

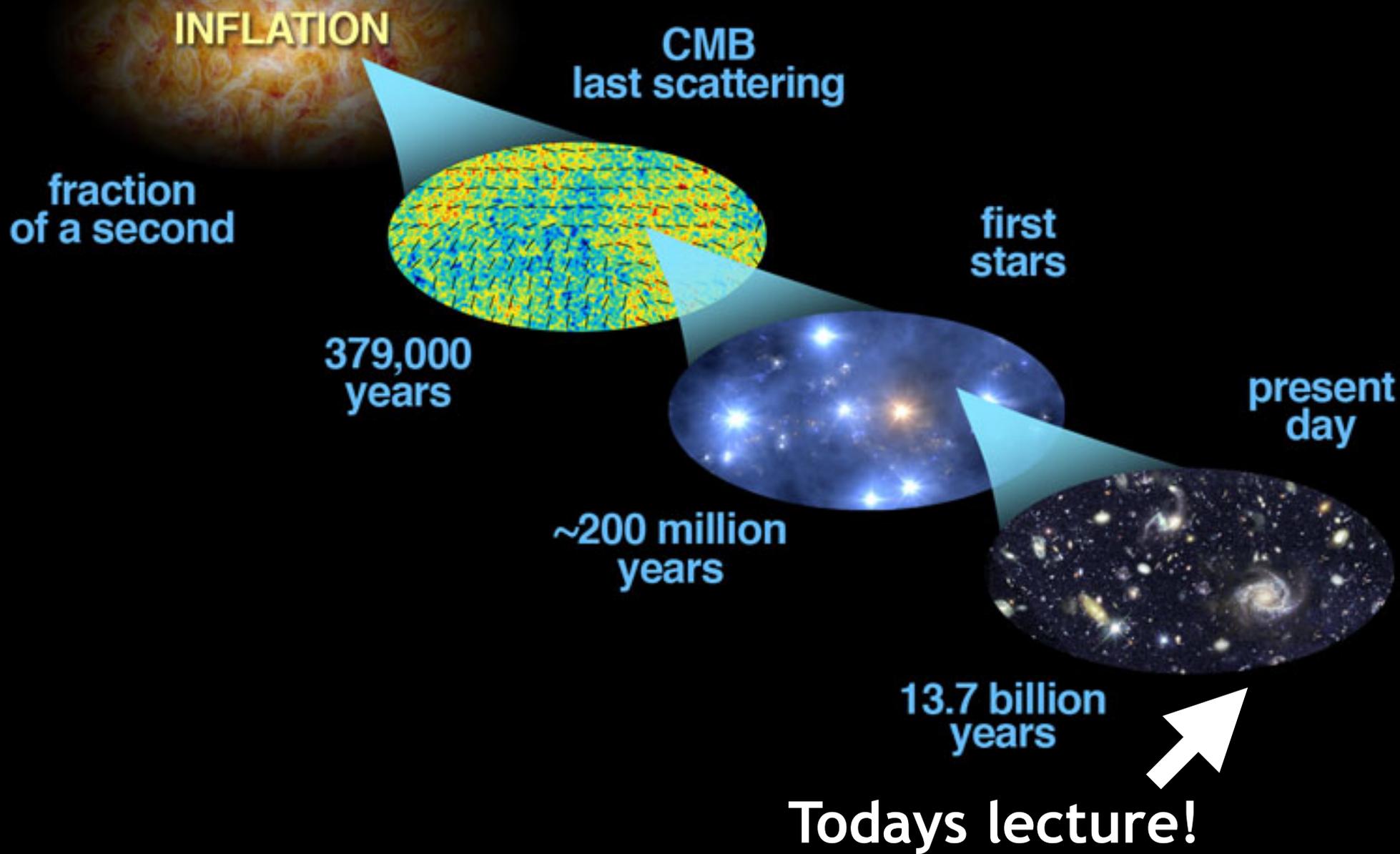
Compton Lectures Fall 2014
Shining light on the Dark
Side of the Universe

What is Dark Energy?

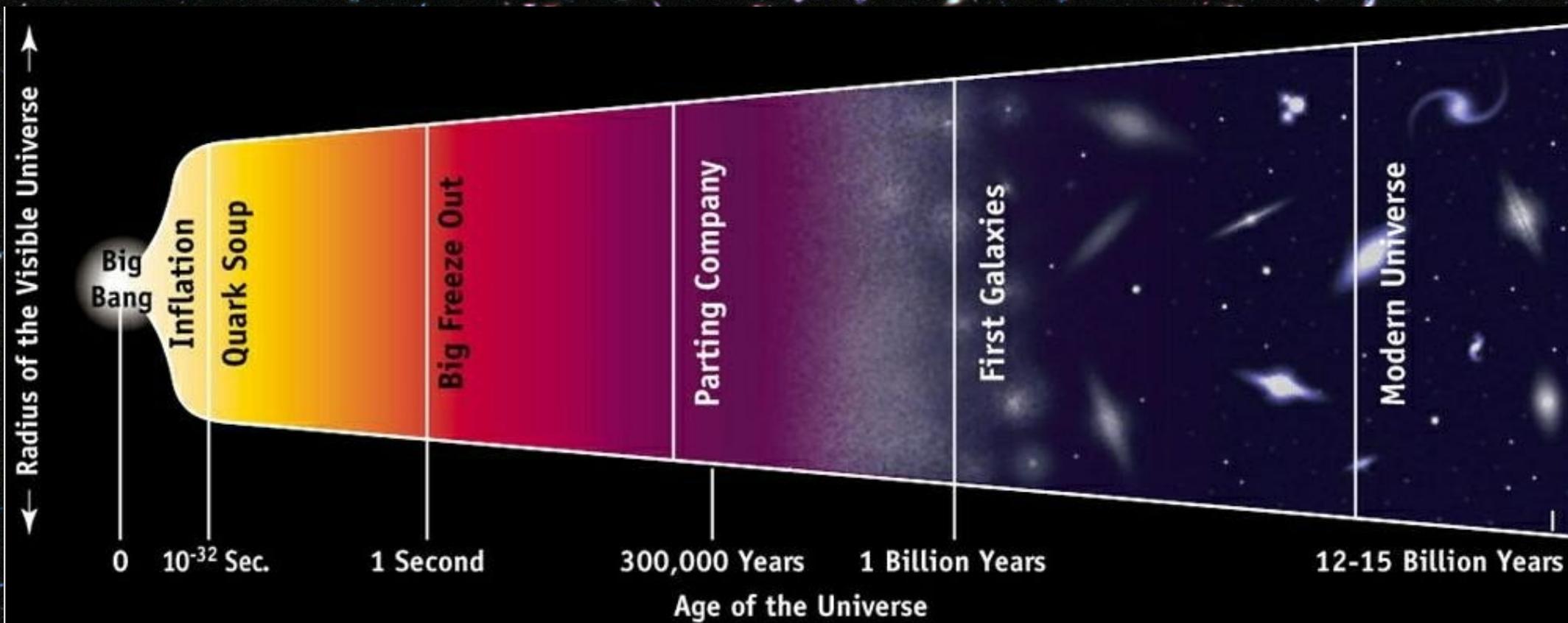
Elise Jennings

**Kavli Institute for Cosmological Physics &
Enrico Fermi Institute
University of Chicago**

The Evolving Universe



Epochs of the Universe



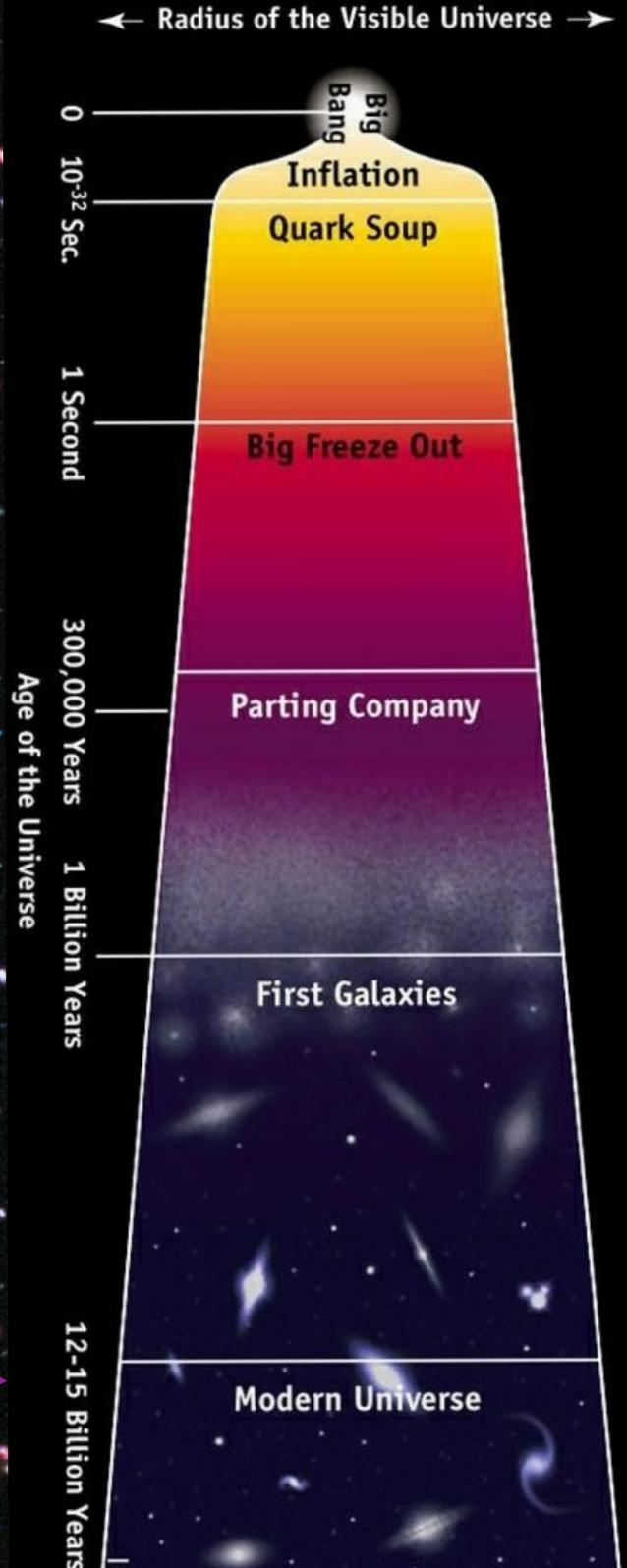
Epochs of the Universe

Dark Energy Era

5 billion years ago

Accelerated expansion.

LSS in superclusters.



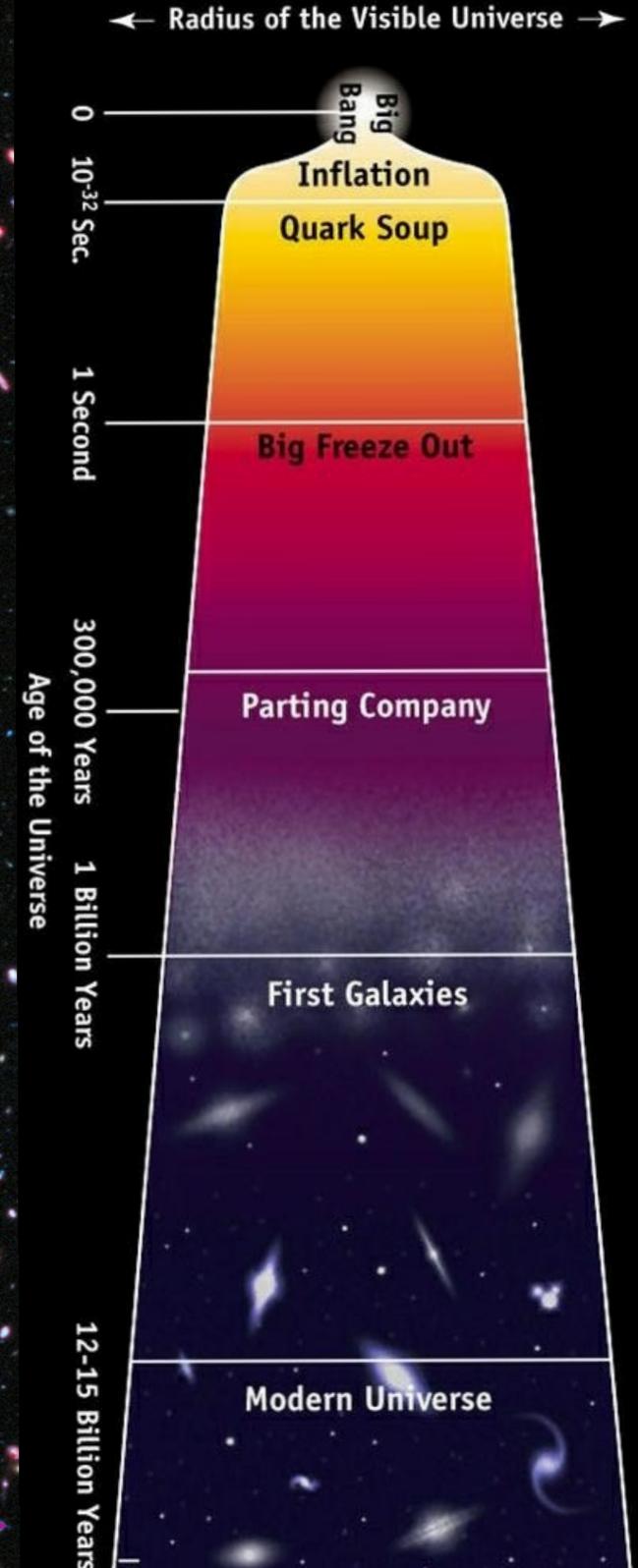
Epochs of the Universe

The End?

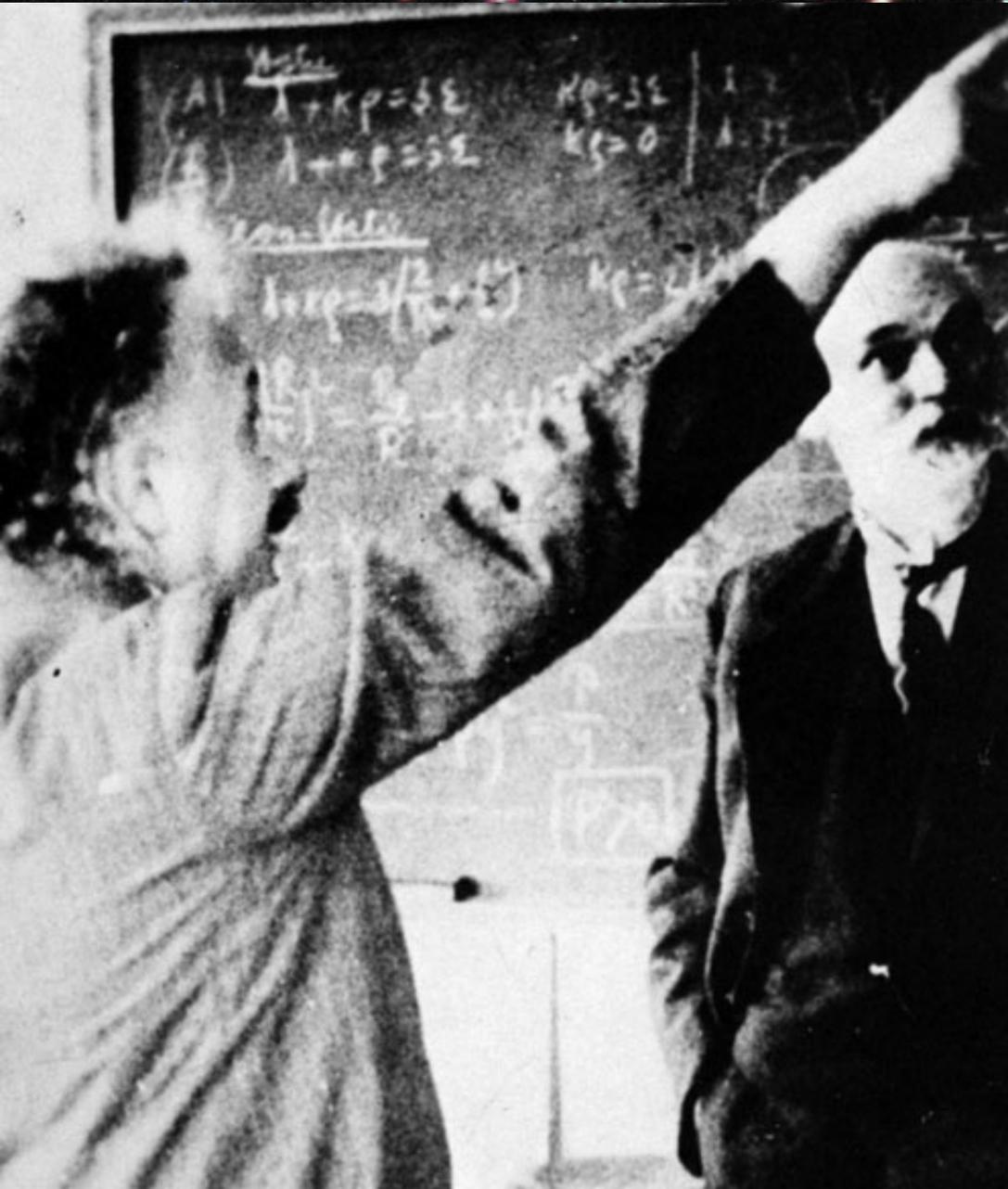
**Milky way & Andromeda collide:
few Gyr**

**Cosmic blackout:
100 Gyr**

**Stellar extinction:
1000 Gyr**



Story of the expanding Universe



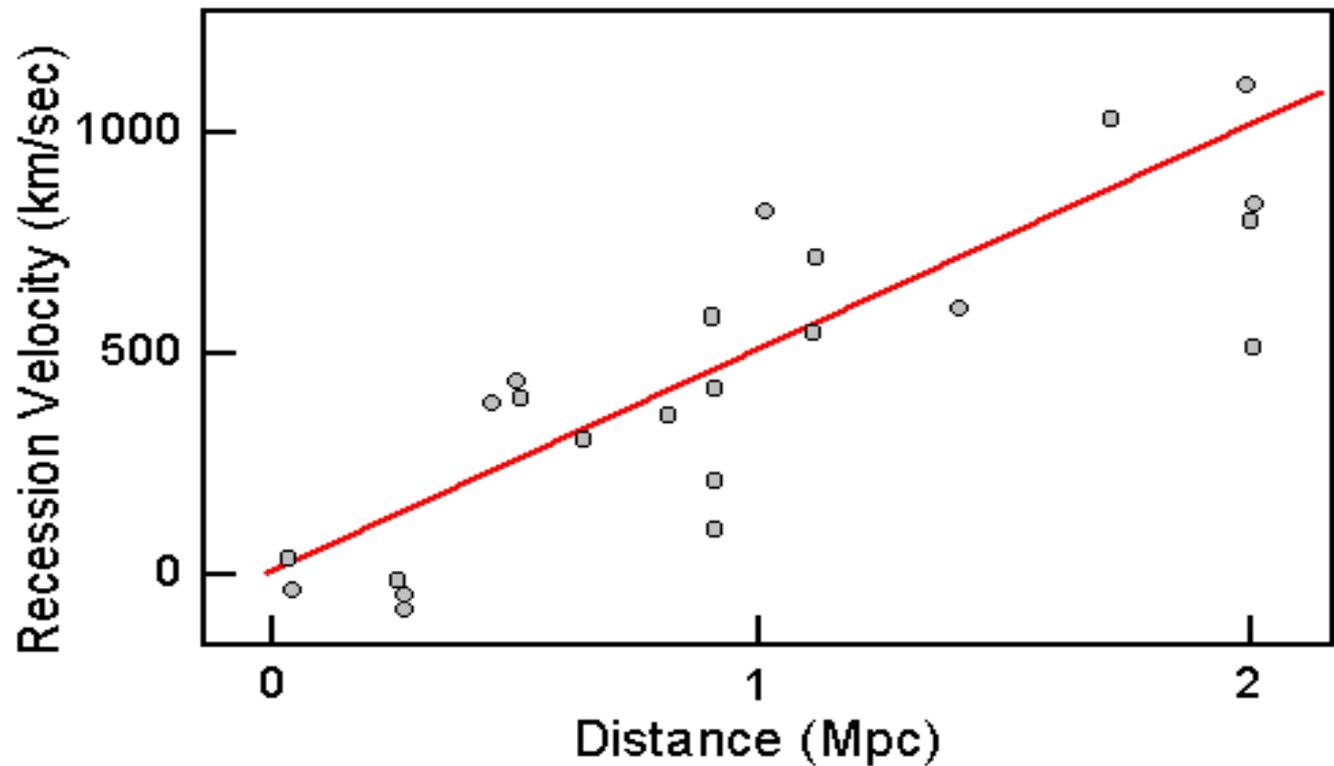
**1915 Einstein's theory
General Relativity
predicted a dynamic
expanding Universe**

1923 Hubble's observations

**The farther away a galaxy is,
the faster it moves away from us.**

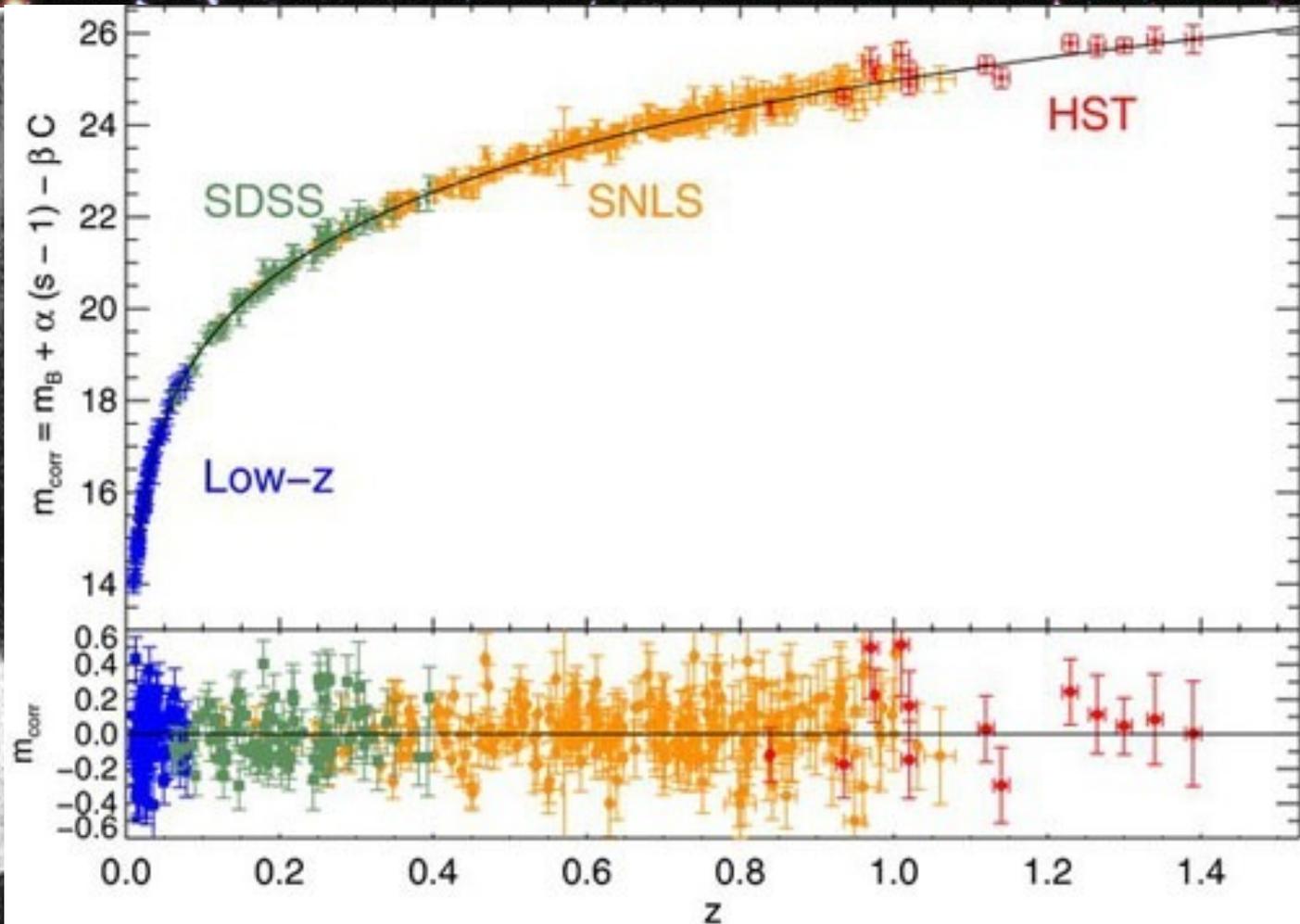


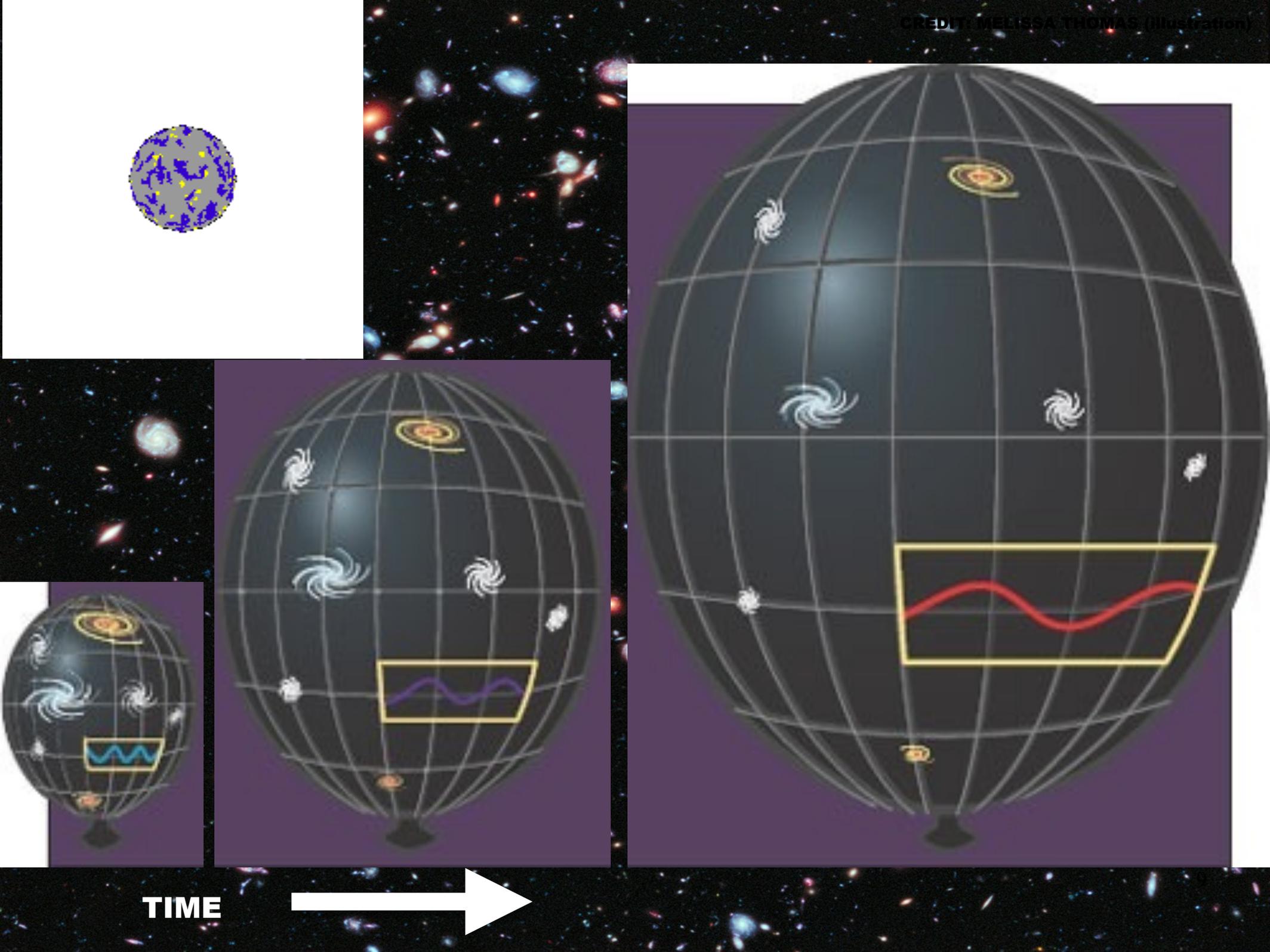
Hubble's Data (1929)



1923 Hubble's observations

The farther away a galaxy is,
the faster it moves away from us.





TIME



Mass/energy in the Universe

$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

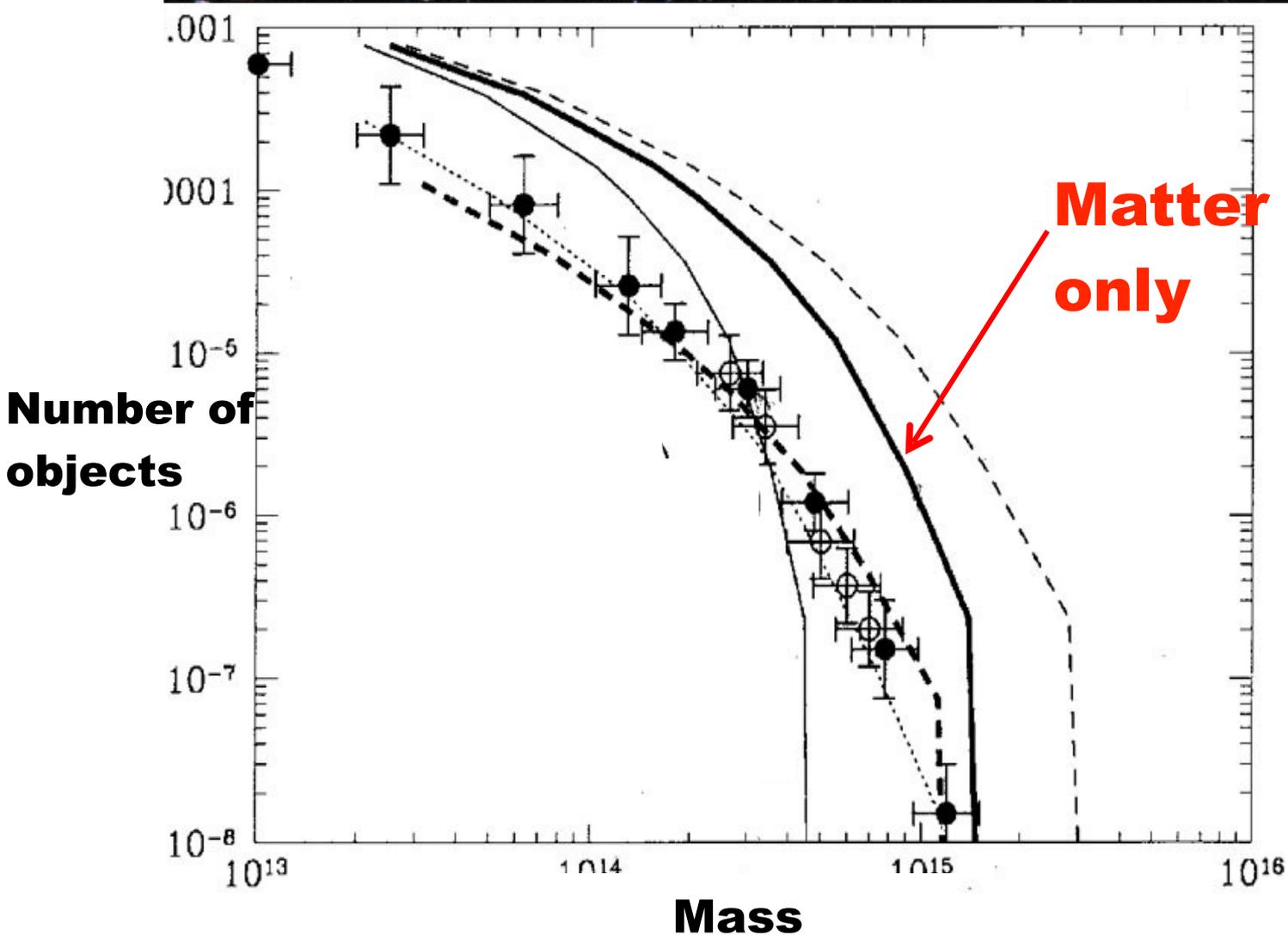
Structure of space-time

Some constants

**General Relativity describes the connection between
the expansion of the Universe &
the energy in the Universe**

Early 1990's

Some observations didn't make sense in the story of the expanding Universe...



Bahcall & Cen 1992

Cosmic age problem

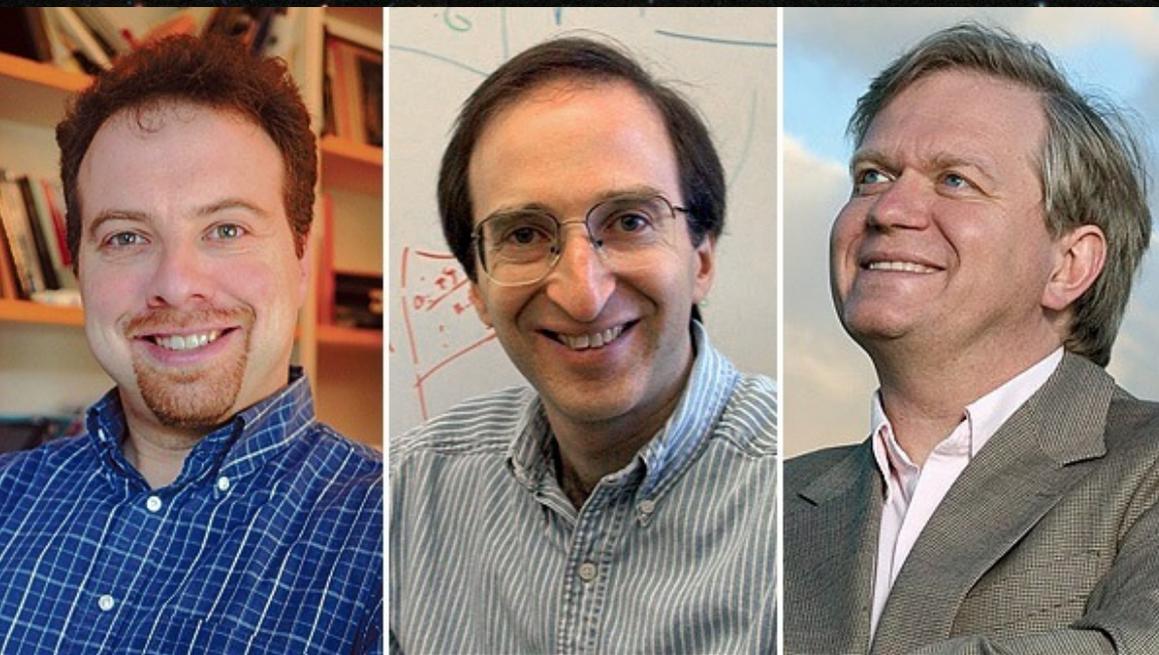
Predicted age of the Universe with matter only

$$8.2 \text{ Gyr} < t_0 < 10.2 \text{ Gyr}$$

**Measured age of the
oldest star clusters**

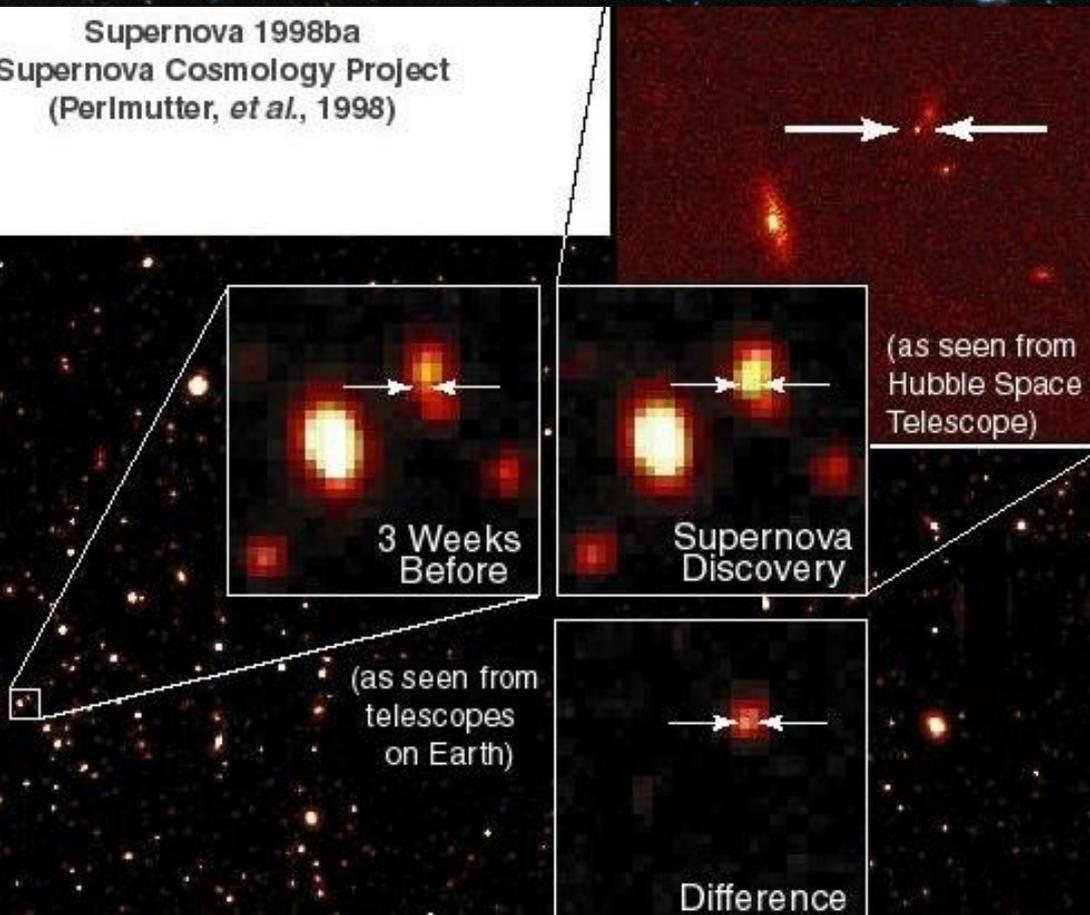
$$15.2 \pm 3.5 \text{ Gyr}$$

Cowan et al 1997



**Adam Riess, Saul Perlmutter
and Brian Schmidt**

Supernova 1982ba
Supernova Cosmology Project
(Perlmutter, *et al.*, 1998)

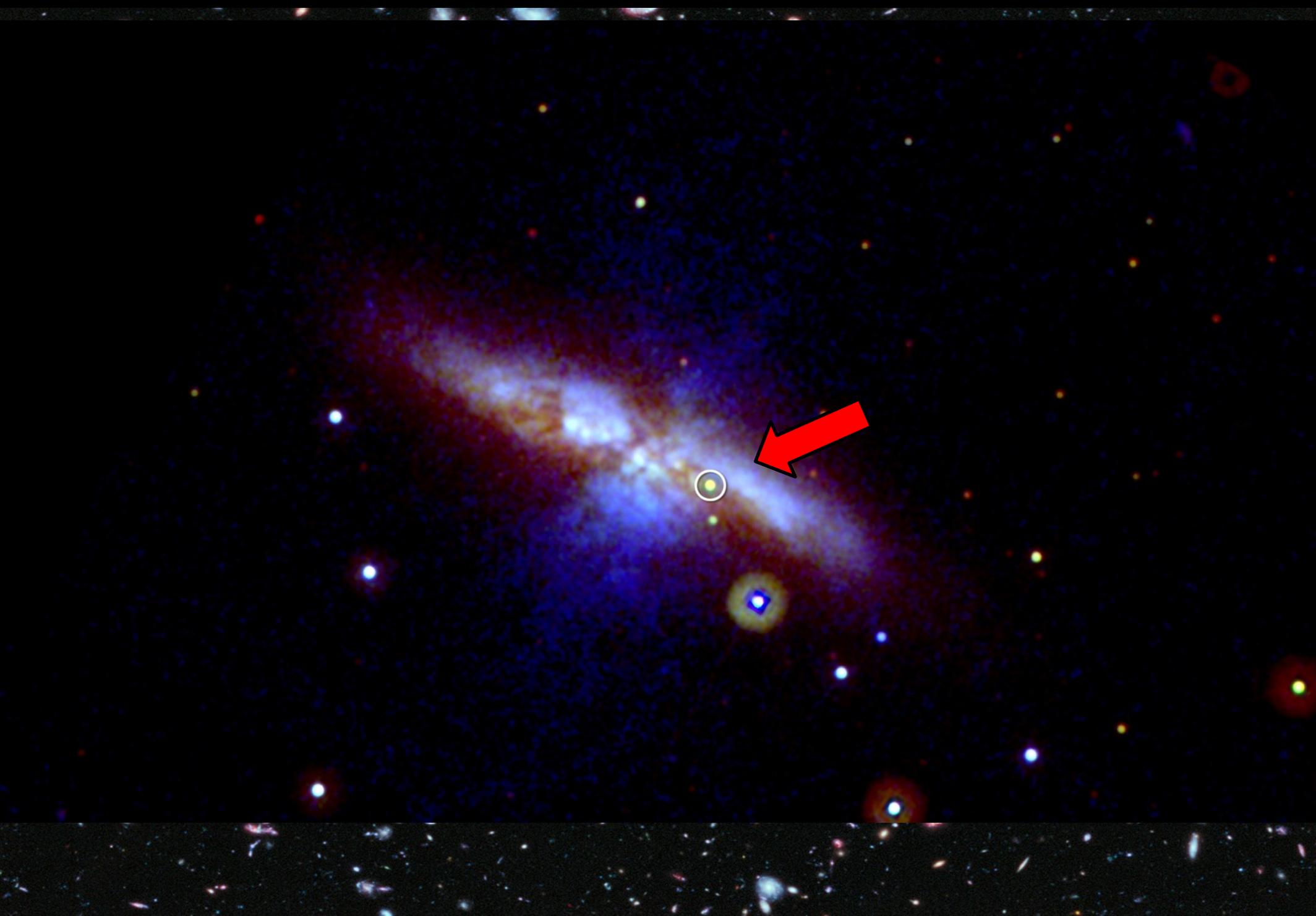


**Supernovae were dimmer
then expected from the
predictions of
General relativity + dark
matter only**

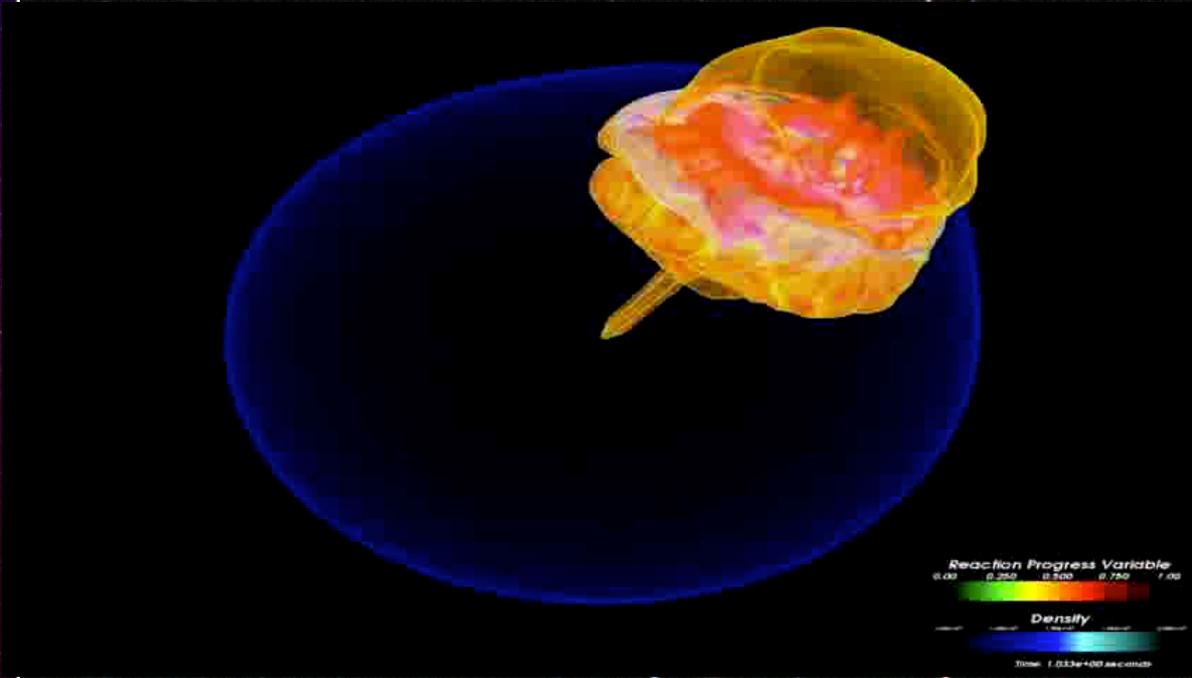
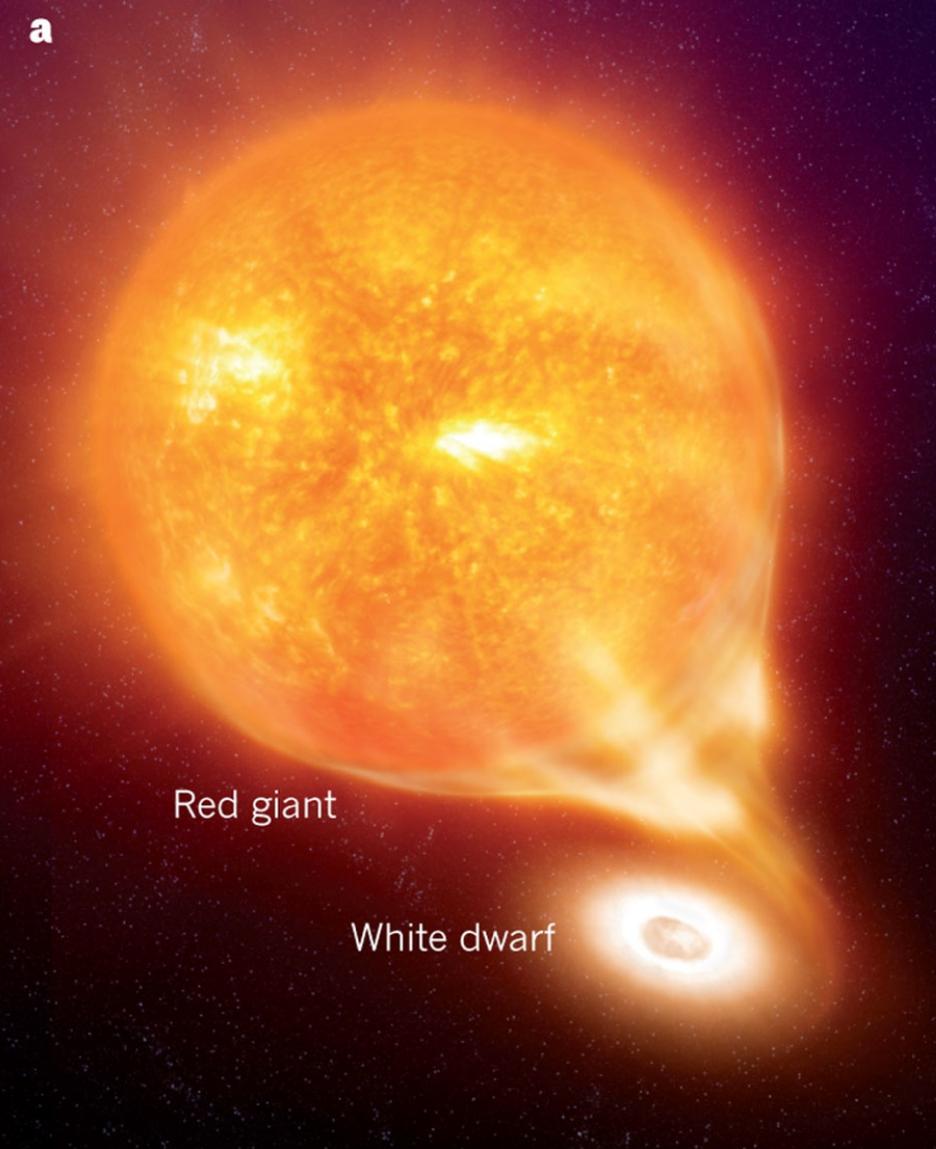
M82 The Cigar Galaxy 2013



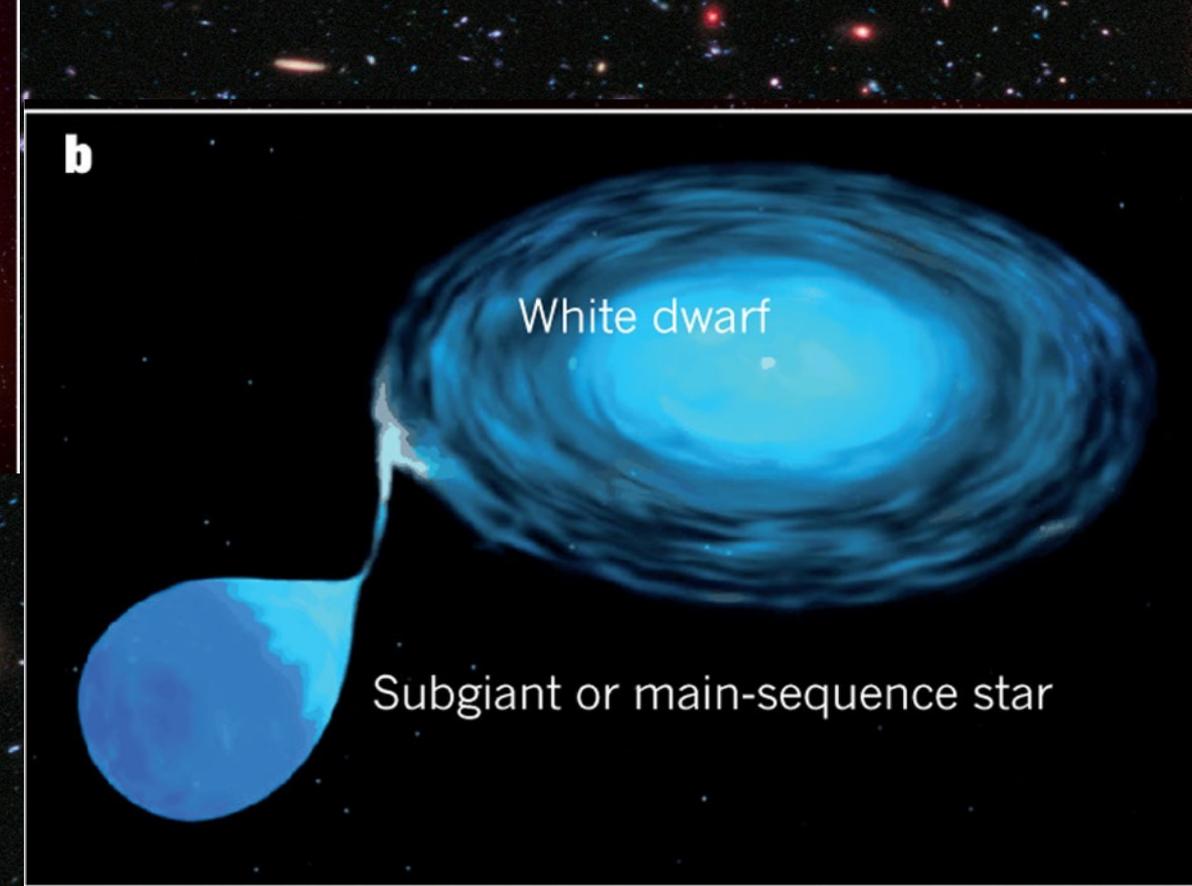
M82 The Cigar Galaxy 22nd Jan 2014



a

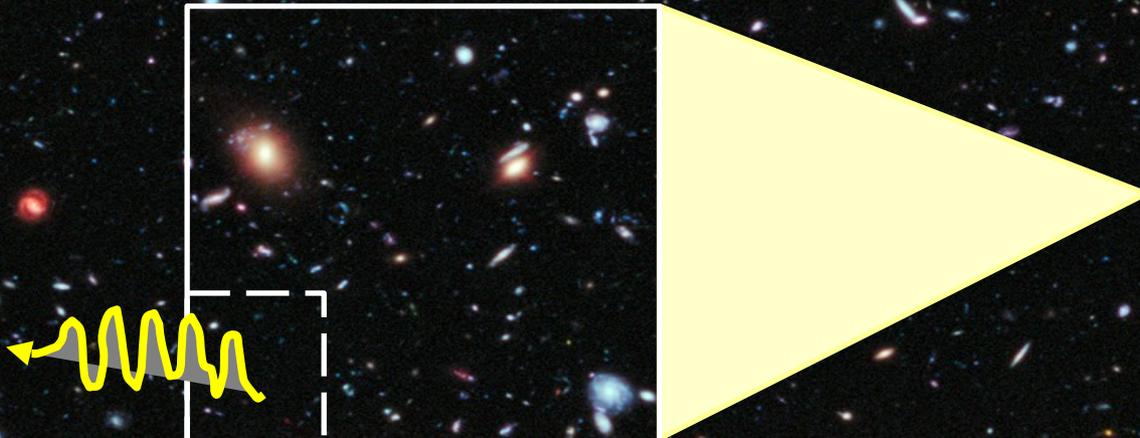
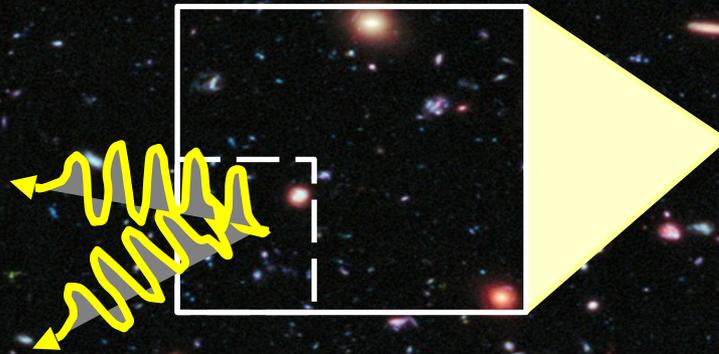
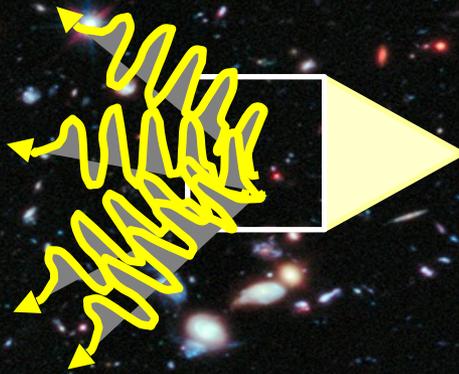


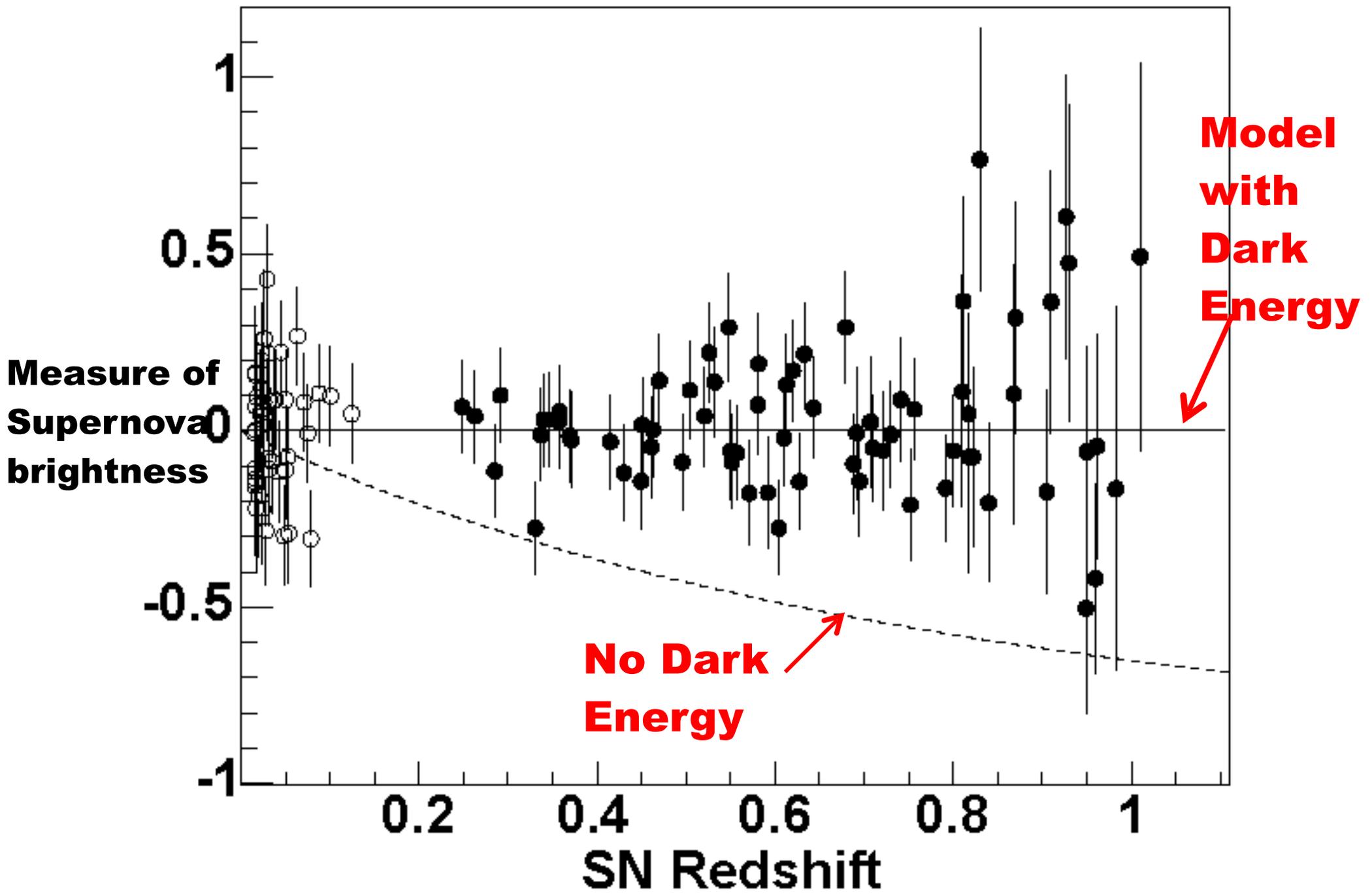
b



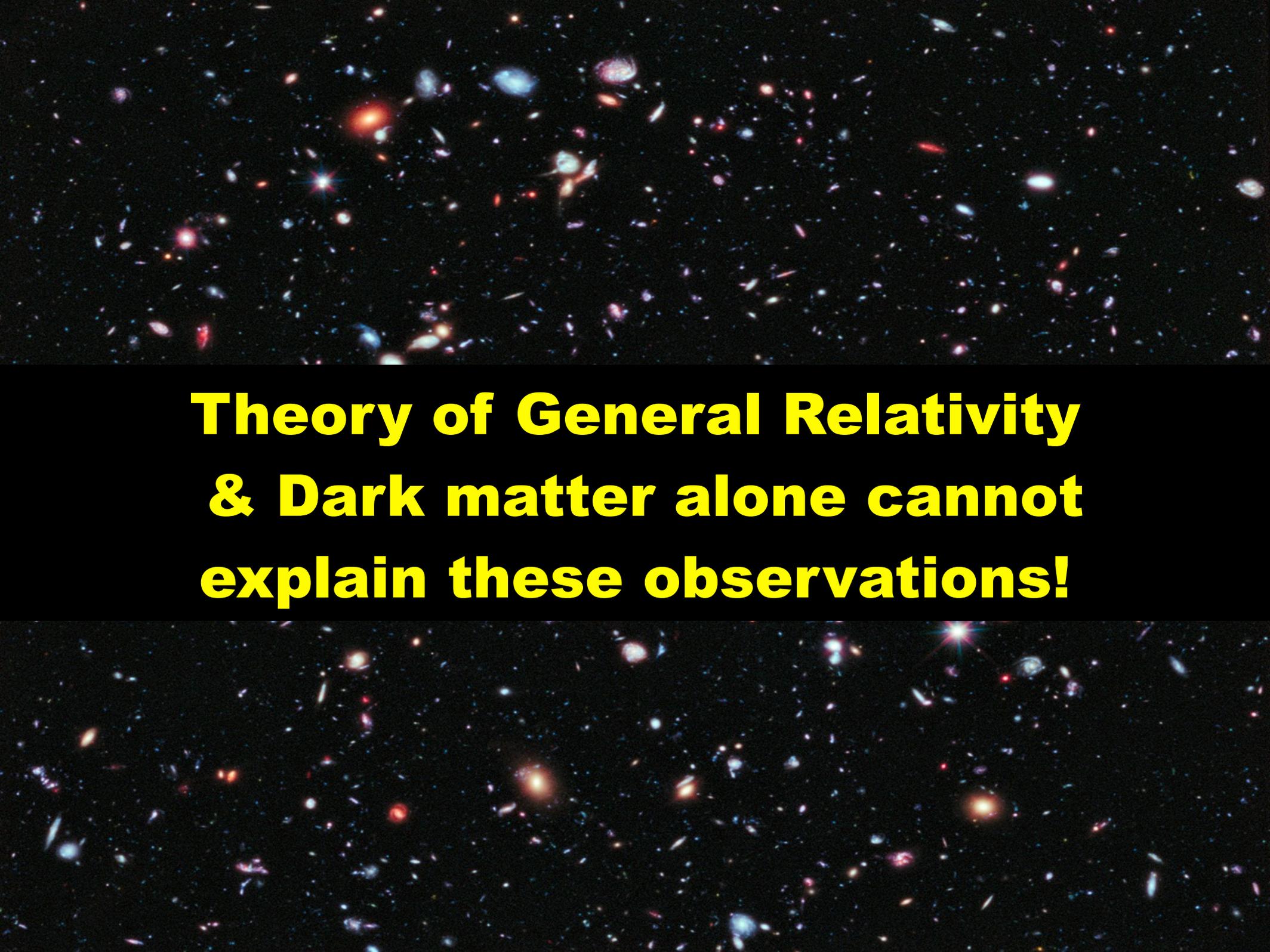
These exploding stars are “Standard candles”

Photons of light that reach Earth

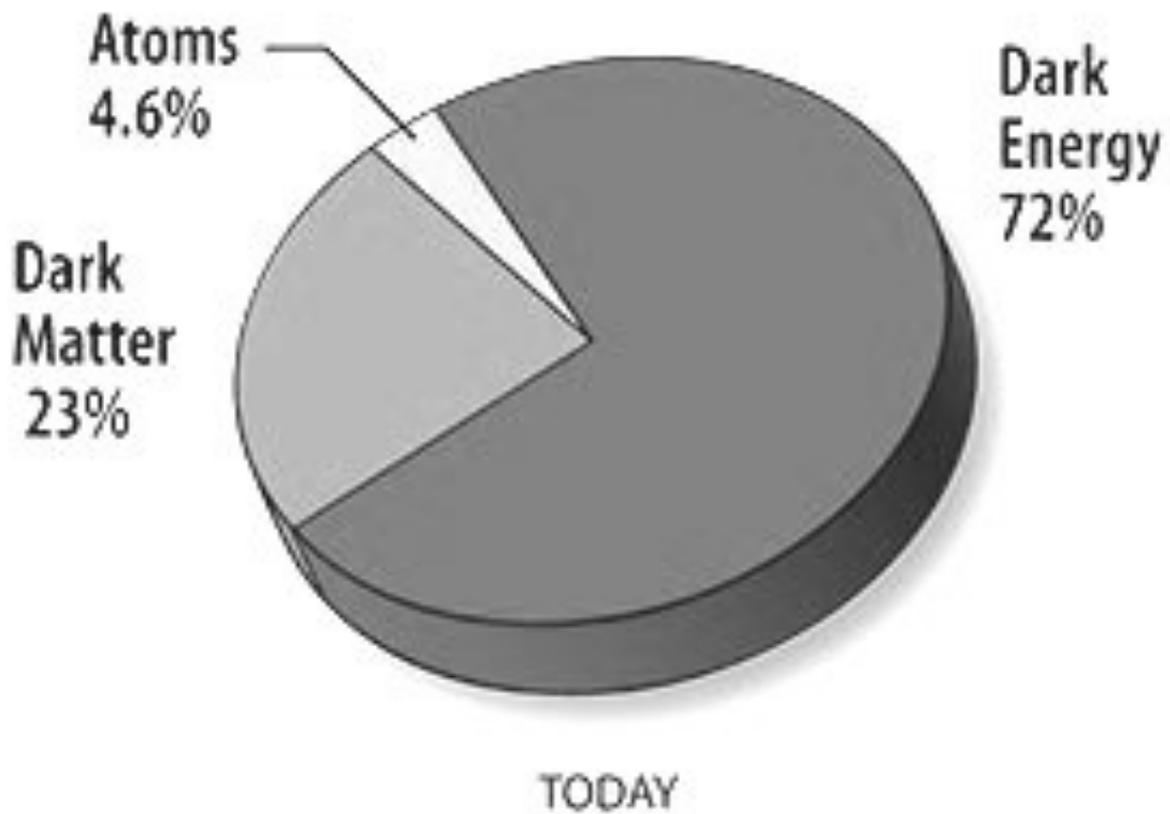




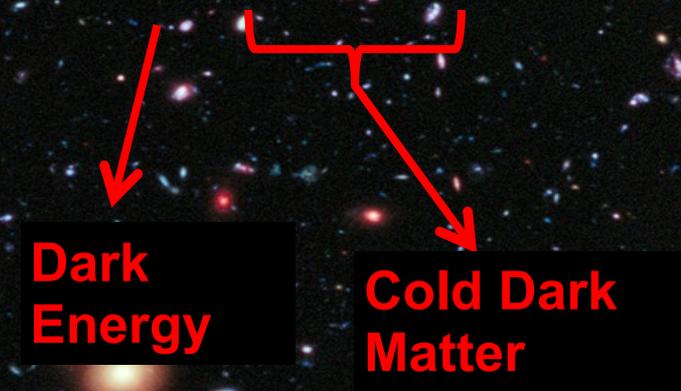
Astier et al 2006



**Theory of General Relativity
& Dark matter alone cannot
explain these observations!**



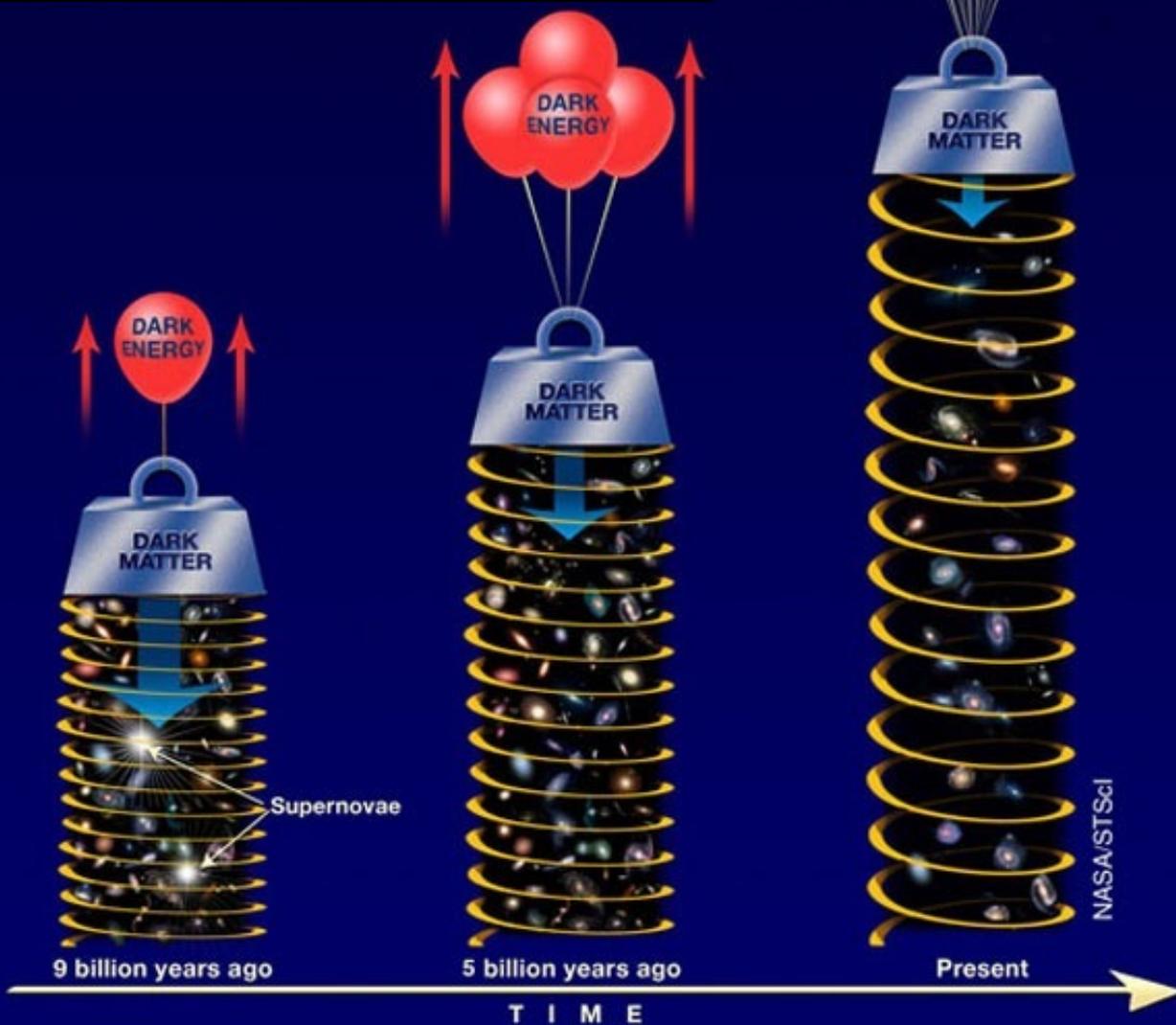
Λ CDM



Dark Energy is not made of massive particles - it is an energy field

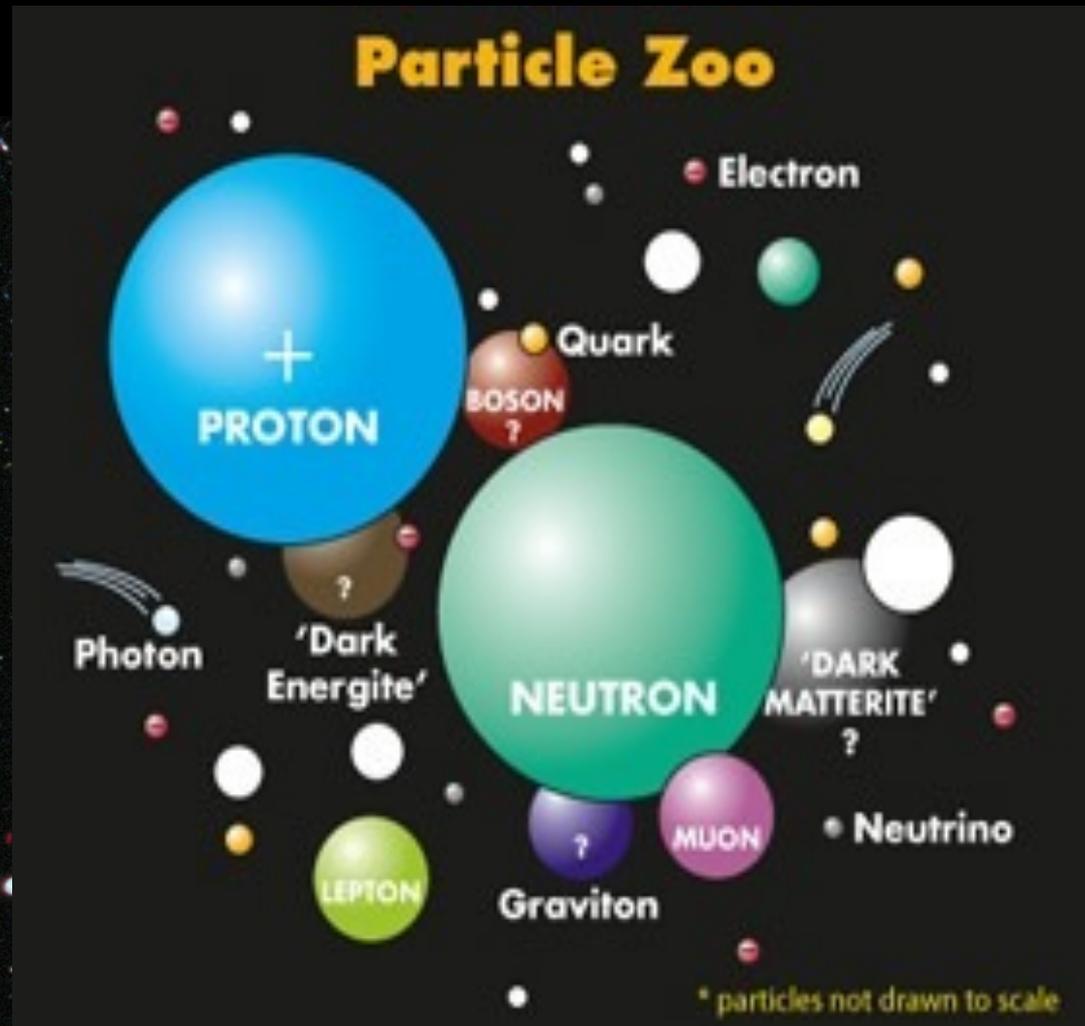


The Dark Energy Era = Cosmic tug of war

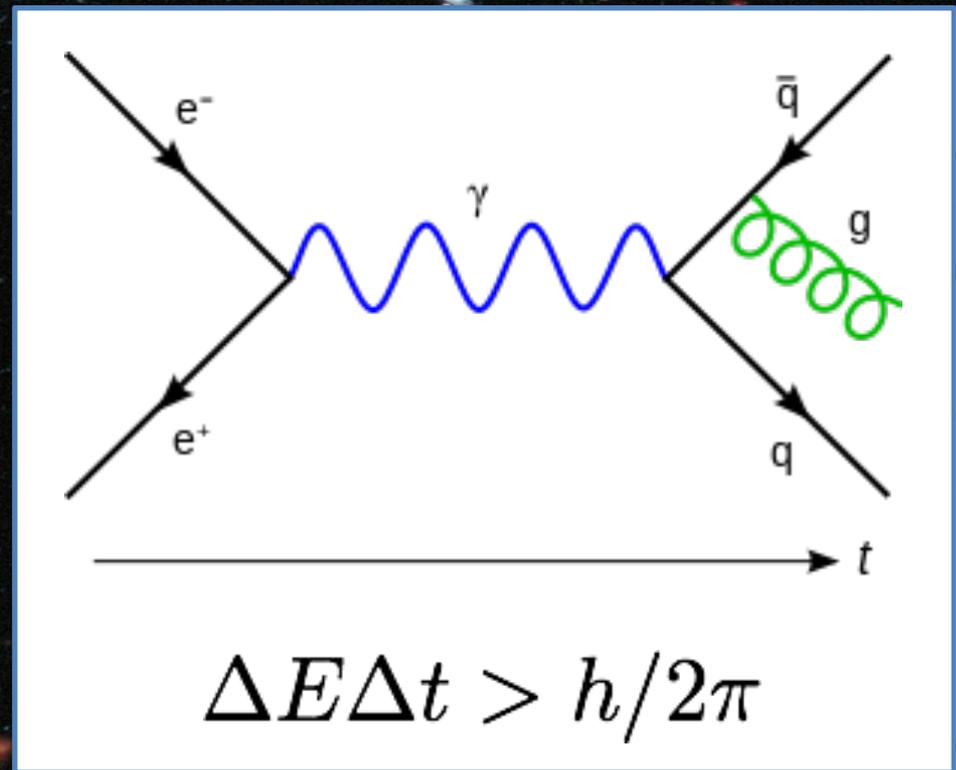


How do we explain these observations?

General Relativity + (some extra component) ??



Quantum Field Theory 1950s

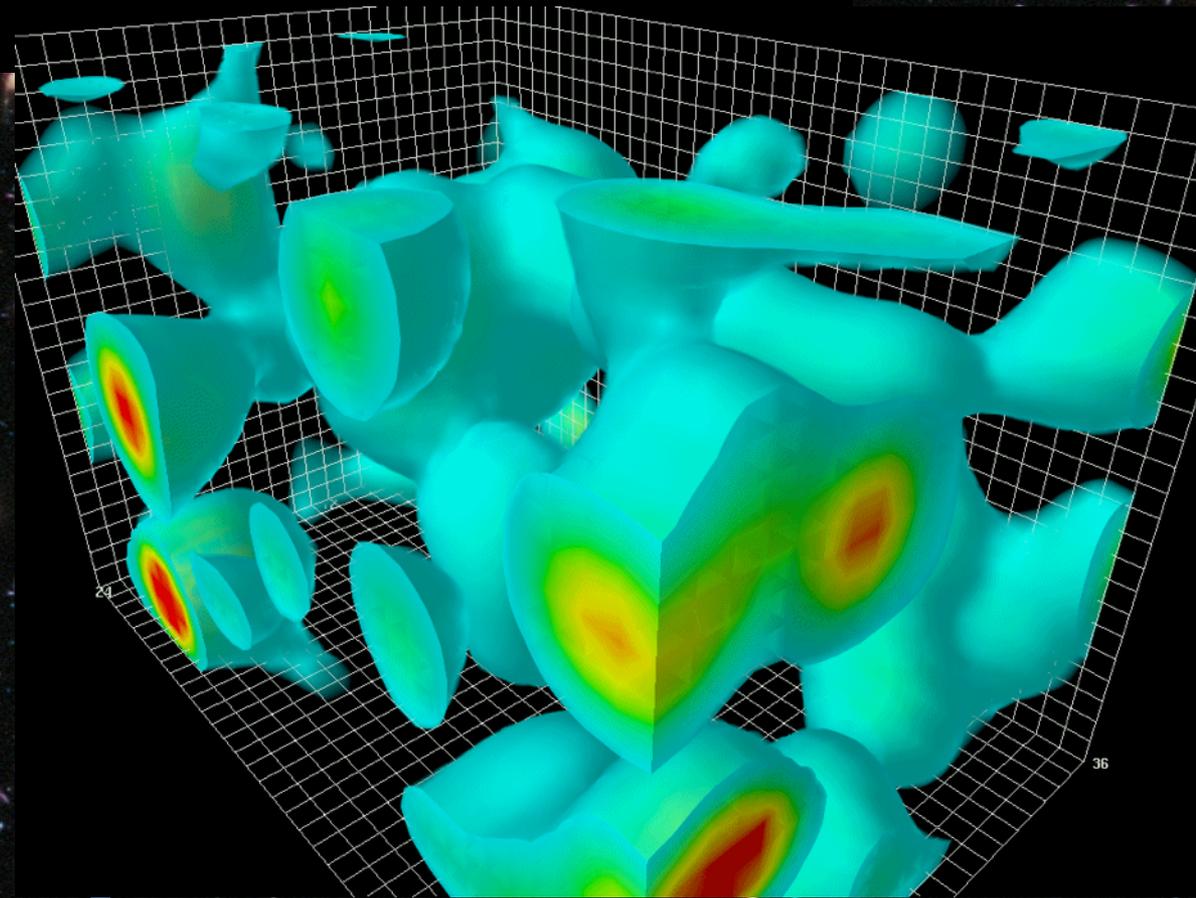
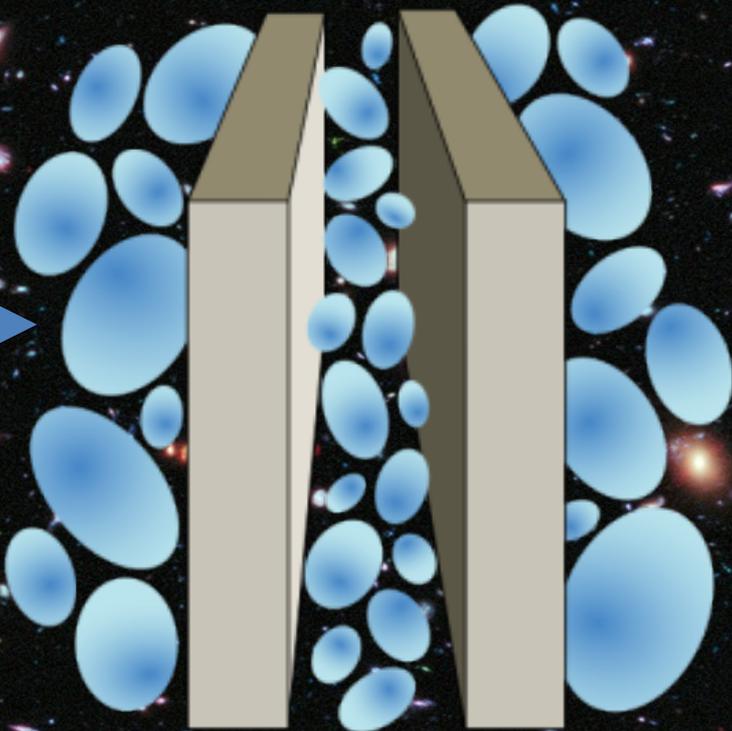


**A quantum vacuum has exactly
the properties of Dark Energy we observe**

The vacuum is never empty

It is full of virtual particles pairs!

The Casimir Effect 1948
virtual photons between
pair of plates generate a
force



QCD Simulation:
Derek leinweber

Great!

**Dark energy = Cosmological Constant
& our theory is complete?**

Observed value

$$\rho_{\Lambda} \approx 10^{-30} \text{ g cm}^{-3}$$

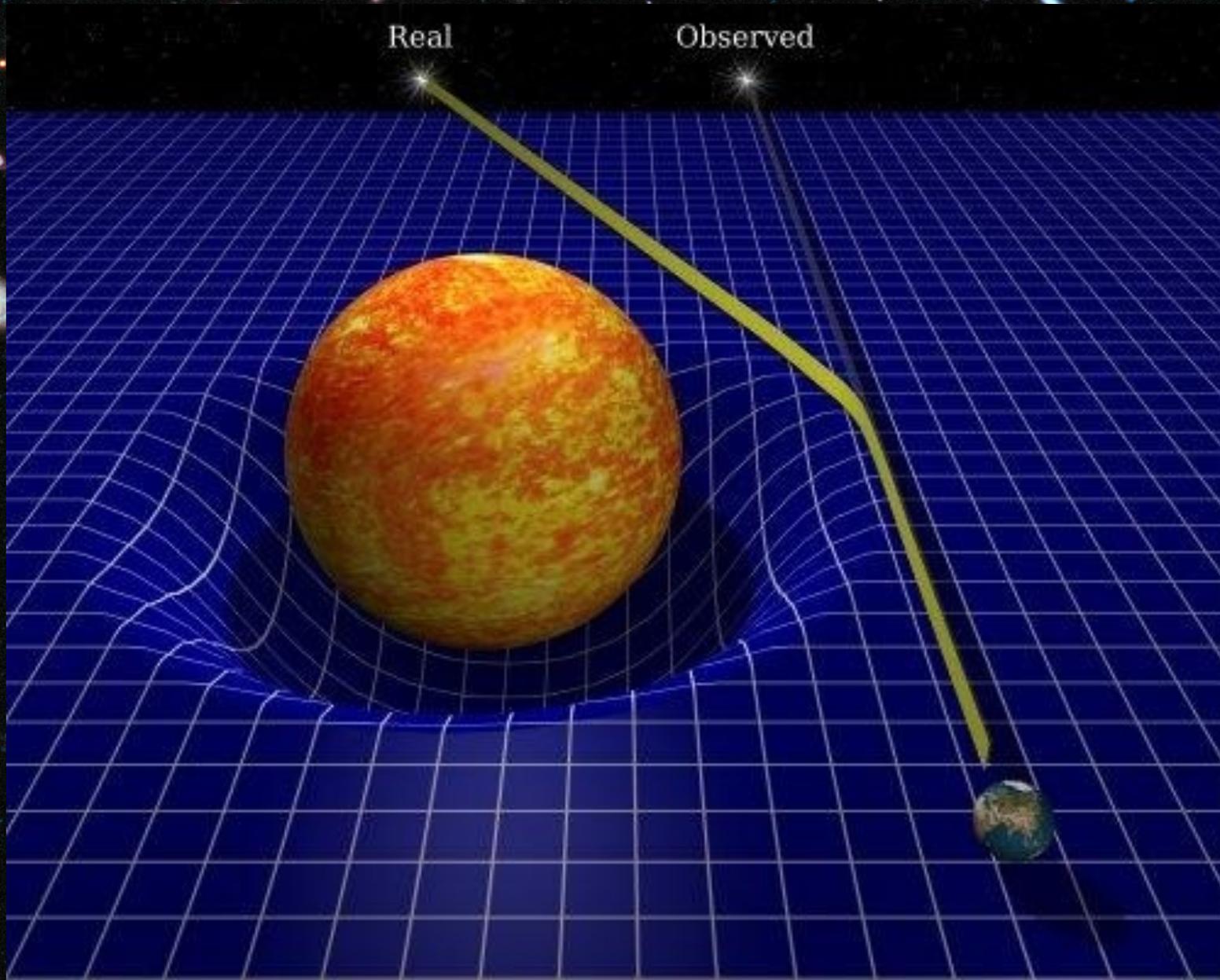
**Predicted value from
theory**

$$\rho_{\text{GUT}} \approx 10^{74} \text{ g cm}^{-3}$$

Difference of $\sim 10^{120}$ is a disaster for this theory

**1 with one hundred & twenty “zeros”
after it !**

**On galactic scales gravity is the most important force
maybe a new theory can explain the accelerating
expansion?**



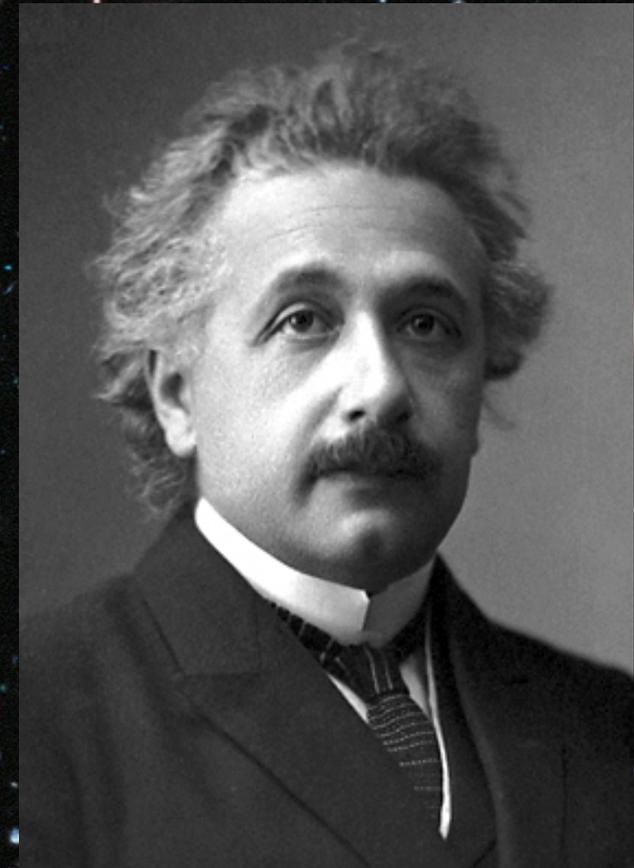
It's not so crazy to think about changing our theory of gravity!

Lessons from history

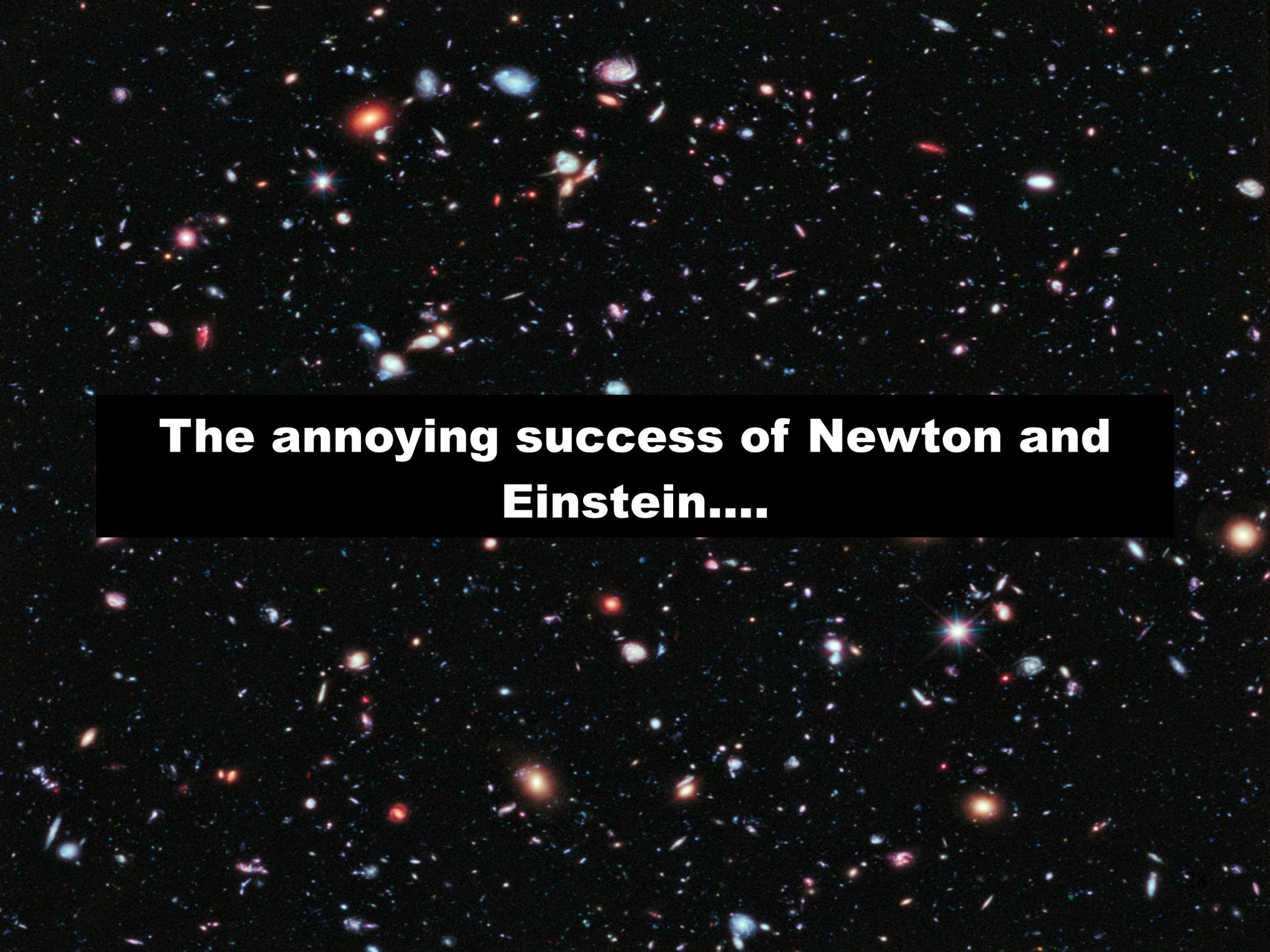
Deviations from Newtonian gravity in the precession of Mercury



**Le Verrier:
new planet
Vulcan?**

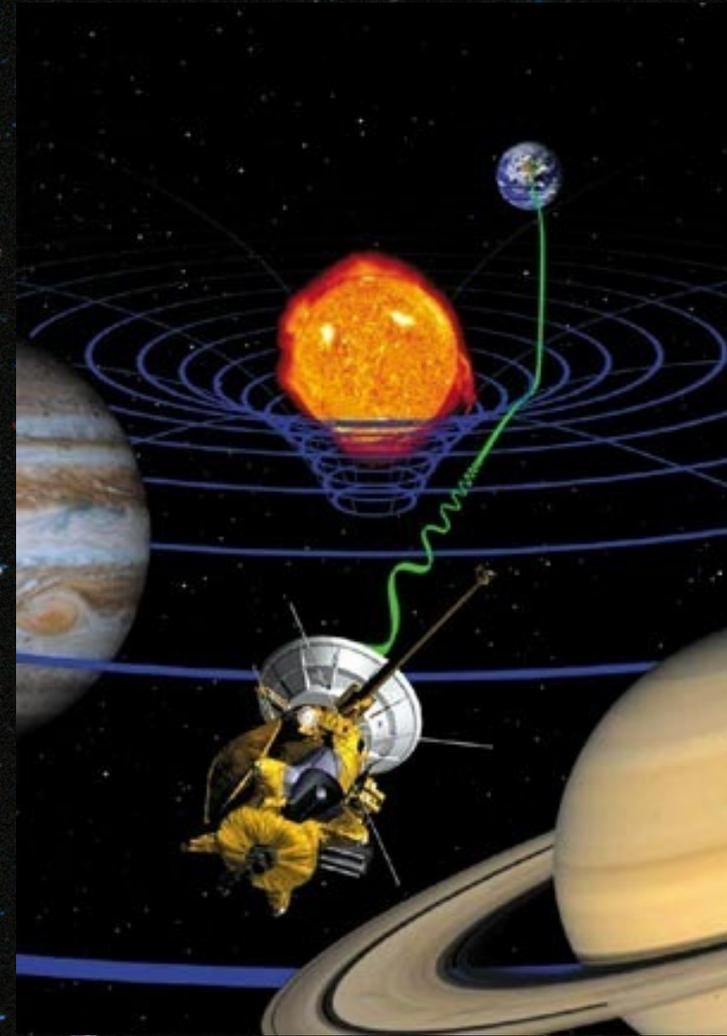


**Einstein:
General Relativity**



**The annoying success of Newton and
Einstein....**

Some Solar system tests of General Relativity



- **Perihelion shift of Mercury**
0.3%

- **Shapiro Time delay**
Cassini Spacecraft:
0.002%

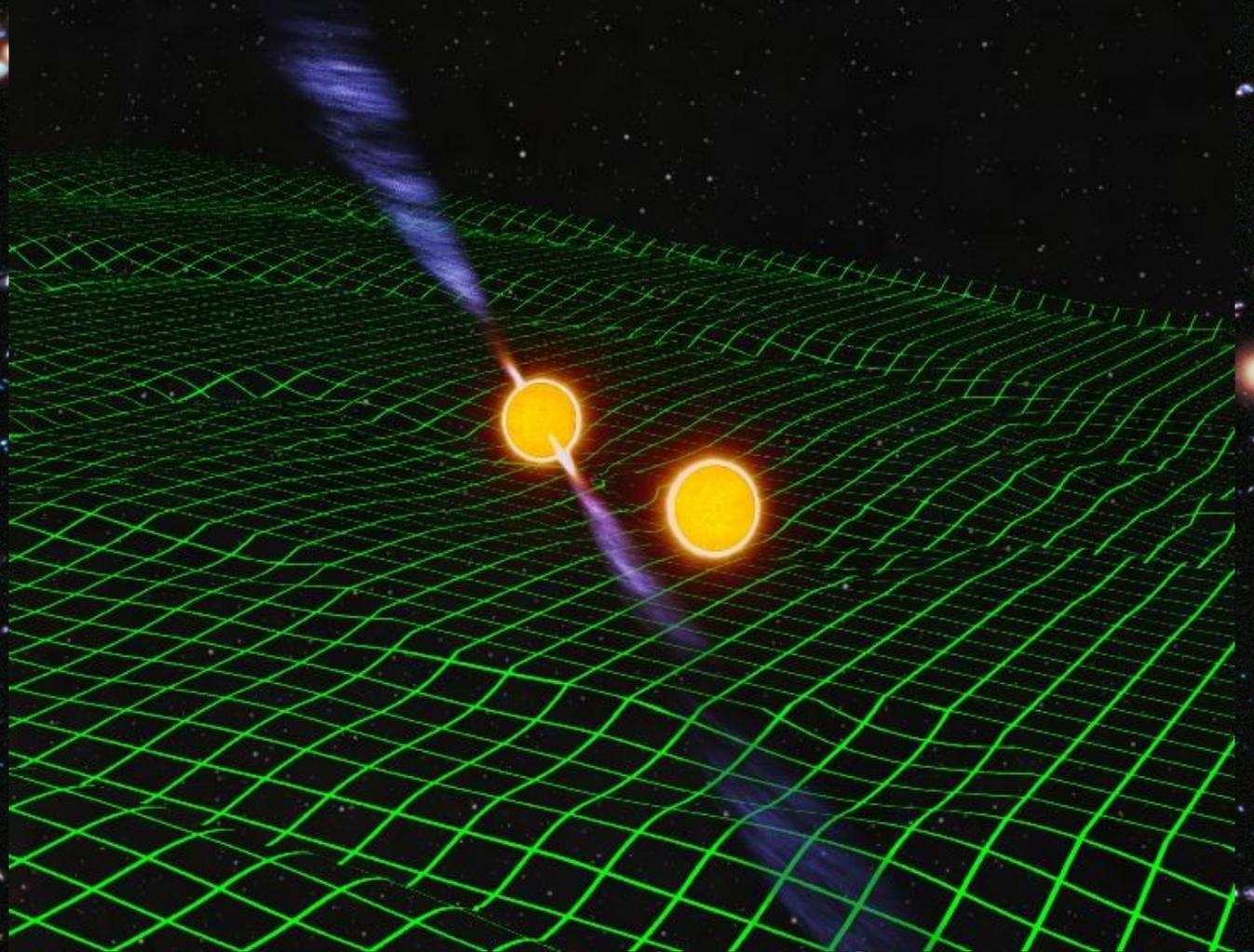
- **Lunar ranging experiments**



Testing Einstein in space

- **Binary Pulsars**
0.2%

- **Gravitational waves ?**



It's tough to modify gravity and still match observations on all scales

$$\begin{aligned}\delta S[g] &= \int \frac{1}{2\kappa} (\delta f(R)\sqrt{-g} + f(R)\delta\sqrt{-g}) d^4x \\ &= \int \frac{1}{2\kappa} \left(F(R)\delta R\sqrt{-g} - \frac{1}{2}\sqrt{-g}g_{\mu\nu}\delta g^{\mu\nu} f(R) \right) d^4x \\ &= \int \frac{1}{2\kappa}\sqrt{-g} \left(F(R)(R_{\mu\nu}\delta g^{\mu\nu} + g_{\mu\nu}\square\delta g^{\mu\nu} - \nabla_\mu\nabla_\nu\delta g^{\mu\nu}) - \frac{1}{2}g_{\mu\nu}\delta g^{\mu\nu} f(R) \right) d^4x\end{aligned}$$

$$\delta S[g] = \int \frac{1}{2\kappa}\sqrt{-g}\delta g^{\mu\nu} \left(F(R)R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}f(R) + [g_{\mu\nu}\square - \nabla_\mu\nabla_\nu]F(R) \right) d^4x.$$

$$G_{\text{eff}} = \frac{1}{8\pi F} \frac{1 + 4\frac{k^2}{a^2 R}m}{1 + 3\frac{k^2}{a^2 R}m},$$

We know that General Relativity is not the full story - singularities!

Destiny of the Universe

Observed accelerating expansion implies a component with a negative pressure.

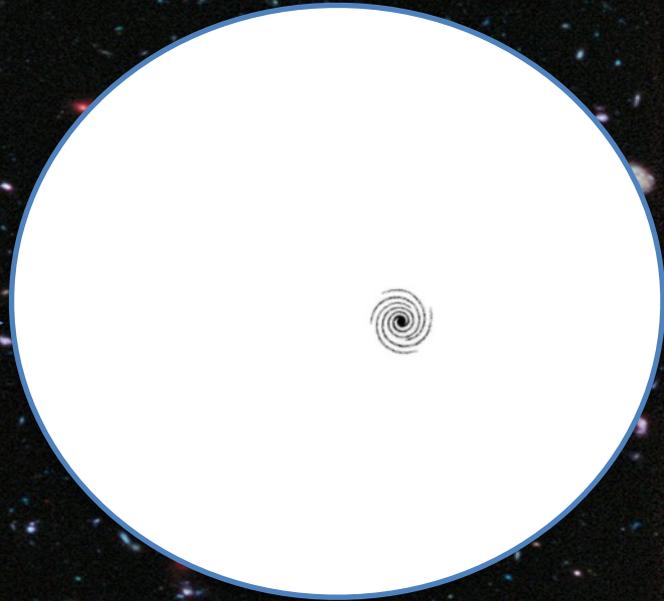
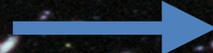
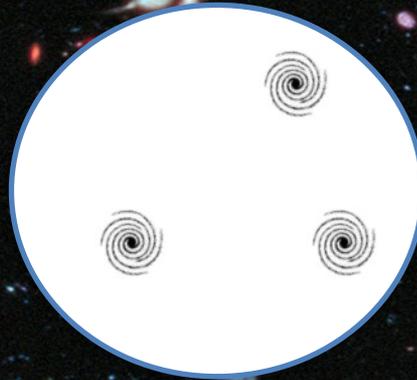
Ultimate fate depends on the properties of Dark Energy.

$$w = \frac{P}{\rho}$$

Destiny of the Universe

Acceleration continues

$$w = -1$$



**Emptiness -
Cosmic Black out
100 billion years**

**Stars burn out
1000 billion years**

**All evidence of
Big Bang is lost**

Big Bang

Today

Destiny of the Universe

Acceleration continues

$$w = -1$$

Acceleration amplified

Cosmic Black out

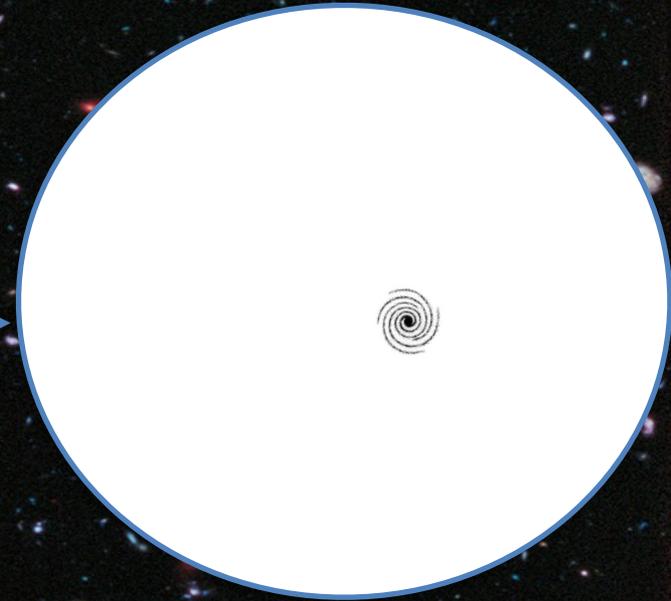
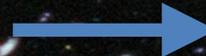
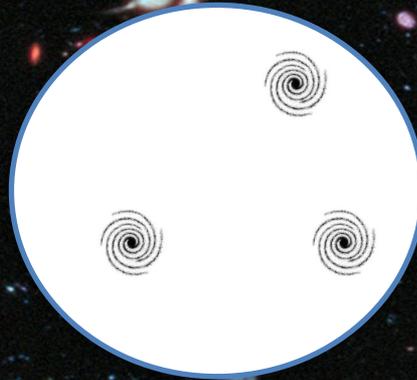
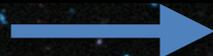
Big Rip

Dark Energy tears apart LSS

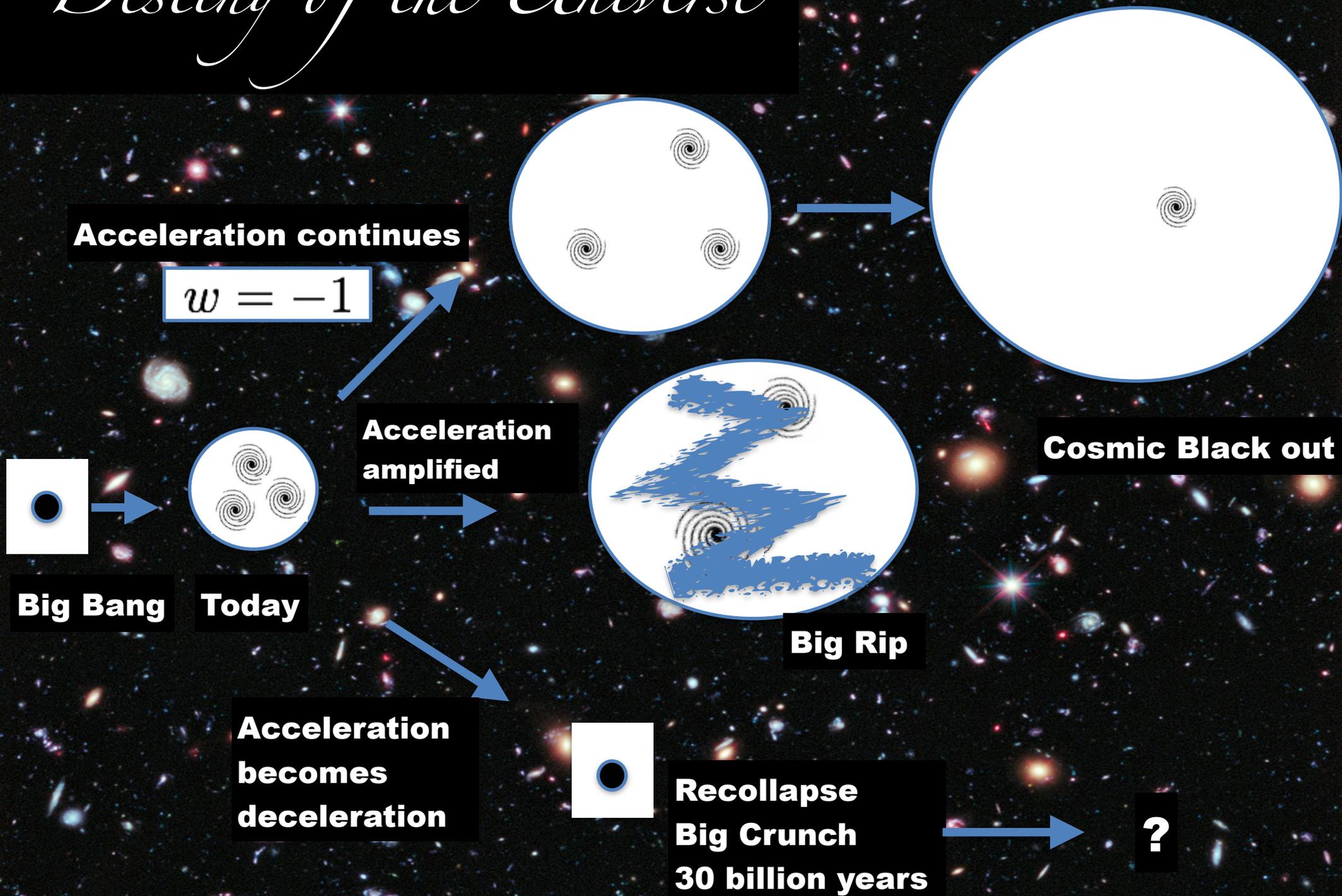
50 billion years

Big Bang

Today



Destiny of the Universe



Acceleration continues

$$w = -1$$

Acceleration amplified

Cosmic Black out

Big Rip

Acceleration becomes deceleration

**Recollapse
Big Crunch
30 billion years**

?

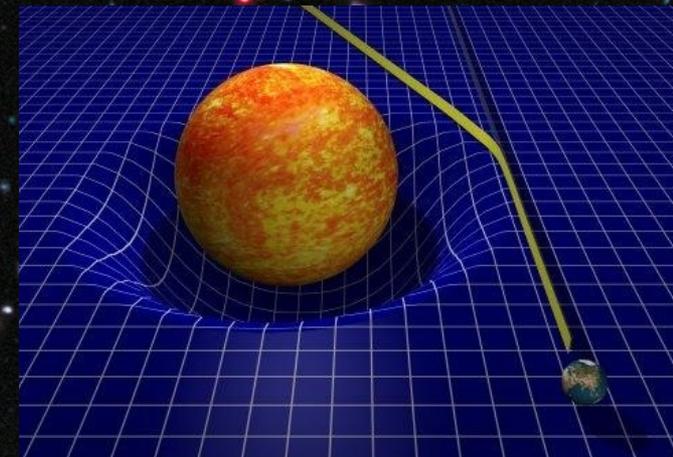
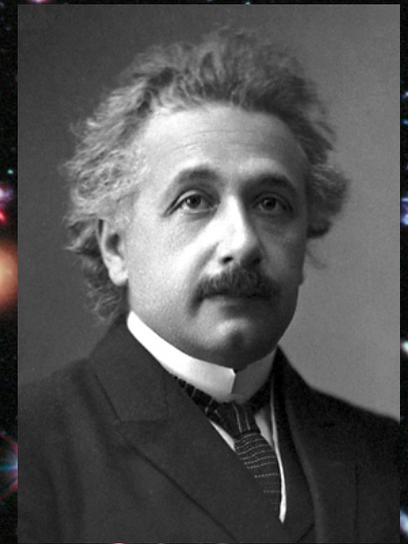
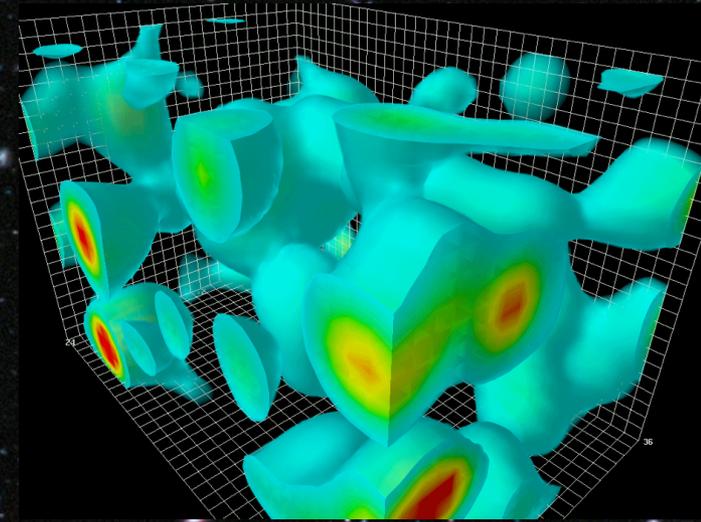
Big Bang

Today

What is Dark Energy??

The
Cliffhanger
Ending

$$w = ???$$



VIRTUAL PARTICLES, by Frank Wilczek

***Beware of thinking nothing's there.
Remove all you can, despite your care
Behind remains a restless seething
Of mindless clones beyond conceiving.***

***They come in a wink, they dance about,
Whatever they touch is seized by doubt:
What am I doing here? What should I weigh?
Such thoughts often lead to rapid decay.***

***Fear not! The terminology's misleading;
Decay is virtual particle breeding
Their ferment, though mindless, does serve noble ends:
Those clones, when exchanged, make a bond between friends.***

***To be or not? The choice seems clear enough,
But Hamlet vacillated. So does this stuff.***