Where baryons start to matter…

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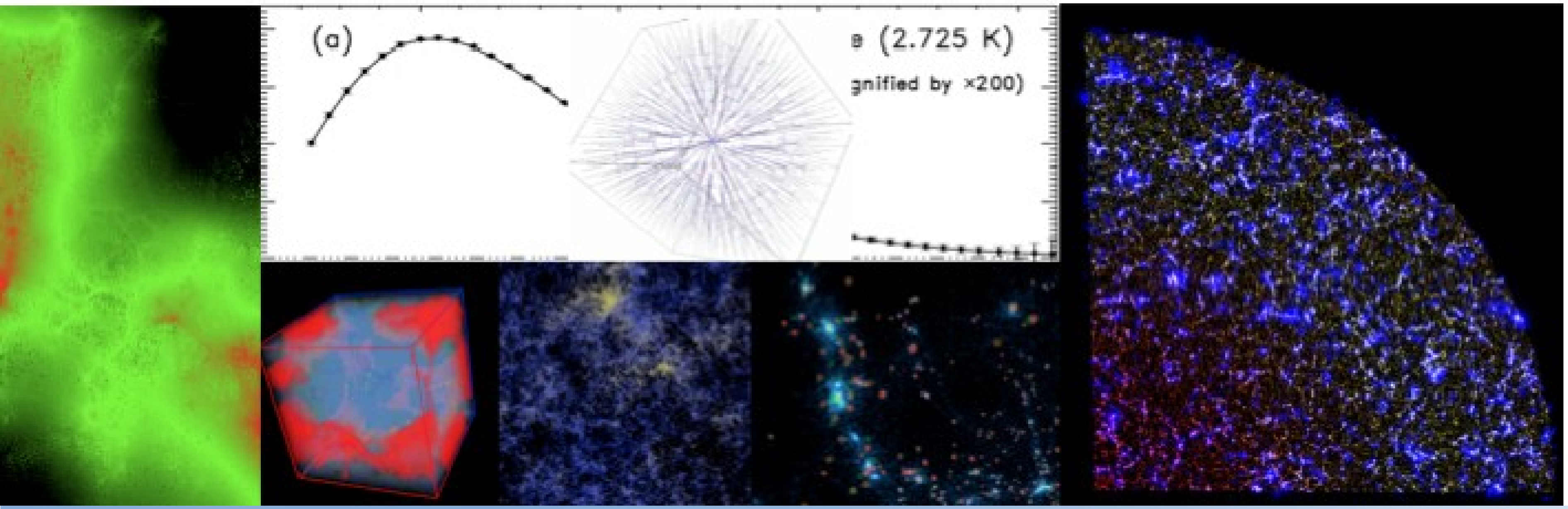
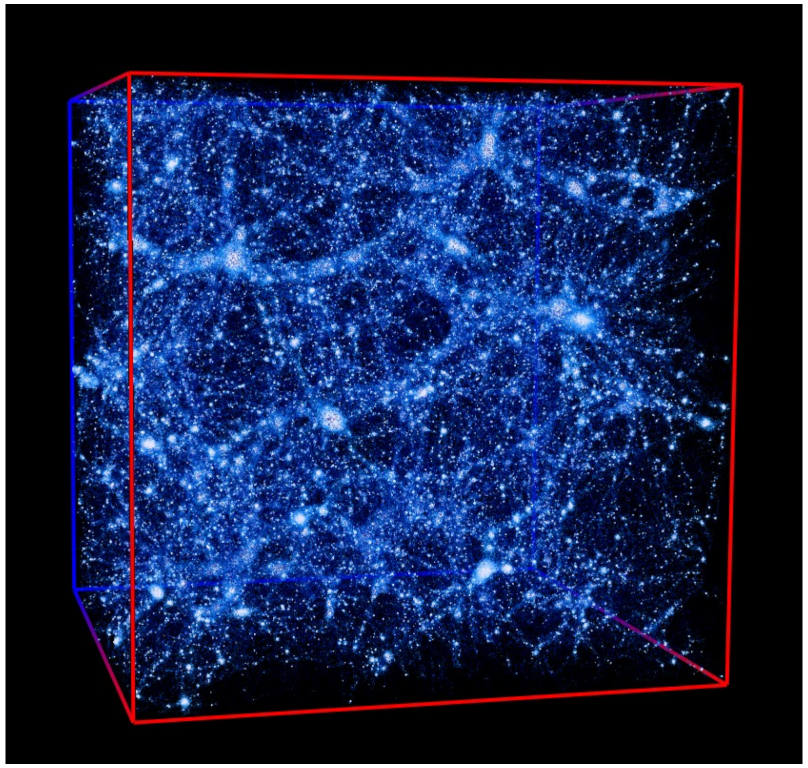
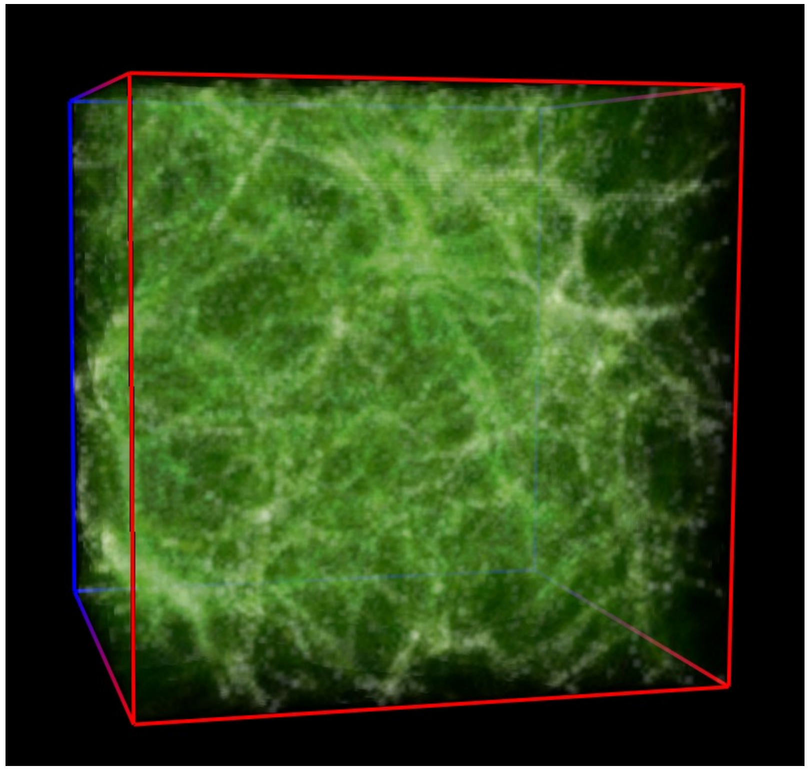
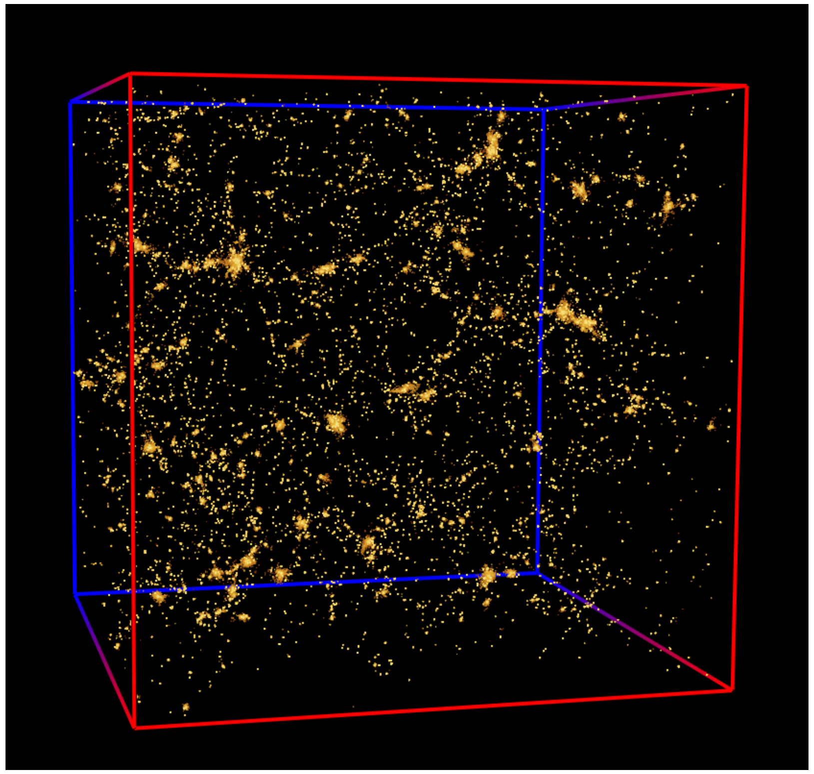
Fermilab



Where baryons matter







Dark matter → Gas → Galaxies

- Since we can only see light, baryons ***always*** matter.
- Sometimes, they are just tracers – simple models can be used to "paint" dark matter with stars.
- If their dynamics is important, there is no choice but to include gas (and stars, and radiation, and …) into simulations.

Where ***baryonic dynamics*** matters

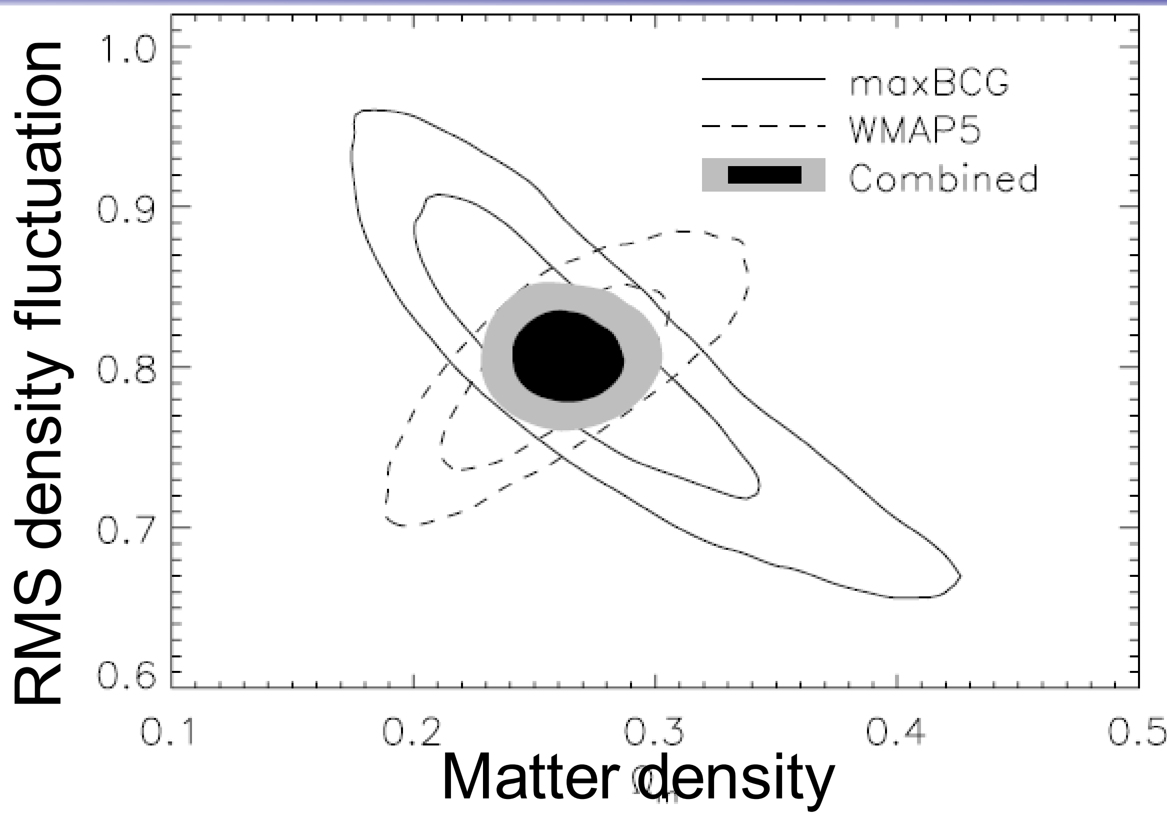
- *Interpreting survey data*
  - Clusters of galaxies (SDSS, DES, LSST)
  - Weak gravitational lensing (DES, LSST)
  - Lyman-alpha forest (BOSS, BigBOSS)

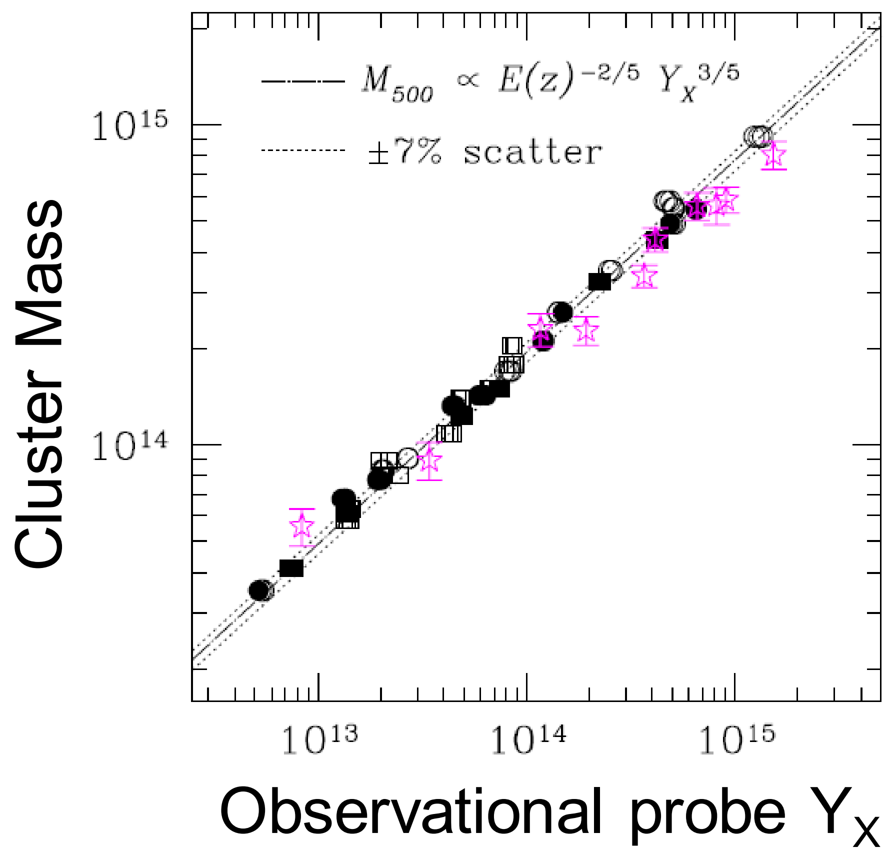
- *Cosmological framework*
  - Sharpening constraints from Cosmic Microwave Background (CMB)
  - Resolving direct dark matter detection controversy

- *"Accelerator science in cosmos"* (futuristic)
  - Galaxies as "cosmic events" – extracting the last decimal place from survey measurements

Clusters of Galaxies

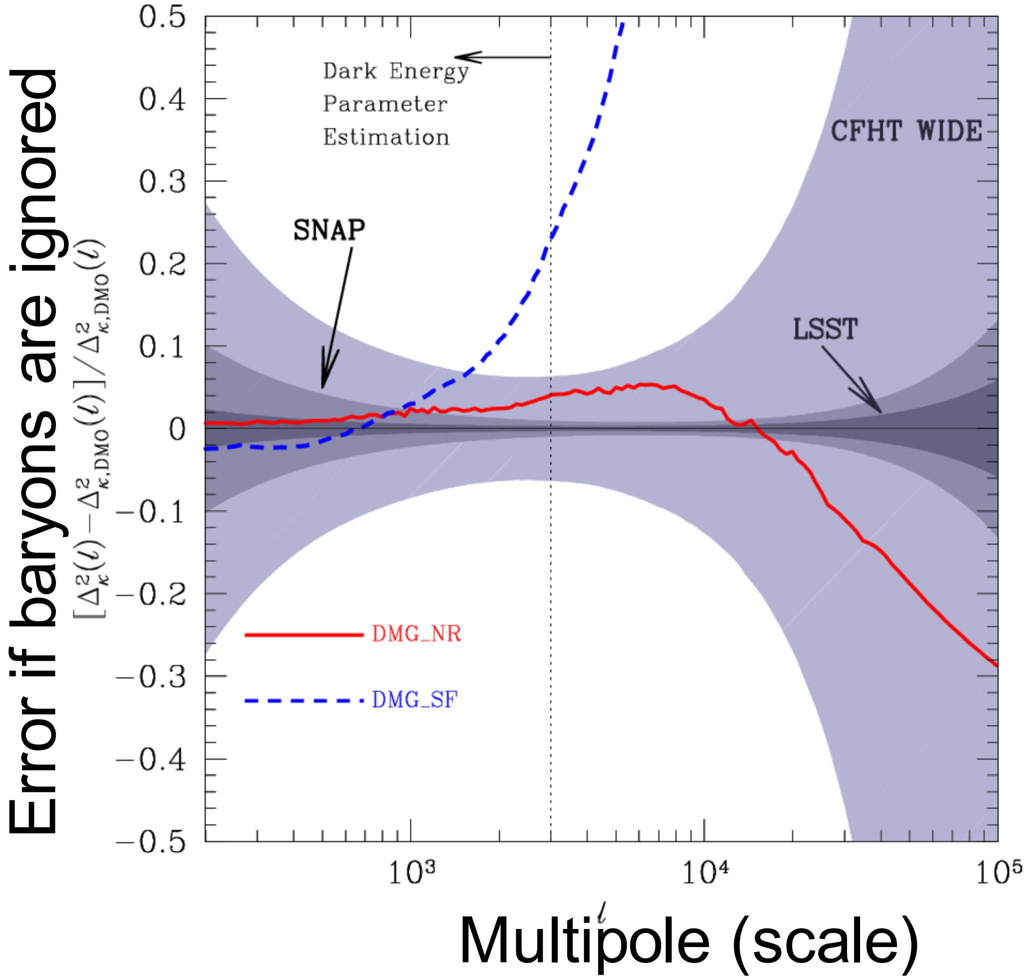
- Clusters of galaxies as probes of dark energy:
  - Systematic effects are severe.
  - Too powerful to ignore.
  - Cheap.
- Use of hydro simulations:
  - Complex physical systems, intrinsic scatter of observed relations cannot be removed.
  - Distribution of scatter should be included in parameter estimation.
  - This distribution can only be measured in simulations.





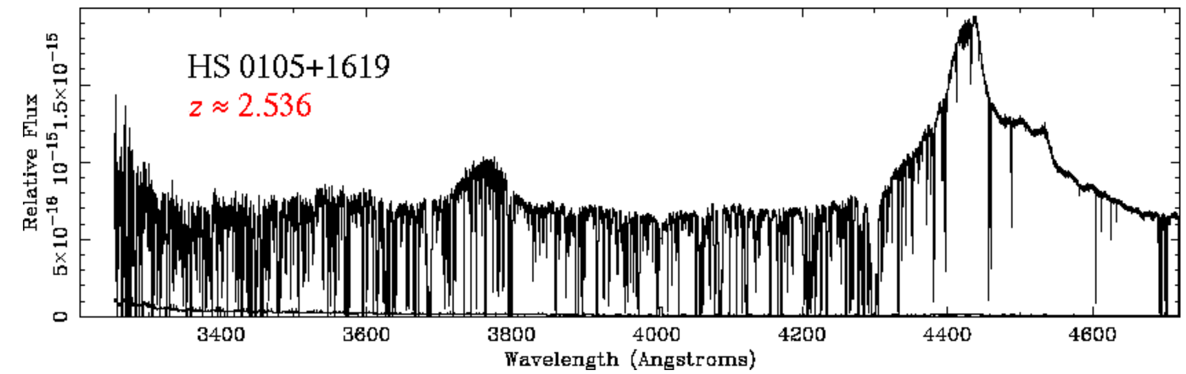
Weak Lensing

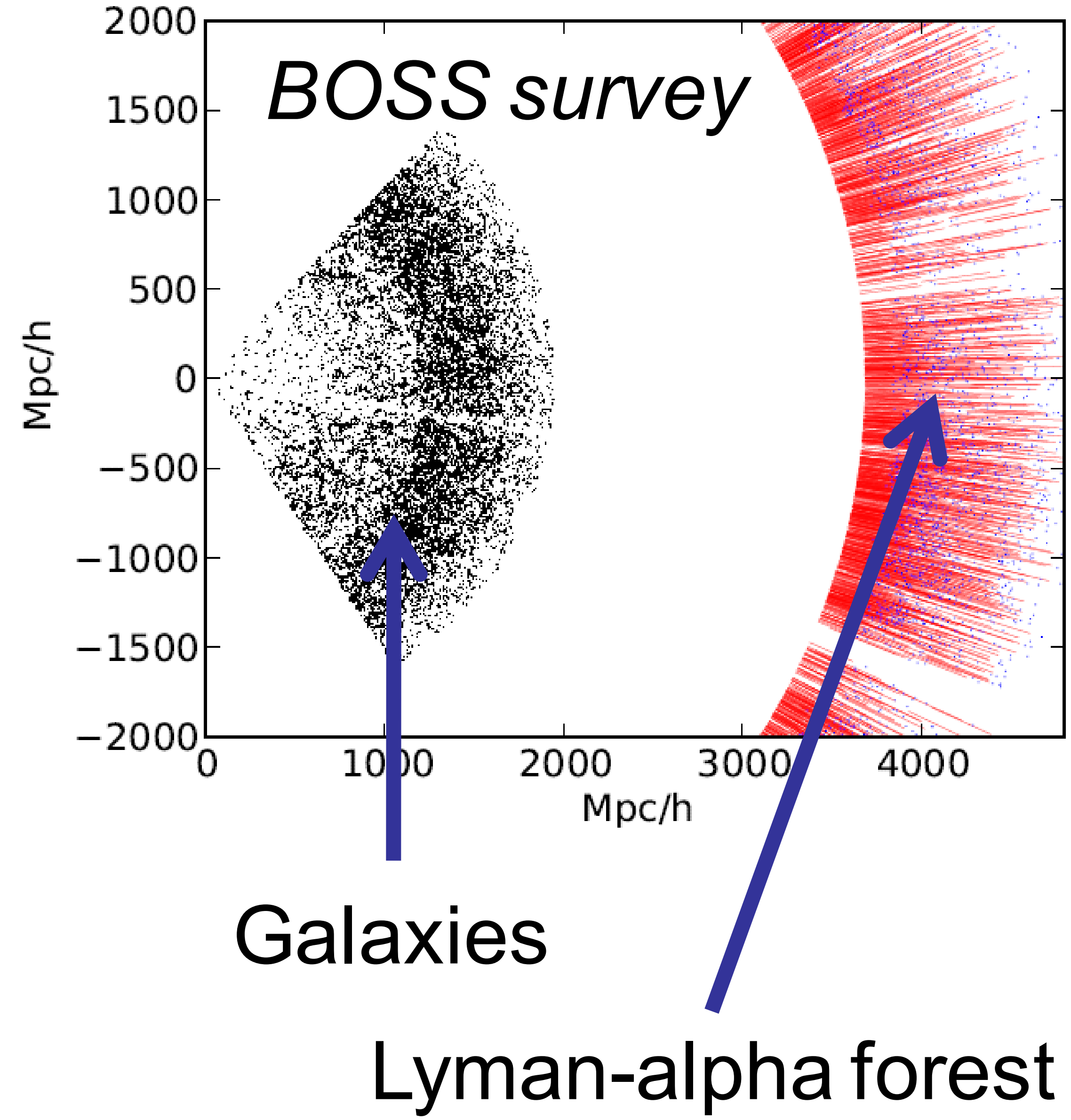
- Weak gravitational lensing as a dark energy probe:
  - Distortion of galaxy images by gravitational bending of light.
  - Measures both geometry of space (how light propagates) and gravity (how space is bent).
- Use of hydro simulations:
  - Dynamics of baryons affects the matter distribution (17% is large when we care about 1% precision).
  - Baryonic effects can be calibrated in simulations.
  - Required computational effort is massive.



Lyman-alpha Forest

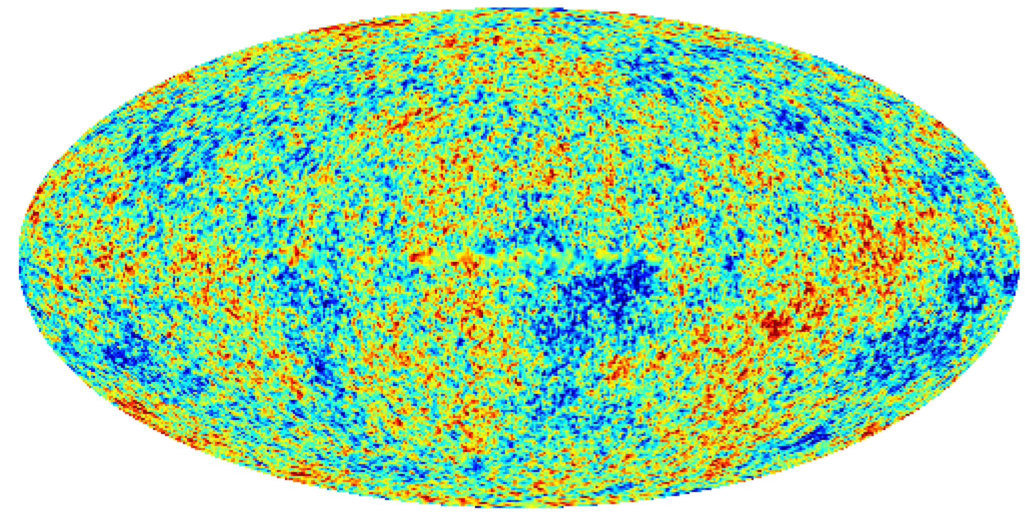
- Lyman-alpha forest as a dark energy probe:
  - “Forest” of numerous absorption lines in spectra of distant quasars.
  - Traces dark matter distribution better than galaxies.
  - Much more numerous (hence, better statistics).
- Use of hydro simulations:
  - No known “dirty” way of modeling Lyman-alpha forest to better than ~10% precision.
  - Fortunately, forest simulations are cheap (thanks to its low density).



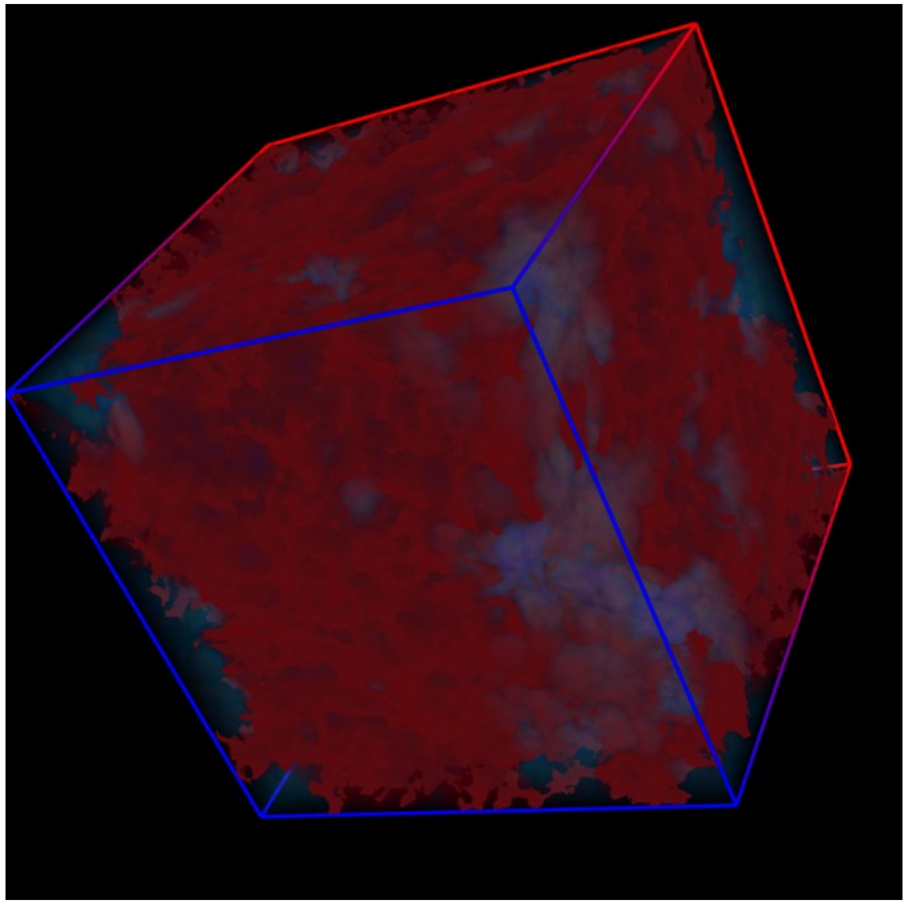


Cosmic Microwave Background (CMB)

- CMB forms a foundation of all modern cosmology research:
  - Tiny fluctuations are the remnants of the inflationary epoch.
  - Their growth is modified by the joint action of dark matter, baryons, and radiation.
  - By far the most precise test of cosmological parameters.
- Use of hydro simulations:
  - Ionization of intergalactic gas by UV and X-ray radiation (aka *reionization*) forms a screen in front of the CMB.
  - Last major systematic effect.
  - We know how to model it well.

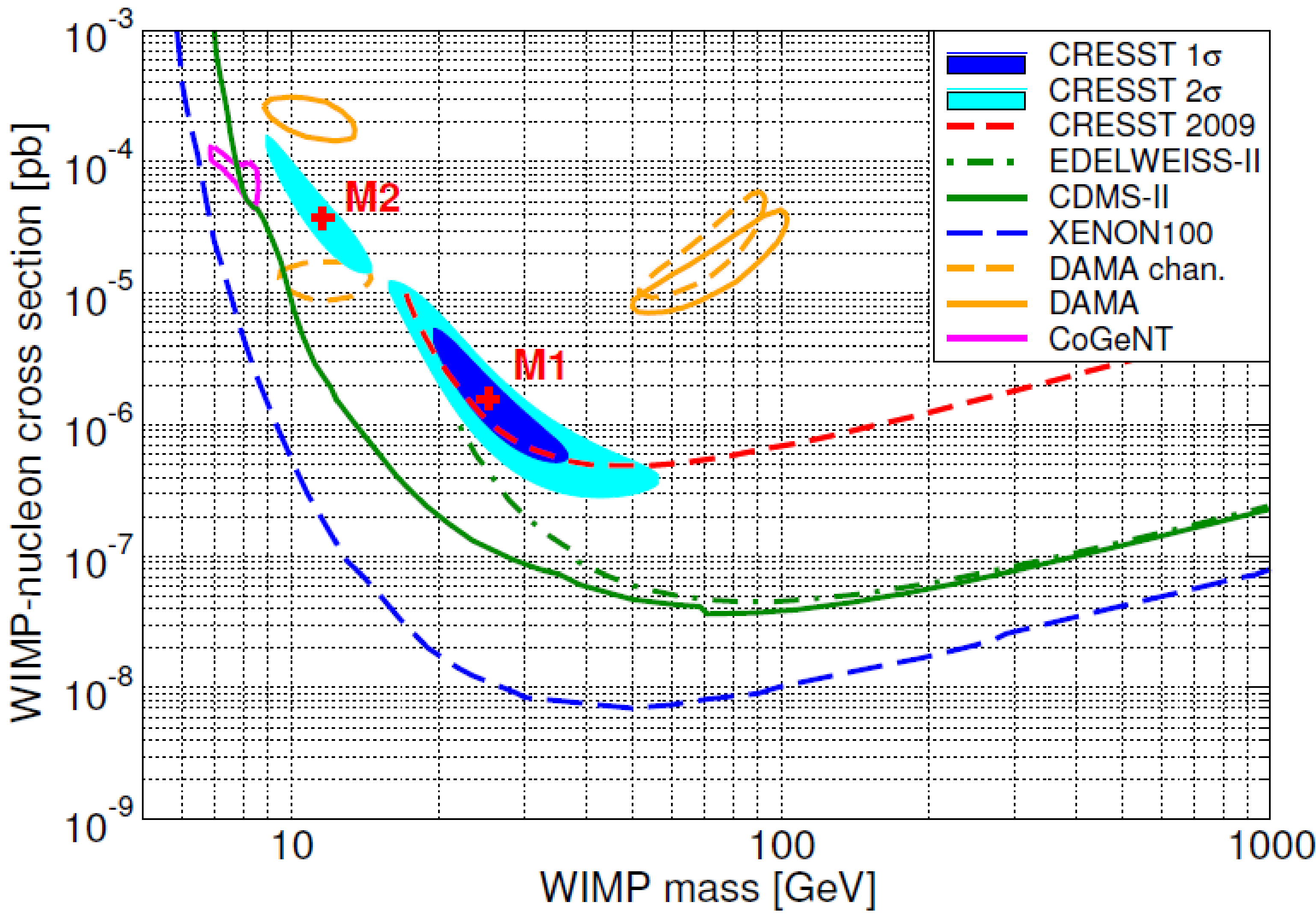


CMB map from *WMAP* satellite



Direct Dark Matter Detection

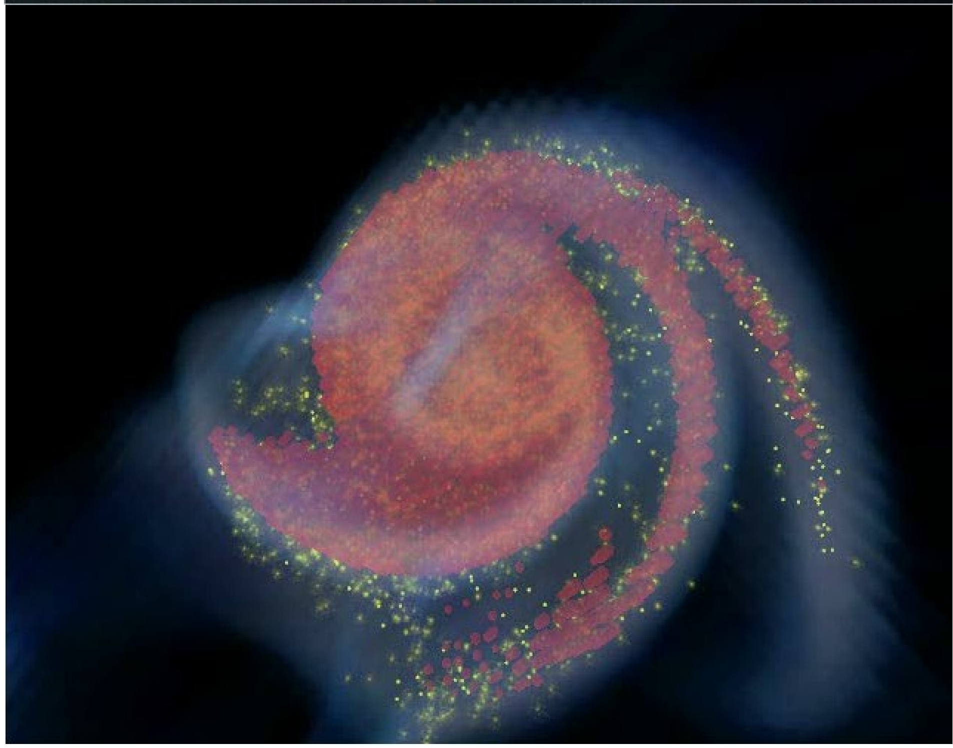
- Direct dark matter detection: *worrisome controversy*
  - 3 experiments (DAMA, CoGeNT, CRESST) claim consistent detections.
  - 3 other experiments (CDMS, XENON-100, EDELWEISS) rule them out.



- *Show stopper*: velocity distribution of dark matter particles in the Milky Way galaxy (appeared unexpectedly fast).
- Hydro simulations are required to model this distribution directly; without them the field is in danger of stagnation.

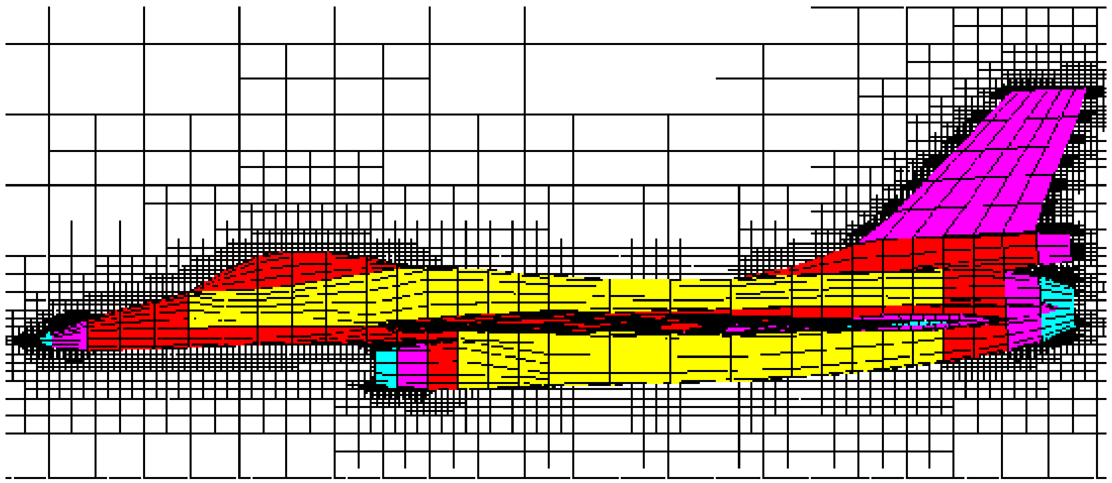
Future: The Last Decimal Place

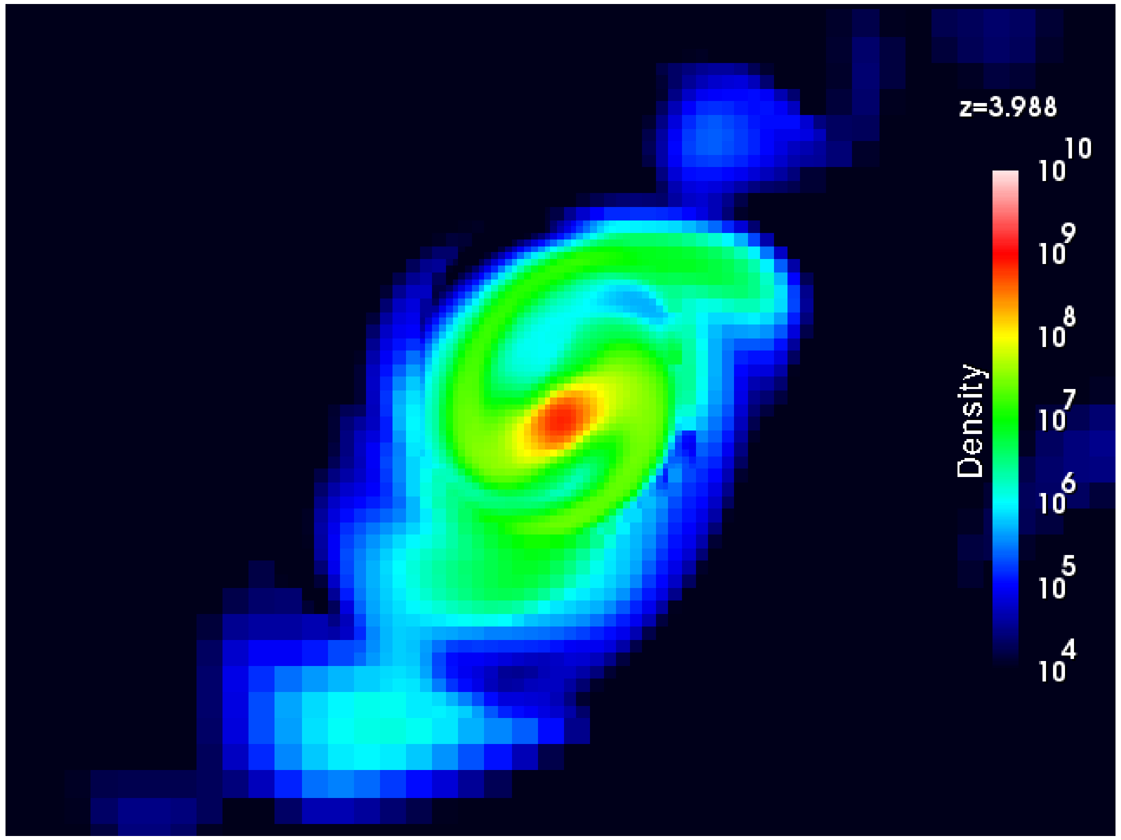
- All observational tests of dark energy rely on modeling of observables:
  - Ultimate precision of experimental measurements is limited by systematic errors.
  - Presently we have to use approximate models to paint galaxies onto large scale structure in simulations.
  - In the future (~10 years) we should be able to directly model ***all observed galaxies*** with sufficient precision (no approximations).
  - Such modeling is needed to extract the last bit of information from the experimental data.
- Directly analogous to accelerator modeling (galaxies are our "events").



Cosmic Gas Dynamics

- "Hydrodynamics" in cosmology means *gas dynamics* (astrophysicists are notorious for using bad terminology).
- We have to start (almost) from scratch – little use of engineering expertise.
  - Very high resolution is required.
  - Complex physics.
  - Gravity is the dominant force.
  - There are no solid boundaries.



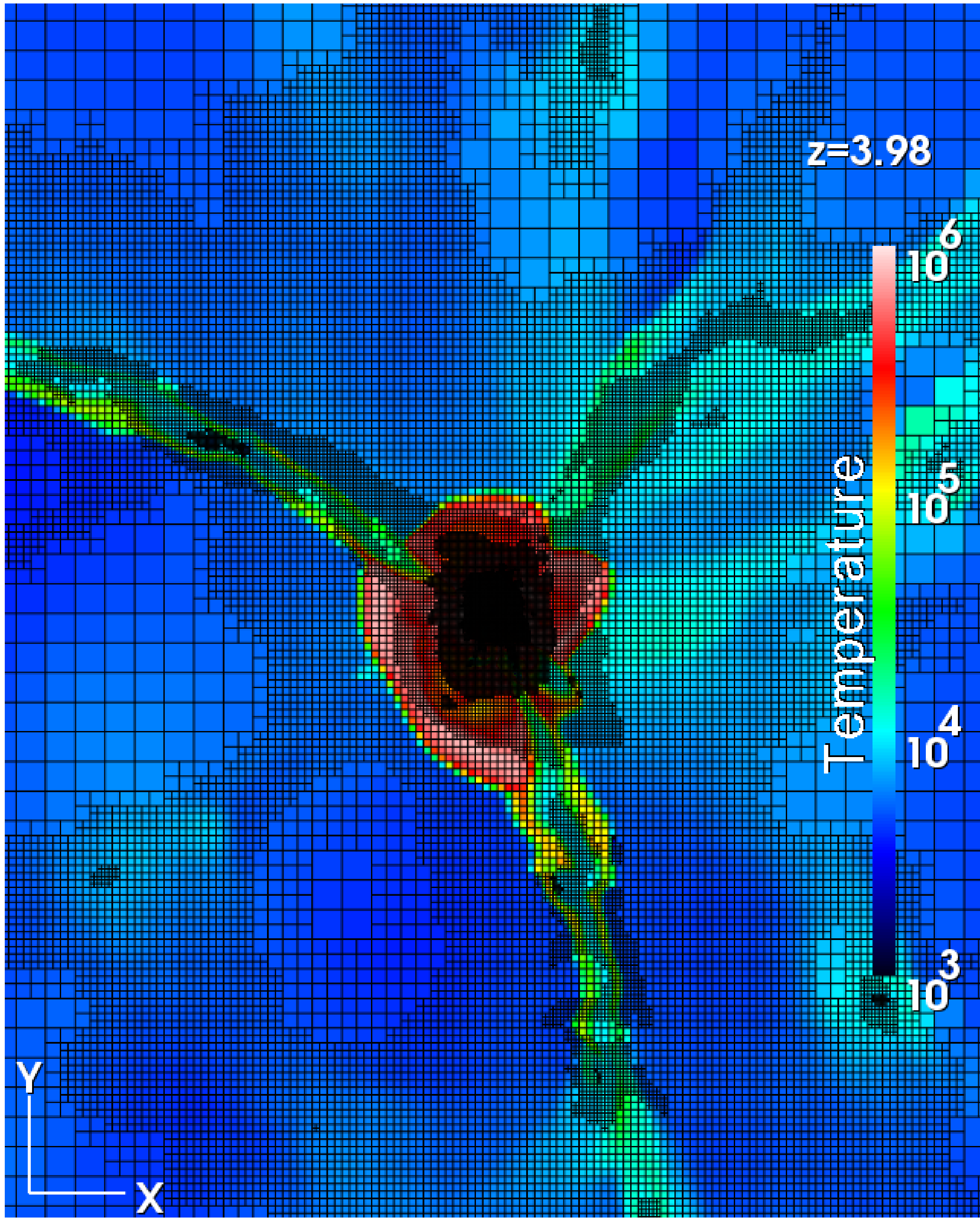


Adaptive Mesh Refinement

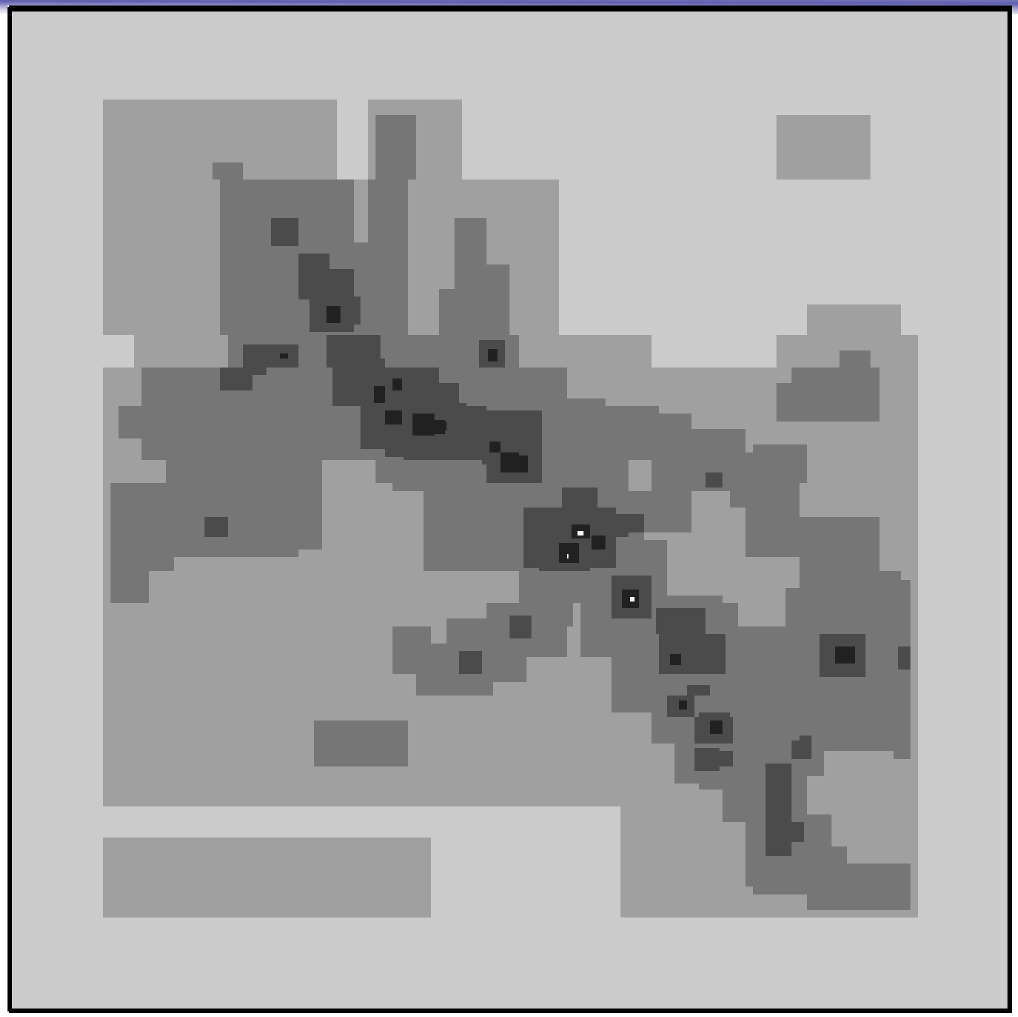
- Efficient, reliable finite element methods *for uniform grids* have been developed for solving equations for gravity and gas dynamics.

- The <u>A</u>daptive <u>M</u>esh <u>R</u>efinement (AMR) methods increase the dynamic range of grid-based numerical algorithms beyond the limits imposed by existing hardware.

- AMR is currently becoming the method of choice in cosmological hydrodynamic simulations.
  - Accurate solutions.
  - Efficient use of resources.
  - Existing expertise in working with complex codes.

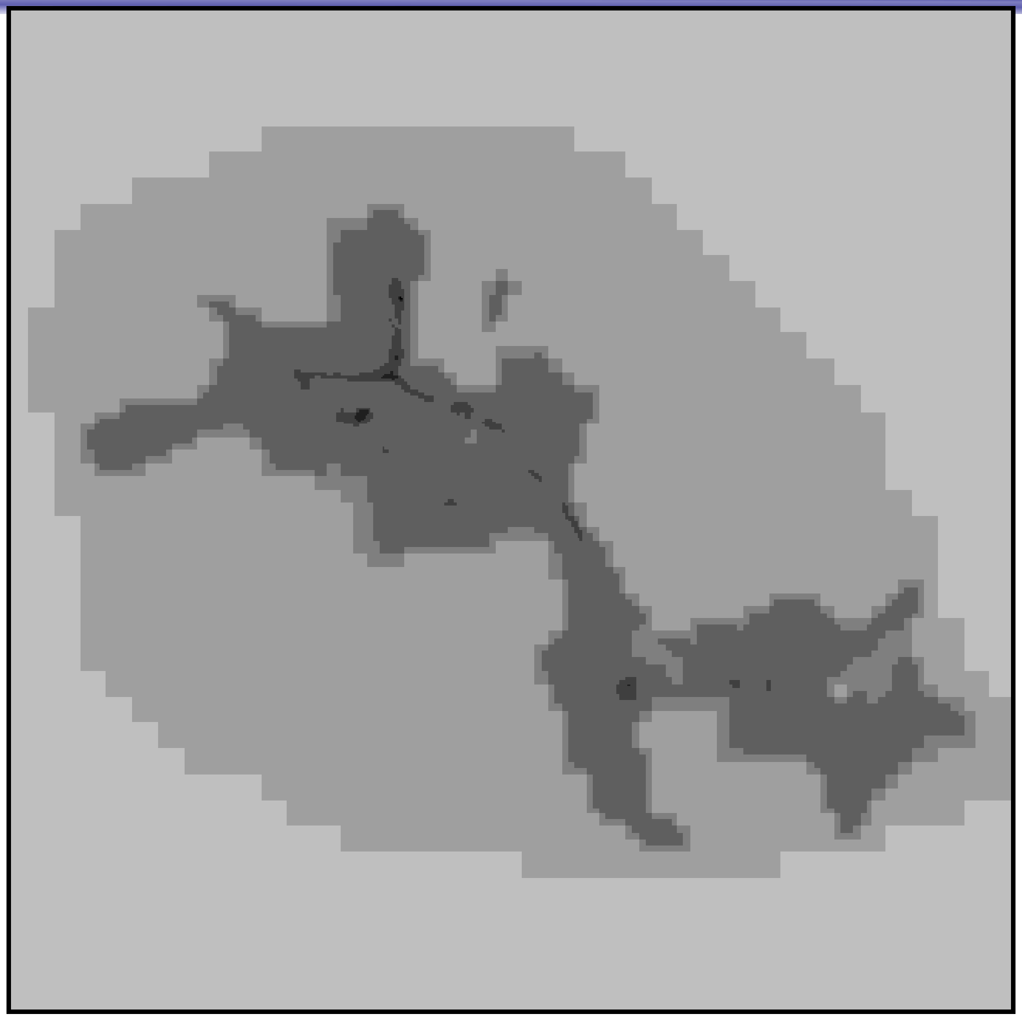


Our Main Codes



Enzo, Nyx

- Block-structured AMR
- Refine in rectangular regions
- Easily scalable to many cores



ART (Adaptive Refinement Tree)

- Oct-based AMR
- Refine in individual cells
- Hard to scale to many cores

Previous Highlights

- To tell the truth, hydro simulations so far had a lesser impact on the field of cosmology than N-body ones (because they are more complex and more computationally demanding).

- By far the biggest success story is the discovery of the Lyman-alpha forest as being the small-scale end of full spectrum of density fluctuations in the universe (1994).

- Other notable successes:
  - Physics of clusters of galaxies, in particular the Y_X observational probe (similar constraining power from 37 X-ray clusters as ~10,000 optical clusters from SDSS).
  - Upper limits on neutrino masses from modeling Lyman-alpha forest.
  - Predicting masses of first stars.
  - Discovery of “cold mode” accretion of gas onto galaxies.
  - Detailed modeling of cosmic reionization.

Parallel Performance

- Performance of codes depends on the specific problem at hand
  - Larger simulations scale better (more elements to distribute around).
  - Higher resolution simulations scale worse (more action in a handful of places).

- For realistic state-of-the-art simulations existing codes are within a factor of a few from the sustained peta-scale performance (quadrillion floating point operations per second, 10^{15} “flops”).
  - Suitable for the next generation of machines (with some modest improvement efforts).
  - Good match to the current and planned experimental efforts.

- Exa-scale (10^{18} flops) performance will require a serious development effort.
  - New parallelization models.
  - New IO methods.
  - Fault tolerance (self-healing codes).

Hydro Simulations of Tomorrow

- "Hydro-Bolshoi"
  - Proto-typical simulation for modeling baryonic effects in weak lensing.
  - Also useful for modeling clusters, validating Lyman-alpha forest simulations, non-DOE related science goals (community service).
  - 2048^3 = 8 billion particles.
  - "Standard" physics (cooling, star formation, no radiative transfer or chemistry).
  - 1 kpc resolution in 250 Mpc box (dynamic range of 250,000).
  - 30,000 cores.
  - 12 million CPU hours.

Conclusions

- Until now, hydro simulations have been only occasionally used for DOE-related science (because of their intrinsic computational expense).
- In the era of peta-scale supercomputers, this is going to change – many scientific problems are of the right size for hydro simulations on peta-scale machines.
- In the longer run, “the whole universe” hydro simulations will be feasible in the era of exa-scale performance.