

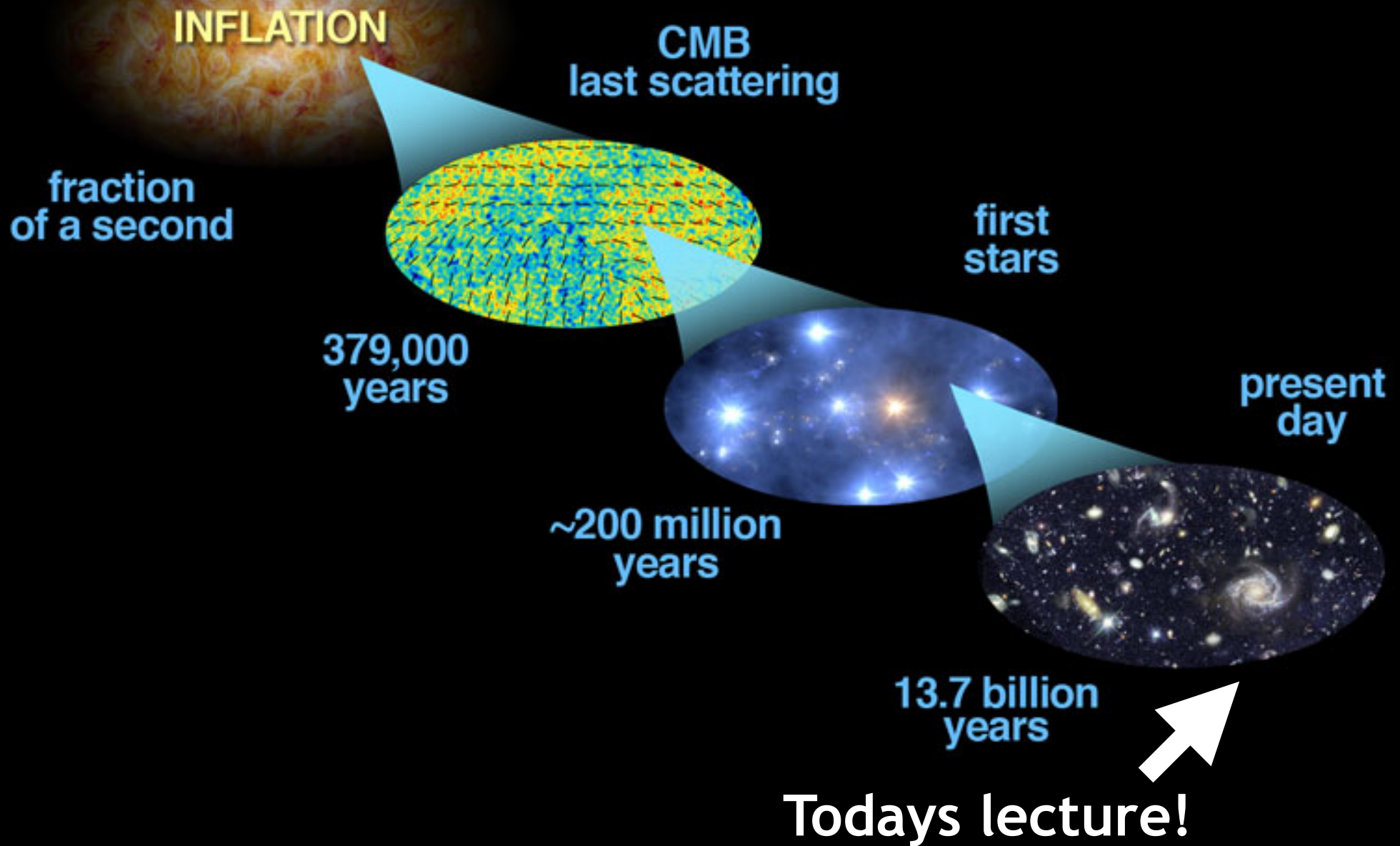
**Compton Lectures Fall 2014**  
**Shining light on the Dark**  
**Side of the Universe**

**What is Dark Energy?**

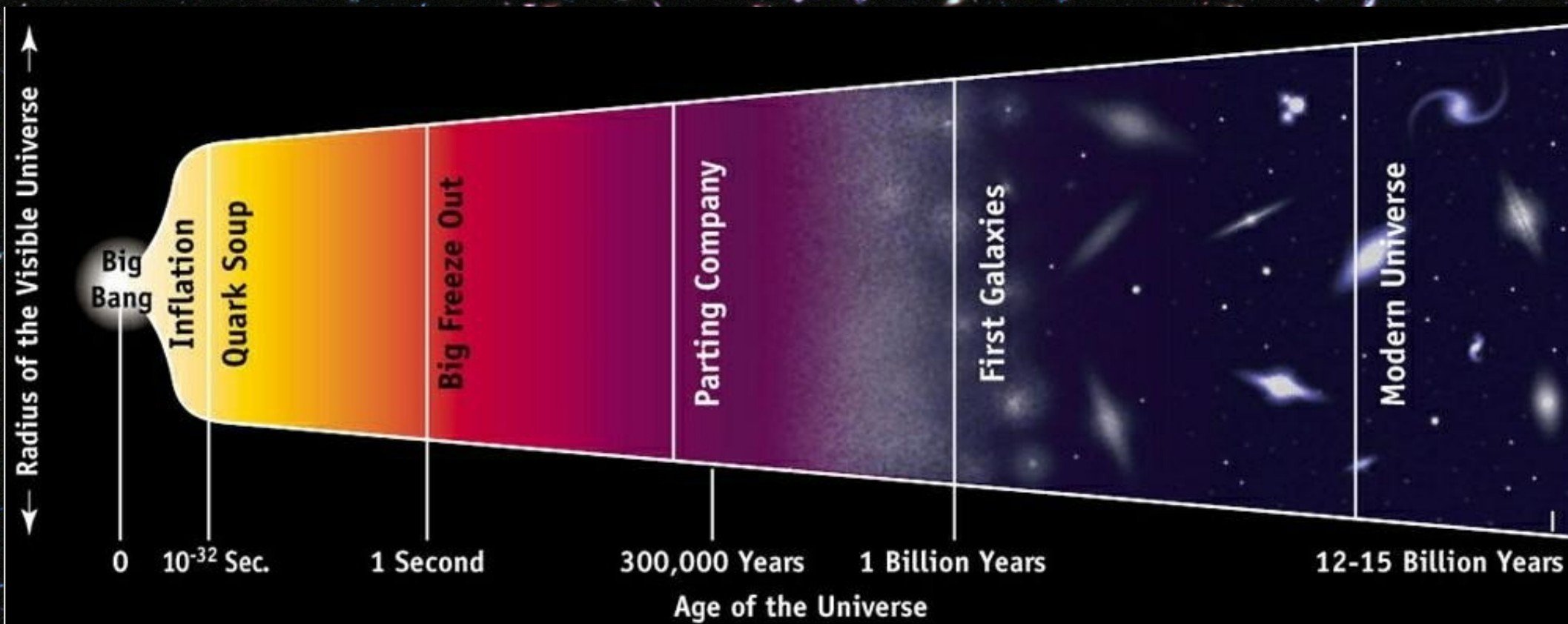
**Elise Jennings**

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

# *The Evolving Universe*



# Epochs of the Universe



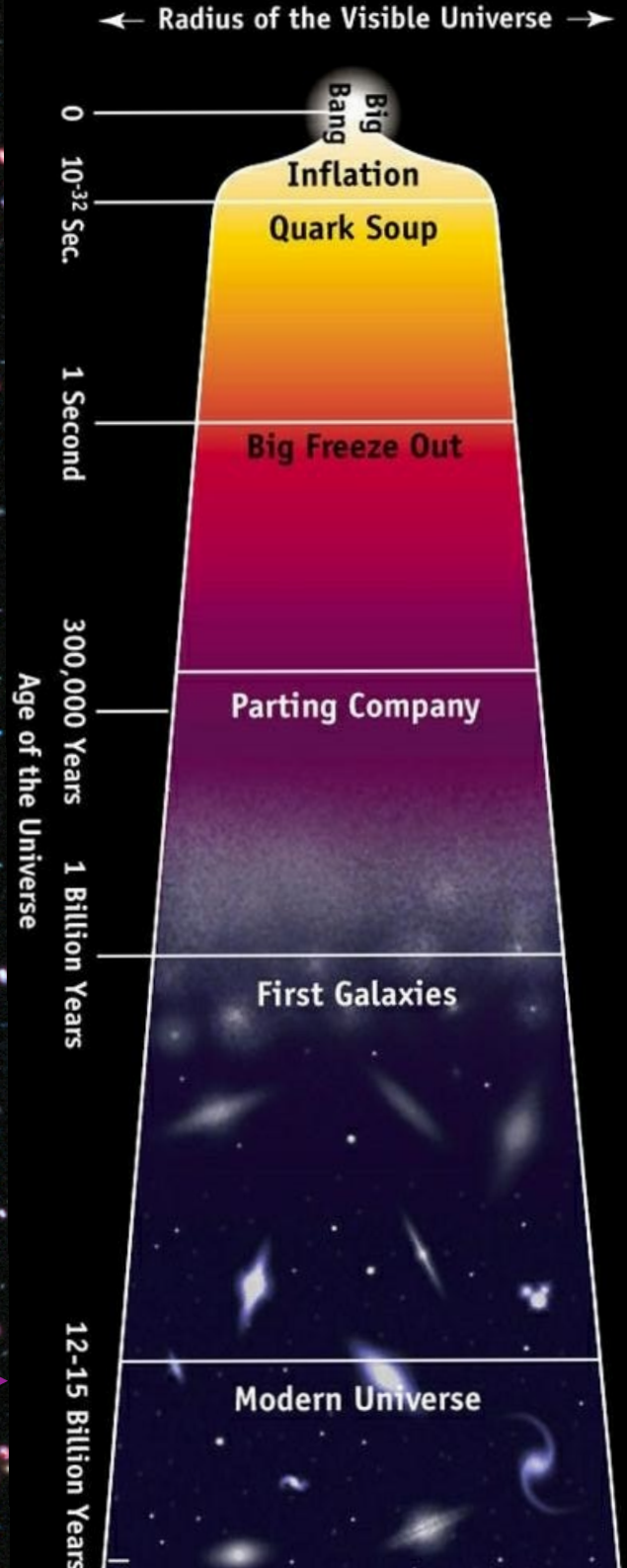
# Epochs of the Universe

*Dark Energy Era*

**5 billion years ago**

**Accelerated expansion.**

**LSS in superclusters.**



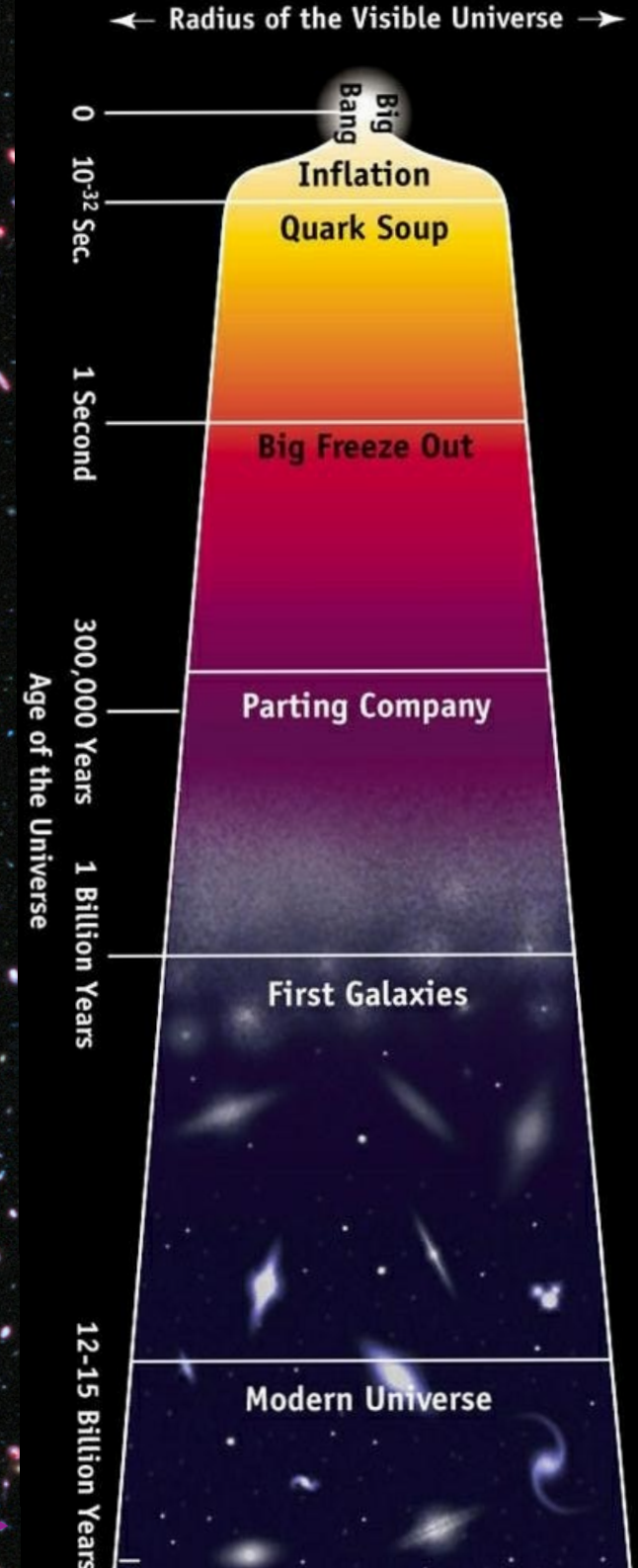
# Epochs of the Universe

*The End?*

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

**Cosmic blackout:  
100 Gyr**

**Stellar extinction:  
1000 Gyr**



# Story of the expanding Universe



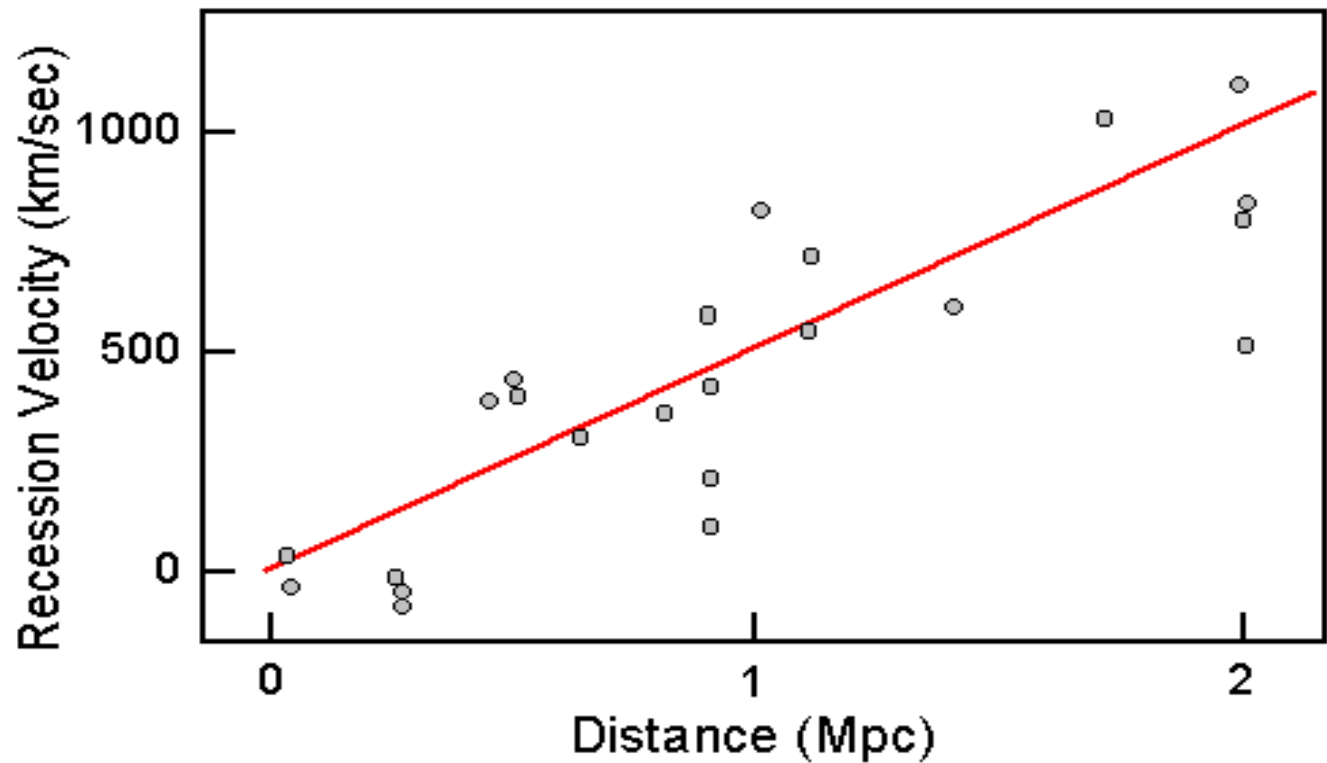
**1915 Einstein's theory  
General Relativity  
predicted a dynamic  
expanding Universe**

# 1923 Hubble's observations

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

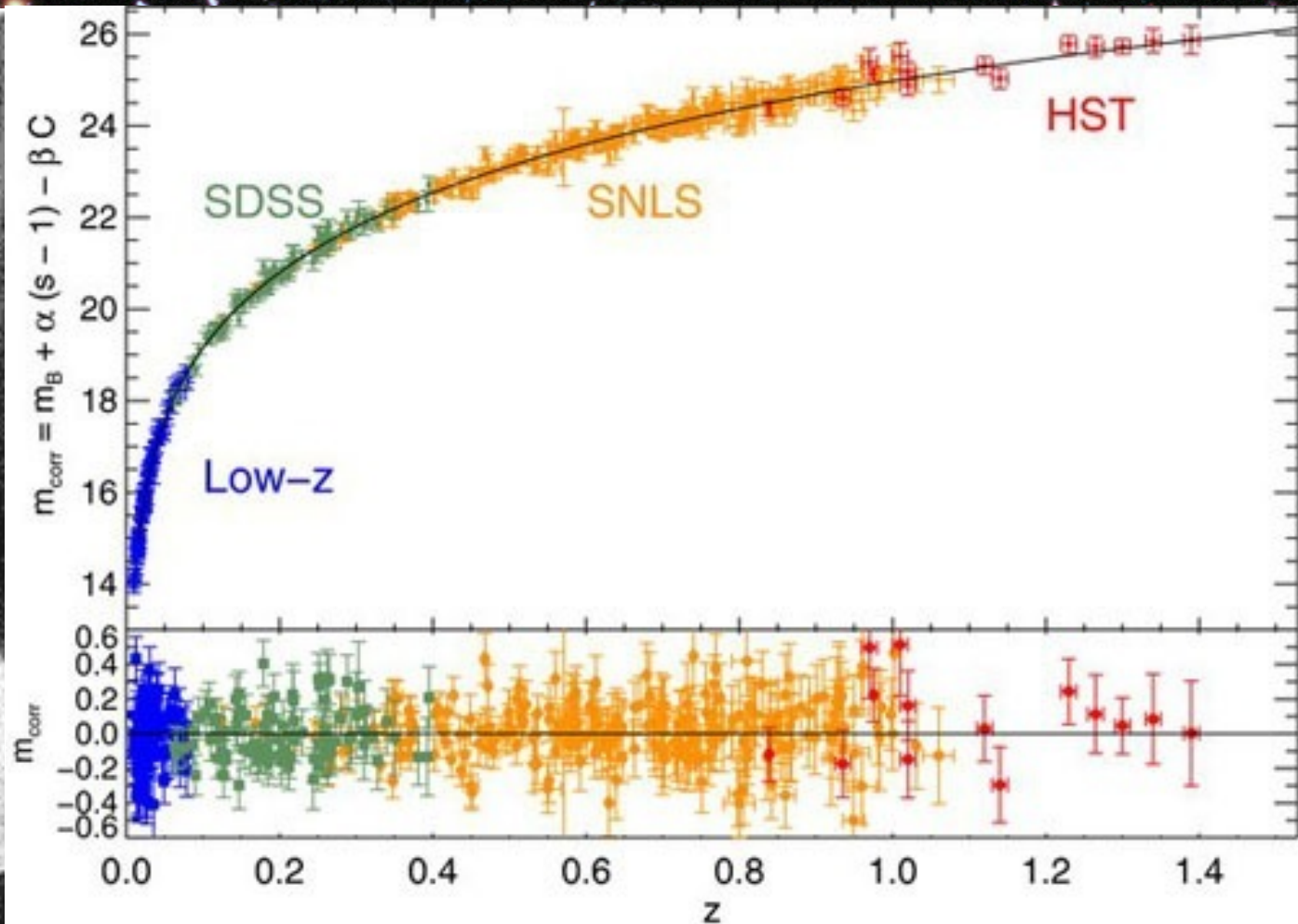


## Hubble's Data (1929)

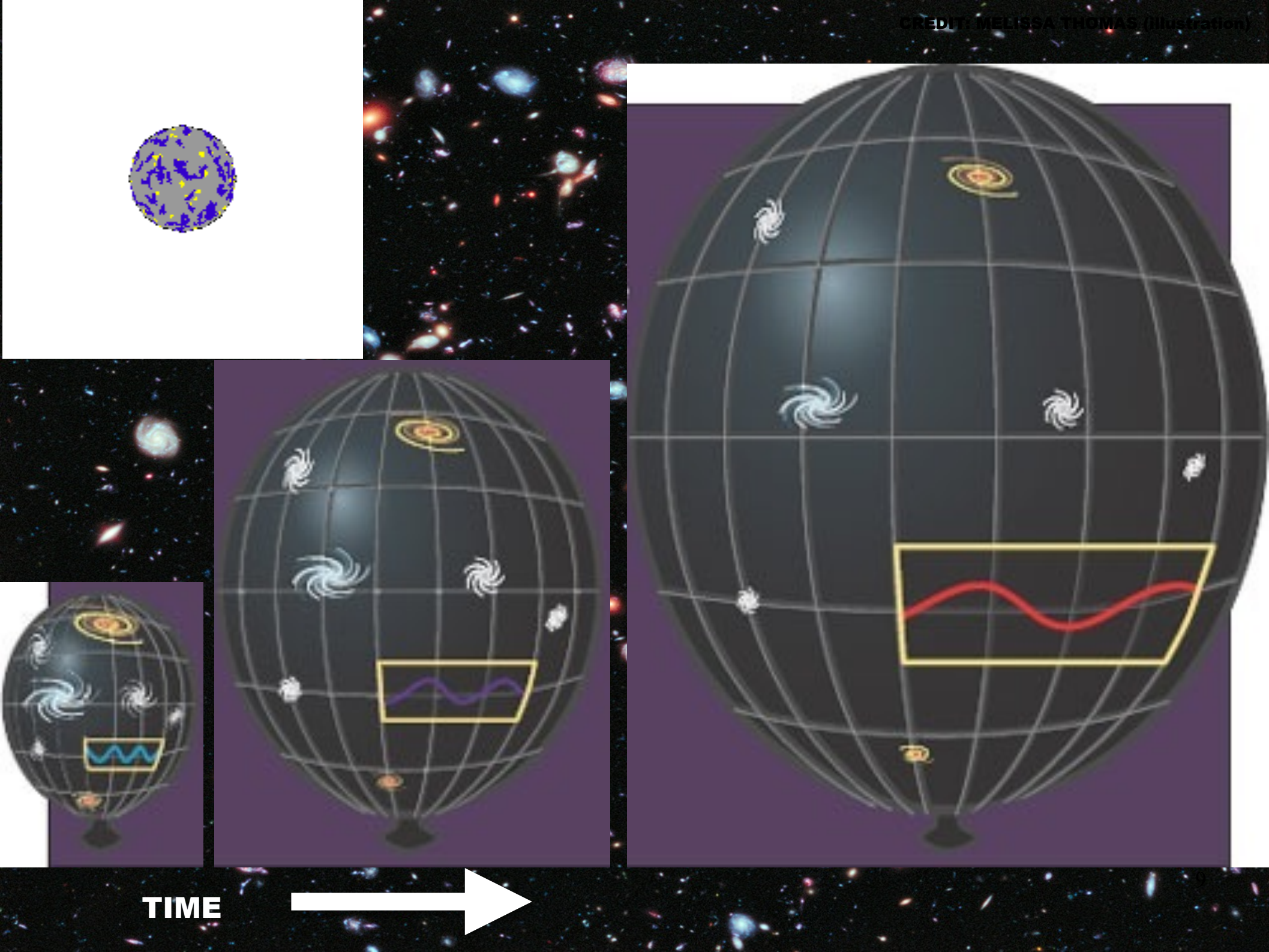


# 1923 Hubble's observations

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







TIME



**Mass/energy in the Universe**

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

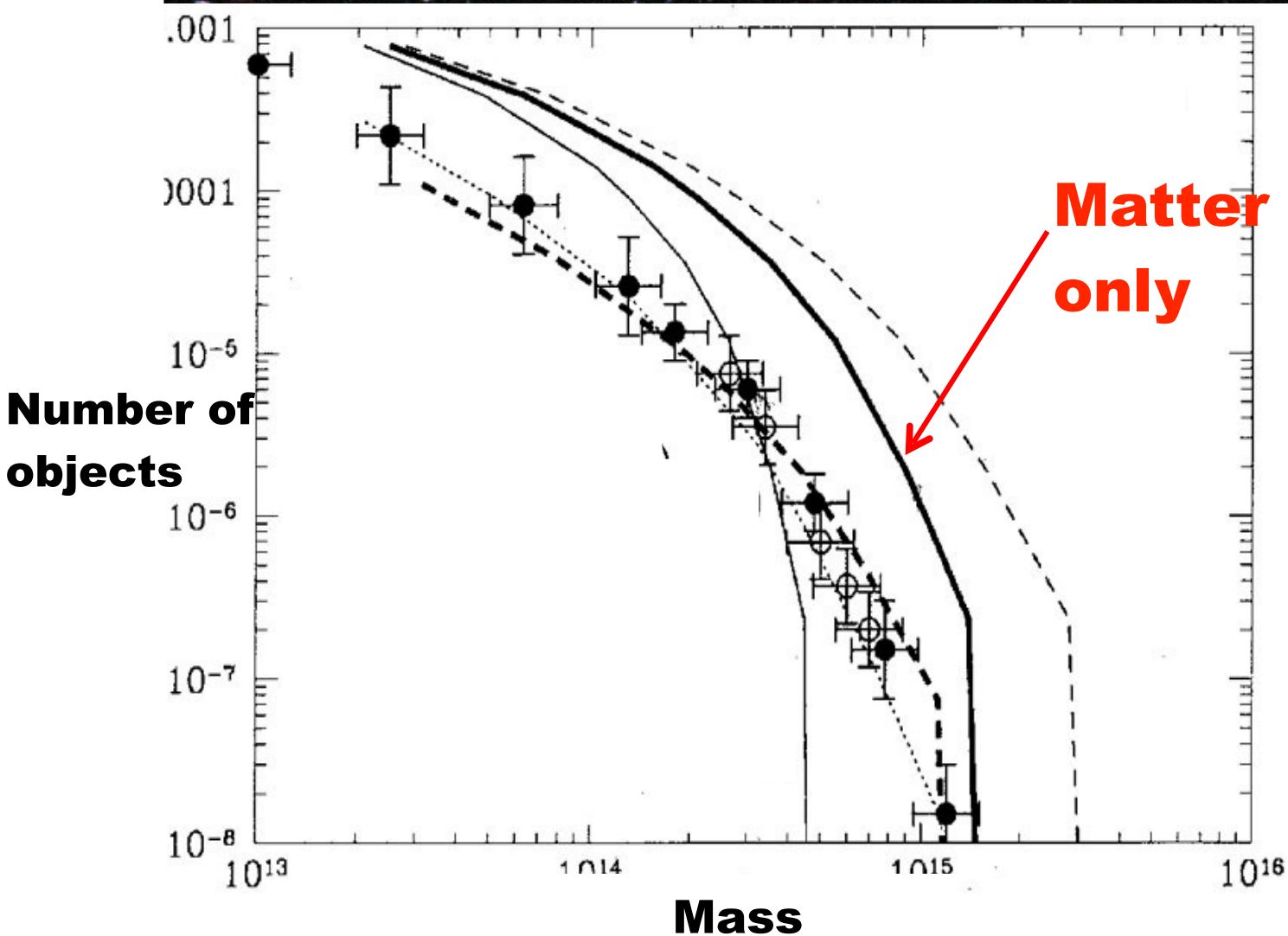
**Structure of space-time**

**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

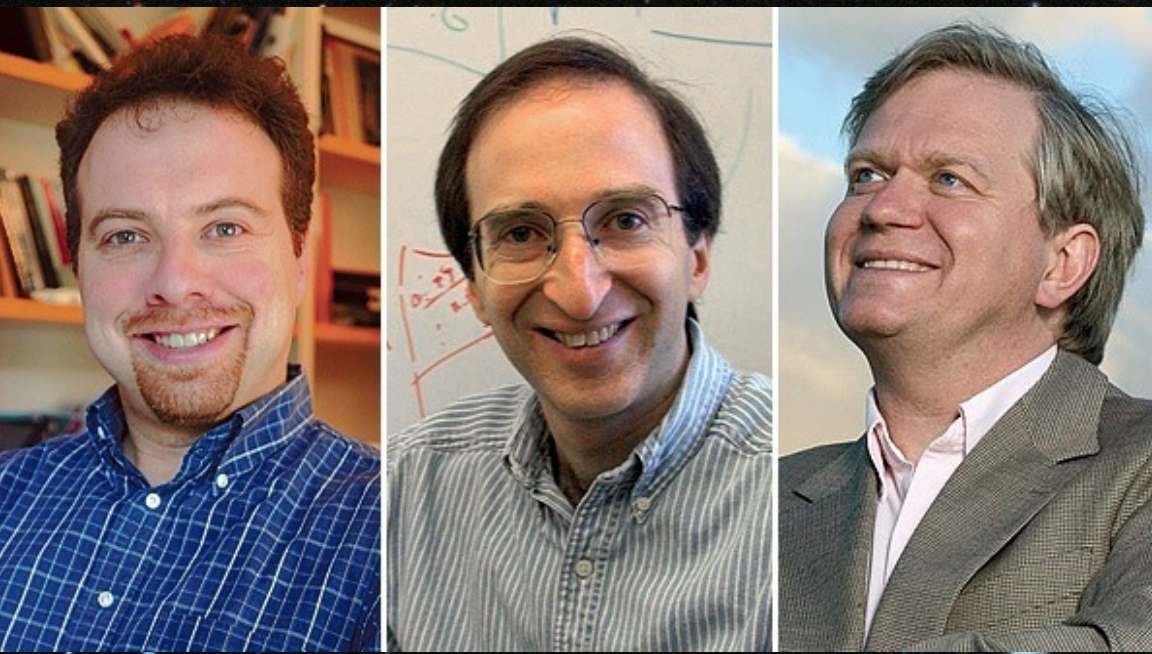
**Predicted age of the Universe with matter only**

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

**Measured age of the  
oldest star clusters**

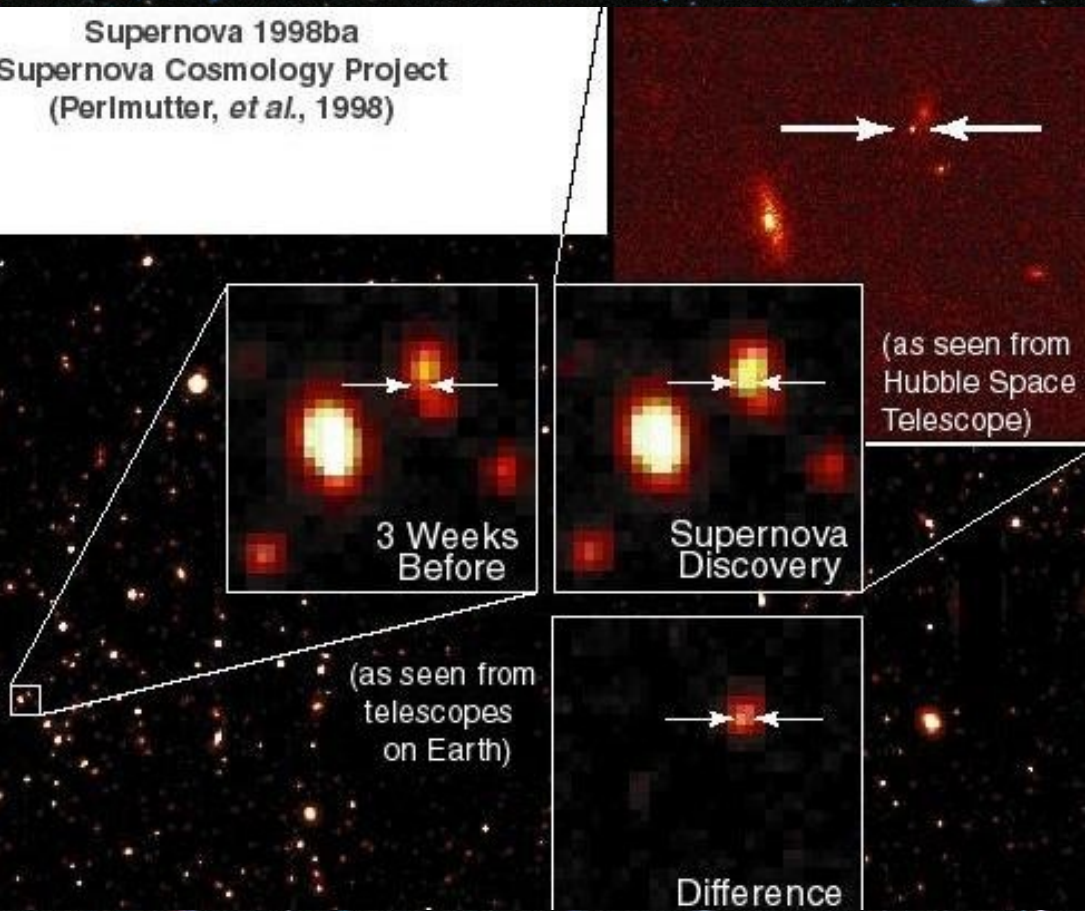
$$15.2 \pm 3.5 \text{ Gyr}$$

Cowan et al 1997



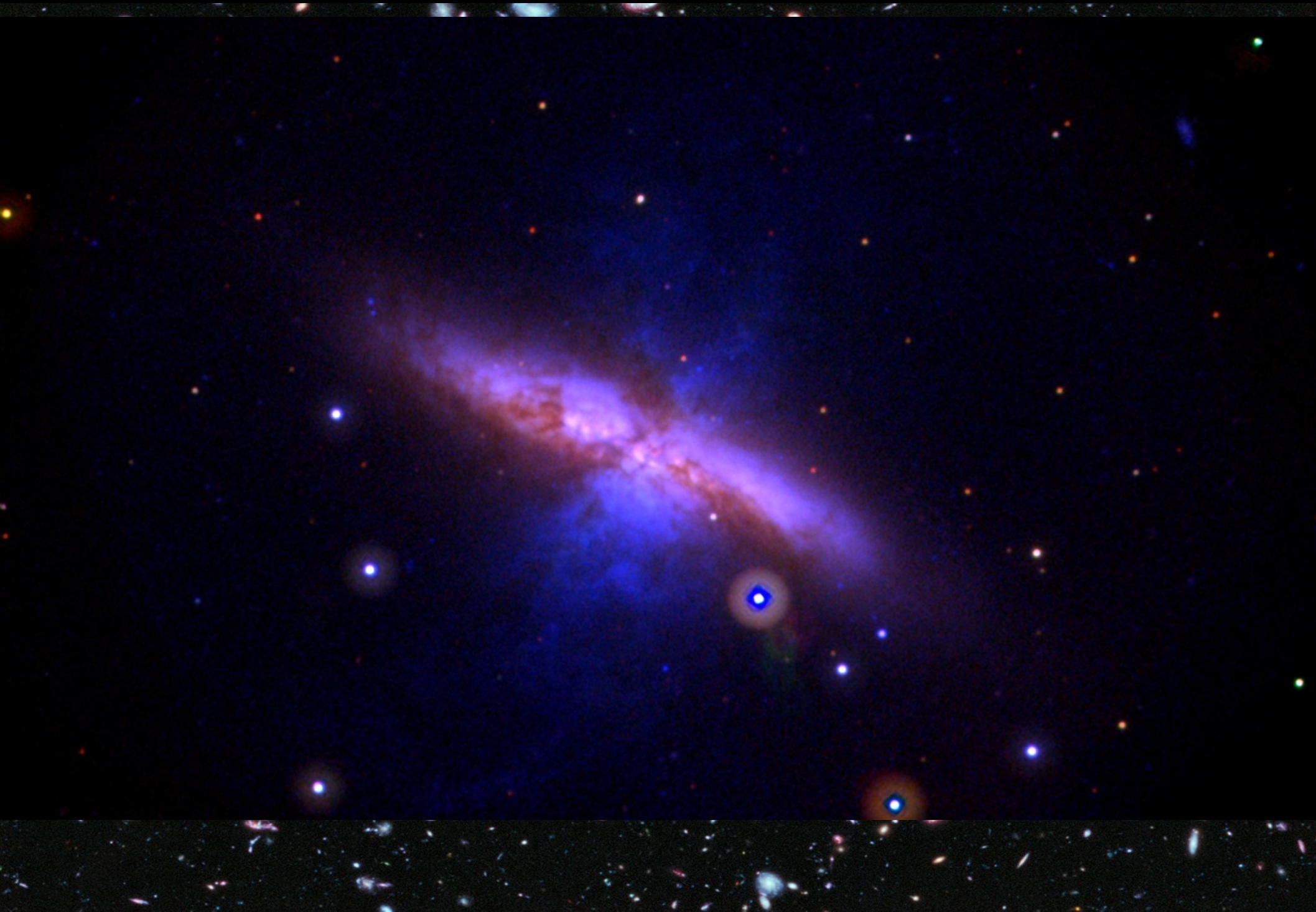
**Adam Riess, Saul Perlmutter  
and Brian Schmidt**

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

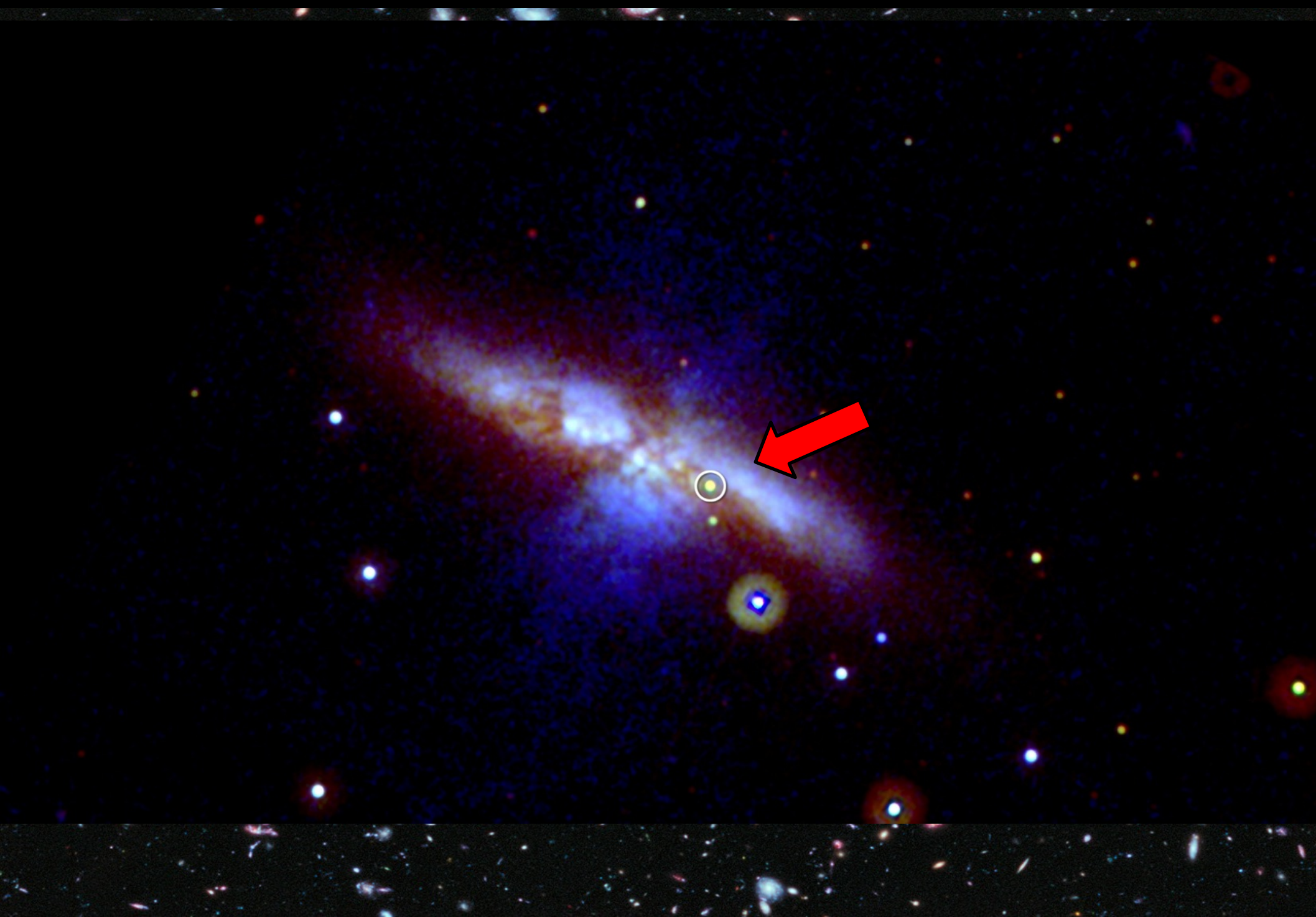


**Supernovae were dimmer  
then expected from the  
predictions of  
General relativity + dark  
matter only**

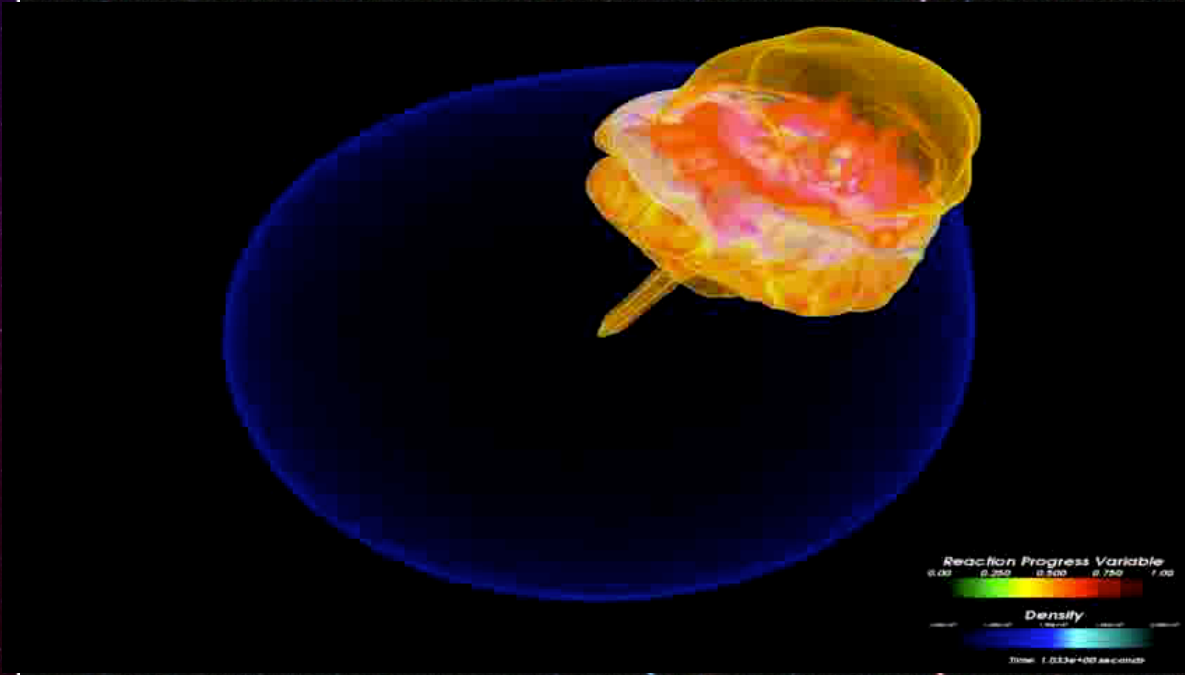
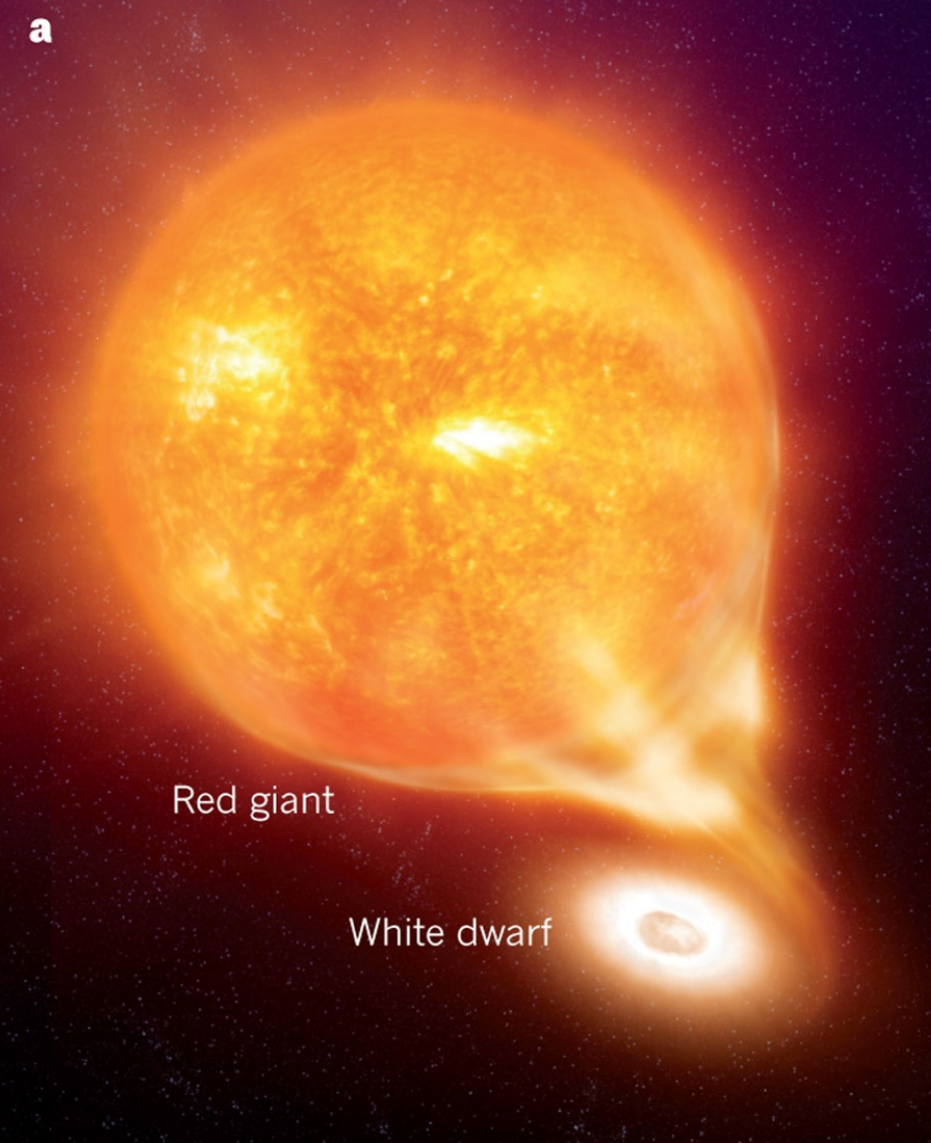
# M82 The Cigar Galaxy 2013



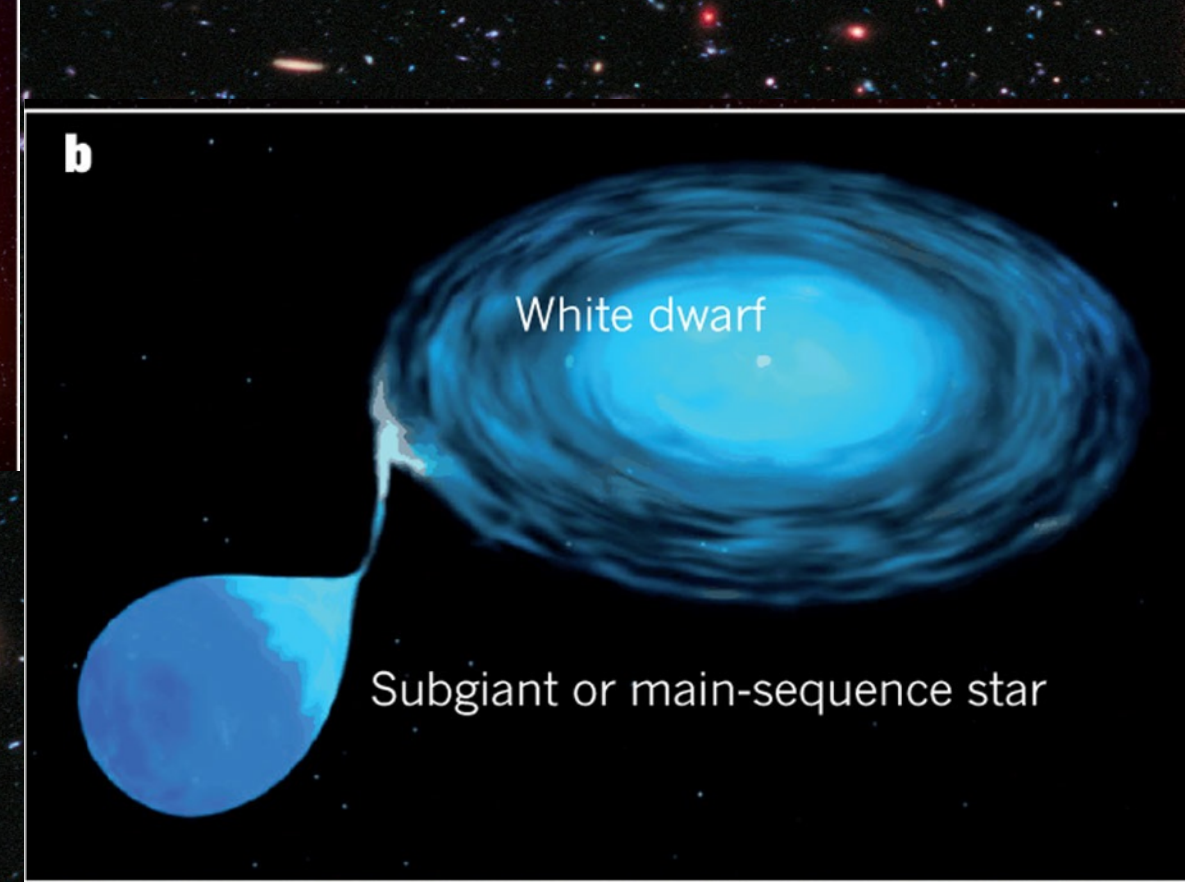
# M82 The Cigar Galaxy 22<sup>nd</sup> Jan 2014



**a**



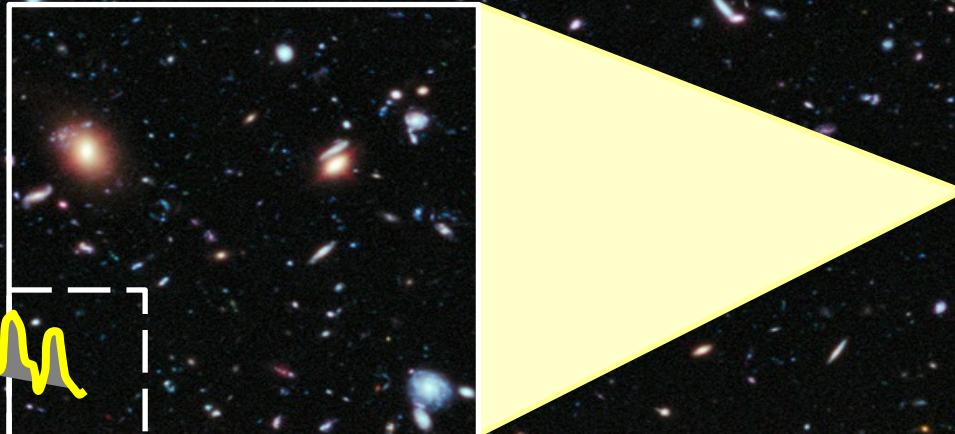
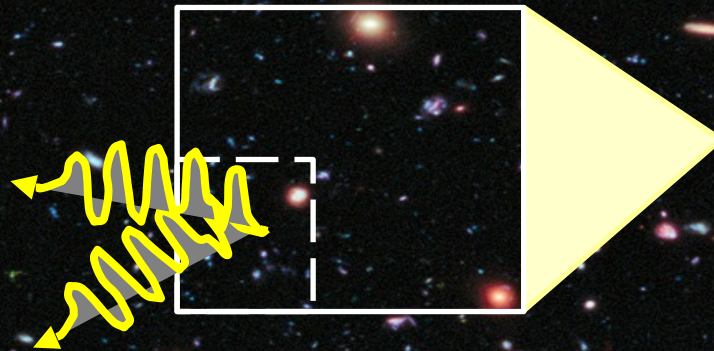
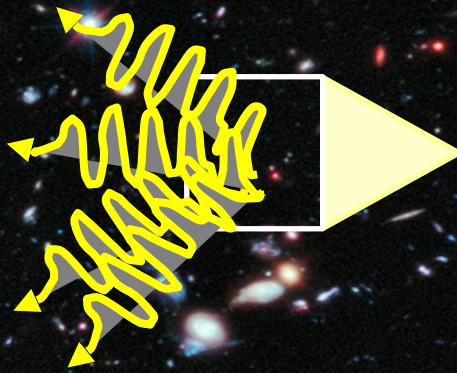
**b**

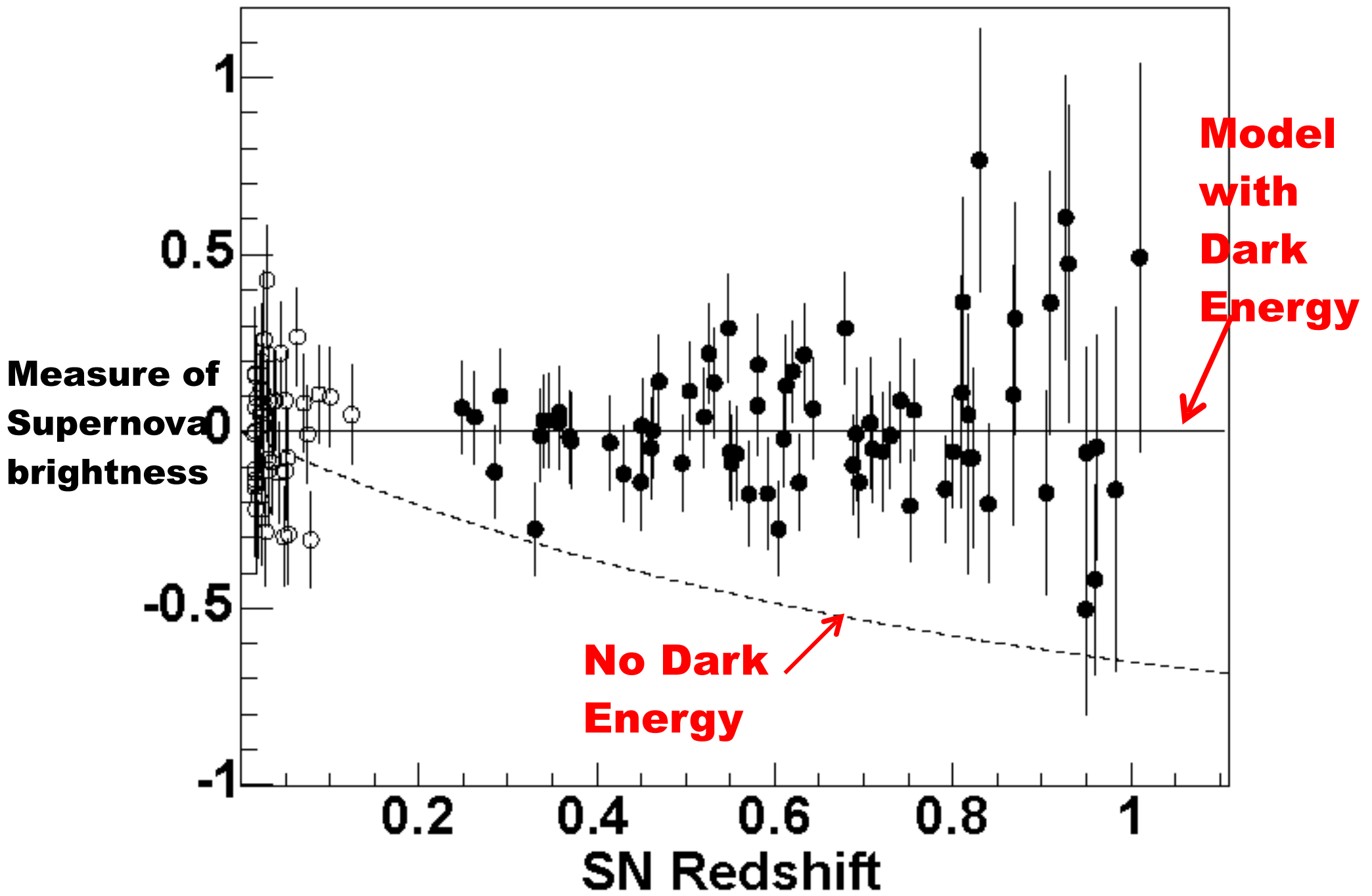




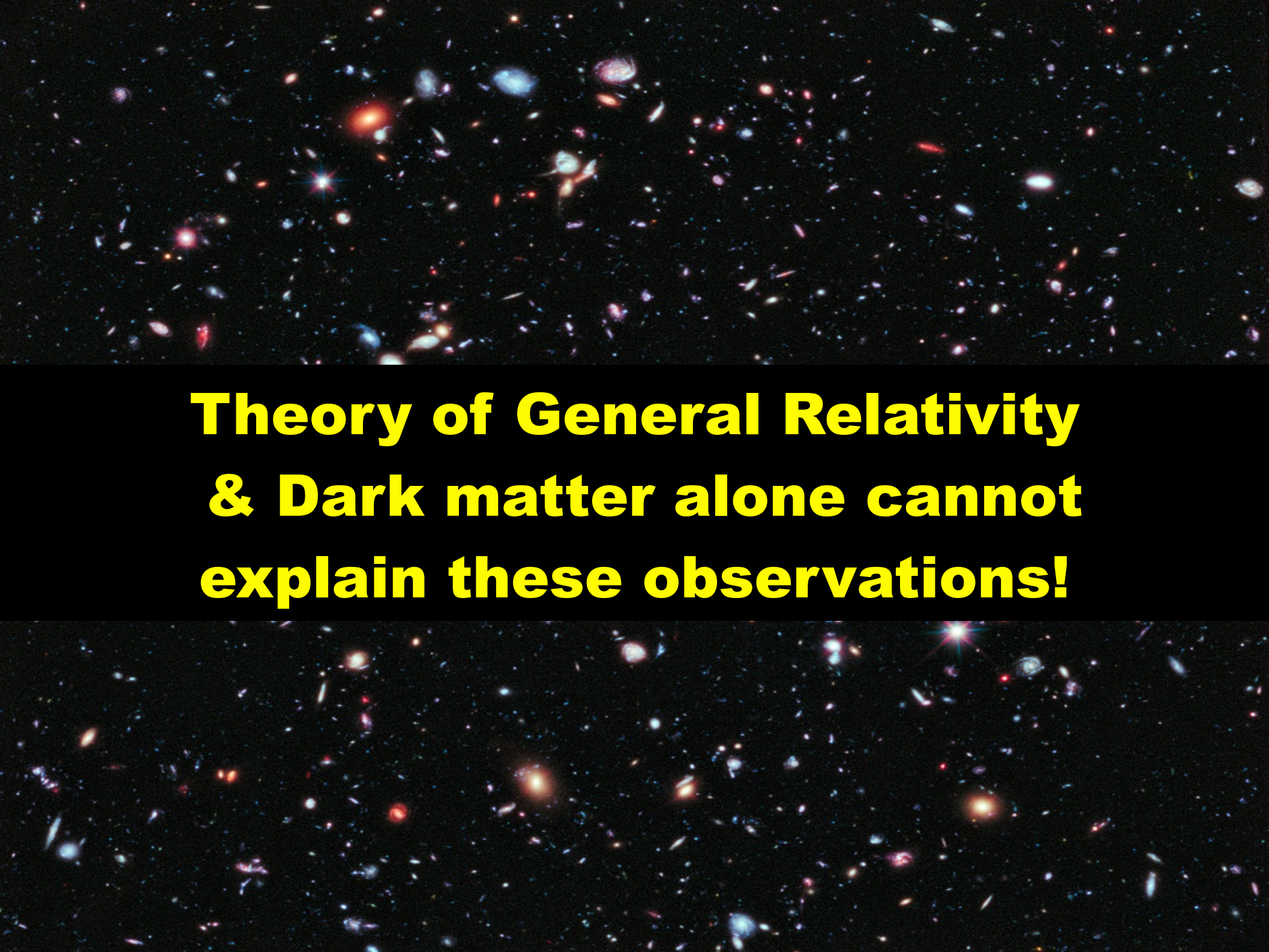
# These exploding stars are “Standard candles”

Photons of  
light that  
reach  
Earth

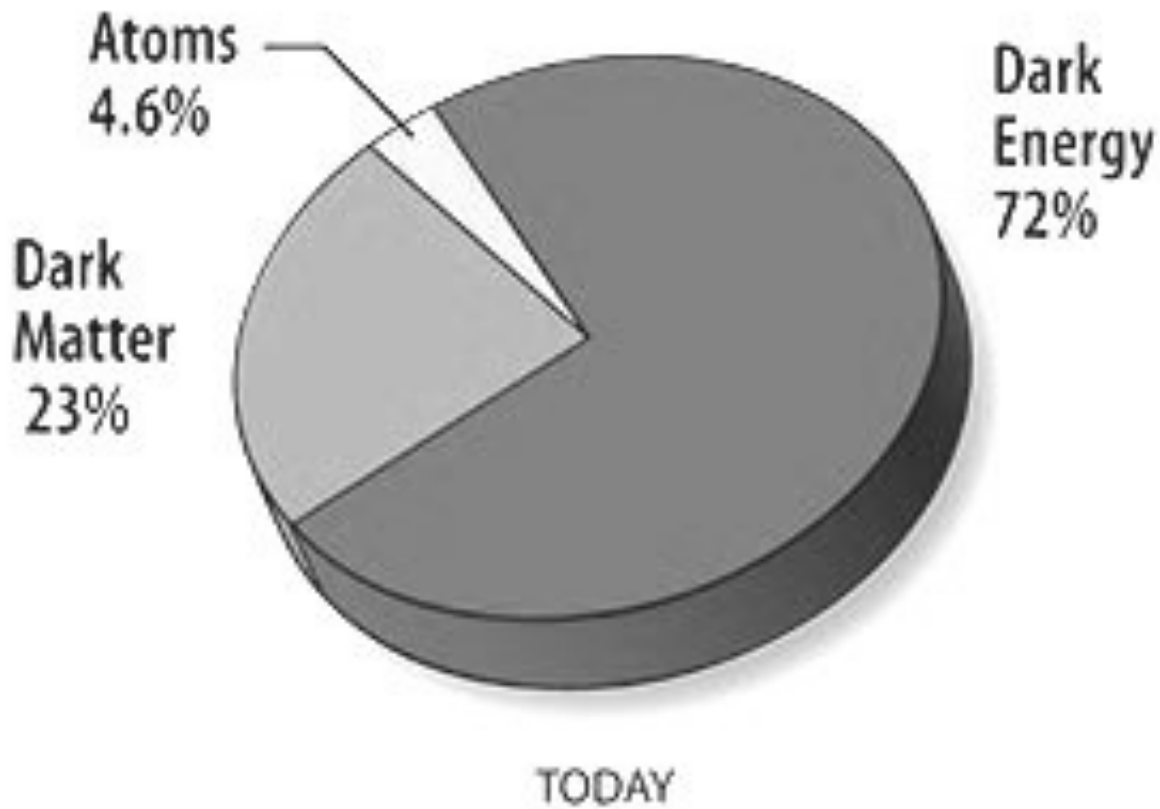




Astier et al 2006



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



$\Lambda$ CDM

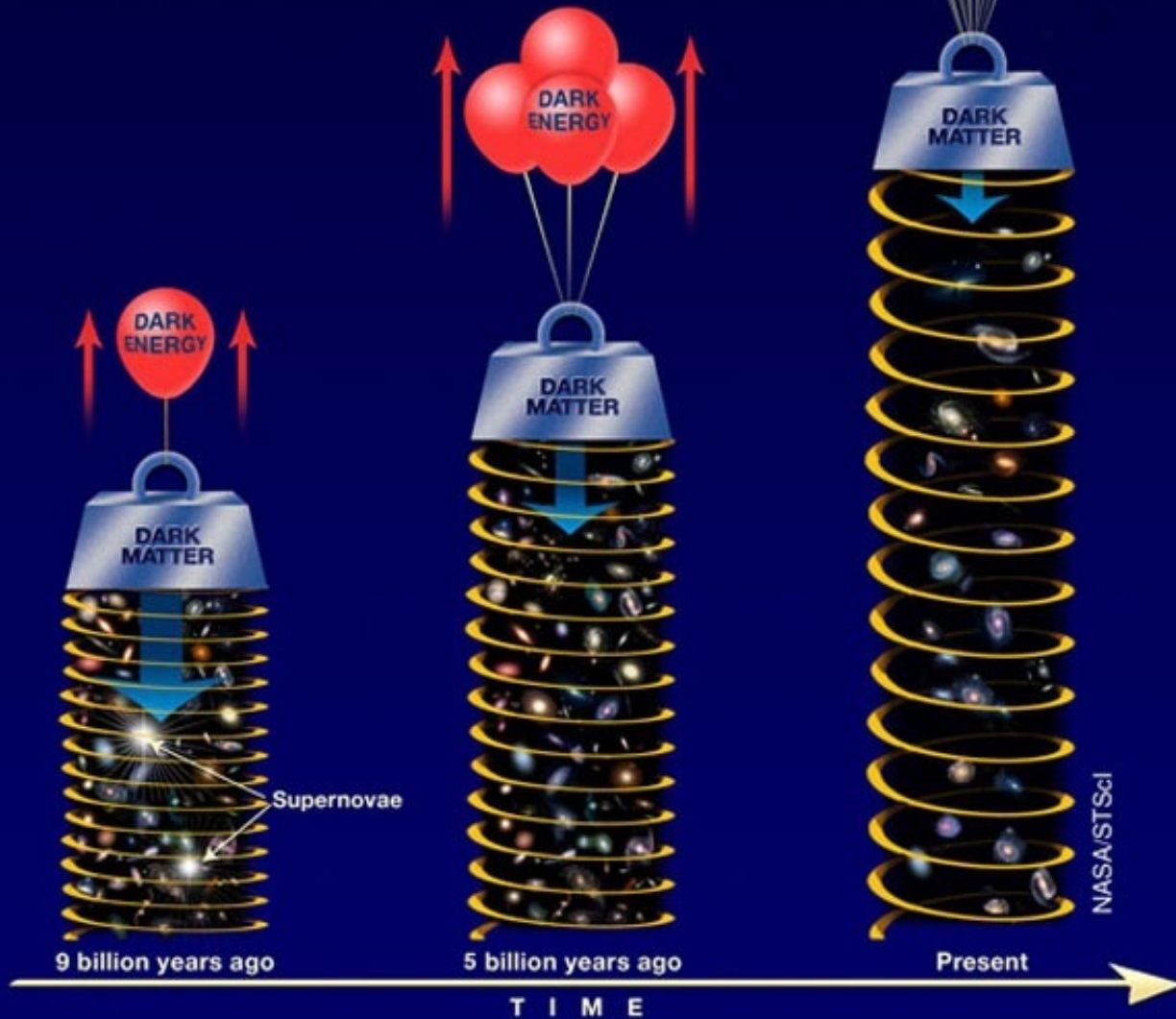
Dark Energy

Cold Dark Matter

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

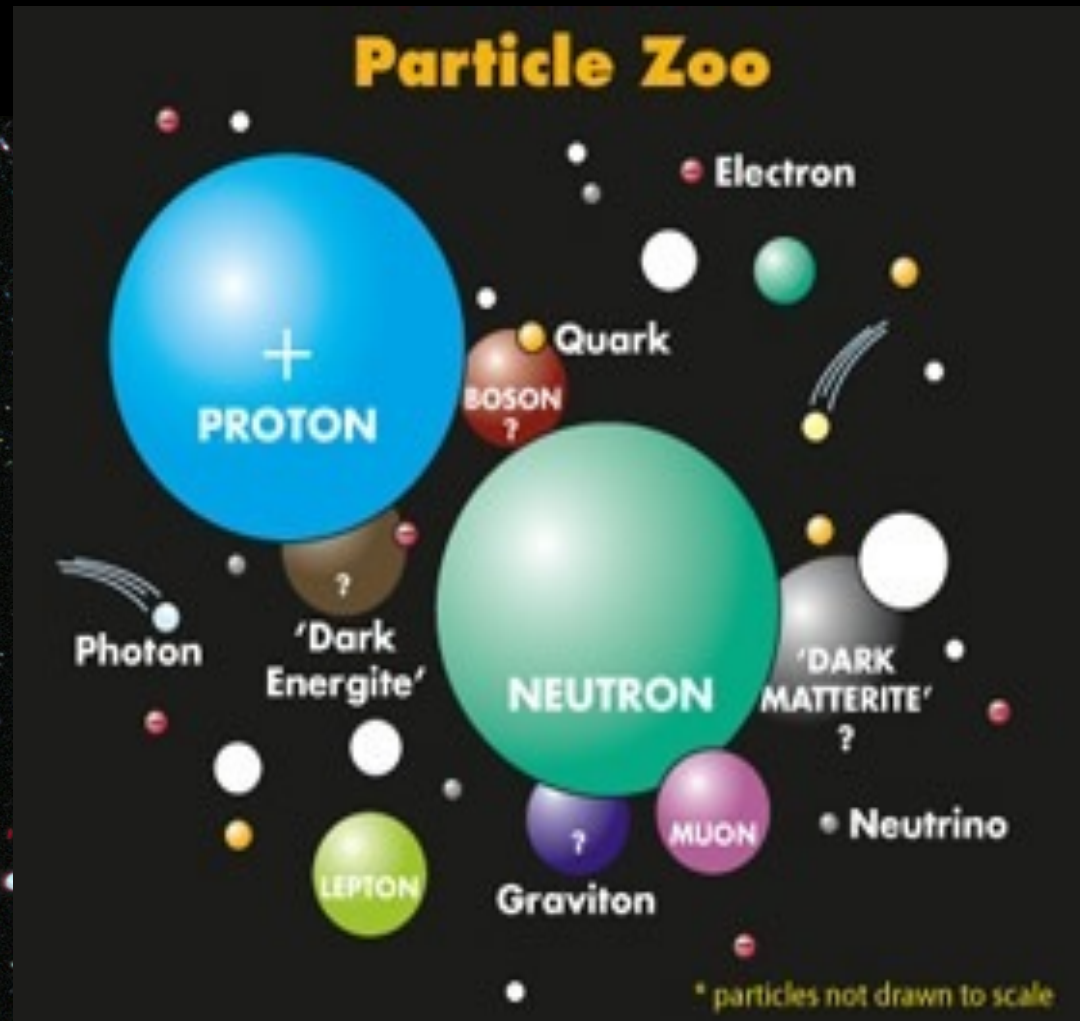


# The Dark Energy Era = Cosmic tug of war

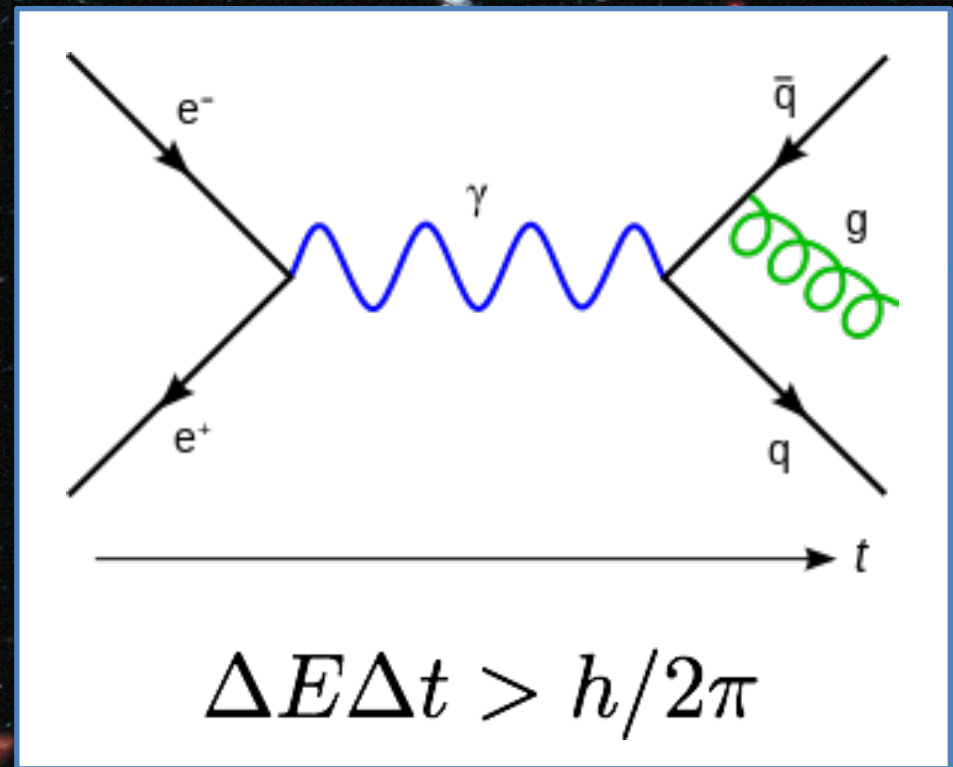


# How do we explain these observations?

**General Relativity + (some extra component) ??**



## Quantum Field Theory 1950s

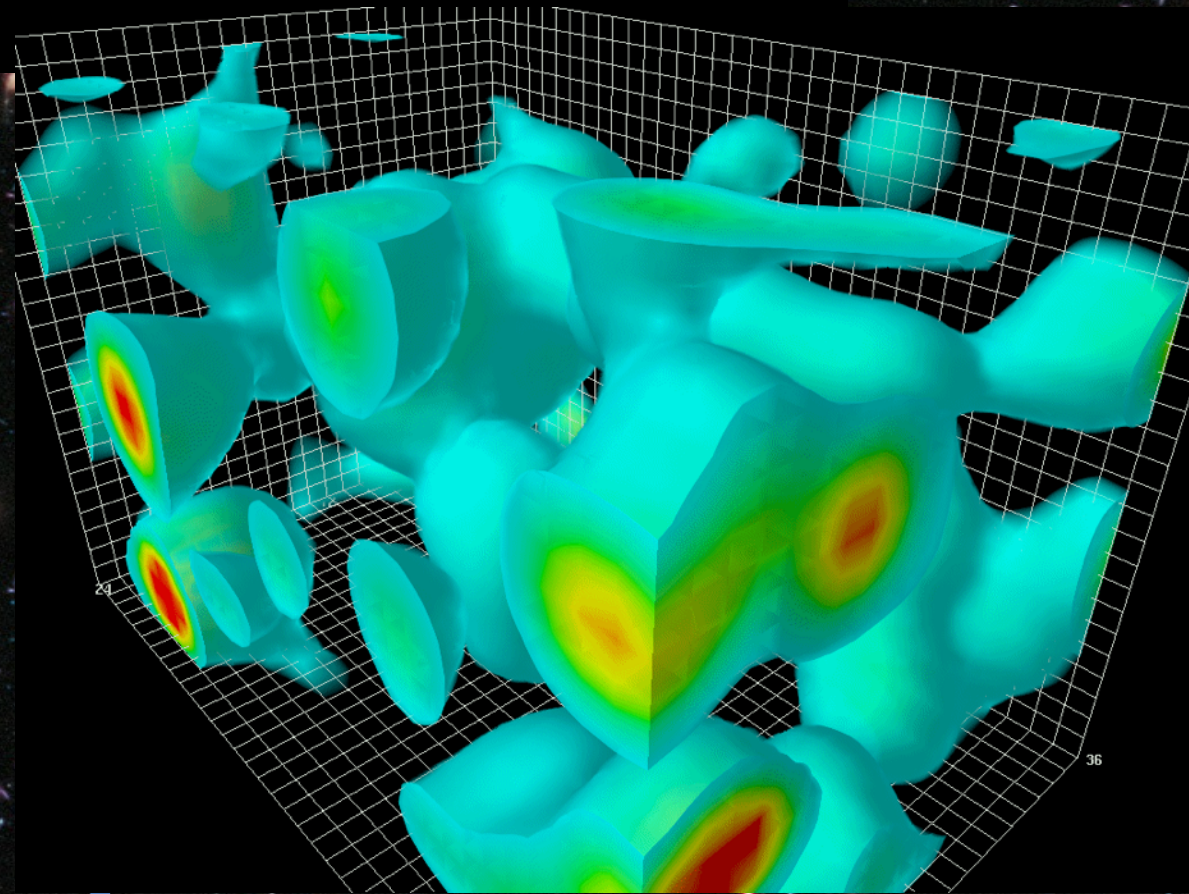
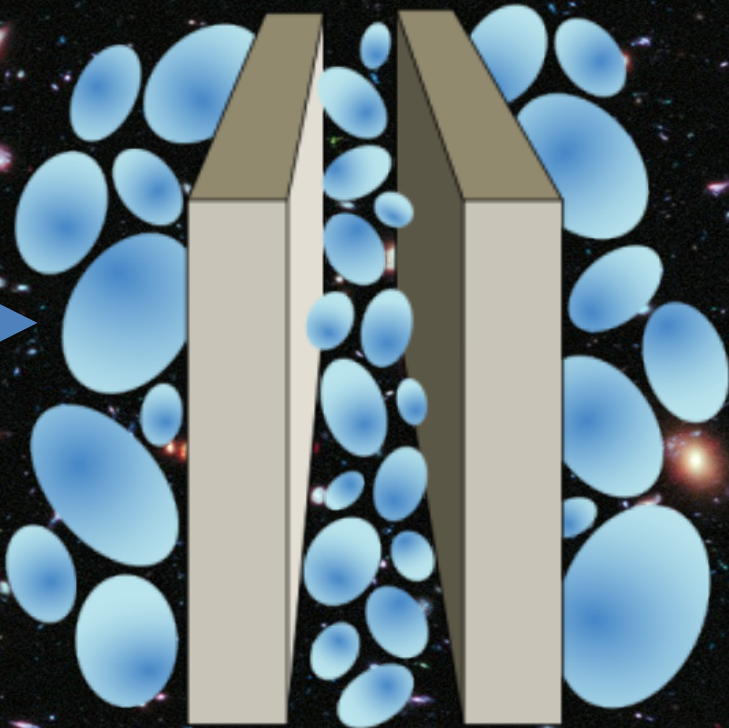


**A quantum vacuum has exactly  
the properties of Dark Energy we observe**

# 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**

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

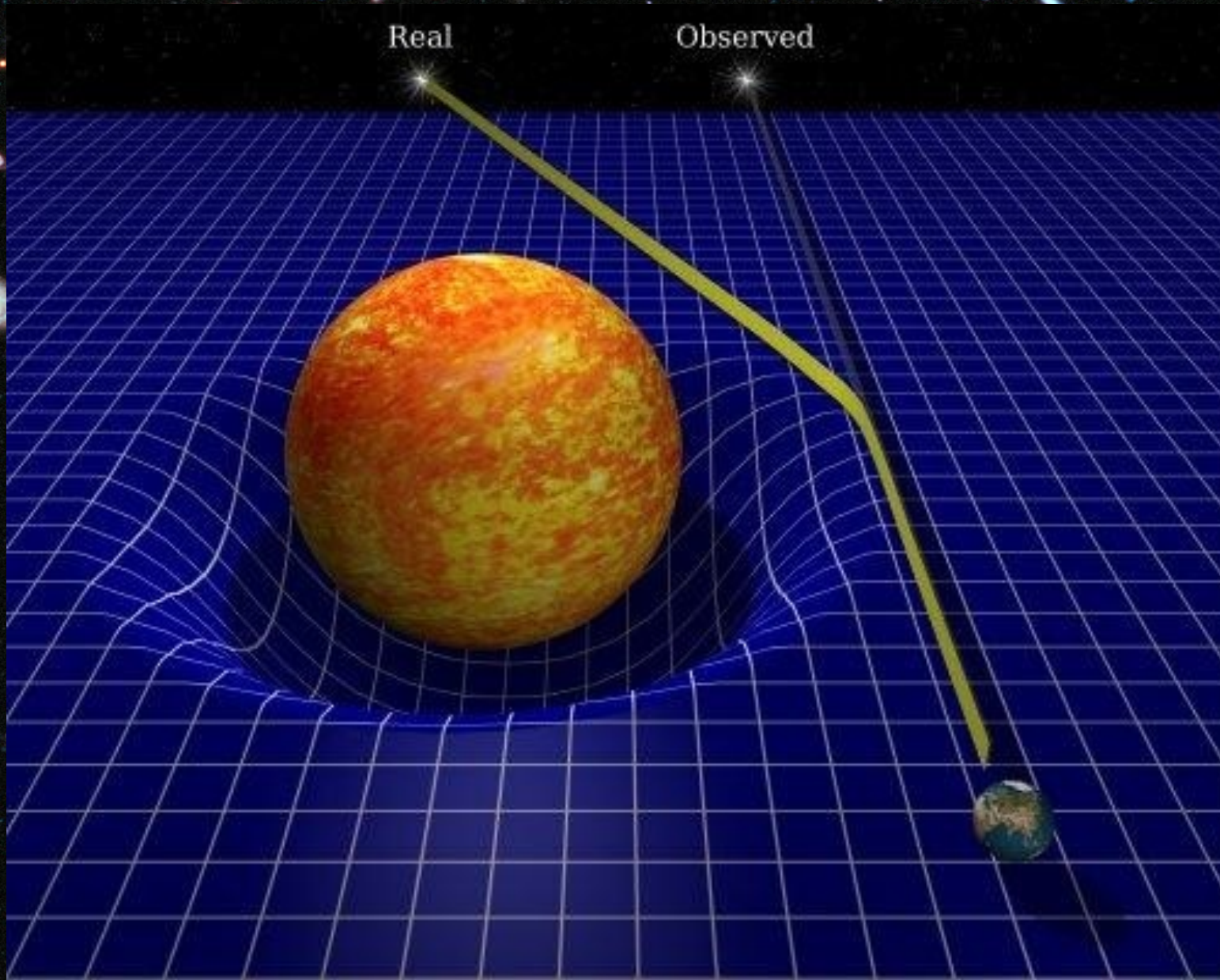
**Predicted value from  
theory**

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

**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?**



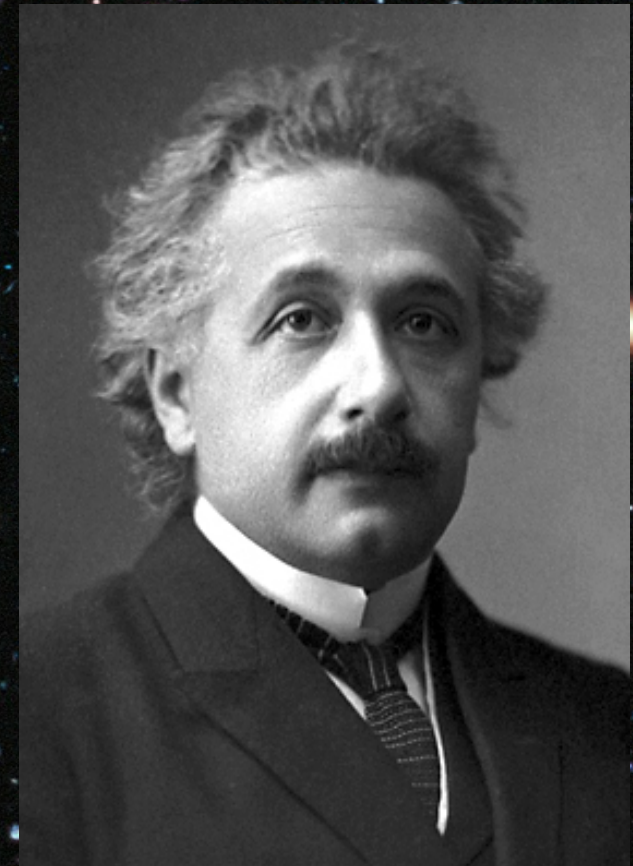
# It's not so crazy to think about changing our theory of gravity!

## 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%**

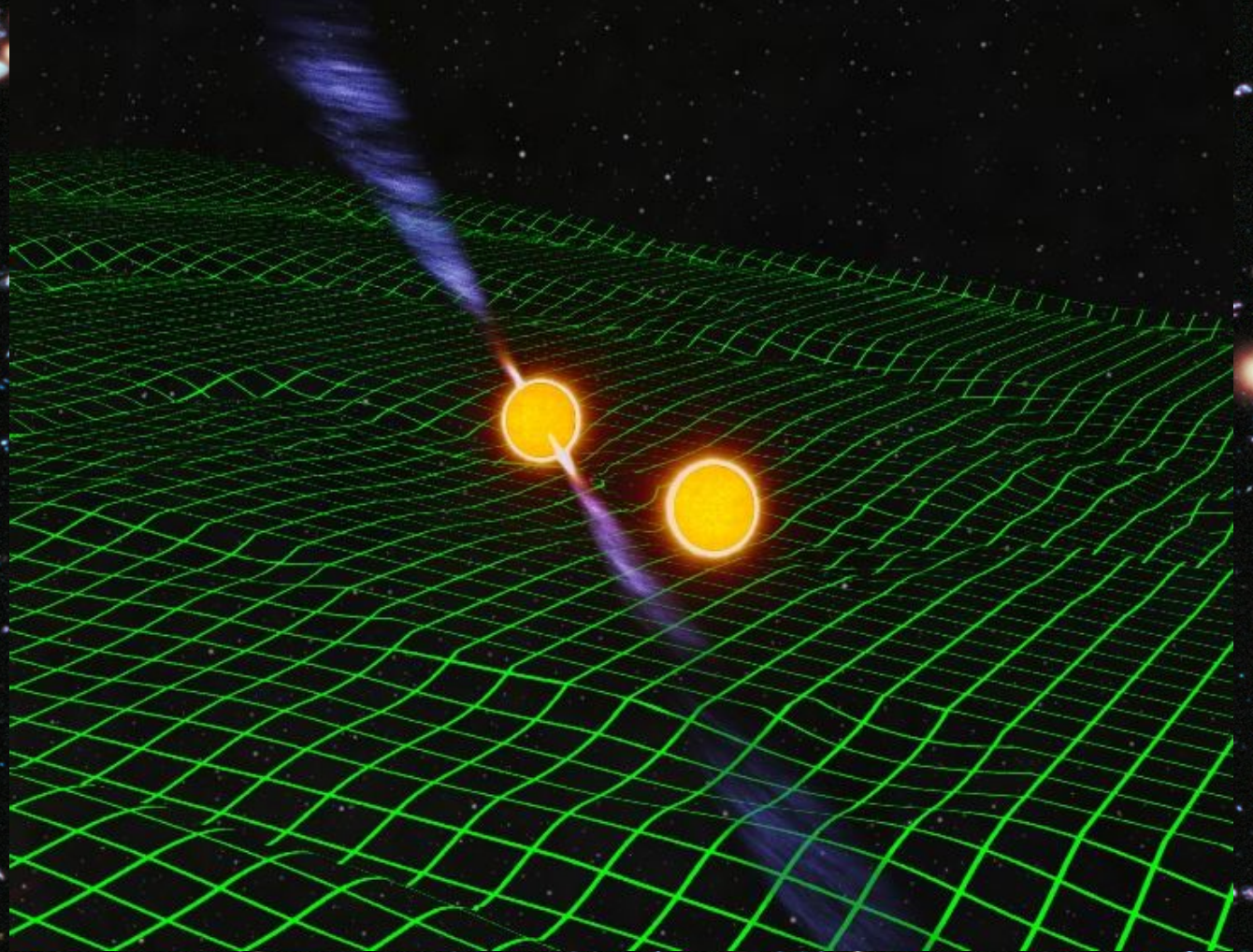
- **Lunar ranging experiments**



# 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.**

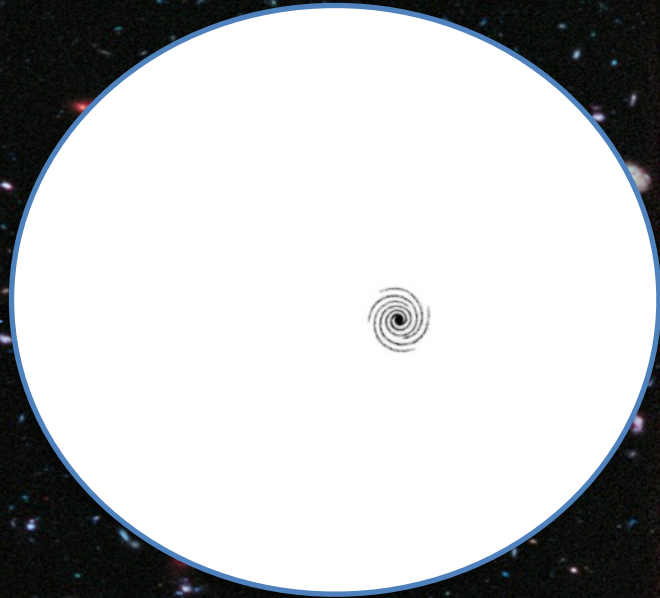
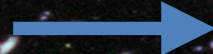
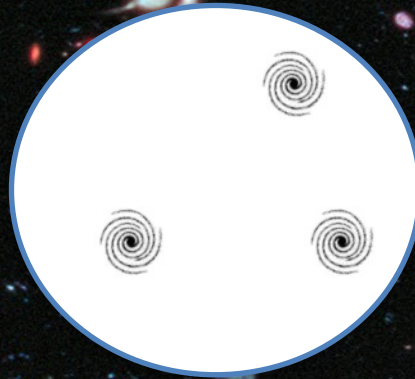
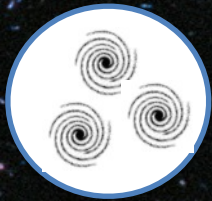
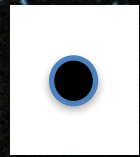
$$w = \frac{P}{\rho}$$



# *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**

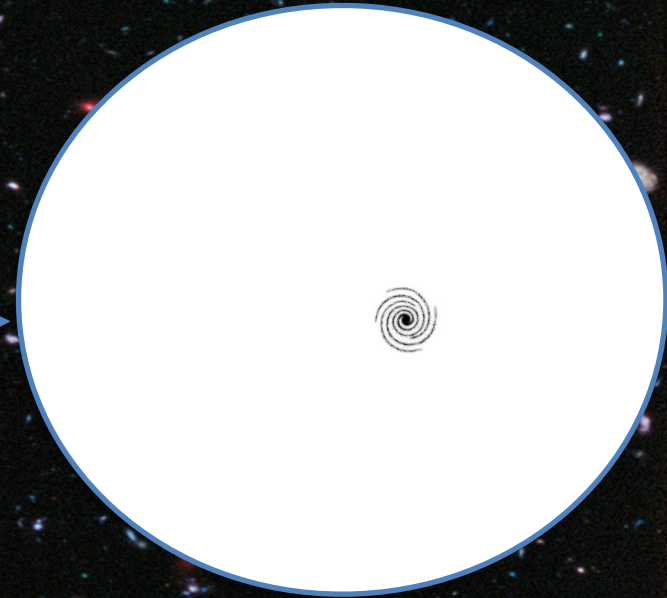
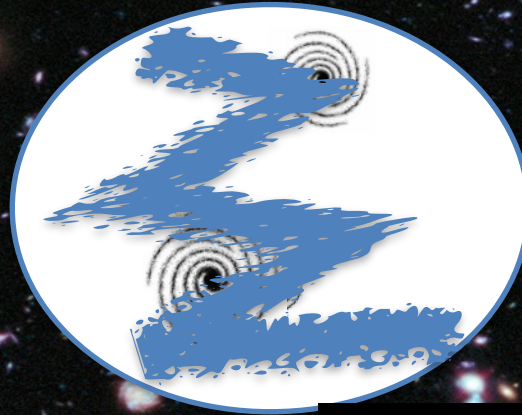
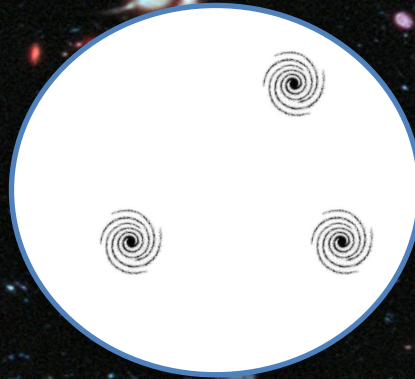
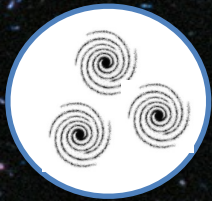
**Big Rip**

**Dark Energy tears apart LSS**

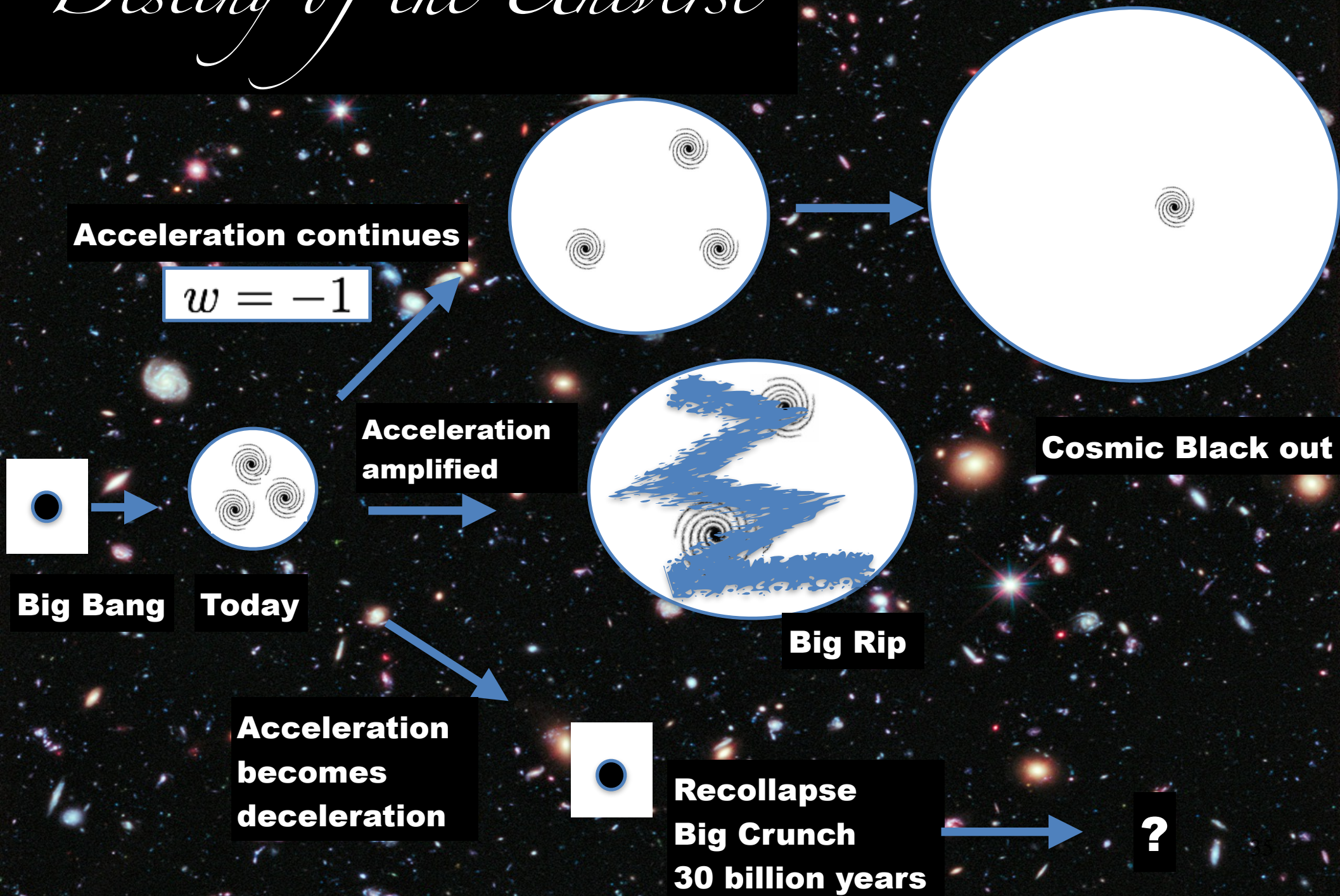
**50 billion years**

**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**

**?**

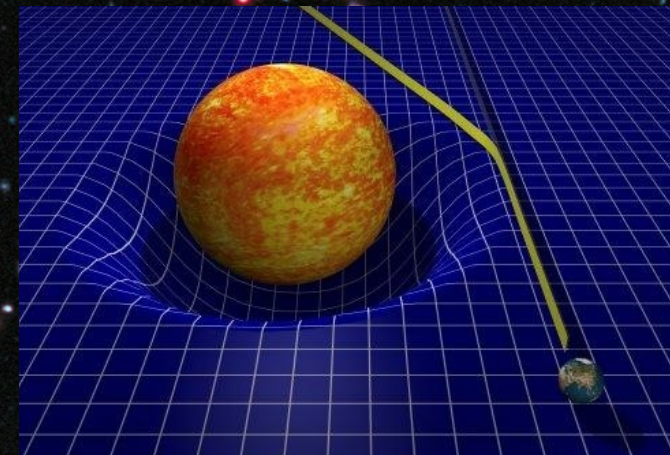
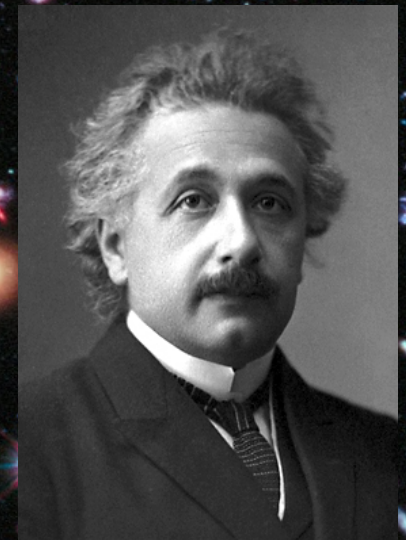
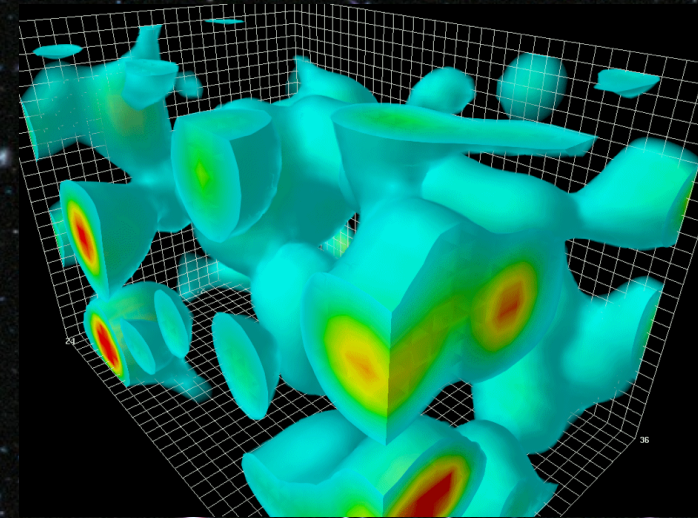
**Big Bang**

**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.***