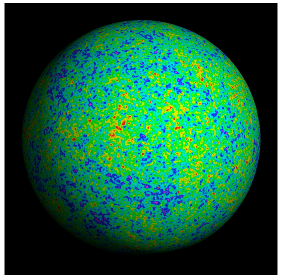
Studying Dark Energy with Supernovae

Marek Kowalski
Physikalisches Institut
Universität Bonn

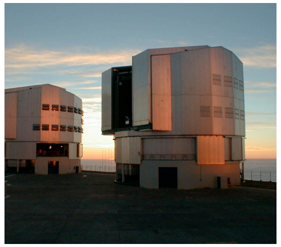
Supernova 1994D

DESY-Seminar
1.12.2009

Content



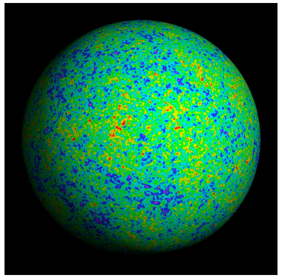
Introduction: the accelerating Universe



SNe observations & cosmological parameters

Constraints on selected Dark Energy models

Content



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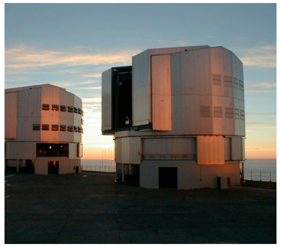

SNe observations & cosmological parameters

Constraints on selected Dark Energy models

Our Cosmological Framework derives from…

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

$\Rightarrow$ Friedman Equation, which governs expansion

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

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

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Matter Density

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Matter Density

Cosmological Constant/
Dark Energy

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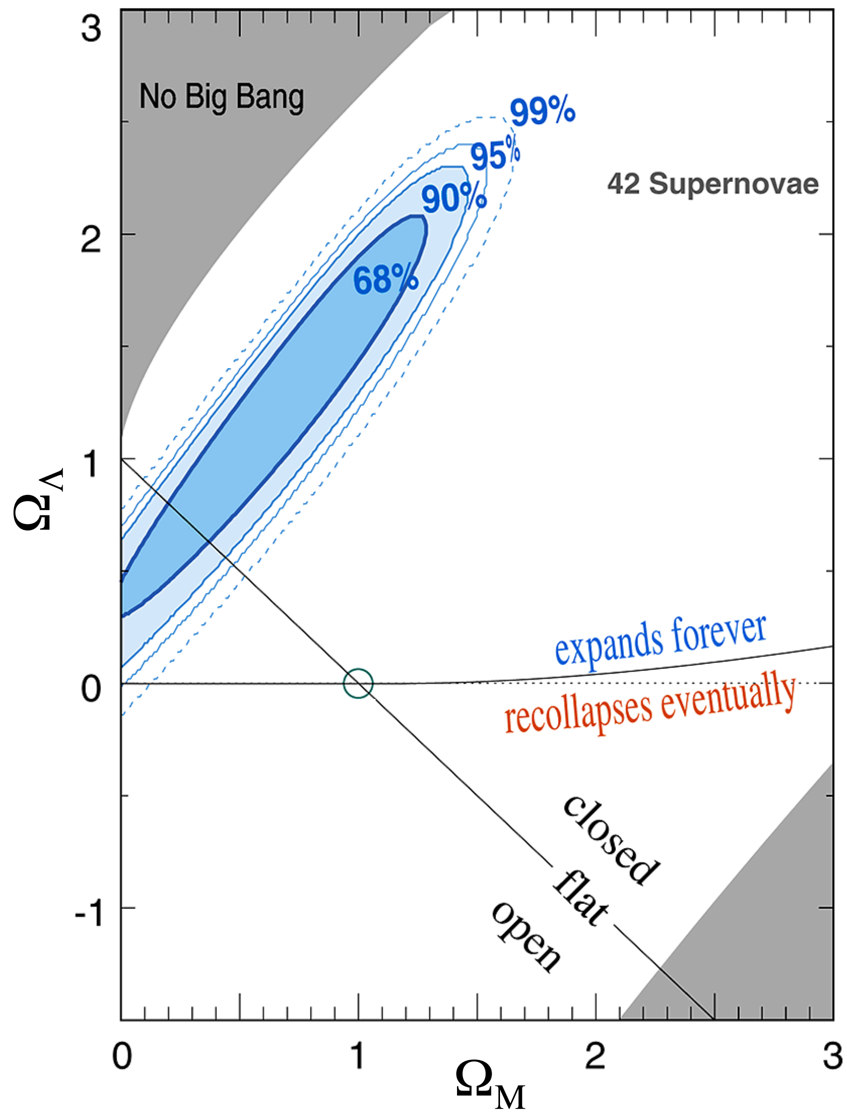
$$\boxed{\Omega_M + \Omega_\Lambda + \Omega_k = 1}$$

Matter Density

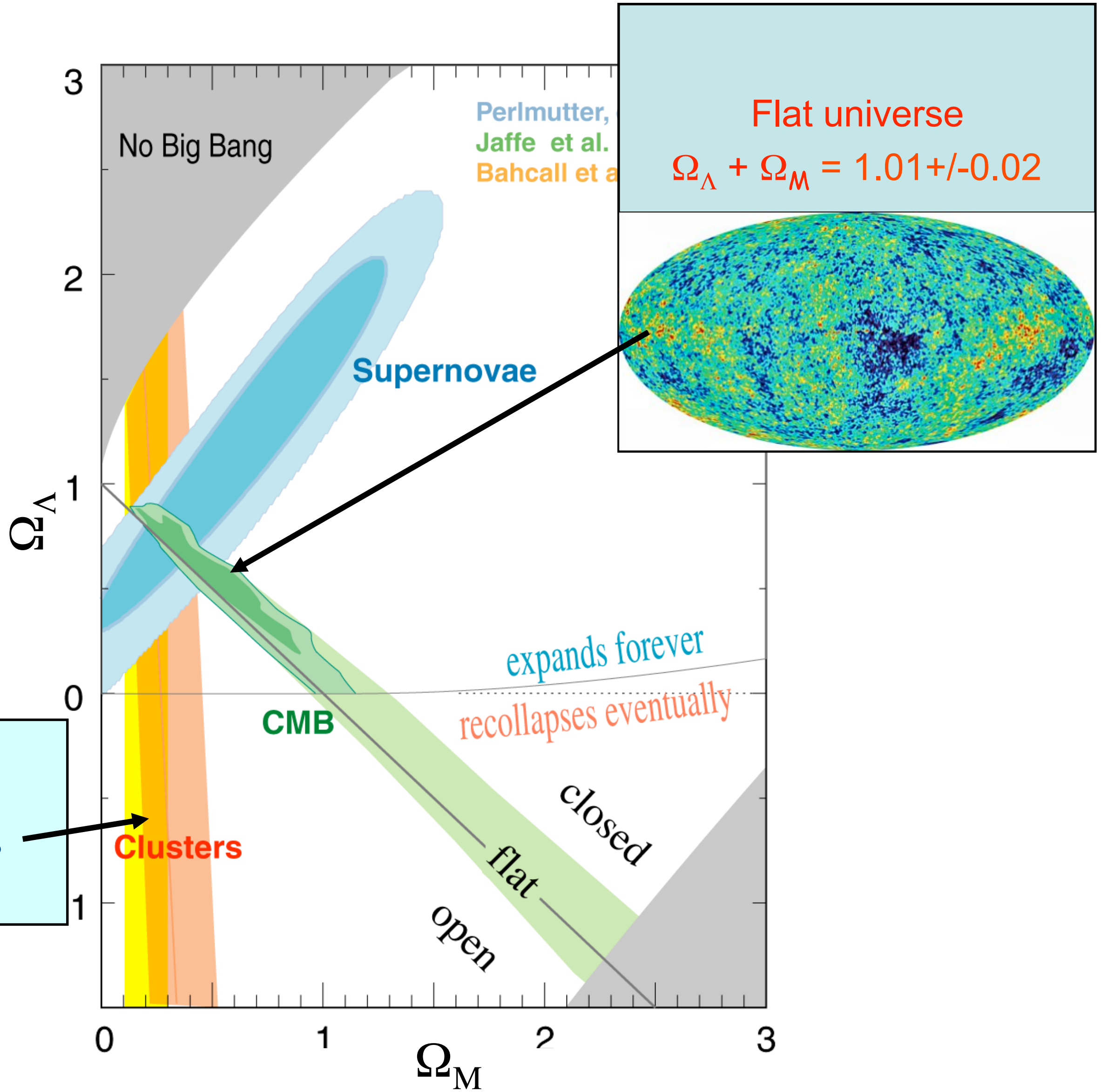
Cosmological Constant/
Dark Energy

Curvature

1998: Discovery of Dark Energy

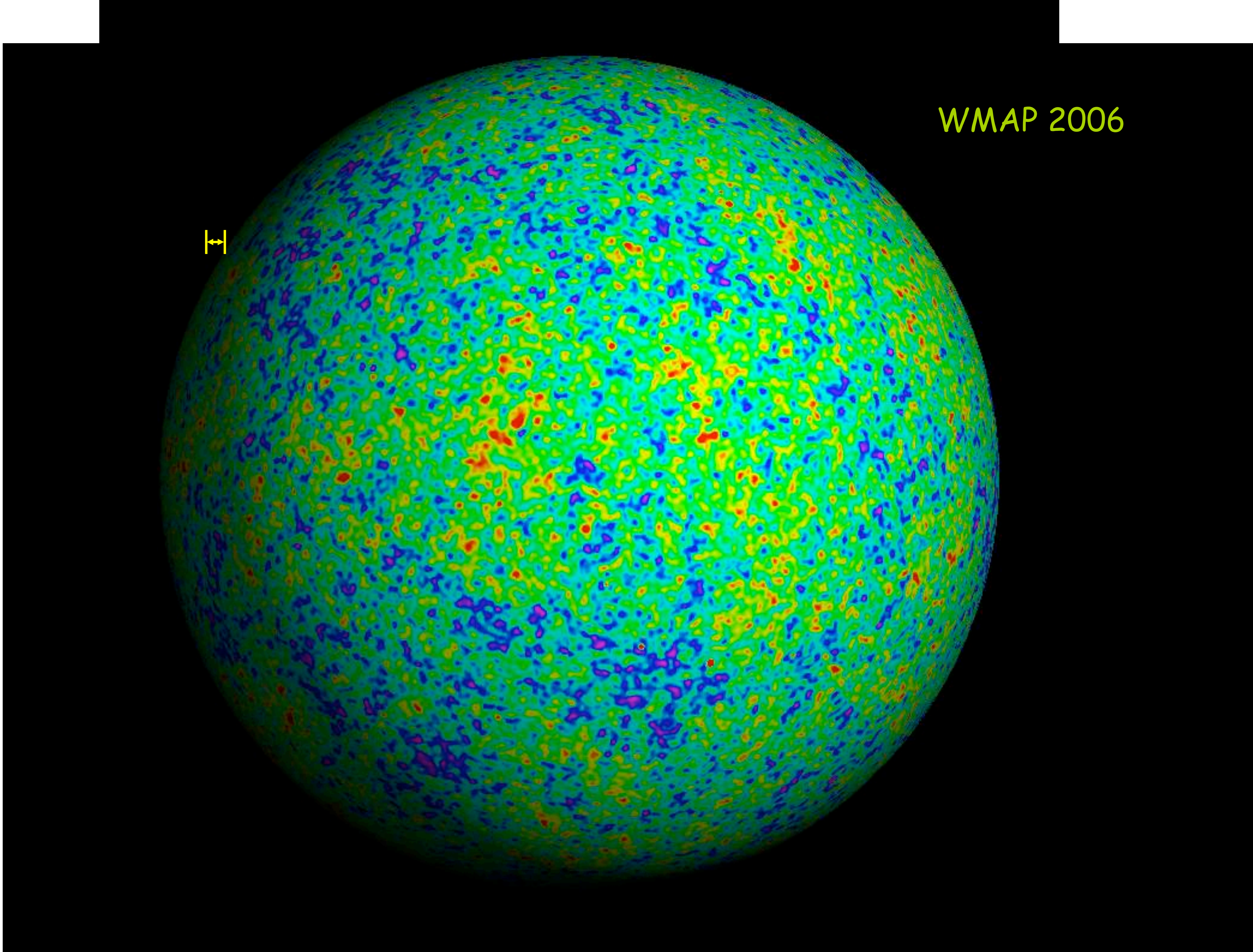


1998: Discovery of Dark Energy

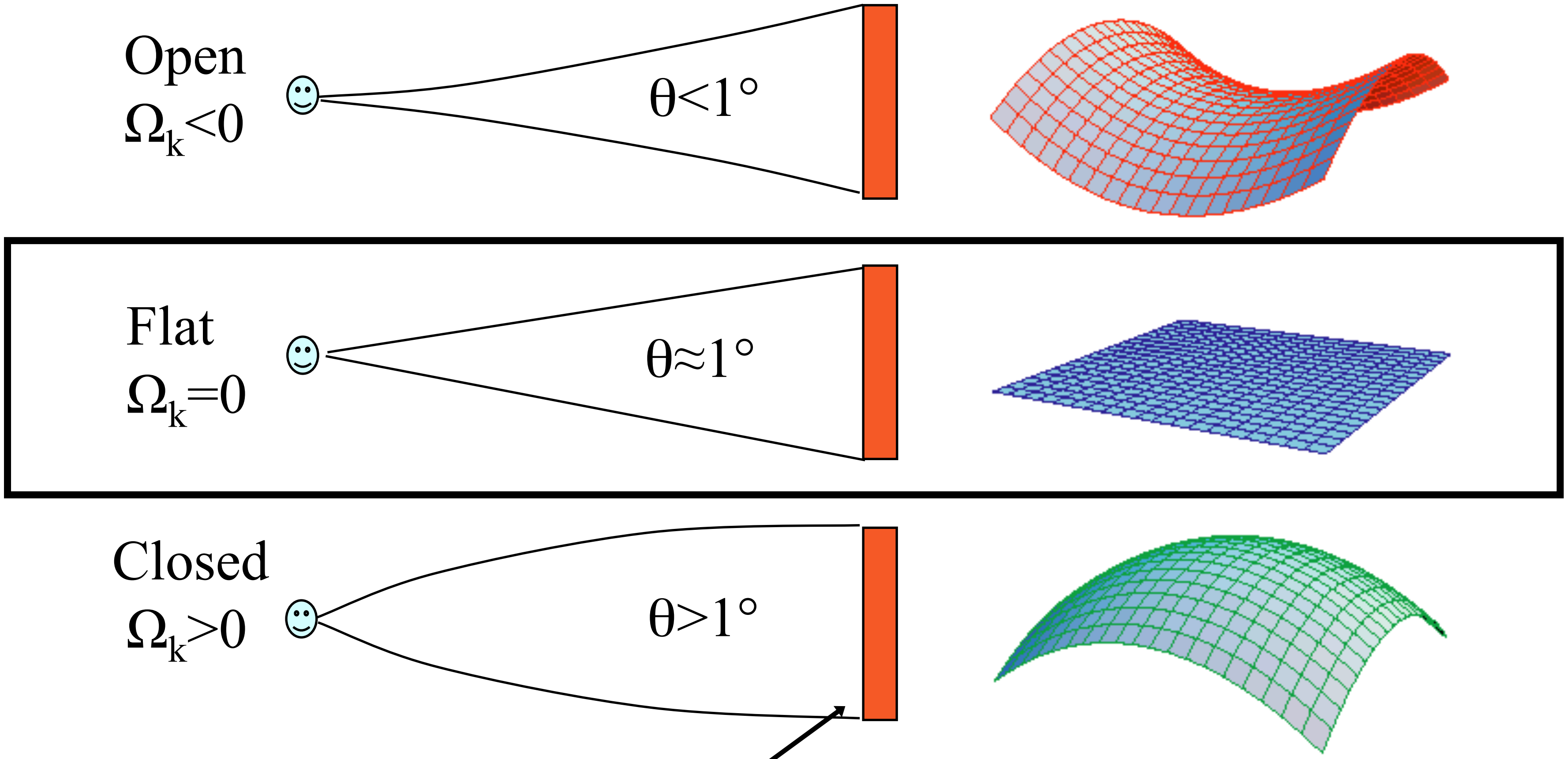


- Weak lensing mass census
- Large scale structure
- Baryon Accoustic Oscillations

$\Omega_M = 0.3$

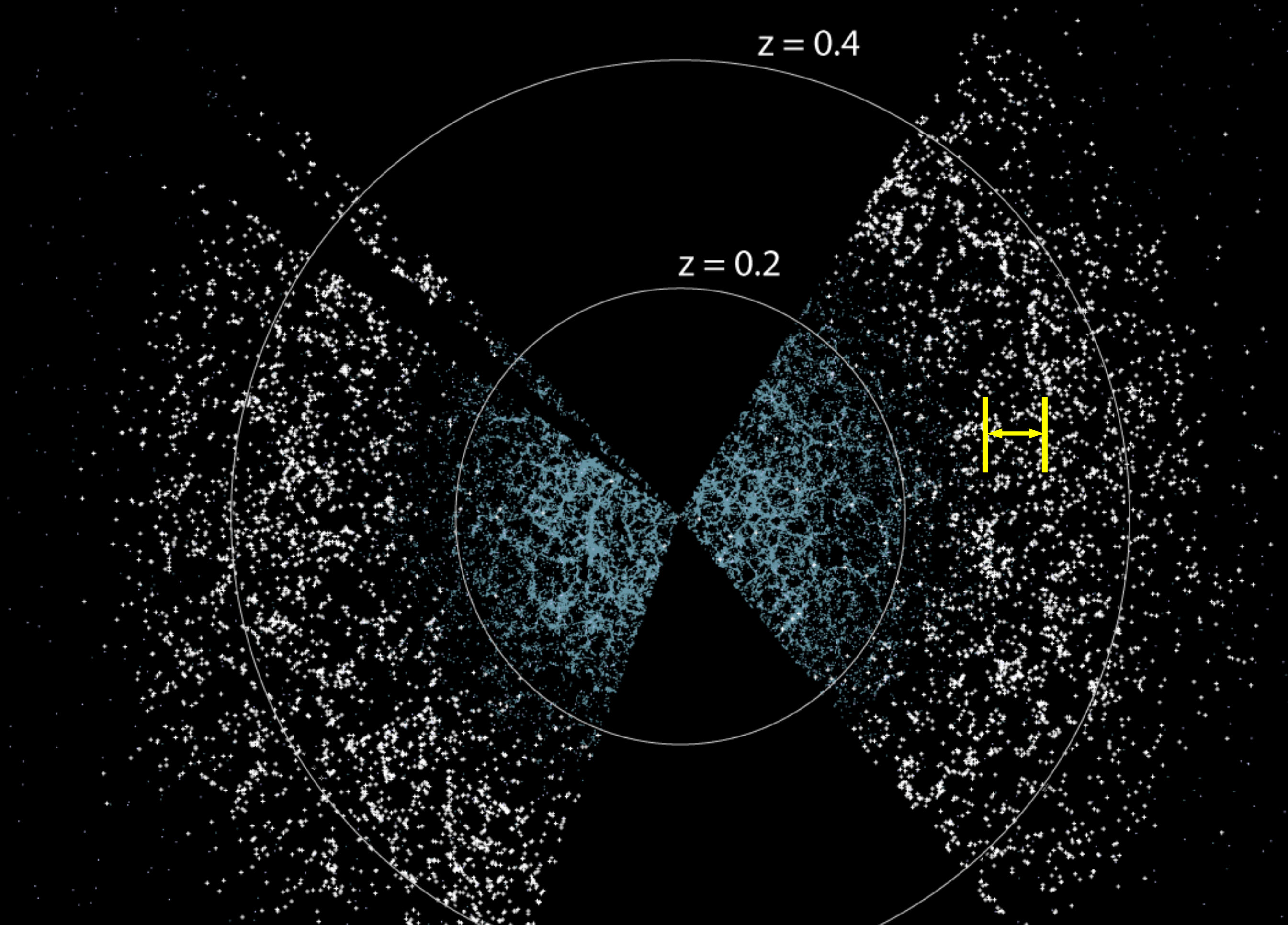

WMAP 2006

Cosmic Microwave Background (CMB) & Curvature of the Universe



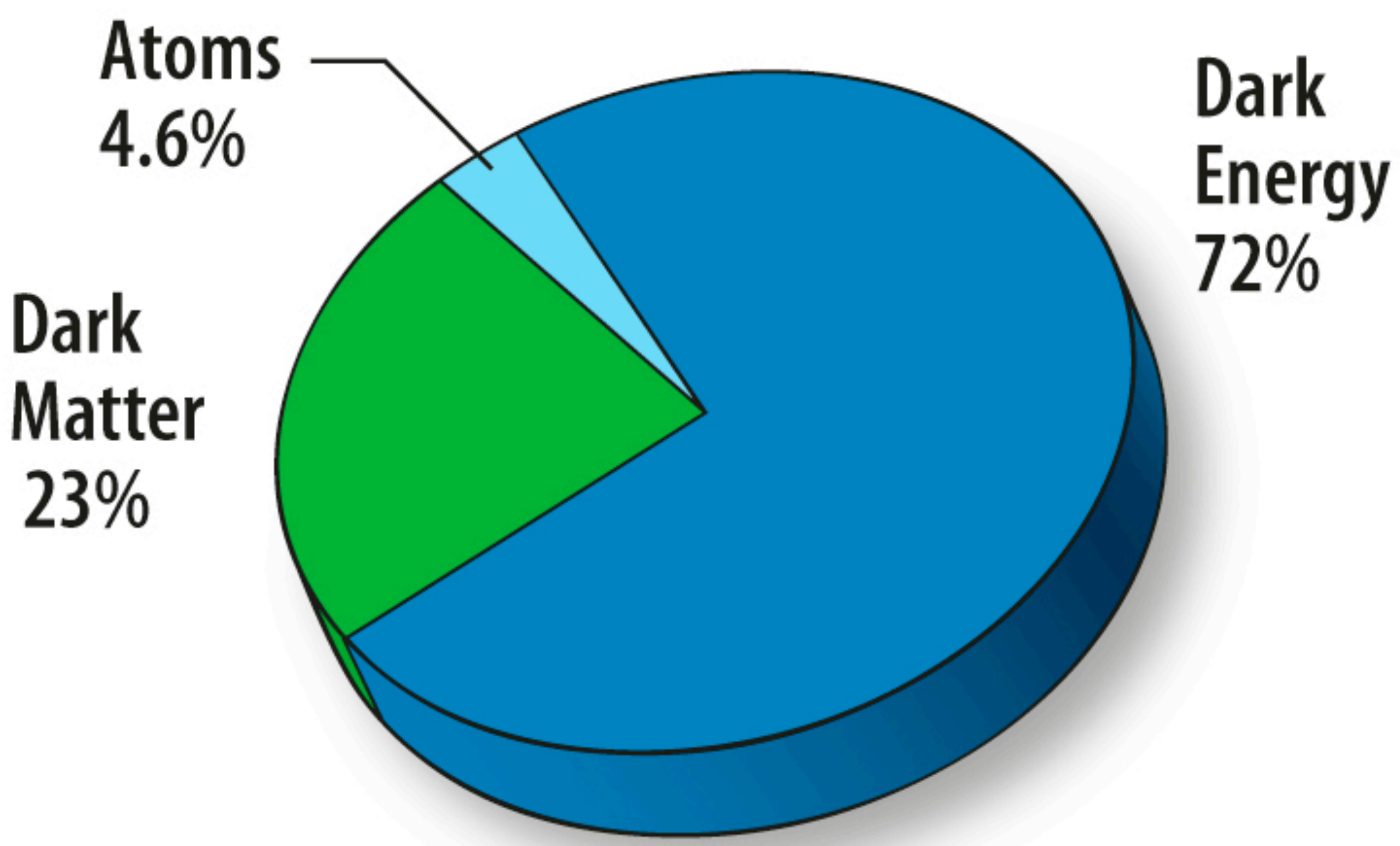
Acustic horizon $\approx v_s t_{dec}$

$$\Rightarrow \Omega_M + \Omega_\Lambda = 1 - \Omega_k \approx 1$$

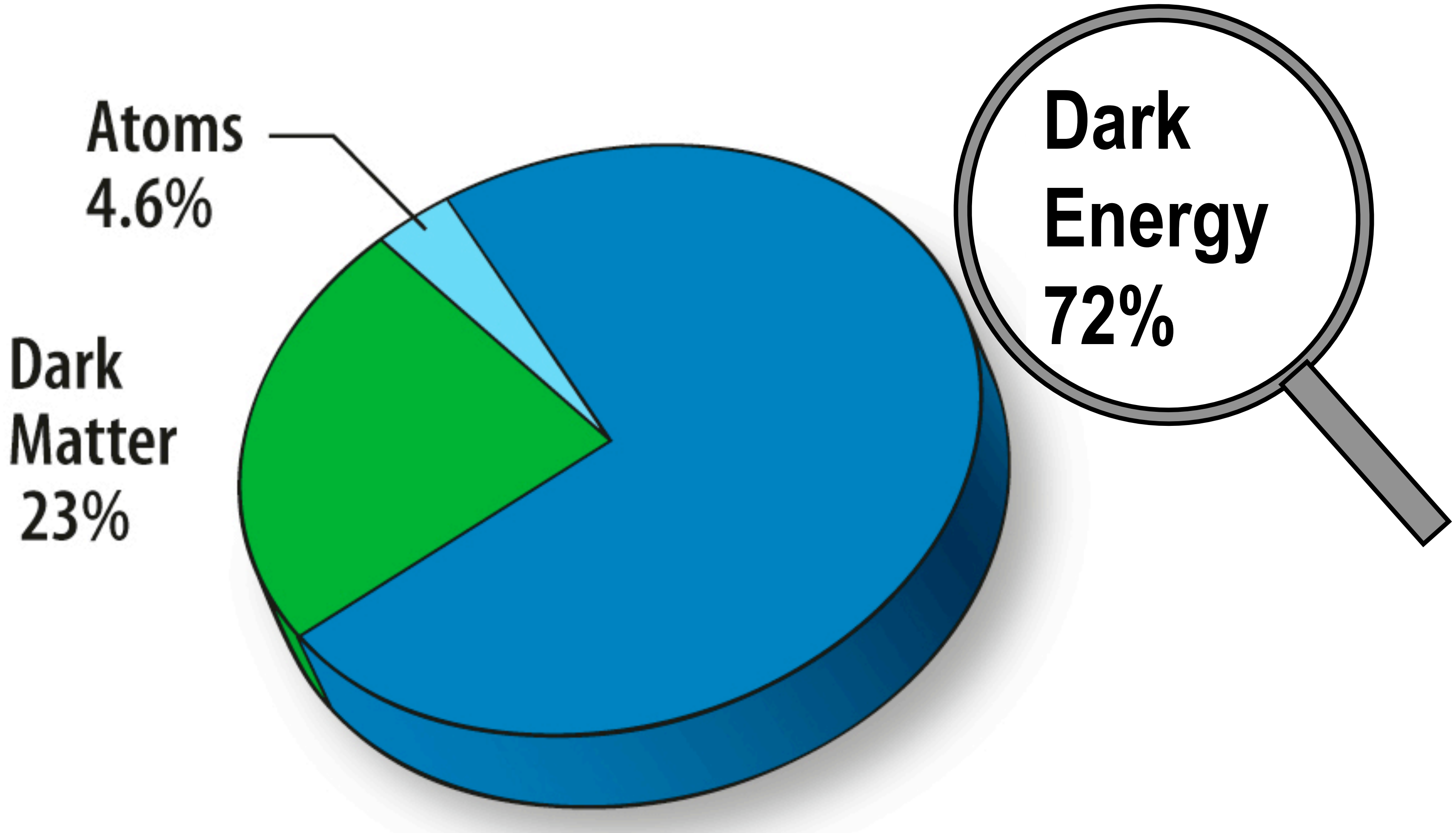


Baryon Acoustic Oscillation (BAO)

SDSS, Eisenstein et al. (2005)



Atoms
4.6%
Dark
Energy
72%
Dark
Matter
23%


Atoms
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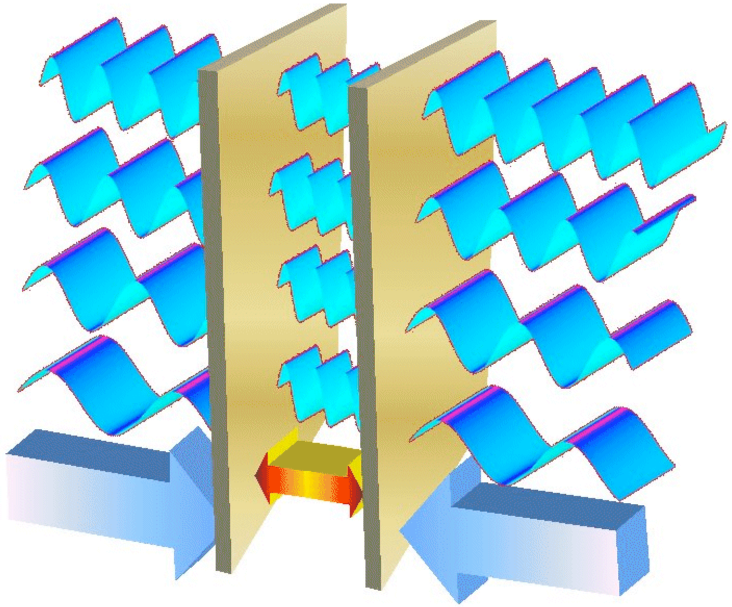
72%

Vacuum Energy

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

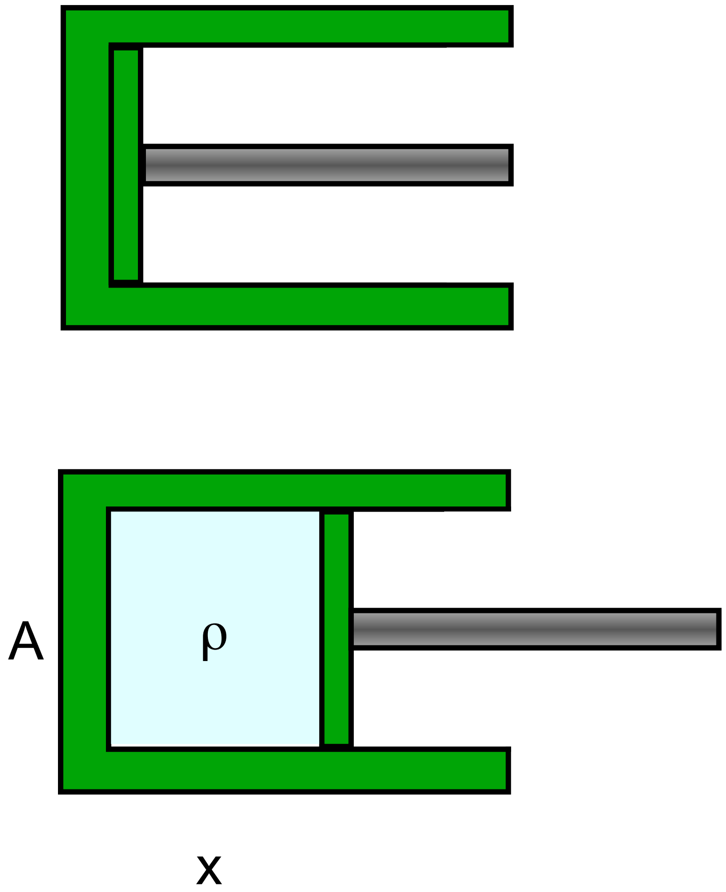
$$\rho_{\mathrm{vac}} = \frac{1}{2}\frac{\hbar}{(2\pi)^3}\int_0^{k_{\mathrm{max}}} k\,d^3k = \frac{\hbar k_{\mathrm{max}}^4}{16\pi^2}$$



Casimir effect ⇔ Energy difference

Vacuum Energy ⇔ Cosmological Constant

Zeldovich 1968



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

Pressure (*p*) of Vacuum energy follows from 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?

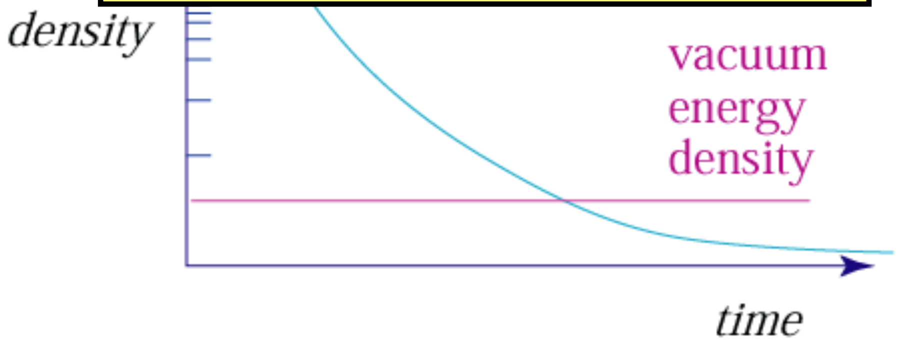
Expectation: $\rho_\Lambda \sim (M_{\mathrm{planck}})^4$
$\Rightarrow$120 orders of magnitudes larger then the observed value!

Why now?

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

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

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

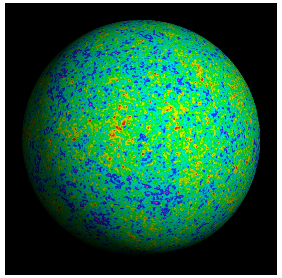


Equation of state: $w=p/\rho$

A few examples:

w_M= 0 (matter)
w_R= 1/3 (radiation)
w_Λ= -1 (cosmological constant)
w_Q> -1 (quintessence)
w_s= -1/3 (cosmic strings)

Content



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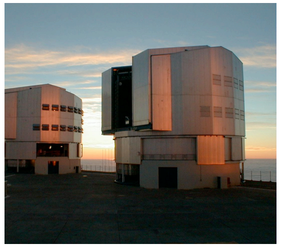
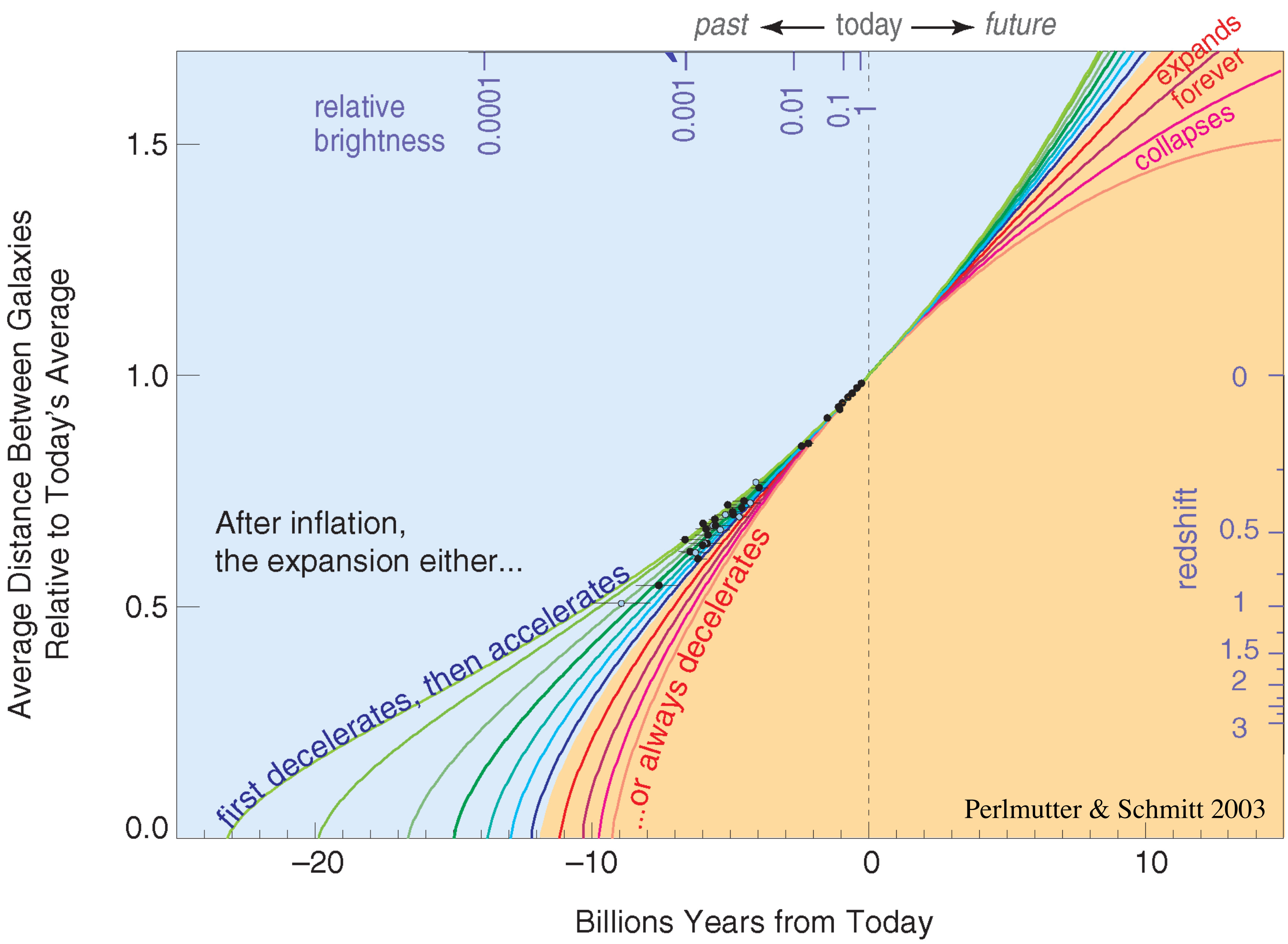


SNe observations&cosmological parameters

Constraints on selected Dark Energy models

Expansion History of the Universe



Supernova Type Ia

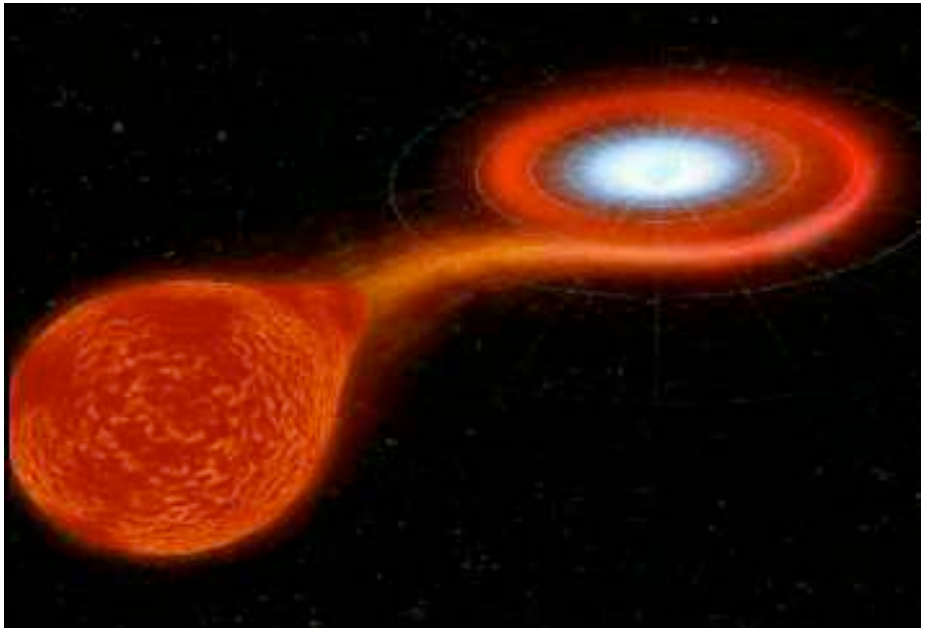
⇒ White dwarf in binary system

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

⇒ Thermonuclear explosion

⇒ Explosion of similar energies

⇒ Visible in cosmic distances

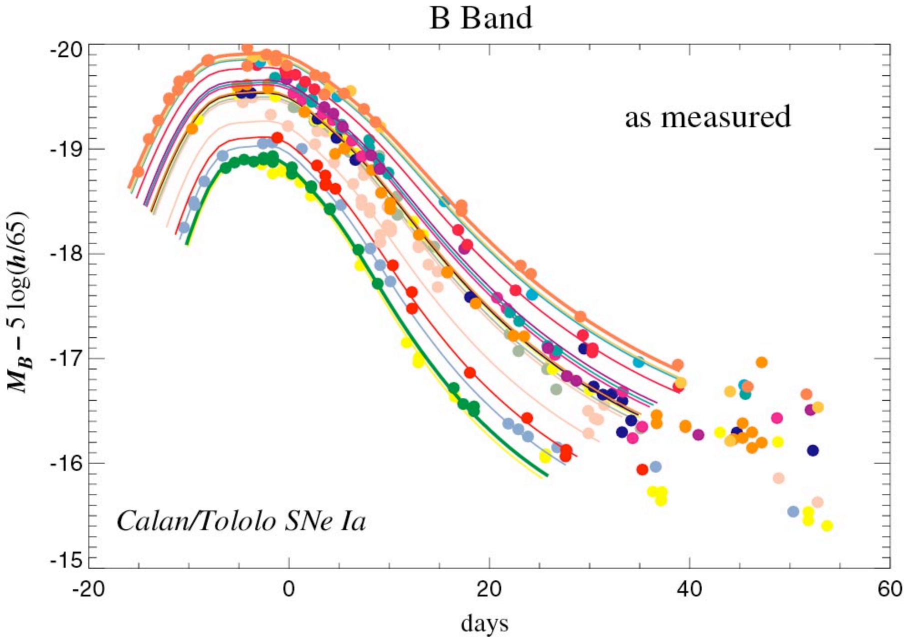


Astronomers think in…

Magnitudes:
$m = -2.5 \log(\text{Flux}) + \text{constant}$

Filter: B,V,R,I,Z (400-900 nm)

“Standard candles“



- Brightness not the same for all SNe

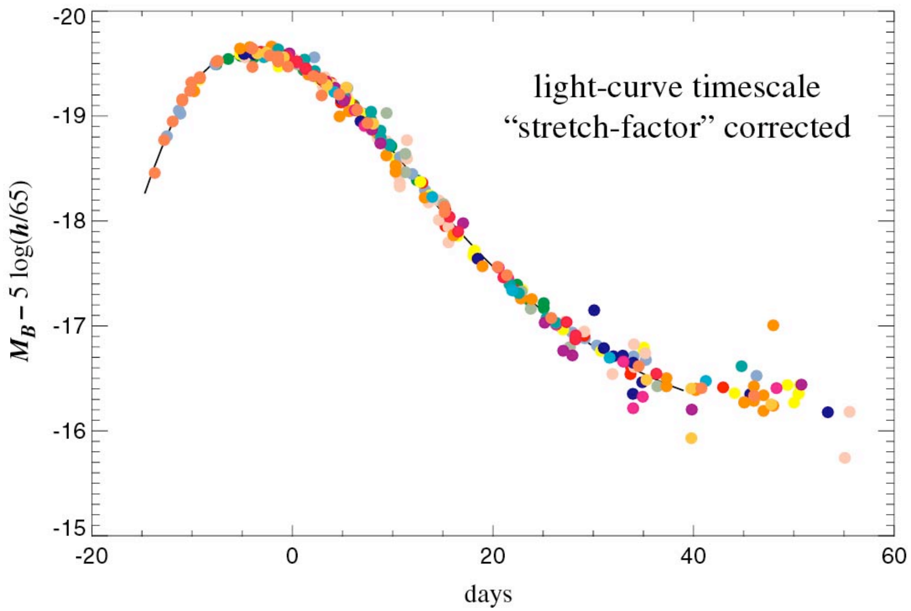
  Brighter SNe have wider light curves.

“Stretching“ of time scale:

$$t' = s \times t$$

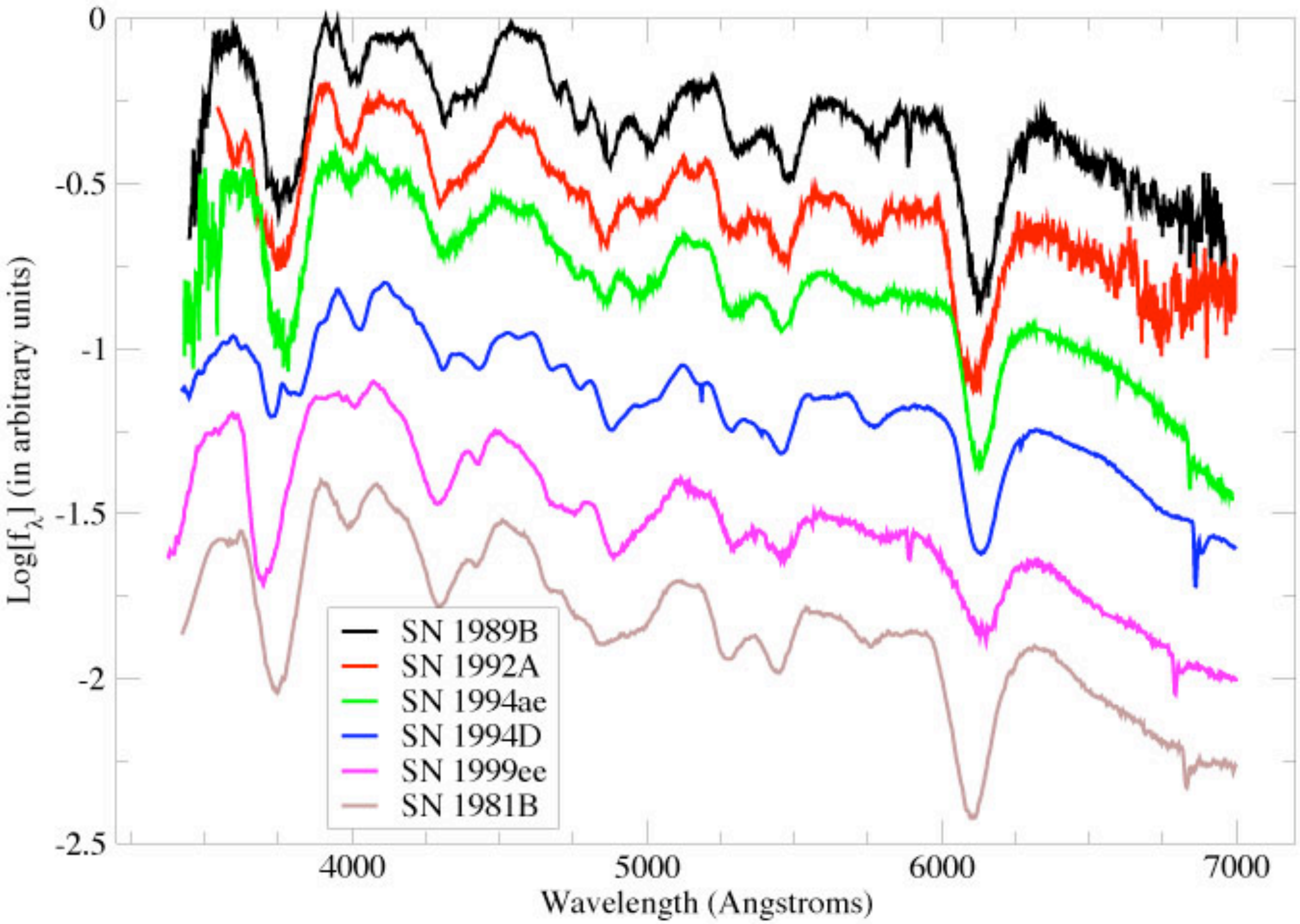
Brightness correction:

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

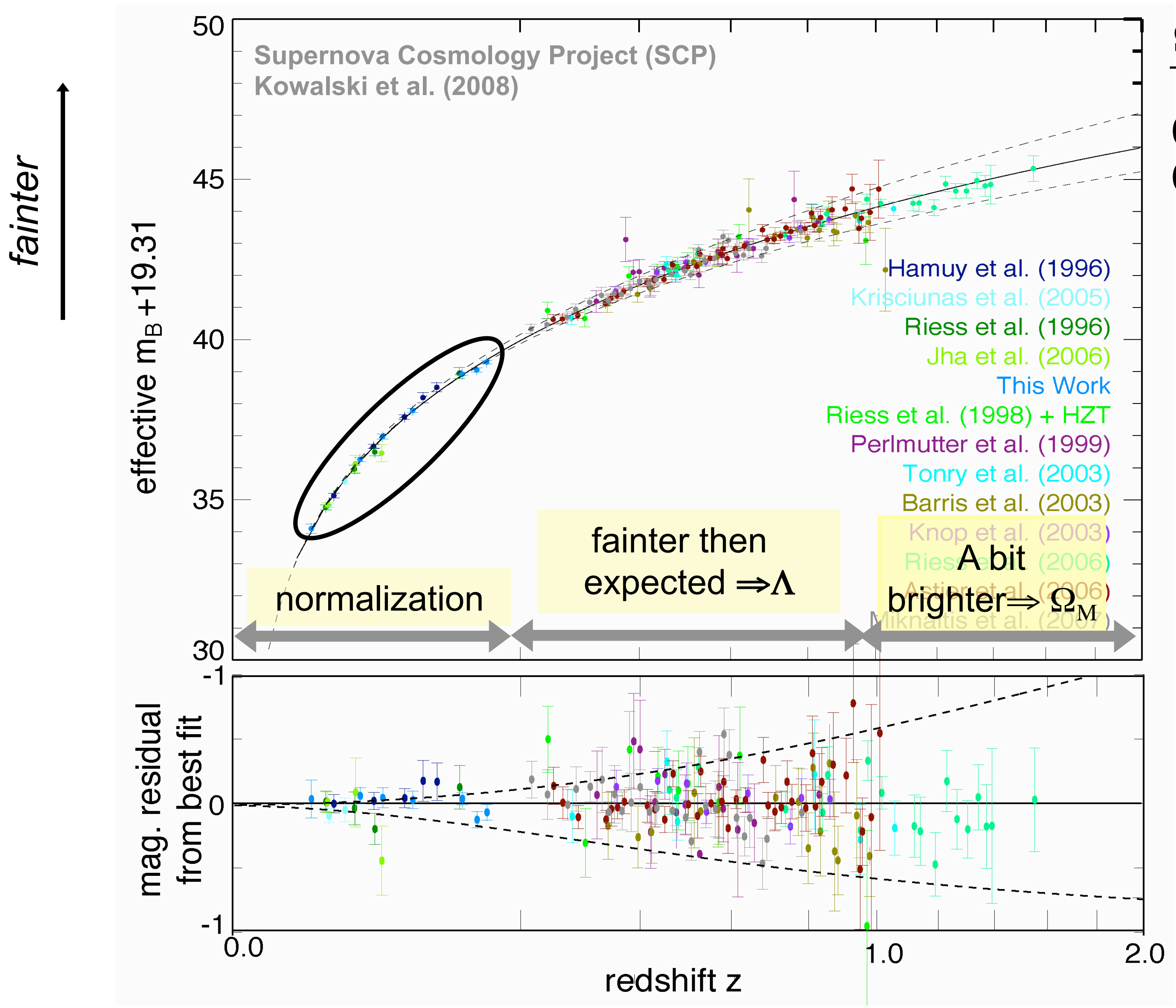


Kim, *et al.* (1997)

Spectra for identification and redshift determination



SNe Ia Hubble Diagram



Ω_Λ	Ω_M
1	0
0.72	0.28
0	1

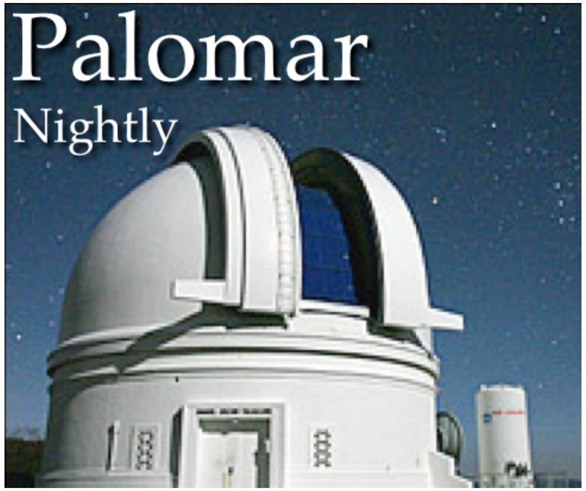
New in Germany…

(artist's concept)

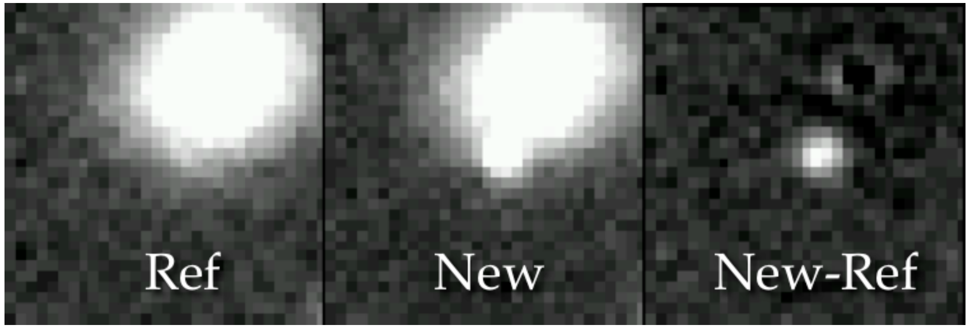
Supernova Factory Collaboration:

Lawrence Berkeley National Lab
Laboratorie de Physique Nucleaire et de Haute Energies de Paris
Institut de Physique Nucleaire de Lyon
Centre de Recherche Astronomy de Lyon
Yale University
Bonn University

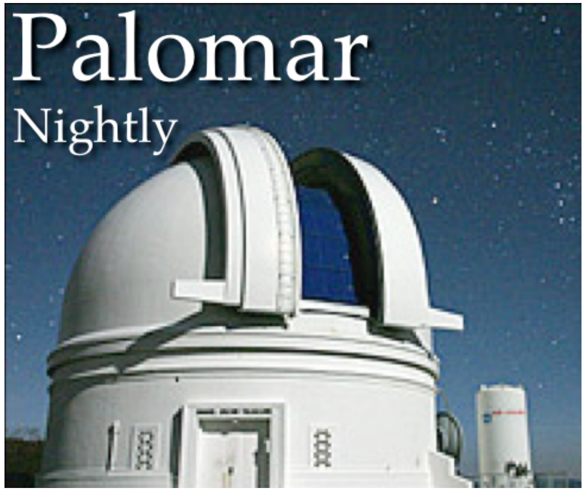
SNfactory: producing unique nearby SNe data



1. Discover



SNfactory: producing unique nearby SNe data



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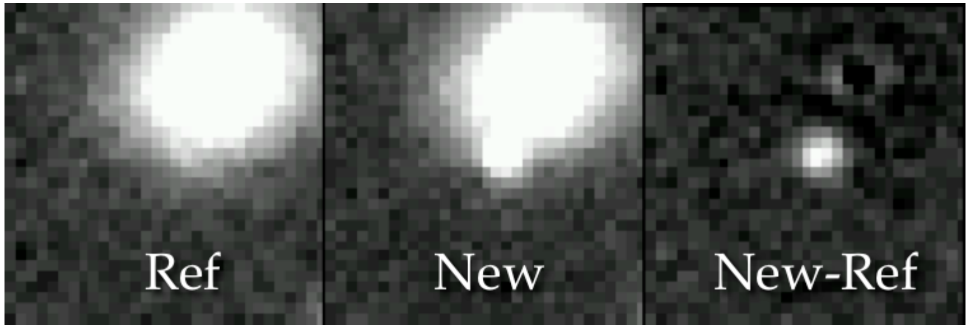
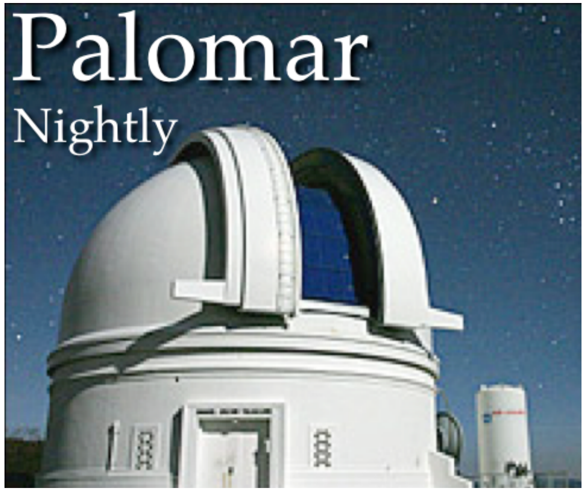


2. Observe

<u>SNIFS</u>: Custom spectrograph for nearby SN observations

SNfactory: producing unique nearby SNe data



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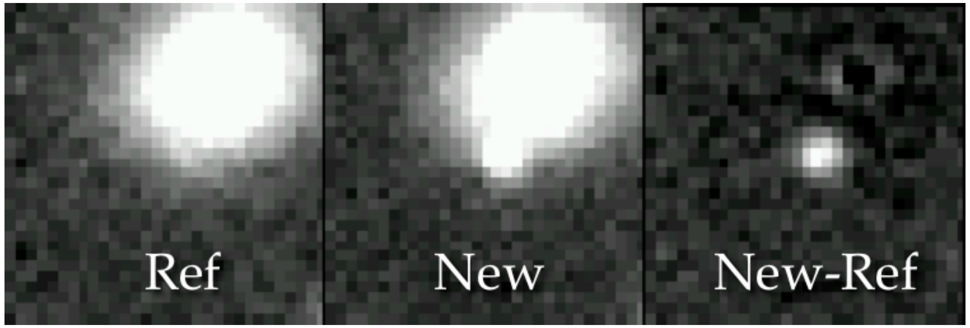
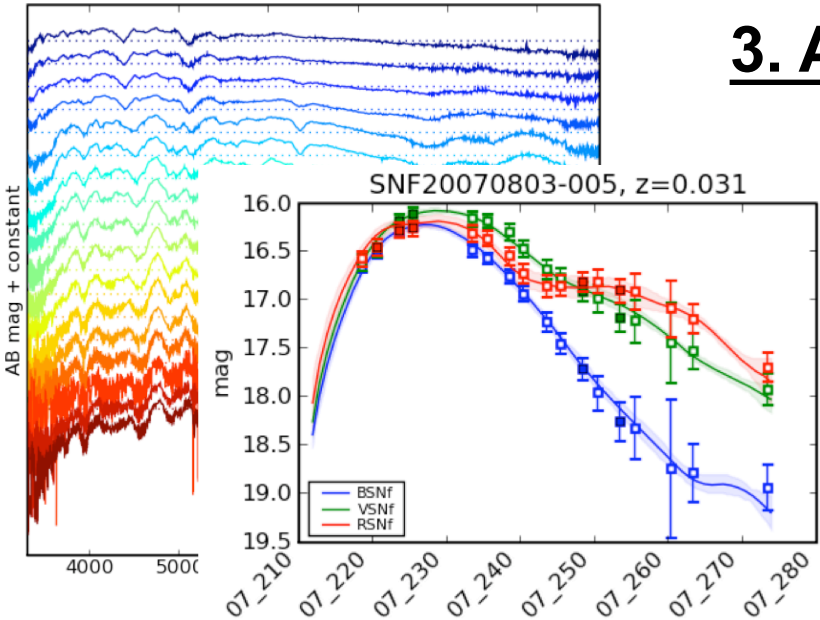


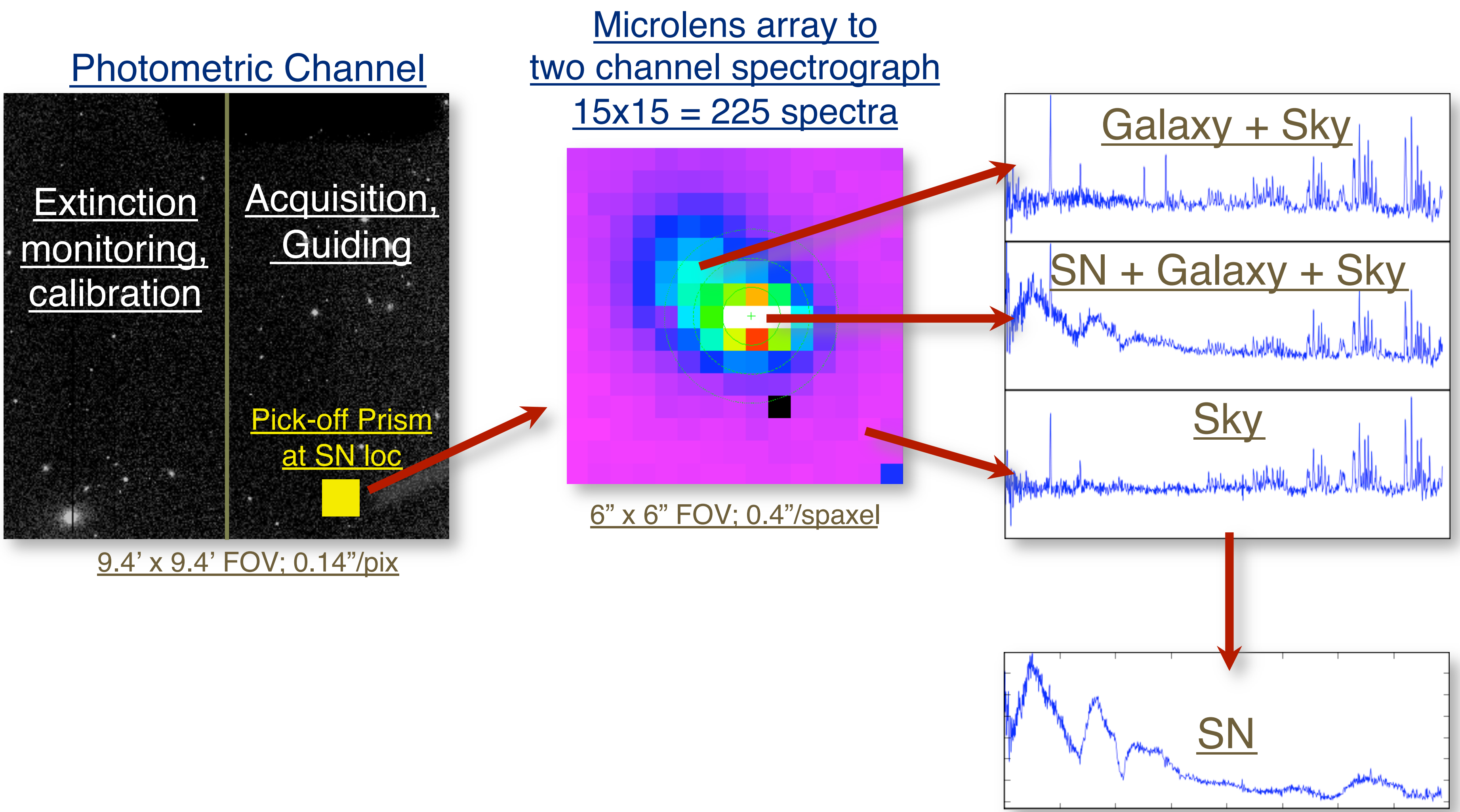
2. Observe

SNIFS: Custom spectrograph for nearby SN observations

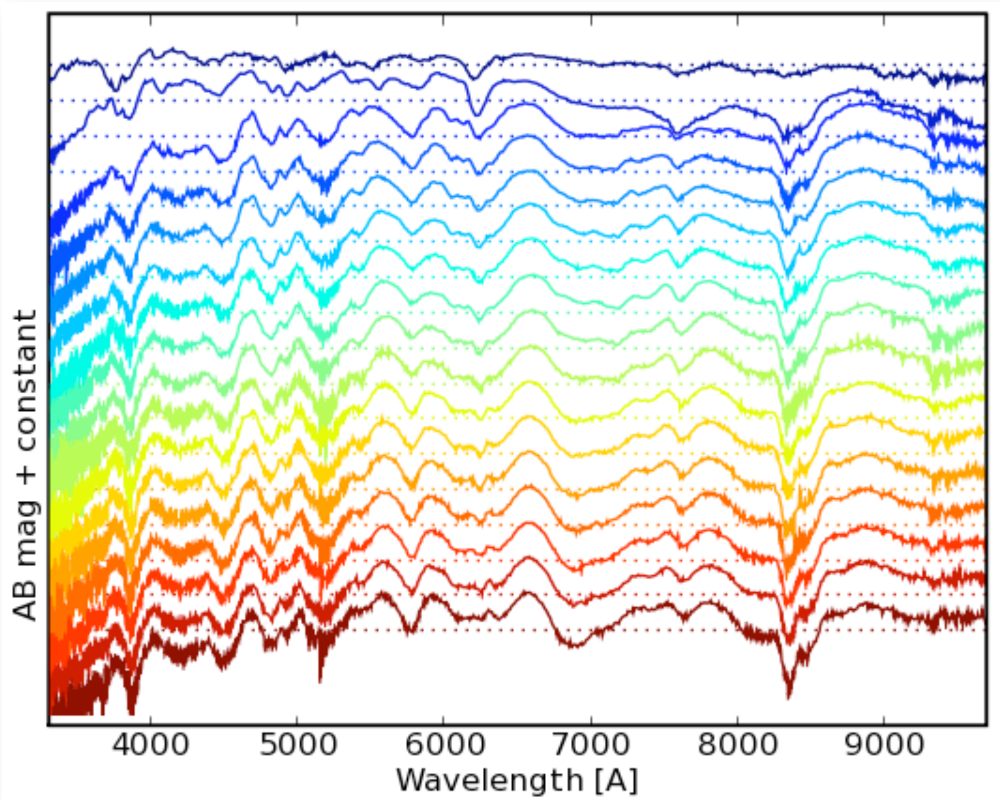
3. Analyses



SuperNova Integral Field Spectrograph (SNIFS)

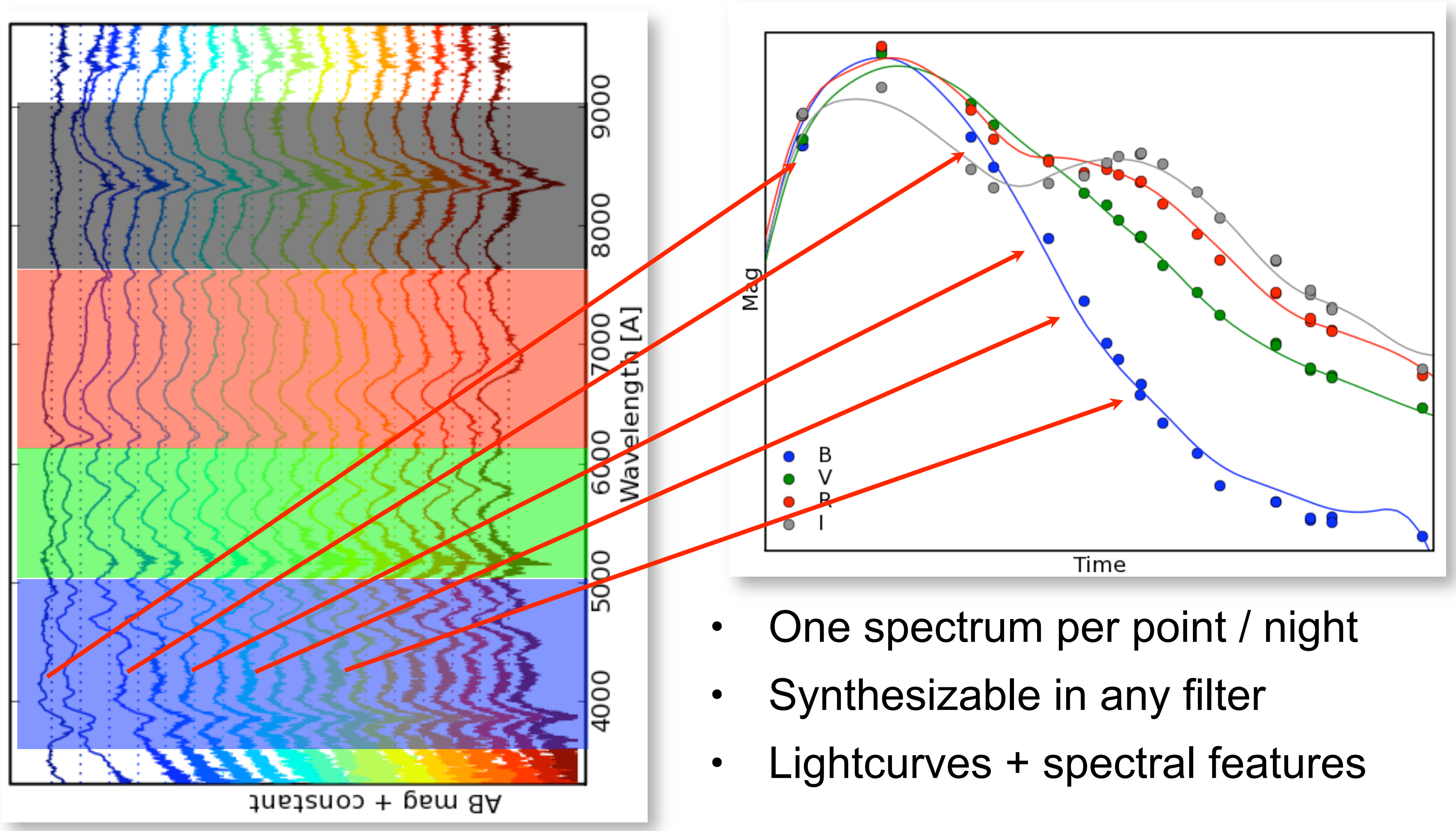


From Spectra to Lightcurves



Slides: Rui Pereira

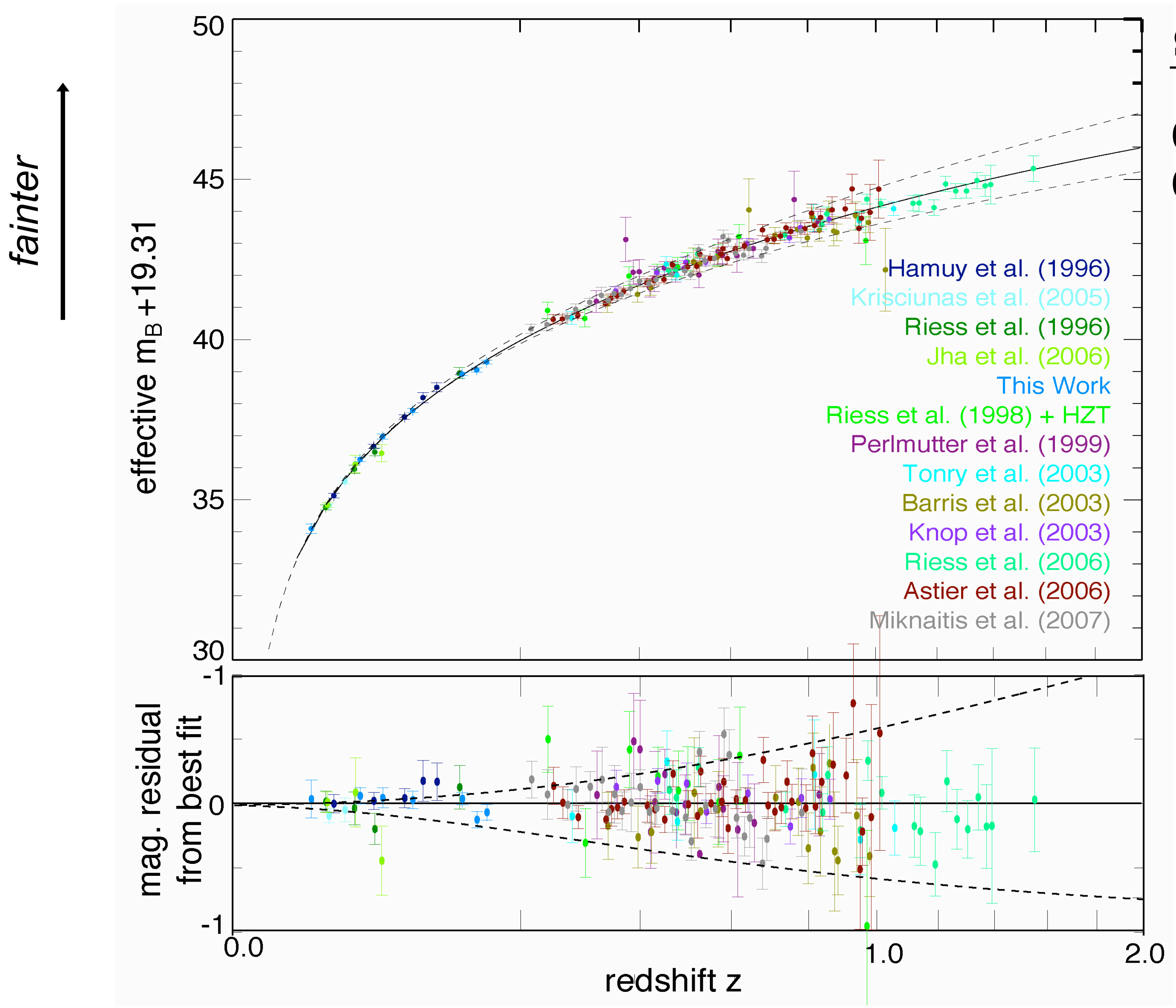
From Spectra to Lightcurves



- One spectrum per point / night
- Synthesizable in any filter
- Lightcurves + spectral features

Slides: Rui Pereira

The Union SNe Compilation



Ω_Λ	Ω_M
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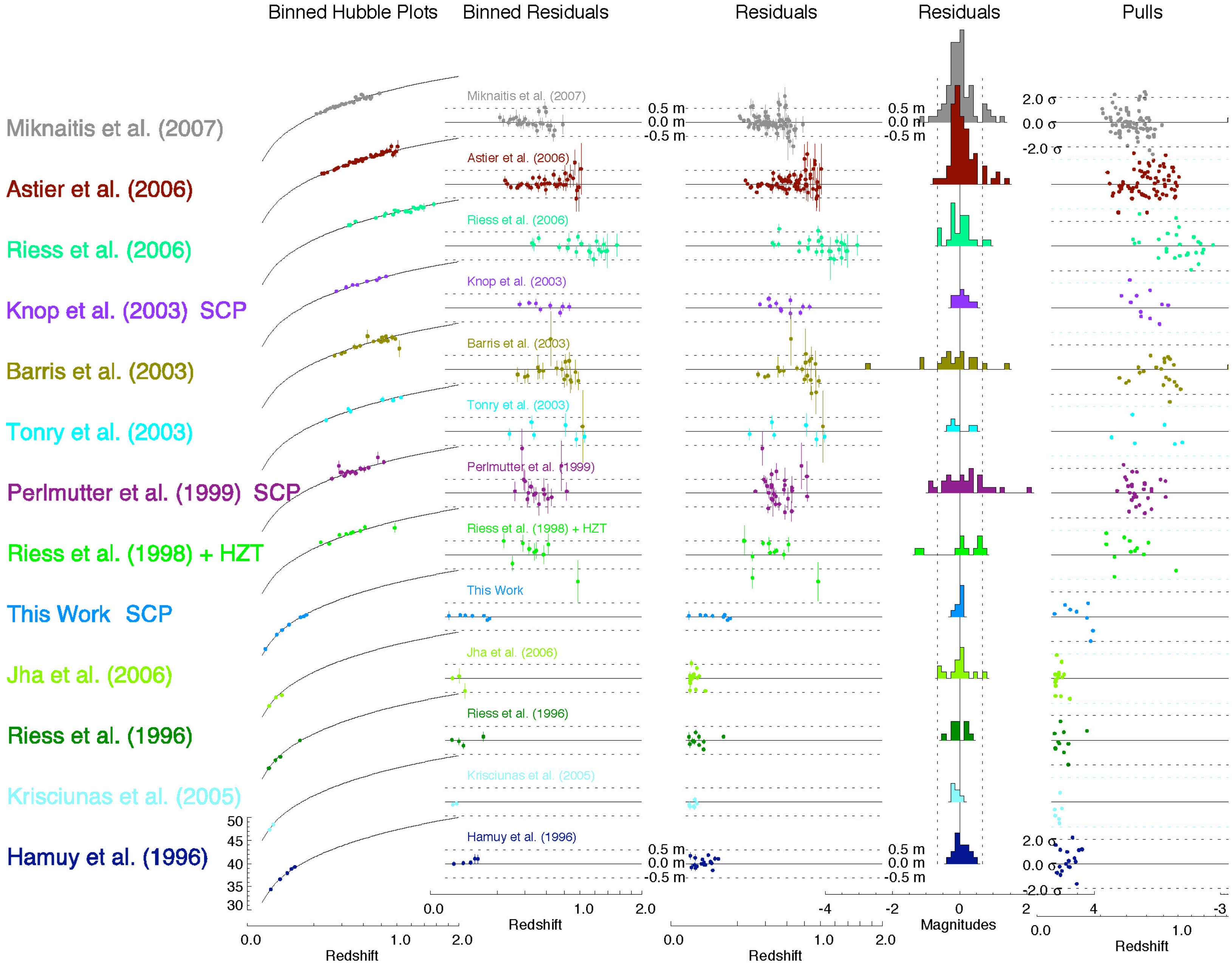
A heterogenous data sample



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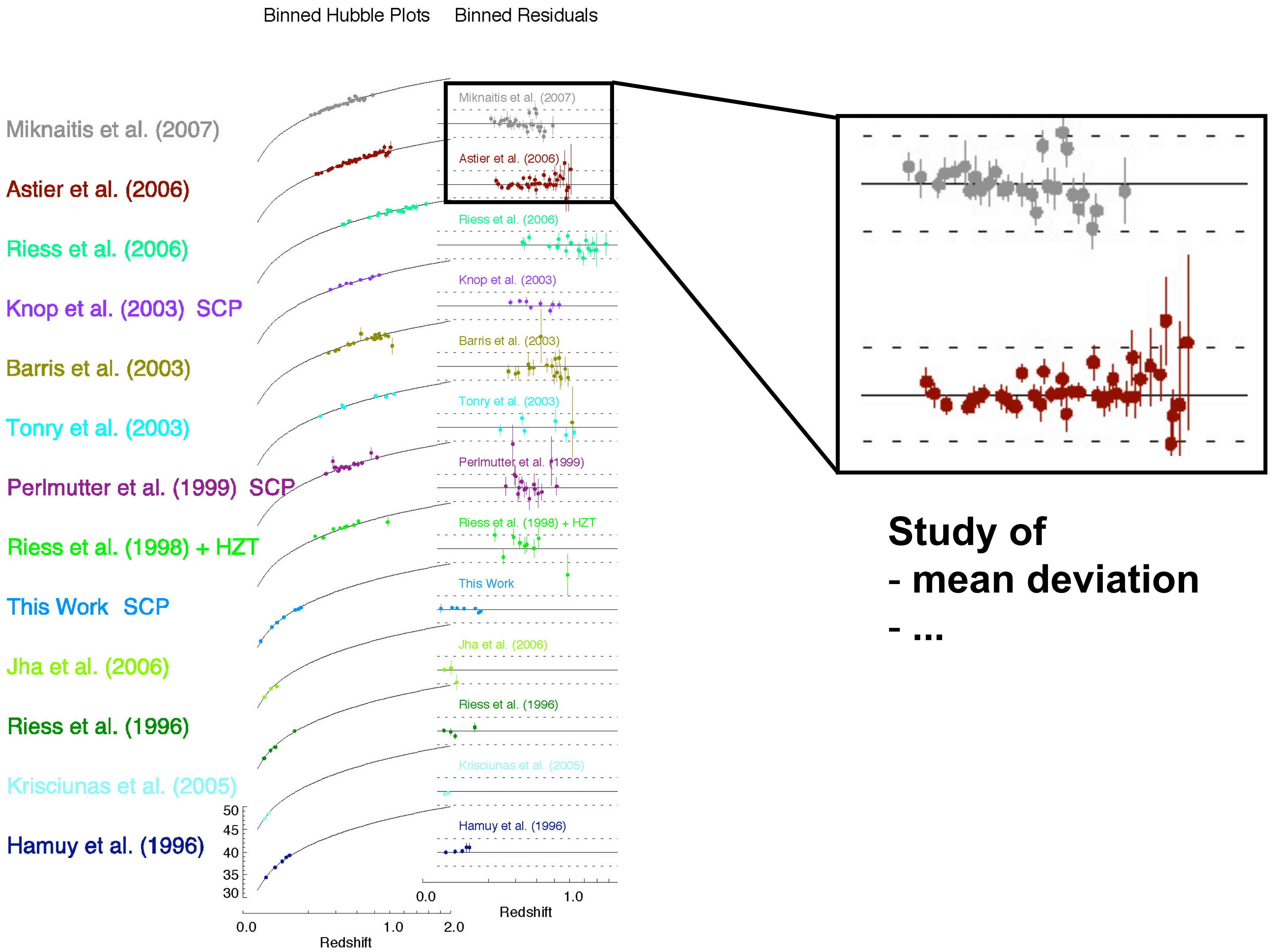
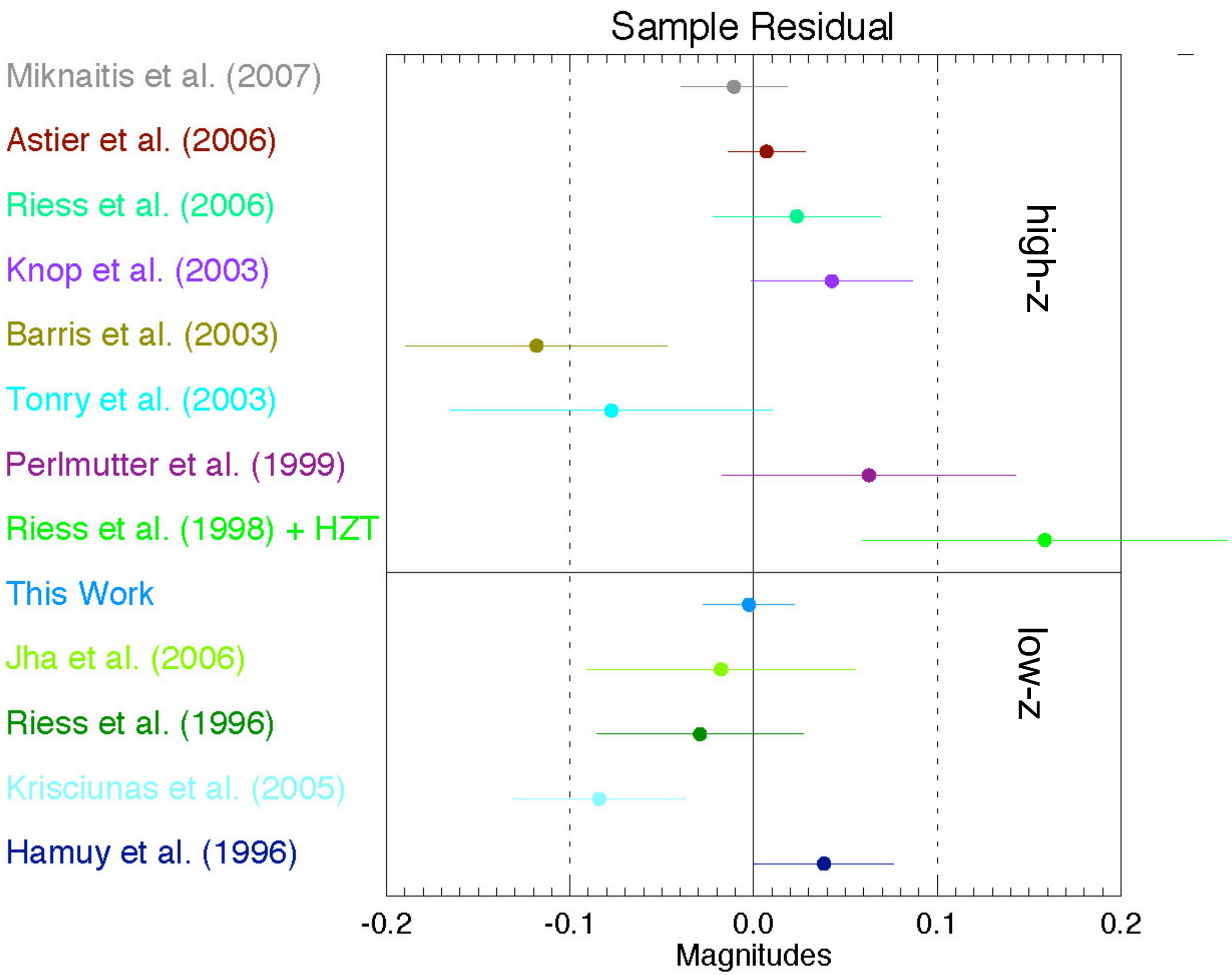


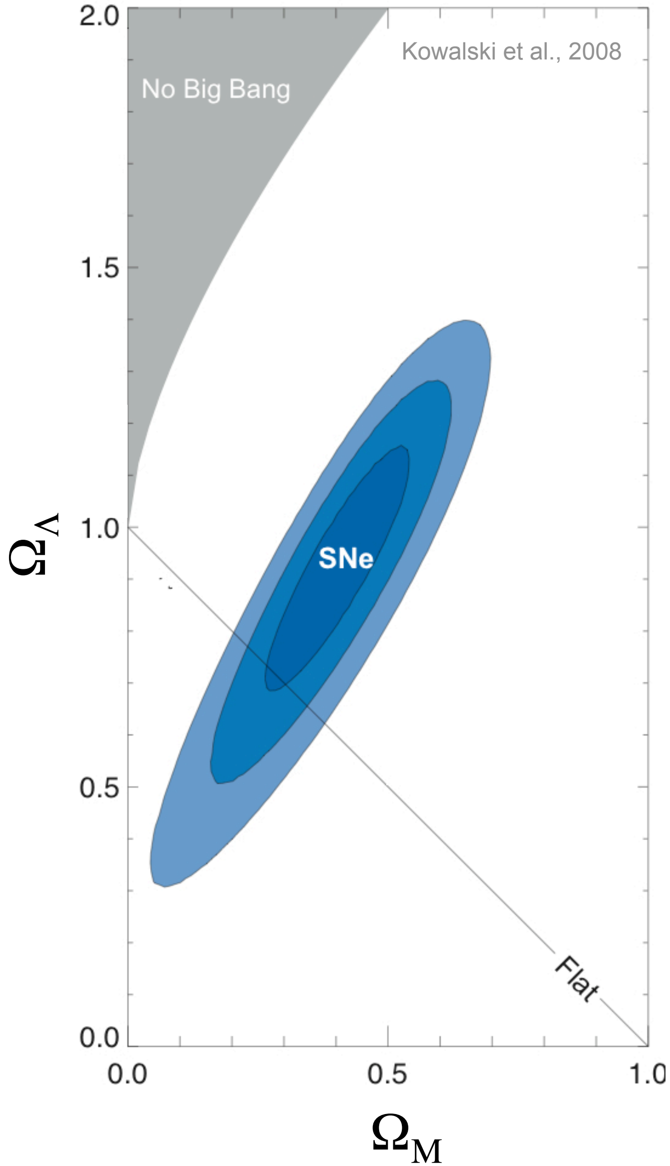
Study of
- mean deviation
- ...

Test for Tension

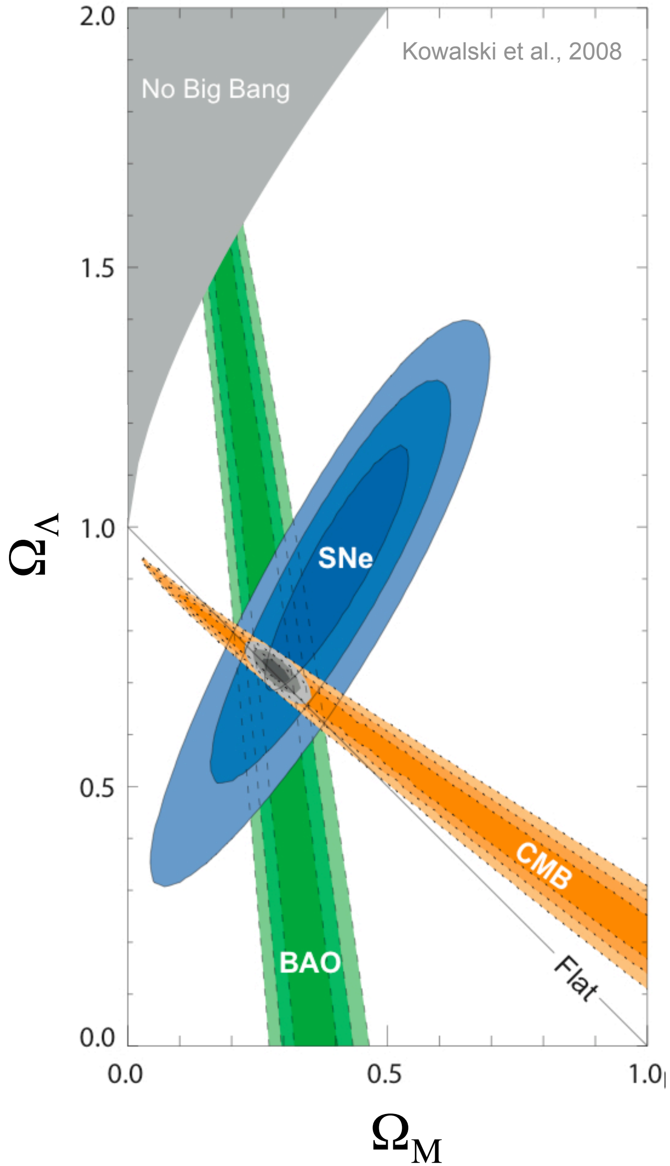


mean deviation: OK

Results: Cosmological Parameters



Results Cosmological Parameters



Combination of SNe with:
BAO (Eisenstein et. al., 2005)
CMB (WMAP-5 year data, 2008)

For a flat Universe:

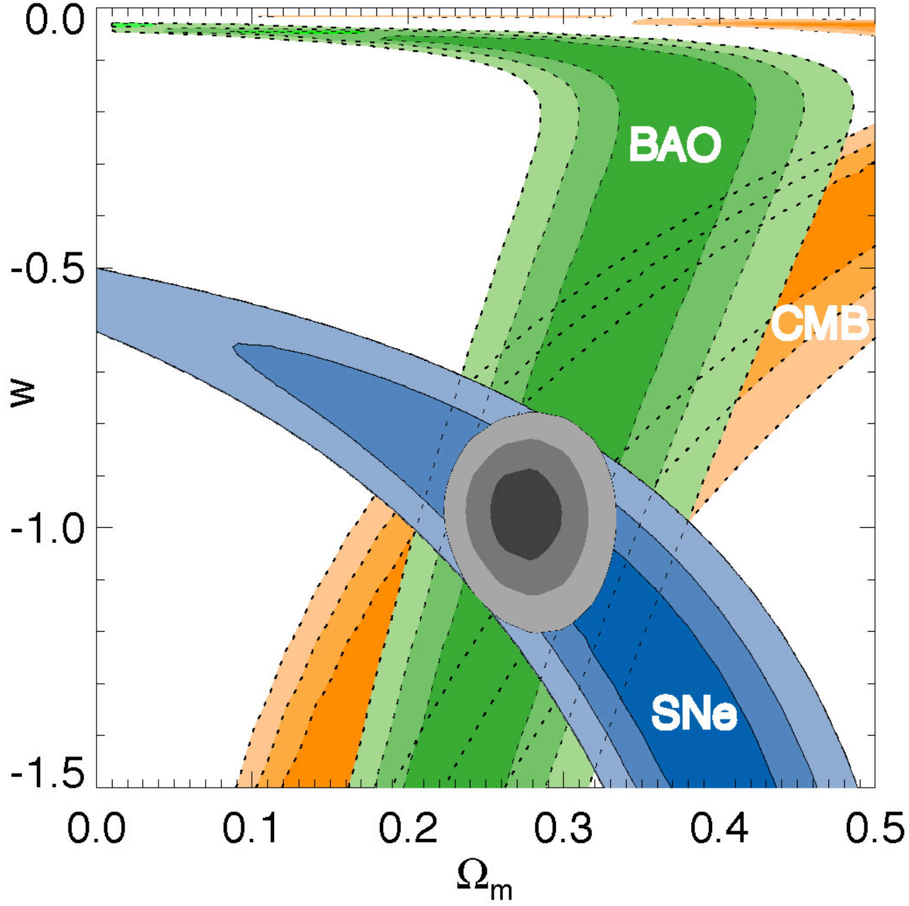
$$\Omega_m = 0.274 \pm 0.016(\mathrm{stat}) \pm 0.012(\mathrm{sys})$$

… and with curvature:

$$\Omega_m = 0.285 \pm 0.020(\mathrm{stat}) \pm 0.010(\mathrm{sys})$$

$$\Omega_k = -0.001 \pm 0.010(\mathrm{stat}) \pm 0.005(\mathrm{sys})$$

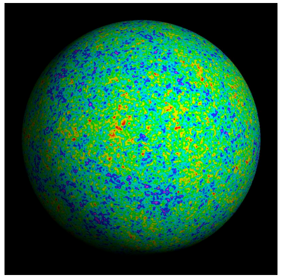
Equation of state: $w=p/\rho$



$$w = -0.97 \pm 0.06(\text{stat}) \pm 0.06(\text{sys})\ ; \quad k = 0$$

$$w = -1.00 \pm 0.07(\text{stat}) \pm 0.08(\text{sys}); \quad k \text{ frei}$$

Content



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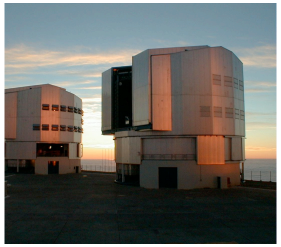


SNe observations&cosmological parameters

Constraints on selected Dark Energy models

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

Menu of possibilities:

1. Quantum Vakuum Energy (static)

+ it exists!

- 60-120 orders of magnitude to large

2. Quintessence (dynamic)

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

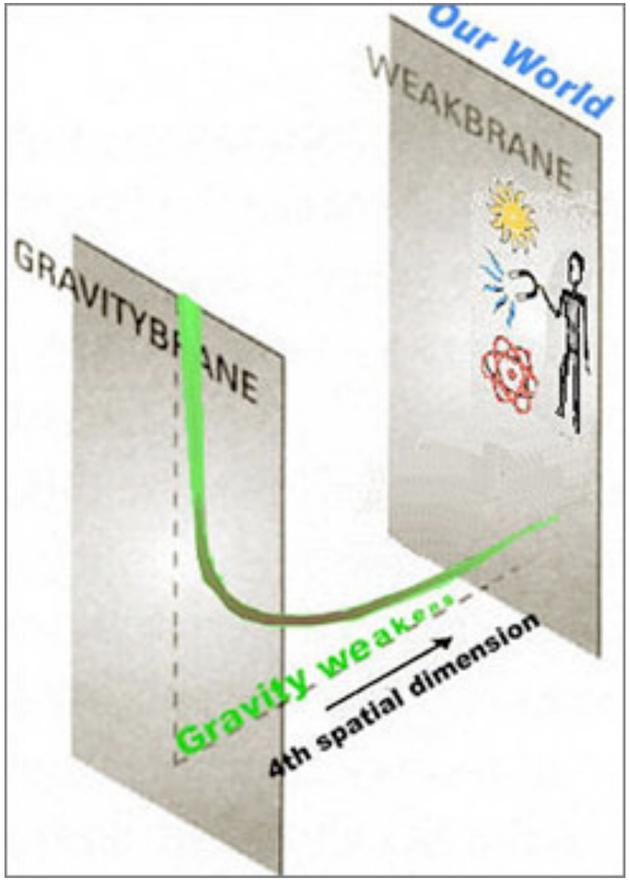
- „smallness“ problem persists, small coupling

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

+ no Dark Energy

- Gravitation in solar system well understood

Braneworld Cosmology

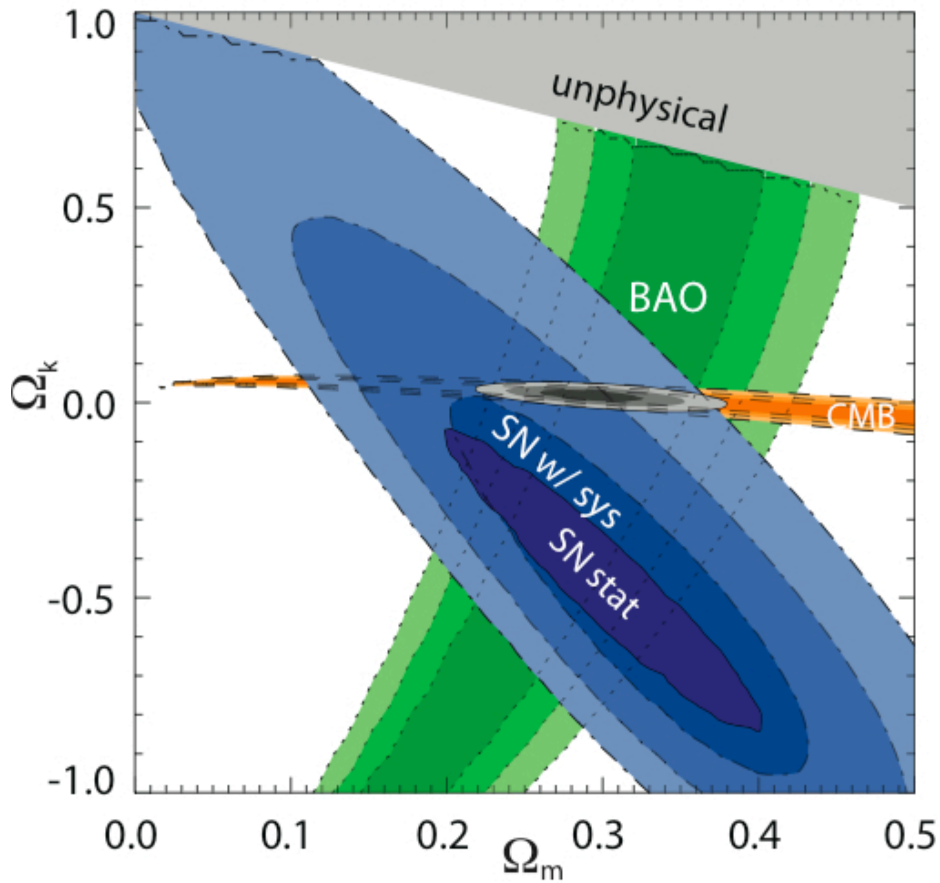


Large extra dimensions
can solve the hierarchy problem of particle physics…
(e.g. unification of forces)
Randall & Sundrum
Arkani-Hamed, Dimopoulos, Dvali

…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

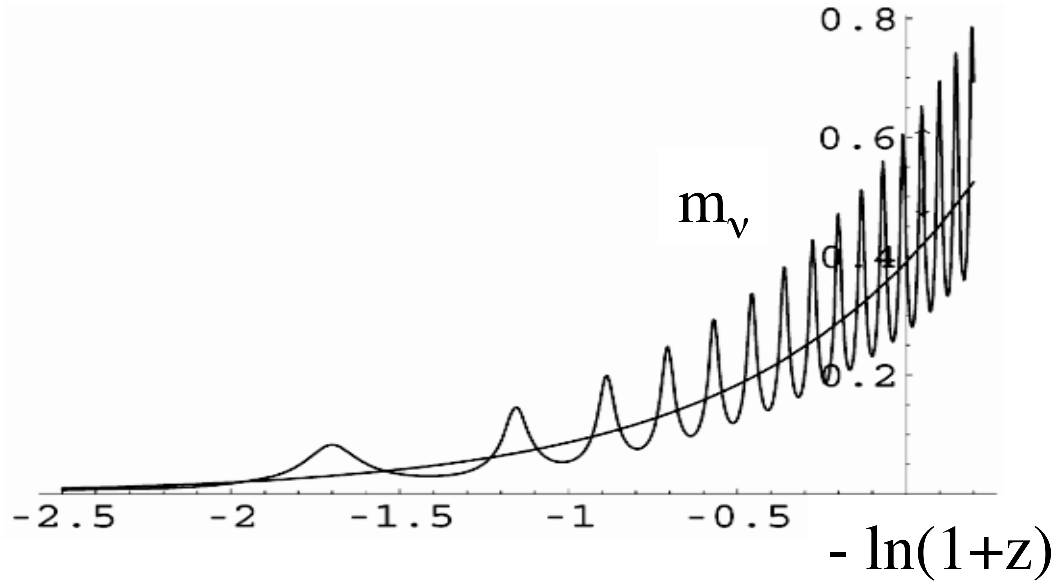
Quintessence Example: Growing Neutrinos

Scalar field couples to massive neutrinos

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

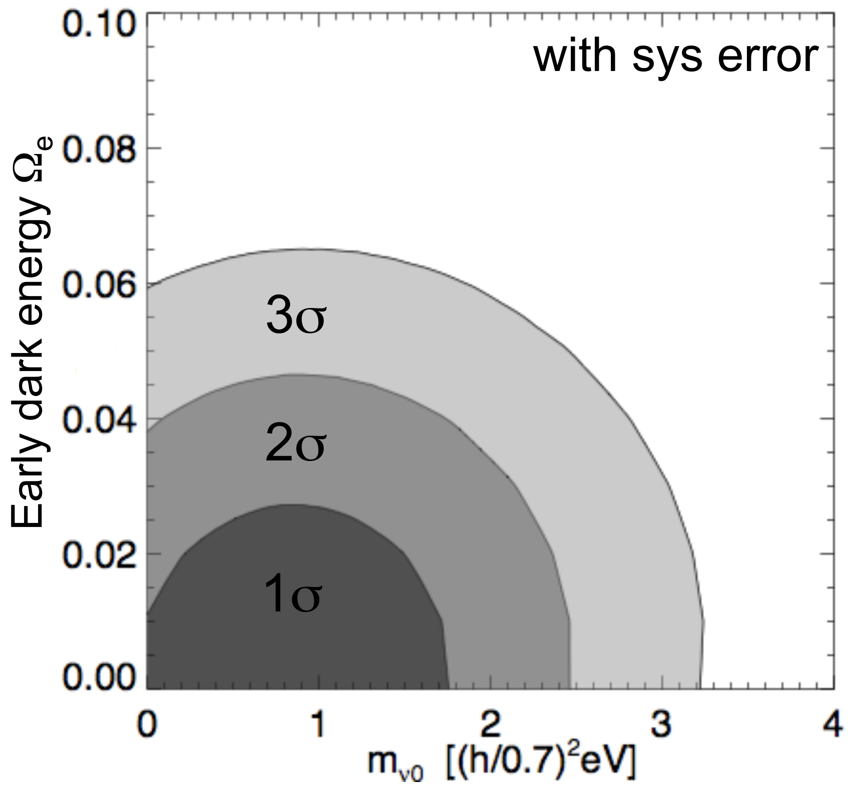
Today: Massive neutrinos and deviation from w =-1

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



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

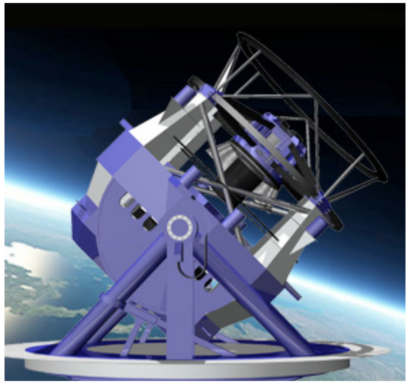
Quintessence Example: Growing Neutrinos



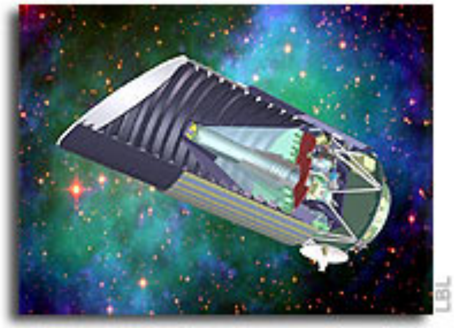
Lab constraints:
$m_\nu \leq 2$ eV
Katrin sensitivity:
$m_\nu \leq 0.2$ eV
ν−oszillations:
$m_\nu \geq 0.05$ eV

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

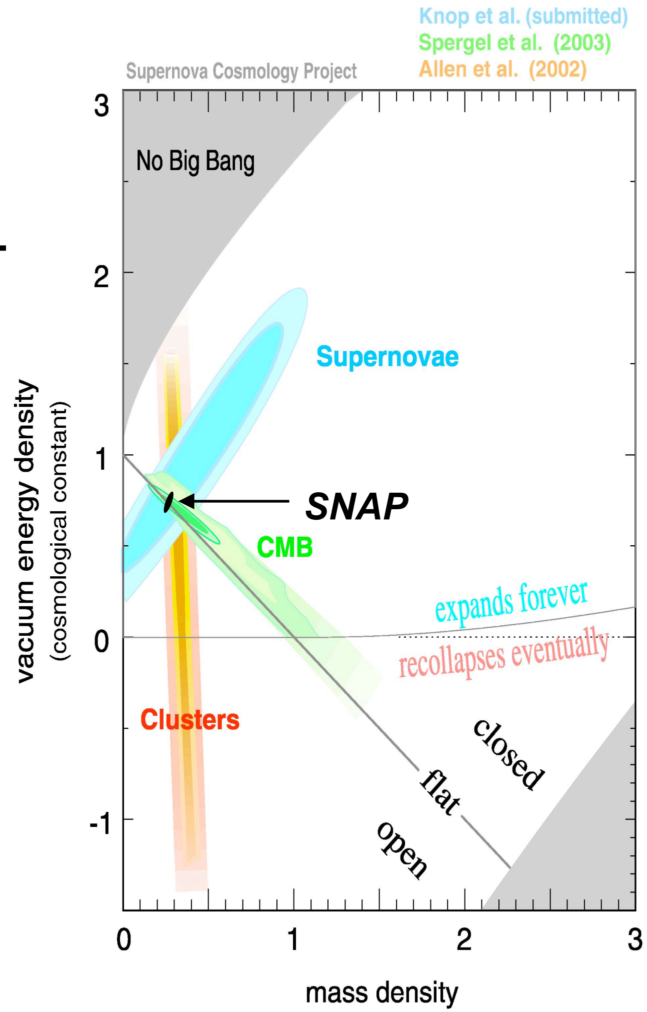
D.Rubin, E. Linder, MK et al., (2009)



Future projects for Dark Energy

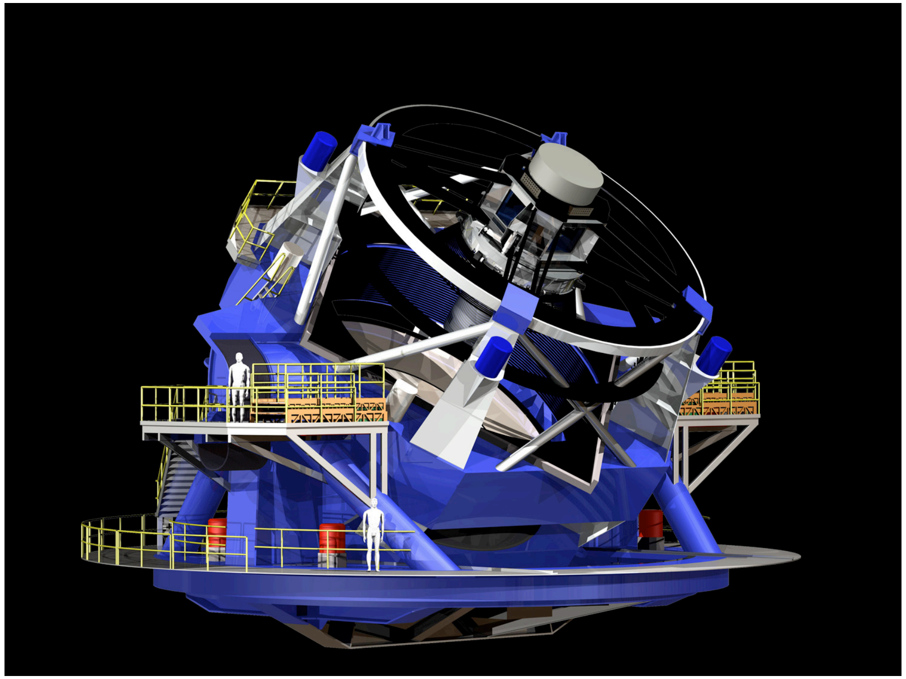


Projekt	z range	# SNe
Pan-STARRS	0.1-0.5	~10^4
DES (2011)	0.2-0.7	~$2x10^3$
LSST (2015)	0.1-0.9	~10^6
SNAP (2017)	0.2-3.0	~$3x10^3$
(JDEM/Euclid)		



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

The possible future of wide field imaging:
Large Synoptic Survey Telescope (LSST)



8.4 m diameter telescope to be build at Cerron Panchon, Chile

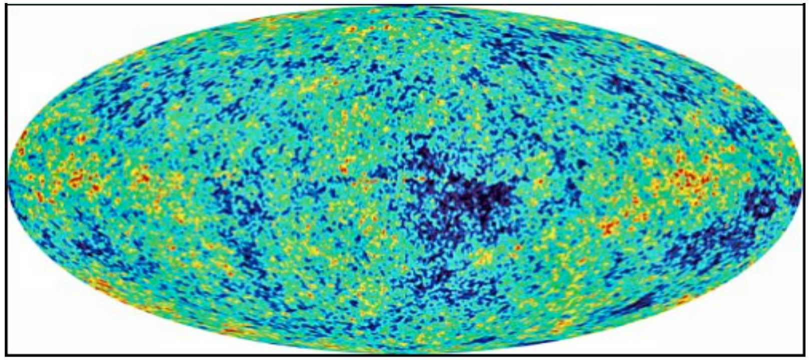
Camera (lead by SLAC):

- 3.5^{o} Field of View
- 3×10^{9} pixels
- 10 s exposures
- 30 TB data per night
- Full survey of sky every 4 days
- First light 2015

Conclusion

- The observed acceleration of the Universe poses one of the most fundamental problems in physics today.
- So far everything looks consistent with cosmological constant.
- Detailed measurement of the dynamics can give insights into the acceleration meachanisms and a new generation of observatories will provide the data.

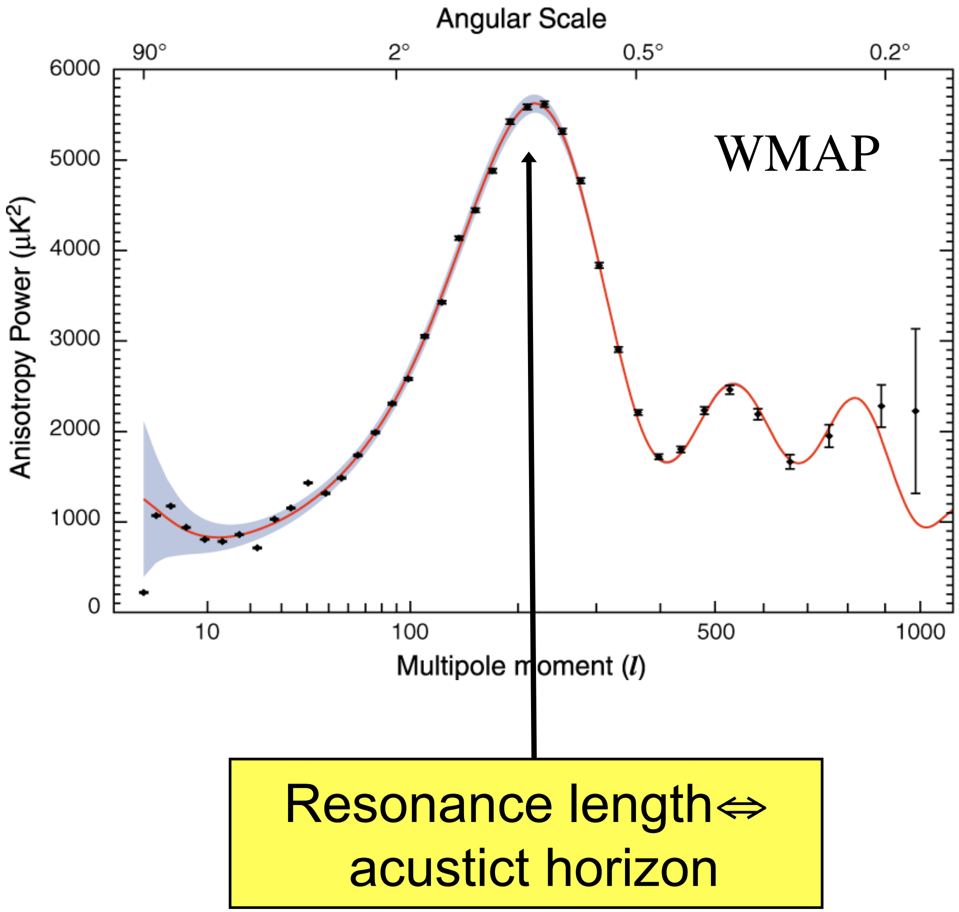
Cosmic Microwave Background (CMB) & Curvature of the Universe



Expand the temperature map with 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 scale:



Quintessence

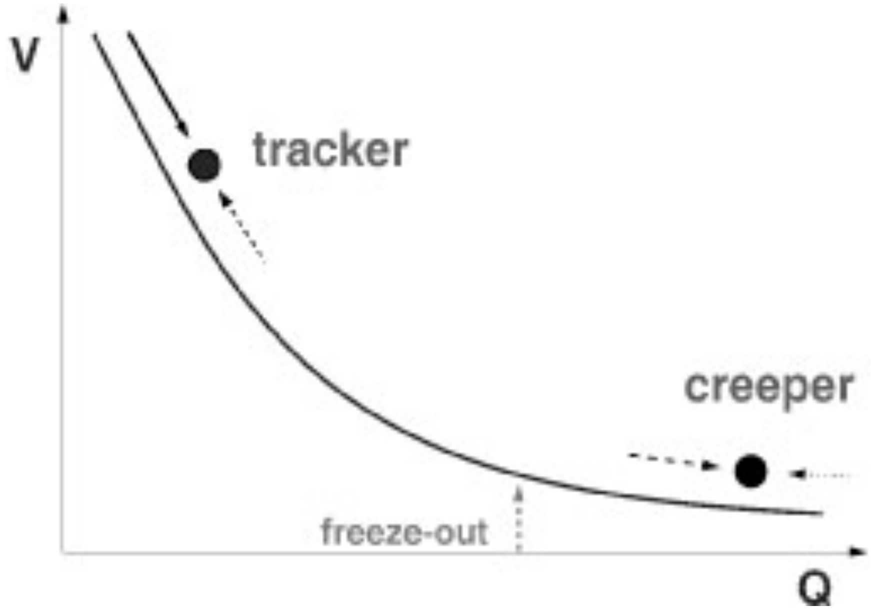
Skalare Field ϕ with potential $V(\phi)$
(similar Inflaton)

$$w = \frac{p}{\rho} = \frac{\frac{1}{2}\dot{\phi}^2 - V(\phi)}{\frac{1}{2}\dot{\phi}^2 + V(\phi)} \leq -1$$

$$w \approx -1 \text{ für } \dot{\phi}^2 \ll V(\phi)$$

Friedmann-Gleichung für ϕ:

$$\ddot{\phi} + 3H\dot{\phi} + V'(\phi) = 0$$



Bei geeignetem Potential folgt die Energiedichte dank „Hubble-Reibung" der Materiedichte (tracker-behavior).
⇒ **Teilweise Lösung des „Warum jetzt" Problems.**
Wetterich (1987)

Testing SN evolution by subdividing the sample

luminosity-width correction coefficient

luminosity-color correction coefficient

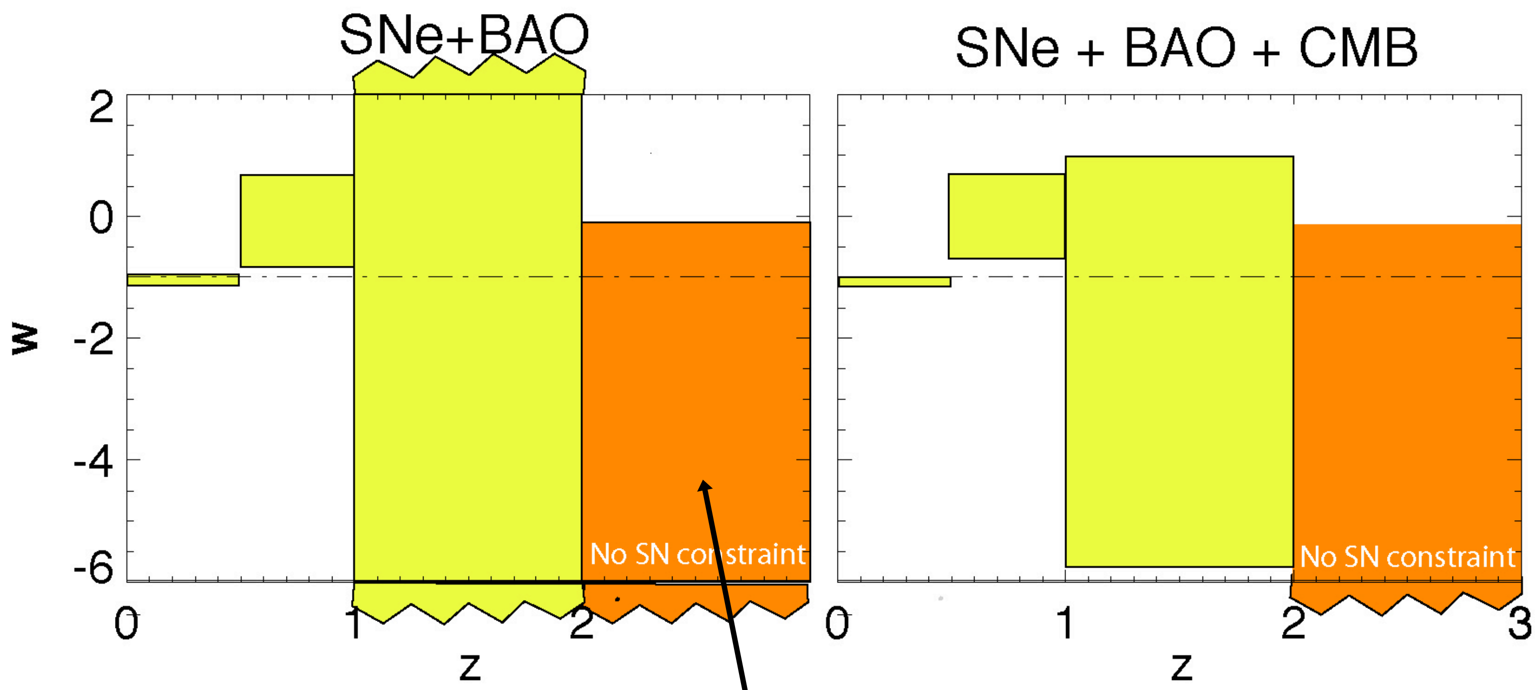
$$\mu_B = m_B^{\max} - M + \alpha(s-1) - \beta c$$

	subset	$N_{\rm SN}$	α	β	$\Omega_{\rm M}^a$	w^b
	all	307	1.26(0.10)	2.28(0.12)	0.28(0.03)	-1.00(0.07)
Evolution test:	$z > 0.2$	250	1.47(0.16)	2.26(0.14)	-	-
Redshift	$z \leq 0.2$	57	1.10(0.12)	2.24(0.21)	-	-
Evolution test:	$s < 0.96$	155	1.56(0.27)	2.18(0.18)	0.27(0.05)	-1.01(0.10)
Population	$s \geq 0.96$	152	1.57(0.34)	2.33(0.17)	0.30(0.04)	-0.96(0.08)

No significant evidence for evolution!

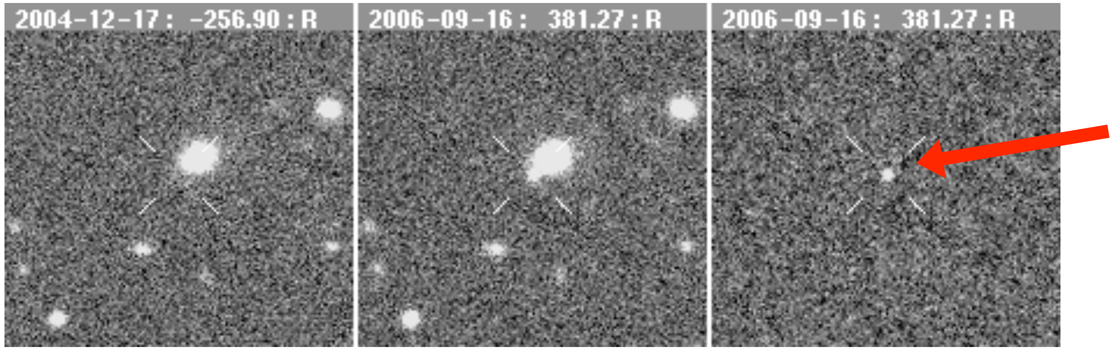
Redshift dependent *w*

Assuming step-wise constant *w*:



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

Supernova-Observations

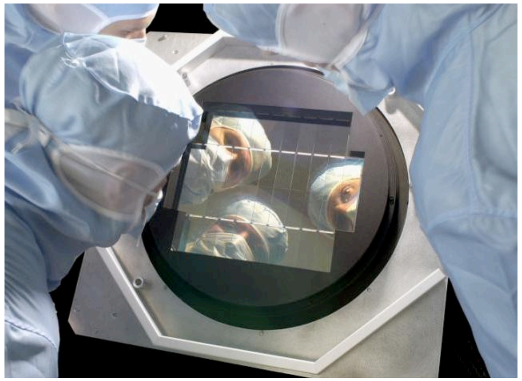


SN-candidate

Reference new image difference

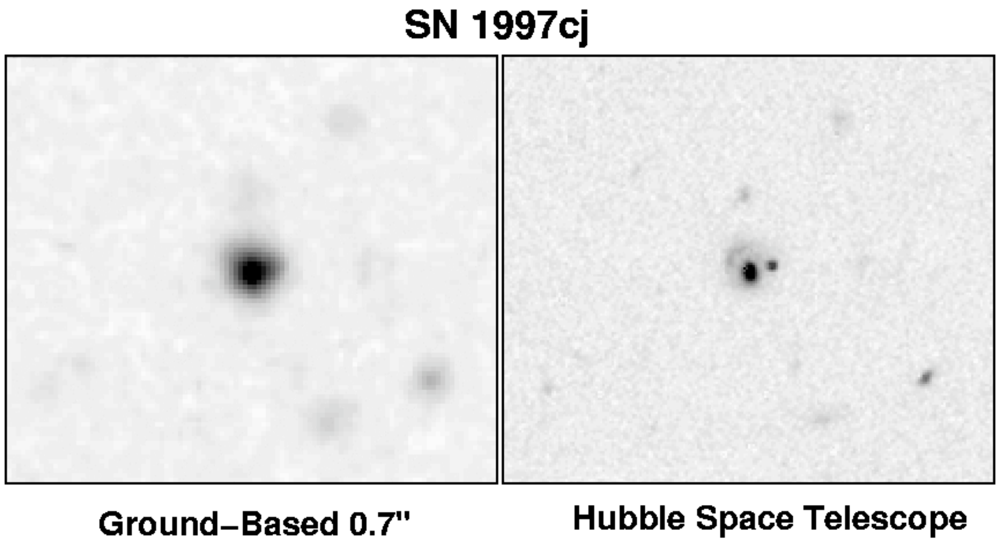
Search for SNe with redshift z<1
e.g. SuperNova Legacy Survey (SNLS) with the CFH-telescope (3.6 meter). Every 3 days observation of the same part of the sky:

$\Rightarrow$ 80 SNe / yr



MegaCam: 340M pixel,
1°x1° field-of-view

SNe at z>1



Twin Keck telescopes on Mauna Kea.

Observations with HST to obtain light curves in the near IR