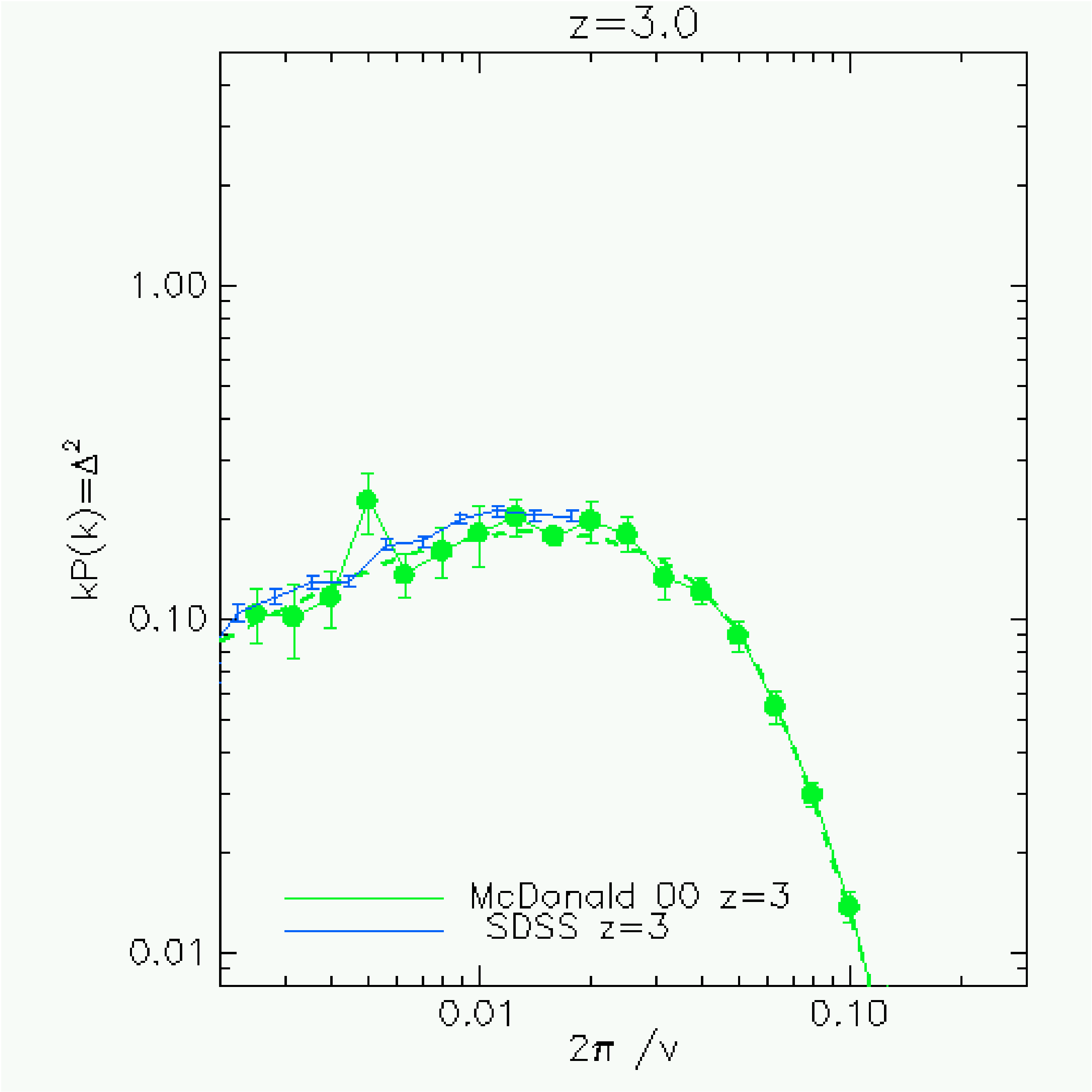
Schaye et al 03

Density

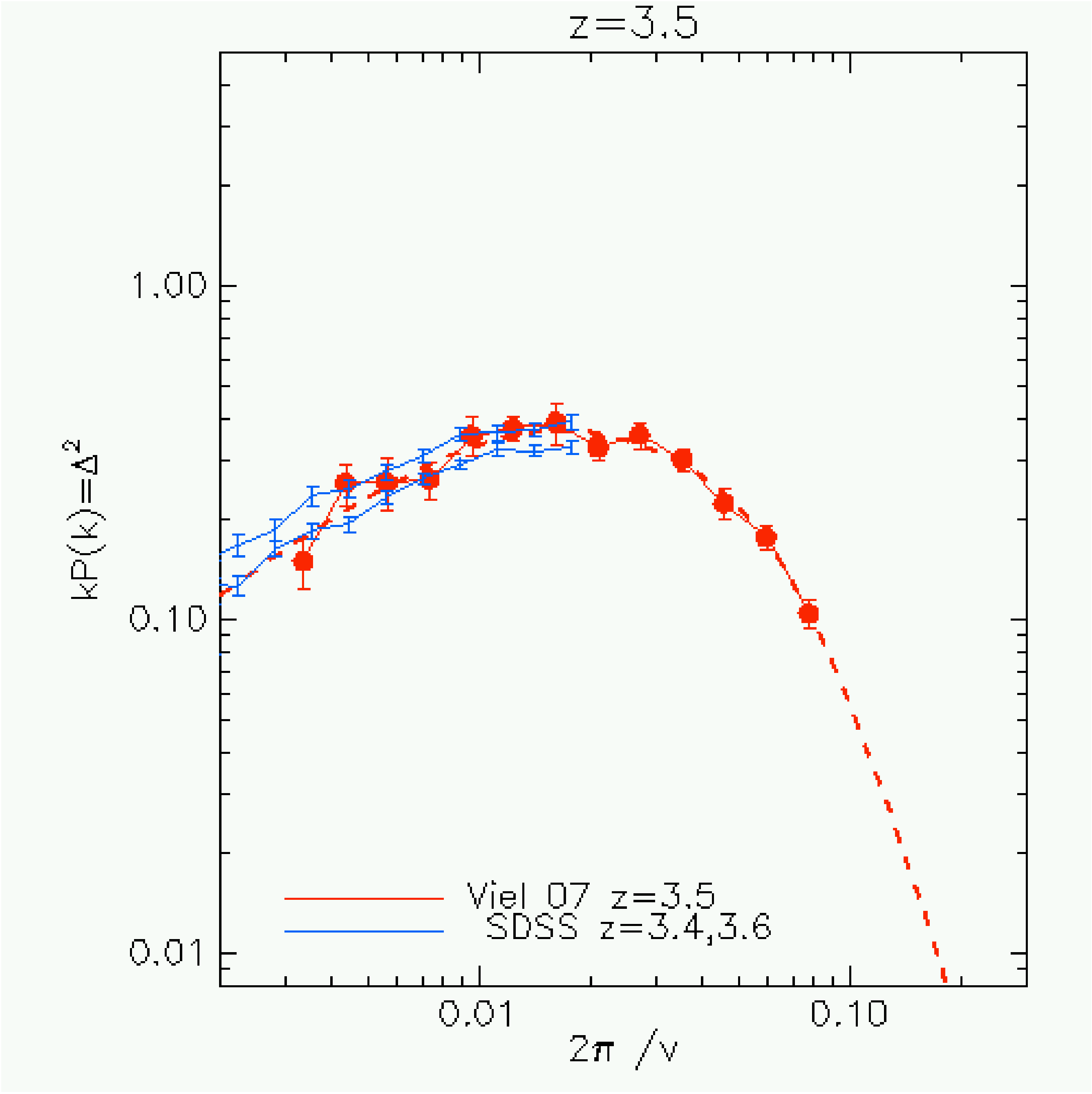
Observations: Mcdonald HiRes / Viel / McDonald SDSS



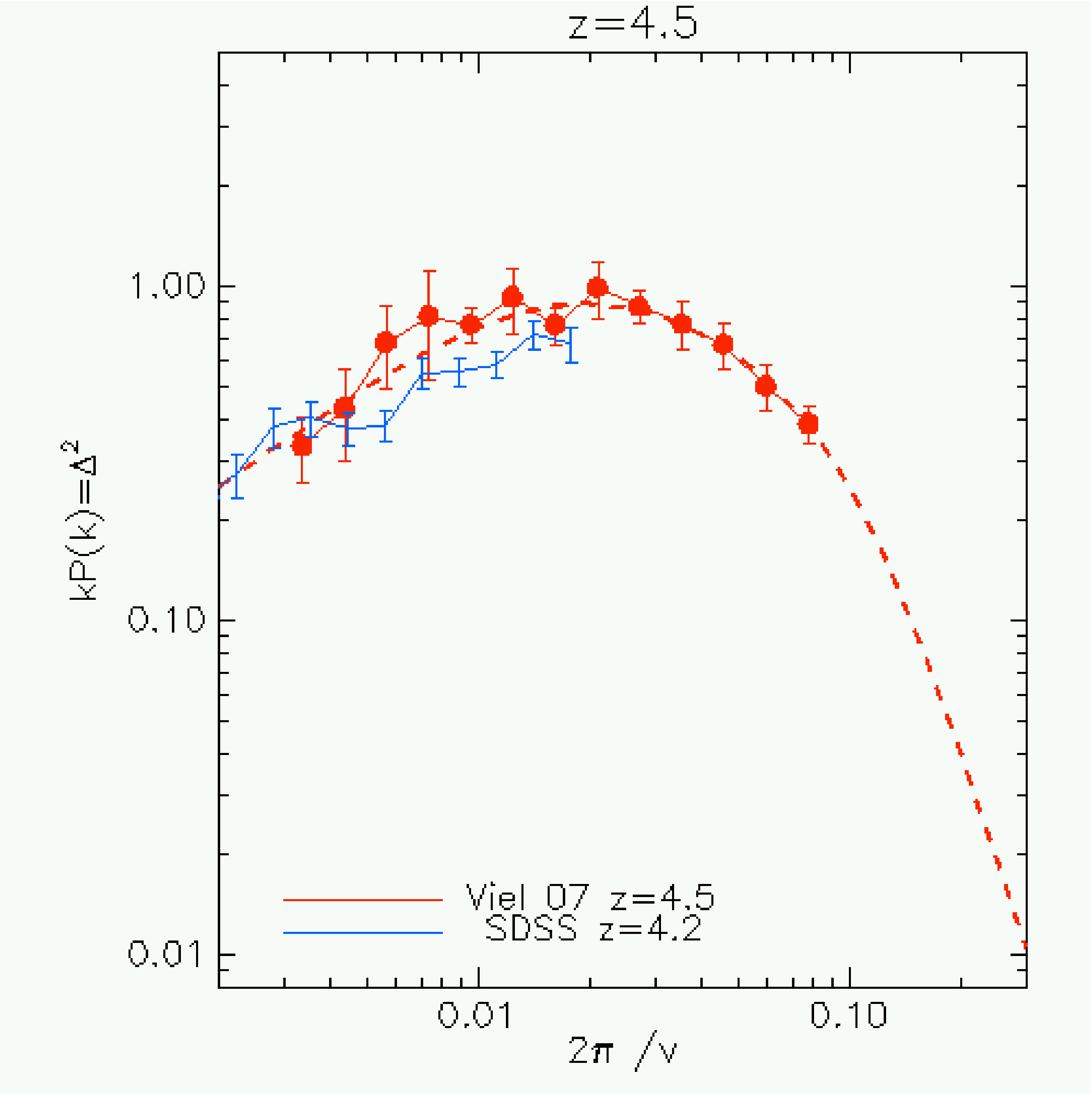
Observations: Mcdonald HiRes / Viel / McDonald SDSS



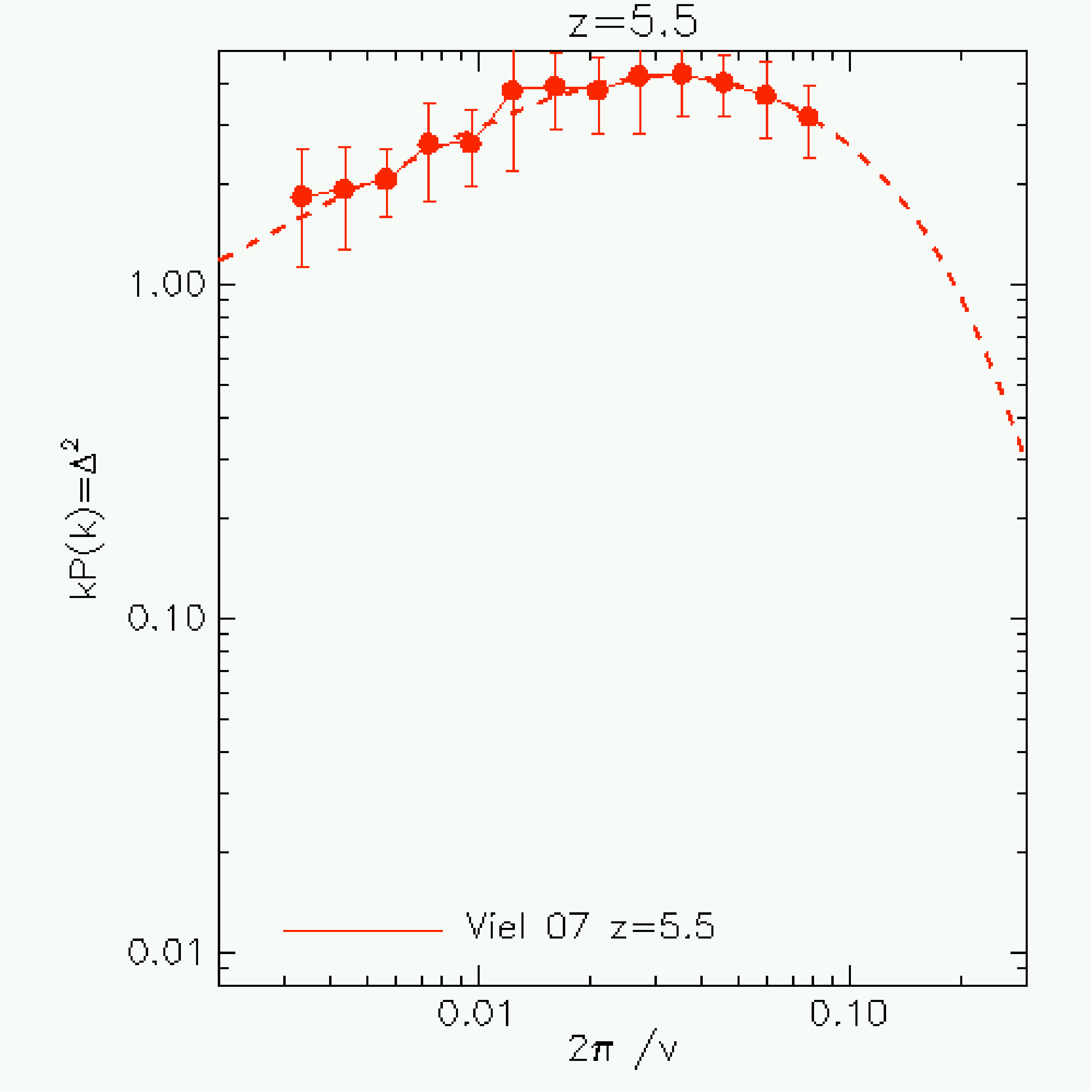
Observations: Mcdonald HiRes / Viel / McDonald SDSS



Observations: Mcdonald HiRes / Viel / McDonald SDSS



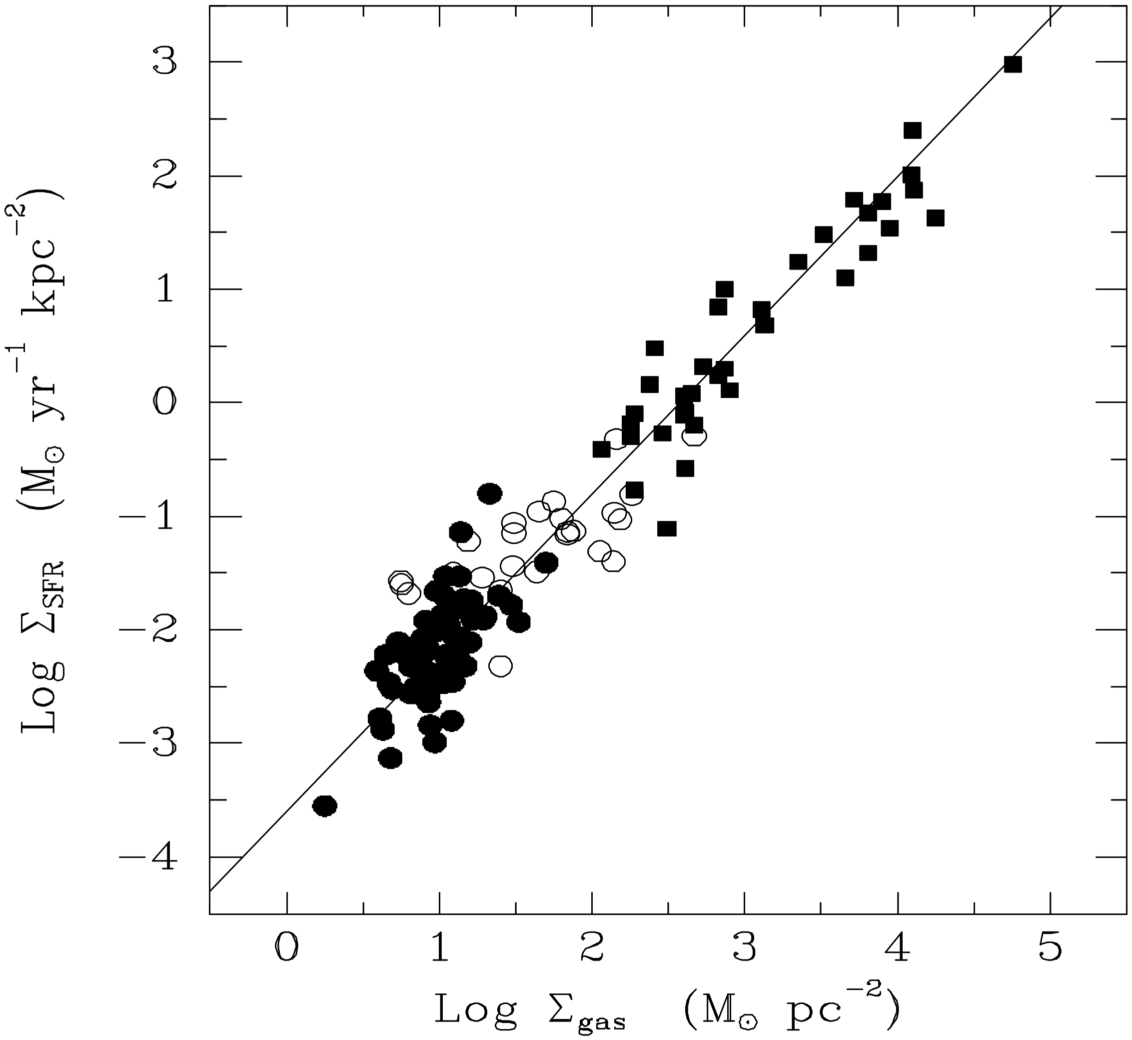
Observations: Mcdonald HiRes / Viel / McDonald SDSS



Observed star formation:

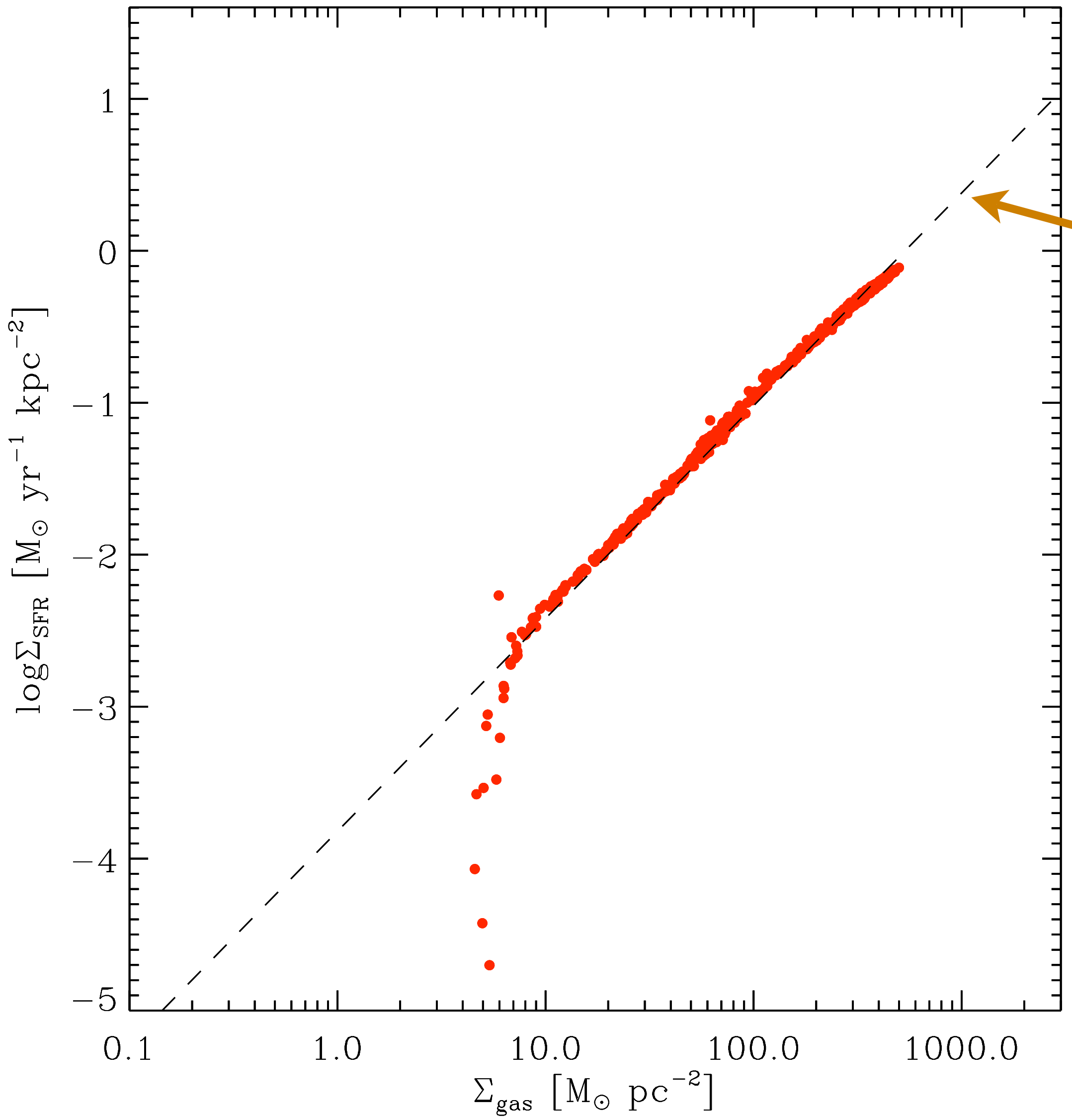
Schmidt law

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



(Kennicutt 1989)

Simulated star formation:

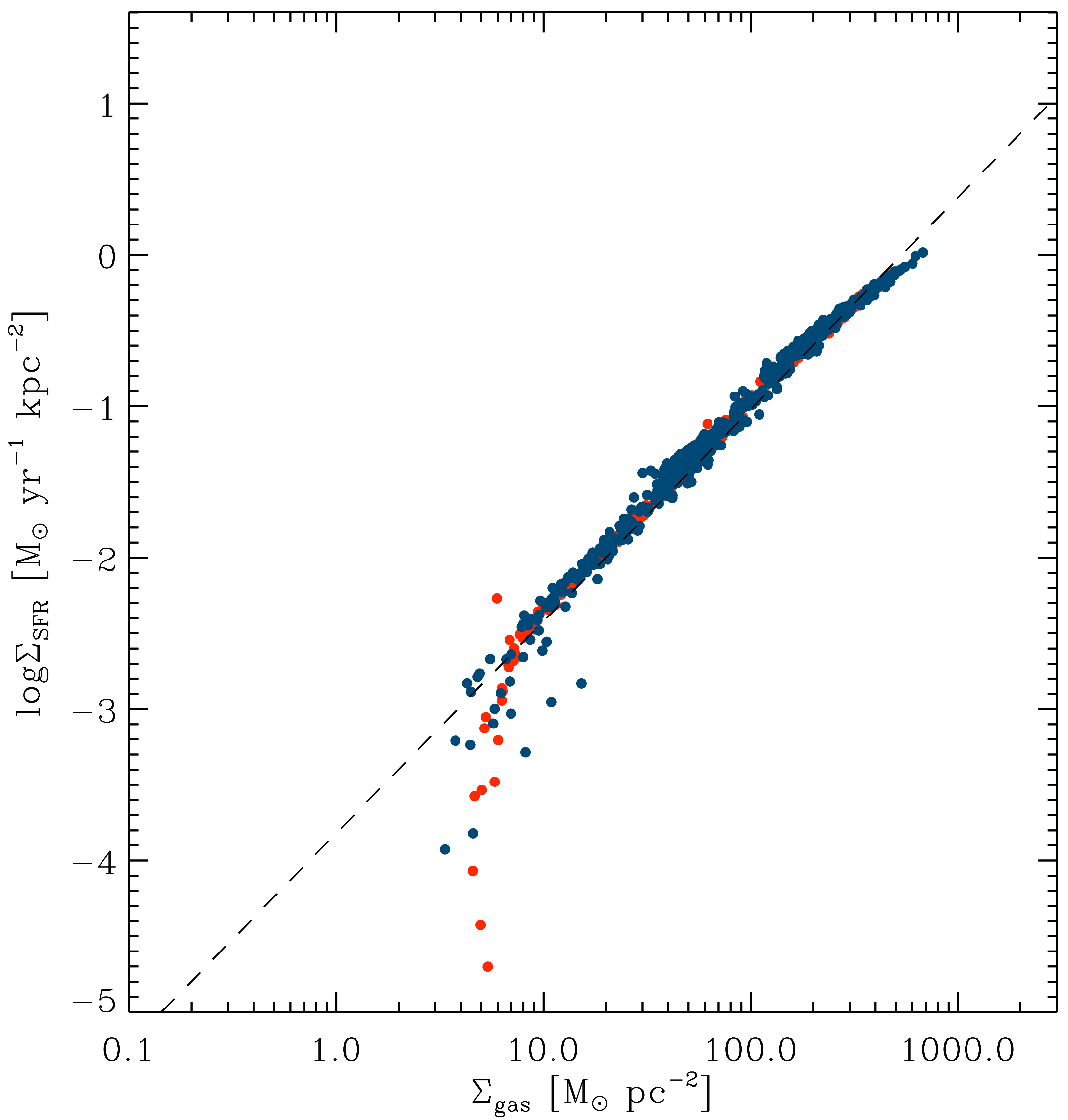


this is not a fit

● $N_{\rm part} = 100$

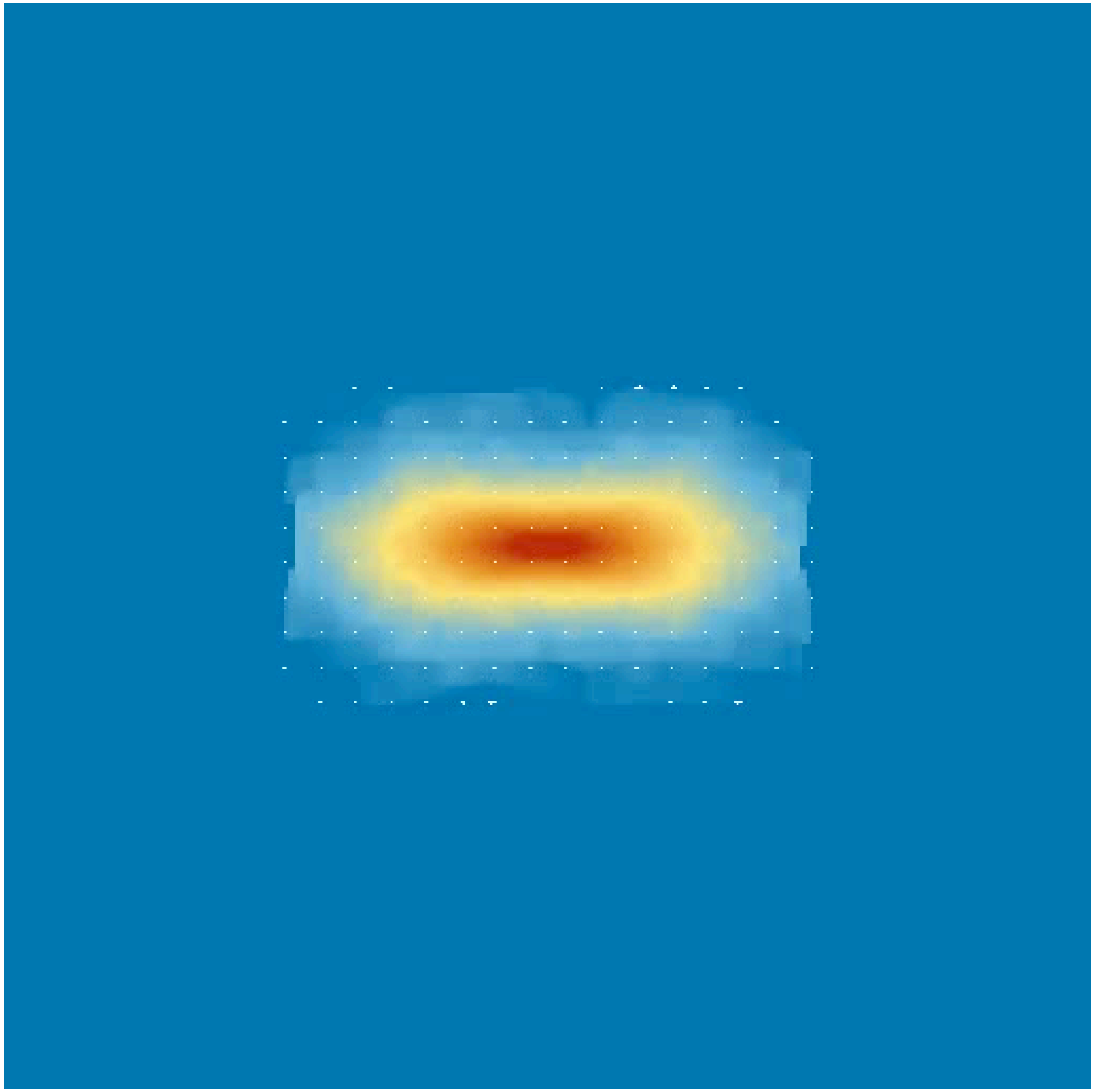
Simulated star formation:

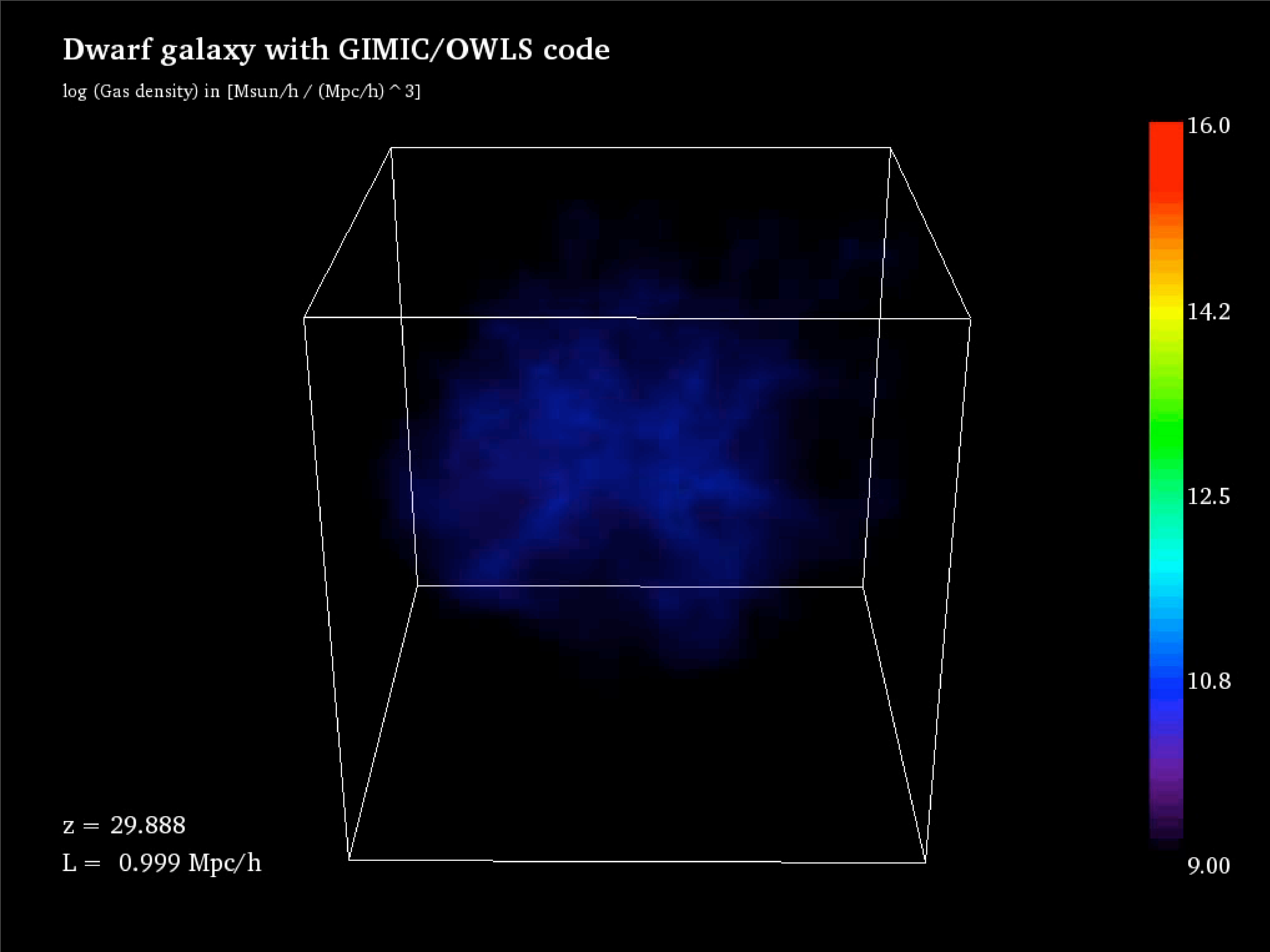
"resolution independent"

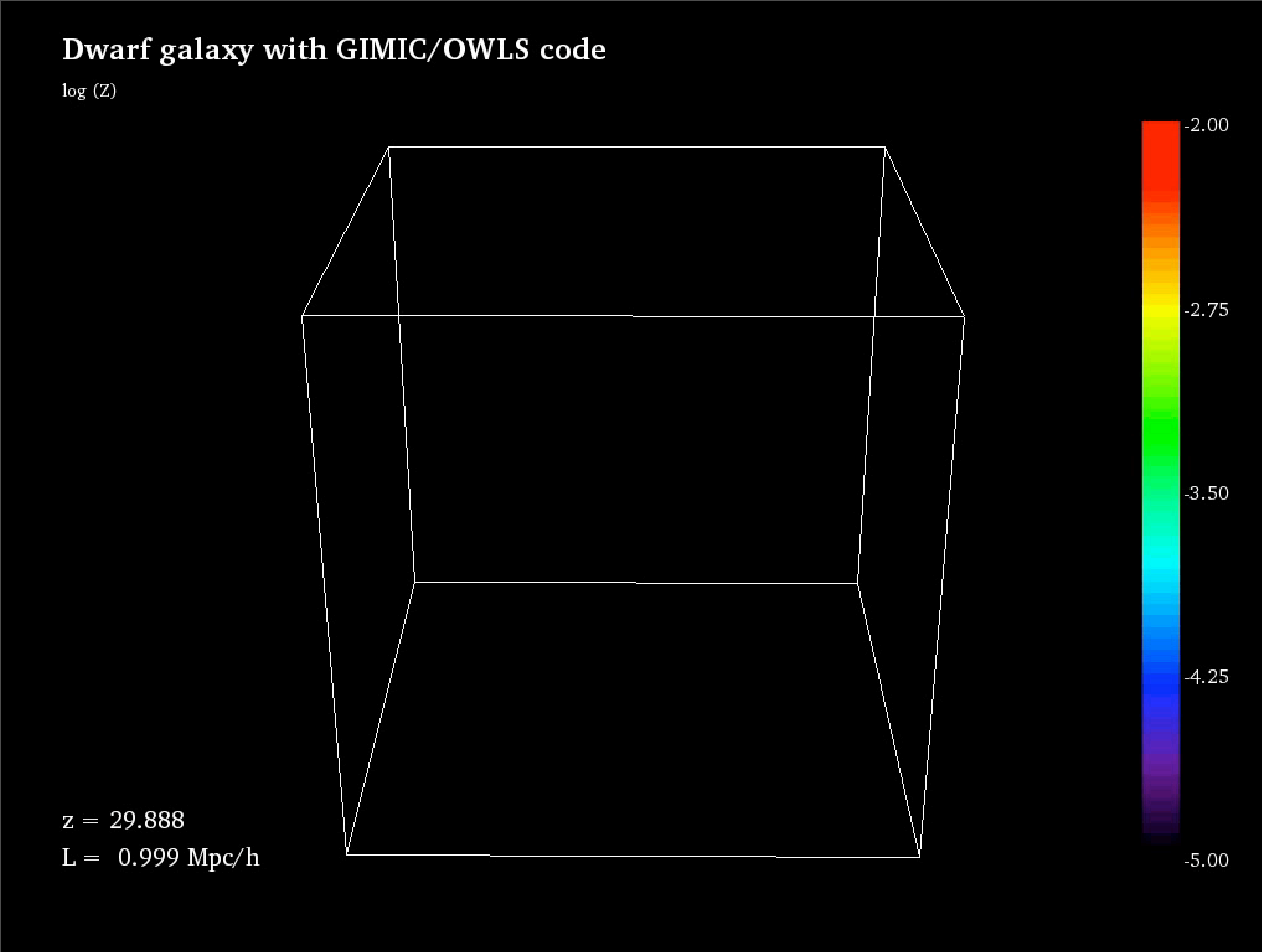


$N_{\rm part} = 100$

$N_{\rm part} = 12$




Dwarf galaxy with GIMIC/OWLS code
log (Gas density) in [Msun/h / (Mpc/h) ^ 3]
16.0
14.2
12.5
10.8
9.00
z = 29.888
L = 0.999 Mpc/h

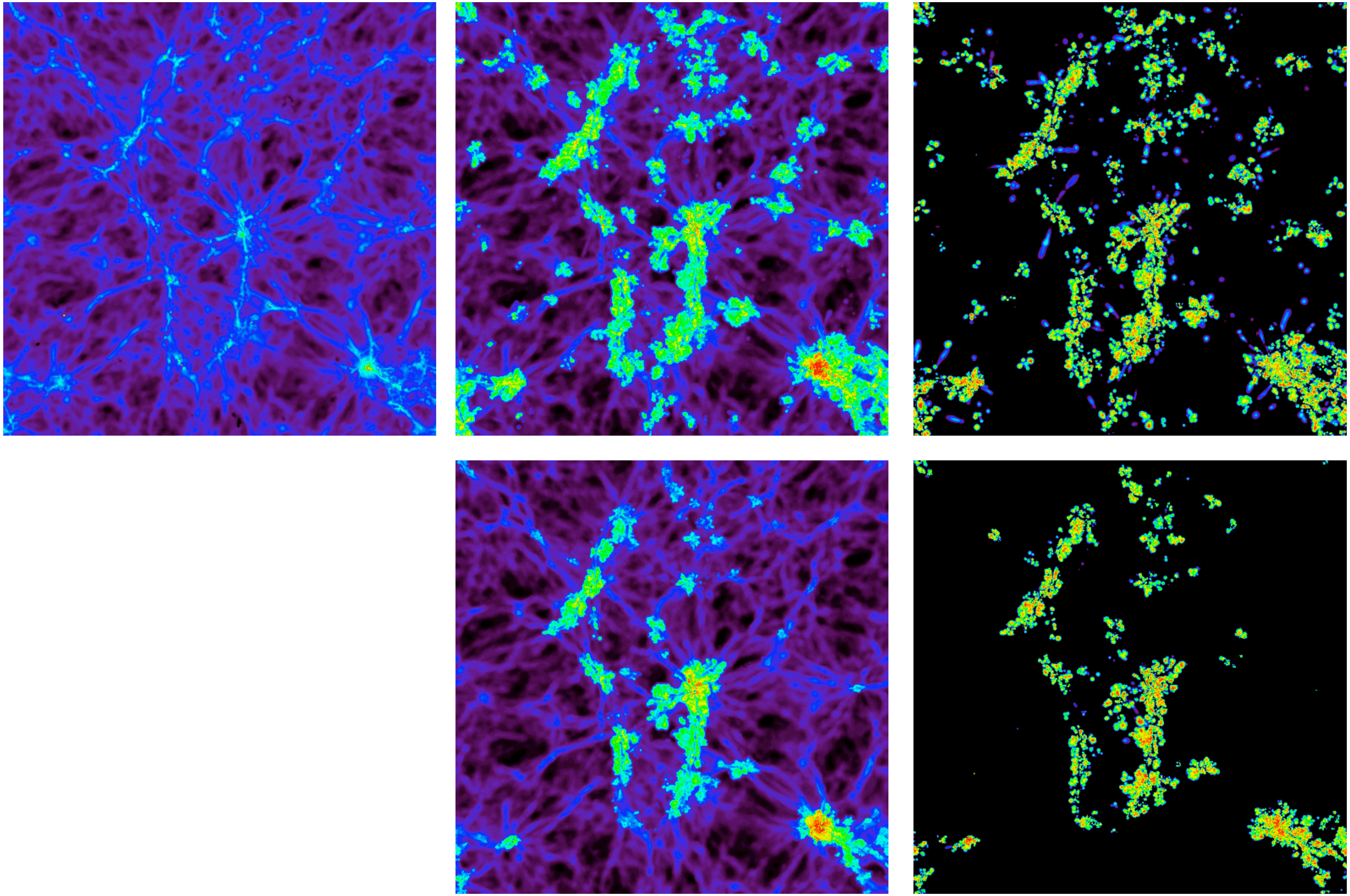


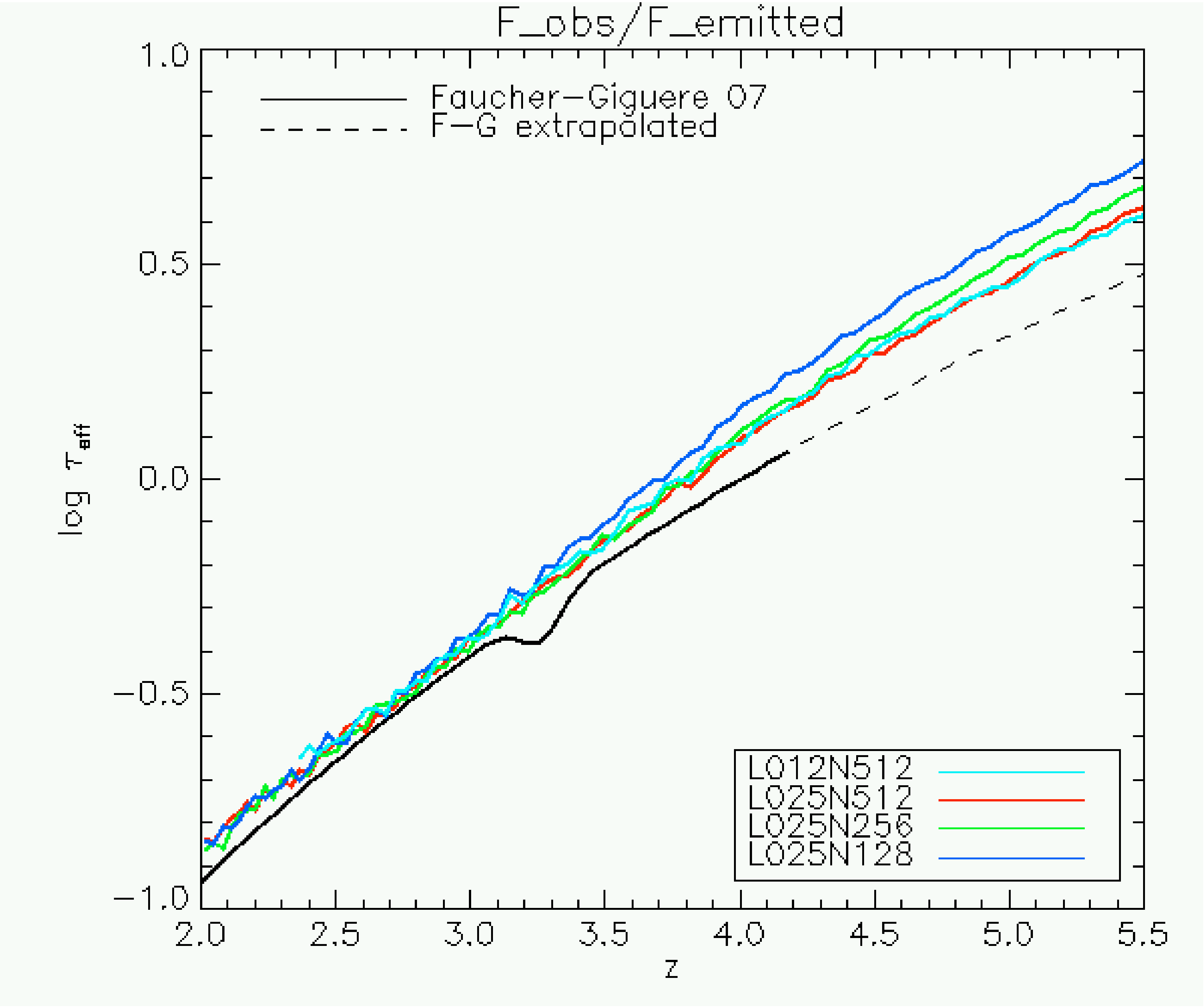
Dwarf galaxy with GIMIC/OWLS code
log (Z)
-2.00
-2.75
-3.50
-4.25
-5.00
z = 29.888
L = 0.999 Mpc/h

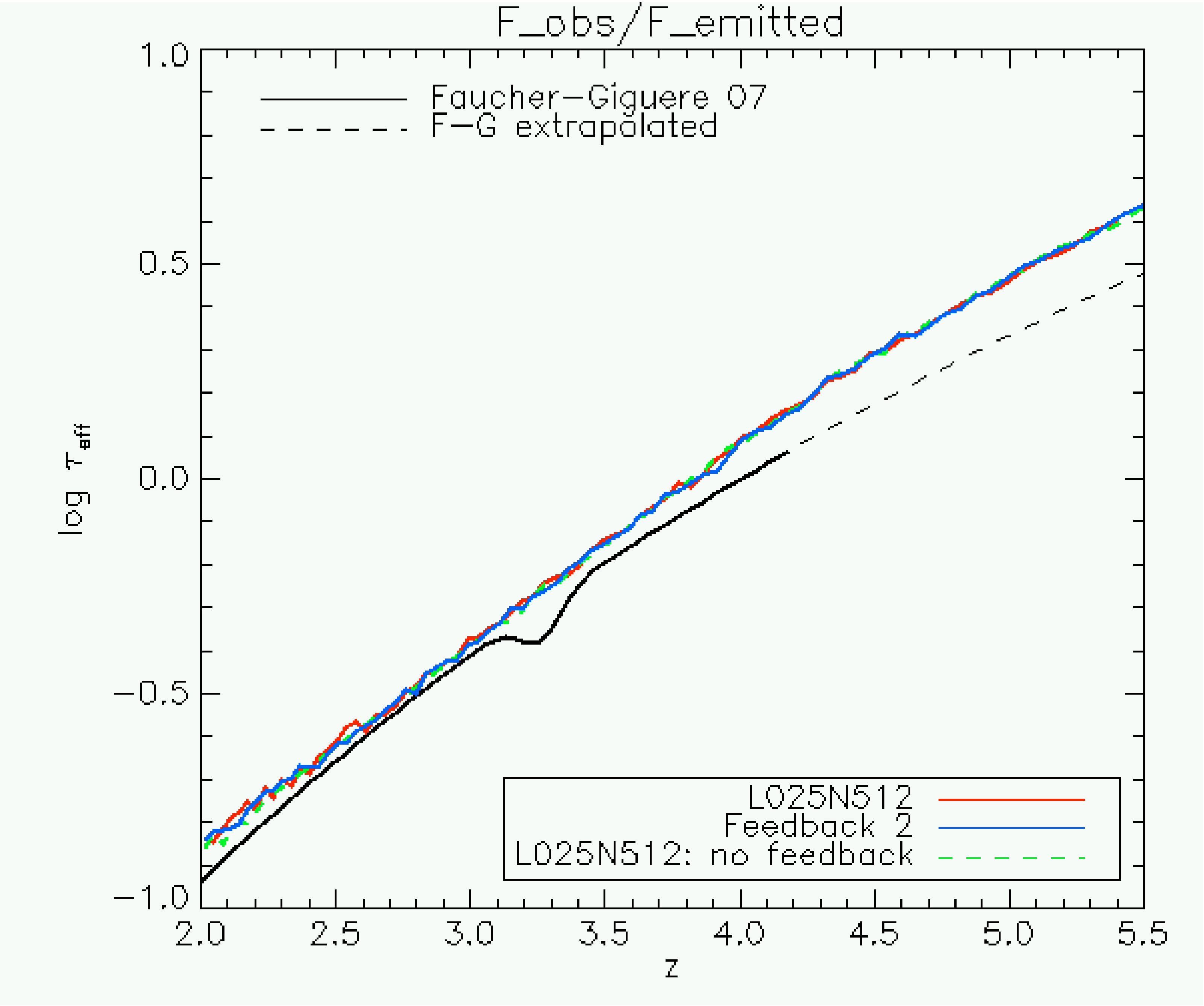
Suite of simulations varying:

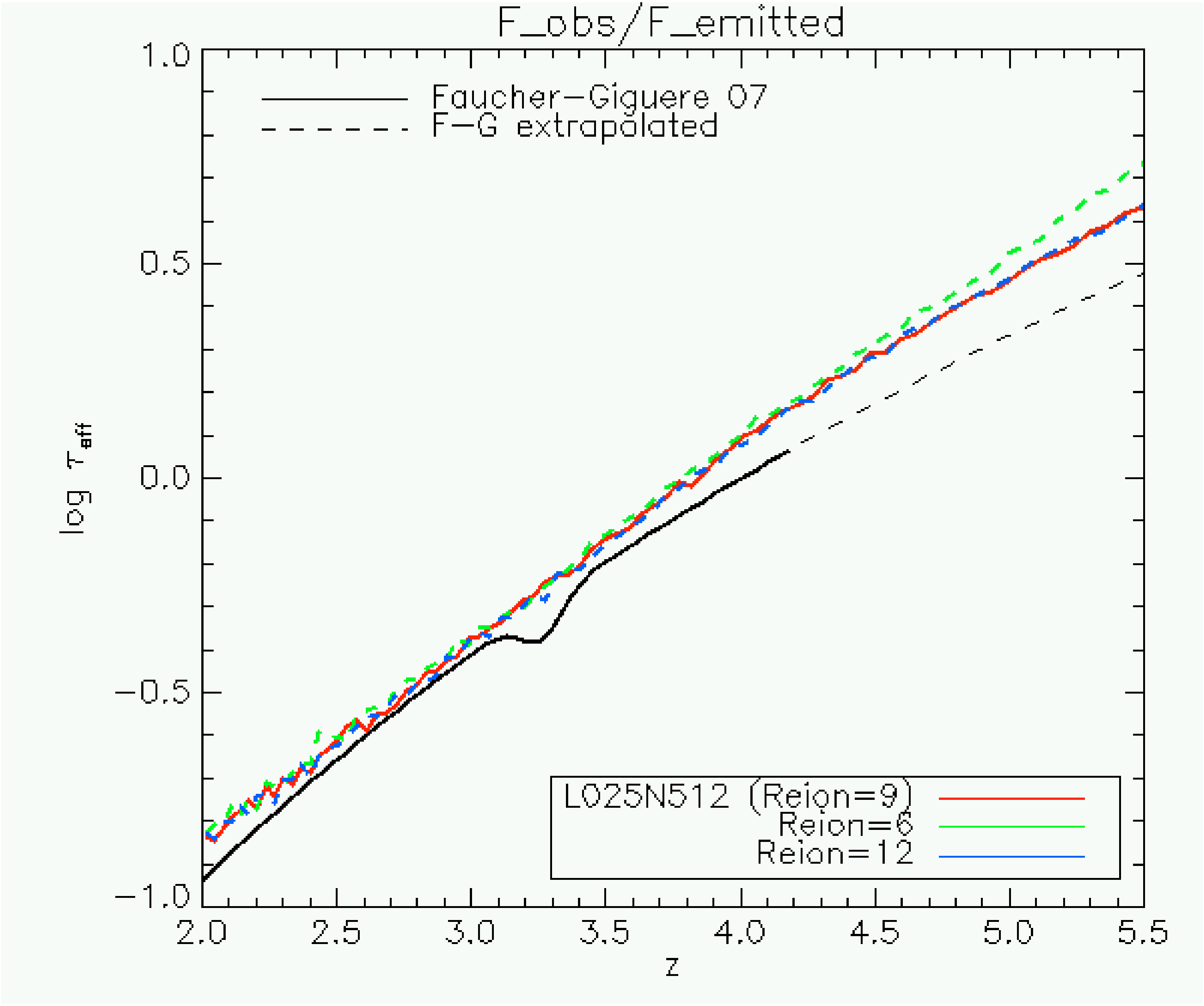
- Star formation parameters
- Wind implementation
- Resolution
- Box size
- Cosmology
- Reionization history

Density Temperature Metallicity

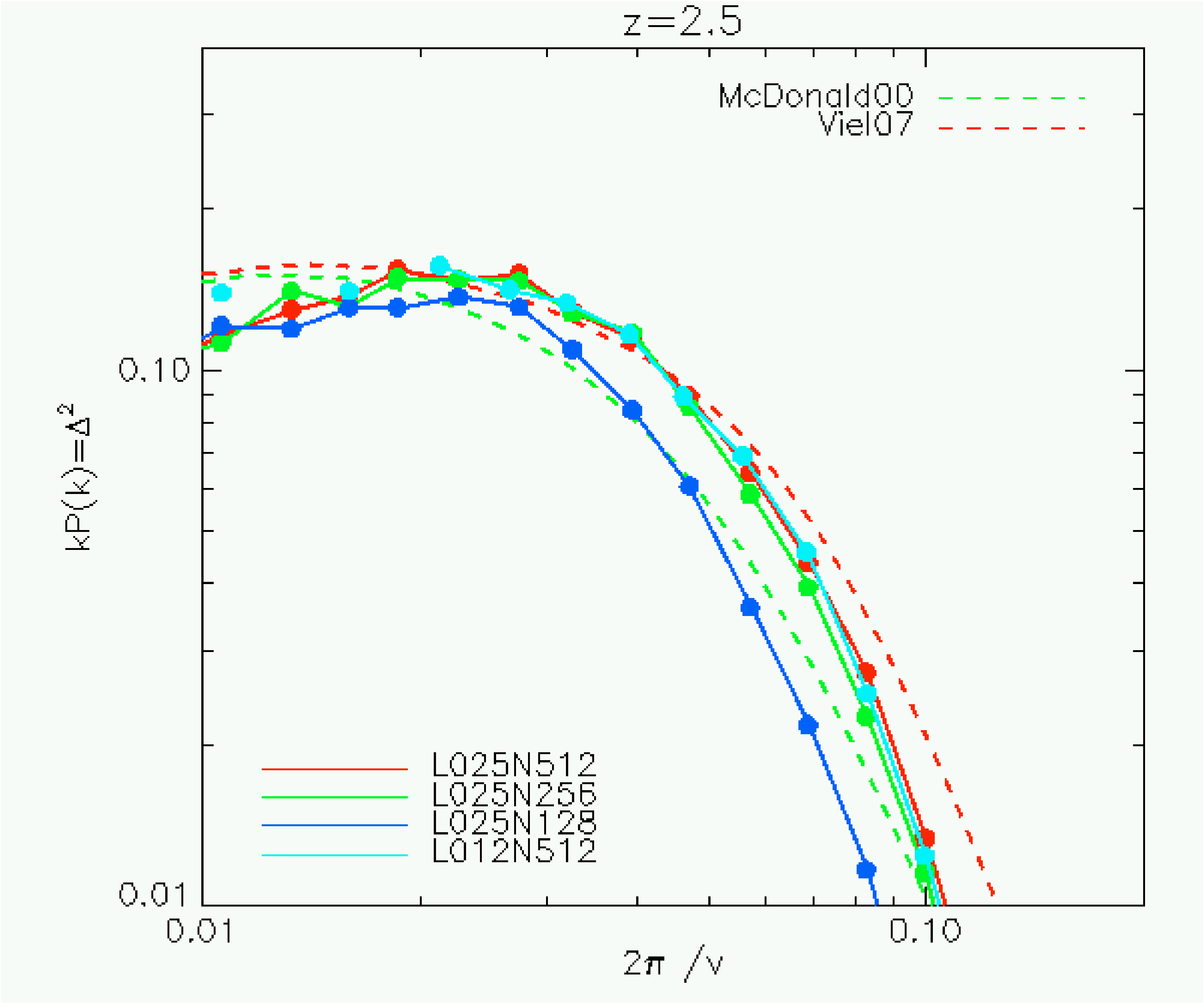



F_obs/F_emitted
Faucher-Giguere 07
F-G extrapolated
L012N512
L025N512
L025N256
L025N128
log τ_{eff}
z
1.0
0.5
0.0
-0.5
-1.0
2.0
2.5
3.0
3.5
4.0
4.5
5.0
5.5

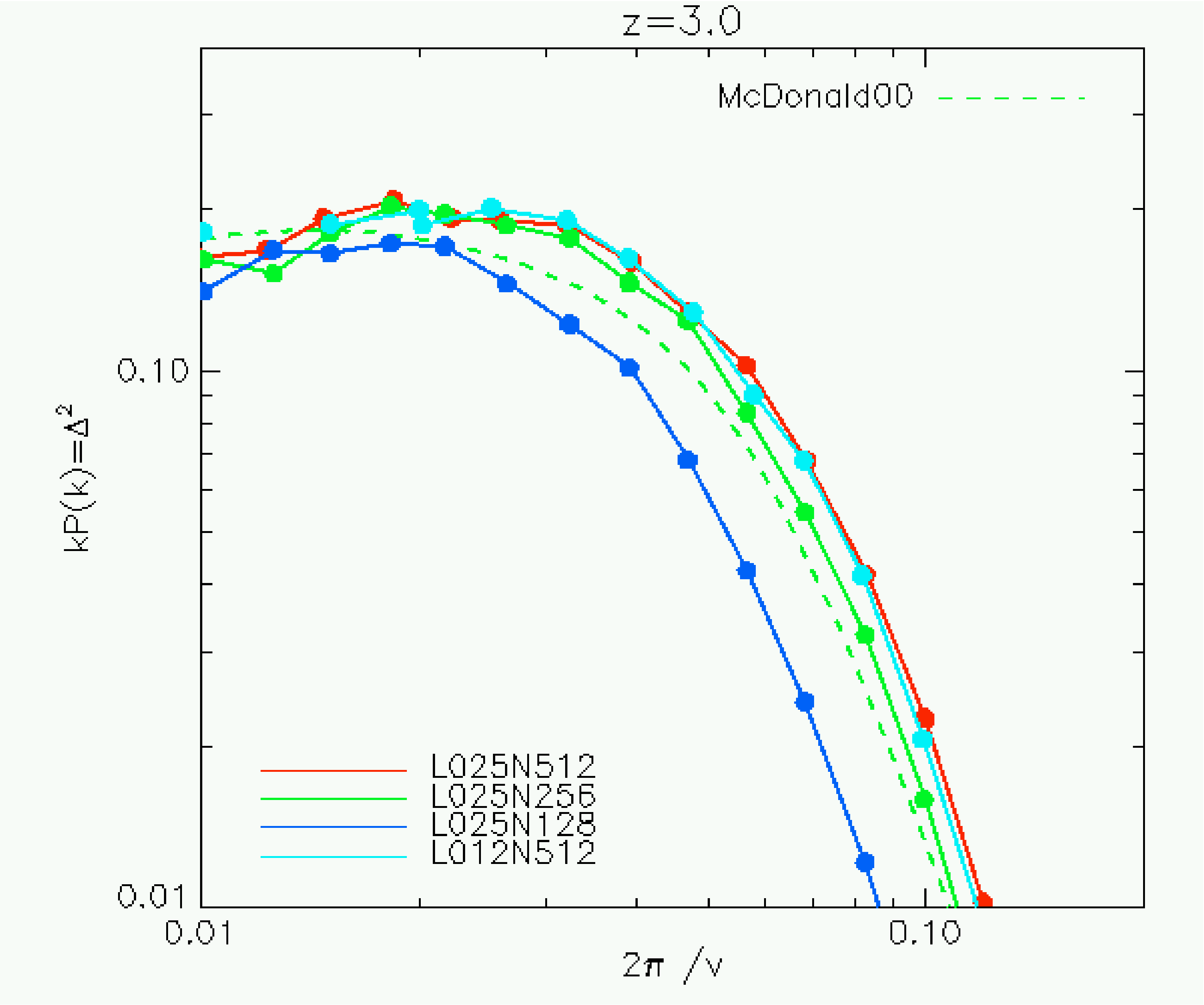

F_obs/F_emitted
Faucher-Giguere 07
F-G extrapolated
L025N512
Feedback 2
L025N512: no feedback
log τ_eff
z
1.0
0.5
0.0
-0.5
-1.0
2.0
2.5
3.0
3.5
4.0
4.5
5.0
5.5


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

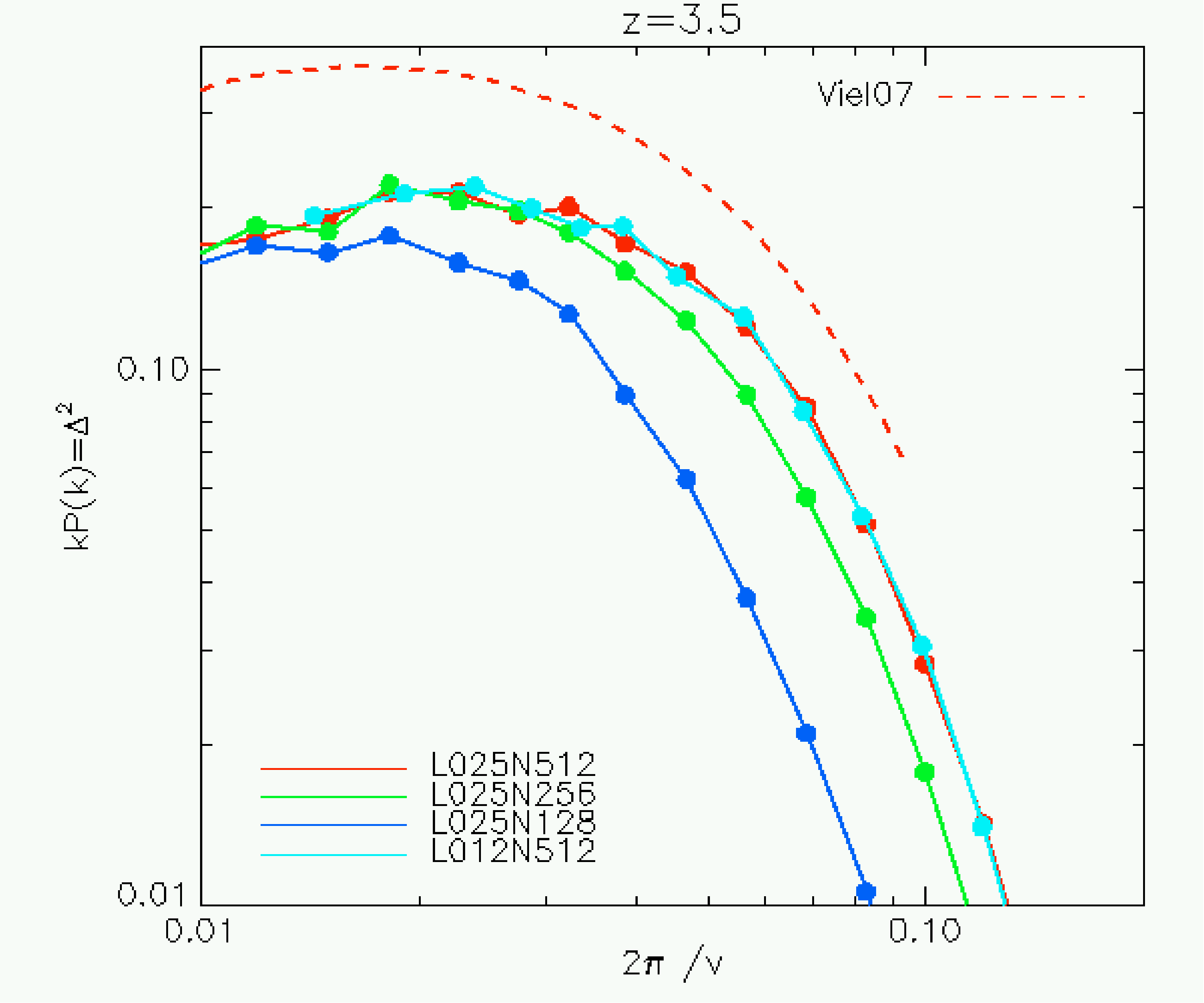
Resolution: low / medium / high / very high



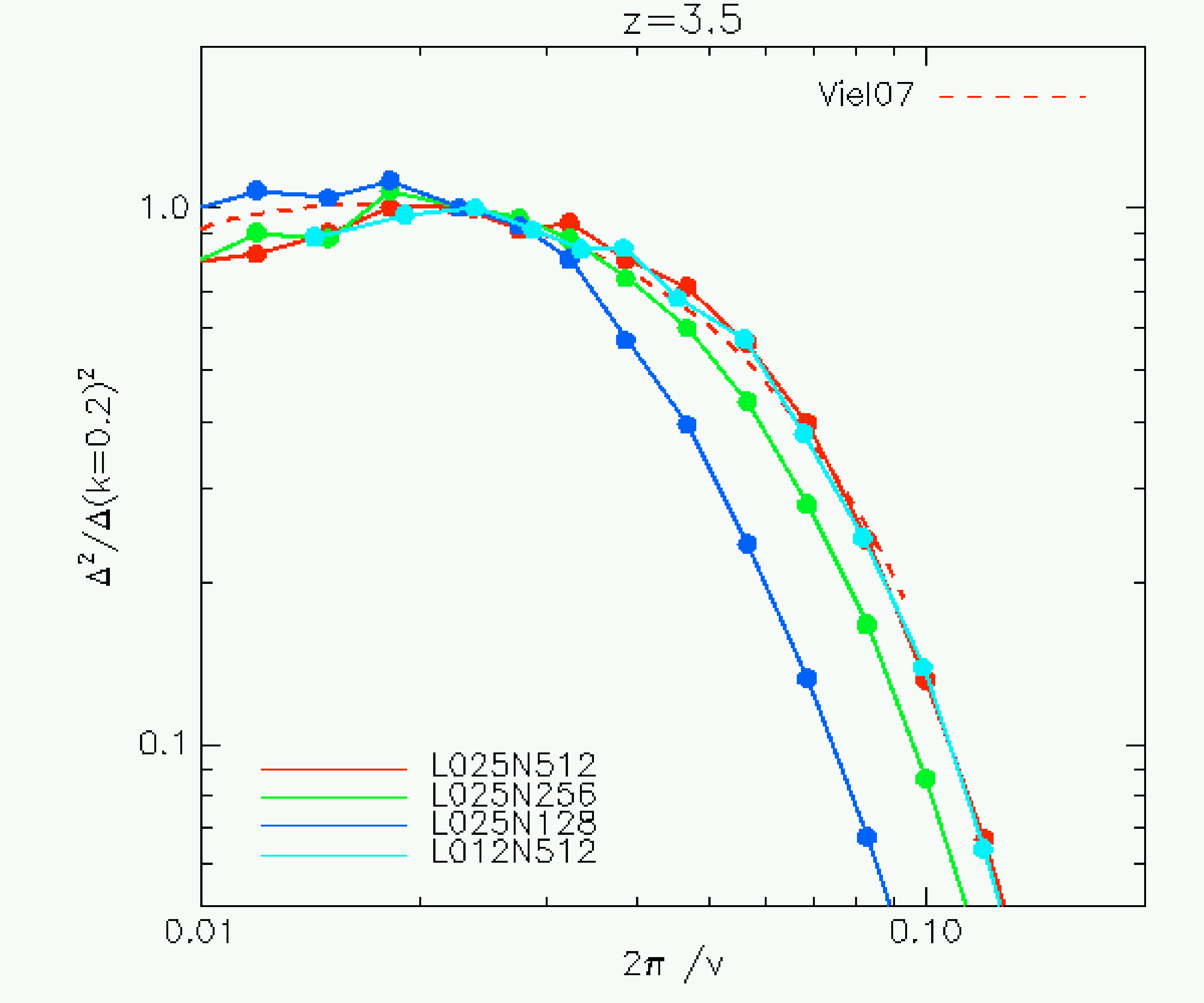
Resolution: low / medium / high / very high



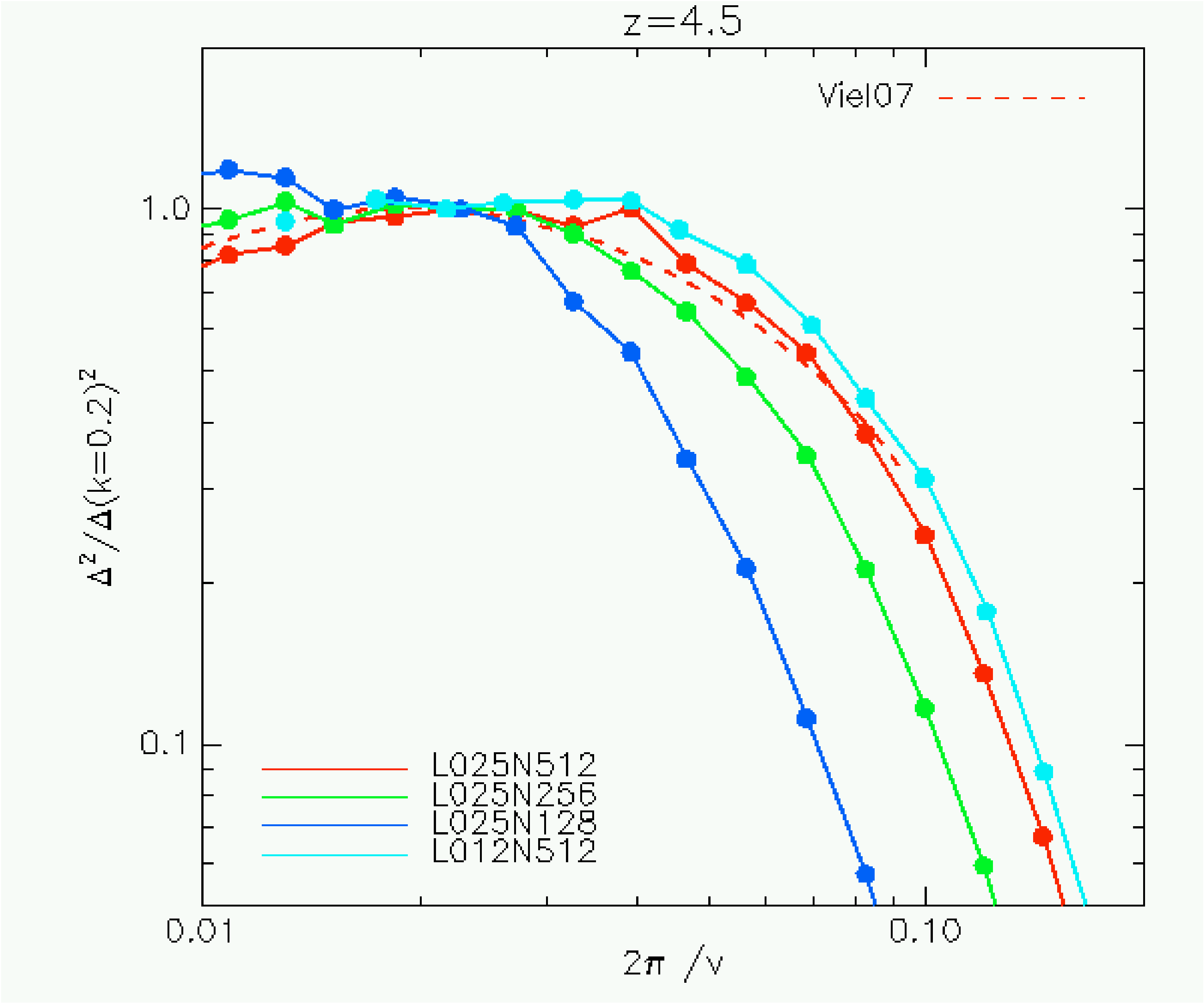
Resolution: low / medium / high / very high



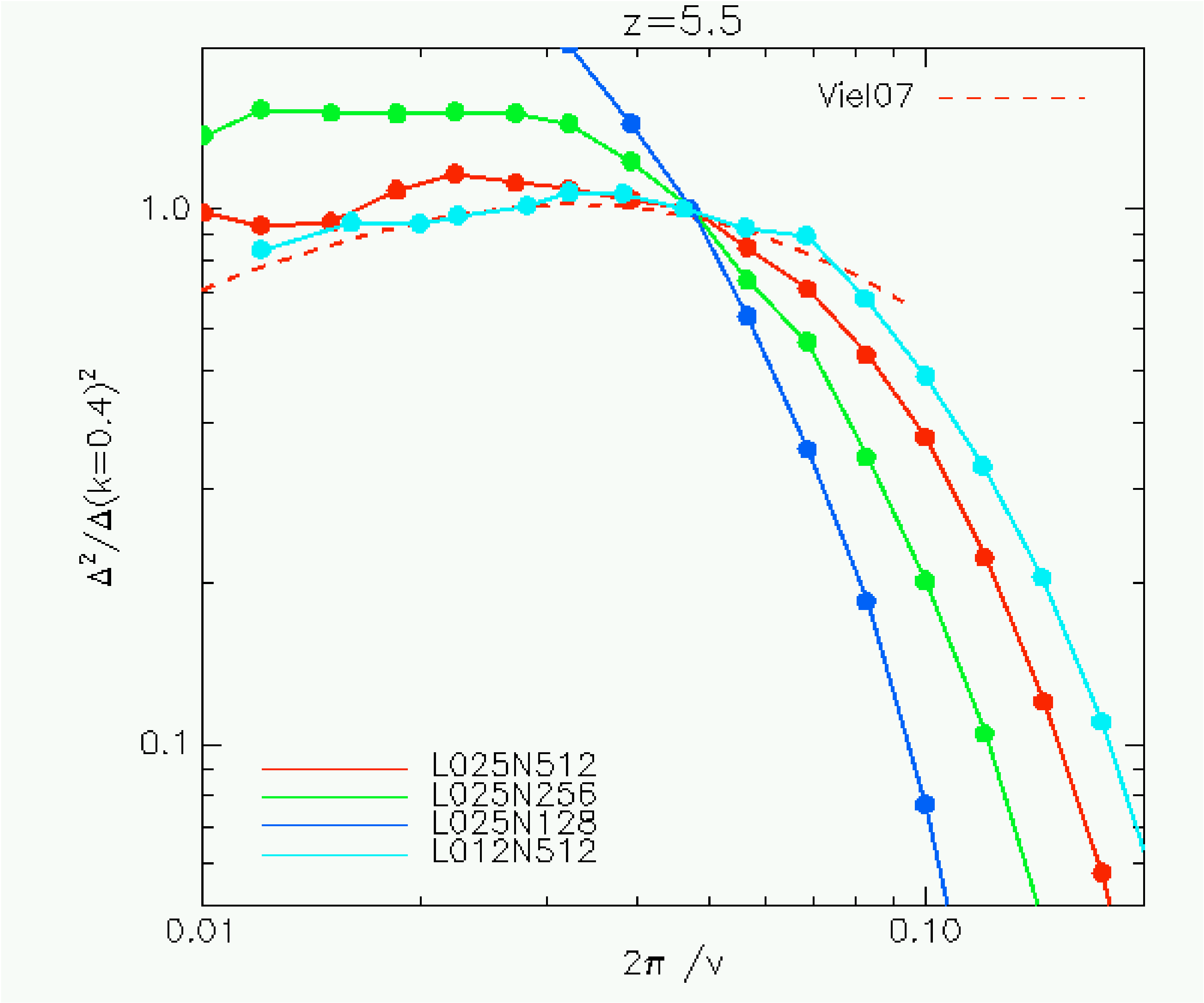
Resolution: low / medium / high / very high



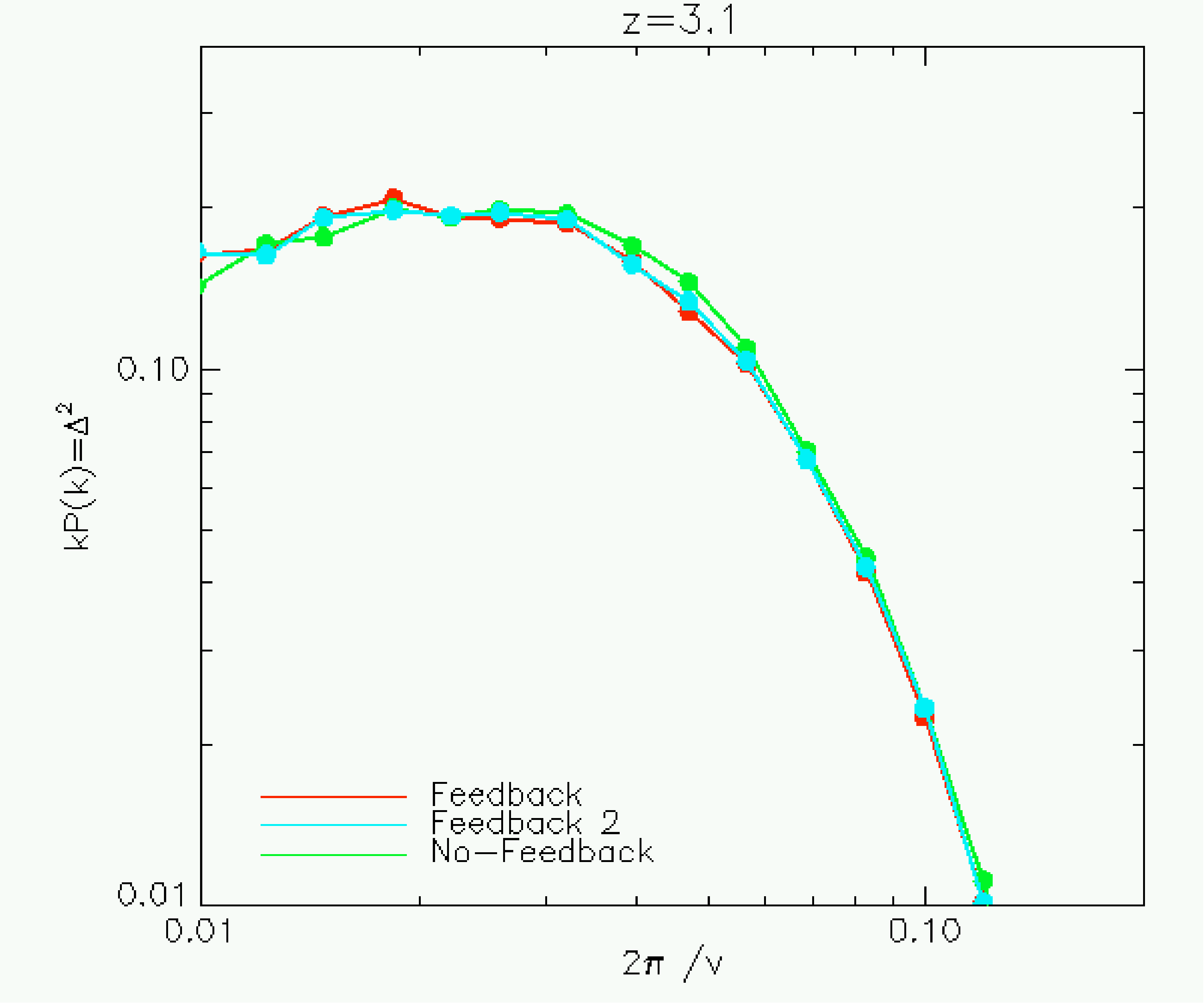
Resolution: low / medium / high / very high

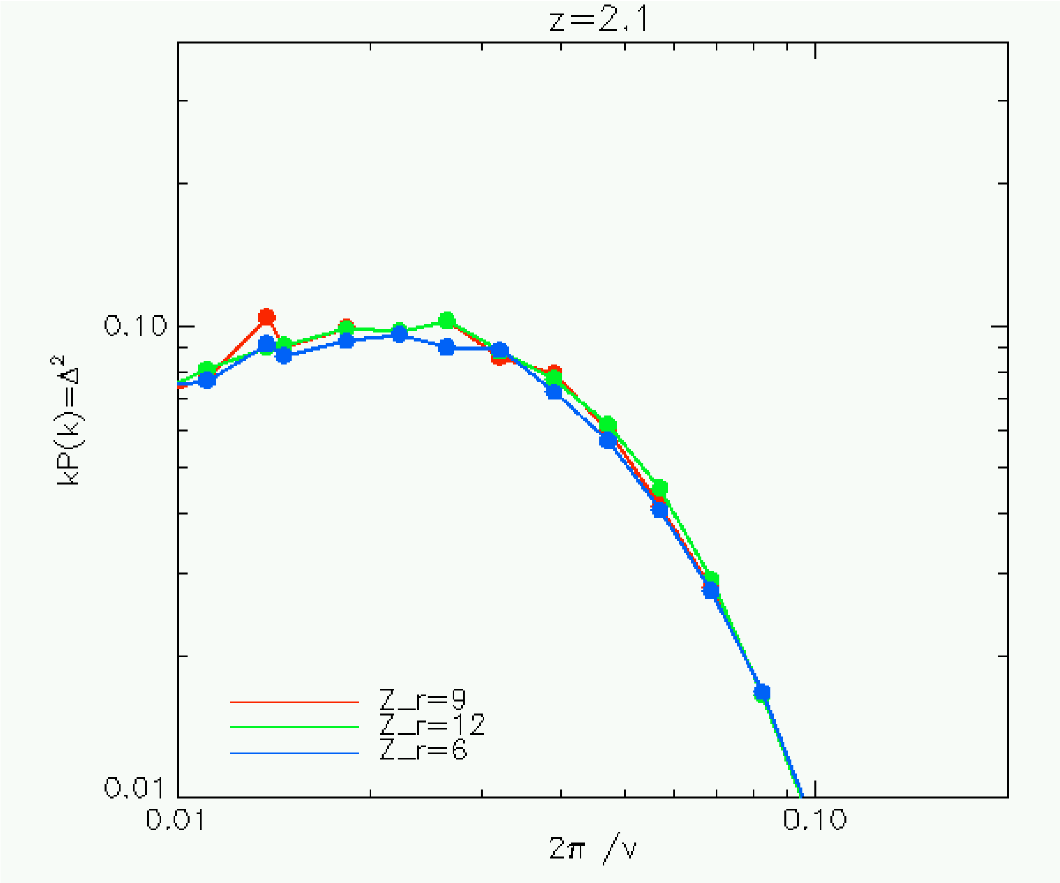


Resolution: low / medium / high / very high



Feedback / Feedback2 / No-Feedback





Epoch of HI reionization:

Z_reion=6/
Z_reion=9/
Z_reion=12