SNAP SuperNova Acceleration Probe

Presentation to the NRC's
Committee on the Physics of the Universe
July 2001

Saul Perlmutter
for the SNAP Collaboration

0. Background on cosmology measurements from supernovae.

1. The science reach of SNAP for dark energy and dark matter.

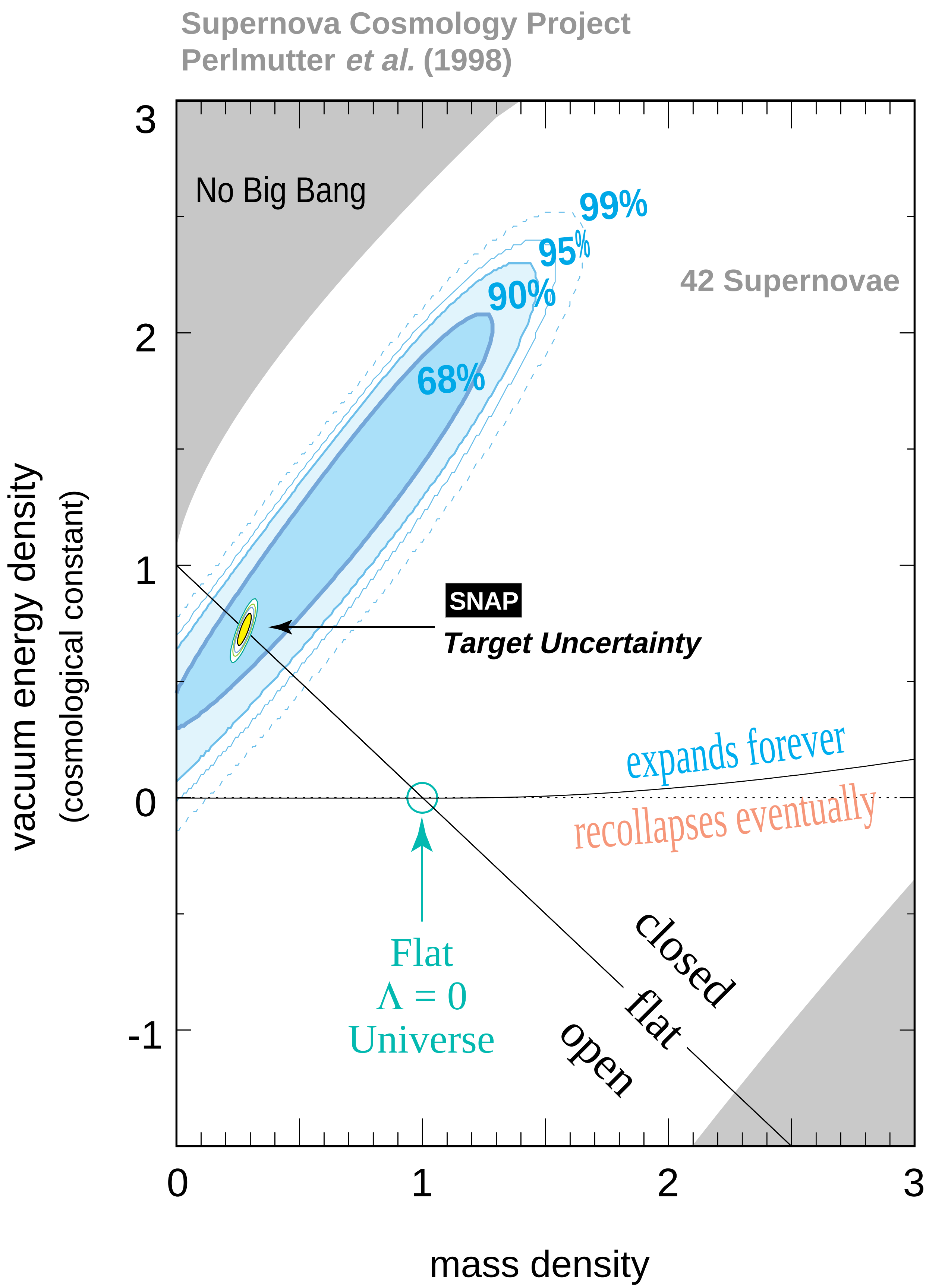
2. Systematic uncertainties -- and the prerequisites for this science.

3. The complementarity of space based and ground based approaches.

4. SNAP technology readiness and technical status.

5. SNAP cost estimates.

6. Necessary interagency cooperation.


Supernova Cosmology Project
Perlmutter et al. (1998)
No Big Bang
99%
95%
90%
68%
42 Supernovae
SNAP
Target Uncertainty
expands forever
recollapses eventually
Flat
Λ = 0
Universe
closed
flat
open
vacuum energy density
(cosmological constant)
mass density
3
2
1
0
-1
0
1
2
3

There are different
levels of precision
at which one can work:

Past "standard cosmology" has been done with

~50%
uncertainties

Recent work is moving towards

~10%
uncertainties

Planned CMB satellite work targets

~1%
uncertainties

At each of these levels there are appropriately matched levels of systematic uncertainties & simplifying assumptions.

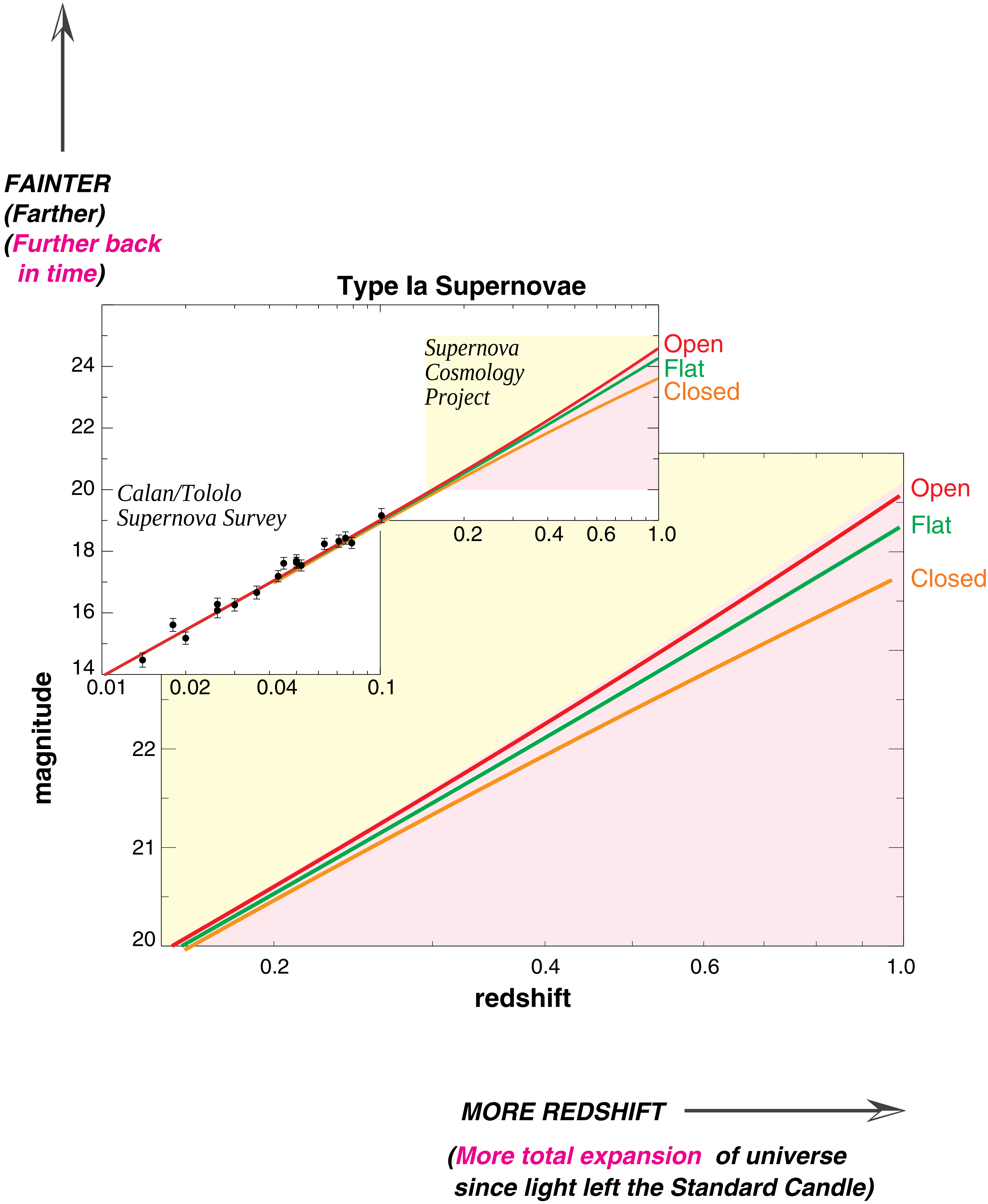
To answer "what we want to know"
we must go from 50%
through the 10% and on to the 1% level.

SNAP SuperNova Acceleration Probe

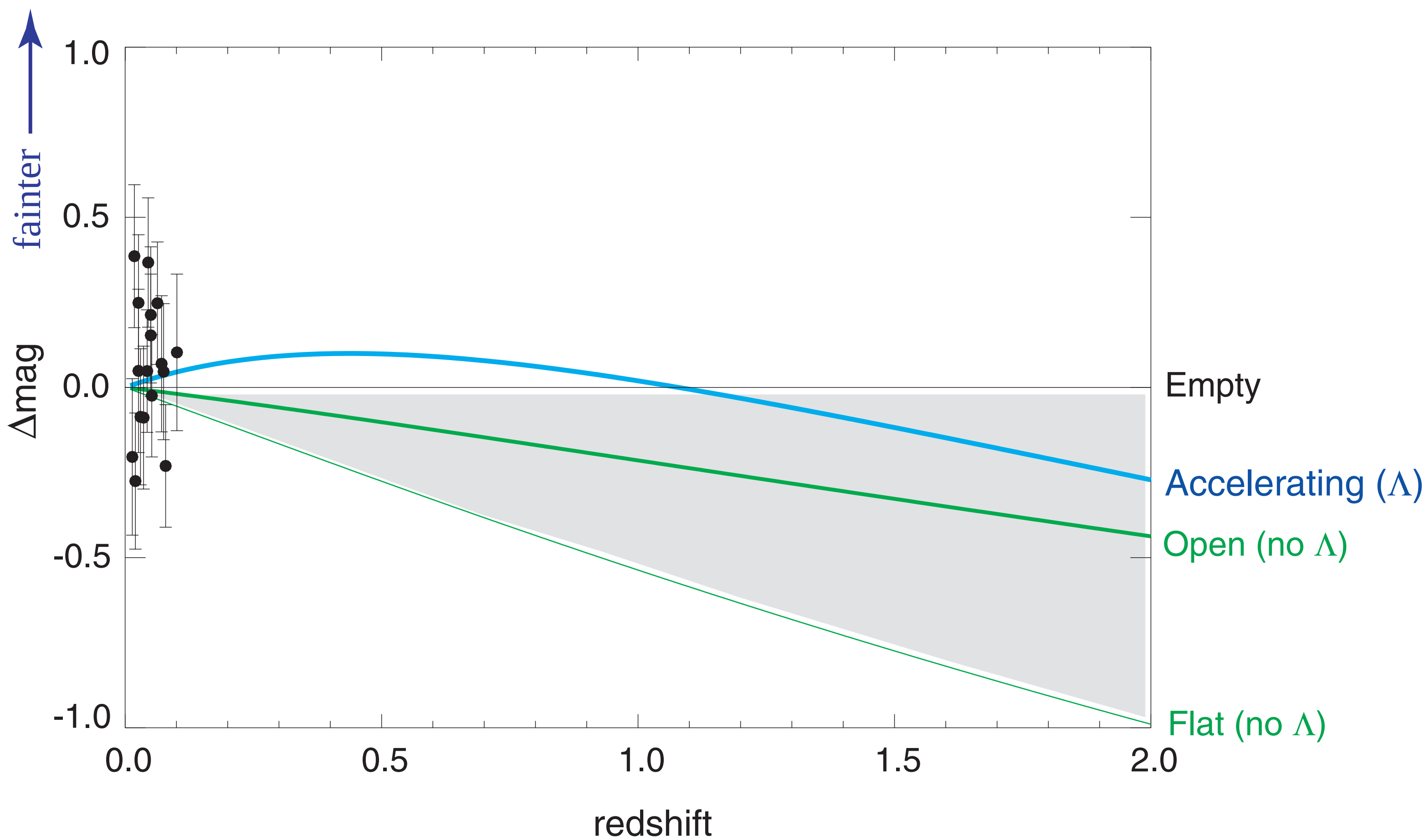
science reach

Planned 1-year baseline statistical and systematic uncertainty on...

Assuming:	Ω_M stat	Ω_M sys	Ω_Λ or $\Omega_{d.e.}$ stat	Ω_Λ or $\Omega_{d.e.}$ sys	w stat	w sys	w' stat	w' sys
$w = -1$	0.02	0.02	0.05	<0.01				
$w = -1$, flat□			0.01	0.02				
$w = const.$, flat□			0.02	0.02	0.05	<0.01		
Ω_M, Ω_k known $w = const.$					0.02	<0.01		
Ω_M, Ω_k known $w(z) = w + w'z$					0.08	<0.01	0.12	0.15

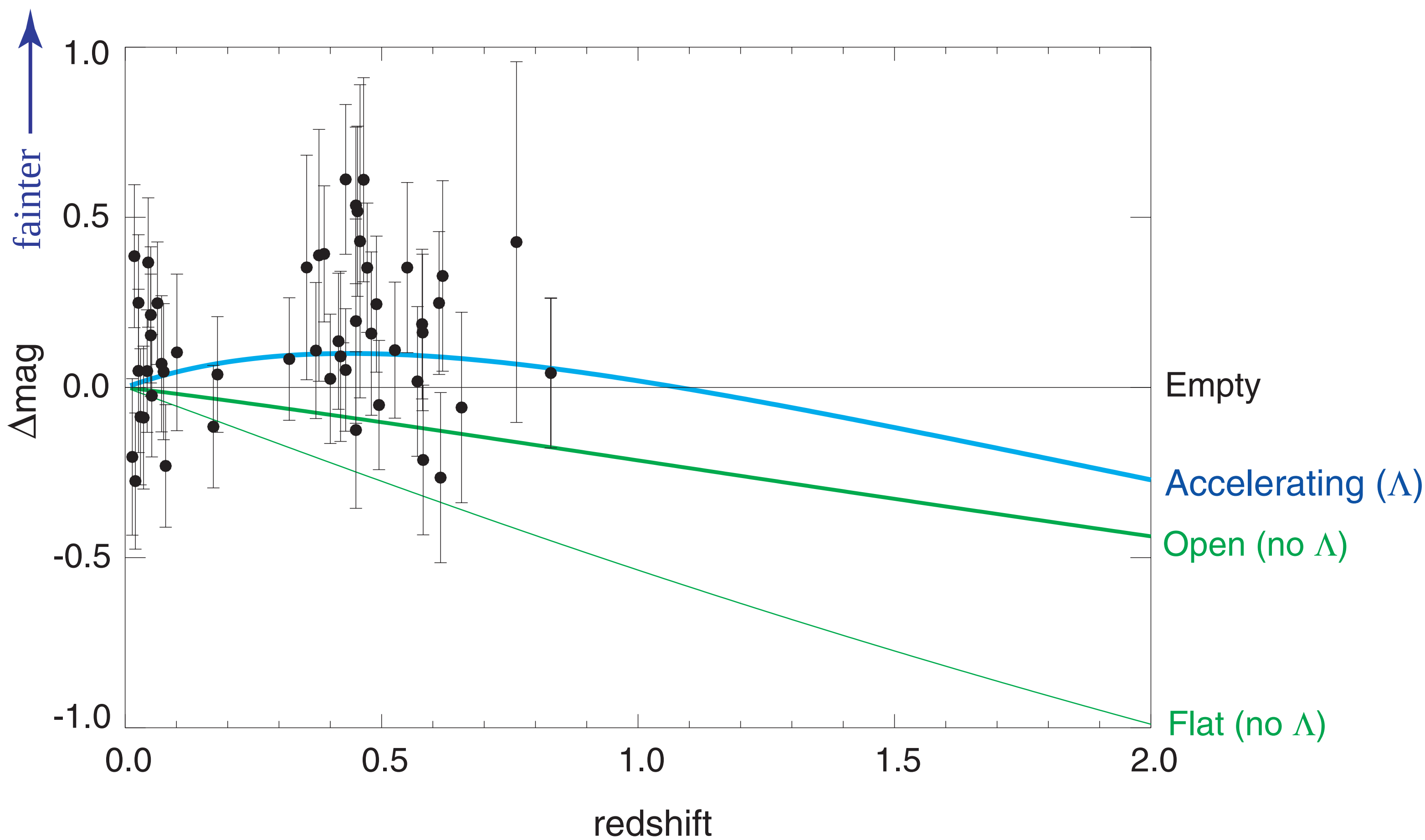


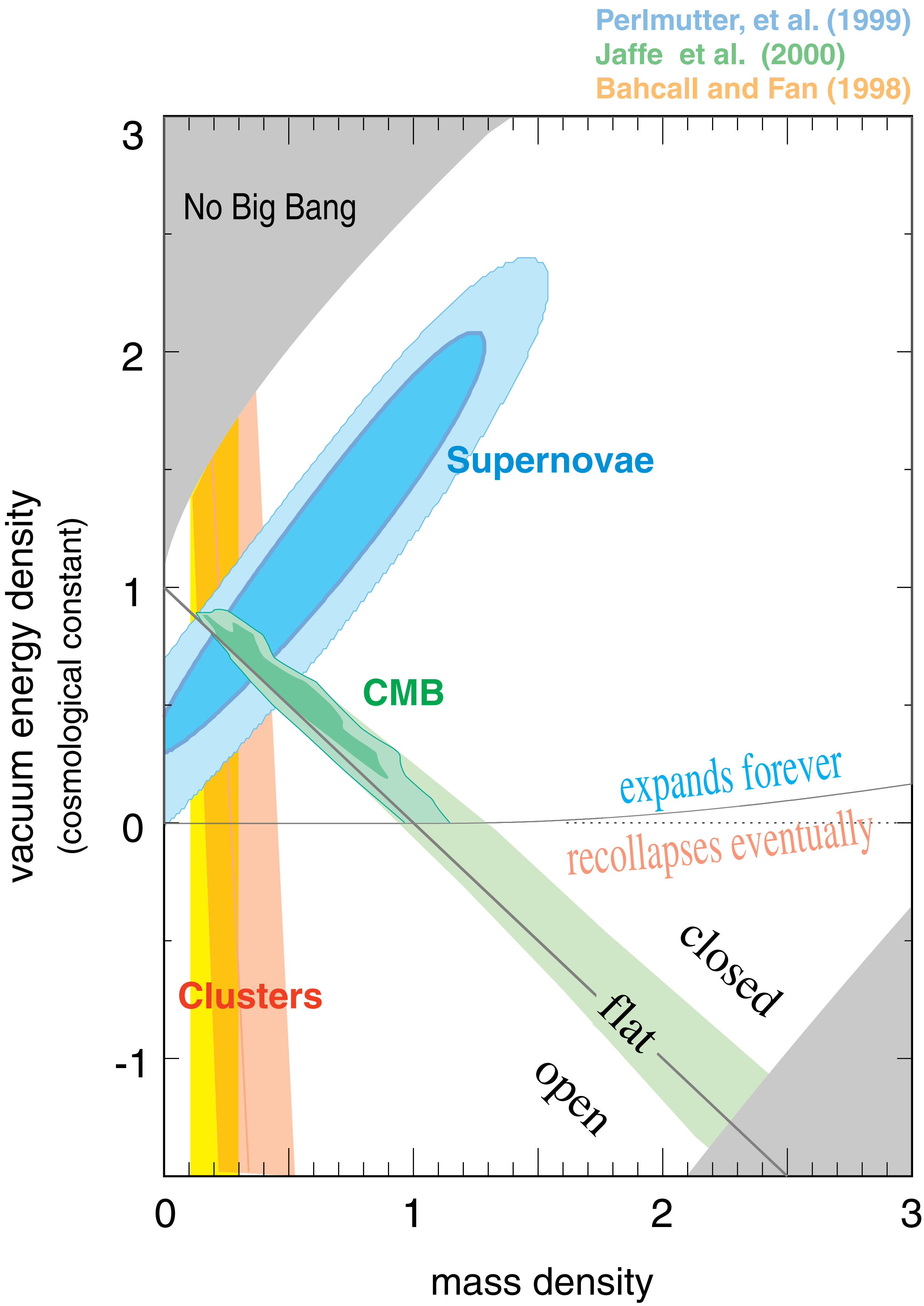
FAINTER
(Farther)
(Further back in time)
Type Ia Supernovae
Supernova Cosmology Project
Open
Flat
Closed
Calan/Tololo Supernova Survey
24
22
20
18
16
14
0.01
0.02
0.04
0.1
0.2
0.4
0.6
1.0
magnitude
22
21
20
0.2
0.4
0.6
1.0
Open
Flat
Closed
redshift
MORE REDSHIFT
(More total expansion of universe since light left the Standard Candle)



fainter
1.0
0.5
0.0
-0.5
-1.0
Δmag
0.0
0.5
1.0
1.5
2.0
redshift
Empty
Accelerating (Λ)
Open (no Λ)
Flat (no Λ)

1998: Acceleration





Perlmutter, et al. (1999)
Jaffe et al. (2000)
Bahcall and Fan (1998)
No Big Bang
Supernovae
CMB
expands forever
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Clusters
vacuum energy density
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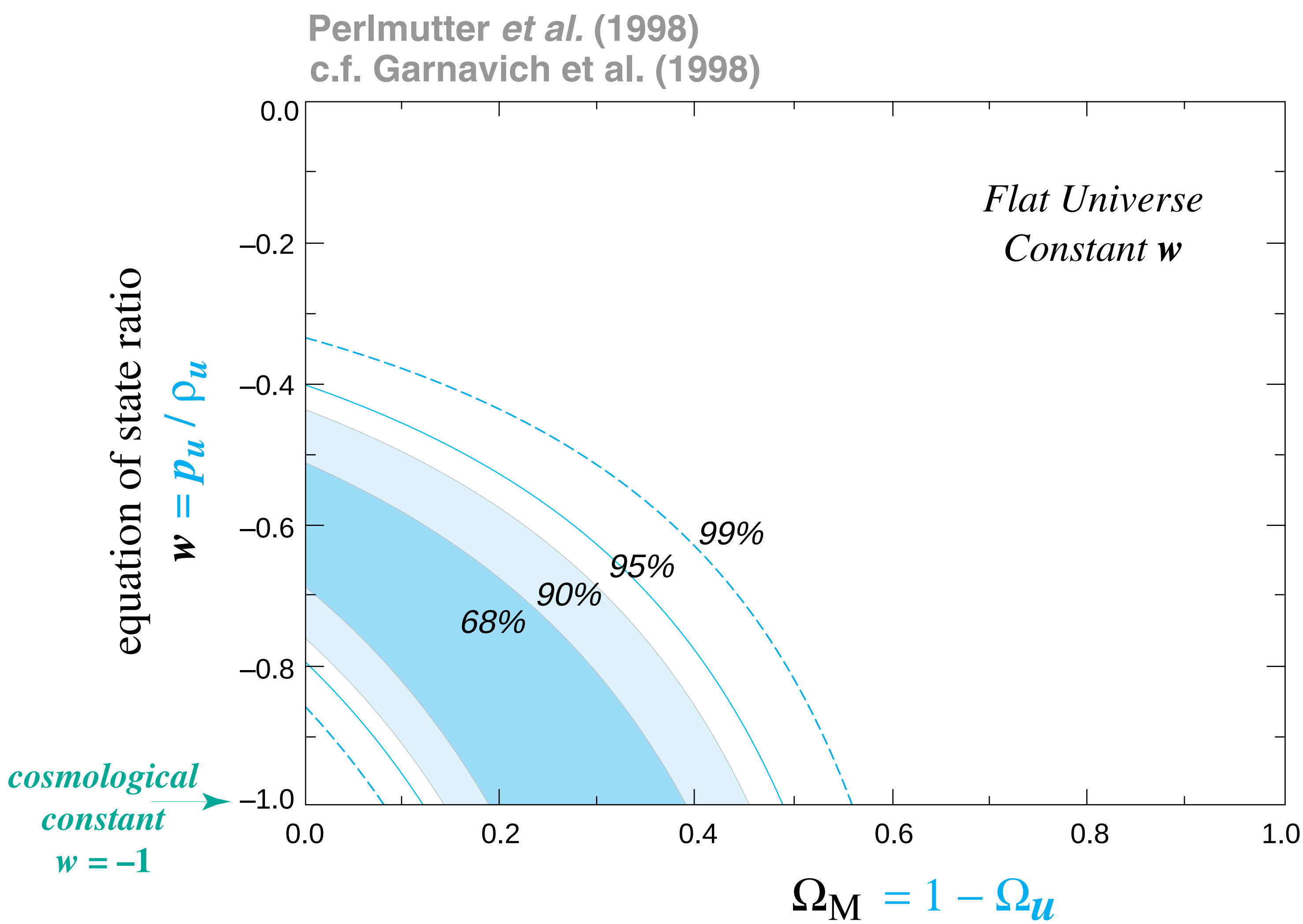
Unknown Component, Ω_u, of Energy Density



What do we now want to know?

- Is our simple cosmological picture on the right track?

  Do we find the same Ω_k @ $z = 1$ and $z = 1000$?

- Strength of our conviction that $\Omega_\Lambda > 0$.

  Find a redshift when
  $m(z)$ for $\Lambda > 0$ is **not** fainter than $m(z)$ with no Λ
  i.e. the "deceleration era."

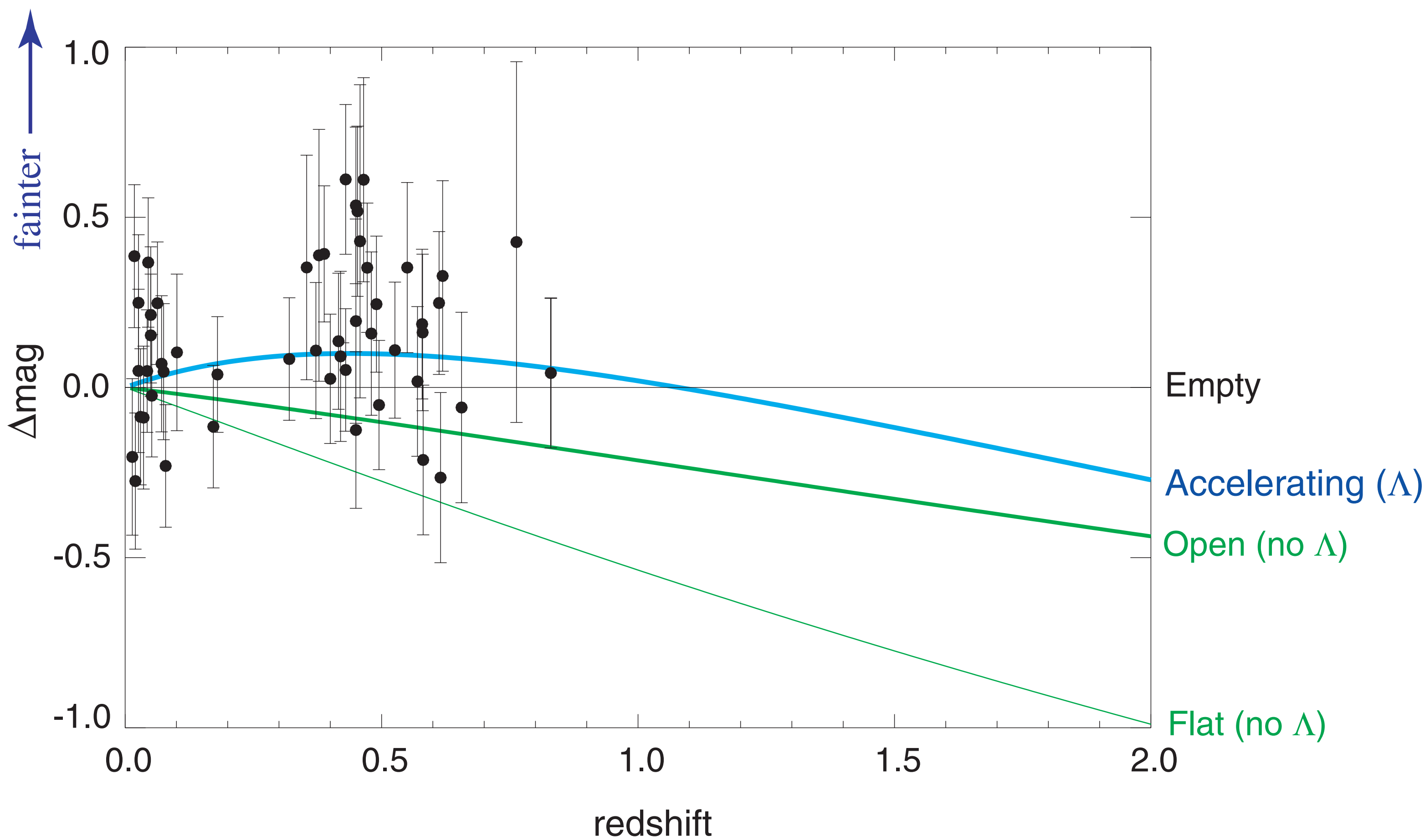
  Get tighter constraints on:
  -- gray dust & other non-standard dust
  -- any SN Ia evolution
  -- gravitational lensing of SNe.

- Identity of, and properties of, "Dark Energy" that is apparently accelerating the universe.

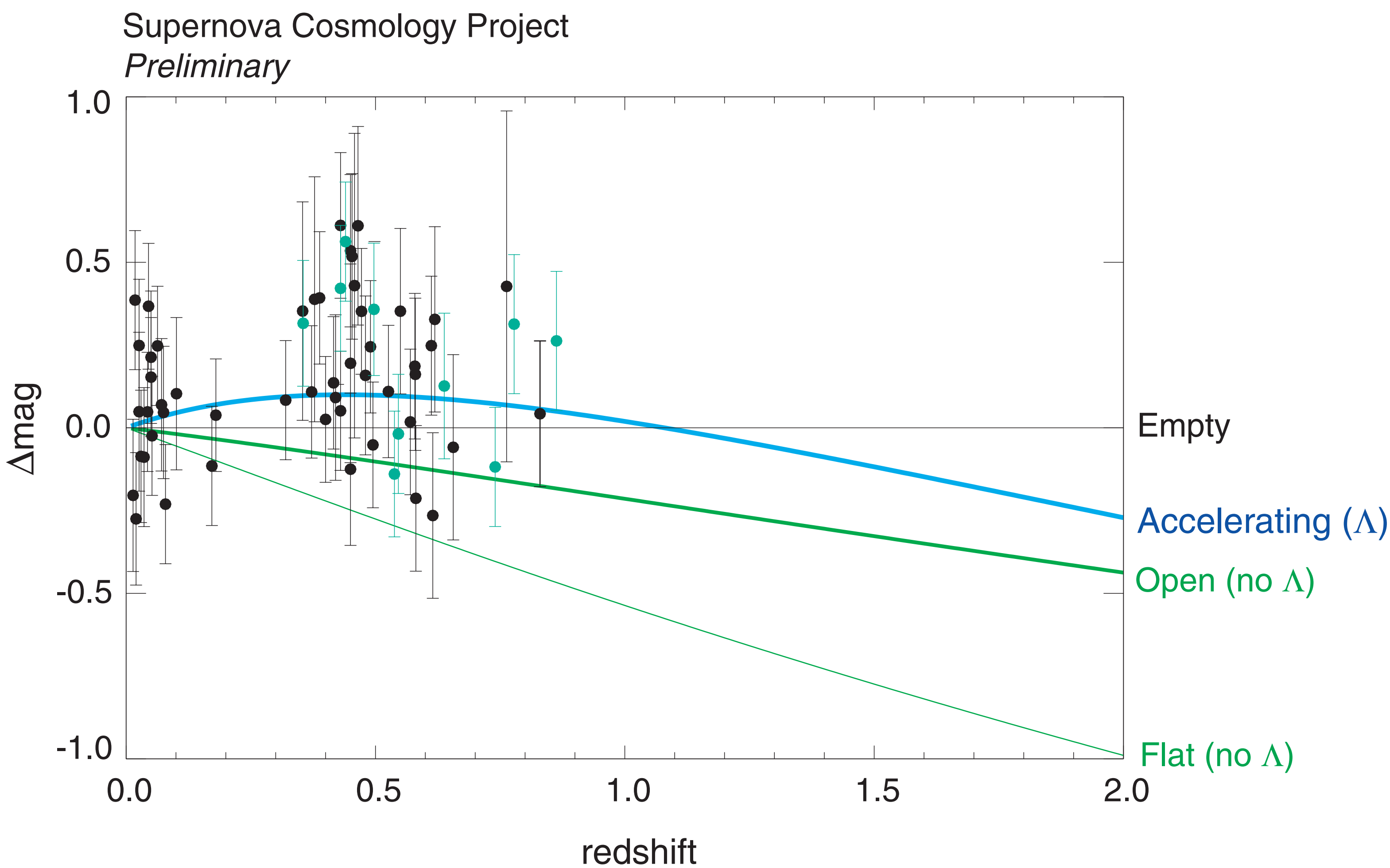
  Measure over a range of redshifts
  to look for varying properties.

A Basic Measurement:
The History of the Universe's Expansion

1998: Acceleration



New HST data



Supernova Cosmology Project
Preliminary
1.0
0.5
0.0
-0.5
-1.0
Δmag
0.0
0.5
1.0
1.5
2.0
redshift
Empty
Accelerating (Λ)
Open (no Λ)
Flat (no Λ)

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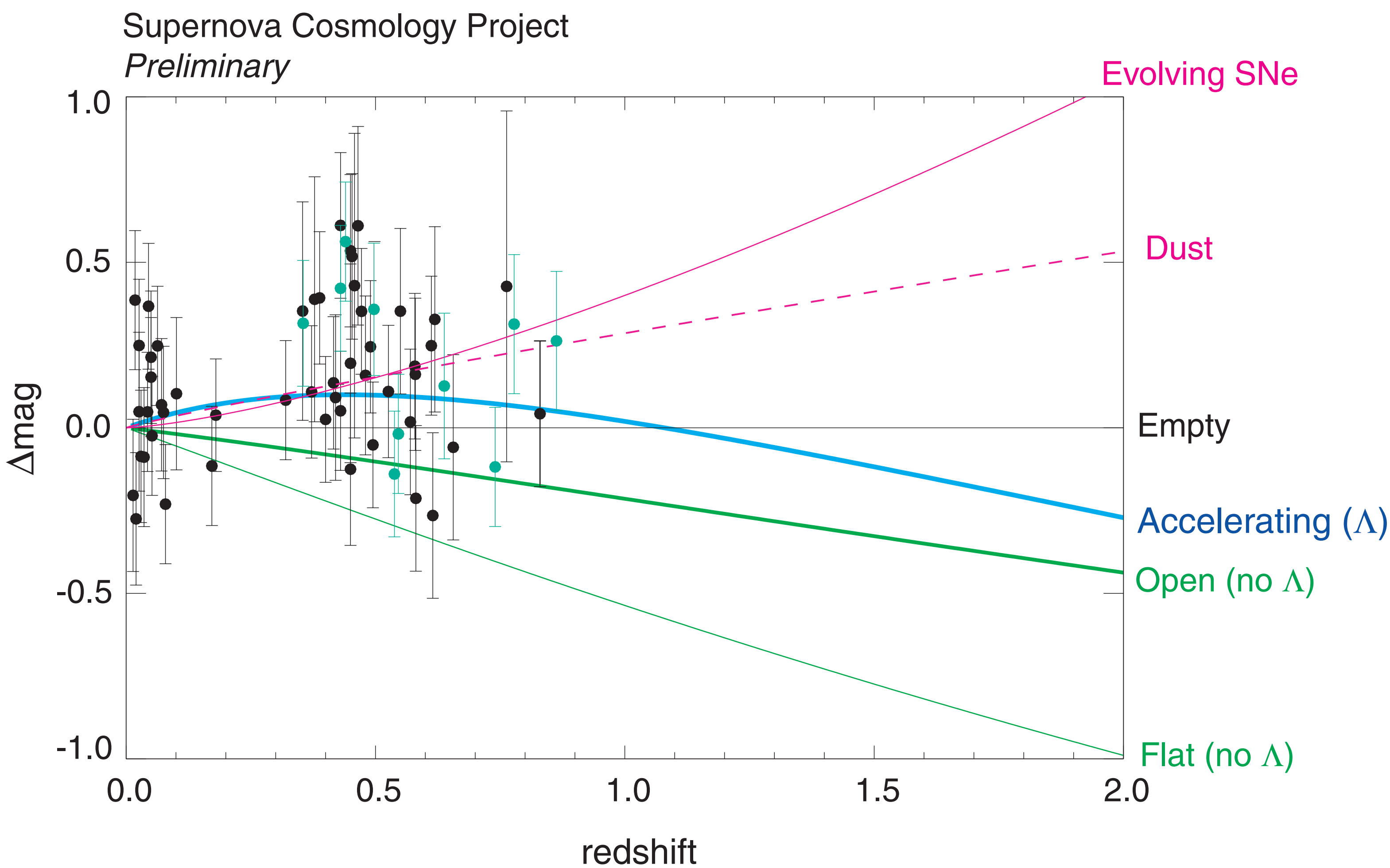
Supernova Cosmology Project
Preliminary
Evolving SNe
Dust
Empty
Accelerating (Λ)
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redshift
1.0
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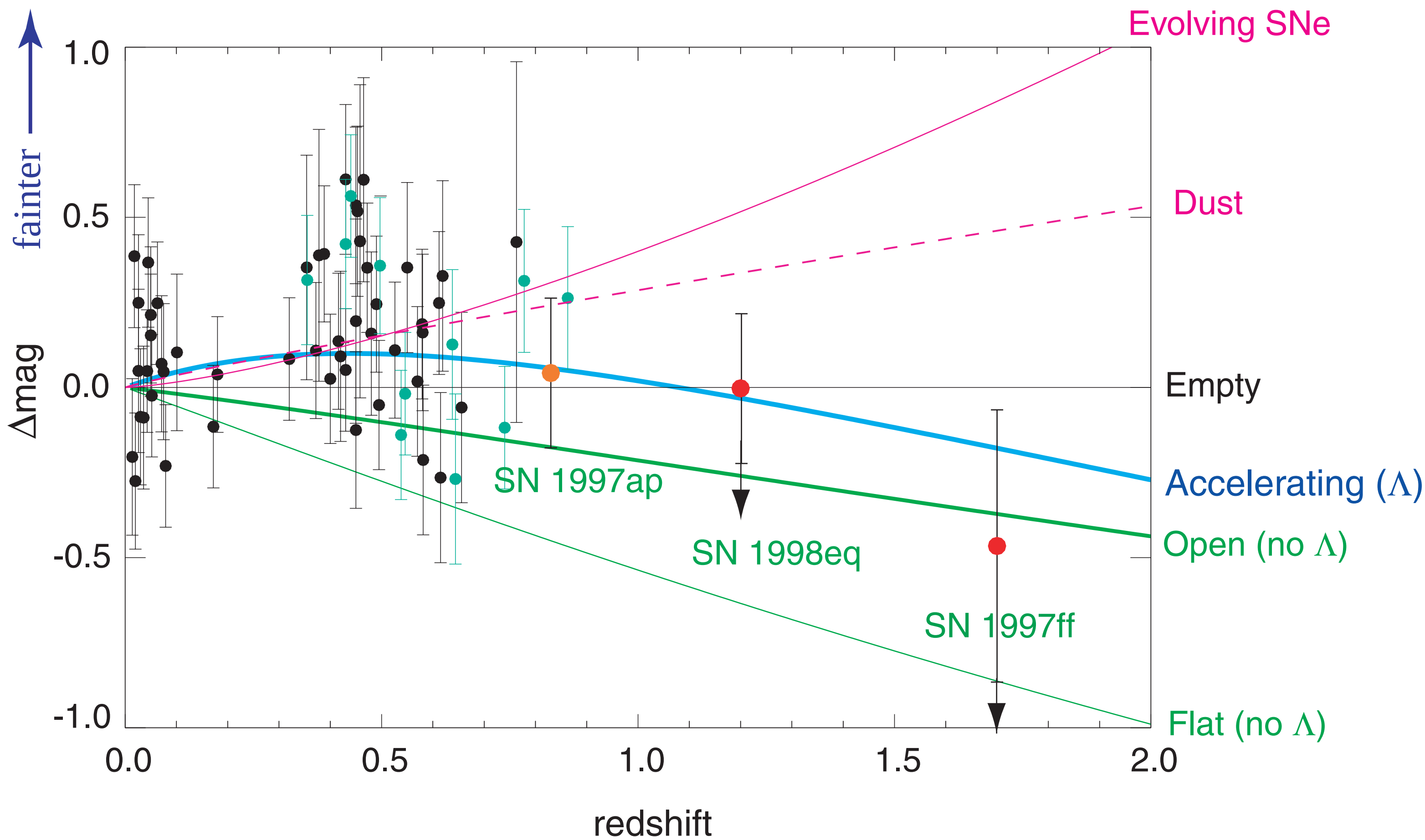
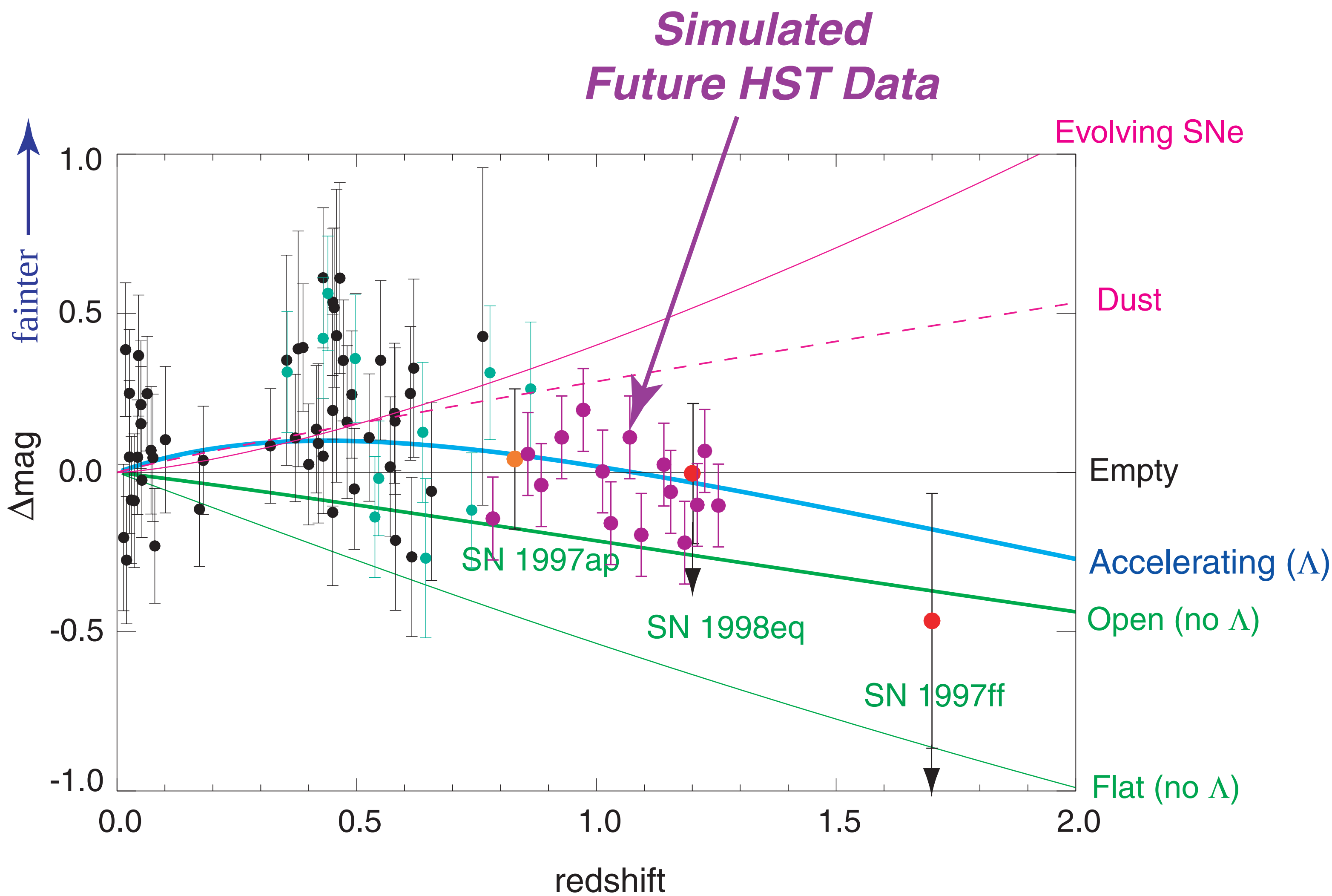
0.5
1.0
1.5
2.0

Supernovae probing
the *deceleration* era
in the near-IR





Simulated
Future HST Data
Evolving SNe
Dust
Empty
Accelerating (Λ)
Open (no Λ)
Flat (no Λ)
SN 1997ap
SN 1998eq
SN 1997ff
fainter
Δmag
redshift
1.0
0.5
0.0
-0.5
-1.0
0.0
0.5
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Score Card of *Current* Uncertainties

on $(\Omega_{M}^{flat}, \Omega_{\Lambda}^{flat}) = (0.28, 0.72)$

Statistical

☑	high-redshift SNe	0.05
☑	low-redshift SNe	0.065
	Total	***0.085***

Systematic

☑	dust that reddens $R_B(z=0.5) < 2\ R_B(\text{today})$	< 0.03
	evolving grey dust	
?	clumpy	
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☑	Malmquist bias difference	< 0.04
?	SN Ia evolution shifting distribution of prog mass/metallicity/C-O/..	
☑	K-correction uncertainty including zero-points	< 0.025
	Total identified entities/processes	***0.05***

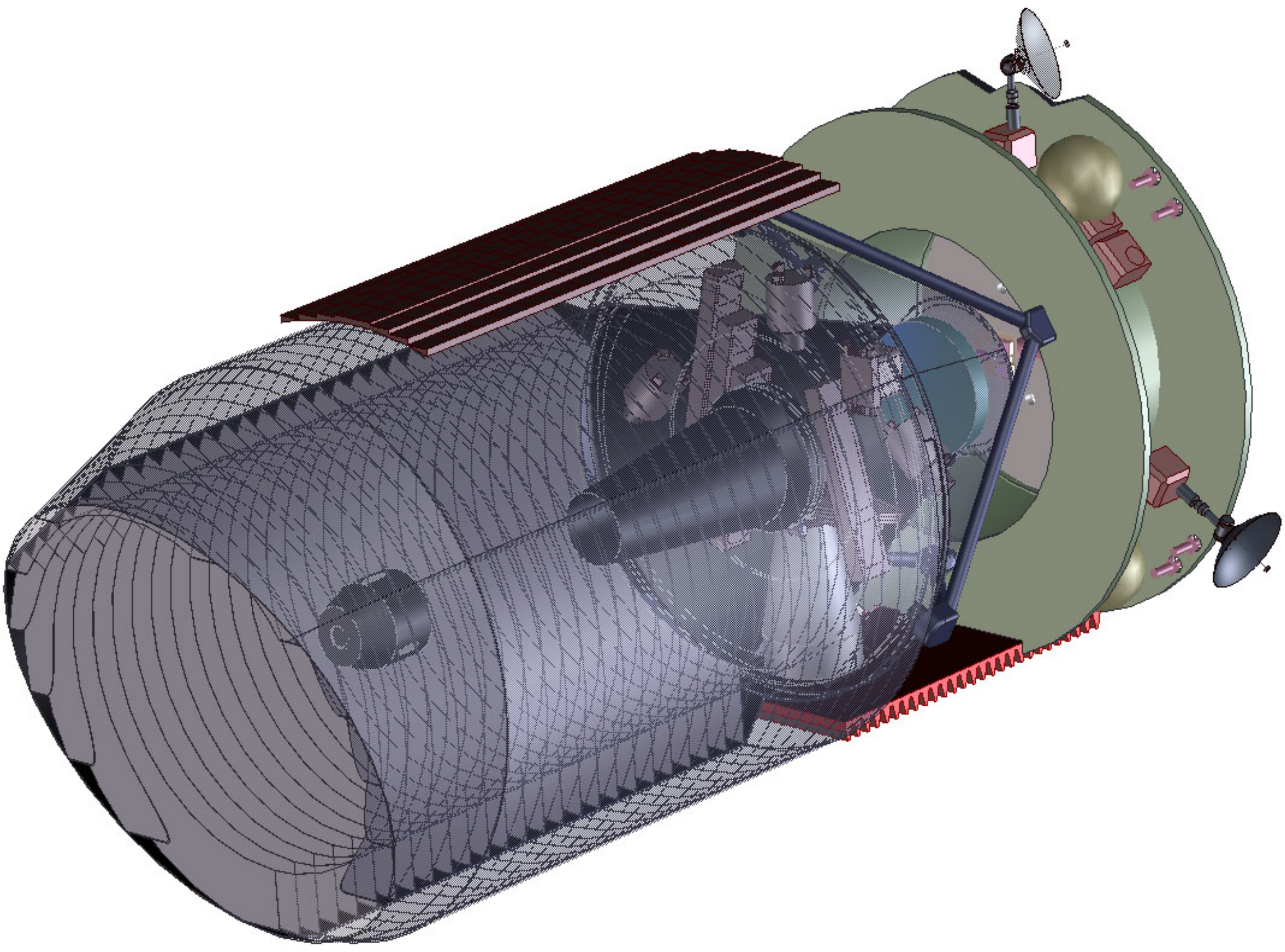
Cross-Checks of sensitivity to

☑	Width-Luminosity Relation	< 0.03
☑	Non-SN Ia contamination	< 0.05
☑	Galactic Extinction Model	< 0.04
☑	Gravitational Lensing by clumped mass	< 0.06

Perlmutter *et al.* (1998)
astro-ph/9812133

A "Third Generation" Experiment

SNAP SuperNova Acceleration Probe



SNAP SuperNova Acceleration Probe

satellite overview

Instruments:

- **~2 m aperture telescope**
  Can reach very distant SNe.
- **1 square degree mosaic camera, 1 billion pixels**
  Efficiently studies large numbers of SNe.
- **0.35um -- 1.7um spectrograph**
  Detailed analysis of each SN.

Satellite:

Dedicated instrument.

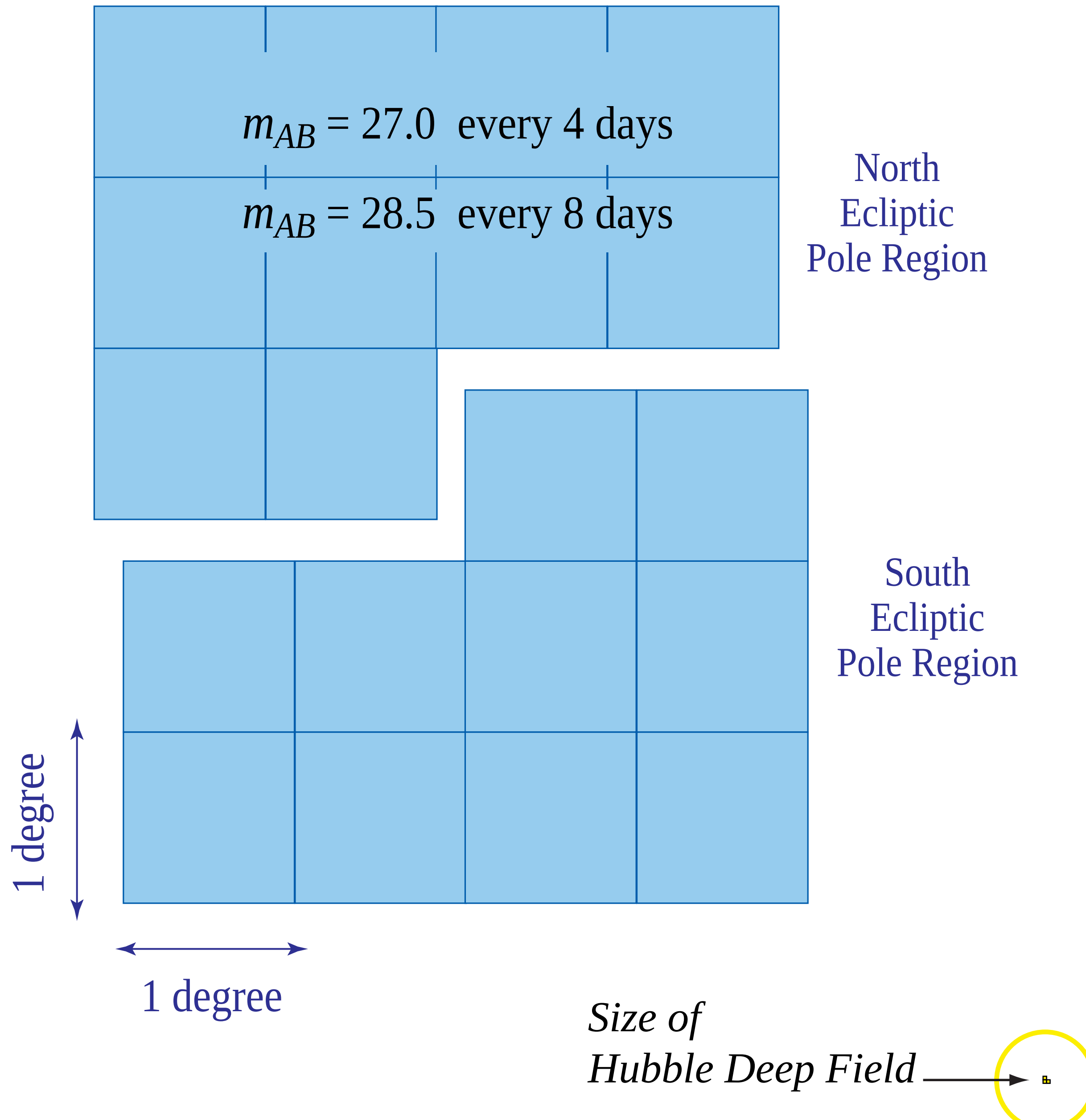
Designed to repeatedly observe an area of sky.

Essentially no moving parts.

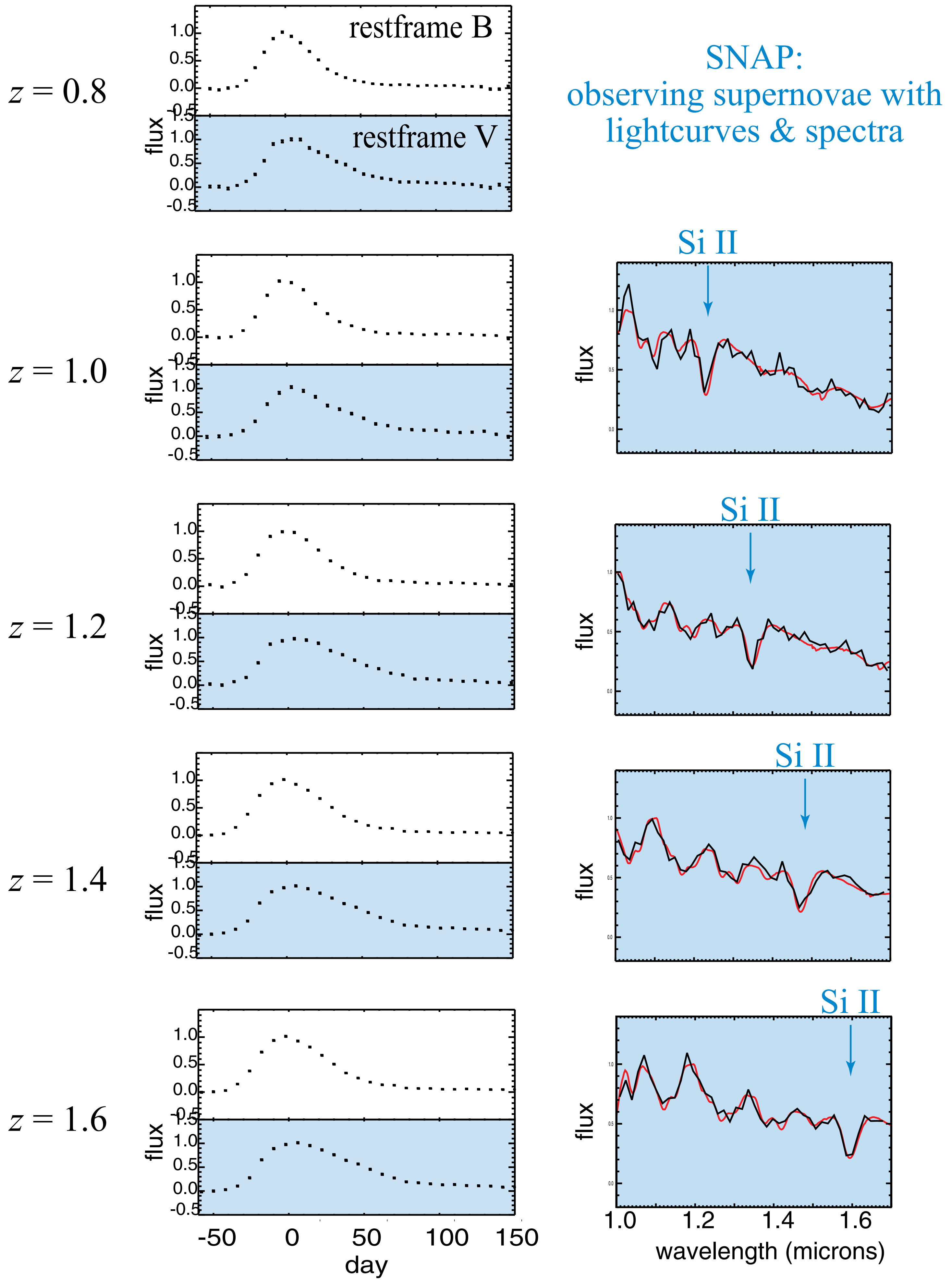
4-year construction cycle.
3-year operation for experiment
(lifetime open-ended).

SNAP SuperNova Acceleration Probe

Survey scale

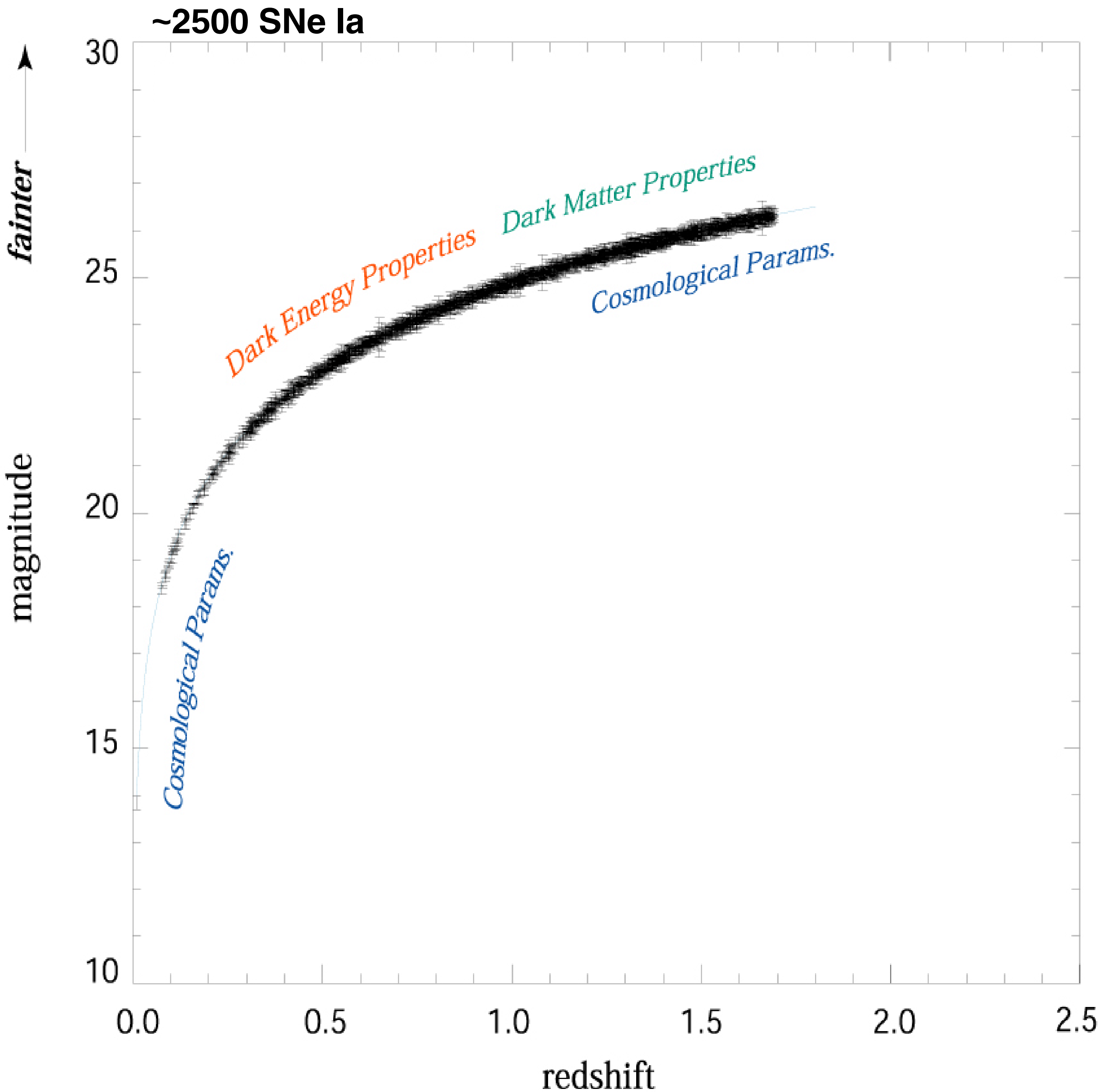


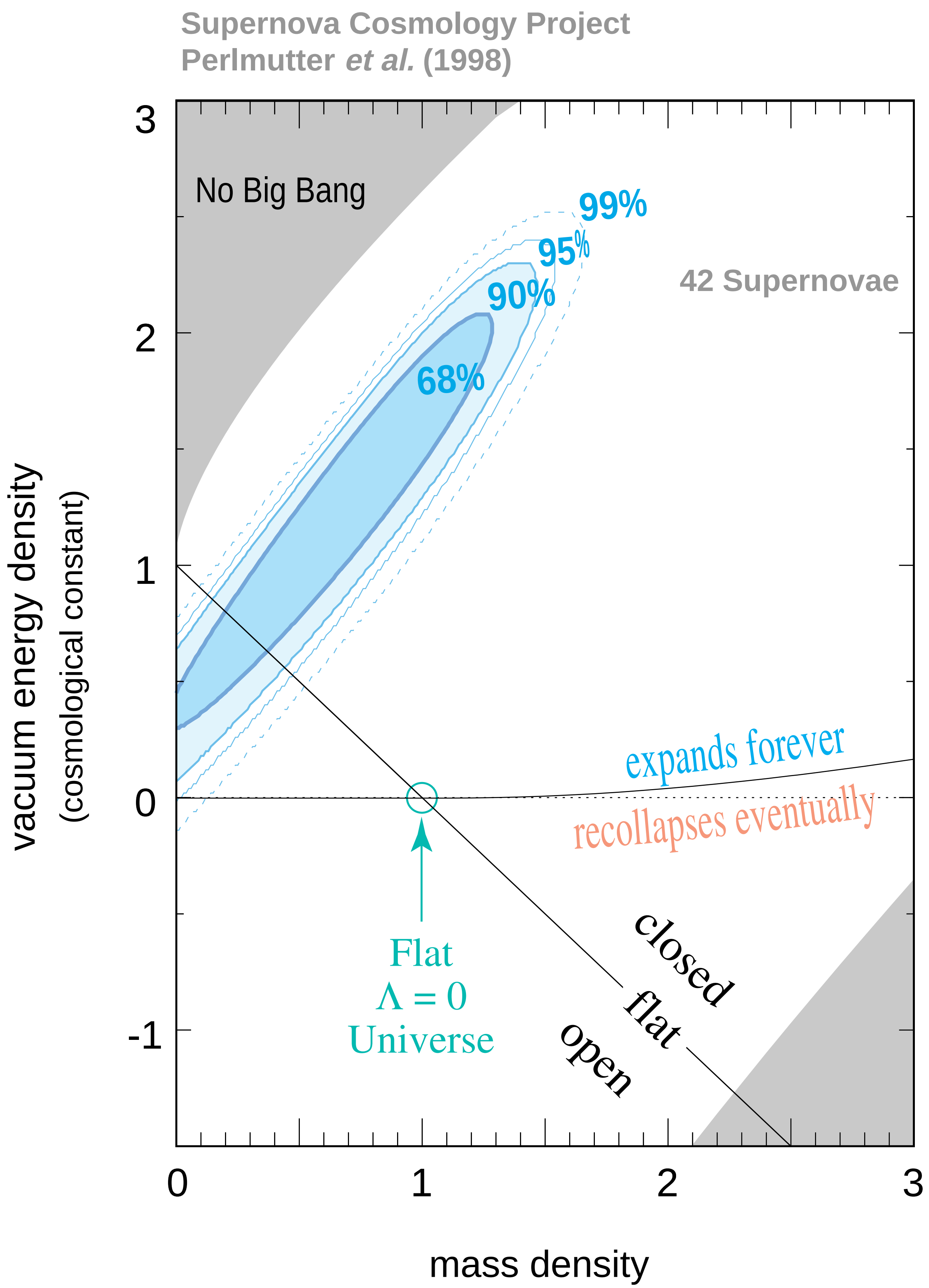
Co-added images: $\boldsymbol{m_{AB}} = 32.0$!



SNAP:
observing supernovae with
lightcurves & spectra
z = 0.8
z = 1.0
z = 1.2
z = 1.4
z = 1.6
restframe B
restframe V
flux
Si II
day
wavelength (microns)

SNAP SuperNova Acceleration Probe





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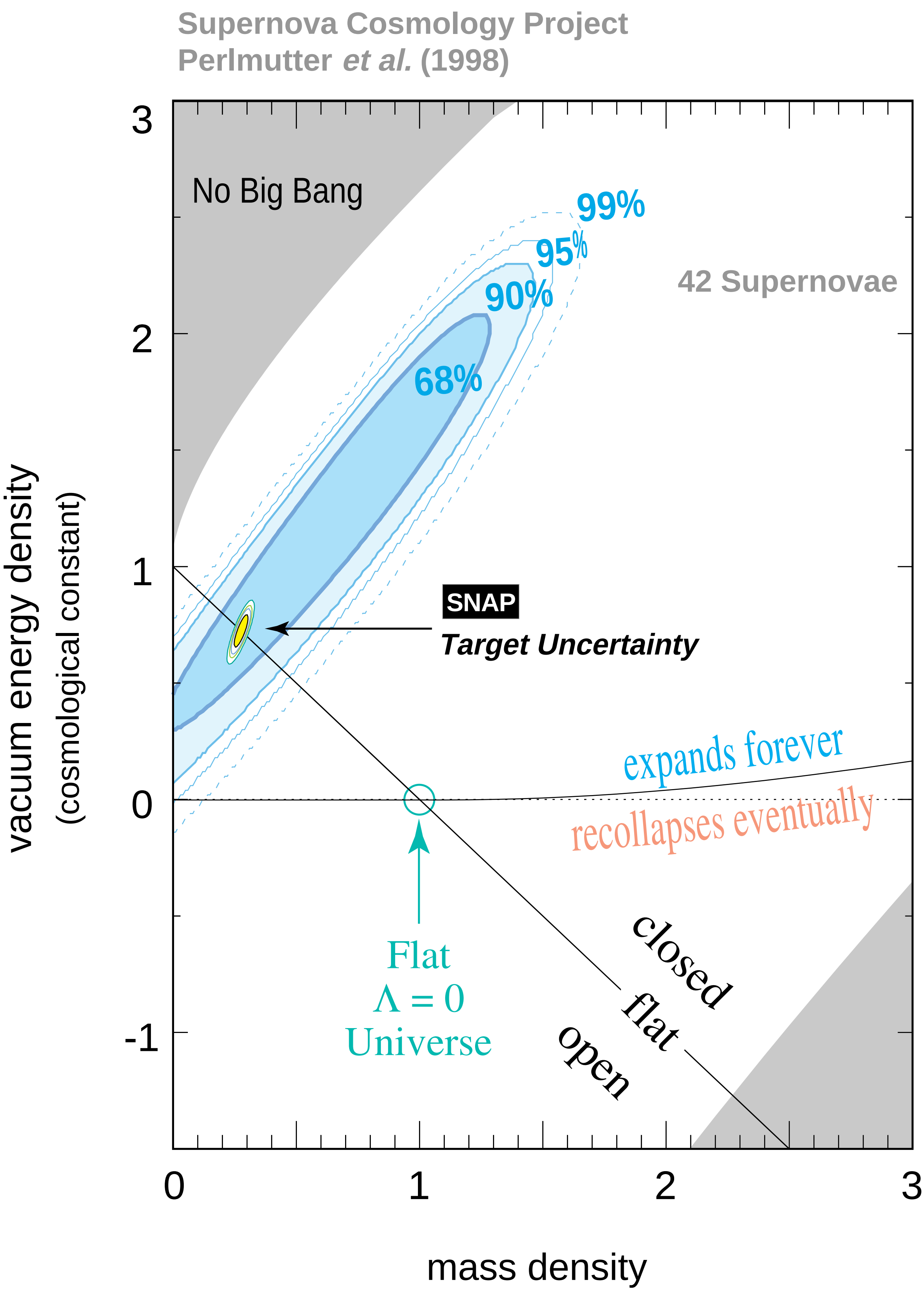

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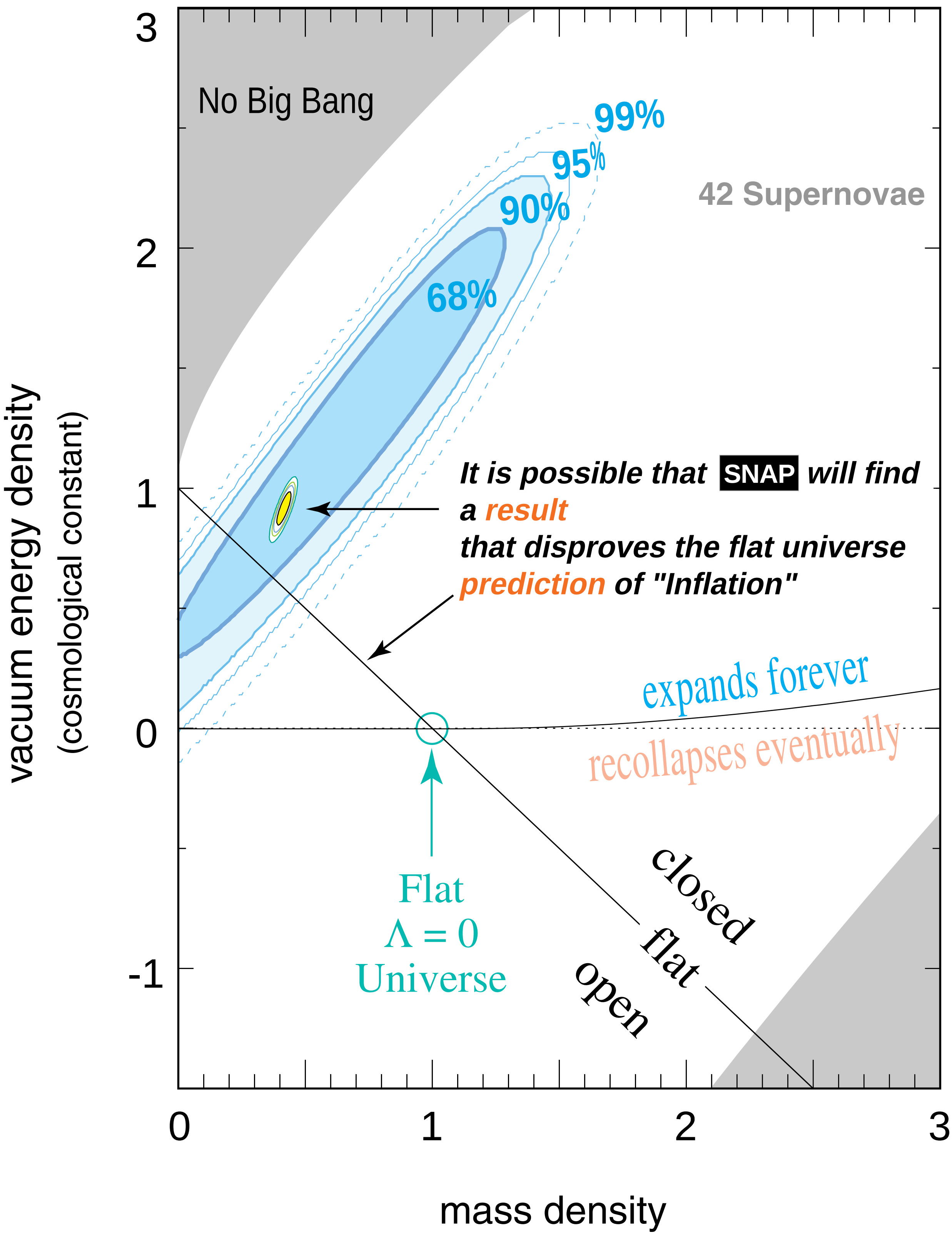
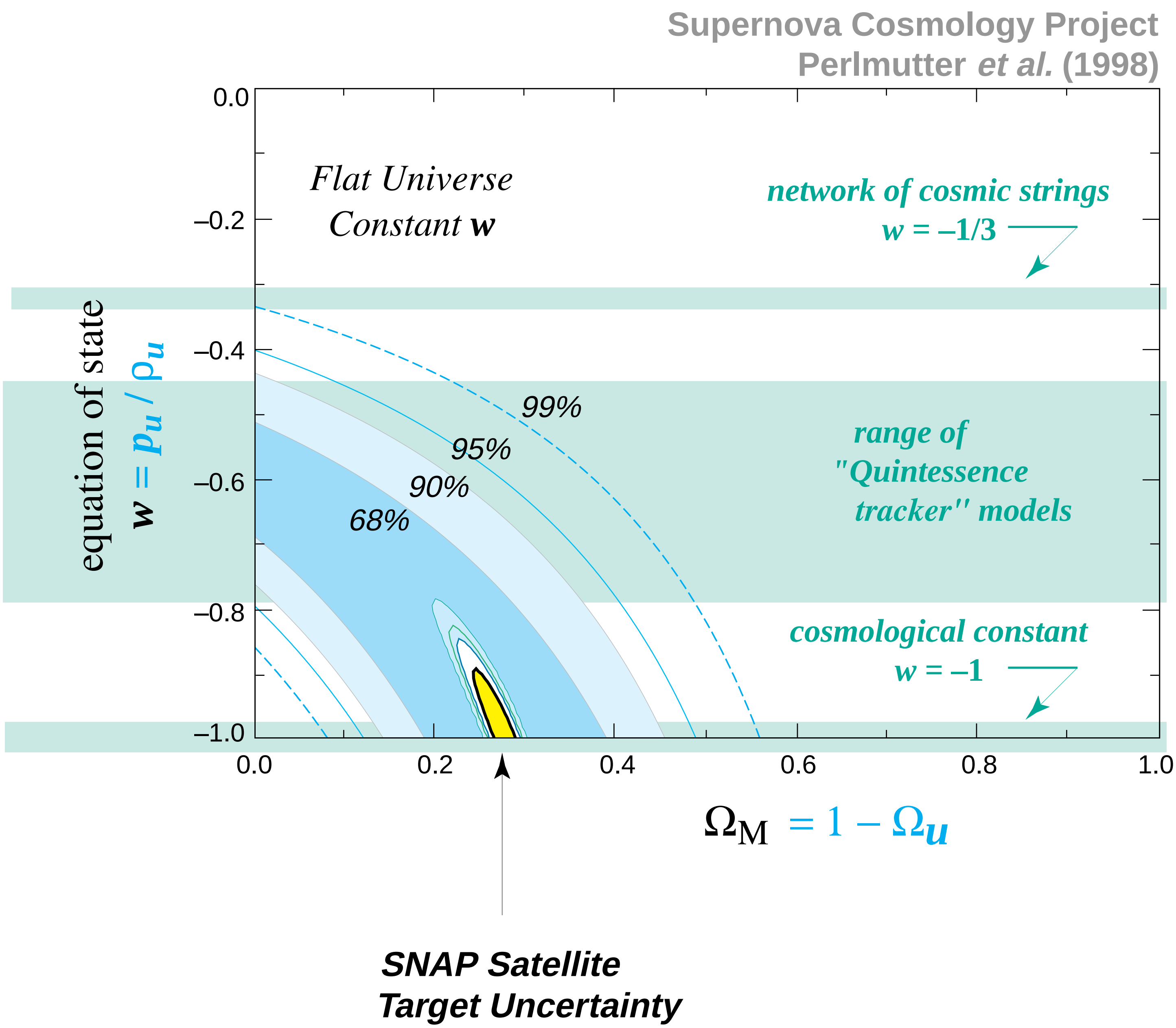


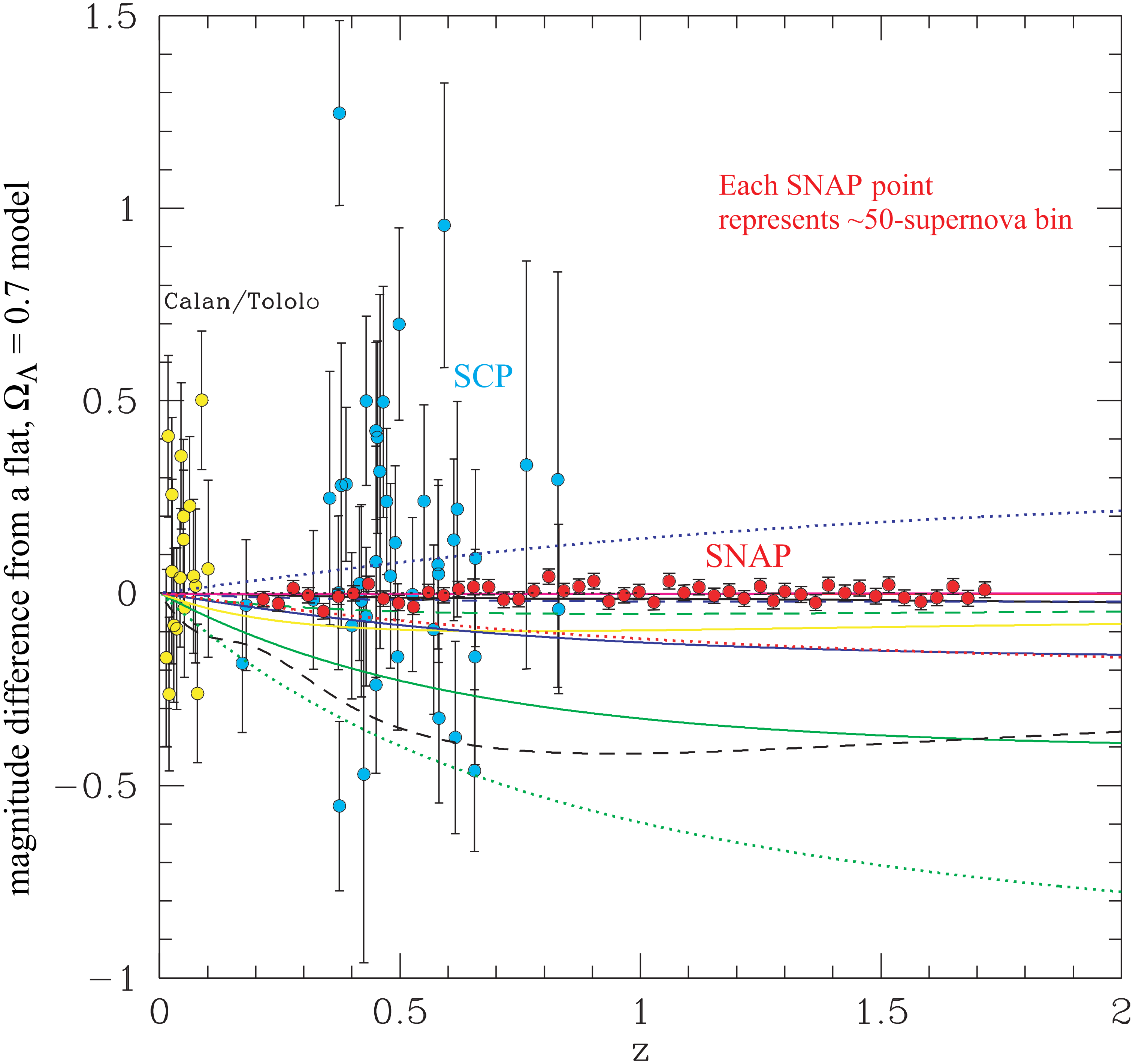
Dark Energy

Unknown Component, Ω_u, of Energy Density



SNAP SuperNova Acceleration Probe

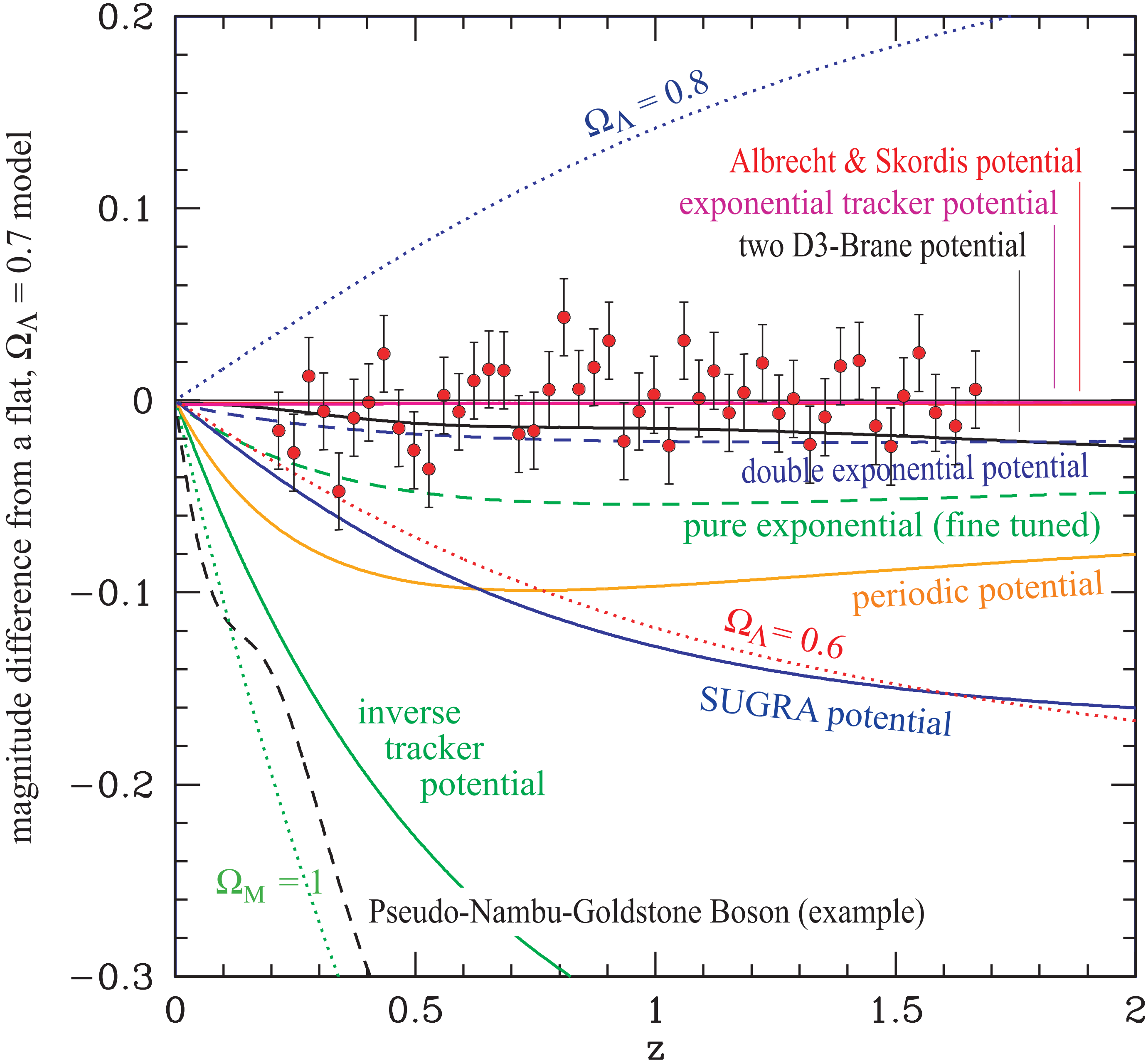
Current ground-based data
compared with binned simulated SNAP data
and a sample of Dark Energy models.



based on
Weller & Albrecht (2001)

SNAP SuperNova Acceleration Probe

Binned simulated SNAP data compared with Dark Energy models currently in the literature.



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Binned simulated SNAP data

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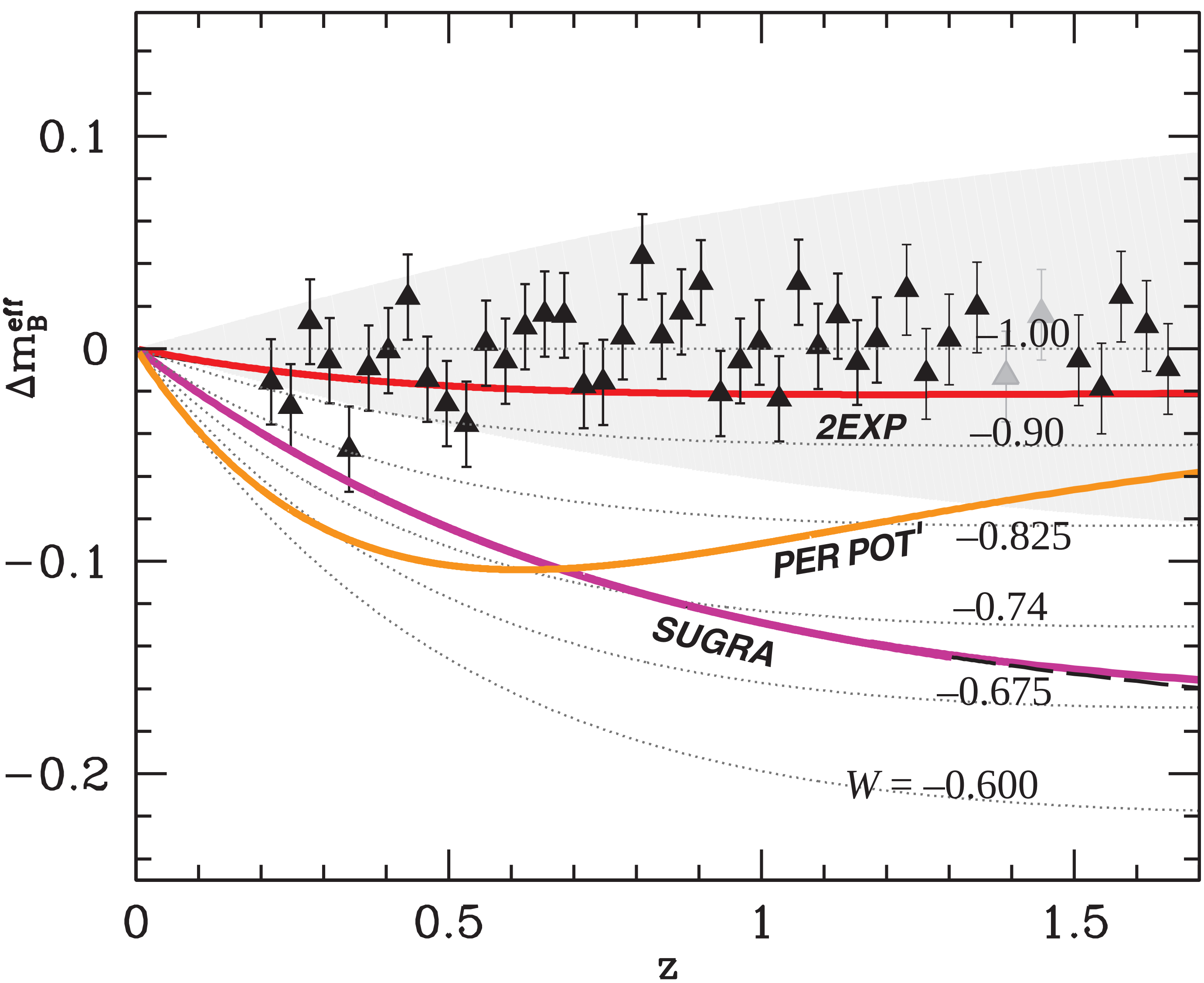


based on

Weller & Albrecht (2000)

SNAP Weak Lensing Science

- Stable instrument and complete knowledge of PSF reduces systematics
- High resolution allows efficient use of faint, high redshift source galaxies
- Near-IR channel allows photo-z to z=3

- **High precision measurements of power spectrum and cosmological parameters:** Ω_m, Ω_Λ, σ_8, etc… **complements SNe and other methods**
- **Maps of the DM distribution: mass limited cluster catalogs, DM in filaments and voids**
- **Evolution of large-scale structure: direct tests of gravitational instability via redshift-dependences**
- **Galaxy-galaxy lensing: galactic mass as function (z,type, environs)**

$\Omega\ \Lambda\ m\ ,\ ,s\ 8$

SNAP SuperNova Acceleration Probe

Science Goals for The First Wide-field Survey in Space

Primary Cosmology Mission: Cosmological Parameters, Dark Matter, Dark Energy,...

Type Ia supernova calibrated candle:
Hubble diagram to $z = 1.7$

Type II supernova expanding photosphere:
Hubble diagram to $z = 1$ and beyond.

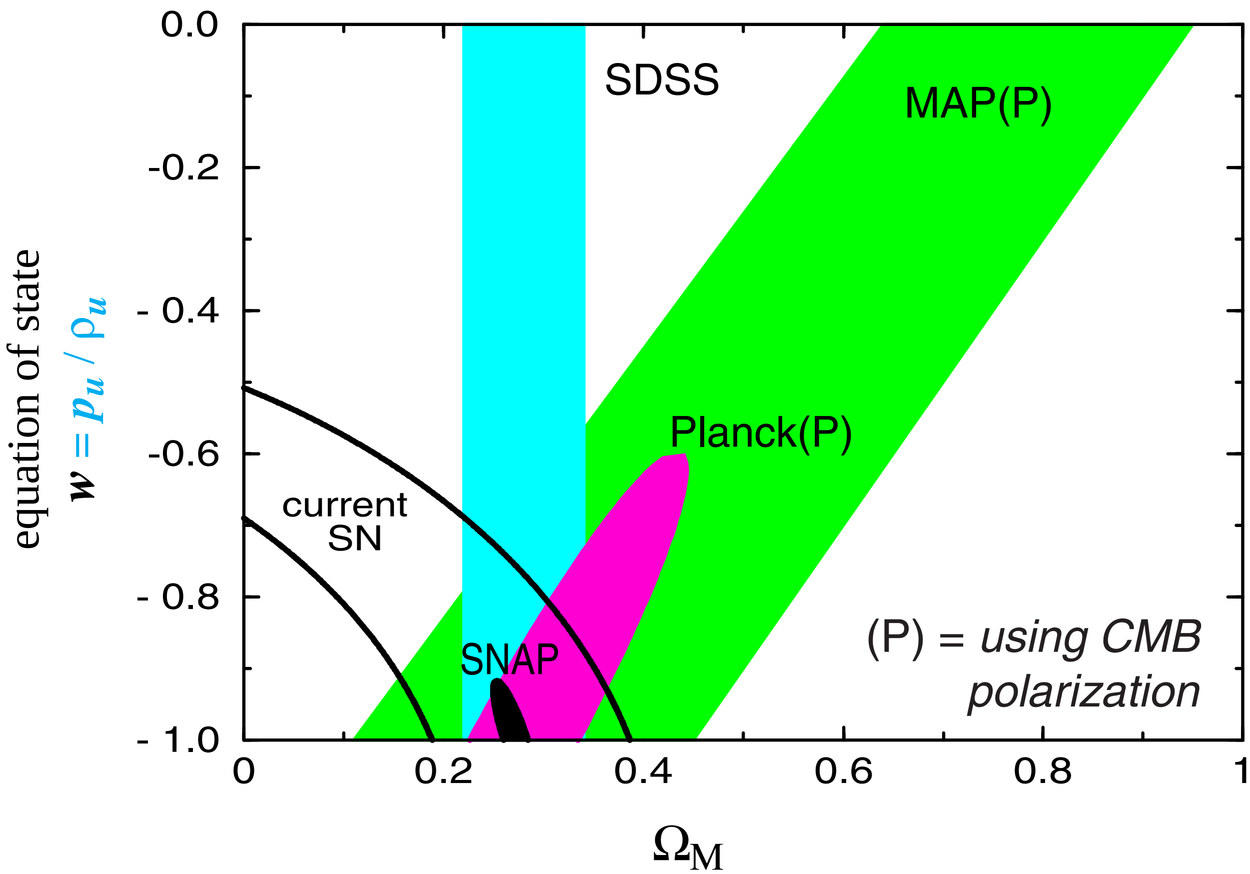
Weak lensing:
Direct measurements of $P(k)$ vs z
Mass selected cluster survey vs z

Strong lensing statistics: Ω_Λ
10x gains over ground based optical resolution, IR channels + depth.

Galaxy clustering:
$W(\Theta)$ angular correlation vs redshift from 0.5 to 3.0

SNAP SuperNova Acceleration Probe

Expected cosmological measurements at time of SNAP results



Other cosmological measurement approaches

Weak Lensing*

Number Counts, $N(z)$

clusters*

galaxies

-- selected by rotation velocity

S-Z angular size

*SNAP measurements using this approach

Are there science prerequisites?

No: Supernova studies are now so developed that we can design an experiment constraining systematic uncertainties.

Ongoing supernova studies (near and far) will improve this further, and make the experiment even more efficient.

Score Card of Current Uncertainties

on $(\Omega_{M}^{flat}, \Omega_{\Lambda}^{flat}) = (0.28, 0.72)$

Statistical

☑	high-redshift SNe	0.05
☑	low-redshift SNe	0.065
	Total	***0.085***

Systematic

☑	dust that reddens $R_B(z=0.5) < 2\ R_B(\text{today})$	< 0.03
	evolving grey dust	
?	clumpy	
?	same for each SN	
☑	Malmquist bias difference	< 0.04
?	SN Ia evolution shifting distribution of prog mass/metallicity/C-O/..	
☑	K-correction uncertainty including zero-points	< 0.025
	Total identified entities/processes	***0.05***

Cross-Checks of sensitivity to

☑	Width-Luminosity Relation	< 0.03
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☑	Gravitational Lensing by clumped mass	< 0.06

Perlmutter *et al.* (1998)
astro-ph/9812133

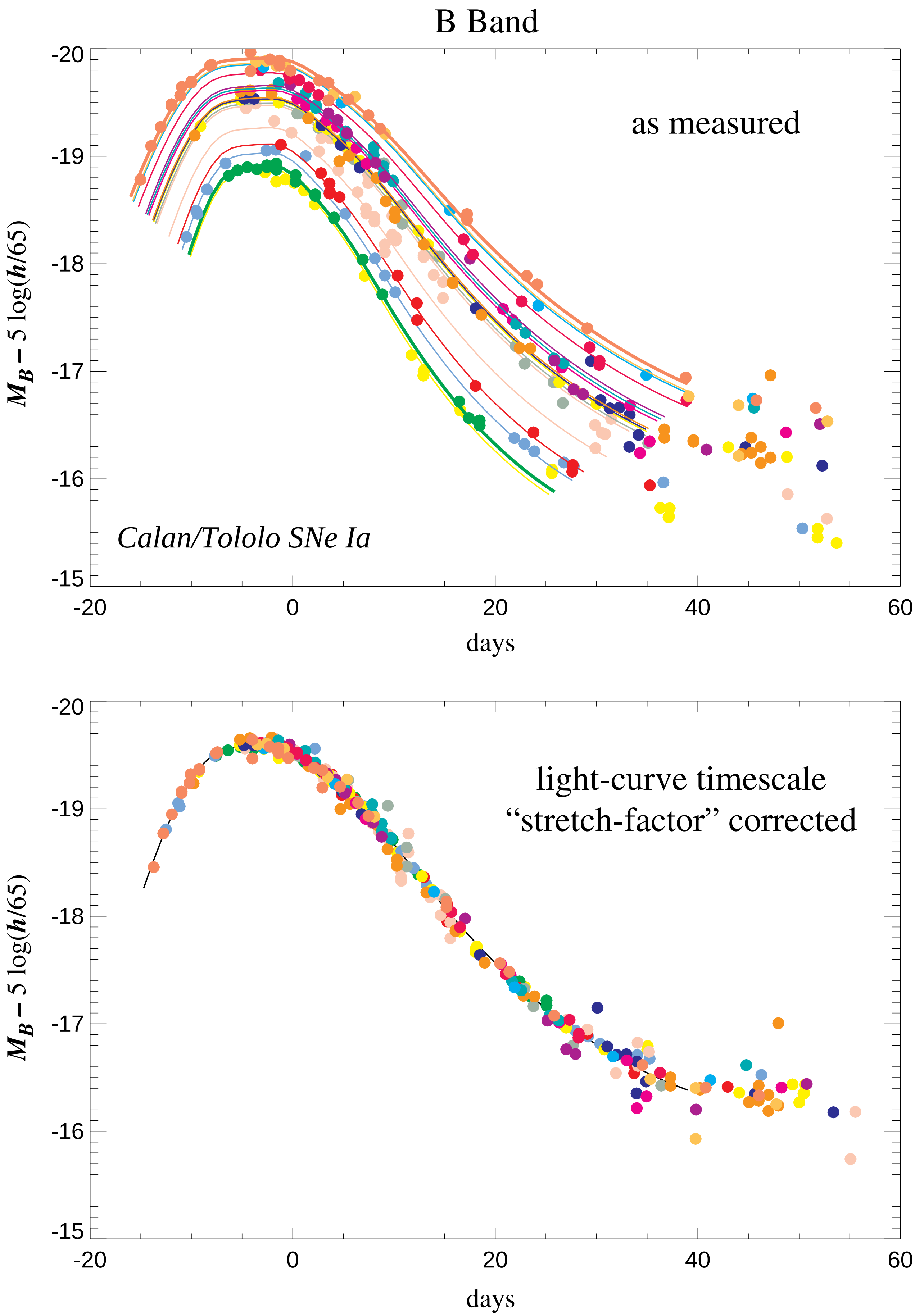
Score Card of Current Uncertainties on $(\Omega_{M}^{flat}, \Omega_{\Lambda}^{flat}) = (0.28, 0.72)$

SNAP Requirement to satisfy $\delta M(\text{peak}) < 0.02$

Statistical		
☑ high-redshift SNe	0.05	Discover and follow 2000+ SN Ia per year
☑ low-redshift SNe	0.065	
Total	***0.085***	
Systematic		
☑ dust that reddens $R_B(z=0.5) < 2\, R_B(\text{today})$	< 0.03	Optical & NIR calibrated spectra to observe wavelength dependent absorption
evolving grey dust		
? clumpy		NIR spectra, go to high redshift
? same for each SN		
☑ Malmquist bias difference	< 0.04	Detection of every SN 2.5 mag below peak for z = 0 to 1.7
? SN Ia evolution shifting distribution of prog mass/metallicity/C-O/..		Spectral features and lightcurve features. Go to high redshift.
☑ K-correction uncertainty including zero-points	< 0.025	Restframe B matched filters, spectral time series, cross wavelength relative flux calibration,
Total identified entities/processes	***0.05***	
Cross-Checks of sensitivity to		
☑ Width-Luminosity Relation	< 0.03	
☑ Non-SN Ia contamination	< 0.05	Restframe SiII.
☑ Galactic Extinction Model	< 0.04	SDSS+SIRTF & SNAP WD spectra
☑ Gravitational Lensing by clumped mass	< 0.06	~75 SN per redshift bin.SNAP microlensing experiments

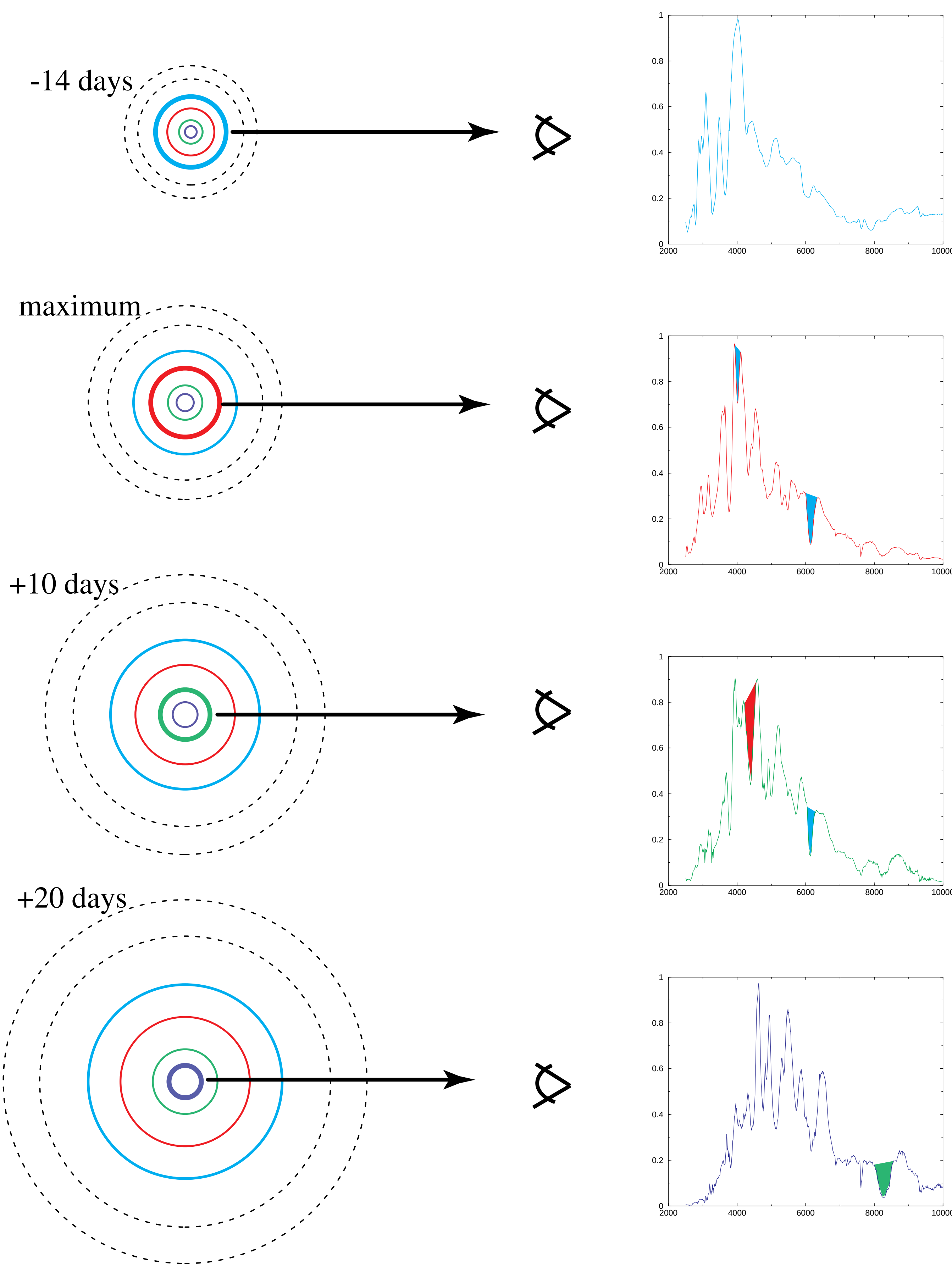
What makes the supernova measurement special?
Control of systematic uncertainties.

At every moment in the explosion event,
each individual supernova is "sending" us a rich stream
of information about its internal physical state.

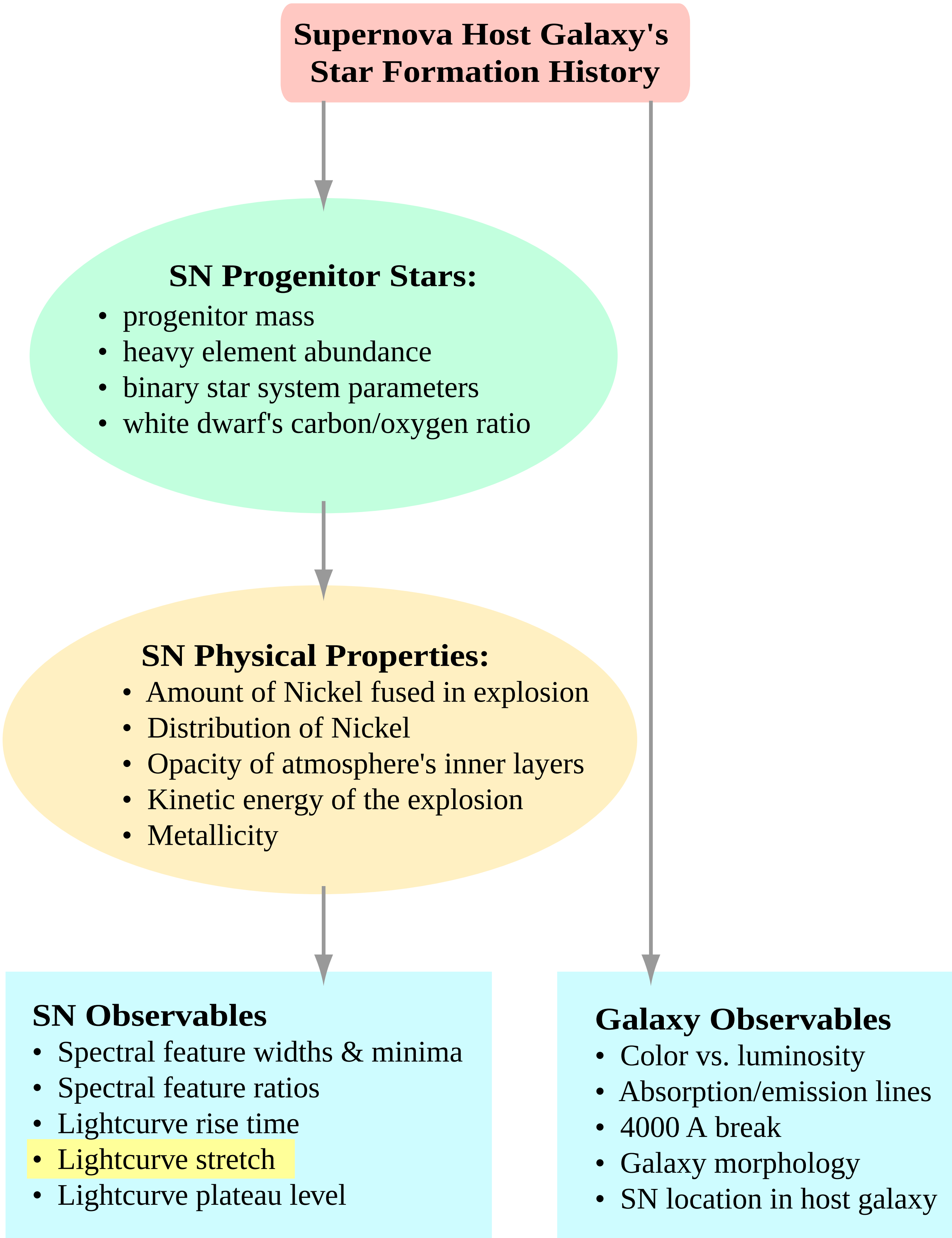


Kim, *et al.* (1997)

The time series of spectra is a “CAT Scan” of the Supernova

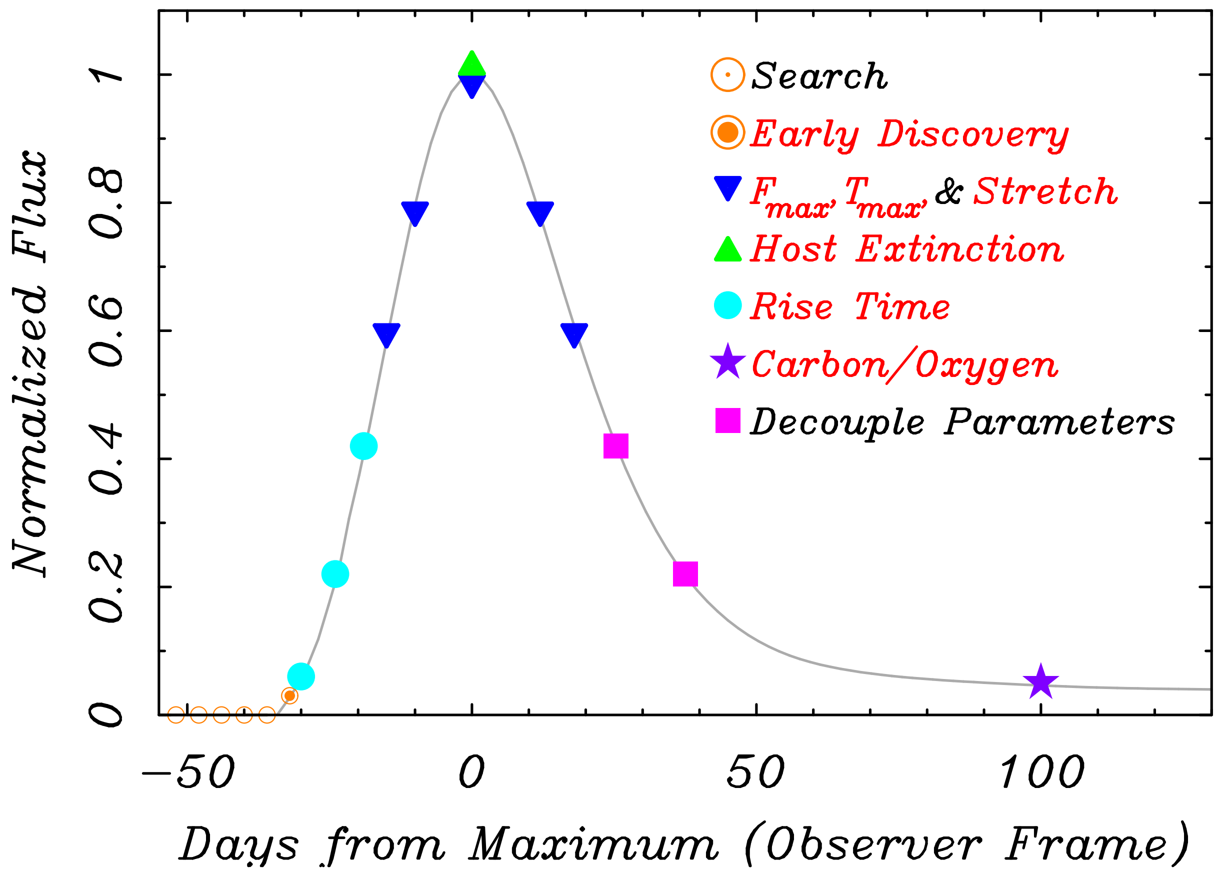


Control of Evolution Systematics: Matching Supernovae



SNAP SuperNova Acceleration Probe

B−band Lightcurve Photometry for z = 0.8 Type Ia



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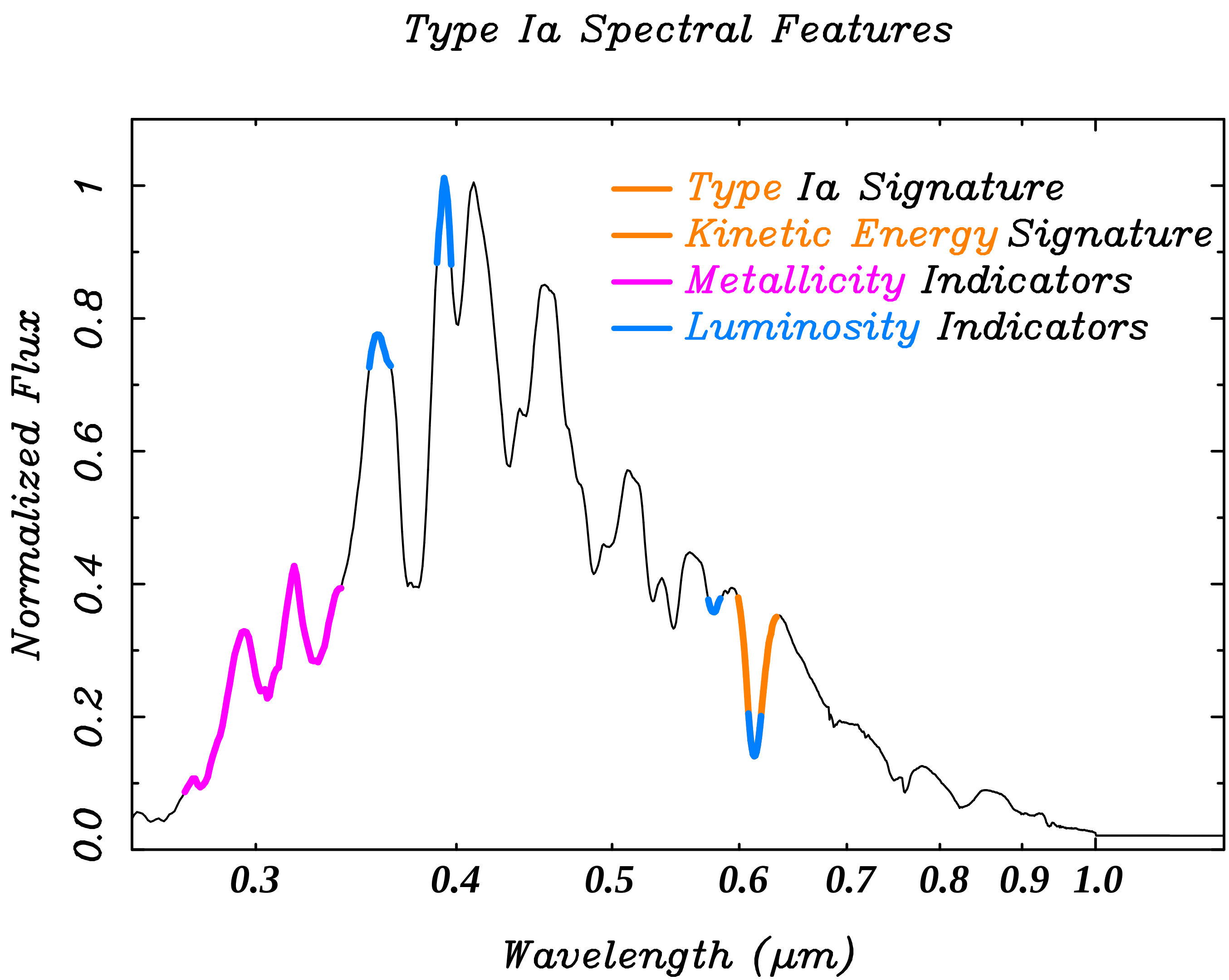
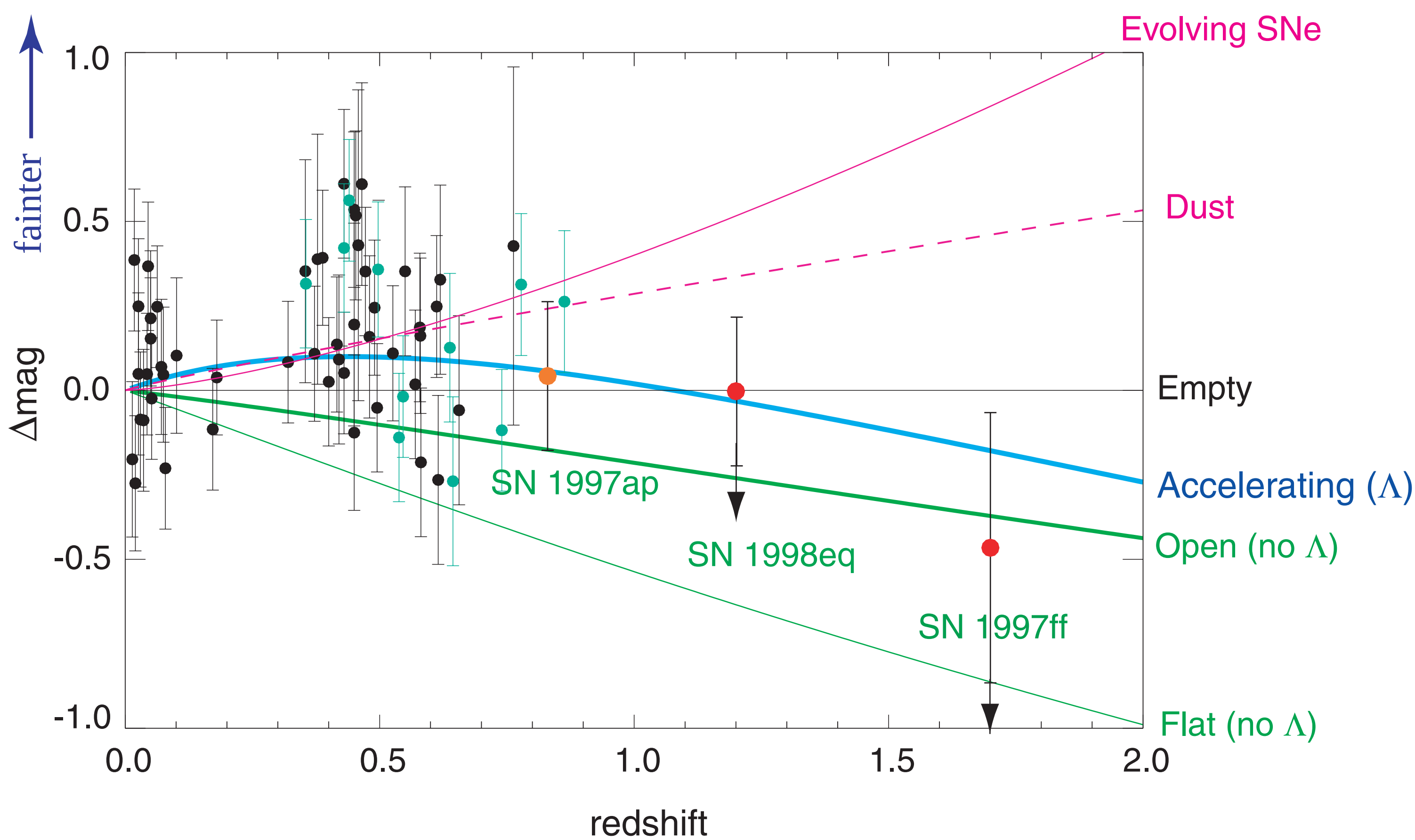


Constraint of Systematics: The Science Prerequisite

In summary, constrain with:

- o *High Redshift*
- o *Near IR*
- o *Spectrophotometry to 1.7 um*



Complementarity of
Space and Ground

Comparison of ground and space based optical surveys

We have completed detailed comparisons of ground based and space based optical surveys from first principles

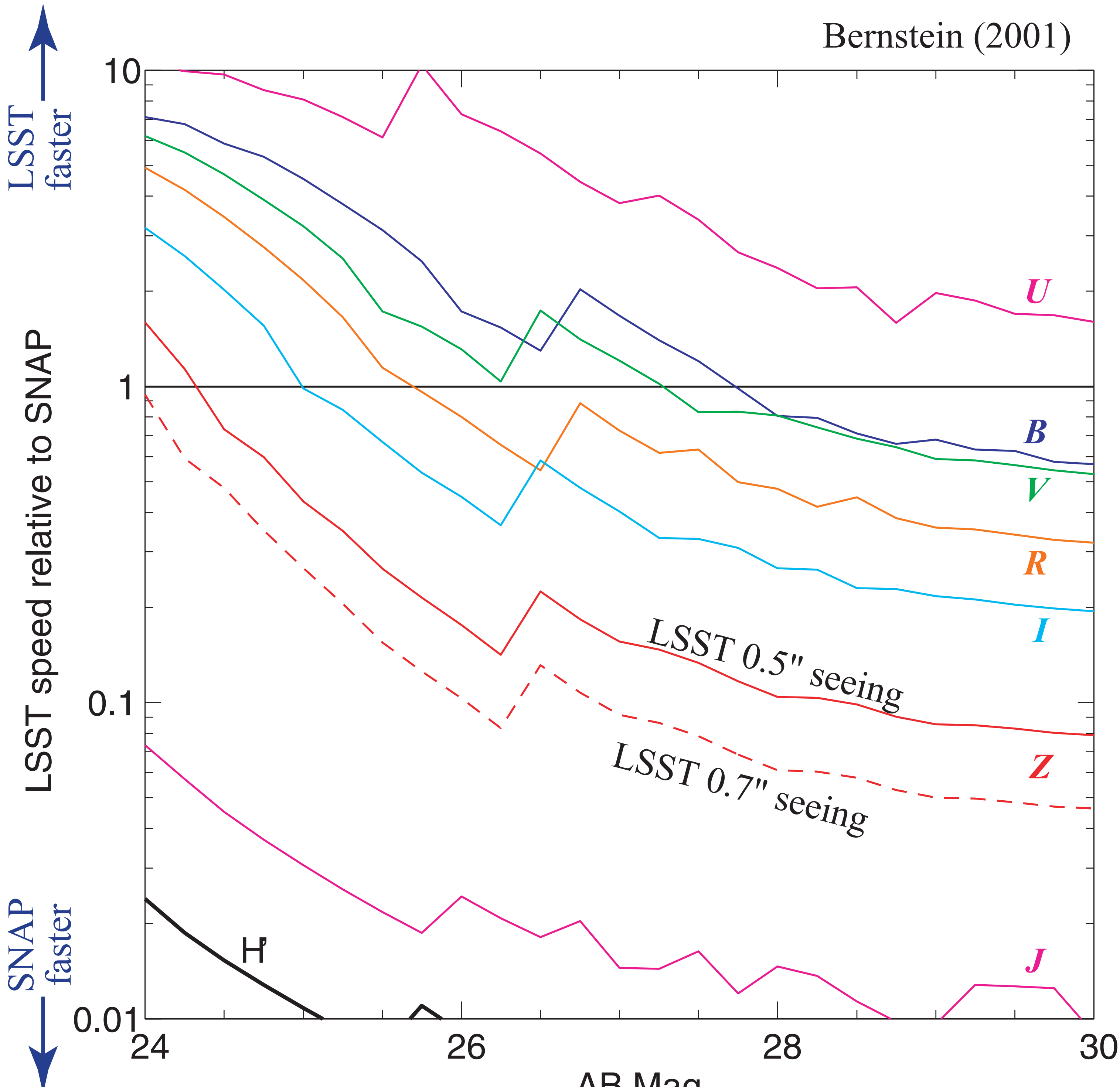
Gary Bernstein, 2001, submitted to PASP

- Calculations for PSF photometry
- Includes undersampled and dithered images
- Includes cosmic ray rates
- Includes intra-pixel sensitivity variations (10% gutters)
- Calculated for point source and galaxy photometry
- Determines astrometric errors
- Determines galaxy shape errors

Allows us to answer some commonly arising questions about imaging strategies:

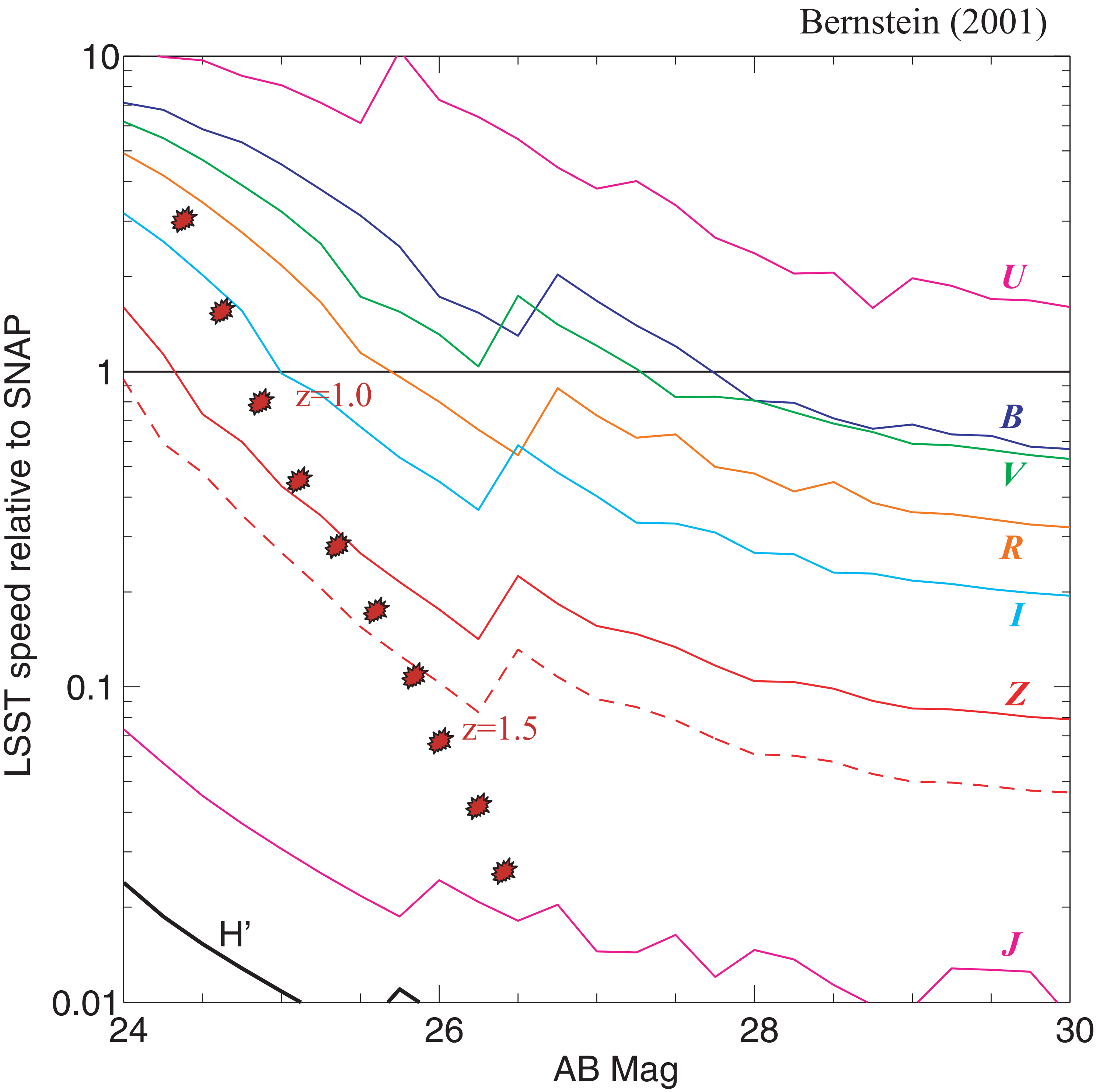
- What amount of dithering is ideal?
- What pixel size optimizes the productivity of a camera?
- Which is more efficient; space-based or ground-based observing?

Supernova survey efficiency for SNAP and LSST



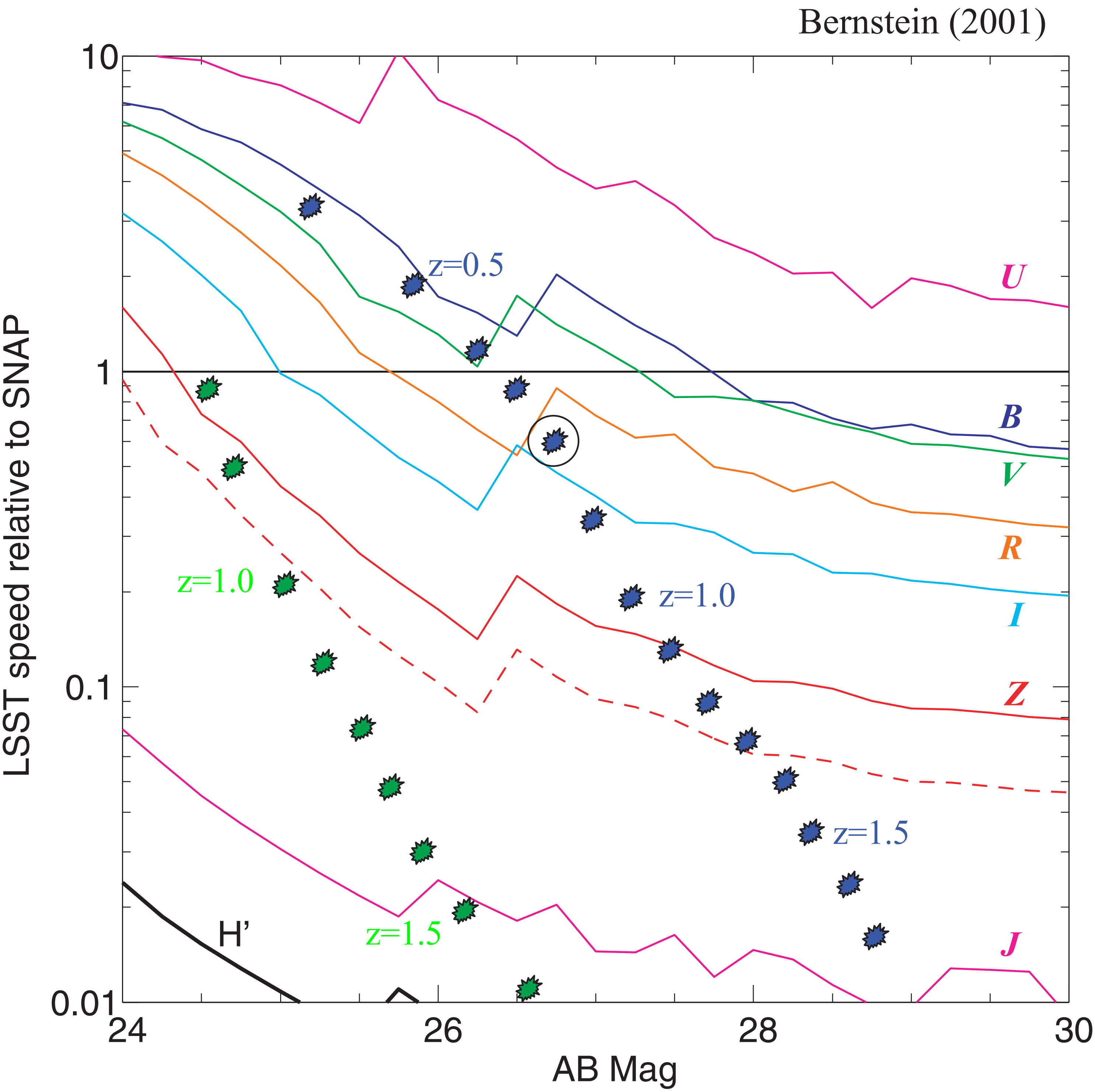
Solid lines are LSST 0.5"seeing; dashed line is 0.7".

Supernova survey efficiency for SNAP and LSST



Brightness and restframe B band wavelength of SNe Ia at peak

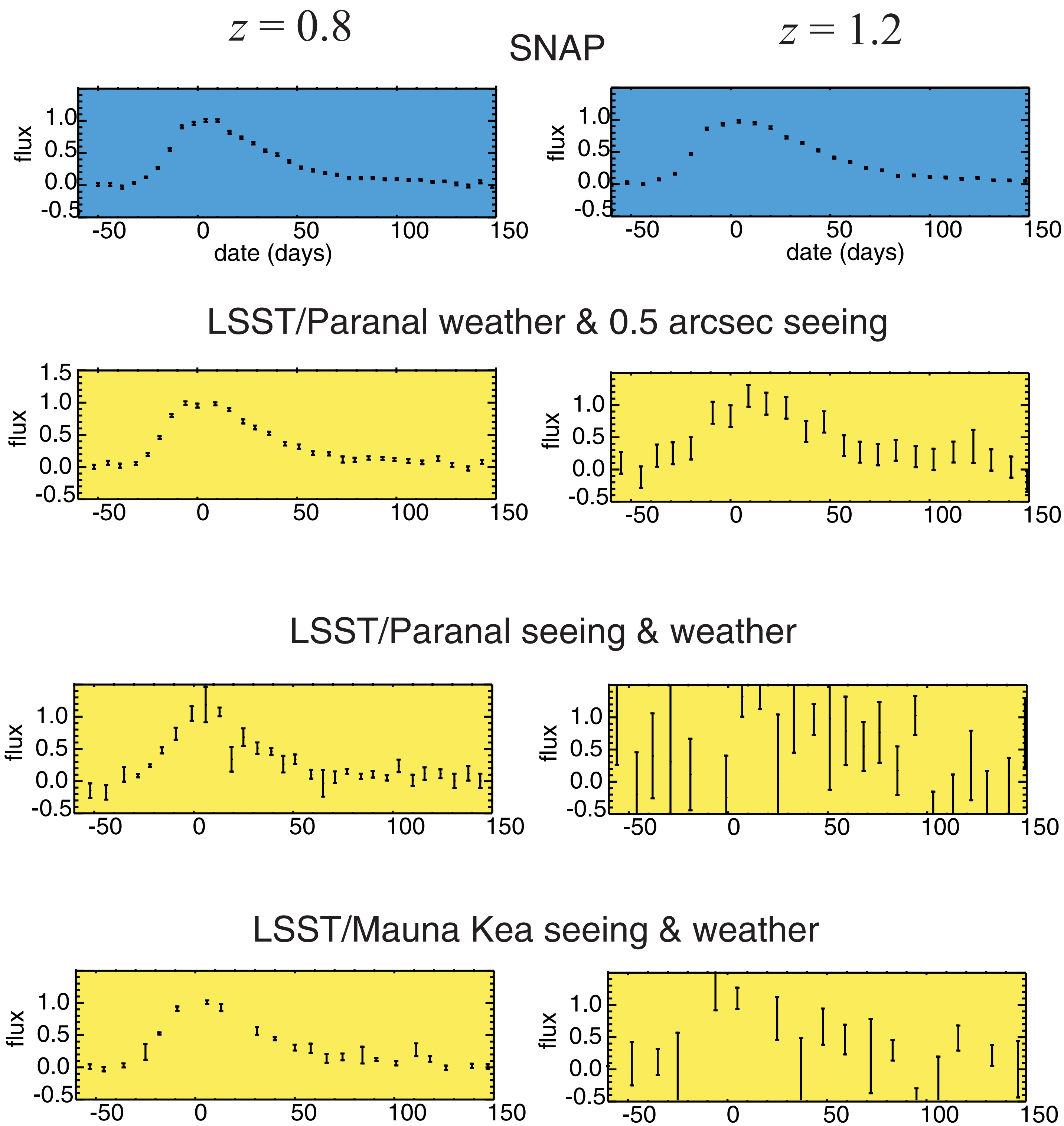
Supernova survey efficiency for SNAP and LSST



- Brightness and V band wavelength of SNe Ia at peak
- Discovery brightness to prevent Malmquist bias

Simulated LSST and SNAP Lightcurves for restframe V-band.

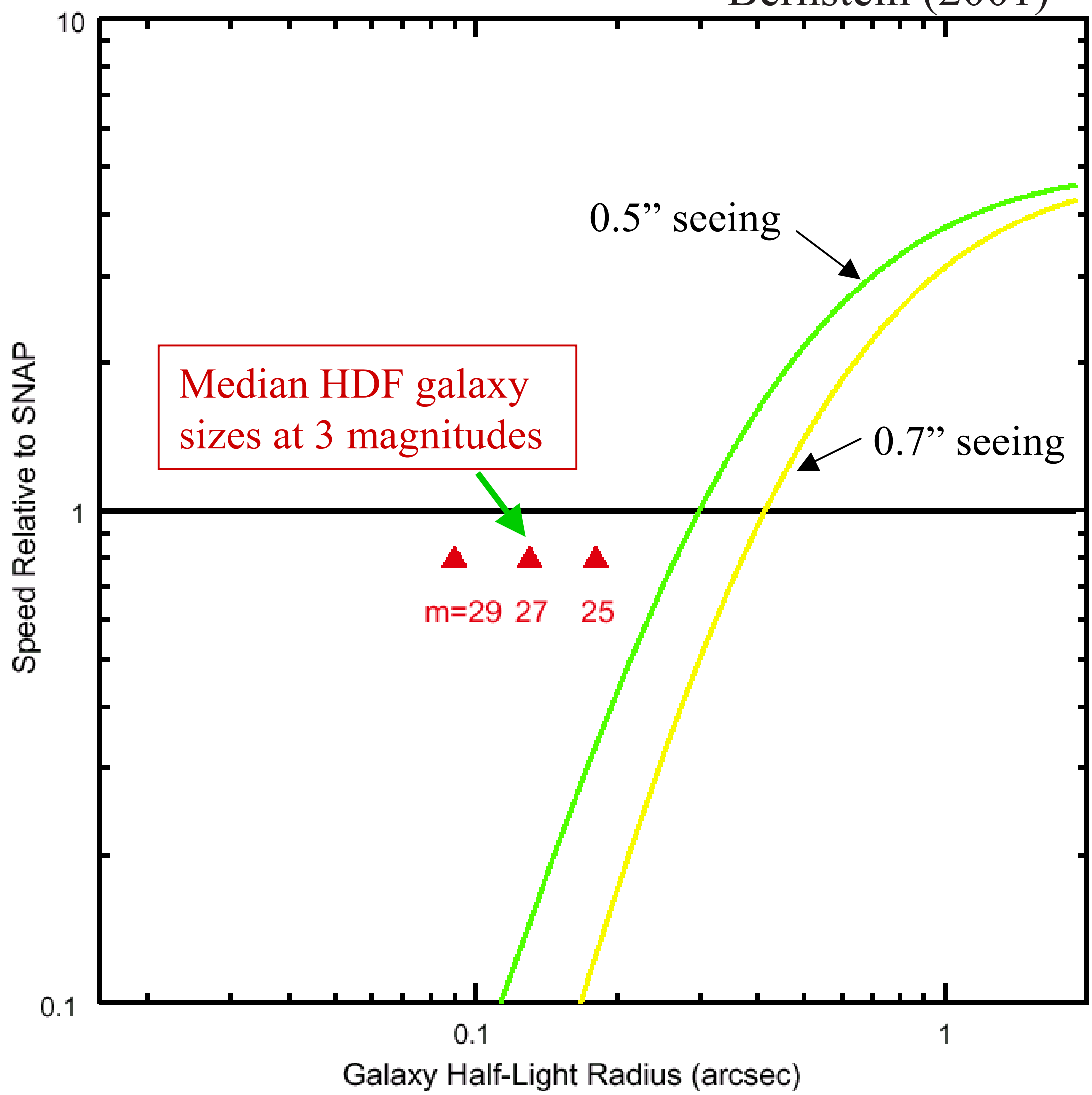
LSST with a NIR camera and 9 hours per filter.



Weak Lensing Survey Speed:
including effects of galaxy size

Galaxies must be resolved for use in weak lensing analyses. HDF studies (Gardner & Satyapal, 2000) show that galaxies become *much* smaller at faint magnitudes.

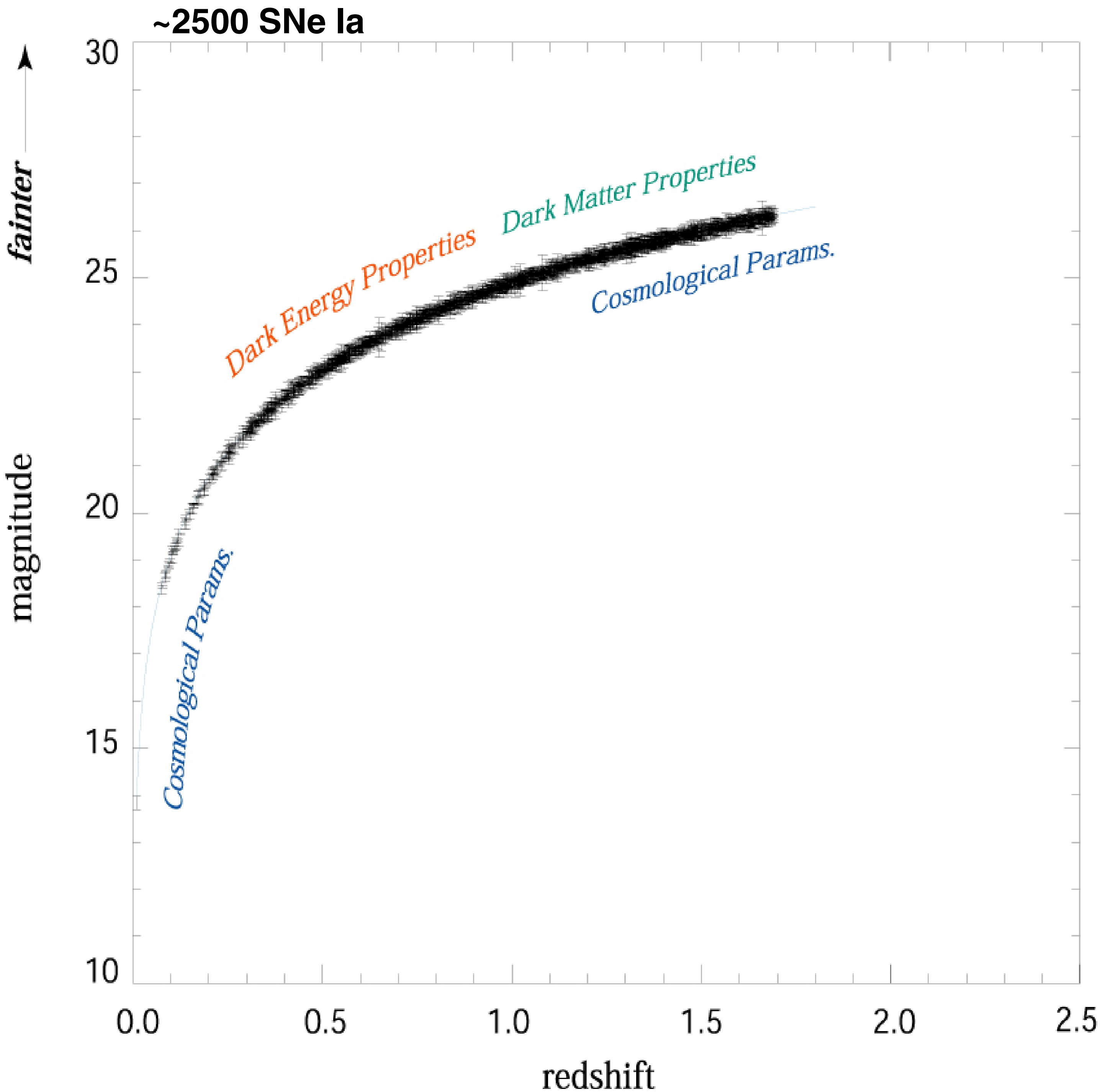
Bernstein (2001)



Approximately 85% of galaxies with r<30 are between r=27 and 30.

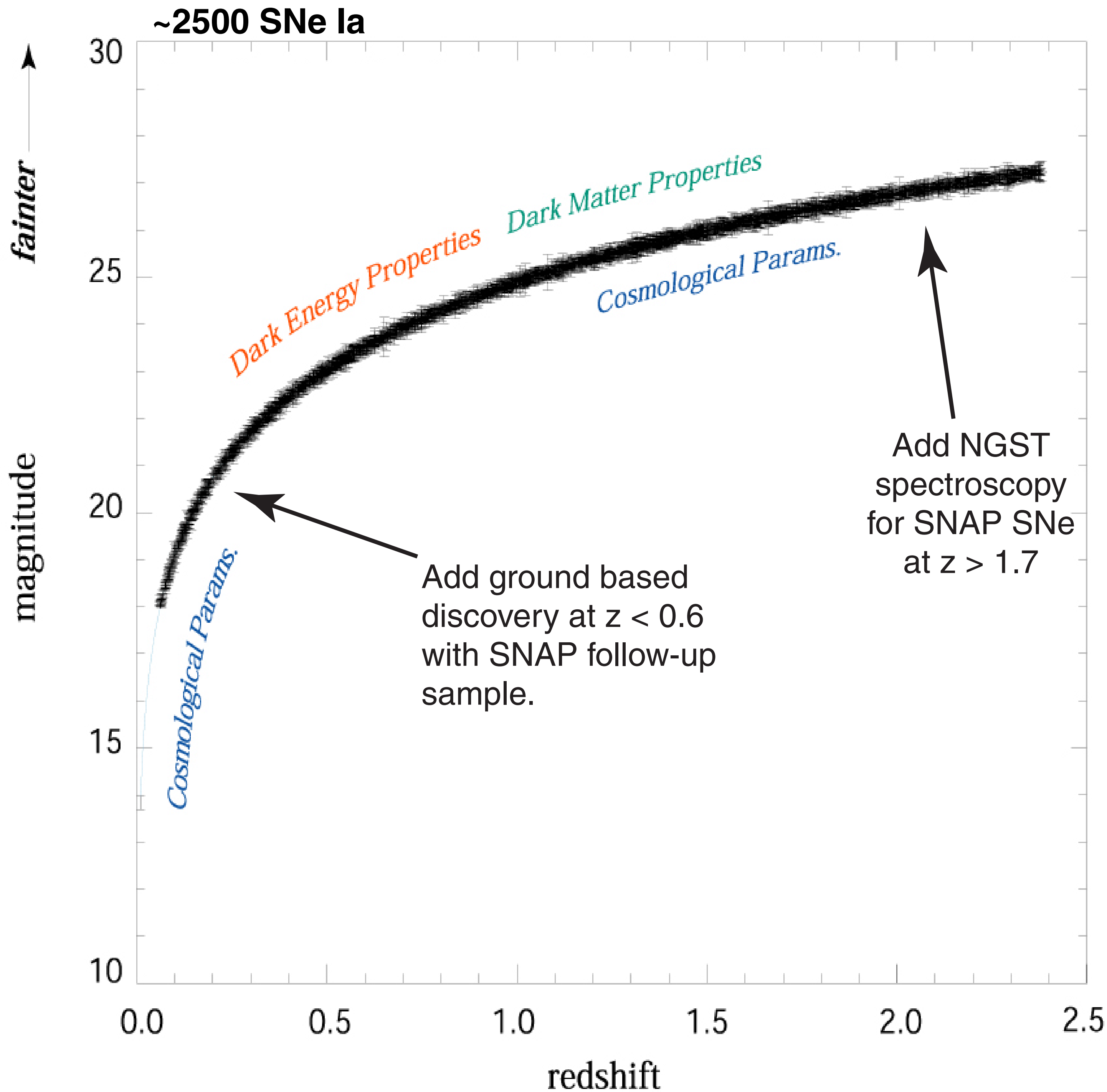
SuperNova Acceleration Probe

Baseline One-Year Sample

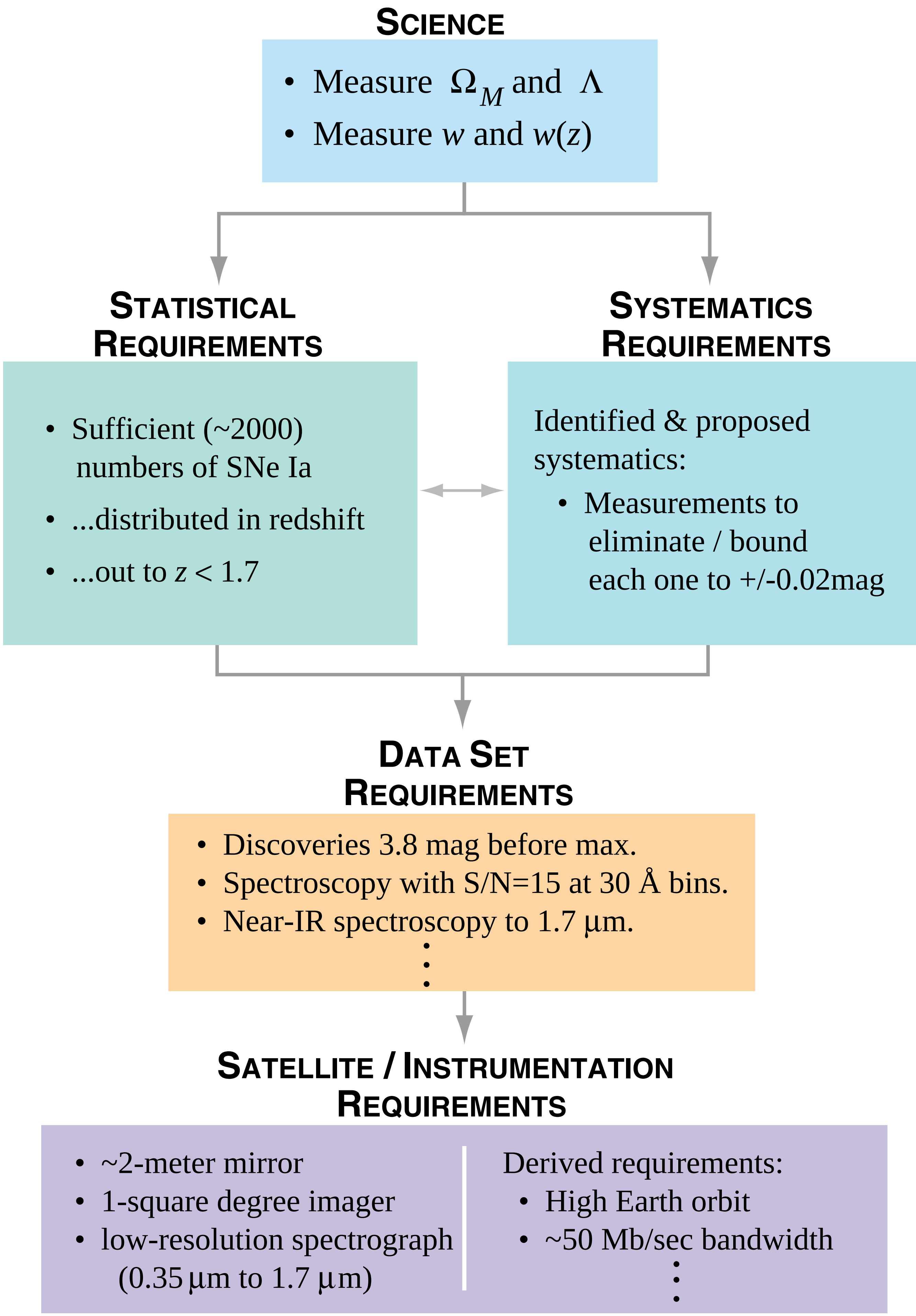


SNAP SuperNova Acceleration Probe

Baseline One-Year Sample



Technical Readiness


SCIENCE
• Measure Ω_M and Λ
• Measure w and $w(z)$
STATISTICAL REQUIREMENTS
• Sufficient (~2000) numbers of SNe Ia
• ...distributed in redshift
• ...out to $z < 1.7$
SYSTEMATICS REQUIREMENTS
Identified & proposed systematics:
• Measurements to eliminate / bound each one to +/-0.02mag
DATA SET REQUIREMENTS
• Discoveries 3.8 mag before max.
• Spectroscopy with S/N=15 at 30 Å bins.
• Near-IR spectroscopy to 1.7 μm.
SATELLITE / INSTRUMENTATION REQUIREMENTS
• ~2-meter mirror
• 1-square degree imager
• low-resolution spectrograph (0.35 μm to 1.7 μm)
Derived requirements:
• High Earth orbit
• ~50 Mb/sec bandwidth

Observatory

Simple Observatory consists of :

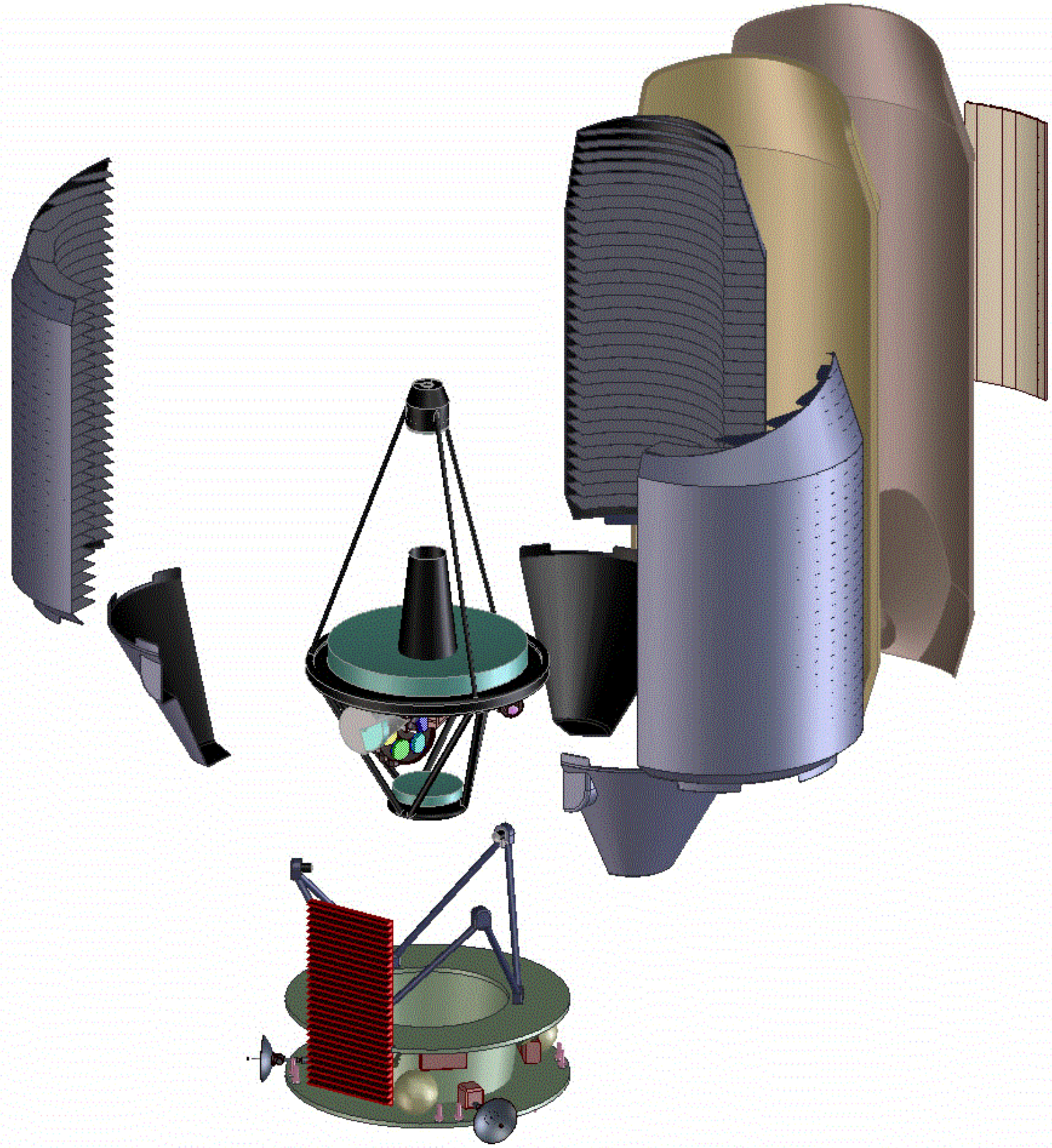
1) 3 mirror telescope w/ separable kinematic mount

2) Optics Bench w/ instrument bay

3) Baffled Sun Shade w/ body mounted solar panel and instrument radiator on opposing side

4) Spacecraft bus supporting telemetry (multiple antennae), propulsion, instrument electronics, *etc*

No moving parts (ex. filter wheels, shutters), rigid simple structure.

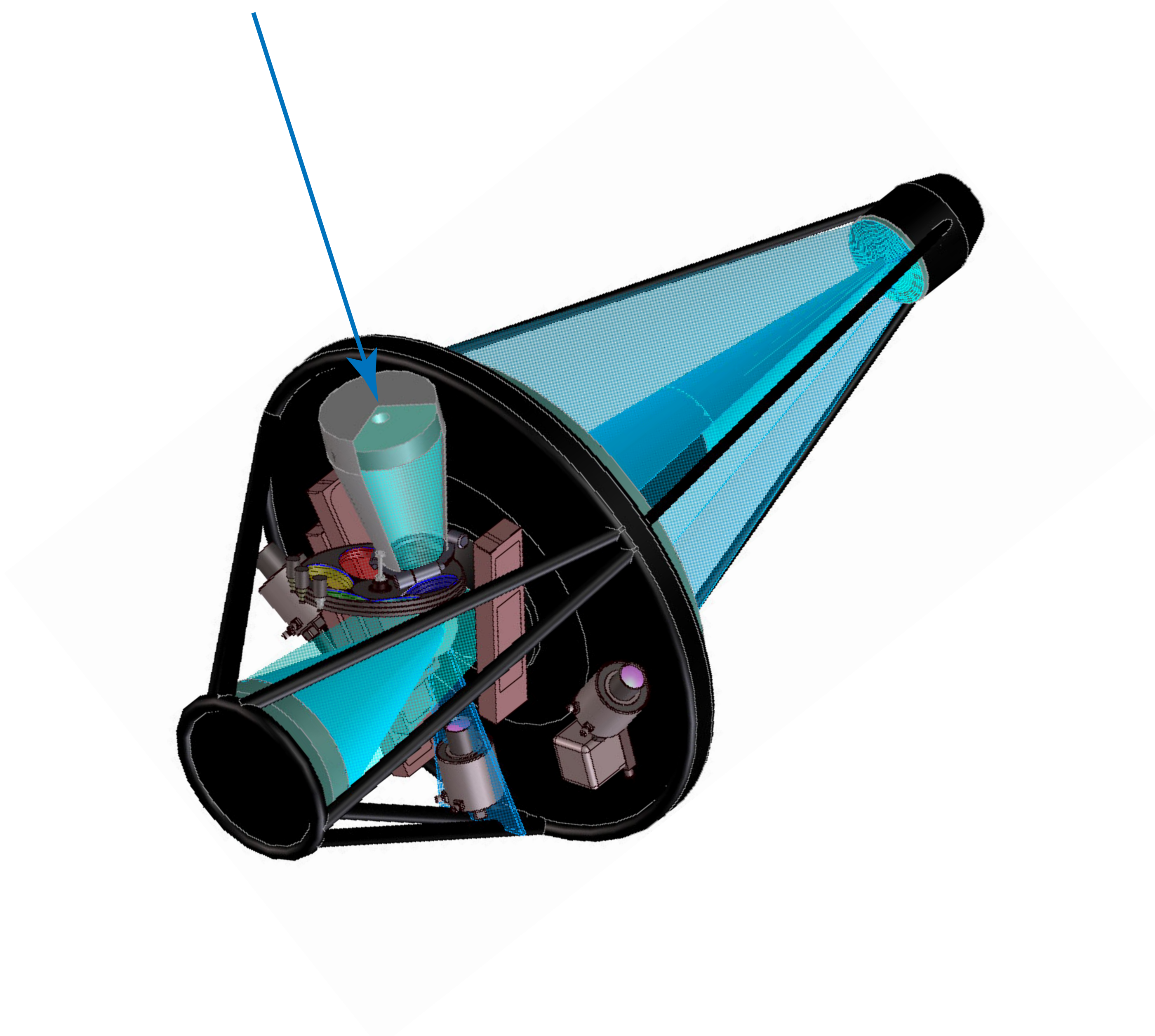


SNAP SuperNova Acceleration Probe

Instrumentation

GigaCam Imager
1 square degree field of view
with CCD's + HgCdTe Devices

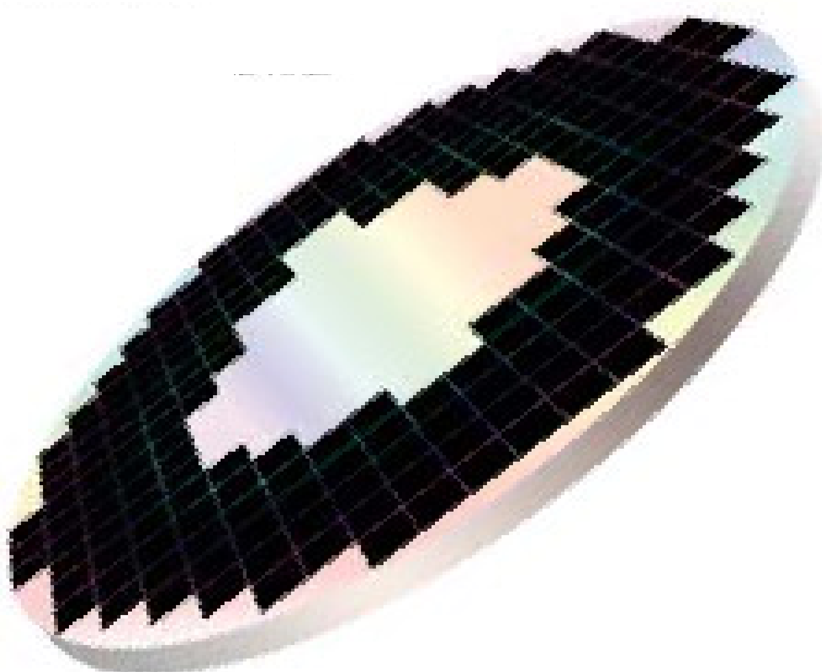
Spectrograph
low resolution, R~75
high throughput
350 nm -- 1700 nm

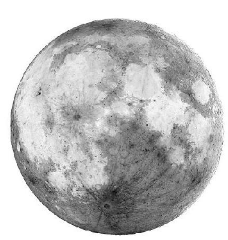


SNAP SuperNova Acceleration Probe

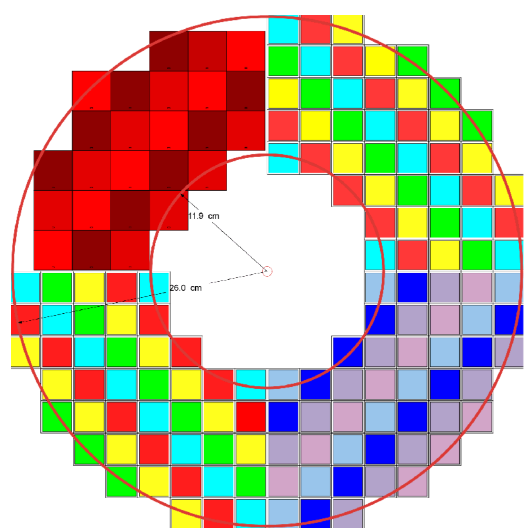
GigaCAM, a one billion pixel array

- Depending on pixel scale approximately 1 billion pixels
- 132 Large format CCD detectors and 25 HgCdTe devices
- Looks like the SLD vertex detector in Si area (0.1 - 0.2 m^2)
- Larger than SDSS camera, smaller than BaBar Vertex Detector (1 m^2)





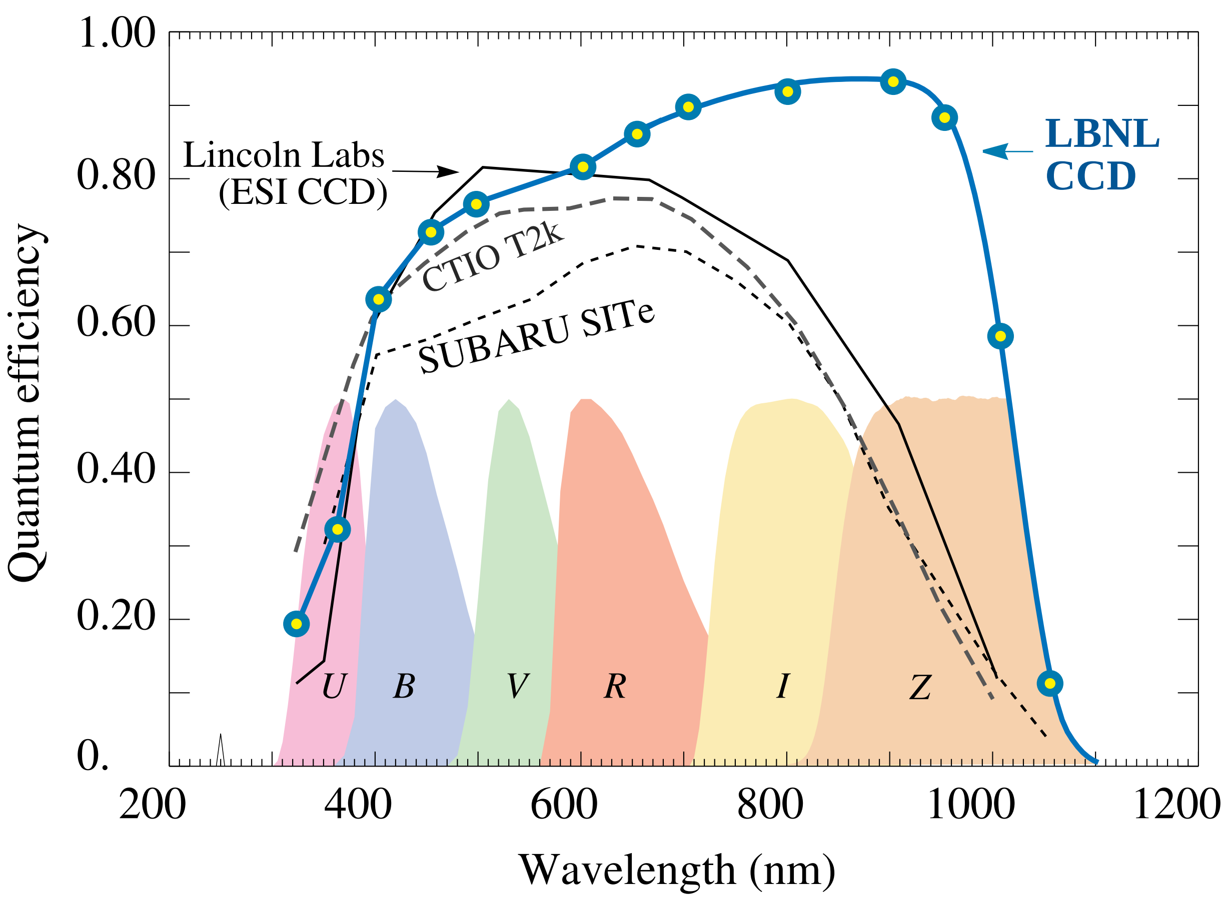
The Moon
(for scale)



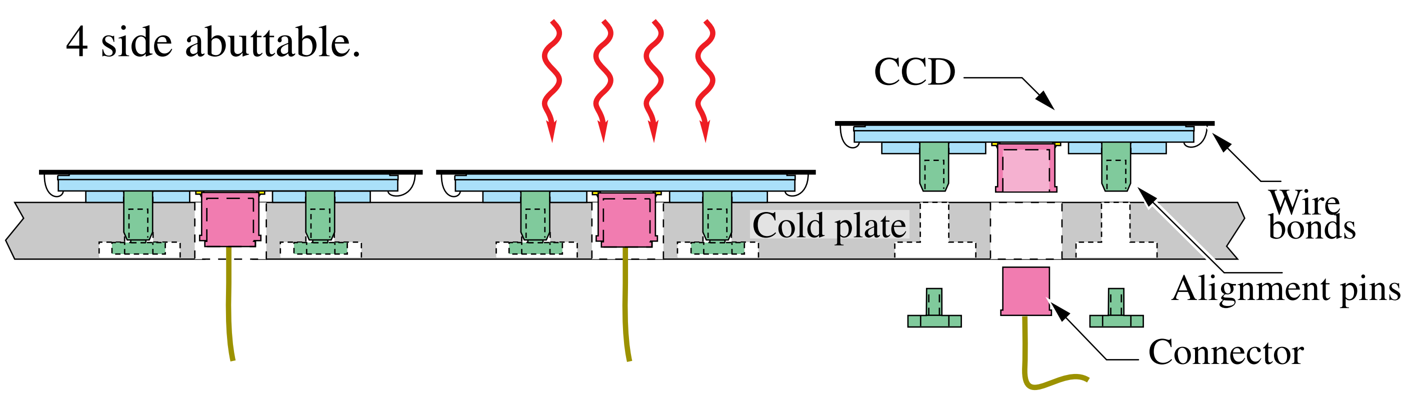
3 IR filters on HgCdTe
8 visible filters on CCD

LBNL CCD Technology

High quantum efficiency from near UV to near IR
No thinning, no fringing.
High yield.
Radiation hard.



4 side abuttable.



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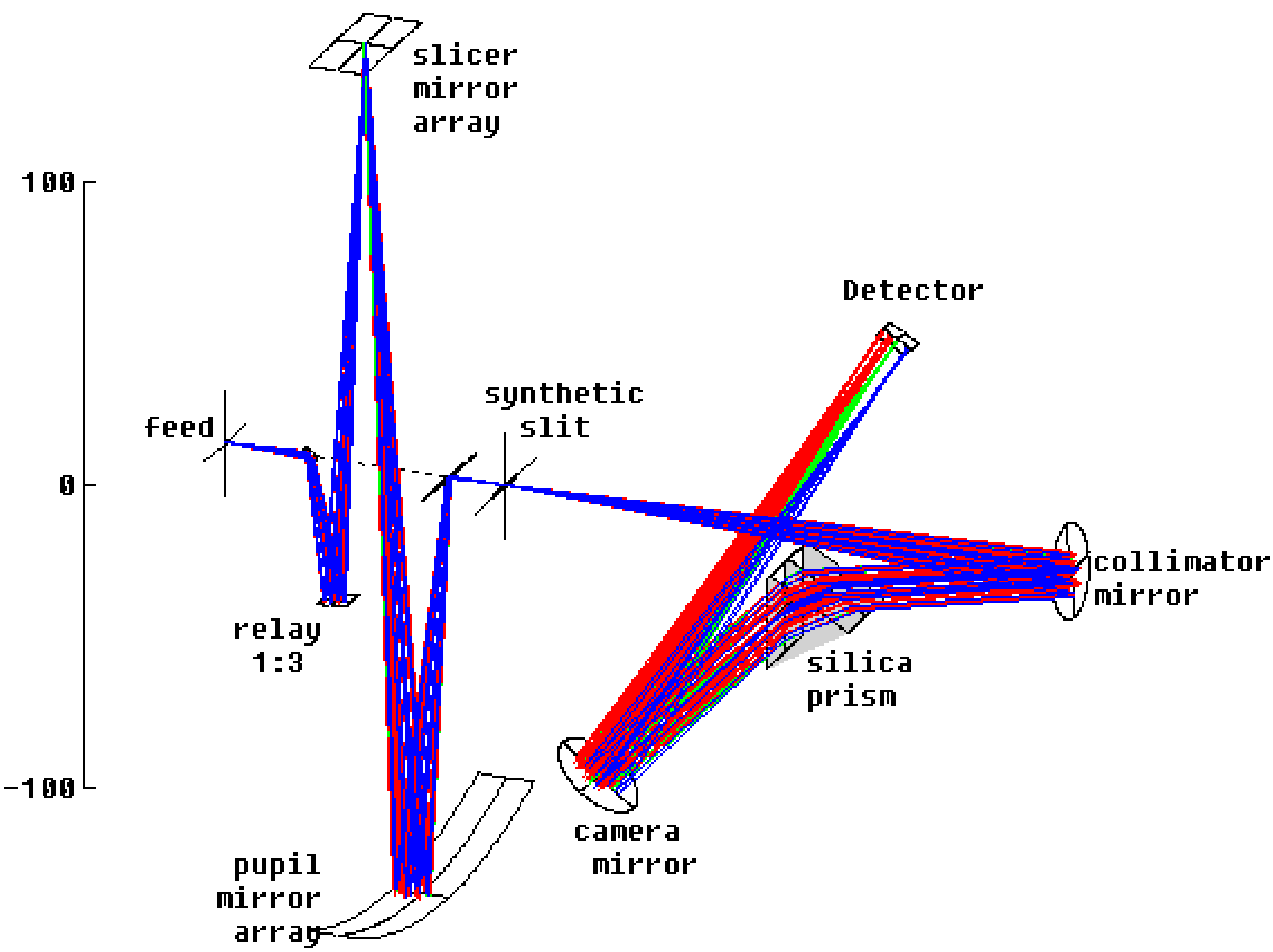
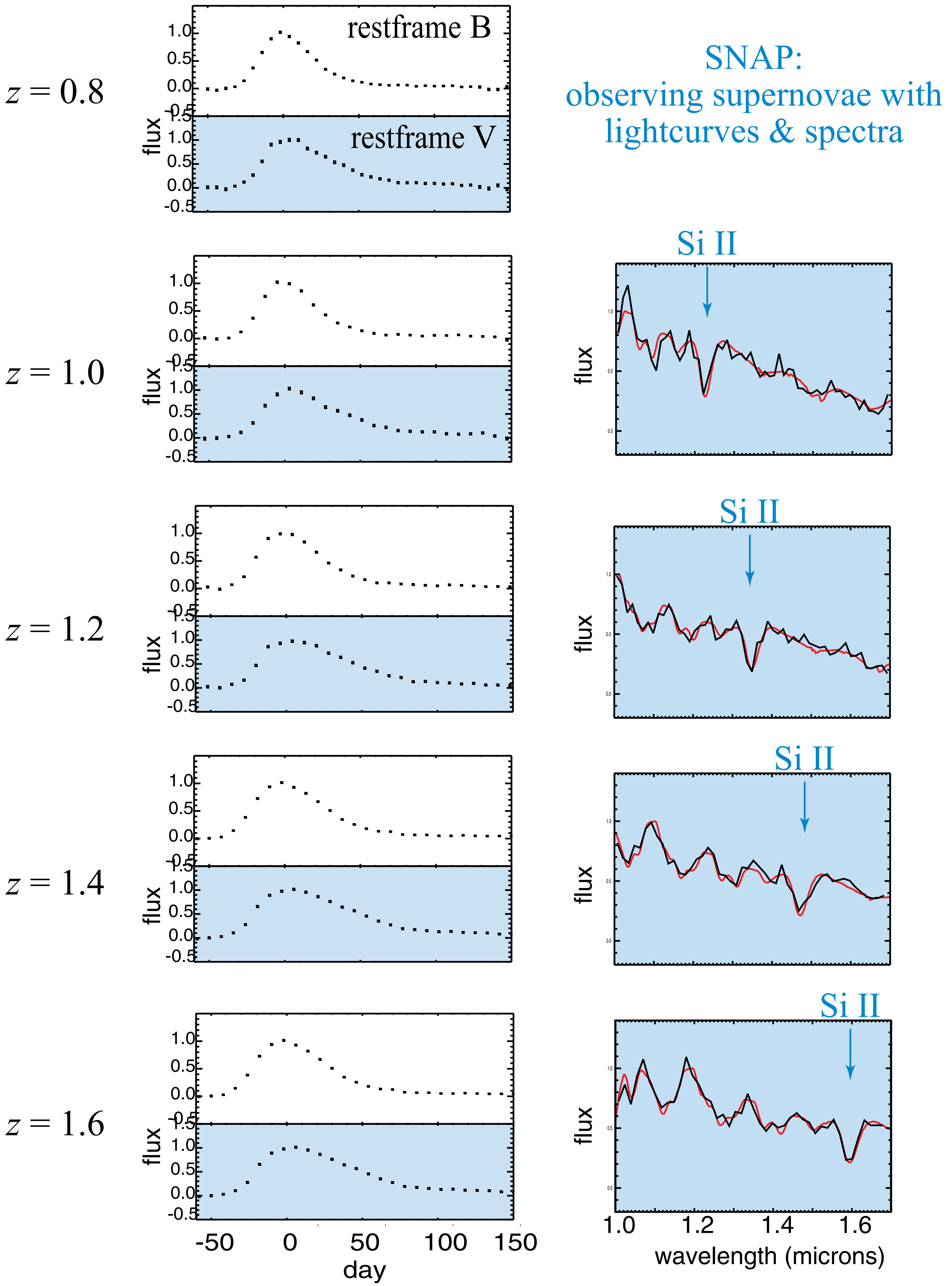
IFU Spectrometer Concept



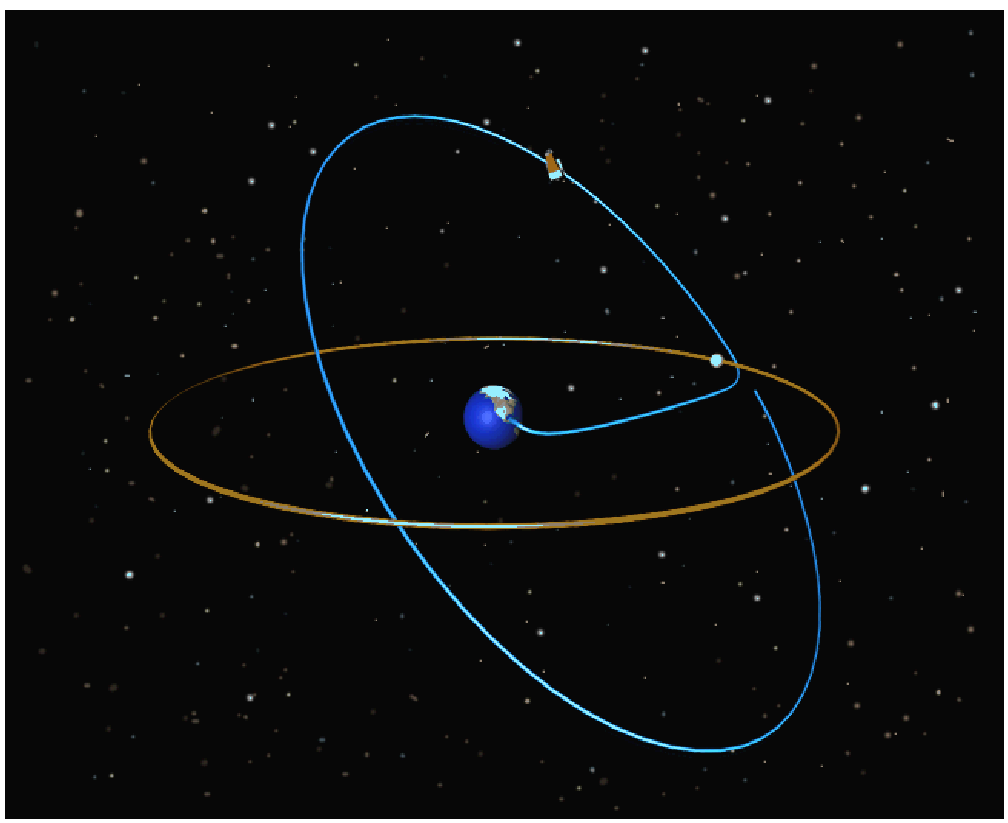


SNAP:
observing supernovae with
lightcurves & spectra
z = 0.8
z = 1.0
z = 1.2
z = 1.4
z = 1.6
restframe B
restframe V
flux
Si II
-50
0
50
100
150
day
1.0
1.2
1.4
1.6
wavelength (microns)

SNAP SuperNova Acceleration Probe

Advantages of particular high earth orbit:

—Minimum Thermal Change on Telescope (annual eclipse) – very stable PSF
—Excellent Telemetry, reduces risk on satellite
—Outside Radiation Belts
—Passive Cooling of Detectors
—Minimizes Earth Albedo
—MAP currently proving orbit concept



Technology readiness and remaining hurdles

NIR sensors

HgCdTe stripped devices are begin developed for NGST and are ideal in our spectrograph.
"Conventional" devices with appropriate wavelength cutoff are being developed for WFC3 and ESO.

CCDs

We have demonstrated radiation hardiness that is sufficient for the SNAP mission.
Extrapolation of earlier measurements of diffusion's effect on PSF indicates we can get to the sub 4 micron level. Needs demonstration.
Industrialization of CCD fabrication has produced useful devices. More wafers have just arrived.
Detectors & electronics are the largest cost uncertainty.
ASIC development is required.

Filters

We are investigating three strategies for fixed filters.

- Suspending filters above sensors
- Gluing filters to sensors
- Direct deposition of filters onto sensors.

Shutter

Goddard has proposed a scale-up of a heritage shutter.

On-board data handling

We have opted to send all data to ground to simplify the flight hardware and to minimize the development of flight-worthy software.
50 Mbs telemetry, and continuous ground contact are required. Goddard has validated this approach.

Calibration

There is an active group investigating all aspects of calibration.

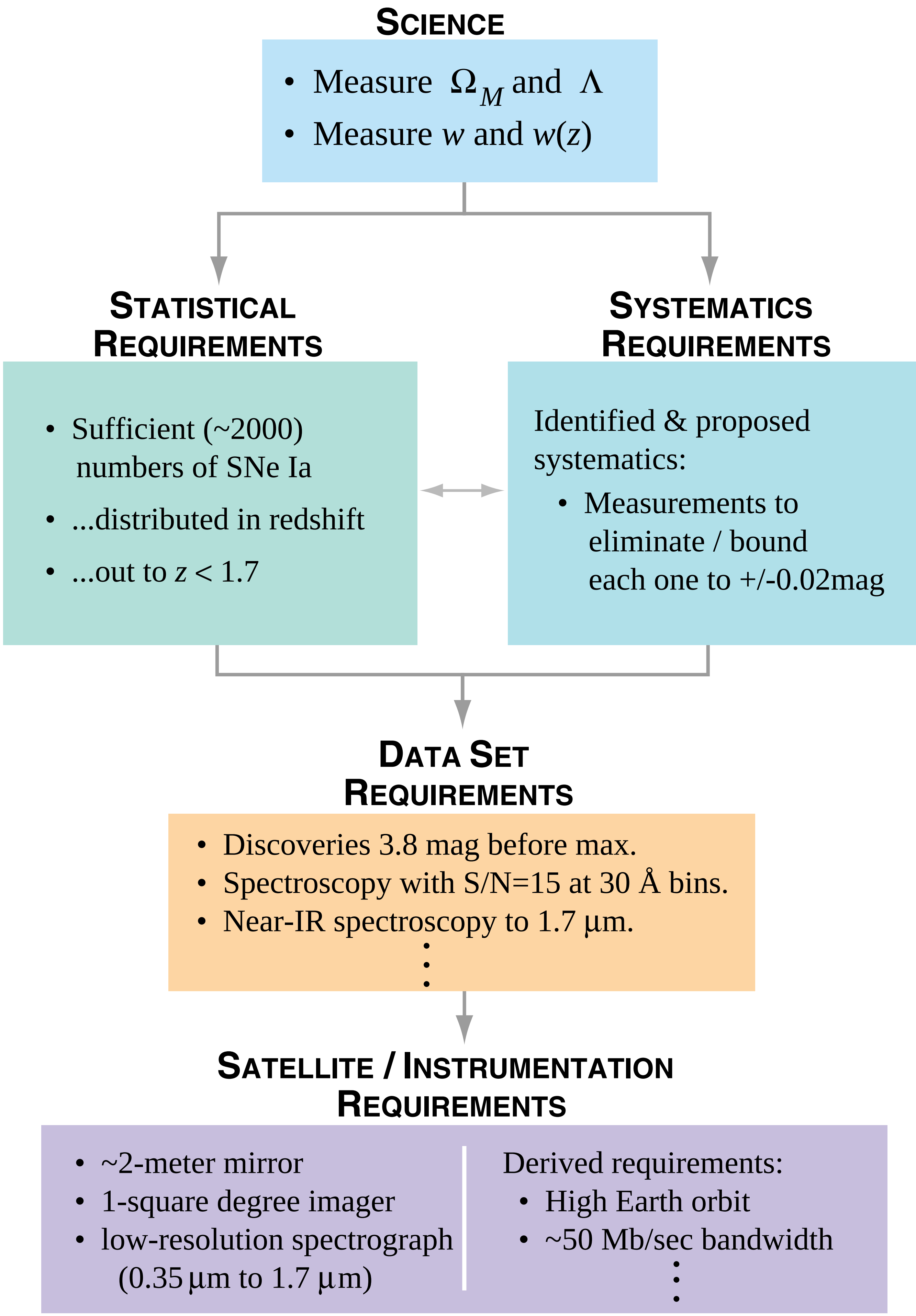
Pointing

The new generation HgCdTe multiplexor and readout IC support high rate readout of regions of interest for generating star guider information.

Next generation attitude control systems may have sufficient pointing accuracy so that nothing special needs be done with the sensors.

Telescope

Ground-based end to end testing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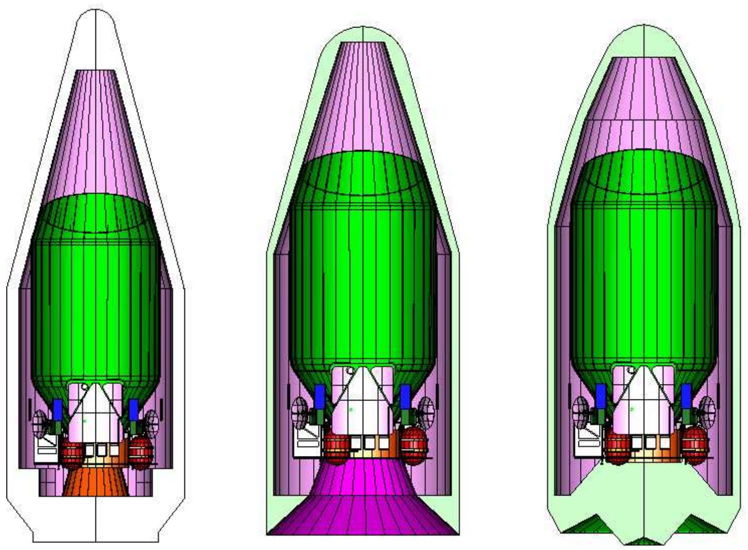
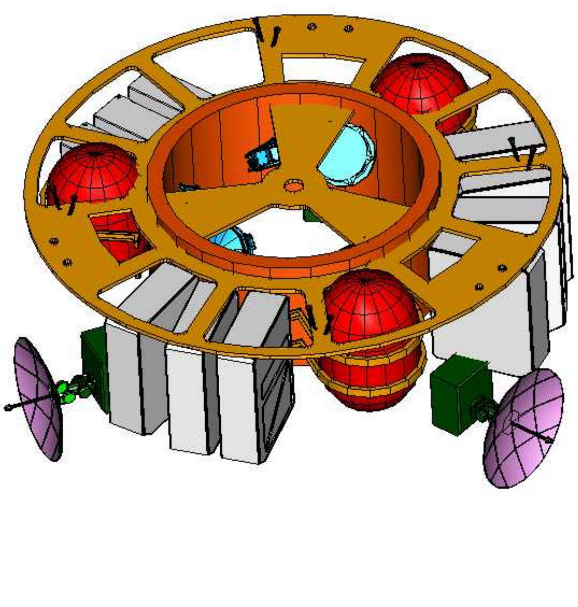
SNAP SuperNova Acceleration Probe

NASA Goddard Integrated Mission Design Center



Atlas-EPF Delta-III Sea Launch



SNAP intensive design study

SNAP Collaboration

Current membership:

31 physicists,
18 astronomers,
and 8 senior engineers.

Current institutions:

Lawrence Berkeley National Laboratory,
University of California Berkeley,
CNRS/IN2P3/CEA/CNES --France
University Paris VI & VII,
University of Michigan,
University of Maryland,
California Institute of Technology,
Space Telescope Sciences Institute,
University of Stockholm, University of Edinburgh,
European Southern Observatory,
and Instituto Superior Tecnico.

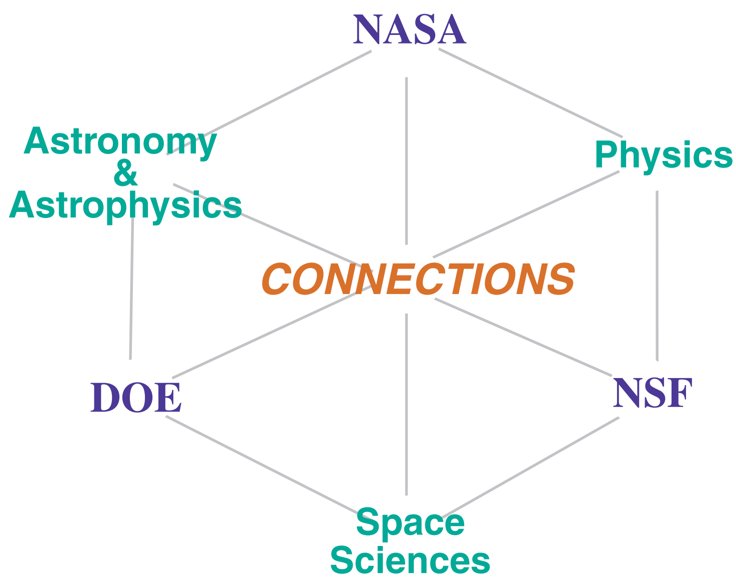
We expect further institutions and personnel to participate including: NASA Goddard, U.S. Universities (Indiana, Ohio State, Purdue, ...), and additional faculty at the above listed institutions

SNAP SuperNova Acceleration Probe

Project Chronology

First public presentation of idea at Fermilab "Inner Space/Outer Space" symposium.	**end of May 1999**
Letter of Intent (pre-proposal) to DOE & NSF-Physics	**Nov 1999**
Review panel for Letter of Intent	**Dec 1999**
Science proposal for study phase to DOE & NSF-Physics	**Feb 2000**
SAGENAP review for DOE & NSF-Physics	**end of March 2000**
SAGENAP peer review panel report	**July 2000**
Study proposal to NSF-Physics Review in process.	**end of Sept 2000**
Presentation to the NASA SEU subcomittee	**Nov 2000**
Dedicated session on SNAP at the 2001 AAS meeting	**Jan 2001**
Study review for DOE	**Jan 2001**

SNAP SuperNova Acceleration Probe



How does a project get proposed and prioritized by peer-review in this multi-disciplinary, multi-agency "Connections" environment?

SNAP SuperNova Acceleration Probe

Science Goals for The First Wide-field Survey in Space

A Resource for the Science Community:
The *only* wide-field deep survey in space -- with HST resolution.

The biggest HST deep survey will be the ACS survey:
6300x smaller than SNAP main survey
and almost as deep
Discovery potential ~6000x greater than ACS deep

Complementary to NGST: target selection for rare objects
1950s+1960s: Palomar 48” feeds 200”
2000: SDSS feeds 8 and 10 meter telescopes
2010: SNAP feeds NGST

→ Archive data distributed

→ Guest Survey Program

Whole sky can be observed every few months

Example One-Year Survey Sensitivities

Magnitudes given are for S/N>=5 detections for 95% of point sources. 2x2 interlacing has been enforced under the assumption that this is a survey mode, so we will want to have minimal aliasing. All magnitudes are AB system.

Band	30,000	3,000	300 square degrees
H'	26.4	27.85	29.25
J	26.6	28.1	29.4
Z	27.35	28.85	30.2
I	27.4	28.9	30.25
R	27.55	29.1	30.4
V	27.25	28.85	30.25
B	27.65	29.3	30.65
U	26.6	28.5	29.9

SNAP SuperNova Acceleration Probe

Science Goals for
The First Wide-field Survey in Space

Ultra-deep 11 band imaging survey

Galaxy populations and morphology to co-added $m = 32$
Low surface brightness galaxies in *H'* band
Quasars to redshift 10 (when is this, how old is universe)
Epoch of reionization through Gunn-Peterson effect
Galaxy evolution studies, merger rate
Evolution of stellar populations
Ultraluminous infrared galaxies
Globular clusters around galaxies
Extragalactic stars (in clusters or otherwise)
Intracluster objects (globulars, dwarf galaxies, etc.)
Lensing projects:
- Mass selected cluster catalogs
- Evolution of galaxy-mass correlation function and its scaling relations
- Maps of mass in filaments

SNAP SuperNova Acceleration Probe

Science Goals for
The First Wide-field Survey in Space

Time-Domain Survey

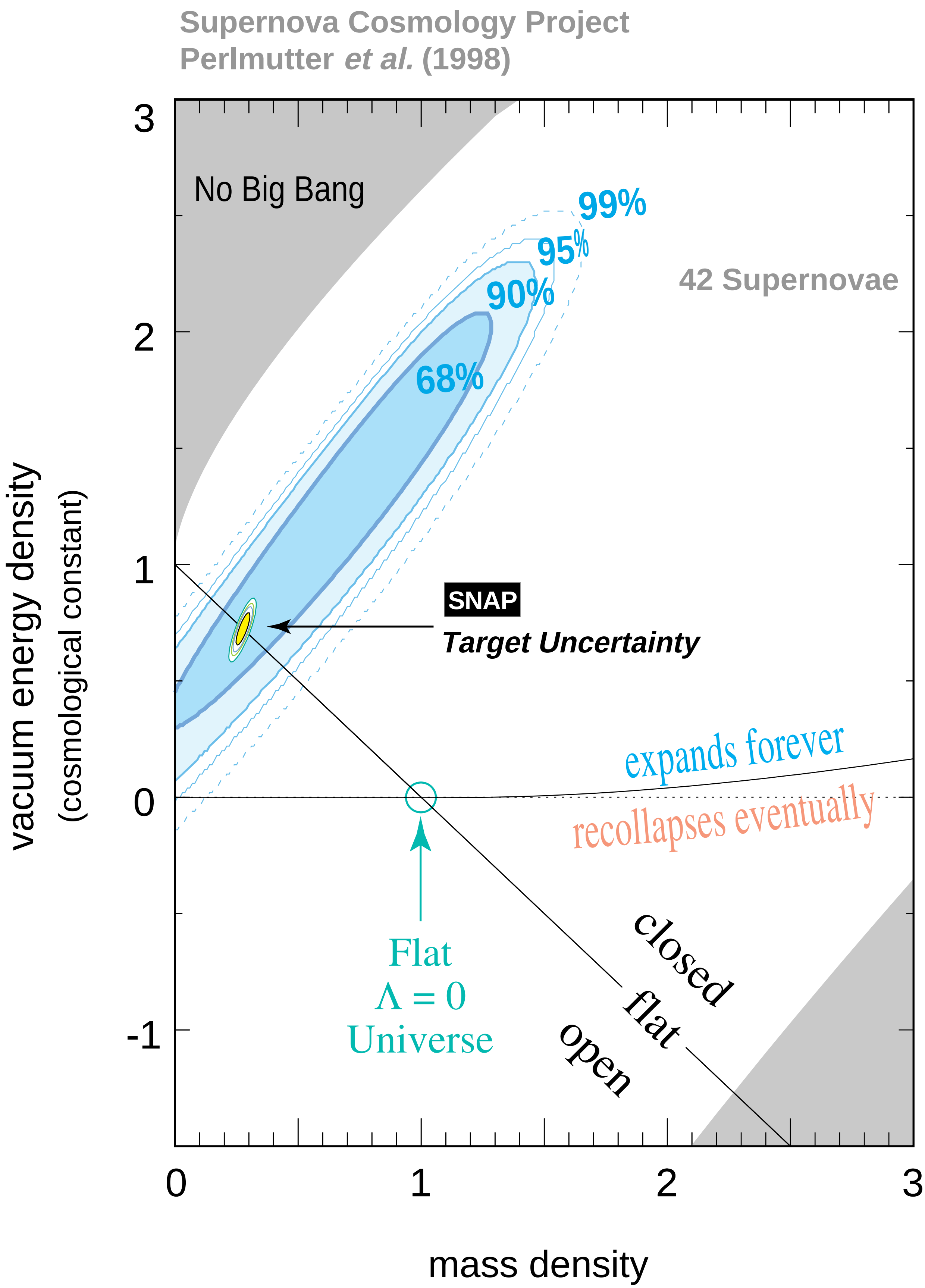
GRB optical counterparts: rates, lightcurves, and spectra
=> GRB afterglows with or without GR satellite
=> unknown fast transients

Kuiper belt objects

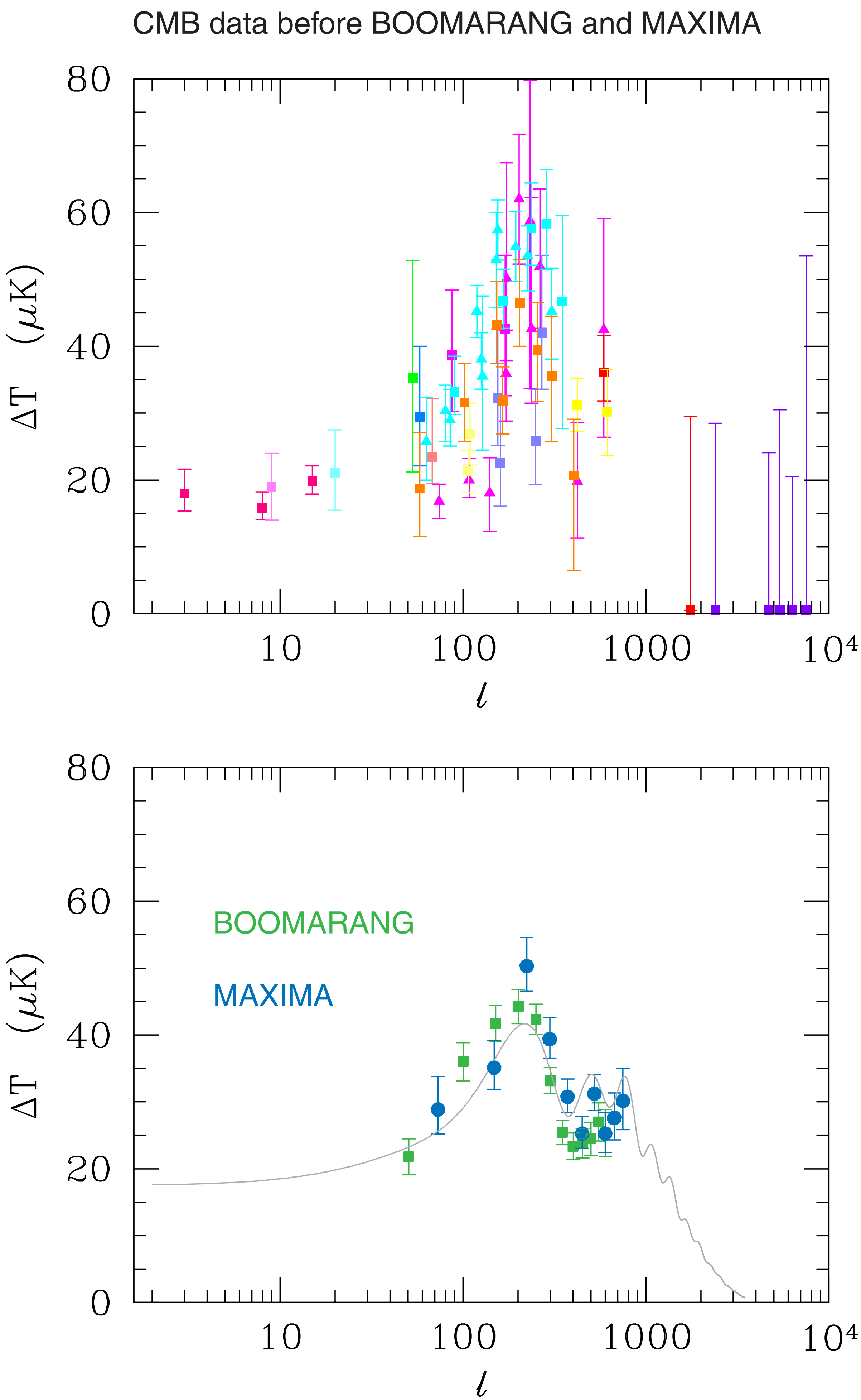
Supernova rates of all types vs. galaxy type
Supernova phenomenology studies for all types

Proper motions for halo objects
L and T dwarfs
Cool white dwarfs and other rare halo objects

Faint comets

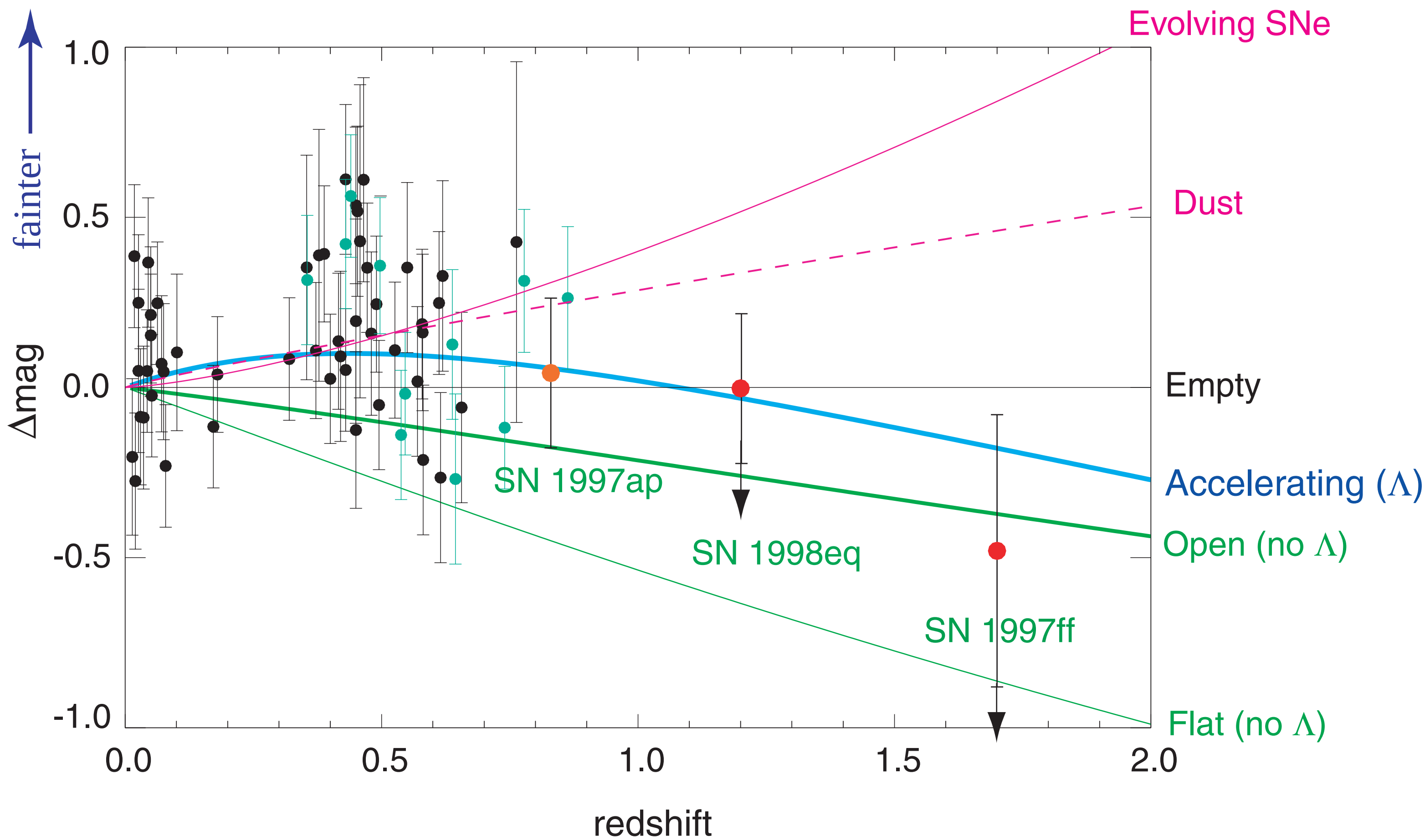


Supernova Cosmology Project
Perlmutter *et al.* (1998)
No Big Bang
99%
95%
90%
68%
42 Supernovae
SNAP
Target Uncertainty
expands forever
recollapses eventually
closed
flat
open
Flat
Λ = 0
Universe
vacuum energy density
(cosmological constant)
mass density
3
2
1
0
-1
0
1
2
3



CMB data before BOOMARANG and MAXIMA
ΔT (μK)
80
60
40
20
0
10
100
1000
10⁴
ℓ
BOOMARANG
MAXIMA

Supernovae probing
the *deceleration* era
with NICMOS



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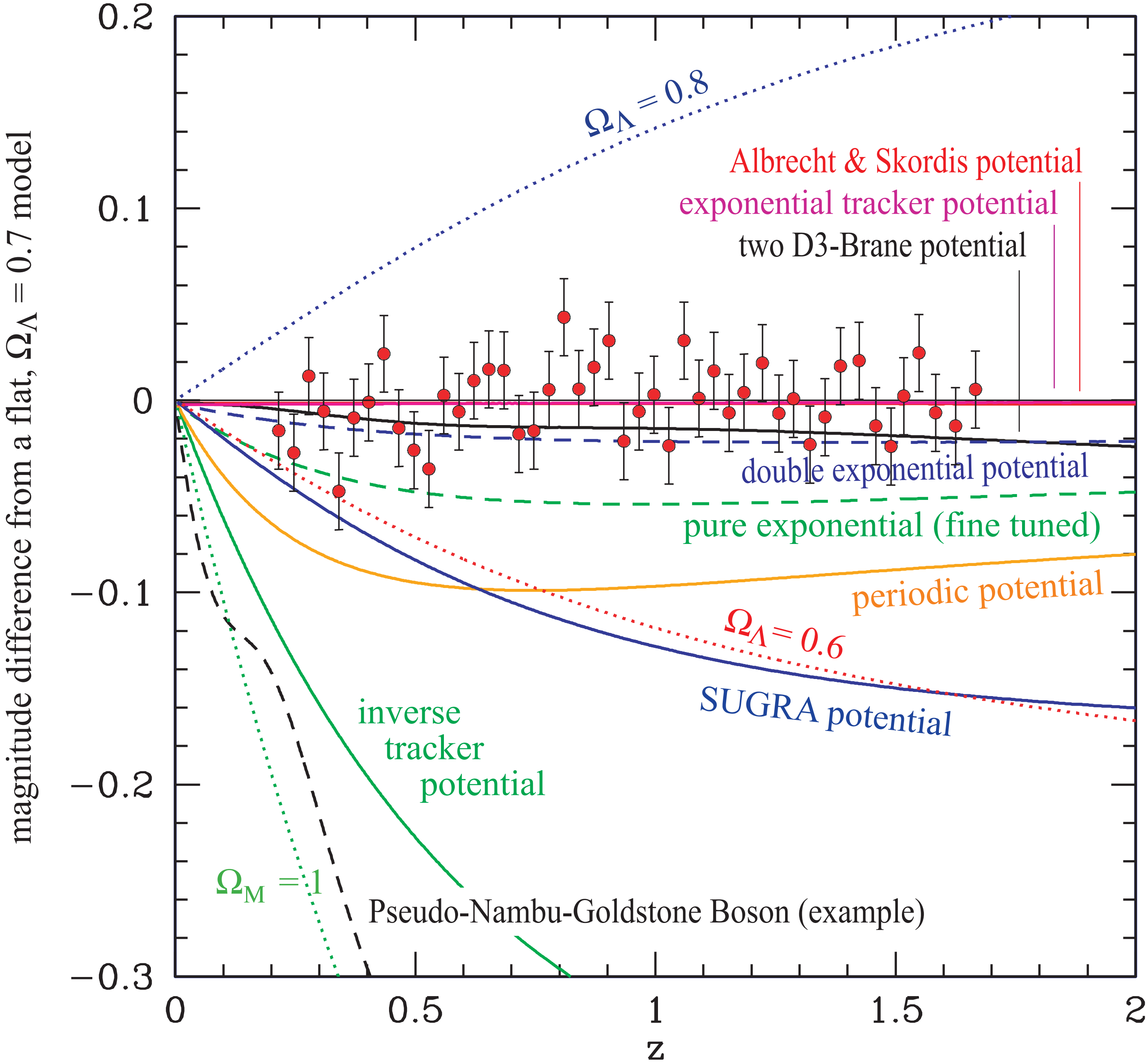
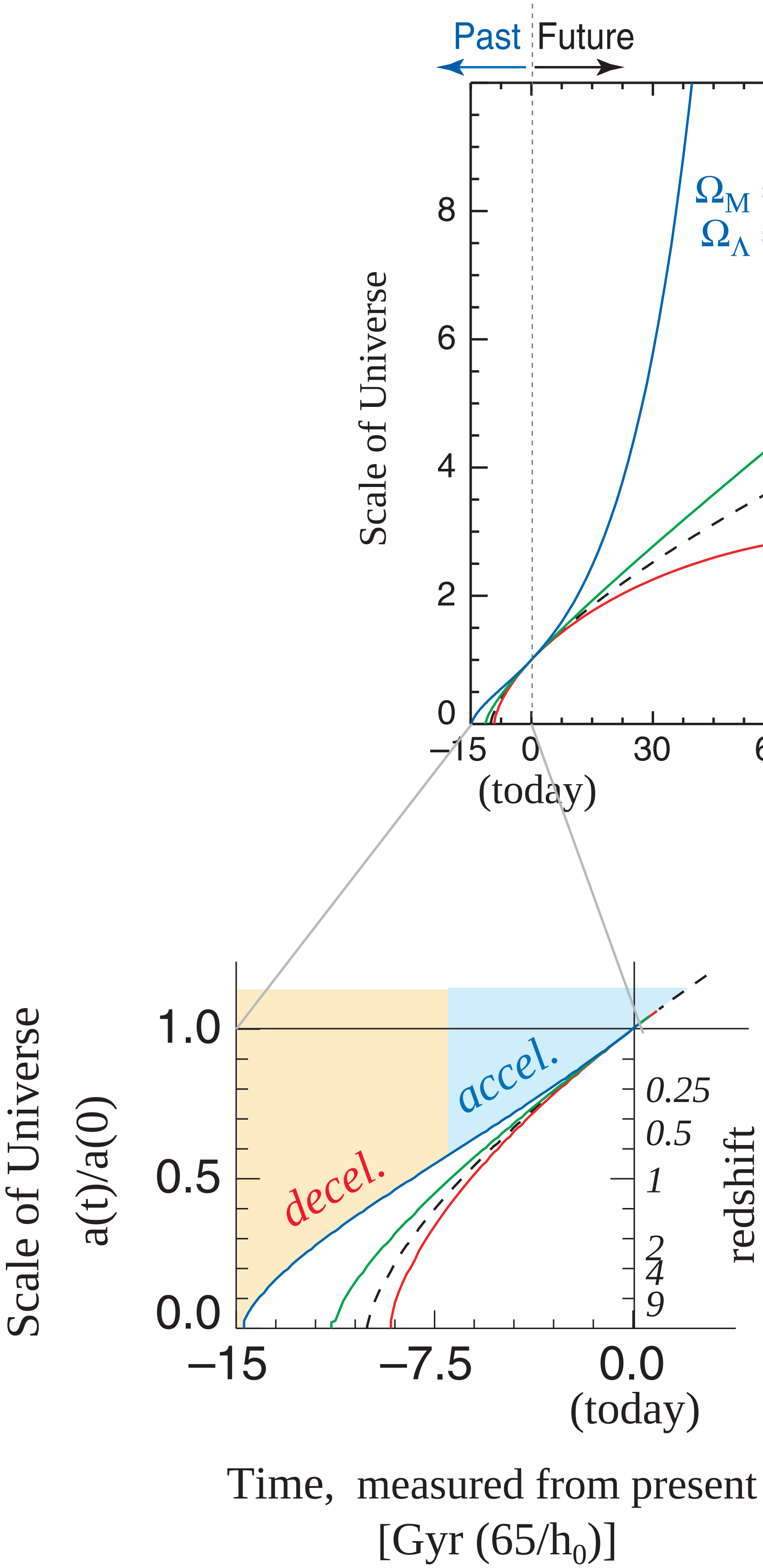
Binned simulated SNAP data compared with Dark Energy models currently in the literature.

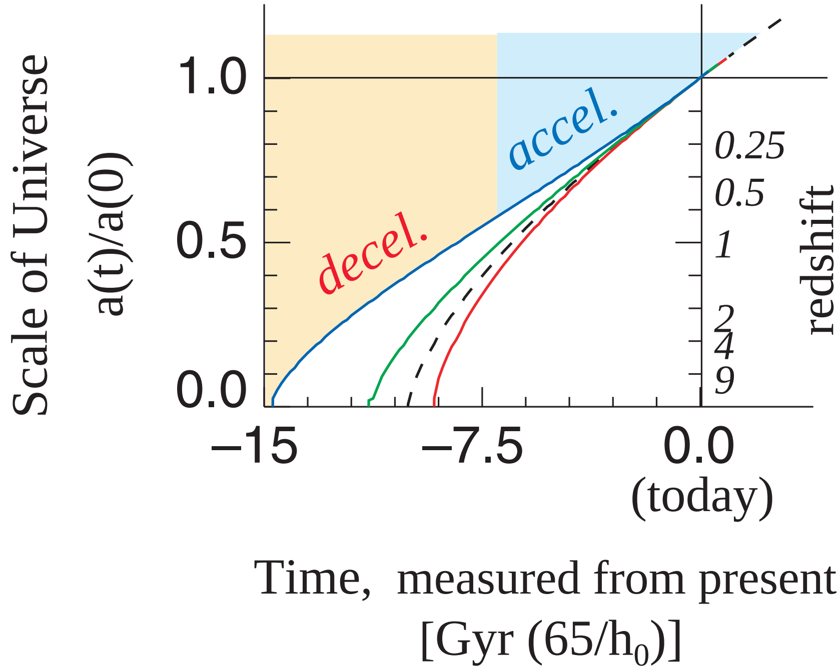


based on

Weller & Albrecht (2001)

Expansion History of the Universe





Conclusions:

1. The mystery of Dark Energy presents us with an extraordinary science opportunity.

2. Supernovae provide the most mature technique.

3. SNAP is the best tool to address this science.