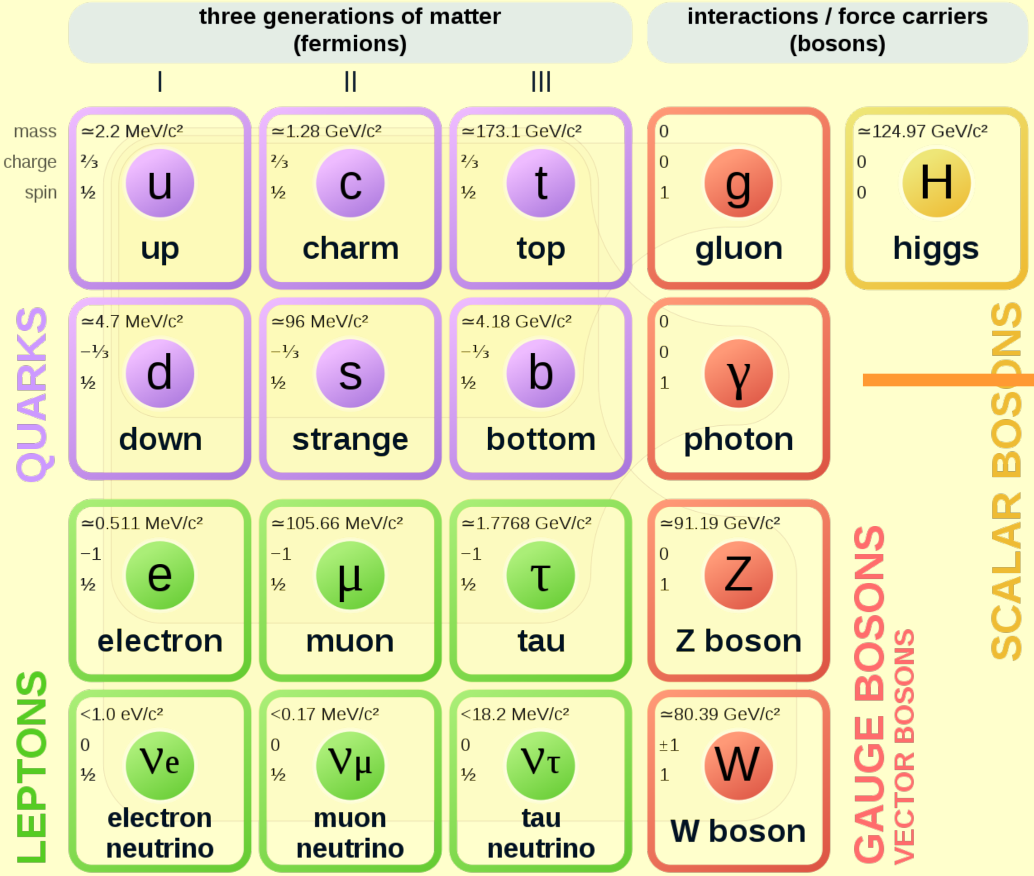
Fundamental Observations

Information carriers

Standard Model of Elementary Particles



	three generations of matter (fermions) I	II	III	interactions / force carriers (bosons)	
mass charge spin	≃2.2 MeV/c² ⅔ ½ u up	≃1.28 GeV/c² ⅔ ½ c charm	≃173.1 GeV/c² ⅔ ½ t top	0 0 1 g gluon	≃124.97 GeV/c² 0 0 H higgs
QUARKS	≃4.7 MeV/c² −⅓ ½ d down	≃96 MeV/c² −⅓ ½ s strange	≃4.18 GeV/c² −⅓ ½ b bottom	0 0 1 γ photon	SCALAR BOSONS
	≃0.511 MeV/c² −1 ½ e electron	≃105.66 MeV/c² −1 ½ μ muon	≃1.7768 GeV/c² −1 ½ τ tau	≃91.19 GeV/c² 0 1 Z Z boson	
LEPTONS	<1.0 eV/c² 0 ½ νe electron neutrino	<0.17 MeV/c² 0 ½ νμ muon neutrino	<18.2 MeV/c² 0 ½ ντ tau neutrino	≃80.39 GeV/c² ±1 1 W W boson	GAUGE BOSONS VECTOR BOSONS

Baryons:
- Meteorites
- Planetary samples
- Cosmic rays

Cosmological/ astrophysical neutrinos

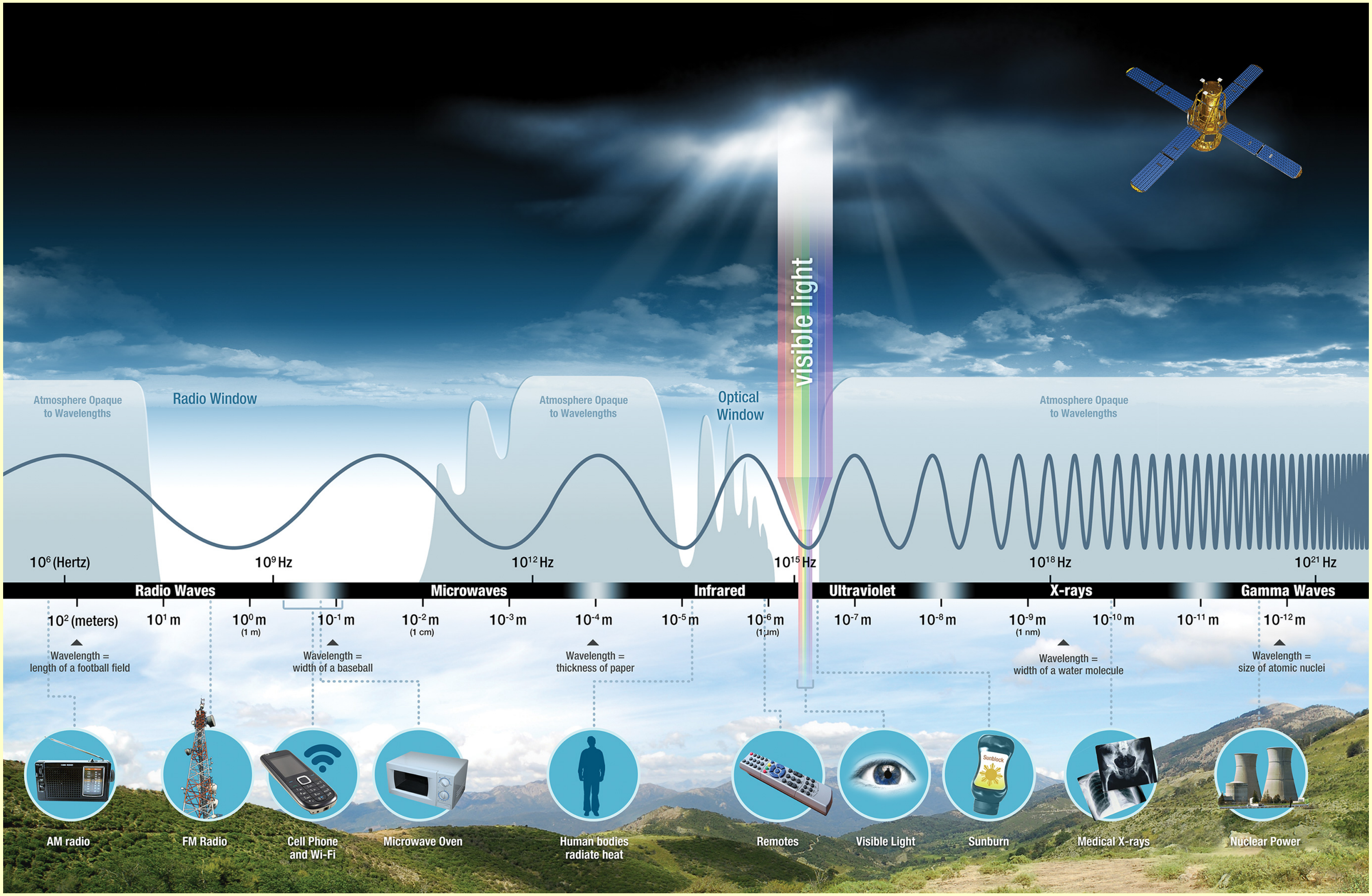
EM spectrum

Graviton?

Gravitational waves

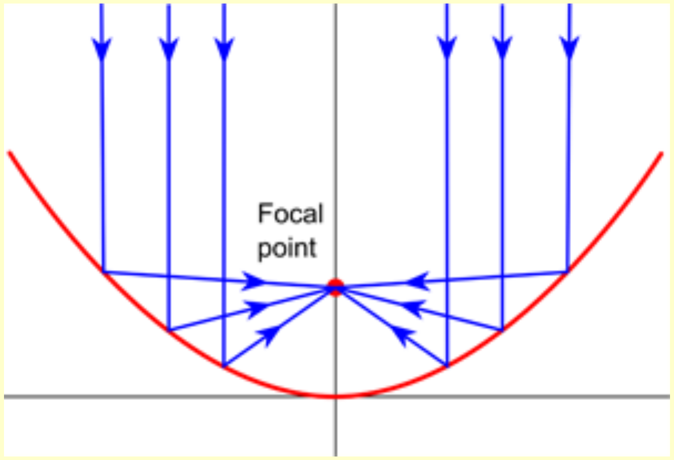
Fundamental Observations

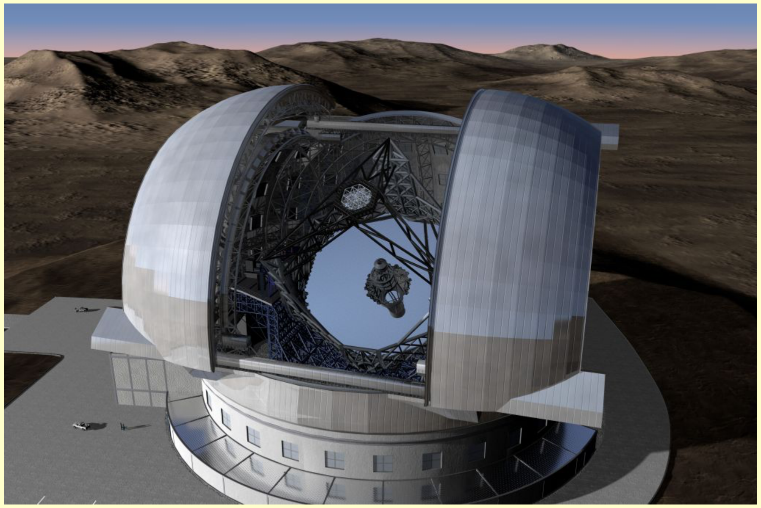
The electromagnetic spectrum



Fundamental Observations

Collecting photons: telescopes





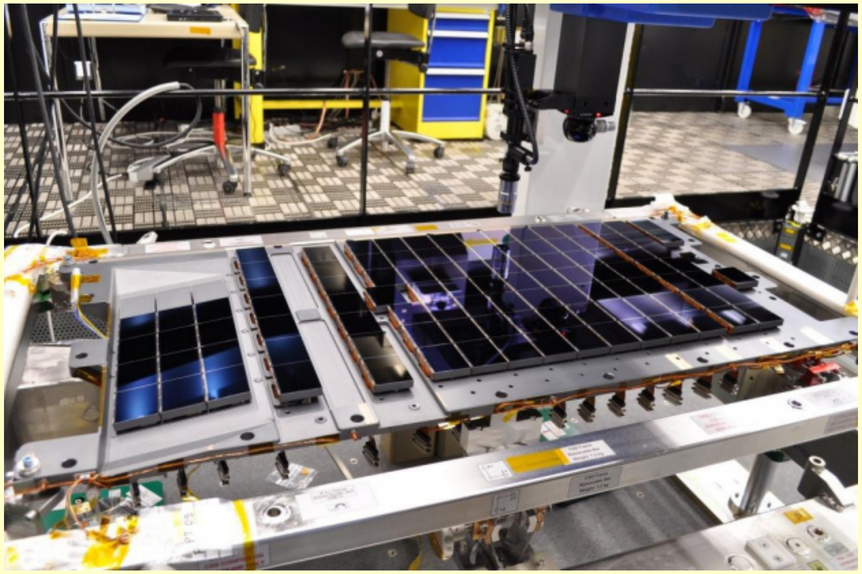
ELT, Chile

GBT, USA

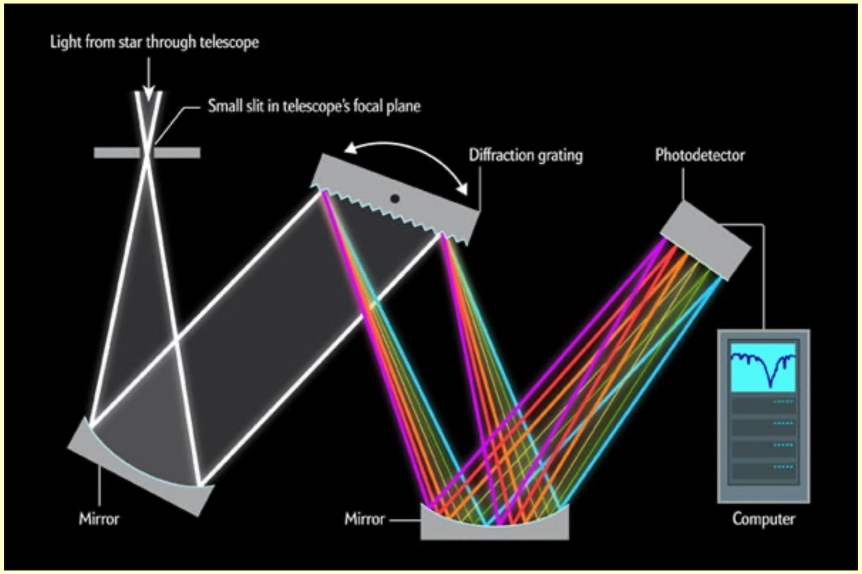
Fundamental Observations

Detecting and analyzing photons

CCD, Gaia focal plane



Schema spectrograph

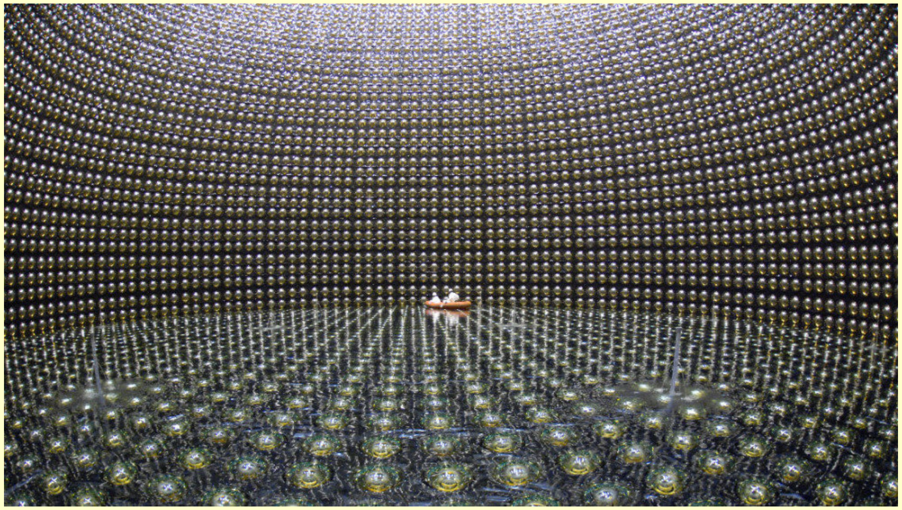


Fundamental Observations

Other types of observatories

GWs, LIGO

Neutrinos, Super kamiokande



Fundamental Observations

Pillars of Modern Cosmological Paradigm

- Universe is isotropic (and homogeneous)
- Night Sky is Dark
- Linear Expansion
- Light Element Abundances
- Microwave Background Radiation

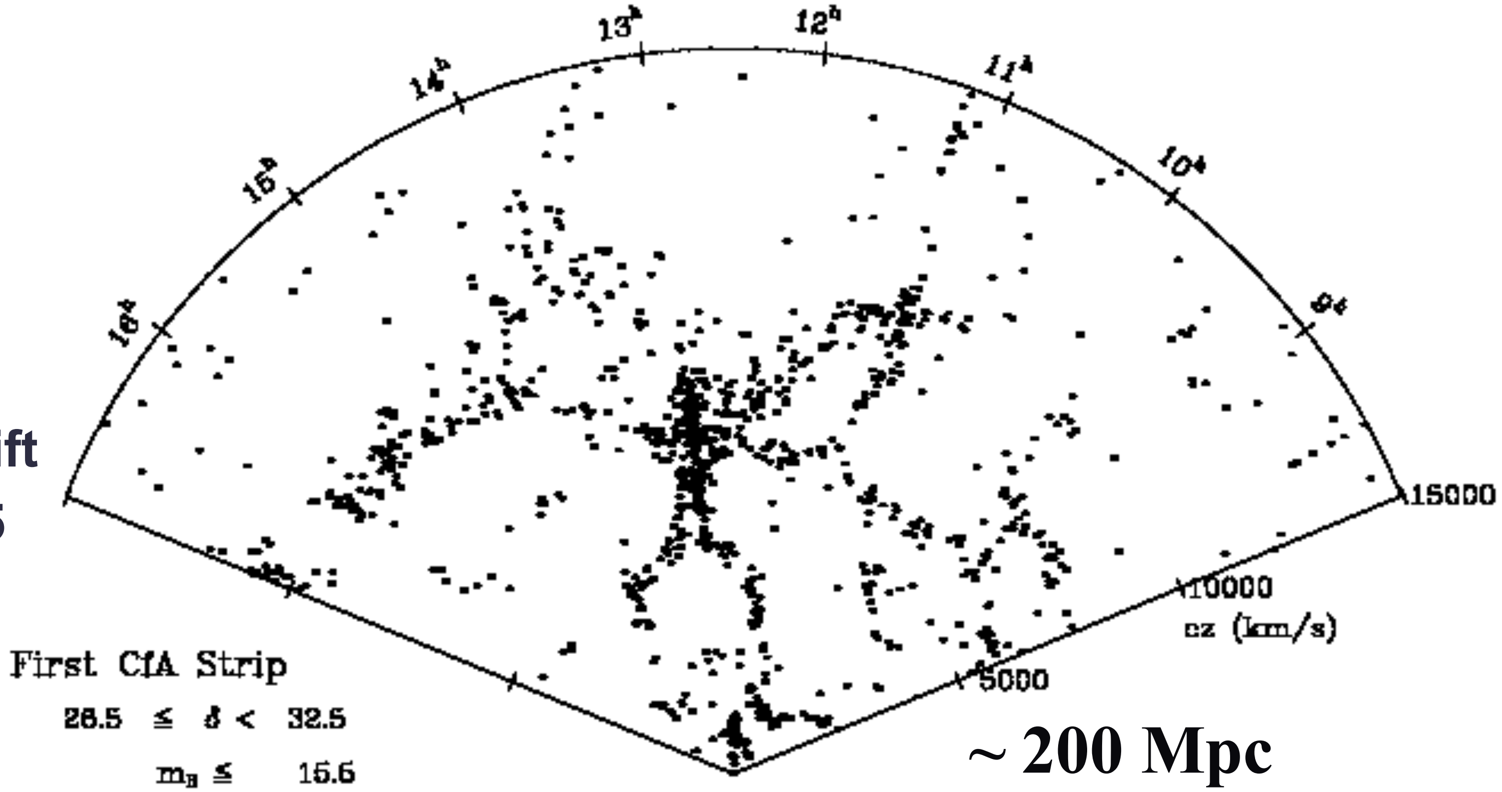
+

- Statistics of “Large-Scale Structures (LSS)”

Cosmological Principle

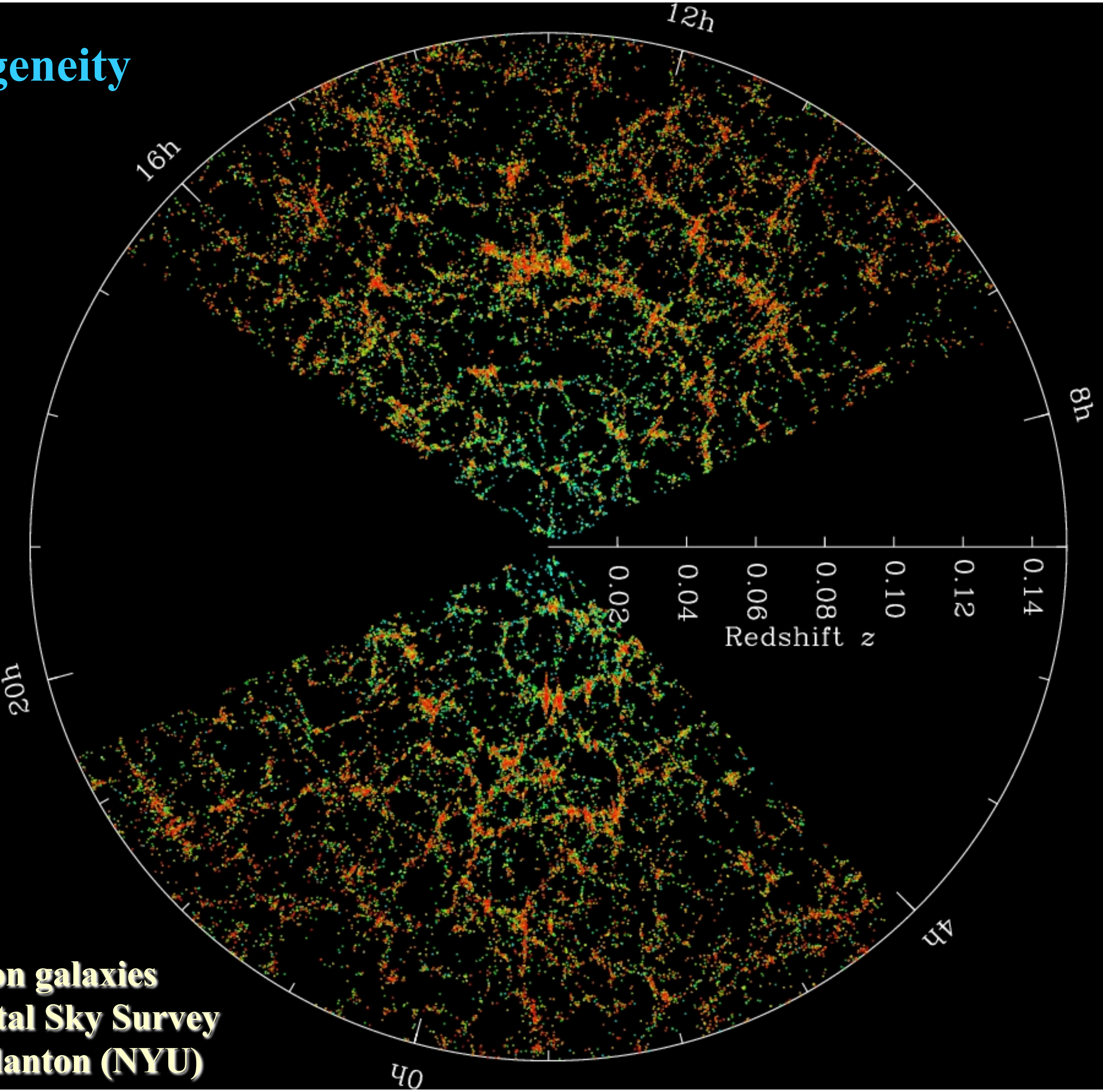
On large scales, the universe is isotropic

redshift
z=0.05



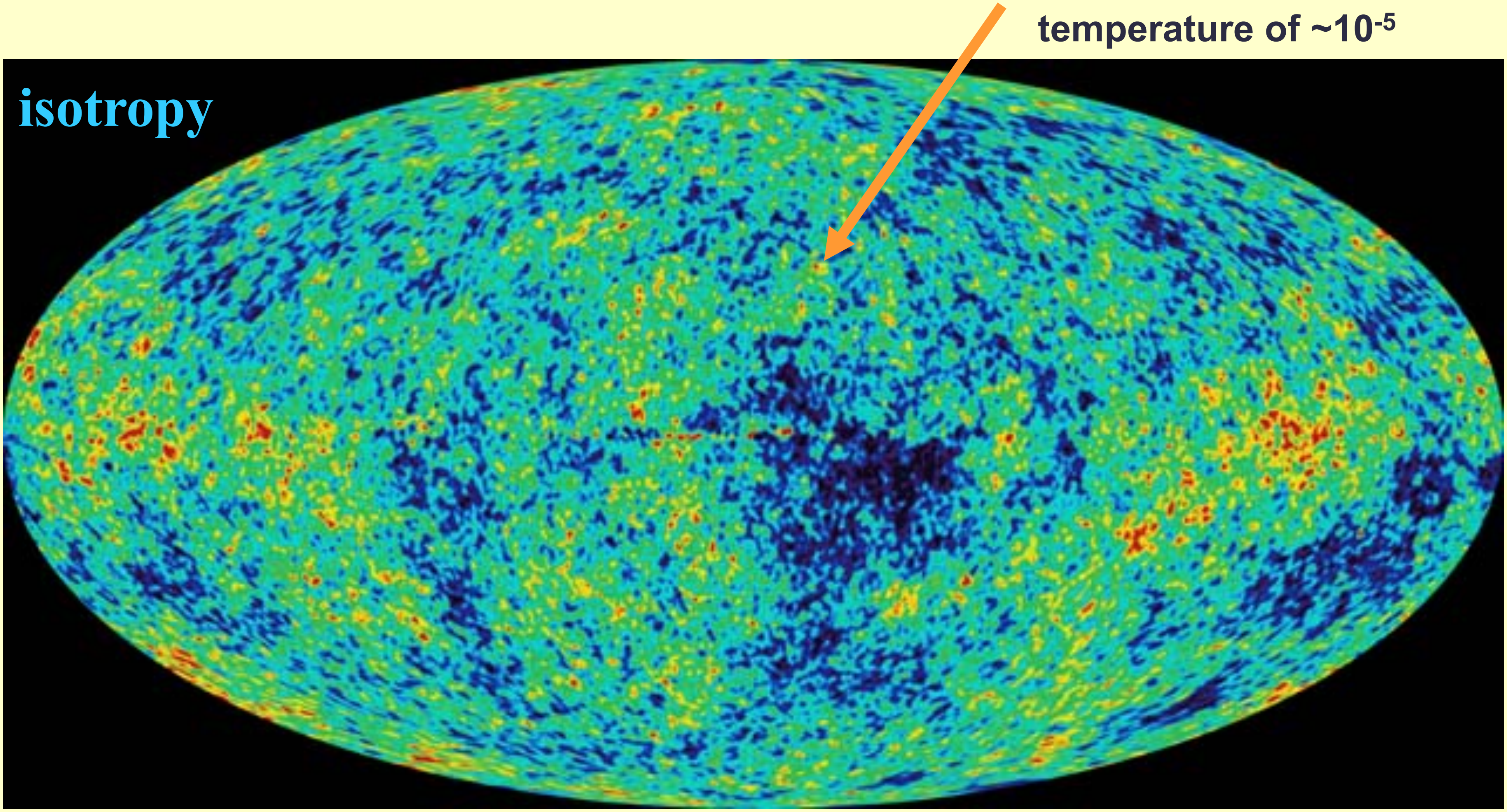
~ 200 Mpc
~1000 galaxies (1982)

homogeneity



~200 million galaxies
Sloan Digital Sky Survey
Michael Blanton (NYU)

The Cosmic Microwave Background (CMB)



Differences in temperature of ~10^{-5}

Wilkinson Microwave Anisotropy Probe: February 13, 2003

Cosmological Principle

- Copernican principle: our location in space is not special
- Isotropy + Copernican principle = homogeneity = “cosmological principle”
- “Perfect cosmological principle”: the universe is isotropic and homogeneous in space AND time, not consistent with observations

Hubble Ultra Deep Field

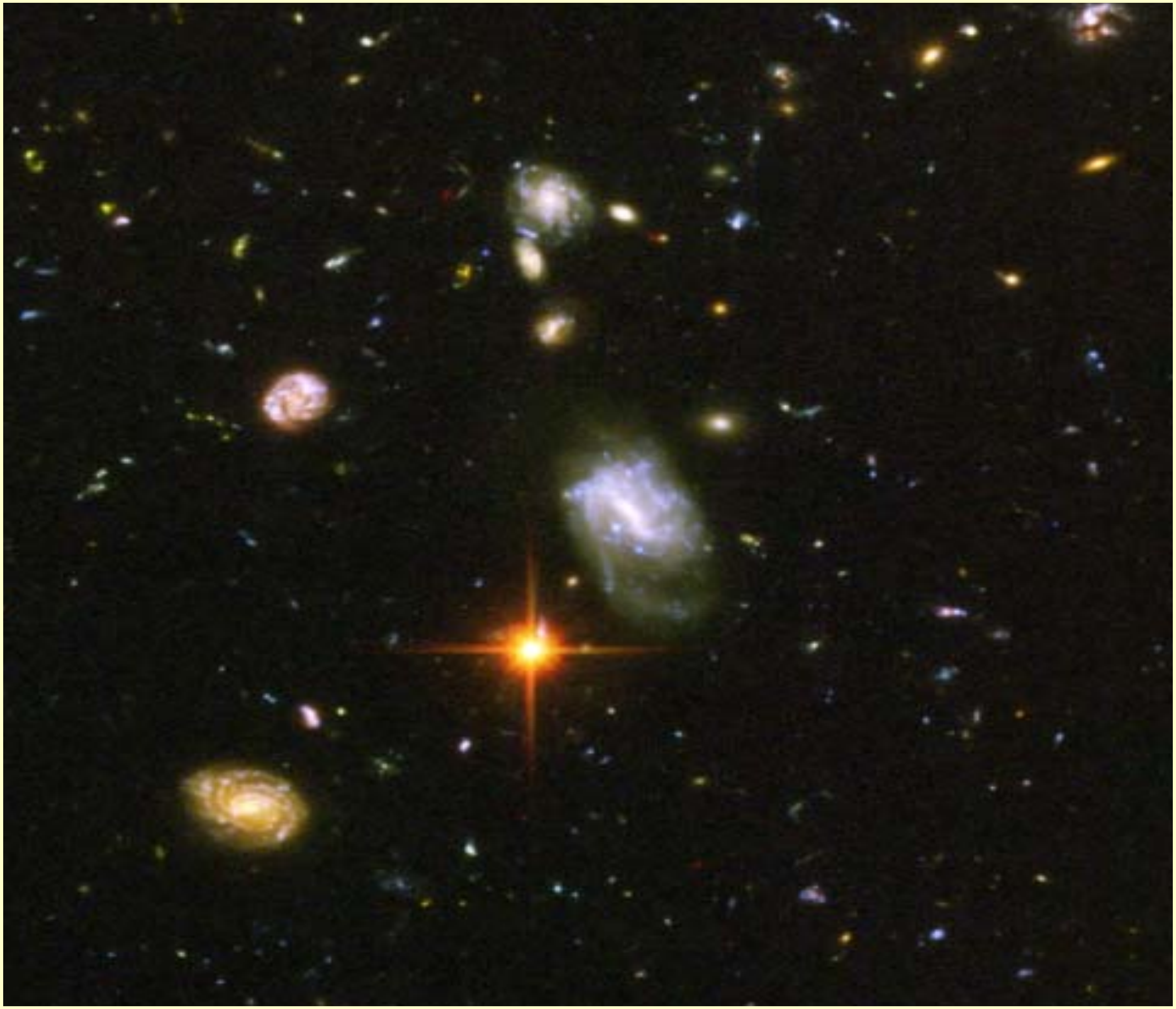
Hubble Ultra Deep Field
Hubble Space Telescope • Advanced Camera for Surveys

NASA, ESA, S. Beckwith (STScI) and the HUDF Team

STScI-PRC04-07a

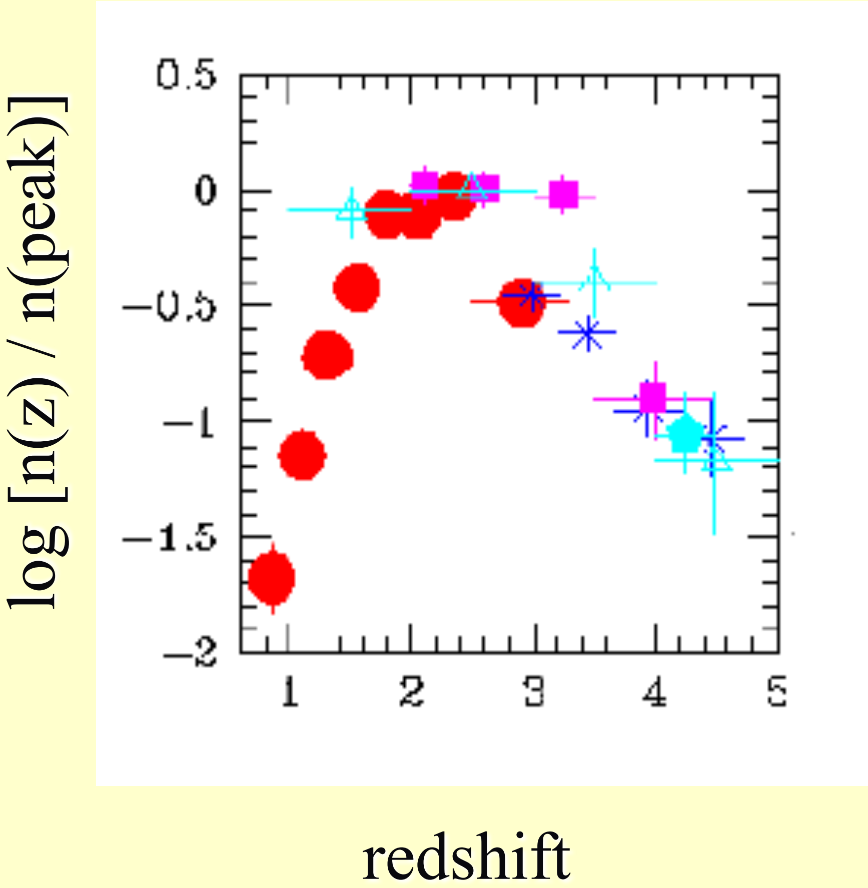
- **Deepest view of the Universe**
- **Most objects are galaxies not stars**
- **Faintest galaxies 13 billion lyr away**
- **Tiny area of sky**
- **Record holders:**
  - **galaxy z~ ~~10.2~~ 11.09**
  - **quasar z~ ~~7.1~~ 7.54**
  - **gamma-ray burst z~8.2**

Hubble Ultra Deep Field – Zoom

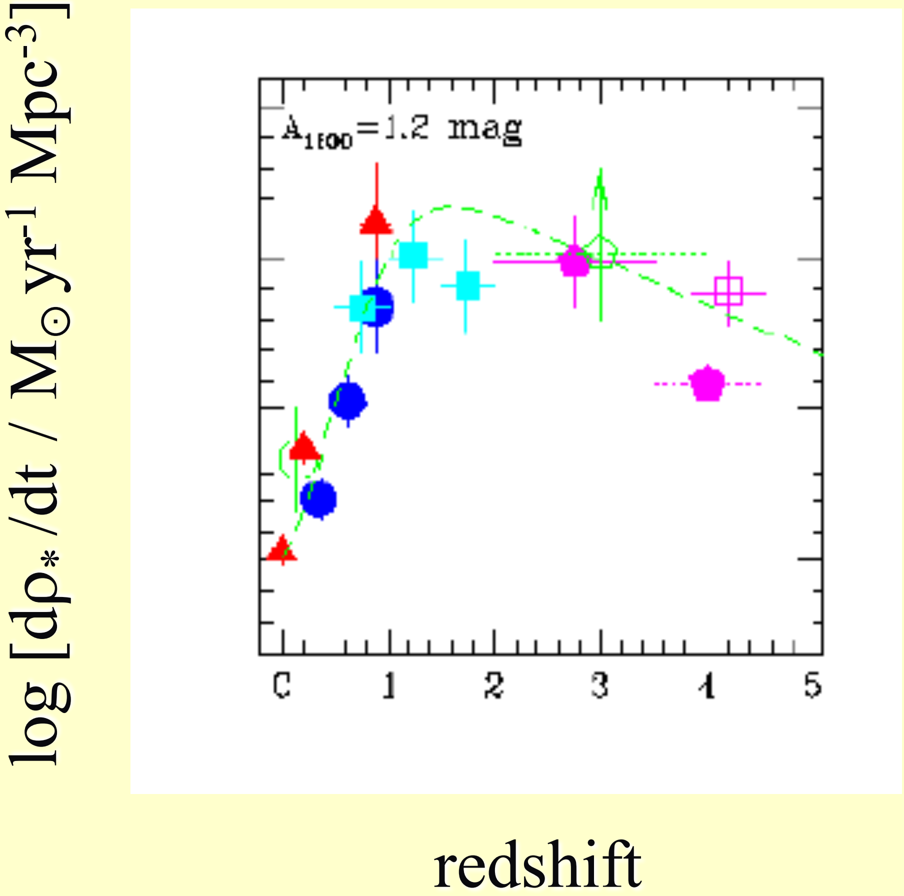


Quasars and Galaxies Evolve

Quasar space density



Star formation rate



(Madau 1999)

Quasars and Galaxies Evolve

- Characteristic epochs of galaxy/quasar activity

  - coincide at z~2

  - which came first, the galaxies or their nuclei?

- Galaxies in the past

  - smaller

  - more irregular

  - preferentially elliptical

  - contain less heavy elements

- Quasars in the past

  - more luminous

  - more numerous

  - same metallicity

Fundamental Observations

Pillars of Modern Cosmological Paradigm

- Universe is isotropic (and homogeneous)
- Night Sky is Dark
- Linear Expansion
- Light Element Abundances
- Microwave Background Radiation

+

- Statistics of Large-Scale Structures

2. The Night Sky is Dark

Is this a problem?

- Not if stars are points of light stuck onto a dome

- But yes, in post-Copernican models
  - stars are scattered through space
  - (or galaxies are…)

The Simplest Model

- Universe infinitely large
- Uniformly filled with stars
- Infinitely old

Surface Brightness of the Sky

- Sum over all stars: J is infinitely large

$$\boldsymbol{J} = \frac{1}{4\pi}\int_0^\infty \frac{\boldsymbol{L}}{4\pi \boldsymbol{r}^2}\boldsymbol{n}(4\pi \boldsymbol{r}^2 \boldsymbol{dr}) = \frac{\boldsymbol{nL}}{4\pi}\int_0^\infty \boldsymbol{dr} = \infty$$

- Sum up to "crowding" distance d=1/(nπR²)

$$\boldsymbol{J} = \frac{\boldsymbol{nL}}{4\pi}\int_0^{\boldsymbol{d}} \boldsymbol{dr} = \frac{\boldsymbol{nL}}{4\pi}\frac{1}{\boldsymbol{n}\,\pi \boldsymbol{R}^2} = \frac{\boldsymbol{L}}{4\pi^2 \boldsymbol{R}^2}$$

Still as bright as *the disk of an individual star*

What does this imply?

- One or more of the assumptions are wrong
  - recognized to be a problem already in 1576 by Thomas Digges (vs Copernicus 1543)

- Obscuring stars by dust does not work
  - proposed as a solution in 1744 by de Chesaux and in 1826 by Heinrich Olbers
  - but dust will heat and radiate at same brightness

- Infinitely old, infinitely large, Euclidean universe is self-contradictory.
  - innocuous-looking puzzle lasts into 20th century (!) until discovery of the expansion of the universe

Fundamental Observations

Pillars of Modern Cosmological Paradigm

- Universe is isotropic (and homogeneous)
- Night Sky is Dark
- Linear Expansion
- Light Element Abundances
- Microwave Background Radiation

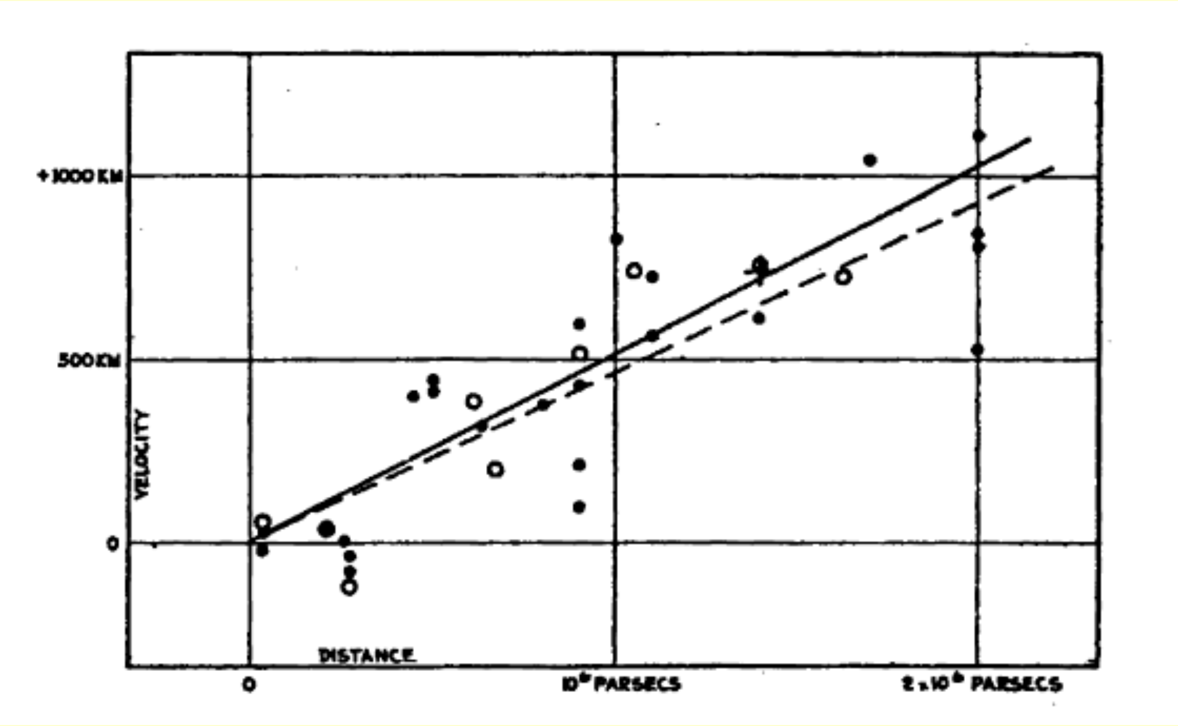
+

- Statistics of Large-Scale Structures

3. Linear Expansion

- Slipher (1912) starts measuring redshifts, interprets redshift $z=(\lambda_{obs} - \lambda_{em}) / \lambda_{em}$ as due to motion of galaxies

- Edwin Hubble* proclaims linear expansion in 1929 using redshift vs distance to 20 galaxies – Cepheids!



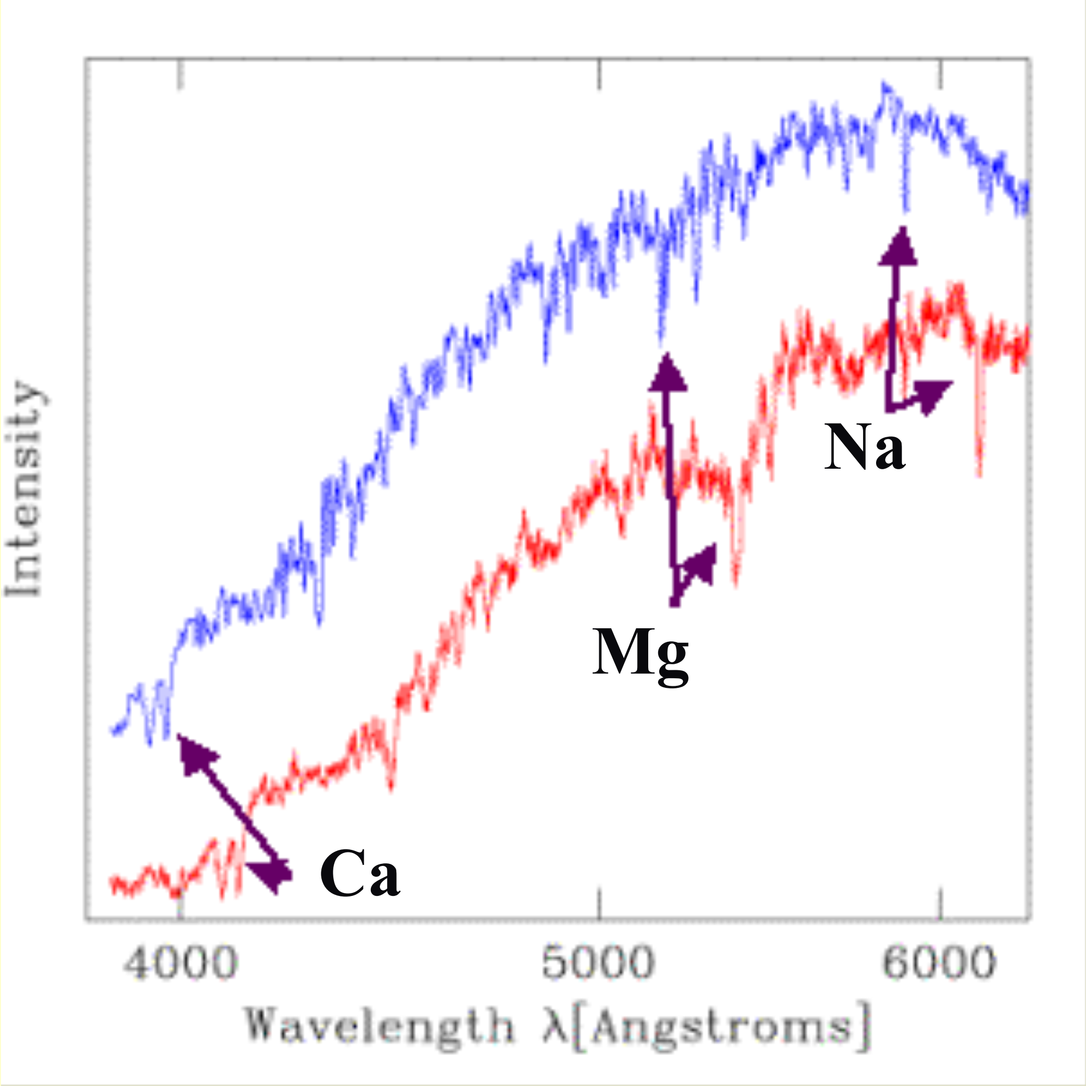
Velocity (km/s)

Distance (1pc = 3 light years)

(*) Georges Lemaitre (1927)

Redshift

spectrum of a nearby star vs a galaxy traveling at 12,000 km/s

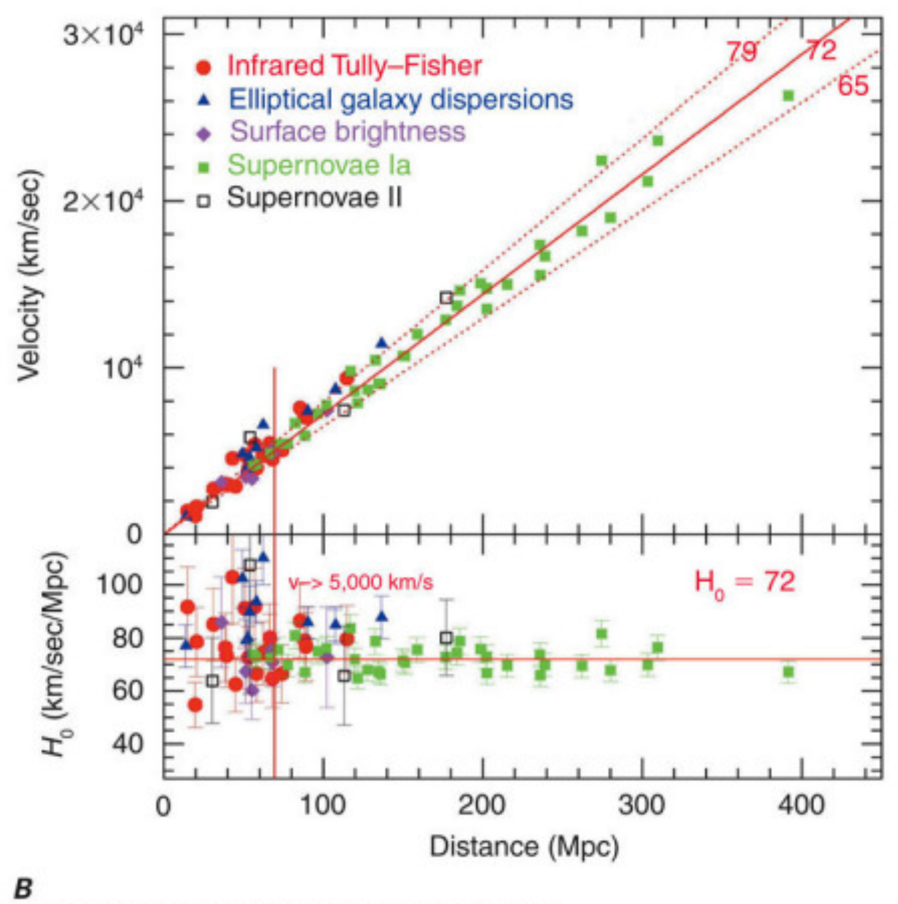


Linear Expansion

- Hubble constant: H_0=v/r=500 km/s/Mpc

- Modern value:
  73±0.8 km/s/Mpc
  (nearby SNe)

- Expansion not
  linear at large
  distance



(Wendy L. Freedman, Observatories of the Carnegie Institution of Washington, and NASA)

"HST key project"

What does this imply?

- Galaxies recede from us (“explosion”)

  - would imply center to the Universe

- Uniform expansion of Universe

  - consistent with cosmological principle

  - extrapolated estimate for age: $1/H_0 = 13.7$ Gyr

  consistent with ages of oldest stars

  - solves Olbers’ paradox (redshift, finite age)

- Inconsistent with Perfect Cosmological Principle

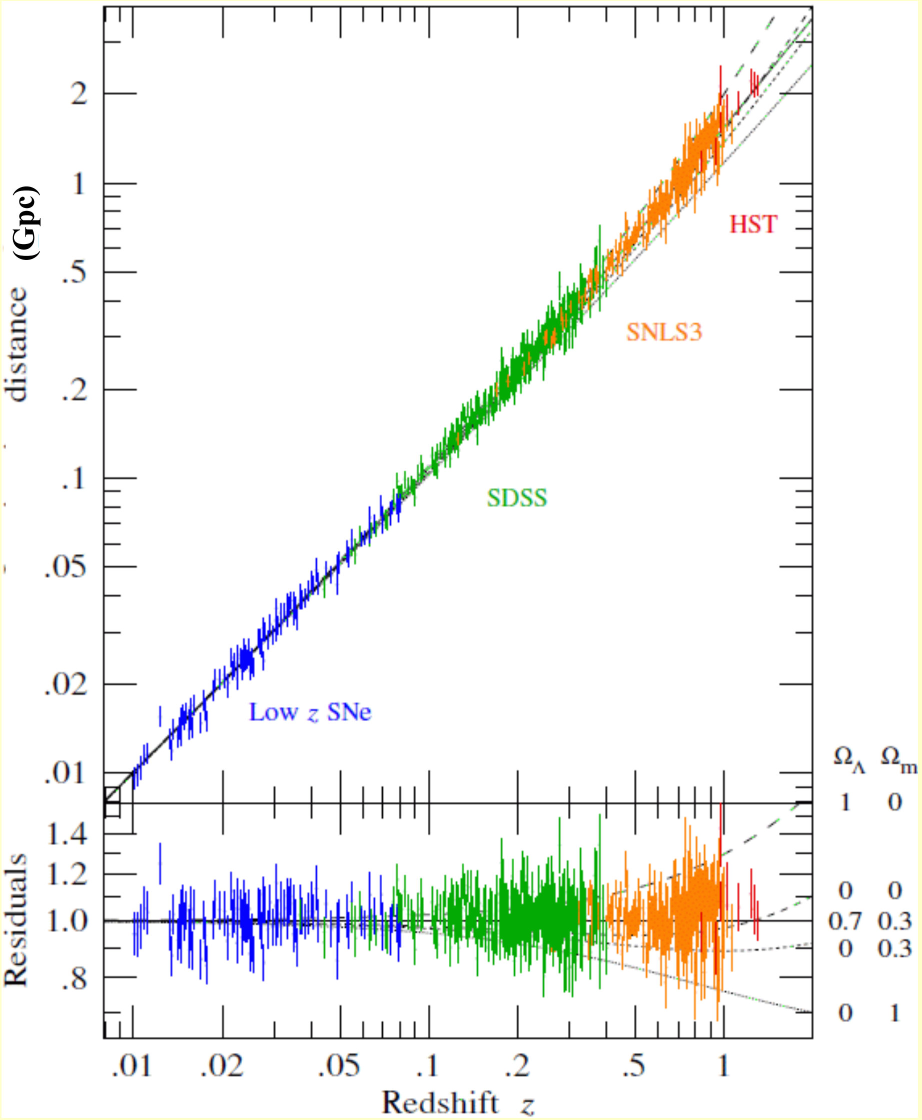
  - inspired steady-state model (late 1940s)

  requires continuous creation of new material at the (tiny) rate

  $d\rho/dt = 3\ H_0\ \rho = 6\times10^{-28}\ \mathrm{kg/m^3/Gyr}$ (= 1 proton/m^3/yr)

Universe is ACCELERATING!

- Gravity always attractive: causes deceleration
- BUT see modern Hubble diagram, based on using supernovae as calibrated "light-bulbs"
- Implies the presence of "something with large negative pressure"



Betoule et al. 2014

Fundamental Observations

Pillars of Modern Cosmological Paradigm

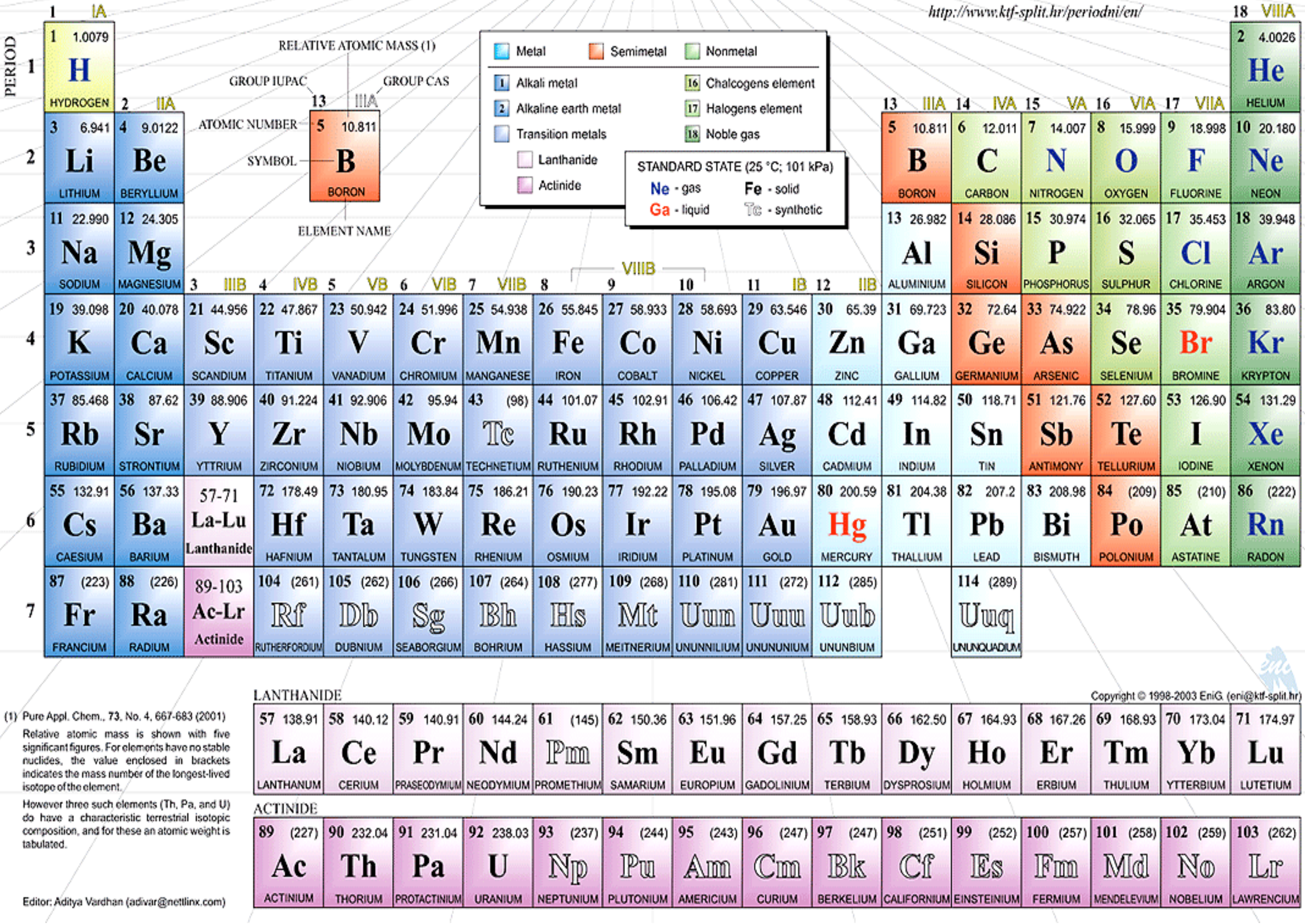
- Universe is isotropic (and homogeneous)
- Night Sky is Dark
- Linear Expansion
- Light Element Abundances
- Microwave Background Radiation

+

- Statistics of Large-Scale Structures

PERIODIC TABLE OF THE ELEMENTS

http://www.ktf-split.hr/periodni/en/



RELATIVE ATOMIC MASS (1)

GROUP IUPAC 13 — GROUP CAS IIIA

ATOMIC NUMBER 5 — 10.811

SYMBOL B

ELEMENT NAME BORON

🟦 Metal	🟥 Semimetal
🟩 Nonmetal	
1 Alkali metal	16 Chalcogens element
2 Alkaline earth metal	17 Halogens element
Transition metals	18 Noble gas
Lanthanide	
Actinide	

STANDARD STATE (25 °C; 101 kPa)

Ne - gas	Fe - solid
Ga - liquid	Tc - synthetic

PERIOD	1 IA	2 IIA	3 IIIB	4 IVB	5 VB	6 VIB	7 VIIB	8 VIIIB	9 VIIIB	10 VIIIB	11 IB	12 IIB	13 IIIA	14 IVA	15 VA	16 VIA	17 VIIA	18 VIIIA
1	1 1.0079 H HYDROGEN																	2 4.0026 He HELIUM
2	3 6.941 Li LITHIUM	4 9.0122 Be BERYLLIUM											5 10.811 B BORON	6 12.011 C CARBON	7 14.007 N NITROGEN	8 15.999 O OXYGEN	9 18.998 F FLUORINE	10 20.180 Ne NEON
3	11 22.990 Na SODIUM	12 24.305 Mg MAGNESIUM											13 26.982 Al ALUMINIUM	14 28.086 Si SILICON	15 30.974 P PHOSPHORUS	16 32.065 S SULPHUR	17 35.453 Cl CHLORINE	18 39.948 Ar ARGON
4	19 39.098 K POTASSIUM	20 40.078 Ca CALCIUM	21 44.956 Sc SCANDIUM	22 47.867 Ti TITANIUM	23 50.942 V VANADIUM	24 51.996 Cr CHROMIUM	25 54.938 Mn MANGANESE	26 55.845 Fe IRON	27 58.933 Co COBALT	28 58.693 Ni NICKEL	29 63.546 Cu COPPER	30 65.39 Zn ZINC	31 69.723 Ga GALLIUM	32 72.64 Ge GERMANIUM	33 74.922 As ARSENIC	34 78.96 Se SELENIUM	35 79.904 Br BROMINE	36 83.80 Kr KRYPTON
5	37 85.468 Rb RUBIDIUM	38 87.62 Sr STRONTIUM	39 88.906 Y YTTRIUM	40 91.224 Zr ZIRCONIUM	41 92.906 Nb NIOBIUM	42 95.94 Mo MOLYBDENUM	43 (98) Tc TECHNETIUM	44 101.07 Ru RUTHENIUM	45 102.91 Rh RHODIUM	46 106.42 Pd PALLADIUM	47 107.87 Ag SILVER	48 112.41 Cd CADMIUM	49 114.82 In INDIUM	50 118.71 Sn TIN	51 121.76 Sb ANTIMONY	52 127.60 Te TELLURIUM	53 126.90 I IODINE	54 131.29 Xe XENON
6	55 132.91 Cs CAESIUM	56 137.33 Ba BARIUM	57-71 La-Lu Lanthanide	72 178.49 Hf HAFNIUM	73 180.95 Ta TANTALUM	74 183.84 W TUNGSTEN	75 186.21 Re RHENIUM	76 190.23 Os OSMIUM	77 192.22 Ir IRIDIUM	78 195.08 Pt PLATINUM	79 196.97 Au GOLD	80 200.59 Hg MERCURY	81 204.38 Tl THALLIUM	82 207.2 Pb LEAD	83 208.98 Bi BISMUTH	84 (209) Po POLONIUM	85 (210) At ASTATINE	86 (222) Rn RADON
7	87 (223) Fr FRANCIUM	88 (226) Ra RADIUM	89-103 Ac-Lr Actinide	104 (261) Rf RUTHERFORDIUM	105 (262) Db DUBNIUM	106 (266) Sg SEABORGIUM	107 (264) Bh BOHRIUM	108 (277) Hs HASSIUM	109 (268) Mt MEITNERIUM	110 (281) Uun UNUNNILIUM	111 (272) Uuu UNUNUNIUM	112 (285) Uub UNUNBIUM		114 (289) Uuq UNUNQUADIUM				

LANTHANIDE

57 138.91 La LANTHANUM	58 140.12 Ce CERIUM	59 140.91 Pr PRASEODYMIUM	60 144.24 Nd NEODYMIUM	61 (145) Pm PROMETHIUM	62 150.36 Sm SAMARIUM	63 151.96 Eu EUROPIUM	64 157.25 Gd GADOLINIUM	65 158.93 Tb TERBIUM	66 162.50 Dy DYSPROSIUM	67 164.93 Ho HOLMIUM	68 167.26 Er ERBIUM	69 168.93 Tm THULIUM	70 173.04 Yb YTTERBIUM	71 174.97 Lu LUTETIUM

ACTINIDE

89 (227) Ac ACTINIUM	90 232.04 Th THORIUM	91 231.04 Pa PROTACTINIUM	92 238.03 U URANIUM	93 (237) Np NEPTUNIUM	94 (244) Pu PLUTONIUM	95 (243) Am AMERICIUM	96 (247) Cm CURIUM	97 (247) Bk BERKELIUM	98 (251) Cf CALIFORNIUM	99 (252) Es EINSTEINIUM	100 (257) Fm FERMIUM	101 (258) Md MENDELEVIUM	102 (259) No NOBELIUM	103 (262) Lr LAWRENCIUM

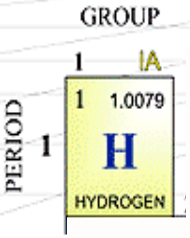
(1) Pure Appl. Chem., 73, No. 4, 667-683 (2001)

Relative atomic mass is shown with five significant figures. For elements have no stable nuclides, the value enclosed in brackets indicates the mass number of the longest-lived isotope of the element.

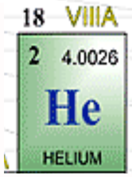
However three such elements (Th, Pa, and U) do have a characteristic terrestrial isotopic composition, and for these an atomic weight is tabulated.

Editor: Aditya Vardhan (adivar@netllinx.com)

PERIODIC TABLE OF THE ELEMENTS



(FOR COSMOLOGISTS)



* everything else is called a "metal"

* universe expands and cools
rapidly, no time to fuse
any other nuclei

* rest of the elements are fused
later, inside long-lived stars

4. Light Element Abundances

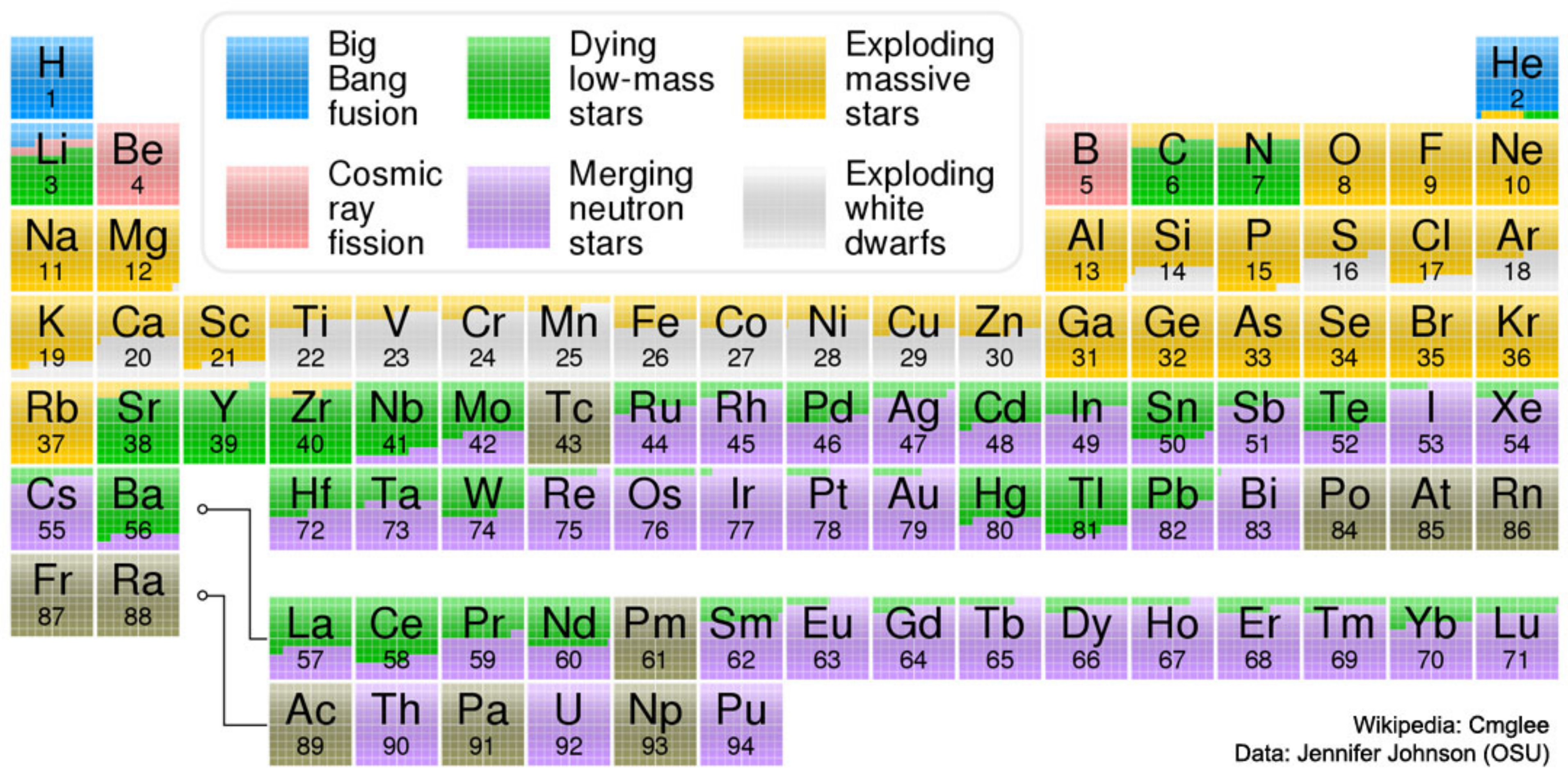
- Observed abundances of light elements

Hydrogen	75%
Helium	24%
Others	1%

- Helium problem:

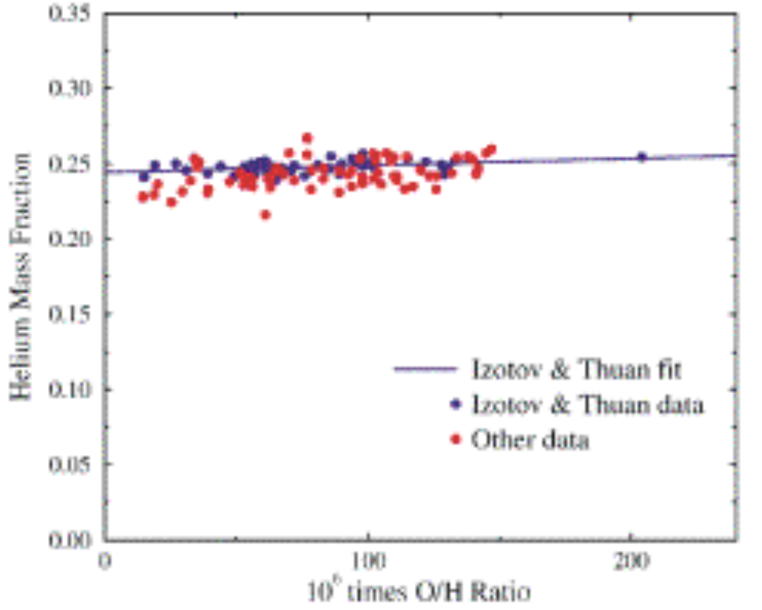
  - stars would fuse He into C, N, O, etc
  - if universe started from 100% hydrogen, we would expect 75% H, 13% He, 12% others
  - problem solved if universe starts out with H + He

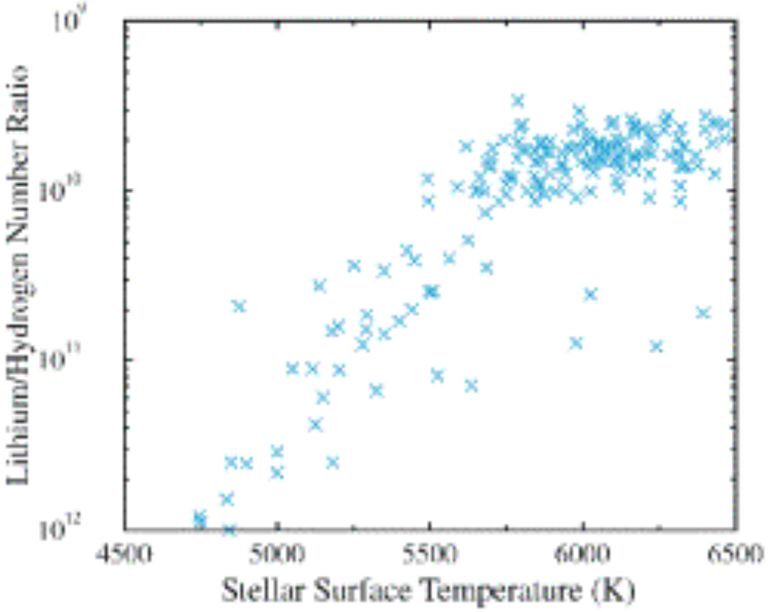
How about the rest of the elements?



Wikipedia: Cmglee
Data: Jennifer Johnson (OSU)

Measuring Light Element Abundances





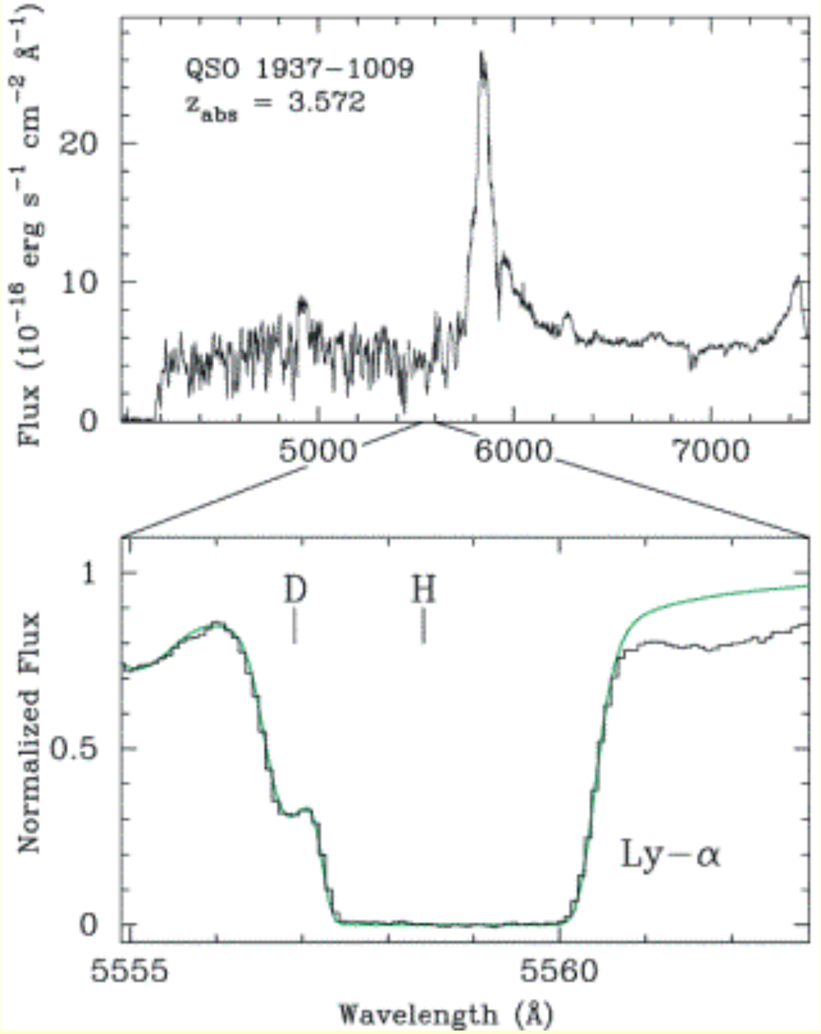
Helium abundance:

- measured in stellar spectra
  (Helium discovered & named after Sun)
- He can be produced in stars, too
- extrapolate to zero metalicity to
  subtract He from stellar nucleosynthesis

Lithium abundance:

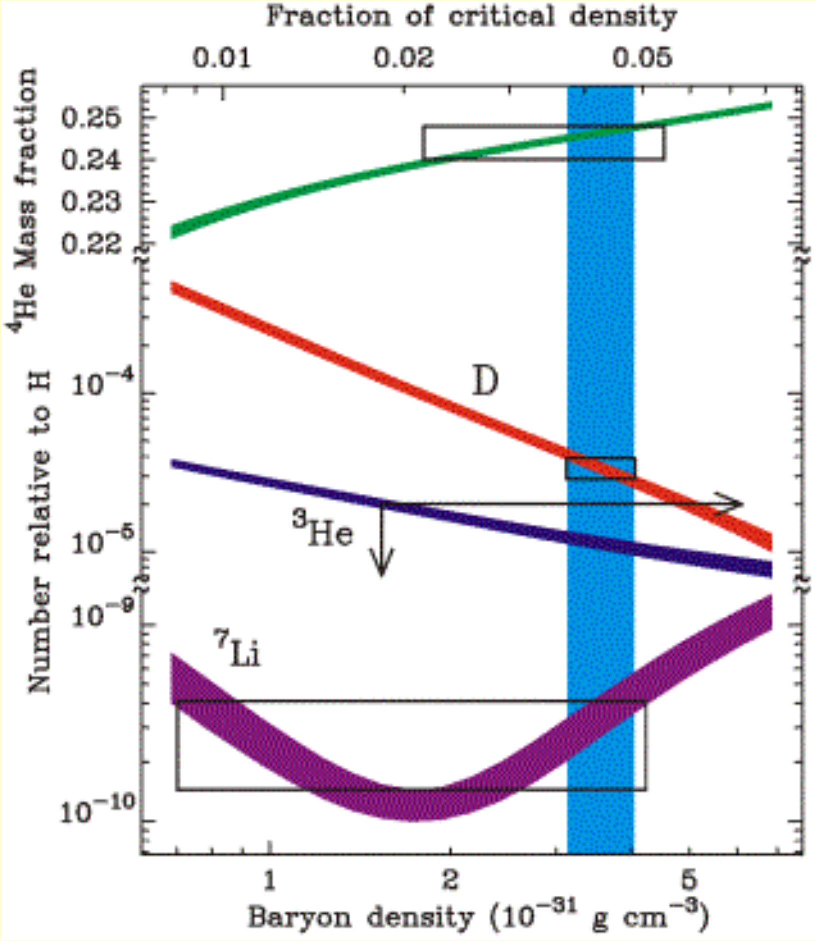
- measured in stellar spectra
- Li is depleted in stars by mixing
- find plateau at high stellar mass
  (these stars have little mixing)

Deuterium Abundance



- Destroyed easily in stars
- Must look for gas that has never cycled through a star
- quasar absorption lines:
  - low-density gas
  - far back in time
  - extra neutron makes electron slightly more tightly bound
  - possible only with 10m telescopes (Keck)
  - D/H = 10^{-5}

Measuring the Density of the Universe



- **Big Bang Nucleosynthesis (BBNS)**
  - **can make precise calculations for relative abundances of light elements**
  - **turns out very sensitive to baryon density**

- **Current results:**
  - **imply 0.2 hydrogen atoms per cubic m**
  - **a small fraction (~4 percent) of the so-called critical density:**

$$\boxed{\Omega(\text{baryons}) \sim 0.04}$$

Dark Matter

There are several other ways to measure mass density of the universe

- Motions of stars in galaxies
- Motions of galaxies in clusters
- Large-scale cosmic flows

$$\boxed{\mathbf{\Omega\ (total\ gravitating\ matter) \sim 0.30 \pm 0.1}}$$

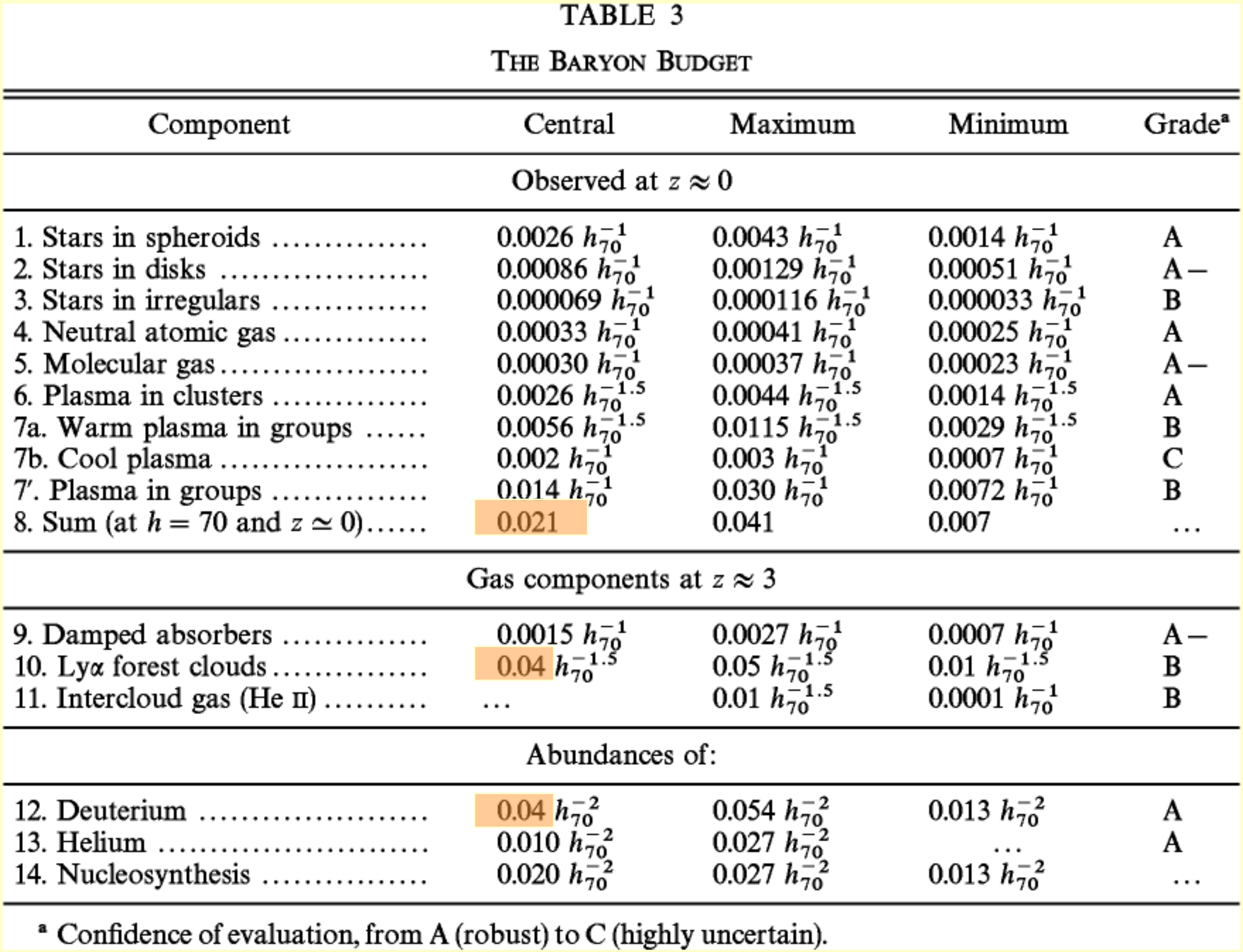


TABLE 3

THE BARYON BUDGET

Component	Central	Maximum	Minimum	Grade[a]
Observed at $z \approx 0$				
1. Stars in spheroids	$0.0026\ h_{70}^{-1}$	$0.0043\ h_{70}^{-1}$	$0.0014\ h_{70}^{-1}$	A
2. Stars in disks	$0.00086\ h_{70}^{-1}$	$0.00129\ h_{70}^{-1}$	$0.00051\ h_{70}^{-1}$	A –
3. Stars in irregulars	$0.000069\ h_{70}^{-1}$	$0.000116\ h_{70}^{-1}$	$0.000033\ h_{70}^{-1}$	B
4. Neutral atomic gas	$0.00033\ h_{70}^{-1}$	$0.00041\ h_{70}^{-1}$	$0.00025\ h_{70}^{-1}$	A
5. Molecular gas	$0.00030\ h_{70}^{-1}$	$0.00037\ h_{70}^{-1}$	$0.00023\ h_{70}^{-1}$	A –
6. Plasma in clusters	$0.0026\ h_{70}^{-1.5}$	$0.0044\ h_{70}^{-1.5}$	$0.0014\ h_{70}^{-1.5}$	A
7a. Warm plasma in groups	$0.0056\ h_{70}^{-1.5}$	$0.0115\ h_{70}^{-1.5}$	$0.0029\ h_{70}^{-1.5}$	B
7b. Cool plasma	$0.002\ h_{70}^{-1}$	$0.003\ h_{70}^{-1}$	$0.0007\ h_{70}^{-1}$	C
7′. Plasma in groups	$0.014\ h_{70}^{-1}$	$0.030\ h_{70}^{-1}$	$0.0072\ h_{70}^{-1}$	B
8. Sum (at $h = 70$ and $z \simeq 0$)......	0.021	0.041	0.007	...
Gas components at $z \approx 3$				
9. Damped absorbers	$0.0015\ h_{70}^{-1}$	$0.0027\ h_{70}^{-1}$	$0.0007\ h_{70}^{-1}$	A –
10. Lyα forest clouds	$0.04\ h_{70}^{-1.5}$	$0.05\ h_{70}^{-1.5}$	$0.01\ h_{70}^{-1.5}$	B
11. Intercloud gas (He II)	...	$0.01\ h_{70}^{-1.5}$	$0.0001\ h_{70}^{-1}$	B
Abundances of:				
12. Deuterium	$0.04\ h_{70}^{-2}$	$0.054\ h_{70}^{-2}$	$0.013\ h_{70}^{-2}$	A
13. Helium	$0.010\ h_{70}^{-2}$	$0.027\ h_{70}^{-2}$	...	A
14. Nucleosynthesis	$0.020\ h_{70}^{-2}$	$0.027\ h_{70}^{-2}$	$0.013\ h_{70}^{-2}$	...

[a] Confidence of evaluation, from A (robust) to C (highly uncertain).

Fukugita, Hogan, Peebles 1998

What does this imply?

- Light element abundances strongly support nucleosynthesis in “hot” big bang
- Presence of dark matter that cannot be baryonic (i.e. cannot affect nuclear reactions)

  weakly interacting massive particle (WIMP)?

Fundamental Observations

Pillars of Modern Cosmological Paradigm

- Universe is isotropic (and homogeneous)
- Night Sky is Dark
- Linear Expansion
- Light Element Abundances
- Microwave Background Radiation

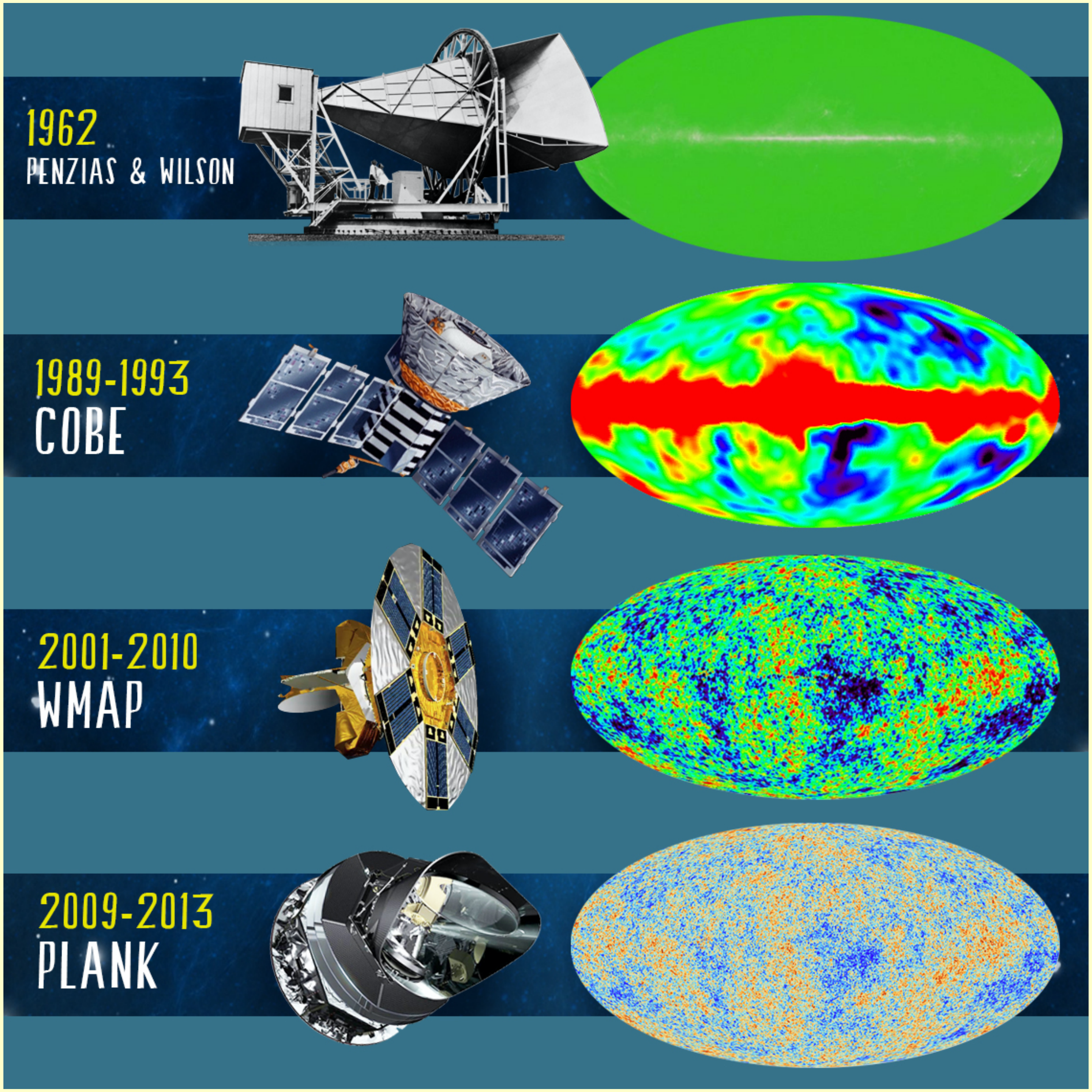
+

- Statistics of Large-Scale Structures

5. Cosmic Microwave Background

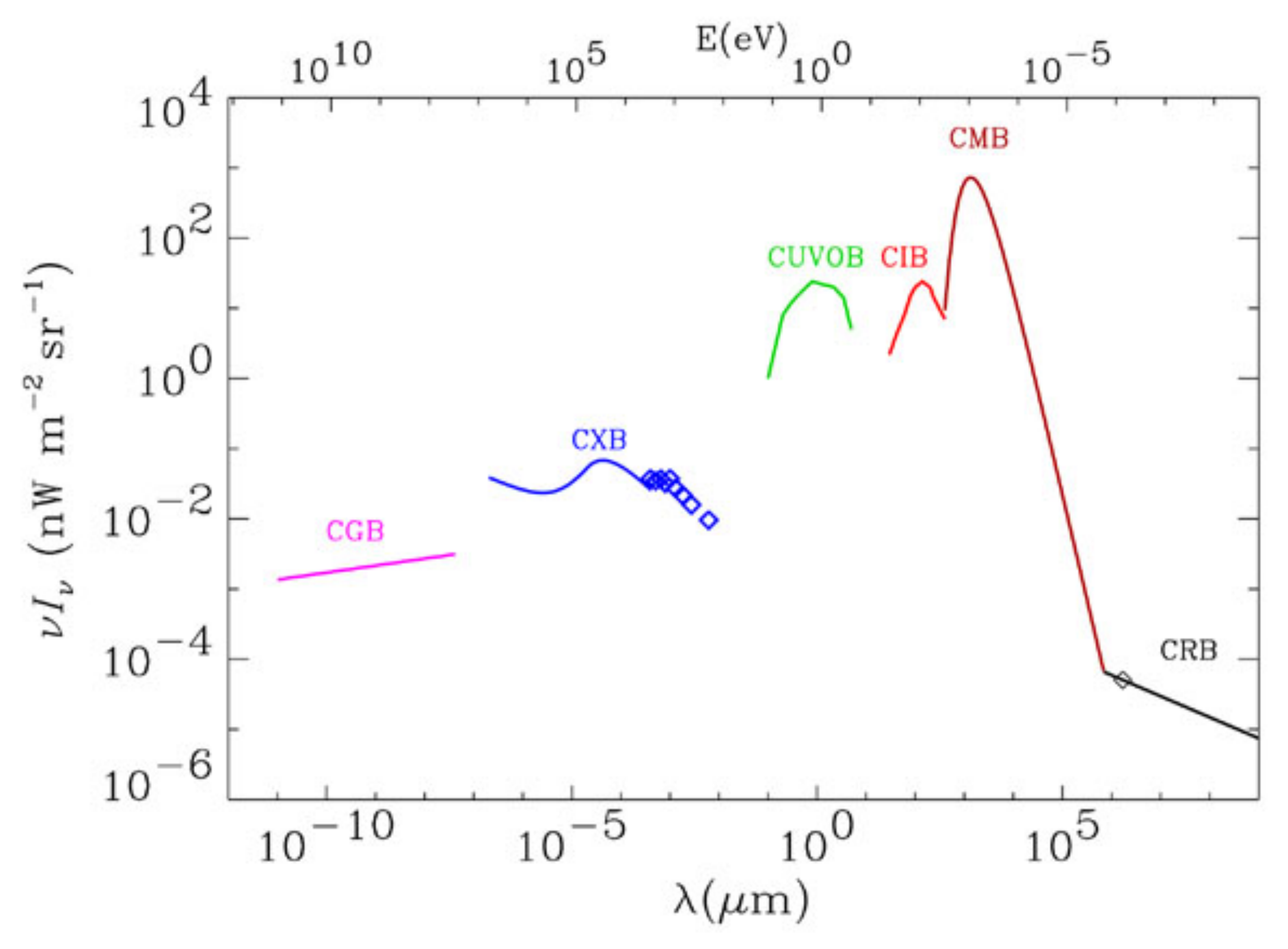
- Hot radiation from the big bang, which has cooled to ~3 Kelvin by present epoch
- Predicted in 1948 (Alpher & Herman)
- First observed in 1965 (Penzias & Wilson)
- Extremely smooth, but seeds of structure discovered by COBE satellite (1992)
- Accounts for 3% of the static on your TV screen!

Cosmic Microwave Background progress

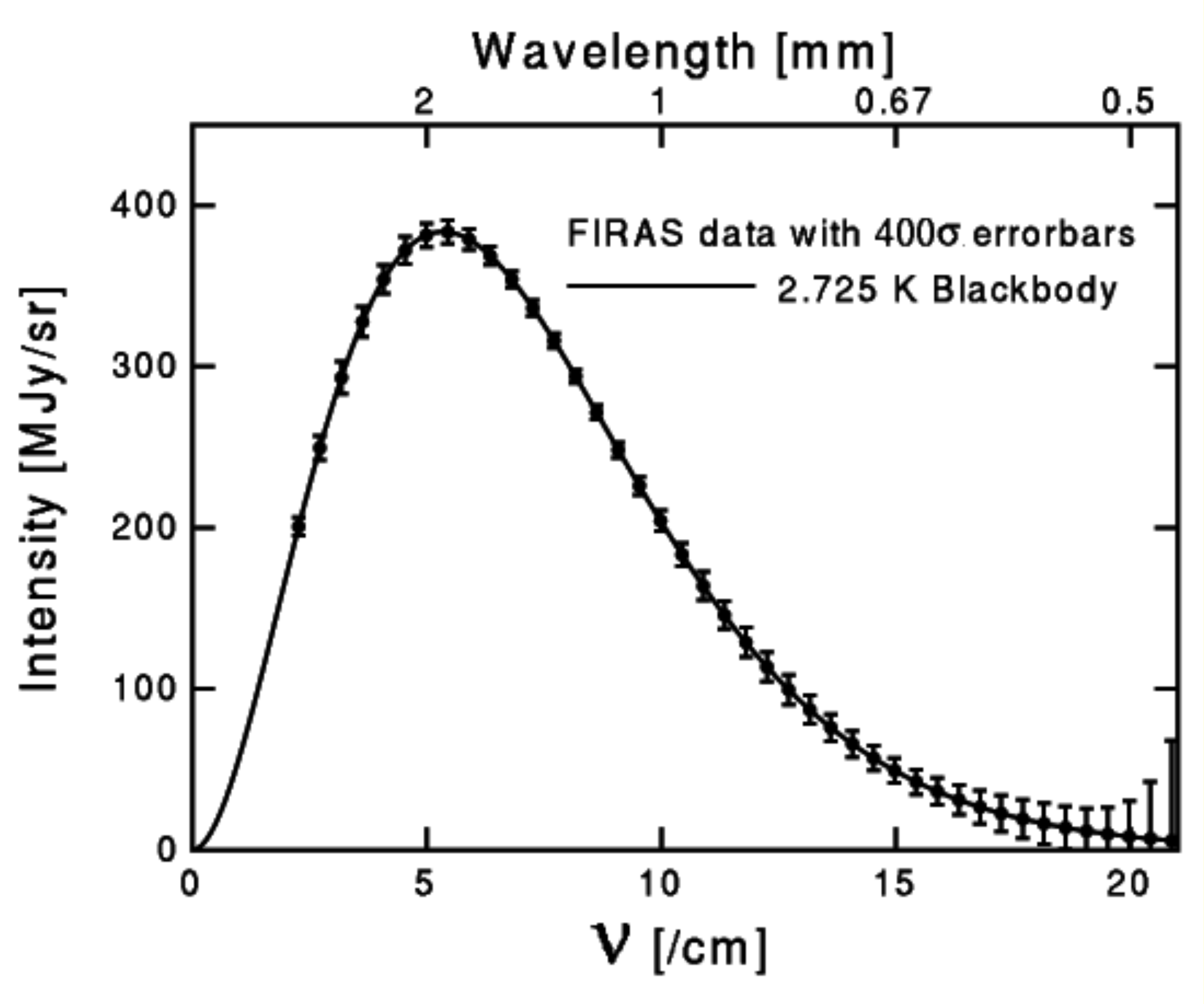


The CMB compared with other backgrounds

Extragalactic Background (Hauser & Dwek 2001)



Spectrum of CMB (from COBE; 1992)



Thermal Spectrum

- Extremely accurately measured quantity
- The most precisely measured example of a black-body spectrum

$$\varepsilon(f)df = \frac{8\pi h}{c^3}\frac{f^3 df}{\exp(hf/kT)-1}$$

- Implies thermal equilibrium
- Too cold and dilute to achieve equilibrium today
  - real puzzle outside the big bang model
  - natural by product of hot dense phase

Cosmic Microwave Background

- Mean temperature: T=2.725 ± 0.001 K
- Spectral Deviation: Compton-y parameter

$$y \equiv \int \sigma_T n_e \frac{kT}{m_e c^2} dl \leq 1.5 \times 10^{-5} \quad \text{(COBE 1992)}$$

- Energy Density:

$$u = a_B T^4 = 4.8 \times 10^{-34}\, g/cm^3$$

$$n_\gamma = 420 cm^{-3}$$

$$\langle h\nu \rangle = 6.3 \times 10^{-4}\, eV$$

$$\Omega_\gamma = 5 \times 10^{-5} \approx 10^{-3} \Omega_b$$

$$n_\gamma / n_b = 2 \times 10^9$$

What does this imply?

Supports:

- Cosmological principle (isotropy)
- Laws of nature not varying even over cosmic scales
- Universe expanded
- Universe was much hotter in the past
- A puzzle: horizon problem. Inflation?

Fundamental Observations

Pillars of Modern Cosmological Paradigm

- Universe is homogeneous and isotropic
- Night Sky is Dark
- Linear Expansion
- Light Element Abundances
- Microwave Background Radiation

+

- Statistics of Large-Scale Structures

CMB Anisotropies

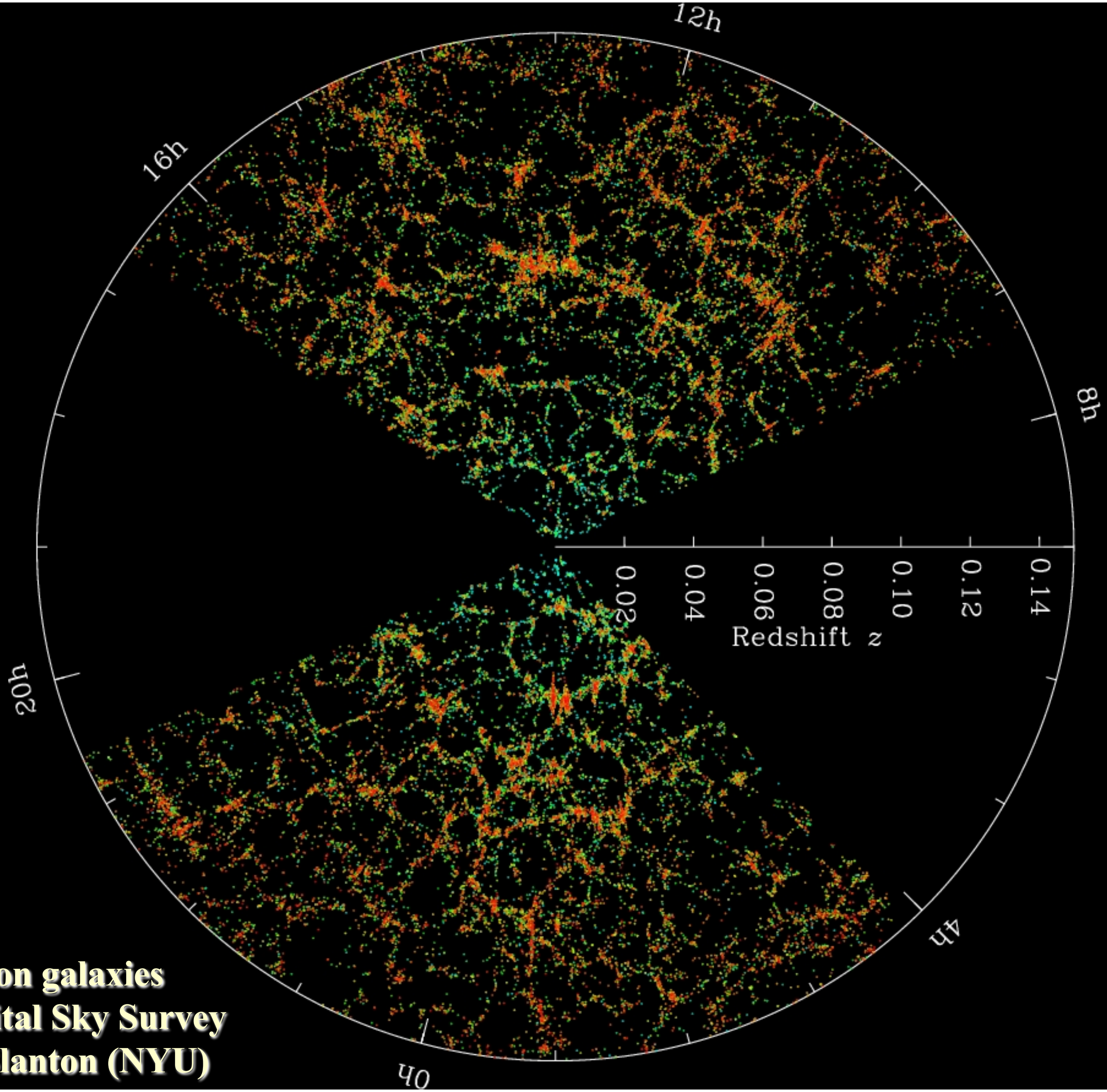
- CMB angular and frequency structures contain a wealth of cosmological information
- Amplitude & statistics of temperature fluctuations consistent with gravitational structure formation
- This wealth of detail (to be discussed in future lectures) is all consistent with the hot big bang + cold dark matter structure formation model
- hard feat for alternative to replicate / postdict!

6. Large-Scale Structures

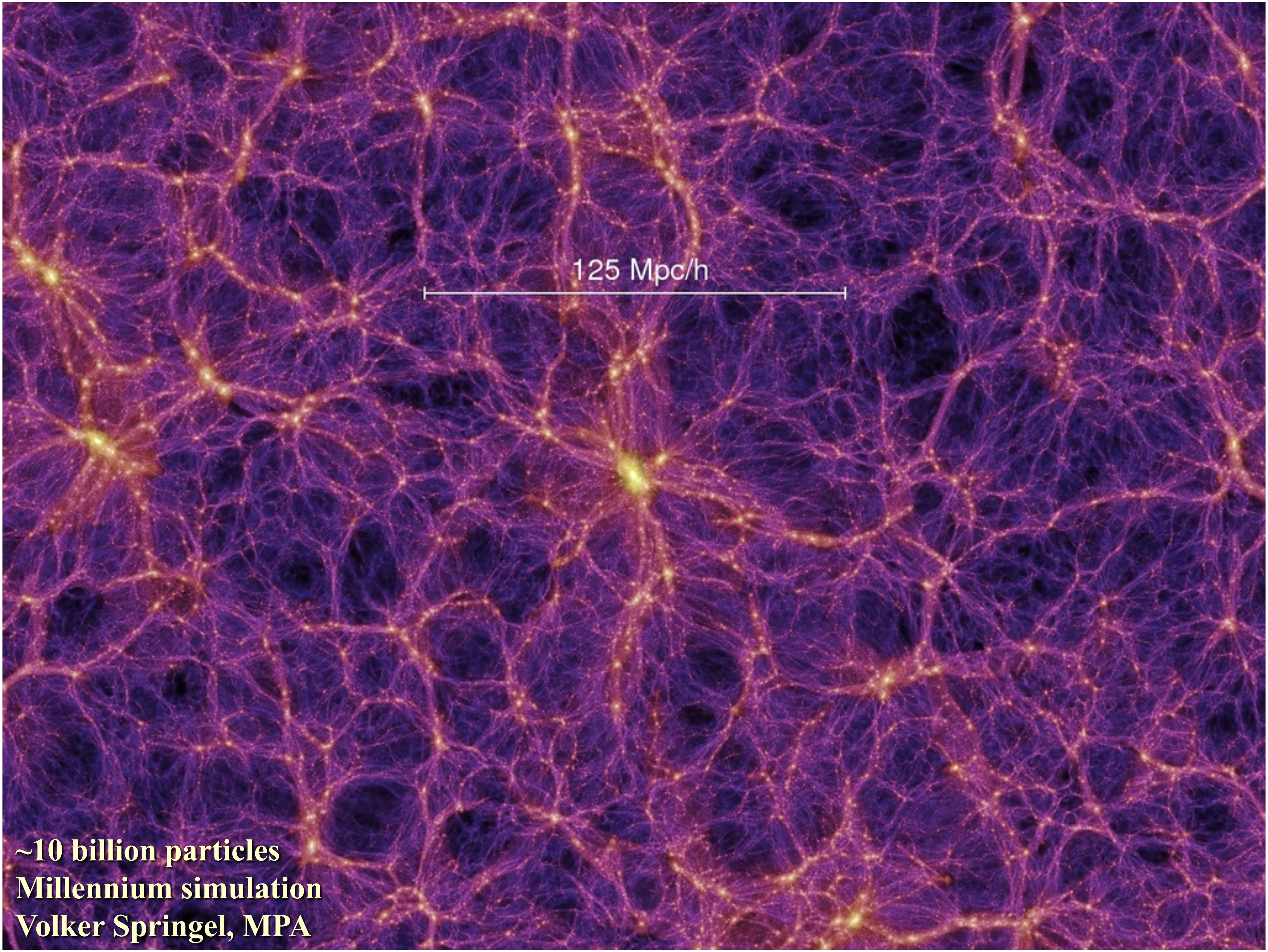
Modern Pillars of Standard Model:

based on <u>inhomogeneities</u>

- CMB anisotropies – e.g. power spectrum
- Galaxy distribution – e.g. power spectrum
- Abundance of galaxy clusters
- Weak gravitational lensing statistics
- Lyman alpha forest absorption statistics

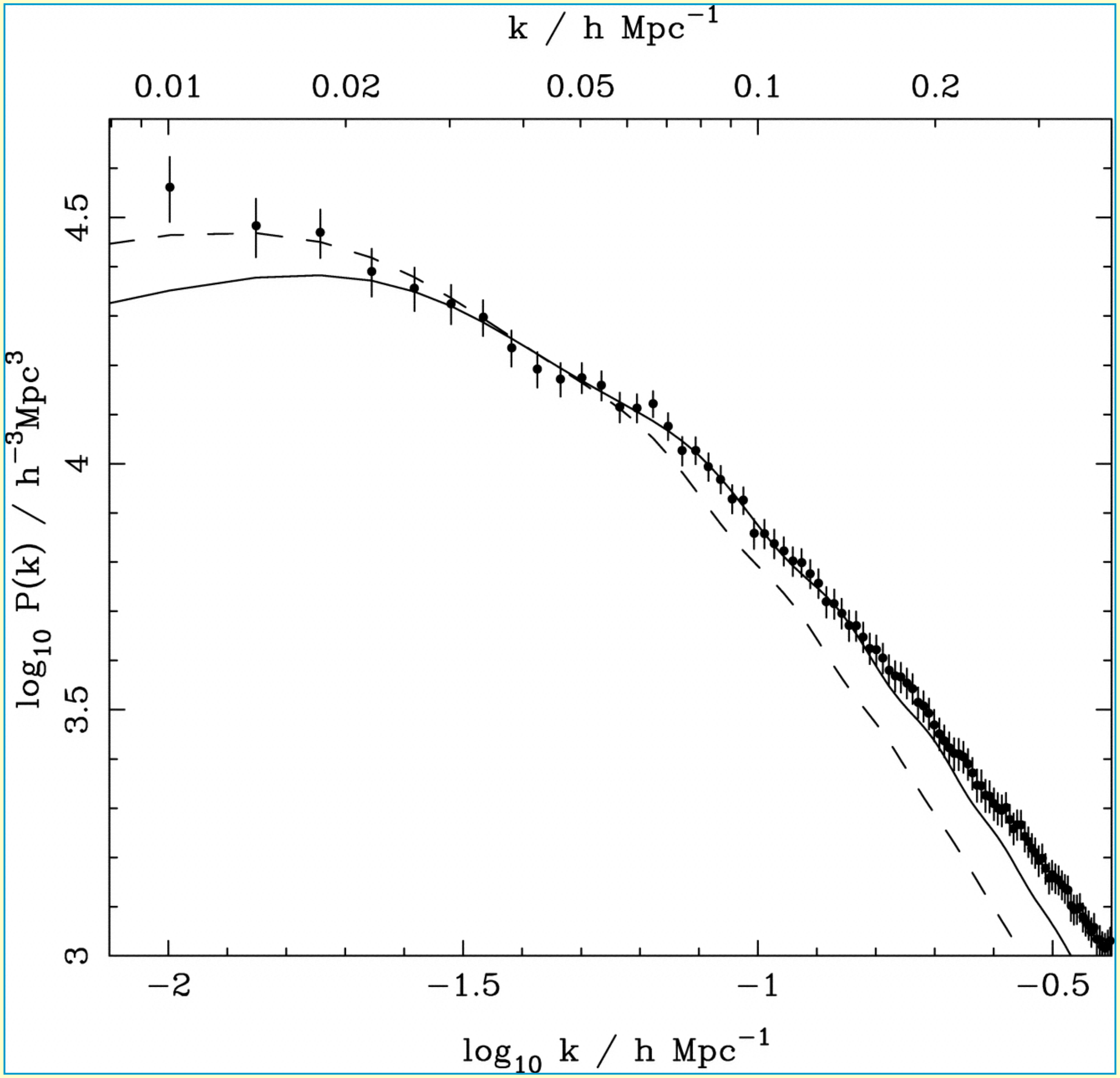


~200 million galaxies
Sloan Digital Sky Survey
Michael Blanton (NYU)



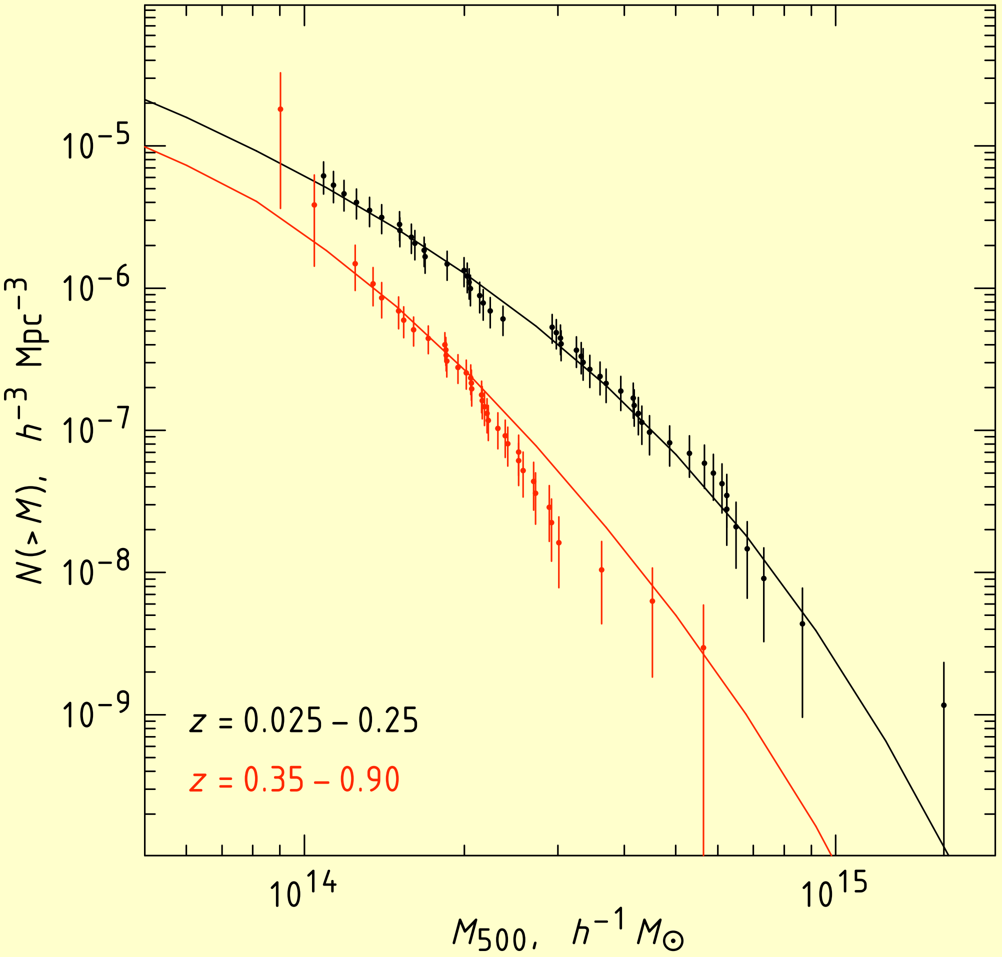
~10 billion particles
Millennium simulation
Volker Springel, MPA

Galaxy Power Spectrum

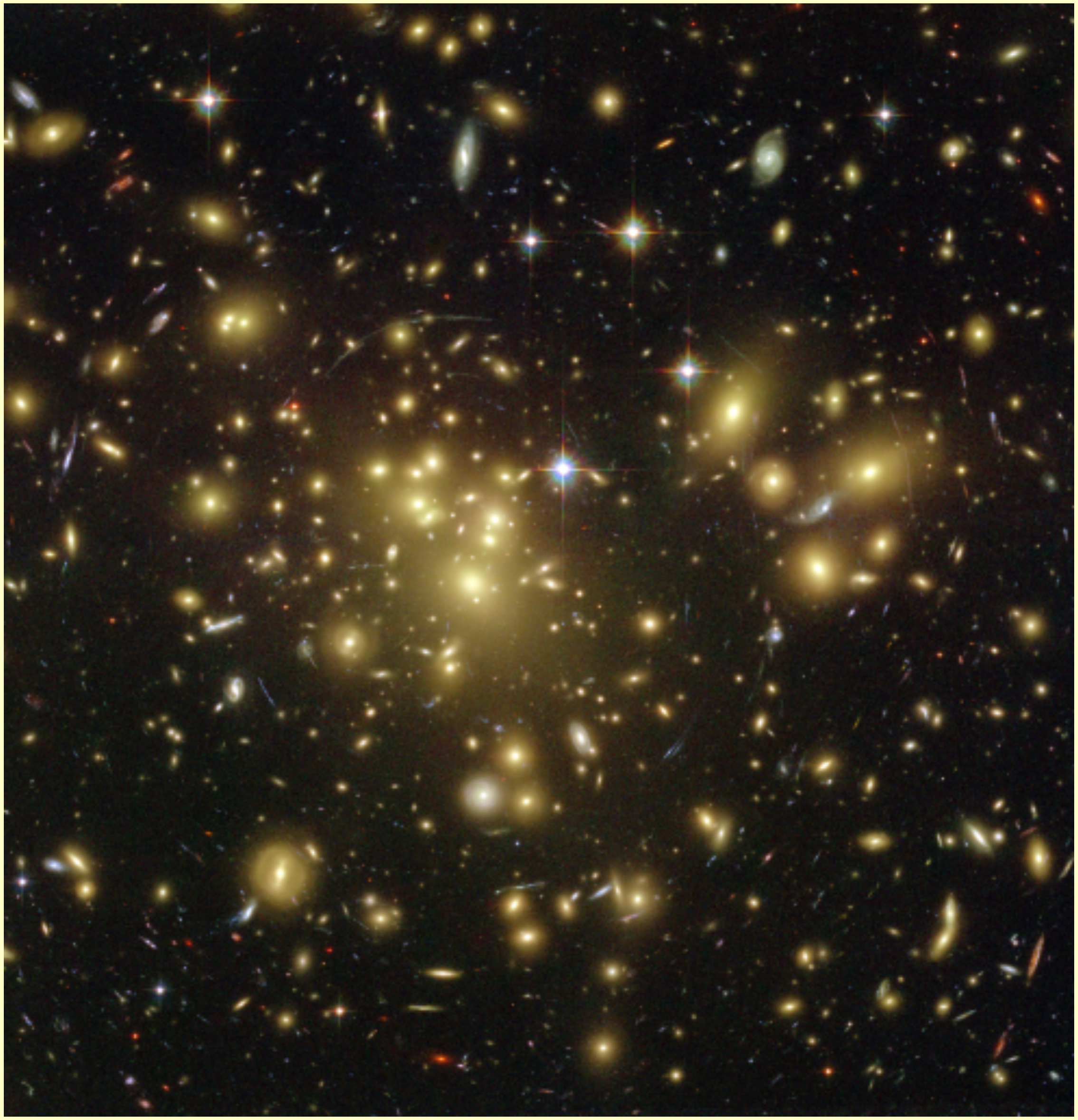


Galaxy Cluster Abundance

Large X-ray survey with Chandra (Vikhlinin et al. 2009)



Weak Gravitational Lensing



Abell 1689

Weak Gravitational Lensing Power Spectrum

Forecast by Song & Knox (2006);
measured in 2016-2021 surveys (CFHTLenS, DES, KiDS, HSC)