

Studying Dark Energy with Supernovae

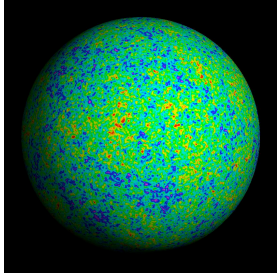
The background of the slide is a composite image. The upper portion shows a galaxy with a bright, multi-colored core (red, purple, blue) and a surrounding dust lane. The lower portion shows a bright, point-like source with a blue-white color and a diffraction pattern, identified as Supernova 1994D.

Marek Kowalski
Physikalisches Institut
Universität Bonn

Supernova 1994D

DESY, Standort Zeuthen
24.3.2010

Content



Introduction: the accelerating Universe

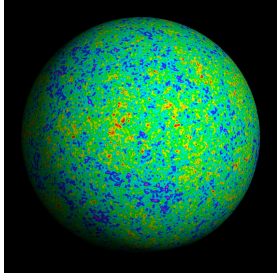


SNe observations & cosmological parameters



Constraints on selected Dark Energy models

Content



Introduction: the accelerating Universe



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

⇒ 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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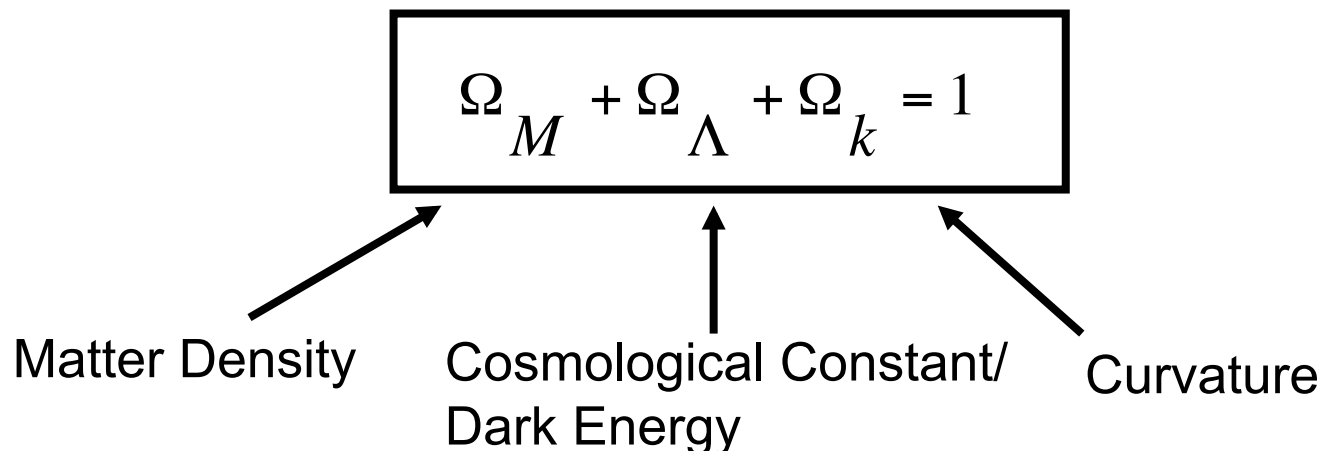
Cosmological Constant/
Dark Energy

Our Cosmological Framework derives from...

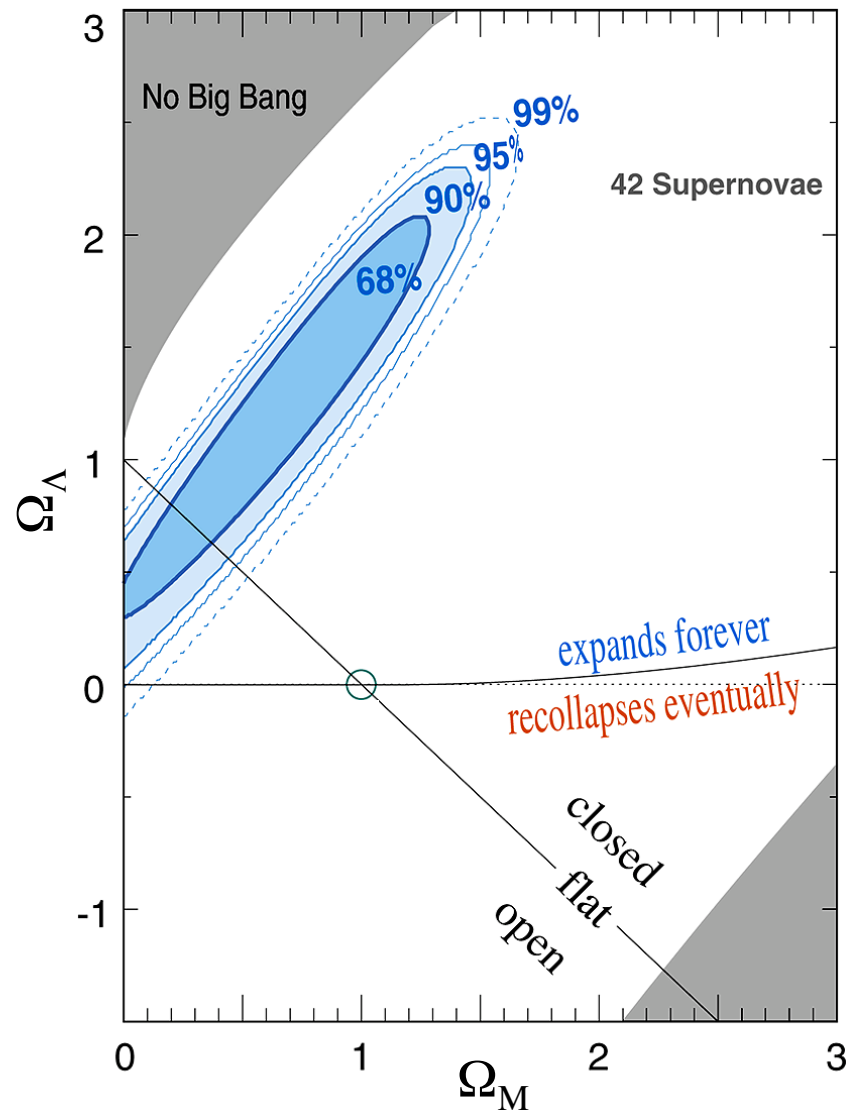
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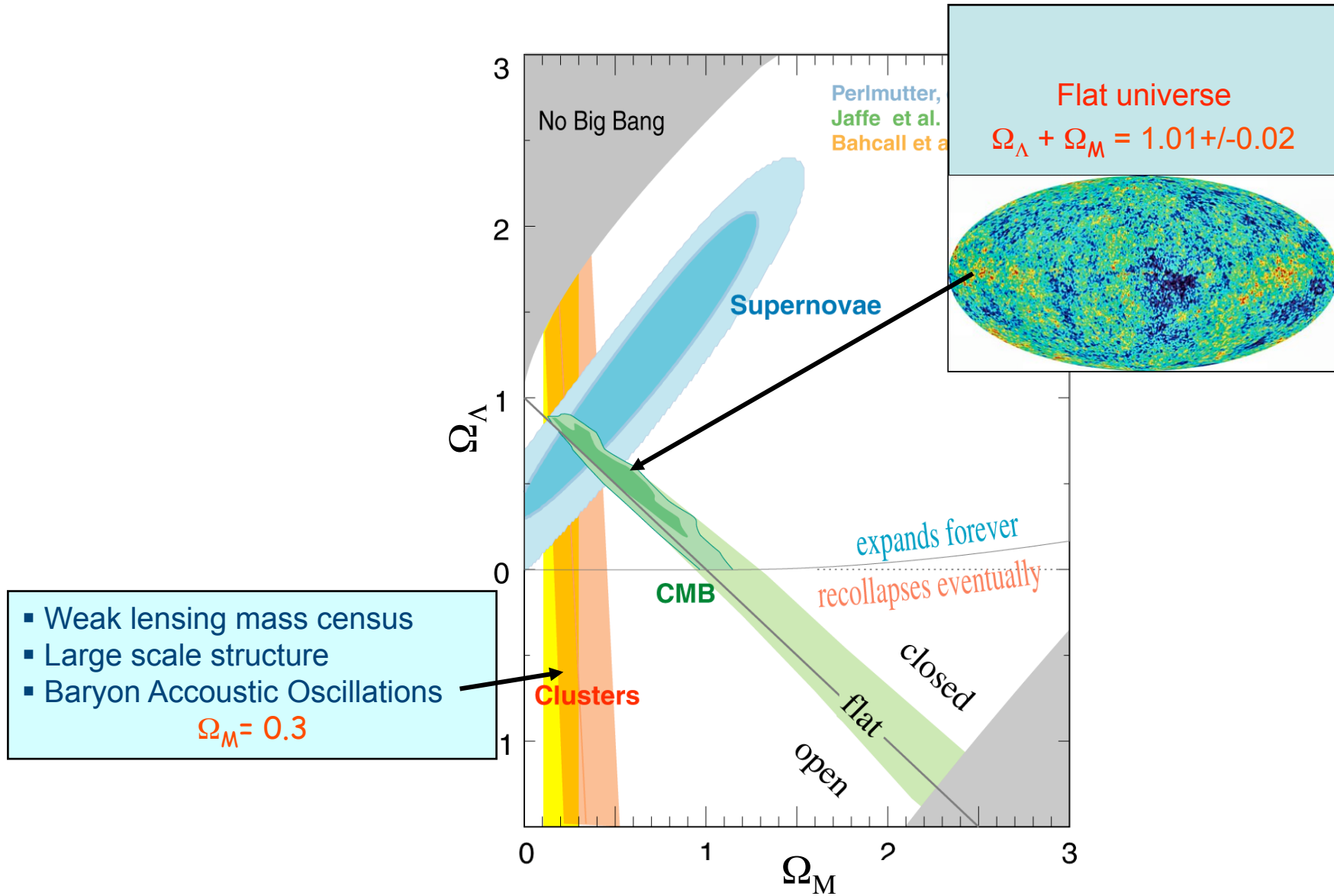
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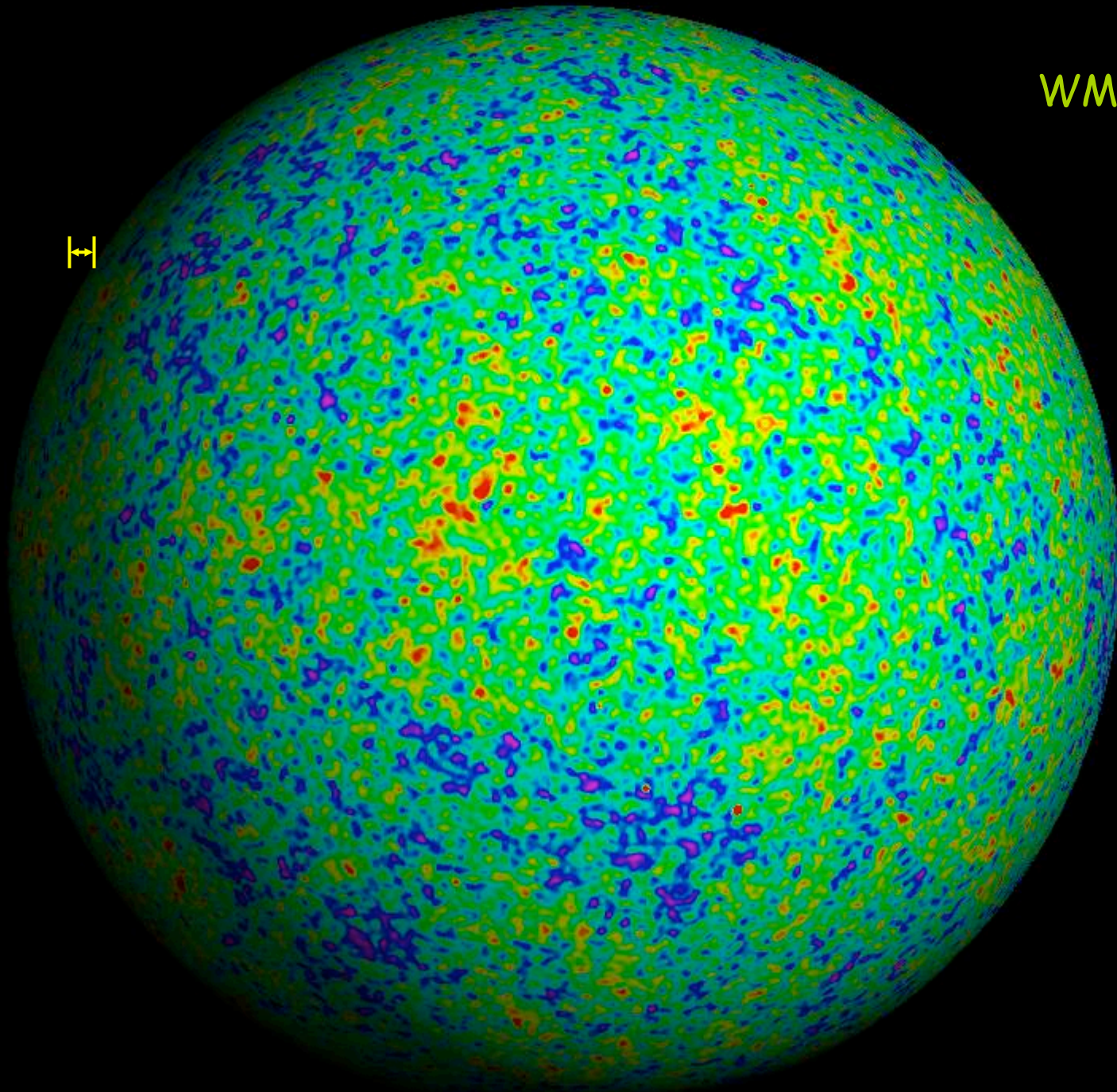
1998: Discovery of Dark Energy



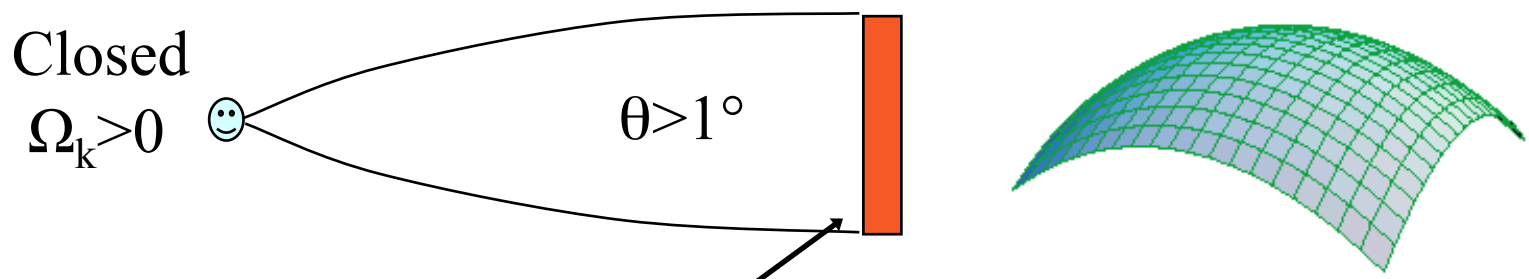
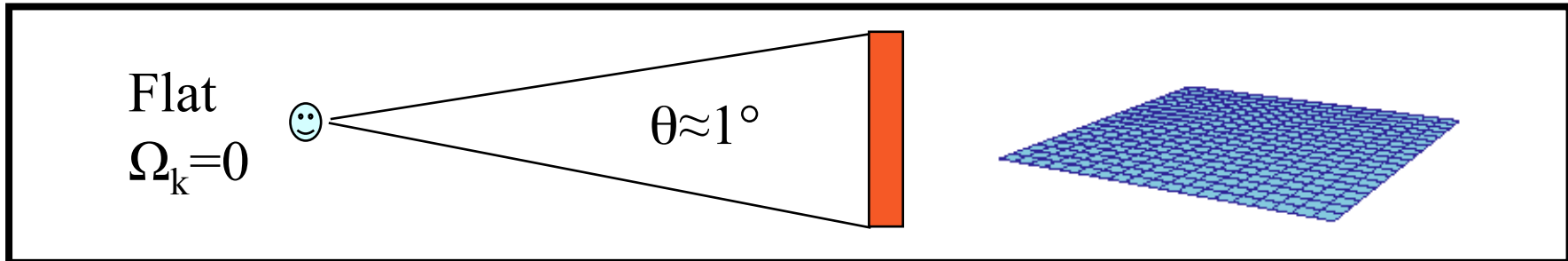
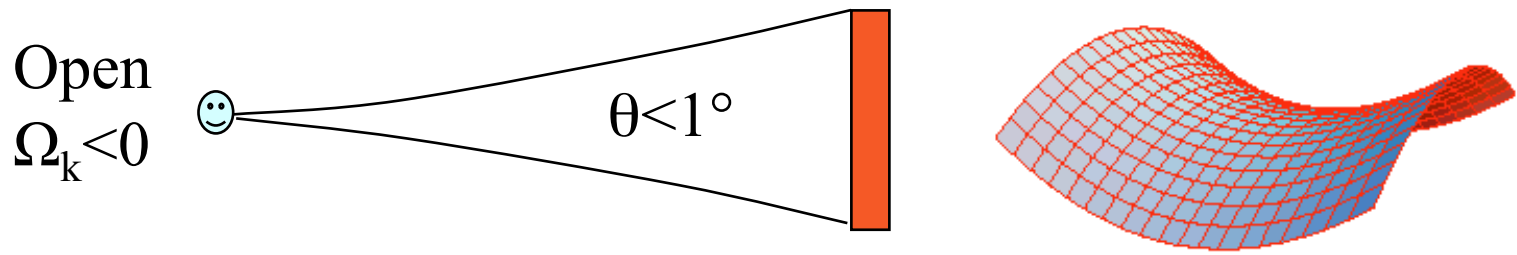
1998: Discovery of Dark Energy



WMAP 2006

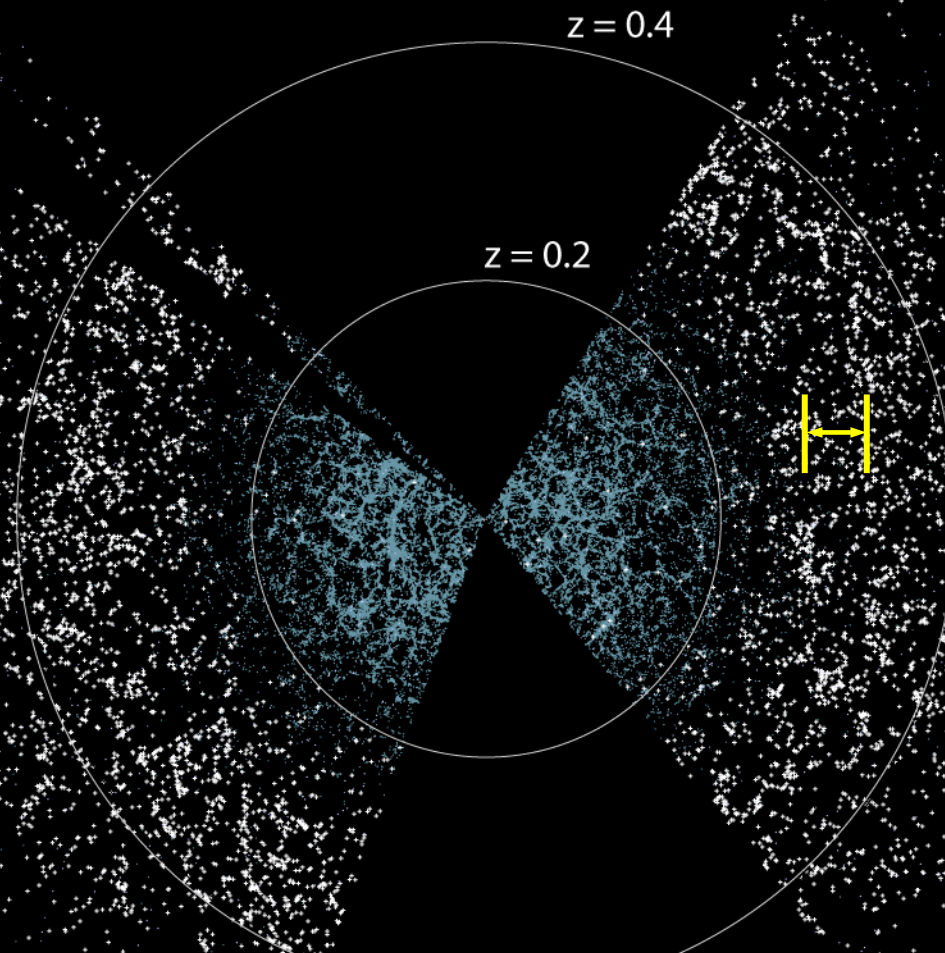


Cosmic Microwave Background (CMB) & Curvature of the Universe



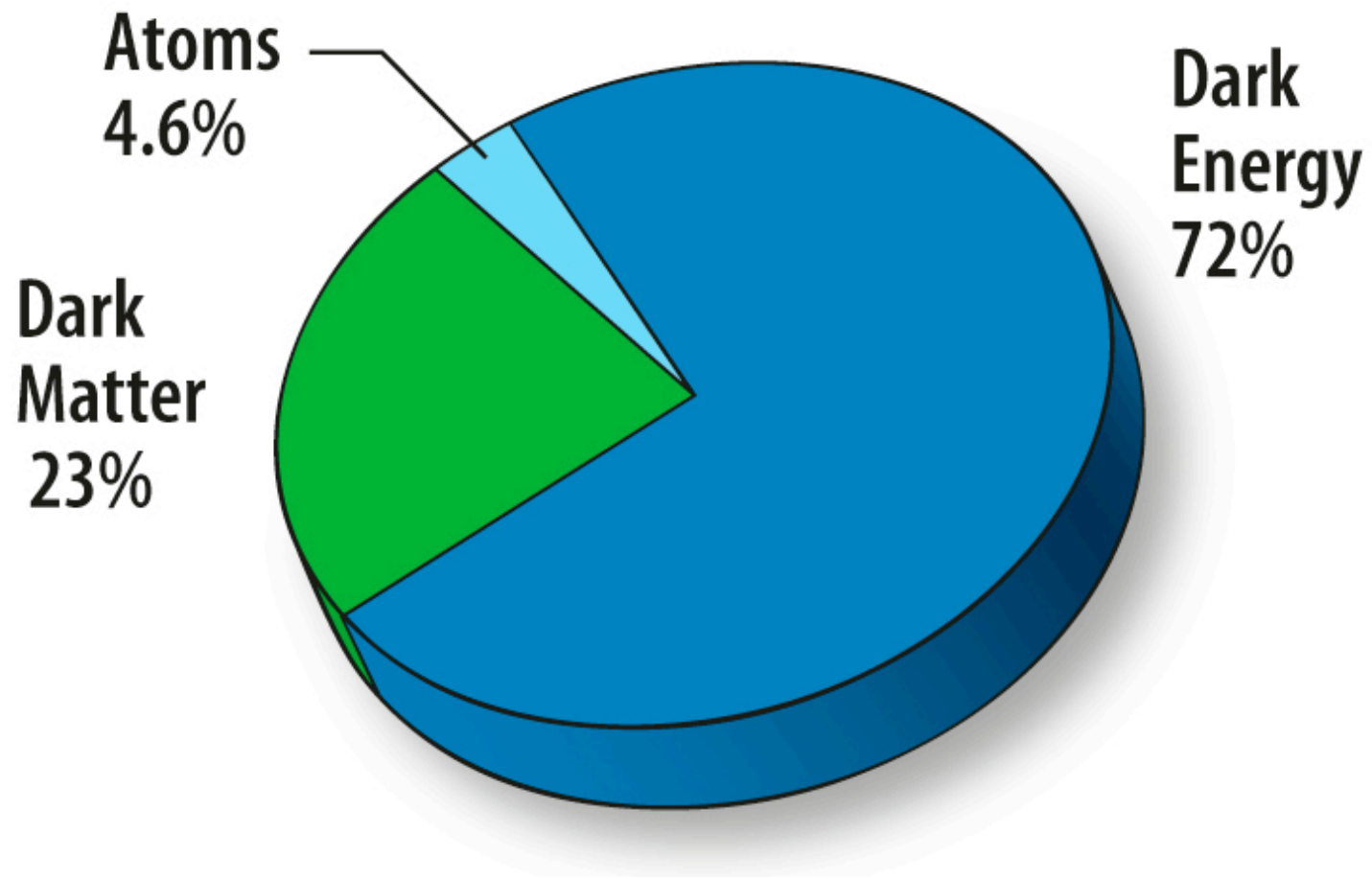
Acoustic horizon $\approx v_s t_{dec}$

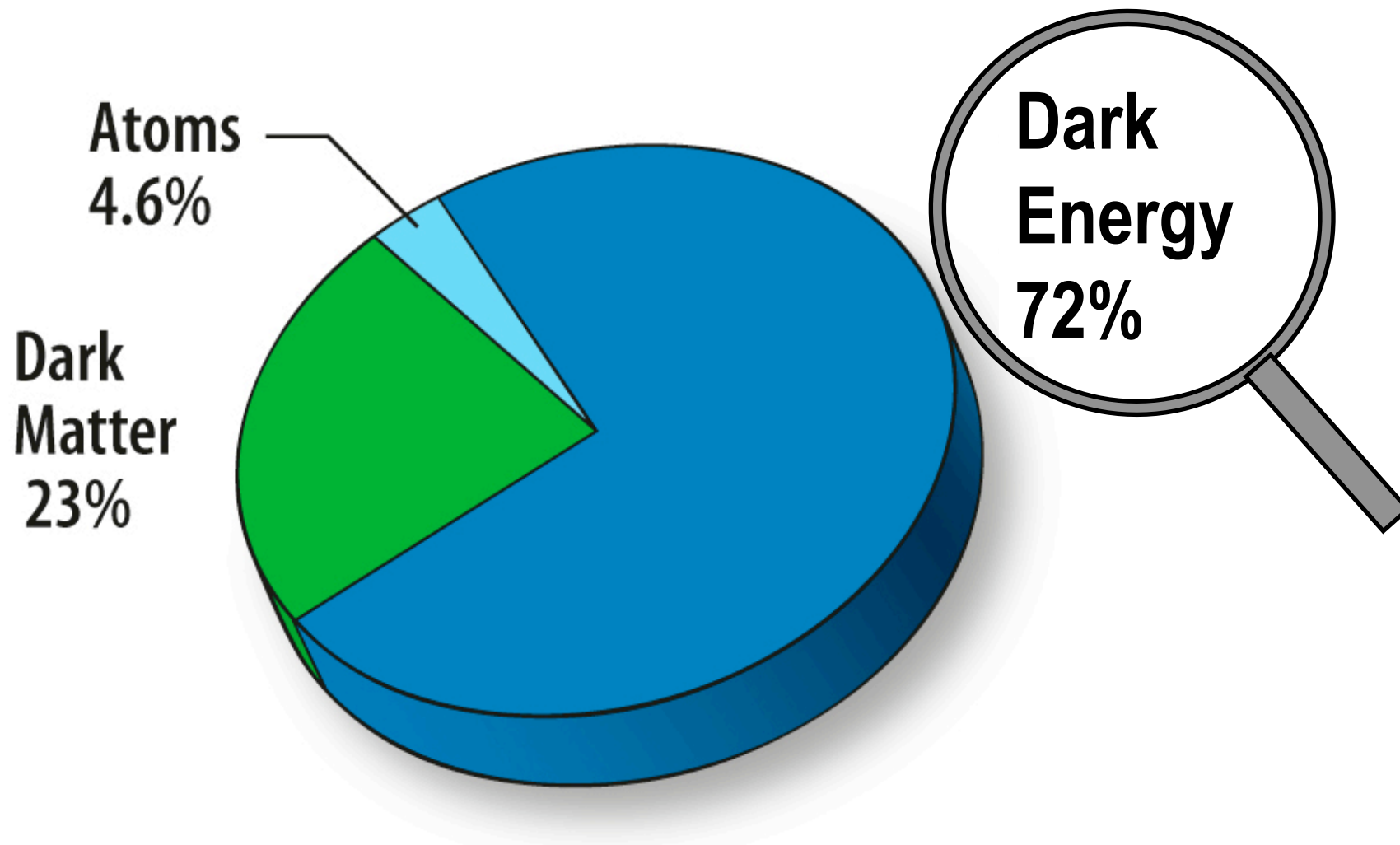
$$\Rightarrow \Omega_M + \Omega_\Lambda = 1 - \Omega_k \approx 1$$



Baryon Acoustic Oscillation (BAO)

SDSS, Eisenstein et al. (2005)

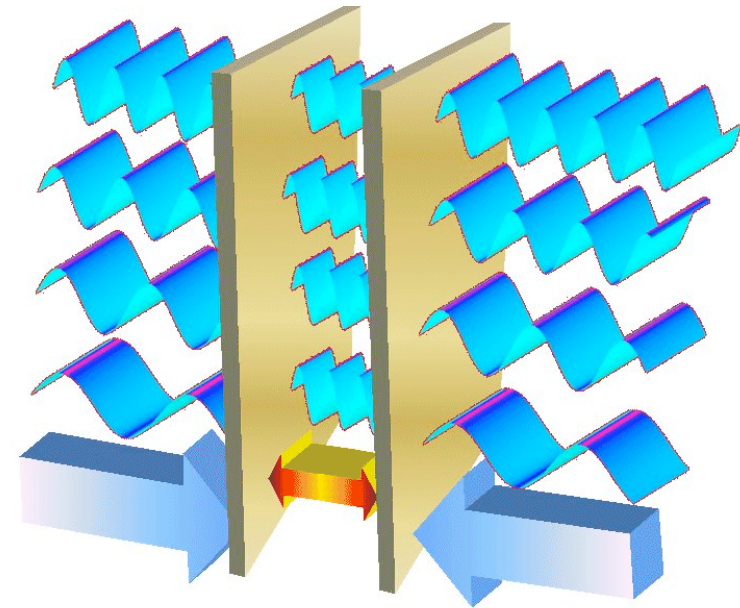




Vacuum Energy

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

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



Casimir effect \Leftrightarrow energy difference

Fundamental Problems of Vacuum Energy/Cosmological Constant:

Why so small?

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

Why now?

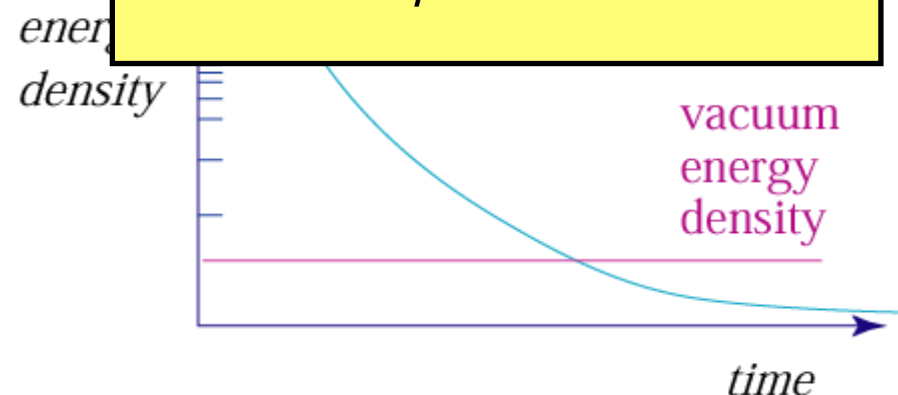
Matter: $\rho \propto R^{-3}$
Vakuum Energy: $\rho = \text{constant}$

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:

$$w_M = 0 \text{ (matter)}$$

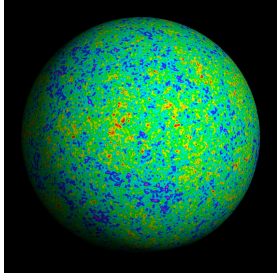
$$w_R = 1/3 \text{ (radiation)}$$

$$w_\Lambda = -1 \text{ (cosmological constant)}$$

$$w_Q > -1 \text{ (quintessence)}$$

$$w_s = -1/3 \text{ (cosmic strings)}$$

Content



Introduction: the accelerating Universe

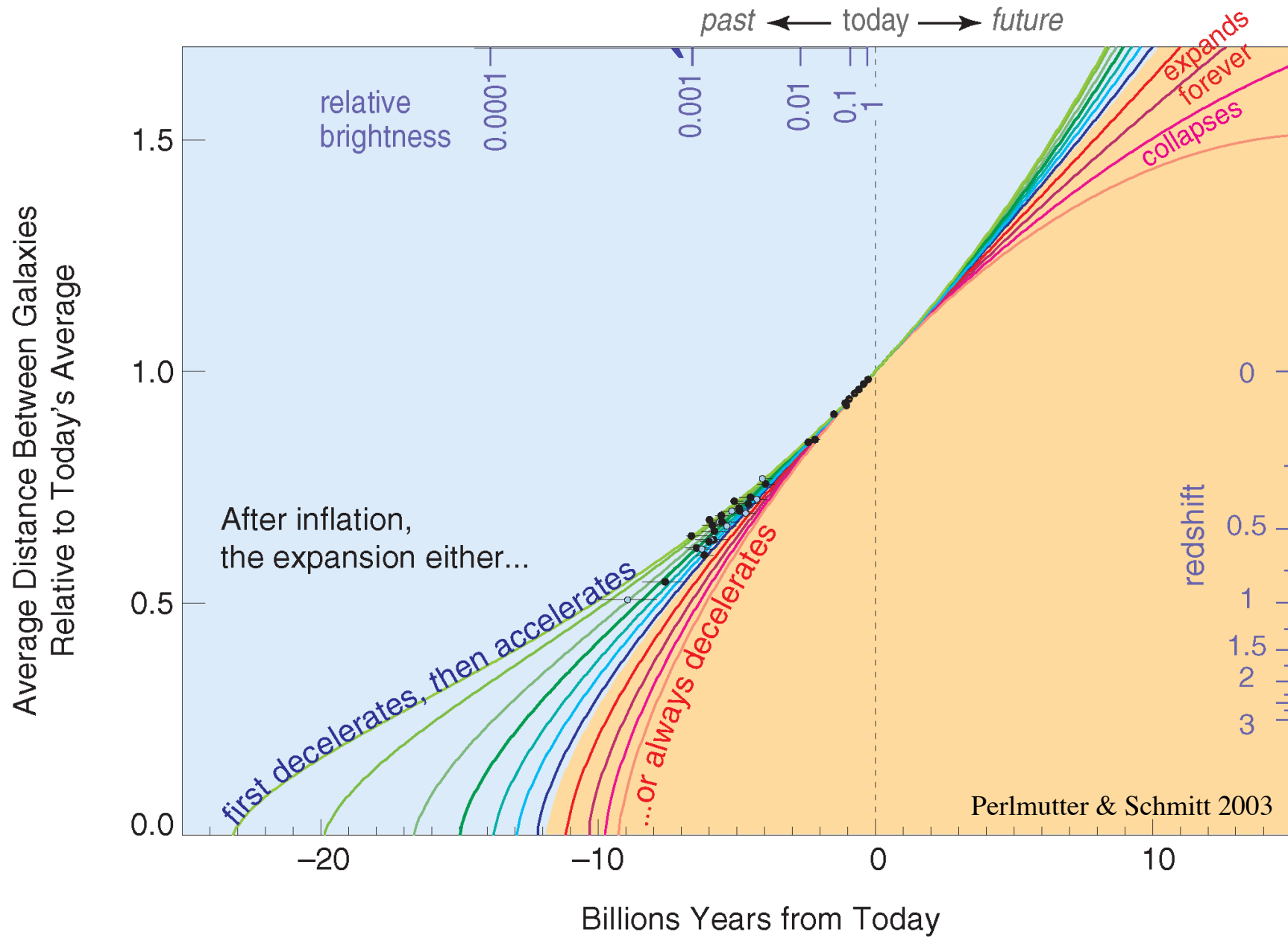


SNe observations & cosmological parameters



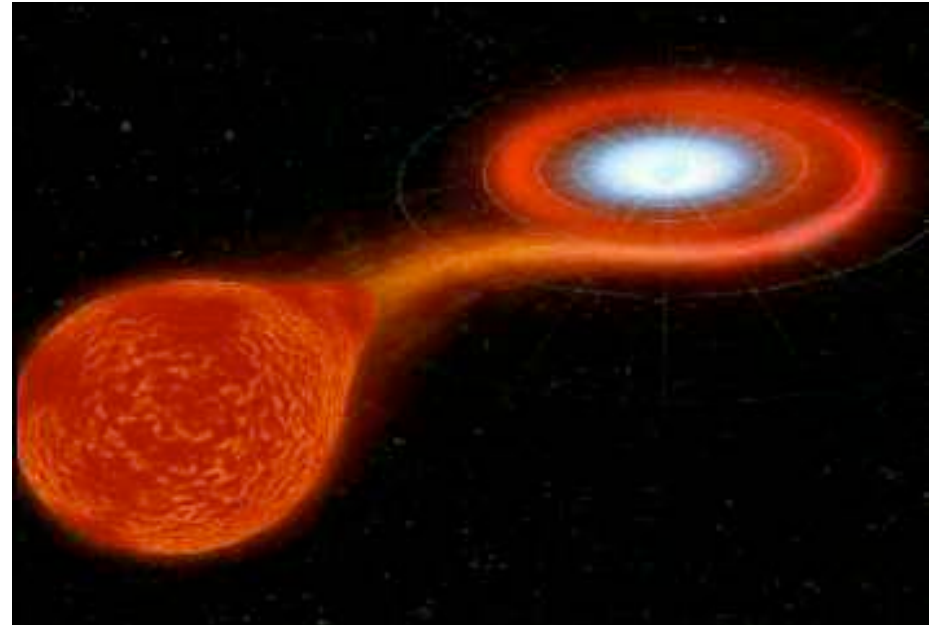
Constraints on selected Dark Energy models

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

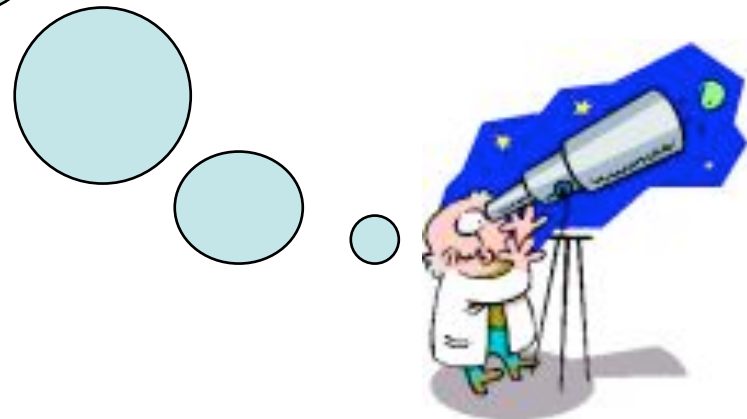


Astronomers think in...

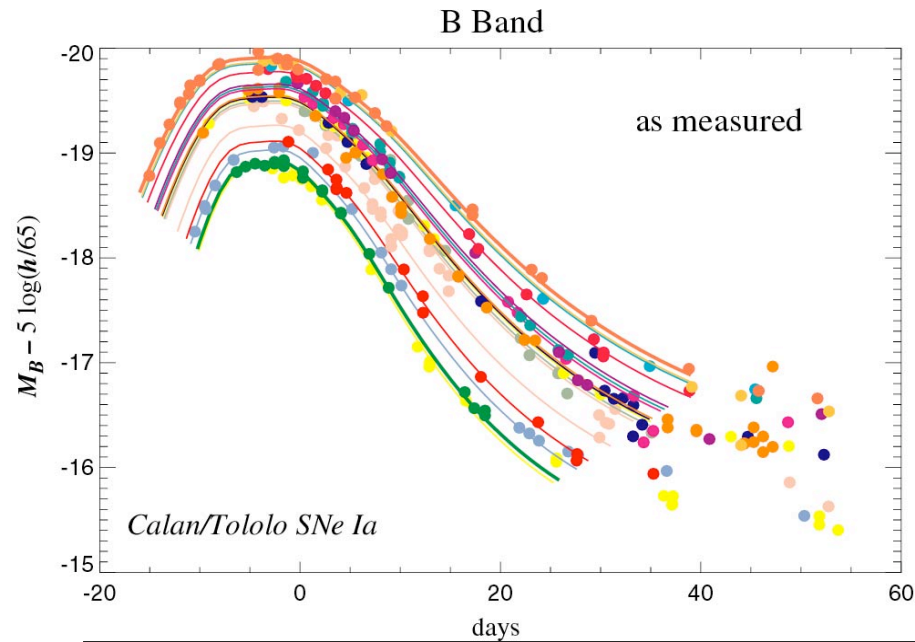
Magnitudes:

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

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



“Standard candles”



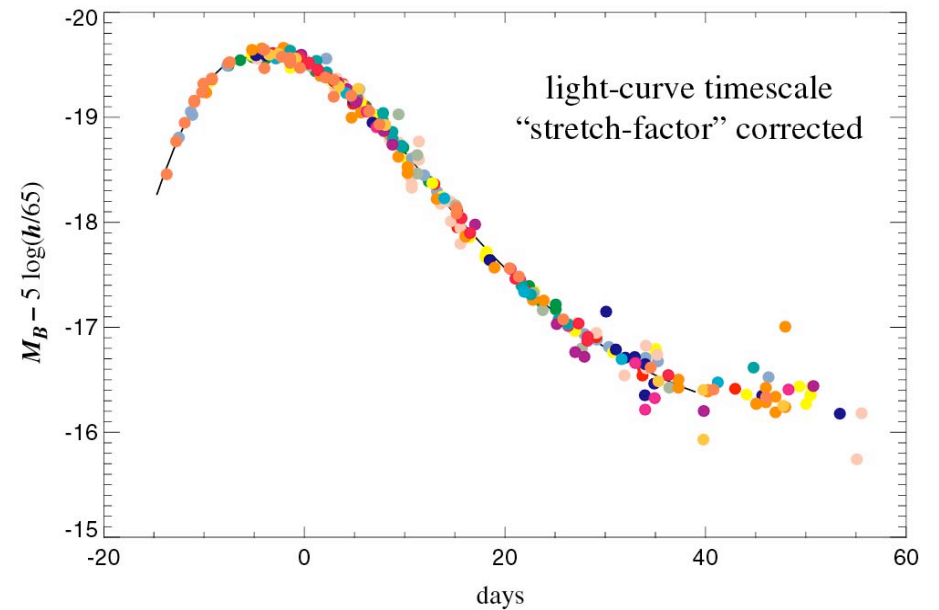
- Brightness not the same for all SNe
- Brighter SNe have wider light curves.

“Stretching” of time scale:

$$t' = s \times t$$

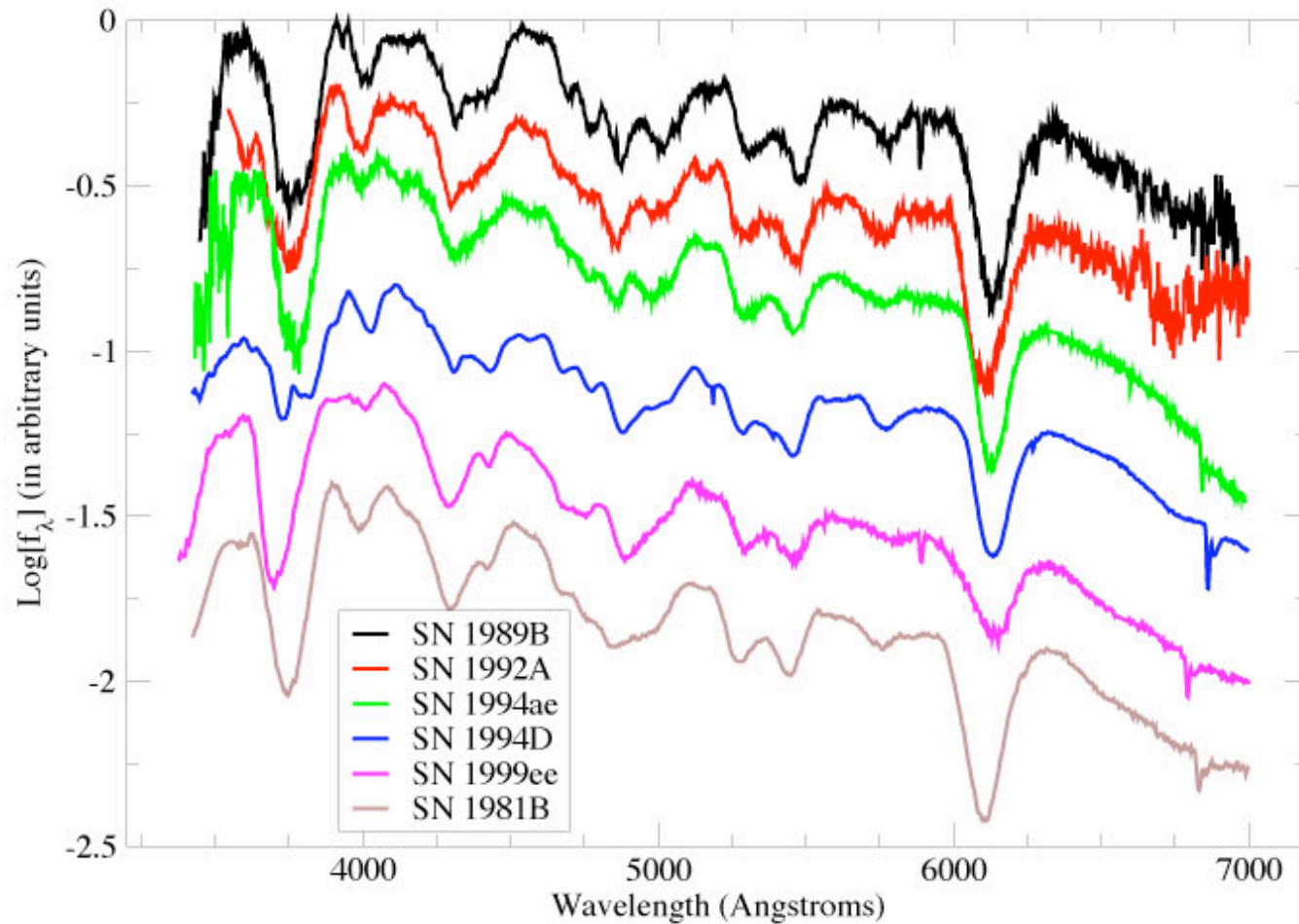
Brightness correction:

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

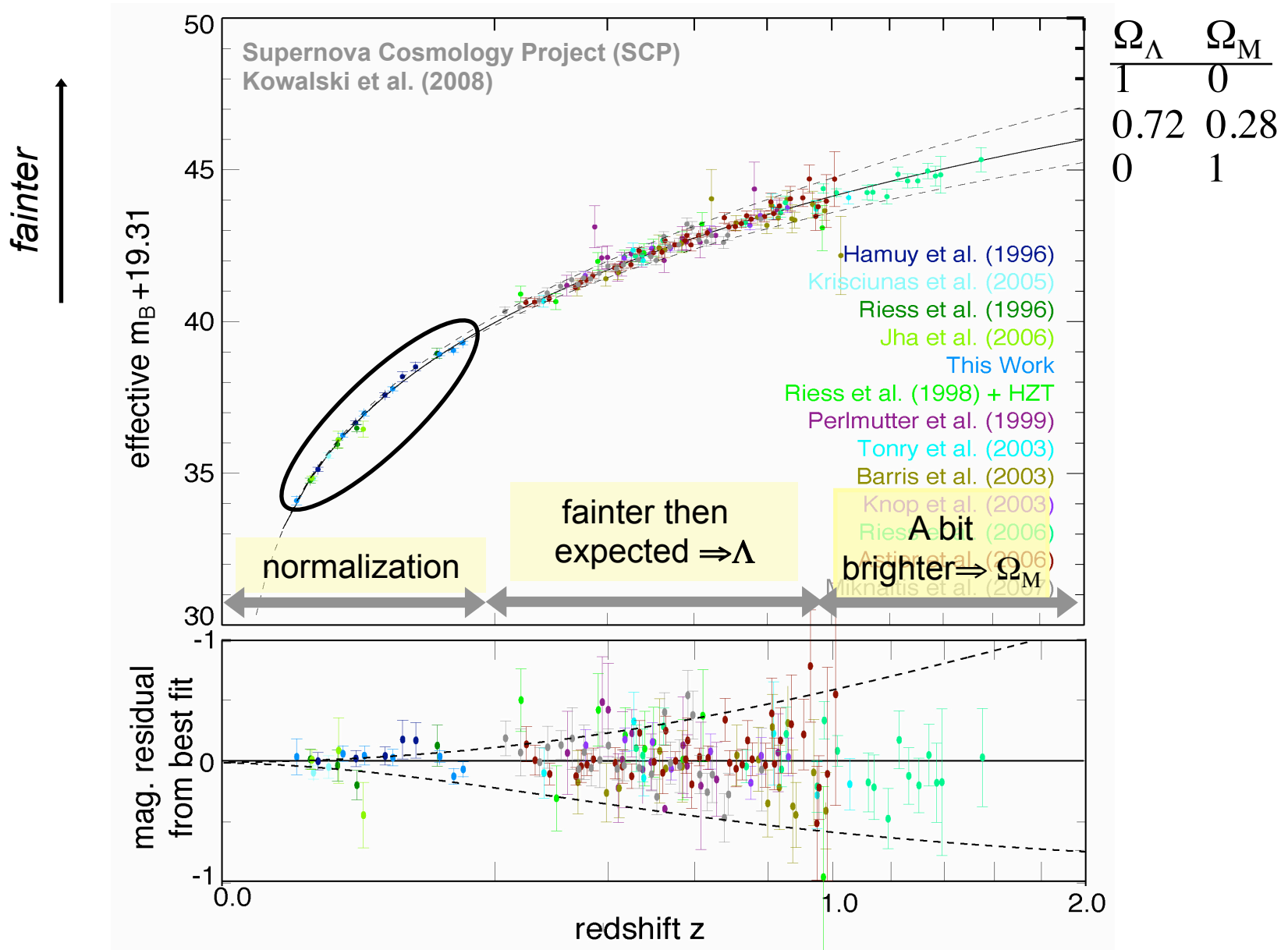


Kim, et al. (1997)

Spectra for identification and redshift determination



SNe Ia Hubble Diagram



Supernova Factory



(artist's concept)

Supernova Factory Collaboration:

Lawrence Berkeley National Lab

Laboratoire de Physique Nucleaire et de Haute Energies de Paris

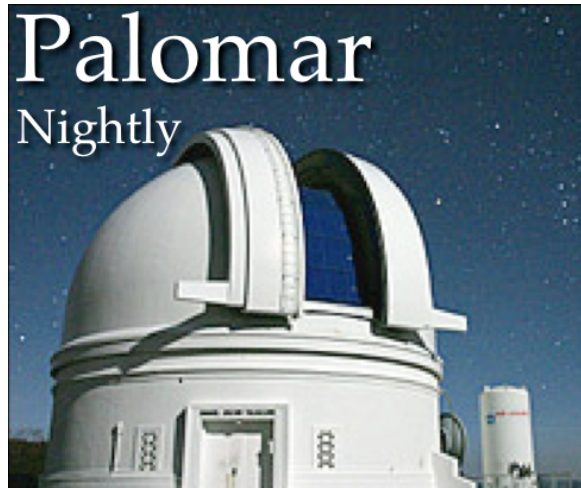
Institut de Physique Nucleaire de Lyon

Centre de Recherche Astronomy de Lyon

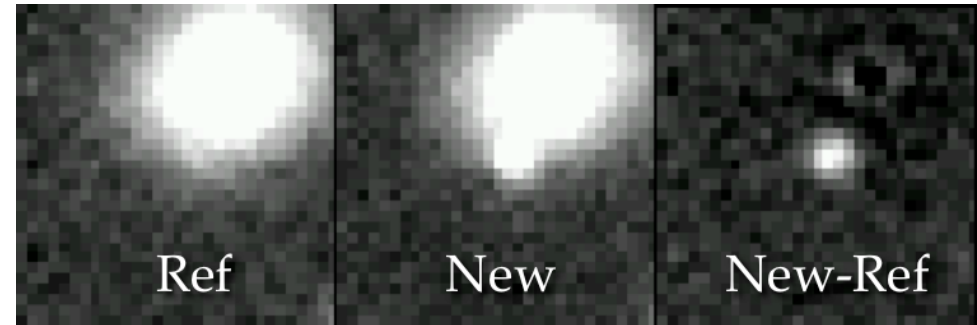
Yale University

Bonn University

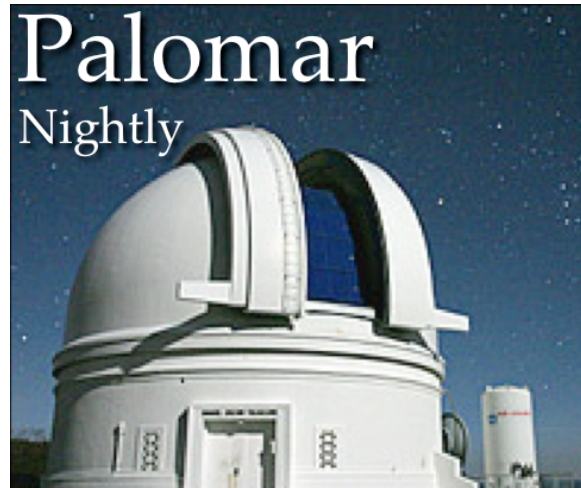
SNfactory: producing unique nearby SNe data



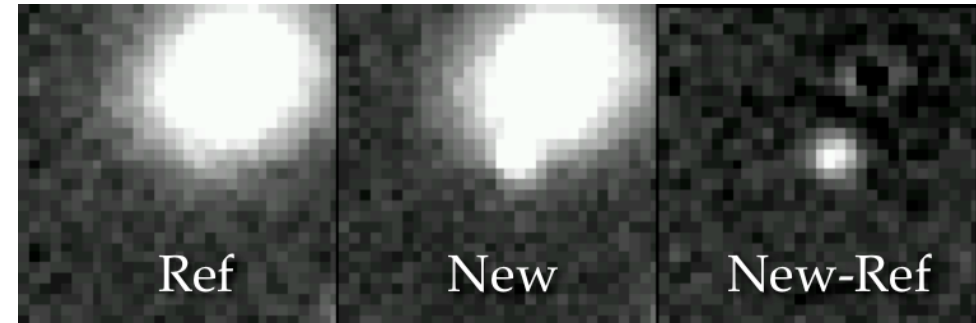
1. Discover



SNfactory: producing unique nearby SNe data



1. Discover

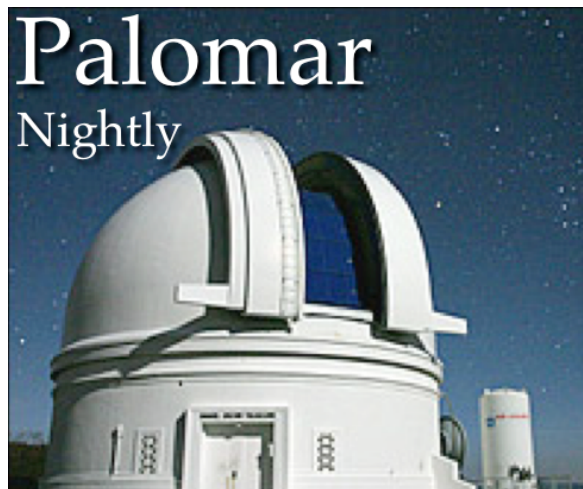


2. Observe

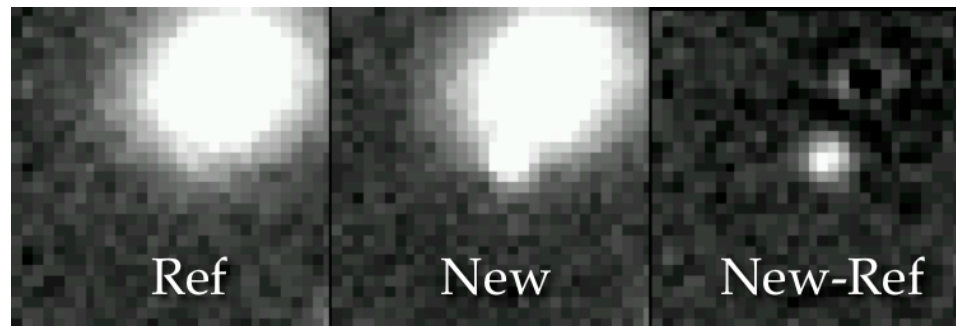


SNIFS: Custom spectrograph for nearby SN observations

SNfactory: producing unique nearby SNe data



1. Discover

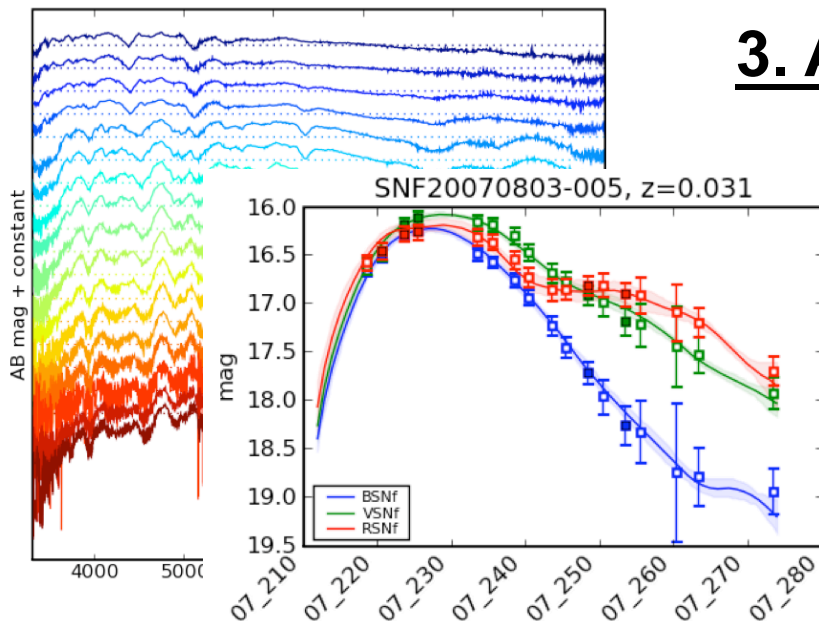


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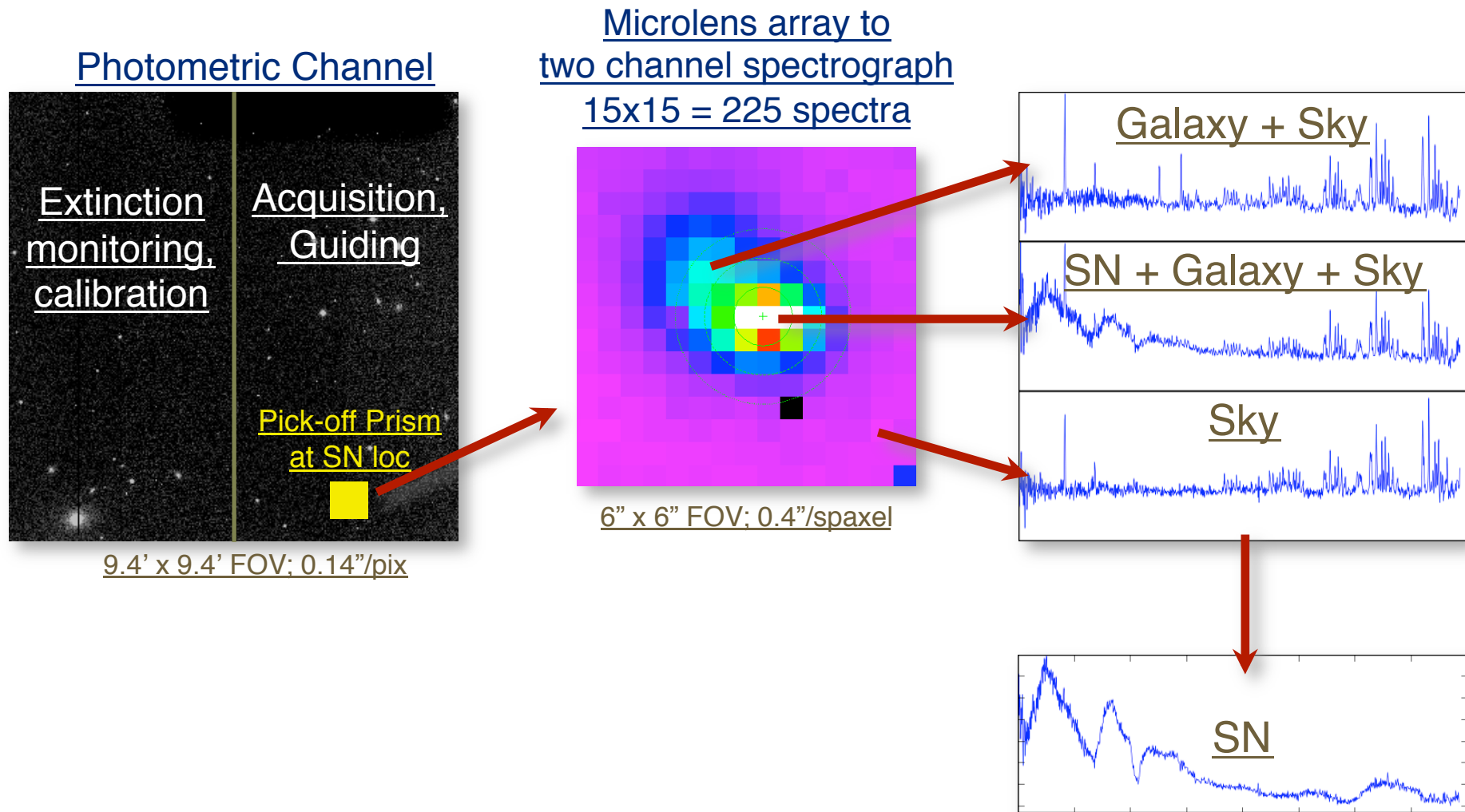


SNIFS: Custom spectrograph for nearby SN observations

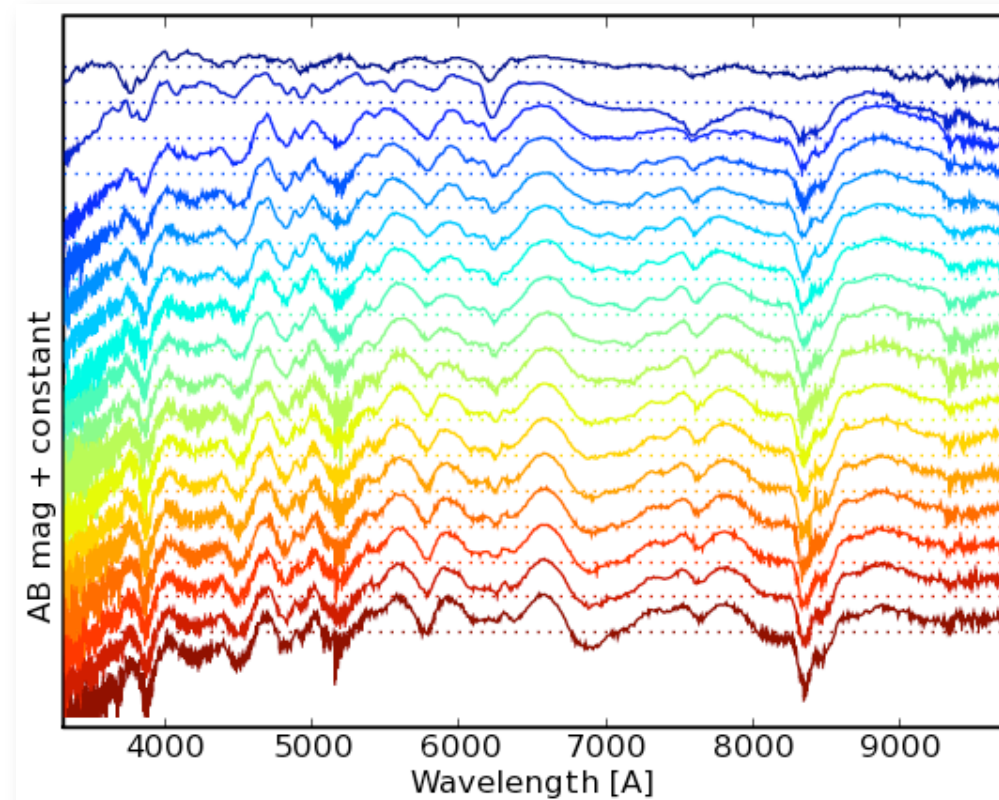
3. Analyses



SuperNova Integral Field Spectrograph (SNIFS)

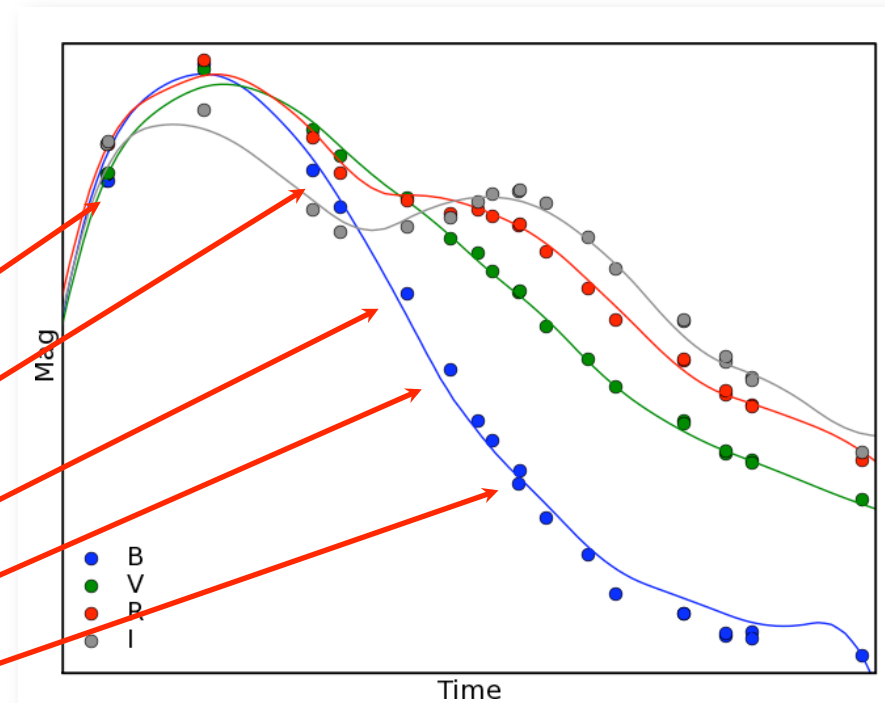
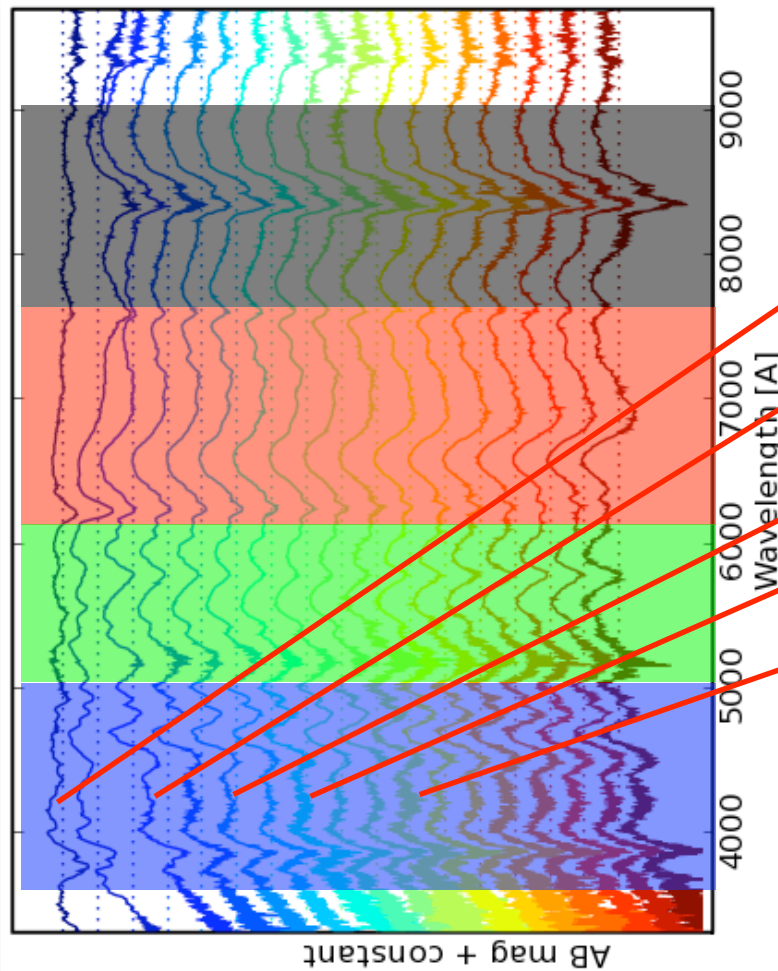


From Spectra to Lightcurves



Slides: Rui Pereira

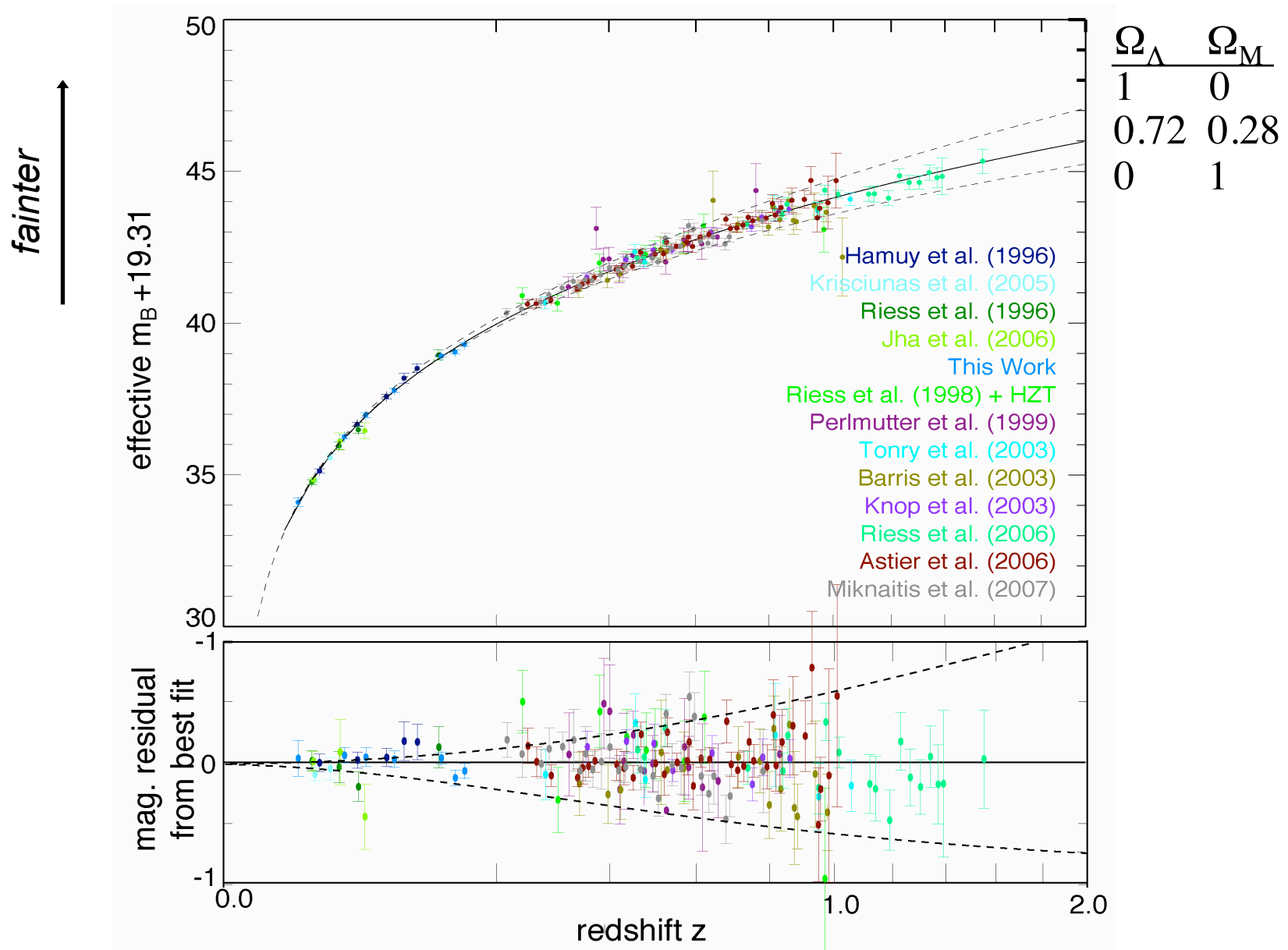
From Spectra to Lightcurves



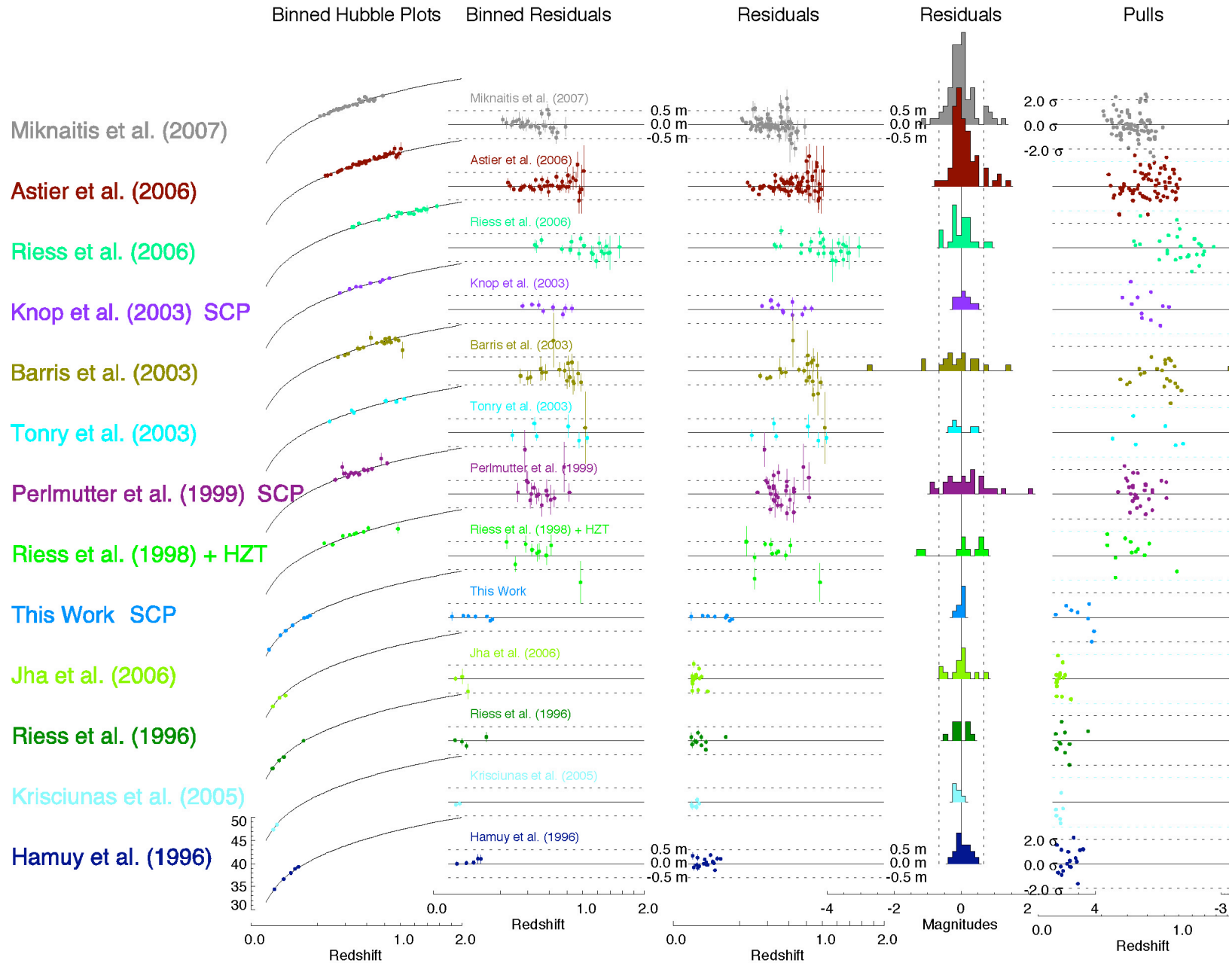
- One spectrum per point / night
- Synthesizable in any filter
- Lightcurves + spectral features

Slides: Rui Pereira

The Union SNe Compilation

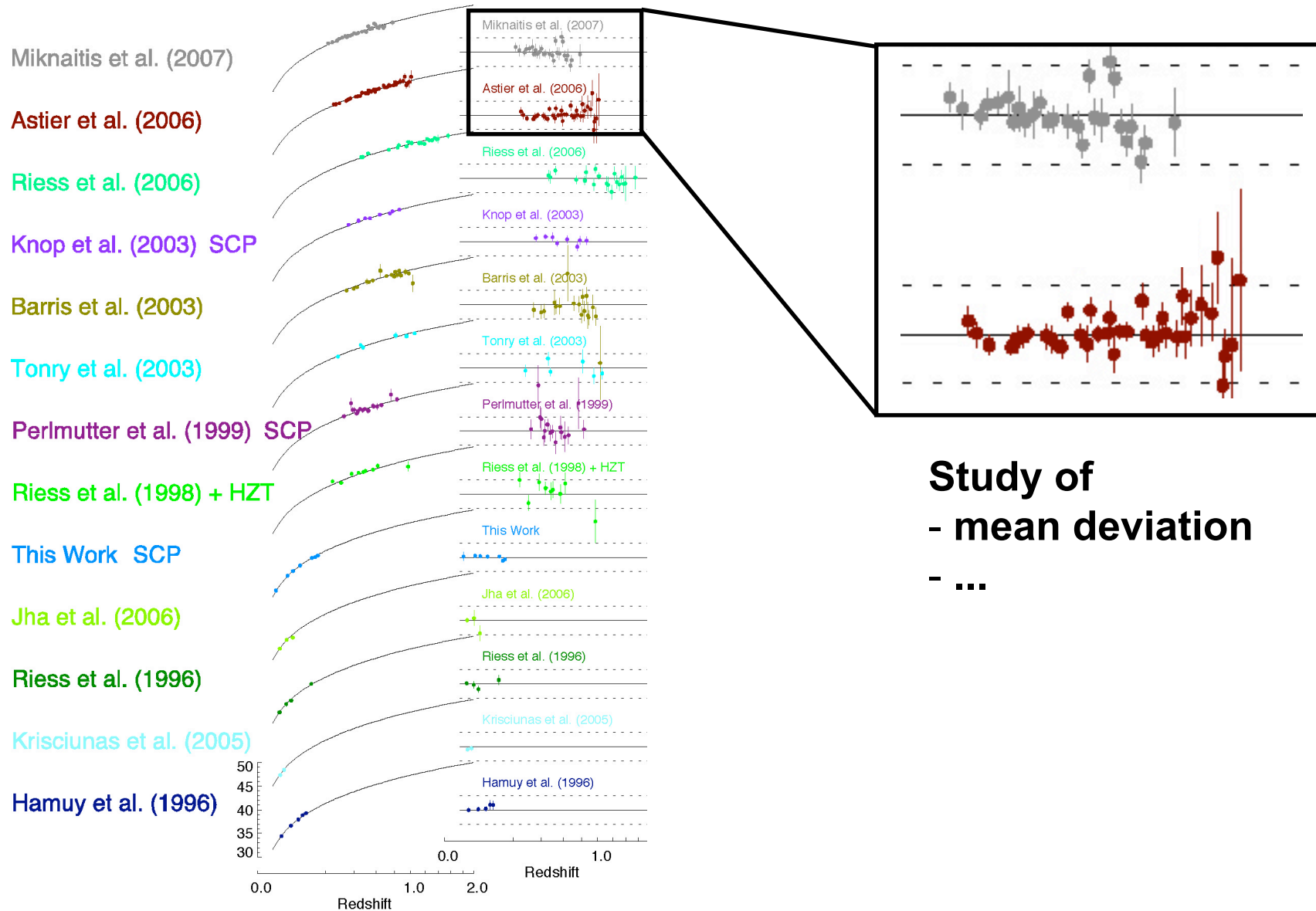


A heterogenous data sample

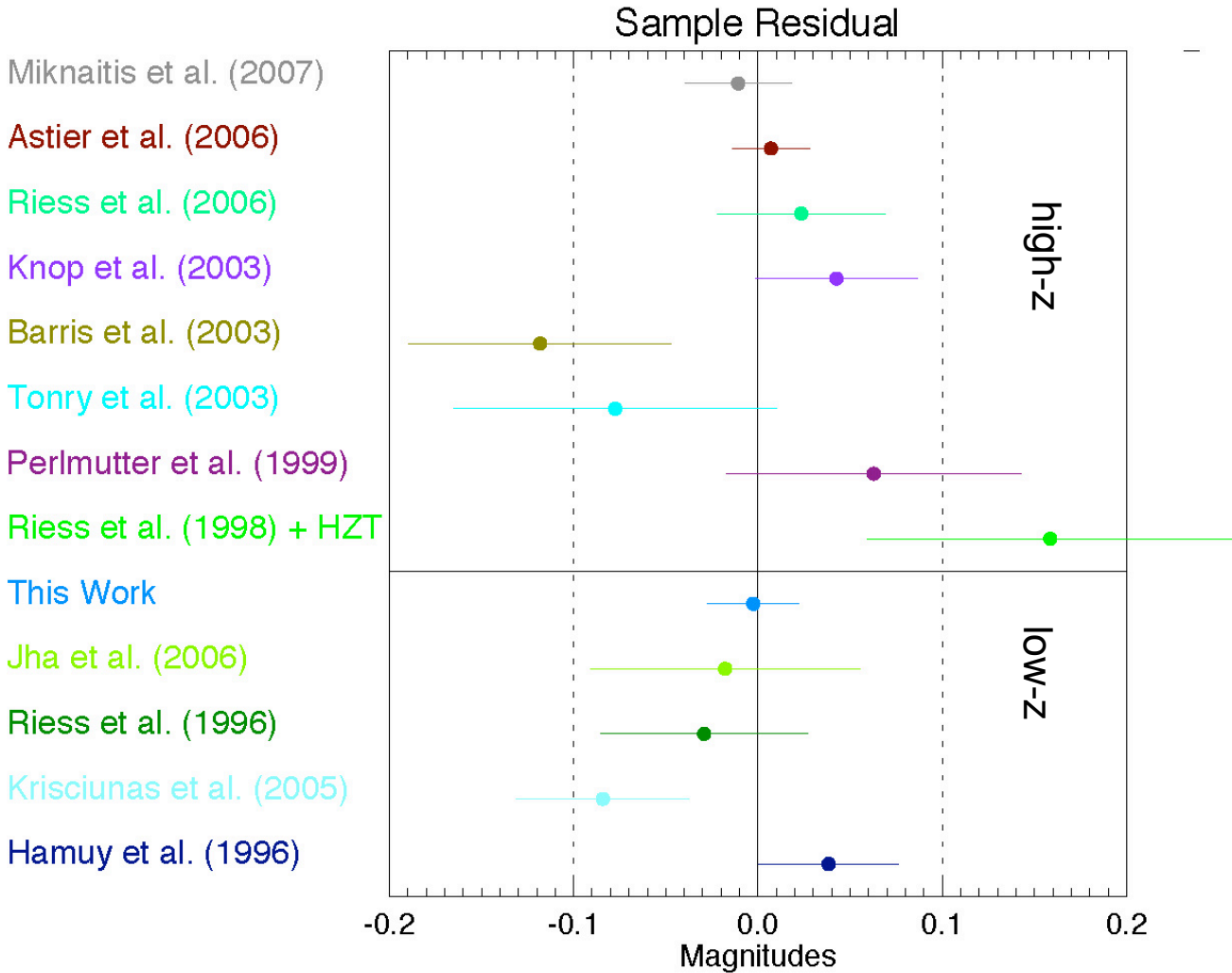


A heterogenous data sample

Binned Hubble Plots Binned Residuals

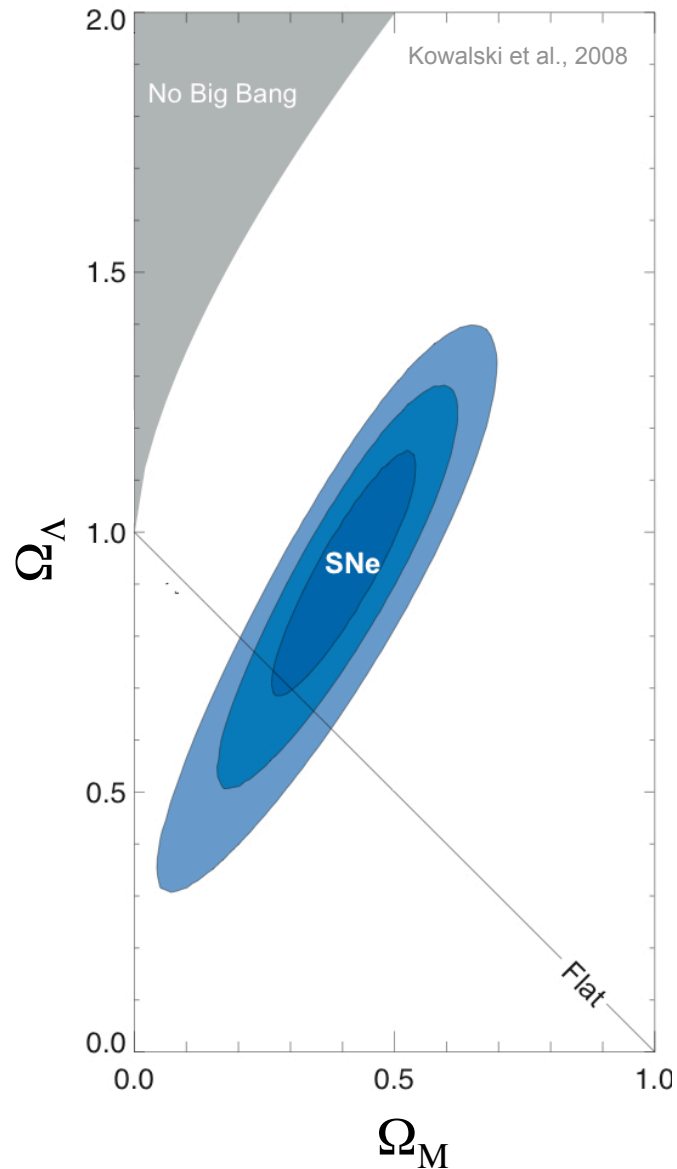


Test for Tension

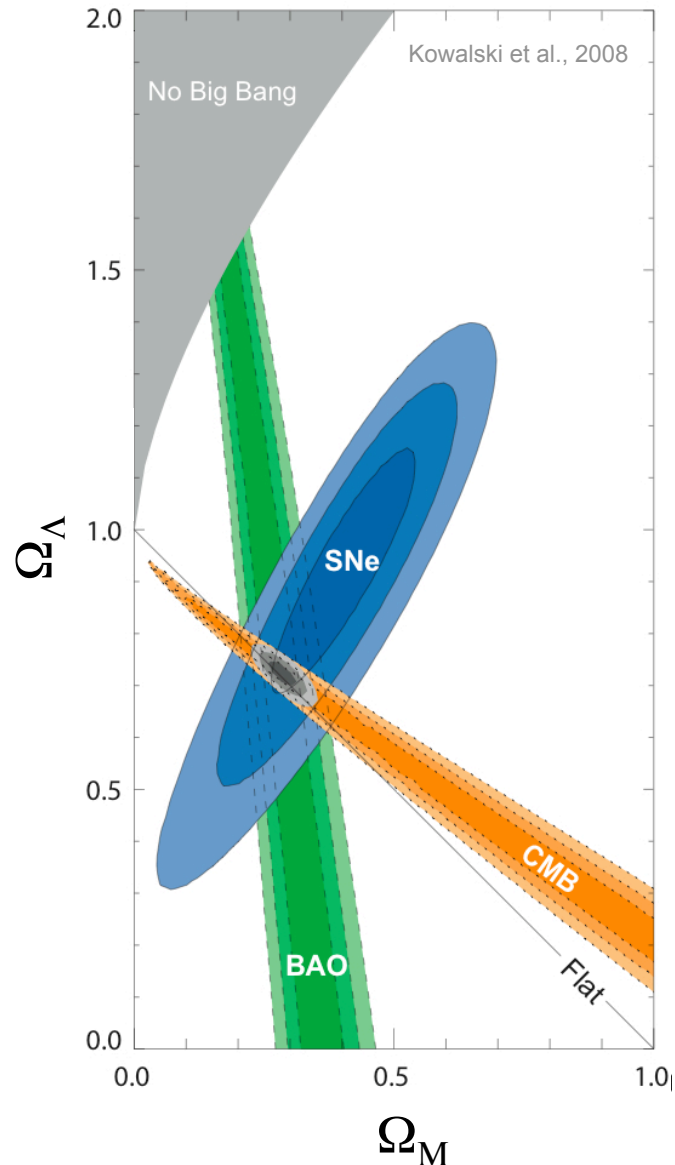


mean deviation: **OK**

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:

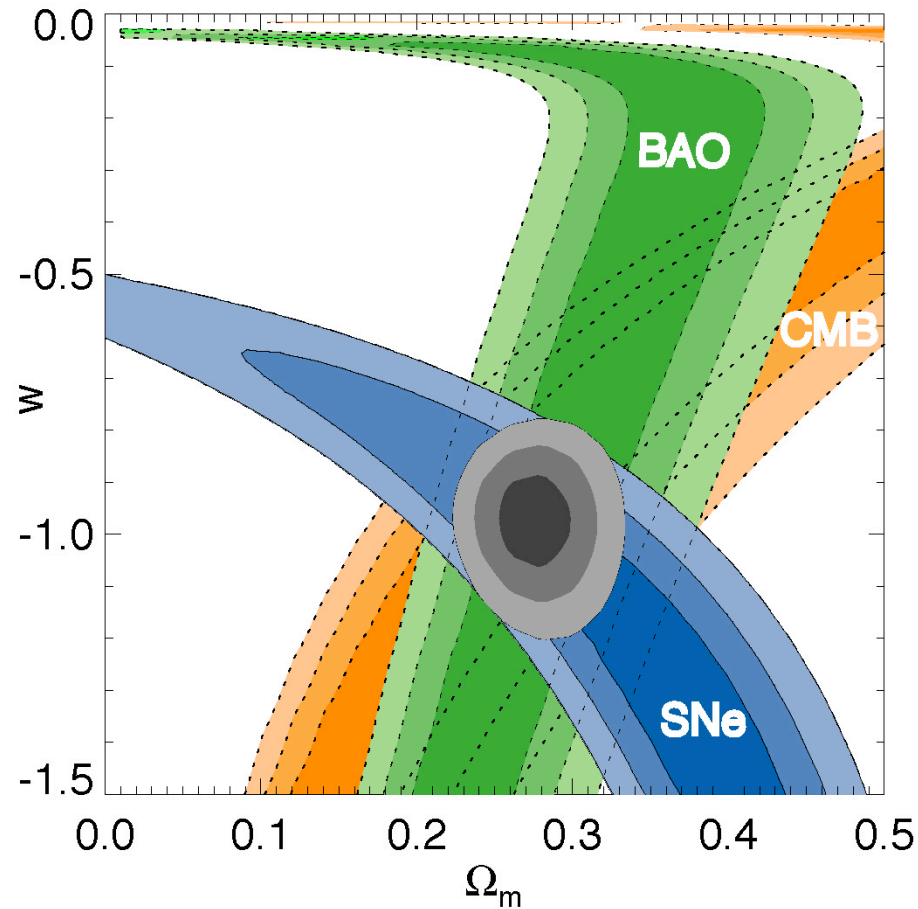
$$\Omega_m = 0.274 \pm 0.016(\text{stat}) \pm 0.012(\text{sys})$$

... and with curvature:

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

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

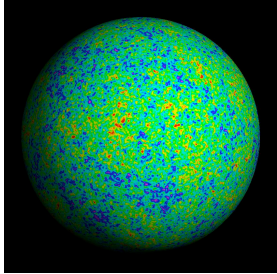
Equation of state: $w=p/\rho$



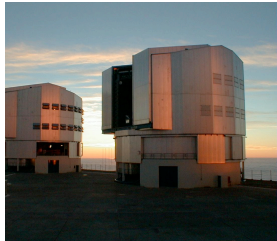
$$w = -0.97 \pm 0.06(\text{stat}) \pm 0.06(\text{sys}) ; k = 0$$

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

Content



Introduction: the accelerating Universe



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

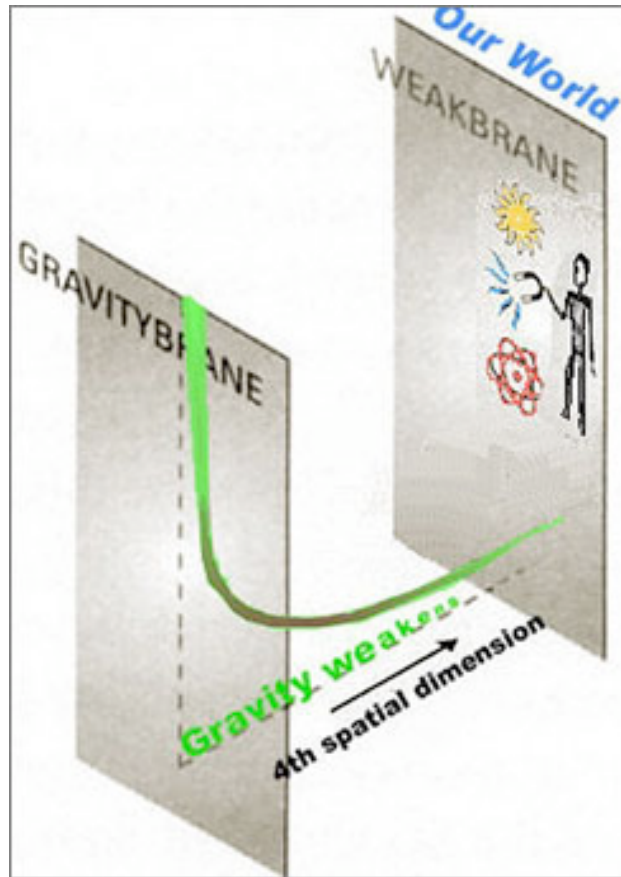
2. Quintessence (dynamic)

- + 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

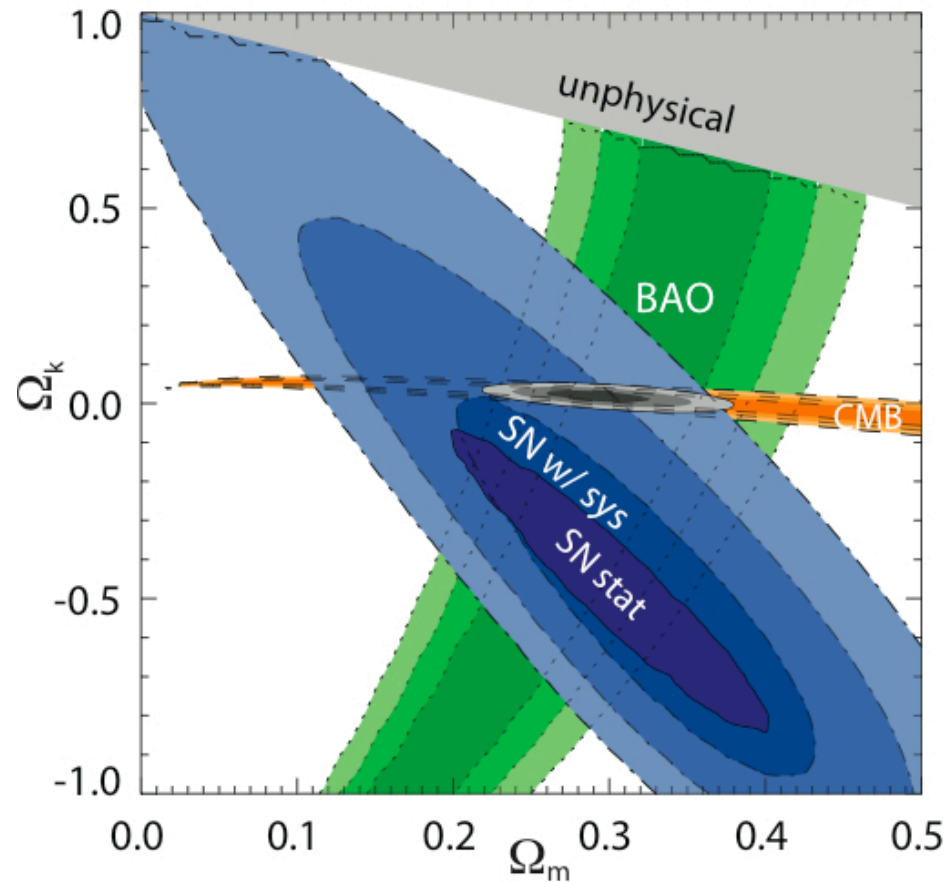
Arkani-Hamed, Dimopoulos, Dvali

...and will weaken Gravity
at large distances

(Dvali, Gabadadze, Porrati - DGP)

⇒ **apparent acceleration**

Braneworld Cosmology



DGP-model versus Λ CDM

Without systematic: $\Delta \chi^2_{\text{stat}} = 16.1$

With systematic: $\Delta \chi^2_{\text{sys}} = 4.0$

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

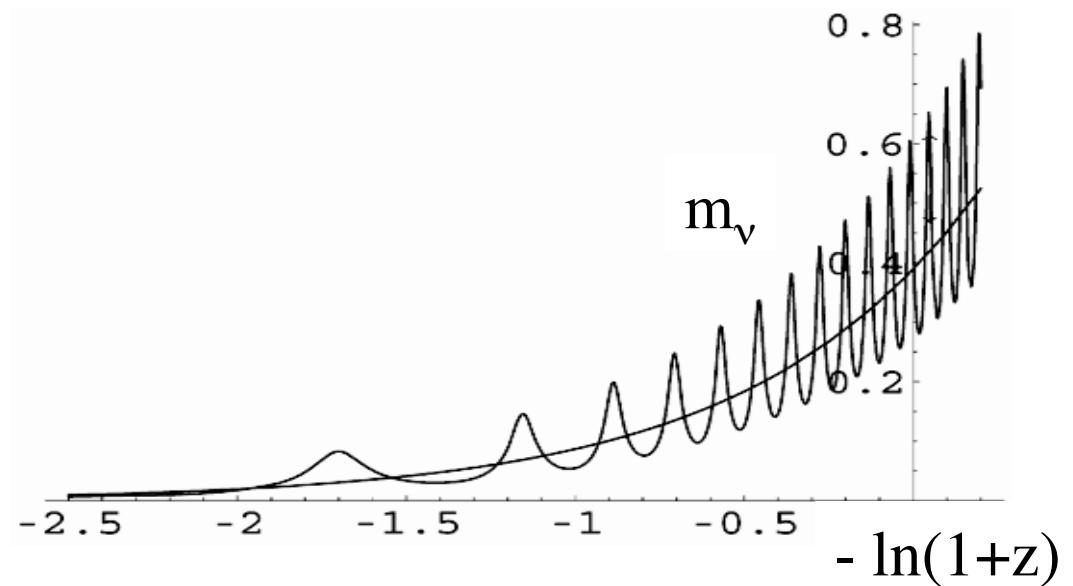
Quintessence Example: Growing Neutrinos

Scalar field couples to massive neutrinos

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

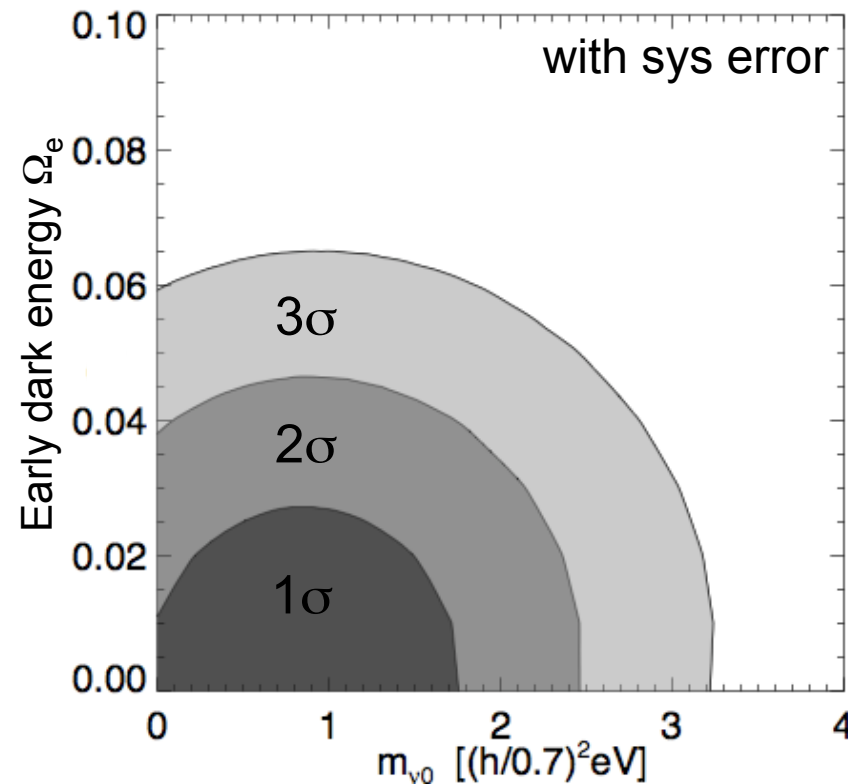
Today: Massive neutrinos and deviation from $w = -1$

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



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

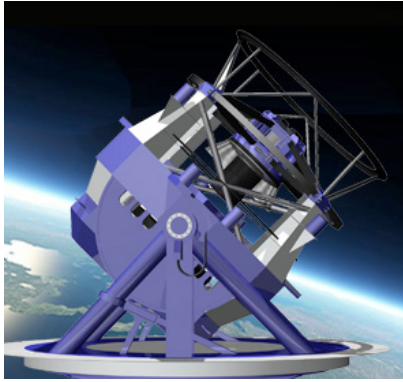
Quintessence Example: Growing Neutrinos



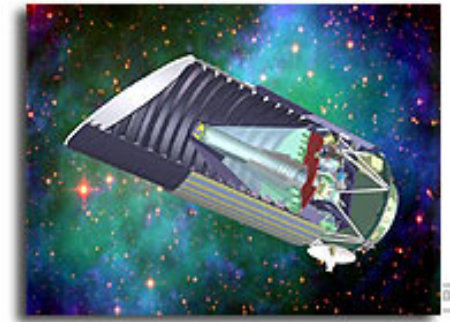
Lab constraints:
 $m_{\nu} \leq 2 \text{ eV}$
KATRIN sensitivity:
 $m_{\nu} \leq 0.2 \text{ eV}$
 ν -oscillations:
 $m_{\nu} \geq 0.05 \text{ eV}$

$m_{\nu} < 1.2 (h/0.7)^2 \text{ eV}$ @ 95 CL stat error only
 $m_{\nu} < 2.1 (h/0.7)^2 \text{ eV}$ @ 95 CL with sys error

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



Future projects for Dark Energy

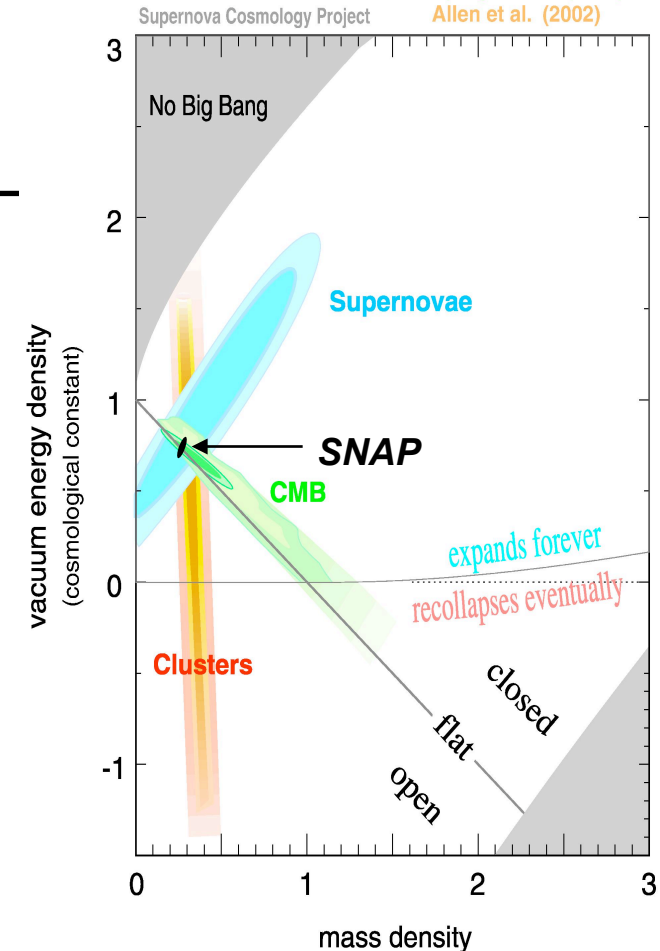


Knop et al. (submitted)
Spergel et al. (2003)
Allen et al. (2002)

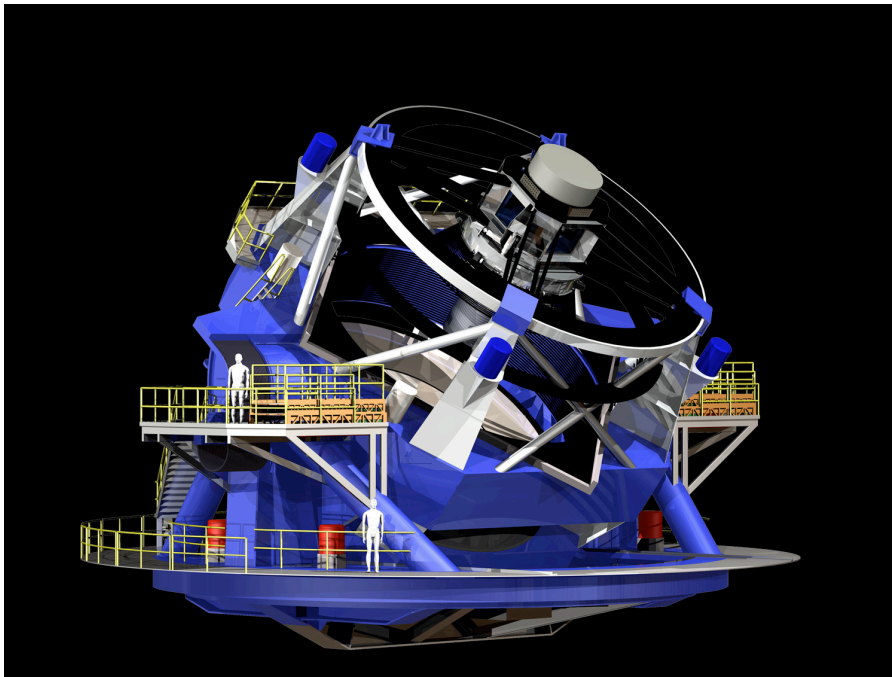
Projekt	z range	# SNe
Pan-STARRS	0.1-0.5	$\sim 10^4$
DES (2011)	0.2-0.7	$\sim 2 \times 10^3$
LSST (2015)	0.1-0.9	$\sim 10^6$
SNAP (2017)	0.2-3.0	$\sim 3 \times 10^3$
(JDEM/Euclid)		

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
built at Cerron Panchon, Chile

Camera (lead by SLAC):

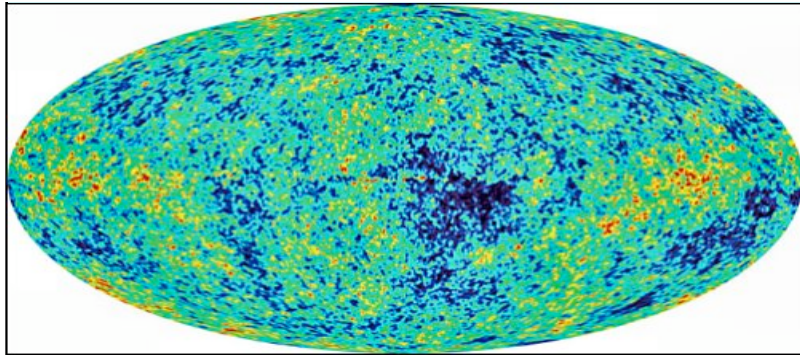
- 3.5° Field of View
- 3×10^9 pixels
- 10 s exposures
- 30 TB data per night
- Full survey of sky every 4 days
- First light 2015

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 mechanisms and a new generation of observatories will provide the data.



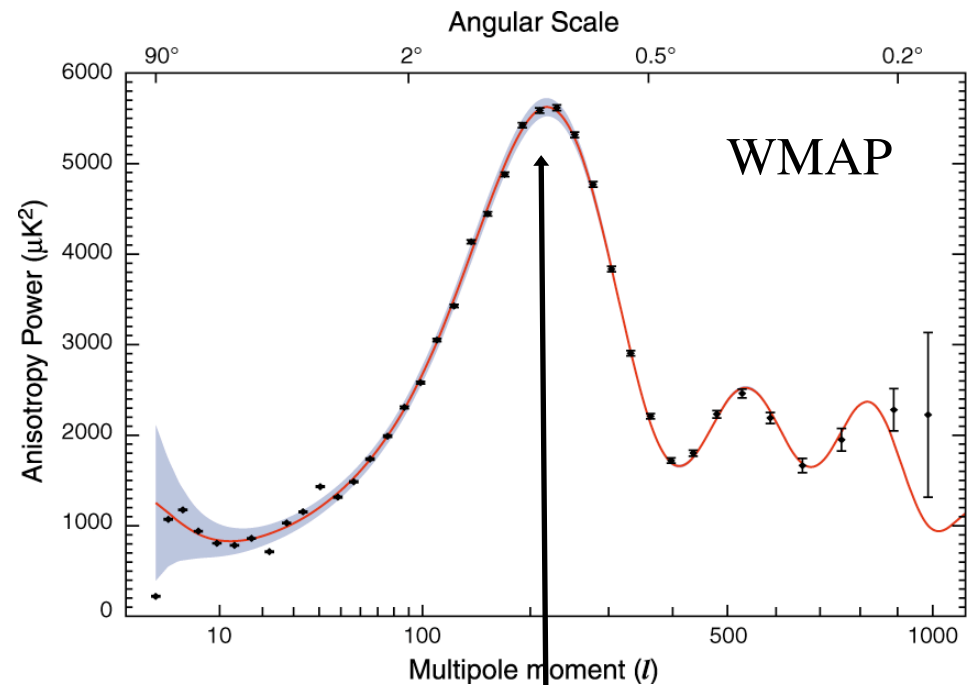
Cosmic Microwave Background (CMB) & Curvature of the Universe



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:



Resonance length ↔
acustict horizon

Quintessence

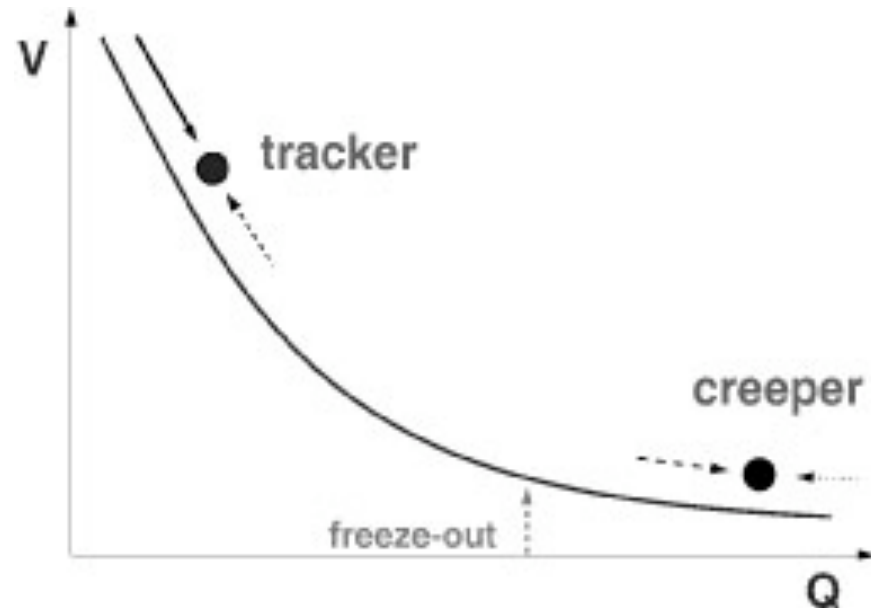
Skalare Field ϕ with potential $V(\phi)$
(similar Inflaton)

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

$$w \approx -1 \text{ f\u00fcr } \dot{\phi}^2 \ll V(\phi)$$

Friedmann-Gleichung f\u00fcr ϕ :

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



Bei geeignetem Potential folgt die Energiedichte dank „Hubble-Reibung“ der Materiedichte (tracker-behavior).

⇒ **Teilweise L\u00f6sung des „Warum jetzt“ Problems.**

Wetterich (1987)

Testing SN evolution by subdividing the sample

luminosity-width
correction coefficient

luminosity-color
correction coefficient

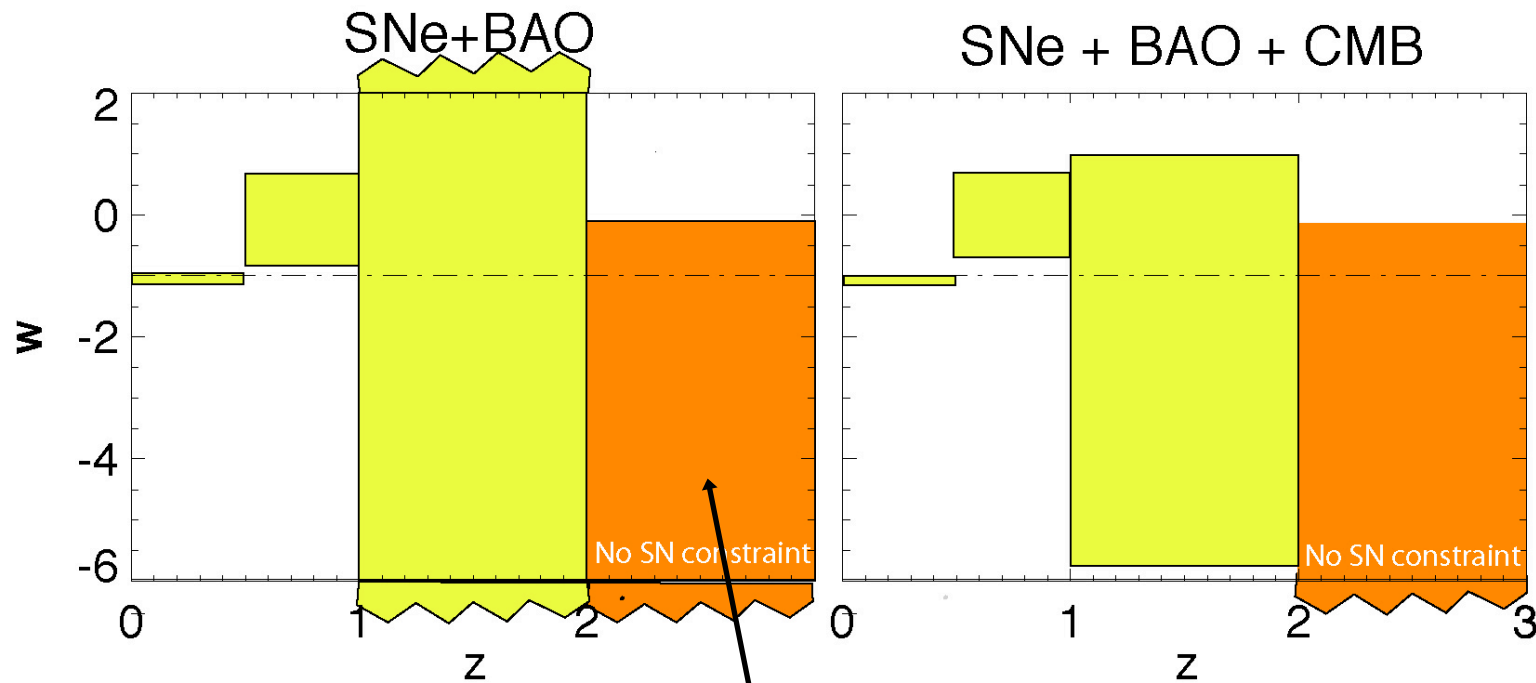
$$\mu_B = m_B^{\max} - M + \alpha(s - 1) - \beta c$$

	subset	N_{SN}	α	β	Ω_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!

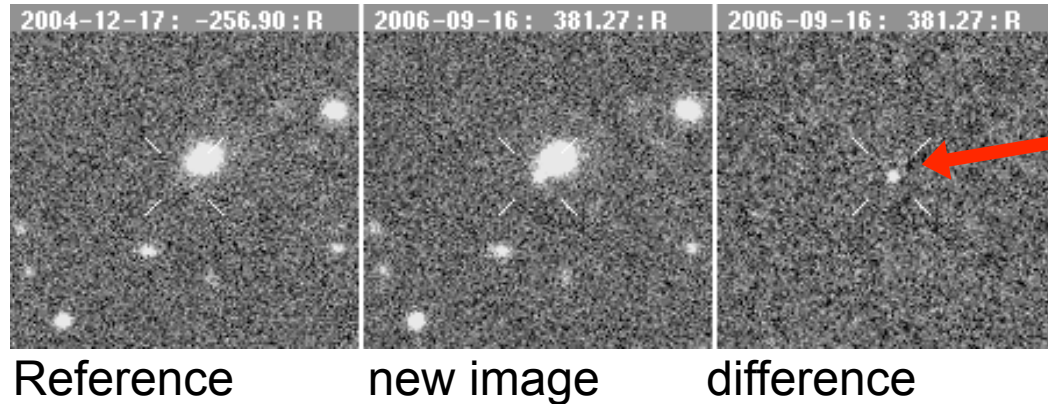
Redshift dependent w

Assuming step-wise constant w :



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

Supernova-Observations



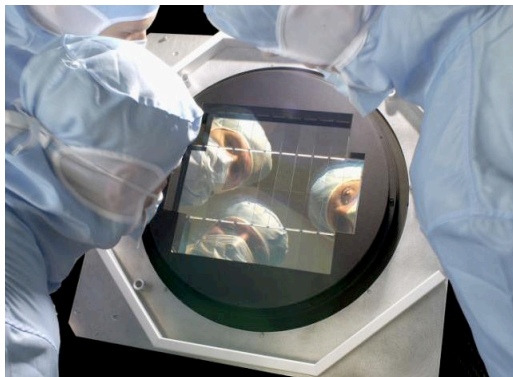
SN-candidate



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:

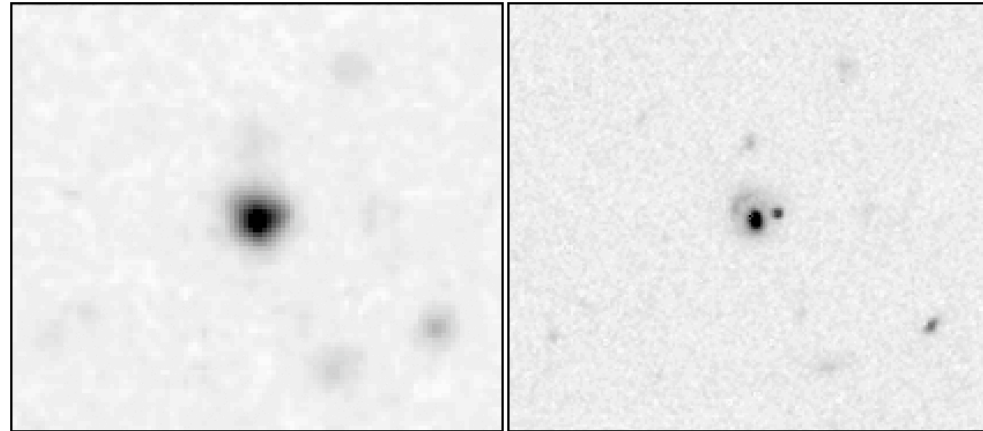
⇒ 80 SNe / yr



MegaCam: 340M pixel,
 $1^\circ \times 1^\circ$ field-of-view

SNe at $z > 1$

SN 1997cj



Ground-Based 0.7"

Hubble Space Telescope



Twin Keck telescopes on Mauna Kea.



Observations with HST to obtain light curves in the near IR