The Runaway Universe

Martin Hendry
School of Physics and Astronomy
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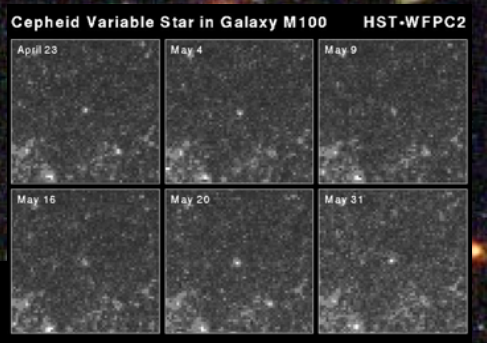
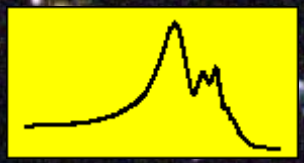
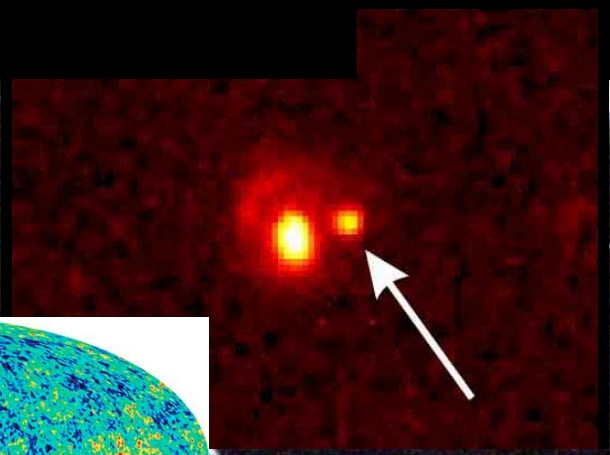
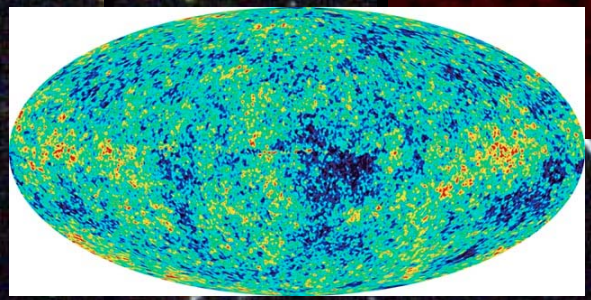






$\Omega, \Omega_b, \Lambda, \tau, h$
$n, n_T, Q, T/S$



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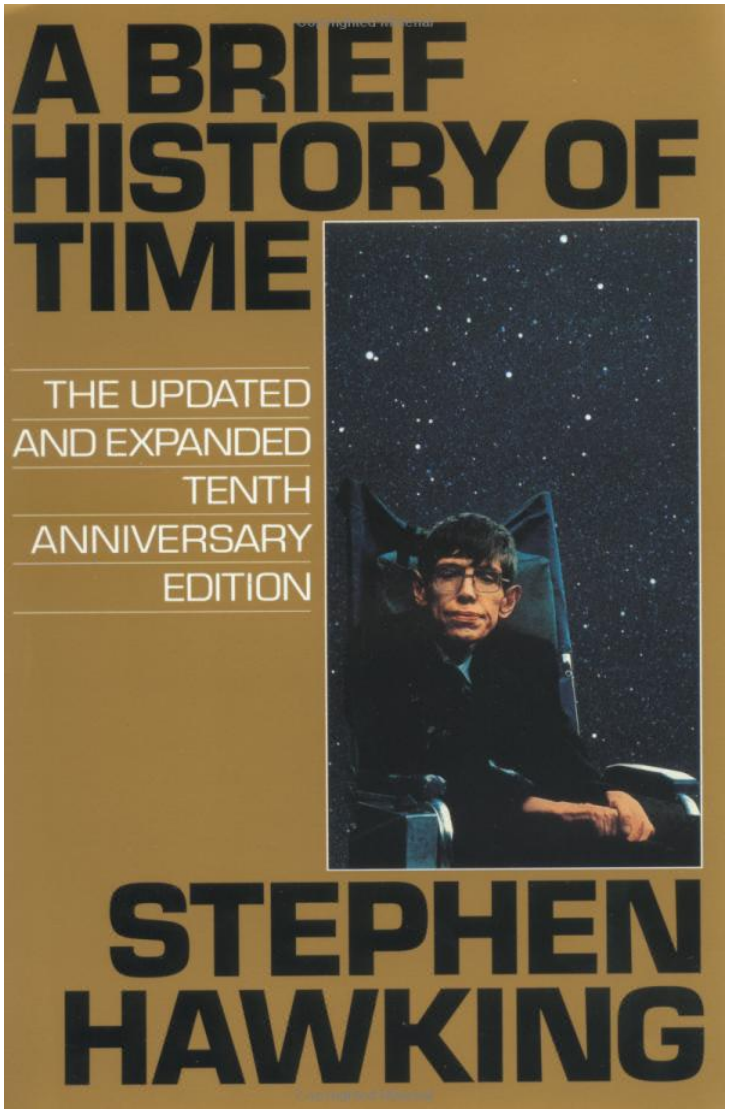
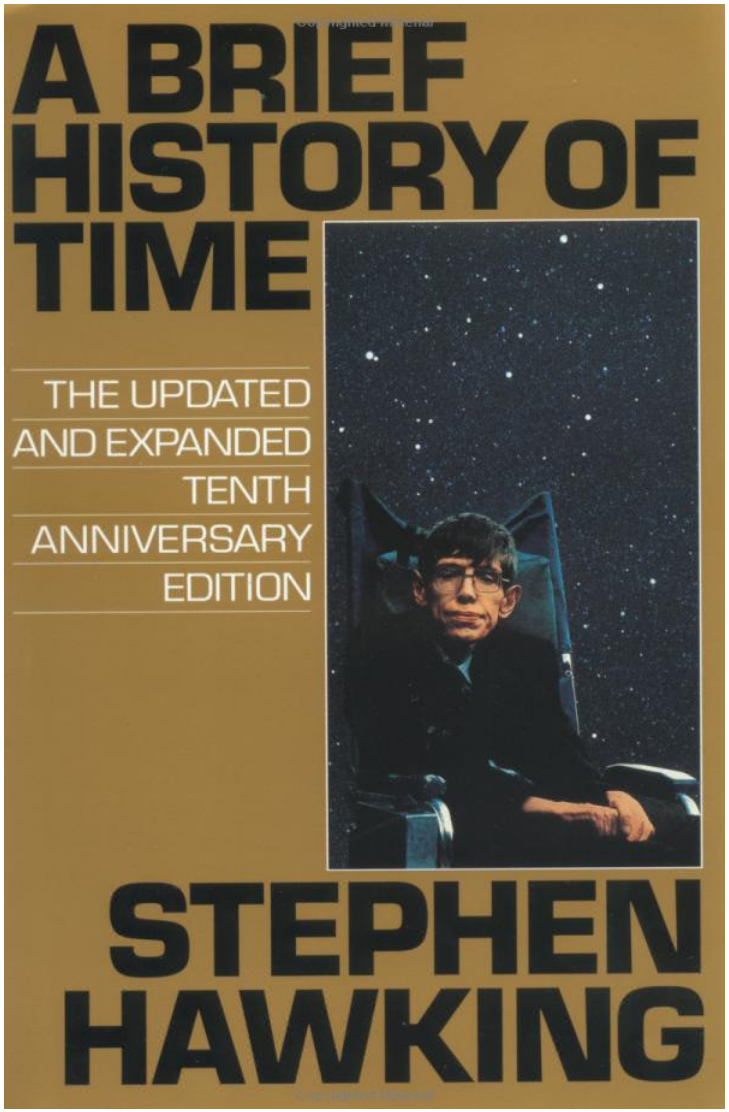

A BRIEF HISTORY OF TIME
THE UPDATED AND EXPANDED TENTH ANNIVERSARY EDITION
STEPHEN HAWKING

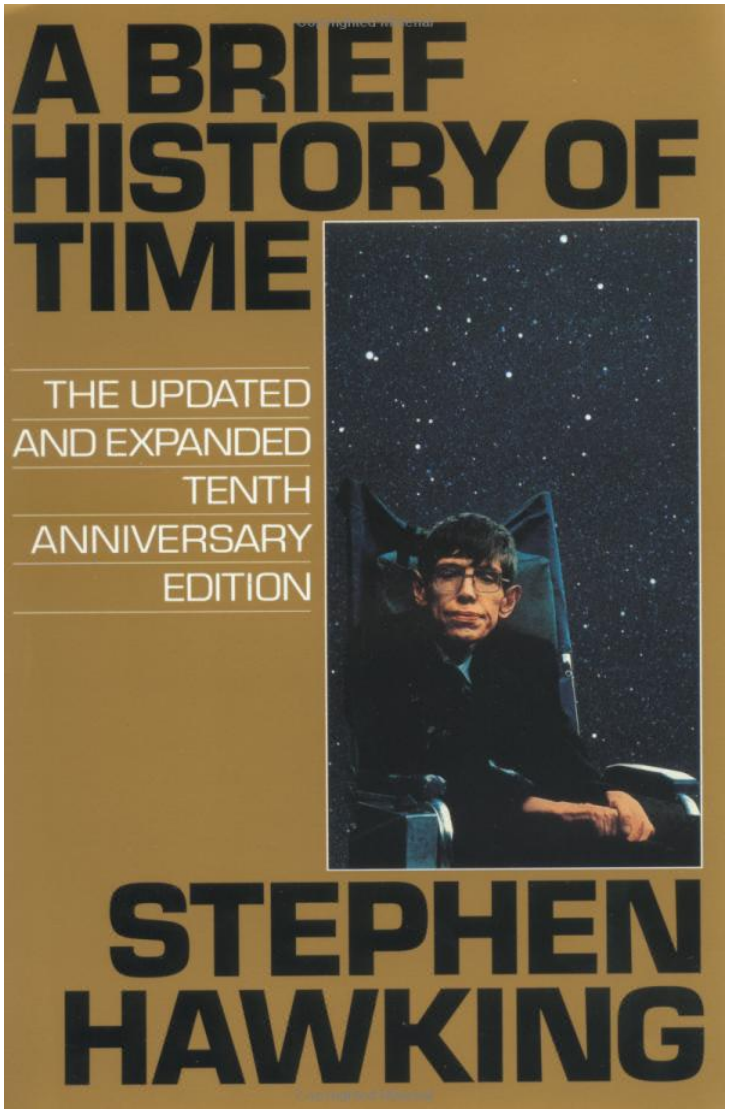


CHAPTER 1

OUR PICTURE OF THE UNIVERSE

…A little old lady at the back of the room got up and said: "What you have told us is rubbish. The world is really a flat plate supported on the back of a giant tortoise." The scientist gave a superior smile before replying "What is the tortoise standing on?"

"You're very clever young man, very clever," said the old lady. "**But it's turtles all the way down!**"


A BRIEF HISTORY OF TIME
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STEPHEN HAWKING


it's turtles all the way down

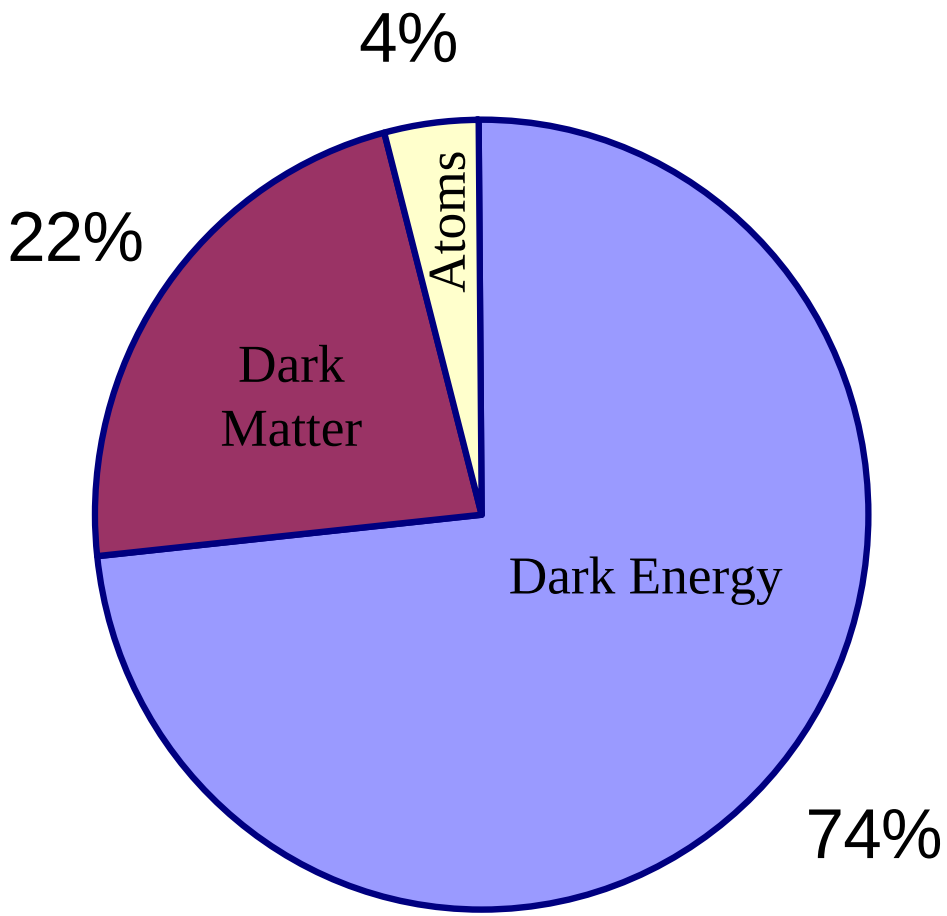
Overview

- ***Where are we?***
- ***How did we get there?***
- ***Where are we going?***

Overview

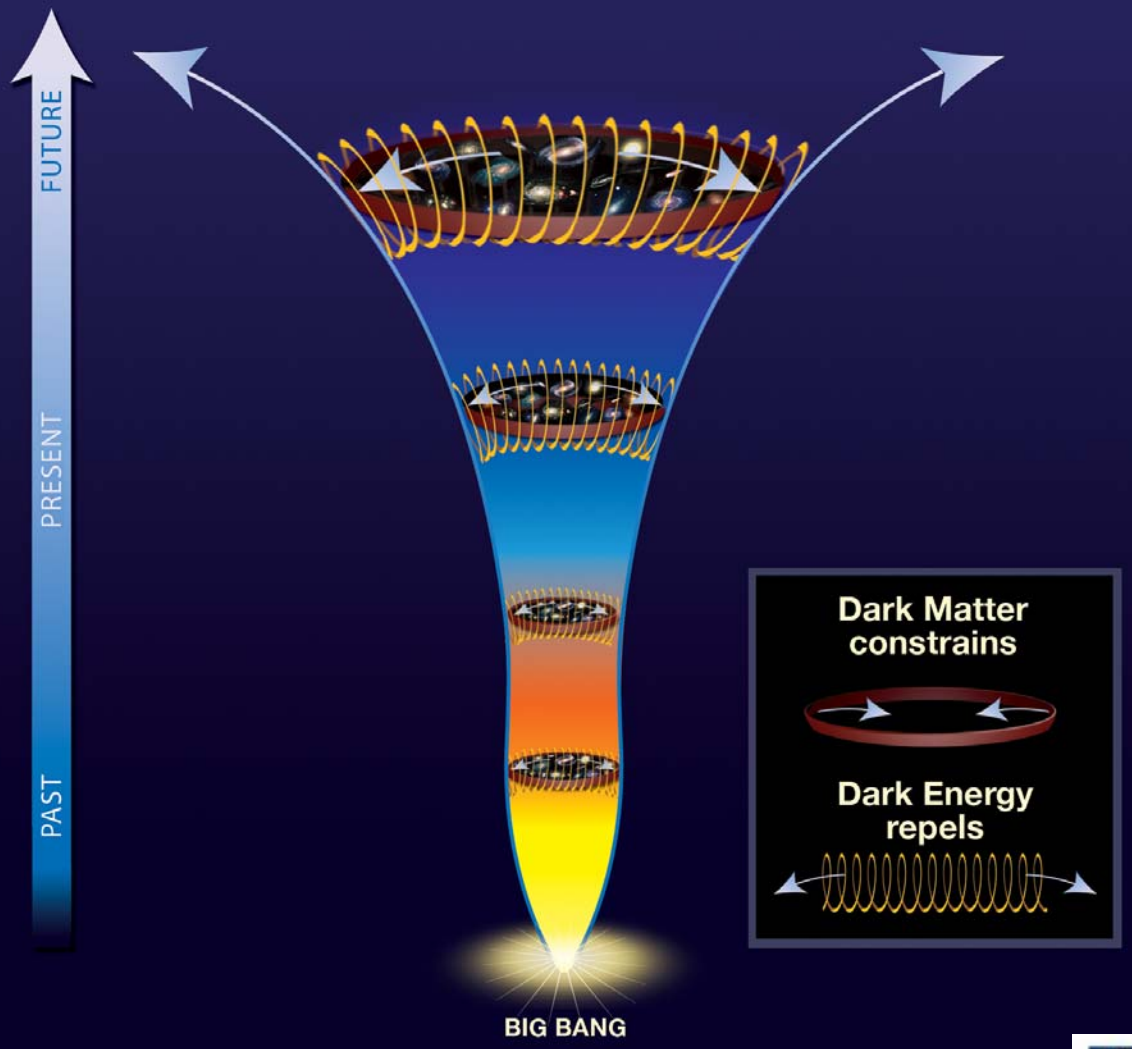
- ***Where are we?***
- *How did we get there?*
- *Where are we going?*

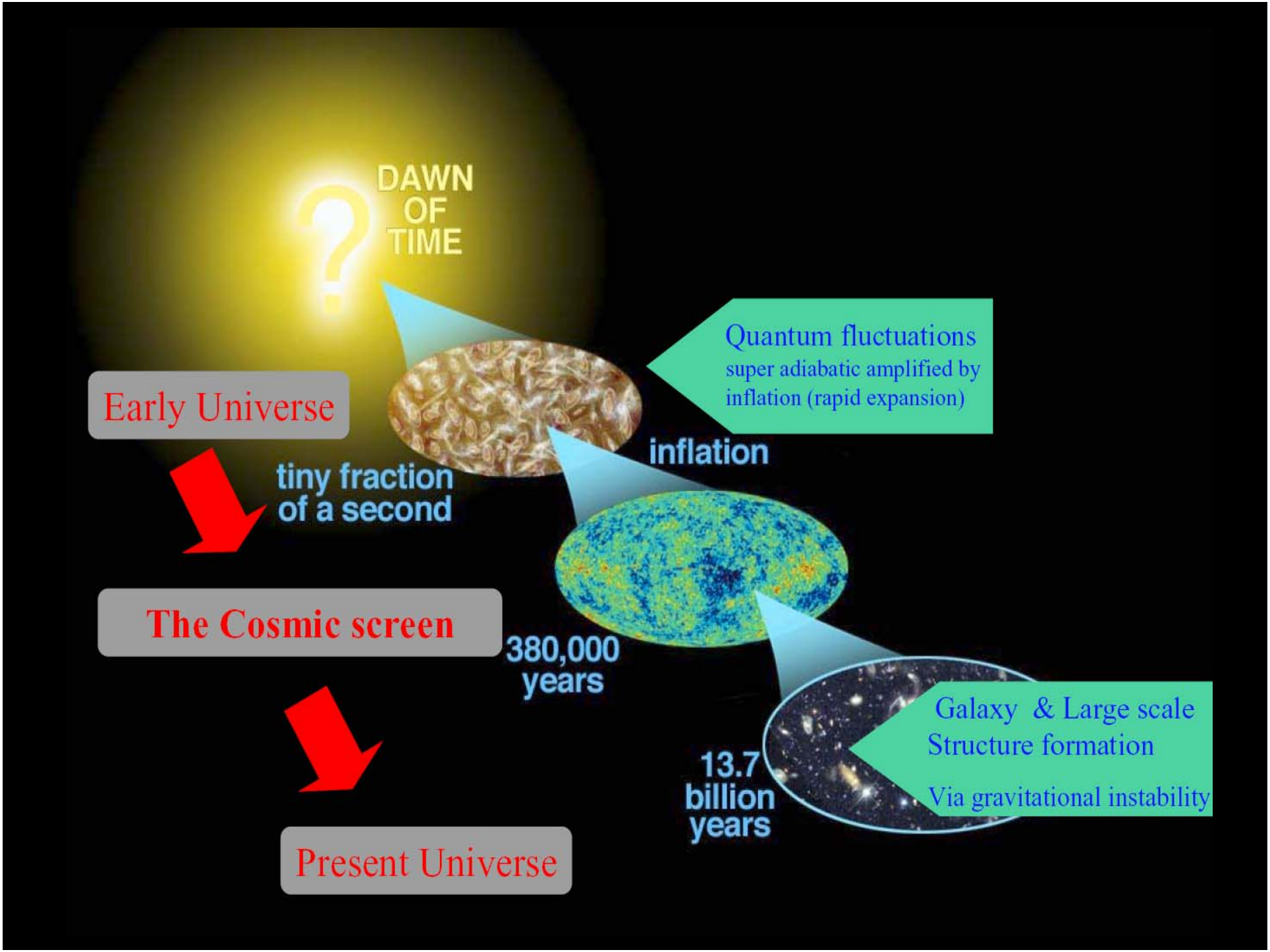
State of the Universe – Sep 2010



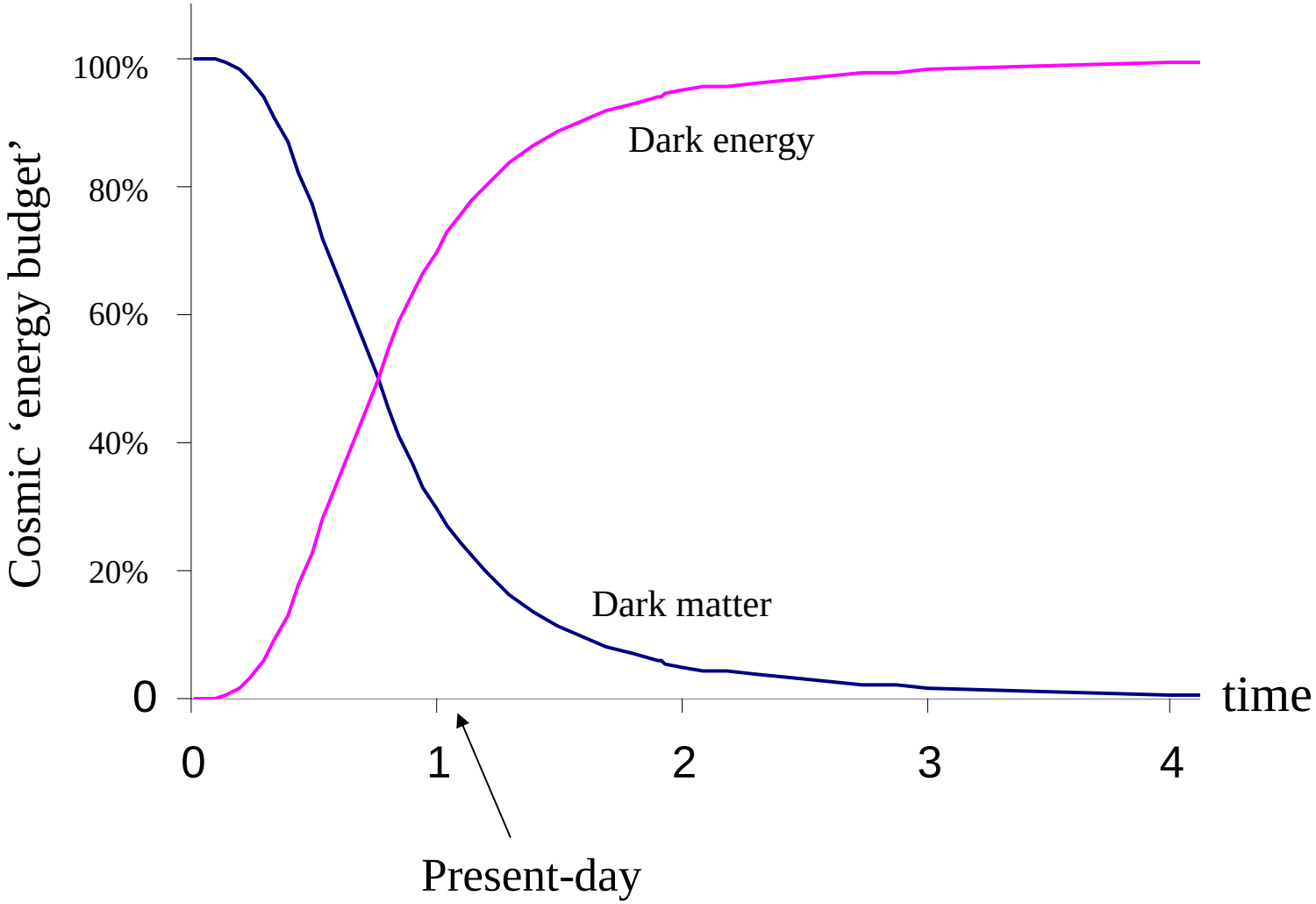
Cosmic tug of war

The force of dark energy surpasses that of dark matter as time progresses.




DAWN
OF
TIME
Quantum fluctuations
super adiabatic amplified by
inflation (rapid expansion)
Early Universe
inflation
tiny fraction
of a second
The Cosmic screen
380,000
years
Galaxy & Large scale
Structure formation
Via gravitational instability
13.7
billion
years
Present Universe

The ‘why now?’ problem

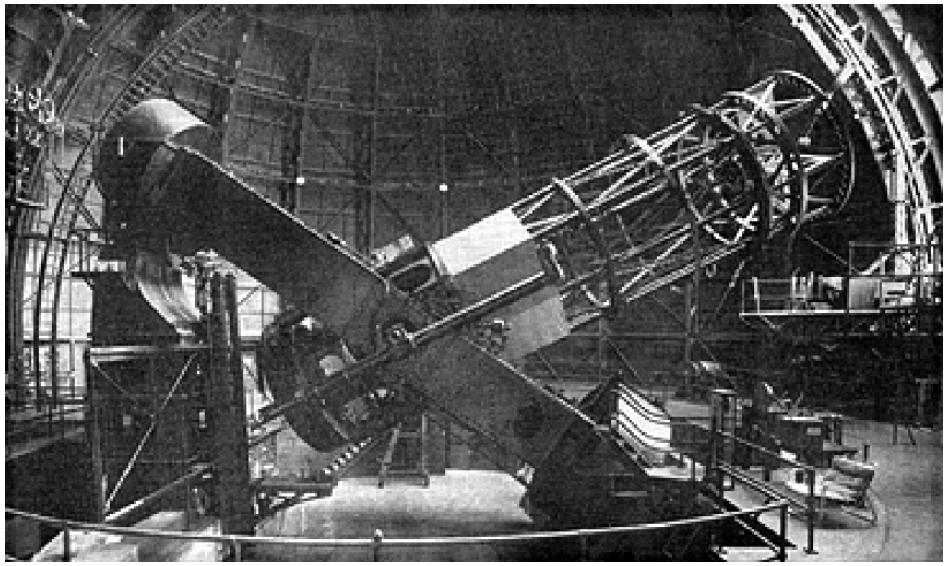


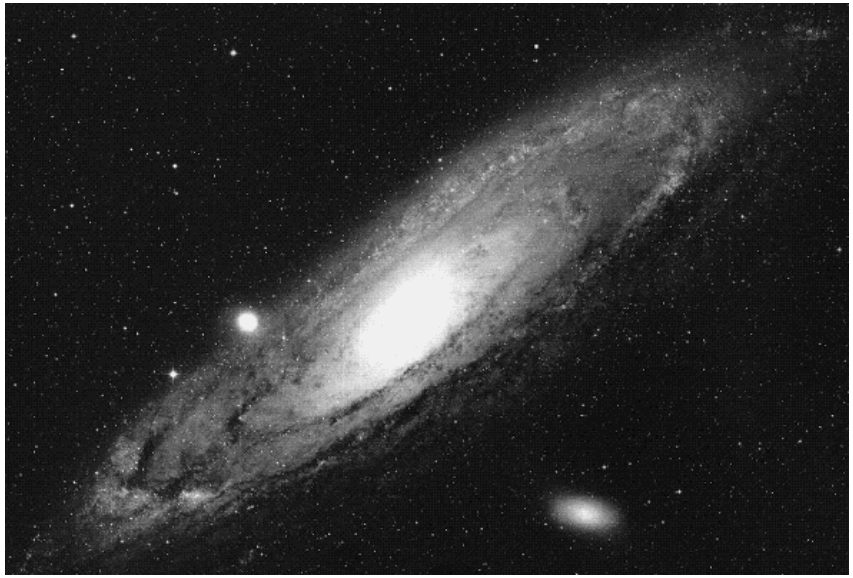
Overview

- *Where are we?*
- ***How did we get there?***
- *Where are we going?*

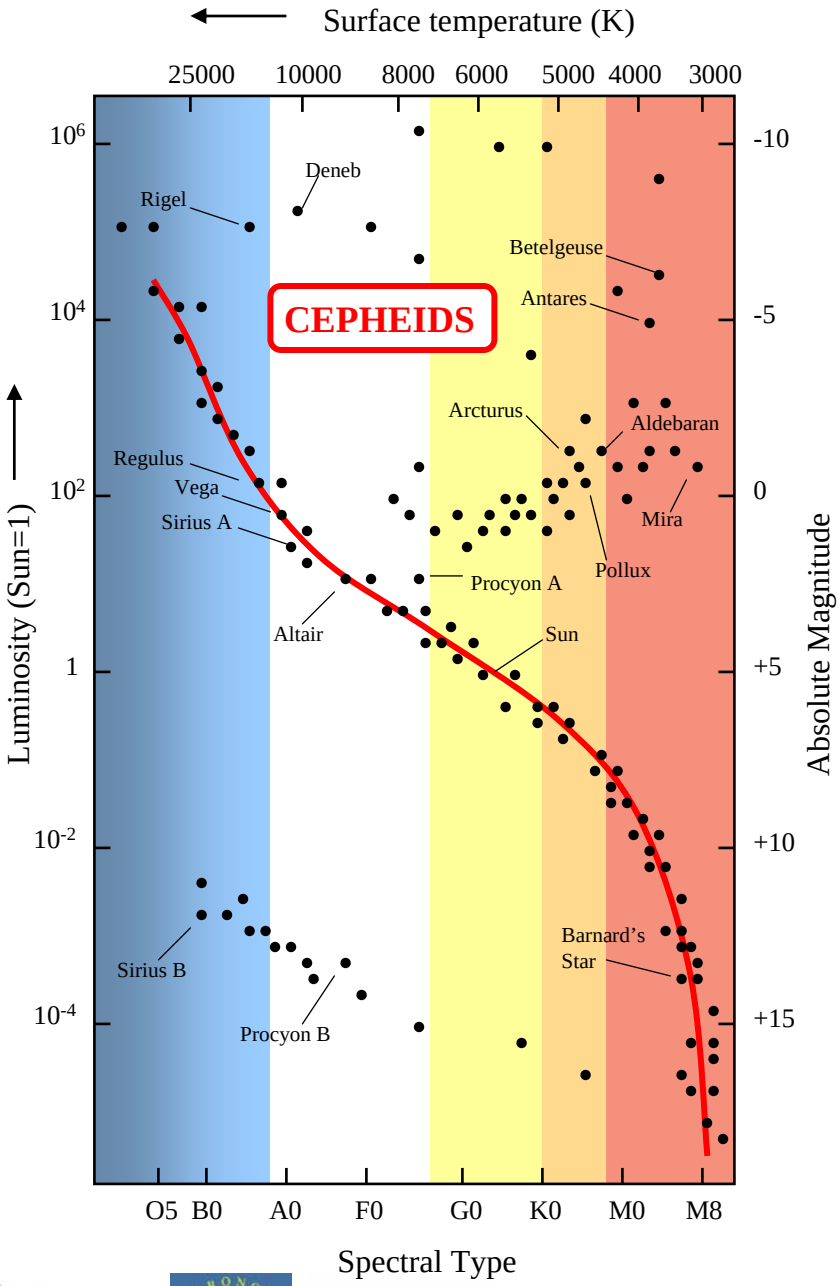
A long time ago,

in a galaxy far, far away…





Edwin Hubble



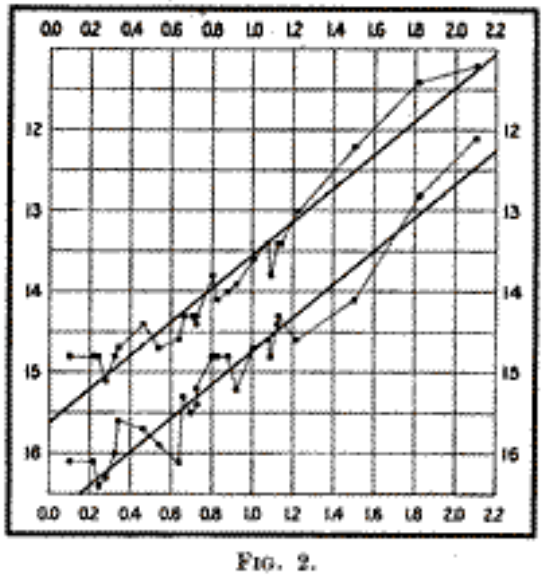
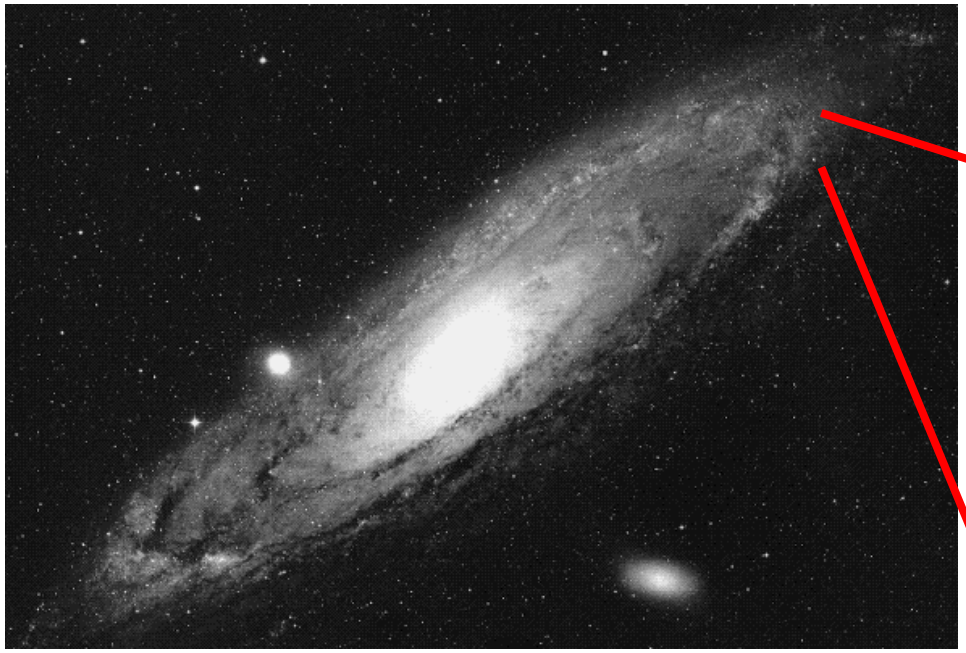
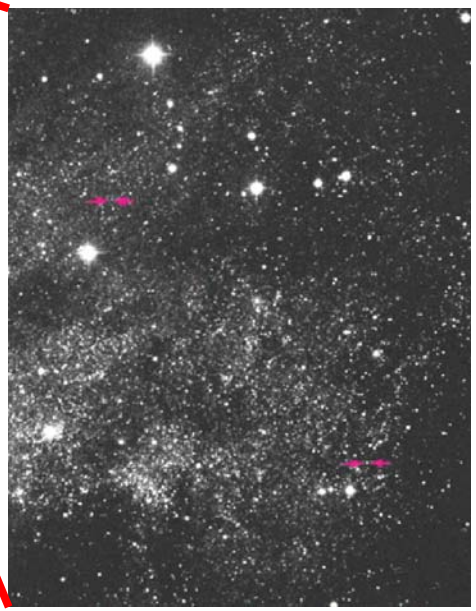
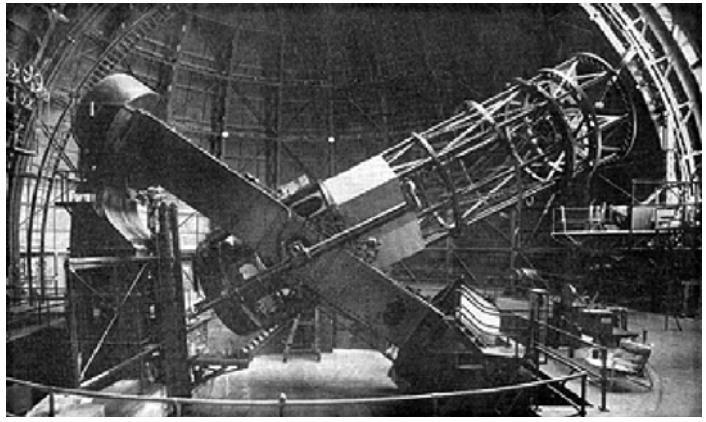


FIG. 2.

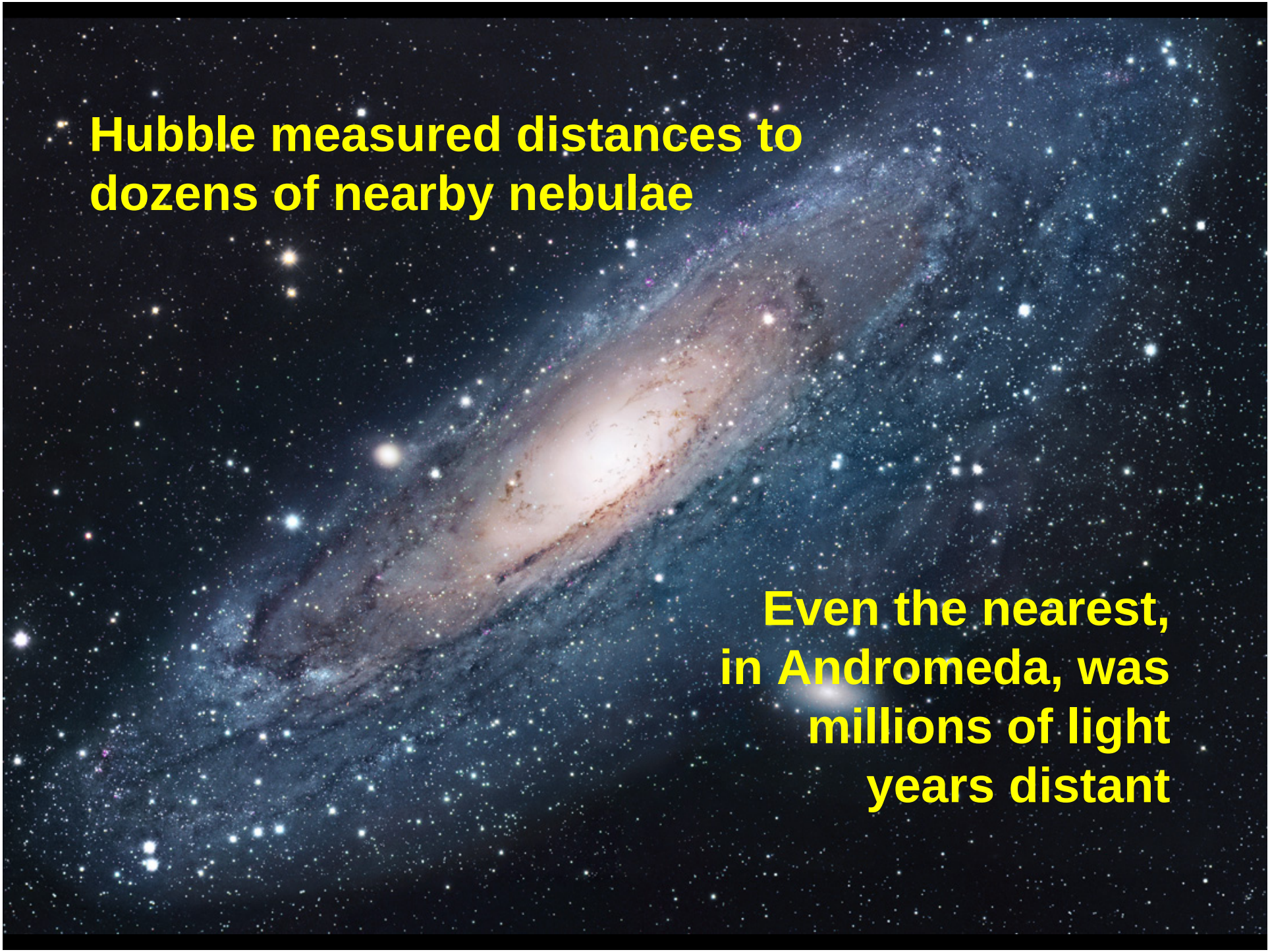
Pickering 1912





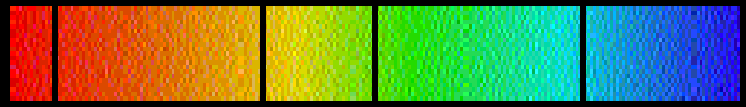


1922: Hubble finds Cepheids in the Great Nebula in Andromeda


Hubble measured distances to dozens of nearby nebulae
Even the nearest, in Andromeda, was millions of light years distant

Hubble also measured the shift in colour, or *wavelength*, of the light from distant galaxies.

Galaxy

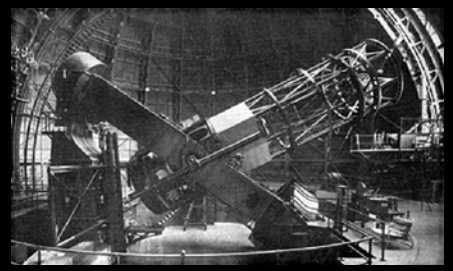


Hubble also measured the shift in colour, or *wavelength*, of the light from distant galaxies.

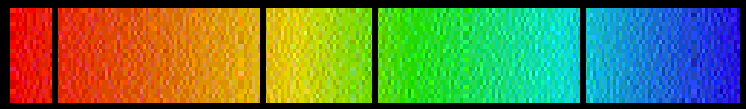
Galaxy

Laboratory

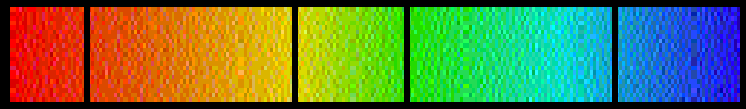
Hubble also measured the shift in colour, or *wavelength*, of the light from distant galaxies.

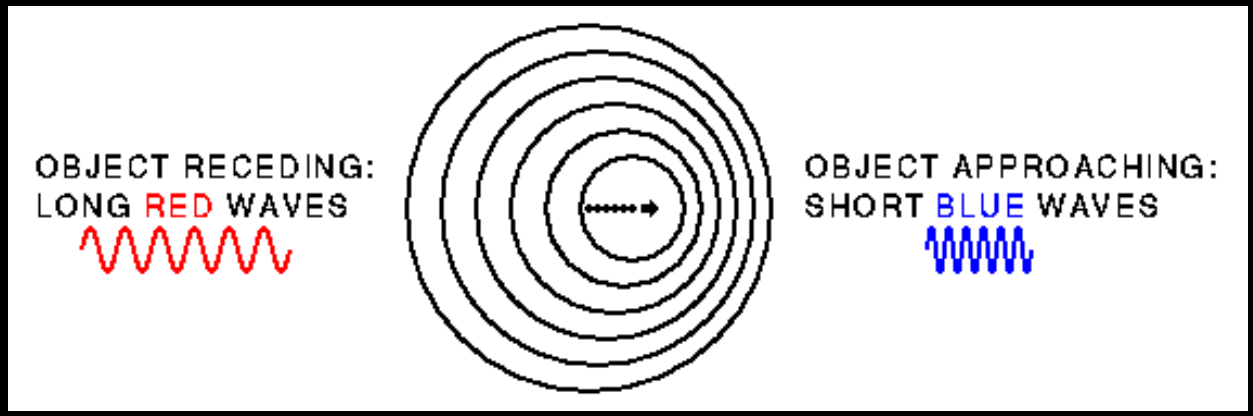


Galaxy

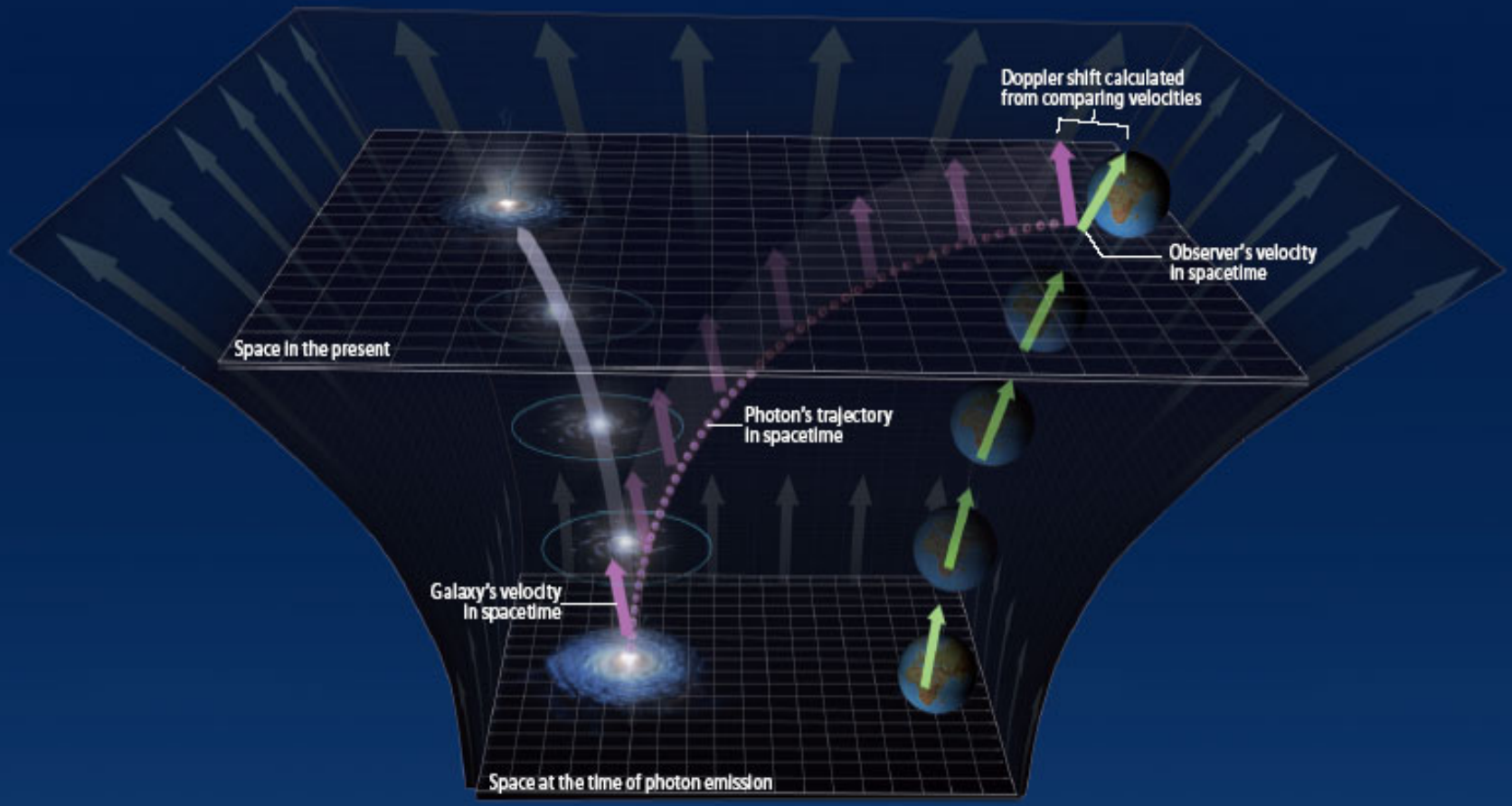


Laboratory





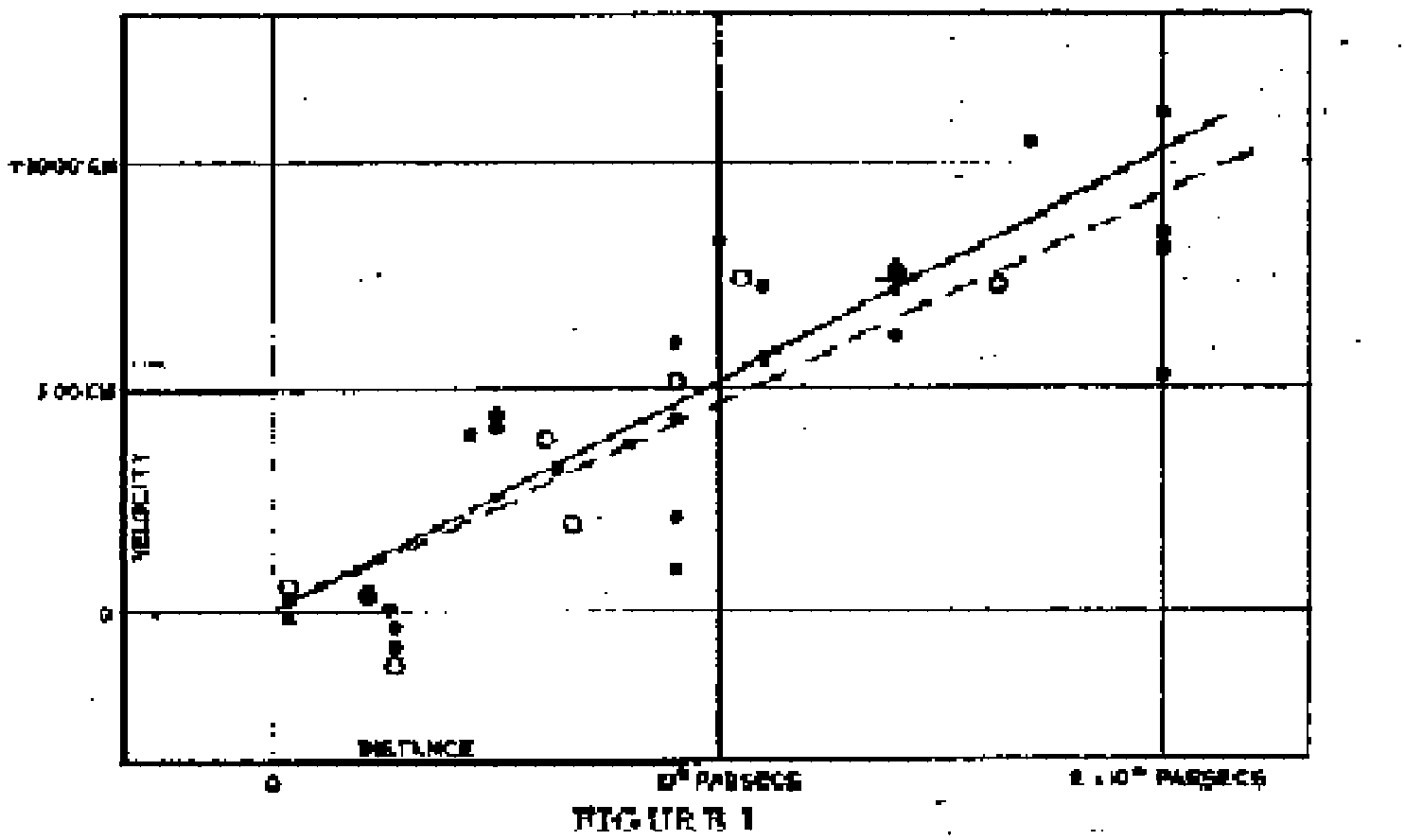
Scientific American, July 2010. (Tamara Davis)



GALAXY REDSHIFT AS A DOPPLER SHIFT

A galaxy's redshift is identical to the Doppler shift an observer would see when watching a police car recede at the same relative velocity as the galaxy—as long as "relative velocity" is interpreted in the appropriate way. First, one must trace the trajectories of the galaxy and of the observer not in space but in spacetime. (In the schematic view here, space is an evolving two-dimensional surface; spacetime trajectories cut through it.) Second, one must compare the velocity of the galaxy at the time when it emitted the photon (*purple arrow*) with the velocity of the observer at the time when the photon was received (*green arrow*) and then—using the appropriate math derived from general relativity—calculate the relative velocity. The Doppler shift calculated from this relative velocity coincides with the galaxy's redshift, suggesting that the galaxy's redshift can be interpreted as the result of relative motion, rather than of the expansion of space. Therefore, no energy is lost.

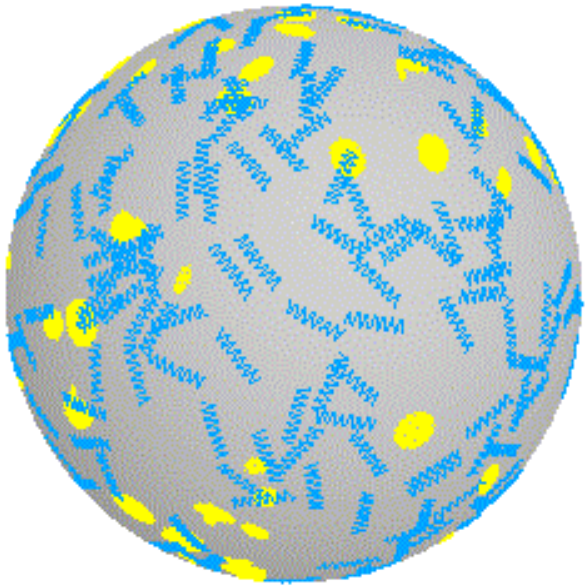
Hubble's Law

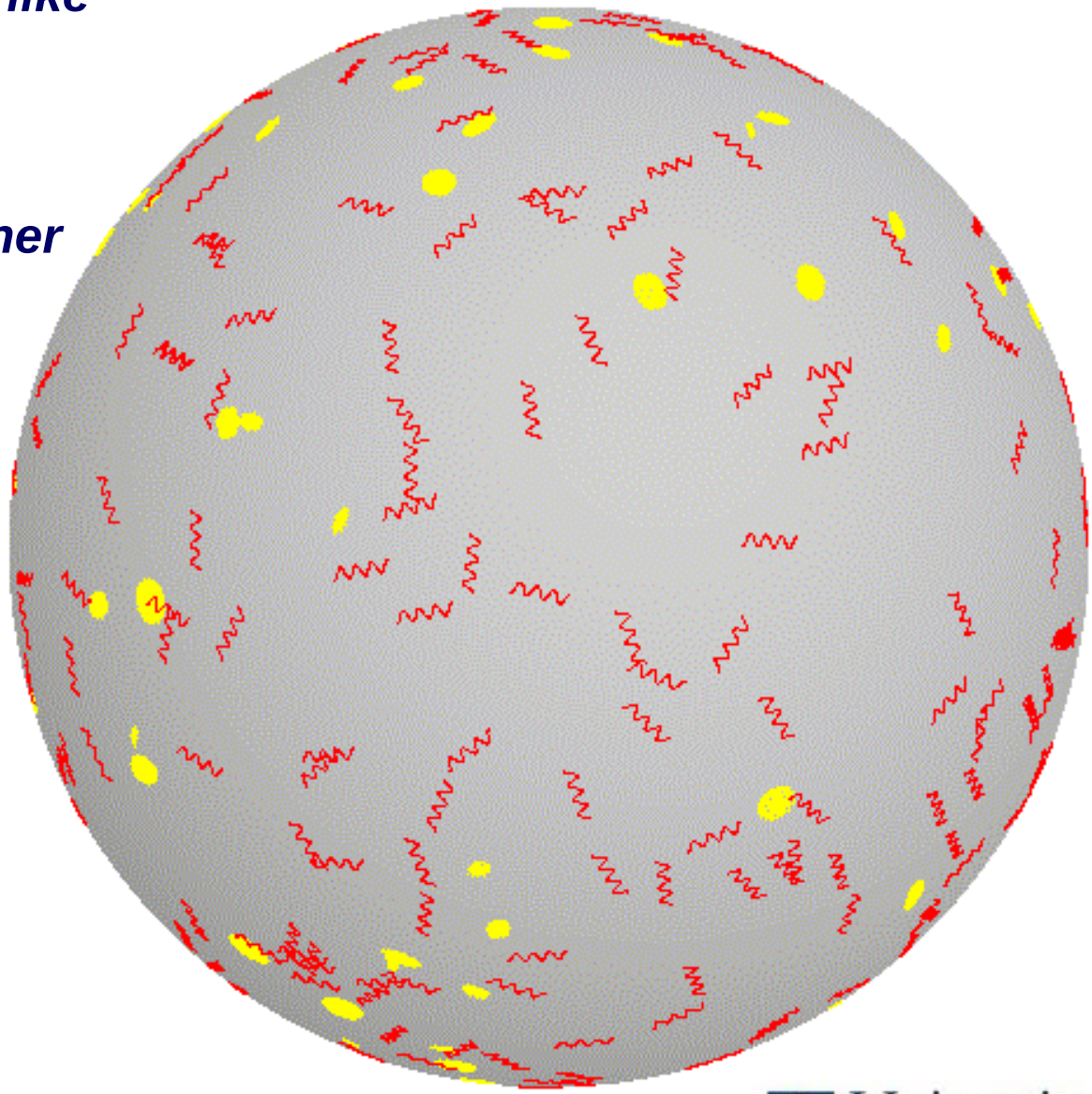


Distant galaxies are moving away from us with a speed proportional to their distance

Spacetime is expanding like the surface of a balloon.

As the balloon expands, galaxies are carried farther apart





1916. № 7.

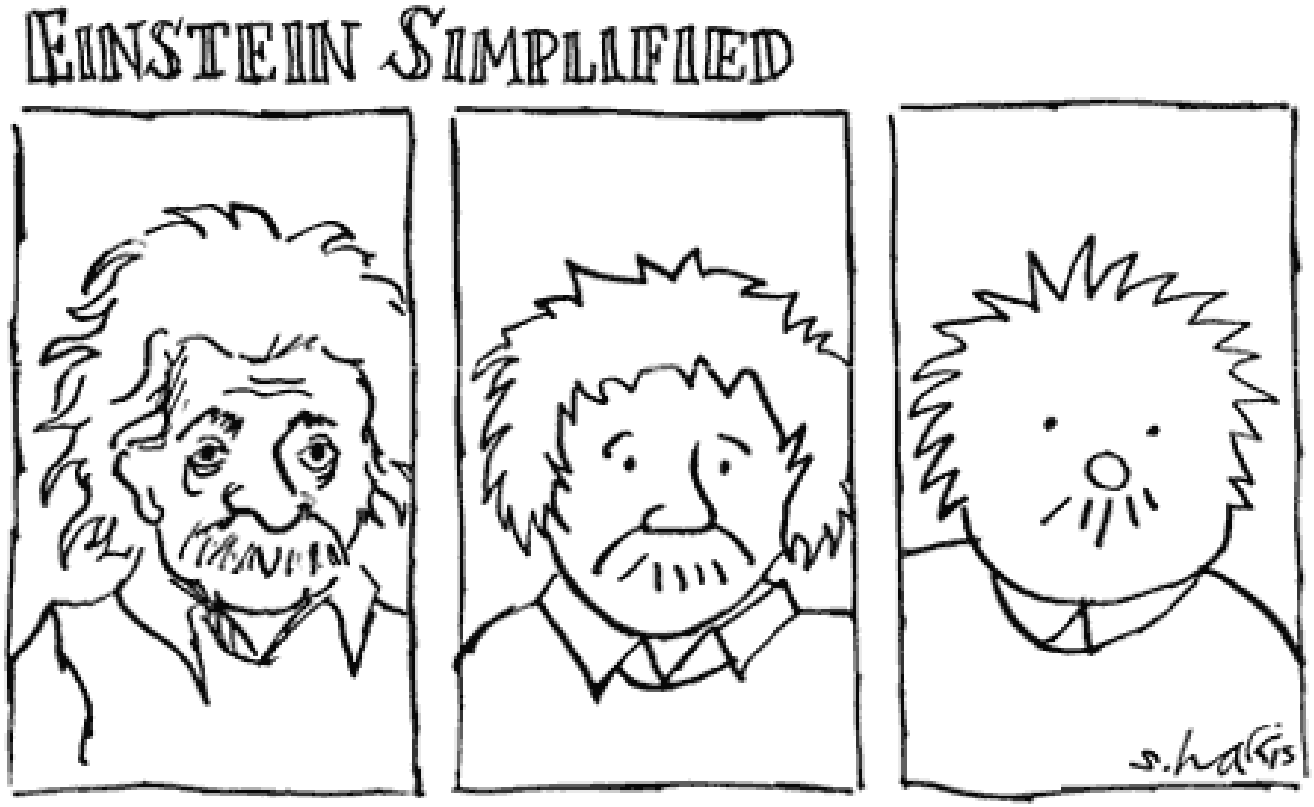
ANNALEN DER PHYSIK.

VIERTE FOLGE. BAND 49.

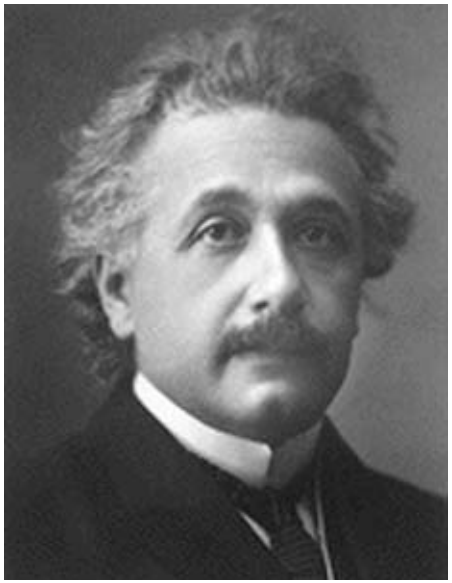
1. *Die Grundlage der allgemeinen Relativitätstheorie;* von *A. Einstein.*

Die im nachfolgenden dargelegte Theorie bildet die denkbar weitgehendste Verallgemeinerung der heute allgemein als „Relativitätstheorie" bezeichneten Theorie; die letztere nenne ich im folgenden zur Unterscheidung von der ersteren „spezielle Relativitätstheorie" und setze sie als bekannt voraus. Die Verallgemeinerung der Relativitätstheorie wurde sehr erleichtert durch die Gestalt, welche der speziellen Relativitätstheorie durch Minkowski gegeben wurde, welcher Mathematiker zuerst die formale Gleichwertigkeit der räumlichen Koordinaten und der Zeitkoordinate klar erkannte und für den Aufbau der Theorie nutzbar machte. Die für die allgemeine Relativitätstheorie nötigen mathematischen Hilfsmittel lagen fertig bereit in dem „absoluten Differentialkalkül", welcher auf den Forschungen von Gauss, Riemann und Christoffel über nichteuklidische Mannigfaltigkeiten ruht und von Ricci und Levi-Civita in ein System gebracht und bereits auf Probleme der theoretischen Physik angewendet wurde. Ich habe im Abschnitt B der vorliegenden Abhandlung alle für uns nötigen, bei dem Physiker nicht als bekannt vorauszusetzenden mathematischen Hilfsmittel in möglichst einfacher und durchsichtiger Weise entwickelt, so daß ein Studium mathematischer Literatur für das Verständnis der vorliegenden Abhandlung nicht erforderlich ist. Endlich sei an dieser Stelle dankbar meines Freundes, des Mathematikers Grossmann, gedacht, der mir durch seine Hilfe nicht nur das Studium der einschlägigen mathematischen Literatur ersparte, sondern mich auch beim Suchen nach den Feldgleichungen der Gravitation unterstützte.

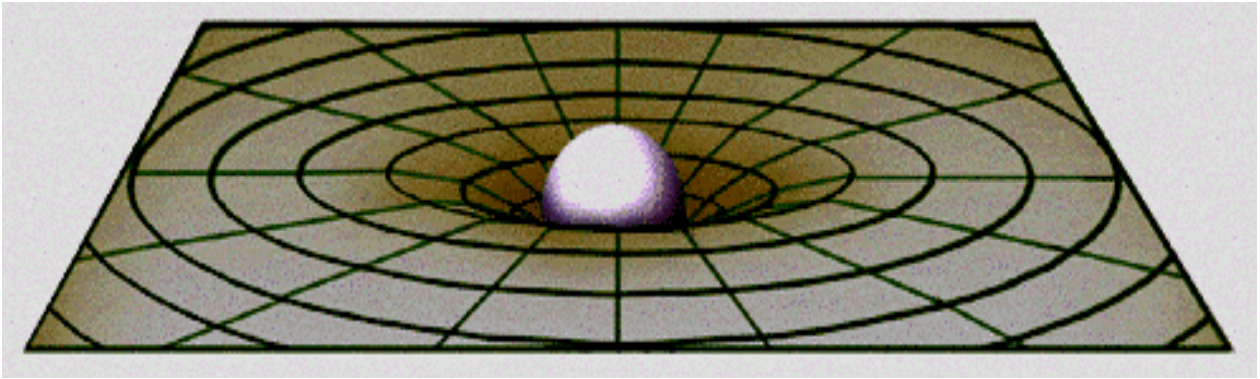
Einstein's general relativity has a reputation for being a very complex and highly mathematical theory

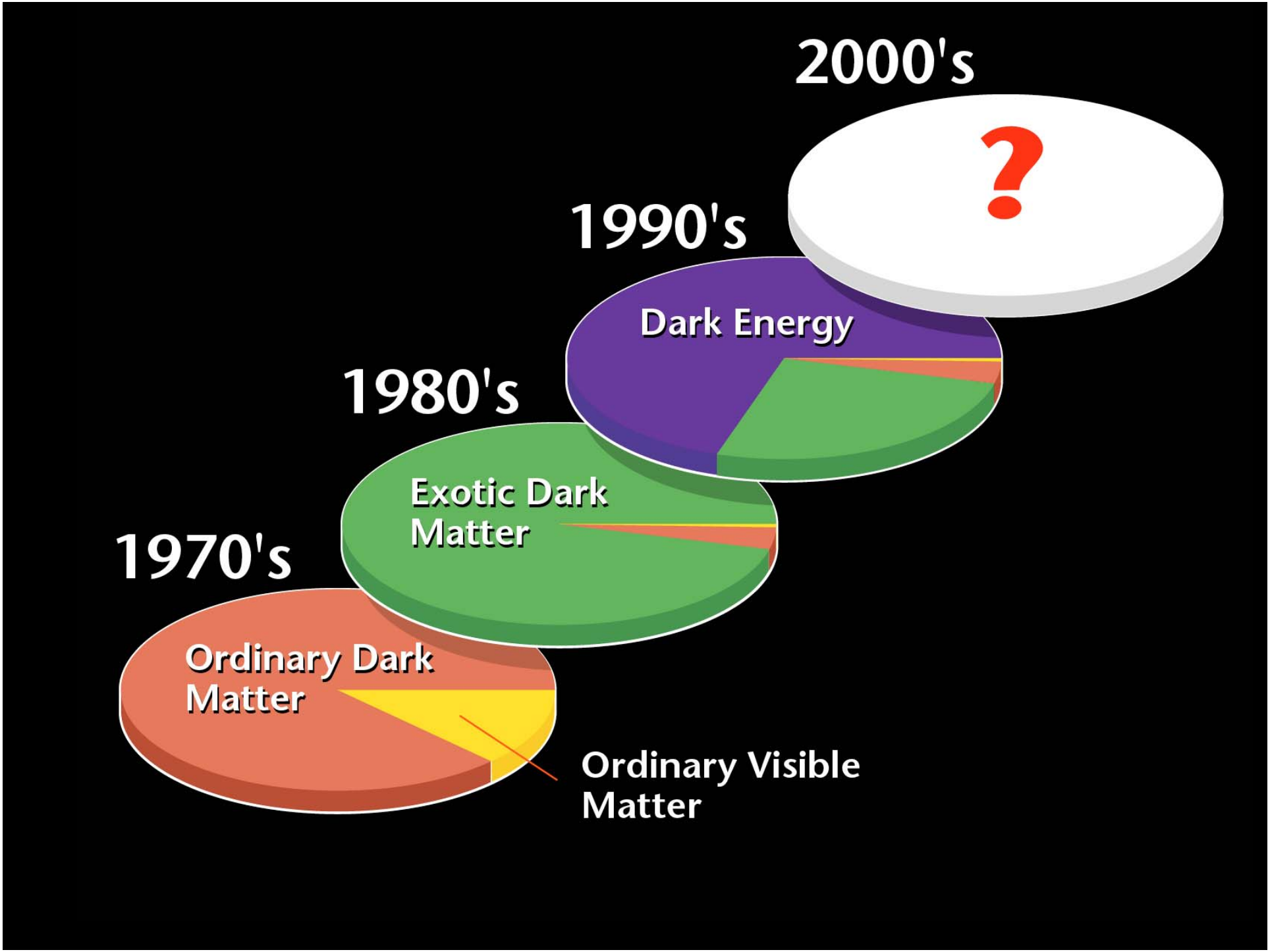


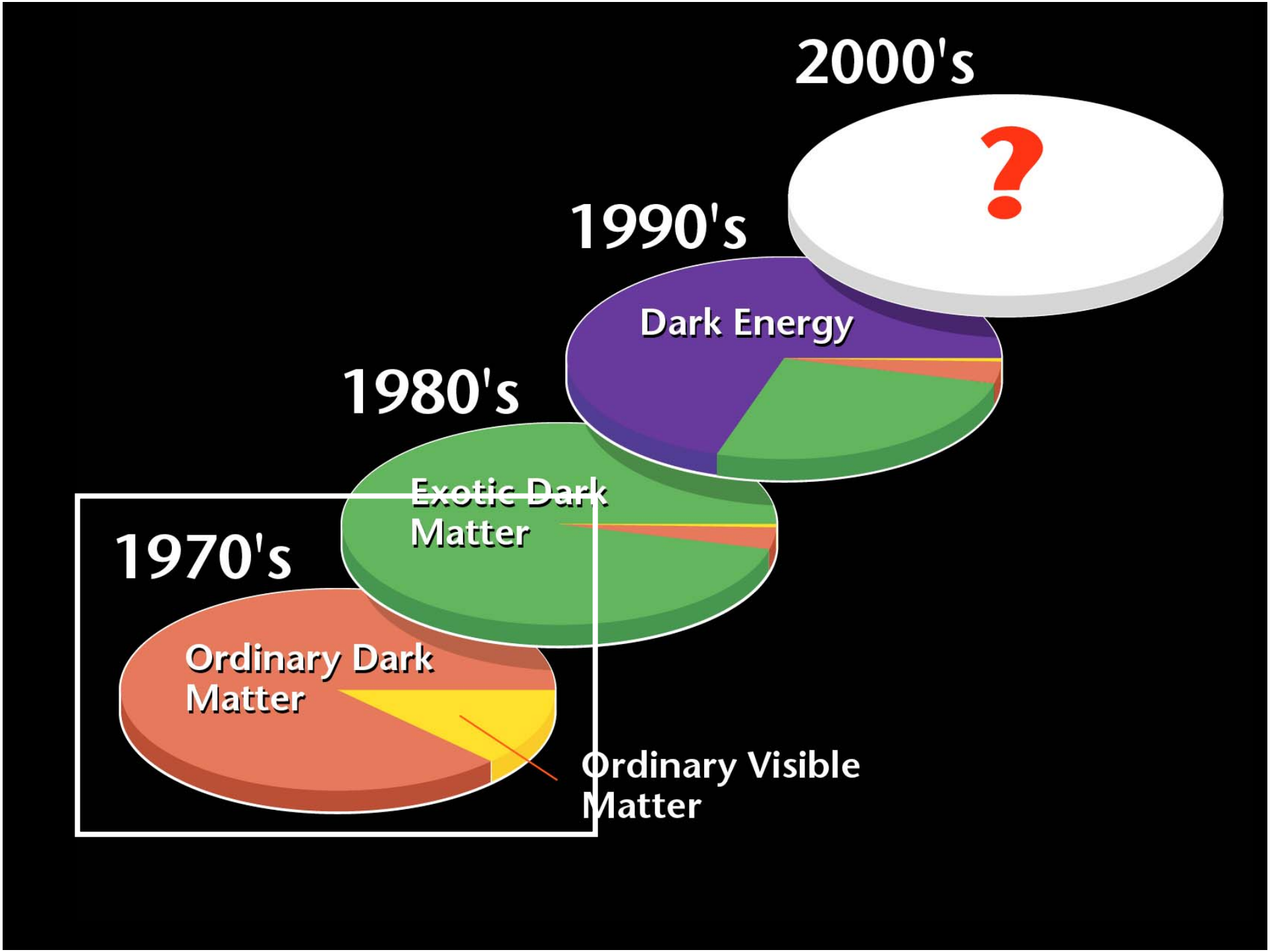
Gravity in Einstein's Universe



"Spacetime tells matter how to move, and matter tells spacetime how to curve"




2000's
?
1990's
Dark Energy
1980's
Exotic Dark Matter
1970's
Ordinary Dark Matter
Ordinary Visible Matter


2000's
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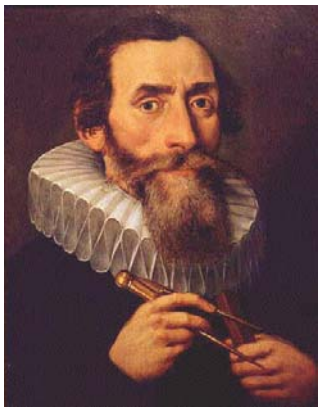
Ordinary Dark Matter
Ordinary Visible Matter

Weighing the Universe

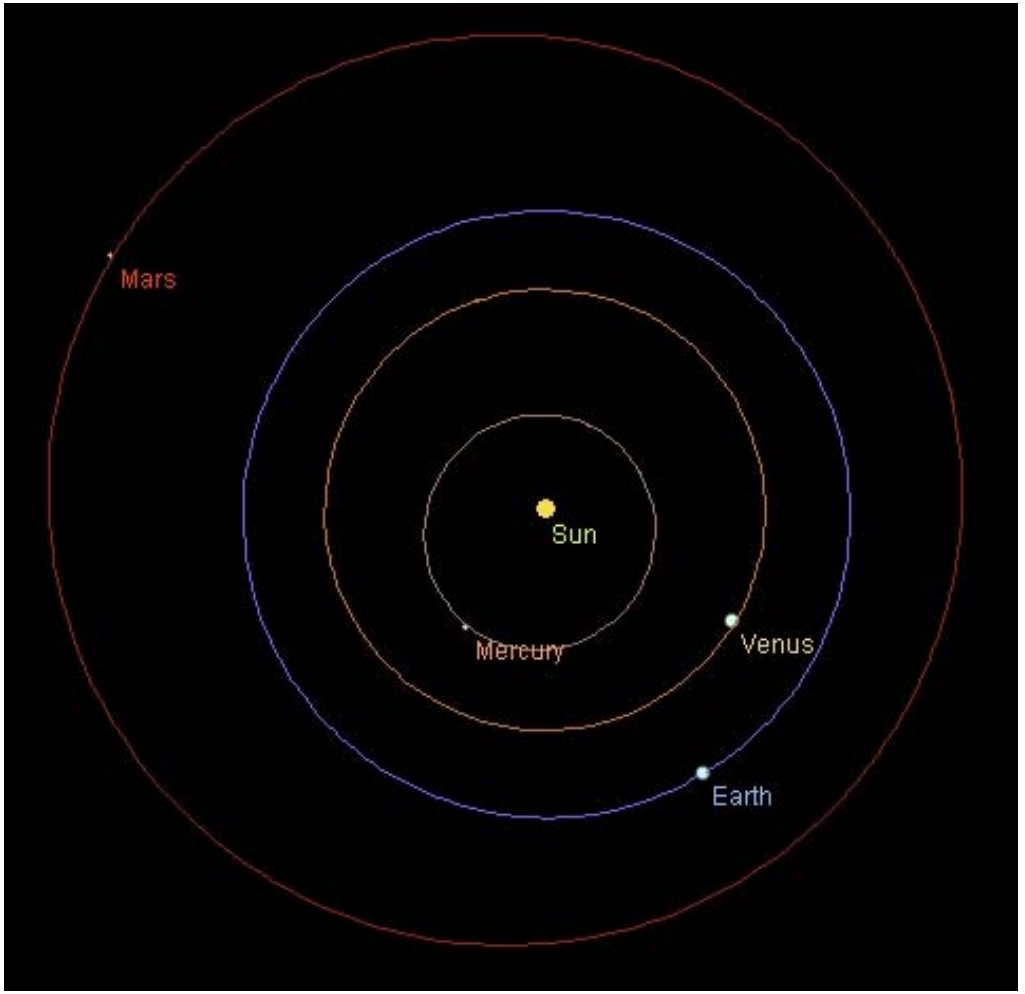
Can we assume light traces mass?...

Weighing the Solar System

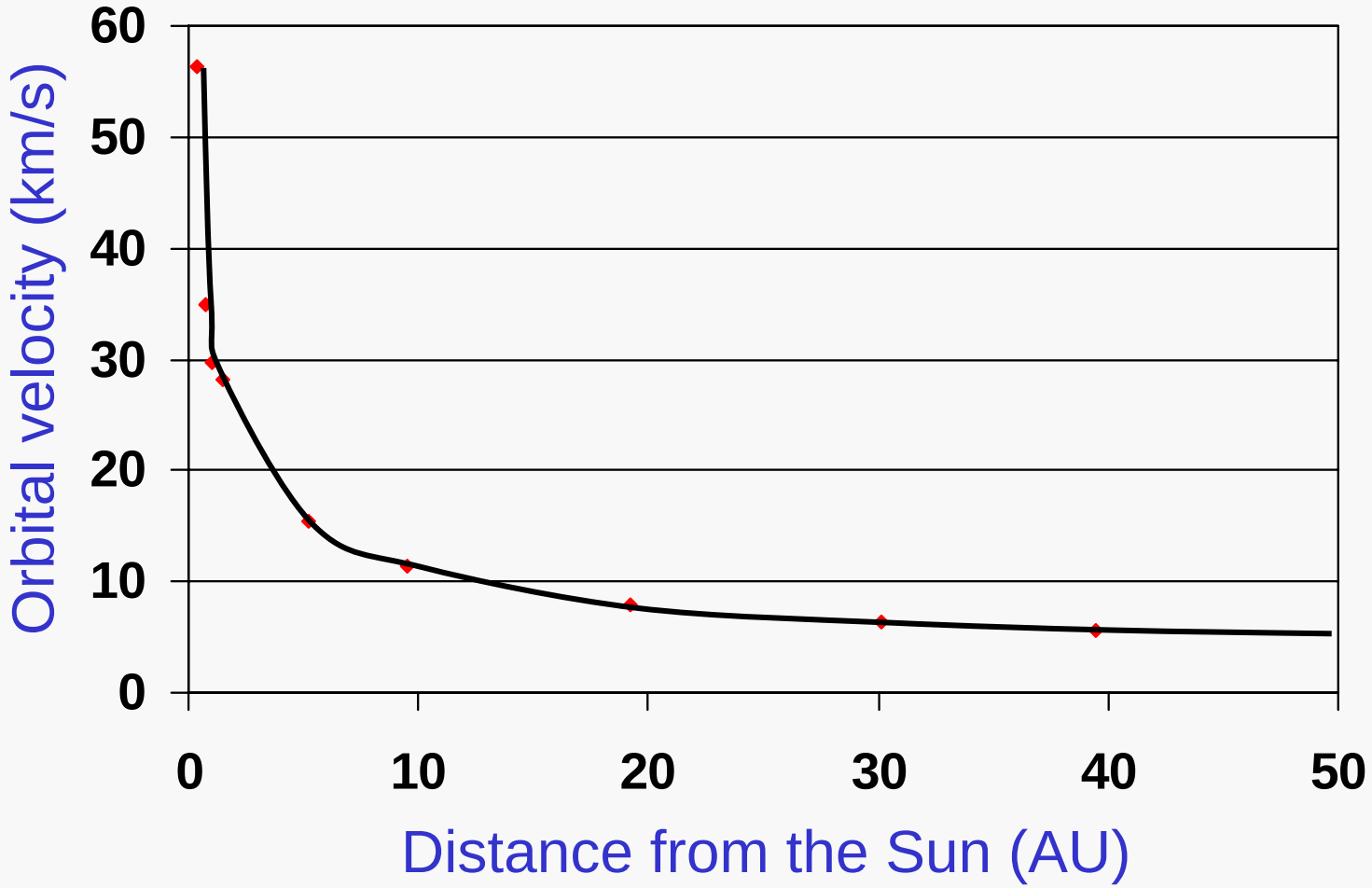


Johannes Kepler

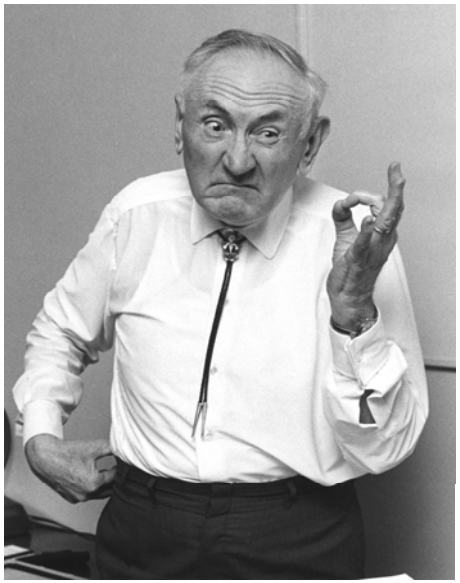
Isaac Newton



Weighing the Solar System

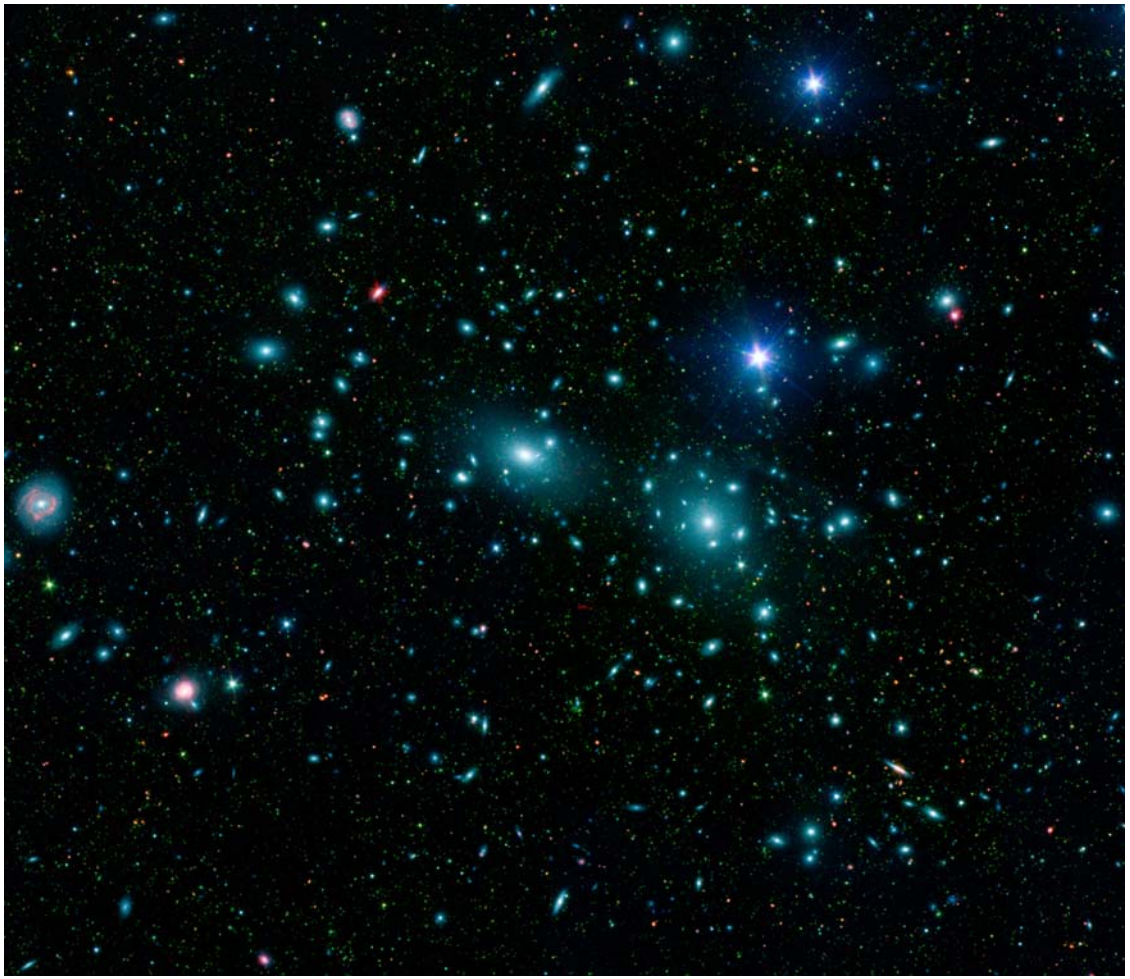


More than meets the eye?...



Fritz Zwicky

1933: finds evidence for **dark matter** in the Coma galaxy cluster



Weighing galaxies

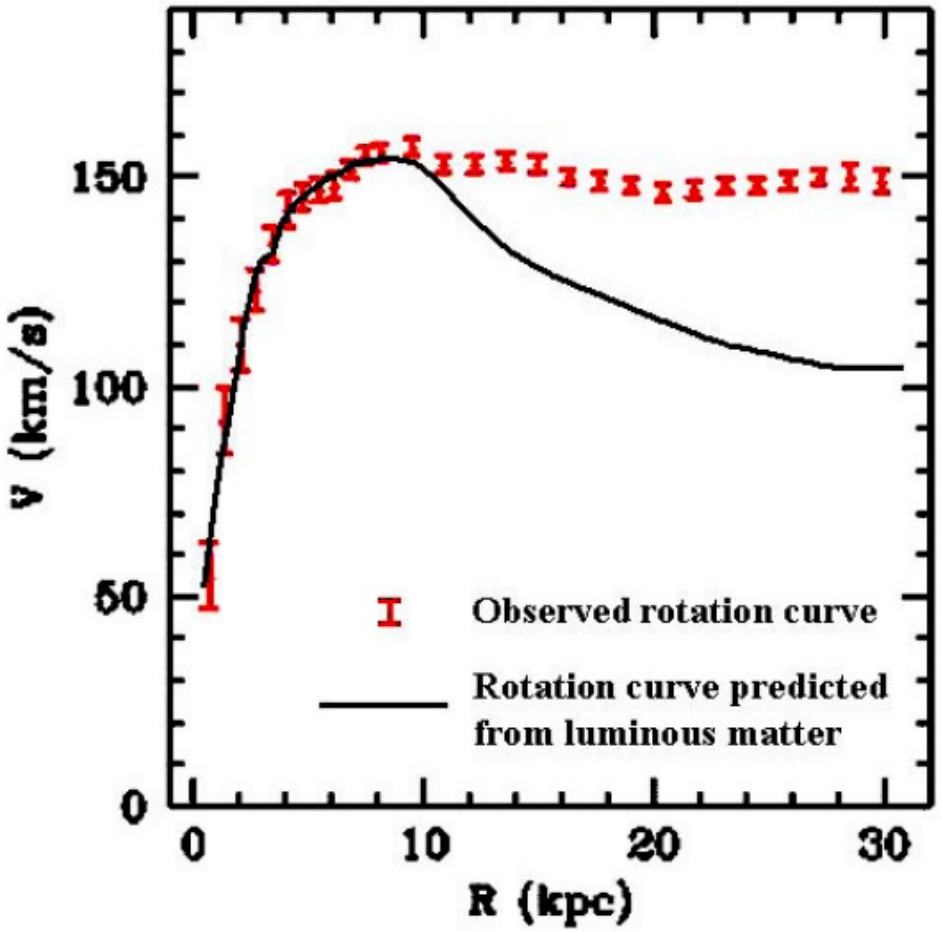
Vera Rubin

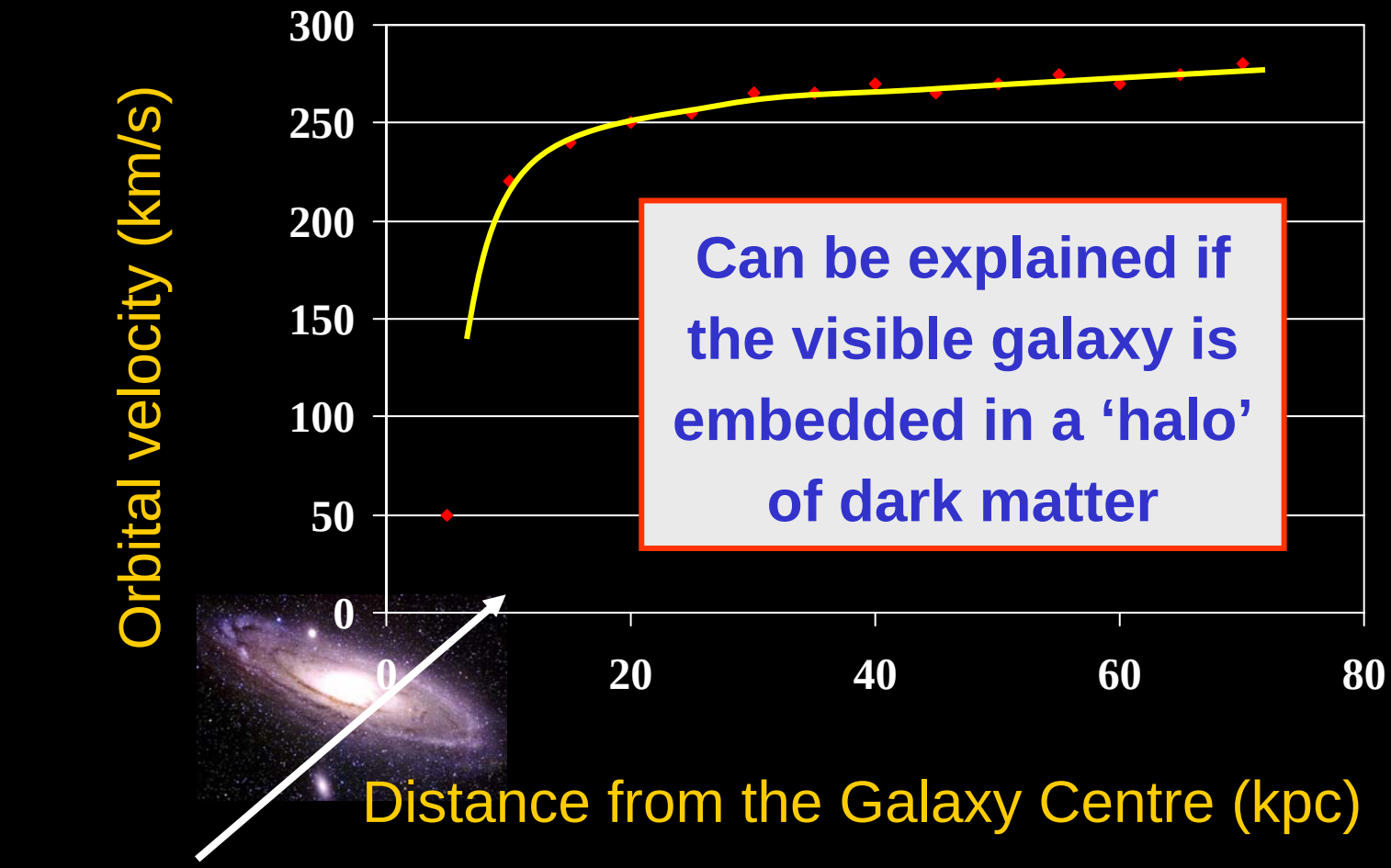
1970s: studies the **rotation curves** of spiral galaxies, and finds that they are **flat**.

Weighing galaxies

Vera Rubin

1970s: studies the **rotation curves** of spiral galaxies, and finds that they are **flat**.



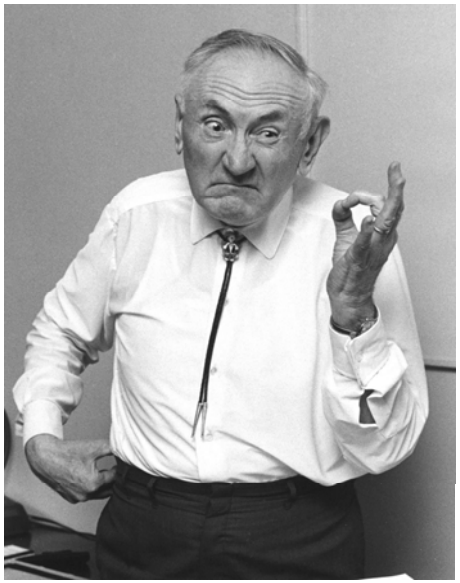

Orbital velocity (km/s)
300
250
200
150
100
50
0
0
20
40
60
80
Distance from the Galaxy Centre (kpc)
Can be explained if the visible galaxy is embedded in a ‘halo’ of dark matter
Typical size of galaxy disk

What we see

10 times as much as the luminous matter in the visible galaxy

What is really there….

Even more dark matter in clusters…



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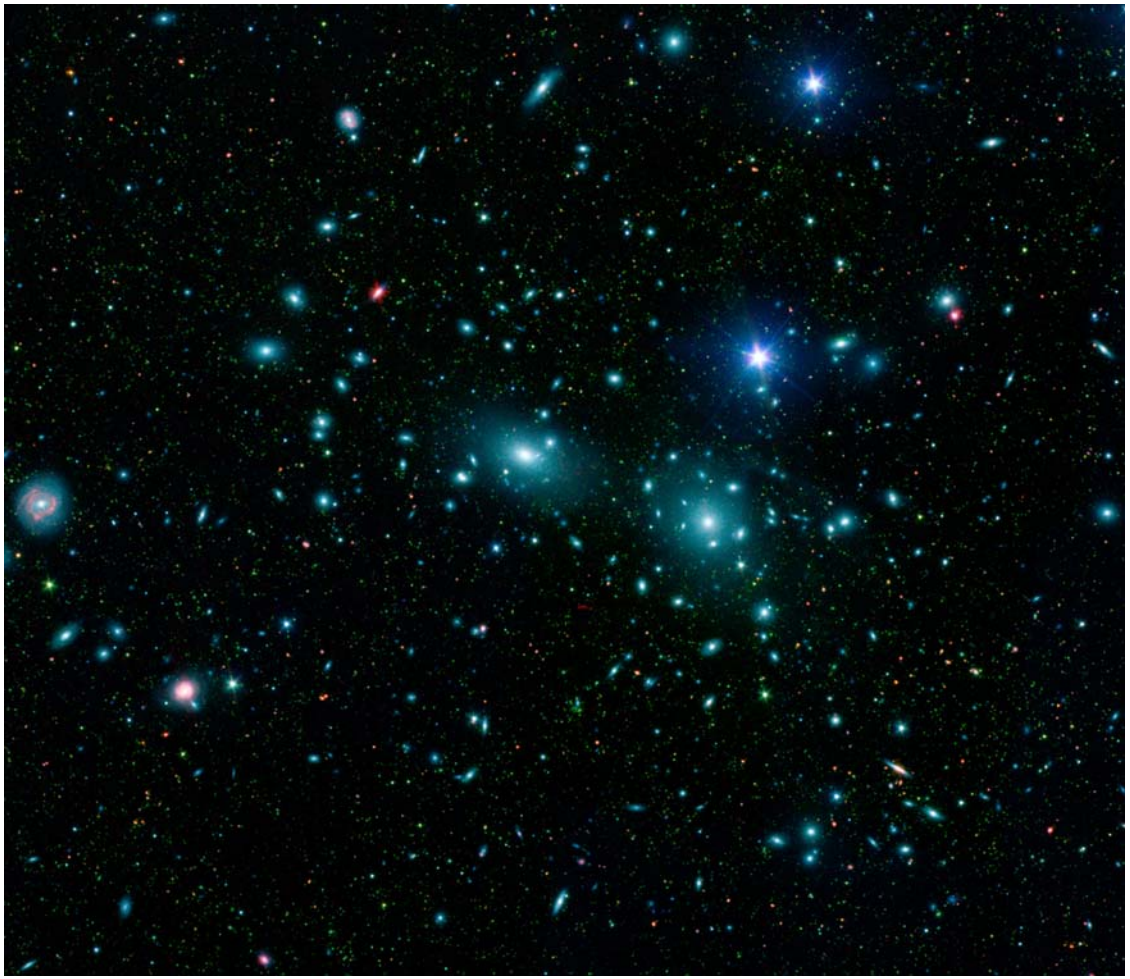

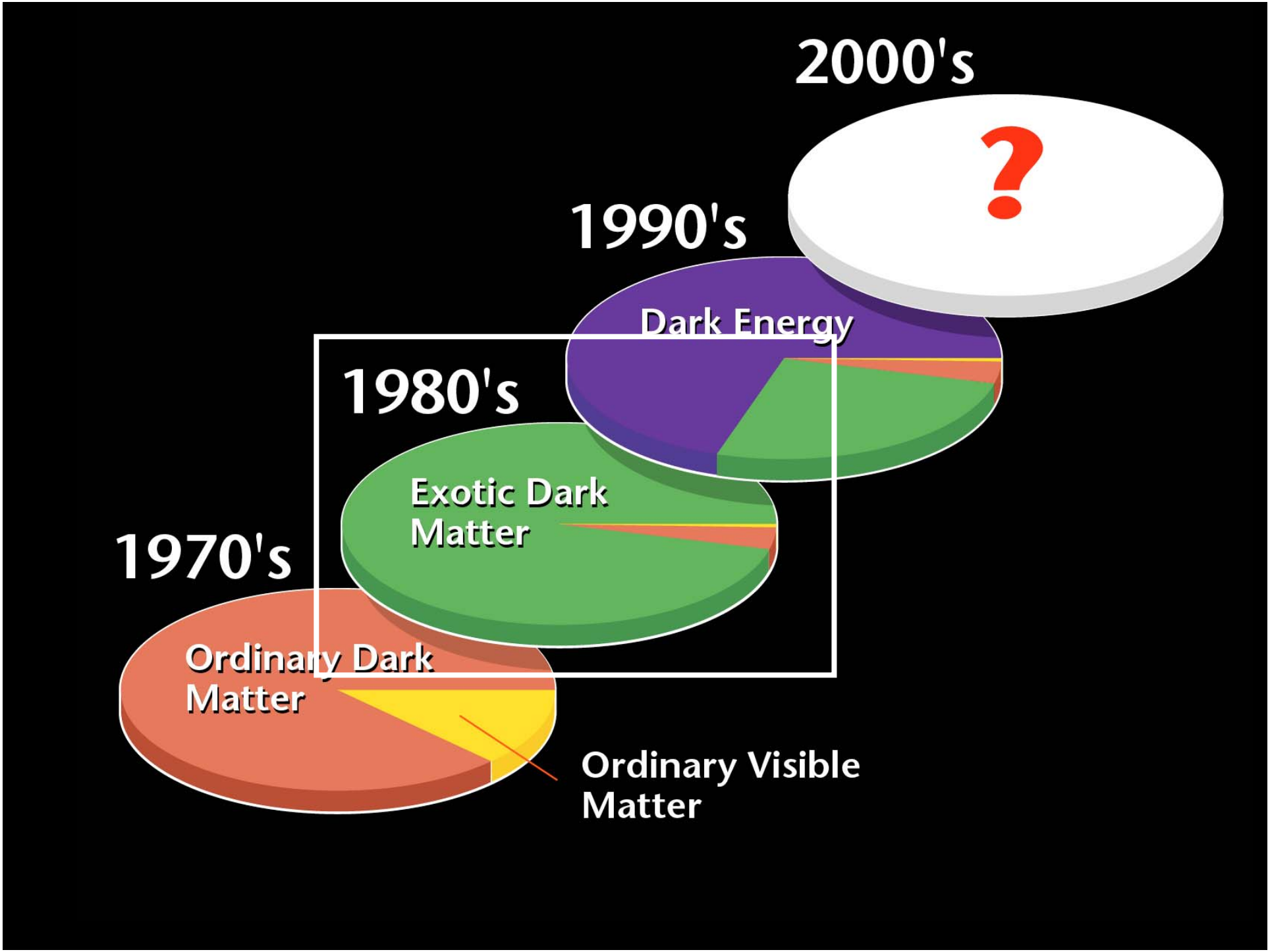
2000's
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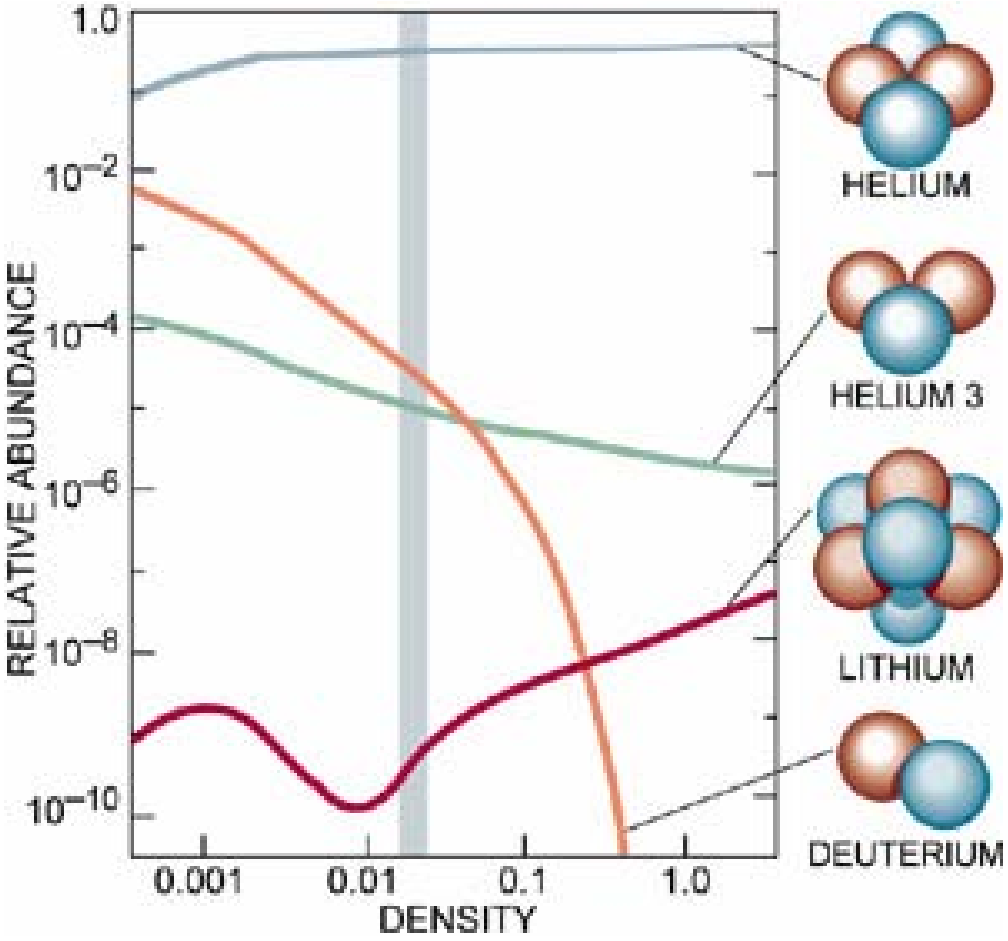
1980s: Cosmic Cookery

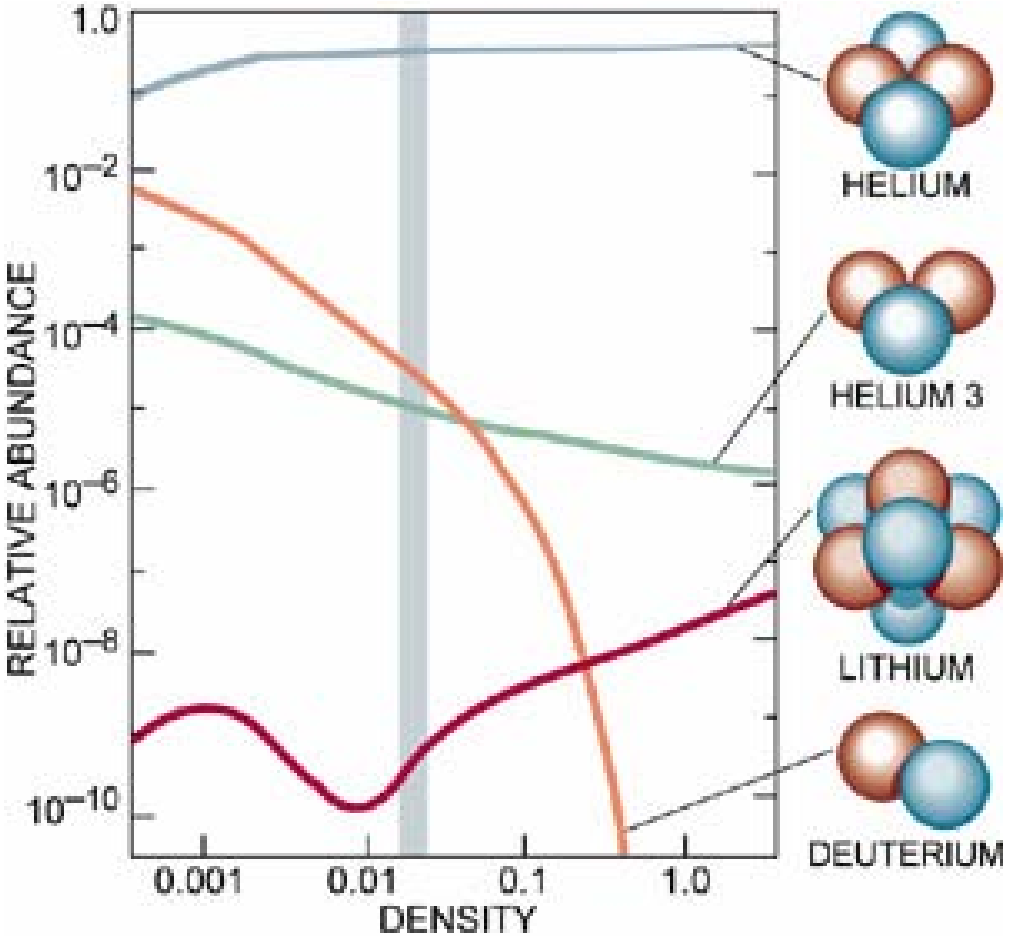
Lightest elements made during first 3 minutes after the Big Bang…

$$p + n \longleftrightarrow d + \gamma$$
$$d + n \longrightarrow H^3 + \gamma$$
$$H^3 + p \longrightarrow He^4 + \gamma$$
$$d + p \longrightarrow He^3 + \gamma$$
$$He^3 + n \longrightarrow He^4 + \gamma$$
$$\vdots$$



1980s: Cosmic Cookery

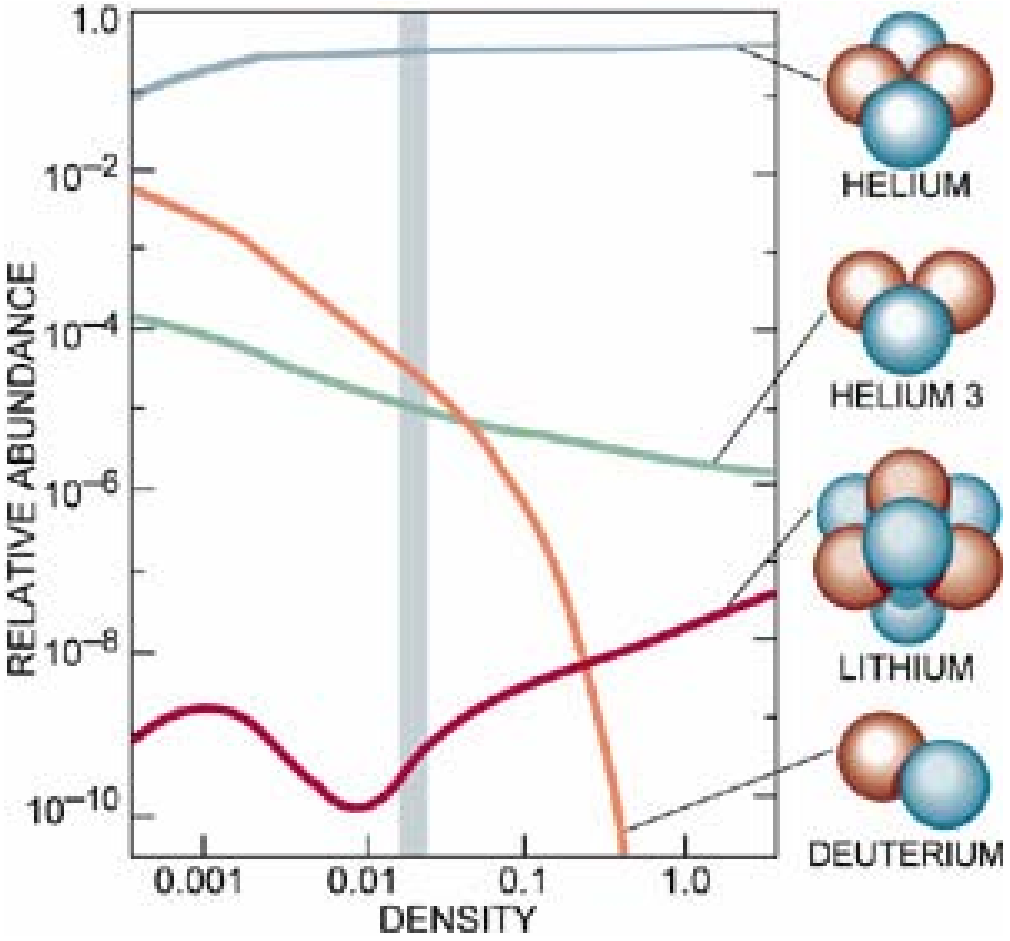
Amount of each element depends on the density of **baryons.**



1980s: Cosmic Cookery

Amount of each element depends on the density of **baryons.**

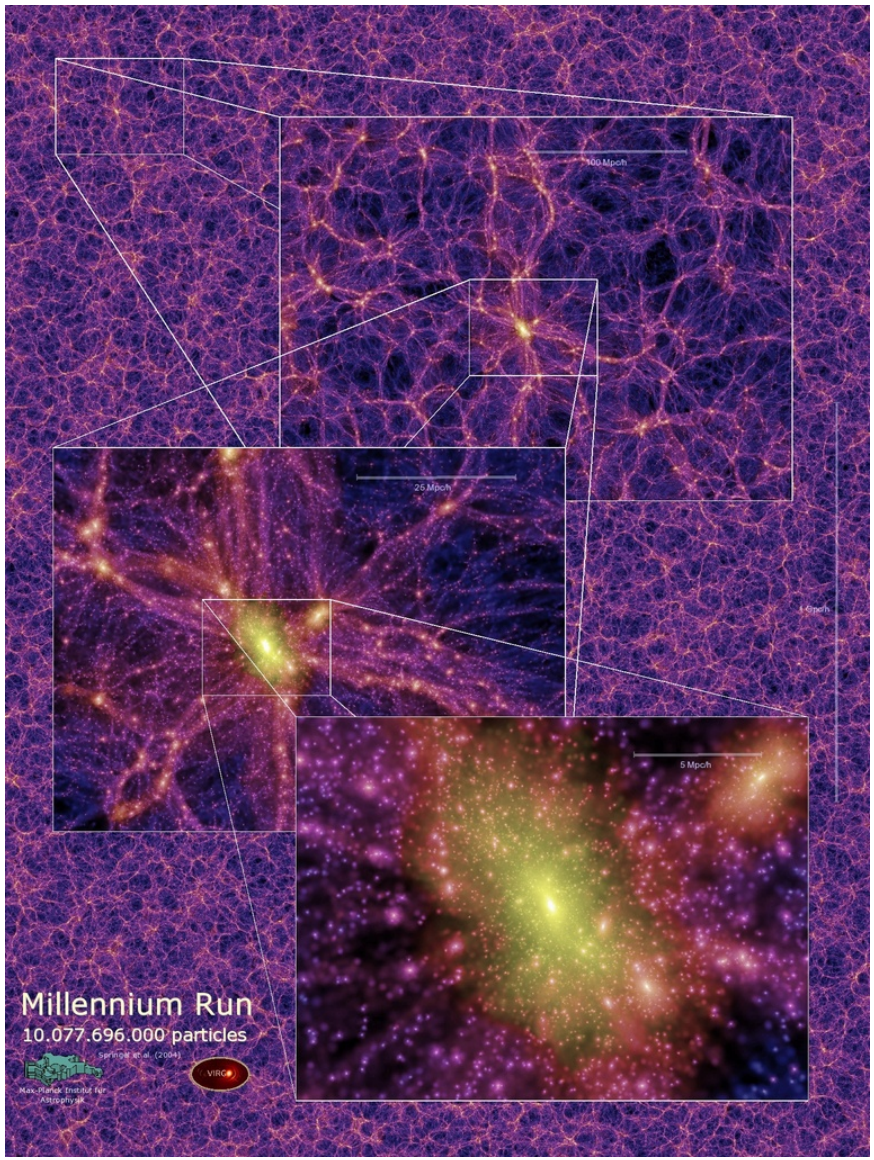
Observed amounts match predictions very well, but ***only*** if baryons make up about 15% of all the dark matter.



So what exactly *is* this dark matter?...

Computer models of galaxies tell us that it must be **cold** – i.e. not moving at speed of light.

Cold dark matter



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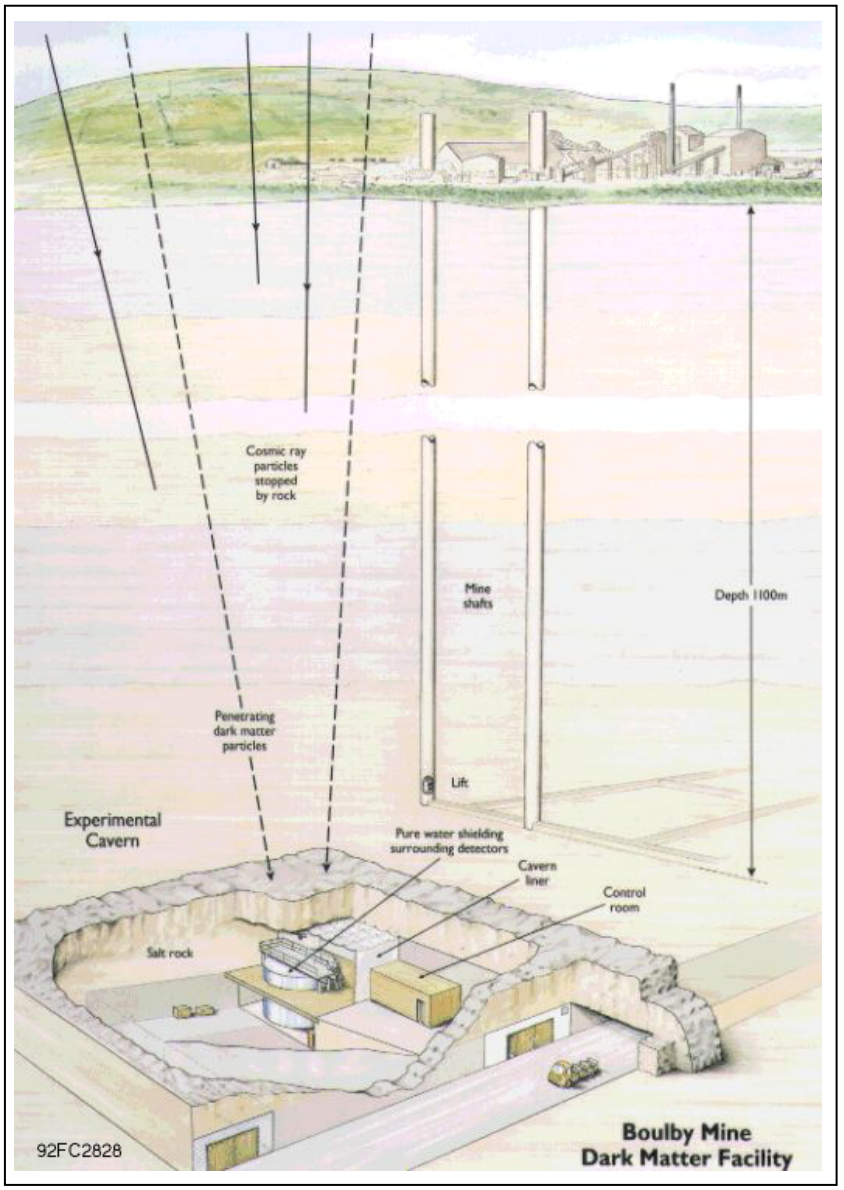

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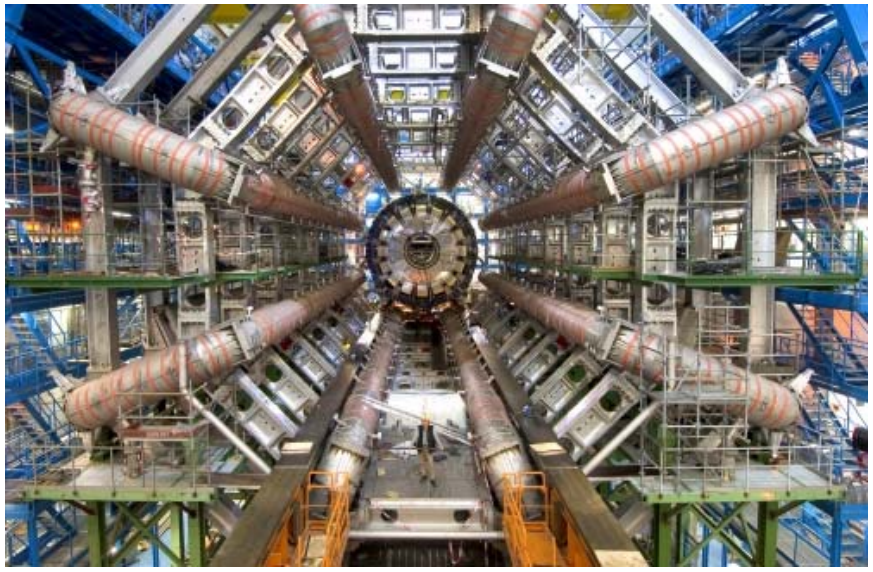
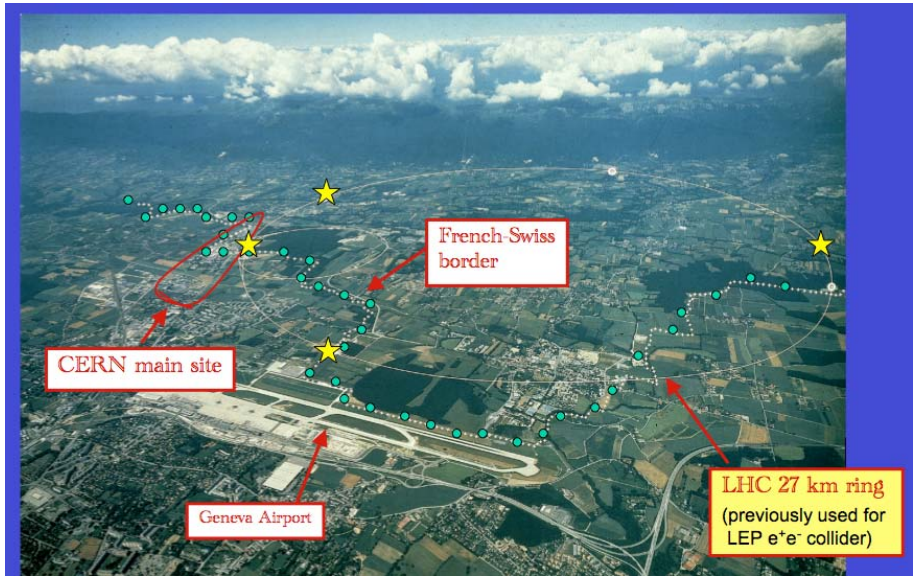
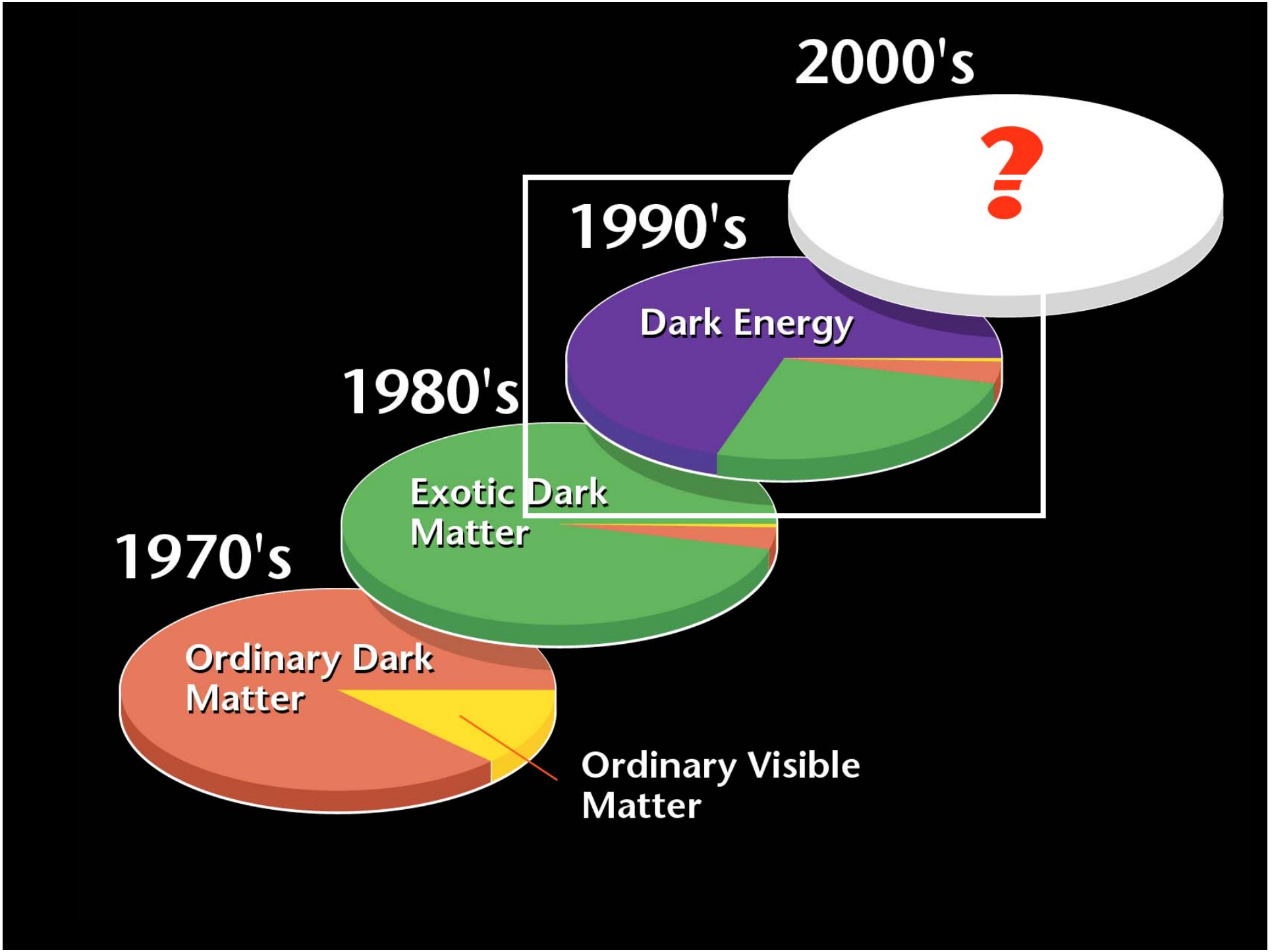
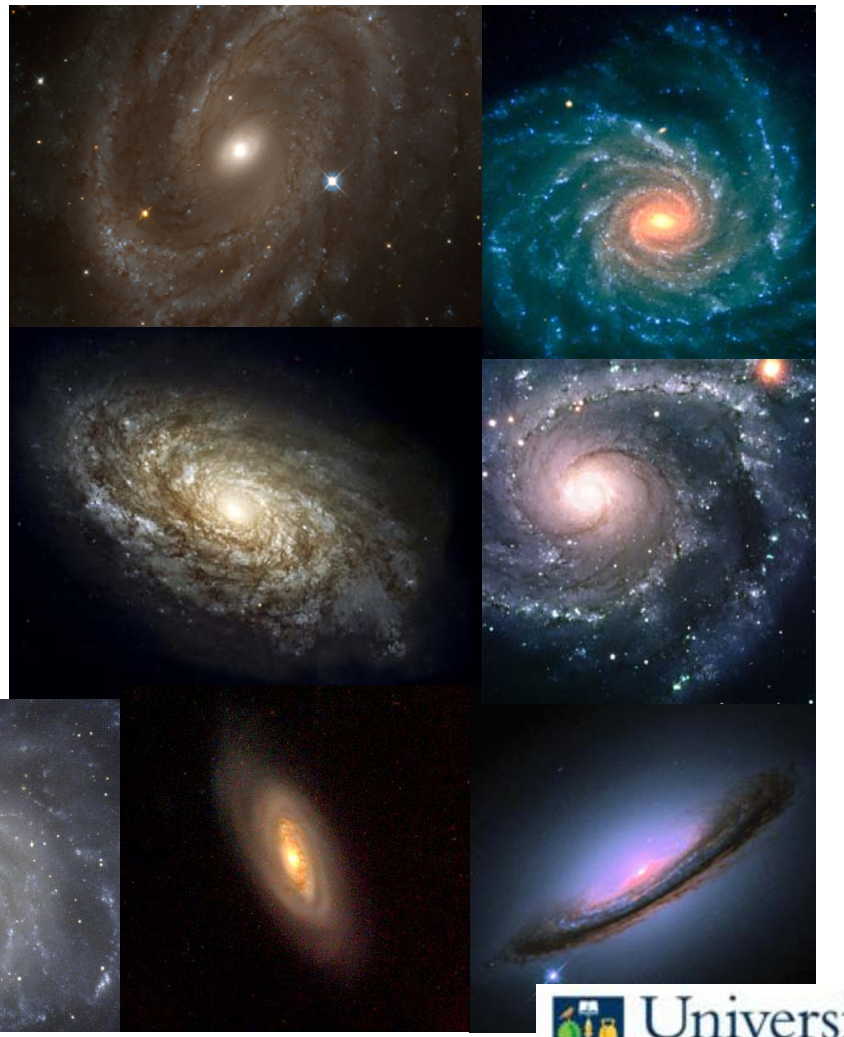
Cold dark matter





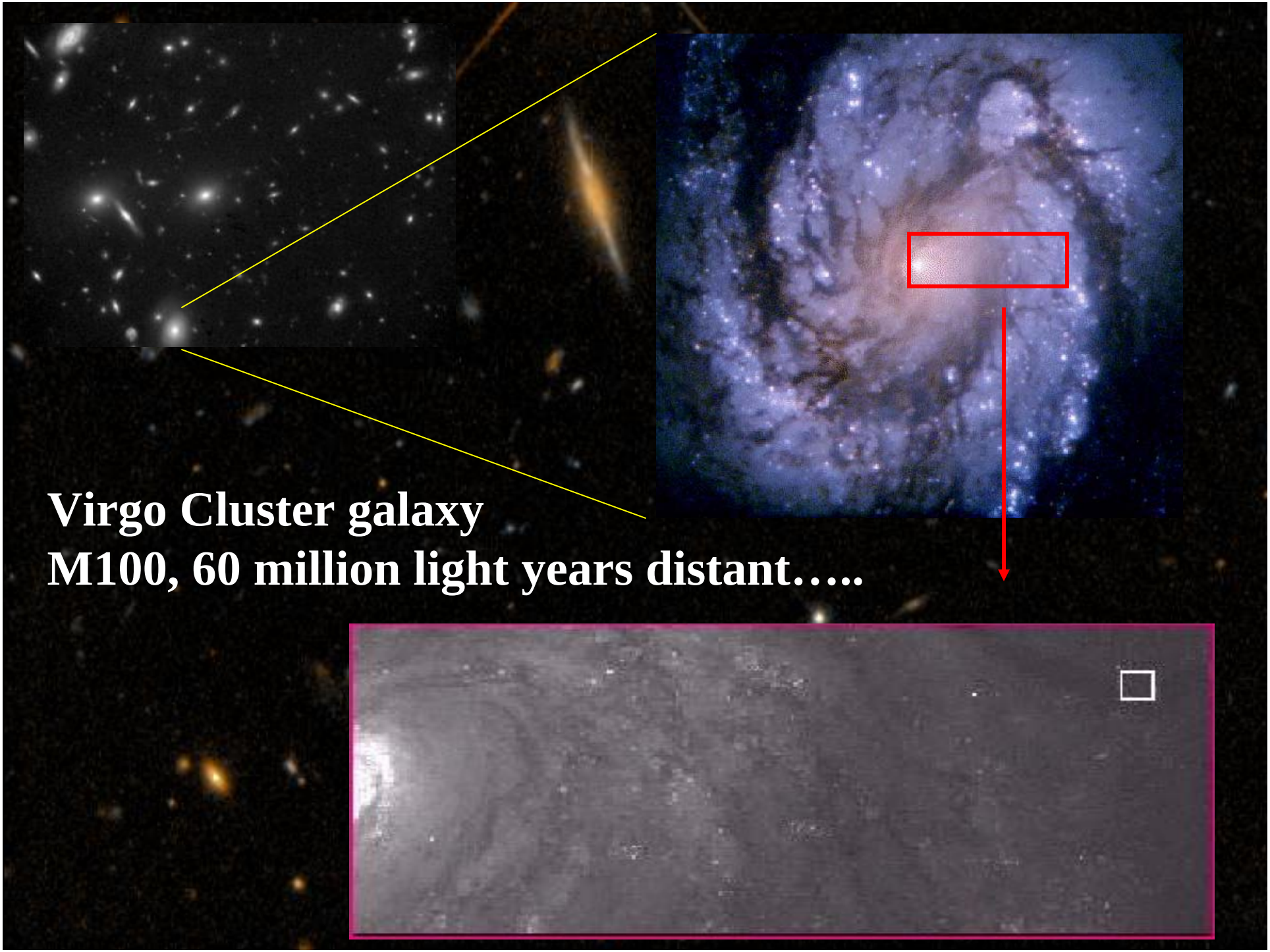

2000's
?
1990's
Dark Energy
1980's
Exotic Dark Matter
1970's
Ordinary Dark Matter
Ordinary Visible Matter

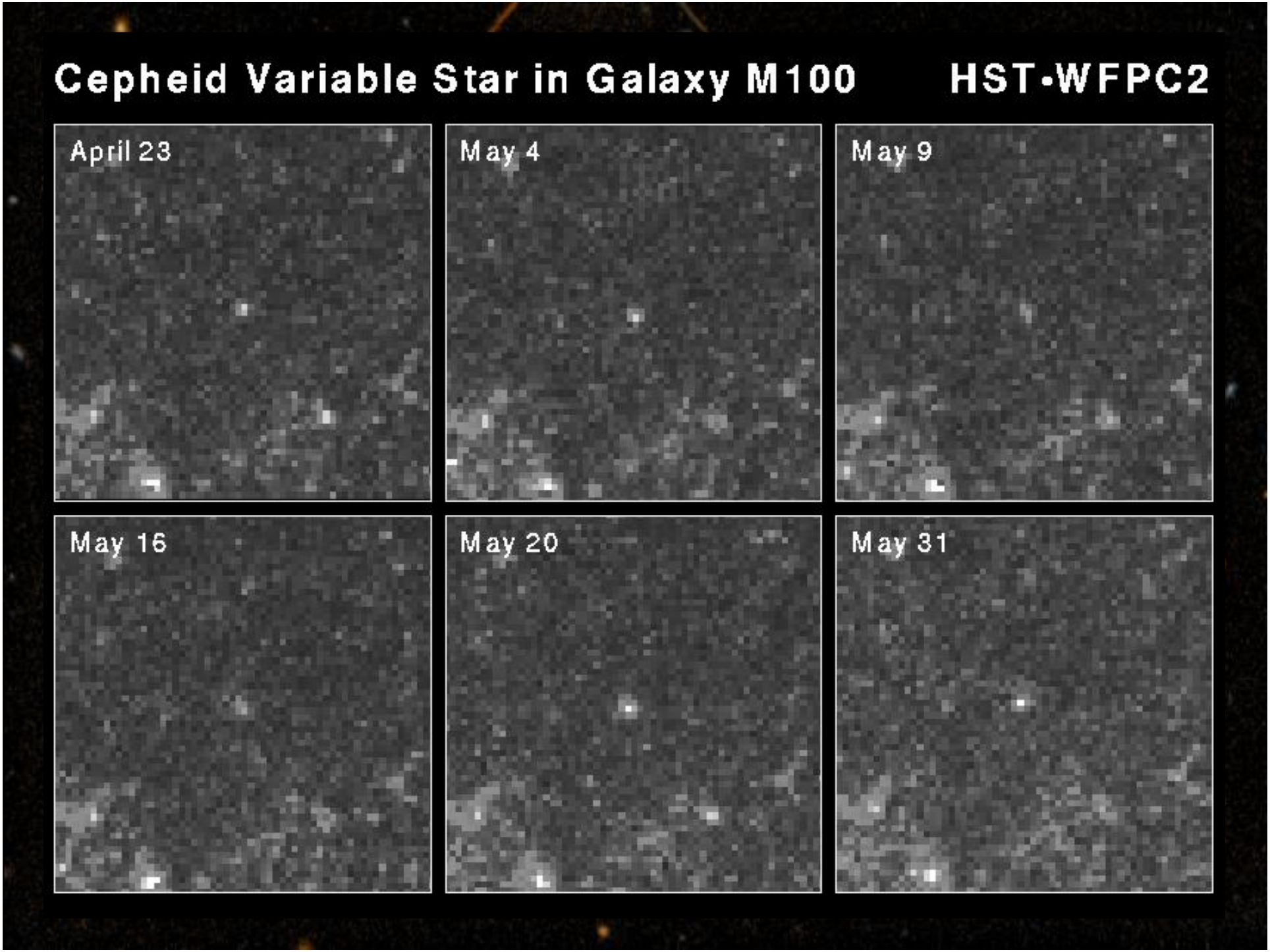
How fast is the Universe expanding?



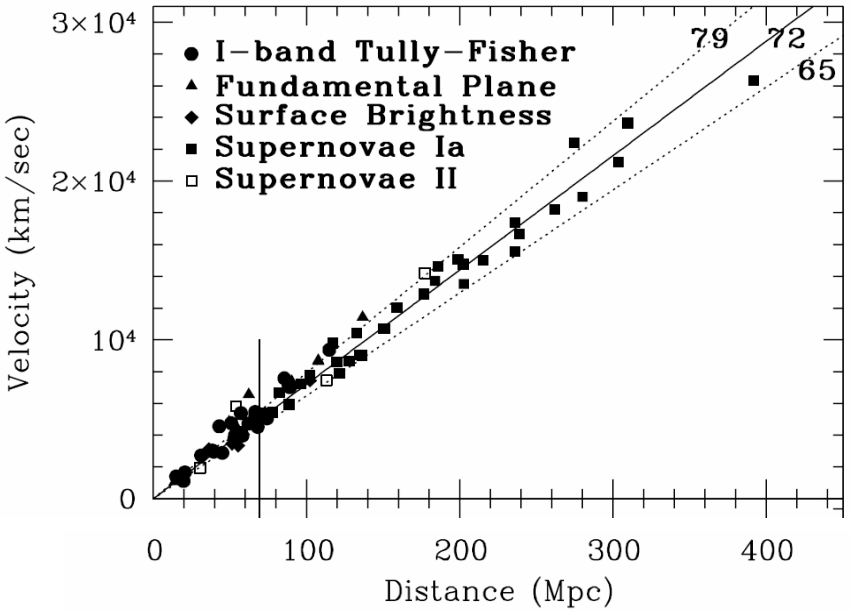
Hubble space Telescope Key Project: 1990-2000

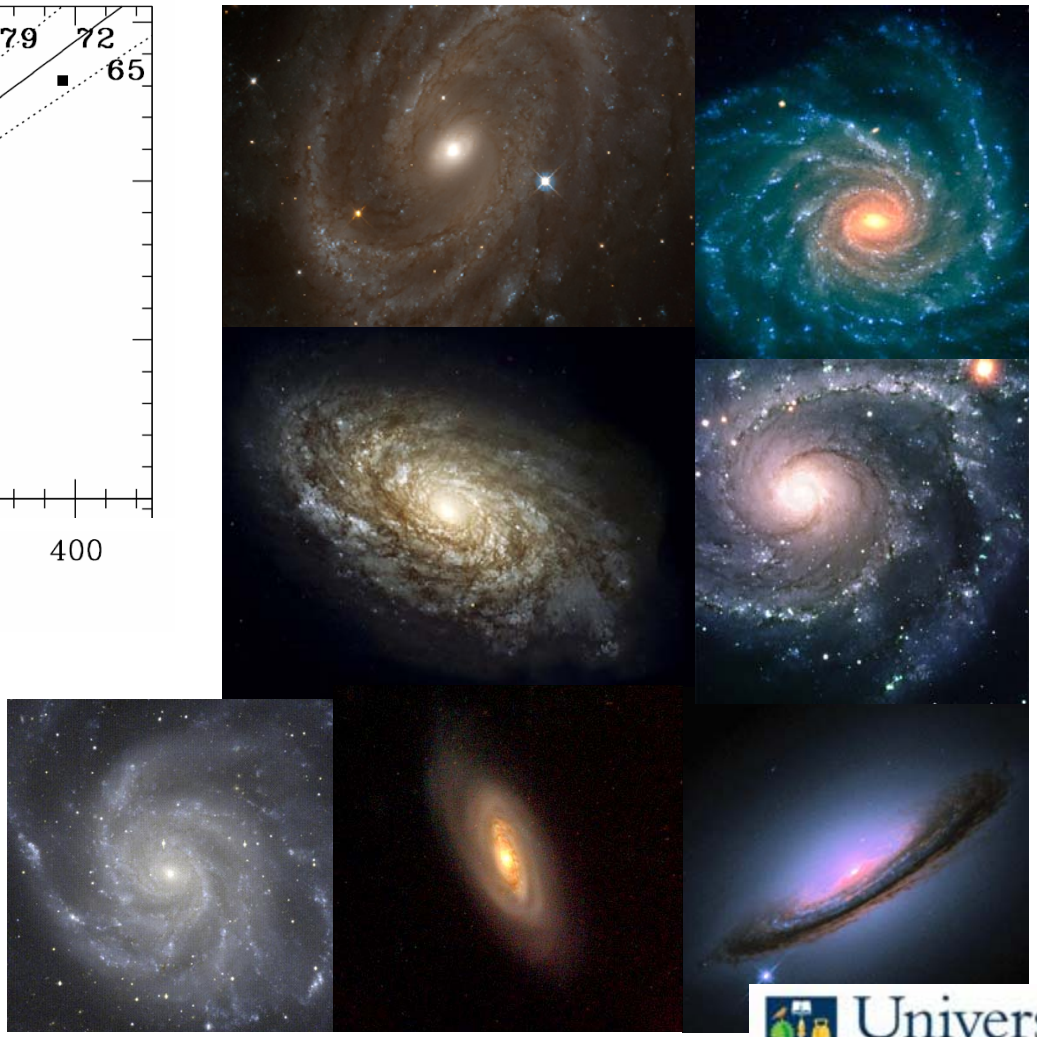
Cepheid distances to ~30 galaxies, linking to other **standard candles**


Virgo Cluster galaxy
M100, 60 million light years distant…..


Cepheid Variable Star in Galaxy M100
HST•WFPC2
April 23
May 4
May 9
May 16
May 20
May 31

How fast is the Universe expanding?



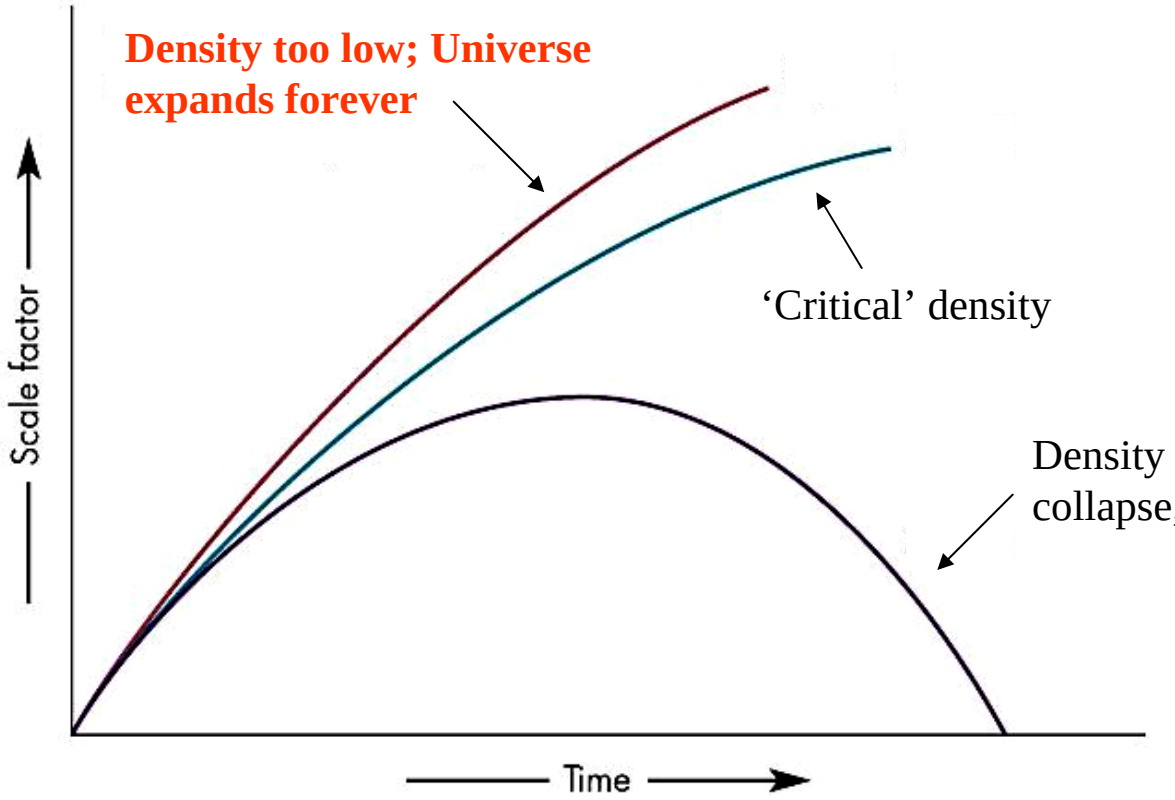


Hubble space Telescope Key Project: 1990-2000

Cepheid distances to ~30 galaxies, linking to other **standard candles**

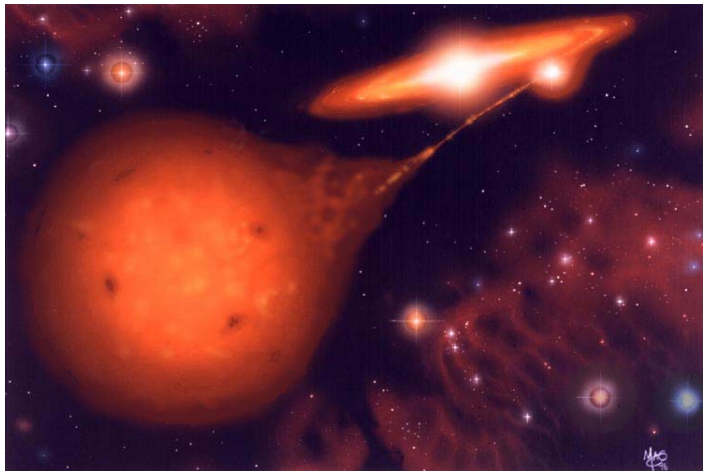
Will the Universe expand forever?

Answer depends on the density of ***matter*** in the Universe.

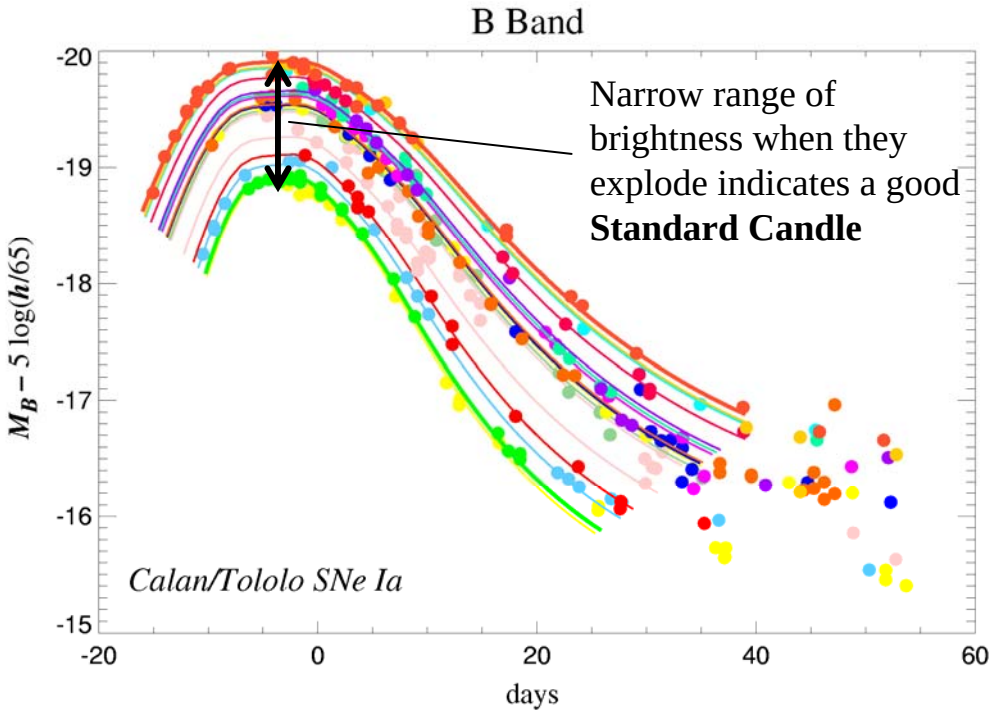


So, *is* the expansion slowing down?

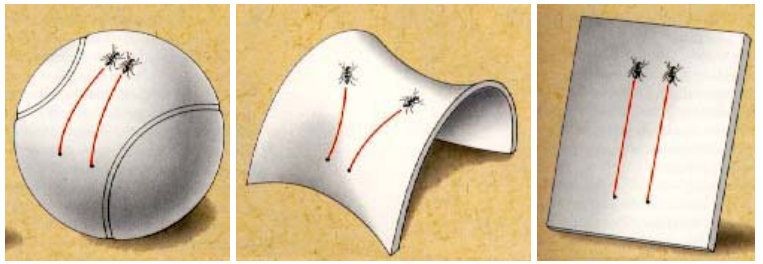
Is the Universe speeding up or slowing down?



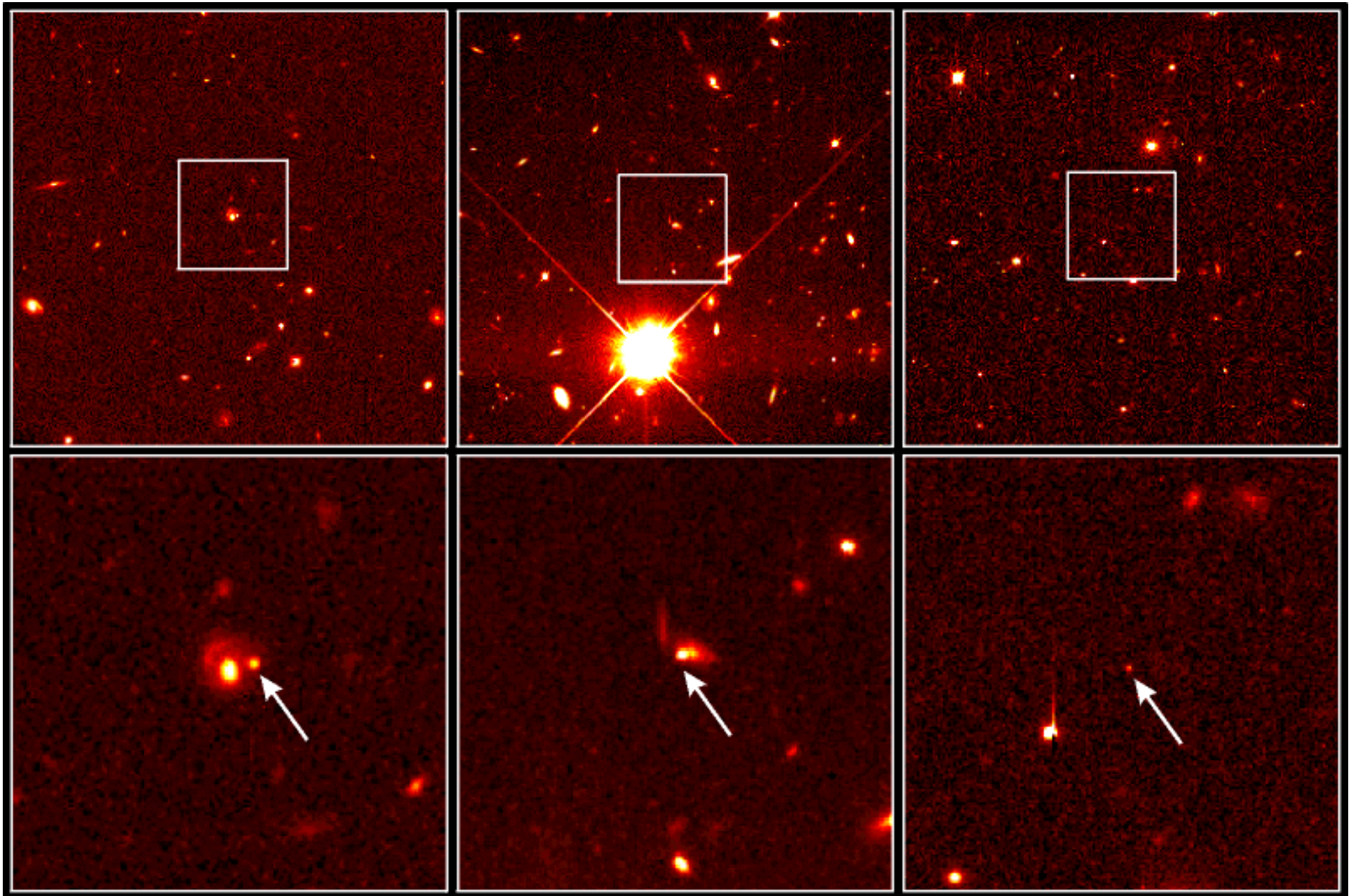
We can answer this question using **type Ia supernovae**



Shape of the universe affects the relationship between redshift and distance of remote supernovae



Closed **Open** **Flat**



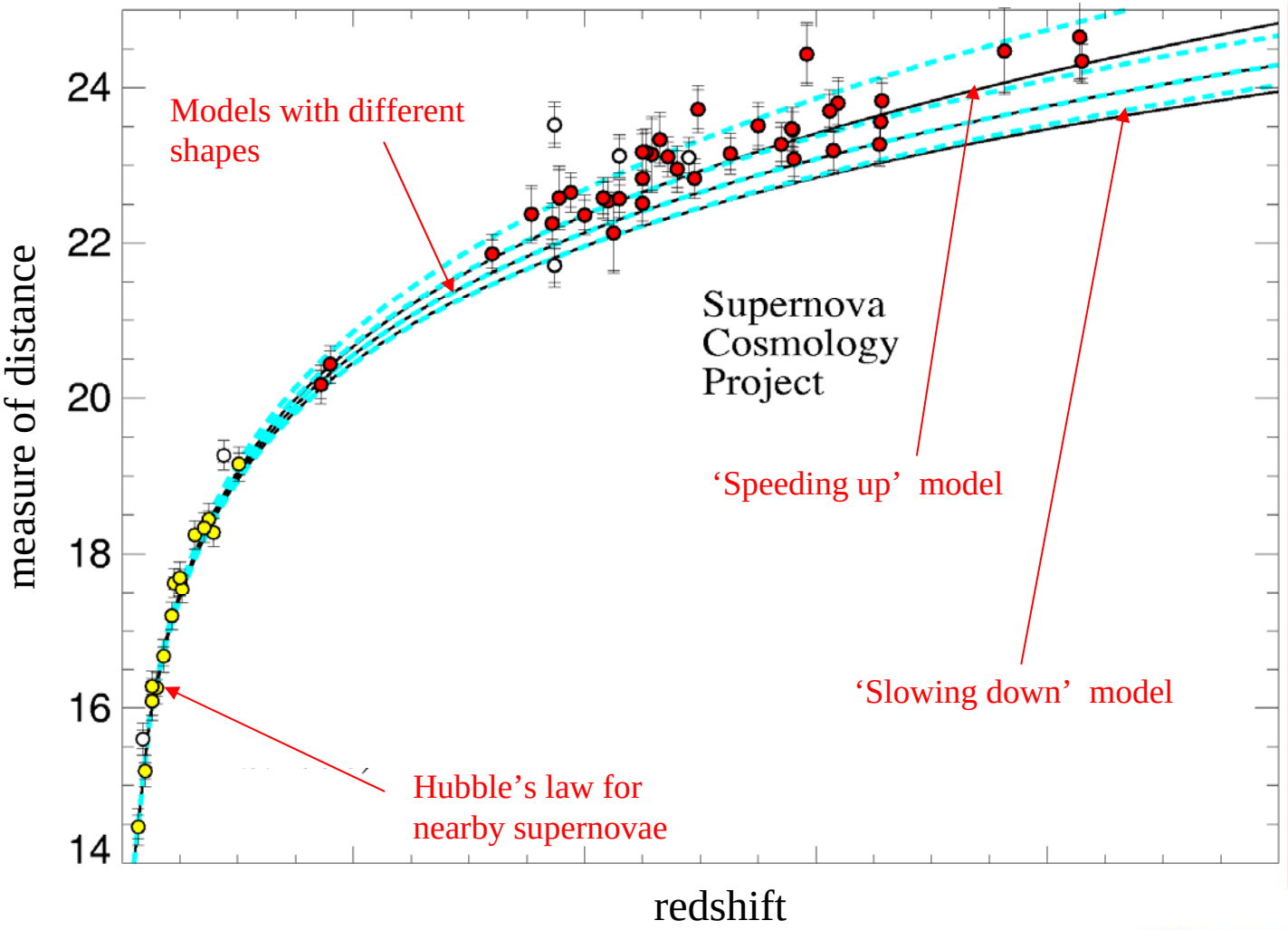
Distant Supernovae

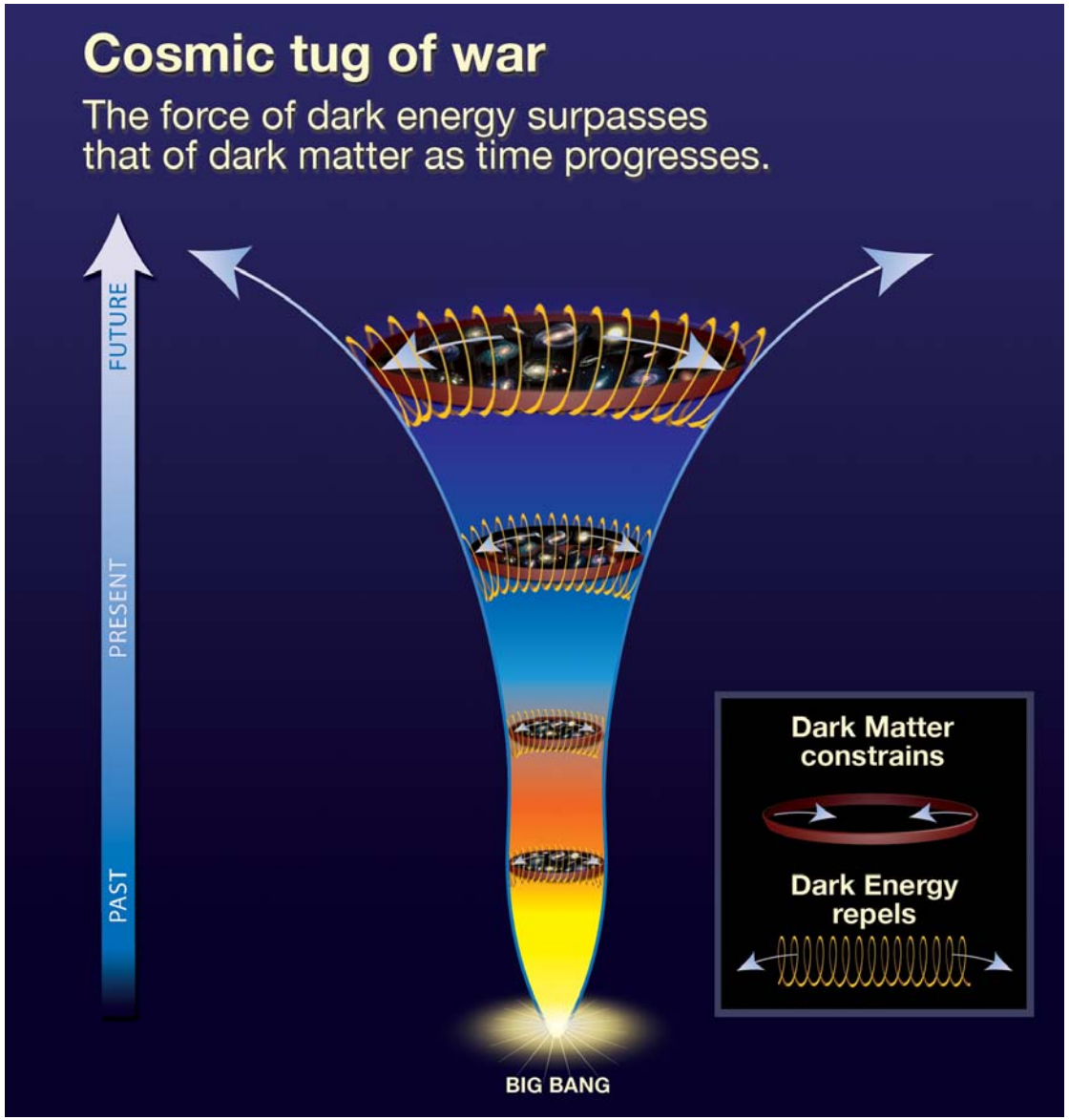
HST • WFPC2

PRC98-02 • January 8, 1998 • ST ScI OPO

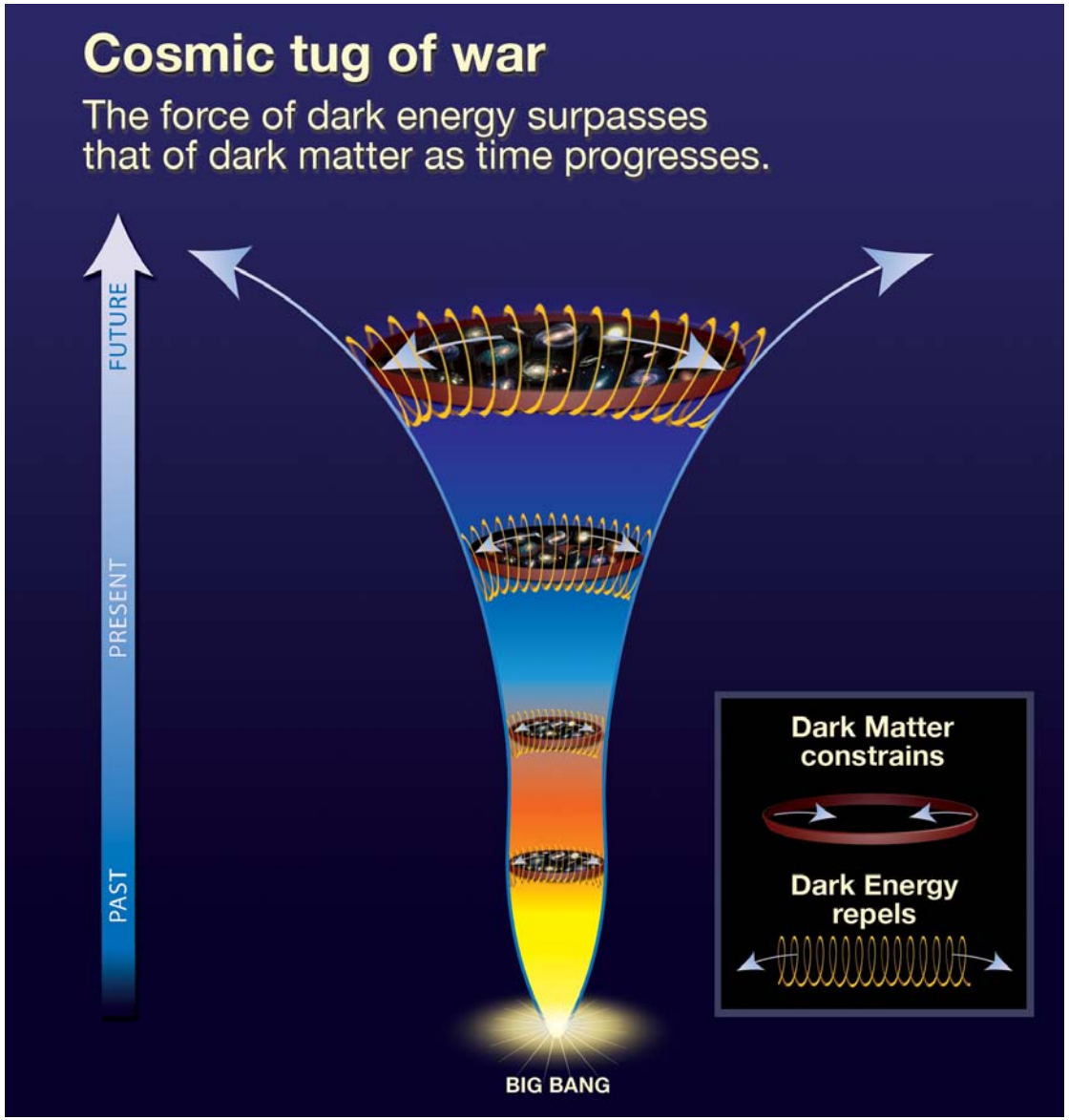
P. Garnavich (Harvard-Smithsonian Center for Astrophysics) and NASA

Hubble diagram of distant supernovae





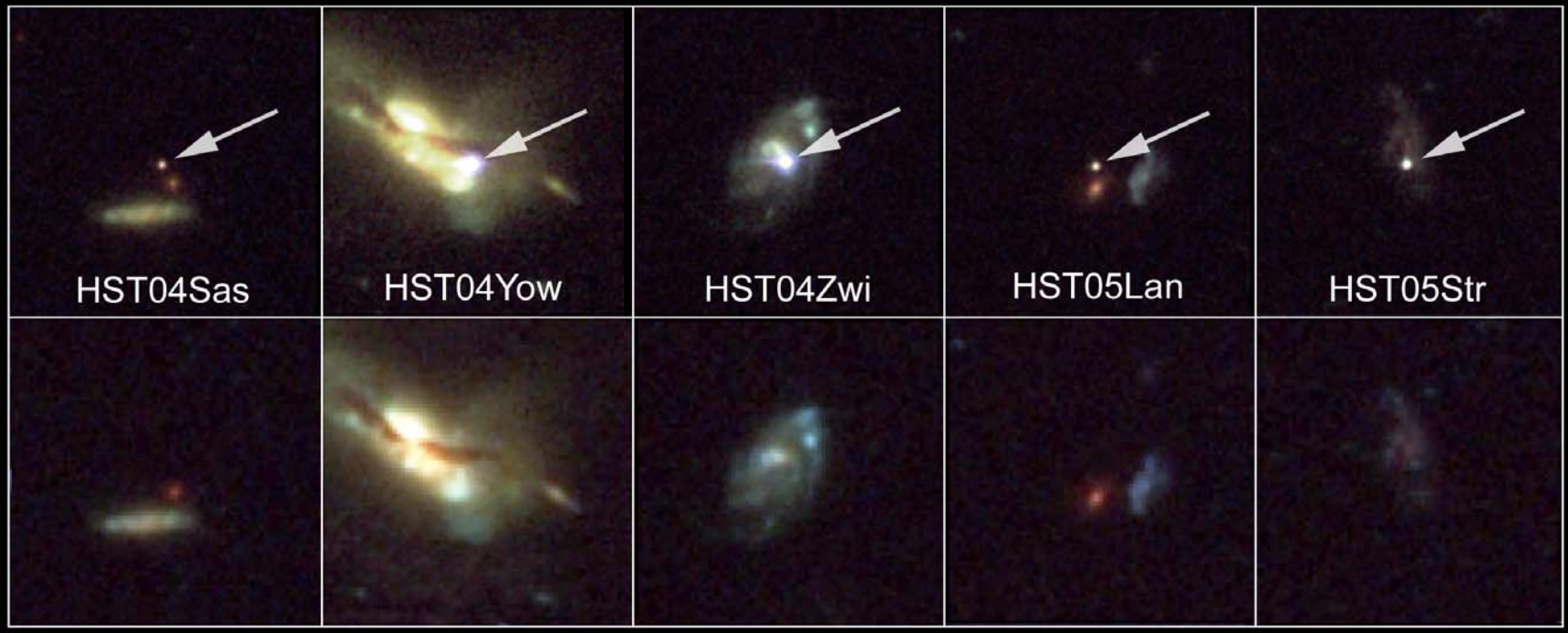
So what exactly *is* this dark energy?...



So what exactly *is* this dark energy?...

Einstein's "cosmological constant"?...

Energy of the quantum vacuum?...



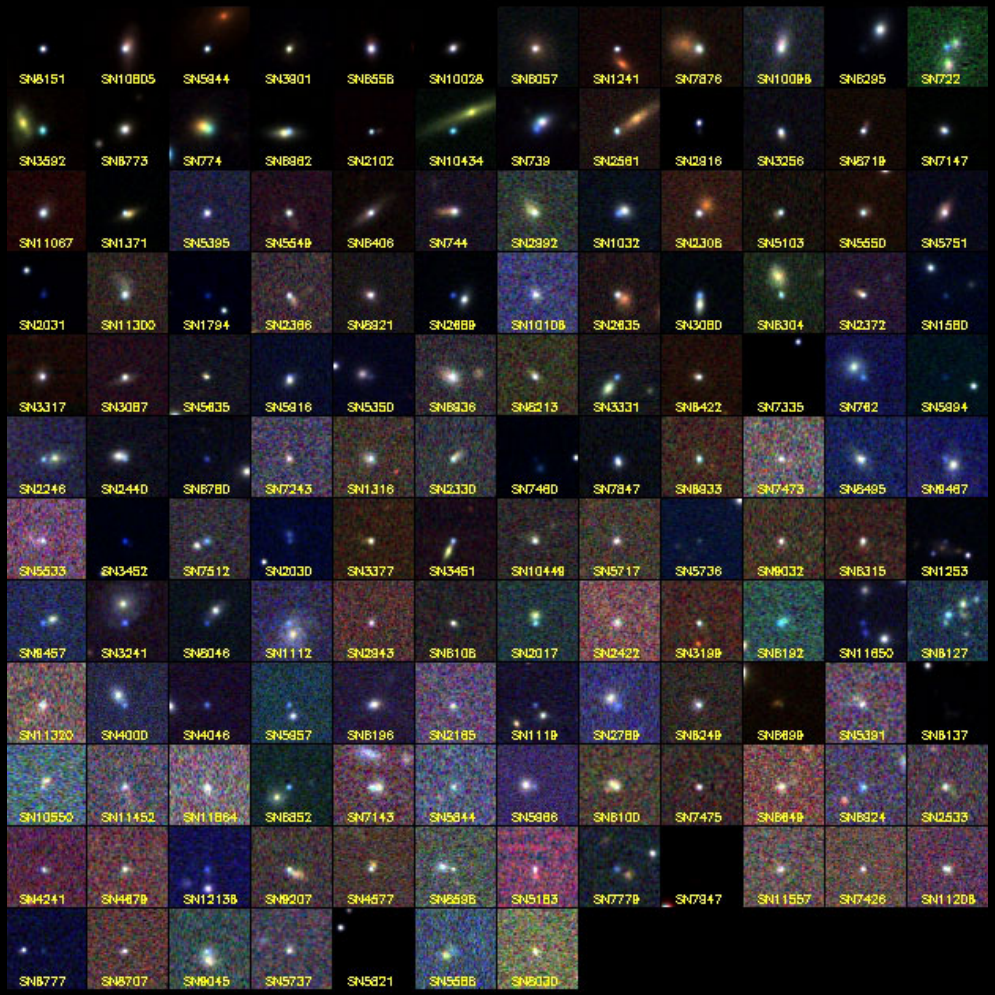
Host Galaxies of Distant Supernovae

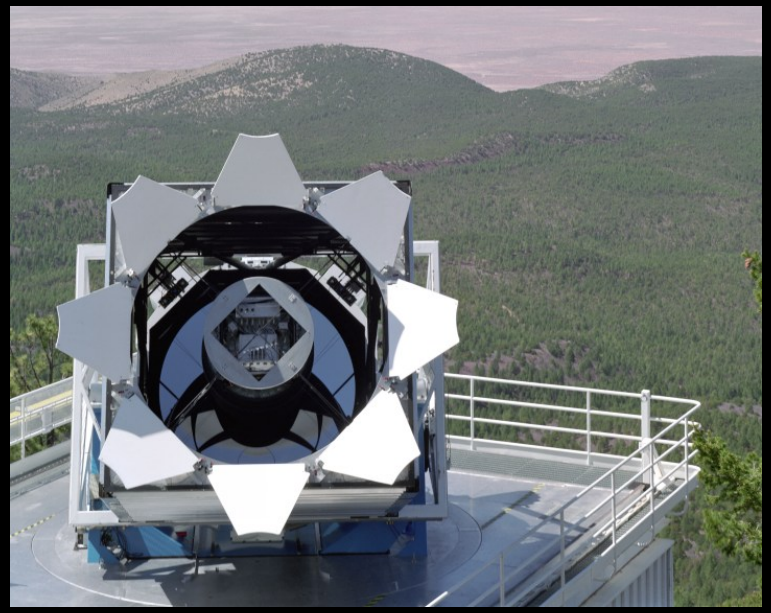
Hubble Space Telescope ▪ Advanced Camera for Surveys

NASA, ESA, and A. Riess (STScI)

STScI-PRC06-52

SDSS II: 139 SN Ia in 2005

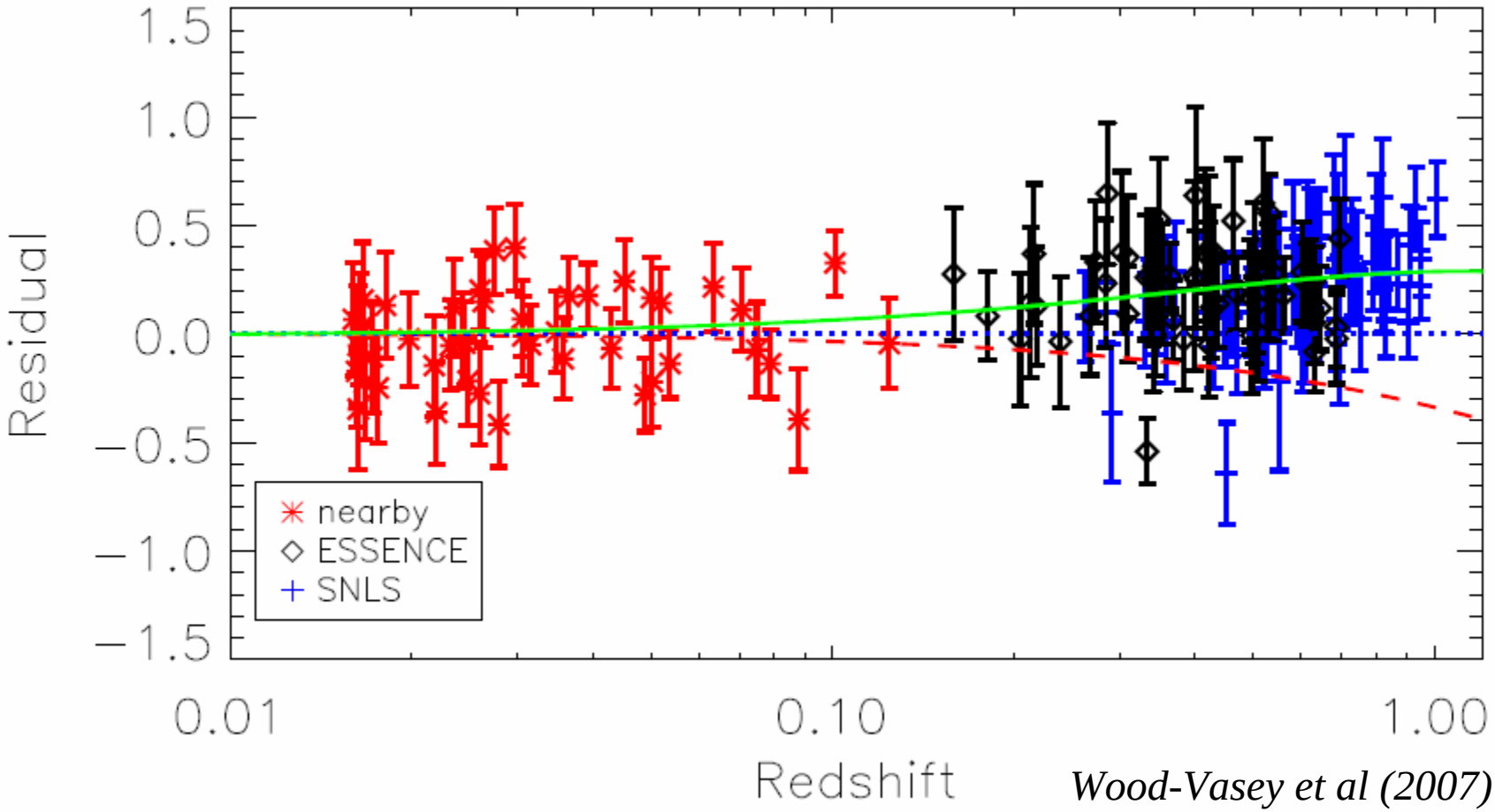




Sloan Digital Sky Survey

Caithness, Sep 2010

Latest results: still speeding up!!!



Wood-Vasey et al (2007)

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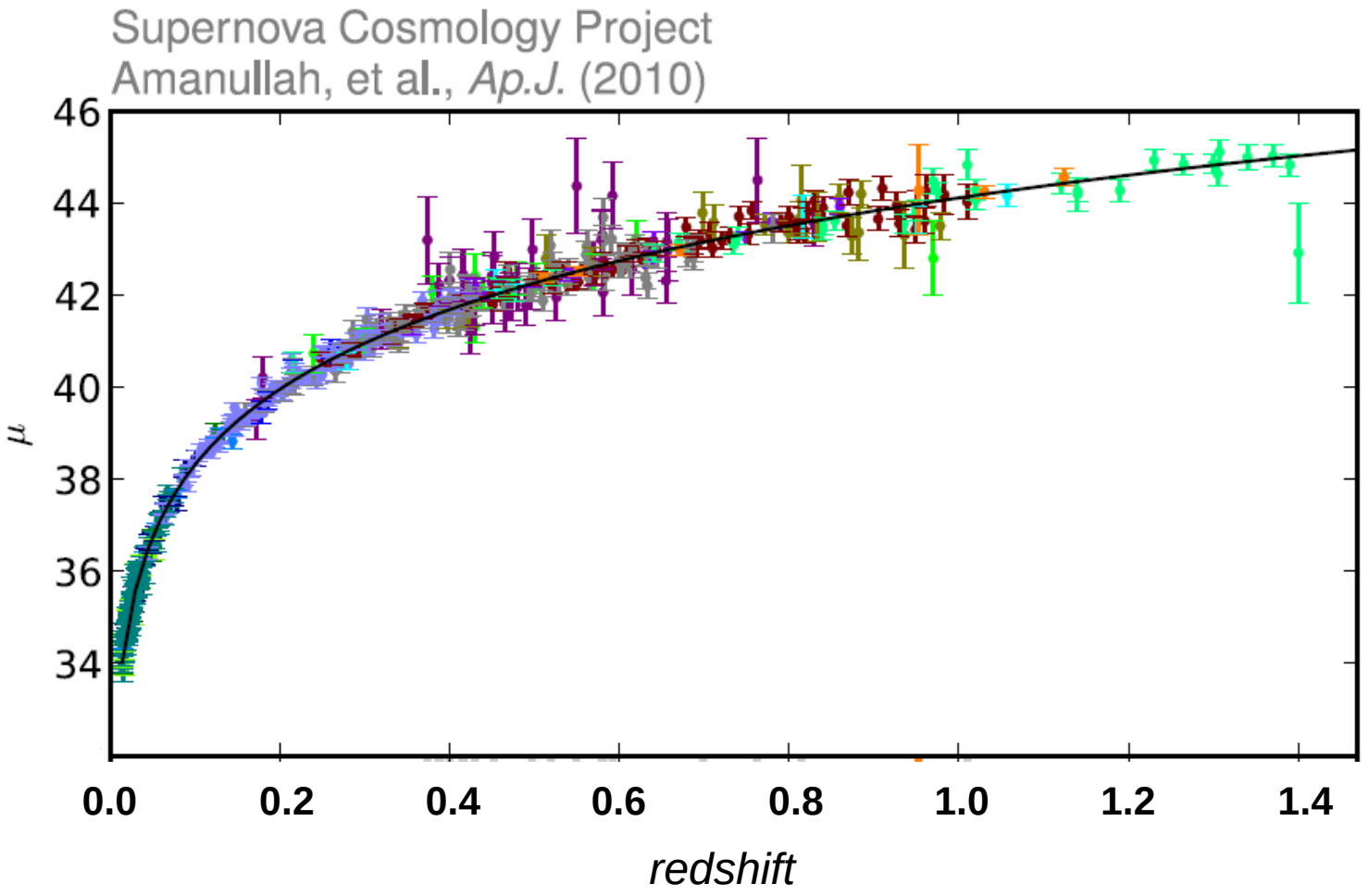


The Background Radiation

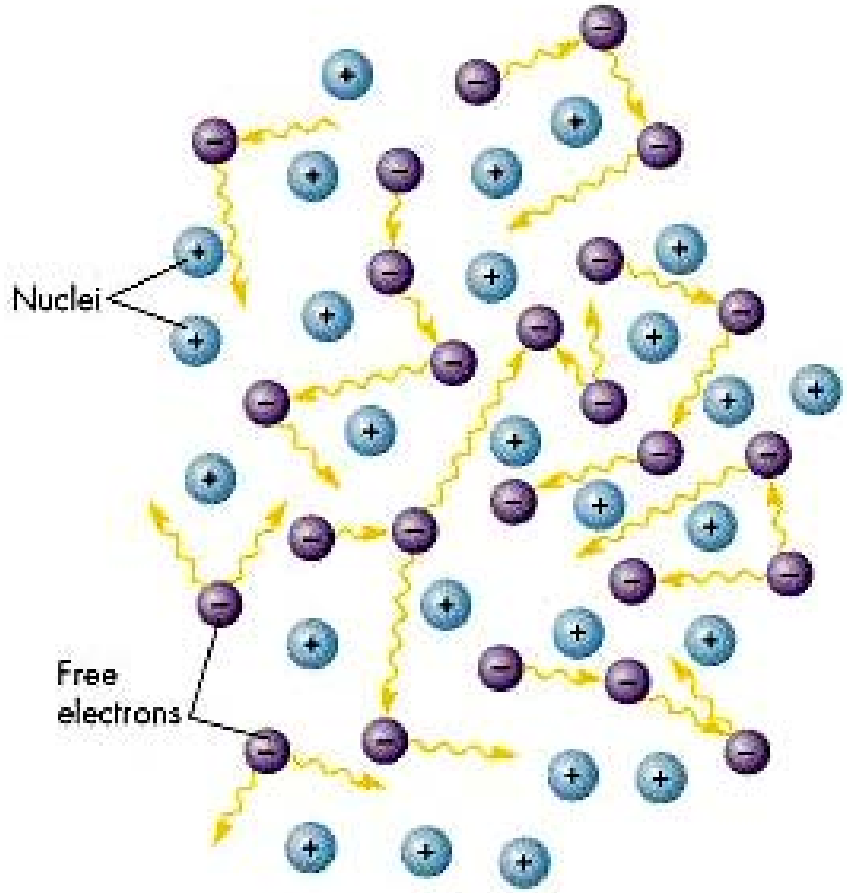
Since 2003, measurements of the **Cosmic Background Radiation** have helped to convince us that the Universe *really is* accelerating, and dominated by dark energy.

CBR = relic radiation from the Big Bang itself.

Appears to us like a 'bank of fog'

Early Universe too hot for neutral atoms to exist

Free electrons scatter light (as in a fog)



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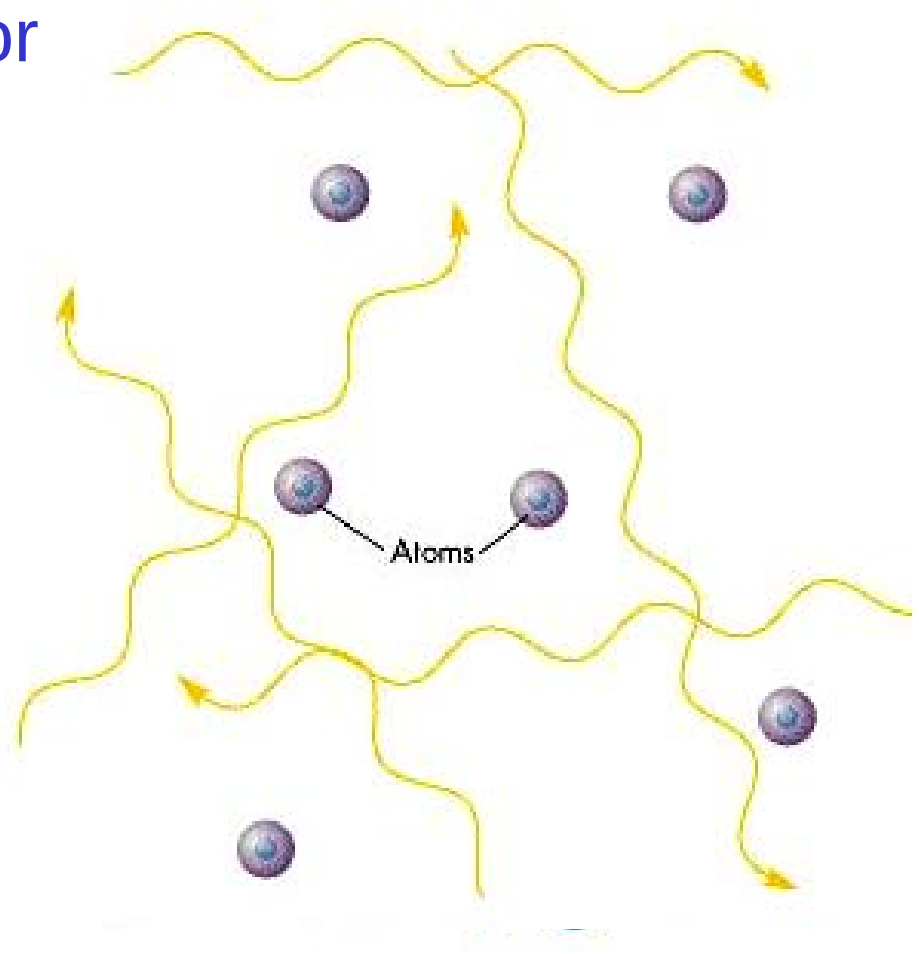
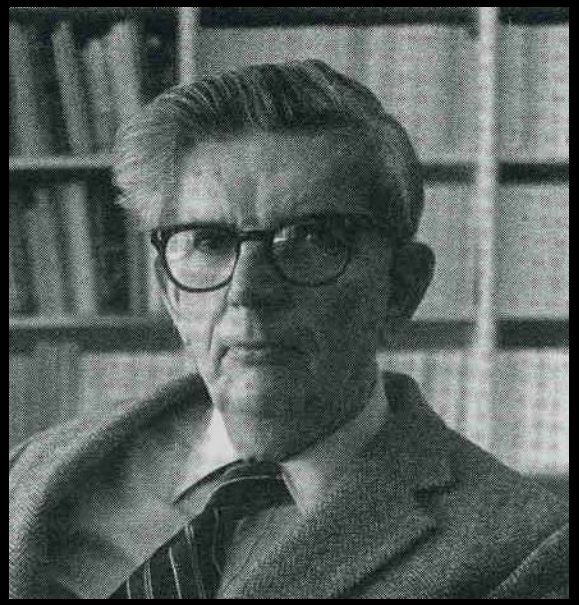


After ~380,000 years, Universe cool enough for neutral hydrogen to form: the fog clears!

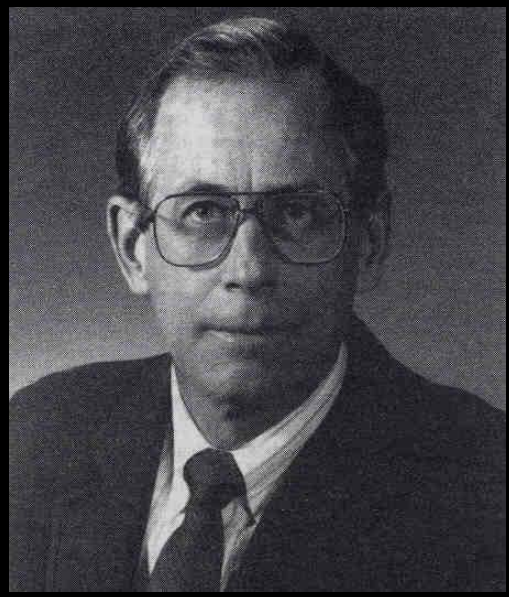
Background radiation predicted in 1950s and 1960s by Gamov, Dicke, Peebles.

Discovered in 1965 by Penzias and Wilson



Robert Dicke

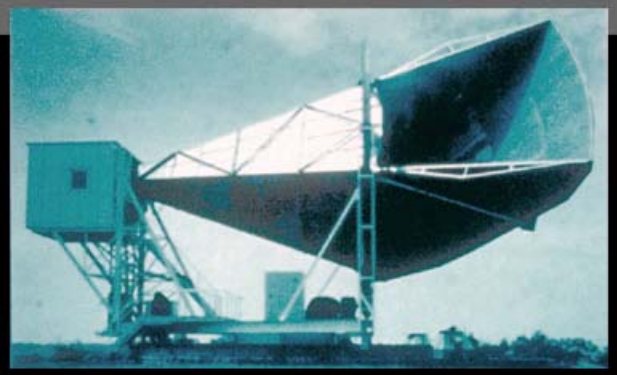
Arno Penzias and Robert Wilson

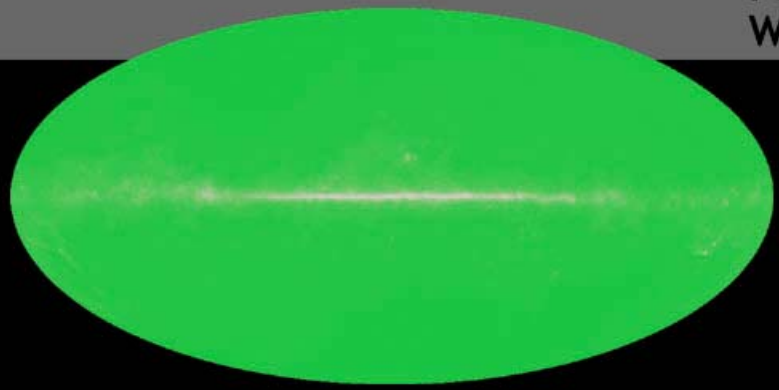


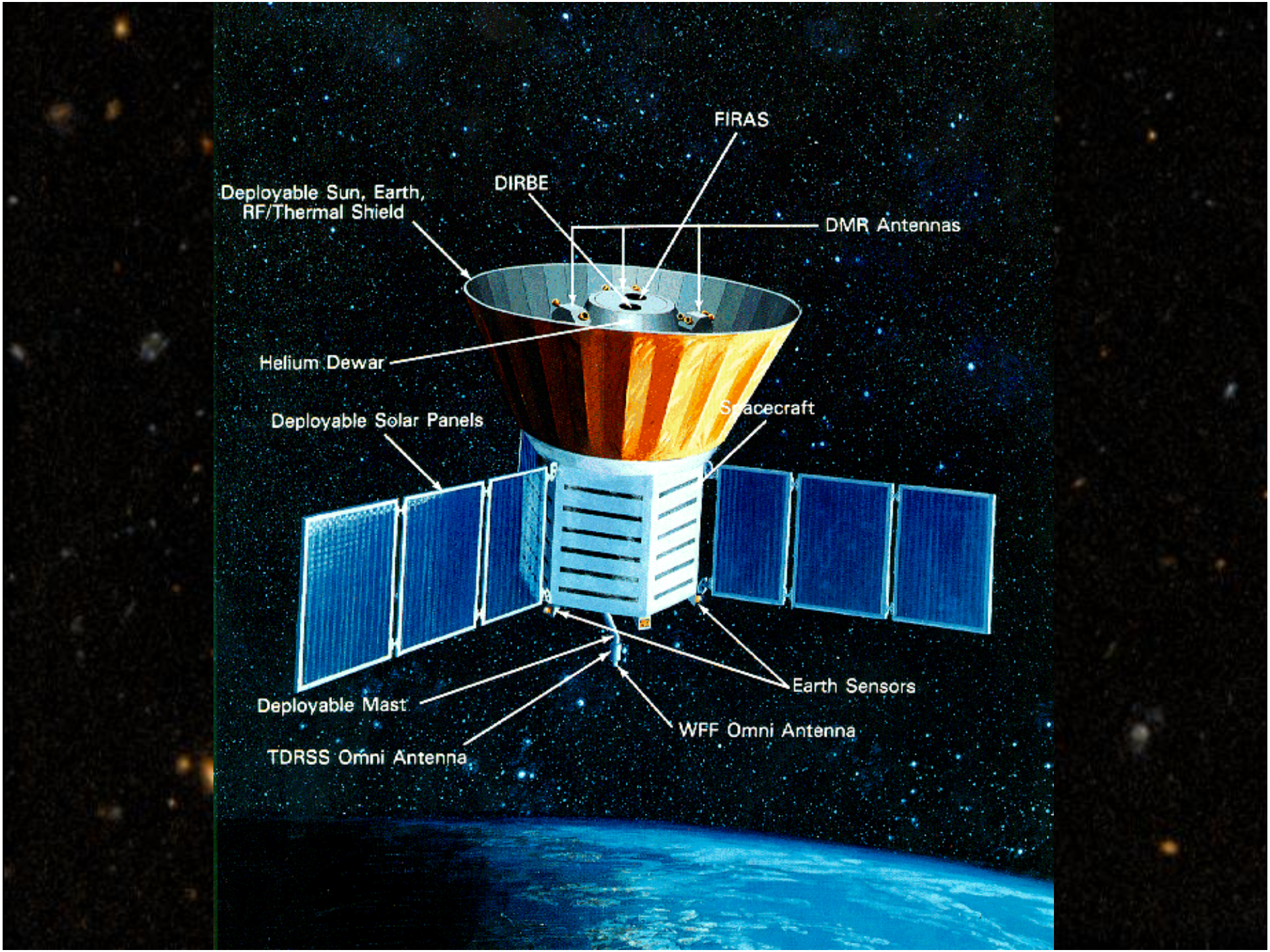
Jim Peebles

1965

Penzias and Wilson

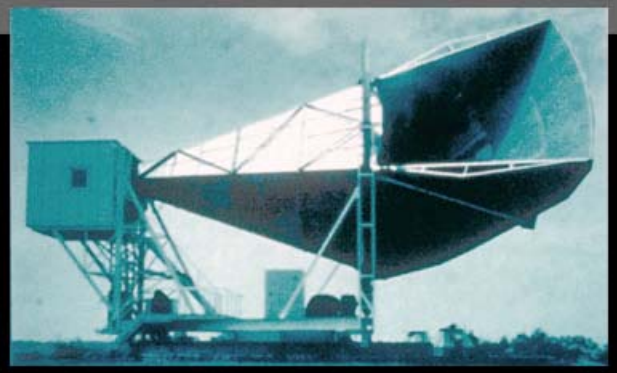


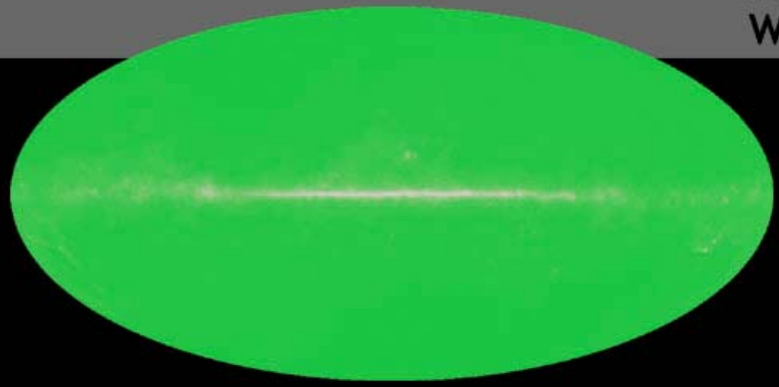



FIRAS
DIRBE
Deployable Sun, Earth,
RF/Thermal Shield
DMR Antennas
Helium Dewar
Deployable Solar Panels
Spacecraft
Earth Sensors
Deployable Mast
WFF Omni Antenna
TDRSS Omni Antenna

1965

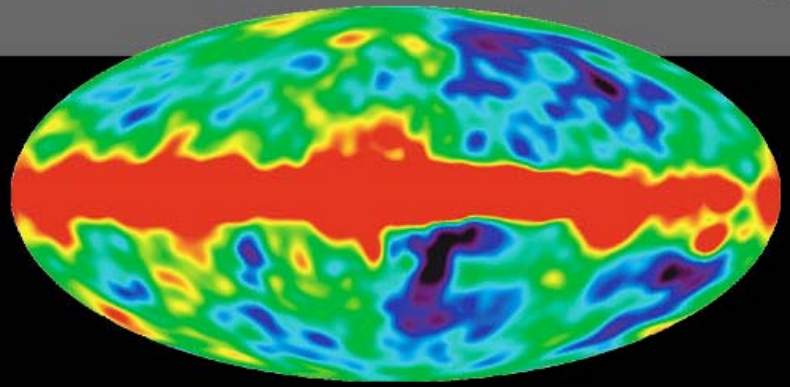
Penzias and Wilson



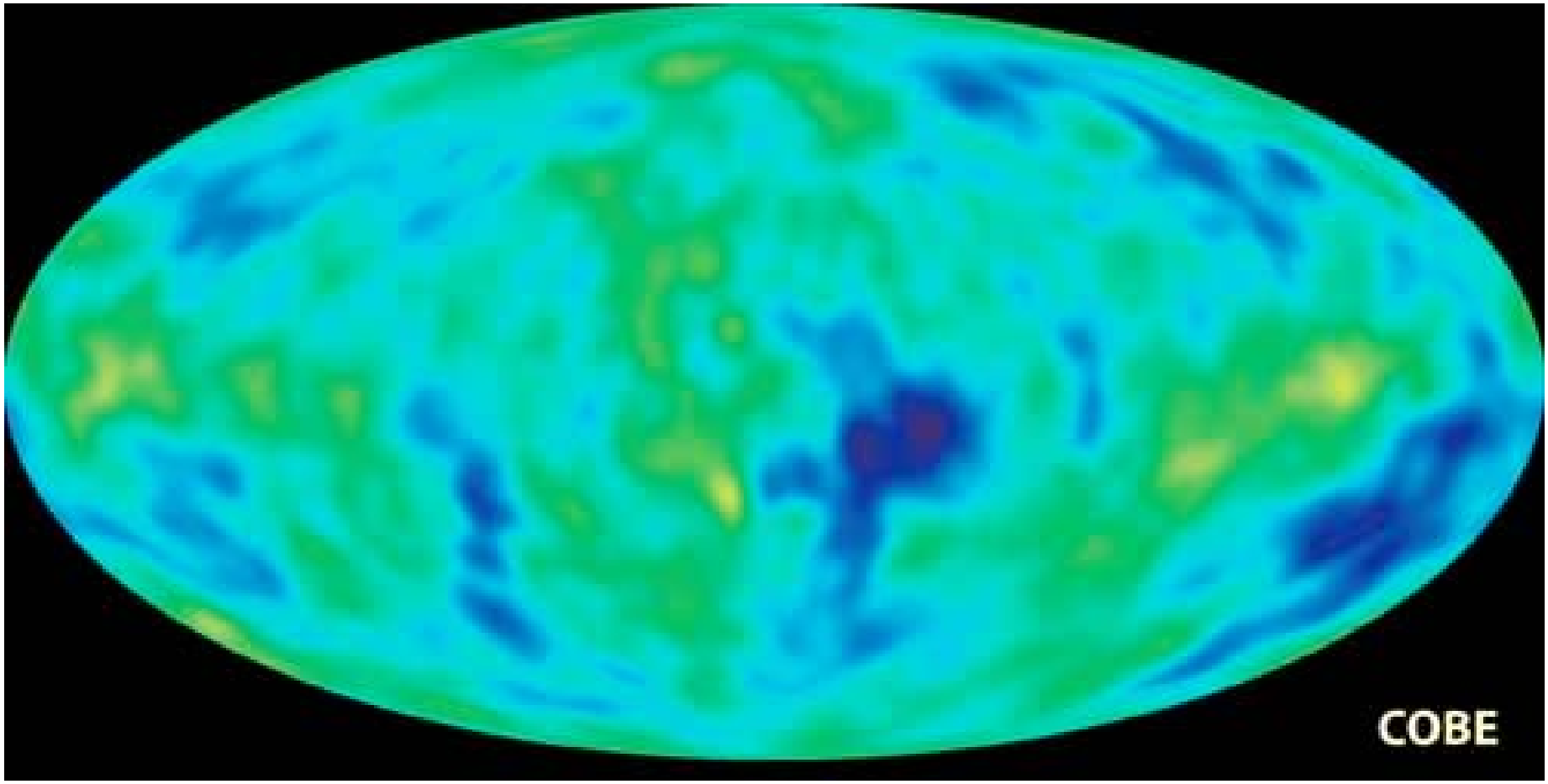


1992

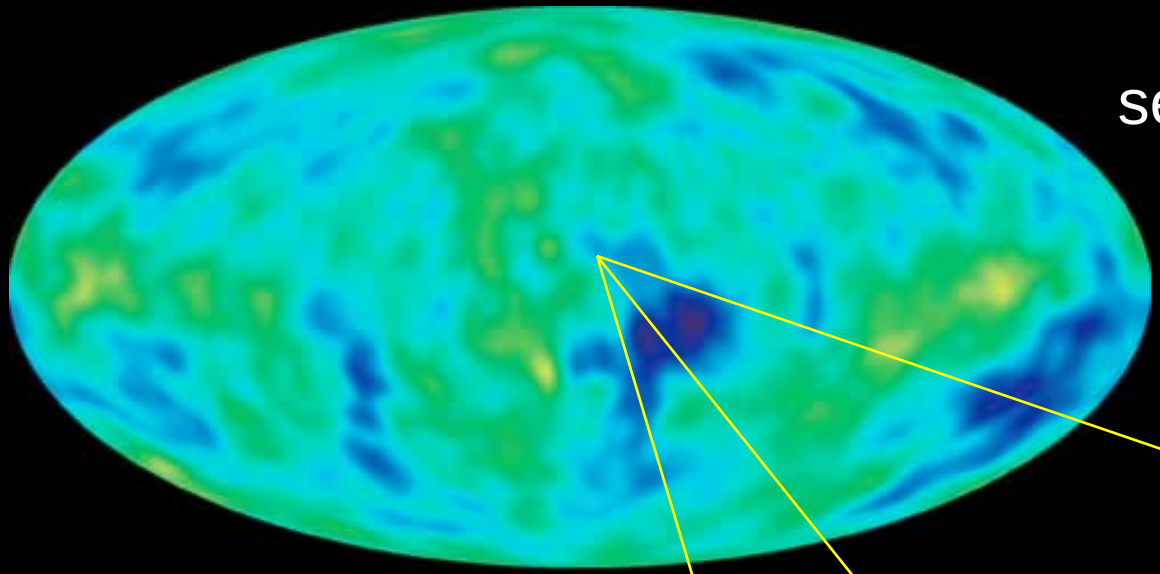
COBE

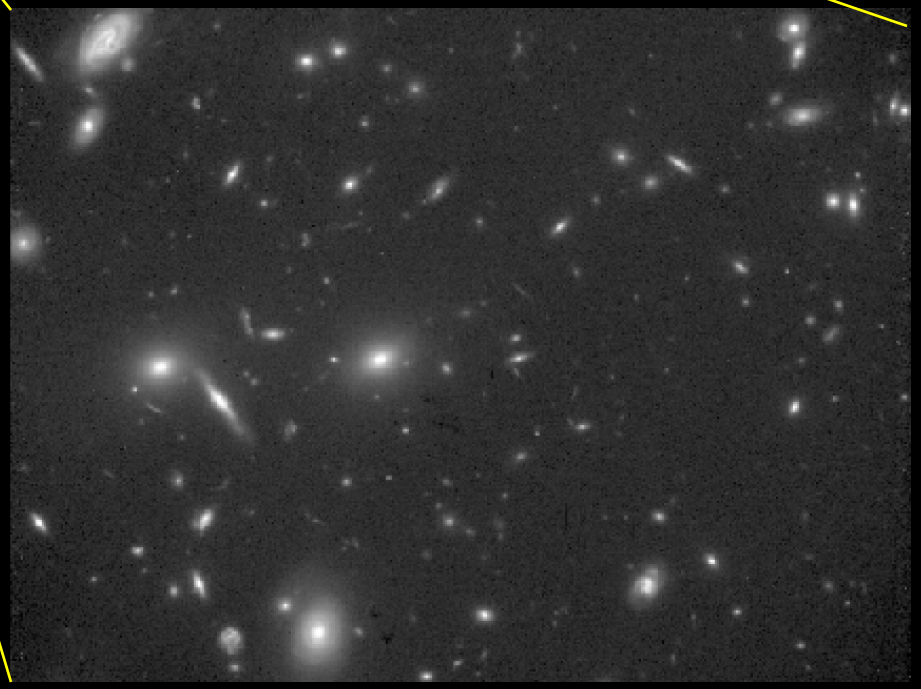


COBE map of temperature across the sky

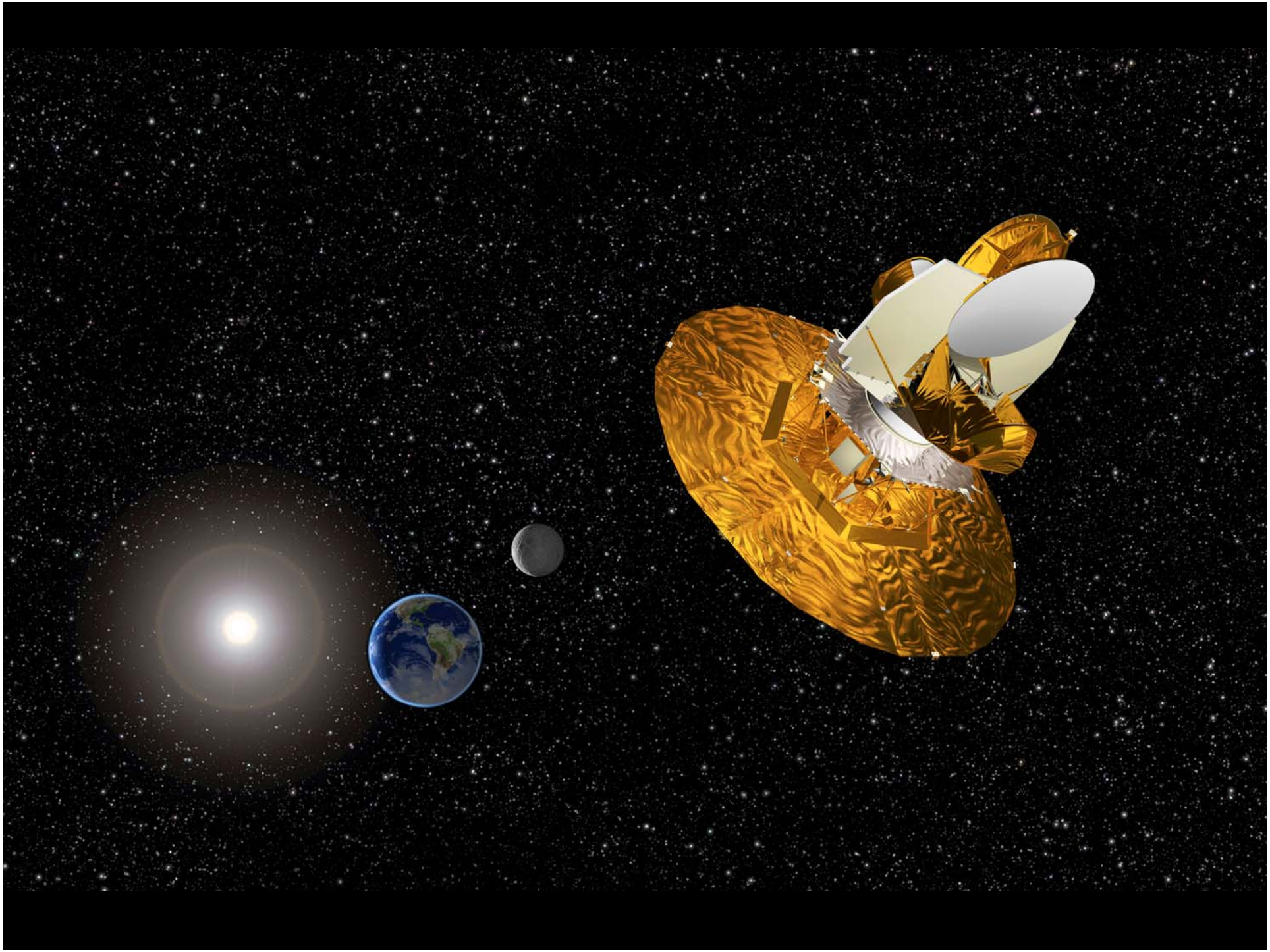


CBR ‘ripples’ are the seeds of today’s galaxies



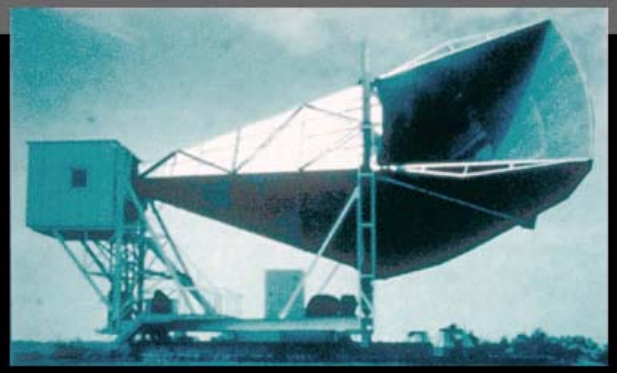


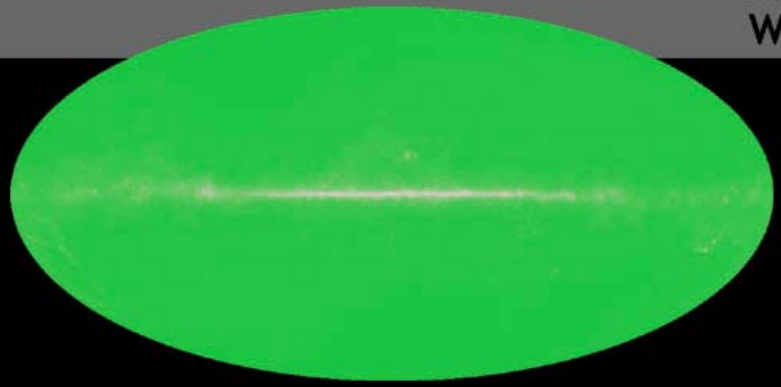
Galaxy formation is highly sensitive to the pattern, or power spectrum, of CBR temperature ripples



1965

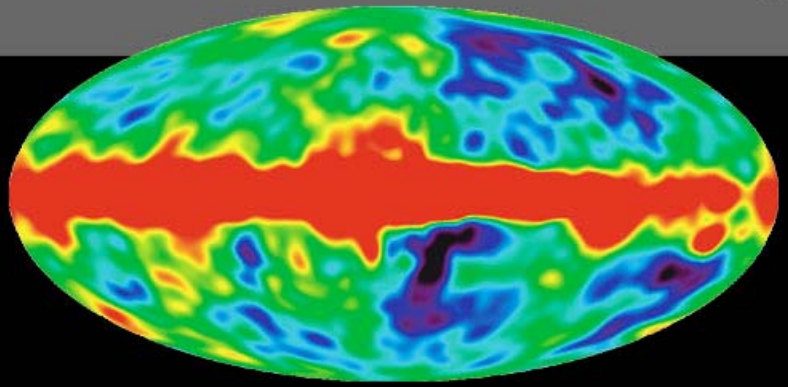
Penzias and Wilson





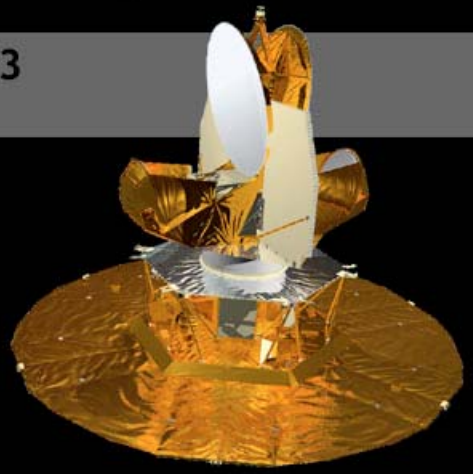
1992

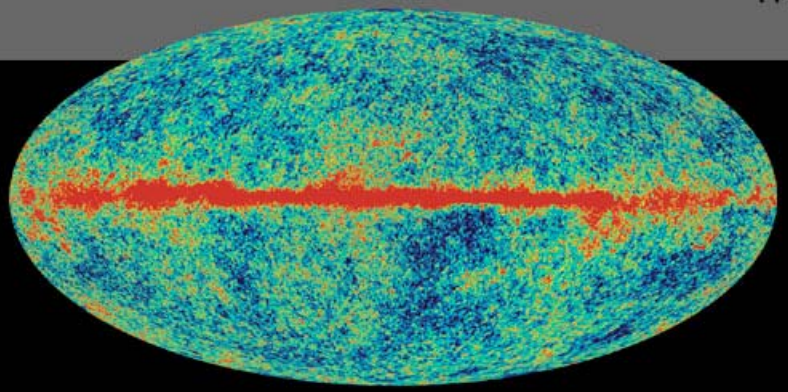
COBE



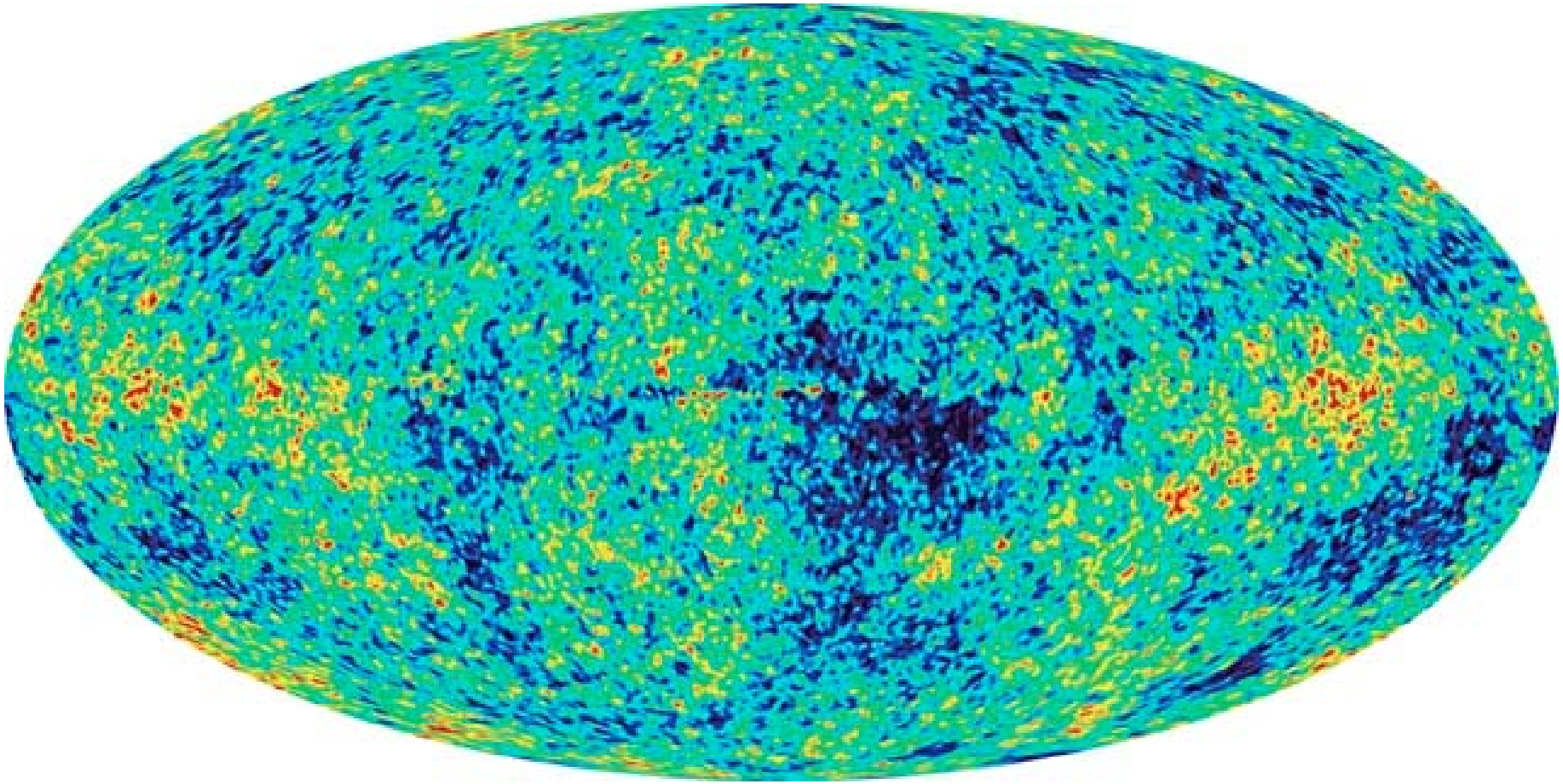
2003

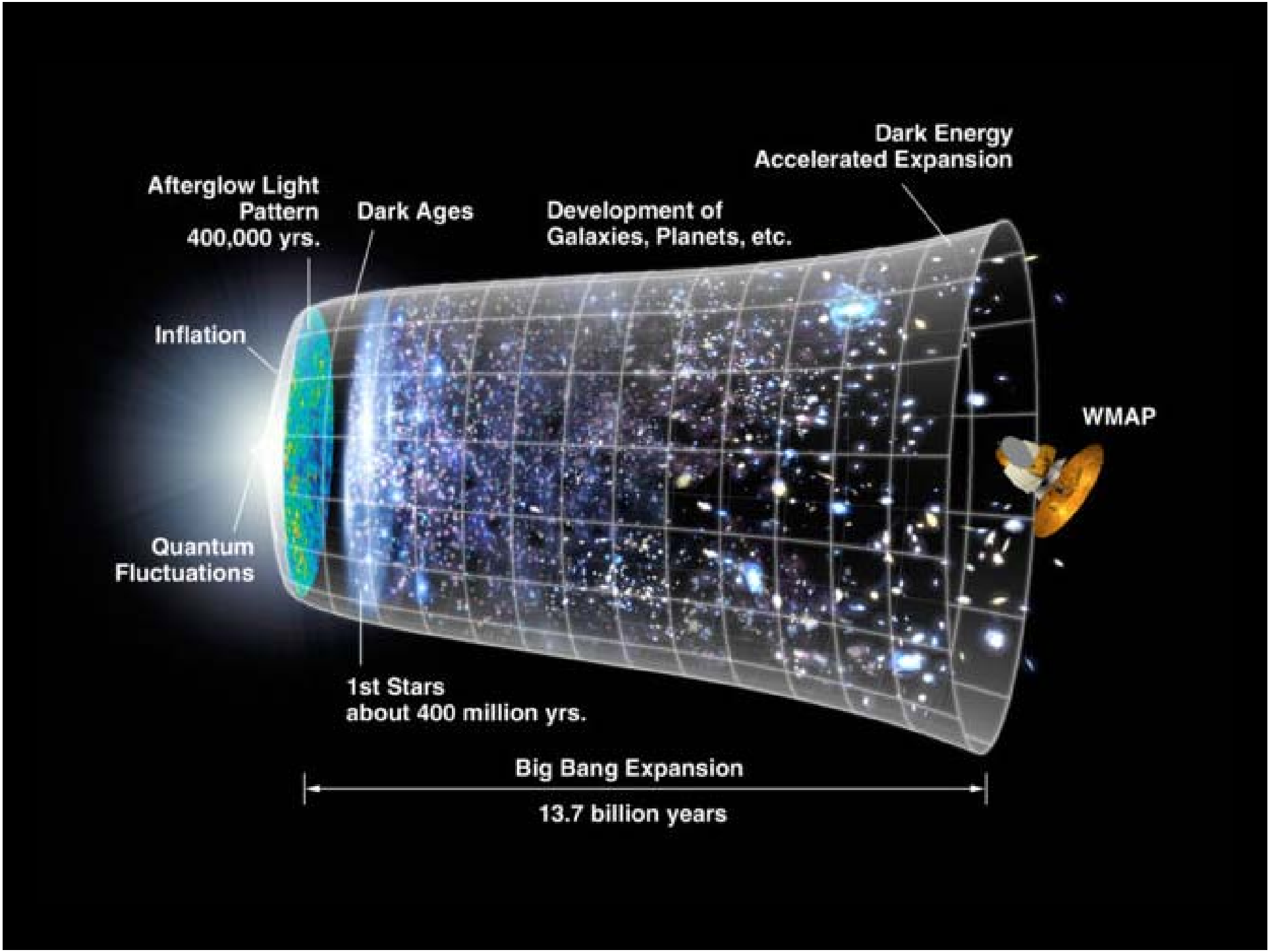
WMAP



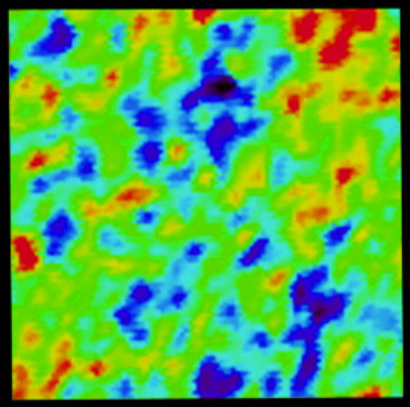


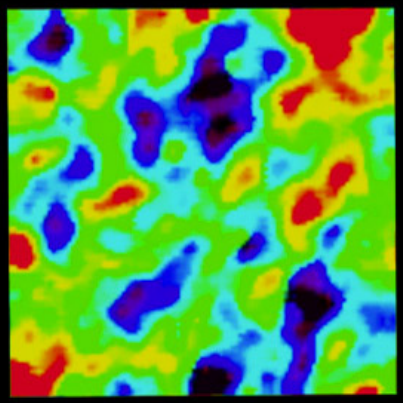
WMAP map of temperature across the sky

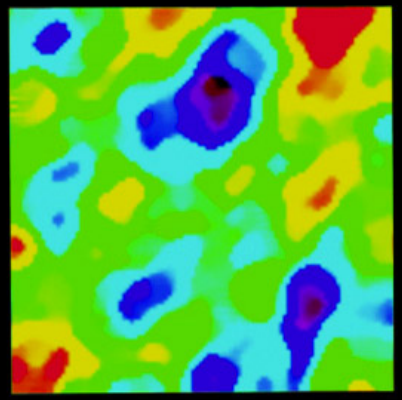


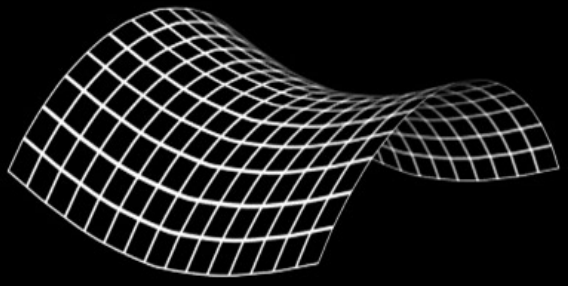

Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
400,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
WMAP
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.7 billion years

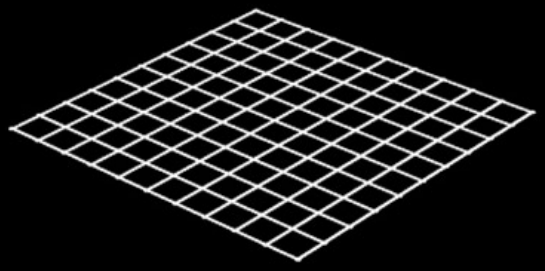
GEOMETRY OF THE UNIVERSE

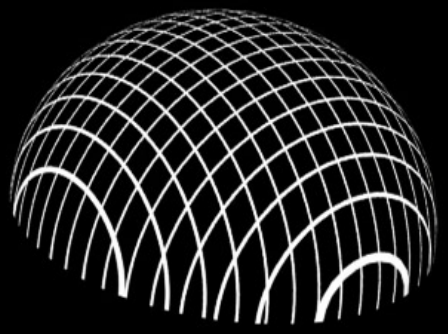








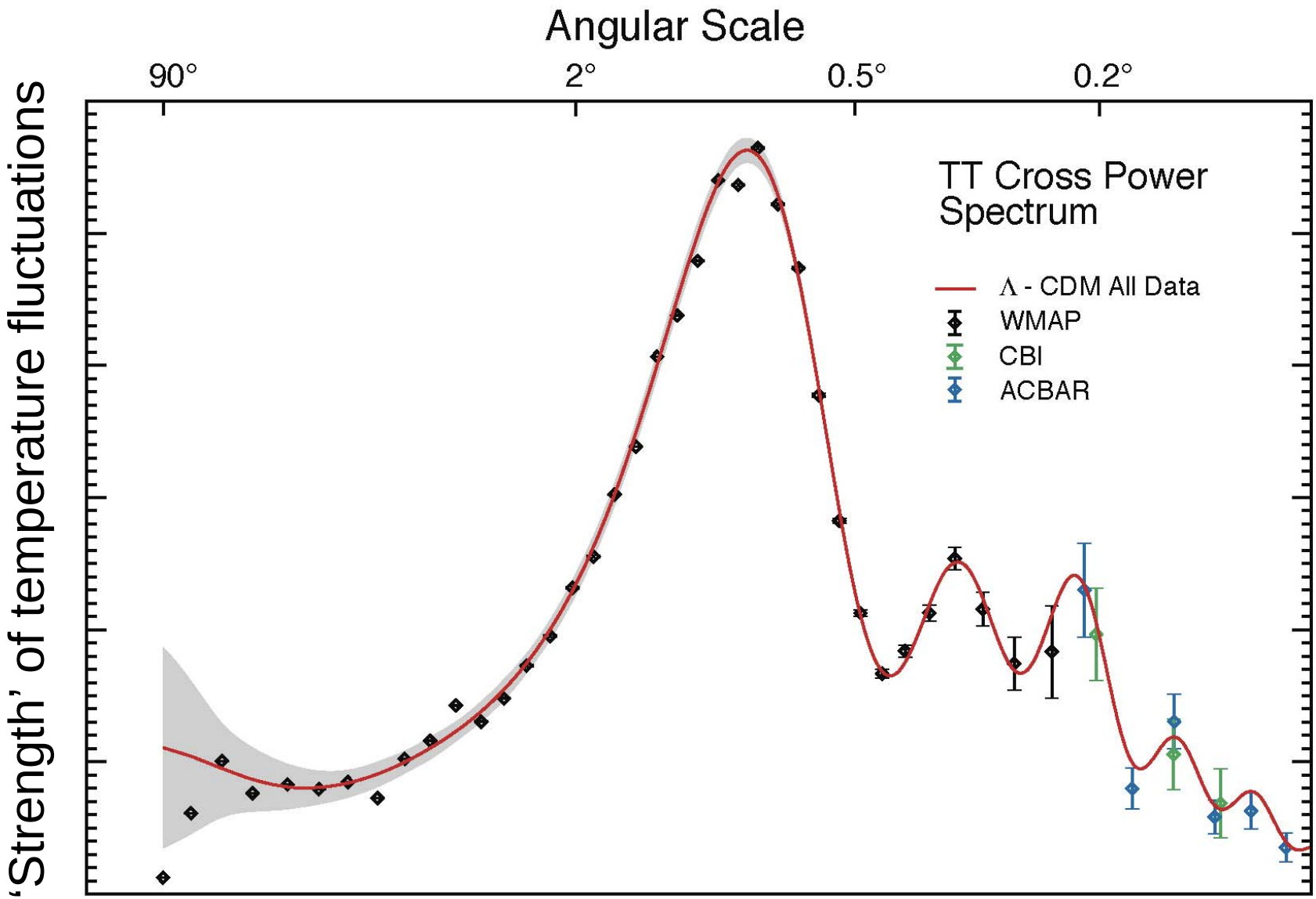


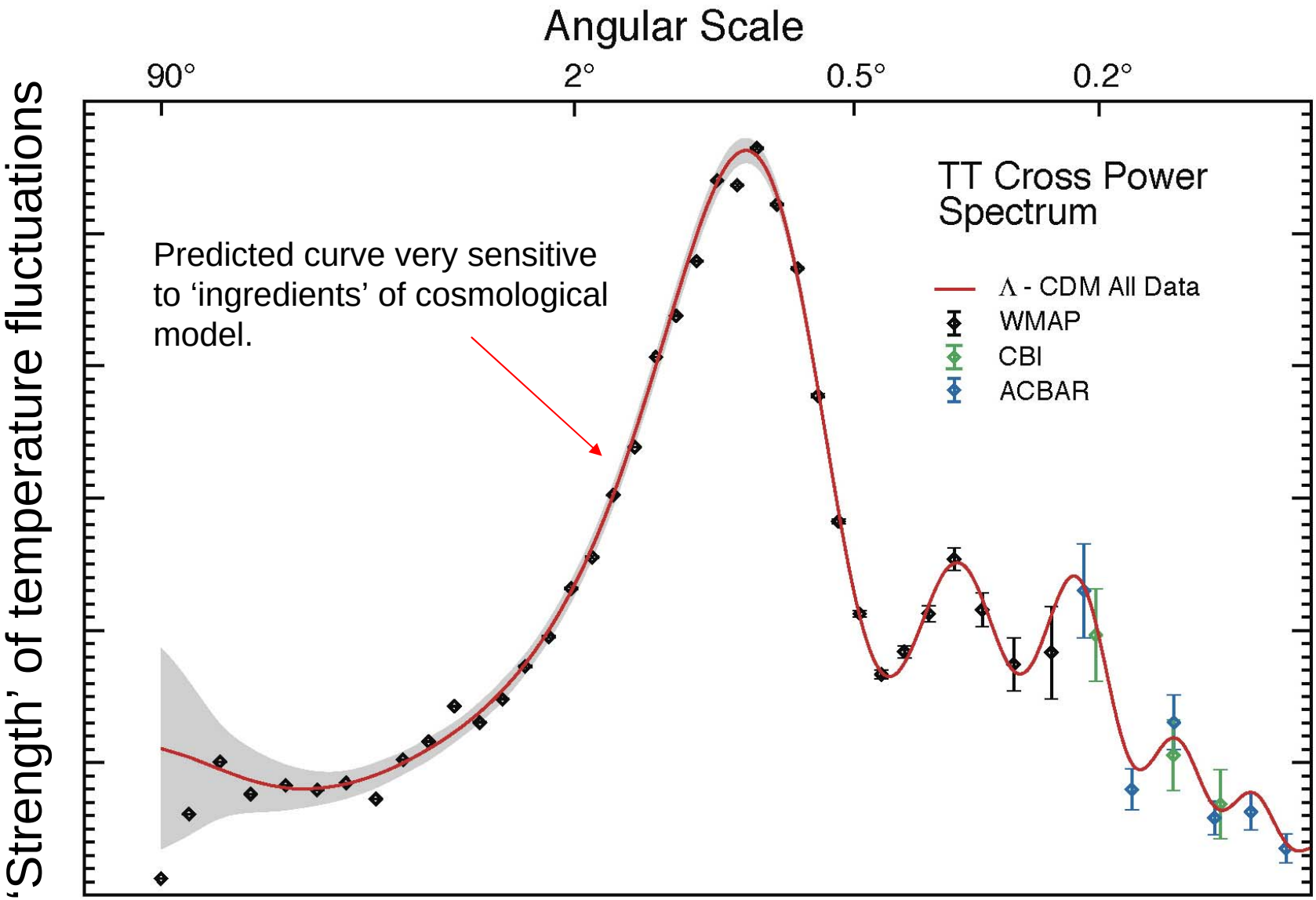


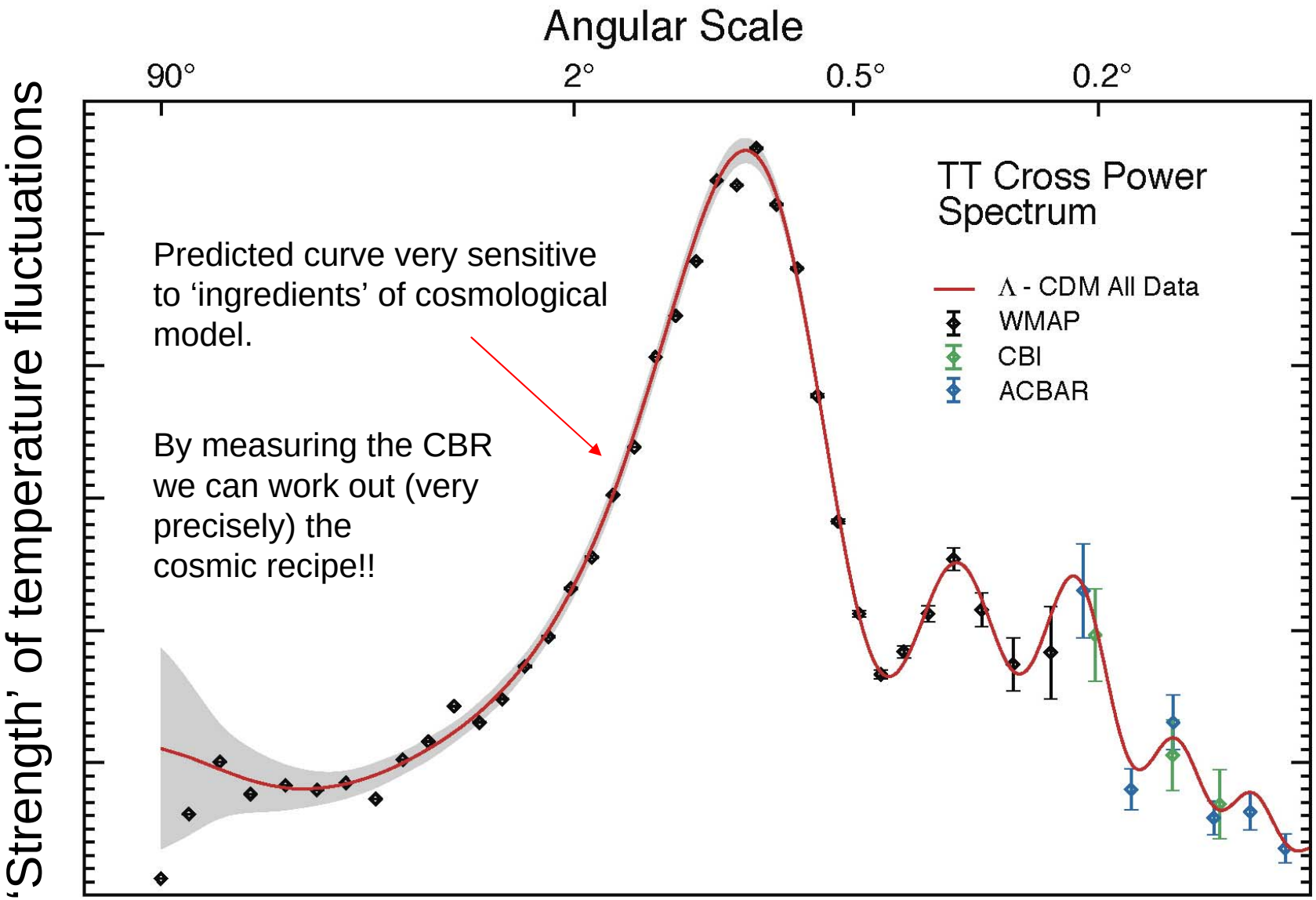
OPEN

FLAT

CLOSED


Angular Scale
90°
2°
0.5°
0.2°
'Strength' of temperature fluctuations
TT Cross Power Spectrum
Λ - CDM All Data
WMAP
CBI
ACBAR


Angular Scale
90°
2°
0.5°
0.2°
'Strength' of temperature fluctuations
Predicted curve very sensitive to 'ingredients' of cosmological model.
TT Cross Power Spectrum
Λ - CDM All Data
WMAP
CBI
ACBAR


Angular Scale
90°
2°
0.5°
0.2°
'Strength' of temperature fluctuations
TT Cross Power Spectrum
Λ - CDM All Data
WMAP
CBI
ACBAR
Predicted curve very sensitive to 'ingredients' of cosmological model.
By measuring the CBR we can work out (very precisely) the cosmic recipe!!

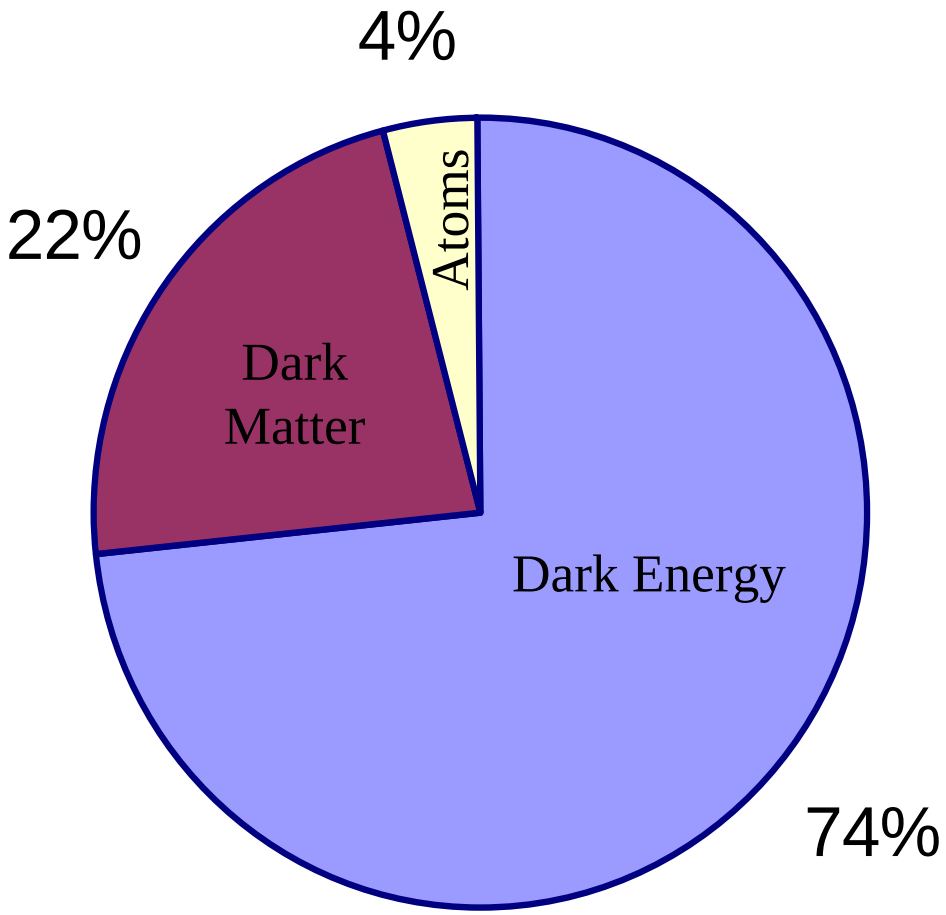
Summary:

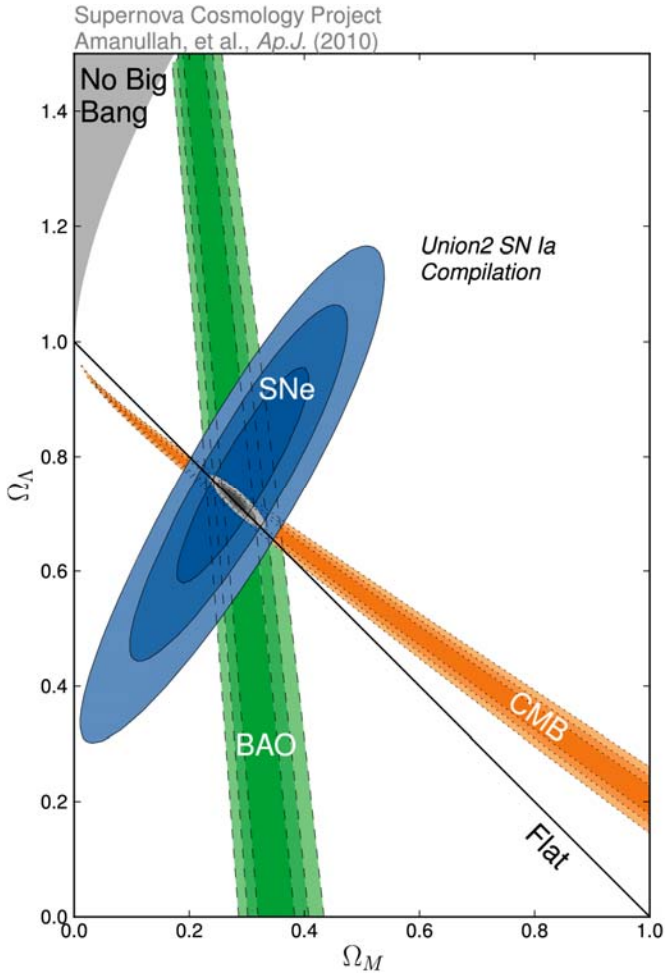
The shape of the Universe is FLAT

The Universe will continue to expand for ever

The expansion is <u>accelerating</u>

State of the Universe – Sep 2010





Overview

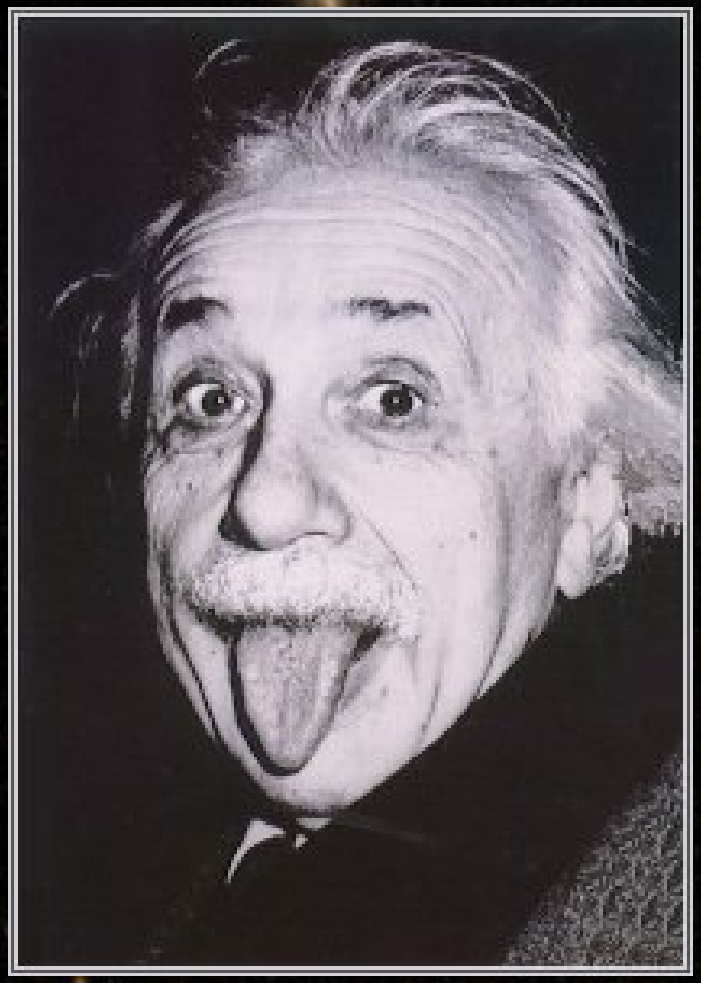
- *Where are we?*
- *How did we get there?*
- ***Where are we going?***

The future of the Universe?

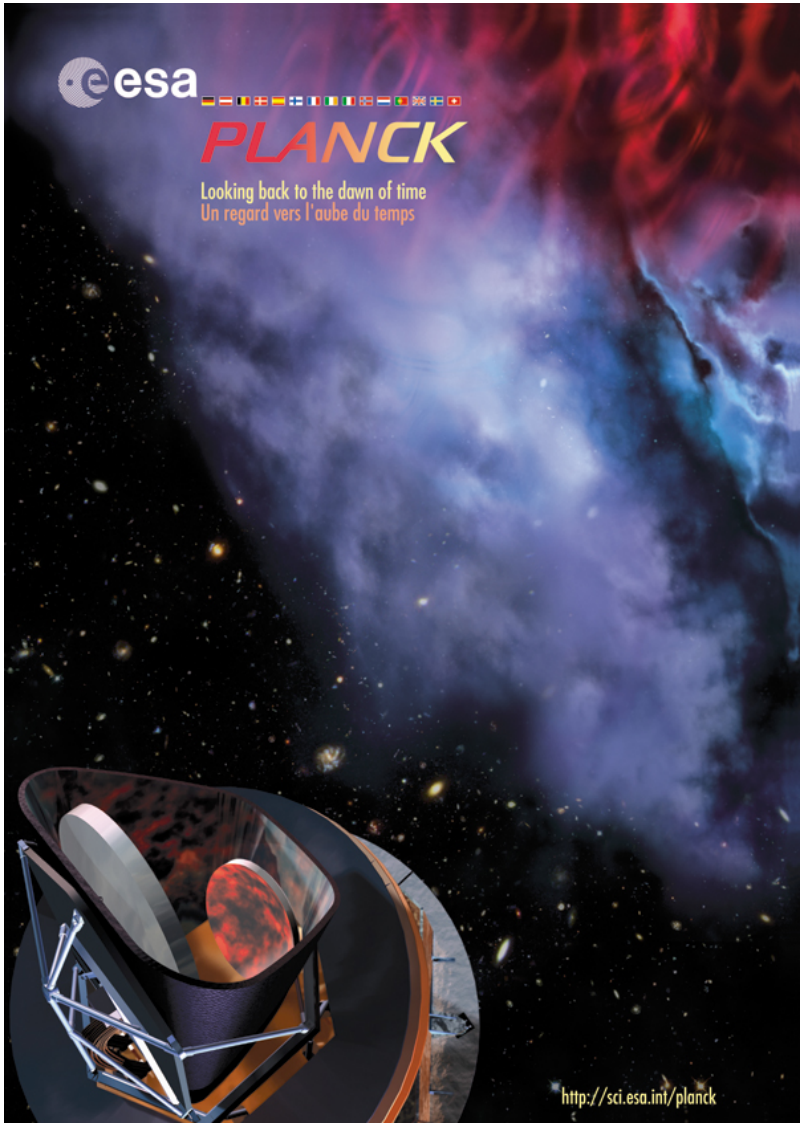
No Big Crunch!!!

Caithness, Sep 2010

The future of cosmology?...



Caithness, Sep 2010



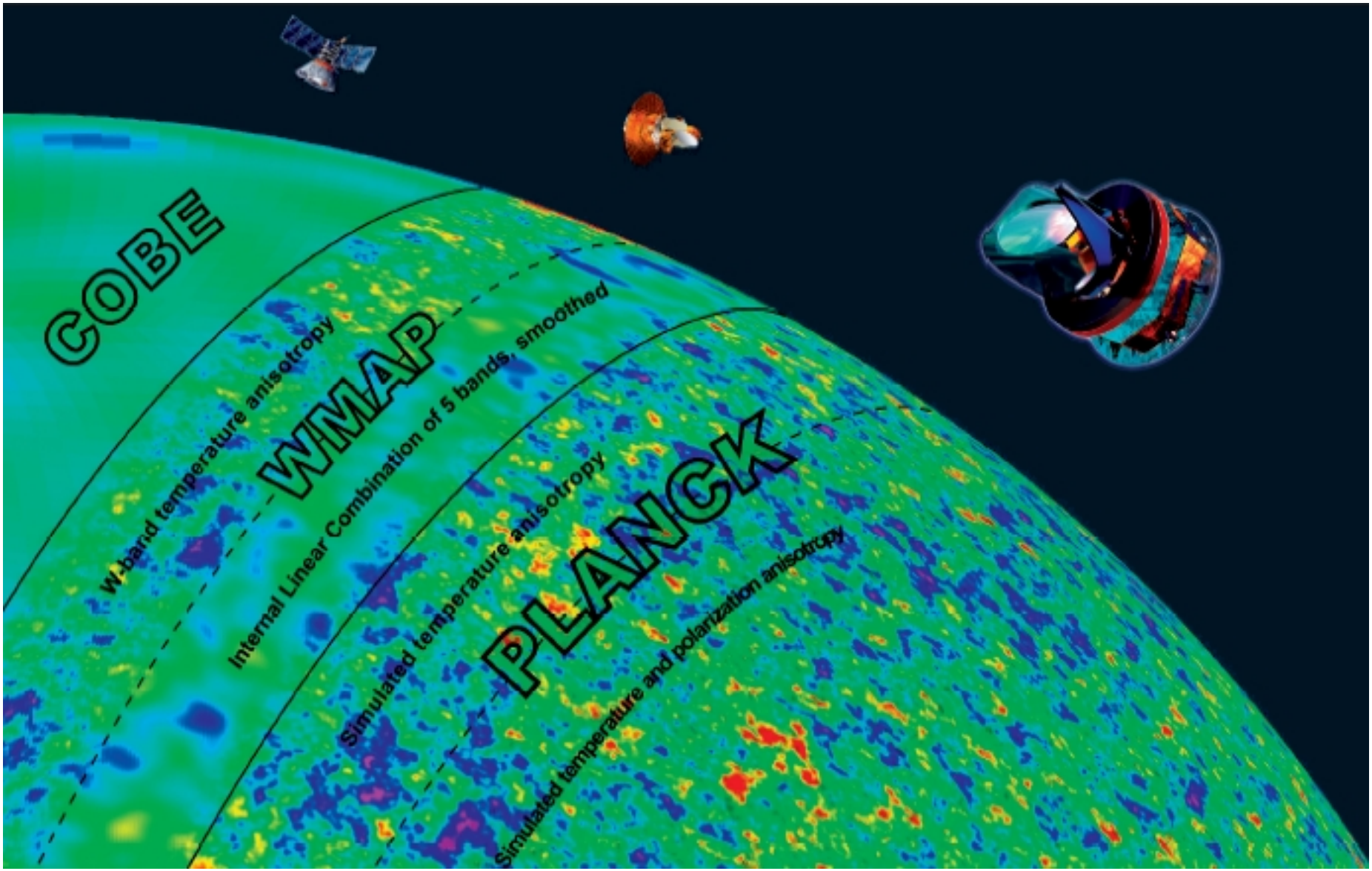
Planck launched May 2009

SUPA

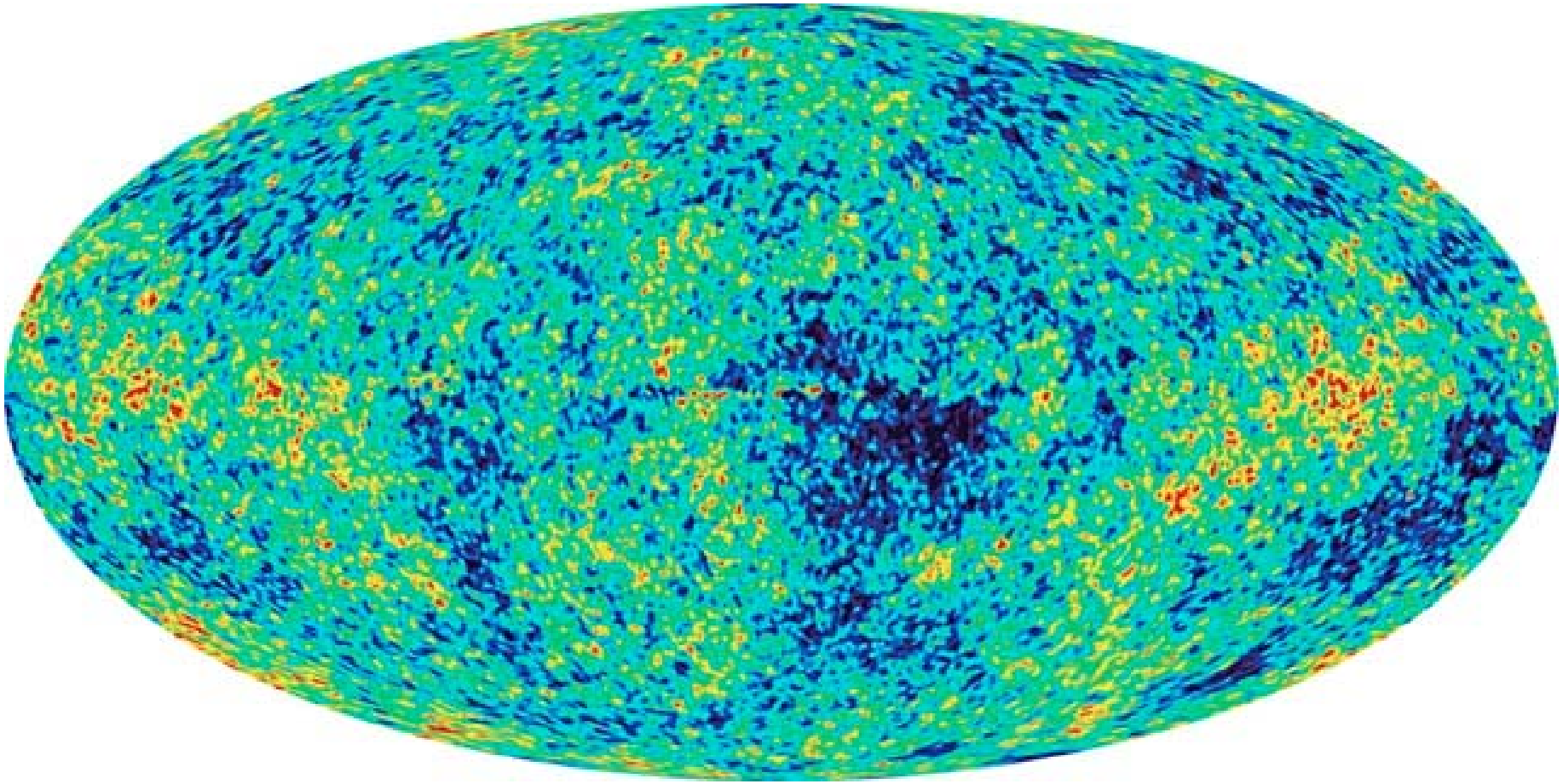
IGR

Caithness, Sep 2010

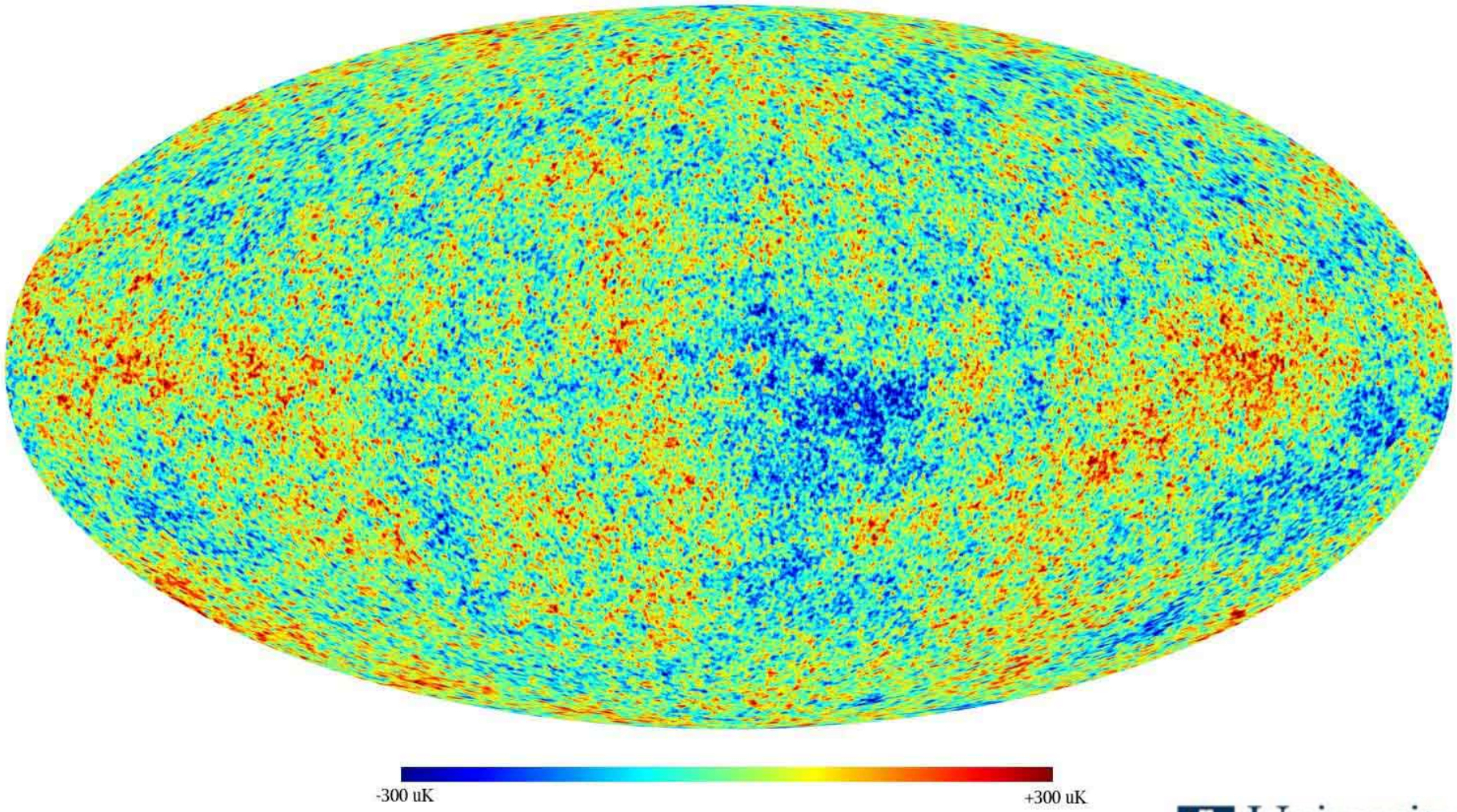
University of Glasgow

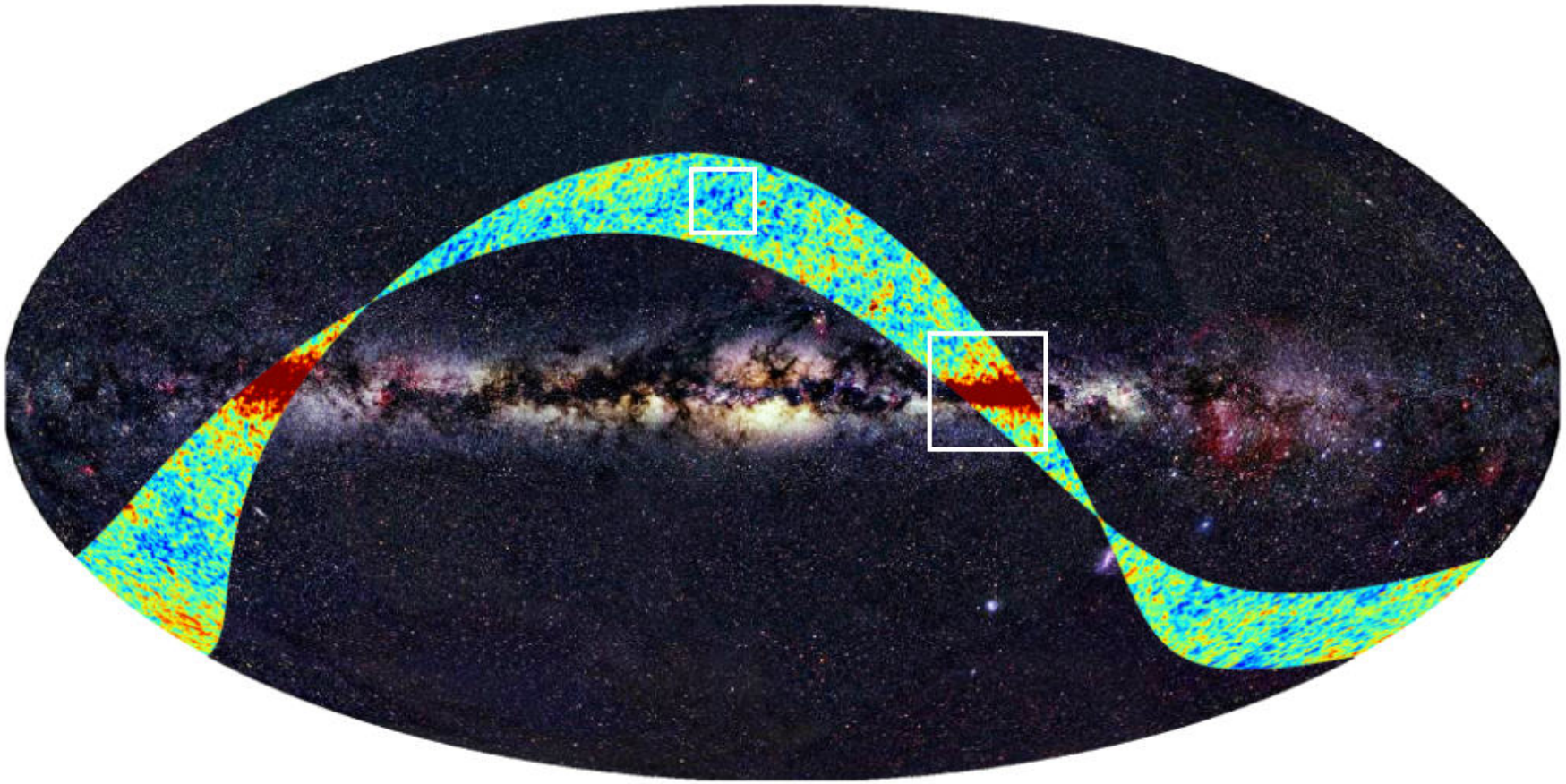

COBE
W-band temperature anisotropy
WMAP
Internal Linear Combination of 5 bands, smoothed
PLANCK
Simulated temperature anisotropy
Simulated temperature and polarization anisotropy

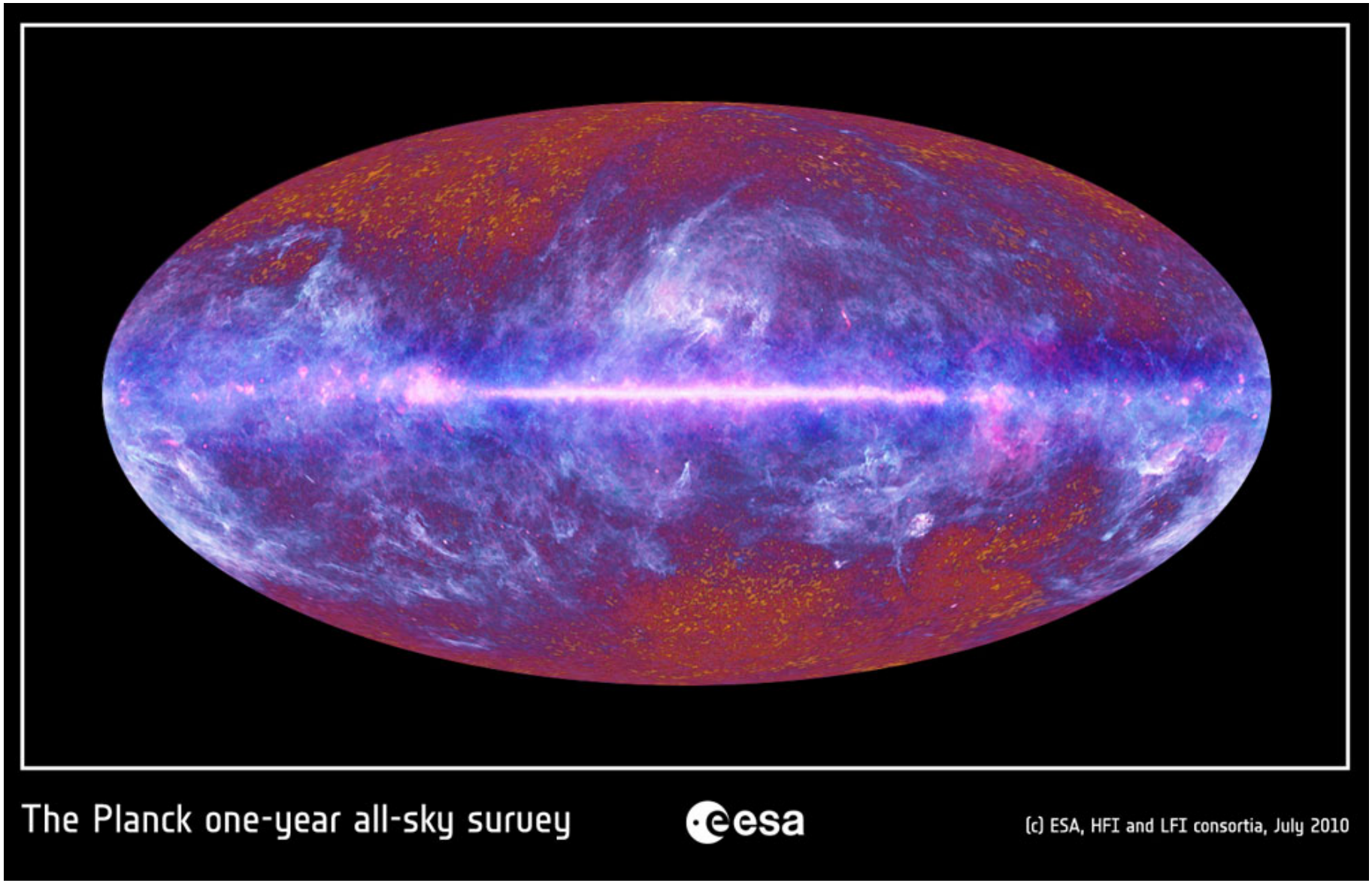
WMAP map of temperature across the sky

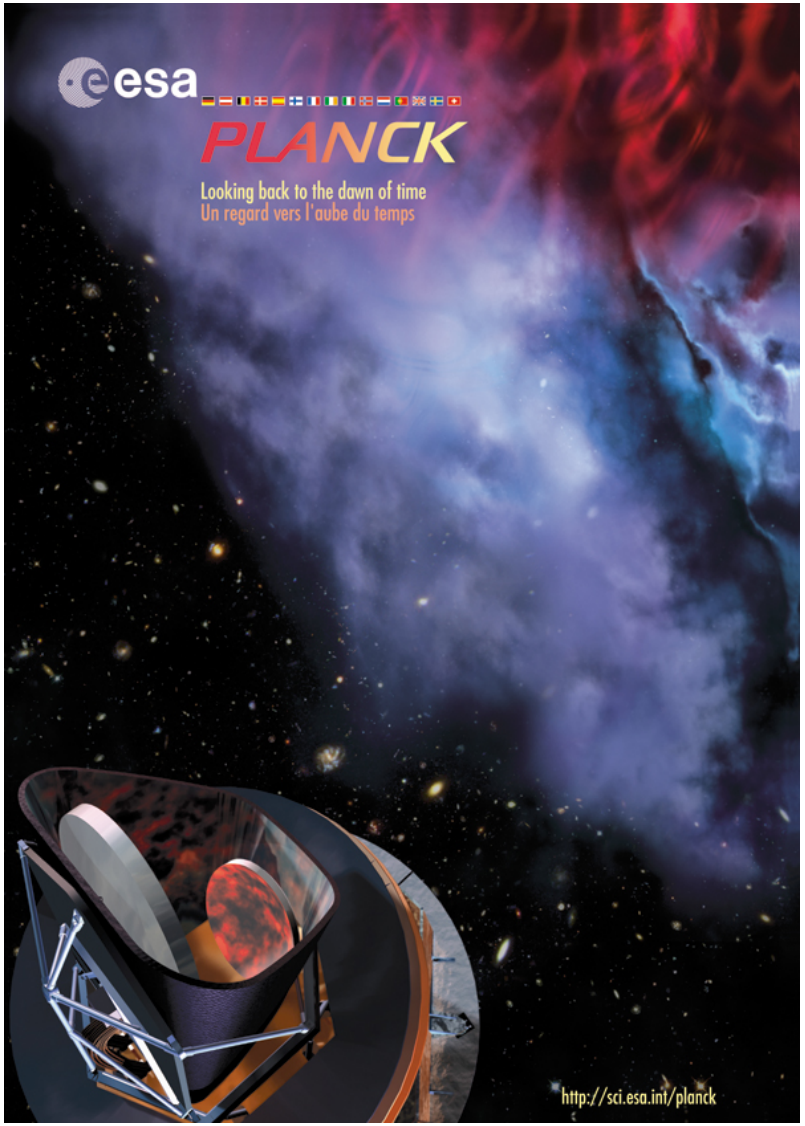


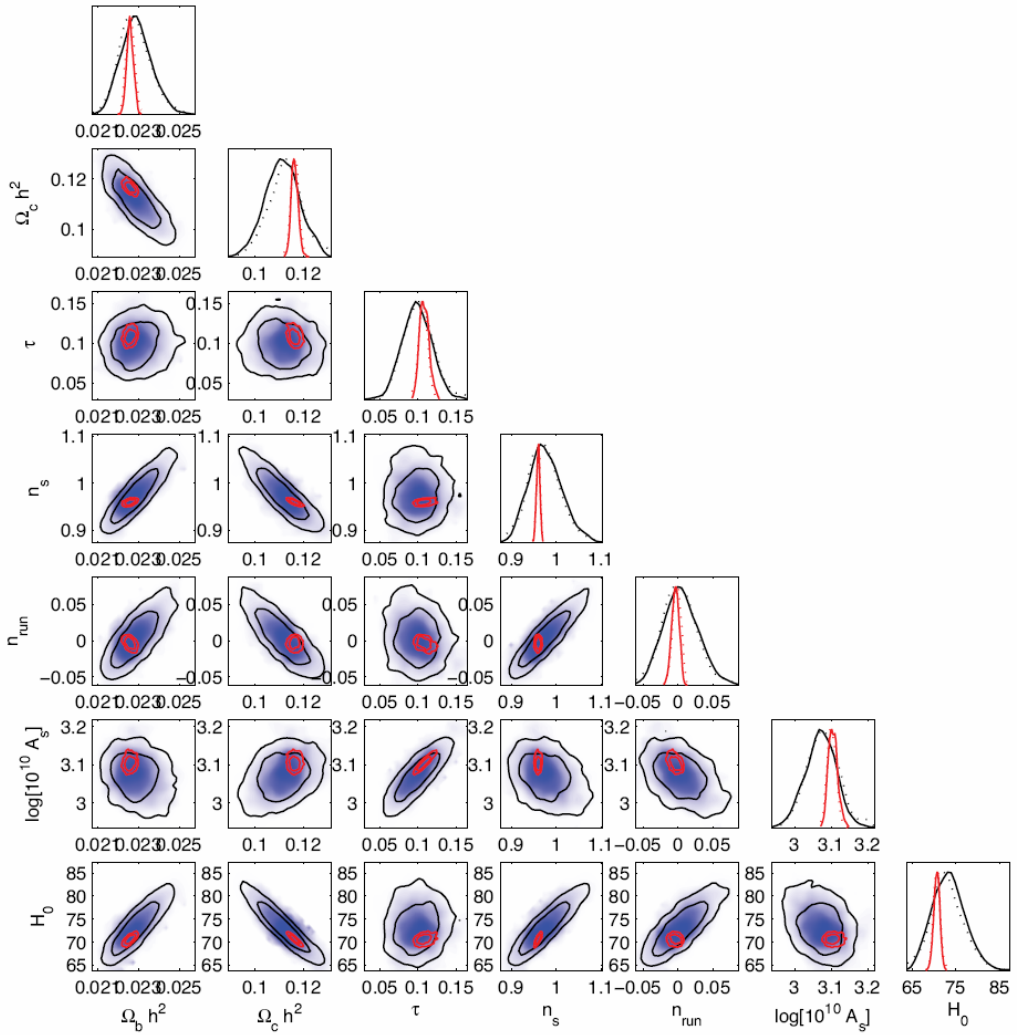
Simulated Planck temperature map






The Planck one-year all-sky survey
esa
(c) ESA, HFI and LFI consortia, July 2010

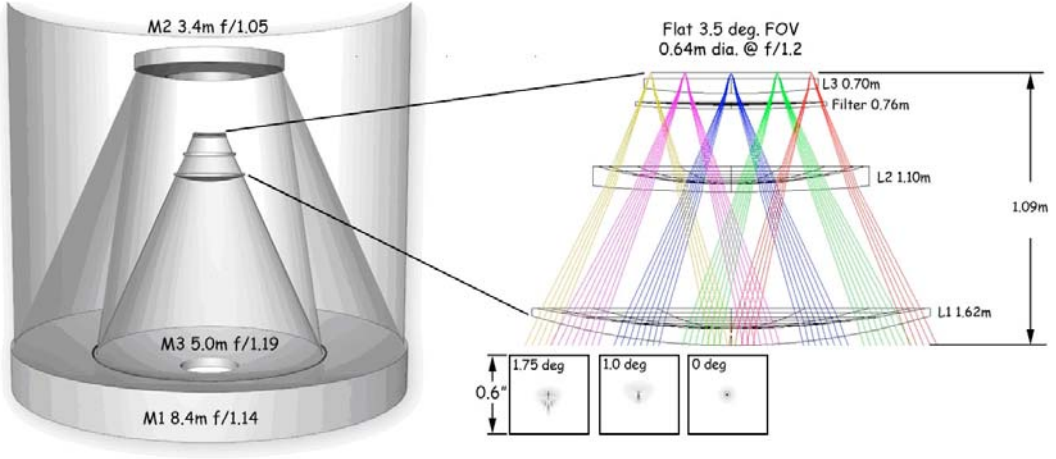


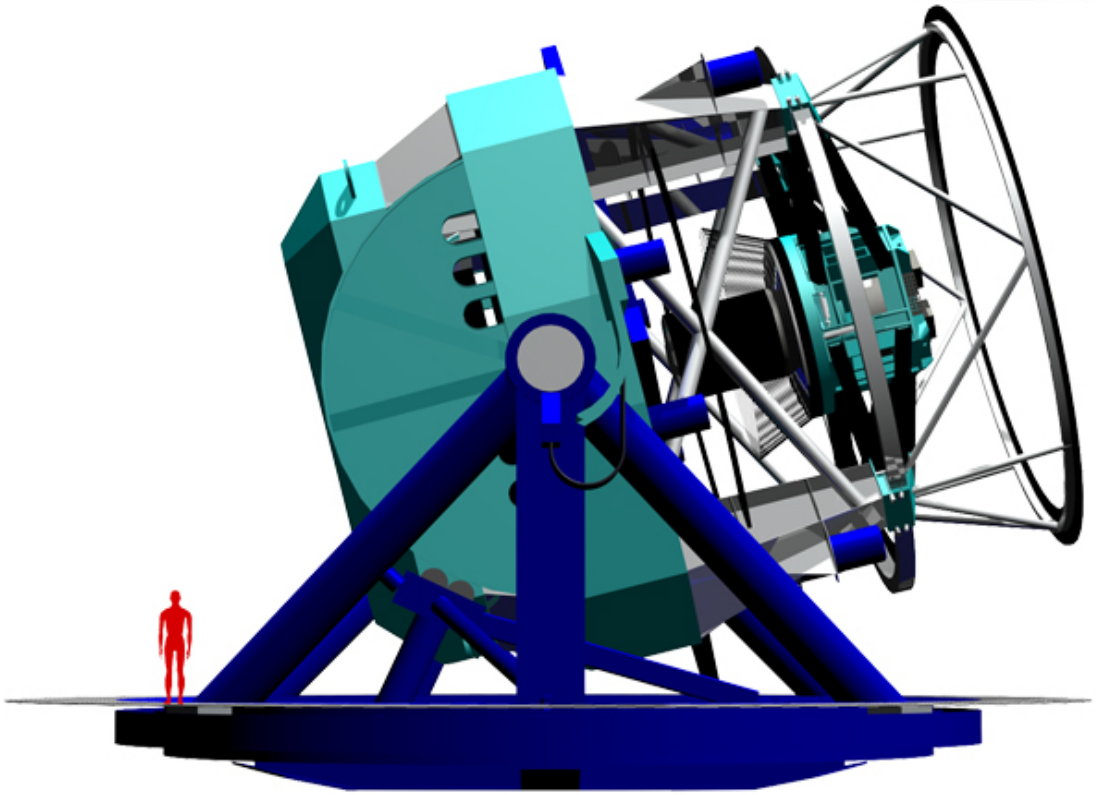


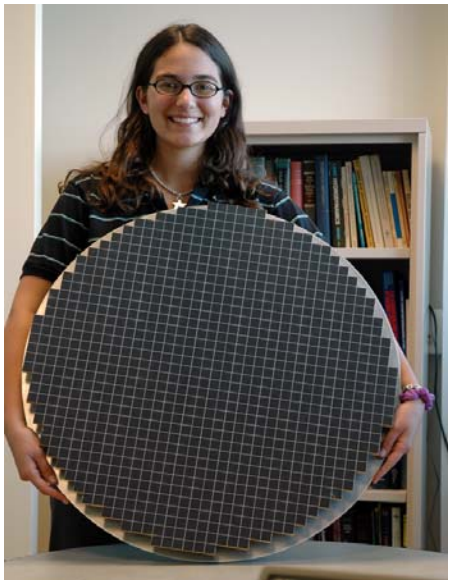
Caithness, Sep 2010

LSST

Large Synoptic Survey Telescope





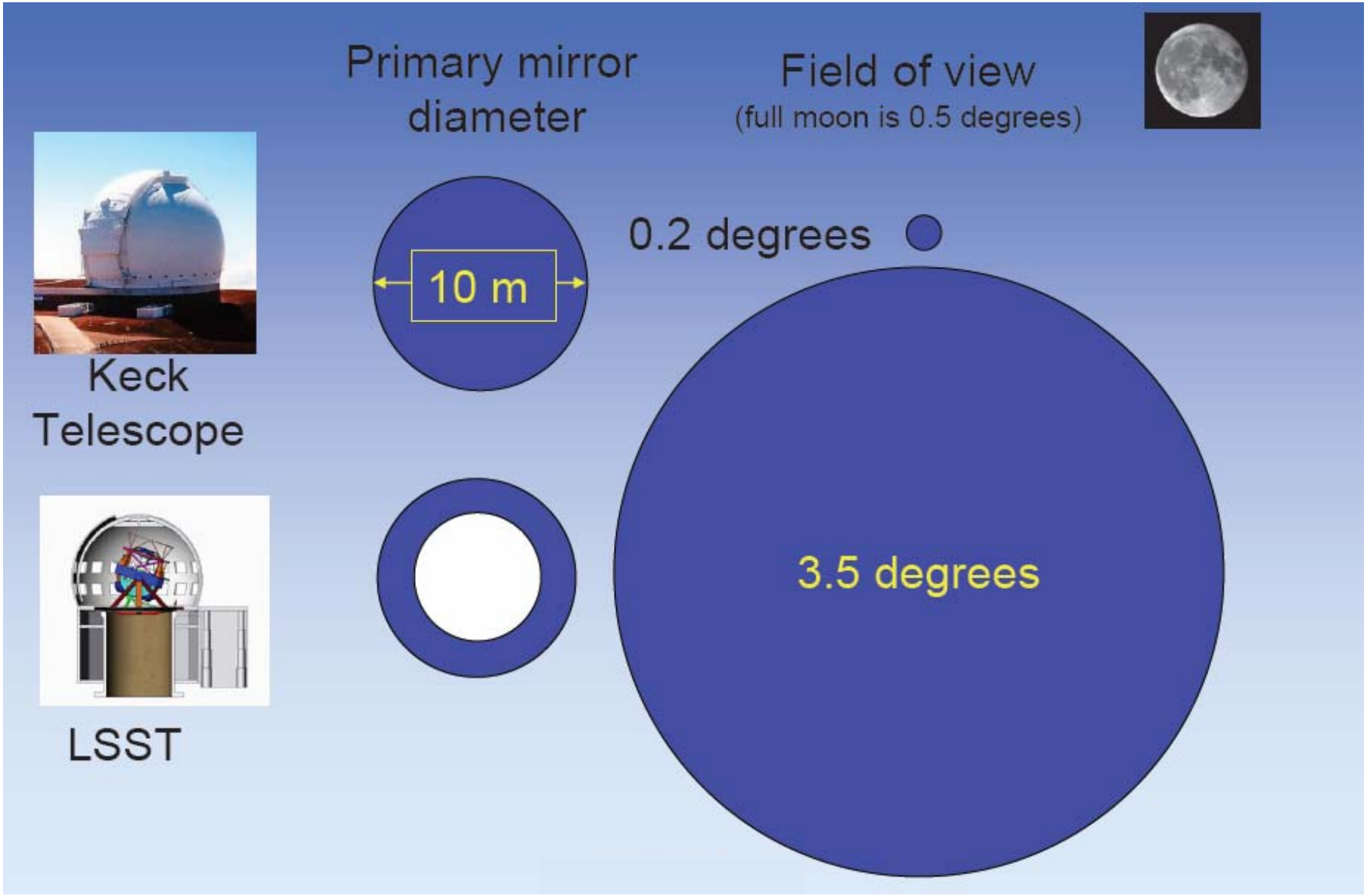


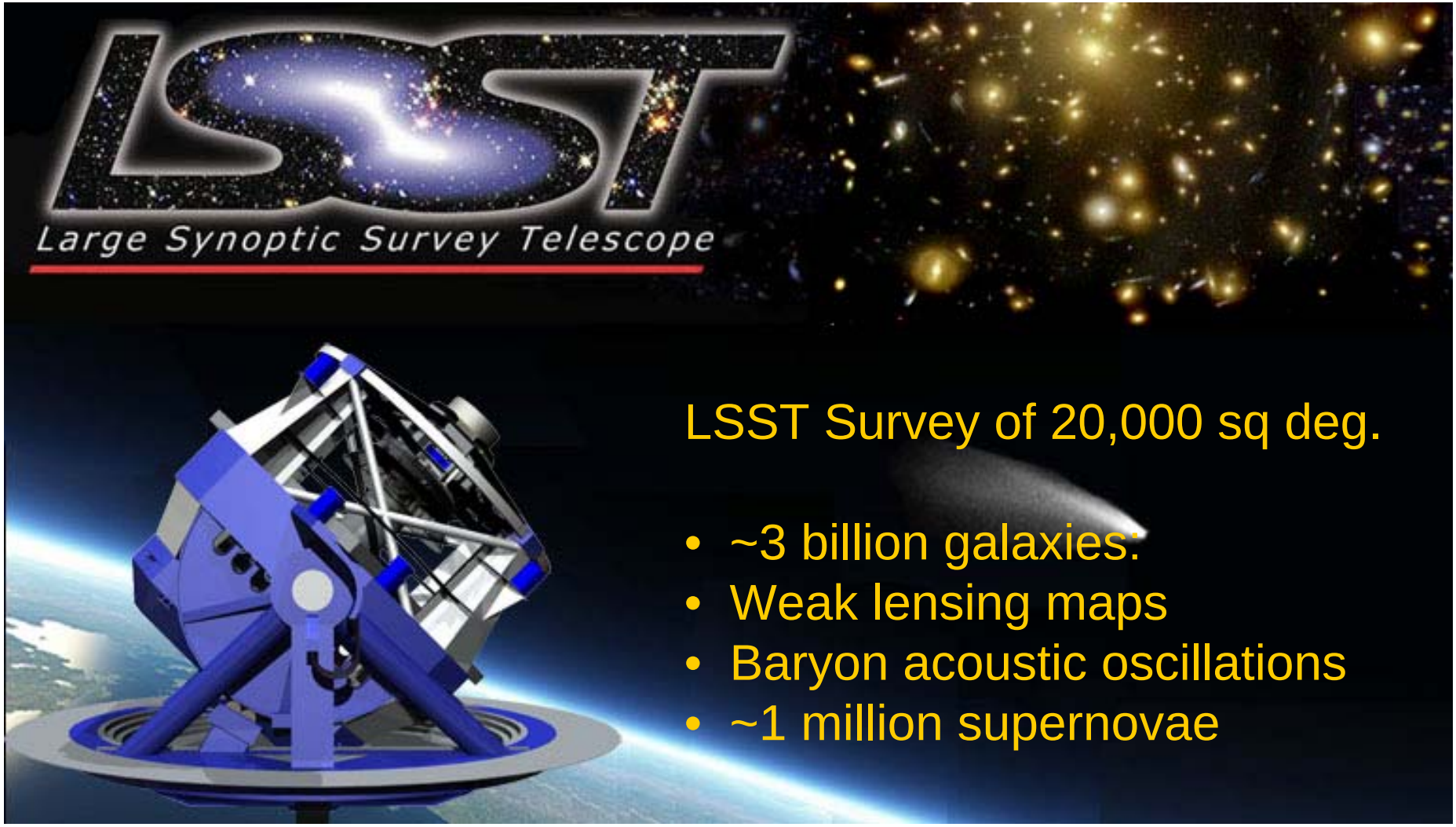
SUPA

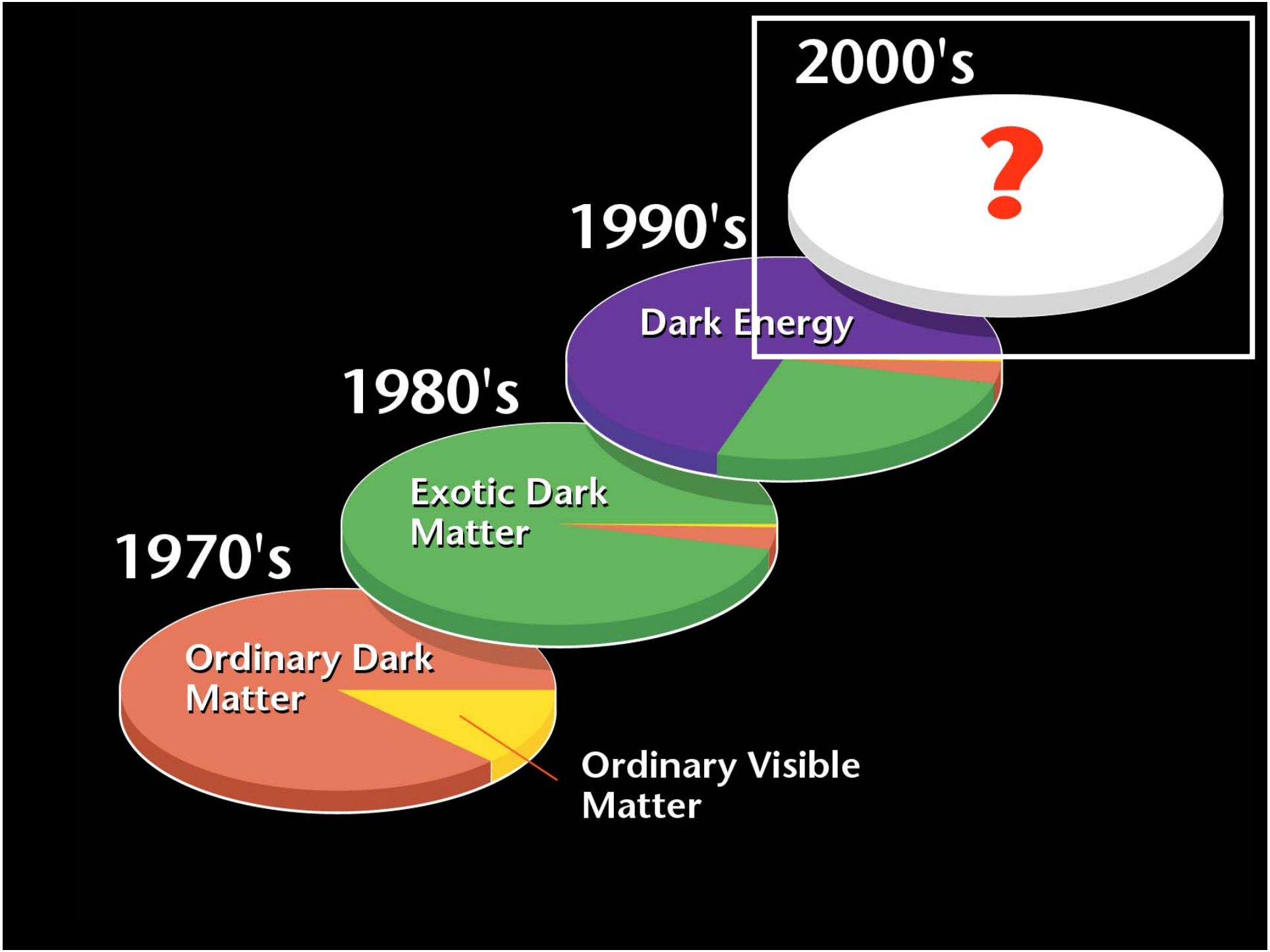
IGR

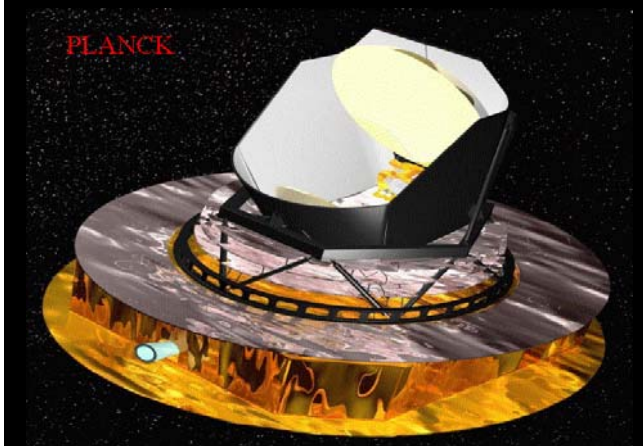
Caithness, Sep 2010

University of Glasgow


Primary mirror diameter
Field of view
(full moon is 0.5 degrees)
Keck Telescope
10 m
0.2 degrees
LSST
3.5 degrees


LSST
Large Synoptic Survey Telescope
LSST Survey of 20,000 sq deg.
• ~3 billion galaxies.
• Weak lensing maps
• Baryon acoustic oscillations
• ~1 million supernovae


2000's
?
1990's
Dark Energy
1980's
Exotic Dark Matter
1970's
Ordinary Dark Matter
Ordinary Visible Matter


PLANCK