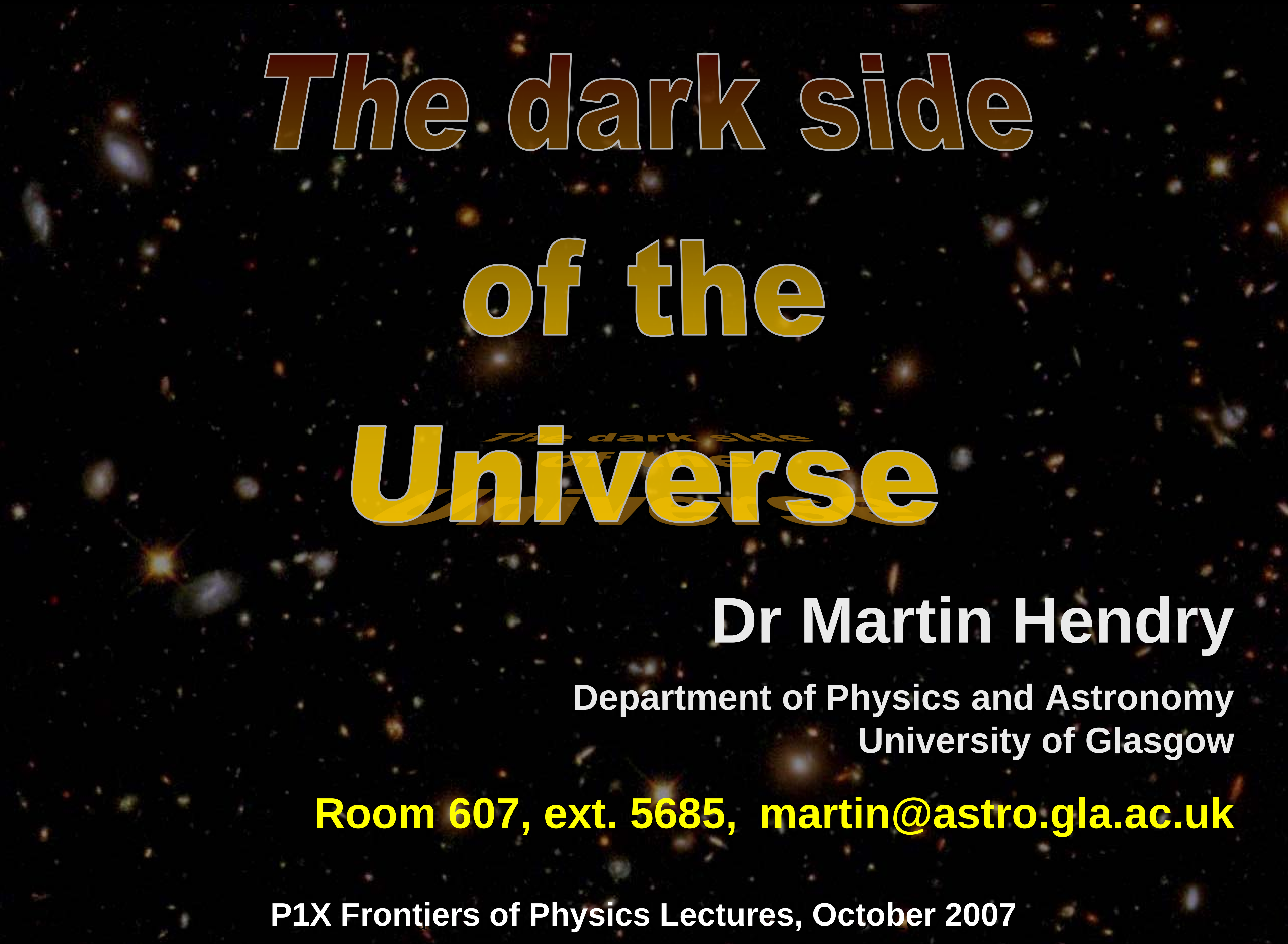

The dark side of the Universe

Dr Martin Hendry

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University of Glasgow

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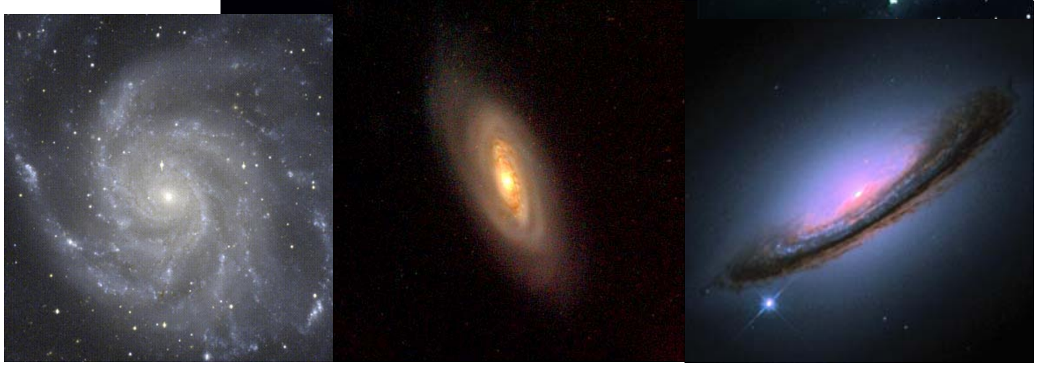
P1X Frontiers of Physics Lectures, October 2007

How fast is the Universe expanding?

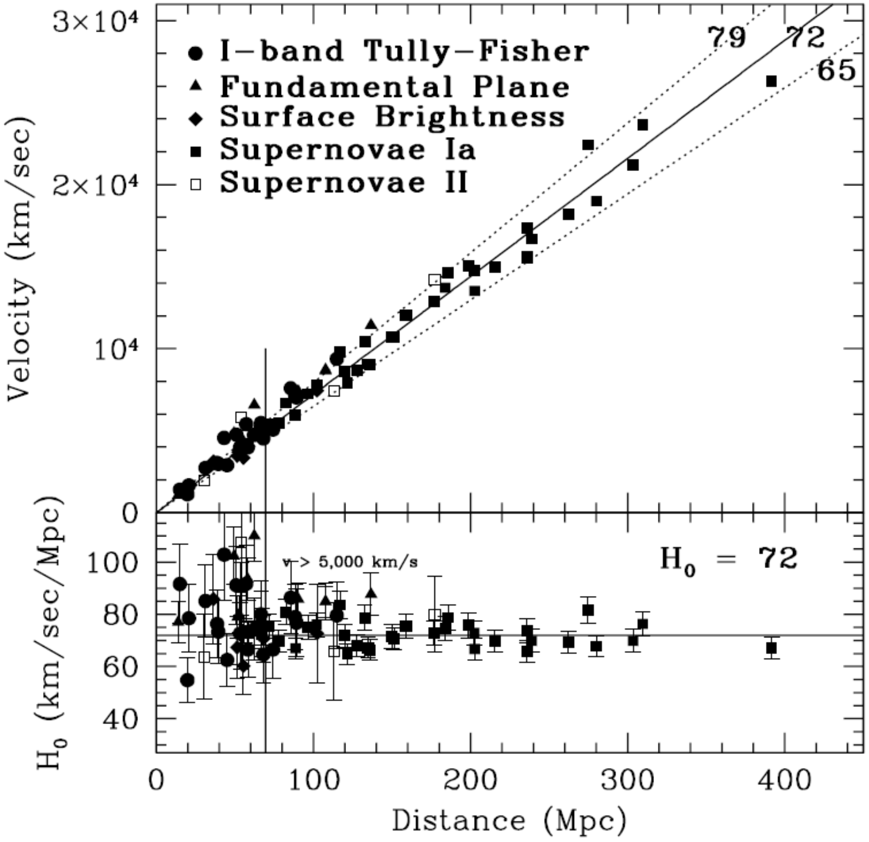


HST Key Project:

Measure distances to ~30 nearby galaxies, linking to more distant **standard candles**

Final answer:

$$H_0 = 72\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$$



(from Freedman et al 2001)

Result of combining many different galaxy distance indicators.

Note: **Hubble's constant has units of [time]$^{-1}$**

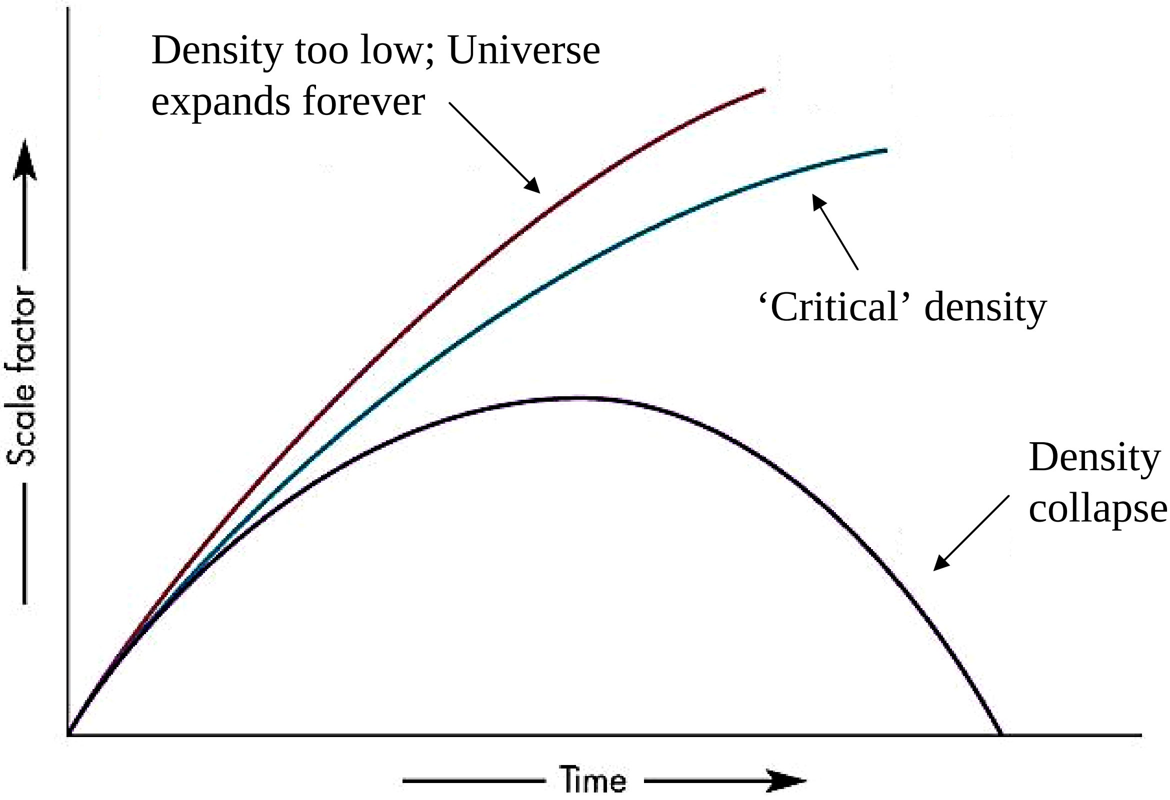
If we (naively) assume the Universe has ***always*** expanded at this rate, then

$$\text{Age of the Universe} = H_0^{-1}$$

$$= 13.6 \times 10^9\ \text{yr}$$

Will the Universe expand forever?.....

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



Gravity acts to ***slow down*** the expansion

The physics here is analogous to **escape speed** from a planet's gravity

Consider a simplistic Newtonian analogy:

Total energy of a galaxy, of mass m , at distance d.

$$\boxed{E_{\text{tot}} \quad = \quad \tfrac{1}{2}m\left(H_0 d\right)^2 - \tfrac{4}{3}\pi G m \rho d^2}$$

K.E. term, using Hubble's law

P.E. term, due to sphere of matter of radius d centred on our galaxy.

Density of matter in the universe

If we derive this equation rigorously, using **General Relativity**, we get the same answer!!

Critical density corresponds to $E_{\mathrm{tot}} = 0$

which re-arranges to give

$$\boxed{\rho_{\mathrm{crit}} = \frac{3H_0{}^2}{8\pi G}}$$

Plugging in $H_0 = 72\,\mathrm{kms}^{-1}\mathrm{Mpc}^{-1}$ and converting units,

this works out to be about **5.8 protons per cubic metre**.

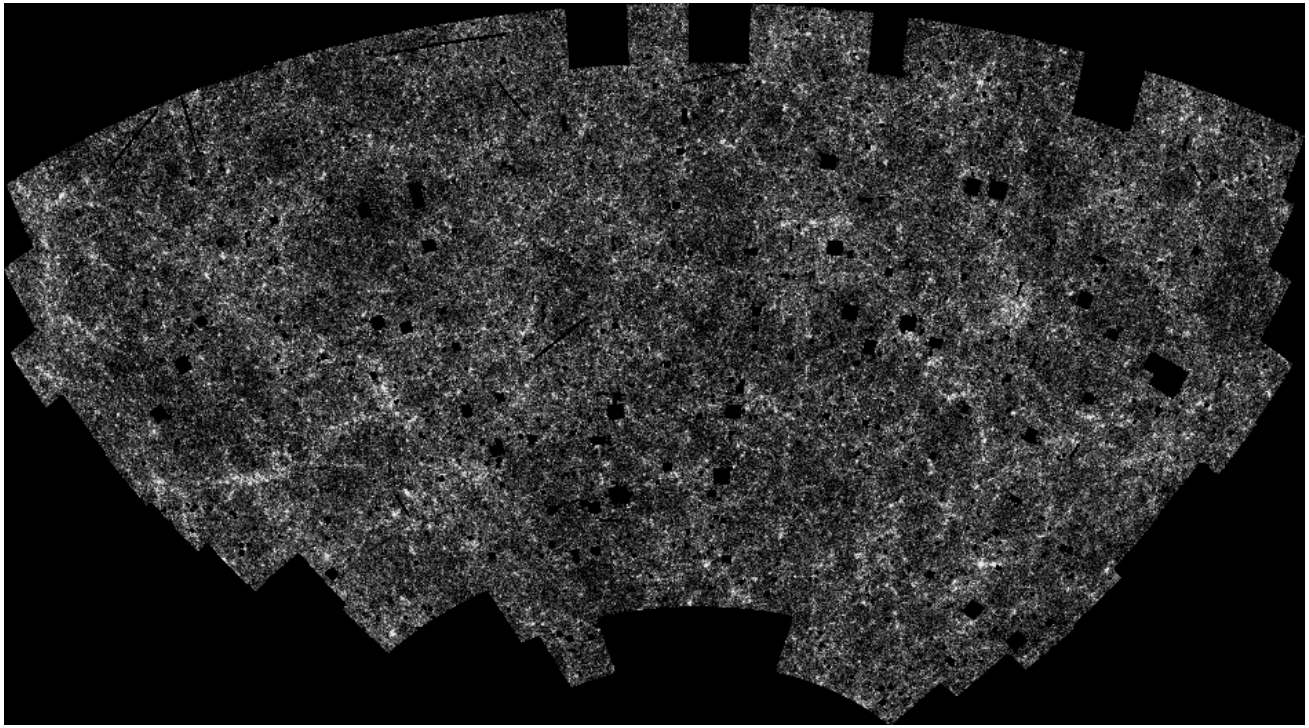
We write $\Omega = \rho / \rho_{\mathrm{crit}}$ dimensionless density parameter

So how dense is the Universe?....

Weighing the Universe

Suppose we add up the mass of all the stars and galaxies we can see….

We can do this using **galaxy surveys**



Luminous matter makes up only 0.5% of the critical density of the Universe

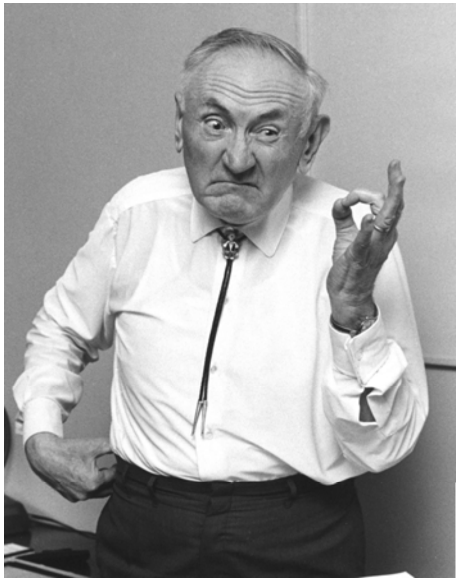
Weighing the Universe

Suppose we add up the mass of all the stars and galaxies we can see….

We can do this using **galaxy surveys**

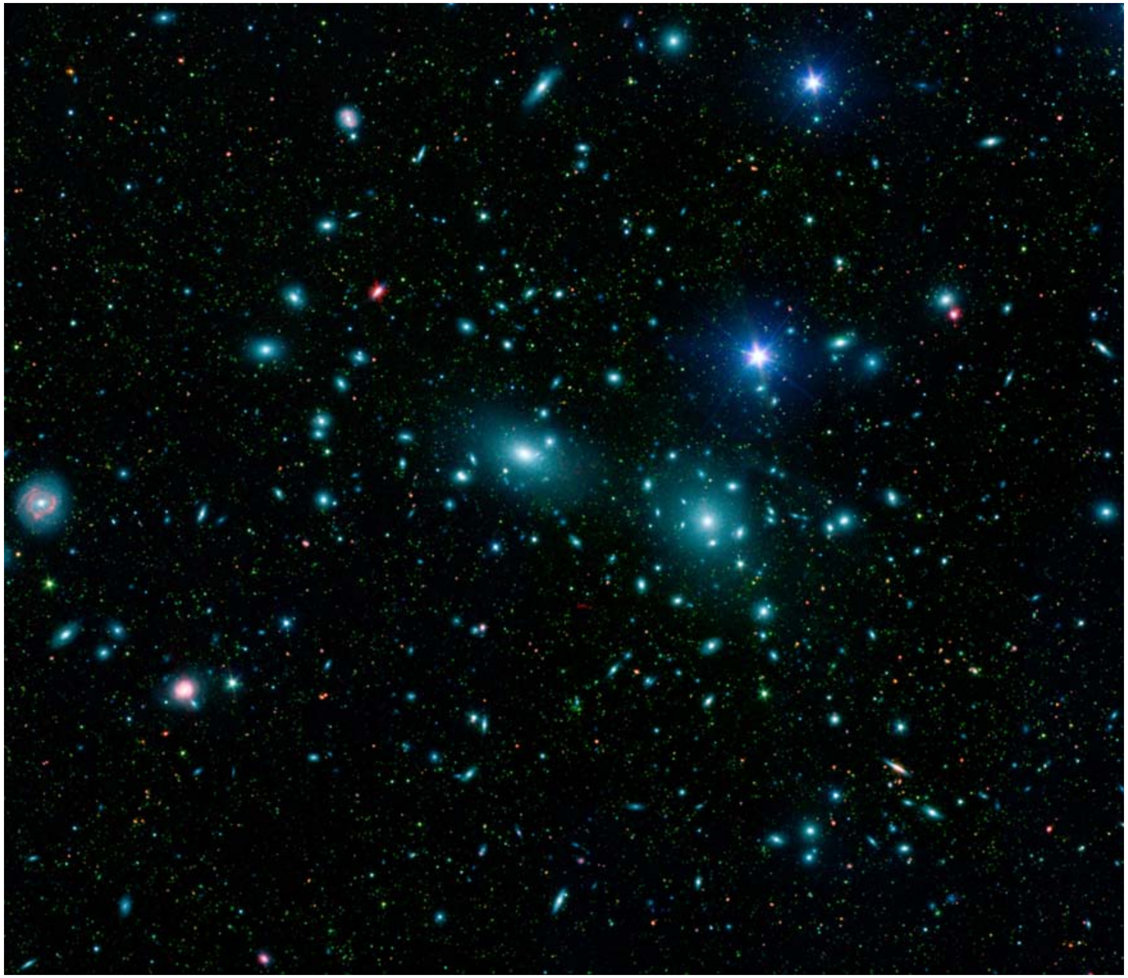
What if we wanted to know the population of the Earth?

More than meets the eye?...

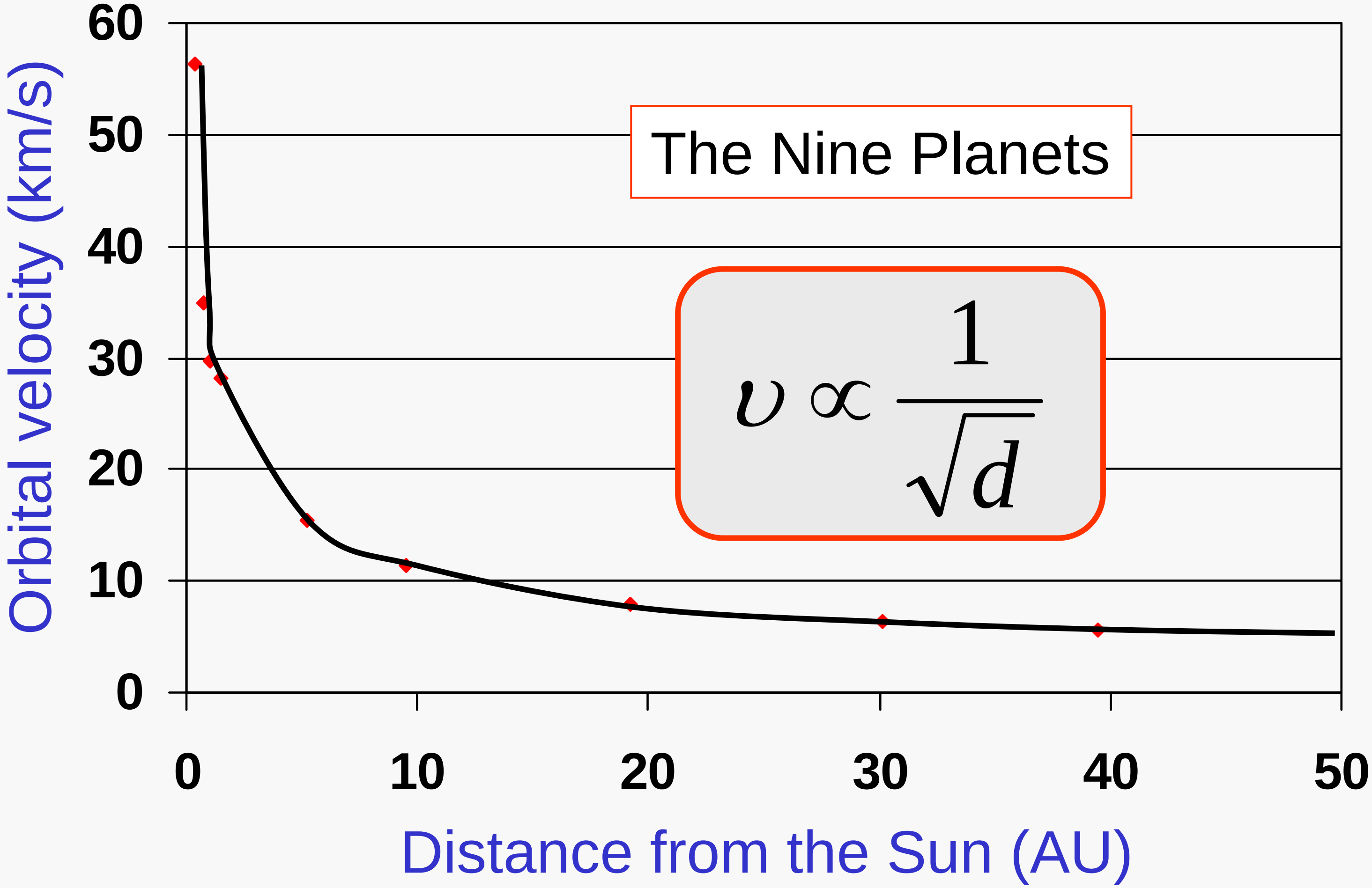


Fritz Zwicky

1933: finds evidence for **dark matter** in the Coma galaxy cluster, by studying the **speed** of the galaxies.



Weighing the Solar System

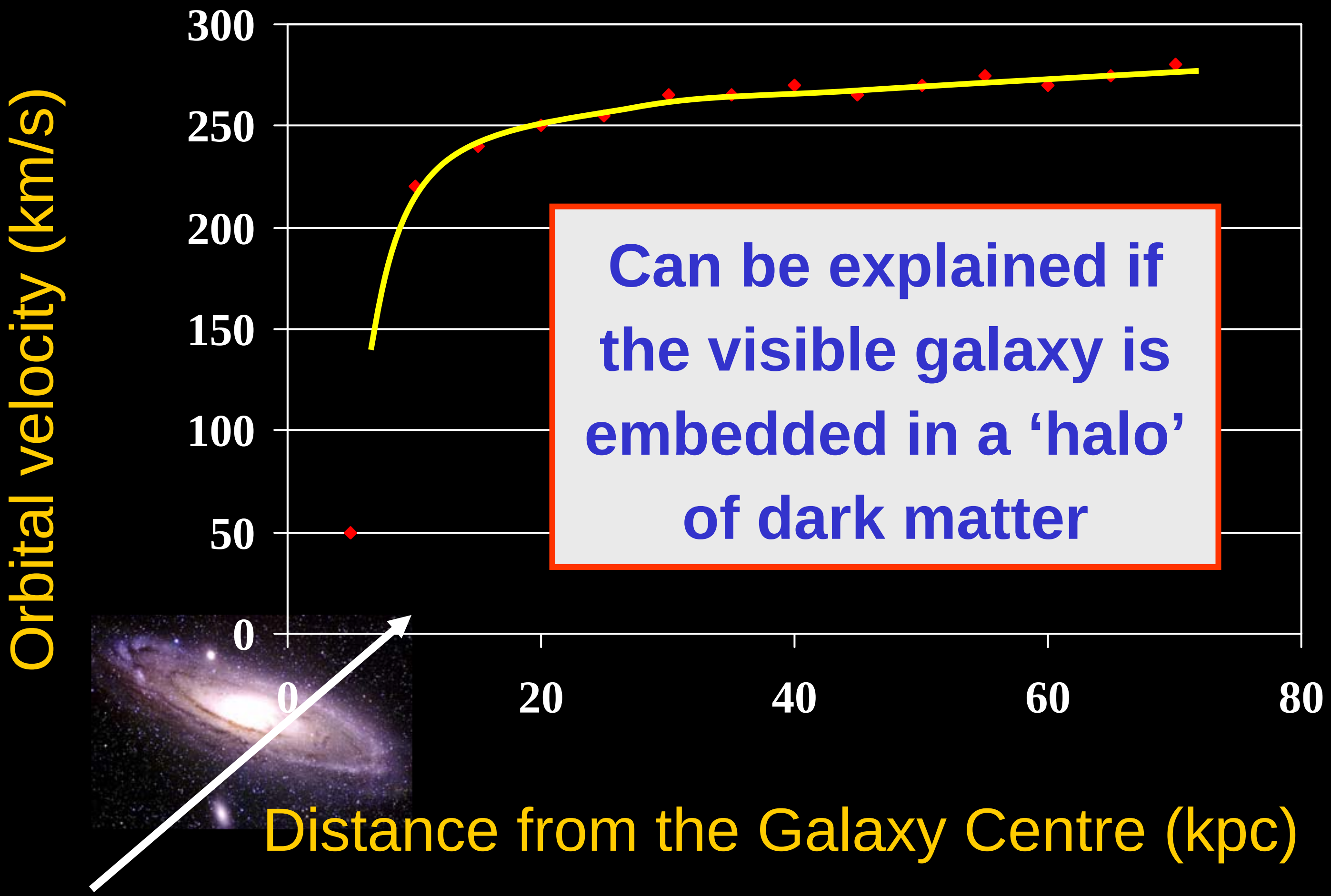


$$\upsilon \propto \frac{1}{\sqrt{d}}$$

Weighing galaxies

Vera Rubin

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



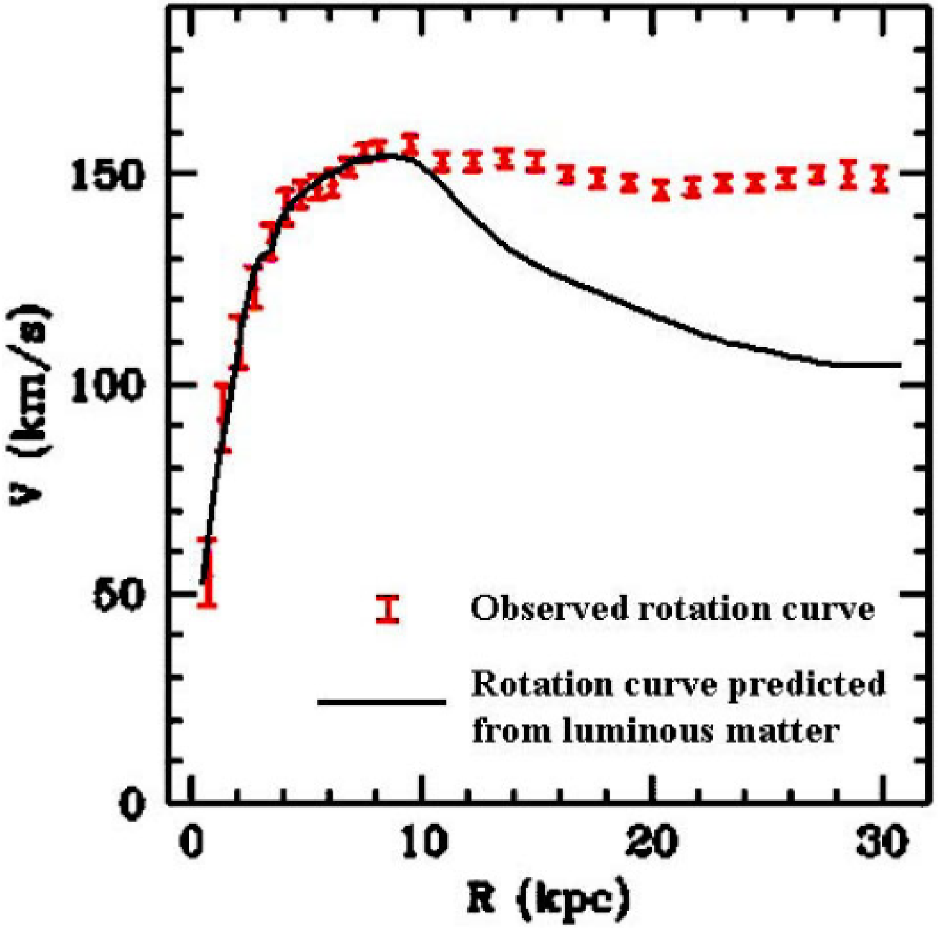
Can be explained if the visible galaxy is embedded in a ‘halo’ of dark matter

Typical size of
galaxy disk

Weighing galaxies

Vera Rubin

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

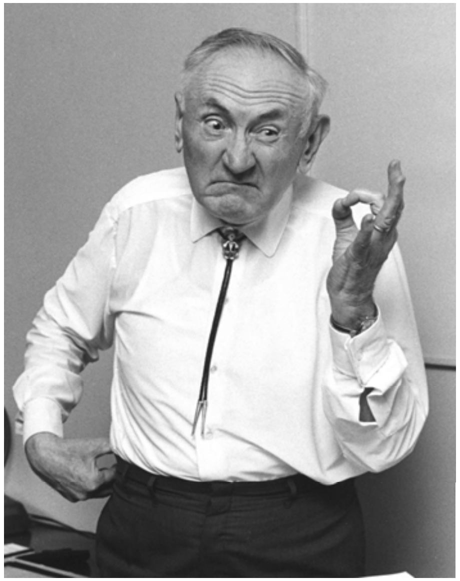


What we see

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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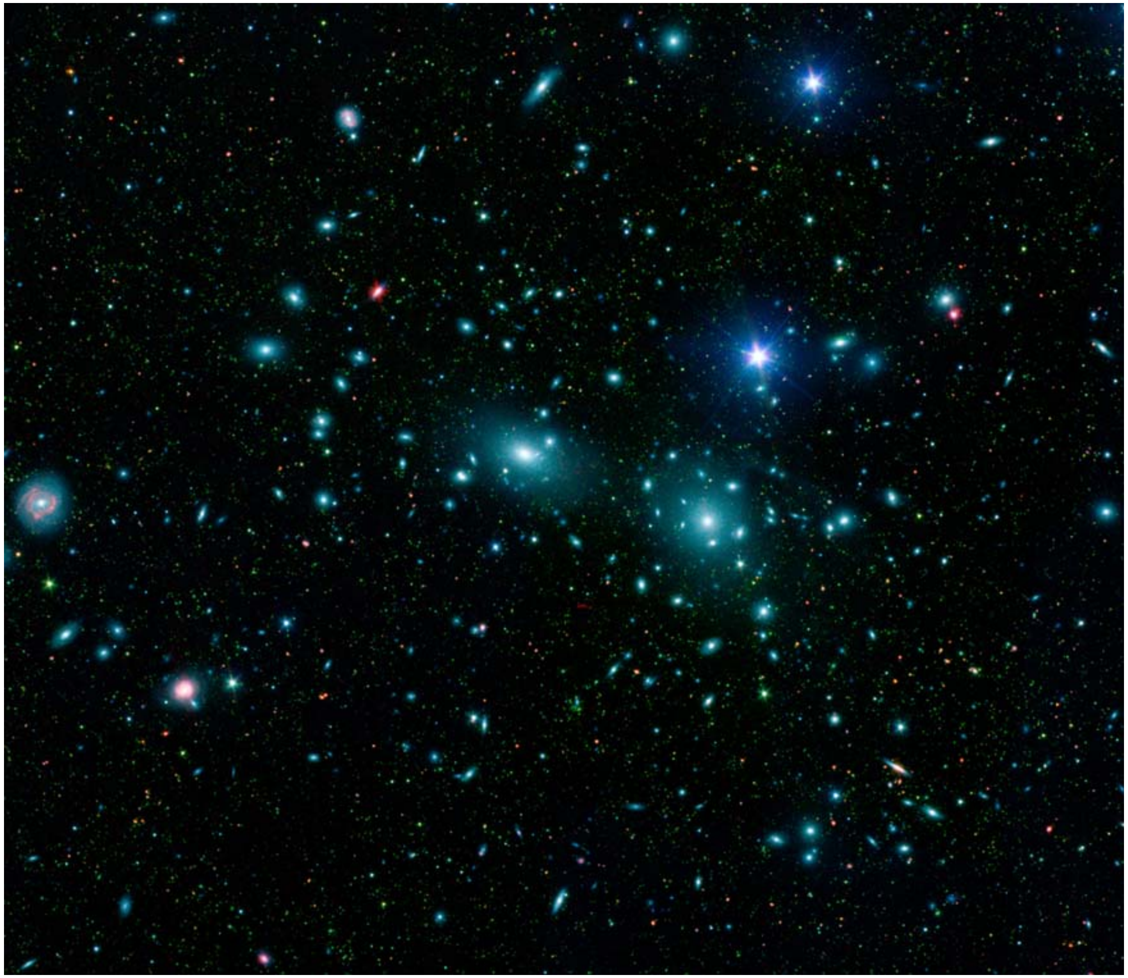
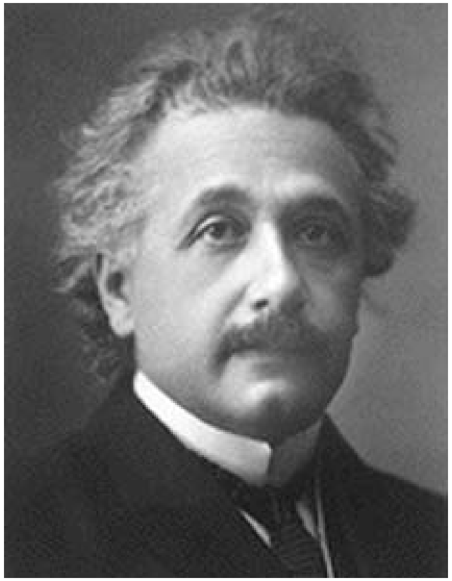
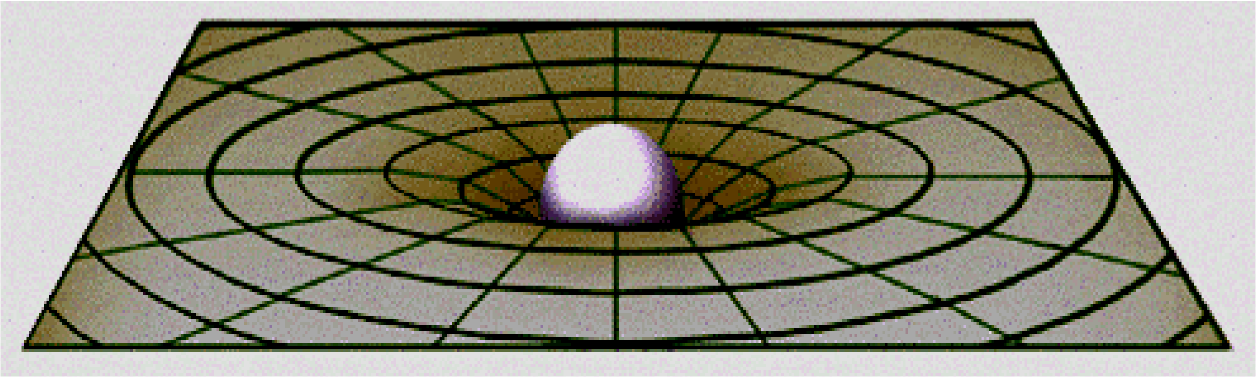


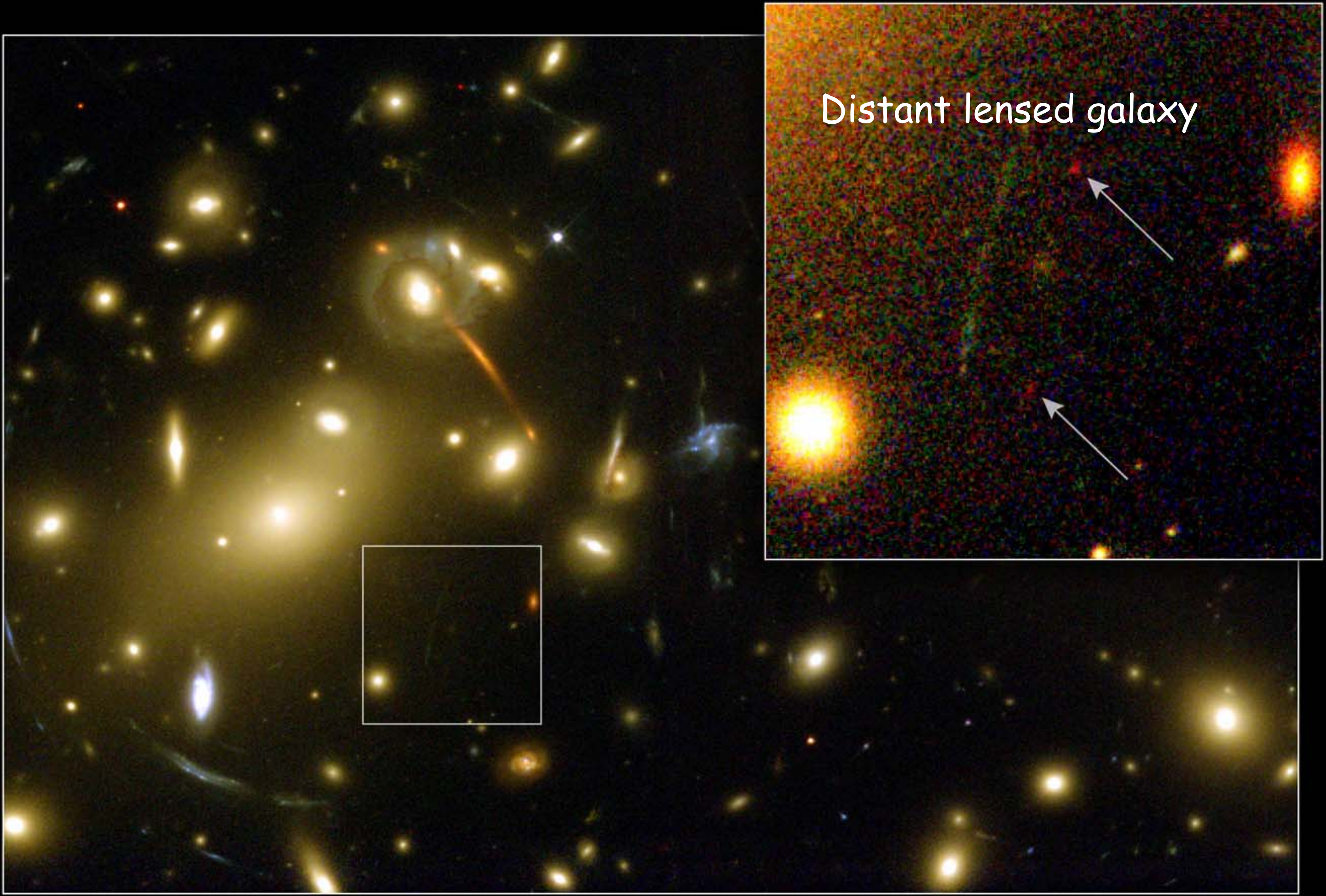
About 30% of the critical density…

Mapping dark matter with gravitational lensing



As light passes close to a star its path is bent by the curved spacetime

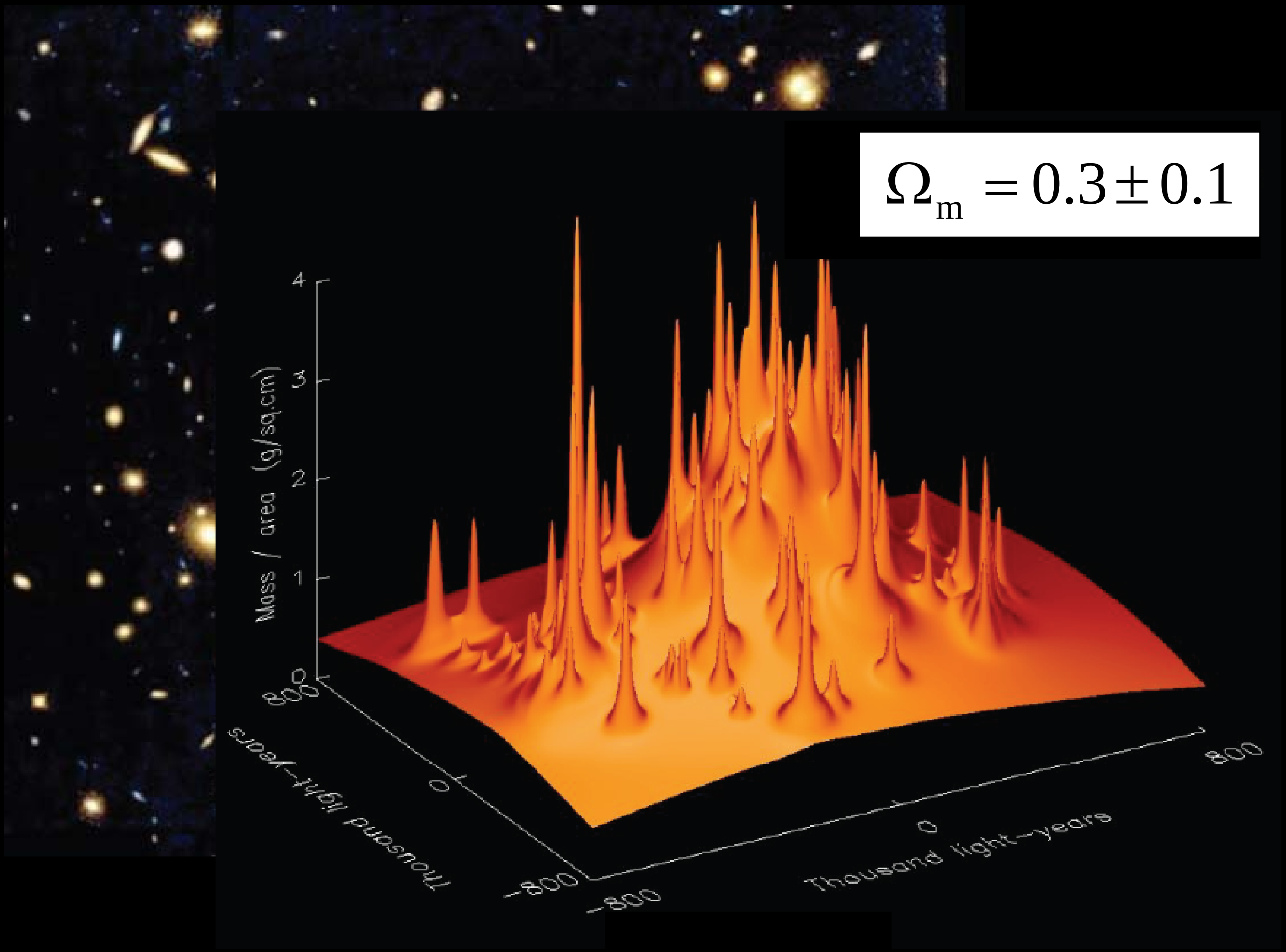




Distant lensed galaxy

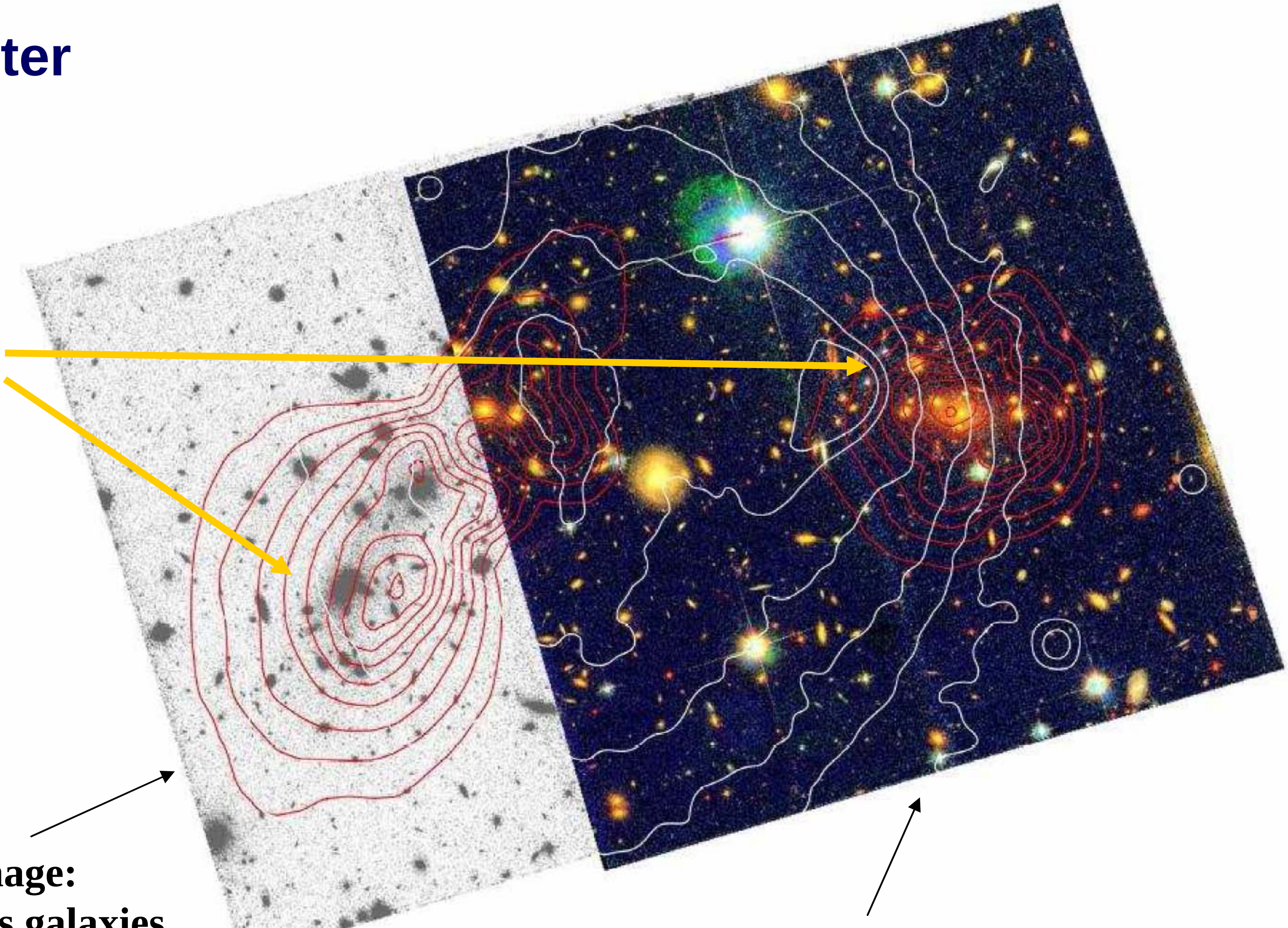
Distant Object Gravitationally Lensed by Galaxy Cluster Abell 2218
Hubble Space Telescope • WFPC2

NASA, ESA, R. Ellis (Caltech) and J.-P. Kneib (Observatoire Midi-Pyrenees) • STScI-PRC01-32



$$\Omega_m = 0.3 \pm 0.1$$

Bullet cluster



Dark matter, reconstructed from lensing

HST optical image: shows luminous galaxies

Chandra X-ray image: also shows ‘dark’ cluster gas

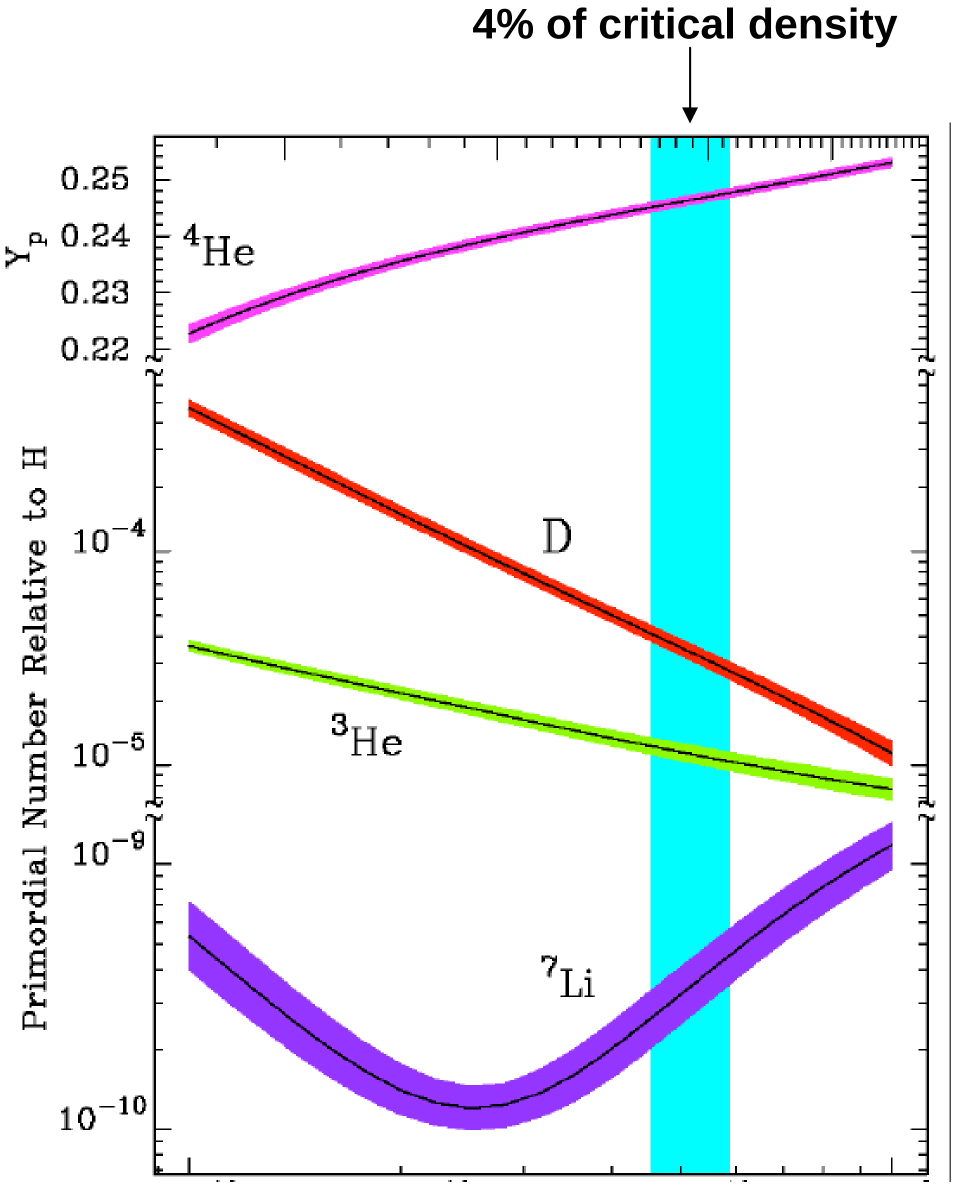
Much of the cluster dark matter must be **non-baryonic** (not made of atoms)

Lensing maps are consistent with the limits from light element Formation (from the 1980s):

Predicted abundances depend on the density of **baryons** (protons + neutrons).

These ***only*** match observed abundances if the density of baryonic mass is about 4% of the critical density.

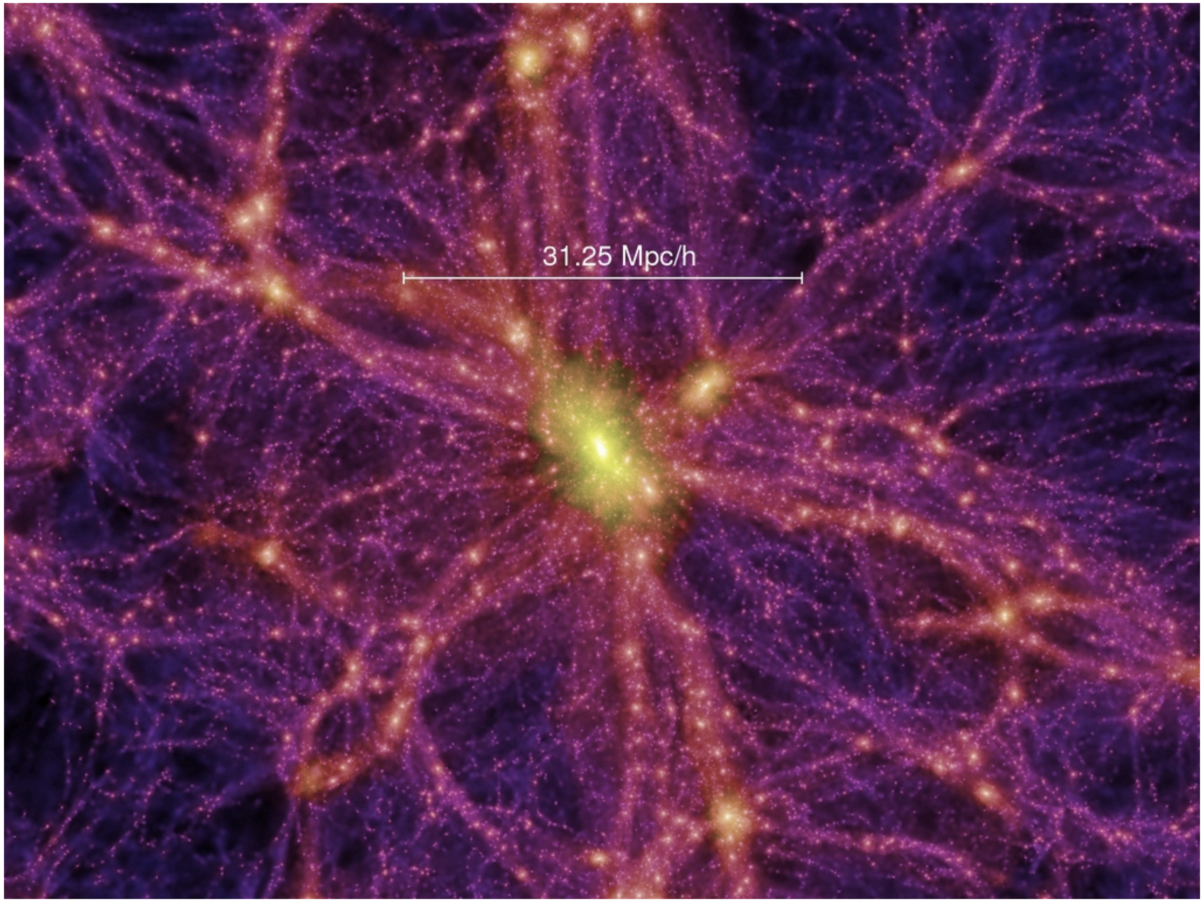
This also fits well with the value of H_0 measured by HST.



But it means that most dark matter is non-baryonic.

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

Computer models of how galaxies form tell us that it must be **cold** – i.e. not moving at relativistic speeds.



Millennium run computer simulation by the Virgo consortium

Cold dark matter

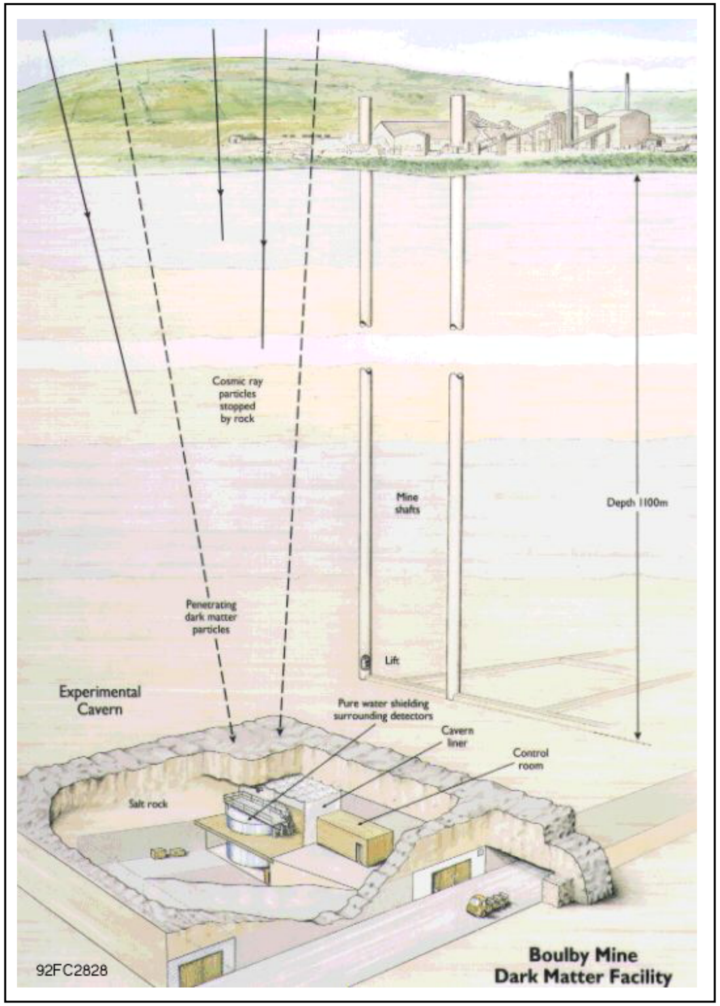
This rules out **neutrinos** (too hot) as a dark matter candidate.

So CDM must be **weakly interacting**, which makes it hard to detect.

Most candidates are exotic elementary particles (e.g. from **supersymmetry**):

- Axions
- Monopoles
- WIMPZillas
- Planck relics
- Quark nuggets
- Primordial black holes
- Neutralinos
- Cosmic strings….

Watch this space….



The **UK Dark Matter Experiment** has tried to find DM directly.

http://hepwww.rl.ac.uk/ukdmc/ukdmc.html

Any other possible theories?...

MOND = MOdified Newtonian Dynamics

This explains flat galaxy rotation curves by modifying Newton’s second law, $\vec{F} = m\vec{a}$

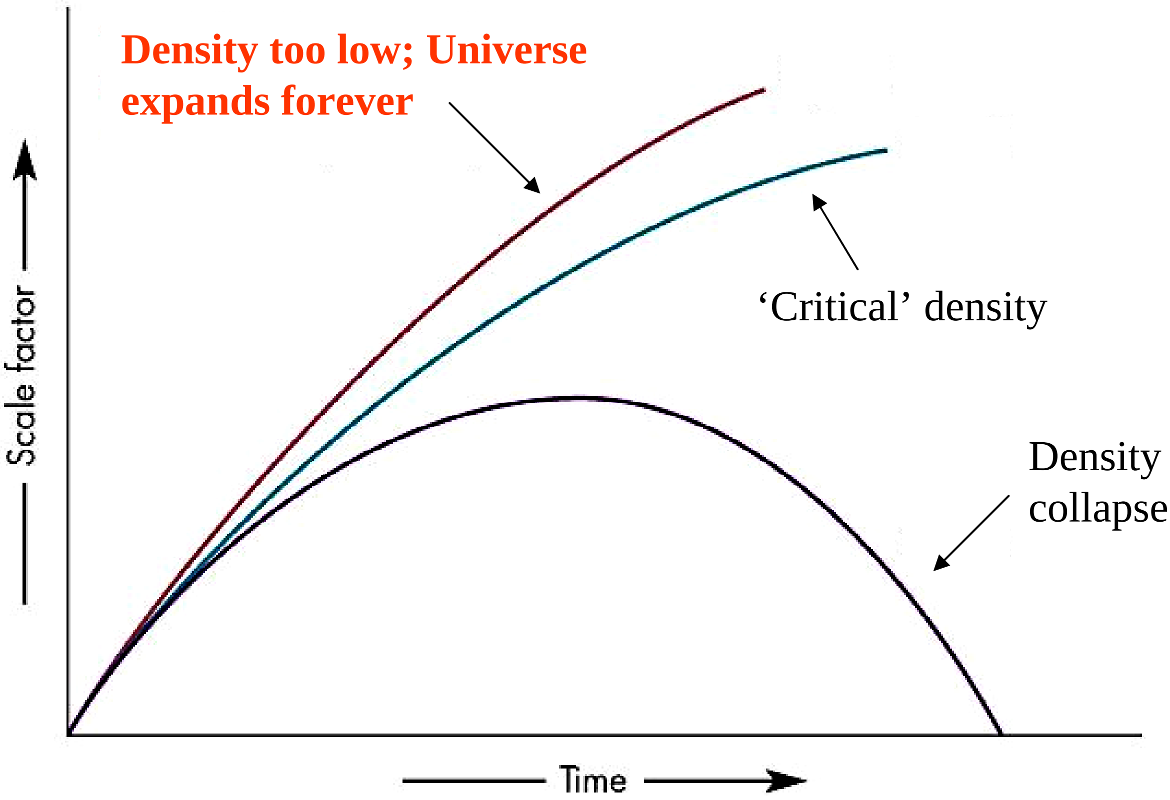
MOND has had many critics because it lacks a deep physical foundation (like GR) but this problem has been largely solved by Bekenstein’s TeVeS theory (2004).

Challenges to MOND:

The pattern of temperature variations in the CMBR (see later)

Large-scale mapping of dark matter with gravitational lensing

Whatever the dark matter is, it should be slowing down the cosmic expansion



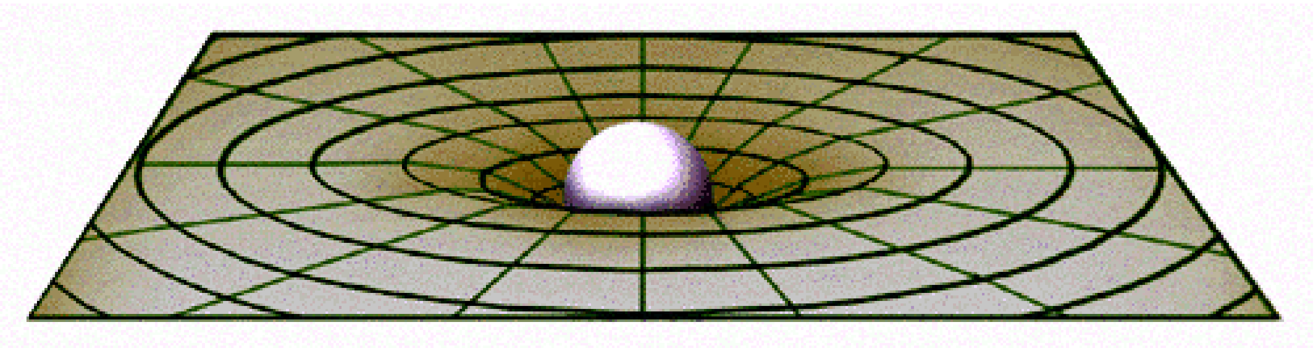
Density too low; Universe expands forever

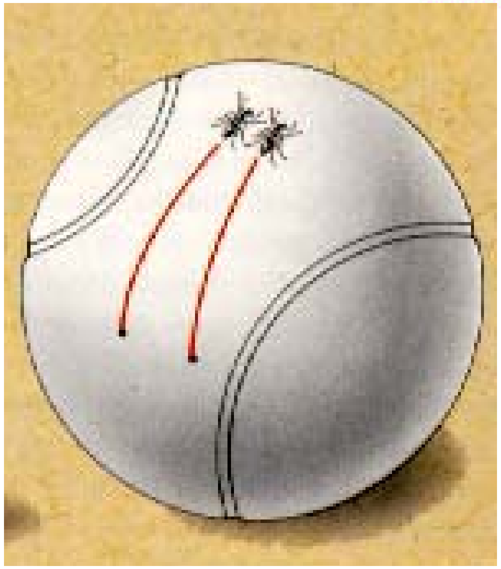
'Critical' density

Density high enough to cause re-collapse, leading to 'Big Crunch'

So, *is* the expansion slowing down?....

Answer depends on the **shape** of the Universe





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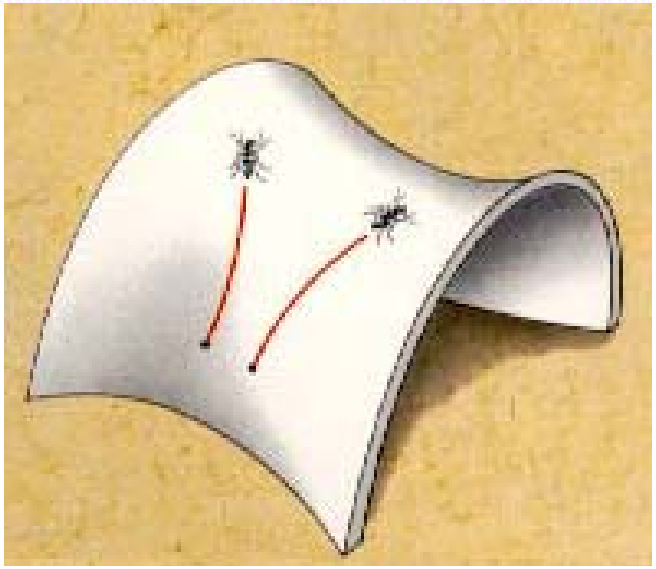

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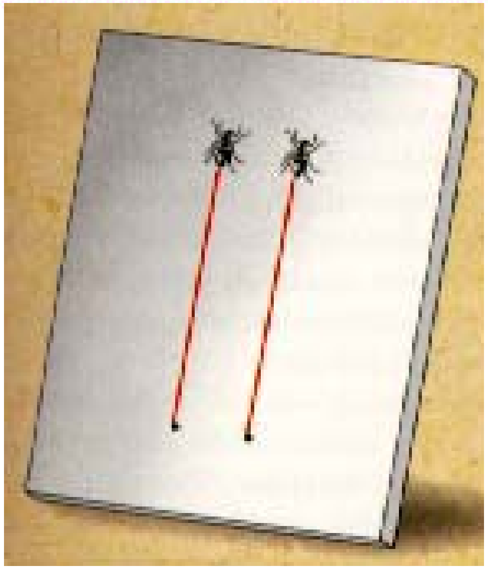
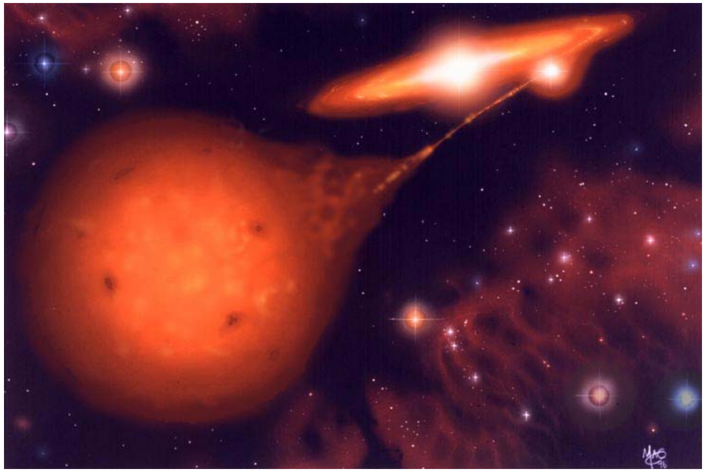
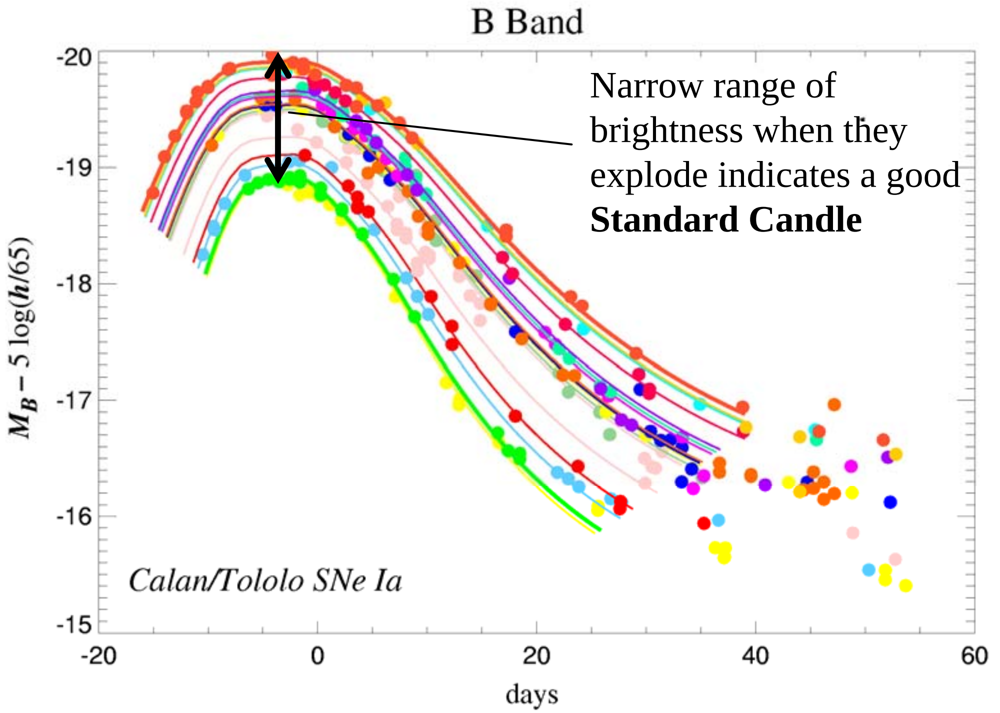


Flat

Is the Universe speeding up or slowing down?

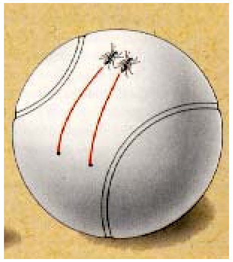


We can answer this question using **supernovae**



Narrow range of brightness when they explode indicates a good **Standard Candle**

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



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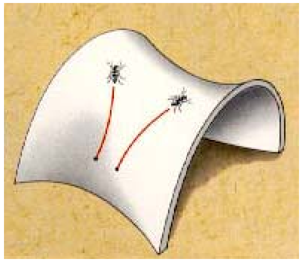

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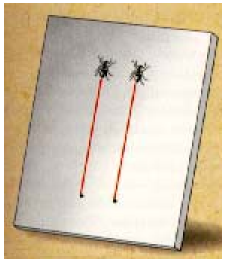
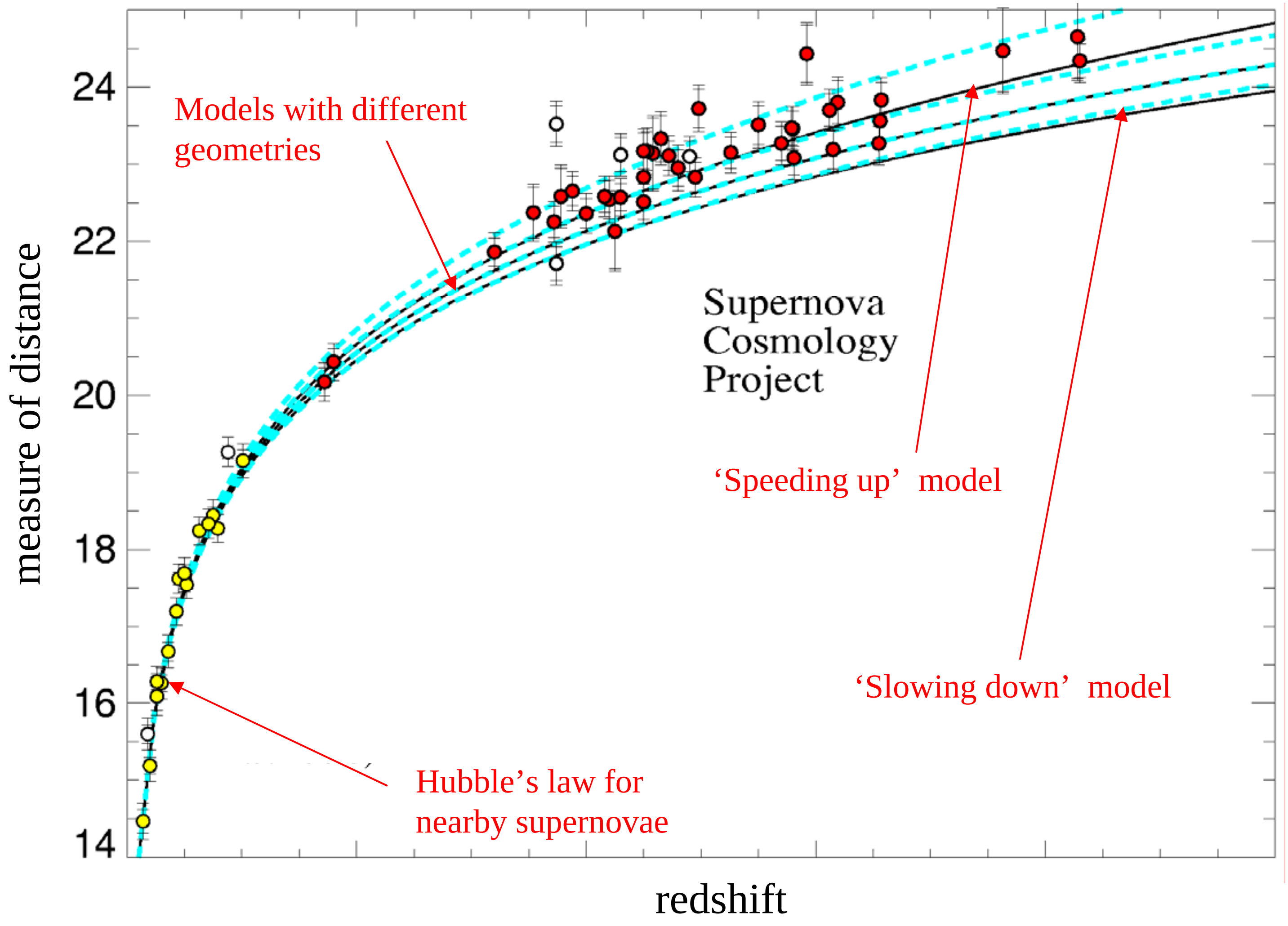


Flat

‘Hubble diagram’ of distant supernovae

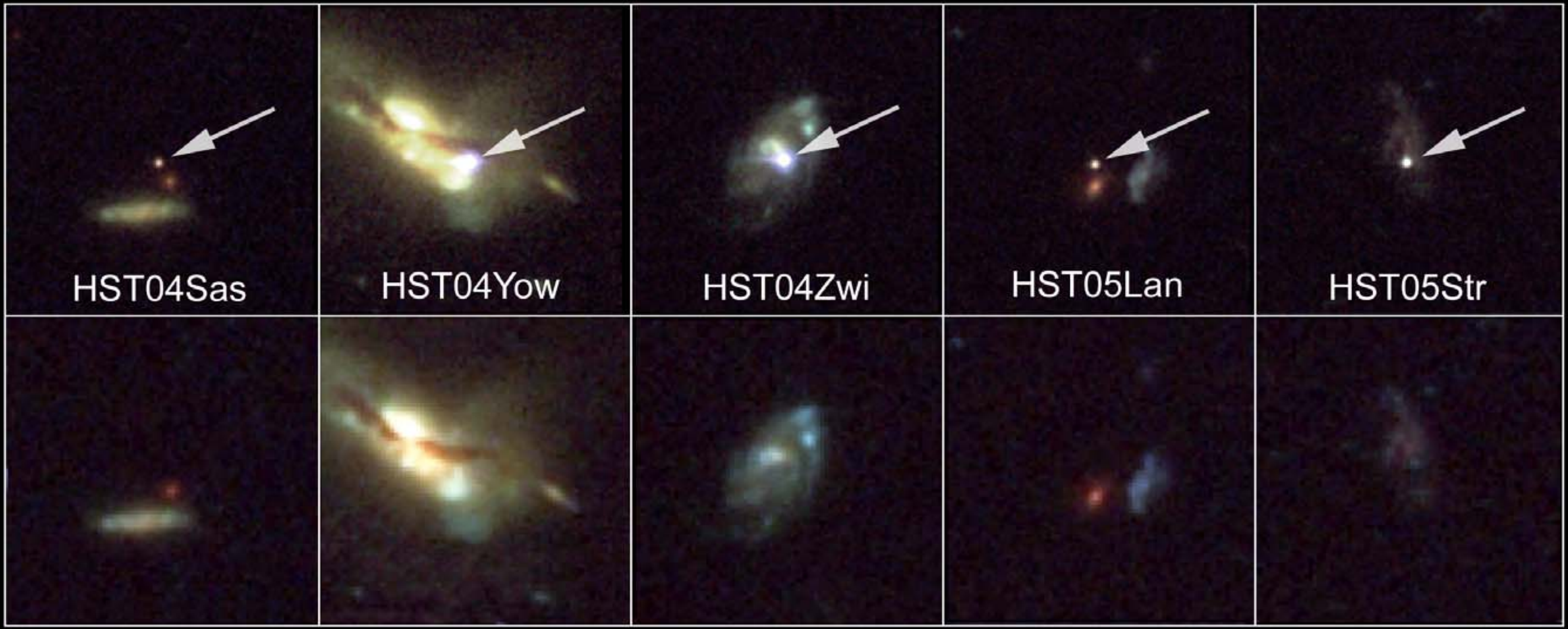


Models with different geometries

‘Speeding up’ model

‘Slowing down’ model

Hubble’s law for nearby supernovae



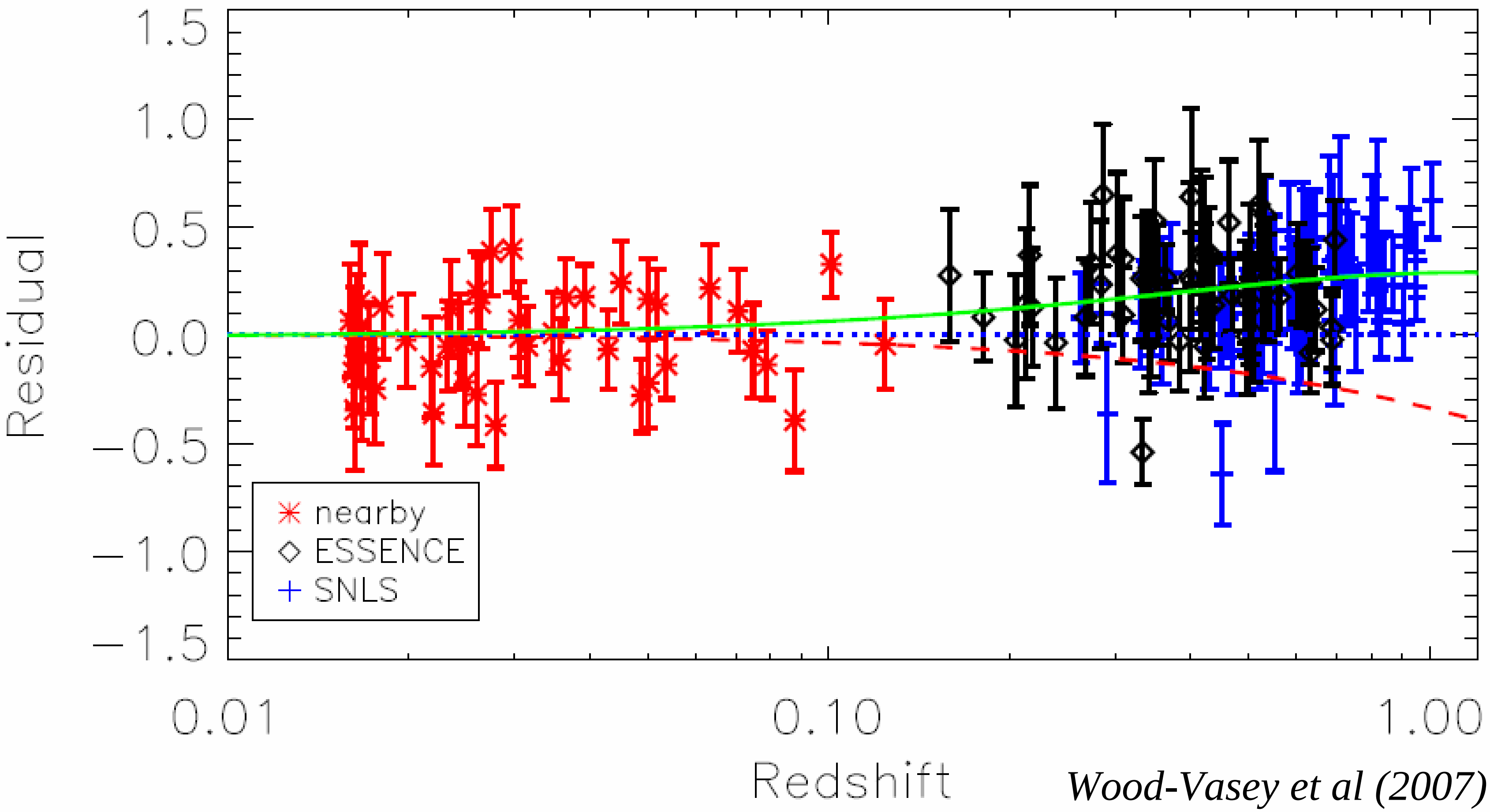
Host Galaxies of Distant Supernovae

Hubble Space Telescope ▪ Advanced Camera for Surveys

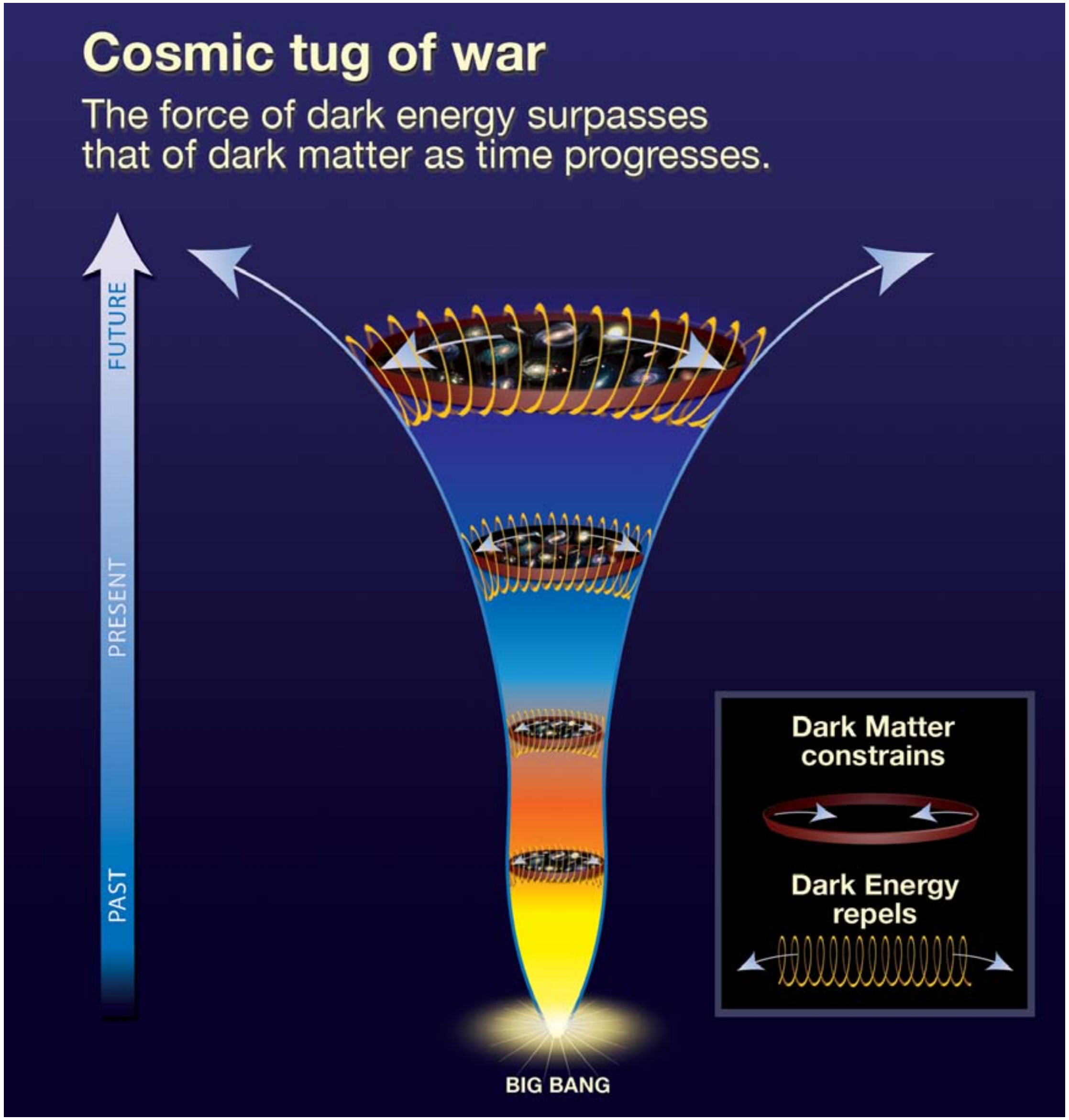
NASA, ESA, and A. Riess (STScI)

STScI-PRC06-52

Latest results: still speeding up!!!



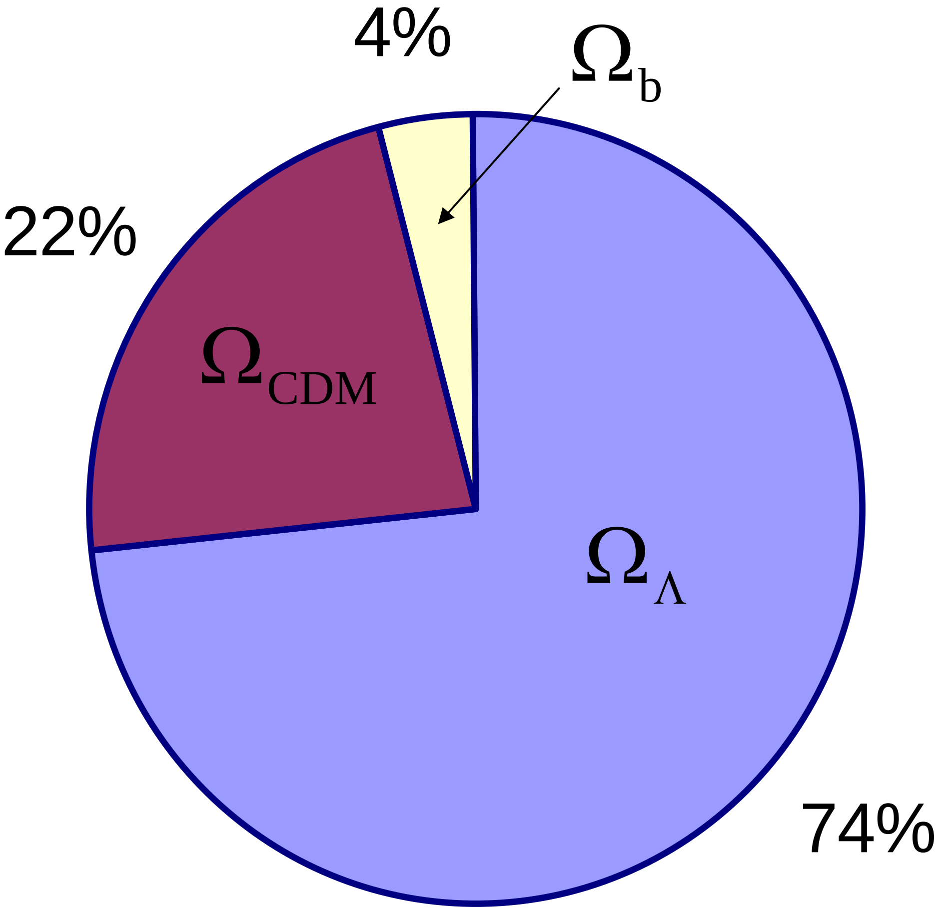
Wood-Vasey et al (2007)



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

Einstein’s “cosmological constant”?...

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



Einstein’s “cosmological constant”?...

Einstein introduced his cosmological constant Λ to keep the Universe **static**. Mathematically, he could ‘tune’ the value to do this, although it was **unstable**.

(Later he would refer to this as his ‘greatest blunder’)

A different value of Λ in Einstein’s equations could make the expansion proceed even ***faster*** – acting like ‘anti-gravity’.

What, physically, could produce such an effect?...

The quantum vacuum

- In quantum physics empty space isn’t empty, but a ‘sea’ of virtual particle-antiparticle pairs continually popping in and out of existence.

- The lowest energy state of a quantum system is not zero (crudely, this would violate the Heisenberg uncertainty principle) and could be large (see later).

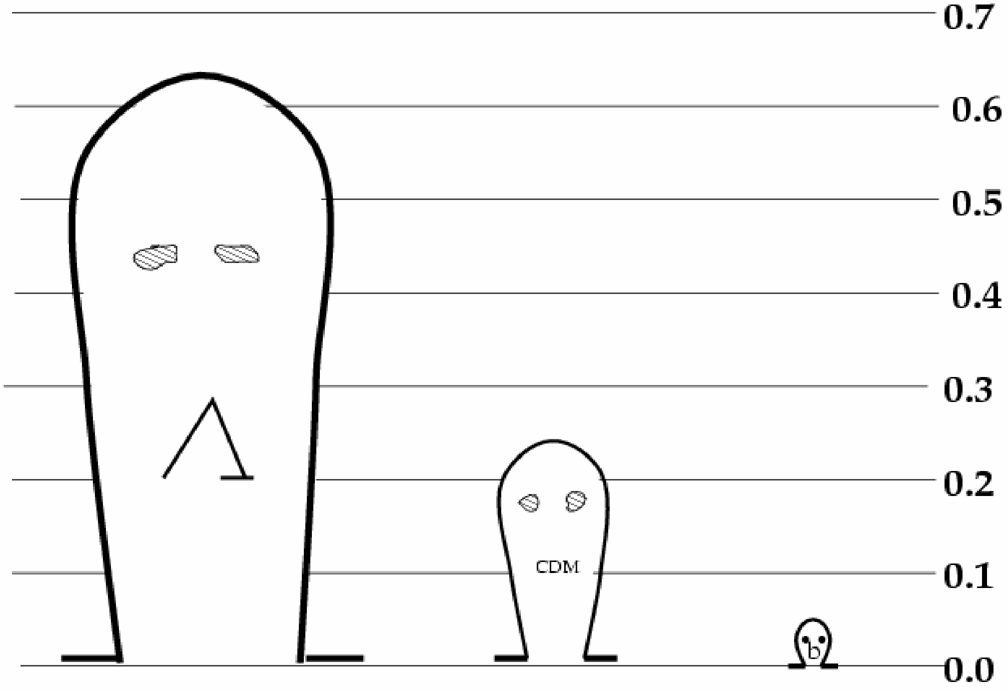
- **In order that the zero-point energy of the vacuum looks the same to all uniformly moving observers** (recall P1X Relativity lectures) **it must be *repulsive* – i.e. it causes accelerated expansion**

Cosmology's Most Wanted

ΛCDM

Figure 3. A line up of cosmological culprits Ω_Λ is the big shot controlling the Universe. He's going to make it blow up. Ω_{CDM} would like to make the Universe collapse but can't compete with Ω_Λ. Ω_b just follows Ω_{CDM} around. Like all dangerous criminals, one can never be sure of Ω_Λ until he is behind bars. The CMB police is being beefed up. Hundreds of heroic CMB observers are now planning his capture.

From Lineweaver (1998)



Ω_Λ	Ω_{CDM}	Ω_b
cosmological constant energy of the vacuum He never clumps His evil plan is to blow up the Universe	cold dark matter He likes to clump but has never been detected directly His evil plan is to make the Universe collapse	normal baryonic matter a pawn in the cosmic game who just follows CDM around. He thinks he's a complex life form but is really just a bunch of hydrogen

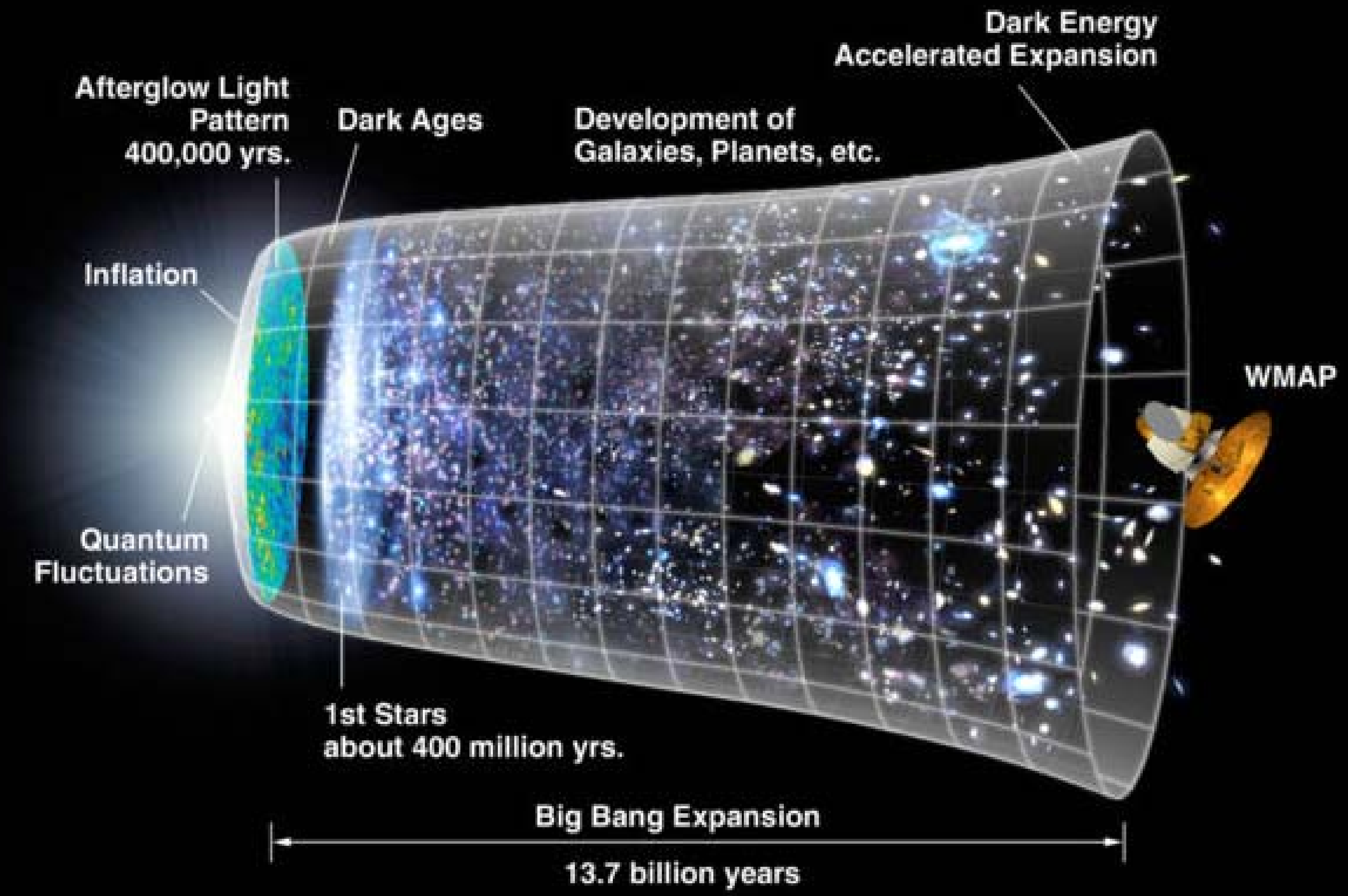
Have we been there before?...

Period of **inflation**: accelerated expansion in the very early Universe ($t < 10^{-34}\,\mathrm{s}$), first proposed in 1980.

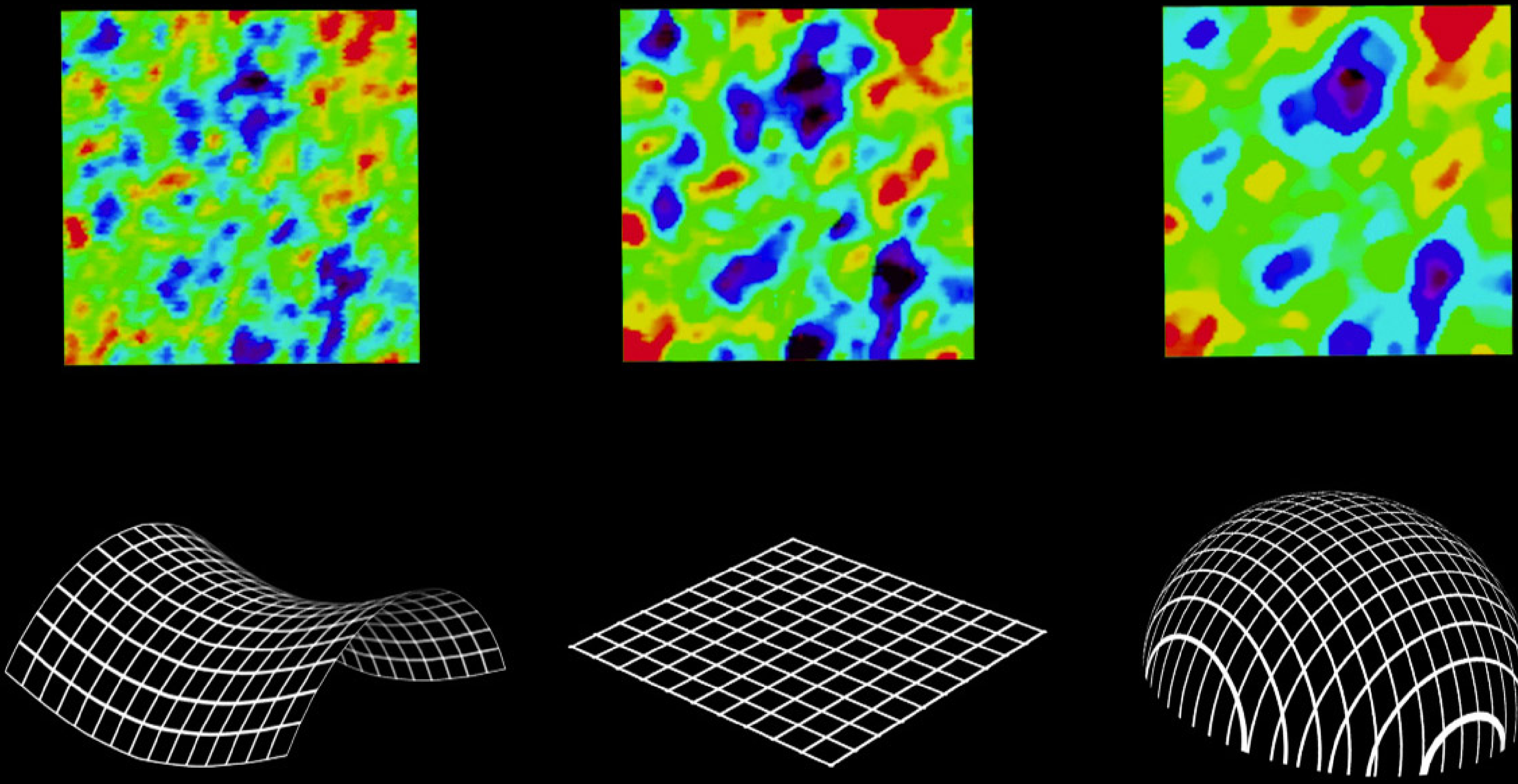
Inflation not yet accepted by everyone, but explains a lot of puzzles:

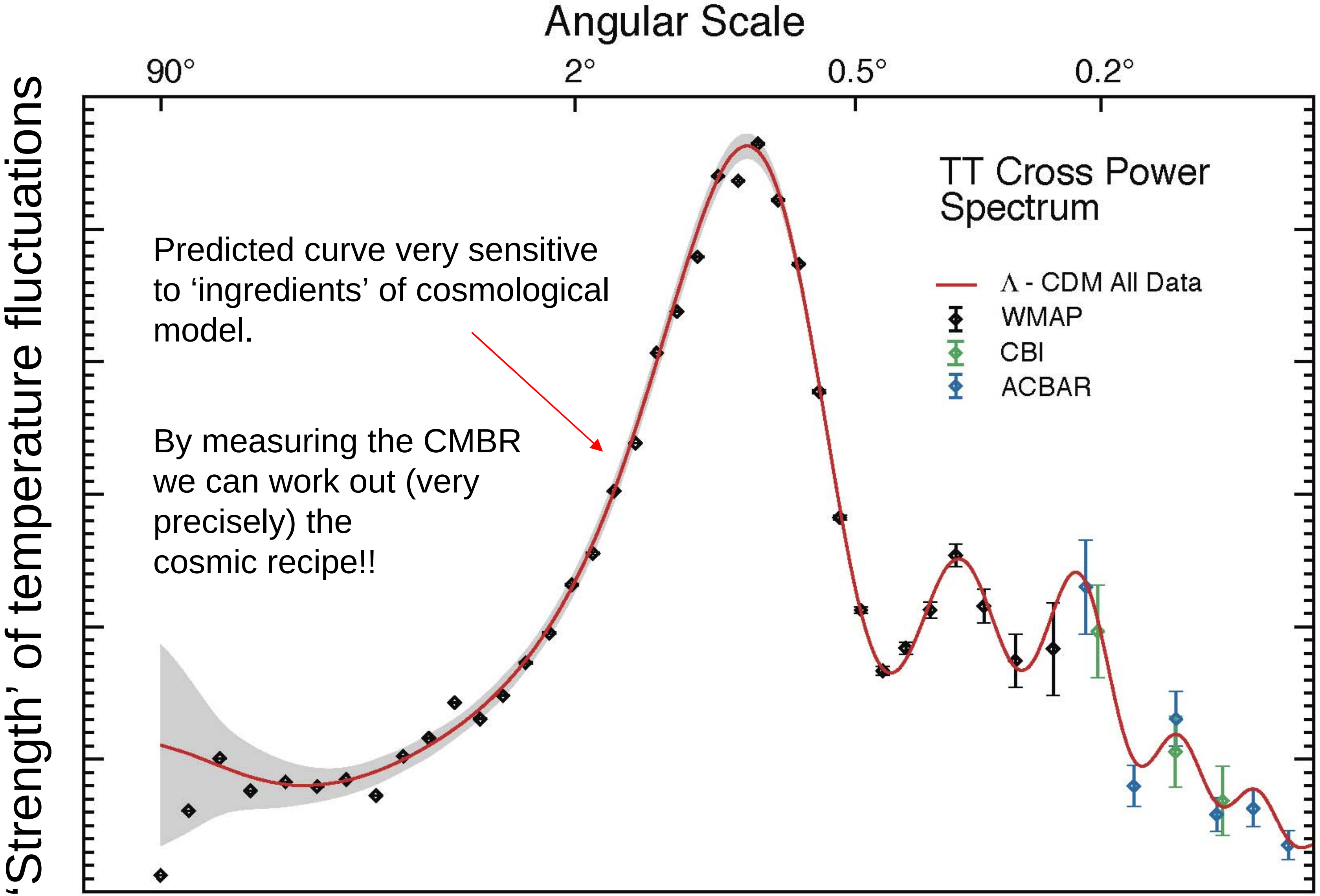
- why is $\Omega_\Lambda + \Omega_{\mathrm{matter}} = 1$?
- why is the CMBR so smooth?
- where do the tiny CMBR ripples come from?

For more info see Wikipedia entry on 'cosmic inflation'


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





Predicted curve very sensitive to 'ingredients' of cosmological model.

By measuring the CMBR we can work out (very precisely) the cosmic recipe!!

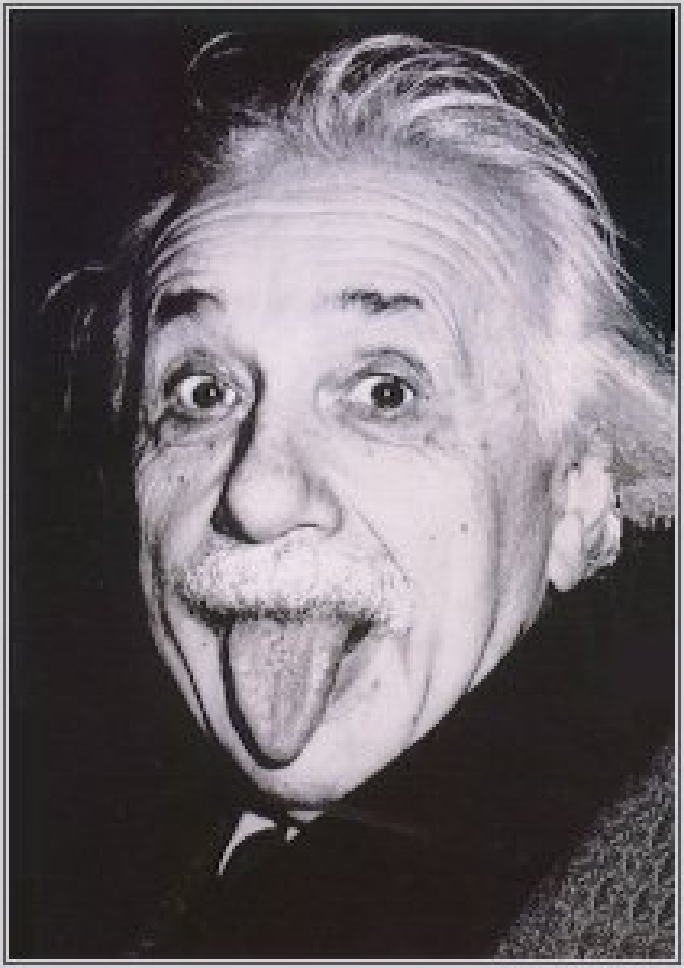
Very strong support for the Concordance Model

The future of the Universe?

No

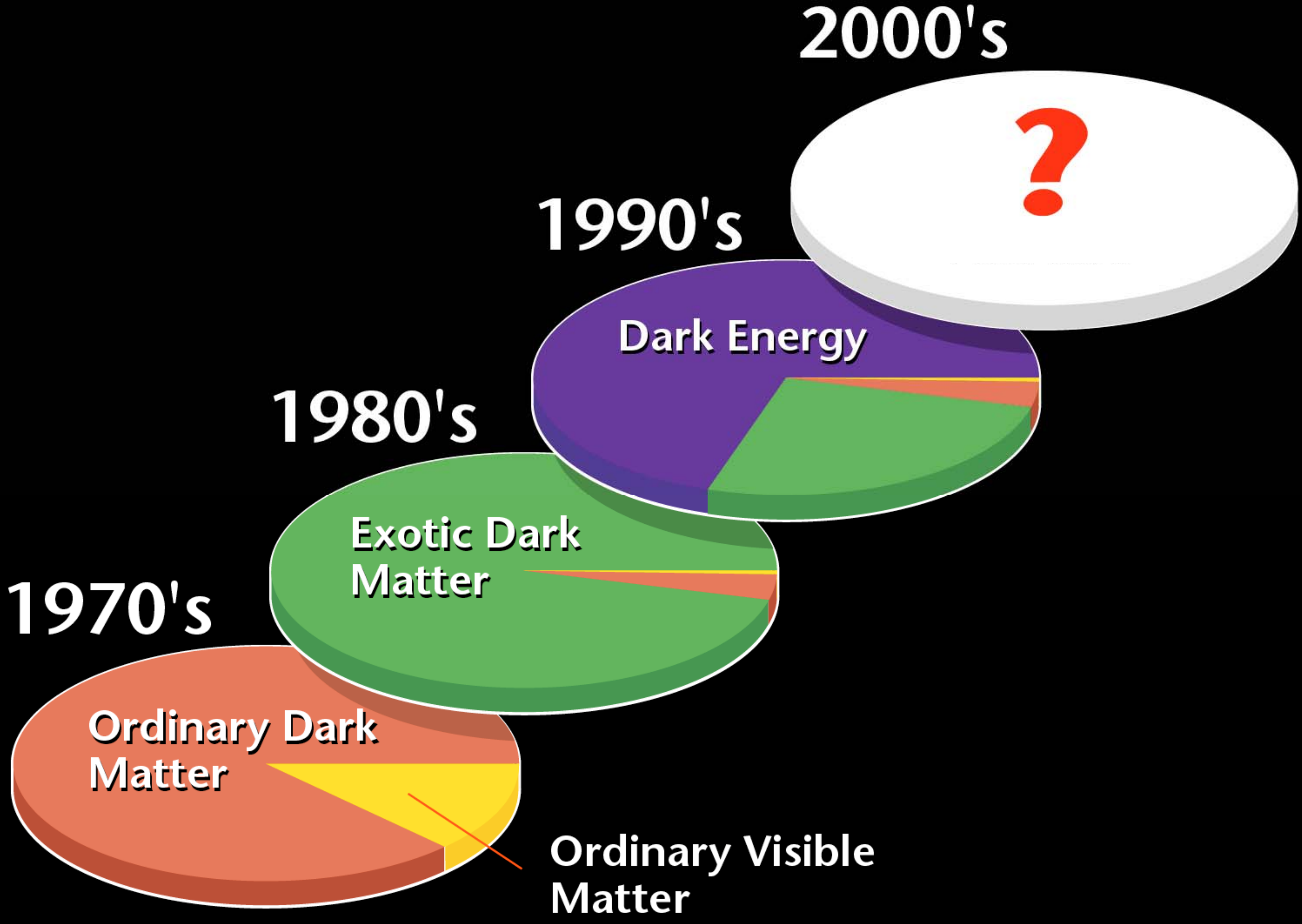
Big Crunch!!!

The future of cosmology?...



“What exactly *are* dark matter and dark energy?”

Was Einstein right all along?...


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

Cosmological Constant problem

What's wrong with Λ as the source of Dark Energy anyway?...

What we observe

$$\rho_\Lambda \;=\; \Omega_\Lambda \times \frac{3H_0{}^2}{8\pi G}$$

$$= \quad 0.74 \times \frac{3\times\left(72/3.086\times10^{19}\right)^2}{8\pi\times6.673\times10^{-11}} \ \mathrm{kg\,m^{-3}}$$

$$= \quad 7.2\times10^{-27}\ \mathrm{kg\,m^{-3}}$$

What we might expect from theory…

A natural length scale for quantum effects is the **Planck length**.

This is the (unique) combination of $G, c, \hbar$ with dimensions of length.

Reduced Planck constant $\hbar = \frac{h}{2\pi} = 1.055 \times 10^{-34}$ Js

Planck length $\ell_{\text{Planck}} = \sqrt{\frac{\hbar G}{c^3}} = 1.616 \times 10^{-35}\,\text{m}$

Similarly, **Planck mass** $m_{\text{Planck}} = \sqrt{\frac{\hbar c}{G}} = 2.176 \times 10^{-8}\,\text{kg}$

So a natural scale for the density of the quantum vacuum is

$$\rho_{\text{vacuum}} = \frac{m_{\text{Planck}}}{\left(\ell_{\text{Planck}}\right)^{3}} = 5.175\times10^{96}\ \text{kgm}^{-3}$$

But this differs from the measured density by more than

120 orders of magnitude!!!!!

Why is the vacuum energy so incredibly small compared with its naturally prediction?

Would it not make more sense if it were exactly zero?....

This question has led to more general Dark Energy or Quintessence models that might avoid this ‘fine tuning’:

Convenient description: ‘Equation of State’

$$P = w\,\rho$$

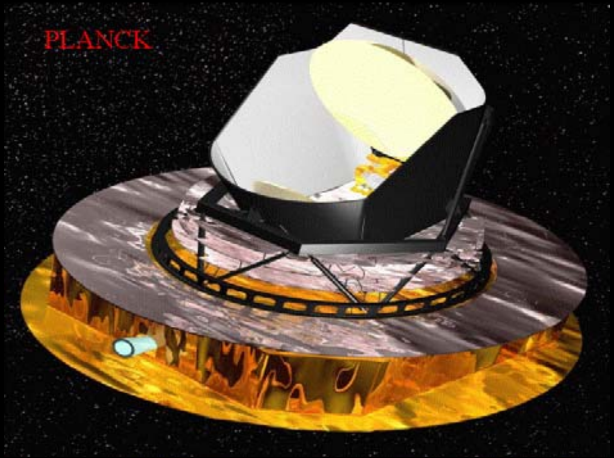
Density

Pressure

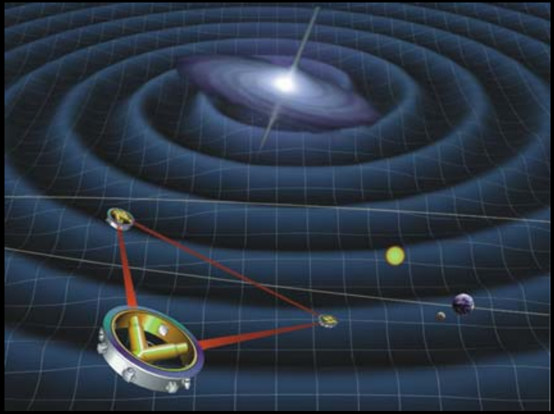
Can we measure $w(t)$?

This is a major goal of many space missions or ground-based facilities planned for the next 10 – 20 years.

	w_i
Dust	0
Radiation	1/3
Curvature	-1/3
‘Lambda’	-1
Quintessence	$w(t)$

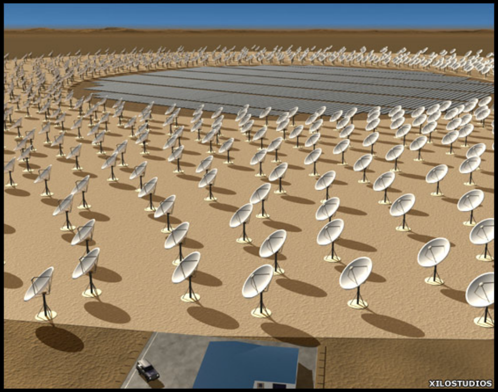


Planck

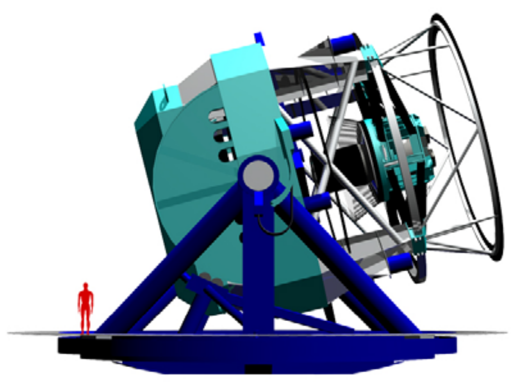


LISA

JDEM



SKA



LSST

See moodle site for weblinks to all these projects, and more…