Dark Energy

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3.6.2019

1. Introduction

Our Cosmological Framework derives from…

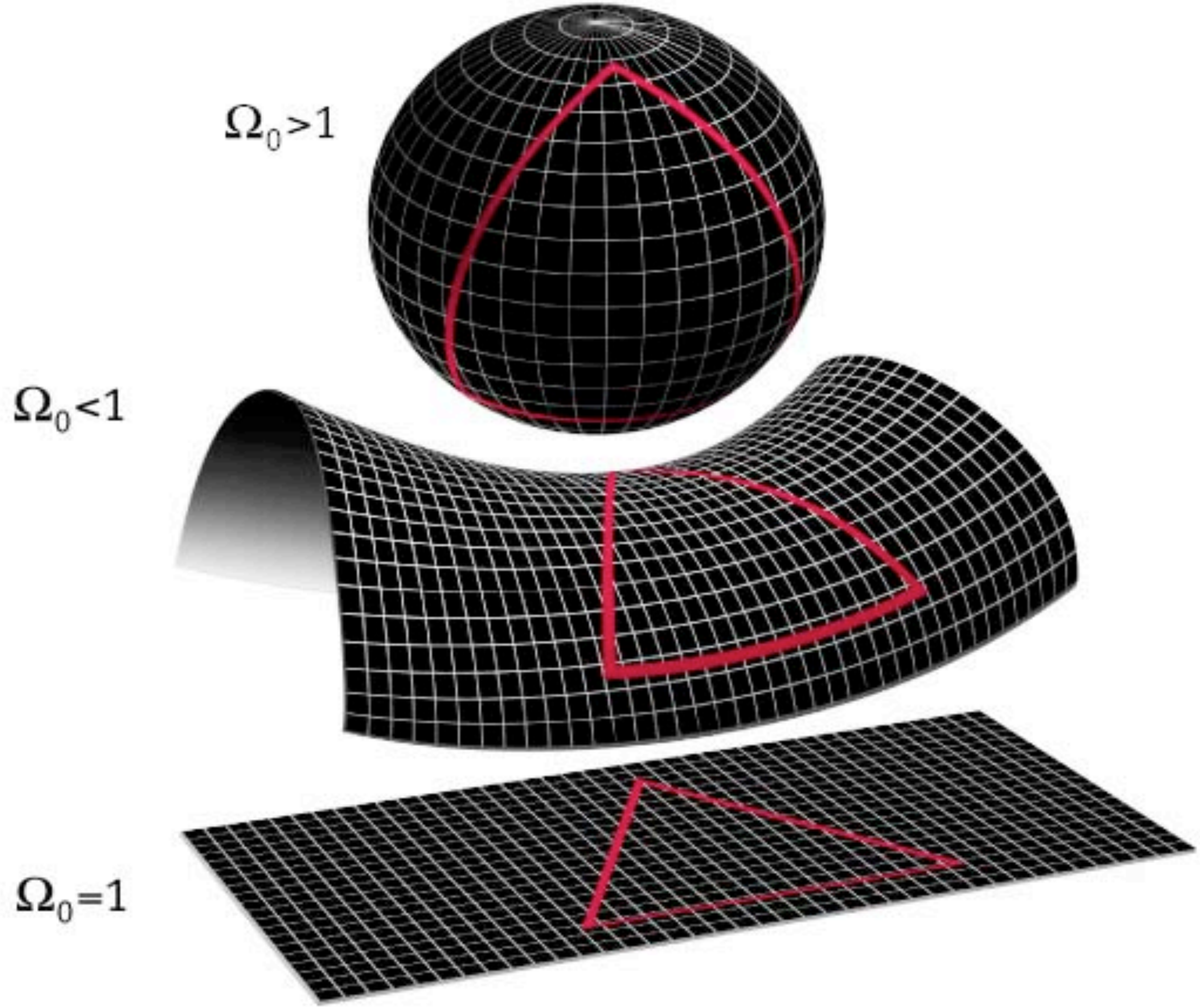
Observation:	The Universe is expanding
Principles:	Homogeneous, isotropic
Theory:	General Relativity

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:
The Universe can have curvature

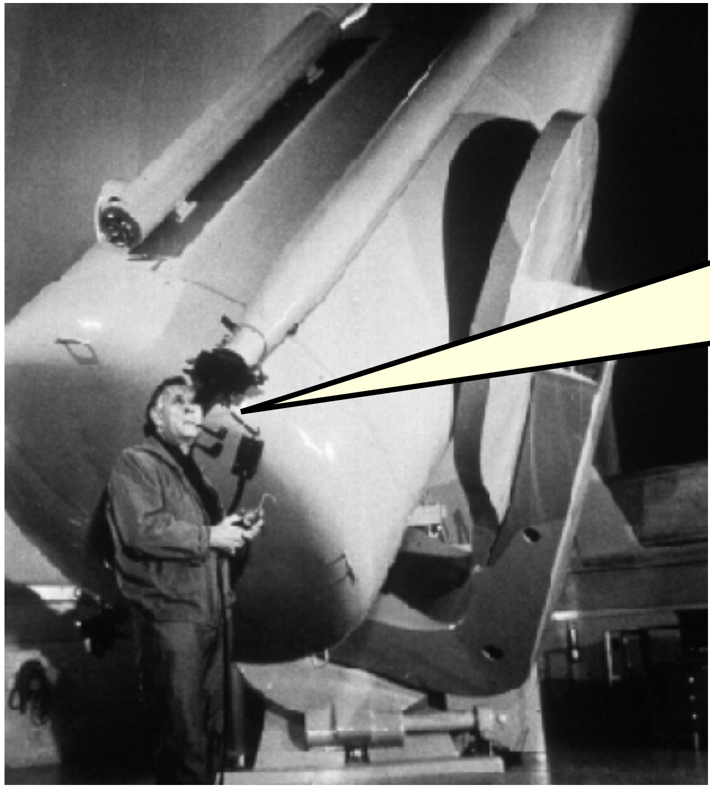


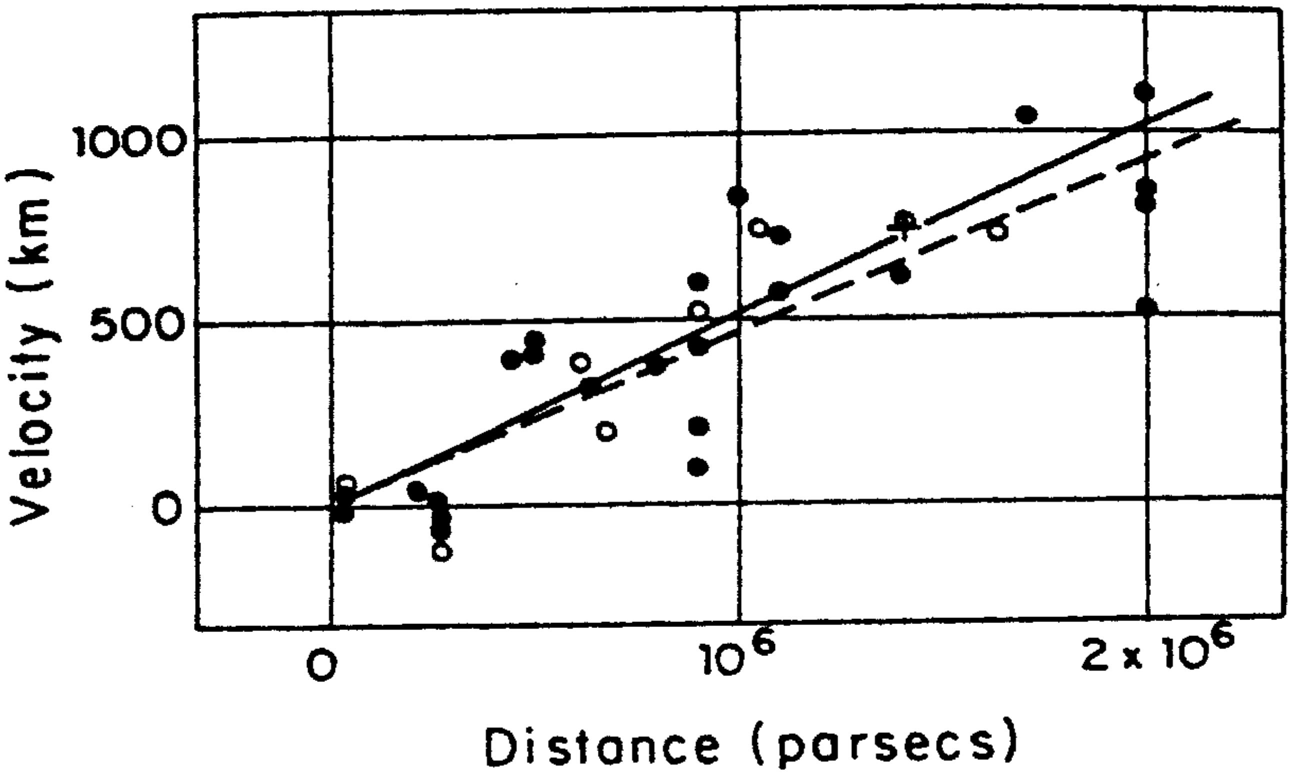
Einstein, 1916:
General Relativity

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





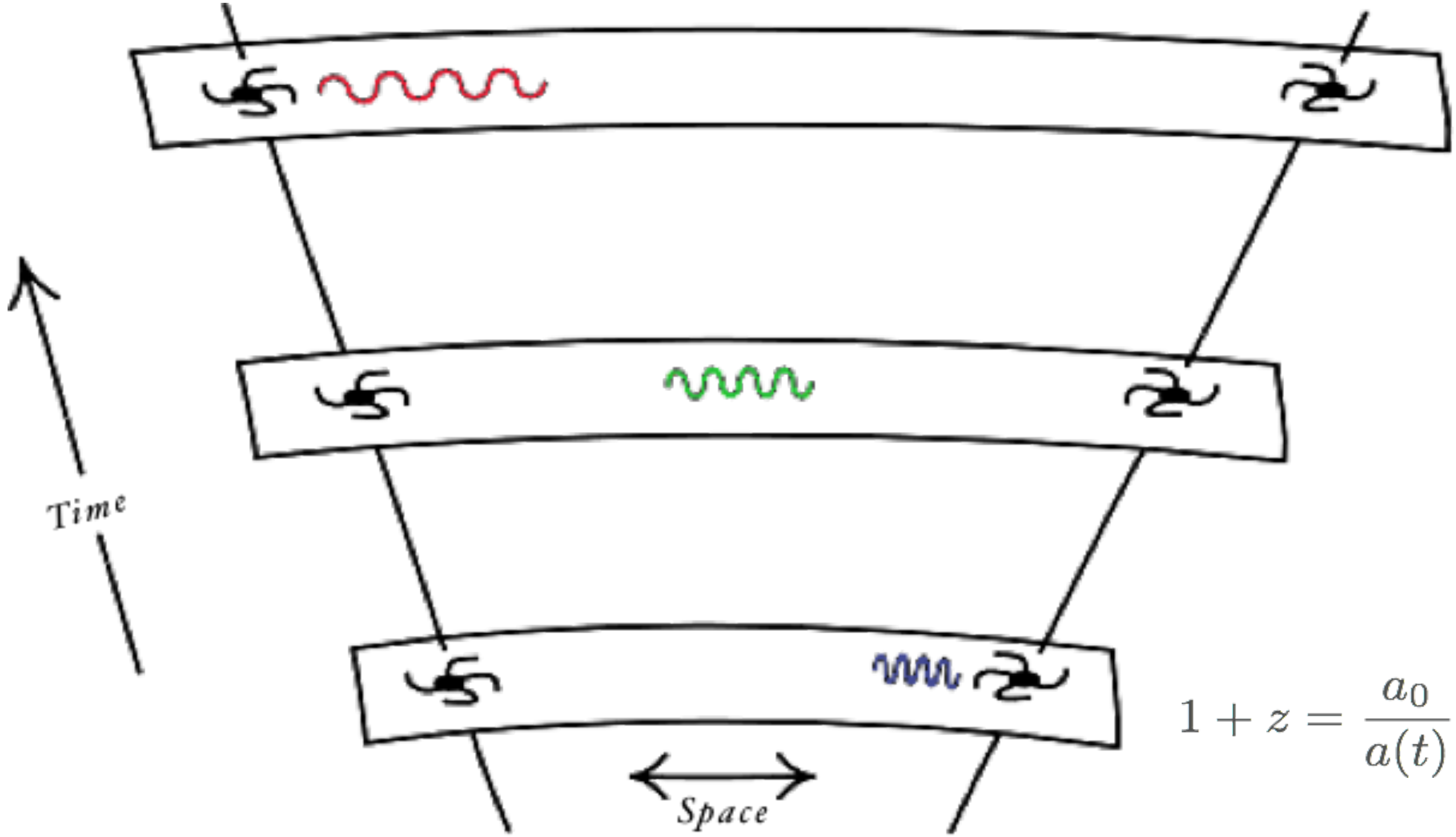
Redshift of spectral lines:

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

"Doppler effect"

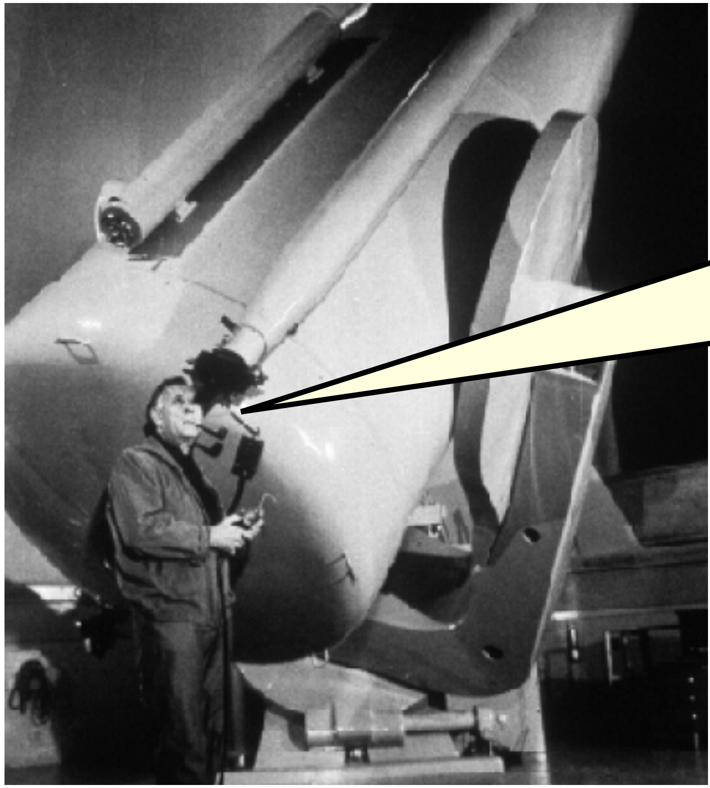
$$v \approx z \cdot (\text{speed of light})$$

Cosmological Redshift



$$1 + z = \frac{a_0}{a(t)} = \frac{\lambda_{\text{emmitted}}}{\lambda_{\text{received}}}$$

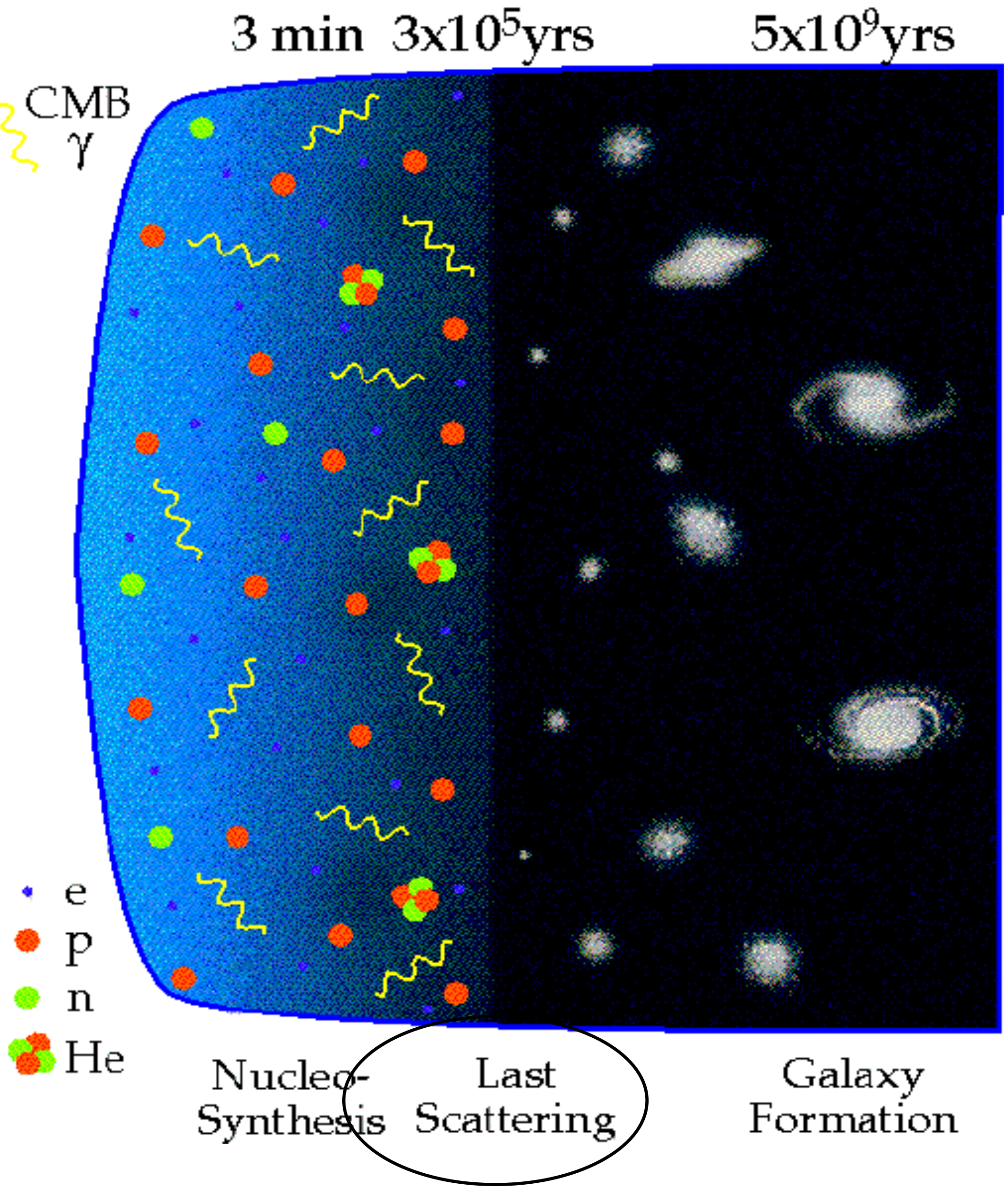
The expansion of the Universe stretchs the photon’s wavelength



Hubble:
The Universe is expanding!

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

The Big Bang Universe: A very brief History

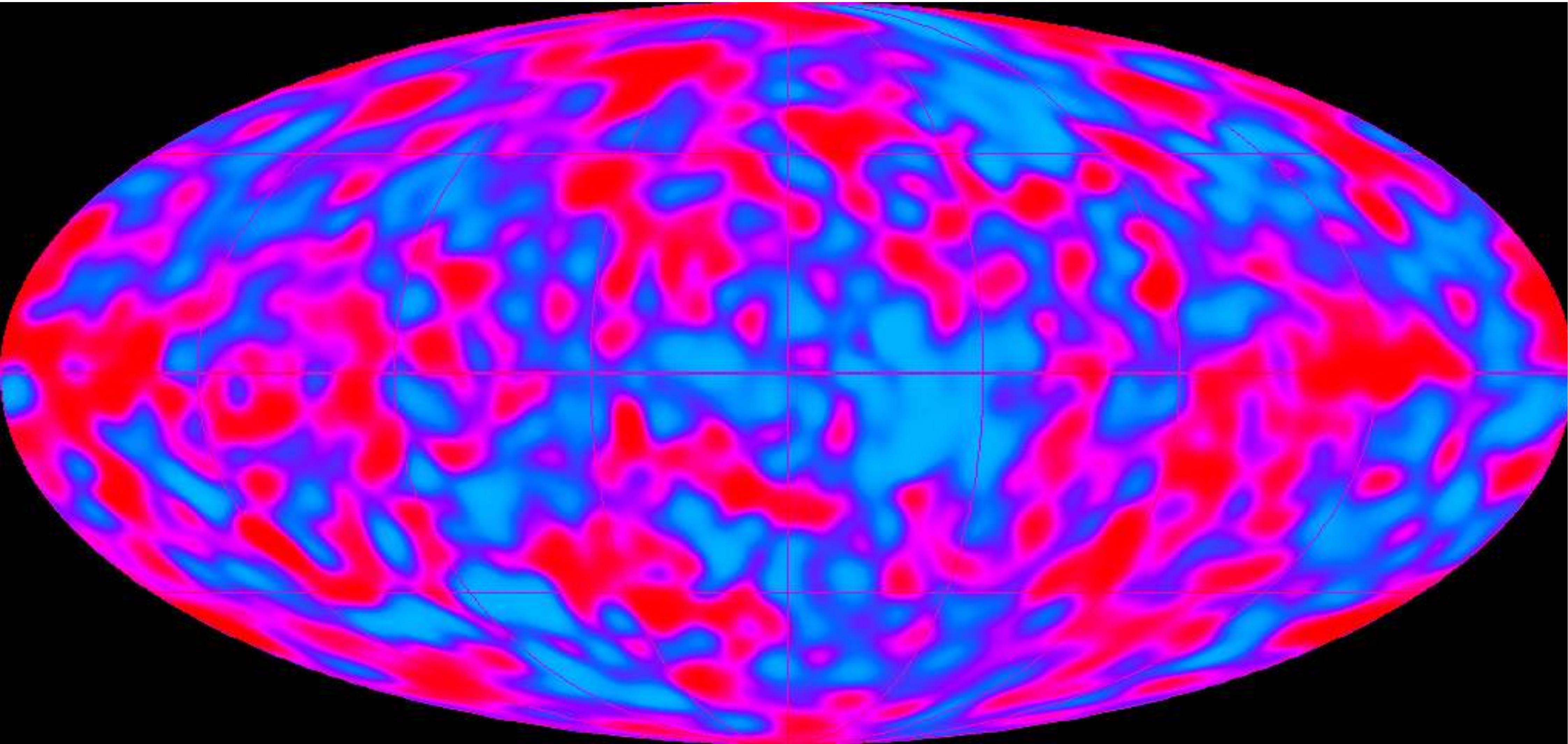


From W. Hu

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

COBE Map of CMB Fluctuations

2.725 K +/- ~ 30 μK rms, 7° beam



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$\Rightarrow$ Friedman Equation, which governs expansion

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

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$$\Omega_M + \Omega_\Lambda + \Omega_k = 1$$

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Matter Density

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Matter Density

Cosmological Constant/ Dark Energy

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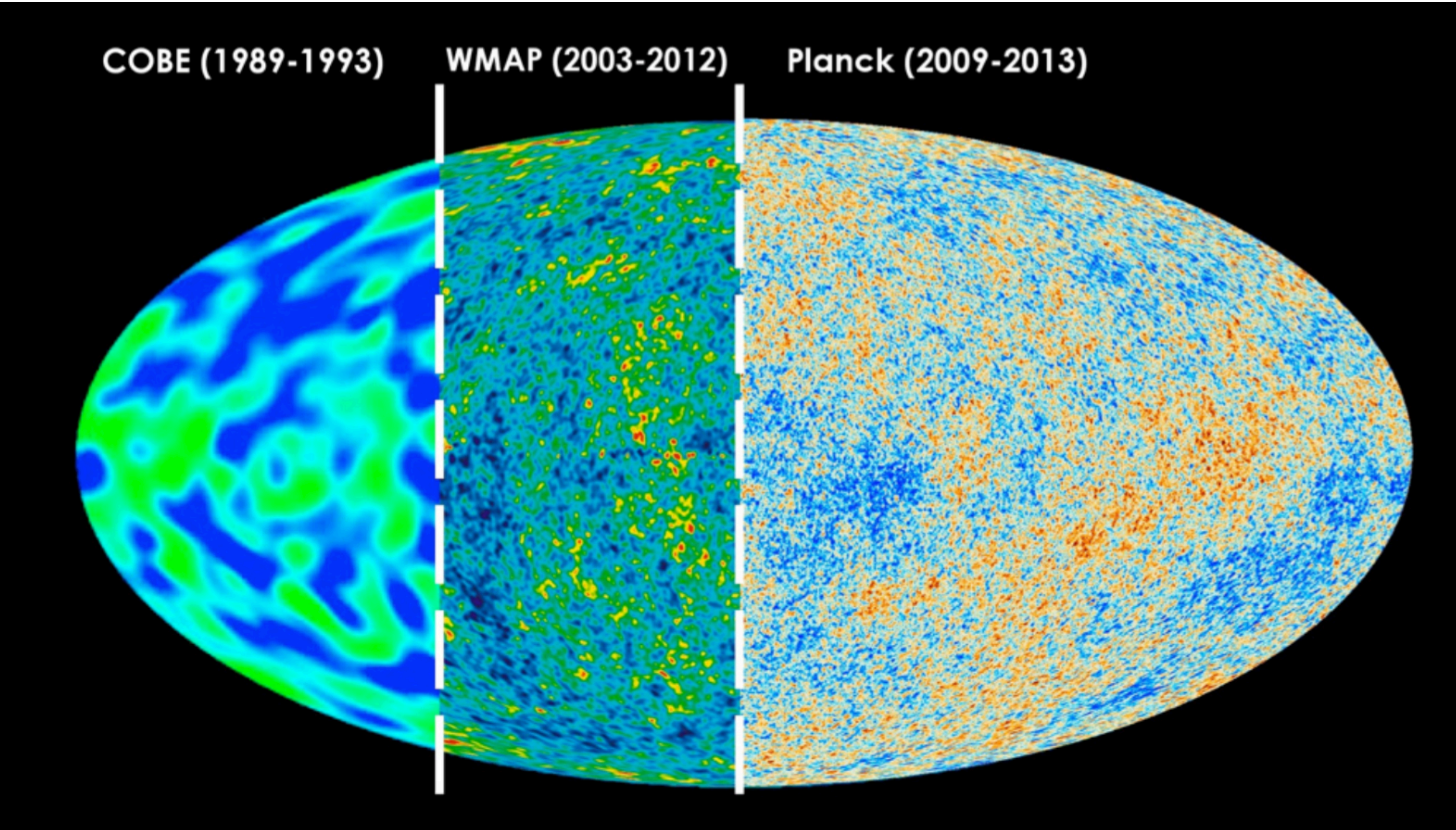
Matter Density → Ω_M

Cosmological Constant/ Dark Energy → Ω_Λ

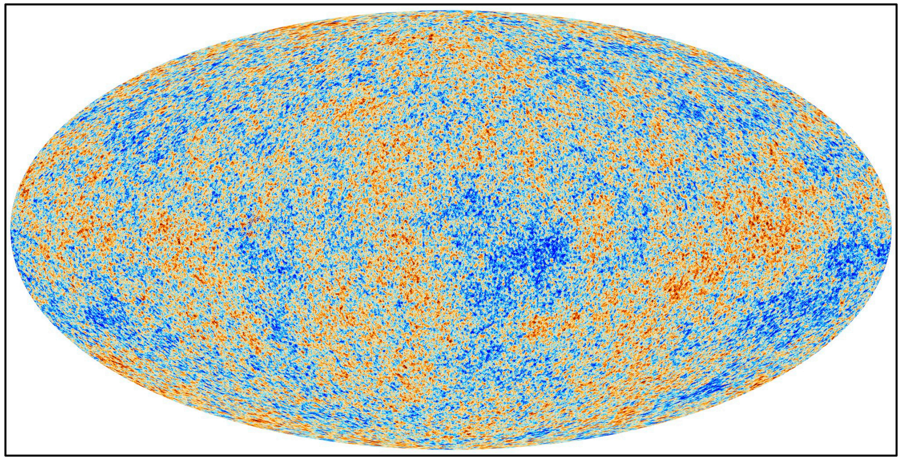
Curvature → Ω_k

Curvature of the Universe & Cosmic Microwave Background (CMB)



Curvature of the Universe & Cosmic Microwave Background (CMB)

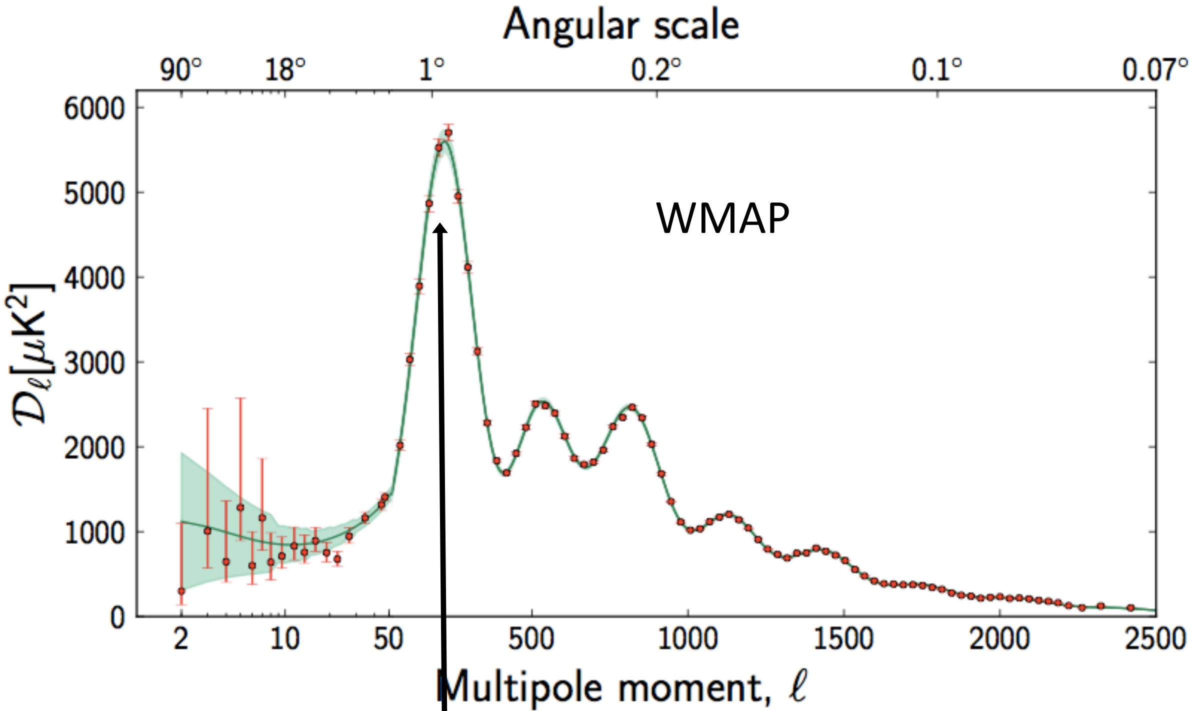
Planck



Representation of temperature map
In Spherical Harmonics:

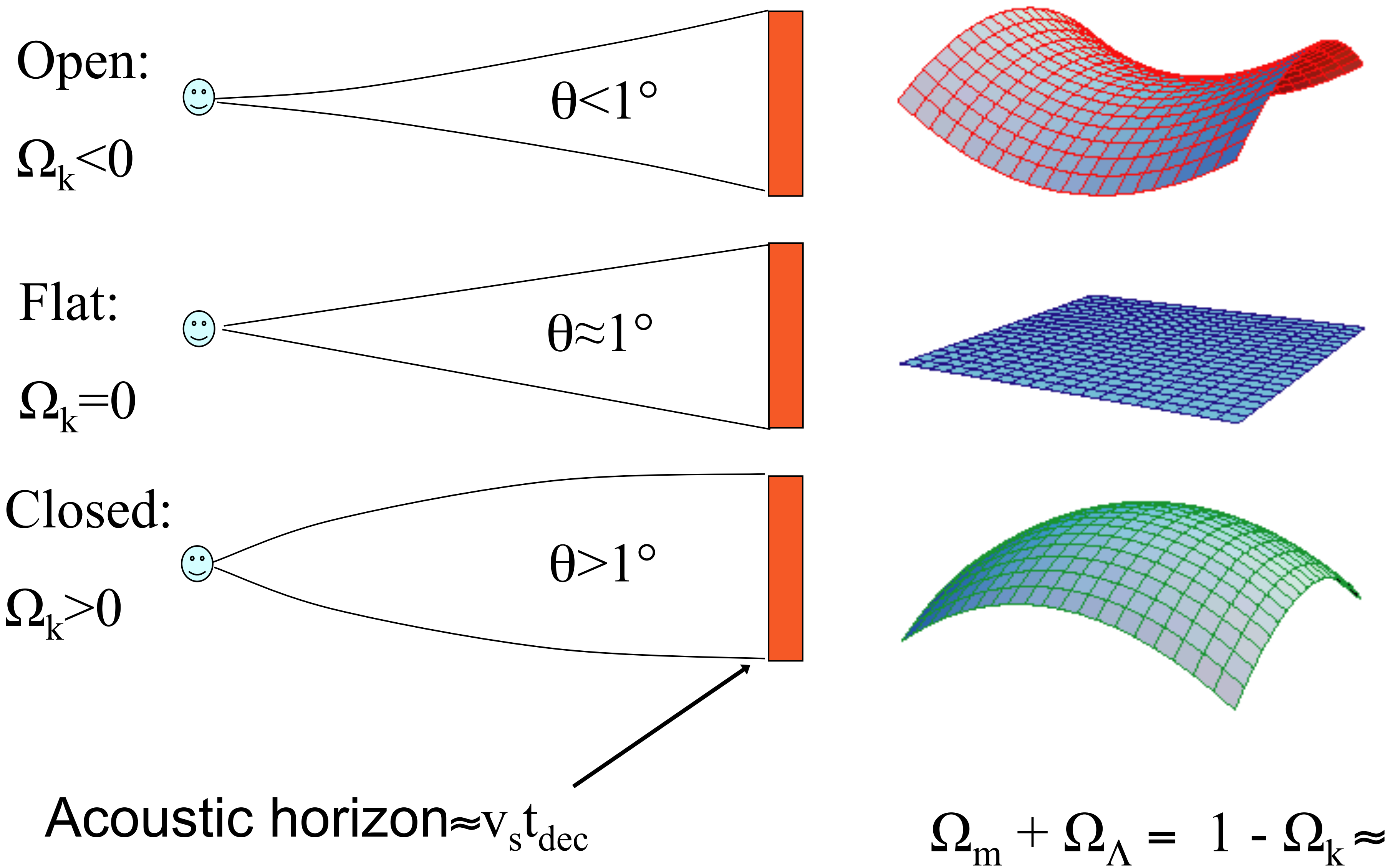
$$\frac{\Delta T}{T} = \sum_{l=2}^{\infty} \sum_{m=-l}^{m=l} a_{lm} Y_{lm}(\theta,\phi)$$

Power spectrum as a function of angular separation



Resonance length ⇔ acoustic horizon

Curvature of the Universe & Cosmic Microwave Background (CMB)



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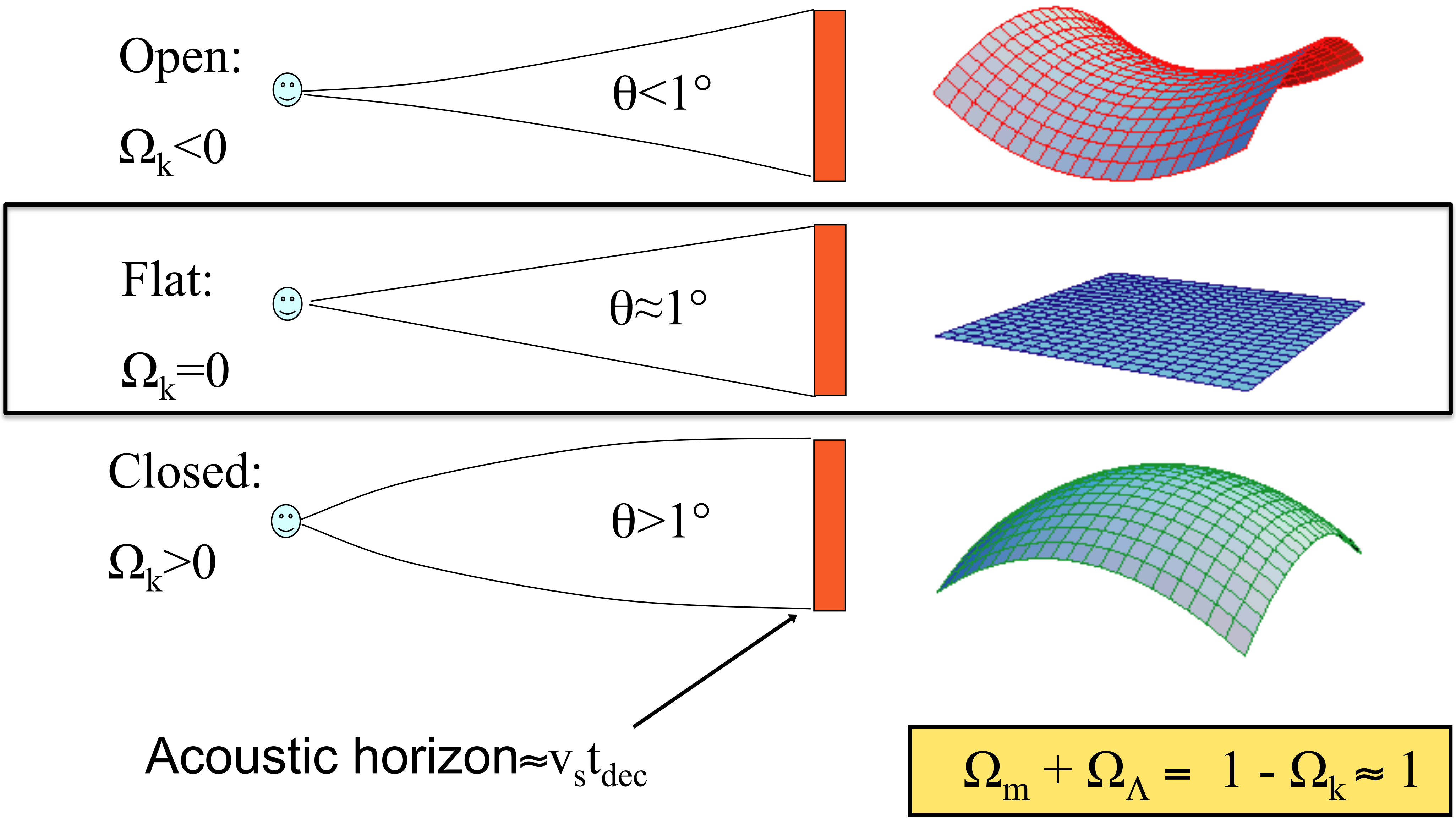


(Dark) Matter in the Universe

Coma: ~650 galaxies

Galaxy Clusters (F. Zwicky, 1933)

$$\underline{\textit{Virial} \quad \textit{Theorem}:}$$

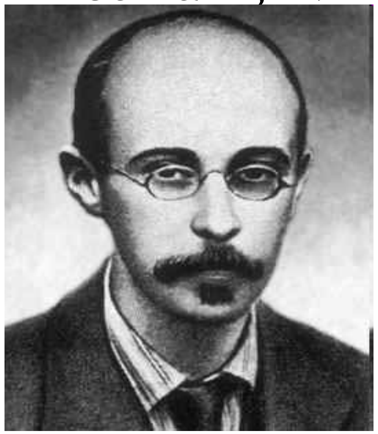
$$E_{\text{kin}} = \frac{1}{2} E_{\text{potential}}$$

Visible matter can not explain high velocities!

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

The cosmological constant Λ

Friedmann, 1922:

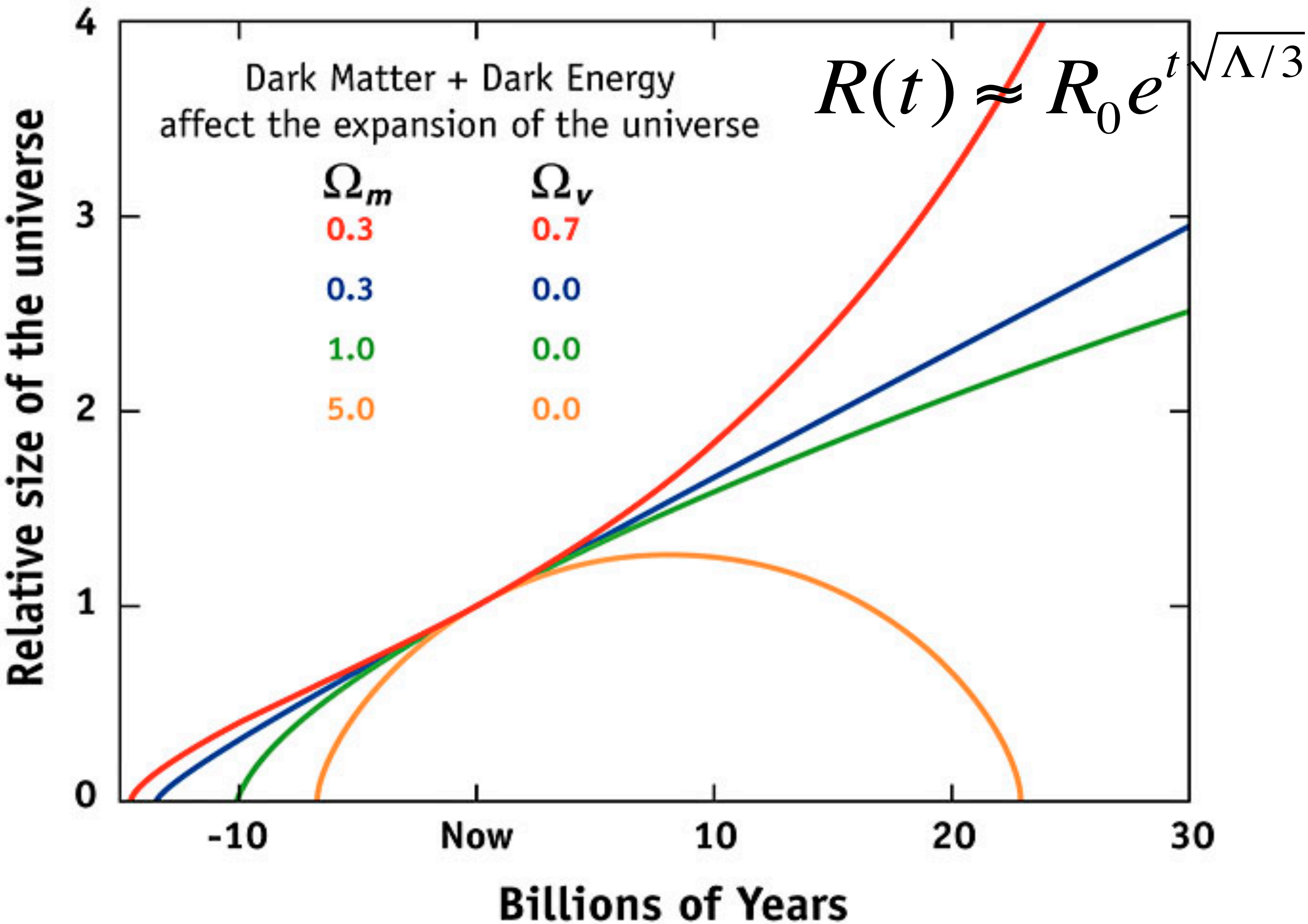


$$\left(\frac{\dot{R}}{R}\right)^2 = \frac{8\pi G}{3}\rho_M + \frac{\Lambda}{3}$$

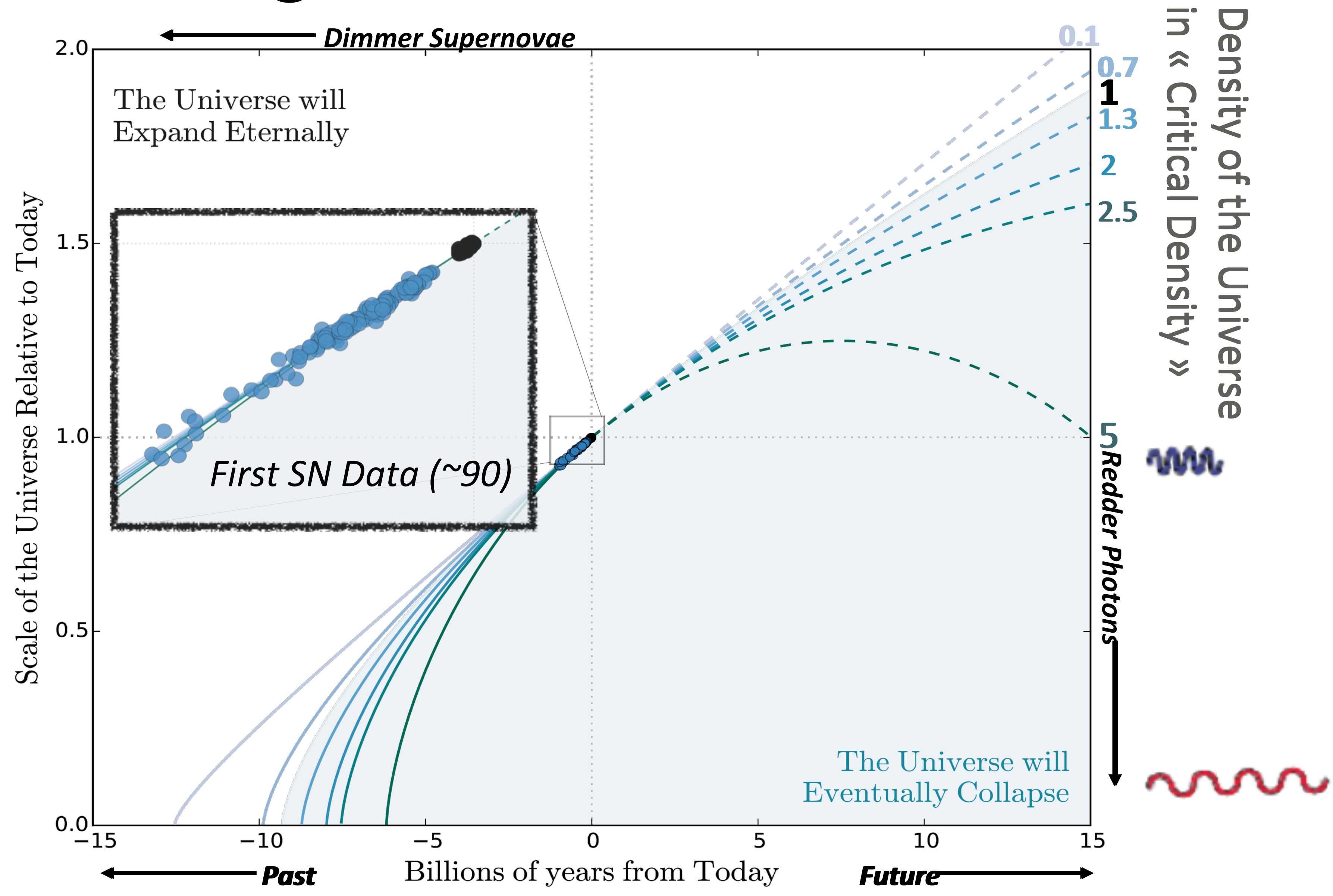
For a Universe without matter, $\rho_M = 0$, the solution is simple :

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

The cosmological constant Λ



Measuring the Fate of the Universe



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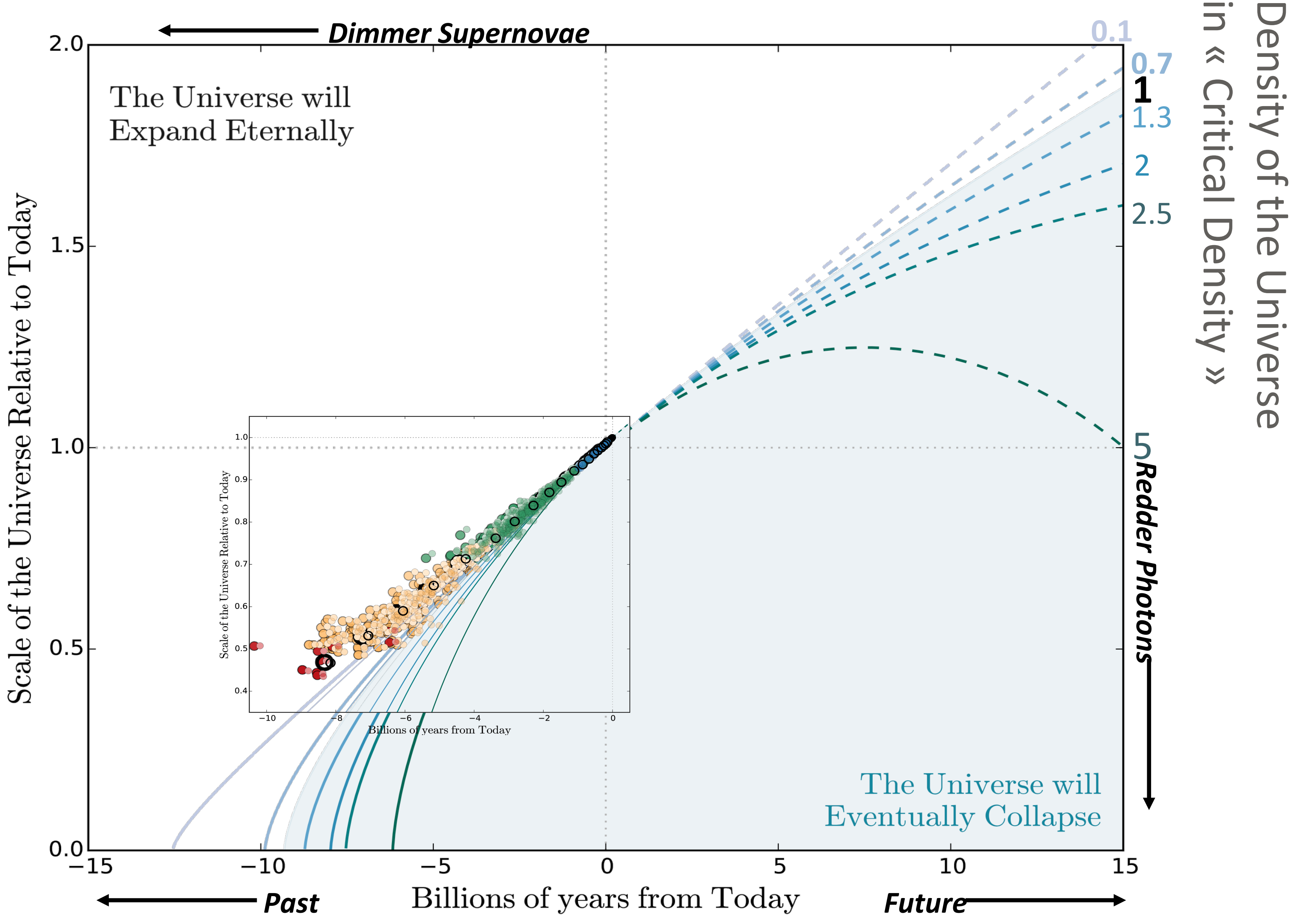
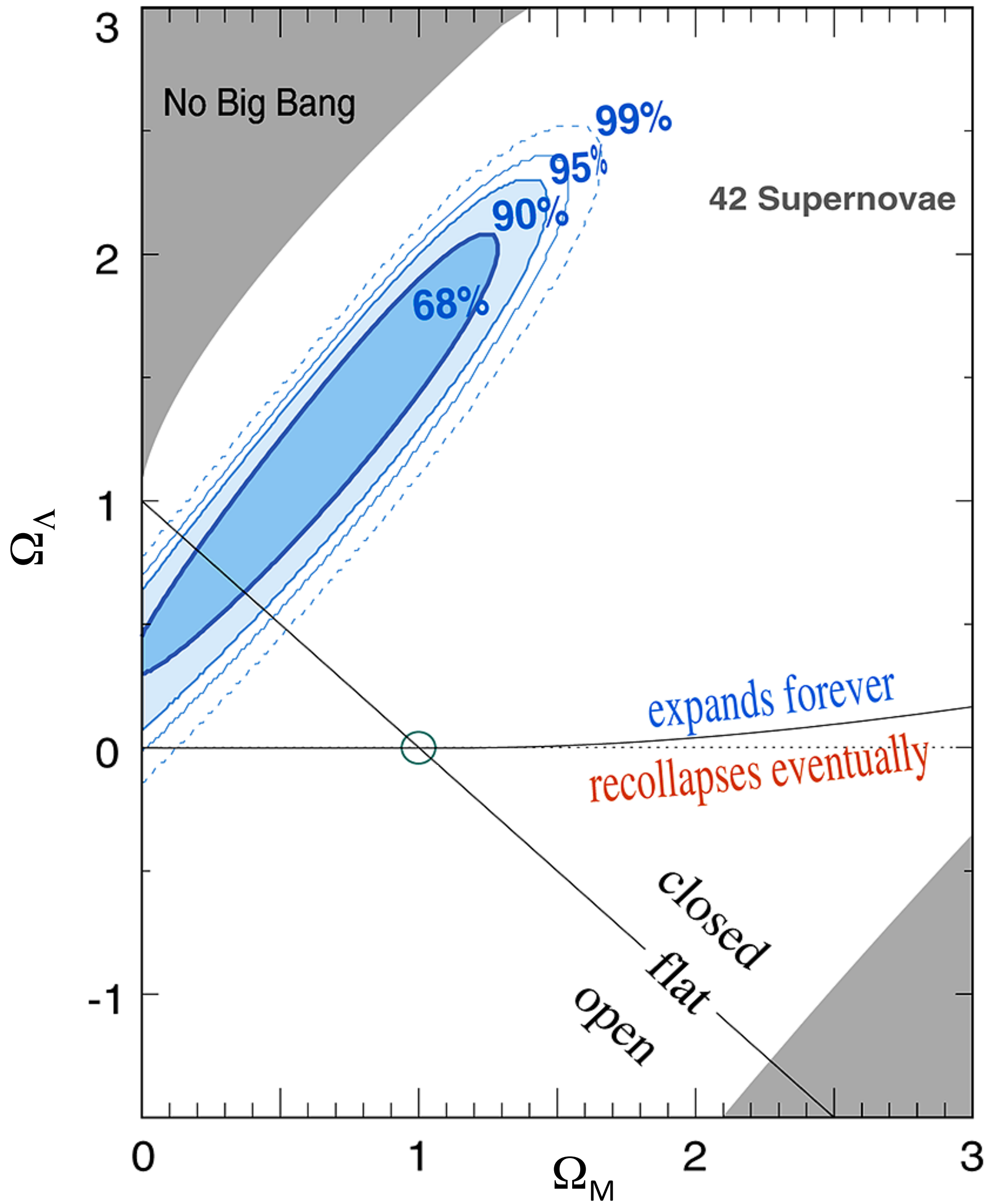
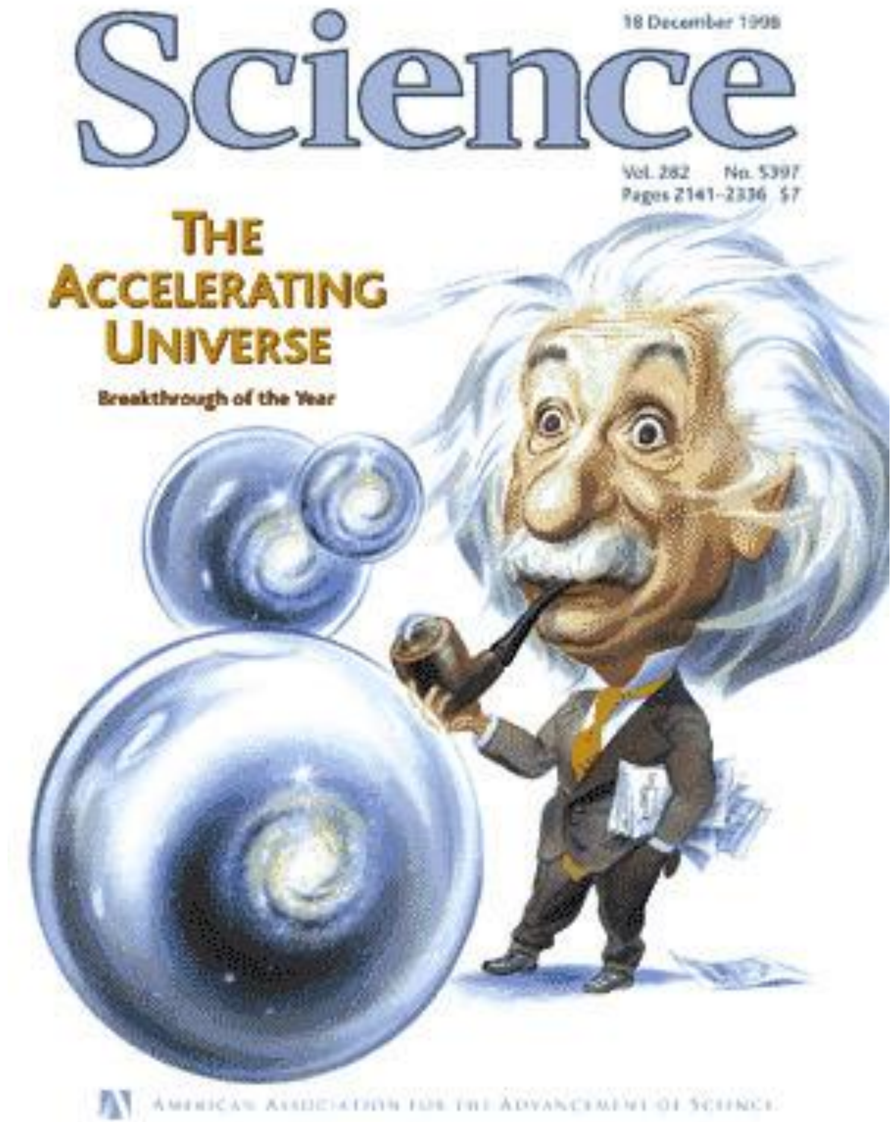


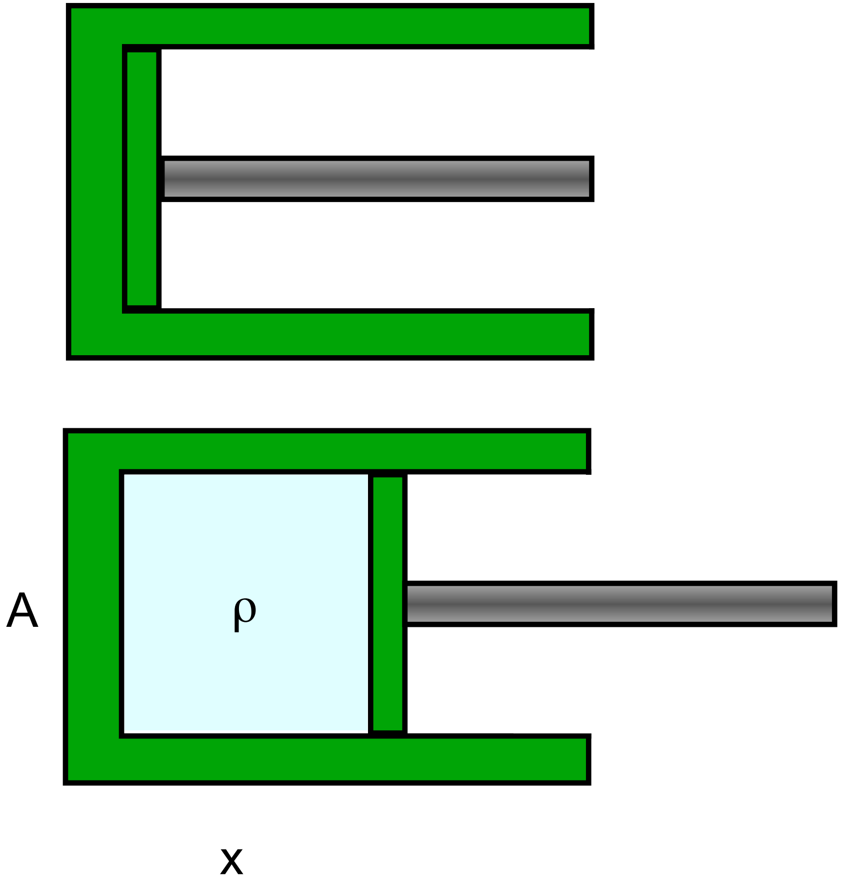
1998: Discovery of Dark Energy





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.

Fundamental Problems of Vacuum Energy/Cosmological Constant:

Why so small?

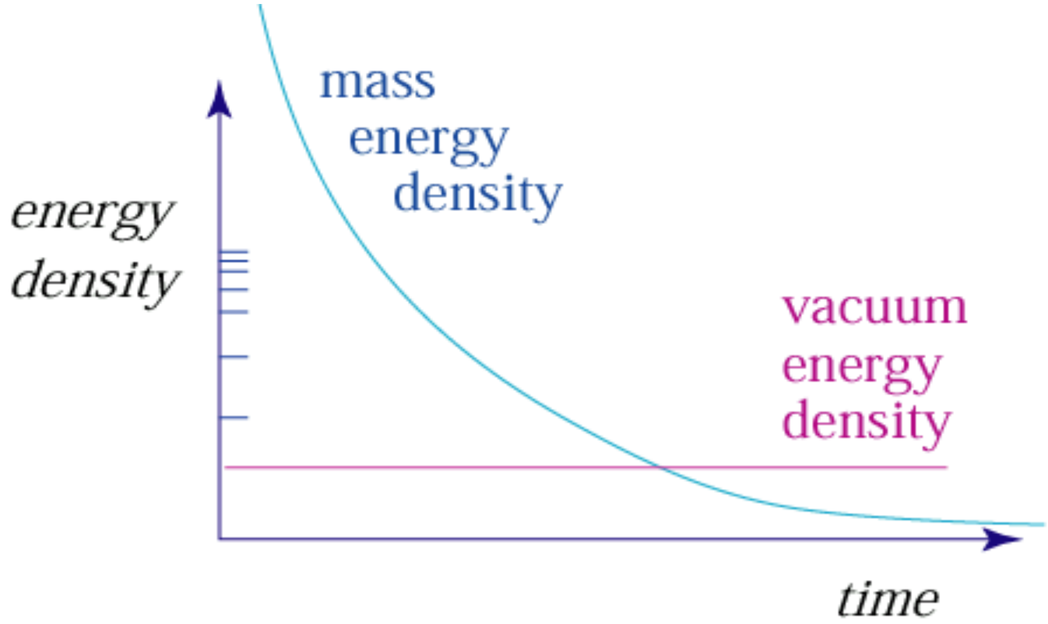
Expectation: $\rho_\Lambda \sim (M_{\text{planck}})^4$
$\Rightarrow$120 orders of magnitudes larger then the observed value!

Why now?

Matter: $\rho \propto R^{-3}$
Vakuum Energy: $\rho = constant$

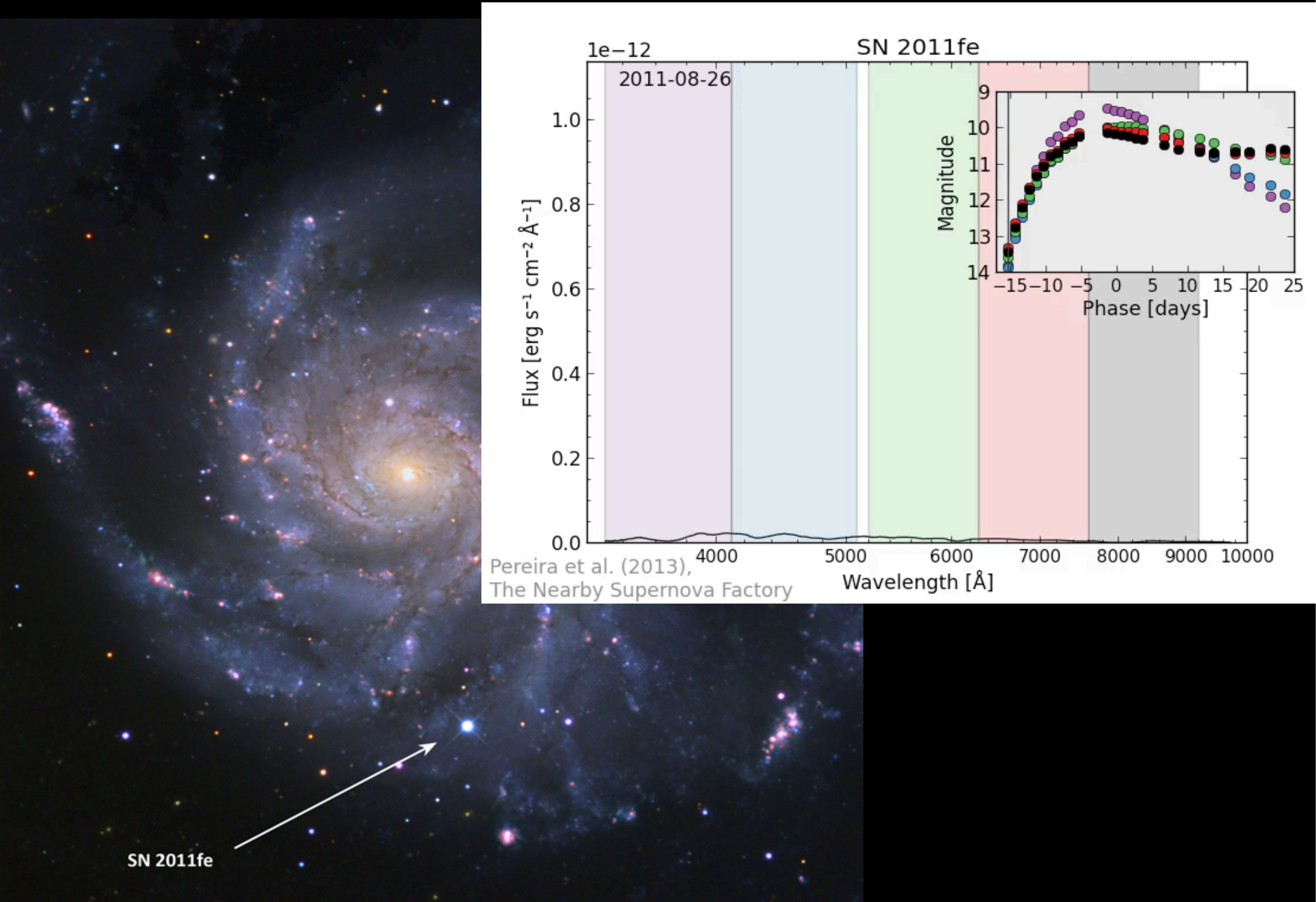
Dark Energy with equation-of-state:
$p = w\rho$
(p = pressure; ρ = density)

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



Observations & Parameters


SN 2011fe


SN 2011fe
1e−12
2011-08-26
Flux [erg s⁻¹ cm⁻² Å⁻¹]
0.0
0.2
0.4
0.6
0.8
1.0
4000
5000
6000
7000
8000
9000
10000
Wavelength [Å]
Magnitude
9
10
11
12
13
14
−15
−10
−5
0
5
10
15
20
25
Phase [days]
Pereira et al. (2013),
The Nearby Supernova Factory
SN 2011fe

Supernova Type Ia

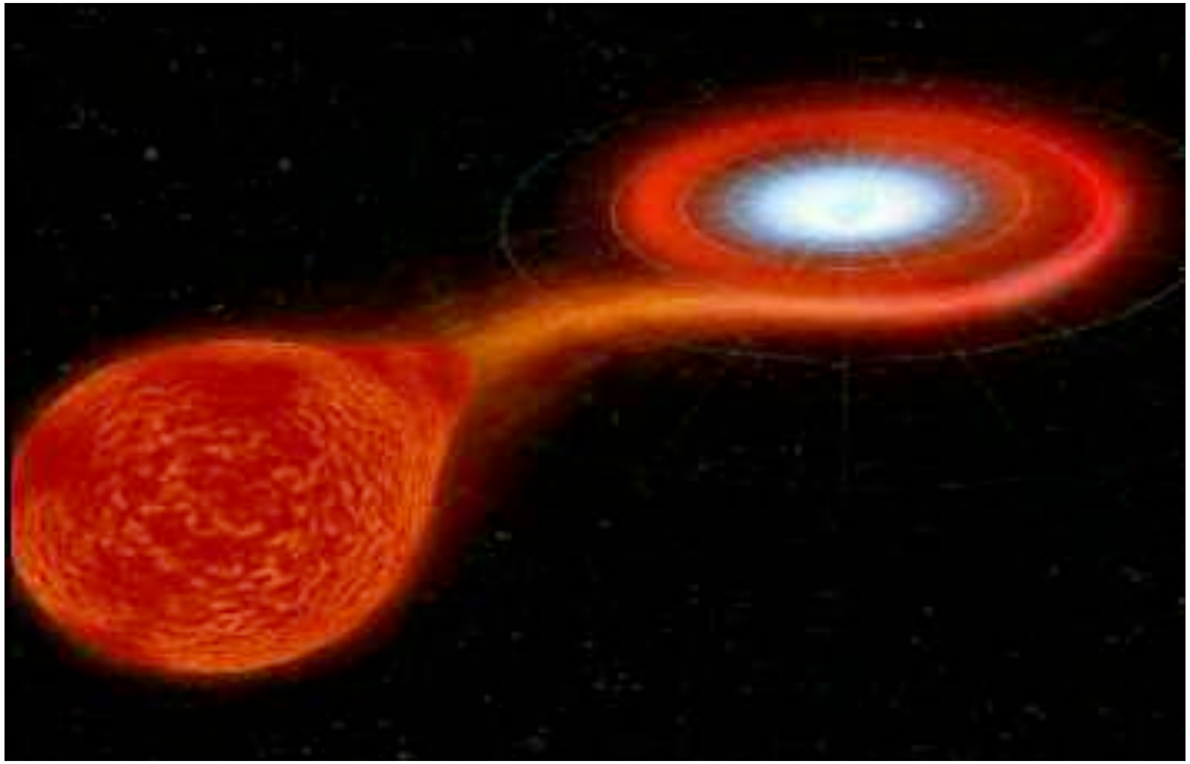
⇒White dwarf in binary system

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

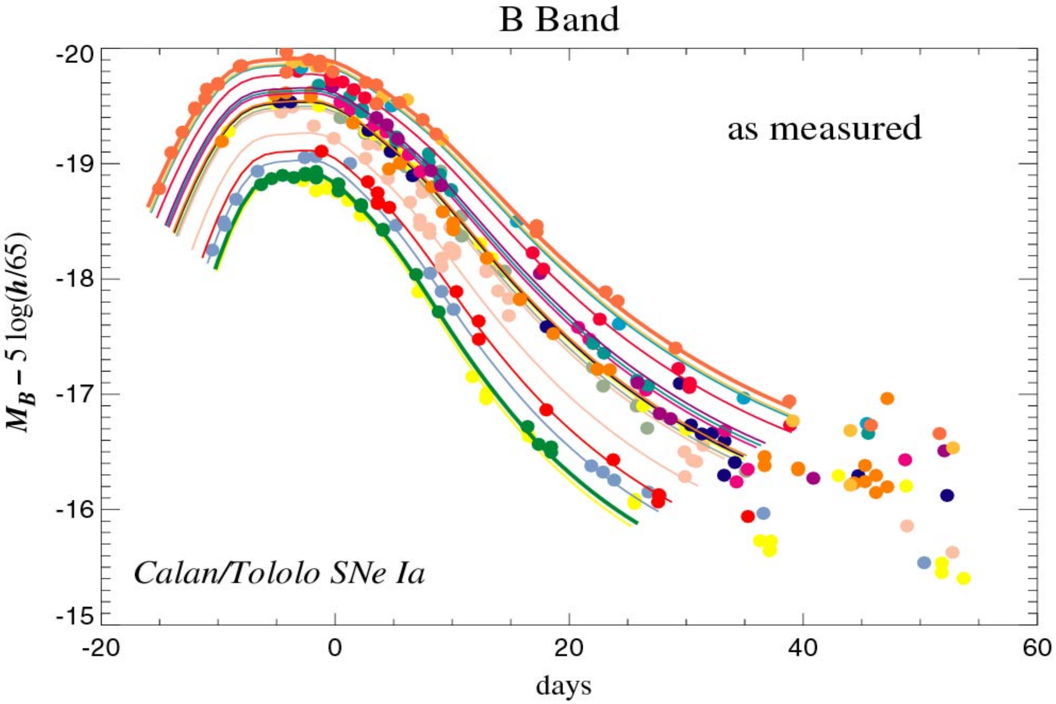
⇒Thermonuclear explosion

⇒Explosion of similar energies

⇒Visible in cosmic distances



SNe Ia as "standard" Candles



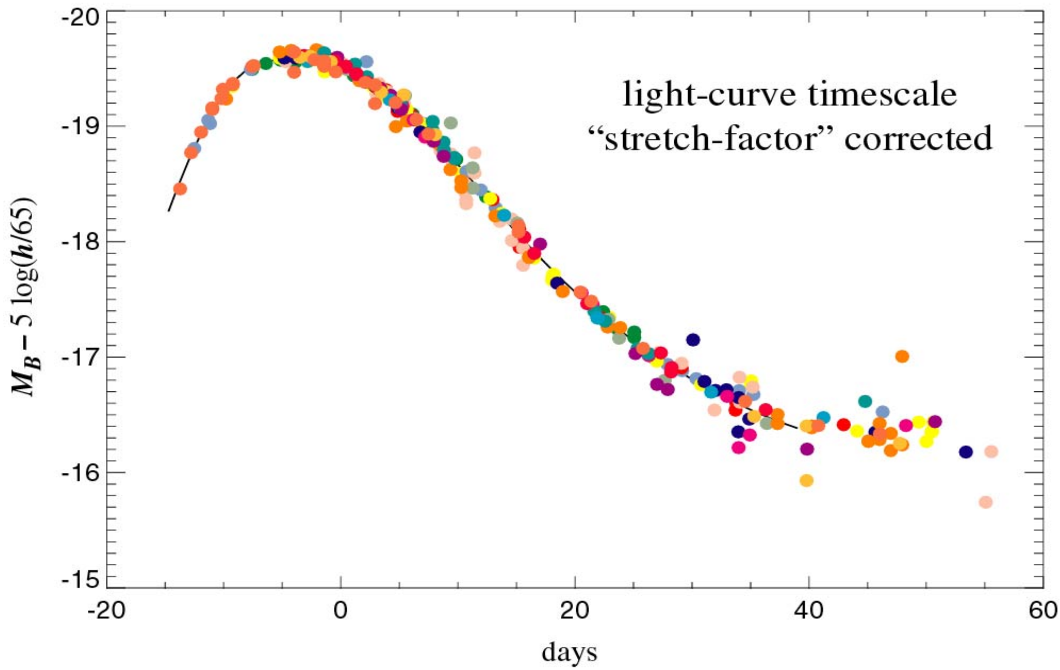
- Nearby supernovae used to study SNe light curve (z<0.1)
- Intrinsically brighter SNe have wider lightcurves.

Stretching the timescale:

$$t' = s \times t$$

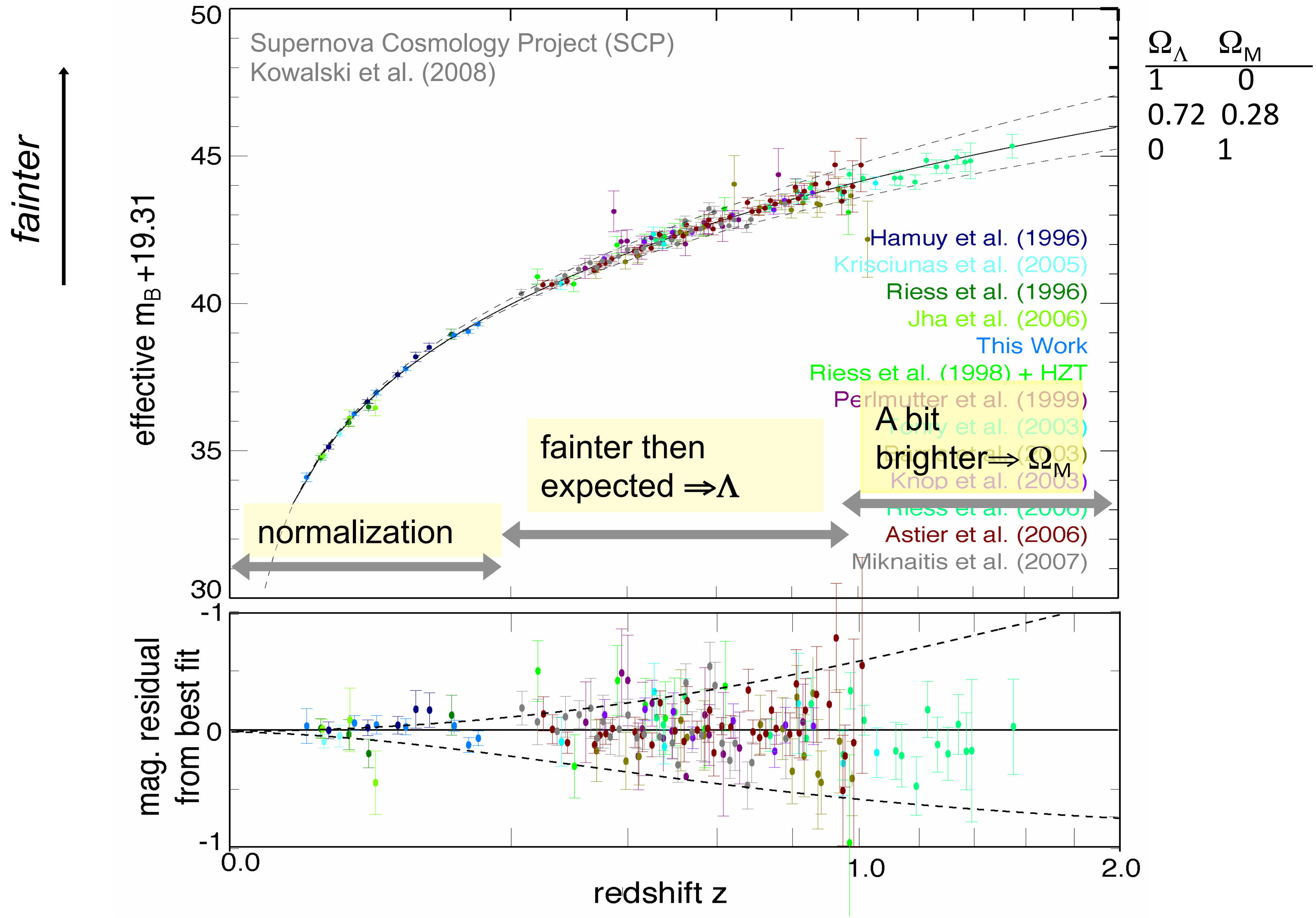
Correcting the brightness

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



Kim, *et al.* (1997)

SNe Ia Hubble Diagram



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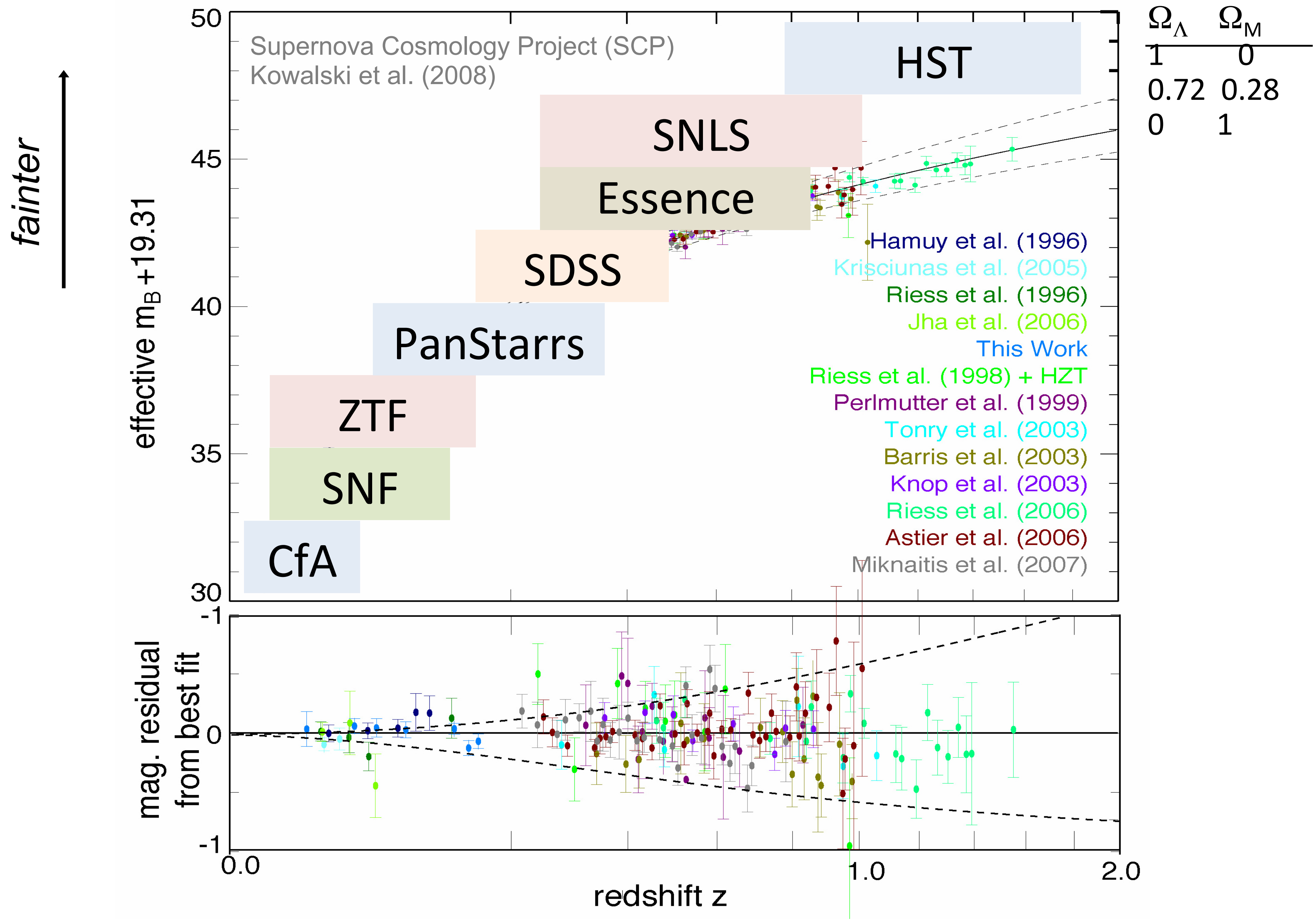
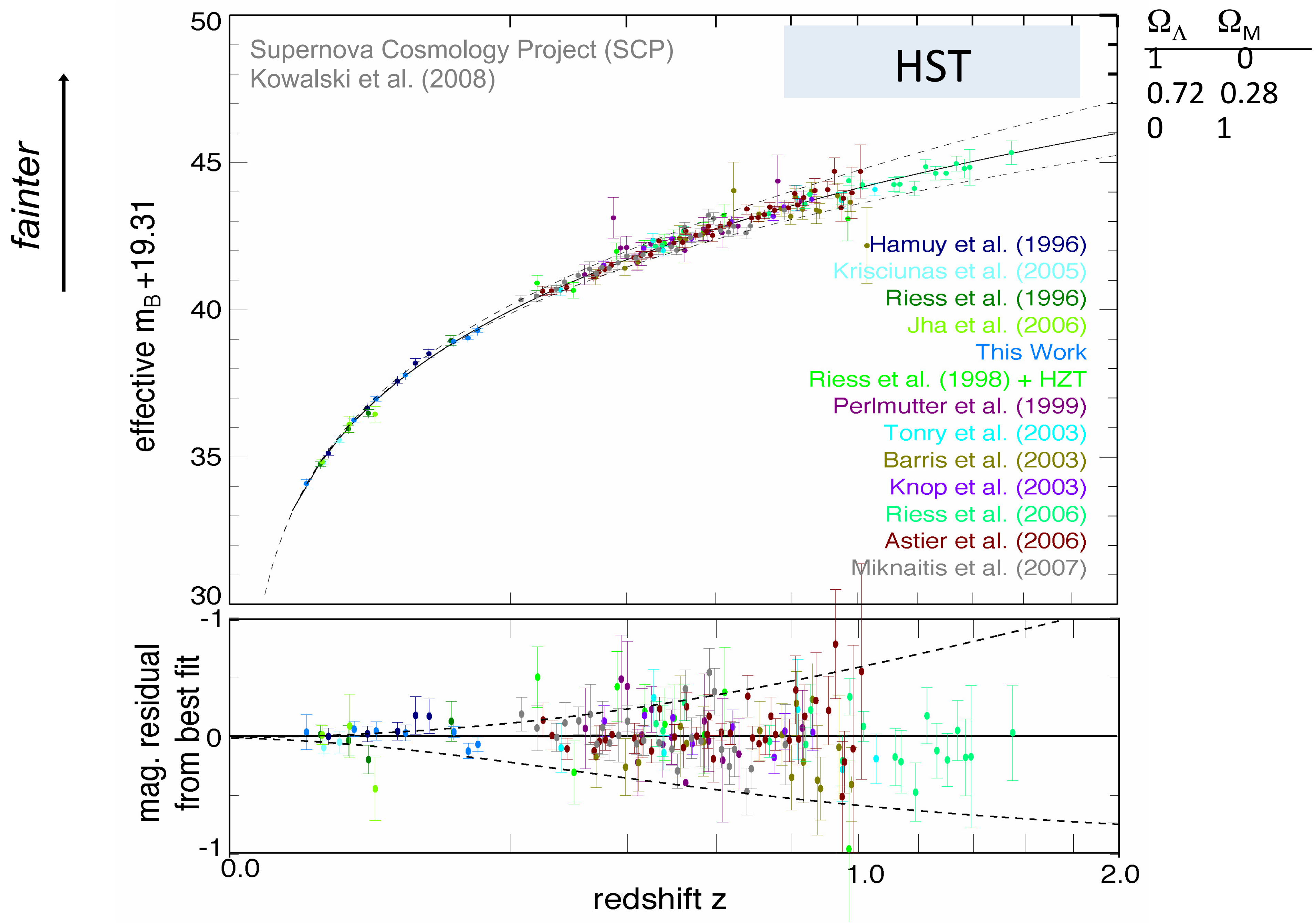
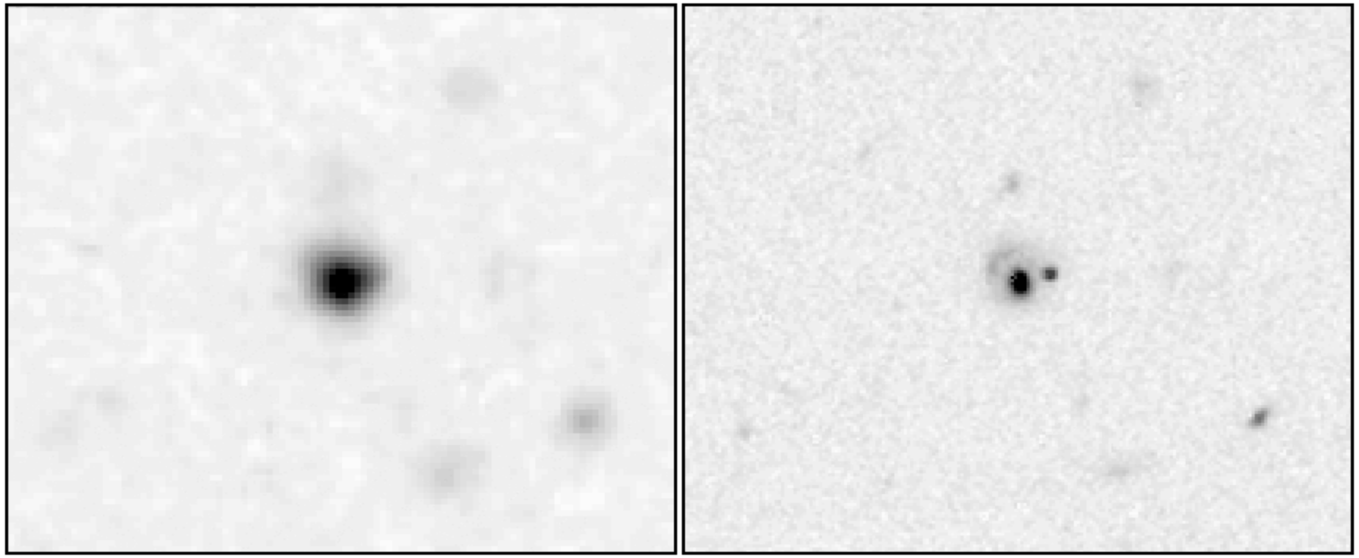


SNe Ia Hubble Diagram



SNe at large Redshifts (z>1)

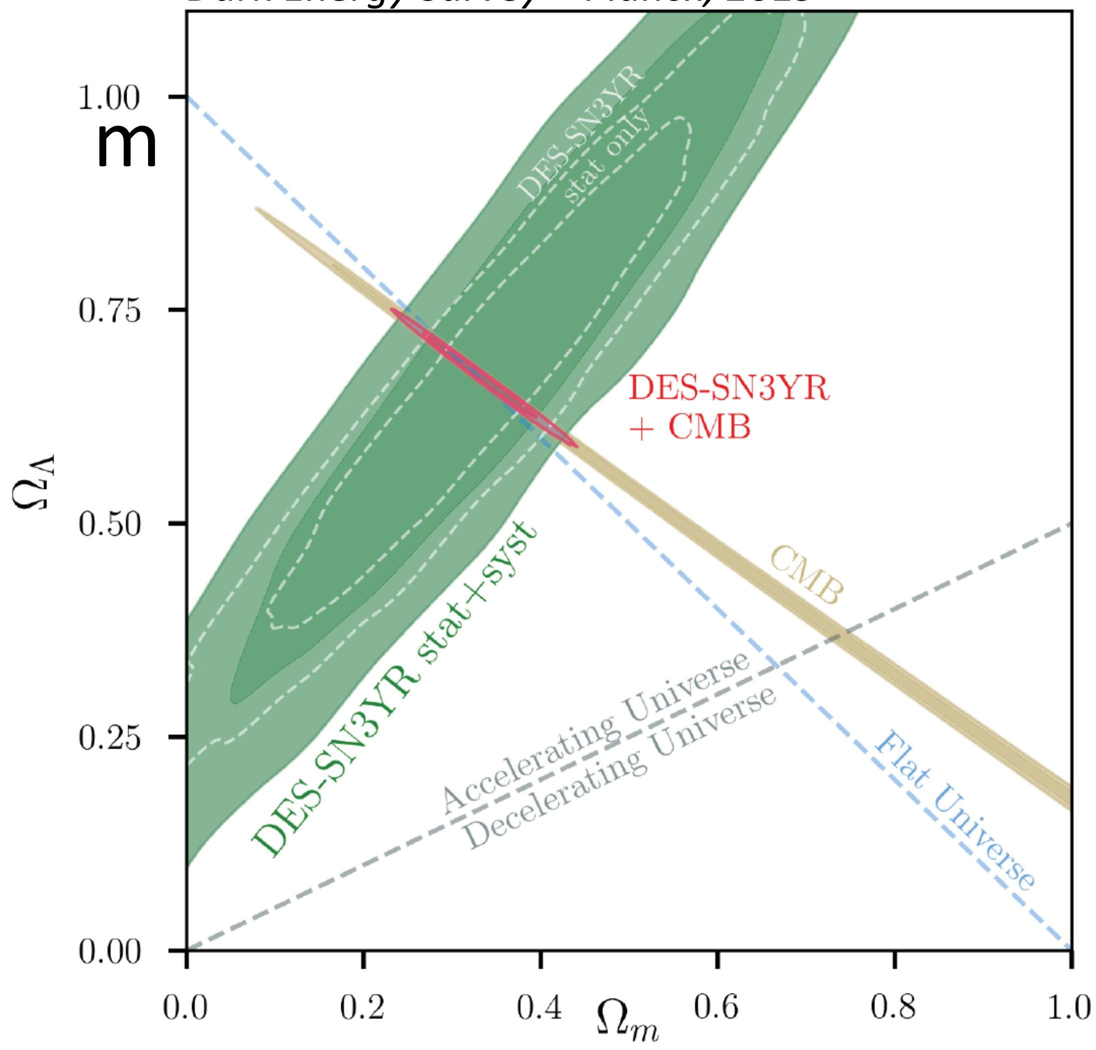
SN 1997cj



Twin Keck telescopes on Mauna Kea.

Cosmological parameters

Dark Energy Survey + Planck, 2019



$\Omega_\Lambda = 0.690 \pm 0.008$

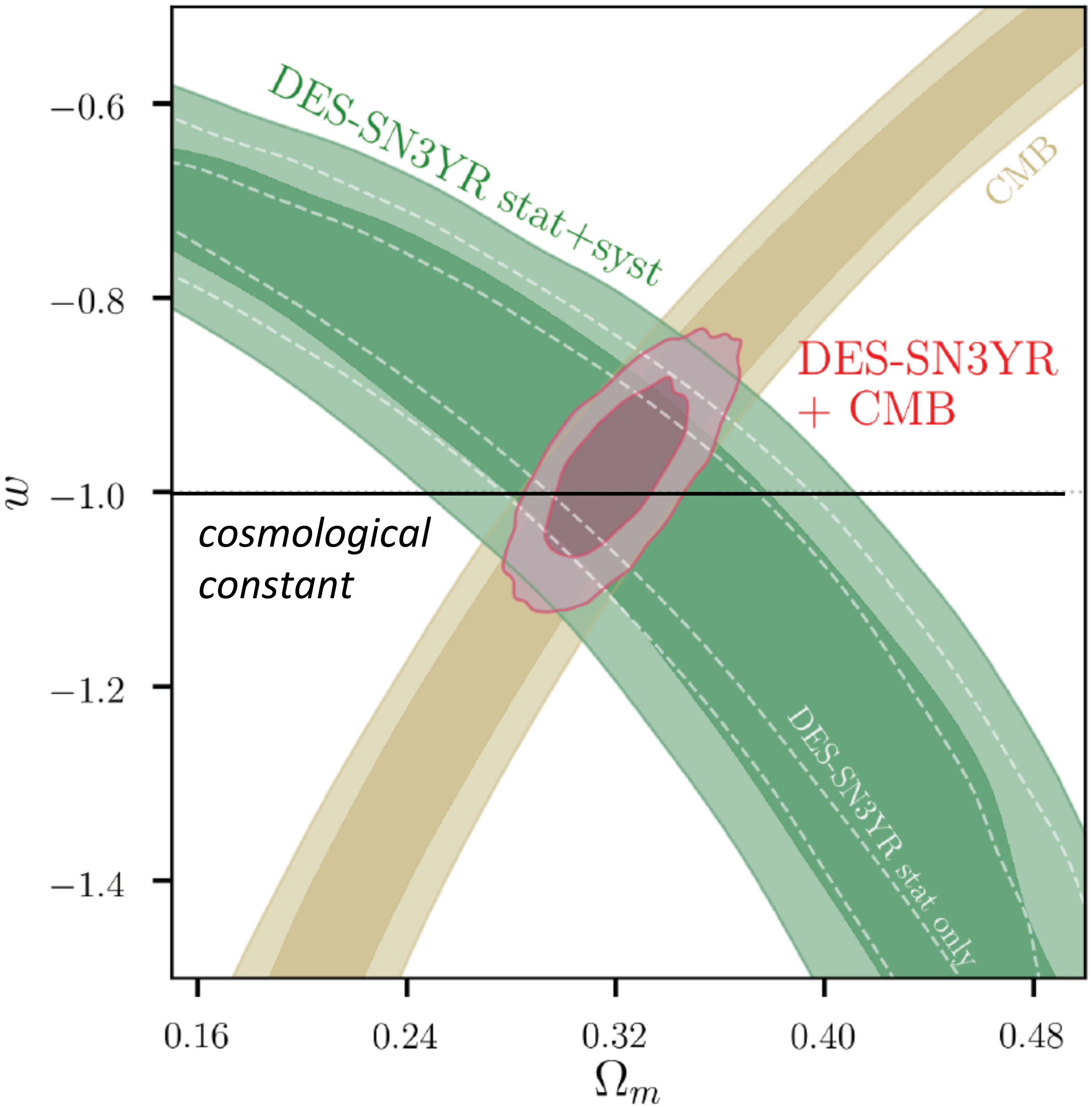
$\Omega_M = 0.308 \pm 0.008$

Universe dominated by DE

Universe flat to within ~0.5%

Cosmological Parameters

Dark Energy Survey + Planck, 2019



Equation of state: *p=wρ*

Constant w:

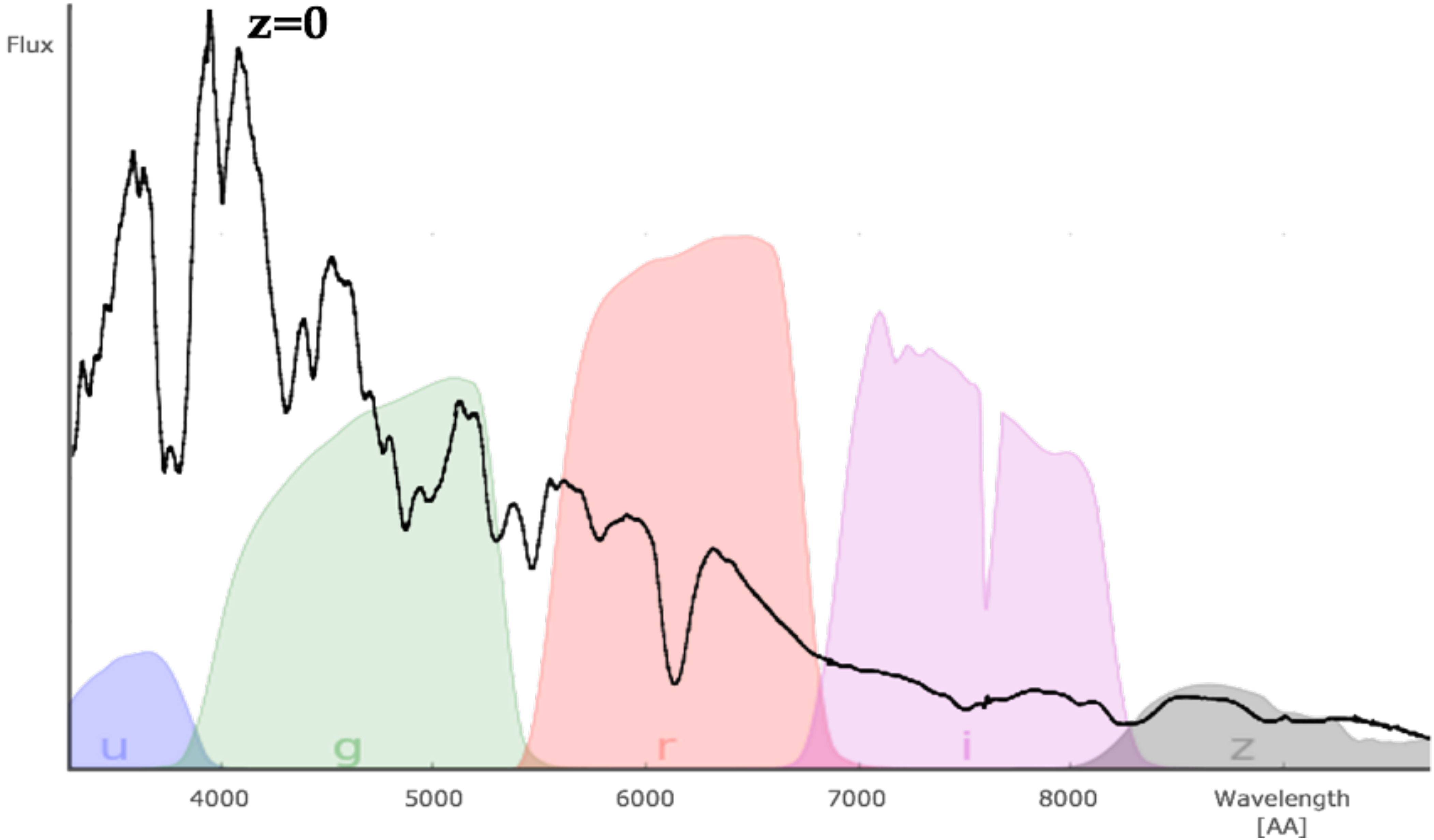
w=-0.978±0.059

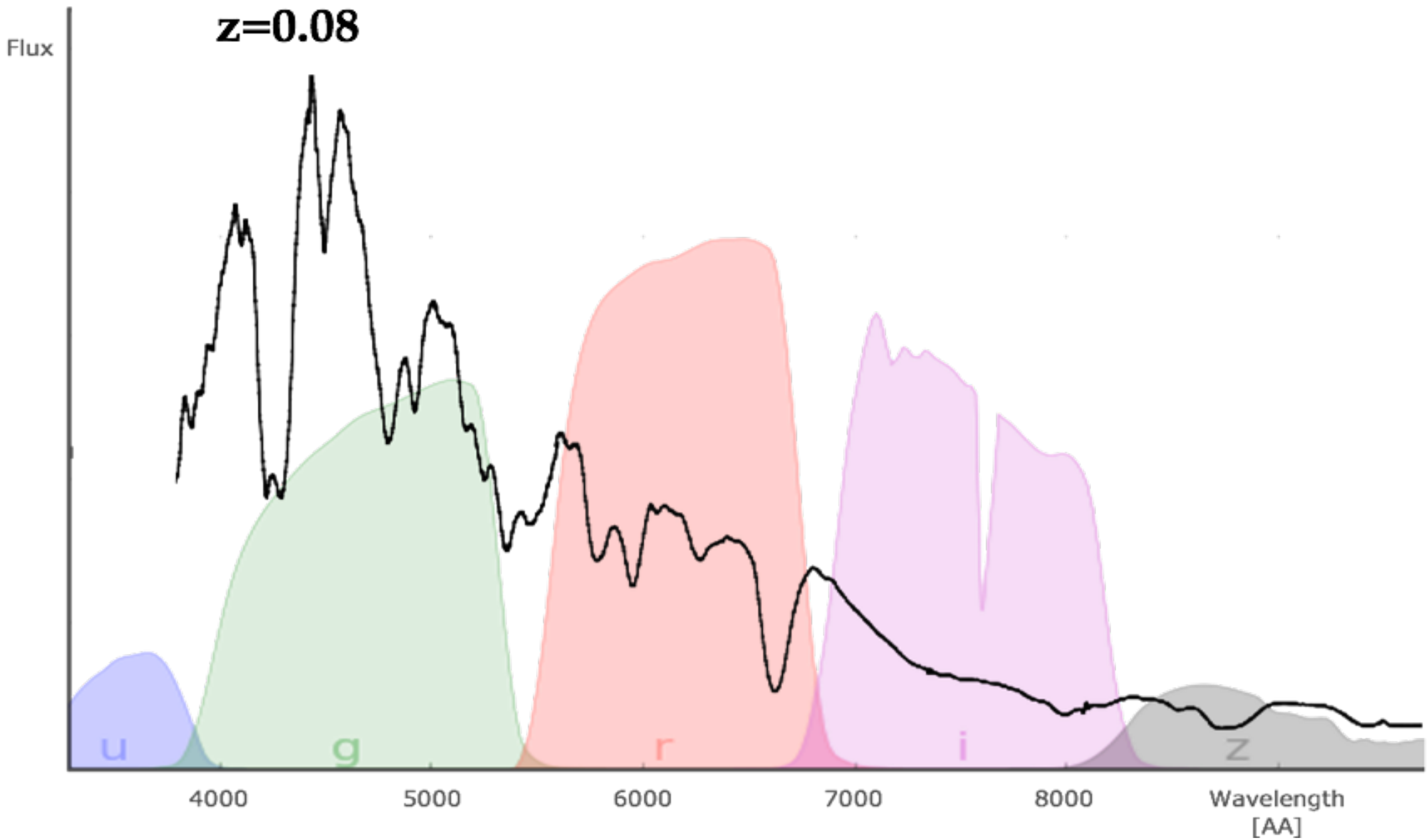
A bit of dirty laundrary

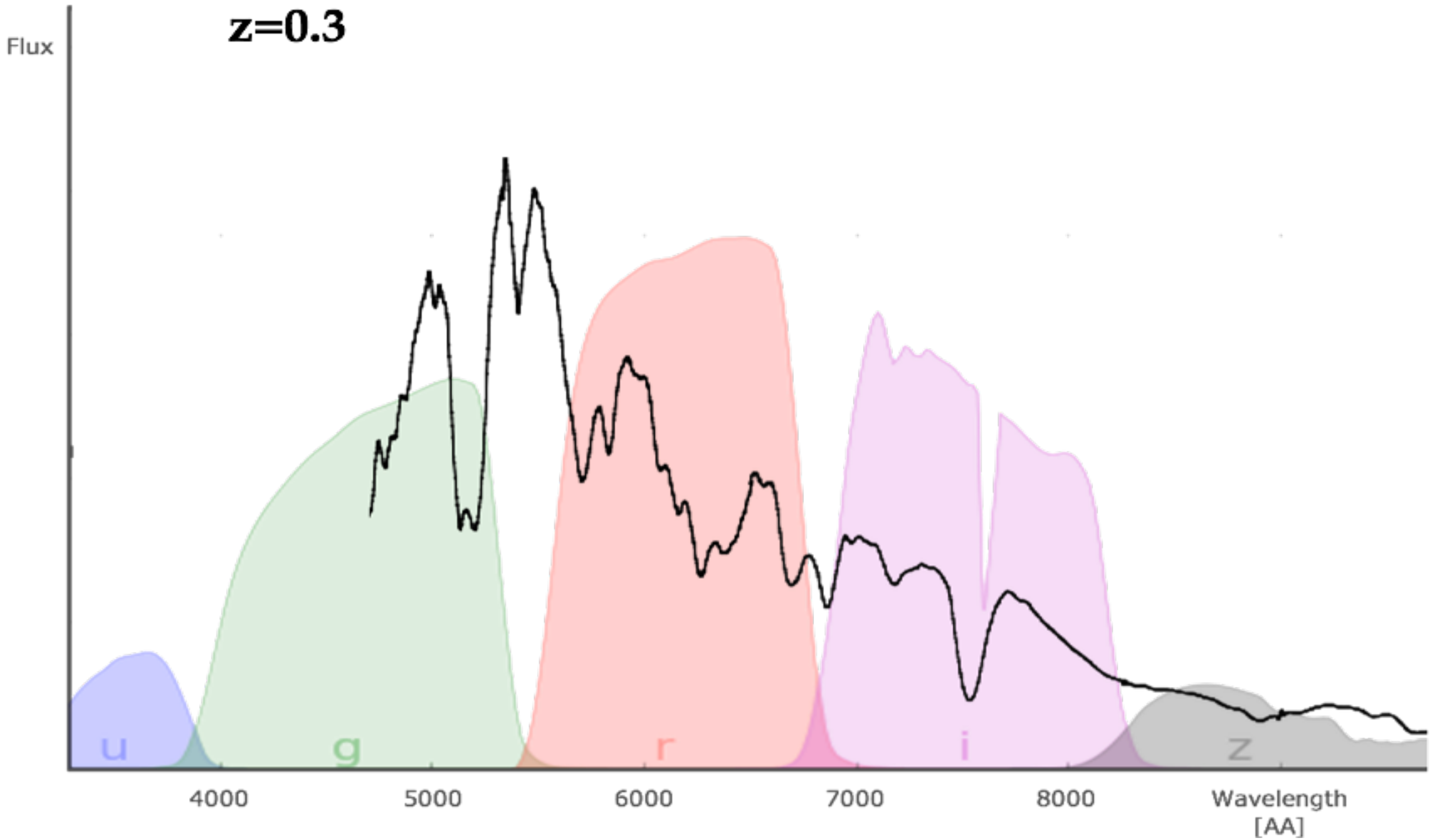
Dark Energy Equation-of-State parameter:

$$w = -0.978 \pm 0.042 \text{ (stat)} \pm 0.042 \text{ (sys)}$$

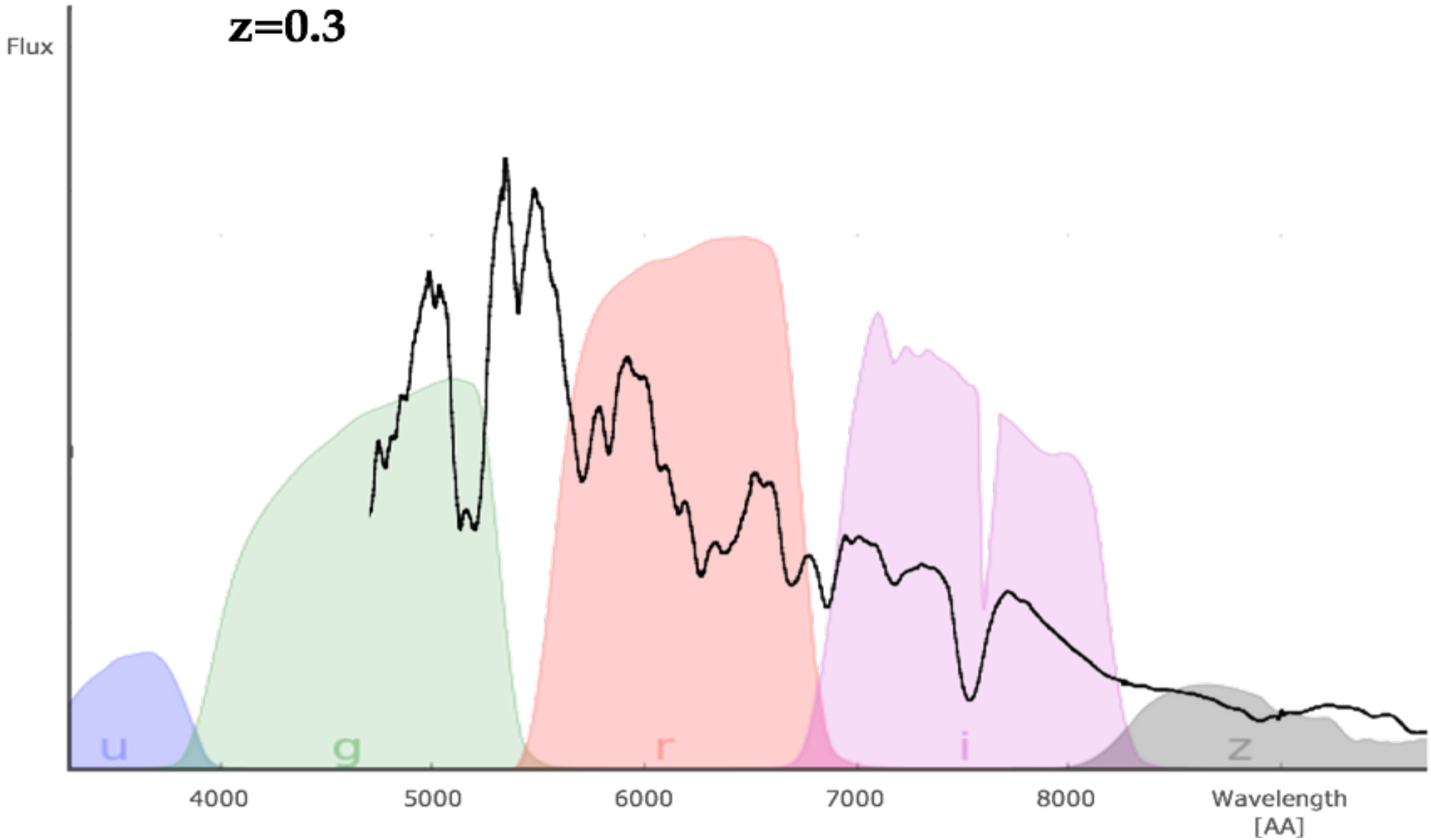
Dark Energy Survey, 2019


z=0
Flux
u
g
r
i
z
4000
5000
6000
7000
8000
Wavelength
[AA]


z=0.08
Flux
u
g
r
i
z
4000
5000
6000
7000
8000
Wavelength
[AA]



z=0.3
Flux
u
g
r
i
z
4000
5000
6000
7000
8000
Wavelength
[AA]

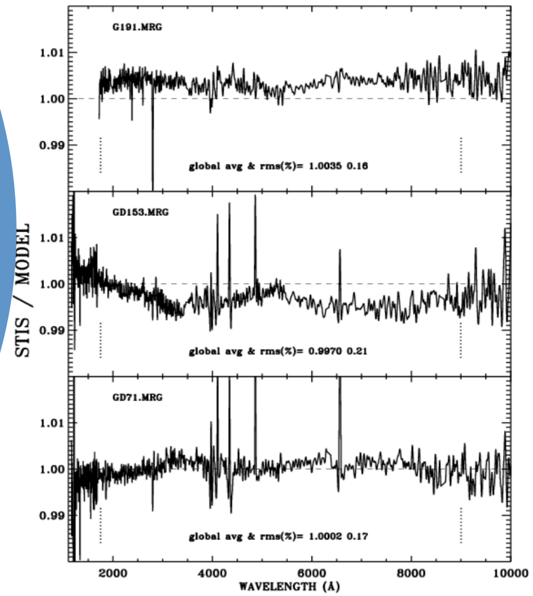

z=0.3
Flux
u
g
r
i
z
4000
5000
6000
7000
8000
Wavelength
[AA]

The problem of Flux calibration

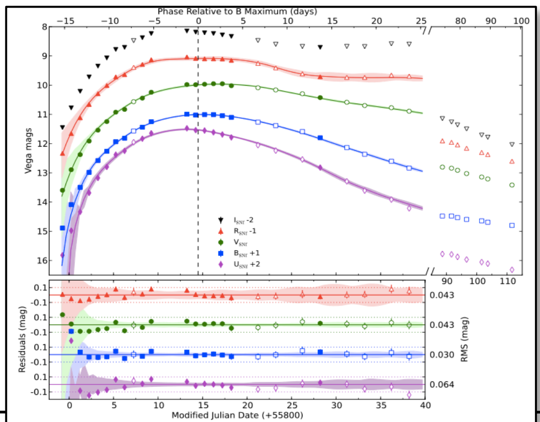
Model
White dwarf NLTE atmosphere models

Bohlin & Gordon 2014

Primary standards
STSI Observation of WDs:
G191B2B, GD153, GD71



Science objects SNe, WDs,...

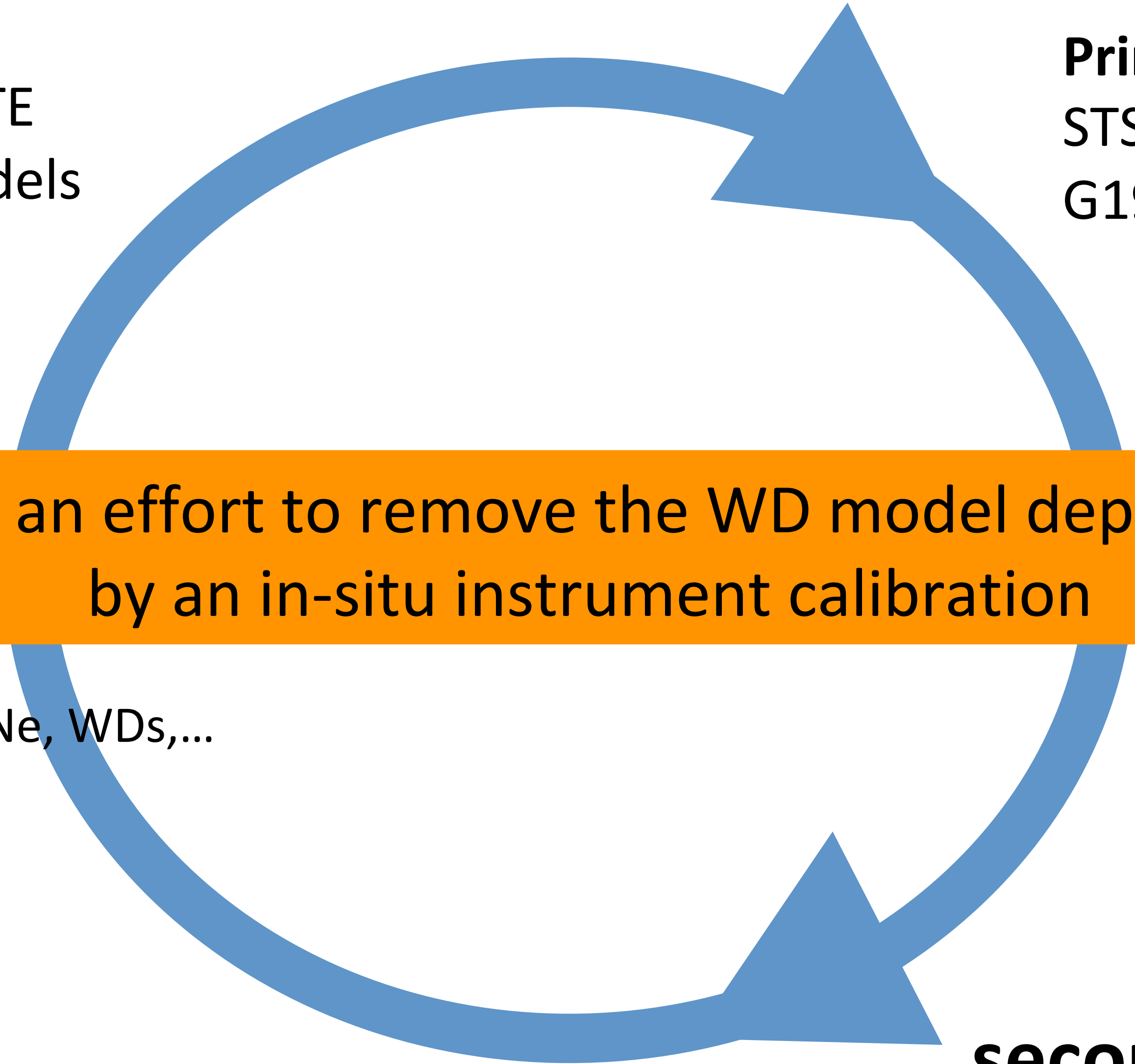


Tertiary standards SDSS,...

secondary standards CALSPEC

The problem of Flux calibration

Bohlin & Gordon 2014



Model
White dwarf NLTE
atmosphere models

Primary standards
STSI Observation of WDs:
G191B2B, GD153, GD71

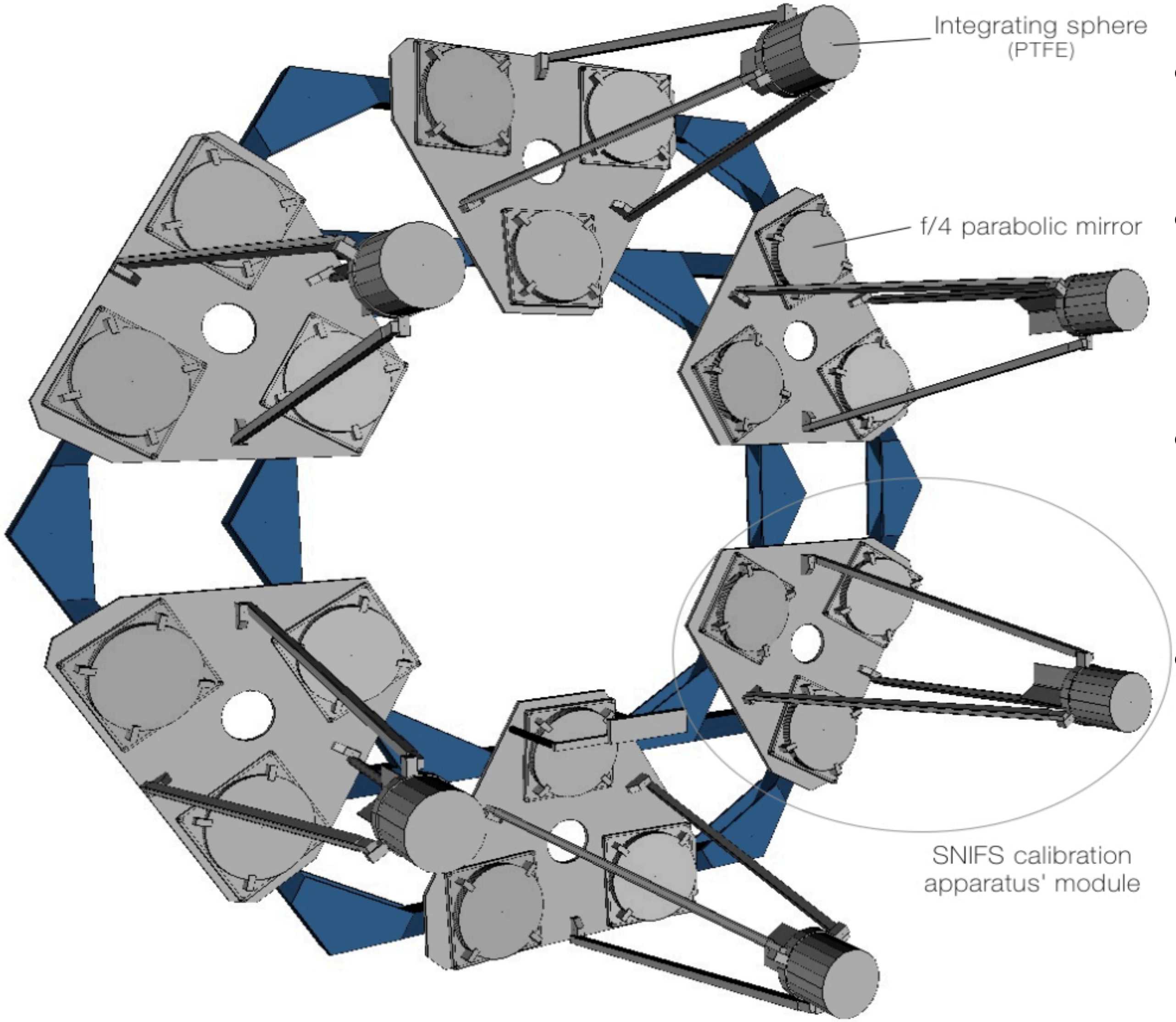
SCALA: an effort to remove the WD model dependence
by an in-situ instrument calibration

Science objects SNe, WDs,…

secondary standards CALSPEC

Tertiary standards SDSS,…

SNIFS Calibration Apparatus (SCALA)

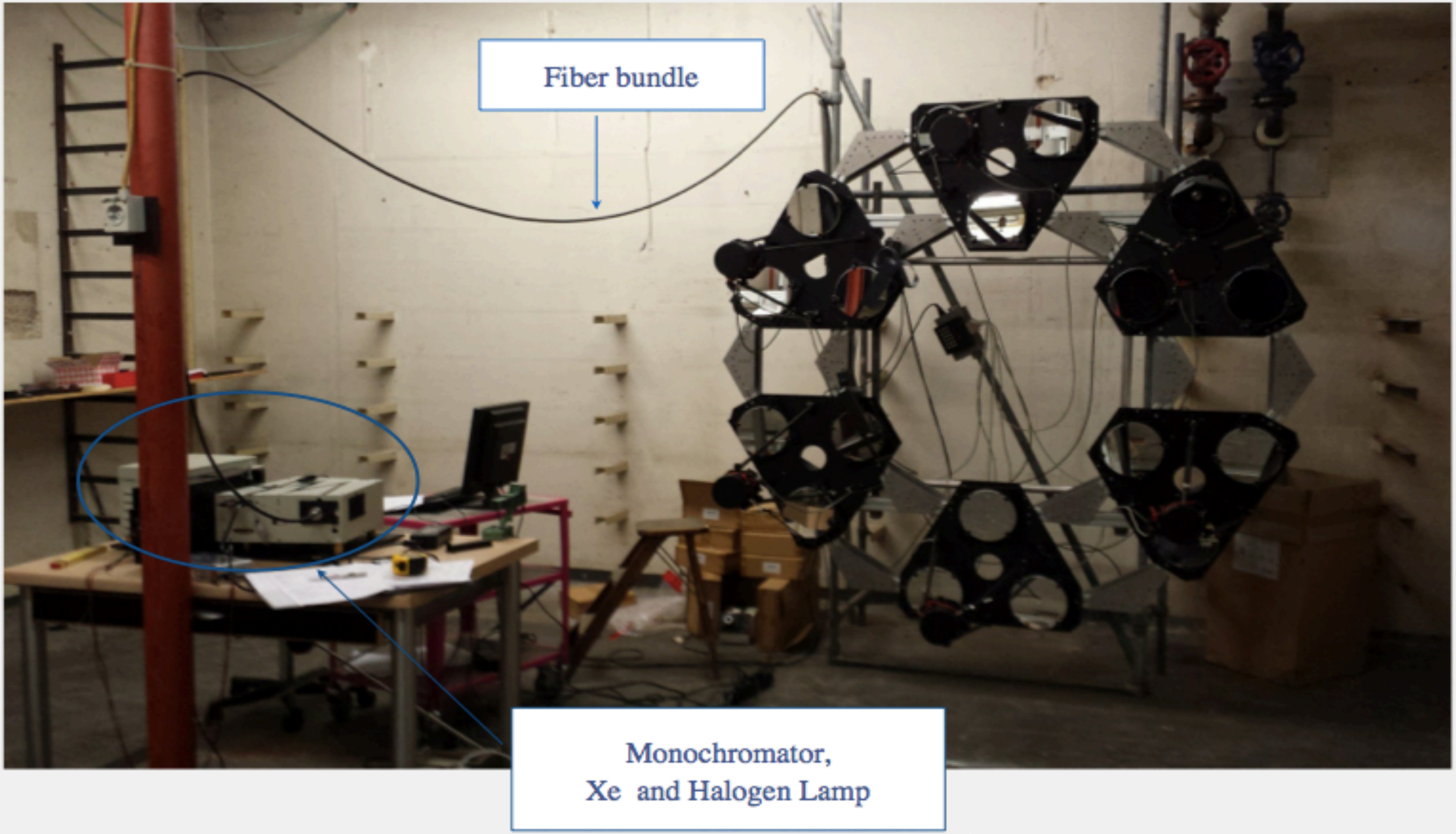


- Tunable wavelength
- Mirrors illuminated by integrating spheres
- 1 degree wide, flat beams
- Photon flux monitored through calibrated PDs.

“ artificial planet”

SNIFS Calibration Apparatus (SCALA)

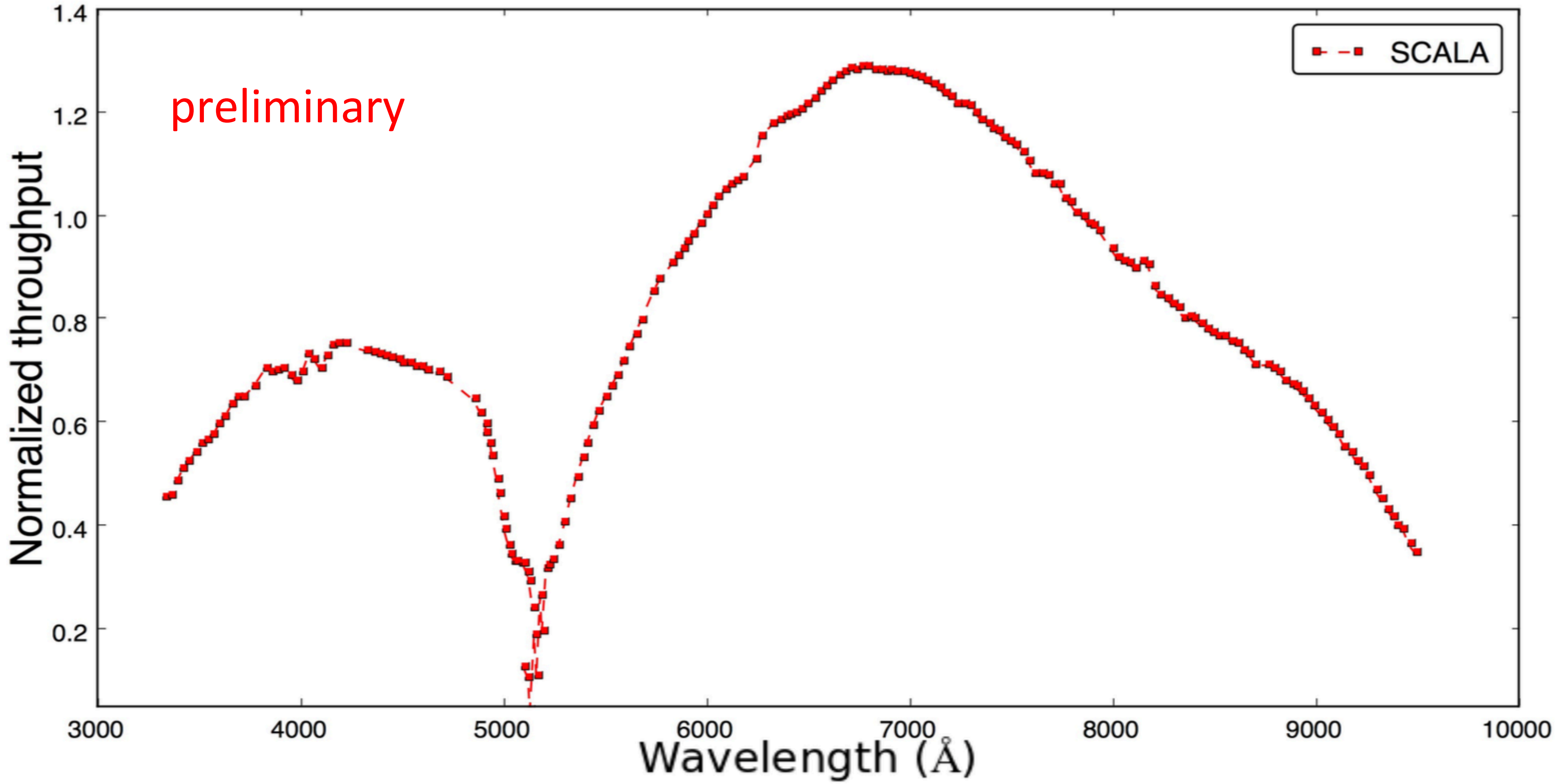
⇒Flux calibration of instrument with artifical light source



SNIFS Calibration Apparatus (SCALA)

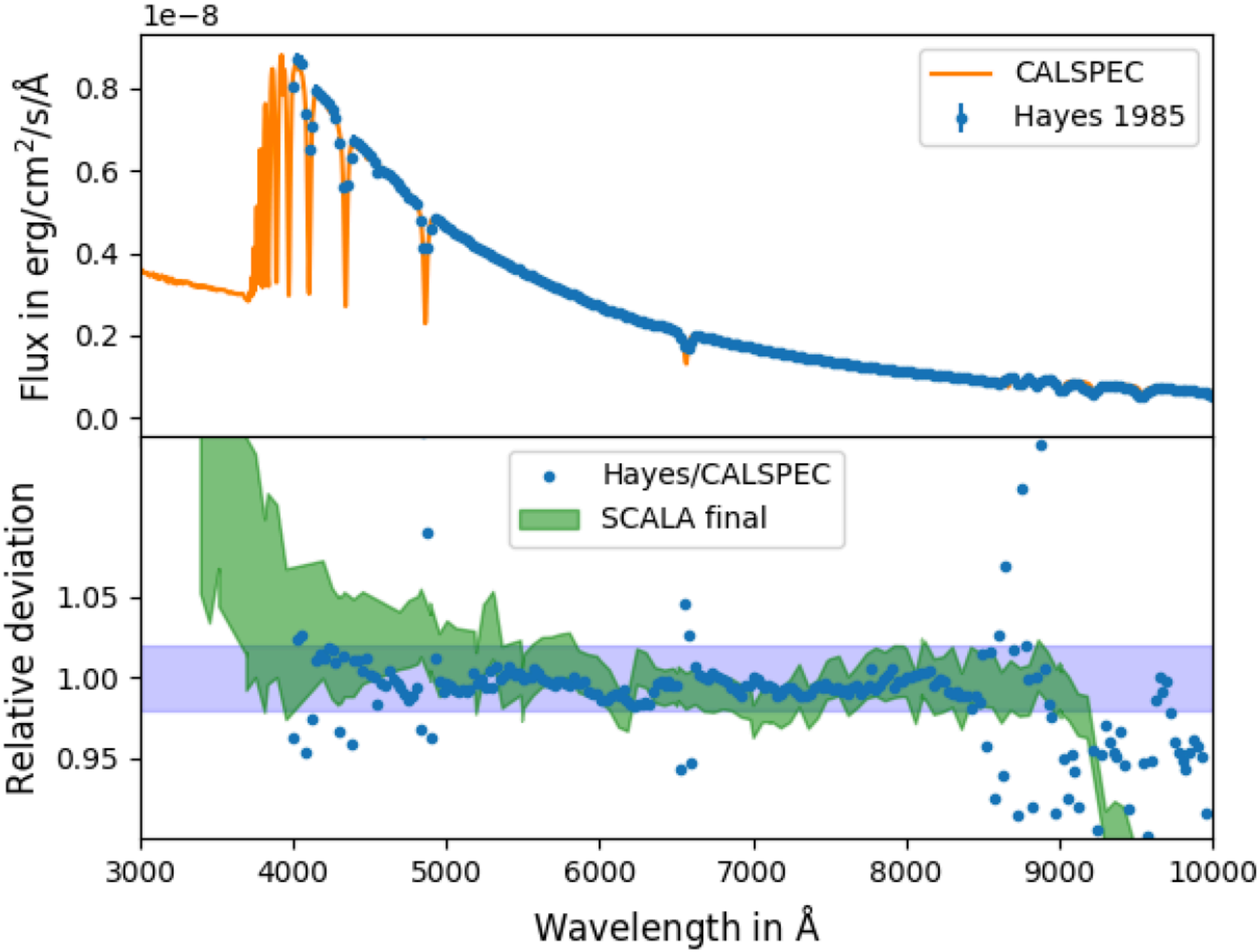
SNIFS Calibration Apparatus (SCALA)

SNIFS throughput



➔allows to provide bottom up-calibration of standard star network

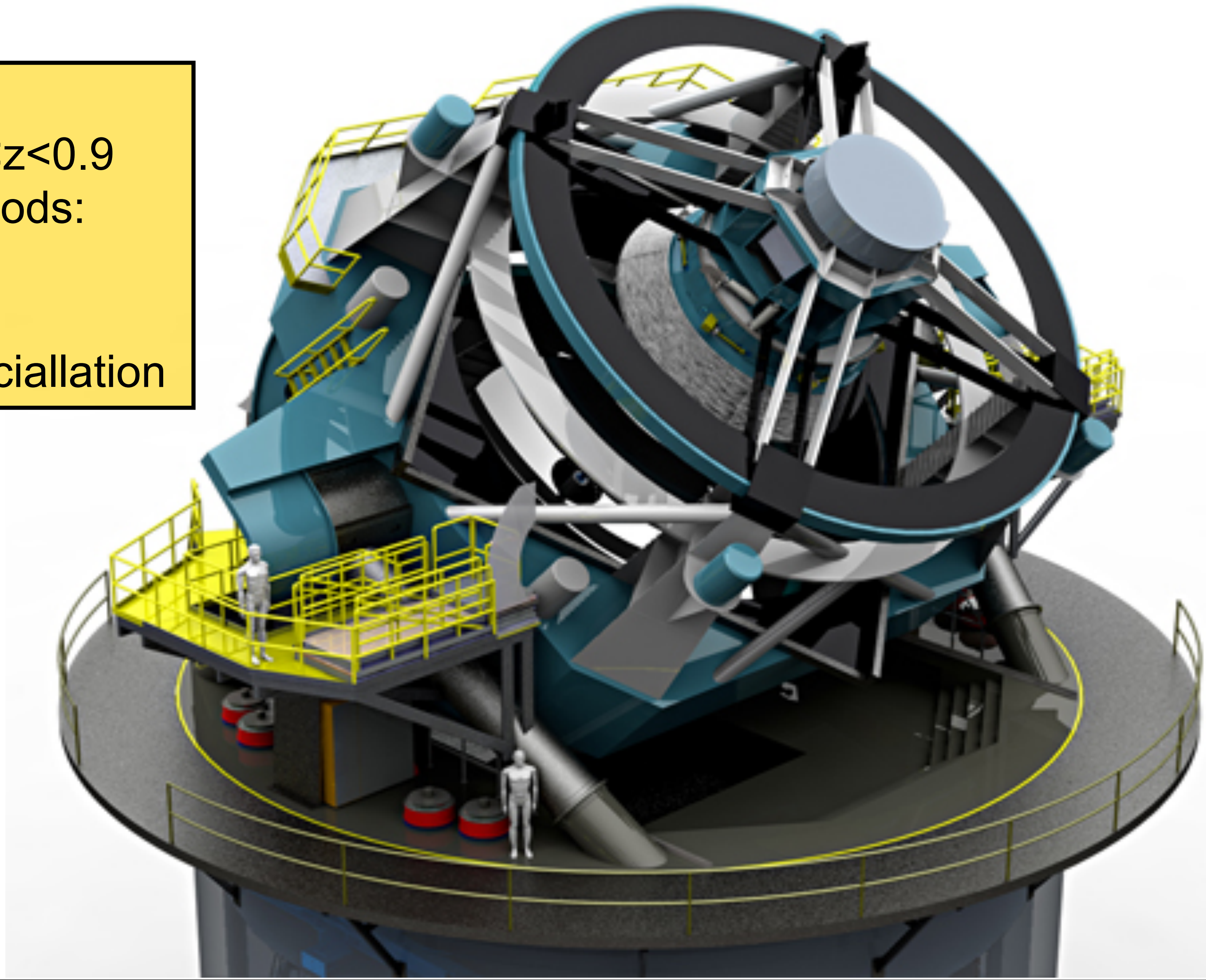
SNIFS vs Standard stars: ~1% agreement



Outlook

The Large Synoptic Survey Telescope

Starting 2022:
~10^5 SNe / yr @ $0.1<z<0.9$
Other important methods:
✓Weak lensing
✓Cluster rates
✓Baryon acoustic osciallation



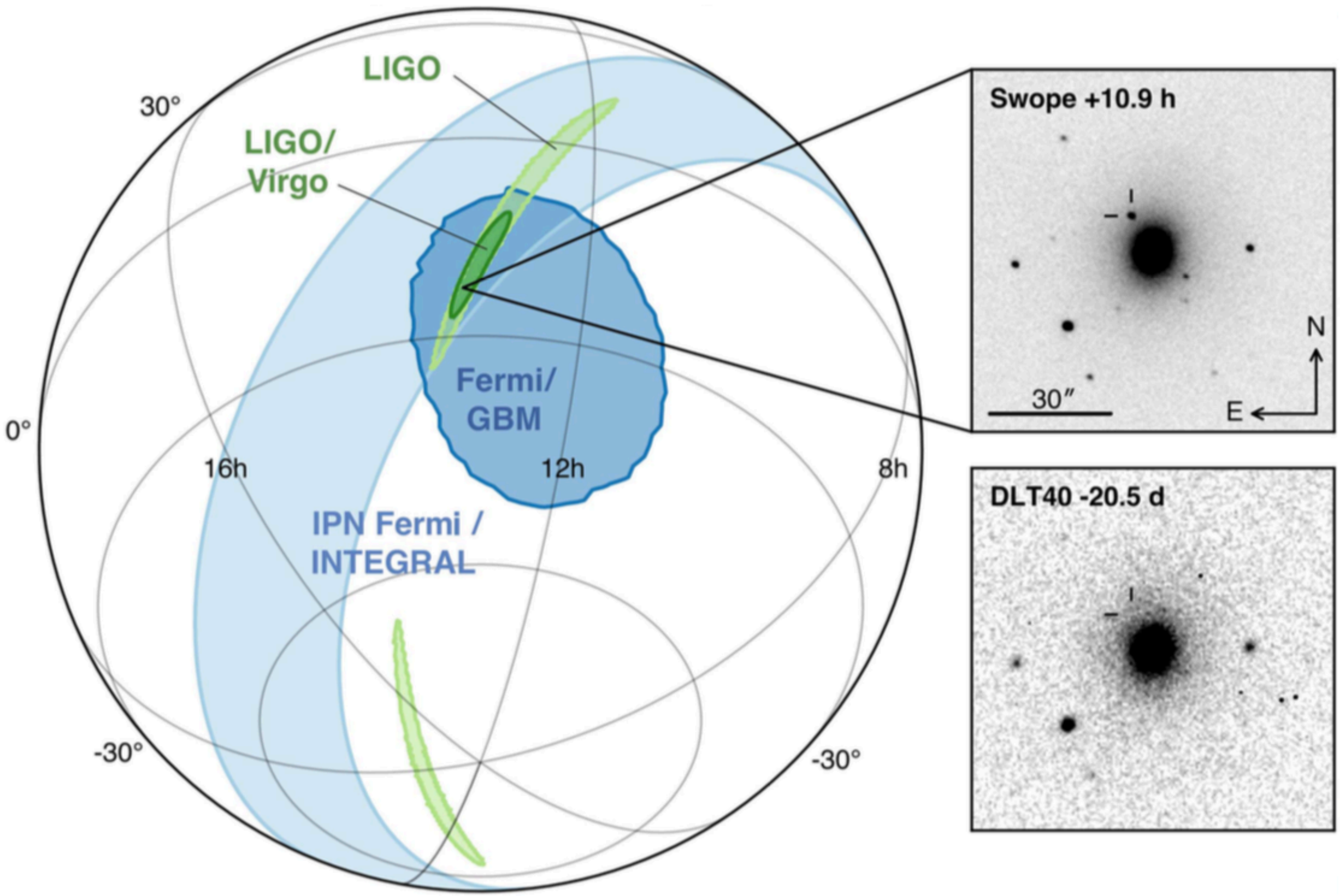
8.4 m diameter
9.6 sq.deg FOV
3.2×10^9 pixels
15 s exposures

Multi-messenger cosmology: Hubble constant

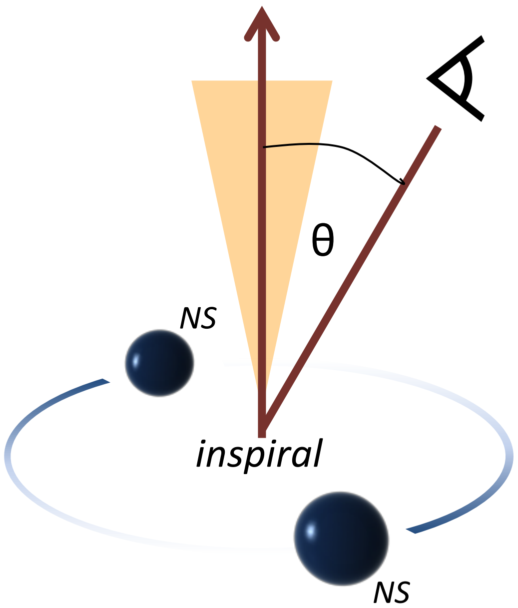
"I report here how gravitational wave observations can be used to determine the Hubble constant, H_0. [...] **The signal is easily identified** and contains enough information to determine the **absolute distance to the binary**, independently of any assumptions about the masses of the stars. Ten events out to 100 Mpc may suffice to measure the Hubble constant to 3% accuracy."

- *Bernard Schutz, Nature 1986*

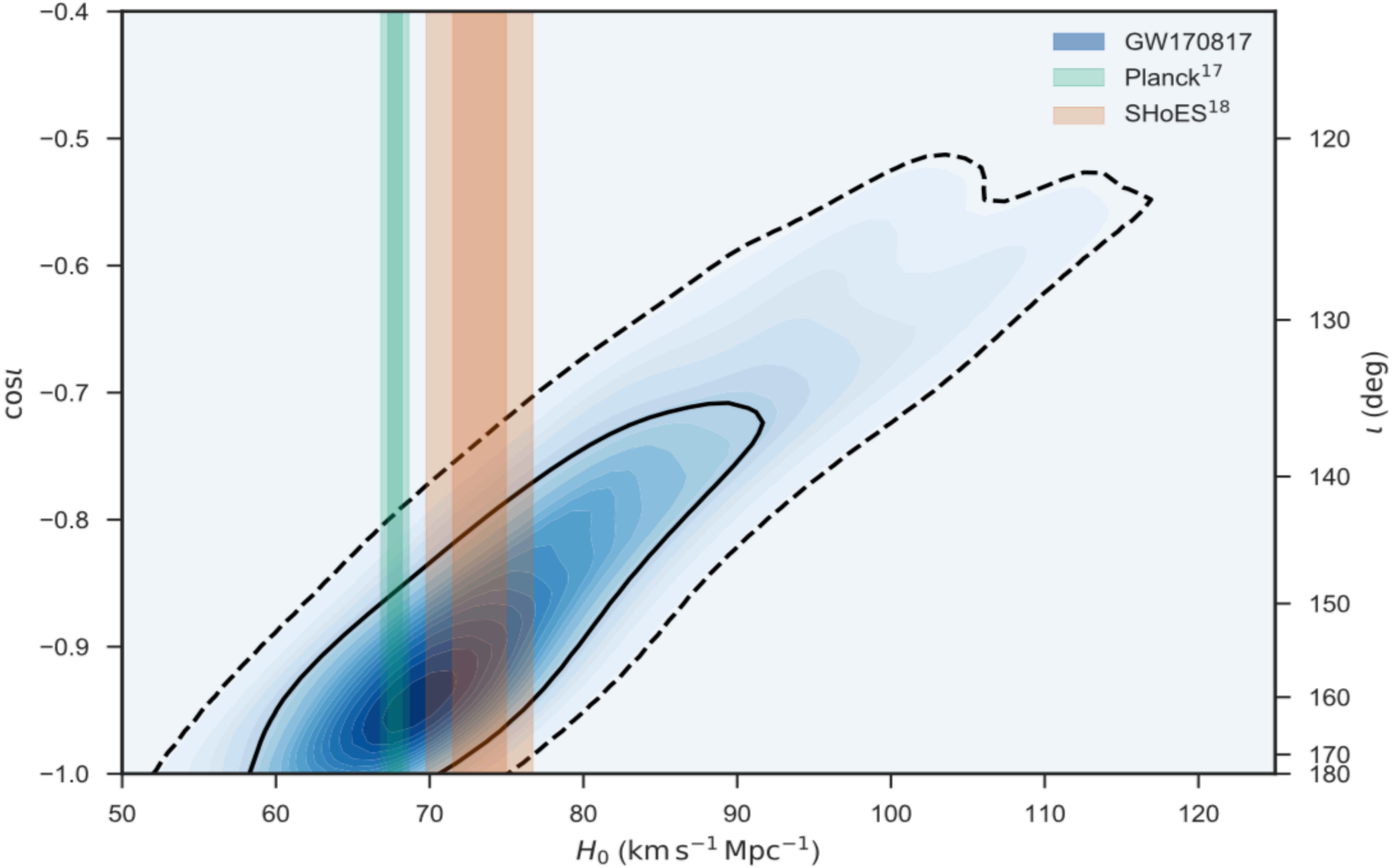
Multi-messenger cosmology: Hubble constant



Multi-messenger cosmology: Hubble constant

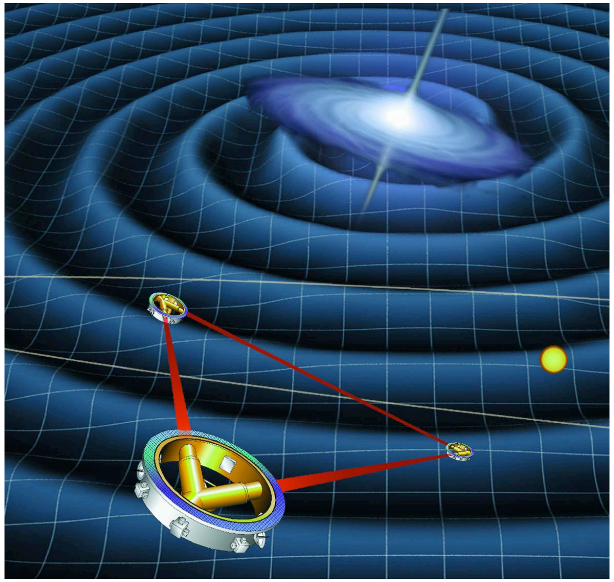


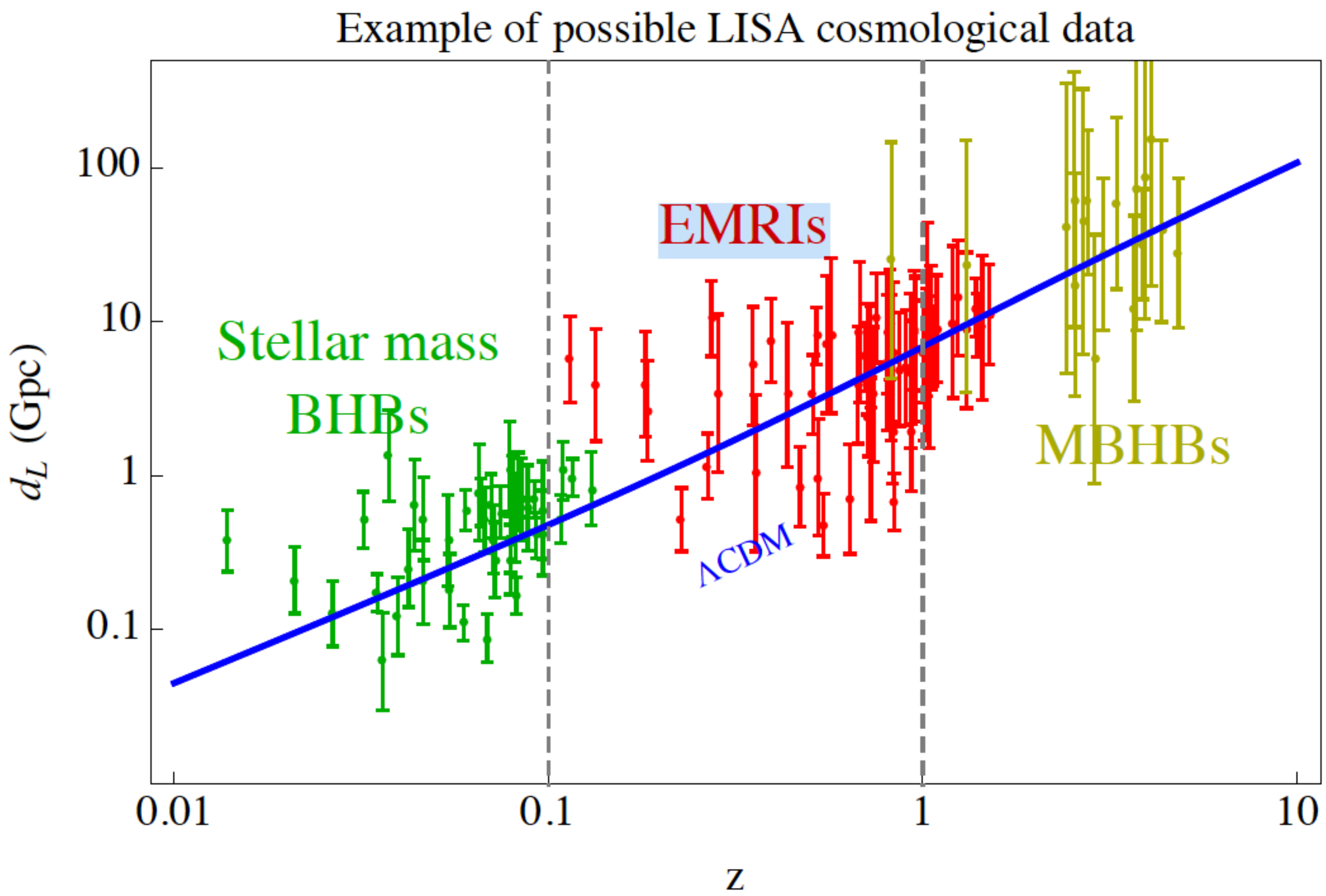
$H_0 = 70^{+12}_{-8}\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$



Nature 551 (2017) 7678, 85-88

GW 2030+





Tamanini, 2016

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 much progress expected!