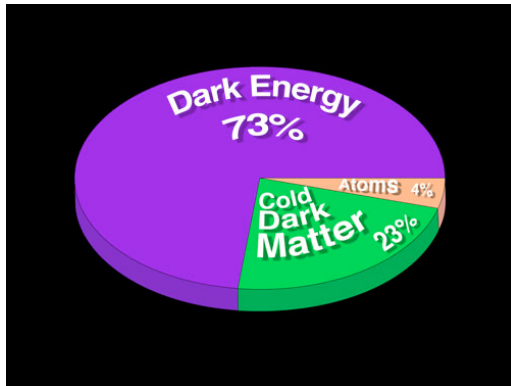


# Structure formation and the nature of the dark matter



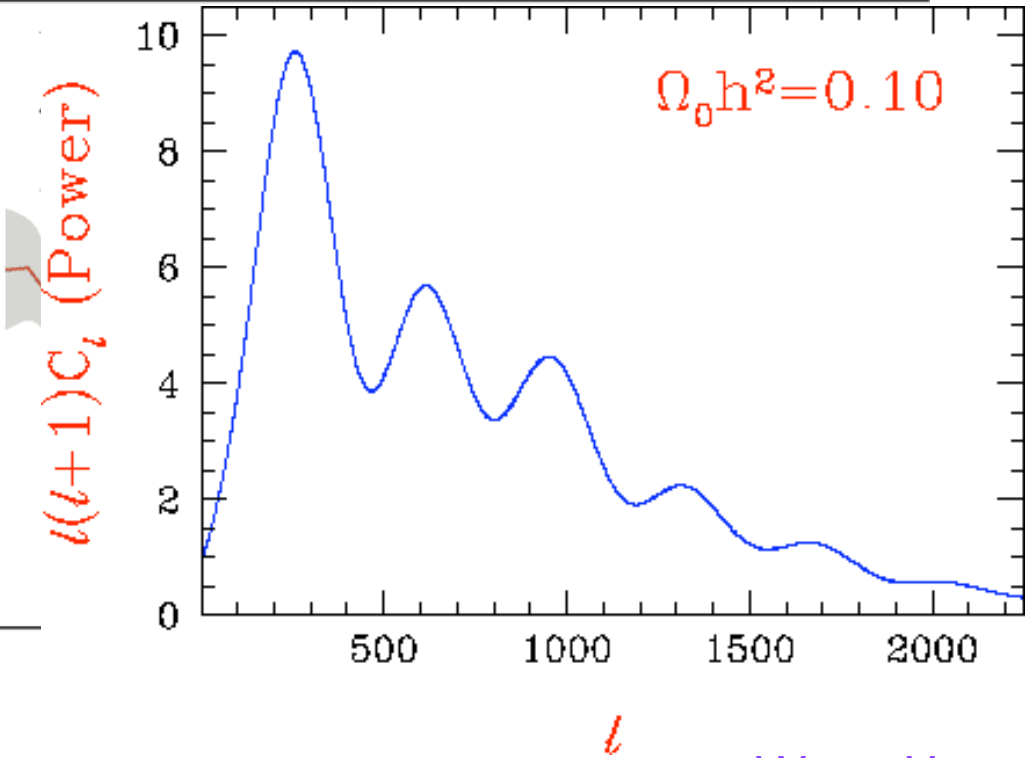
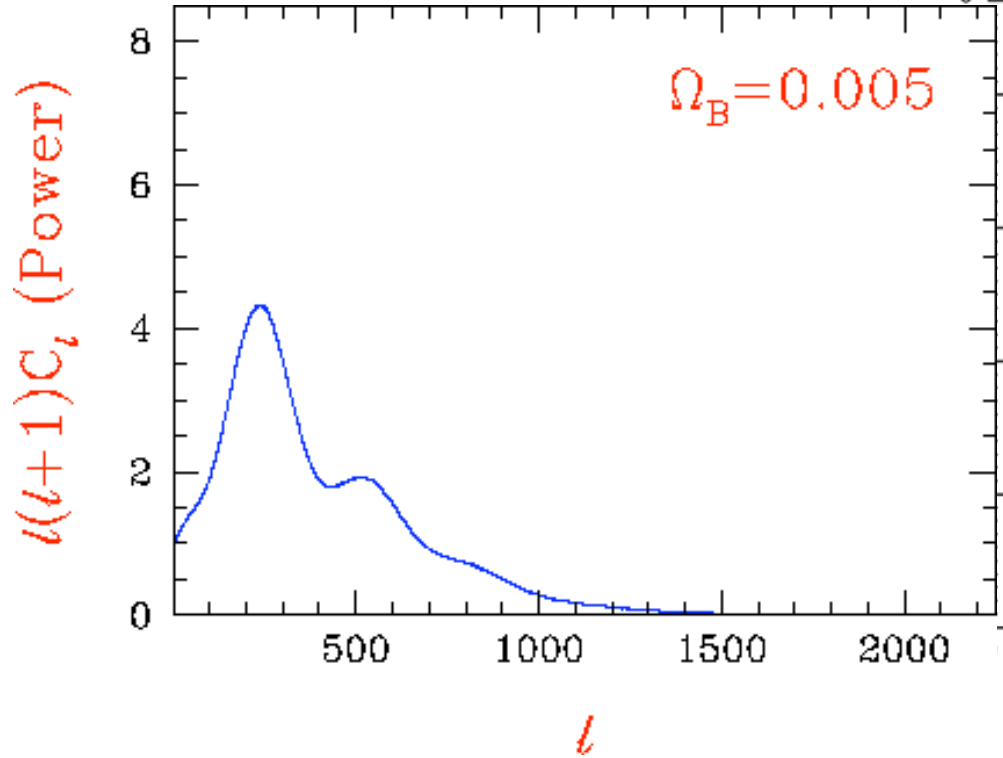
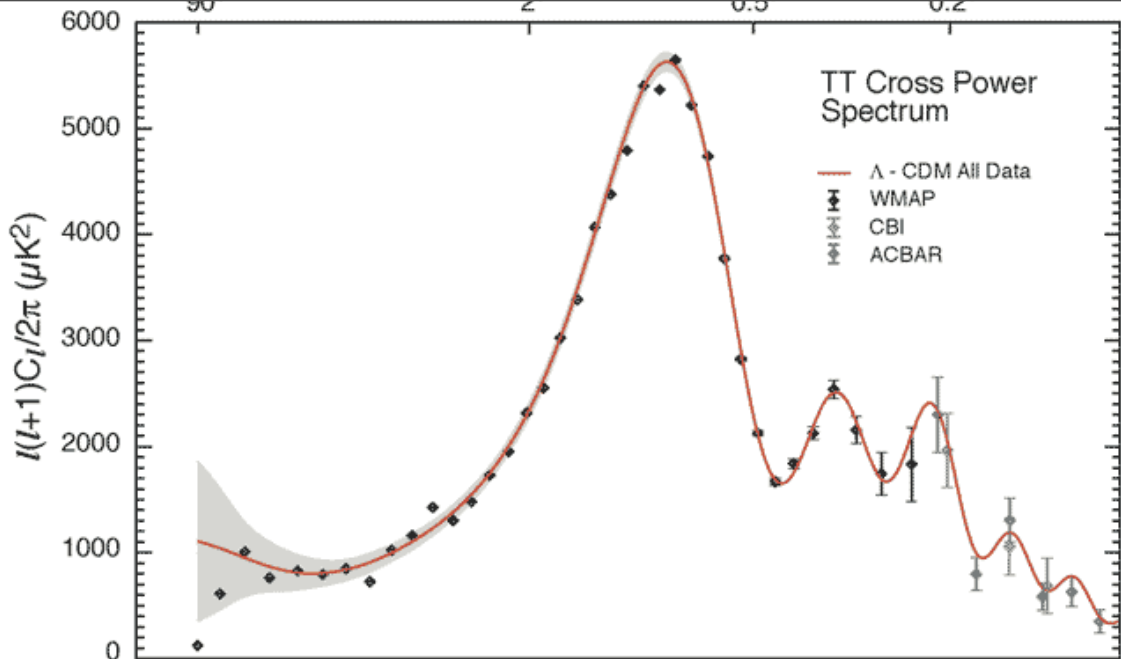
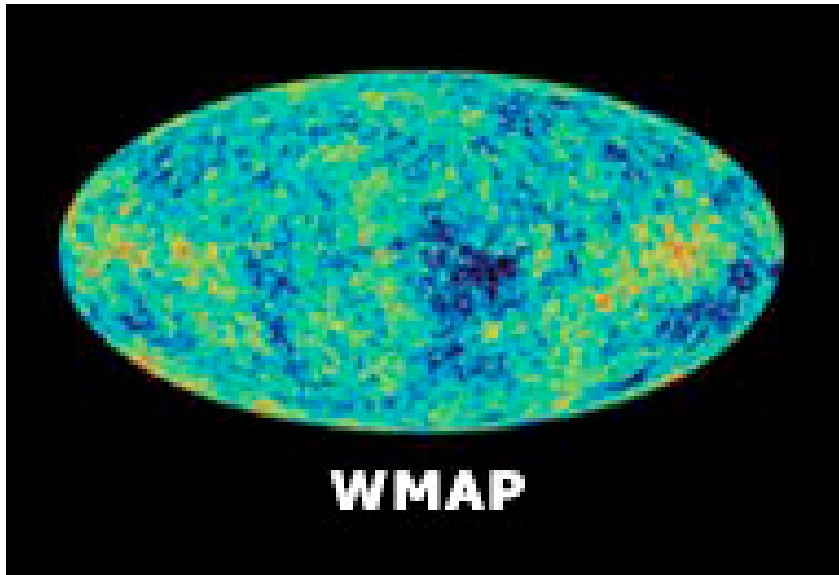
## Contents of the Universe



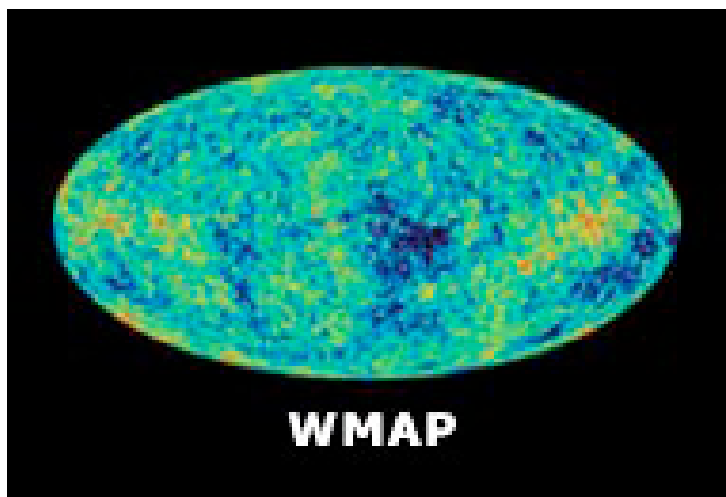
Tom Theuns

Institute for Computational Cosmology  
Ogden Centre for Fundamental Physics  
Durham University, UK  
and  
University of Antwerp  
Belgium

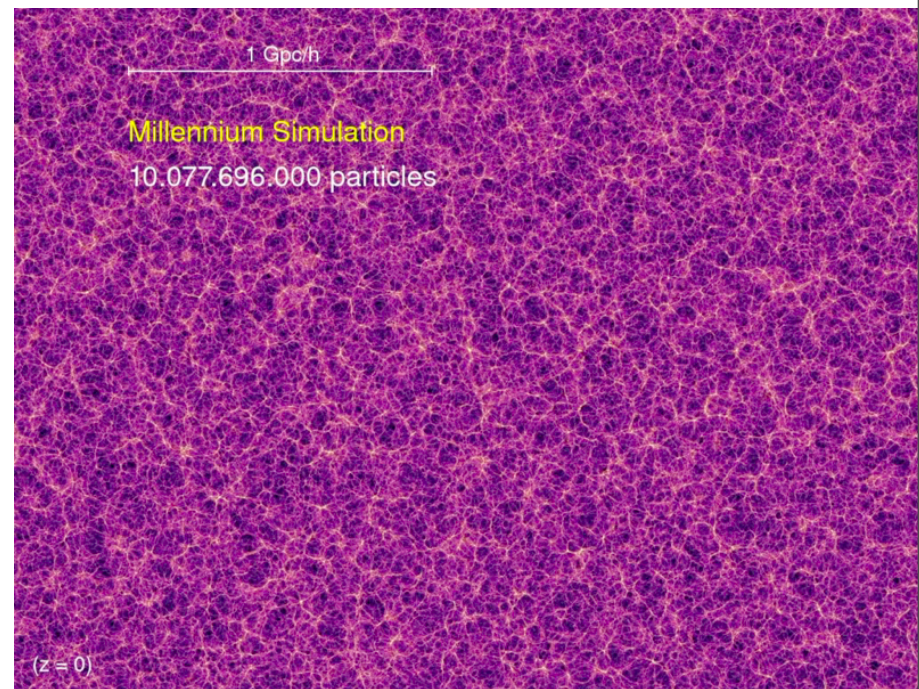
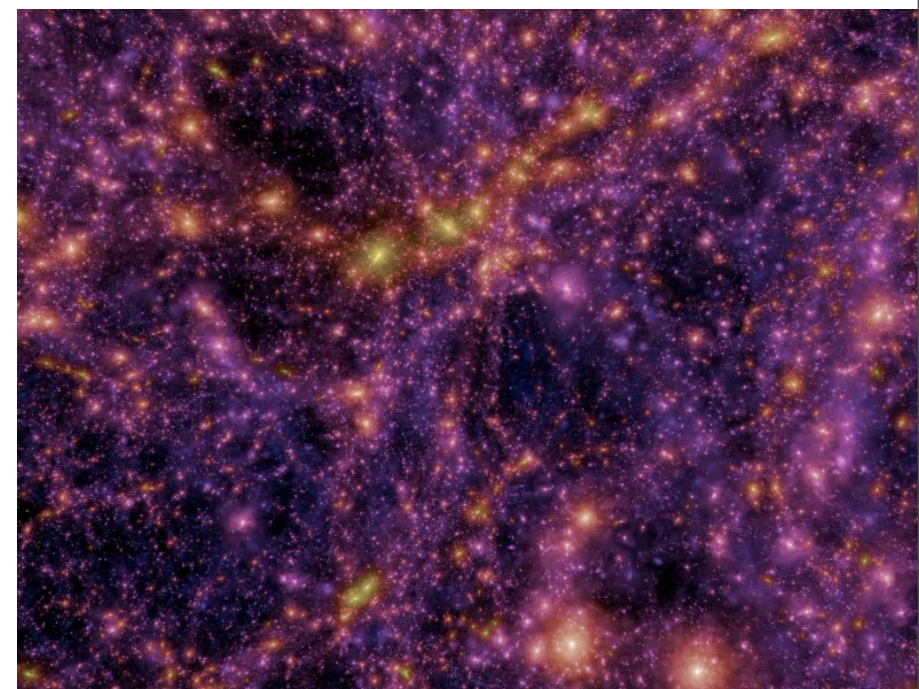
- Introduction
- Success of dark matter models
- Possible issues with Cold Dark Matter
- Dark matter candidates
- Constraints on the nature of the dark matter
  - Lyman-alpha forest
  - First stars

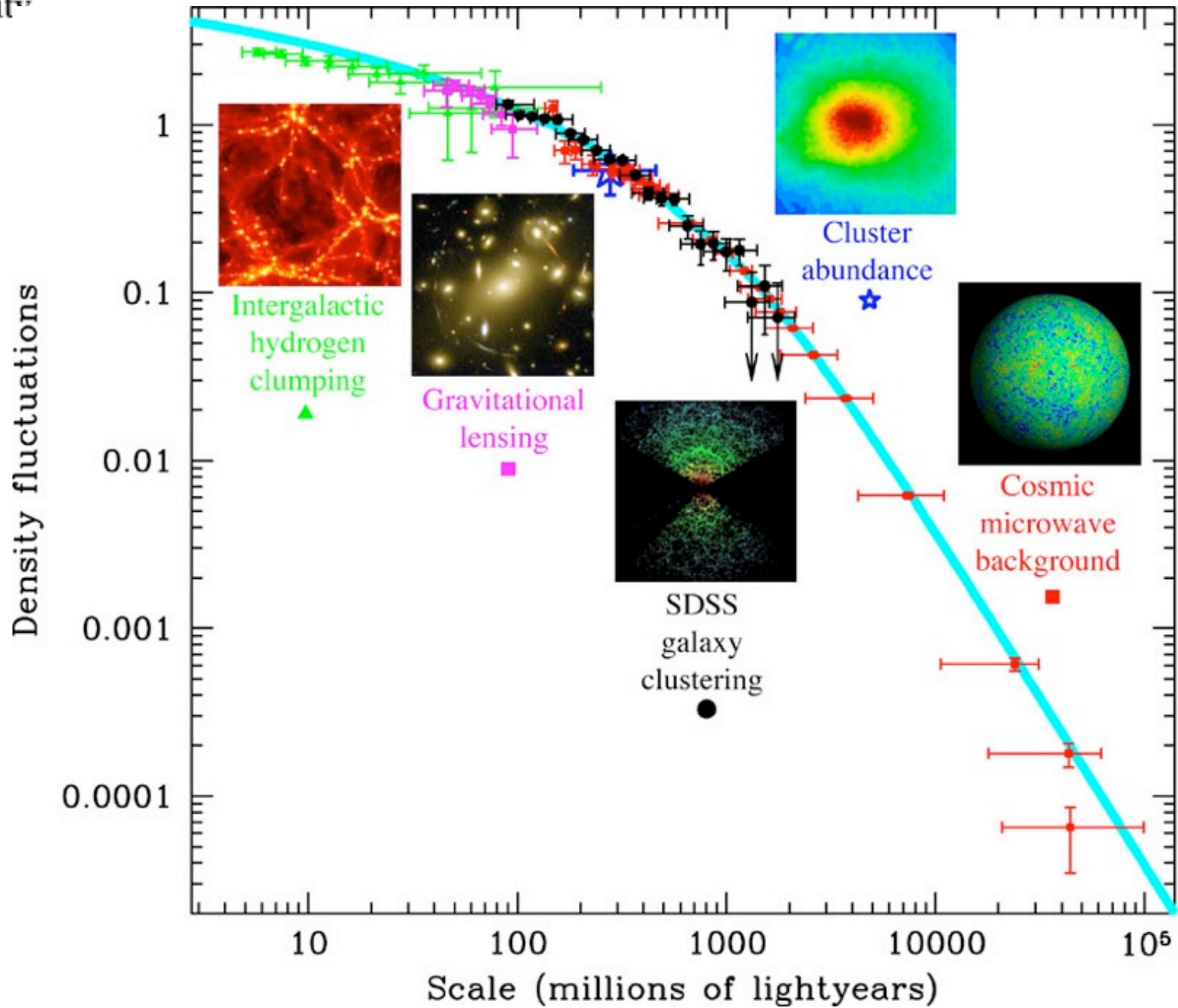


Wayne Hu



→  
**+ Gravity**





A visualization of the cosmic web from the Millennium Simulation. The image shows a complex, interconnected network of dark matter filaments and nodes, rendered in shades of purple and blue. The filaments form a dense, web-like structure that fills the entire frame. A scale bar at the top indicates a distance of 1 Gpc/h. The text 'Millennium Simulation' and '10,077,696,000 particles' is overlaid on the left side. The redshift is indicated as (z = 0) in the bottom left corner. The VIRGO logo is in the top right corner.

1 Gpc/h

Millennium Simulation

10,077,696,000 particles

VIRGO

( $z = 0$ )

$z = 36.0$

Aquarius project: the  
Milky Way's dark halo

$M = 0.000E+00$

VIRGO



# Dark Matter and Particle Physics:

no lack of candidates!

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

These decouple at different times, depending on nature are relativistic or not when entering the horizon:

Hot vs Warm vs Cold Dark Matter

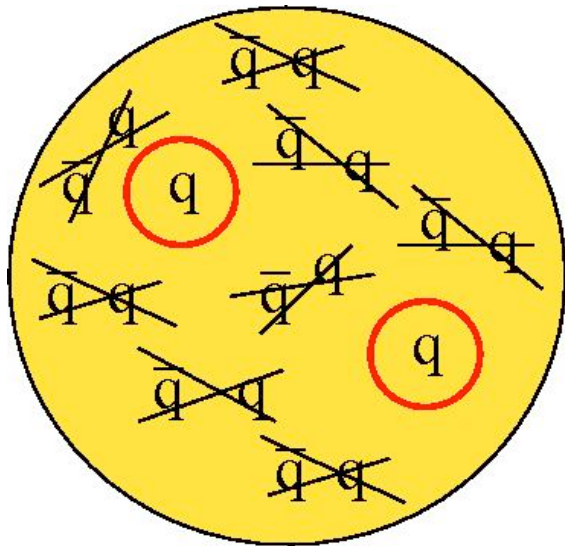
# Particle physics motivation for new physics:

## 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

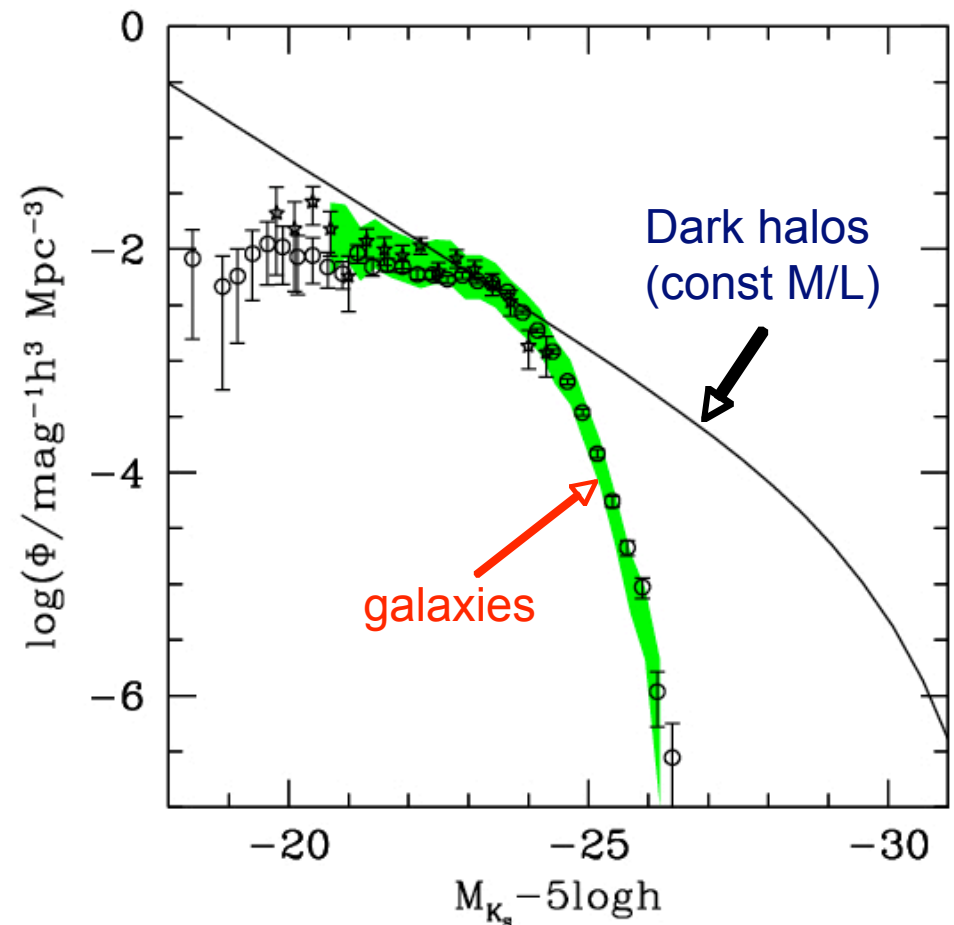
## \* Axion

- Light CDM relic

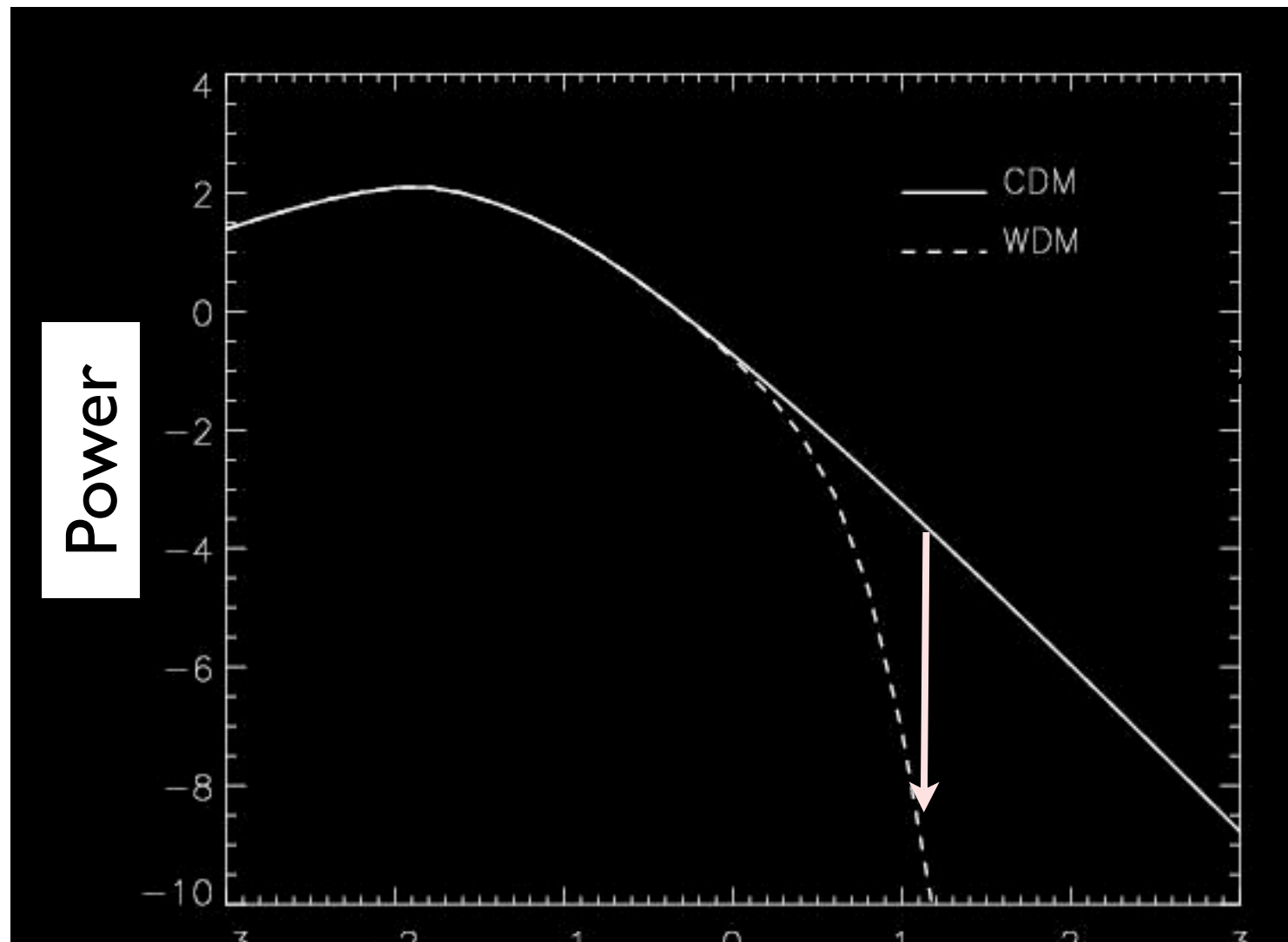
# Possible issues with Cold Dark Matter:

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

“Gastrophysics?”



# How does nature of the dark matter affect structure formation?



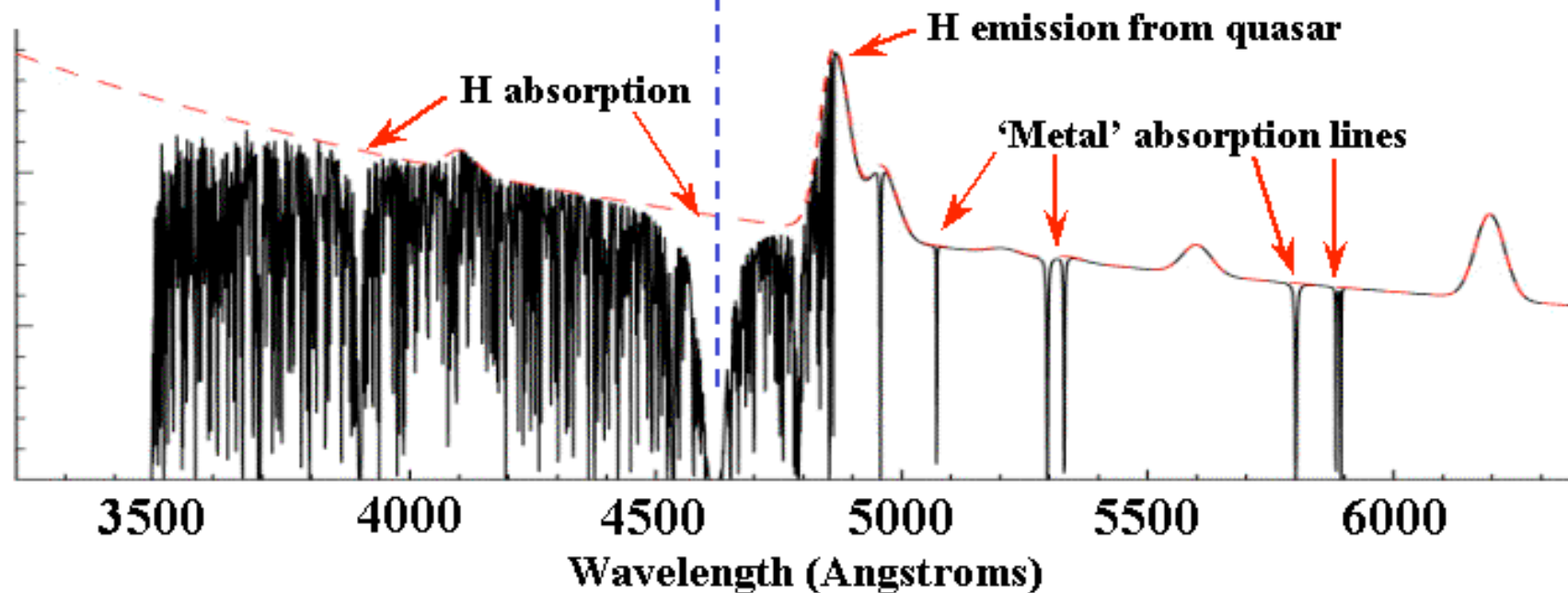
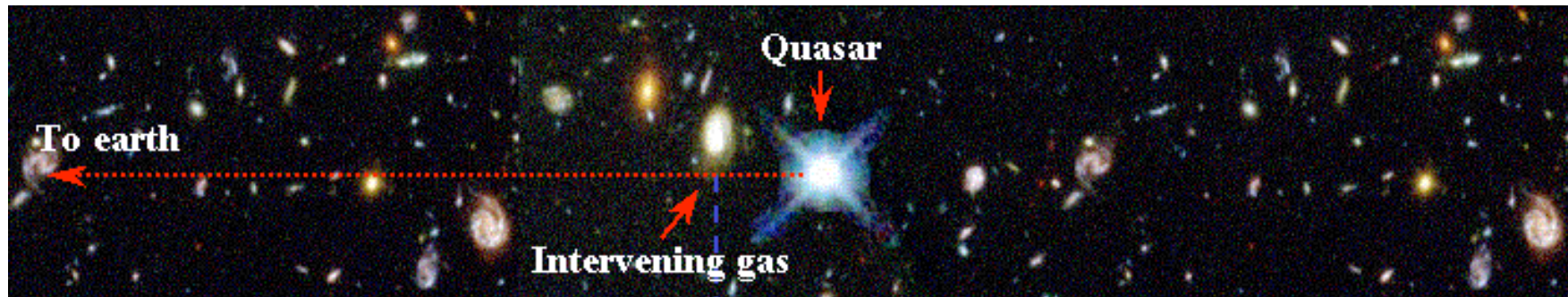
Large scales

Small scales Tom Theuns

# Cosmological constraints on the nature of the dark matter

- Lyman-alpha forest
- First stars

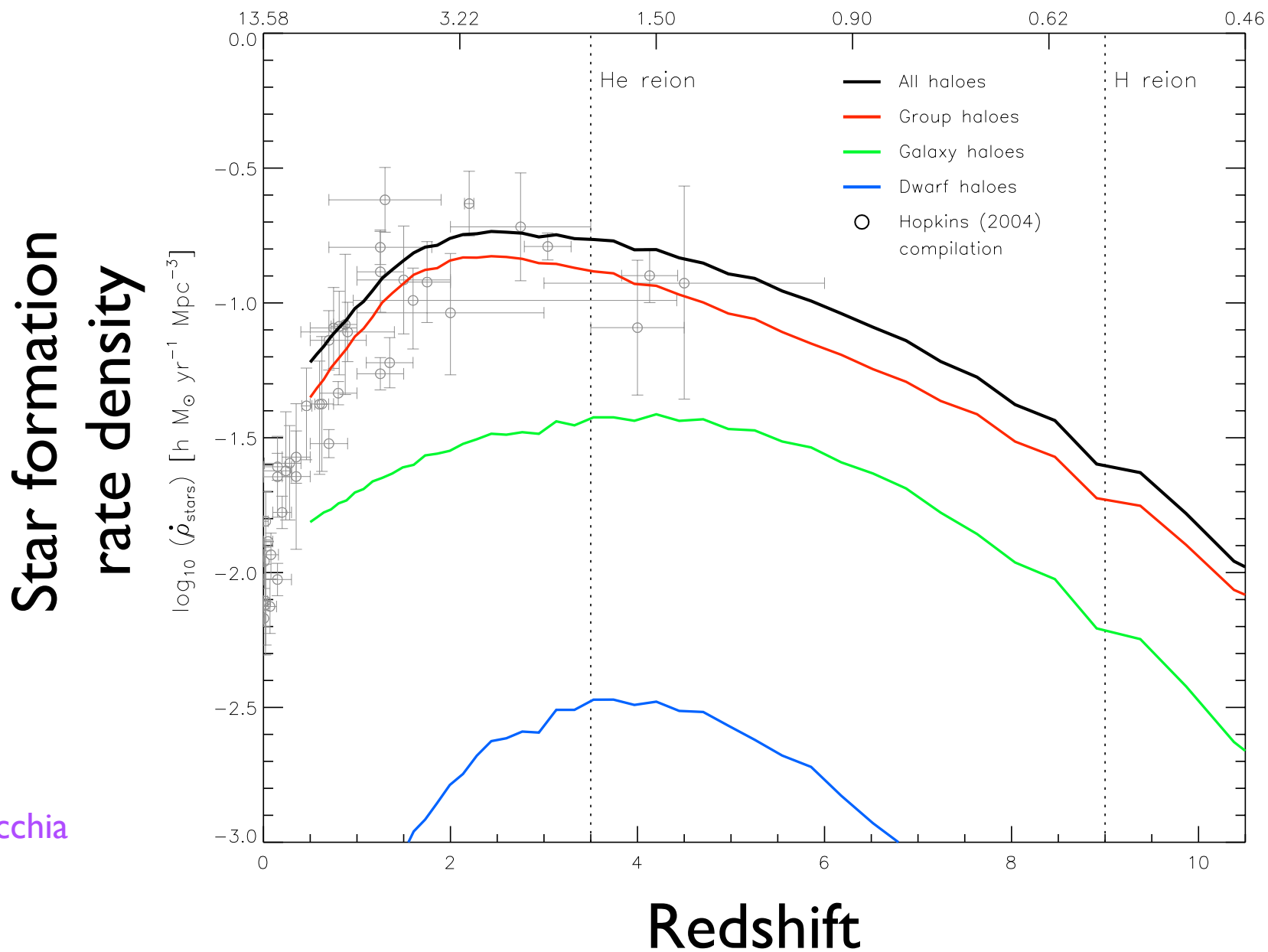
# Lyman-alpha forest:



Quasar spectra sample the matter distribution along the line of sight

# Simulating galaxies and the intergalactic medium

## Cosmic star formation history

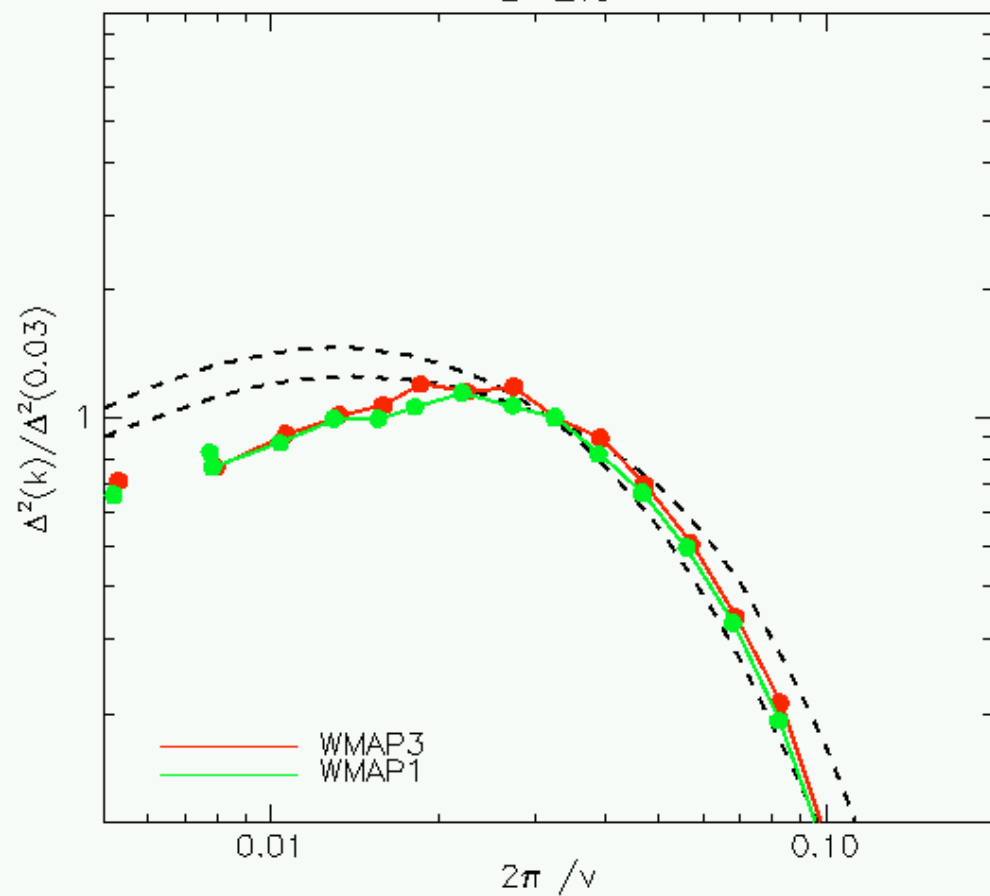


Schaye  
Dalla Vecchia  
Springel  
TT

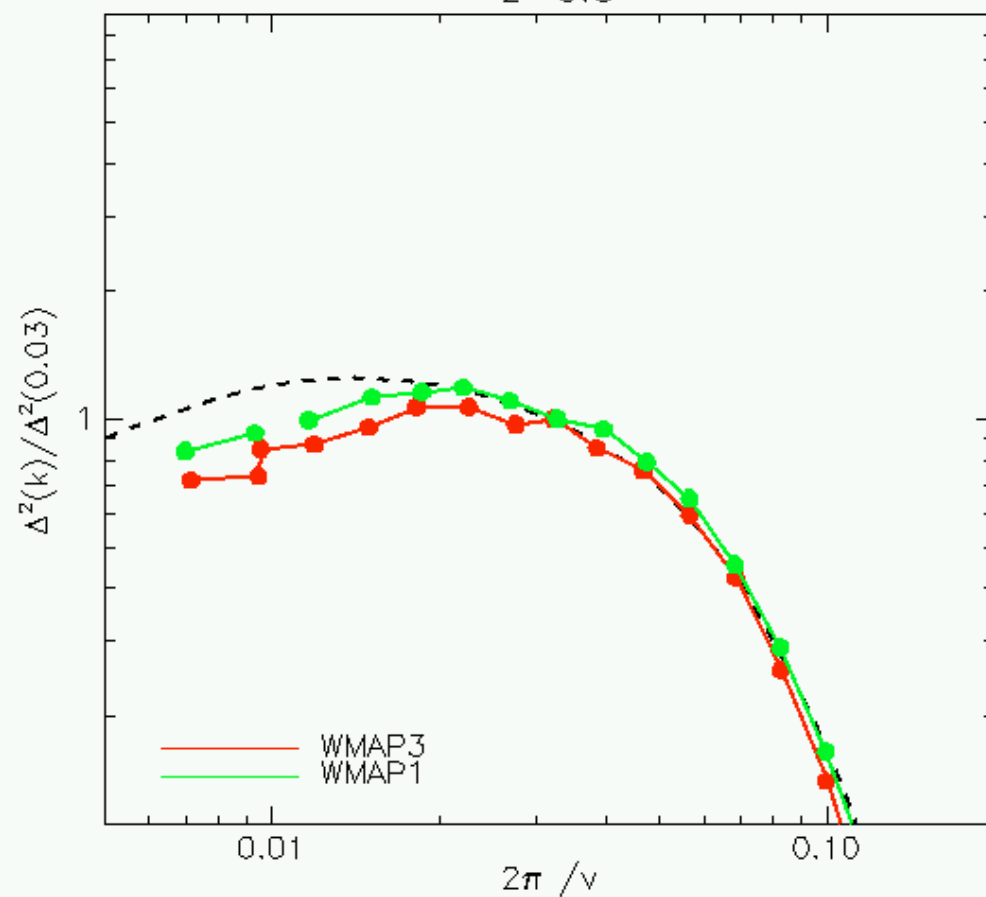
# Effect of cosmology:

WMAP3/WMAP1

$z=2.5$



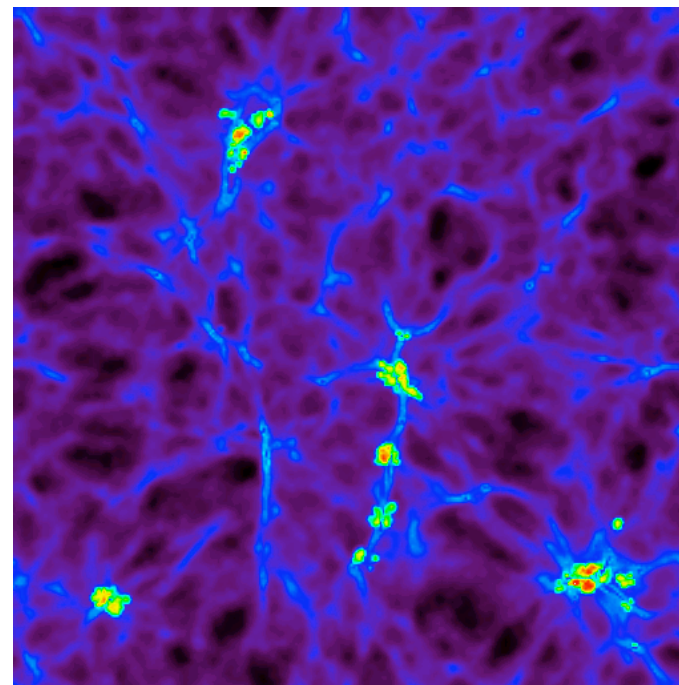
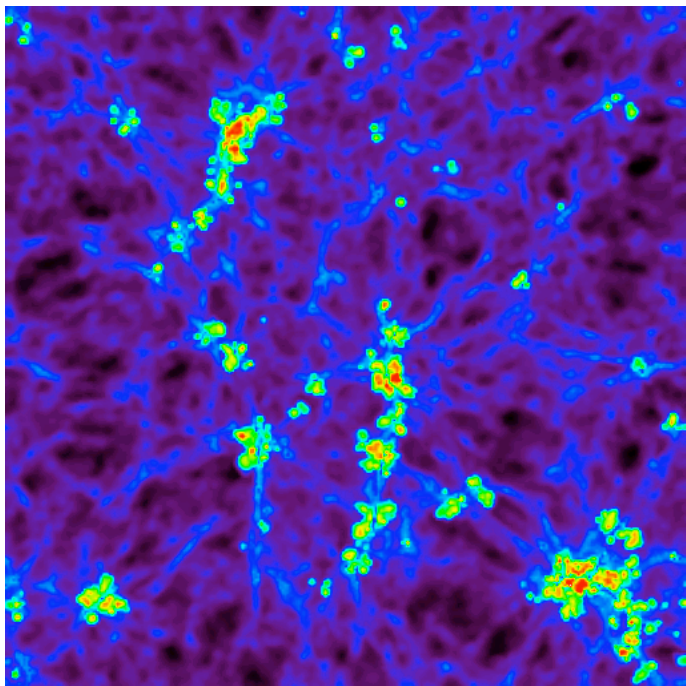
$z=3.5$



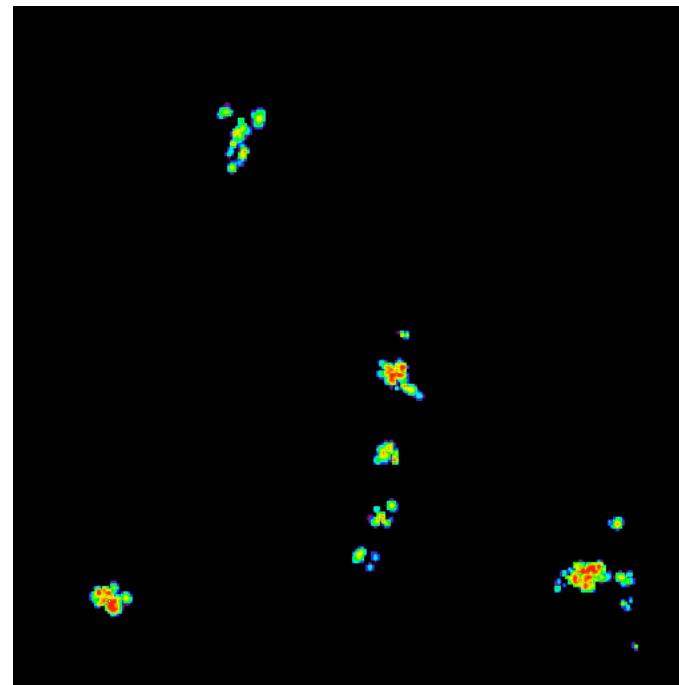
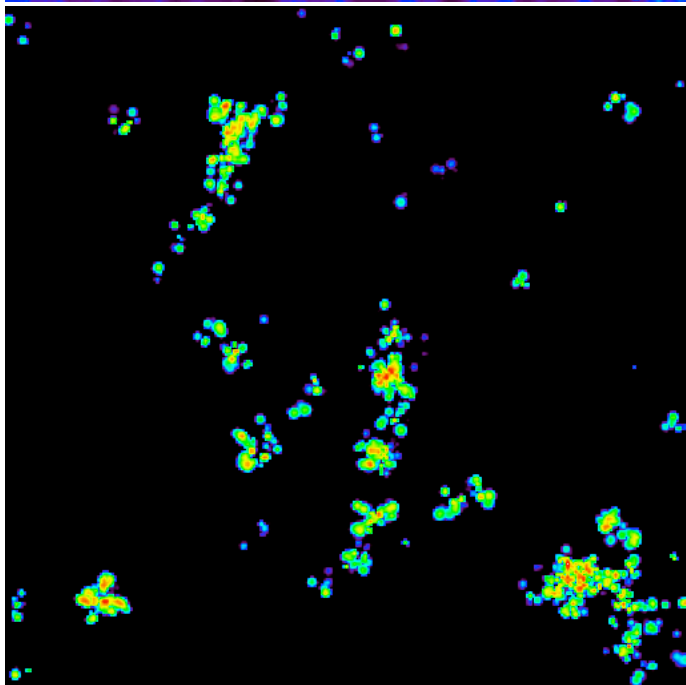
# Effect of dark matter type

7 keV

1 keV



temperature

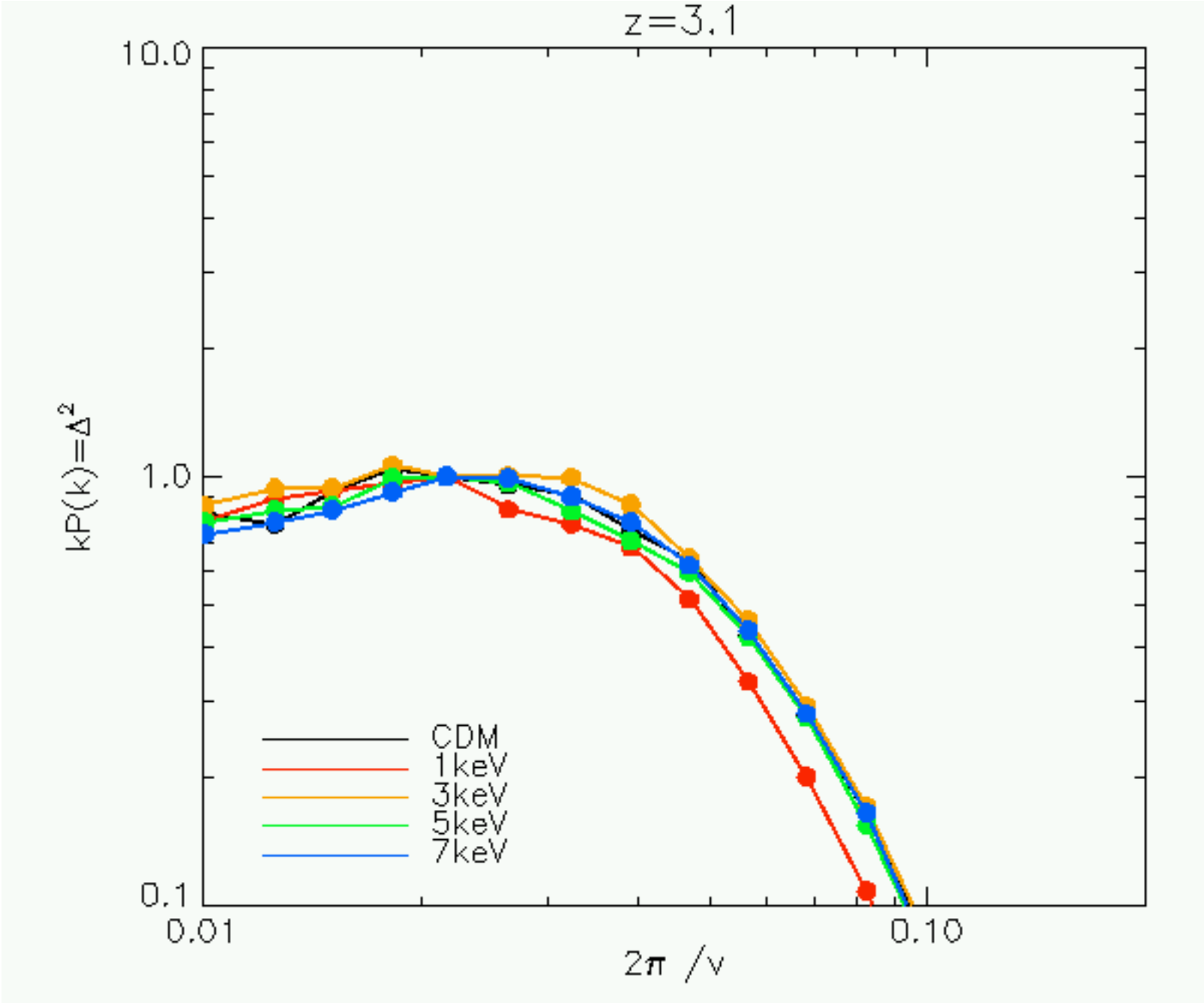


metallicity

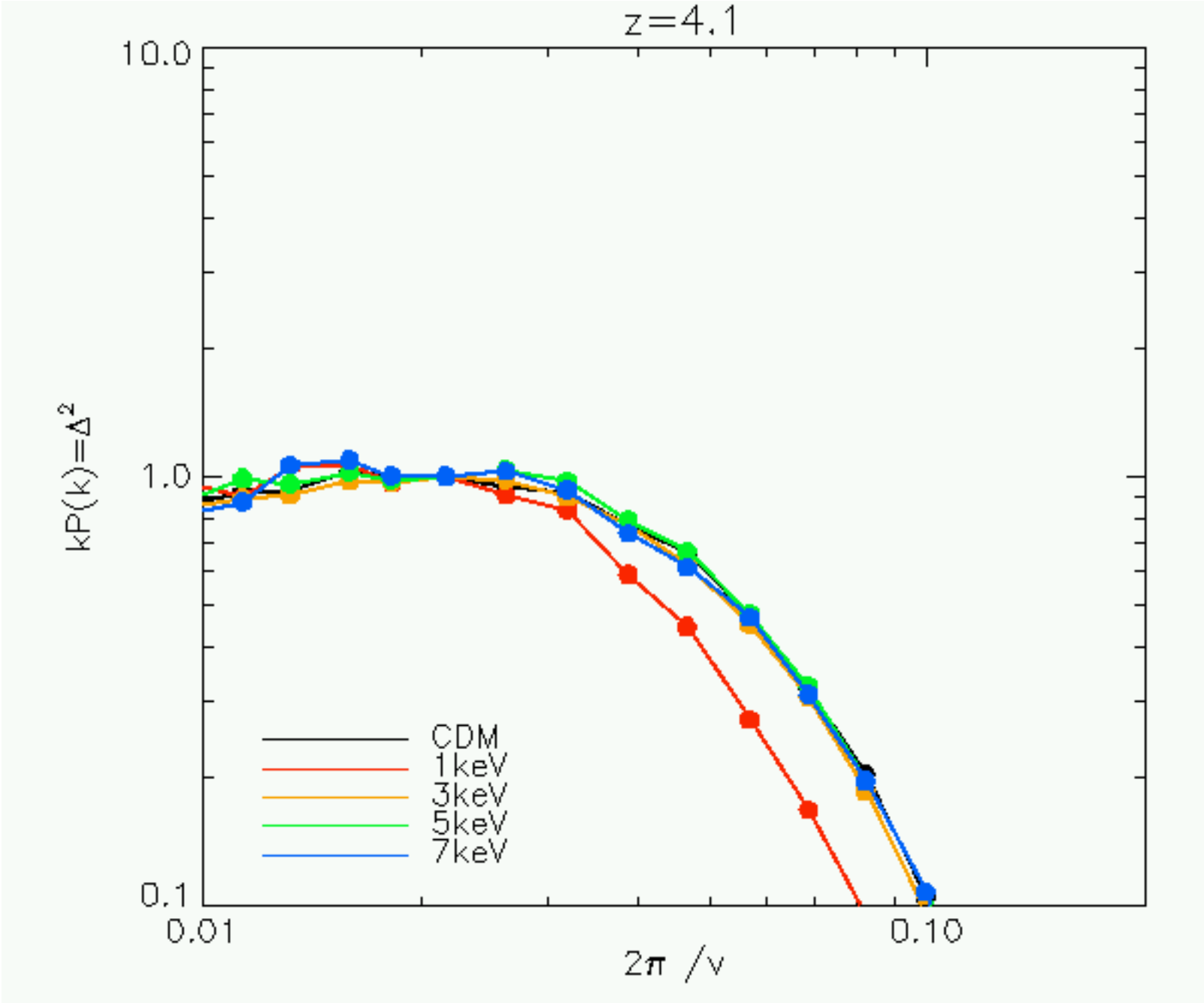
Redshift = 4

Tom Theuns

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



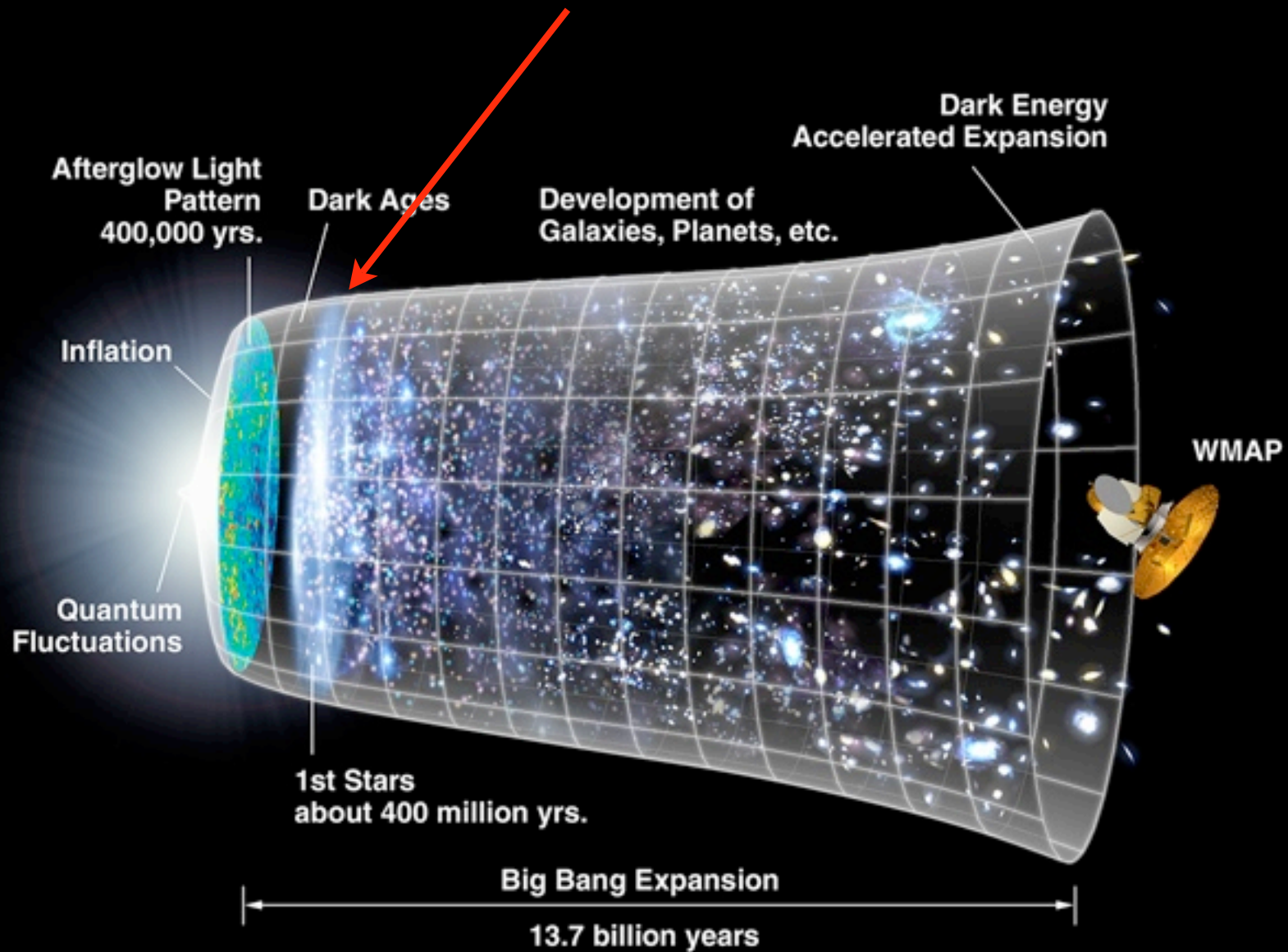
dark matter: 1keV / 3 keV / 5keV / 7keV / CDM



# Conclusion from Lyman-alpha forest:

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

# Formation of first stars:

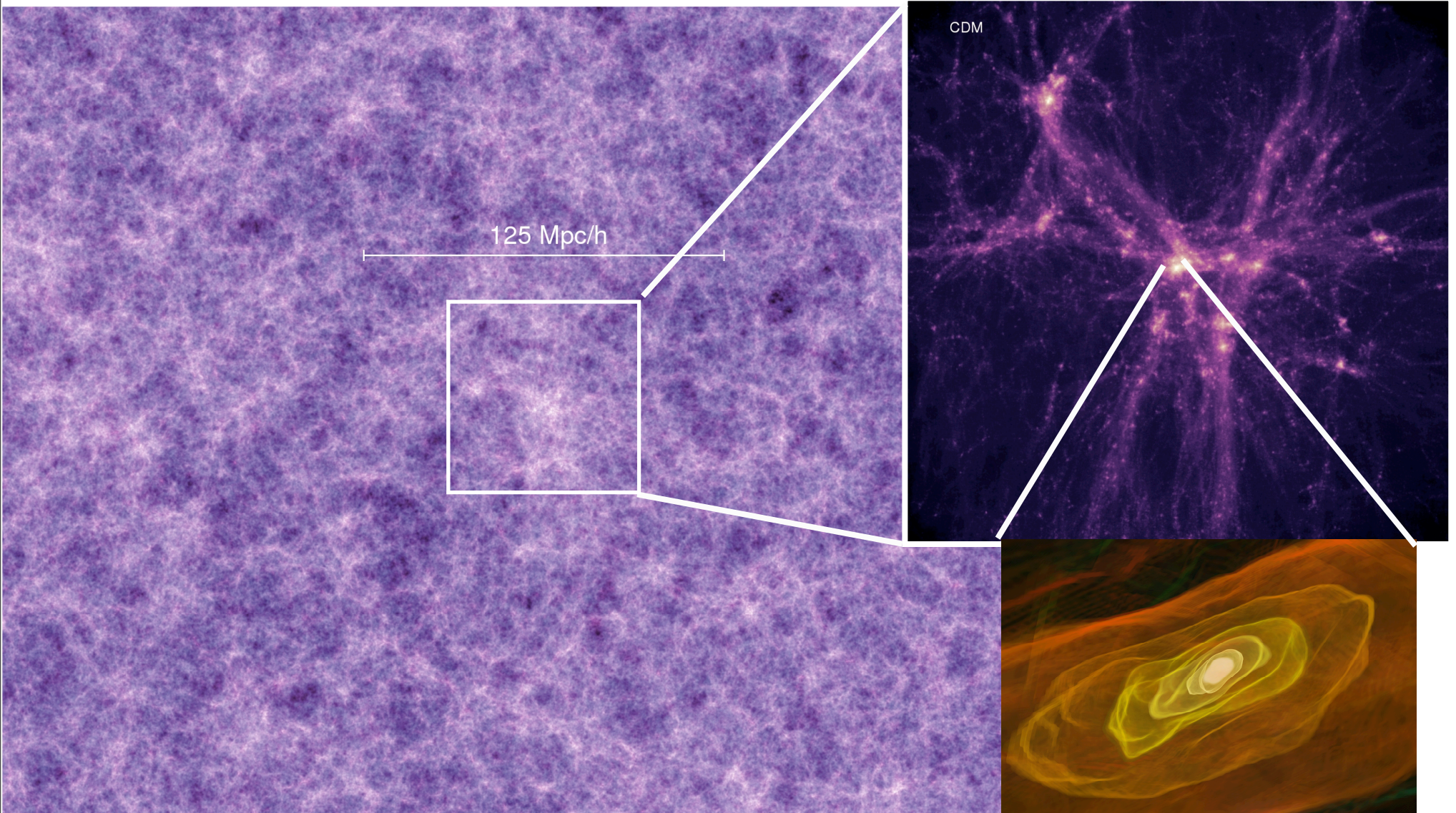


# Formation of first stars:

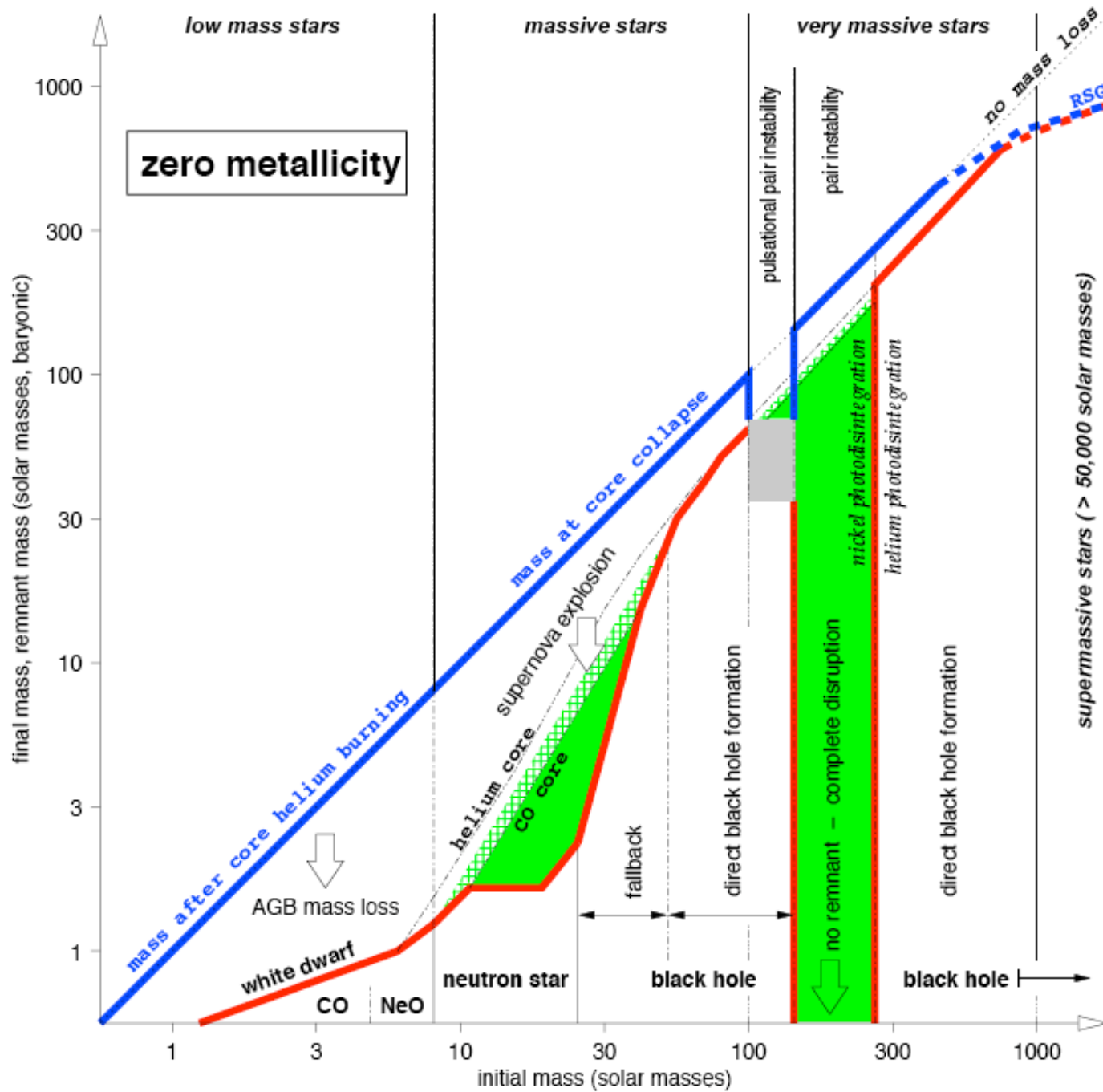
- haloes too cold for HI cooling ( $T < 10^4 \text{K}$ )
- cooling by molecular Hydrogen,  $\text{H}_2$
- $\text{H}_2$  formation requires high temperature ( $T > 8000 \text{K}$ )
- Cold dark matter halos at  $z > 15$

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

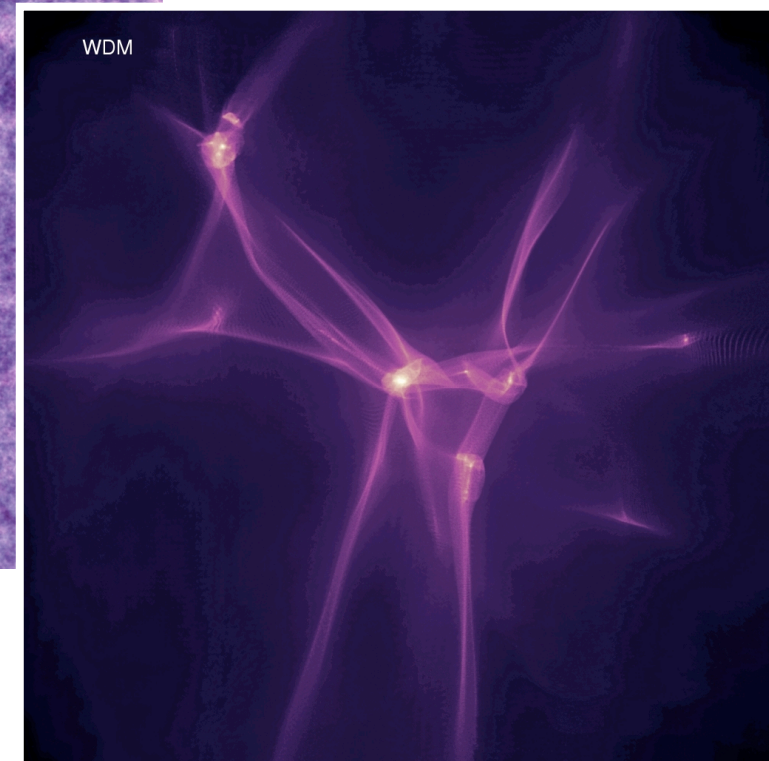
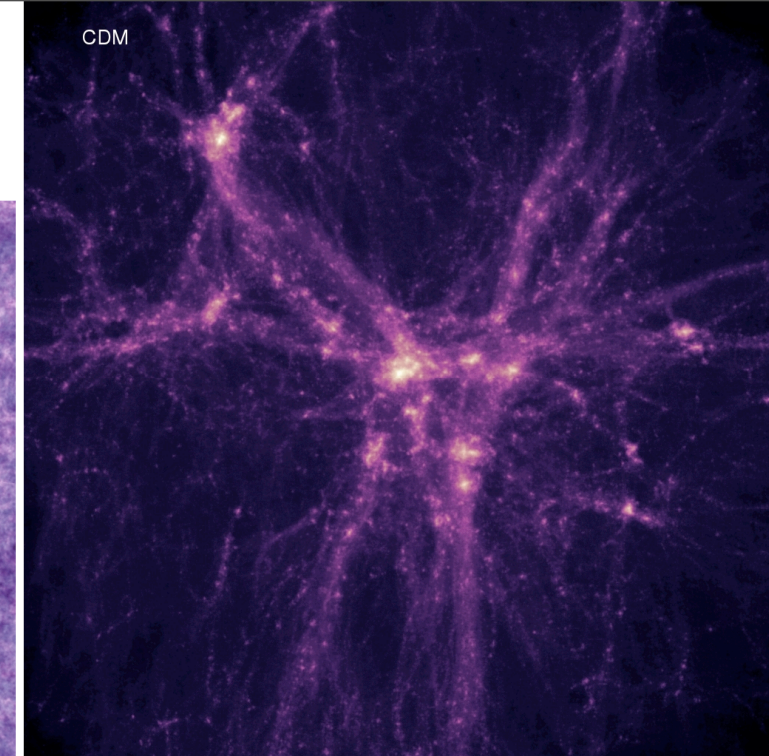
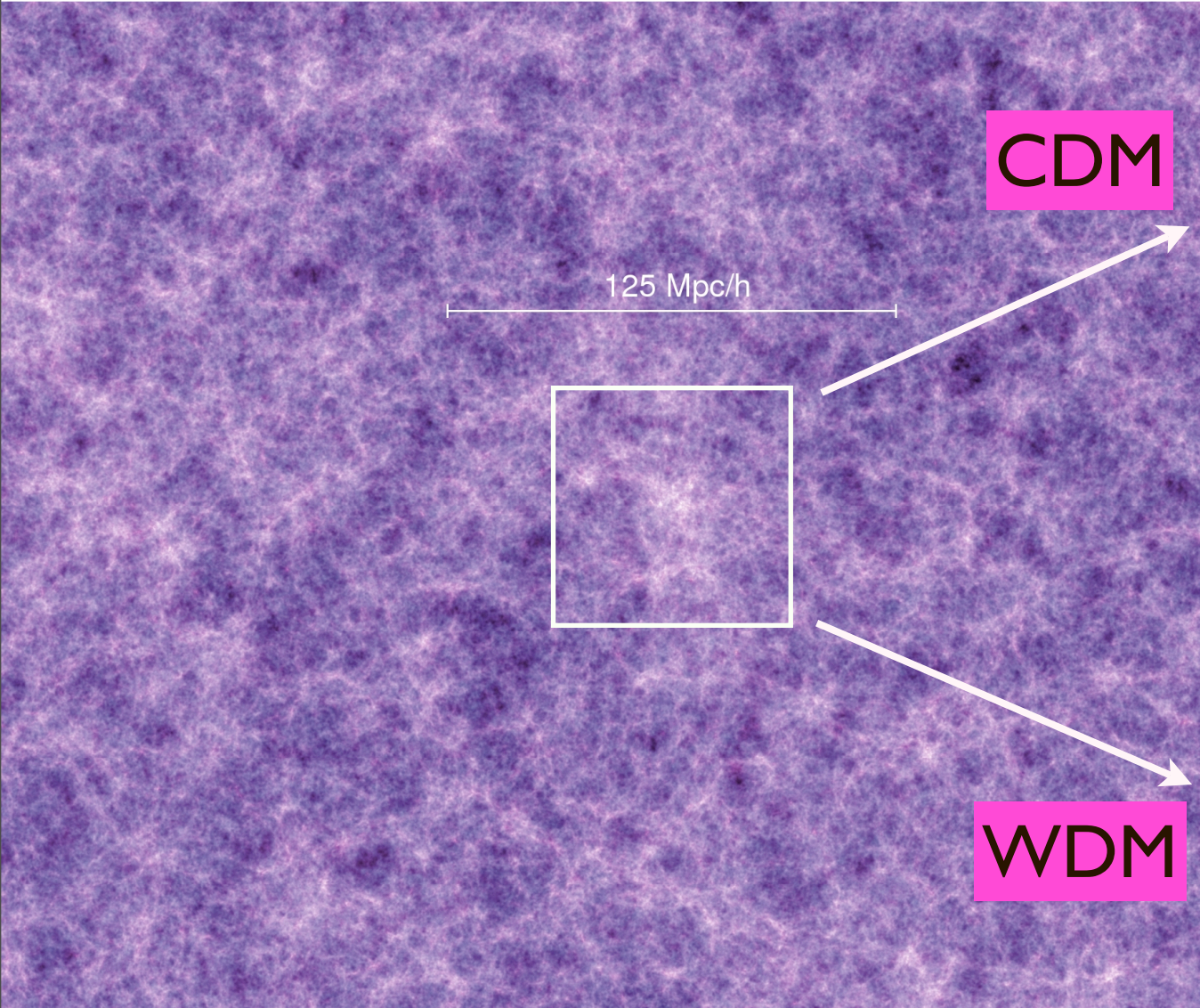
# Formation of first stars in CDM



Gao et al  
Abel et al

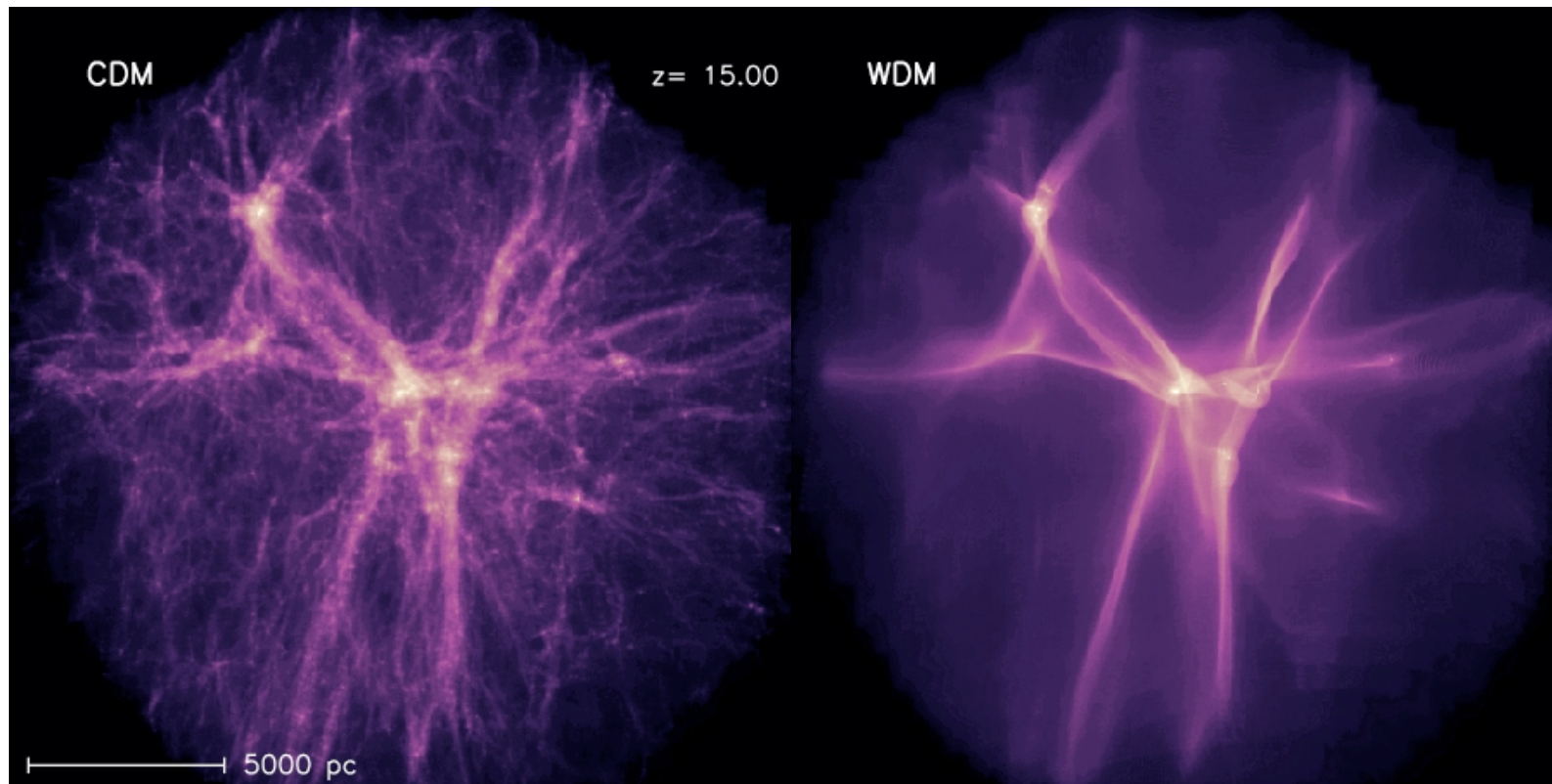


# CDM: some haloes massive enough for star formation



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

# Structure formation is suppressed below warm dark matter free streaming scale

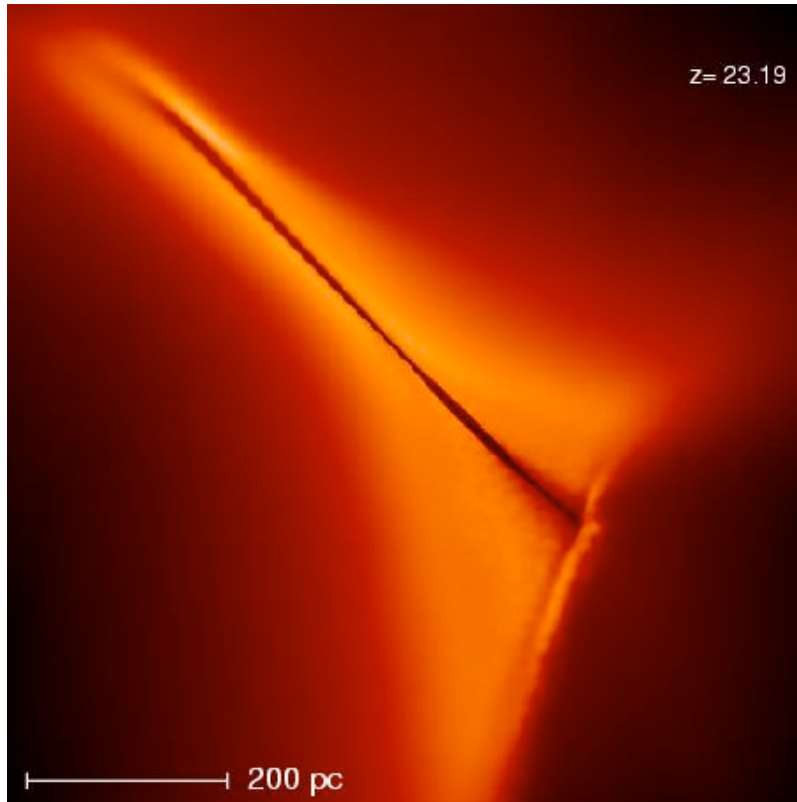


$M_{\text{dm}} = 3 \text{ keV}$ ,  $M_{\text{fs}} \sim 3 \times 10^8 \text{ solar masses}$

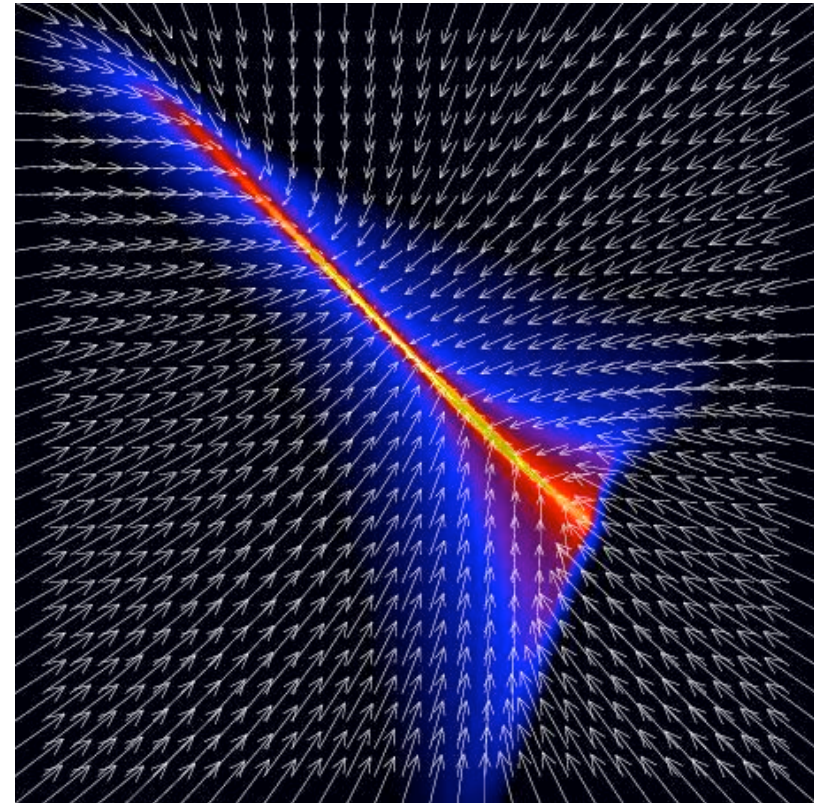
Time= 92.790 million years

—| 30 kpc

# First structure in WDM



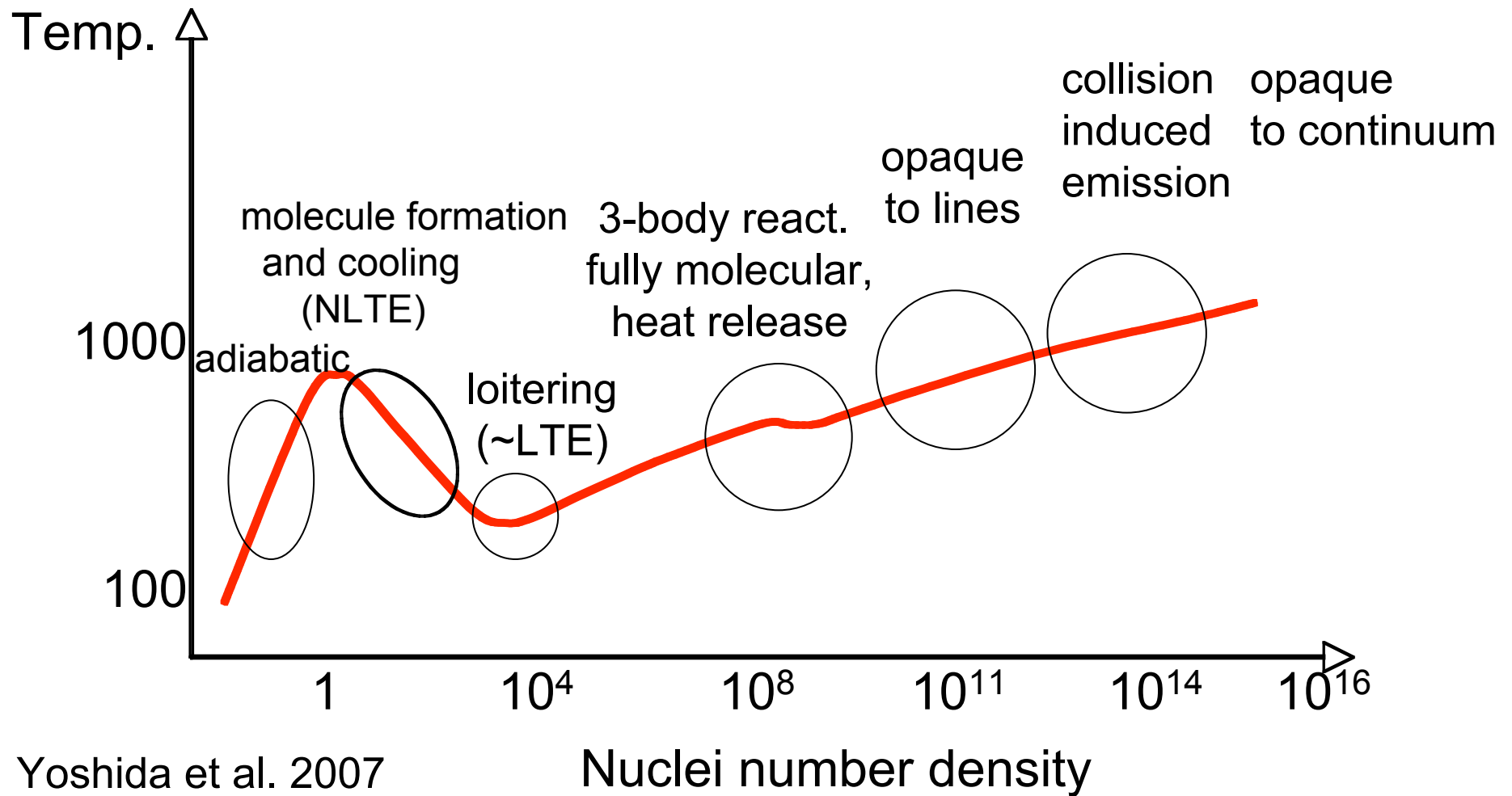
Temperature



Density

$M_{\text{dm}} = 3 \text{ keV}, M_{\text{fs}} \sim 3 \times 10^8 \text{ solar masses}$

# Stability of filament is determined by H<sub>2</sub> physics



# Application to a primordial filament: I

## When does filament fragment?

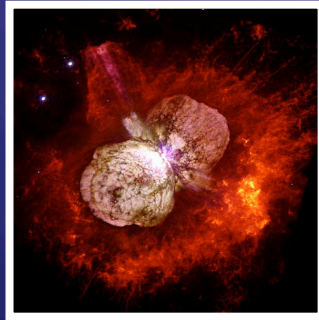
Two density scales where collapse of filament slows and fragmentation can occur:

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

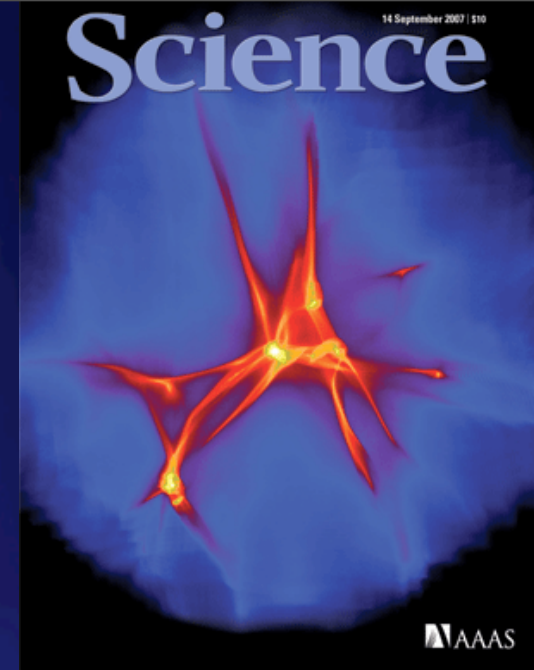
# Application to a primordial filament: II

## What induces fragmentation?

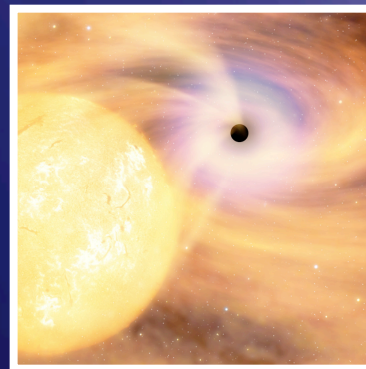
- No small-scale power!
- Tidal field induces fragmentation
- Huge star burst, stars with range of mass  $<1$  to  $> 100$  solar masses



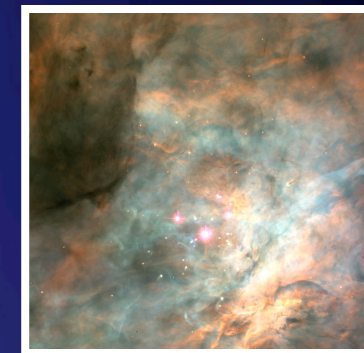
Massive stars



Gao & Theuns  
Science 2007



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

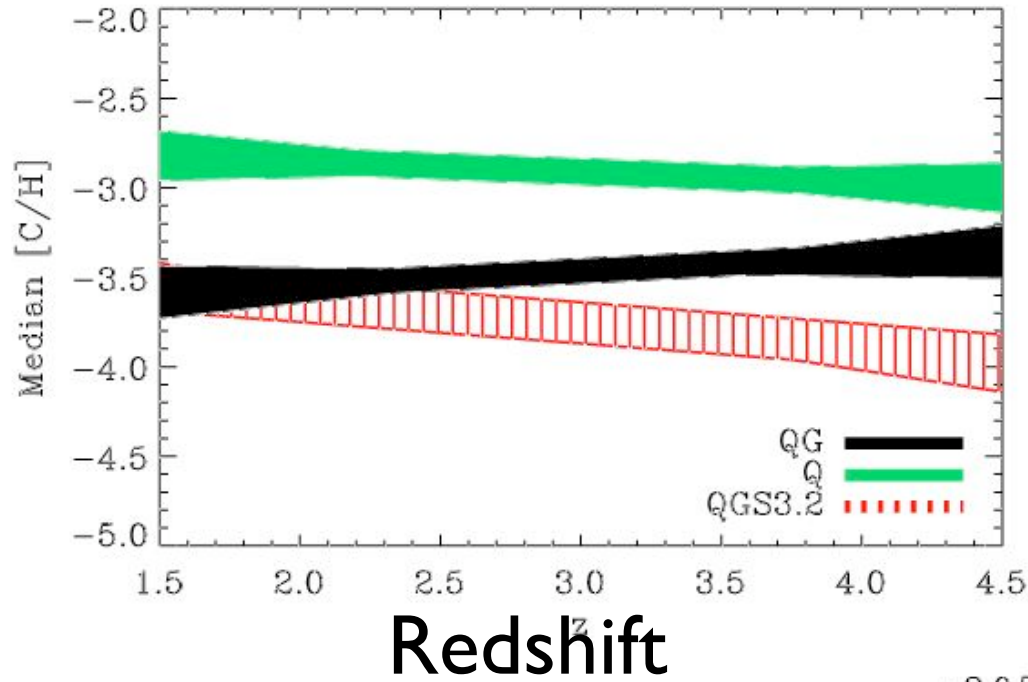
Thoughts:

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

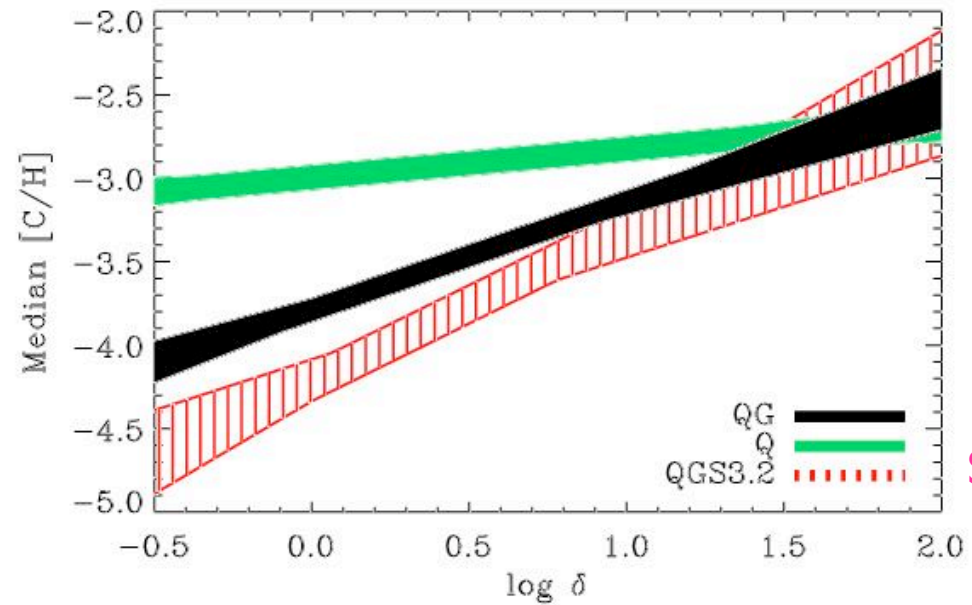
Freese et al

Thank you!

# Delta = 3



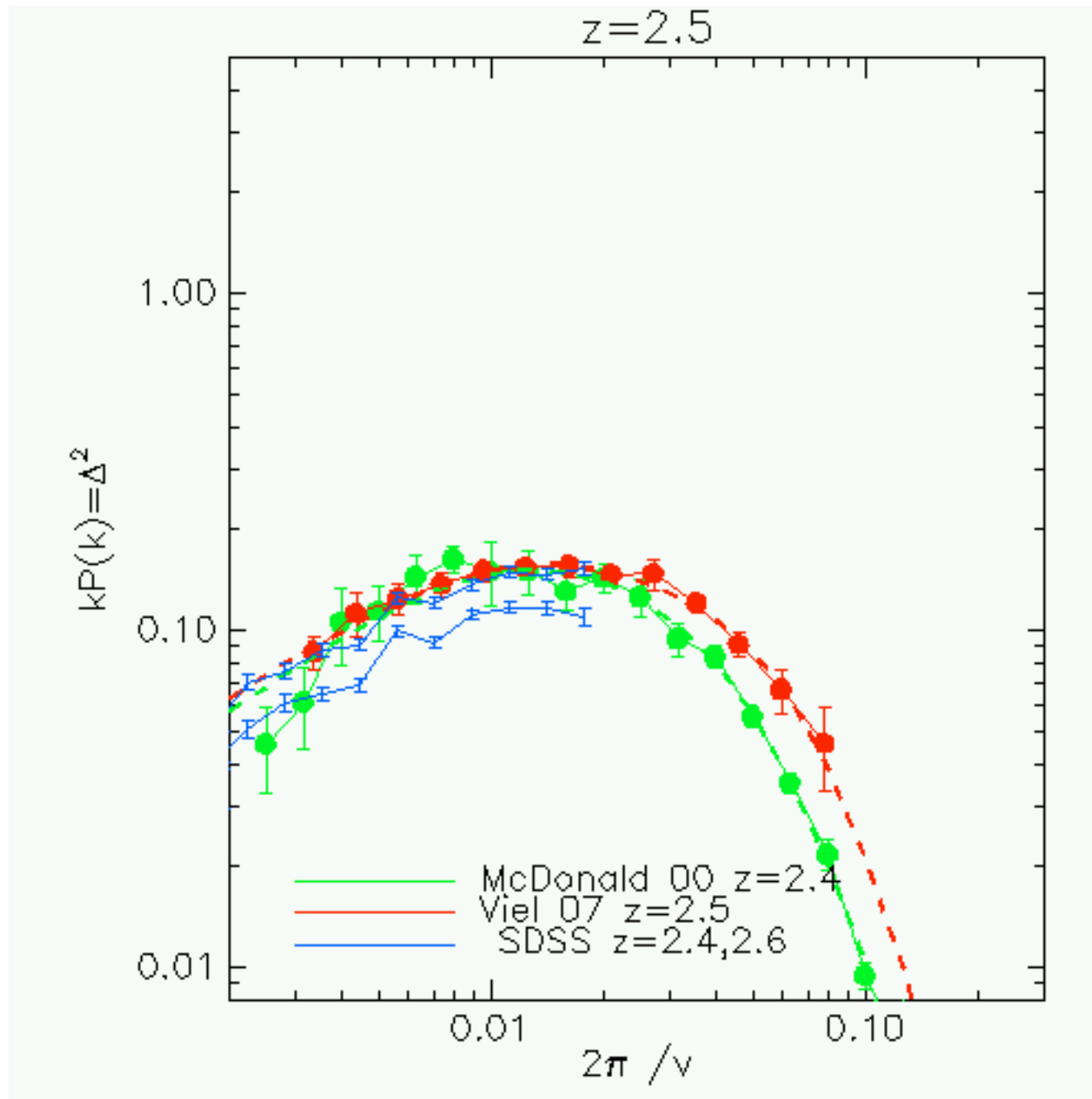
# z=3



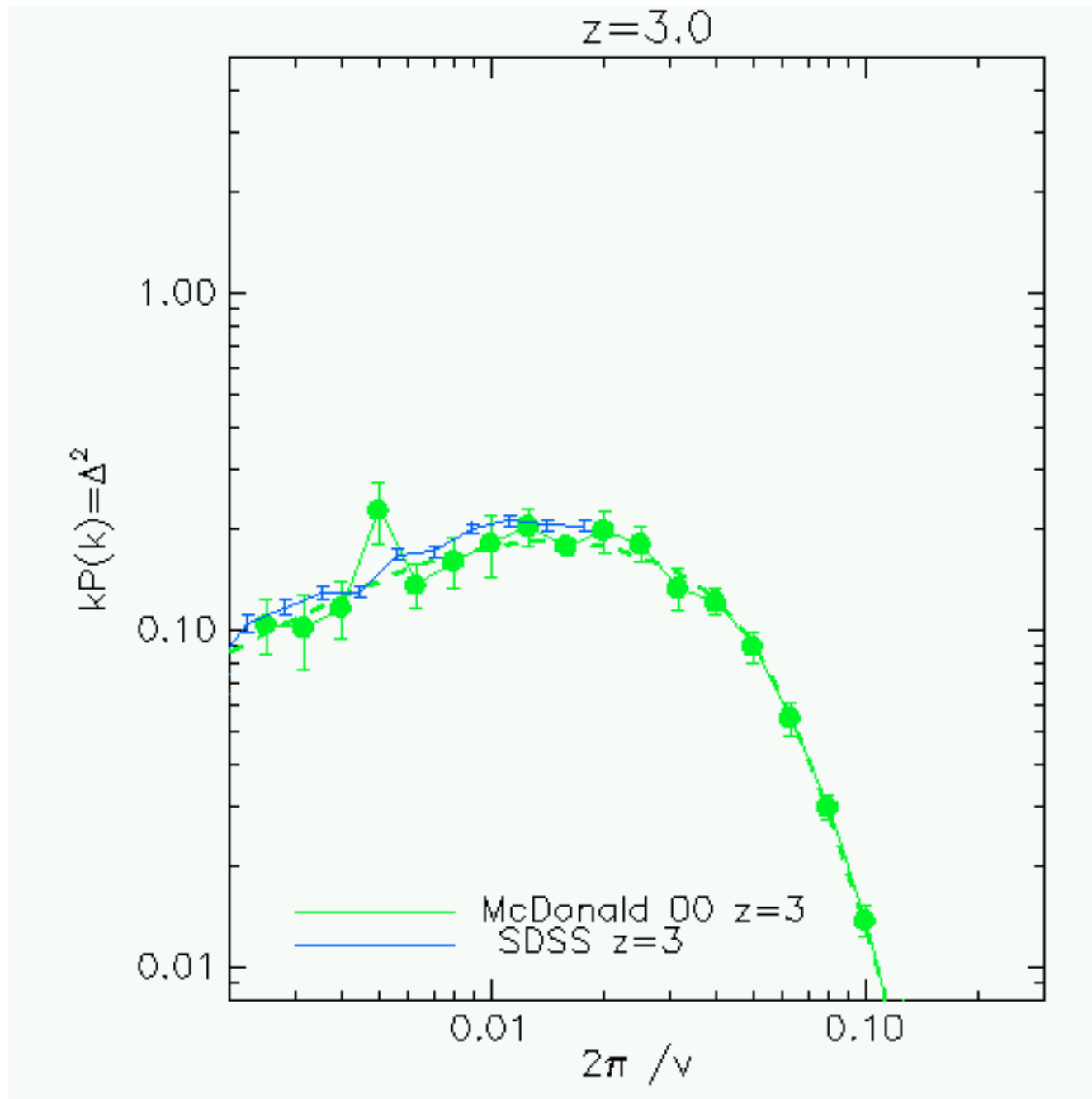
# Density



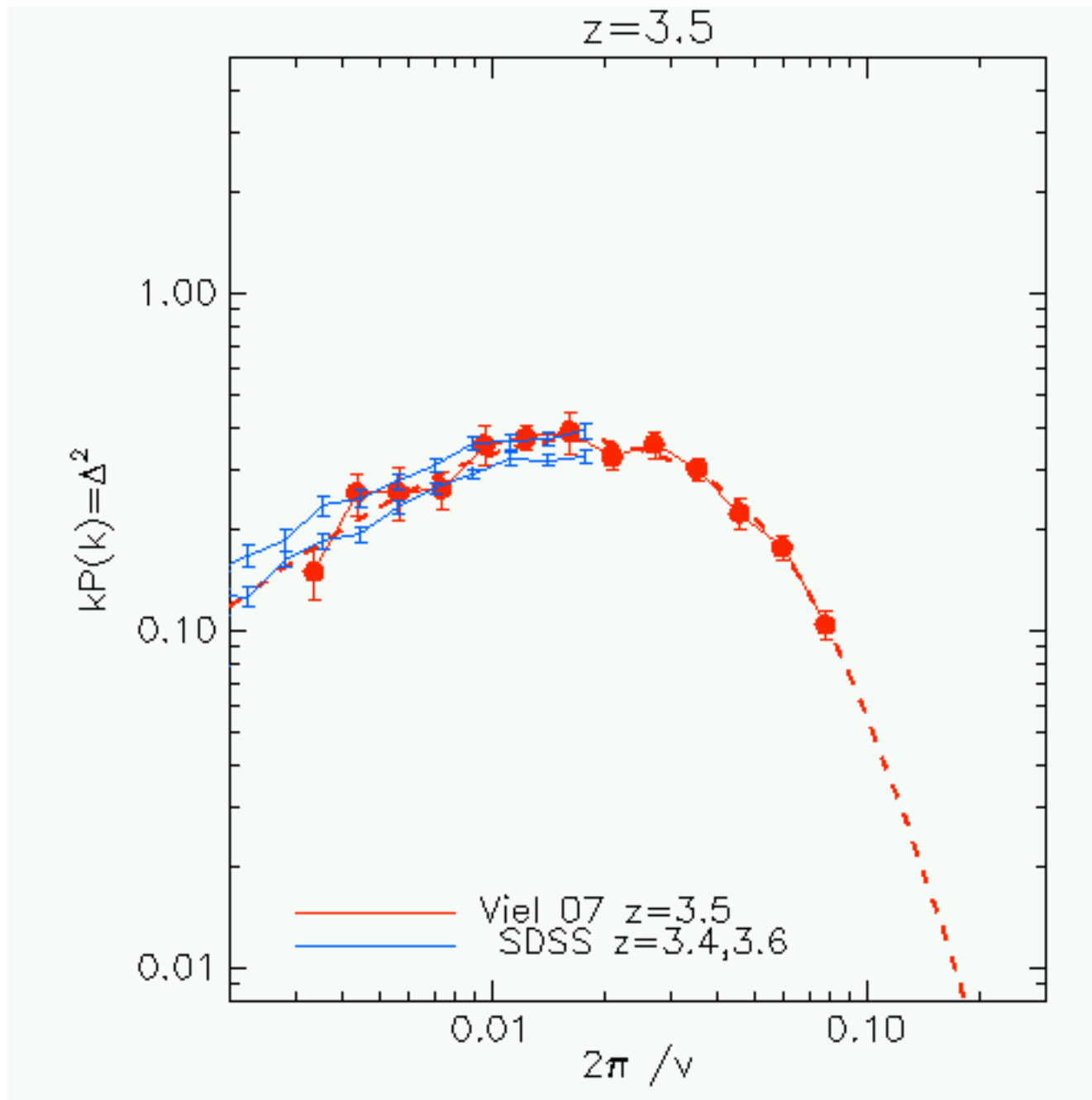
# Observations: Mcdonald HiRes / Viel / Mc Donald SDSS



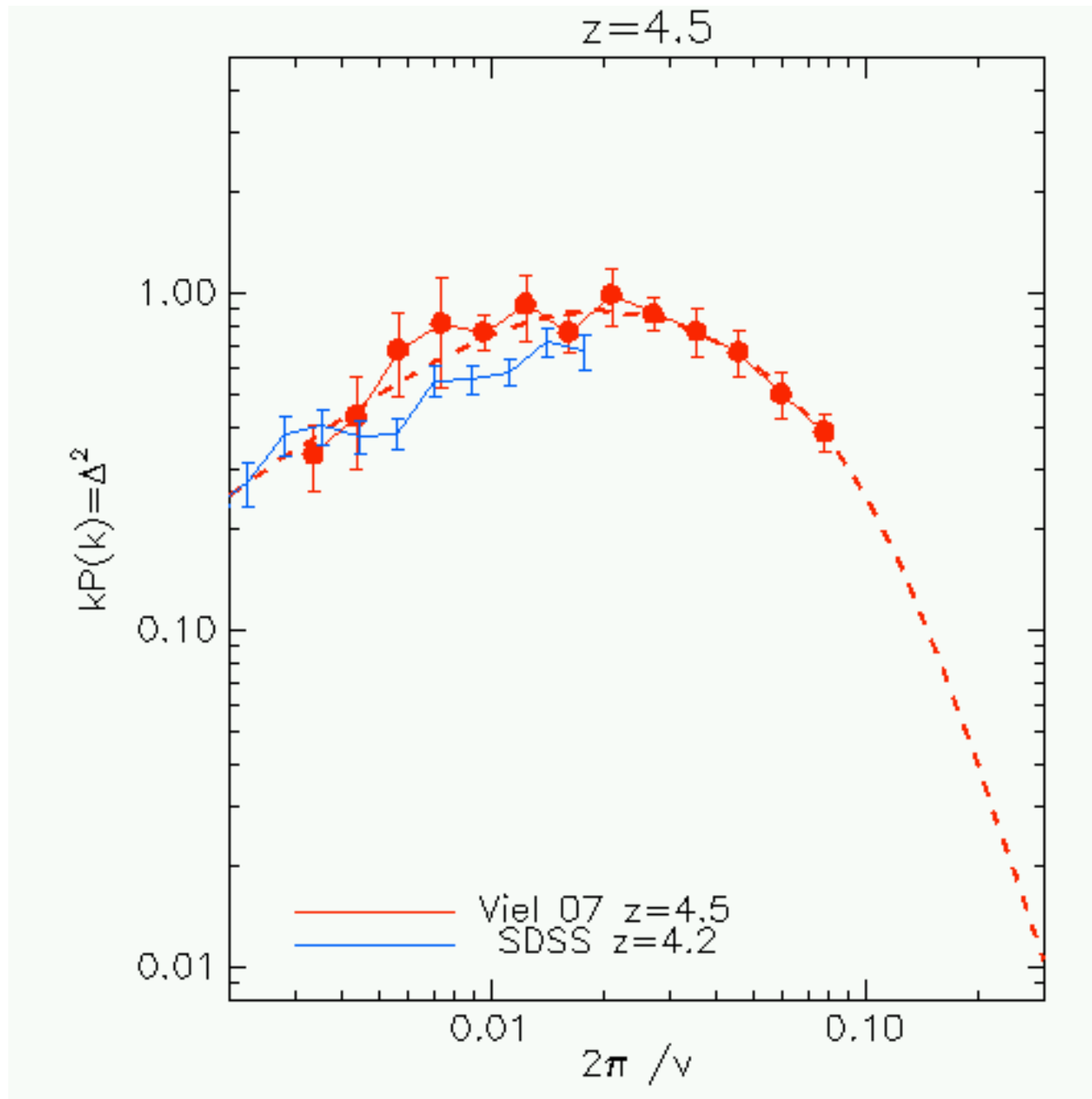
# Observations: Mcdonald HiRes / Viel / Mc Donald SDSS



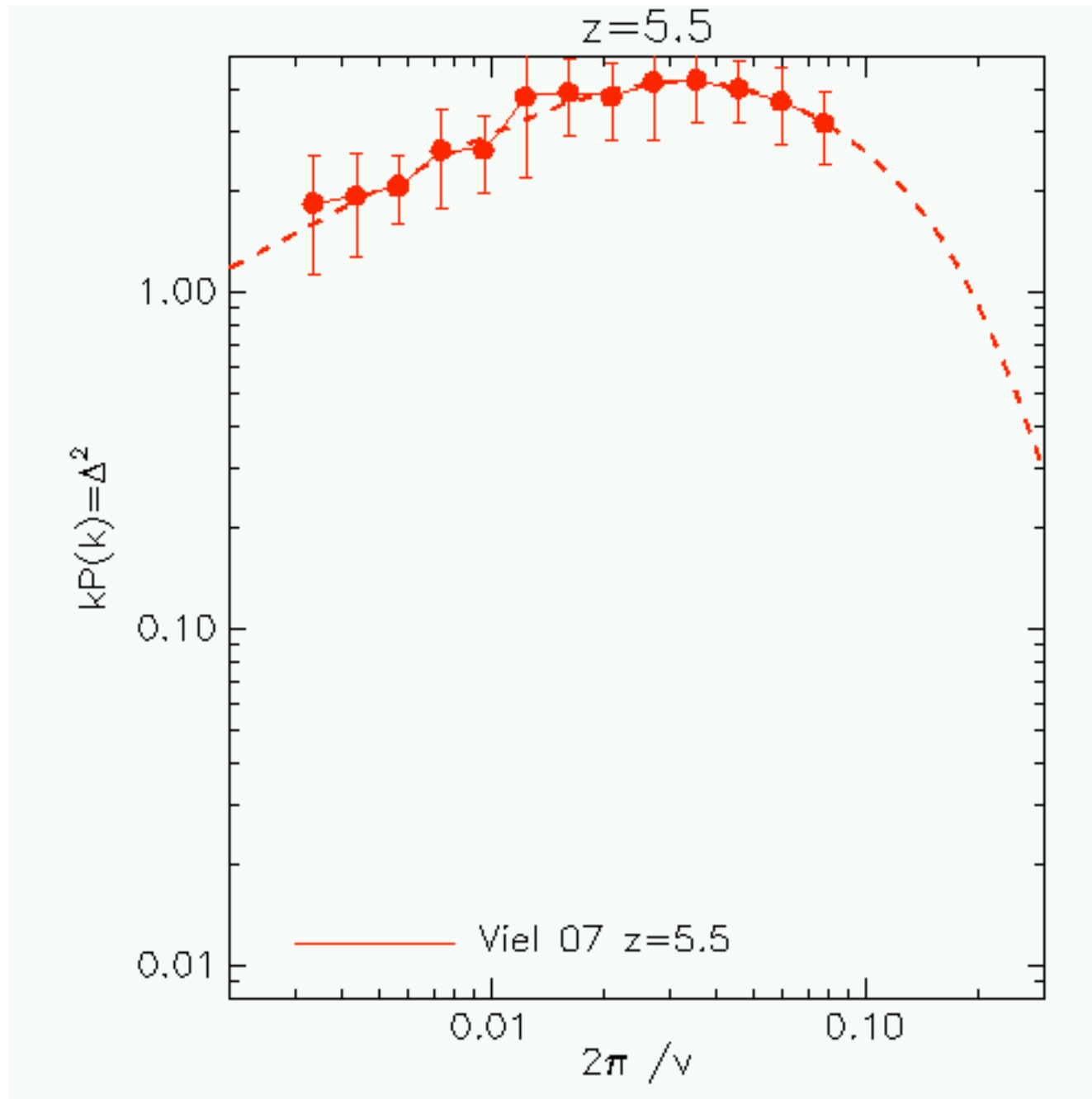
# Observations: Mcdonald HiRes / Viel / Mc Donald SDSS



# Observations: Mcdonald HiRes / Viel / Mc Donald SDSS



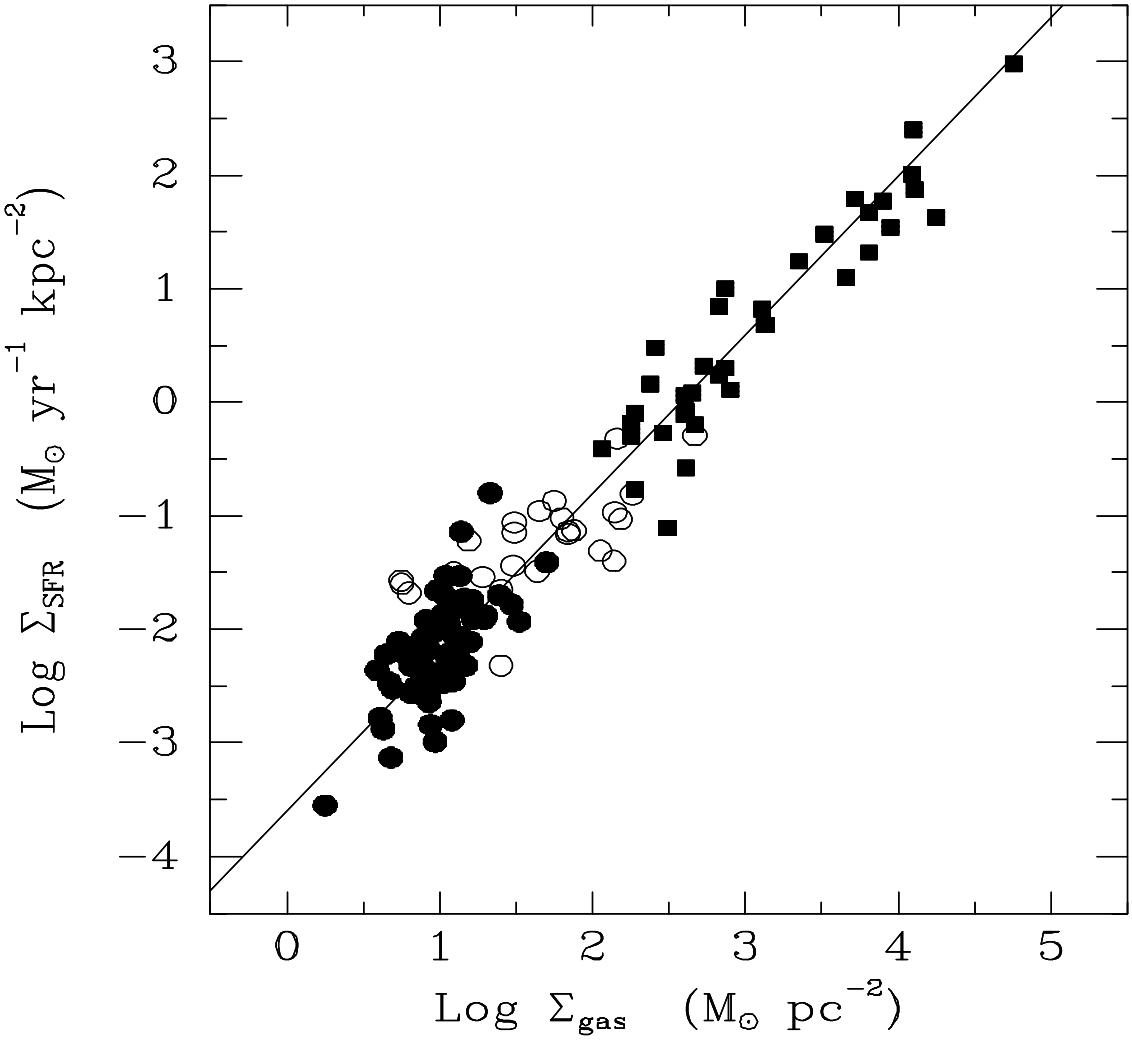
# Observations: Mcdonald HiRes / Viel / McDonald SDSS



# Observed star formation:

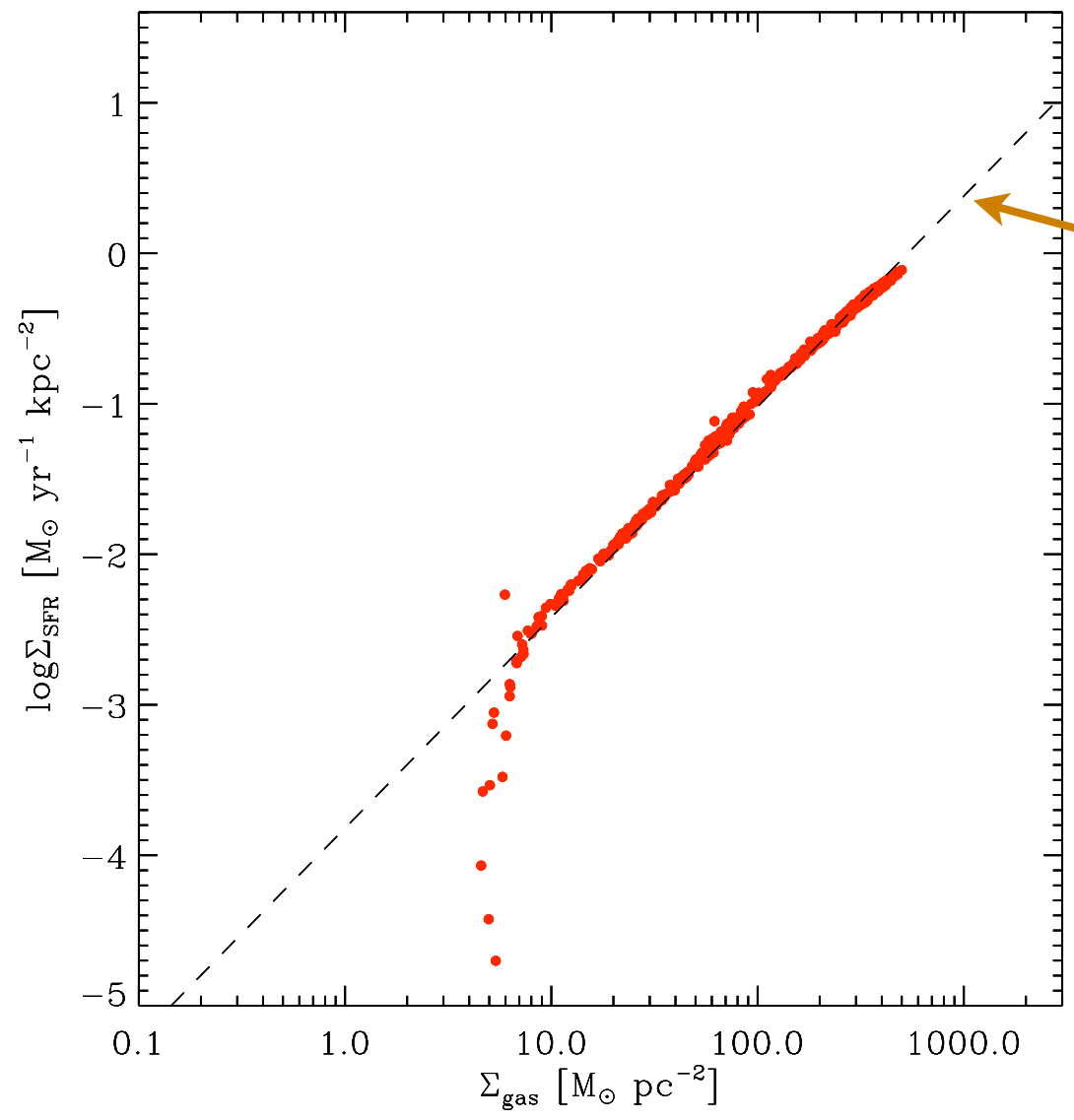
# Schmidt law

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



(Kennicutt 1989)

# Simulated star formation:

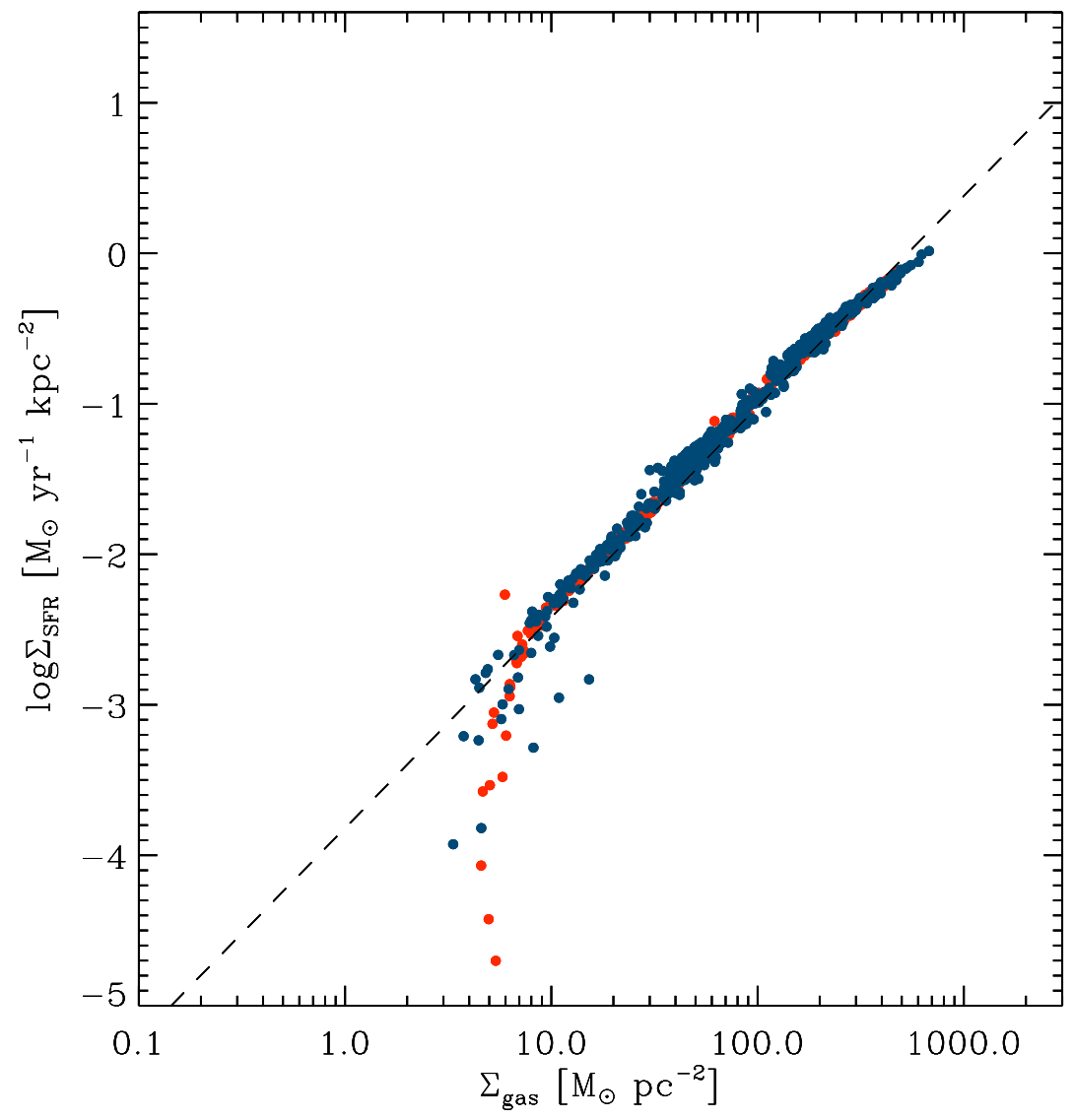


this is not a fit

●  $N_{\text{part}} = 100$

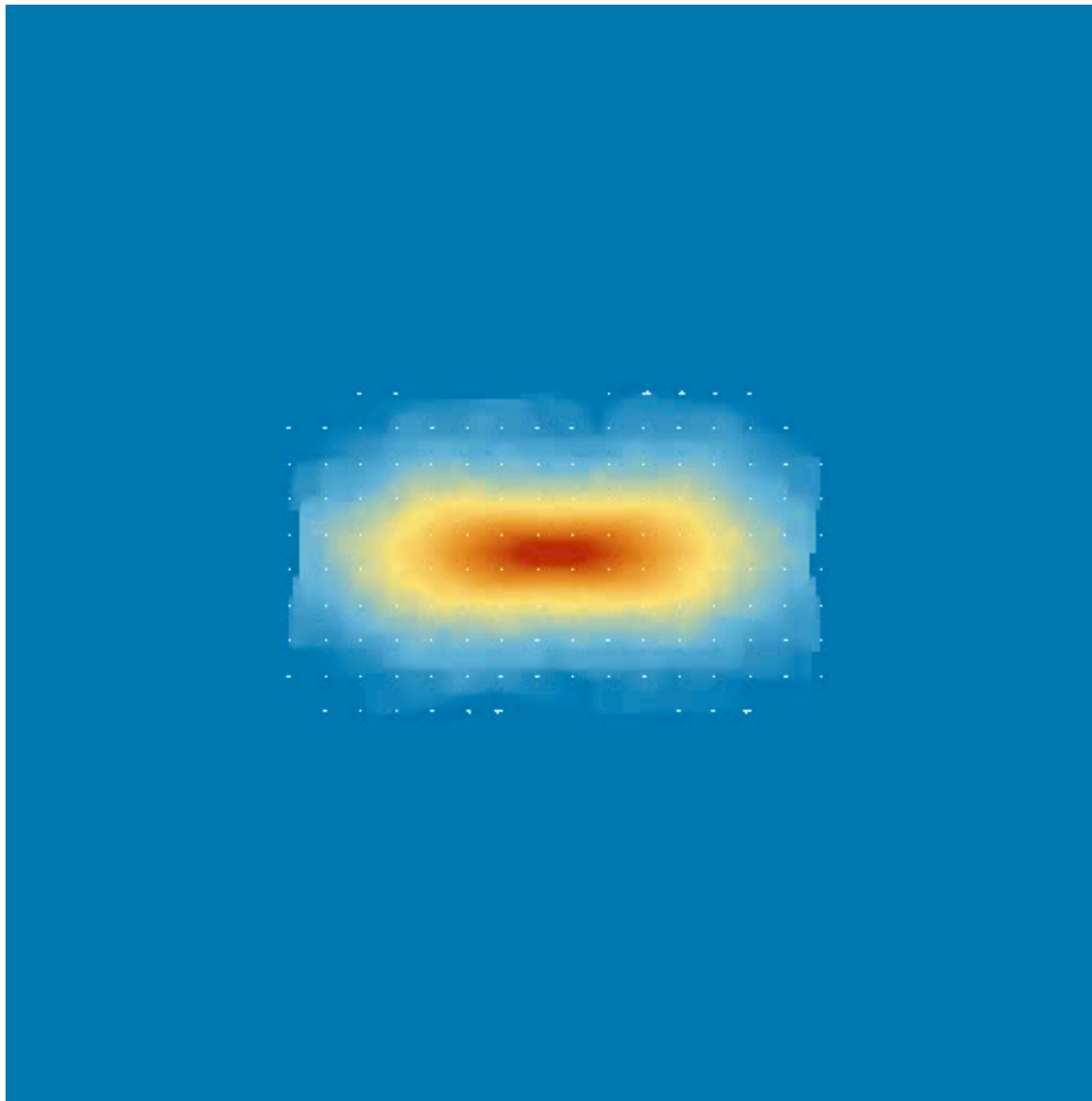
# Simulated star formation:

“resolution independent”



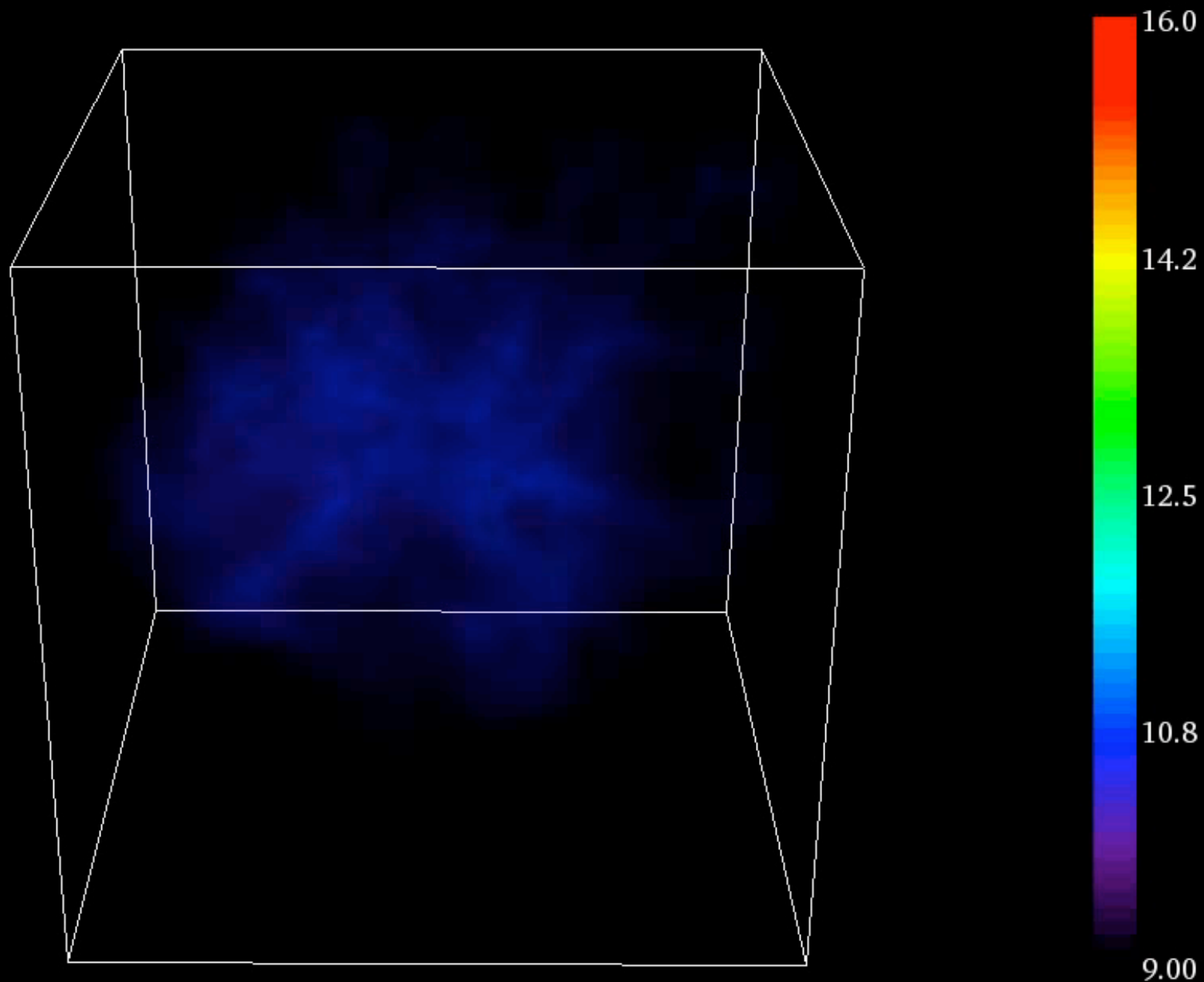
●  $N_{\text{part}} = 100$

●  $N_{\text{part}} = 12$



# Dwarf galaxy with GIMIC/OWLS code

$\log(\text{Gas density})$  in  $[\text{Msun}/h / (\text{Mpc}/h)^3]$

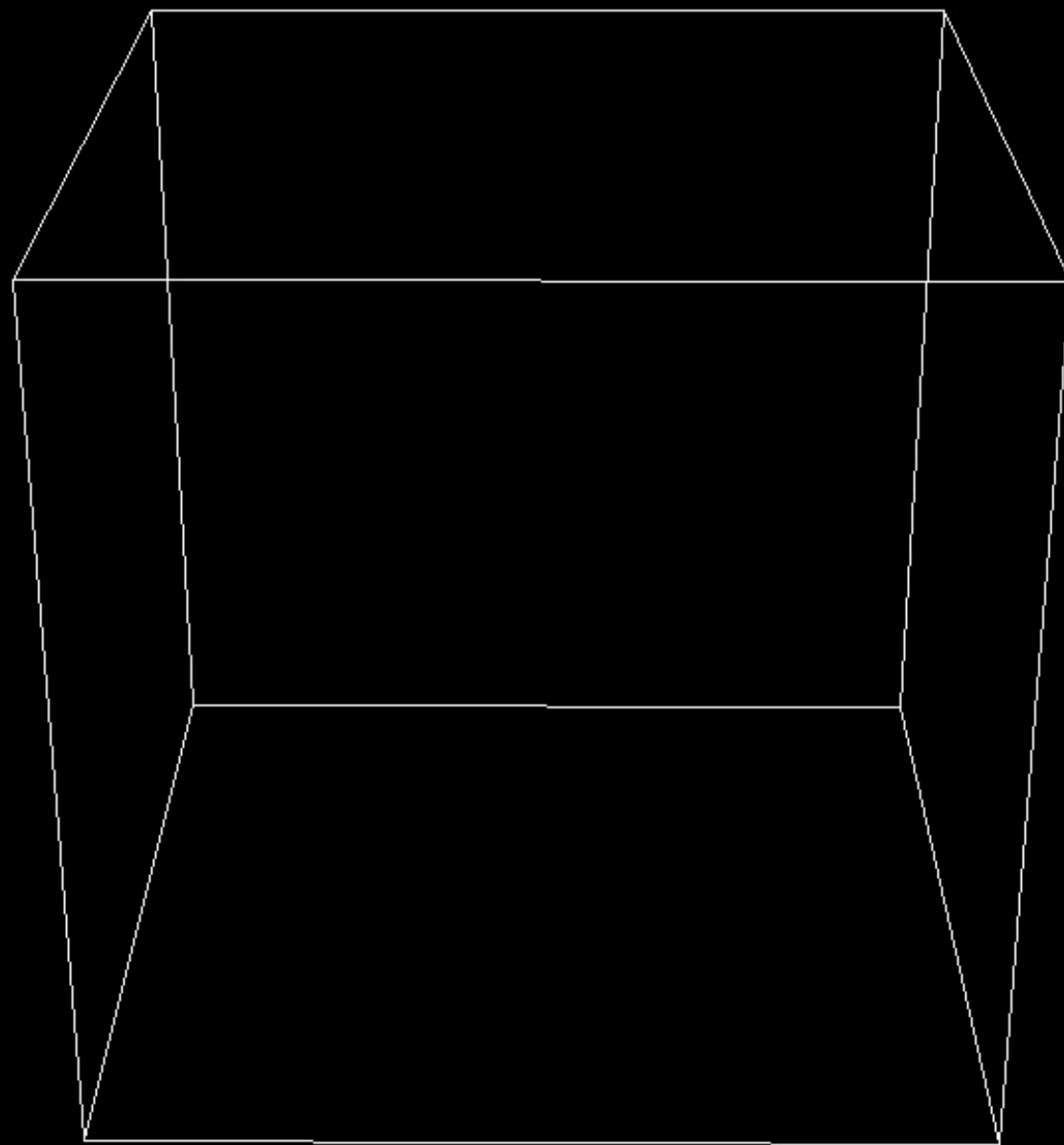


$z = 29.888$

$L = 0.999 \text{ Mpc}/h$

# Dwarf galaxy with GIMIC/OWLS code

$\log(Z)$



$z = 29.888$

$L = 0.999 \text{ Mpc}/h$

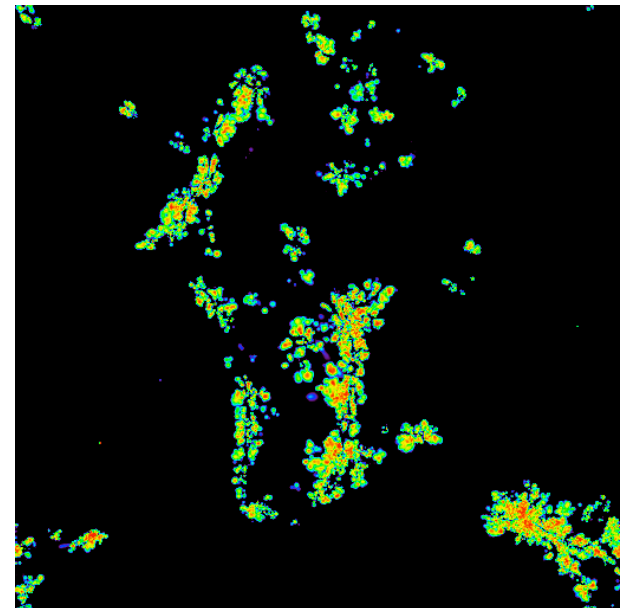
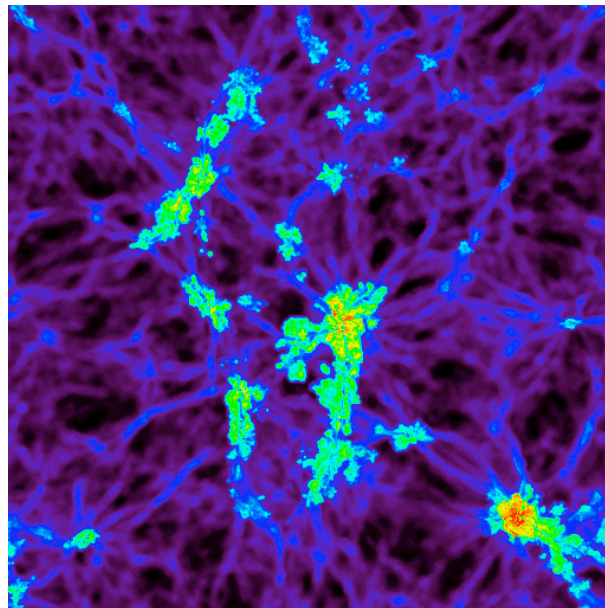
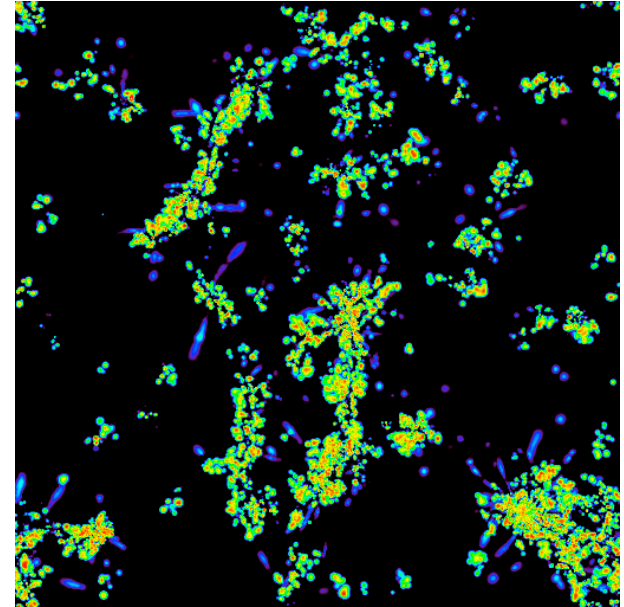
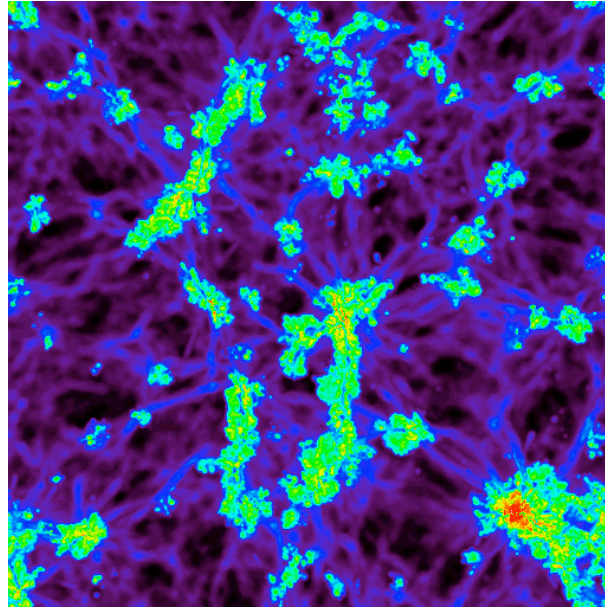
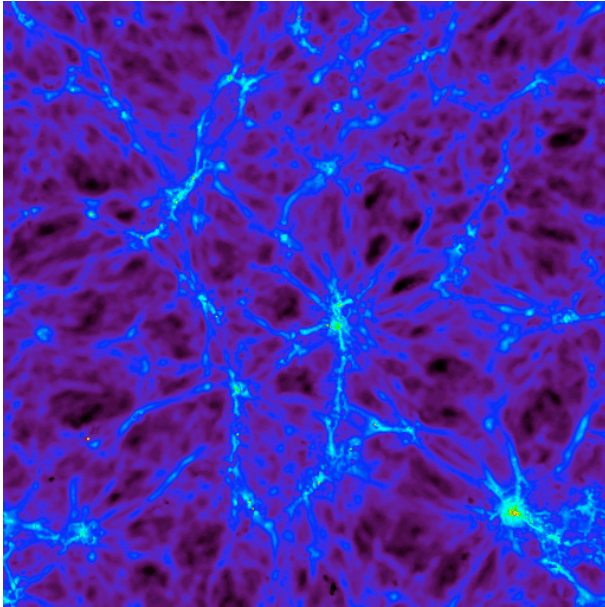
## Suite of simulations varying:

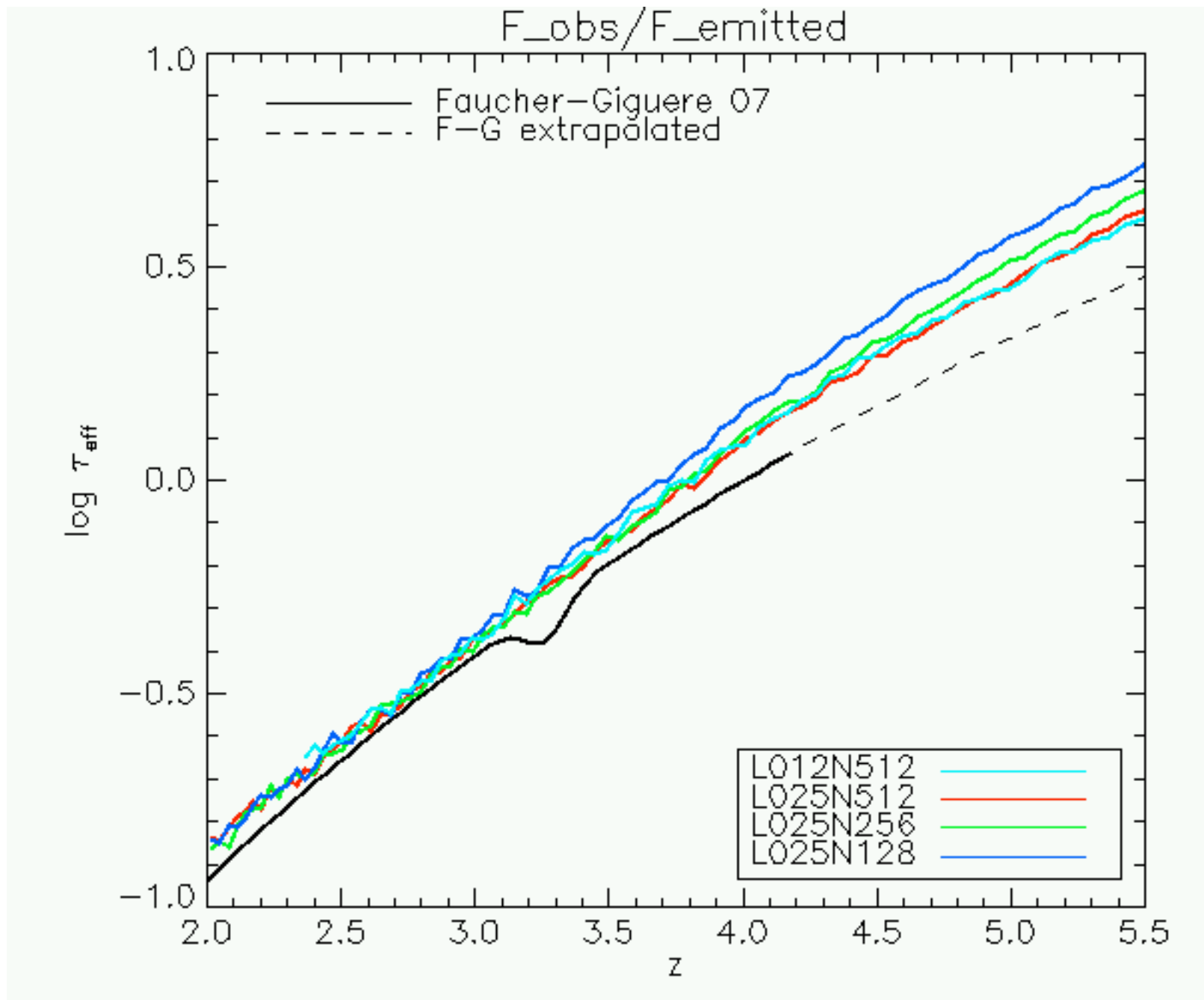
- Star formation parameters
- Wind implementation
- Resolution
- Box size
- Cosmology
- Reionization history

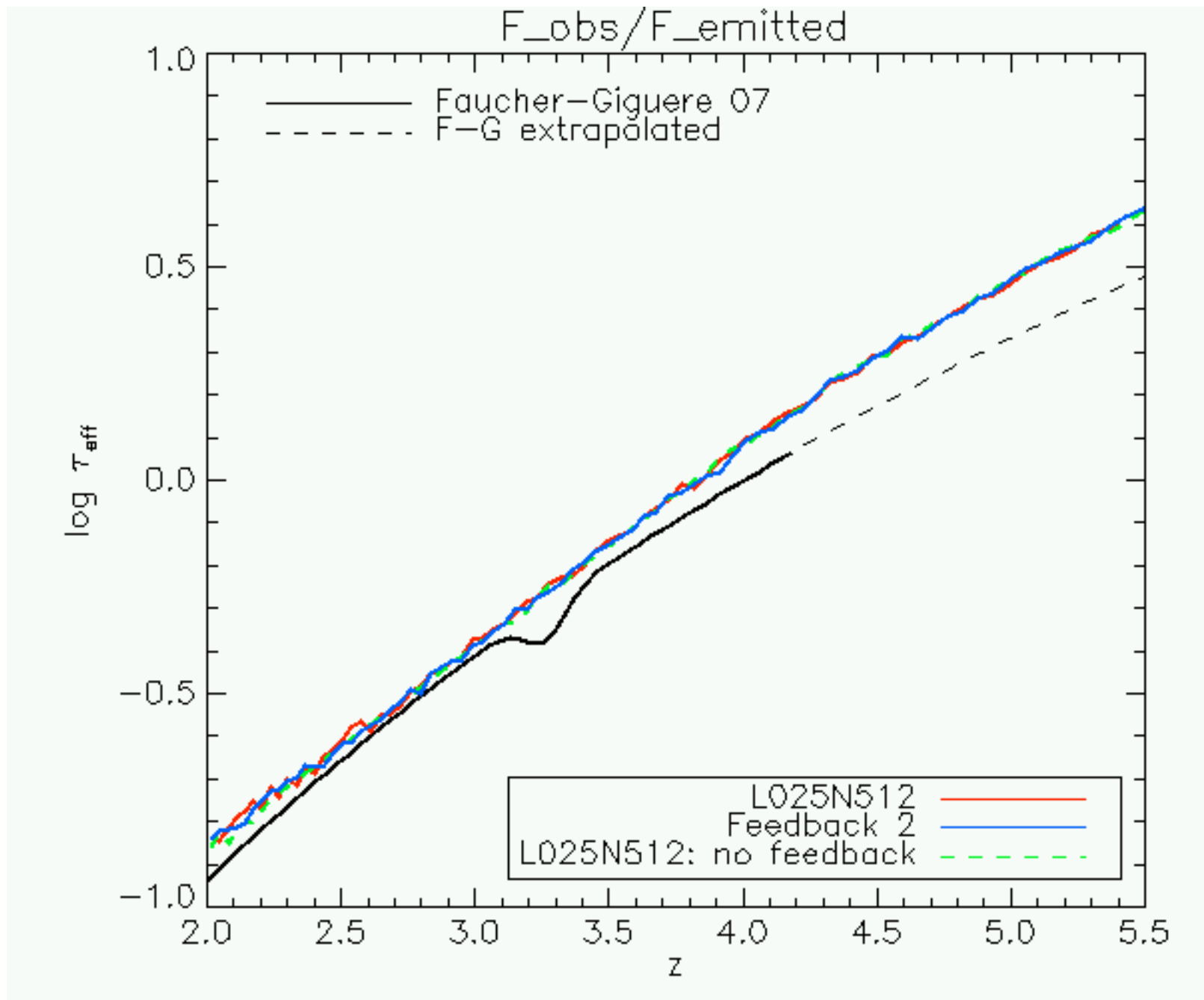
# Density

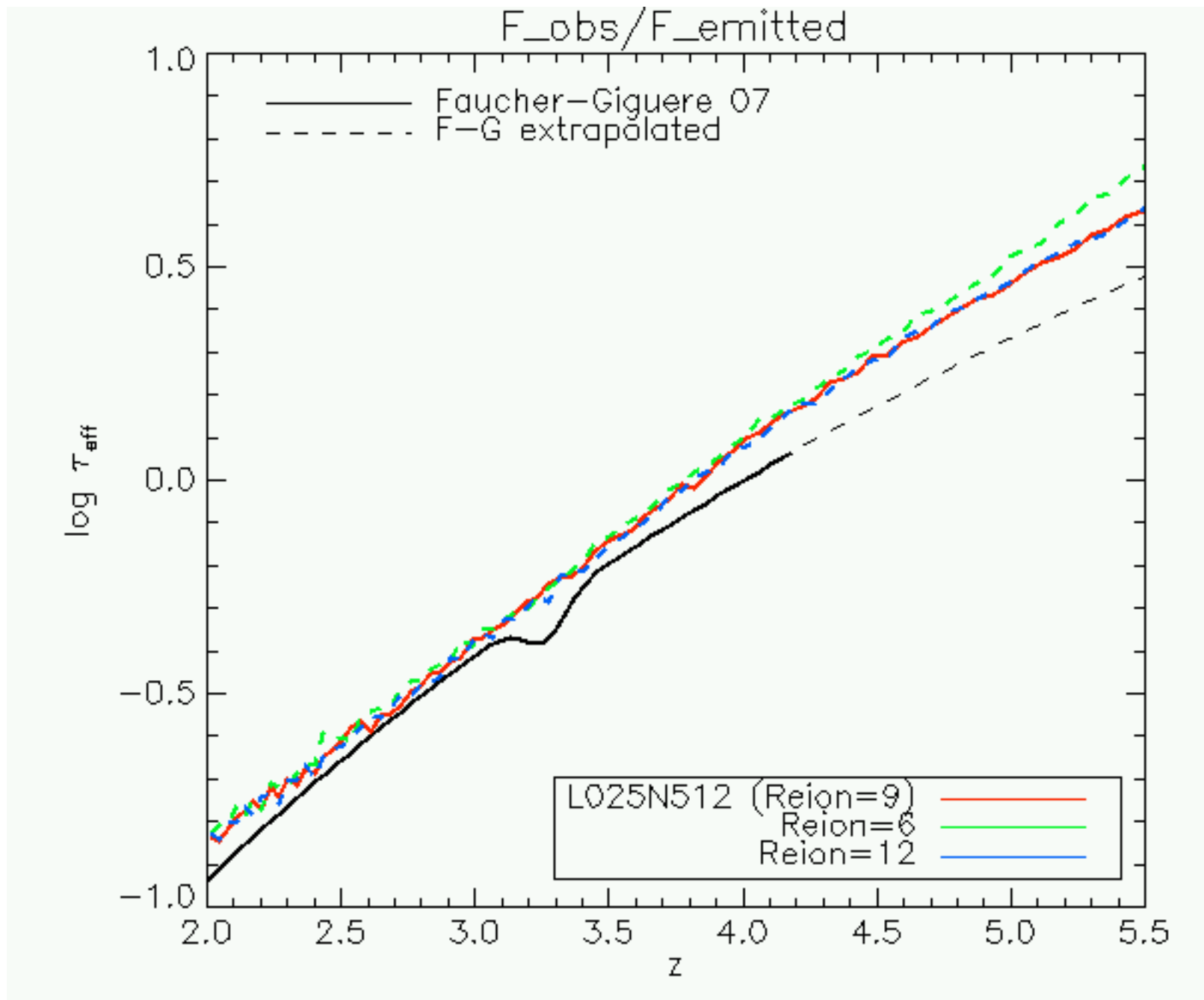
# Temperature

# Metallicity

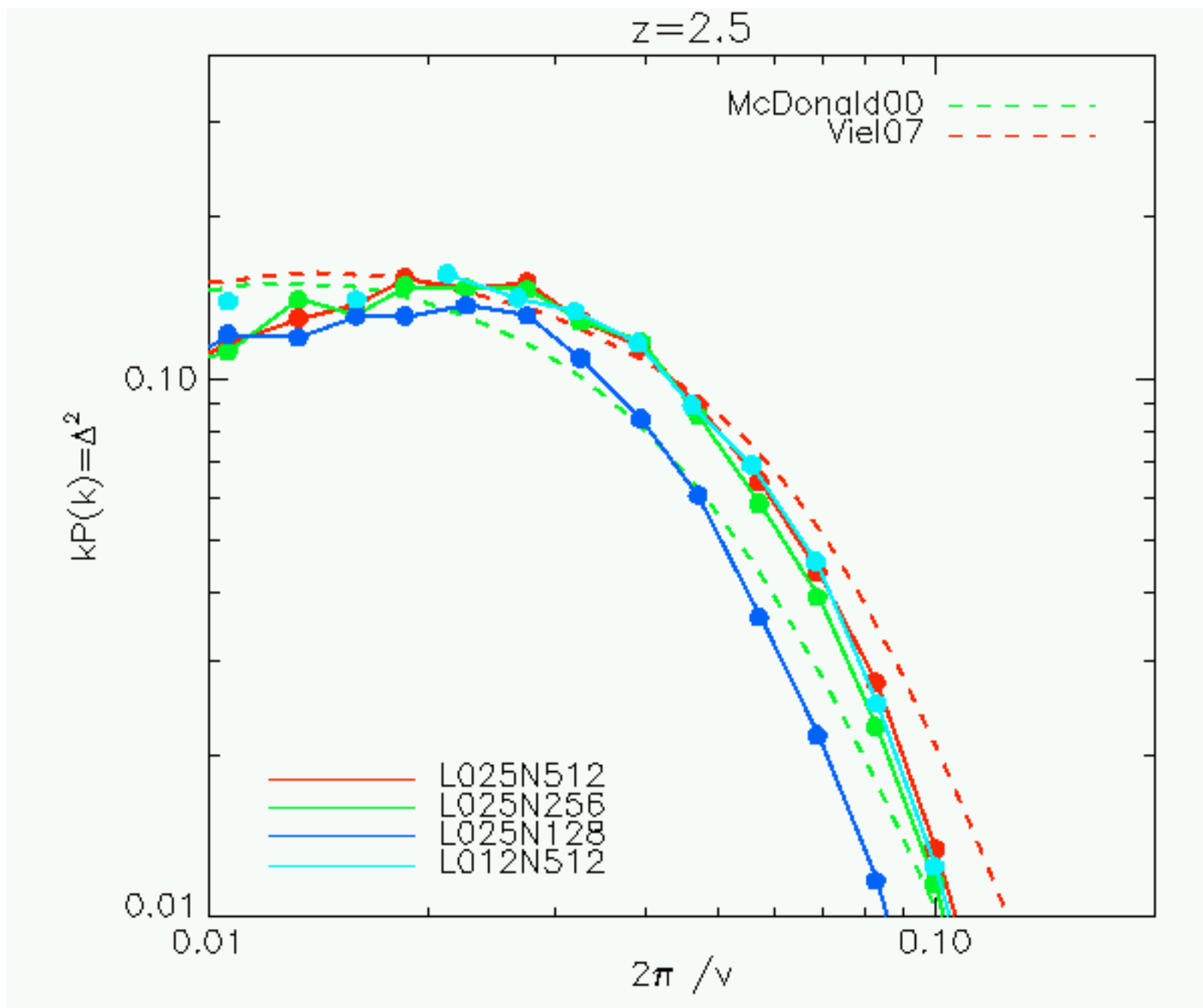




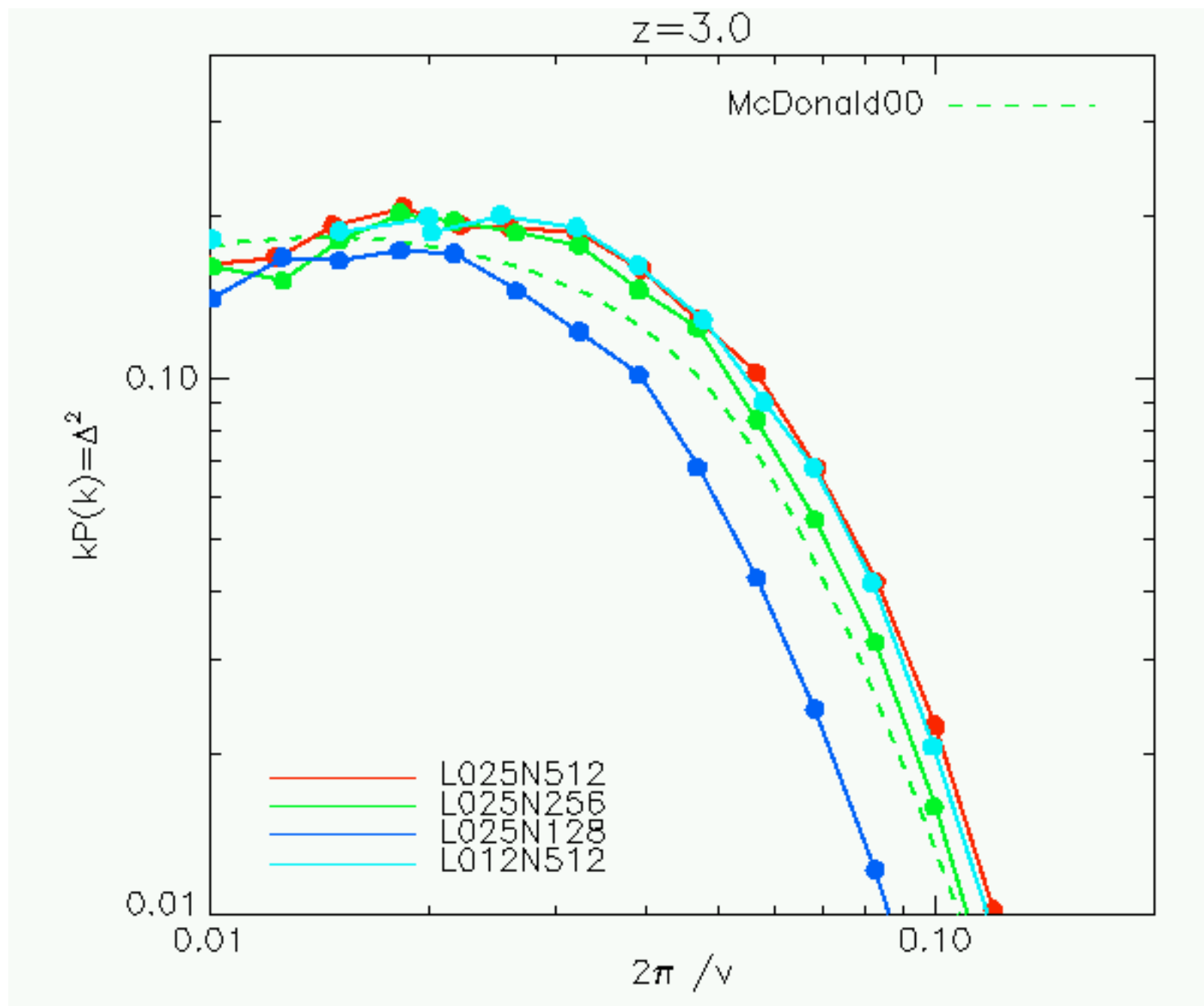




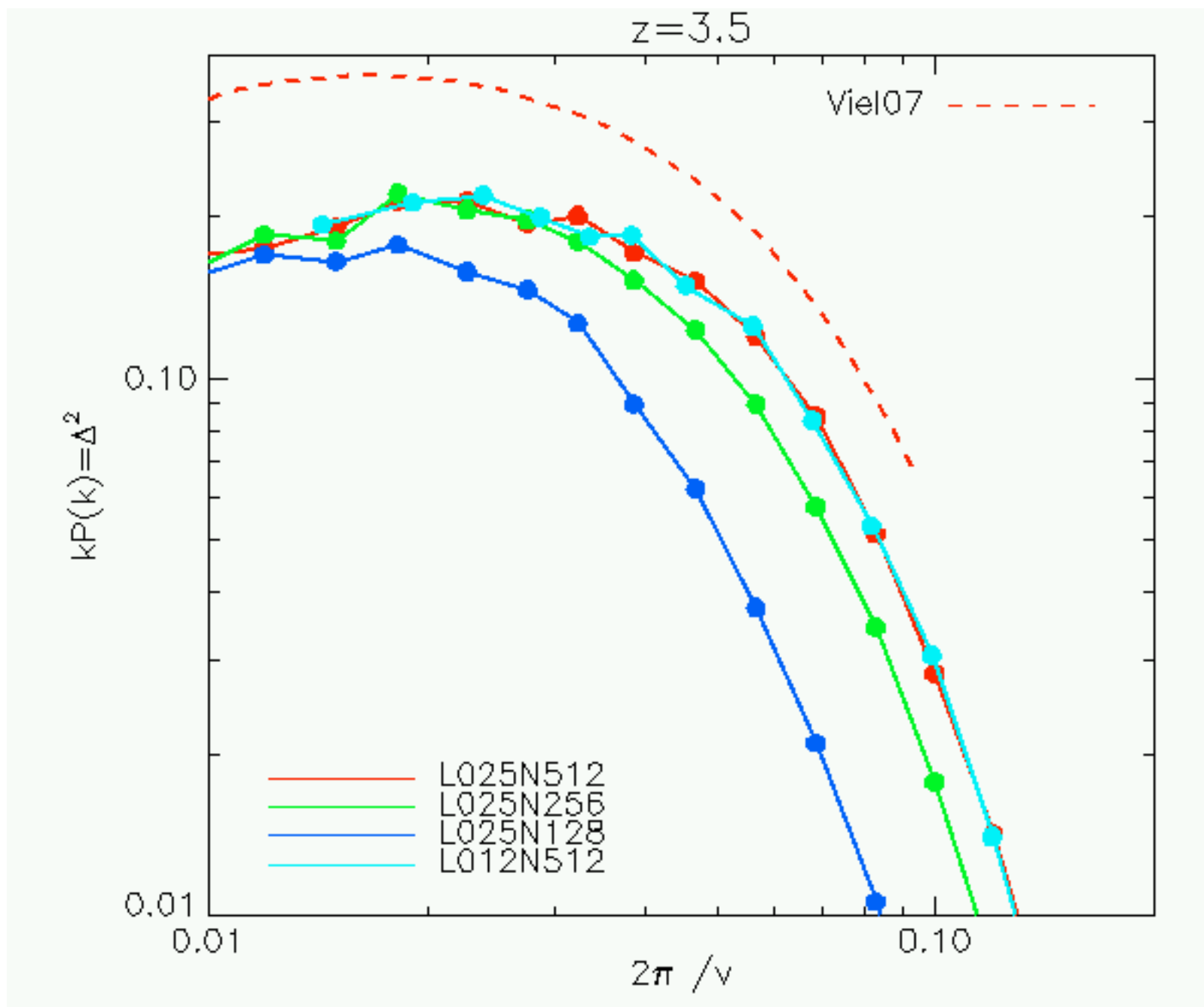
Resolution: low / medium / high / very high



# Resolution: low / medium / high / very high

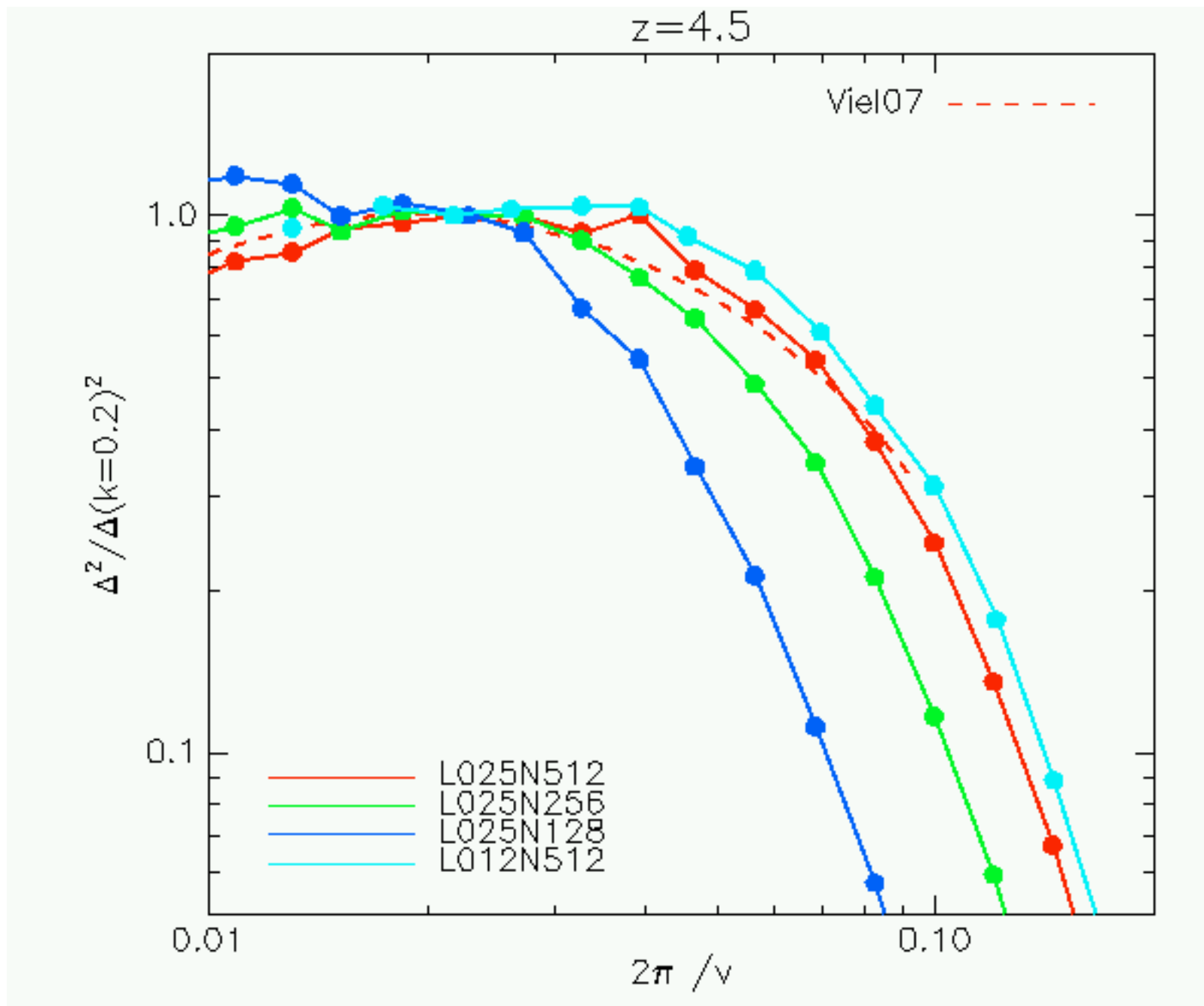


Resolution: low / medium / high / very high

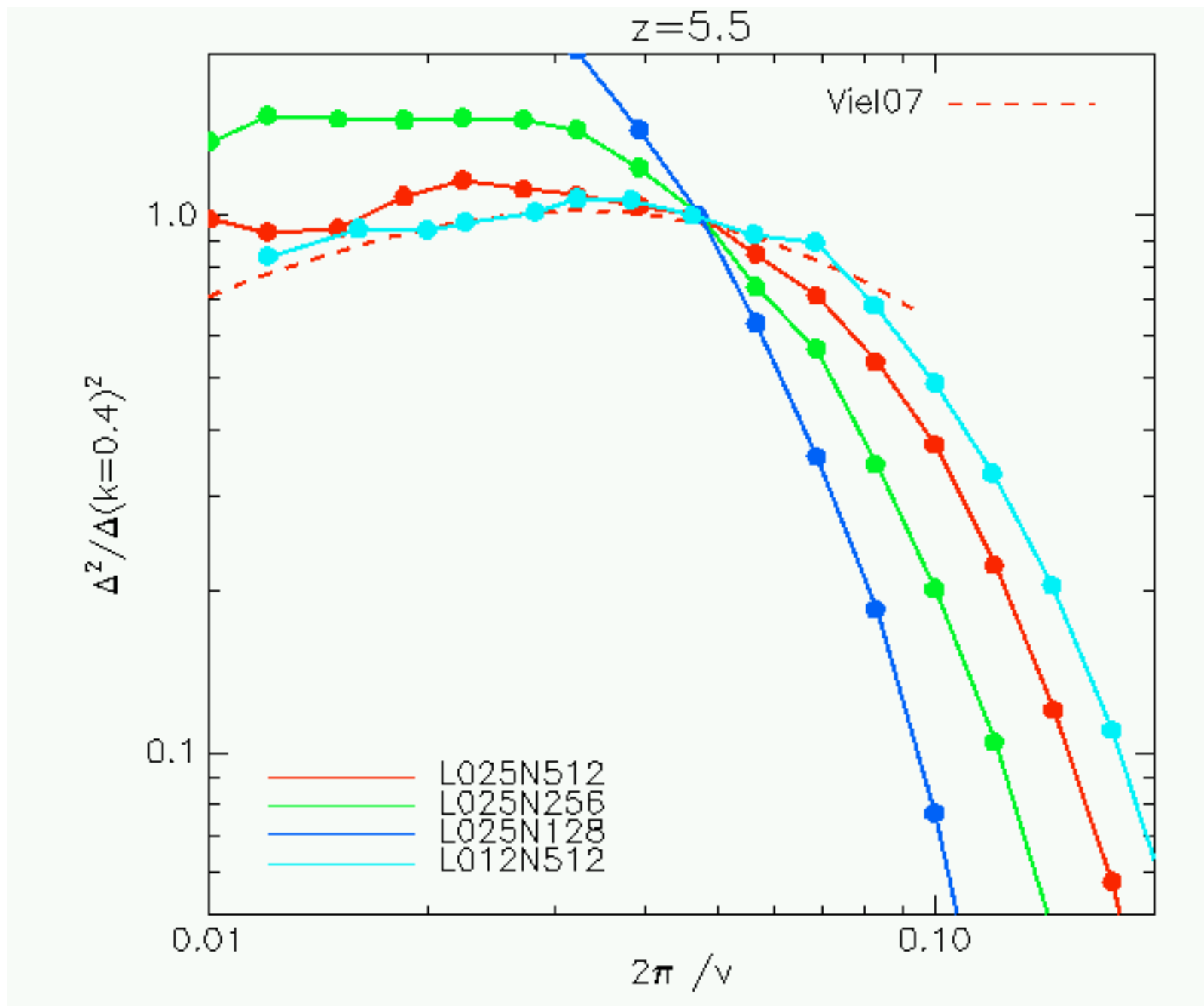




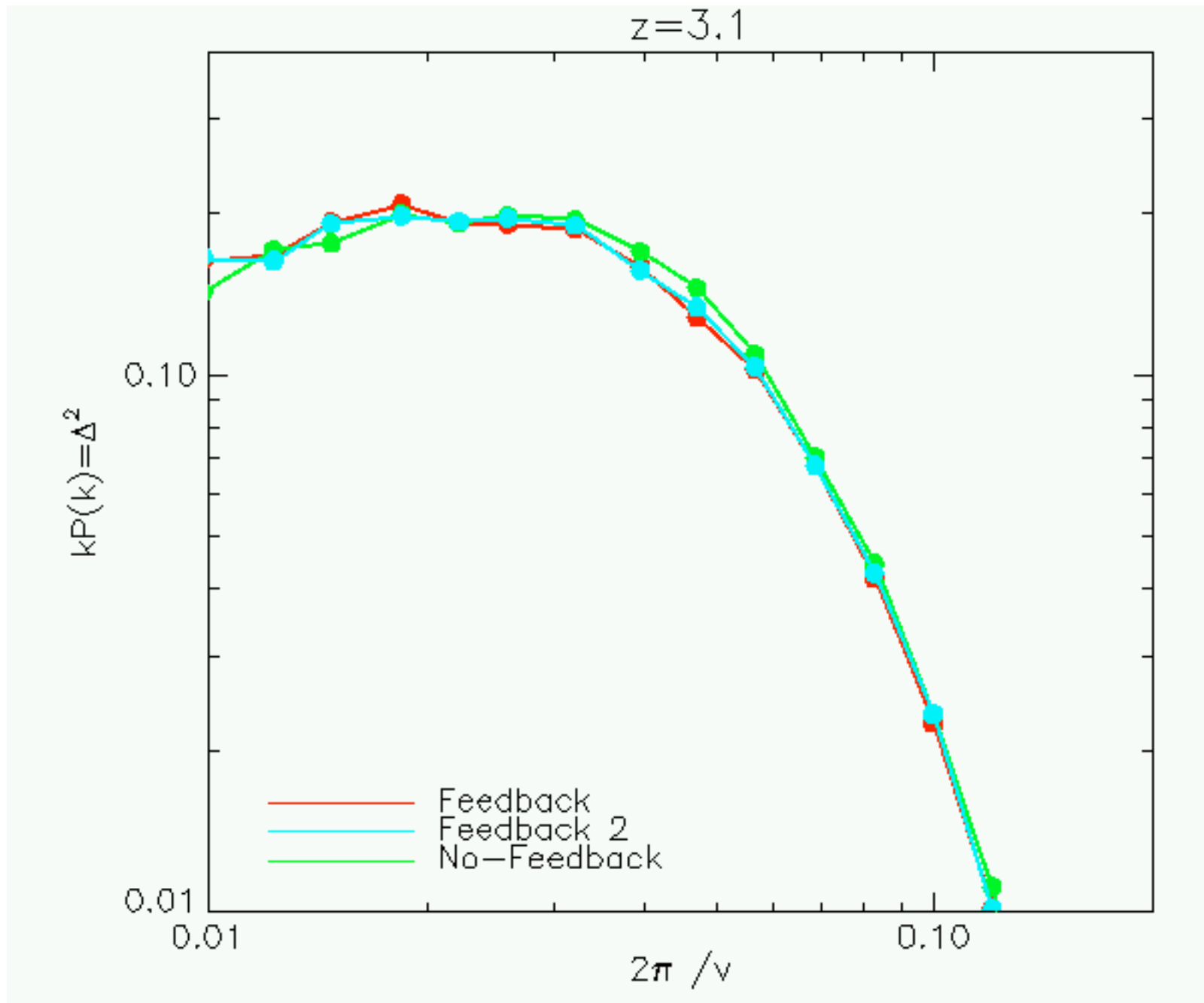
Resolution: low / medium / high / very high



Resolution: low / medium / high / very high



# Feedback / Feedback2 / No-Feedback



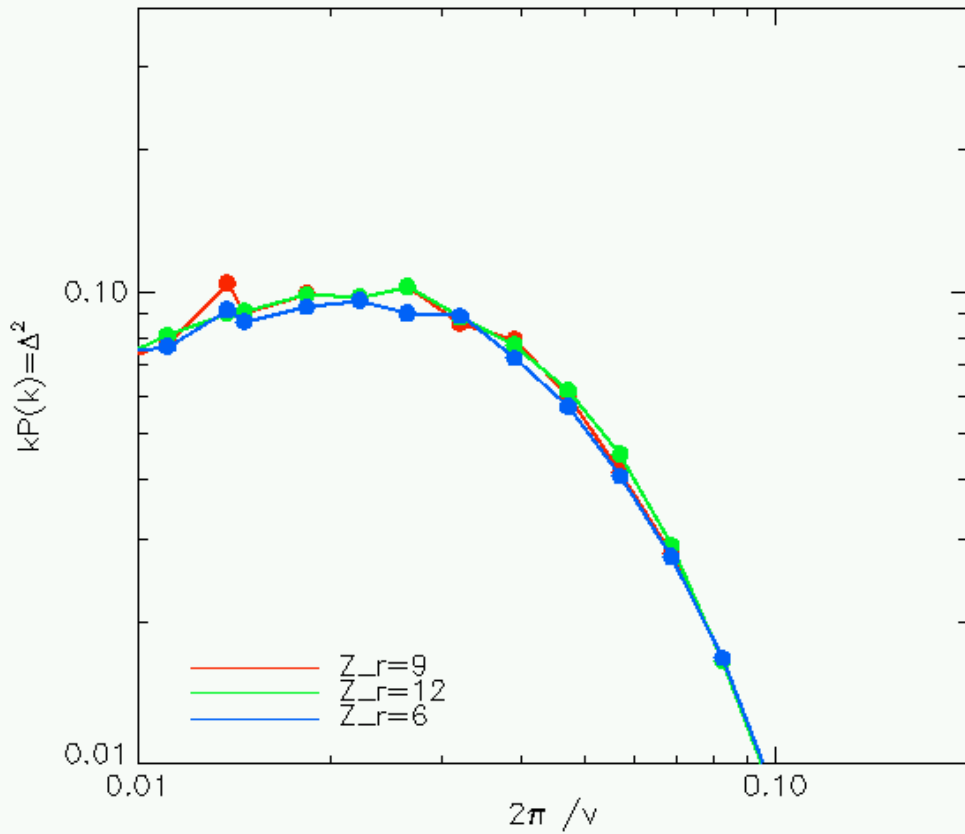
# Epoch of HI reionization:

$Z_{\text{reion}}=6/$

$Z_{\text{reion}}=9/$

$Z_{\text{reion}}=12$

$z=2.1$



$z=3.1$

