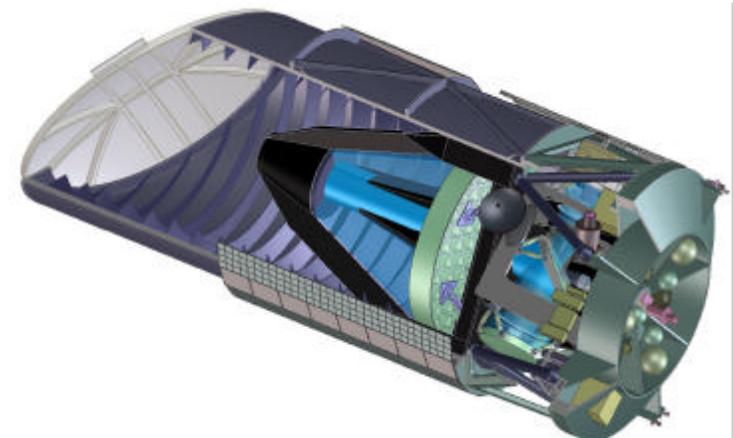
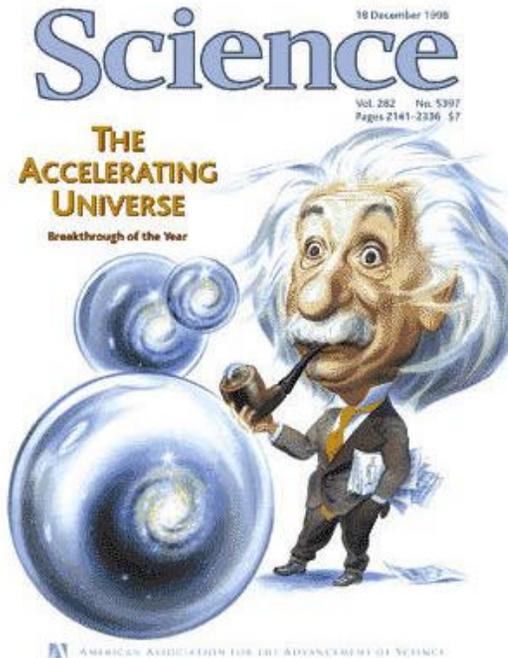

Mapping the History and Fate of the Universe

Frontiers in Science, FAU

Eric Linder

Lawrence Berkeley National Laboratory



Our Expanding Universe



Our Expanding Universe



The Big Bang and Expanding Universe

Space is expanding from an initial moment called the Big Bang. As it expands, the universe cools and becomes less dense. All distant galaxies are moving apart from each other and away from us. On large scales, the universe looks the same in all directions and all parts of space. There is no preferred center. Our current understanding of the early universe is called the Big Bang model. Much more will be learned from astronomical observations and from accelerator-based experiments in the coming years.

Cosmology and Relics of History

Cosmology is the study of the universe as a whole. As an archeologist, cosmology finds clues to the past in relics. Looking out a distance d in space is looking back in time, because $v = dc$ (light travels at a finite speed c). The laws of nature discovered on Earth can be applied to the early universe and tested by observing relics.

A Relic from the Early Universe
The Cosmic Microwave Background (CMB) is a universal bath of lightwaves (photons) from the hot dense, early universe. They are stretched by the expansion of space. To a part in 100,000, the CMB is the same as matter, where you look (in its spectrum). The remaining tiny variations (shown in figure) are imprints of the seeds that later form galaxies and larger cosmic structures.

Age of the Universe A marvelous agreement that the age of the universe is about 14 billion years comes from studying its expansion and the lifetimes of stars and also by dating meteorites.

History of the Universe

Three major eras in the expansion history followed the hot, dense condition of the earliest universe. During each era, the expansion depended on the nature of the matter or energy that dominated the universe at that time.

Era 1 - Acceleration: Inflation speeds expansion.
Observations seem to imply that the very early universe underwent an extremely rapid, accelerating expansion called **inflation**. In a tiny fraction of a second, inflation expanded each part of space by a factor of at least 10^{27} . Before inflation, the portion of the universe visible to us today was a smooth patch much smaller than a proton. As inflation ended, the visible universe had grown to the size of a ball (very approximately). Inflation explains how quantum fluctuations in the otherwise smooth and isotropic universe yielded tiny ripples that would eventually grow into galaxies and structures. In the 14 billion years after inflation, the universe expanded by another factor of about 10^{27} .

Eras 2-3 - Deceleration: Expansion slows and structures form.
After inflation, the universe was a jumble of fundamental particles. Photons and fast moving particles, generically called **radiation**, gradually lost energy (cooled) as the universe expanded (the energy went into the expansion). Eventually, slow-moving matter became dominant over radiation. Over time, larger and larger structures grew from galaxies to clusters of galaxies to superclusters. These began as small differences in the density of matter, but gravitational attraction made more and more matter clump together. Several interesting stages are indicated in the central figure. Stars created the lightest elements that eventually became part of Earth and of us. The early universe had both matter and antimatter in abundance, but today it is almost exclusively matter. How this came about is not fully understood.

Era 4 - Acceleration: Dark energy speeds expansion.
A mysterious, unknown universe cause (acceleration) and might even reverse the expansion. So it was a great surprise in 1998 when observations showed that the expansion of the universe is now accelerating (see the "Expansion History" plot). This implies the existence of a new form of energy, referred to as **dark energy**. Scientists are pursuing the nature of dark energy.

Our Cosmic Address

Our sun is one of 400 billion stars in the Milky Way galaxy, which is one of more than 100 billion galaxies in the visible universe.

THE HISTORY AND FATE OF THE UNIVERSE

Eight major stages in the evolution of the universe are illustrated below. The Big Bang occurred everywhere in the universe. Here one region has been illuminated and followed through time. The expansion is far greater than can be shown here.

ERA 1 Time: 10^{-44} s to 10^{-32} s. Unknown. Particles: photon, antiquark, lepton, quark, gluon, W-boson, Z-boson, neutrino, electron, muon, tau, photon.

ERA 2 Nucleons form: 10^{-4} s. Particles: antiquark, quark, nucleon, photon, electron, muon, tau, neutrino.

ERA 3 Atoms form: 3×10^5 yr. Particles: nucleus (anti), nucleus, photon, electron, muon, tau, neutrino.

ERA 4 First Stars and Galaxies form: 3×10^8 yr. Particles: photon, nucleus, electron, muon, tau, neutrino.

Today: 14×10^9 yr. Particles: photon, nucleus, electron, muon, tau, neutrino.

Redshifts and Expansion

Lightwaves stretch with the expansion of space. As the wavelength of visible light increases, it becomes redder (as shown for the photons in the central figure). Measuring this redshift tells us the velocity of the source. In 1929, Hubble discovered that all distant objects are receding with a velocity proportional to their distance. This information and modern telescope observations show that the universe is expanding uniformly in all directions. Objects that are bound together (such as galaxies and stars) do not expand as space expands.

The same bread represents a portion of the universe, and the holes represent galaxies. Due to the stretching of the bread, the distance of spots, even though they are near each other, does not expand as space expands.

Expansion History of the Universe

The large plot shows data from Type Ia supernovae explosions that occurred in the past 9 billion years. Measurements of these supernovae show an accelerating expansion began billions of years ago. The yellow figure is the best fit to the data. The smaller plot emphasizes the extremely early universe.

Fate of the Universe

Whether the expansion of the universe will speed up, slow down, or even possibly reverse into collapse depends through gravity on the amount and types of matter and energy in it.

The ordinary matter - atoms and nuclei - that formed in the early universe can account for the visible mass in galaxies and clusters. But it falls far short of the total mass needed to hold them together gravitationally and explain their internal motions. So an extraordinary new type of matter, not made of atoms or nuclei, must exist; it is called **dark matter** because it is not directly visible.

Each stranger, more accelerating observations of supernovae in distant galaxies show that the expansion of the universe is in fact **accelerating**. An exotic **dark energy** may be causing this acceleration through a cosmic repulsion that overwhelms the pull of gravity due to matter.

The nature of dark energy and dark matter are two of the great questions facing cosmology and particle physics. Perhaps dark energy is the cosmological constant, introduced by Einstein in 1917. Perhaps both are new parts of particle physics, just to the very earliest moments of the universe and having to do with the nature of physics and spacetime itself.

Not all answers in science are known yet! With the research and experiments under way in astrophysics and particle physics, we may be the first generation to learn what most of the universe is made of and what is the fate of the universe.

Learn more at UniverseAdventure.org and at CPEPweb.org

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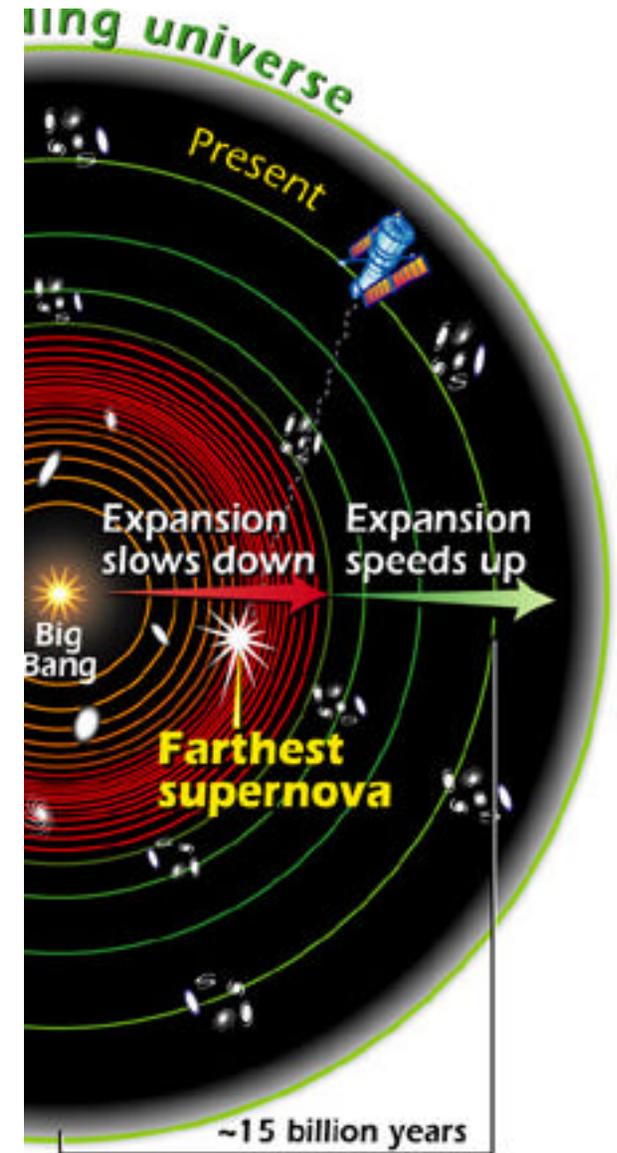
Our Expanding Universe



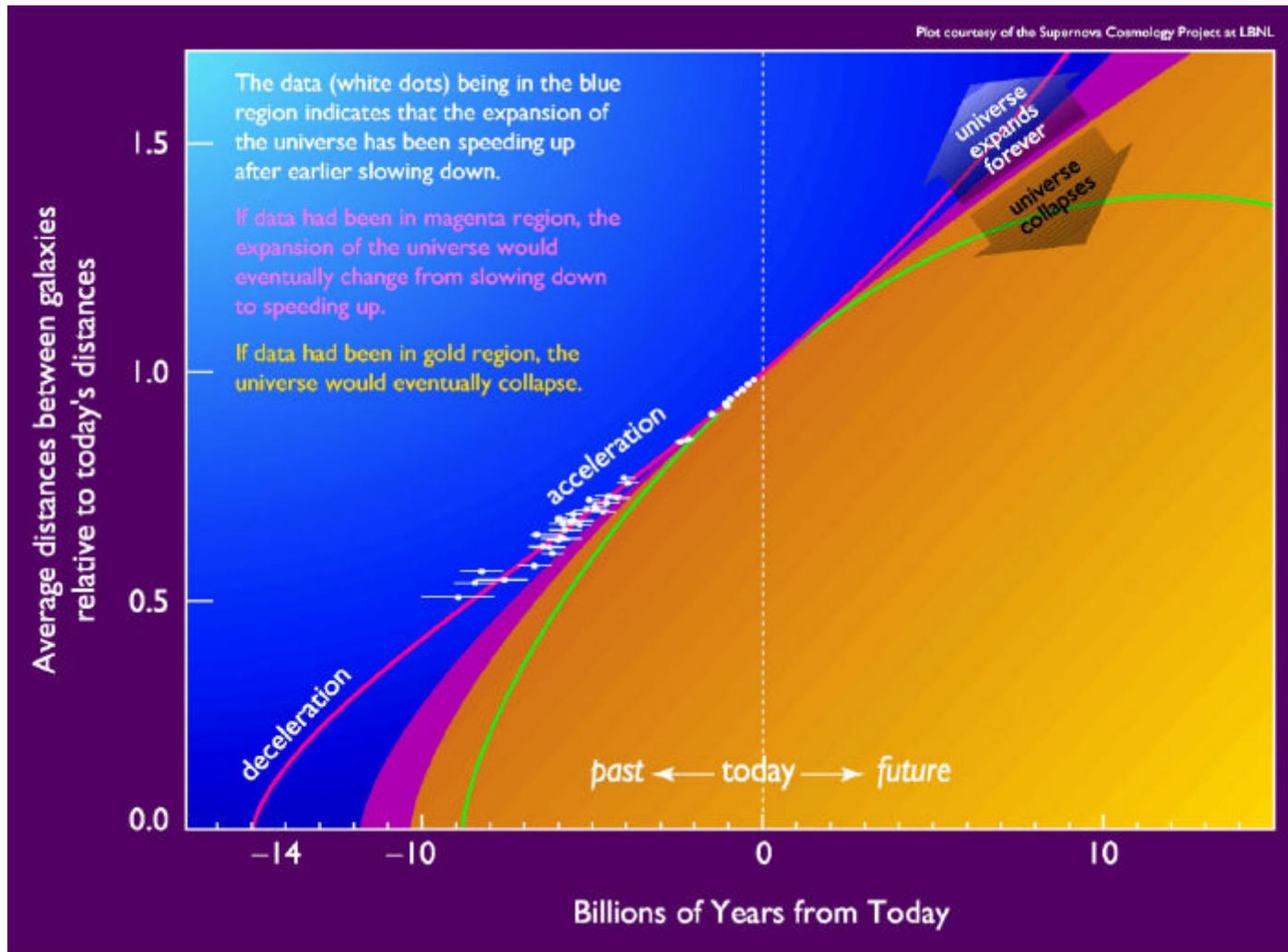
Mapping Our History



The subtle slowing down and speeding up of the expansion, of distances with time: $a(t)$, maps out cosmic history like tree rings map out the Earth's climate history.



Discovery! Acceleration



**Barnett,
Linder,
Perlmutter, &
Smoot,
for the
Office of the
President's
Science
Adviser**



Exploding stars – **supernovae – are bright beacons that allow us to measure precisely the expansion over the last 10 billion years.**

Discovery! Acceleration

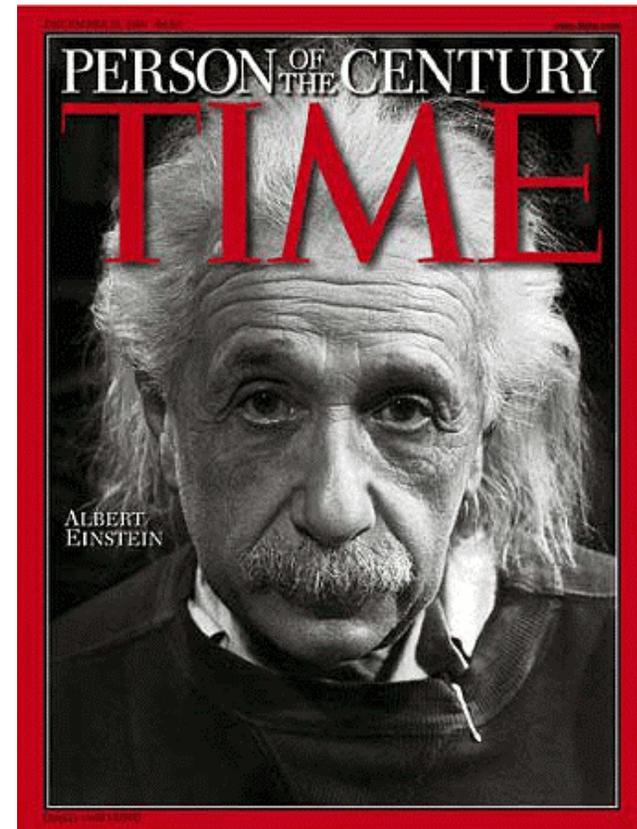


In 1998, the Supernova Cosmology Project discovered the expansion was speeding up

– but gravity pulls things together and should slow the expansion. What is counteracting gravity?

Einstein said that energy contributes to mass:

$$E=mc^2$$



Gravitation



$$E=mc^2$$

Gravity arises from all energy, not just the usual mass.

The pressure P of a substance affects the gravity, but this is usually very tiny (because the speed of light c is large, so mc^2 is much bigger than P).

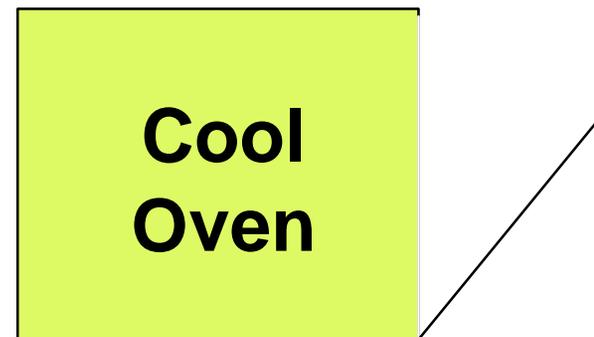
But doesn't this just add to the gravity? Unless the pressure is negative.

Negative pressure



What does negative pressure mean?

When something expands, it usually cools (loses energy).



But if you expand (stretch) a spring, it gains energy.

Antigravity?



Quantum physics predicts that the very structure of spacetime should act like springs.

Space has a “**stretchiness**”.

This gives a negative pressure. Add this to the usual mass (galaxies, stars). If there's enough quantum stuff, it will win out, and the universe will act like the total mass is negative!

Is this antigravity? **No.**

No – it's gravity just as Einstein predicts it, but since it acts like negative mass, it doesn't bring galaxies together, it pulls them apart.

Dark Energy



Normal gravity is attractive. This is repulsive.

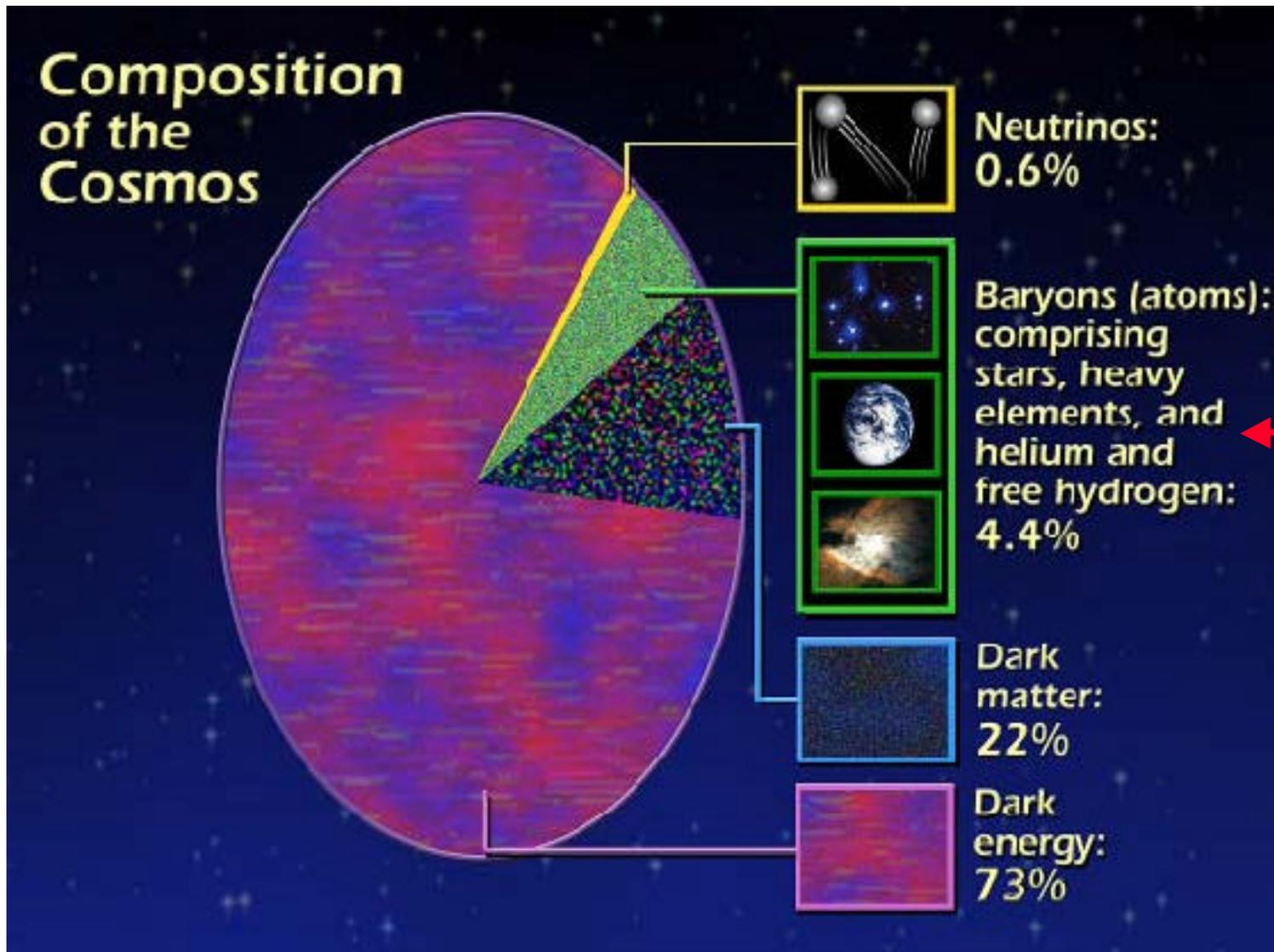
(Not being judgmental, so call it:)

Dark Energy

Dark energy speeds up the expansion of the universe. By measuring the acceleration using our tree ring (supernova) method, we find that dark energy makes up ~75% of the universe!

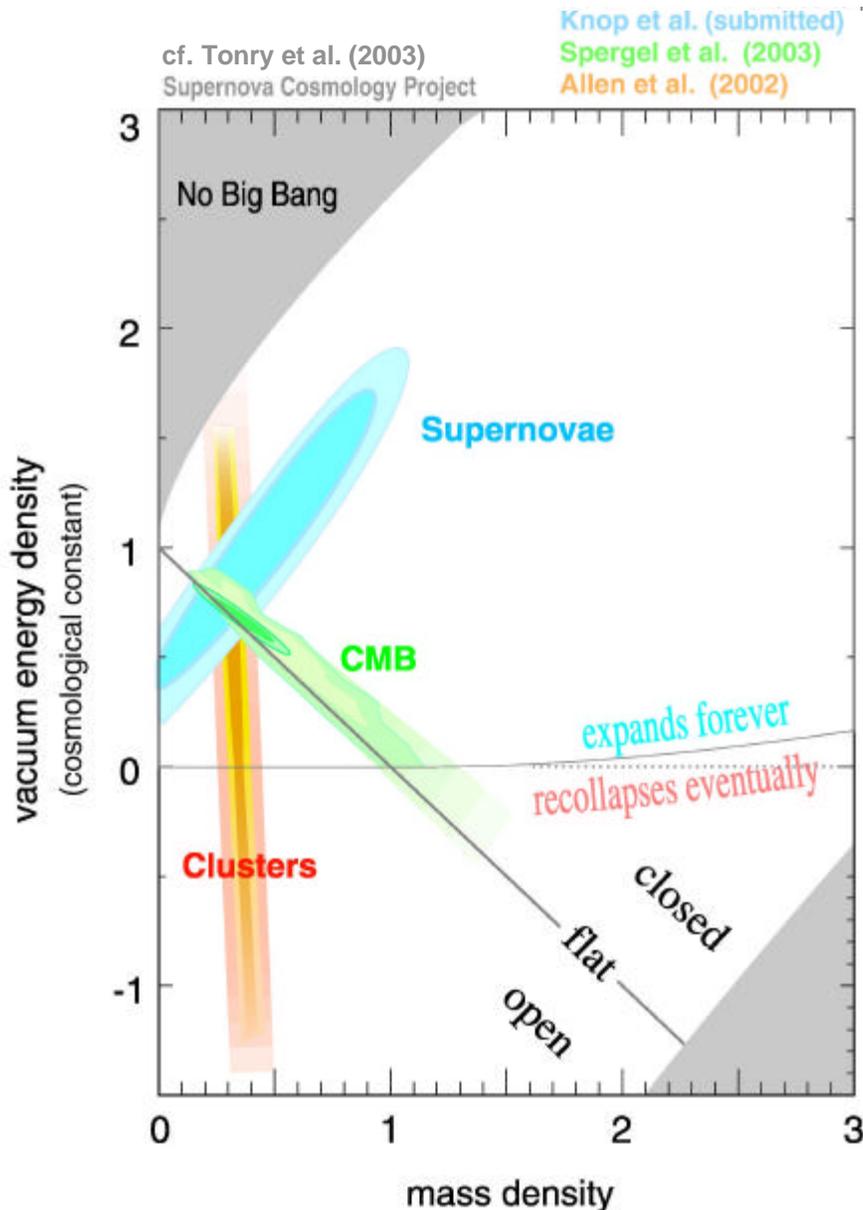
Because it dominates over the matter contents (which make up only ~25%), dark energy will govern the expansion, and the fate of the universe.

Frontiers of Cosmology



95% of the universe is unknown!

Cosmic Concordance



- *Supernovae alone*

- ↳ Accelerating expansion

- ⇒ $L > 0$

- *CMB alone*

- ↳ Flat universe

- ↳ $L > 0$

- *Any two of SN, CMB, LSS*

- ↳ Dark energy ~75%

Dark Energy Is...



- 75% of the energy density of the universe
- Accelerating the expansion, like inflation did when the universe was only 10^{-35} seconds old
- Determining the fate of the universe

But what is it?

Einstein considered something like it when he first invented general relativity. He wanted just enough negative pressure to balance the mass, so the universe would be static. He called it the **cosmological constant**, but abandoned it later when observations showed the universe *was* expanding.

What's the Matter with Energy?



Why not just bring back the cosmological constant (L)?

When physicists calculate how big L should be, they don't quite get it right.

They are off by a factor of

1,000,000,000,000,000,000,000,000,000,000,000,
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What's the Matter with Energy?



This is modestly called the **fine tuning** problem.

But it gets worse: because the cosmological constant is constant, it is the same throughout the history of the universe.

Why didn't it take over the expansion billions of years ago, before galaxies (and us) had the chance to form?

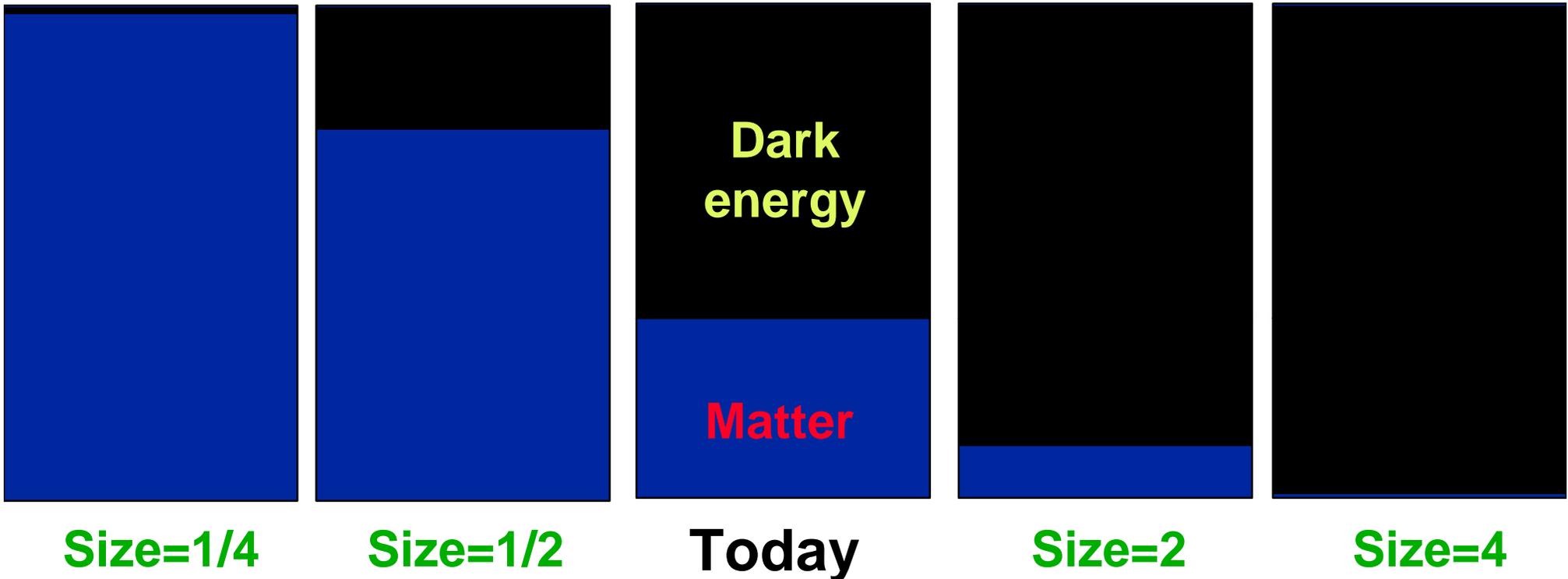
Or why didn't it wait until the far future, so today we would never have detected it?

This is called the **coincidence** problem.

Cosmic Coincidence?



Think of the energy in L as the level of the quantum “sea”. At most times in history, matter is either drowned or dry.



On Beyond L!



On beyond L! It's high time you were shown
That you really don't know all there is to be known.

-- à la Dr. Seuss, *On Beyond Zebra*

We need to explore further frontiers in high energy physics, gravitation, and cosmology.

New quantum physics?

Quintessence (atomic particles, light, neutrinos, dark matter, and...)

New gravitational physics?

Quantum gravity, supergravity, extra dimensions?

We need new, highly precise data

Type Ia Supernovae

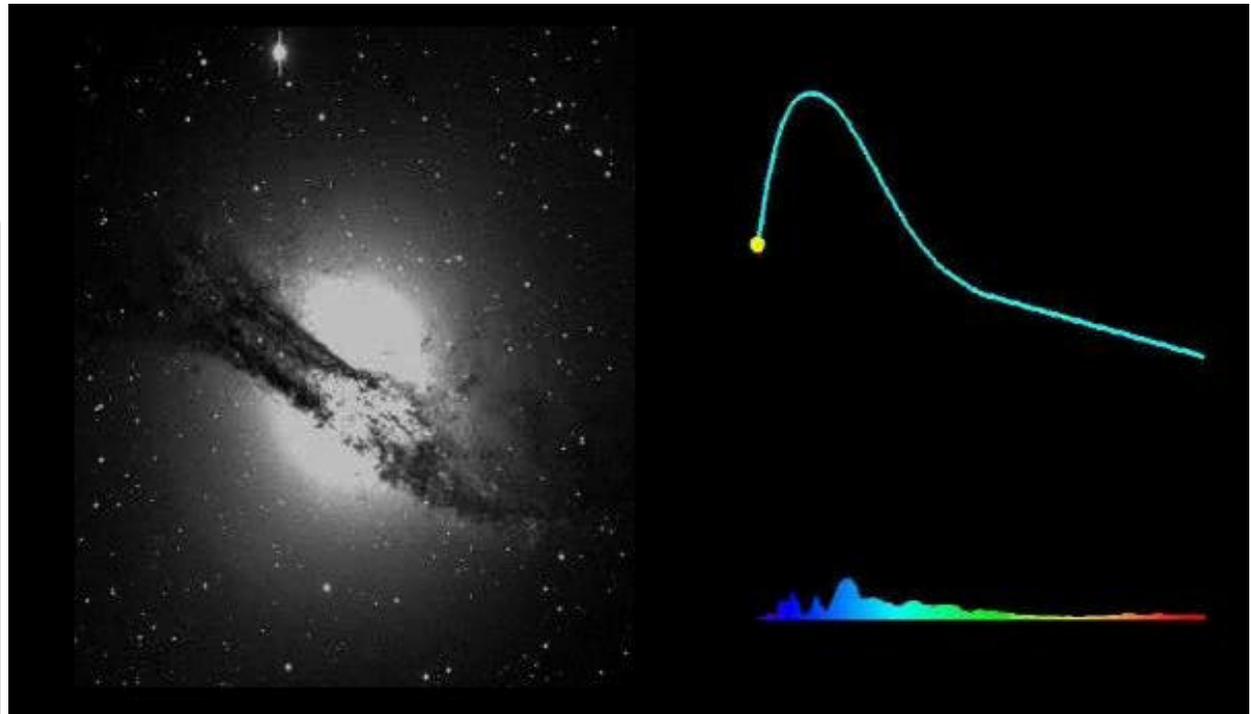
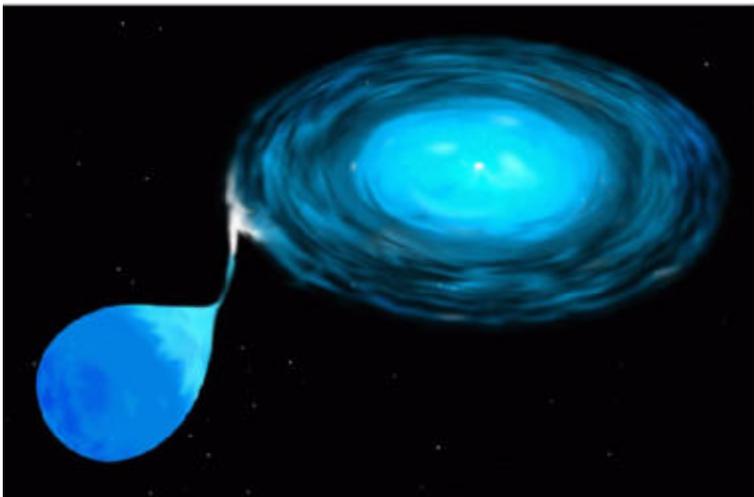


- Exploding star, briefly as bright as an entire galaxy
- Characterized by no Hydrogen, but with Silicon
- Gains mass from companion until undergoes thermonuclear runaway

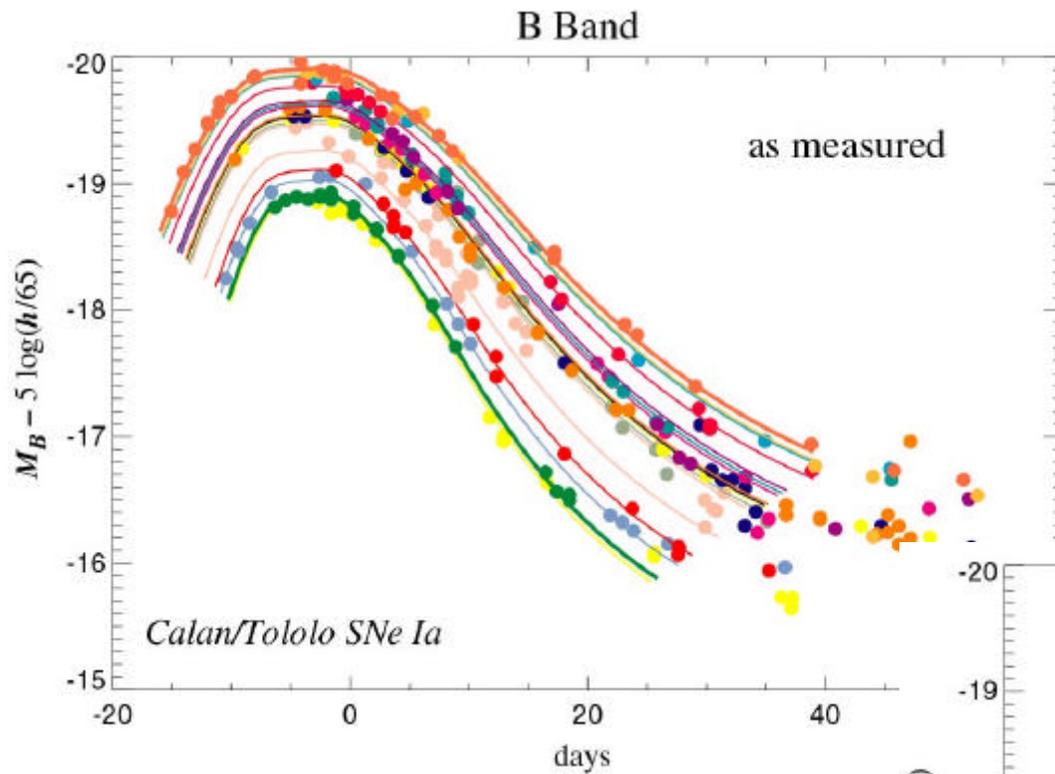
Standard explosion from nuclear physics

Insensitive to initial conditions:
“stellar amnesia”

Höflich, Gerardy, Linder, & Marion
2003

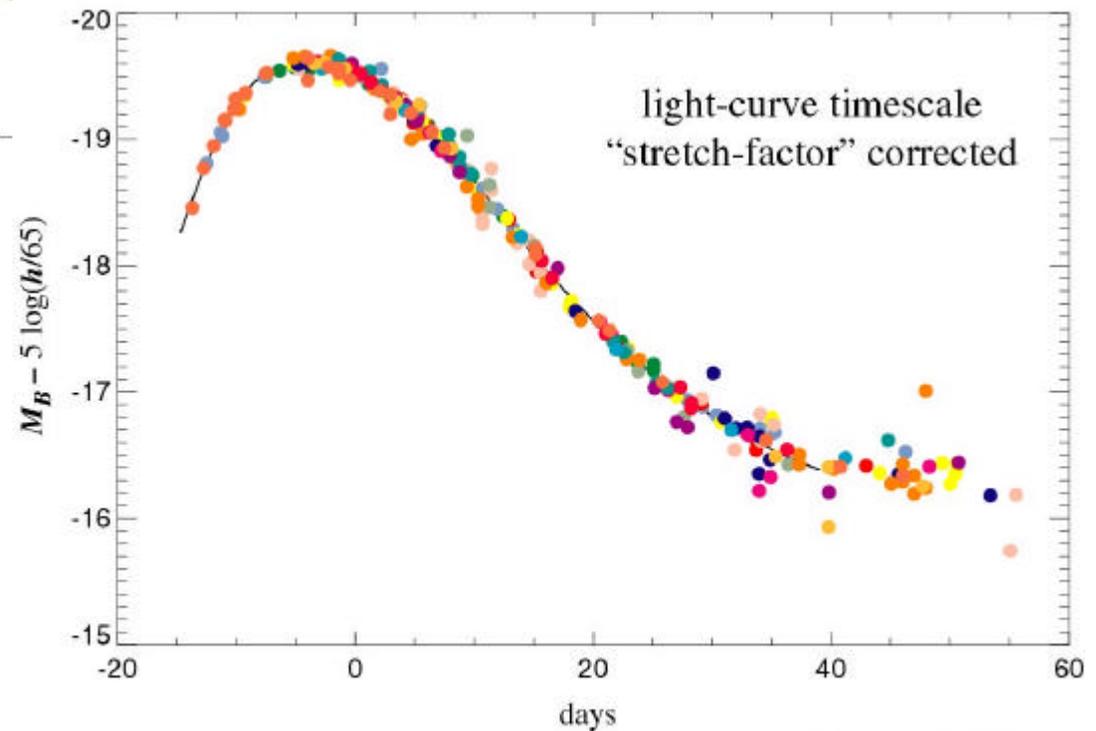


Standard Candle



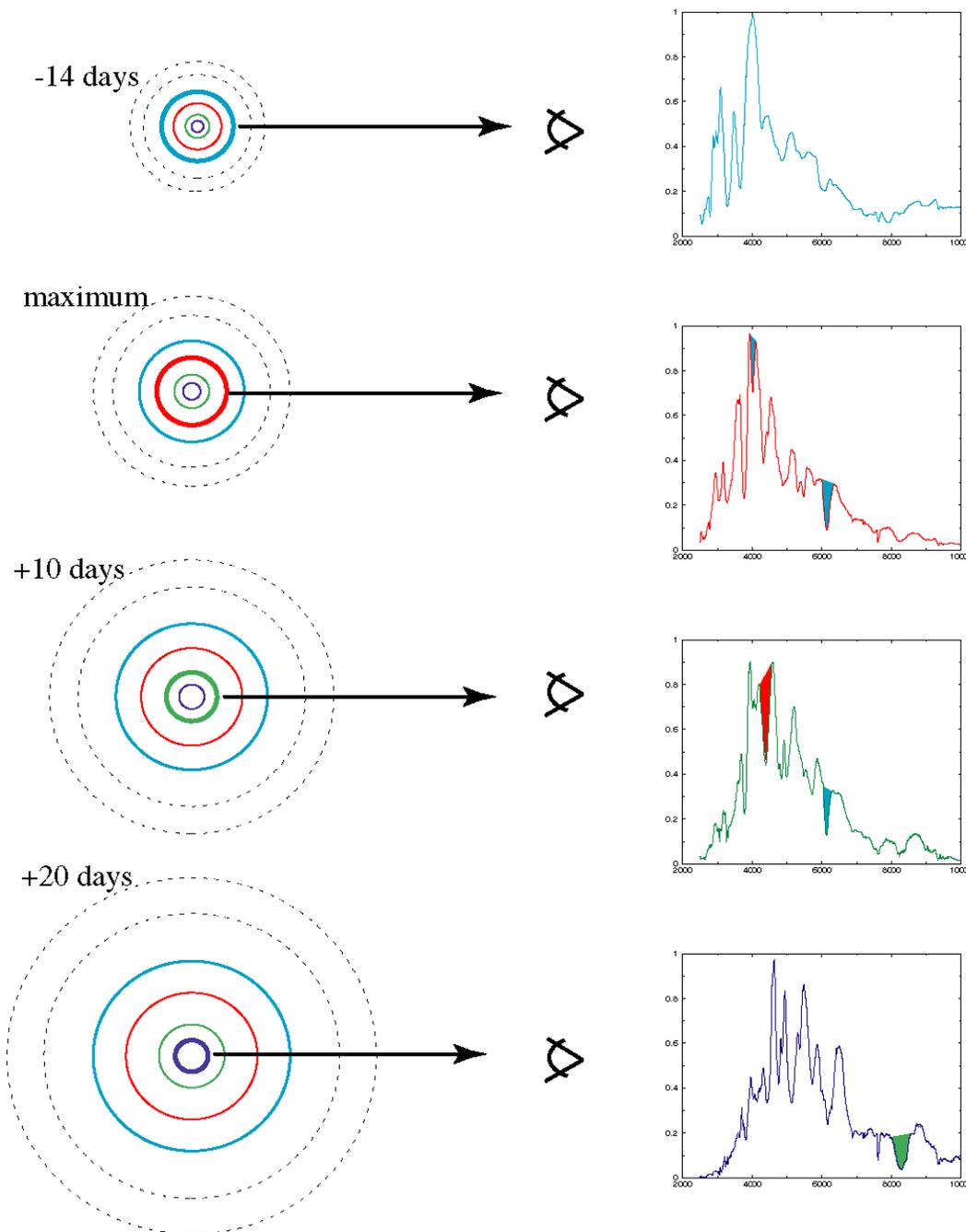
Brightness

Time after explosion



Kim, *et al.* (1997)

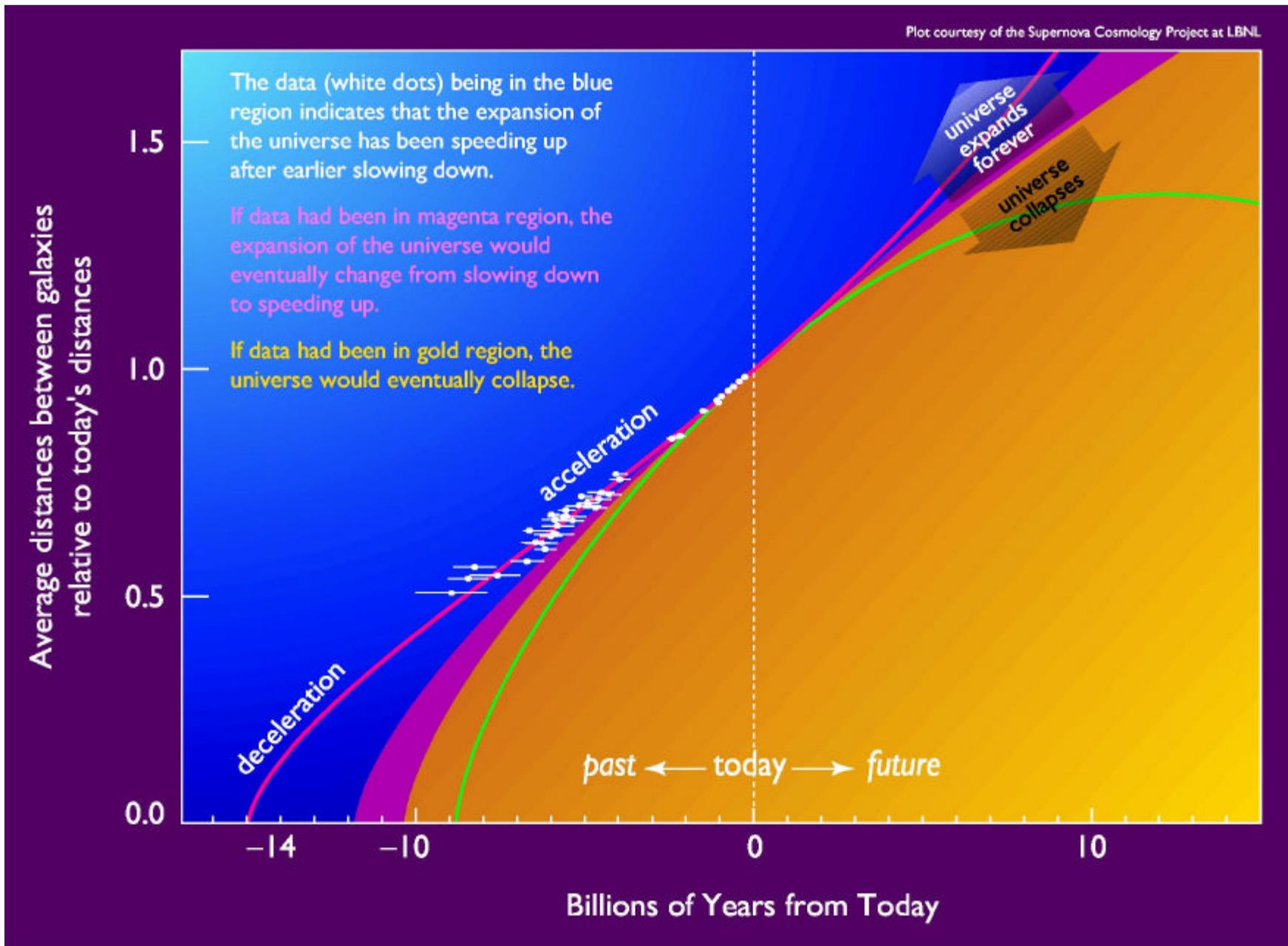
Supernova “CAT Scan”



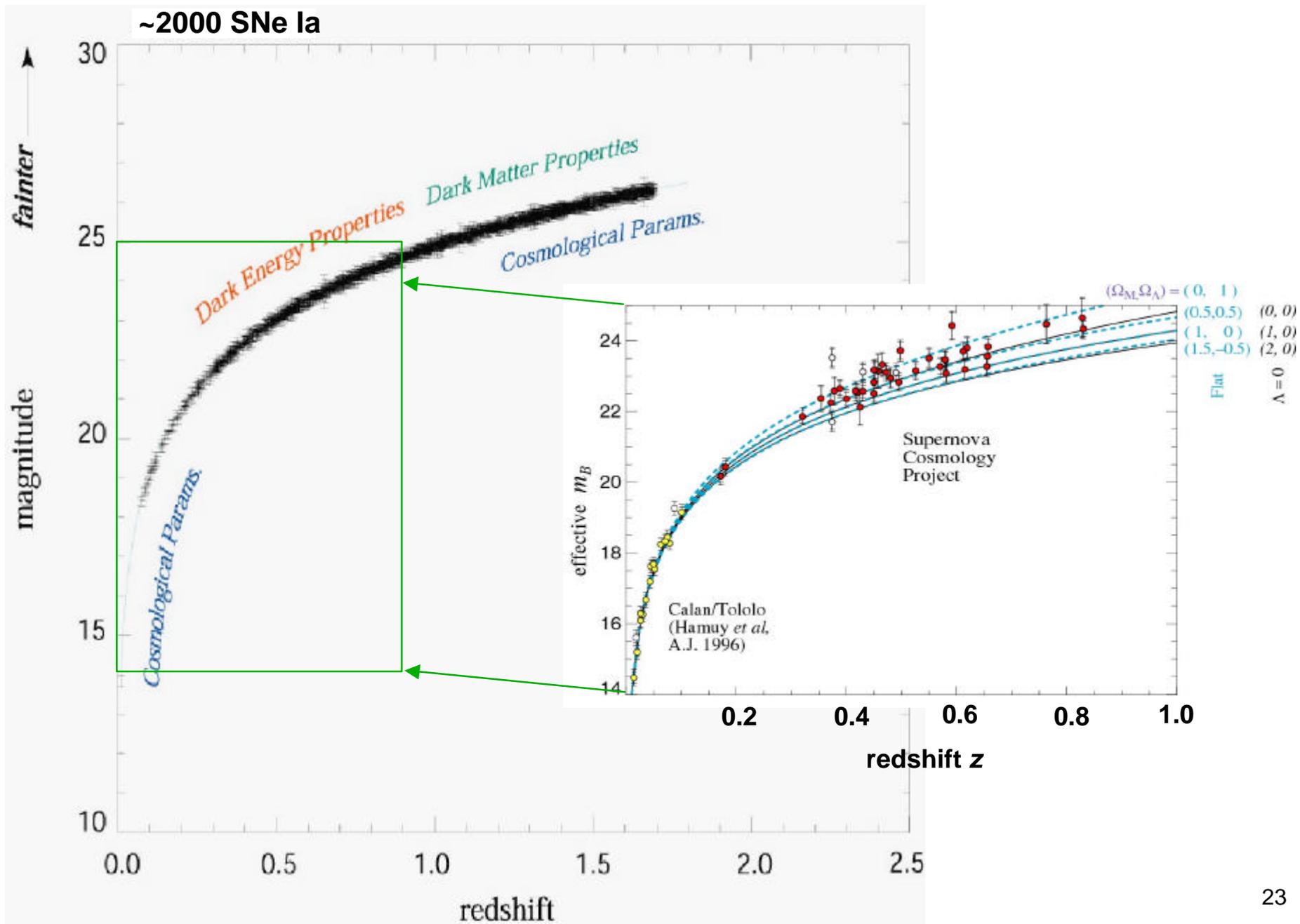
The energy spectrum of a supernova tells us in fine detail about its origin and properties.

Over time the SN atmosphere expands and thins, allowing us to see every layer.

History & Fate



Hubble Diagram



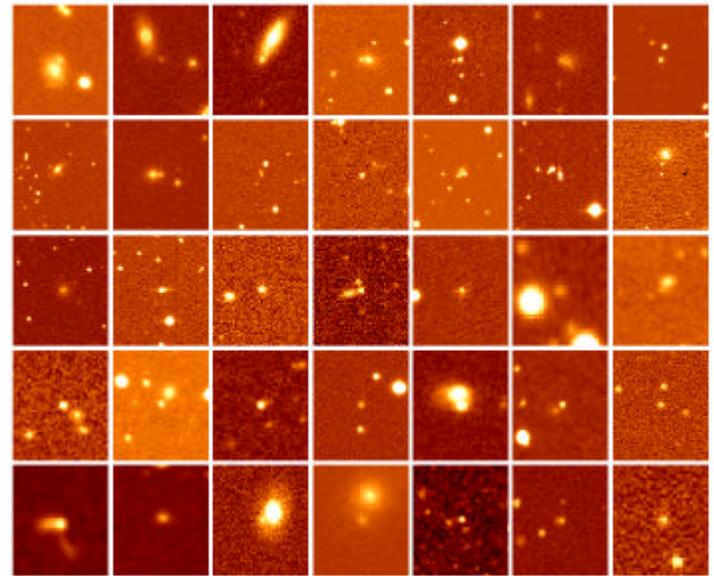
Understanding Supernovae



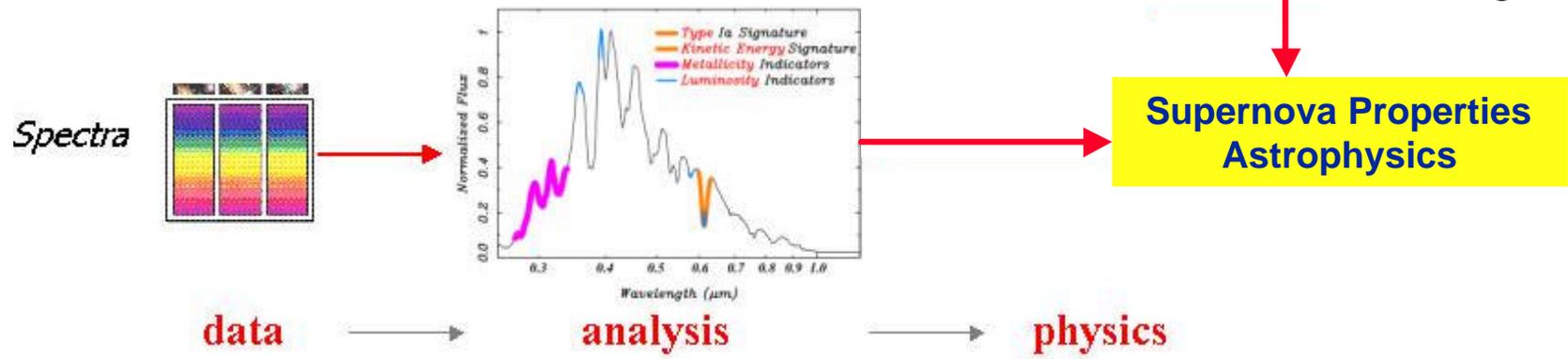
Nearby Supernova Factory

Best rookie year ever: 37 SNe (2002)

Leading the world in 2003: 44 SNe + ...



G. Aldering (LBL)

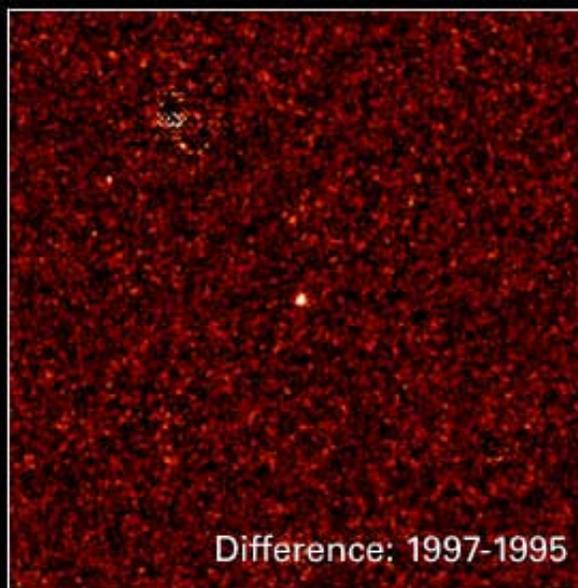
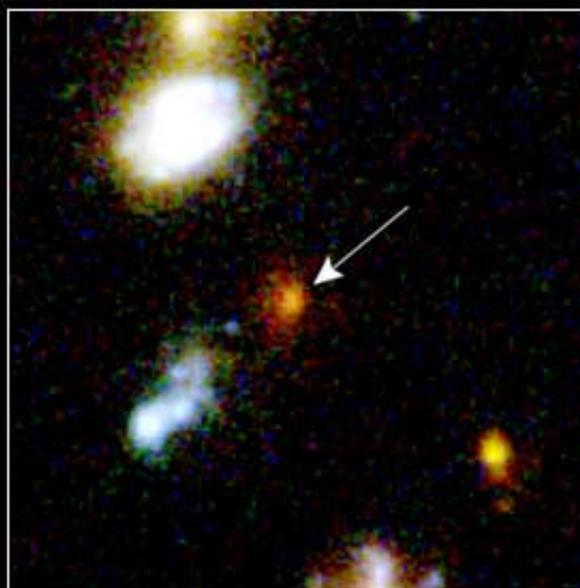


Cleanly understood astrophysics leads to cosmology

Looking Back 10 Billion Years

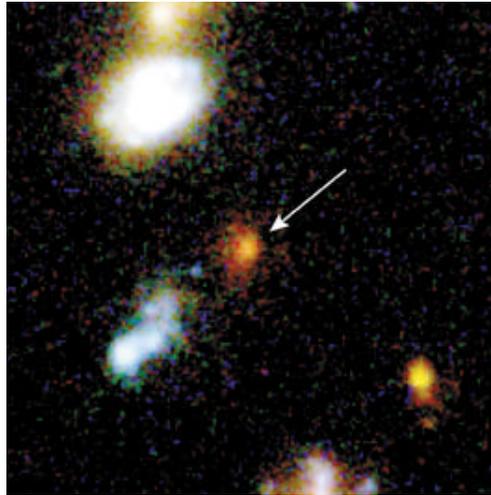


Looking Back 10 Billion Years



Distant Supernova in the Hubble Deep Field HST • WFPC2
NASA and A. Riess (STScI) • STScI-PRC01-09

Looking Back 10 Billion Years



To see the most distant supernovae, we must observe from space.

A Hubble Deep Field has scanned 1/25 millionth of the sky.

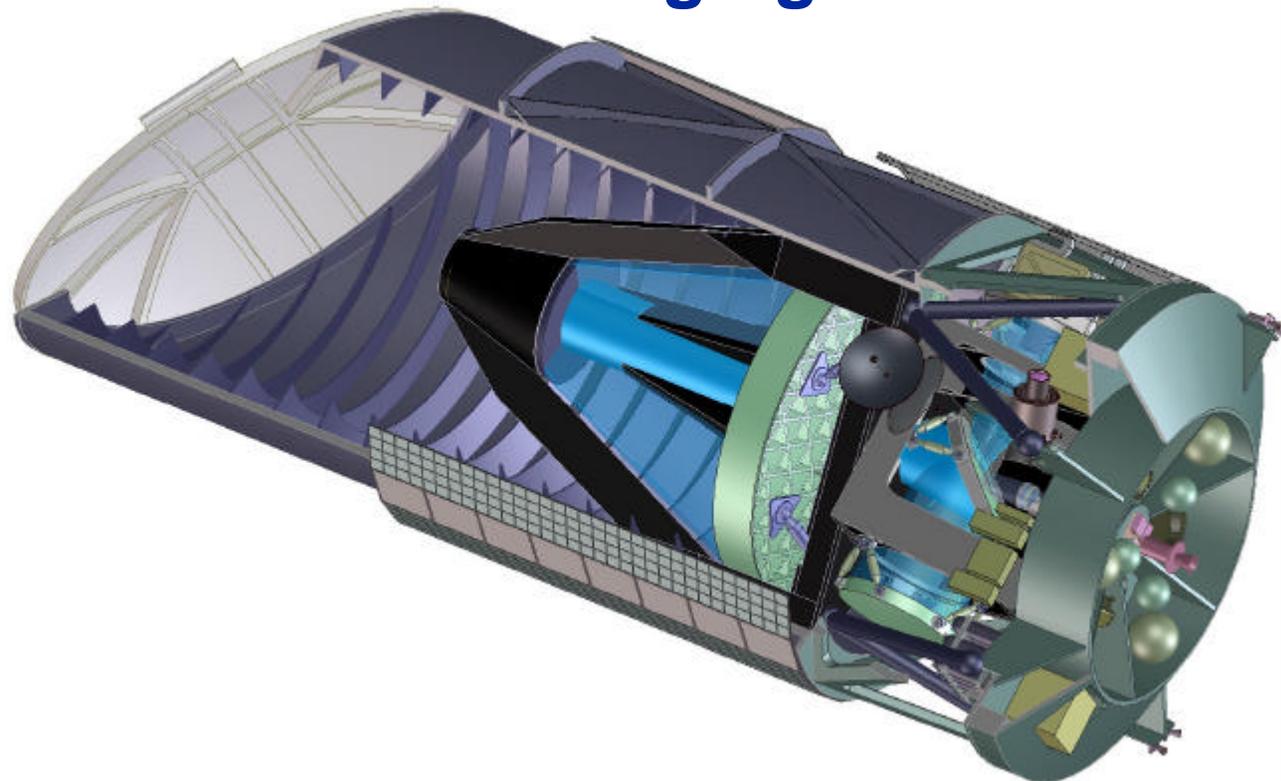
This is like meeting 10 people and trying to understand the complexity of the entire population of the US!

SNAP: The Next Generation



Supernova/Acceleration Probe (2010)

- Dedicated exploration of dark energy $L(t)$
- Maps expansion history $a(t)$
- Reveals dark matter through gravitational lensing



SNAP: Mission Design



- **~2 m aperture telescope**

Reach very distant SNe.

- **1 degree mosaic camera, 1/2 billion pixels**

Efficiently study large numbers of SNe.

- **0.35 – 1.7 μ m spectrograph**

Analyze in detail each SN.

Dedicated instrument designed to repeatedly observe an area of sky.

Essentially no moving parts.

4 year operation for experiment
(lifetime open ended).



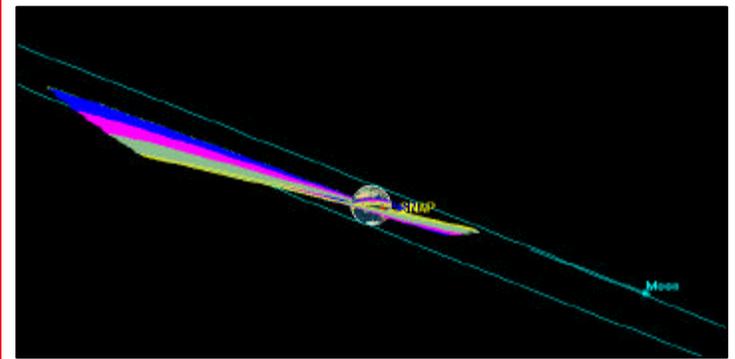
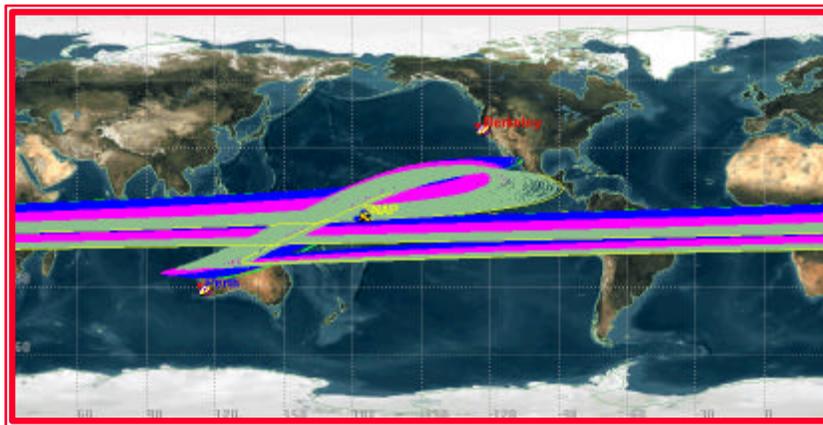
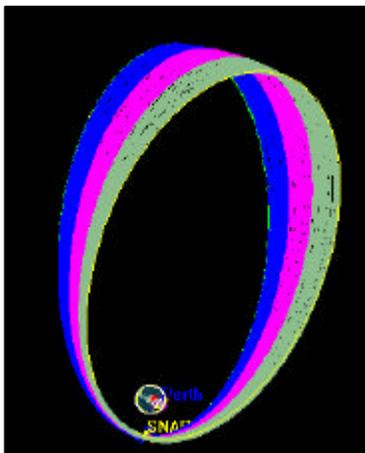
SNAP: Technical Details



Launch by Delta IV (from KSC) in 2010

High earth, 3 day synchronous orbit

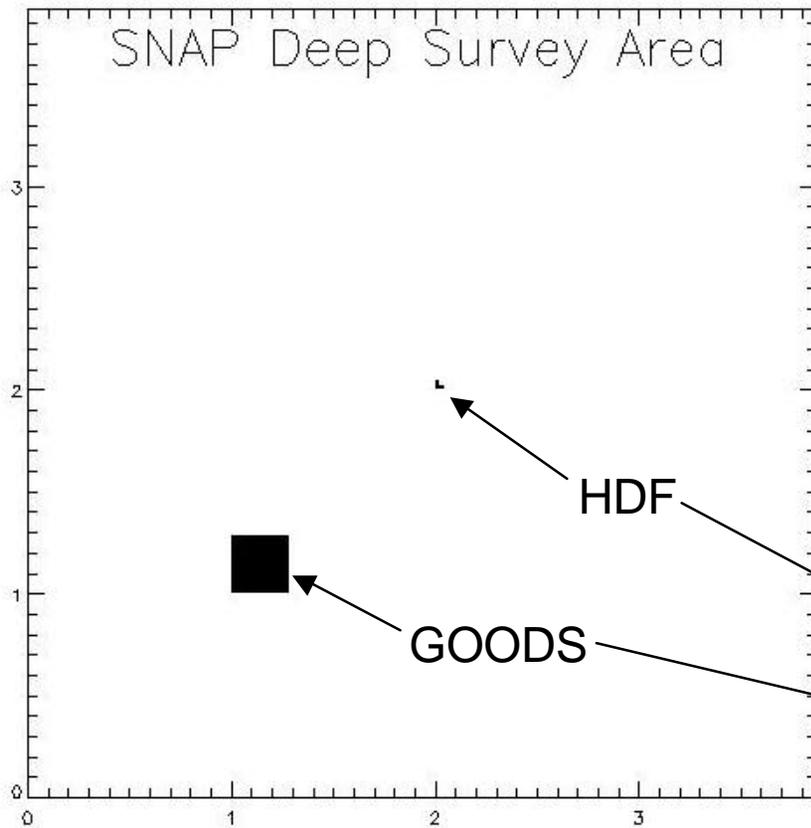
- minimal thermal changes
- outside radiation belts
- passive cooling
- excellent groundstation coverage



SNAP Survey Fields

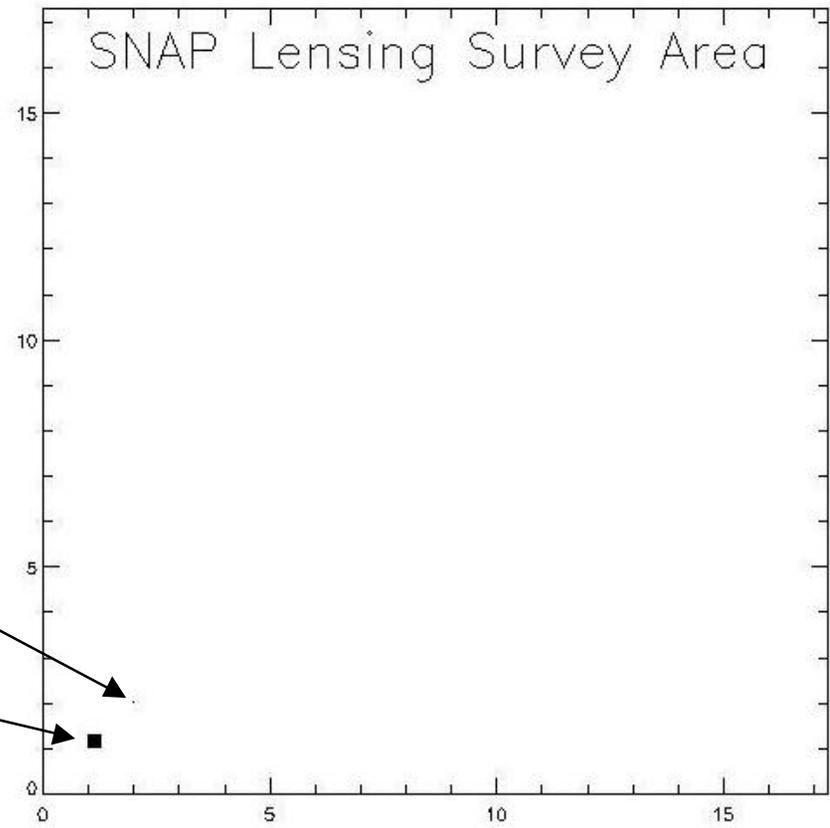


15 sq.deg. Deep Survey



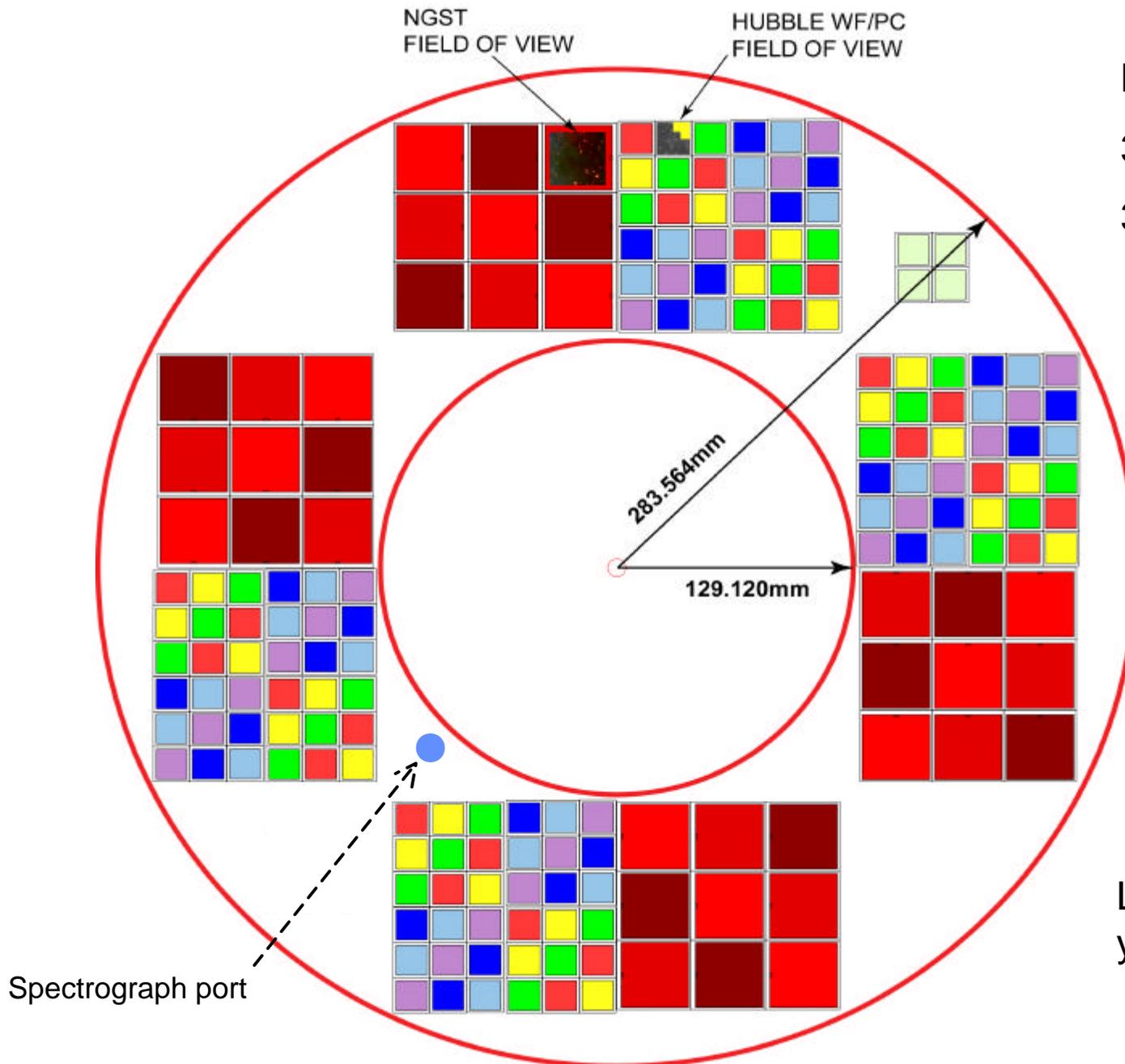
- 9 filters
- $m_{AB}=27.7$ every 4 days
- 120 epochs
- coadd AB=30.3 (31)

~300 sq.deg. Wide Survey



- 9 filters
- $m_{AB}=28.1$

Astronomical Imaging



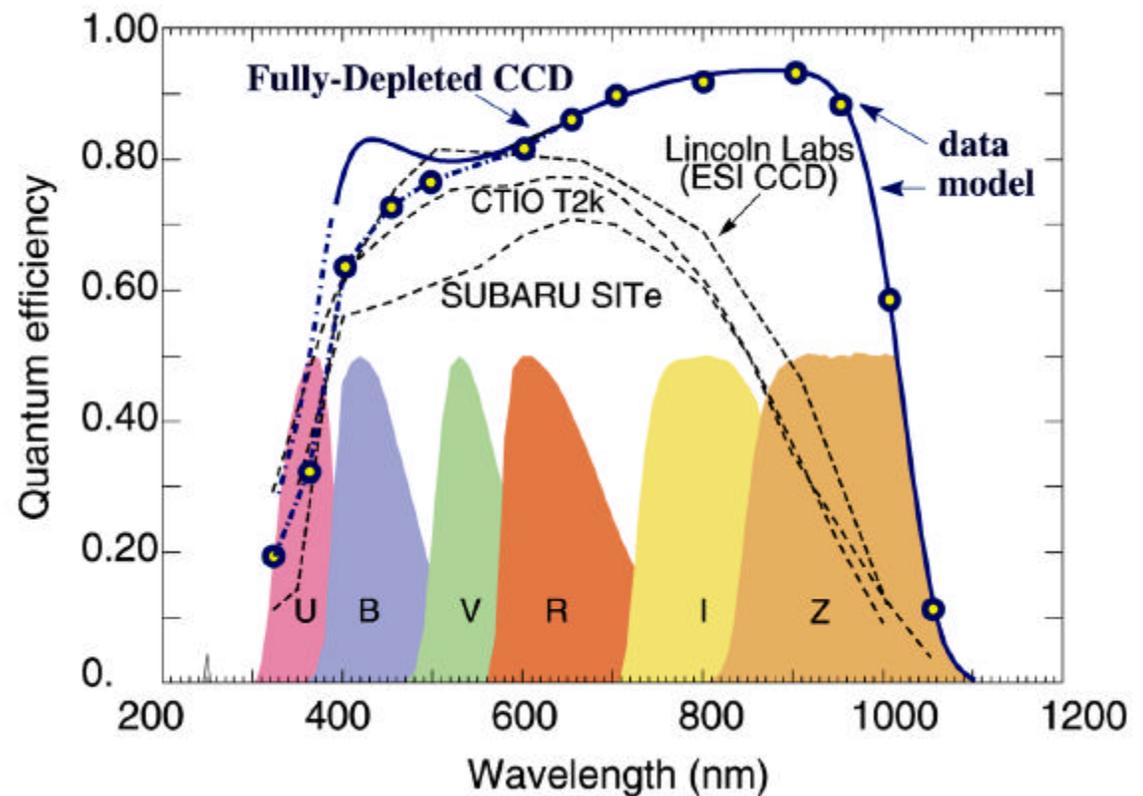
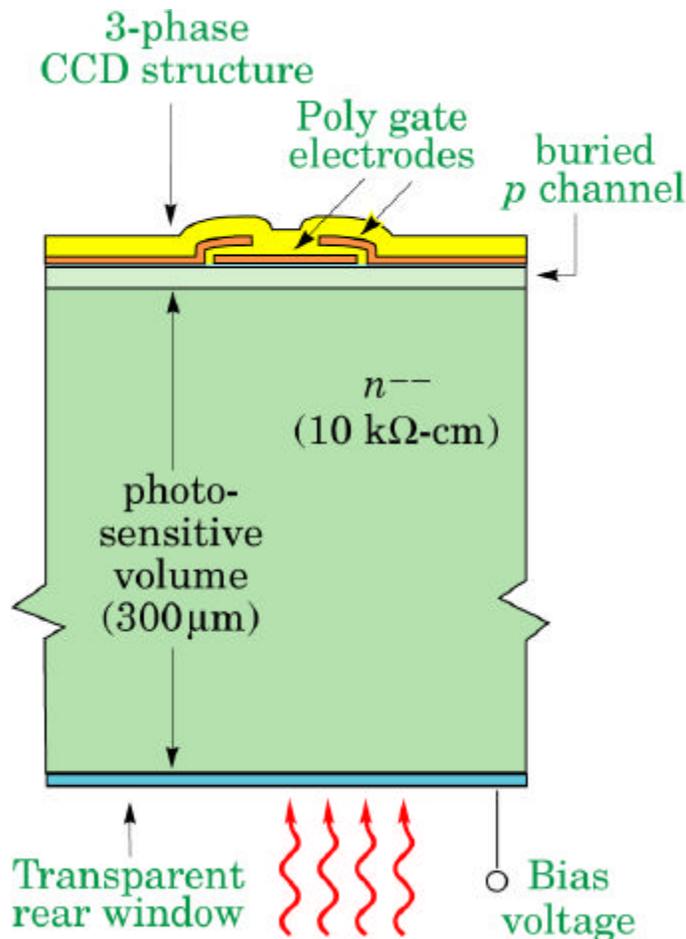
Half billion pixel array
36 optical CCDs
36 near infrared detectors

Larger than any camera
yet constructed

New Technology CCD's



- New kind of CCD detector developed at LBNL
- Radiation hard for space ; High efficiency
- Able to be combined into large arrays



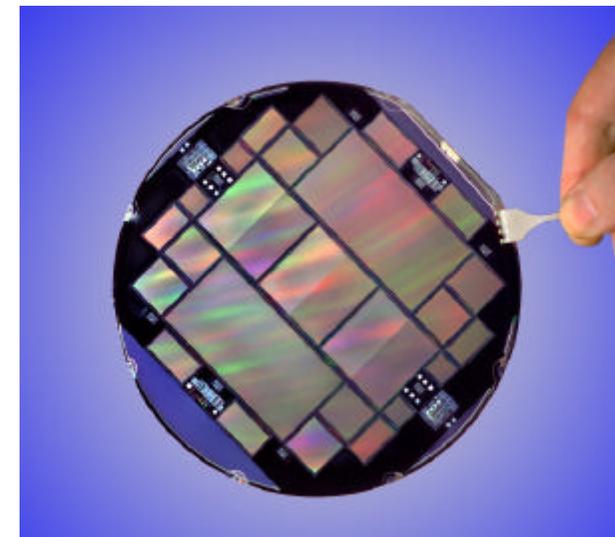
LBNL CCD's at NOAO



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 HeI 10124Å.

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

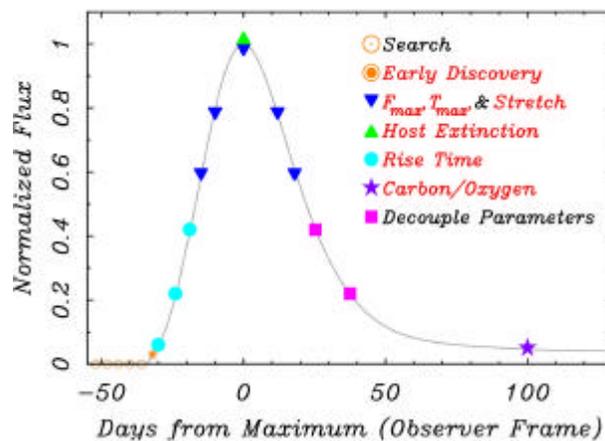
What makes the SN measurement special? Control of systematic uncertainties



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

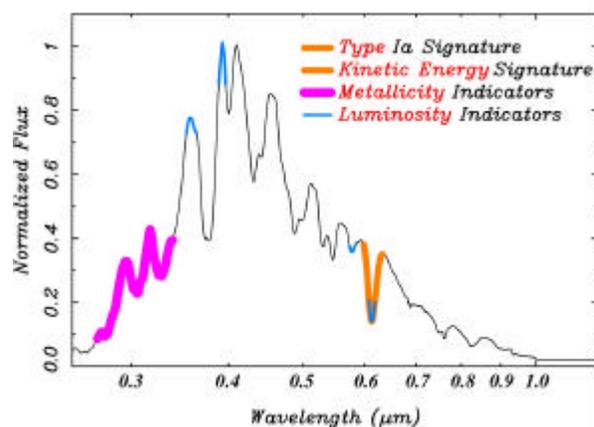
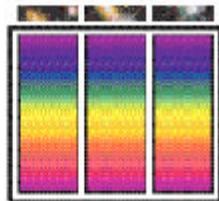
Lightcurve & Peak Brightness

Images



Redshift & SN Properties

Spectra



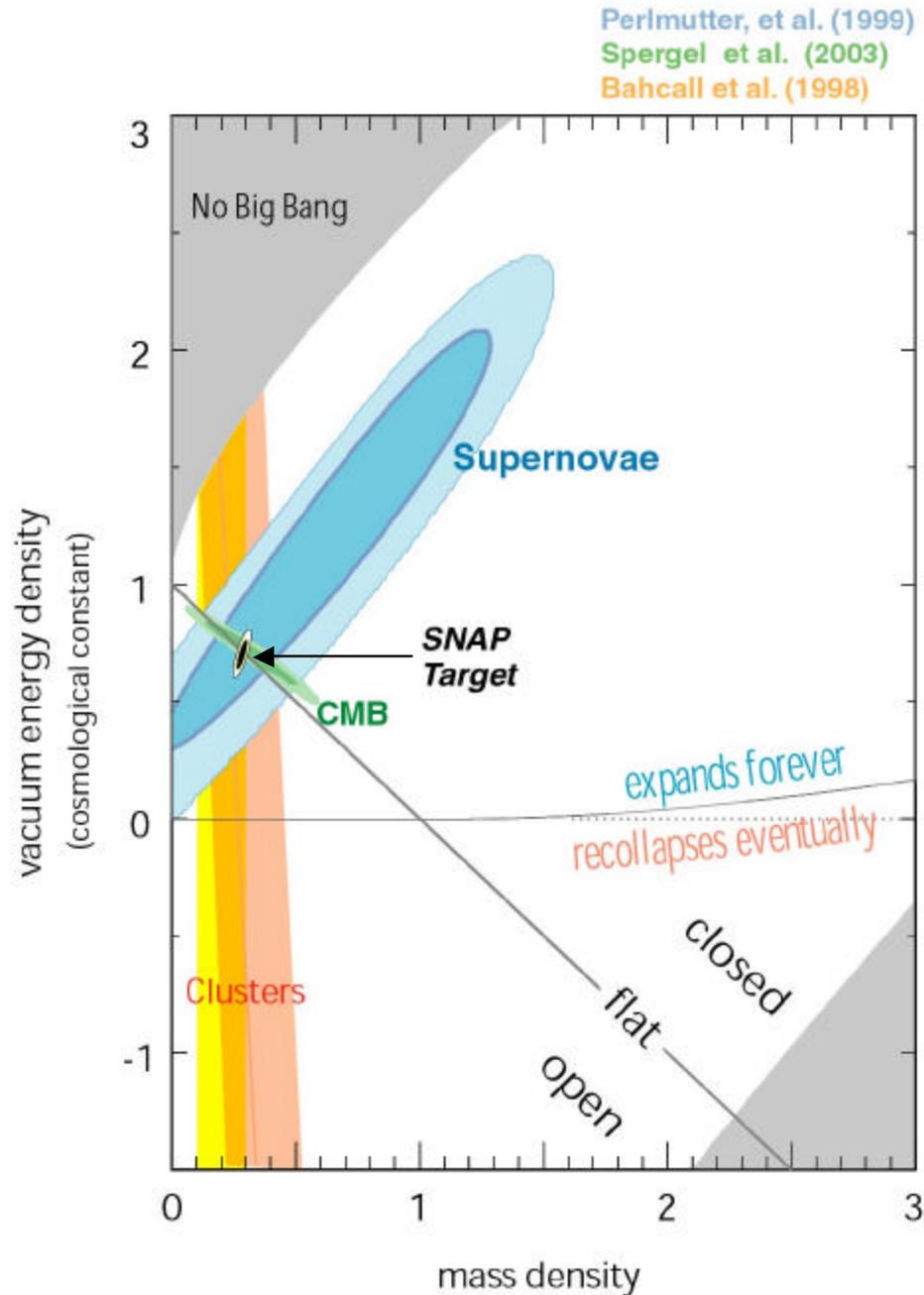
W_M and W_L
Dark Energy Properties

data

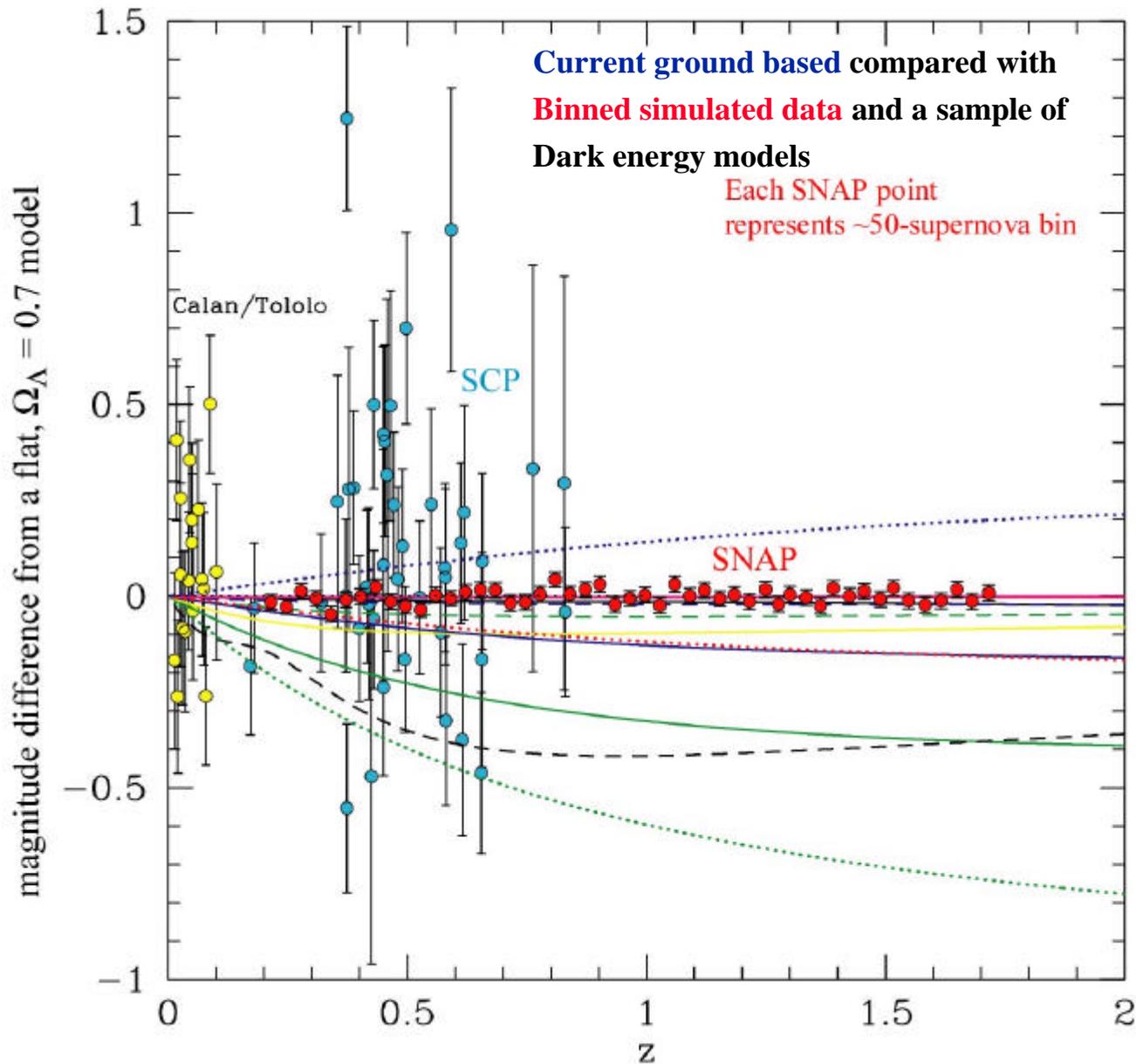
analysis

physics

SNAP: The Third Generation



Exploring Dark Energy



based on
Weller & Albrecht (2001)

Science Reach



SNAP parameters from 2000 supernovae *including systematics*

Matter density:	0.25 ± 0.02
Dark energy density:	0.75 ± 0.04
“Springiness of space” (w):	-1.00 ± 0.05
Time variation of “springiness” (w'):	0.00 ± 0.19

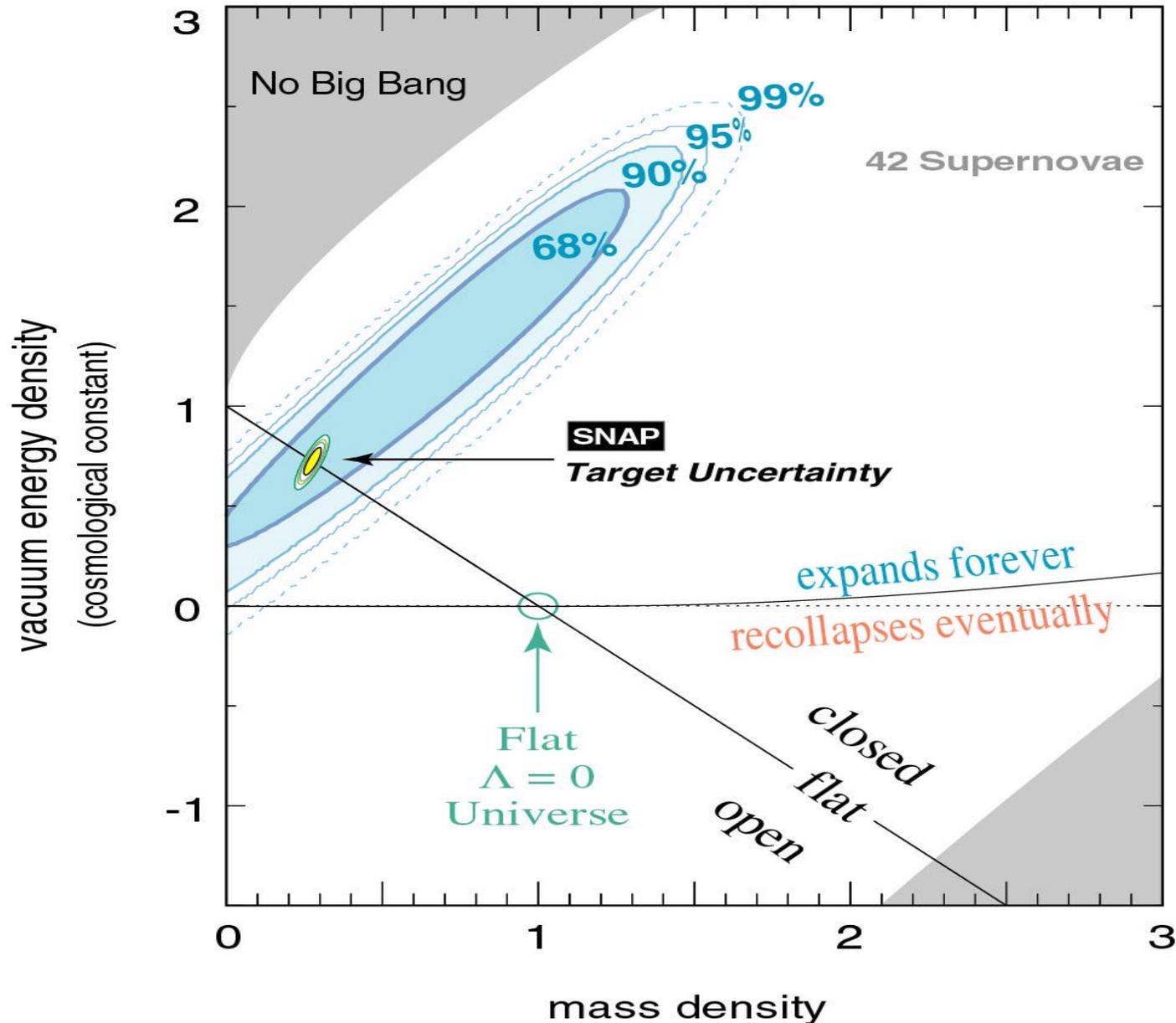
Key Cosmological Studies

- Type II supernovae (collapse to black holes)
- Weak gravitational lensing
- Strong lensing (gravitational telescope)
- Galaxy clustering and populations
- Structure formation and evolution
- Star formation and reionization

SNAP: The Third Generation

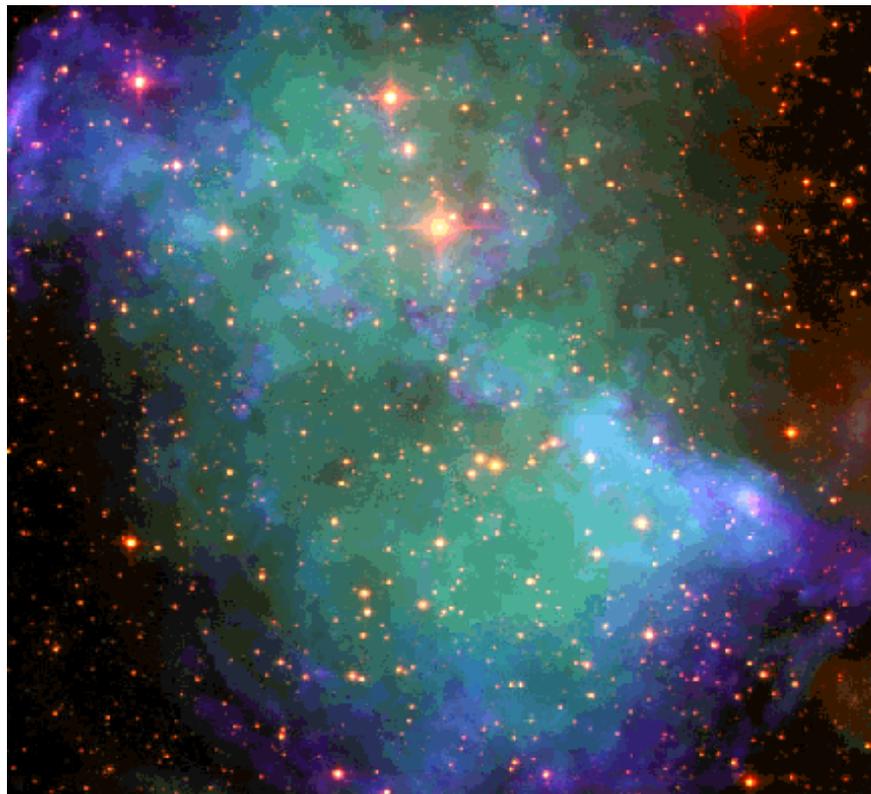


Supernova Cosmology Project
Perlmutter *et al.* (1999)



SNAP is wide, deep, and colorful

- 9000 times the area of Hubble Deep Field
- Sees objects twice as faint as HDF
- 9 color bands, from visible light to near infrared
- 120 revisits (time domain) to find variable objects

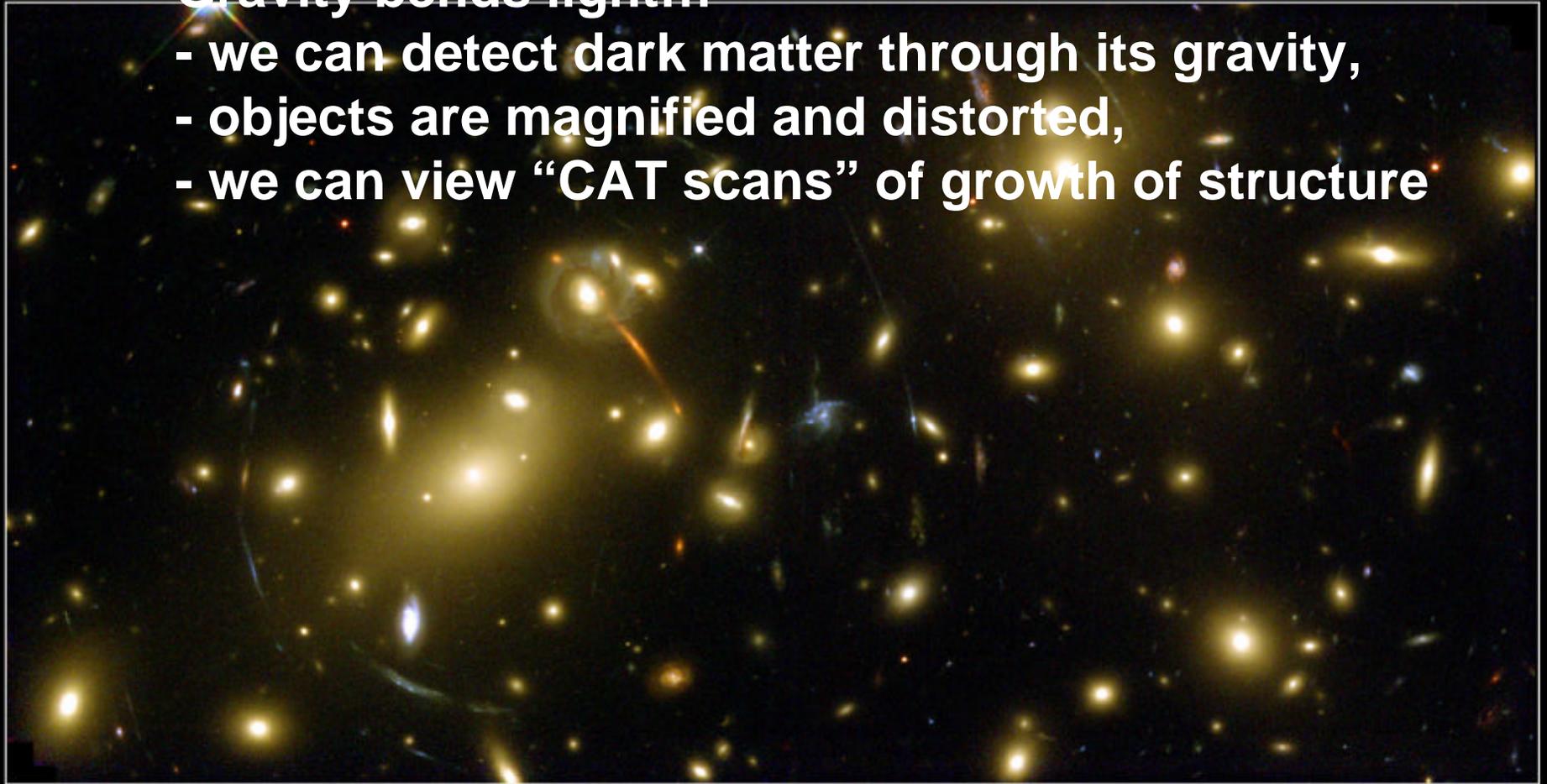


Gravitational Lensing



Gravity bends light...

- we can detect dark matter through its gravity,
- objects are magnified and distorted,
- we can view “CAT scans” of growth of structure



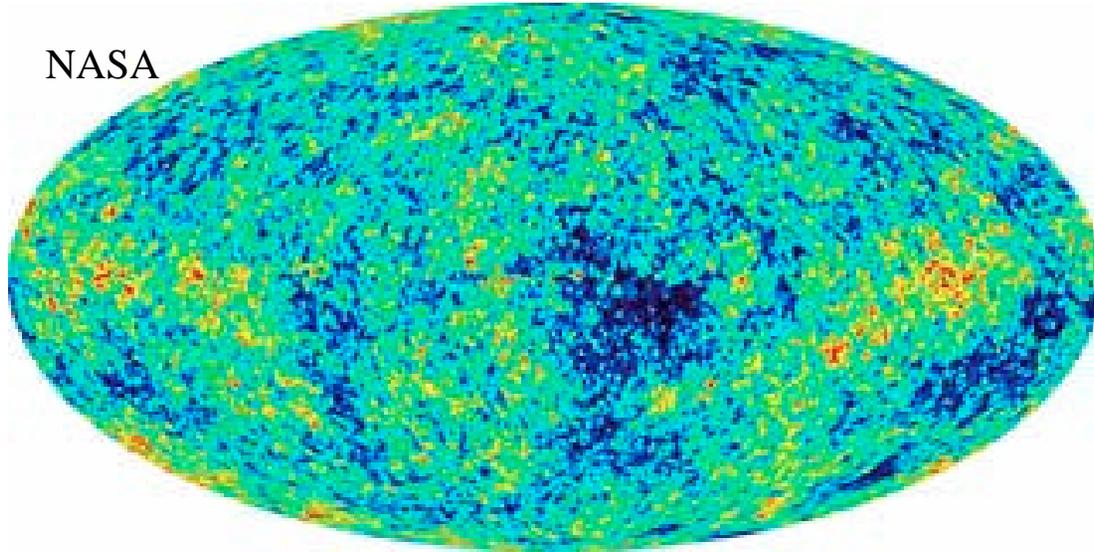
Galaxy Cluster Abell 2218
Hubble Space Telescope • WFPC2

NASA, A. Fruchter and the ERO Team (STScI) • STScI-PRC00-08

Cosmic Background Radiation



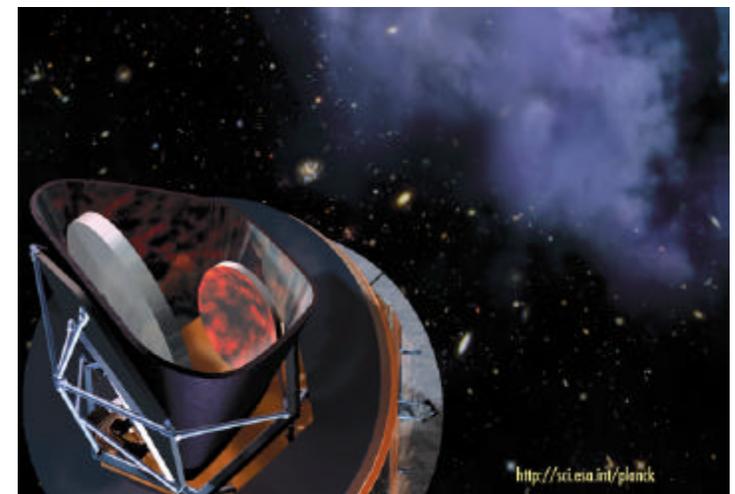
NASA



Snapshot of universe at 380,000 years old, 1/1100 the size

Hot and cold spots simultaneously the **smallest** and **largest** objects in the universe: single quantum fluctuations in early universe, spanning the universe at the time of decoupling.

Planck satellite (2007)

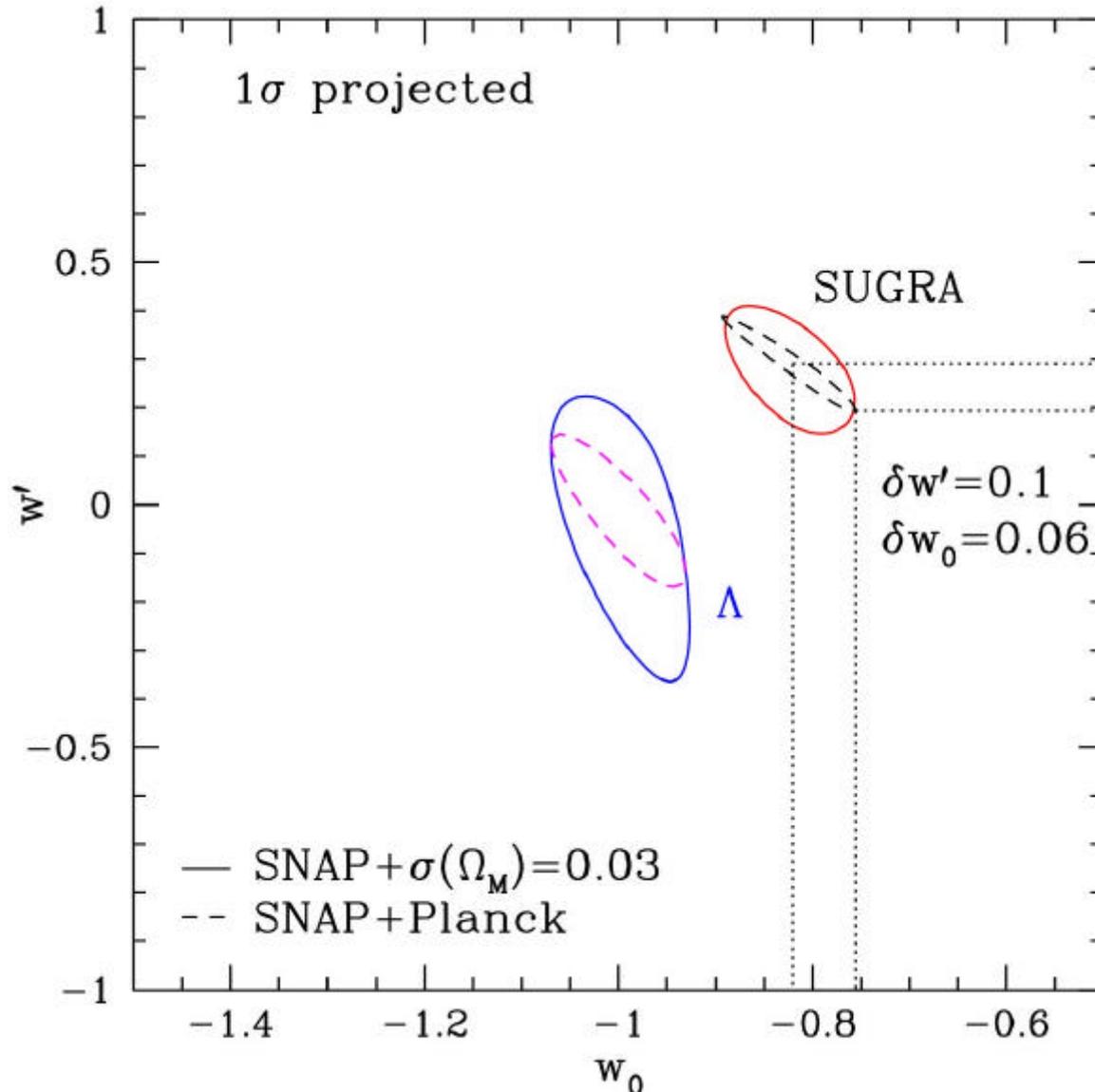


ESA

Complementarity



**SNAP tightly constrains dark energy models...
And plays well with others.**



**SNAP+Planck
have excellent
complementarity,
equal to a prior
 $s(W_M) \approx 0.01$.**

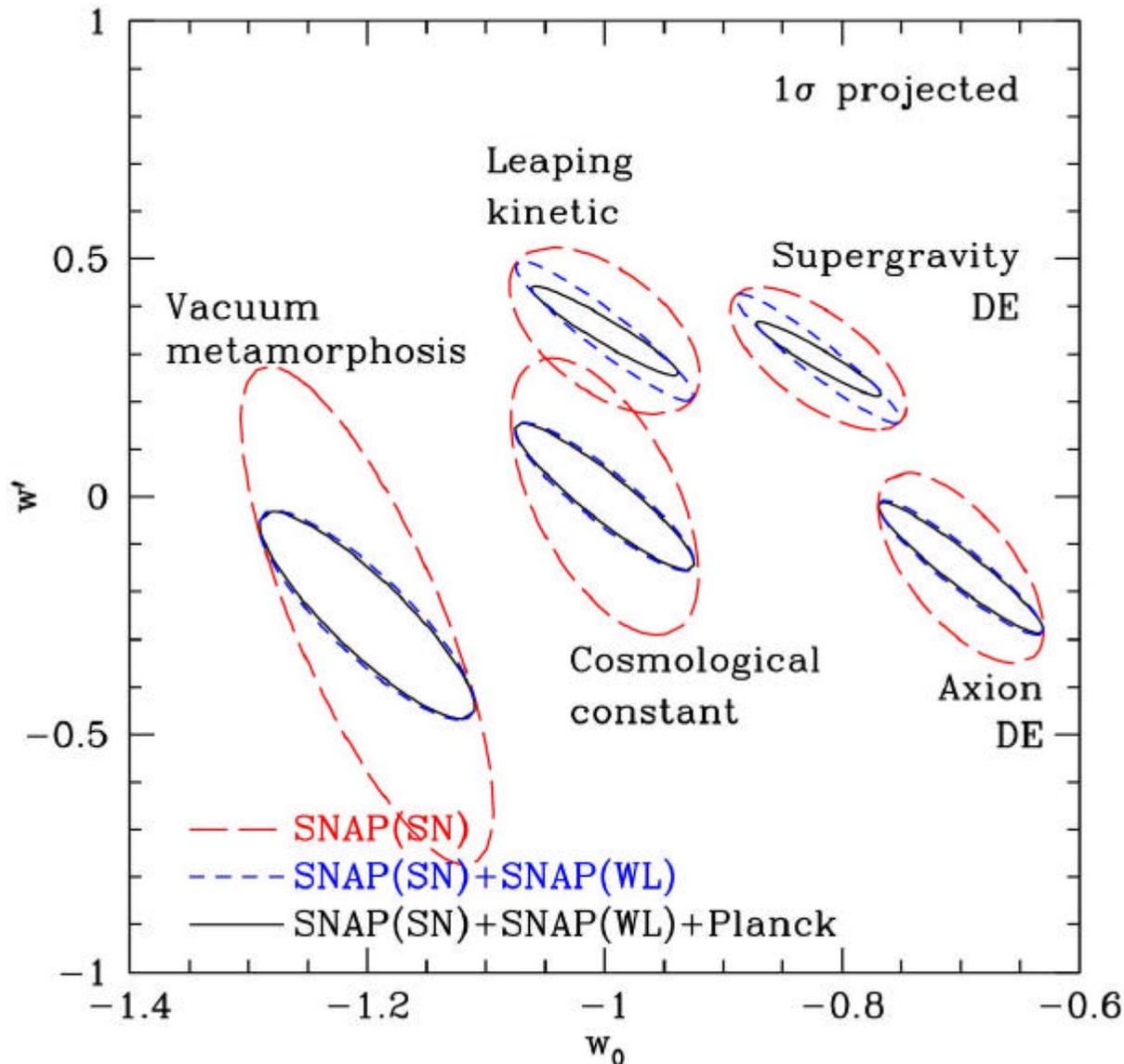
Frieman, Huterer, Linder, & Turner
2002

**SNAP+Planck
can detect
time variation w'
at 99% cl
(e.g. SUGRA).**

Fundamental Physics

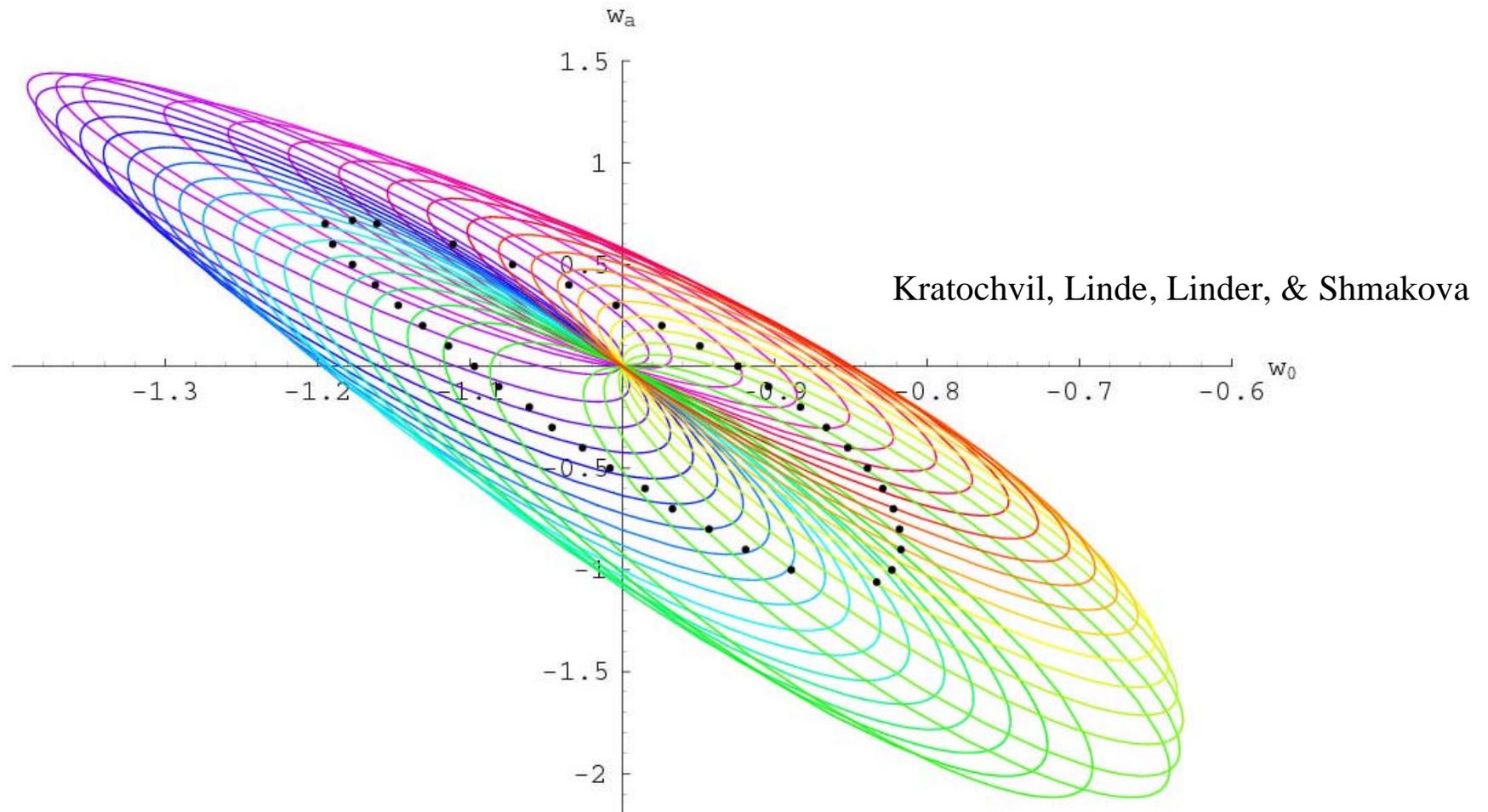


Next generation data will map the acceleration of the universe so precisely that it can probe:



- Nature of dark energy
- Structure of the vacuum
- High energy physics
- Gravitation
- Extra dimensions

Beyond Einstein



If data from SNAP lie outside the curve of black dots, then we rule out Einstein's cosmological constant, and are led to exotic physics.

Mapping Galaxies, Mapping Gravity

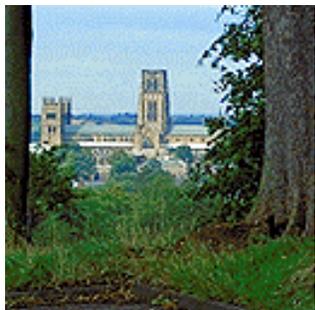
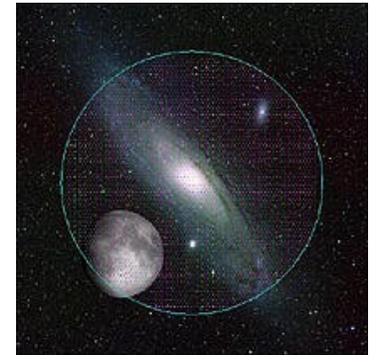


Gemini Observatory



Kilo-Aperture Optical Spectrograph

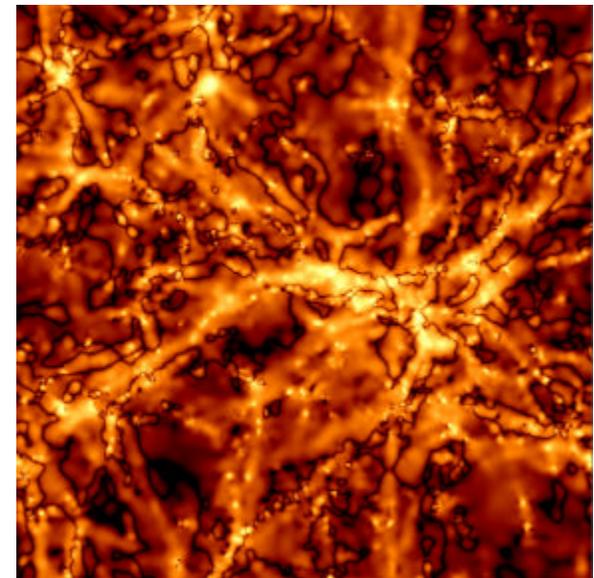
Next generation instrument
observing 4000 galaxies at once.



Computer simulations of the formation of galaxies, in collaboration with A. Jenkins (Durham University, England)



Institute for Computational Cosmology

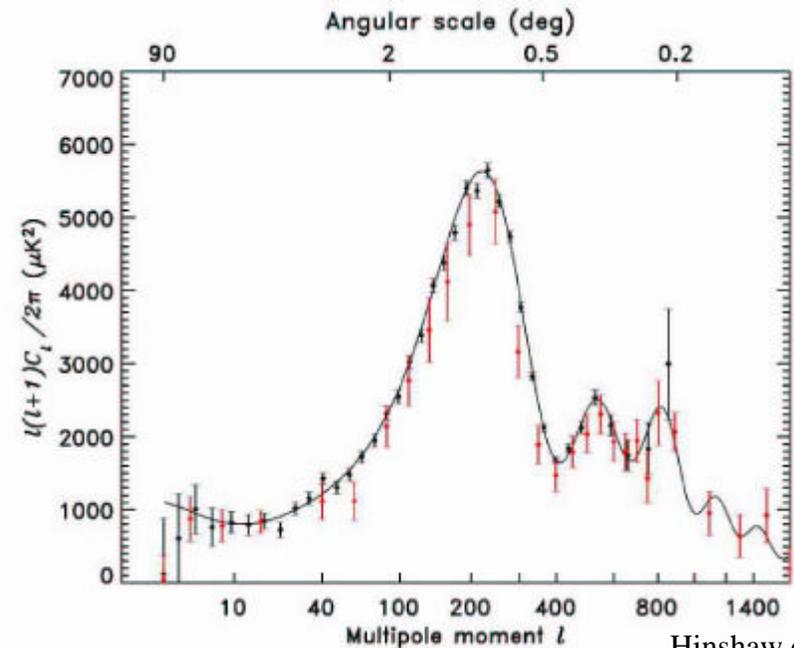


Primordial Imprints – Oscillations



CMB Power Spectrum

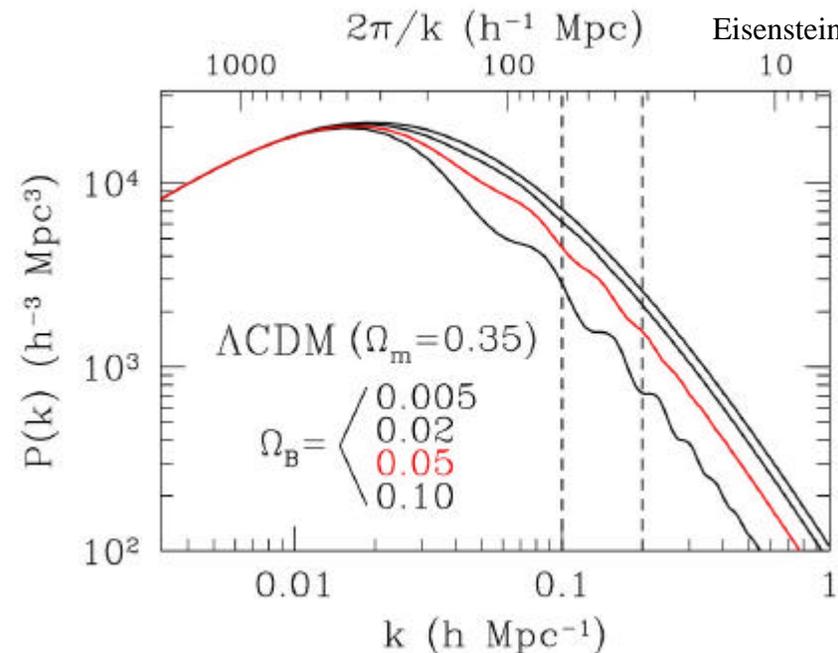
- Temperature fluctuations
- Acoustic Oscillations (Sakharov 1965)
- Baryon-Photon Fluid at $z=1100$



Hinshaw et al. 2003

Matter Power Spectrum

- Density fluctuations
- Acoustic Oscillations
- Baryon imprints amid dominating Dark Matter



Eisenstein 2002

® wiggles

Cosmic Doomsday



What if the dark energy decays?

In some models the negative pressure can turn positive.

The universe is driven to collapse!

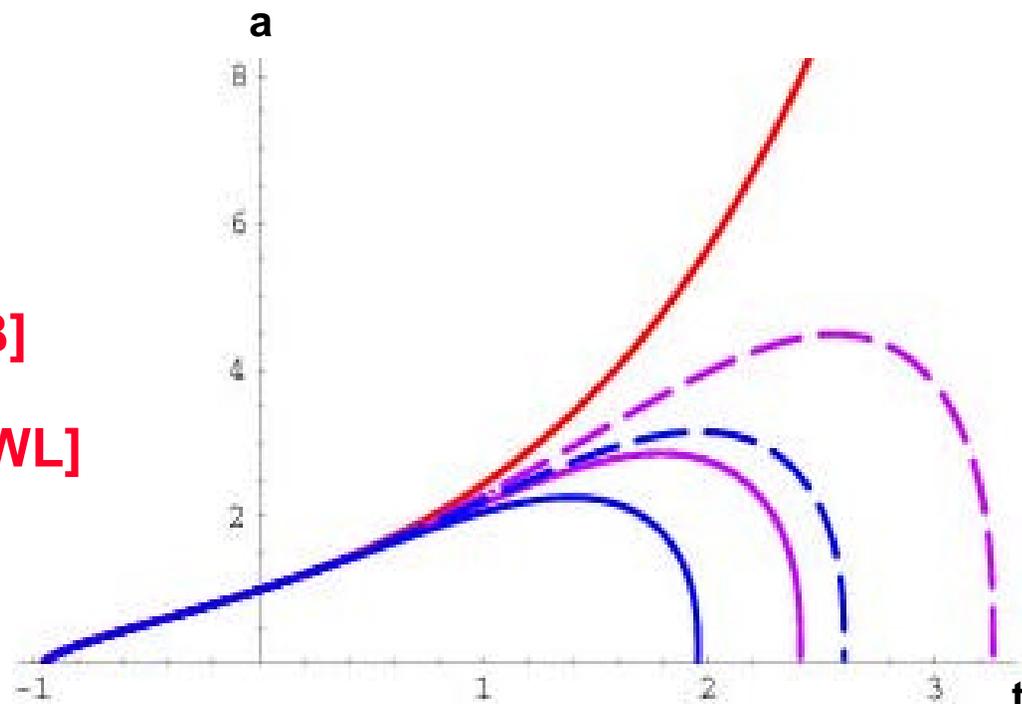
If we measure expansion **history** sufficiently precisely, we can predict the **fate** of the universe.

$$t_{\text{doom}} = \int (L)$$

$$t_{\text{doom}} > 29 \text{ Gyr [95\% SNAP]}$$

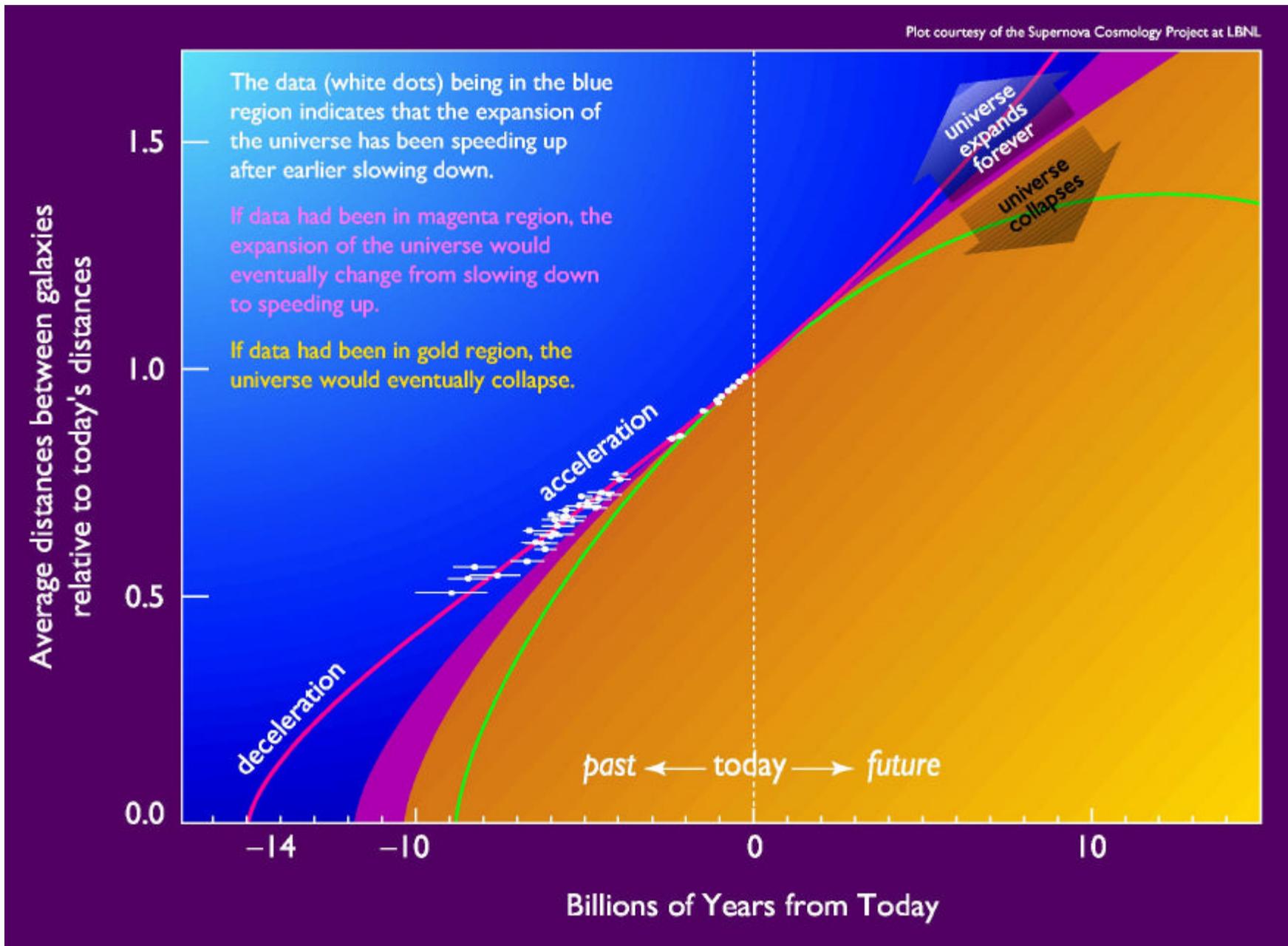
$$t_{\text{doom}} > 35 \text{ Gyr [95\%SNAP+CMB]}$$

$$t_{\text{doom}} > 40 \text{ Gyr [95\% SN+CMB+WL]}$$



Kallos, Kratochvil, Linde, Linder, & Shmakova 2003

Fate of the Universe



The SS logo depicts a globe of Earth with a satellite in orbit. The letters 'SS' are positioned to the right of the globe.The NASA logo is the classic blue circular emblem with a white satellite and the word 'NASA' in white.The Department of Energy logo is a circular seal with a green border, featuring an eagle and a shield with a lightning bolt, surrounded by the text 'DEPARTMENT OF ENERGY' and 'UNITED STATES OF AMERICA'.The Office of Science logo consists of a stylized orange and white graphic resembling an eye or a lens, with the text 'Office of Science' and 'U.S. Department of Energy' below it.

NASA-DOE

Joint Dark Energy Mission

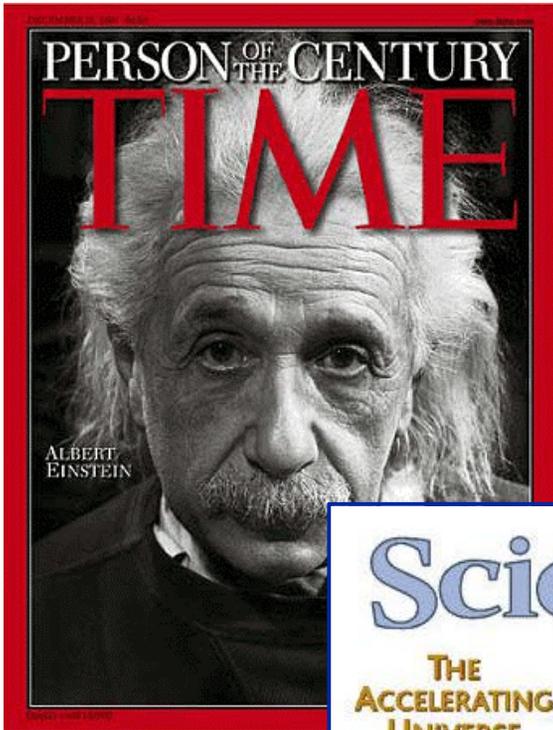
Paul Hertz / NASA

Robin Staffin / DOE

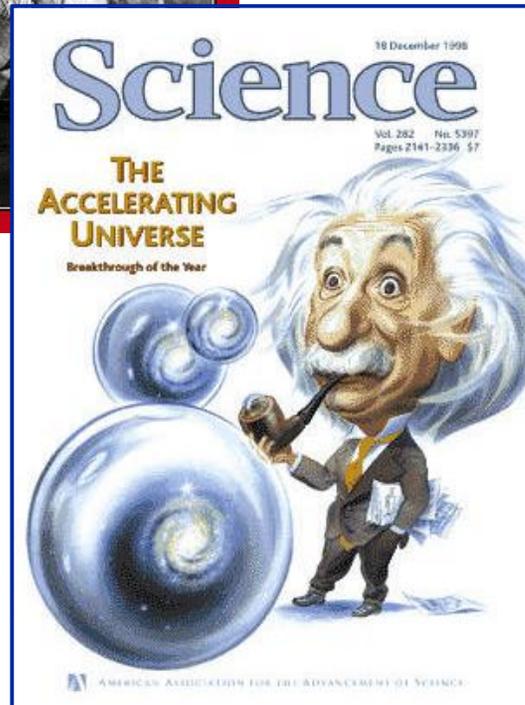
Endorsed by

Raymond L. Orbach Director of the Office of Science Department of Energy	Edward J. Weiler Associate Administrator for Space Science NASA
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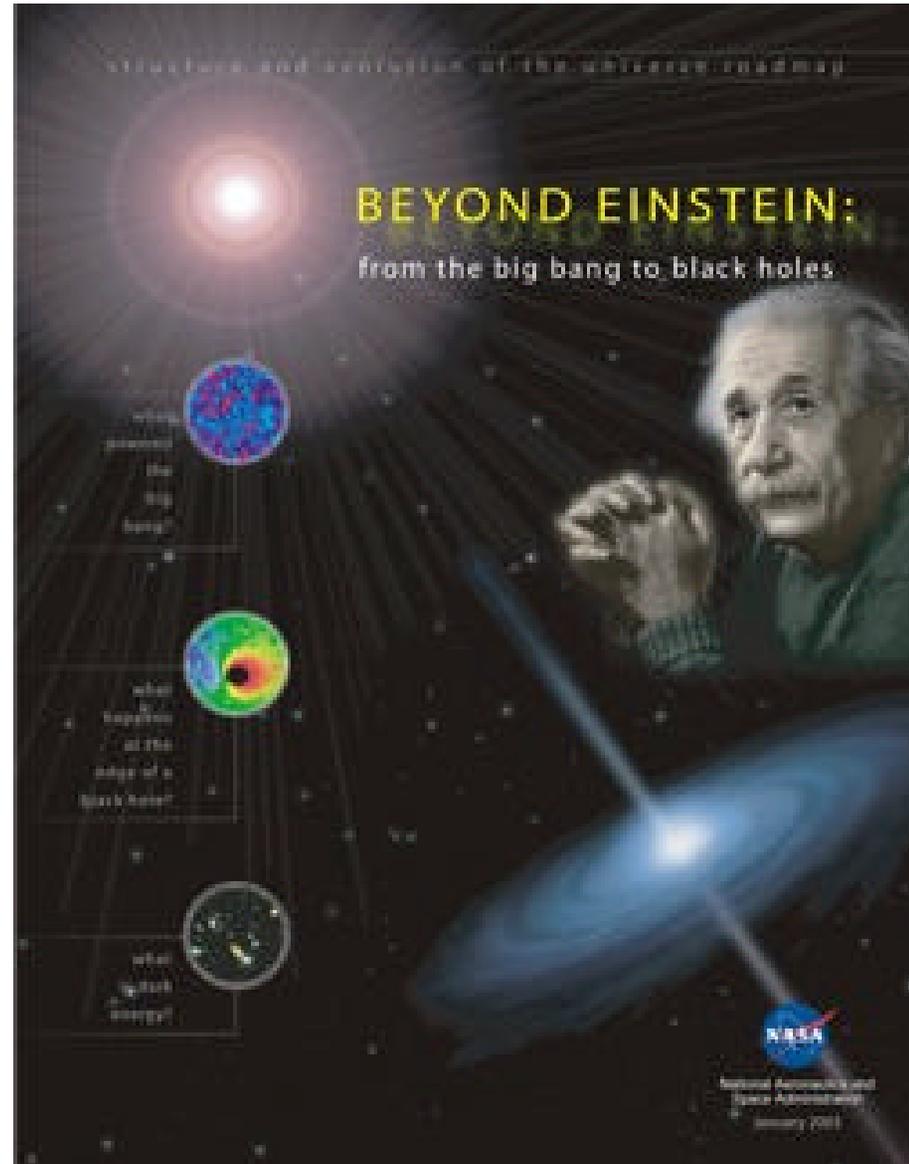
Frontiers of the Universe



1919



Breakthrough of the Year 1998



In the next decade...?