Supernova Cosmology Today

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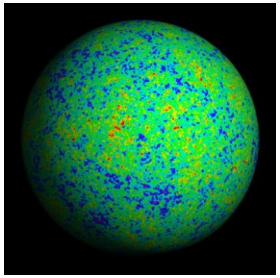
Physikalisches Institut
Universität Bonn

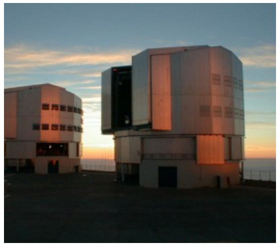
Supernova 1994D

DESY, 28.2.2012

Content



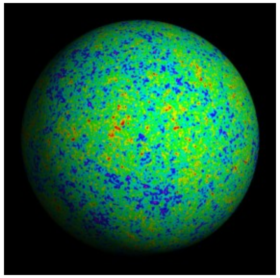
Introduction: the accelerating Universe



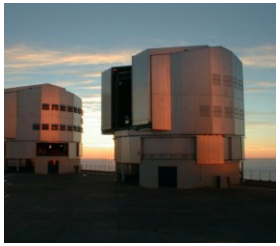
SNe observations & cosmological parameters

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

$\Rightarrow$ Friedman Equation, which governs expansion

$$H^2 \equiv \left(\frac{\dot{R}}{R}\right)^2 = \frac{8\pi G}{3}\rho_M + \frac{\Lambda}{3} - \frac{k}{R^2} \quad \Big| \; \frac{1}{H^2}$$

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

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

Matter Density

Our Cosmological Framework derives from…

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Principles: Homogeneous, isotropic
Theory: General Relativity

⇒ Friedman Equation, which governs expansion

$$H^2 \equiv \left(\frac{\dot{R}}{R}\right)^2 = \frac{8\pi G}{3}\rho_M + \frac{\Lambda}{3} - \frac{k}{R^2} \quad \Big| \; \frac{1}{H^2}$$

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Matter Density

Cosmological Constant/
Dark Energy

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$\Rightarrow$ Friedman Equation, which governs expansion

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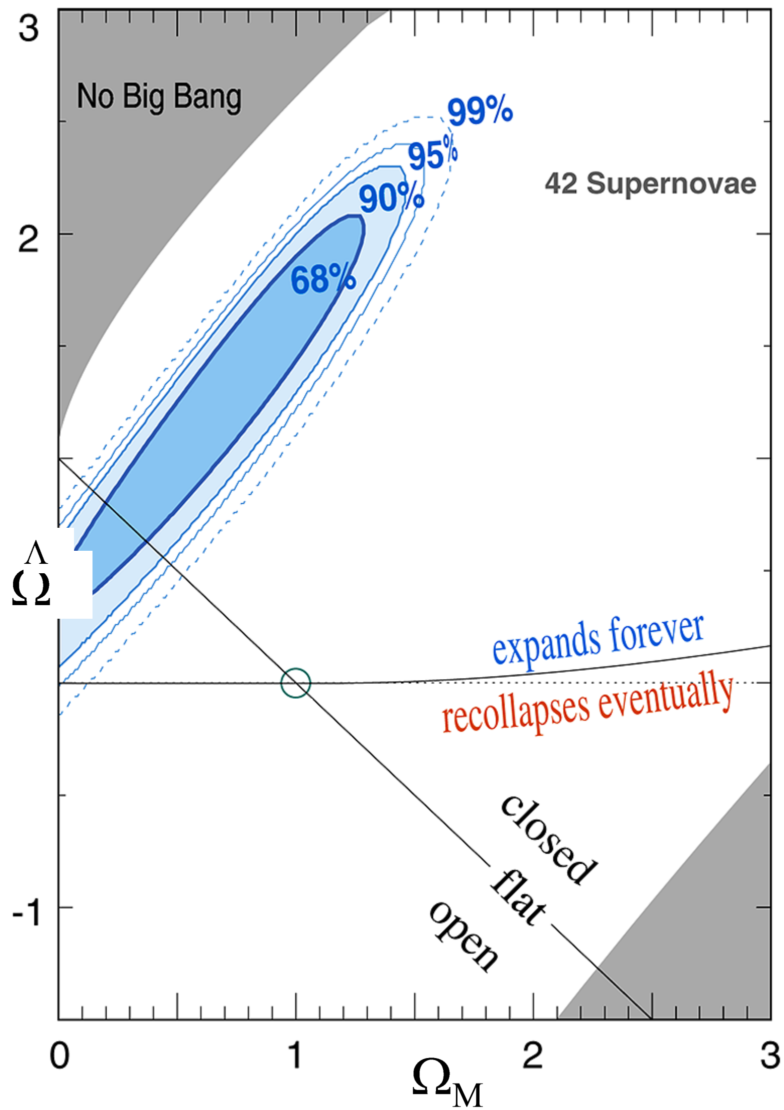
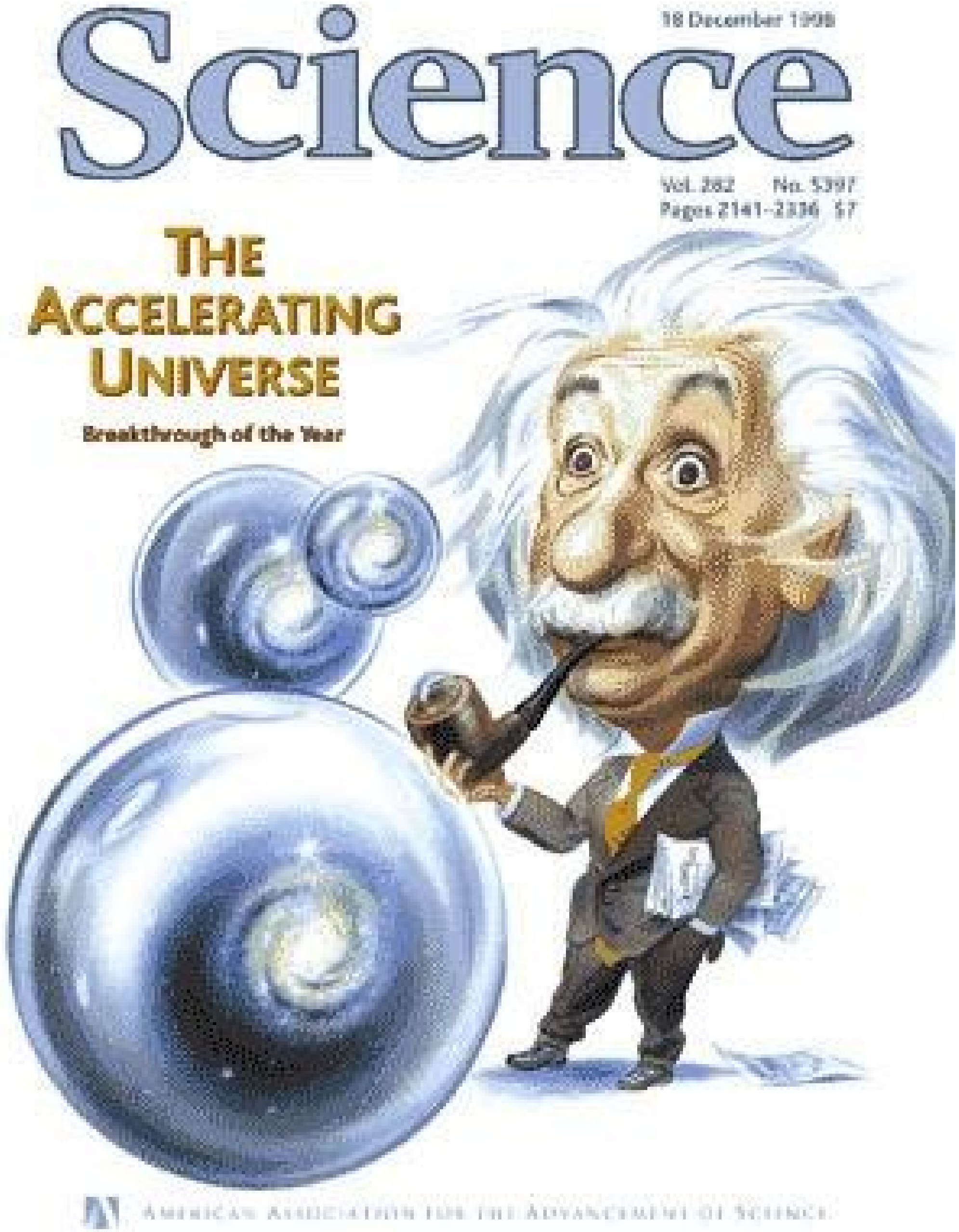
$$\Omega_M + \Omega_\Lambda + \Omega_k = 1$$

Matter Density — Cosmological Constant/ Dark Energy — Curvature

1998: Discovery of Dark Energy




Science
18 December 1998
Vol. 282 No. 5397
Pages 2141-2336 $7
THE ACCELERATING UNIVERSE
Breakthrough of the Year
AMERICAN ASSOCIATION FOR THE ADVANCEMENT OF SCIENCE

Nobel prize for physics 2011

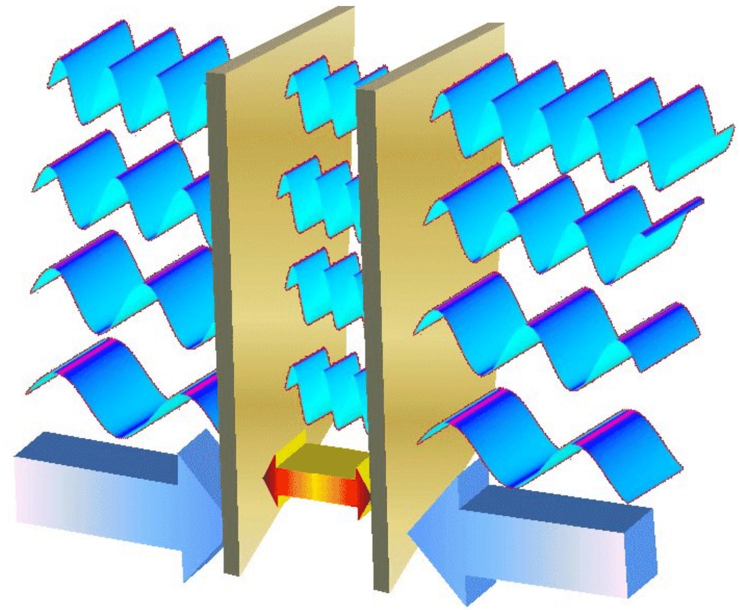
Nobel prize for physics 2011

Vacuum Energy

Vacuum energy density:

(with cut-off k_{max})

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



Casimir effect ⇔ 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 then the observed value!

Why now?

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

Vakuum Energy: ρ = *constant*

Dark Energy with equation-of-state:

$\underline{p=w\rho}$

(p = pressure; ρ = density)

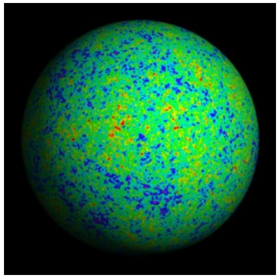
$\Rightarrow \rangle \propto R^{-3(1+w)}$

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

A few examples:

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

Content



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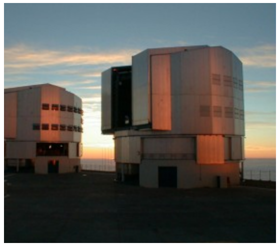
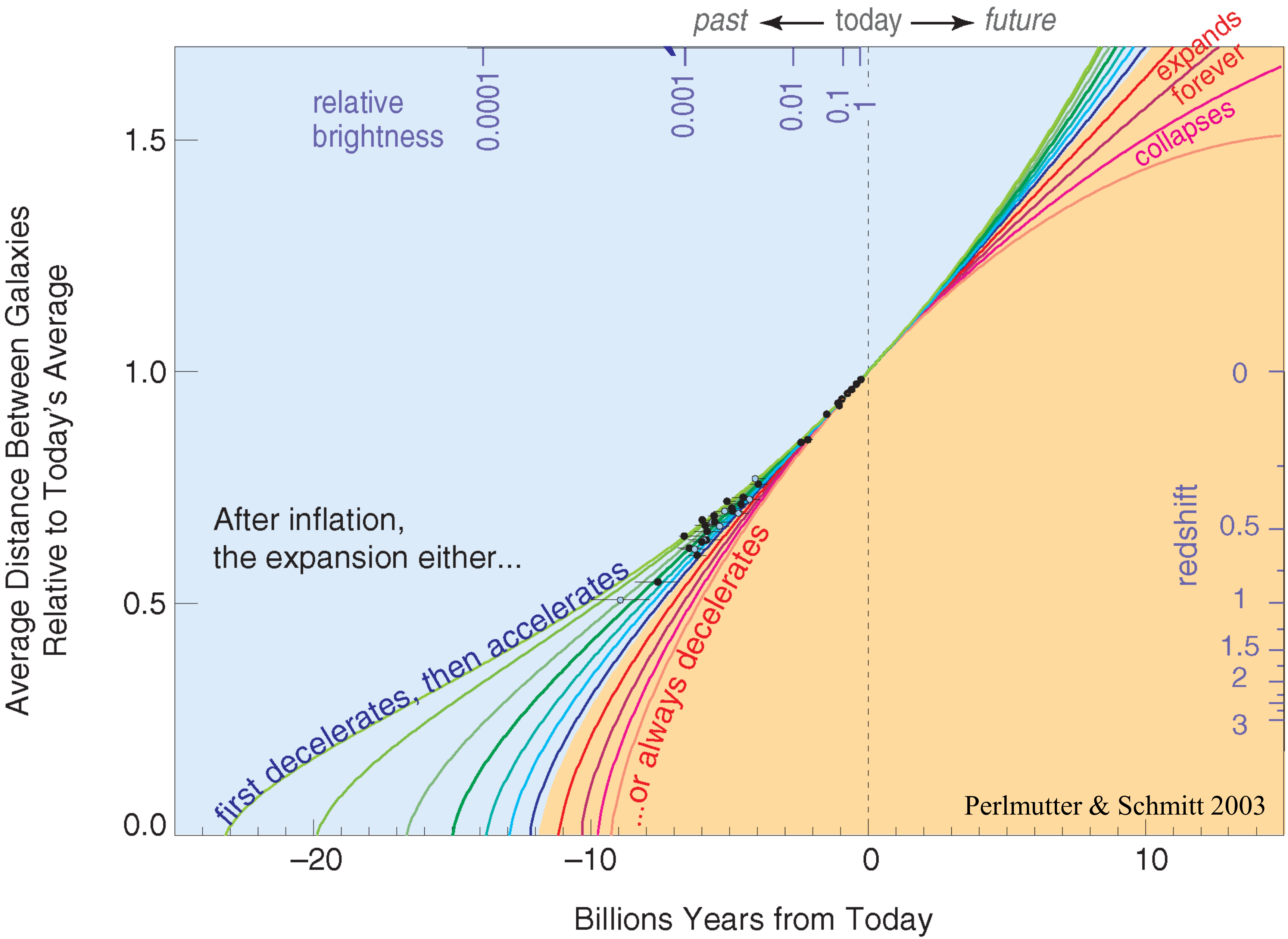


SNe observations&cosmological parameters

Constraints on selected Dark Energy models

Expansion History of the Universe



Supernova Type Ia

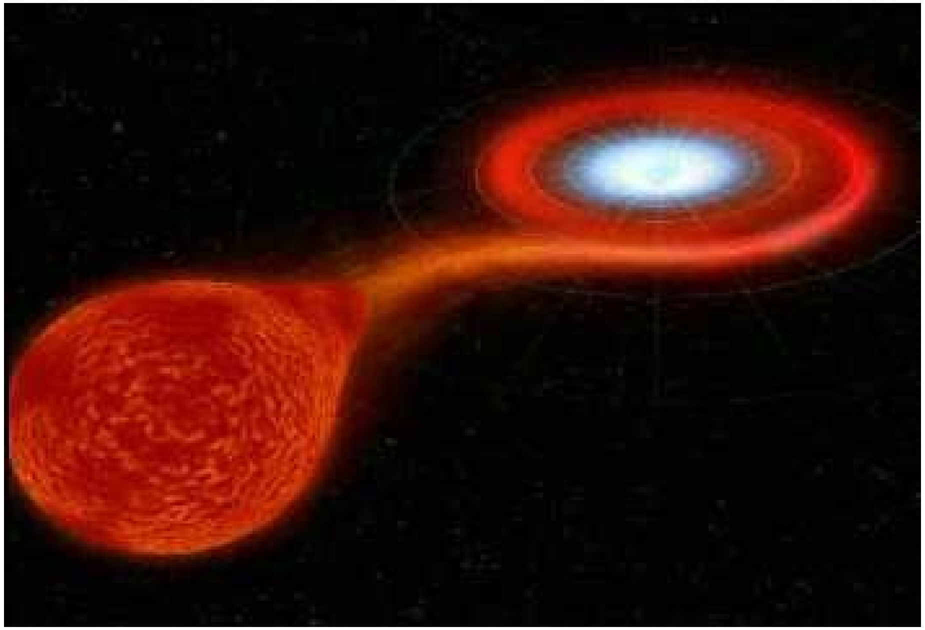
⇒ White dwarf in binary system

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

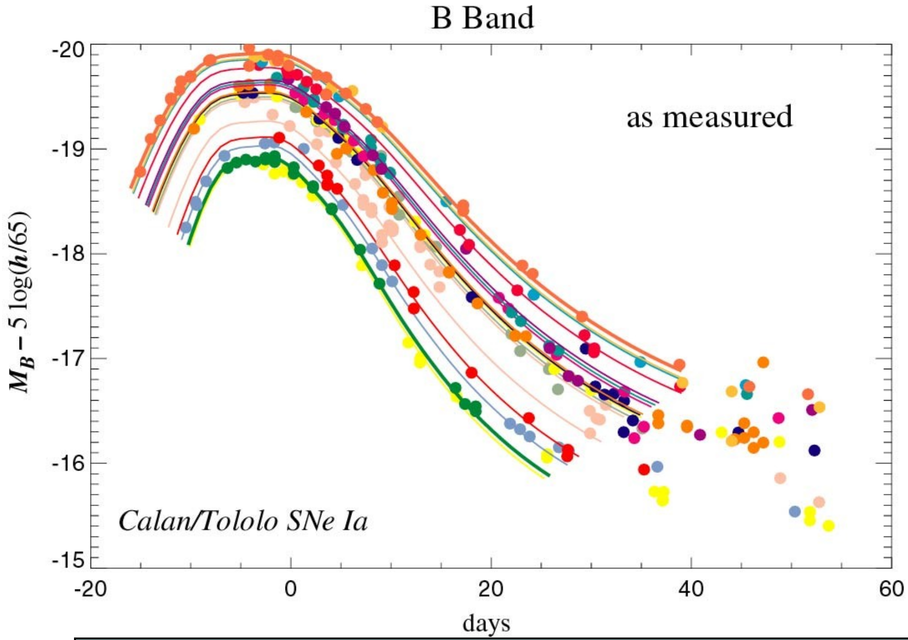
⇒ Thermonuclear explosion

⇒ Explosion of similar energies

⇒ Visible in cosmic distances



“Standard candles“



- Brightness not the same for all SNe

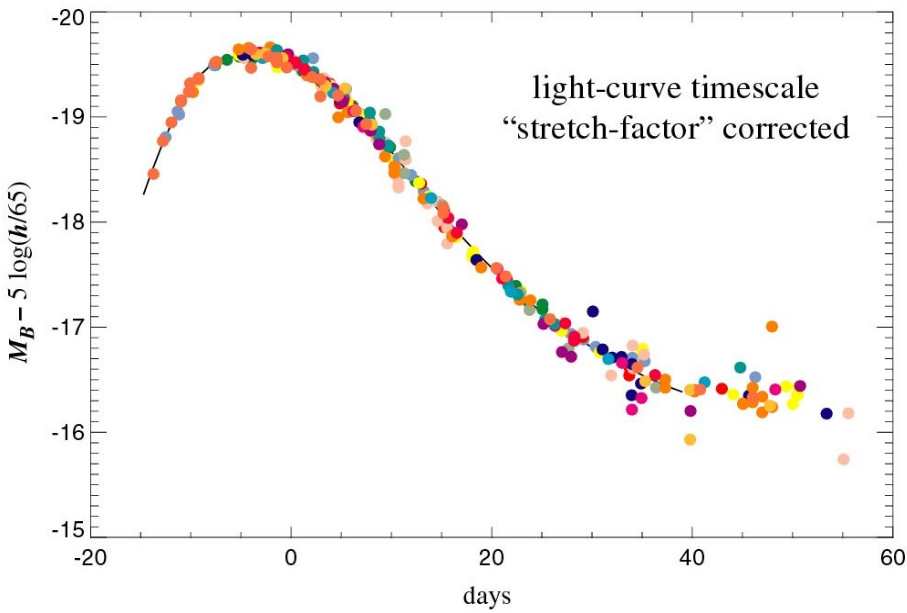
  Brighter SNe have wider light curves.

“Stretching“ of time scale:

$$t' = s \times t$$

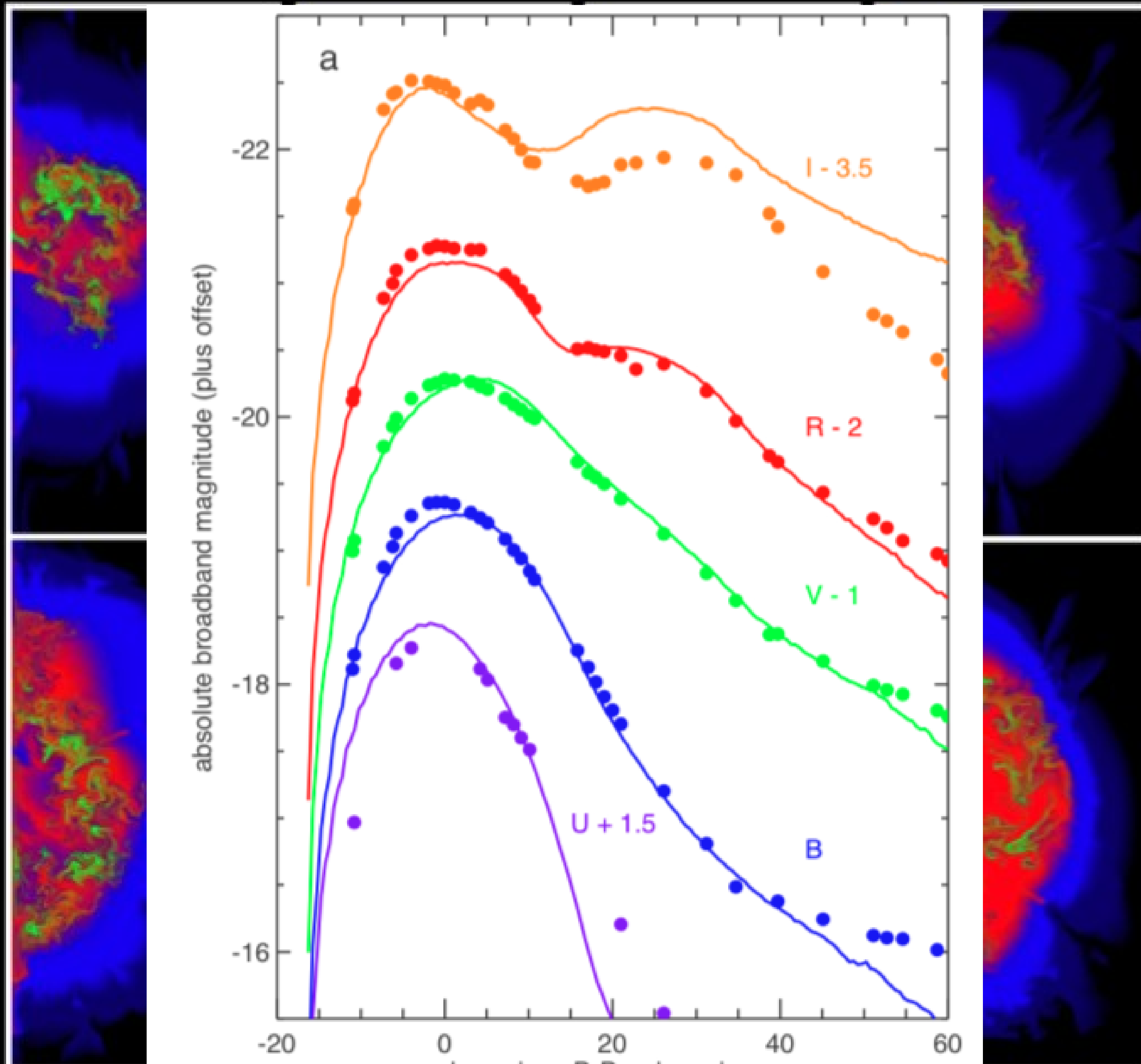
Brightness correction:

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



Kim, *et al.* (1997)

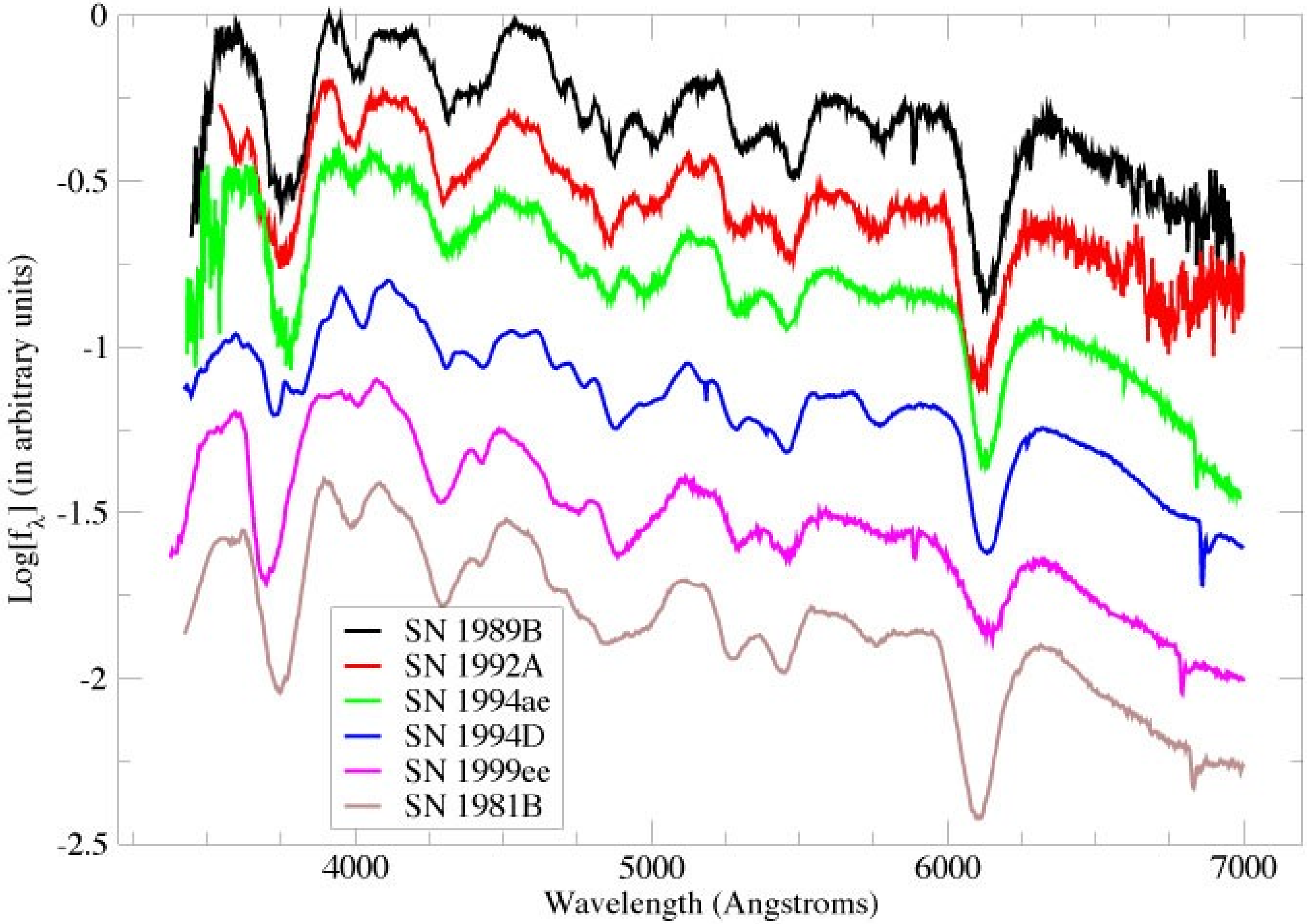
strong deflagration
weak detonation

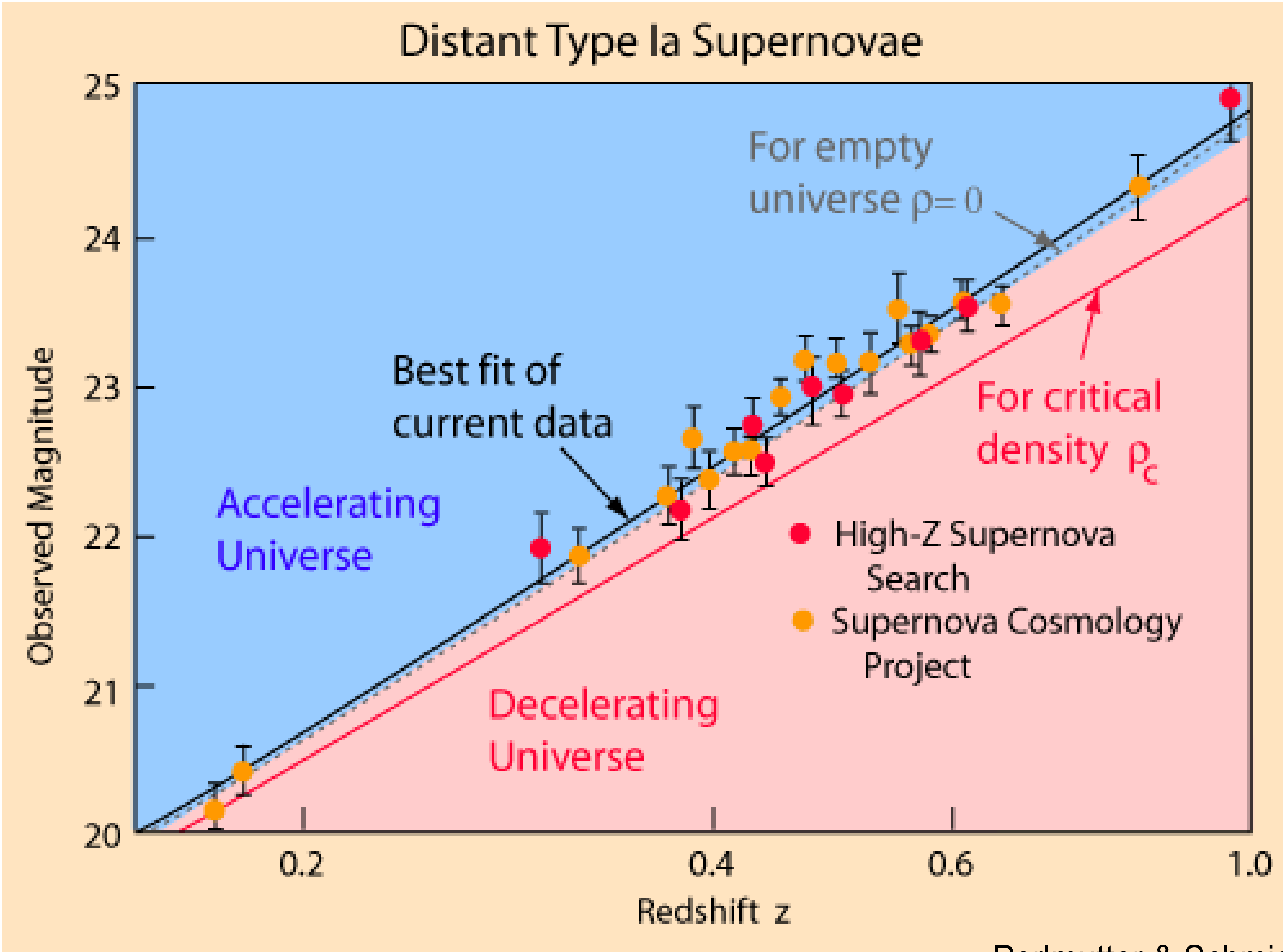


weak deflagration
strong detonation

Kasen.
Röpke,
Woosely,
Nature 2009

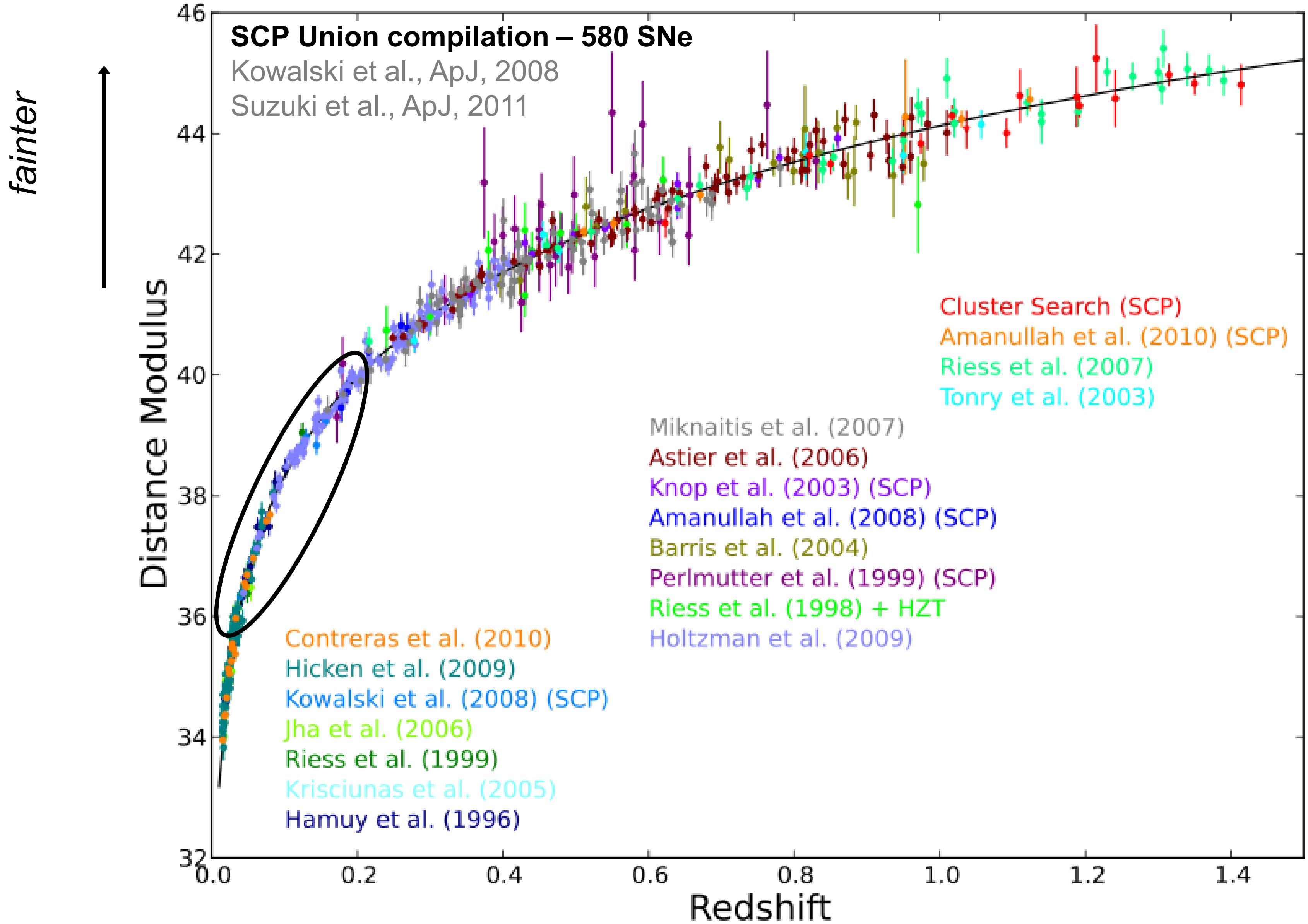
Spectra for identification and redshift determination





Perlmutter & Schmidt 1998

A modern SNe Ia Hubble Diagram



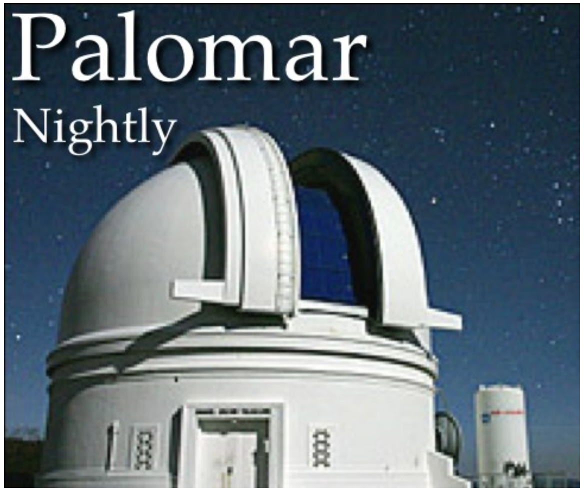
Supernova Factory

(artist's concept)

Supernova Factory Collabo

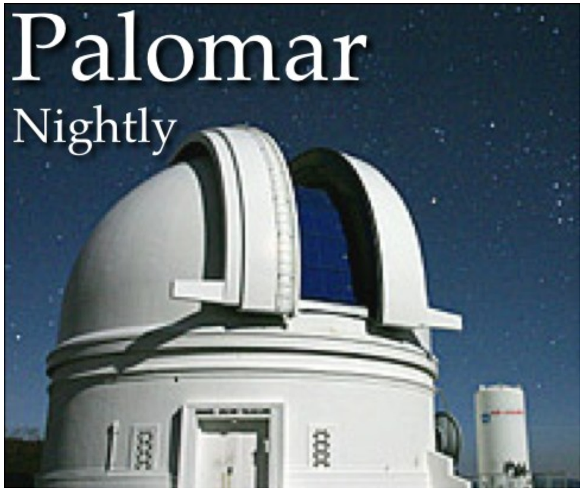
Lawrence Berkeley National Lab
Laboratorie de Physique Nucleaire et de Haute Energies de Paris
Institut de Physique Nucleaire de Lyon
Centre de Recherche Astronomy de Lyon
Yale University
Bonn University
Tsinguha University, Bejing
MPA, Garchingen

SNfactory: producing unique nearby SNe data



1. Discover

SNfactory: producing unique nearby SNe data



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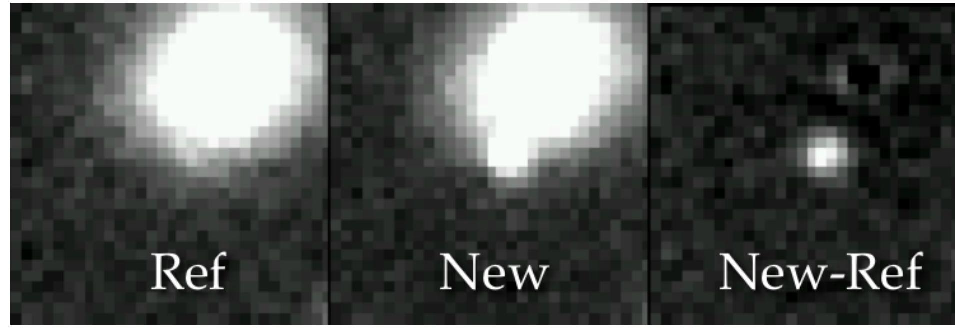
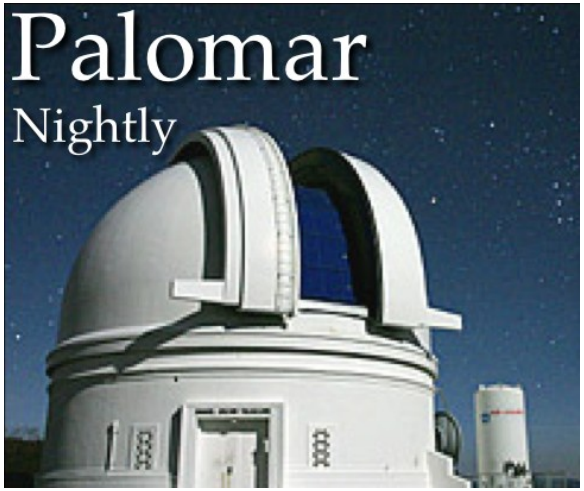


2. Observe

SNIFS: Custom spectrograph for nearby SN observations

SNfactory: producing unique nearby SNe data



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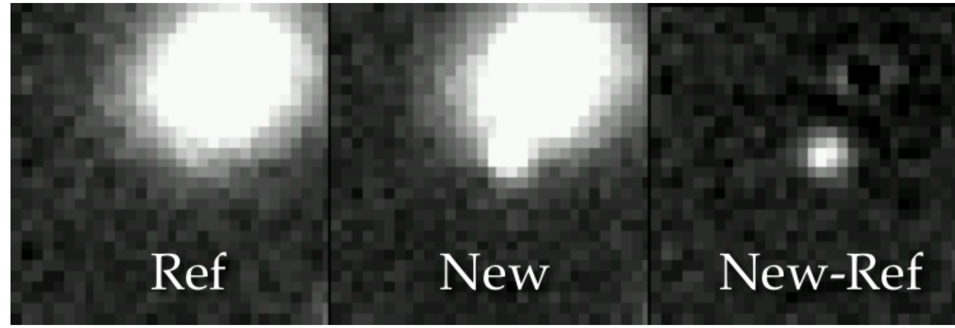
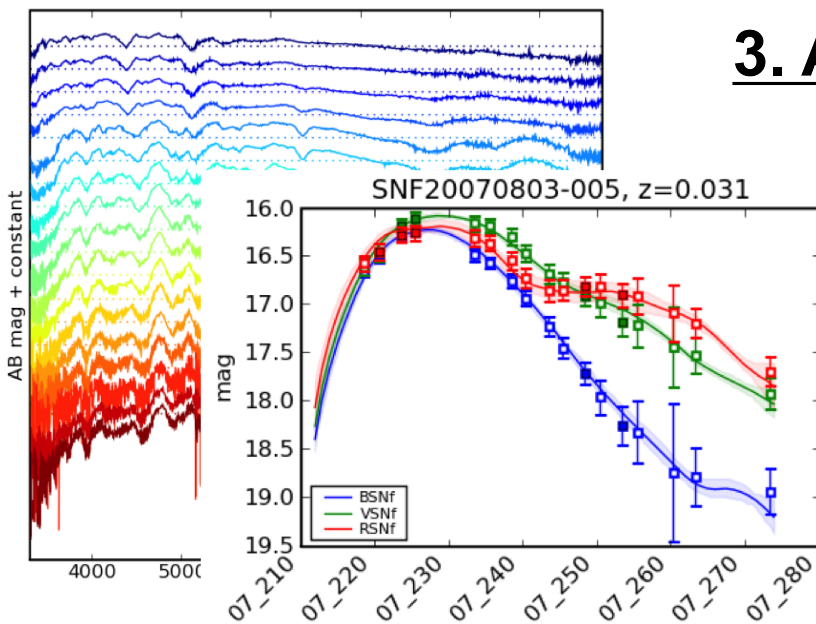


2. Observe

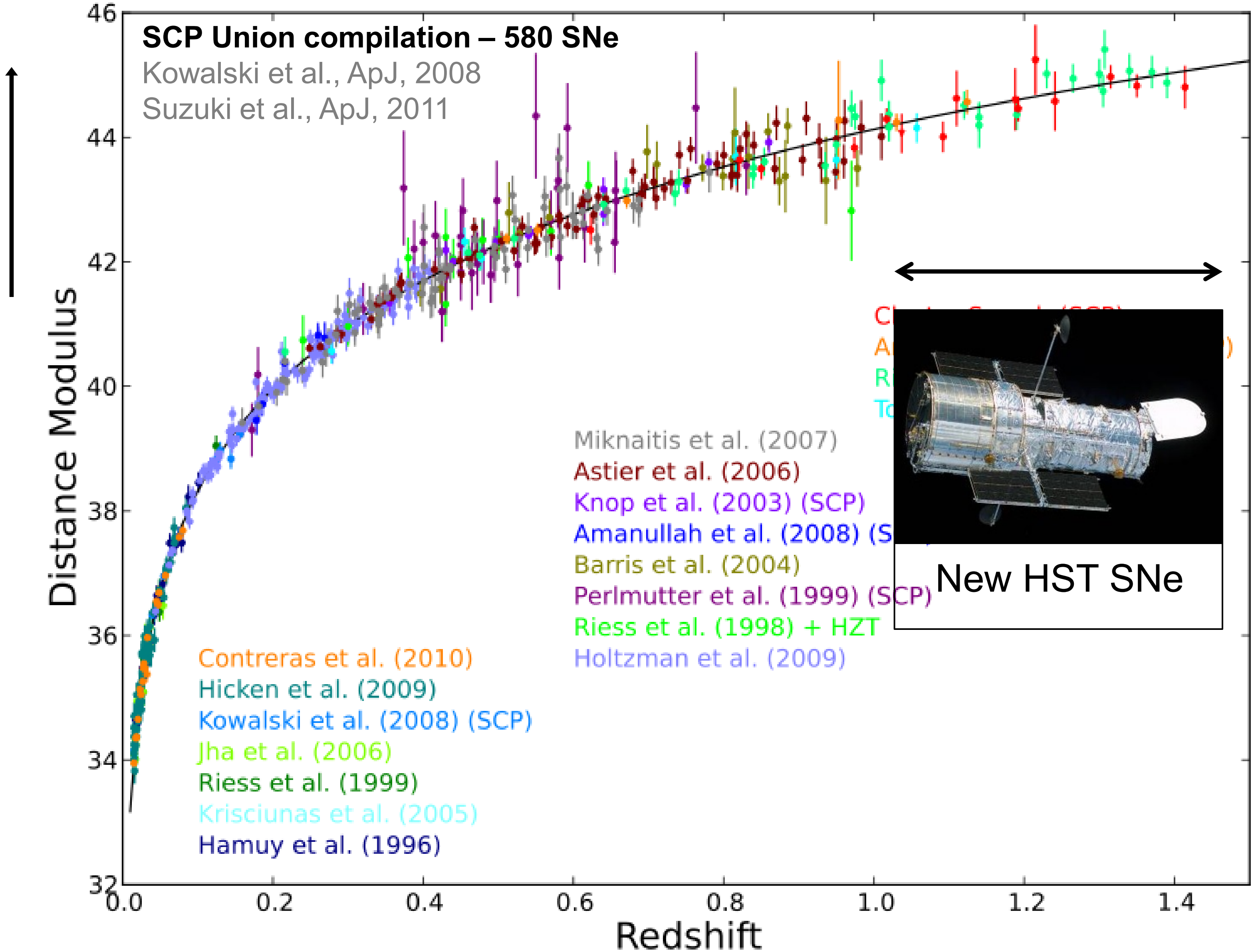
SNIFS: Custom spectrograph for nearby SN observations

3. Analyses



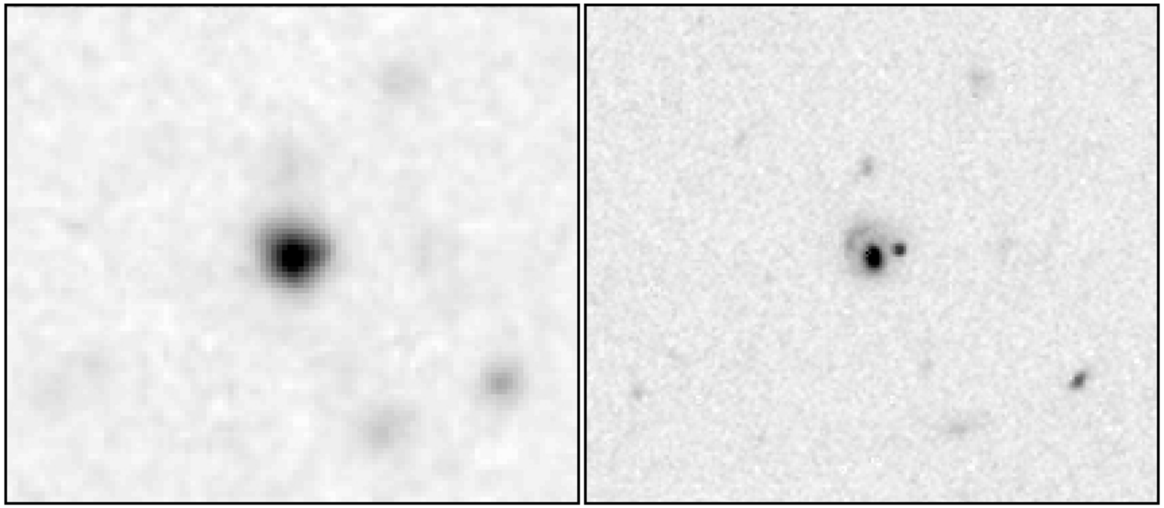
A modern SNe Ia Hubble Diagram

fainter



SNe at large Redshifts (z>1)

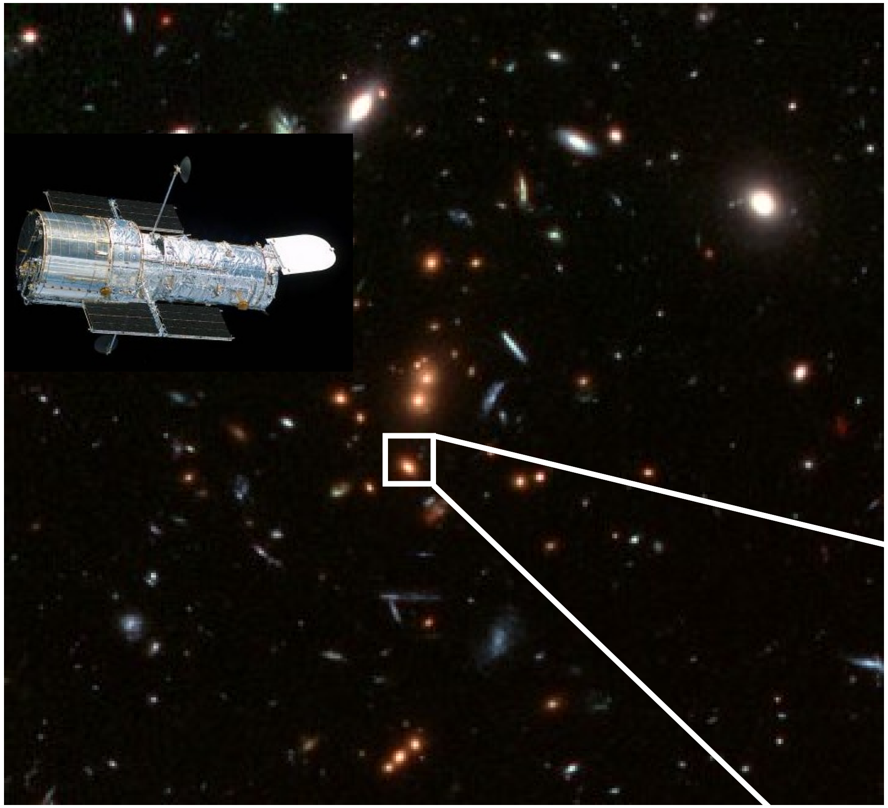
SN 1997cj



Twin Keck telescopes on Mauna Kea.

+ NIR sensitivity

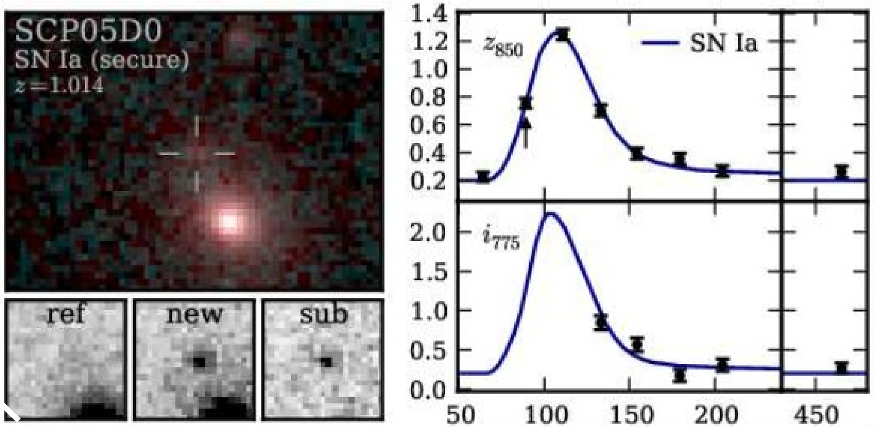
HST Survey of Clusters with z ≥ 1



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

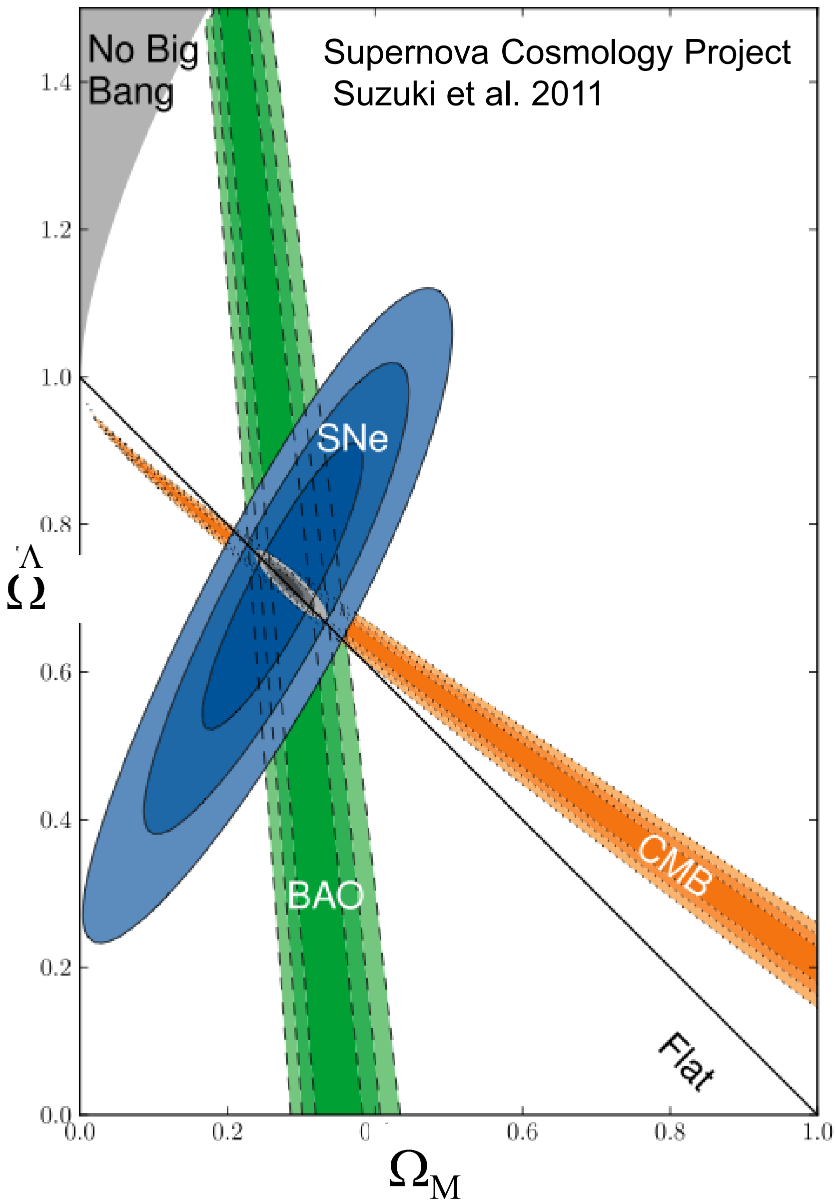
Survey of z>0.9 galaxy clusters
⇒ SNe from cluster & field
⇒ about 2 x more efficient
⇒ 10 high quality z>1 SNe

Nearly doubling number of z>1 SNe!



Suzuki et al. (SCP), 2011

Results: Cosmological Parameters



Combination of SNe with:
BAO (Percival et. al., 2010)
CMB (WMAP-7 year data, 2010)

For a flat Universe:

$\Omega_m = 0.282 \pm 0.016$

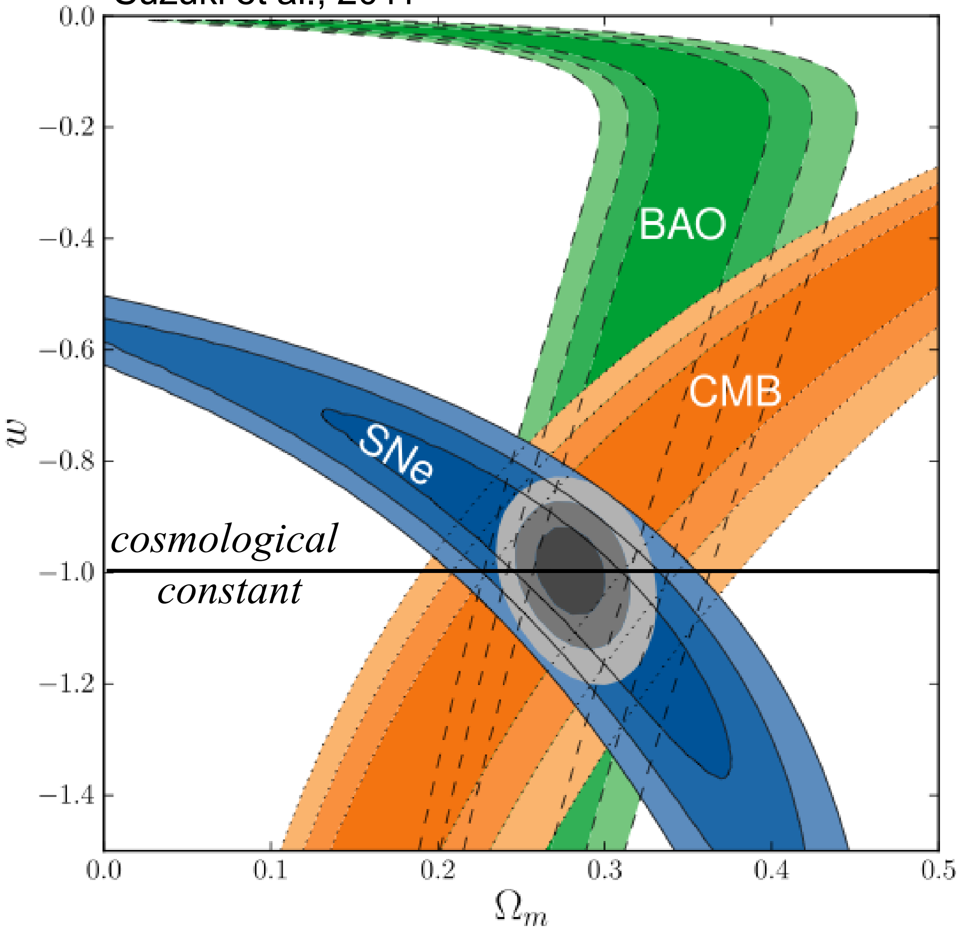
… and with curvature:

$\Omega_m = 0.286 \pm 0.017$

$\Omega_k = -0.004 \pm 0.006$

Dark Energy

Supernova Cosmology Project
Suzuki et al., 2011



Equation of state: *p=wρ*

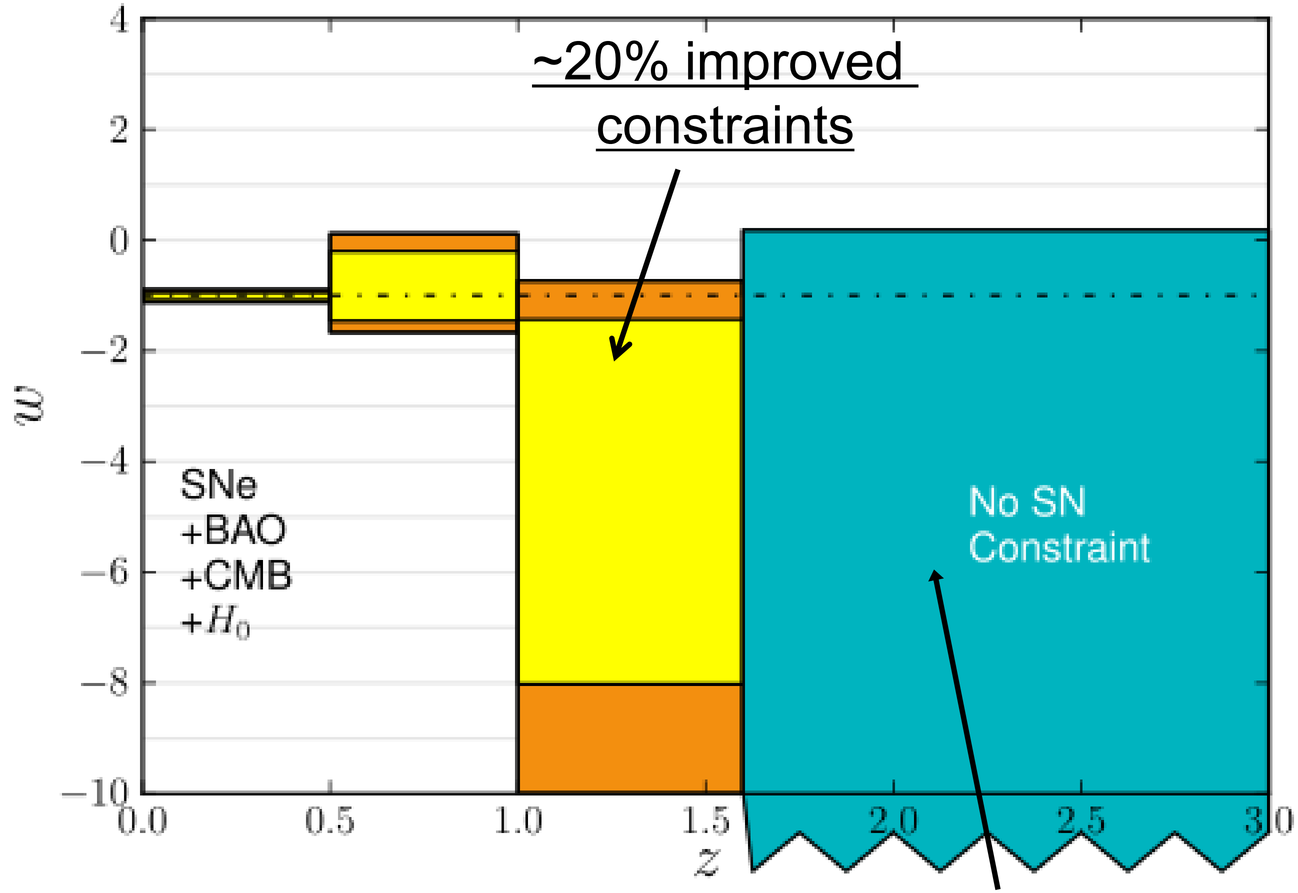
constant w:

w= -0.951±0.053(stat)±0.057(stat)

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

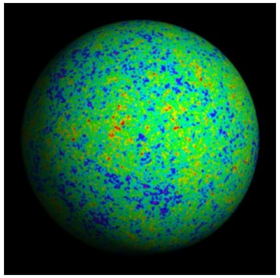
Redshift dependent EOS

Assuming step-wise constant *w*:



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

Content



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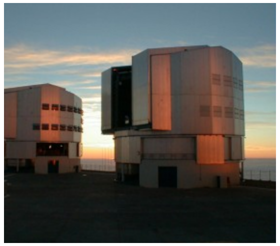


SNe observations & cosmological parameters

Constraints on selected Dark Energy models

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

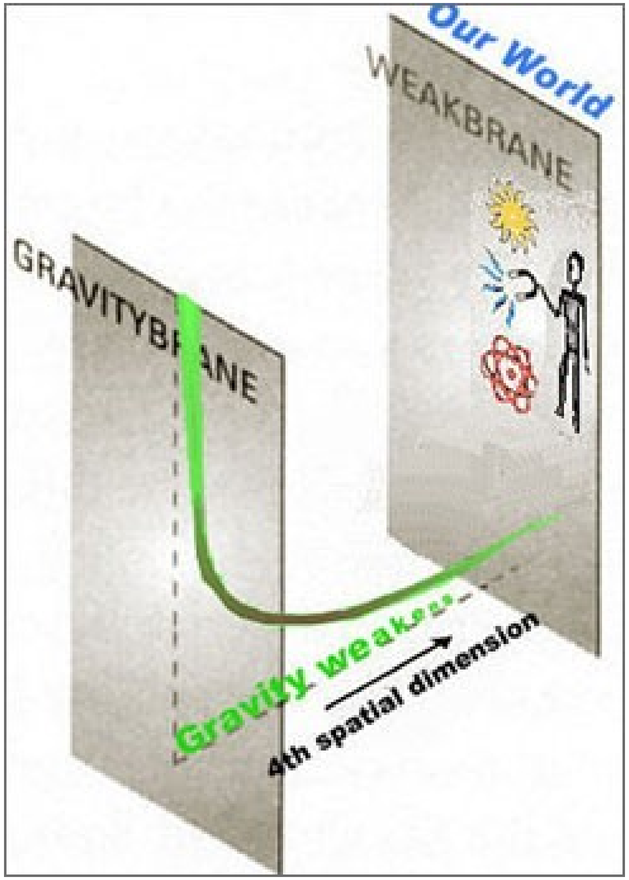
Menu of possibilities:

1. **Quantum Vacum 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

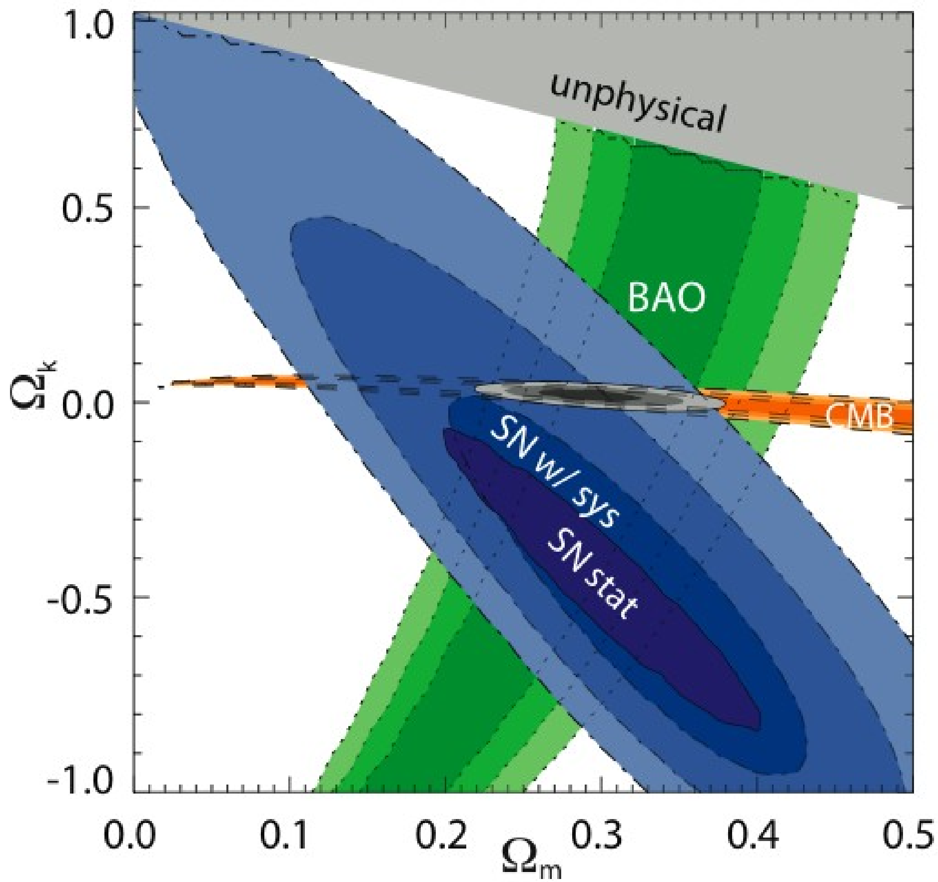


Large extra dimensions
can solve the hierarchy
problem of particle physics…
(e.g. unification of forces)
Randall & Sundrum
Arkani-Hamed, Dimopoulos, Dvali

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

$\Rightarrow$**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

Quo Vadis, Supernova Cosmology?

$w = -0.951 \pm 0.053\ (\text{stat}) \pm 0.057\ (\text{sys})$

Union 2.1, Suzuki et al. 2011

Control of systematic errors crucial!

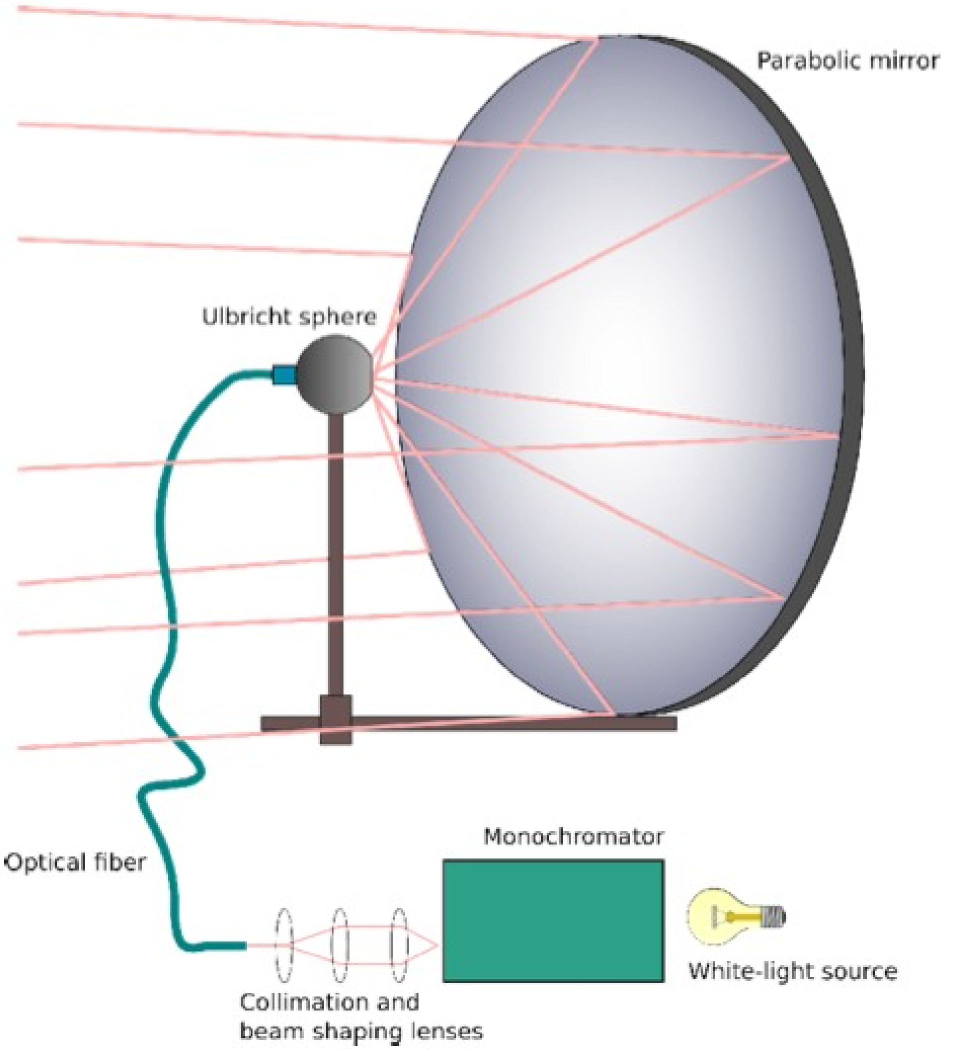
Example from Union2 compilation (Amanullah et al, 2010)

Source	Error on w
Galactic Extinction Normalization	0.012
Rest-Frame U-Band	0.010
Contamination	0.021
Malmquist Bias	0.026
Intergalactic Extinction	0.012
Light curve Shape	0.009
Color Correction	0.026
Quadrature Sum (not used)	*0.073*
Summed in Covariance Matrix	0.063

Control of systematic errors crucial!

Calibration unit for SNIFS (under construction)

Parabolic mirror
+ Integrating sphere
= artificial planet

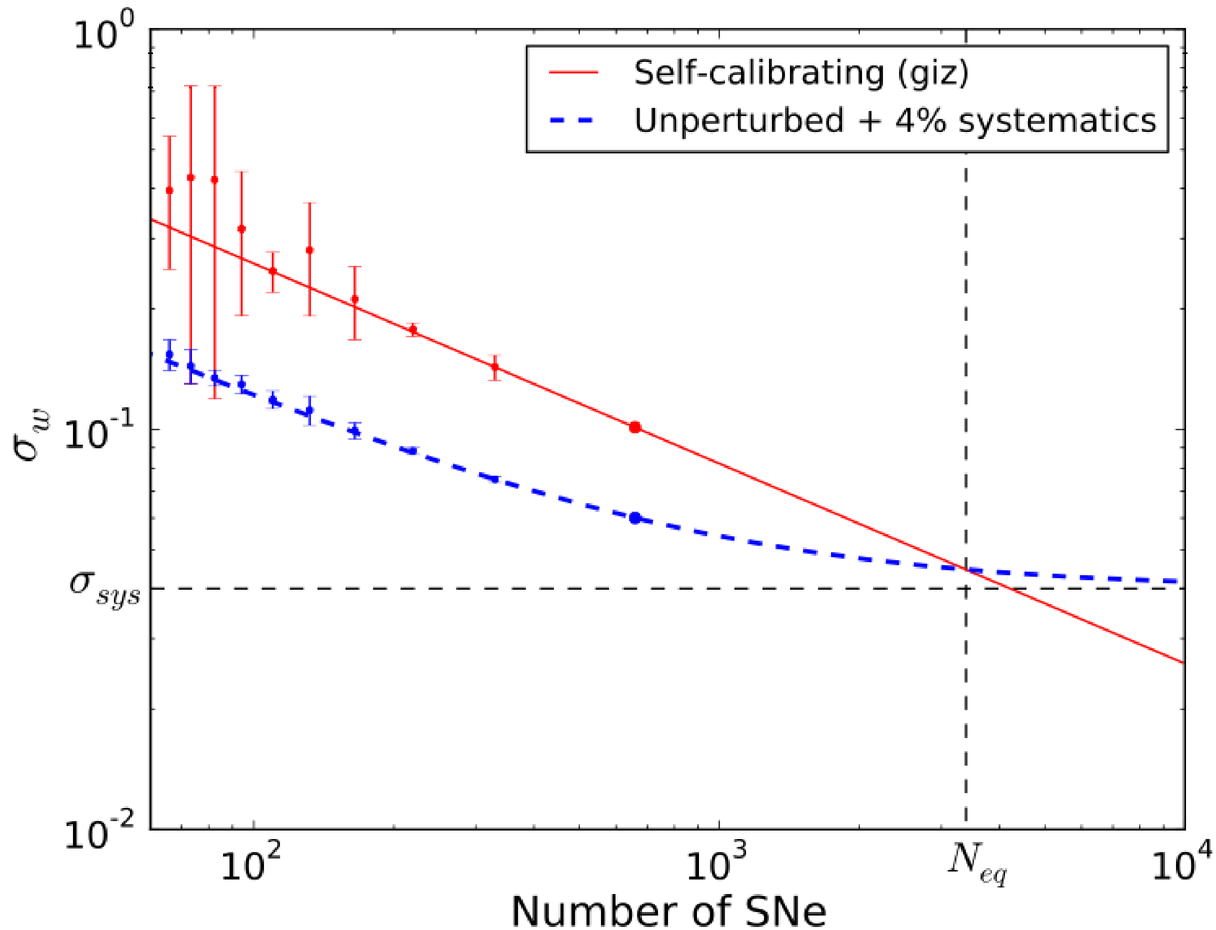


Control of systematic errors crucial...
...but SN statistics helps, too!

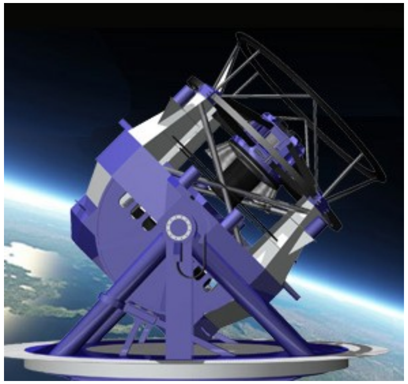
Self-calibrating Hubble diagram:
Flux calibration offsets determined with SN data itself

No inconsistency seen so far: σ(flux)≈1%

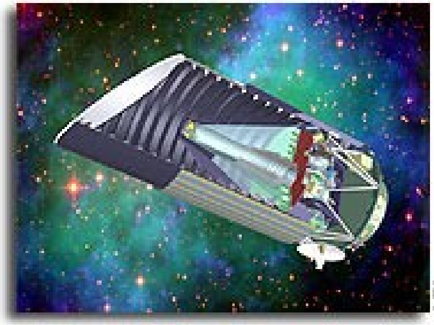
Method outperforms conventional one for >3000 Sne



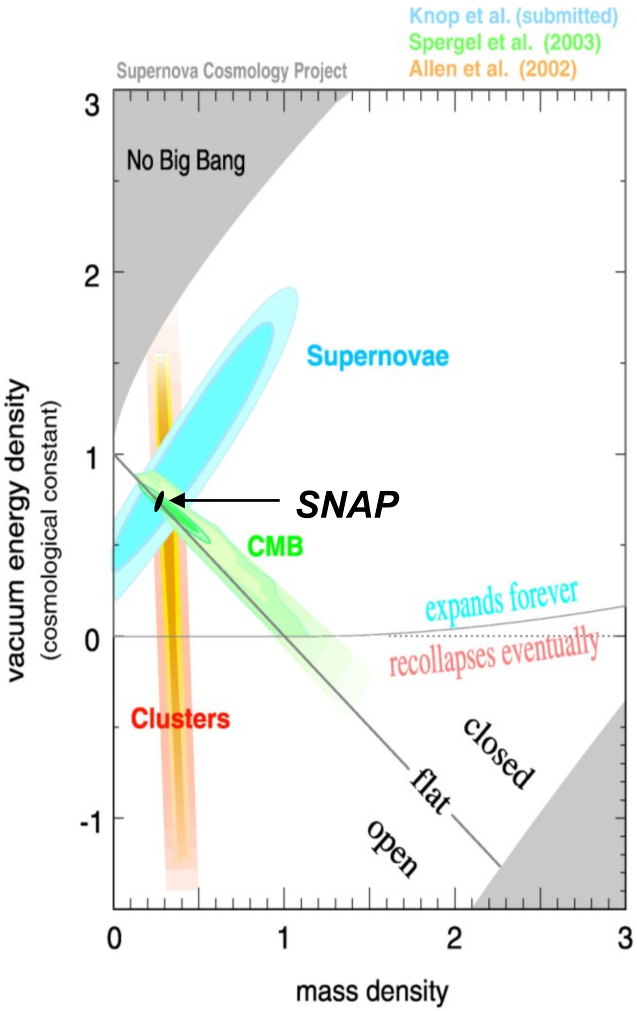
U. Feindt, K. Paech, MK, arXiv:1201.0765



Future projects for Dark Energy



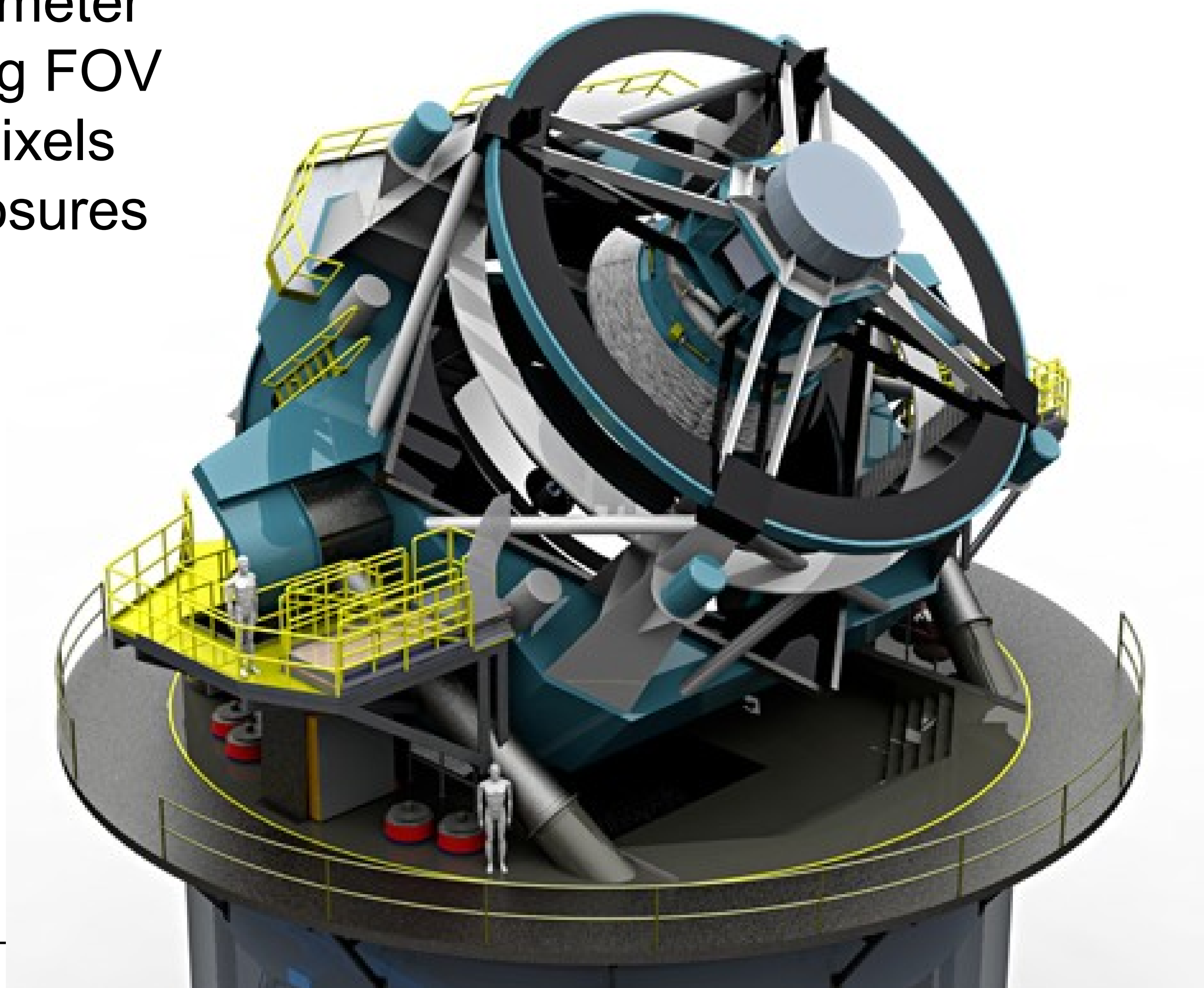
Project	z-range	# SNe
Current	0-1.5	580
LSST (2020)	0.1-0.9	~10^6
Euclid (2020)	0.9-2.0	~2000



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



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.