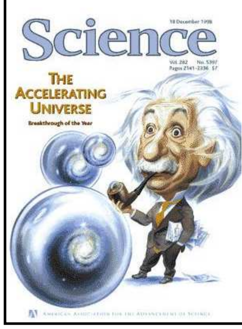
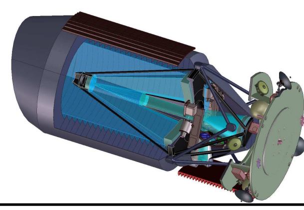
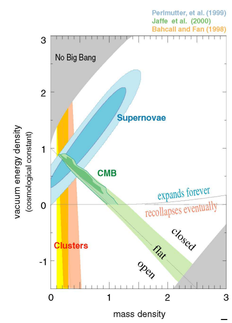
Dark Energy,
Expansion History of the Universe,
SNAP

Eric Linder
Berkeley Lab







Evidence for Acceleration

Supernovae Ia:

Ω_{DE} , w=p/ρ , w´=dw/dz

Observation -- Magnitude-redshift relation

Age of universe:

Contours of t_0 parallel CMB acoustic peak angle: t_0=14.0±0.5 Gyr

[*Flat universe, adiabatic perturbations*] Knox et al. 2001

CMB Acoustic Peaks:

Substantial dark energy, *e.g.* $0.53 < \Omega_\Lambda < 0.7$ Bond et al. 2002

[*Small GW contribution, LSS, H_0*]

Large Scale Structure:

Power spectrum P_k, Growth rate, "looks"

[*simulations*]

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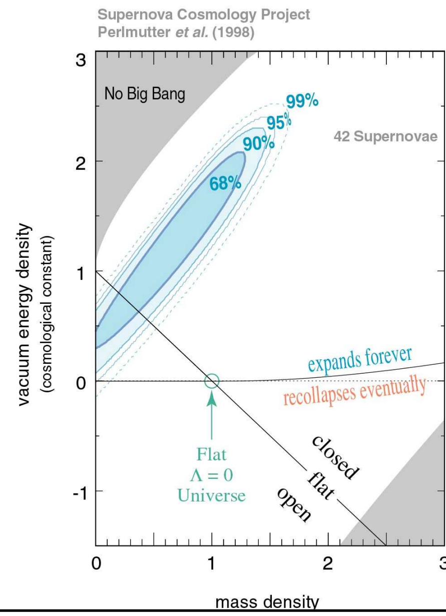
Supernova Cosmology



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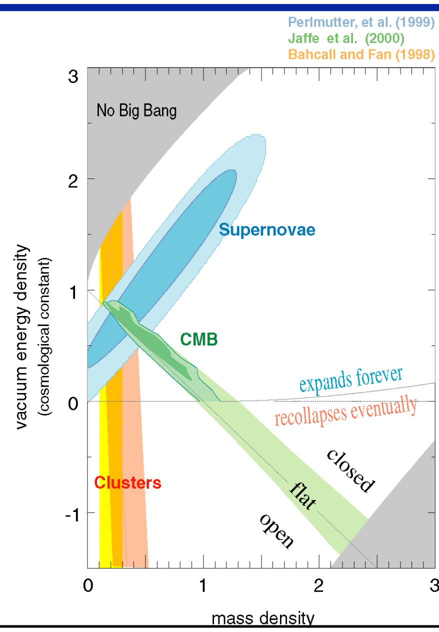
A Dark Energy Universe



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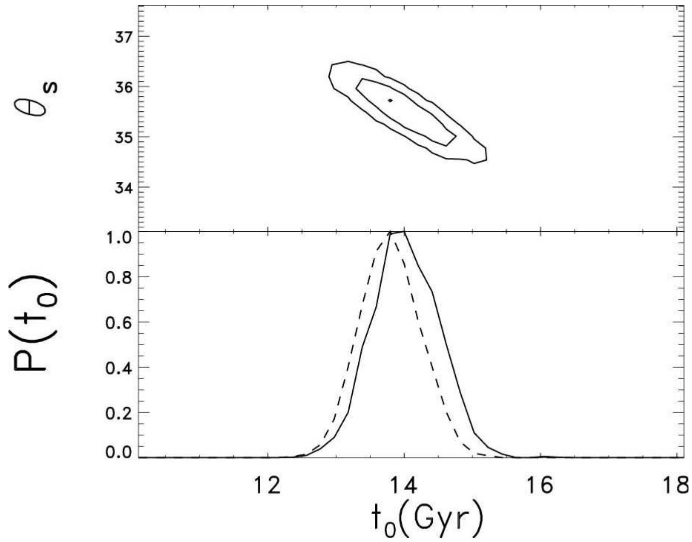
Correlation of Age with CMB Peak Angle



Knox, Christensen, Skordis 2001

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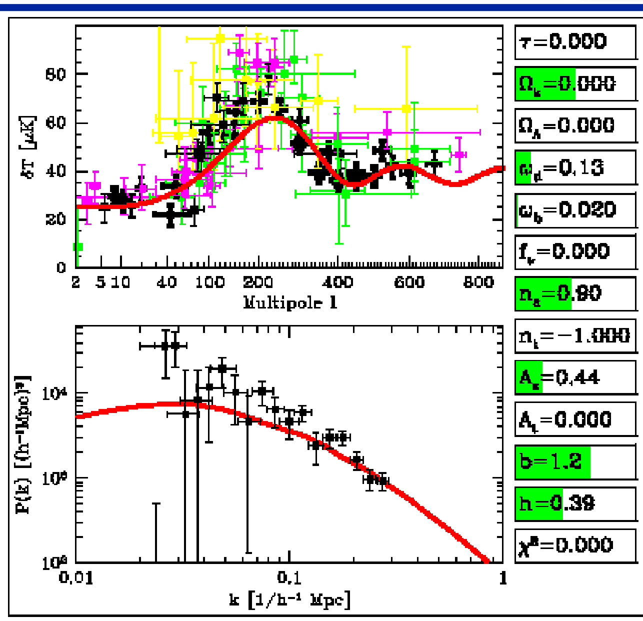
CMB Power Spectrum and Ω_Λ



Tegmark

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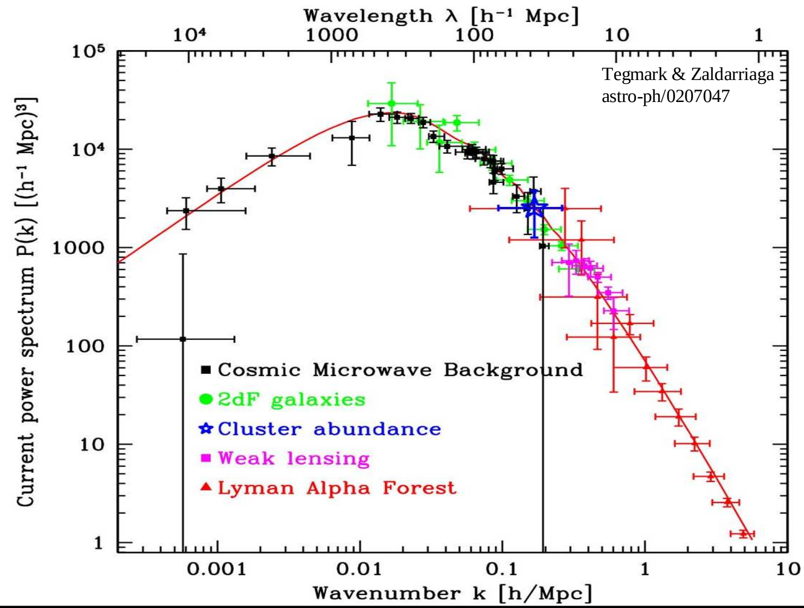
Matter Power Spectrum



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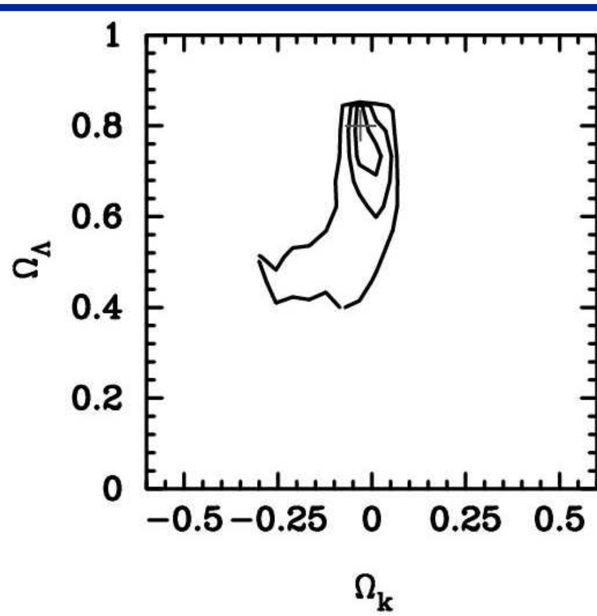
CMB + 2dF (no SN)



$1-\Omega = 0 \pm 0.04$

$\Omega_m = 0.313 \pm 0.055$

Percival et al.
astro-ph/0206256

Efstathiou et al.
astro-ph/0109152

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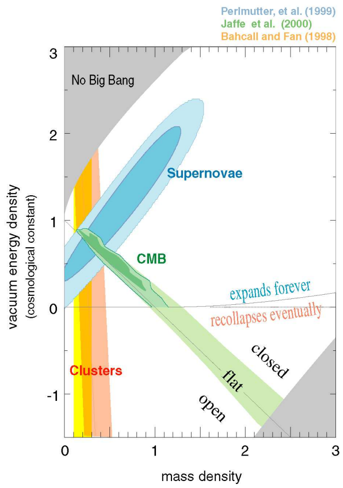
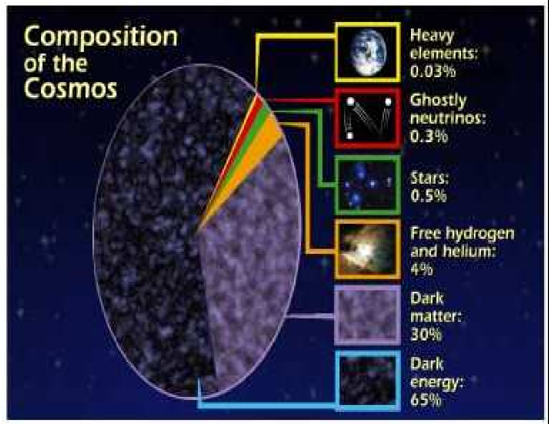
Dark Energy

SNAP

- Supernova data shows an acceleration of the expansion, implying that the universe is dominated by a new Dark Energy!
- Remarkable agreement between Supernovae & recent CMB and LSS results.





courtesy STScI

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Dark Energy Theory

SNAP

1970s – Why $\Omega_M \sim \Omega_k$?

1980s – Inflation! Not curvature.

1990s – Why $\Omega_M \sim \Omega_\Lambda$?

2000s – Quintessence! Not Λ?

Lensing $\rightarrow \Lambda=0.7^{+0.1}_{-0.2}$ Chiba & Yoshii

Supernovae $\rightarrow \Lambda=0.72^{+0.08}_{-0.09}$ SCP, HiZ

Lyα Forest $\rightarrow \Lambda=0.66^{+0.09}_{-0.13}$ D. Weinberg et al.

Cosmological constant is an ugly duckling

Dynamic scalar field is a beautiful swan

Lots of theories, little data.

We want to say, for example:

2010: A dynamical scalar field with

equation of state today $w(z=0) \equiv w_0 = -0.82\pm0.05$

time variation of the EOS $dw/dz \equiv w' = 0.29\pm0.11$

consistent with Supergravity inspired field theories

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Fundamental Physics

Equation of state $w=p/\rho$

$$\rho_\phi(a) = \rho_\phi(0)\, e^{-3\int d\ln a(1+w)} \sim a^{-3(1+w)}$$

Time variation *dw/dz* is a critical clue

Astrophysics → Cosmology → Field Theory

SN, CMB, etc. → r(z) → Equation of state w(z) → V(ϕ)

V (ϕ(a(t)))

Is Λ=0 ?

- **Fine tuning problem – why so small?**
- **Coincidence problem – why now?**

What is the dark energy?

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Dark Energy Effects

- Dynamical Effect on *a(t)* – clean and accurate
- Small CMB late time Sachs-Wolfe effect – buried in cosmic variance
- Effect on growth rate of large scale structure – need to separate from astrophysics
- Superhorizon inhomogeneities or quantum effects?

Map the expansion history of the universe

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Cosmological Probes

A handful of promising cosmological probes:
What are the systematics?

- **SZ Effect -- cluster counts**
  Projection effects
  Mass-temperature relation
  Limiting cluster mass
  needed better than 10% dex
  for 3 σ bias
- **SZ Effect with X-ray data -- angular distance**
  Clumpy electron medium, asphericity
  Cluster map resolution
- **Galaxy halo counts**
  Mass -- halo velocity profile relation
- **CMB**
  Weak dependence on w
  through ISW effect
  Cosmic variance
- **Weak Lensing**
  B modes not all zero
  Lensing model: NFW, SIS halos?
  Nonlinear part of power spectrum
  needed better than 5%
  for 1 σ bias
- **Strong Lensing**
  Lens mass distribution
- **Alcock-Paczynski Effect**
- **Peculiar Velocities**
- **Type Ia Supernovae**
  Evolution
  Extinction
  Gravitational Lensing

CfCP Dark Energy Workshop (Chicago,2001)

New large scale structure simulations with *w´* – Frenk, Linder, et al.

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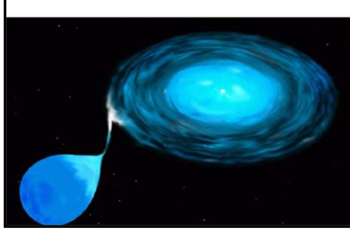
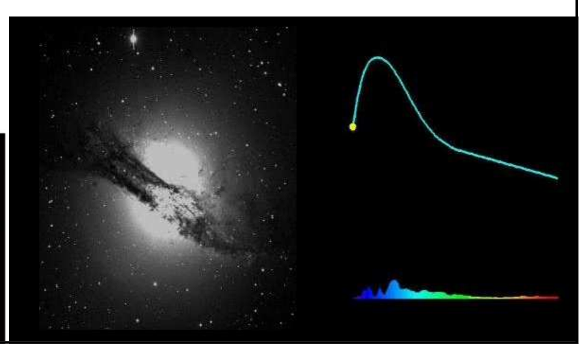
Type Ia Supernovae

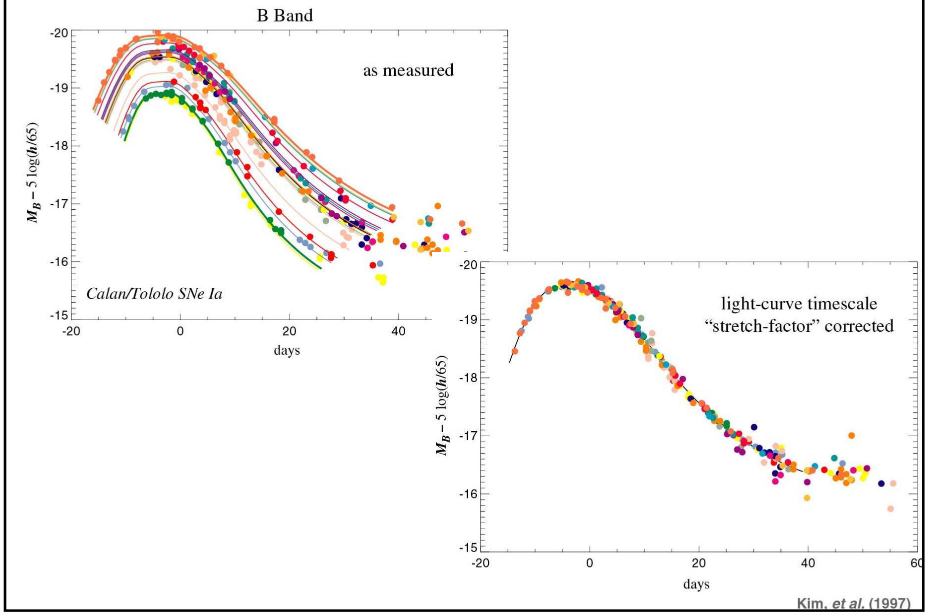
- Characterized by no Hydrogen, but with Silicon
- Progenitor C/O White Dwarf accreting from companion
- Just before Chandrasekhar mass, thermonuclear runaway

Standard explosion from nuclear physics

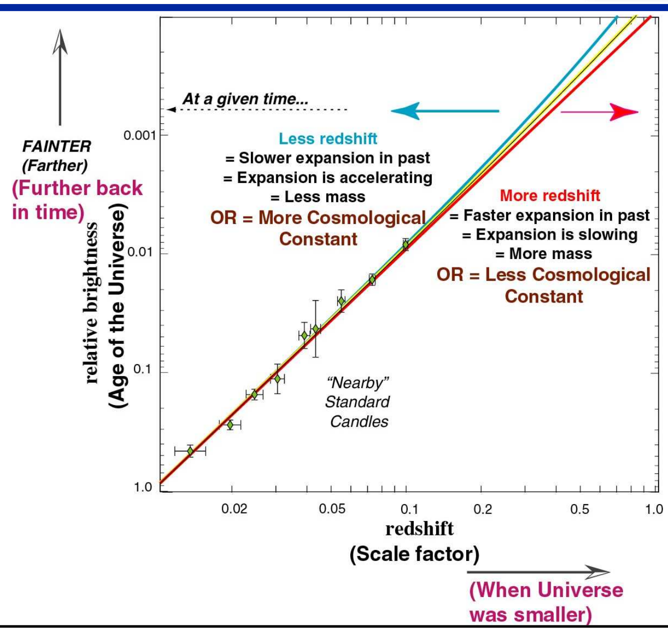




1 Parameter Family Homogeneity



Hubble diagram – low z



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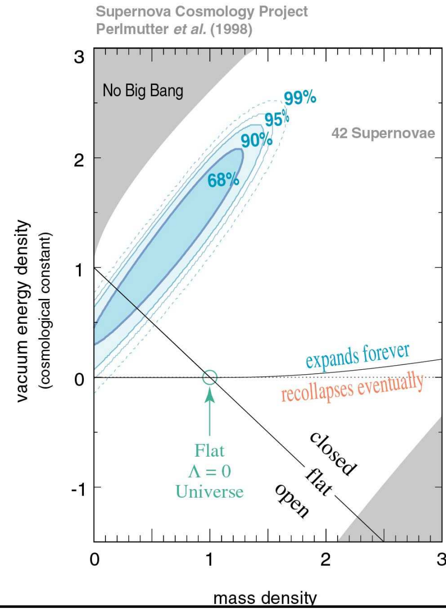
Supernova Cosmology

SNAP



In flat universe:

Ω_M=0.28 [±.085 stat][±.05 syst]

Prob. of fit to Λ=0 universe: 1%

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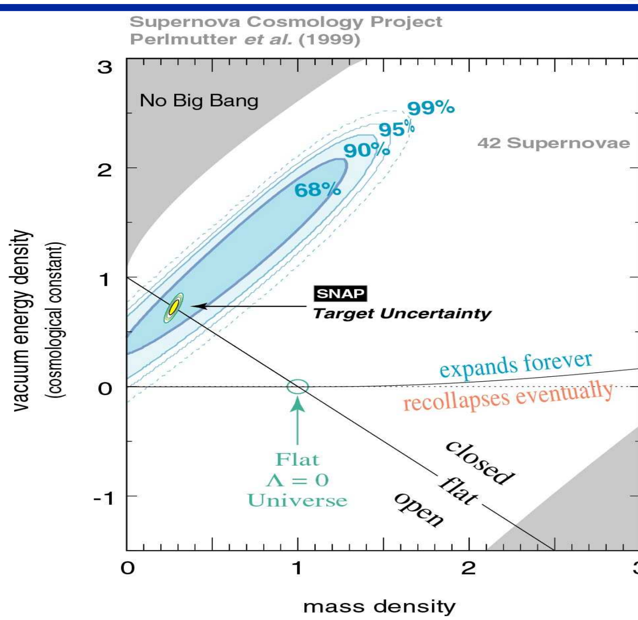
SNAP: The Third Generation

SNAP



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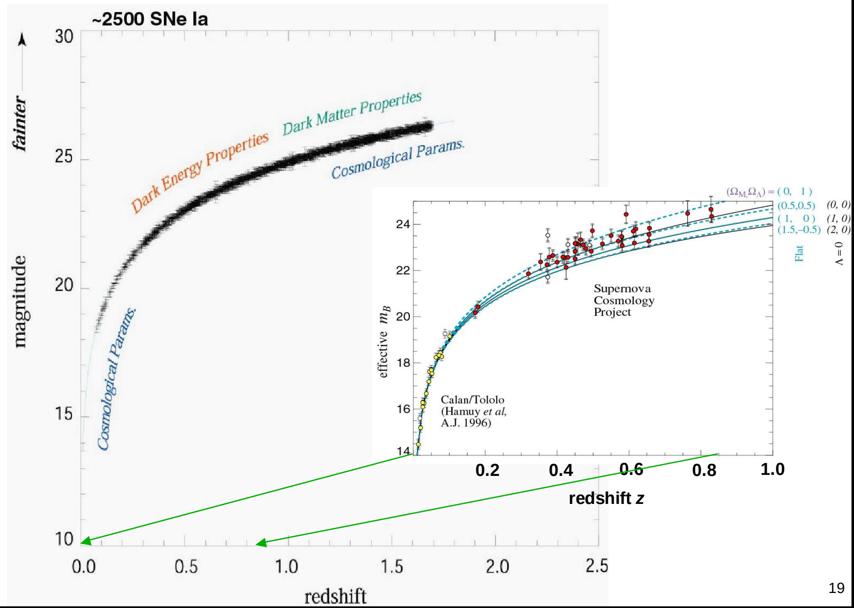
Hubble Diagram



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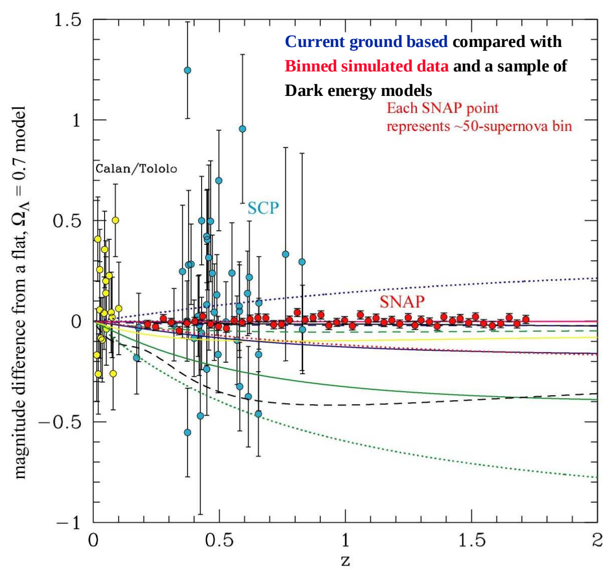
Dark Energy Exploration with SNAP



based on
Weller & Albrecht (2001)

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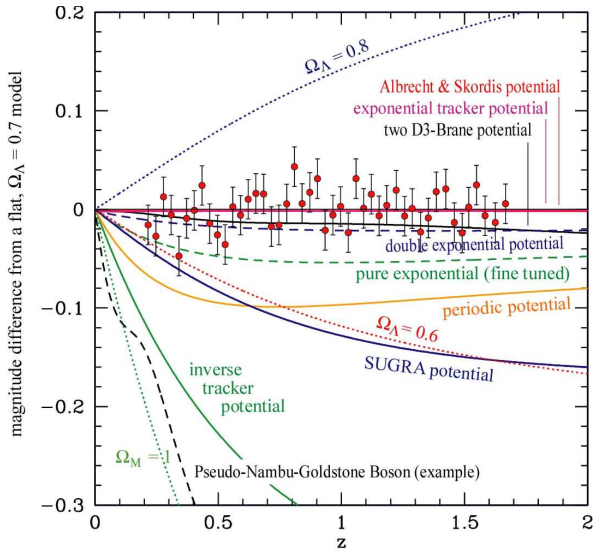
Probing Dark Energy Models

SNAP



based on
Weller & Albrecht (2001)

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From Science Goals to Project Design

SNAP

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 and proposed systematics:
- Measurements to eliminate / bound each one to +/–0.02 mag

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
- Spectrograph (0.35 µm to 1.7 µm)

Derived requirements:
- High Earth orbit
- ~50 Mb/sec bandwidth

⋮

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Mission Design

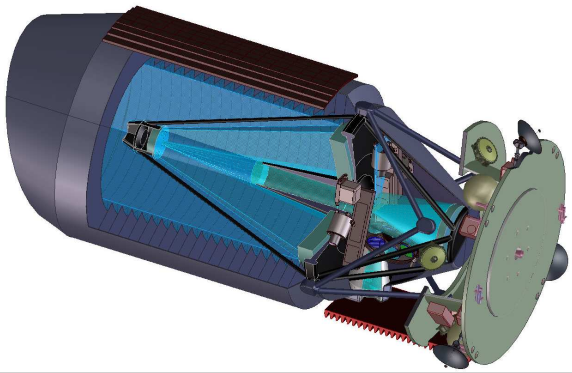
SNAP

- **~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.

Dedicated instrument designed to repeatedly observe an area of sky.

Essentially no moving parts.

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



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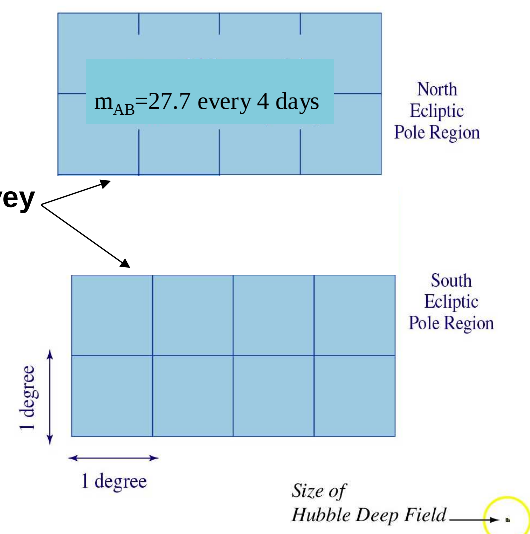
SNAP Survey Fields

SNAP



15 sq.deg. deep survey

300 sq.deg. wide weak lensing survey

Co-added images: m_{AB} = 31.0 !

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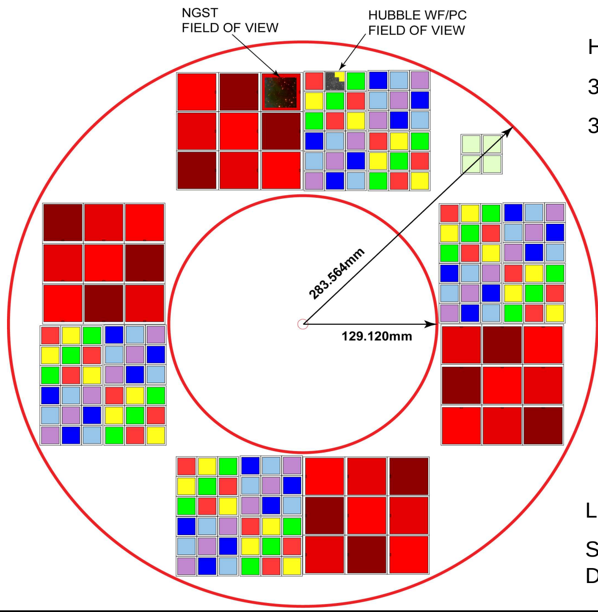
Focal Plane Layout with Fixed Filters



Half billion pixel array

36 optical CCDs

36 near infrared detectors

Larger than Sloan camera

Smaller than HEP Vertex Detector

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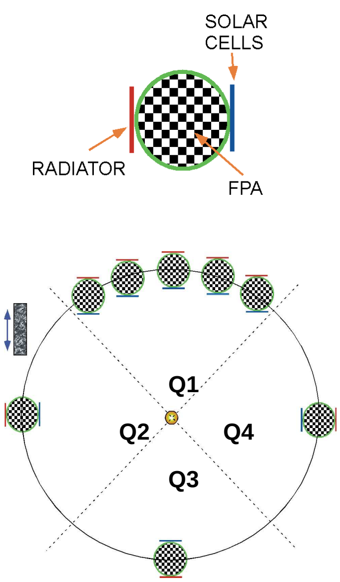
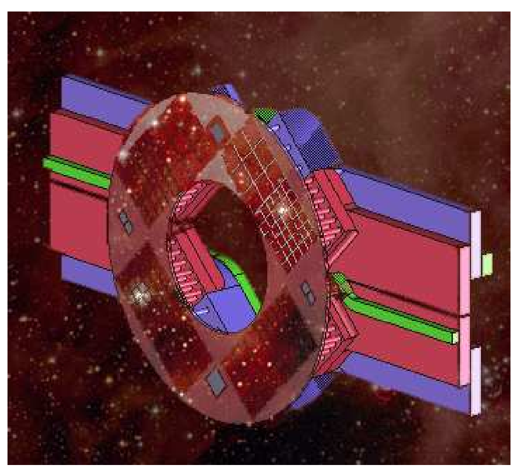
Step and Stare and Rotation





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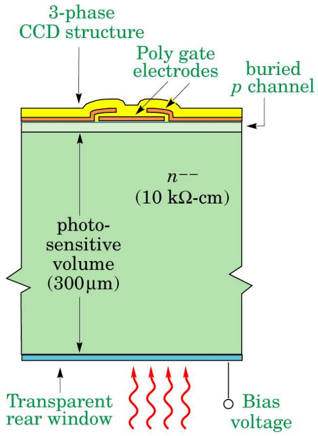
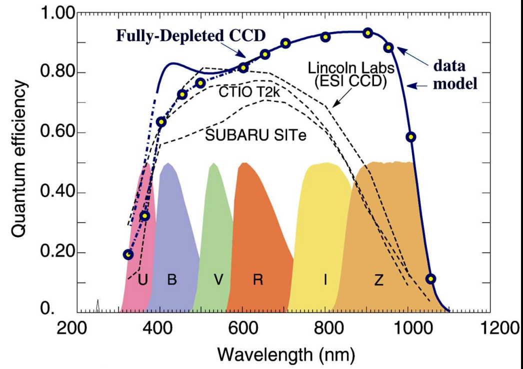
New Technology CCD's

SNAP

- New kind of CCD developed at LBNL
- Better overall response than more costly "thinned" devices in use
- High-purity silicon has better radiation tolerance for space applications
- The CCD's can be abutted on all four sides enabling very large mosaic arrays
- Measured Quantum Efficiency at Lick Observatory (R. Stover):





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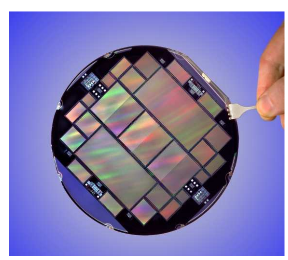
LBNL CCD's at NOAO

SNAP

Cover picture taken at WIYN 3.5m with LBNL 2048 x 2048 CCD (Dumbbell Nebula, NGC 6853)

Science studies to date at NOAO using LBNL CCD's:

1) Near-earth asteroids
2) Seyfert galaxy black holes
3) LBNL Supernova cosmology



Blue is H-alpha
Green is SIII 9532Å
Red is HeII 10124Å.

See September 2001 newsletter at http://www.noao.edu

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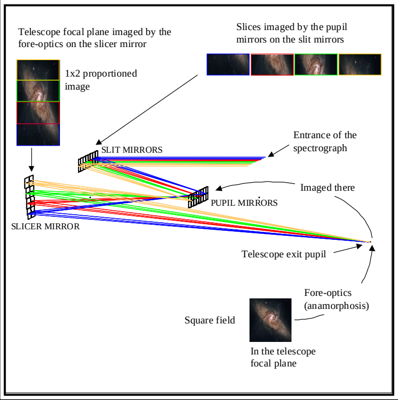
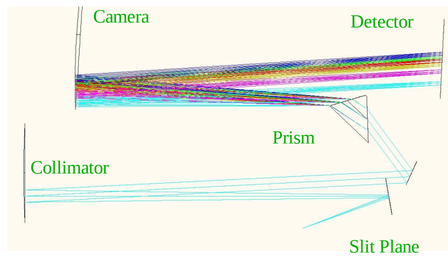
Integral Field Unit Spectrograph Design

Spectrograph architecture	Integral field spectrograph
Wavelength coverage	350-1700nm
Spatial resolution of slicer	0.12 arcsec
Field-of-View	2" x 2"
Detector Architecture	1k x 1k, HgCdTe
Detector Array Temperature	130 - 140 K
Throughput	35%
Read Noise	4 e- (multiple samples)
Dark Current	1 e-/min/pixel



SNAP Design:



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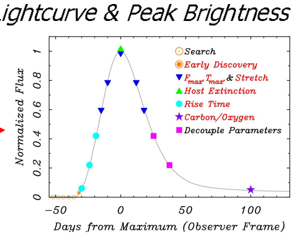
What makes the SN measurement special? Control of systematic uncertainties

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

Lightcurve & Peak Brightness

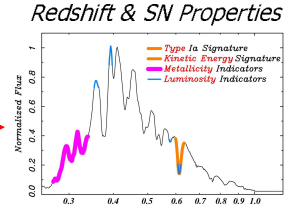
Images



Ω_M and Ω_Λ
Dark Energy Properties

Redshift & SN Properties

Spectra



data → **analysis** → **physics**

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Science Reach

SNAP

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 known, $w = const.$					0.02	<0.01		
Ω_M known, $w(z) = w + w'z$					0.08	<0.01	0.12	0.15

Key Cosmological Studies
- Type II supernova
- Weak lensing
- Strong lensing
- Galaxy clustering
- Structure evolution
- Star formation/reionization

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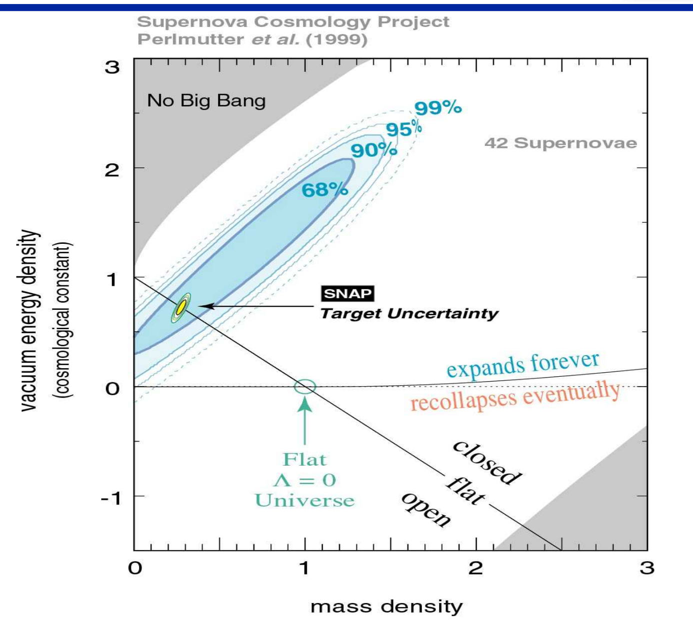
SNAP: The Third Generation

SNAP



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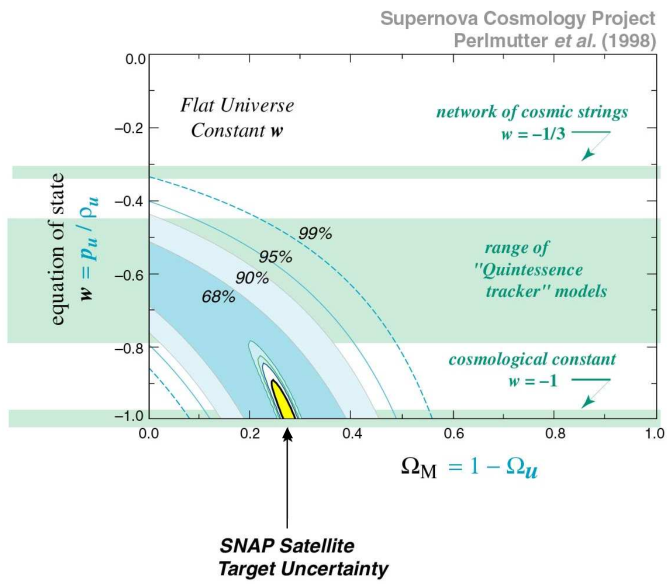
Dark Energy Equation of State

SNAP

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



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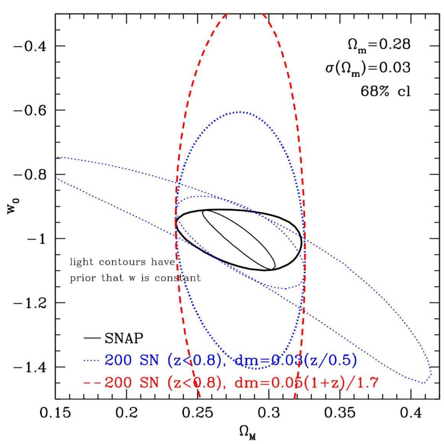
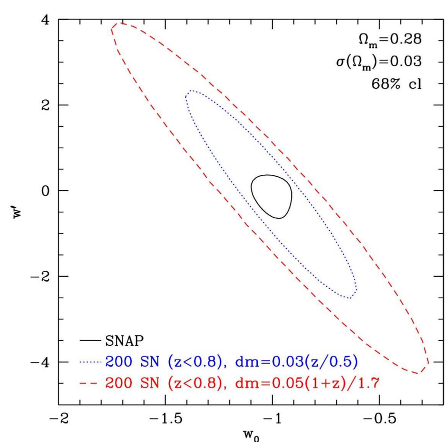
From Ground to Space

SNAP





SNAP Cosmology Fitting
Working Group

Deep SN surveys represent a major advance in understanding dark energy

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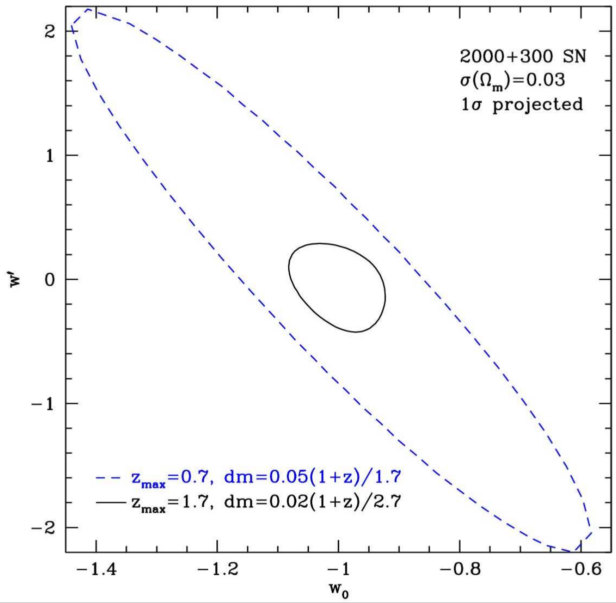
From Ground to Space



Deep SN surveys represent a major advance in understanding dark energy

SNAP Cosmology Fitting Working Group

in Linder & Huterer 2002 astro-ph/0208138

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Parametrization of Dark Energy EOS

Equation of state w generically is not constant but has evolution *w(z)*.

Time variation w´ is a critical clue to fundamental physics.

How do we parameterize it?

Linear approximation only good at low redshifts:

$$w(z)=w_0+w_1 z$$

Deep surveys, e.g. to $z=1.7$, strain the approximation.

And what about matching to CMB constraints from $z_{lss}=1100$?

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New Parametrization for Dark Energy EOS

New parametrization

$$w(a)=w_0+w_a\,(1-a)$$

Linder 2002
astro-ph/0208512

- Model independent parametrization
- Only 2D phase space
- Well behaved at high z
- Simple physical interpretation
- More accurate reconstruction
- More sensitive to data!

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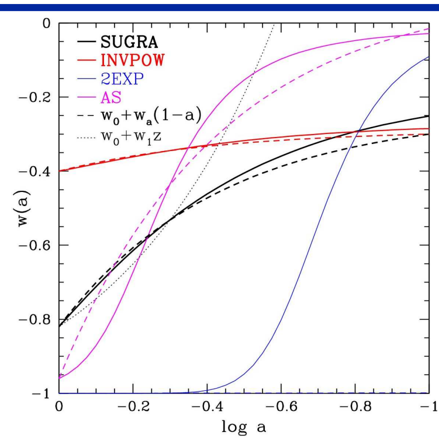
Evolving Equation of State



Linder 2002, astro-ph/0210217
following
Corasaniti & Copeland 2002

$$w(a) = w_0+w_a(1-a)$$

Even better approximation to true EOS!

Accurate to 3% in EOS back to $z=1.7$ (vs. 27% for w_1).

Accurate to 0.2% in distance back to $z_{lss}=1100$!

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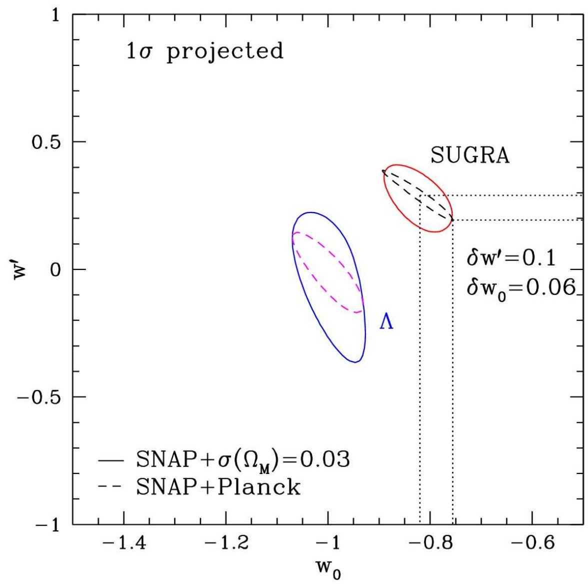
SN + CMB Complementarity



SNAP tightly constrains dark energy models.

SNAP+Planck have excellent complementarity, equal to a prior $\sigma(\Omega_M) \leq 0.01$.

Frieman, Huterer, Linder, & Turner 2002

SNAP+Planck can detect time variation w´ at 99% cl

(e.g. SUGRA).

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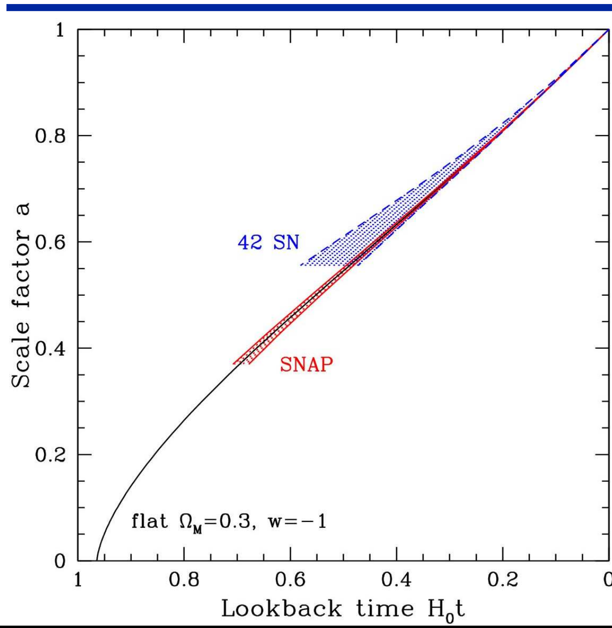
Expansion History of the Universe



SNAP will map the expansion history, uncovering physics just like the thermal history revealed early universe physics.

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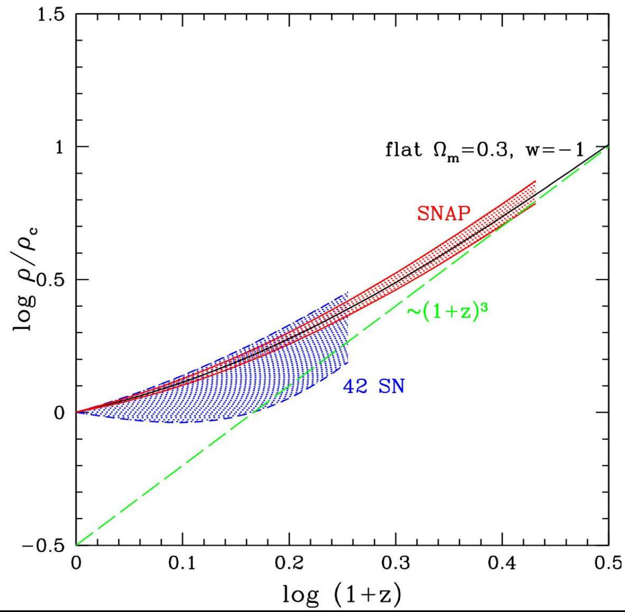
Density History of the Universe



SNAP will map the density history precisely, back to the matter dominated epoch.

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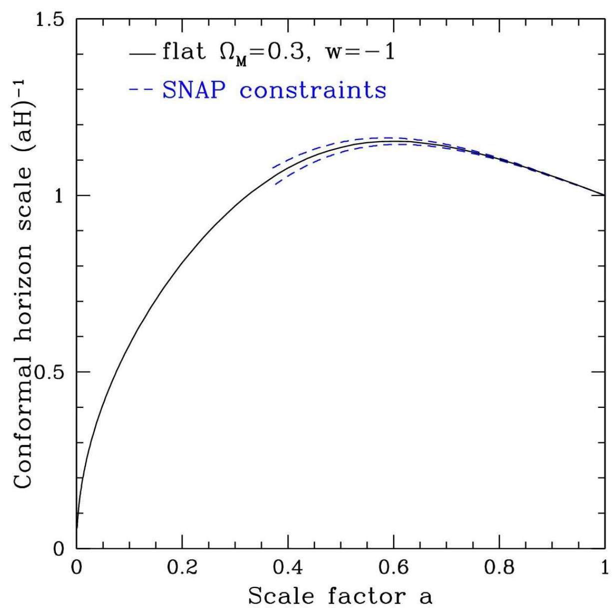
Present Day Inflation



SNAP will map the expansion history precisely and see the transition from acceleration to deceleration.

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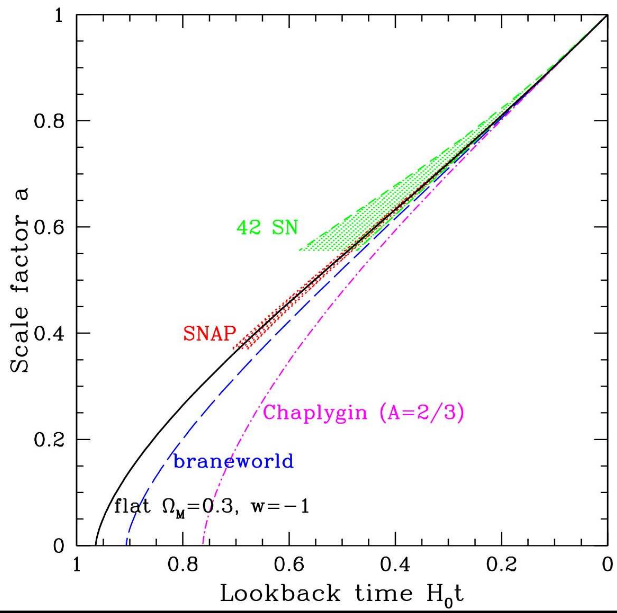
Beyond Dark Energy



SNAP can not only determine dark energy parameters, but test the cosmology framework – alternative gravitation, higher dimensions, etc.

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Primary Science Mission Includes…

Requiring complementary measurements of cosmological parameters, Dark Matter, Dark Energy,...

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

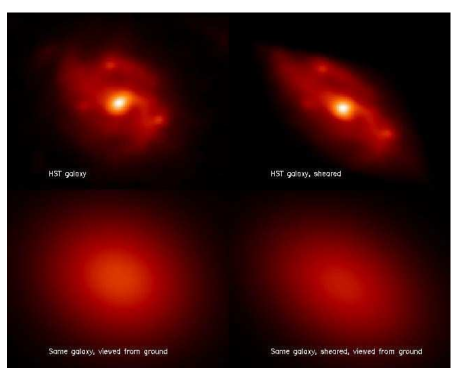
Type II supernova expanding photosphere:
Hubble diagram to $z = 1$ and beyond.

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

Weak lensing galaxy shear observed from space vs. ground



Bacon, Ellis, Refregier 2000

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..And Beyond

- 10 band ultradeep imaging survey
- Feed NGST, CELT (as Palomar 48” to 200”, SDSS to 8-10m)
- Quasars to z=10
- GRB afterglows to z=15
- Galaxy populations and morphology to coadd m=31
- Galaxy evolution studies, merger rate
- Stellar populations, distributions, evolution
- Epoch of reionization thru Gunn-Peterson effect
- Low surface brightness galaxies in H’ band, luminosity function
- Ultraluminous infrared galaxies
- Kuiper belt objects
- Proper motion, transient, rare objects

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

→ Guest Survey Program

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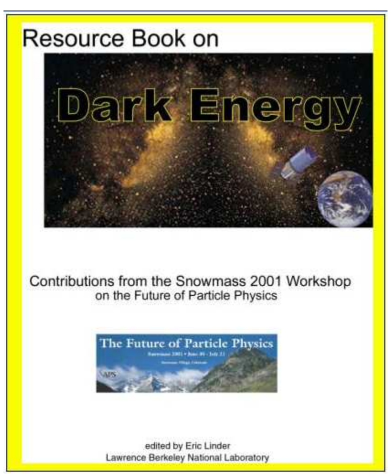
SNAP at Snowmass 2001



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SNAP at the American Astronomical Society Jan. 2002 Meeting

Oral Session 111. Science with Wide Field Imaging in Space:

The Astronomical Potential of Wide-field Imaging from Space	S. Beckwith (Space Telescope Science Institute)
Galaxy Evolution: HST ACS Surveys and Beyond to SNAP	G. Illingworth (UCO/Lick, University of California)
Studying Active Galactic Nuclei with SNAP	P.S. Osmer (OSU), P.B. Hall (Princeton/Catolica)
Distant Galaxies with Wide-Field Imagers	K. M. Lanzetta (State University of NY at Stony Brook)
Angular Clustering and the Role of Photometric Redshifts	A. Conti, A. Connolly (University of Pittsburgh)
SNAP and Galactic Structure	I. N. Reid (STScI)
Star Formation and Starburst Galaxies in the Infrared	D. Calzetti (STScI)
Wide Field Imagers in Space and the Cluster Forbidden Zone	M. E. Donahue (STScI)
An Outer Solar System Survey Using SNAP	H.F. Levison, J.W. Parker (SwRI), B.G. Marsden (CfA)

Oral Session 116. Cosmology with SNAP:

Dark Energy or Worse	S. Carroll (University of Chicago)
The Primary Science Mission of SNAP	S. Perlmutter (Lawrence Berkeley National Laboratory)
SNAP: mission design and core survey	T. A. McKay (University of Michigan
Sensitivities for Future Space- and Ground-based Surveys	G. M. Bernstein (Univ. of Michigan)
Constraining the Properties of Dark Energy using SNAP	D. Huterer (Case Western Reserve University)
Type Ia Supernovae as Distance Indicators for Cosmology	D. Branch (U. of Oklahoma)
Weak Gravitational Lensing with SNAP	A. Refregier (IoA, Cambridge), Richard Ellis (Caltech)
Strong Gravitational Lensing with SNAP	R. D. Blandford, L. V. E. Koopmans, (Caltech)
Strong lensing of supernovae	D.E. Holz (ITP, UCSB)

Poster Session 64. Overview of The Supernova/Acceleration Probe:

Supernova / Acceleration Probe: An Overview	M. Levi (LBNL)
The SNAP Telescope	M. Lampton (UCB)
SNAP: An Integral Field Spectrograph for SN Identification	R. Malina (LAMarseille,INSU), A. Ealet (CPPM)
SNAP: GigaCAM - A Billion Pixel Imager	C. Bebek (LBNL)
SNAP: Cosmology with Type Ia Supernovae	A. Kim (LBNL)
SNAP: Science with Wide Deep Fields	E. Linder (LBNL)

Look for SNAP Special Session at 201st AAS, Jan. 2003

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Resource for the Science Community

For Cosmologists

- Mapping the expansion history of the universe through the accelerating phase back into the decelerating epoch
- Precision determination of cosmological parameters

For Astronomers

- SNAP main survey will be 4000x larger (and as deep) than the biggest HST deep survey, the ACS survey
- Complementary to NGST: target selection for rare objects
- Can survey 300 sq. deg. in a year to J=28 (AB mag)
- Archive data distributed
- Guest Survey Program

Whole sky can be observed every few months

For Fundamental Physicists

- Exploring the nature of dark energy
- Testing higher dimension theories
- Testing alternate theories of gravitation

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