

Hubble Trouble:

The Expanding Universe

&

Dark Energy Enigma

G. Gabadadze, March 13, 2012

Reminder

We live on Earth

Earth orbits the Sun

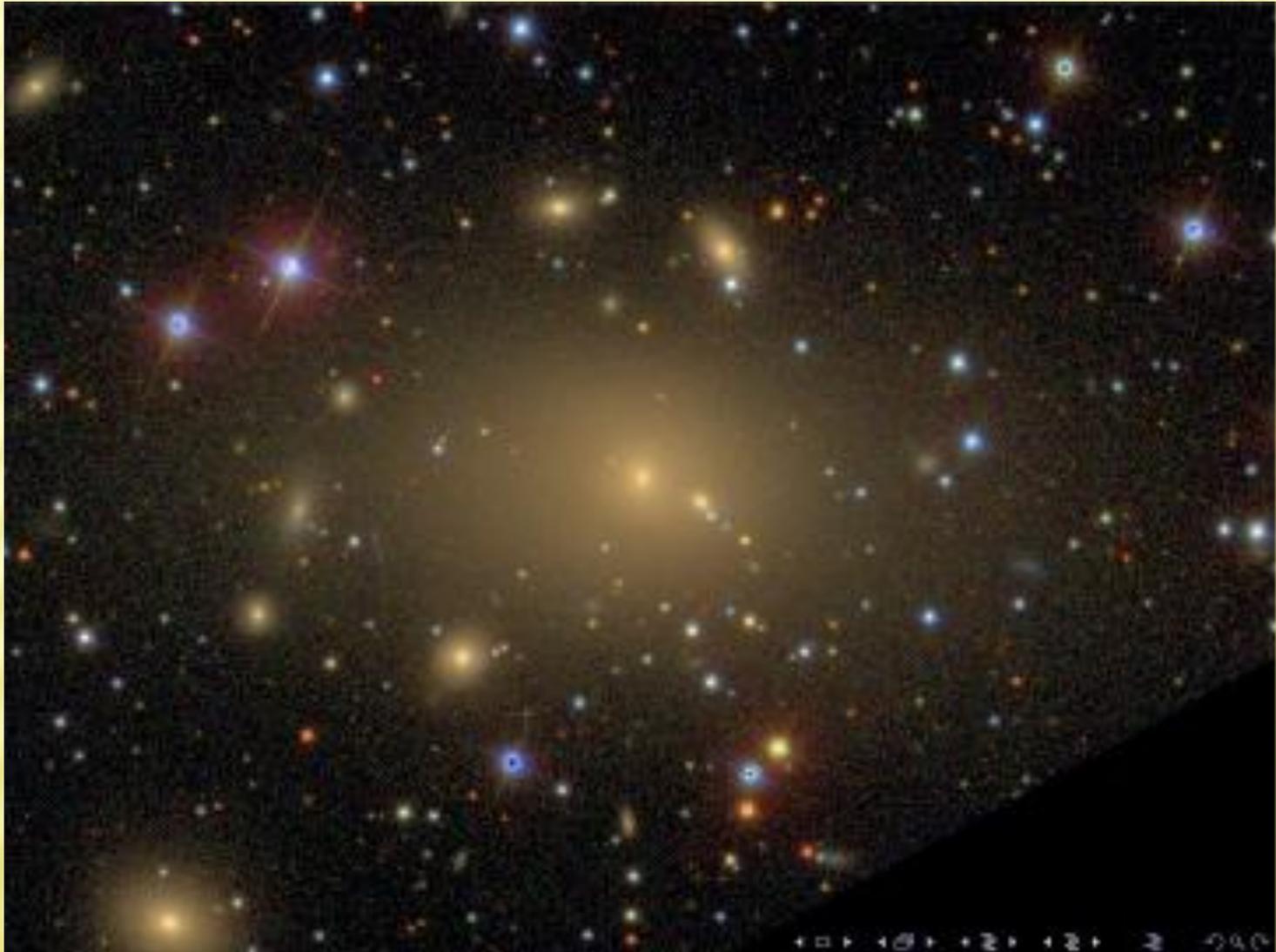
Sun in the Milky Way Galaxy

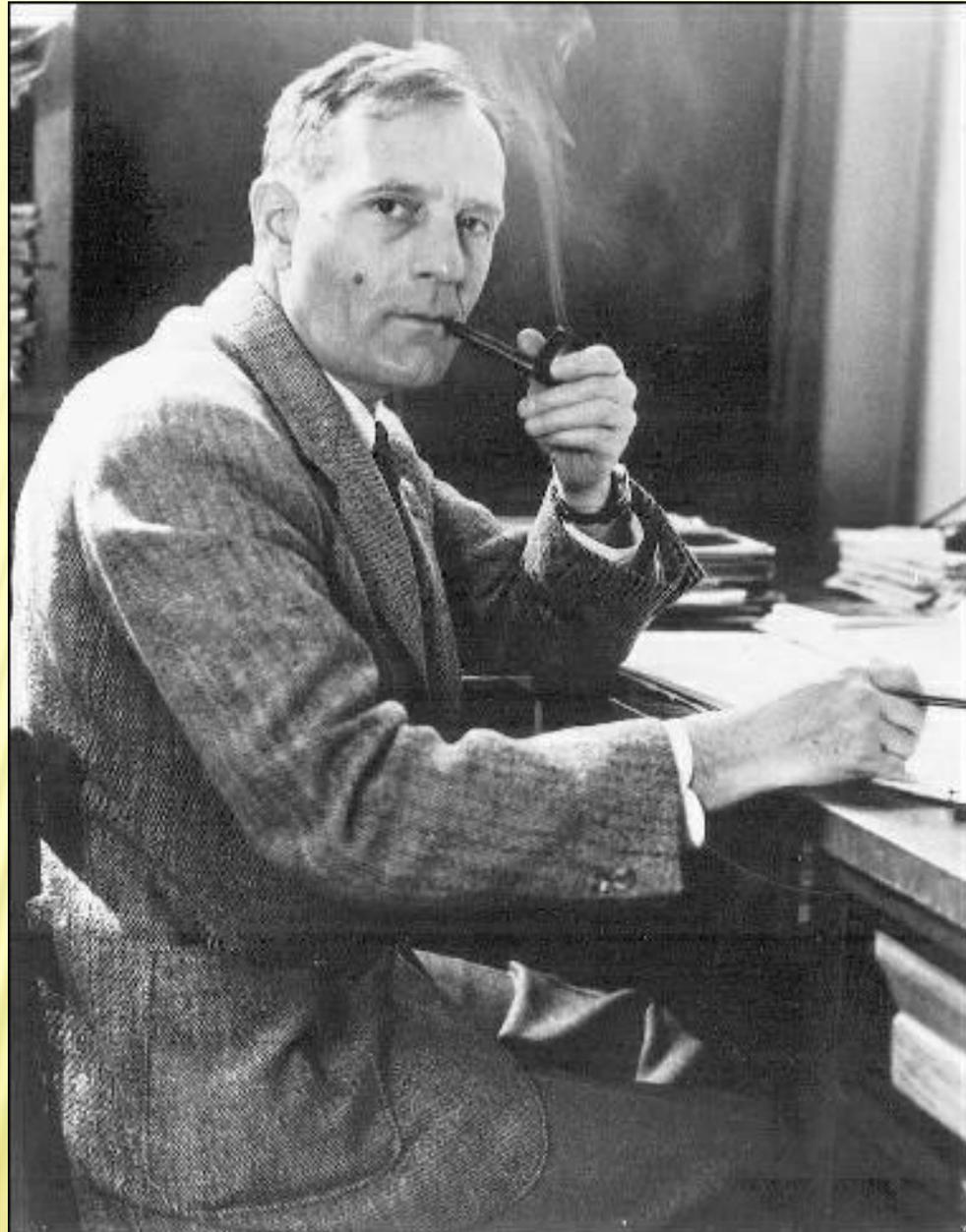




HST

There are about ten billion galaxies in the visible Universe





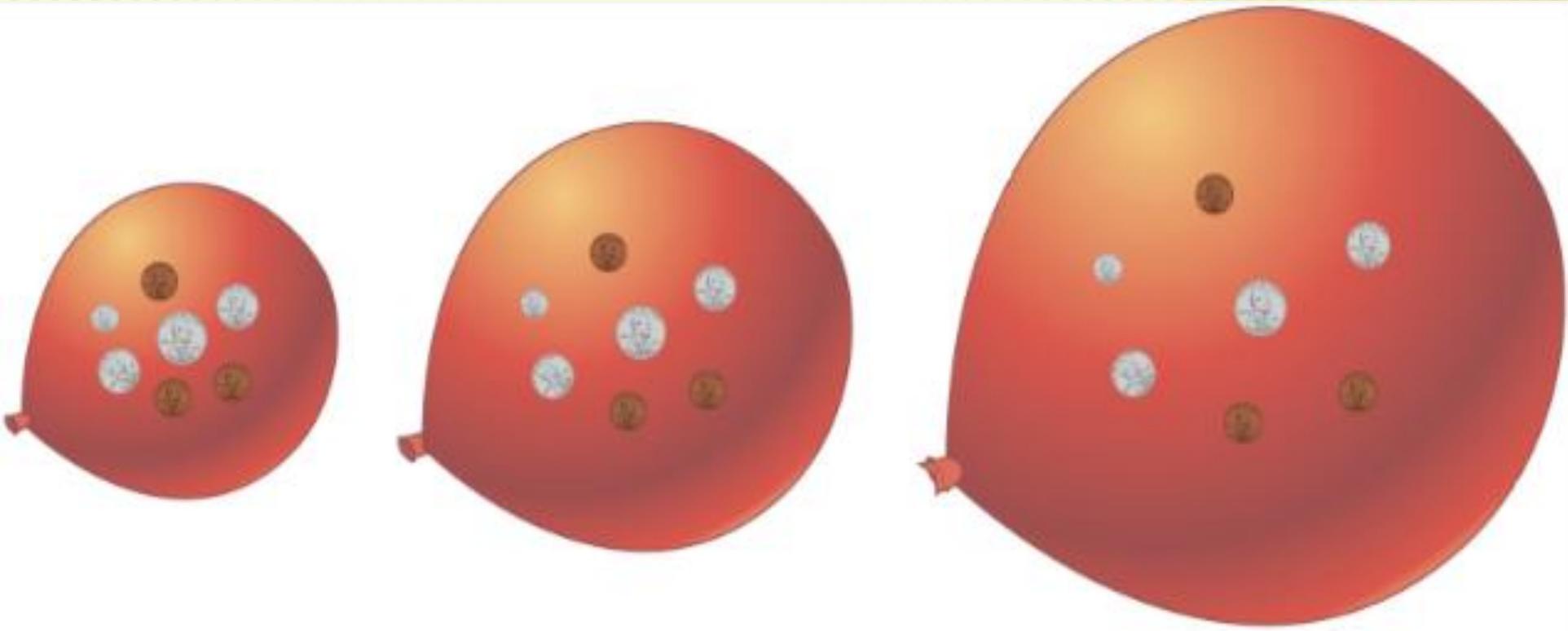
Edwin Hubble: 1920-1930 expansion of the Universe

Universe is expanding: galaxies are receding with velocities proportional to their separation

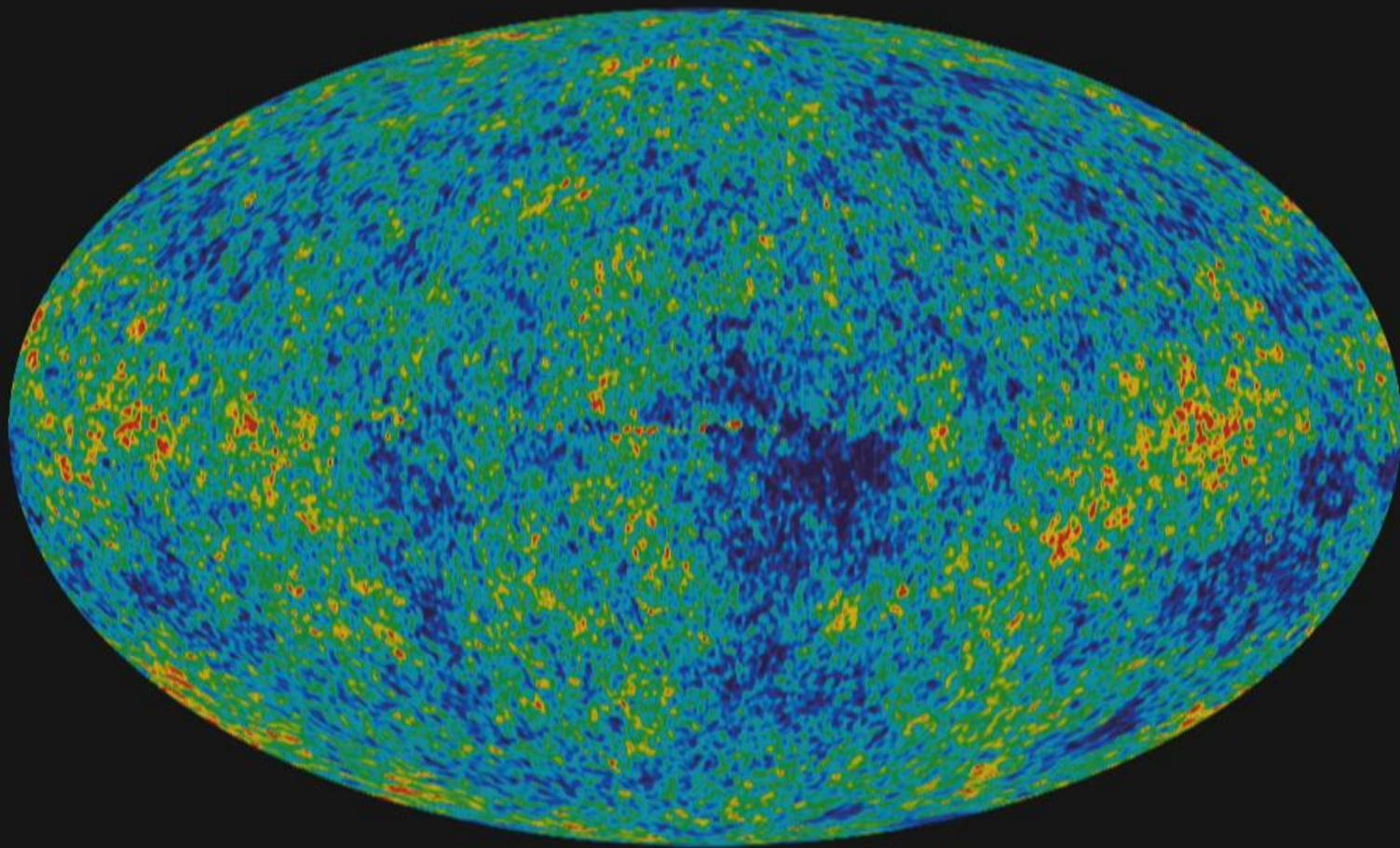
The expansion does not require that there be a center: “everyone” sees the cosmos recede away

Bound objects are not expanding:
atoms, living beings, planets Solar System,
Galaxies

A classroom exercise

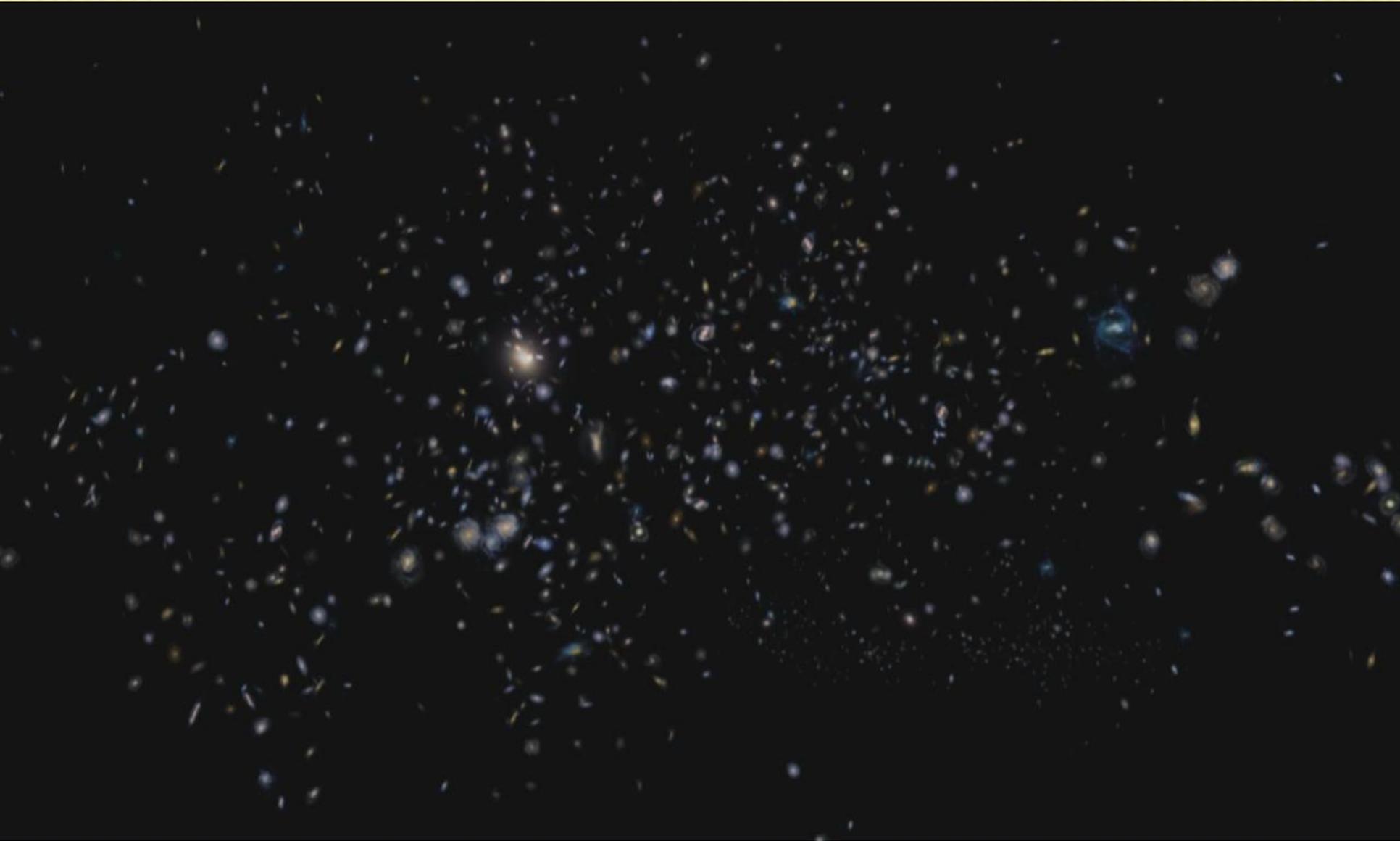


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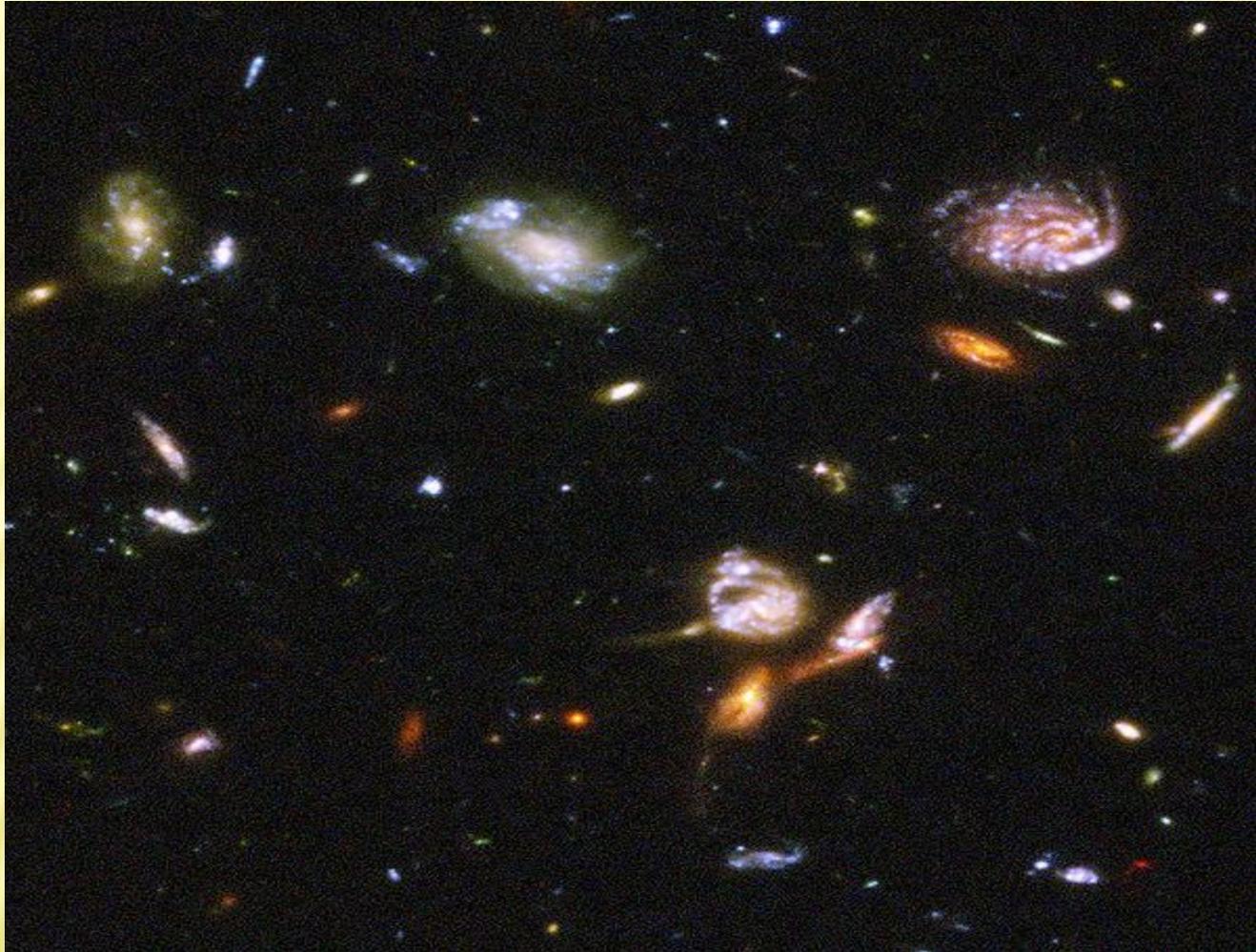


Credit to NASA

Evidence for Accelerated Expansion



Unknown substance between Galaxies (clusters of galaxies)



This substance, dubbed Dark Energy, acts as “anti-gravity”

How is Dark Energy Distributed in the Universe?

Uniform distribution: Cosmic Mist

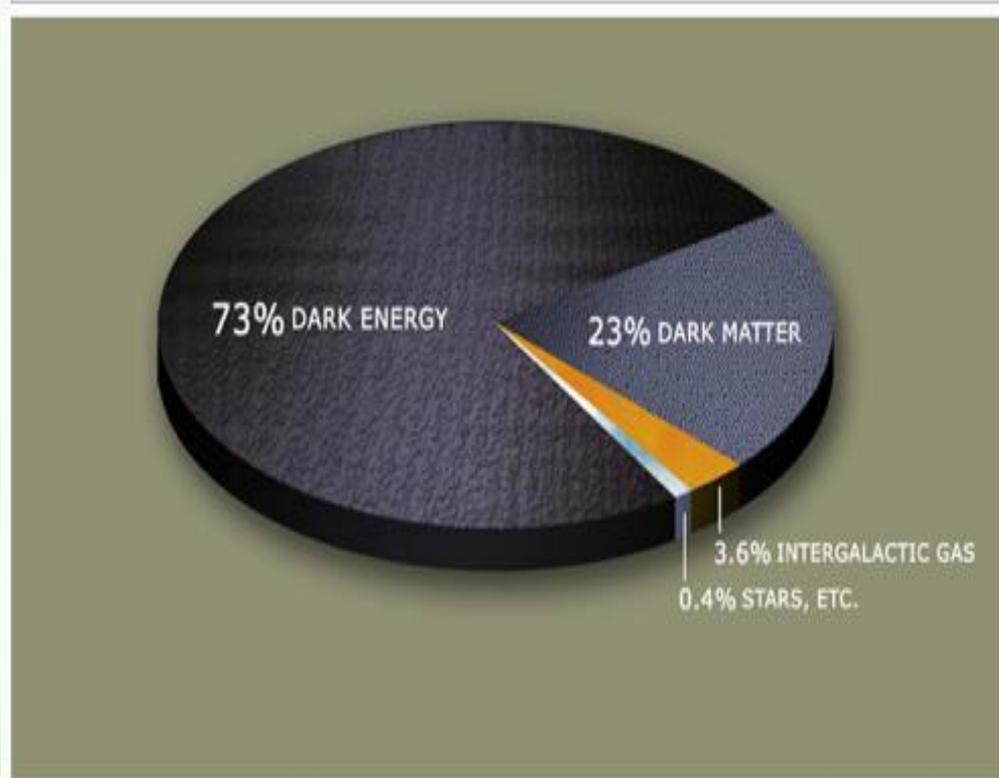


How much Dark Energy is there?



The “weight” of Dark Energy in a coffee cup
=
the weight of an electron

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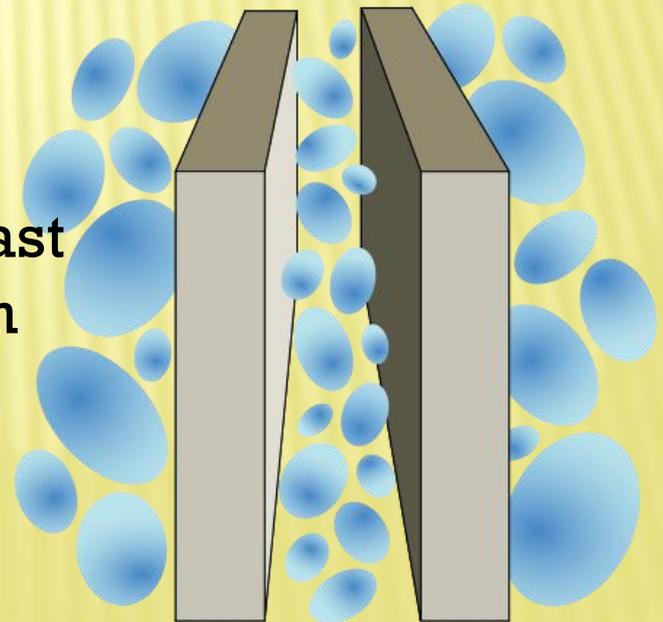
What is Dark Energy? What will it do?

1. Vacuum Energy (or its cousins)?

Quantum nature of the micro-world: nothing is at rest

Vacuum fluctuations \Rightarrow vacuum energy

The only problem: the value is at least 60 orders of magnitude greater than what has been observed. Too much VE !!!

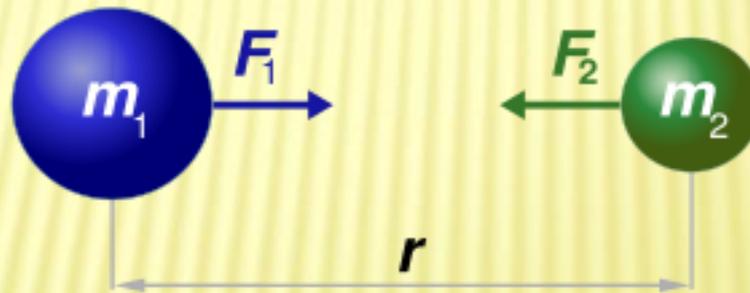




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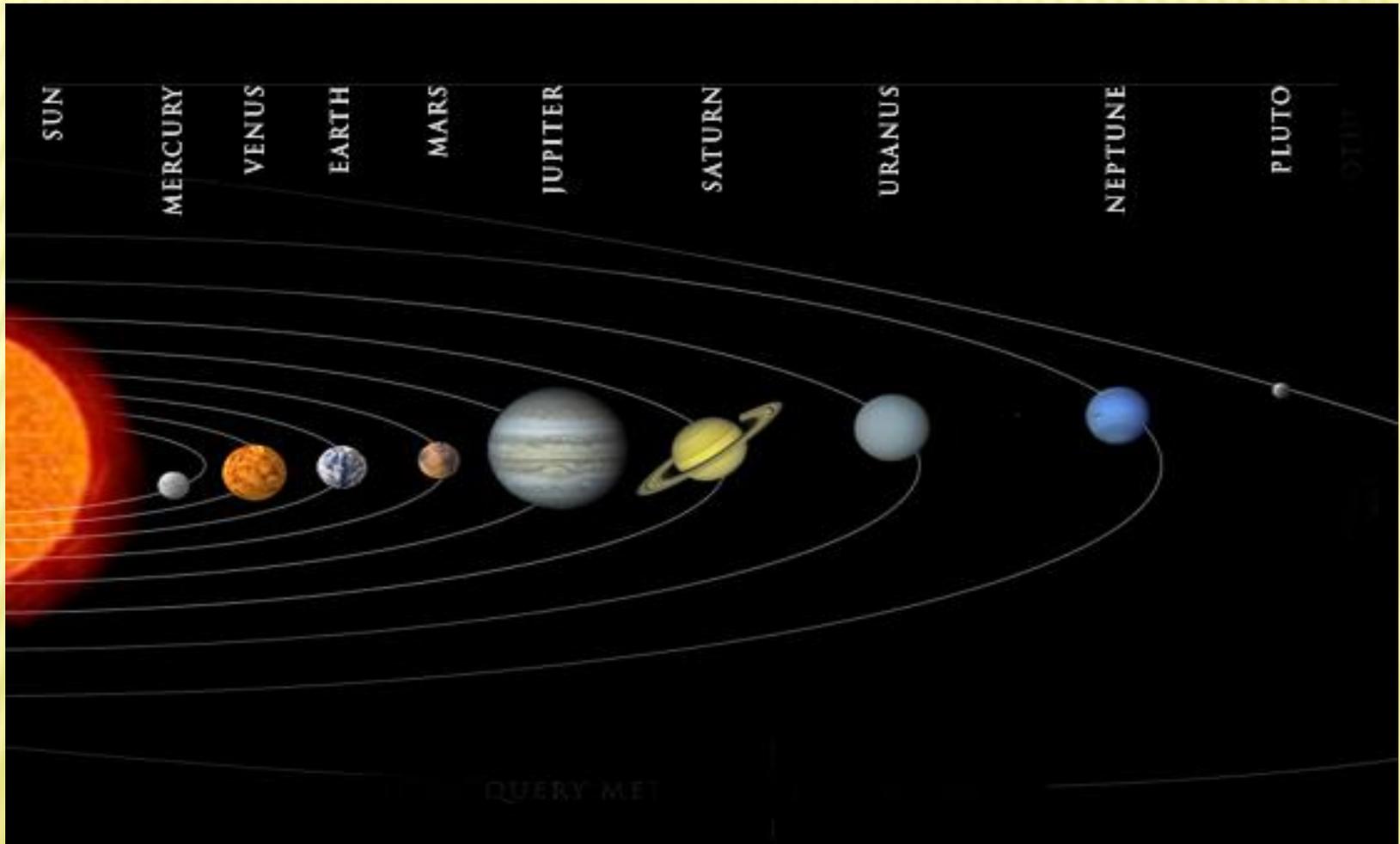
2. Extending Einstein's Theory of Gravity ?

What is gravity?



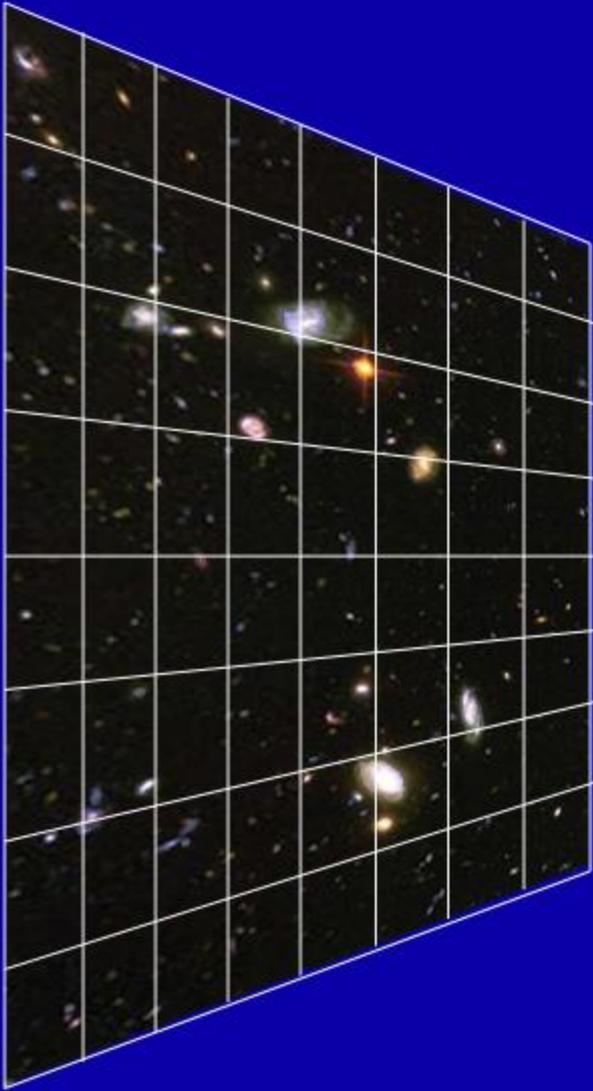
$$F_1 = F_2 = G \frac{m_1 \times m_2}{r^2}$$

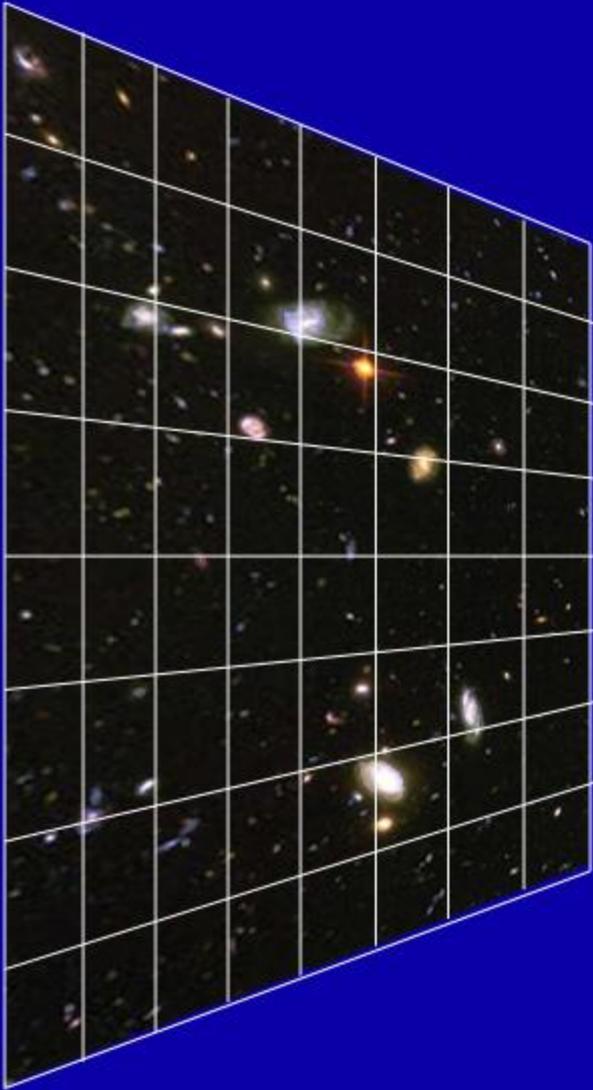
Einstein's extension of Newton's theory: precise description of planetary motion



Cosmic acceleration: beyond Einstein ???

Extra dimensions?





Cosmic acceleration: beyond Einstein ???

Extra dimensions?

Get rid of the “elephant”

Gravitational pull-back
of extra dimensions
on our world:
self-acceleration!

Deffayet, Dvali, Gabadadze

Massive gravity: de Rham, Gabadadze, Tolley

Gravity acquires an inertia; as a result, gravity acts as a fluid that resembles dark energy.

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Dato Pirtskhalava



Lasha Berezhiani



Giga Chkareuli



The ultimate jurors: observations and experiments

(J. Frieman et al. SDSS II 09)

