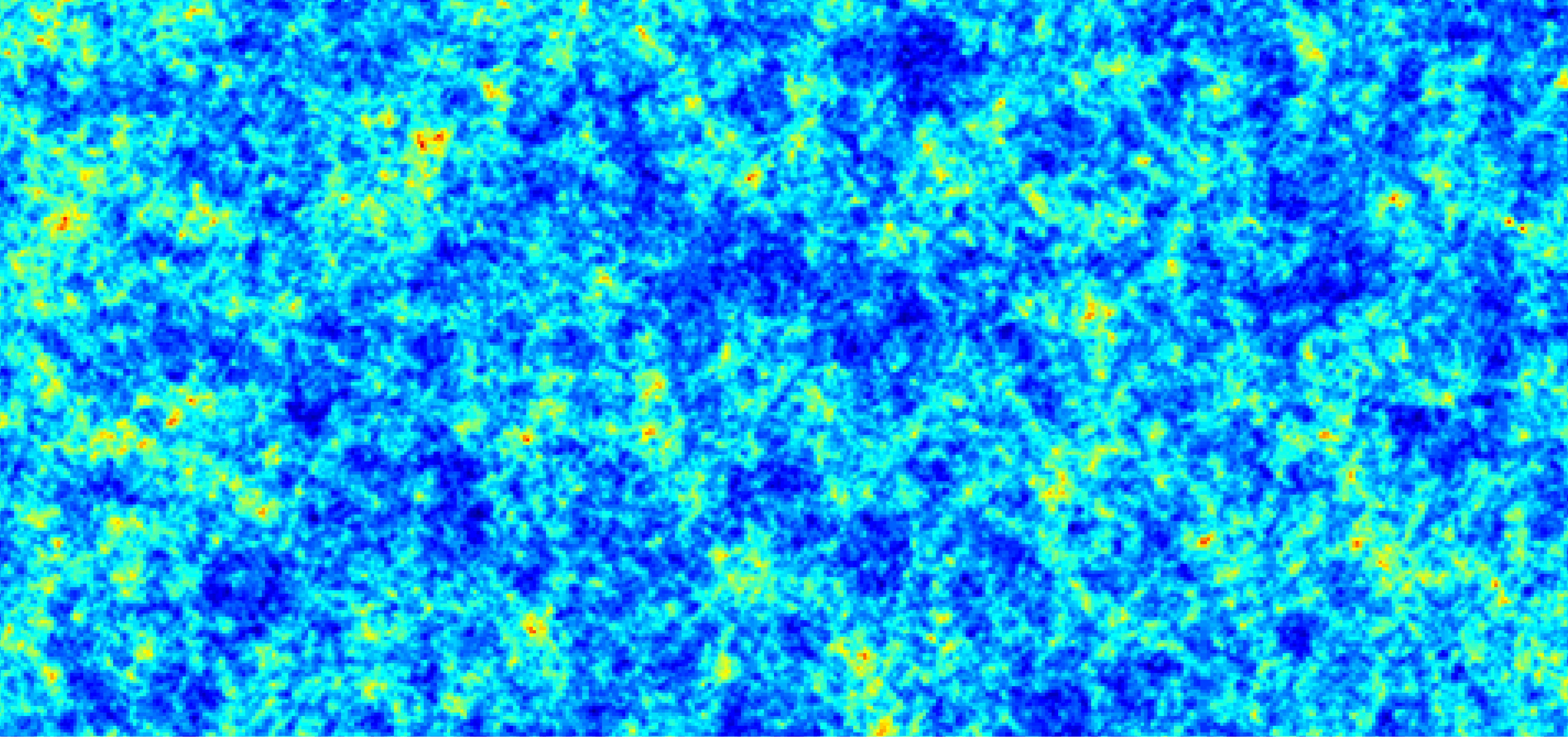


Multi-Scale Initial Conditions

Oliver Hahn (KIPAC/Stanford)

Hahn & Abel (2011)

Some pre-to-post-CMB physics:

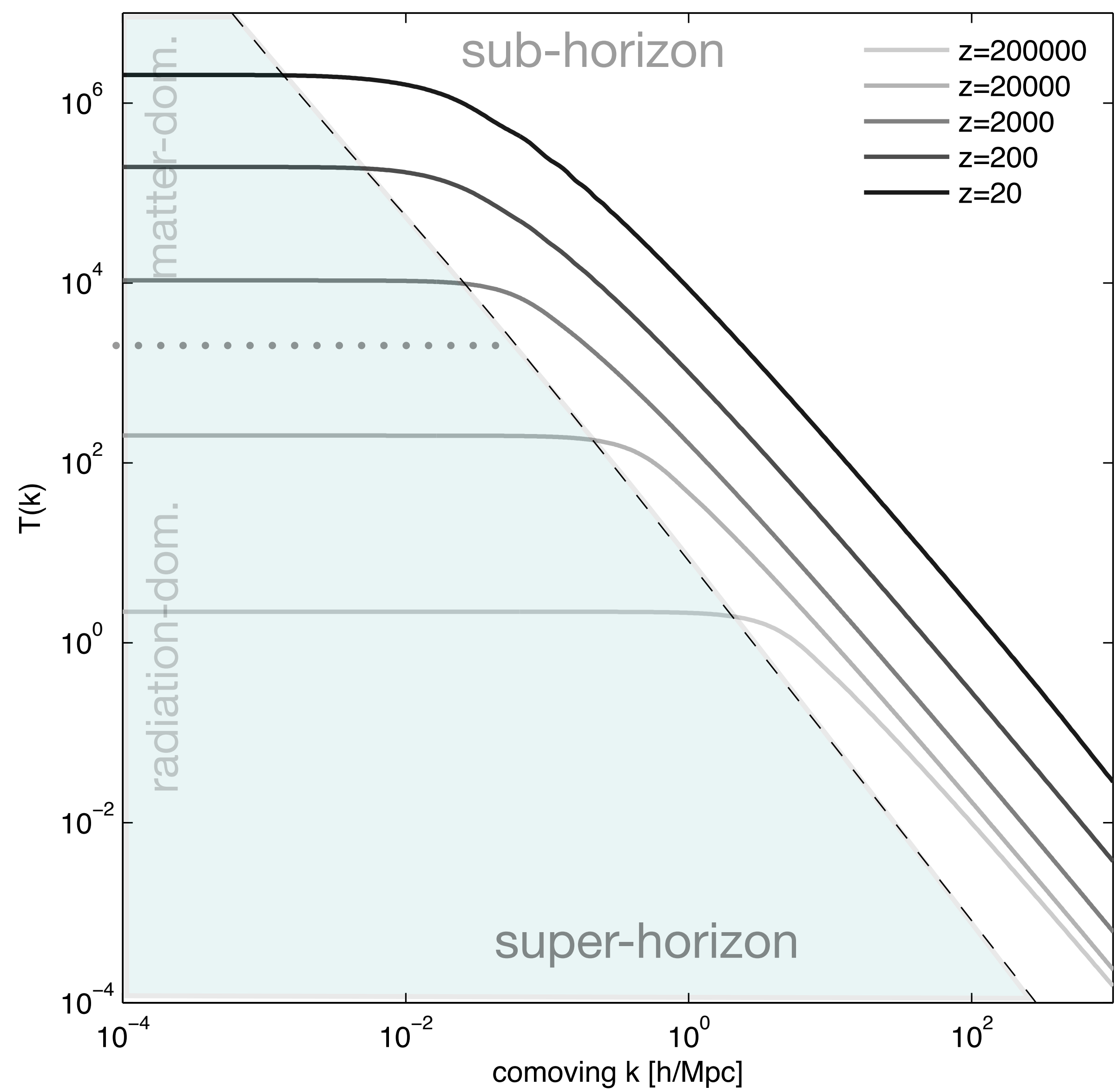
Inflation leads to near scale-invariant primordial density spectrum

$$P_{\rm prim}(k) = \langle \delta\bar{\delta} \rangle \propto k^{n_s} \qquad n_s \lesssim 1$$

Gets processed by growth on sub- and super-horizon scales (GR):

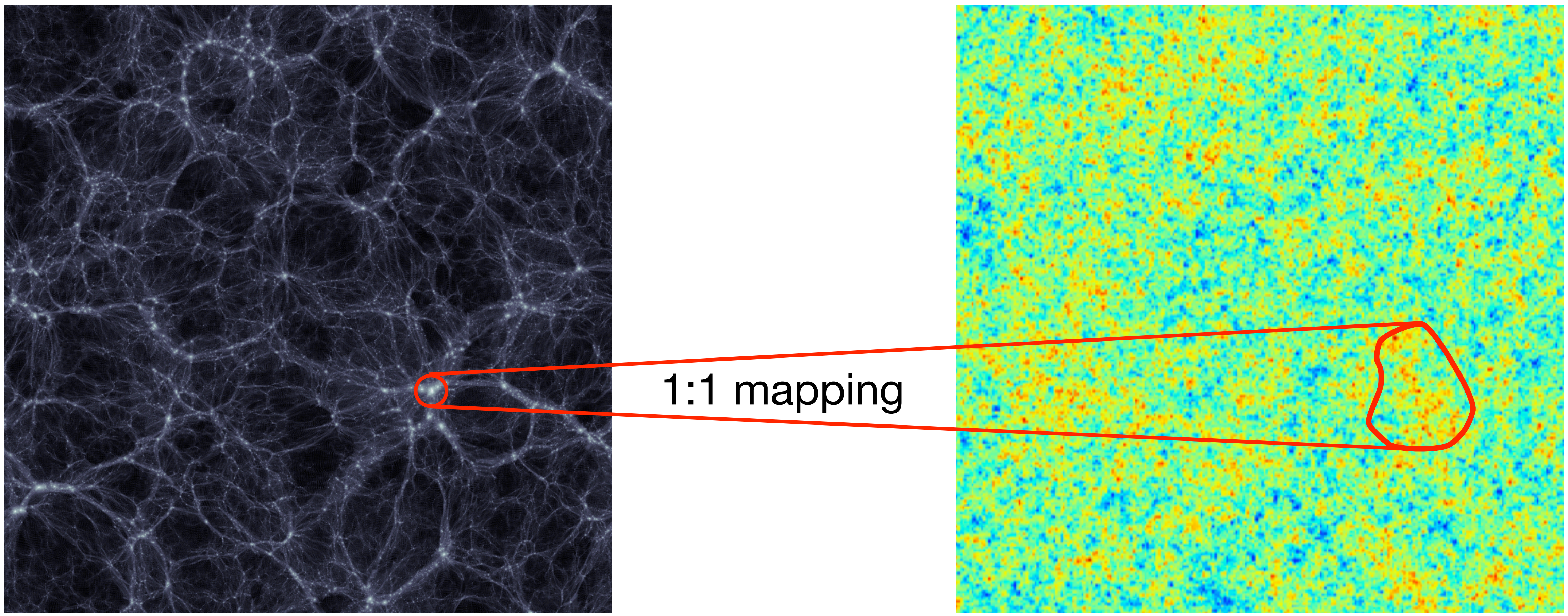
$$P_{\rm late}(k) \propto T^2(k)\, P_{\rm prim}(k)$$

Multi-species fluid of CDM+baryon+photon+neutrino
→**linear** Boltzmann solver
(e.g. Ma & Bertschinger 1995)



Peaks vs. halos

Identify the peak (or region) from which an object forms



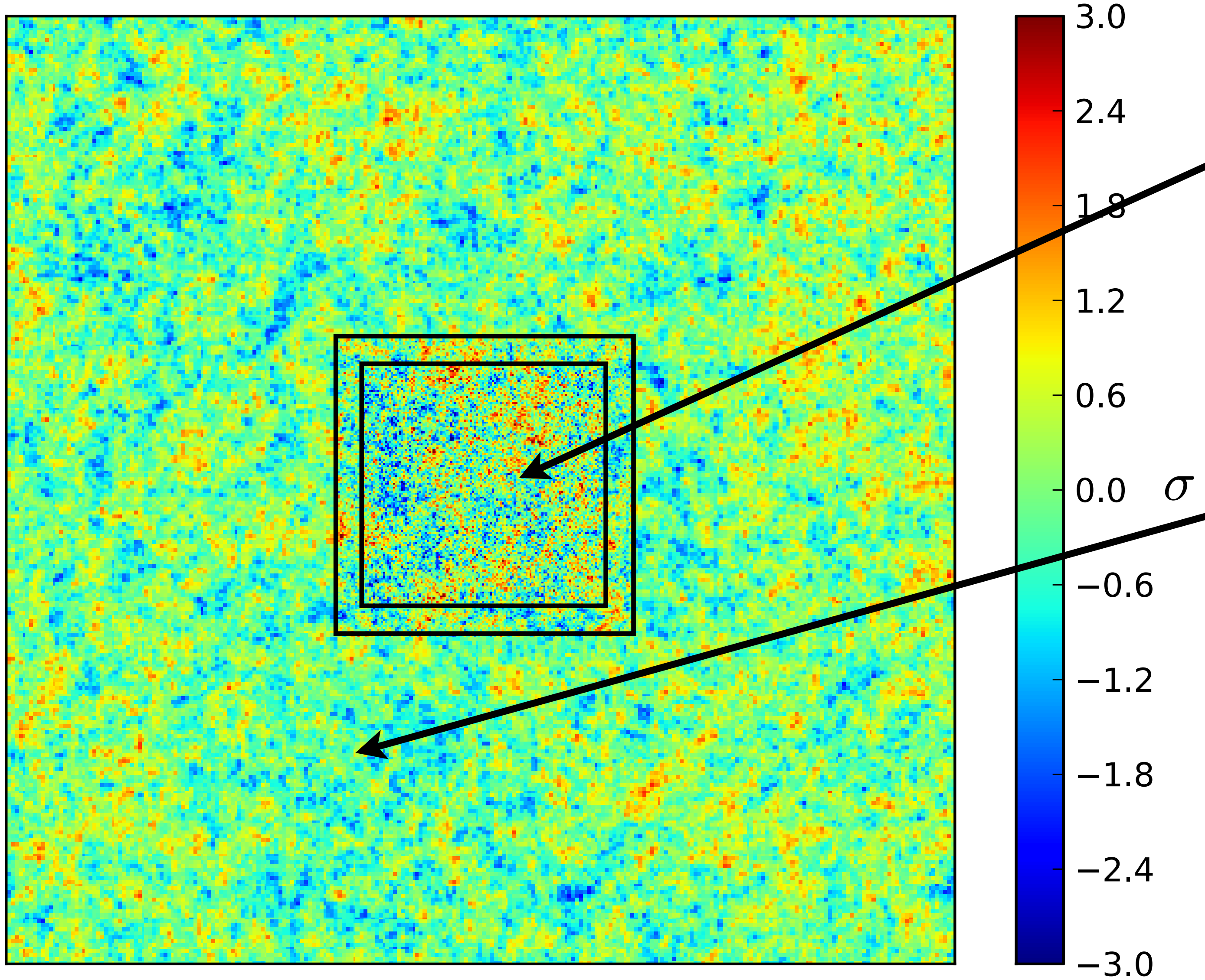
e.g. cluster halo at z=0

corresponding peak patch
in white noise field

We want to increase the resolution locally in this patch...

Disentangling scales...adaptive meshes

Gaussian density perturbation field:



Region of interest at high resolution
galaxy, cluster, first star...

Large-scale modes at low resolution
environment, sample variance

Need to find an algorithm to generate such multi-scale density perturbation fields

hard in Fourier space!
(cf. Bertschinger 2001, GRAFIC-2)

Thinking in real space...

because that's where the peak patch lives...

Remember the generation of a density field with given power spectrum:

$$\delta(\vec{r}) = \mathcal{F}^{-1}\left\{k^{n_s/2}\,T(k)\,G(0,1)\right\}$$

These are products in k-space, and thus become convolutions (cf. also Salmon 1996)

$$\delta(\vec{r}) = \mathcal{F}^{-1}\left\{k^{n_s/2}\,T(k)\right\} \star \mathcal{F}^{-1}\left\{G(0,1)\right\}$$

$$= T(r) \star G(0,1)$$

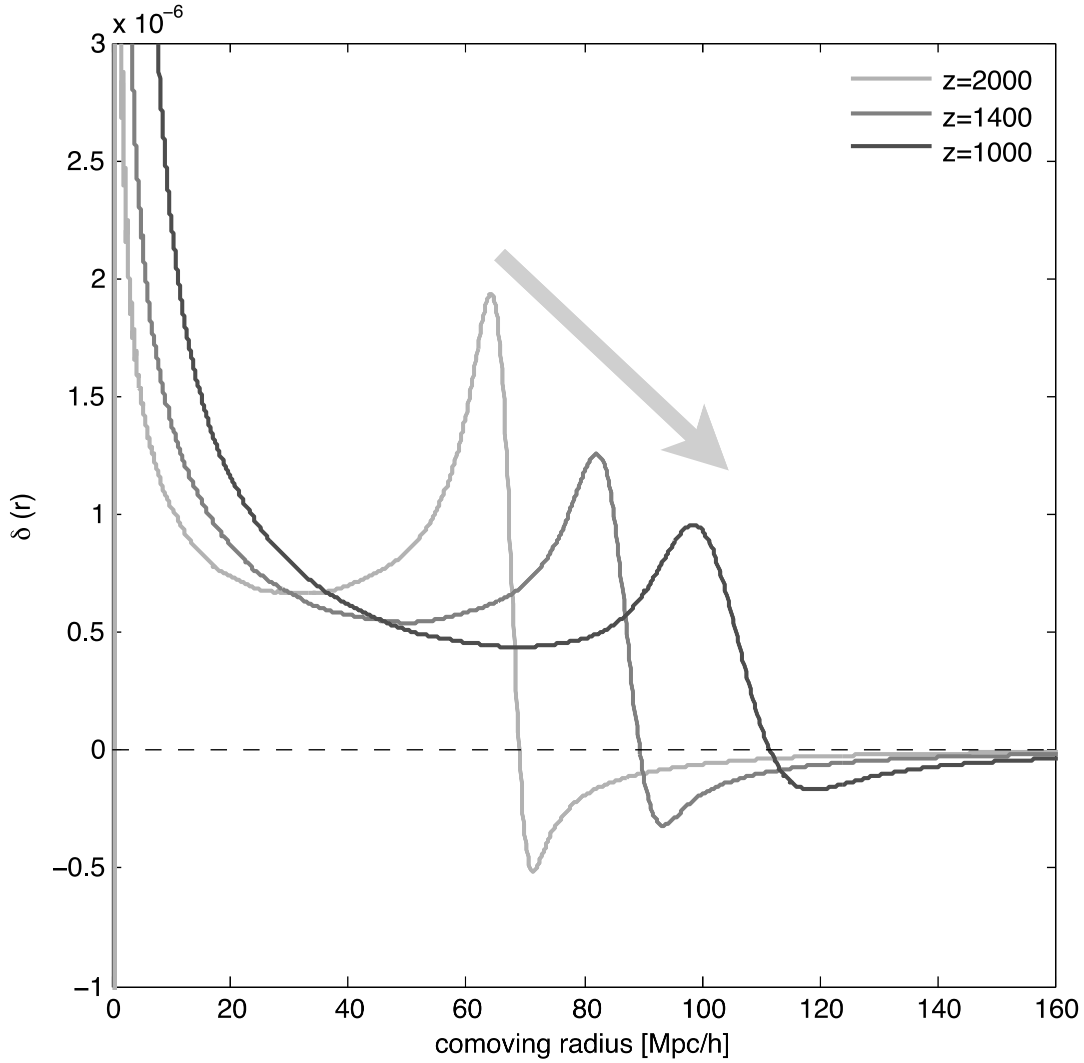
real space TF   Gaussian white noise

What does it mean?

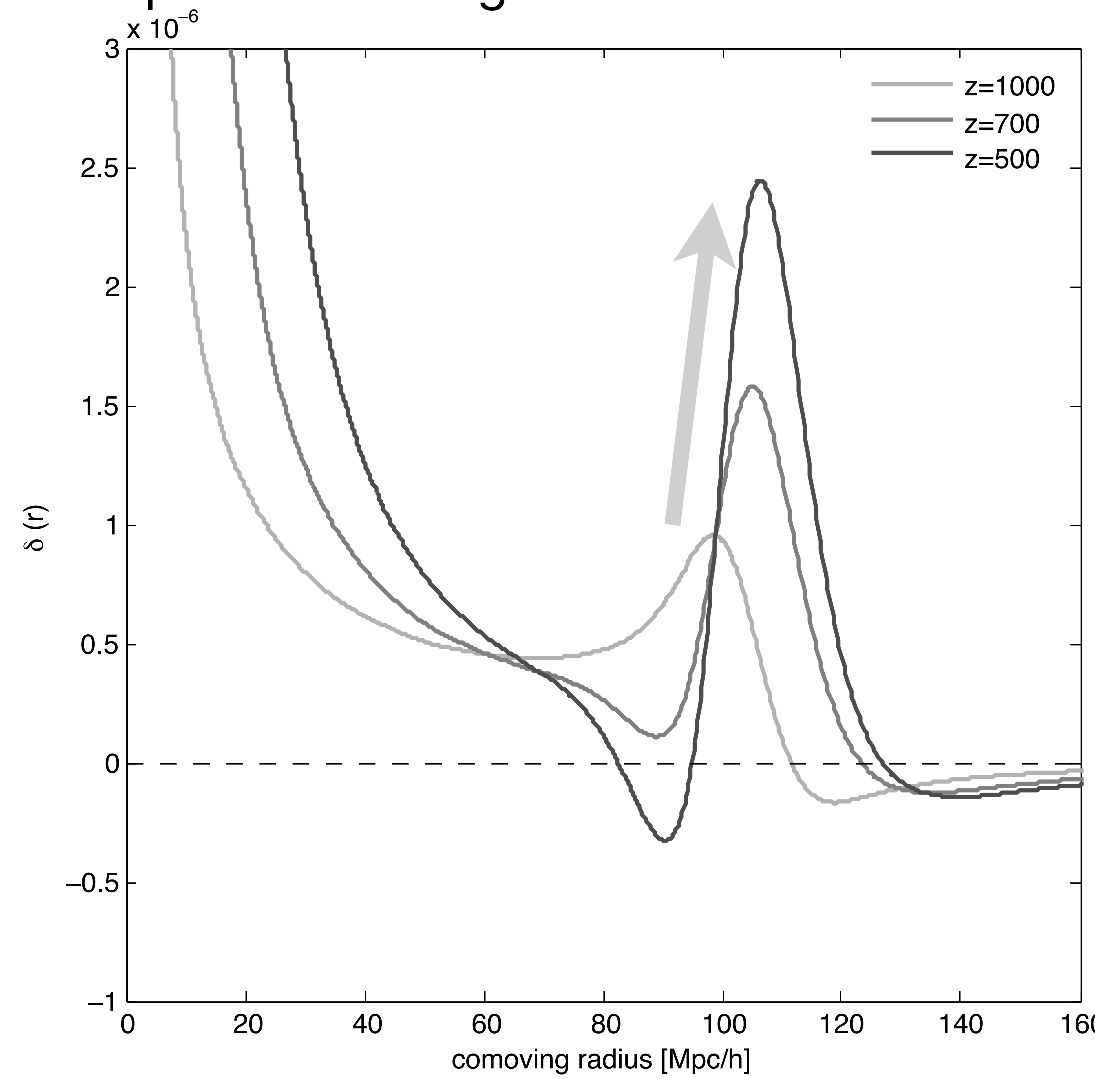
Real space : the baryon acoustic wave

The T(r) kernel for baryons over cosmic time:

Propagating wave for z>1000
sound speed ~ c/3



Stalled wave for z<1000
sound speed drops after recomb
perturbations grow



Convolution superimposes waves and growing modes on noise.
Linear regime: no interaction between waves.

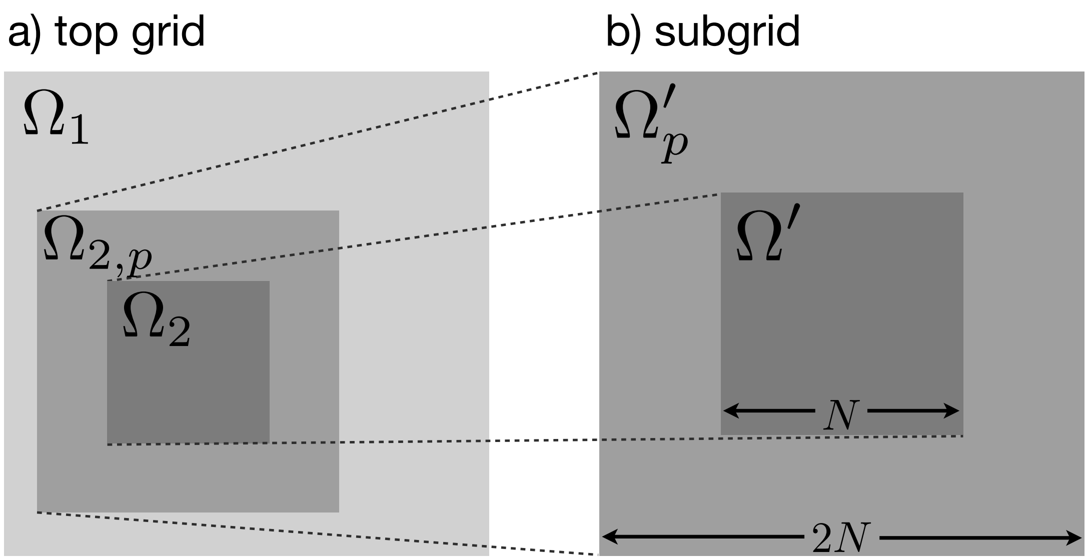
Multi-scale convolution picture

$$\delta(\vec{r}) = T(r) \star G(0,1)$$

Advantages:

- Operating in real space
- No inherent periodicity (Sirko 2005)
- Easy to deal with finite support
- No problems with sharp boundaries

Multi-scale convolutions relatively easy to deal with:
sample "propagator" at different resolutions



important: need to be locally-mass conserving

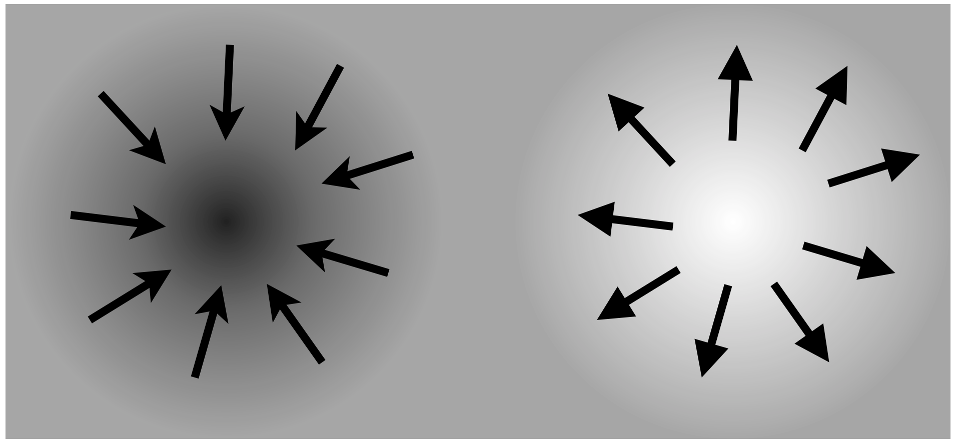
DM (N-body) initial conditions

Lagrangian perturbation theory
relates density perturbations to displacements and velocities

$$\mathbf{x}(t) = \mathbf{q} + \mathbf{L}(\mathbf{q},t), \quad \dot{\mathbf{x}}(t) = \frac{\mathrm{d}}{\mathrm{d}t}\mathbf{L}(\mathbf{q},t)$$

at 1st order, displacement field is proportional to **gravitational force** (Zel'dovich 1970)

$$\mathbf{L}(\mathbf{q}) \propto \boldsymbol{\nabla}_\mathbf{q}\Phi(\mathbf{q},t)$$



need to solve **Poisson's equation**

$$\Delta_\mathbf{q}\Phi \propto \delta$$

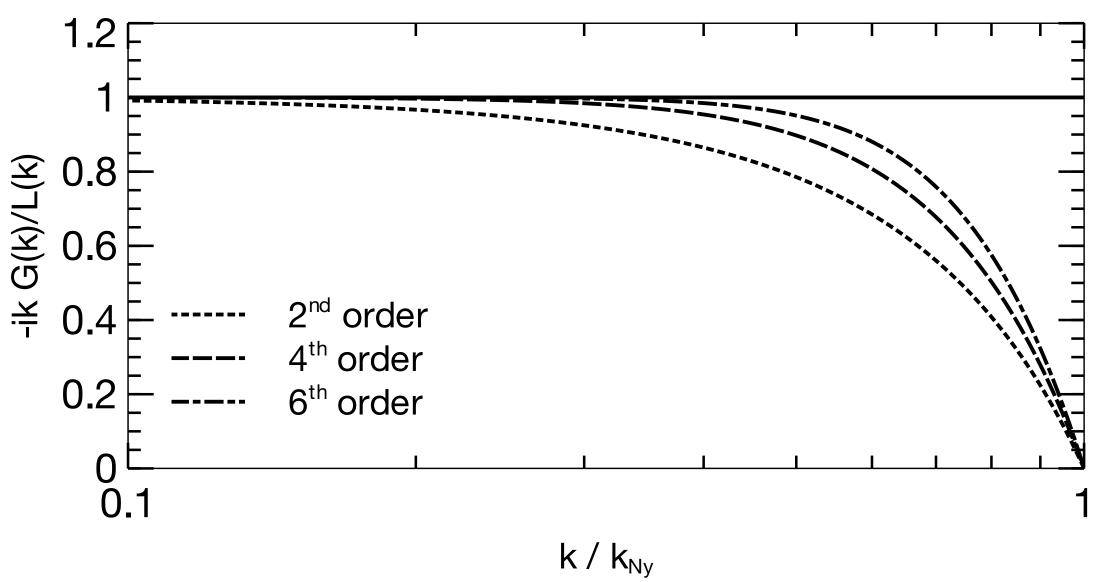
adaptive **multi-grid** (Fedorenko 1961, Brandt 1973,1977)
can achieve this on nested grids. But uses **finite differences**!

straightforward to generalize to 2LPT

Fourier space properties of finite differences

Order n	Laplacian L	Gradient G
exact:	∂_x^2	∂_x
2:	$\left[\ 1 \quad -2 \quad 1\ \right]$	$\frac{1}{2}\left[\ -1 \quad 0 \quad 1\ \right]$
4:	$\frac{1}{12}\left[\ -1 \quad 16 \quad -30 \quad 16 \quad -1\ \right]$	$\frac{1}{12}\left[\ 1 \quad -8 \quad 0 \quad 8 \quad -1\ \right]$
6:	$\frac{1}{180}\left[\ 2 \quad -27 \quad 270 \quad -490 \quad 270 \quad -27 \quad 2\ \right]$	$\frac{1}{60}\left[\ -1 \quad 9 \quad -45 \quad 0 \quad 45 \quad -9 \quad 1\ \right]$
exact:	$-k^2$	$-i\,k$
2:	$-2\left[-\cos(k)+1\right]$	$-i\,\sin(k)$
4:	$-\frac{1}{6}\left[\cos(2k)-16\,\cos(k)+15\right]$	$-\frac{i}{6}\left[-\sin(2k)+8\sin(k)\right]$
6:	$-\frac{1}{90}\left[-2\cos(3k)+27\,\cos(2k)-270\,\cos(k)+245\right]$	$-\frac{i}{30}\left[\sin(3k)-9\sin(2k)+45\sin(k)\right]$

Attenuation of power on small scales!



Bad with CDM

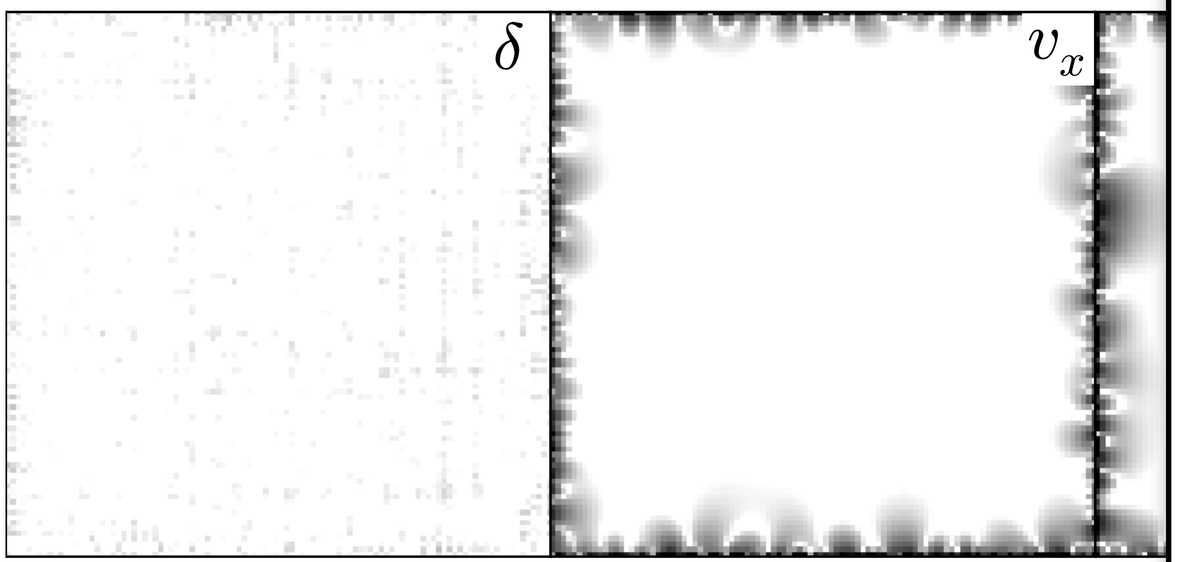
Need a hybrid Poisson solver.

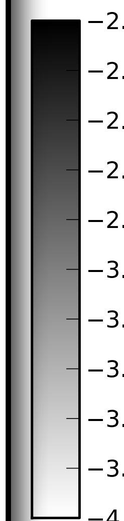
$$\widetilde{v}'_j(\mathbf{k}) = \left[i\,\frac{k_j}{k^2} - \frac{\mathrm{G}_j^{(n)}}{\mathrm{L}^{(n)}} \right]\ \widetilde{f}(\mathbf{k})$$

Correct displacements/velocities on finest grid.
Keep long-range, inter-grid interaction from multi-grid

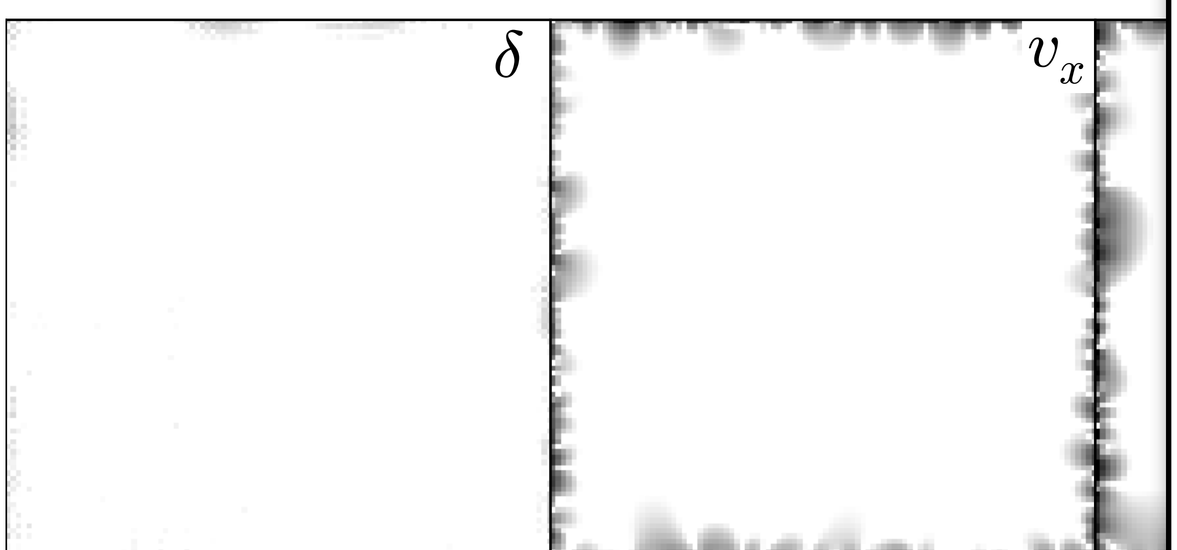
Multi-scale initial conditions (IC errors)

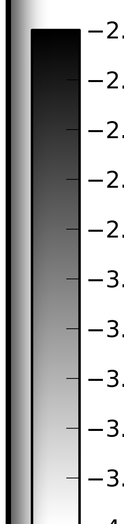
1 level, error in std. dev of the field

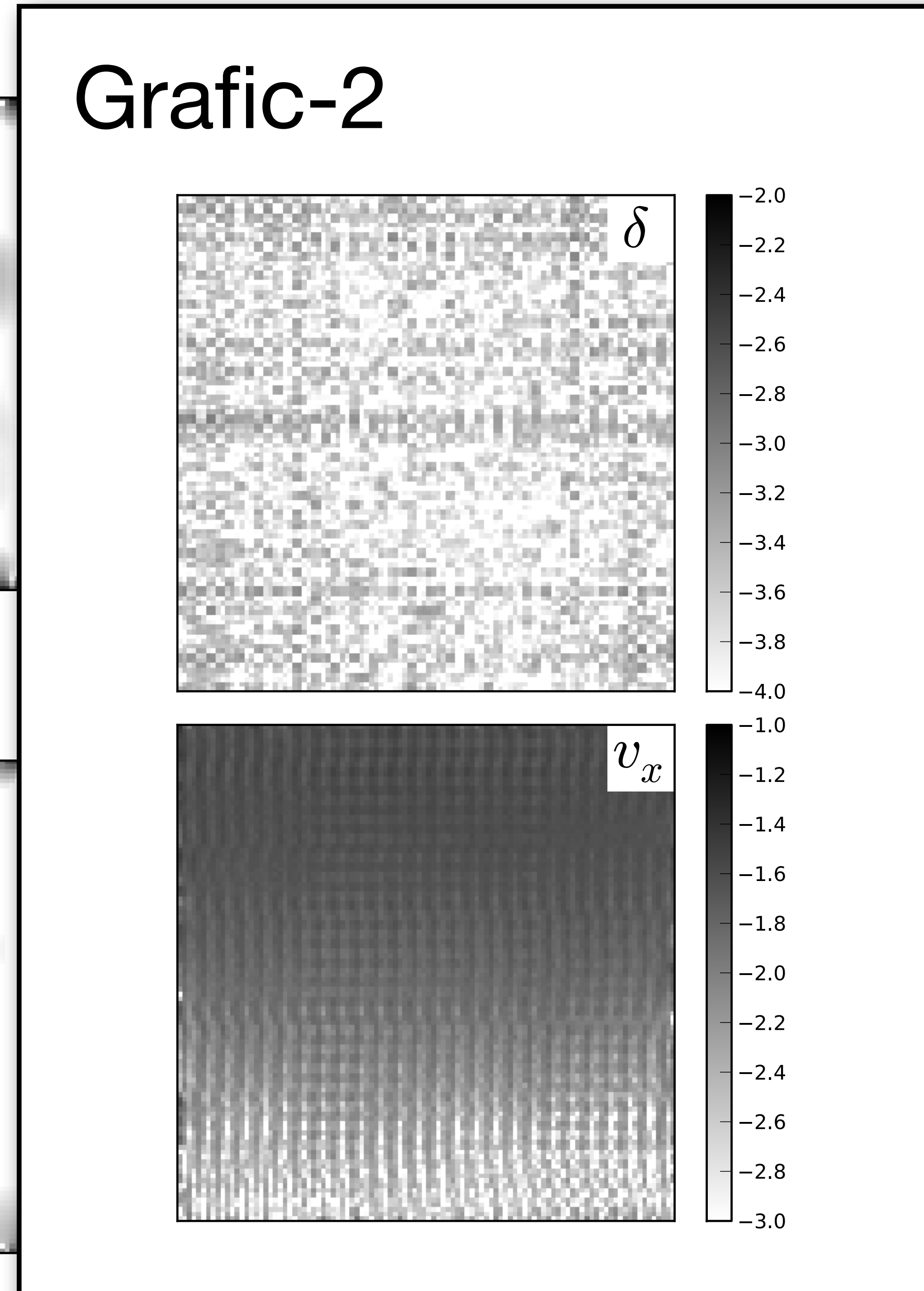




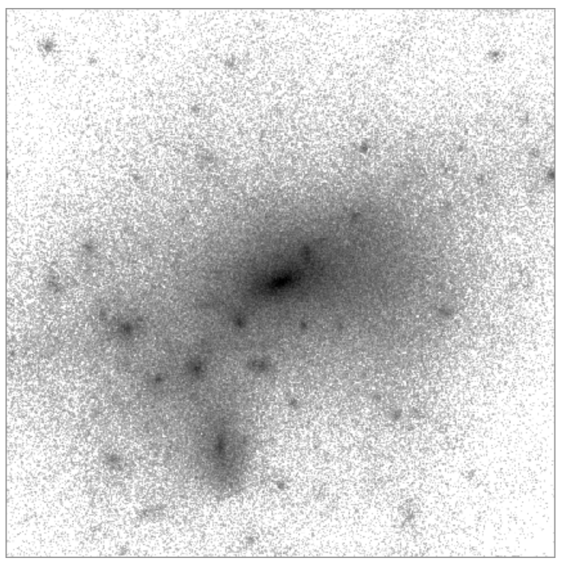
2 level, error in std. dev of the field



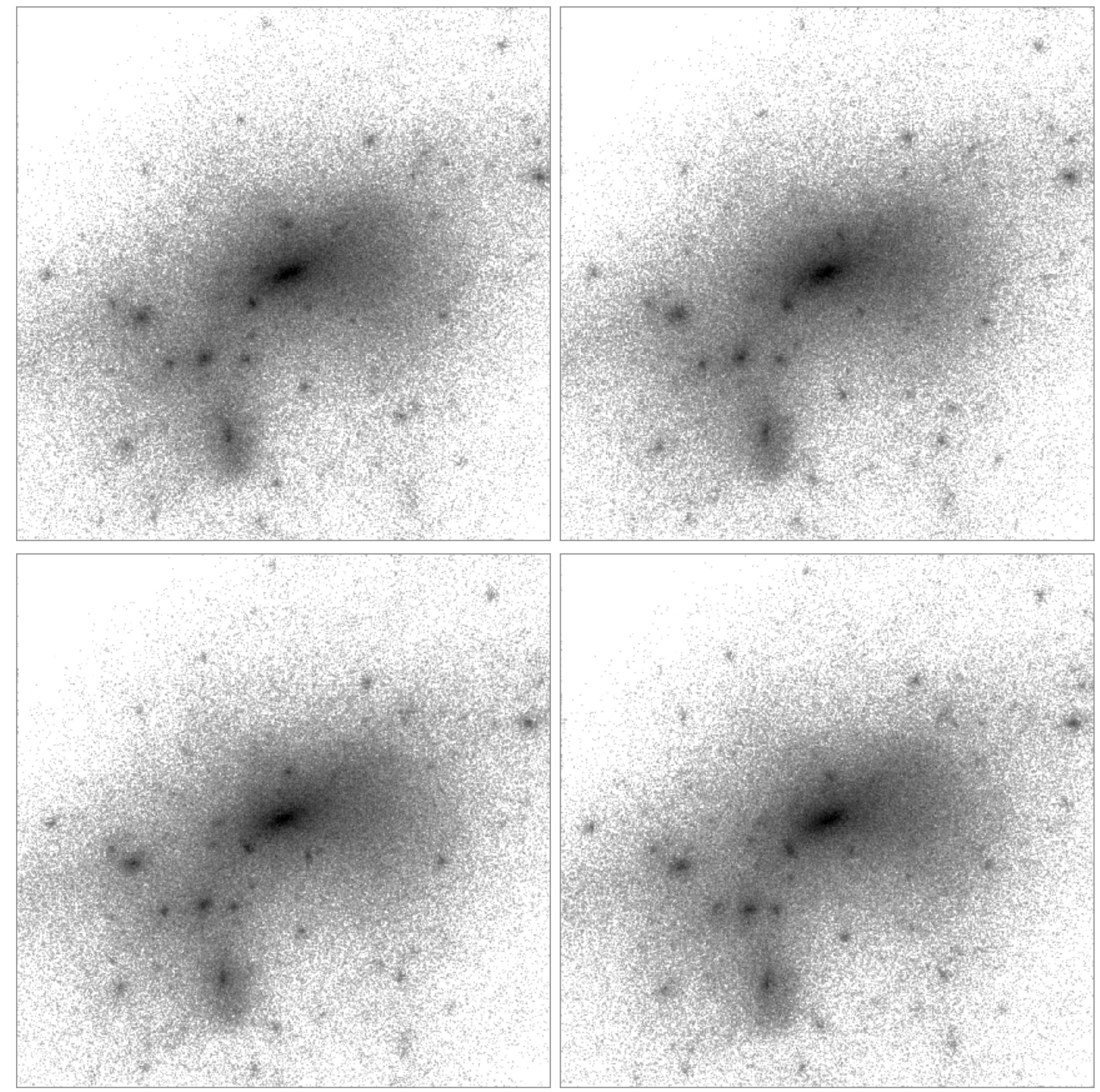




Resimulating a galaxy cluster...



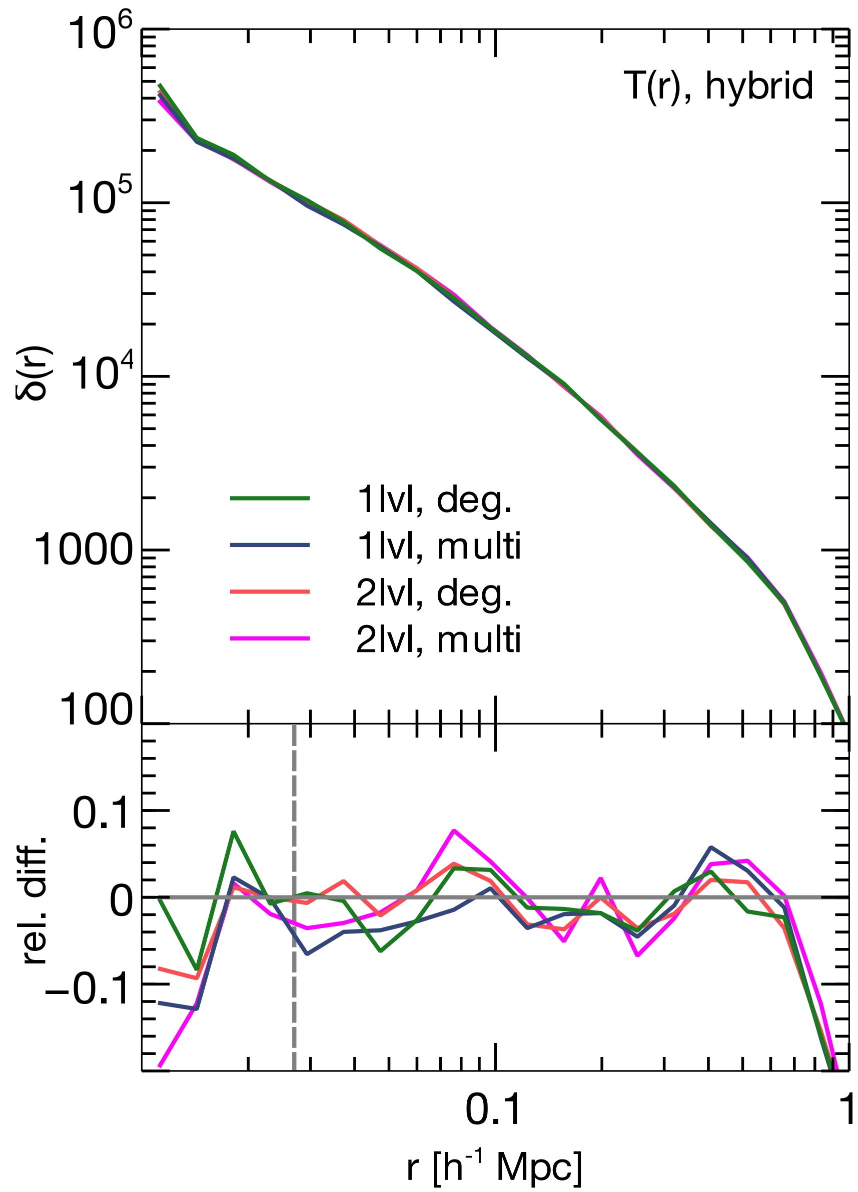
To test, refine region just around
the cluster peak patch

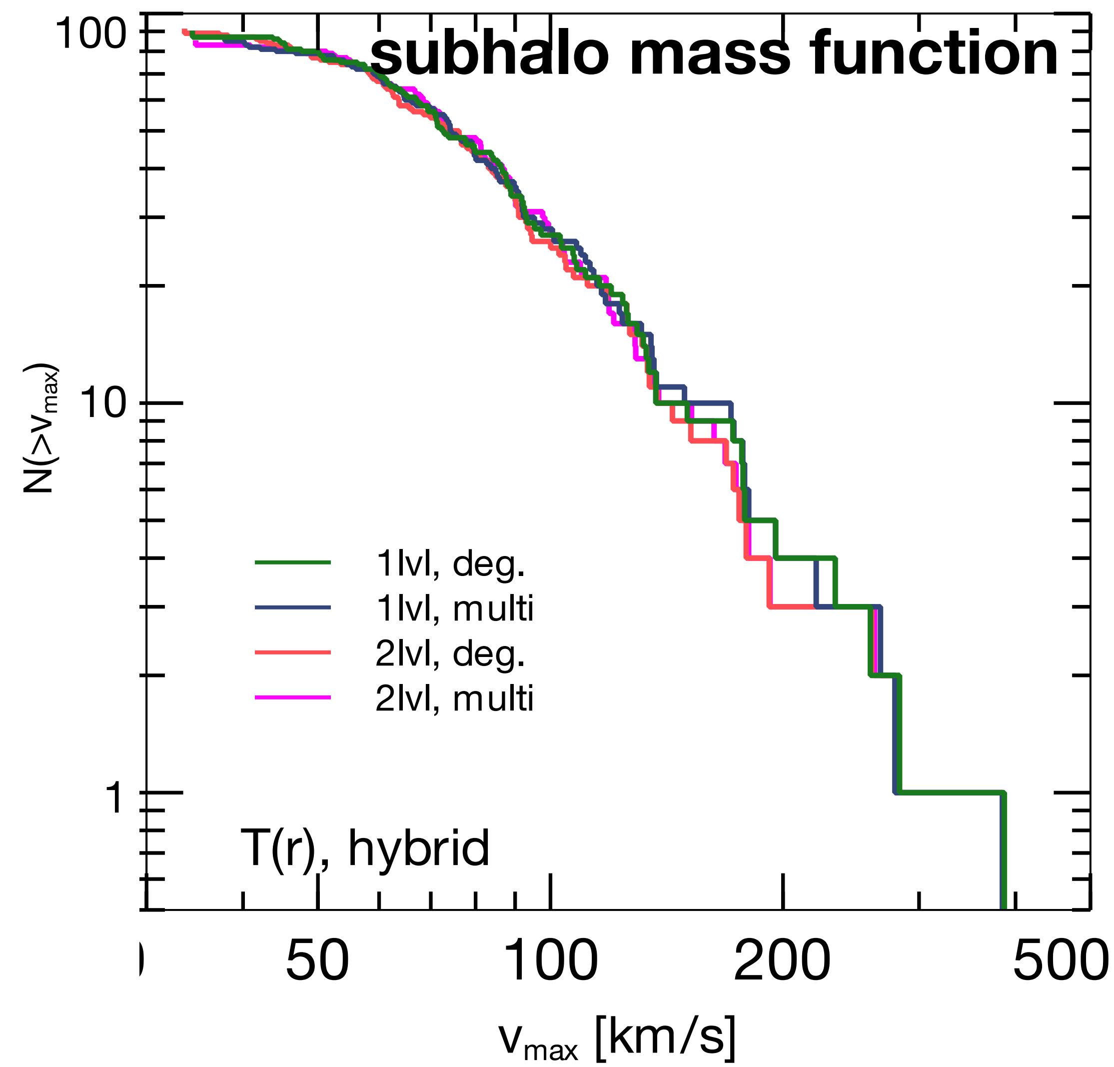


See José Oñorbe’s talk for details about errors related to the choice of Lagrangian region and resolution...

Ready for precision: halo properties

some scatter in **density profiles**

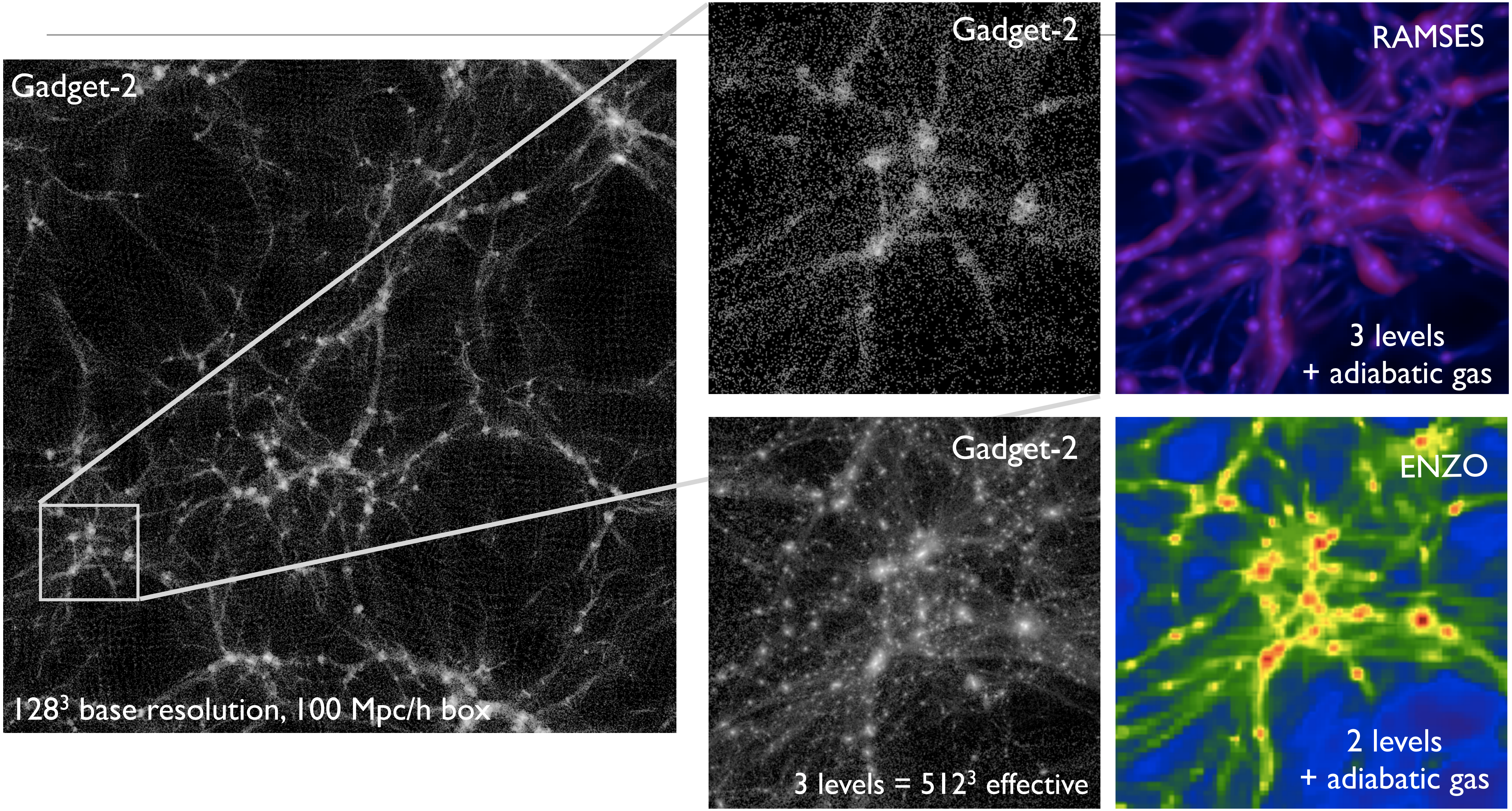




<1% errors in gross halo properties

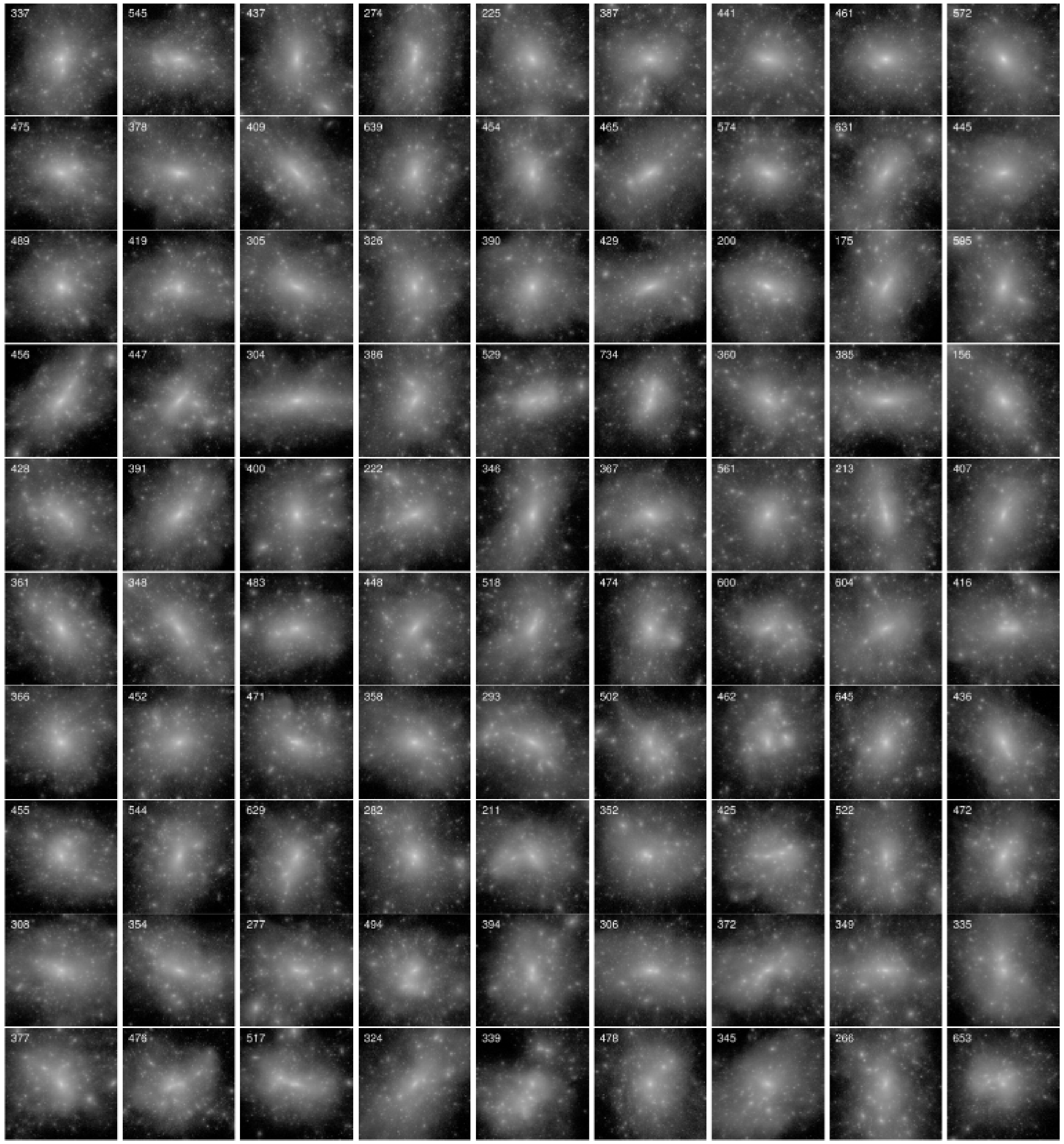
Mvir, Rvir,
Vmax,
spin parameter,
3D velocity dispersion,
shape parameters

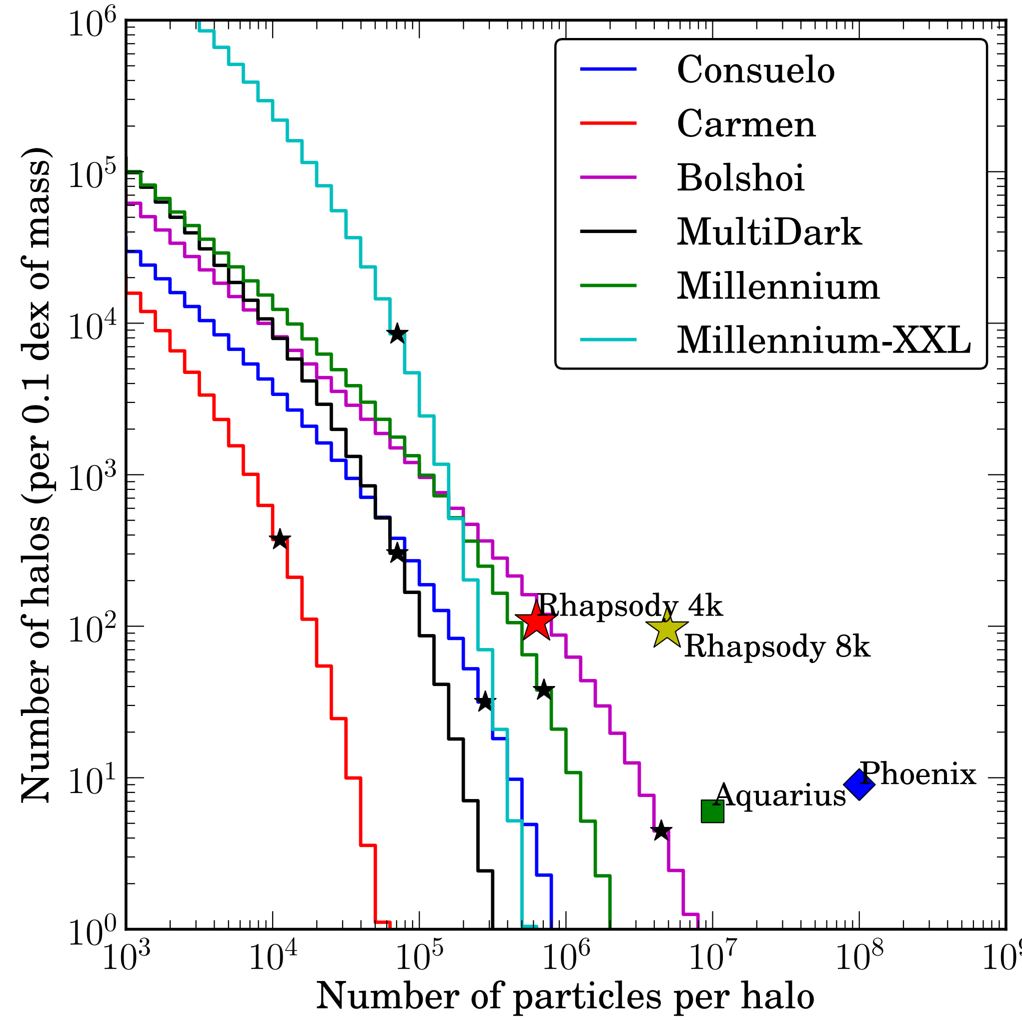
Combining several codes is easy....



Multiple codes supported by plugins, more can be easily added...
output for a different code? change one line!

Rhapsody: sampling rare objects with zoom sims





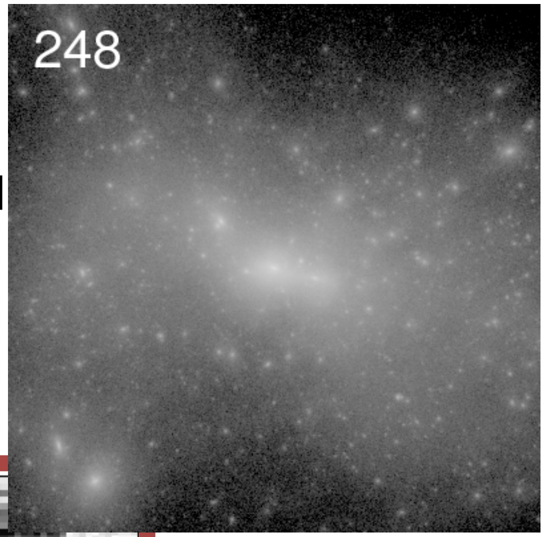
Wu et al. 2012a/b, to be submitted

Analyzing Rhapsody

A Web Interface

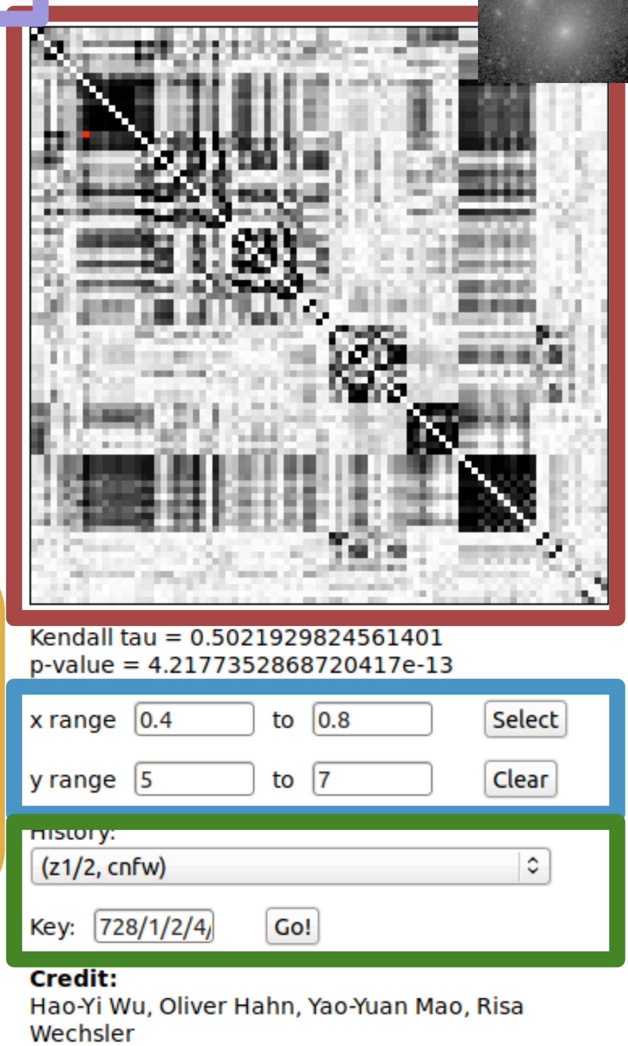
[Implemented by Yao-Yuan Mao]

- Made with **Javascript only**, no PHP/SQL. Can run locally.
- All halo properties and correlation coefficients are pre-calculated and stored as ASCII files.
- Scatter plots generated **on the fly** with **Google Charts API**.



Choose two halo properties to show a scatter plot.

Each point represent one halo. Mouse hover to show the image of the halo. Click to mark halos in red.



Clicking on the correlation matrix brings you to the scatter plots.

Mark red points (halos) in a specified range.

Browse history and sharing key.

MUSIC 101: the parameter file

```
[setup]
boxlength          = 100
zstart             = 50
levelmin           = 7
levelmin_TF        = 9
levelmax           = 12
padding            = 8
overlap            = 4
ref_center         = 0.5, 0.5, 0.5
ref_extent         = 0.2, 0.2, 0.2
align_top          = yes
baryons            = no
use_2LPT           = no
use_LLA            = no
periodic_TF        = yes


[cosmology]
Omega_m            = 0.276
Omega_L            = 0.724
Omega_b            = 0.045
H0                 = 70.3
sigma_8            = 0.811
nspec              = 0.961
transfer           = eisenstein

[random]
seed[7]            = 12345
seed[8]            = 23456
seed[9]            = 34567
seed[10]           = 45678
seed[11]           = 56789
seed[12]           = 67890
```

```
[output]
##generic MUSIC data format (used for testing)
format             = generic
filename           = debug.hdf5

##ENZO - also outputs the settings for the parameter file
format             = enzo
filename           = ic.enzo

##Gadget-2 (type=1: high-res particles, type=5: rest)
format             = gadget2
filename           = ics_gadget.dat

##Grafic2 compatible format for use with RAMSES
##option 'ramses_nml'=yes writes out a startup nml file
format             = grafic2
filename           = ics_ramses
ramses_nml       = yes

##Gasoline/PKDgrav compatible format
format             = tipsy
filename           = ics_tipsy.dat
```

Current Feature List of MUSIC

- Publicly available now (ask me to get access).
  Full public access probably in September
- Supports
  Gadget, ENZO, RAMSES, Gasoline (ART in progress)
- Zeldovich approx or 2LPT for dark matter
- Local-lagrangian approx for baryons w/ grid codes
- can take input from CAMB, comes also with a Boltzmann code, or fitting formulae
- Experimental motion-compensation to reduce Galilean invariance errors with grid codes
- Universe encoded in parameter file, can pass around easily, increase resolution, enlarge region...
- C++ factory patterns for plugins for output, linear cosmology part