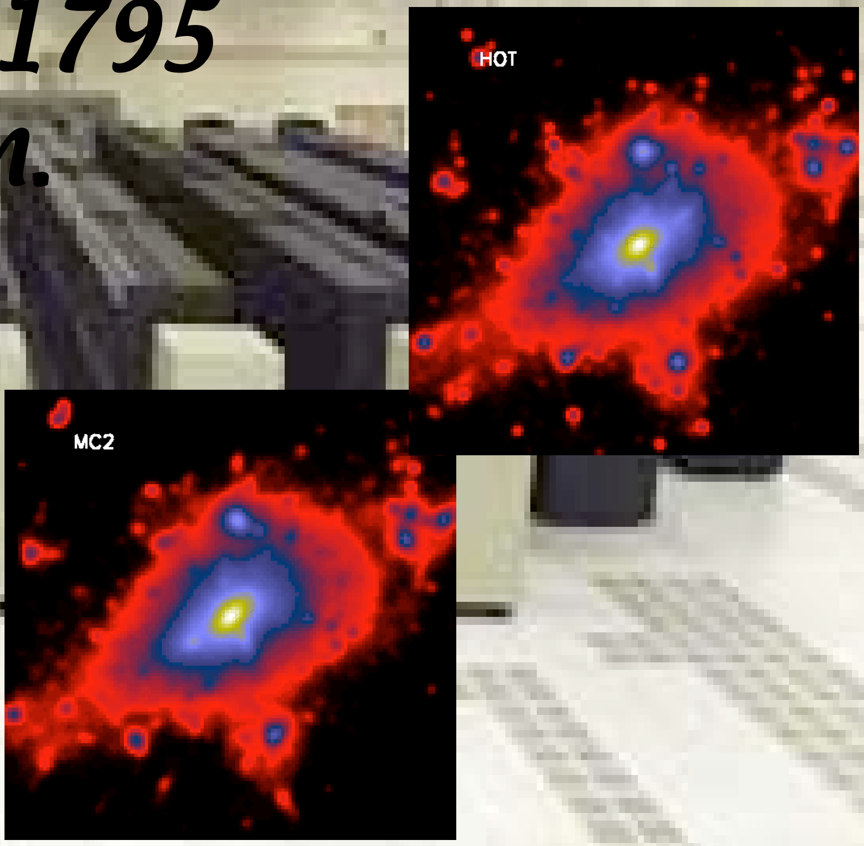
Robustness of Cosmological Simulations

astro-ph/0411795

ApJS subm.



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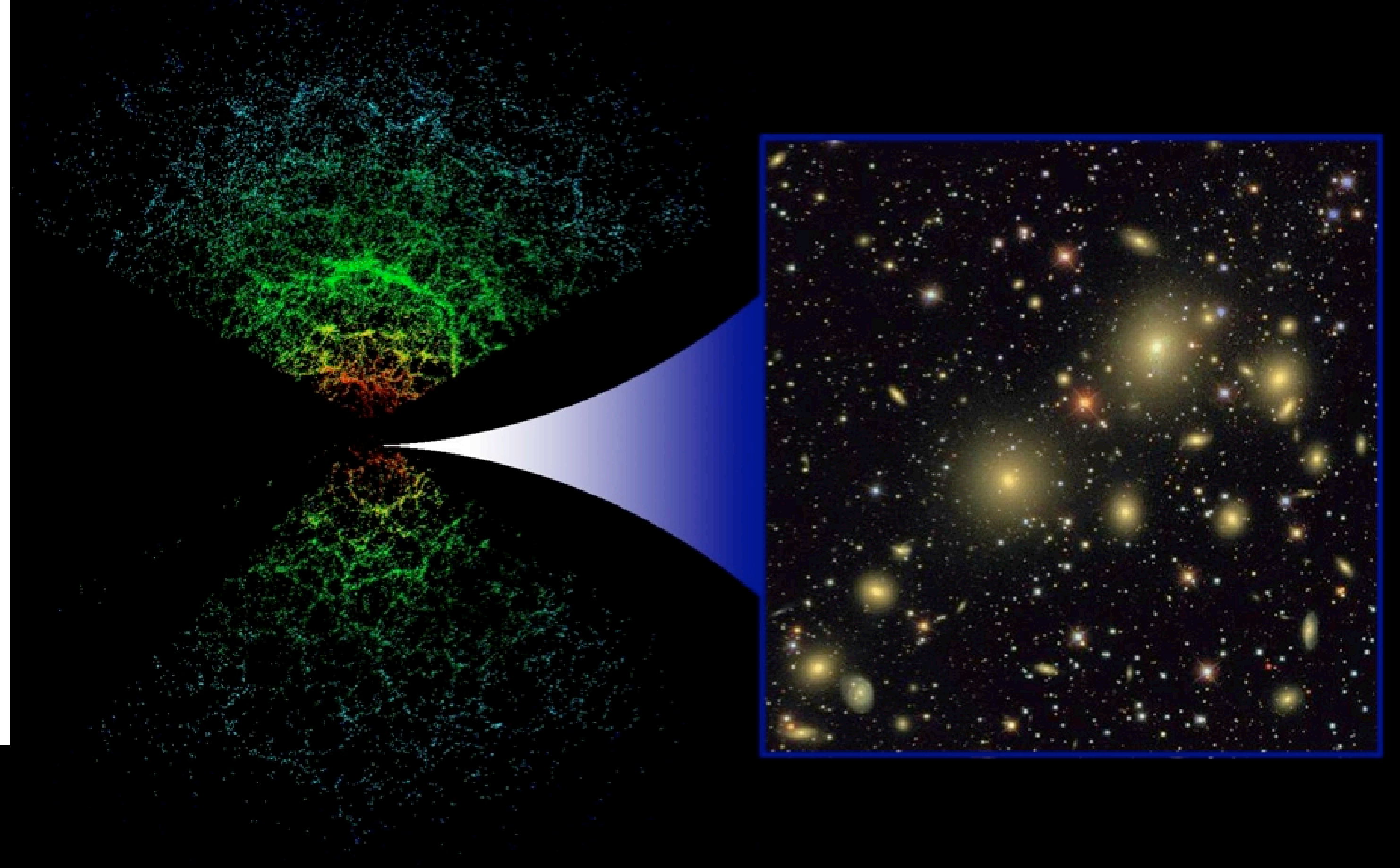
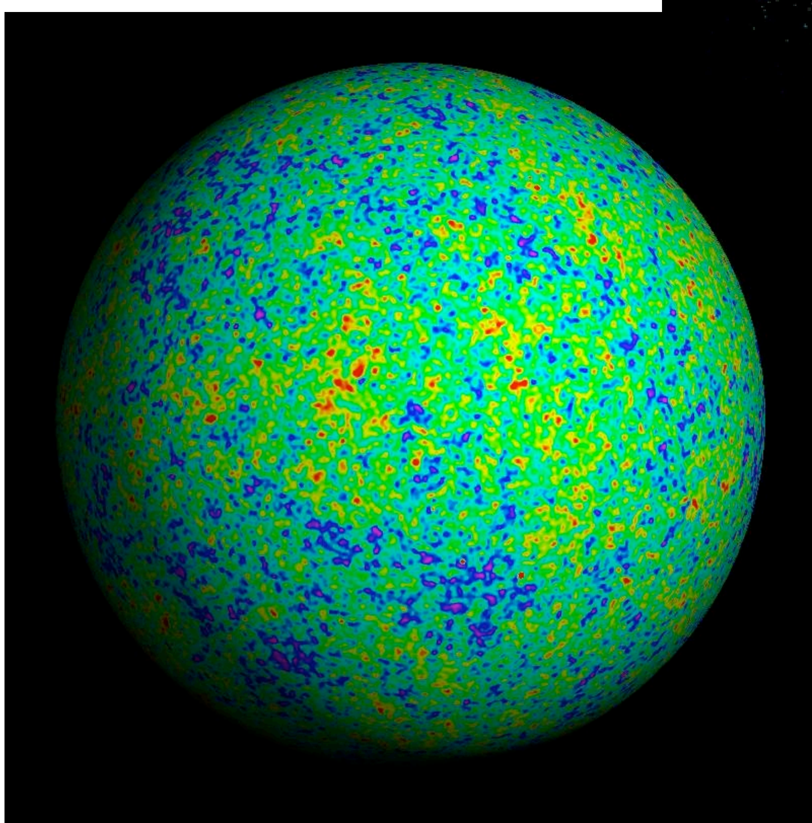
The Gravitational Instability

- very early time: Universe smoother and denser than today
- superposed on smooth background: fluctuations in temperature of the CMB and in density of matter
- CMB: snapshot of the Universe at very early times
- redshift surveys: highly concentrated structure
- under action of gravity, fluctuations in matter density grow leading to observed structure; nonlinear regime of structure formation requires numerical simulations
- cold dark matter: interacts only gravitationally, small initial velocities

Precision Cosmology: Observations

SNAP (Supernova Acceleration Probe):
2000 supernovae on 15 square degree, 300-1000 square degree lensing survey,
Ωm, $\Omega\Lambda$, Ωtot: 1% accuracy,
ω: 4%, $d\omega/dt$: 10%

SPT (South Pole Telescope):
10 meter diameter telescope, many thousands of clusters, strong constraints on ω

LSST (Large Synoptic Survey Telescope):
8.4 meter, digital imaging across entire sky, supernovae etc., constraints on ω

DES (Dark Energy Survey):
galaxy cluster study, weak lensing, 2000 SNe Ia, constraints on ω at the one percent level

What about Theory?

- Era of "precision cosmology", ongoing and up-coming surveys will measure cosmological parameters to high accuracy
- Weak lensing surveys: will probe matter distribution in the Universe directly, require precision to about 1-2% for matter power spectrum calibration (Huterer & Takada, astro-ph/0412142), measurement of nonlinear power spectrum
- Constraints on cosmological parameters (especially ω) from cluster surveys: $P_{Cluster}$, dN/dz (Majumdar & Mohr 2003, –)
- Halo model (semi-analytic model) relies on accurate fits of power spectrum, mass function, halo profiles

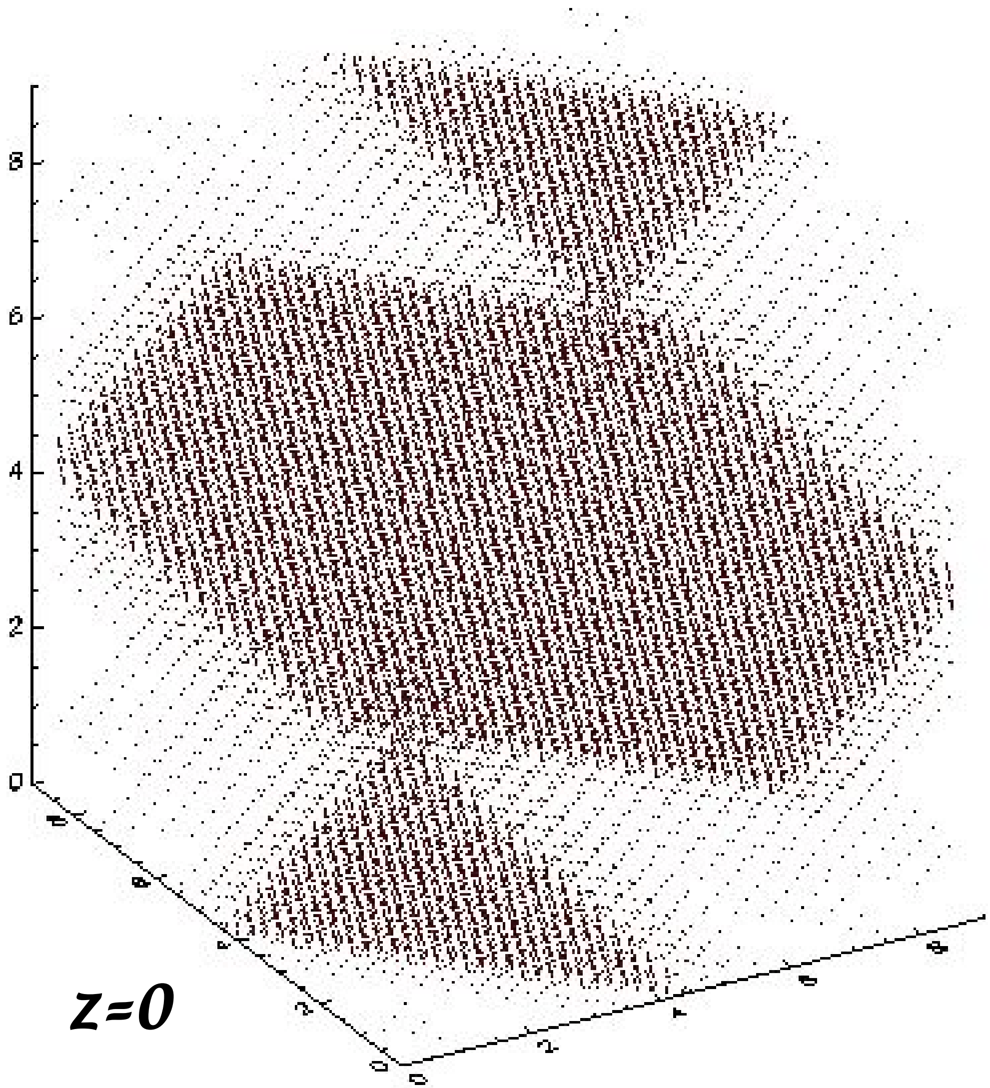
How good are Simulations?

- due to dynamical complexity of the gravitational instability, no rigorous error control theory exists
- test and compare 6 different N-body codes for simulations of structure formation, dark matter only
- 4 different test problems: Zel'dovich pancake test, Santa Barbara cluster, 360 Mpc - ΛCDM cosmology, 90 Mpc- ΛCDM cosmology
- medium resolution regime: 10-100 kpc (baryons and hence gas dynamics, star formation etc. neglected)
- every code starts from identical particle initial conditions
- results are analyzed with the same set of analysis codes
- investigation of particle-2-point functions, velocity statistics, halo catalogs, etc.

The Six Codes

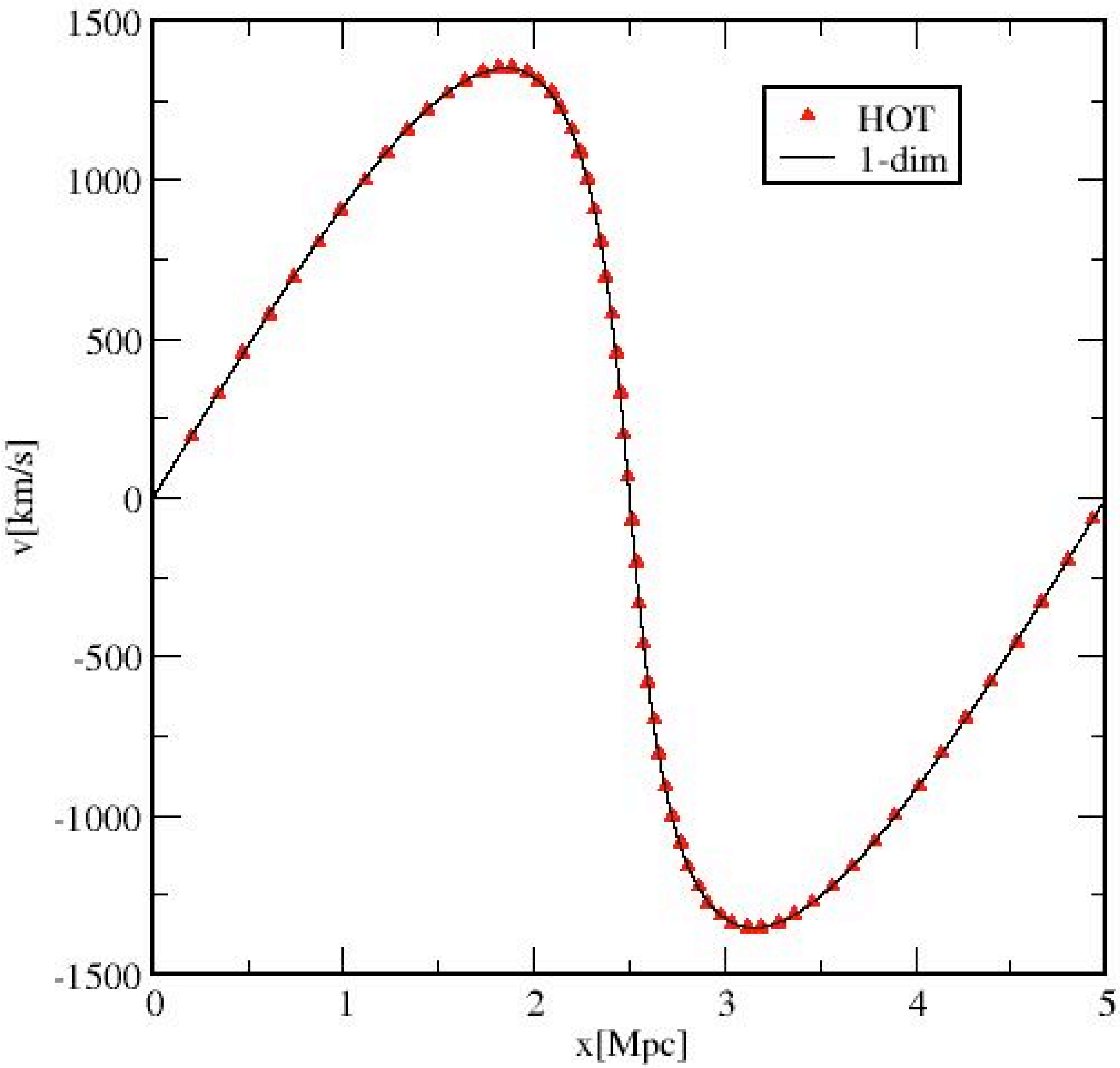
- *Mesh-based Cosmology Code, multi-species particle mesh code (Habib et al. in prep.)*
- *FLASH, adaptive mesh refinement hydrodynamics + dark matter code (Fryxell et al. 2000)*
- *Hashed-Oct Tree, tree code with SPH (Warren & Salmon 1993)*
- *GAlaxies with Dark matter and Gas intEracTions, tree code with SPH (Springel et al. 2001)*
- *HYDRA, AP^3M code with SPH (Couchman et al. 1995)*
- *TreePM, pure dark matter code (Xu 1995, Bode et al. 2000)*

The Zel'dovich Pancake



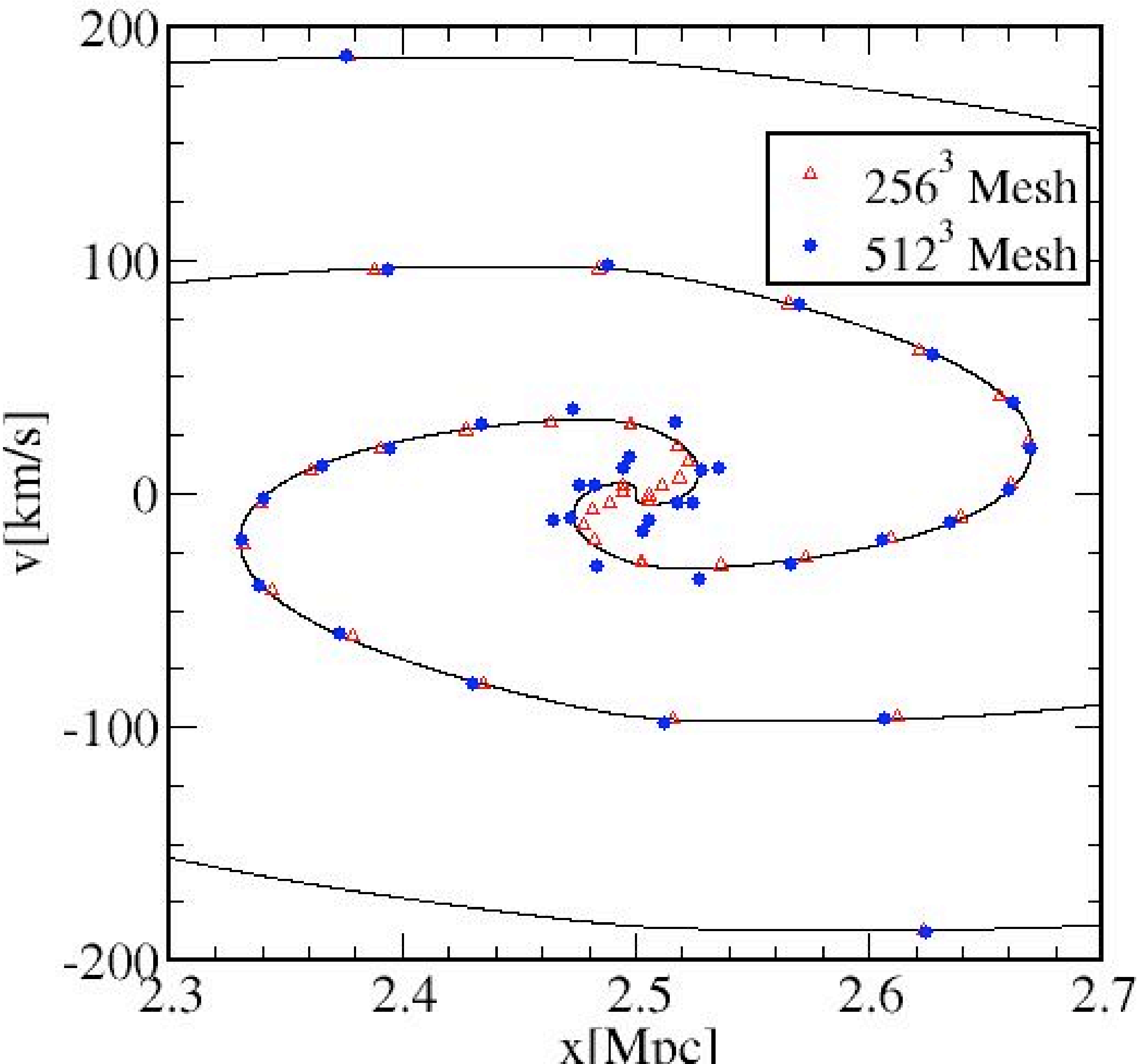
- single plane wave at an angle to the simulation box
- $$x = q - \frac{1+z_c}{1+z}\frac{\sin kq}{k}$$
- formation of caustics after critical redshift
- Mellot et al 1997: claim to detect unphysical collisionality in high resolution simulations
- would such a failure lead to problems for cosmological simulations?
- test: 64^3 particles, different resolutions

The Zel'dovich Pancake at z=7



- *Result from HOT (tree-code) at z=7, before caustic formation*
- *Phase-space plot*
- *Comparison with high-resolution 1-dim run*
- *Every red triangle sits on top of a layer of 64 triangles*
- *HOT traces the exact solution precisely, as do all other codes at this redshift*

The Zel'dovich Pancake at z=0



* Results from FLASH at z=0 after several caustics have formed

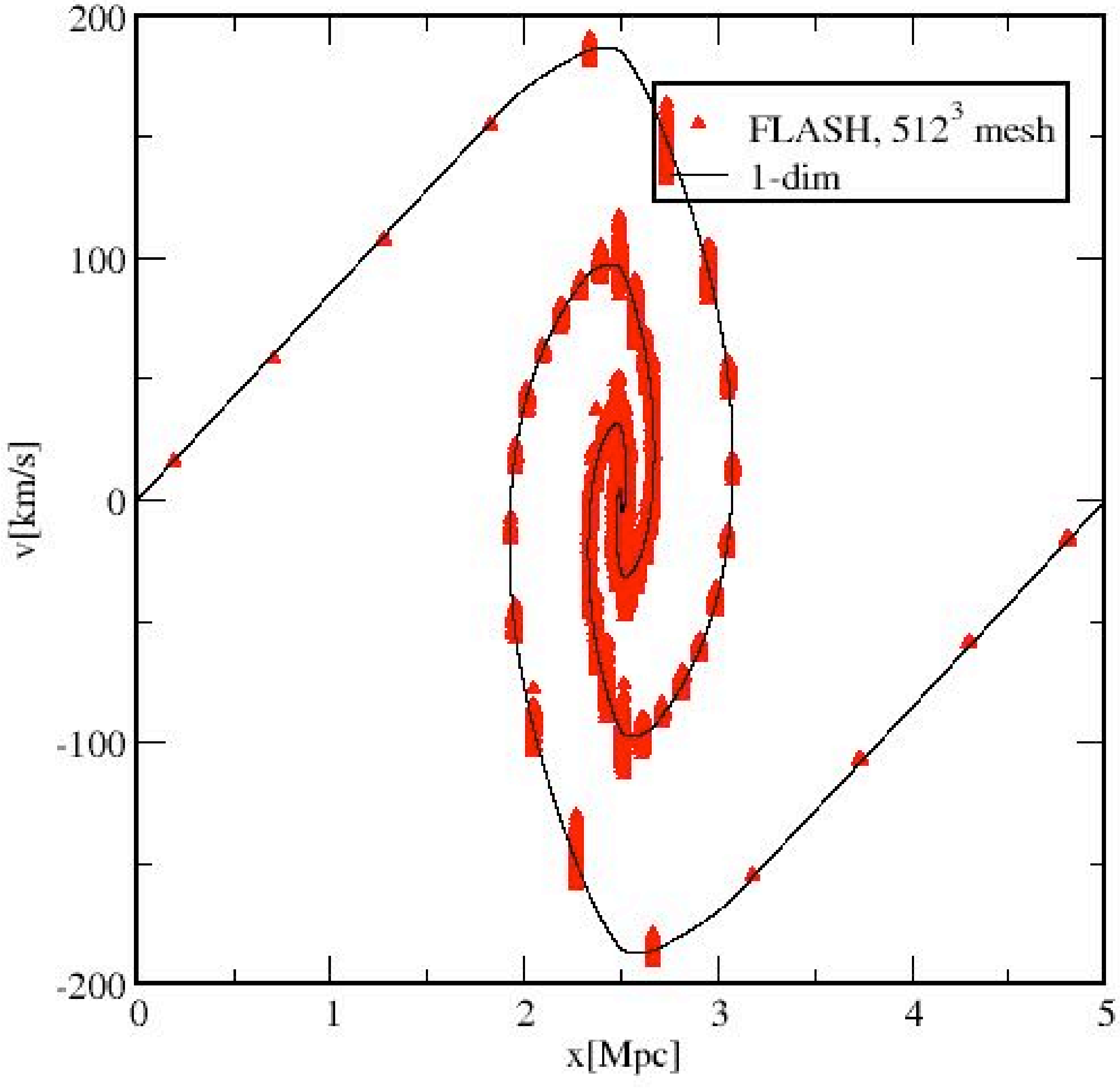
* three different resolutions, but NO AMR!

* nice convergence!

* Results from MC² with even higher resolution (lower resolution same as FLASH results), zoom into center of spiral

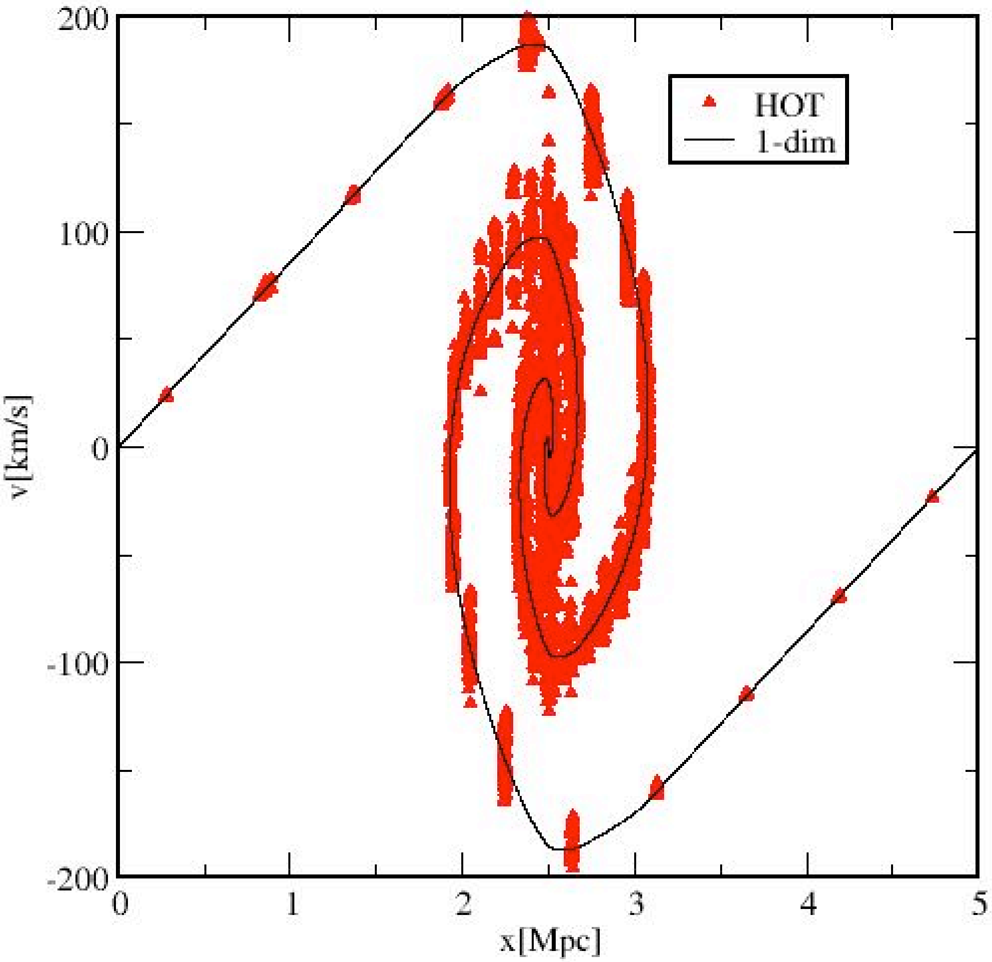
* Collisional effects!

The Zel'dovich Pancake at z=0



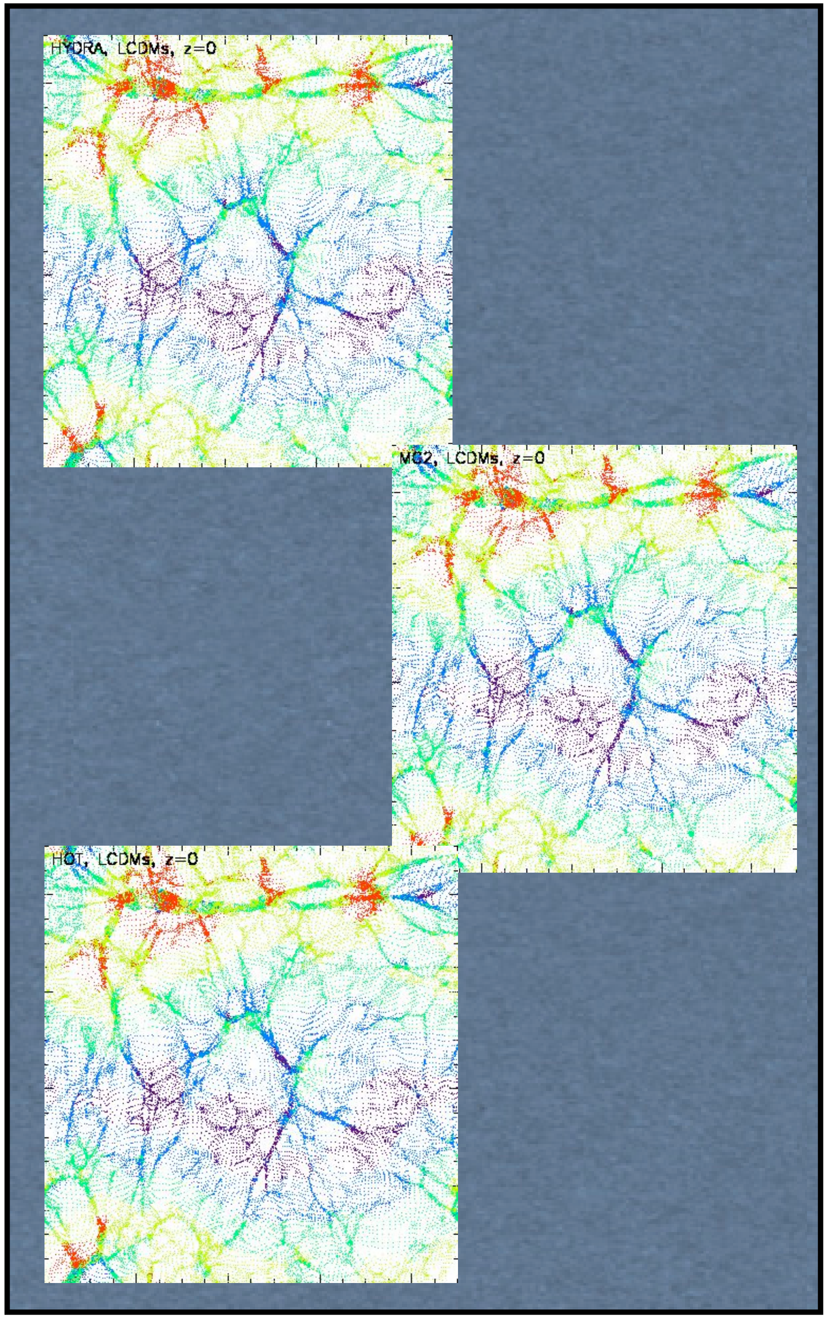
- FLASH result with AMR!
- effective resolution: 512^3, same as for MC^2
- particles cannot track the correct solution anymore, artifacts much worse than mild lack of convergence in plain PM simulation
- failure of maintaining planar symmetry of pancake problem

Lessons from the Pancake Test



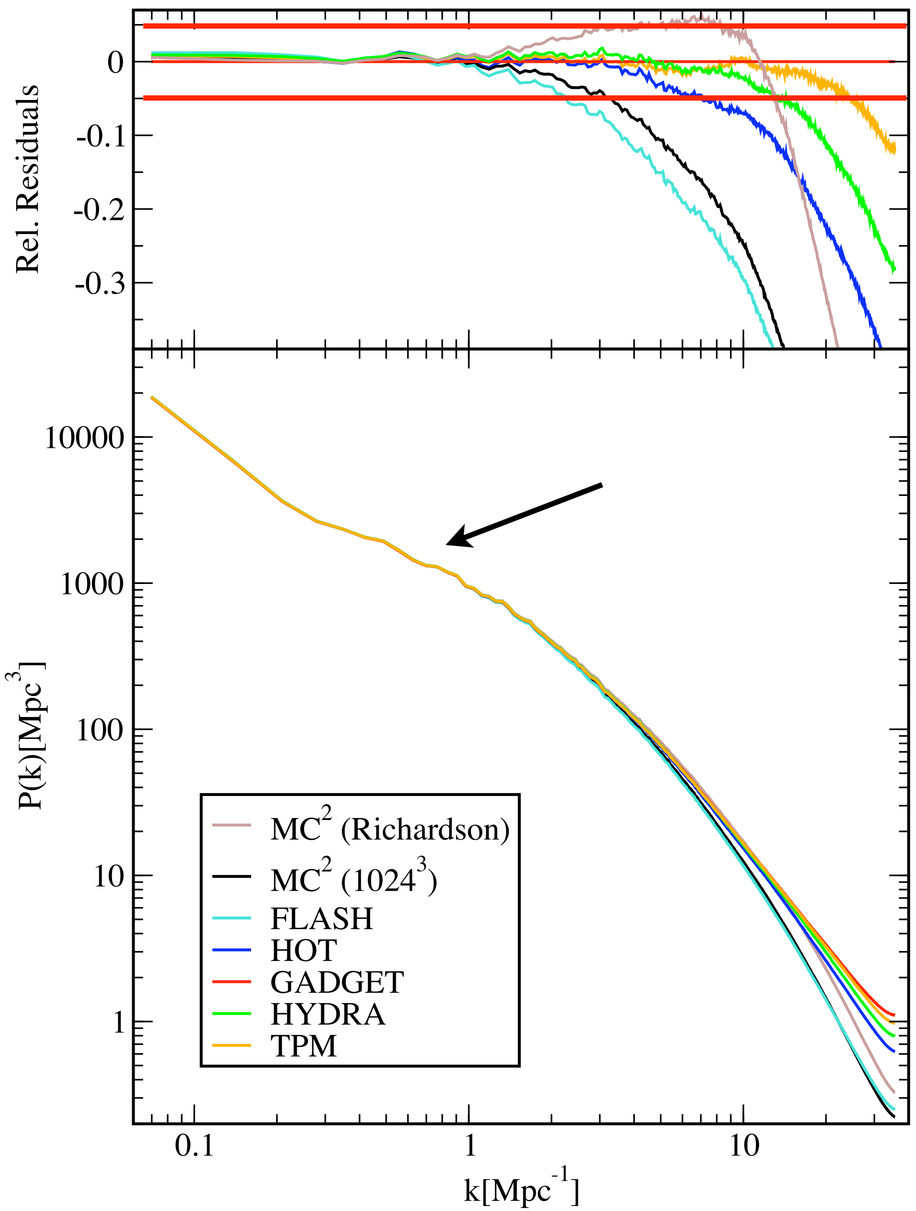
- *similar results as for FLASH are found for HOT (tree) and HYDRA (AP³M)*
- *GADGET and TPM didn't finish*
- *basic problem is NOT collisionality but the maintenance of planar symmetry*
- *"tough" problem, in cosmological simulation usually no "head-on" collision*
- *perhaps no problem in realistic simulations?*

ΛCDM Cosmology



- ***Standard concordance model** (Spergel et al. 2002)*
- *90 Mpc* ***and 360 Mpc boxes***
- ***parameter range is typical of larger "application" simulations***
- ***Particle statistics: "slices",** power spectrum, **correlation function, velocity statistics***
- ***Halo statistics:** mass function, power spectrum, **correlation function, velocity statistics, comparison of individual halos***

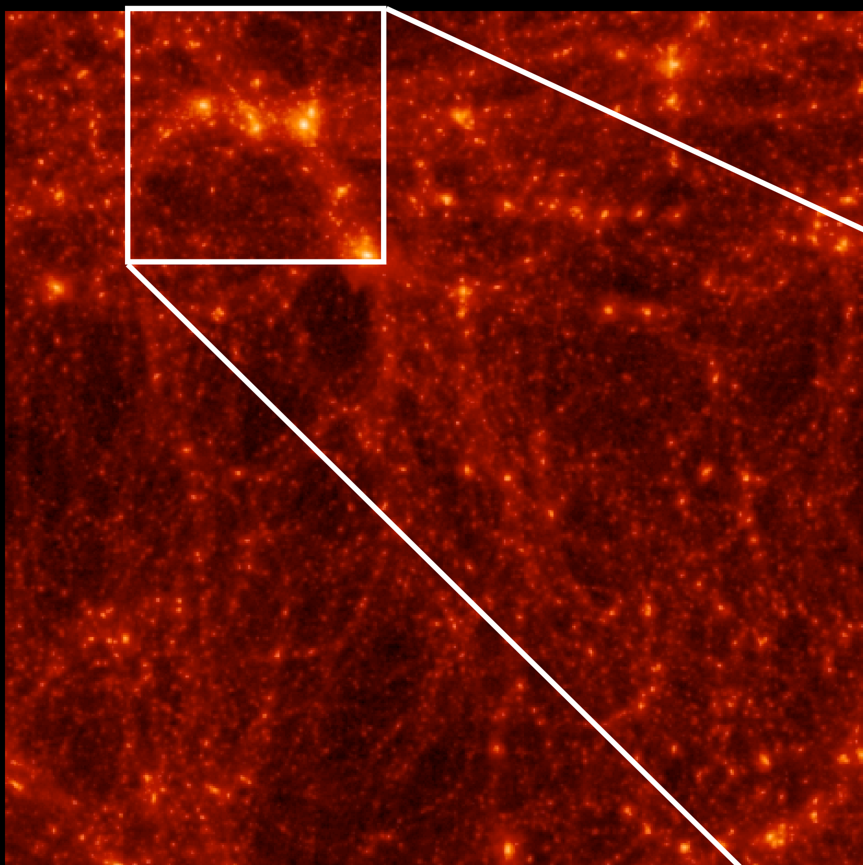
The Matter Power Spectrum

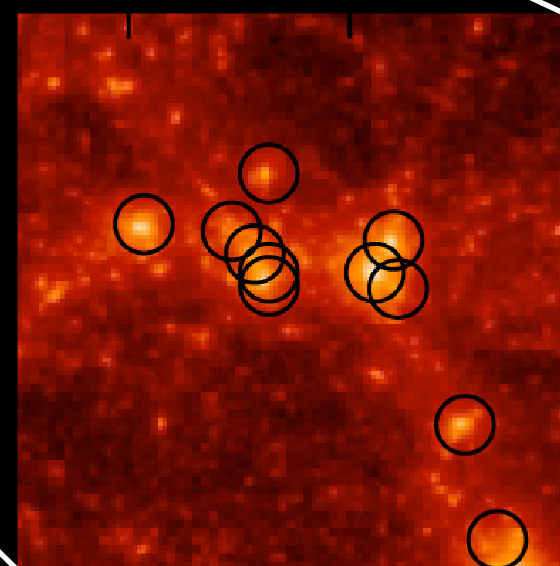


- *P(k) measured from particles*
- *nonlinear turn-over at roughly 0.7 Mpc^{-1}*
- *two grid codes have less resolution, fall off consistent with grid size*
- *FLASH: 40.8% fully refined*
- *agreement: 5-10%*
- *discrepancies in high resolution codes needs further investigation*

Halos

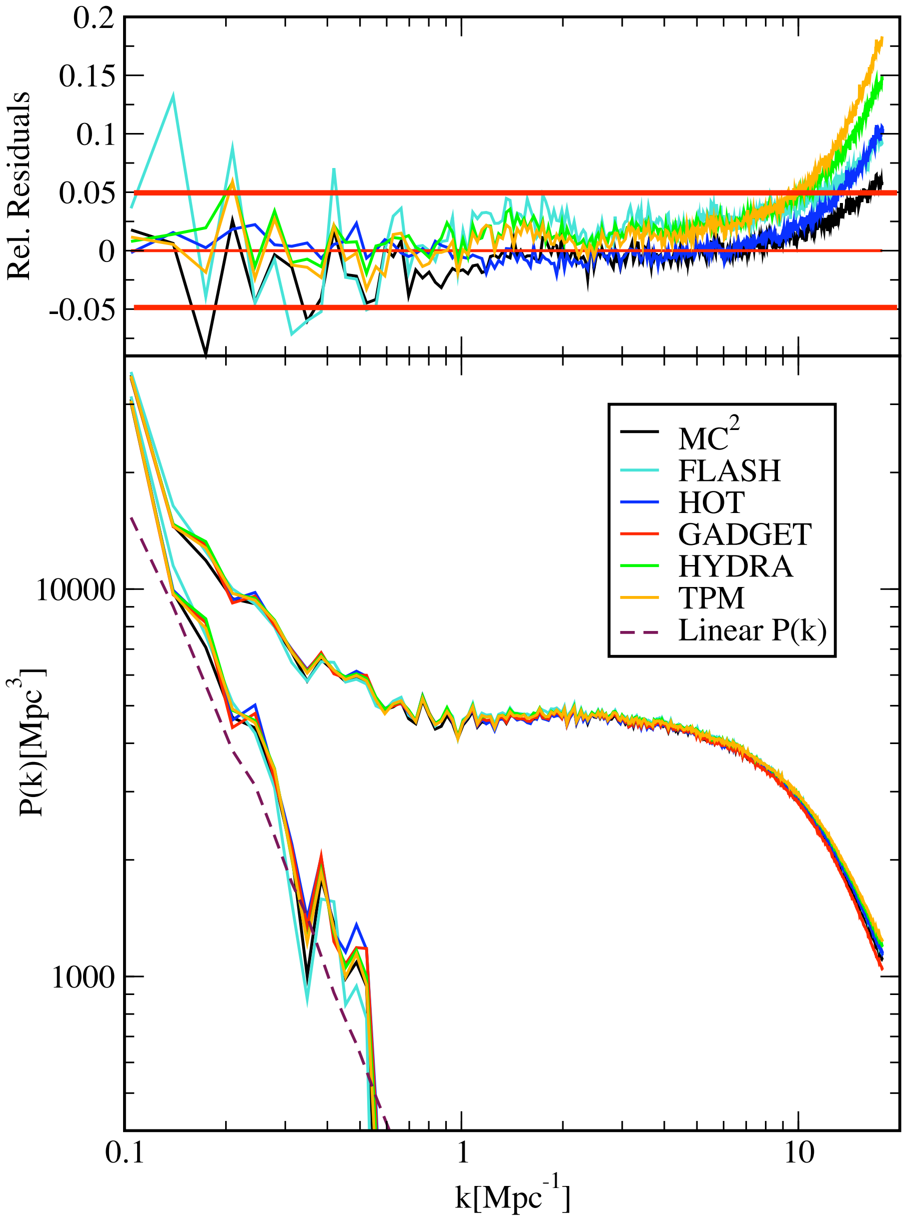
- How to find/define them?
  → overdensity, nearest neighbor
- Observational relevance?
  → galaxy and cluster surveys





marked halos ≥ 10,000 particles
halos identified ≥ 10 particles
particle mass ≈ $2\ 10^{9} M_{\odot}$

The Halo Power Spectra

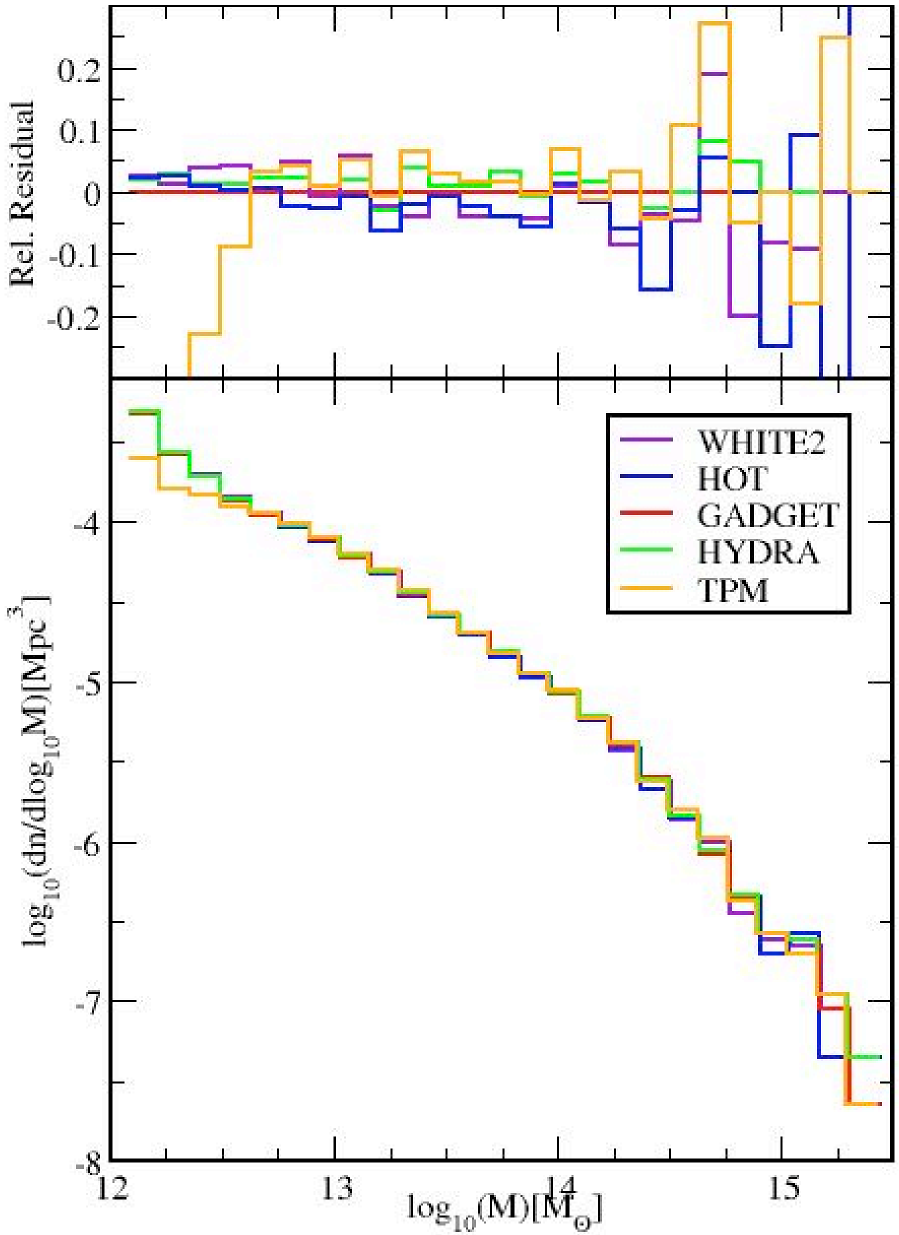


- *Halo P(k)*
- *consider only halos with more than 100 particles*
  → roughly 5000 halos
- *upper curve: 512^3 FFT*
- *less than 5% deviation for $k < 10 Mpc^{-1}$*
- *lower curve: denoising and sharpening*
- *statistics not good enough for qualitative statements*

The Mass Function

- n(M): number density of clusters/halos with mass > M in comoving volume element (depends on definition of M!)
- evolution of mass function is highly sensitive to cosmology because matter density controls rate at which structure grows
- after Press/Schechter: semi-analytic fits by Sheth &Tormen (1999) and Jenkins et al. (2001) using simulations (CAUTION: fits only reliable for cosmologies they are tuned to!)
- fits and their evolution are controlled by growth function D(z), which itself is a function of Ωm, $\Omega\Lambda$, and ω
- mass function is powerful probe of cosmological parameters! BUT: systematic errors in measurements of cluster masses (including inconsistency in definition of the cluster mass) also amplify exponentially

The Mass Function



Number of halos:

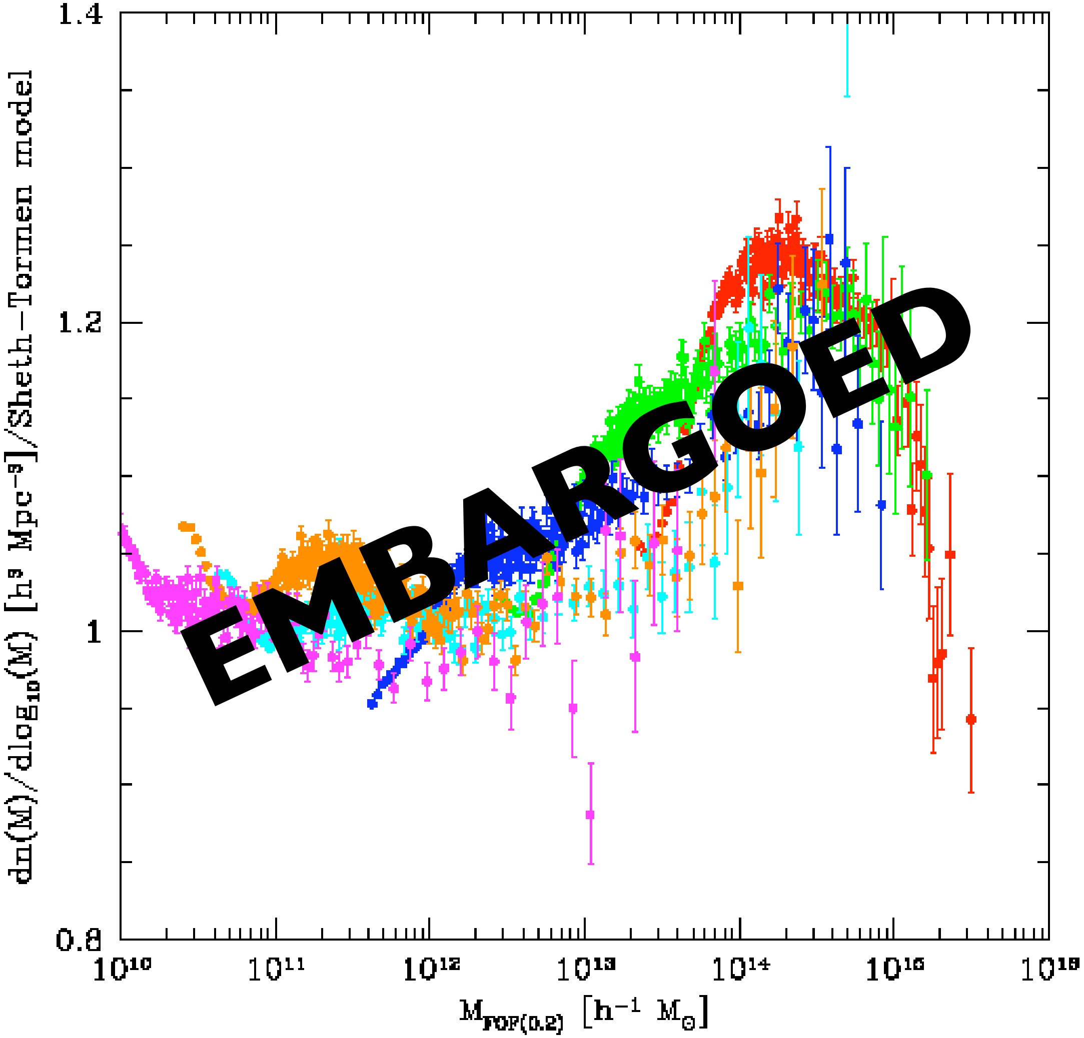
MC²	FLASH	HOT
49087	32494	54417
GADGET	TPM	HYDRA
55854	34367	54840

- FOF halo finder, b=0.2
- FLASH, TPM lower than others
- FLASH: understood
- TPM: only problem with this particular treePM code
- 5-10% deviation

The Mass Function - Some News...

M.S. Warren, K. Abazajian, D. Holz, L. Teodoro, in prep.

Relative Mass Function from different boxes



- *15 simulations with 1-2 billion particles each*
- *different box sizes, 96Mpc/h - 6144Mpc/h*
- *5 orders of dynamic range in mass*
- *statistical sampling bias at 10% in FoF halo finder!*
- *new mass function fit after correction*

Conclusions

- *Comparison of six different codes (PM, AMR, Tree, TPM, AP^3M) in medium resolution regime*
- *agreement in general ~5%*
- *larger disagreements usually understandable (e.g. insufficient force resolution)*
- *code agreement in one or two tests is no guarantee of overall performance (e.g., mass function in TPM)*
- *BUT: in order to achieve accuracy necessary for future surveys, this is NOT sufficient!*
- *WE NEED: development of multi-step error control methodology; perhaps hopeless for some tasks but maybe viable for others*
- *in addition: analysis tools have to be under control*
- *Cosmic Data ArXiv started!*

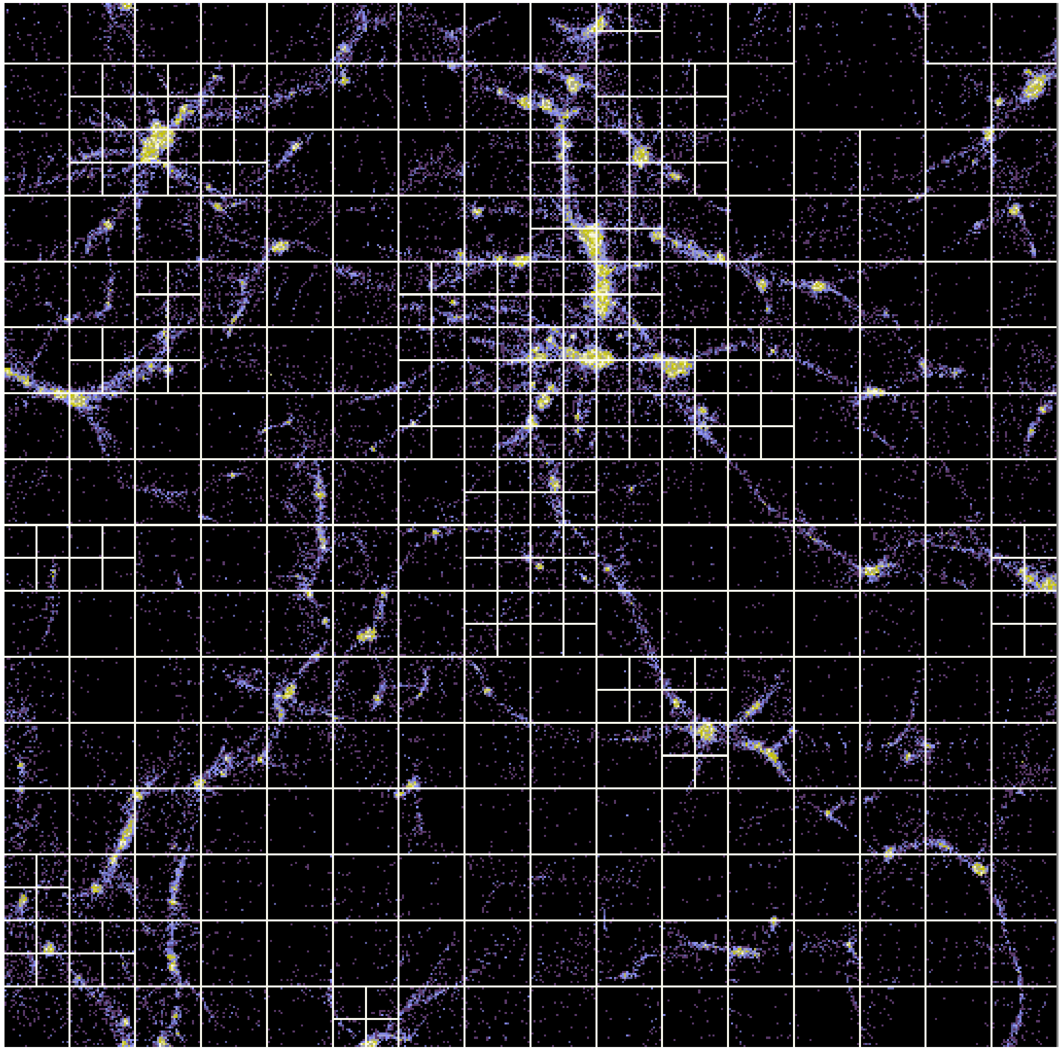
The Cosmic Data ArXiv

- Home
- About this Project
- The Data ArXiv
- People
- Codes
- Machines

Image: M81, Credit: N.A. Sharp (NOAO/AURA/NSF)

http://t8web.lanl.gov/people/heitmann/arxiv

Adaptive Mesh Refinement



AMR refinement levels superposed on a partial density slide

- base grid for FLASH: 256^3, refined up to 1024^3
- initially, resolution not sufficient to form small halos
- time goes on: refinement of high density regions, small halos can't be recovered
- very good results for large halos and their properties but suppression of mass function for small masses
- solution: AMR-specific initial conditions (Lukic et al. in prep.)