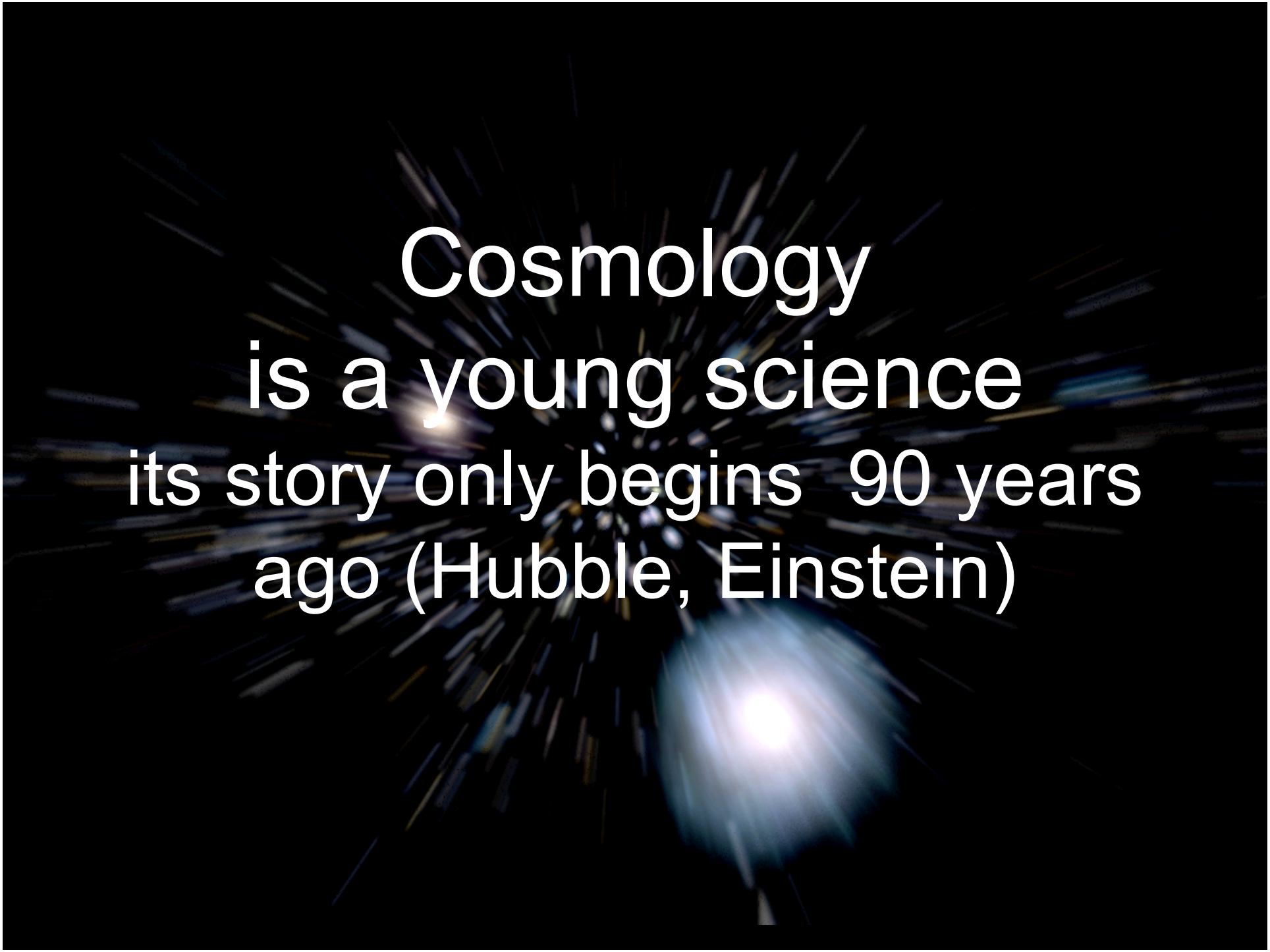
The Cosmic Frontier

Computing at the Cosmic Frontier
13 September 2011

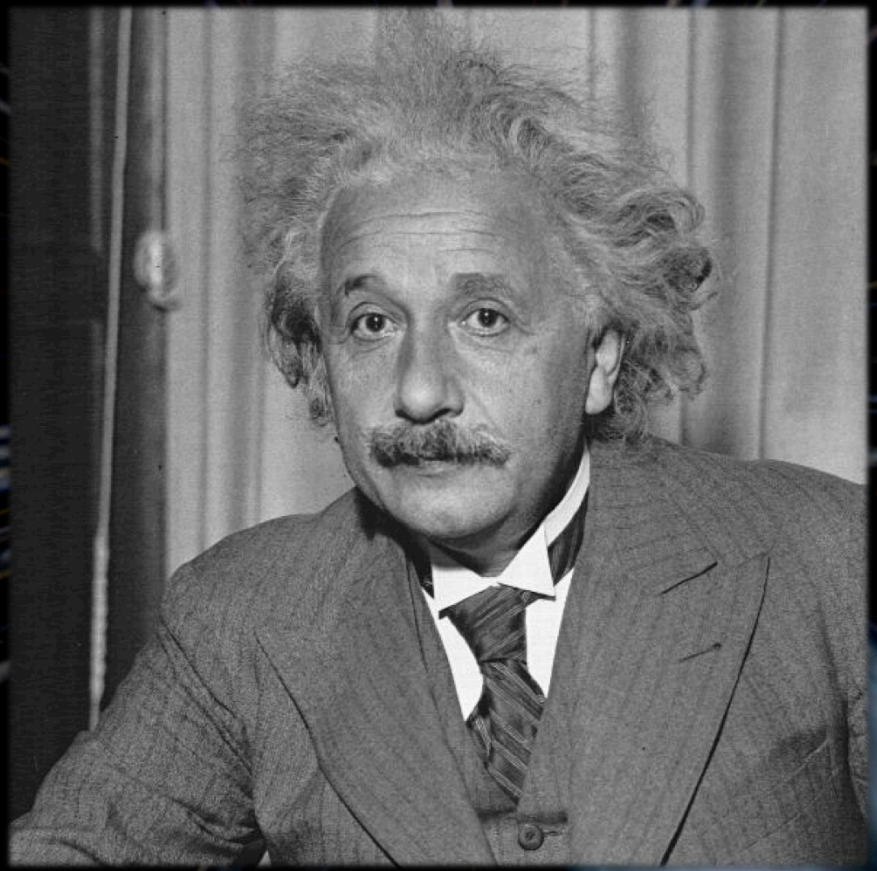
Michael S. Turner
Kavli Institute for Cosmological Physics
The University of Chicago

Where we are today

Highly successfully cosmological model that accommodates all the data and points to big discoveries ahead about the Universe and the fundamental laws that govern it

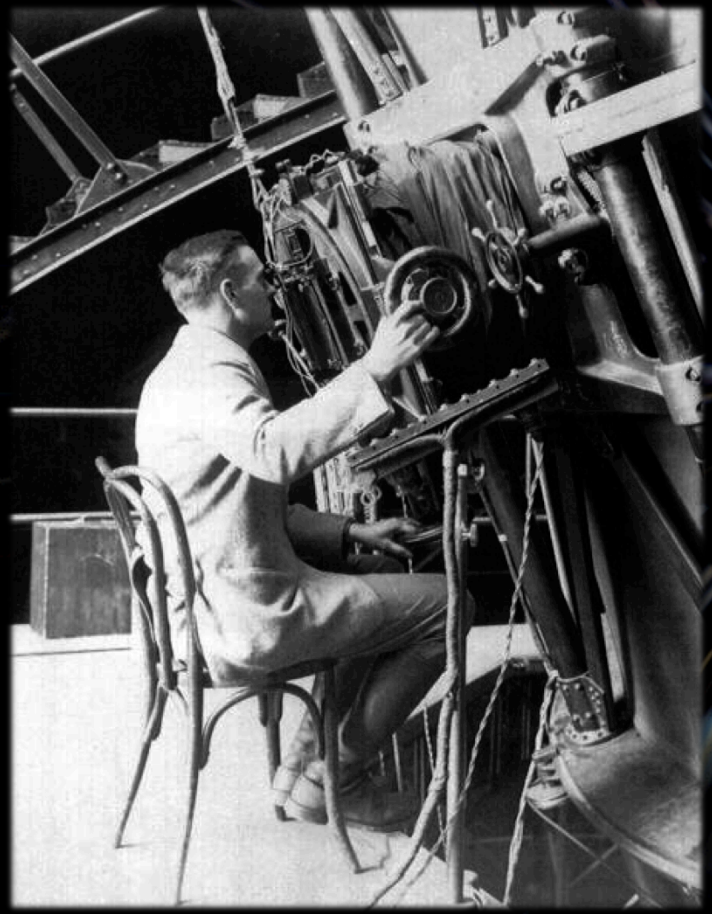

Cosmology
is a young science
its story only begins 90 years
ago (Hubble, Einstein)

1916-1918: General Relativity

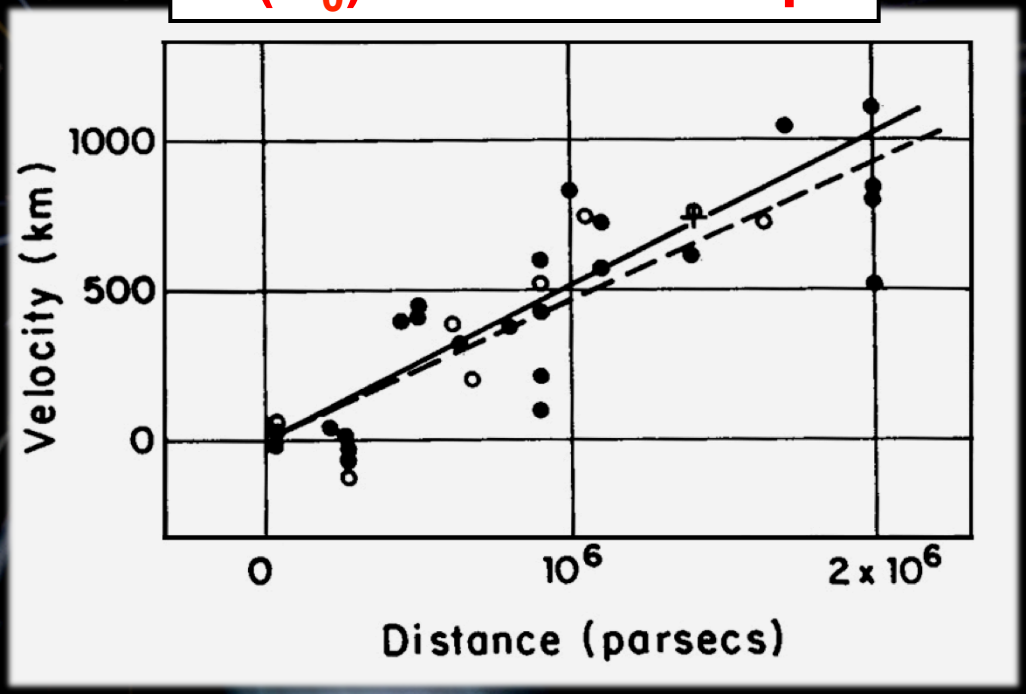


1929: Just One Number K

(error bars not needed, velocity in km)



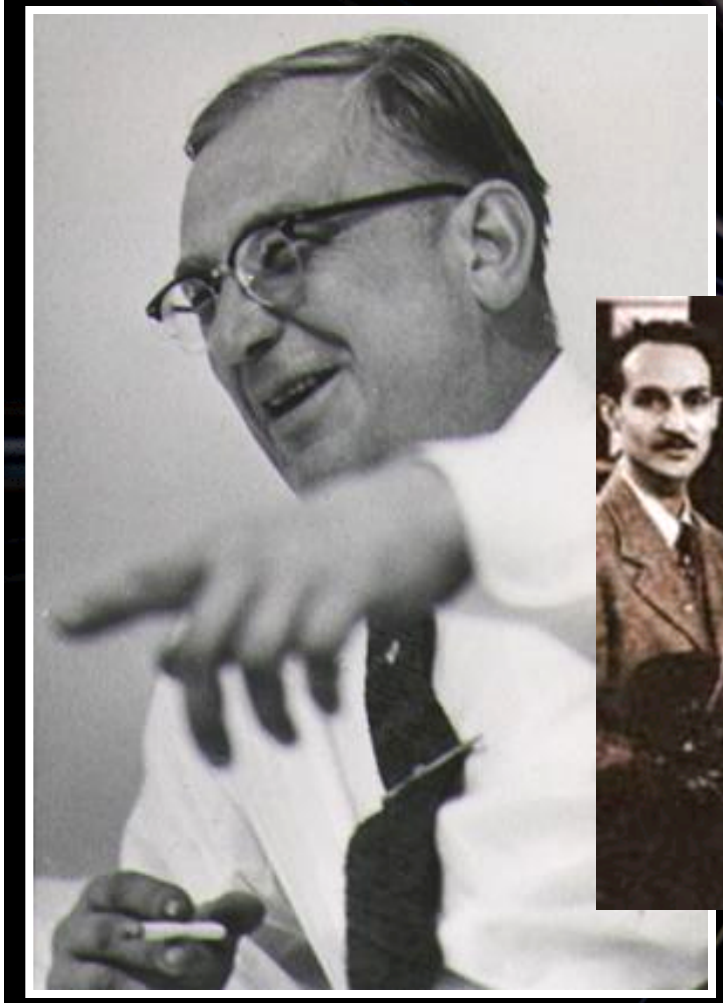
K (H_0) = 550 km/s/Mpc

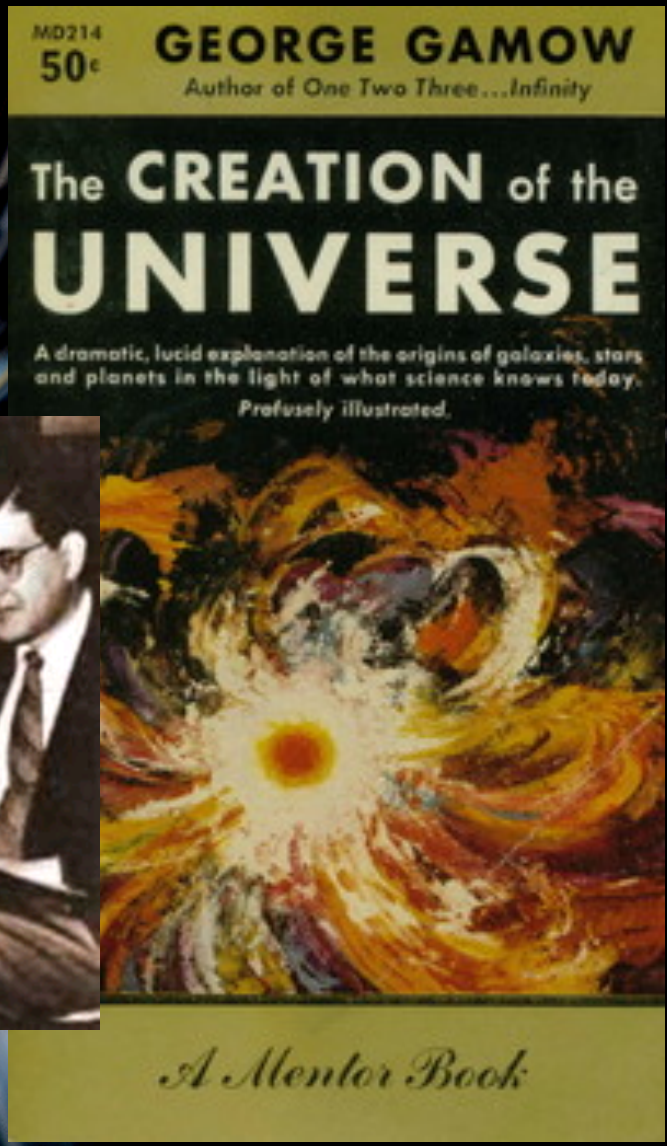


Hubble & Humanson: few 100 galaxies, z < 0.1

Gamow's Hot Big Bang

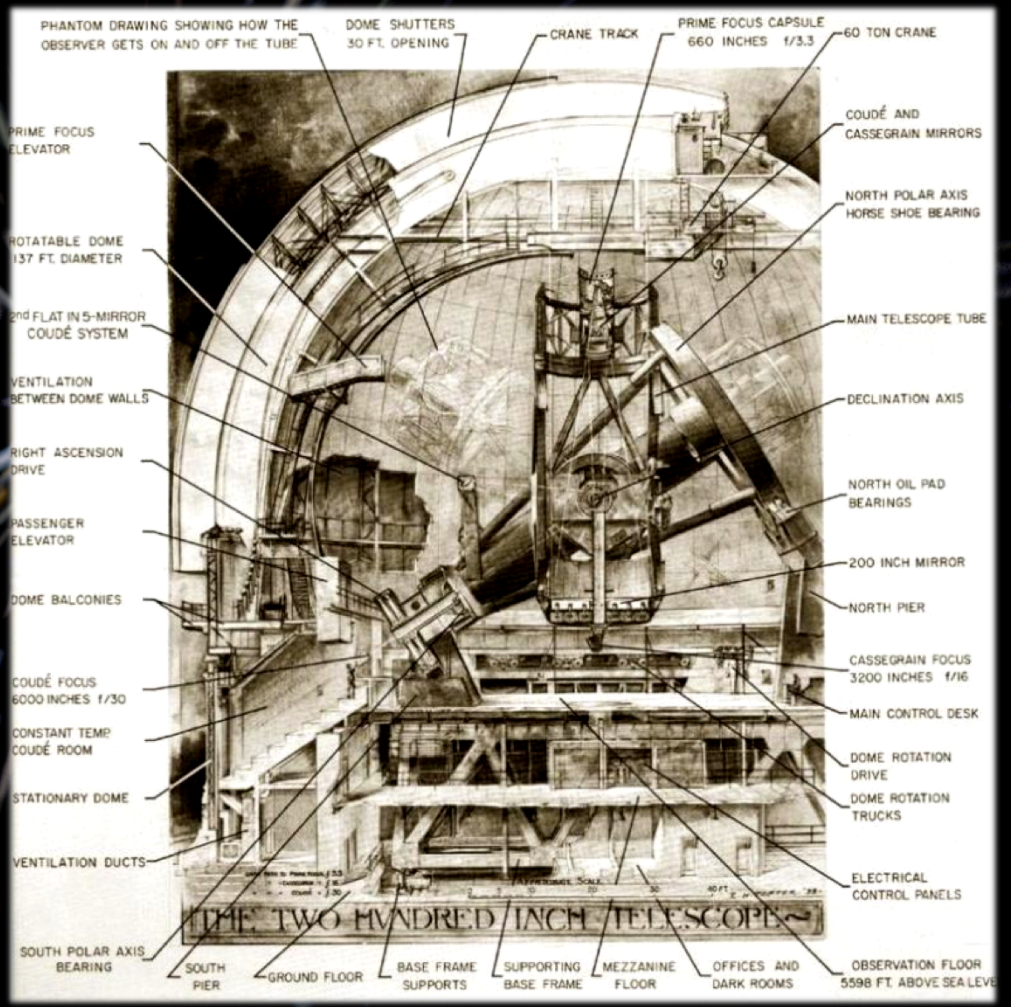
"alpher, bethe, gamow," 1948



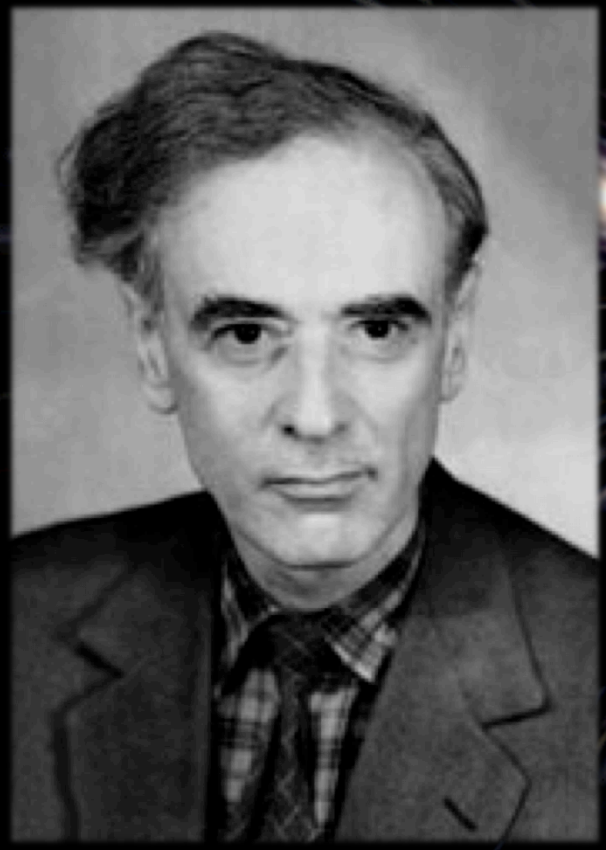


1948: Steady State Theory

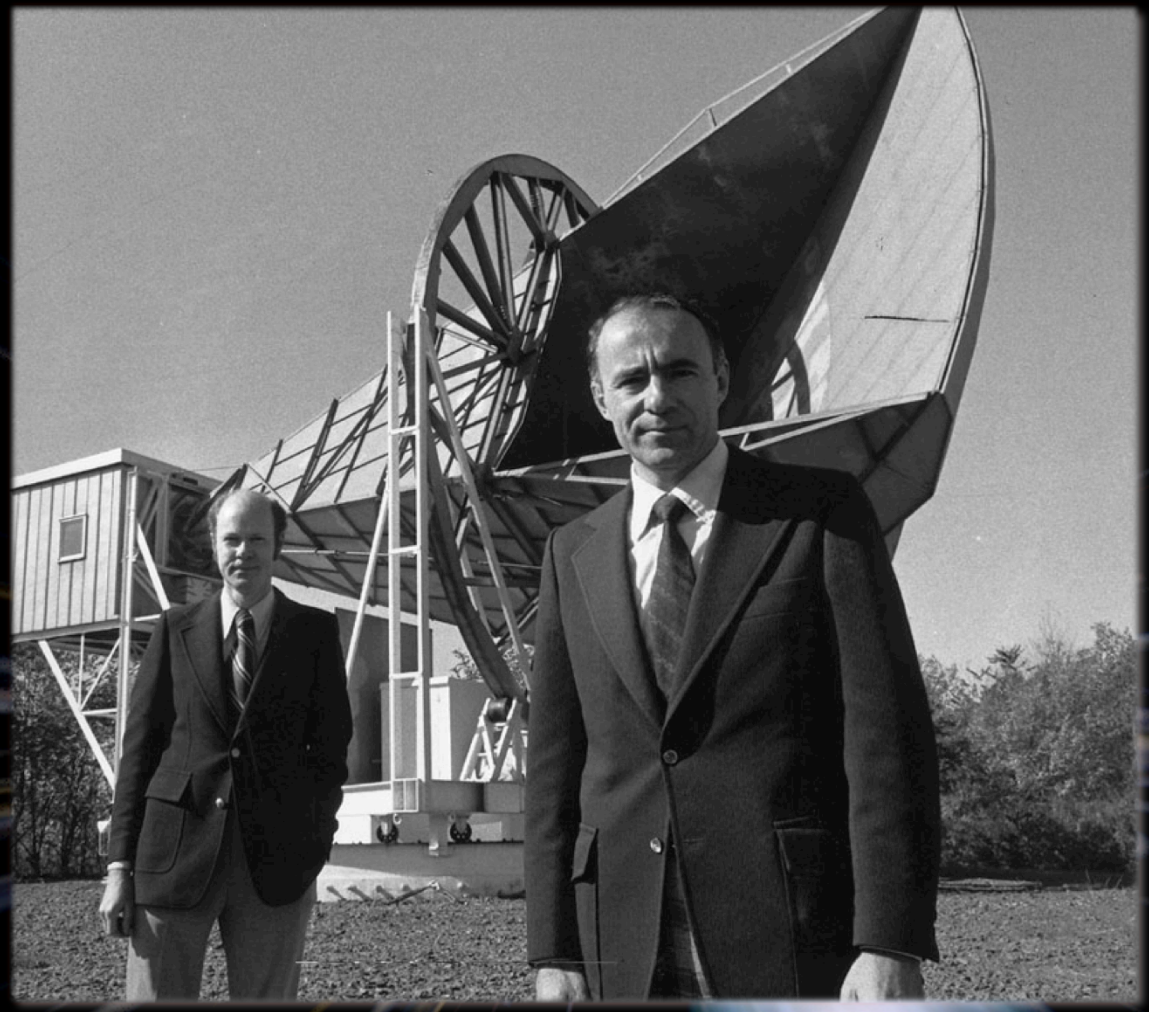
Cosmology: The Search for Two Numbers … Sandage 1970



Landau on Cosmologists



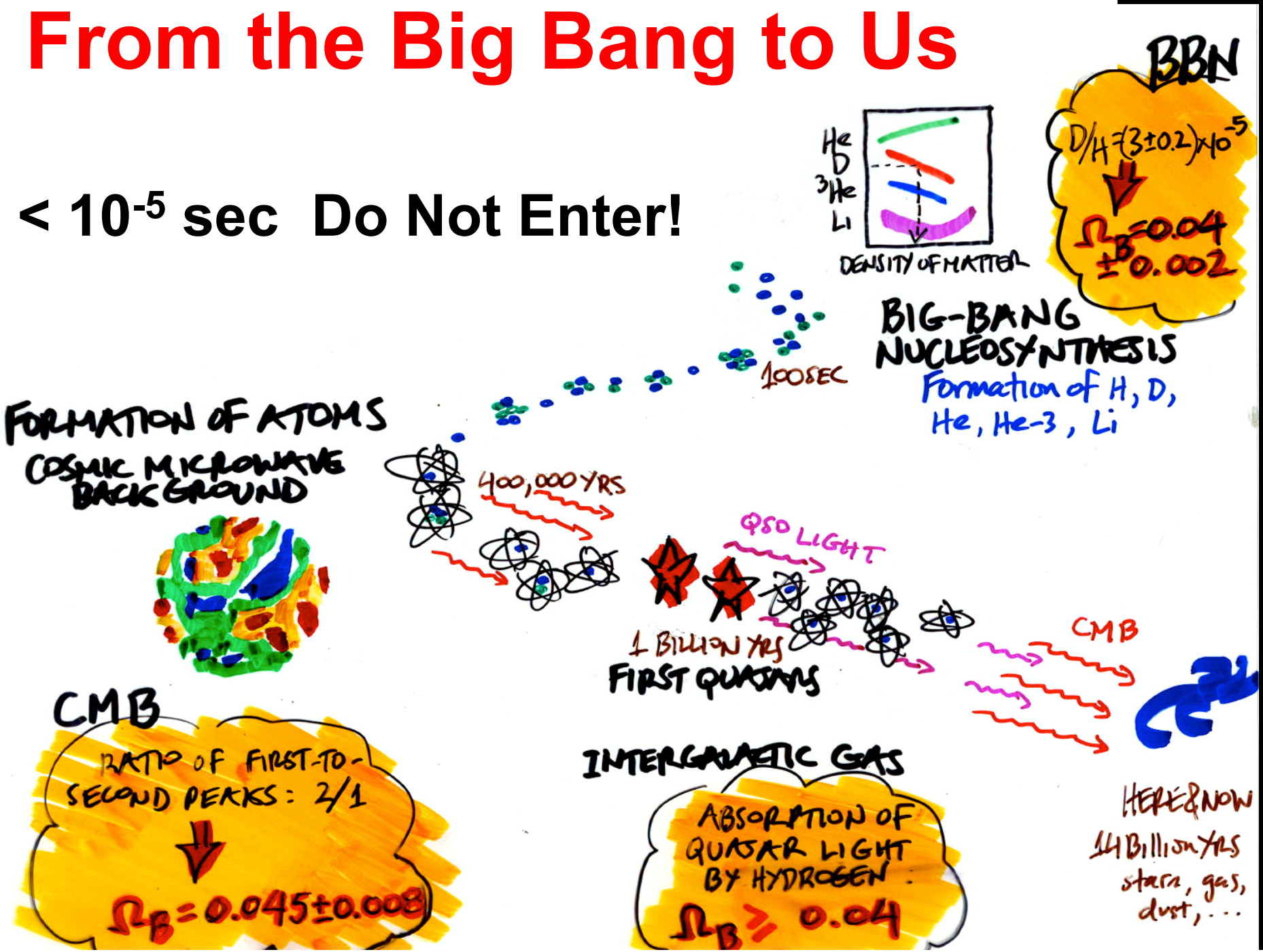
Often in Error,
Never in Doubt!



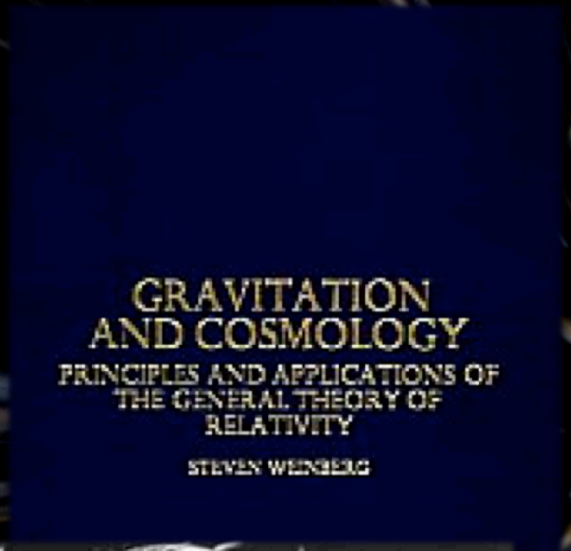
Discovery of Cosmic Microwave Background, 1964 → Hot Big Bang

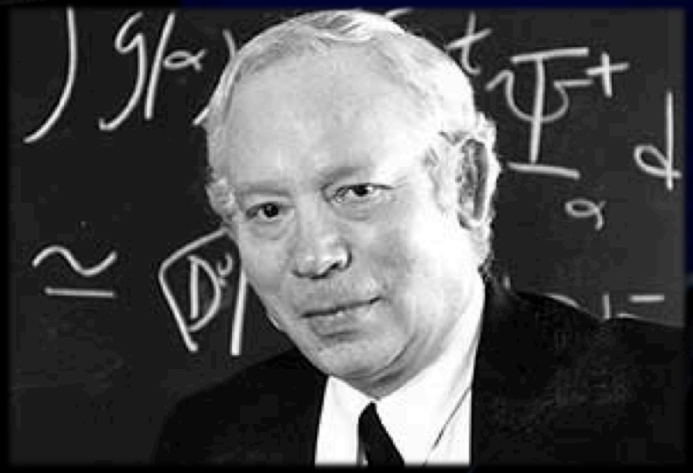
From the Big Bang to Us

$< 10^{-5}$ sec Do Not Enter!



“The Standard Model” Hot Big Bang (circa 1972)





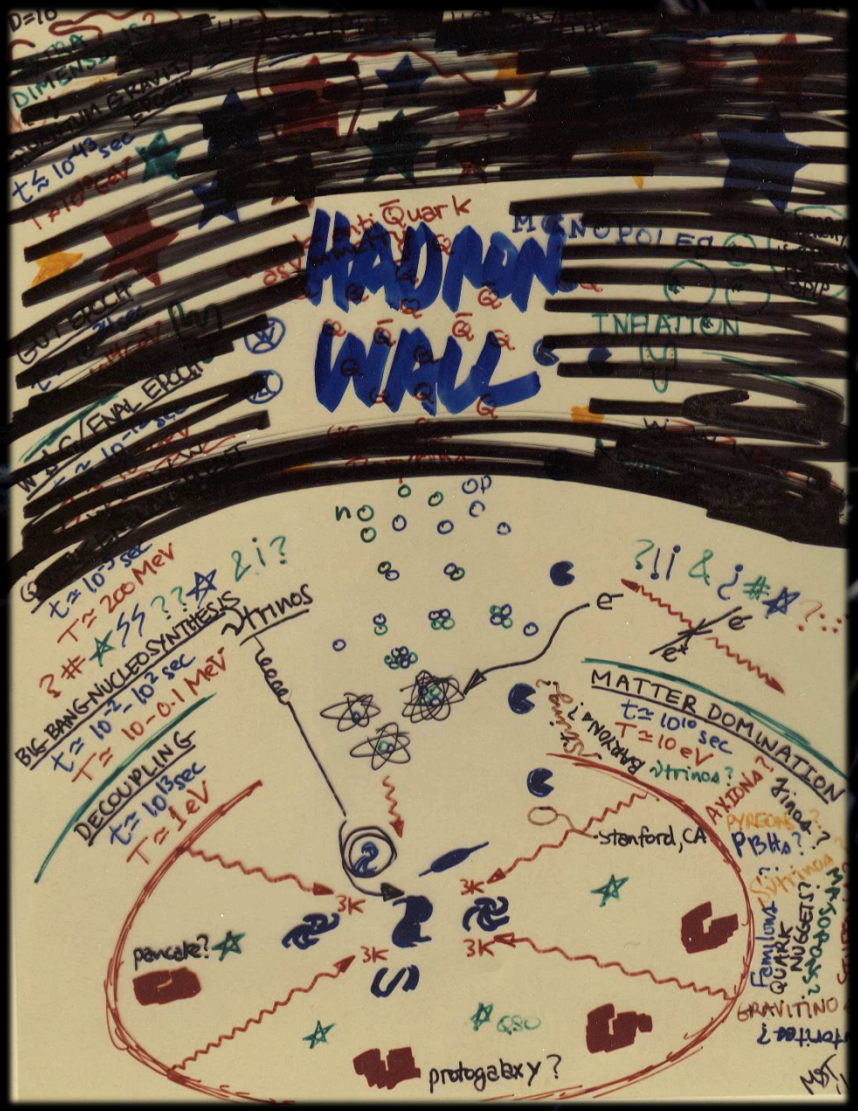
“Reality (physics) Based”

- BBN (nuclear physics)
- CMB (atomic physics)
- Structure Formation (grav. physics)
- Begins at 0.01 sec
- $\Omega_0 \sim 0.1$ (baryons)

Big Questions

- “The naughts”: H_0, t_0, Ω_0
- Large entropy per baryon
- Hadron Wall
- Origin of density perturbations

The Hadron Wall



S. Weinberg in *Gravitation & Cosmology*

11 The Very Early Universe

The thermal history of the universe was traced in Section 15.6 back to an era when the temperature was about 10^{12}°K. At this early time, the universe was filled with particles—photons, leptons, and antileptons—whose interactions are hopefully weak enough to allow this medium to be treated as a more or less ideal gas. However, if we look back a little further, into the first 0.0001 sec of cosmic history when the temperature was above 10^{12}°K, we encounter theoretical problems of a difficulty beyond the range of modern statistical mechanics. At such temperatures, there will be present in thermal equilibrium copious numbers of strongly interacting particles—mesons, baryons, and antibaryons—with a mean interparticle distance less than a typical Compton wavelength. These particles will be in a state of continual mutual interaction, and cannot reasonably be expected to obey any simple equation of state.

However, the temptation to try to construct some sort of model of the very early universe is irresistible. There are in fact two extremely different simple models that have been widely considered in recent years, and that reflect two divergent views of the nature of the strongly interacting particles. Although neither model can be taken seriously in detail, the hope is that one or the other of these models may come close enough to reality to lead to useful insights about the very early universe.

The first of these two pictures may be called the *elementary particle model*. It is supposed that all particles are made up of a small number of elementary

ORDINA

INFLATION
BARYOGENESIS

FORMATION O
COSMIC MICR
BACKGRO

CMB
RATIO OF
SECOND PE
$\Omega_B = 0$

US

BBN
$D/H = (3 \pm 0.2) \times 10^{-5}$
$\Omega_B = 0.04 \pm 0.002$

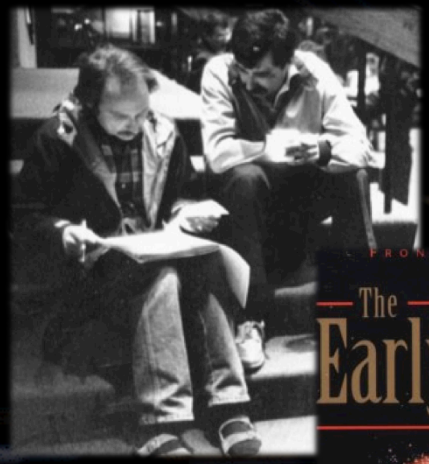
TER

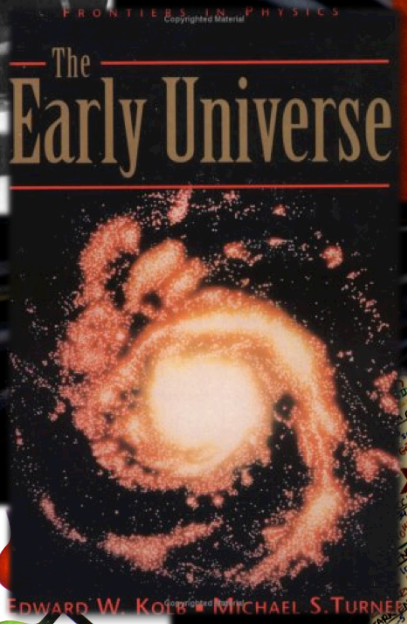
BANG
OSYNTHESIS
ation of H, D,
He-3, Li

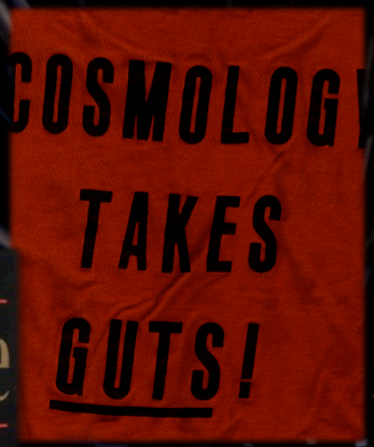
CMB

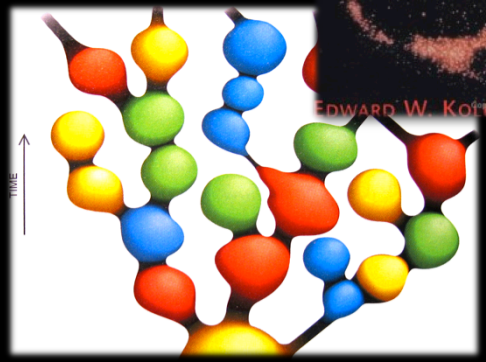
HERE & NOW
14 Billion YRS
stars, gas,
dust, ...

1980s: The Go Go Junk Bond Days of Early Universe Cosmology





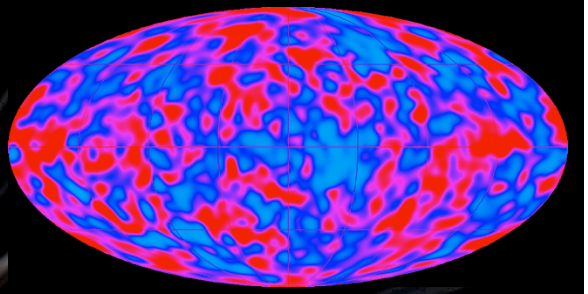




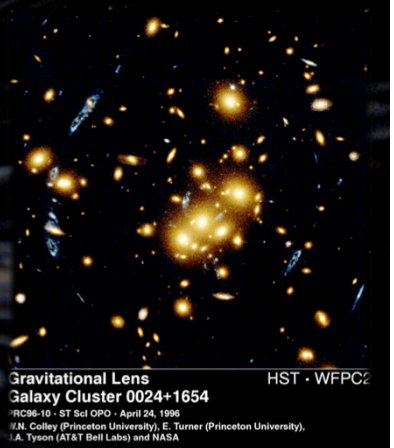
"Creativity Based"

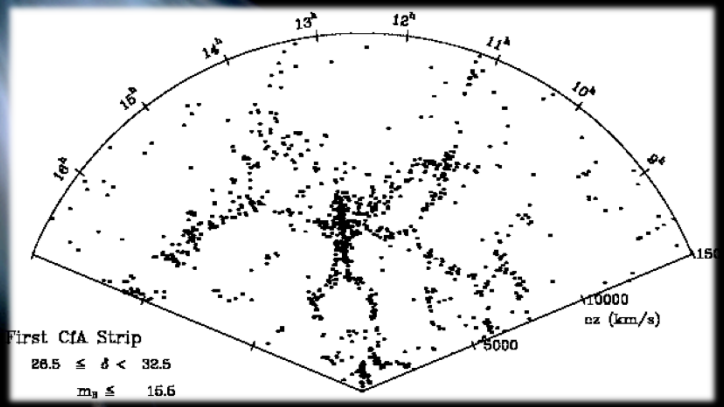
- Inflation
- Cosmic Strings
- Baryogenesis
- Magnetic Monopoles
- Phase Transitions
- Hot and Cold Dark Matter
- Decaying Particles
- Kaluza-Klein

1990s: Beginning of Data-driven Cosmology



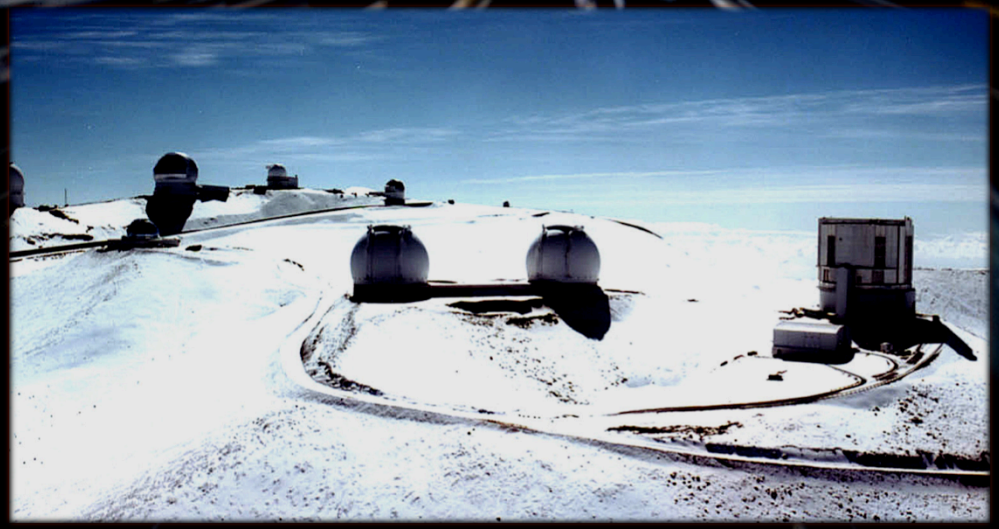
- COBE! and CMB experiments
- Redshift surveys (CfA, IRAS, 2dF, SDSS)
- Large-scale velocity field measurements
- Gravitational lensing
- Big telescopes (Keck, …) with big CCD cameras
- HST, X-ray, gamma-ray, IR, …





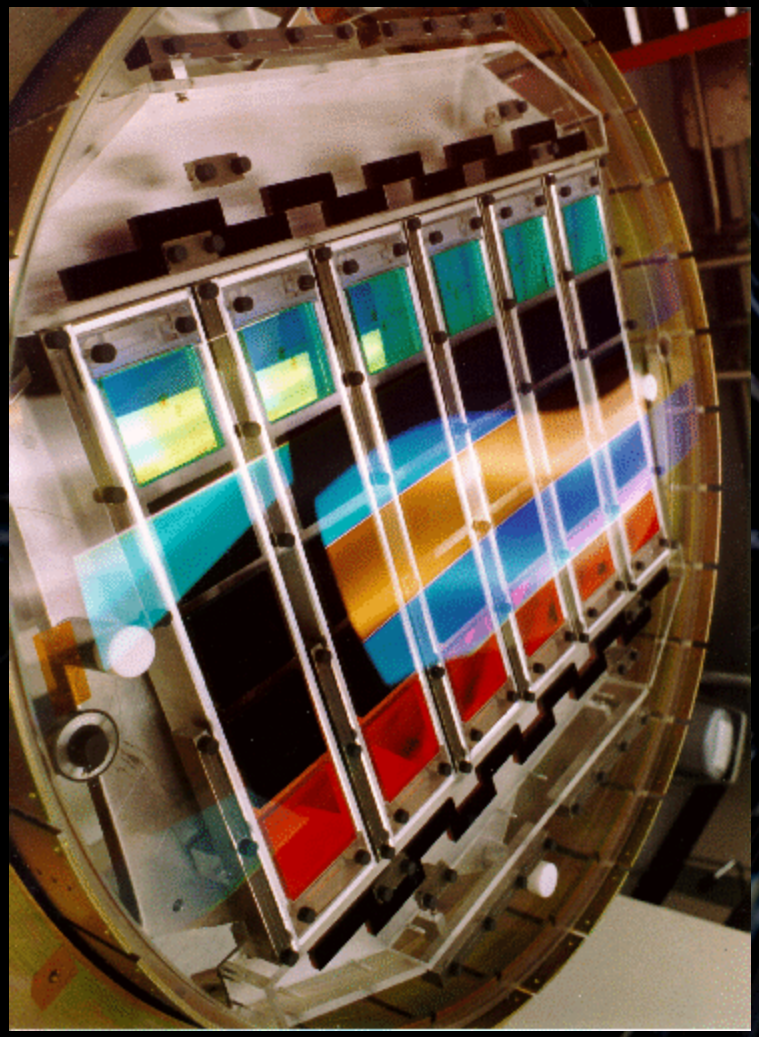
Big science:
4 VLT, 2 Kecks, 2 Geminis and 2 Magellans on the ground



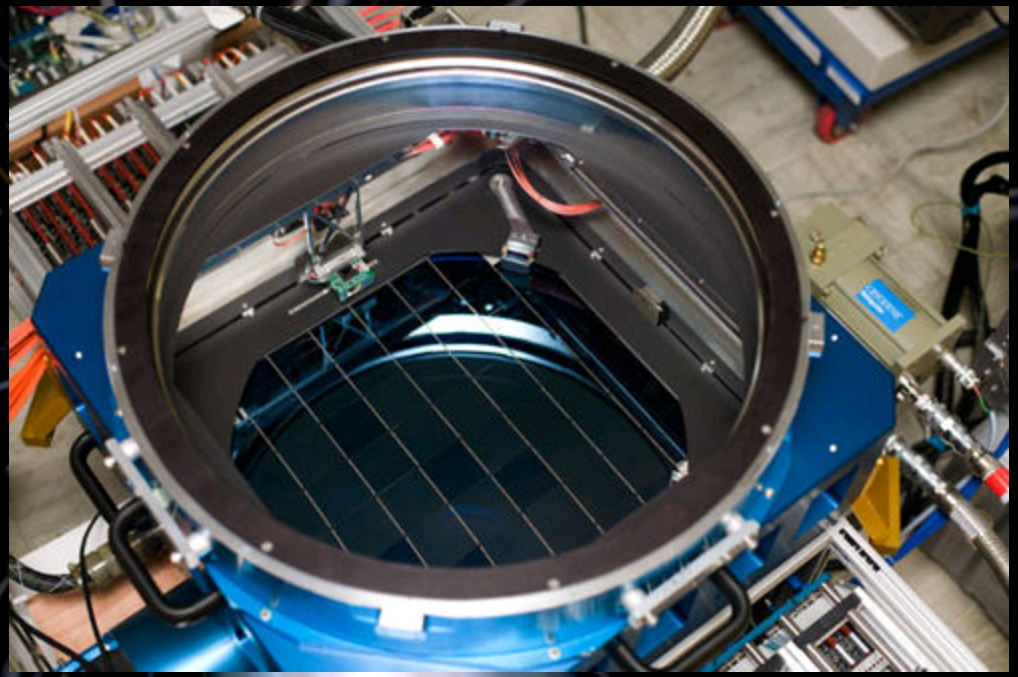



Hubble, Spitzer, Chandra, and Fermi in space

Giant CCD Cameras

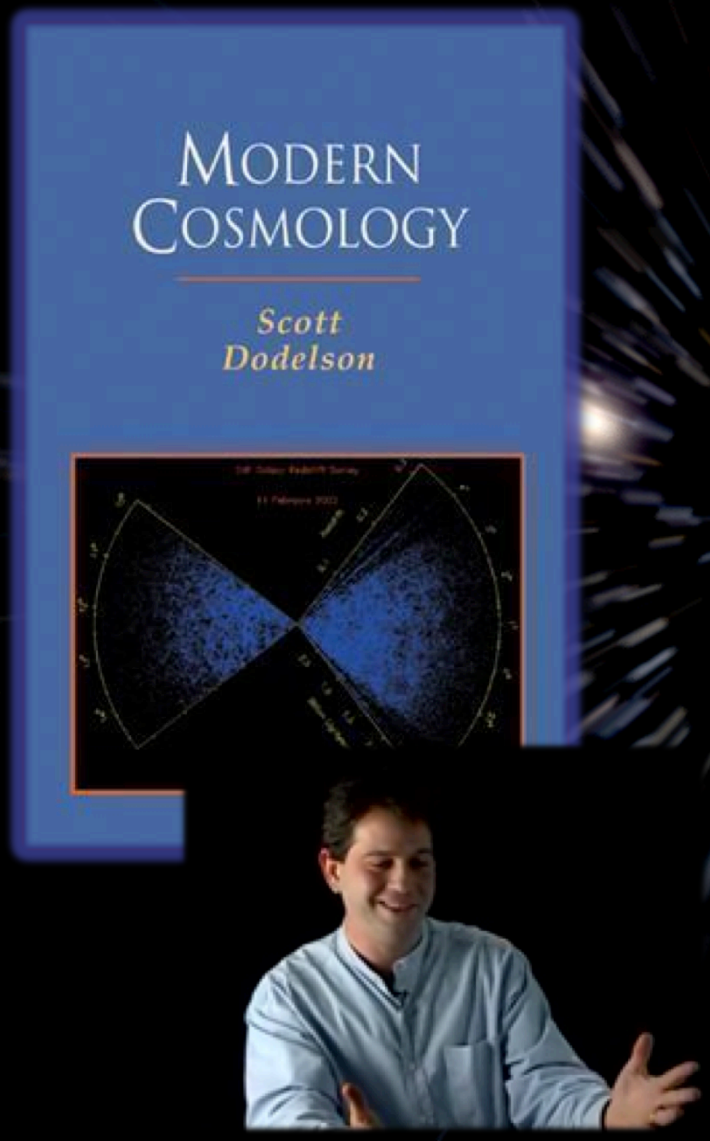


100 Megapixel



Gigapixel

2000s: Era of Precision Cosmology



"Fisher Based"

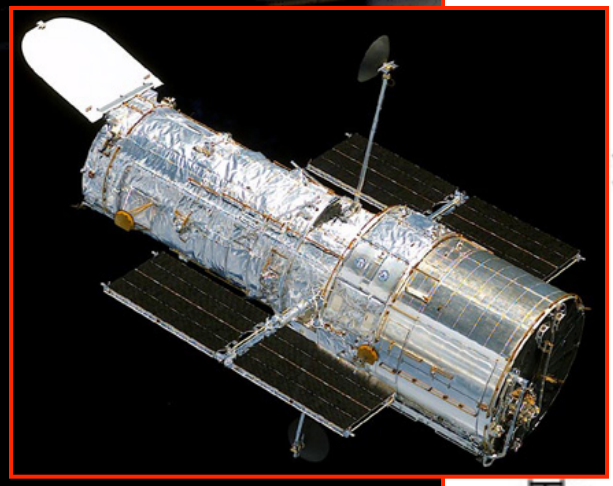
- Cosmological parameters
- Tests of inflation, CDM
- Correlating large, complex data sets
- Cosmological Consistency
- Physical parameters (e.g., neutrino mass)

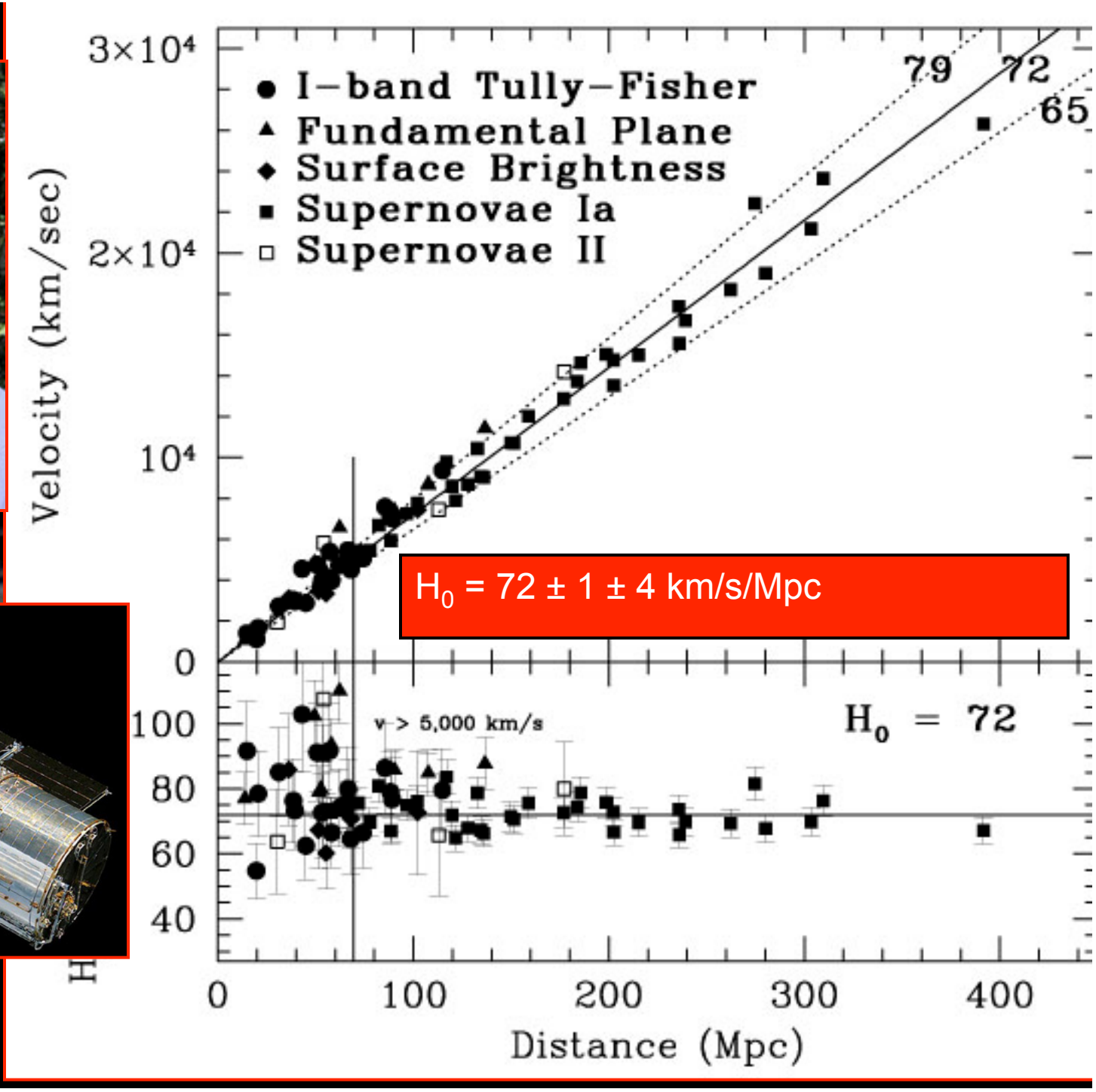
Today's "Consensus Cosmology"

based upon precision measurements

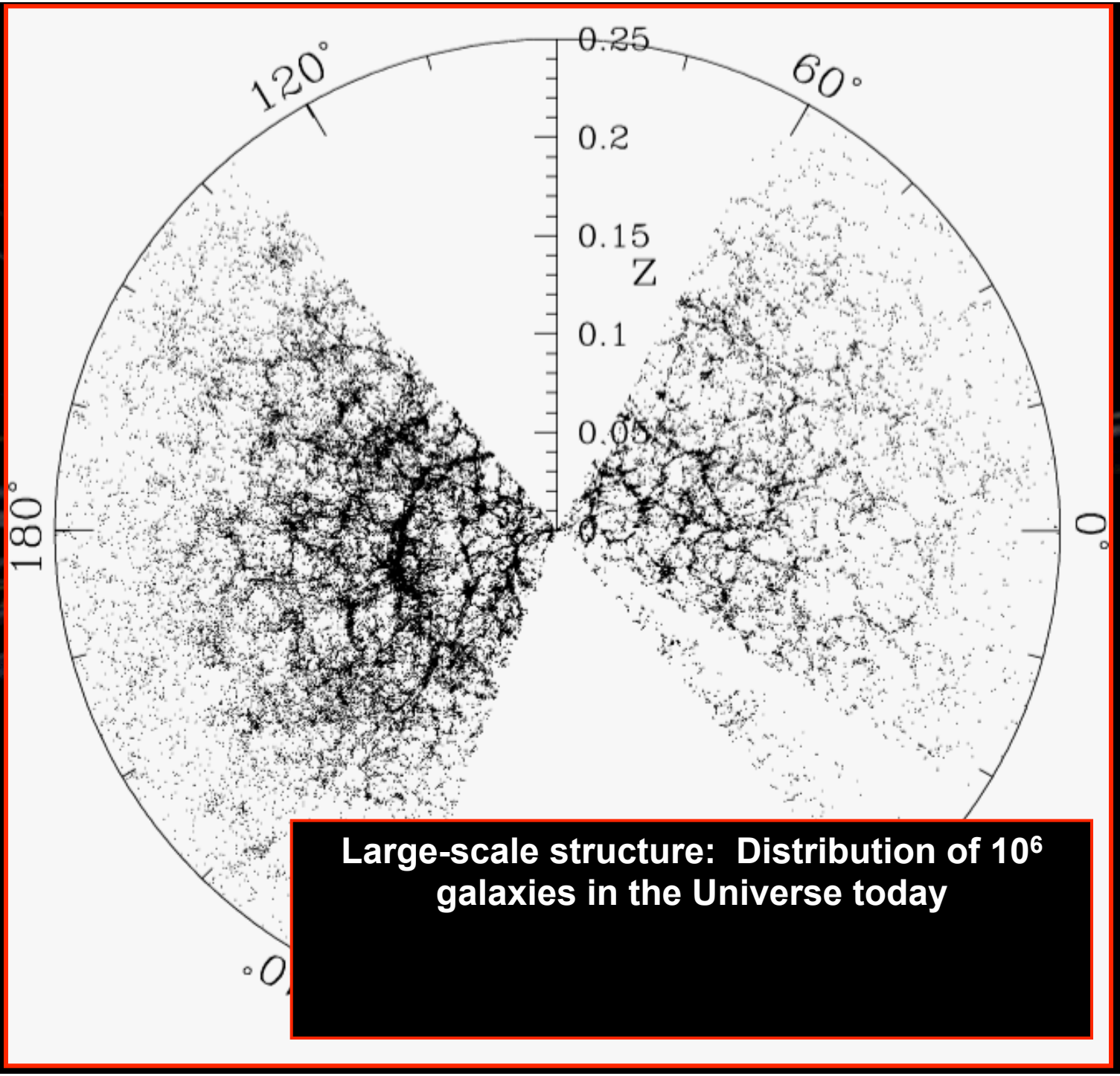
- From quark soup to nuclei and atoms to galaxies and large-scale structure
- Flat, accelerating Universe
- Atoms, exotic dark matter & dark energy
- Consistent with inflation
- Precision cosmological parameters
  - $\Omega_0 = 1.005 \pm 0.006$ (uncurved)
  - $\Omega_M = 0.273 \pm 0.014$
  - $\Omega_B = 0.046 \pm 0.0016$
  - $\Omega_{DE} = 0.73 \pm 0.015$
  - $H_0 = 70.4 \pm 1.3$ km/s/Mpc
  - $t_0 = 13.75 \pm 0.11$ Gyr
  - $N_\nu = 3.86 \pm 0.42$

Consistent with all data, laboratory and cosmological!



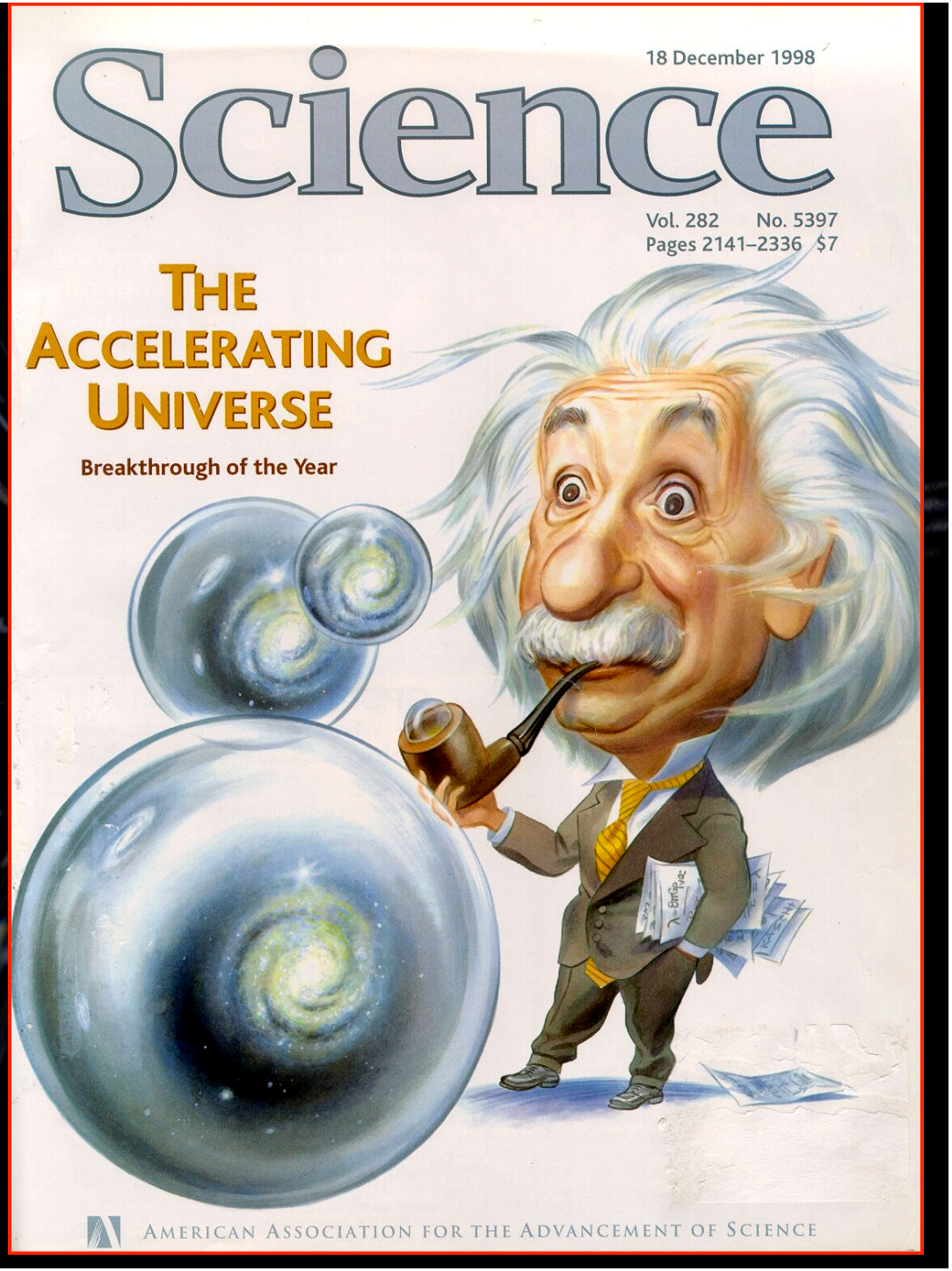

3×10⁴
2×10⁴
10⁴
0
Velocity (km/sec)
I−band Tully−Fisher
Fundamental Plane
Surface Brightness
Supernovae Ia
Supernovae II
79
72
65
H₀ = 72 ± 1 ± 4 km/s/Mpc
v > 5,000 km/s
H₀ = 72
100
80
60
40
0
100
200
300
400
Distance (Mpc)

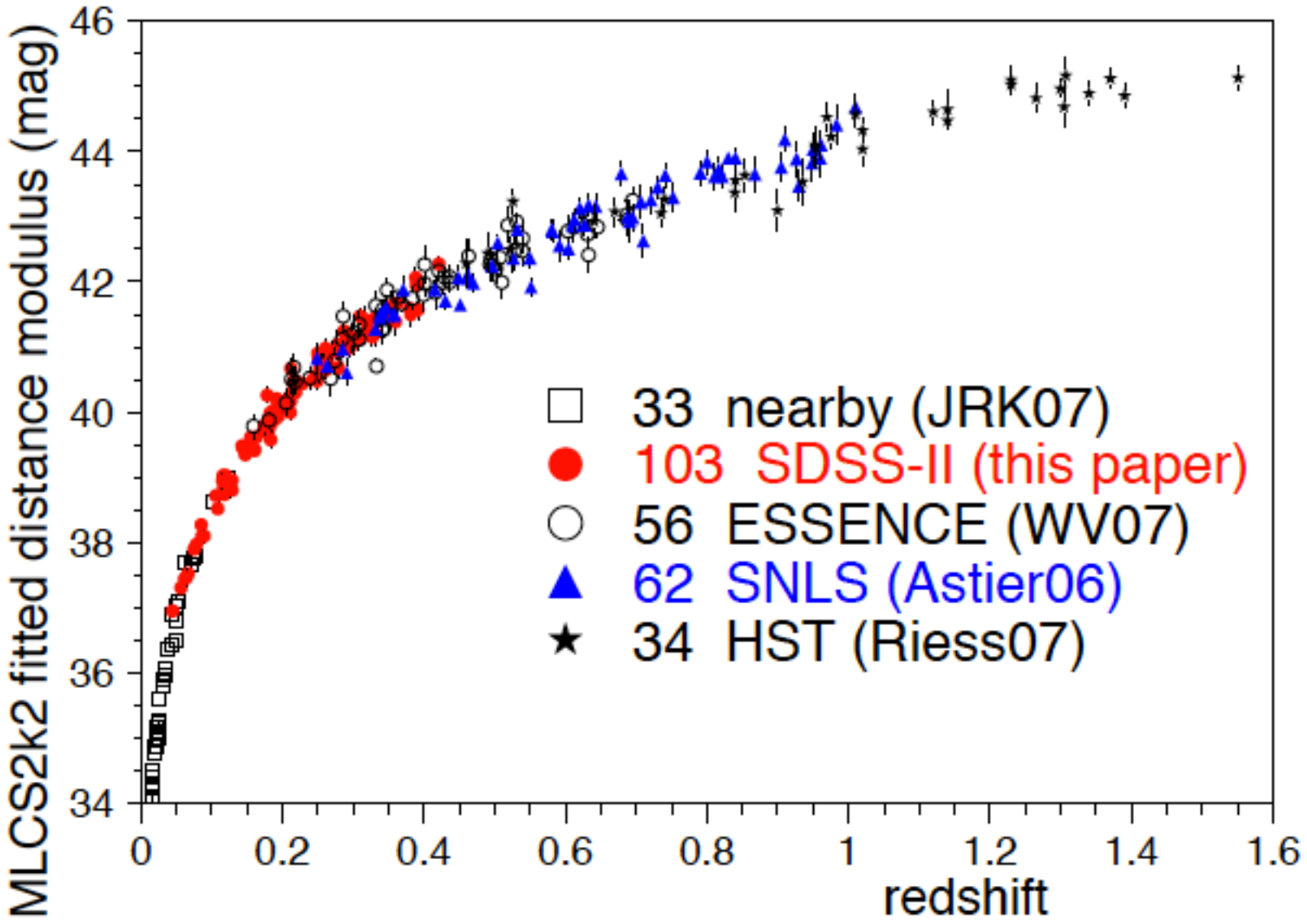
Sloan Digital Sky Survey
sdss.org

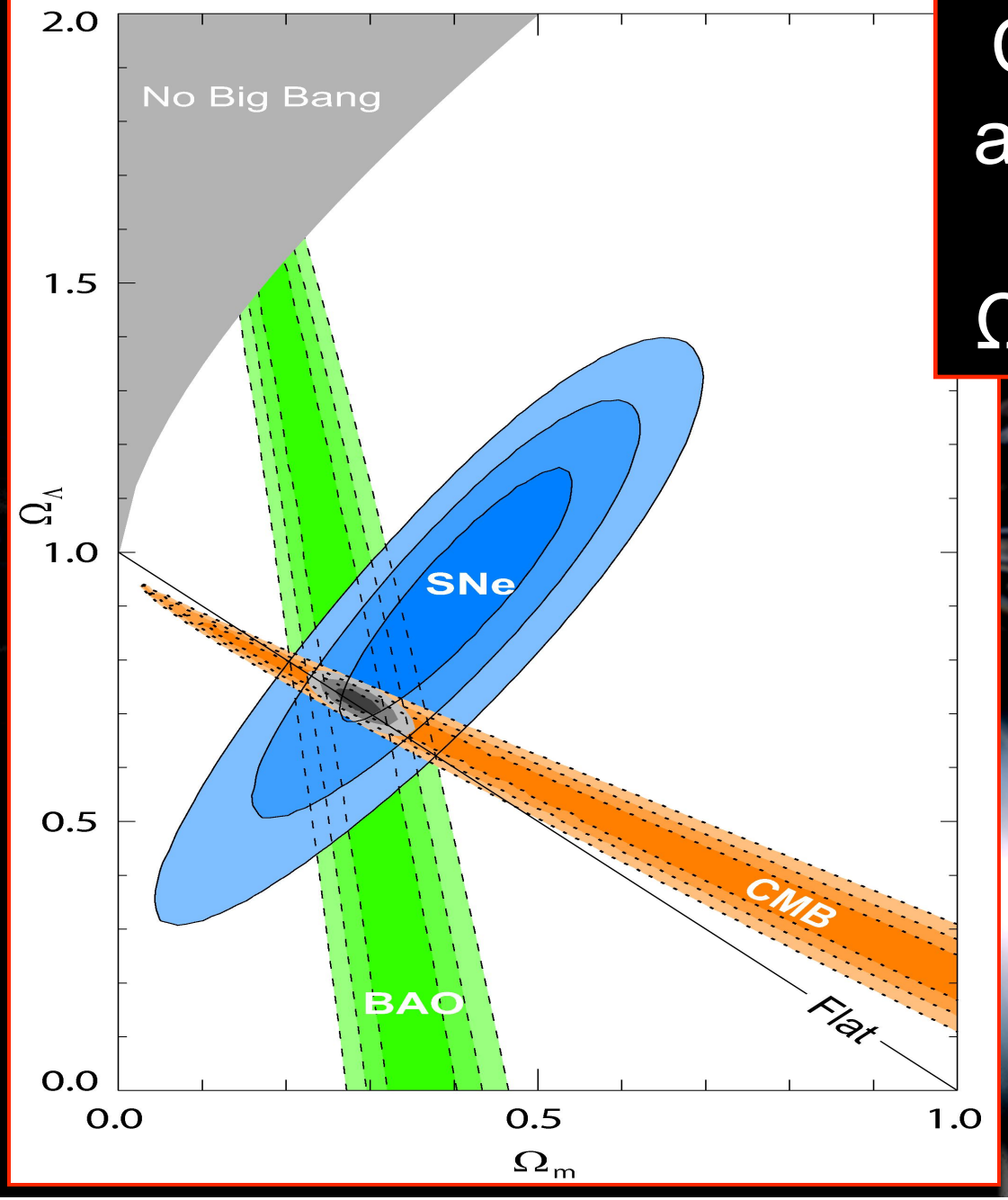


Large-scale structure: Distribution of 10^6 galaxies in the Universe today

… and Dr. Sandage, H_0 is now measured and q_0 is negative!




MLCS2k2 fitted distance modulus (mag)
46
44
42
40
38
36
34
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
redshift
33 nearby (JRK07)
103 SDSS-II (this paper)
56 ESSENCE (WV07)
62 SNLS (Astier06)
34 HST (Riess07)



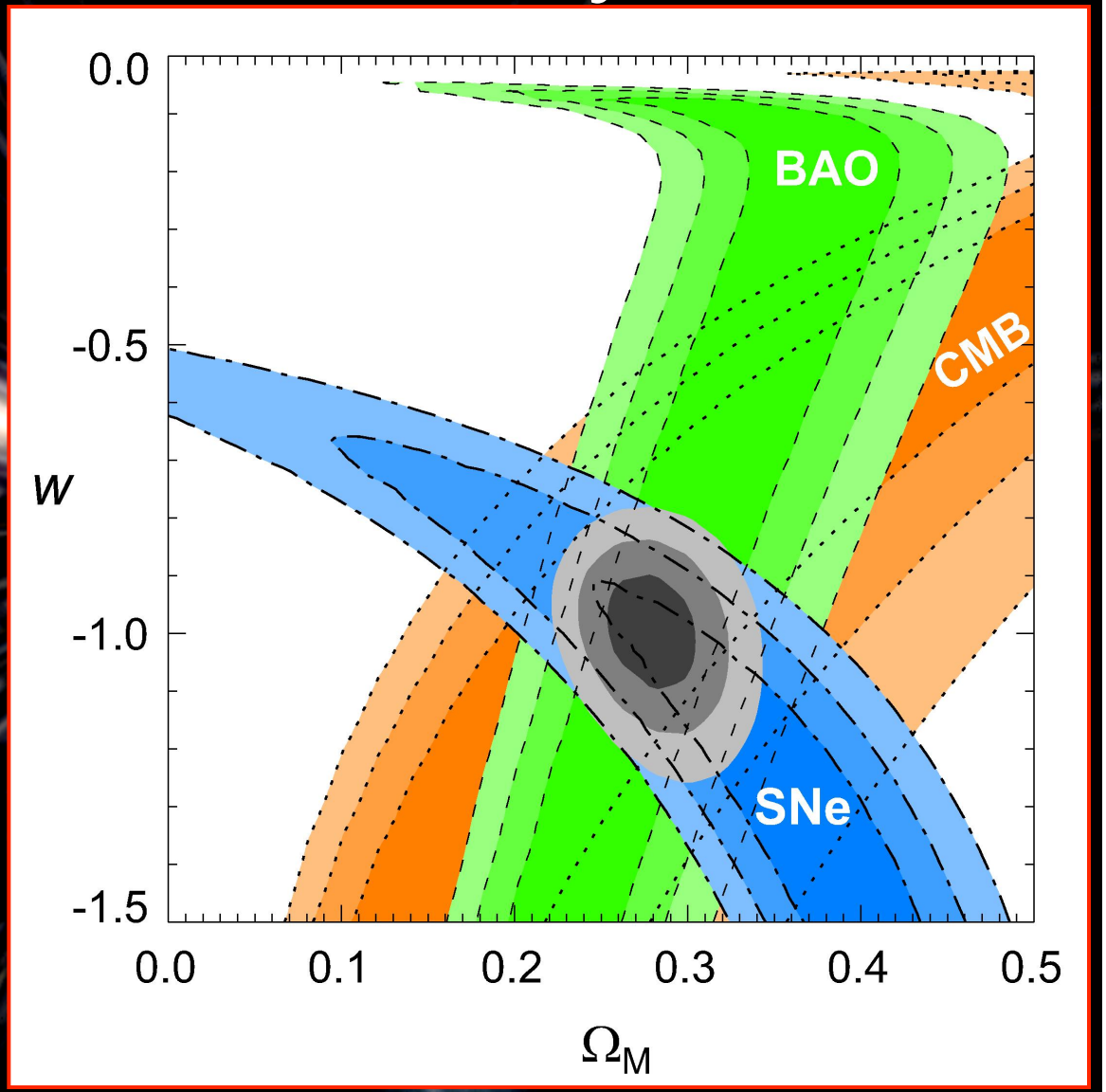
Consistent with all observations:

$\Omega_\Lambda = 0.73 \pm 0.02$

Where We Are Today

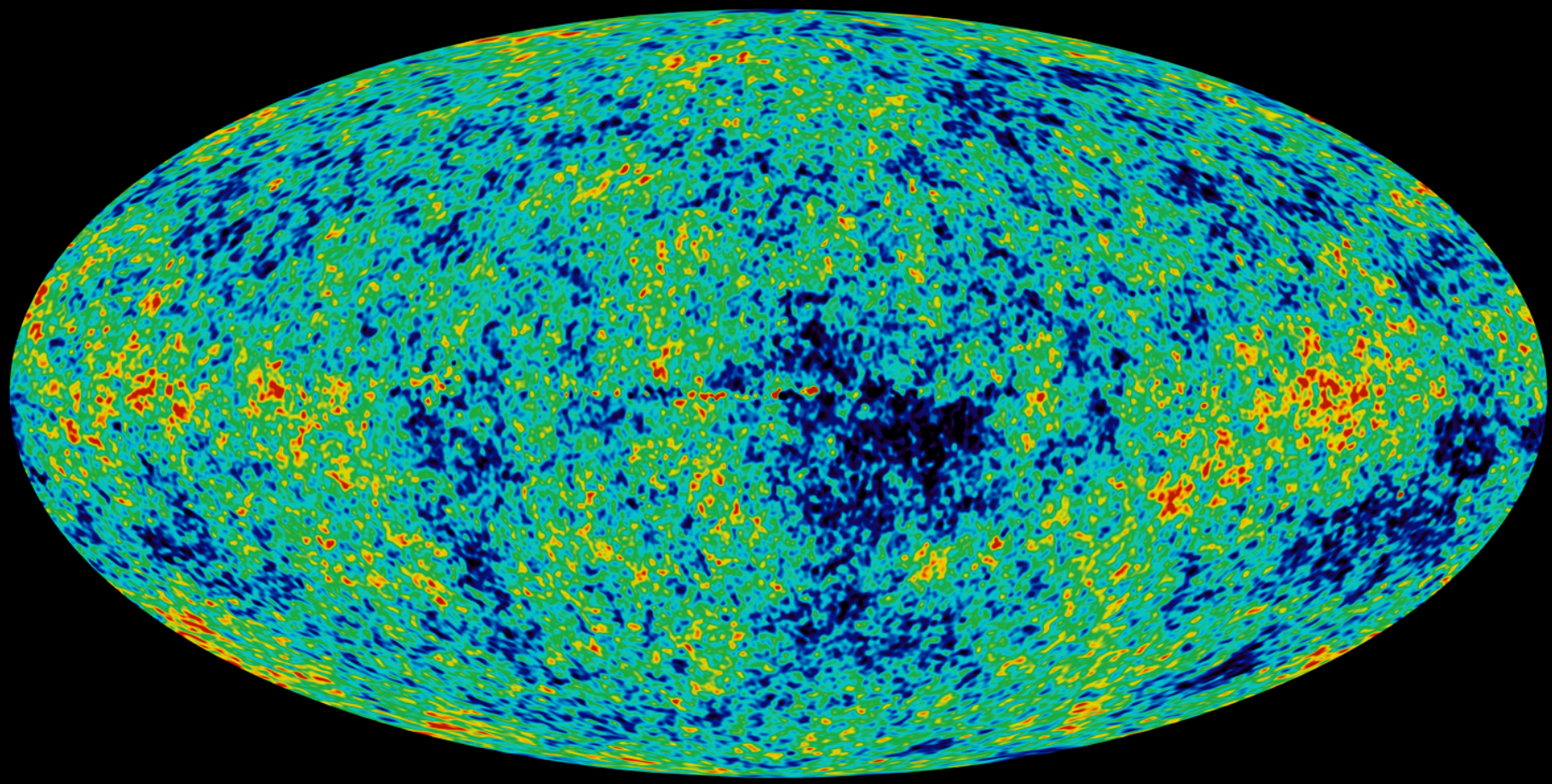
Dark Energy:
$\Omega_{DE} = 0.73 \pm 0.02$
$w = -0.94 \pm 0.1$
$(\pm 0.1$ sys$)$

Looks just like vacuum energy

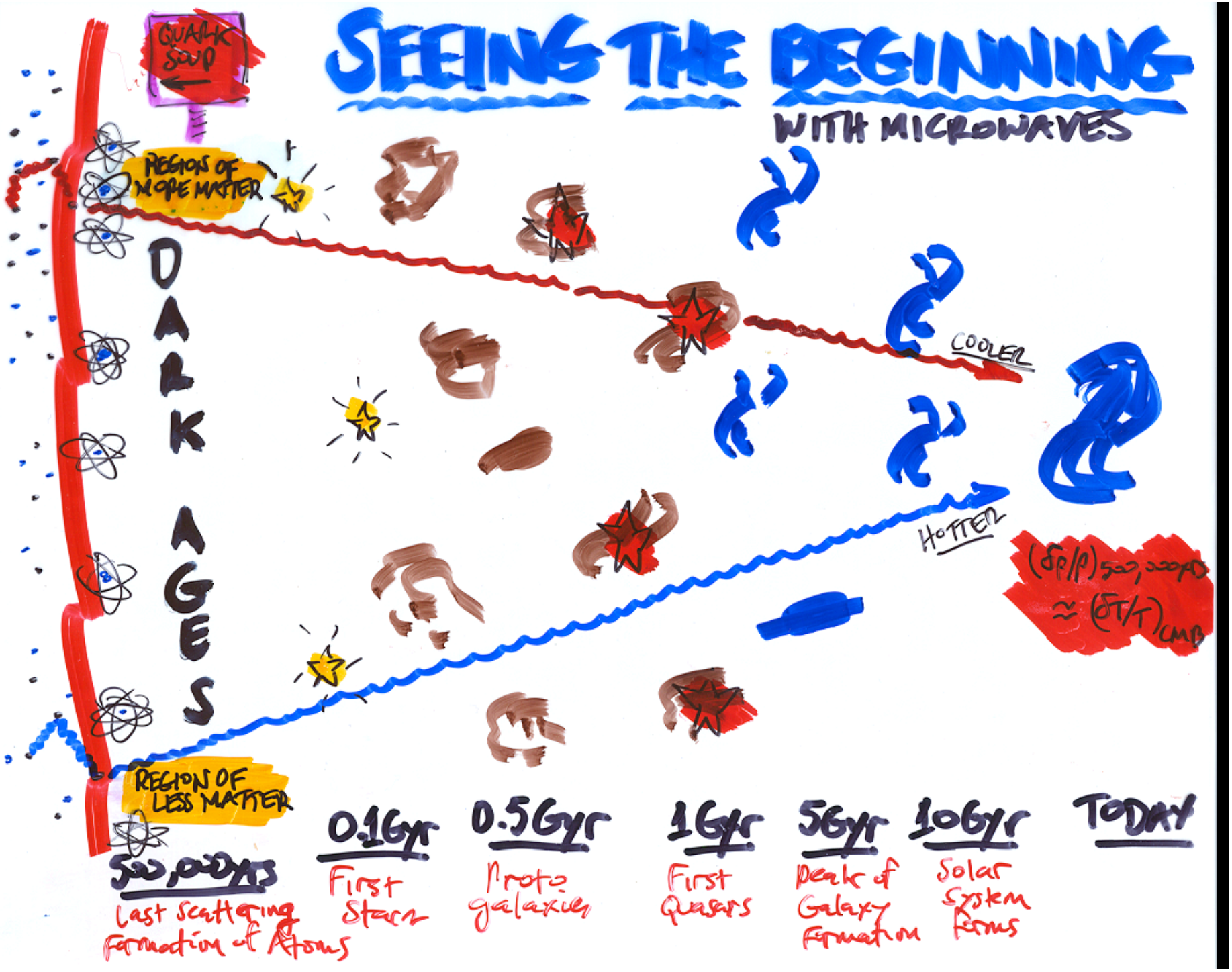


The Universe circa 380,000 yrs

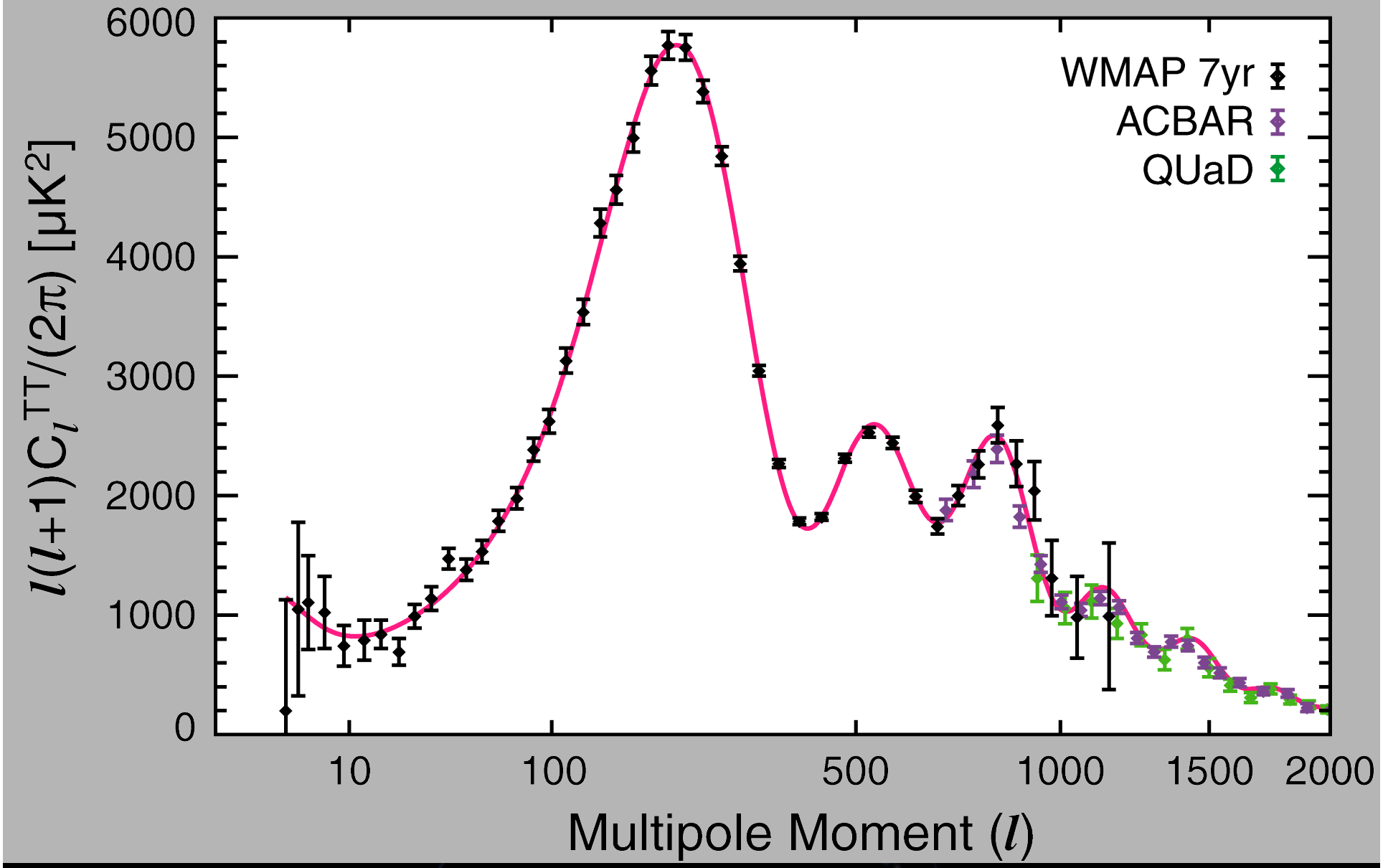
WMAP



±0.001% fluctuations ~10μK

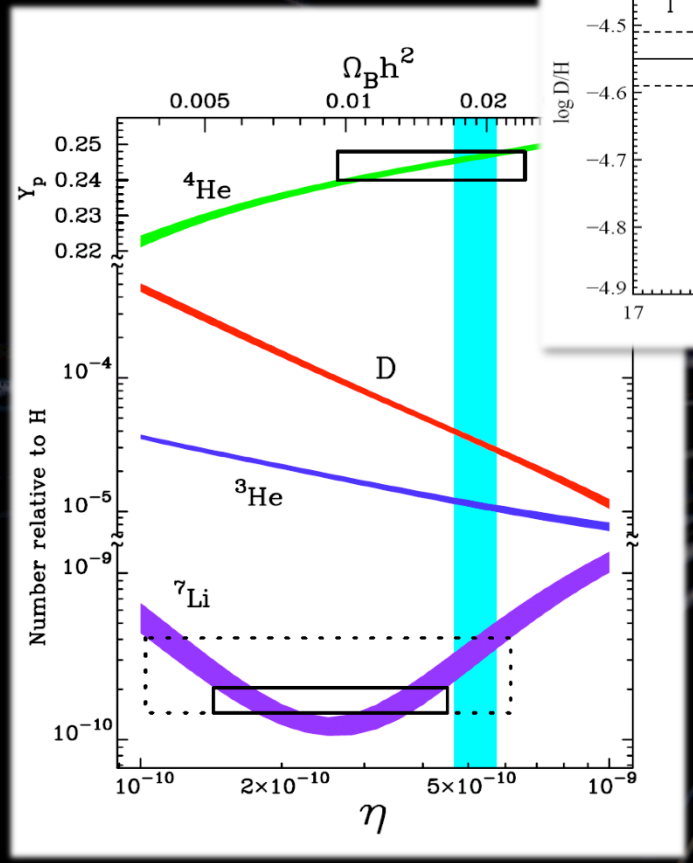

SEEING THE BEGINNING
WITH MICROWAVES
QUARK SOUP
REGION OF MORE MATTER
DARK AGES
REGION OF LESS MATTER
COOLER
HOTTER
(δρ/ρ)500,000yrs ≈ (δT/T)CMB
500,000yrs
Last scattering
Formation of Atoms
0.1Gyr
First Stars
0.5Gyr
Proto galaxies
1Gyr
First Quasars
5Gyr
Peak of Galaxy Formation
10Gyr
Solar System forms
TODAY

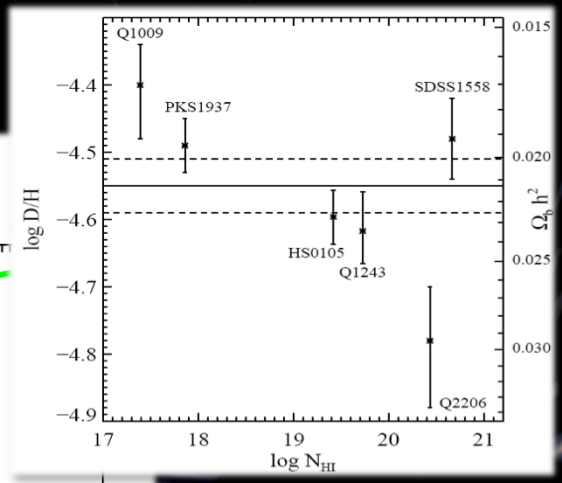
Curve = concordance cosmology

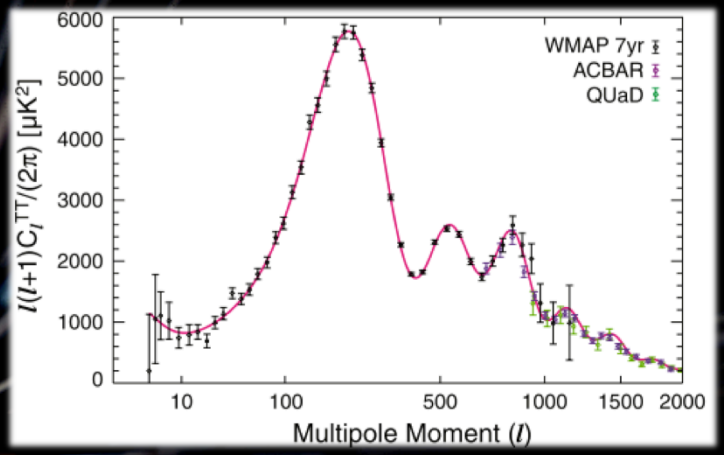


Curve = concordance cosmology

Precision Cosmology Indeed!







CMB (first to second peak)
$\Omega_b h^2 = 0.0225 \pm 0.0006$
vs.
BBN (Deuterium)
$\Omega_b h^2 = 0.0213 \pm 0.0013$
~5% agreement

$\Omega_B = 0.045 \pm 0.002$

$h = H_0/100$ km/s/Mpc ~ 0.7

The Consensus Cosmology

Rests upon three mysterious pillars

All implicate new physics!


The path forward

Dark matter

- Identify DM particle(s) (LHC, Direct detection, indirect detection)
- Determine its properties and distribution in the Galaxy and the Universe
- Consistency testing and completeness

20 σ Gap Between Matter and Baryons

Baryons: 21 ± 1

Matter: 130 ± 5

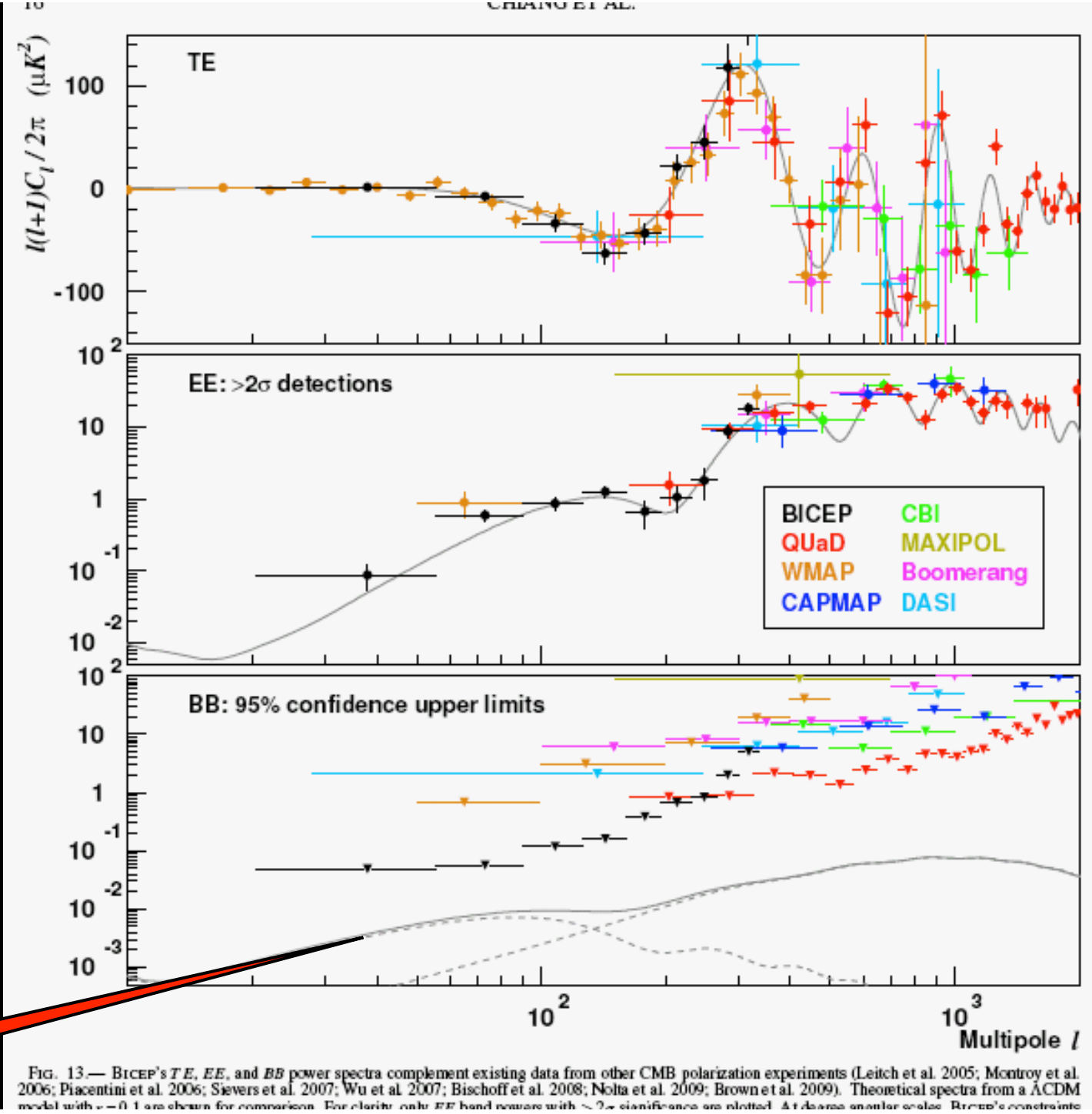
(1000 x Ωh^2)

→ Most of the matter is not baryonic

Inflation

- Finish precision testing: flatness, spectrum of perturbations, Gaussianity (CMB, LSS)
- Search for gravitational waves: CMB polarization signature, future GW experiment – e.g., SPT-Pol
- Connect to fundamental theory and/or find a better paradigm

Polarization: Where we are today
Chiang et al, arXiv: 0906.1181



r = 0.1

FIG. 13.— BICEP's *TE*, *EE*, and *BB* power spectra complement existing data from other CMB polarization experiments (Leitch et al. 2005; Montroy et al. 2006; Piacentini et al. 2006; Sievers et al. 2007; Wu et al. 2007; Bischoff et al. 2008; Nolta et al. 2009; Brown et al. 2009). Theoretical spectra from a ΛCDM model with $r = 0.1$ are shown for comparison. For clarity, only *EE* band powers with $> 2\sigma$ significance are plotted. At degree angular scales, BICEP's constraints

Dark energy

- Test null hypothesis (vacuum energy) to high precision (per cent or better) and consistency of GR framework (per cent level) – DES, SPT, WFIRST, LSST, BoSS, …
- Look for other clues (variation of w, new forces, …)

DARK ENERGY

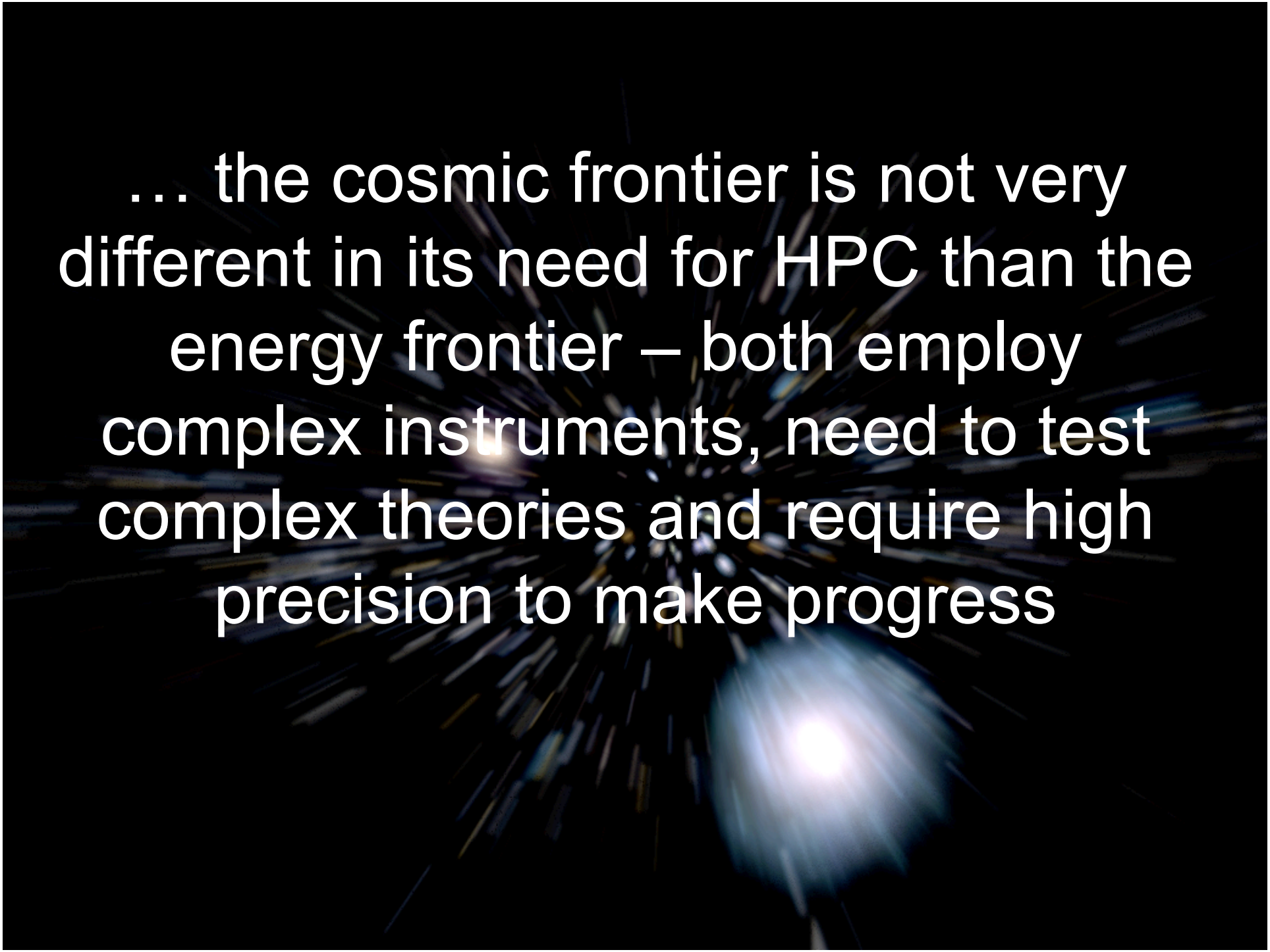
MAY BE THE MOST PROFOUND PROBLEM IN ALL OF SCIENCE TODAY

Youbetcha Katie, I believe in Dark Energy – we can see it from Alaska!

Drill for Dark Energy!

Cosmological computing is essential to progress

- Connecting theory with observations through numerical simulation
- Large datasets generated by complex instruments: DES, LSST, BoSS, CMB
- Simulation to understand/control systematics, especially astrophysical systematics (e.g., SNe1a, clusters)


… the cosmic frontier is not very different in its need for HPC than the energy frontier – both employ complex instruments, need to test complex theories and require high precision to make progress