Fundamental Physics through Astrophysics

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Astrophysical Evidence for New Physics

- Matter-antimatter asymmetry
  - Baryon number & CP violation in early universe?
- Non-baryonic Dark Matter
  - New particle physics sector?
- Neutrino oscillations, mass constraints
  - Non-zero masses, mixing/oscillations
- Non-zero Cosmological Constant, Λ
  - Evidence for weirdness in the vacuum
  - Puzzle #1: why is Λ so small?
  - Puzzle #2: why is Λ so large?

Theoretical Context is Evolving

- Stringy ideas may produce observable effects
- Growing appreciation of the importance of the gravitational sector
- Speculative models for Λ-physics, some even falsifiable
- Even in the absence of the evidence for cosmic acceleration, this would motivate testing gravitational physics on *all* accessible length scales

Focus is shifting…

10 years ago

- What's the Dark Matter?
- What are the values of the cosmological parameters (Ω, q_0, H_0)?
- What's the connection between primordial fluctuations and observed large scale structure?

Now

- What's the Dark Matter?
- What physics is responsible for nonzero Λ?
- What's the connection between primordial fluctuations, dark matter, and observed galactic structure?
- How can we probe the foundations of gravity?

A Cosmic Sum Rule

General Relativity + isotropy and homogeneity require that (in the relevant units)

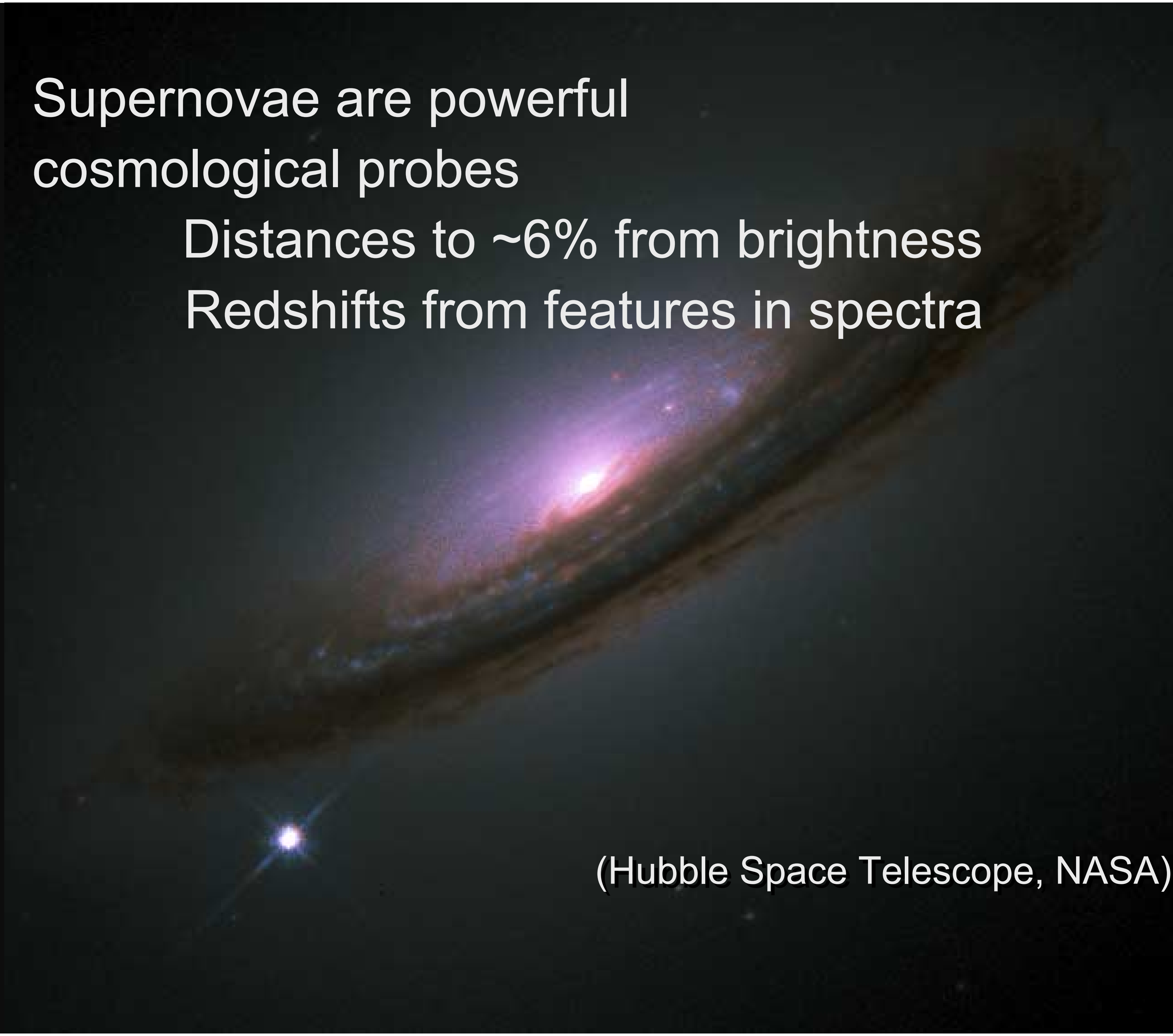
$$\Omega_{geometry} + \Omega_{matter} + \Omega_{\Lambda} = 1$$

If the underlying geometry is flat, and if Ω_m <1 then the cosmological constant term *must* be non-zero.

So it would seem……..

Supernovae are powerful cosmological probes

- Distances to ~6% from brightness
- Redshifts from features in spectra



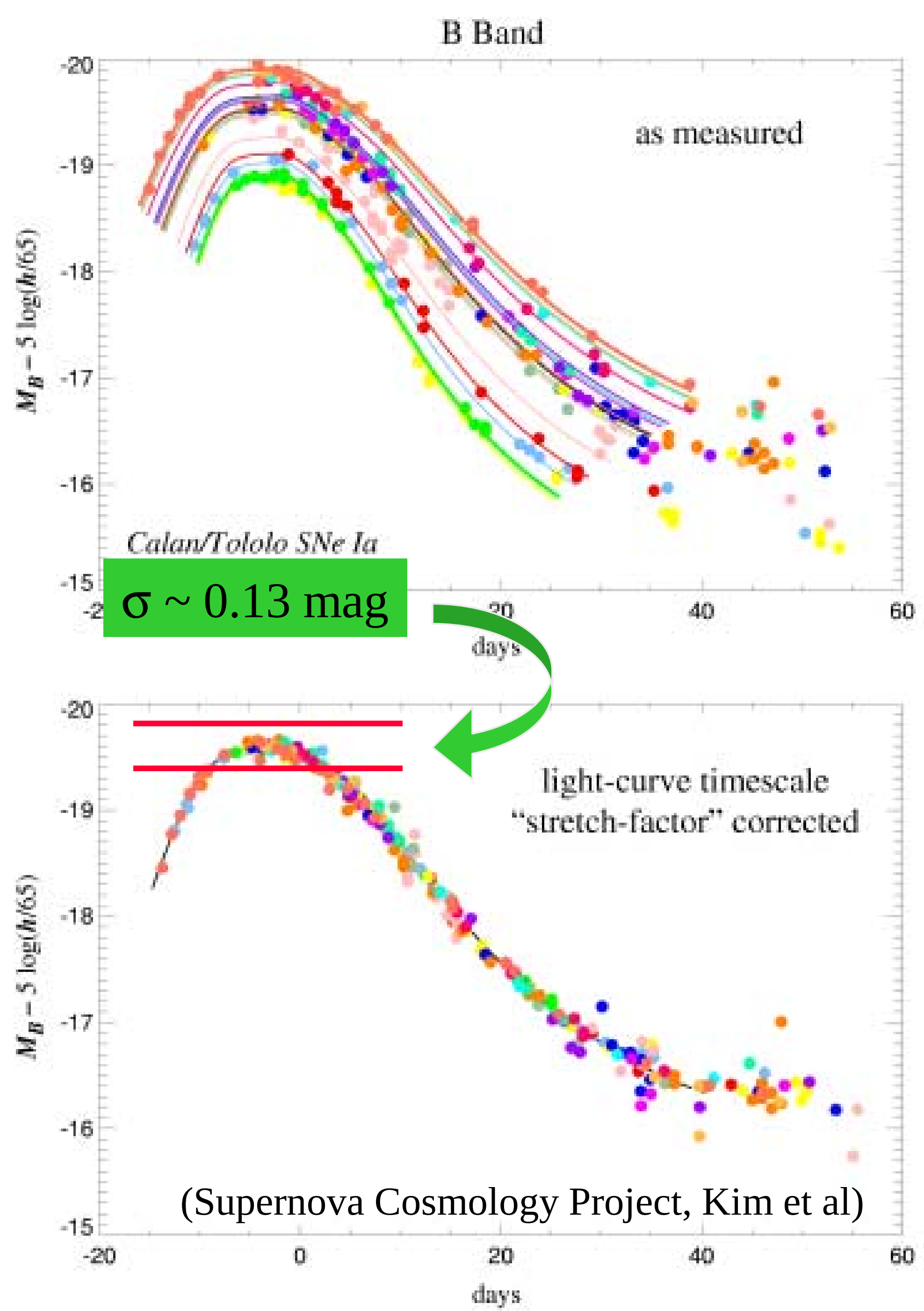
(Hubble Space Telescope, NASA)

One parameter family

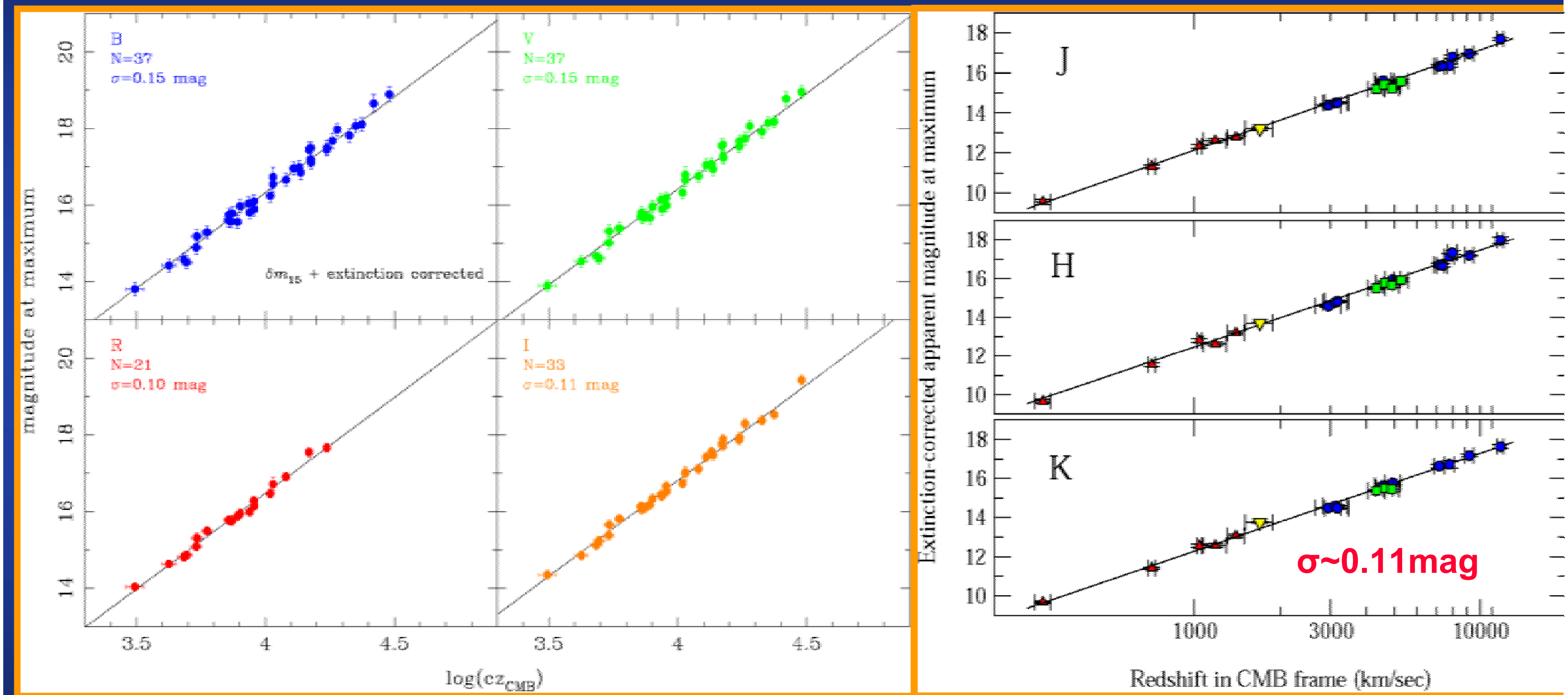
Color

Rate of decline

Peak brightness

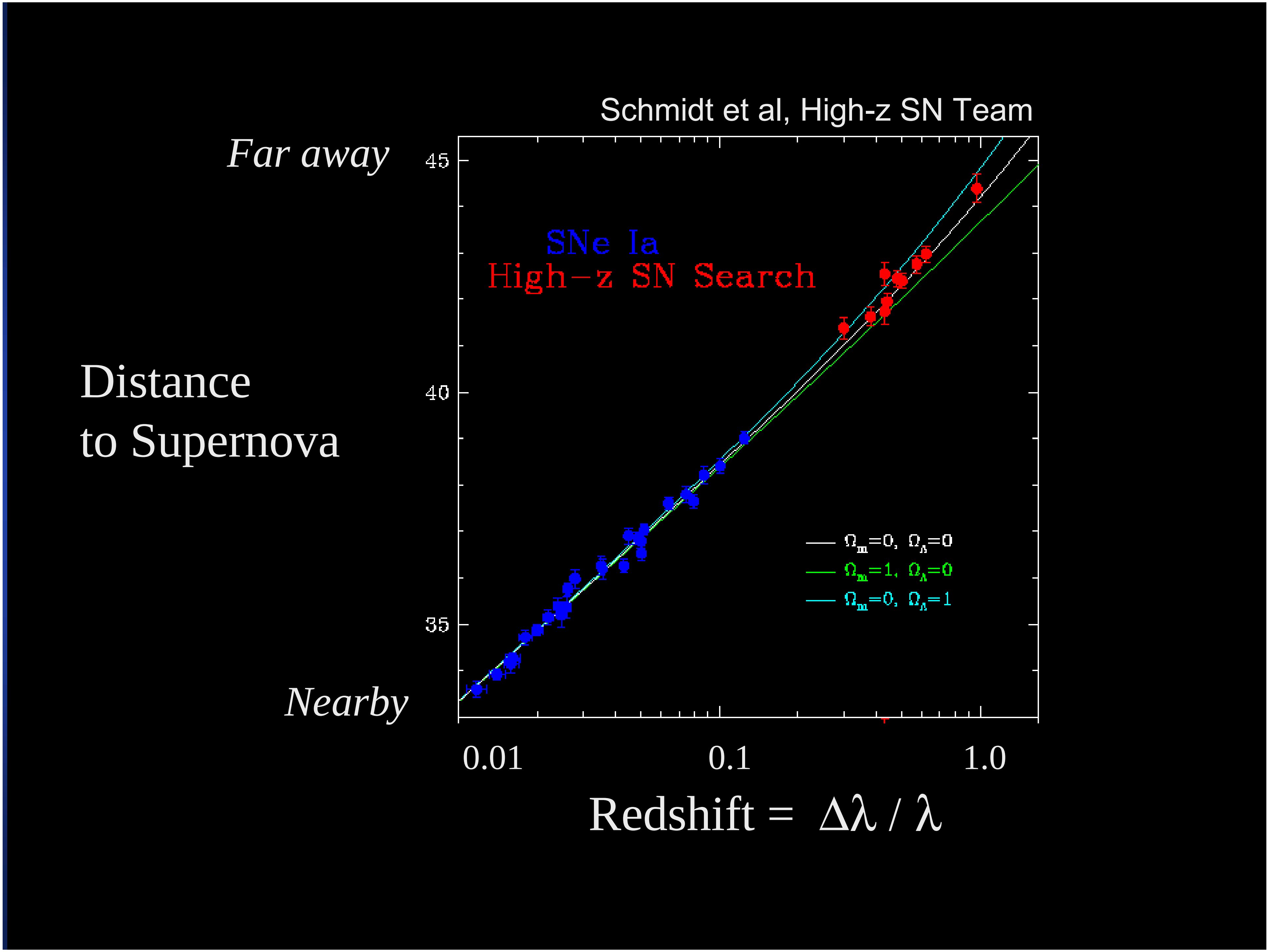


Type Ia SNe are precise candles



Jose Luis Prieto

Krisciunas et al (2003)


Schmidt et al, High-z SN Team
Far away
Distance
to Supernova
Nearby
45
40
35
SNe Ia
High-z SN Search
Ω_m=0, Ω_Λ=0
Ω_m=1, Ω_Λ=0
Ω_m=0, Ω_Λ=1
0.01
0.1
1.0
Redshift = $\Delta\lambda / \lambda$

Extinction by “gray” dust?

Careful multicolor measurements, esp. in IR
Exploit different z-dependence
Look at SNe behind clusters of galaxies

“Evolutionary” Effects?

Use stellar populations of different ages as a proxy

Selection differences in nearby vs. distant samples?

Increase the sample of well-monitored Sne
Calibrate detection efficiencies

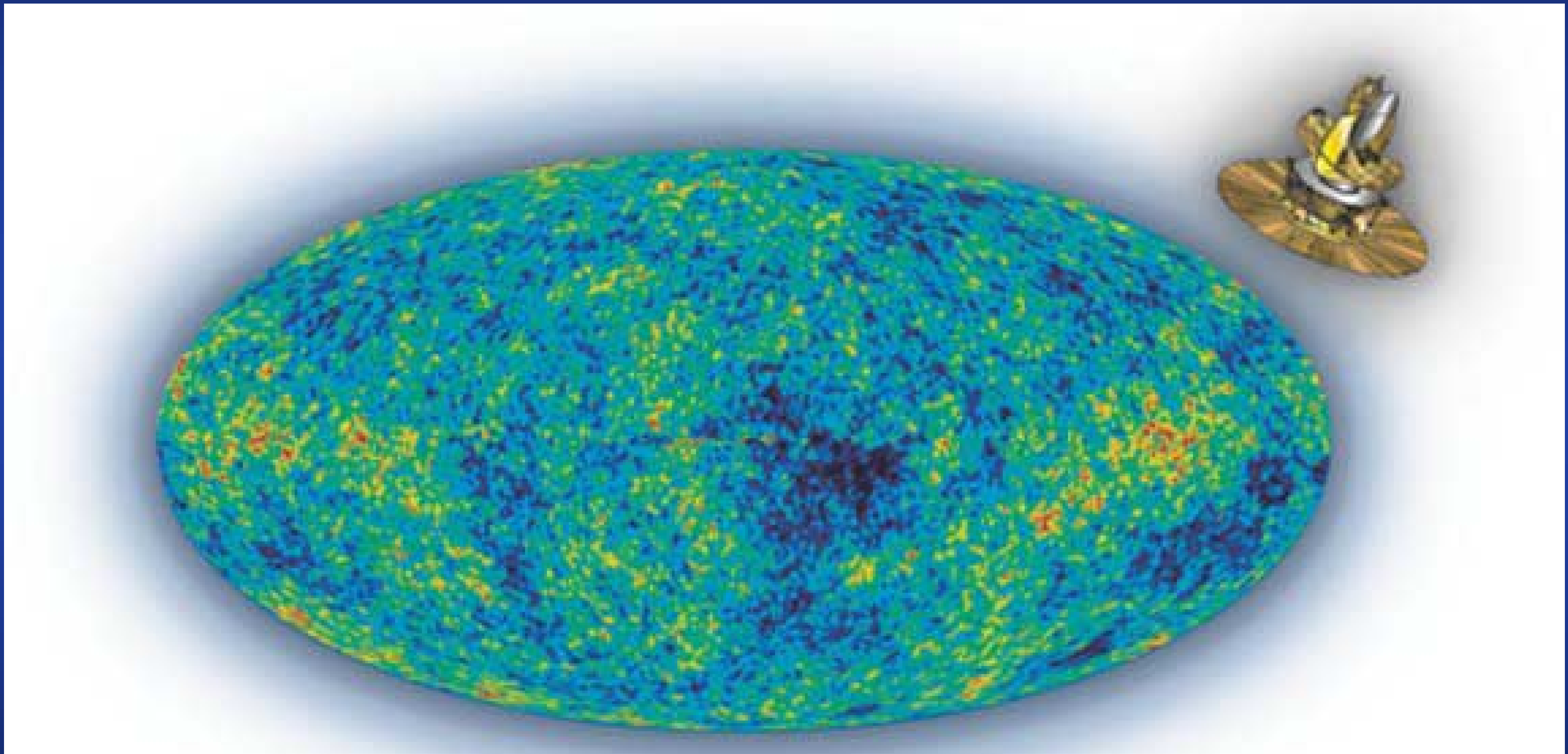
K-corrections, Galactic extinction, photometric zeropoints....

See *Leibundgut, astro-ph/0003326*

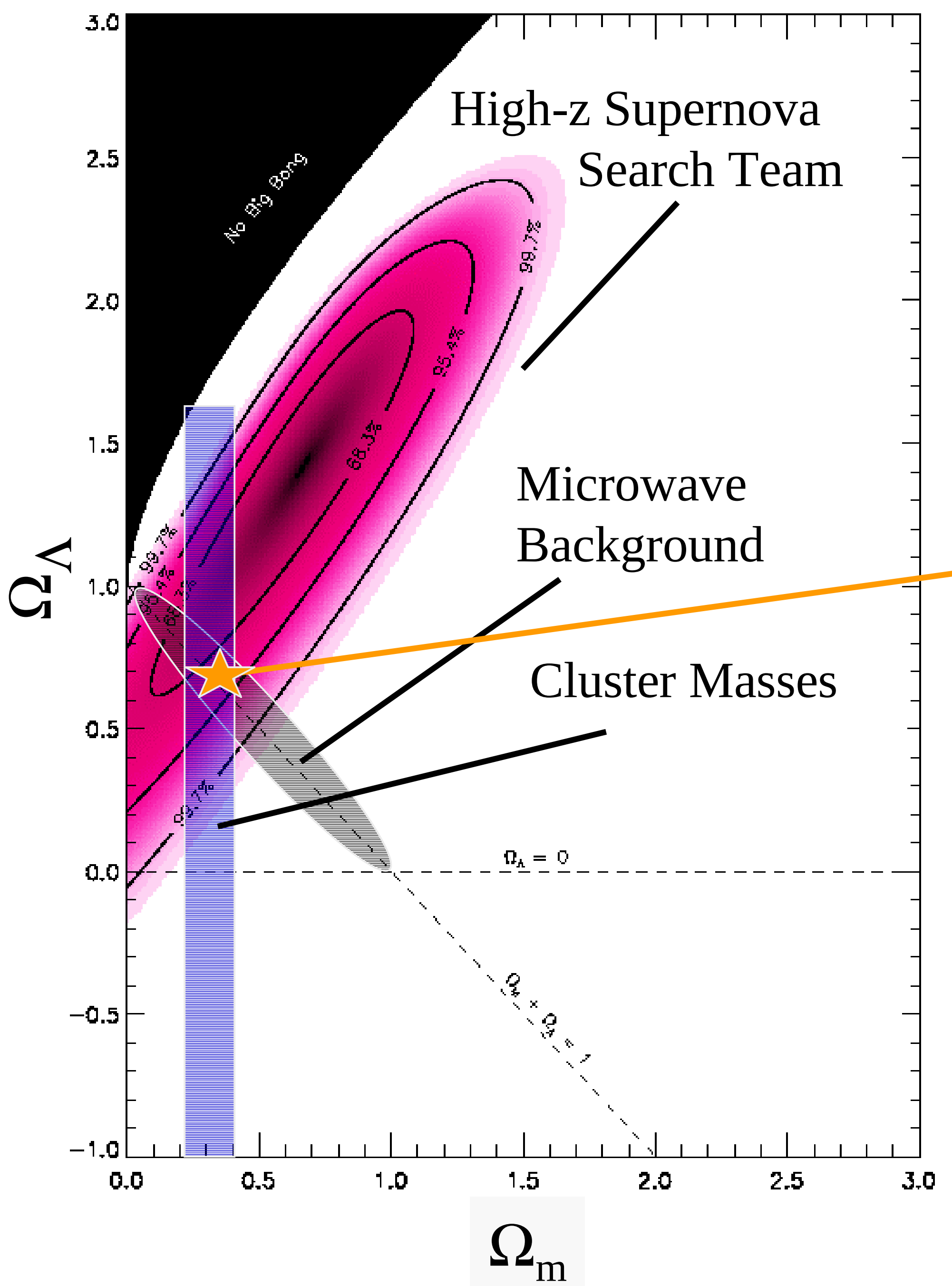
This picture is supported by multiple independent lines of evidence

- Lower bound on age, from stars
- Inventories of cosmic matter content
- Measurements of expansion history using supernovae
- Primordial element abundances
- CMB provides strong confirmation…. WMAP

WMAP- The Relic Hiss of the Big Bang



(NASA)



Insufficient mass to halt the expansion

Rate of expansion is increasing…

"Best Fit" at

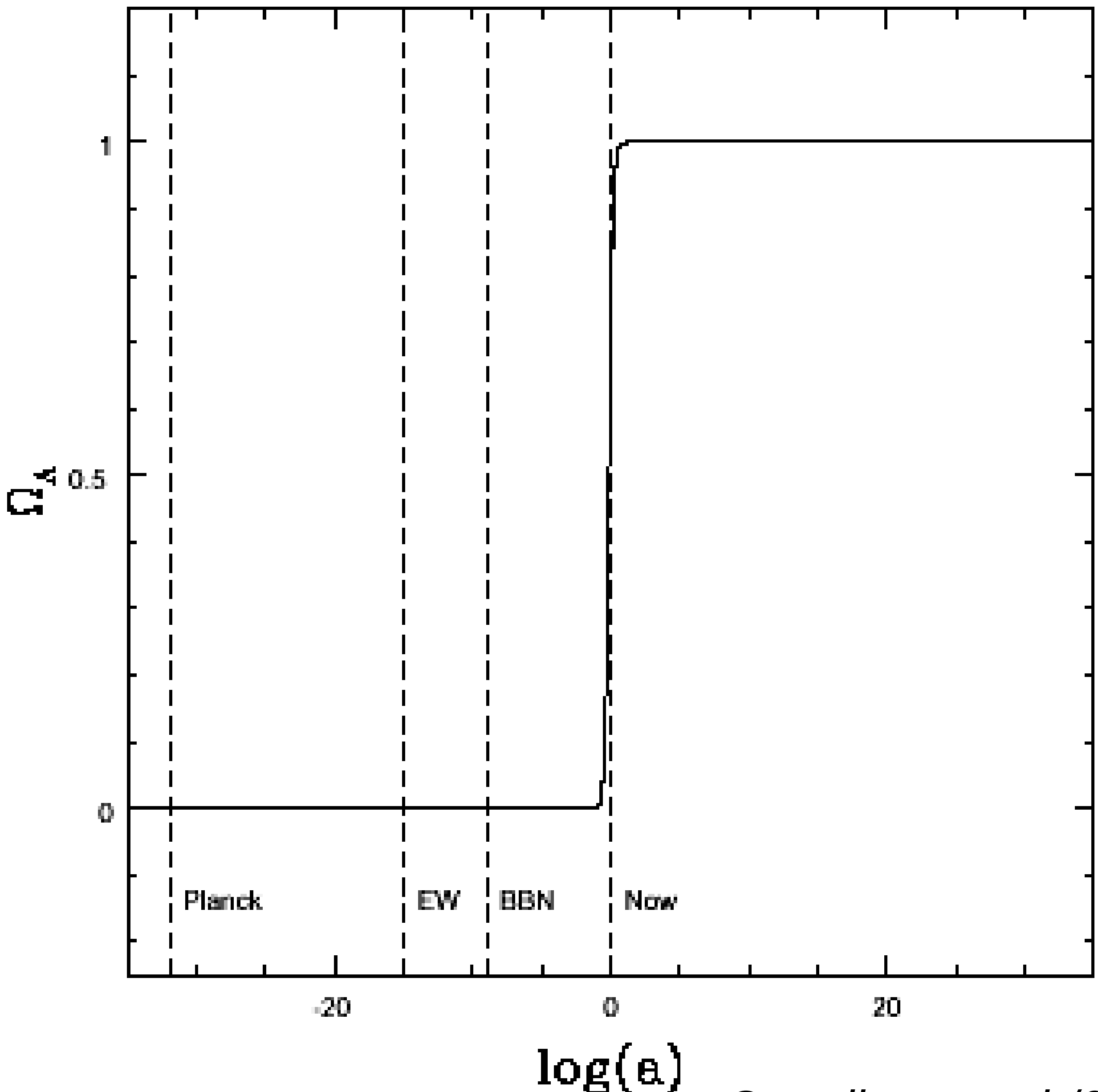
$\Omega_{mass} \sim 0.3$

$\Omega_\Lambda \sim 0.7$

Is the expansion *really* accelerating?

What does this mean?

A Repulsive Result!



Carroll, astro-ph/0004075

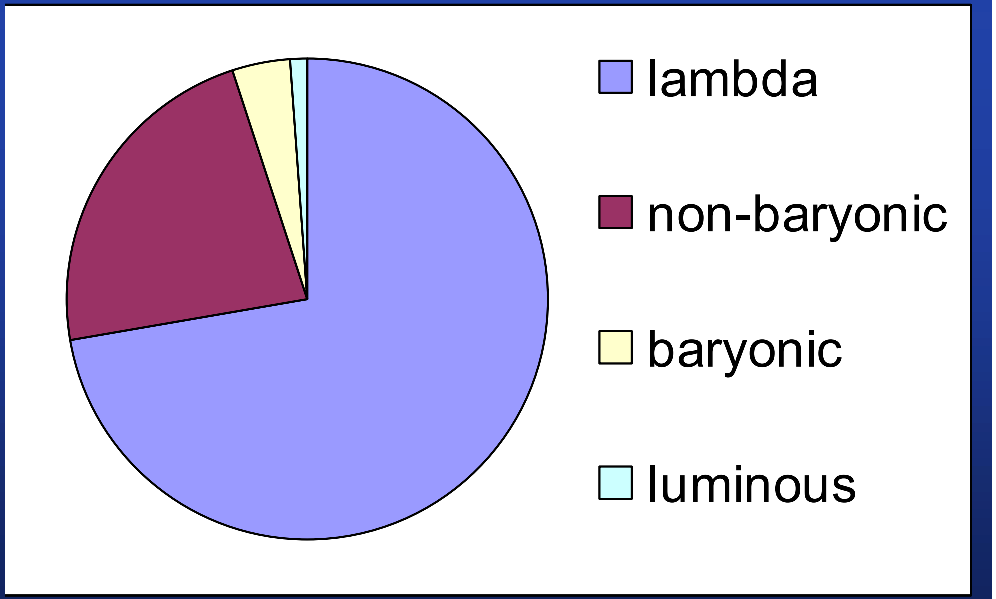
Emergence of a Standard Cosmology

Our geometrically flat Universe started in a hot big bang 13.7 Gyrs ago.

The evolution of the Universe is increasingly dominated by the phenomenology of the vacuum.

Matter, mostly non-baryonic, is a minor component.

Luminous matter comprises a preposterously low fraction of the mass of the Universe.



Two philosophically distinct possibilities…

- A "classical" cosmological constant, as envisioned by Einstein, residing in the gravitational sector.
- A "Vacuum energy" effect, arising from quantum fluctuations in the vacuum, acting as a "source" term

In either case, it's new fundamental physics!

Dark Energy's Equation of State

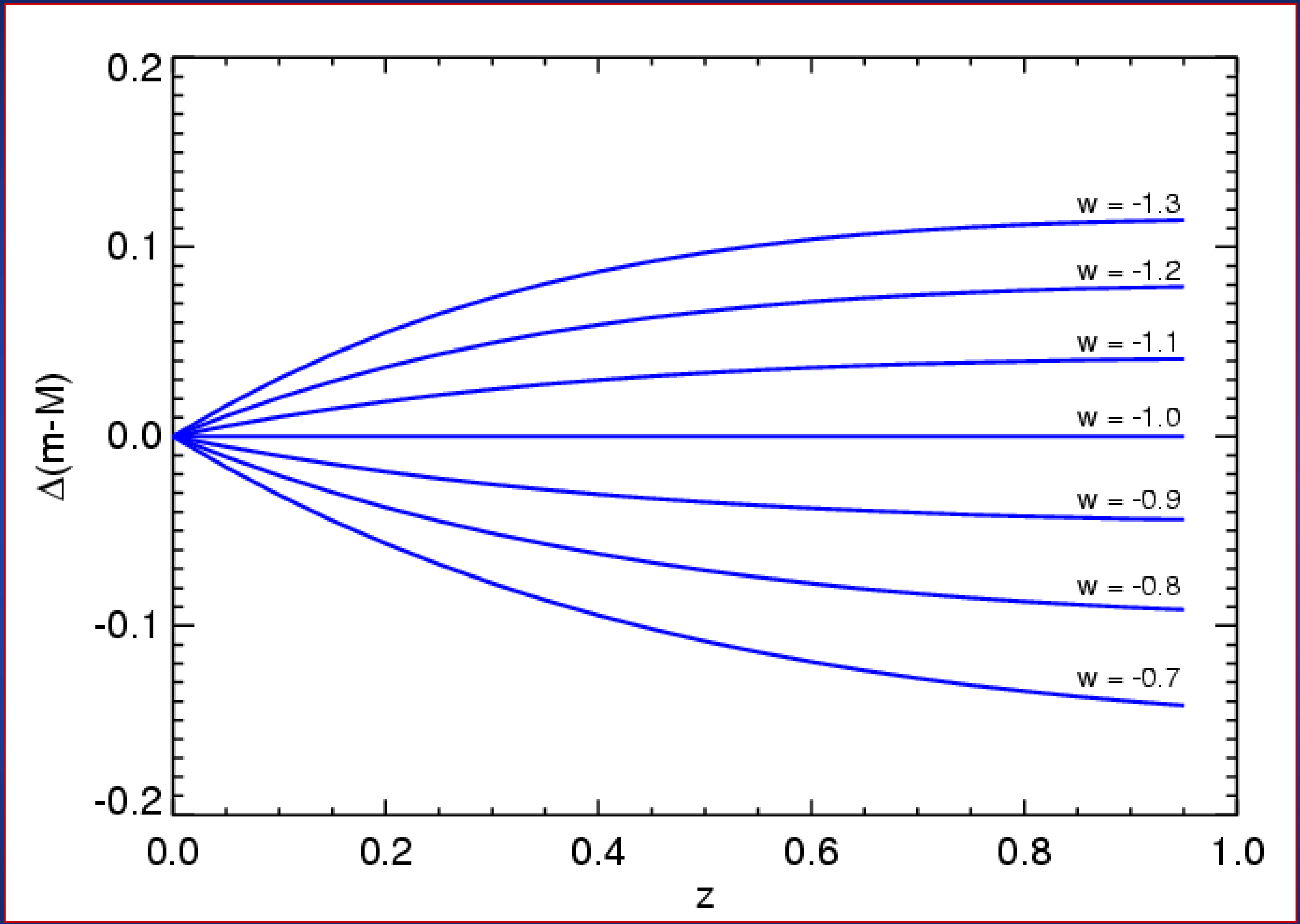
P = wρ

$$
\begin{cases}
w = 0, \text{ matter} \\
w = 1/3, \text{ radiation} \\
w = -1, \ \Lambda \\
w = -N/3, \text{ topological defects}
\end{cases}
$$

$$D_L(z) = \frac{c(1+z)}{H_0} \int_0^z \sqrt{(1-\Omega_\Lambda)(1+z')^3 + \Omega_\Lambda (1+z')^{3(1+w)}} \; dz'$$

For a flat Universe, luminosity distance depends only upon z, Ω_Λ, w.
(assumes w is constant)

Equation of State Dependence



Difference in apparent SN brightness vs. z

Ω_Λ=0.73, flat cosmology

The ESSENCE Survey

- Our goal is to determine the equation of state parameter to 10%
- This should help determine whether Λ belongs on the left or right side of the Einstein equations…
- w ≠ –1 or dw/dz ≠ 0 favors QM
- Supernovae are well suited to this task – they probe directly the epoch of accelerating expansion.

ESSENCE Survey Team

Claudio Aguilera --- CTIO/NOAO

Brian Barris --- Univ of Hawaii

Andy Becker --- Bell Labs/Univ. of Washington

Peter Challis --- Harvard-Smithsonian CfA

Ryan Chornock --- Harvard-Smithsonian CfA

Alejandro Clocchiatti --- Univ Catolica de Chile

Ricardo Covarrubias --- Univ of Washington

Alex V. Filippenko --- Univ of Ca, Berkeley

Peter M. Garnavich --- Notre Dame University

Stephen Holland --- Notre Dame University

Saurabh Jha --- Harvard-Smithsonian CfA

Robert Kirshner --- Harvard-Smithsonian CfA

Kevin Krisciunas --- CTIO/NOAO

Bruno Leibundgut --- European Southern Observatory

Weidong D. Li --- Univ of California, Berkeley

Thomas Matheson --- Harvard-Smithsonian CfA

Anthony Miceli --- Univ of Washington

Gajus Miknaitis --- Univ of Washington

Armin Rest --- Univ of Washington/CTIO

Adam G. Riess --- Space Telescope Science Institute

Brian P. Schmidt --- Mt. Stromlo Siding Springs Observatories

Chris Smith --- CTIO/NOAO

Jesper Sollerman --- Stockholm Observatory

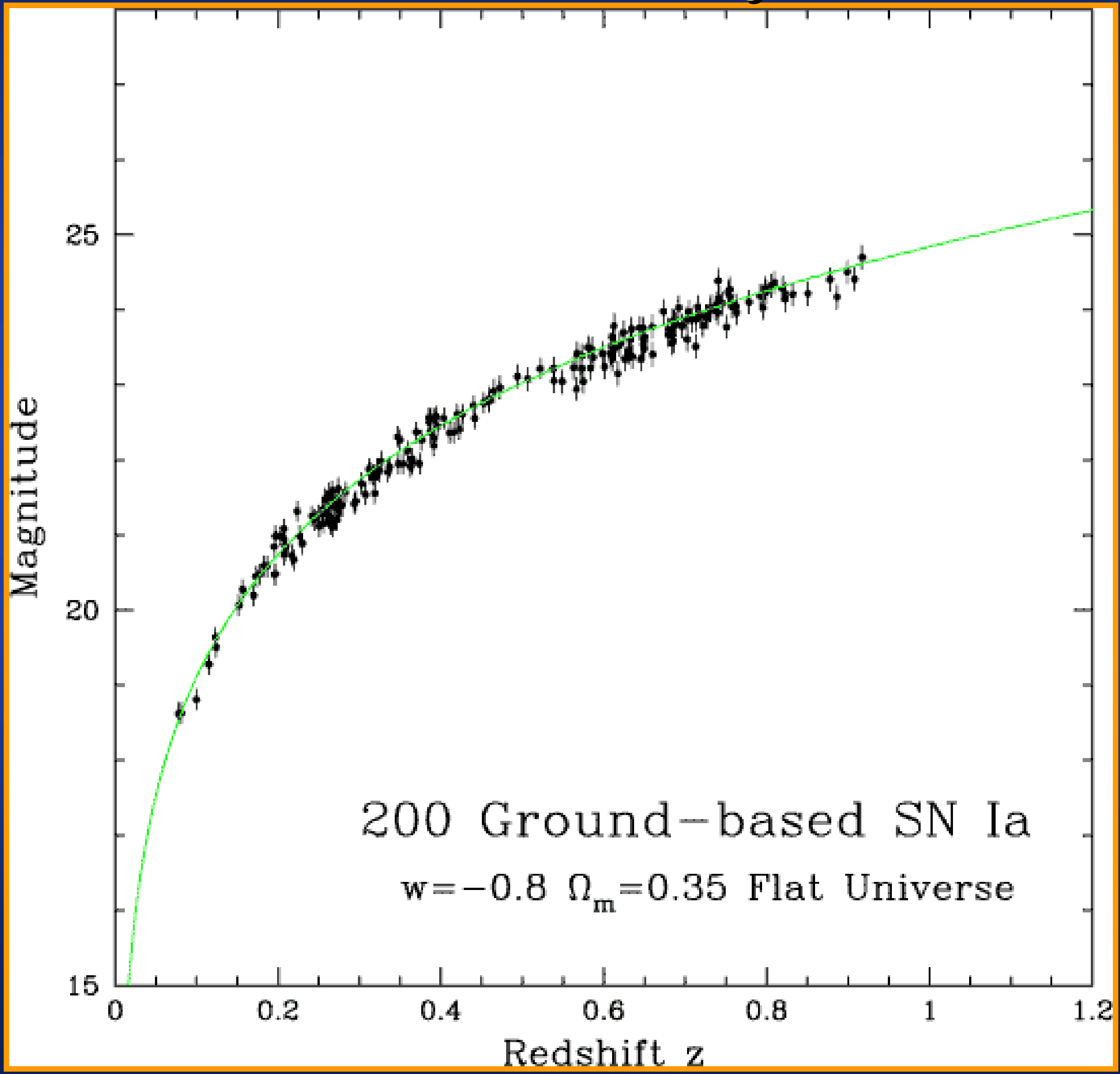
Jason Spyromilio --- European Southern Observatory

Christopher Stubbs --- Univ of Washington

Nicholas B. Suntzeff --- CTIO/NOAO

John L. Tonry --- Univ of Hawaii

A 200-SN Hubble Diagram, with particular attention to systematics



(ESSENCE team Monte Carlo, Garnavich et al, in prep)

Implementation

5 year project on 4m telescope at CTIO in Chile

Wide field images in 3 bands

Same-night detection of SNe

Spectroscopy

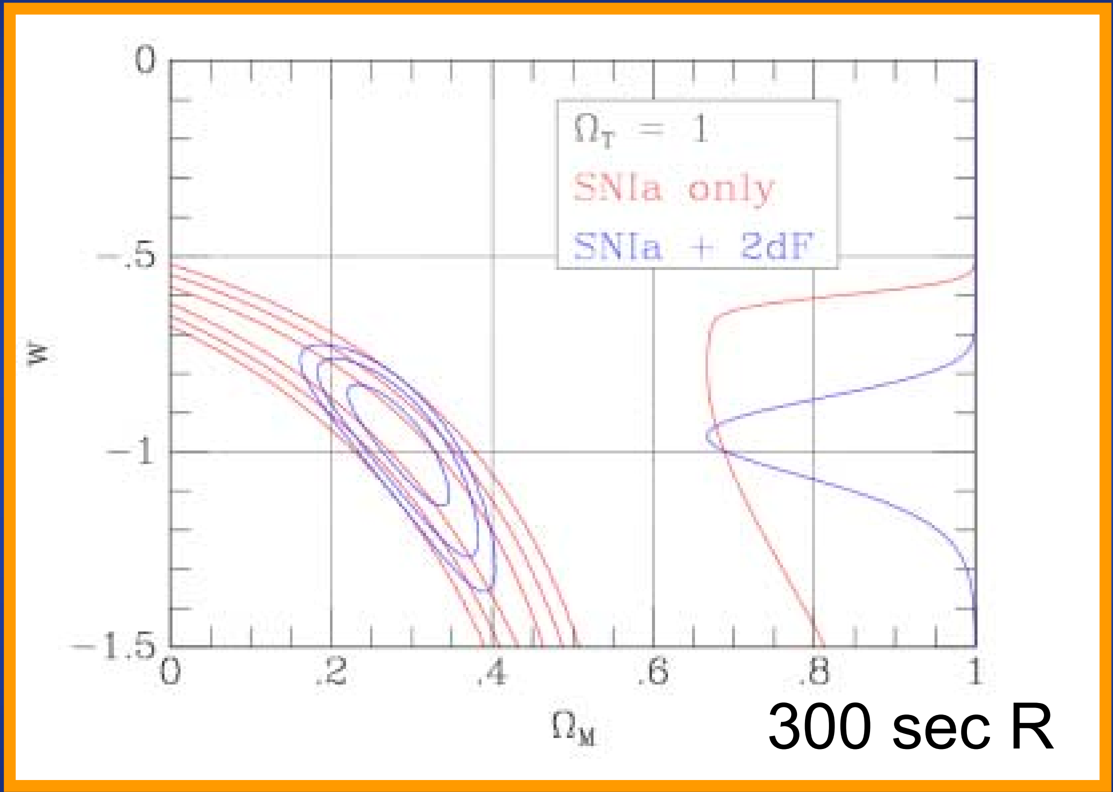
- Magellan, Keck, Gemini telescopes

Near-IR from Hubble

Goal is ~200 SNe, $0.2<z<0.8$

Distances to 2% in $\Delta z=0.1$ bins

Anticipated Cosmology Limits



Goal: Identify and classify variability in real time

1. Remove instrumental artifacts
2. Frame subtraction
   - Geometrical registration
   - Convolution with varying kernel
   - Subtraction
   - Object identification on difference image
3. Classification (SN, asteroid, etc.)
4. Ingest into Postgres database structure

Image Subtraction

Epoch 1 | Epoch 2 (3 weeks later) | Epoch 2 - Epoch 1

(High-z Supernova Team)

Hardware for “real-time” reductions

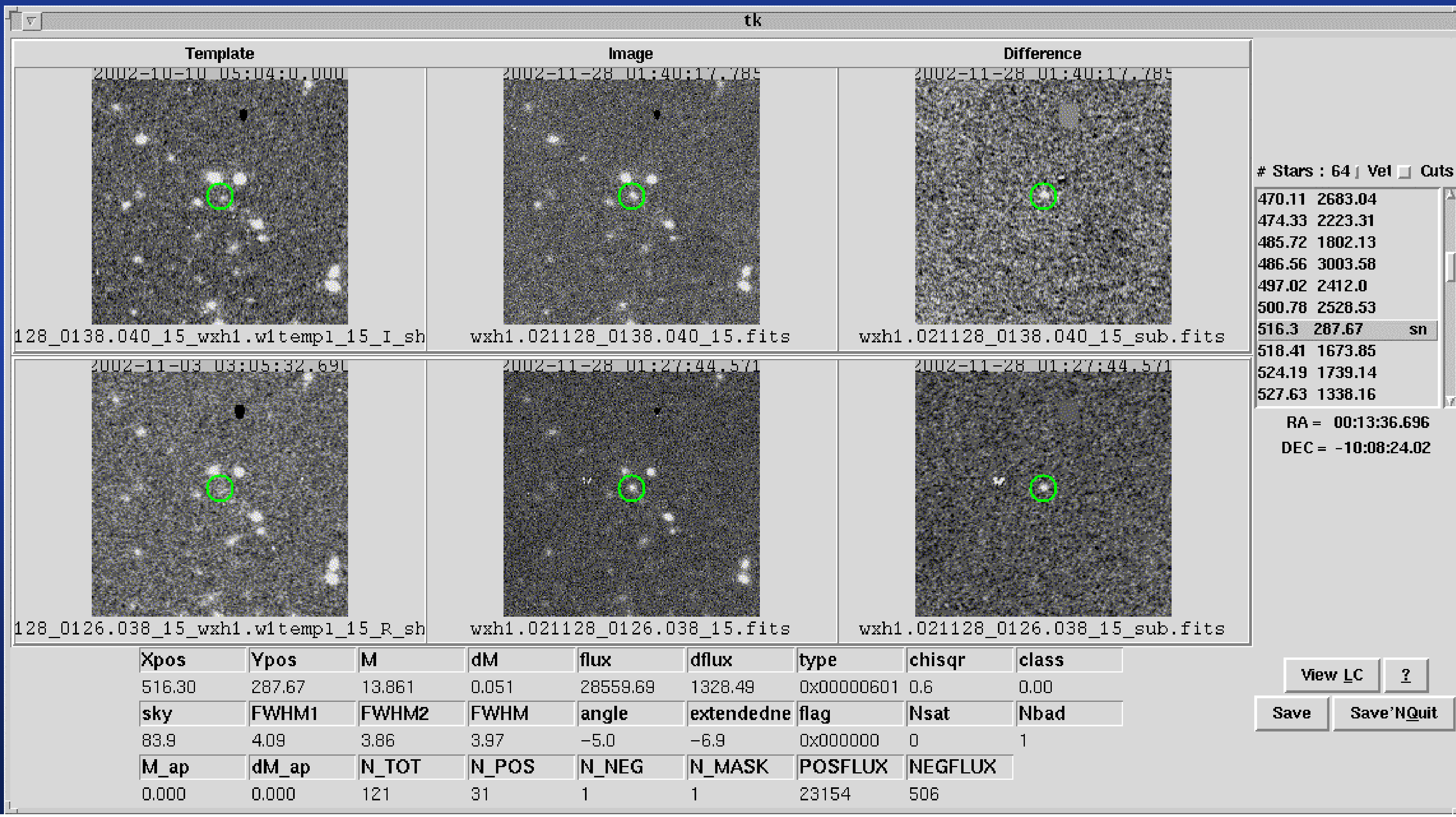
Dual networks
- 1 Gb/sec compute link
- 100 Mb/s admin link

10 compute nodes
- 2 x 1.2 GHz CPUs
- 1 GB RAM each
- 300 GB local IDE disk

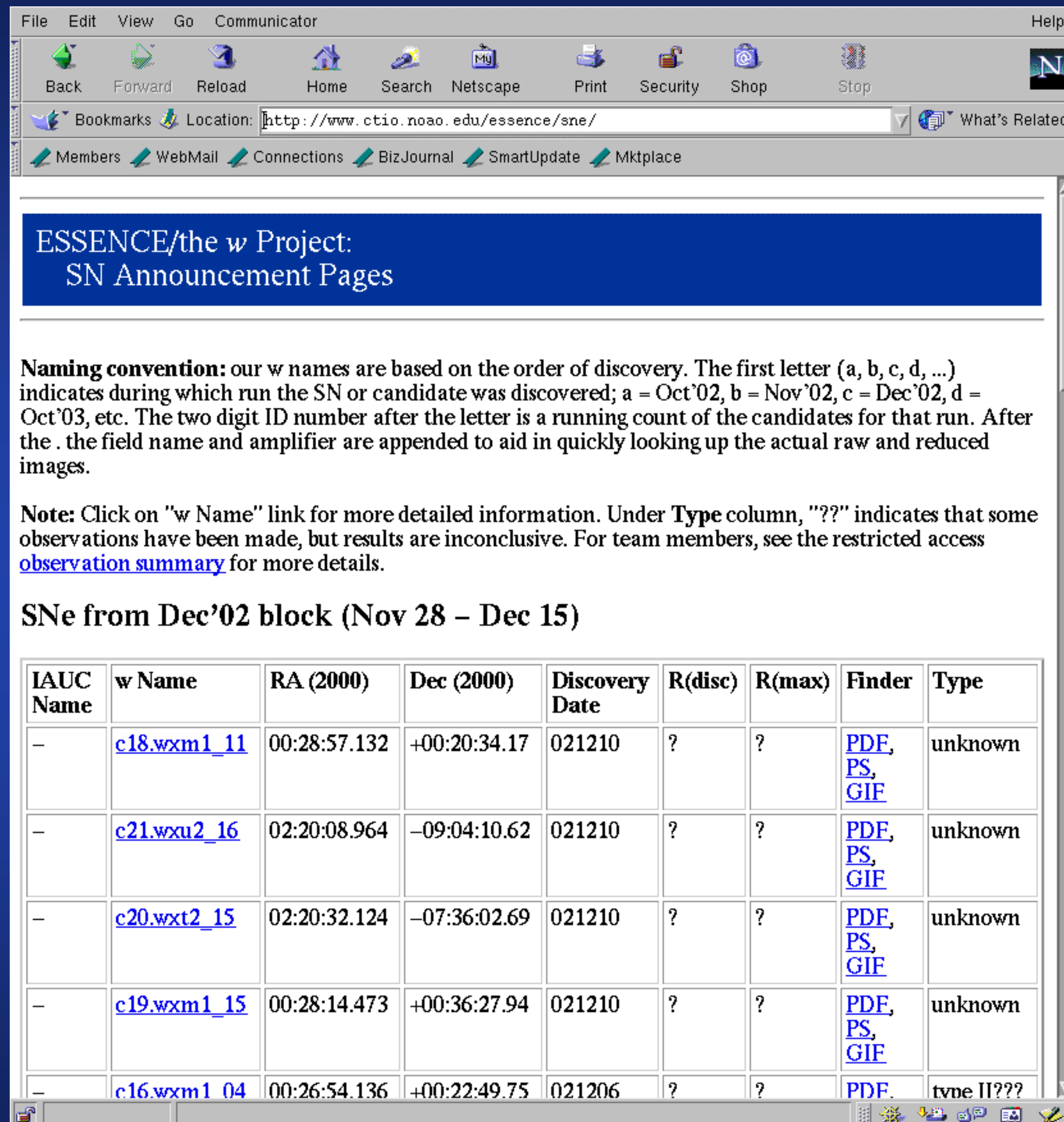
1 TB SCSI RAID disk array

2 TB IDE RAID disk array

Astrometry, magnitudes, and finding charts are published to the web.



Discoveries are announced immediately on our web site.



File Edit View Go Communicator Help

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Bookmarks Location: http://www.ctio.noao.edu/essence/sne/ What's Related

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ESSENCE/the *w* Project:
SN Announcement Pages

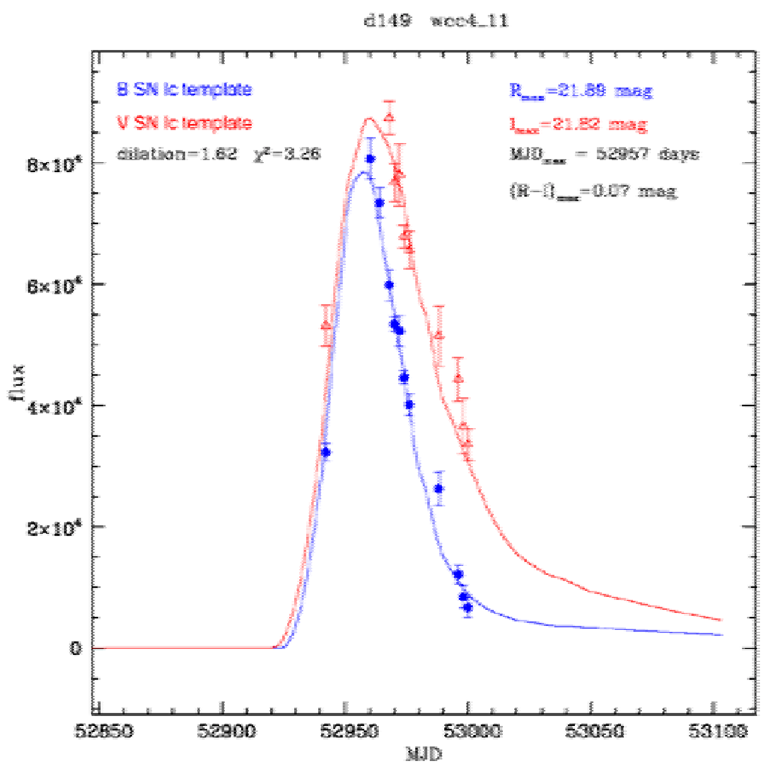
Naming convention: our w names are based on the order of discovery. The first letter (a, b, c, d, ...) indicates during which run the SN or candidate was discovered; a = Oct'02, b = Nov'02, c = Dec'02, d = Oct'03, etc. The two digit ID number after the letter is a running count of the candidates for that run. After the . the field name and amplifier are appended to aid in quickly looking up the actual raw and reduced images.

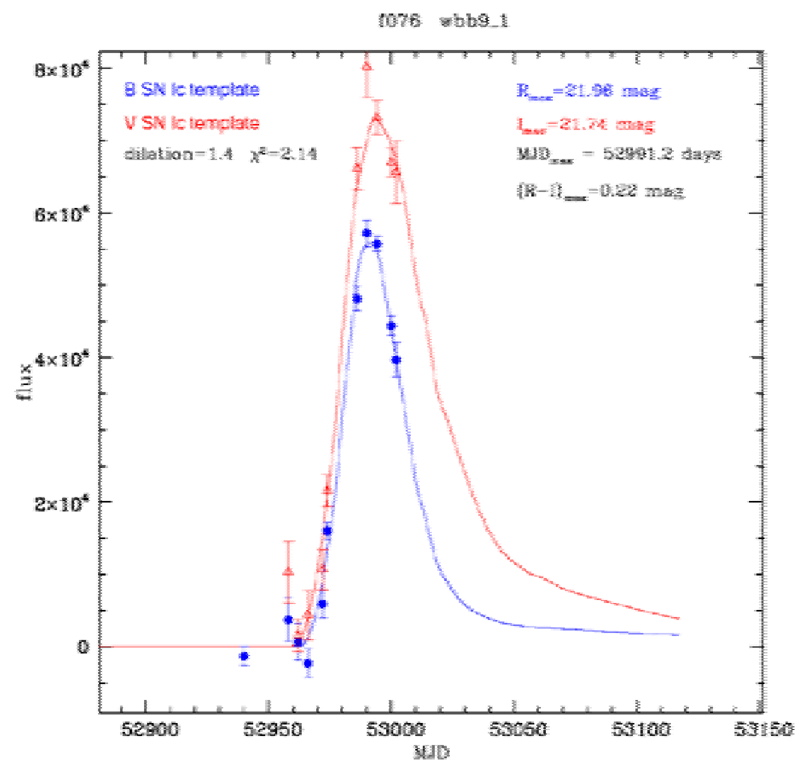
Note: Click on "w Name" link for more detailed information. Under **Type** column, "??" indicates that some observations have been made, but results are inconclusive. For team members, see the restricted access observation summary for more details.

SNe from Dec'02 block (Nov 28 – Dec 15)

IAUC Name	w Name	RA (2000)	Dec (2000)	Discovery Date	R(disc)	R(max)	Finder	Type
–	c18.wxm1_11	00:28:57.132	+00:20:34.17	021210	?	?	PDF, PS, GIF	unknown
–	c21.wxu2_16	02:20:08.964	–09:04:10.62	021210	?	?	PDF, PS, GIF	unknown
–	c20.wxt2_15	02:20:32.124	–07:36:02.69	021210	?	?	PDF, PS, GIF	unknown
–	c19.wxm1_15	00:28:14.473	+00:36:27.94	021210	?	?	PDF, PS, GIF	unknown
–	c16.wxm1_04	00:26:54.136	+00:22:49.75	021206	?	?	PDF,	type II???

Sample light curves (I)

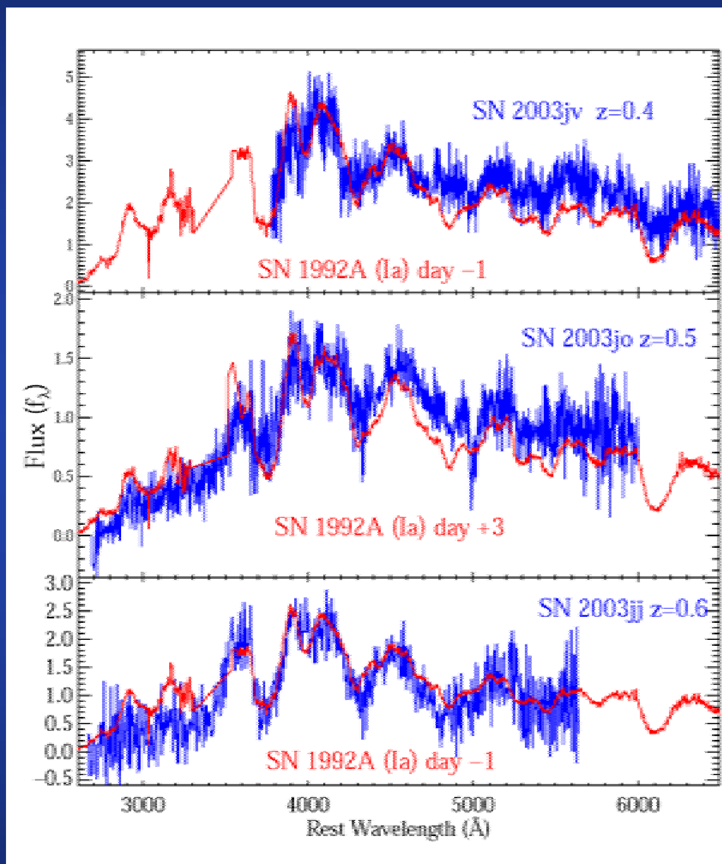


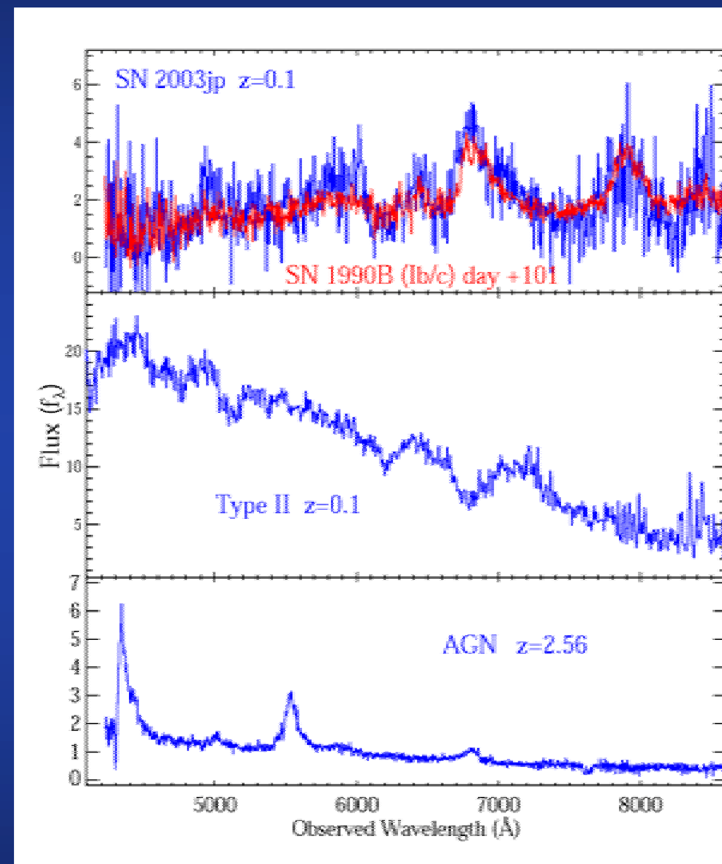


z = 0.34

z = 0.40

Spectra from 2003





from Matheson et al, astro-ph/0411357

ESSENCE Survey Progress to date – 3 of 5 seasons completed

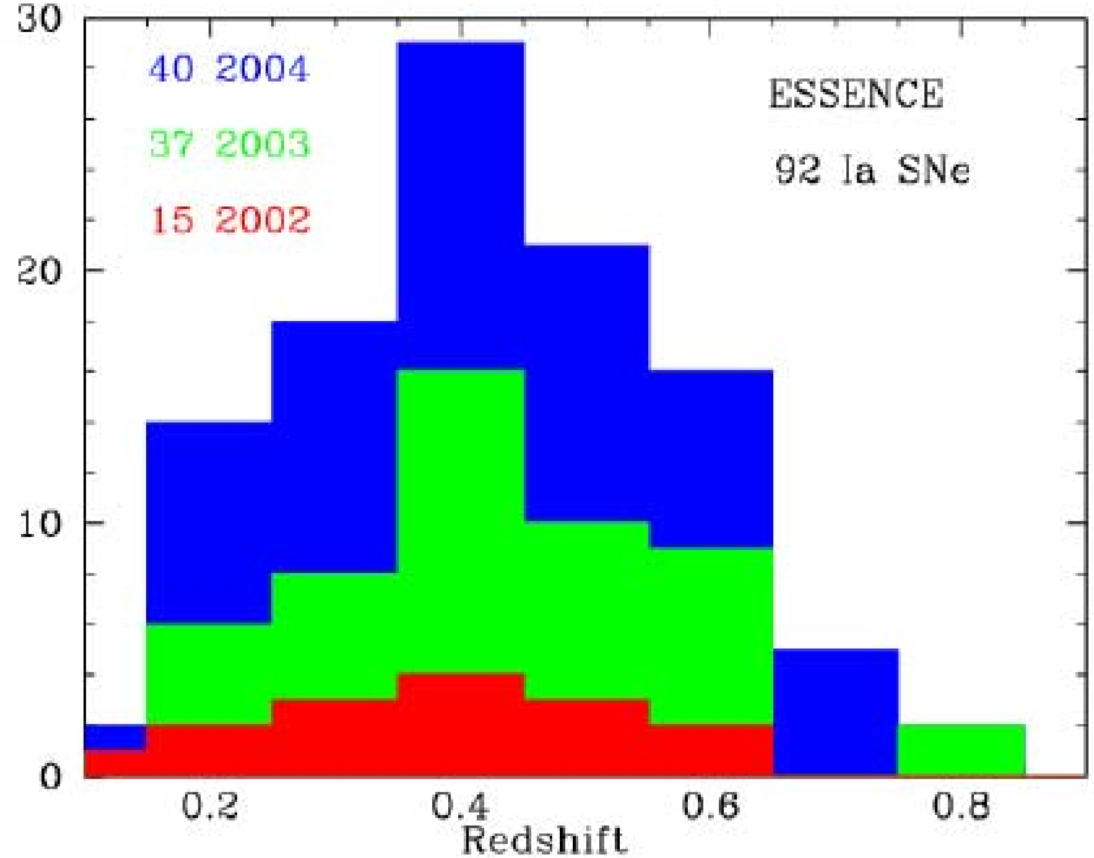


Fig.2 - Redshift distribution of the observed ESSENCE SNe Ia.

Some recent SN results

- "High-z supernova team" (Tonry et al) and Supernova Cosmology Project (Knop et al) presented new results

- "Higher-z SN team" (Reiss et al) detected distant SNe with HST

High-Z Team Results (I)

230 SNe

27+22 new SNe

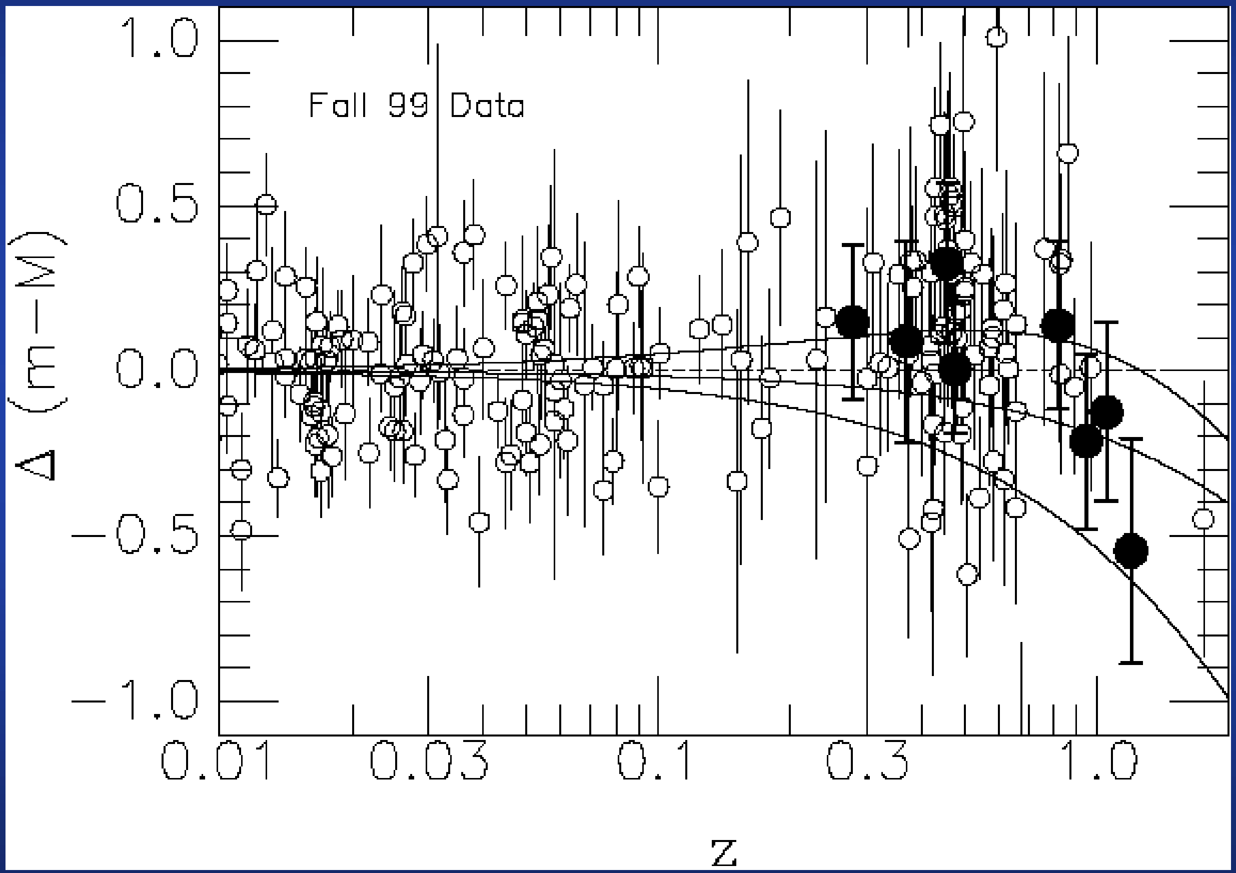
$0.3 < z < 1.2$

$(\Omega_M, \Omega_\Lambda)$ =

(0.3,0.7),

(0.3,0.0),

(1.0,0.0)



Tonry et al (2003), Barris et al (2003)

High-Z SN Team Results (II)

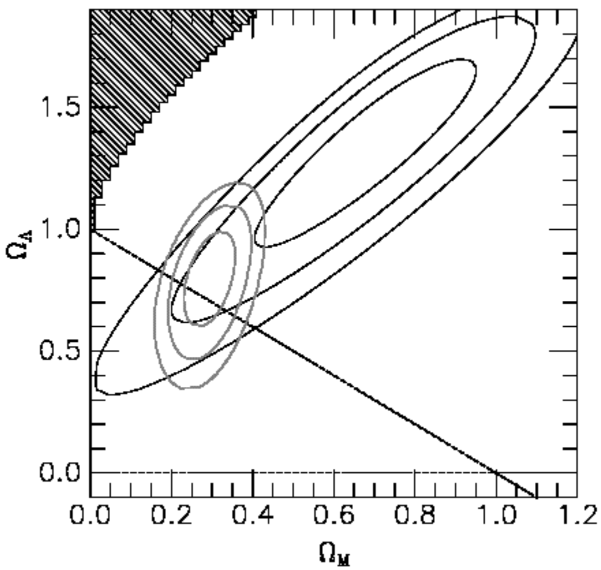


Fig. 12.— Probability contours for Ω_Λ versus Ω_M are shown at 1σ, 2σ, and 3σ with $w = -1$. We also give 1σ, 2σ, and 3σ contours when we adopt a prior of $\Omega_M h = 0.20 \pm 0.03$ from the 2dF survey (Percival et al. 2001). These constraints use the full sample of 172 SN Ia with $z > 0.01$ and $A_V <$ 0.5 mag.

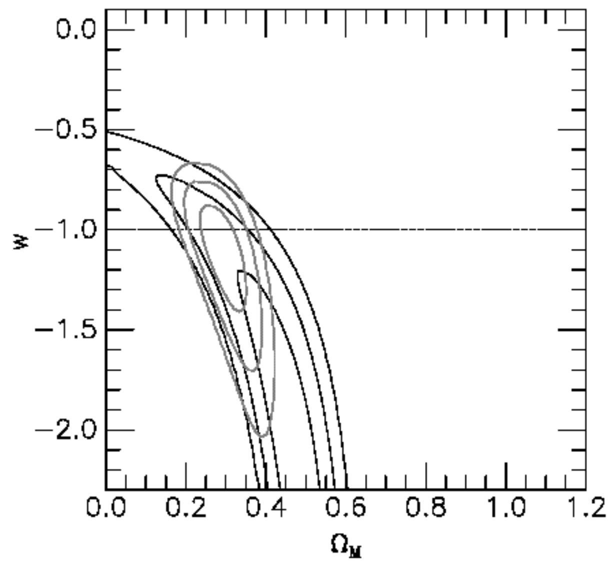


Fig. 13.— Probability contours for dark energy parameter w versus Ω_m are shown at 1σ, 2σ, and 3σ when $\Omega_{tot} = 1$. We also give 1σ, 2σ, and 3σ contours when we adopt a prior of $\Omega_M h = 0.20 \pm 0.03$ from the 2dF survey (Percival et al. 2001). This sample includes all 172 SN Ia with $z > 0.01$ and $A_V < 0.5$ mag.

Tonry et al (2003)

Tonry et al, astro/ph 0305008

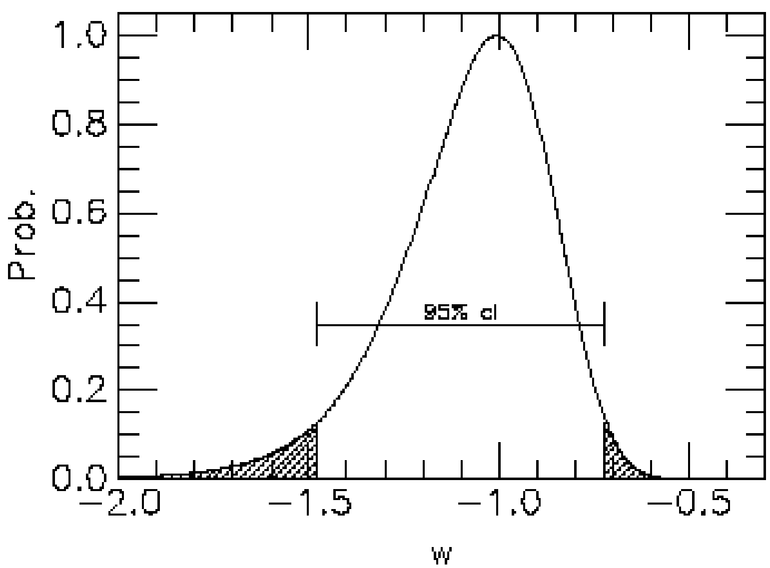


Fig. 14.— The probability distribution for w using the 2dF prior, marginalized over Ω_M. The 95% confidence limits are $-1.48 < w < -0.72$.

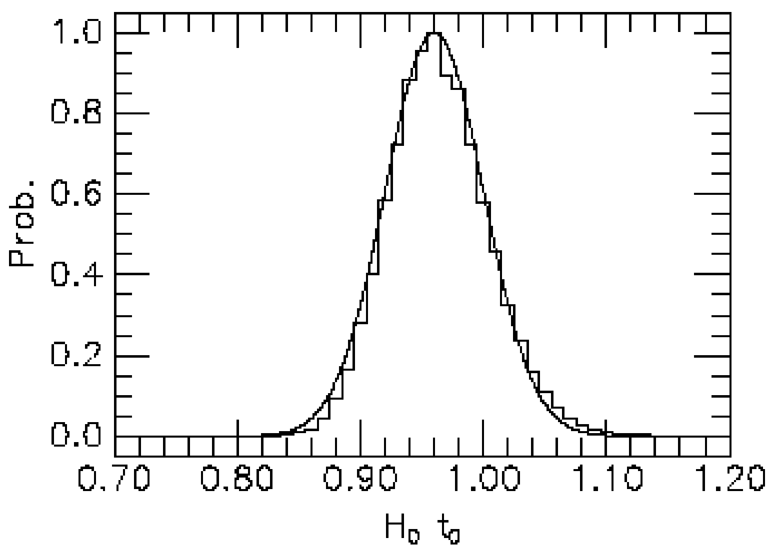
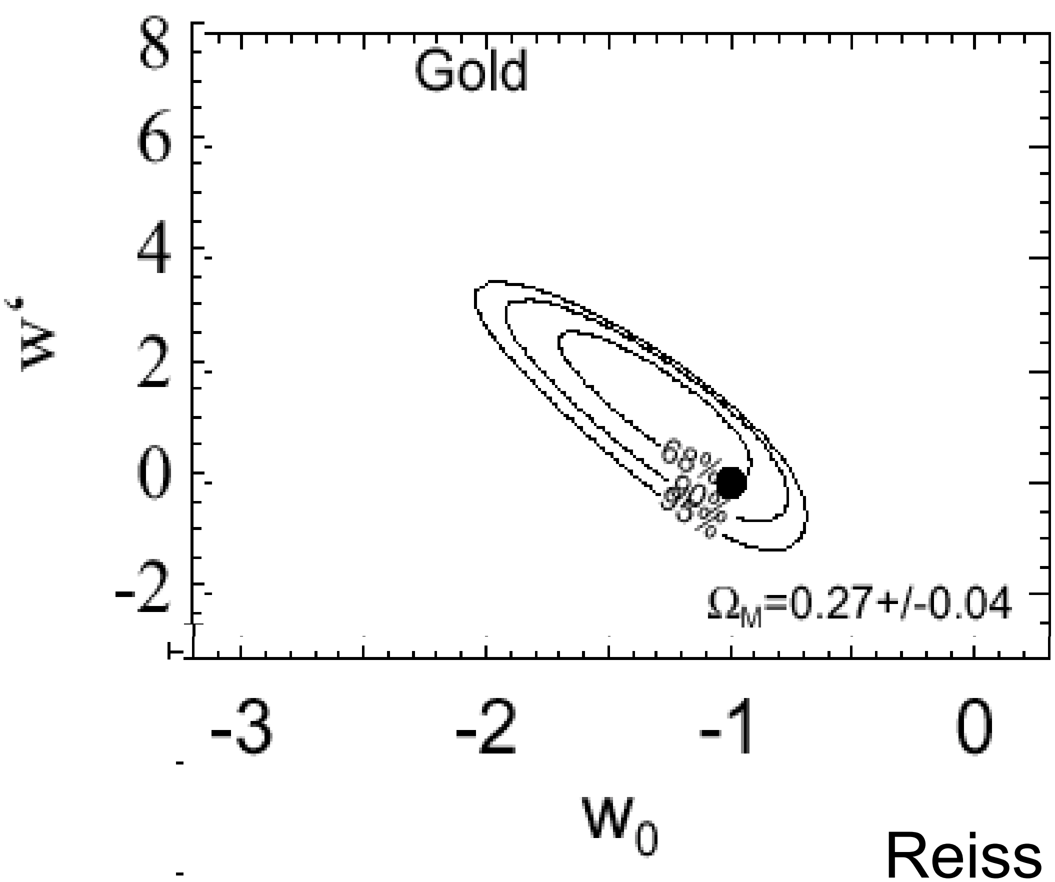


Fig. 15.— The probability distribution for $H_0 t_0$ given the SN Ia observations is tightly constrained to 0.96 ± 0.04, and an approximating Gaussian curve.

Sure looks a lot like Λ...

For $w(z) = w_0 + w`z$, $w` = dw/dz|_{z=0}$



Reiss et al

Importance of non-zero Λ.

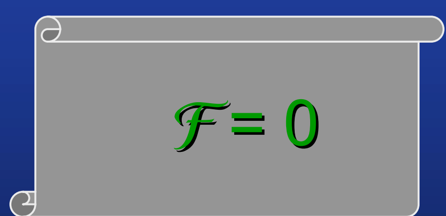
- If true, this is clear evidence for new physics at an interface we don't presently understand

- Most recent shift in cosmological paradigm:
  - Heliocentric
  - Big Bang
  - Dark Matter >> luminous/baryonic matter
  - Inflationary paradigm
  - Dark Energy >> Dark matter >> luminous material

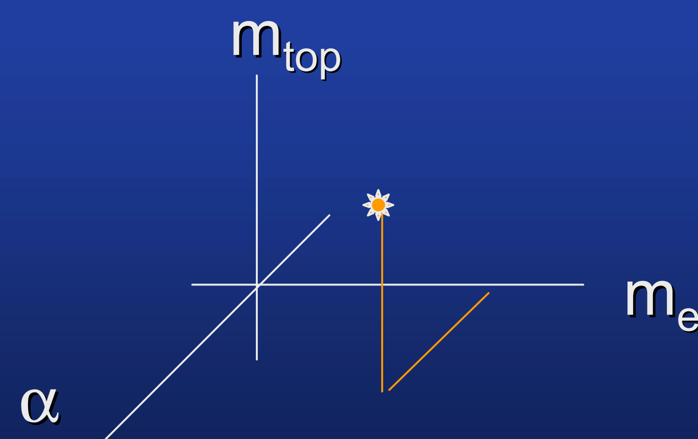
Has non-zero Λ toppled reductionism!?

- The reductionist approach to physics has been very successful
  - Newton's Universal law of gravitation
  - Atoms, Electricity & Magnetism
  - Quarks and Leptons
  - Unification of fundamental interactions...

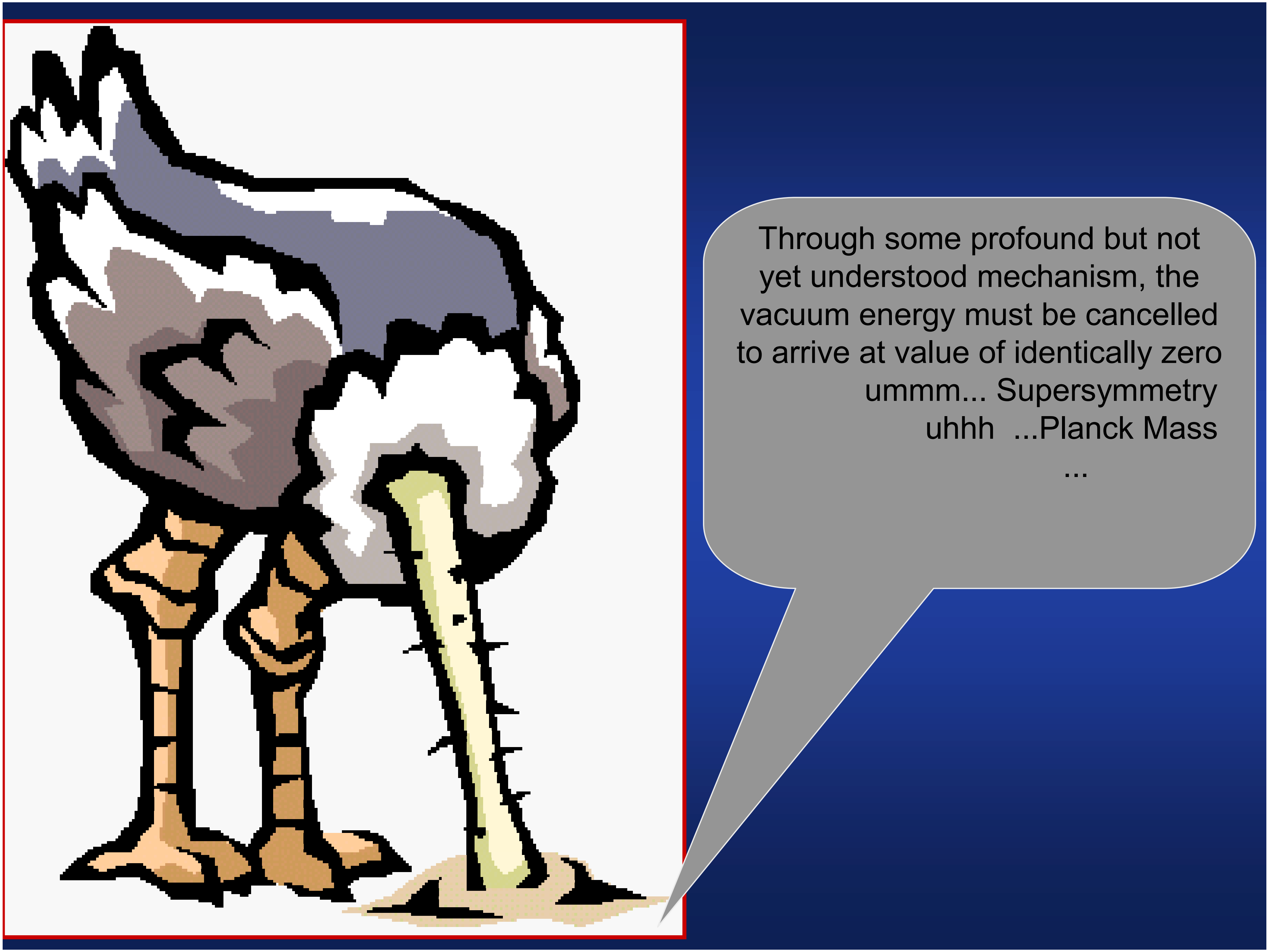
The goal:



Elegant TOE equation



Constrained parameters


Through some profound but not yet understood mechanism, the vacuum energy must be cancelled to arrive at value of identically zero
ummm... Supersymmetry
uhhh ...Planck Mass
...

Two possible "natural" values

- Vacuum energy integrated up to Planck scale $\Omega_\Lambda \sim 10^{120}$
- Cancellation via tooth fairy:

$$\Omega_\Lambda = 0.0000000000000000000000000000....$$

- But it's measured to be around 0.7!

From string theory perspective...

- Constraining Ω_Λ =0 reduces number of candidate vacuum configurations ("landscapes").
- With non-zero Ω_Λ, get of order 10^{1000} landscapes, each with potentially different kinds of physics
- What picks the one we inhabit?

Anthropic predictions for vacuum energy and neutrino masses

Levon Pogosian[1], Alexander Vilenkin[1], and Max Tegmark[2]

[2]

It is argued that
could be due to
separately from
made under the
calculate predict
mass. In the se
We find that th
with observation

Scientific alternatives to the anthropic principle

Lee Smolin*

Physics,
2W9, Canada, and

Anthropic predictions: the case of the cosmological constant

Alexander Vilenkin
Institute of Cosmology, Department of Physics and Astronomy,

Anthropi
falsified at a
prediction of
nature of the
and implicati

28 Jul 2004

Anthropic Reasons for Non-zero Flatness and Lambda

John D. Barrow[1], Håvard Bunes Sandvik[2], and João Magueijo[2]
[1]*DAMTP, Centre for Mathematical Sciences,*
Cambridge University, Wilberforce Rd.,
Cambridge CB3 0WA, UK
[2]*Blackett Laboratory, Imperial College,*
Prince Consort Rd., London, SW7 2BZ, UK
()

In some cosmological theories with varying constants there are anthropic reasons why the expansion

The "selection effect" viewpoint

- From all possible (presumably equally likely) sets of parameters and interaction strengths, only a small subset could produce heavy elements and evolve life.
- This selection effect is what determines observables, such as m_e/m_p, coupling strengths, etc, and *not* something deep and fundamental!

Ouch.

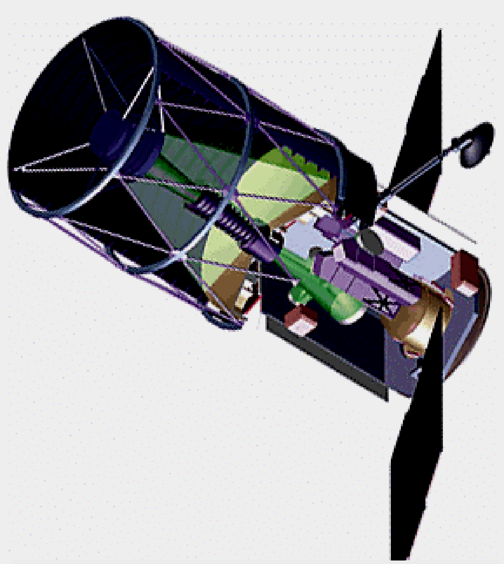
Next-Generation Facilities

Microwave background -
- Better angular resolution CMB maps
- Detection of clusters of galaxies vs. z

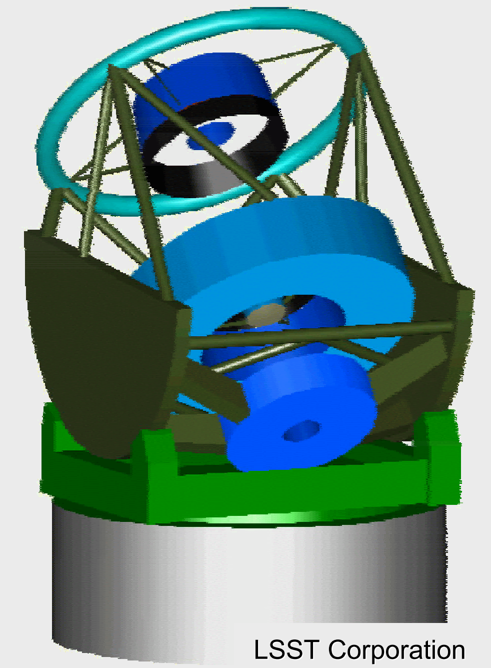
Supernovae –
- Dedicated Dark Energy satellite mission
- Large Synoptic Survey Telescope (LSST)

Weak Gravitational Lensing
- Both ground-based and space based

Probing the foundations of gravity
- Equivalence principle
- Inverse square law



SNAP, Lawrence Berkeley Laboratory



LSST Corporation

What would an optimized ground-based facility look like?

- Large collecting area
- Wide field of view
- Real-time analysis of data
- Significant leap in figure-of-merit
  - Area x Field of View

Large Synoptic Survey Telescope

Highly ranked in Decadal Survey

Optimized for time domain

- scan mode
- deep mode

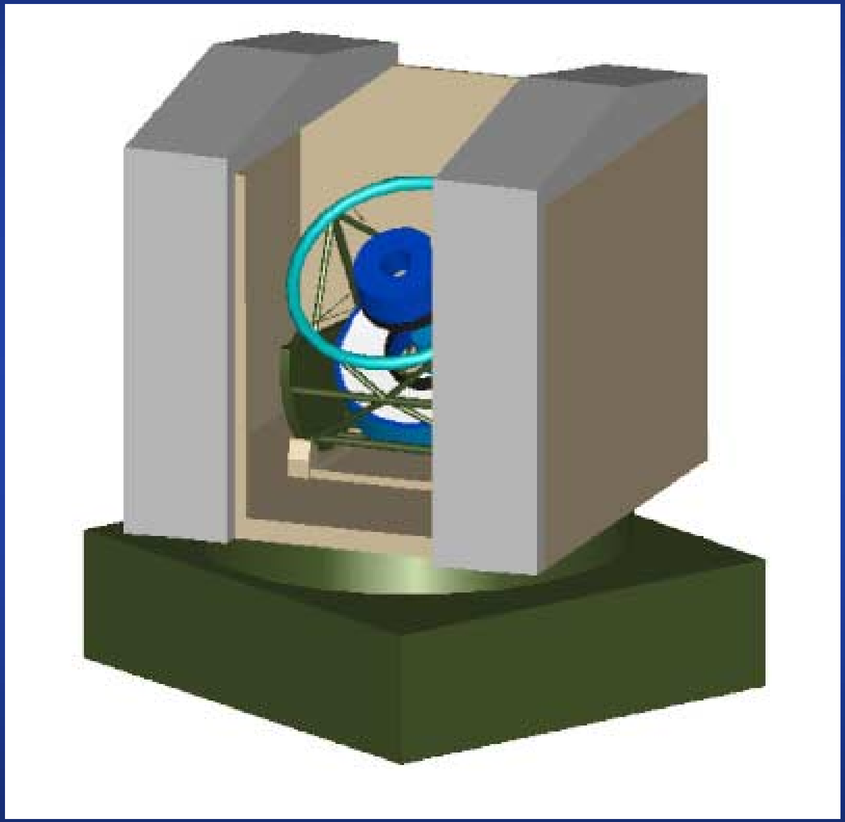
9.6 square degree field

6.5m effective aperture

24th mag in 20 sec

> 5 Tbyte/night

Real-time analysis



Simultaneous multiple science goals

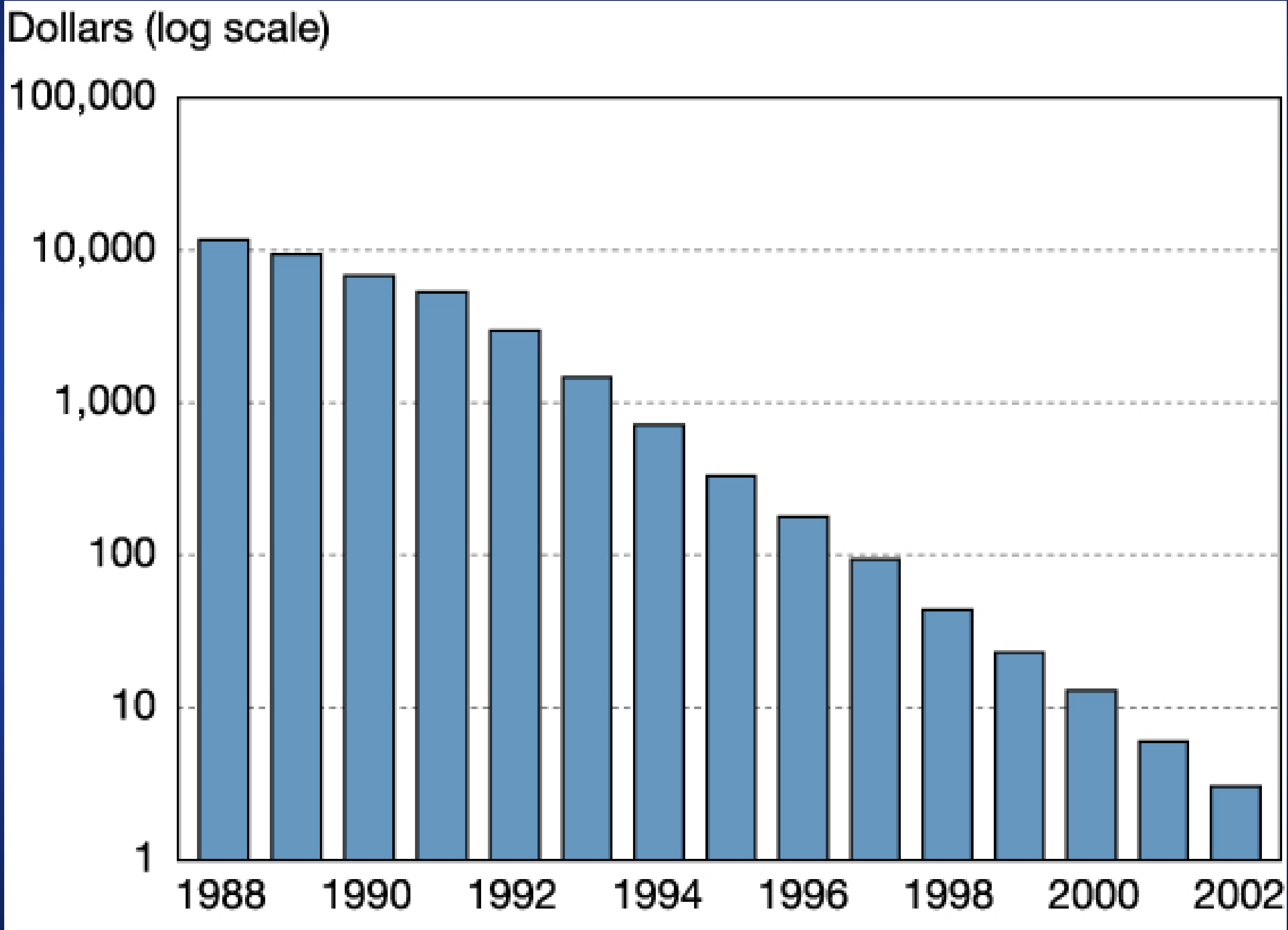
LSST Merges 3 Enabling Technologies

- Large Aperture Optics
- Computing and Data Storage
- High Efficiency Detectors

Large Mirror Fabrication

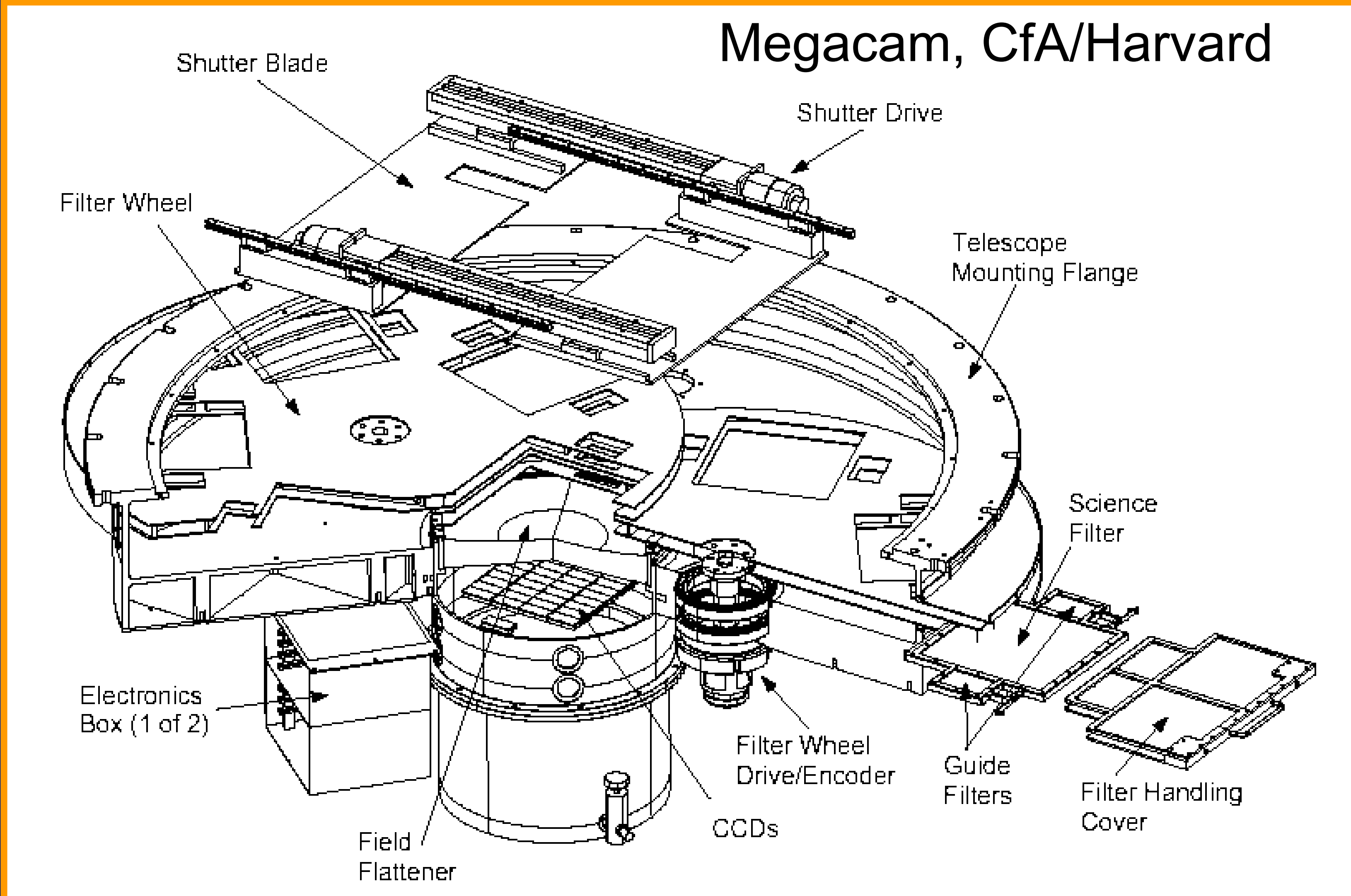
University of Arizona

Cost per Gigabyte

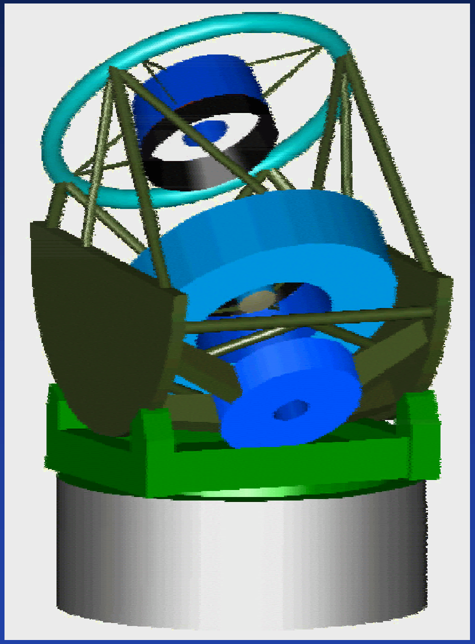


NOTES: 2001 and 2002 data are projected.

Large Format CCD Mosaics



So Why Should Physicists Care About the Large Synoptic Survey Telescope?



Fundamental Physics via Astrophysics

- Nature of Dark Matter (strong, weak and μlensing)
- Dark Energy (SNe, lensing, Large Scale Structure)
- Extreme Systems (linkages with LISA, EXIST…)

Qualitative leap in capabilities (AΩ product)

Some Examples

- Thousands of type Ia supernovae
  - ➢ Detailed study of Λ physics
  - ➢ Isotropy of Hubble diagram
  - ➢ Subdivide data set
    - Host galaxy type
    - Redshift shells
    - SN color/decline parameter
- Time delays from strongly lensed SNe
  - ➢ Constrains nature of dark matter
- Weak Lensing of galaxies as a probe of evolution of structure
- Optical counterparts to gravity wave sources
  - ➢ Break degeneracy in $(1+z)M_{chirp}$

Near Earth Asteroids

- Inventory of solar system is incomplete
- R=1 km asteroids are dinosaur killers
- R=300m asteroids in ocean wipe out a coastline
- Demanding project: requires mapping the sky down to 24th every few days, individual exposures not to exceed ~20 sec.
- LSST will detect NEAs to 300m

LSST Challenges

- Large effective aperture wide field telescope
- 3 Gpix focal plane
- Analysis pipeline
- Automated Variability Classification
- Database schema/structure and indexing

Summary

Astrophysics is a fruitful avenue for exploring new fundamental physics

- Makes sense to go where the signal is!

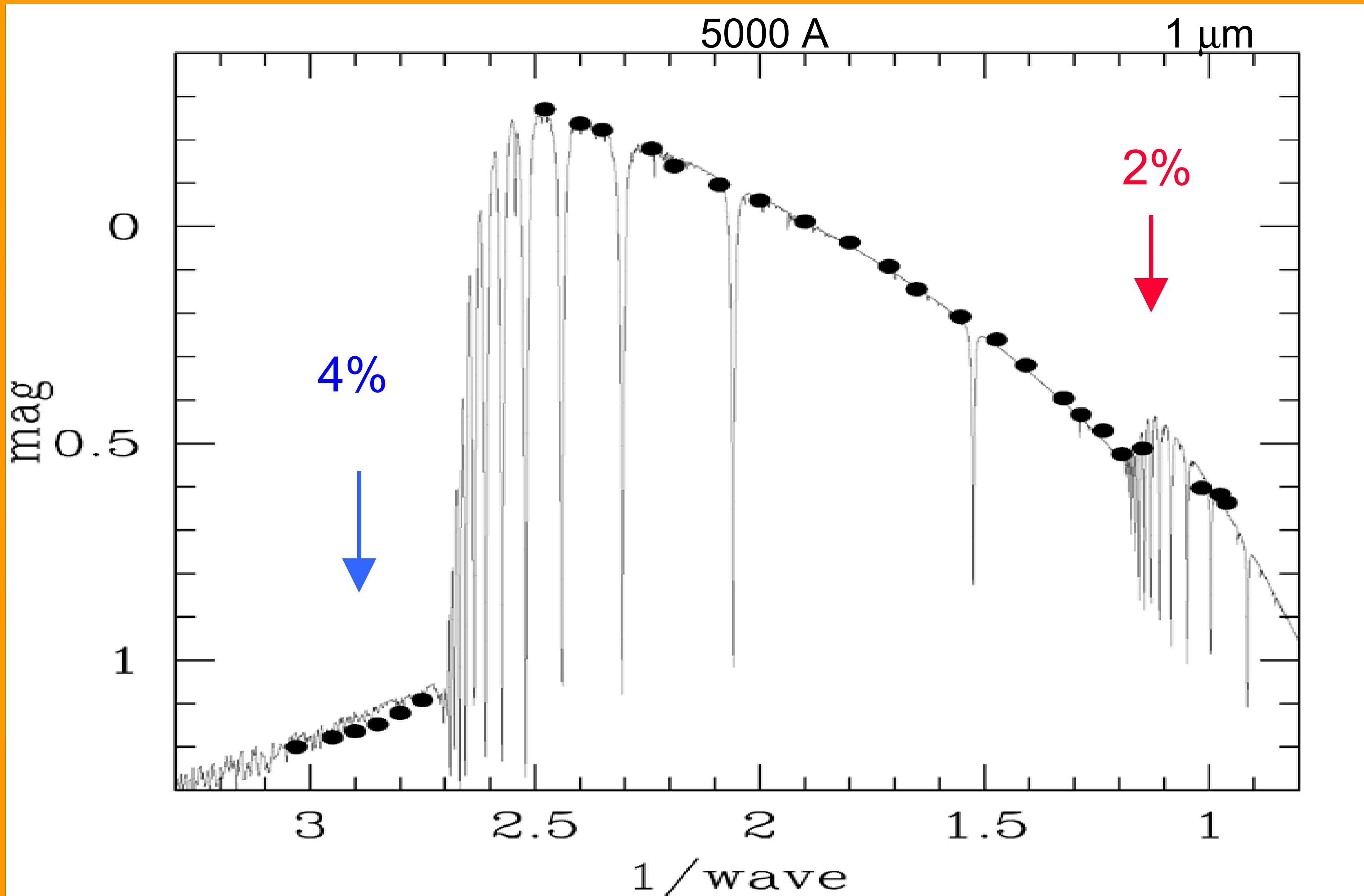
Imperatives include

- Understanding the physics of an apparent non-zero Λ
- Determining nature and distribution of dark matter
- Probing foundations of gravity

Current Metrology Chain for Ground-based Astronomical Flux Measurements.

Supernova measurements require knowing relative instrumental sensitivity vs. λ

Vega is primary celestial calibrator



Detector-based Radiometry

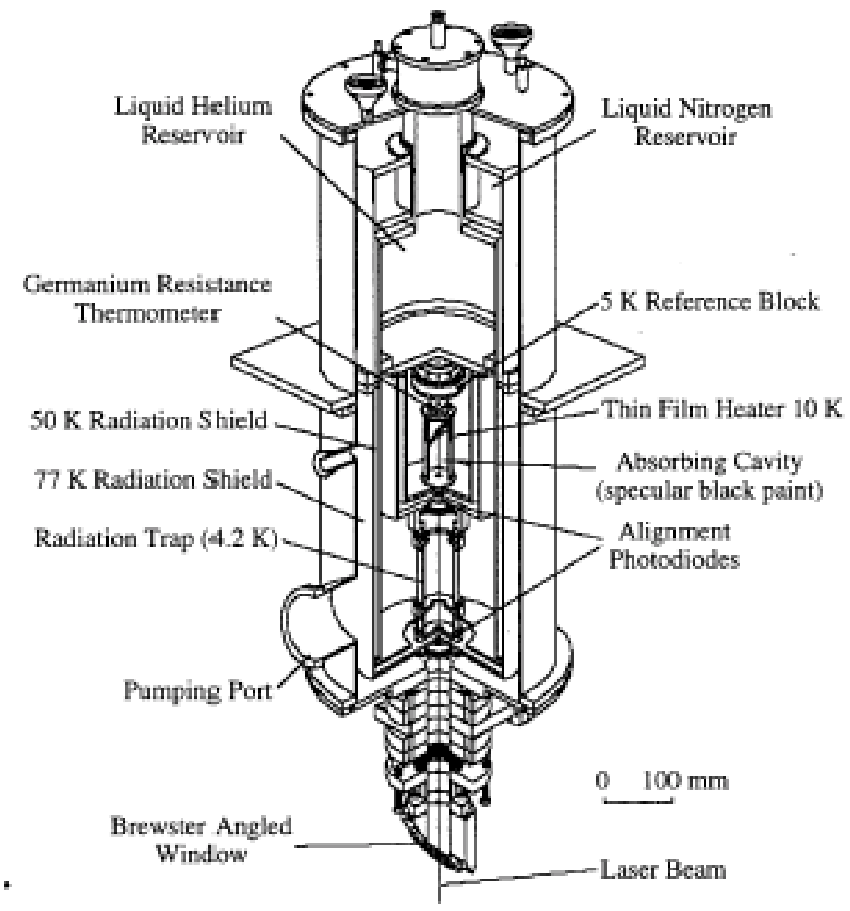


Figure 5.1. NIST High Accuracy Cryogenic Radiometer (HACR).

Modern metrology for radiometric measurements is based on detectors, not sources.

Larson, Bruce and Parr, NIST special publication 250-41

Transferring flux standard to photodiodes

Through 1 intermediate step, this calibration is transferred to Si photodiodes

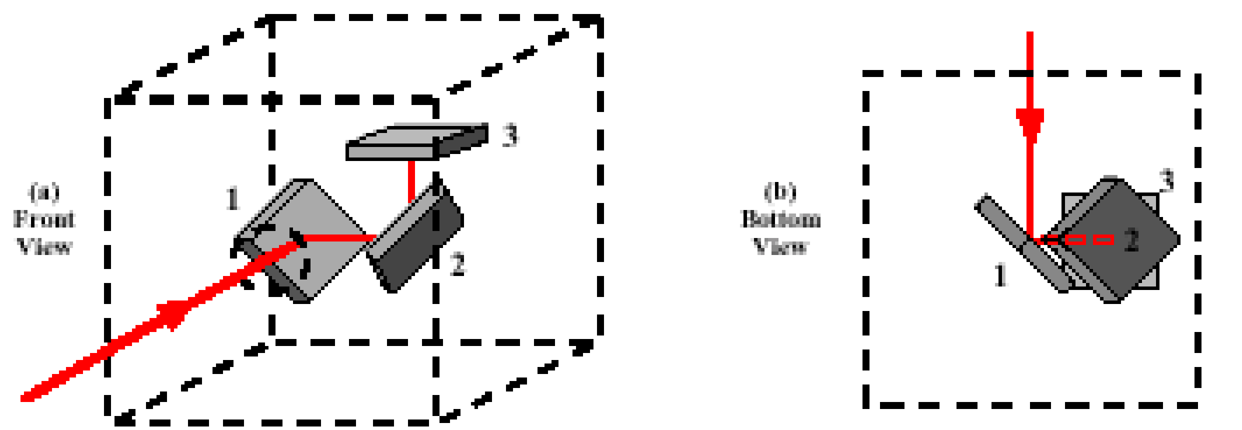


Figure 5.2. Trap detector arrangement of photodiodes minimizes light lost to reflections.

An alternative calibration approach

Calibrate end-to-end relative system response

- primary
- corrector optics
- filter
- detector

relative to Si photodiode.

Opotek tunable laser
~100 mW