SNAP SuperNova Acceleration Probe

Presentation to the DOE's
Review Committee on
SNAP R&D
January 25, 2001

Saul Perlmutter

Executive Session 8:30

SNAP R&D Review Agenda — Thursday

Oddone	- Welcome	9:00
Turner	- Introduction	9:05
Perlmutter	- SNAP Science (40+10)	9:10
Aldering	-Systematics & Requirements (35+10)	10:00
Break - 15 min.		**10:45**
Ellis	- Weak Lensing (15+5)	11:00
Levi	- Project Overview (35+10)	11:20
Working Lunch		**12:05**
Bebek	- GigaCam (40+10)	12:35
Von der Lippe	- Electronics Architecture (20+5)	1:25
Genat	- ASIC Development (15+5)	1:50
Tarle	- NIRcam (15+5)	2:10
Break - 15 min.		**2:30**
LeFevre	- Spectrograph (20+5)	2:45
Graham	- HgCdTe Technology for SNAP (15+5)	3:10
Breakout Sessions		**3:30**
1. GigaCAM/Electronics		50A-5132
2. NIRcam & Spectrograph		50B-6208
Executive Session		**5:00**

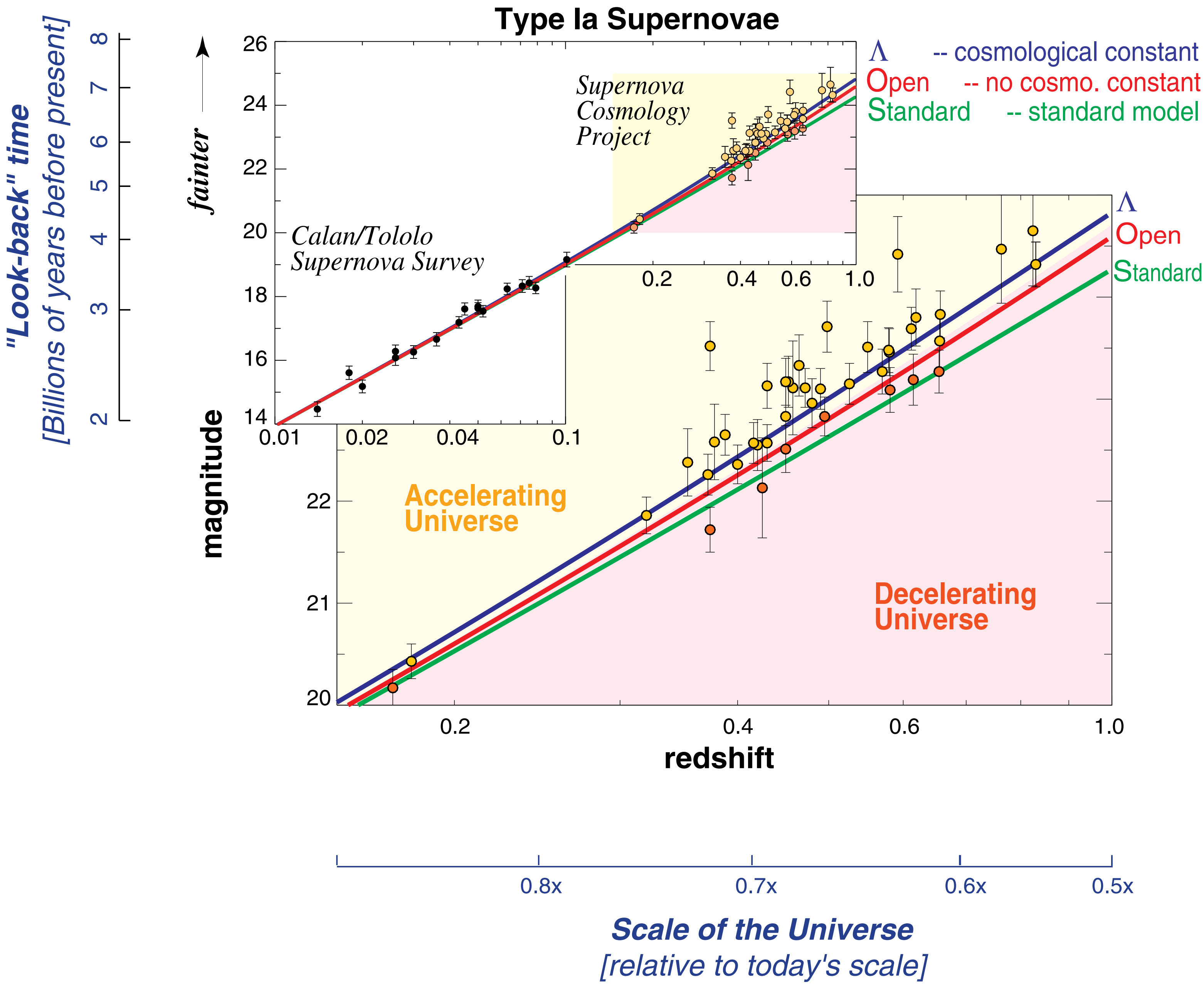
Friday: *Spacecraft, Telescope, Computing, Management*

SuperNova / Acceleration Probe (SNAP)

An Experiment to Measure the Properties of the Dark Energy of the Universe

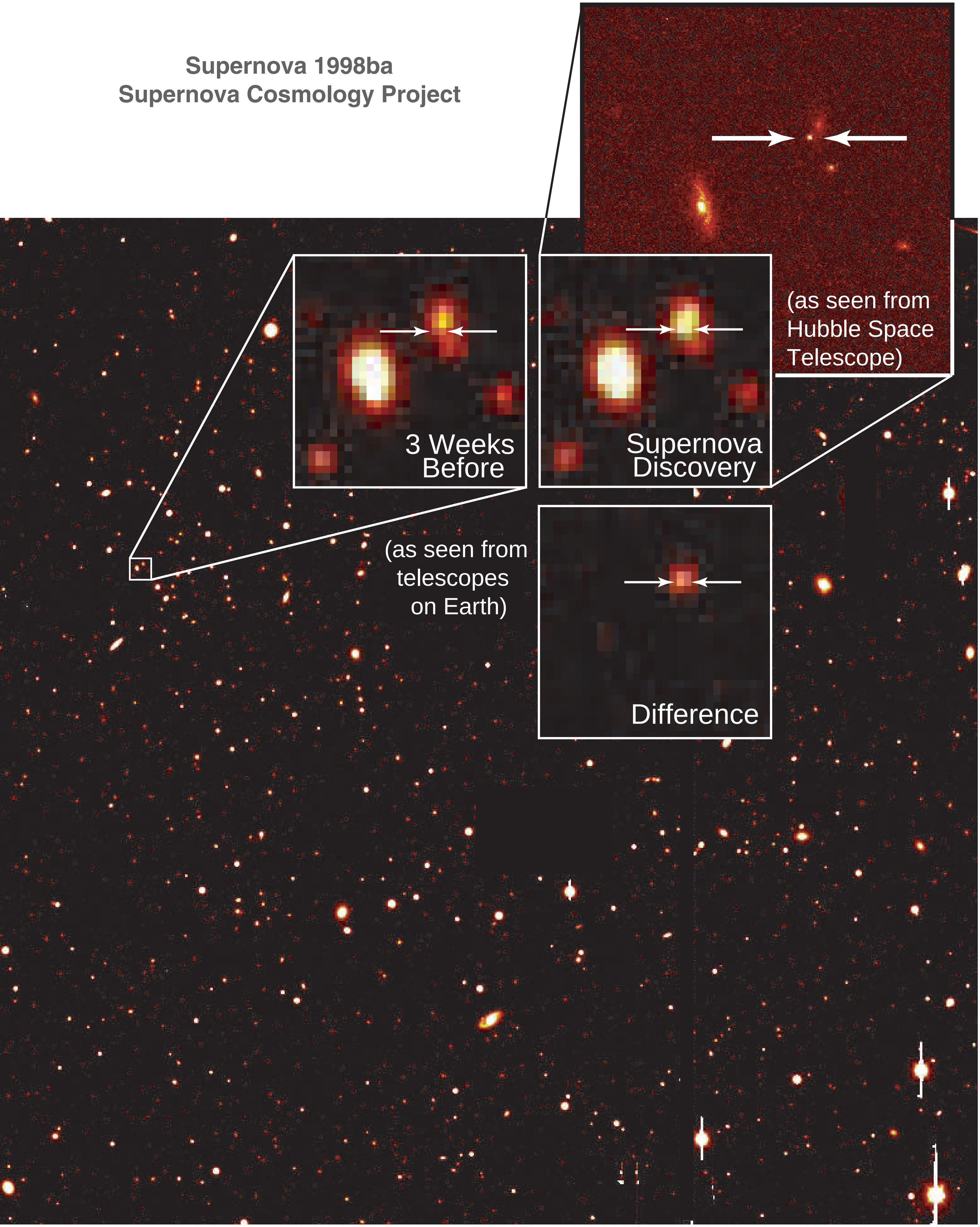
The Institutions of the SNAP Collaboration

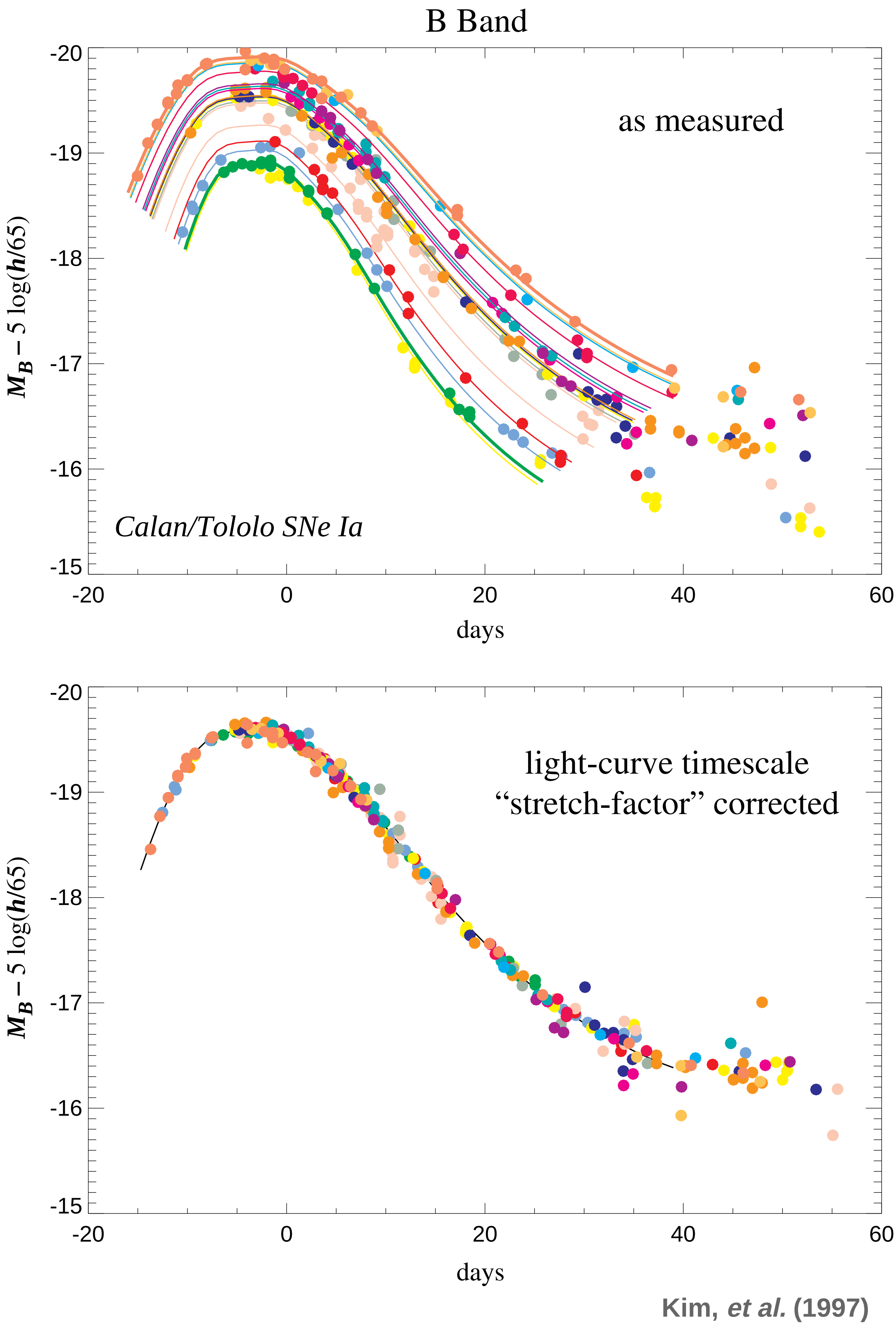
University of California, Berkeley
Lawrence Berkeley National Laboratory
CNRS-IN2P3, LPNHE, and University Paris VI & VII
University of Maryland, College Park, MD
Cornell University
University of Chicago
Space Telescope Sciences Institute
California Institute of Technology
CEA/DAPNIA, Saclay, France
Gemini Observatory
European Southern Observatory
University of Stockholm
University of Lisbon



Type Ia Supernovae
Λ -- cosmological constant
Open -- no cosmo. constant
Standard -- standard model
Supernova Cosmology Project
Calan/Tololo Supernova Survey
fainter
magnitude
redshift
Accelerating Universe
Decelerating Universe
Λ
Open
Standard
"Look-back" time [Billions of years before present]
Scale of the Universe [relative to today's scale]
0.8x
0.7x
0.6x
0.5x

Supernova 1998ba
Supernova Cosmology Project





B Band
as measured
Calan/Tololo SNe Ia
$M_B - 5\log(h/65)$
days
-20
-19
-18
-17
-16
-15
-20
0
20
40
60
light-curve timescale
"stretch-factor" corrected
$M_B - 5\log(h/65)$
days
Kim, et al. (1997)

The implications of an accelerating universe:

1. The expansion is not slowing to a halt and then collapsing (i.e., the universe is *not* "coming to an end"). In the simplest models, it will expand forever.

2. There is a previously unseen energy pervading all of space that accelerates the universe's expansion.

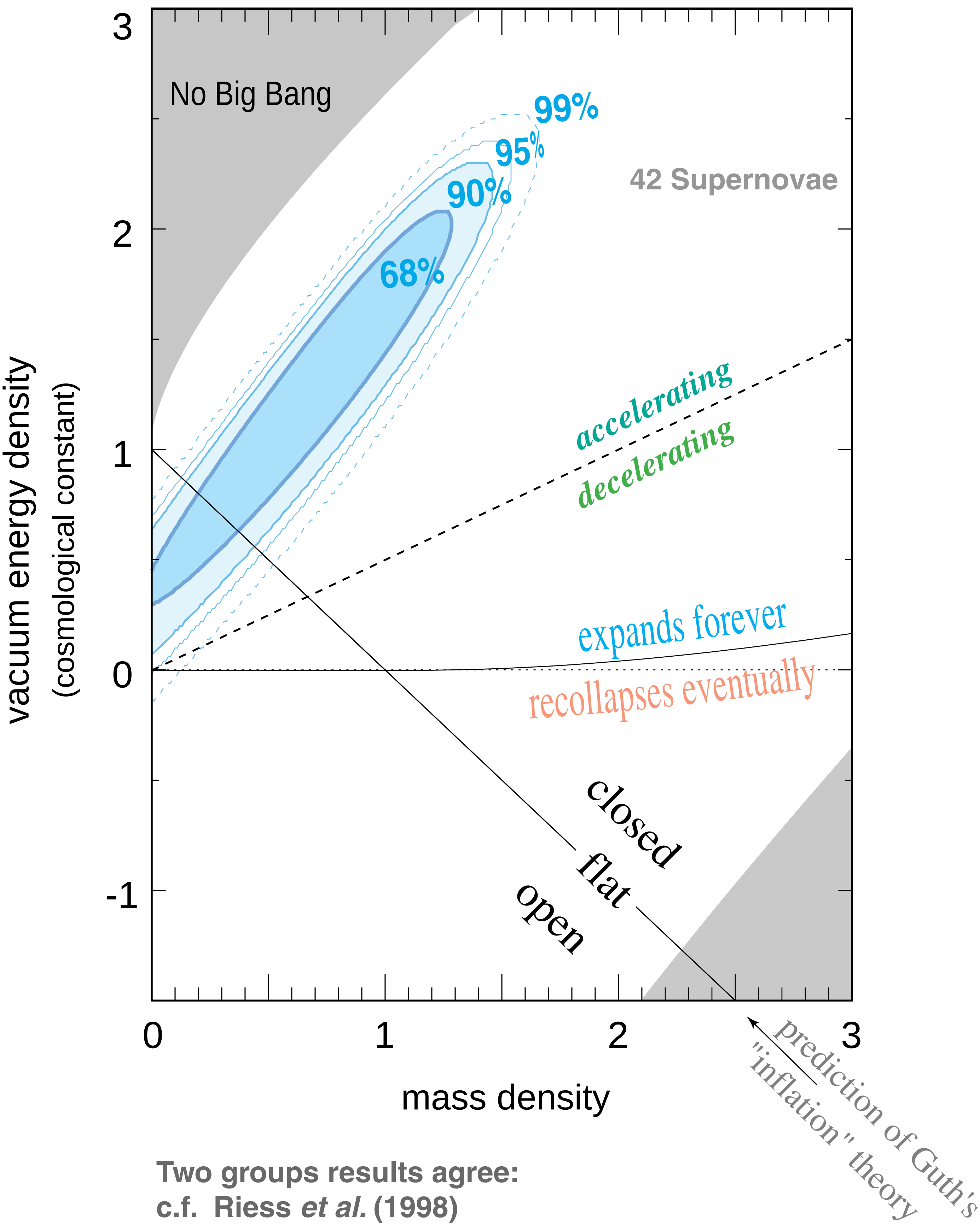
   This new accelerating energy ("dark energy") has a larger energy density than the mass density of the universe (or else the universe's expansion wouldn't be accelerating).

What we don't know is:

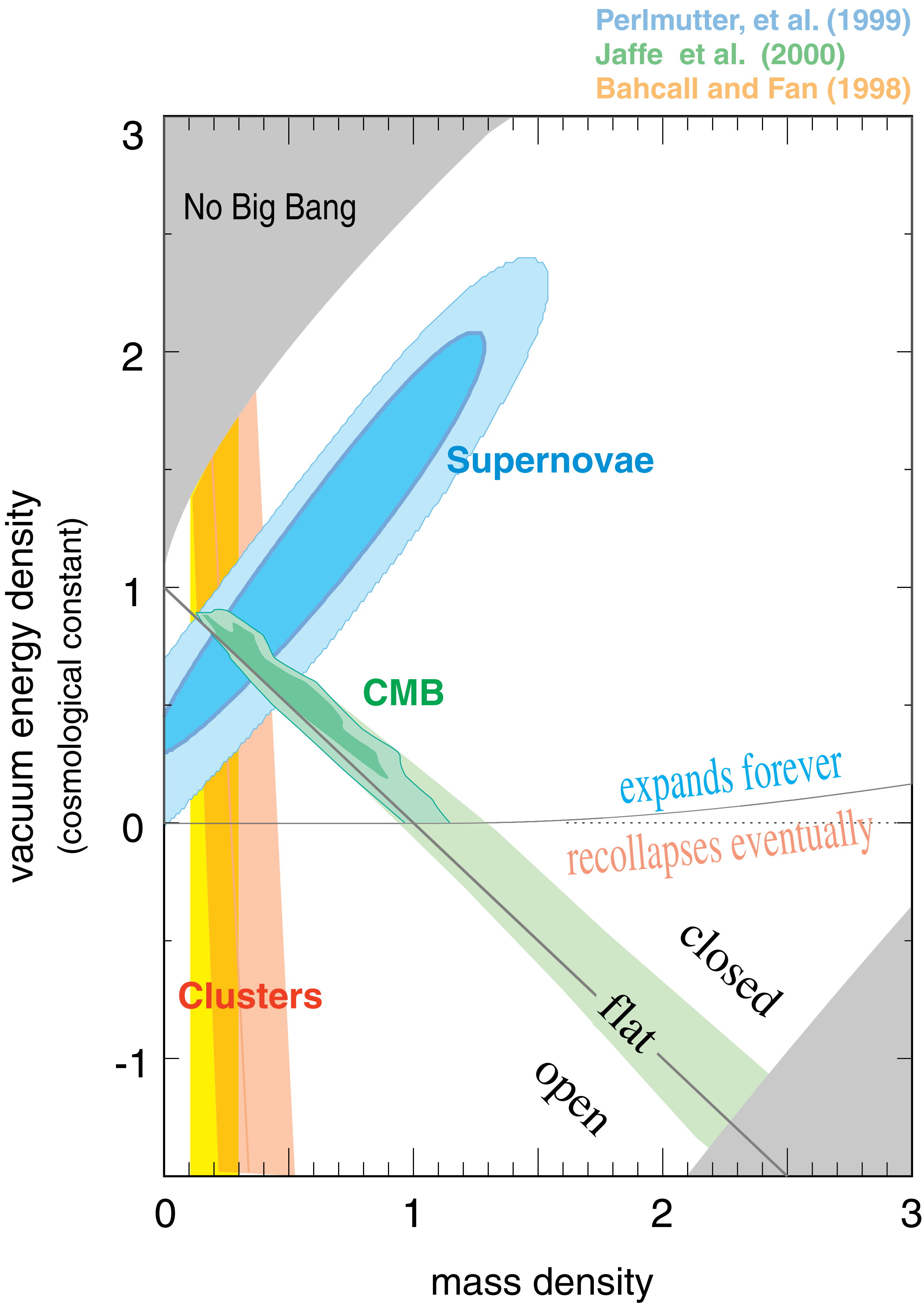
1. How much of mass density and dark energy density is there? I.e., how much dark matter and dark energy do we need to look for?
   The answer to this question determines the "curvature" of the universe, and can tell us about the extent of the universe: infinite or finite.

2. What is the "dark energy"? Particle physics theory proposes a number of alternatives, each with different properties that we can measure. Each of the alternative theories raises some important questions/problems of fundamental physics.

Supernova Cosmology Project
Perlmutter *et al.* (1998)



Two groups results agree:
c.f. Riess *et al.* (1998)



Perlmutter, et al. (1999)
Jaffe et al. (2000)
Bahcall and Fan (1998)
No Big Bang
Supernovae
CMB
expands forever
recollapses eventually
closed
flat
open
Clusters
vacuum energy density
(cosmological constant)
mass density
3
2
1
0
-1
0
1
2
3

What's wrong with a non-zero vacuum energy / cosmological constant?

Two coincidences:

- ***Why so small?***

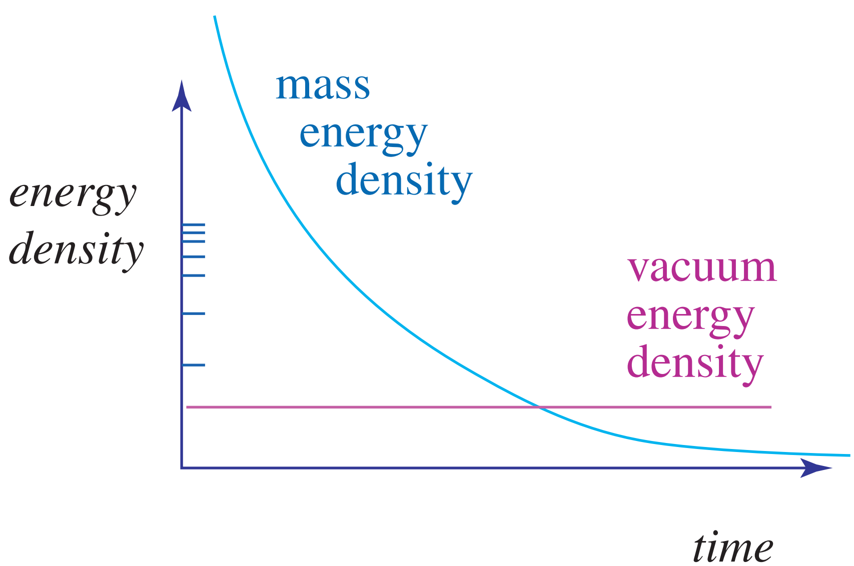
  Might expect $\frac{\Lambda}{8\pi G} \sim m^4_{\mathrm{Planck}}$

  This is off by ~120 orders of magnitude!

- ***"Why now?"***

$$\frac{\ddot{R}}{R} = -\frac{4\pi G}{3}(\rho + 3p)$$

MATTER:	$p = 0$	$\longrightarrow \rho \propto R^{-3}$
VACUUM ENERGY:	$p = -\rho$	$\longrightarrow \rho \propto constant$



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VACUUM ENERGY: $p = -\rho \longrightarrow \rho \propto constant$

What are the alternatives?

New Physics:

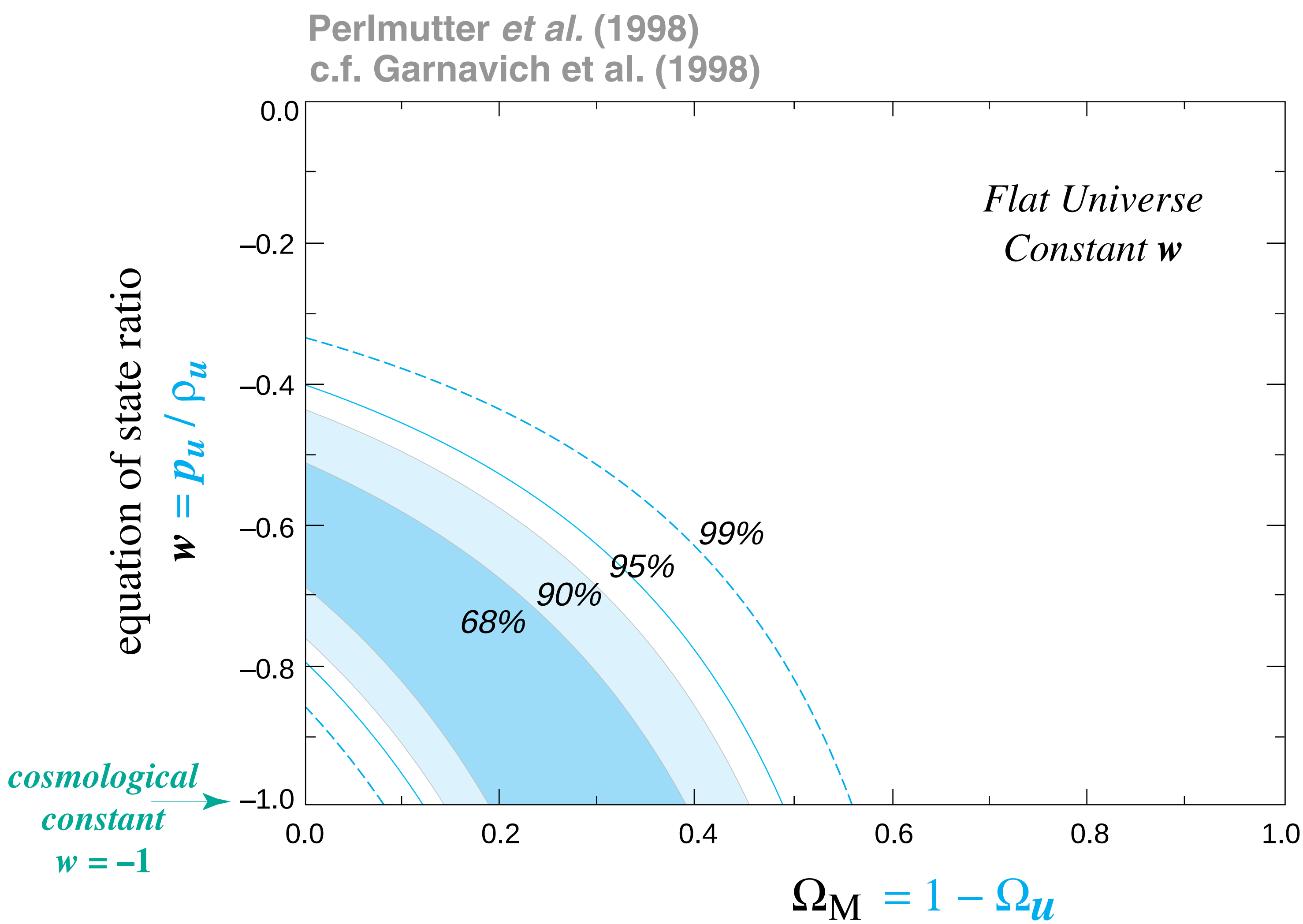
"Dark energy": Dynamical scalar fields, "quintessence",...

COSMIC STRINGS: $p = -1/3\,\rho \longrightarrow \rho \propto R^{-2}$

General Equation of State: $p = w\rho \longrightarrow \rho \propto R^{-3(1+w)}$

and w can vary with time

Unknown Component, Ω_u, of Energy Density



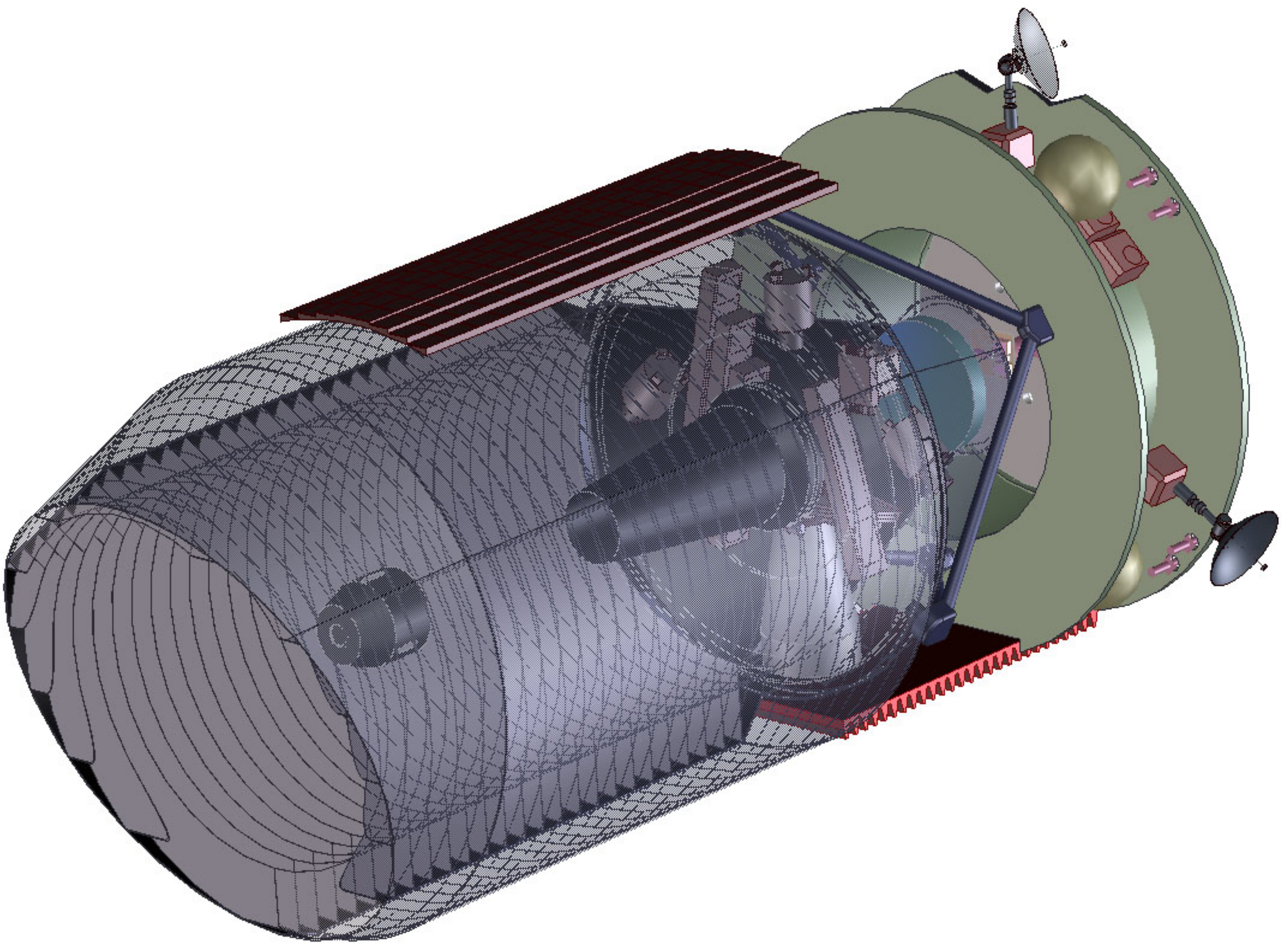
SNAP SuperNova Acceleration Probe

For a definitive measurement
to provide a pillar of our cosmological theory
requires

- a much larger statistical sample of supernovae,
- with much better controlled measurements,
- over a much larger range of redshifts,

that cannot be obtained
with existing or planned facilities.

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.

- **3-arm spectrograph, 0.35um -- 1.7um**

  Detailed analysis of each SN.

Satellite:

Dedicated instrument.

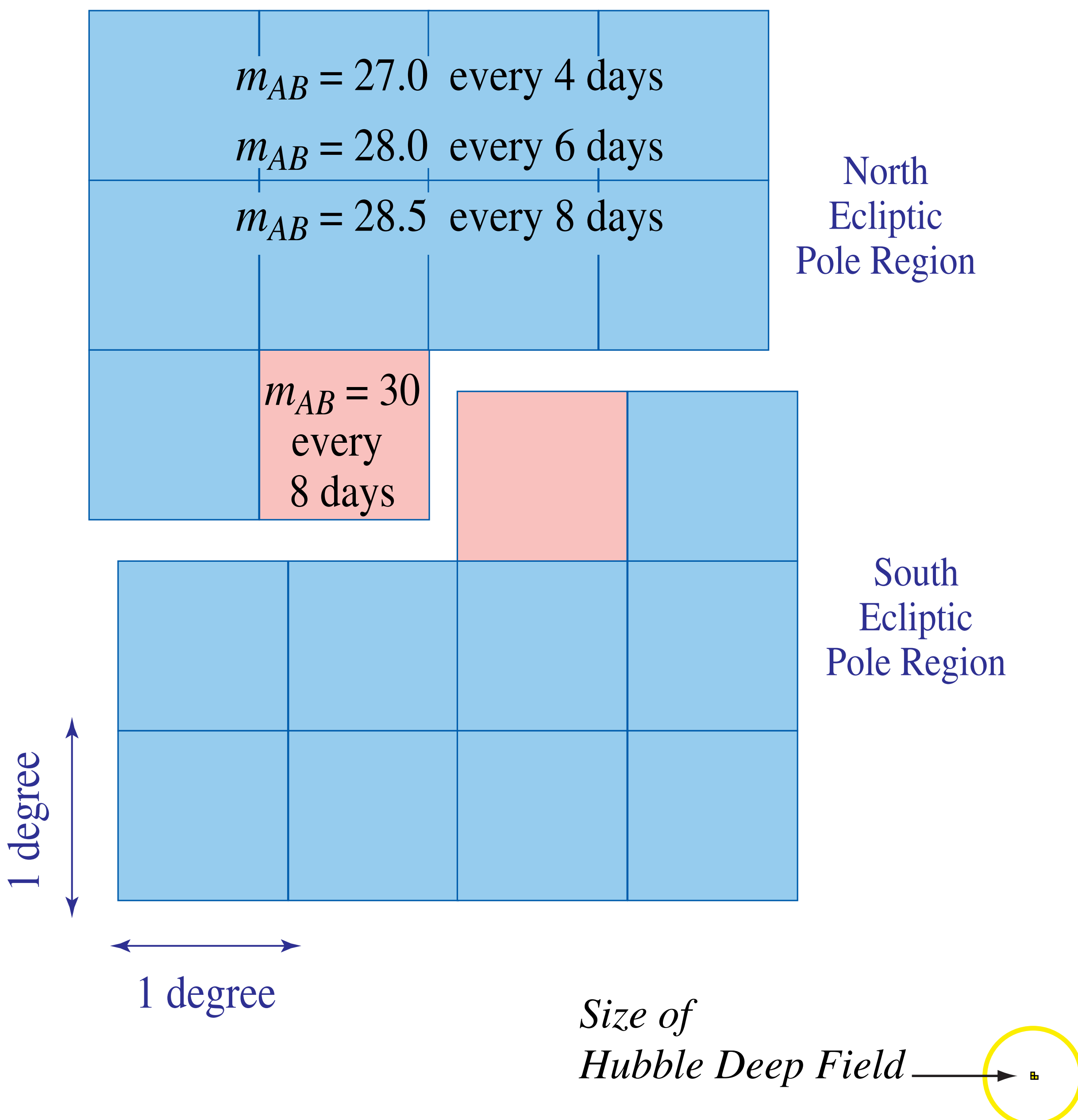
Designed to repeatedly observe an area of sky.

Essentially no moving parts.

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

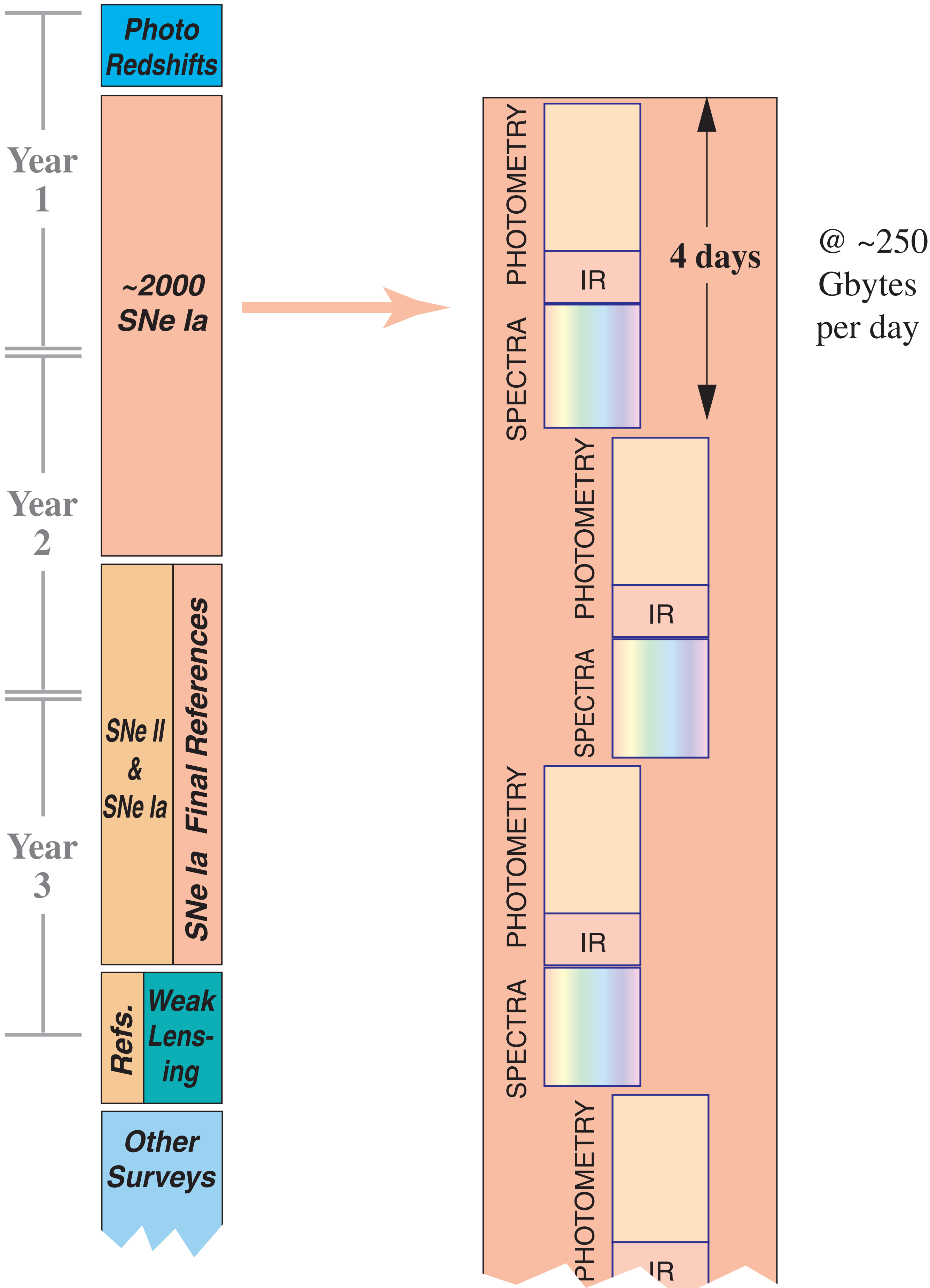
SNAP SuperNova Acceleration Probe

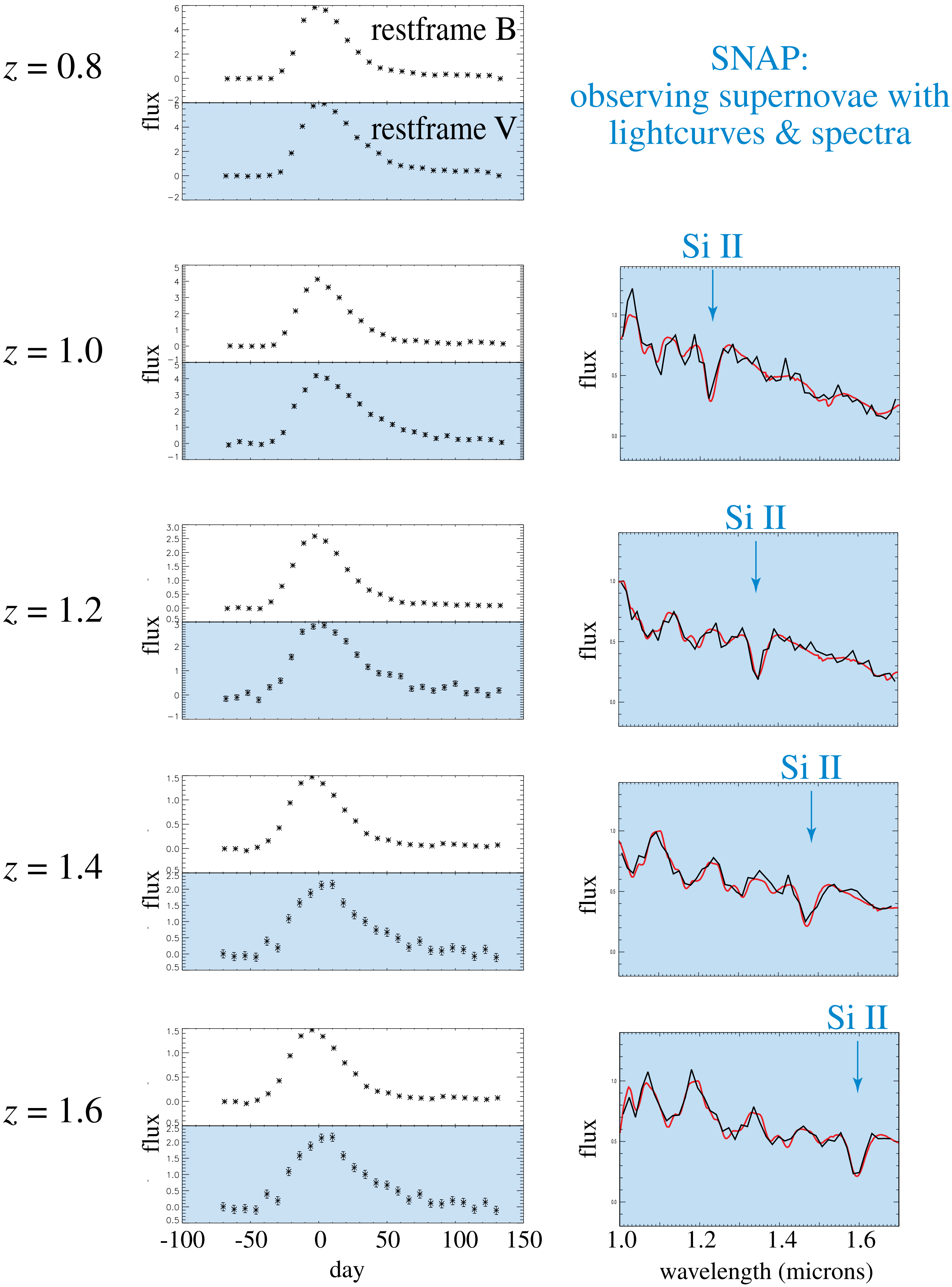
Imaging strategy

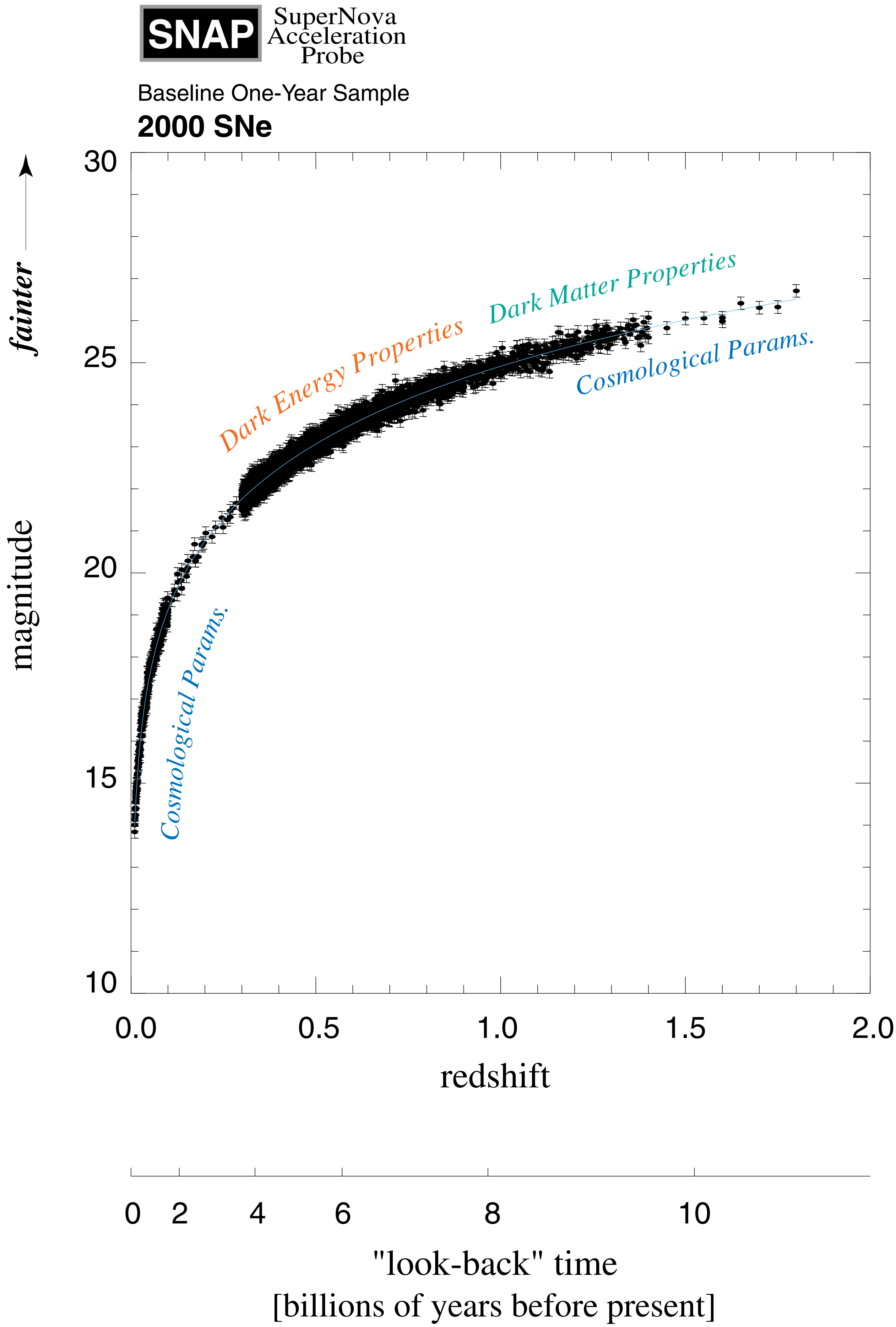


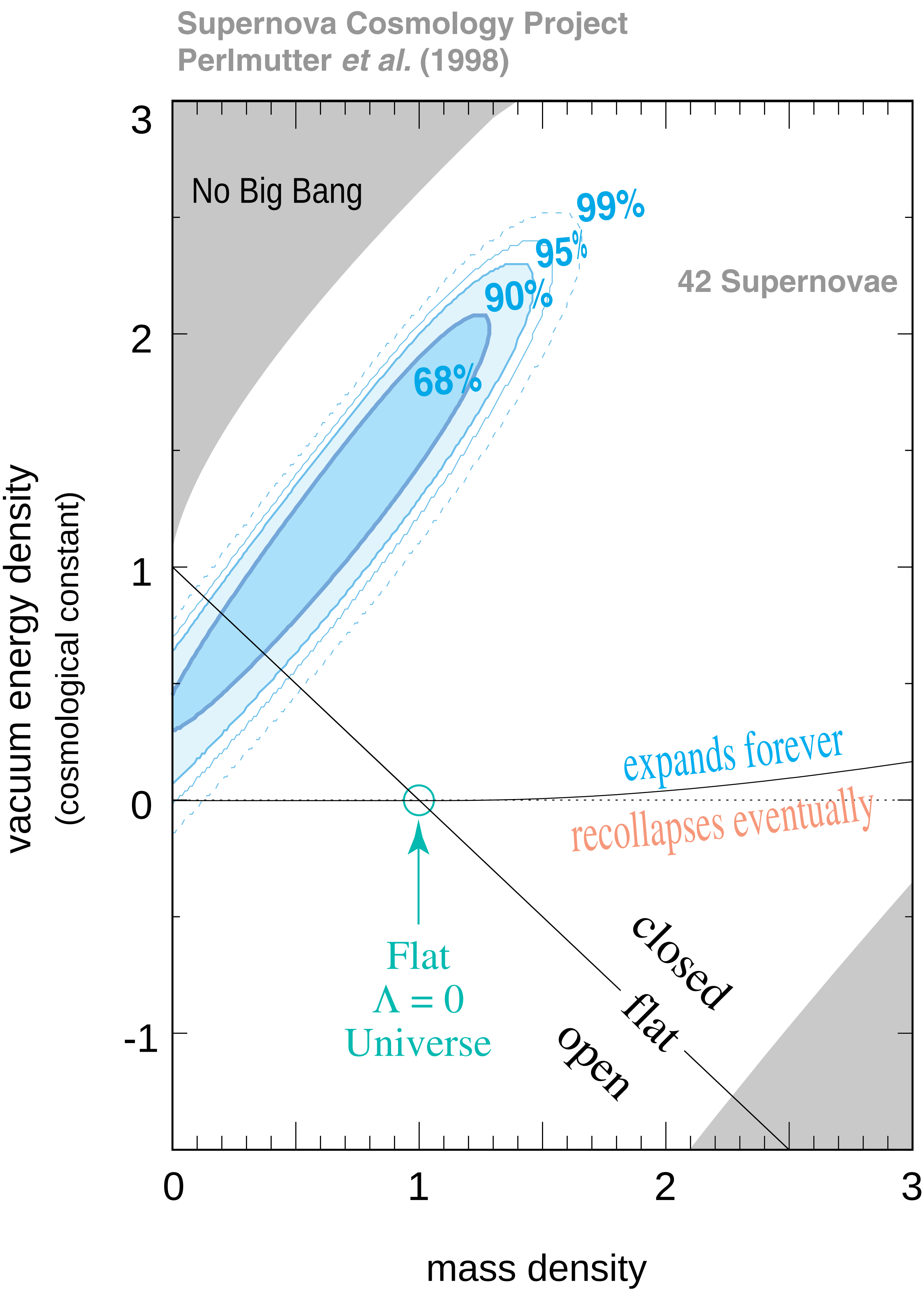
Co-added images: $\boldsymbol{m_{AB}} = 32.0$!

Sample Observation Schedule




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
-100
-50
0
50
100
150
day
1.0
1.2
1.4
1.6
wavelength (microns)


SNAP
SuperNova Acceleration Probe
Baseline One-Year Sample
2000 SNe
fainter
magnitude
30
25
20
15
10
0.0
0.5
1.0
1.5
2.0
redshift
Dark Energy Properties
Dark Matter Properties
Cosmological Params.
Cosmological Params.
0
2
4
6
8
10
"look-back" time
[billions of years before present]



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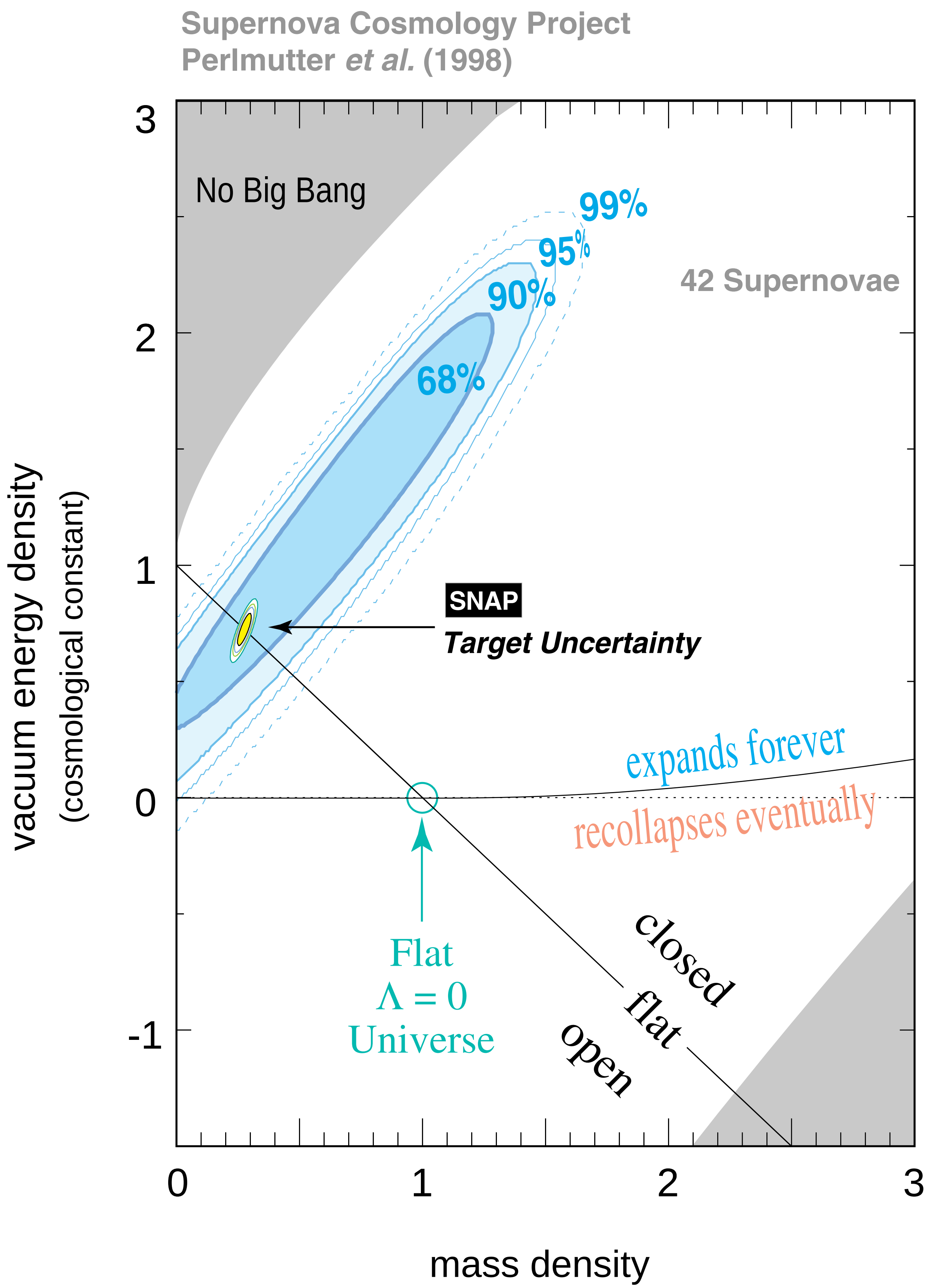
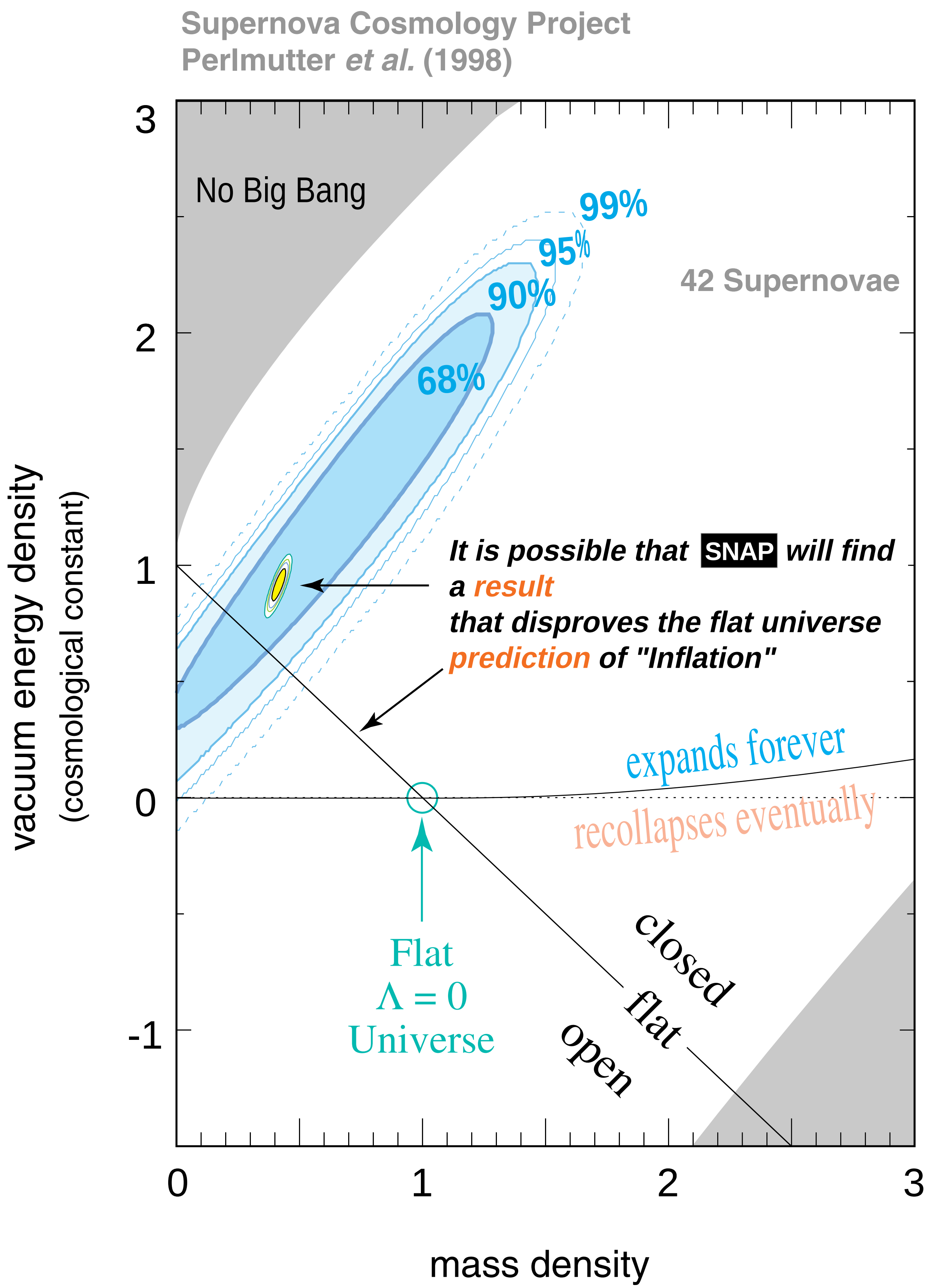
0
1
2
3



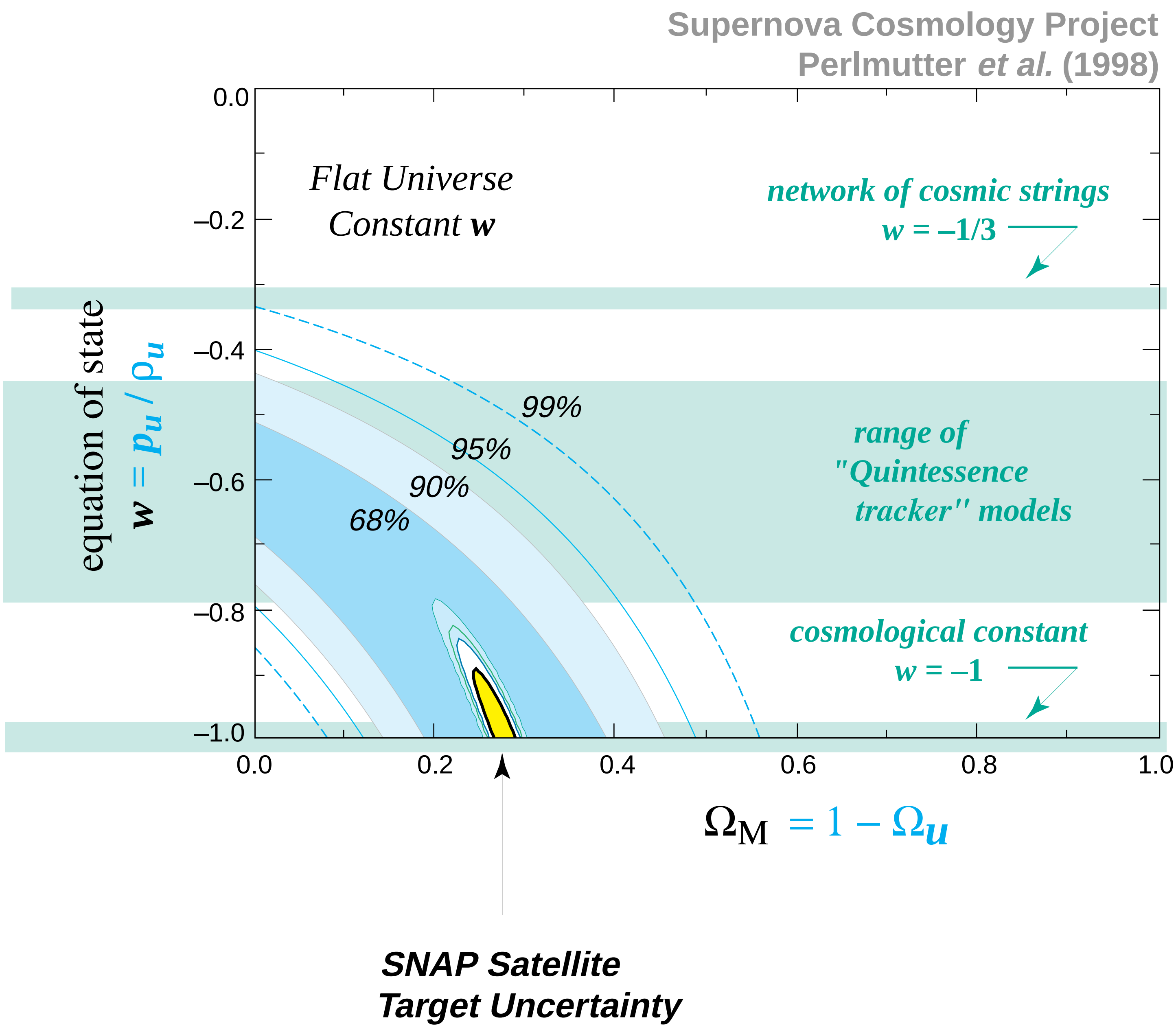
Supernova Cosmology Project
Perlmutter et al. (1998)
No Big Bang
99%
95%
90%
68%
42 Supernovae
SNAP
Target Uncertainty
expands forever
recollapses eventually
Flat
Λ = 0
Universe
closed
flat
open
vacuum energy density
(cosmological constant)
mass density
3
2
1
0
-1
0
1
2
3



Supernova Cosmology Project
Perlmutter et al. (1998)
No Big Bang
99%
95%
90%
68%
42 Supernovae
It is possible that SNAP will find a result that disproves the flat universe prediction of "Inflation"
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

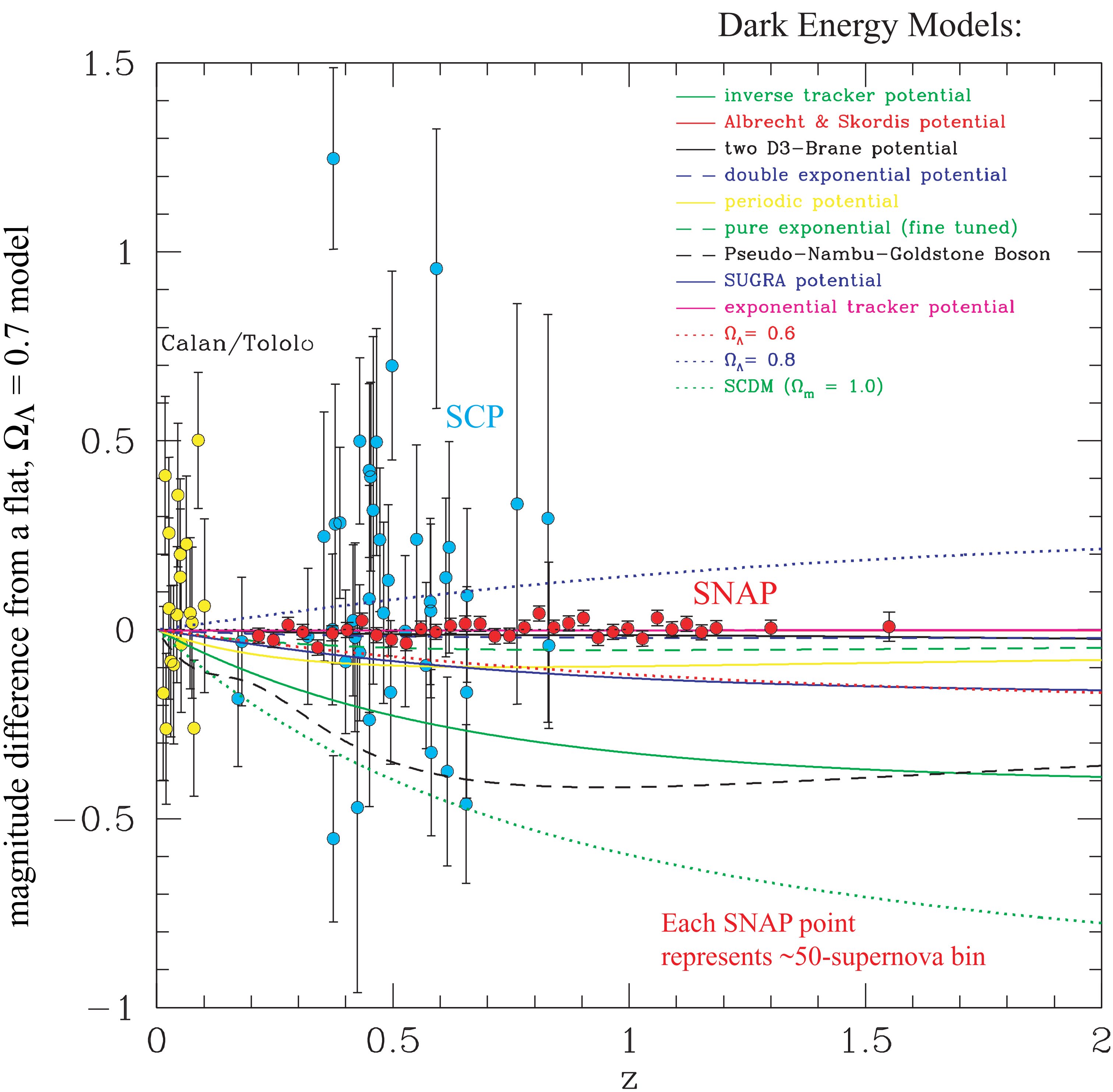
Dark Energy

Unknown Component, Ω_u, of Energy Density



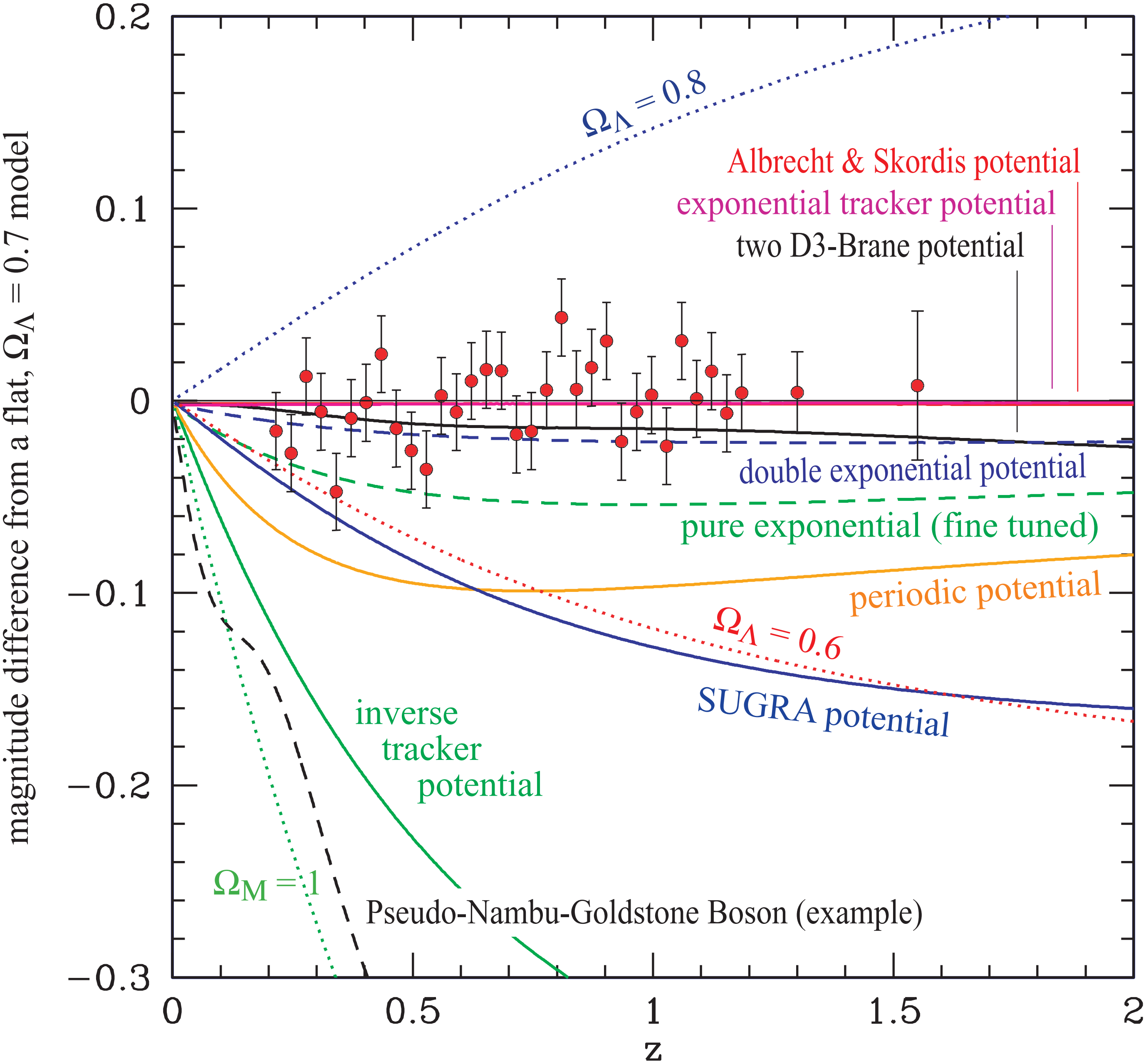
SNAP SuperNova Acceleration Probe

Current ground-based data
compared with binned simulated SNAP data.



SNAP SuperNova Acceleration Probe

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



Weller & Albrecht

SNAP SuperNova Acceleration Probe

science goals

Cosmological Parameters, Dark Matter,...

Type Ia supernova calibrated candle
Type II supernova expanding photosphere
Weak lensing
Strong lensing statistics. Ω_Λ
Galaxy clustering, $P(k)$
$z > 1$ clusters and associated lensing
. . .

...and Beyond

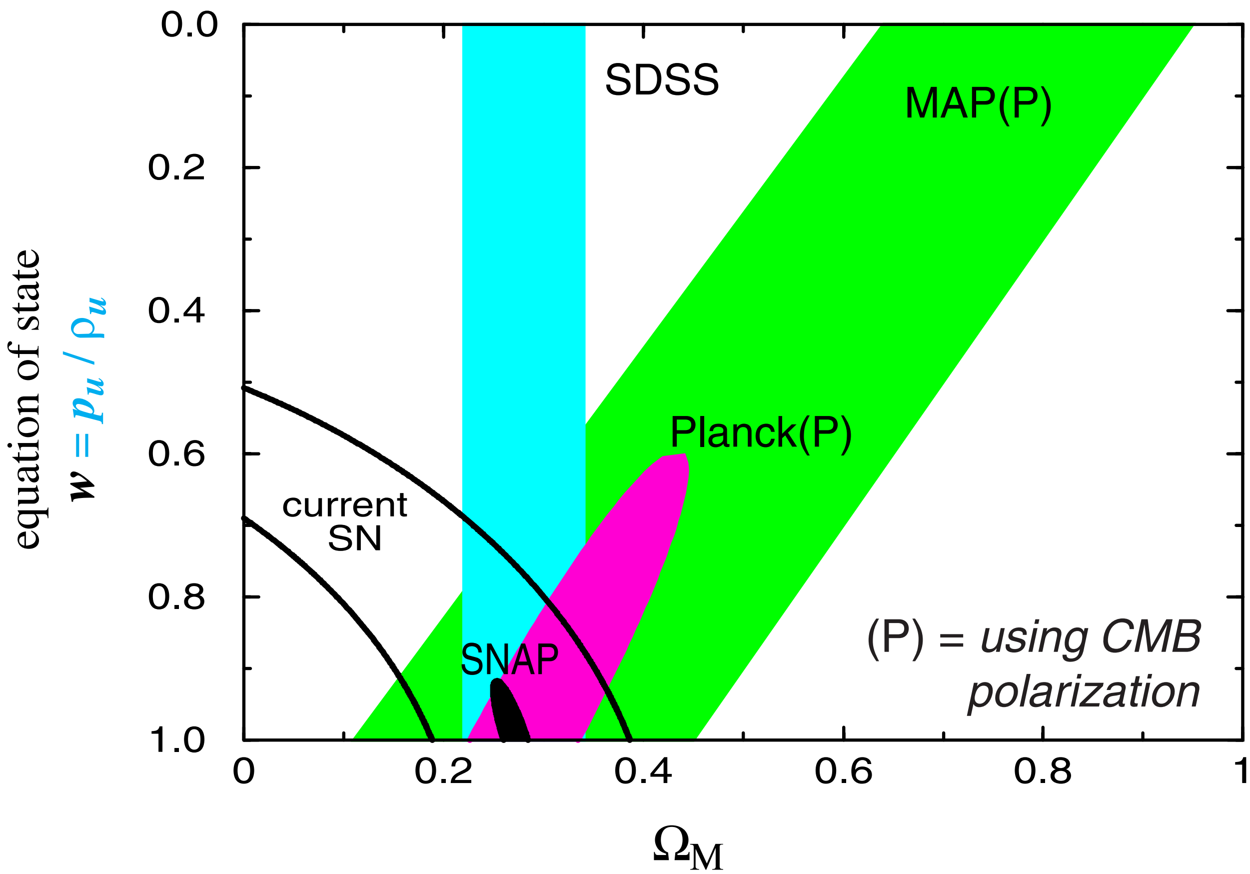
GRB optical counterparts: rates, lightcurves, and spectra
MACHO optical counterparts by proper motion
Galaxy populations and morphology to co-added $m = 32$
Target selection for NGST
Kuiper belt objects
Supernova rates, star formation rates
Supernova phenomenology studies
Low surface brightness galaxies, luminosity function
. . .

→ Archive data distributed:
deeper than Hubble Deep Field
and 7000 times larger

→ Guest Survey Program

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

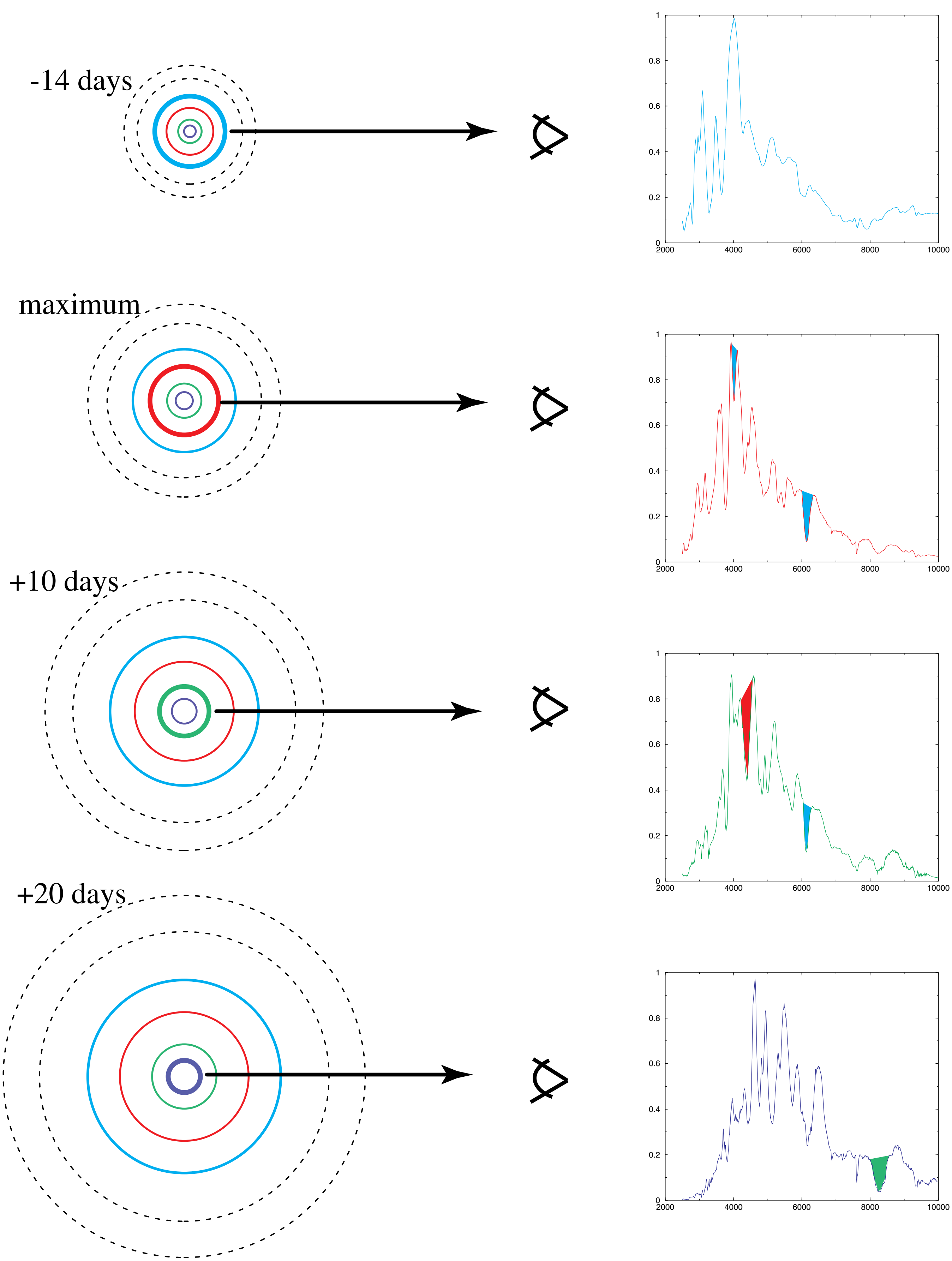
*SNAP measurements using this approach

SNAP SuperNova Acceleration Probe

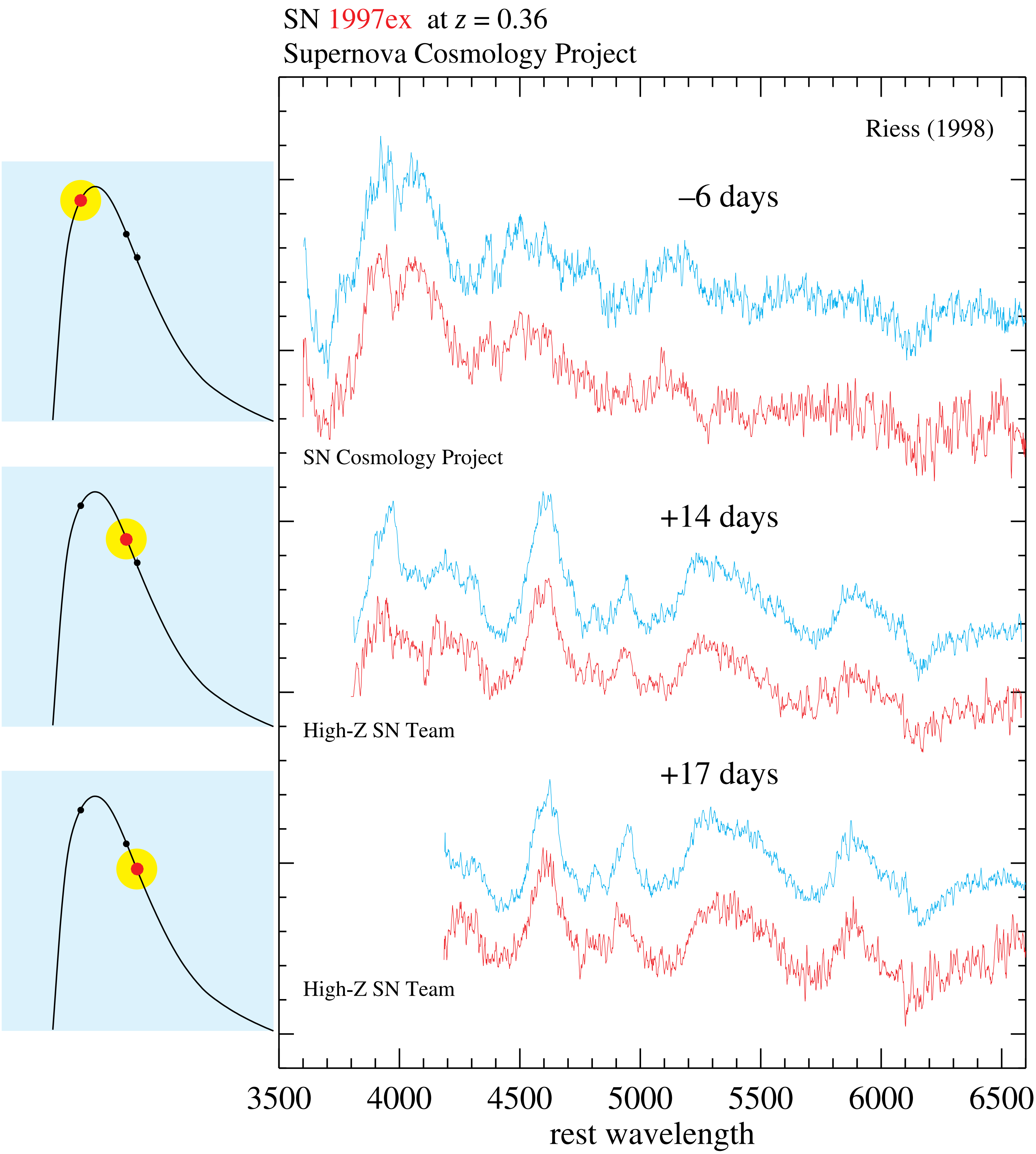
What makes the supernova measurement special?
Control of systematic uncertainties.

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

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



Time Series of Low-Redshift and High-Redshift Spectra



SNAP SuperNova Acceleration Probe

What makes the supernova measurement special?

Control of systematic uncertainties.

However,

for a definitive supernova cosmology measurement...

...it is necessary but NOT sufficient to find and study

- *more SNe Ia*
- *farther SNe Ia*

because the statistical uncertainty is already
within a factor of two of the systematic uncertainty.

The most demanding SNAP data requirements are devoted to eliminating and controlling all sytematic uncertainties.

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***

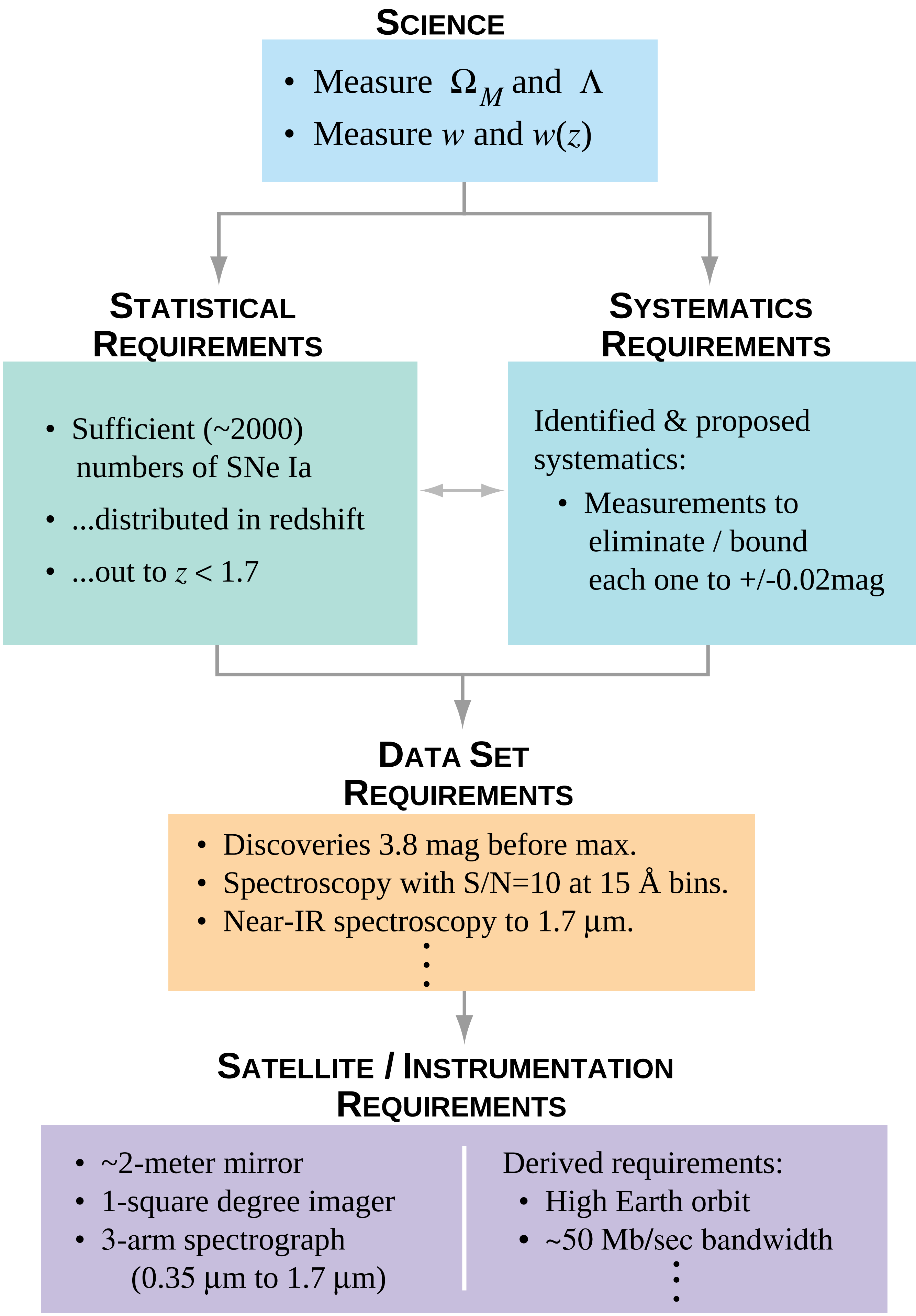
Systematic

✓	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
✓	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


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=10 at 15 Å bins.
• Near-IR spectroscopy to 1.7 μm.
SATELLITE / INSTRUMENTATION REQUIREMENTS
• ~2-meter mirror
• 1-square degree imager
• 3-arm spectrograph (0.35 μm to 1.7 μm)
Derived requirements:
• High Earth orbit
• ~50 Mb/sec bandwidth

How **mature** is our picture of cosmology?

Typical "naive" questions remind us how much of our current picture is built on simplifying assumptions -- and theory-driven.

- How do we **know** that the "local" visible universe is the same as other regions?
- How do we **know** that the universe used to be decelerating and now it's accelerating?
- How do we **know** what the future of the universe will be?
- How do we **know** that the universe is spatially infinite?
  (And what would curved space be?)

We have a responsibility to **doubt** and test, and measure empirically (perhaps especially in a field where there are competing creation myths).

c.f. Disney (2000)

How could you tell if our cosmological picture was mature?

One important indicator: when the theoretical model stops being modified -- and made more complicated -- with almost every major new data set that is added to the empirical knowledge.

I.e., look for the end of the era of big surprises in a field, and an end to big differences between theorists' certainty that an answer is known and experimentalists/observers' desire to **measure**

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Symptoms of Immaturity

- Discovery of Dark Matter problem
  - Expectation of theorists that measurements of Ω_m would keep growing with the scale of measurements until $\Omega_m = 1$; Surprise (and doubt) of theorists with evidence that this "curve of growth" was flattening off around $\Omega_m = 0.2$ -- 0..4.
- Penzias & Wilson's microwave "noise" (expected or unexpected?)
  - Cycle of theoretical predictions of CMB anisotropy at a given level, followed by measurements that found **no** anisotropy there.
  - Desire of CMB experimentalists/observers to measure the position of the first acoustic peak, despite theorists' conviction that it was already clearly indicating $\Omega_{total} = 1$
  - Unexpected low-level (missing?) second acoustic peak in recent CMB results.
- Supernova results indicating accelerating expansion and positive value for Λ
  - Gravitational Lens measurements indicating low value for Λ

SNAP SuperNova Acceleration Probe

Two major scientific goals:

1 Firmly establish what we now "know."

2 Move forward from this base to explore unknown physics: Dark Energy

SNAP SuperNova Acceleration Probe

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We have often had to rely on a few different measurements -- each with obvious assumptions and loopholes -- to make a case for a part of our cosmological model.

Now we have the possibility of putting at least a few of the measurements on more solid ground, so they can act as empirical pillars of our cosmological picture.

CMB With COBE --> MAXIMA/BOOMARANG --> MAP --> PLANCK, we have moved (and are moving) CMB into this role.

SNe The first goal of SNAP is to begin to place supernovae on this same firm footing.

These would provide two *complimentary* pillars.

SNAP SuperNova Acceleration Probe

What will it take to establish what we "know"?

A supernova data set that combines detailed measurements to address remaining questions/loopholes, together with key "sanity check" tests.

-- broad wavelength range to address non-standard dust questions.

-- high signal-to-noise colors to correct for extinction.

-- detailed observations of light curves and spectra to recognize/classify/measure physics differences.

-- wide range of host-galaxy environments at each redshift, and morphology/color information to recognize/classify/measure these host galaxies.

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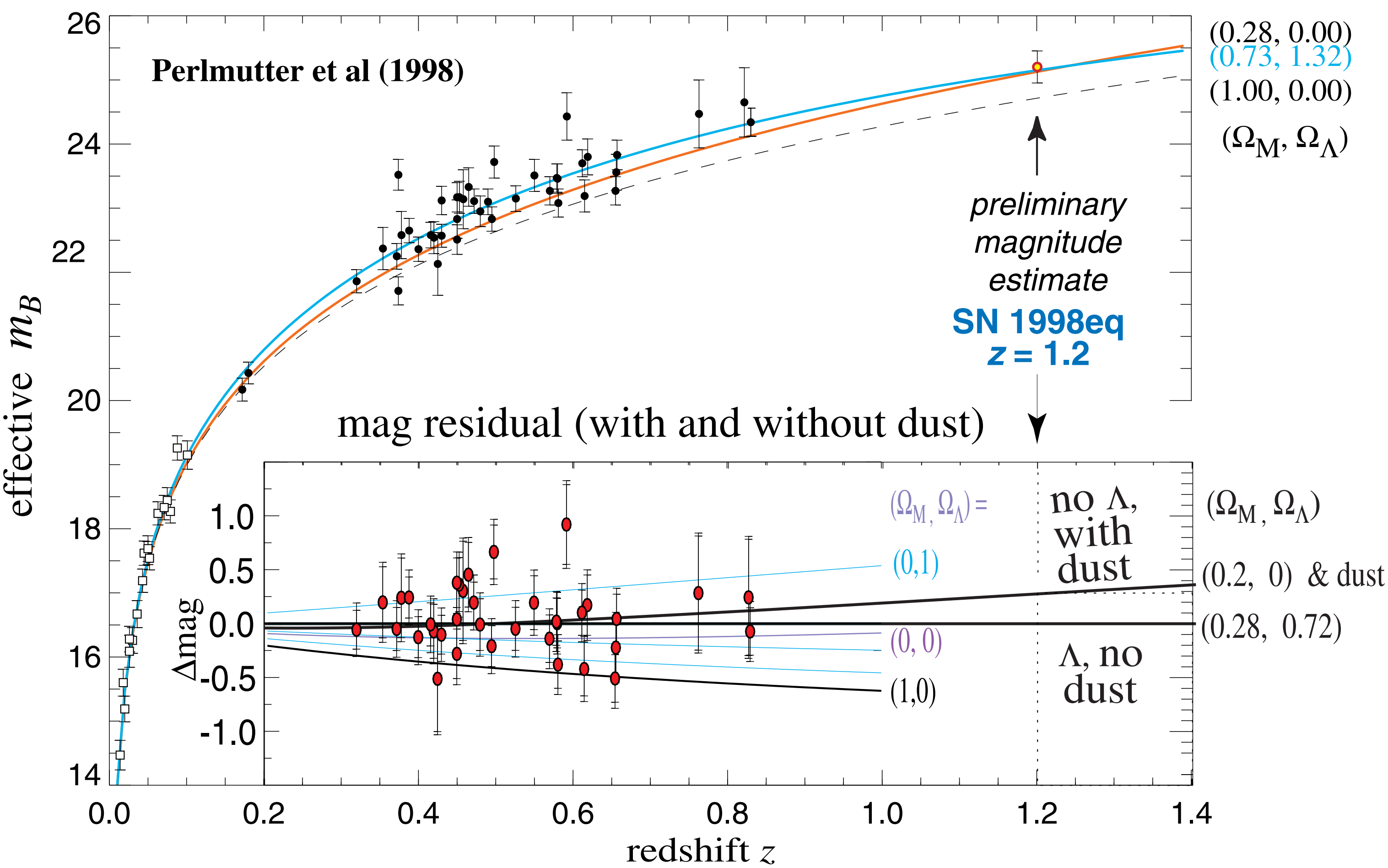
-- large enough redshift range to study SNe in the decelerating epoch, when they begin to appear brighter than dust or evolution would predict.

-- wide range of redshifts to *test* curvature measurement of CMB. NEW SCIENCE

-- large enough sample of SNe at each redshift bin to average out effect of gravitational lensing.



Perlmutter et al (1998)
(0.28, 0.00)
(0.73, 1.32)
(1.00, 0.00)
(ΩM, ΩΛ)
preliminary magnitude estimate
SN 1998eq
z = 1.2
effective mB
mag residual (with and without dust)
(ΩM, ΩΛ) =
no Λ, with dust
(ΩM, ΩΛ)
(0.2, 0) & dust
(0.28, 0.72)
(0,1)
(0, 0)
(1,0)
Λ, no dust
Δmag
redshift z

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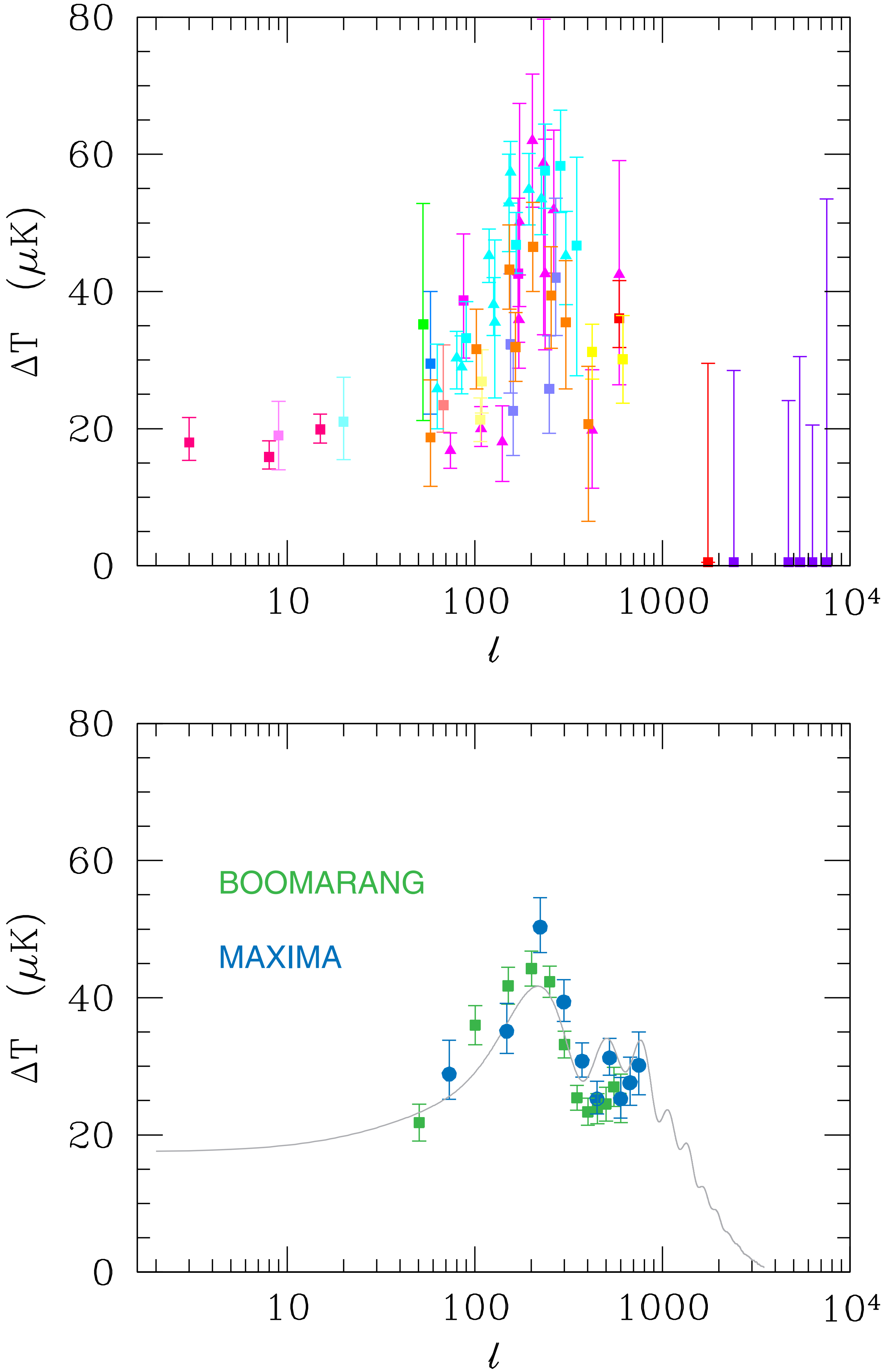
-- wide range of redshifts to *test* curvature measurement of CMB.

-- large enough sample of SNe at each redshift bin to average out effect of gravitational lensing.

-- a compelling, complete, consistent data set, in which everybody can see the effects.

CMB data before BOOMARANG and MAXIMA



SNAP SuperNova Acceleration Probe

Two major scientific goals:

1 Firmly establish what we now "know."

2 Move forward from this base to explore unknown physics: Dark Energy

The fundamental physics implication of the accelerating universe may be the first major crack in out "standard model" for many years.

The expansion history of the universe between $z \sim 0.3$ and 1.2 is currently the only known tool to approach this new physics.

We want to constrain the wide-open range of possible theoretical models with empirical results.

--As some better-motivated theories of Dark Energy become available, this data can then provide tests and fits to the parameters of the theory.

(Huterer & Turner 2000)

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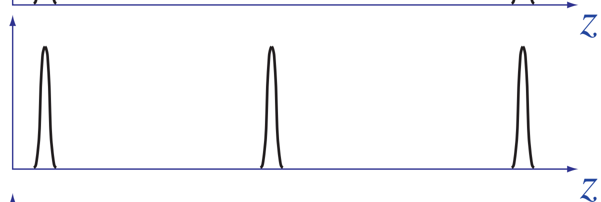
1 Firmly establish what we now "know."

2 Move forward from this base to explore unknown physics: Dark Energy

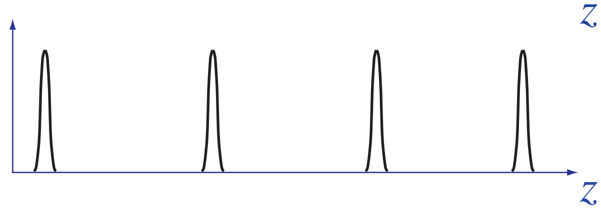
-- measure constant value of $w = p/\rho$

Ω_m requires

Ω_m, Ω_Λ requires

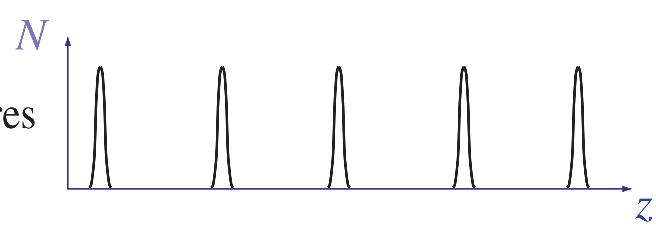


Ω_m, Ω_Λ, w requires



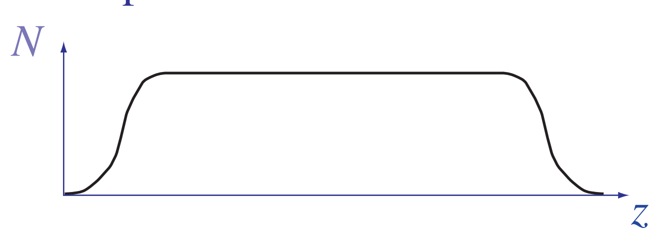
-- measure effective first-derivative and constant value of $w(z)$

Ω_m, Ω_Λ, w, w' requires



-- different Dark Energy models put their action at different times in past

look for derivatives
(need Δz bins with
good stats and systematics)



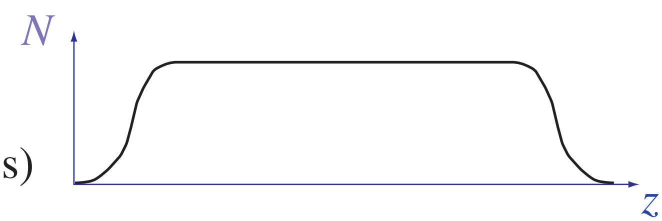
SNAP SuperNova Acceleration Probe

Two major scientific goals:

1 Firmly establish what we now "know."

2 Move forward from this base to explore unknown physics: Dark Energy

Look for derivatives (need Δz bins with good stats and systematics)



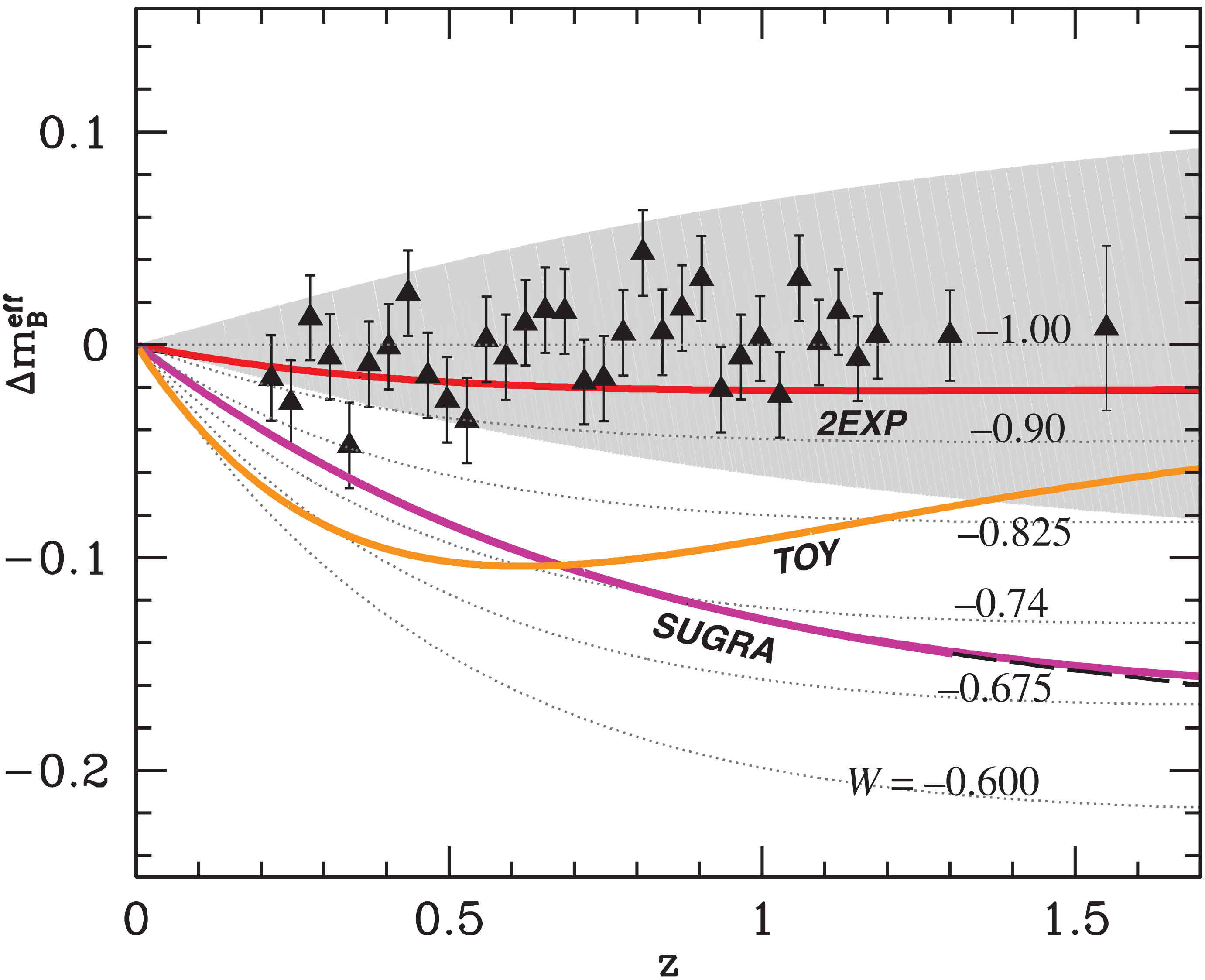
This w' measurement becomes particularly interesting if we can independently pin down Ω_m .

Maor, Brustein, & Steinhardt (2000)
Weller & Albrecht (2000)

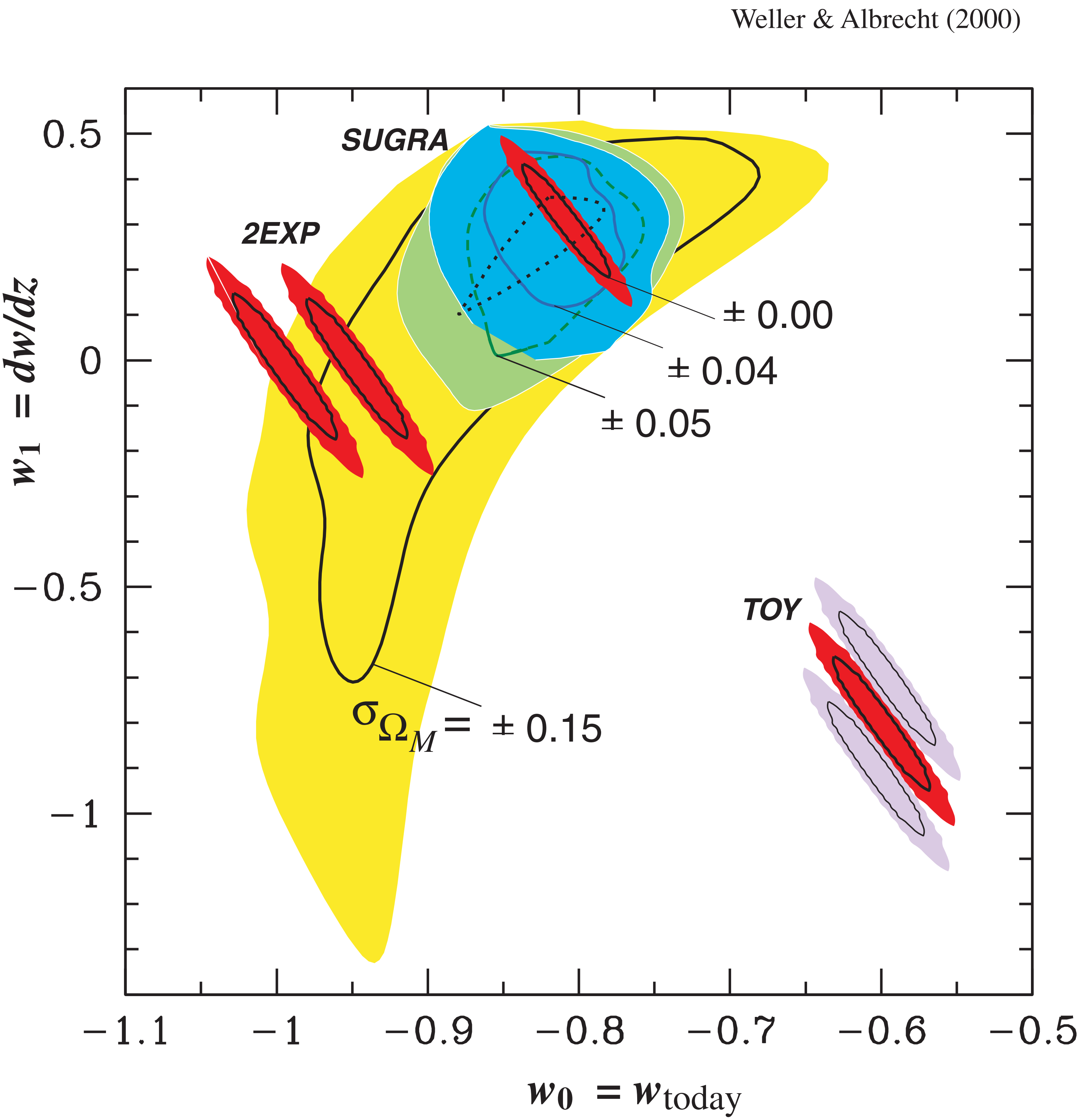
---> Weak lensing at large scales looks promising for this purpose. SNAP will provide this weak lensing data set from space.

SNAP SuperNova Acceleration Probe

Binned simulated SNAP data
compared with Dark Energy models.



Weller & Albrecht (2000)


Weller & Albrecht (2000)
SUGRA
2EXP
TOY
± 0.00
± 0.04
± 0.05
σ_{Ω_M} = ± 0.15
0.5
0
−0.5
−1
−1.1
−1
−0.9
−0.8
−0.7
−0.6
−0.5
$w_1 = dw/dz$
$w_0 = w_{\rm today}$

SNAP SuperNova Acceleration Probe

Why do these science goals drive us to the SNAP design?

Detailed SN measurements & key "sanity check" tests:

W = Wide-field Imager in Space

S = Efficient Low-Resolution Spectrograph in Space

S -- broad wavelength range to address non-standard dust questions.

W -- high signal-to-noise colors to correct for extinction.

W S -- detailed observations of light curves and spectra to recognize/classify/measure physics differences.

W -- wide range of host-galaxy environments at each redshift, and morphology/color information to recognize/classify/measure these host galaxies.

W -- large enough redshift range to study SNe in the decelerating epoch, when they begin to appear brighter than dust or evolution would predict.

W -- wide range of redshifts to *test* curvature measurement of CMB.

W -- large enough sample of SNe at each redshift bin to average out effect of gravitational lensing.

-- a compelling, complete, consistent data set, in which everybody can see the effects.

SNAP Proposal Signatories

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SNAP SuperNova Acceleration Probe

Working Groups (Preliminary)

Science Working Groups

- Type Ia Supernovae
- Type II Supernovae
- Weak Lensing
- Other Transients
- Other Astronomy/Astrophysics

Instrument Working Groups

- Optical Imager and Detectors
- IR Imager and Detectors
- Spectrograph System
- Calibration

Weak Lensing Working Group

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Type II Supernovae Working Group

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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**
Study review for DOE	**Jan 2001**

SNAP SuperNova Acceleration Probe

Peer Review by the DOE and NSF's SAGENAP panel.

(Reports to HEPAP to establish High Energy Physics' priorities, parallel to Decadal Survey establishing Astronomy's priorities).

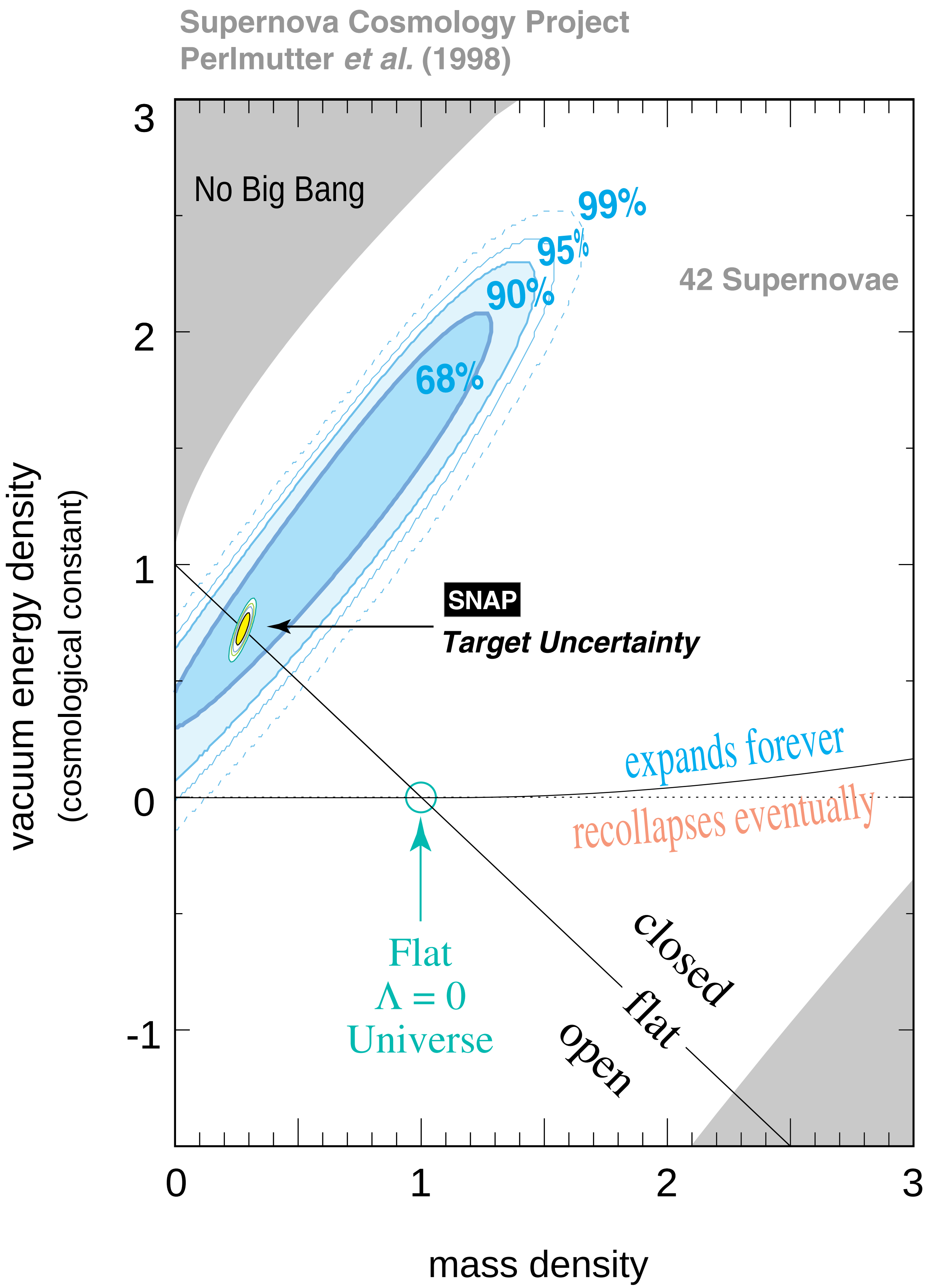
The project was successfully reviewed by SAGENAP March 29-31, 2000; panel's report released July 21, 2000:

"In summary, the SAGENAP discussions indicate enthusiastic agreement by the panel that the **science goals** are on questions of great **importance to physics and cosmology**.

Further, it was considered that at the present stage in the measurement of the cosmological parameters, **new experimentation** is fully warranted and that the **SN Ia technique** will continue to play a crucial part.

The panel members were **favorably impressed** with the proposers' consideration of the sources of **systematic error** and were largely convinced that a fully **satellite-based experiment** is likely to be the preferred approach."

"There was unanimity on SAGENAP that a substantial R&D program is required soon to insure a successful SNAP experiment."



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

Expansion History of the Universe