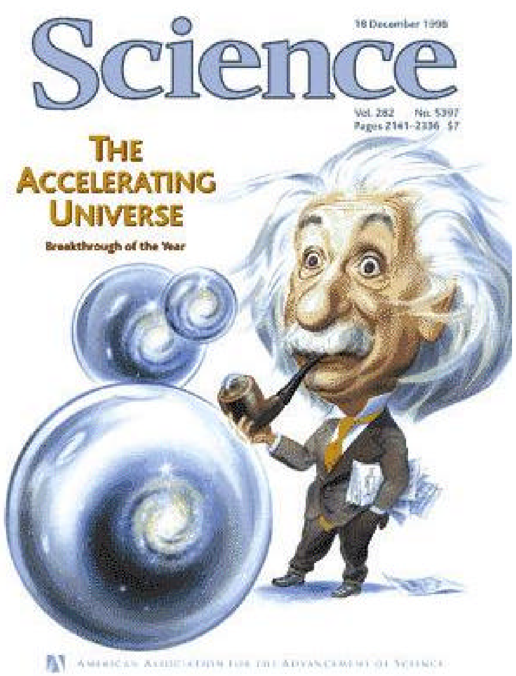
Mapping the

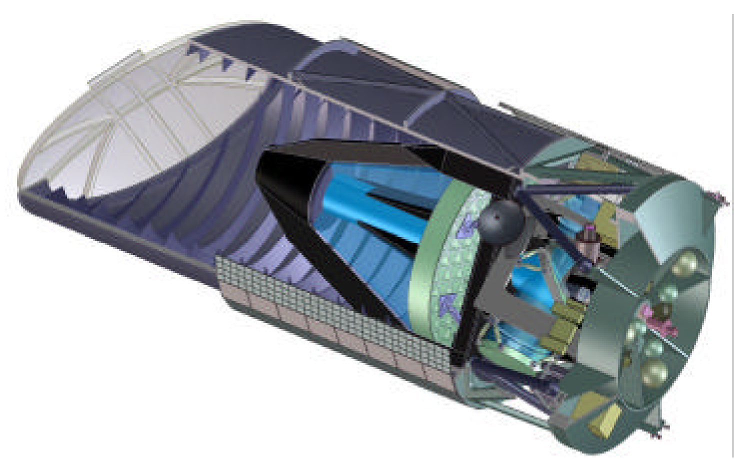
History and Fate of the Universe

Frontiers in Science, FAU

Eric Linder

Lawrence Berkeley National Laboratory

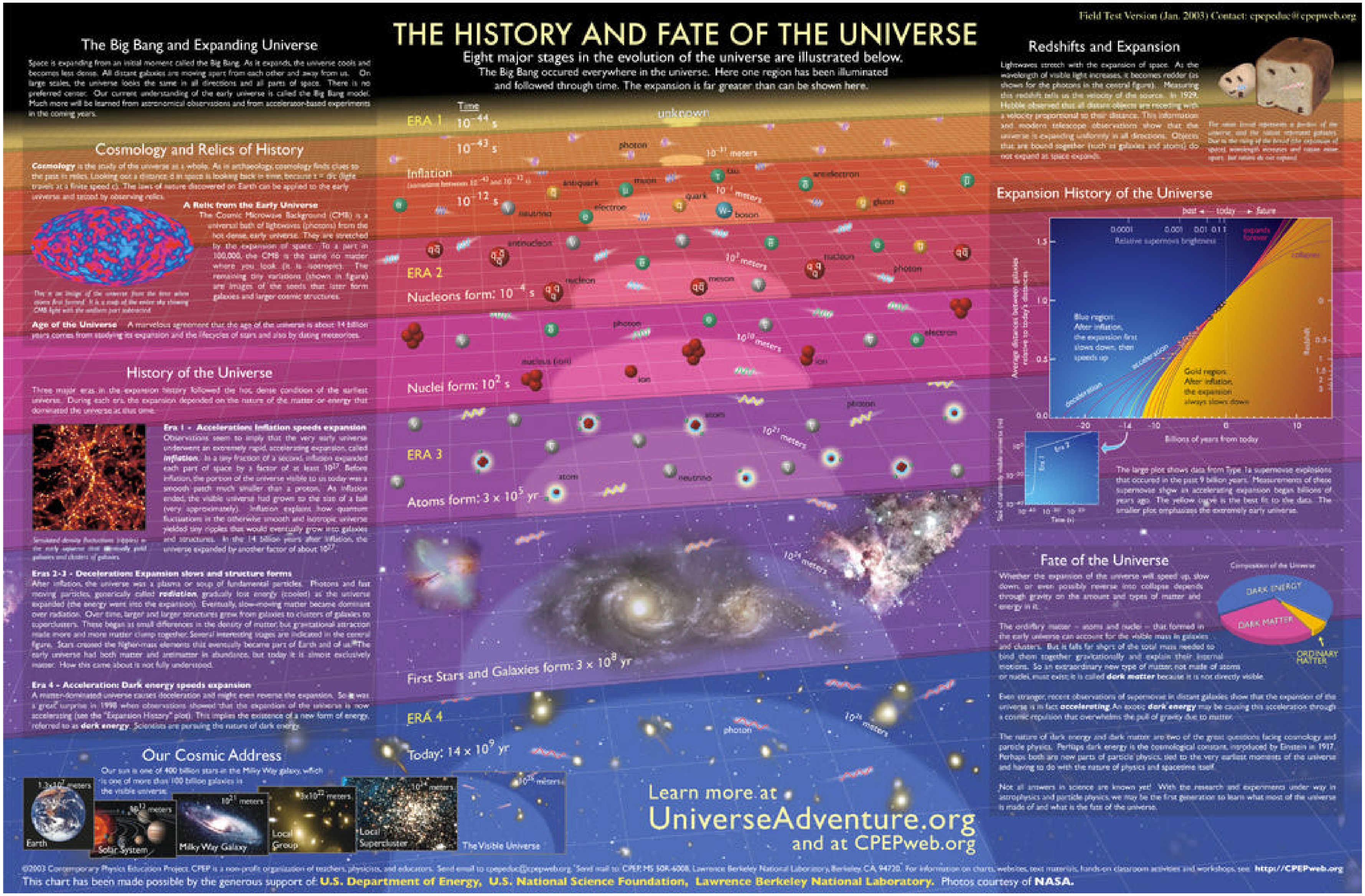




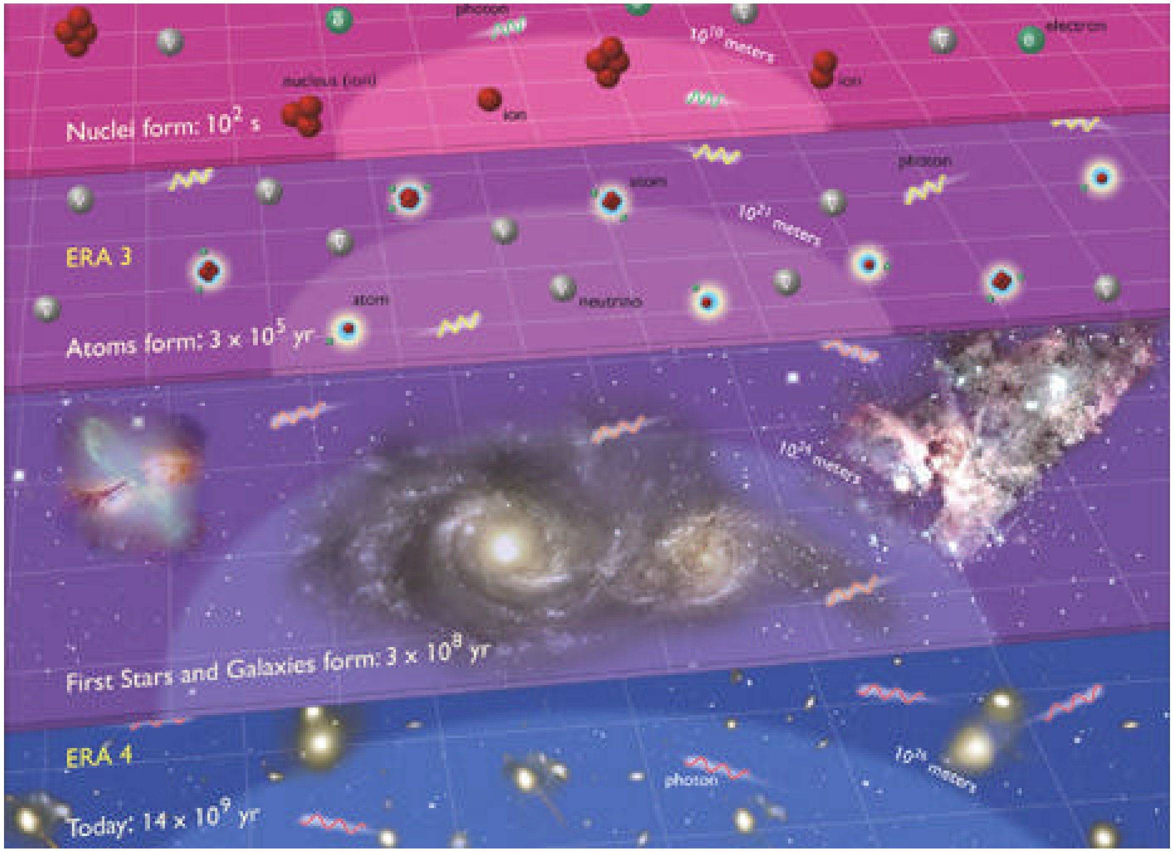
Our Expanding Universe

Bertschinger & Ma ; courtesy Ma

Our Expanding Universe



Our Expanding Universe

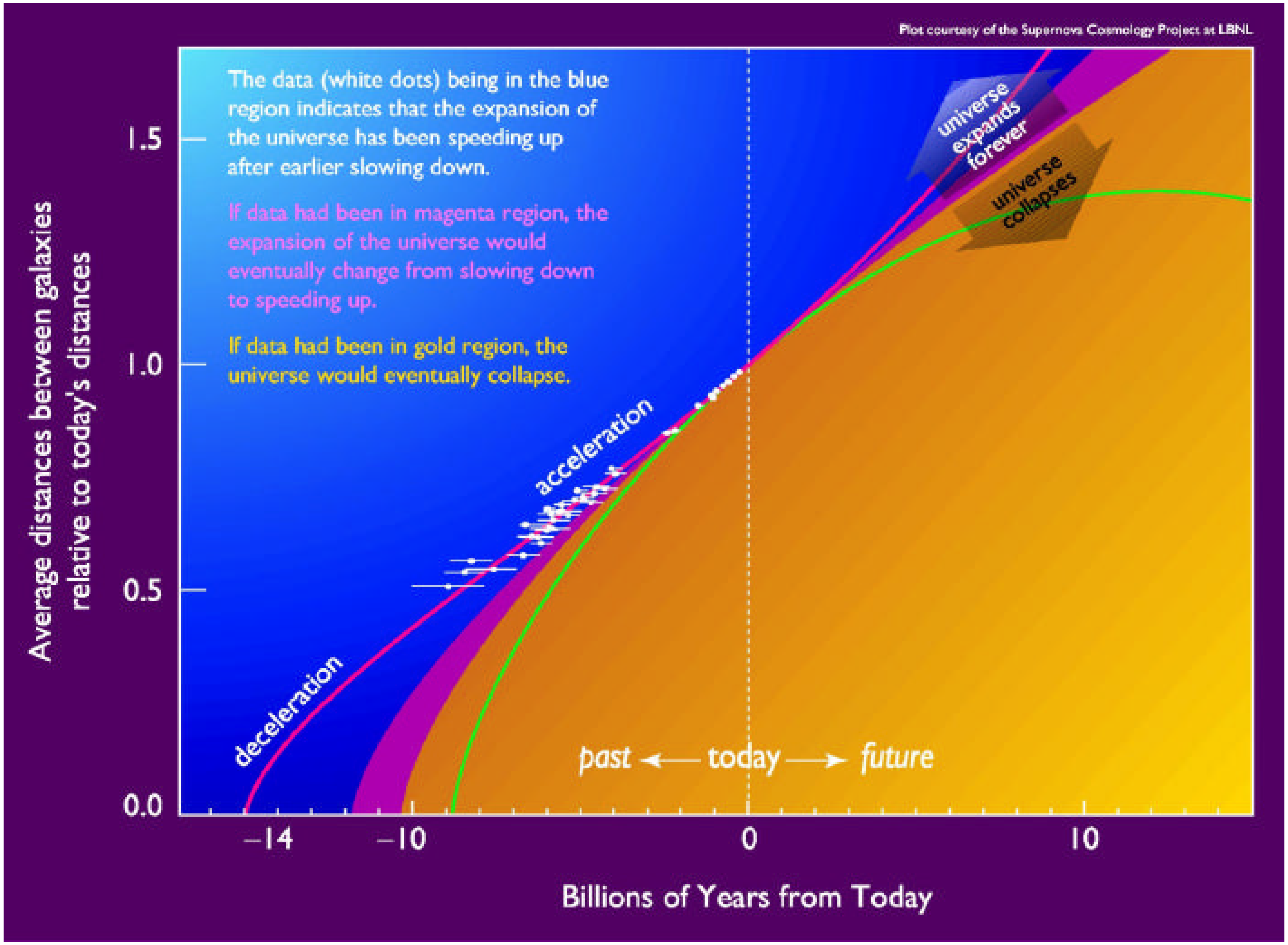


Mapping Our History

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.

STScI

Discovery! Acceleration



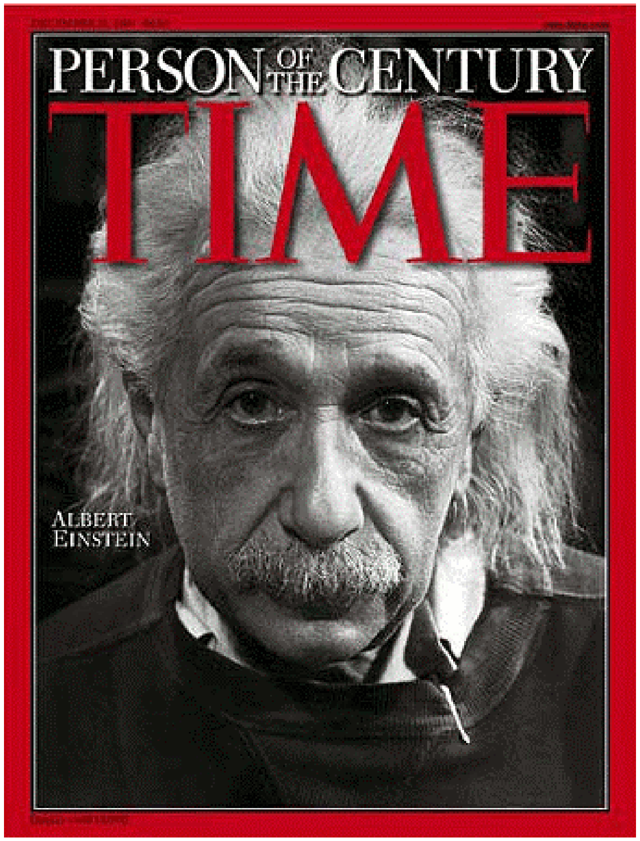
Barnett, Linder, Perlmutter, & Smoot, for the *Office of the President's Science Adviser*

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.

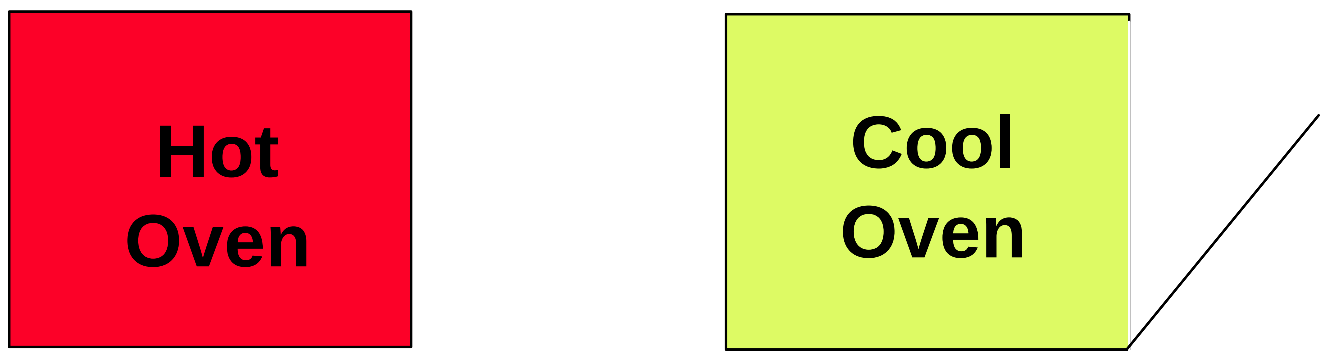
The pressure P of a substance affects the gravity, but this is usually very tiny (because the speed of light c is large, so mc^2 is much bigger than P).

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.

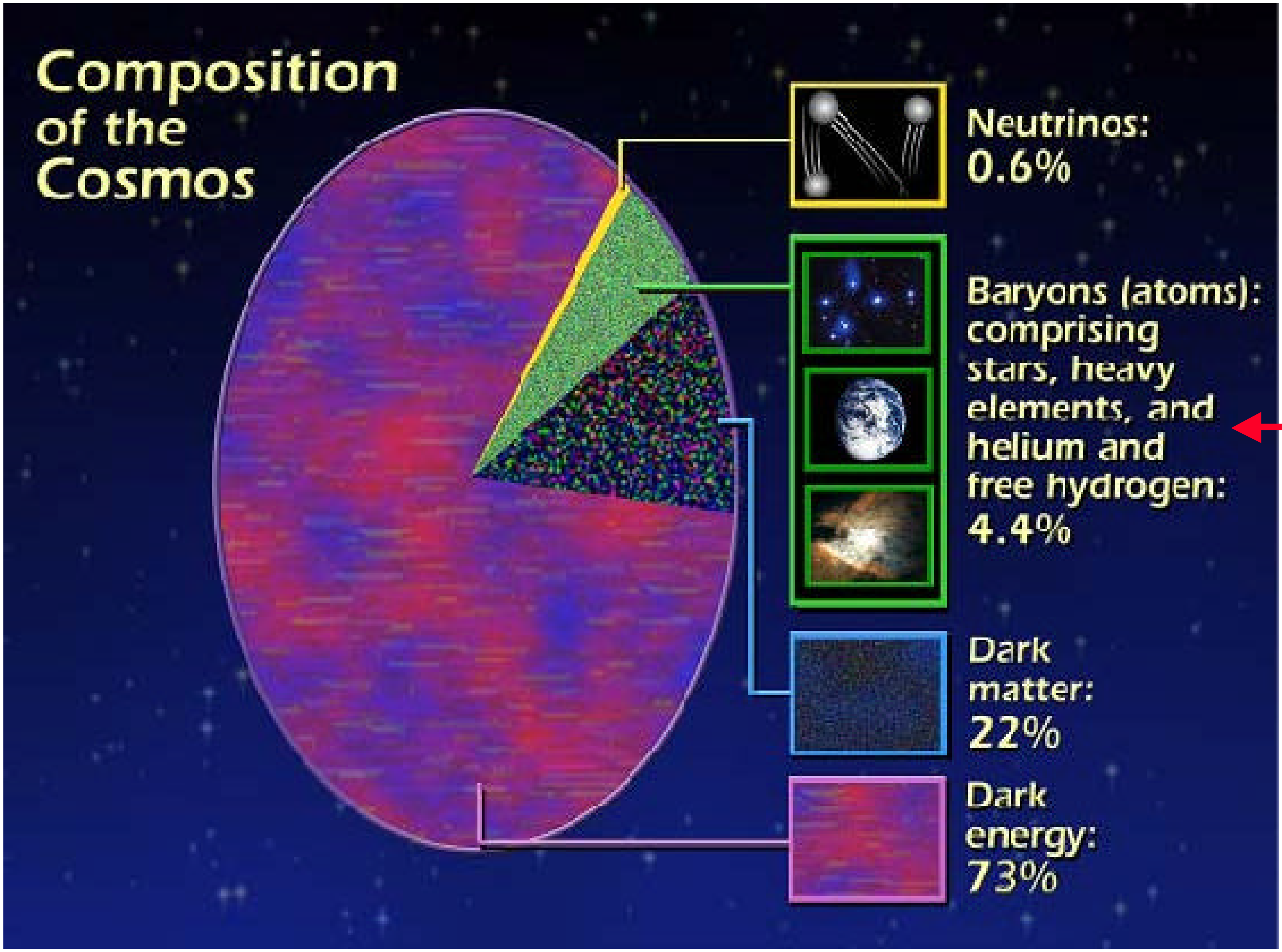
(Not being judgmental, so call it:)

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

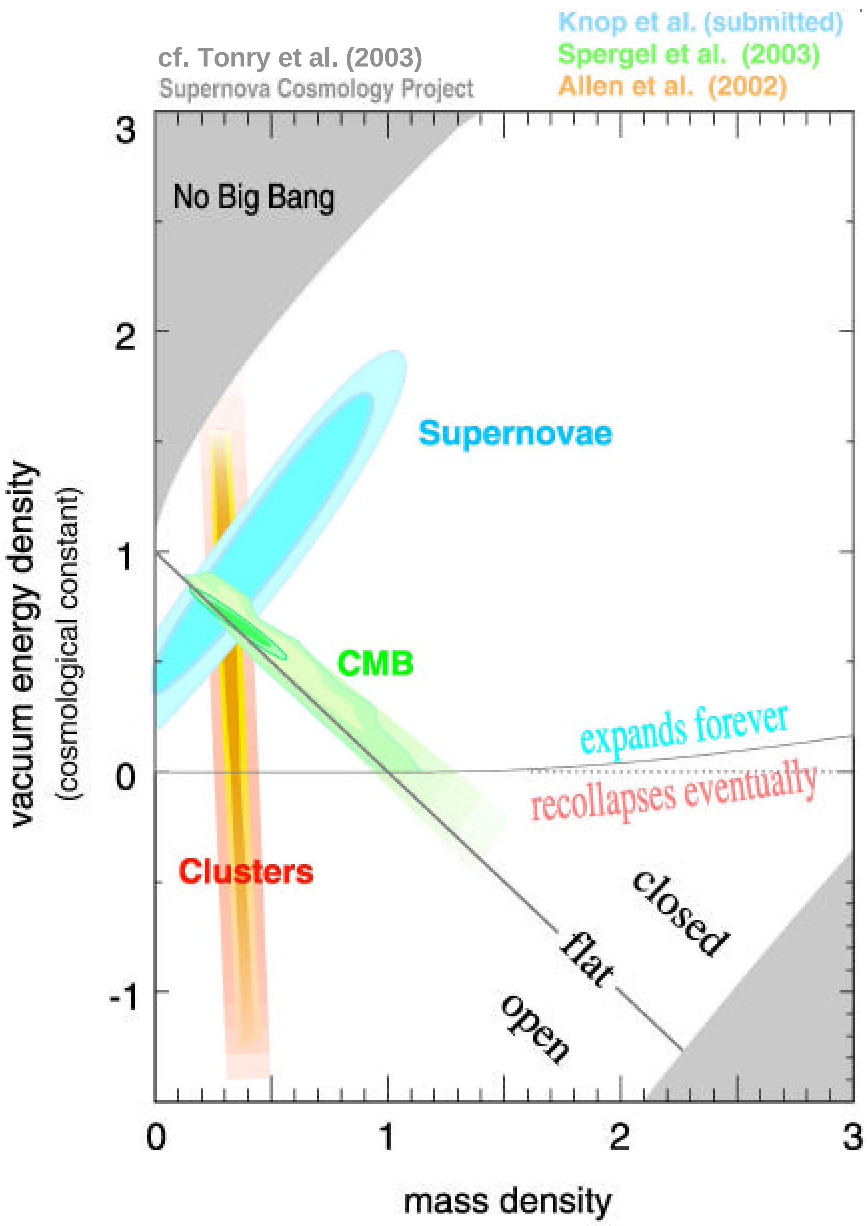


Us

STScI

95% of the universe is unknown!

Cosmic Concordance



- ***Supernovae alone***

Þ **Accelerating expansion**

⇒ L **> 0**

- ***CMB alone***

Þ **Flat universe**

Þ L **> 0**

- ***Any two of SN, CMB, LSS***

Þ **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

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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.

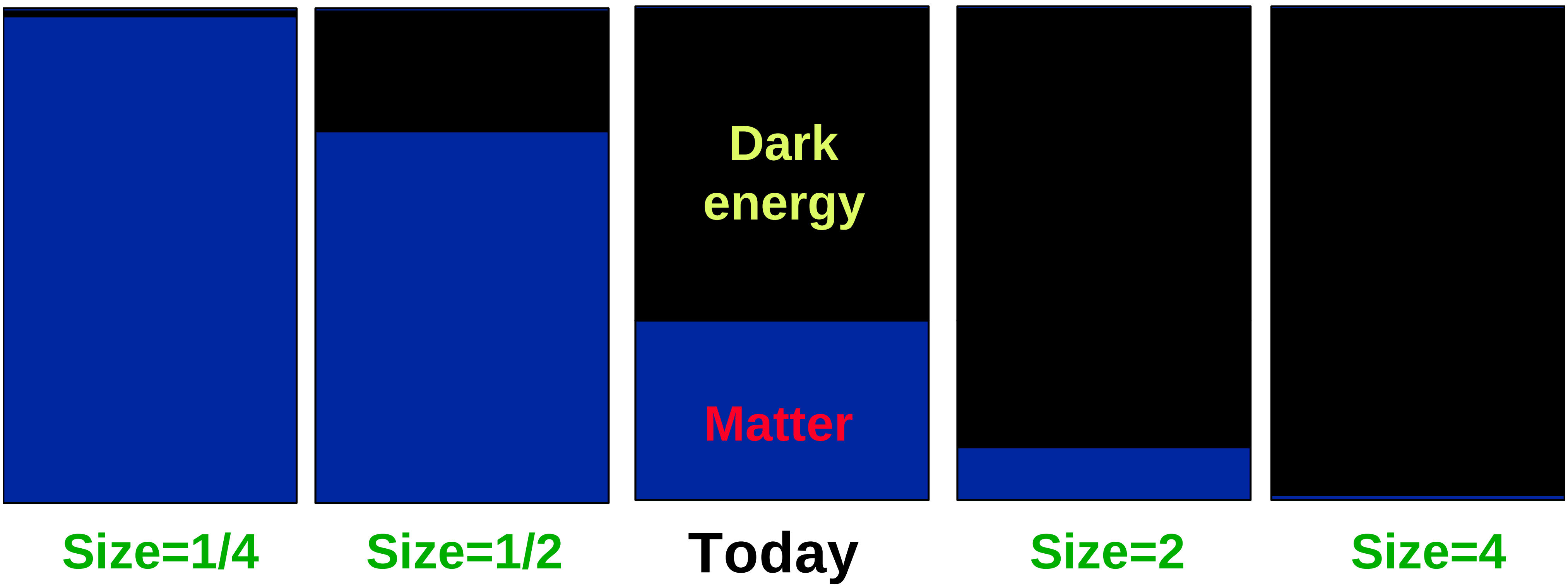
Why didn't it take over the expansion billions of years ago, before galaxies (and us) had the chance to form?

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?

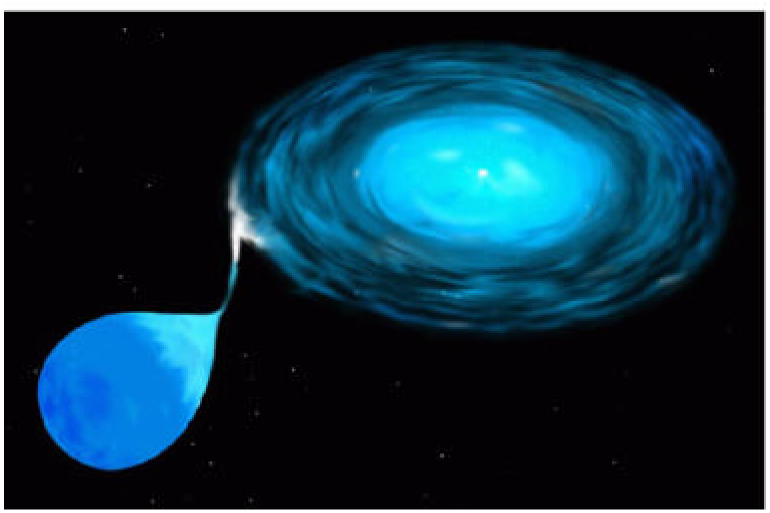
We need new, highly precise data

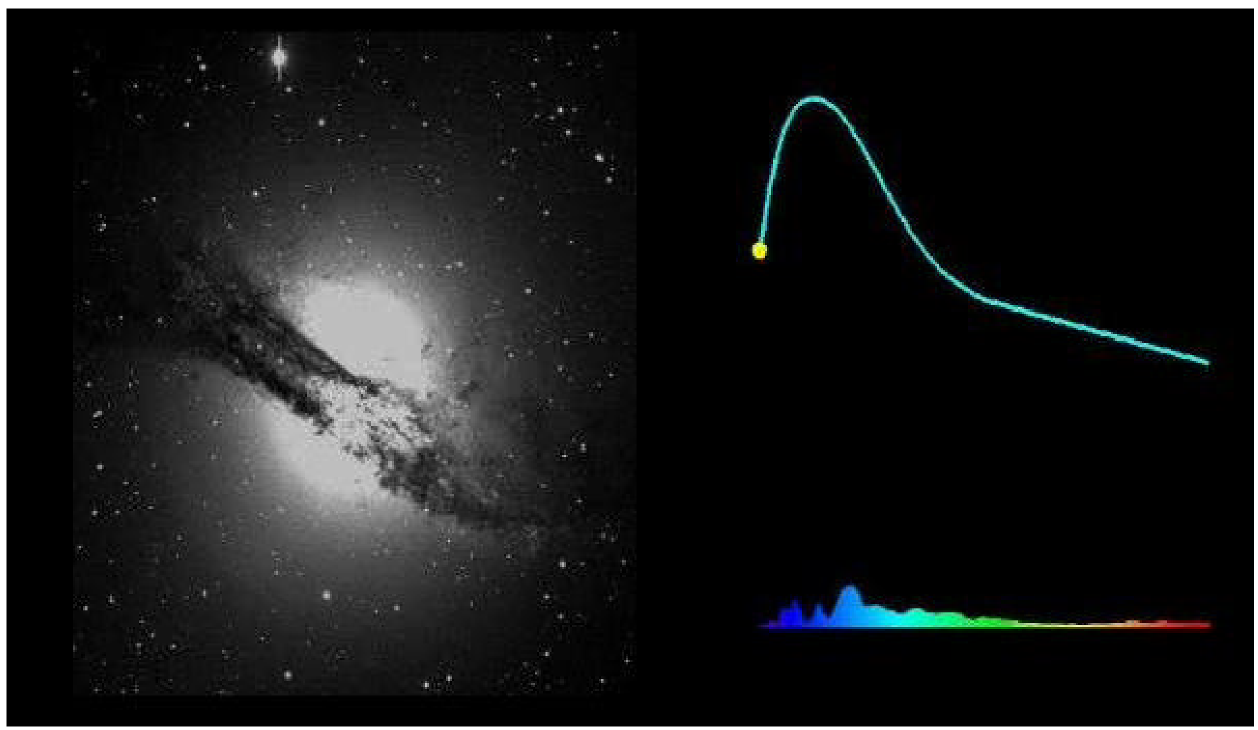
Type Ia Supernovae

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

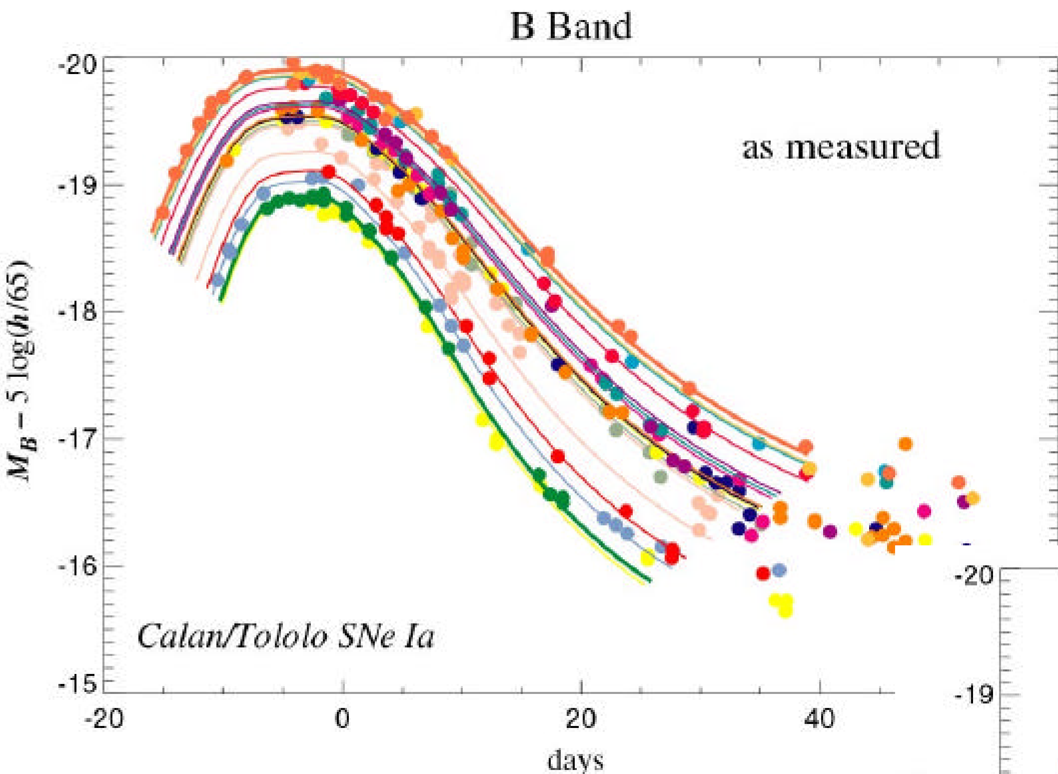
Standard explosion from nuclear physics

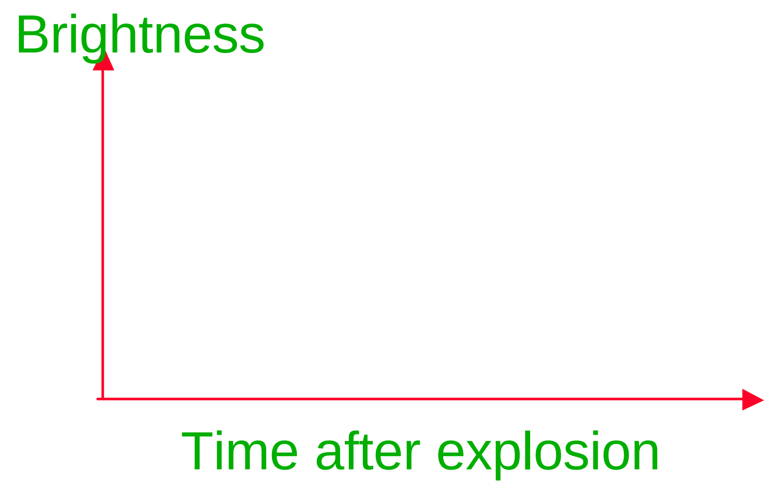
Insensitive to initial conditions:
"stellar amnesia"
Höflich, Gerardy, Linder, & Marion 2003

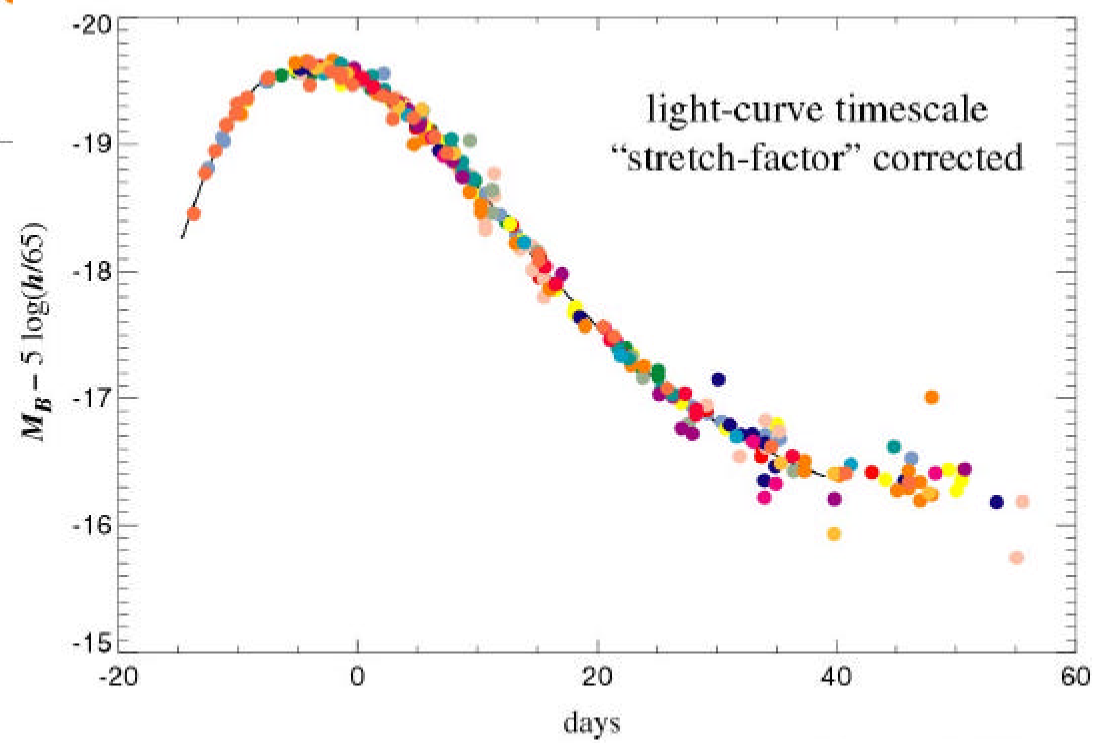




Standard Candle

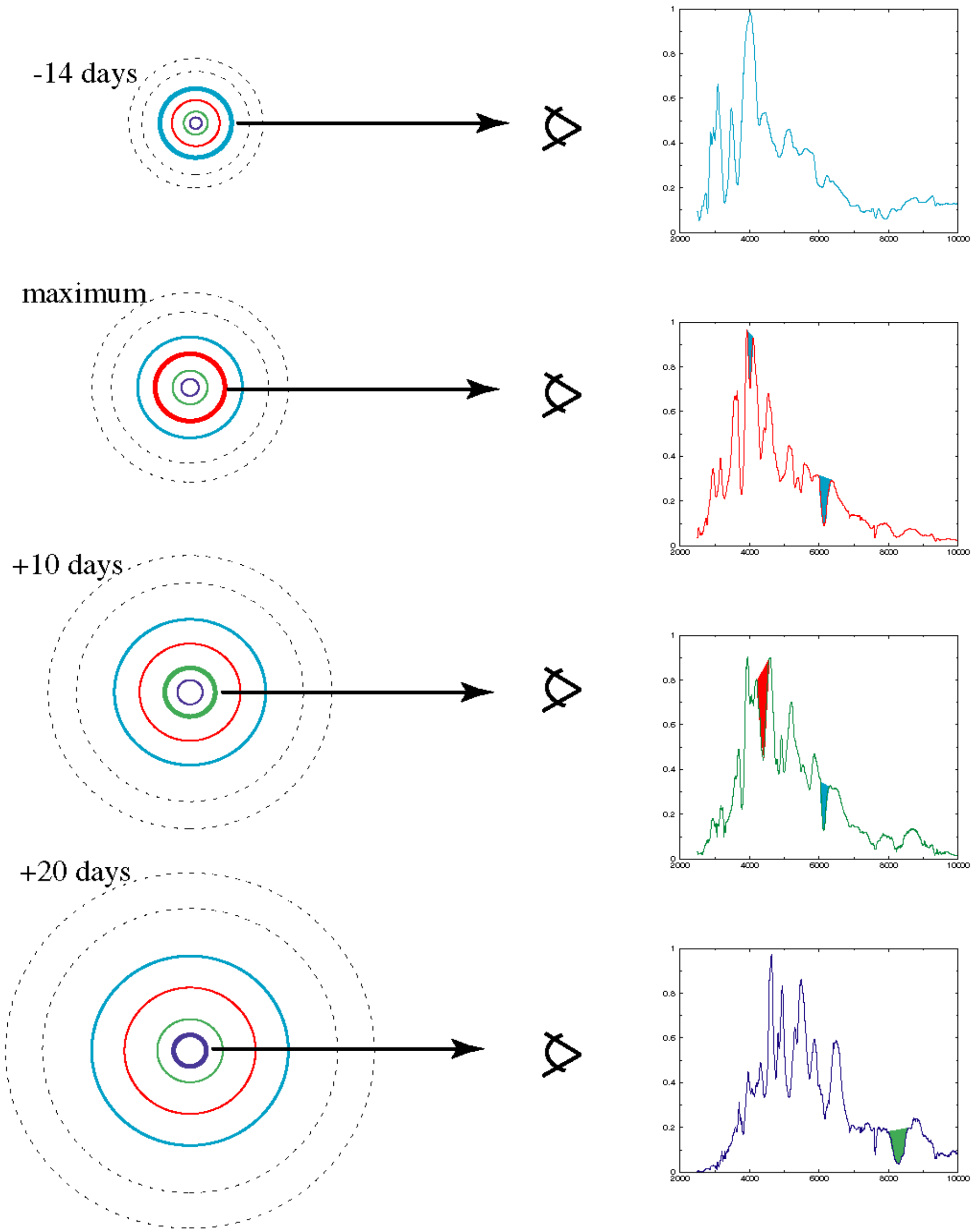






Kim, *et al.* (1997)

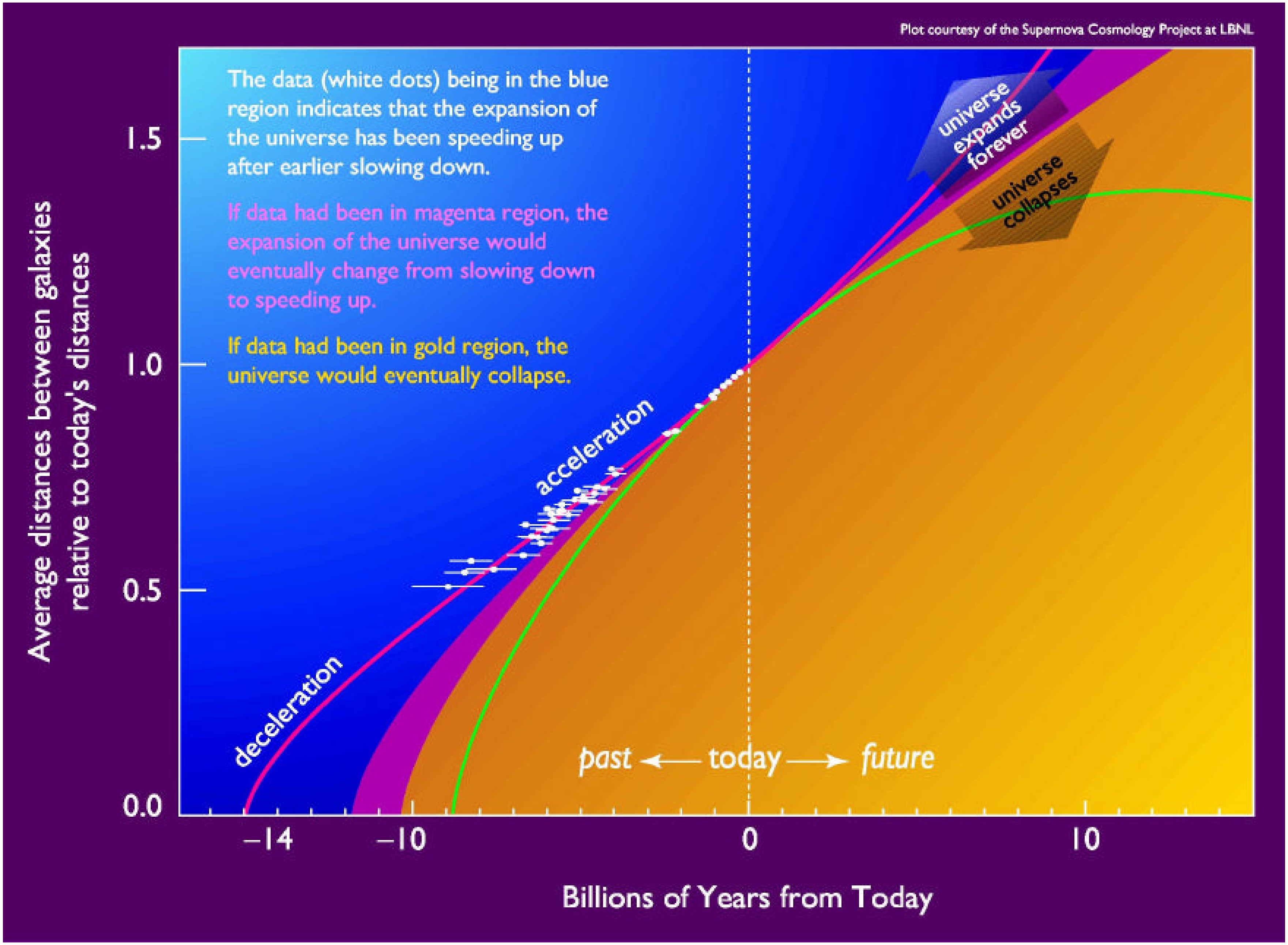
Supernova "CAT Scan"



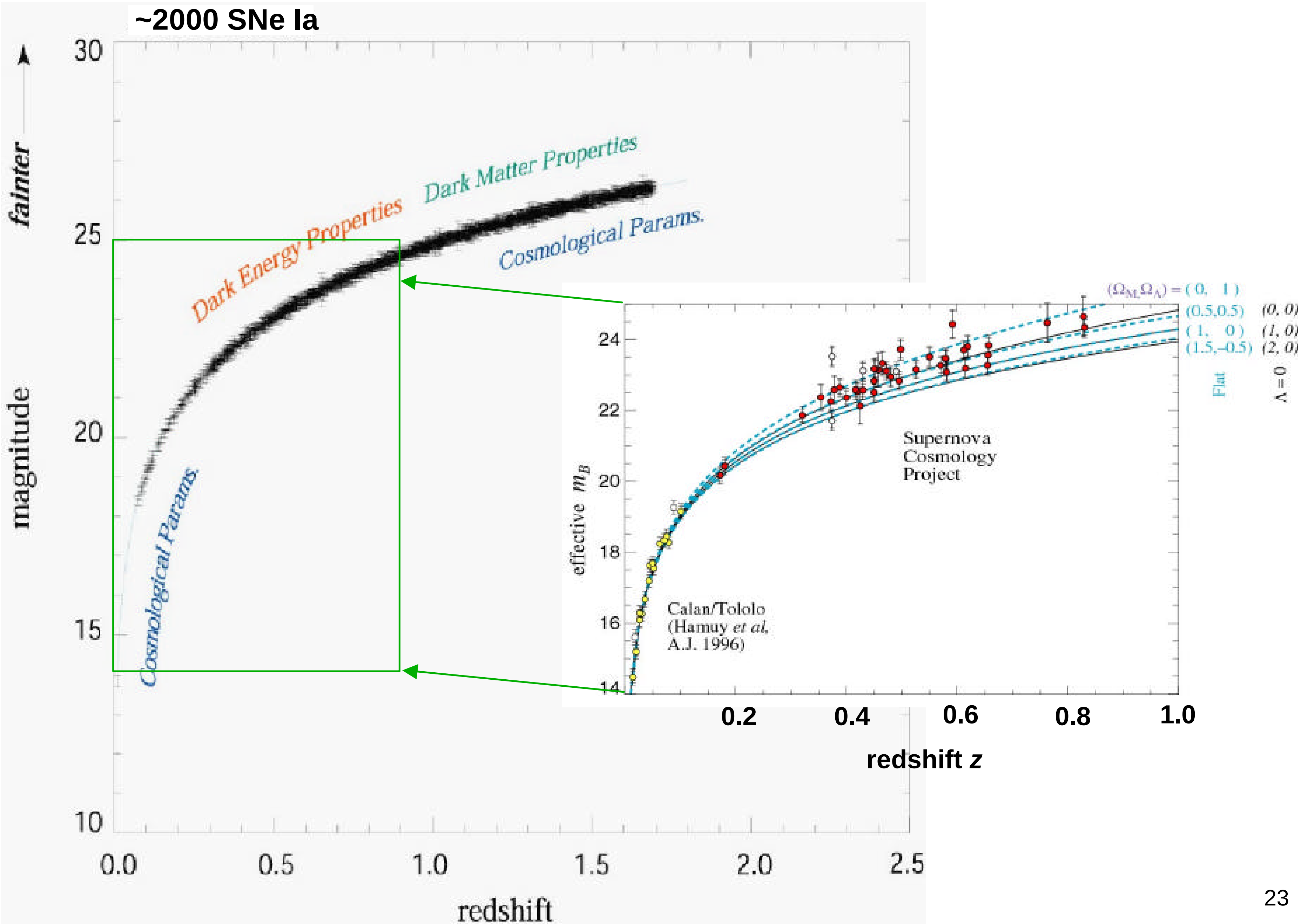
The energy spectrum of a supernova tells us in fine detail about its origin and properties.

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

History & Fate

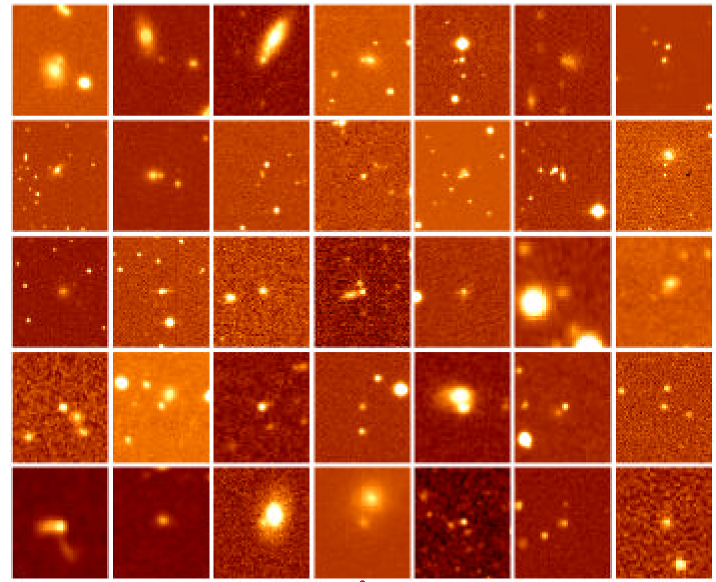


Hubble Diagram



Understanding Supernovae

Nearby Supernova Factory

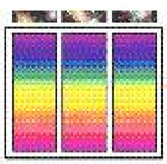


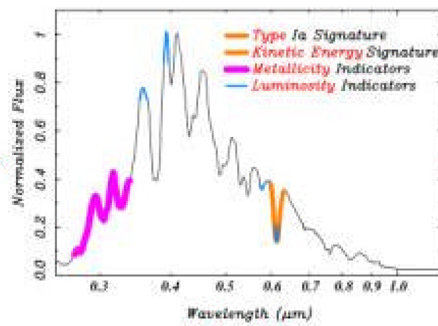
Best rookie year ever: 37 SNe (2002)

Leading the world in 2003: 44 SNe + …

G. Aldering (LBL)

Spectra





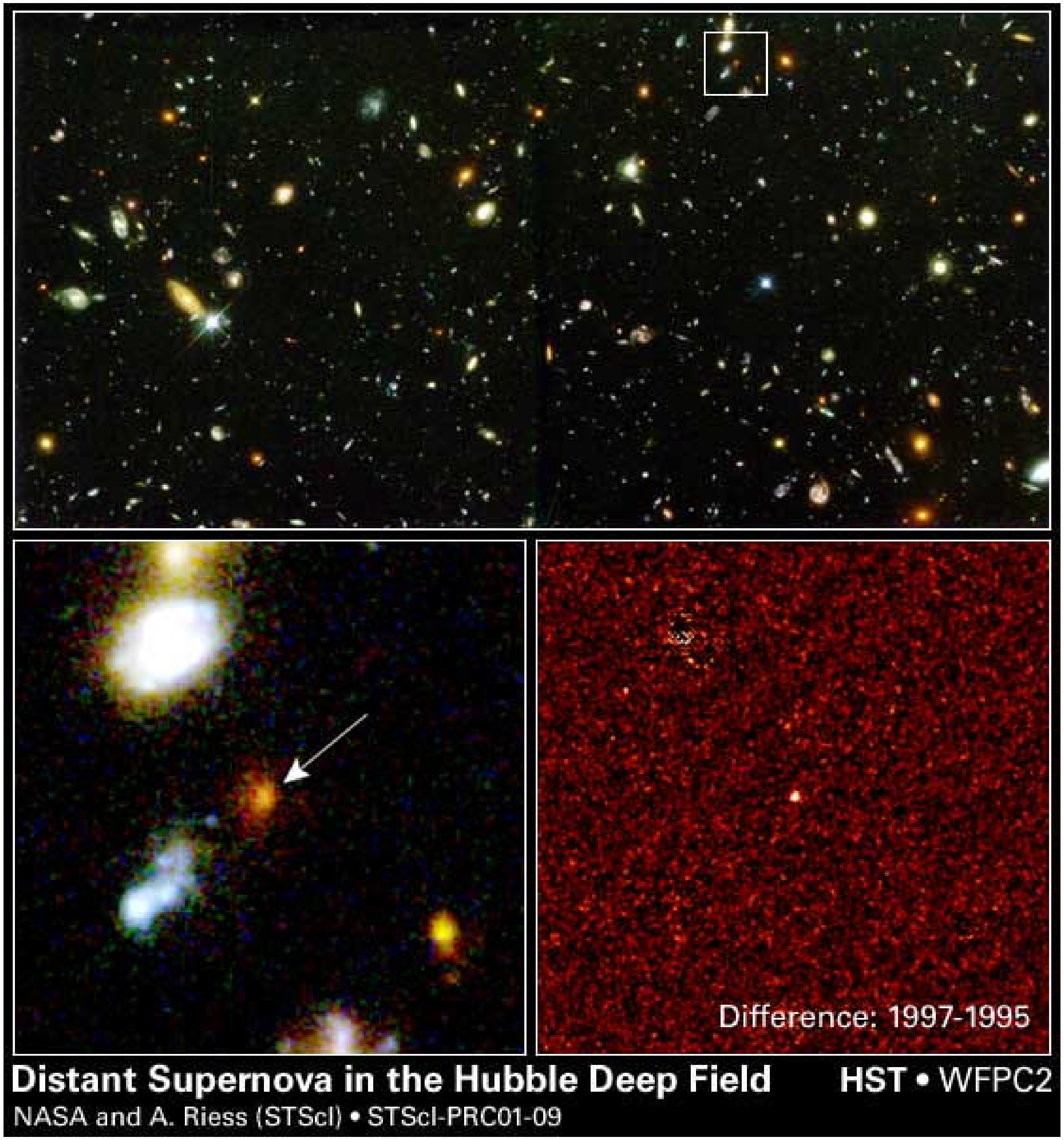
Supernova Properties Astrophysics

data → analysis → physics

Cleanly understood astrophysics leads to cosmology

Looking Back 10 Billion Years

Looking Back 10 Billion Years



Looking Back 10 Billion Years

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

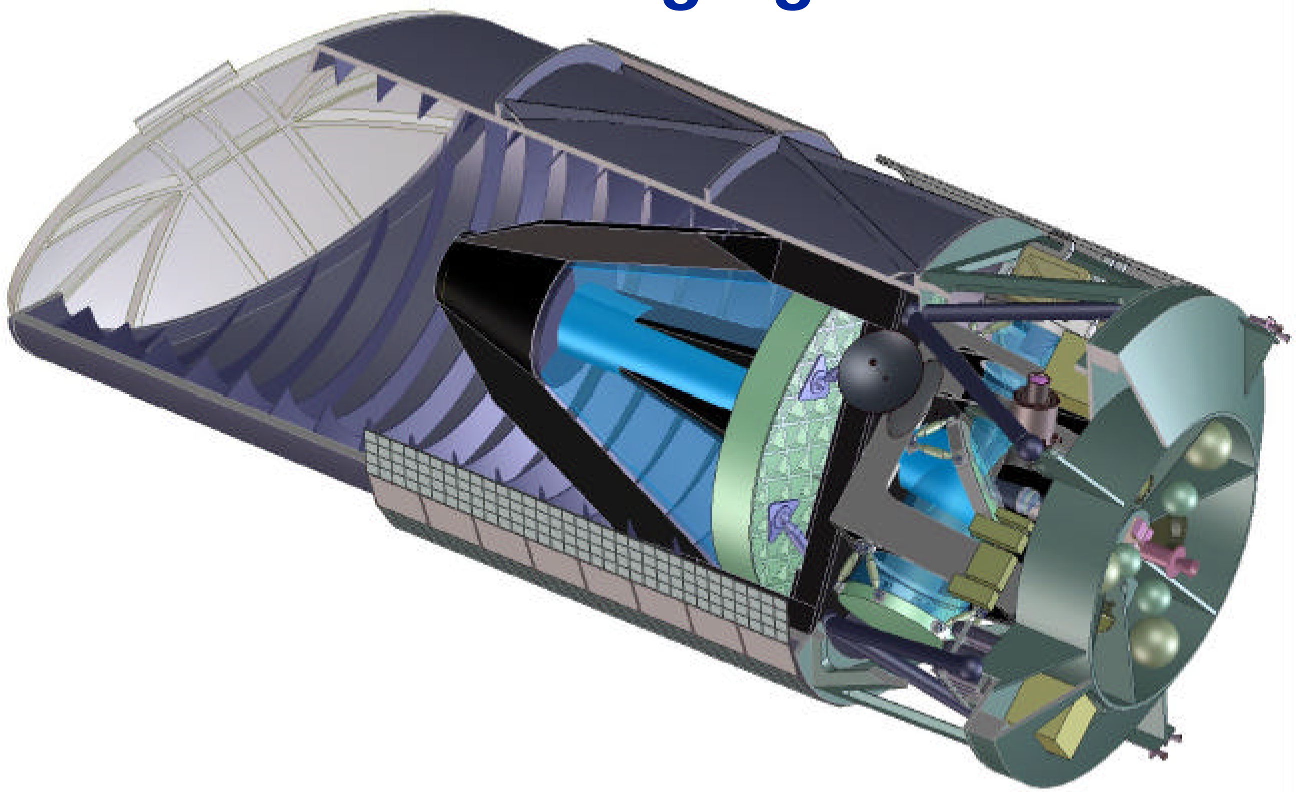
A Hubble Deep Field has scanned 1/25 millionth of the sky.

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 Λ(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, ½ billion pixels**

  Efficiently study large numbers of SNe.

- **0.35 – 1.7 μm spectrograph**

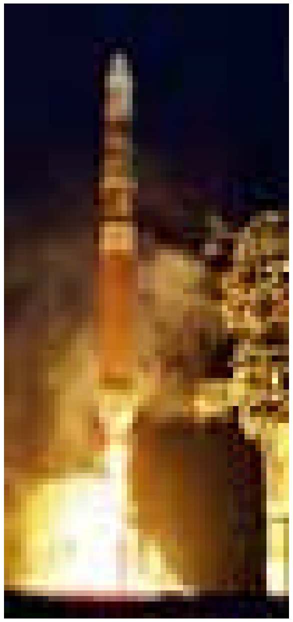
  Analyze in detail each SN.

Dedicated instrument designed to repeatedly observe an area of sky.

Essentially no moving parts.

4 year operation for experiment (lifetime open ended).

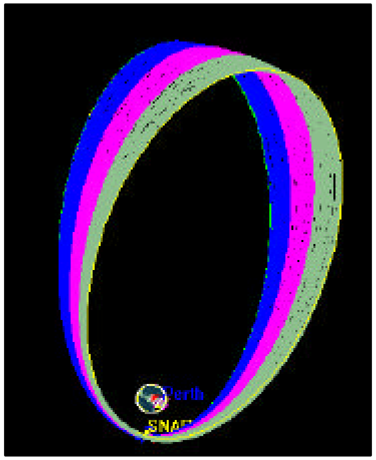
SNAP: Technical Details

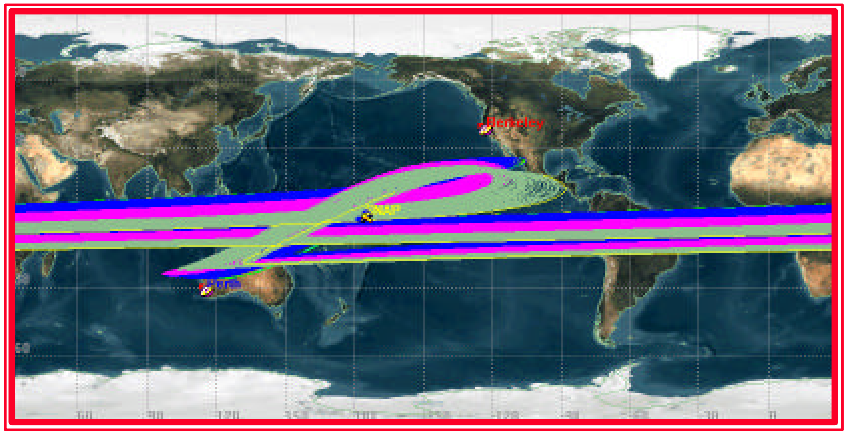


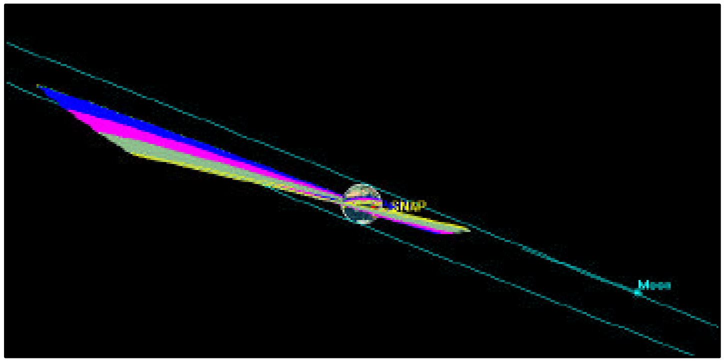
Launch by Delta IV (from KSC) in 2010

High earth, 3 day synchronous orbit

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



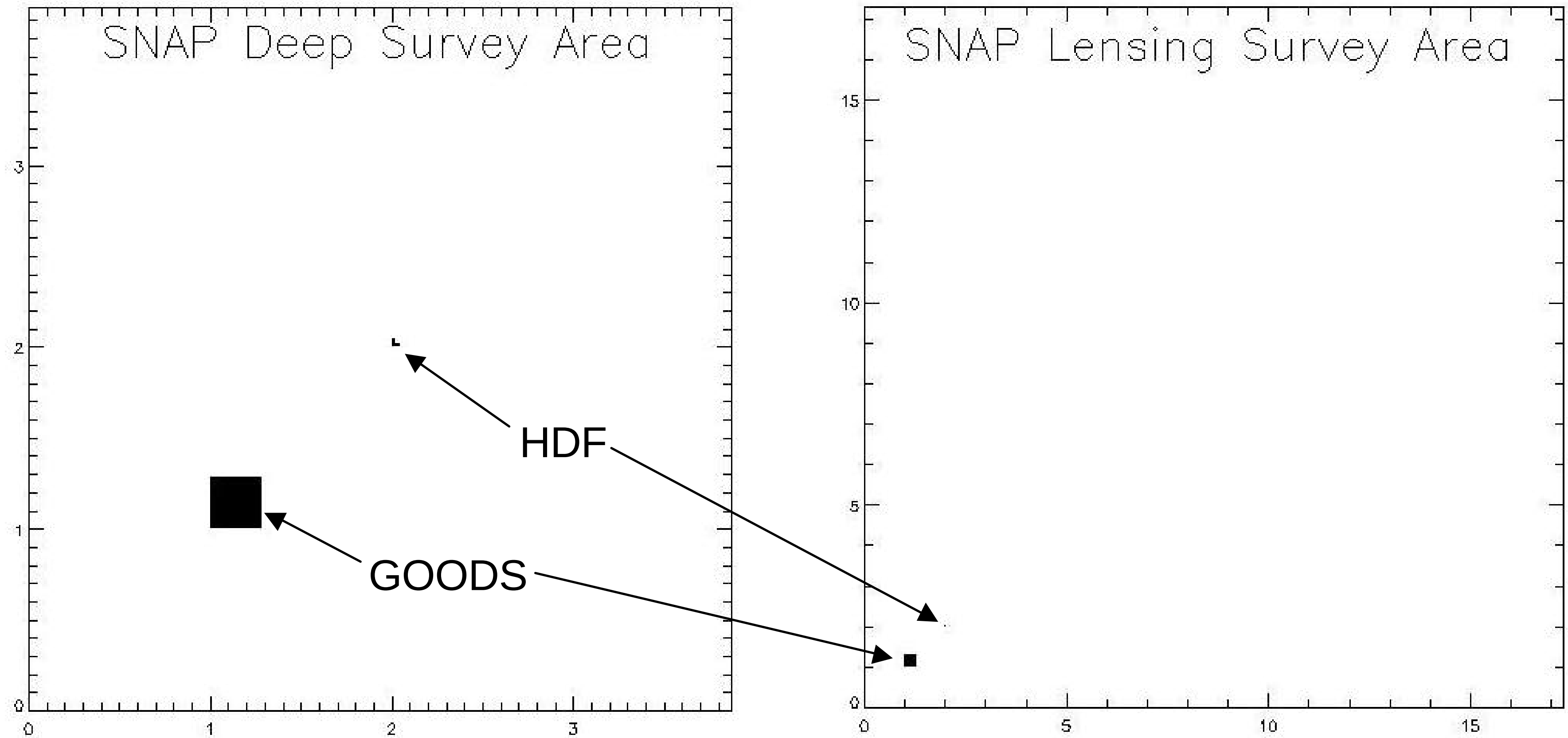




SNAP Survey Fields

15 sq.deg. Deep Survey

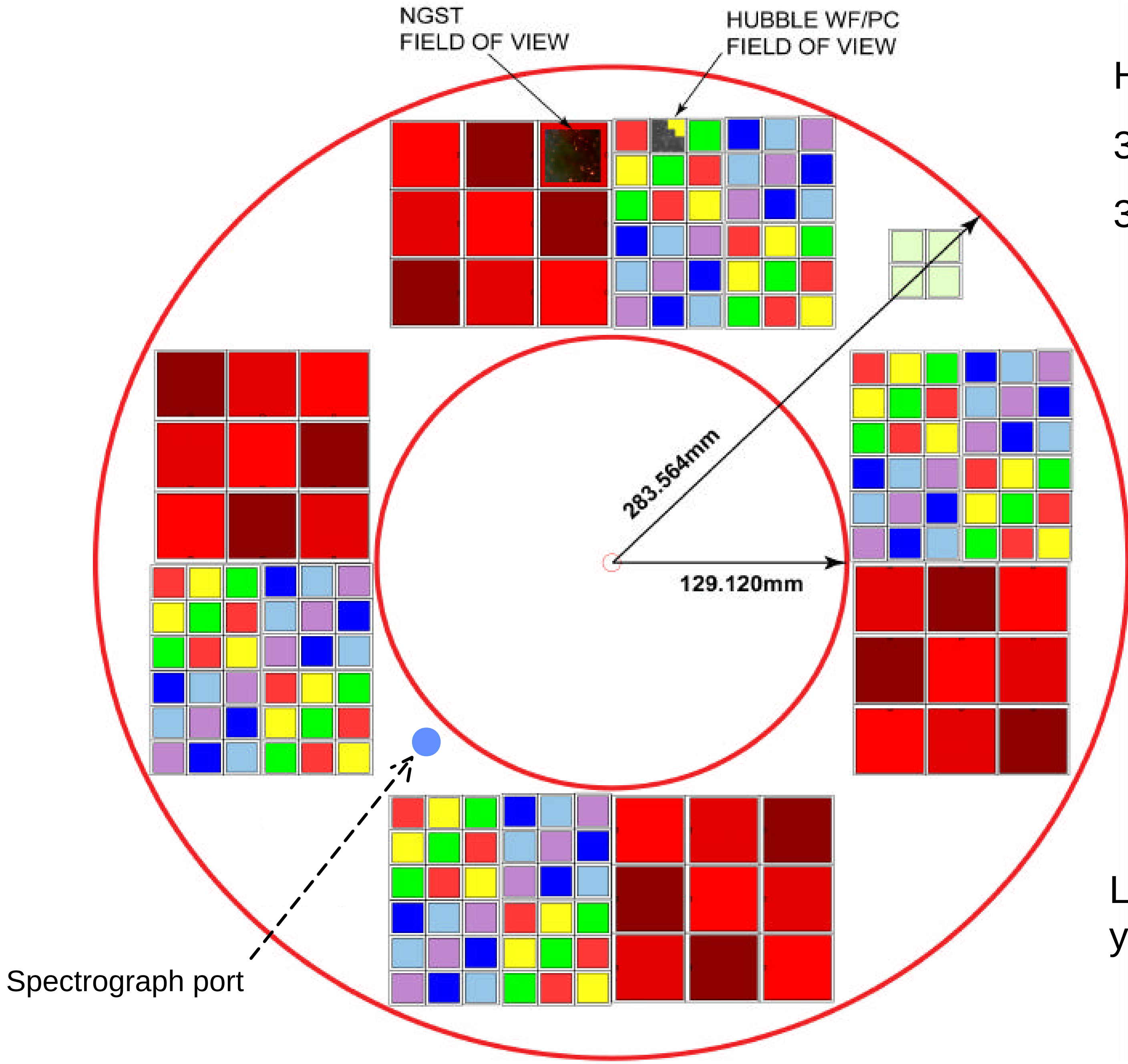
~300 sq.deg. Wide Survey



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

- 9 filters
- m_{AB}=28.1

Astronomical Imaging



Half billion pixel array

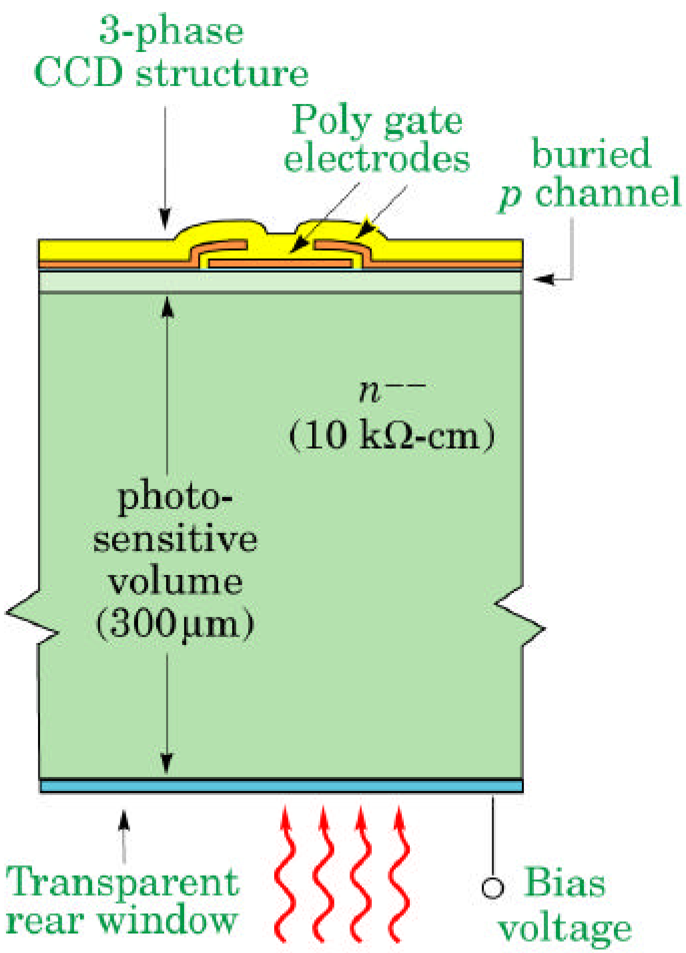
36 optical CCDs

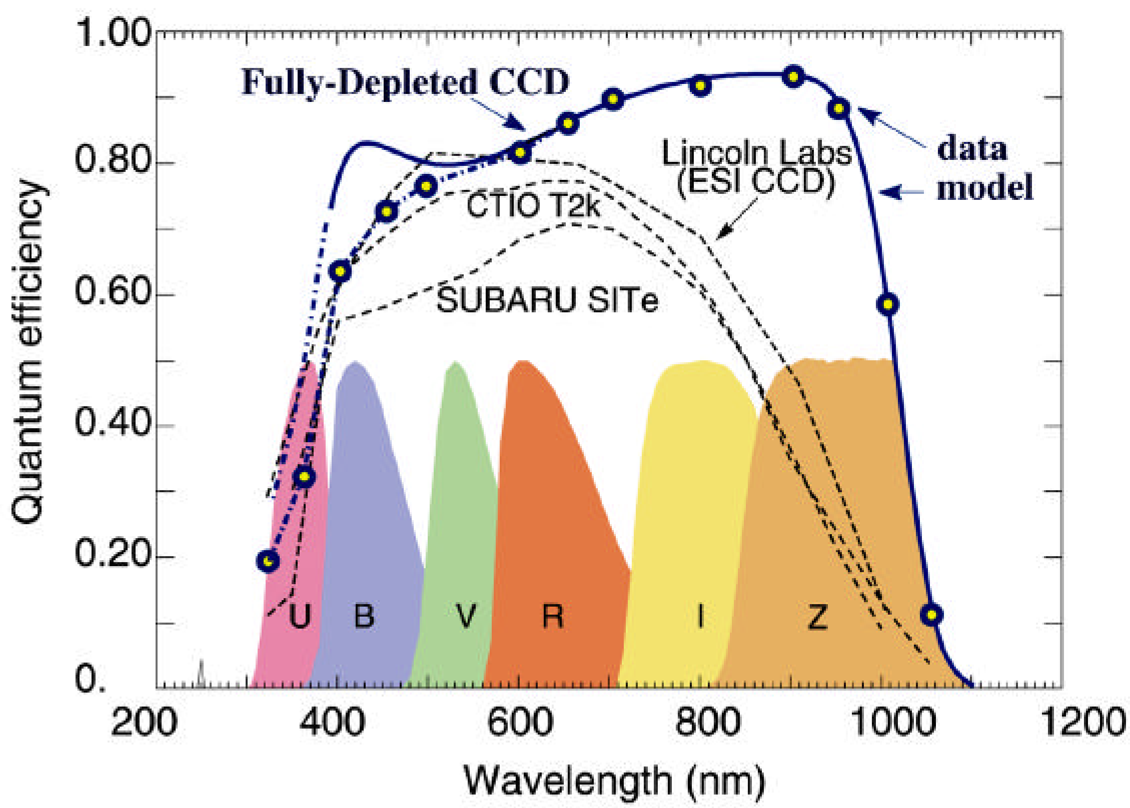
36 near infrared detectors

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



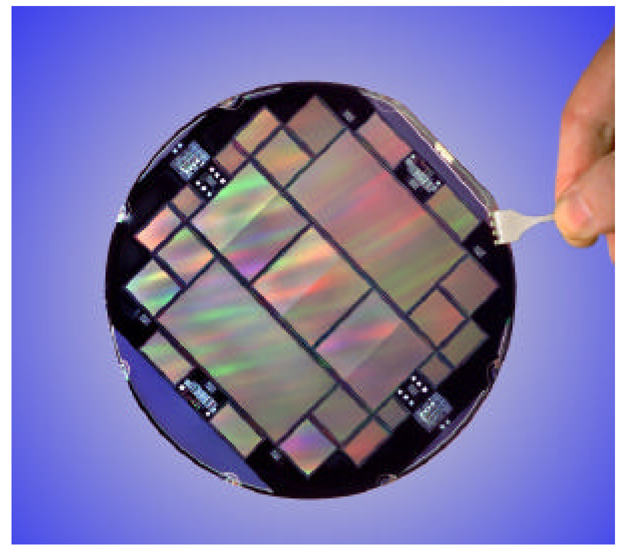


LBNL CCD's at NOAO

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 HeII 10124Å.

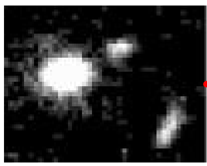
See September 2001 newsletter at http://www.noao.edu

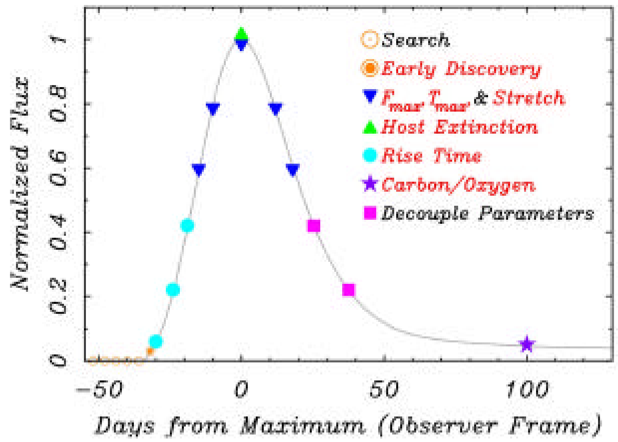
What makes the SN measurement special?
Control of systematic uncertainties

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

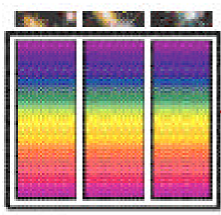


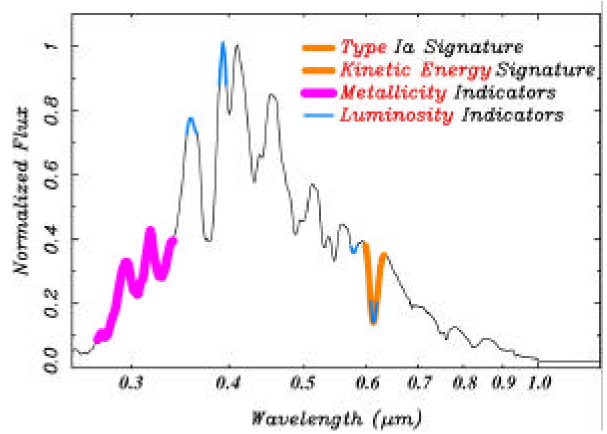


W_M **and** W_L
Dark Energy Properties

Redshift & SN Properties

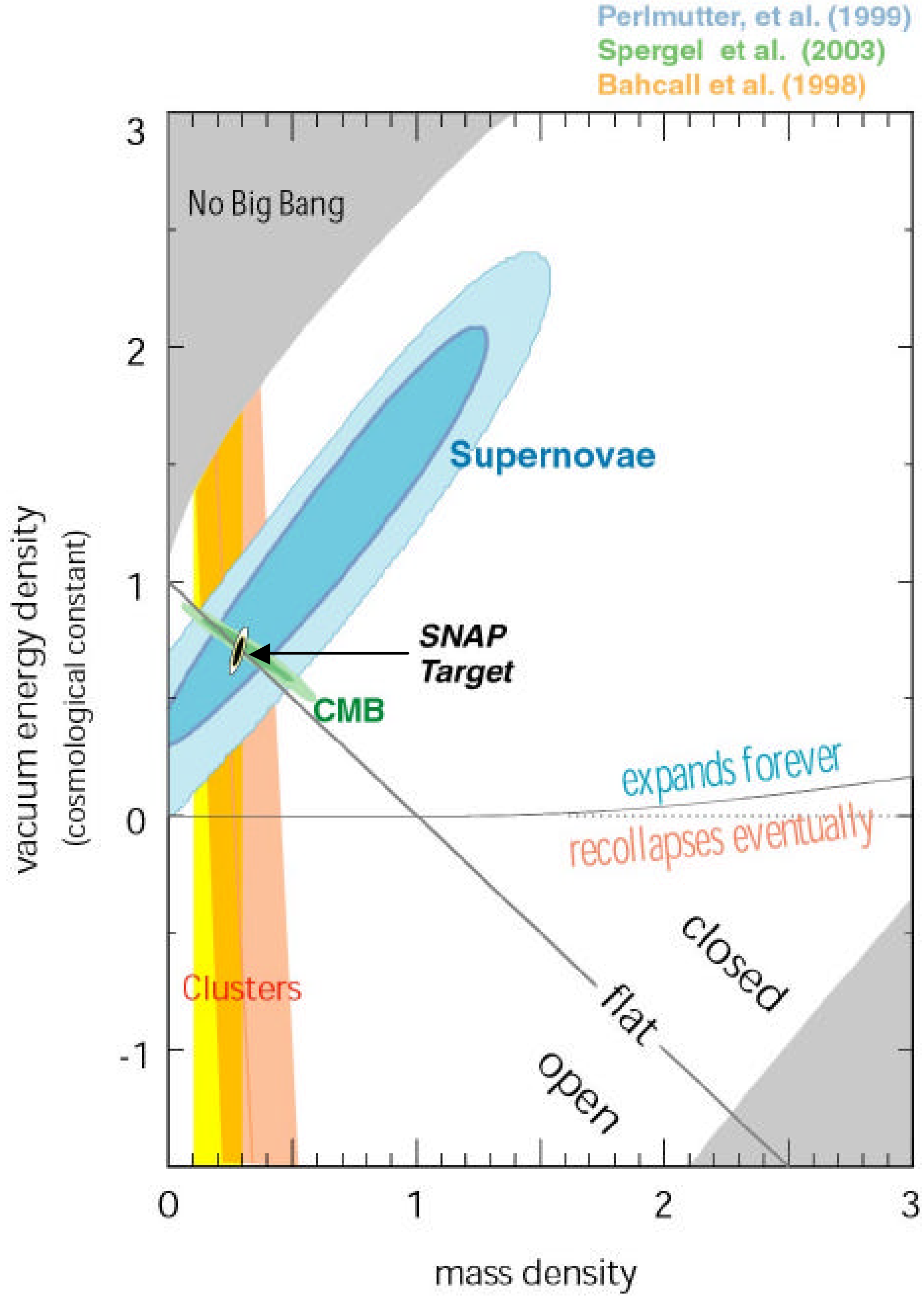
Spectra



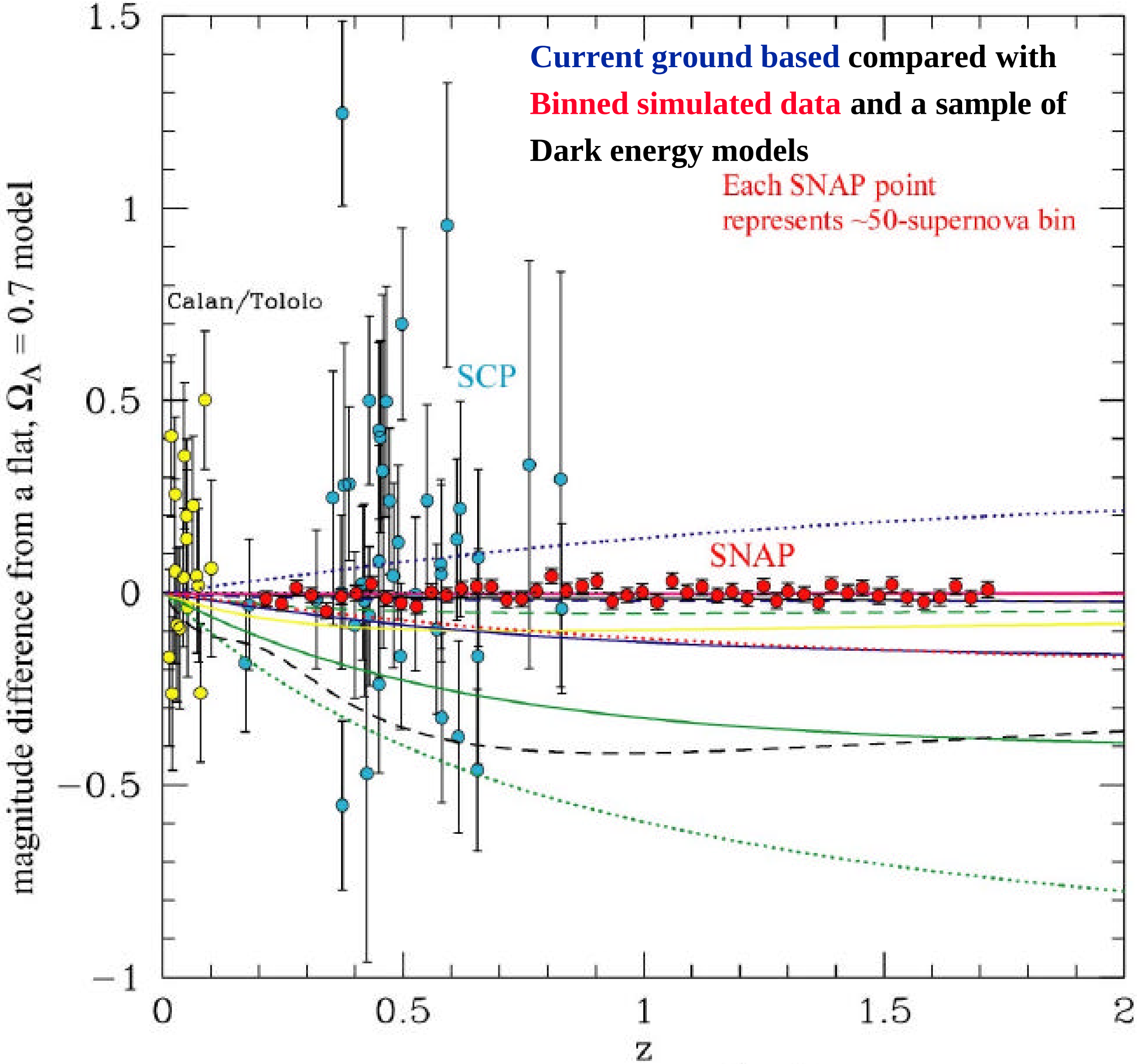


data → **analysis** → **physics**

SNAP: The Third Generation



Exploring Dark Energy



based on
Weller & Albrecht (2001)

Science Reach

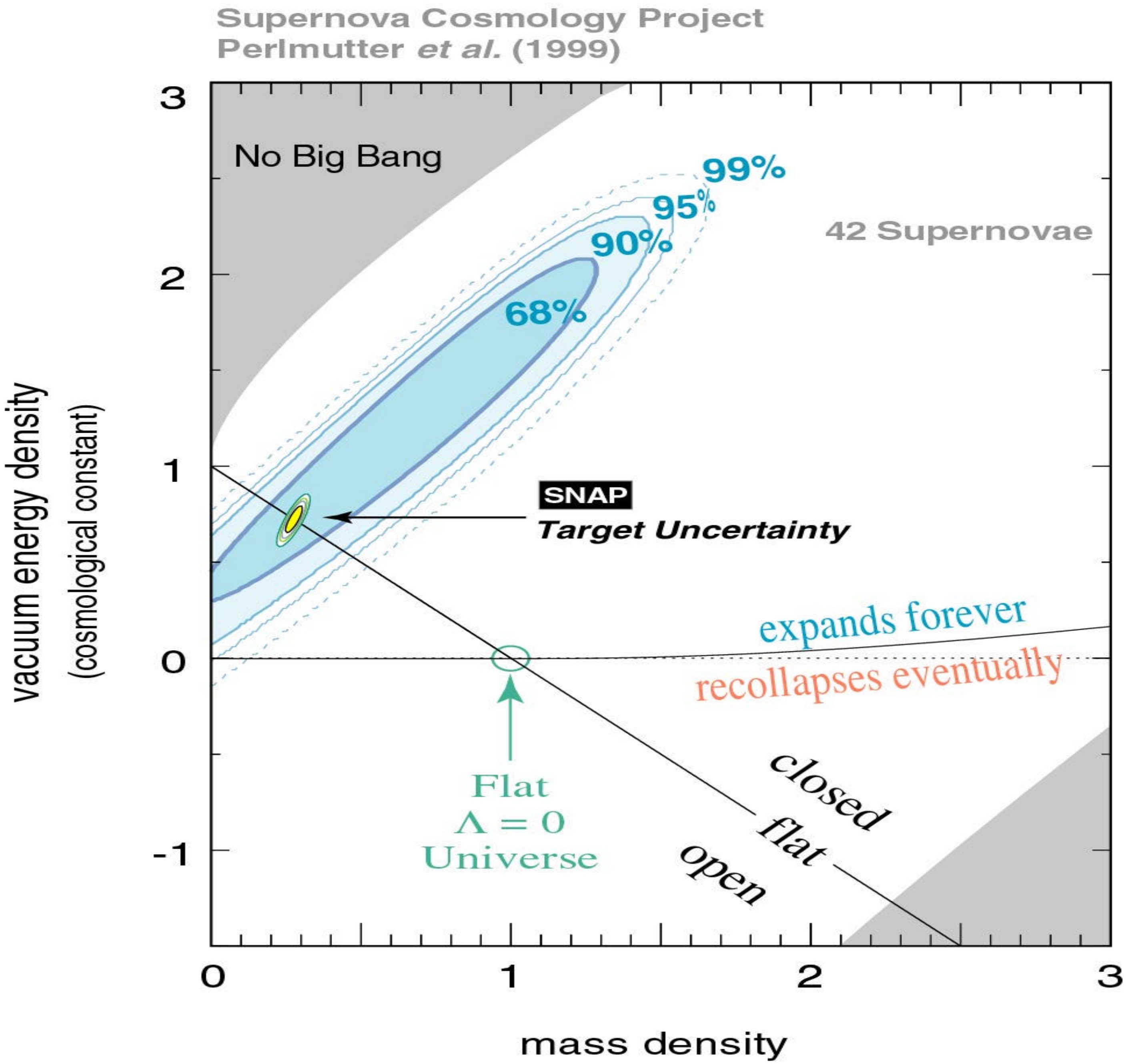
SNAP parameters from 2000 supernovae *including systematics*

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



Astronomy

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

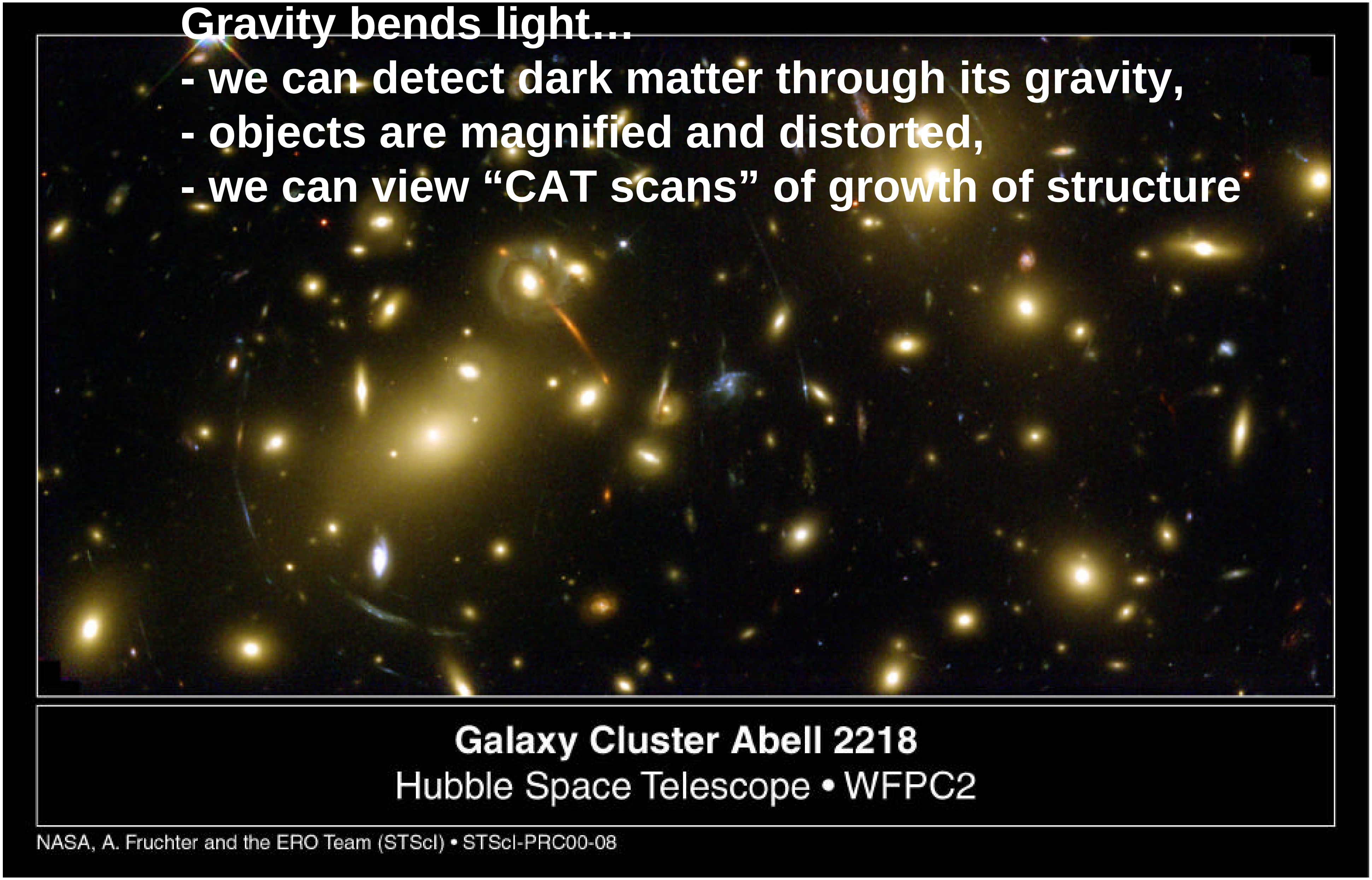
Gravitational Lensing

Gravity bends light…

- we can detect dark matter through its gravity,

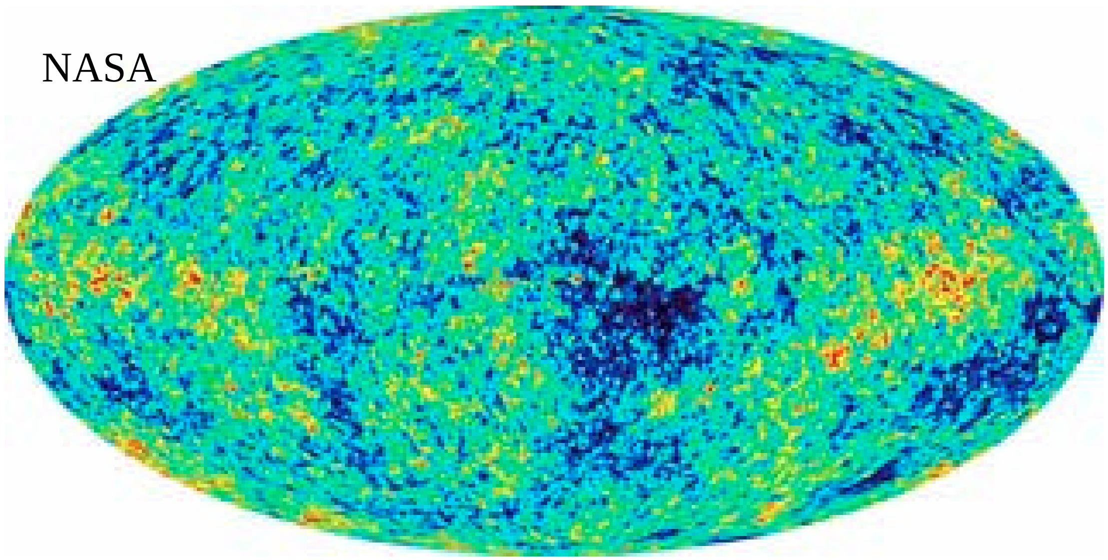
- objects are magnified and distorted,

- we can view “CAT scans” of growth of structure



Cosmic Background Radiation

NASA

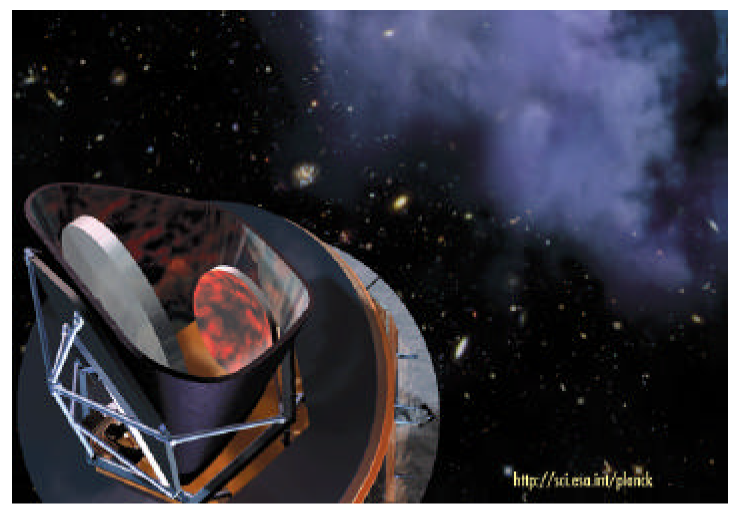


Snapshot of universe at 380,000 years old, 1/1100 the size

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)

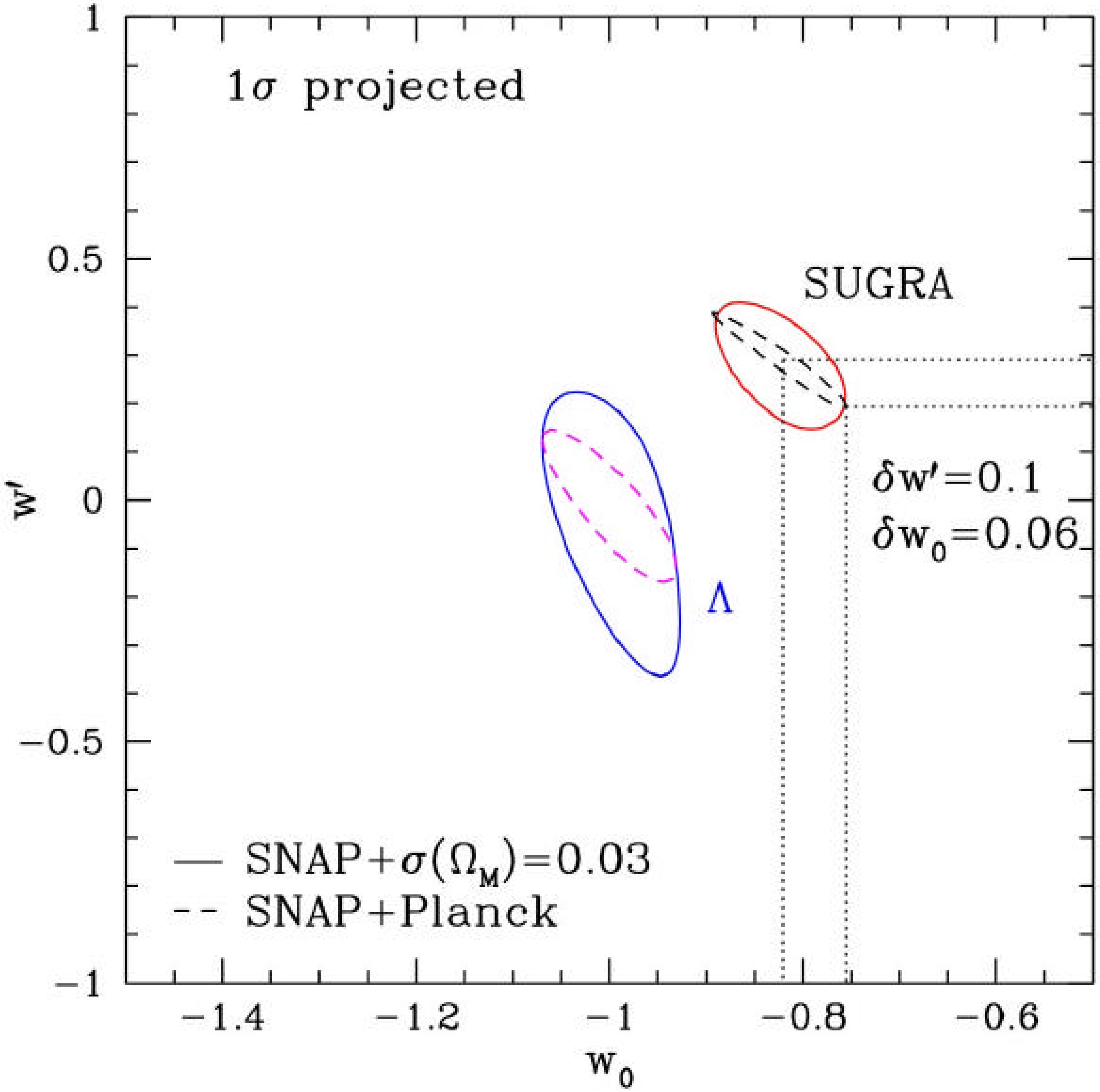
ESA



Complementarity

SNAP tightly constrains dark energy models…

And plays well with others.



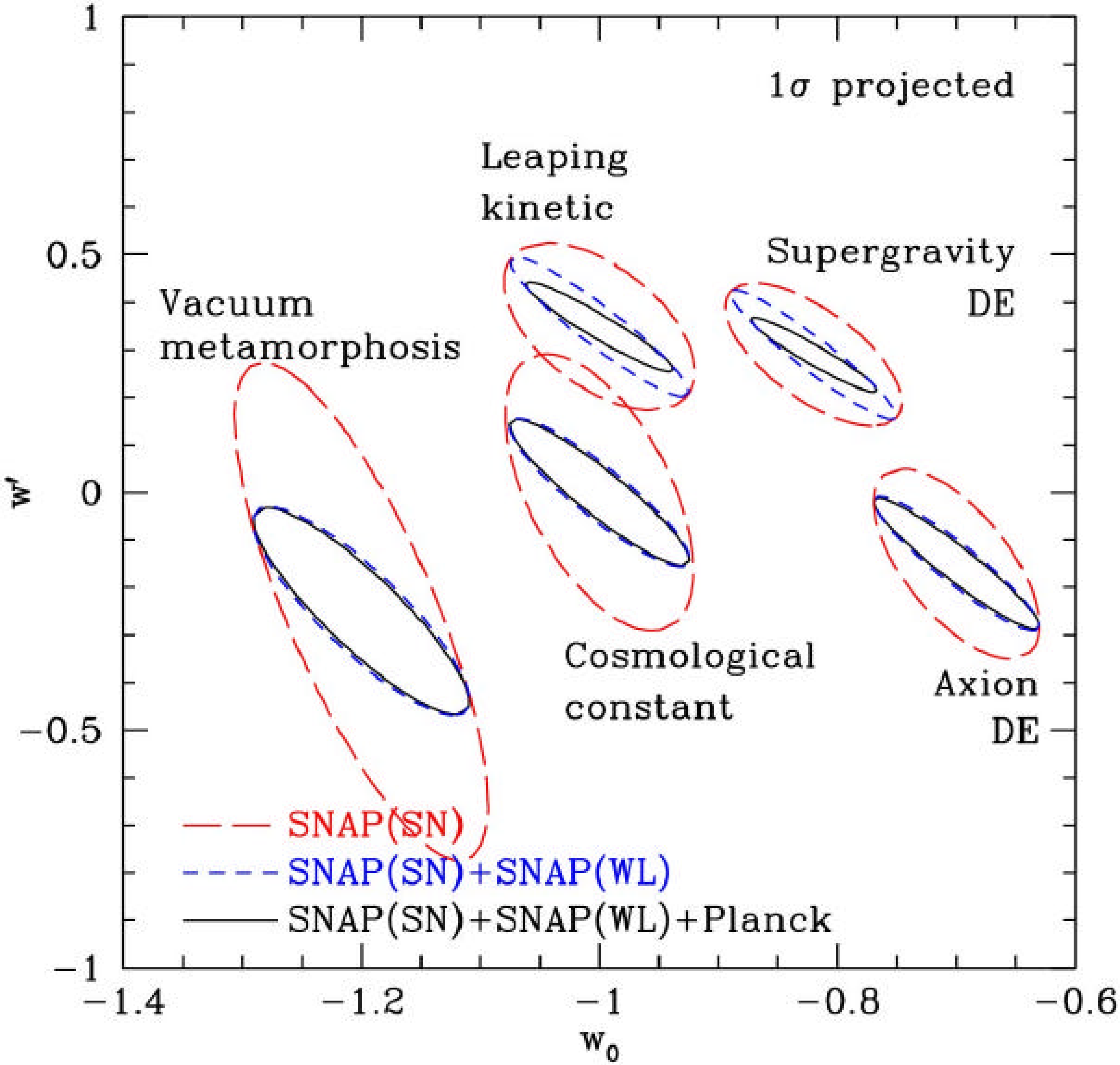
SNAP+Planck have excellent complementarity, equal to a prior $\sigma(\Omega_M) \leq 0.01$.

Frieman, Huterer, Linder, & Turner 2002

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

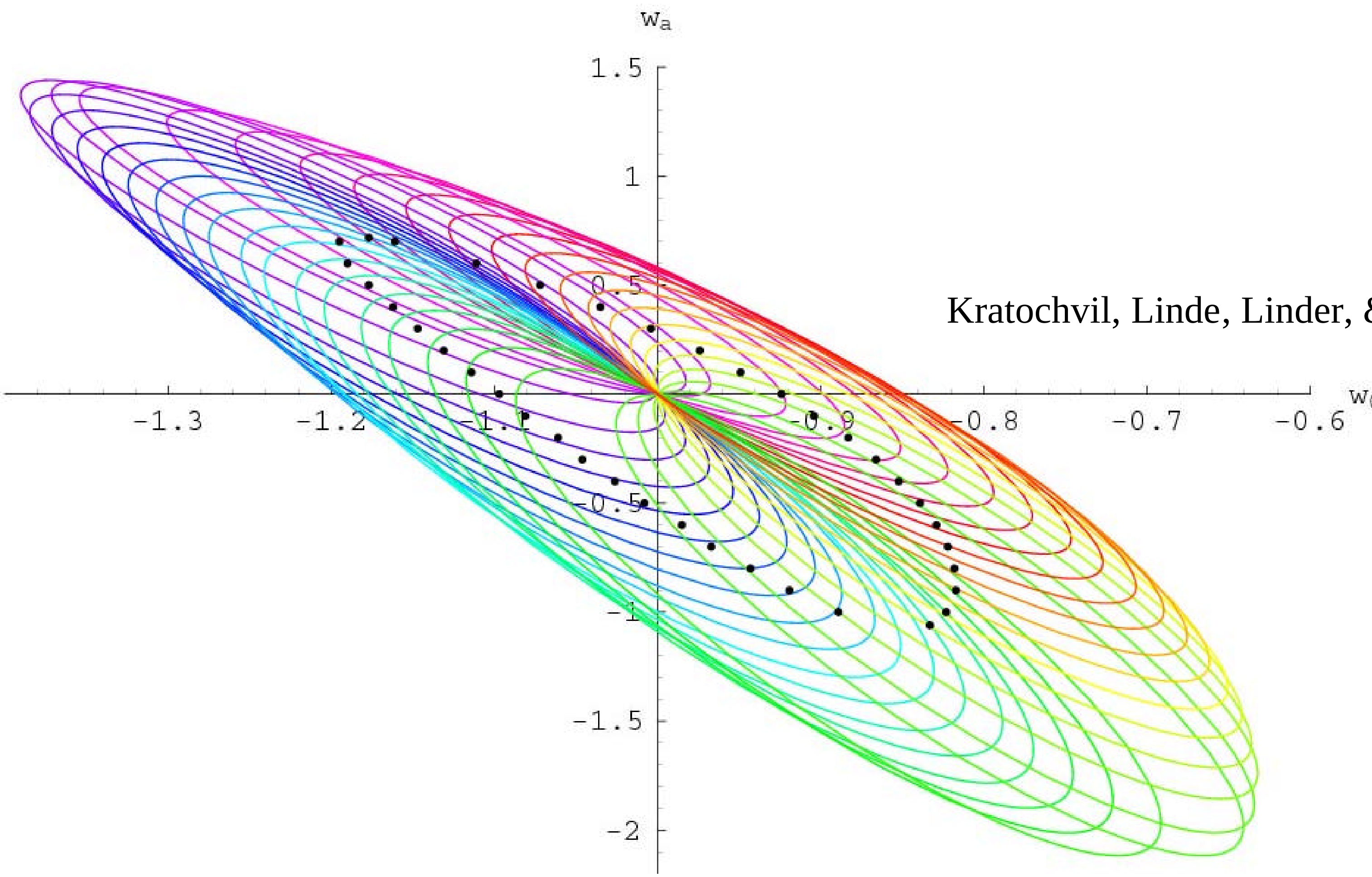
Fundamental Physics

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

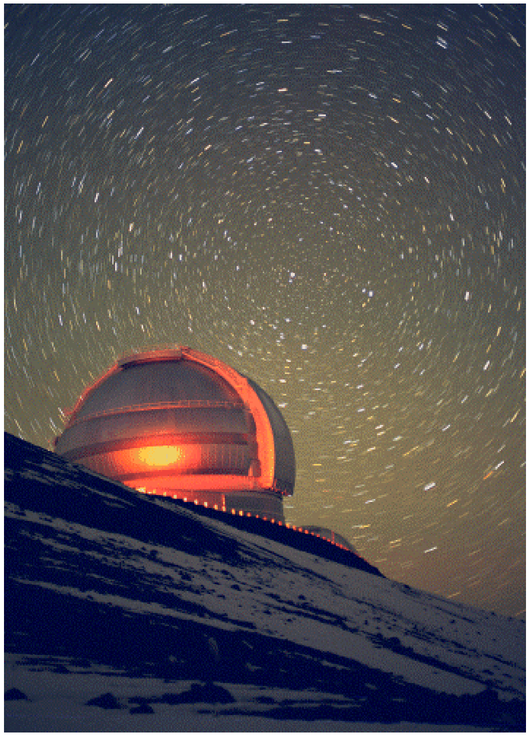


Kratochvil, Linde, Linder, & Shmakova

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

SNAP

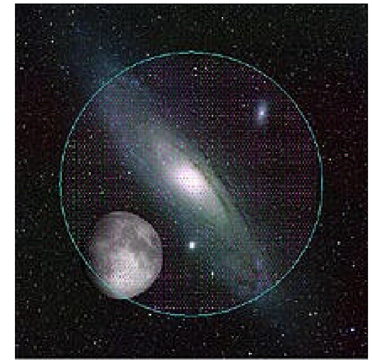


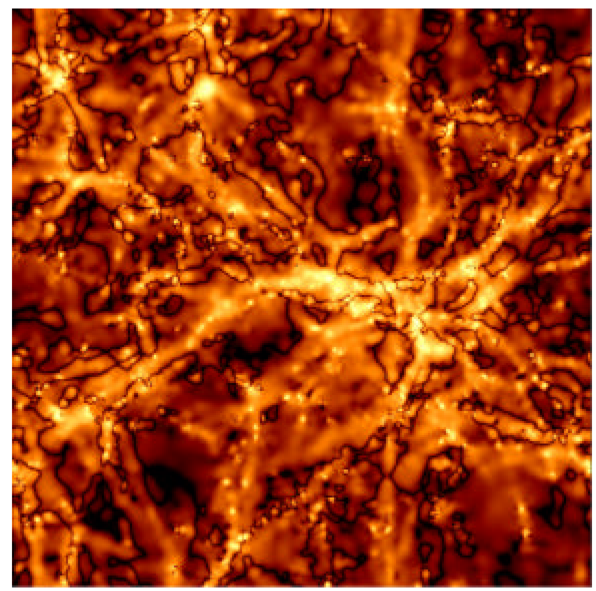
Gemini Observatory

K.A.O.S.

Kilo-Aperture Optical Spectrograph

Next generation instrument observing 4000 galaxies at once.





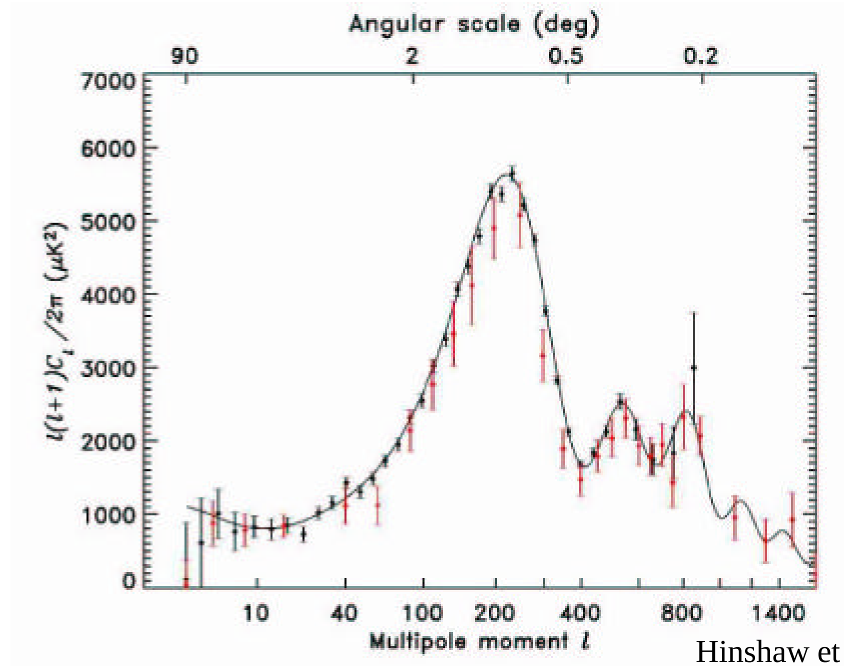
Computer simulations of the formation of galaxies, in collaboration with A. Jenkins (Durham University, England)

ICC Institute for Computational Cosmology

Primordial Imprints – Oscillations

CMB Power Spectrum

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



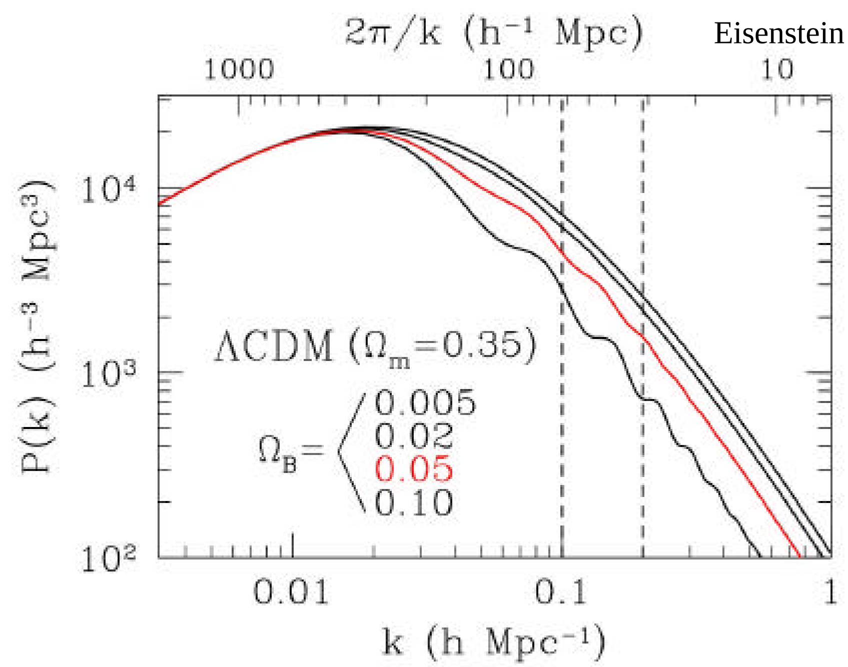
Hinshaw et al. 2003

Matter Power Spectrum

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

® wiggles

Eisenstein 2002



Cosmic Doomsday

What if the dark energy decays?

In some models the negative pressure can turn positive.

The universe is driven to collapse!

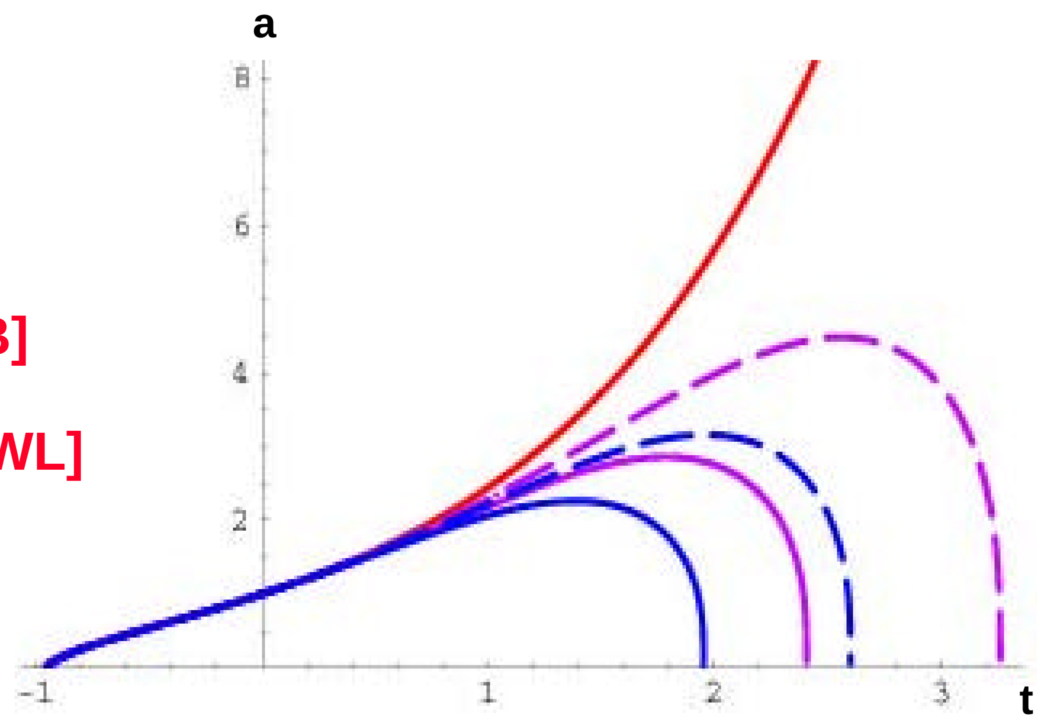
If we measure expansion history sufficiently precisely, we can predict the fate of the universe.

t_{doom}= ¥ (L)

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

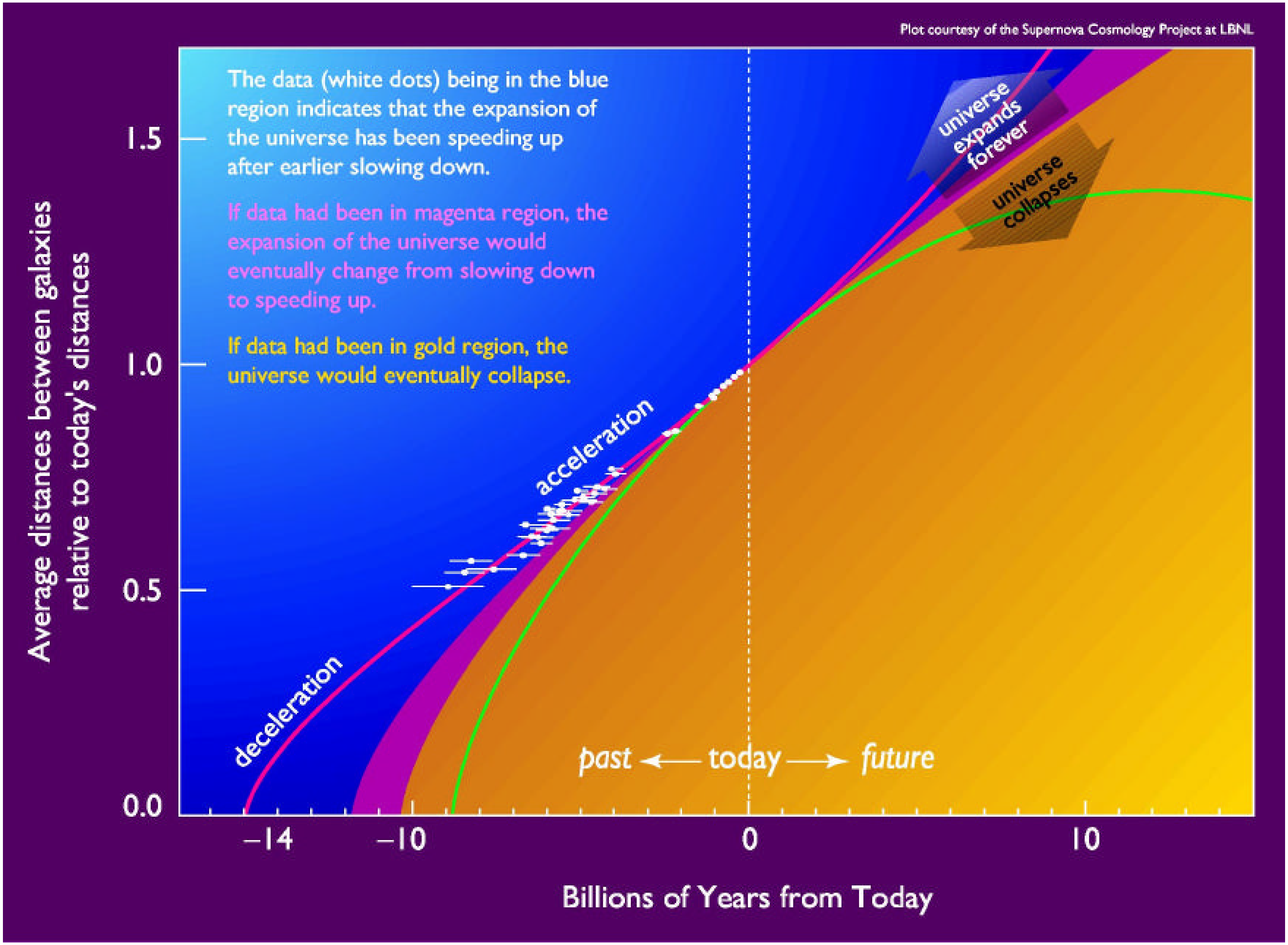
t_{doom} > 35 Gyr [95%SNAP+CMB]

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



Kallosh, Kratochvil, Linde, Linder, & Shmakova 2003

Fate of the Universe



Frontiers of the Universe

NASA-DOE
Joint Dark Energy Mission

Paul Hertz / NASA

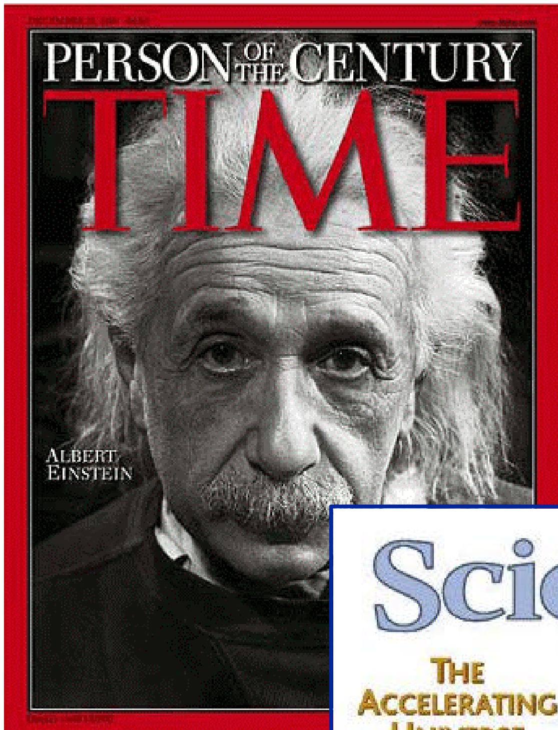
Robin Staffin / DOE

Endorsed by

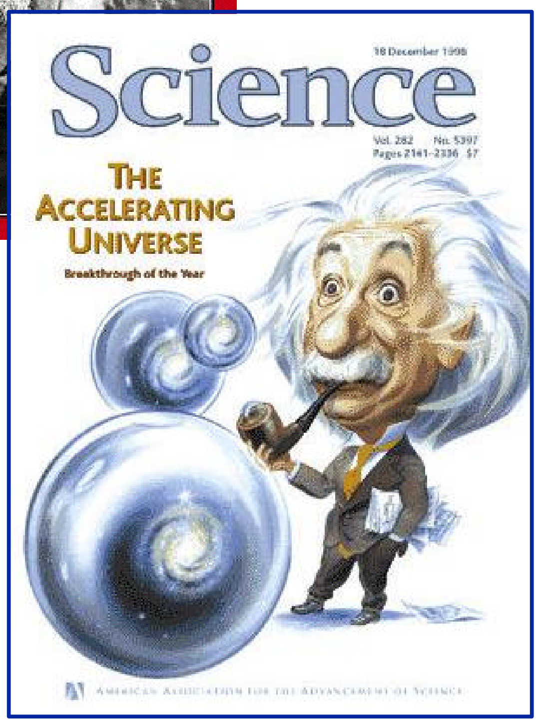
Raymond L. Orbach
Director of the Office of Science
Department of Energy

Edward J. Weiler
Associate Administrator for Space Science
NASA

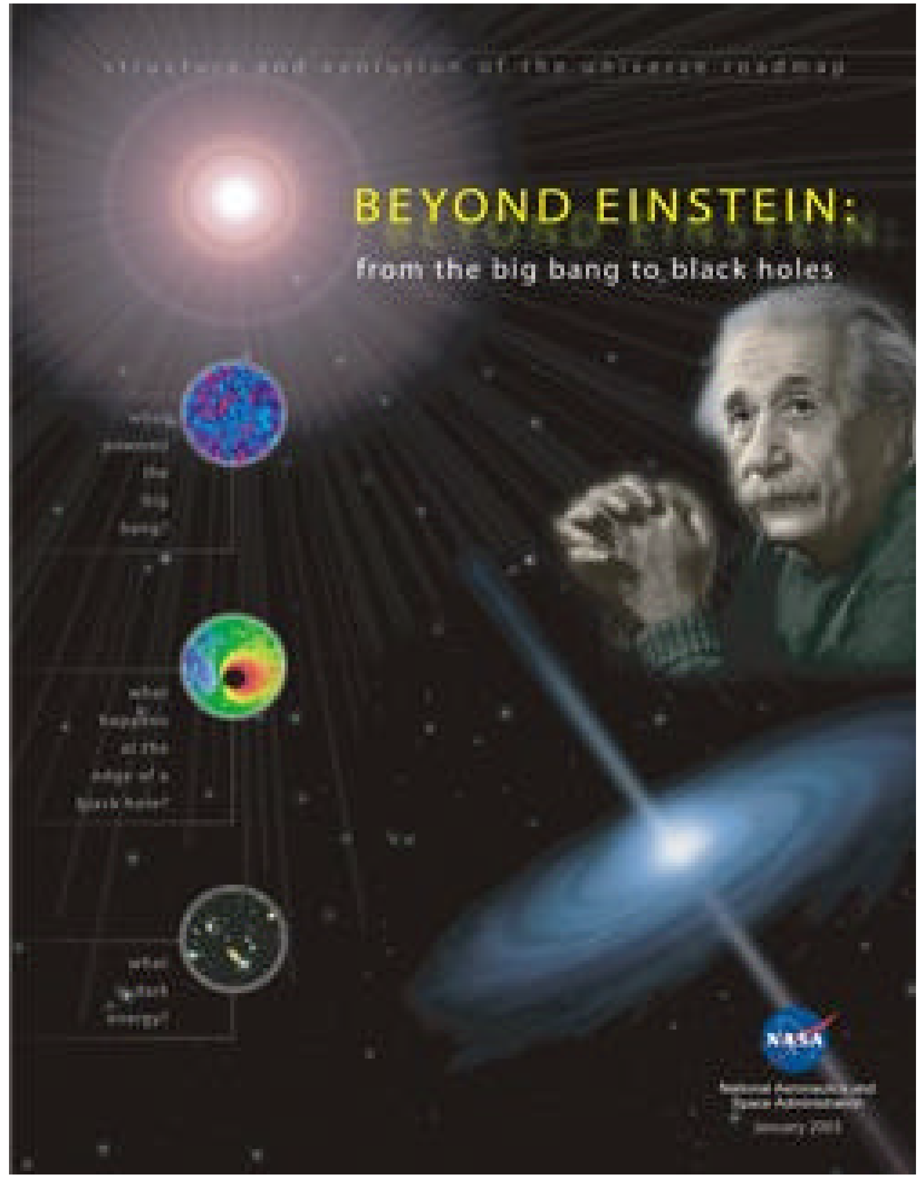
Frontiers of the Universe



1919



Breakthrough of the Year 1998



In the next decade…?