SuperNova / Acceleration Probe (SNAP)

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

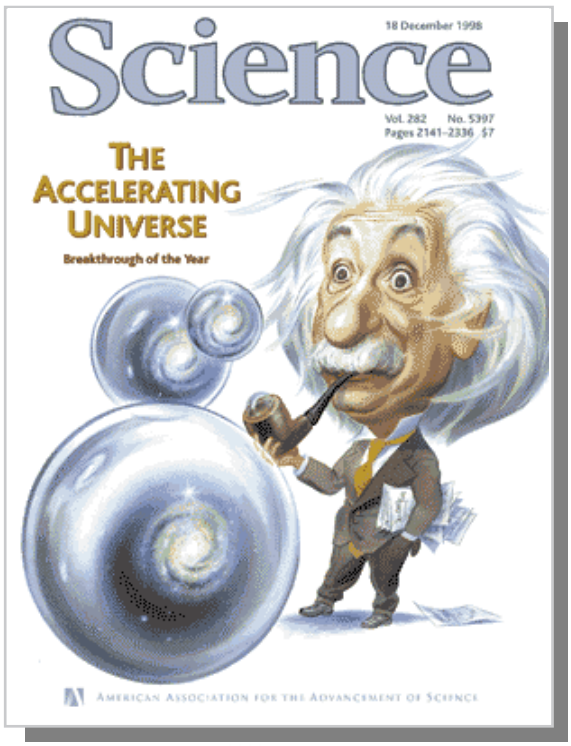
The Institutions of the SNAP Collaboration

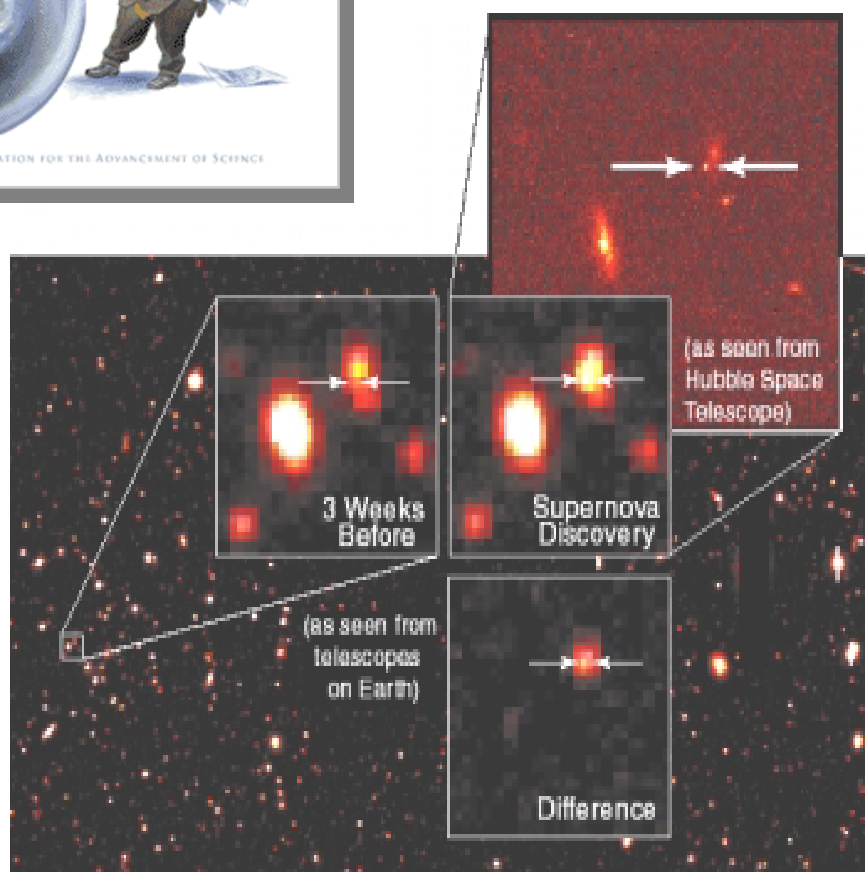
University of California, Berkeley
Lawrence Berkeley National Laboratory
CNRS-IN2P3, LPNHE, and University Paris VI & VII
University of Maryland, College Park, MD
Cornell University
University of Chicago
Space Telescope Sciences Institute
California Institute of Technology
CEA/DAPNIA, Saclay, France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

Using NSF-developed science and technology,
we have an unusual opportunity
to answer fundamental questions of physics
with a definitive, precision cosmology measurement.

CENTER FOR PARTICLE ASTROPHYSICS
NSF SCIENCE & TECHNOLOGY CENTER

Science's Breakthrough of the Year: The Accelerating Universe





Fundamental Questions:

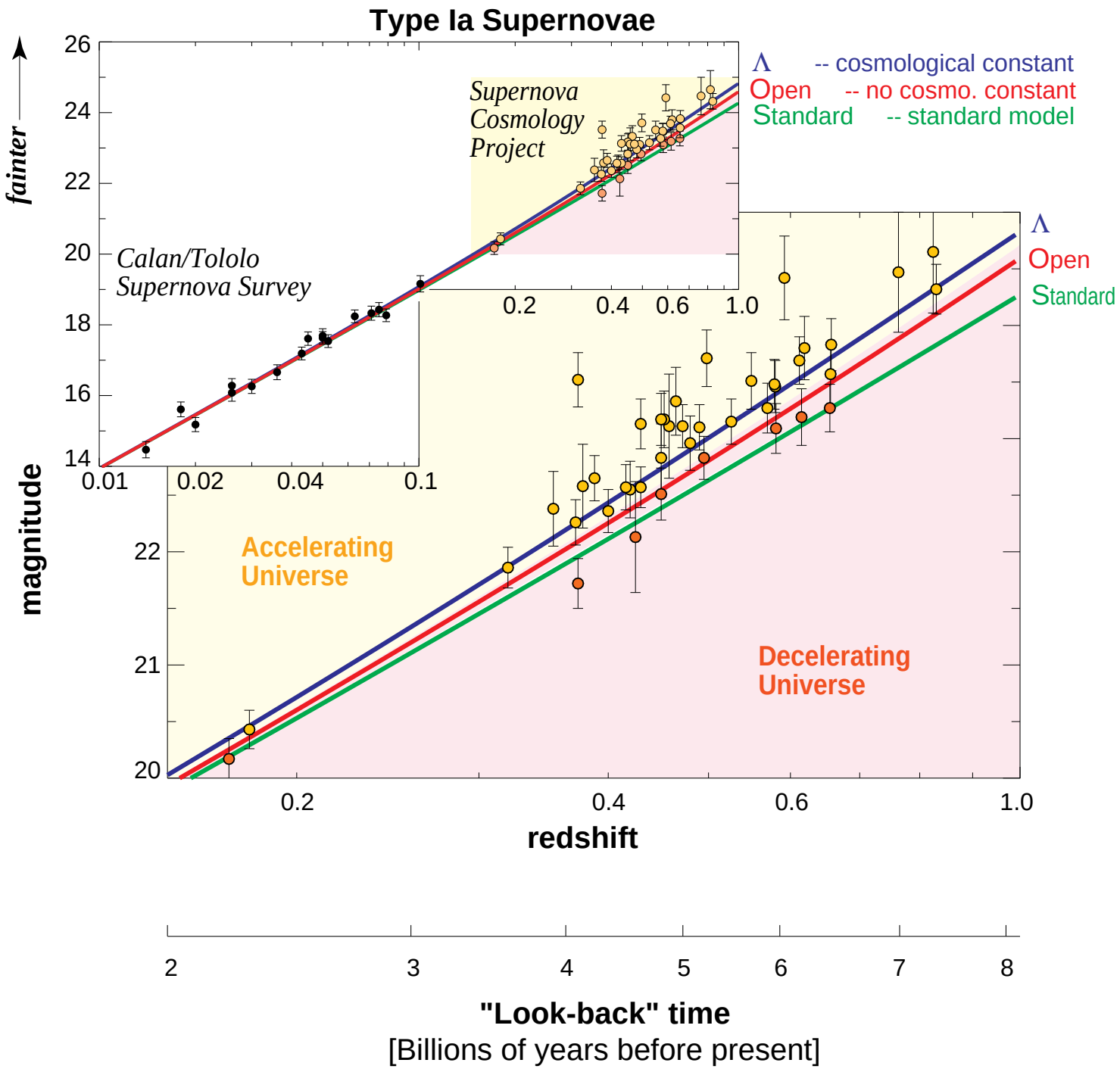
- *Will the universe last forever?*
- *Is the universe infinite?*
- *What is the universe made of?*

An unusual moment in human history:

At the beginning of this century, Einstein developed the conceptual tools to address these questions empirically.

In the past decade or so, technology has advanced to the point that we can now make the measurements that begin to answer these fundamental questions.

Progress is now being made with large scientific programs, including the Supernova Cosmology Project and the Cosmic Microwave Background satellites: COBE, MAP, and PLANCK.


Type Ia Supernovae
fainter
magnitude
Λ -- cosmological constant
Open -- no cosmo. constant
Standard -- standard model
Supernova Cosmology Project
Calan/Tololo Supernova Survey
Accelerating Universe
Decelerating Universe
redshift
"Look-back" time
[Billions of years before present]

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.

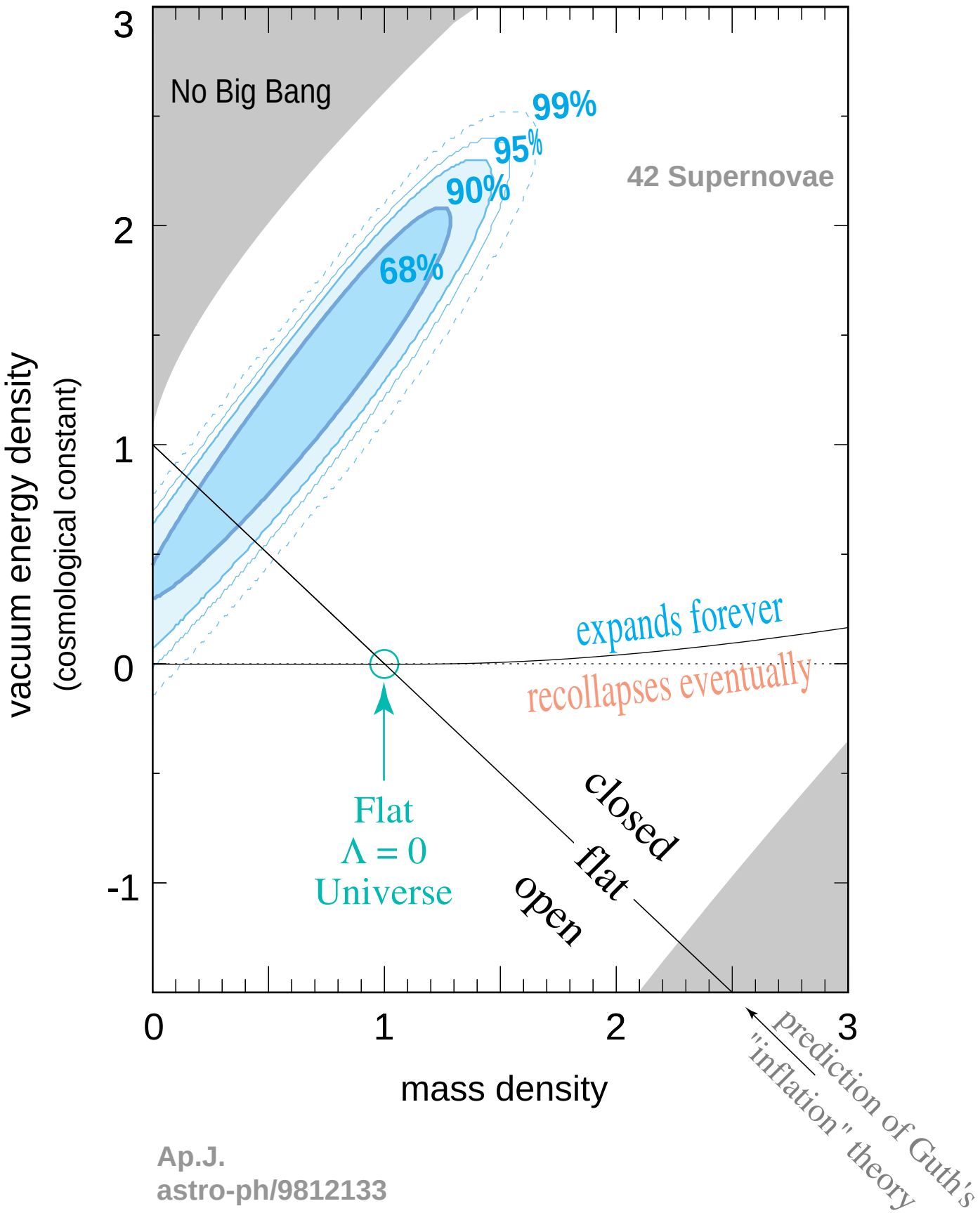
   This new accelerating energy ("dark energy") has a larger energy density than the mass density of the universe (or else the universe's expansion wouldn't be accelerating).

What we don't know is:

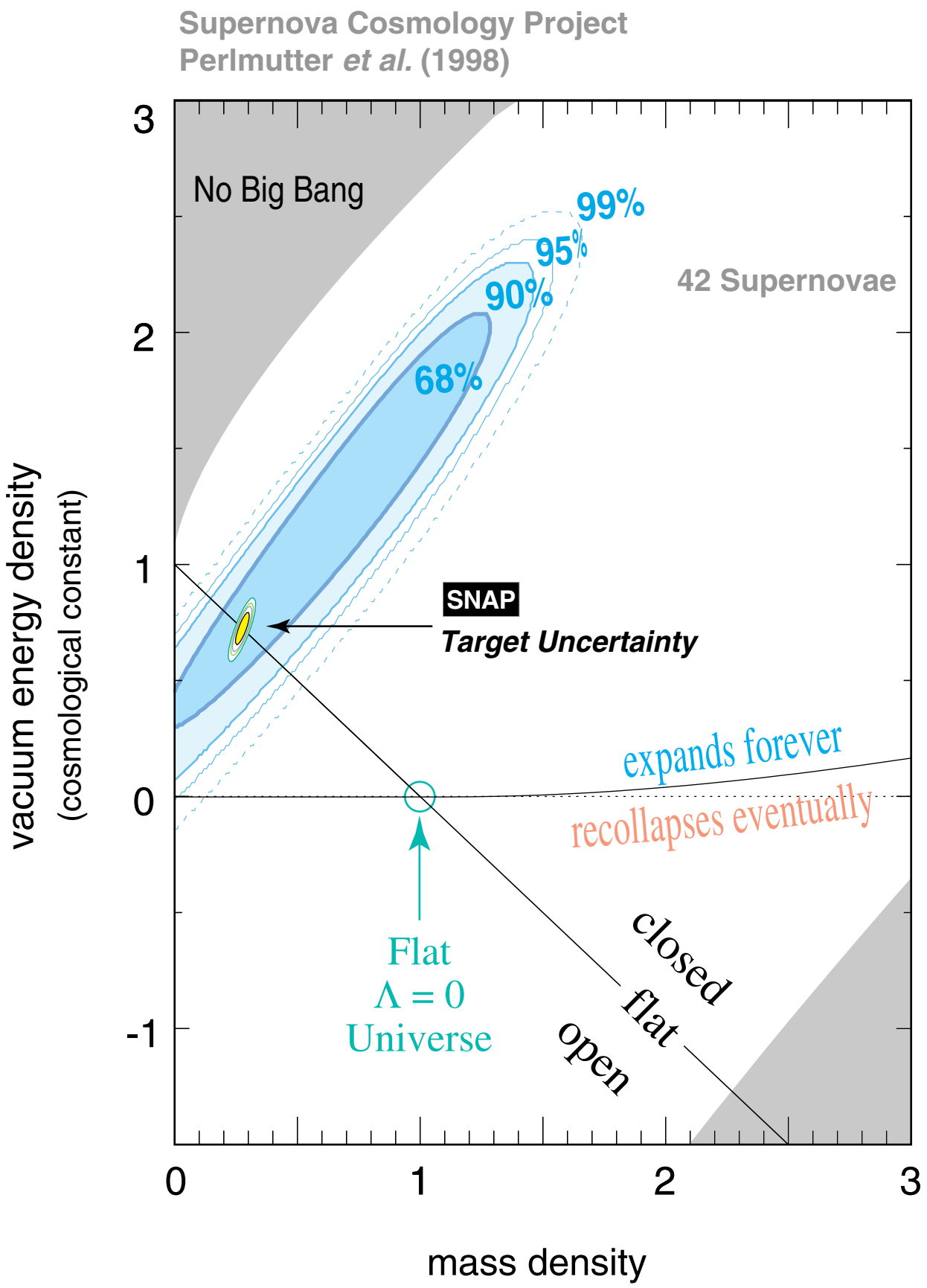
1. How much of mass density and dark energy density is there? I.e., how much dark matter and dark energy do we need to look for?
   The answer to this question determines the "curvature" of the universe, and can tell us about the extent of the universe: infinite or finite.

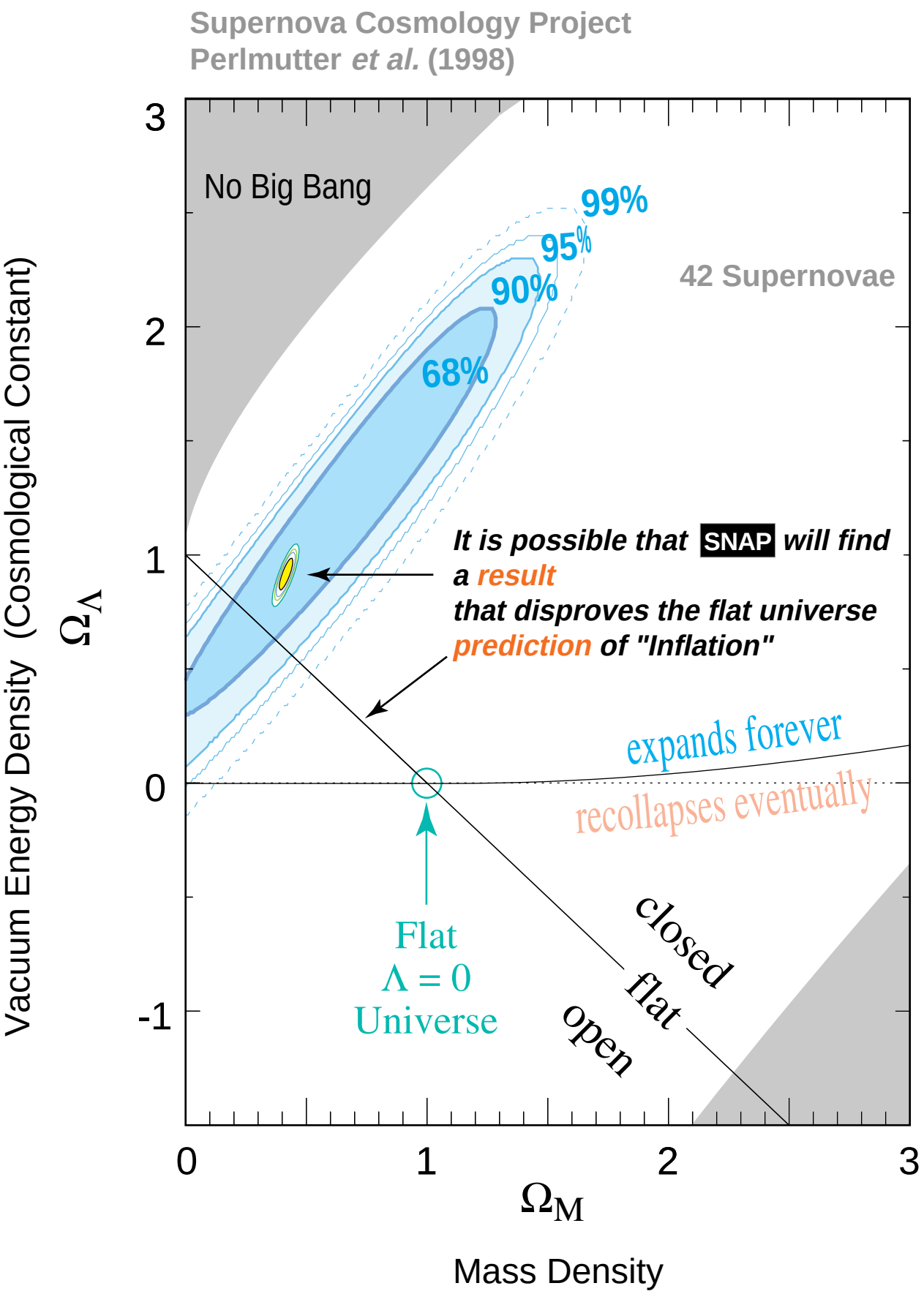
2. What is the "dark energy"? Particle physics theory proposes a number of alternatives, each with different properties that we can measure. Each of the alternative theories raises some important questions/problems of fundamental physics.

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



Ap.J.
astro-ph/9812133


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)
Ω_Λ
Ω_M
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 $\frac{\Lambda}{8\pi G} \sim m_{\text{Planck}}^4$

  This is off by ~120 orders of magnitude!

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

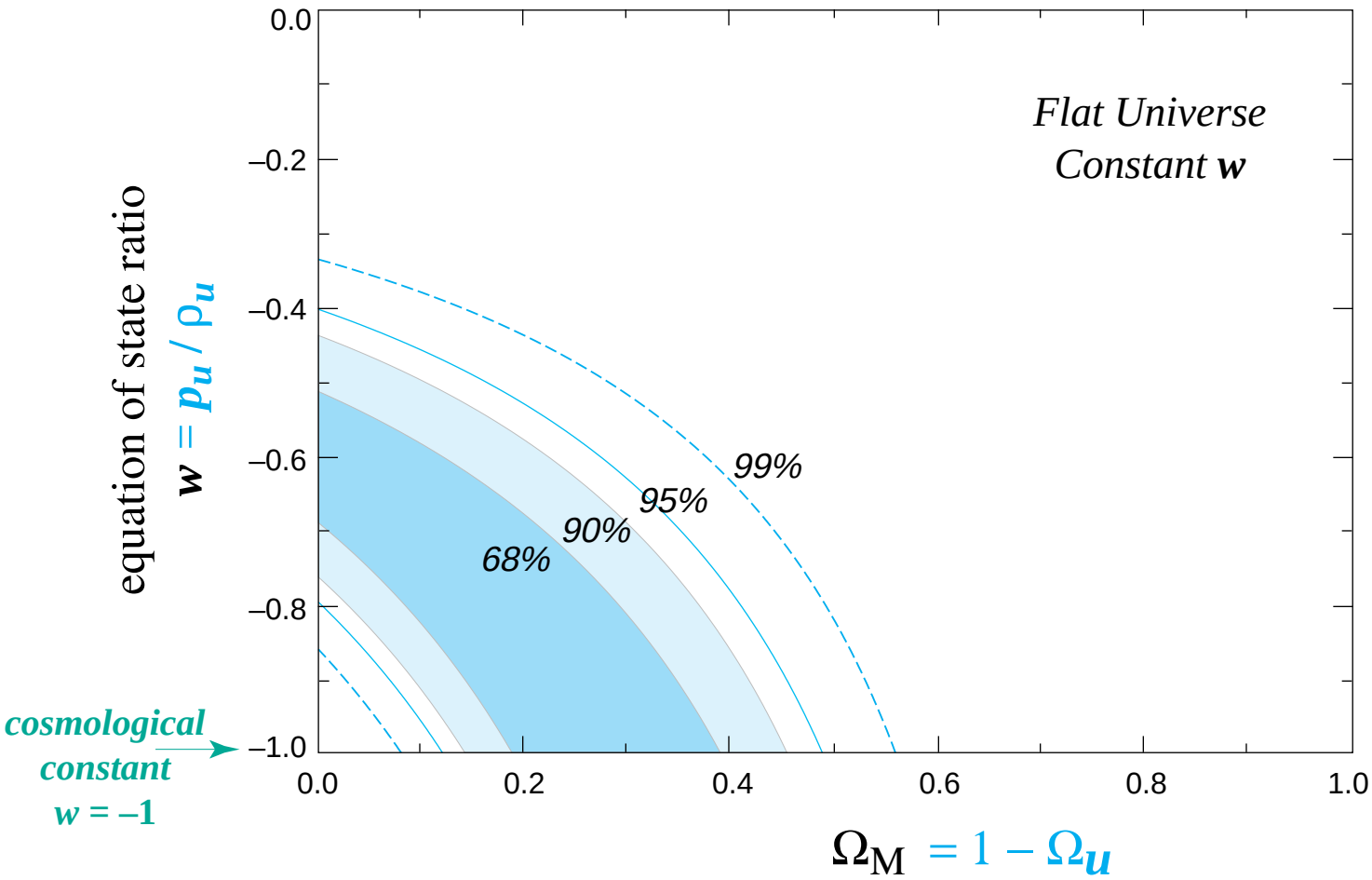
$$\frac{\ddot{R}}{R} = -\frac{4\pi G}{3}(\rho + 3p)$$

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

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

Unknown Component, Ω_u, of Energy Density

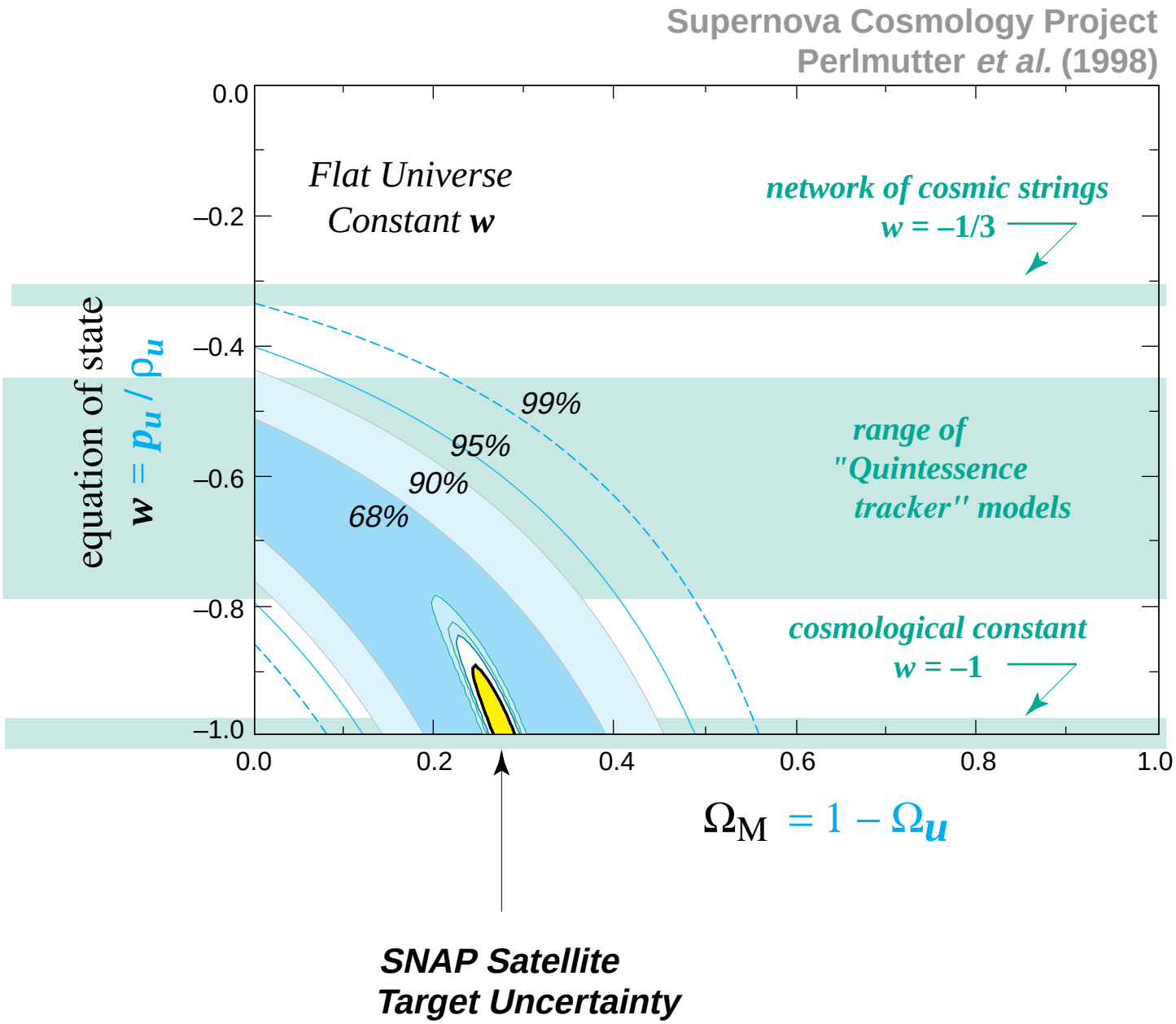
Perlmutter *et al.* (1998)



c.f. Garnavich et al. (1998)

Dark Energy

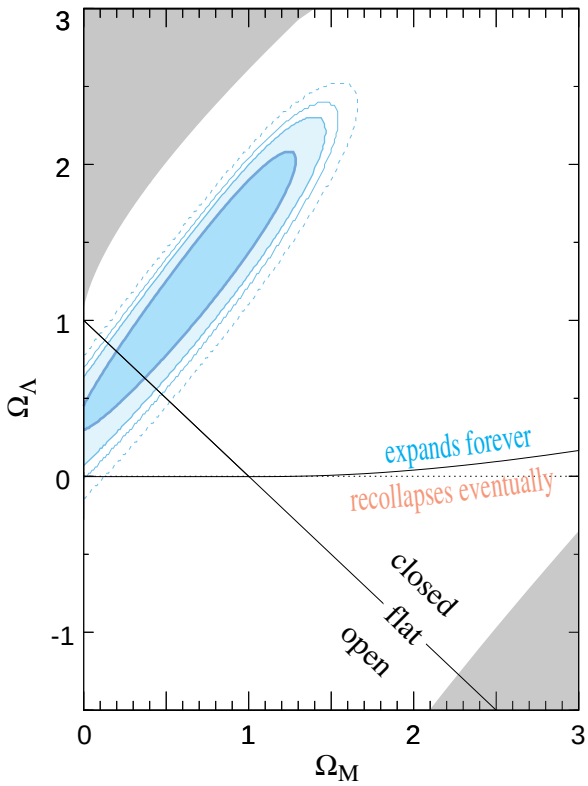
Unknown Component, Ω_u, of Energy Density



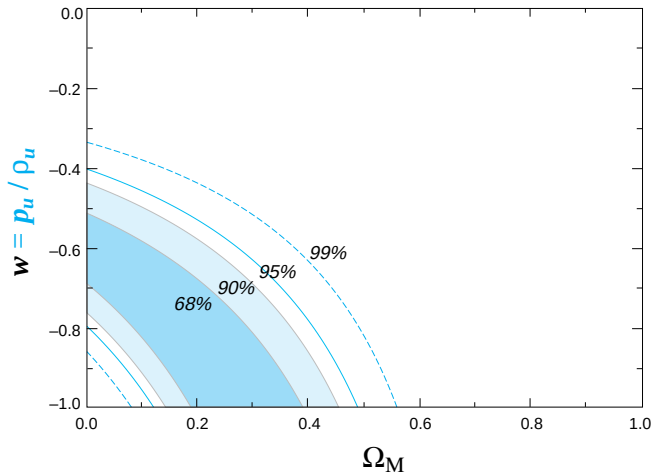
SNAP Satellite
Target Uncertainty

How can we address these new questions?

Greatly improve:



and:



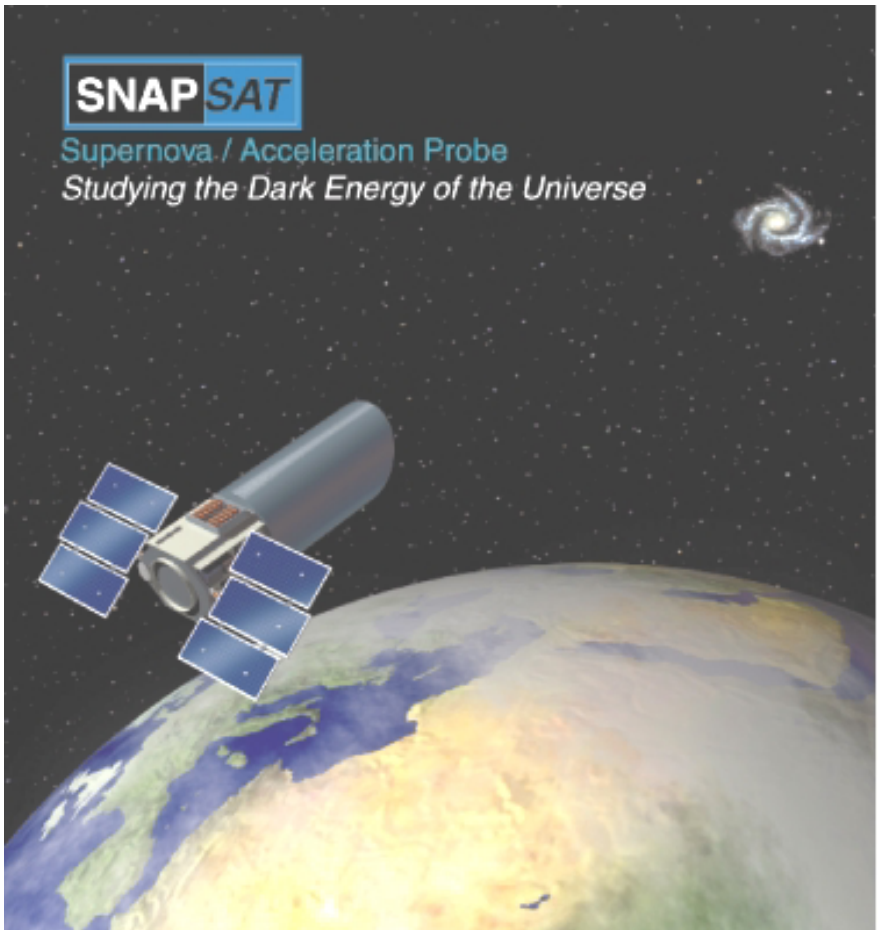
...And look for details of w(z).

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.

Proposed Satellite Probe of the Fundamental Properties of the Universe



Scope

- ~2 meter aperture
- 1 square degree mosaic camera (1 billion pixels)
- 3 channel spectroscopy 0.3 μm -- 1.8 μm

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-channel spectroscopy, 0.3um -- 1.8um**
  Detailed analysis of each SN.

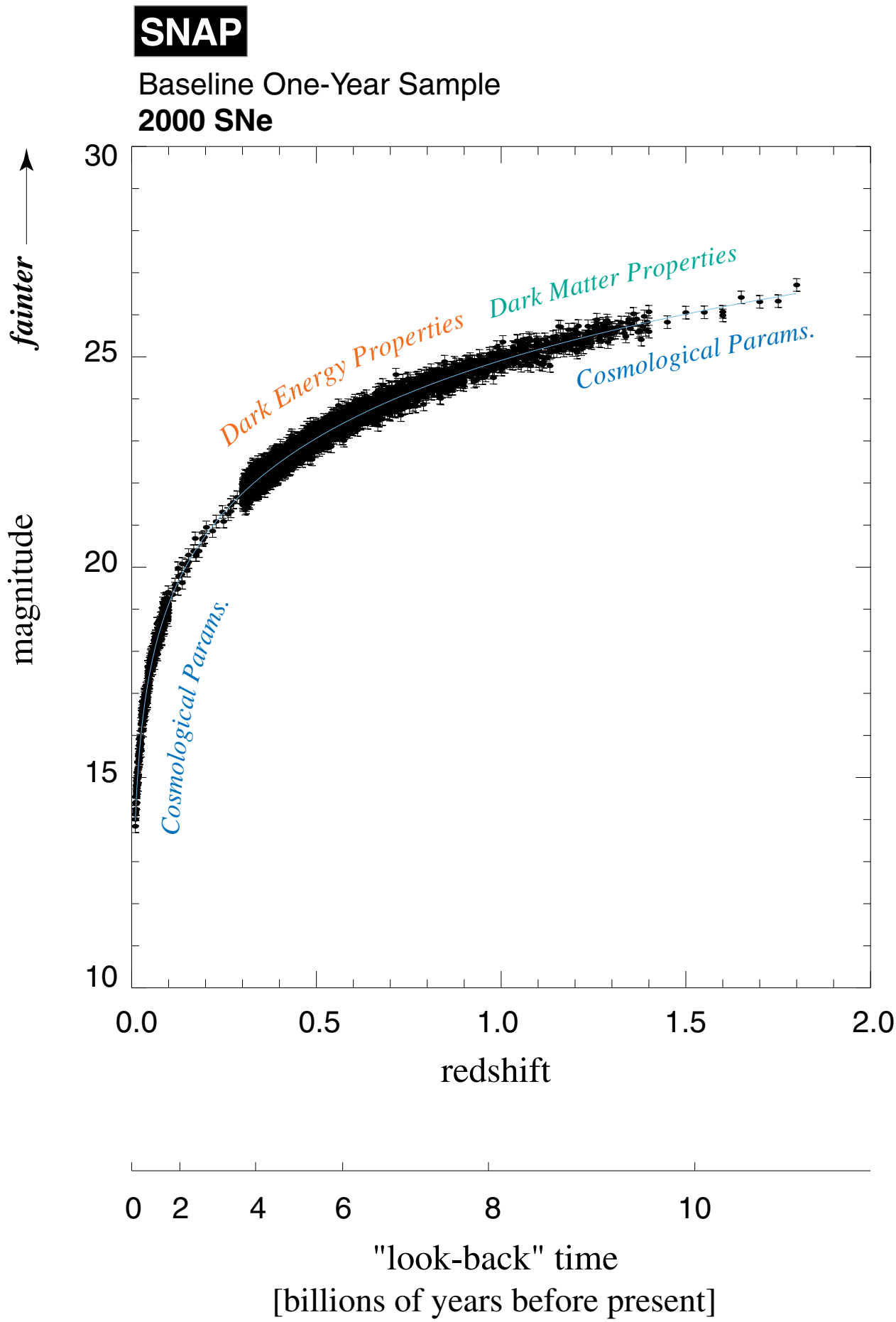
Satellite:

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

SNAP

supernova acceleration probe

baseline science goals

Target Parameter	*Constraint*	*Target Stat. + Syst. Uncertainty*
Determine mass density, vacuum energy density, and curvature		
mass/vacuum energy Ω_M, Ω_Λ	in flat universe Ω_k=0	0.01
curvature Ω_k	(indep. of CMB)	0.05
mass density Ω_M	unconstrained Ω_k	0.02
vacuum energy Ω_Λ	"	0.05
Properties of Dark Energy		
Eq. of State w vs Ω_M	in flat universe	
Eq. of State w	with $\Omega_M = 0.3$	0.05
Study time-varying $w(t)$ by studying $d_L(z)$ with $\Delta z = 0.03$ bins.		

A definitive supernova cosmology measurement.

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-channel spectrograph (0.3 µm to 1.7 µm)

Derived requirements:

- High Earth orbit
- ~5 Mb/sec bandwidth

⋮

Why a New Satellite?

Ground-based telescopes:

A dedicated 8-meter with 9-square-degree imager...

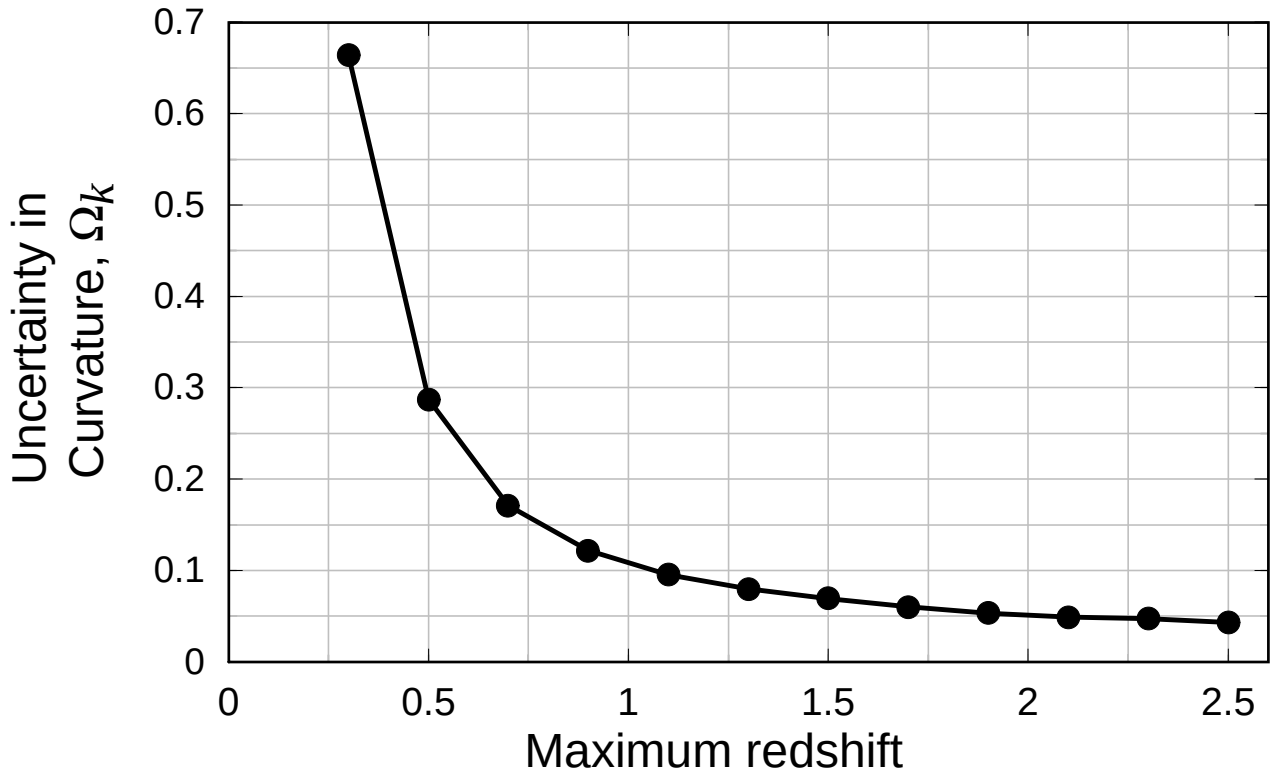
- cannot discover SNe within 2 restframe days of explosion beyond z = 0.6.

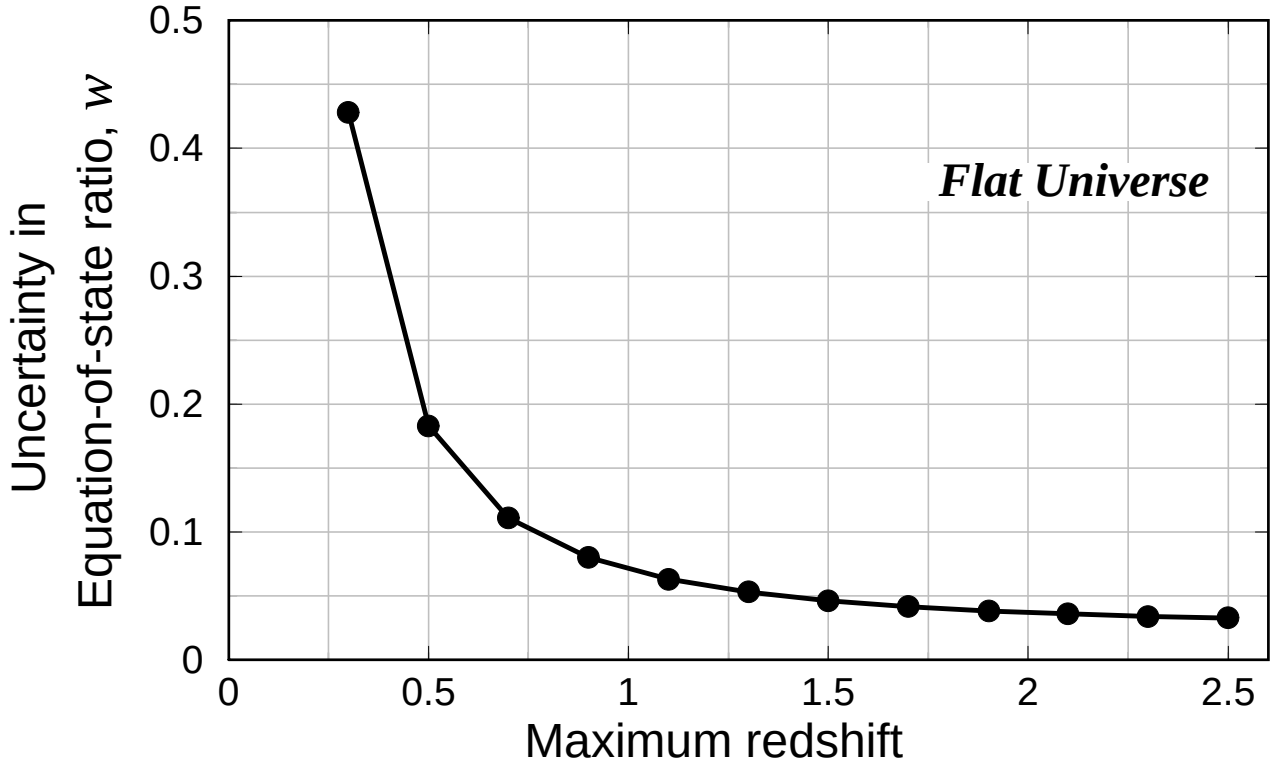
- cannot measure SN plateau level (>45 days after peak) beyond z = 0.7.

- cannot obtain 2% uncertainty on photometry within 15 days of peak, beyond z = 0.75.

- even limiting redshifts to z = 0.6, can only study fewer than 300 SNe/year.

How do uncertainties improve as we extend the range of redshifts?





Why a New Satellite?

Space-based (HST or NGST) telescopes:

NGST targets different and complementary science — higher redshifts ($z \gg 1$), fewer (~100) SNe and fewer observations (~4) per SN.

- NGST 16-square-arcminute field of view much too small to efficiently find SNe in the target redshift range.

- Using NGST to obtain spectroscopy of the SN discovered by SNAP would be wasteful: Most of the time for over half a year would be spent slewing the NGST.

SNAP

science cross-checks

With the little (or no) additional effort/data, we can make cross-check measurements of the cosmological parameters several ways.

(Note that these other measurements are much more model dependent.)

- The "other" supernovae (Type II) provide a completely independent measurement technique.
- Gravitational lensing of background galaxies in the field distorts the galaxy shapes. Studies of this phenomenon give an alternative cosmological-parameter measurement.
- Gravitational lensing can split distant quasar images into two (or more) images. The number of such events bounds the cosmological constant.
- Galaxy clustering at great distances is an indicator of the cosmological parameters.

complementary science

- What are "Gamma Ray Bursts"? Find the corresponding optical signals that can tell us where and what they are.
- What are the massive objects ("MACHOs") in the halo of our galaxy that are causing "microlensing"? Look for faint objects that move over a year in our images.
- Find the most distant objects in our Solar System.
- Discover the progenitors of supernovae, and the rates of star formation. When did the first stars form?

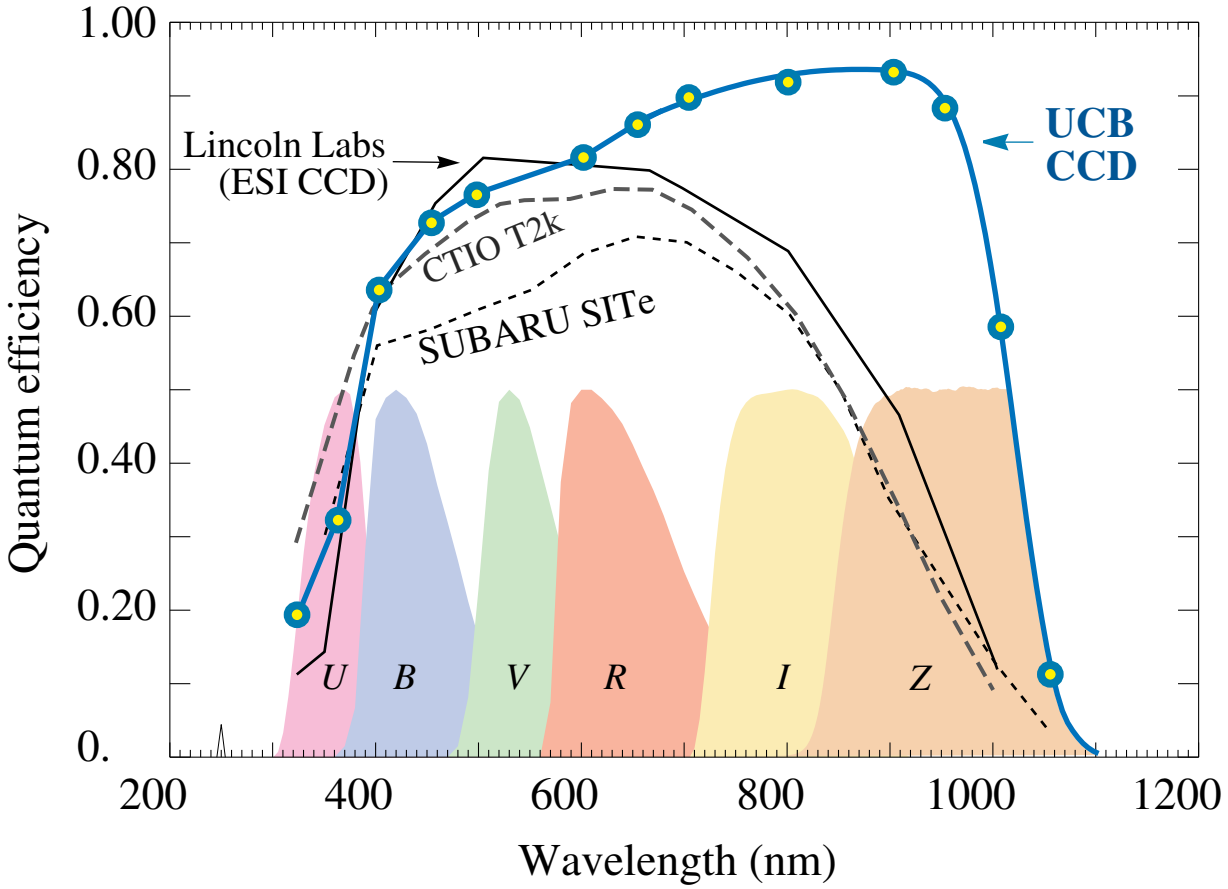
UCB CCD Technology (NSF/ATI Grant 9876605)

- Fabricated on ultra-high purity silicon wafers,
  as used in HEP vertex detectors -- SSC heritage.

- High quantum efficiency
  from near UV to near IR.

- Better overall response than
  more costly "thinned" devices in current use.

- High-purity silicon has better radiation tolerance
  for space applications.



SNAP camera with NSF CCD Technology

- SNAP imager would be largest CCD camera ever constructed
  (10 x Sloan Digital Sky Survey),
  but smaller than SLAC's SLD vertex detector.

- CCD's are mechanically stable
  and can be assembled into large array

Education

Two components for SNAP education and outreach efforts:

1) K-14 and public outreach
2) Graduate students and undergraduates in science and engineering

K-14 and public outreach: SNAP and Science Literacy

Students in elementary and secondary schools
First and second year college students in 2 and 4 year colleges
General public

Public participation in the SNAP mission: access to SNAP images and spectra

Software to utilize SNAP data
"Patch of sky" for students
Virtual SNAP mission control

Provide: Activities in Cosmology and observational astrophysics

Spaceship earth: the universe as a time machine
Centered on SNAP Engineering, Technology and Applied Science
Research experiences for non-science undergraduates and educators

Partnerships: Chabot Space and Science Center (Challenger Mission, Virtual Science Center)

Astronomical Society of the Pacific (project Astro, Amateur Astronomers)
UC Berkeley's Lawrence Hall of Science (HOU, GEMS)
UC Berkeley's Space Sciences Lab Center for Science Education (SEGway)

Education

Train undergraduate science majors and first year students.
National program, also attract students from HBCUs, MIE, and minority serving institutions

First class students become first class scientists and engineers by first learning how to utilize first class equipment and techniques.

Goal: Provide students with hands-on experiences in modern techniques.
Provide graduate students to learn mentoring -- help develop summer program for, and work with, undergraduates.

Students:
-- work with state-of-the-art instruments and software
-- participate in forefront cosomology research
-- are mentored by first-class scientists and engineers
-- understand and address a problem: what are you trying to measure
-- develop direct knowledge of tools and techniques

Students acquire useful skills and are eagerly sought for:
Academia: PhD graduate work, faculty positions
Research Laboratories (public, private)
Private sector

STATUS

* U.S. University Faculty curently involved are: Prof. A. Baden, Prof. R. Ellis, Prof. J. Graham, Prof. J. Goodman, Prof. G. Goldhaber, Prof. R. Lin, Prof. M. Metzger, Prof. G. Smoot, Prof. G. Sullivan, Prof. M. Turner

* Mission Feasibility and rough-order-of-magnitude cost study with aerospace industry ($125M, excludes launch, launch services, spacecraft bus, study phase, operations).

* Science Preview by distinguished panel, December 1, 1999. Comments from ad hoc committee.

* Policy of "launch for other agencies" a route for NASA participation.
  A joint NSF/DOE experiment --- NASA *only* provides launch vehicle and launch services.

* SAGENAP review scheduled for end of March, 2000.

* Initiating study phase (eventual $14M effort to develop CDR, cost, schedule, key technologies) .

* Strong role for NSF: project management, science, key technologies (CCD's large area silicon detectors), electronics, computing, data reduction and analysis, education (K-12, undergraduate, graduate, public)

* Next Step: 1) develop funding scenario, 2) develop management plan, 3) NSF point-of-contact

New York Times

November 30, 1999

Physicists Fret About "Nothing"

By James Glanz

"Right now, not only for cosmology but for elementary particle theory, this is the bone in our throat."

—Steven Weinberg

"...Maybe the most fundamentally mysterious thing in basic science."

—Frank Wilczek

"...Would be No. 1 on my list of things to figure out."

—Edward Witten

"Basically, people don't have a clue as to how to solve this problem."

—Jeff Harvey

"This is the biggest embarrassment in theoretical physics,"

—Michael Turner

Using NSF-developed science and technology,

Supernova Cosmology Project
CMB studies
NSF-supported CCD technology
HEP large, complex detector experience
Large silicon detector arrays

we have an unusual opportunity
to answer fundamental questions of physics

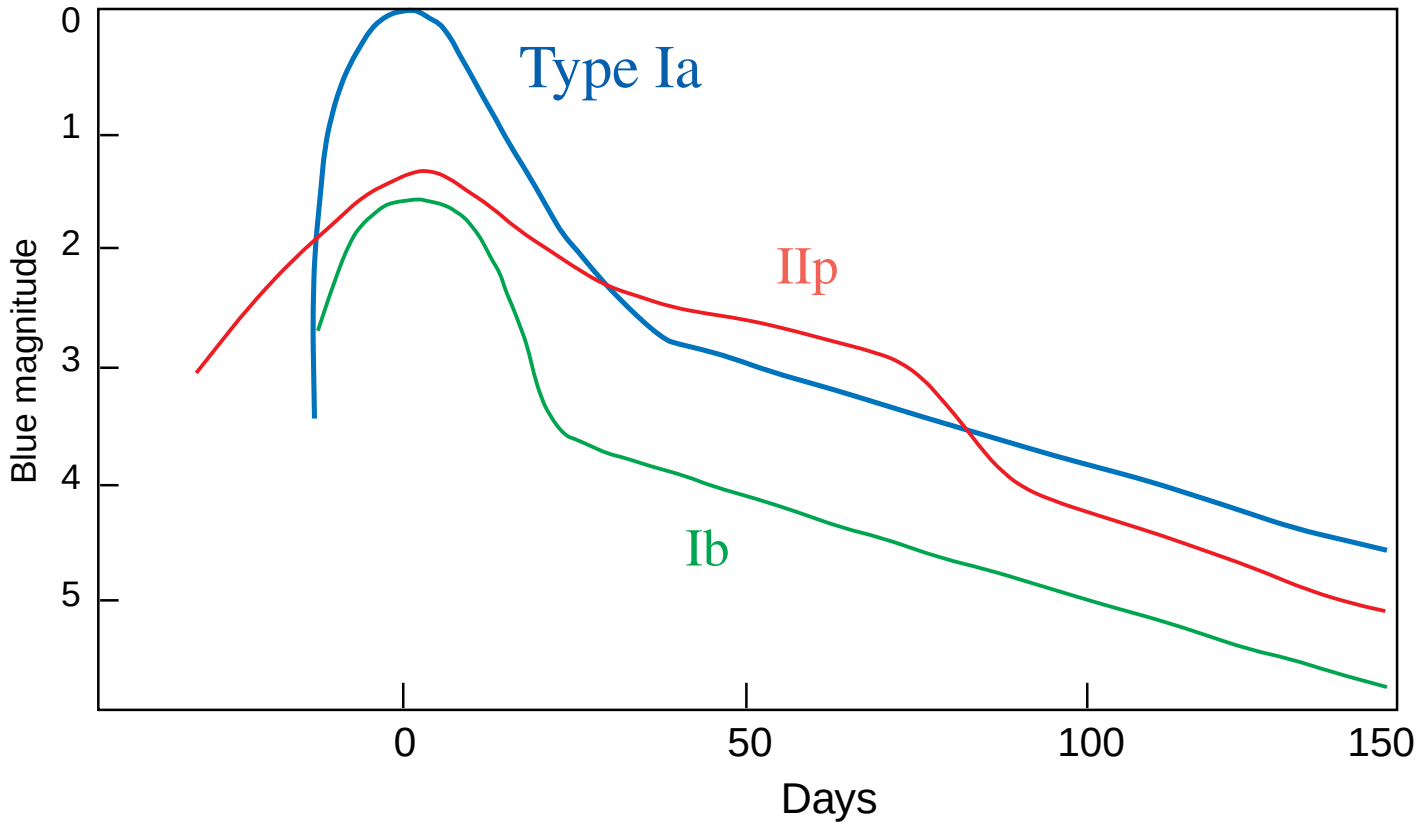
Is the universe infinite?
Is space curved?
What is the fate of the universe?
What is the "Dark Energy" that is causing the universe expansion to accelerate?

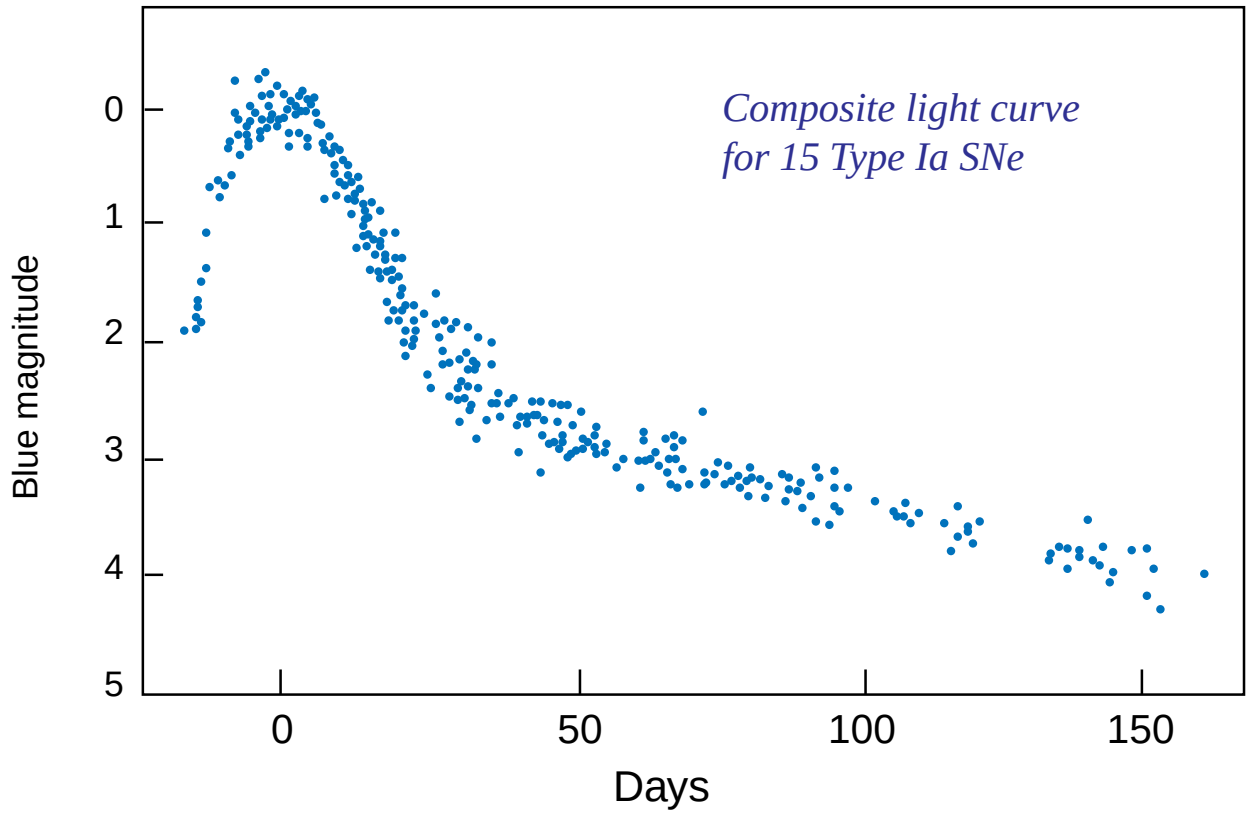
with a definitive, precision cosmology measurement.

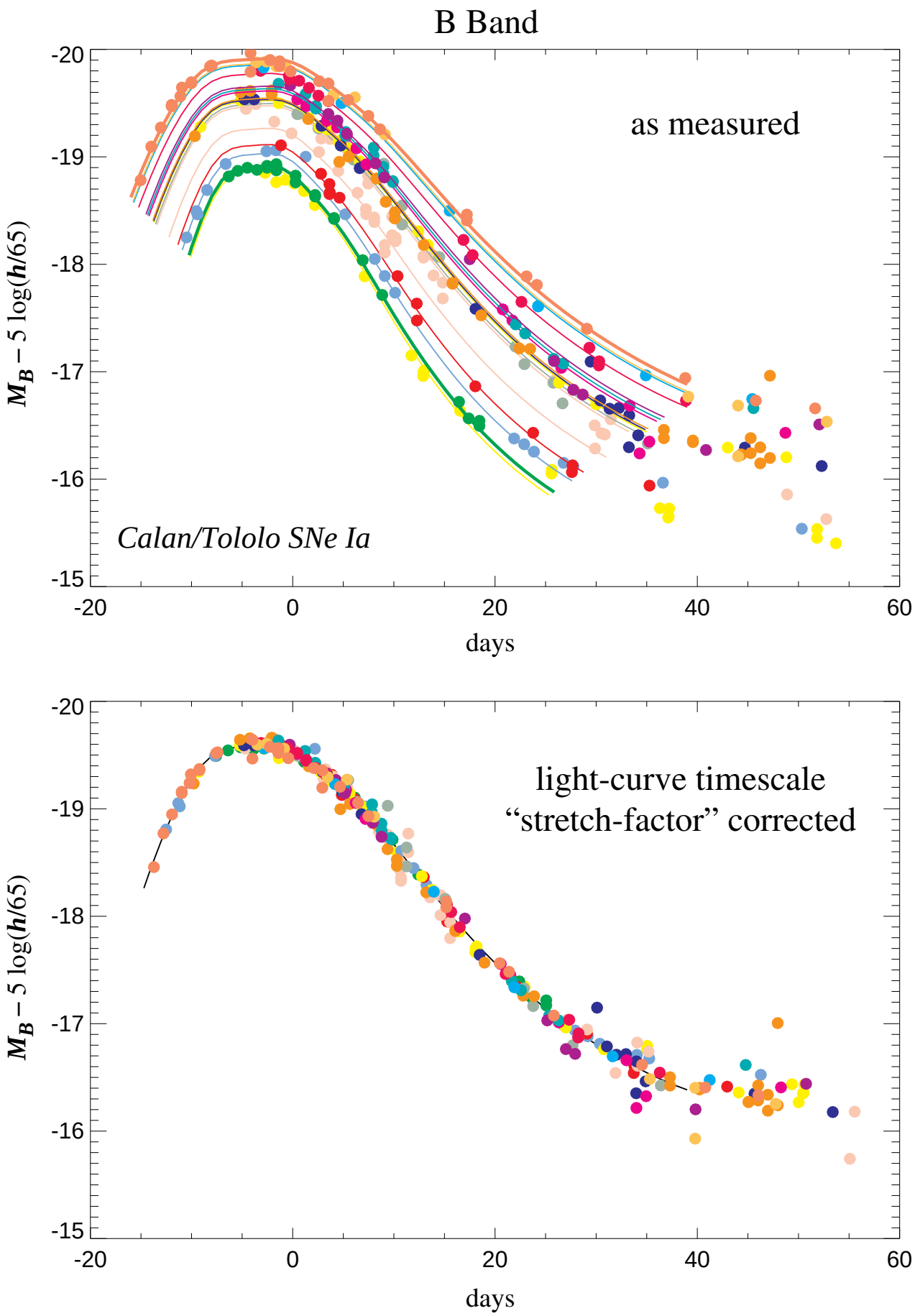
The first complete calibrated supernova dataset, 2 orders of magnitude larger statistics (>2000 SNe), extending much farther in distance and in time.
A 1% measurement of the mass density.
A 5% measurement of the vacuum energy density.
A 5% measurement of the curvature.
A 5% measurement of the Equation of State of the "Dark Energy"

Additional Background Materials

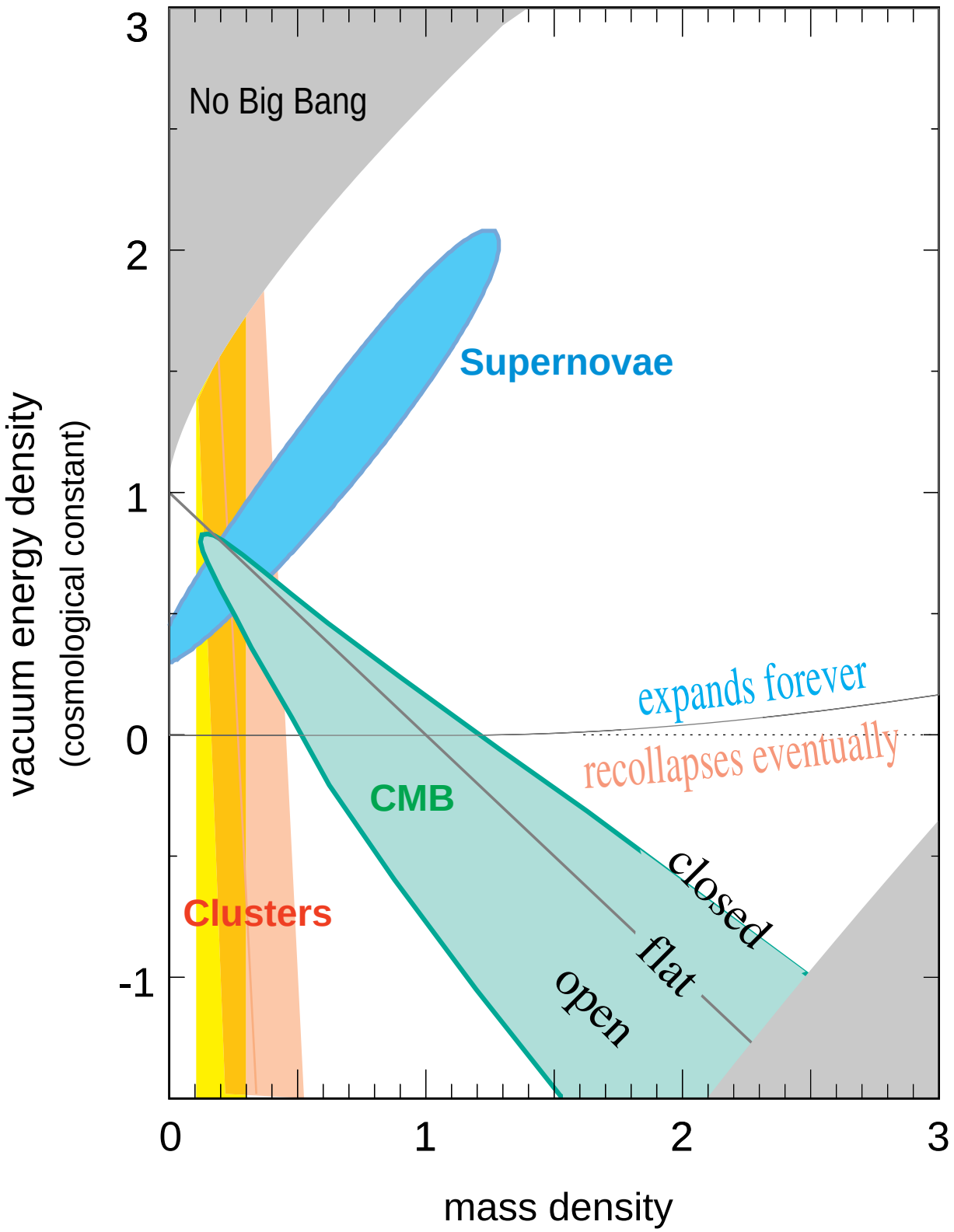
Supernova Light Curves







Kim, *et al.* (1997)


No Big Bang
Supernovae
expands forever
recollapses eventually
CMB
closed
flat
open
Clusters
vacuum energy density
(cosmological constant)
mass density
3
2
1
0
-1
0
1
2
3

SNAP*SAT*

supernova acceleration probe

one-year baseline data package

Full sample of 2000 SNe between z = 0.3 and 1.7

Discovery within ~2 days of explosion (i.e. ~2 weeks before max).
Most dense coverage between z = 0.3 and 1.0

- Spectra at max for all SNe. (0.3 -- 1.8um)
- Lightcurve points at least 1/week (restframe)
  from -15 to +60 days (restframe)

Discover *every* SN in the field

Nearly continuous monitoring of
~2 sq. deg. to $m_{AB}\,(@1\mathrm{um}) \approx$ 28.5+
~10 sq. deg. to $m_{AB}\,(@1\mathrm{um}) \approx$ 25+
~100 sq. deg. to $m_{AB}\,(@1\mathrm{um}) \approx$ 24+

Satellite follows additional 200 SNe at z < 0.15

Discovery from ground, follow-up from space to ensure matching spectroscopy/photometry across redshifts.

Subsample of 200 SNe from the full sample

Selected to span
- lightcurve timescales
- galaxy environments
  (morphology, galactocentric radius)
- redshifts

- Spectra at least 2/week (restframe) first month
  1/week (restframe) later

- Synthetic "filter-tuned" photometry from spectra
  for perfect K-corrections

SNAP*SAT*

supernova acceleration probe

controls for systematics

Dust and Extinction

Determine individual extinctions laws for a given supernova, using range of color measurements into near IR.

Determine gray dust contribution (if any), tracking $d_L(z)$ to high z.

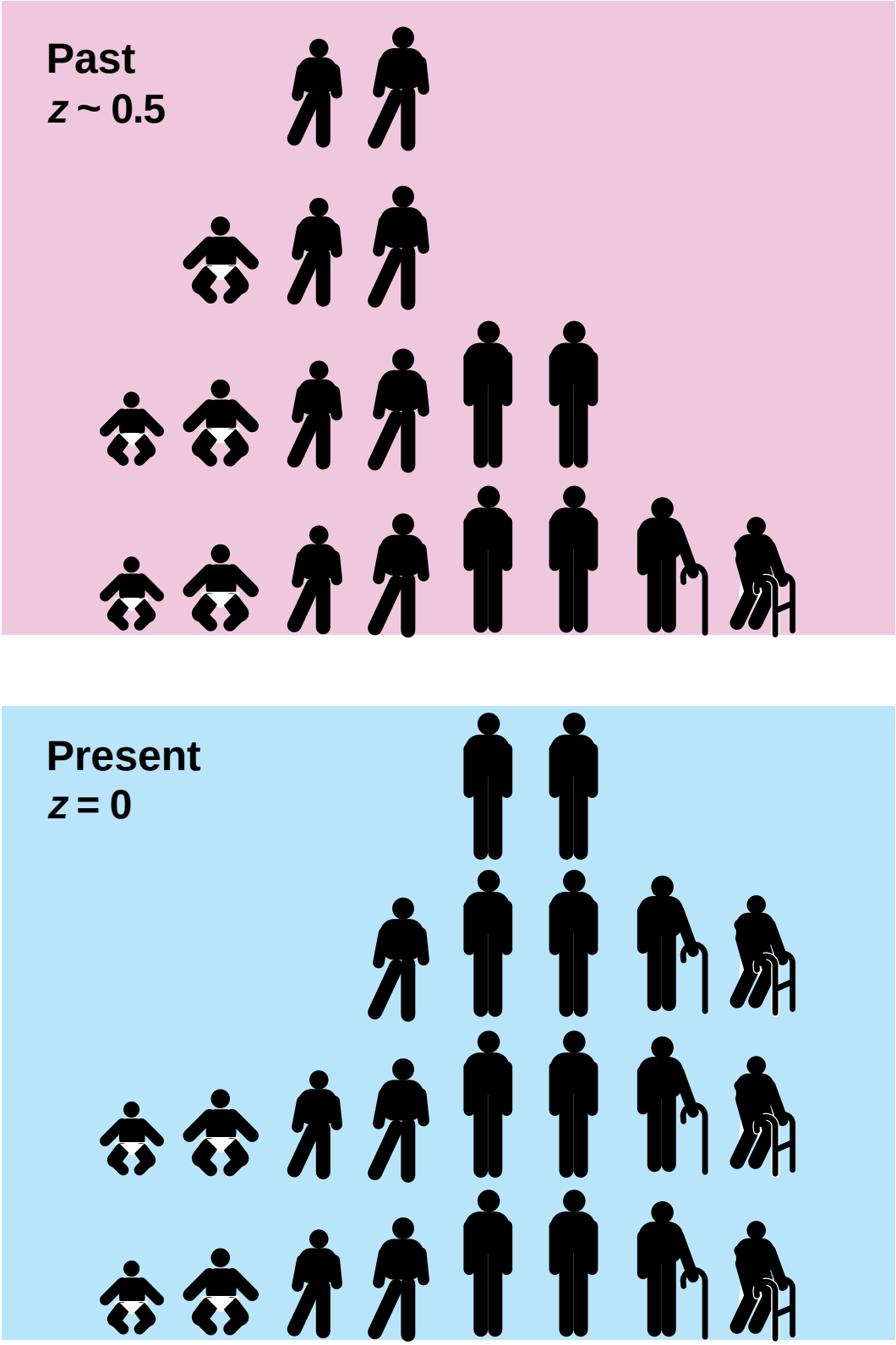
SN Progenitor Age and Metallicity Effects

Studies of lightcurve-timescale (and spectral) luminosity indicators with significant sample of SNe in all host galaxy environments.

Measurement Systematics

Observe all SNe at all redshifts with single, calibrated, stabile photometry/spectroscopy system.
(Avoid multiple instruments with different atmospheric/moon conditions.)

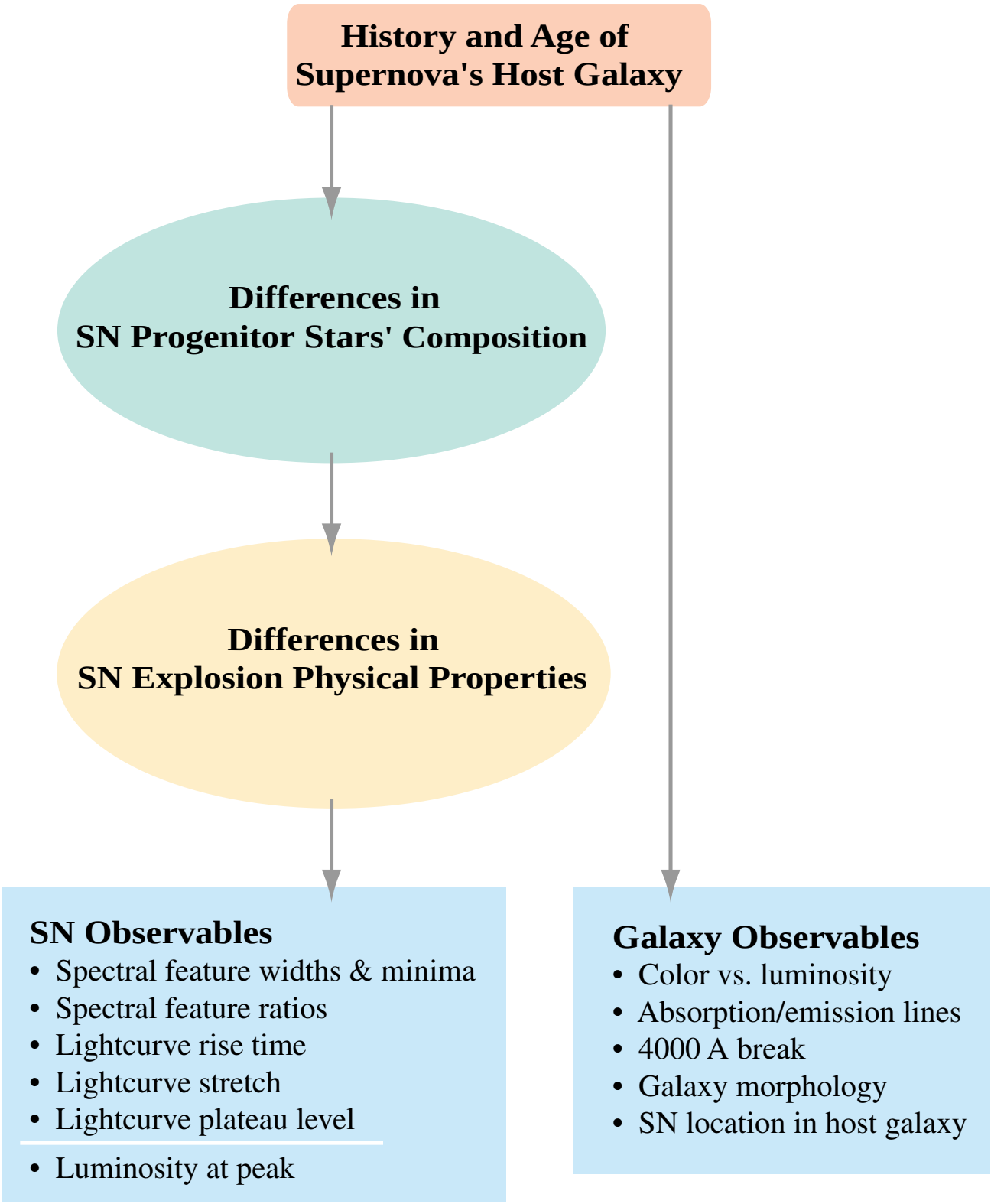
Supernova Demographics



Galaxy Environment Age

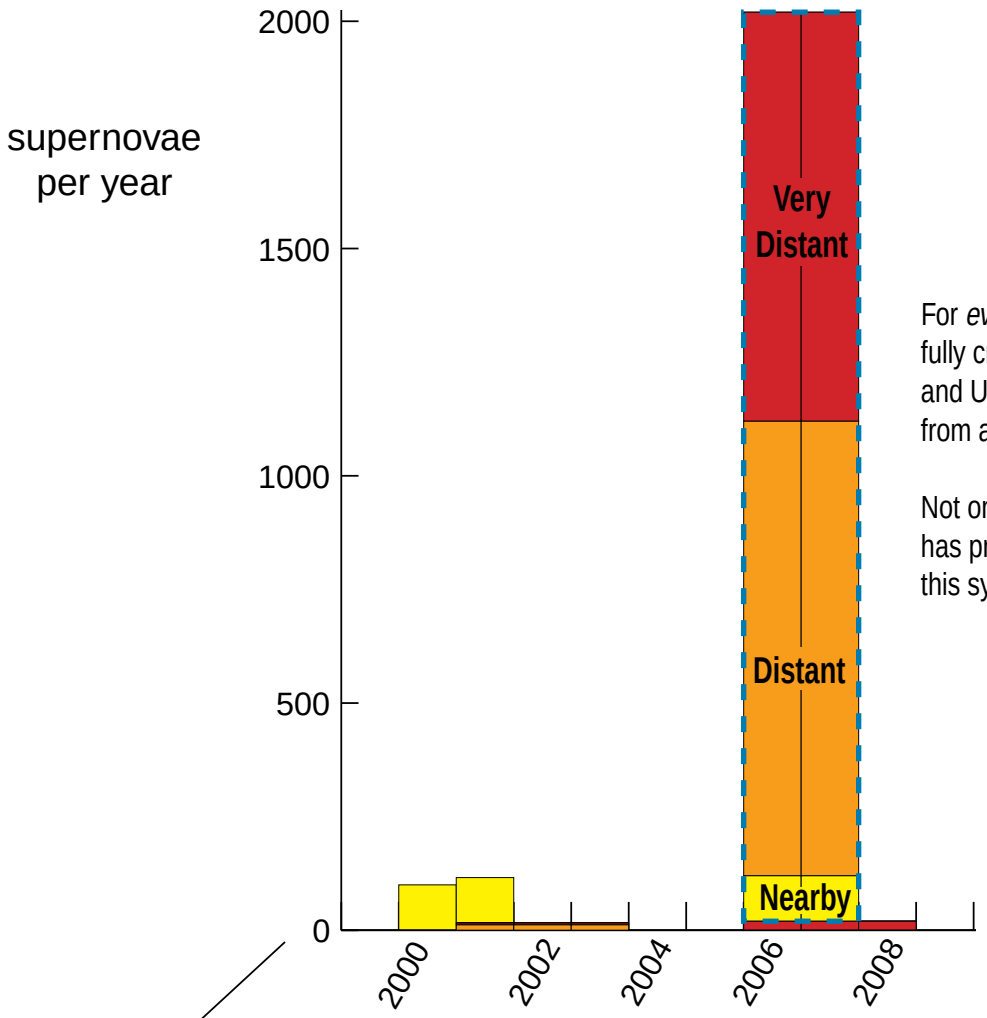
← *Younger* *Older* →

Matching SN Evolutionary States



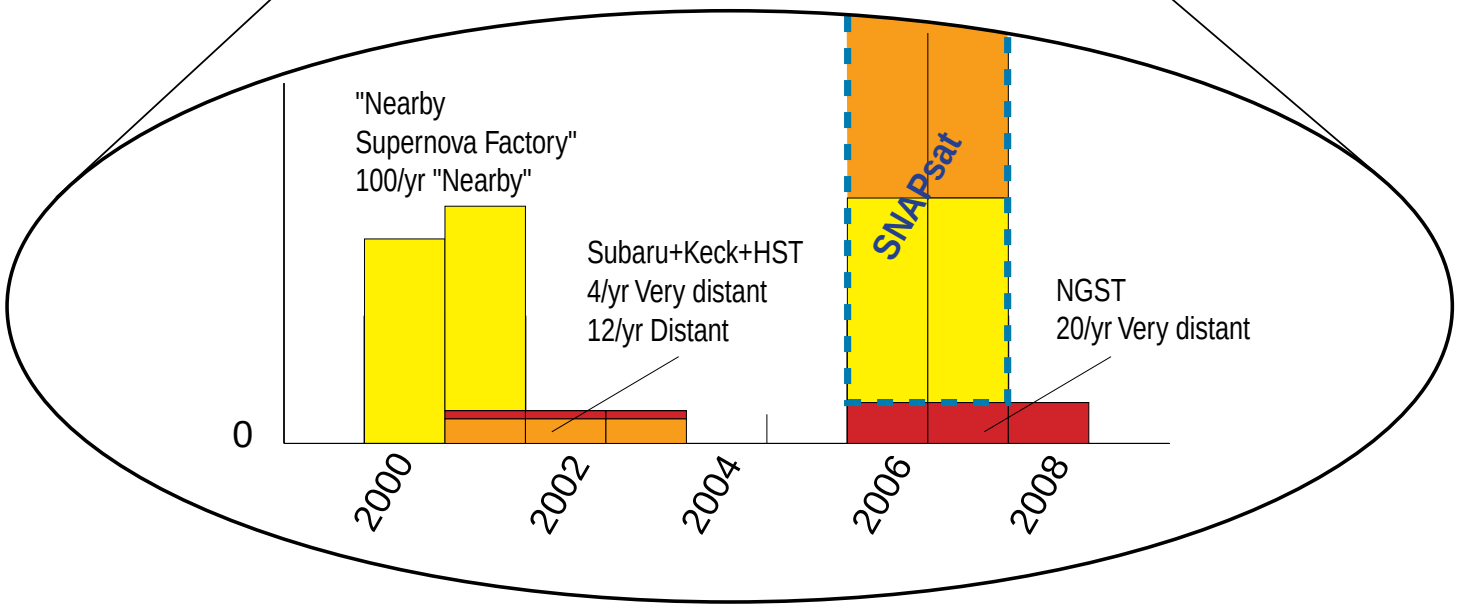
Roadmap for the Supernova Cosmology Project

SNAPsat
900/yr Very distant (~10 billion years back)
1000/yr Distant (~5 billion years back)
100/yr "Nearby" (<1 billion years back)

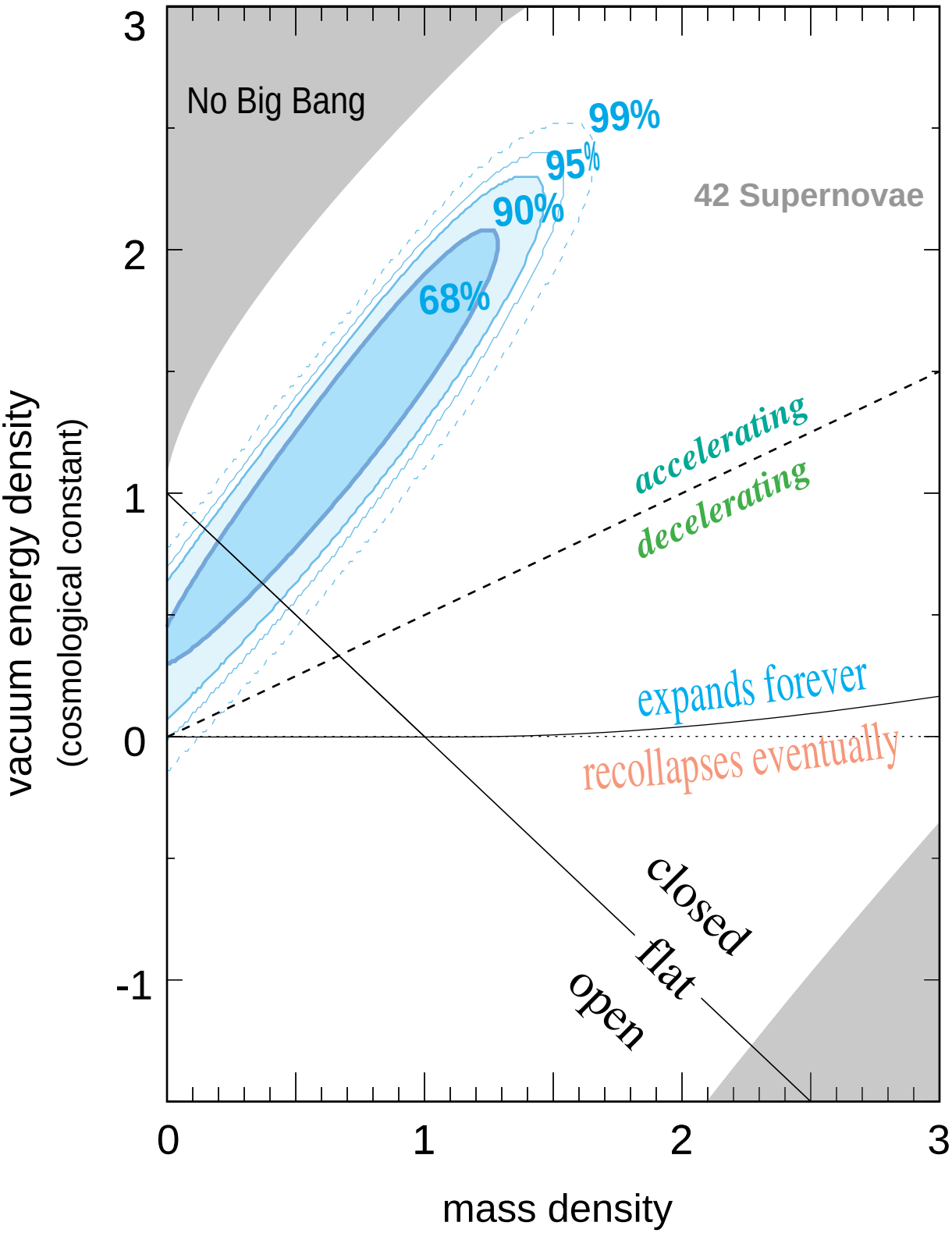


For *every* SNAPsat supernova:
fully cross-calibrated lightcurves
and UV-to-IR spectra
from a standard instrument set.

Not one single supernova
has previously been studied
this systematically.



Supernova results provide surprising direct evidence that there is an accelerating energy.



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

Ap.J.
astro-ph/9812133