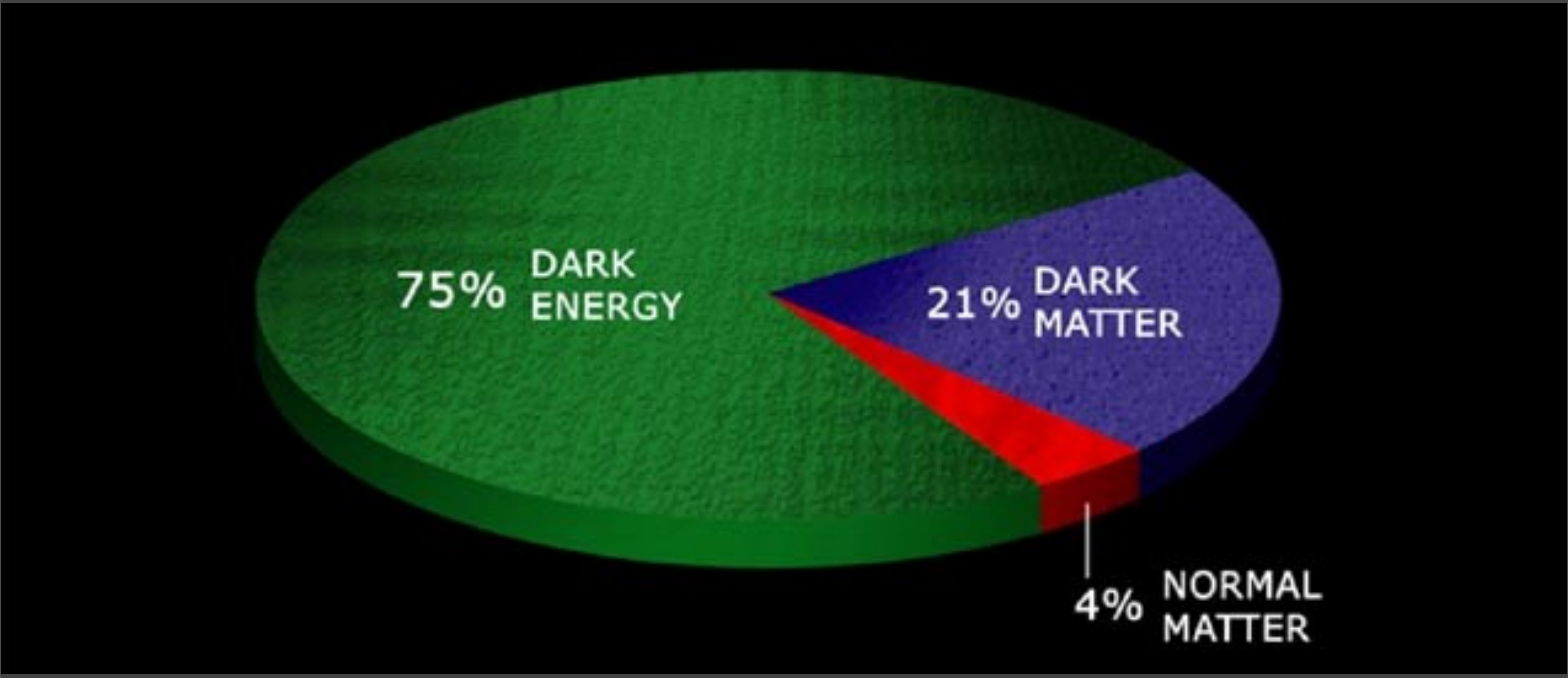
Cosmic Acceleration and Dark Energy

Josh Frieman

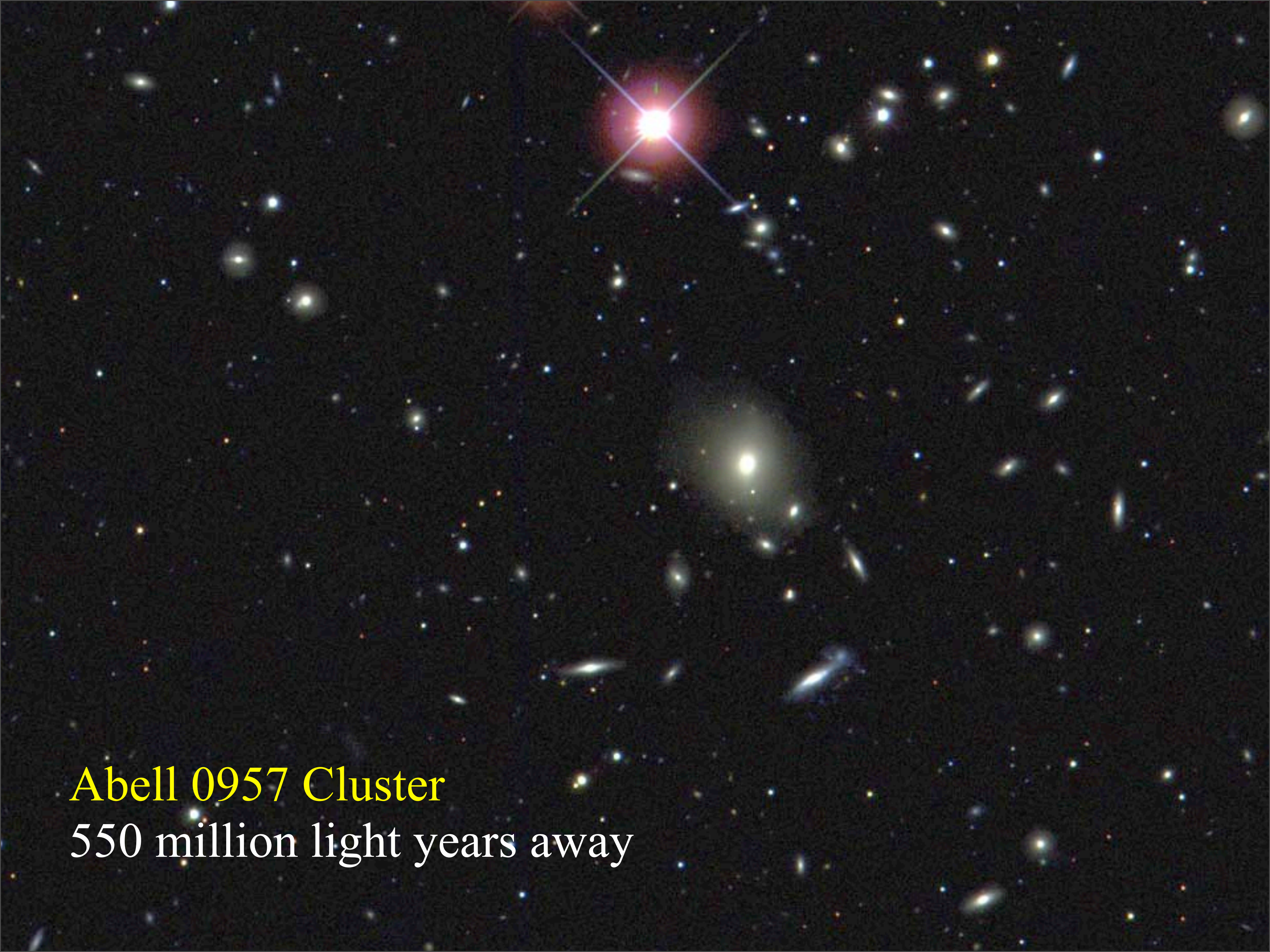
Fermilab and the University of Chicago

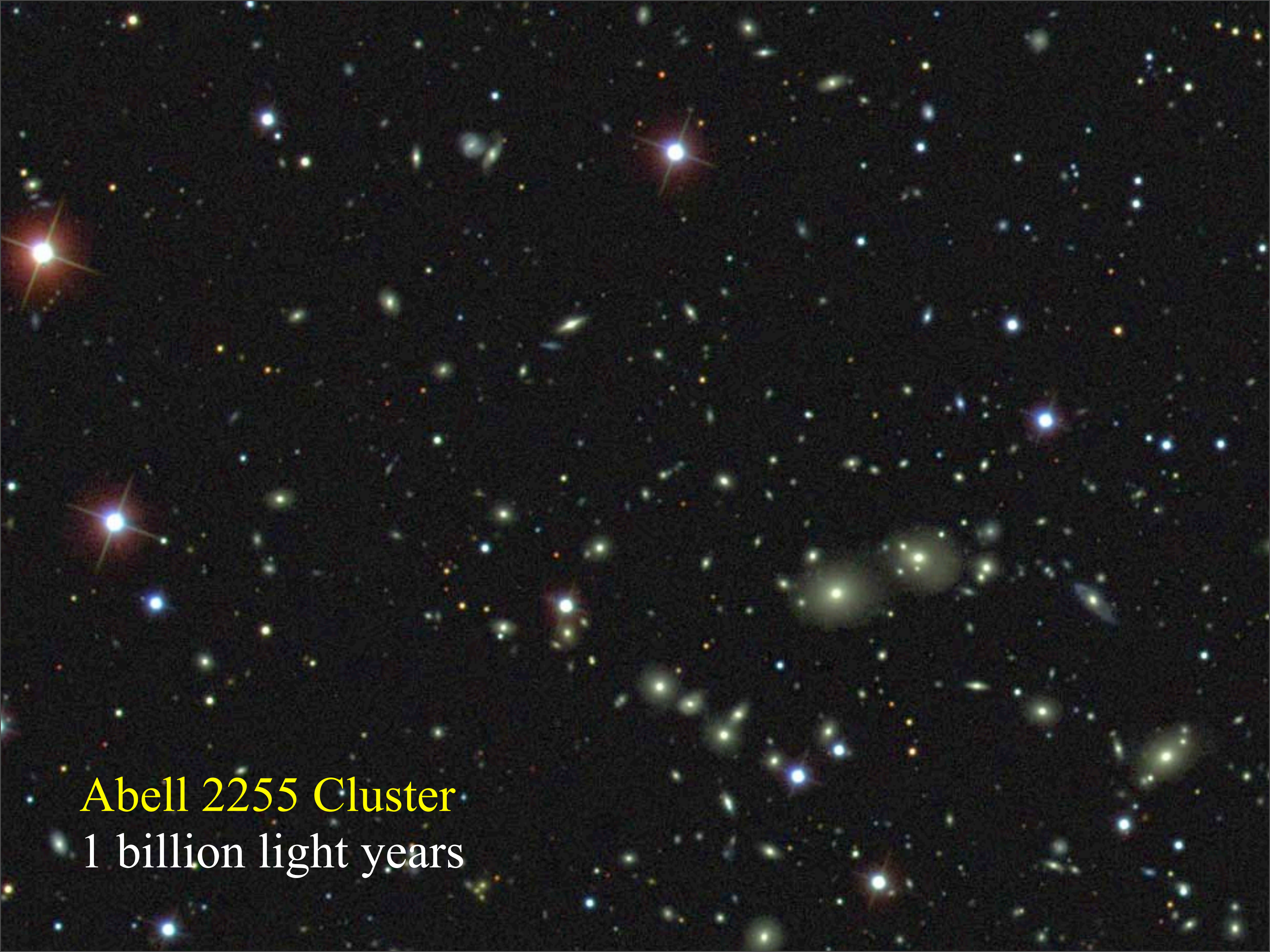
KICP Cosmology Short Course:
The Dark Universe
Sept. 2010

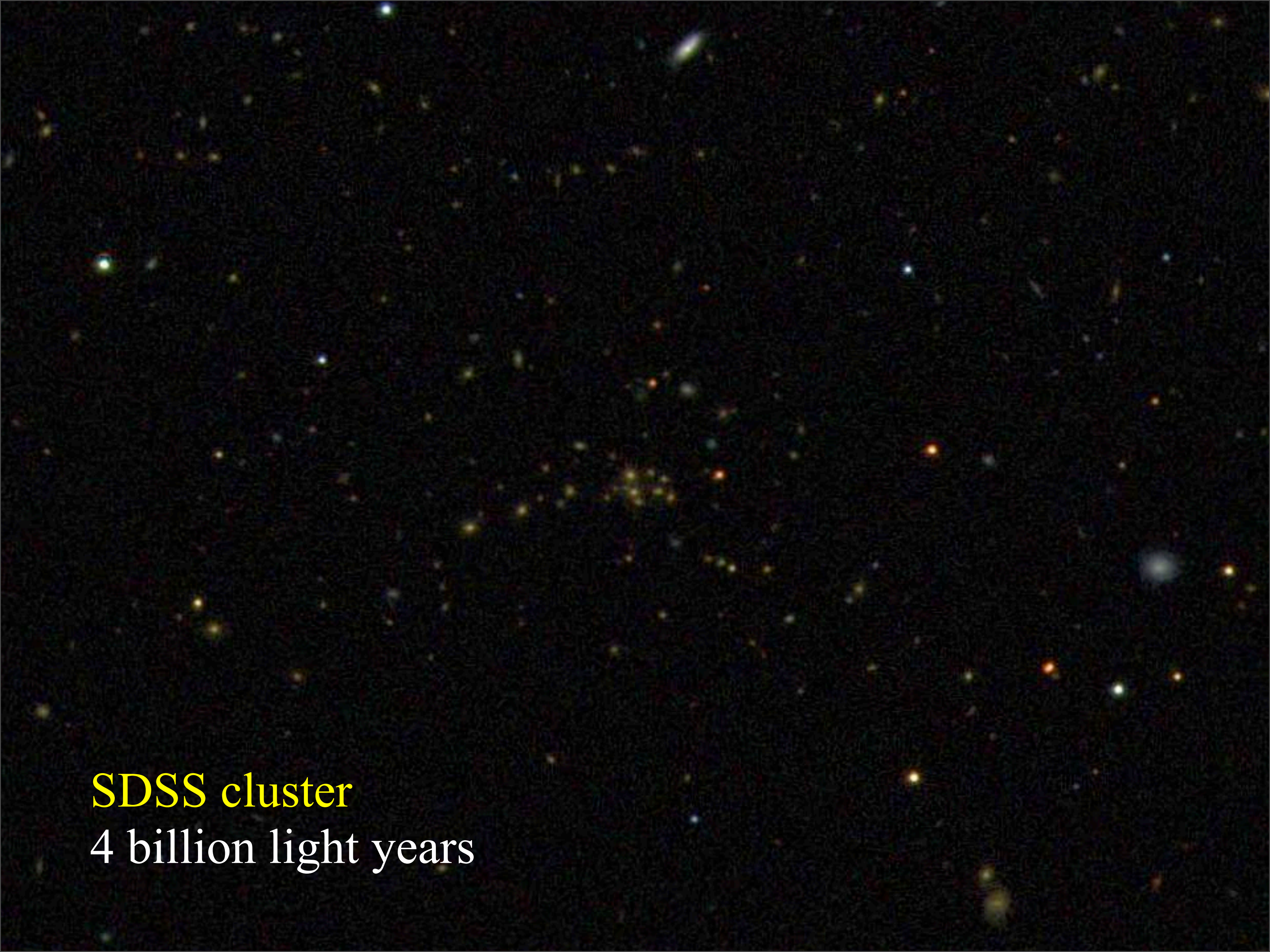
Components of the Universe

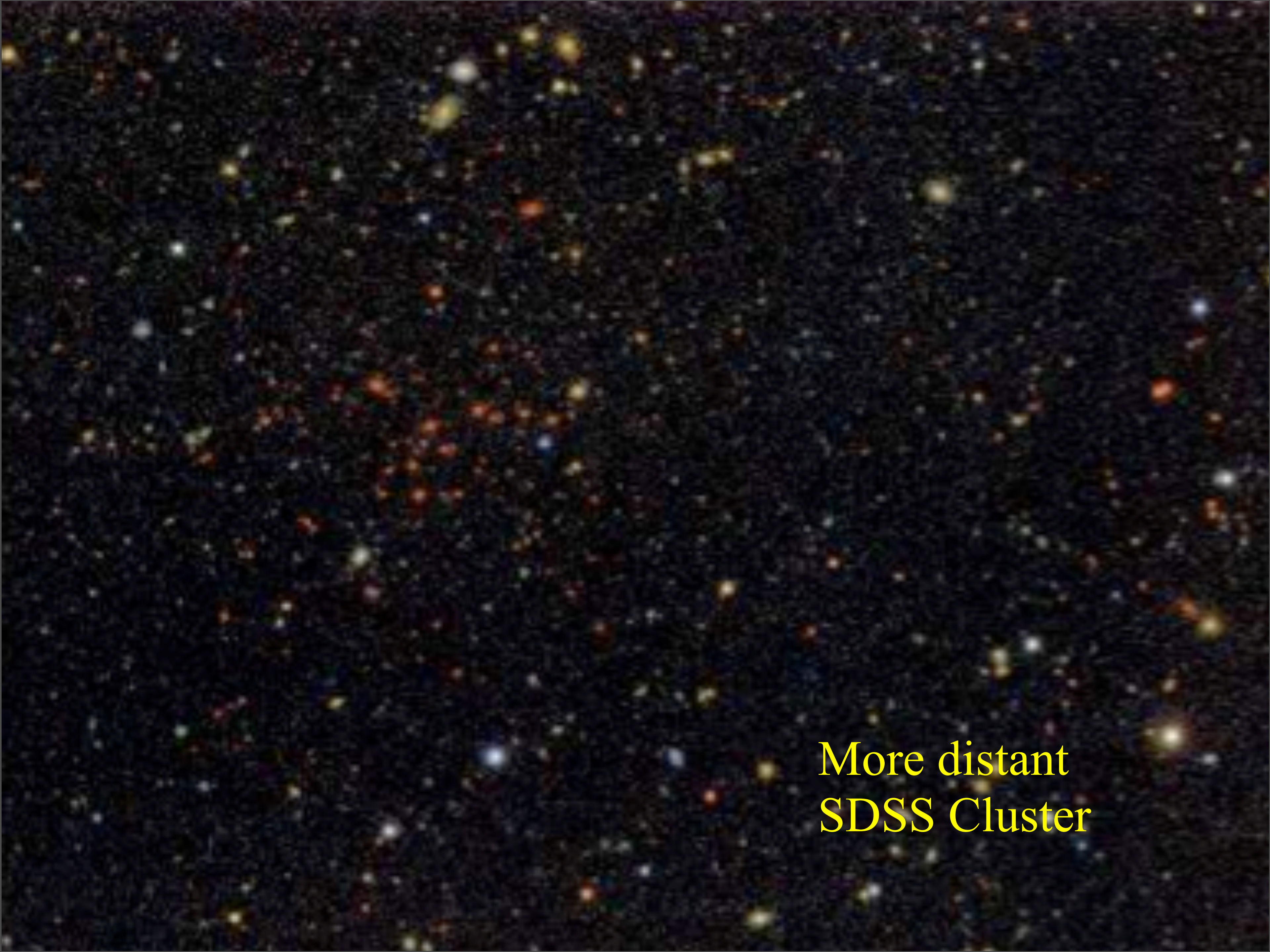


Dark Matter: holds galaxies together
Dark Energy: causes the expansion of the Universe to speed up


Abell 0957 Cluster
550 million light years away


Abell 2255 Cluster
1 billion light years


SDSS cluster
4 billion light years

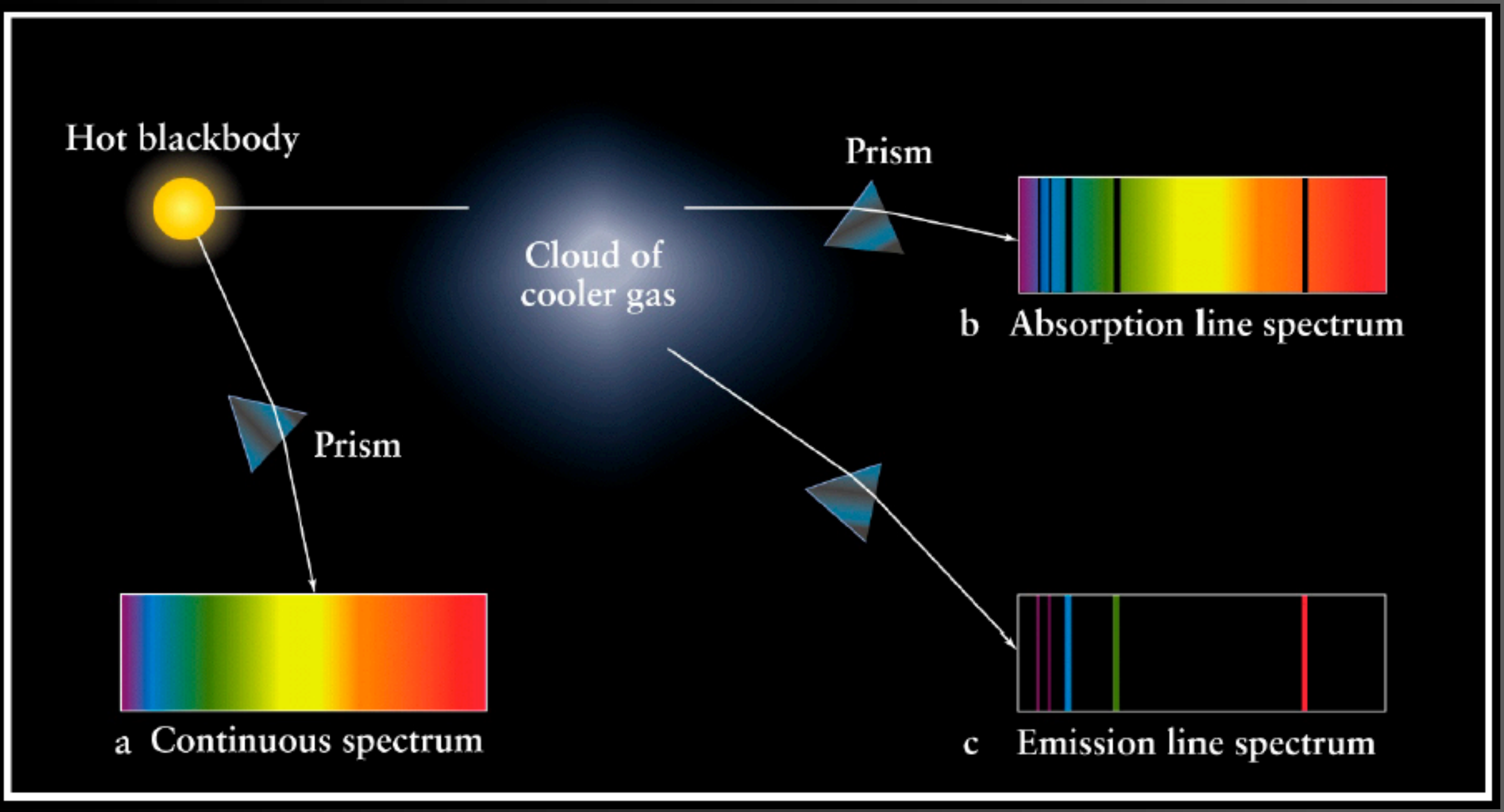

More distant
SDSS Cluster

More distant galaxies appear redder than those nearby

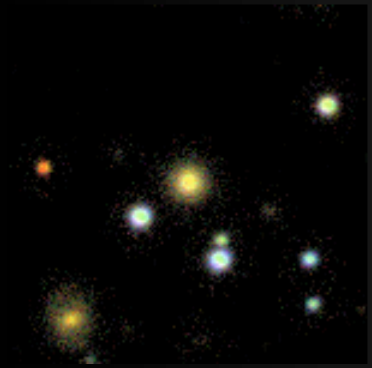
The amount of color (frequency) change
is called the Redshift

Redshift of light is like the Doppler shift
of sound as a train or racecar passes by:
it is a measure of the speed of the galaxy

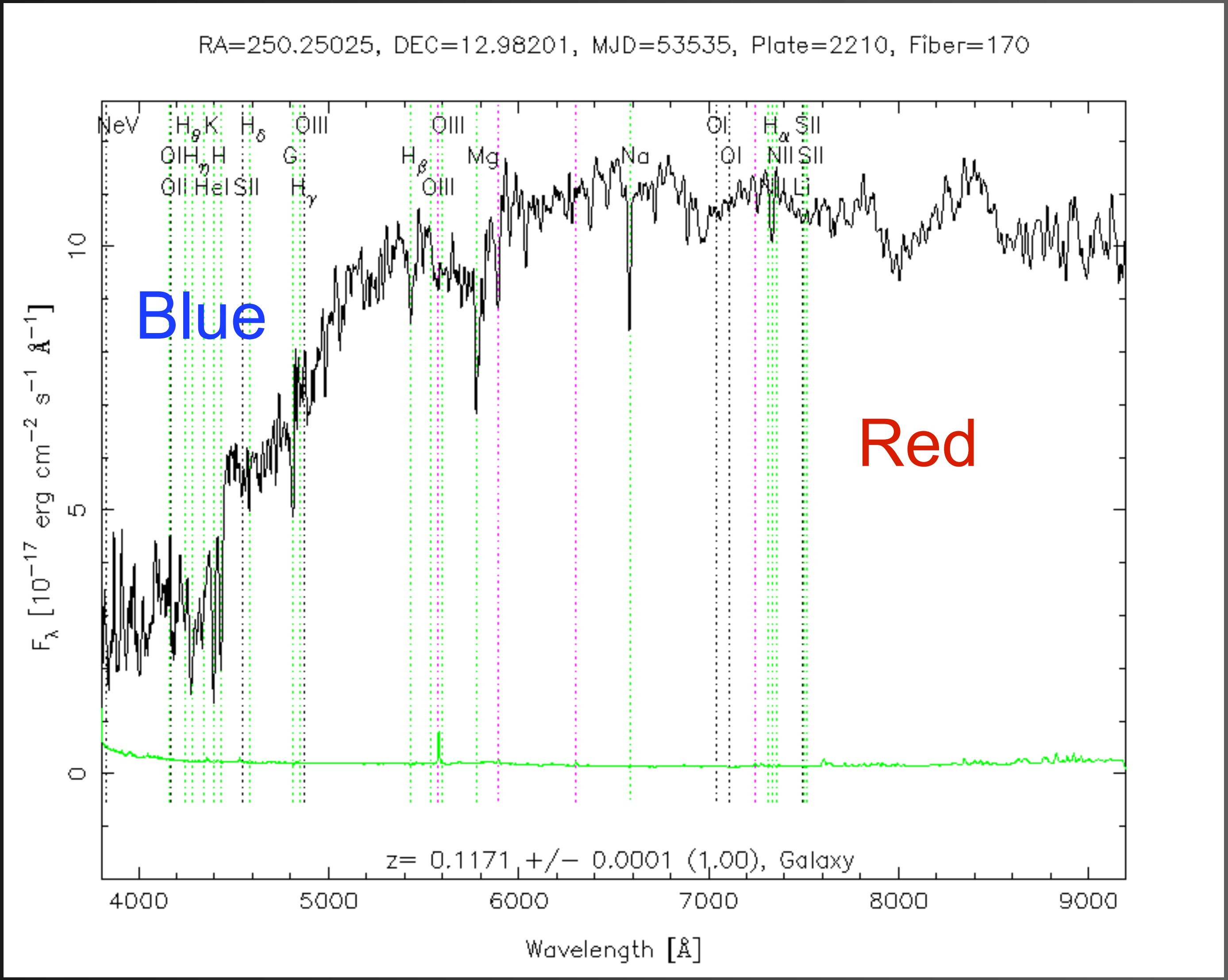
Astronomical Spectra

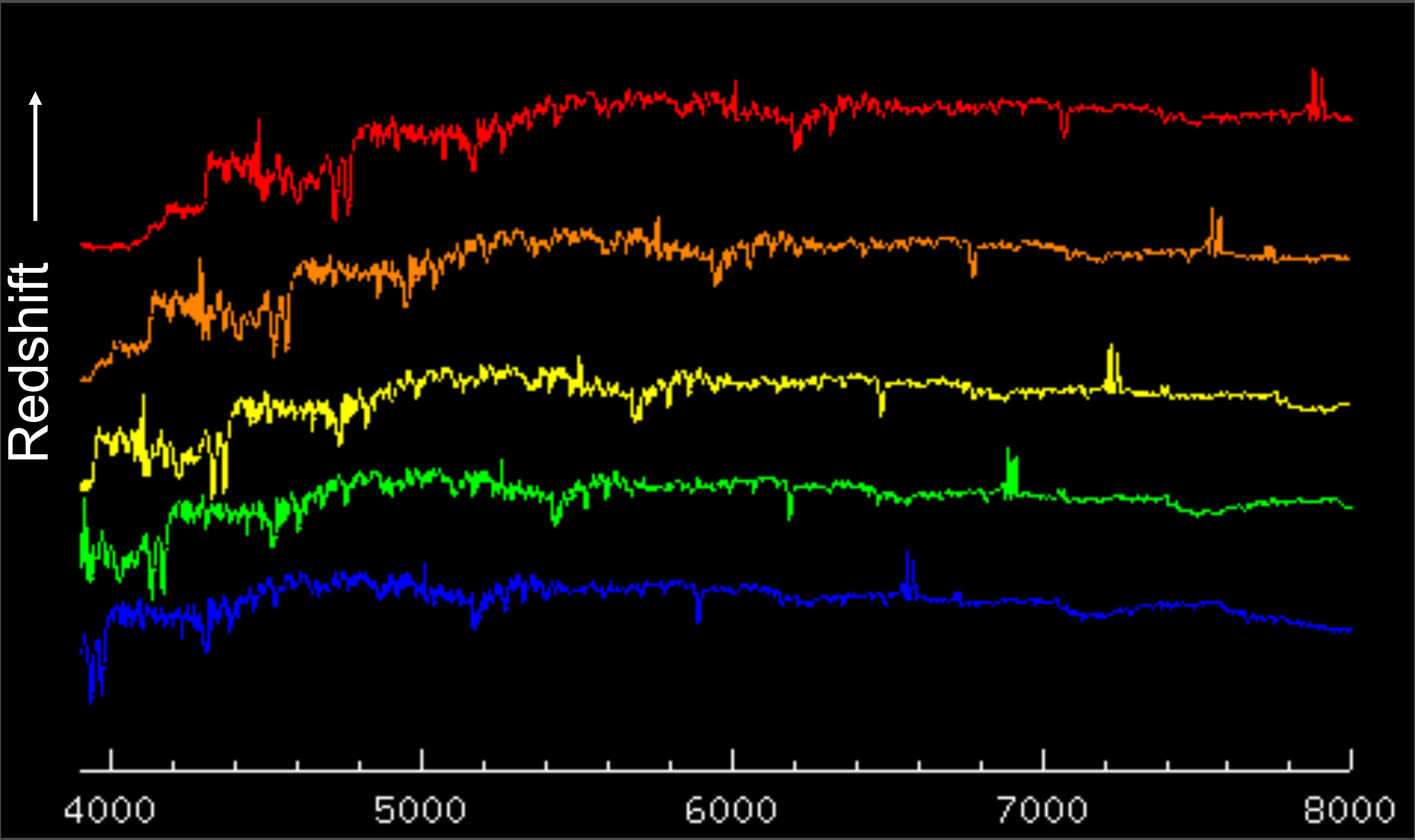


Elliptical Galaxy Spectrum



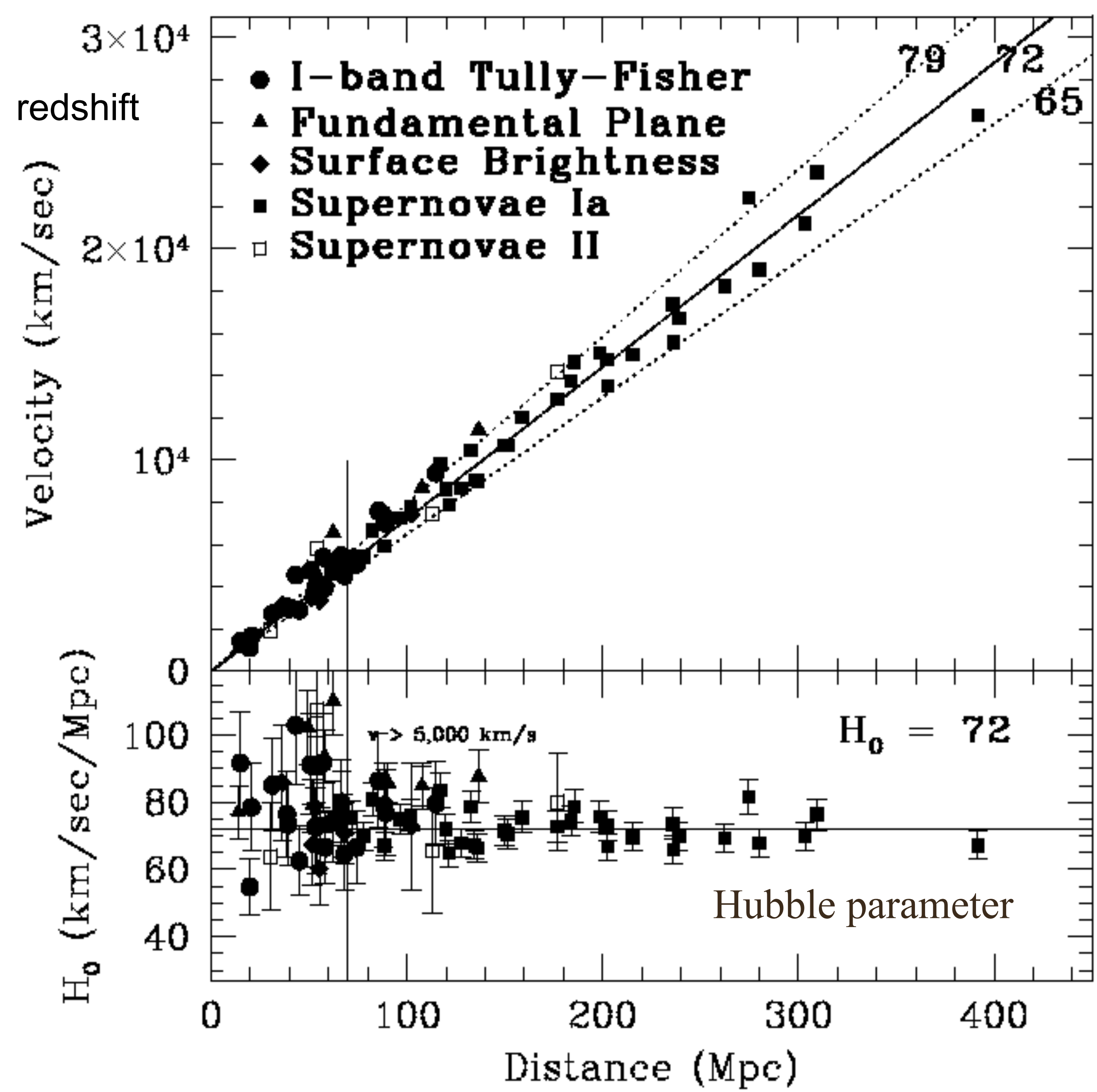
Composite of red stars





Light wavelength (Angstroms)

Hubble Space Telescope



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The Expanding Universe

Spectra of distant galaxies shifted to the red

They are moving away from us, with:

speed ∝ distance   Hubble 1929

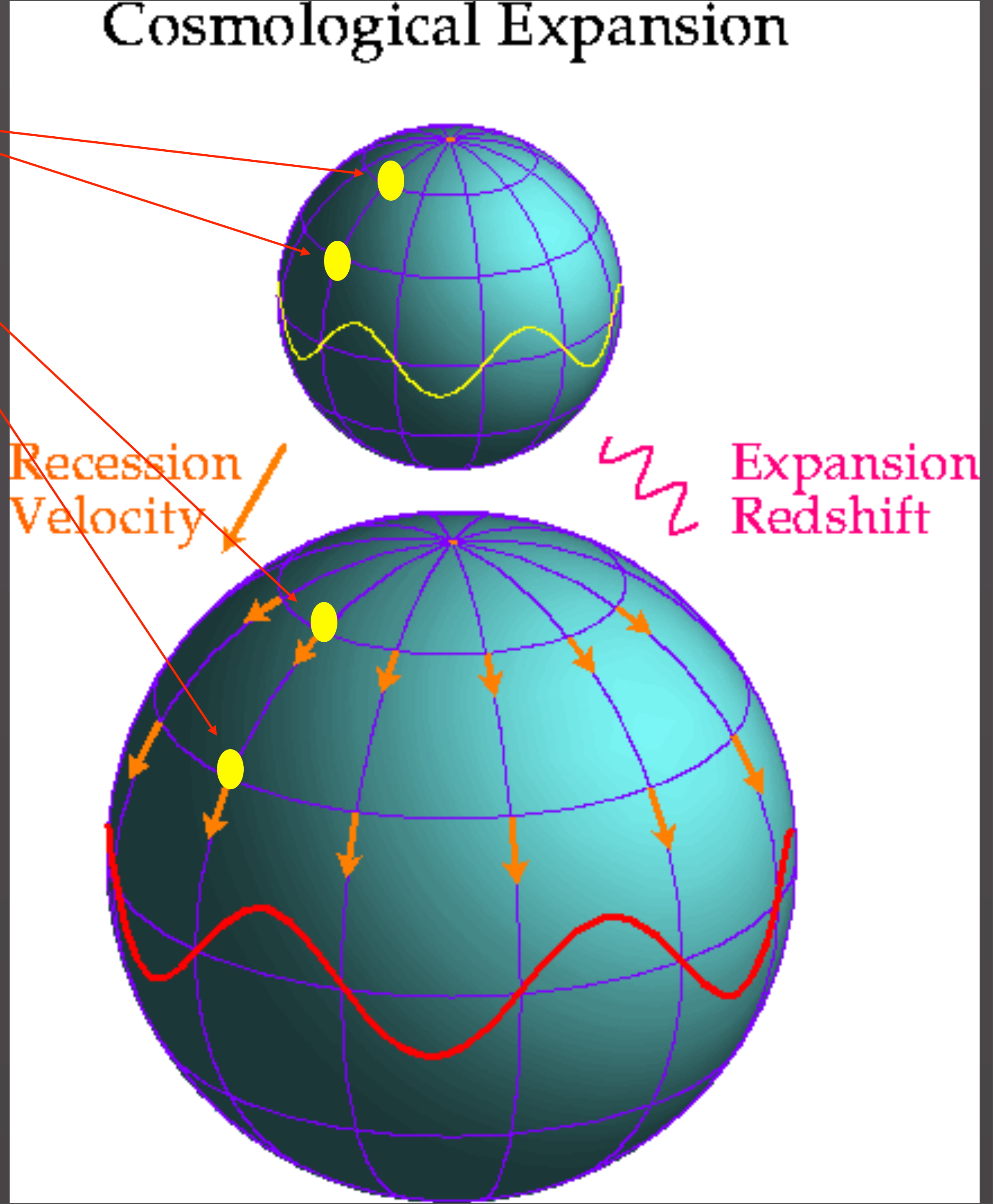
A galaxy 100 Million light years away is receding from us at 2000 miles per second

A galaxy 200 Million light years away is receding from us at 4000 miles per second

The Expanding Universe

The distance *between* galaxies increases with time

On average, galaxies are <u>at rest</u> in these expanding coordinates and are not themselves expanding



Distance between galaxies:

$$d(t) = a(t)r$$

where

$r =$ fixed (comoving) distance

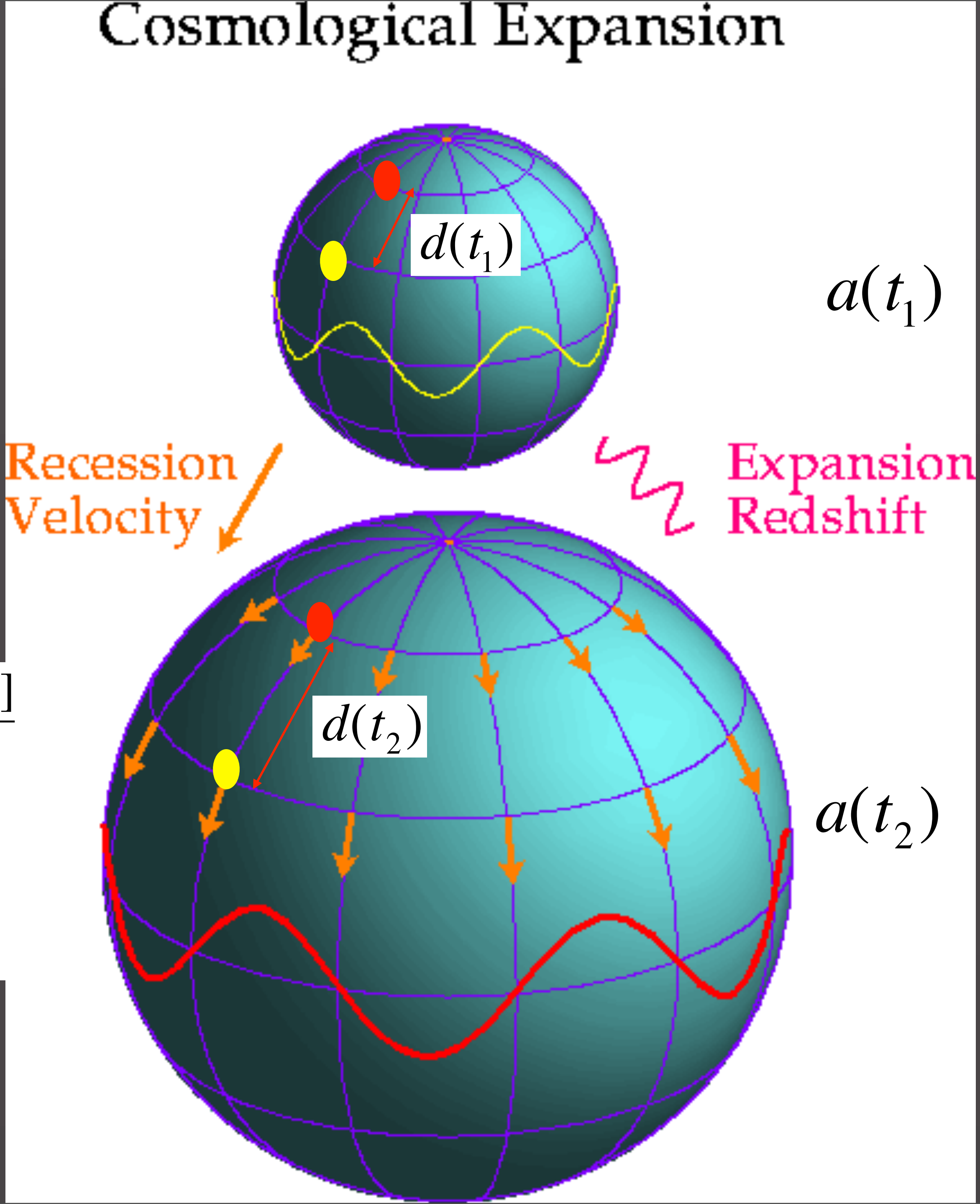
Recession speed:

$$\upsilon = \frac{d(t_2) - d(t_1)}{t_2 - t_1} = \frac{r[a(t_2) - a(t_1)]}{t_2 - t_1}$$

$$= \frac{d}{a}\frac{\Delta a}{\Delta t} \equiv dH(t)$$

$$\approx dH_0 \text{ for `small' } t_2 - t_1$$

Hubble's Law (1929)



Wavelength of light grows with scale factor:

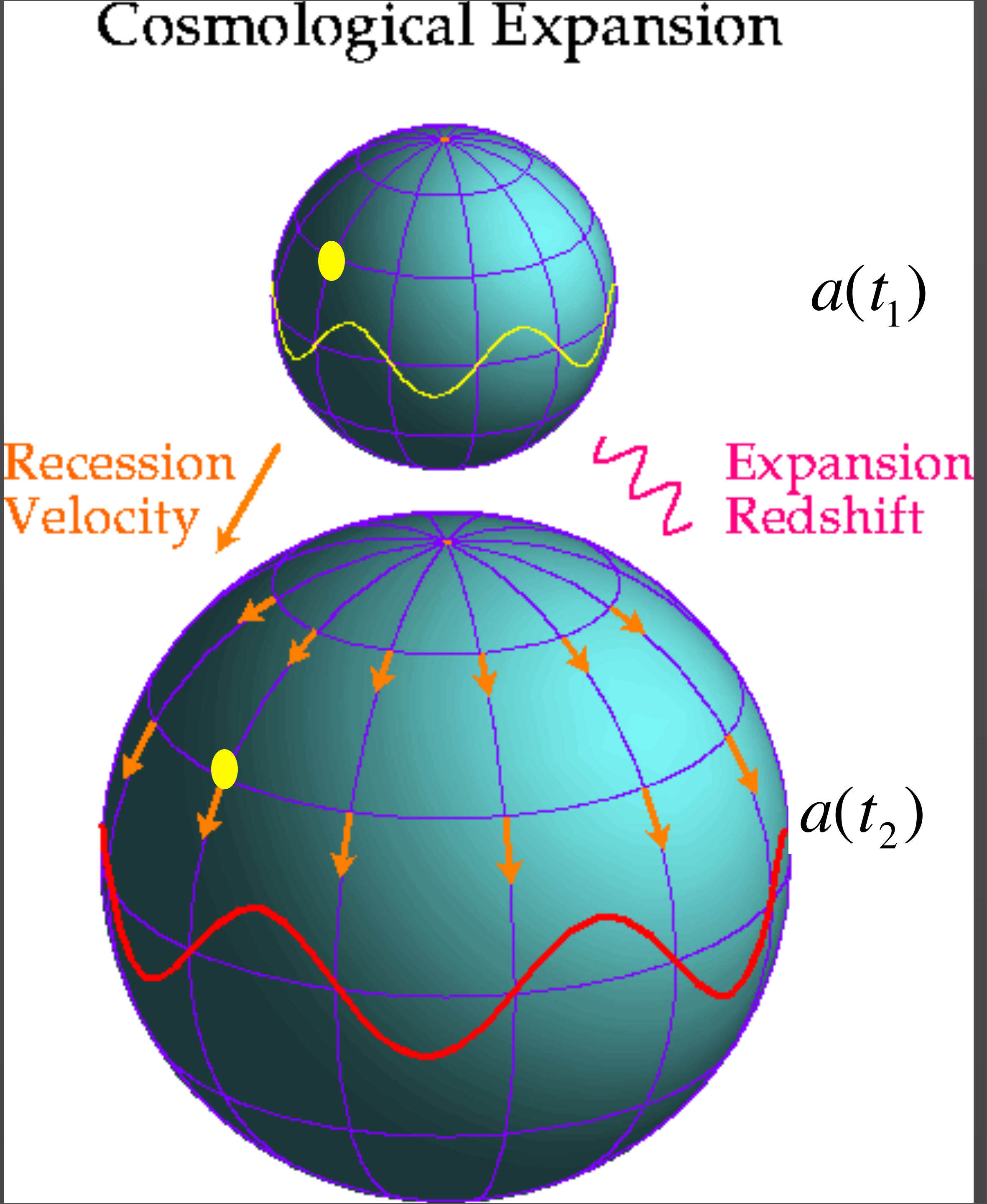
$$\lambda \sim a(t)$$

Redshift of light:

$$1 + z = \frac{\lambda(t_2)}{\lambda(t_1)} = \frac{a(t_2)}{a(t_1)}$$

emitted at t_1, observed at t_2

Redshift directly indicates relative size of Universe when light was emitted



Does the expansion of the Universe change over time?

Gravity:

everything in the Universe gravitationally attracts everything else

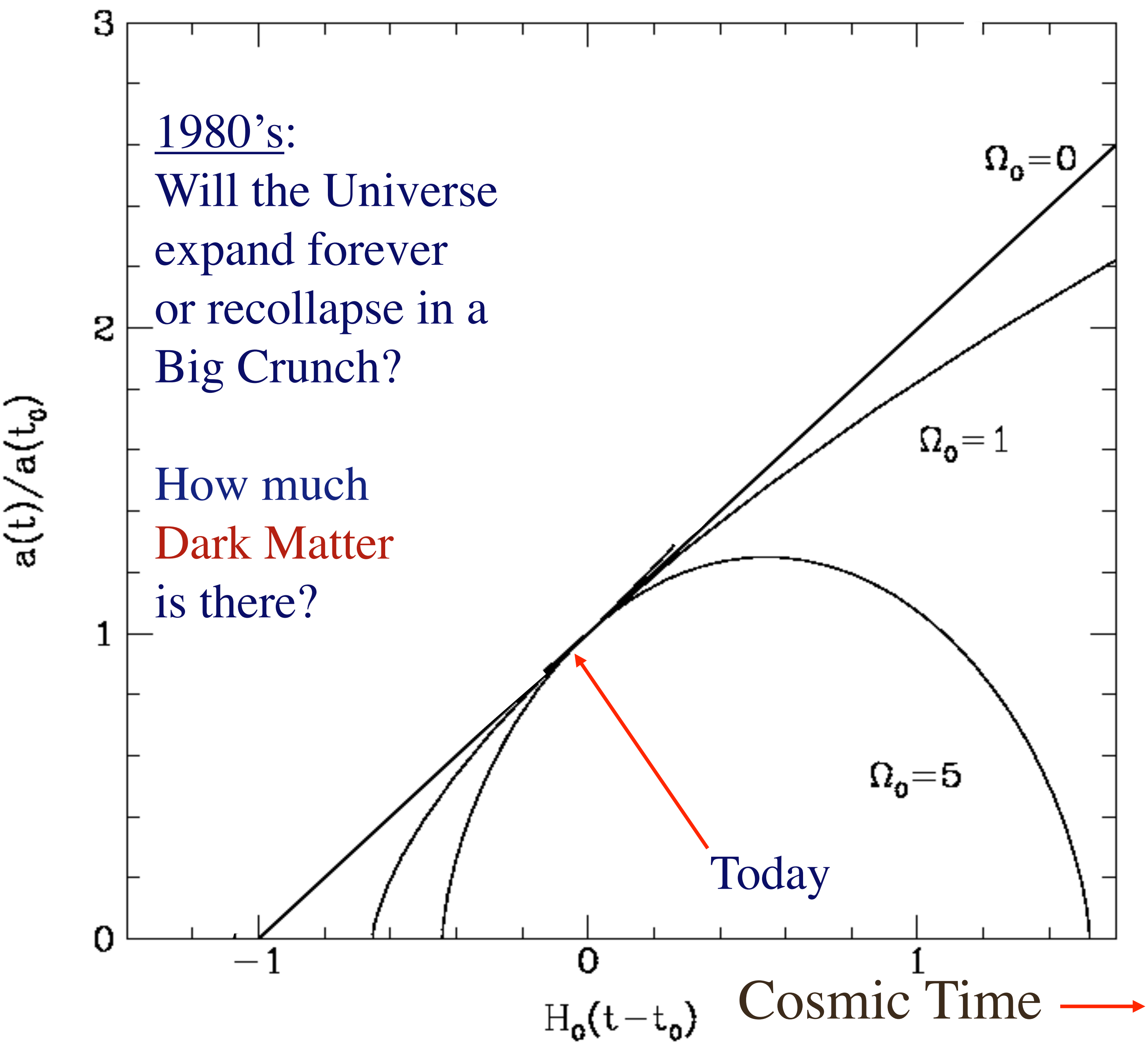
↓

the expansion of the Universe* *should* slow down over time

*and therefore the recession speed of a galaxy

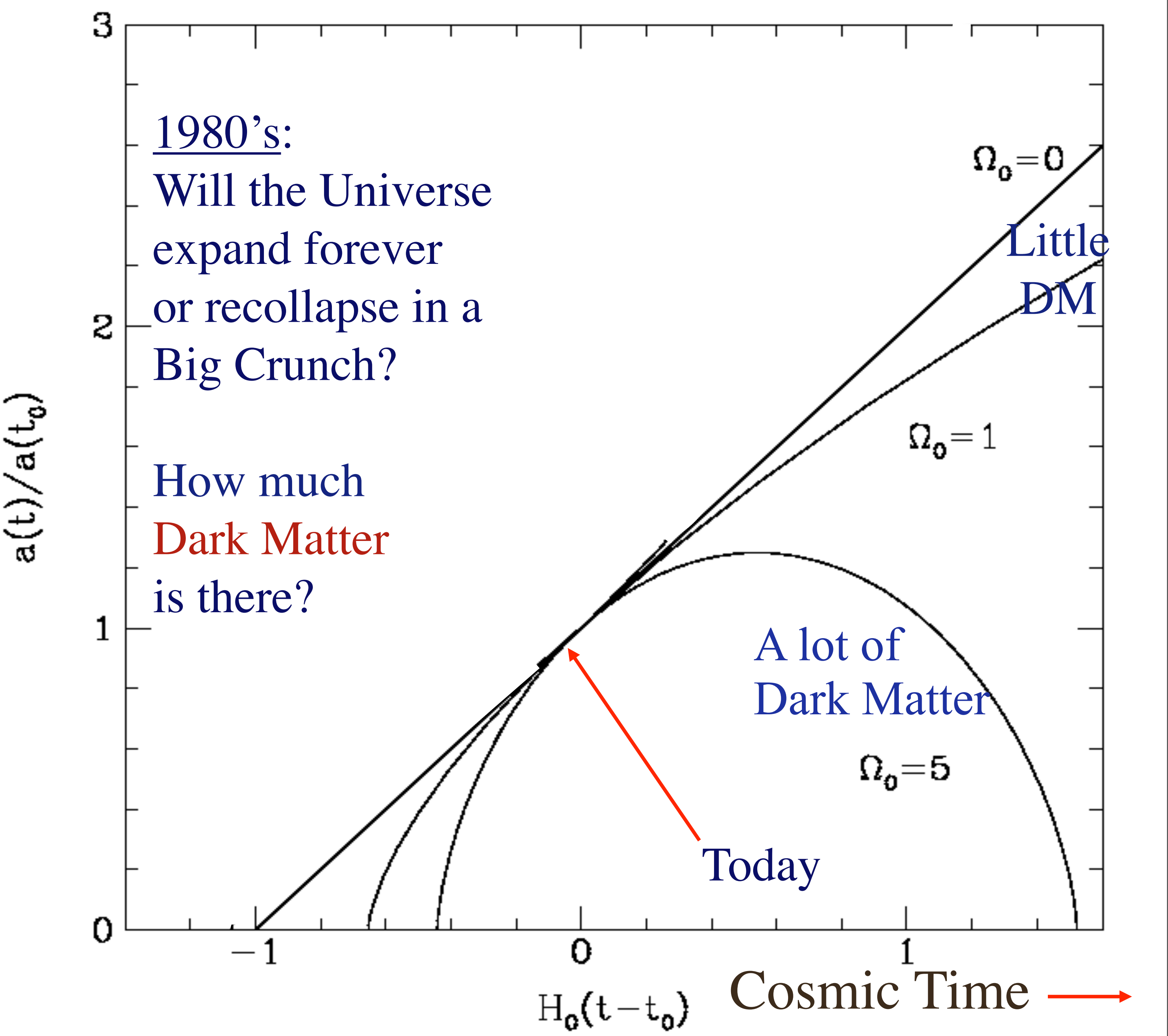
Distance between two galaxies

In all these cases, expansion *slows down* due to gravity

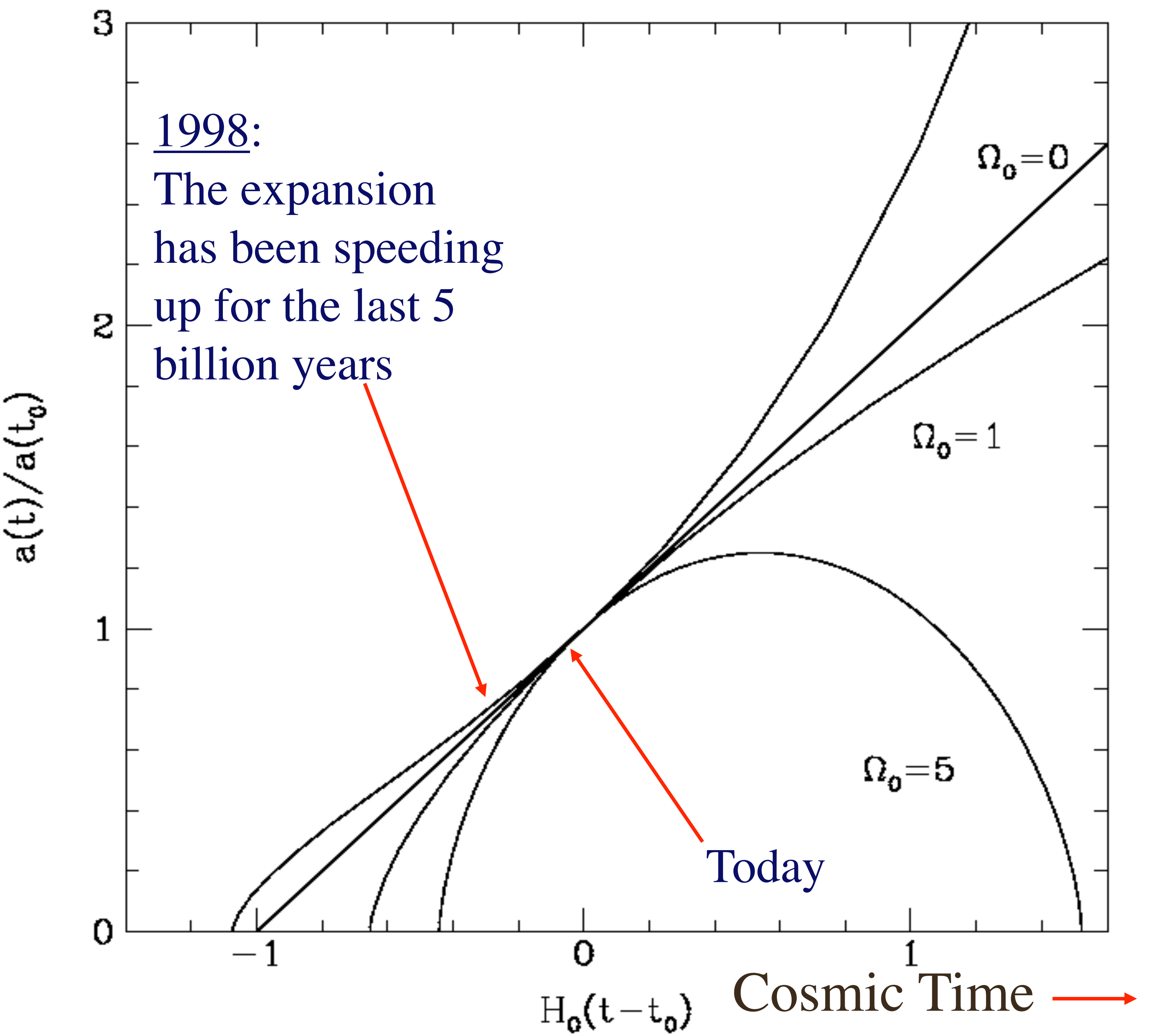


Distance between two galaxies

In all these cases, expansion *slows down* due to gravity



Distance between two galaxies



Early 1990's: Circumstantial Evidence

The theory of primordial inflation successfully accounted for the large-scale smoothness of the Universe and the large-scale distribution of galaxies.

Inflation predicted what the total density of the Universe should be: the critical amount needed for the geometry of the Universe to be flat.

Measurements of the total amount of matter (mostly dark) in galaxies and clusters indicated not enough dark matter for a flat Universe: there must be additional unseen stuff to make up the difference, if inflation is correct.

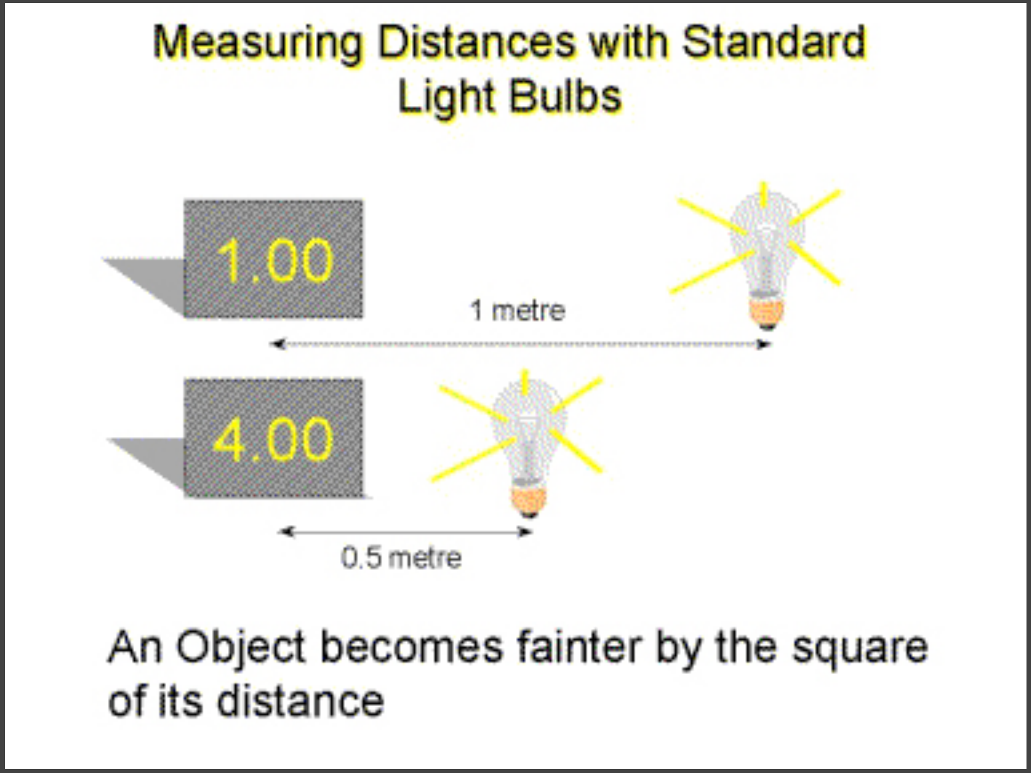
In 1998, we called this Missing Energy.
Post-supernova discovery: Michael Turner called it Dark Energy, and that stuck.

What is the evidence for cosmic acceleration?

What could be causing cosmic acceleration?

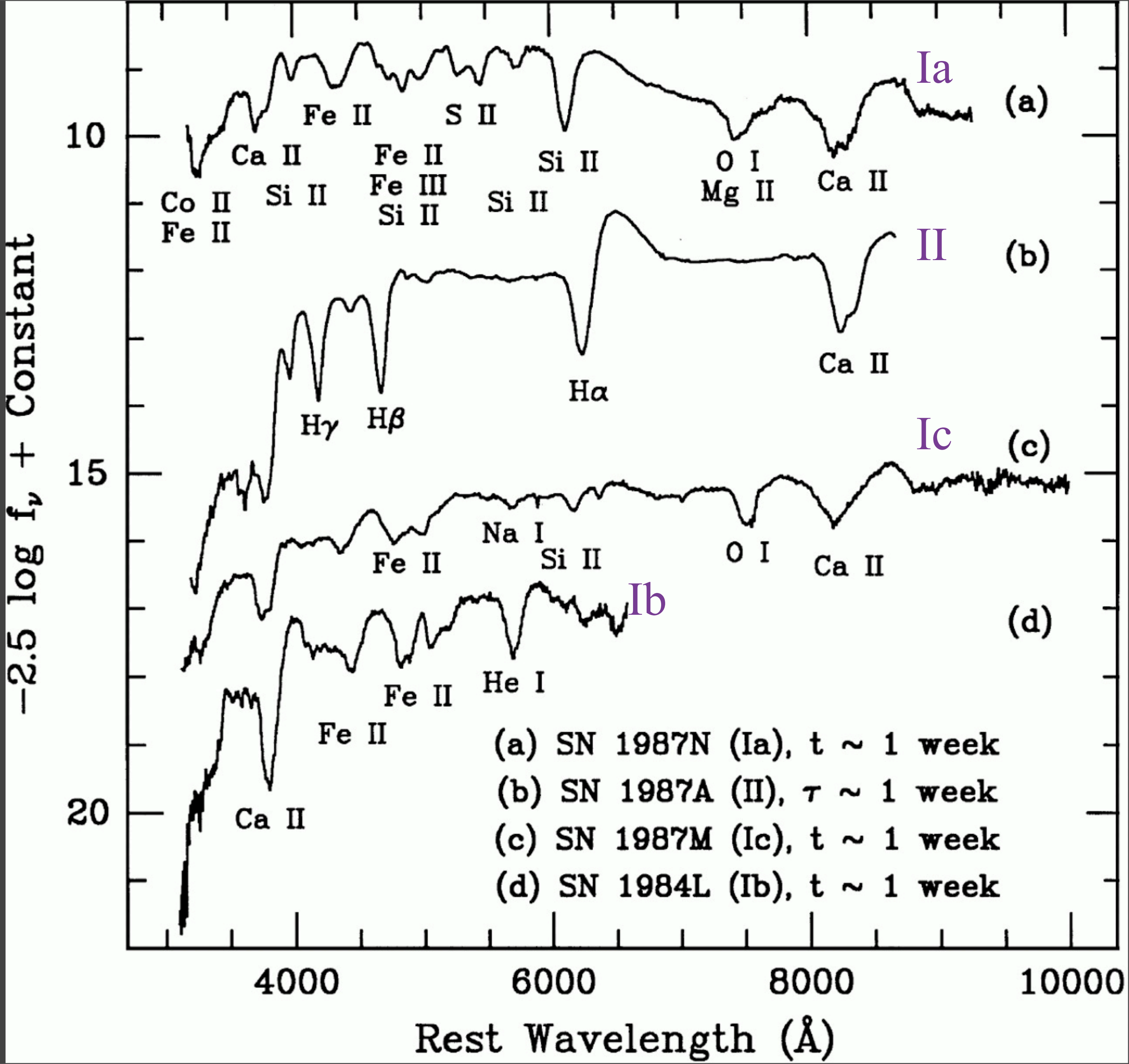
How do we plan to find out?

Cosmic Standard Candles



SN 1994D (Type Ia)

Spectrum of Light from different types of Supernovae

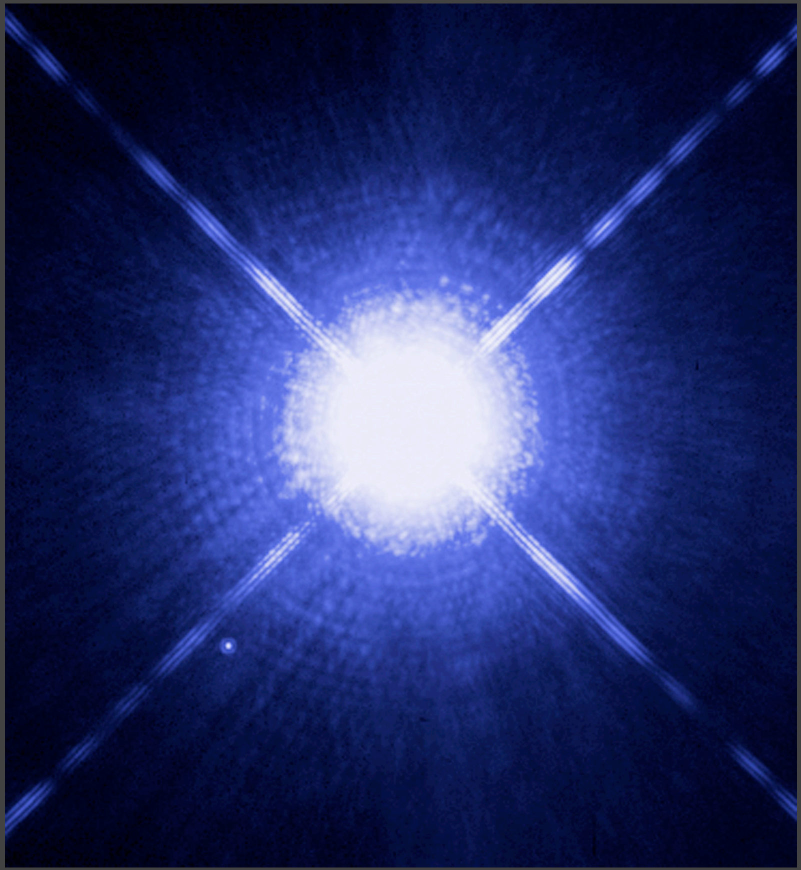


Classification of Supernovae

Type	Ia	Ib	Ic	II
Spectrum	No Hydrogen			Hydrogen
	Silicon	No Silicon		
		Helium	No Helium	
Physical mechanism	Nuclear explosion of low mass star	Core collapse of evolved massive star (may have lost its hydrogen or even helium envelope during red-giant evolution)		
Light curve	Reproducible	Large Variations		
Neutrinos	Insignificant	~ 100 × Visible energy		
Compact Remnant	None	Neutron star (typically appears as pulsar) Sometimes black hole ?		
Rate/h^2SNu	0.36 ± 0.11	0.14 ± 0.07		0.71 ± 0.34
Observed	Total ~ 2000 as of today (nowadays ~200/year)			

Georg Raffelt, Max-Planck-Institut für Physik (München)

White Dwarf Stars



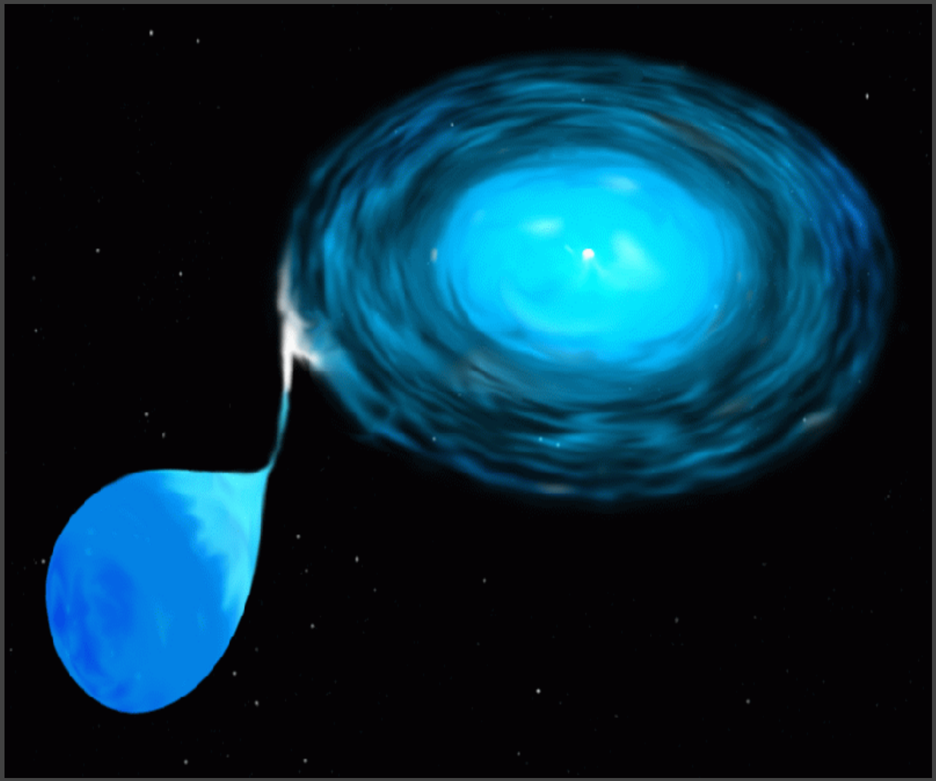
Sirius A and B seen by the Hubble Space Telescope

- Stars with about the mass of the Sun but with the size of the Earth:

density~1000 kg/cubic centimeter

- The end state of most stars after they have finished burning Hydrogen and Helium to Carbon and Oxygen

Type Ia Supernovae



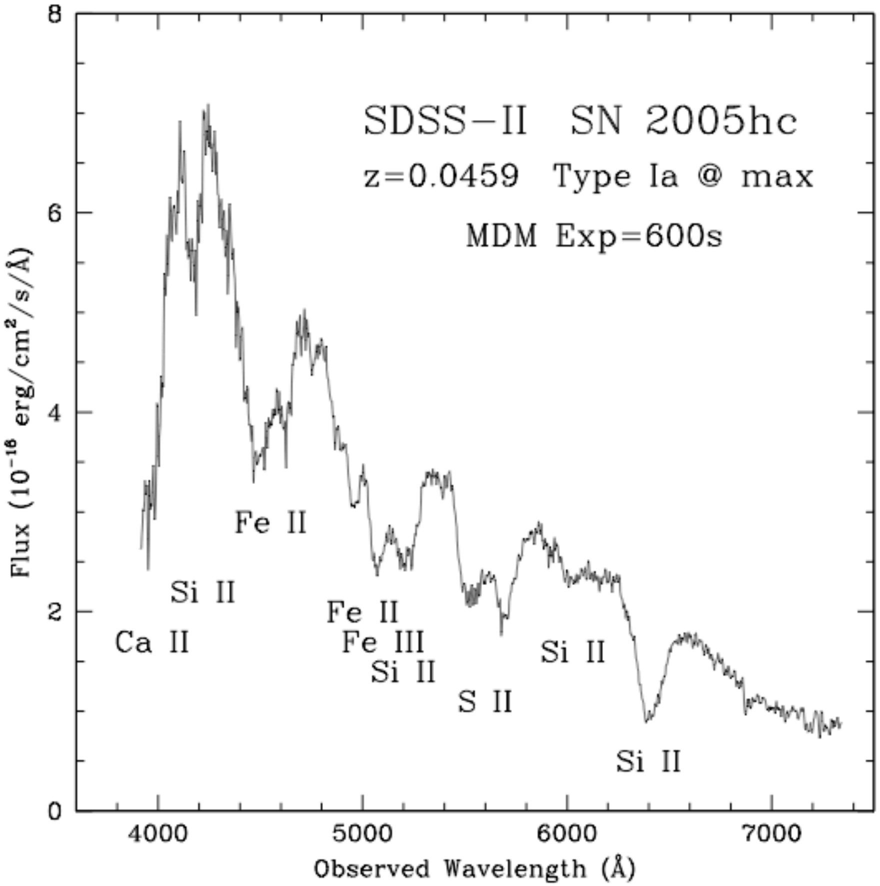
Thermonuclear explosions of White Dwarf stars

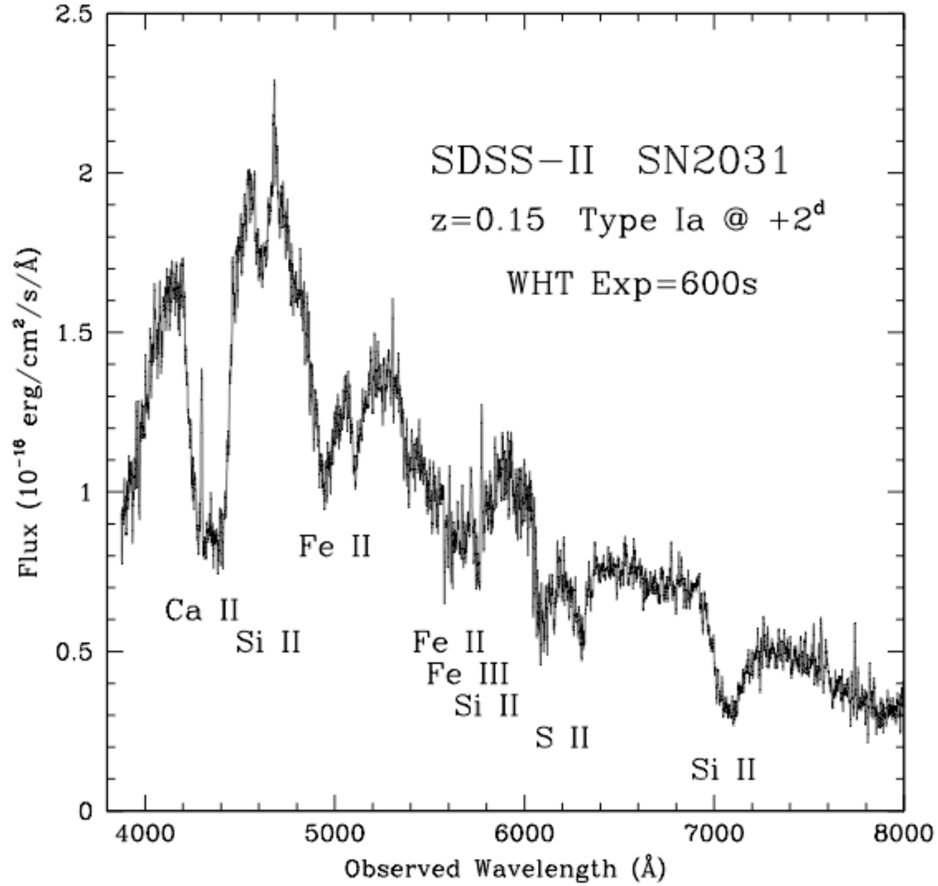
Accrete mass from a binary companion, grow to a critical mass, (1.4 times the mass of the Sun)

After slow thermonuclear "cooking", a violent explosion is triggered at or near the center; the star is completely incinerated within seconds; details are *not* understood

Radioactive decay of Nickel makes it shine for a couple of months

SNe Ia: Homogeneous class of events

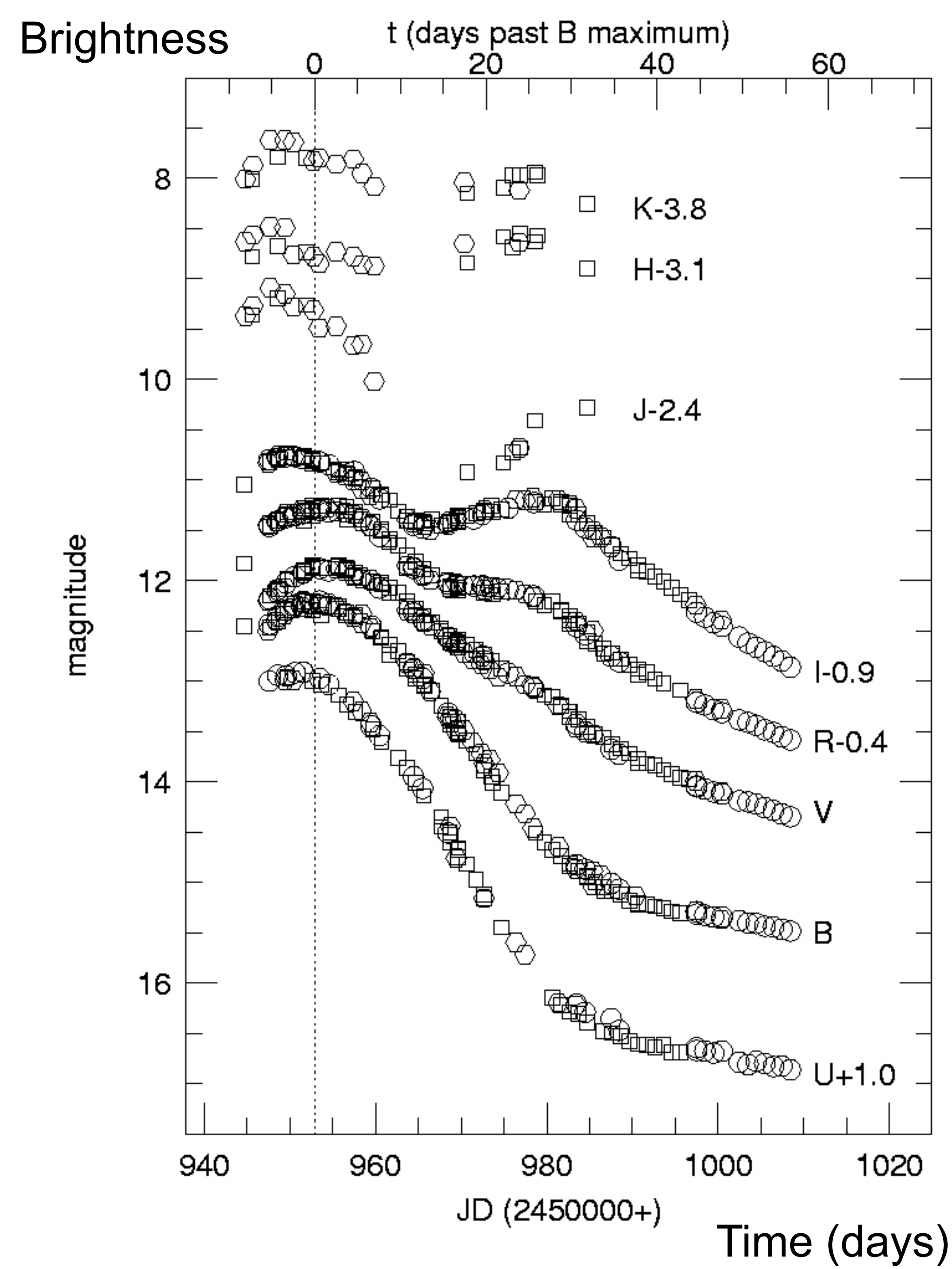




from SDSS Supernova Survey

Supernova 1998bu: Type Ia Multi-band Light curve

SN Ia light curves look very similar to each other and get as bright as an entire galaxy of stars

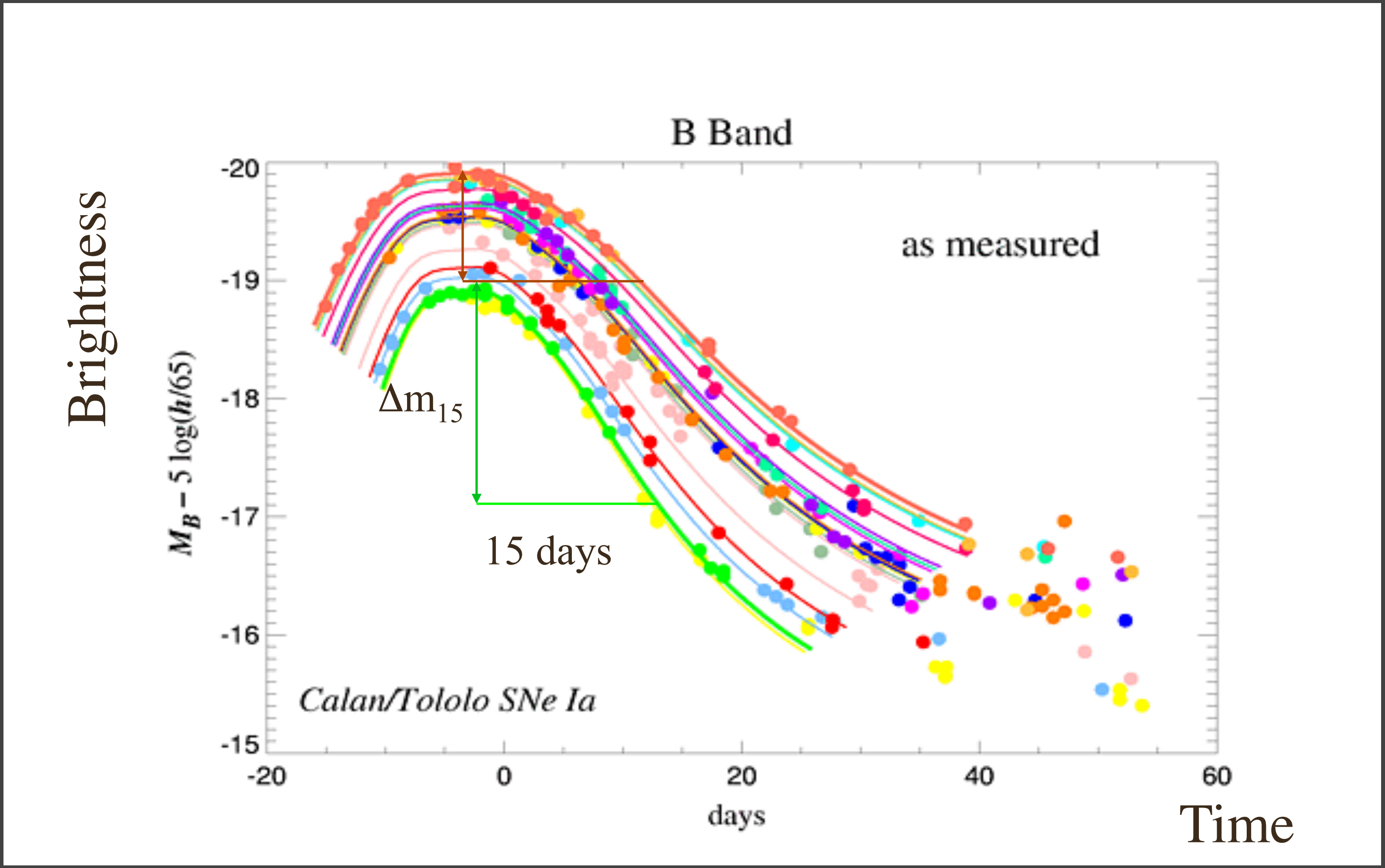


Near-infrared

Red

Blue

Ultraviolet



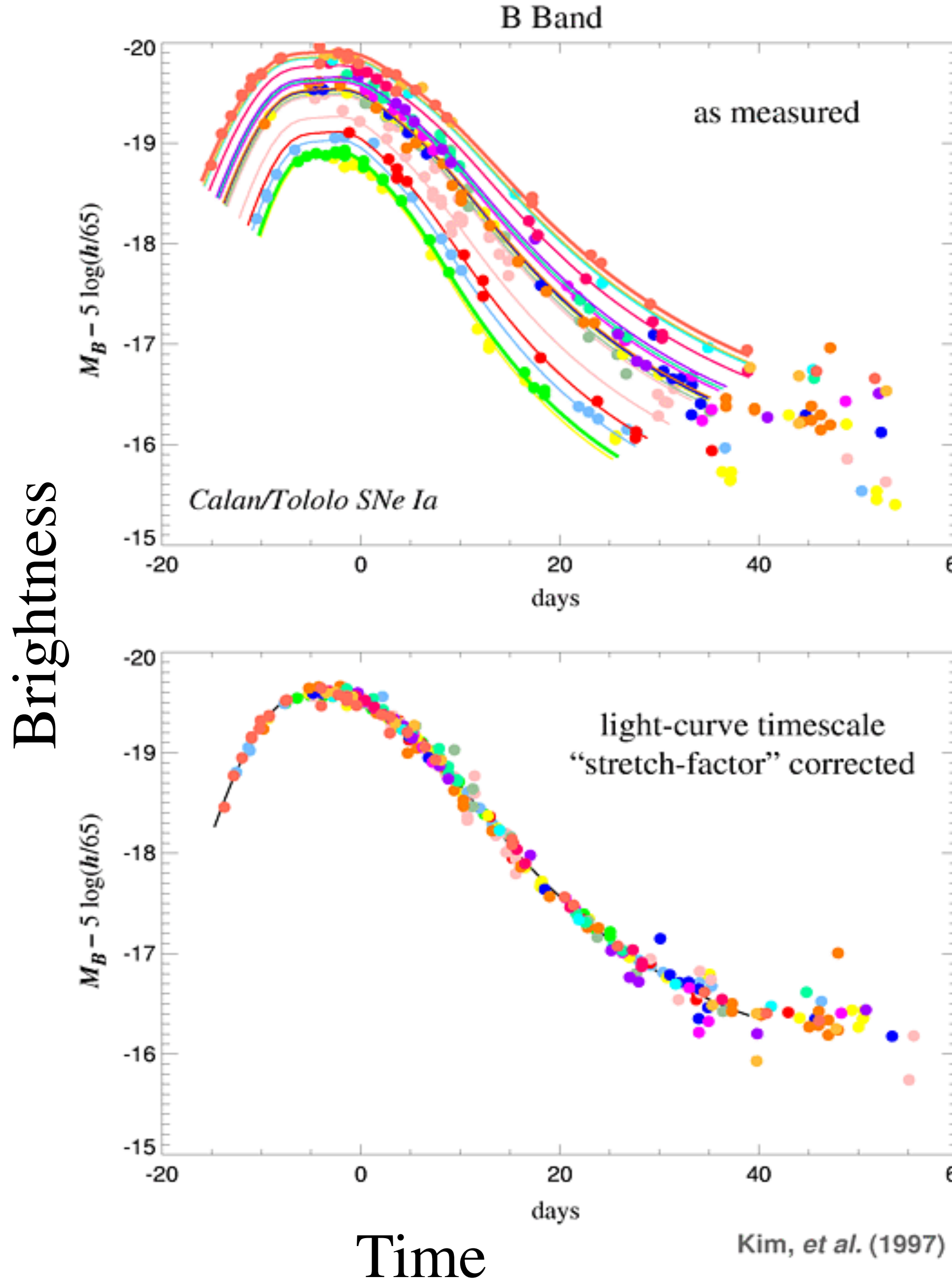
Brighter supernovae decline more slowly

Phillips 1993

Type Ia SN
Peak Brightness as calibrated Standard Candle

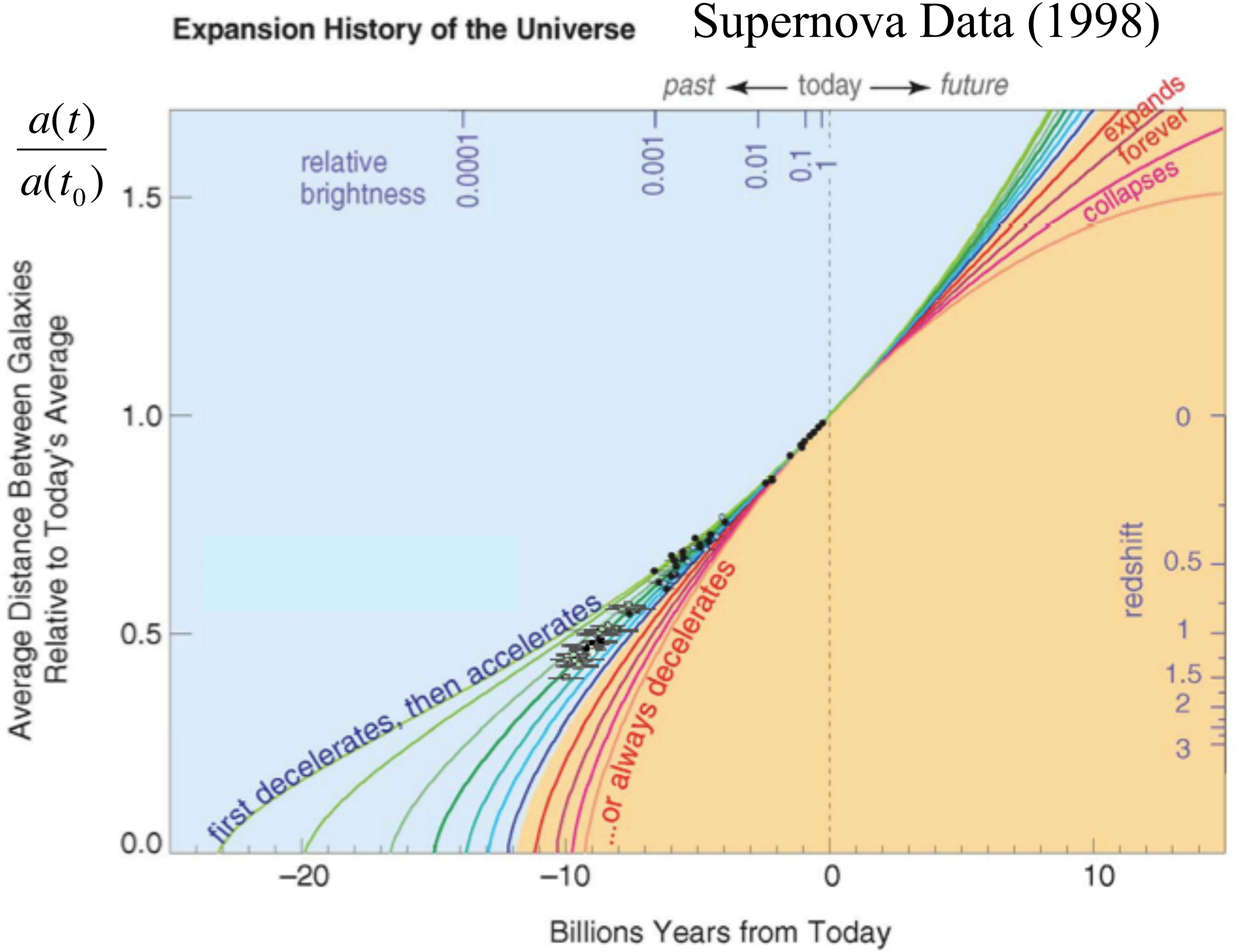
Peak brightness correlates with decline rate

Measure relative supernova distances to a precision of 7%



Supernova Data (1998)

$$\frac{a(t)}{a(t_0)}$$



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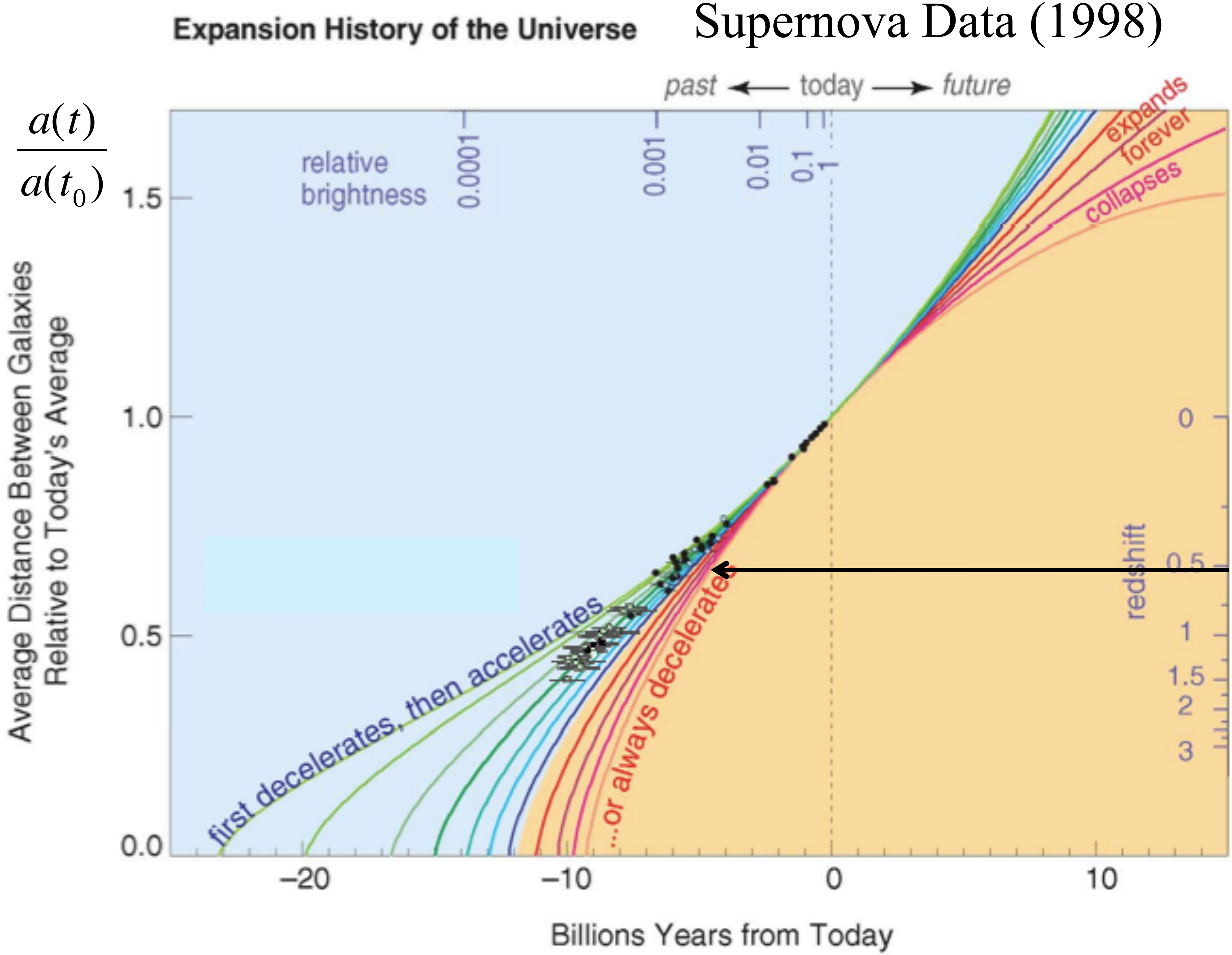

Supernova Data (1998)

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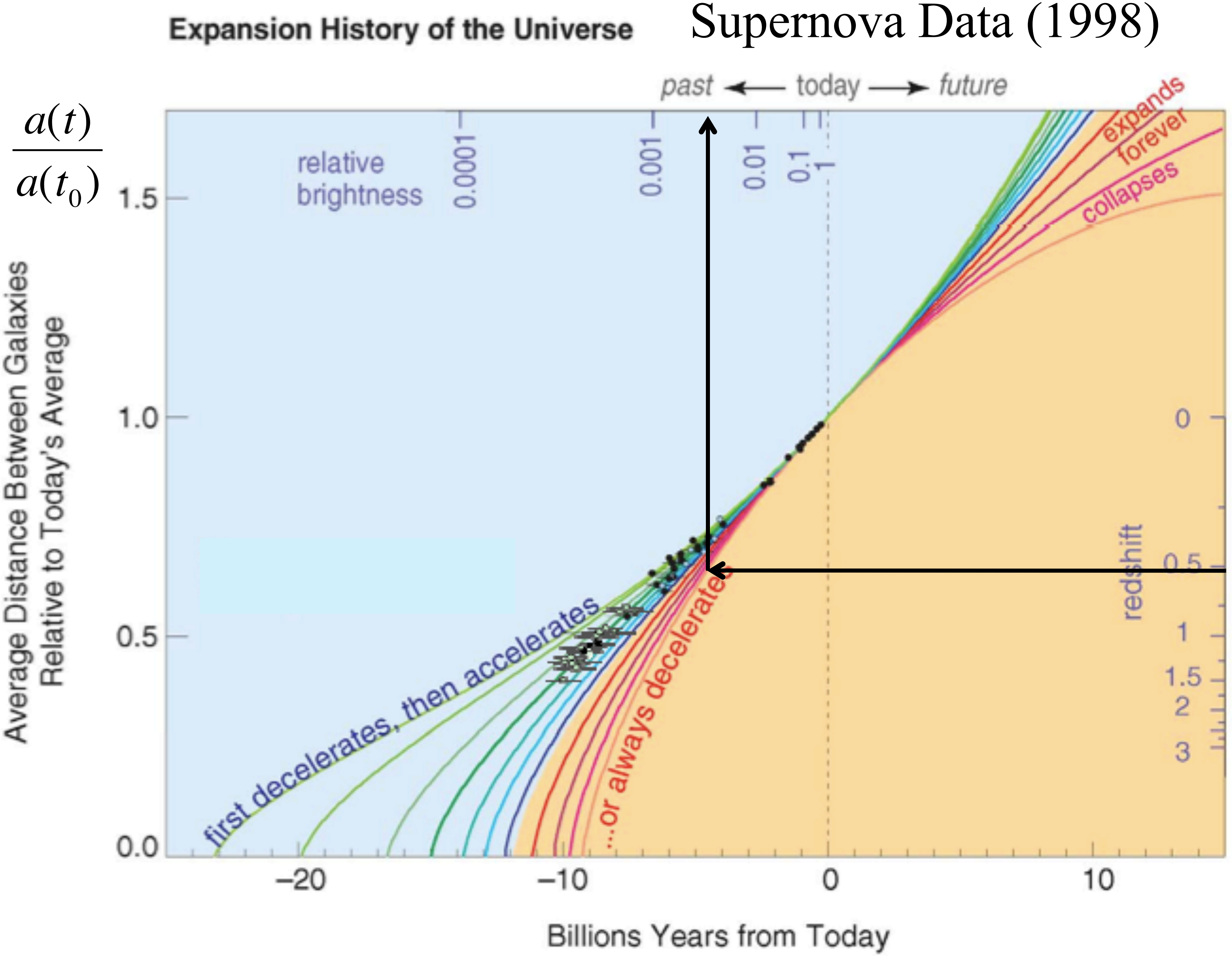

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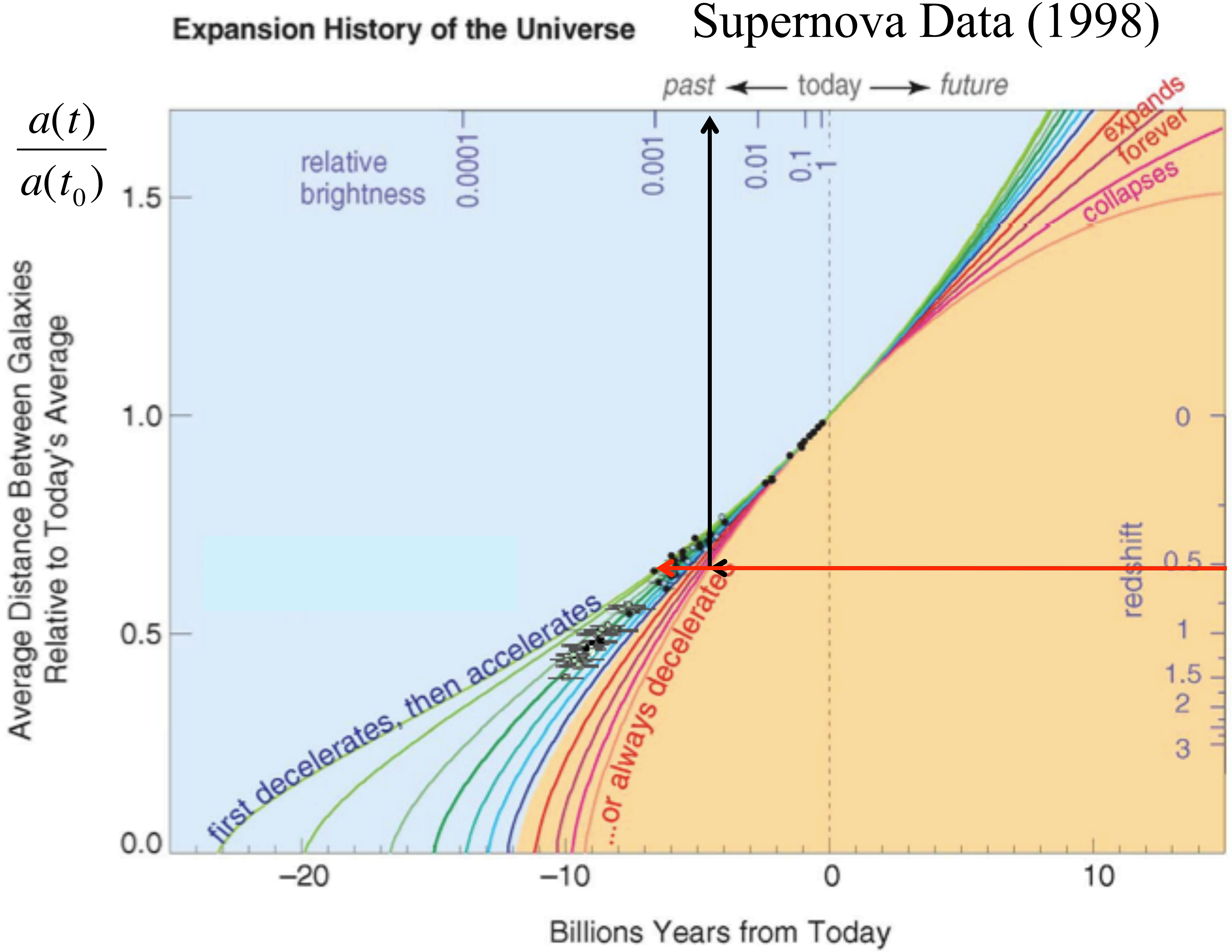

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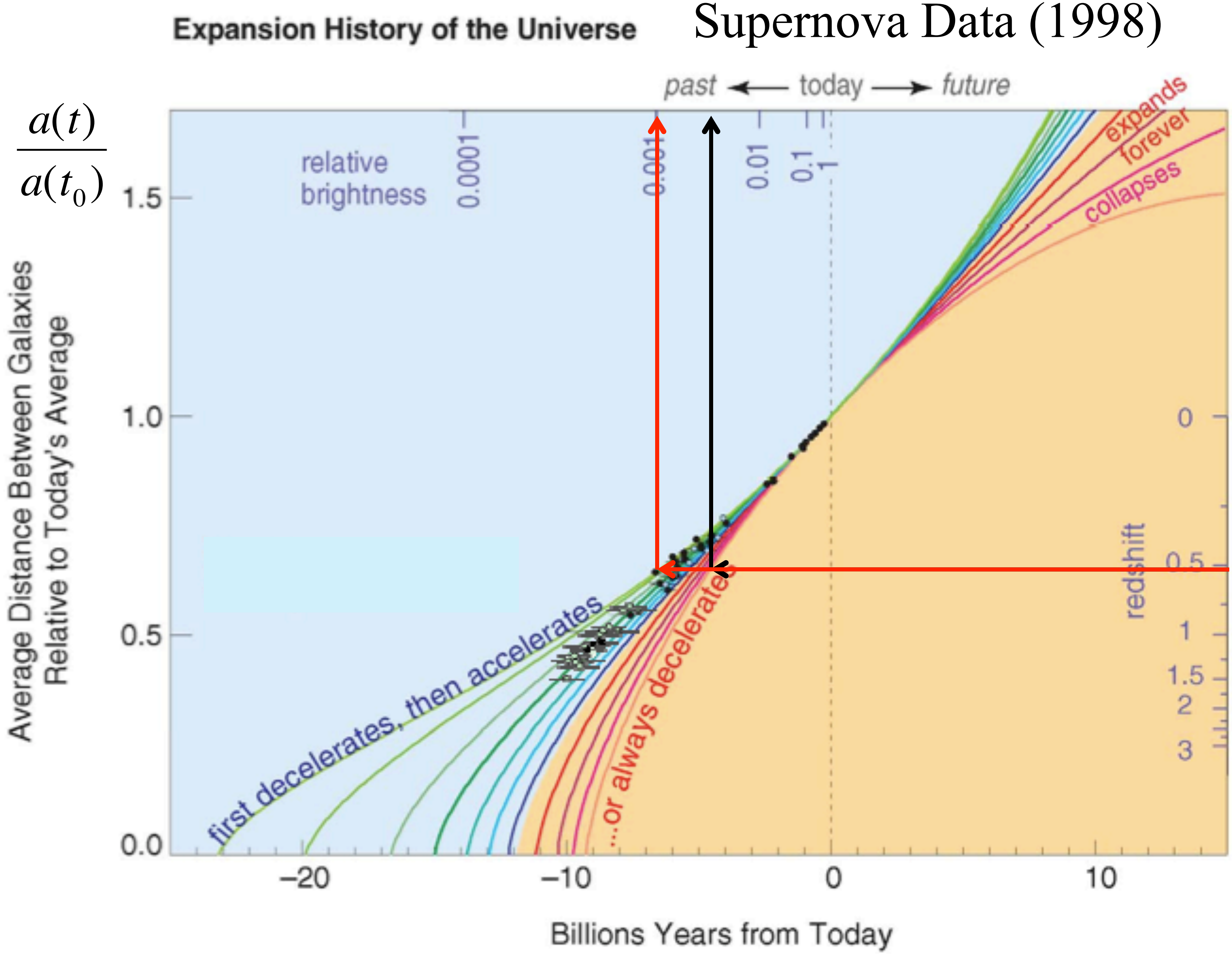
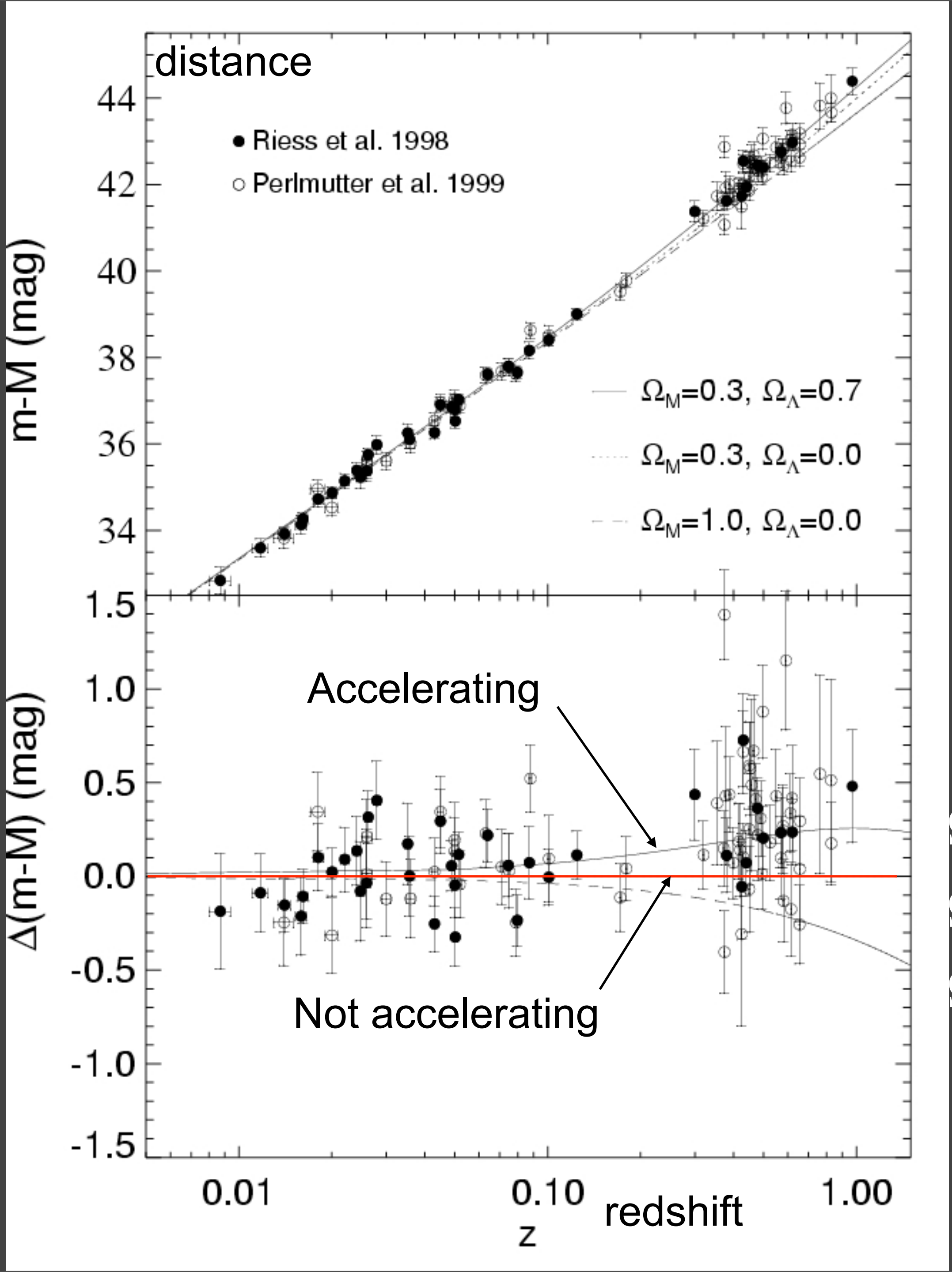


Discovery of Cosmic Acceleration from High-redshift Supernovae

Apply *same* Brightness-Decline relation at High-z

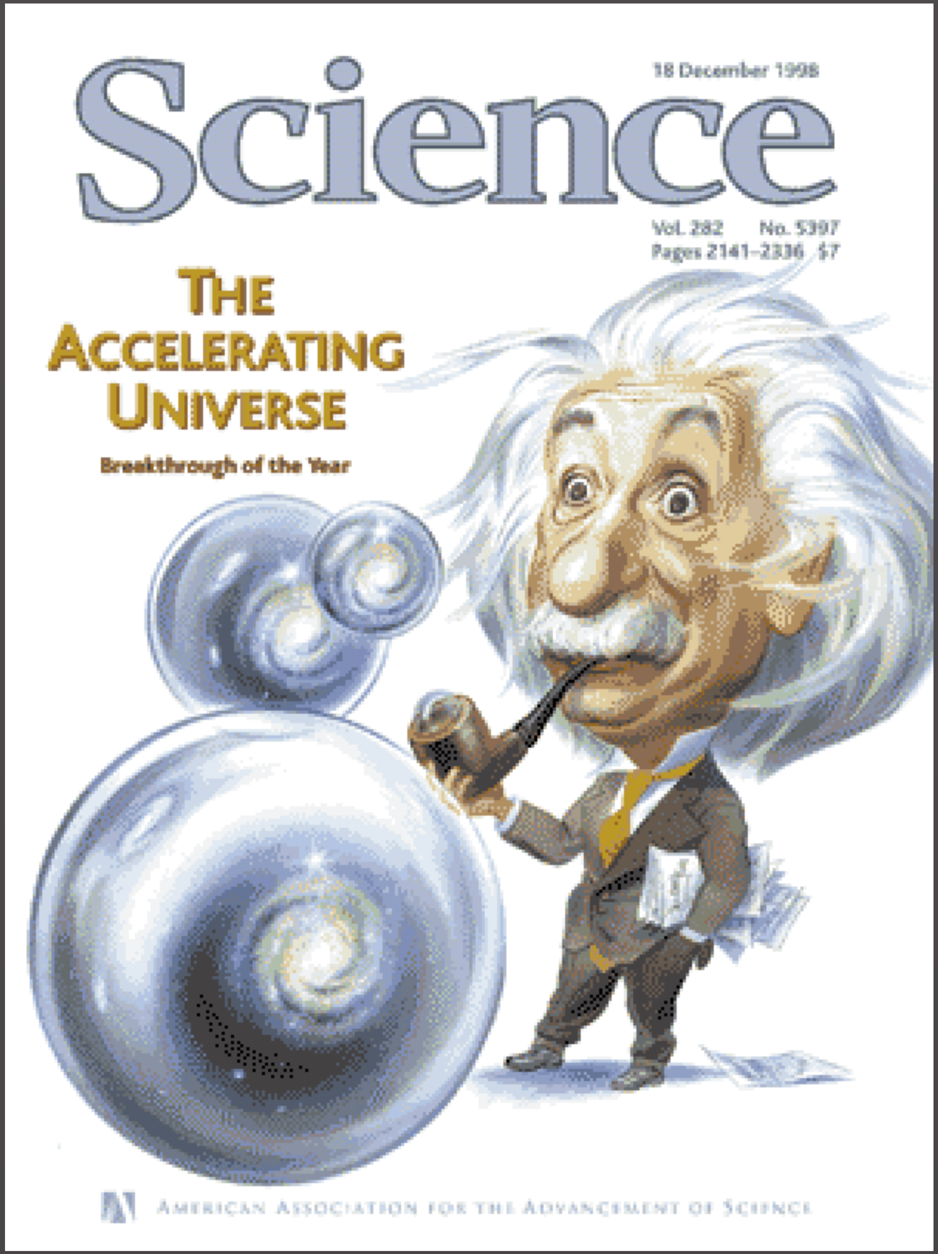
SNe that exploded when the Universe was 2/3 its present size are ~25% fainter than expected



$\Omega_\Lambda = 0.7$

$\Omega_\Lambda = 0.$

$\Omega_m = 1.$


18 December 1998
Science
Vol. 282 No. 5397
Pages 2141–2336 $7
THE ACCELERATING UNIVERSE
Breakthrough of the Year
AMERICAN ASSOCIATION FOR THE ADVANCEMENT OF SCIENCE

What causes Cosmic Acceleration?

Three possibilities:

1. The Universe is filled with stuff that gives rise to `gravitational repulsion'. We now call this

   Dark Energy

2. Einstein's theory of General Relativity (gravity) is wrong on cosmic distance scales.

See Scott Dodelson's talk tomorrow

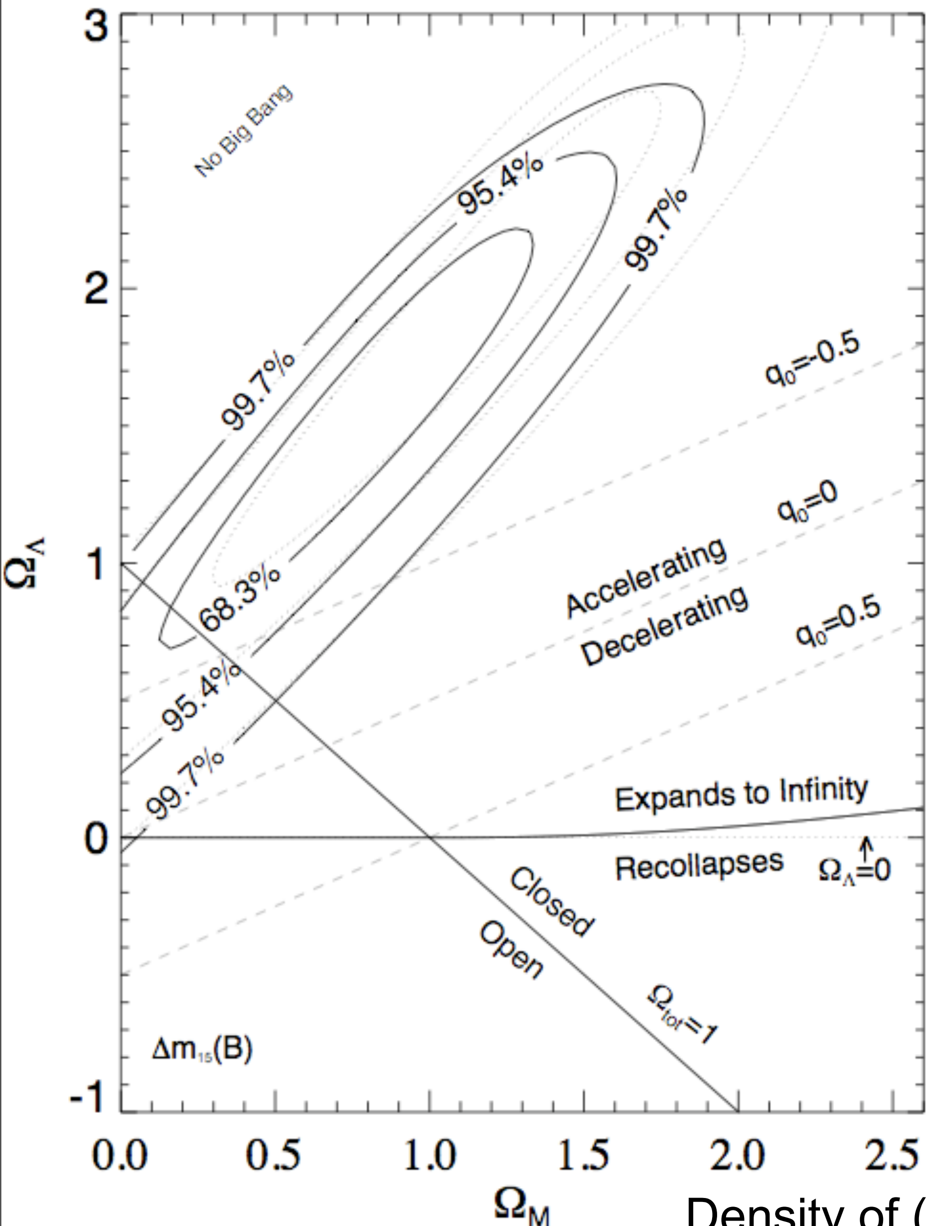
What is Dark Energy?

A form of energy that has negative pressure. It is smoothly distributed throughout the Universe, unlike dark matter, which clumps in galaxies.

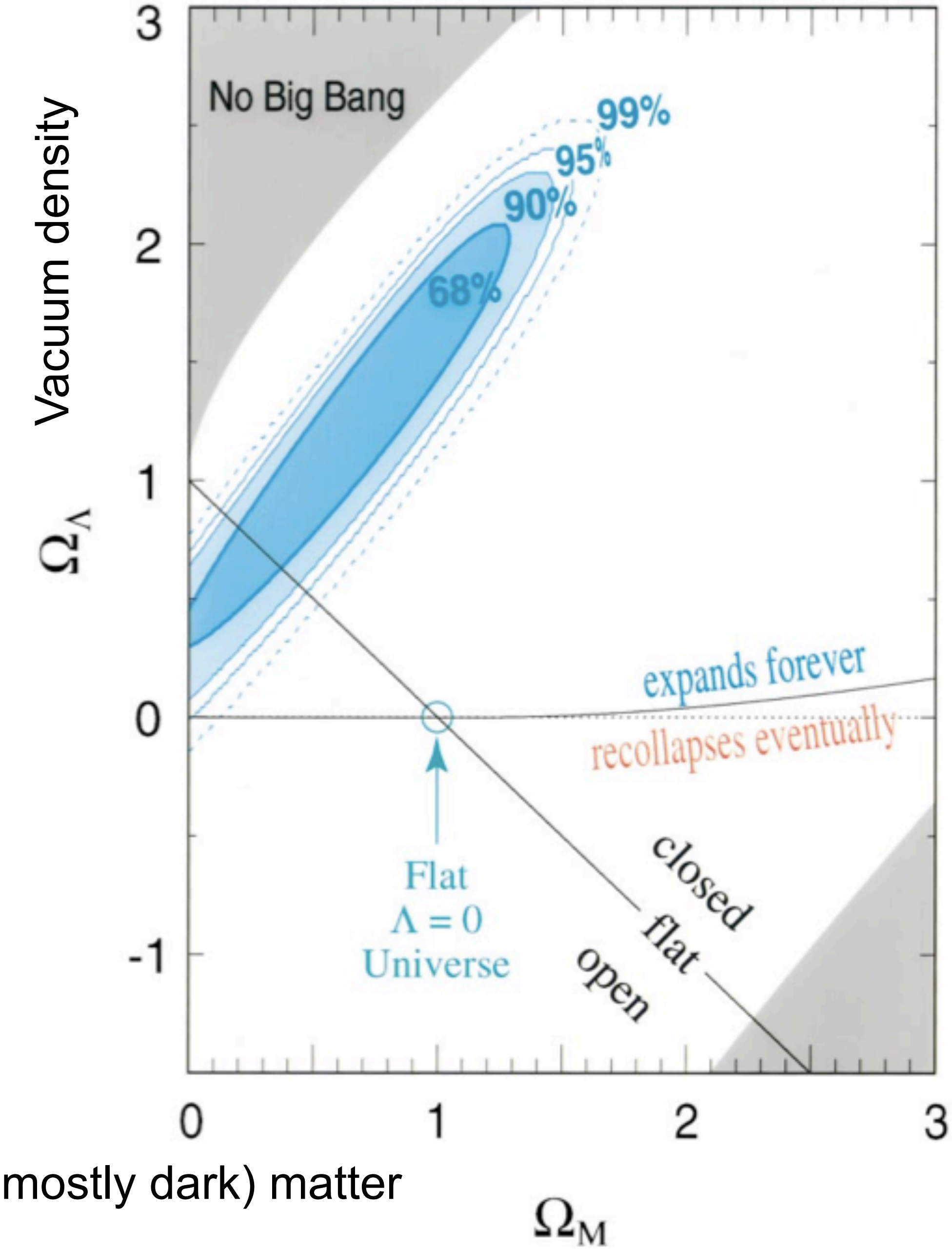
The oldest example is Einstein's cosmological constant Λ, a term he introduced into his theory of gravity in an attempt to make the Universe static (Don't ask).

It was later realized that the cosmological constant corresponds to the energy of empty space (the vacuum). The theory of quantum mechanics (Heisenberg's uncertainty principle) predicts this energy should be there.

Riess et al. (1998, AJ)



Perlmutter et al. (1999, ApJ)



Density of (mostly dark) matter

The Cosmological Constant Problem

Quantum zero-point fluctuations: space is filled with virtual particles that continuously fluctuate into and out of the vacuum.

These fluctuations carry energy. When we calculate that energy (per unit volume), we get infinity.

When we try to fix that problem, we still get an answer that is too big by a factor of about
100000000000000000000000000000000000000000000
000000000000000000000000000000000000000000000
0000000000000000000000000000000000000000
This problem continues to stump particle physicists and string theorists.

Tragic History of the Cosmological Constant

Λ periodically invoked to solve cosmological crises,
then dropped when they passed:

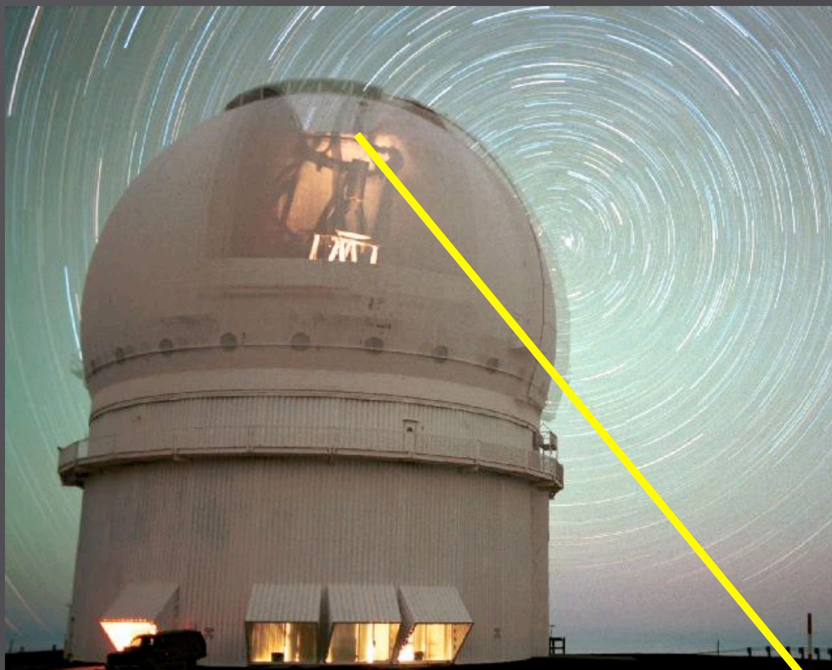
1916: Einstein: static Universe
1929: 1st `age crisis': Universe younger than Earth
1967: apparent clustering of quasars at fixed redshift
1974: inferred distances using galaxy brightness
1995: 2nd 'age crisis': Universe younger than stars

1998: Supernovae

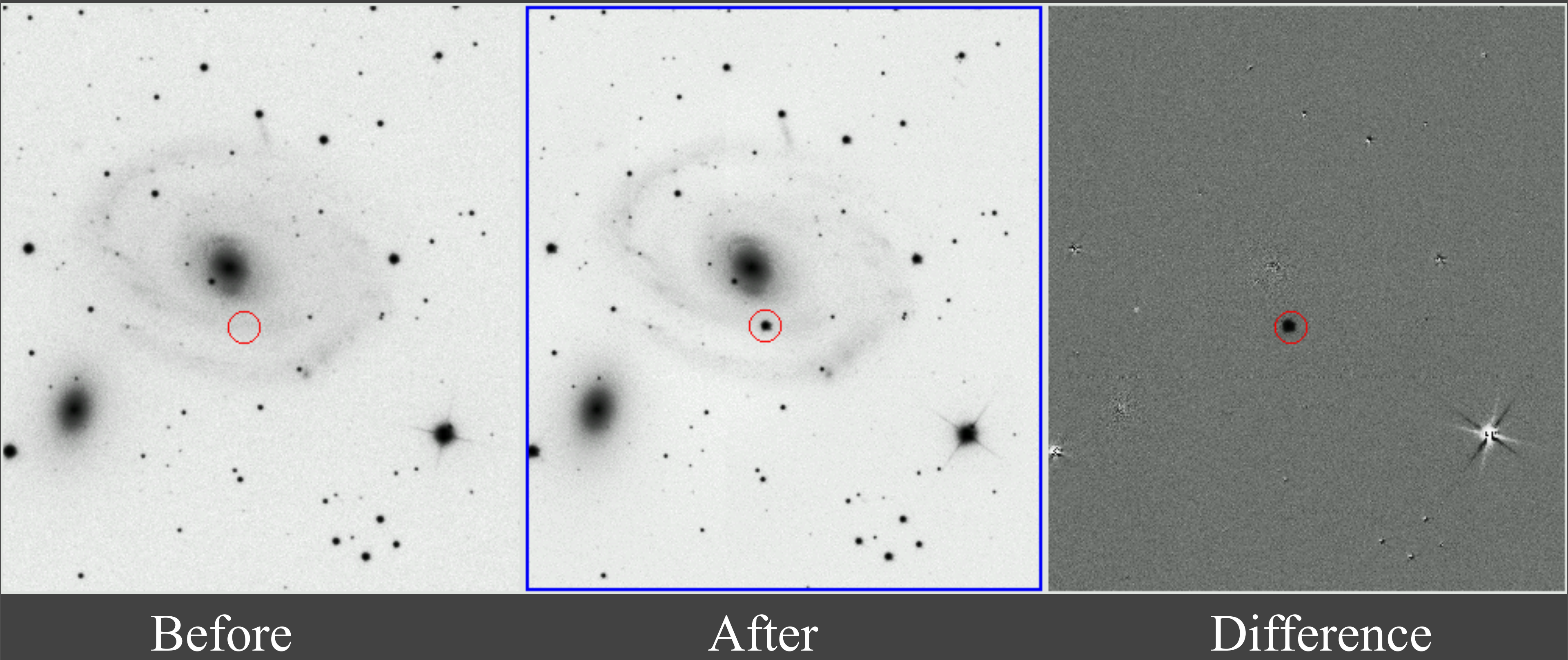
Why do we think it's different now?

Supernova Legacy Survey (SNLS, 2003-2008)

- Measured over 300 distant SNe
- Used 3.6-meter Canada-France-Hawaii telescope
- Megacam with 36 CCDs, 4 optical filters
- Spectroscopic follow-up on 8-10meter telescopes

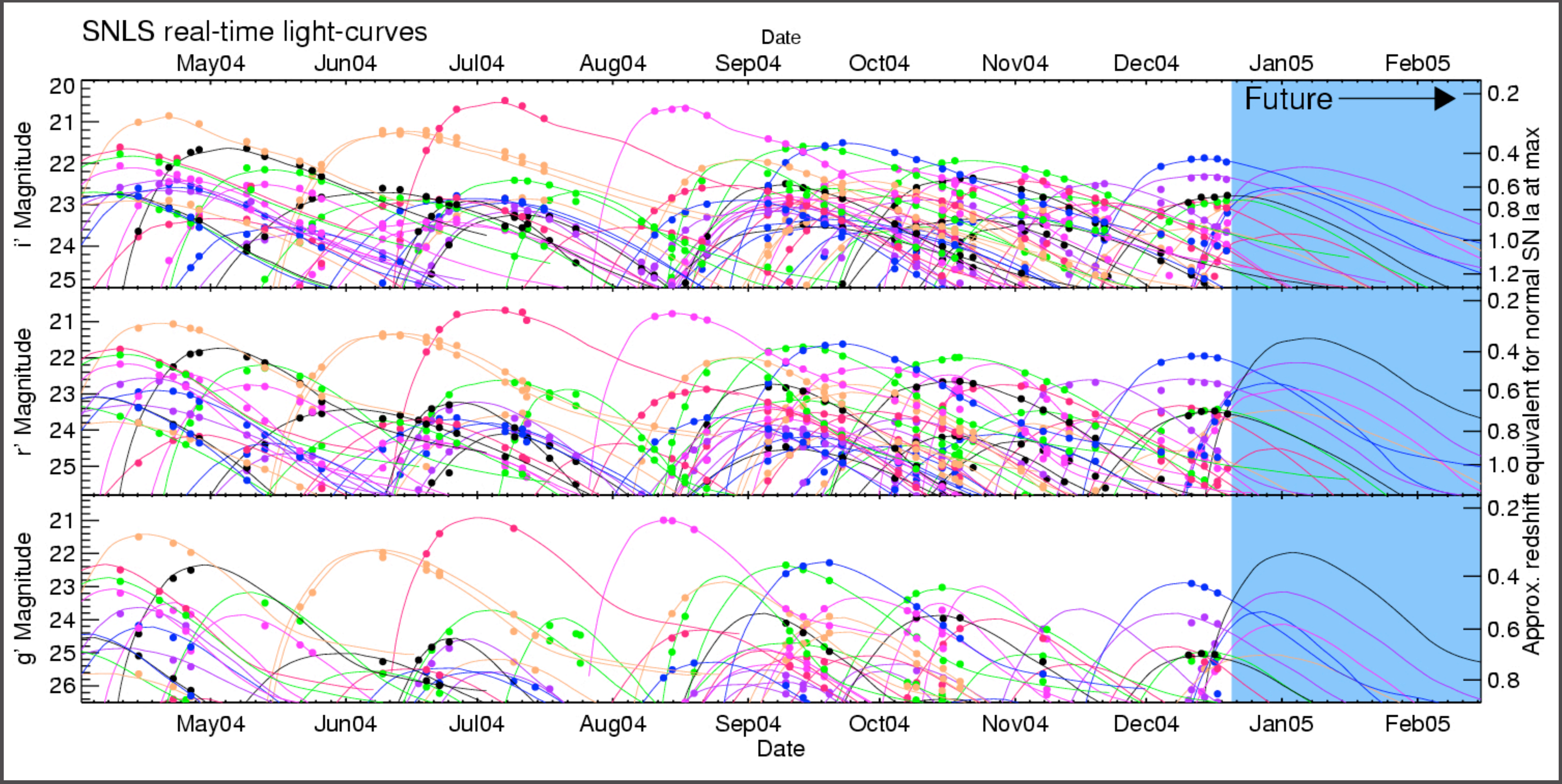


Finding Supernovae: Image Subtraction



SN 2002ha (Ia) z = 0.014

SNLS Rolling Search

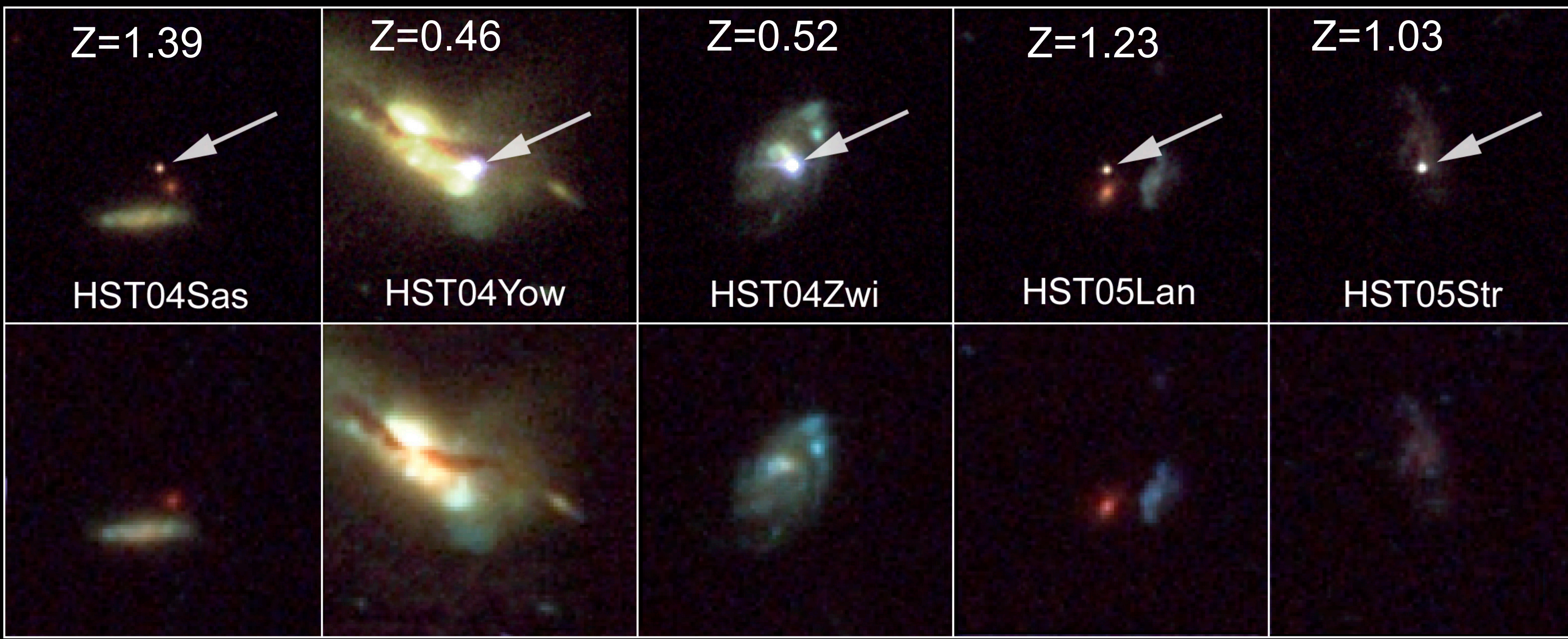


Light curves

The ESSENCE Survey

- 6-year project on CTIO 4m telescope in Chile; 12 sq. deg.
- Wide-field images in 2 bands
- Same-night detection of SNe
- Spectroscopy
  - Keck, VLT, Gemini, Magellan
- Goal is 200 SNeIa, $0.2<z<0.8$
- Data and SNeIa public real-time

Higher-z SNe Ia from ACS



Host Galaxies of Distant Supernovae

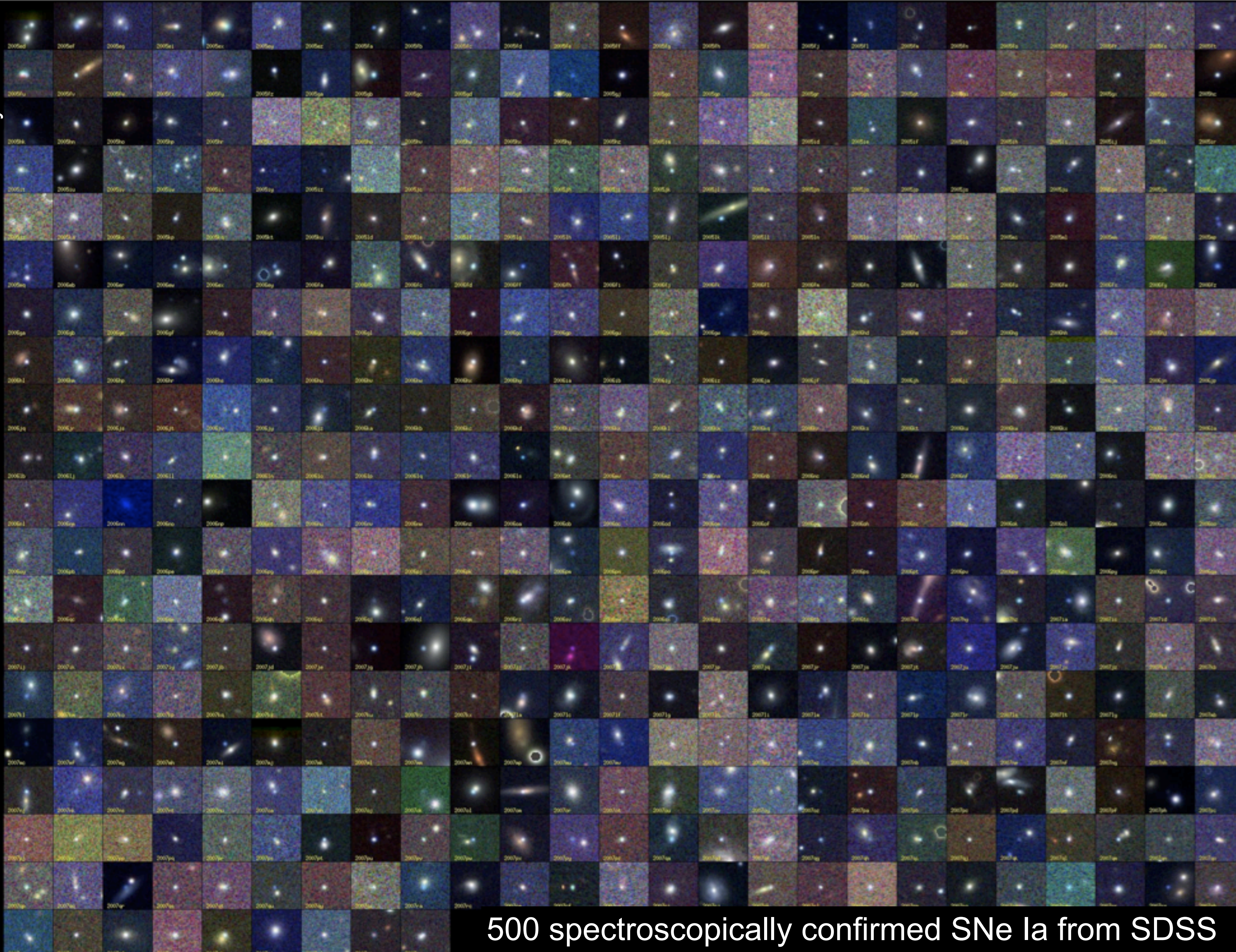
Hubble Space Telescope ▪ Advanced Camera for Surveys

50 SNe Ia, 25 at $z>1$

Riess, etal


Sloan Digital Sky Survey 2.5 meter telescope
Apache Point Observatory
New Mexico

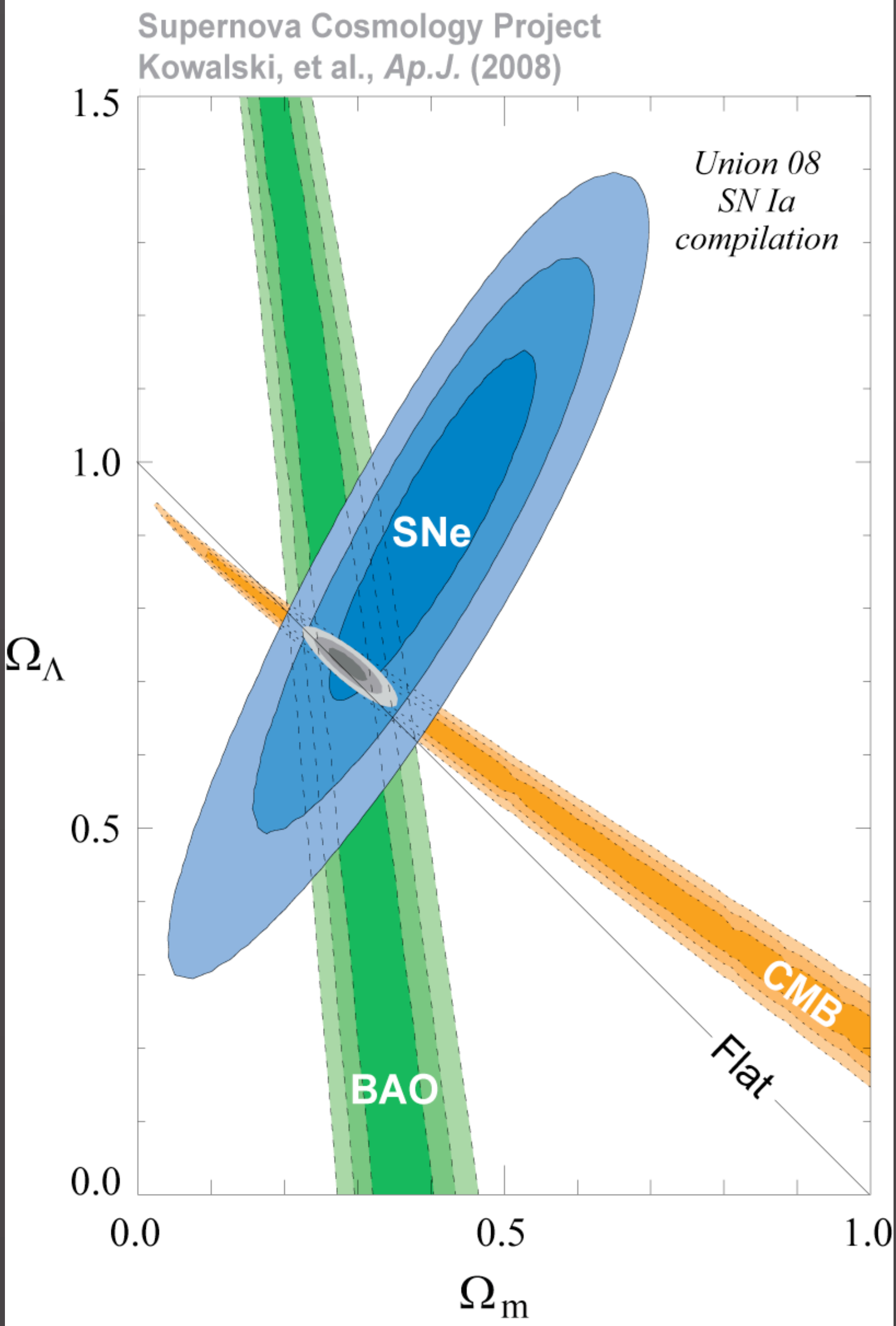
B. Dilday



500 spectroscopically confirmed SNe Ia from SDSS

B. Dilday

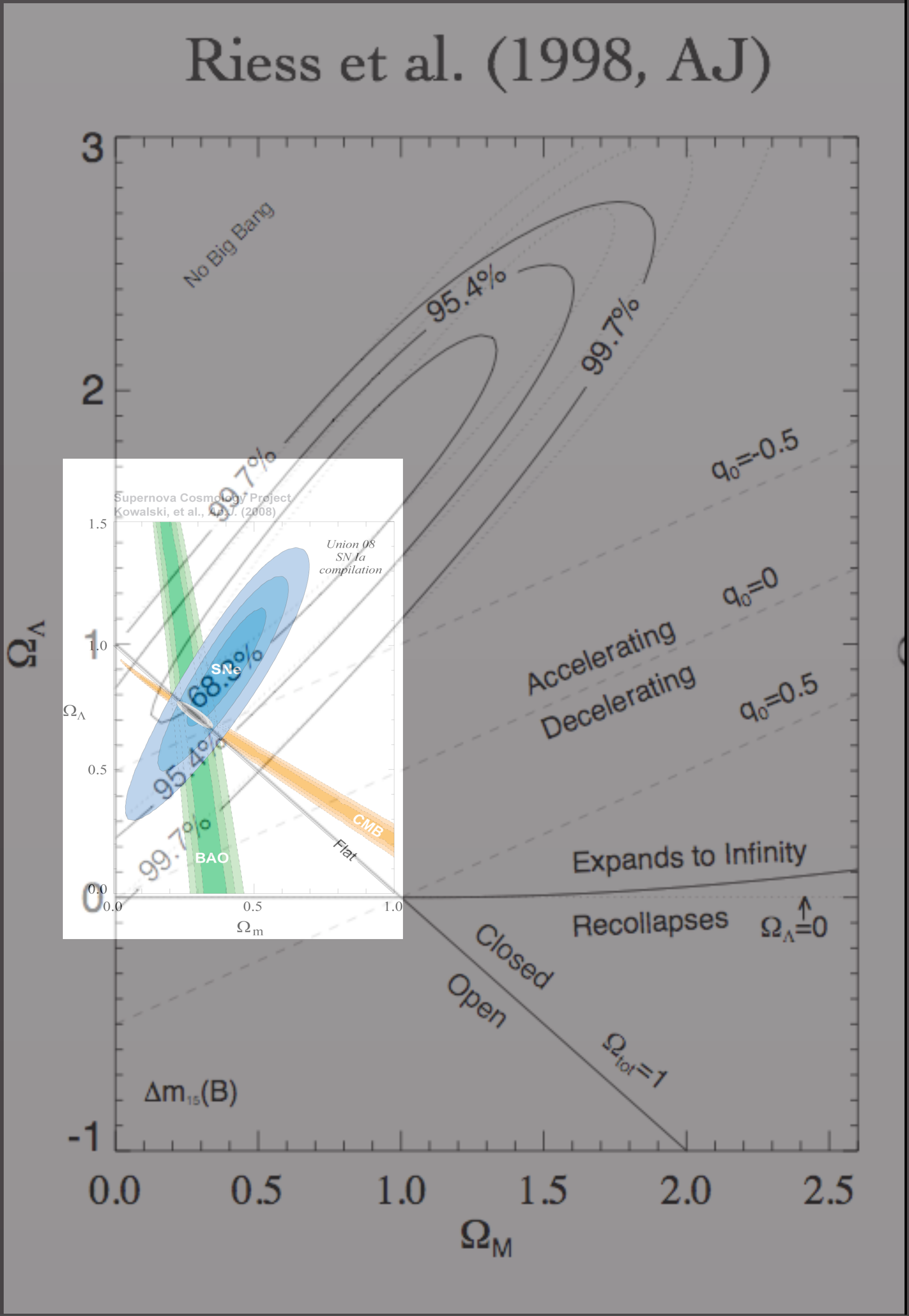
500 spectroscopically confirmed SNe Ia from SDSS



Recent Dark Energy Constraints

Constraints from Supernovae, Cosmic Microwave Background Anisotropy (WMAP) and Large-scale Structure (Baryon Acoustic Oscillations, SDSS)

Progress over the last decade



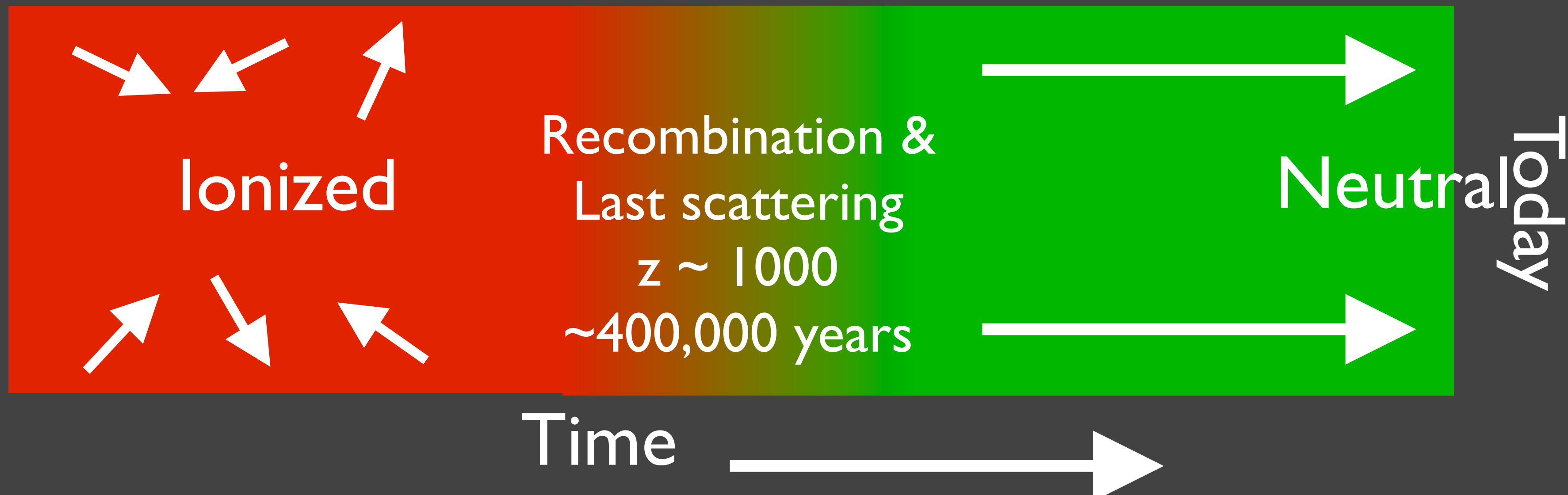
Cosmic Microwave Background Radiation: Sound Waves in the Early Universe

Before H recombination:

- Universe is ionized.
- Photons provide enormous pressure and restoring force.
- Photon-baryon perturbations oscillate as acoustic waves.

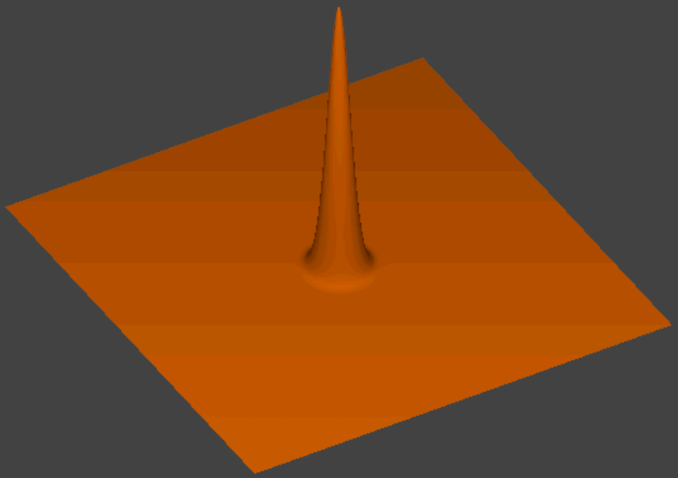
After H recombination:

- Universe is neutral.
- Photons can travel freely past the baryons.
- Phase of oscillation at t_{rec} affects late-time amplitude.



Sound Waves

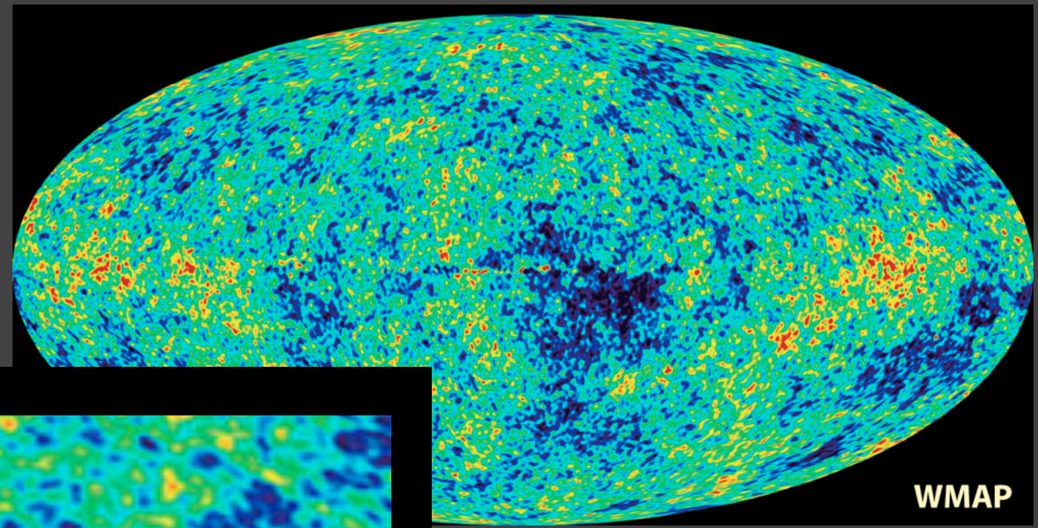
- Each initial overdensity (in dark matter & gas) is an overpressure that launches a spherical sound wave.
- This wave travels outwards at 57% of the speed of light.
- Pressure-providing photons decouple at recombination, and wave stalls. Photons travel to us from these spheres.

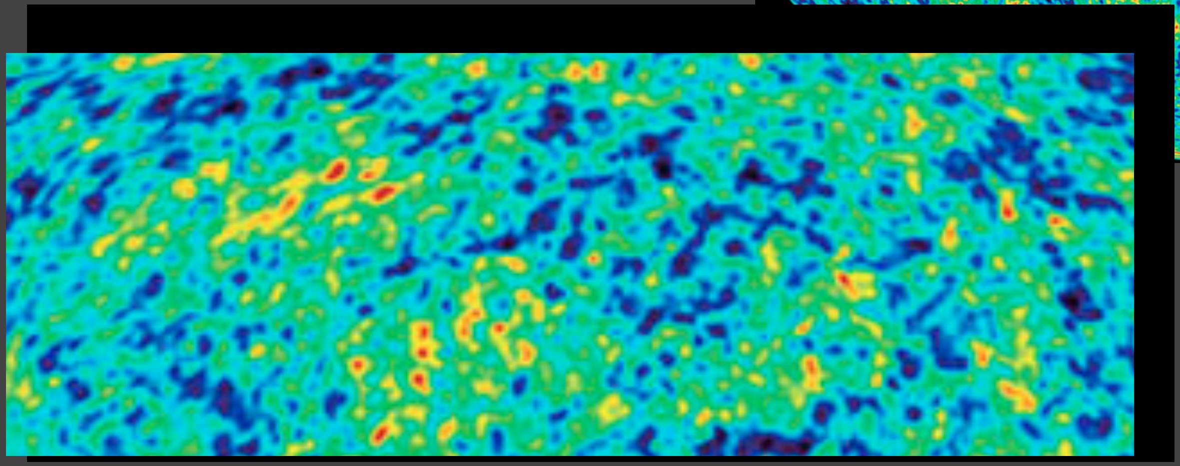


Eisenstein

Anisotropies in the CMB

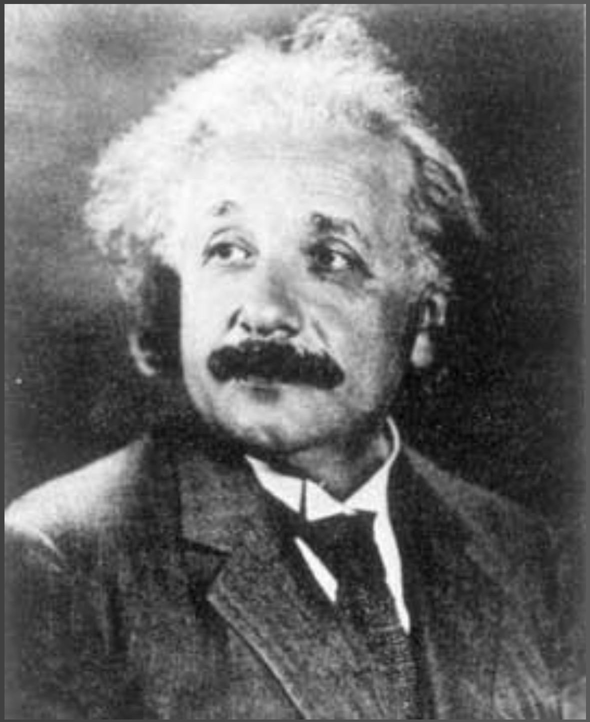
Temperature map of the cosmic microwave background radiation





- There is a characteristic angular scale, ~ 1 degree on the sky, set by the distance sound waves can travel just before neutral atoms form: sound horizon *s*, a standard ruler

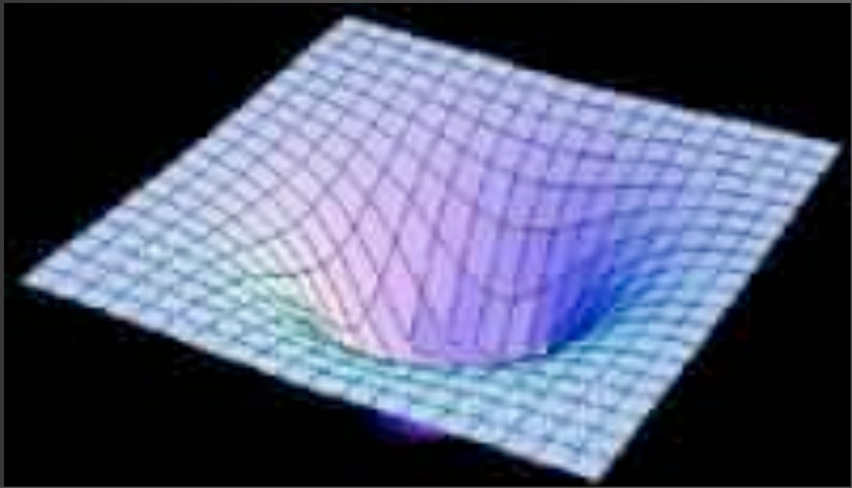
Einstein's General Relativity



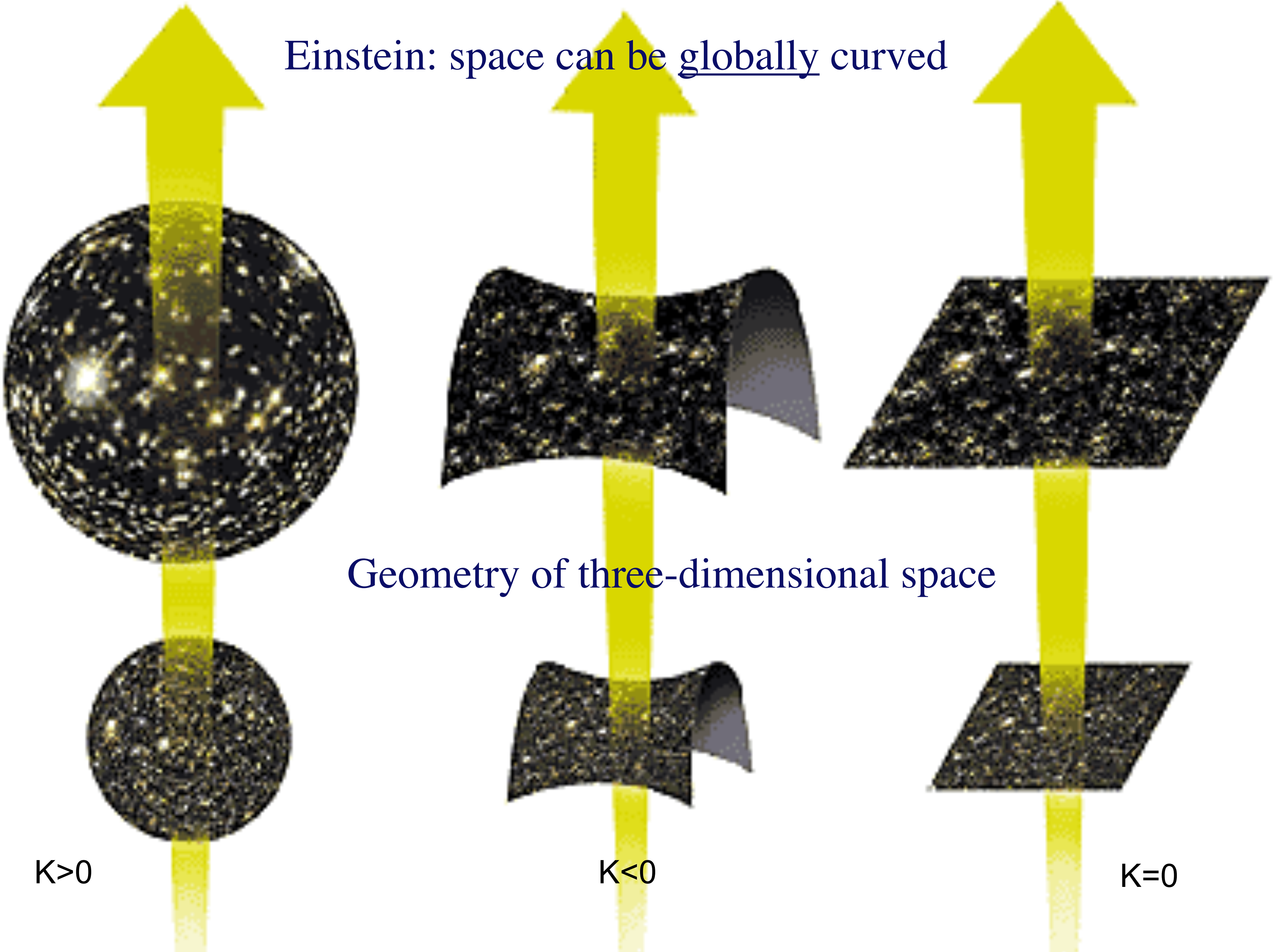
Matter and Energy curve
Space-Time

Everything moves in this
curved Space-time

A massive star attracts nearby objects by distorting spacetime

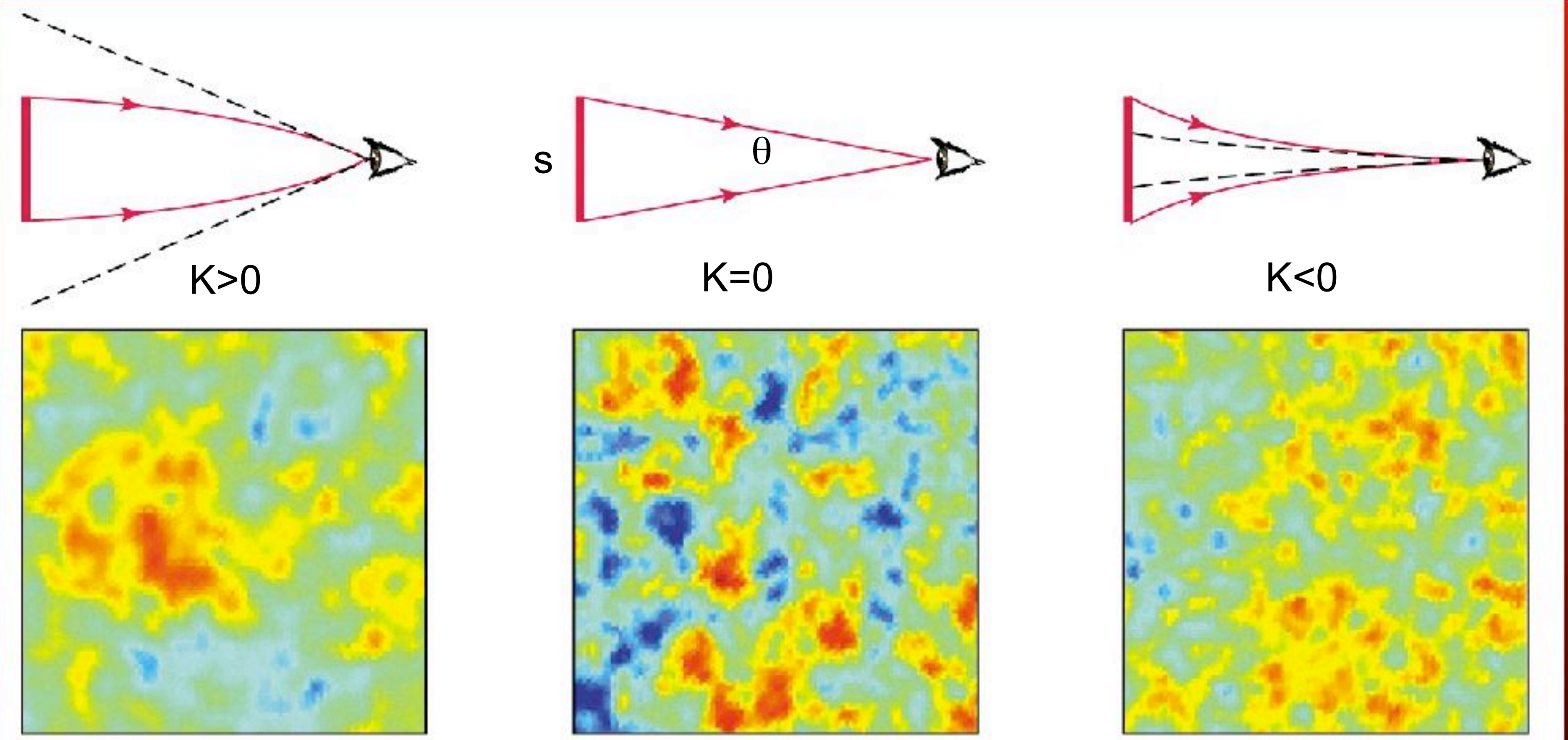


Einstein: space can be globally curved



Geometry of three-dimensional space

Seeing the Sound Horizon



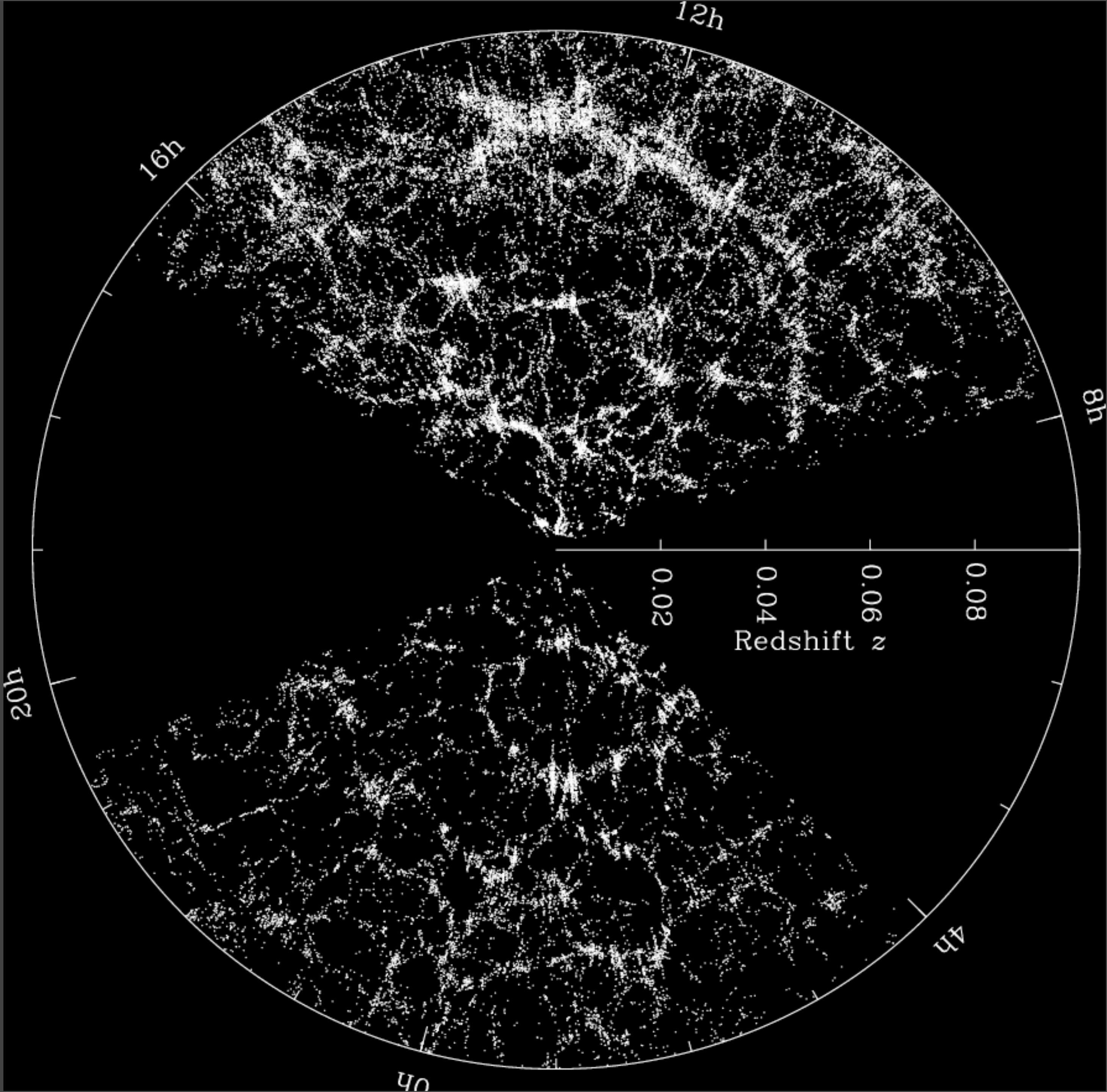
a If universe is closed, "hot spots" appear larger than actual size

b If universe is flat, "hot spots" appear actual size

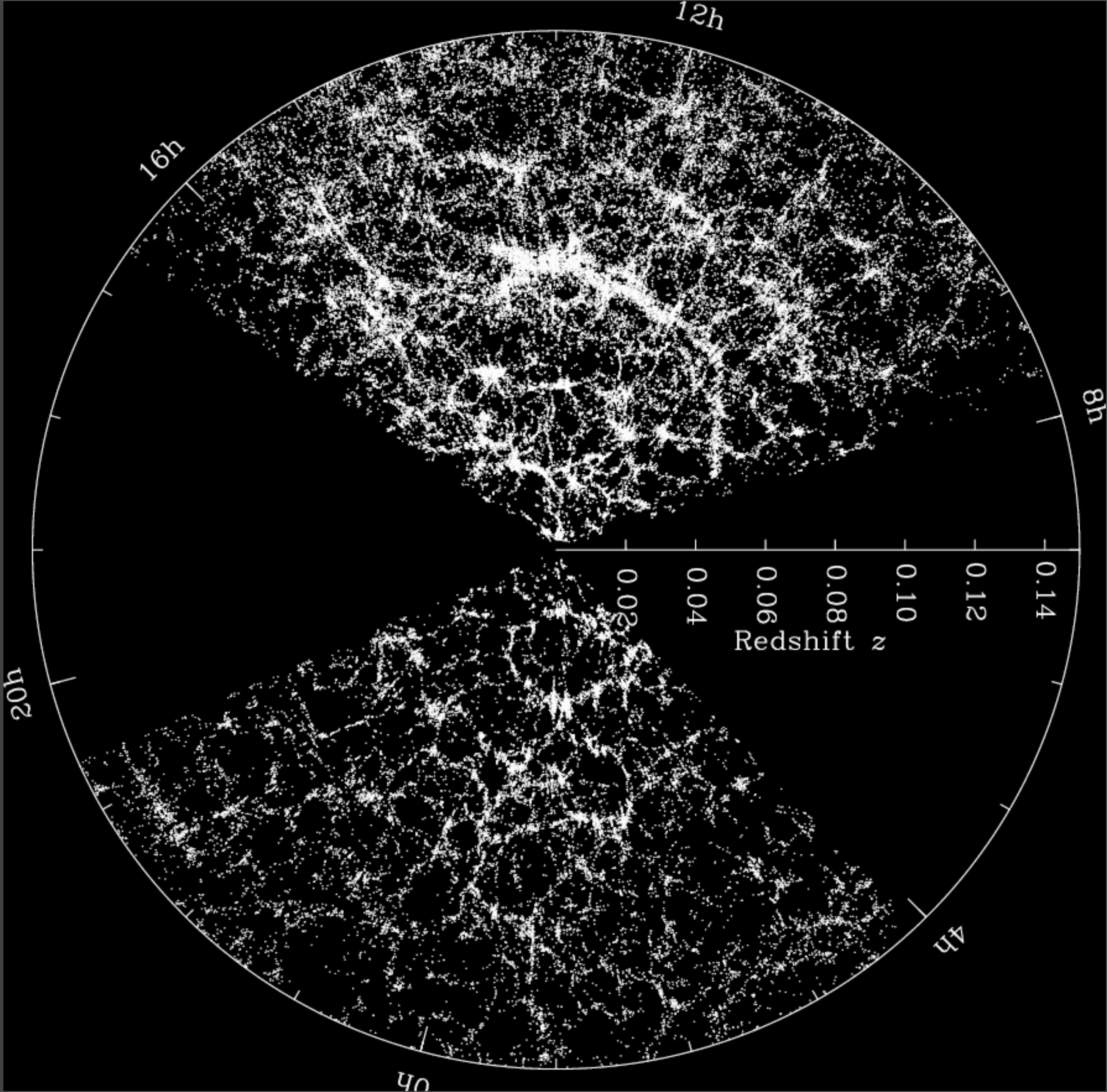
c If universe is open, "hot spots" appear smaller than actual size

CMB Maps tell us space is nearly flat

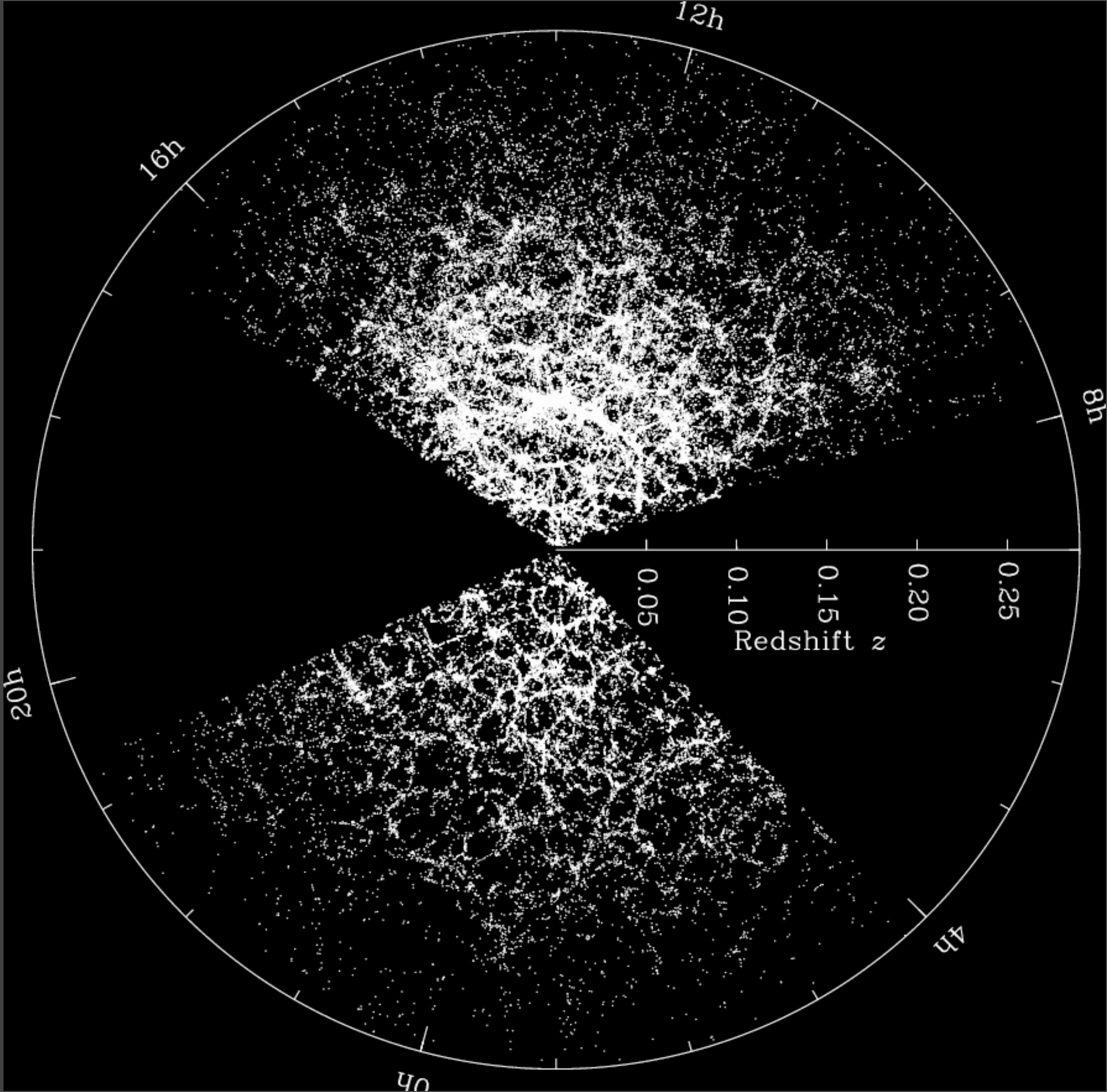
SDSS Galaxy Distribution



SDSS Galaxy Distribution



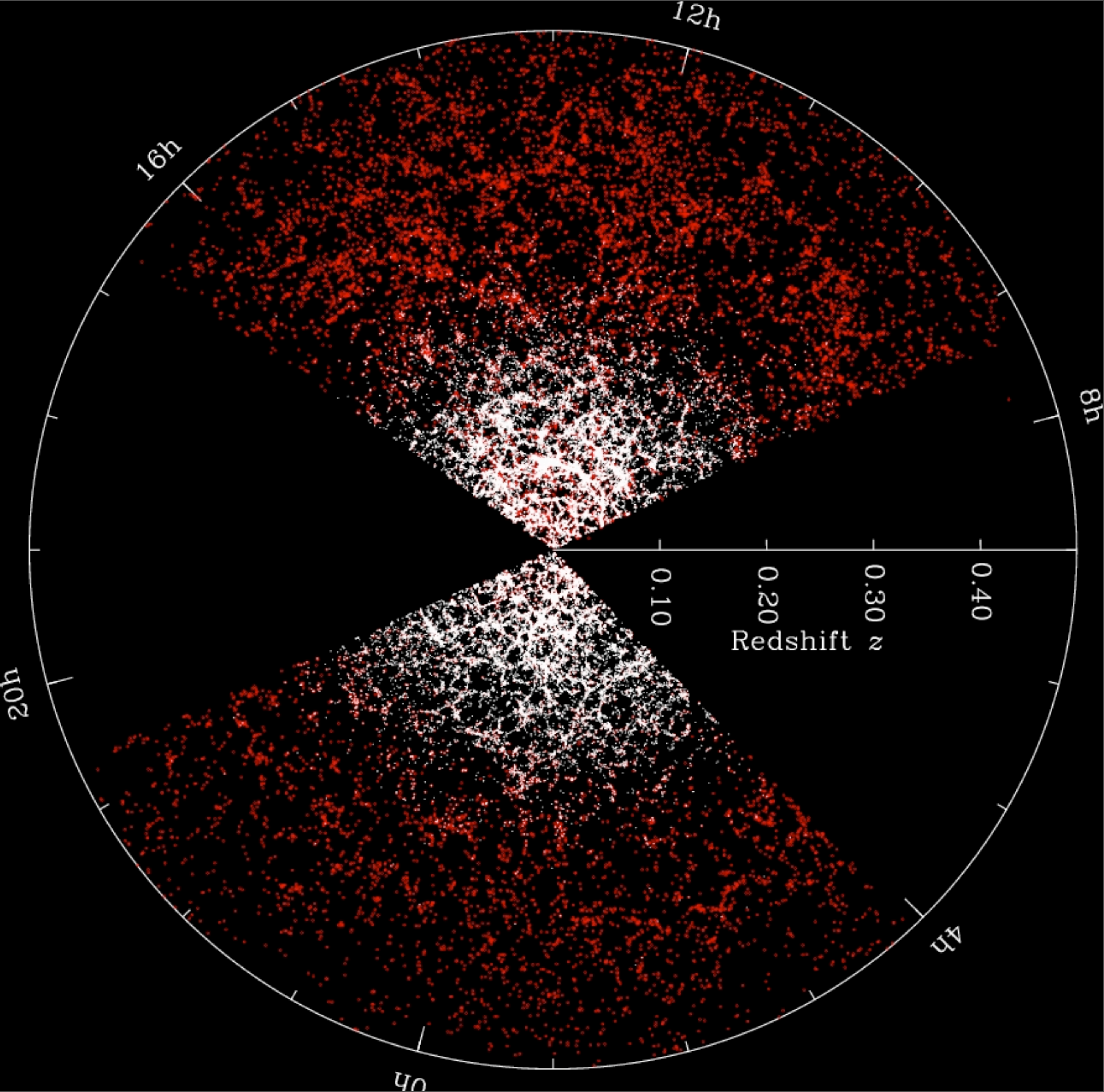
SDSS Galaxy Distribution



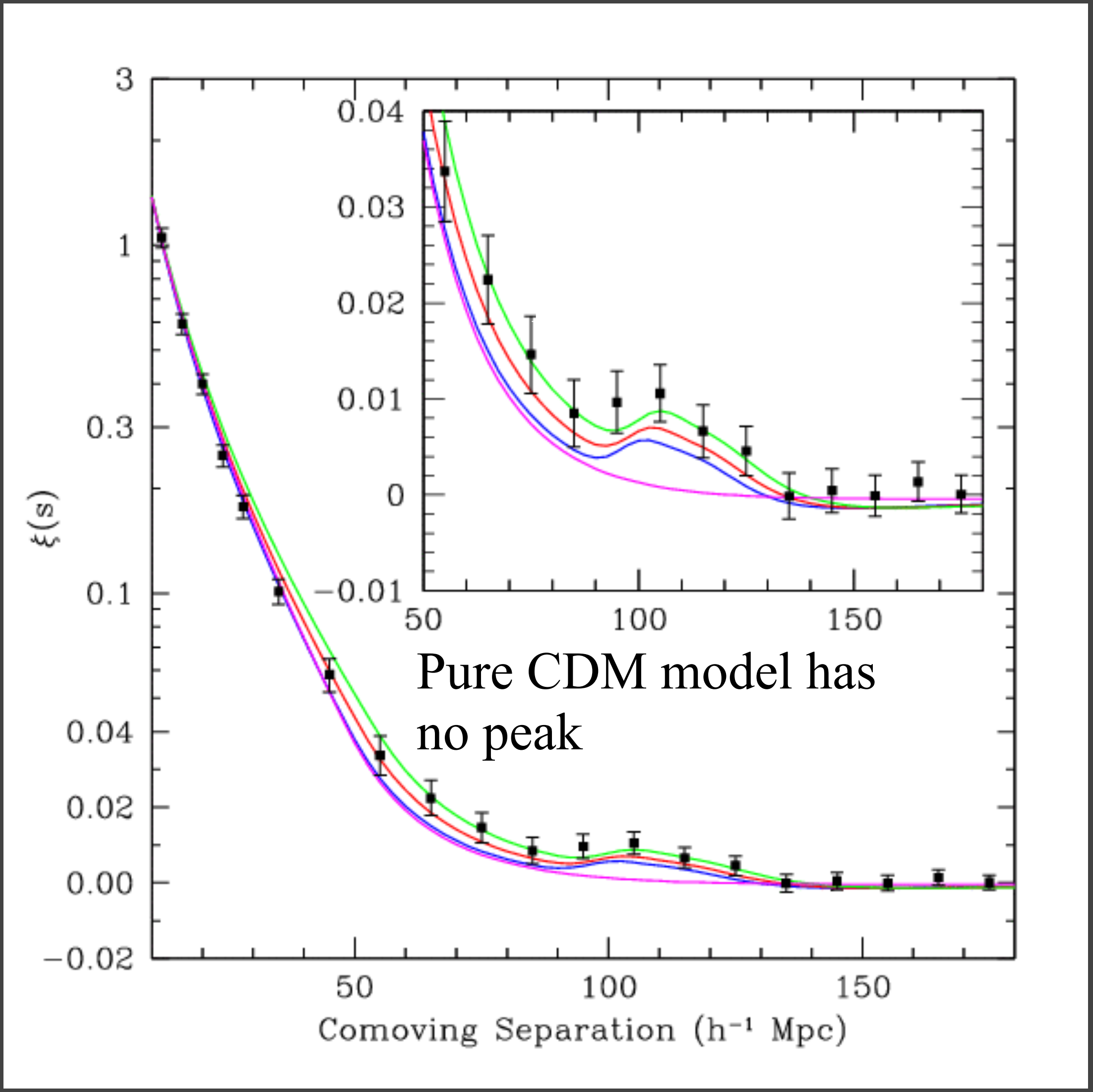
SDSS Galaxy Distribution

Luminous Red Galaxies

Their distribution also shows imprint of the sound horizon



Large-scale Correlations of SDSS Luminous Red Galaxies

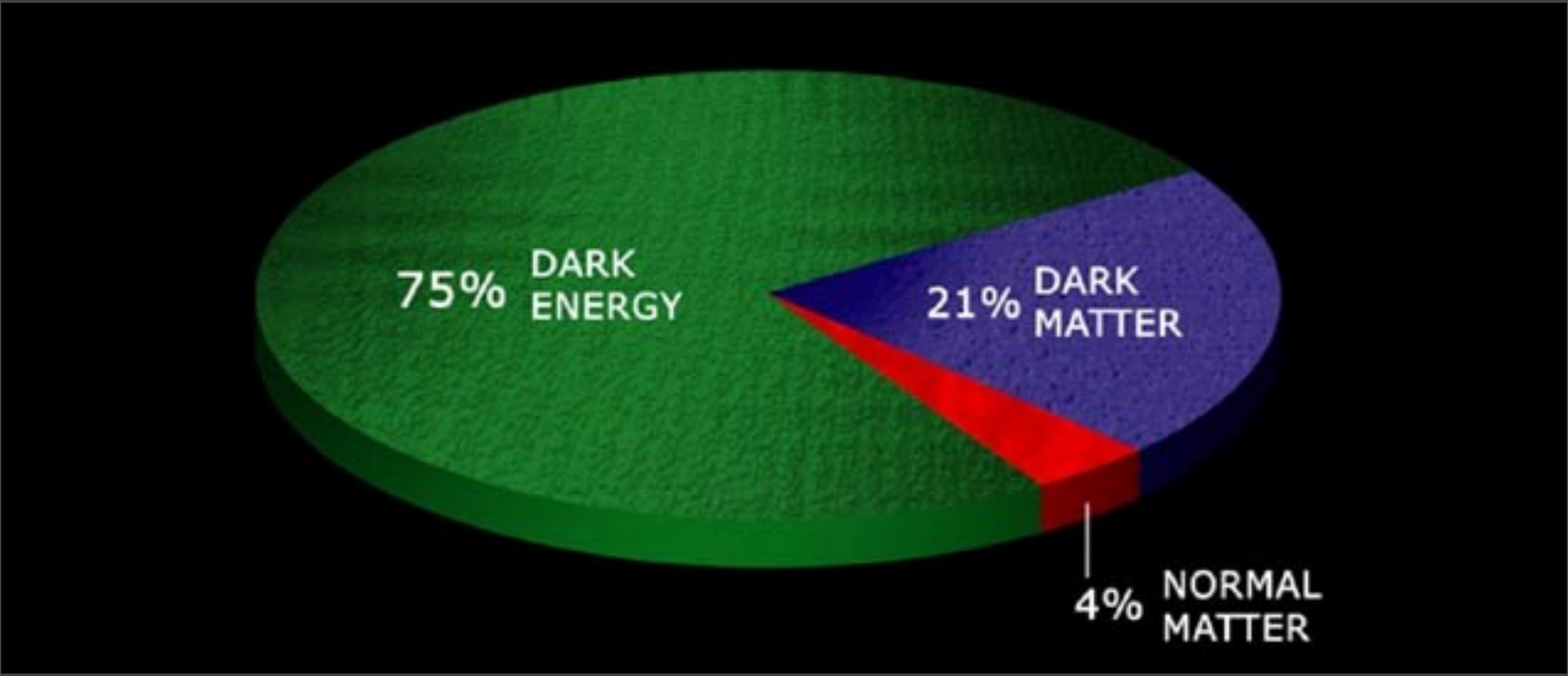


Baryon Acoustic Oscillations seen in Large-scale Structure:

mean distance to galaxies at z~0.35

Eisenstein, etal 2005

Components of the Universe

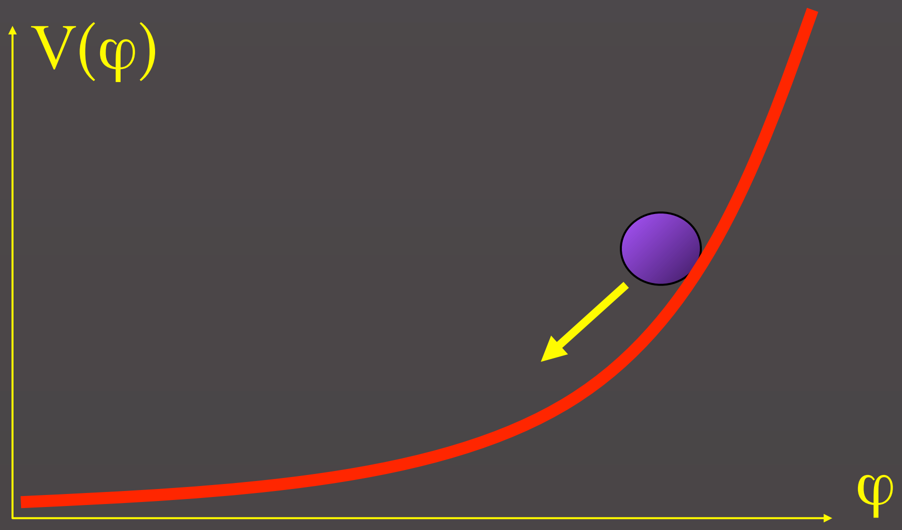


Combined picture from supernovae, CMB, Large-scale structure

Scalar Field as Dark Energy

(aka `Quintessence' in the Trenton, NJ suburbs)

- Dark Energy could also a very slowly rolling `scalar field'
- This particle must be many orders of magnitude less massive than other elementary particles.
- Evidence suggests an earlier period of cosmic acceleration shortly after the Big Bang, possibly due to a scalar field (``primordial inflation'')



- Scalar field dark energy can have different effect on the expansion rate than vacuum energy: test

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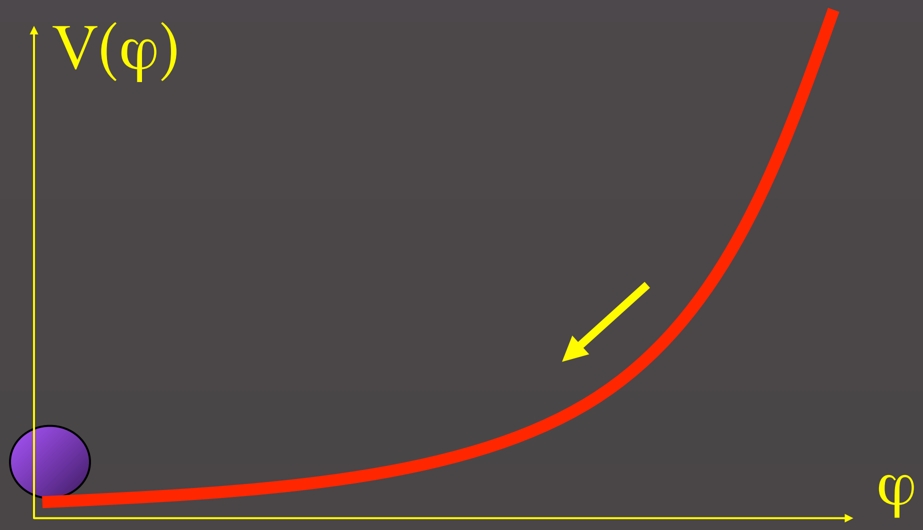
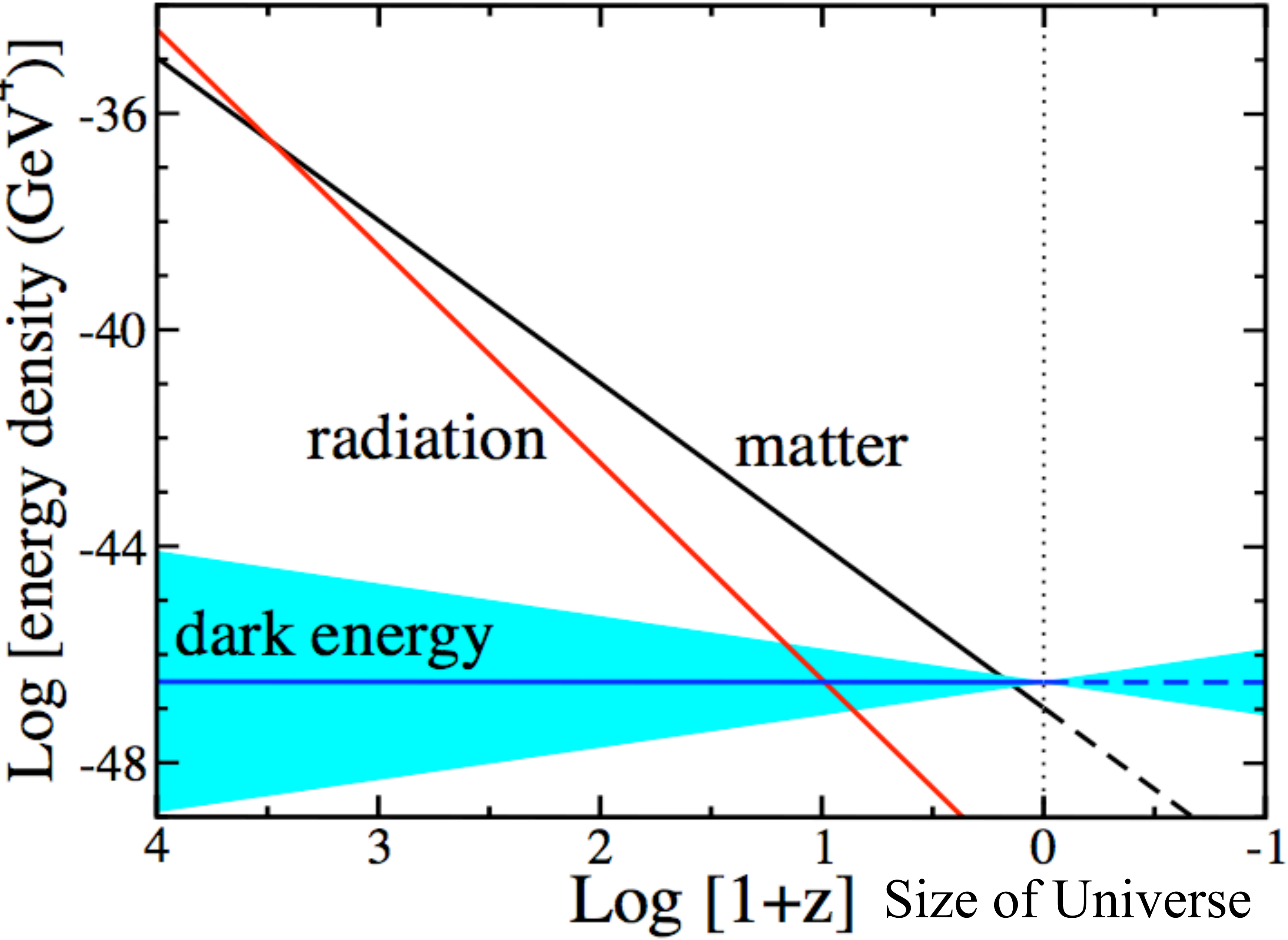


- Scalar field dark energy can have different effect on the expansion rate than vacuum energy: test

Why do we live at the `special' epoch when matter and dark energy are comparable?



Dark Energy and the Fate of the Universe

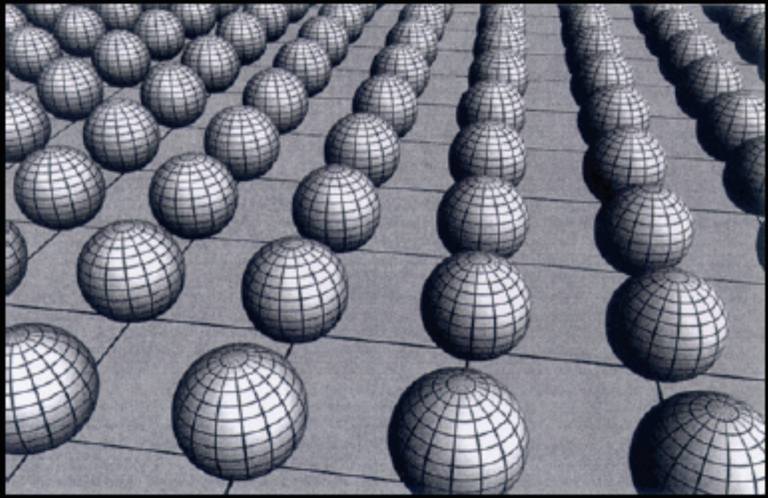
•Nature of Dark Energy determines future evolution of the Universe

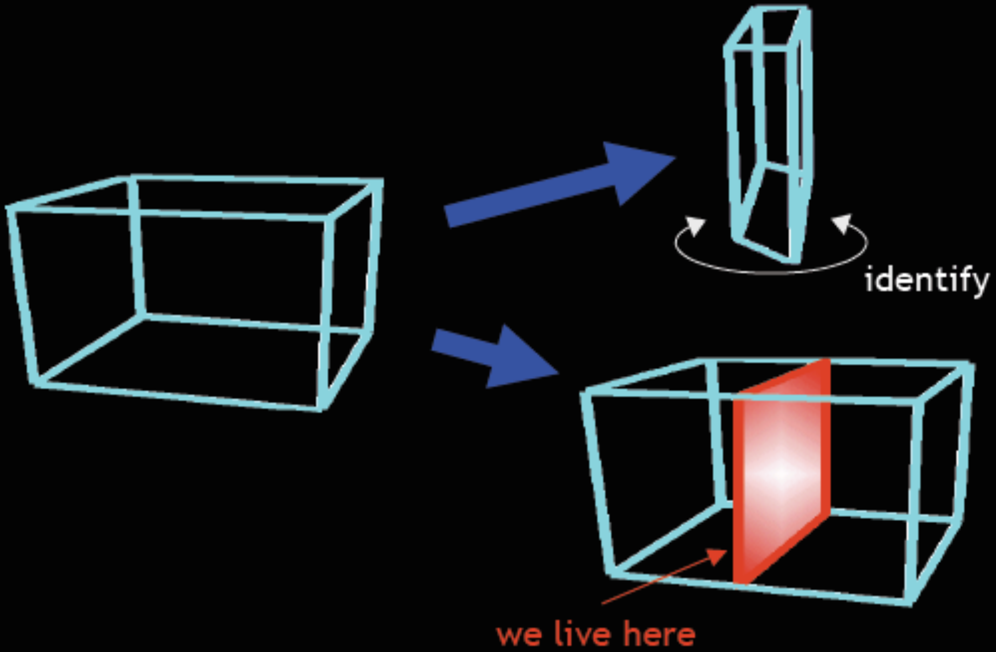
•Continued acceleration: the Universe beyond the Local Group of galaxies will disappear beyond the horizon in ~100 billion years

•`Phantom Dark Energy': in some models, dark energy density increases in time, leading to ever-increasing expansion rate: eventually galaxies, stars, atoms would be split apart

Extra dimensions of spacetime

String theory does predict that there are extra dimensions which we can't see. They might alter the way in which vacuum energy influences spacetime curvature.





Old-school compactification:
curl up dimensions until they're too small to see (Kaluza & Klein)

New-fangled approach:
imagine we are confined to a "brane"

Gravity can leak off brane

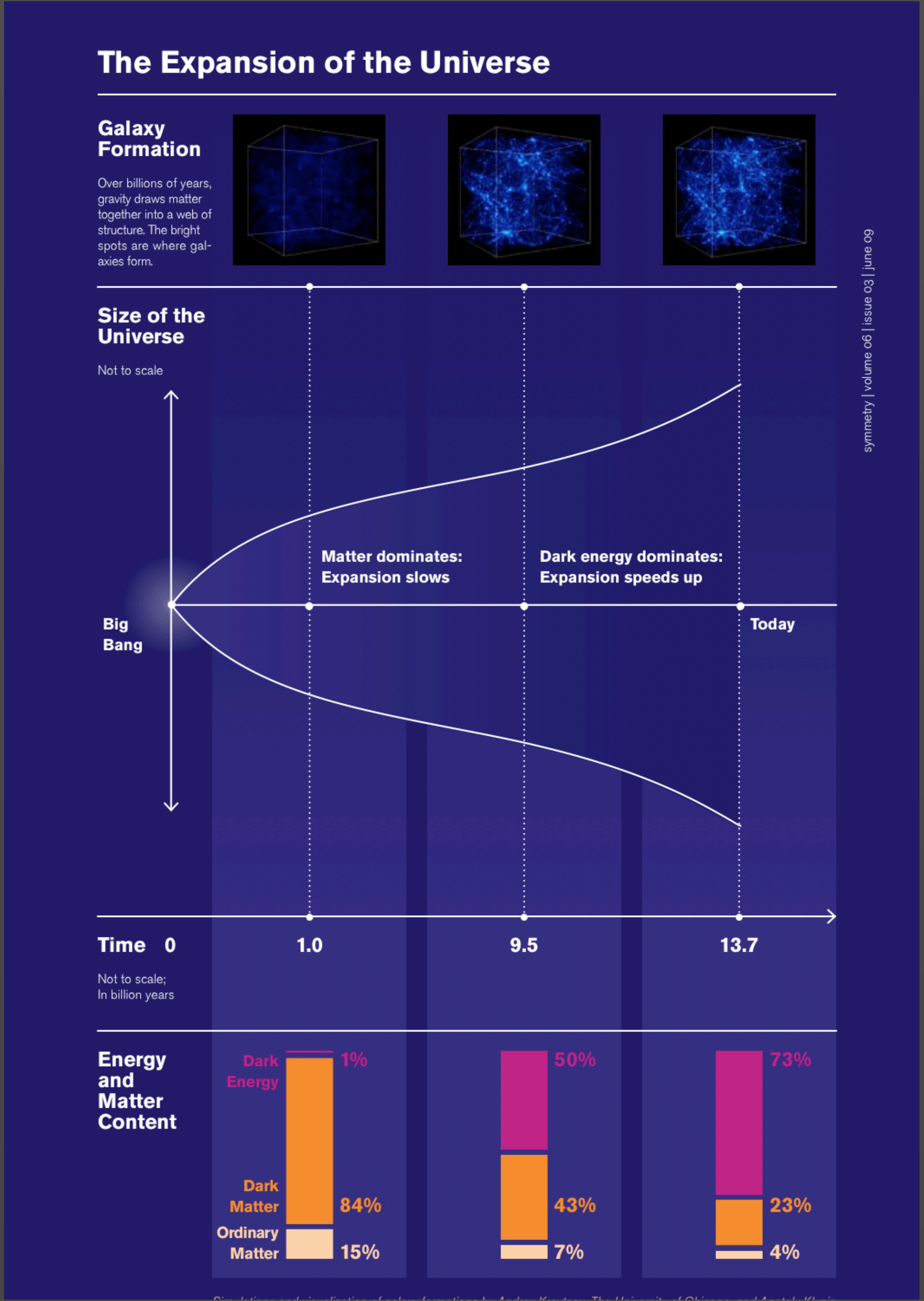
Is cosmic acceleration due to Dark Energy or Weird Gravity?

If Dark Energy, is it the cosmological constant (vacuum energy) or something else?

How do we plan to find out?

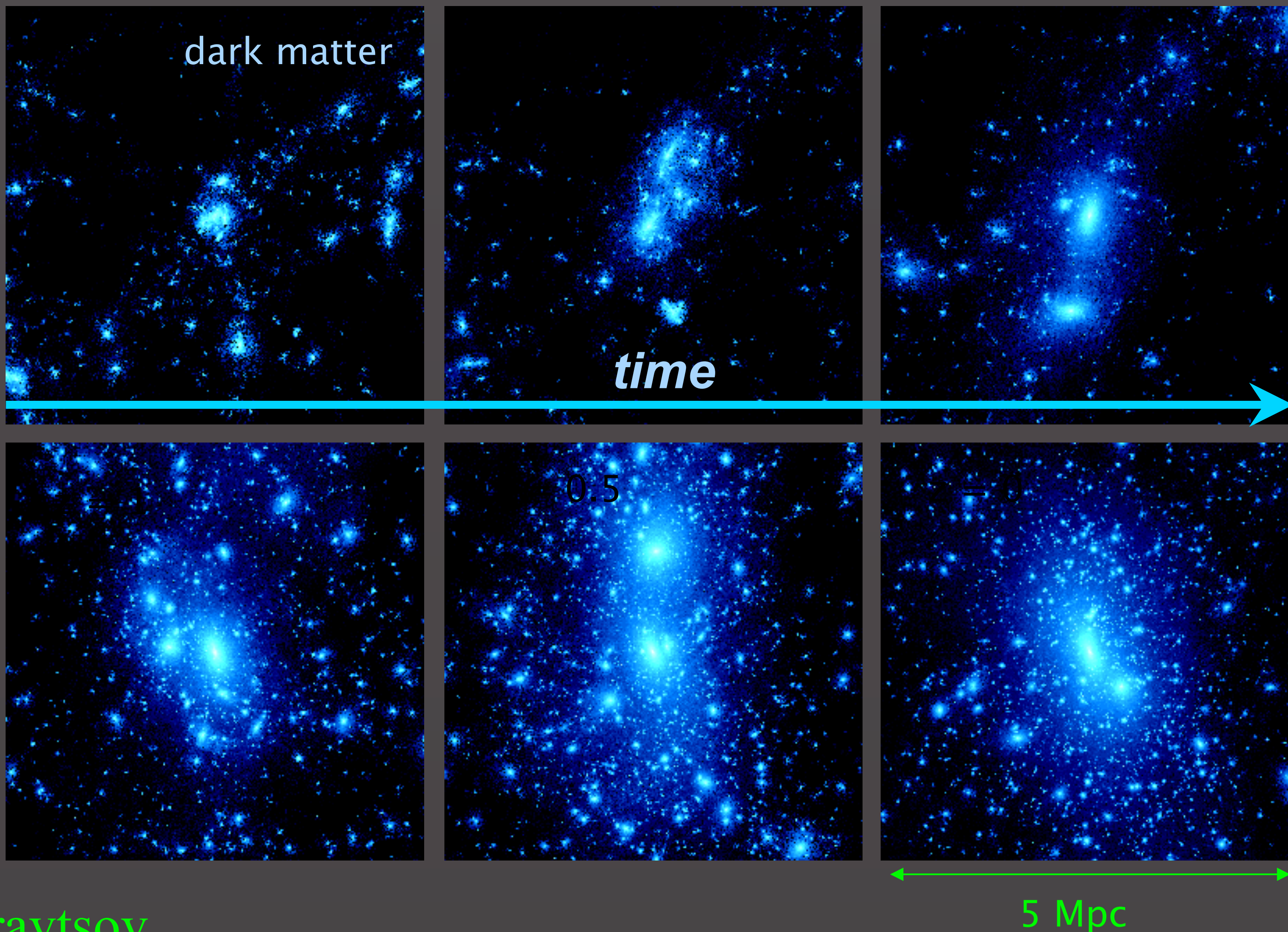
Probes of Cosmic Expansion History and the Growth of Large-scale Structure:

- Supernovae
- Weak Gravitational Lensing
- Large-scale Galaxy Distribution
- Clusters of Galaxies



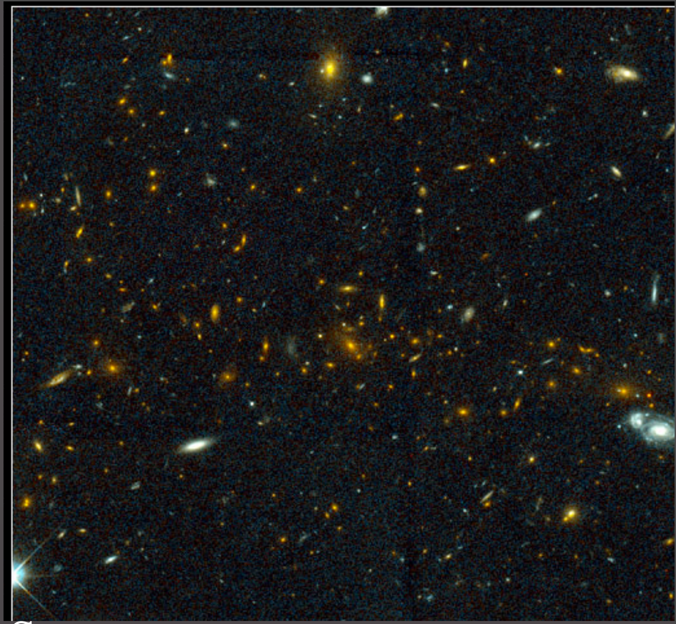
The Expansion of the Universe
Galaxy Formation
Over billions of years, gravity draws matter together into a web of structure. The bright spots are where galaxies form.
Size of the Universe
Not to scale
Matter dominates: Expansion slows
Dark energy dominates: Expansion speeds up
Big Bang
Today
Time 0
1.0
9.5
13.7
Not to scale; In billion years
Energy and Matter Content
Dark Energy
Dark Matter
Ordinary Matter
1%
84%
15%
50%
43%
7%
73%
23%
4%
symmetry | volume 06 | issue 03 | june 09

Dark Energy affects Cluster Formation



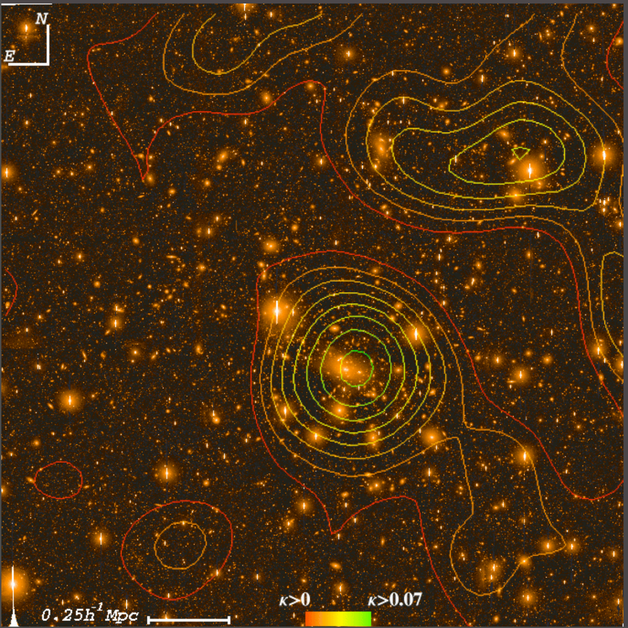
Kravtsov

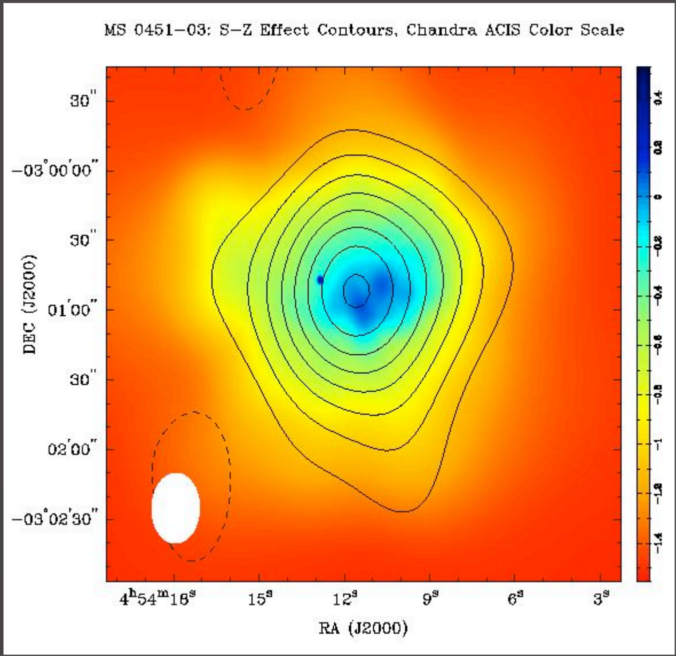
Clusters of Galaxies



Techniques for Probing Clusters:

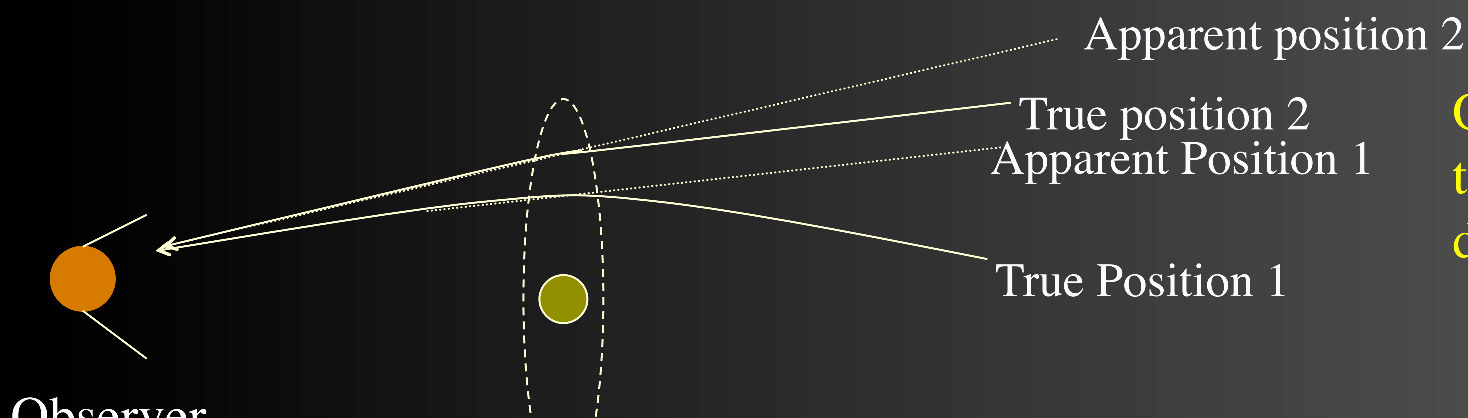
- Optical galaxy concentration
- Weak Gravitational Lensing
- Cluster gas scatters CMB electrons
- Hot Cluster gas shines in X-rays



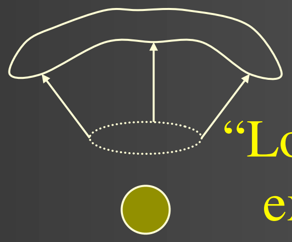


Gravitational Lensing

magnification and distortion (shear)

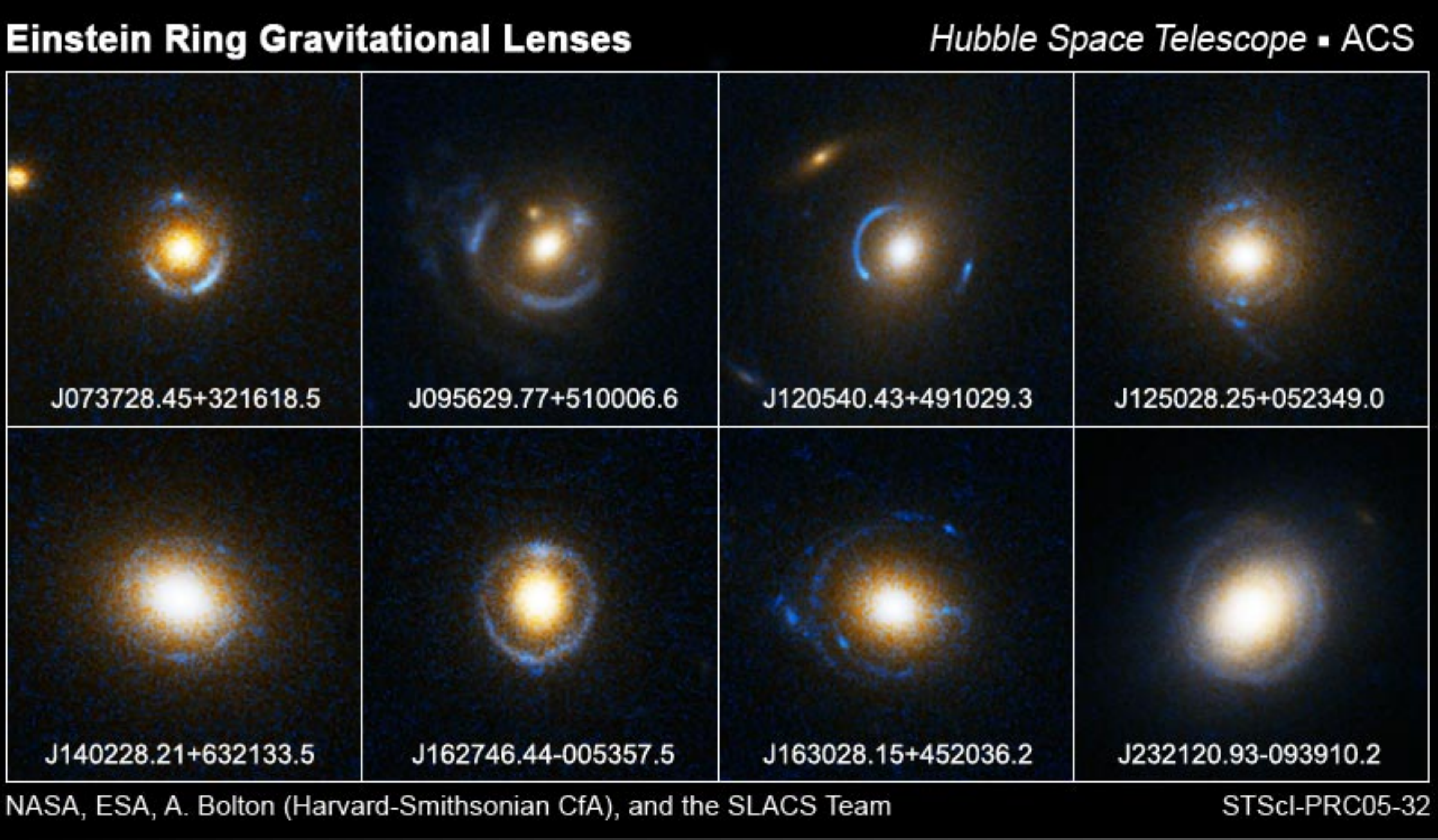


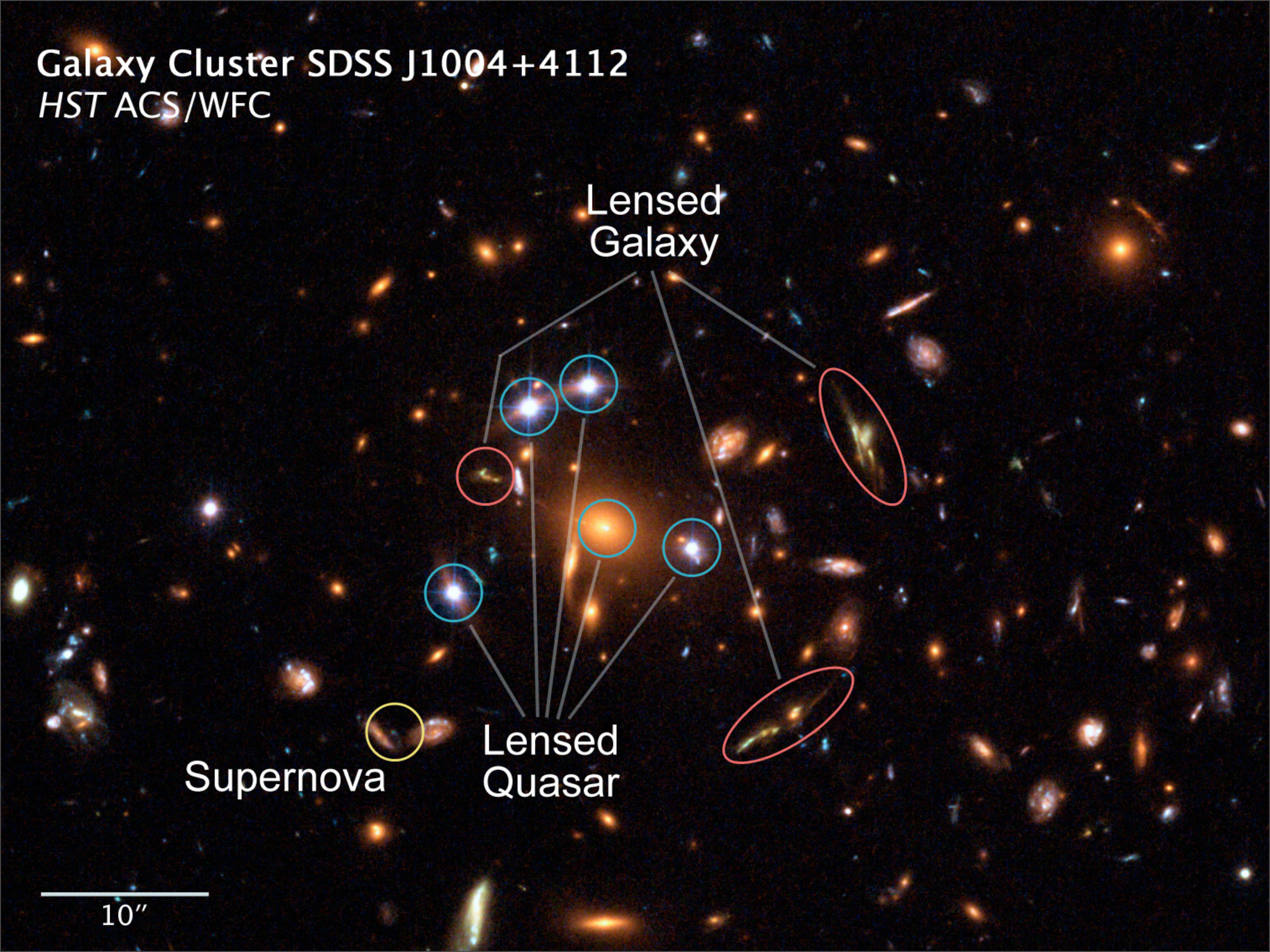
Objects farther from the line of sight are distorted less.



"Looking into" the lens: extended objects are tangentially distorted

HST Imaging of Strongly Lensed Galaxies Found in SDSS

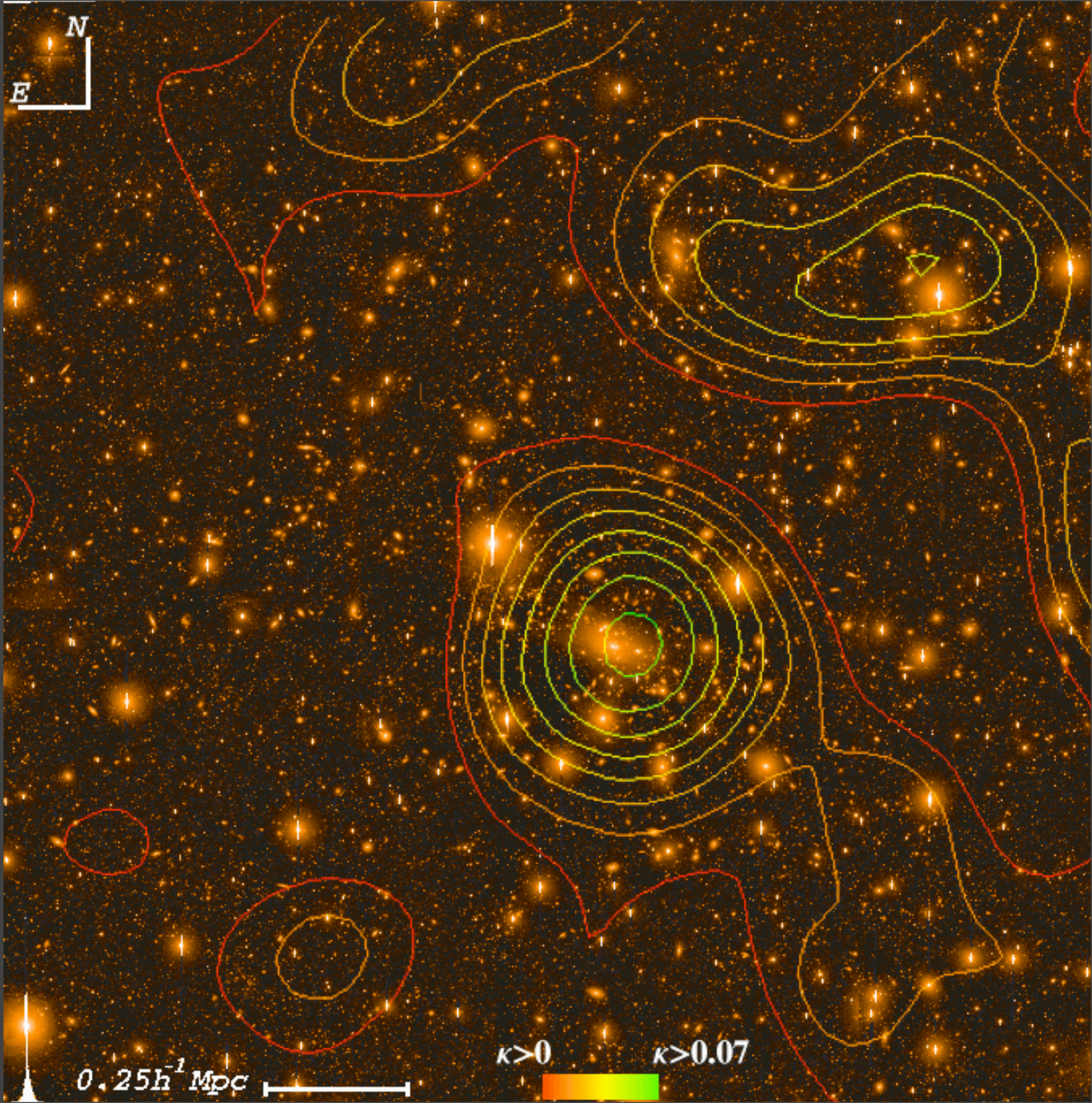



Galaxy Cluster SDSS J1004+4112
HST ACS/WFC
Lensed
Galaxy
Supernova
Lensed
Quasar
10″

Mapping the Dark Matter in a Cluster of Galaxies via Weak Gravitational Lensing

Data from Blanco 4-meter at CTIO

Joffre, etal



SDSS Weak Galaxy-galaxy Lensing

Luminous Galaxies are surrounded by Massive Halos of Dark Matter

December 14, 1999

Science Tim

The New York Times

Galaxies' Vastness Surprises Scientists

By JAMES GLANZ

Using a technique akin to overlaying thousands of faint X-ray images to create one sharp picture, astronomers have discovered that typical galaxies may be twice as large and contain twice as much mass as suggested by previous measurements. The new observations, which have emerged from a five-year census of the heavens called the Sloan Digital Sky Survey, indicate that an average galaxy extends invisibly for well over a million light-years into space and weighs the equivalent of at

1

2

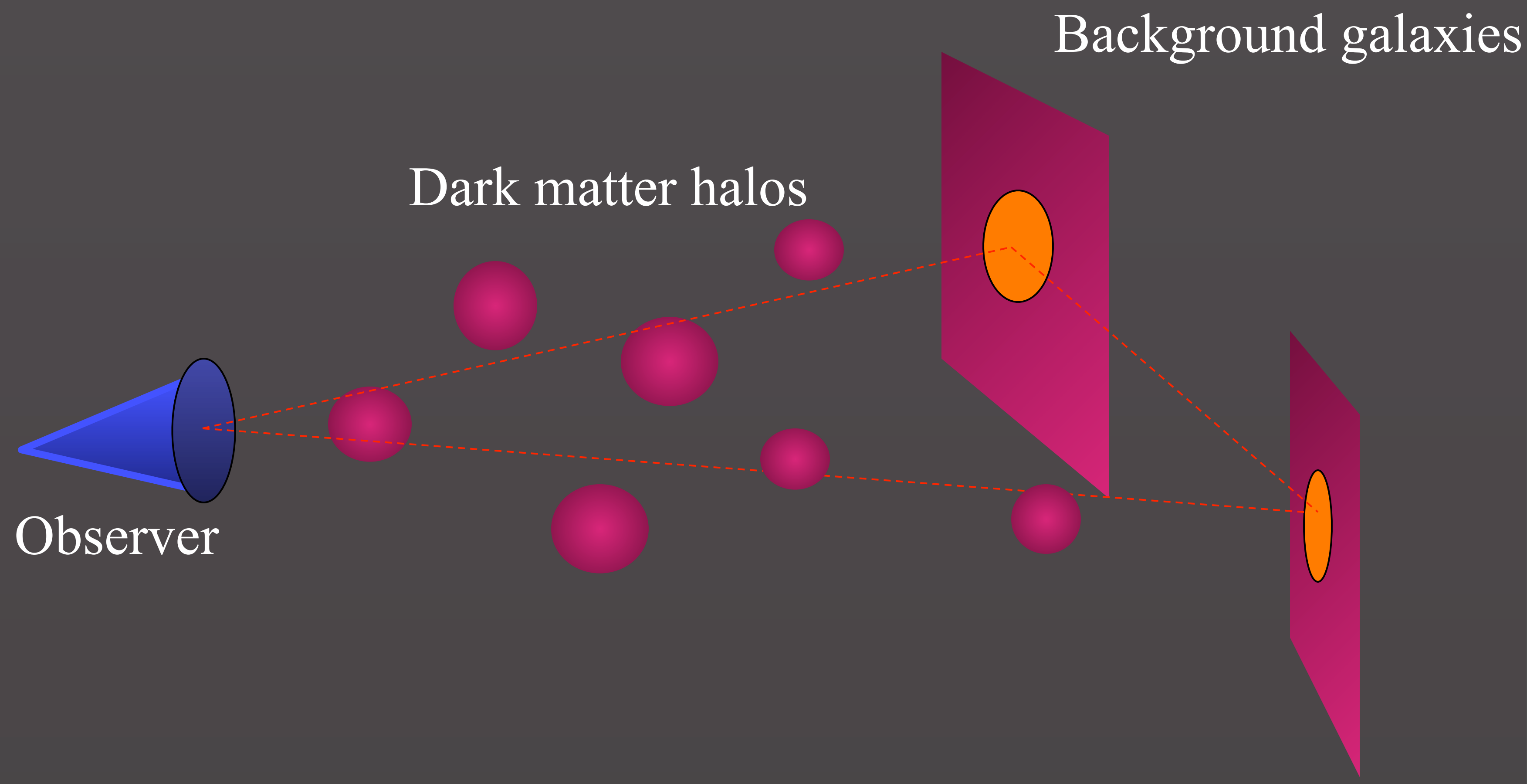
A portrait of a woman far different from the cavewoman stereotype is emerging from these Stone Age Venuses: above is Venus of Willendorf in Austria; at right, the back and front views of Venus of Kostenki in Russia; far right, Venus of Lespugue, with prominent buttocks and a "grass" skirt, in southwest France.

Furs fo But C The S Sta

By NATALIE ANGIER

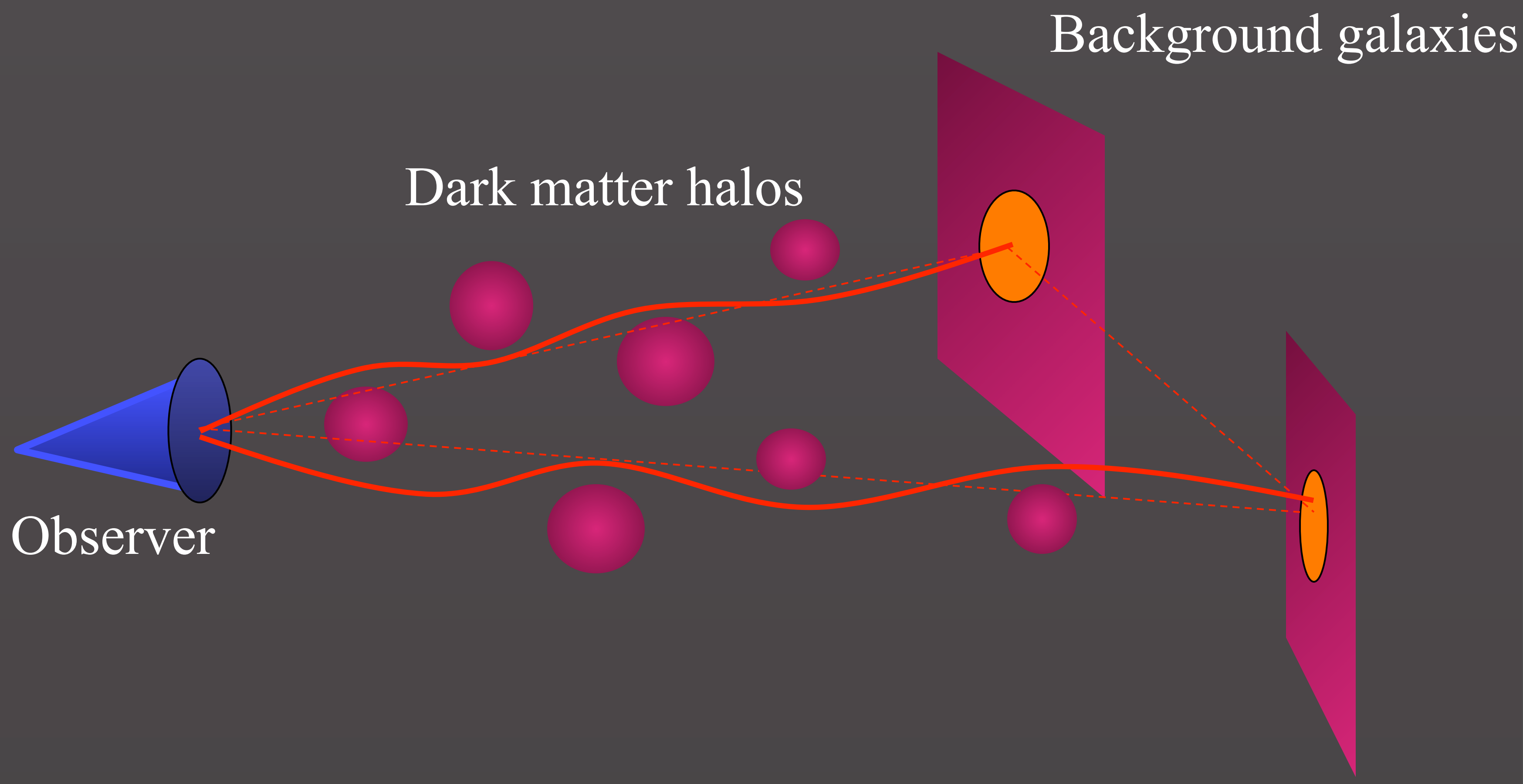
Ah, the poor Stone Age woman of our kitschy imagination. When she isn't getting bonked over the head with a club and

Cosmic Shear Weak Lensing



Look for spatially coherent distortions of background galaxy shapes

Cosmic Shear Weak Lensing

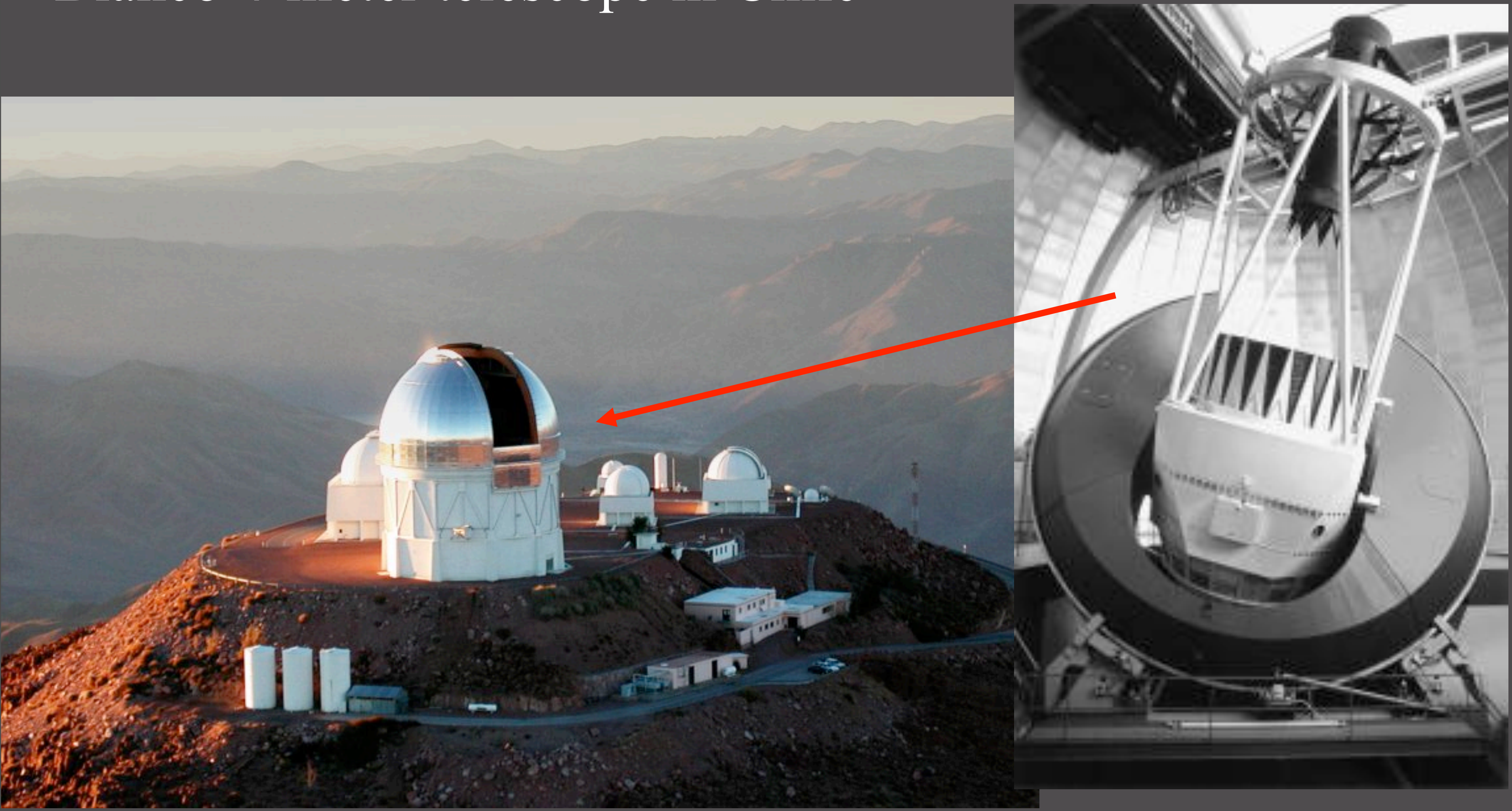


Look for spatially coherent distortions of background galaxy shapes

The Dark Energy Survey

2012-2017

Blanco 4-meter telescope in Chile



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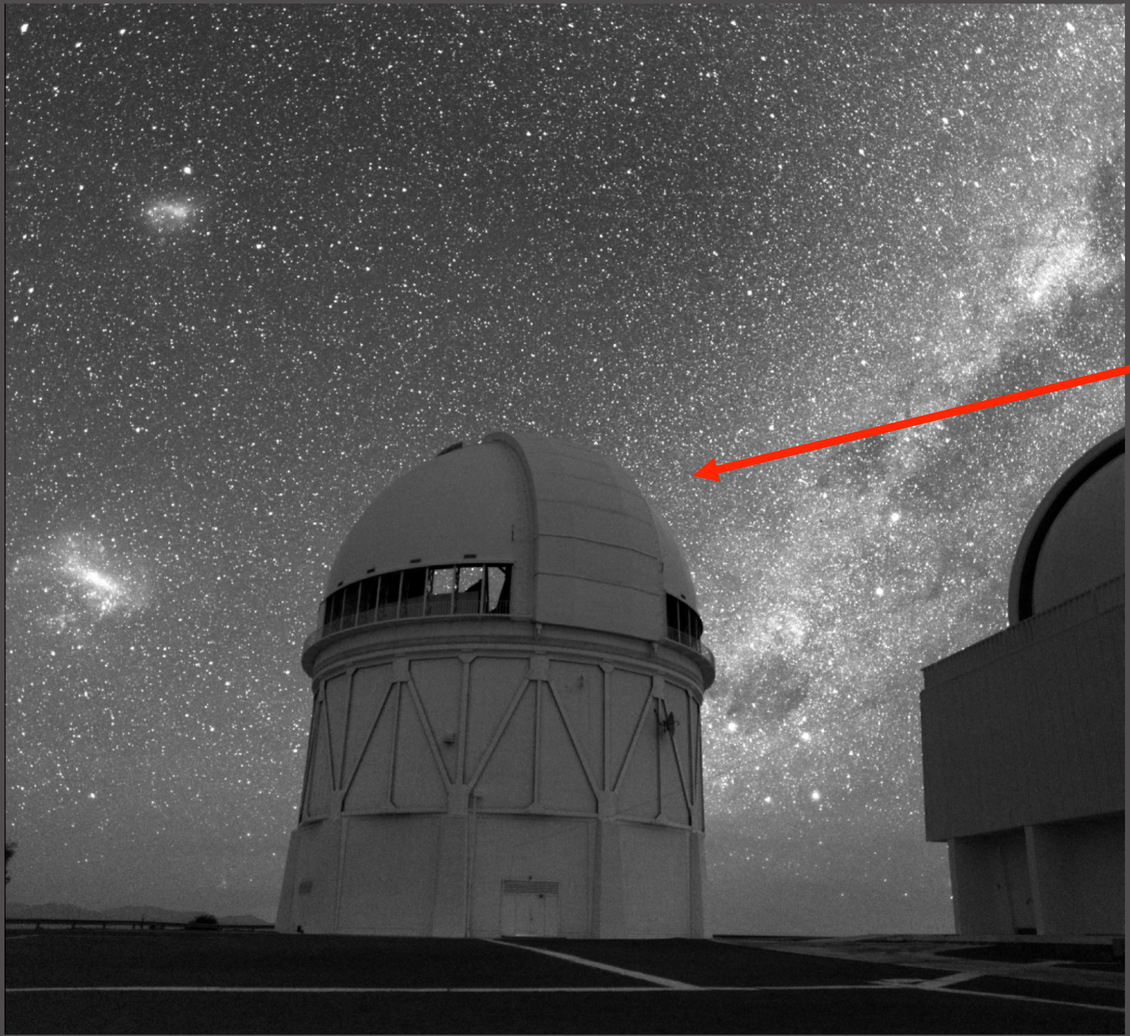
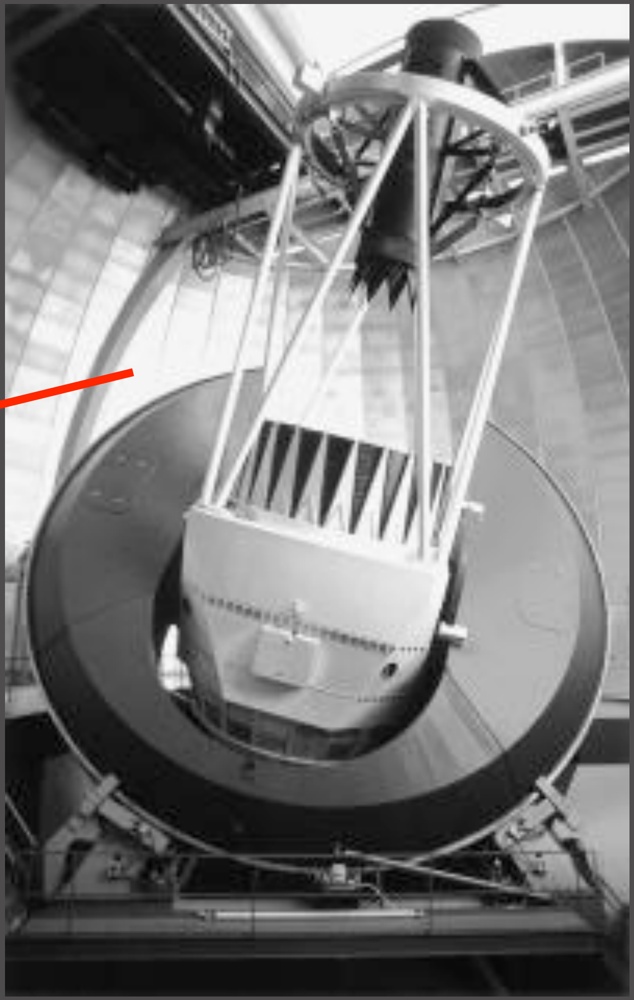
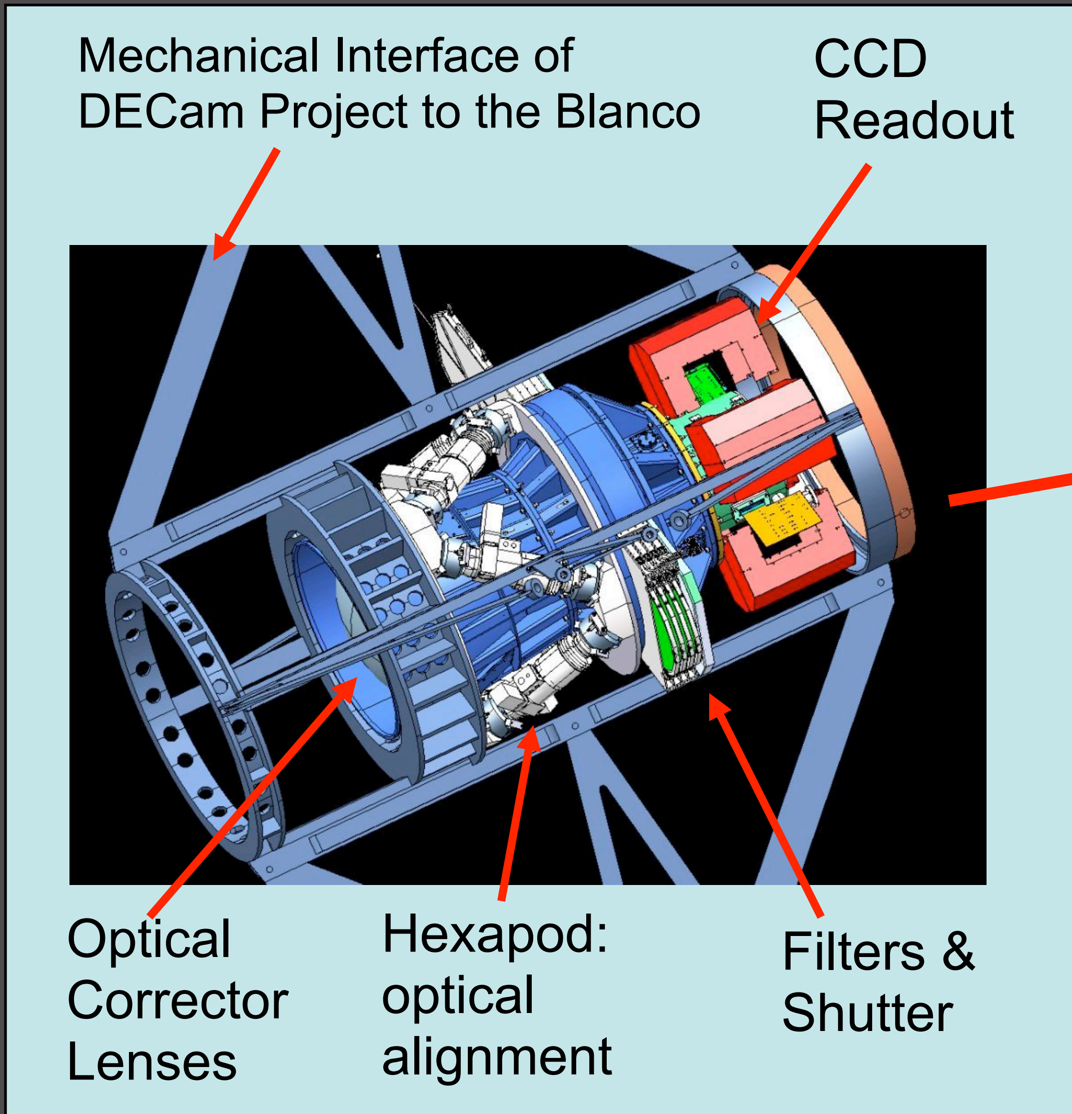


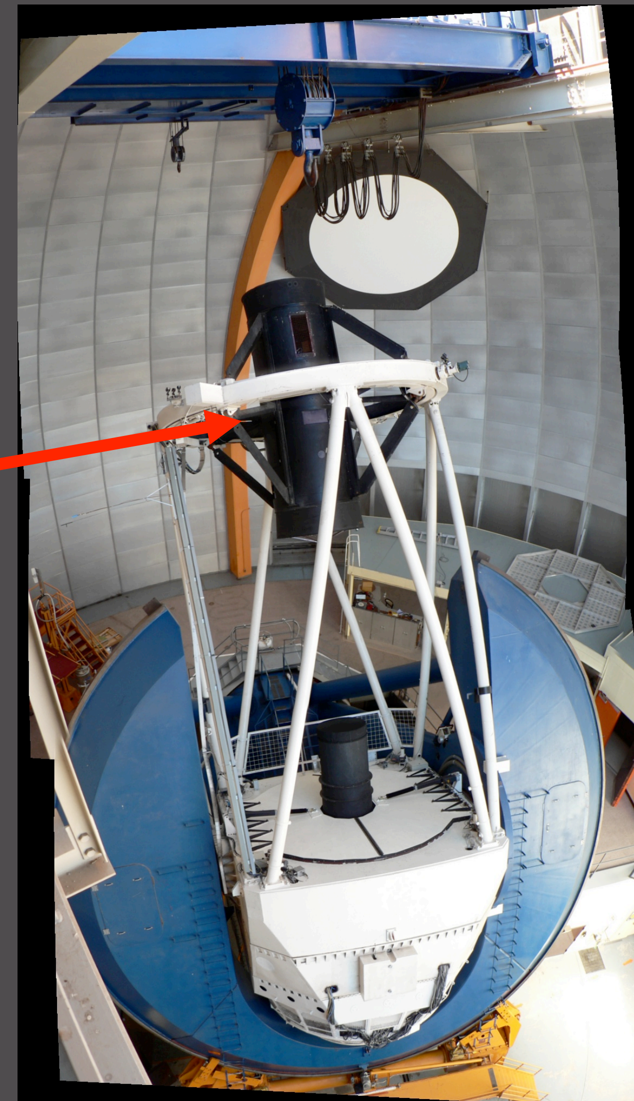


The Dark Energy Survey

Blanco 4-meter telescope in Chile

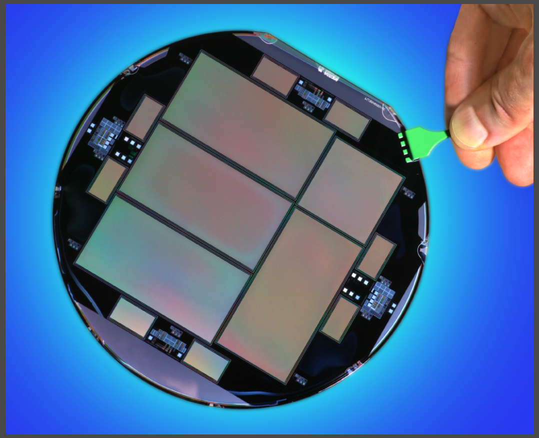
DES Instrument: DECam

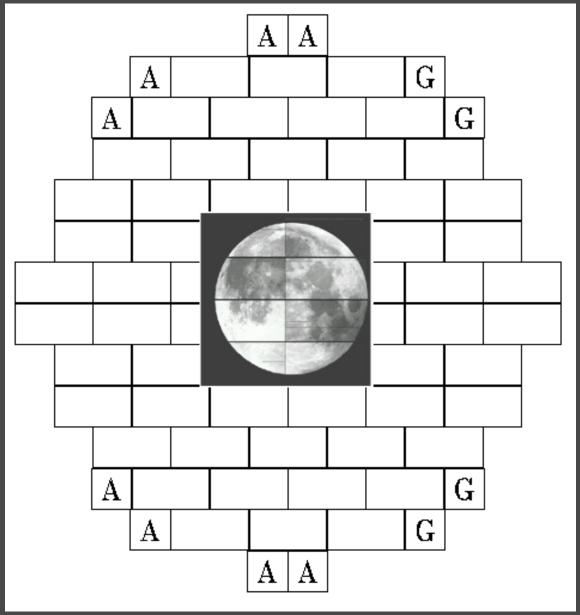


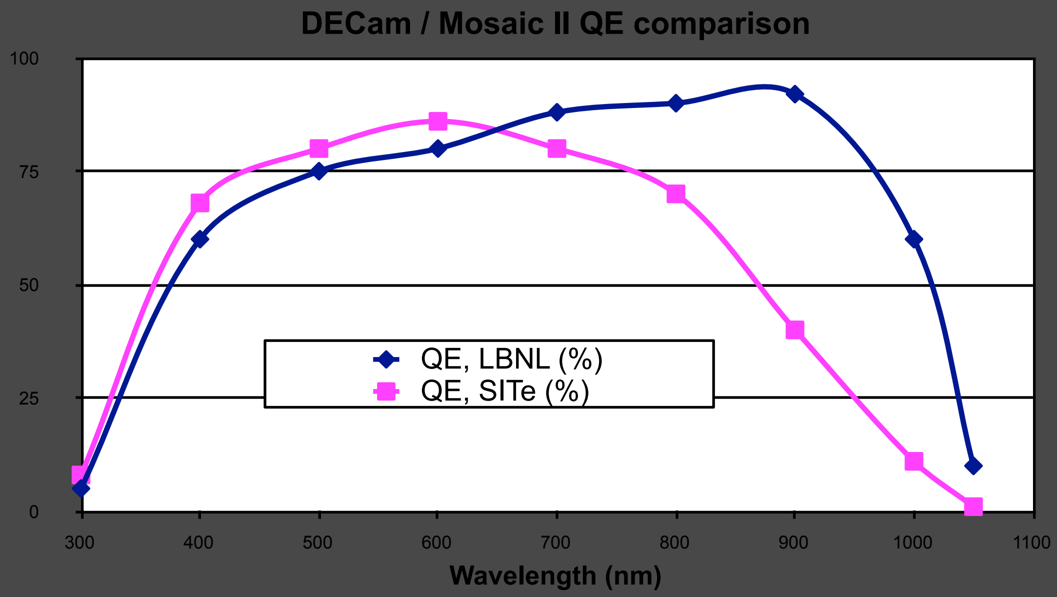


DECam

520 Megapixel camera with 5 optical filters







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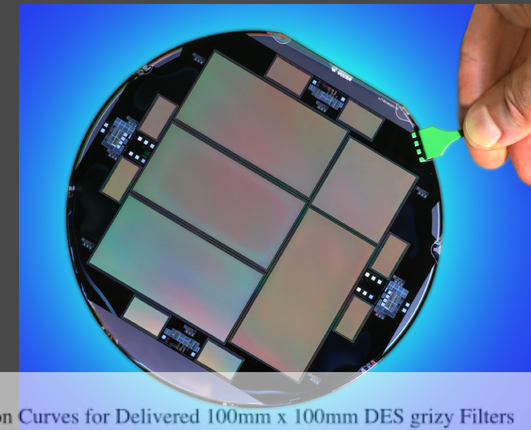
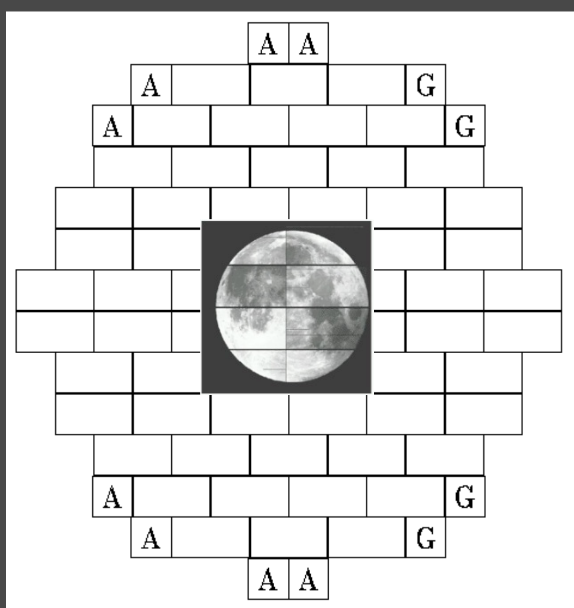
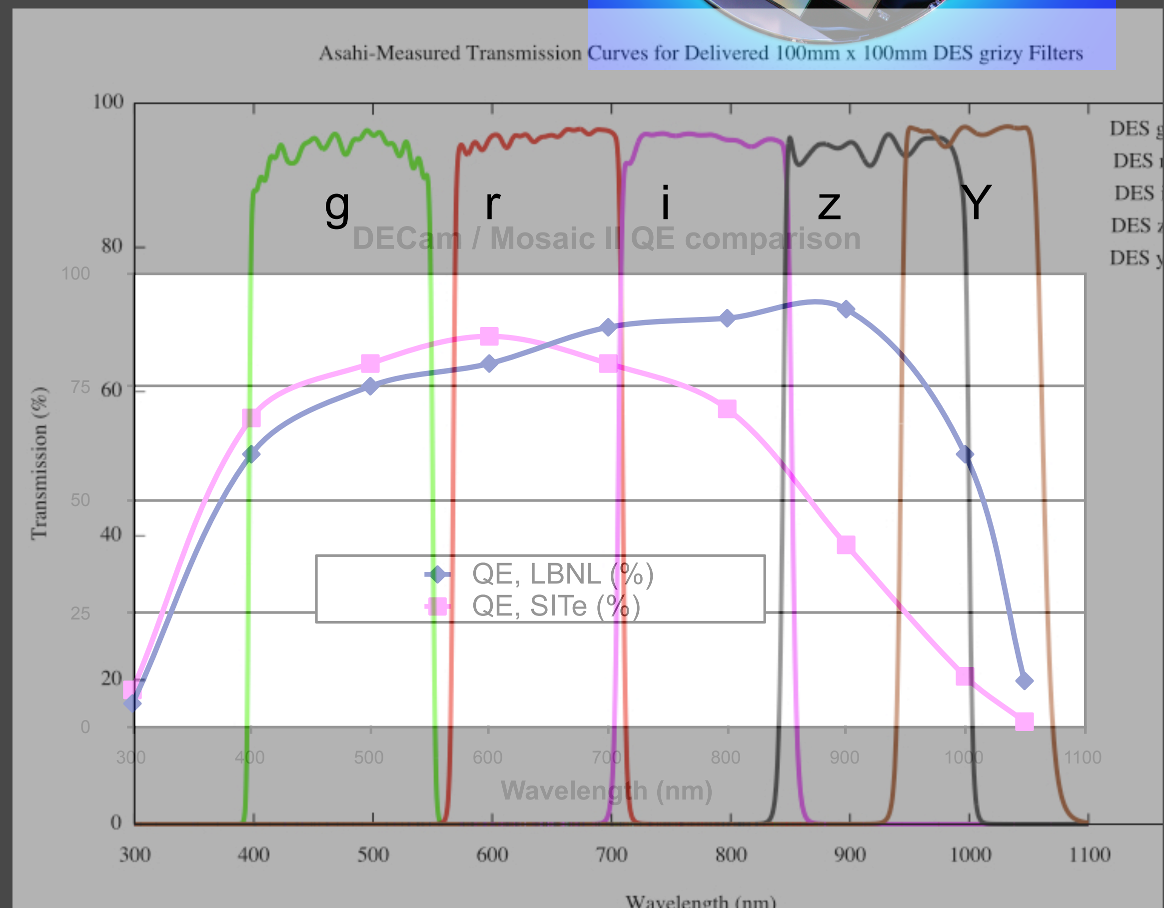
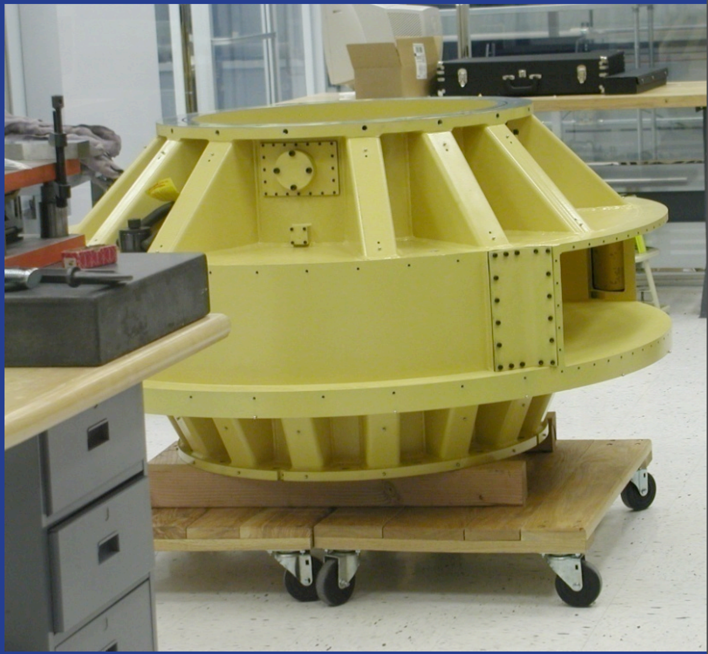
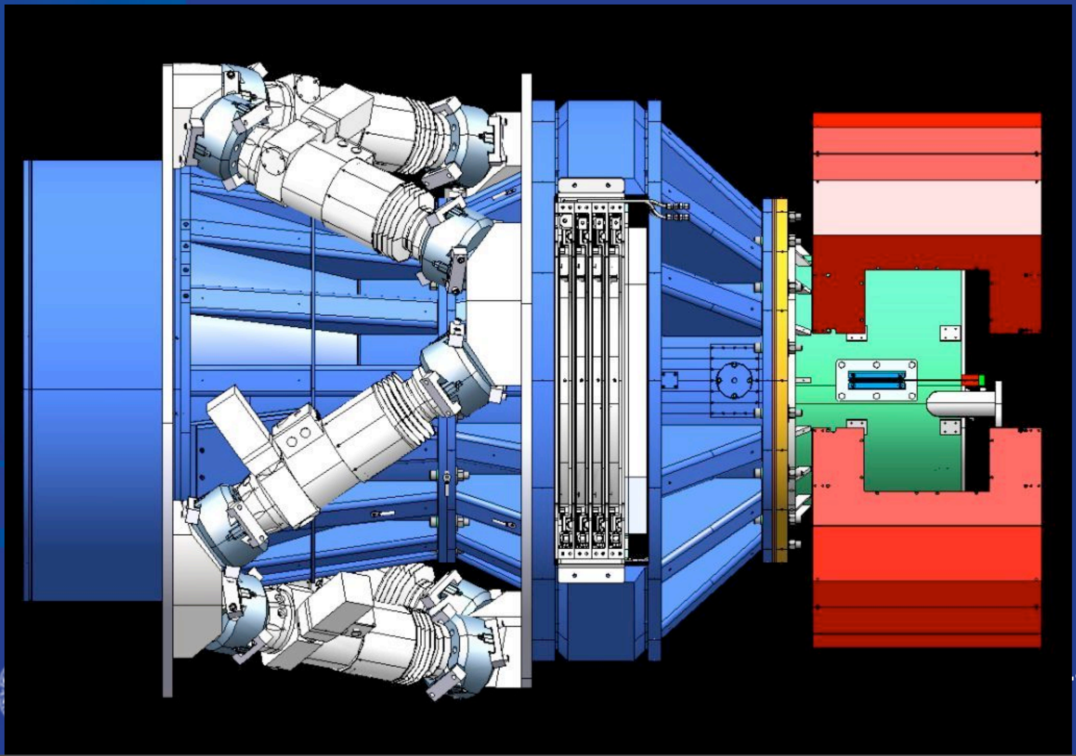


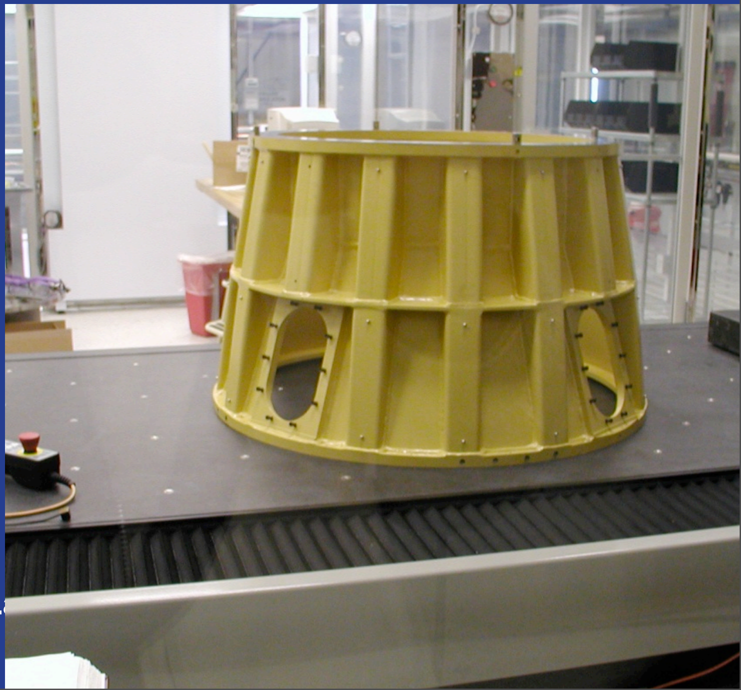




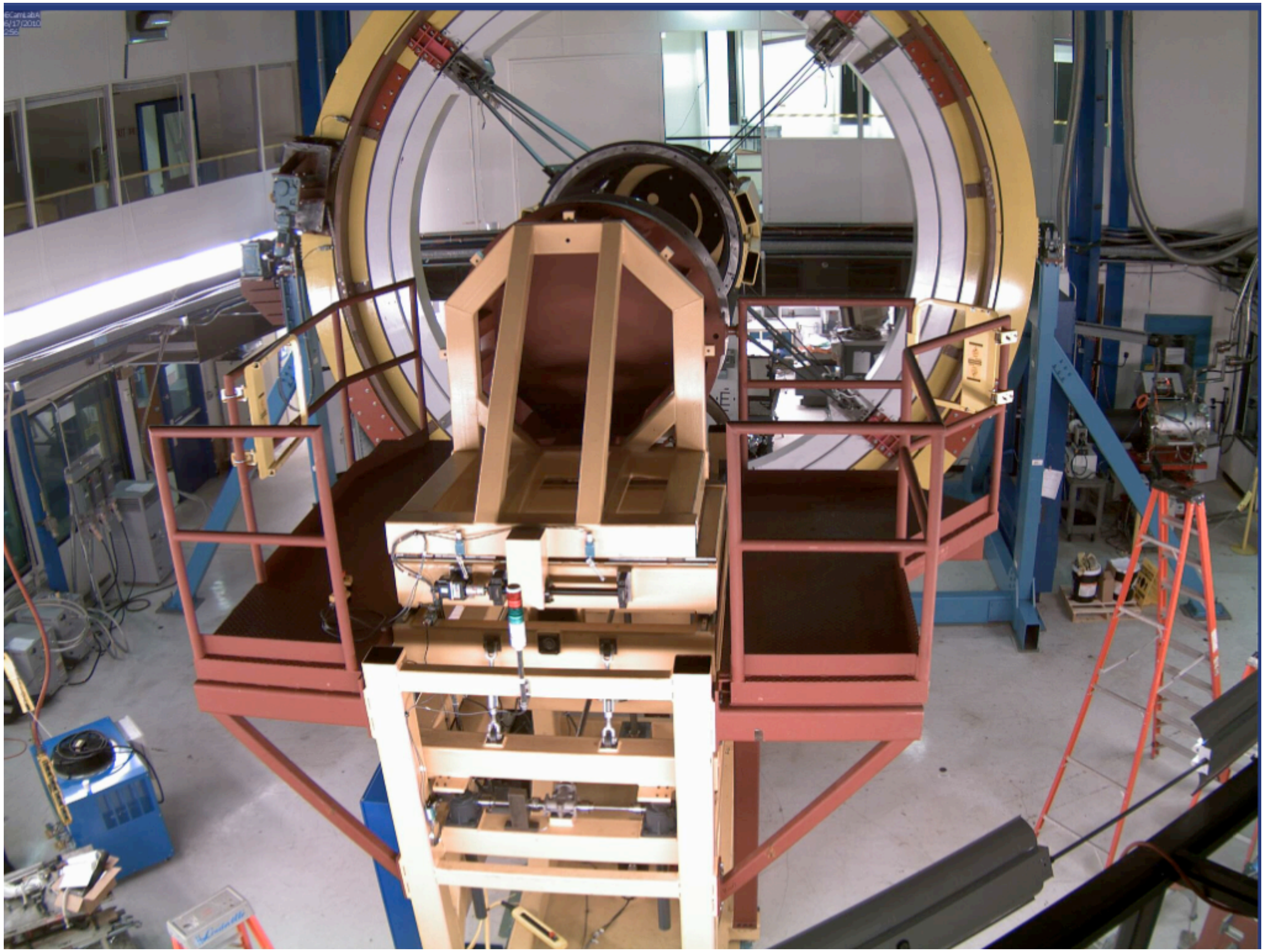
Assembly at Fermilab







Telescope Simulator

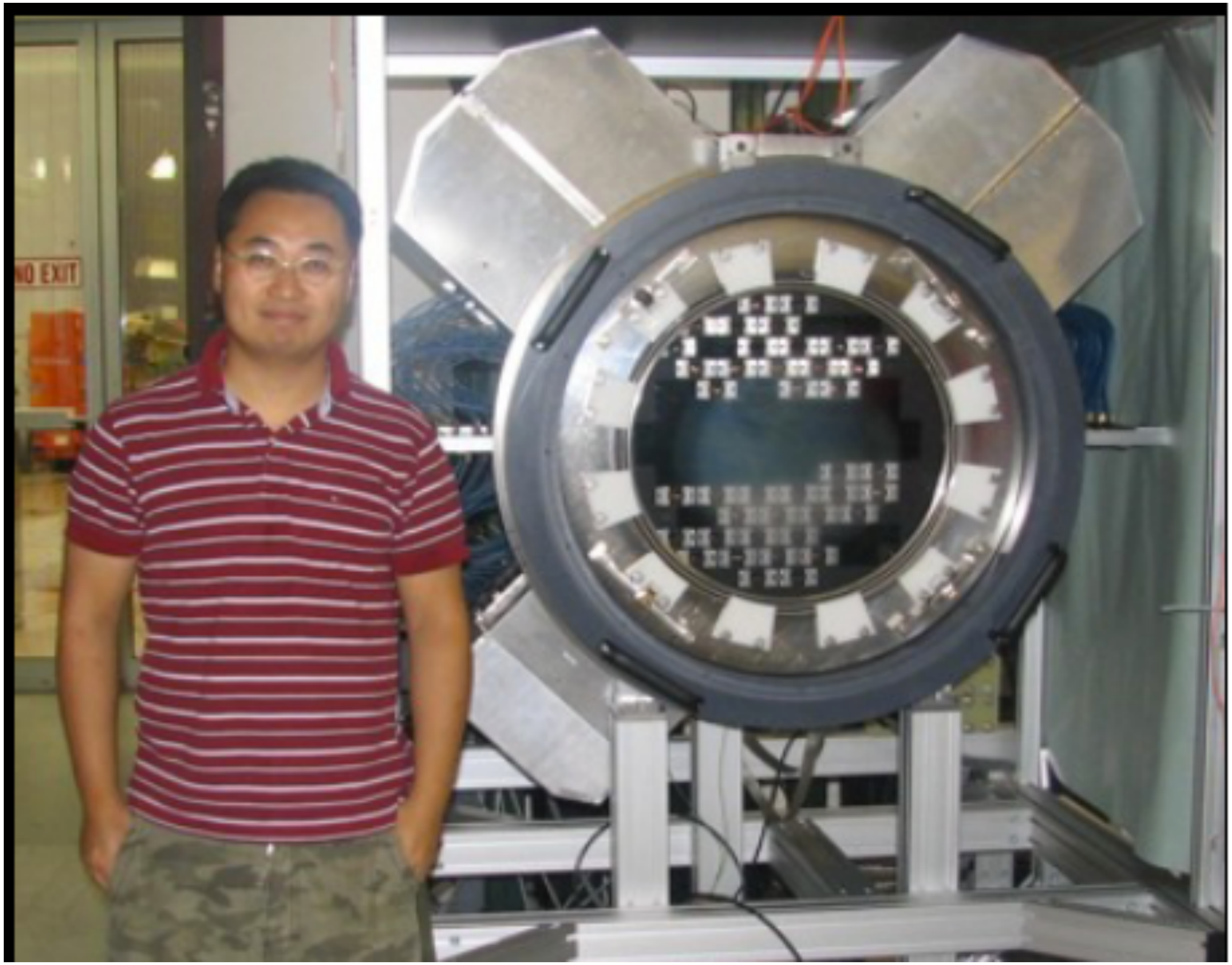


http://decamlaba.fnal.gov

DARK ENERGY
SURVEY

DECam Vessel

Fermilab postdoc Jiangang Hao with DECam



DARK ENERGY SURVEY

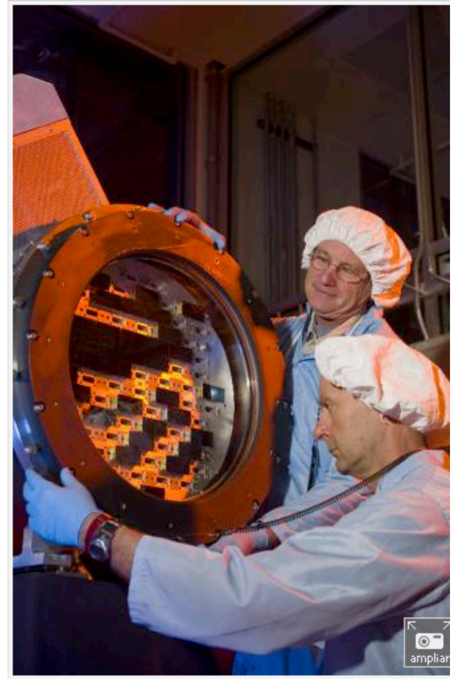
REPORTAJE

A la caza de la energía oscura

Un equipo internacional ultima una cámara para observar 300 millones de galaxias - Los científicos investigan por qué se acelera la expansión del universo

ALICIA RIVERA - Madrid - 15/09/2010

Cuando los científicos tropiezan con una sorpresa, con algo que no comprenden, no se quedan de brazos cruzados, extasiados, sino que inmediatamente se ponen a inventar experimentos y observaciones para vencer el misterio, y más si se trata de un descubrimiento que altera en gran medida el conocimiento que tiene de la evolución del universo. Se trata de la energía oscura, cuya existencia se desconocía hace poco más de una década y que ahora atrae la atención de los cosmólogos de todo el mundo. No es para menos: según las observaciones más precisas realizadas, la energía oscura supone el 72% de todo el universo y no se sabe qué es ni a qué ley obedece, pero está ahí y se nota.



Expertos de Fermilab montan la cámara para estudiar la energía oscura (arriba) y el mapa del universo primitivo hecho por el telescopio *Planck*.- FERMILAB

La noticia en otros webs

- webs en español
- en otros idiomas

El aparato tiene 74 detectores CCD y cuesta 39 millones de euros

La constante cosmológica de Einstein puede explicar el efecto

Para intentar aclarar su naturaleza se están preparando media docena de cámaras astronómicas especiales. Una estará lista el año próximo. La están haciendo en EE UU y los astrónomos captarán con ella unos 300 millones de galaxias, algunas tan antiguas que emitieron la luz que ahora llega a la Tierra cuando el universo acababa de empezar, pocos miles de millones de años después del Big Bang. Se llama Dark Energy Camera y en el proyecto participan especialistas de varios países, incluida España.

"Nuestro objetivo principal es determinar la naturaleza de la energía oscura", explicó recientemente en el Centro Pedro Pascual de Benasque (Huesca) Josh Frieman, director del proyecto DES, que está haciendo la cámara estadounidense. "La energía oscura tiene dos efectos en los que nos basaremos para investigar su naturaleza: acelera la expansión del universo y modifica la velocidad a la que se forman las galaxias, y esto, a su vez, afecta al número de galaxias y a su distribución en el espacio. Así pues, contando las galaxias y midiendo su distribución obtendremos pistas sobre qué es".

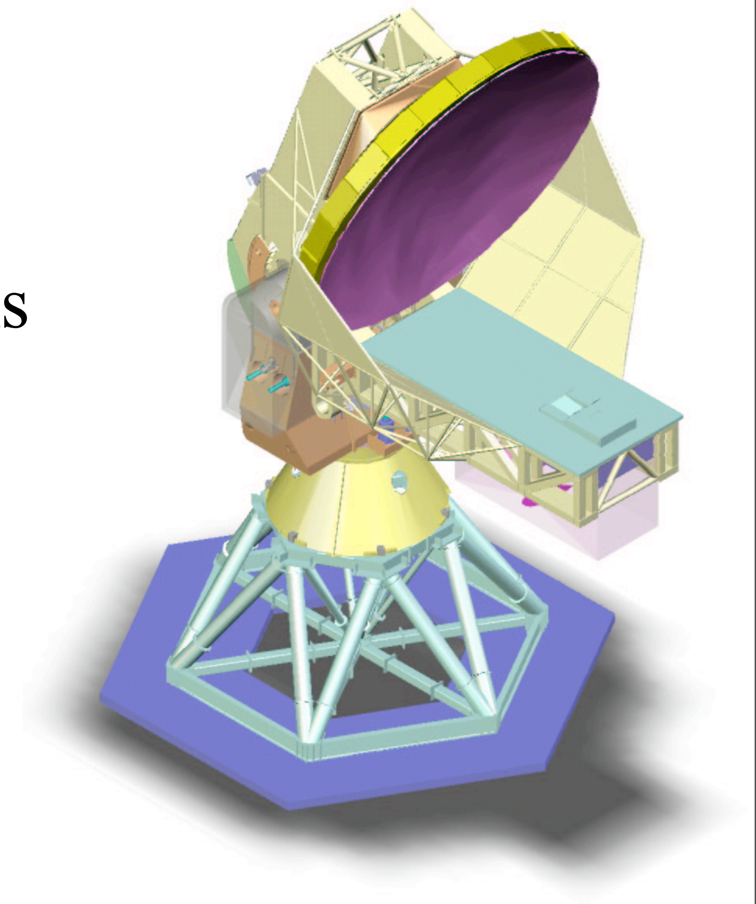
Esa aceleración fue, efectivamente, la primera pista que encontraron dos equipos de astrónomos hace 12 años. Hasta ese momento, la cosmología venía a decir que el universo, que está en expansión desde hace 13.700 millones de años, se expandiría cada vez más despacio debido a la atracción gravitatoria de su propia materia. Pero en 1998

10-meter South Pole Telescope

Sunyaev-Zel'dovich effect

Compton scattering of CMB photons
by hot gas in clusters

Synergize with Dark Energy Survey



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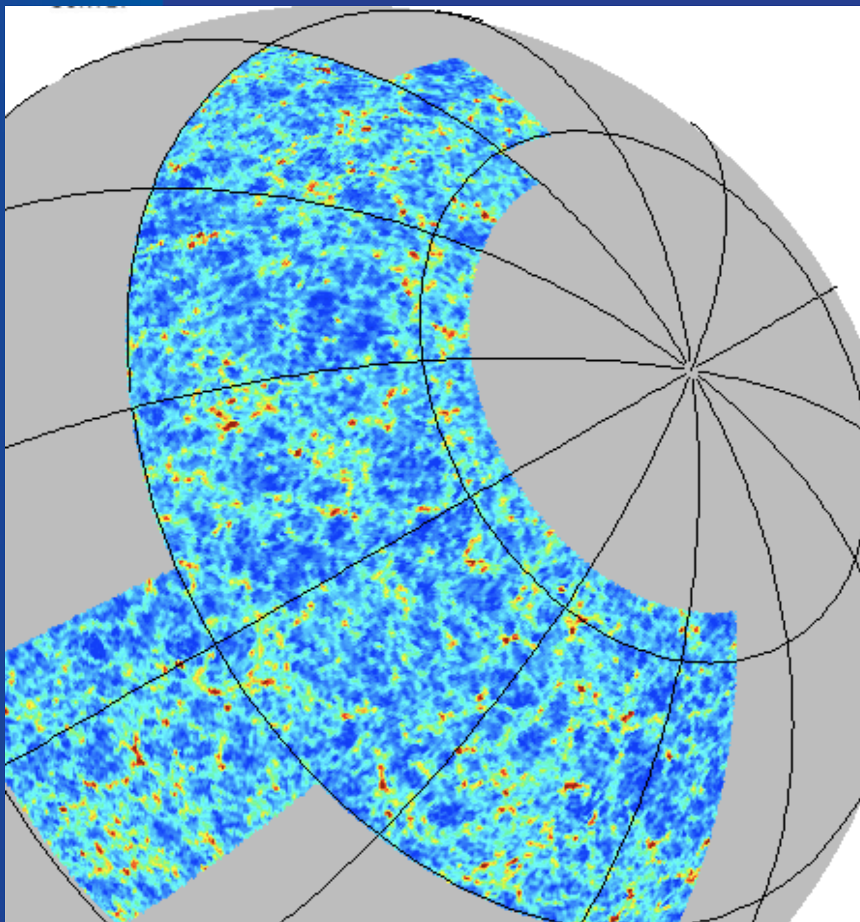
Synergize with Dark Energy Survey

Synergy with South Pole Telescope

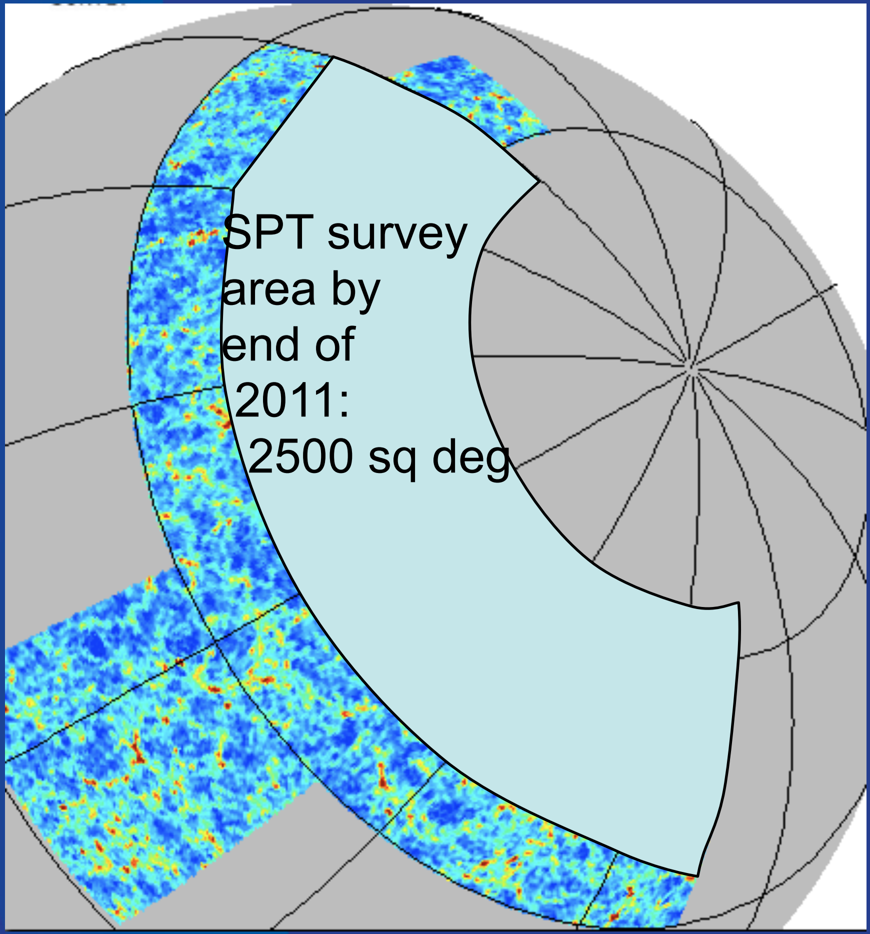
DES footprint: 5000 sq deg

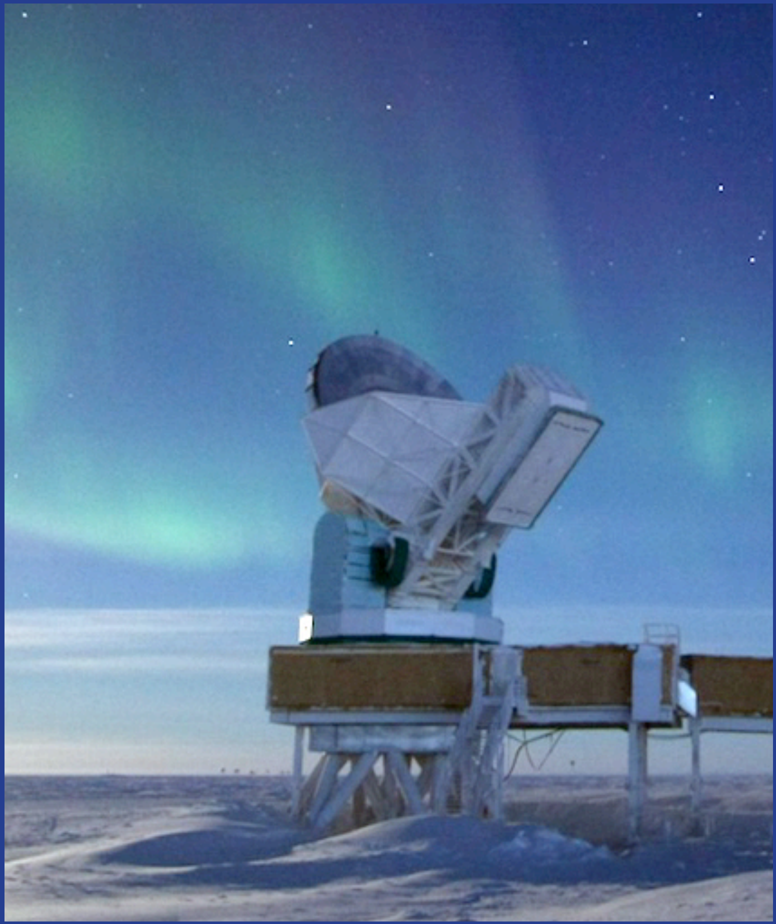


DES survey area encompasses SPT Sunyaev-Zel'dovich Cluster Survey

Synergy with South Pole Telescope

DES footprint: 5000 sq deg





DES survey area encompasses SPT Sunyaev-Zel'dovich Cluster Survey

U.S. DEPARTMENT OF ENERGY

Fermilab

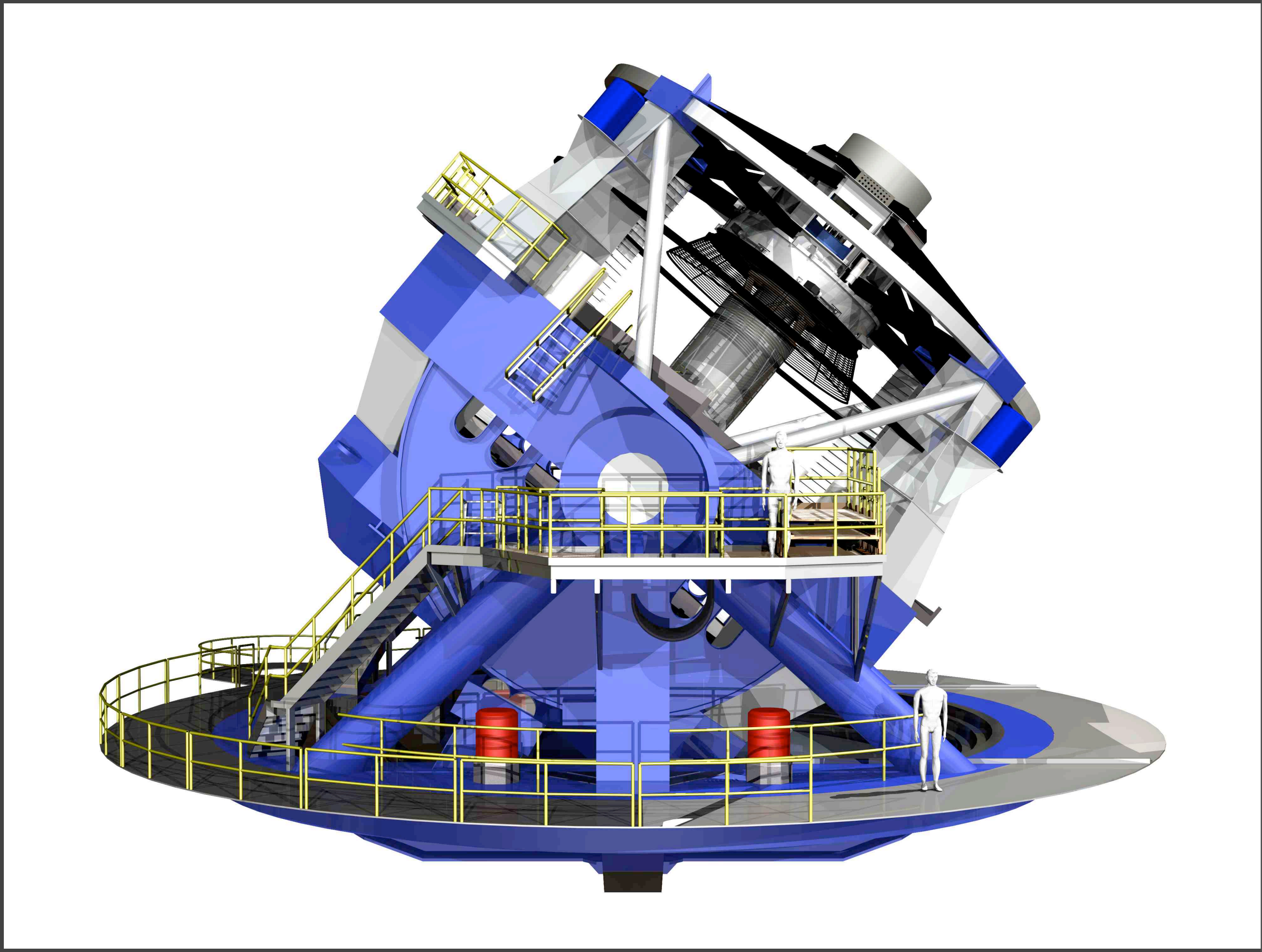
Large Synoptic Survey Telescope

8.4-meter telescope with wide field of view

5000 Gbytes/night of data

Top-ranked ground-based project in recent Astro2010 Decadal Survey

Other ground-based projects as well



WFIRST

- Near-infrared imager and spectrograph on 1.5-meter telescope in space
- Top-ranked priority for space mission by the Astro2010 Decadal Survey