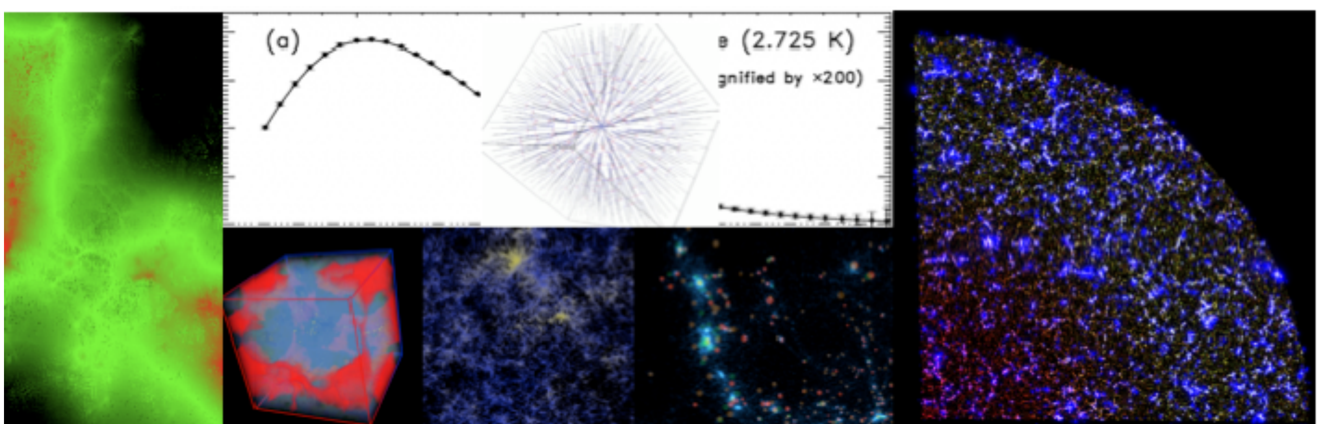
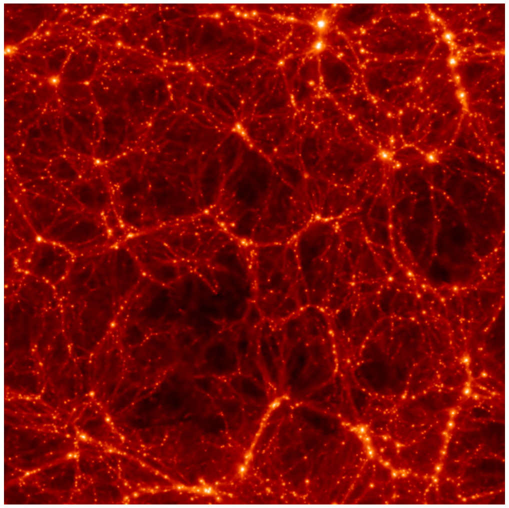
Cosmic Probes

Martin White
UCB/LBNL



Structure formation probes of fundamental physics

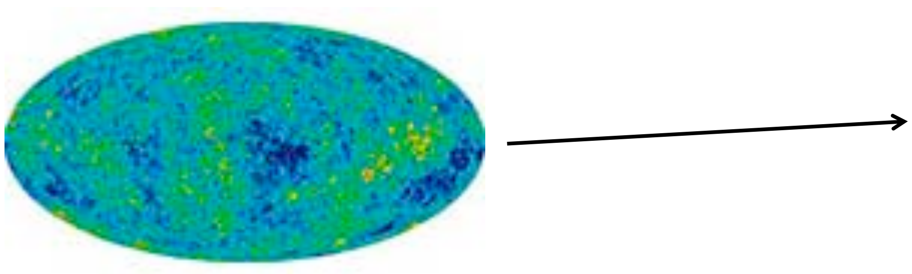
- The DOE has recognized the importance and relevance of these cosmic discoveries to the High Energy Physics program by introducing the Cosmic Frontier as a new and complementary thrust to be pursued, along with the traditional High Energy Frontier and High Intensity Frontier of accelerator-based science.
- Just as computational science has been vital to advance the accelerator based programs on both the experimental and theoretical sides, so too is it the case in cosmological and astrophysical research.

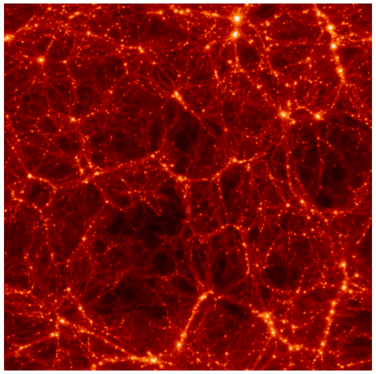


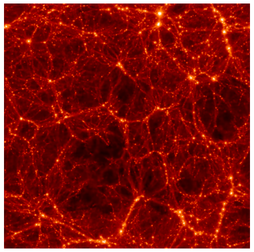
To understand and calibrate the response of experiments to the fundamental physics requires a coordinated and disciplined program of cosmological simulations, with outputs designed around the experiment capabilities

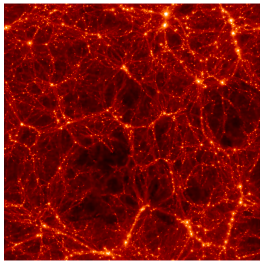
Structure formation

- Initial conditions laid down in the early Universe by inflation.
- Perturbations in density grow through gravitational instability in a DM dominated Universe.
- Growth rate is a competition between attraction of gravity and expansion of space.
- Properties of DM modify behavior on "small" scales ("pressure").
- All probes are essentially measures of the DM density field, or things related to it.
- Early universe, linear PT appropriate -- hugely successful: CMB.
  - Anchors all of our models (Nobel 2006).
  - Have a standard "fluctuation spectrum" (c.f. standard candle)
- Last half of the Universe by age: non-linear structure dominates, non-gravitational physics important -- by and large not amenable to analytic calculation.
  - But can be simulated.



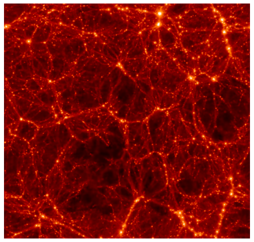


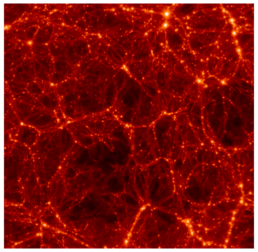




The role of simulations

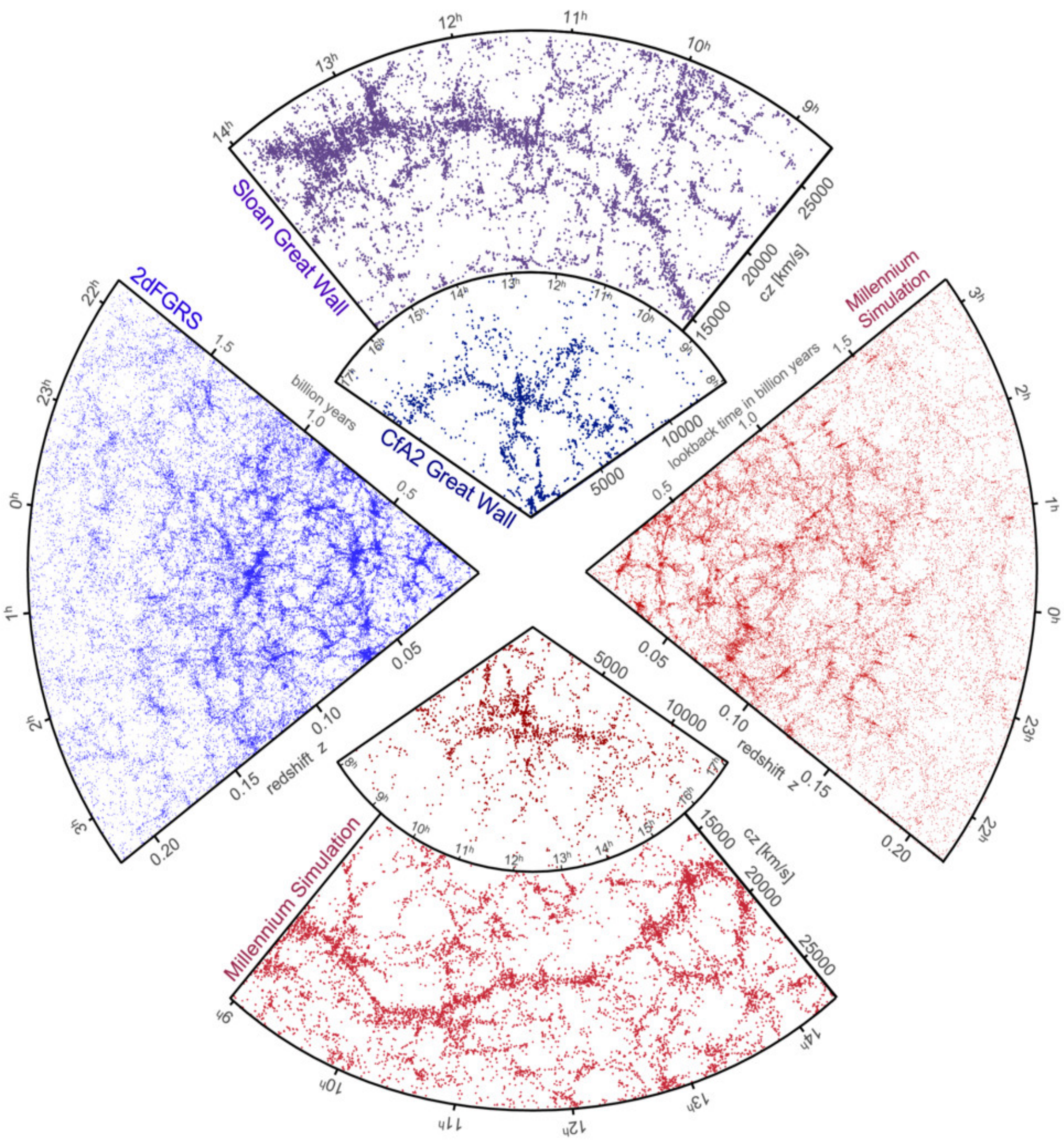
- Simulation by itself makes fundamental advances in basic science.
  - The best simulations are the most realistic physical descriptions of the known universe.
- Simulations are often the only “theory” with which to compare observational data.
  - Matching simulations to observations validates physical models and constitutes the key scientific return from observations.
  - Simulations can be used in a Monte-Carlo fashion to assess statistical significance or determine error bars.
  - Data to science.
- Simulations play a key role in mission optimization.
  - Simulations are crucial for trade-off studies and studying the impact of systematic errors.
  - Simulations can be used to design, refine and test data processing and mission operations.





Observational workhorse: galaxy surveys

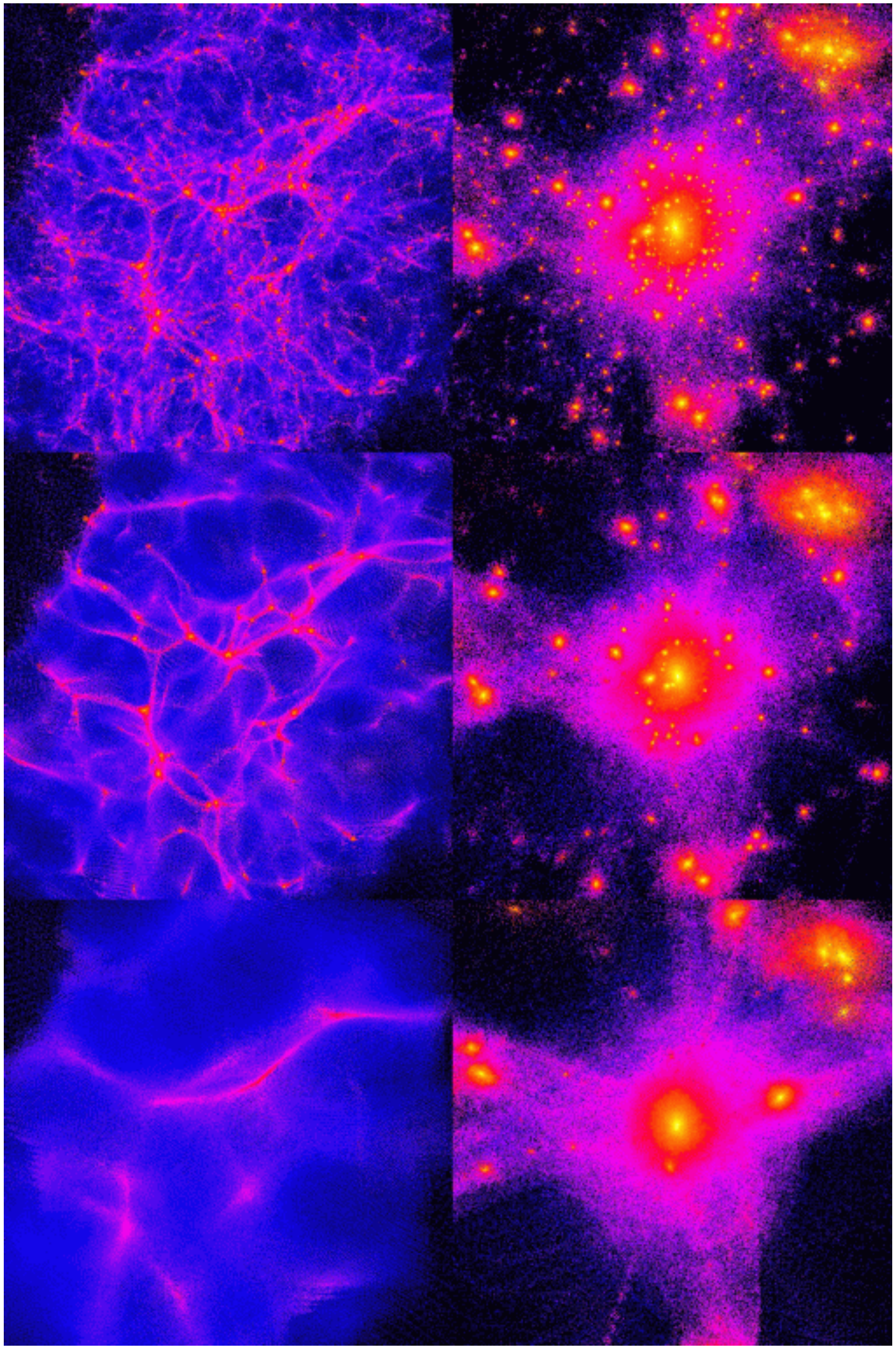
Volker Springel



Since the mid-1980s a series of ever larger surveys of galaxies have provided constraints on our world model and fundamental physics.

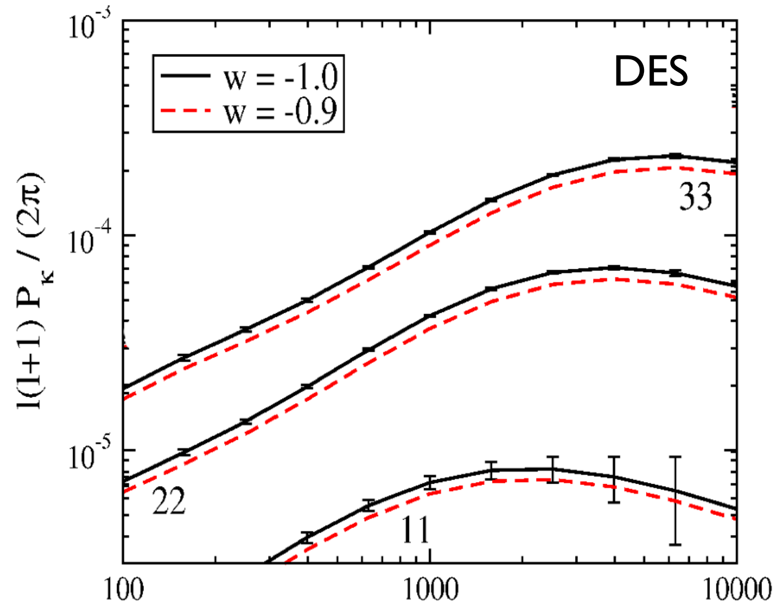
Defining the paradigm

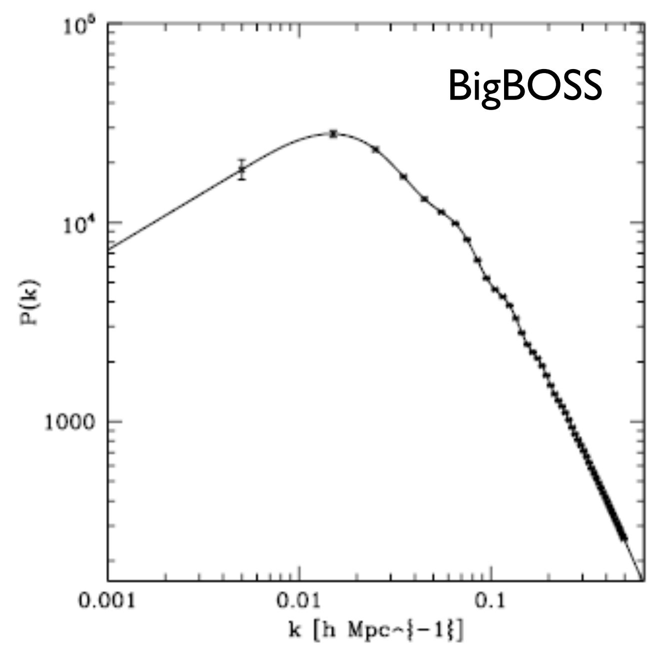
- Early surveys showed that galaxies are not randomly oriented, but live in a hierarchy of structures.
- Best fit by a model incorporating:
  - Initial fluctuations from inflation
  - A low (matter) density Universe (with DE)
  - (Non-baryonic) dark matter
  - Which is “cold”, not hot or warm.
- Further advances require more/better data and more/ better “theory”.



Probes

- Qualitative descriptions and "by eye" comparisons are no longer enough.
- Precision observations need to be rigorously compared to precision theoretical predictions, both having well-defined error estimates.
- Probes:
    - Low order statistics of galaxy distribution.
    - Weak lensing.
    - Galaxy clusters.
    - IGM



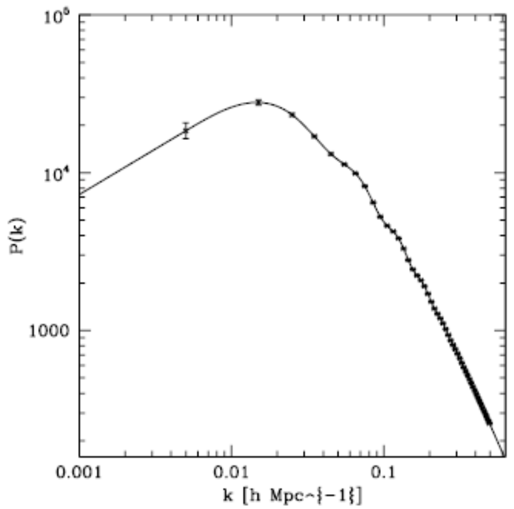


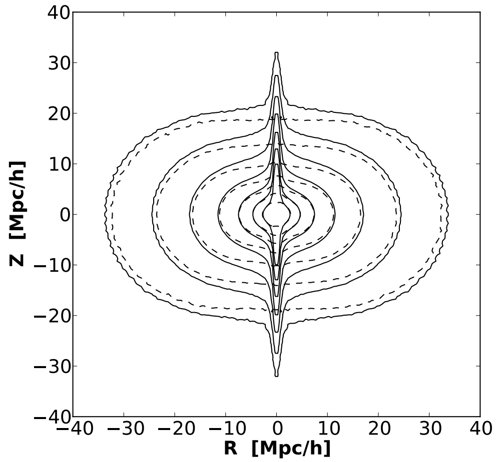
Damn lies and statistics

- Initial fluctuations are quantum "noise", amplified by gravity into the structures we see today.
- Need to compare statistical properties of observed field to statistical properties of models … not individual objects.
- Define dimensionless variables:
  - $\delta_r = [\rho(r) - \langle\rho\rangle]/\langle\rho\rangle$; $\delta_k = \mathrm{FT}[\delta_r]$
- Underlying theory is translationally invariant:
  - Look at moments:
    - $\langle\delta_{r1}\delta_{r2}\rangle = \xi(r_1 - r_2)$; $\langle\delta_k\delta_k\rangle = P(k)$
    - $\langle\delta_{r1}\delta_{r2}\delta_{r3}\rangle$, $\langle\delta_{r1}\delta_{r2}\delta_{r3}\delta_{r4}\rangle$, …

Probes I

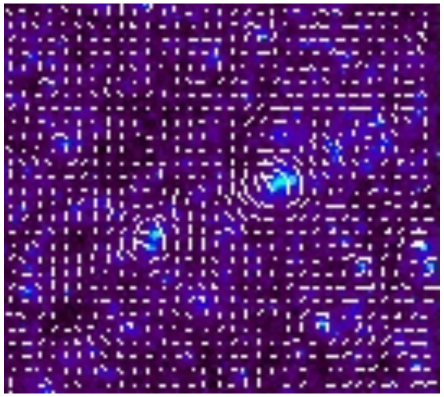
- The observed galaxy power spectrum:
  - Sharp features
    - Baryon Acoustic Oscillations: a characteristic scale in the correlation function or “wiggle” in power spectrum.
    - A robust standard ruler to infer the expansion history.
  - Broad band power
    - Encodes information about non-Gaussianity, the slope of the initial fluctuations, thermal properties of dark matter, …
  - Angular dependence
    - Redshift Space Distortions: arise from motions of objects with respect to the Universal reference frame.
    - Such motions are generated by gravitational potentials, RSDs probe the matter and test our theory of gravity in much the same way as lensing.
    - In fact redshift space distortions and lensing are complementary in that they employ non-relativistic and relativistic tracers (respectively), thereby probing perturbations to the metric in different ways.





Historically most of our cosmological constraints have come from power spectrum studies

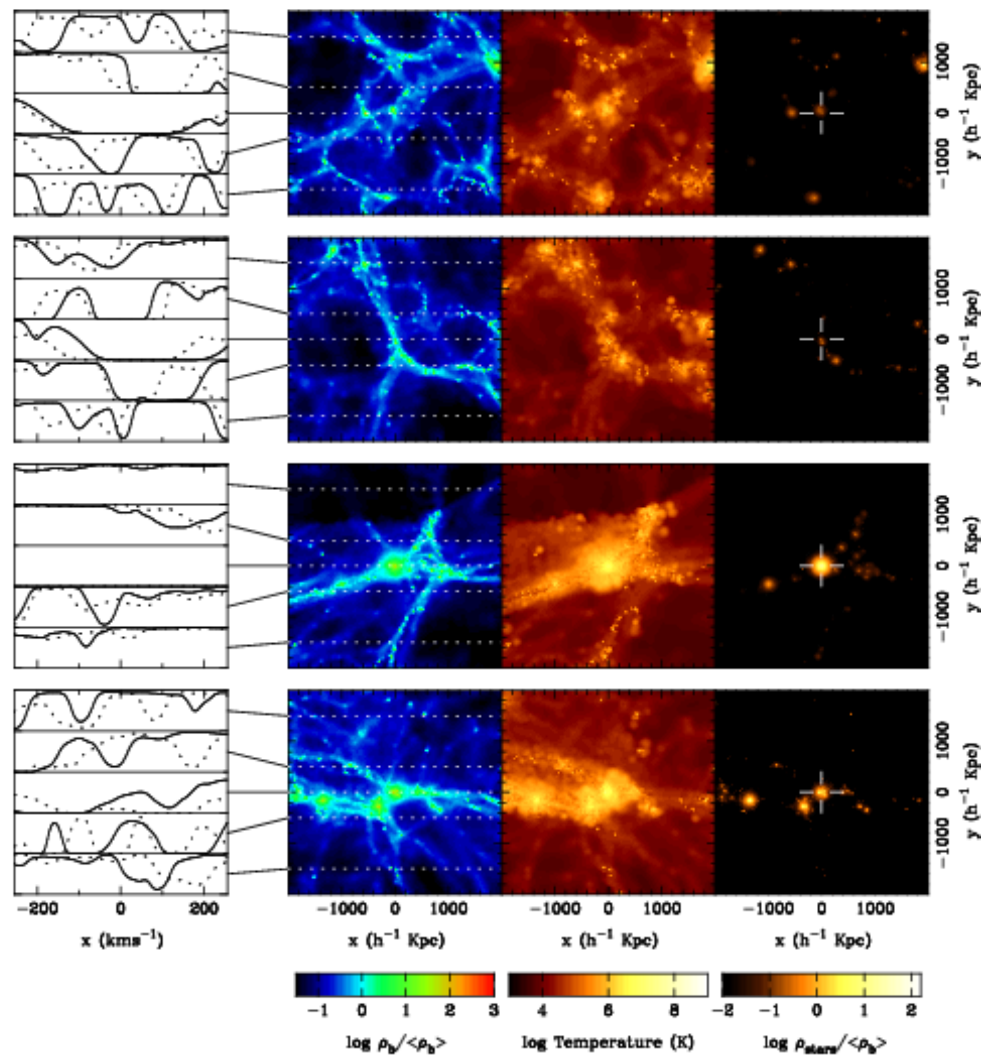
Probes II



- Weak Lensing:
  - Signal lies in the shapes of galaxies, not just their positions.
  - Deflection of light by Φ associated with large-scale structure distorts images of background galaxies in a way that can be detected statistically.
  - Probes the distribution of luminous and dark matter in the cosmic web. The amplitude of the lensing signal depends on geometric 'efficiency' factors and the amplitude of mass perturbations in the Universe.
  - This allows, in principle, a measurement of both geometry and structure growth.
- Galaxy Clusters:
  - Arise from the highest peaks in the initial density field.
  - Are the largest collapsed structures today
    - Endpoint of structure formation.
  - Counts over time depend on geometry, growth of structure, and distribution of initial fluctuations (from inflation).
- Higher order functions
  - Rather than focus on extrema of the field (clusters) can study higher order correlators (e.g. 3-point statistics).

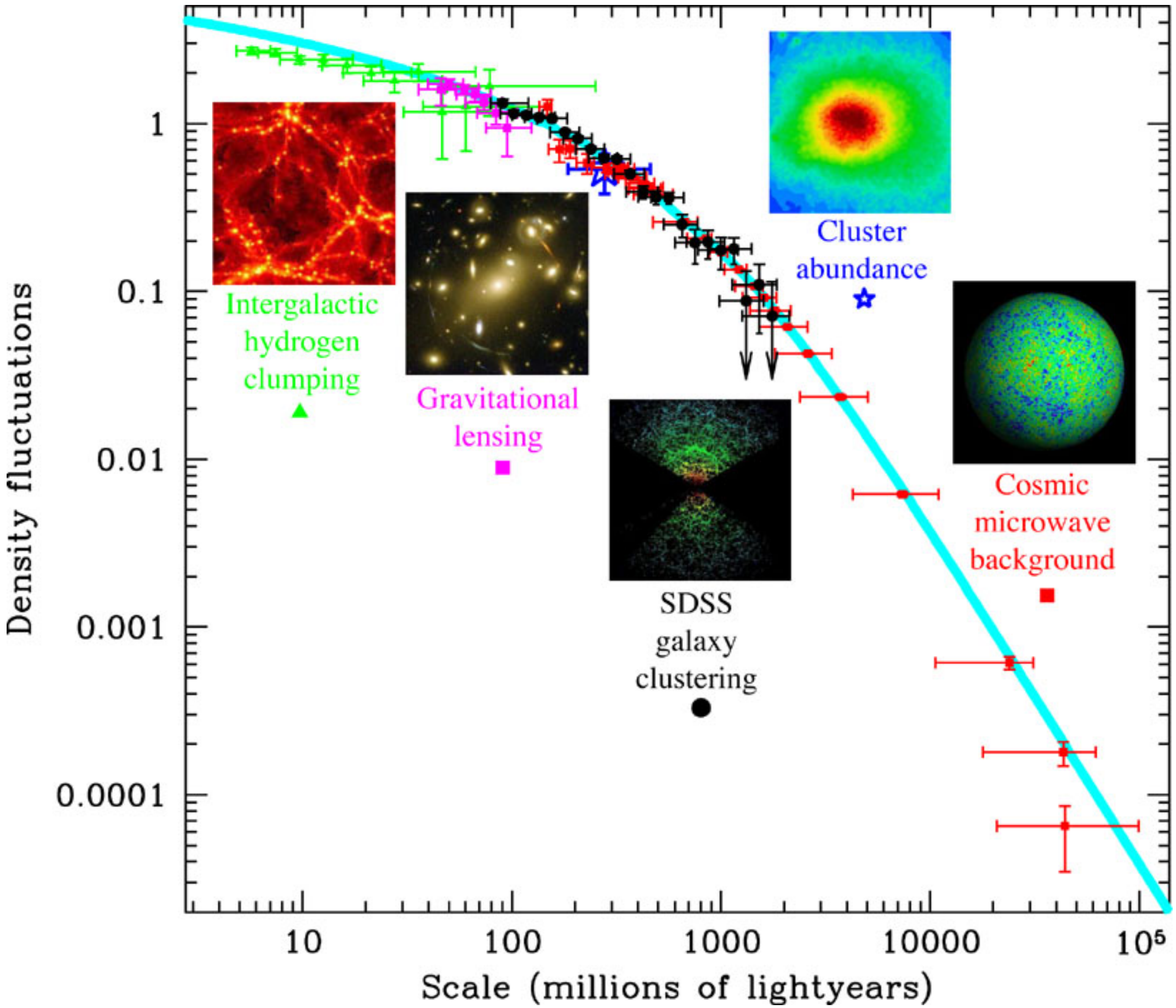
Probes III

- Lyα/IGM
  - Fluctuations in the cosmic web imprint absorption features in the spectra of distant quasars.
  - The features come from fluctuations in the web “between” galaxies and other luminous objects.
  - Sensitive to m_ν, “warm” DM, running index from inflation.
  - New: measures large-scale structure (e.g. BAO).
  - Only accessible to spectroscopic surveys.
  - Spectral features only observable at “high” redshift.



(Croft++02)

The power spectrum



From Max Tegmark

Computing challenges

- Dynamic range
  - Modern galaxy surveys cover Gpc^3 of volume, while to even track (not form!) mock galaxies requires kpc resolution.
    - Linear dynamic range: $>10^6$
    - For LSST the challenges are particularly severe:
      - Gold sample (i<25) at z~0.1 is ~$10^9 M_{sun}$ halos!
      - At 10^3 particles per halo: $10^6 M_{sun}$ particles.
      - Out to z=1.5, $1Gpc^3$ box covers 300 sq. deg.
      - $1Gpc^3$ box = 10^{14} particles.

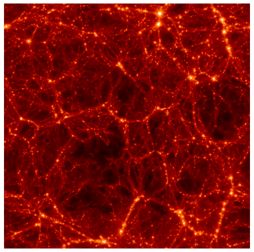
  - Similar requirements hold for other probes
    - e.g. clusters and IGM.

  - Monte-Carlo methods
    - Large data sets, big memory requirements, error control, …

- Complex workflow
  - Emphasis on modularity.
  - Lots of home-grown solutions, few standards even among surveys with large personnel overlap.

Computing challenges

- Complex, multi-scale physics
    - Gas cools dramatically in deep potential wells, reaching high densities in a clumpy, multiphase, turbulent, magnetized ISM where it can form stars, which give off winds and radiation and go supernova injecting momentum and energy into the surrounds and have active galactic nuclei which can impart energy to their environments, …
    - Thermal conduction and turbulence in clusters.
    - Radiative transfer in the IGM.
    - etc
- Need well-designed experiments to analyze which properties are robust to uncertain physics and which are not.
- Need phenomenological models matched to detailed observations where *ab initio* modeling is insufficiently accurate.



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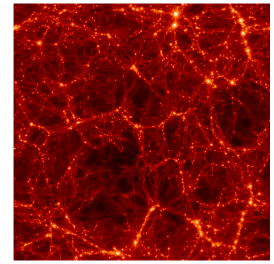

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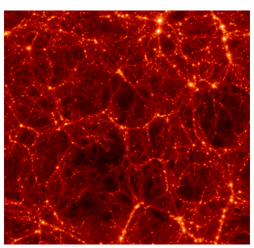

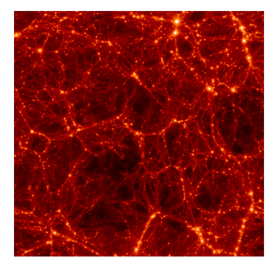

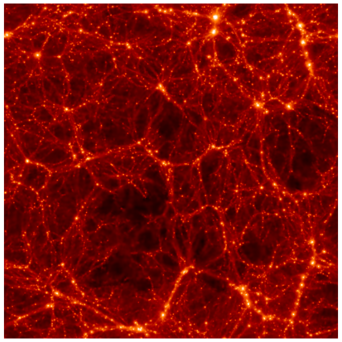

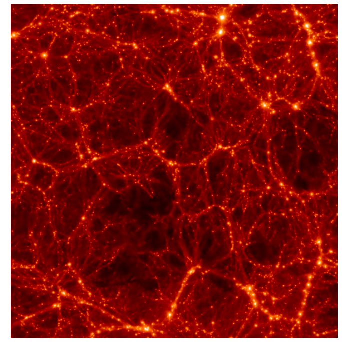

Conclusions

- The scientific impact of discoveries in this research area is profound:
  - the determination of the equation of state of dark energy,
  - distinguishing between dark energy and modifications of general relativity,
  - measuring the masses and interactions of dark matter,
  - measuring the sum of the neutrino masses, and
  - probing the fields responsible for primordial fluctuations.
- But it can’t be done without a sustained effort to build a simulation capability and a *community* of simulators and users.