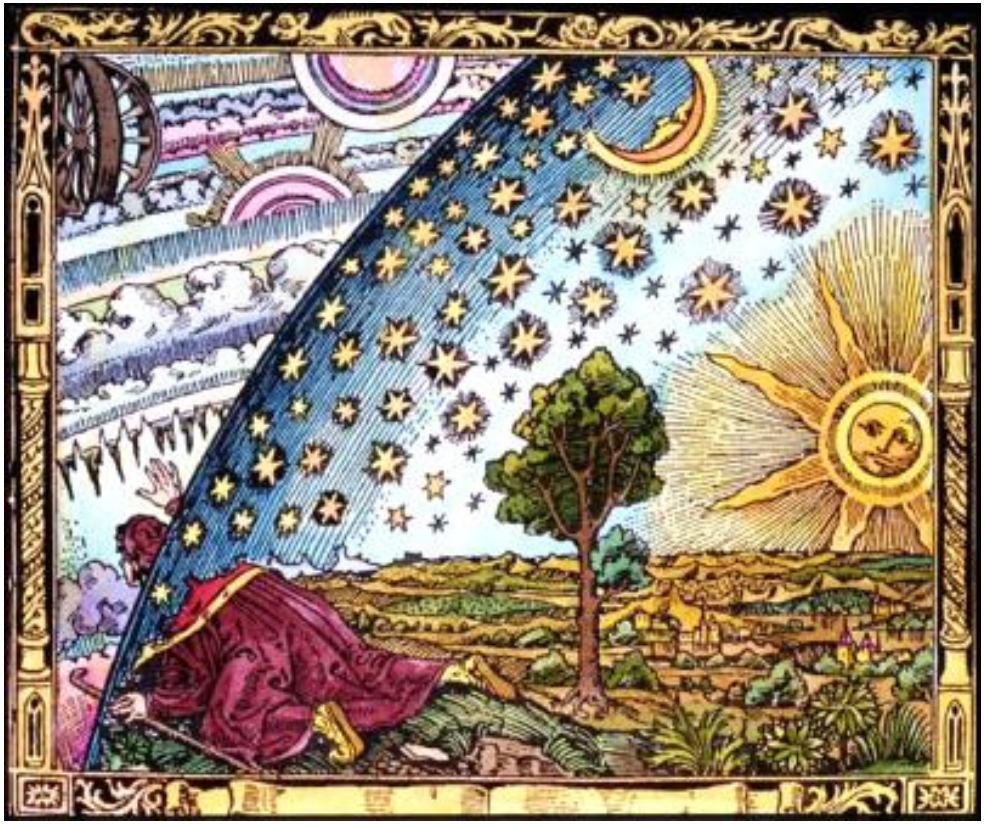
Observational Cosmology

- a laboratory for fundamental physics



BND School
Bruessel 2013
Marek Kowalski

universitätbonn

Outline

1. The standard model of cosmology
2. Cosmological probes & constraints
3. Beyond the standard model
4. Upcoming surveys

Part 1:
The standard model of cosmology

Our Cosmological Framework derives from…

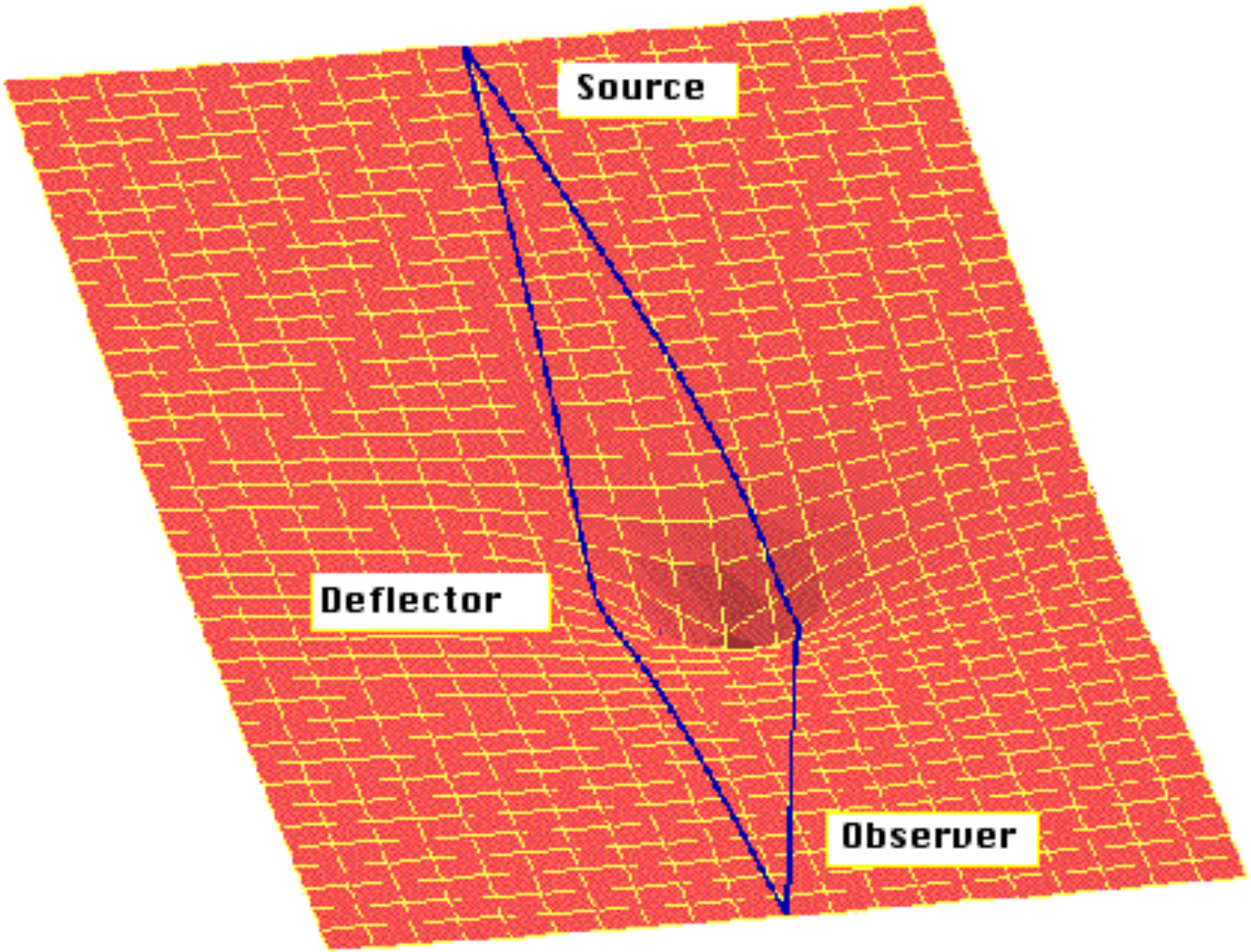
Observation:	The Universe is expanding
Principles:	Homogeneous, isotropic
Theory:	General Relativity

General relativity

Einstein, 1916:
General Relativity

$$\underbrace{-8\pi G T_{\mu\nu}}_{\text{Energy}} = \underbrace{R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R}_{\text{Curvature}}$$

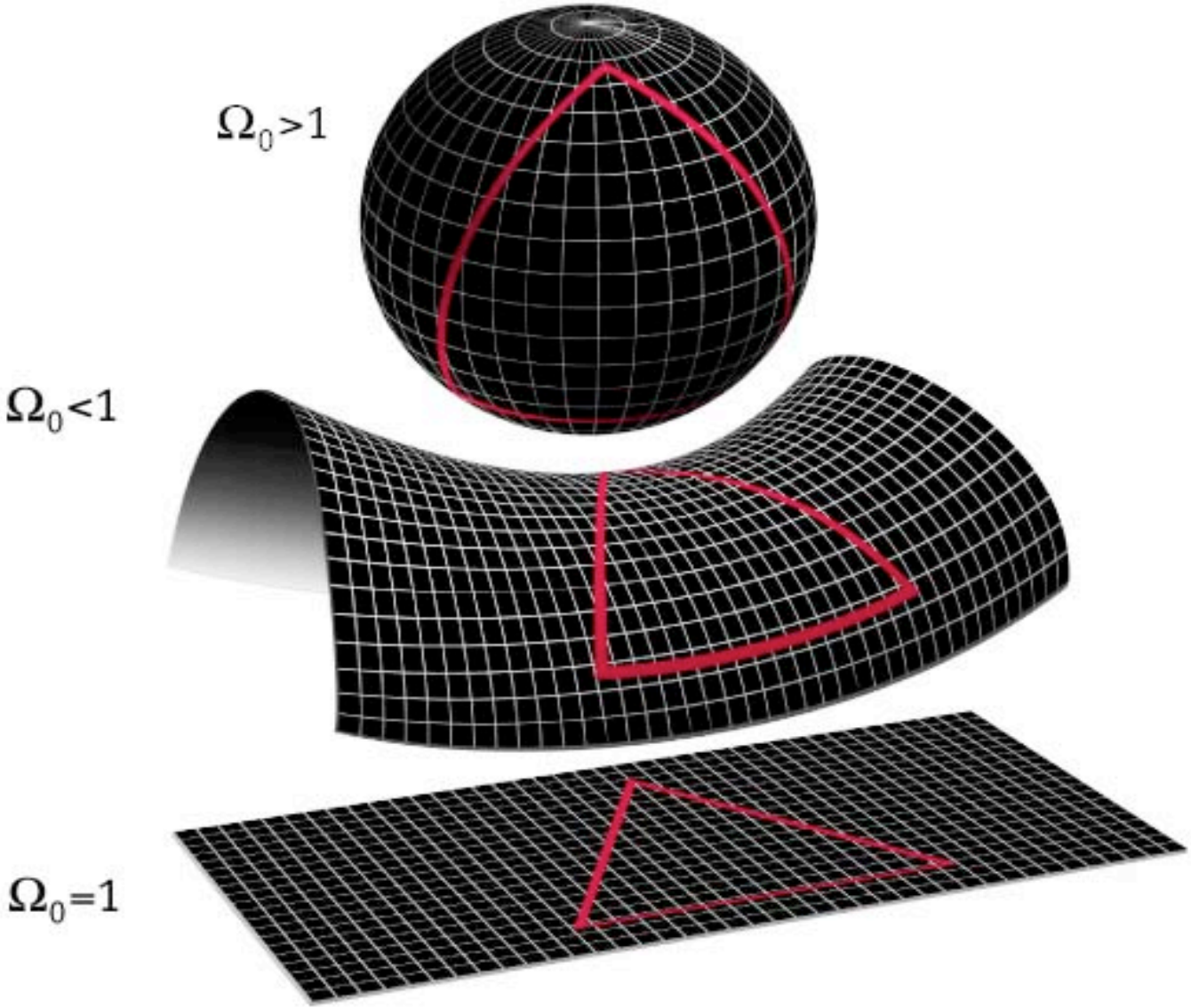
General Relativity: Gravitational bending of light



General Relativity: Gravitational bending of light

Abell 2218: A Galaxy Cluster Lens, Andrew Fruchter et al. (HST)

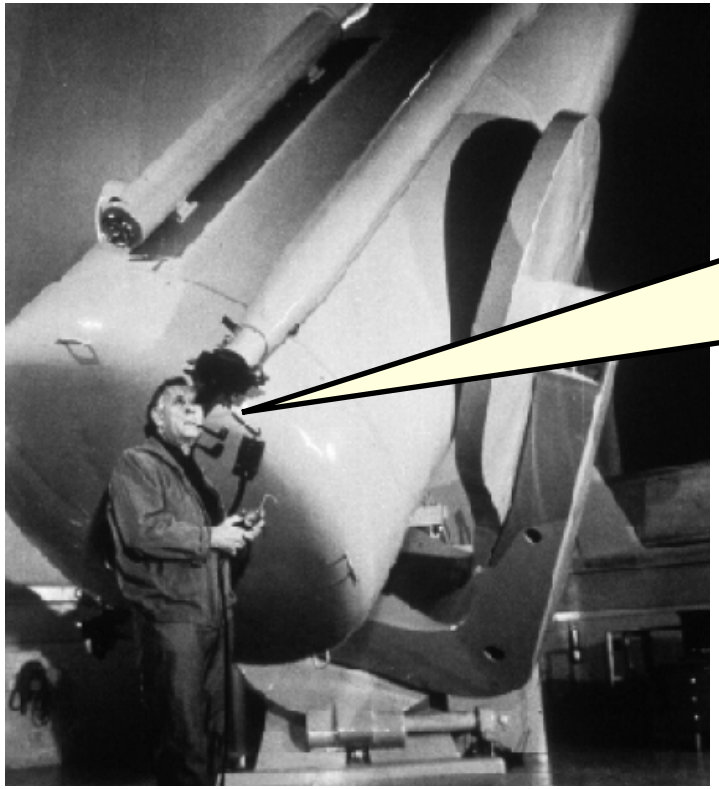
General Relativity:
The Universe can have curvature



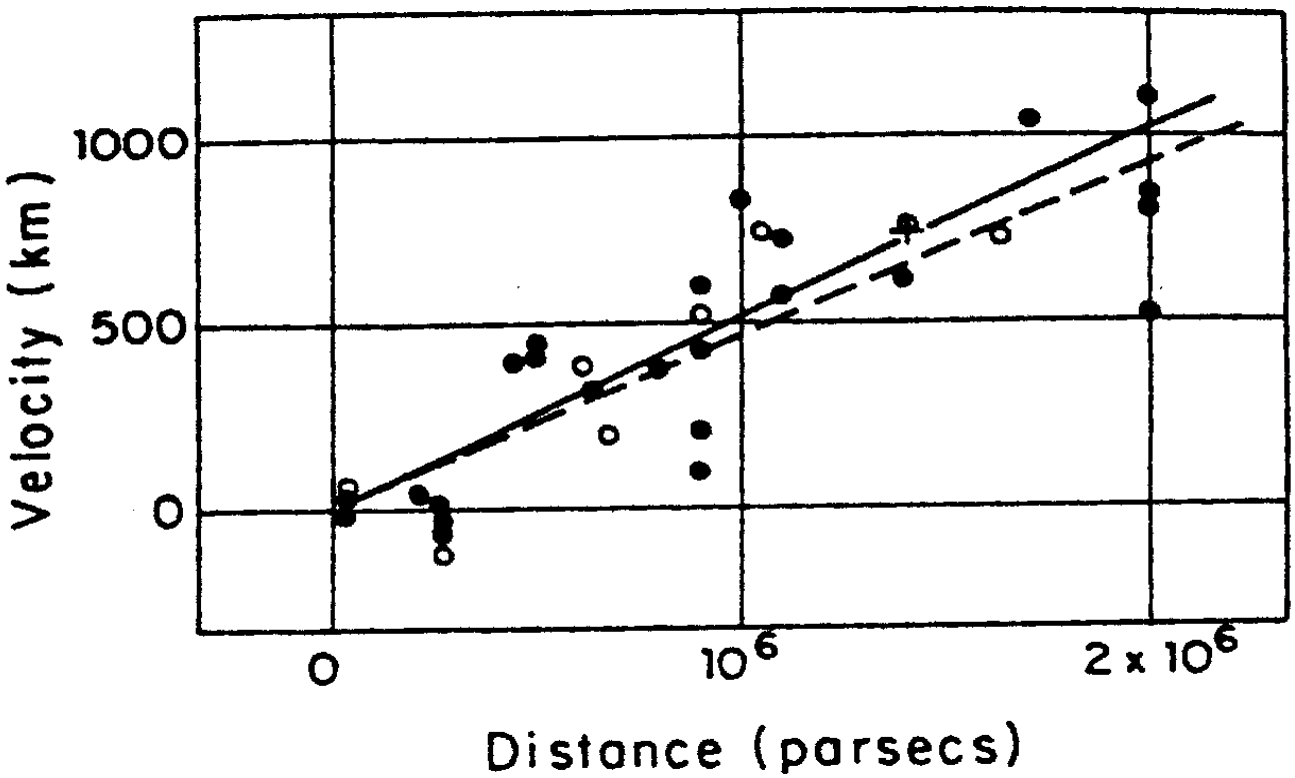
Einstein, 1916:
General Relativity

I want a **static Universe** -
I'll add a **cosmological constant**

$$\underbrace{-8\pi G T_{\mu\nu}}_{\text{Energy}} = \underbrace{R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R}_{\text{Curvature}}$$



The larger the distance to a Galaxy, the faster it is flying away from us: velocity = H_0 x distance

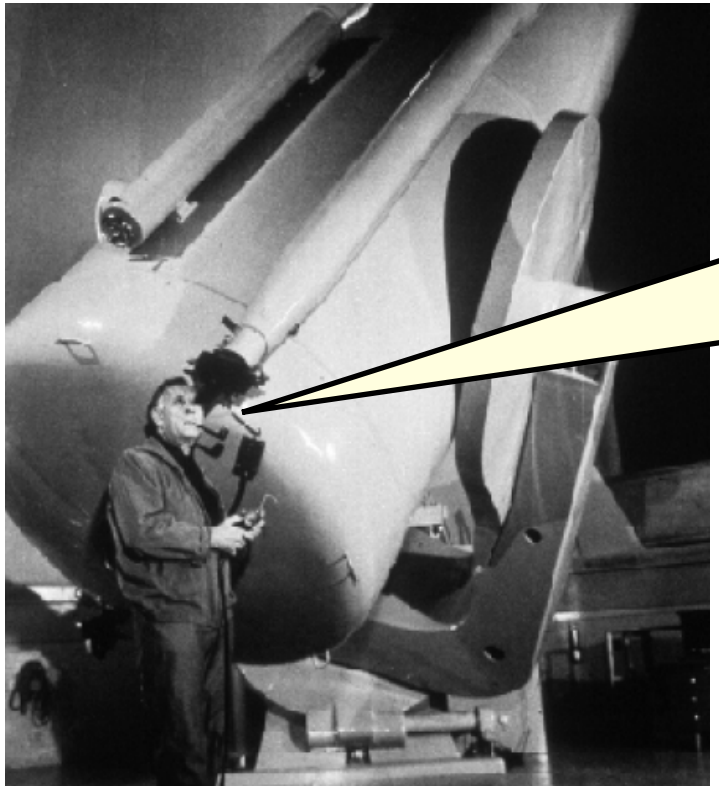


Redshift of spectral lines:

$$z = \frac{\lambda_{obs} - \lambda_{emit}}{\lambda_{emit}}$$

"Doppler effect"

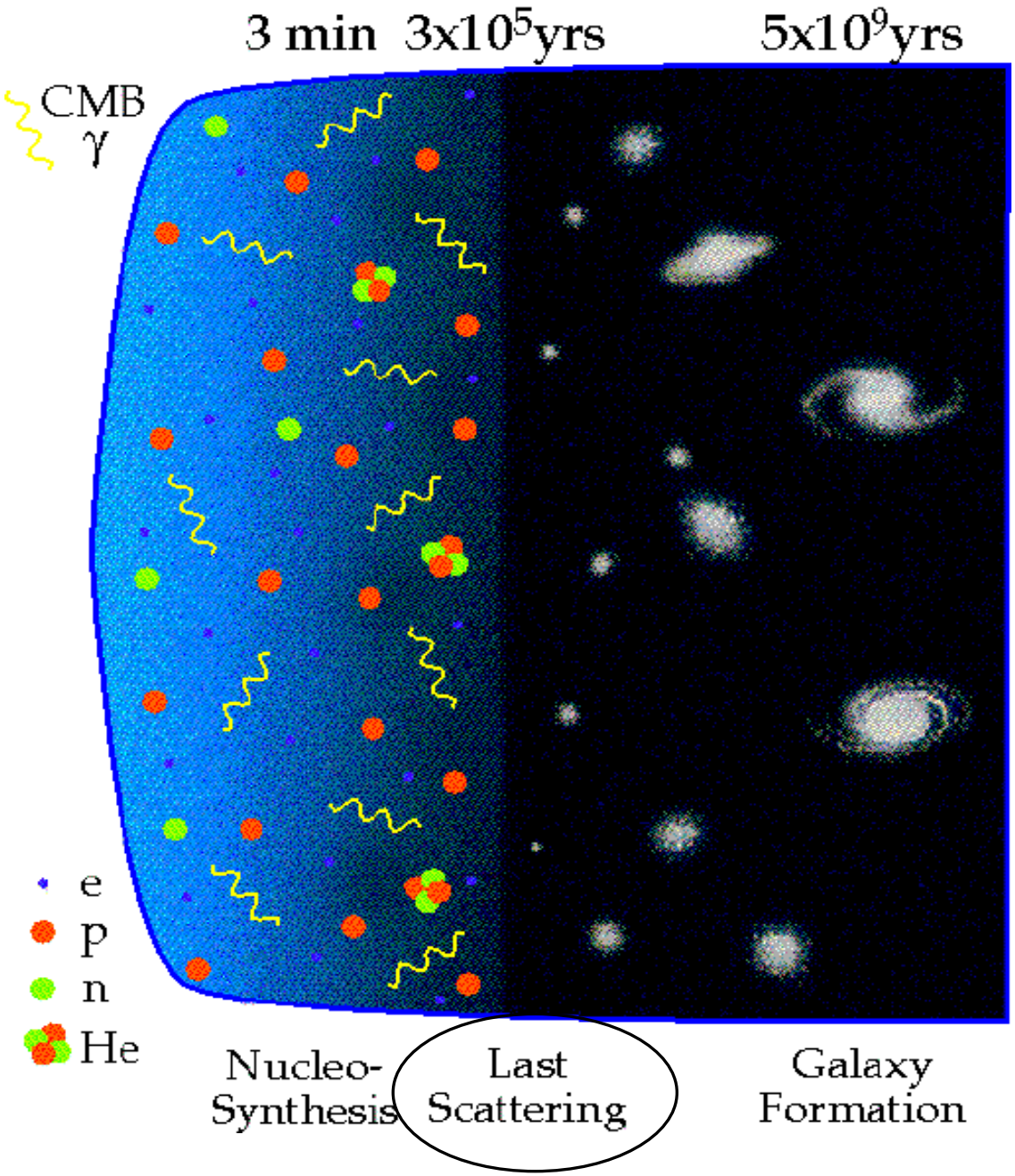
$$v \approx z \cdot (\text{speed of light})$$



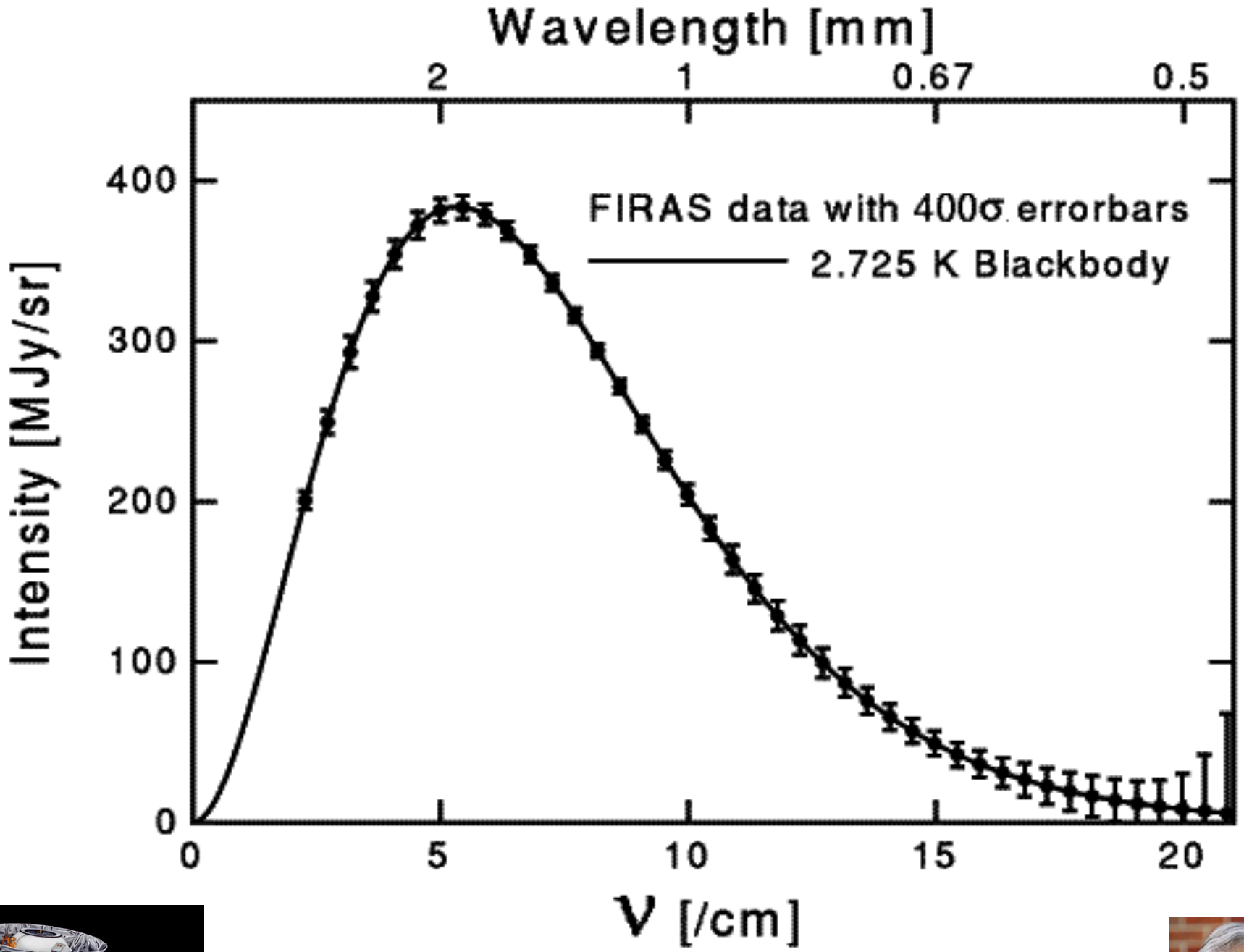
Hubble:
The Universe is expanding!

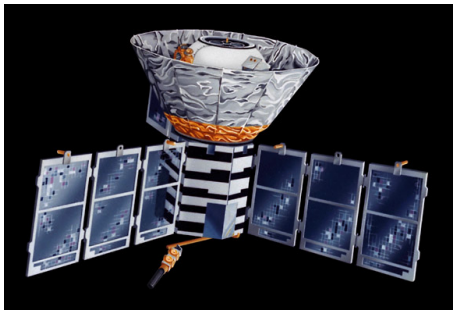
Einstein (much later):
The cosmological constant was the biggest Blunder of my life

(Very) Brief History

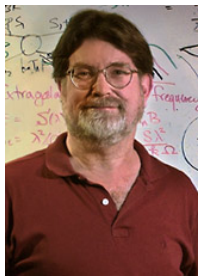


From W. Hu

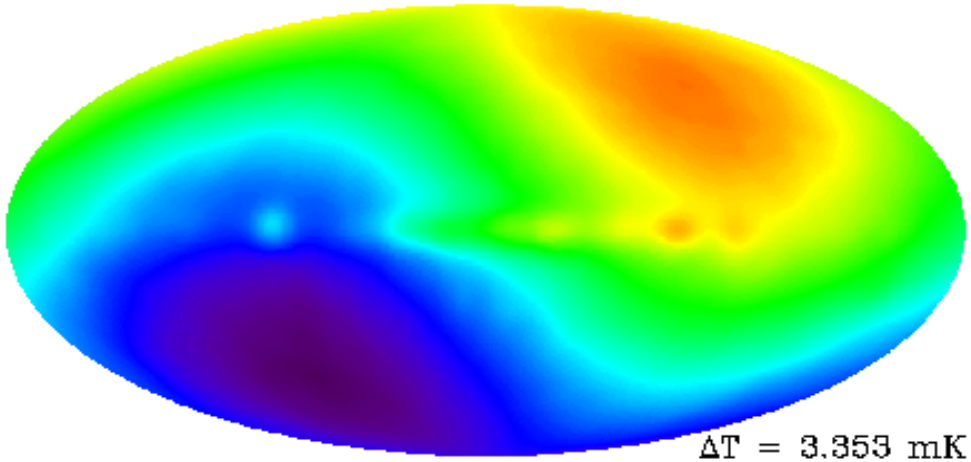




COBE, 1989-1993,
Nobel prize 2006:
George Smoot & John Mather

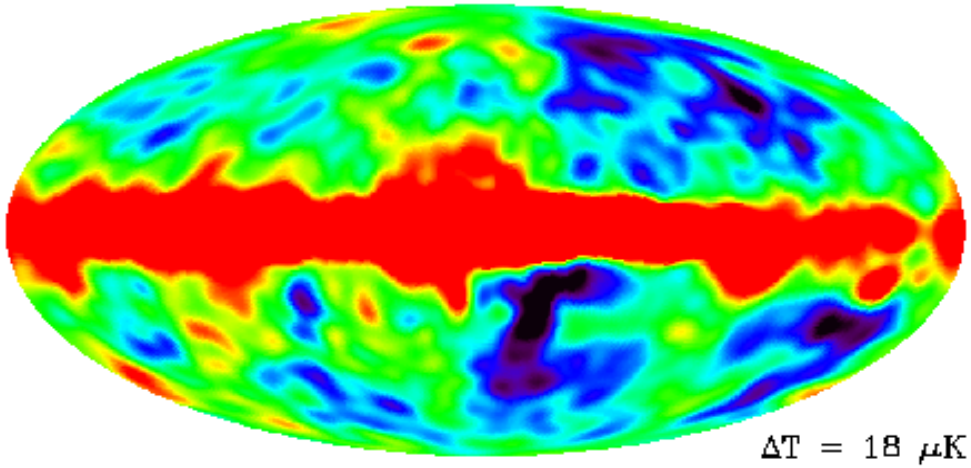


Temperatur-Map



600 km/s Doppler
-Dipol

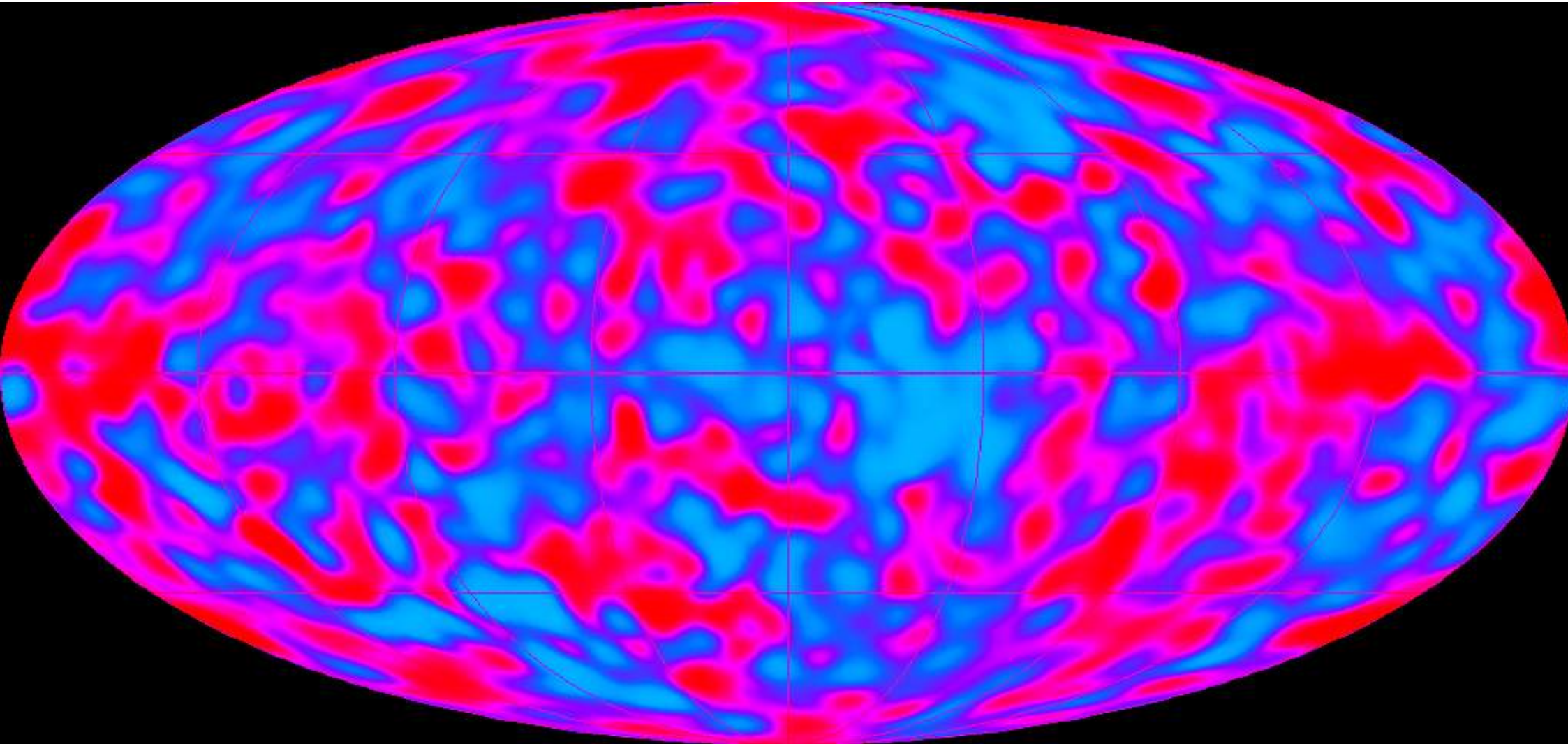
Galactic plane



Dipol subtracted

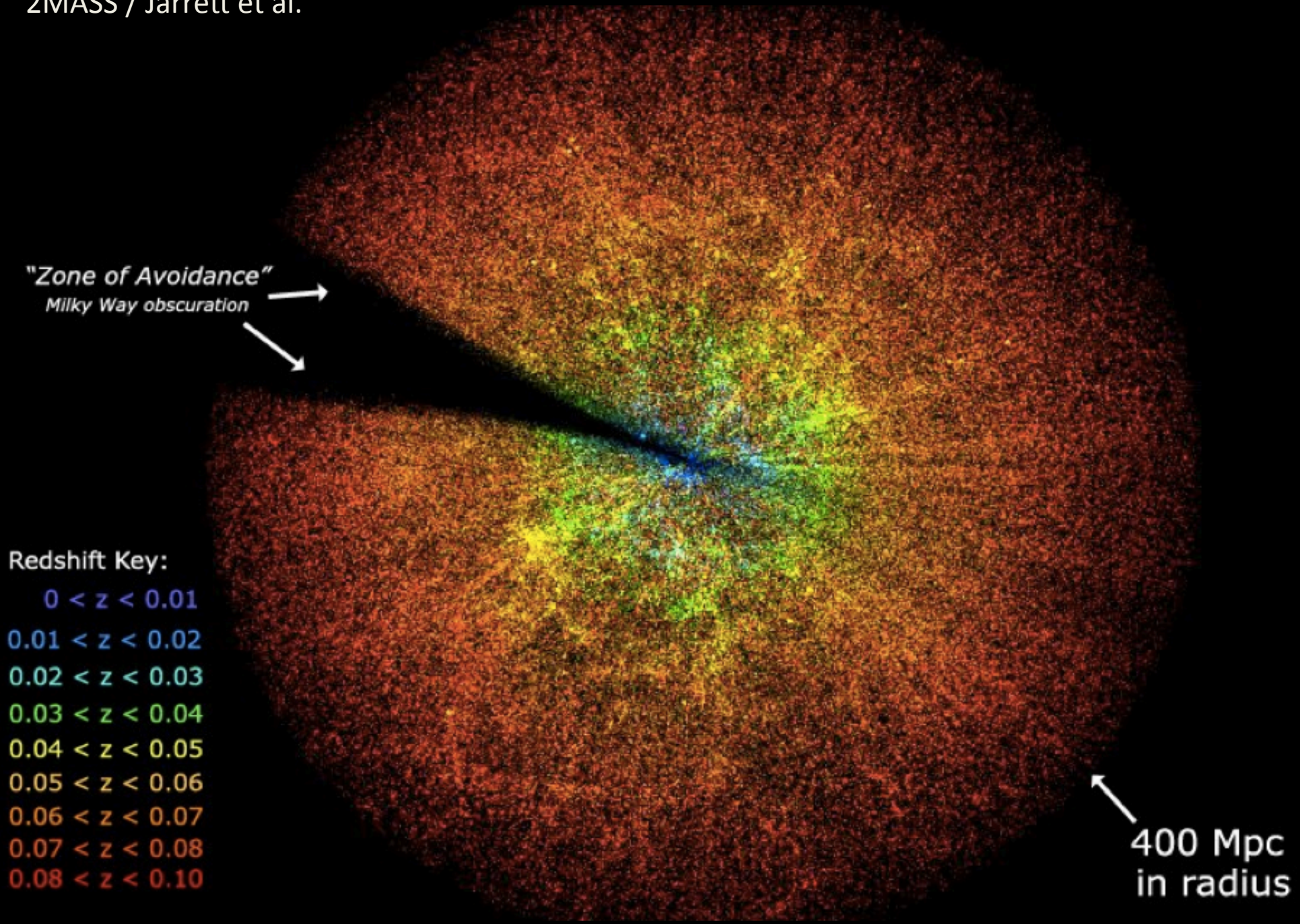
The Universe (i.e. CMB) is remarkable isotropic

COBE Map of CMB Fluctuations
2.725 K +/- ~ 30 μK rms, 7° beam



... and homogeneous on large scales

2MASS / Jarrett et al.



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$$H^2 \equiv \left(\frac{\dot{R}}{R}\right)^2 = \frac{8\pi G}{3}\rho_M + \frac{\Lambda}{3} - \frac{k}{R^2}$$

Friedmann, 1922

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$$\boxed{\Omega_M + \Omega_\Lambda + \Omega_k = 1}$$

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Matter Density

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Matter Density

Cosmological Constant/ Dark Energy

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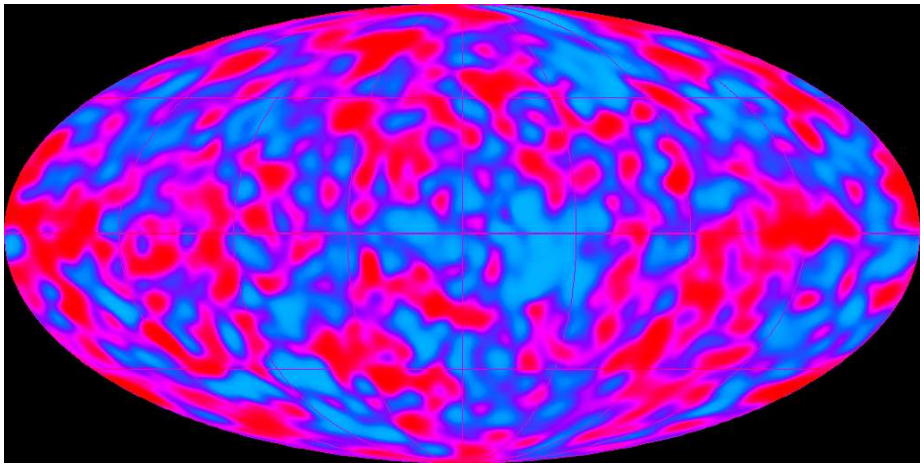
Matter Density

Cosmological Constant/ Dark Energy

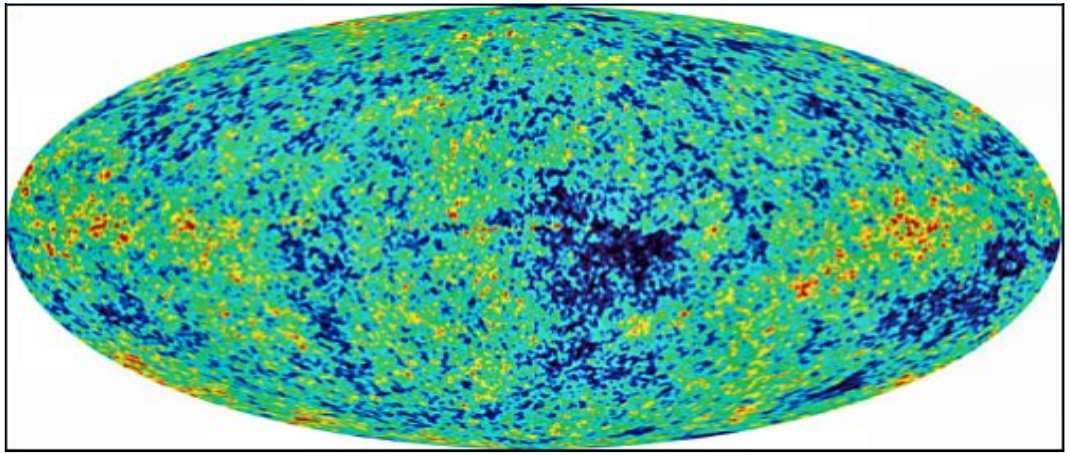
Curvature

Curvature of the Universe & Cosmic Microwave Background (CMB)

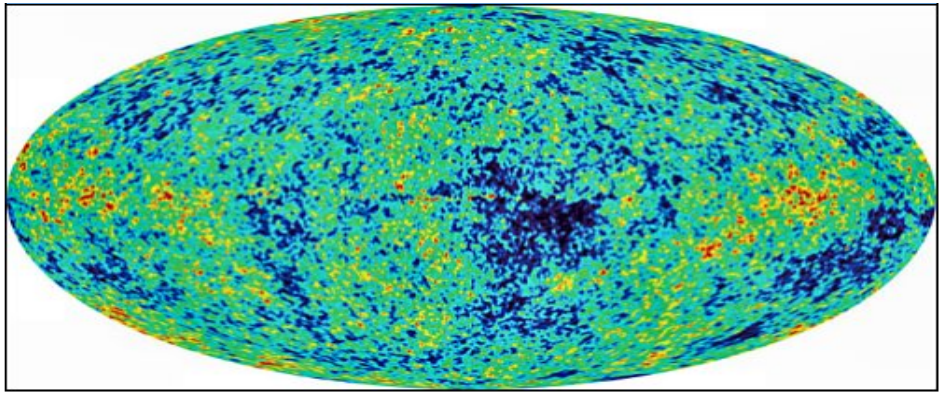
Cobe (1989-1992)



WMAP (2001-2013)



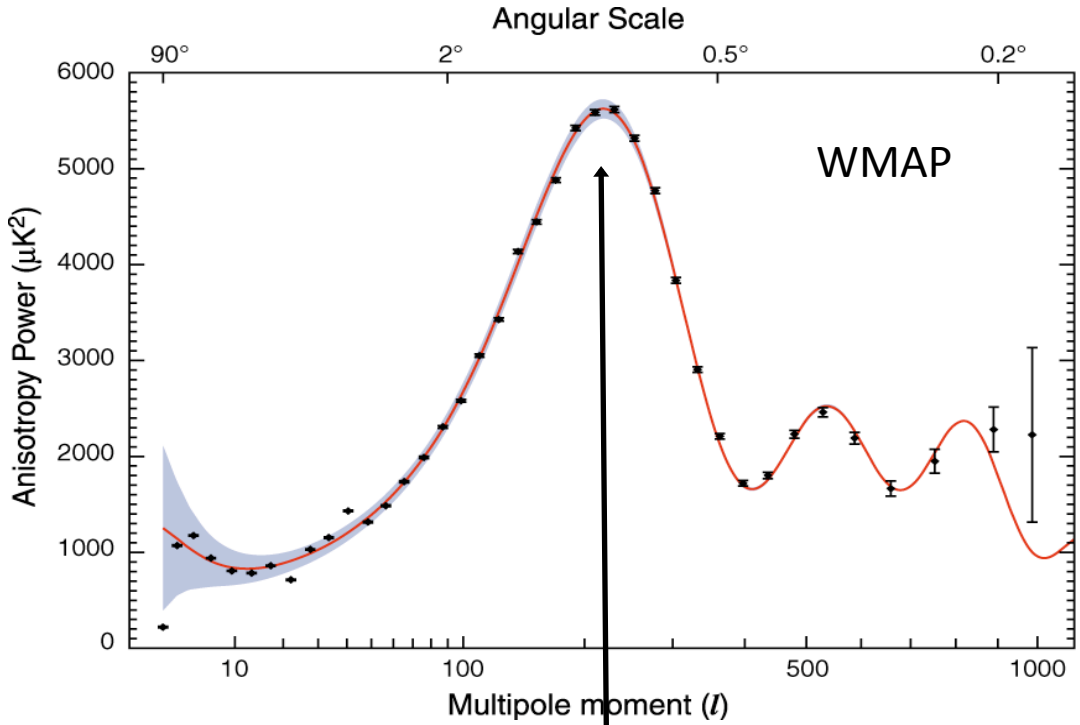
Curvature of the Universe & Cosmic Microwave Background (CMB)



Representation of temperature map In Spherical Harmonics:

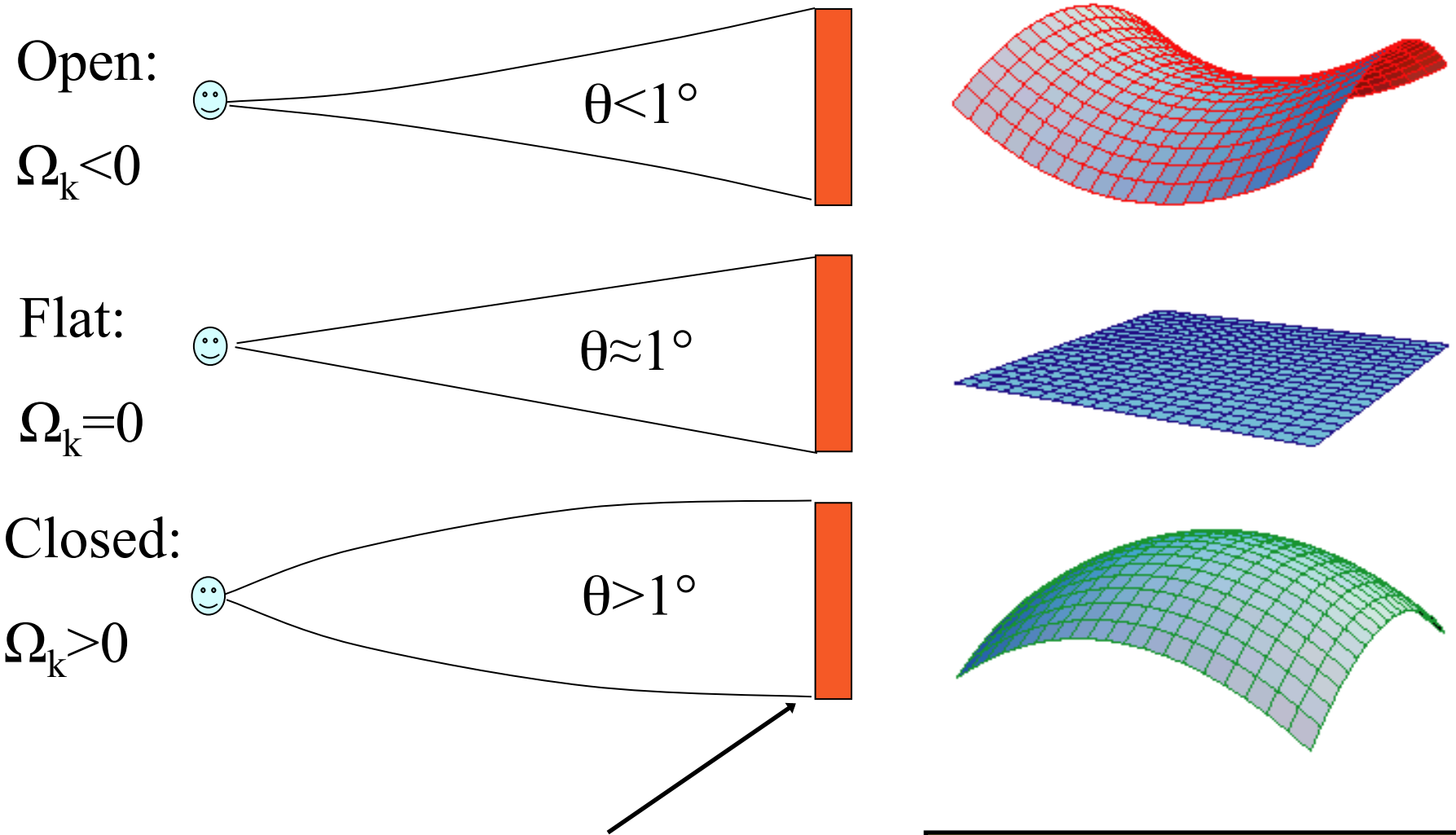
$$\frac{\Delta T}{T} = \sum_{l=2}^{\infty} \sum_{m=-l}^{m=l} a_{lm} Y_{lm}(\theta,\phi)$$

Power spectrum as a function of angular separation



Resonance length ⇔ acoustic horizon

Cosmic Microwave Background (CMB) & Curvature of the Universe



Acoustic horizon$\approx v_s t_{dec}$

$$\Omega_m + \Omega_\Lambda = 1 - \Omega_k \approx 1$$

(Dark) Matter in the Universe

Coma: ~650 galaxies

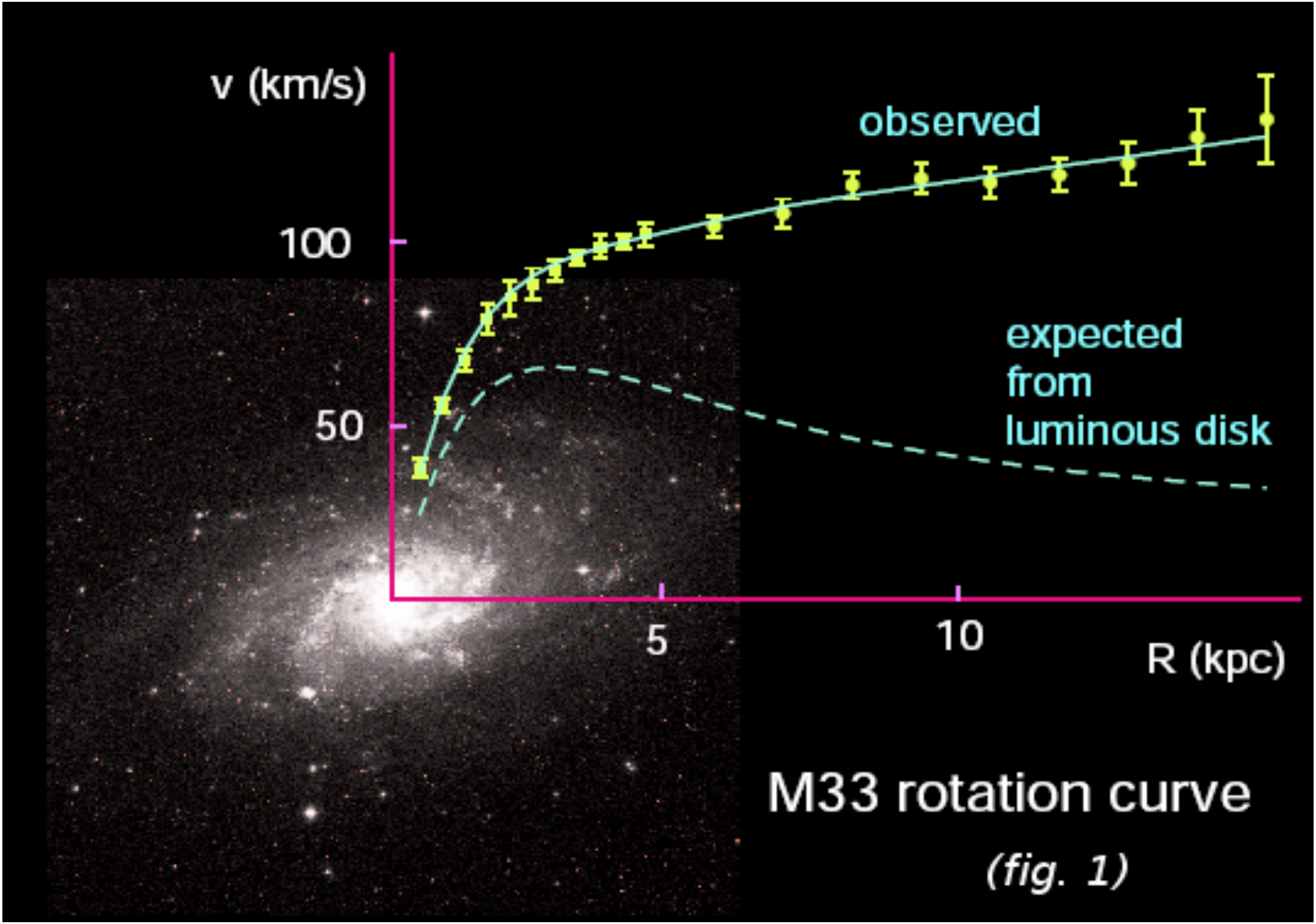
Galaxy Clusters (F. Zwicky, 1933)

Virial Theorem:

$$E_{\text{kin}} = \frac{1}{2} E_{\text{potential}}$$

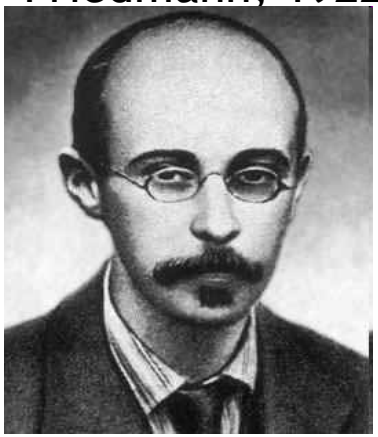
Visible matter can not explain high velocities!

~80% of matter must be **dark**


v (km/s)
observed
100
50
expected
from
luminous disk
5
10
R (kpc)
M33 rotation curve
(fig. 1)

The cosmological constant Λ

Friedmann, 1922:

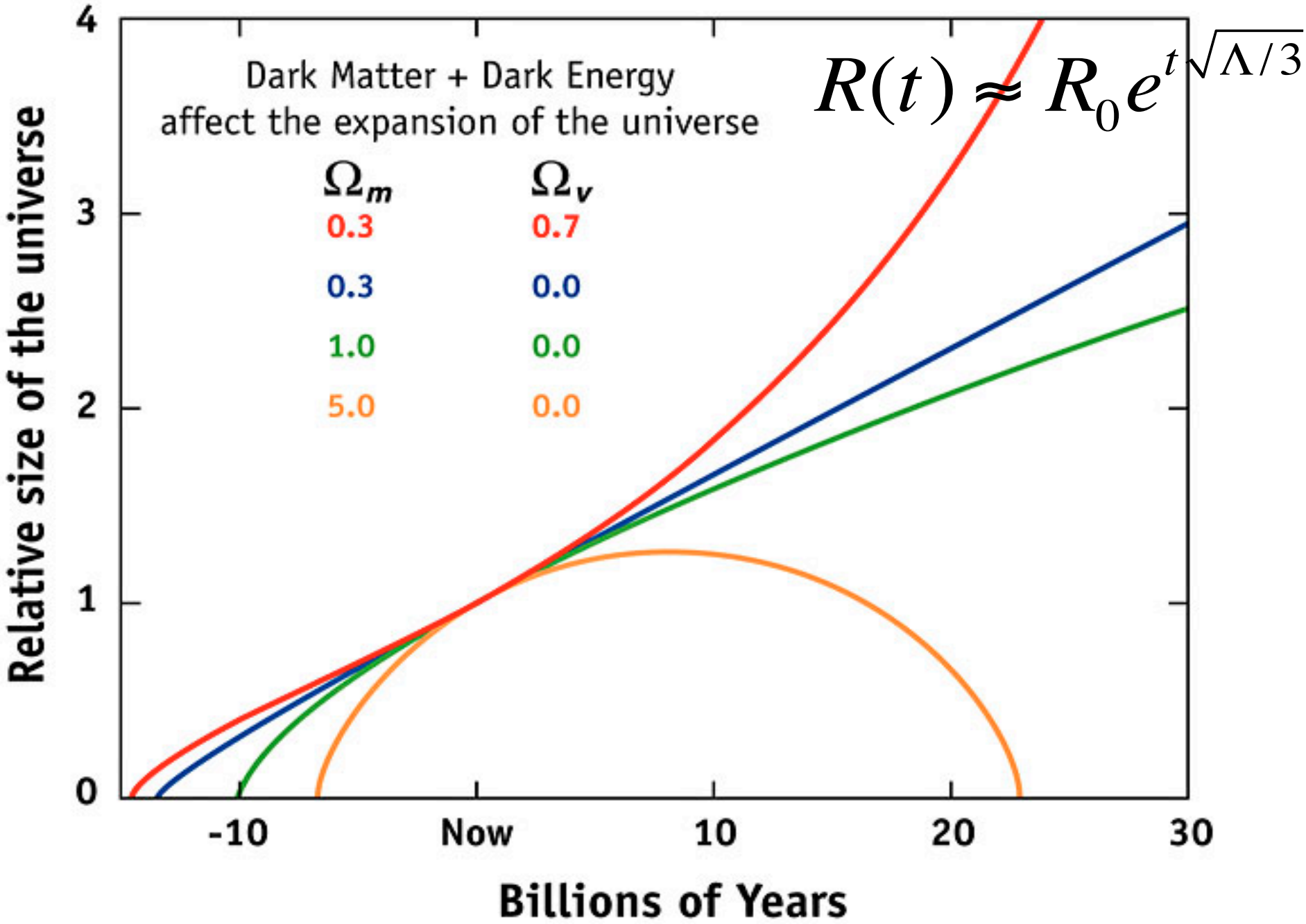


$$\left(\frac{\dot{R}}{R}\right)^2 = \frac{8\pi G}{3}\rho_M + \frac{\Lambda}{3}$$

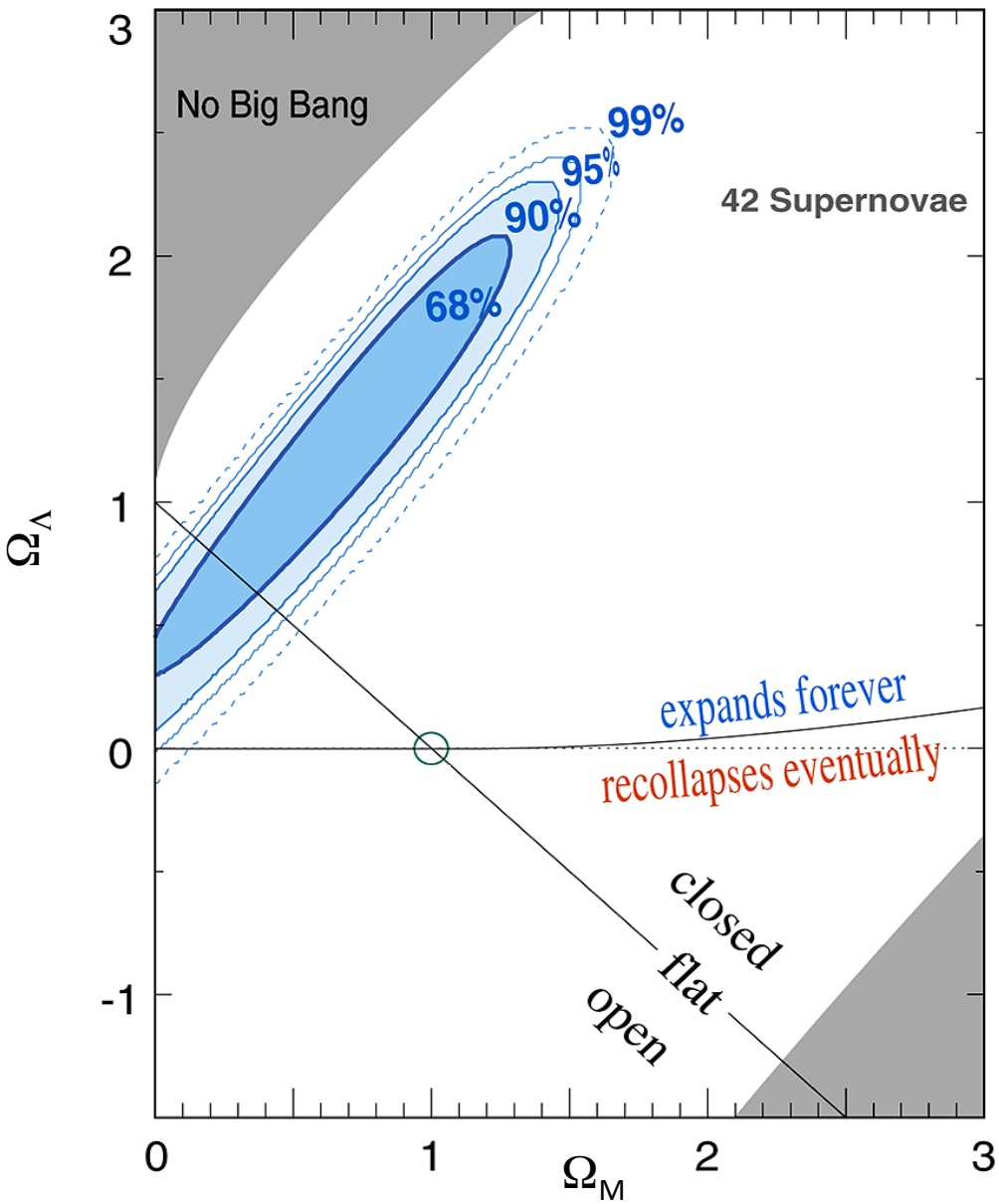
For a Universe without matter, $\rho_M = 0$, the solution is simple:

$$\mathrm{R(t)} \propto \mathrm{e}^{t\sqrt{\Lambda/3}}$$

The cosmological constant Λ

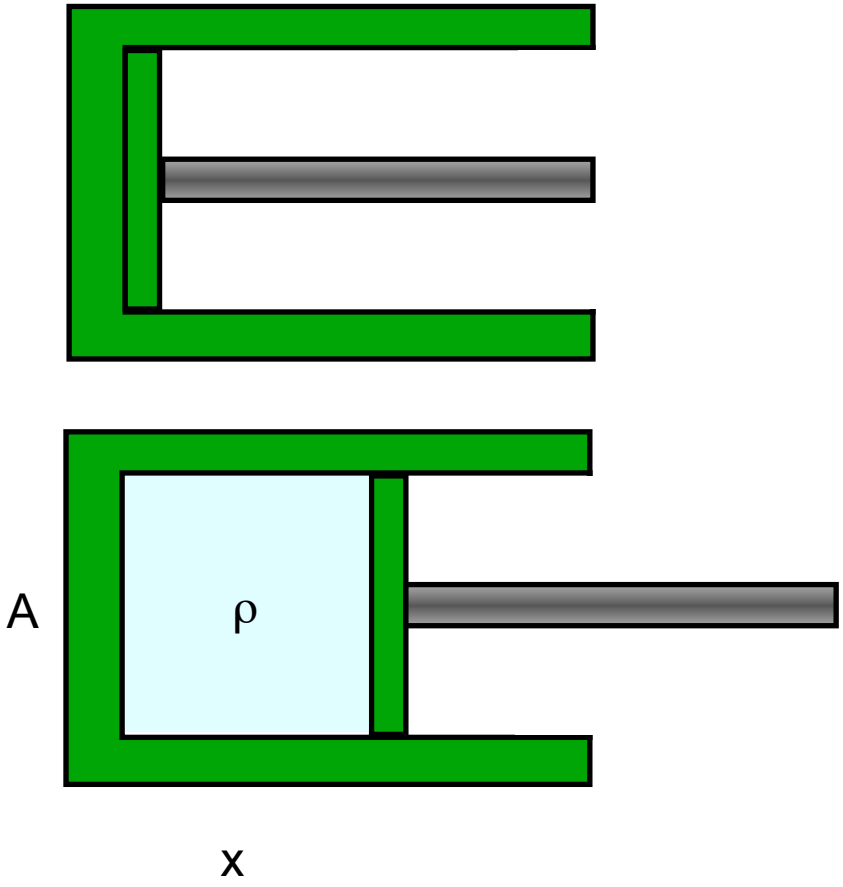


1998: Discovery of Dark Energy



Nobel prize for physics 2011

Vacuum Energy ⇔ Cosmological Constant



Zeldovich 1968

Vacuum energy:
Before: $E = 0$
After: $Ax\rho>0$

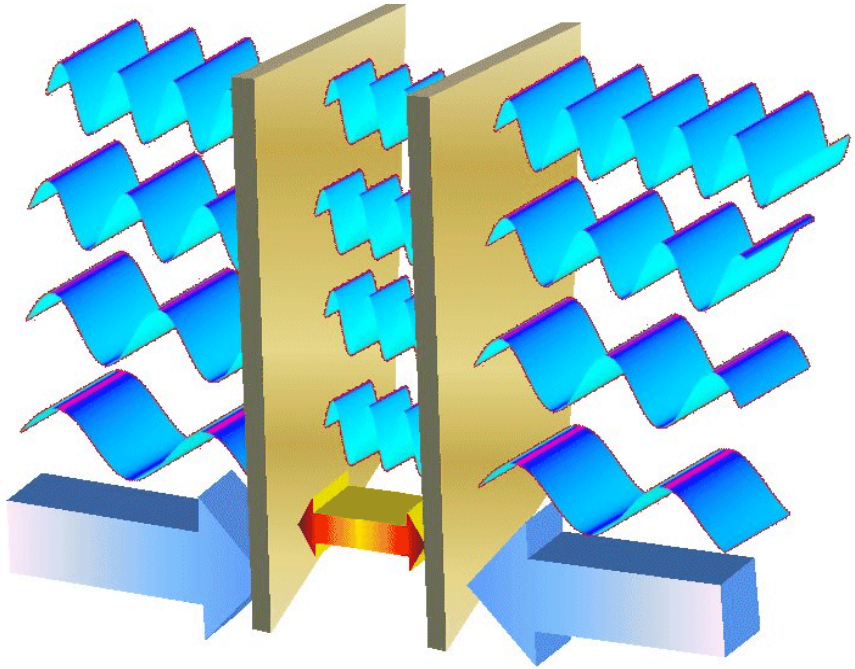
Pressure (*p*) of Vacuum energy follows with assumption of energy conservation:
$Ax\rho+Axp = 0 \Rightarrow \mathbf{p = -\rho}$

Vacuum energy has all the properties of the Cosmological constant Λ, i.e. it has negative pressure.

Vacuum Energy

Ground-state of a scalar Quantum-field:

$$E_0 = \frac{1}{2}\sum_i \hbar\omega_i$$



Casimir effect ⇔ Energy difference

Vacuum-Energy density:
(with ultraviolet cut-off k_{max})

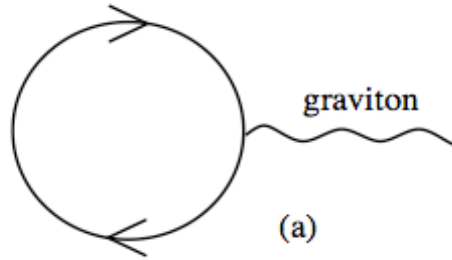
$$\rho_{vac} = \frac{1}{2}\frac{\hbar}{(2\pi)^3}\int_0^{k_{max}} k d^3k = \frac{\hbar k_{max}^4}{16\pi^2}$$

However, there is a problem

Observed energy density

$$\rho_\Lambda^{\text{obs}} \sim (10^{-12}\ \text{GeV})^4 \sim 10^{-7}\text{GeV/cm}^3$$

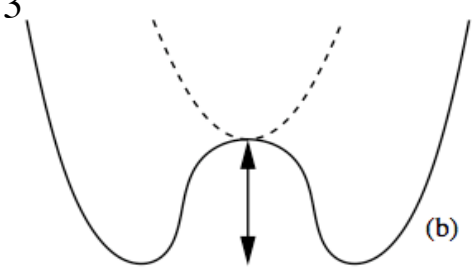
Expected energy density: $\rho \sim k_{\text{max}}^4$



Gravitation: $\rho_\Lambda^{Pl} \sim (M_{\text{Planck}})^4 \sim (10^{18}\text{GeV})^4 \sim 10^{113}\text{GeV/cm}^3$

SUSY: $\rho_\Lambda^{SUSY} \sim (M_{\text{SUSY}})^4 \sim (10^{3}\text{GeV})^4 \sim 10^{53}\text{GeV/cm}^3$

Electroweak: $\rho_\Lambda^{EW} \sim (M_{\text{EW}})^4 \sim (246\ \text{GeV})^4 \sim 10^{51}\text{GeV/cm}^3$



Fundamental Problems of Vacuum Energy/Cosmological Constant:

Why so small?

Expectation: $\rho_\Lambda \sim (M_{\text{planck}})^4$

$\Rightarrow$120 orders of magnitudes larger then the observed value!

Why now?

Matter: $\rho \propto R^{-3}$

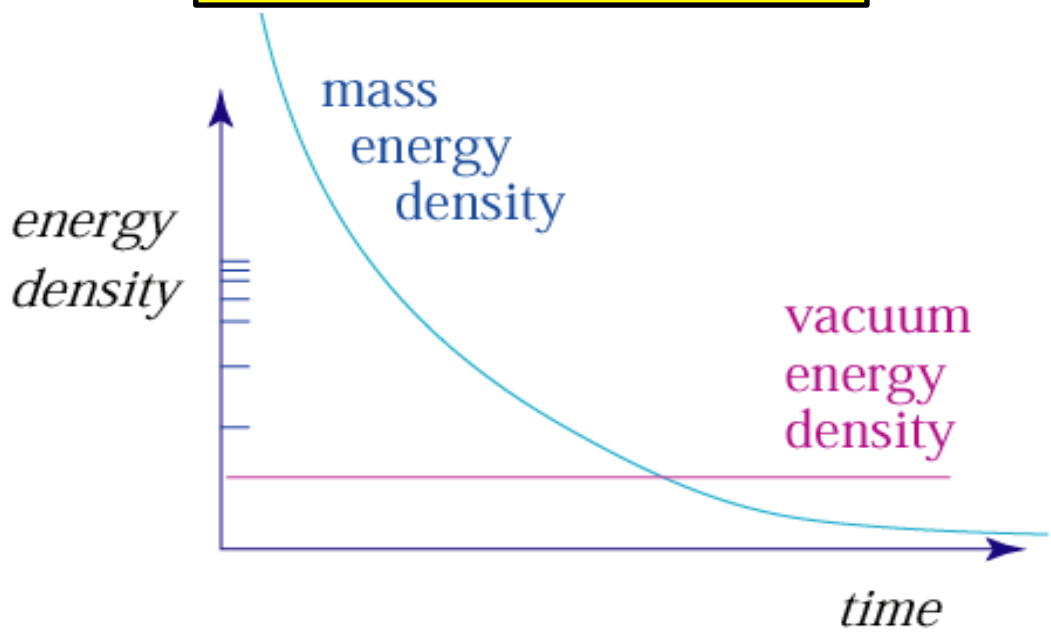
Vakuum Energy: $\rho = constant$

Dark Energy with equation-of-state:

$p = w\rho$

(p = pressure; ρ = density)

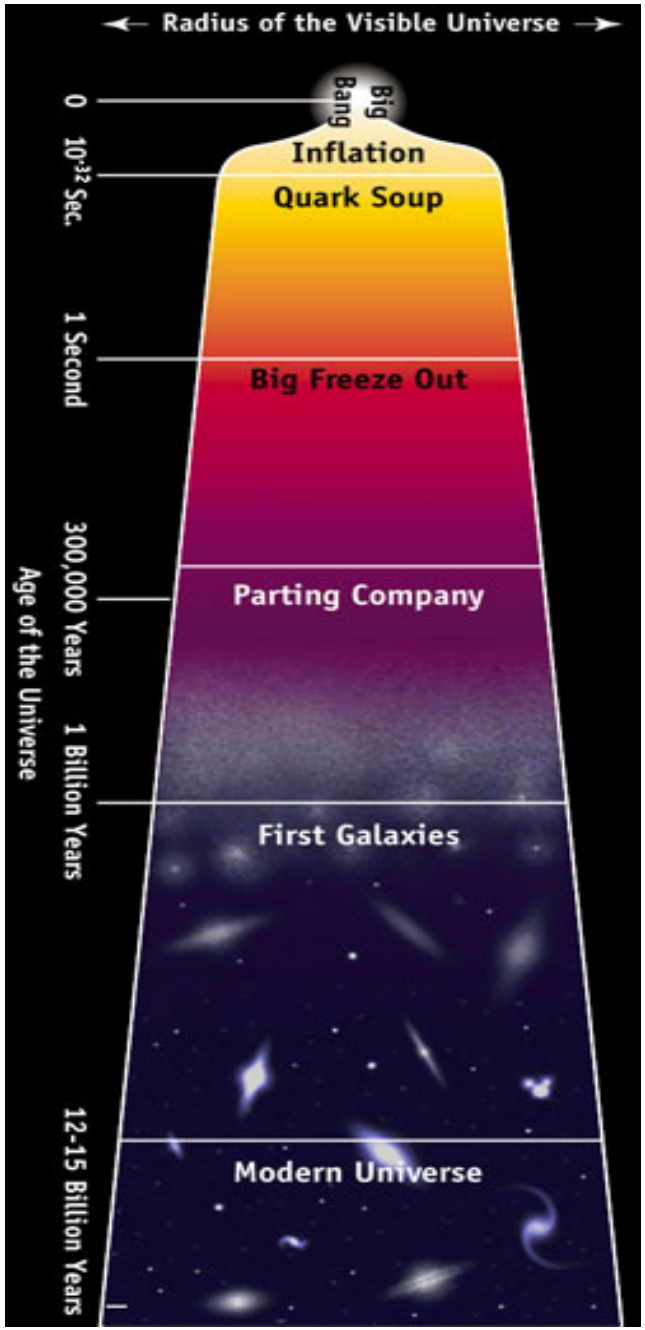
$\Rightarrow \rho \propto R^{-3(1+w)}$



The standard model of cosmology: ΛCDM

Ingredients of ΛCDM:

- Cold Dark Matter
- Cosmological constant
- Baryons
- 3 light neutrino flavors
- Ampl. of primord. fluctuations
- Index of power spectrum



The standard model of cosmology: ΛCDM

Beyond the standard model:

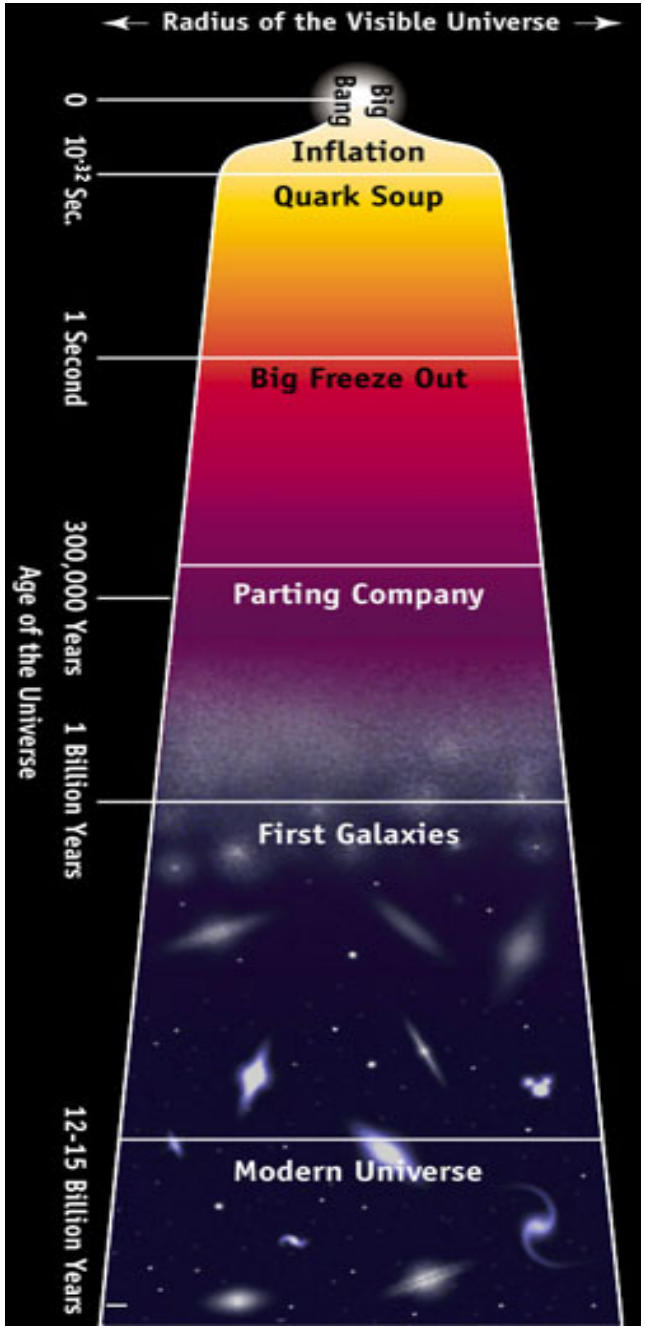
- **Non-Λ dark energy**
- Hot dark matter,

  e.g. **massive neutrinos**
- Additional relativistic species,

  e.g **extra neutrino species**
- Tensor perturbations

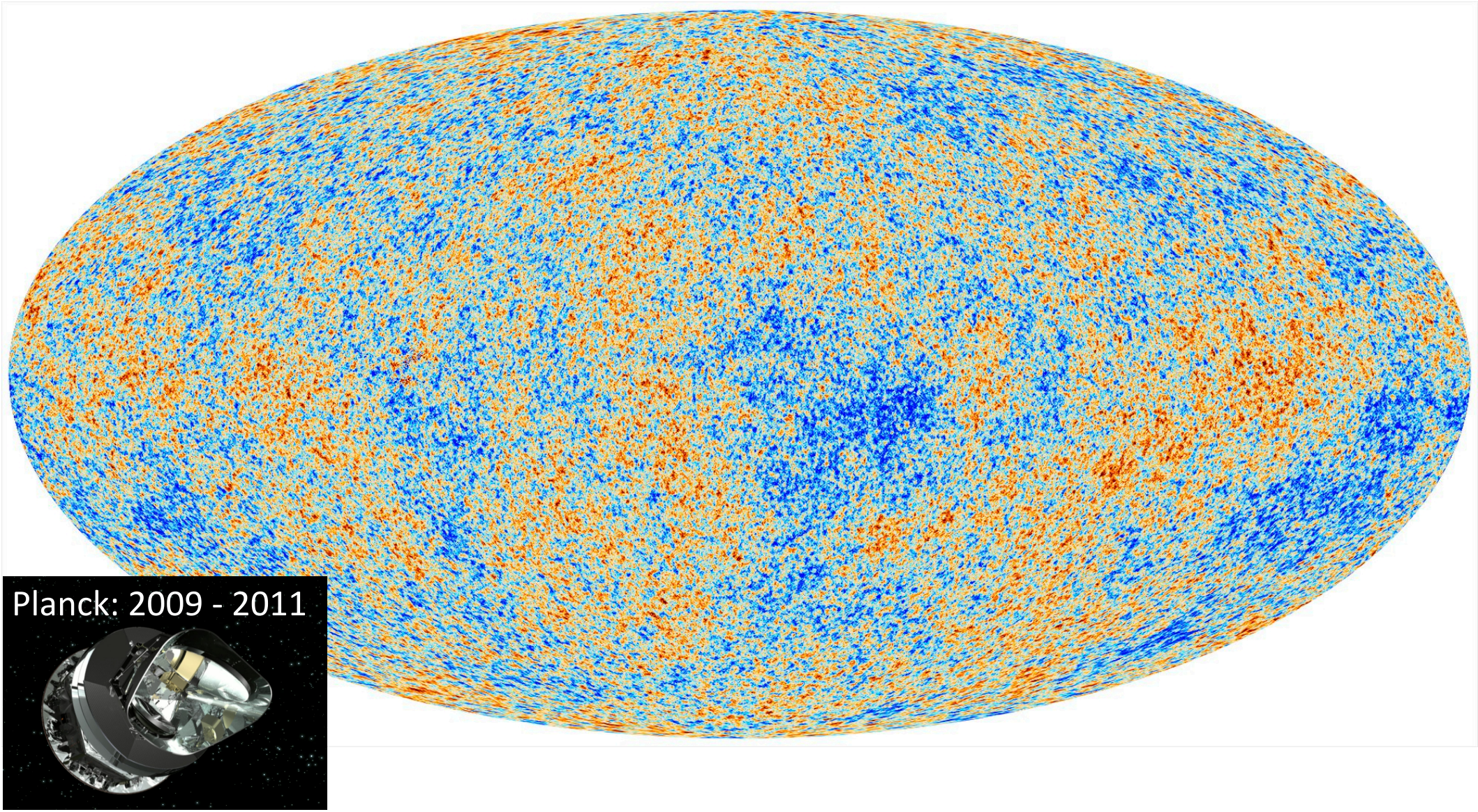
  & running spectral index

  ⇒ **physics of inflation**



Part 2.
Cosmological probes & constraints
Selected new results

Cosmic Microwave Background



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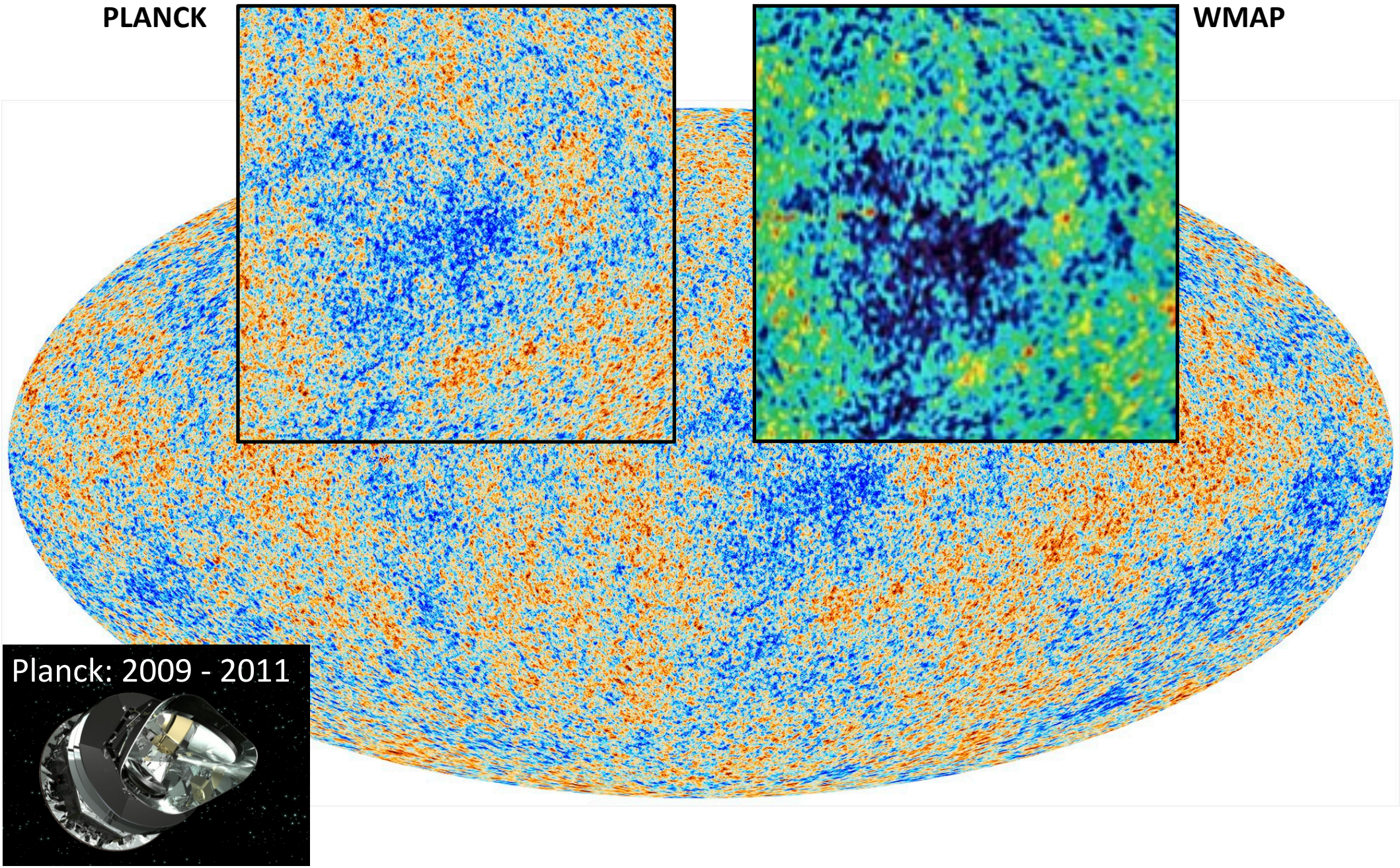

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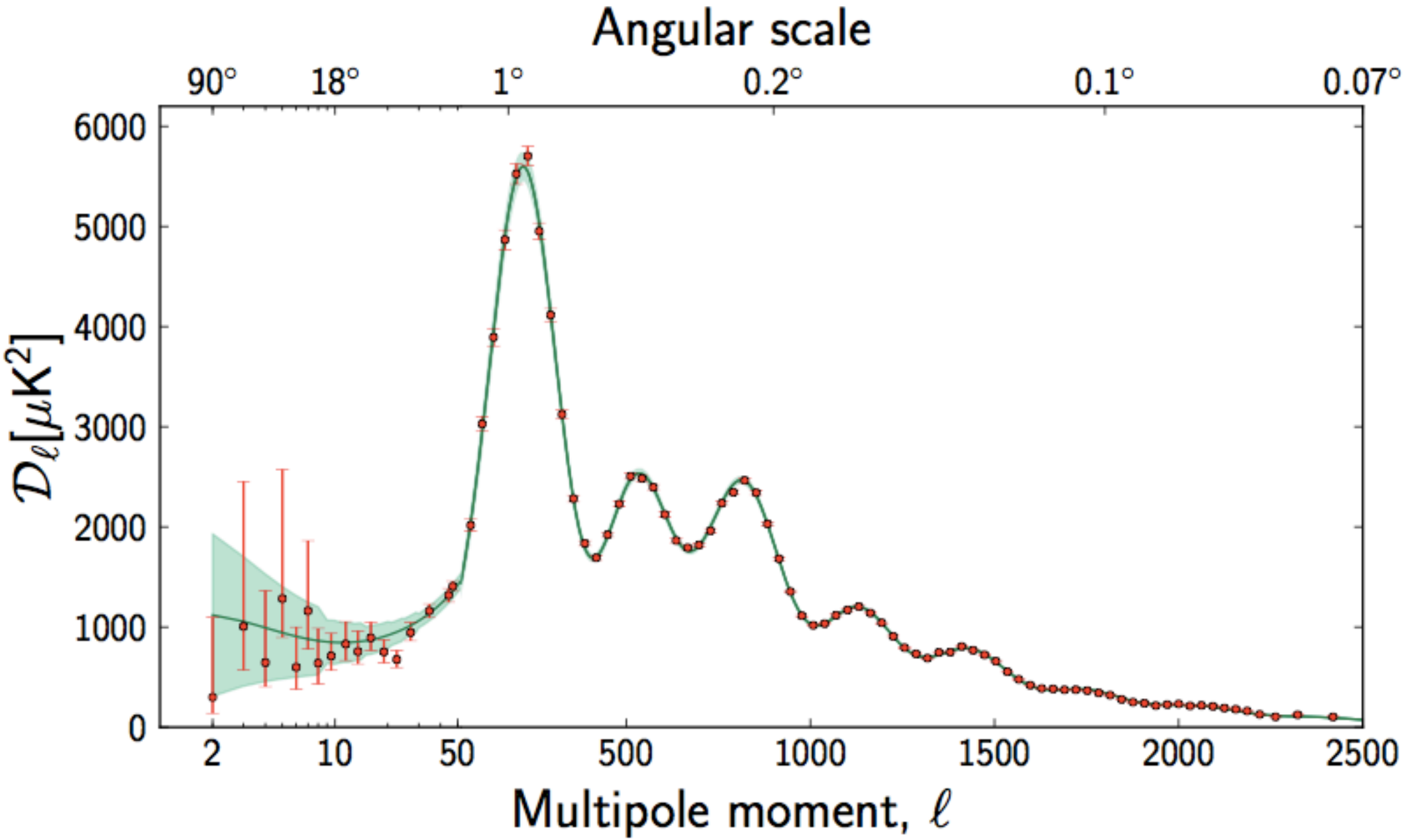

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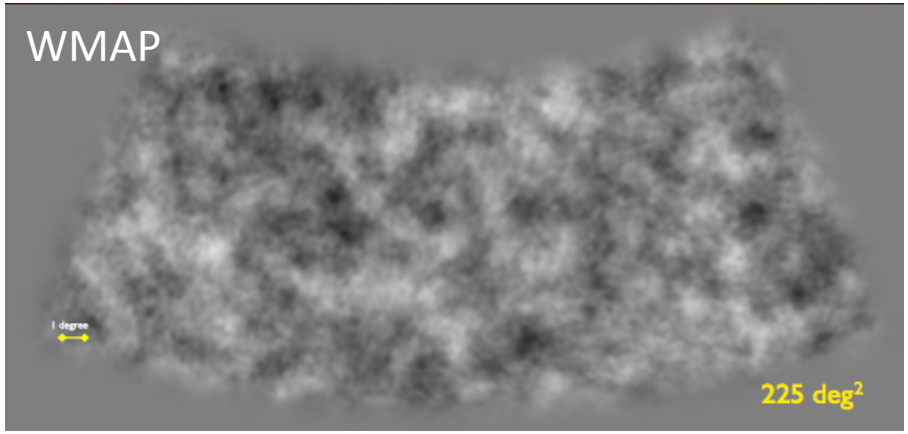
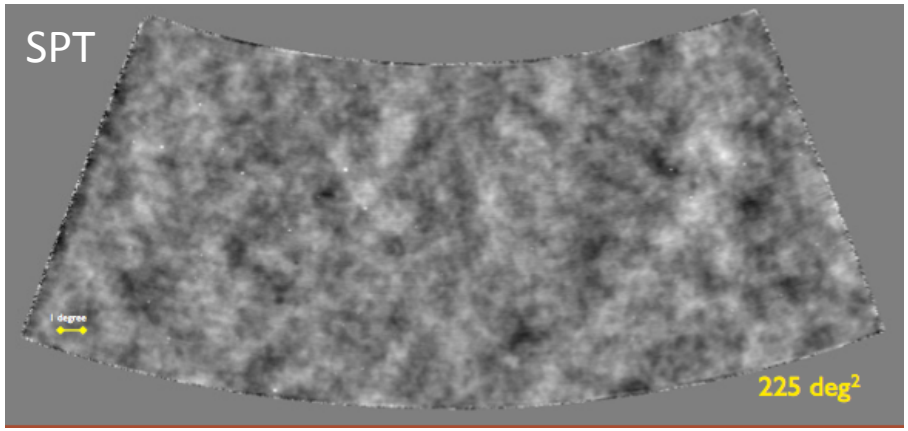
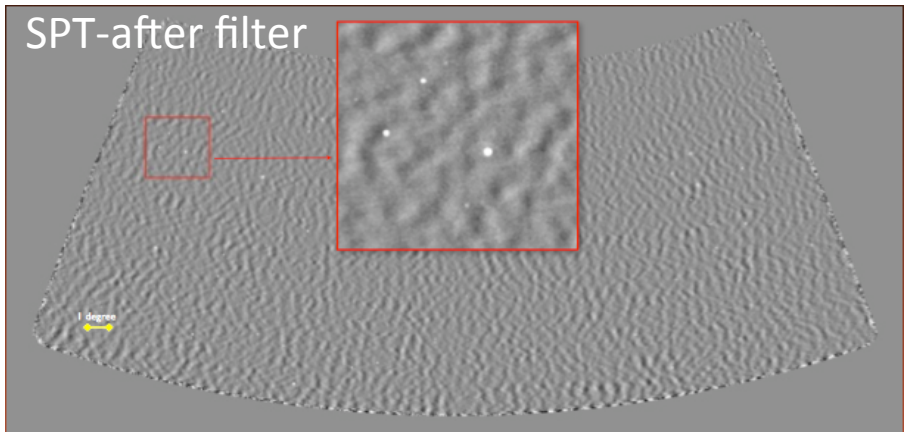
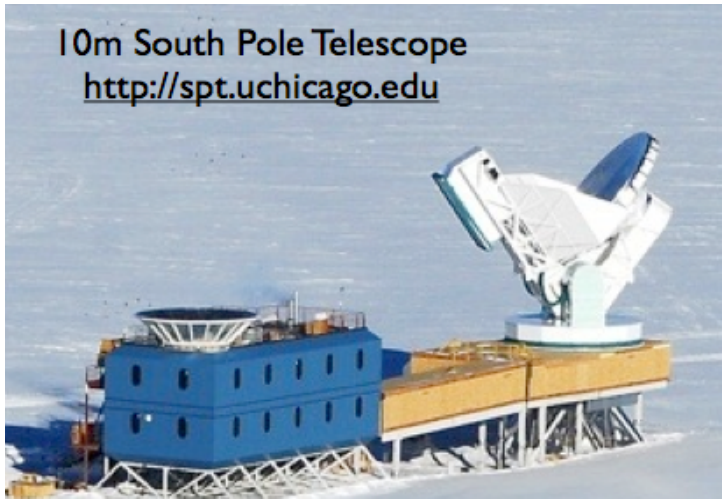






New ground based data from:
South Pole Telescope (SPT) &
Atacama Cosmology Telescope (ACT)



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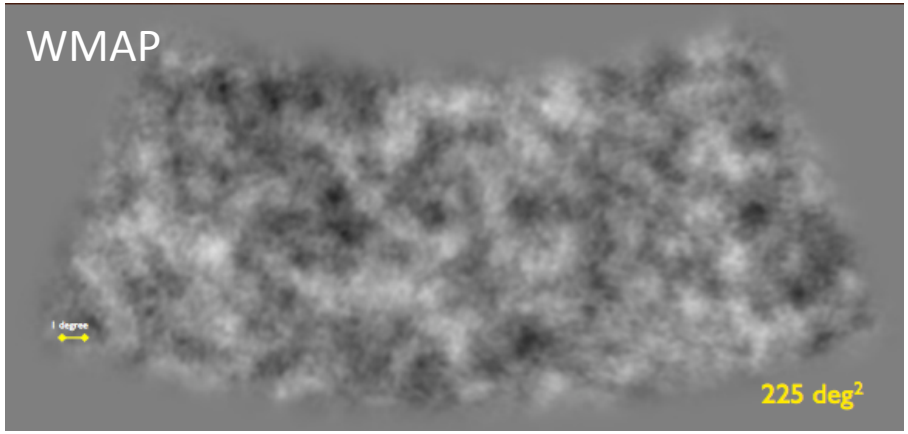

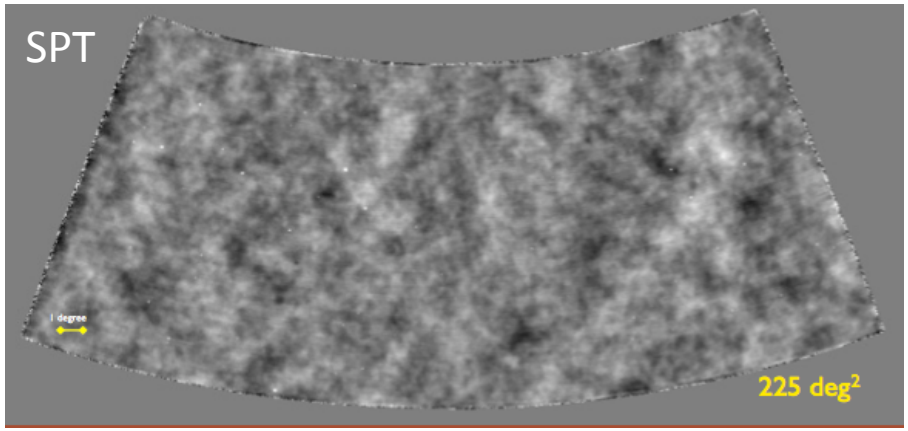

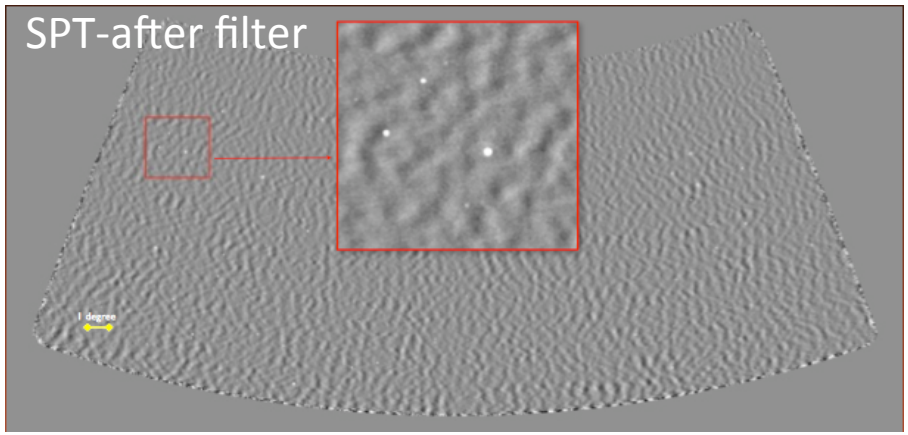

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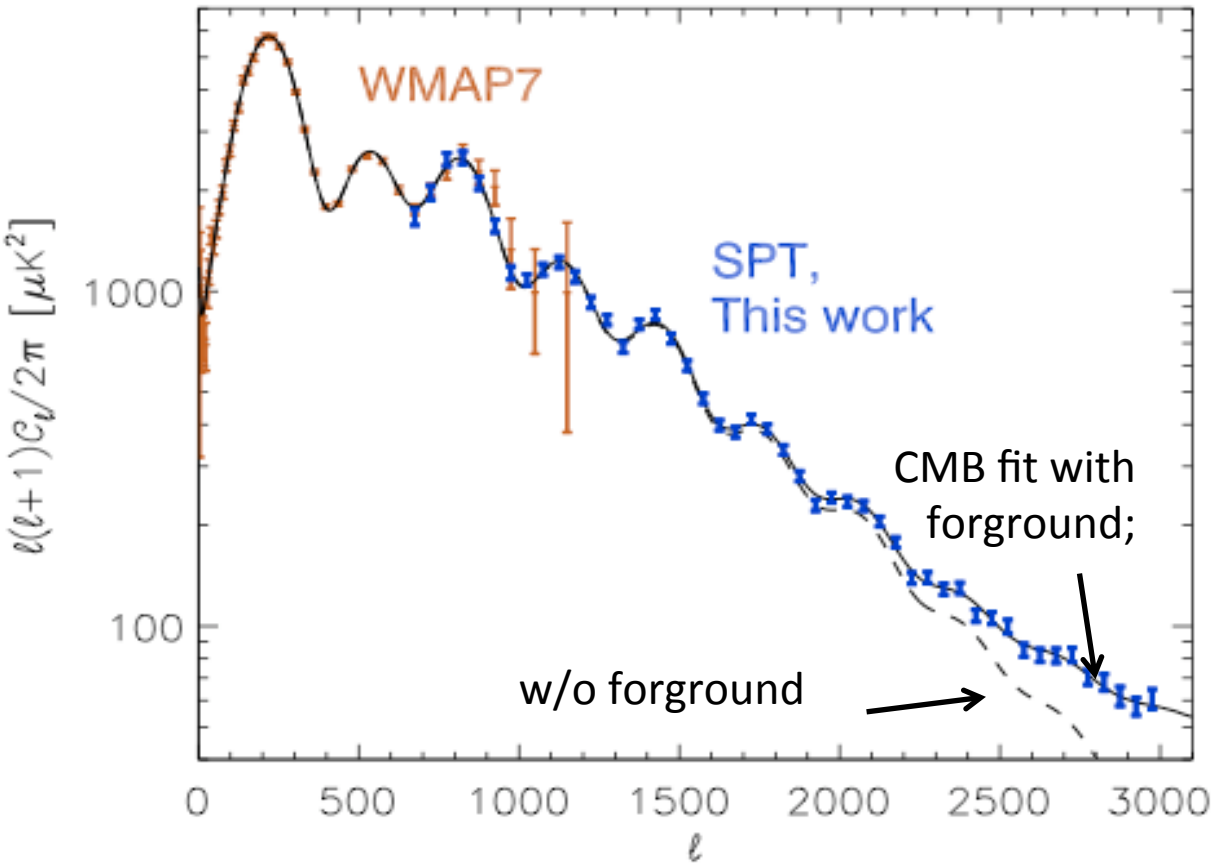

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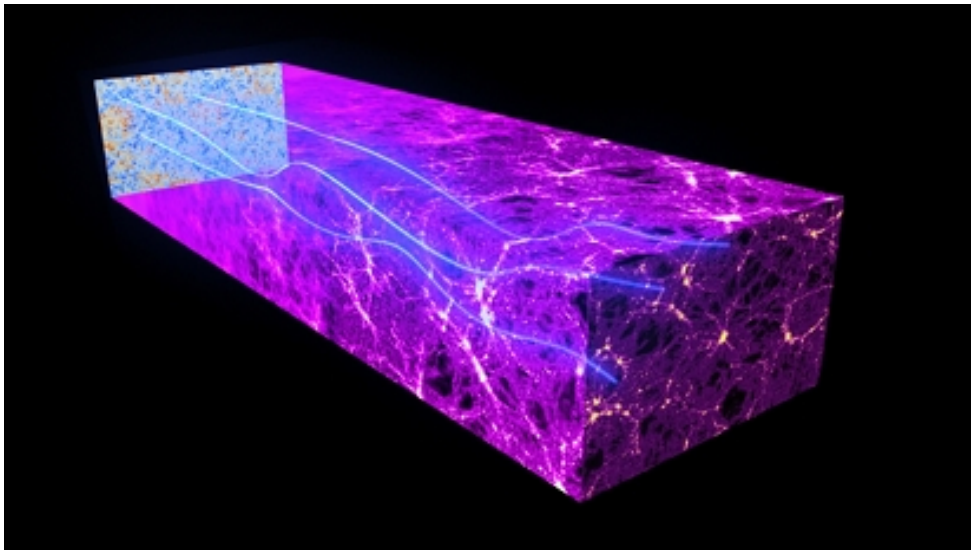
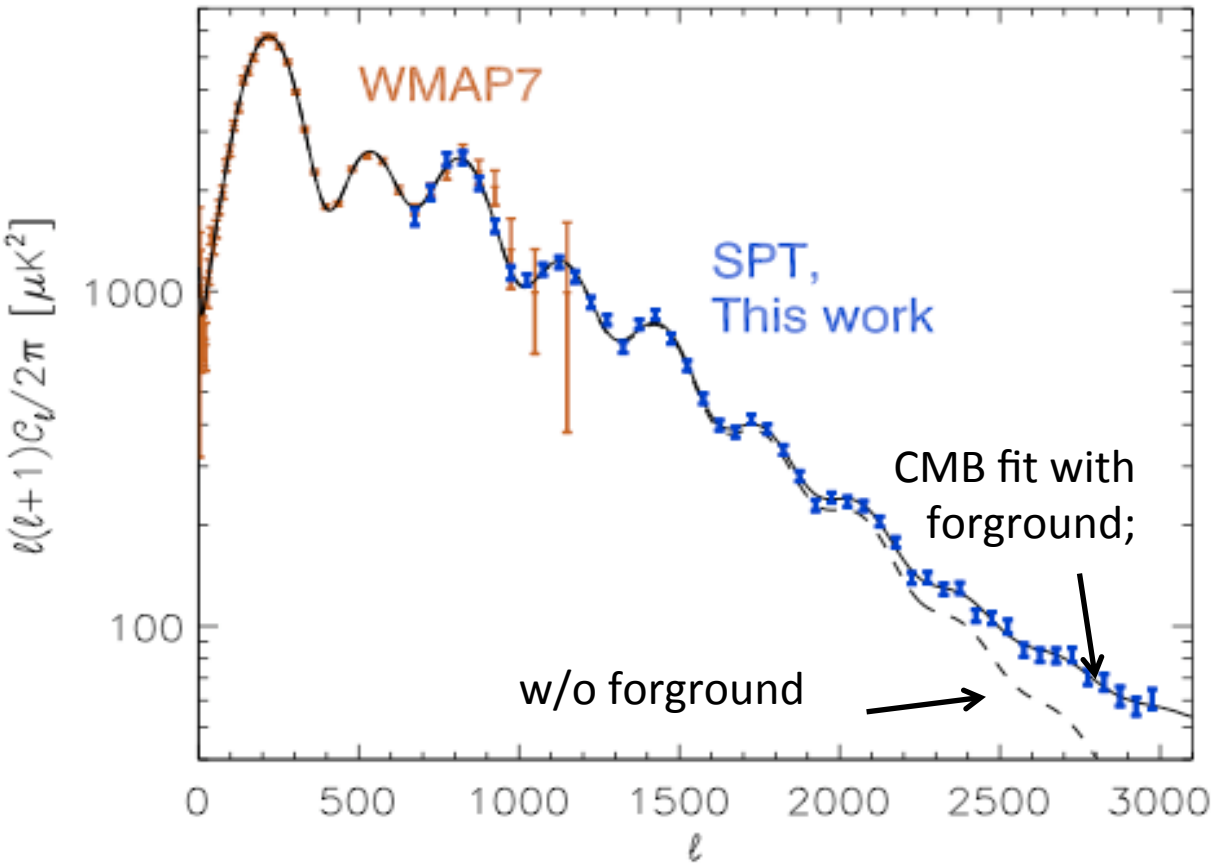
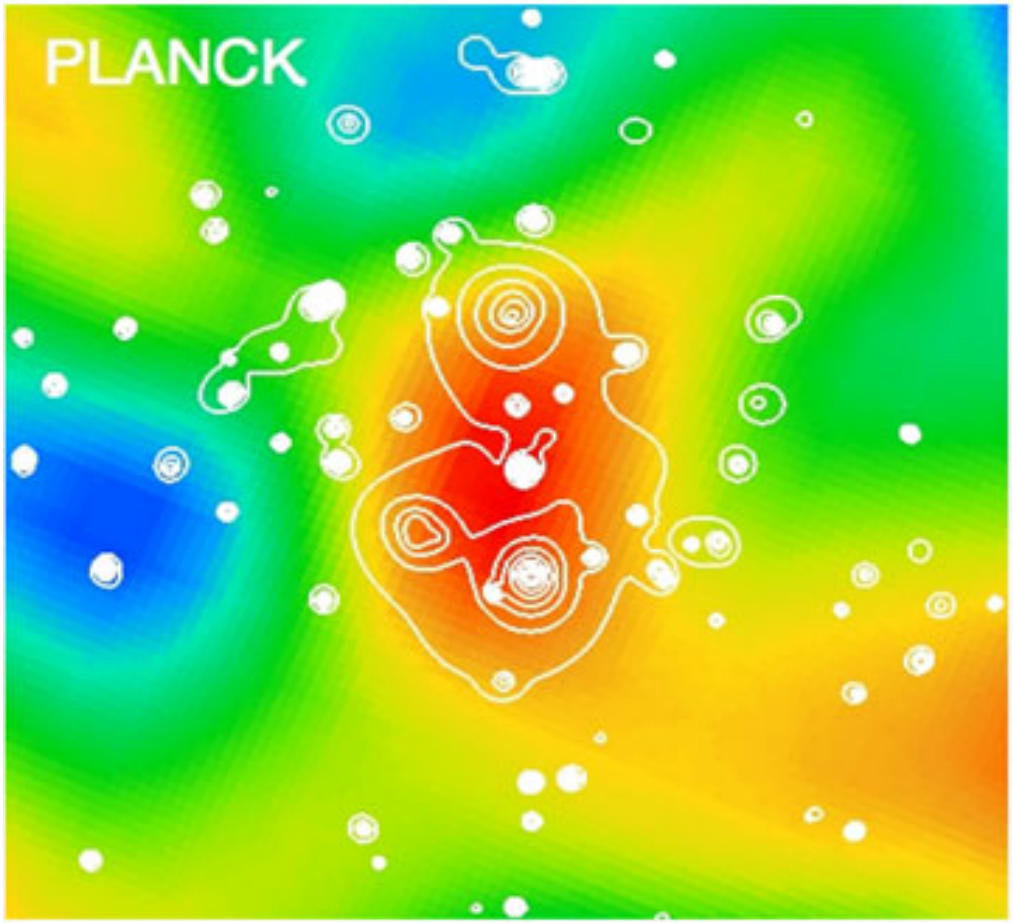




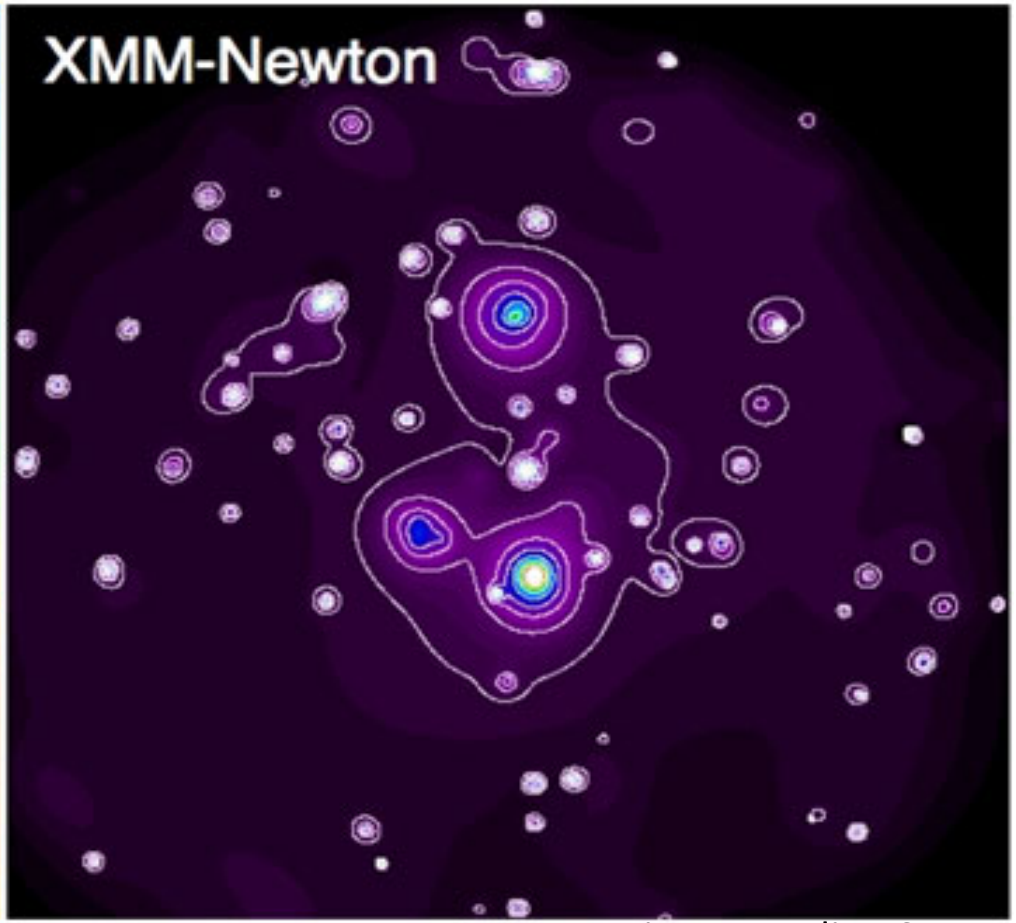
CMB weak lensing:
2012 - 4σ detection by SPT
2013 – 25σ detection by Planck

Galaxy Clusters

CMB footprint



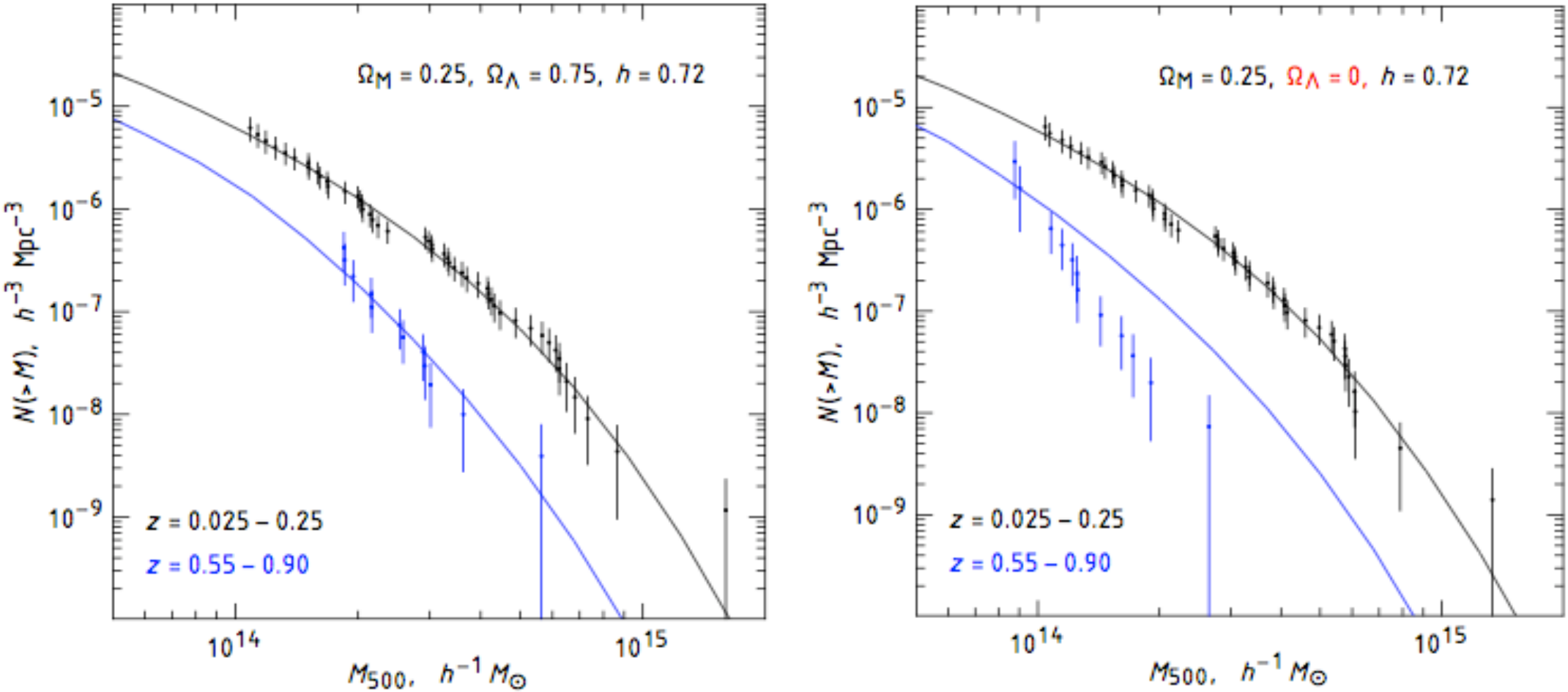
X-ray footprint



Picture credit: ESA

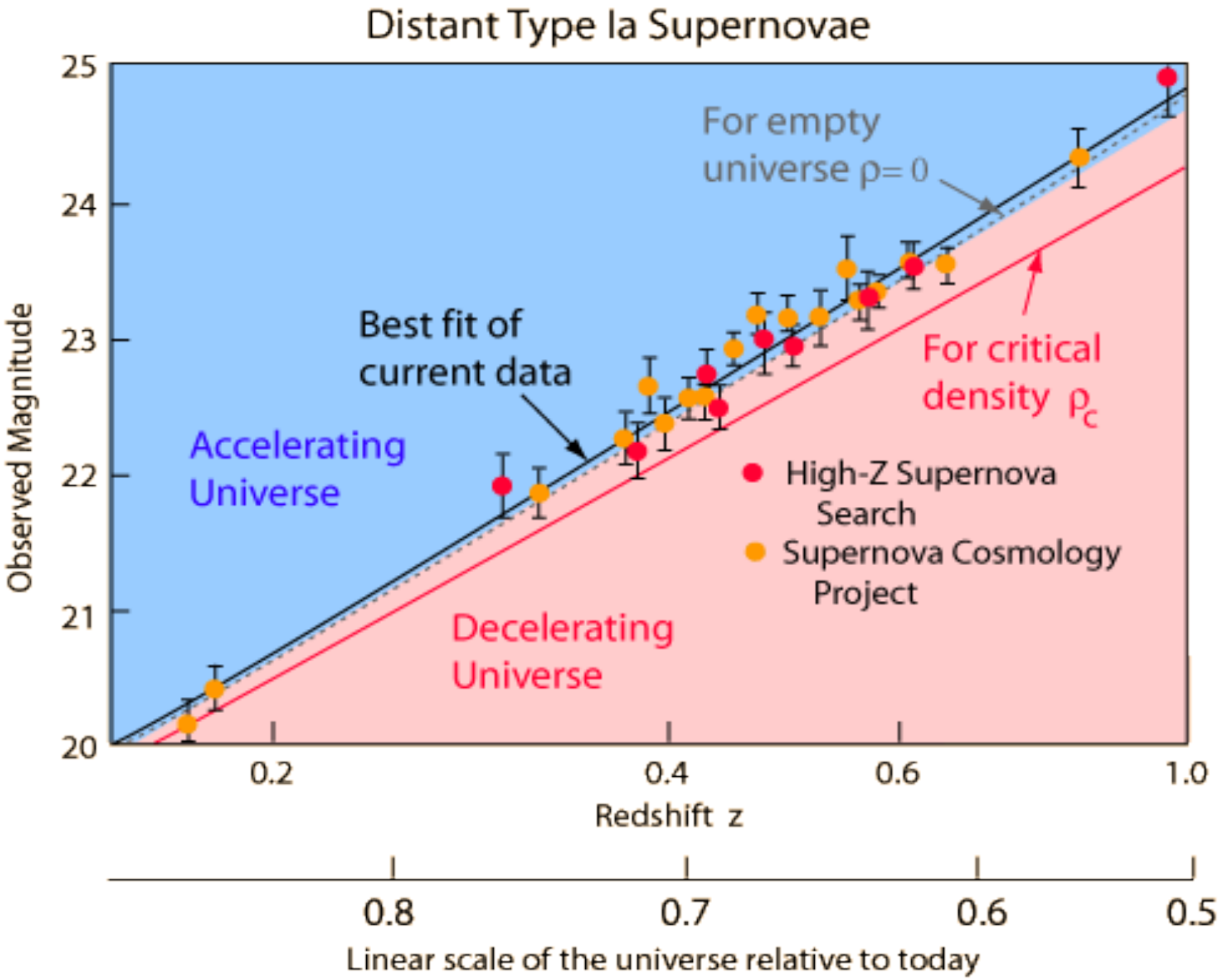
First science results of Planck (A&A, 2011)

Counting Galaxy Clusters



Vikhlinin et al. ApJ, 2009

Upcoming surveys: eROSITA, DES, ...


Distant Type Ia Supernovae
Observed Magnitude
25
24
23
22
21
20
For empty universe ρ= 0
Best fit of current data
For critical density ρc
Accelerating Universe
Decelerating Universe
High-Z Supernova Search
Supernova Cosmology Project
0.2
0.4
0.6
1.0
Redshift z
0.8
0.7
0.6
0.5
Linear scale of the universe relative to today

Supernova Type Ia

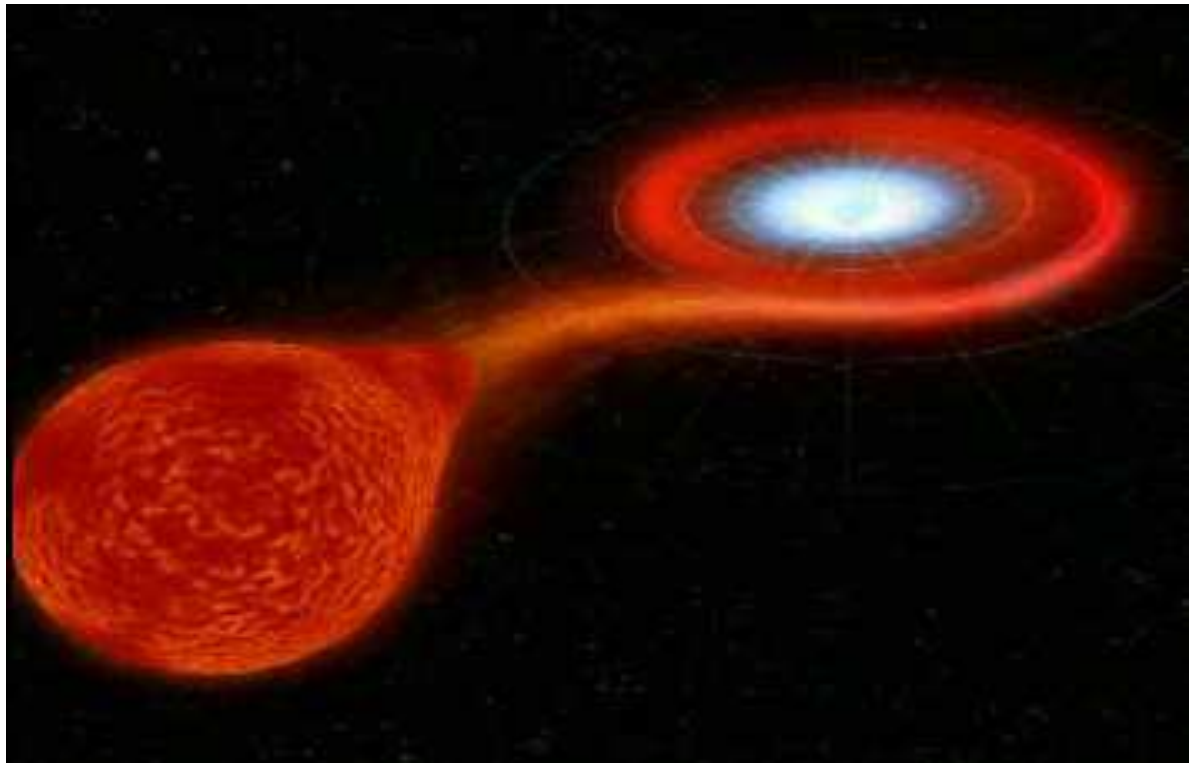
⇒White dwarf in binary system

⇒Mass transfer up to „critical“ Chandrasekhar mass of 1.4 $M_\odot$

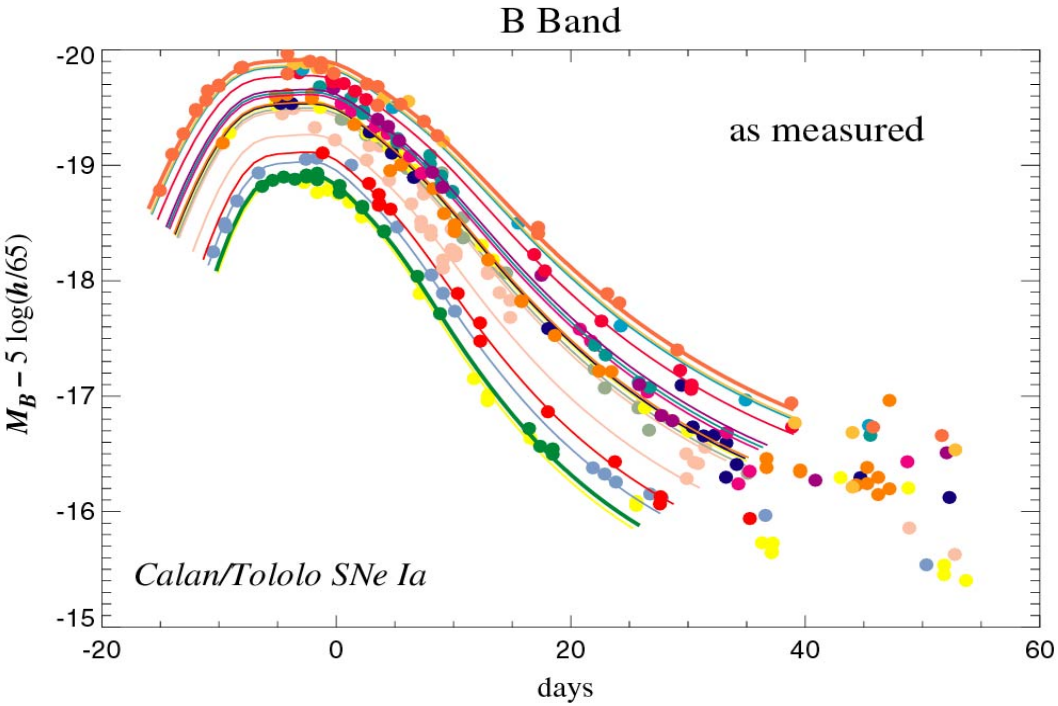
⇒Thermonuclear explosion

⇒Explosion of similar energies

⇒Visible in cosmic distances



SNe Ia as "standard" Candles



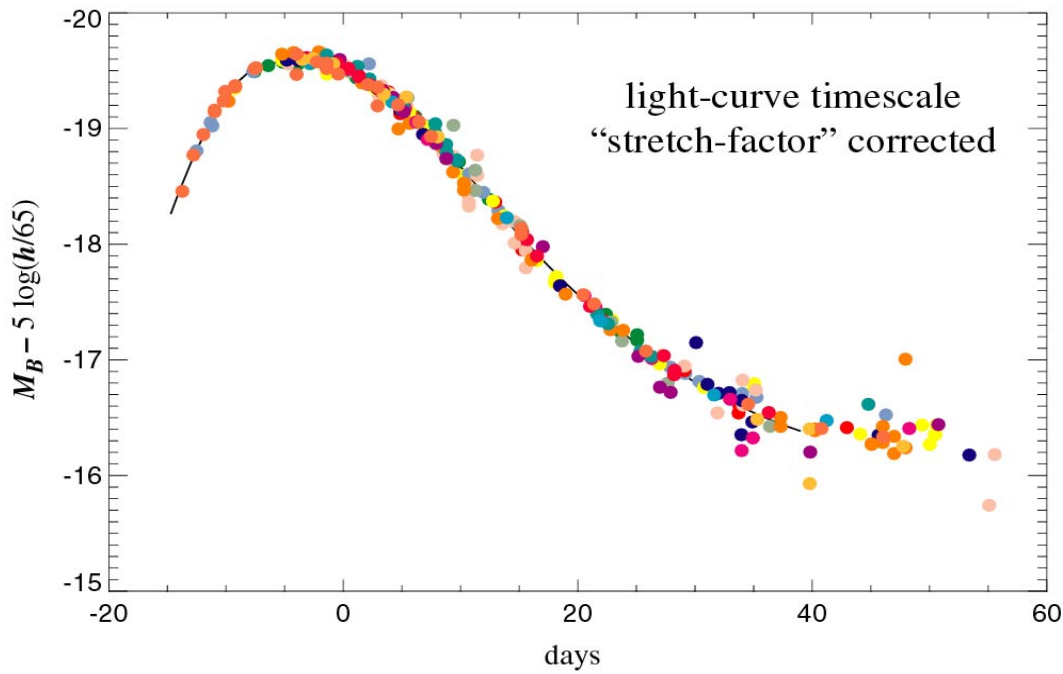
- Nearby supernovae used to study SNe light curve (z<0.1)
- Intrinsically brighter SNe have wider lightcurves.

Stretching the timescale:

$$t' = s \times t$$

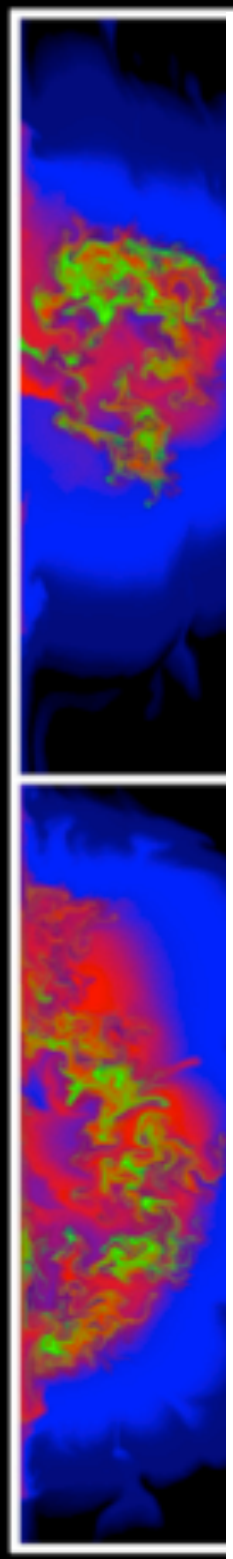
Correcting the brightness

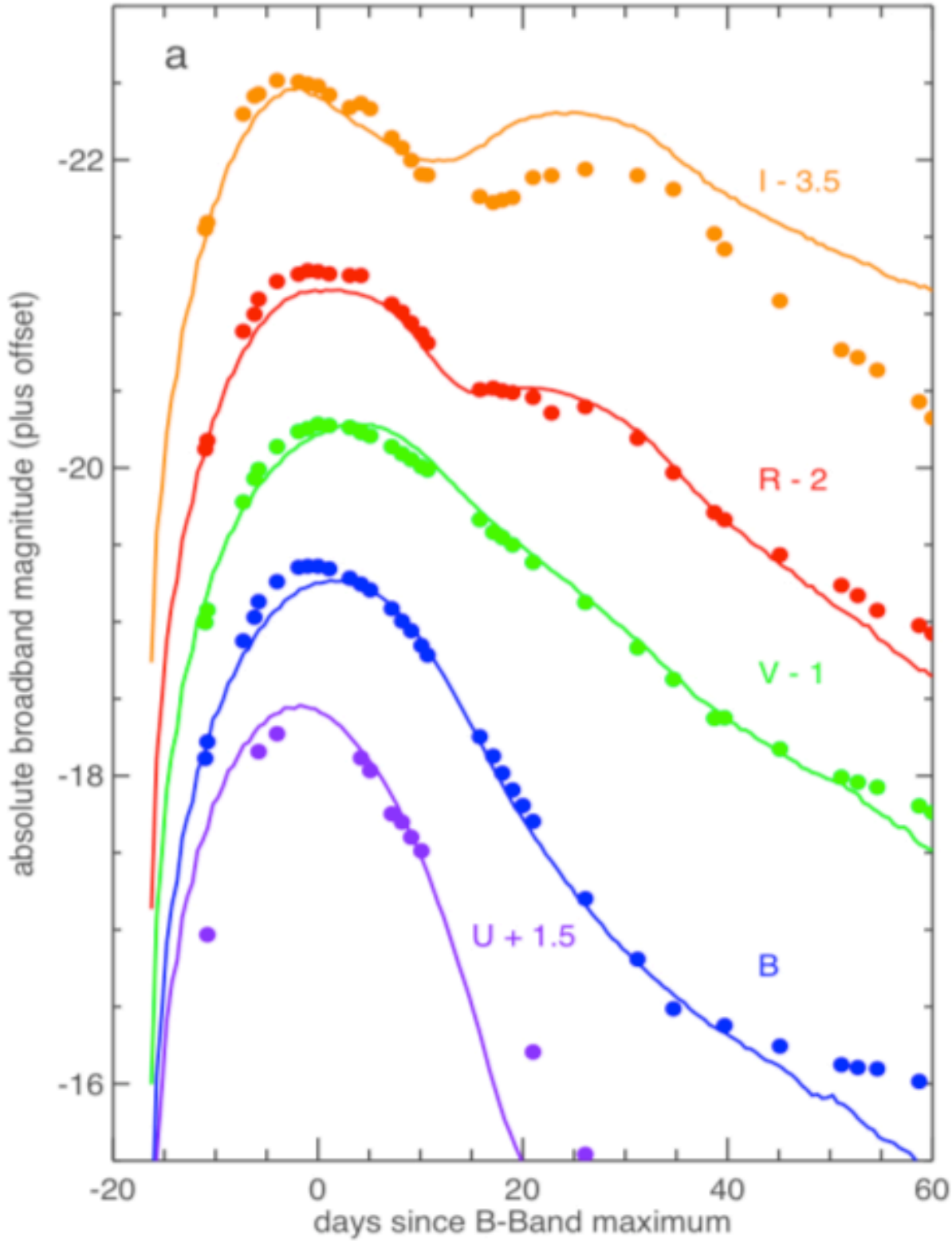
$$M' = M + \alpha\,(s - 1)$$



Kim, *et al.* (1997)

strong deflagration
weak detonation



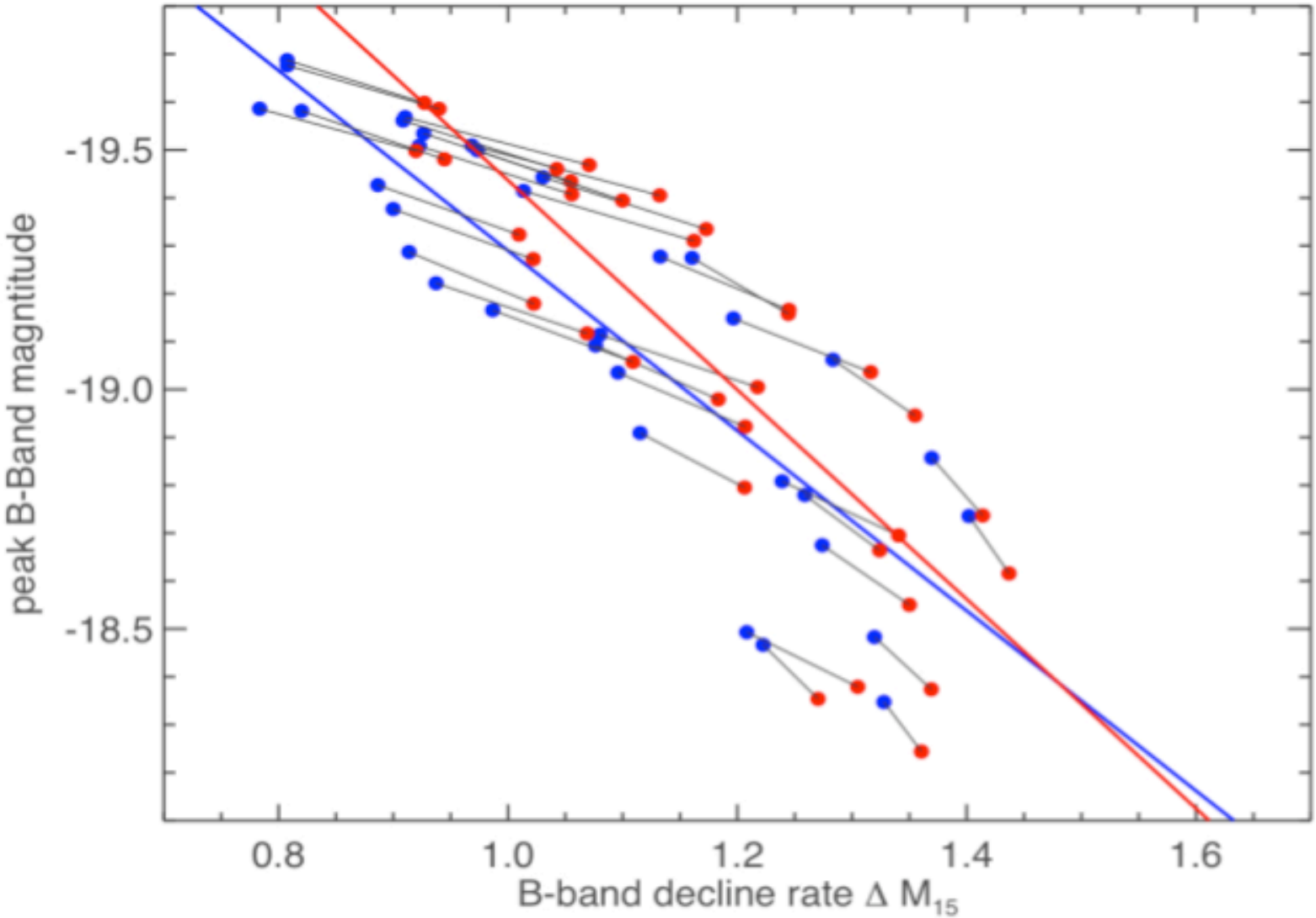


weak deflagration
strong detonation

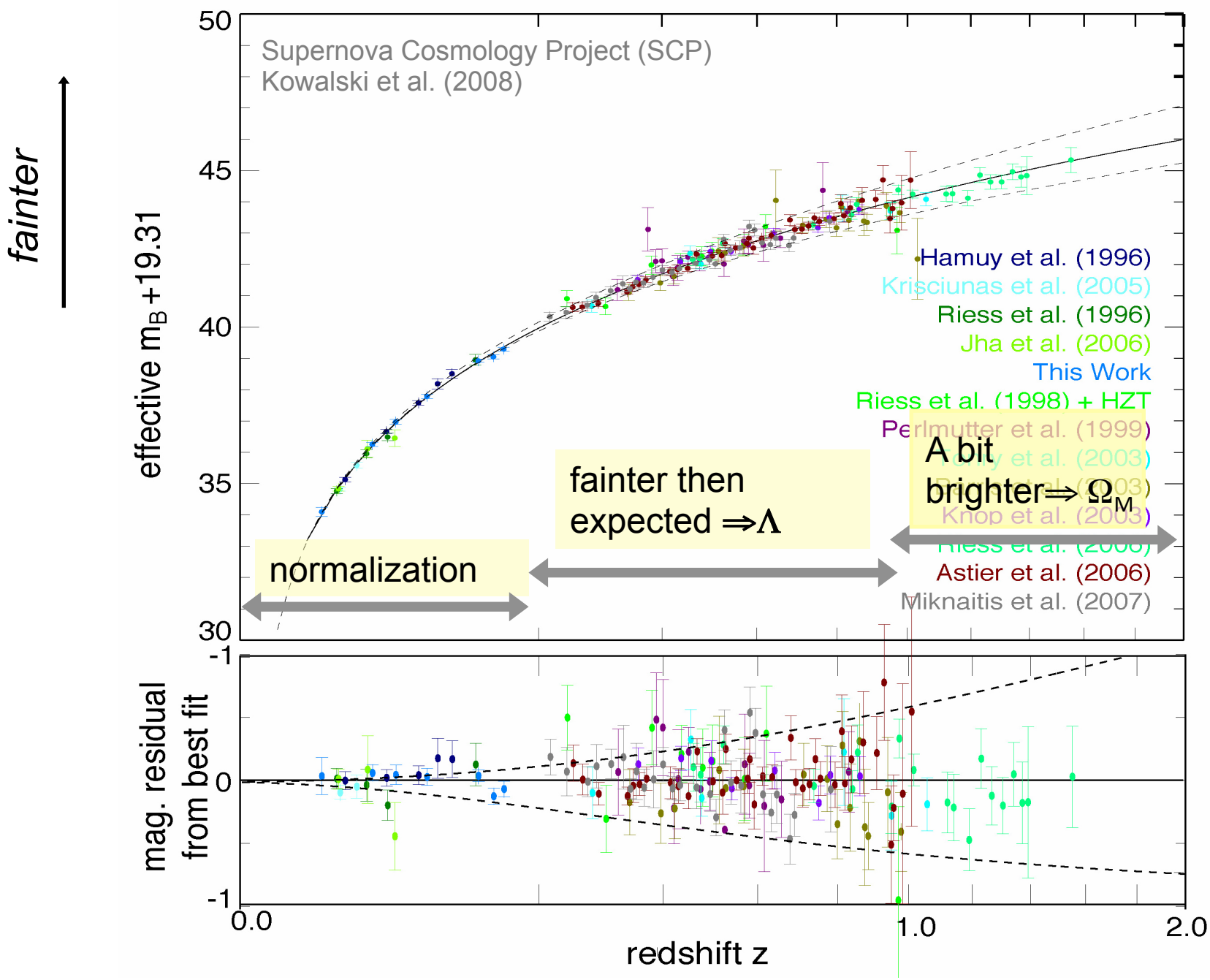
Kasen,
Roepke,
Woosley,
Nature 2009

Simulation of the width-brightness relation

Kasen, Roepke, Woosley, Nature 2009

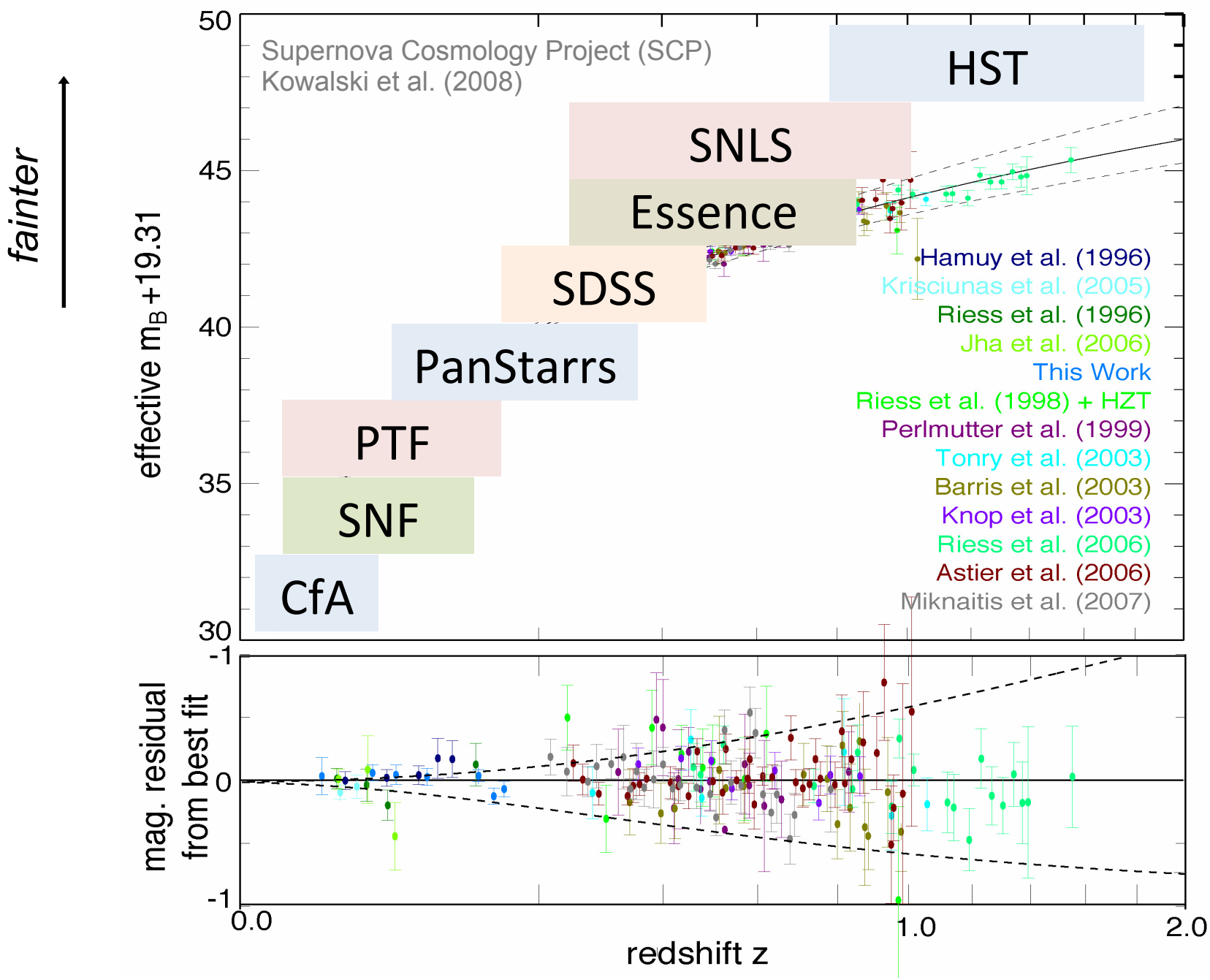


SNe Ia Hubble Diagram



Ω_Λ	Ω_M
1	0
0.72	0.28
0	1

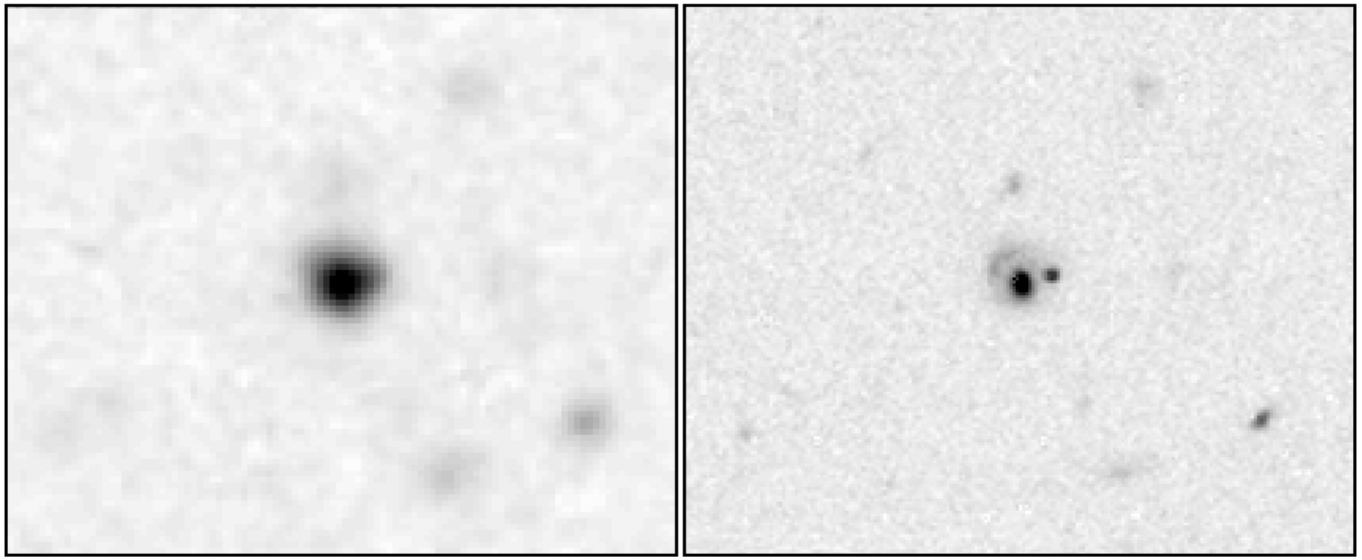
SNe Ia Hubble Diagram



Ω_Λ	Ω_M
1	0
0.72	0.28
0	1

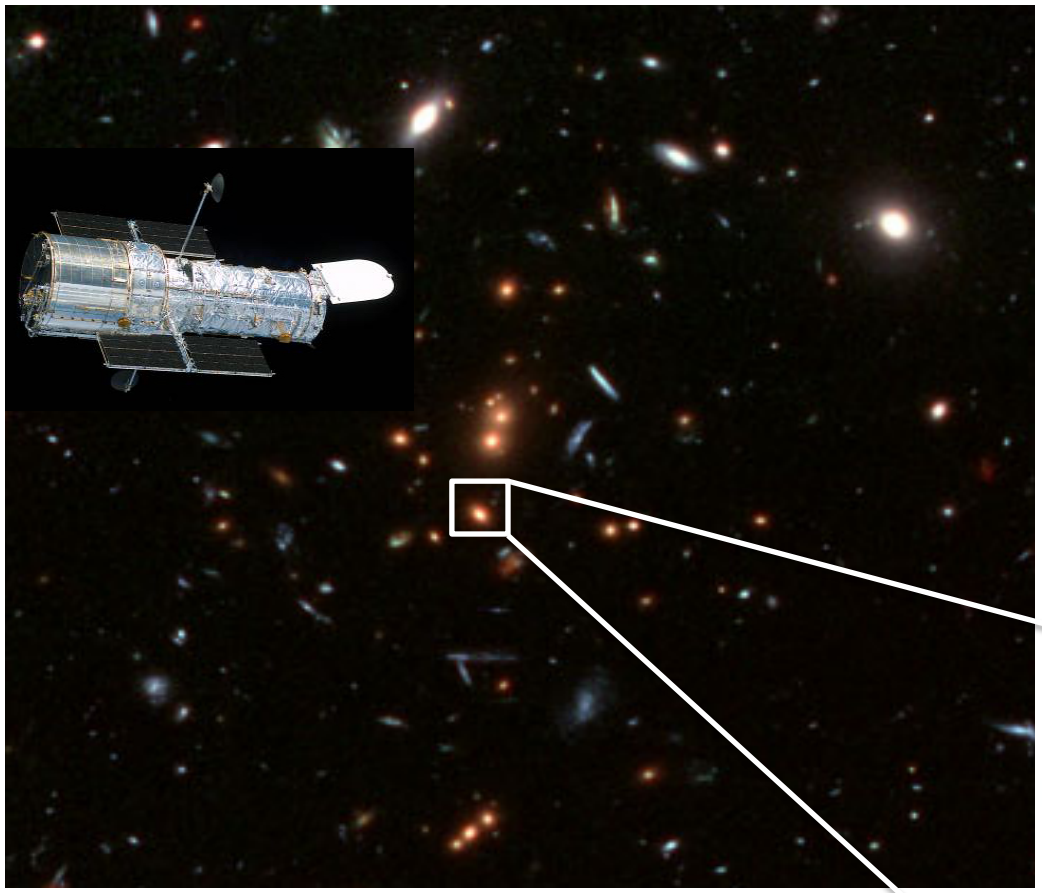
SNe at large Redshifts (z>1)

SN 1997cj



Twin Keck telescopes on Mauna Kea.

HST Survey of Clusters with z ≥ 1



Survey of z>0.9 galaxy clusters

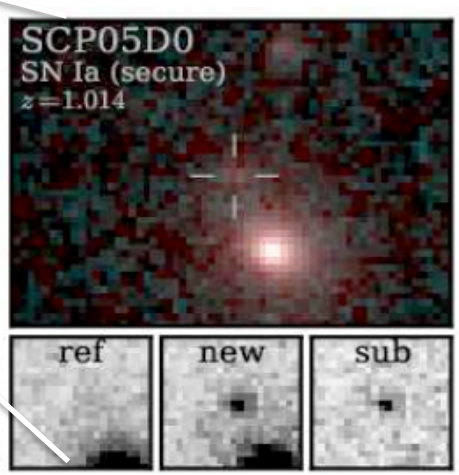
⇒ SNe from cluster & field

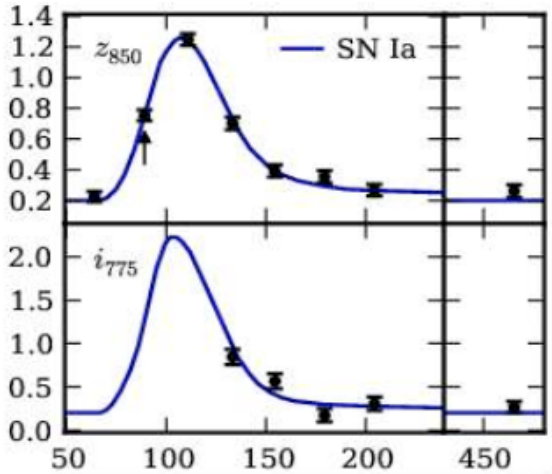
⇒ about 2 x more efficient

⇒ enhencement of early hosts

⇒ 20 new HST SNe

⇒ 10 high quality z>1 SNe!

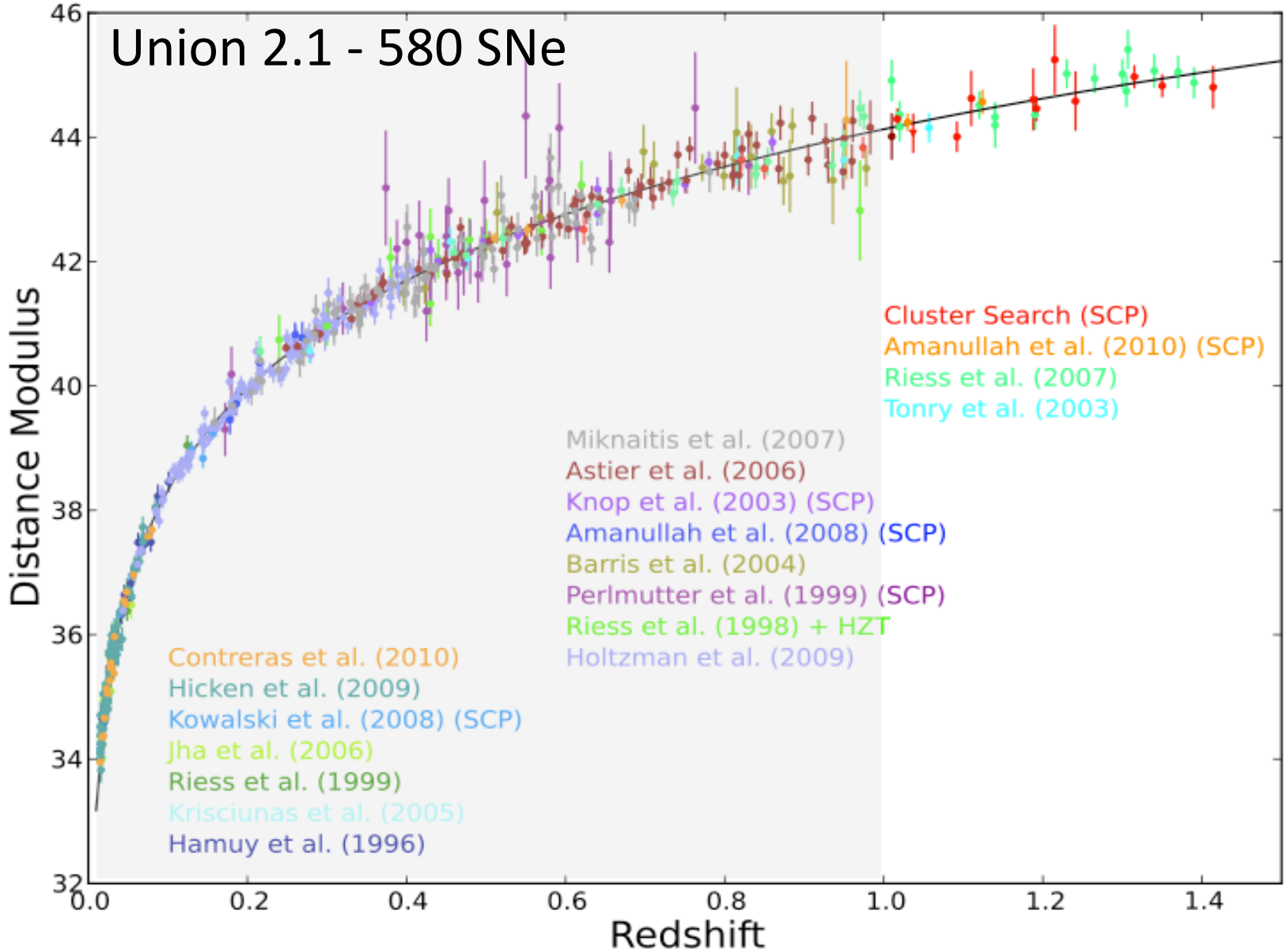


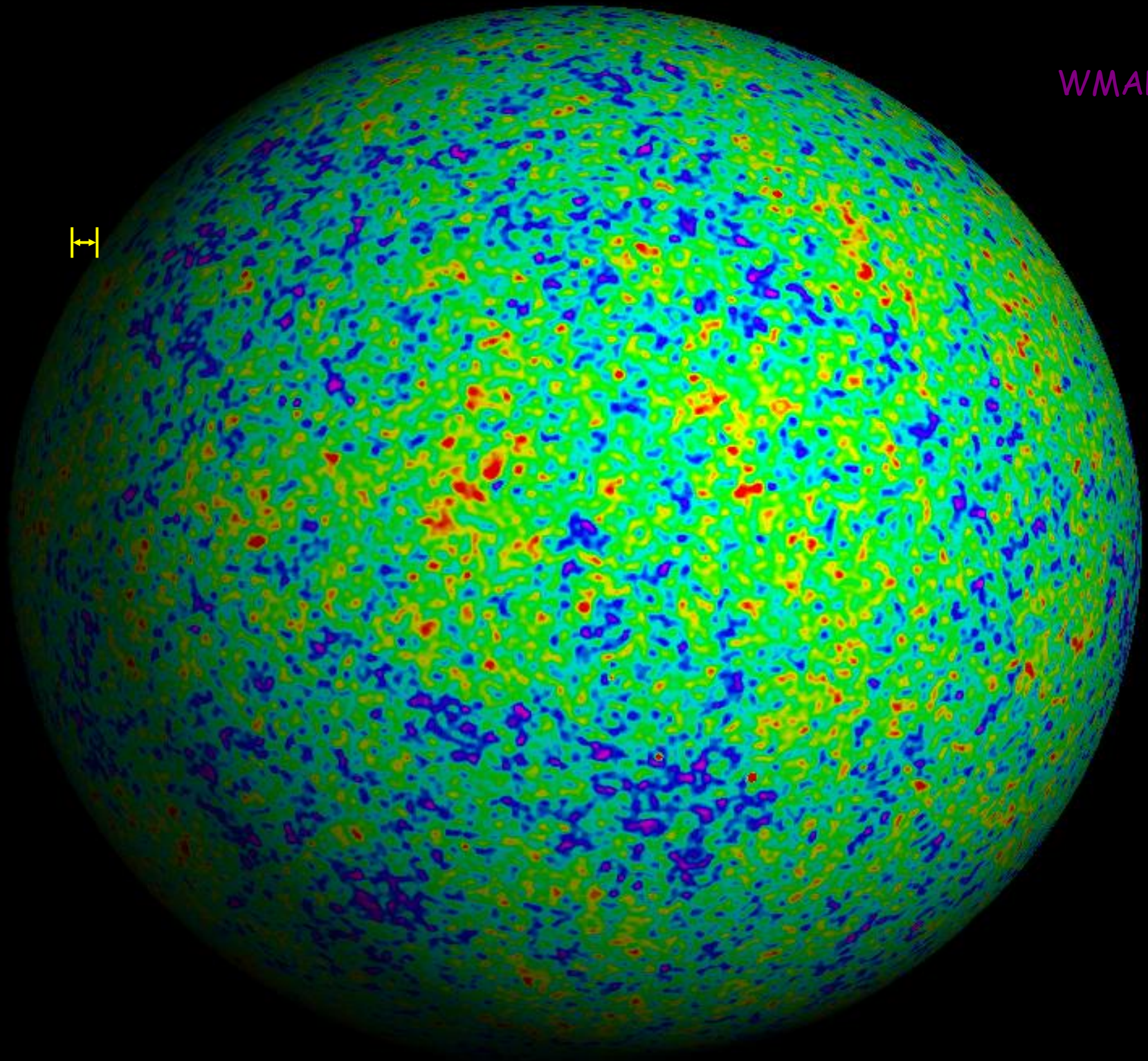


Cycle 14, 219 orbits (PI S. Perlmutter)
24 clusters from RCS, RDCS,IRAC, XMM

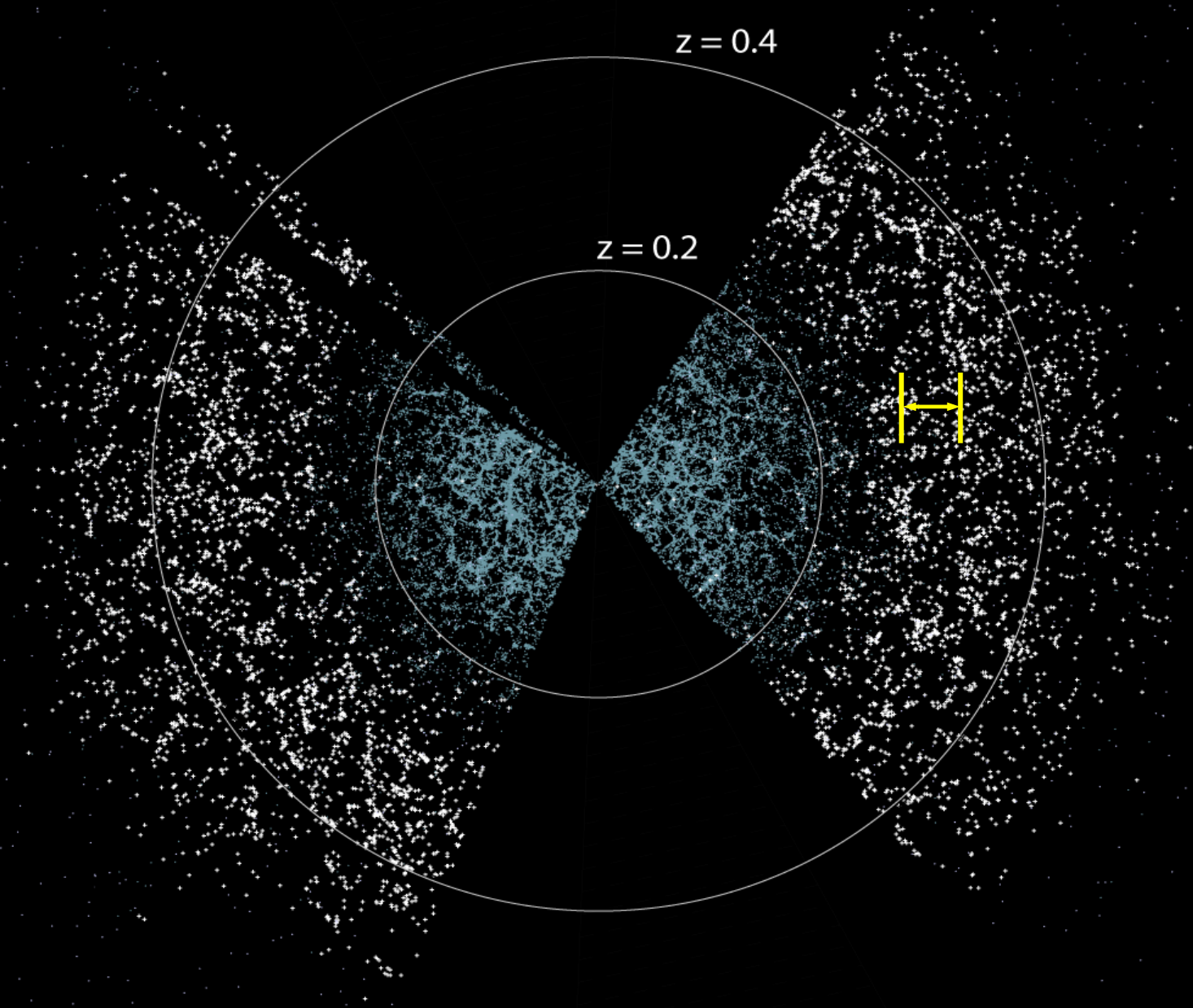
Supernova Cosmology Project
Suzuki et al., 2011

HST Survey of Clusters with z ≥ 1




WMAP 2006

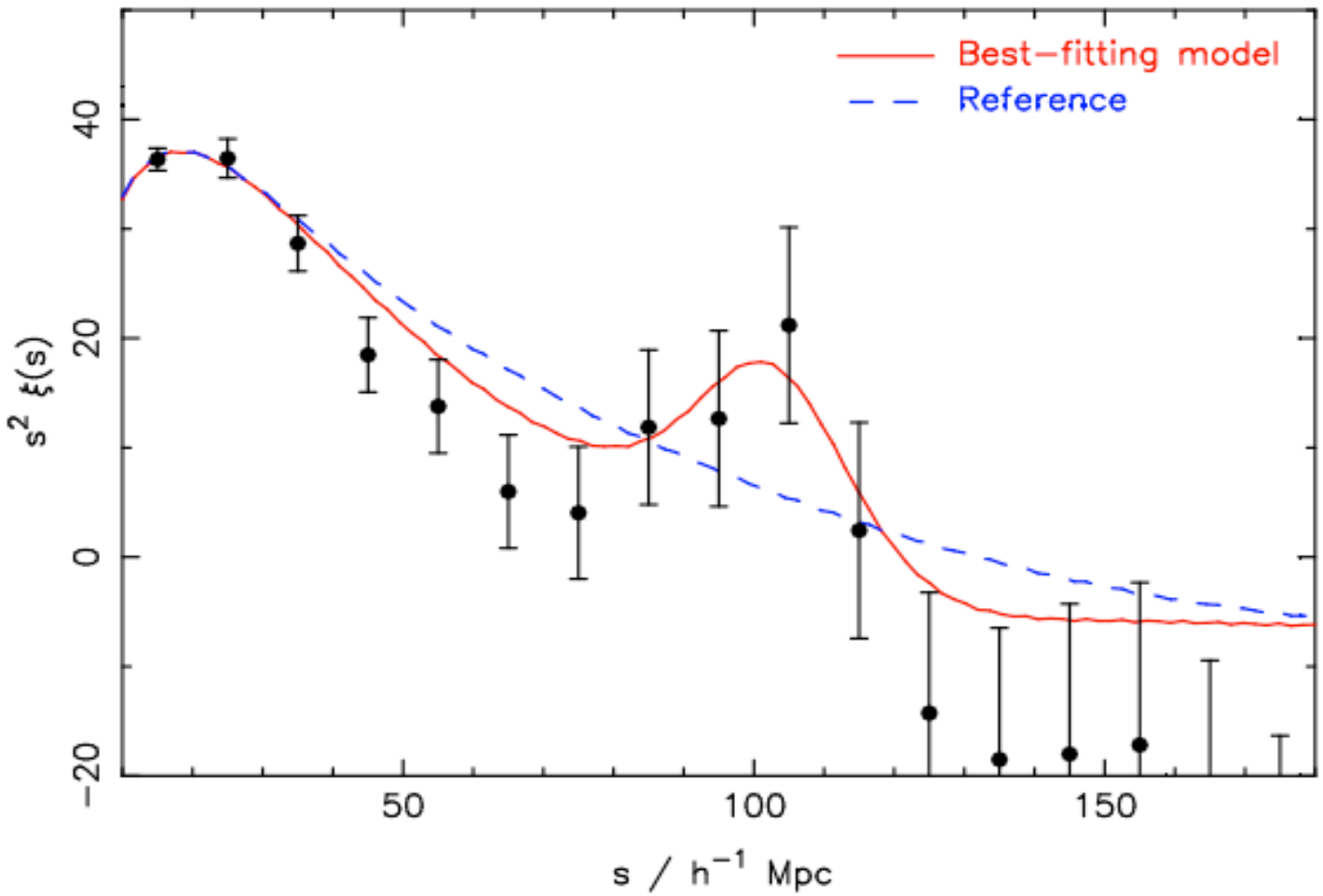
Baryon Acoustic Oscillation



Sloan Digital Sky Survey

Baryon Acoustic Oscillation

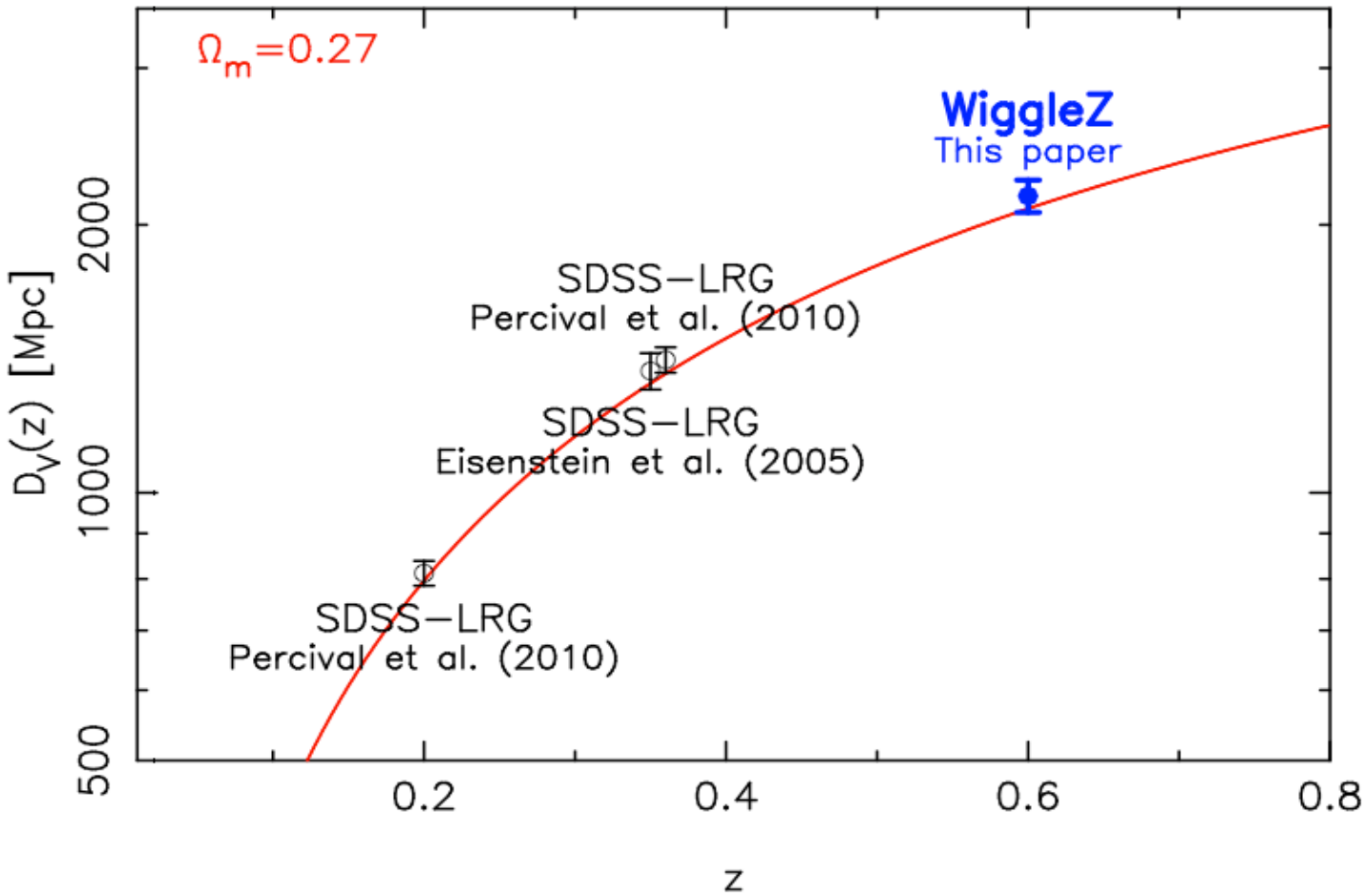
Acoustic „oscillation“ lengh scale from CMB visible in the distribution of galaxies ⇒ Standard ruler of cosmology.



WiggleZ survey – Blake et al, 2011

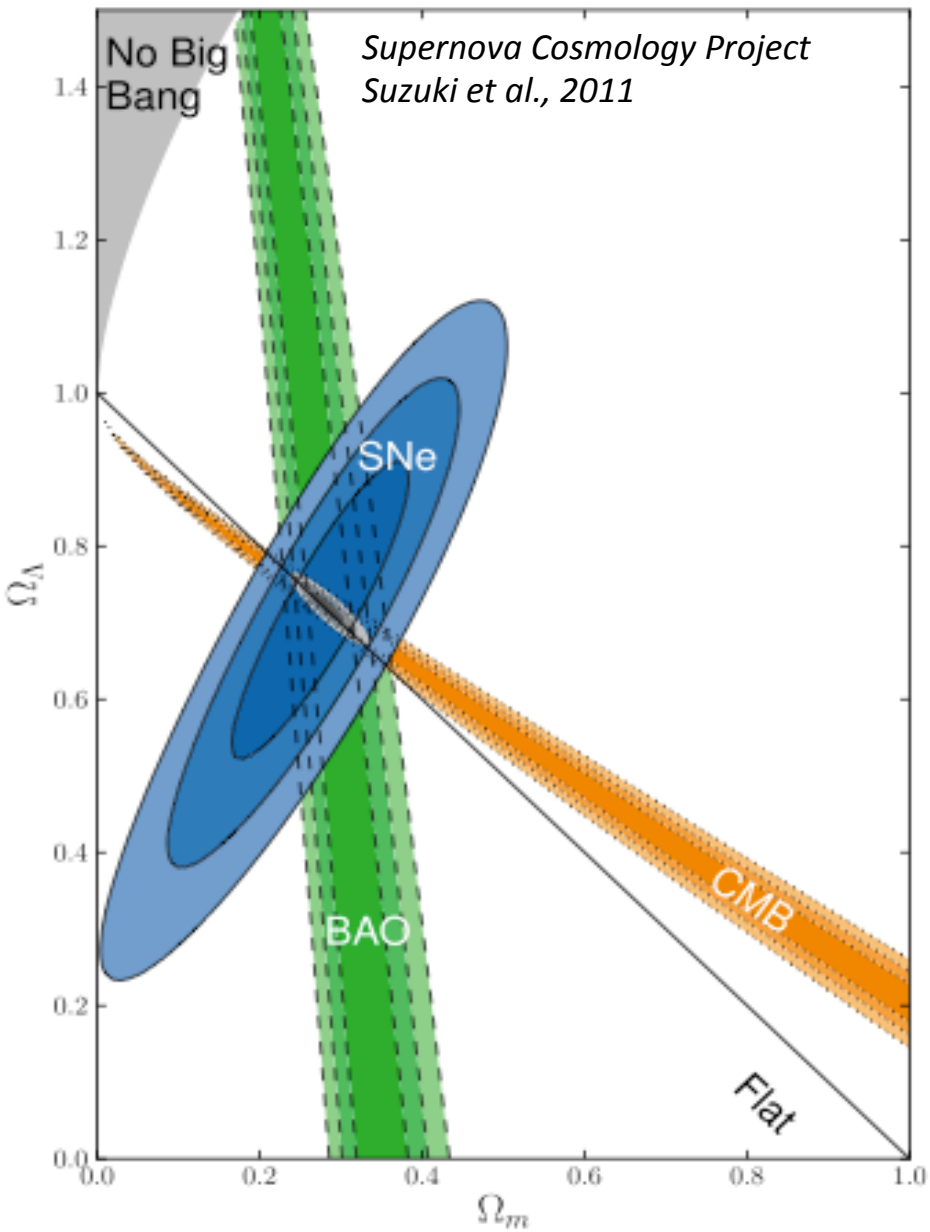
Baryon Acoustic Oscillation

Acoustic „oscillation“ lengh scale from CMB visible in the distribution of galaxies ⇒ Standard ruler of cosmology.



Promising technique & much activity: BOSS, HETDEX,...

Cosmological parameters



SNe (Union 2.1, Suzuki et. al, 2011)
BAO (Percival et. al, 2010)
CMB (WMAP-7 year data, 2010)

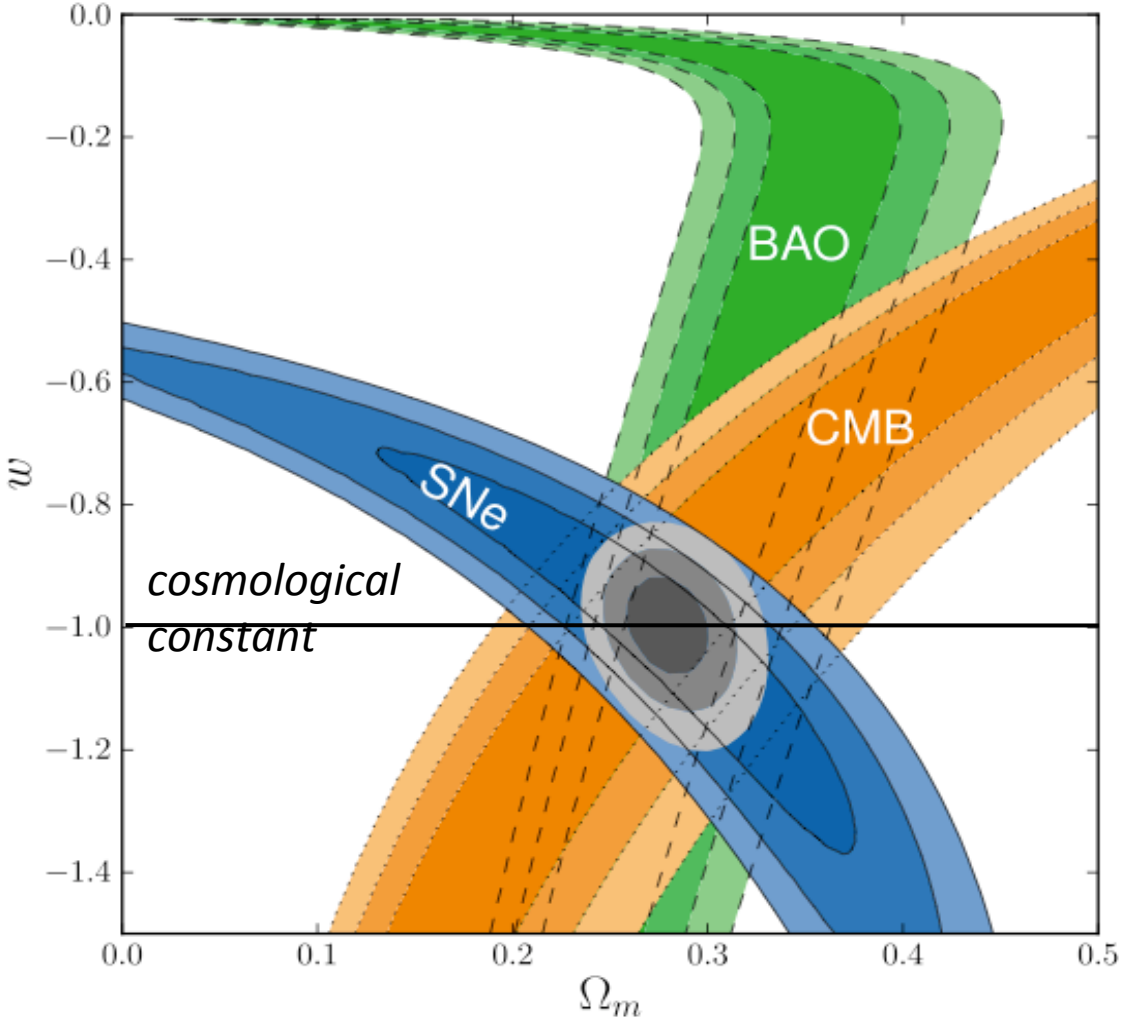
$$\Omega_\Lambda = 0.729 \pm 0.014$$

and allowing for curvature:

$$\Omega_k = 0.002 \pm 0.005$$

Dark Energy

Supernova Cosmology Project
Suzuki et al., 2011

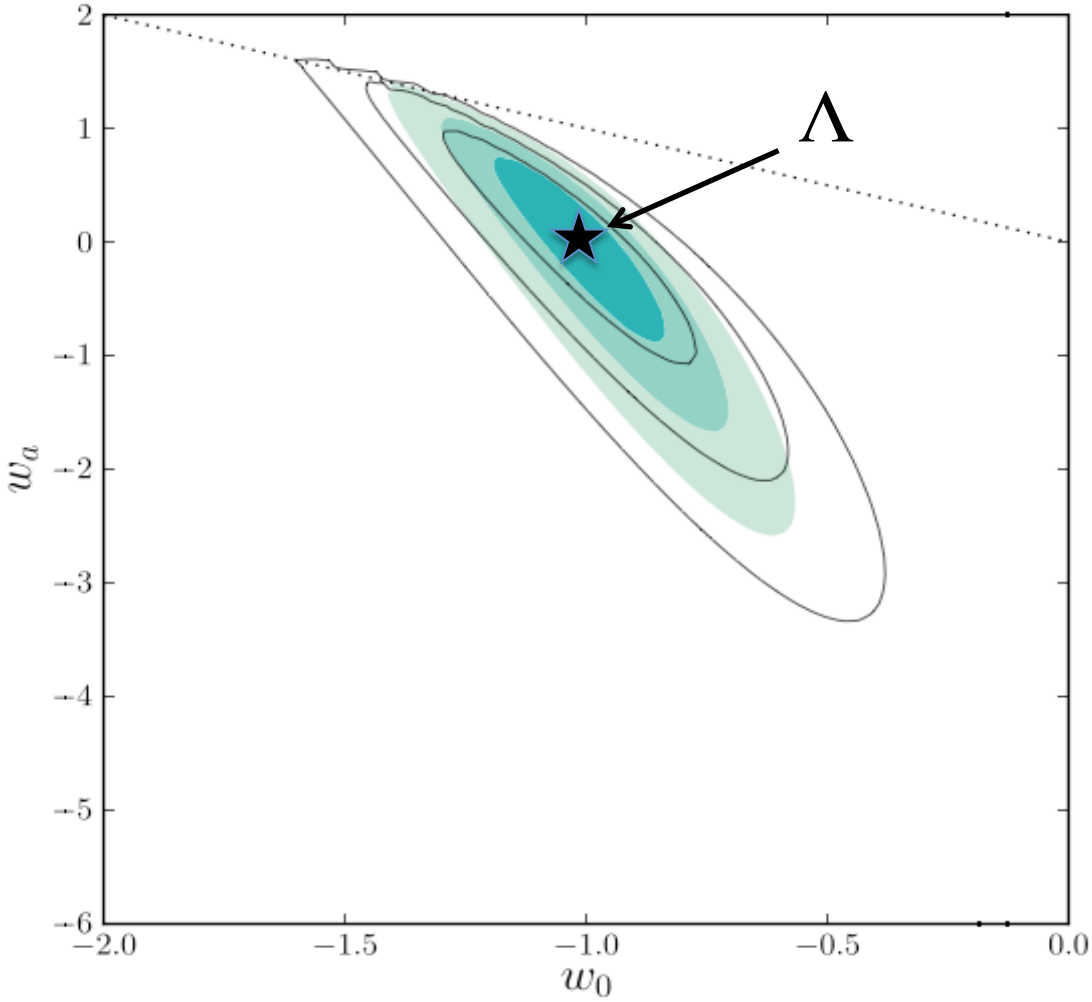


Equation of state: *p=wρ*

Constant w:
w=-0.995±0.078

Dark Energy

Supernova Cosmology Project
Suzuki et al., 2011



Equation of state: *p=wρ*

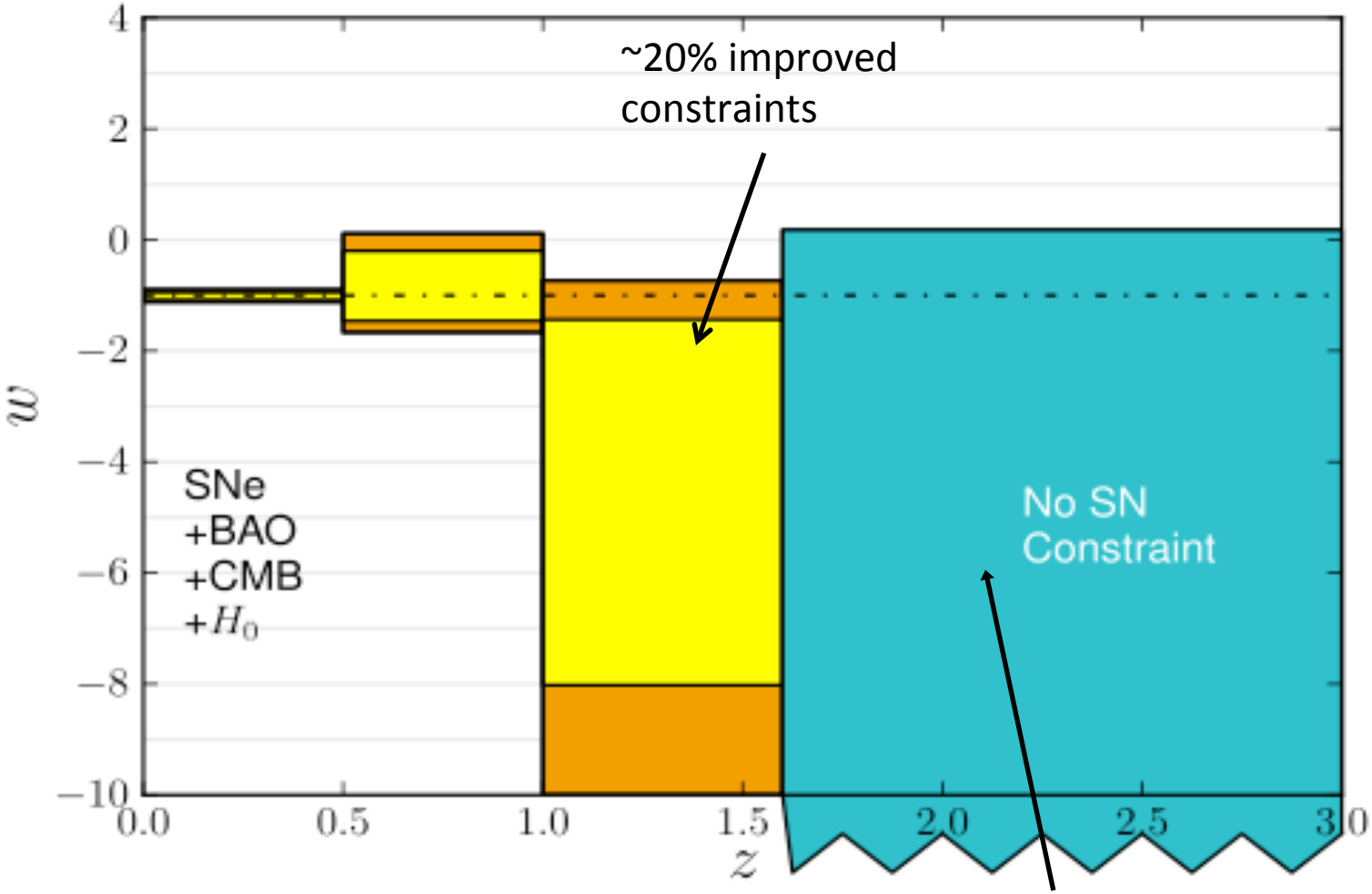
Constant w:
w=-0.951±0.078

Redshift dependent w:
$w(a)=w_0+(1-a) \times w_a$
W_a = 0.14±0.68

No deviation from *w*=-1 (i.e. Λ)

Redshift dependent EOS

Assuming step-wise constant *w*:



A floating non-SNe bin to decouple low from high-redshift constraints

Part 3.

Moving beyond ΛCDM

Part 3.

Moving beyond ΛCDM

- **Dark Energy**

Many models to explain cosmic acceleration exist
… but none without difficulties.

Menu of possibilities:

1. Quantum Vacuum Energy (static)

+ it exists!

- 60-120 orders of magnitude to large

2. Quintessence (dynamic)

+ Solves „why now“ problem, connects to inflation?

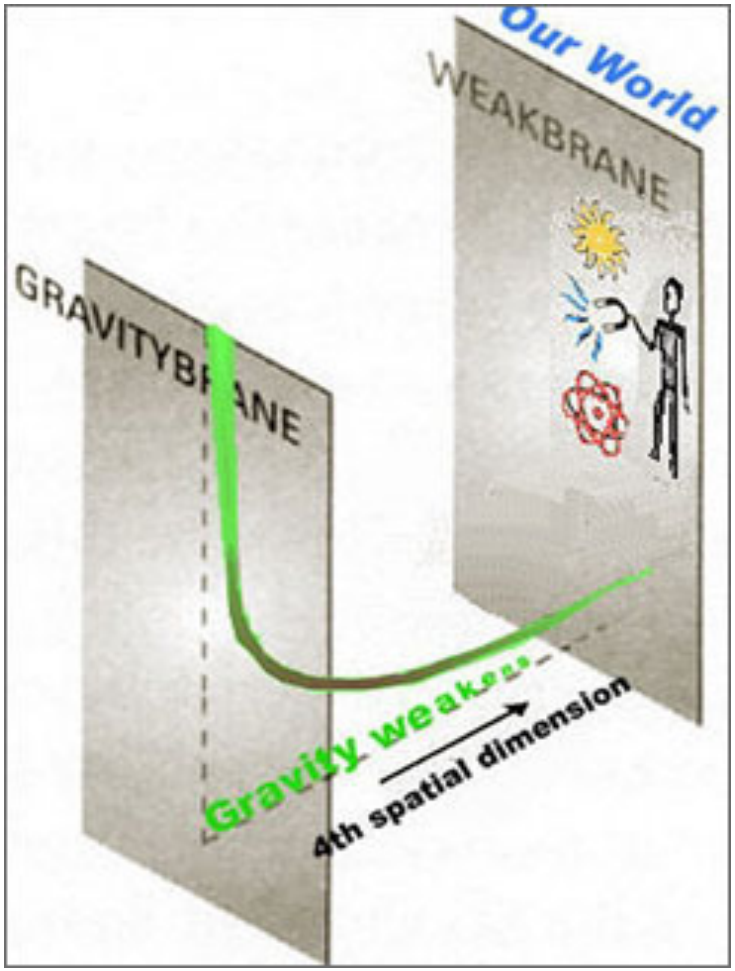
- „smallness“ problem persists, small coupling

3. Modification of gravity (hence, no dark energy)

+ no Dark Energy

- Gravitation in solar system well understood

Braneworld Cosmology

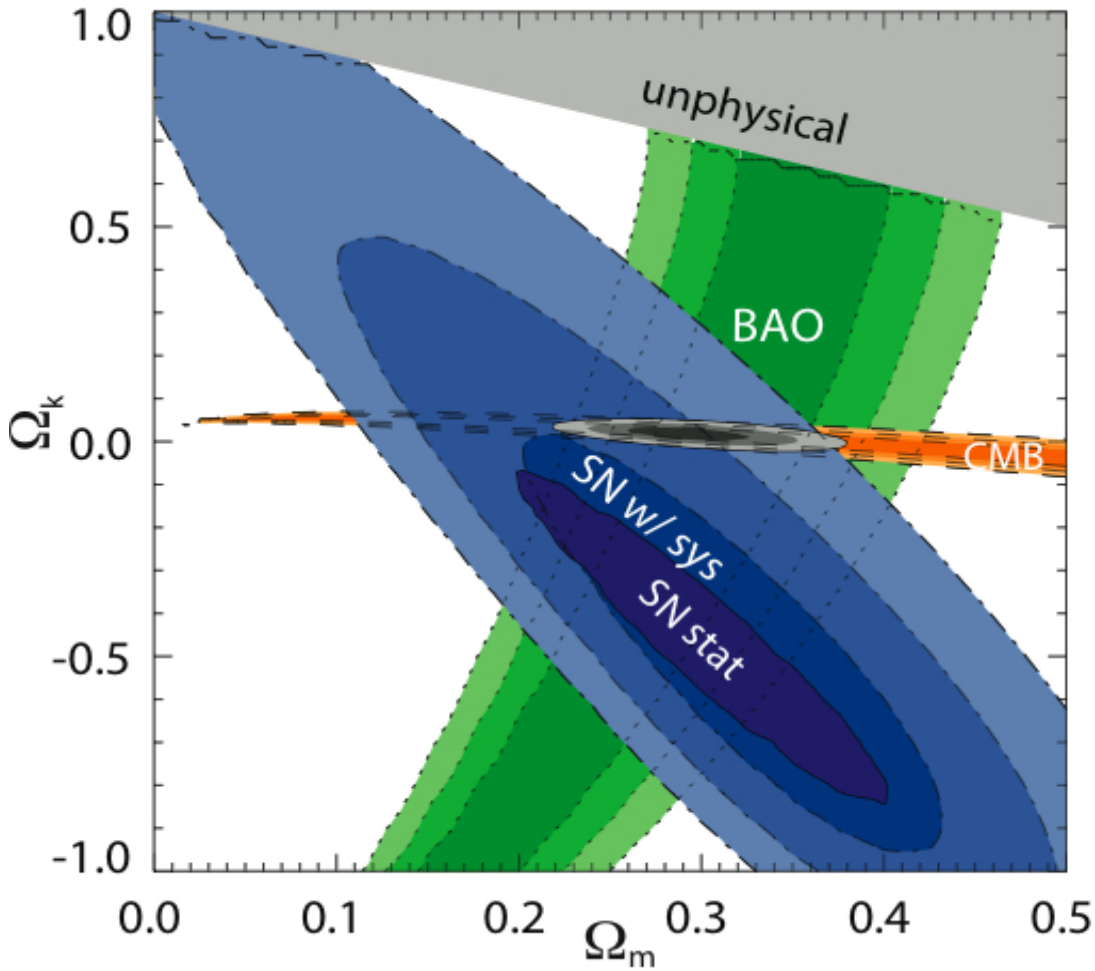


Large extra dimensions can solve the hierarchy problem of particle physics… (e.g. unification of forces)
Randall & Sundrum
Arkani-Hamed, Dimopoulos, Dvali

…and will weaken Gravity at large distances
(Dvali, Gabadadze, Porrati - DGP)

⇒**apparent acceleration**

Braneworld Cosmology



DGP-model versus ΛCDM
Without systematic: $\Delta\,\chi^2_{stat} = 16.1$
With systematic: $\Delta\,\chi^2_{sys} = 4.0$

D. Rubin, E. Linder, MK, et al, 2009

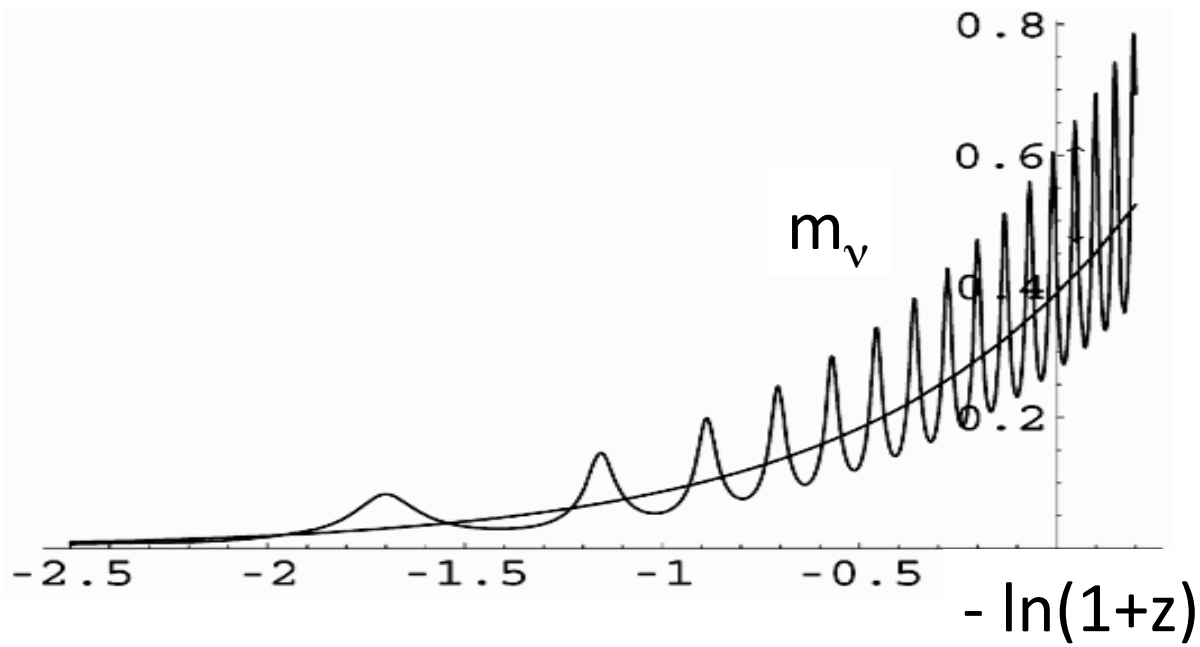
Quintessence Example: Growing Neutrinos

Scalar field couples to massive neutrinos

Once neutrinos become sub-relativistic, one obtains Λ-like behavior.

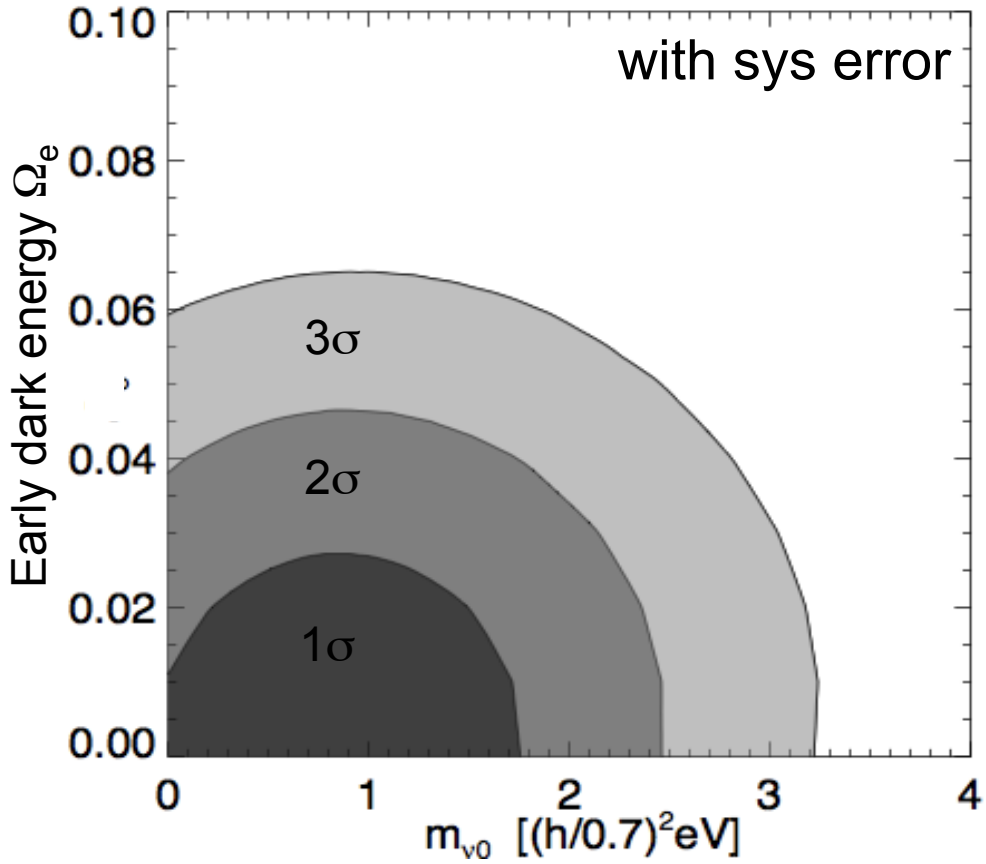
Today: Massive neutrinos and deviation from *w* =-1

$$w_0 = -1 + \frac{m_{\nu,0}}{12\ \mathrm{eV}}$$



C. Wetterich (2007), L. Amendola et al. (2007),

Quintessence Example: Growing Neutrinos

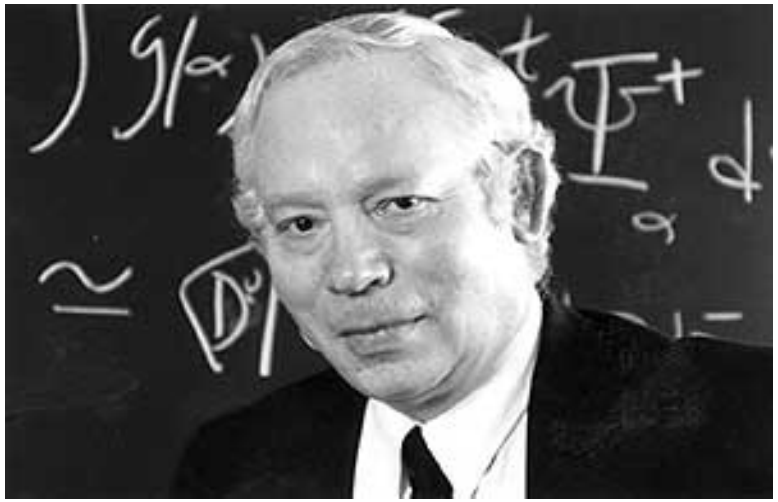


m_ν<1.2 (h/0.7)^2 eV @ 95 CL stat error only
m_ν<2.1 (h/0.7)^2 eV @ 95 CL with sys error

Lab constraints:
$m_\nu \leq 2$ eV
Katrin sensitivity:
$m_\nu \leq 0.2$ eV
ν−oszillations:
$m_\nu \geq 0.05$ eV

D.Rubin, E. Linder, MK et al., (2009)

Antrophic principle & cosmological constant



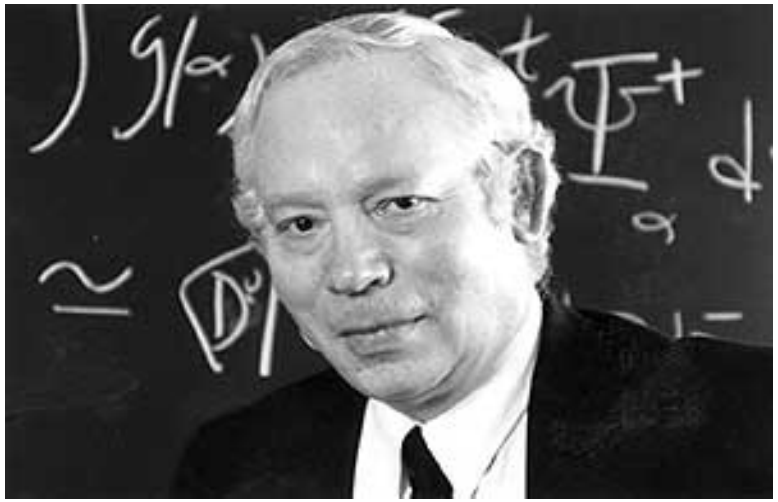
Steven Weinberg,1987

Once the cosmological constant dominates the energy budget, the Universe inflates and struture will stop forming.

Oldest galaxies formed when the Universe was about 1/10 of its current scale - the matter density was 10^3 larger then it was today:

$$\Rightarrow \rho_\Lambda / \rho_\mathrm{m} < 10^3$$

Antrophic principle & cosmological constant



Steven Weinberg,1987

$$-10^3 < \rho_\Lambda / \rho_m < 10^3$$

Once the cosmological constant dominates the energy budget, the Universe inflates and struture will stop forming.

Oldest galaxies formed when the Universe was about 1/10 of its current scale - the matter density was 10^3 larger then it was today.

Galaxies & stars need time to form, the Universe shouldn‘t collapse before.

Part 3.

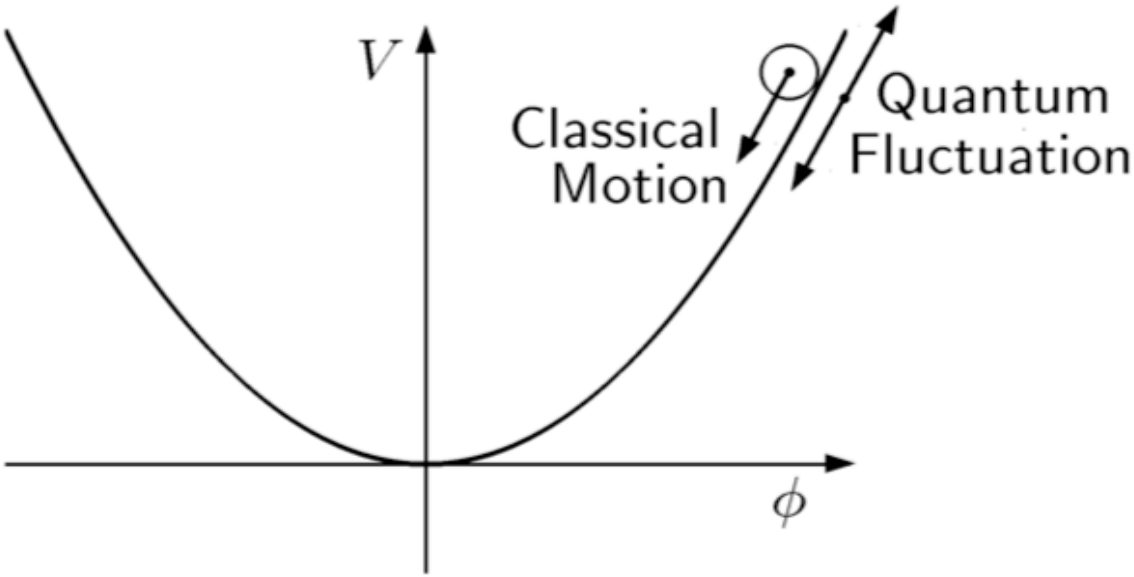
Moving beyond ΛCDM

- **Inflation**

Constraints on Inflation parameters

e.g. Chaotic Inflation (Linde, 1983)

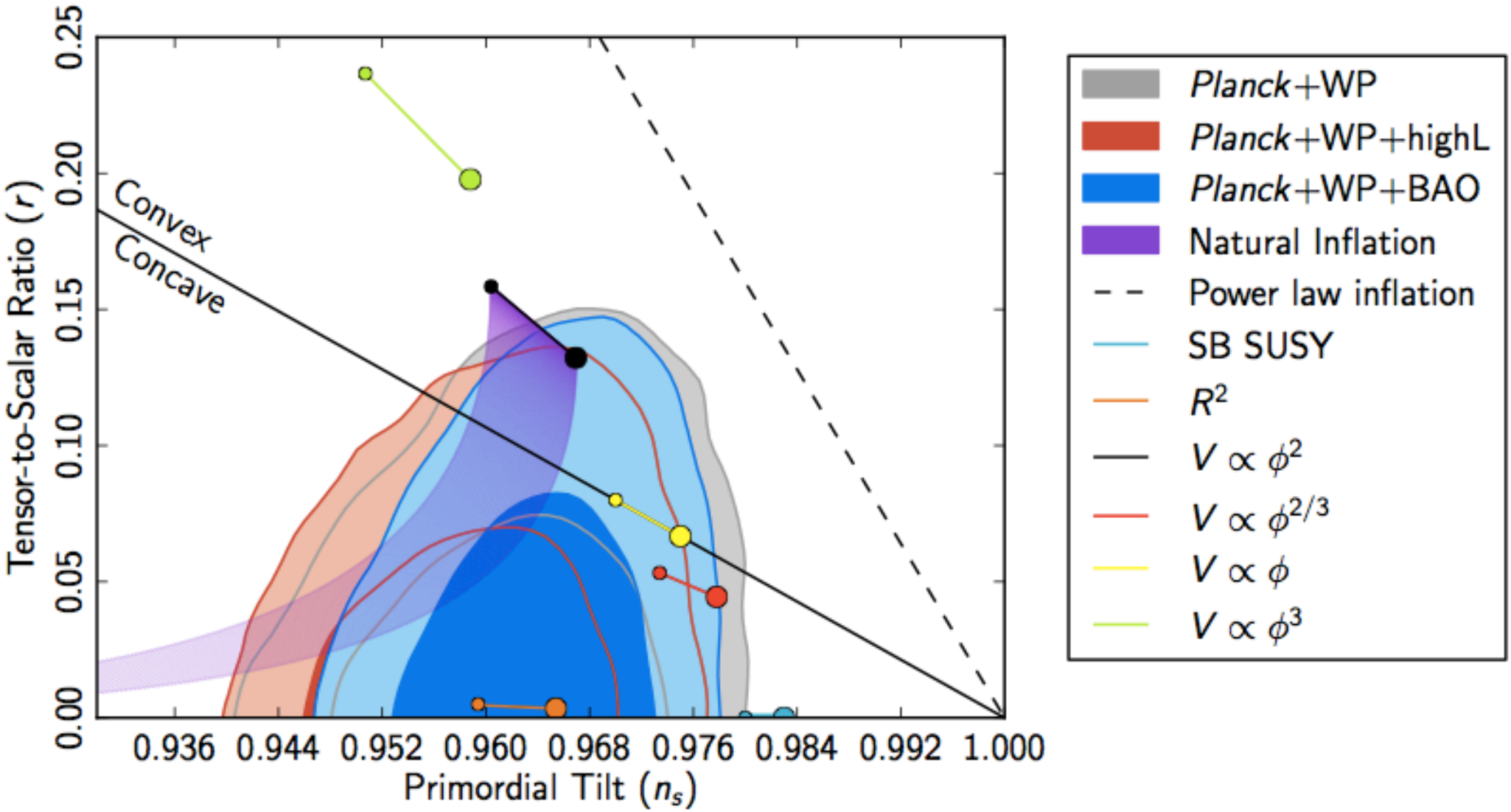
$$V(\phi) = \lambda \phi^p$$



Power spectrum of curvature perturbations

$$\Delta_R^2(k) \propto \left(\frac{k}{k_0}\right)^{n_s - 1}$$

Constraints on Inflation parameters



Planck 2013

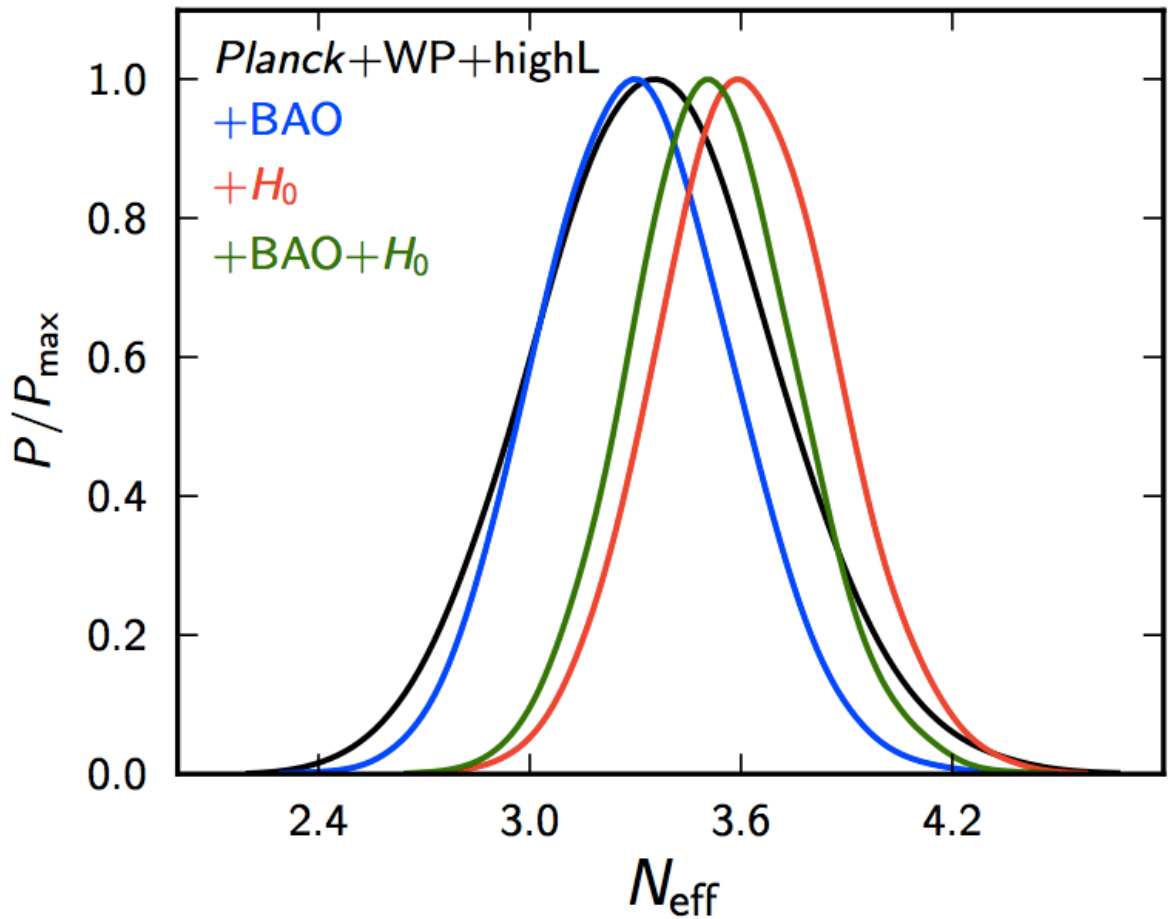
Part 3.

Moving beyond ΛCDM

- extra relativistic species

Number of relativistic species (neutrinos!)

CMB (& Baryon Nucleosynthesis) sensitive to number of neutrino species N_{eff}

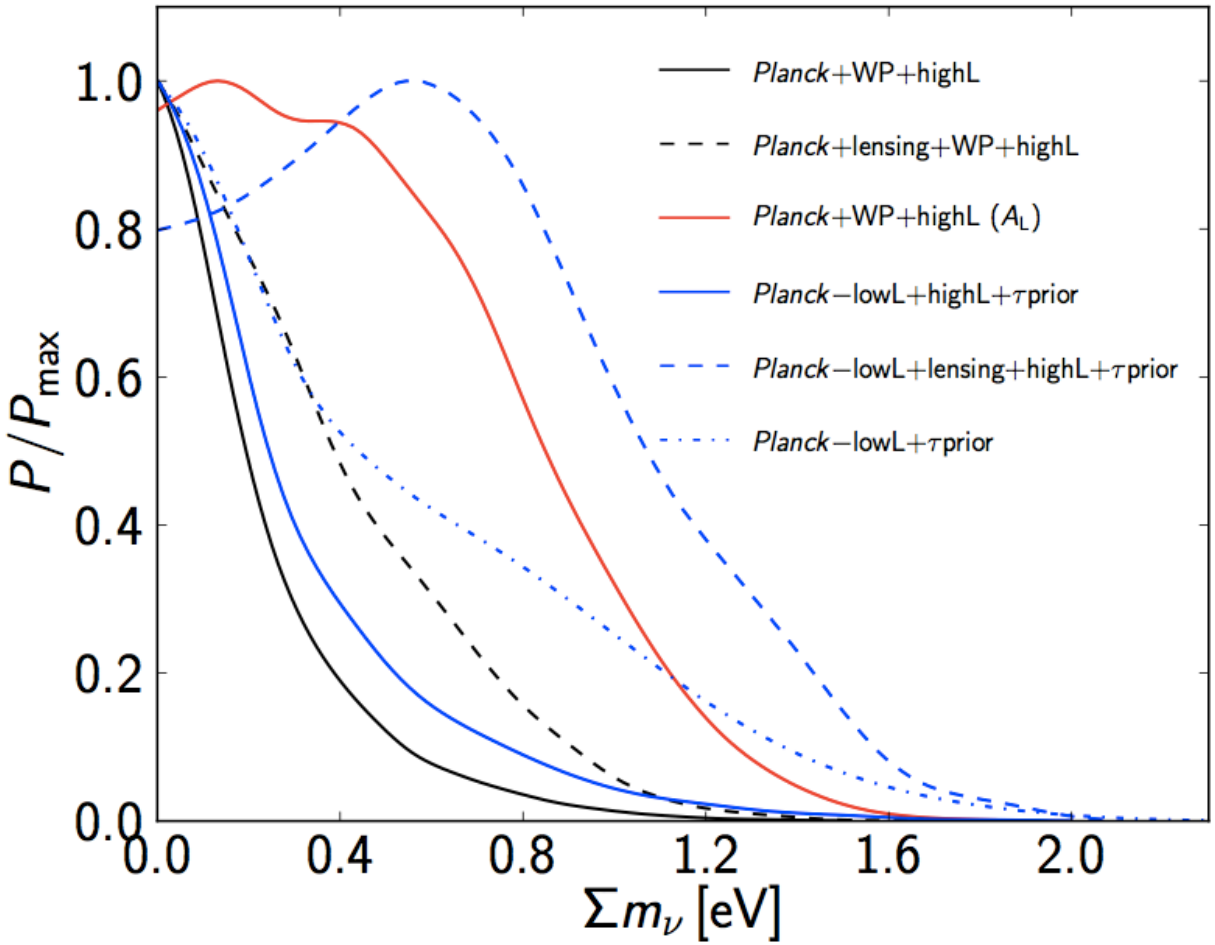


Planck+BAO: $N_{\rm eff}$ = 3.32±0.52 (95% CL)

Neutrino mass from CMB & large scale structure

Damping of correlation power due to free streaming at epoch of radiation-matter equality:

$$\left(\frac{\Delta P}{P}\right) \approx -0.8\left(\frac{\sum m_\nu}{1\ \mathrm{eV}}\right)\left(\frac{0.1}{\Omega_\mathrm{m} h^2}\right)$$

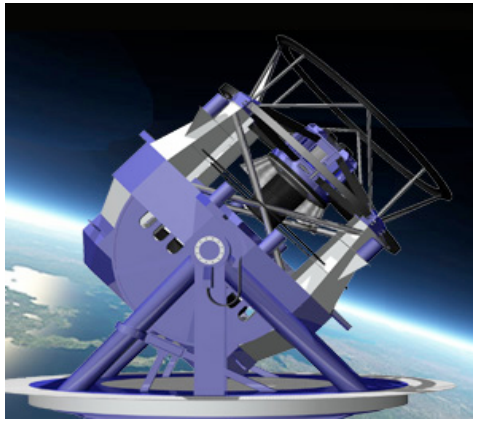


Combination of CMB+BAO:

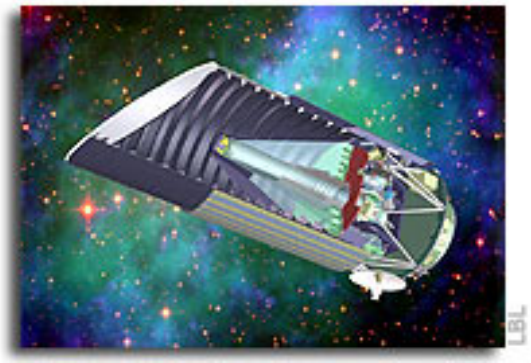
$$\sum m_\nu < 0.3\ \mathrm{eV}\ (95\%\mathrm{CL})$$

Planck (2013)

Part 4.
Observing the future

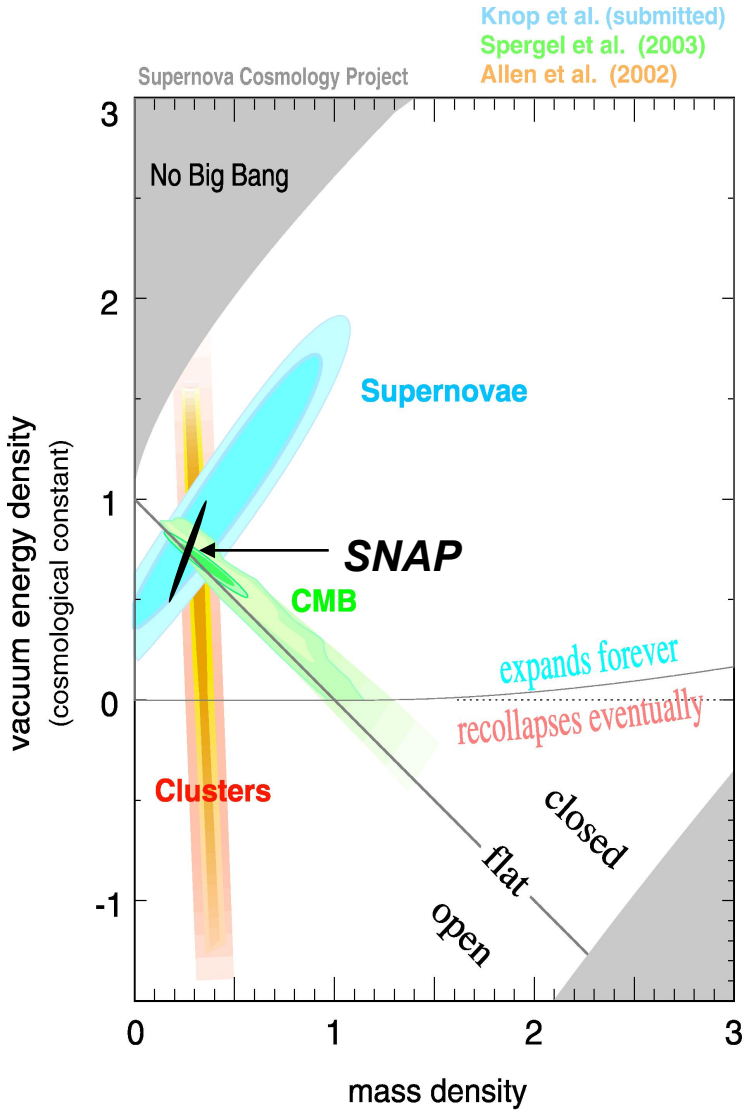


Future projects for Dark Energy



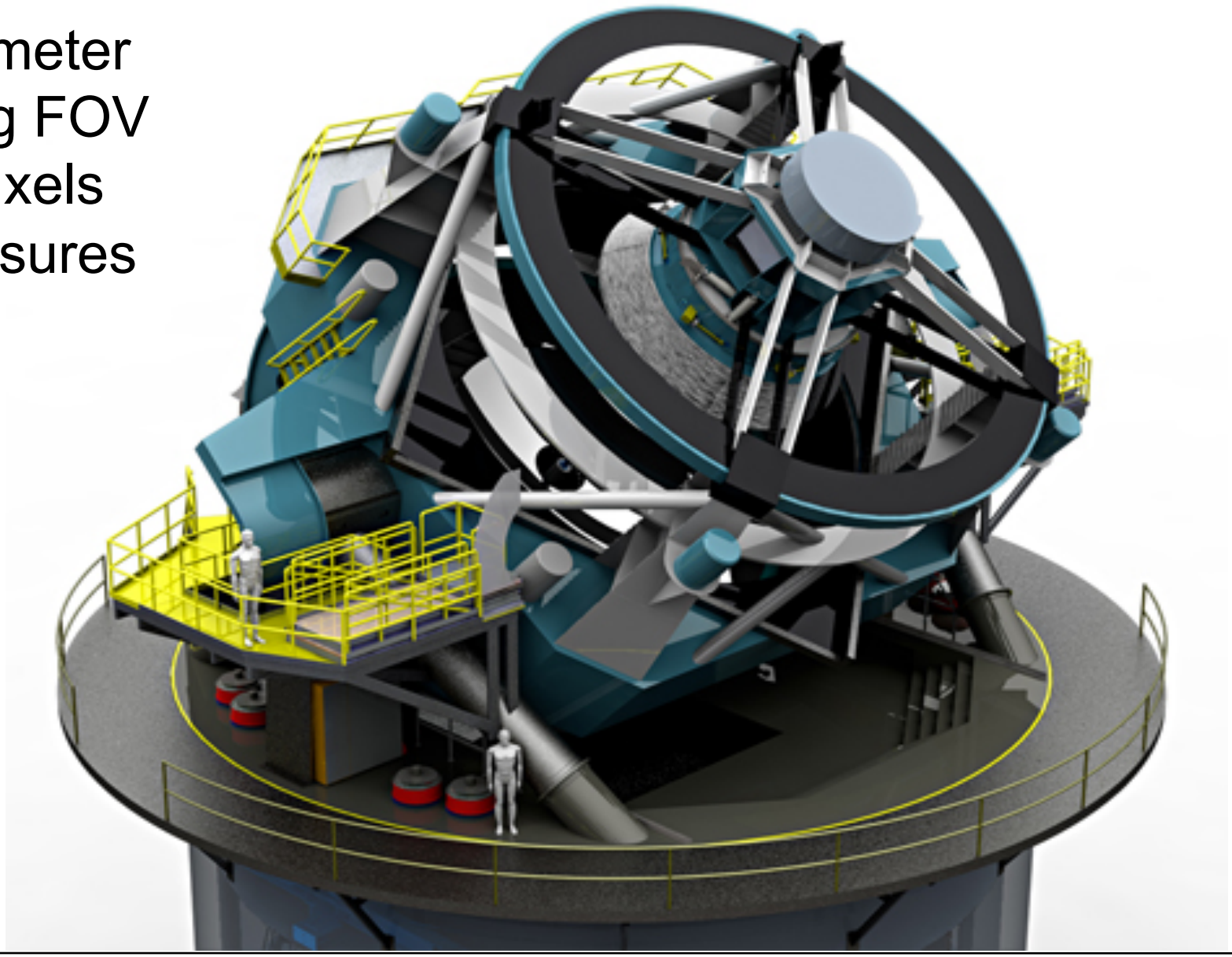
Project	z-range	# SNe
Current	0-1.5	580
LSST (2020)	0.1-0.9	~10^6
Euclid (2020)	0.9-2.0	~2000

Other important future methods:
- ✓Weak lensing
- ✓Cluster rates
- ✓Baryon acoustic osciallation



The Large Synoptic Survey Telescope

8.4 m diameter
9.6 sq.deg FOV
3.2×10^9 pixels
15 s exposures



Summary

- Cosmology today is about precision
- Multiple probes for highest sensitivity
- ΛCDM looks strong so far – despite interpretational problems with dark energy
- Many new surveys committed, hence significant progress expected!

The end