RUPRECHT-KARLS-
UNIVERSITÄT
HEIDELBERG

(The Standard Model of)

Cosmology

Bad Liebenzell, October 2012

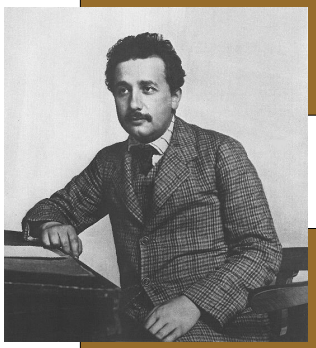
Matthias Bartelmann
Uni Heidelberg, Zentrum für Astronomie,
Institut für Theoretische Astrophysik

ZAH
Zentrum für Astronomie Heidelberg
ARI+ITA+LSW

Foundation

General Relativity

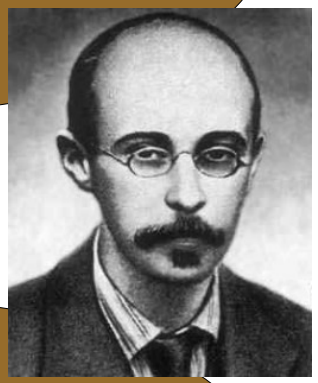
Symmetry Assumptions:
Homogeneity and isotropy
on average



Matter content:

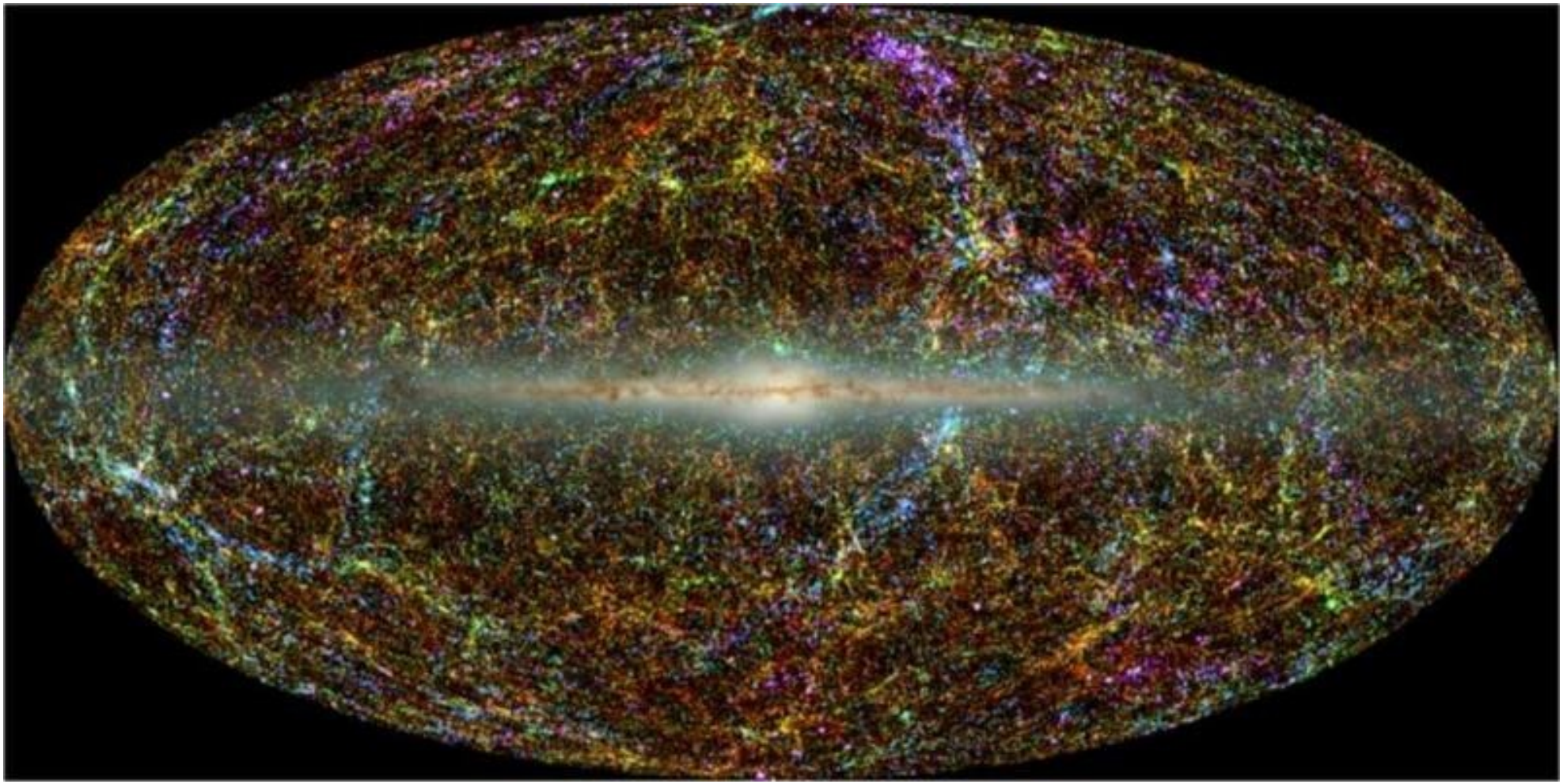
Energy-momentum tensor,
Containing radiation, matter,
anything else

Robertson-Walker
metric



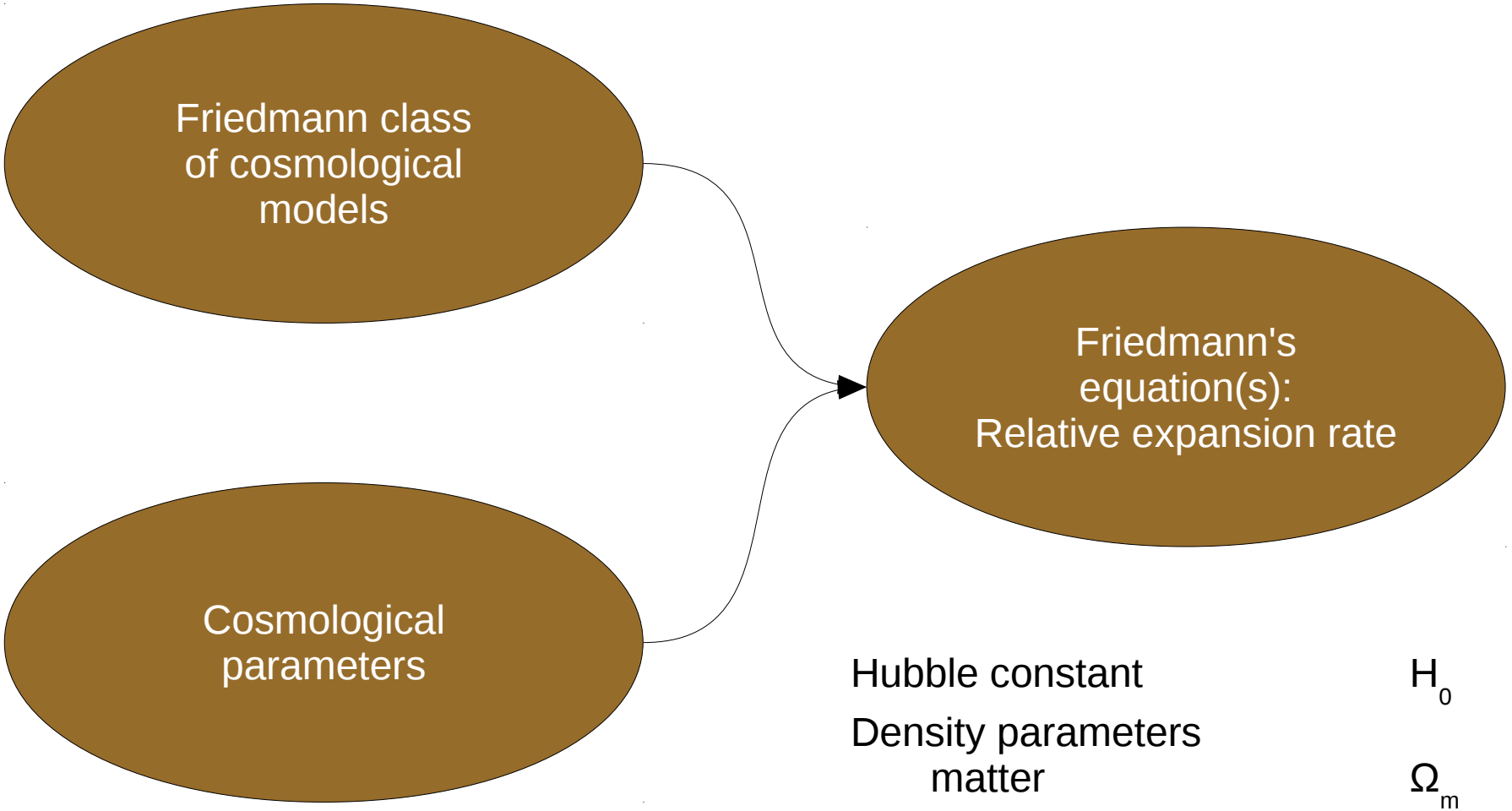
Friedmann class
of cosmological
models

Isotropy?



(2-micron All-Sky Survey, 2-MASS)

Dynamics, Parameters

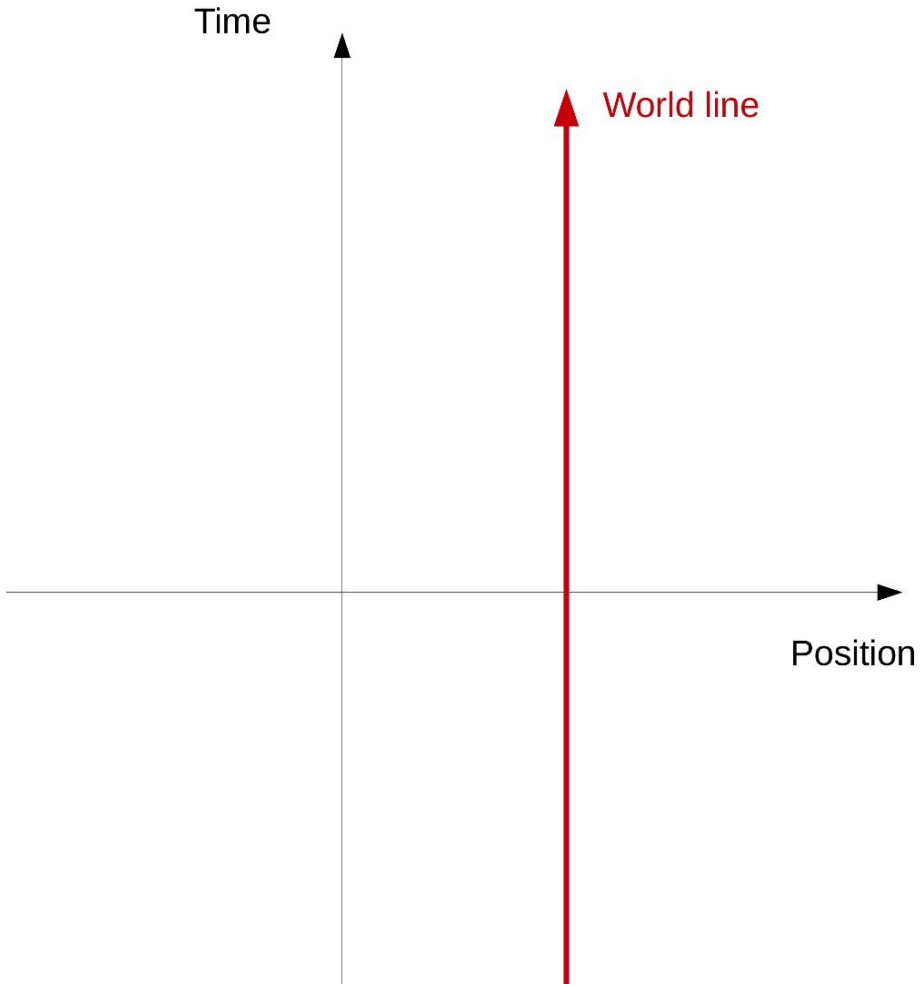


Hubble constant H_0

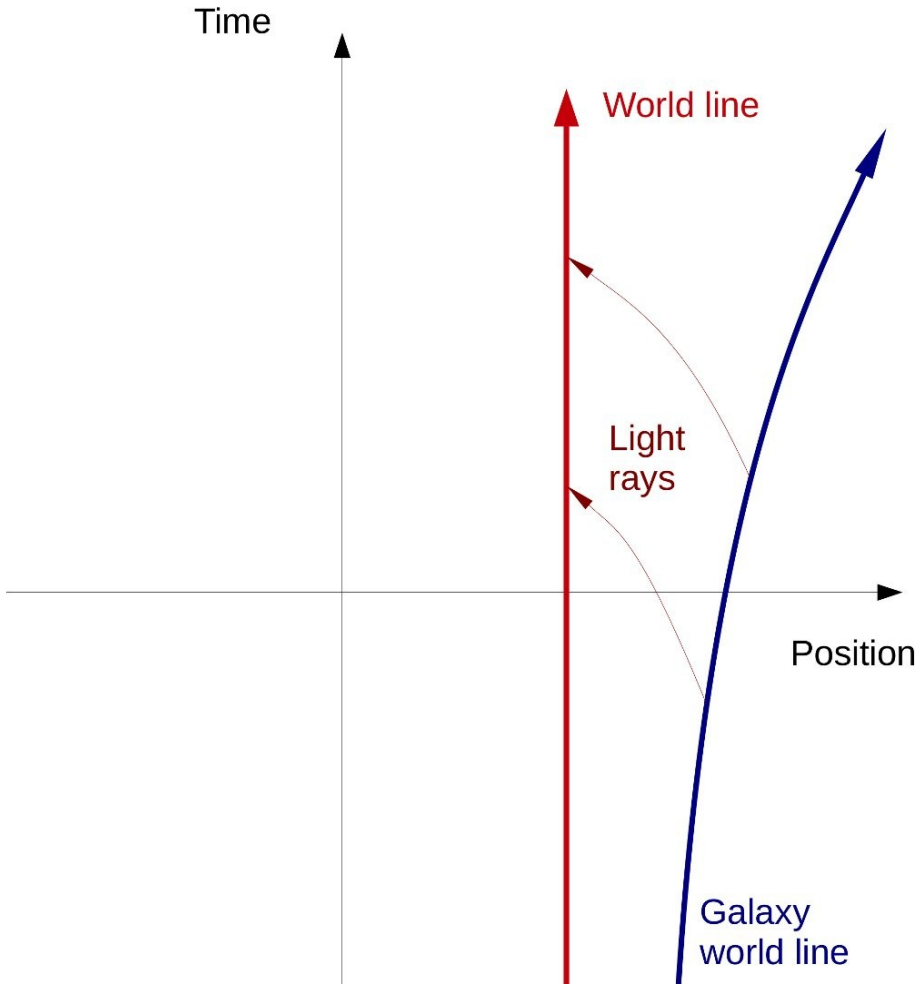
Density parameters

- matter Ω_m
- radiation Ω_r
- cosmological constant Ω_Λ
- several others

Space-Time Diagram, Redshift

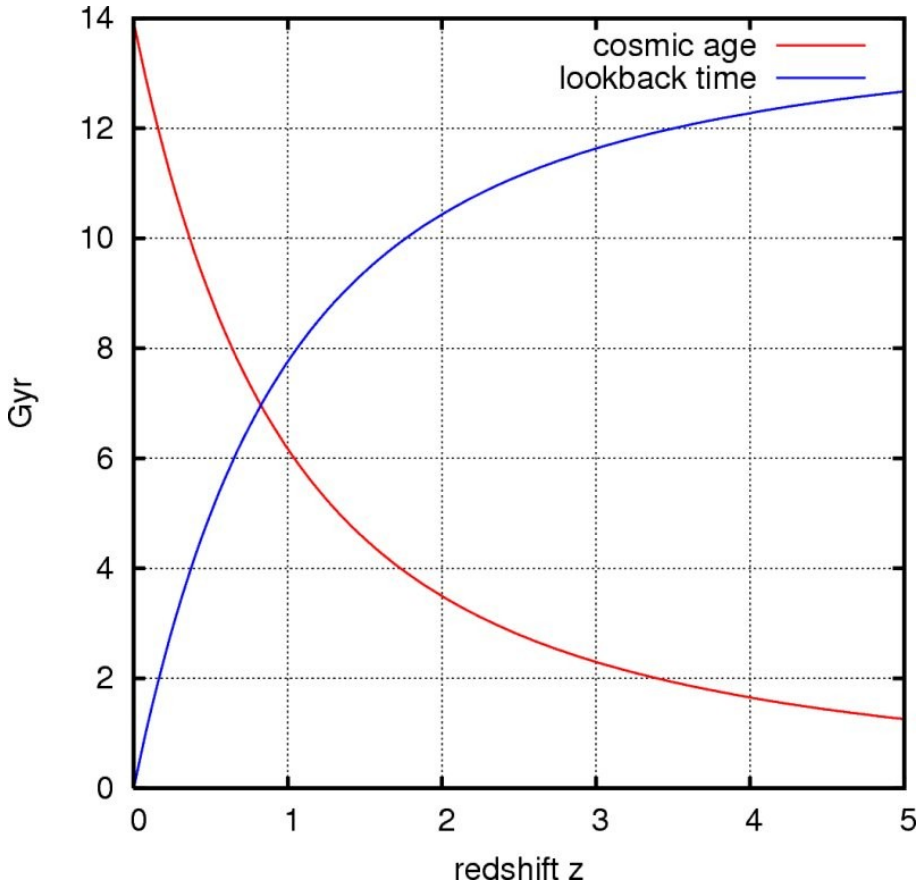


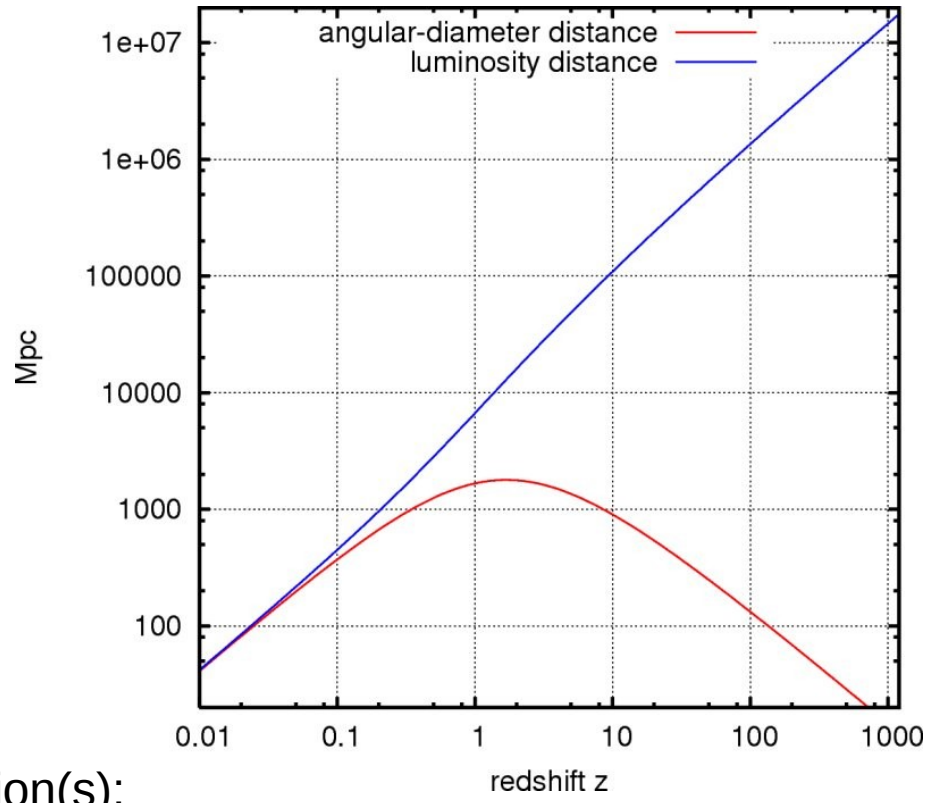
Minkowski diagram



Redshift due to spatial expansion

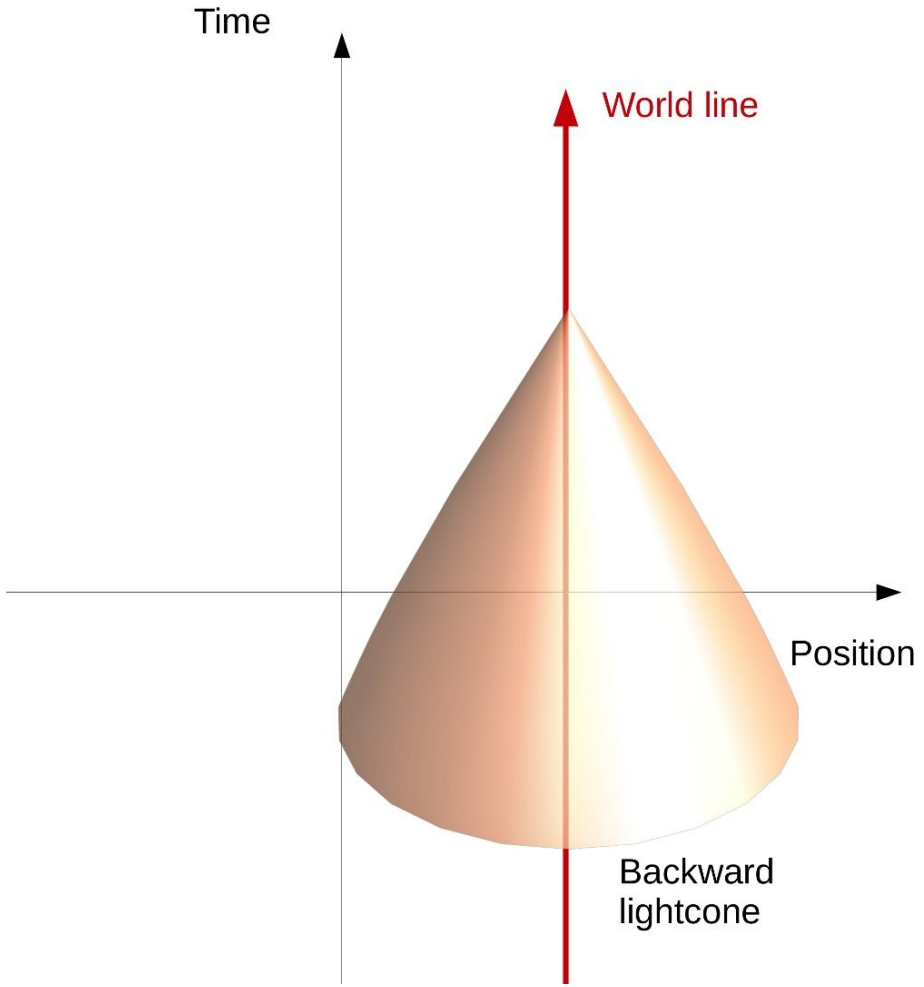
Age and Distances

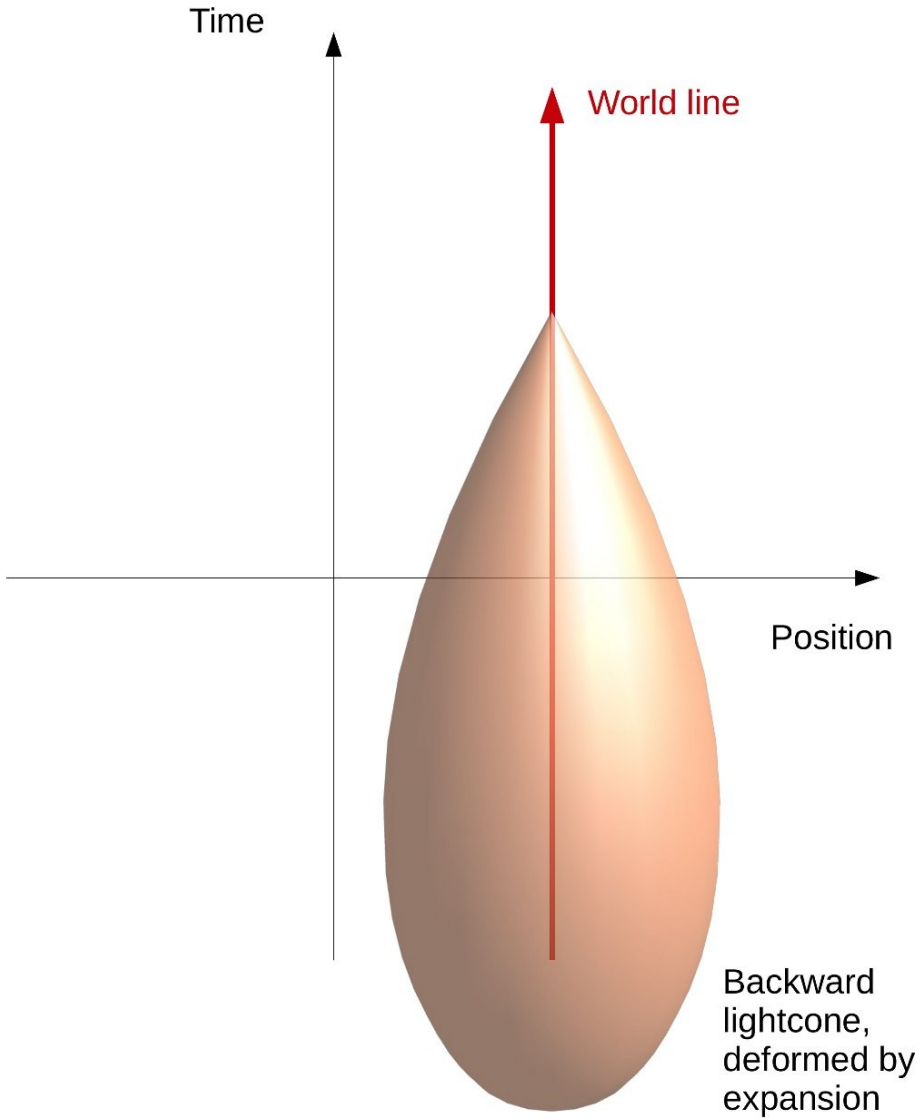




Conclusions from Friedman's equation(s):
– Dynamics of expansion
– Geometry of the Universe

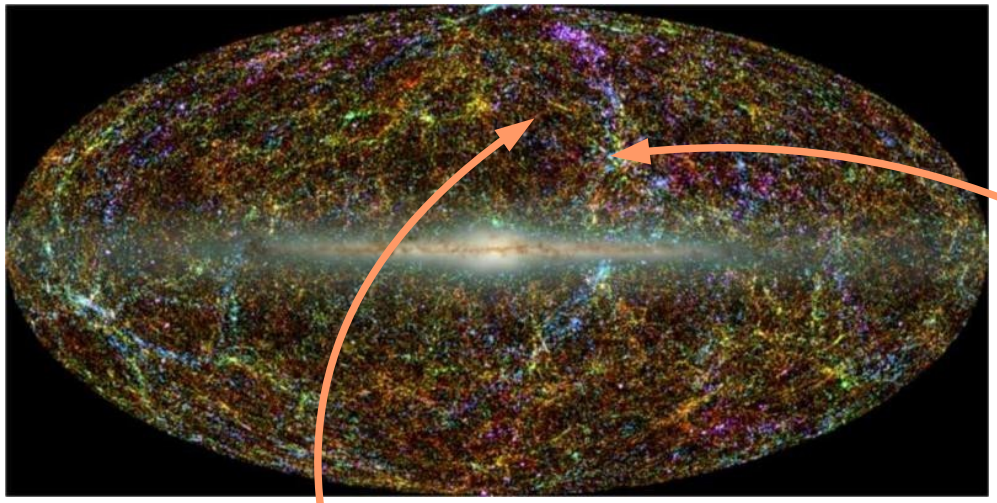
The Observable Universe



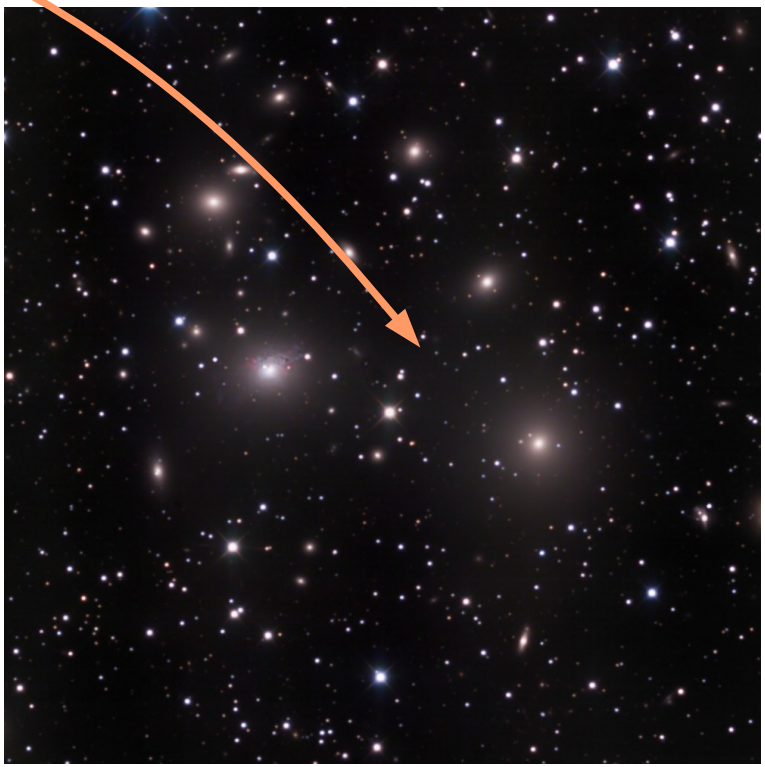


Causality and the observable Universe

Building Blocks



Galaxies

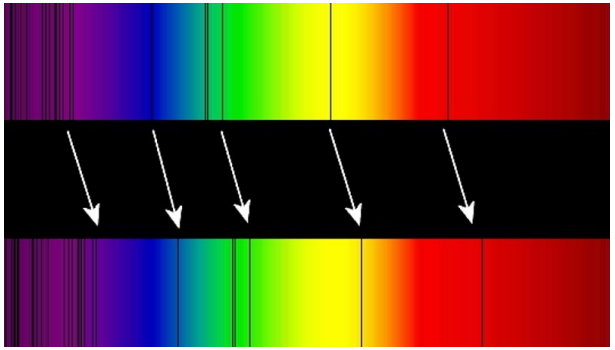


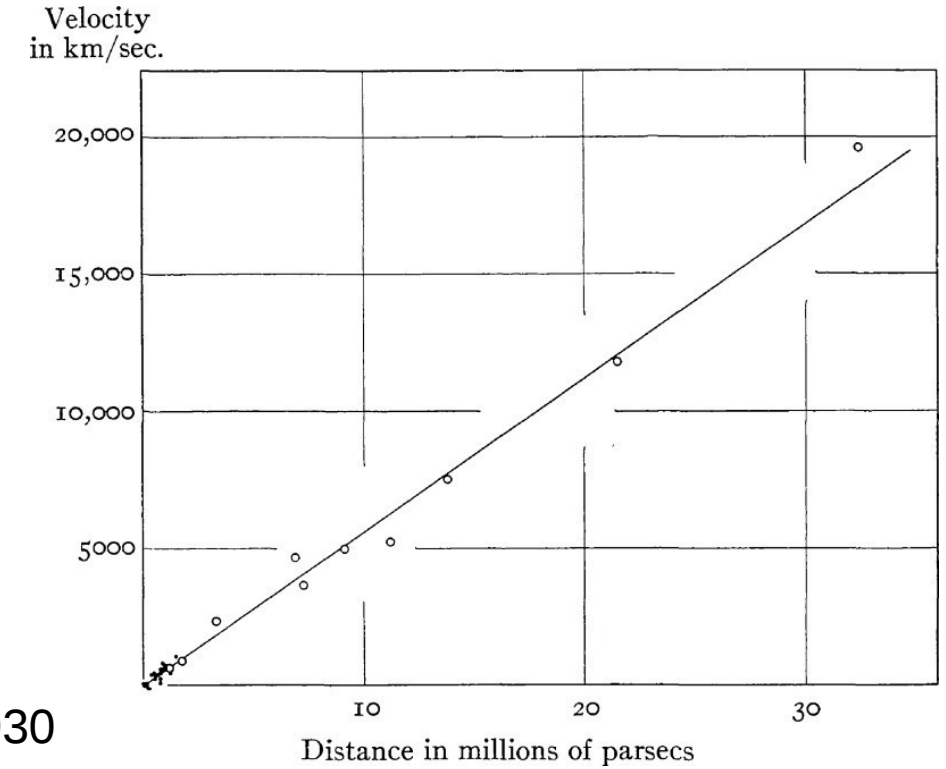
Galaxy clusters

Galaxies recede

Carl Wirtz, Vesto Slipher, 1920s

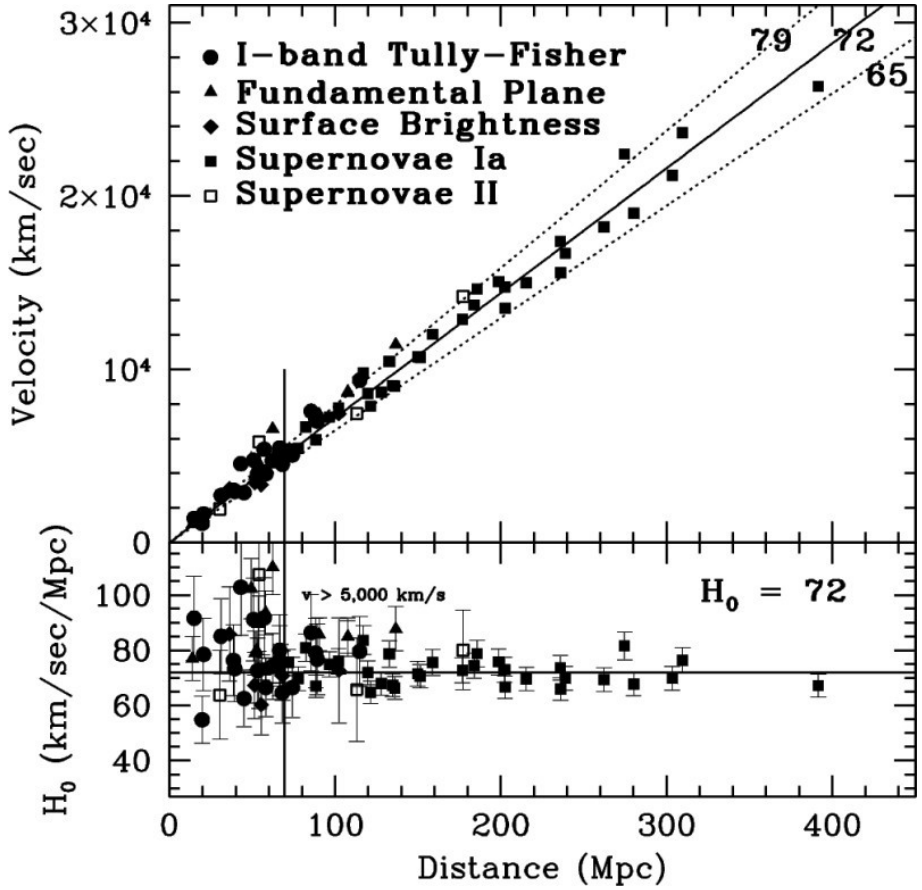
Edwin Hubble





Hubble & Humason 1930

Hubble Constant

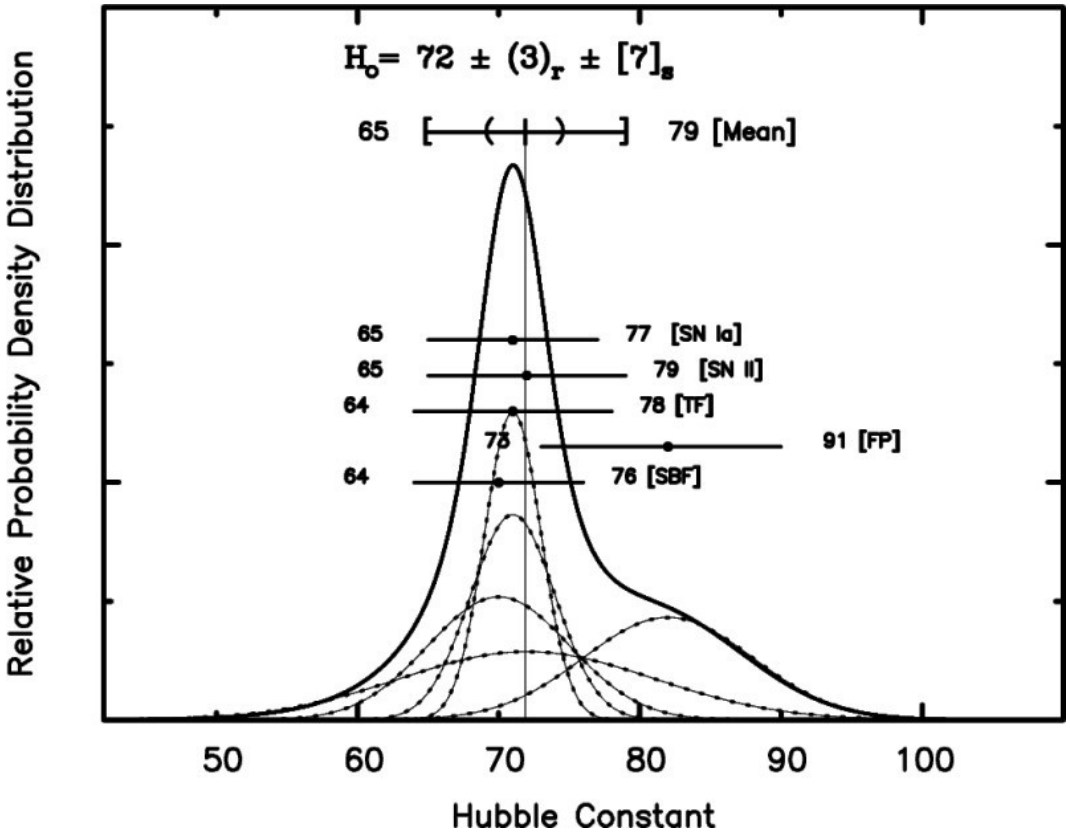


$H_0 = 70.4 \pm 1.3$ km/s/Mpc

$H_0^{-1} = 14$ Gyr

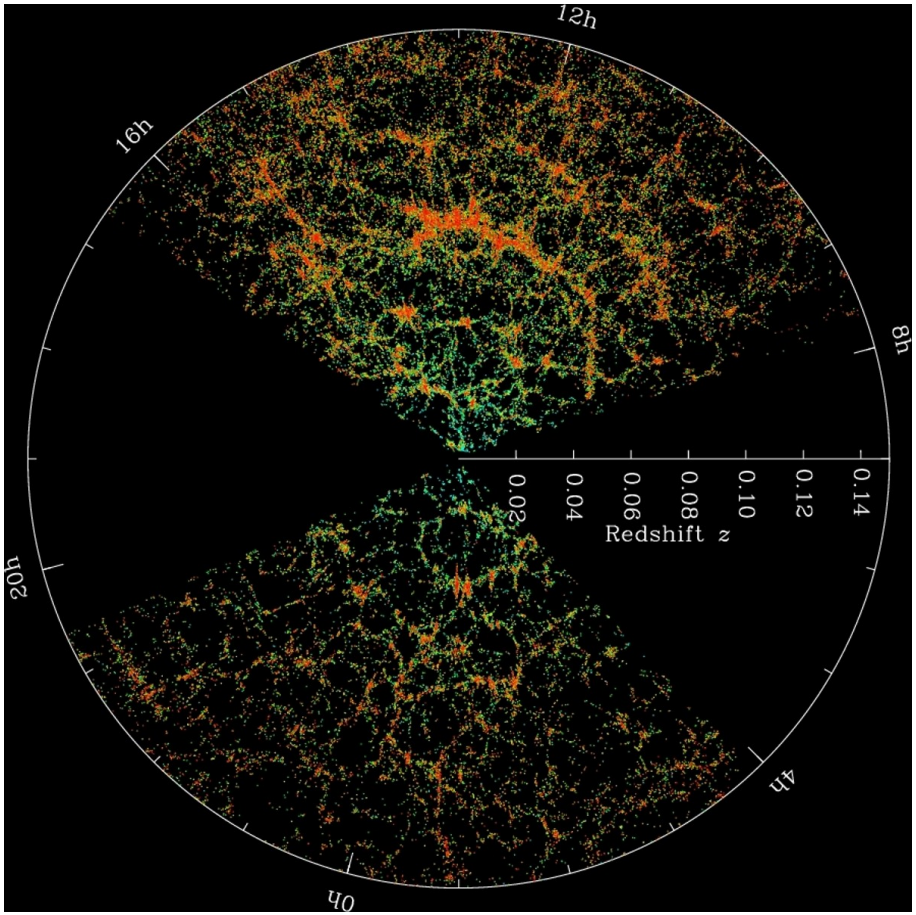
$c/H_0 = 4.3$ Gpc

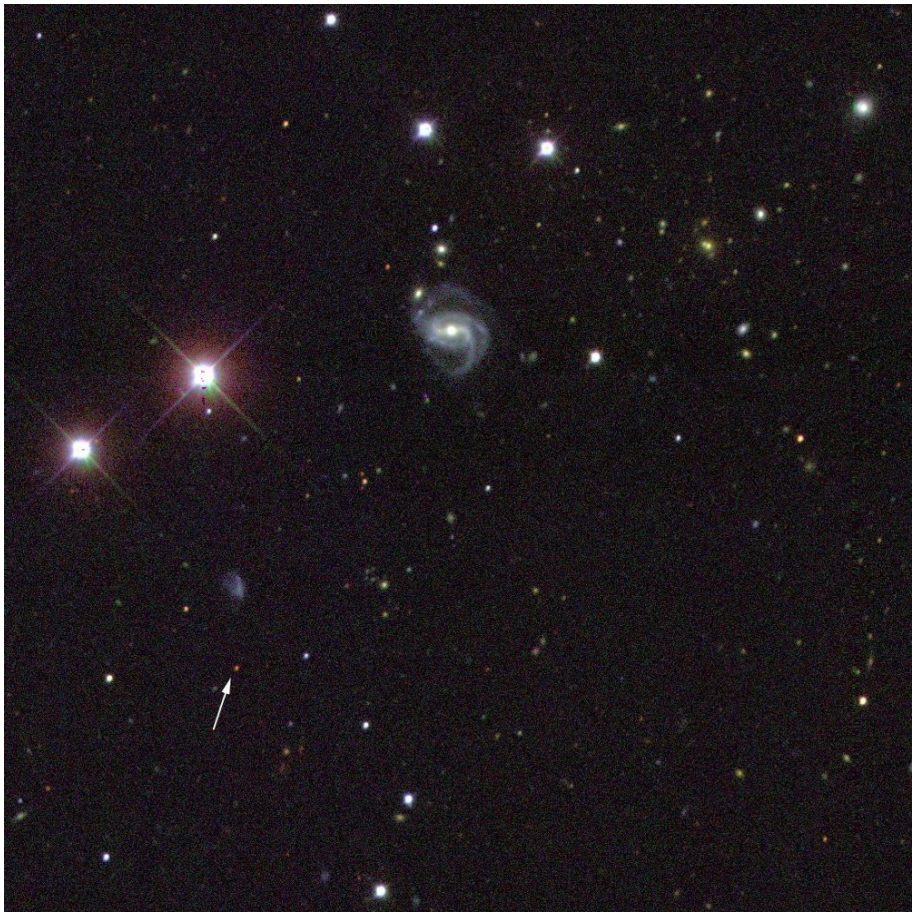
$\rho_{cr} = 9.2 \times 10^{-30}$ g/cm^3



Data from the
Hubble Key Project

A Universe Without Big Bang?

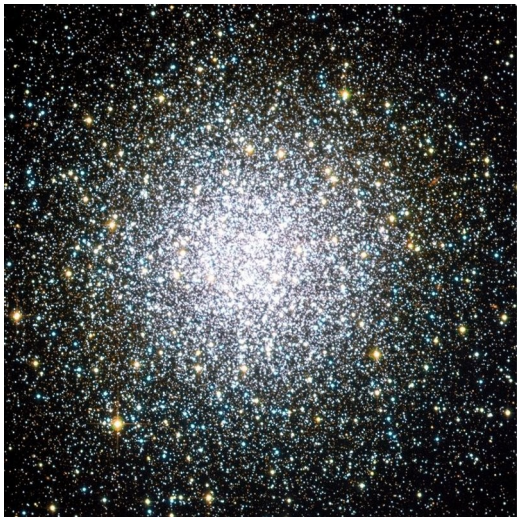




No: lower limits to matter density and cosmological redshift imply Big Bang!

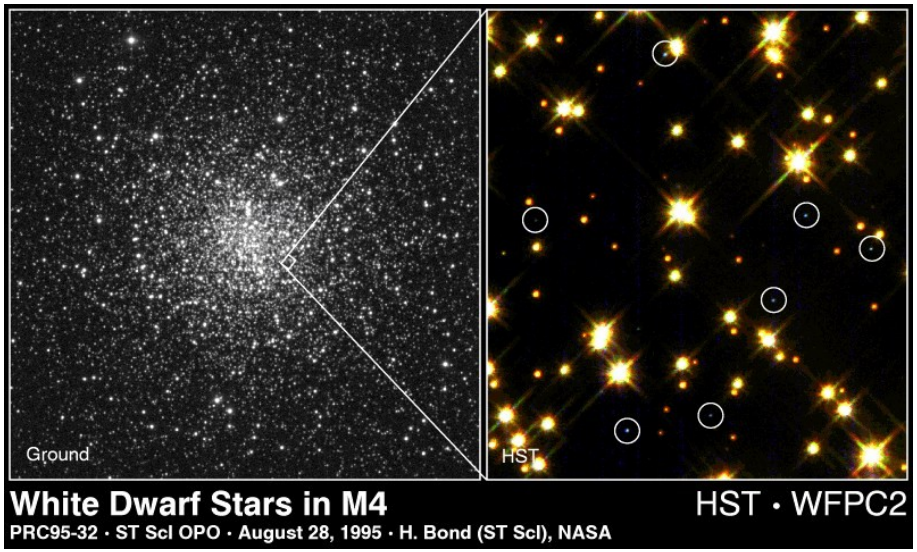
How old is the Universe?

Age of the Galaxy: 6 – 12 Gyr



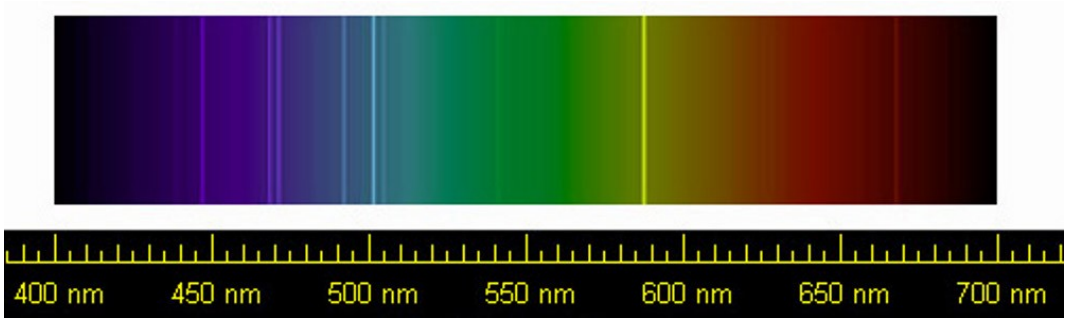
Age of the oldest Stars: 11 – 13 Gyr

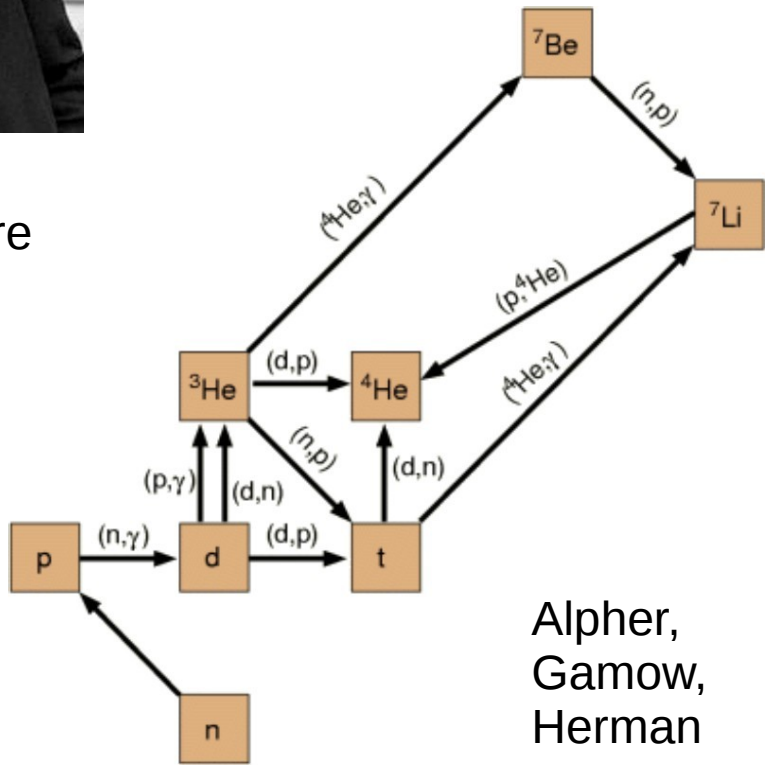
Age of the Earth: 4.6 ± 0.1 Gyr



Helium

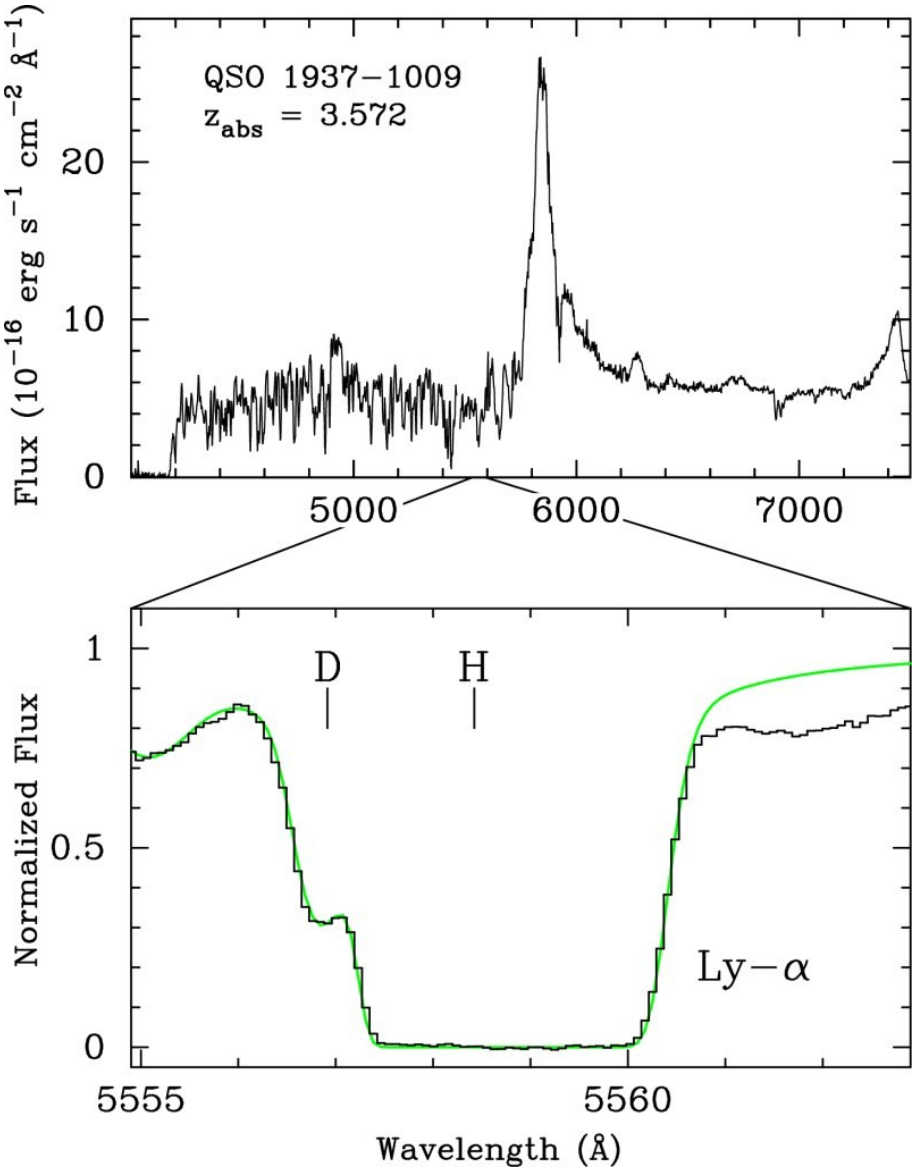
Georges Lemaitre

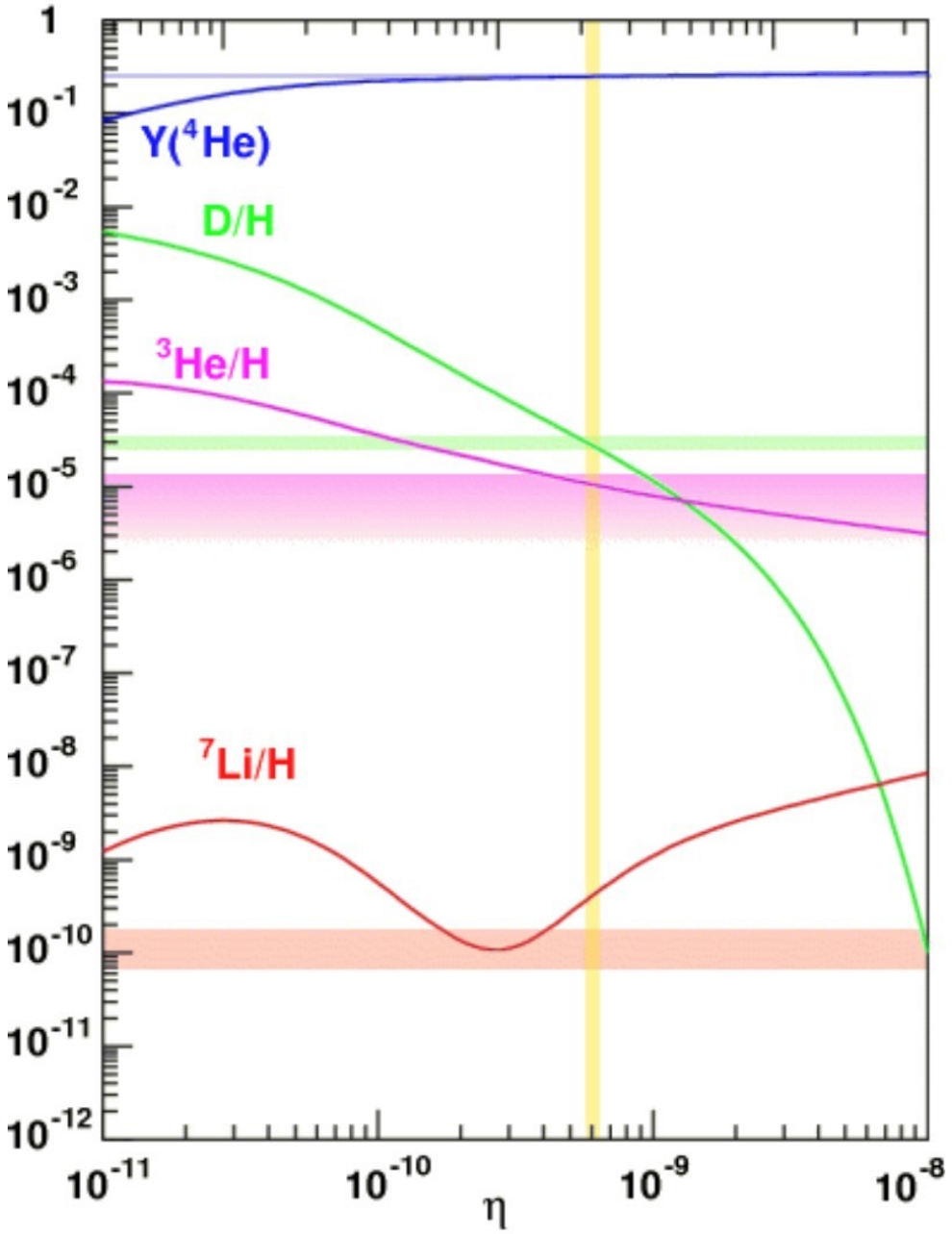




Alpher,
Gamow,
Herman

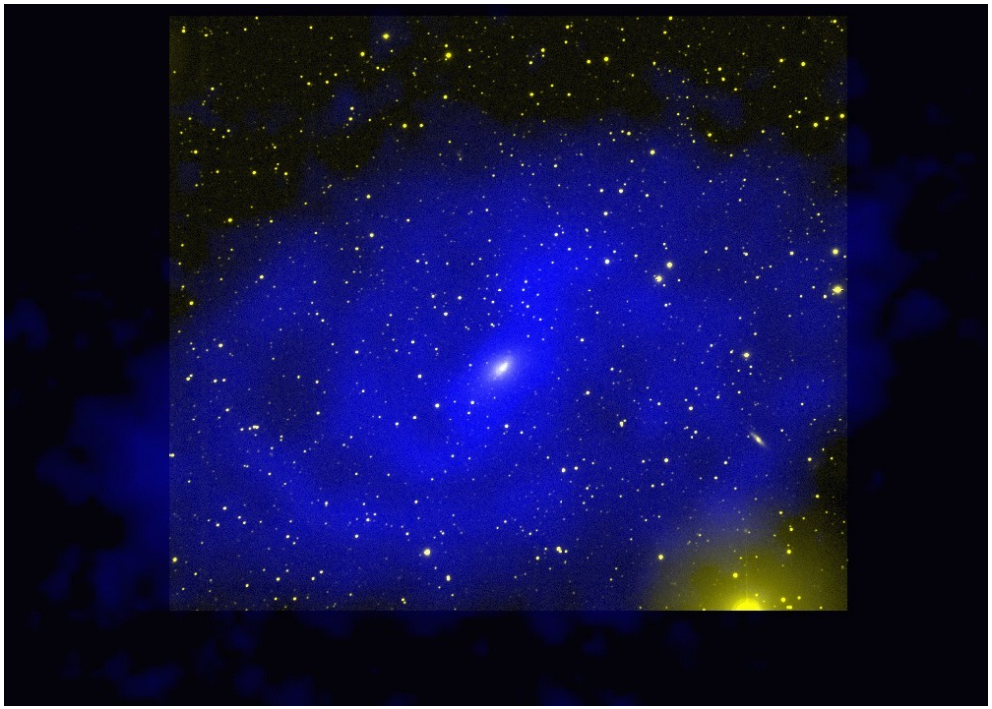
Primordial Nucleosynthesis

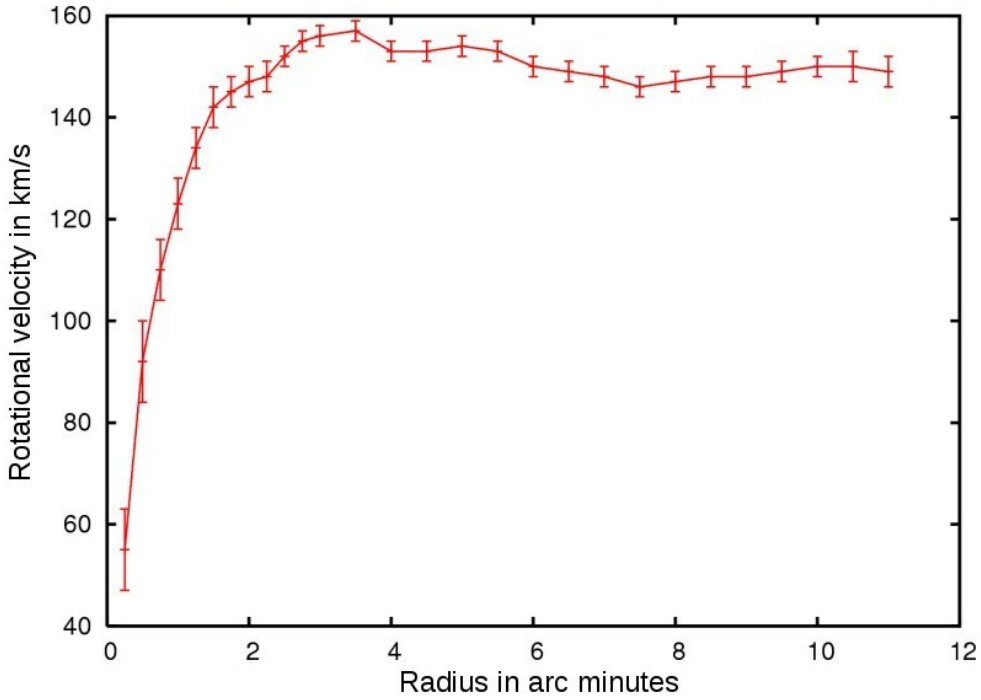




Constraints from light-element abundance

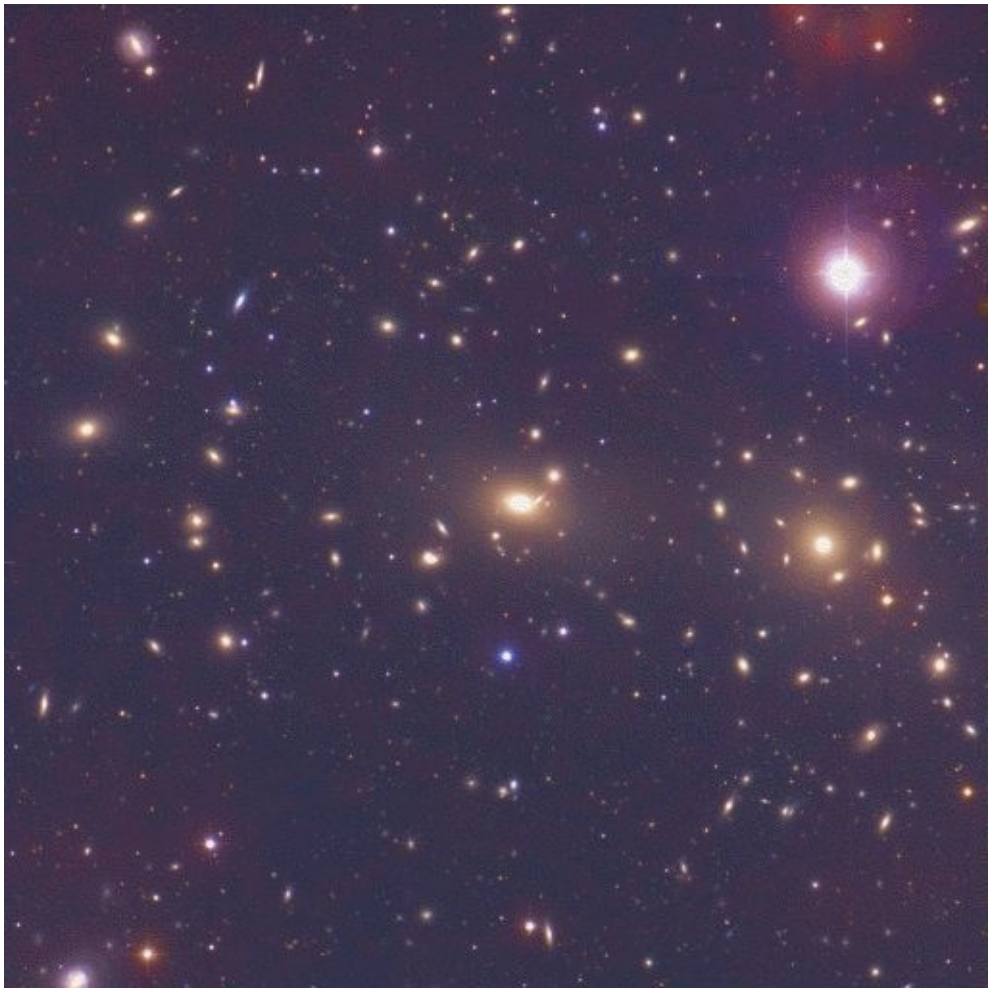
Masses of Galaxies





Dark matter in galaxies:
Constant rotation velocity
to all observable radii

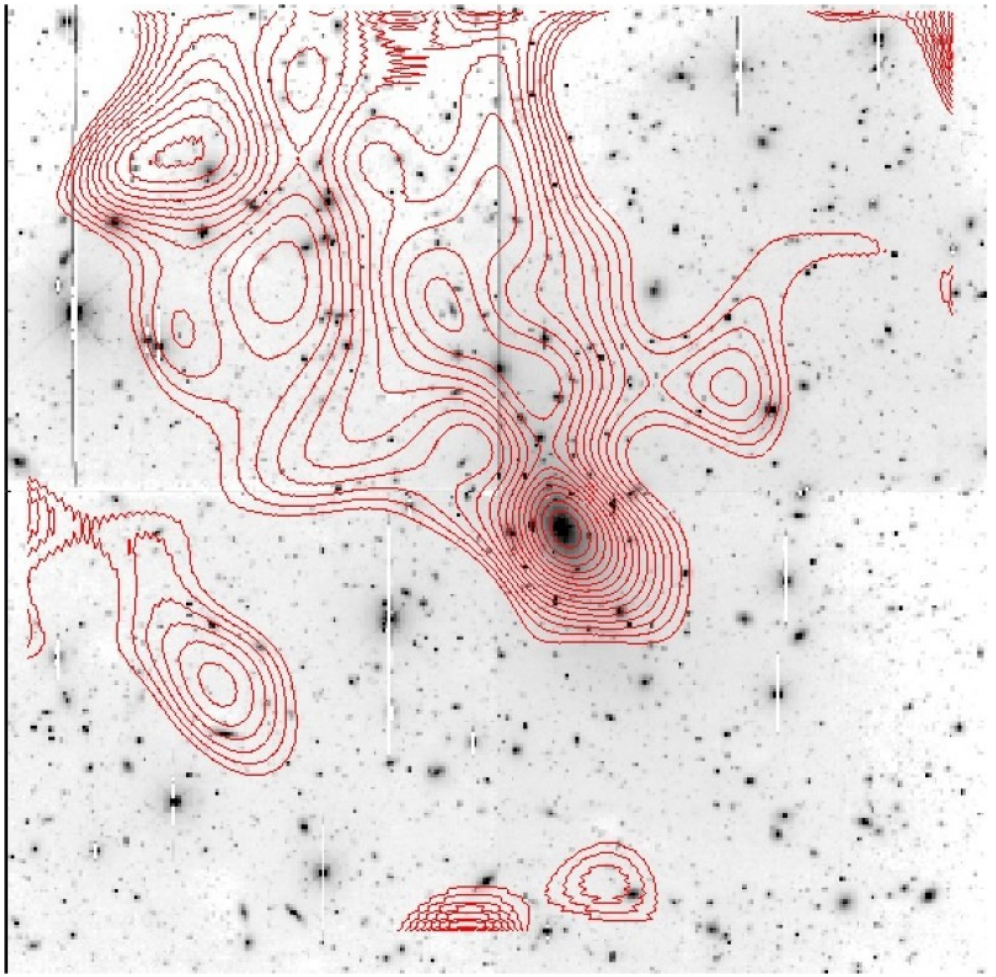
Masses of Galaxy Clusters



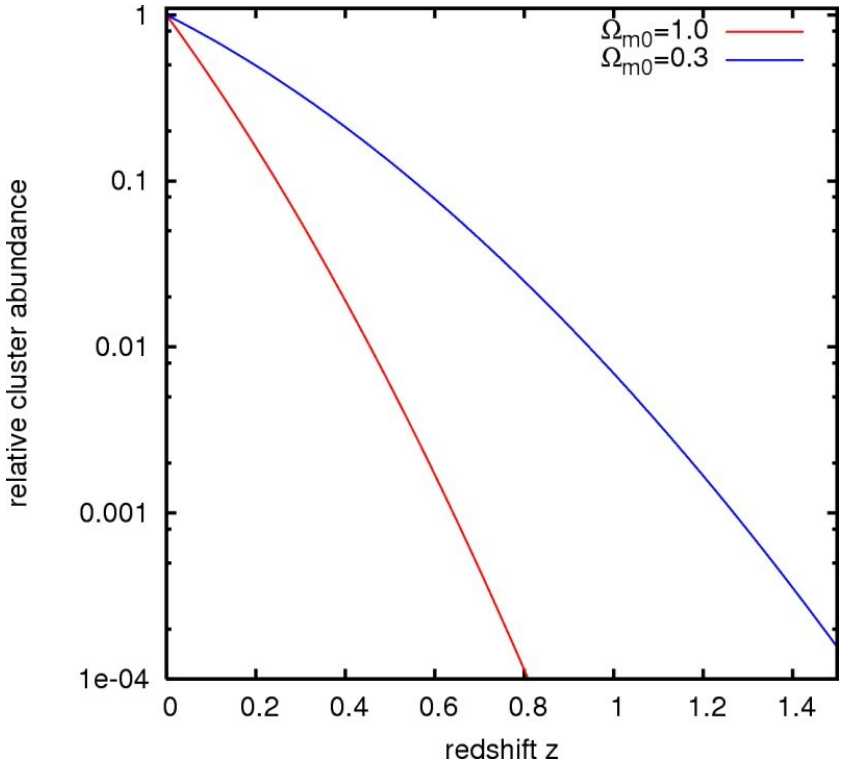
Dark matter and gas in galaxy clusters

Masses from Gravitational Lensing

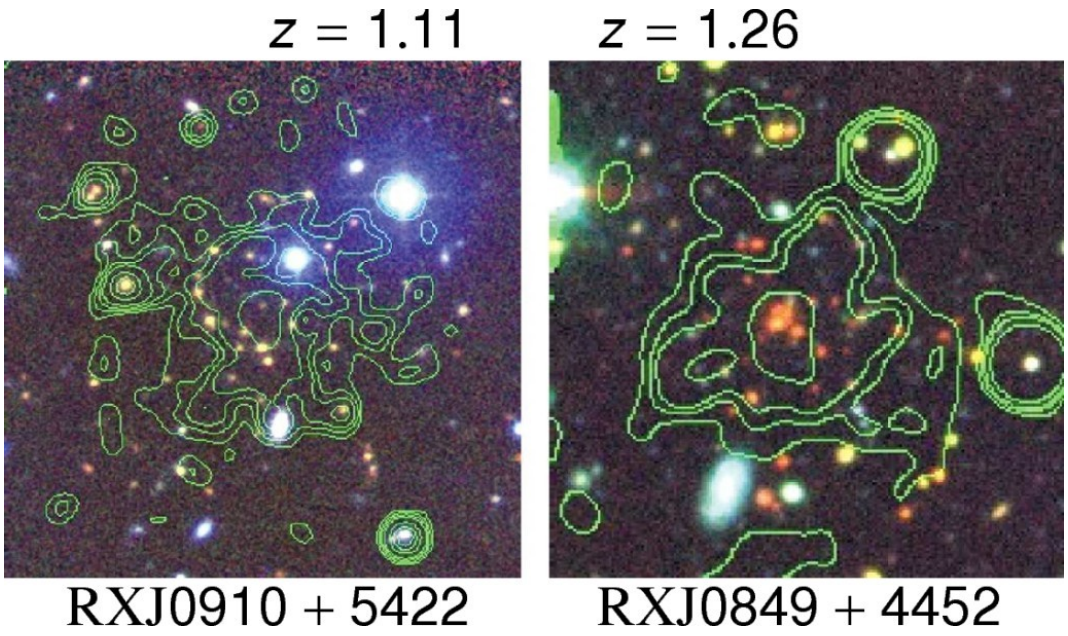
Gravitational lensing allows mapping of dark matter



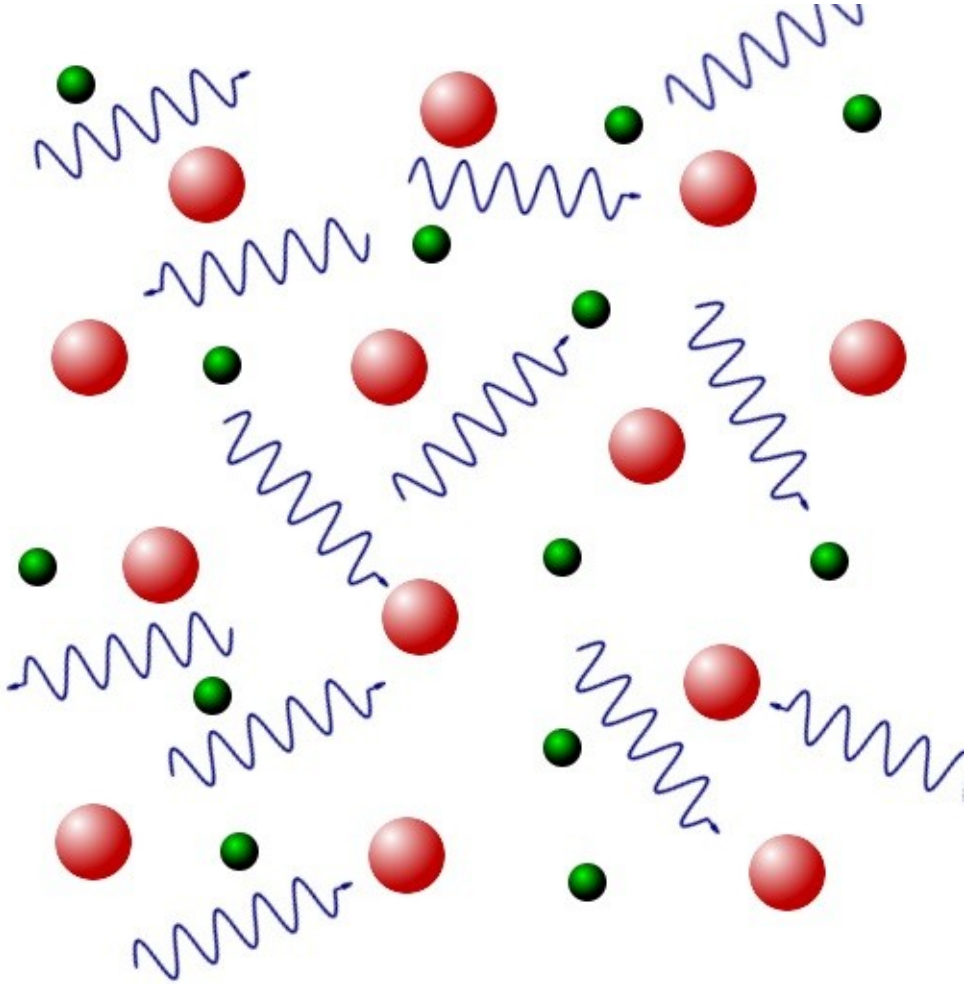
Mass Density from Cluster Evolution



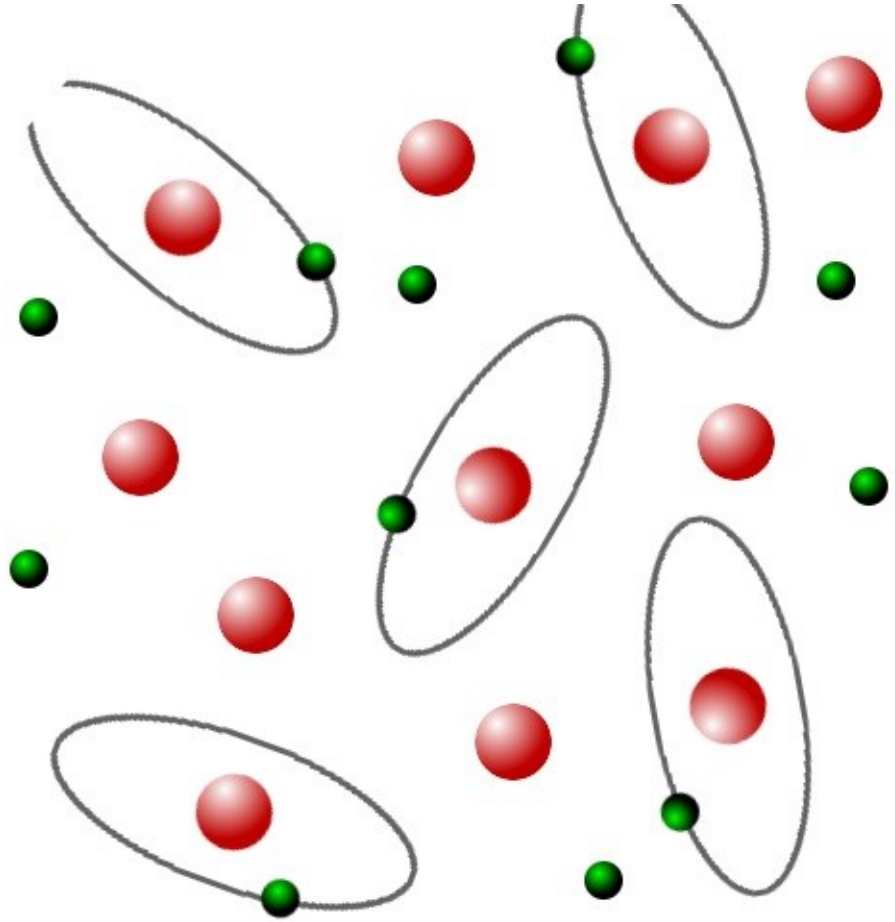
Galaxy clusters at high redshift argue for low matter density



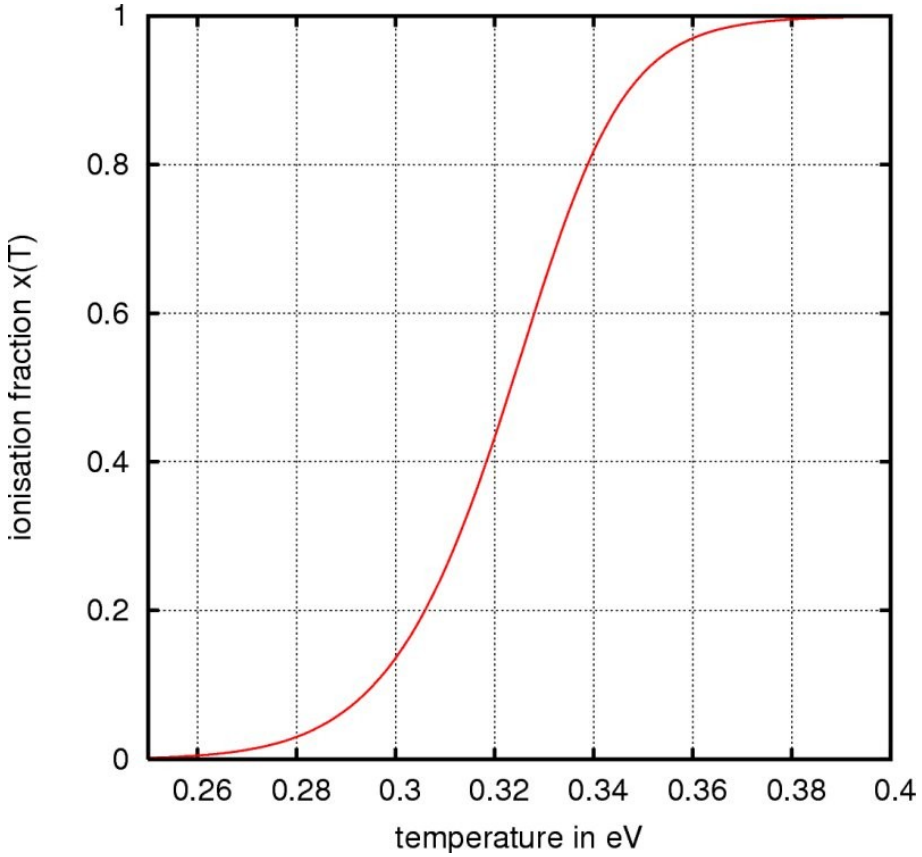
Cosmic Microwave Background



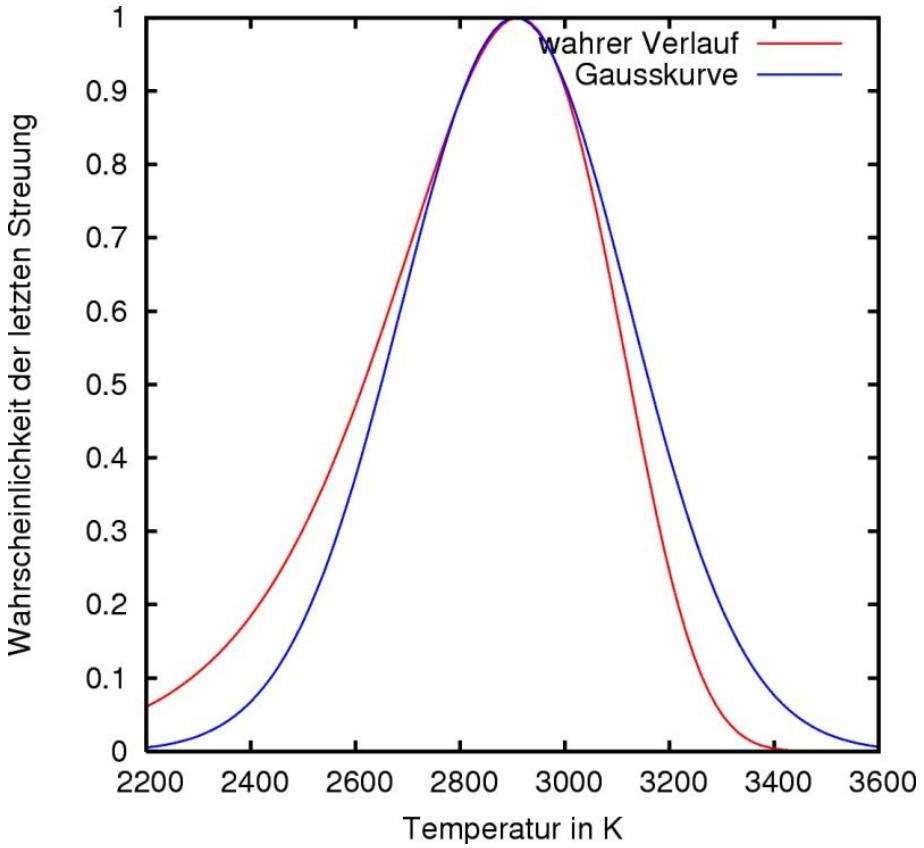
Cosmic Microwave Background decoupled when hydrogen recombined



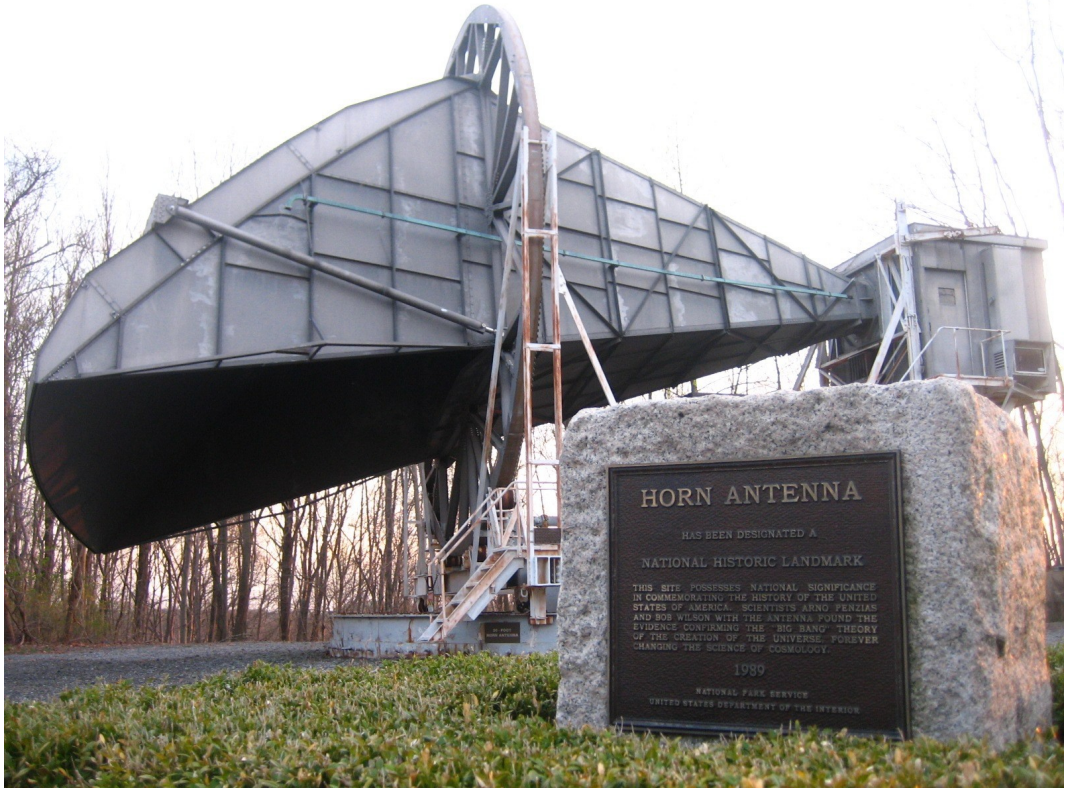
Energy Scale and Duration of Recombination



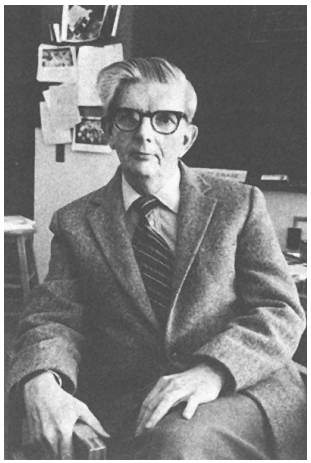
Recombination massively delayed to
0.32 eV instead of 13.6 eV
~ 400000 yr after Big Bang
~ 40000 yr duration



Discovery of the Cosmic Microwave Background

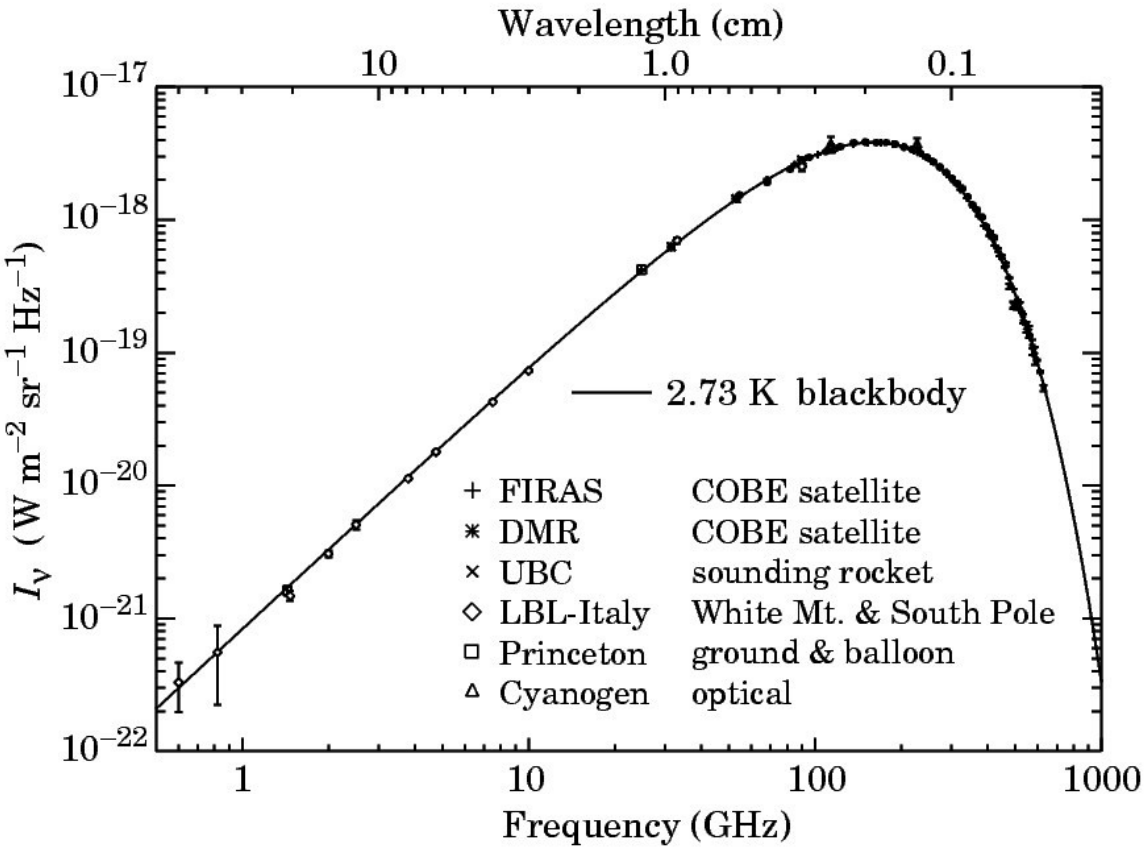


CMB had been predicted
Discovered by Penzias & Wilson 1965



Robert Dicke

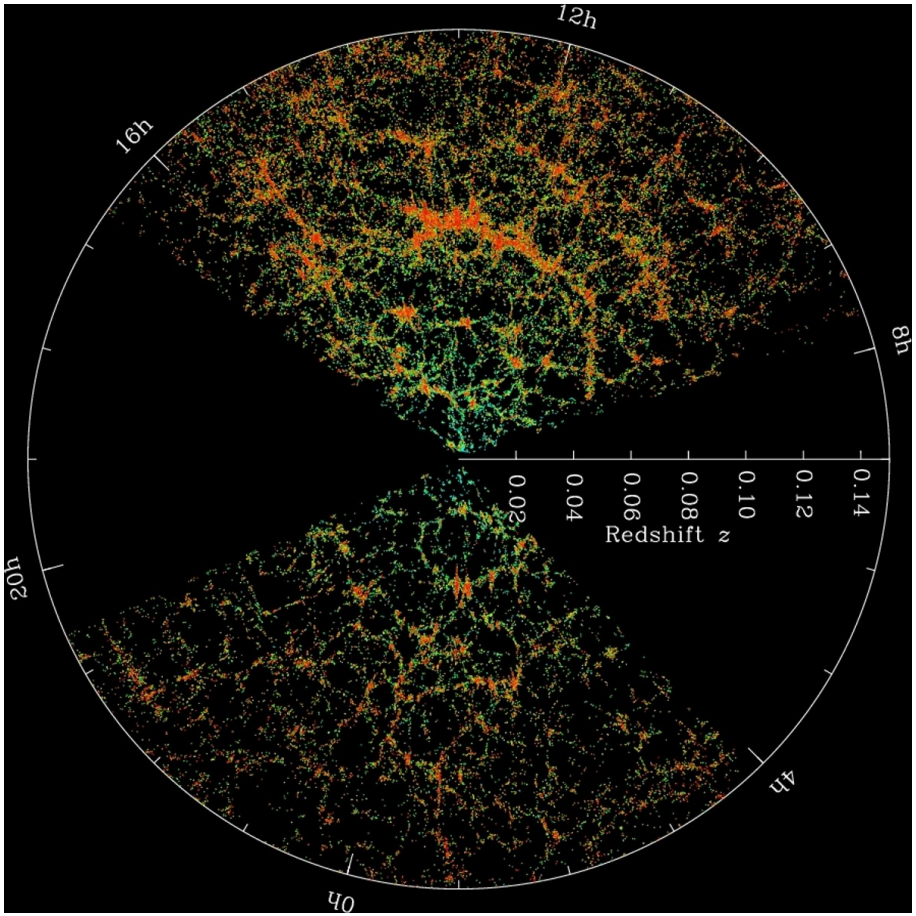
Thermal Radiation?

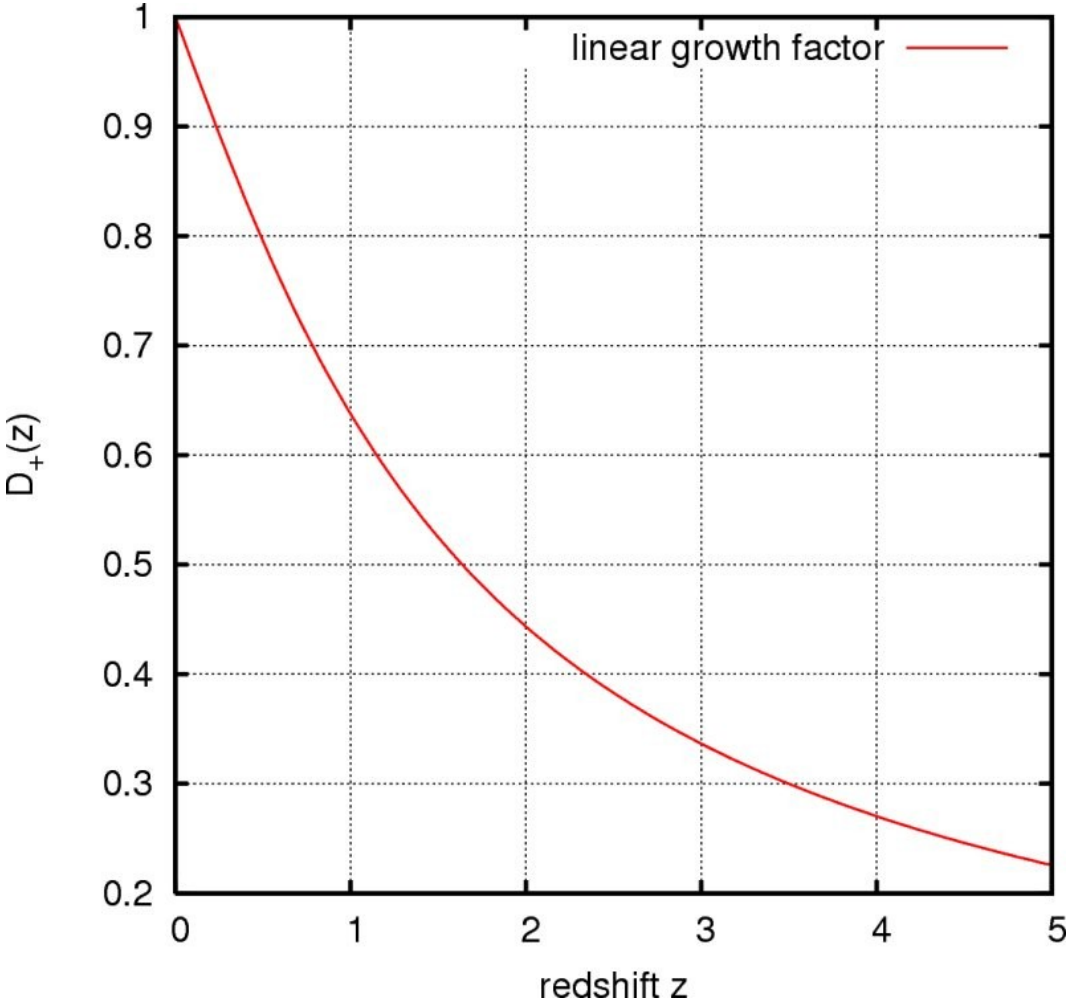


Best measured black-body
Spectrum, COBE 1992

John Mather

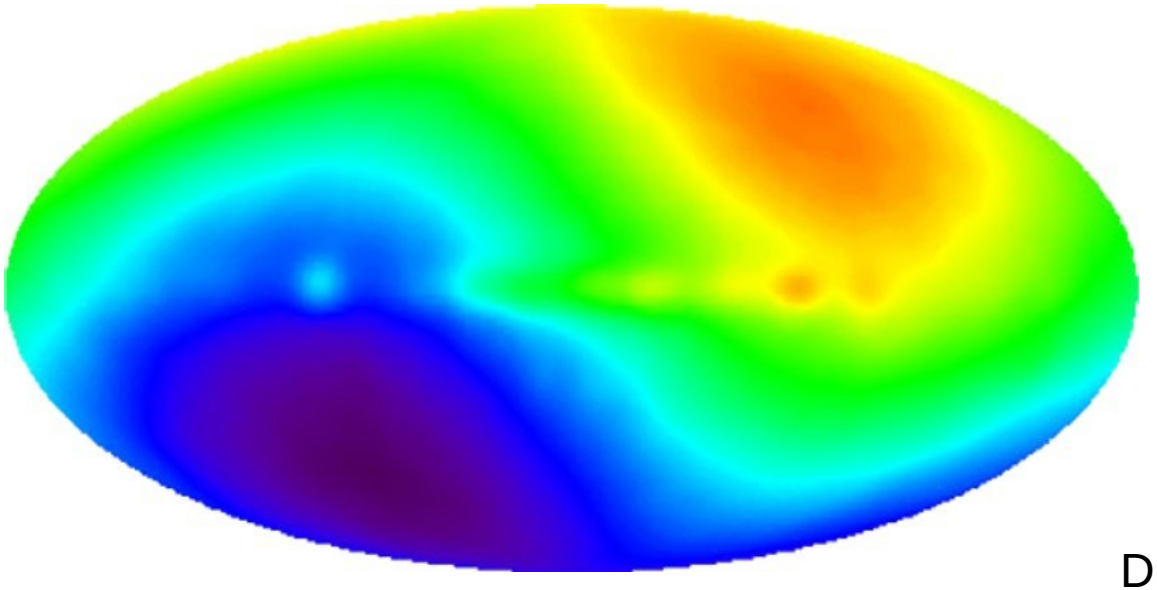
Structures in the CMB?



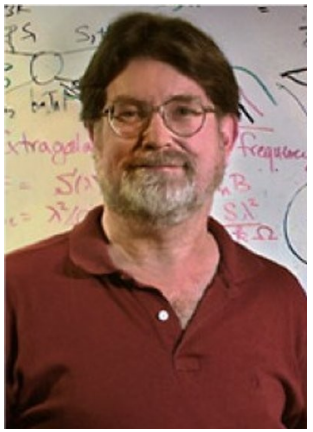


Temperature fluctuations
at mK level expected

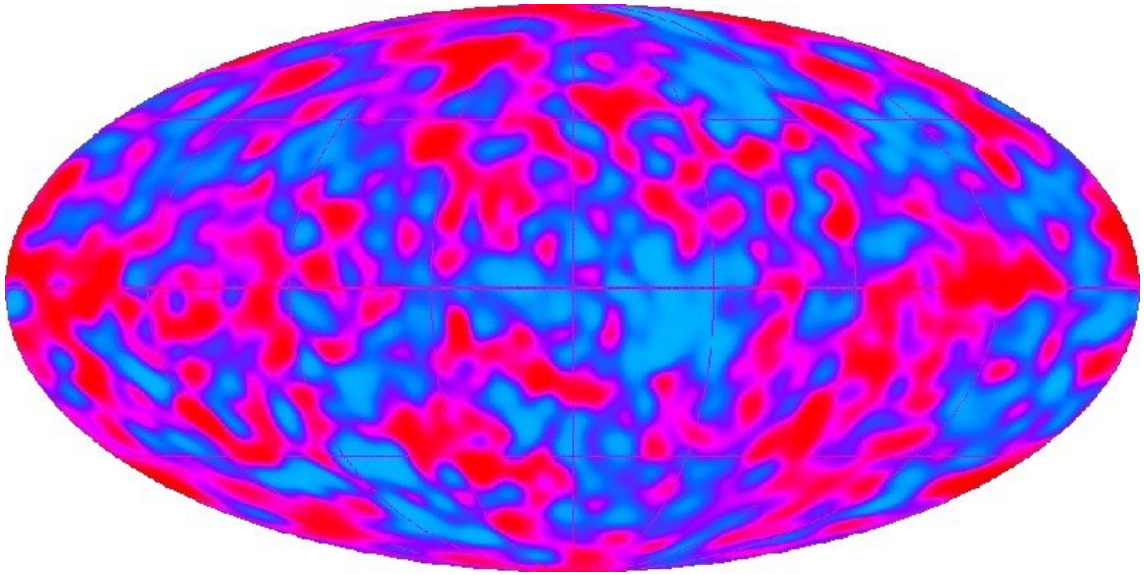
Temperature Fluctuations



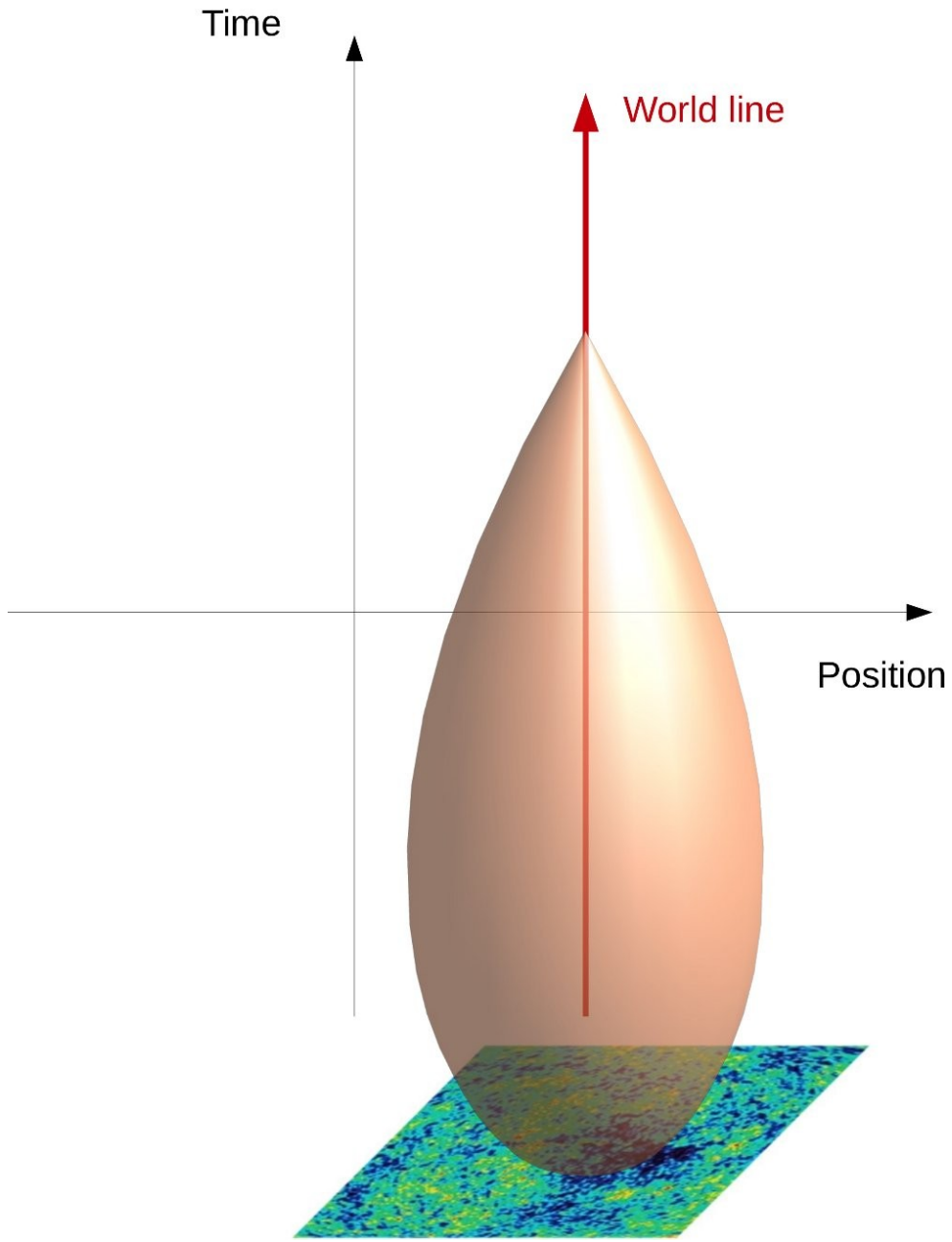
George Smoot



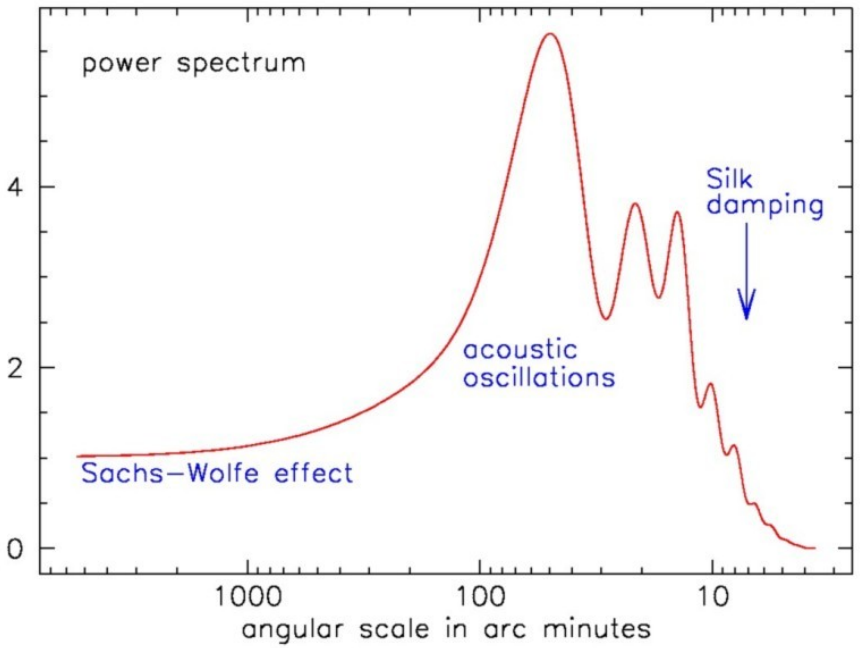
Discovered by COBE at μK level

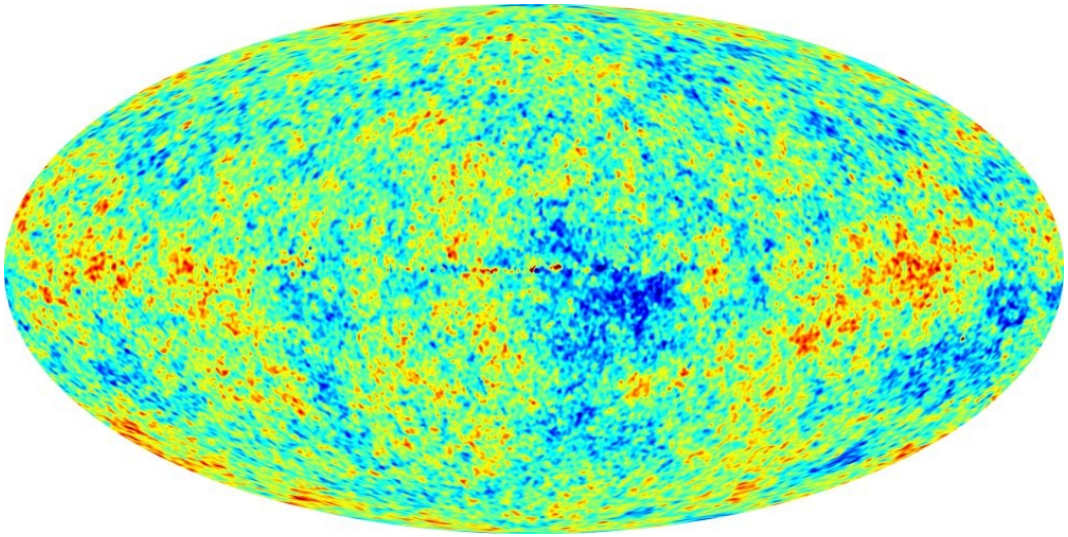


The CMB in the Backward Light Cone



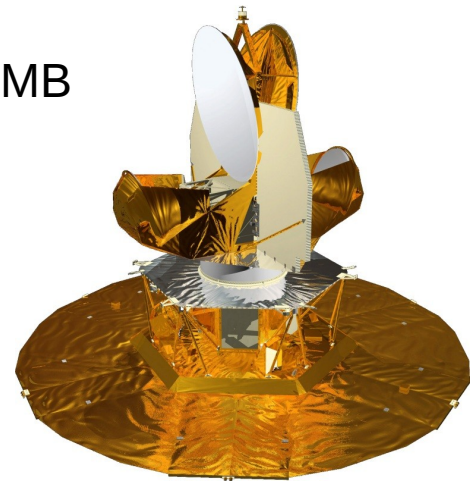
WMAP

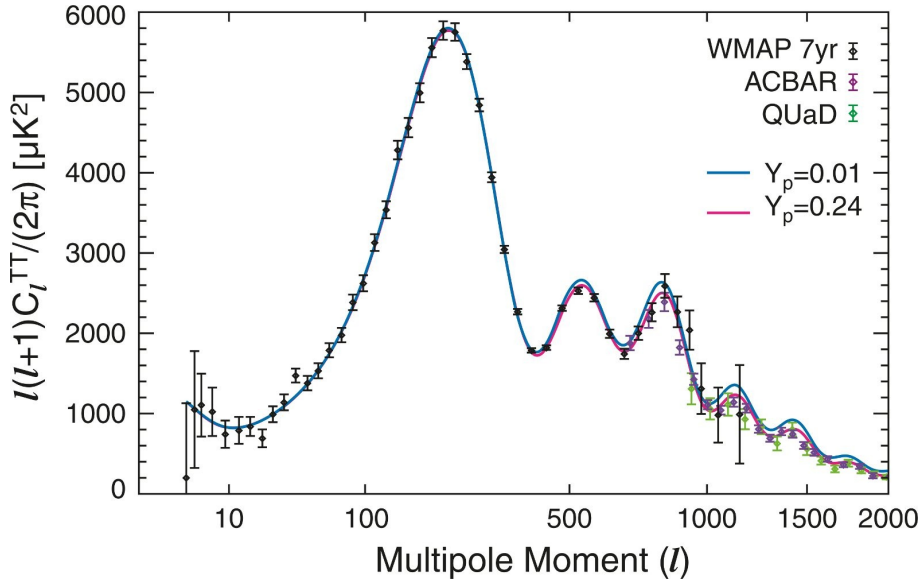




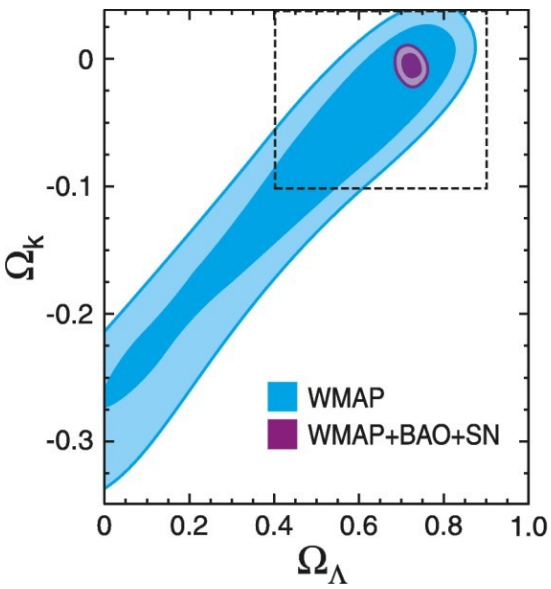
Statistics of CMB temperature fluctuations

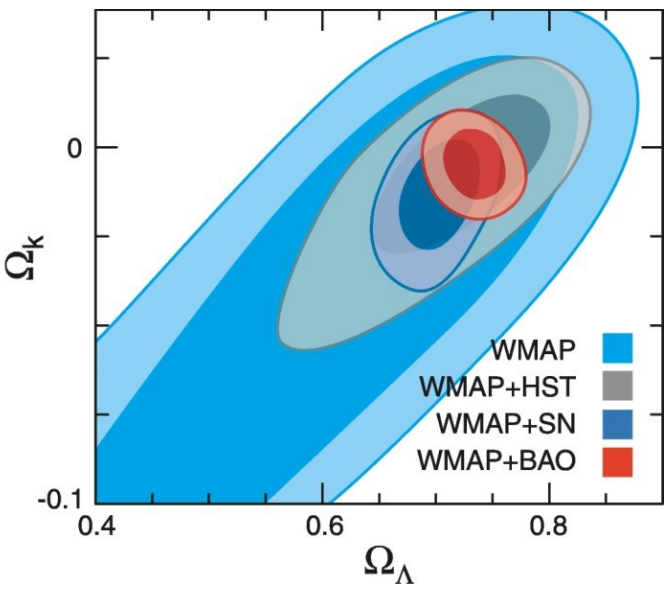
WMAP satellite

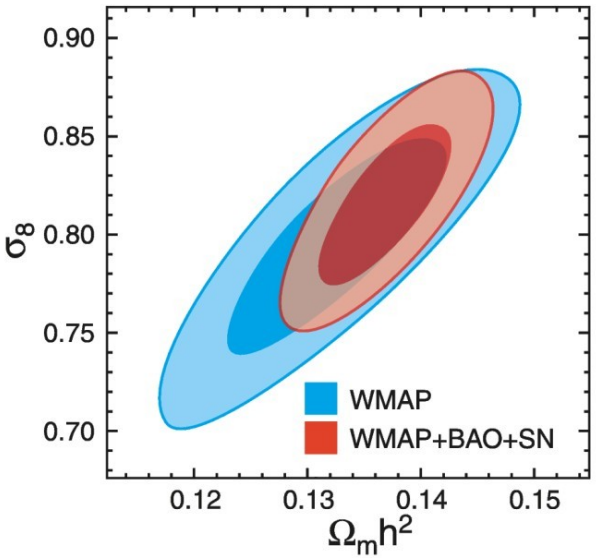


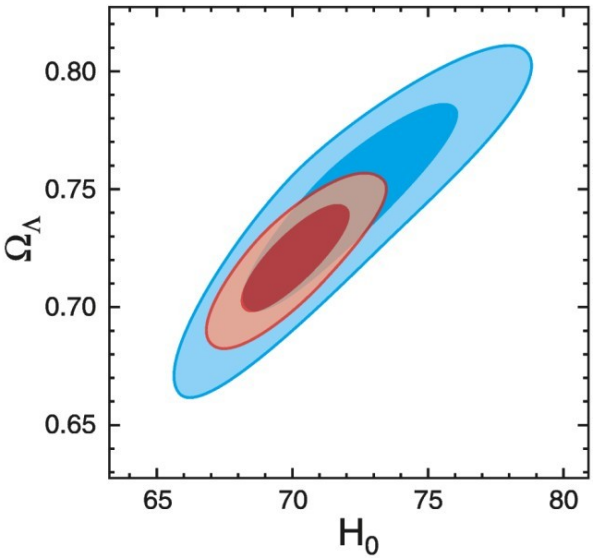


Parameter Constraints

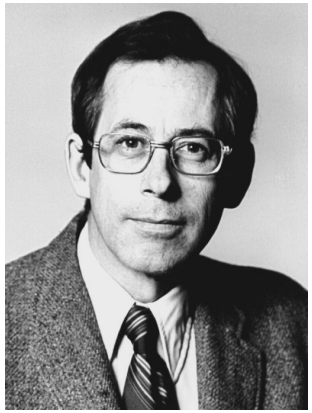




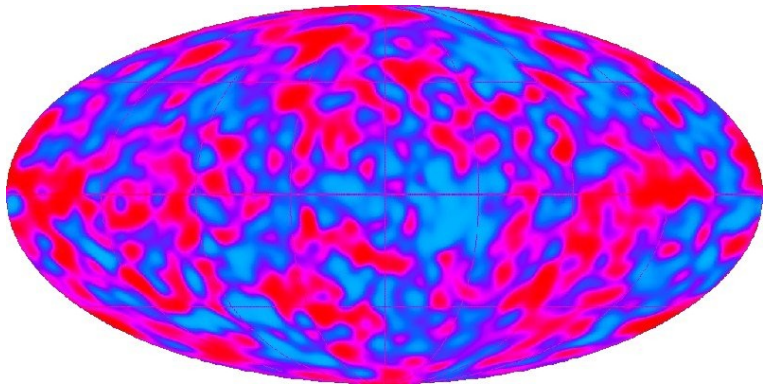


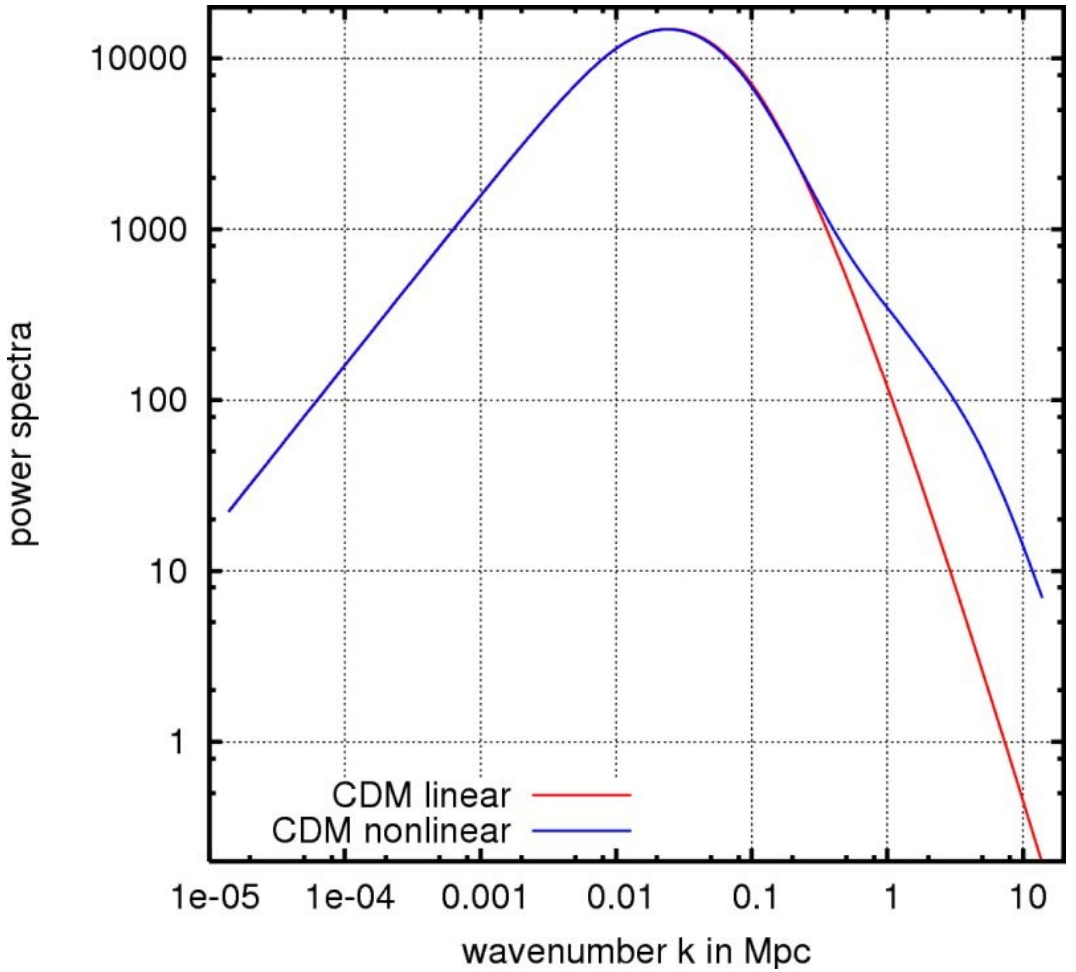


Cold Dark Matter

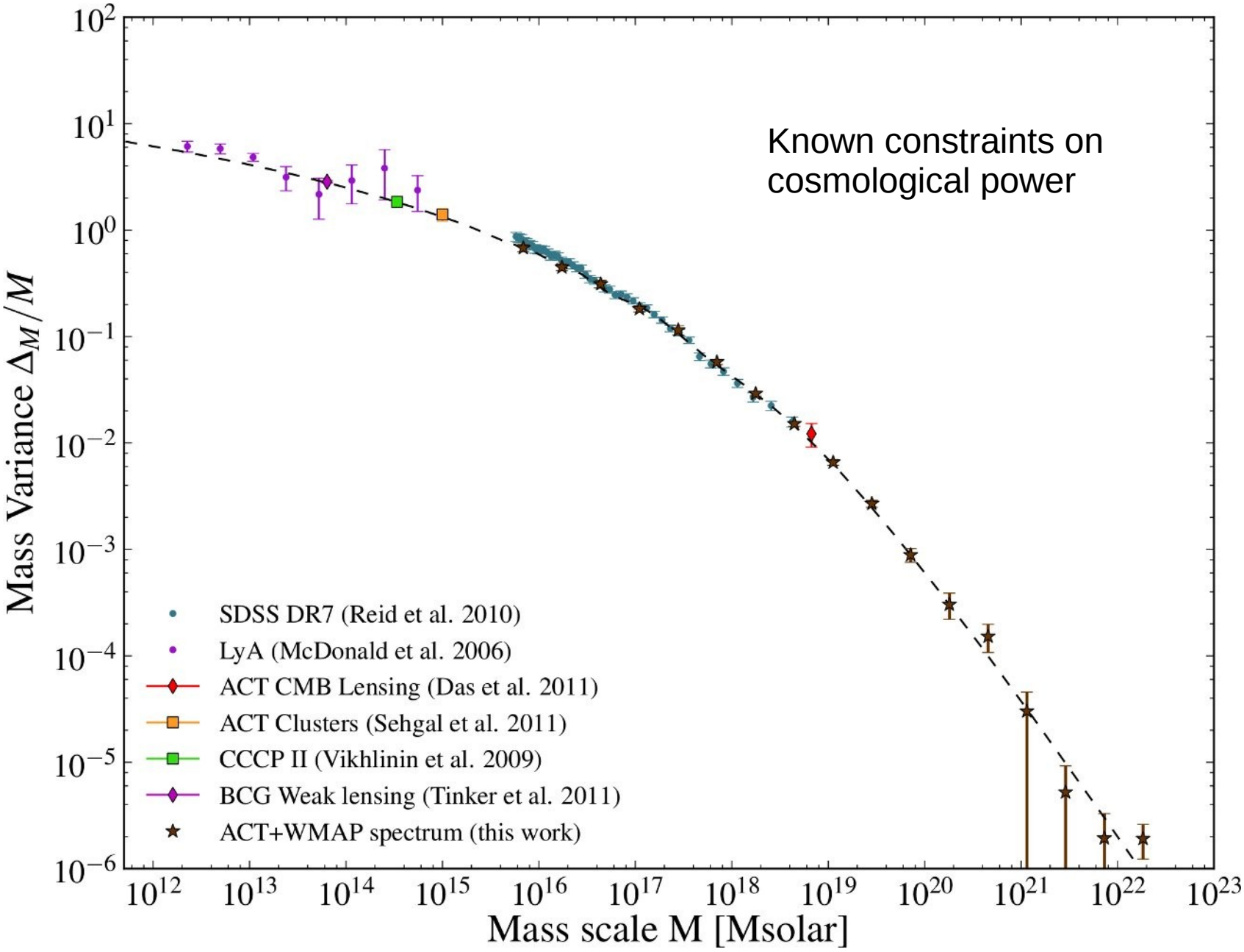


Cold dark matter:
– dark required by CMB
– cold required by structure formation

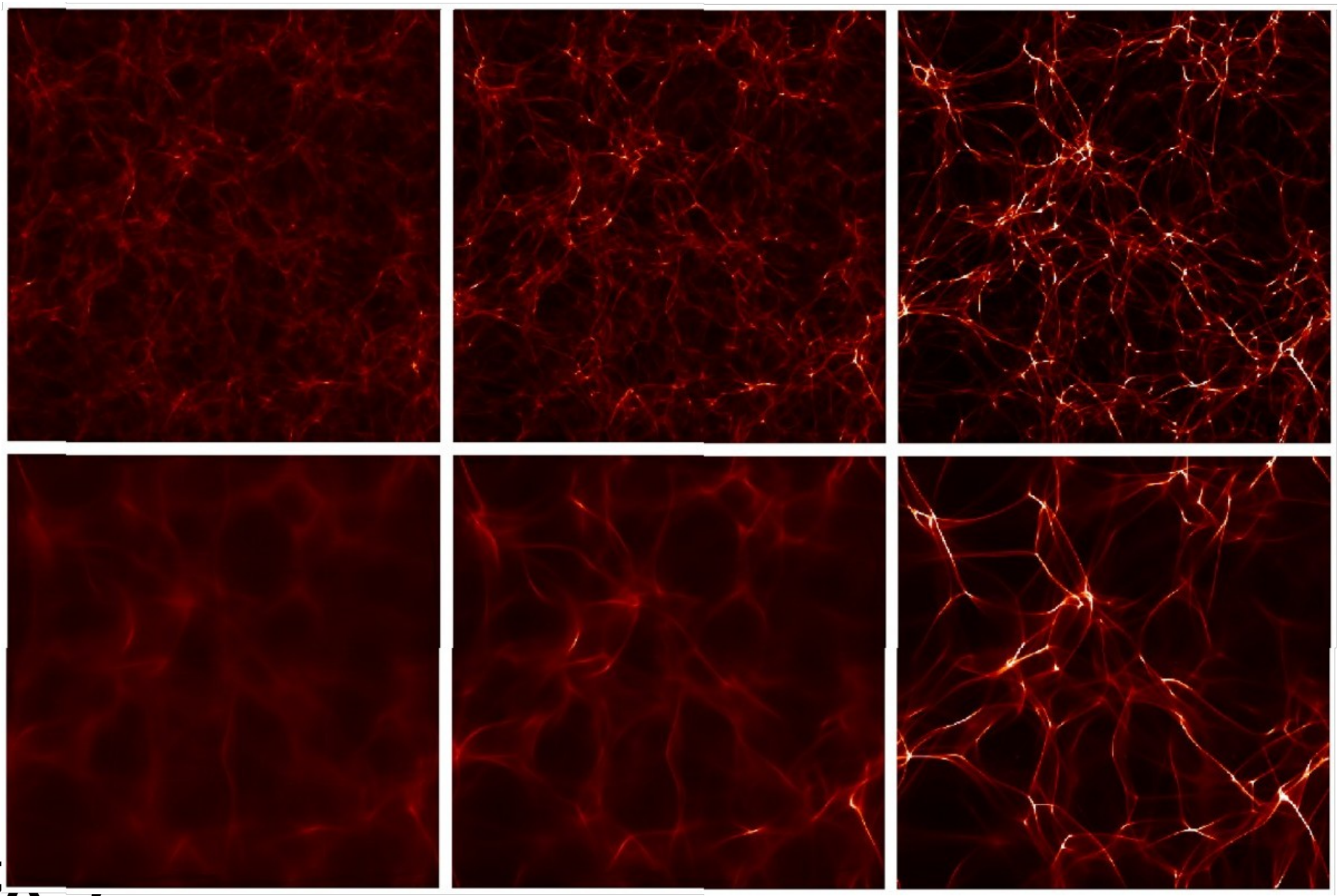




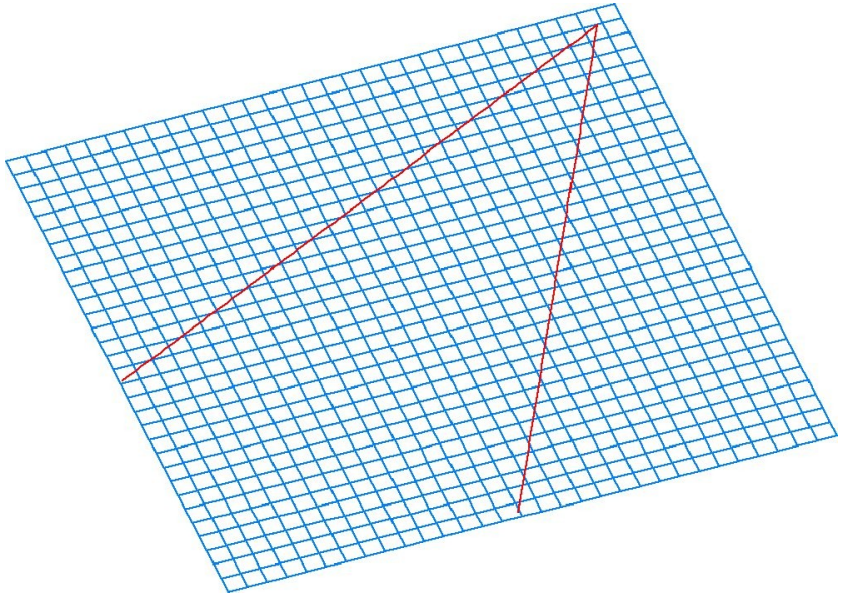
Cold Dark Matter

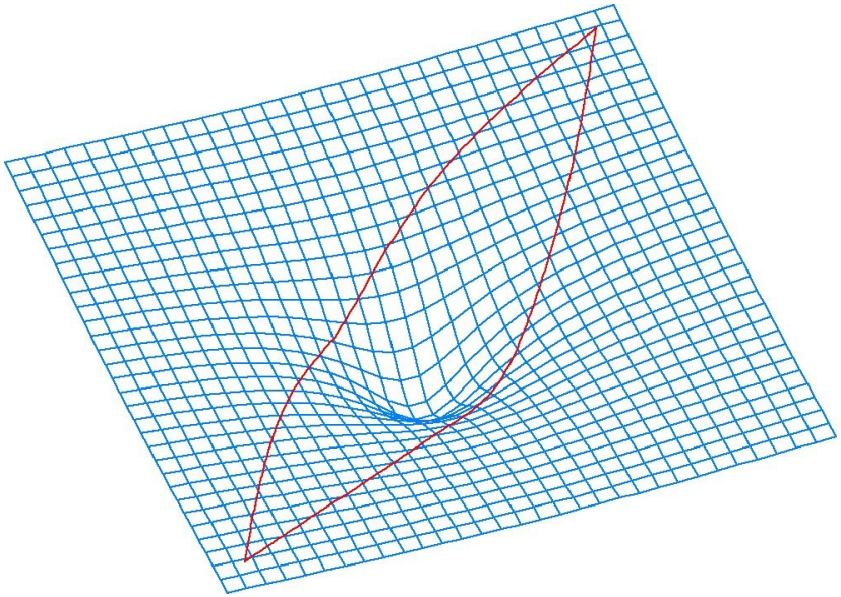


Cold and Hot Dark Matter

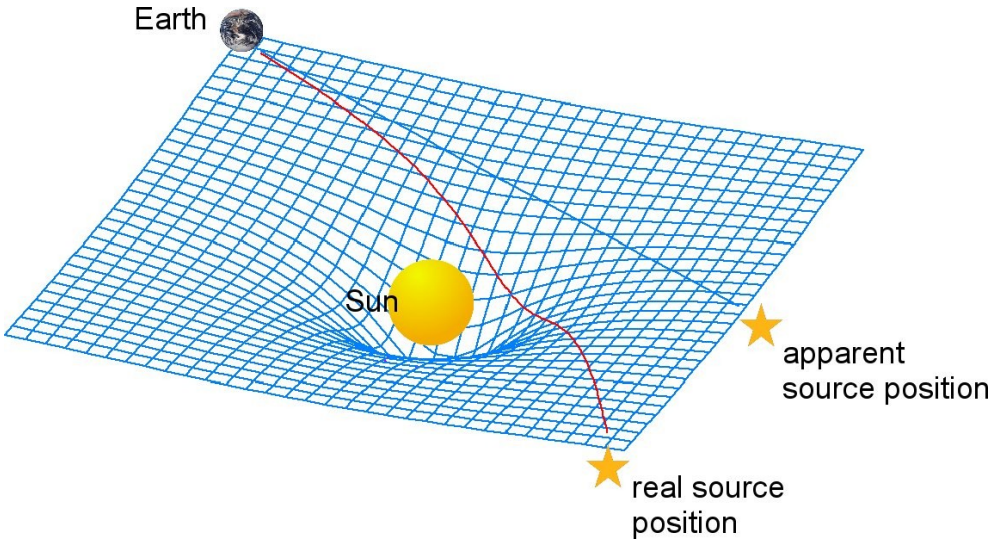


Light Deflection





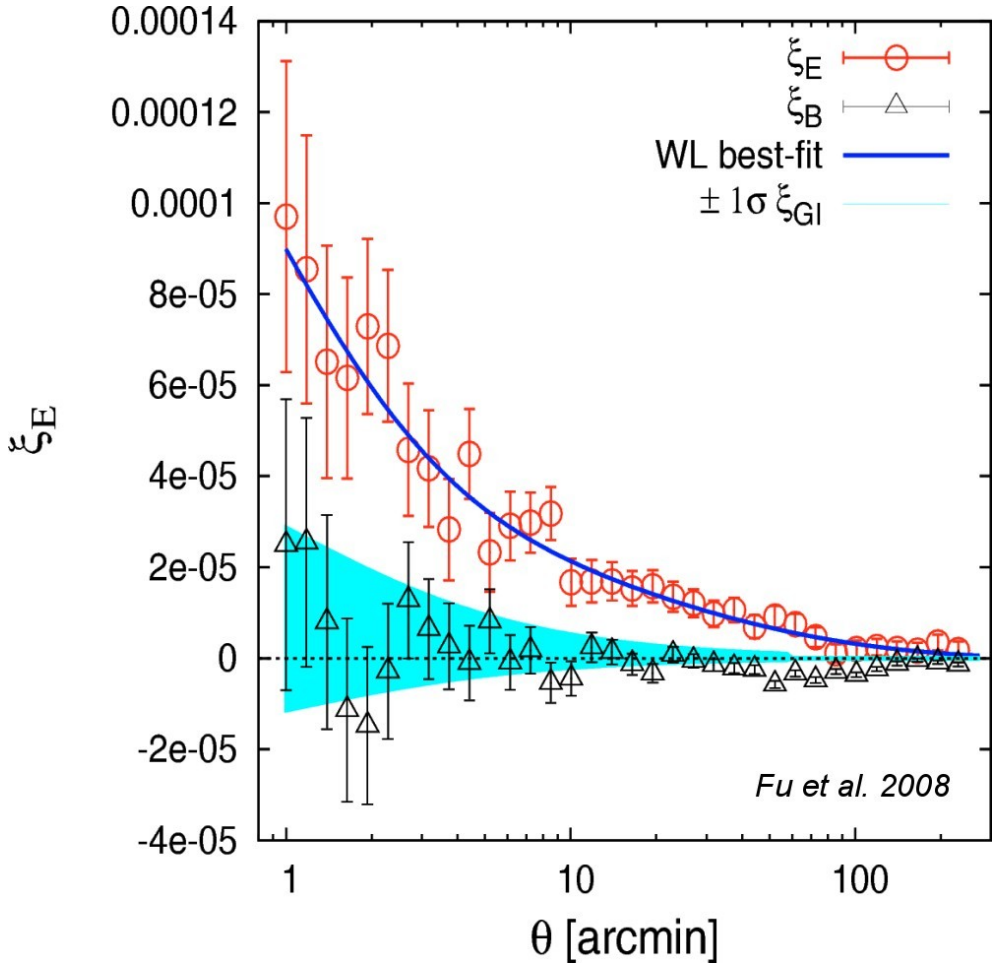
Principle of light deflection
and gravitational lensing

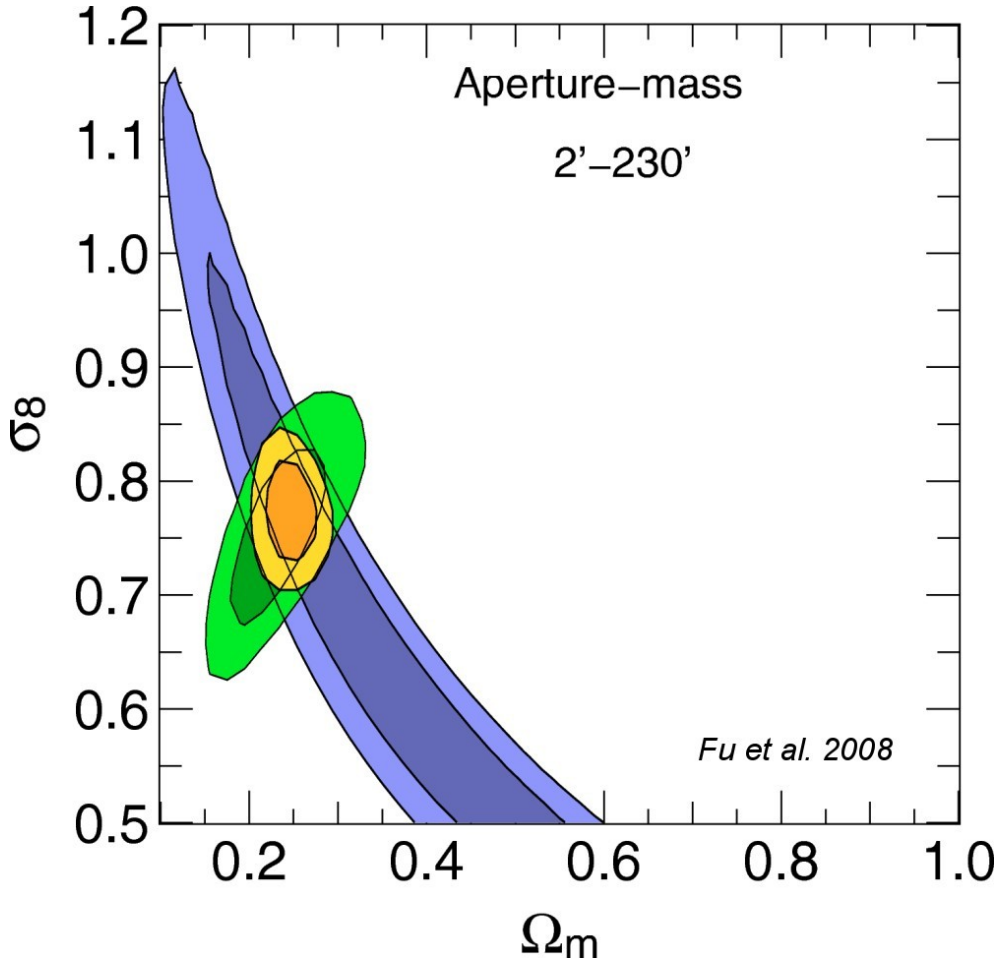


Lensing Distortions

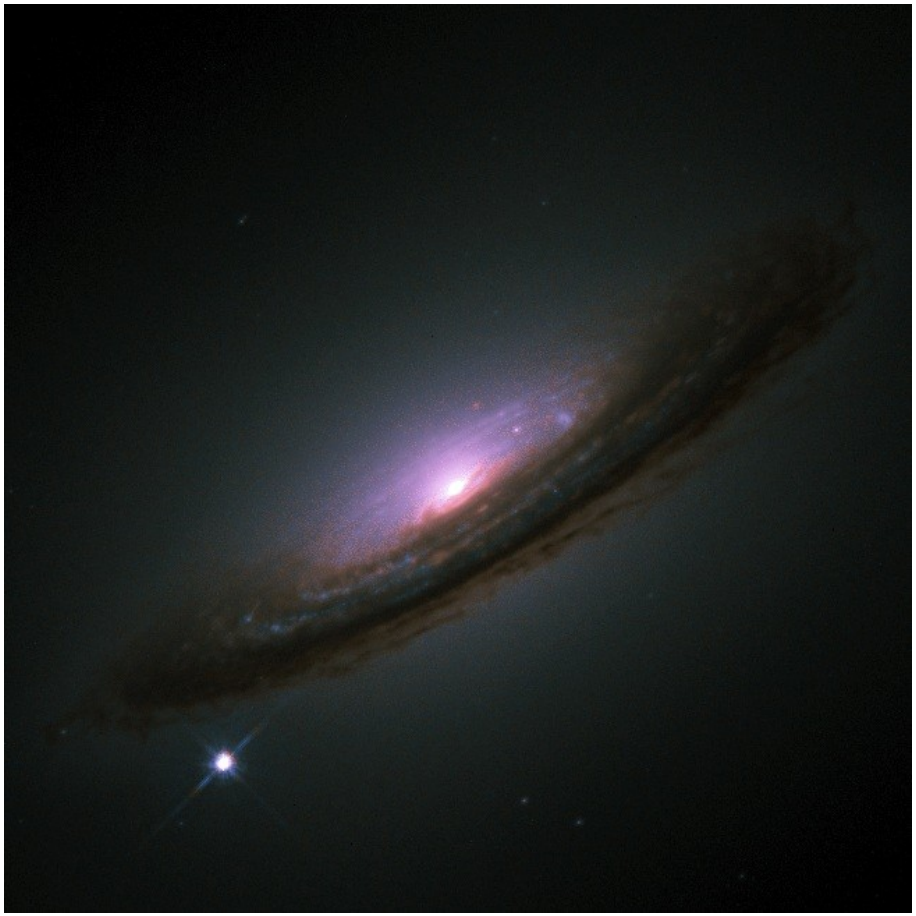
Wide-Field Imaging Surveys

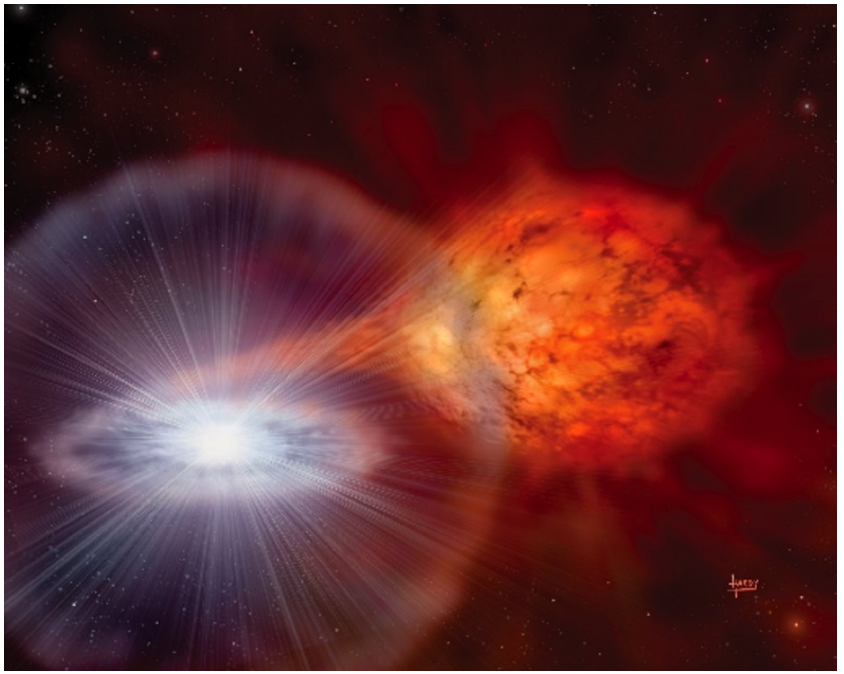
Cosmological Weak Lensing Results

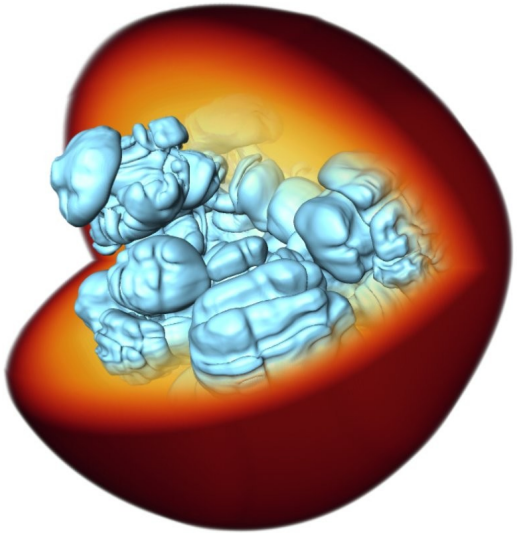




Type-Ia Supernovae







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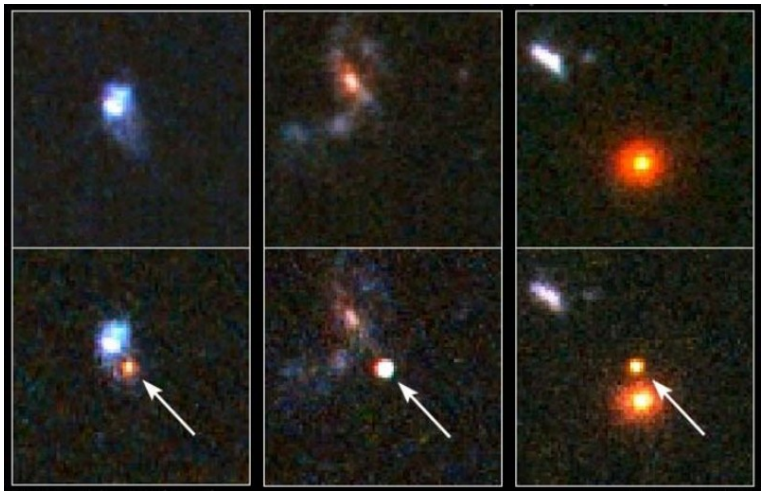
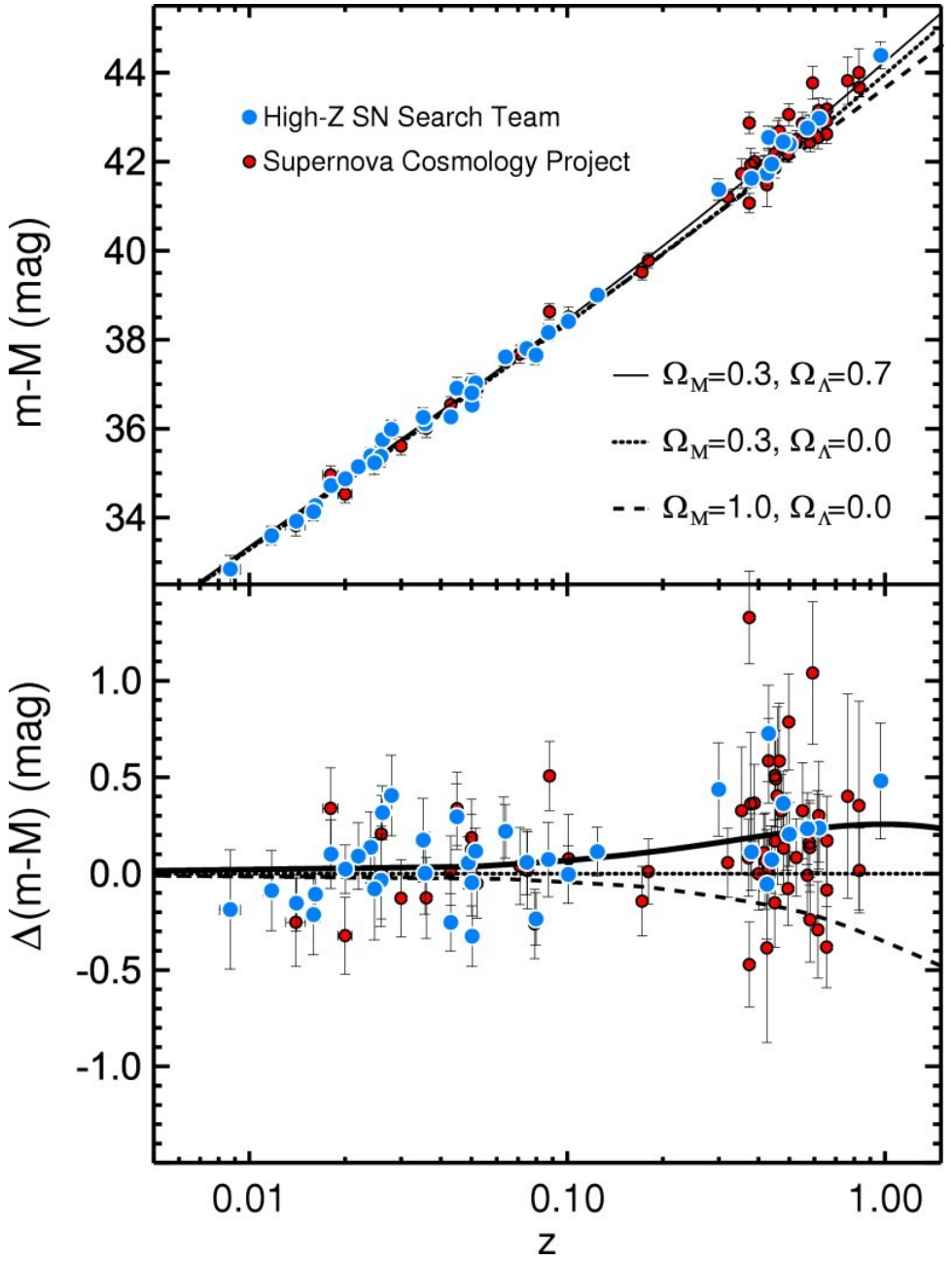
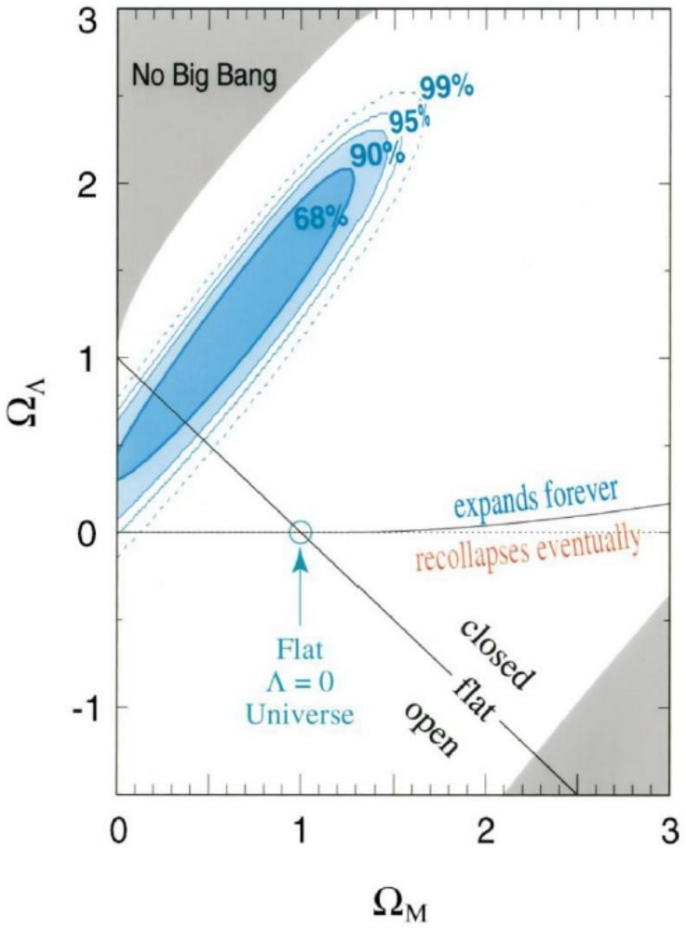
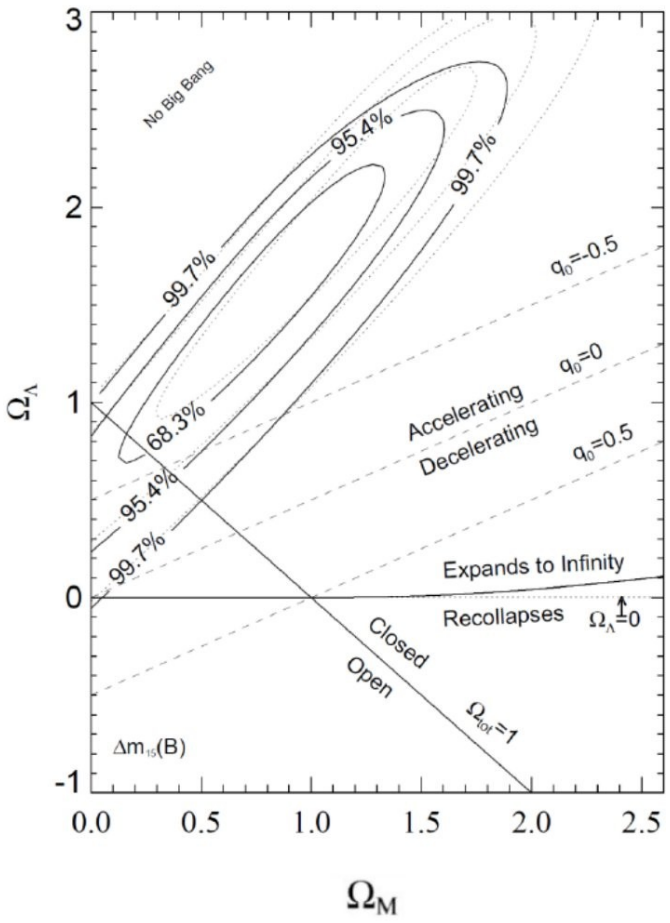


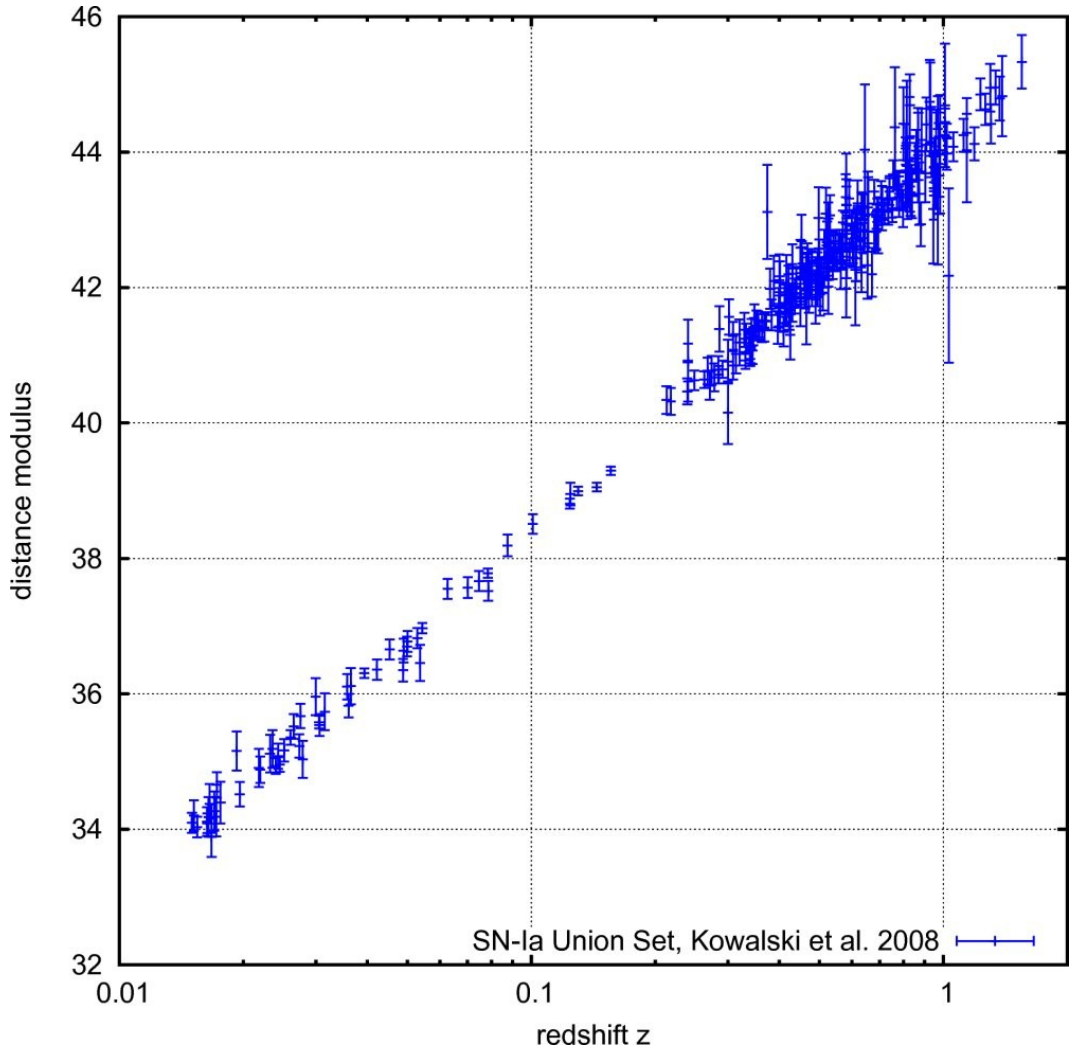


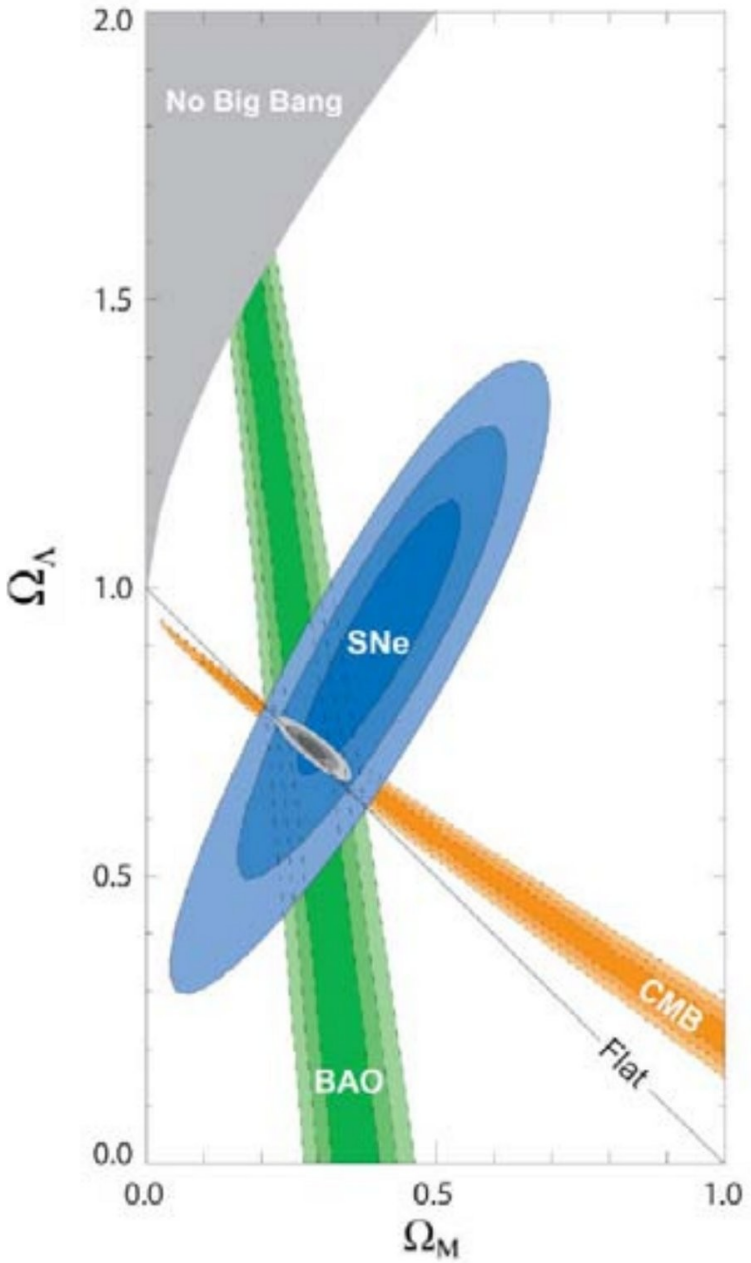
Accelerated Cosmic Expansion



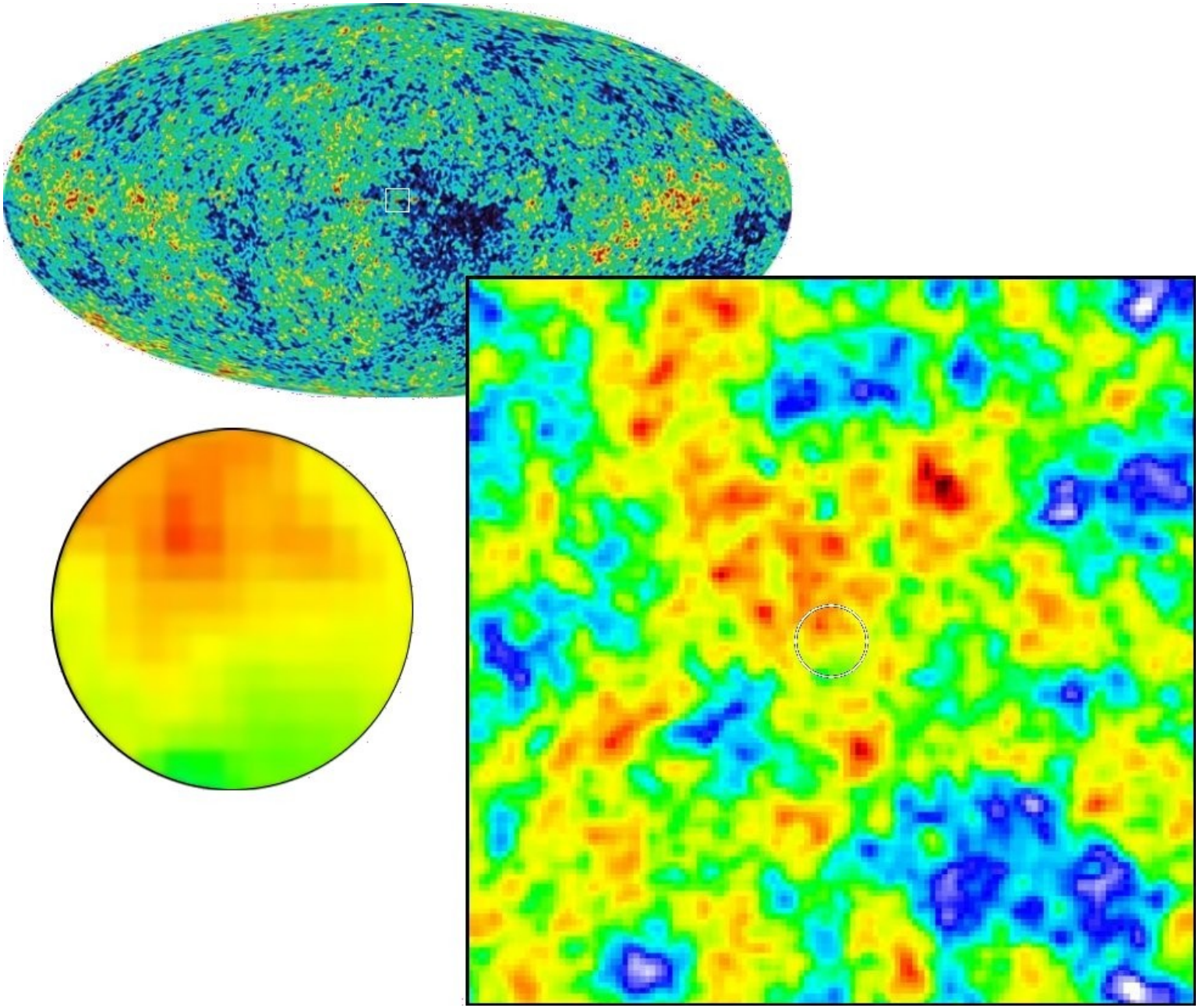


Type-Ia Supernovae, Cosmological Constraints

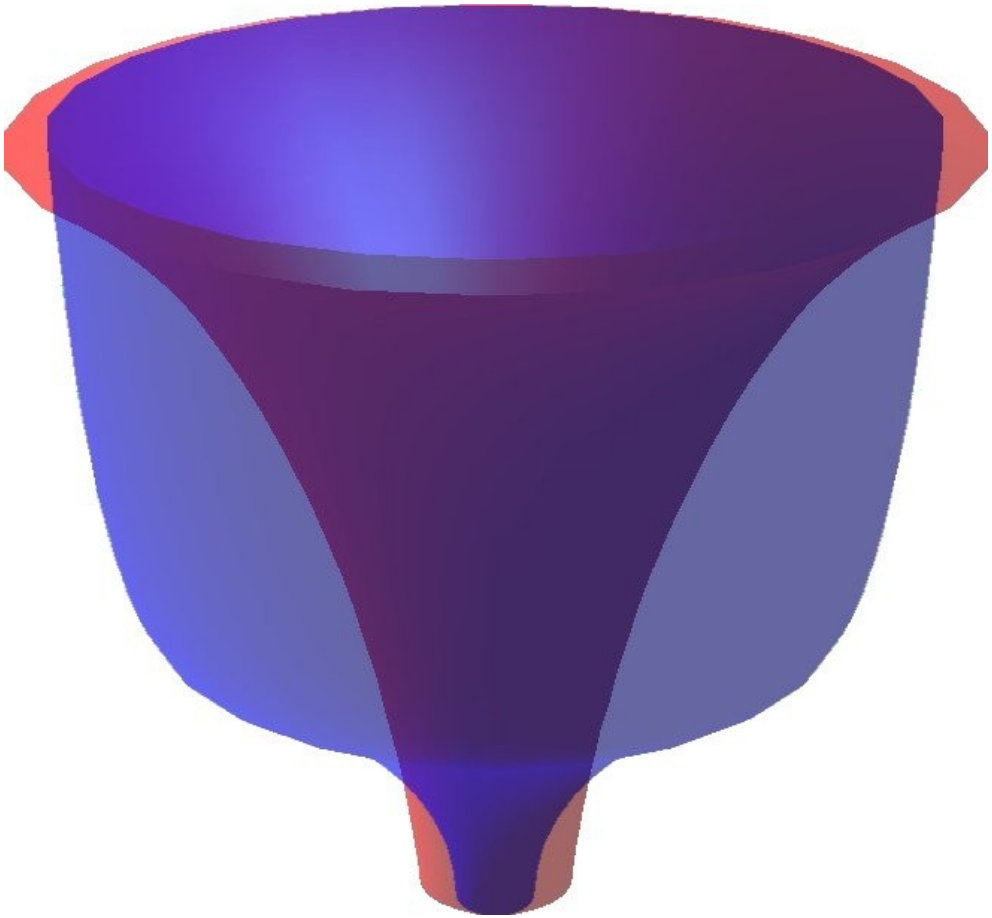


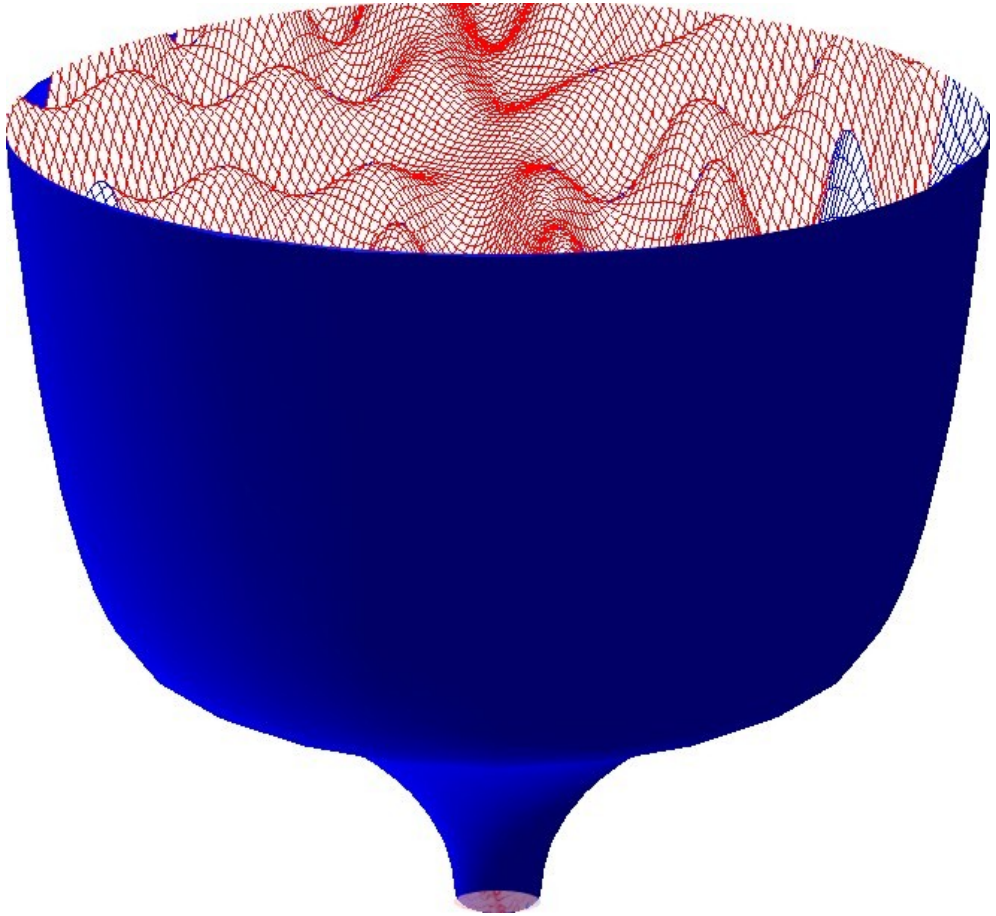


Causality?

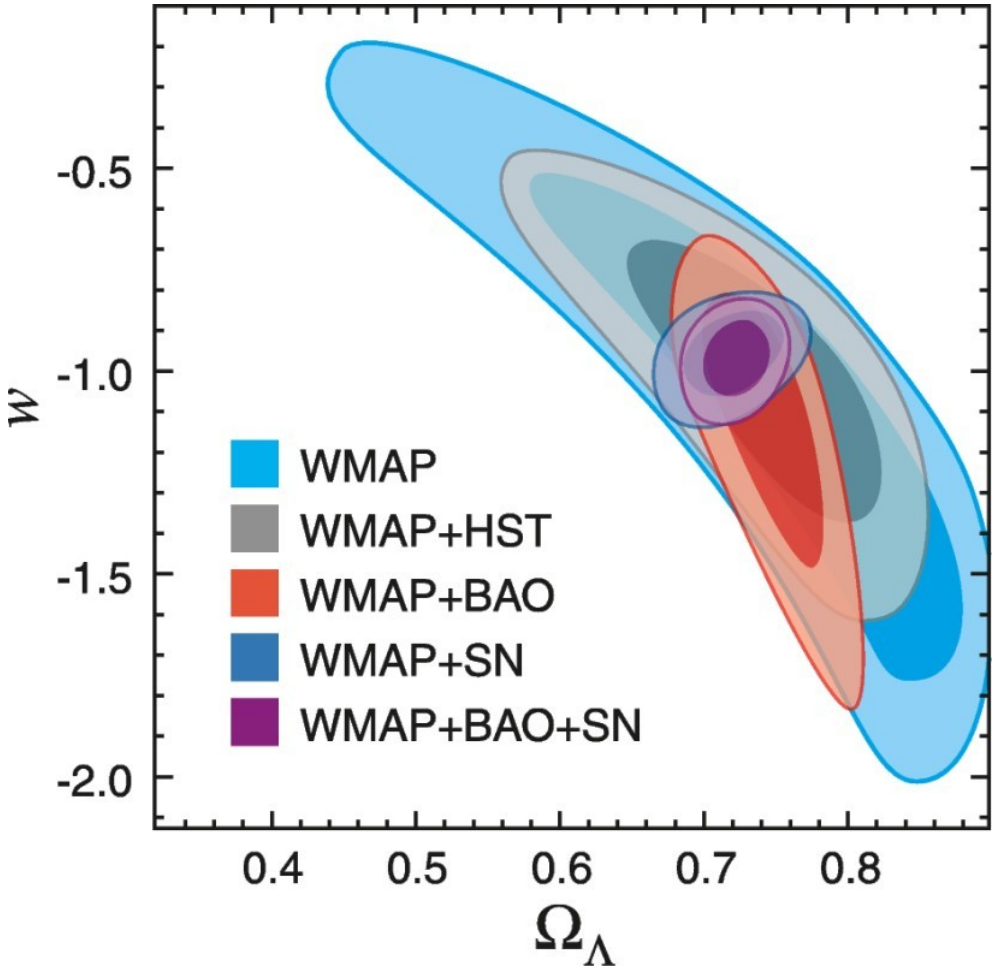


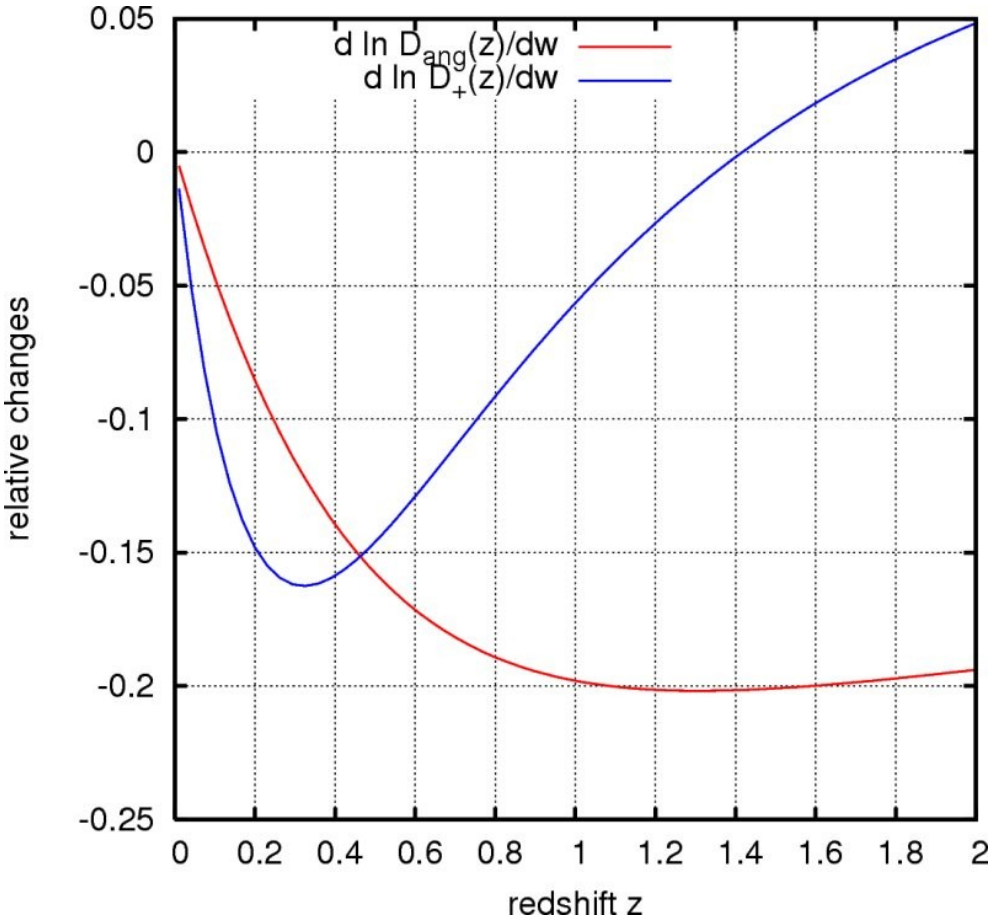
Inflation and its Consequences





Dark Energy or Cosmological Constant?



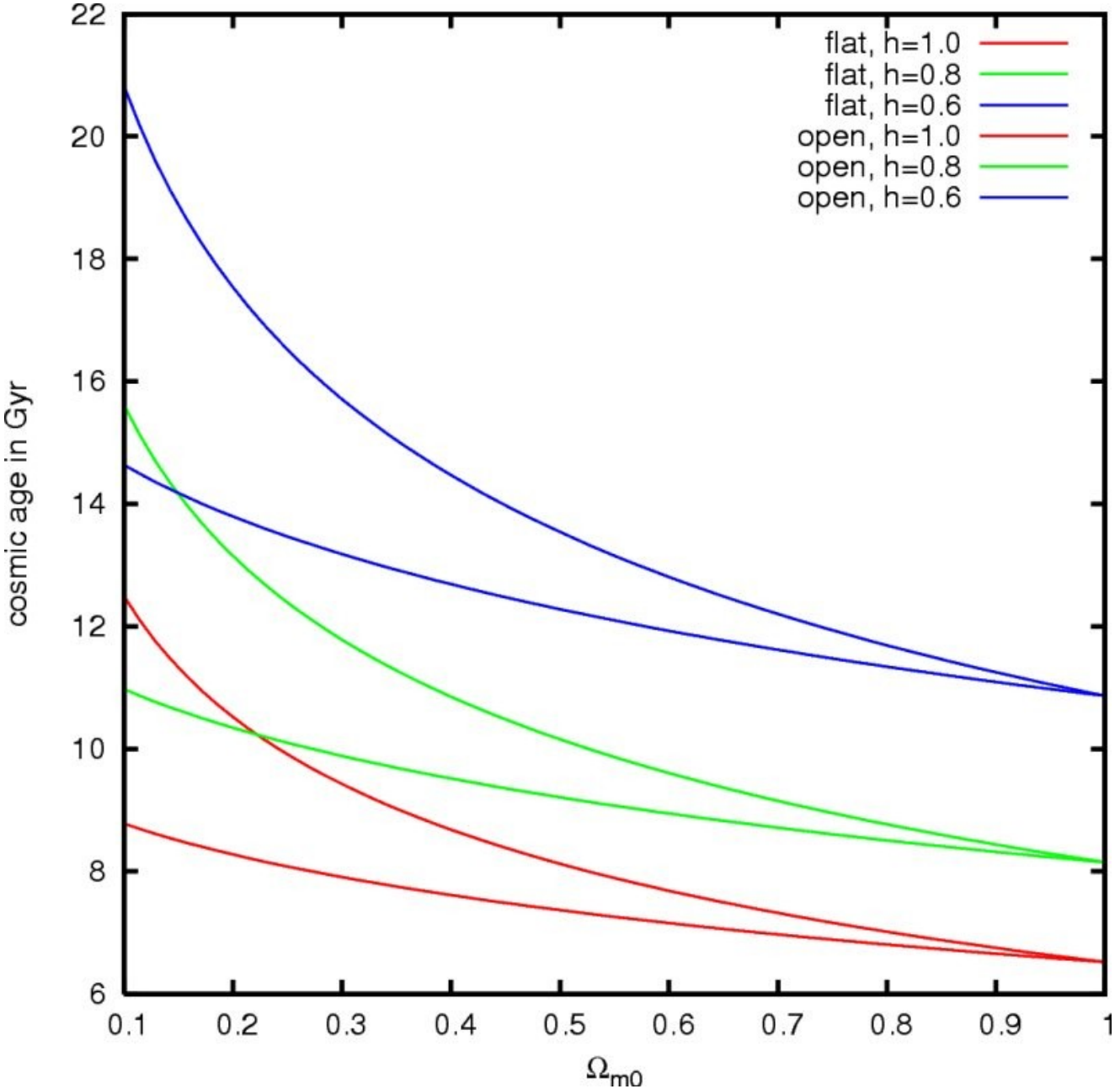


Summary: Parameters

- Current knowledge of cosmological parameters

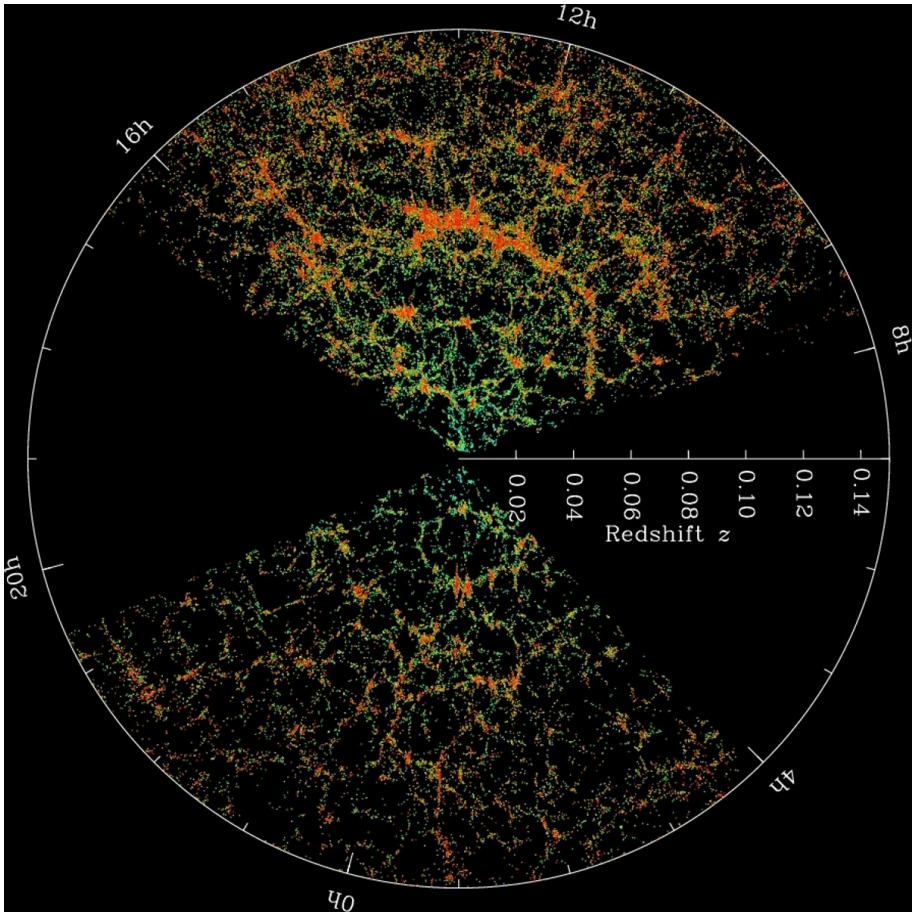
Baryon density parameter	$\Omega_{B0} = 0.0456 \pm 0.0016$
CDM density parameter	$\Omega_{C0} = 0.227 \pm 0.014$
Hubble constant	$H_0 = (70.4 \pm 1.3)$ km/s/Mpc
Cosmological constant	$\Omega_{\Lambda 0} = 0.728 \pm 0.015$
Fluctuation amplitude	$\sigma_8 = 0.809 \pm 0.024$
Fluctuation spectral index	$n_s = 0.963 \pm 0.012$
Age of the Universe	(13.75 ± 0.11) Gyr

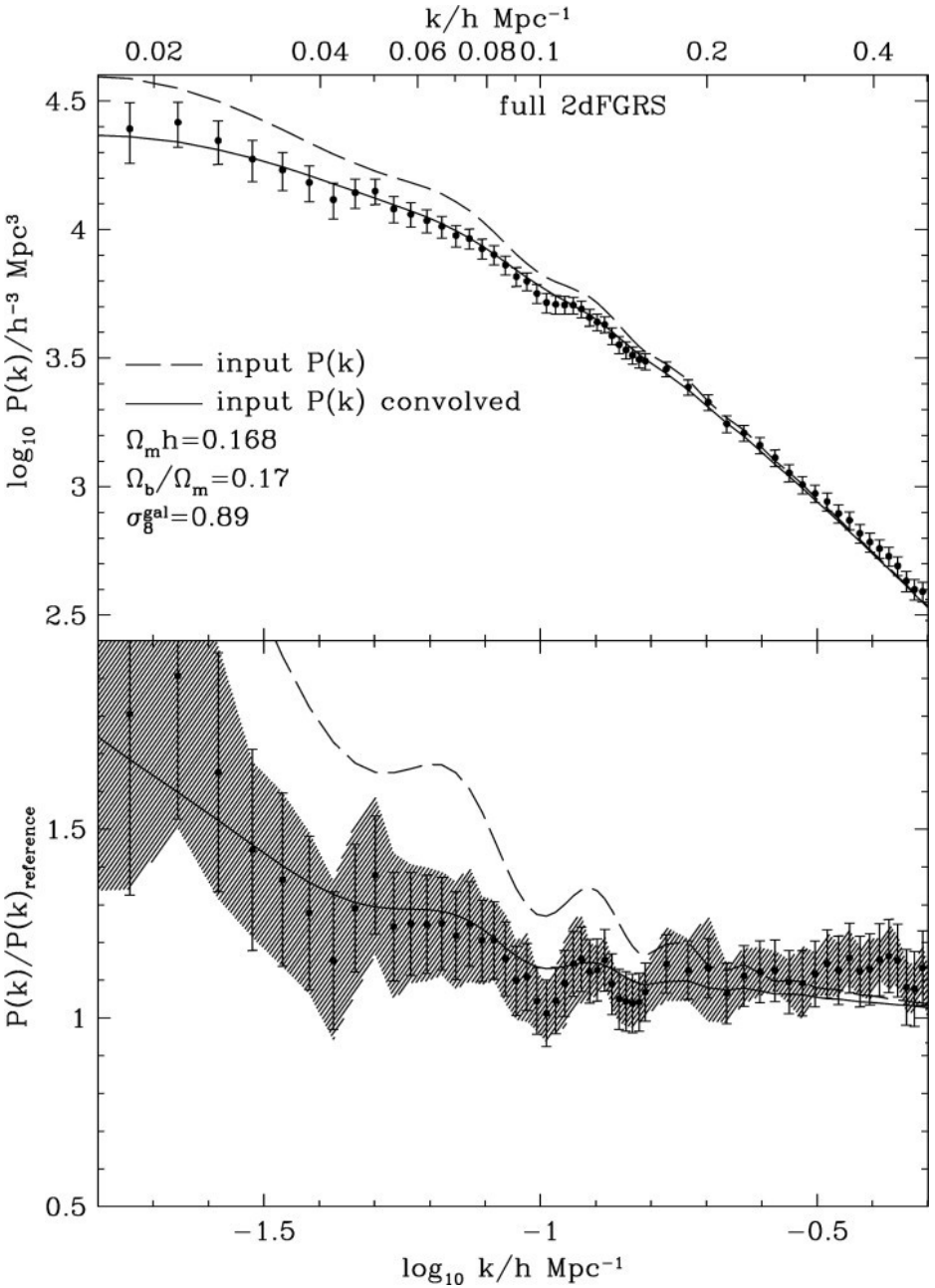
Age of the World



Age of the Universe constrains matter density

Large-Scale Structures





Statistics of cosmological structures: correlation function, power spectrum