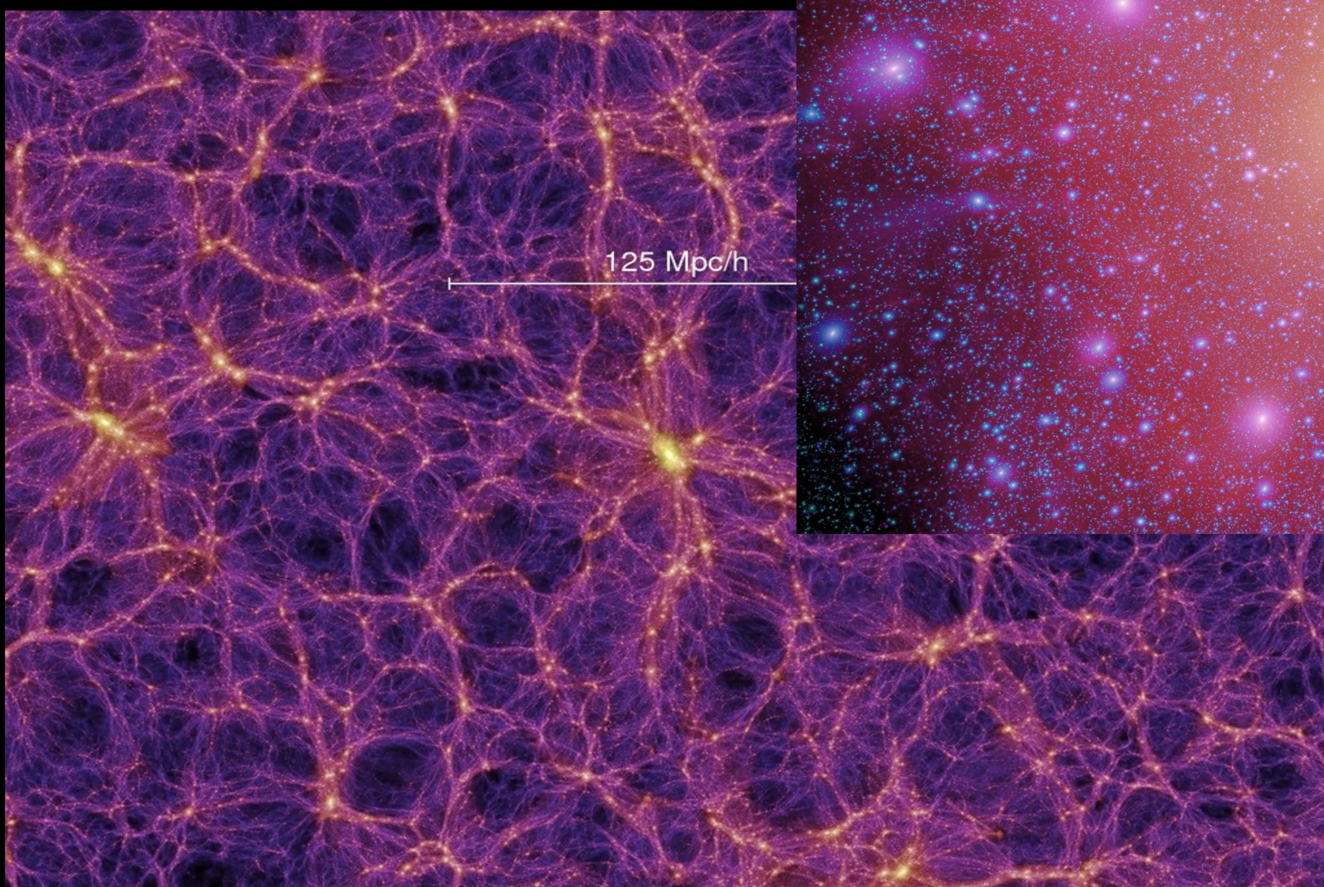
The Largest Structures in the Universe and their Origin

Prof. Dr. Volker Springel

Universität Heidelberg

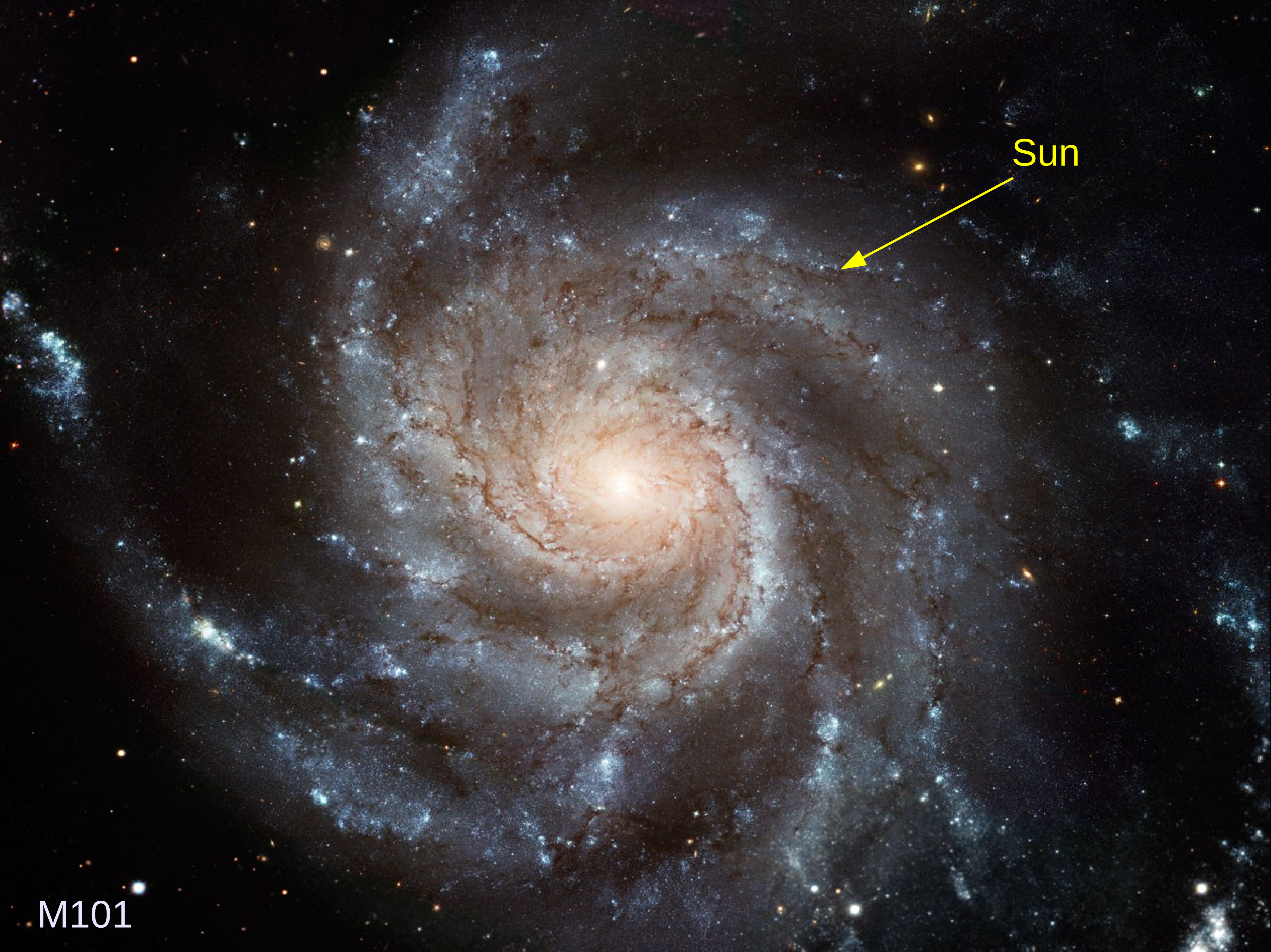
Heidelberg Institute for Theoretical Studies

HITS



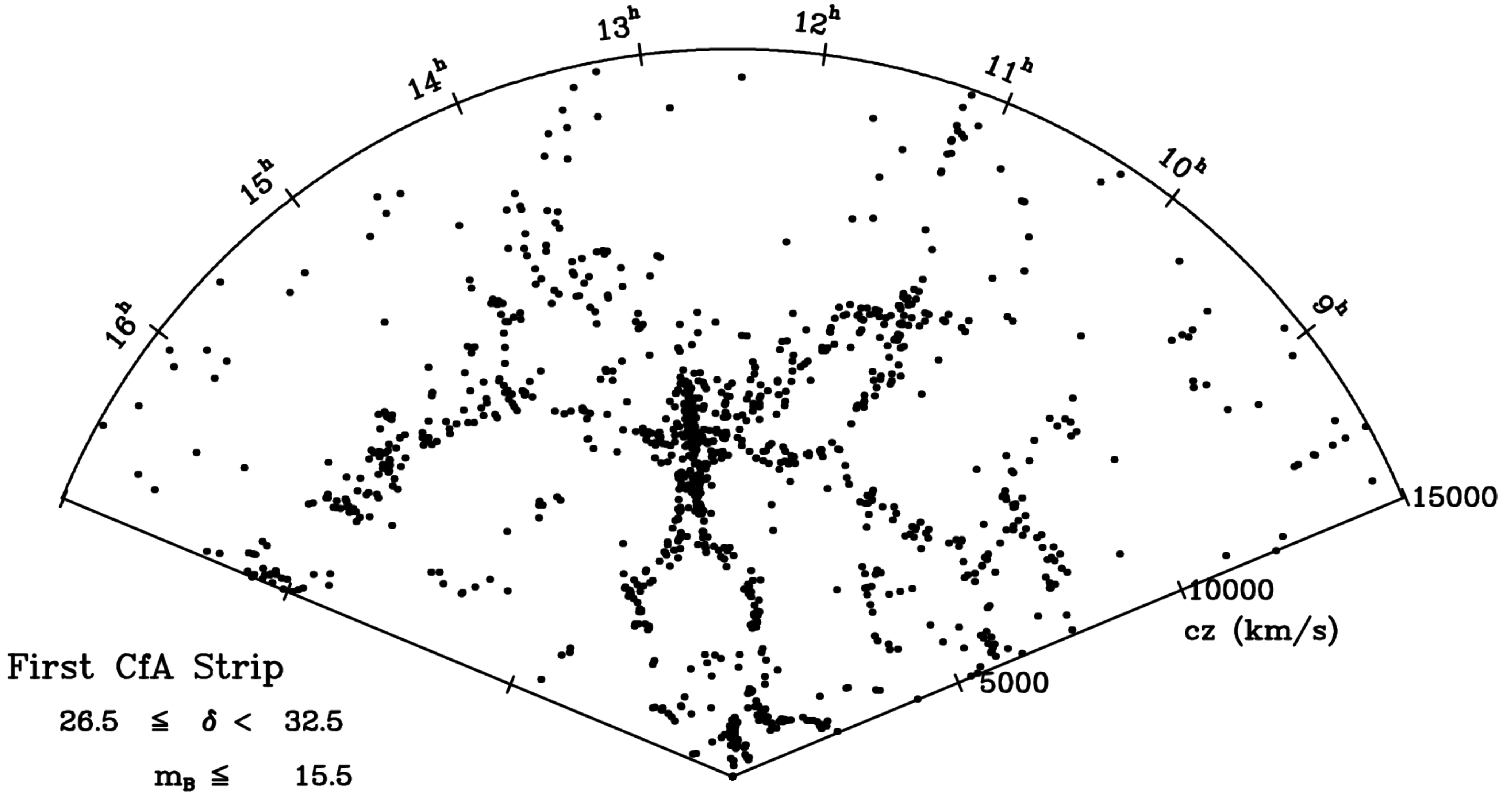
16th Japanese-German Symposium

BBAW, Berlin
May 21, 2011


Sun
M101

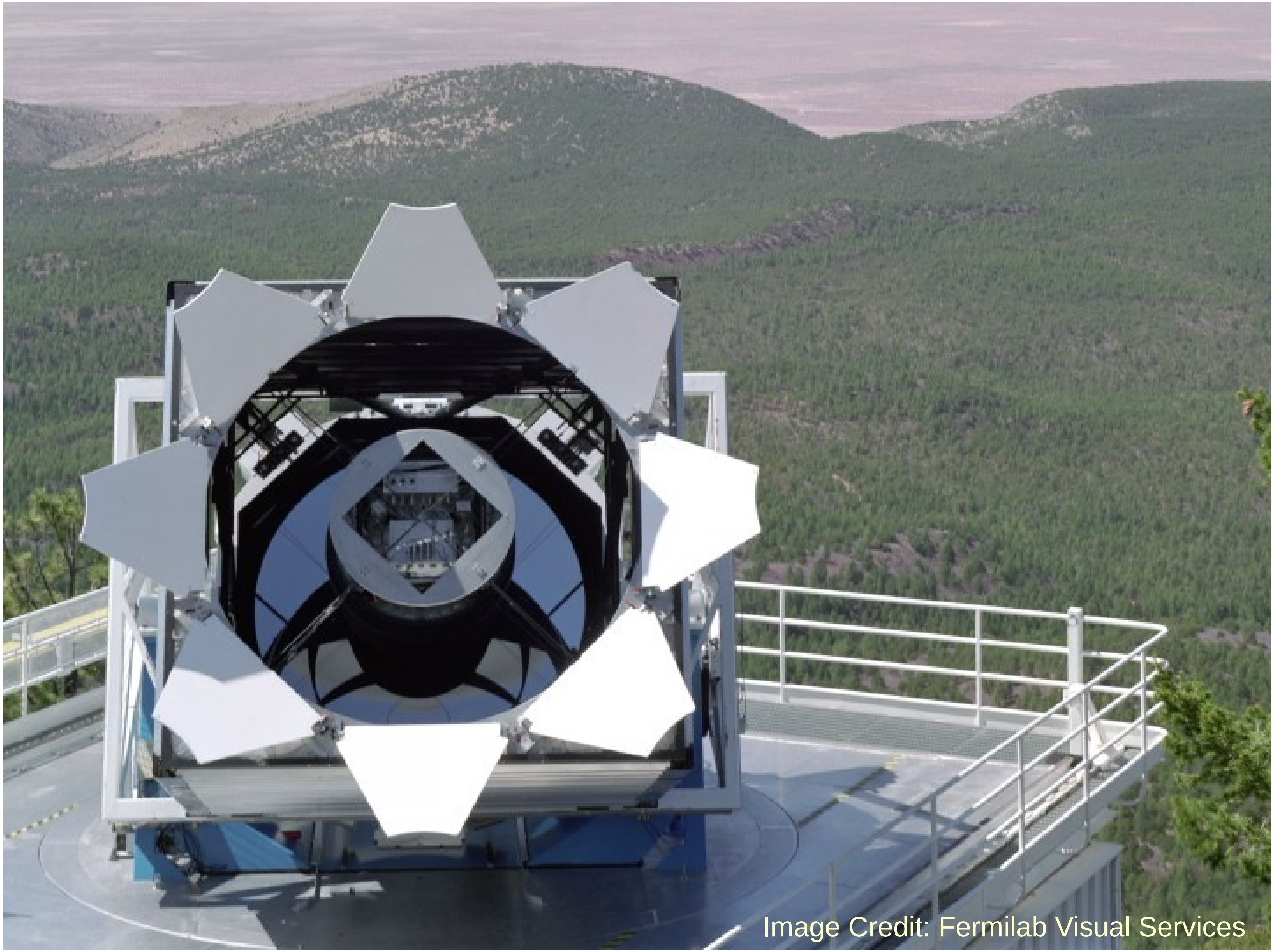
The first slice in the CfA redshift survey

1100 galaxies in a wedge,
6 degrees wide and 110 degrees long

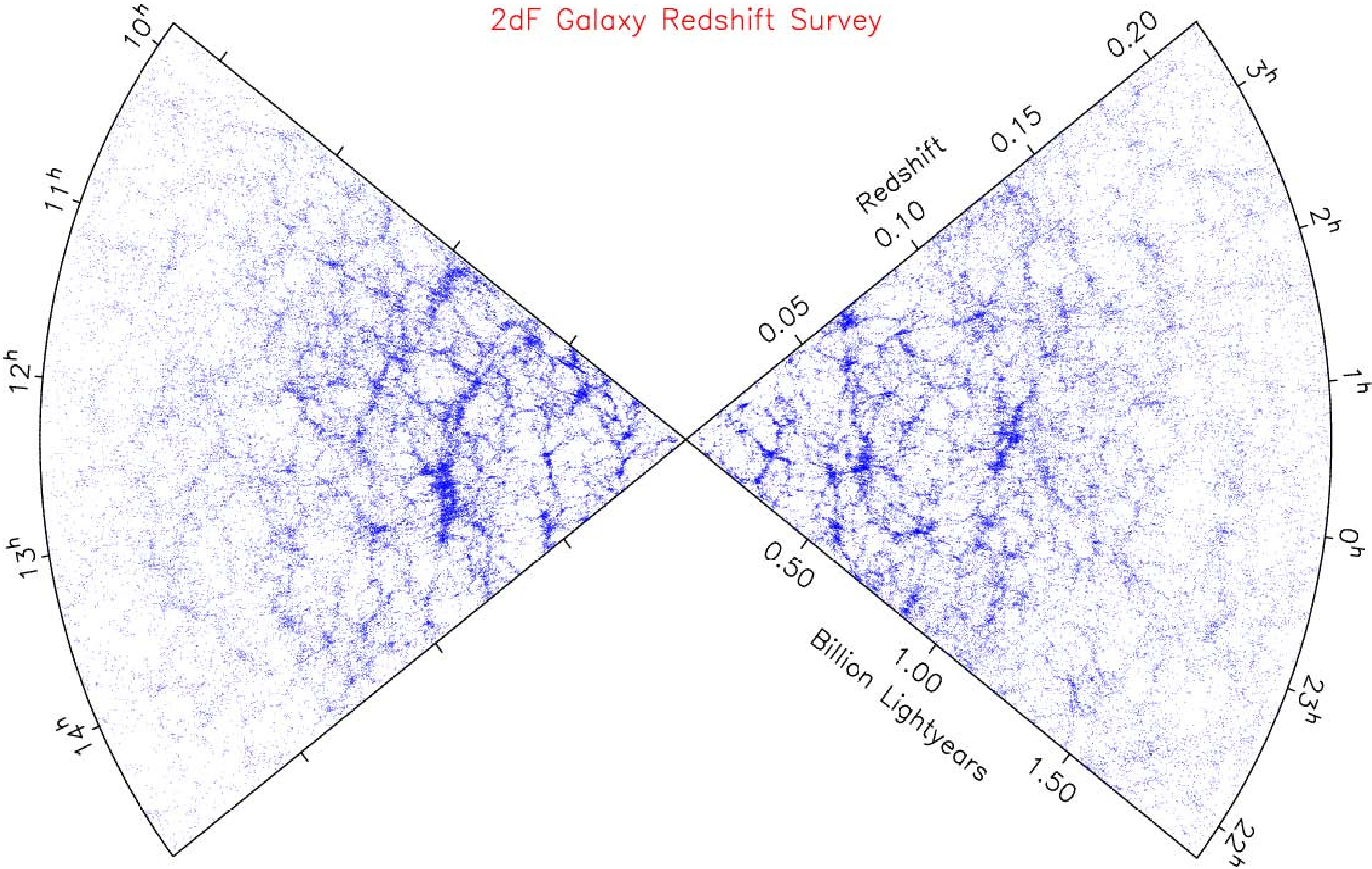


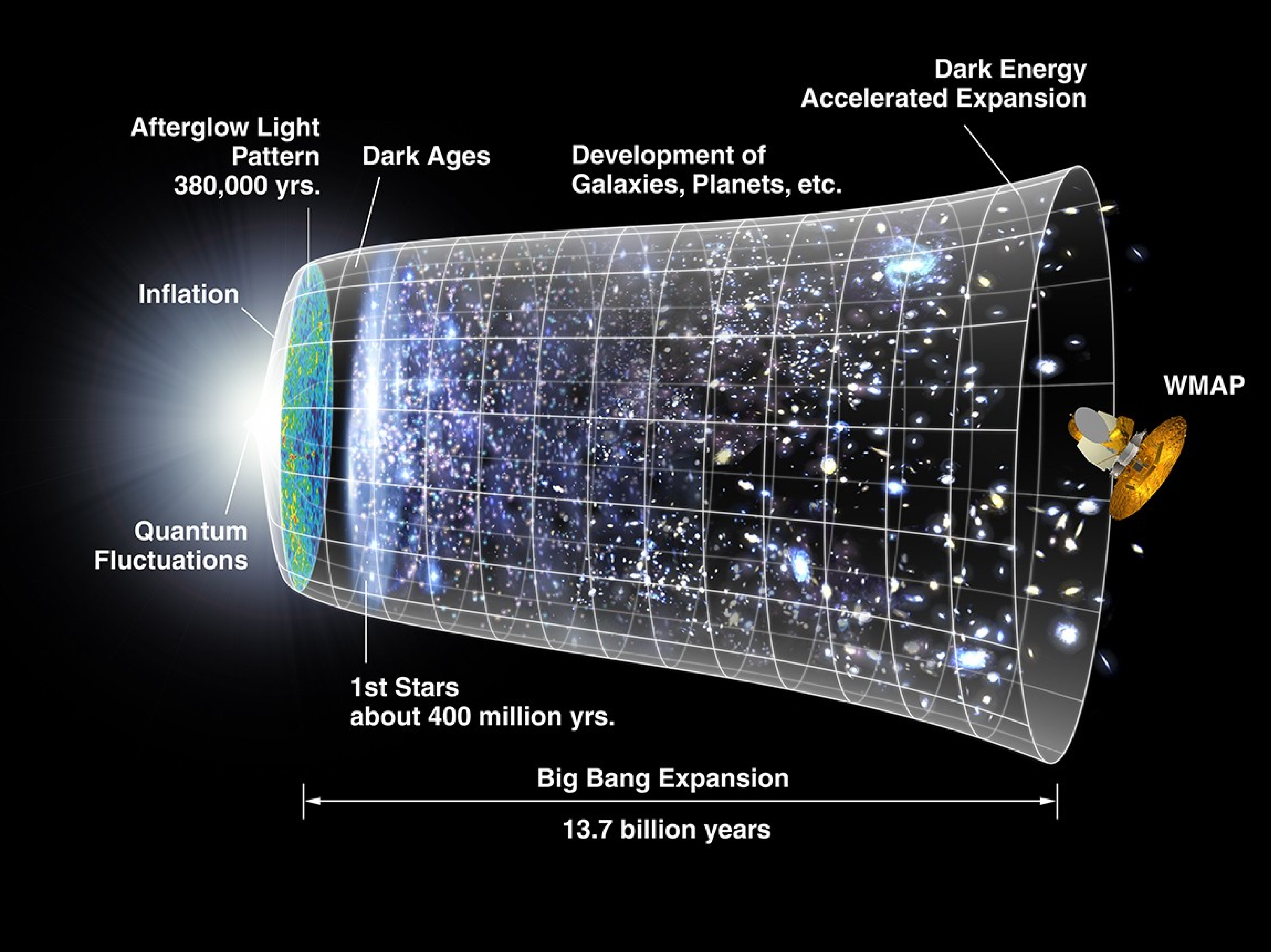
de Lapparent, Geller, Huchra (1986)
Smithsonian Astronomical Observatory

Sloan Digital Sky Survey (SDSS) telescope at Apache Point, New Mexico



Current galaxy redshift surveys map the Universe with several hundred thousand galaxies

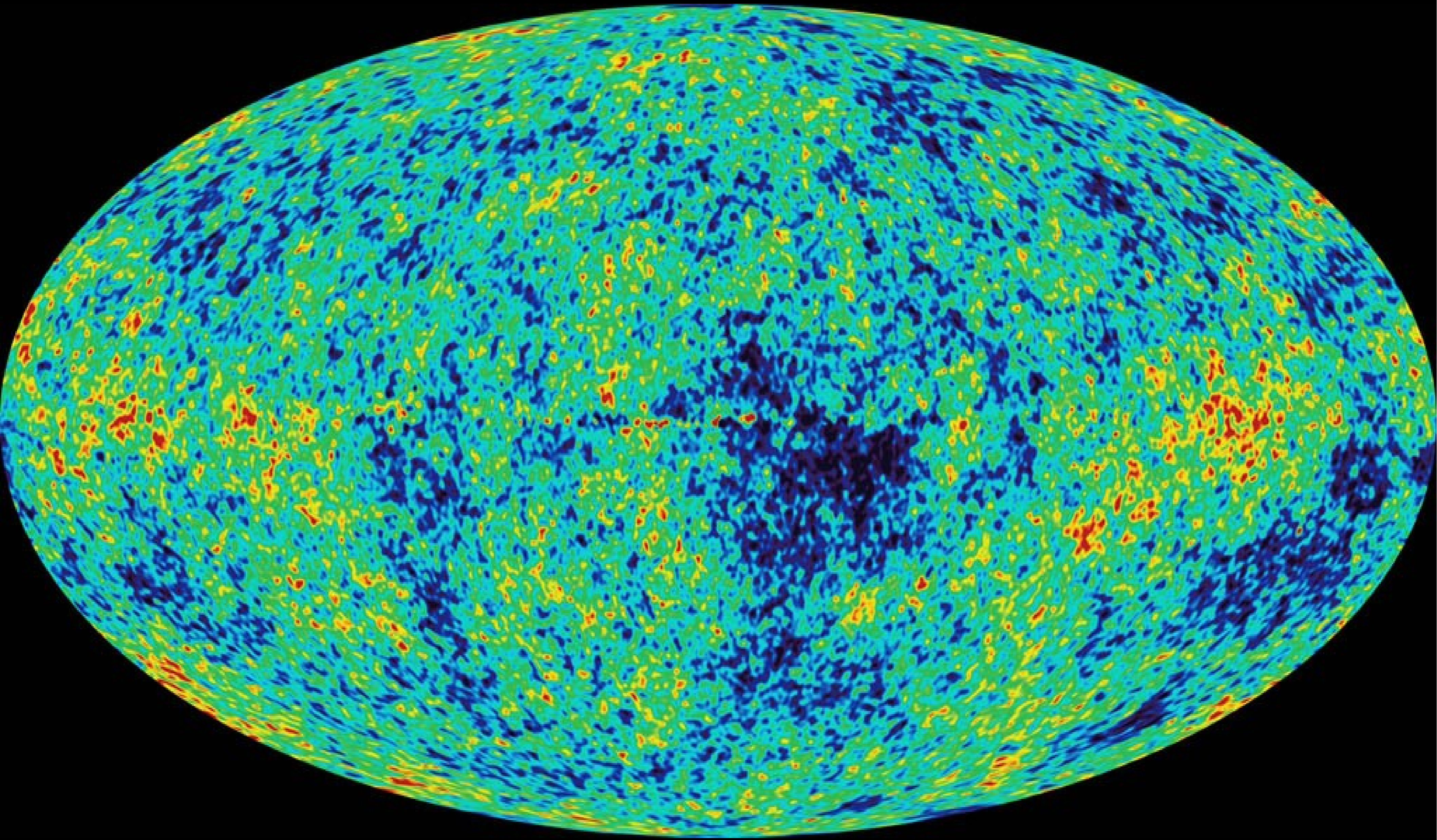




Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
380,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
WMAP
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.7 billion years

The initial conditions for cosmic structure formation are directly observable

THE MICROWAVE SKY



WMAP Science Team (2003, 2006, 2008, 2010)

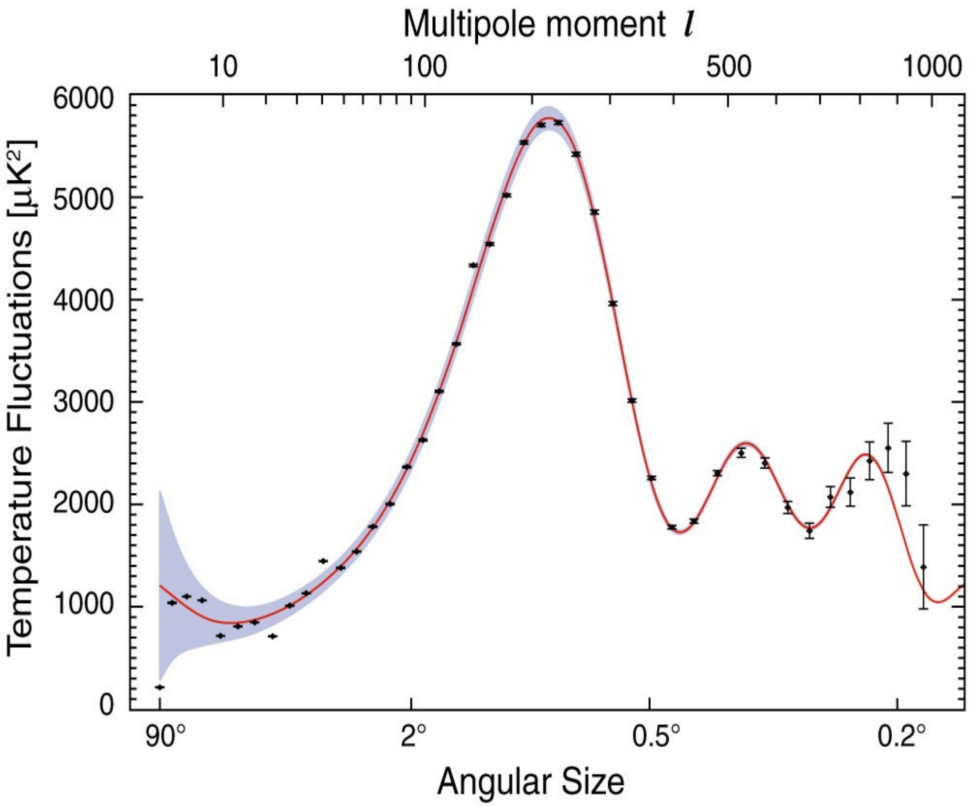
The most important cosmological parameters are well constrained

WMAP-5 CONSTRAINTS, INLCUDING TYPE-IA AND BAO DATA

Minimal, 6-parameter ΛCDM model is a great fit

$$\Omega_c = 0.233 \pm 0.013$$
$$\Omega_b = 0.0462 \pm 0.0015$$
$$\sigma_8 = 0.817 \pm 0.026$$
$$n_s = 0.960^{+0.014}_{-0.013}$$
$$H_0 = 70.1 \pm 1.3 \text{ km s}^{-1} \text{ Mpc}^{-1}$$
$$\tau = 0.084 \pm 0.016$$

$$\Omega_\Lambda = 0.721 \pm 0.015$$
$$t_0 = 13.73 \pm 0.12 \text{ Gyr}$$
$$z_{\rm reion} = 10.8 \pm 1.4$$

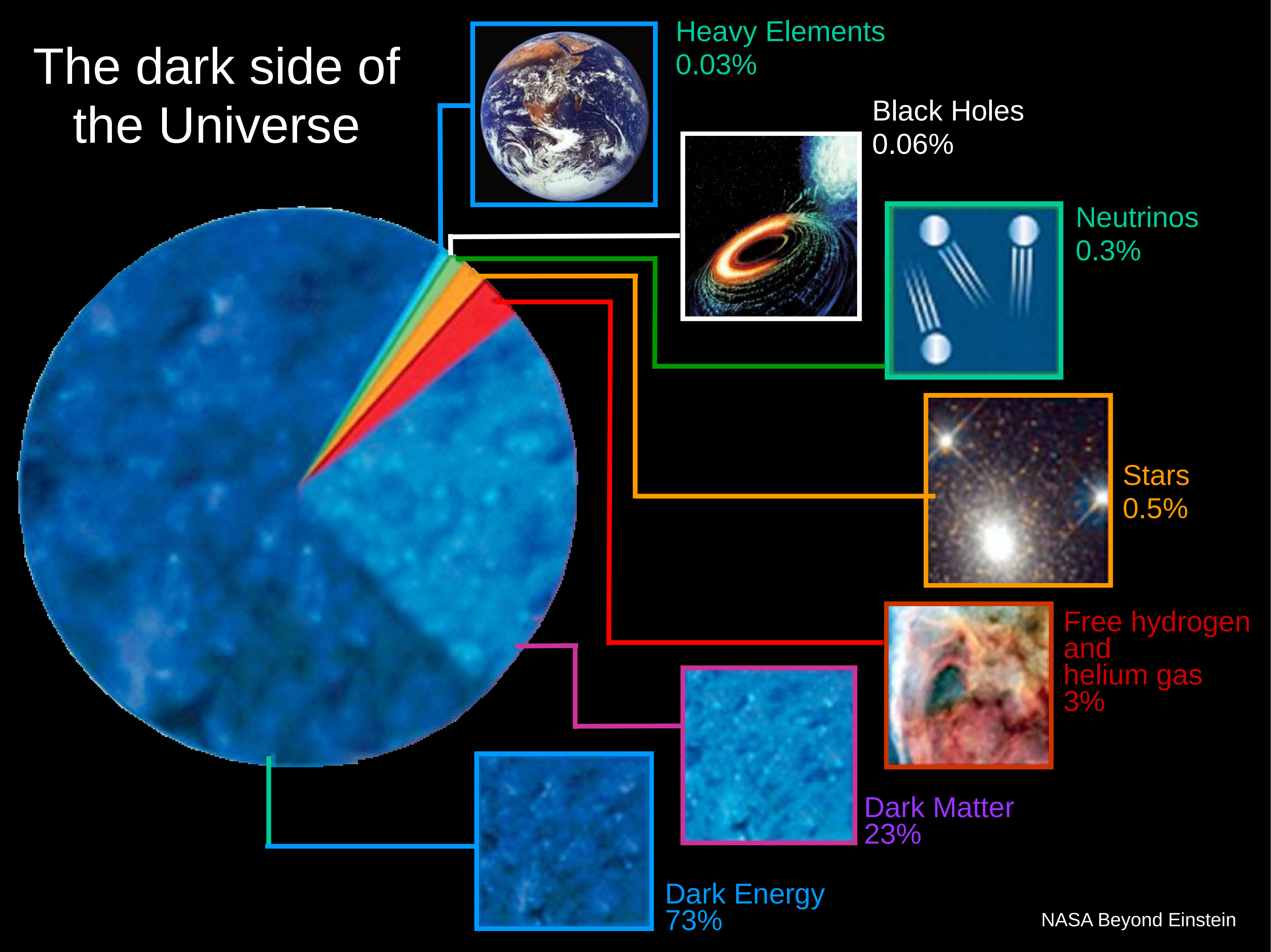


Constraints on dark energy equation of state:

$$-0.11 < 1 + w < 0.14$$
$$-0.0175 < \Omega_k < 0.0085$$

(95% CF, assuming a constant *w*)

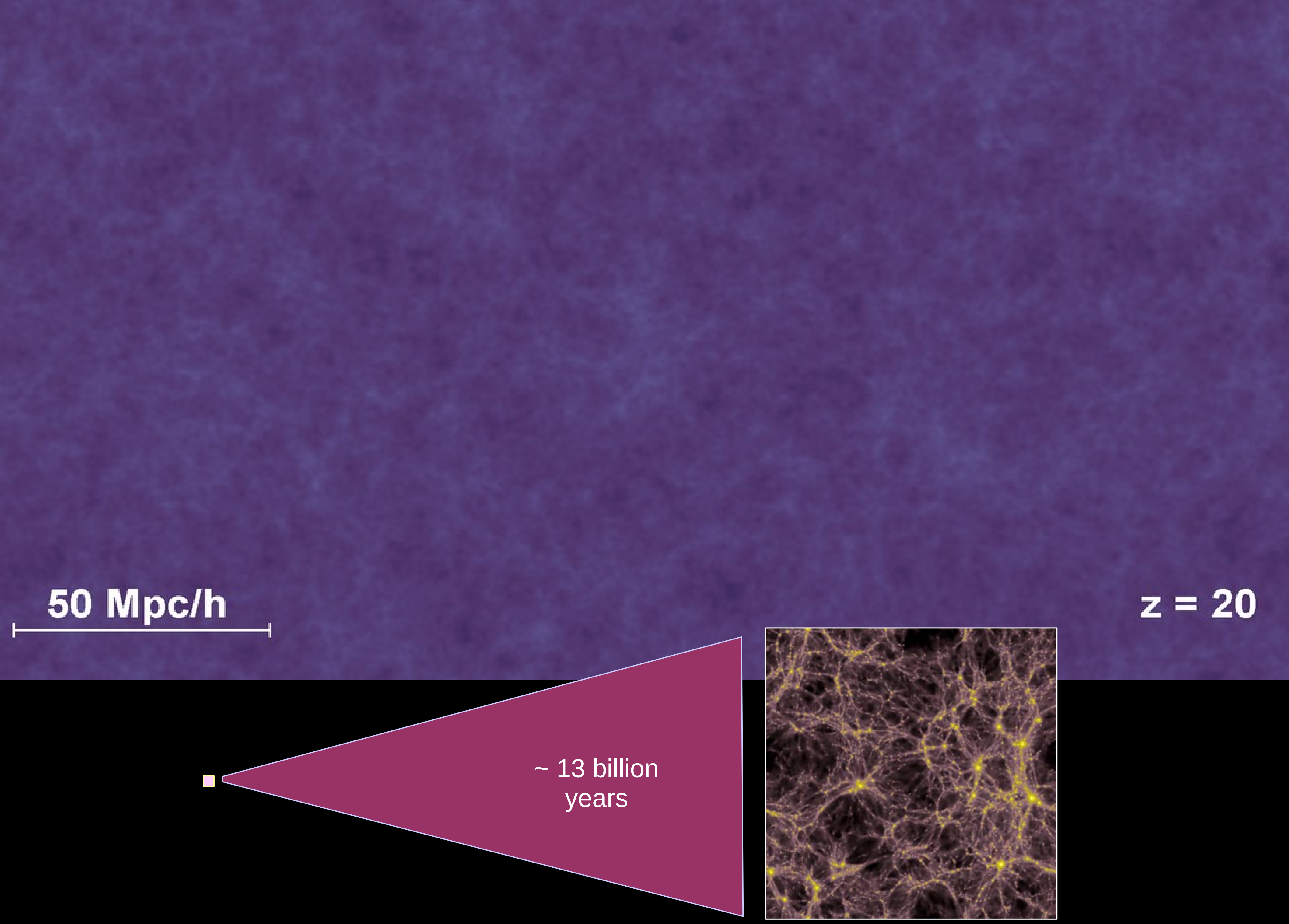
Komatsu et al. (2008)



The dark side of the Universe
Heavy Elements 0.03%
Black Holes 0.06%
Neutrinos 0.3%
Stars 0.5%
Free hydrogen and helium gas 3%
Dark Matter 23%
Dark Energy 73%
NASA Beyond Einstein

Currently the fastest supercomputers carry out up to ~1 petaflop, which are one thousand billion floating point operations per second

HLRB-II IN GARCHING


50 Mpc/h
z = 20
~ 13 billion
years

The basic dynamics of structure formation in the dark matter

BASIC EQUATIONS AND THEIR DISCRETIZATION

Gravitation

General theory of relativity (Newtonian approximation in an expanding space-time)

↓

Dark matter is collisionless

↓

Monte-Carlo integration as **N-body System**

↓

3N **coupled**, non-linear differential equations of second order

Friedmann-Lemaitre model

$$H(a) = H_0 \sqrt{a^{-3}\Omega_0 + a^{-2}(1 - \Omega_0 - \Omega_\Lambda) + \Omega_\Lambda}$$

Collisionless Boltzmann equation with self-gravity

$$\frac{\mathrm{d}f}{\mathrm{d}t} \equiv \frac{\partial f}{\partial t} + \mathbf{v}\frac{\partial f}{\partial \mathbf{x}} - \frac{\partial \Phi}{\partial \mathbf{r}}\frac{\partial f}{\partial \mathbf{v}} = 0$$

$$\nabla^2 \Phi(\mathbf{r}, t) = 4\pi G \int f(\mathbf{r}, \mathbf{v}, t)\mathrm{d}\mathbf{v}$$

Hamiltonian dynamics in expanding space-time

$$H = \sum_i \frac{\boldsymbol{p}_i^2}{2\, m_i\, a(t)^2} + \frac{1}{2}\sum_{ij} \frac{m_i m_j\, \varphi(\boldsymbol{x}_i - \boldsymbol{x}_j)}{a(t)}$$

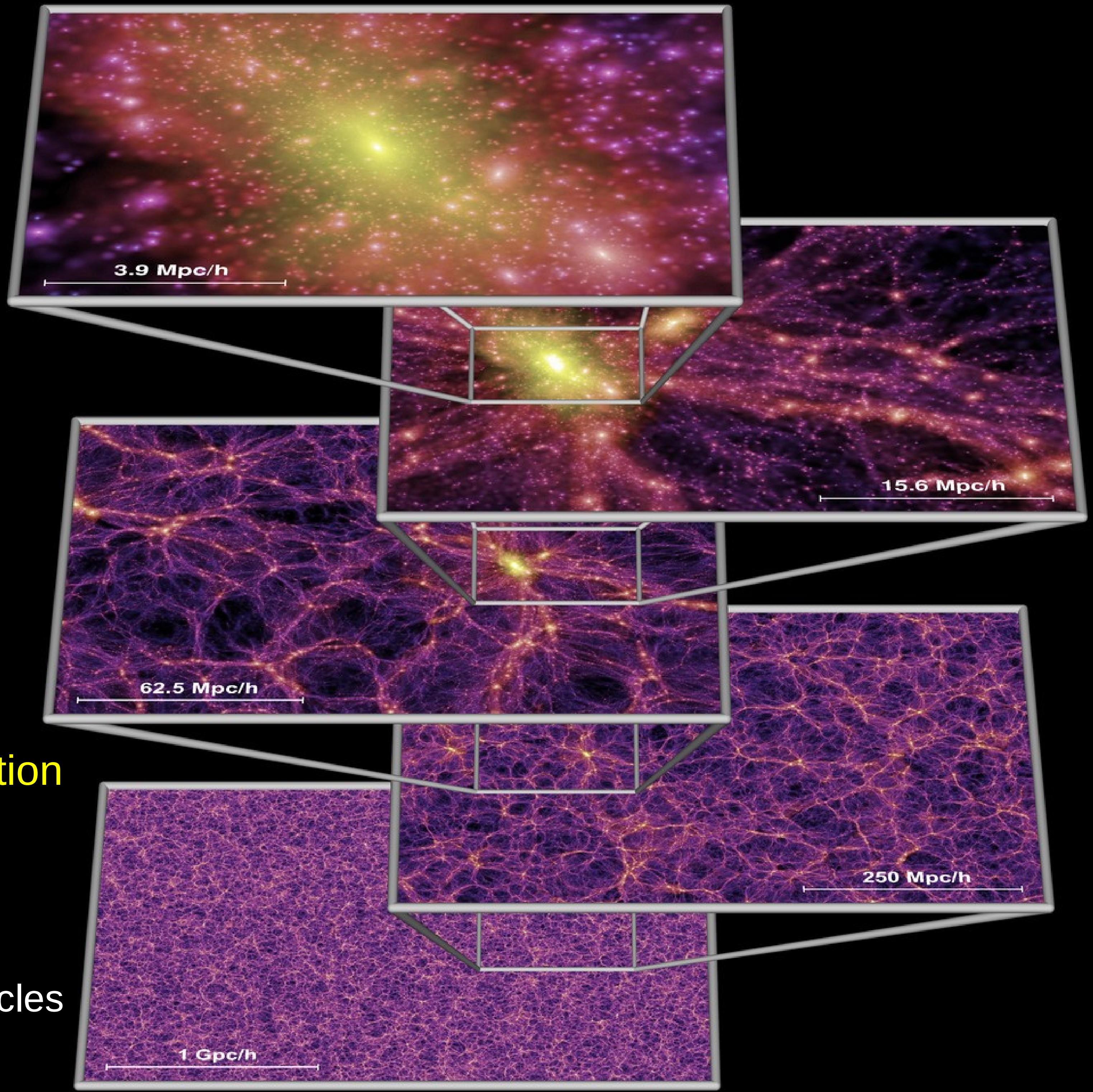
$$\nabla^2 \varphi(\boldsymbol{x}) = 4\pi G \left[-\frac{1}{L^3} + \sum_{\boldsymbol{n}} \tilde{\delta}(\boldsymbol{x} - \boldsymbol{n}L) \right]$$

→

Problems:

N ist very large

All equations are coupled with each other



'Millennium' simulation
Springel et al. (2005)

ΛCDM

10.077.696.000 particles
m=8.6 x 10^8 $M_\odot$/h

The result of this simulation is a list with **60 billion numbers***

PHASE-SPACE COORDINATES OF PARTICLES

x	y	z	v_x	v_y	v_z
314.26001	745.66888	370.33121	-90.20119	191.14938	103.75156
316.67566	766.89337	362.99713	-78.50227	187.55118	51.47593
323.45554	766.38782	344.29709	-63.31614	147.65451	78.05016
313.64520	752.02820	348.20020	-89.03946	147.13419	76.22576
296.03027	745.56812	334.73807	-77.72677	96.25417	87.05463
290.93192	755.60986	350.05496	-102.92673	118.71049	92.43941
281.19543	745.58704	363.56528	-81.56818	155.04465	97.96482
297.71011	759.31812	368.87430	-87.05585	192.59505	81.85943
285.16946	792.66412	377.99277	-105.20398	113.88999	76.50848
286.74234	783.26965	360.67300	-103.60987	121.45312	39.74818
299.97577	774.99866	350.17529	-104.64594	150.62953	37.11148
313.52136	787.29974	337.13708	-116.18470	174.52040	47.26388
304.98846	780.20728	374.62415	-99.49813	174.82487	103.35987
310.32690	791.92212	359.61008	-45.50785	97.64784	95.24279
325.51627	783.05096	373.09677	-69.54211	152.53419	81.62325
322.07971	801.04816	355.36896	-133.34152	151.29596	45.49487
299.65182	807.33673	343.39481	-35.34487	189.76573	121.31456
281.29971	799.37878	344.45026	-26.50418	177.28539	105.39162
290.92722	804.99182	362.11600	-58.94661	121.28194	120.26212
286.76523	805.98090	395.23892	-80.53864	184.44394	24.65293
302.14725	806.95367	381.78494	-59.48125	126.65170	70.45384
307.48138	808.63574	403.45633	-93.62634	145.24239	102.83086
322.93564	804.03632	382.25168	-68.81689	182.46657	136.57527
312.01071	788.37988	393.36658	-92.19463	146.87720	92.00867
312.76831	769.31189	397.57068	-73.25355	189.18690	151.66502
293.00305	774.34839	389.17767	-108.24481	146.13806	97.53626
281.13699	774.25256	412.70383	-129.07332	146.89197	136.00351
294.05652	787.52570	407.09238	-125.62066	186.51022	42.19235

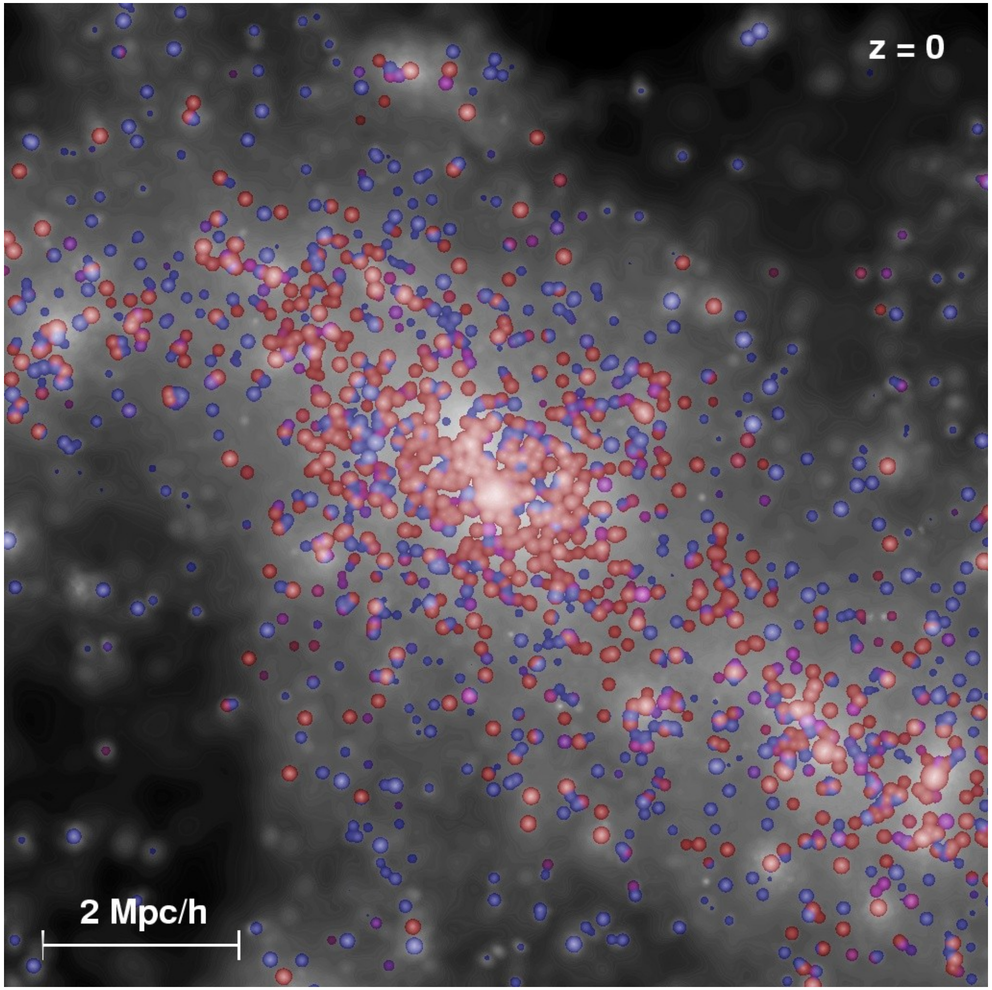
* all outputs together contain **~5000 billion numbers** → **uncovering the patterns of nature from this data volume requires substantial effort**

The first article about the Millennium Simulation made it on the title page of Nature

COMPUTATIONAL PHYSICS PLAYS AN INCREASINGLY IMPORTANT ROLE IN ASTRONOMY

Theoretical models for the distribution of galaxies can be obtained either through **semi-analytic models** or **hydrodynamical simulations**

Example for the galaxy distribution obtained from a semi-analytic model



Crucial for:

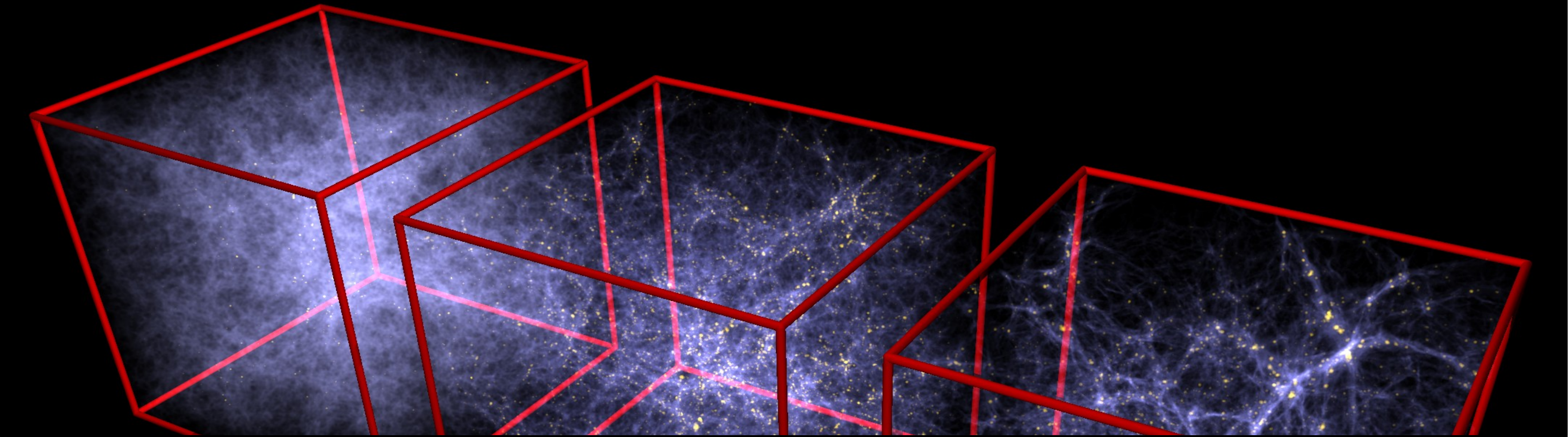
Constraining galaxy formation theory

Understanding systematics in galaxy surveys

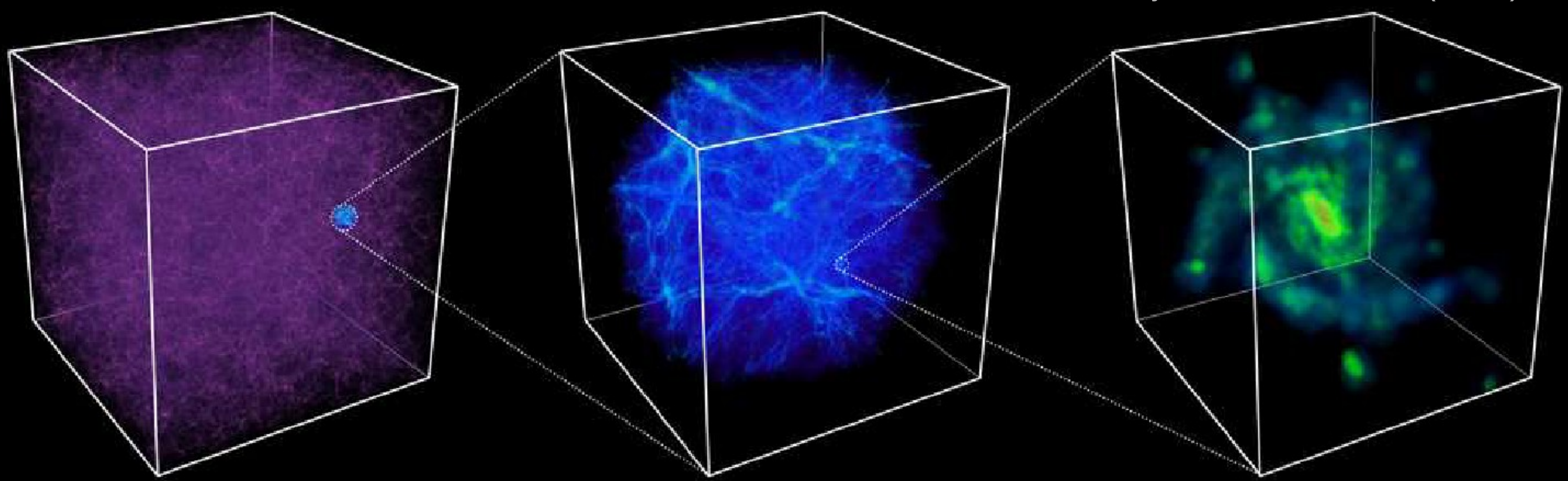
Tests of the cosmological paradigm

Forecasts for future surveys and the cosmological constraints they may yield

Hydrodynamical simulations directly predict galaxy formation

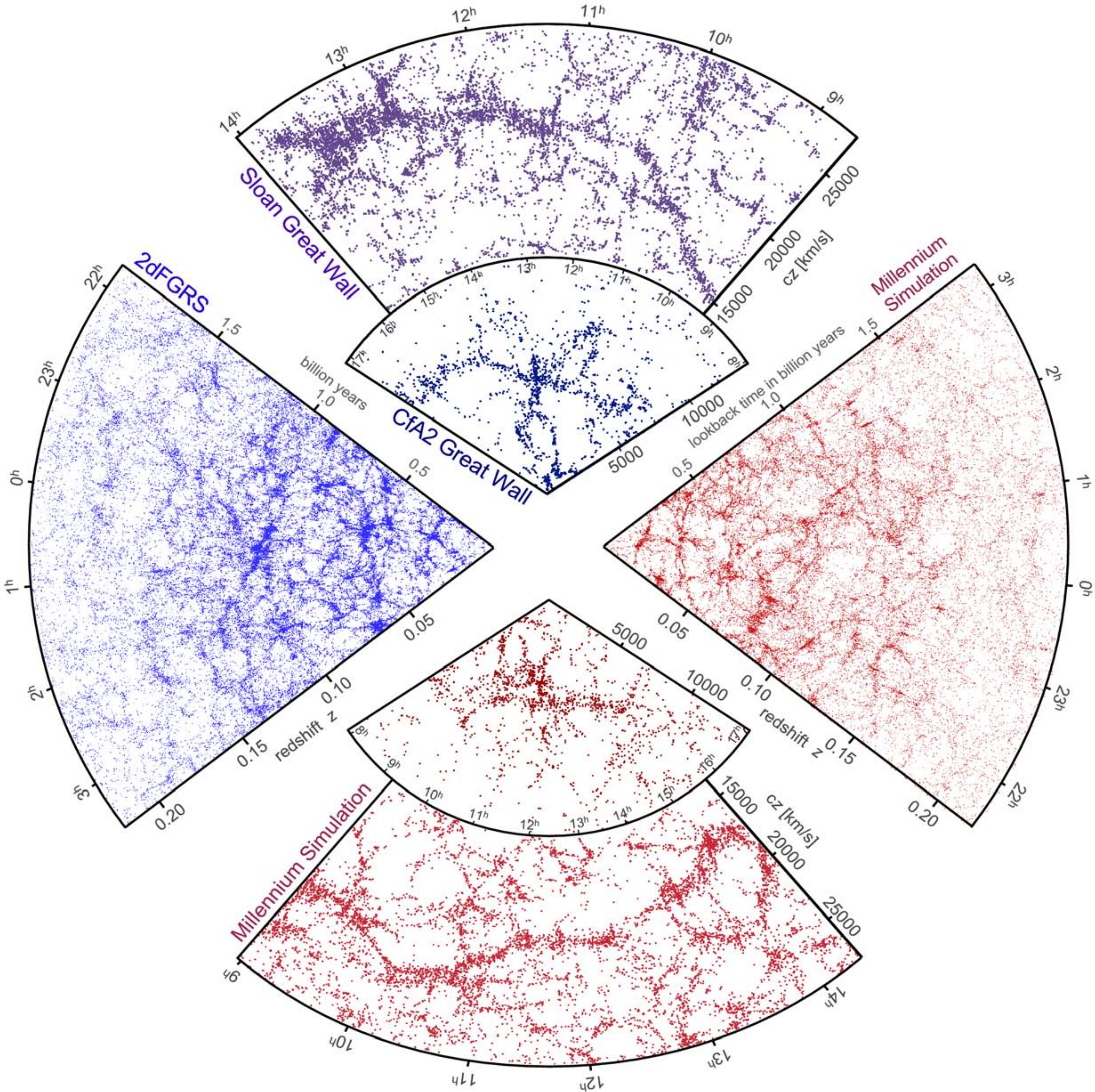


GIMIC Project, Theuns et al. (2009)



Simulated and observed large-scale structure in the galaxy distribution

MOCK PIE DIAGRAMS COMPARED TO SDSS, 2DFGRS, AND CFA-2



Springel et al. (2006)

The two-point correlation function of galaxies is a very good power law

GALAXY TWO-POINT FUNCTION COMPARED WITH THE 2dFGRS