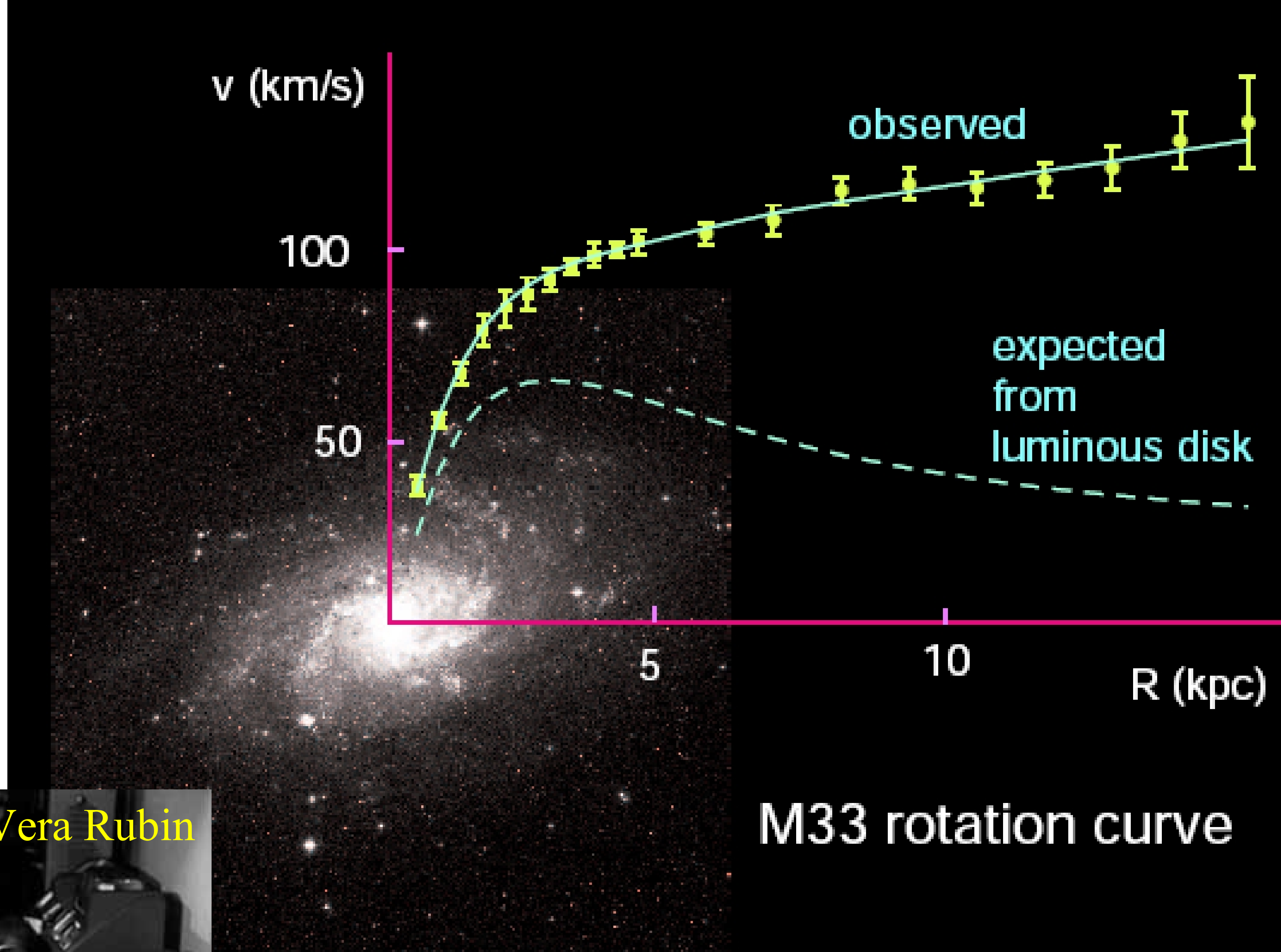
Dark Matters

Simon White
Max Planck Institute for Astrophysics


The Coma Galaxy Cluster
Fritz Zwicky

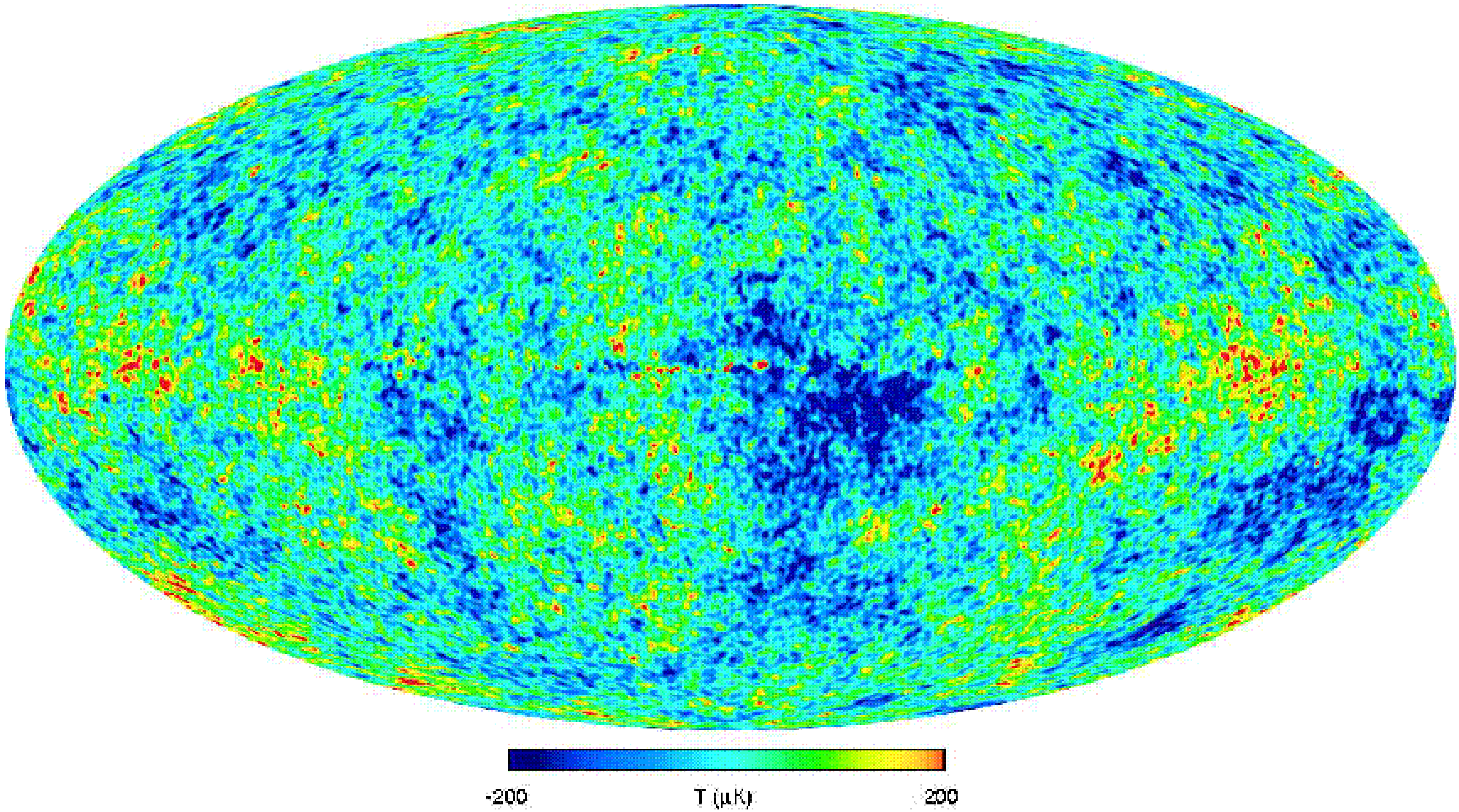
The Triangulum Nebula (M33)


v (km/s)
100
50
observed
expected
from
luminous disk
5
10
R (kpc)
M33 rotation curve


Vera Rubin

The Galaxy Cluster, Abell 2218

The *WMAP* of the Cosmic Microwave Background

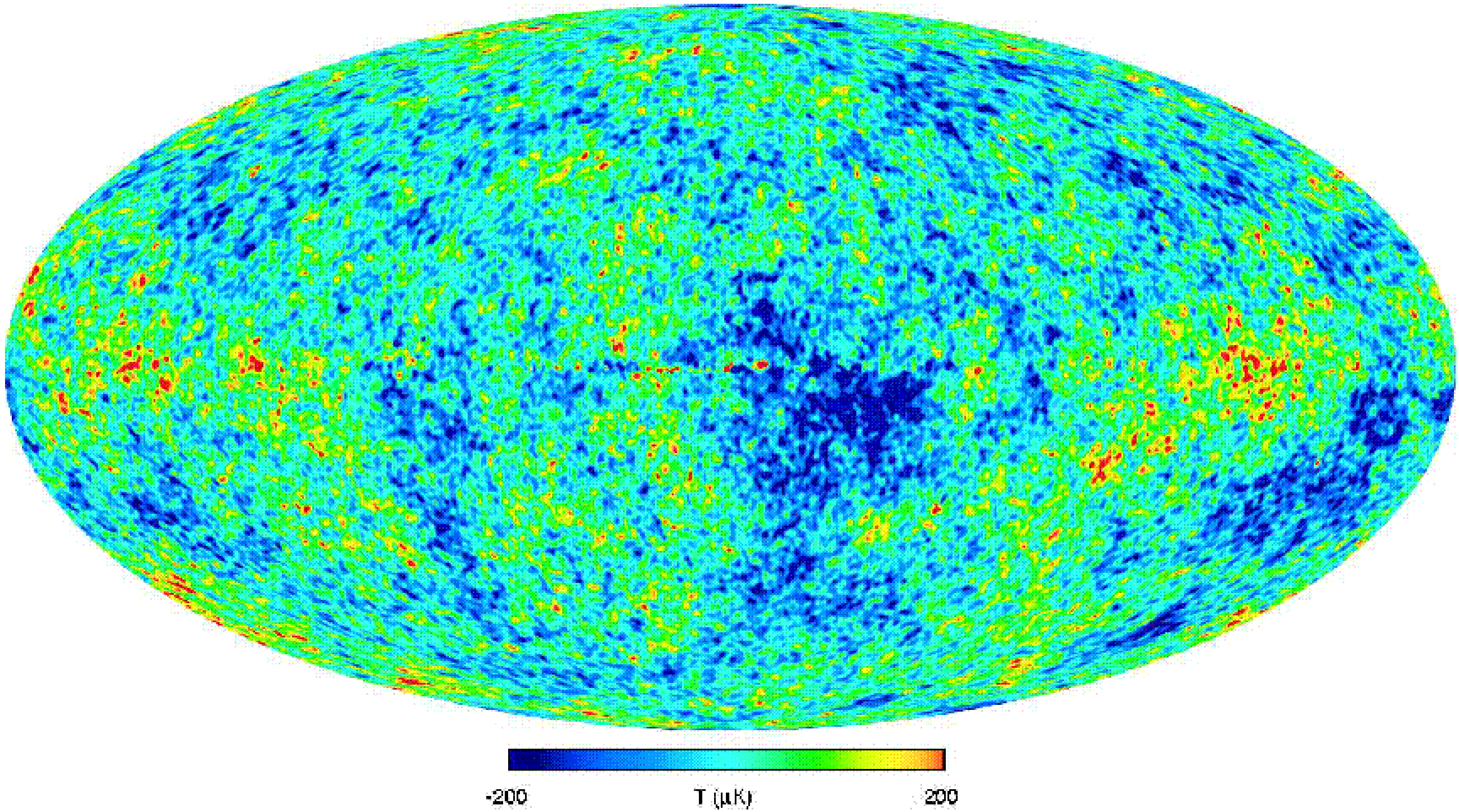


Temperatures fluctuate by ± 200 μK around a mean of 2.73 K

What are we seeing in the CMB?

- The "cloud surface" is at redshift $z = 1000$, just 380,000 yr after the Big Bang, at a present-day distance of 40 billion light-years
- The sharp surface is due to recombination of the primordial plasma
- Its (very nearly uniform) temperature is about 3000 K
- The emitted radiation is black-body to high precision
- The fluctuations are due to gravito-acoustic waves propagating in the plasma/dark matter mix ⟶ characteristic scale $\lambda \sim c_s t_{recom}$
- Fluctuations were imprinted *much* earlier, perhaps during inflation

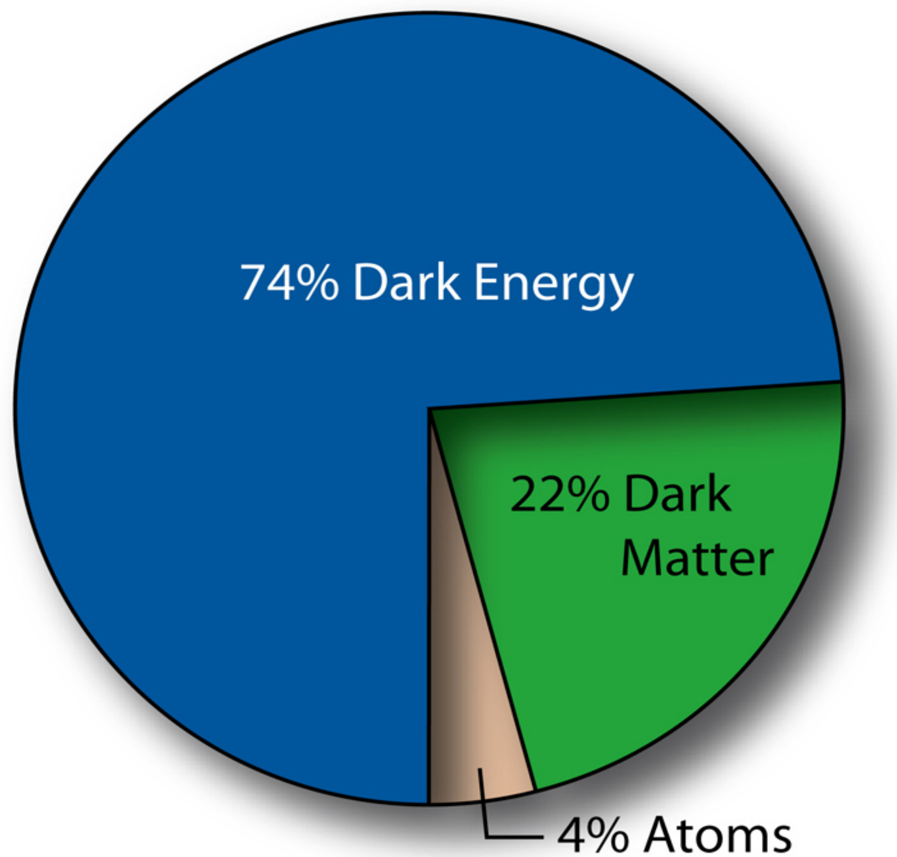
The *WMAP* of the Cosmic Microwave Background



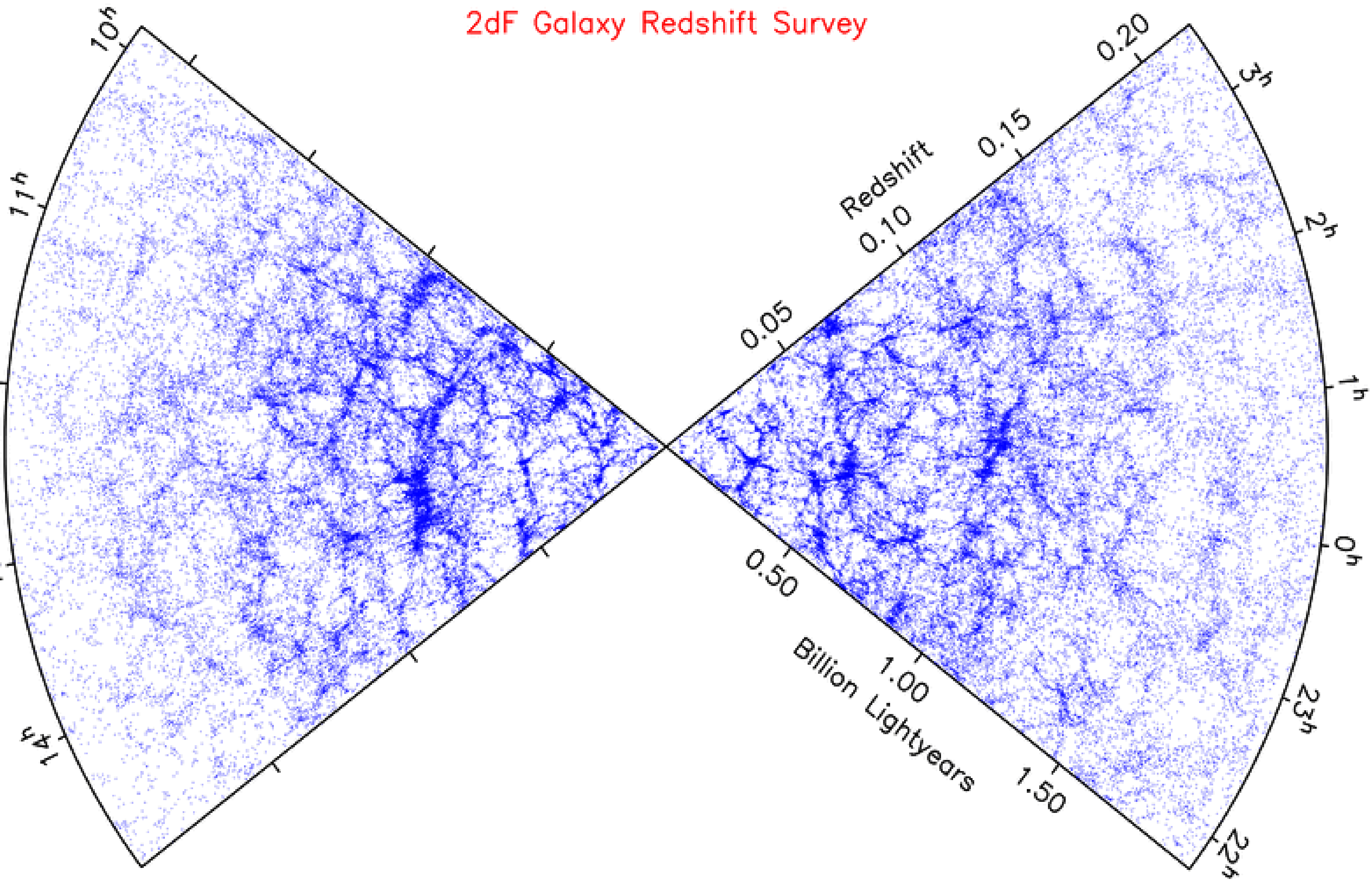
The (apparently gaussian) pattern reflects:
(i) geometry; (ii) material content; (iii) the generating process

What has WMAP taught us?

- Our Universe is flat -- its geometry is that imagined by Euclid
- Only a small fraction is made of ordinary matter -- about 4% today
- About 21% of today's Universe is non-baryonic dark matter (neutralinos? axions? ...)
- About 75% is Dark Energy (Λ? quintessence? new gravity?? ...)
- All structure is consistent with production by quantum fluctuations of the vacuum during early inflation



Nearby large-scale structure



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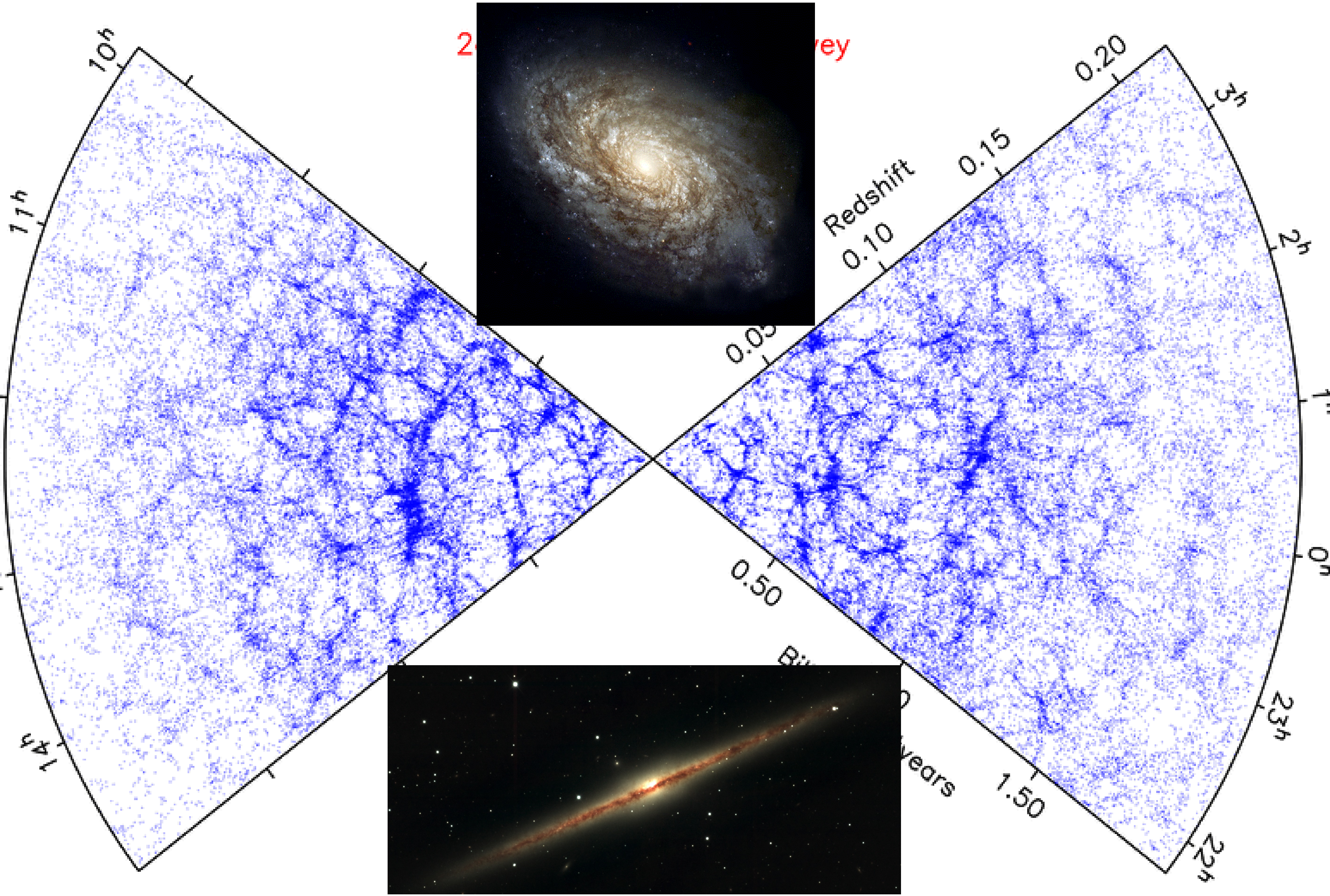
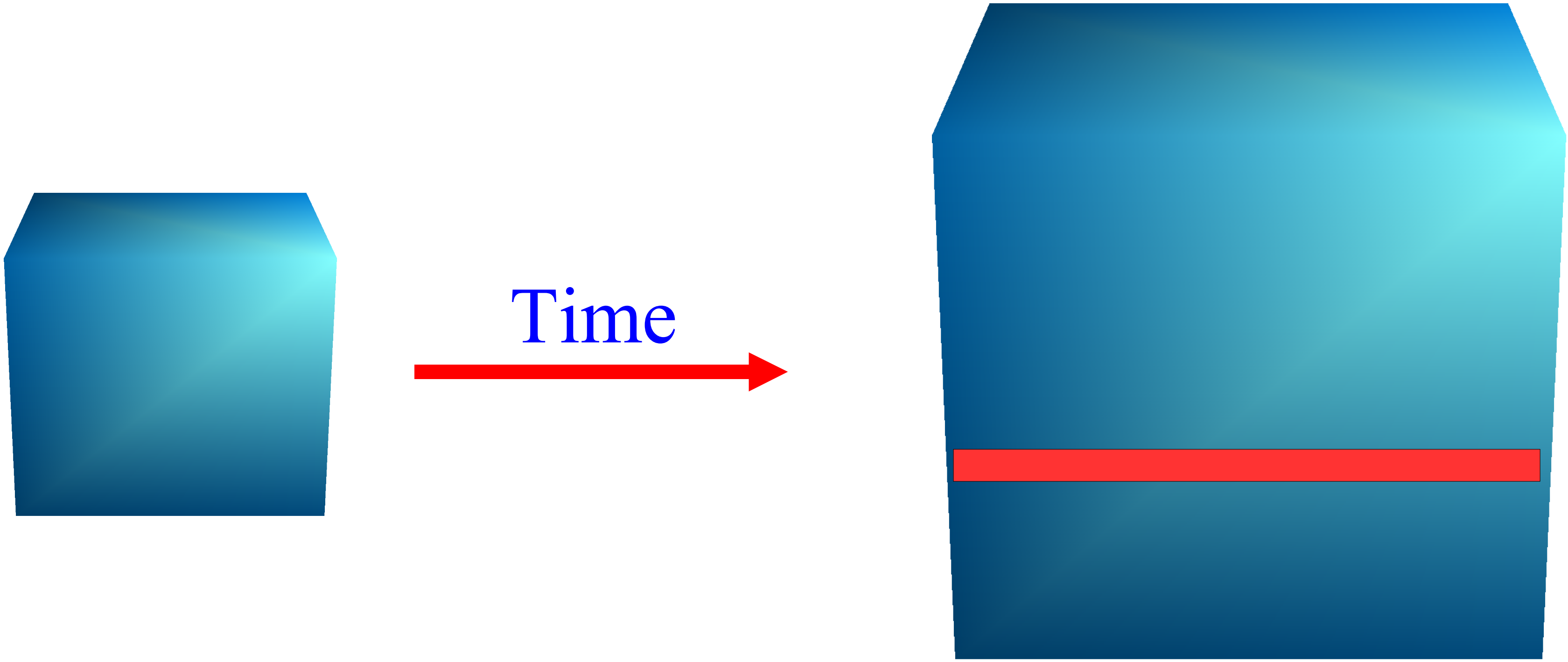


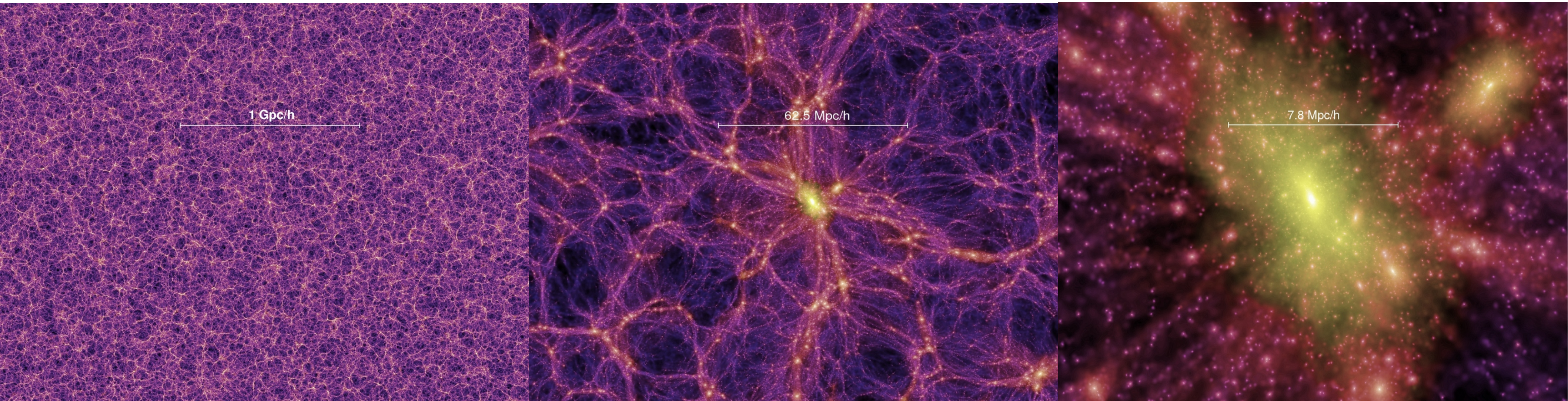
Evolving the Universe in a computer

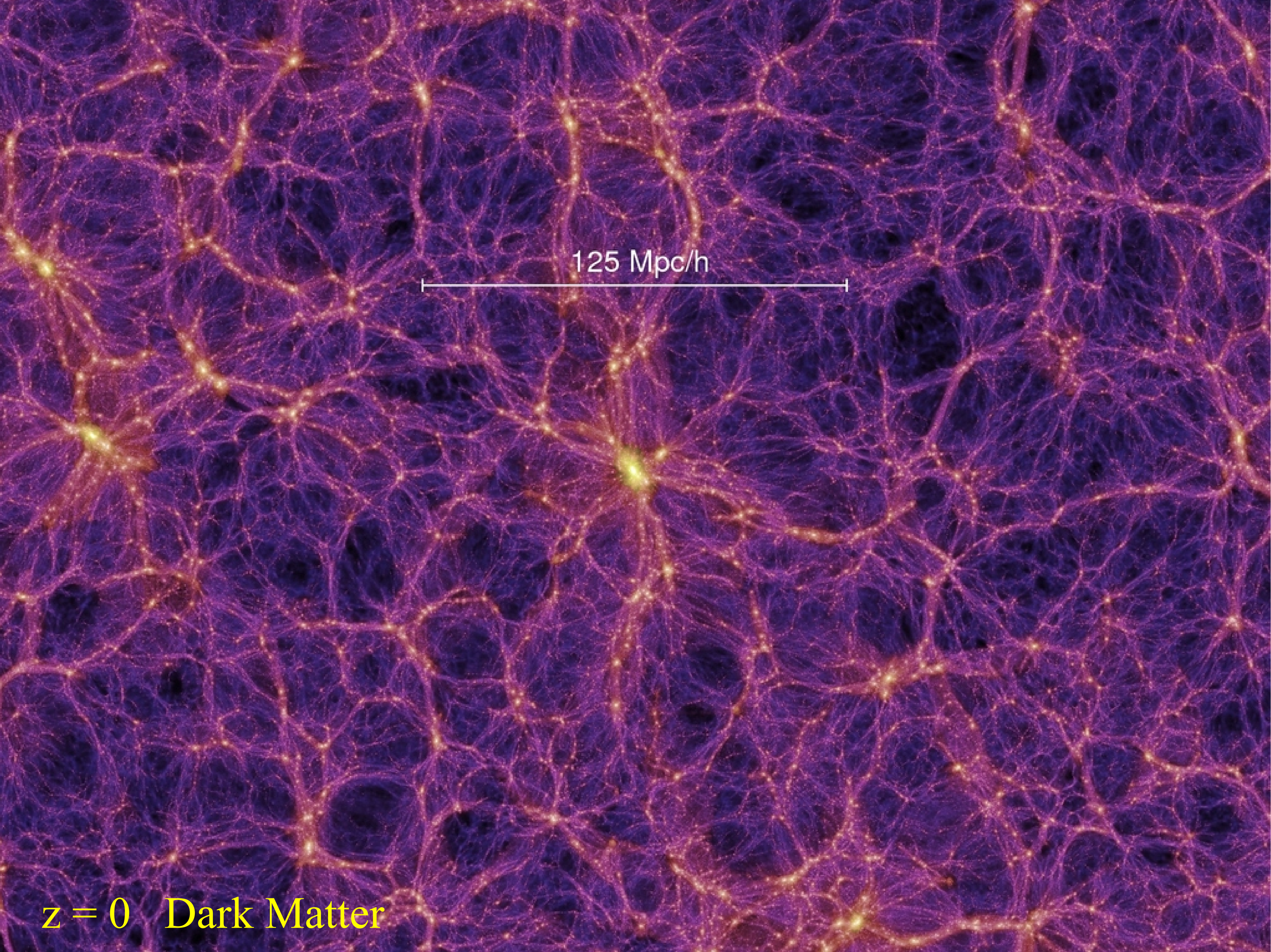


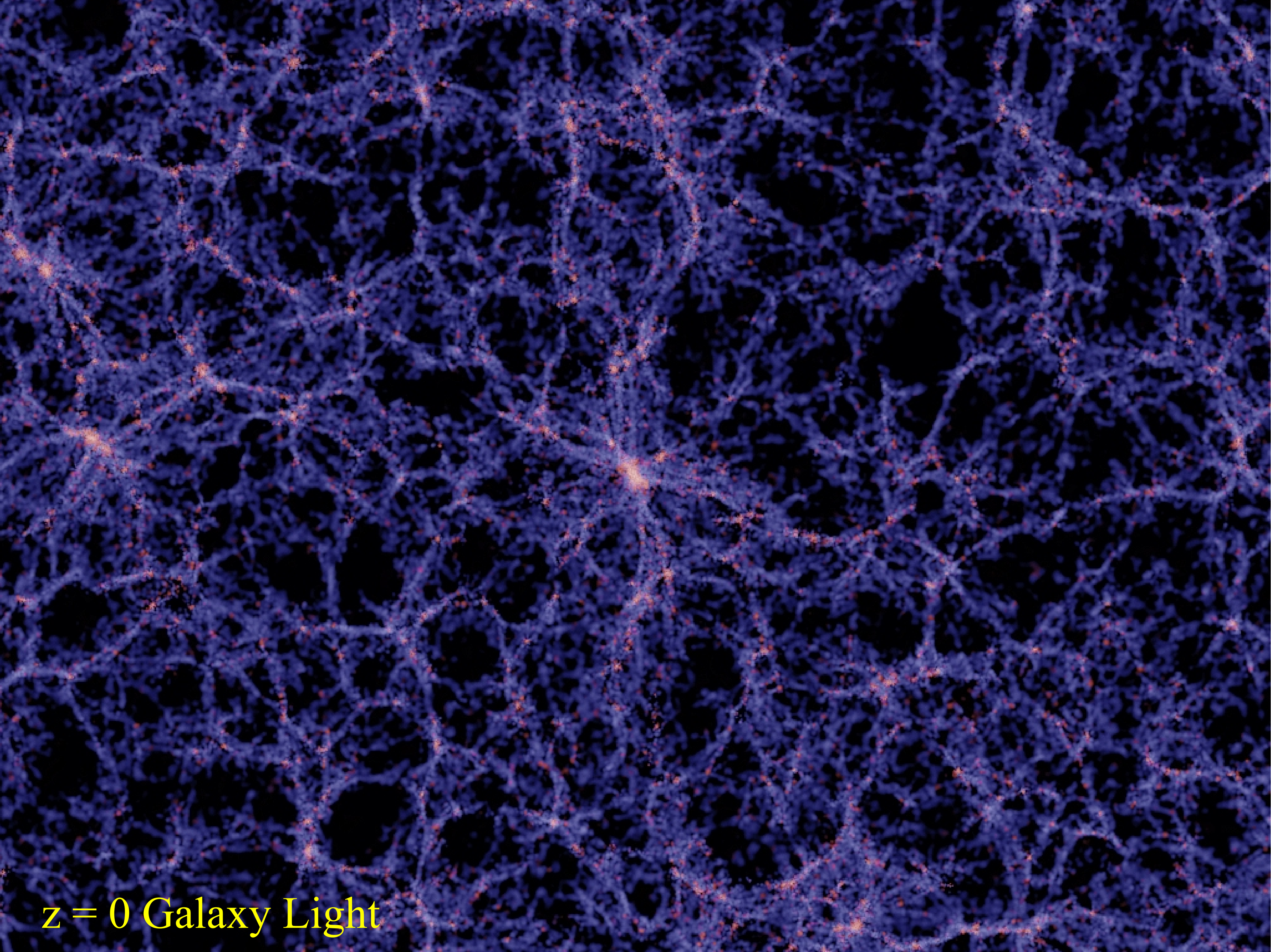
- Follow the matter in an expanding cubic region
- Start 380,000 years after the Big Bang
- Match initial conditions to the observed Microwave Background
- Calculate evolution forward to the present day

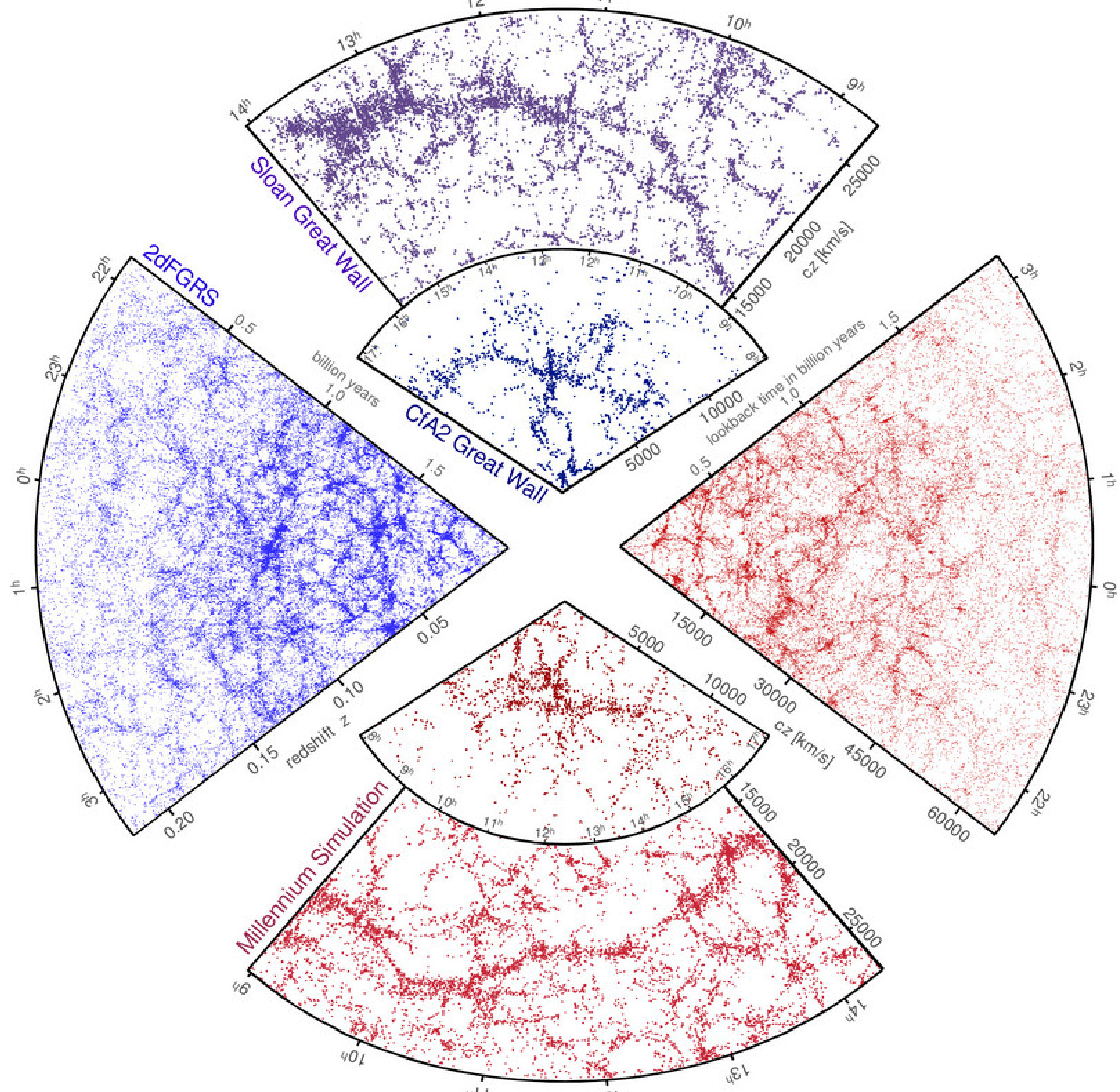
Visualizing Darkness

- The smooth becomes rough with the passing of time
- Uniformity, filamentarity, hierarchy – it all depends on scale
- A short tour of the Universe

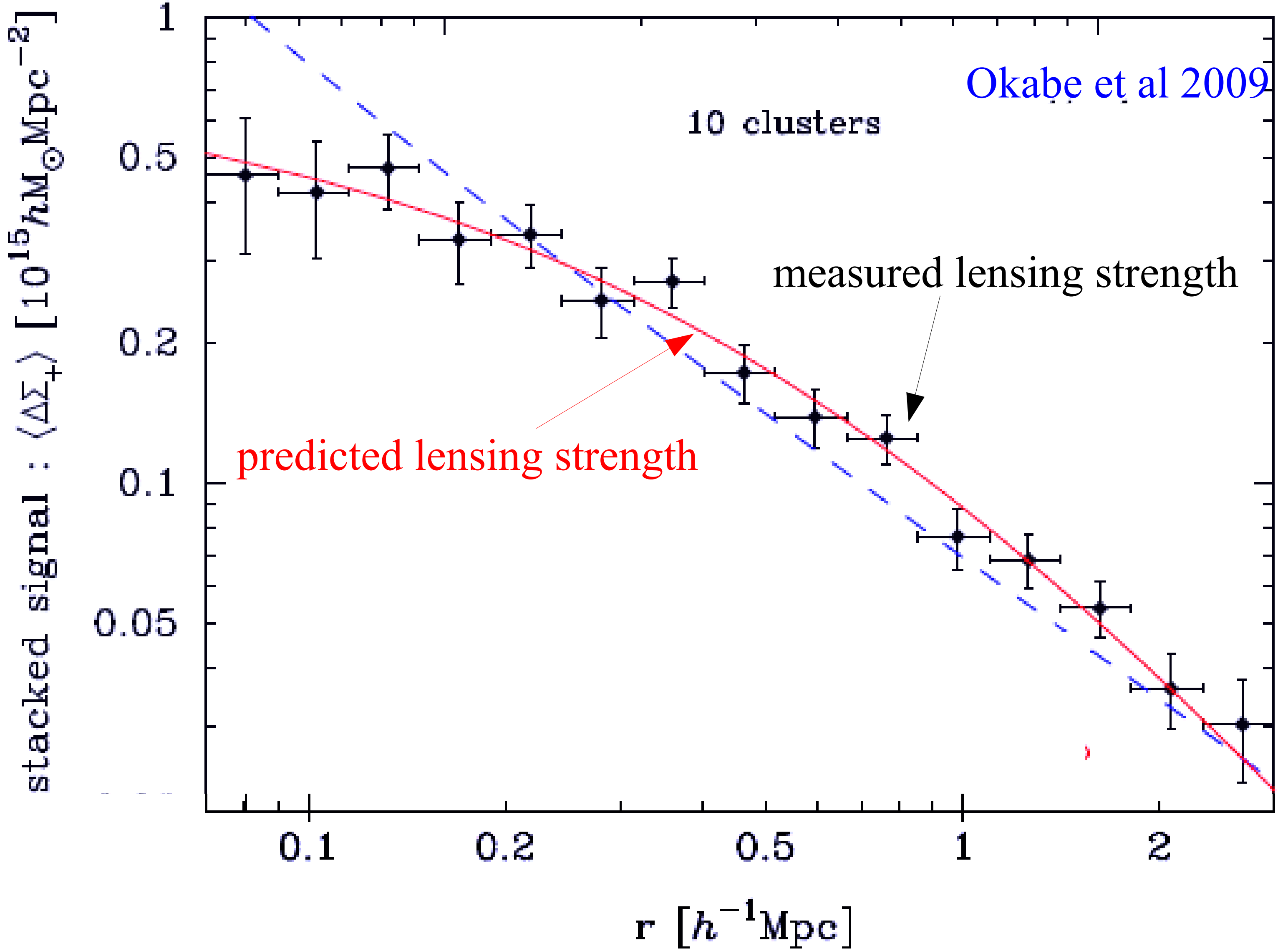


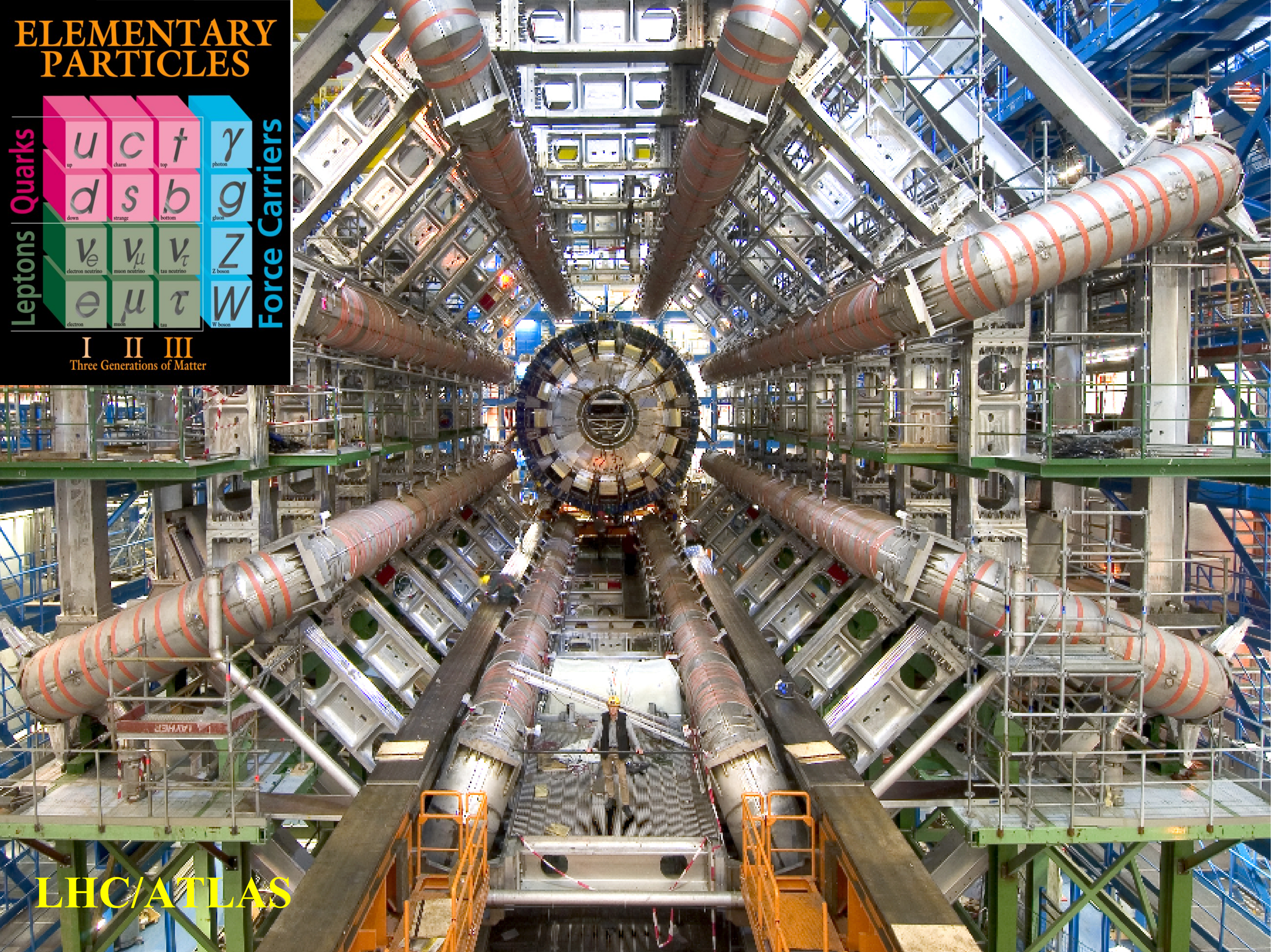

125 Mpc/h
z = 0 Dark Matter


z = 0 Galaxy Light

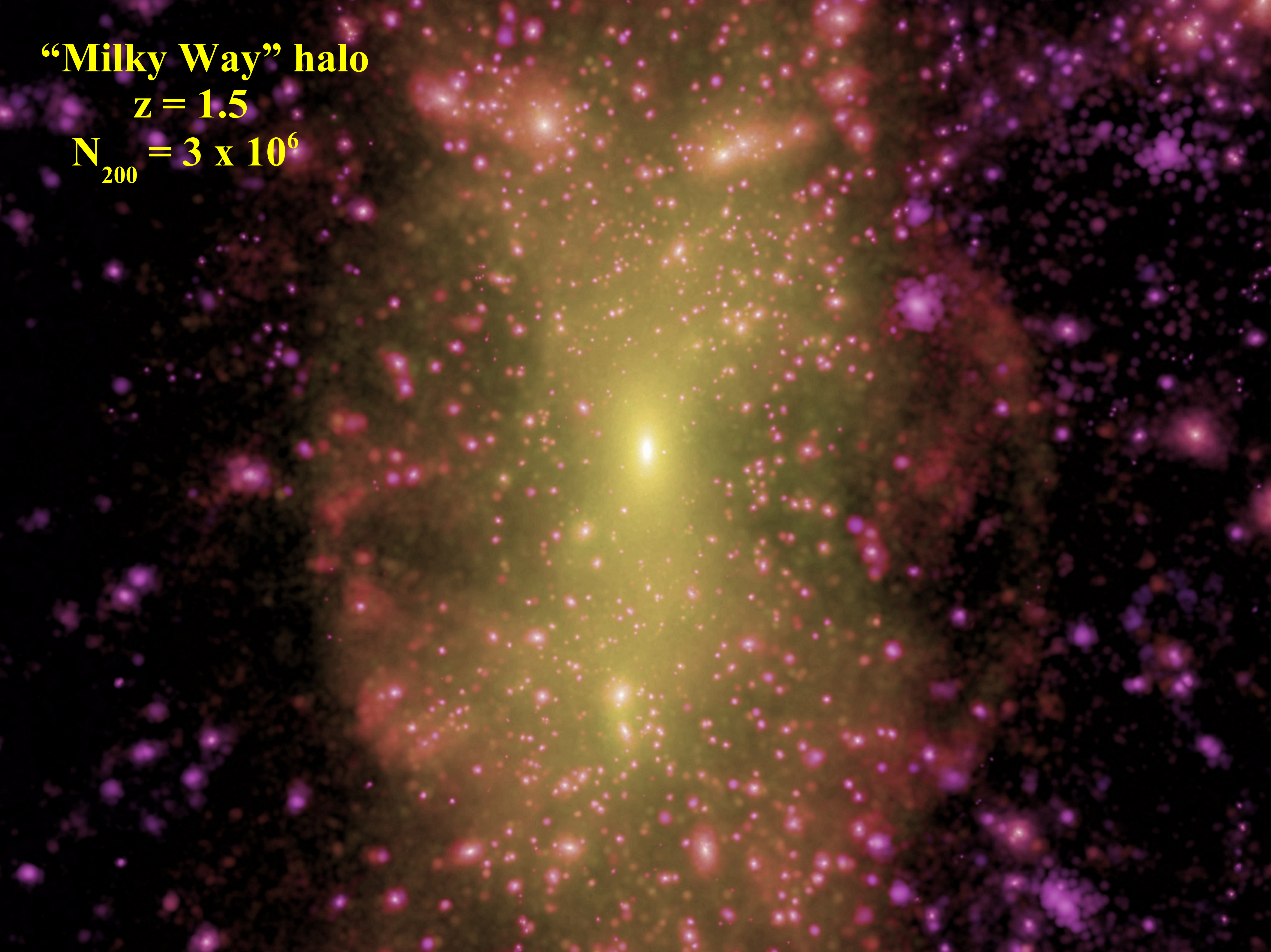

Sloan Great Wall
2dFGRS
CfA2 Great Wall
Millennium Simulation
cz [km/s]
billion years
lookback time in billion years
redshift z

Comparison of lensing strength measured around real galaxy clusters to that predicted by simulations of structure formation




ELEMENTARY PARTICLES
Quarks
Leptons
Force Carriers
u up
c charm
t top
γ photon
d down
s strange
b bottom
g gluon
ν_e electron neutrino
ν_μ muon neutrino
ν_τ tau neutrino
Z Z boson
e electron
μ muon
τ tau
W W boson
I II III
Three Generations of Matter
LHC/ATLAS


100 kpc
Dark Matter around the Milky Way?


"Milky Way" halo
z = 1.5
N200 = 3 x 10^6

"Milky Way" halo
z = 1.5
N200 = 94 x 10^6


"Milky Way" halo
z = 1.5
N200 = 750 x 10^6

ΛCDM galaxy halos (without galaxies!)

- Halos extend to $\gtrsim$10 times the "visible" radius of galaxies and contain $\gtrsim$10 times the mass in the visible regions

- Halos are not spherical but approximate triaxial ellipsoids
  -- more prolate than oblate
  -- axial ratios greater than two are common

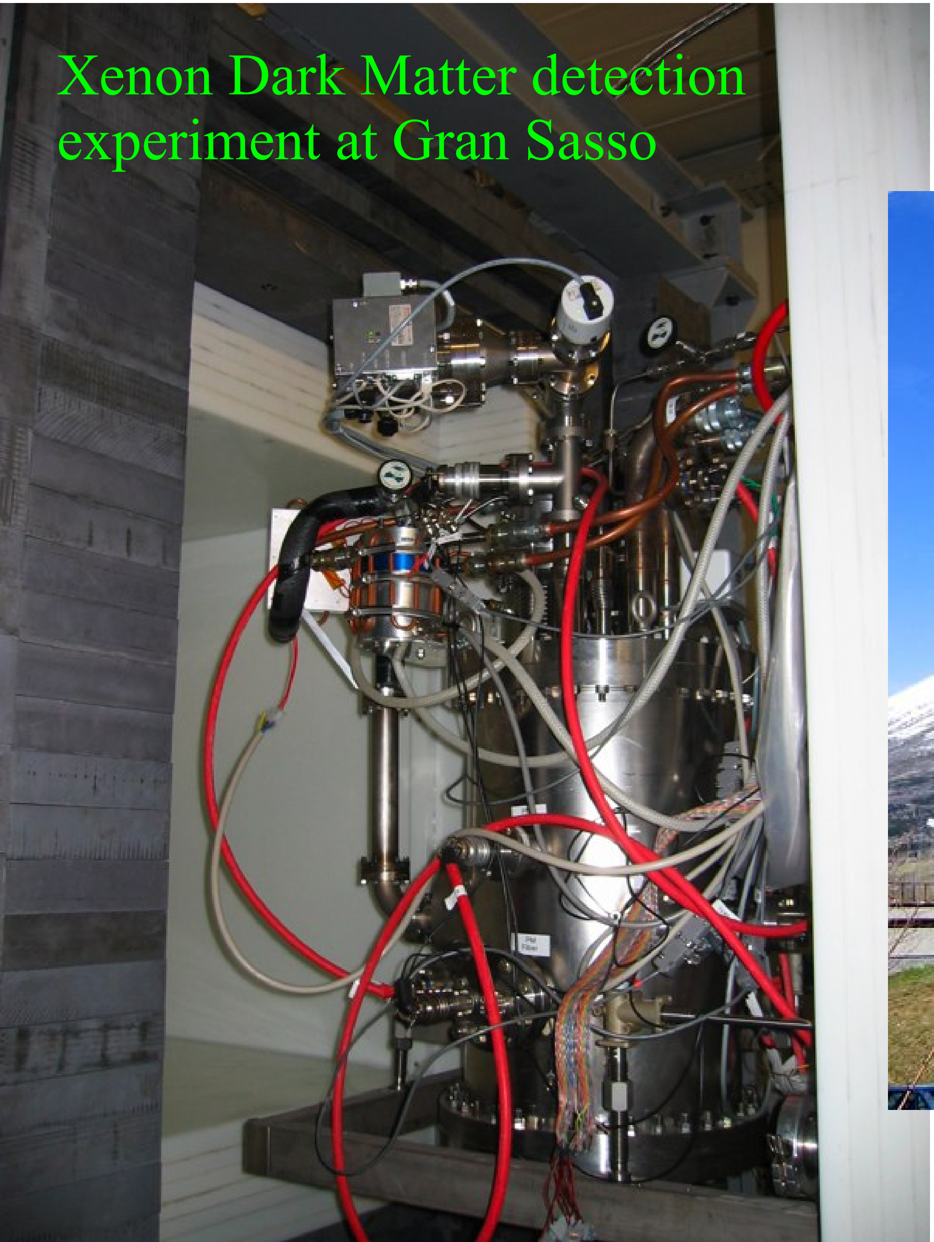
- "Cuspy" density profiles with outwardly increasing slopes
  -- $d \ln \rho / d \ln r = \gamma$ with $\gamma < -2.5$ at large r
  $\gamma > -1.0$ at small r

- Substantial numbers of self-bound subhalos contain ~10% of the total halo mass and have $dN / dM \sim M^{-1.8}$

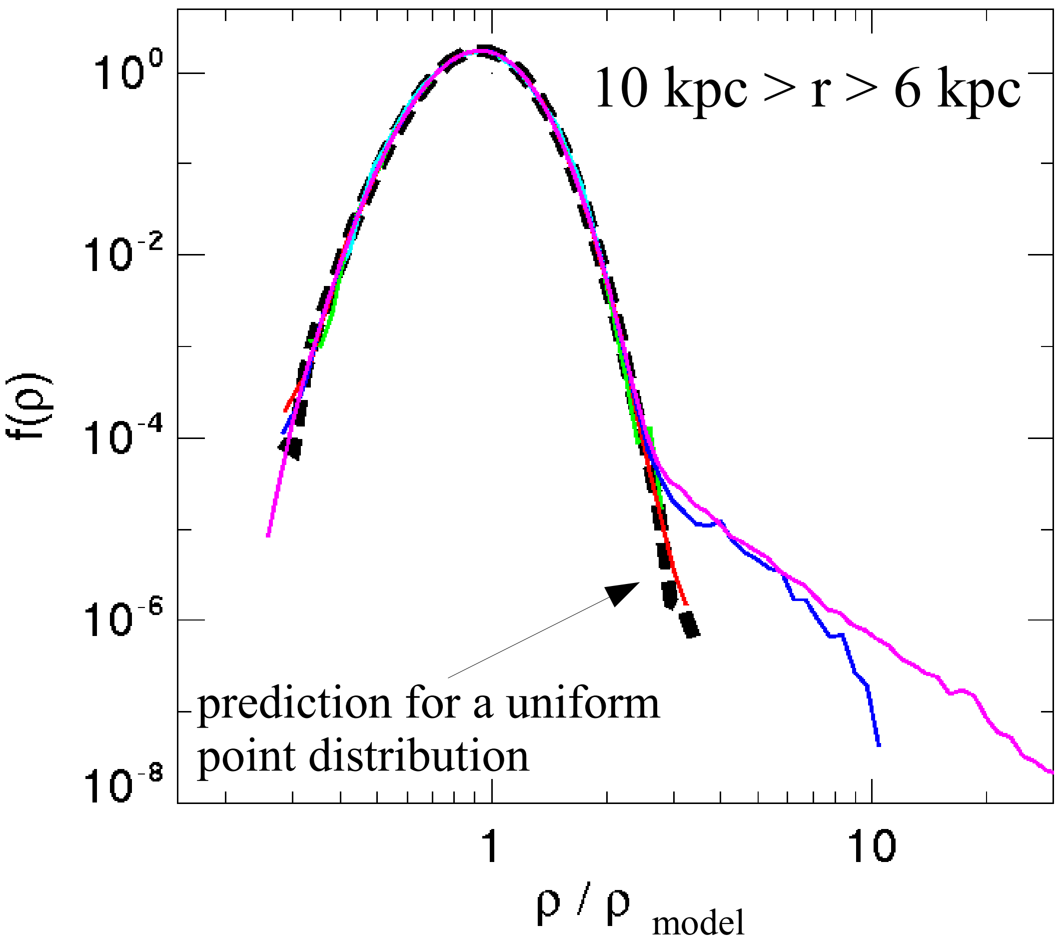
Properties of subhalos

- Subhalos live primarily in the outer parts of halos
- Their radial distribution is almost independent of their mass
- The number of subhalos is proportional to the mass of the host
- The total mass fraction in subhalos converges only weakly as smaller mass objects are included → many small objects
- In the inner halo (near the Sun) subhalos contain a very small fraction of the dark matter ($< 1\%$)

Maybe Dark Matter can be detected in a laboratory?



Local density in the inner halo compared to a smooth ellipsoidal model

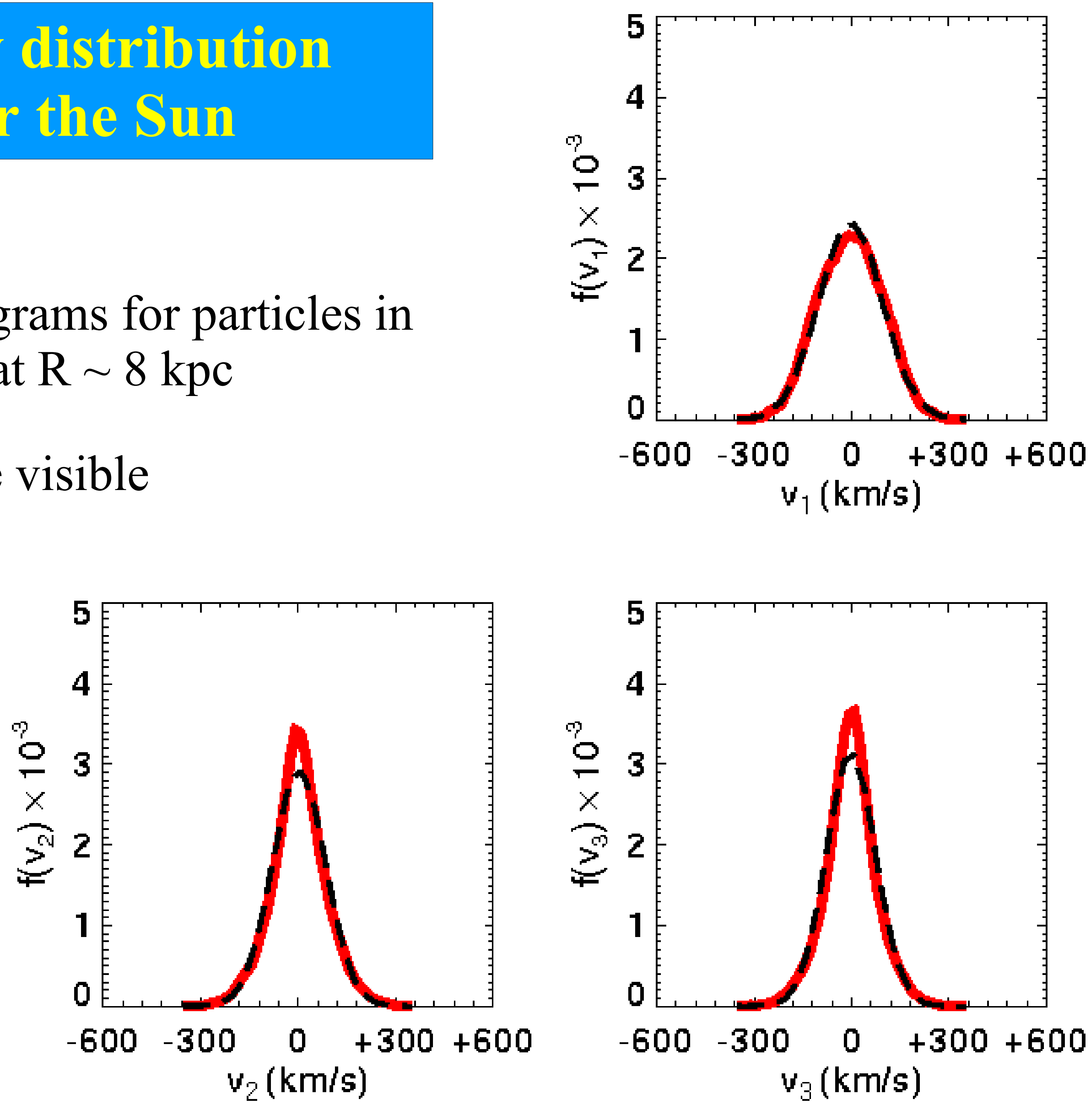


- Estimate a local density ρ at each point by adaptively smoothing the particle distribution
- Fit to a smooth density model stratified on similar ellipsoids
- The chance of a random point lying in a substructure is $< 10^{-4}$
- Elsewhere the scatter about the smooth model is only 4%

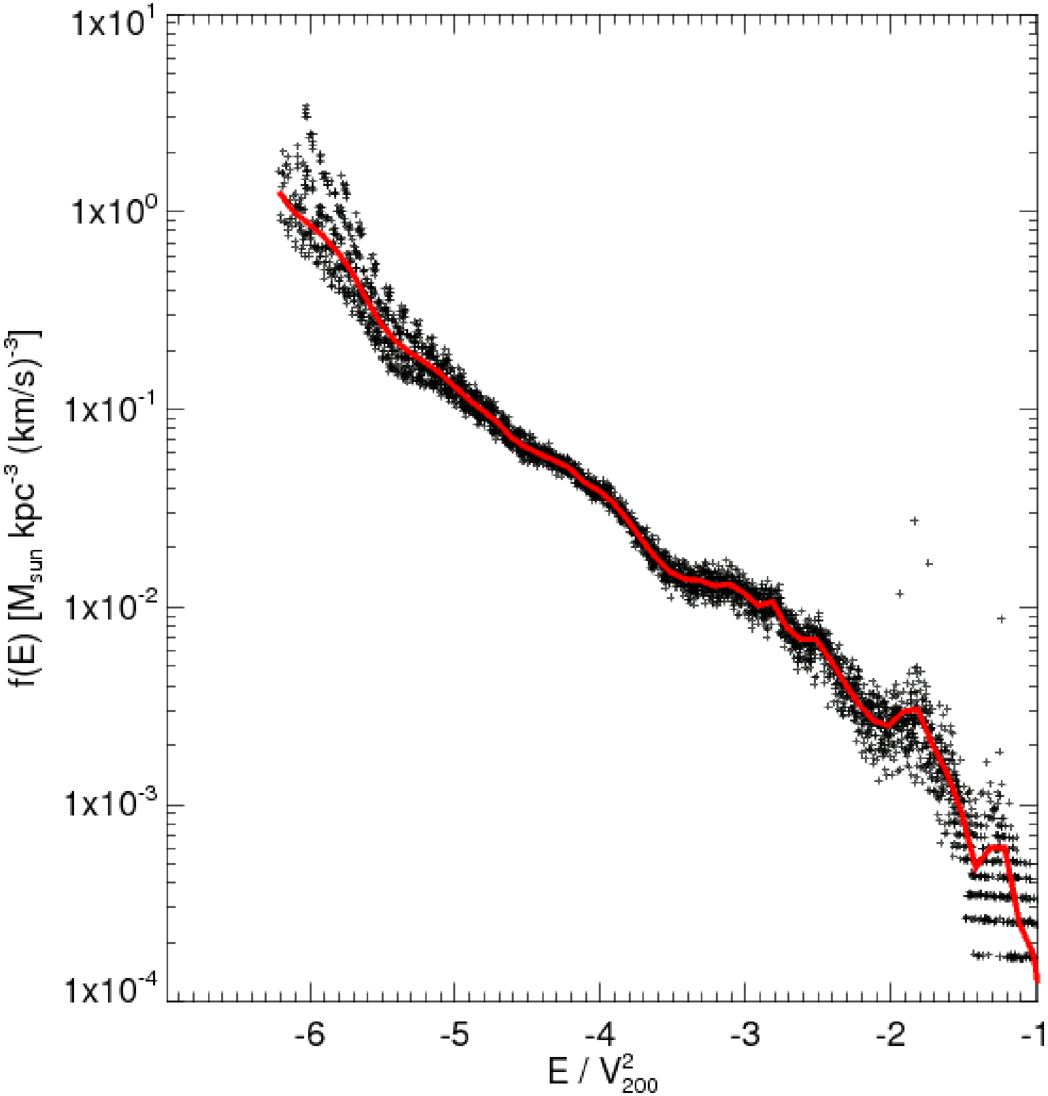
Velocity distribution near the Sun

- Velocity histograms for particles in small regions at R ~ 8 kpc

- No streams are visible



Energy space features – fossils of formation



The distribution of DM particle energies shows bumps which

-- repeat from place to place

-- are stable over Gyr timescales

-- repeat in simulations of the same object at varying resolution

-- are different in simulations of different objects

These are potentially observable fossils of the formation process

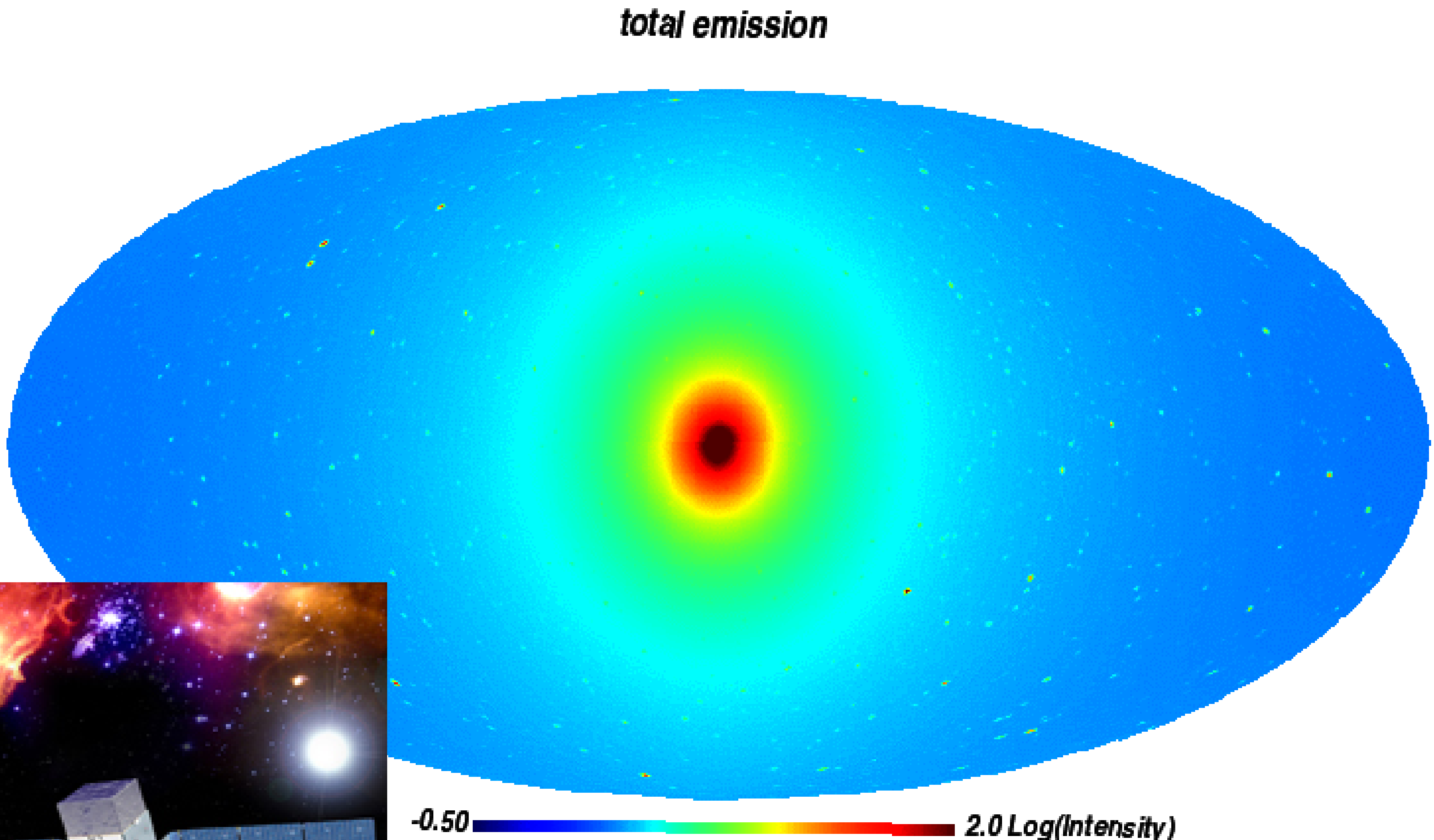
Predictions for direct detection experiments

- With more than 99.9% confidence the Sun lies in a region where the DM density differs from the smooth mean value by < 20%

- The local velocity distribution of DM particles is similar to a trivariate Gaussian with no measurable "lumpiness" due to individual DM streams

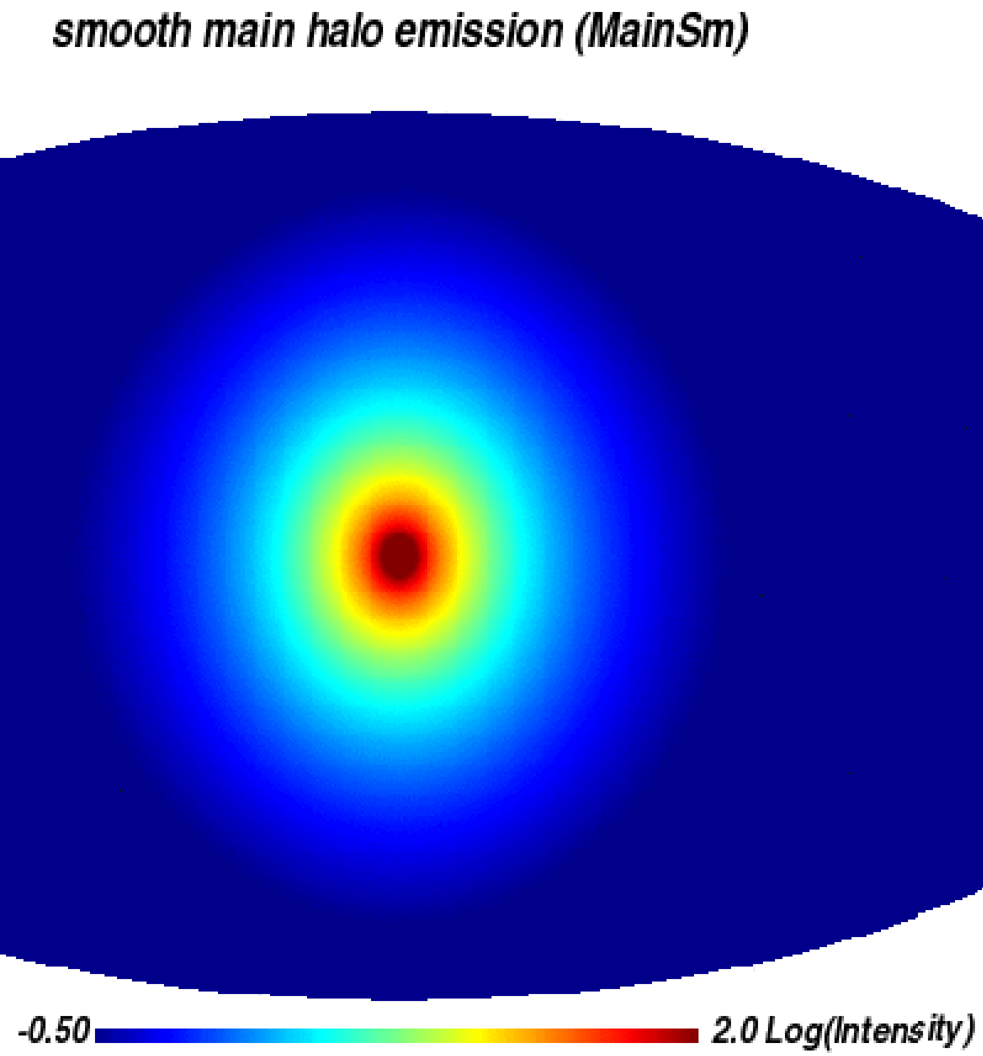
- The energy distribution of DM particles should contain broad features with ~20% amplitude which are the fossils of the detailed assembly history of the Milky Way's dark halo

→ Dark matter astronomy



Maybe the annihilation of Dark Matter will be seen by Fermi?

Milky Way halo seen in DM annihilation radiation



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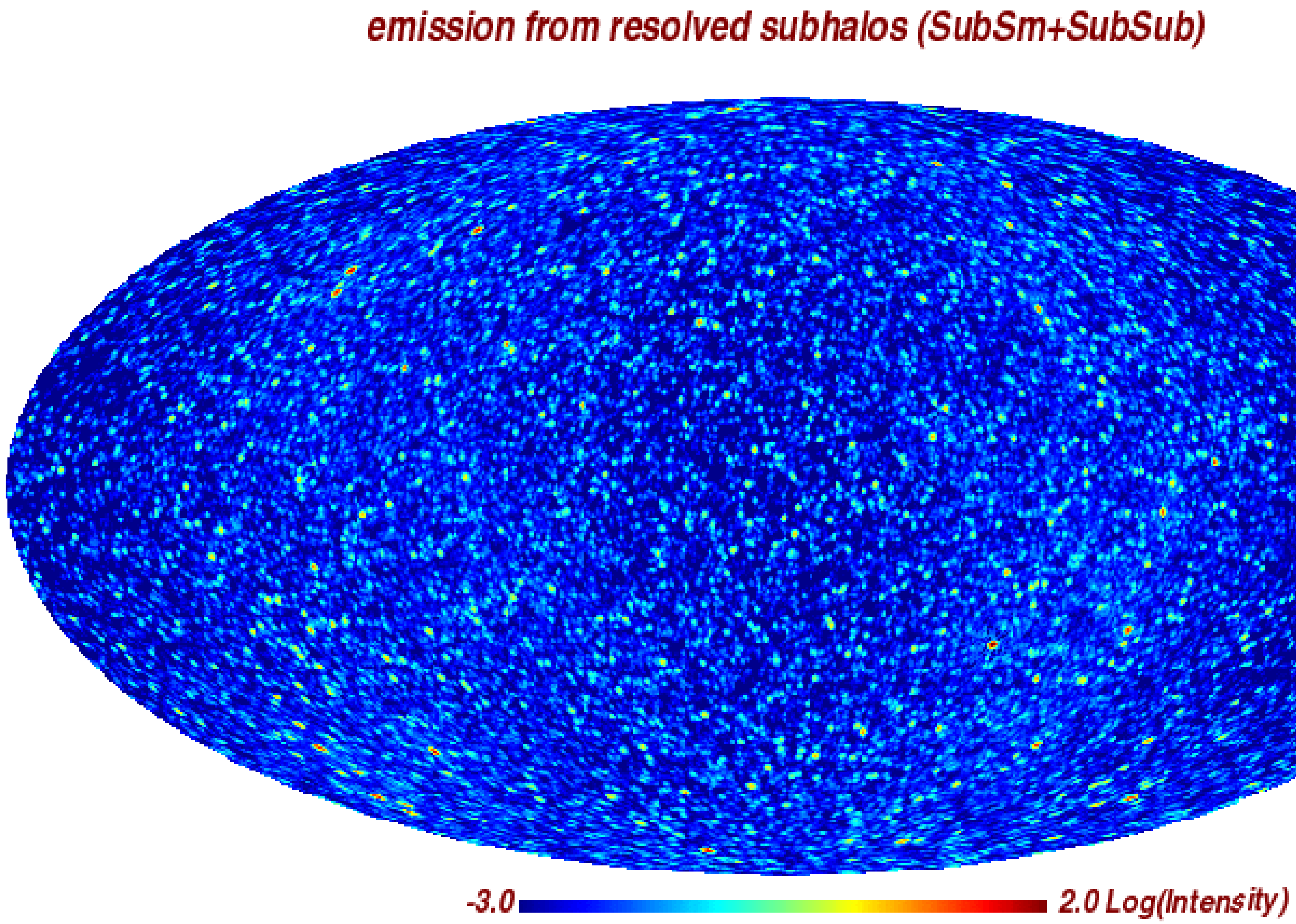

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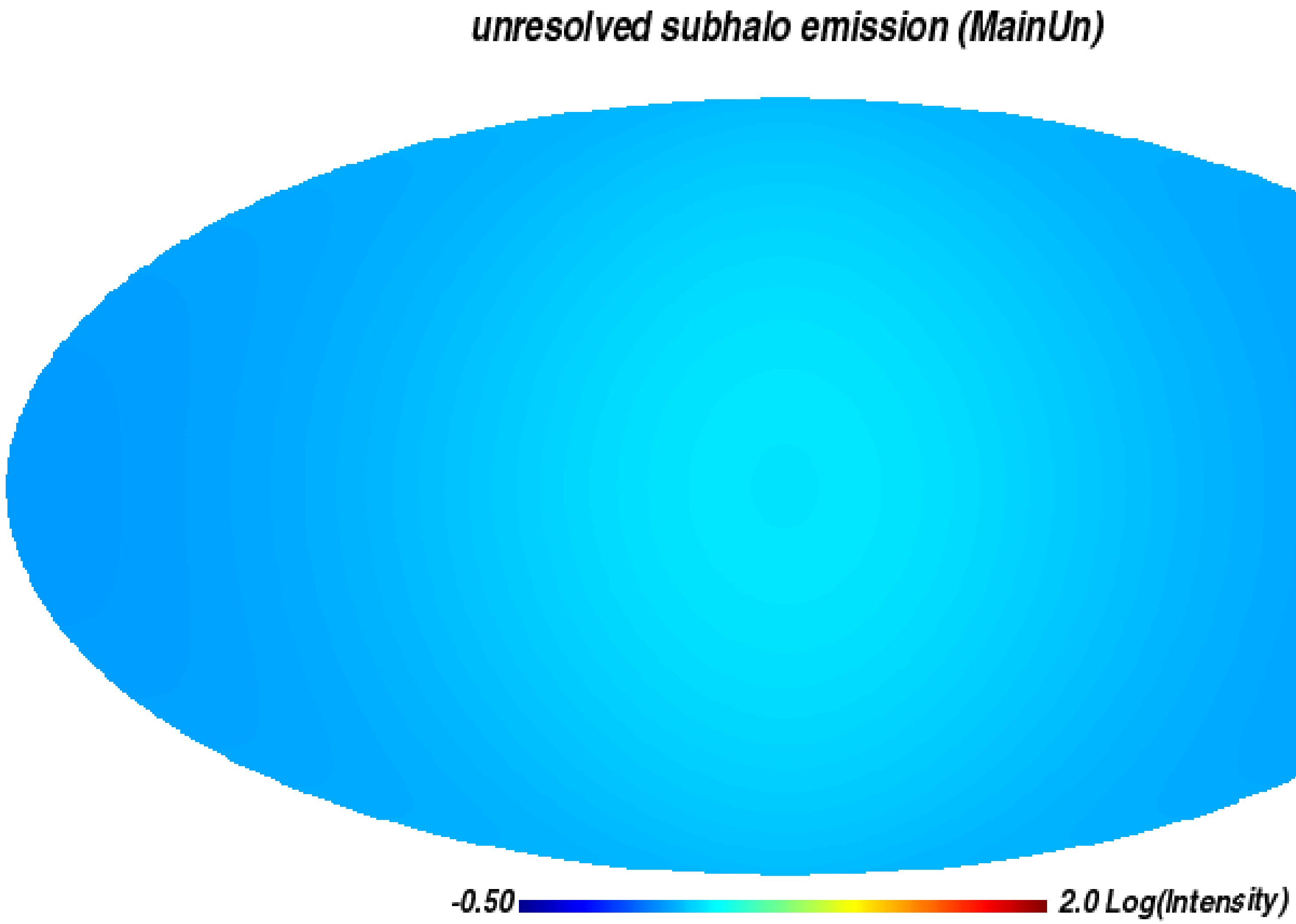

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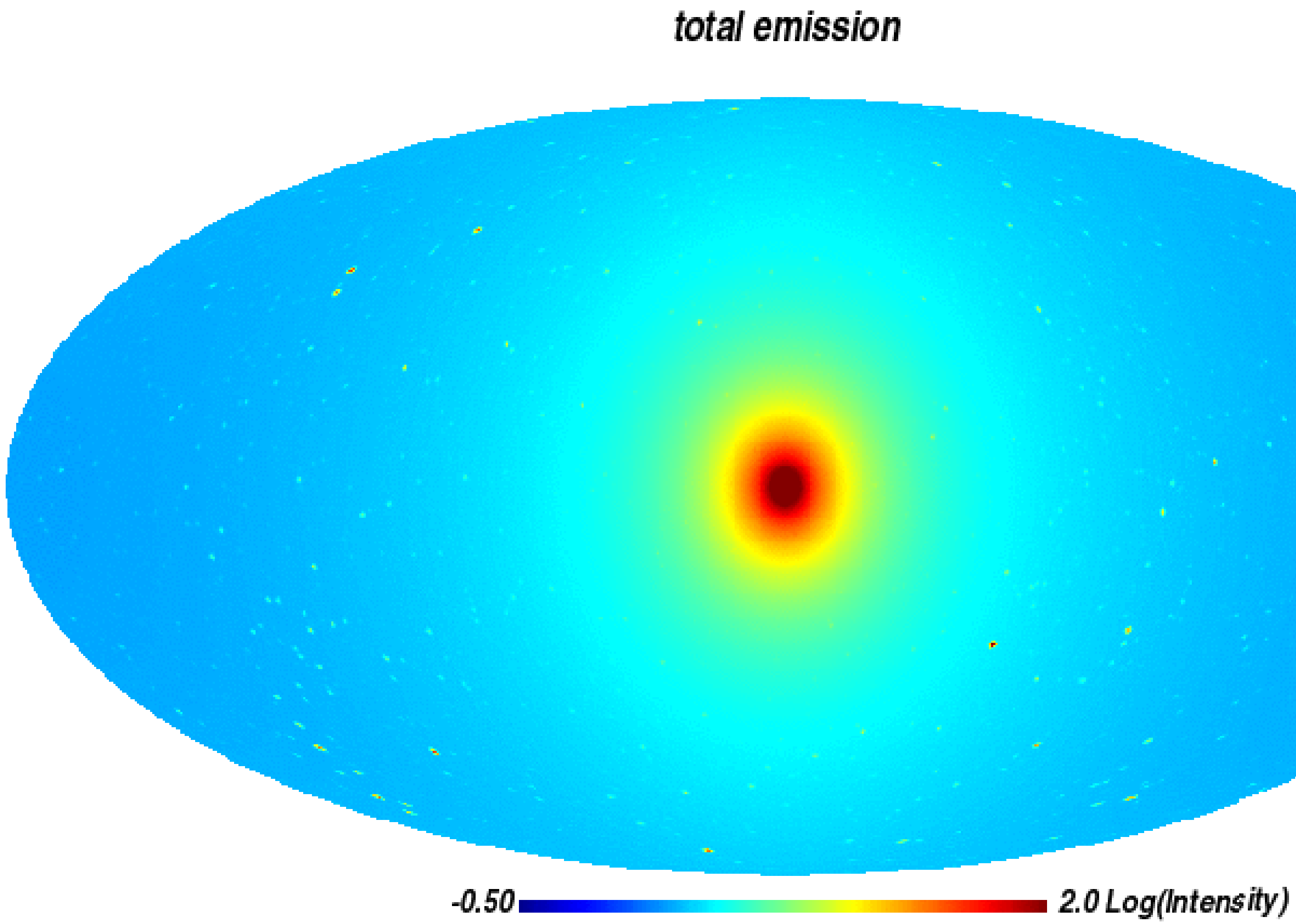
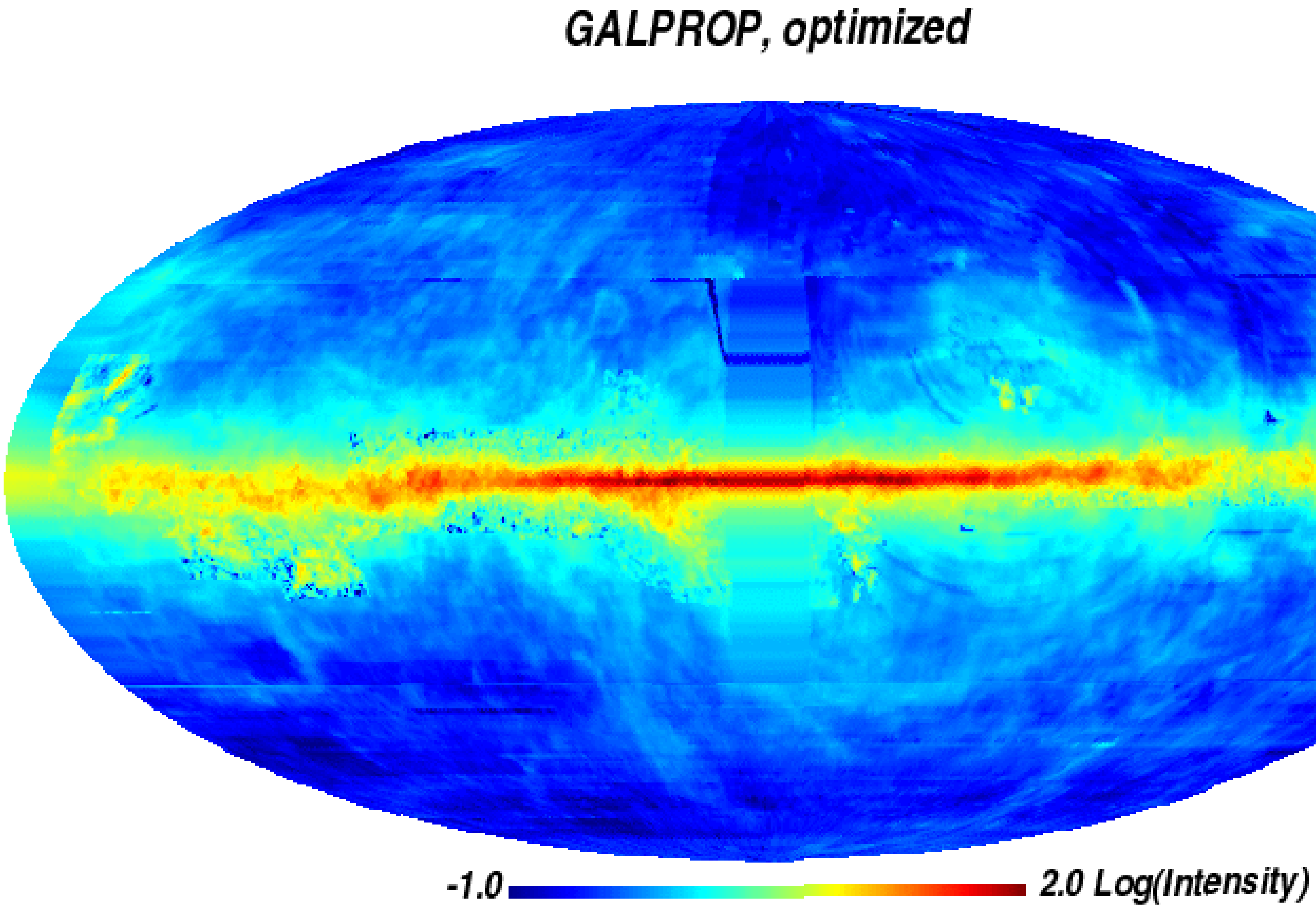


A prediction for foreground γ-ray emission



Small-scale clumping and annihilation

- Subhalos increase the Milky Way's total flux within 250 kpc by a factor of 230 as seen by a distant observer, but its flux on the sky by a factor of only 2.9 as seen from the Sun

- The luminosity from subhalos is dominated by small objects and is nearly uniform across the sky (contrast is a factor of ~1.5)

- Individual subhalos have lower S/N for detection than the main halo but detectability will depend on the structure of the foreground

- The highest S/N *known* subhalo should be the Large Magellanic Cloud, but may be confused by emission from stars

Cold Dark Matter at high redshift (e.g. $z \sim 10^5$)

Well *after* CDM particles become nonrelativistic, but *before* they dominate the cosmic density, their distribution function is

$$f(\boldsymbol{x}, \boldsymbol{v}, t) = \rho(t)\,[1 + \delta(\boldsymbol{x})]\, N\,[\{\boldsymbol{v} - \boldsymbol{V}(\boldsymbol{x})\}/\sigma]$$

where $\rho(t)$ is the mean mass density of CDM,

$\delta(\boldsymbol{x})$ is a Gaussian random field with finite variance $\ll 1$,

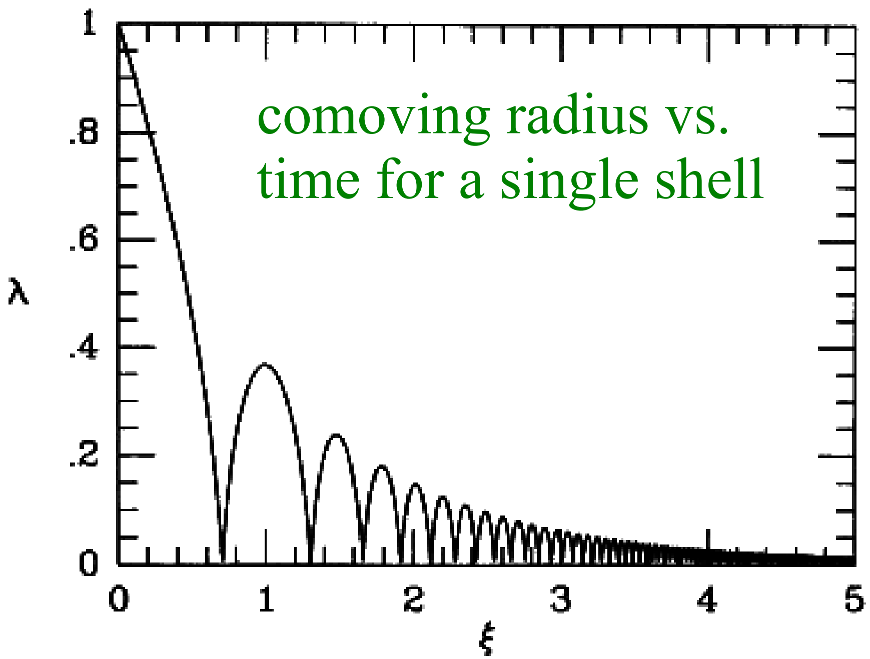
$\boldsymbol{V}(\boldsymbol{x}) = \nabla\psi(\boldsymbol{x})$ where $\nabla^2\psi(\boldsymbol{x}) \propto \delta(\boldsymbol{x})$

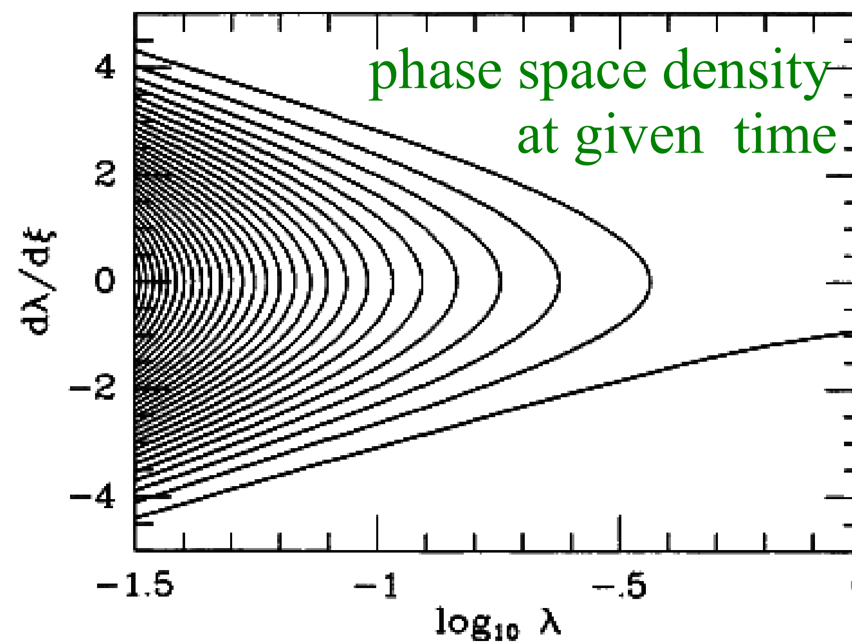
and N is standard normal with $\sigma^2 << \langle|\mathbf{V}|^2\rangle$

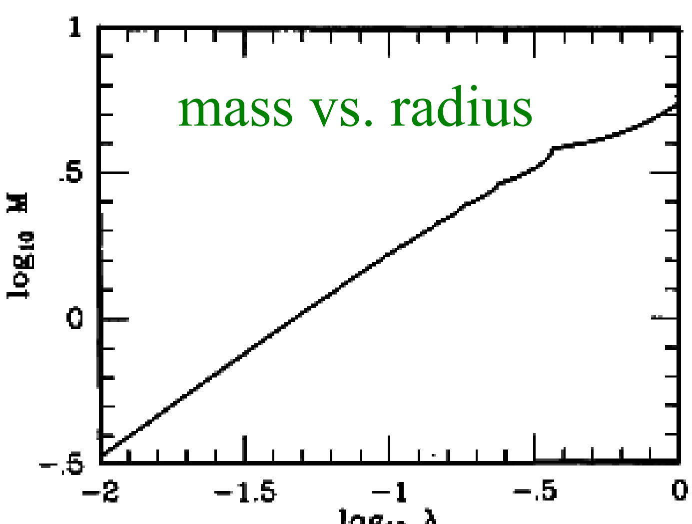
CDM occupies a thin 3-D 'sheet' within the full 6-D phase-space and its projection onto **x**-space is near-uniform.

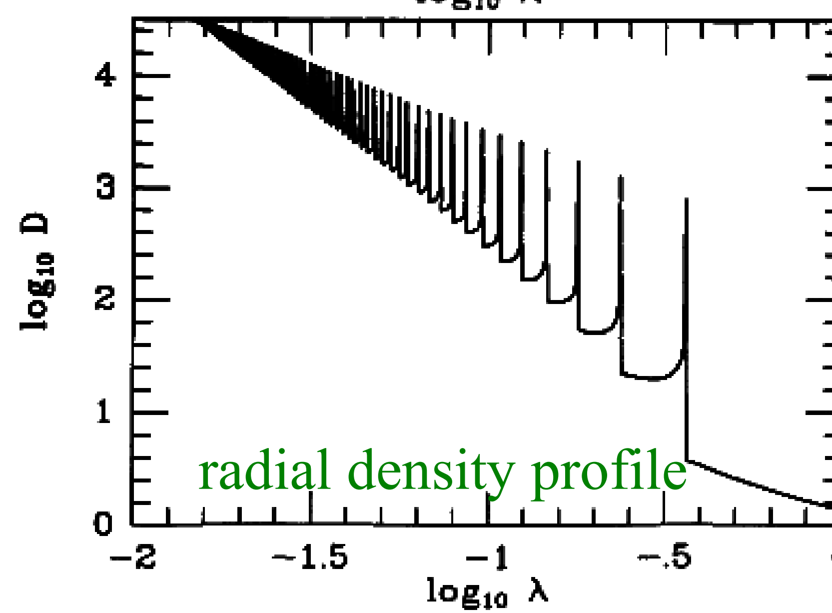
$Df / Dt = 0$ → only a 3-D subspace is occupied at later times.
Nonlinear evolution leads to a complex, multi-stream structure.

Similarity solution for spherical collapse in CDM







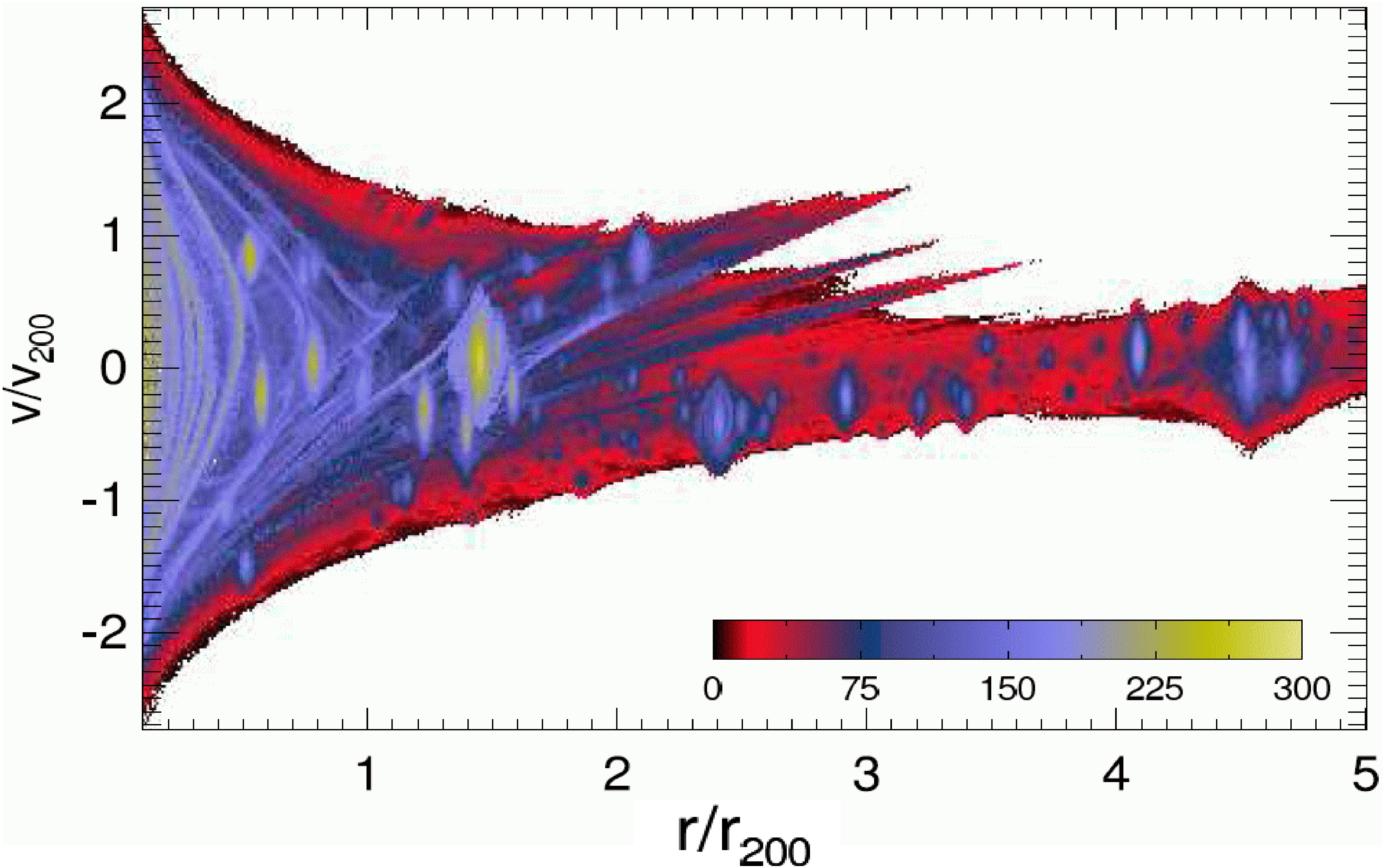


Evolution of CDM structure

Consequences of $Df / Dt = 0$

- The 3-D phase sheet can be stretched and folded but not torn
- At least 1 sheet must pass through every point $\mathbf{x}$
- In nonlinear objects there are typically many sheets at each $\mathbf{x}$
- Stretching which reduces a sheet's density must also reduce its velocity dispersions to maintain $f =$ const.
- At a caustic, at least one velocity dispersion must $\longrightarrow \infty$
- All these processes can be followed in fully general simulations by tracking the phase-sheet local to each simulation particle

Caustic crossing counts in a ΛCDM Milky Way halo



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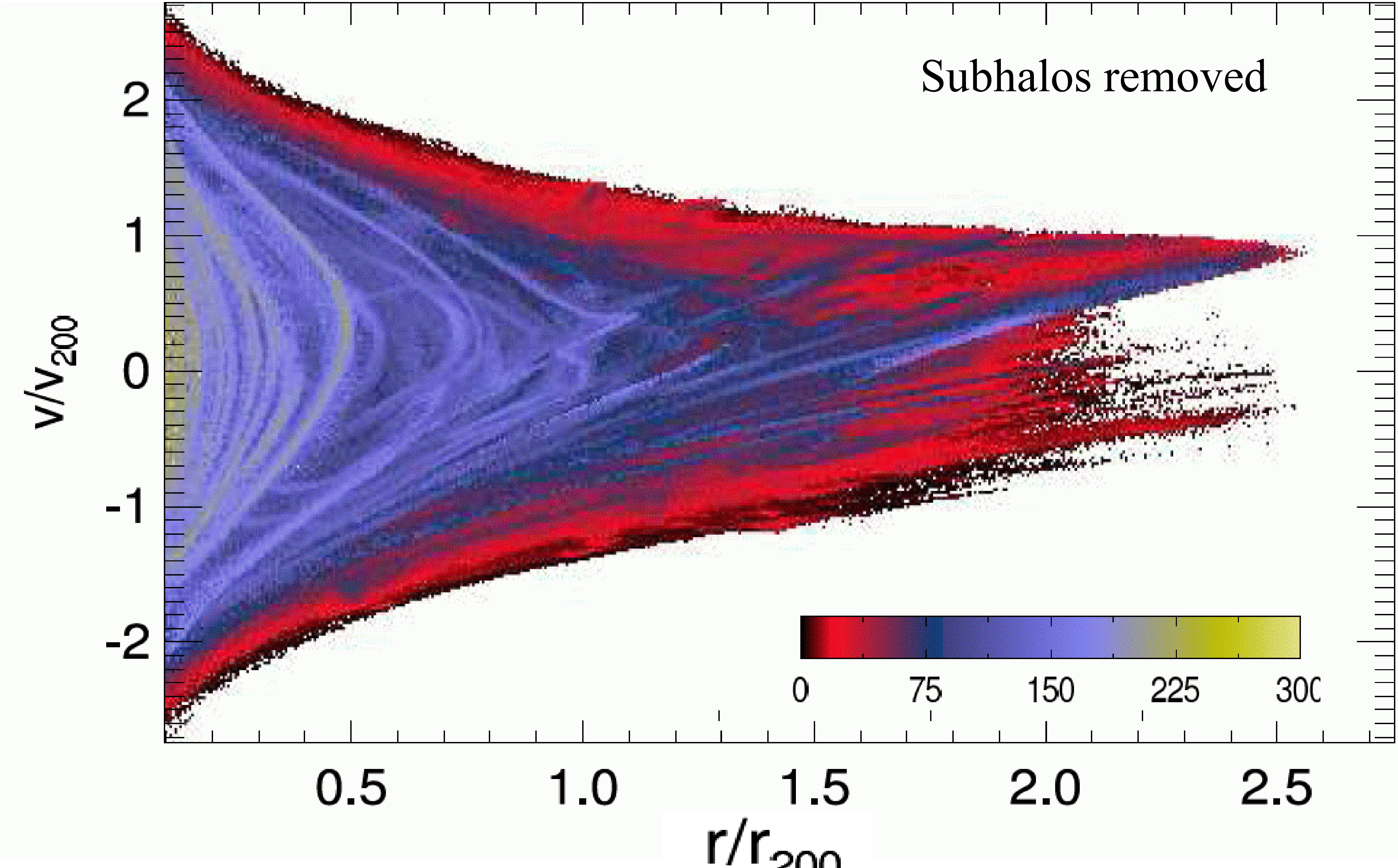

Dark matter caustics and annihilation radiation

- Caustics are less significant in realistic three-dimensional situations than in one-dimensional similarity solutions

- Particles in the inner regions of halos (e.g. near the Sun) have typically passed through several hundred caustics
  → low stream densities and weak caustics

- The annihilation luminosity from caustics is a small fraction of the total, particularly in the inner regions

- If annihilation radiation is detected from external galaxies (e.g. M31) only the outermost caustic is likely to be visible

Final remarks?

- The dark matter problem has been with us since 1933
- Non-baryonic dark matter has been the "solution" since ~1980
- The DM aspects of the current standard paradigm are supported by a wide variety of data at low redshift and by the CMB
- Nevertheless, the nature of DM can only be confirmed by detection of non-gravitational effects on Earth or in the sky

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- Nevertheless, the nature of DM can only be confirmed by detection of non-gravitational effects on Earth or in the sky
- Dark energy was established in the late 1990's
- All known routes to exploring its nature are astronomical
- Understanding dark energy probably requires a good new idea.