Naples '09 Seminar

A glimpse on Cosmology: Mathematics meets the Data

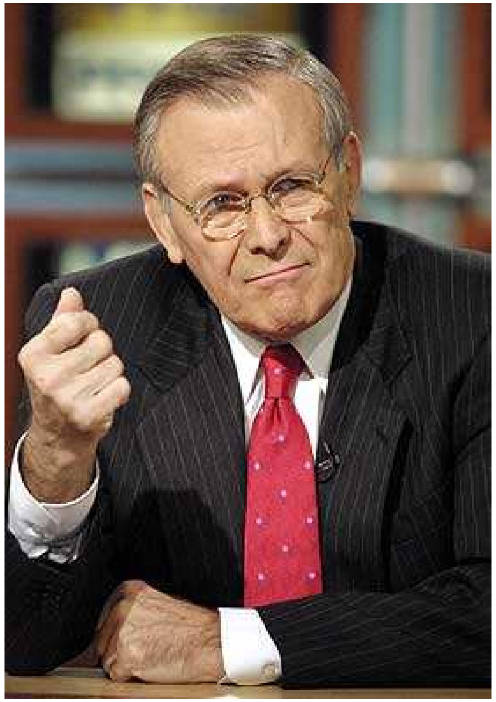
by 

Toward a unified epistemology of Sciences

...As we know,
There are known knowns.
There are things we know we know.

We also know
There are known unknowns.
That is to say
We know there are some things
We do not know.

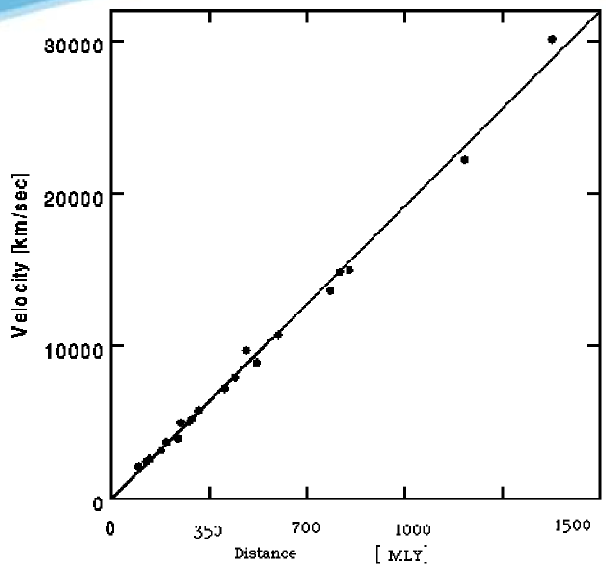
But there are also unknown unknowns,
The ones we do not know
We do not know...



- D.H. Rumsfeld, Feb 12, 2002, Dept. Of Defense news briefing

What do we see out there?

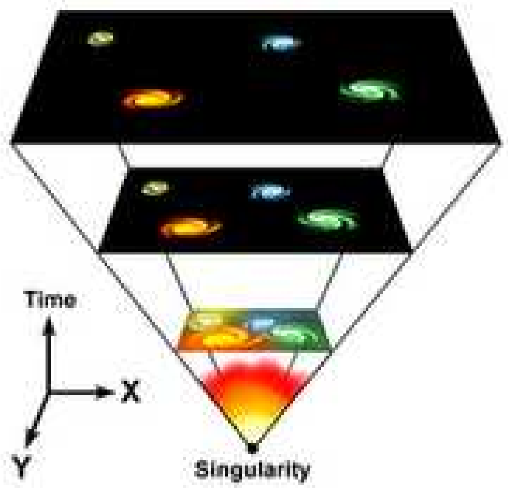
1924: Edwin Hubble showed that *each* galaxy is a collection of stars, just like the Milky Way



1929: Hubble "finds" that the further away a galaxy is, the more rapidly it is moving away from us

$$v = H_0 d$$

It looks the same for *every galaxy...*



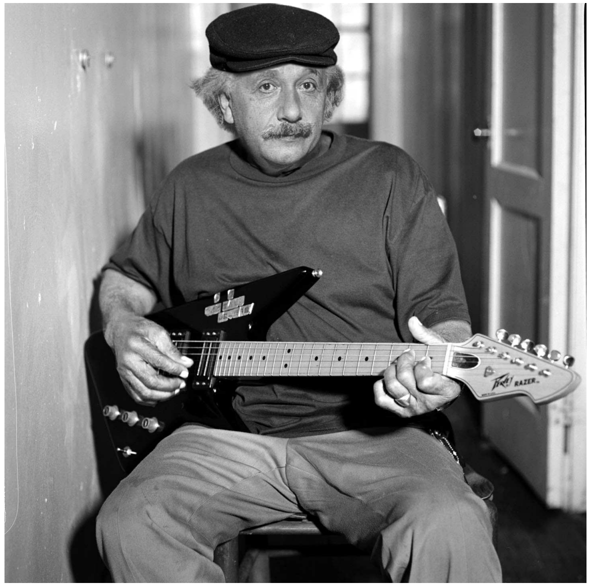
$\Rightarrow$ The universe is expanding!

Relative distance at different times is measured by the *scale factor* a(*t*). Hubble parameter is related to a via

$$H(t) \equiv \dot{a}(t) / a(t)$$

The wonderful gravity

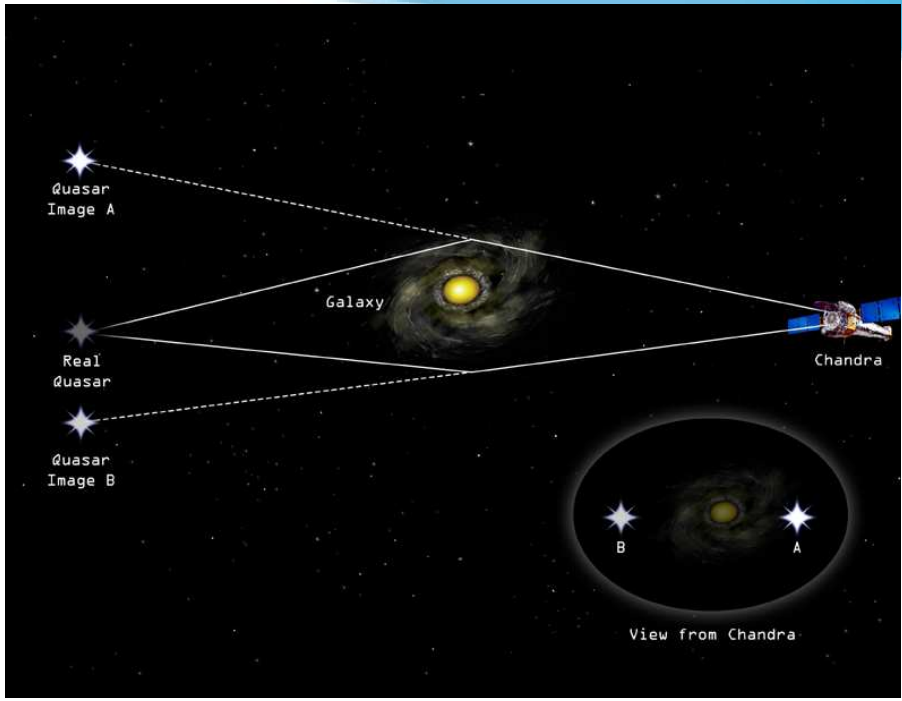
- It was Einstein that figured out that gravity is a manifestation of the spacetime curvature
- Using gravity we can detect *everything* in the universe, even those things that are invisible and transparent somehow (“dark”)
- Everything causes gravity, everything is affected by gravity



$\Rightarrow$ A guess for the search of invisible matter...

Gravitational Lensing

The gravitational field of a galaxy (or a cluster of galaxies) deflects the source light. The more mass, the greater deflection



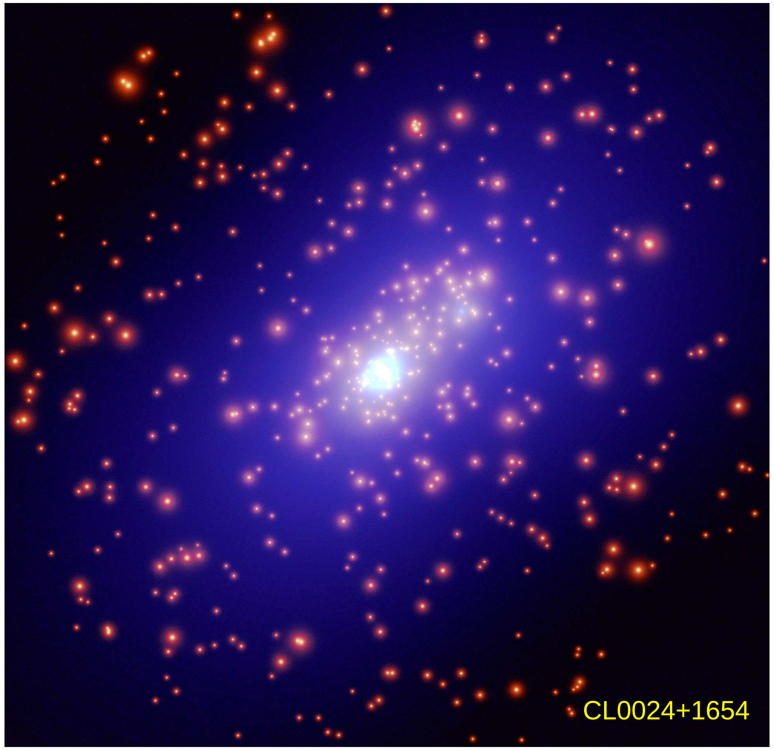
So we can infer the existence of matter even if we cannot see it!

Weighing matter

So... Some matter in our universe is ordinary - i.e., made of the particles of the Standard Model

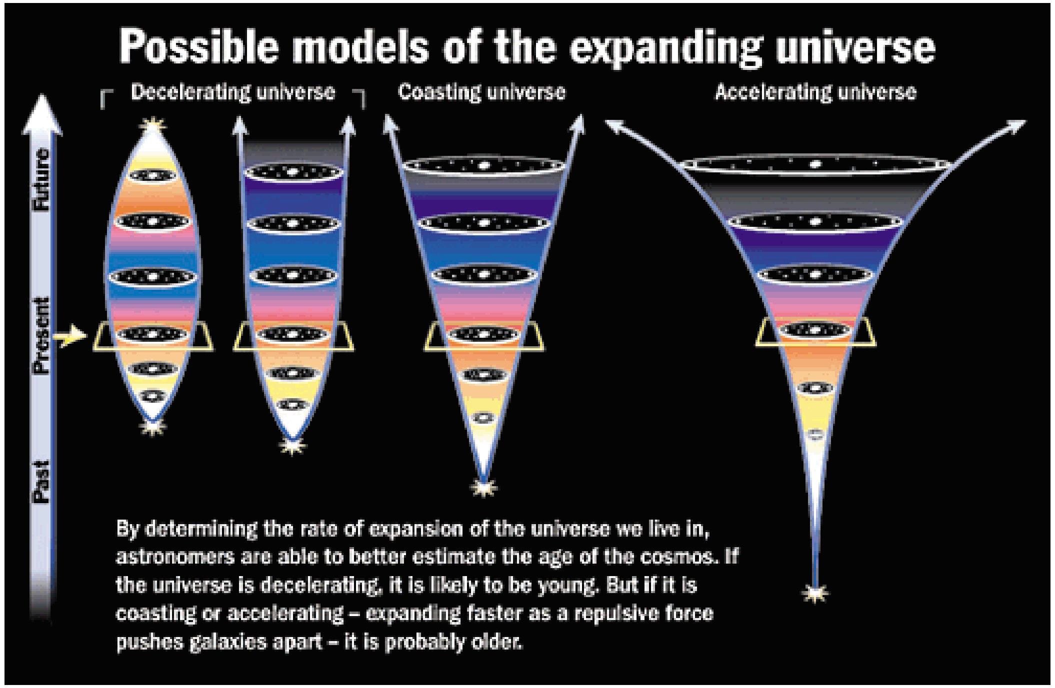
But much of it is dark! There is 5 times as much DM in the universe than ordinary matter

Whatever DM is, it is not made of particle(s) we know - it is something *new*



Weighing our universe

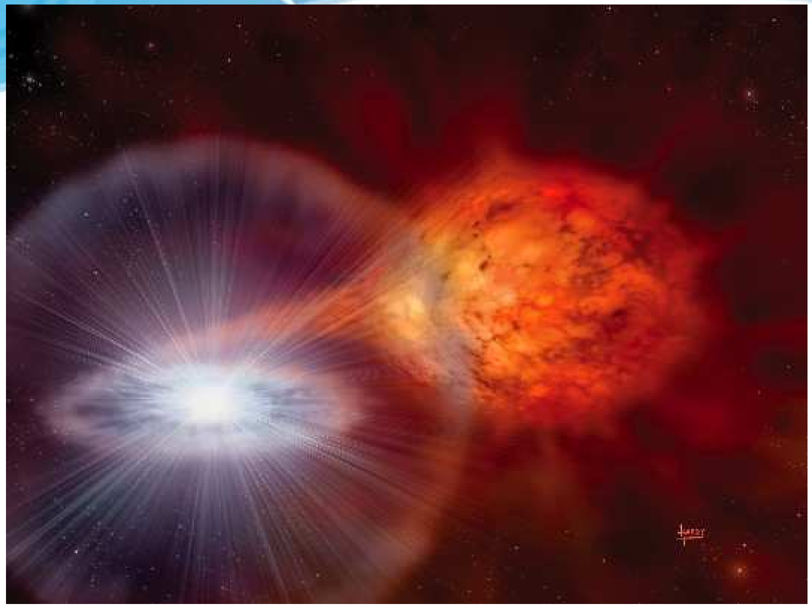
Are ordinary and DM the whole stuff? Is there anything between galaxies (and clusters)?



To weigh the whole universe, measure its expansion rate. We expect it to slow down because of the mutual gravitational pull of all the matter

To track the expansion rate, use the type Ia Supernovae (SnaeIa)

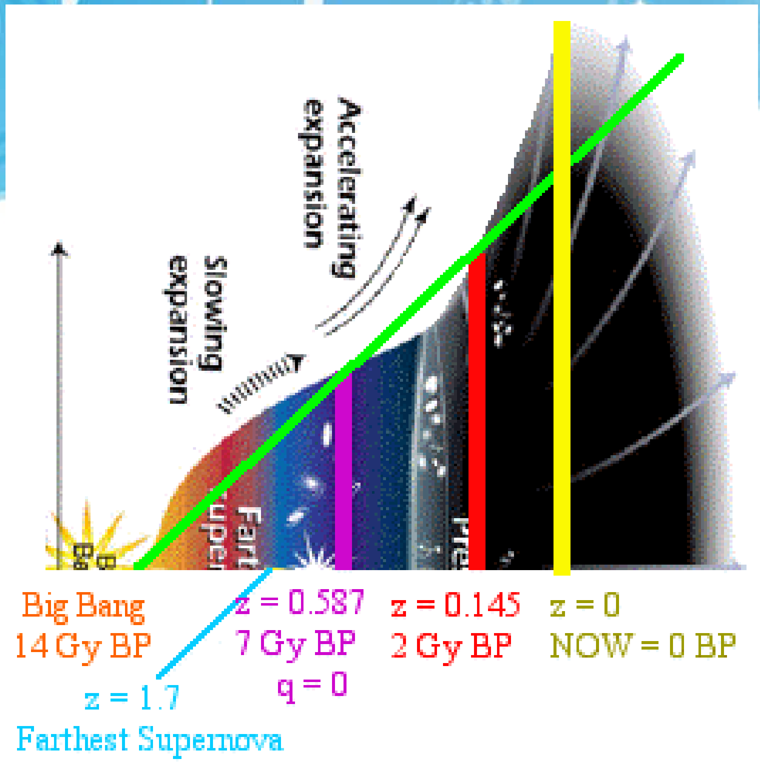
Snaela and what you don’t expect

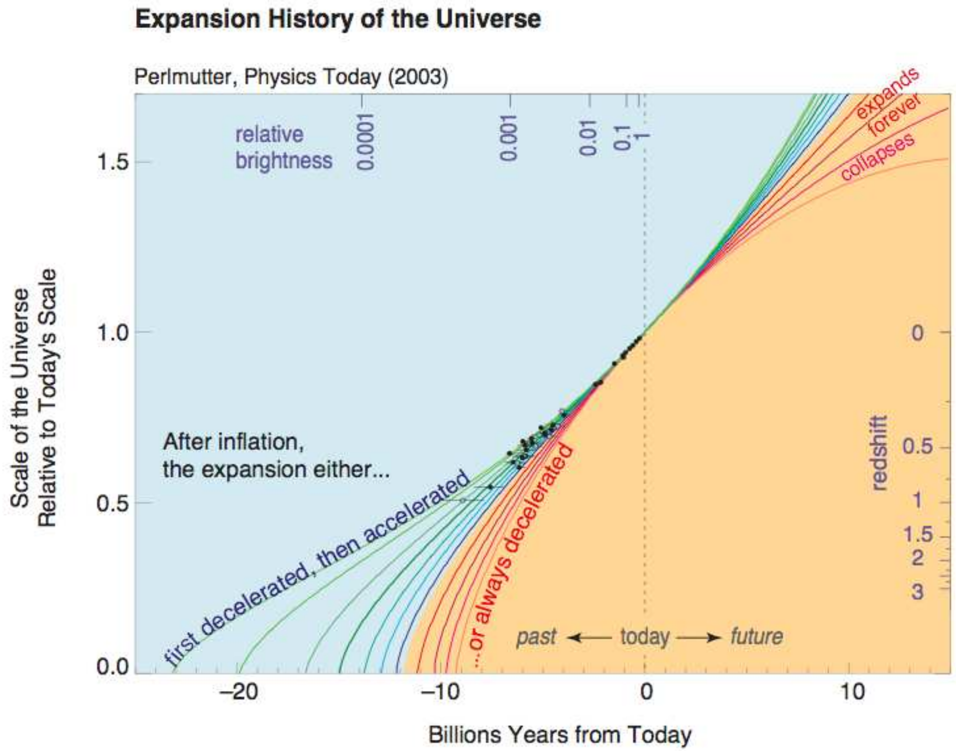


They are exploding white dwarf stars and can be considered as *standardizable candles*

As luminous as an entire galaxy!

The universe is accelerating!





What pushes the accelerator?

Well, Dark Energy!

- A form of energy coming from the *empty space*
- *Smoothly distributed* through space: does not clump into galaxies and clusters
- *Constant density* (or changing very slowly) through cosmic time: not diluted by expansion
- *Invisible* to and *not interacting* with ordinary matter (only detected via gravity)

No direct evidence for DE

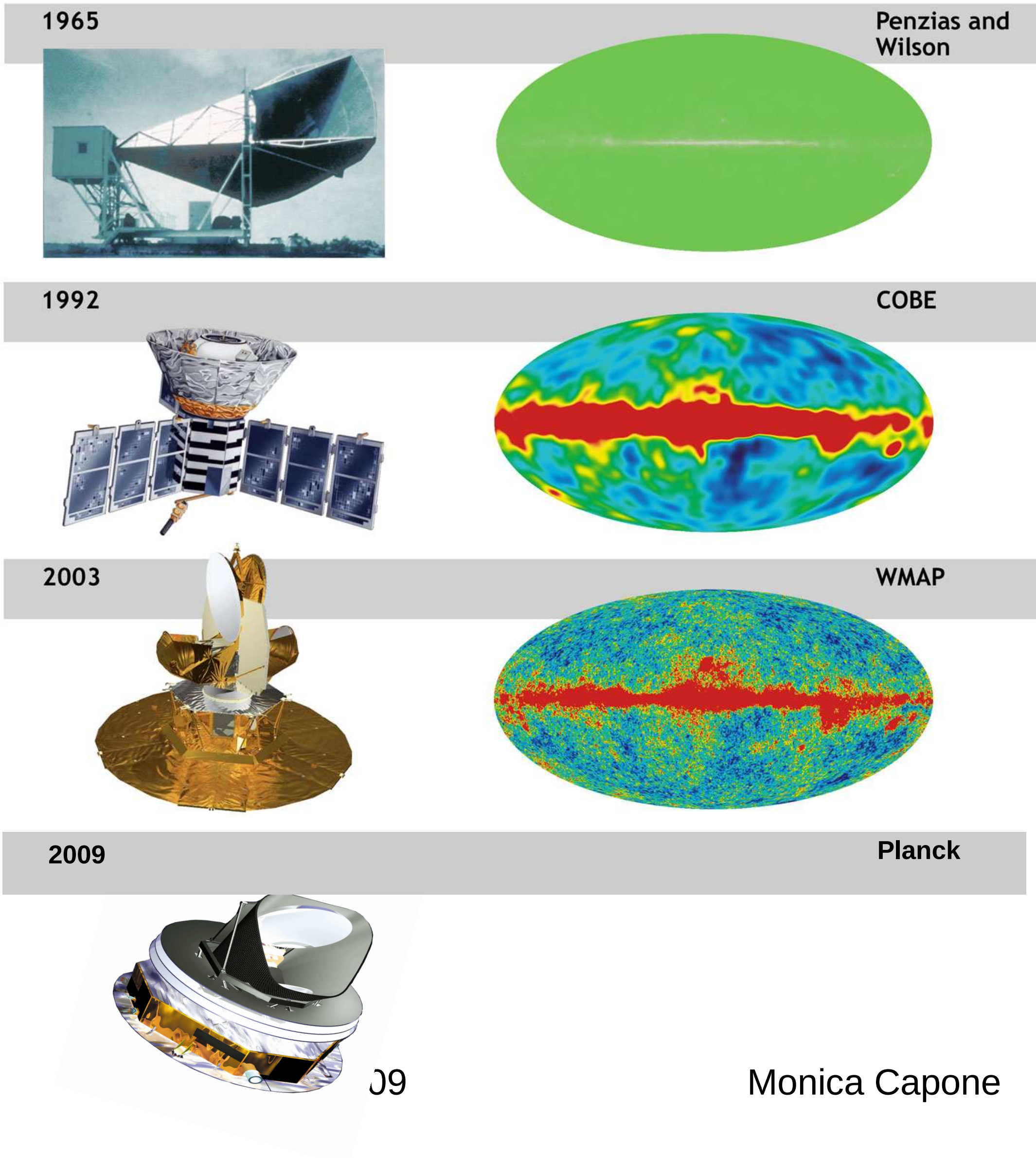
Curvature | Matter | Radiation | Dark Energy

$$H^2 = H_0^2\left[(1-\Omega_{tot})(1-z)^2 + \Omega_m(1+z)^3 + \Omega_r(1+z)^4 + \Omega_w(1+z)^{3(1+w)}\right]$$

CMB | LSS | CMB | *H(z)*

As for DM, we only *infer* the existence of DE

CMBr: from noise to Nobel(s)



The oldest light in universe

Discovered the remnant afterglow from the **Big Bang**.
→ **2.7 K**

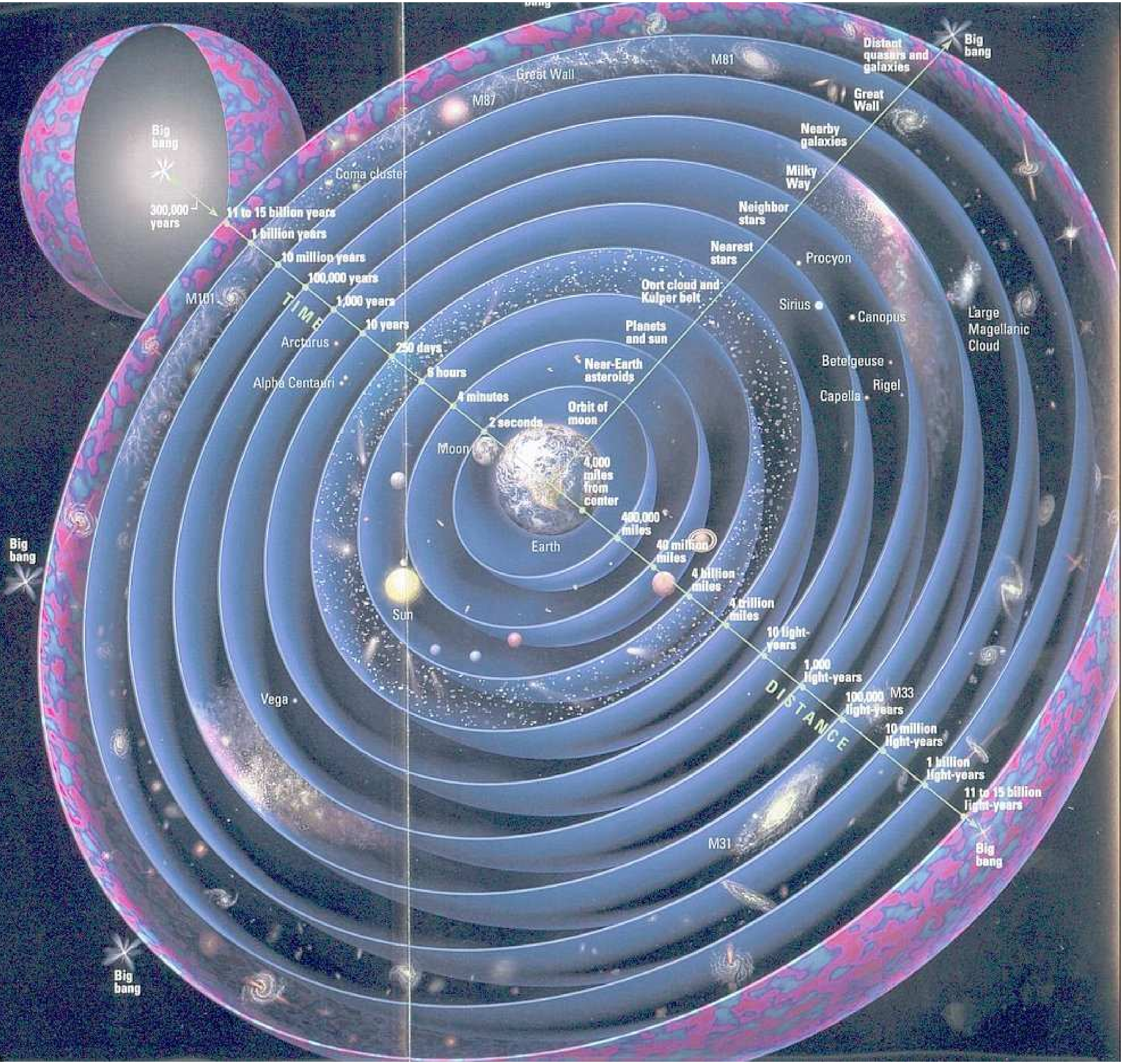
Blackbody radiation, Discovered the patterns (**anisotropy**) in the afterglow.
→ **angular scale ~ 7°** at a level $\Delta T/T$ of 10^{-5}

(Wilkinson Microwave Anisotropy Probe):
→ **angular scale ~ 15'**

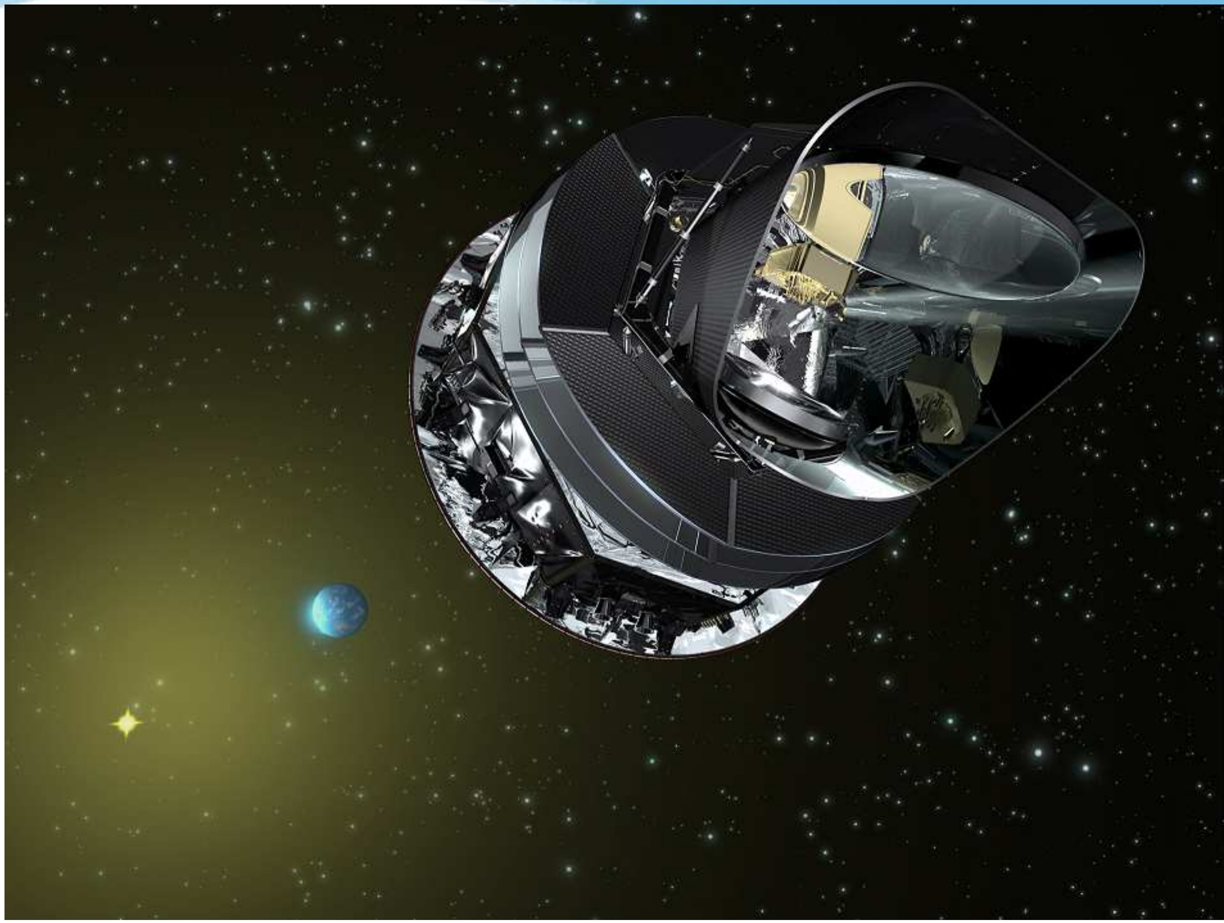
→ **angular scale ~ 5',**
$\Delta T/T \sim 2 \times 10^{-6}$, 30~867 Hz

The view from Earth

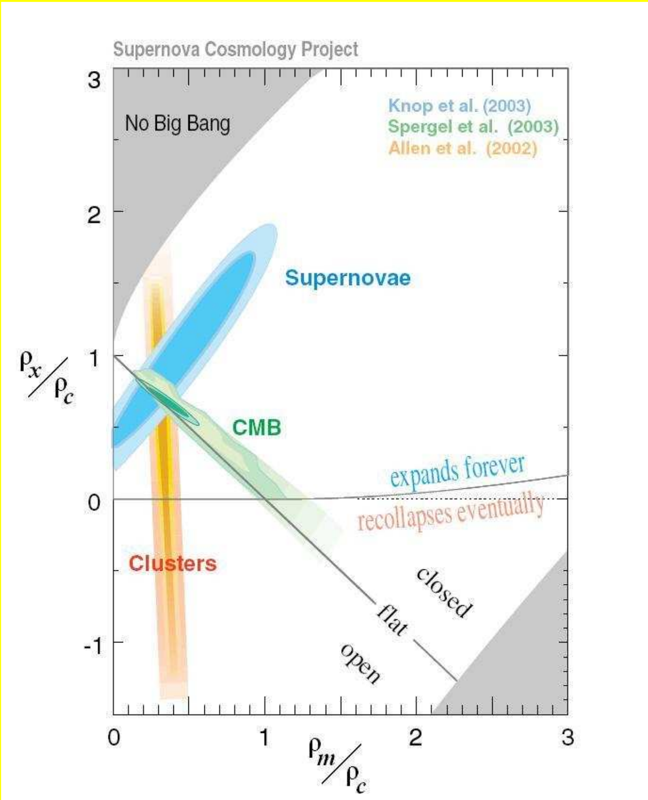
The ancients had it wrong: The Earth is not the center of the universe. But the Earth *is* at the center of the part of the universe that we can see. A being on a planet orbiting, say, a star in the galaxy M87 would see a different part of the universe, one centered on him. In a universe thought to be 11 to 15 billion years old, we can see out a distance of 11 to 15 billion light-years in all directions. From the Earth's viewpoint at midnight GMT, January 1, 2000, the elements of the cosmos will appear as they do here (right). Distances are not shown to scale but increase dramatically as they become more remote. The farther out we look, the farther back in time we see. Light takes 50 million years to arrive from M87, so we see it as it appeared 50 million years ago. The limit of our view is the time when the universe emerged from a state of hot plasma and became transparent, some 300,000 years after the big bang. That period is seen as the glow of the microwave background (shown in red and blue). If we could look beyond that veil, we would see—according to the standard models—the big bang itself, no matter in which direction we looked. [redacted]

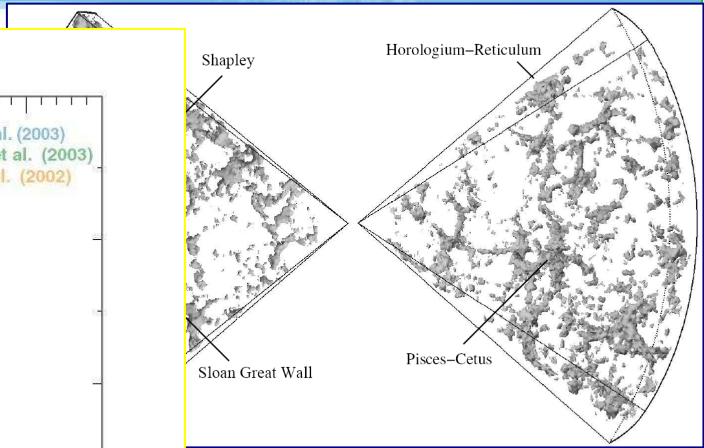


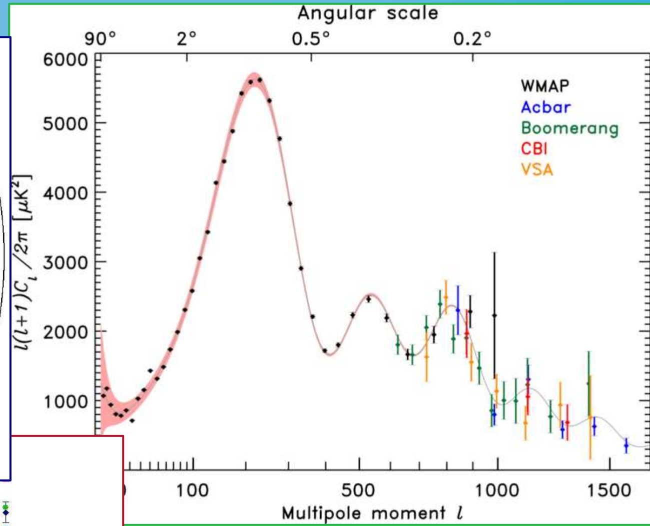
CMB with Planck

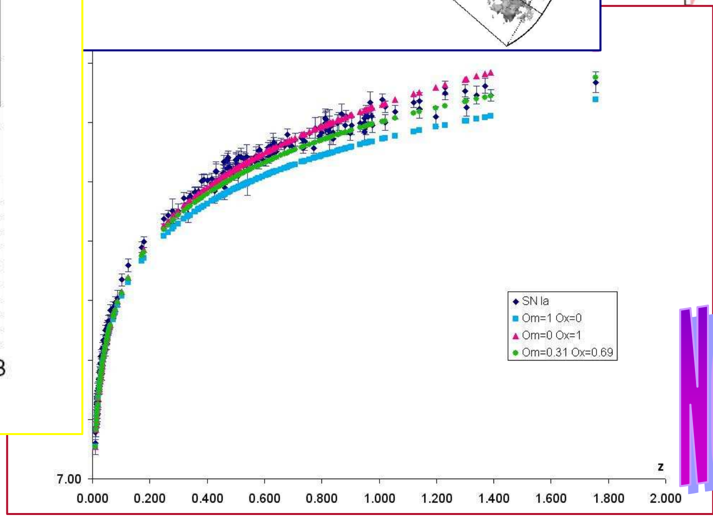


Consistency checks





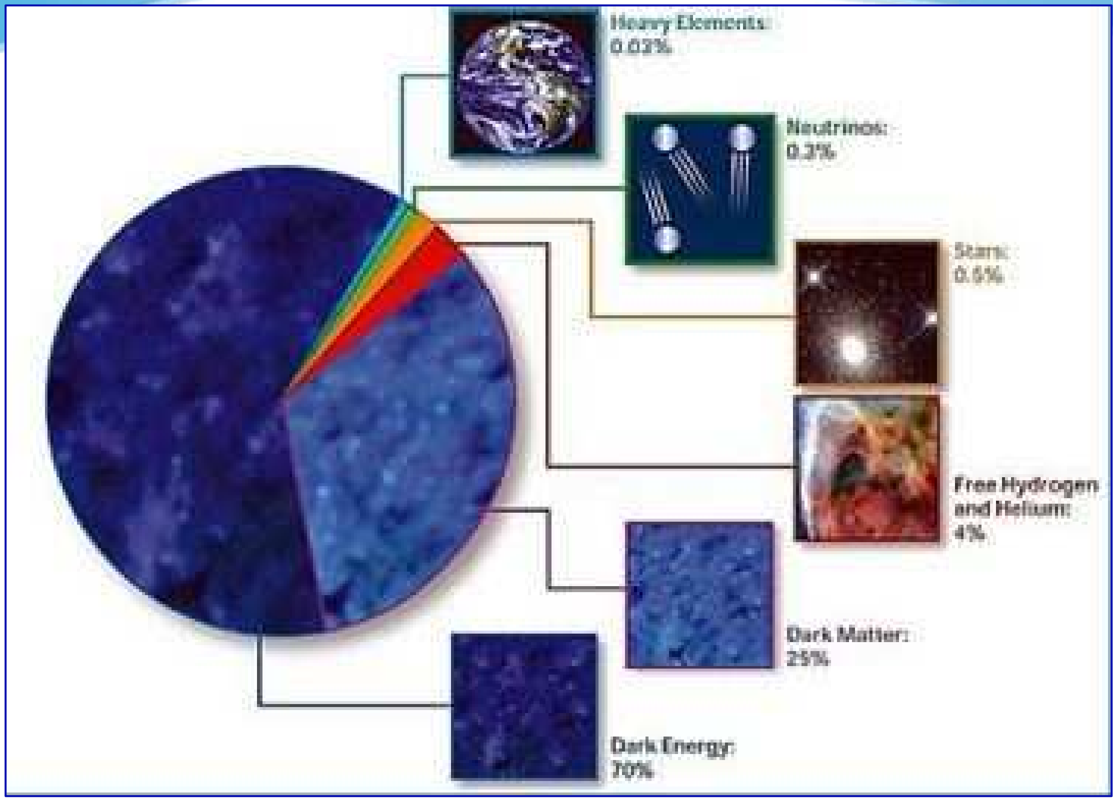




Need for DE confirmed!

$$\rho_{cr} \cong 1.9\times10^{-29}\,\frac{\text{g}}{\text{cm}^3}$$

Join the Dark Side!



- $\rho_b \cong 8.7\times10^{-31}\,\dfrac{\mathrm{g}}{\mathrm{cm}^3}$
- $\rho_{DM} \cong 4.75\times10^{-30}\,\dfrac{\mathrm{g}}{\mathrm{cm}^3}$
- $\rho_r \cong 5\times10^{-34}\,\dfrac{\mathrm{g}}{\mathrm{cm}^3}$
- $\rho_\nu \cong 10^{-32}\,\dfrac{\mathrm{g}}{\mathrm{cm}^3}$
- $\rho_{DE} \cong 1.3\times10^{-29}\,\dfrac{\mathrm{g}}{\mathrm{cm}^3}$

Dark side of the Universe: > 95% !!!

The universe identikit

- (Nearly) spatially homogeneous and isotropic (*Cosmological Principle*)

$$ds^2 = c^2 dt^2 - a^2(t)\left[\frac{1}{1-kr^2}dr^2 + r^2 d\vartheta^2 + r^2 \sin^2\vartheta d\varphi^2\right]$$

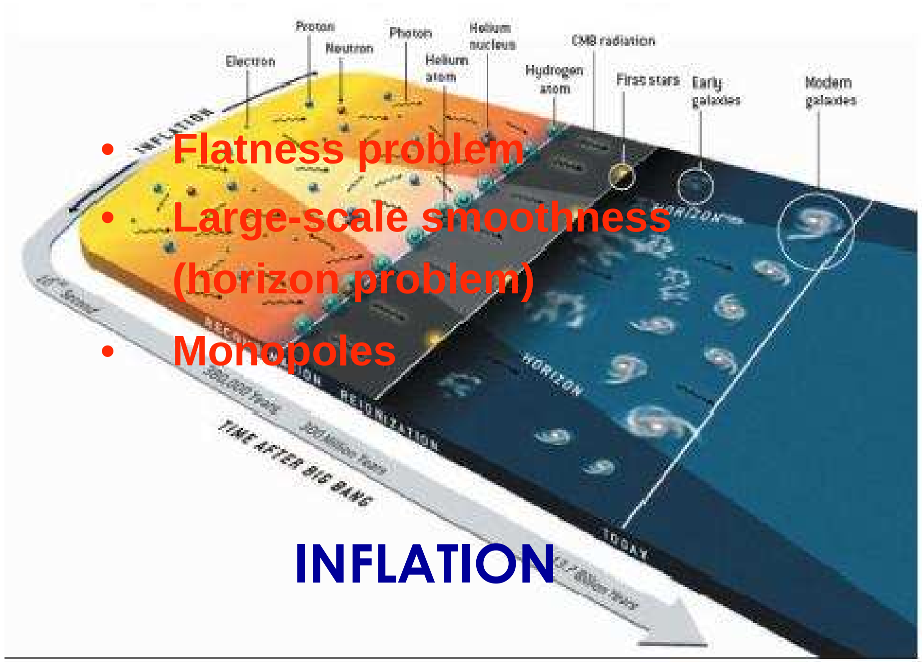
- Spatially flat

- Dominated by dark stuff

Quite a "simple" picture but... so many open issues!

Shadows on the Sun: old and new problems in standard cosmology

Standard cosmology: standard model of particle physics + FRW



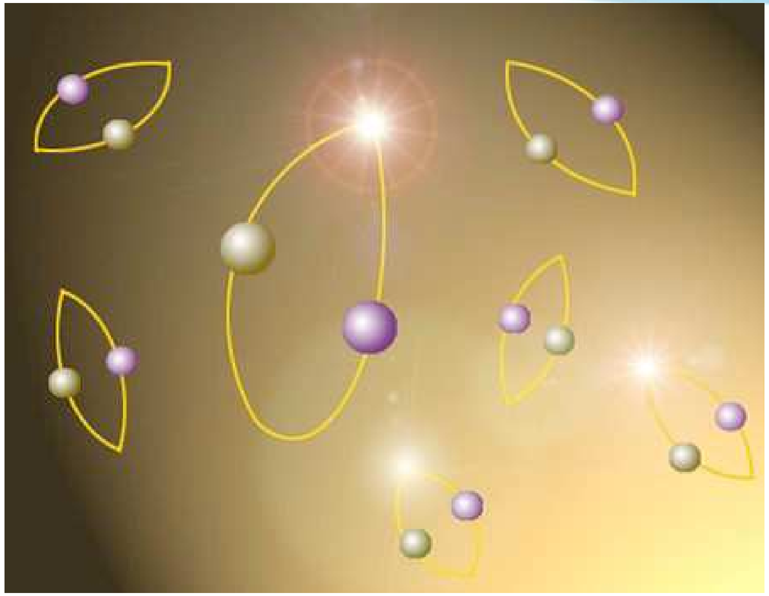
- Flatness problem
- Large-scale smoothness (horizon problem)
- Monopoles

INFLATION

- Galaxies rotation curves
- Large Scale Structure
- Spatially flat universe
- Missing matter/energy
- Accelerating universe

The vacuum is not empty!

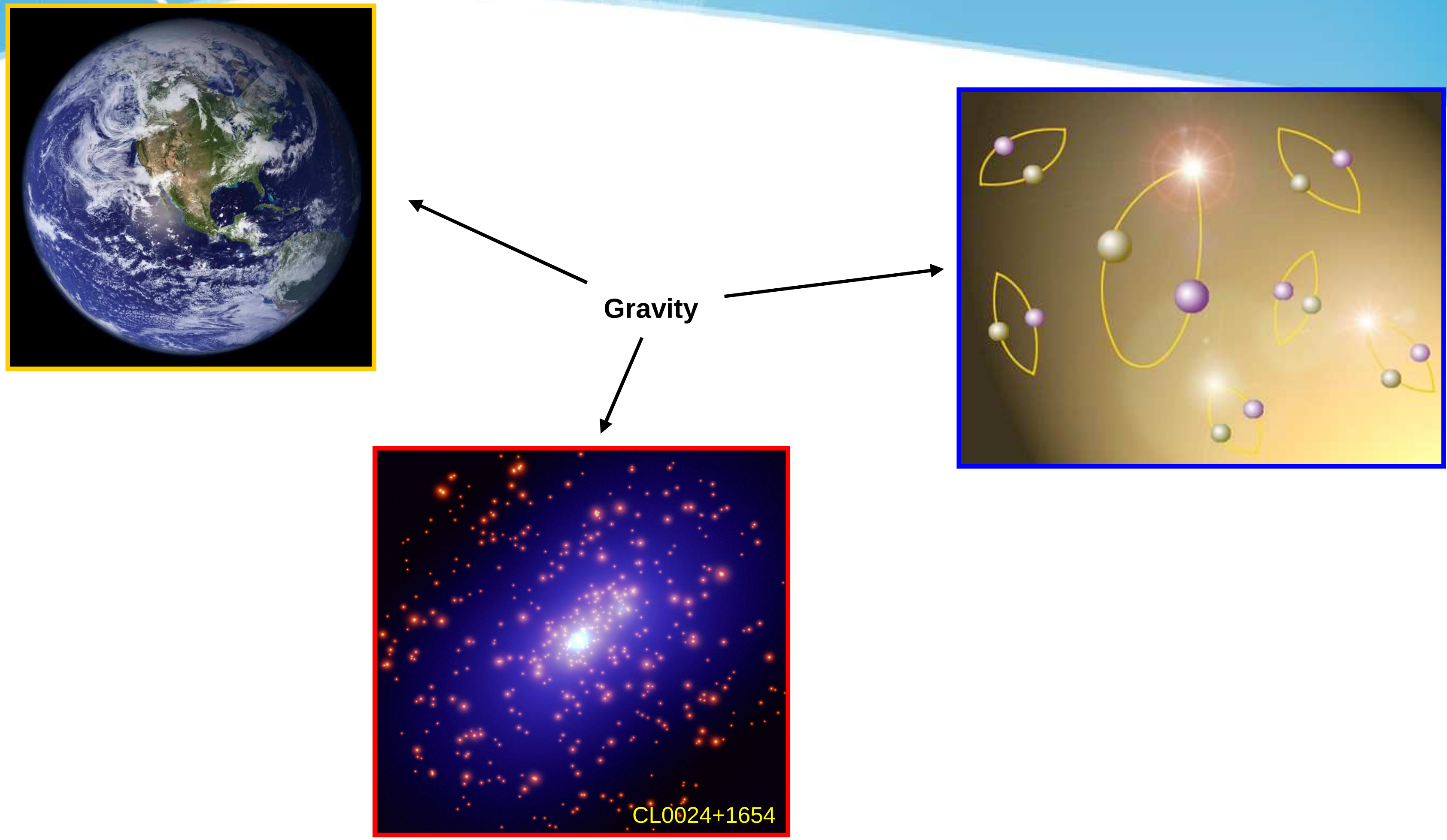
Vacuum is not a boring place: it is "full" of the fluctuations of every field in the universe. We know they are there because they affect other forces beside gravity. They also affect gravity because they carry energy



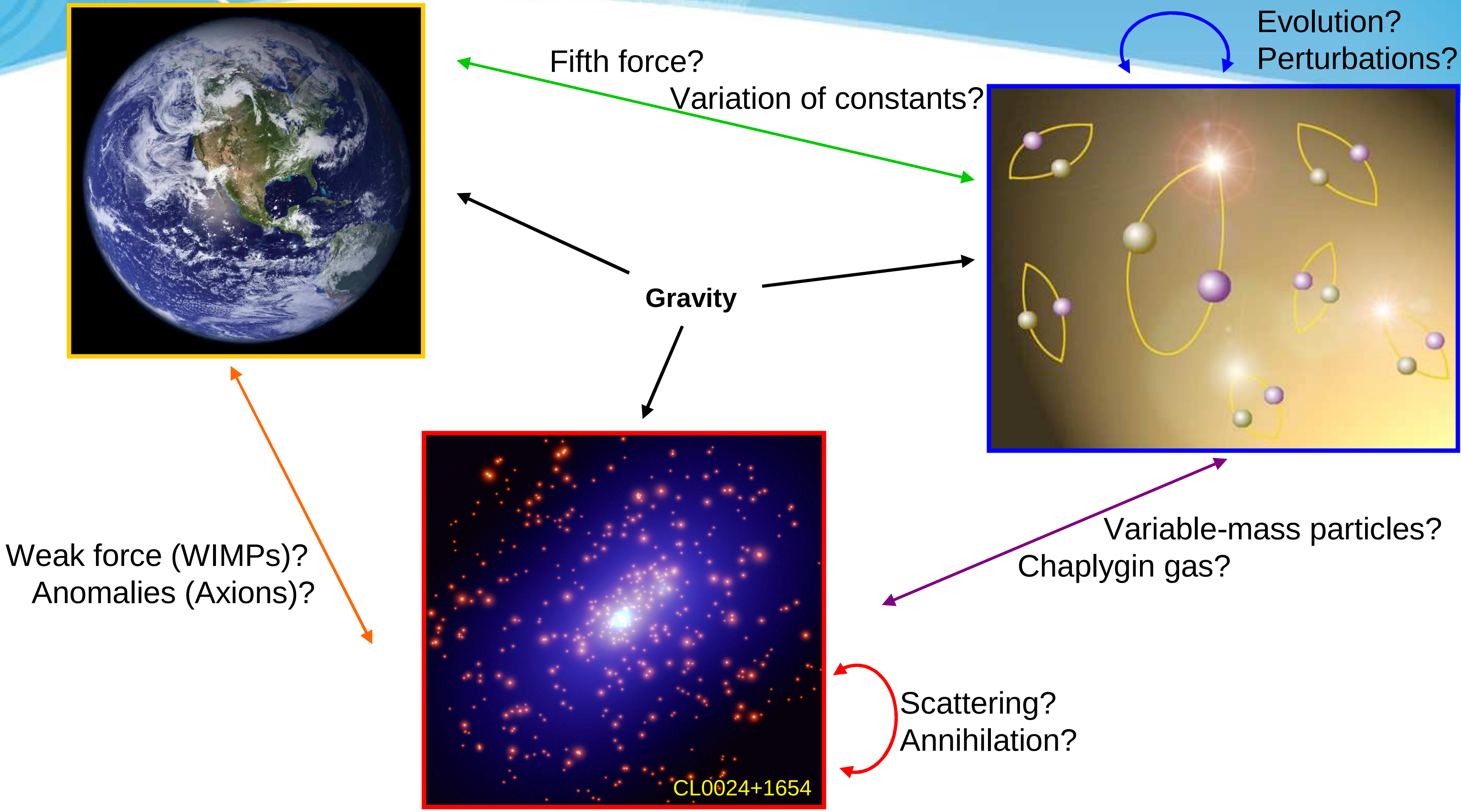
How much energy? ..... Well, ∞!

Renormalize and suitably cut-off and then... $\rho_{th} \propto 10^{120}\, \rho_{exp}$!!!

The universe prom



The universe prom



The Known Unknowns

- Why is there more matter than antimatter?
- Where did the small fluctuations come from?
- Why is the universe smooth on large scales?
- What is the Dark Matter (DM)?
- What is the Dark Energy (DE)?
- Why is the vacuum energy so small?
- Why are matter and DE comparable today?

Not to mention:

- What came before the Big Bang?

Was Einstein wrong?

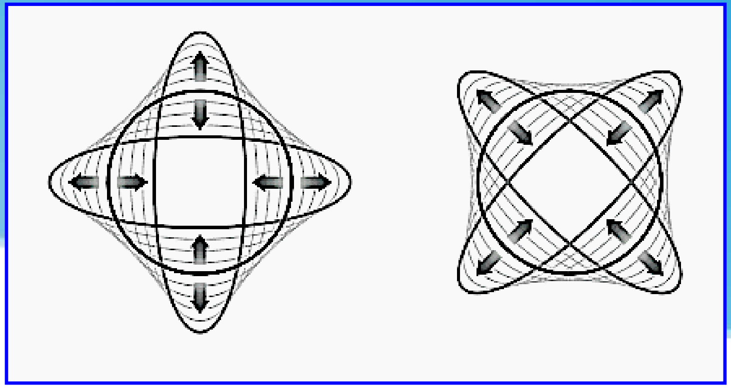
One possibility could surely be a problem with GR

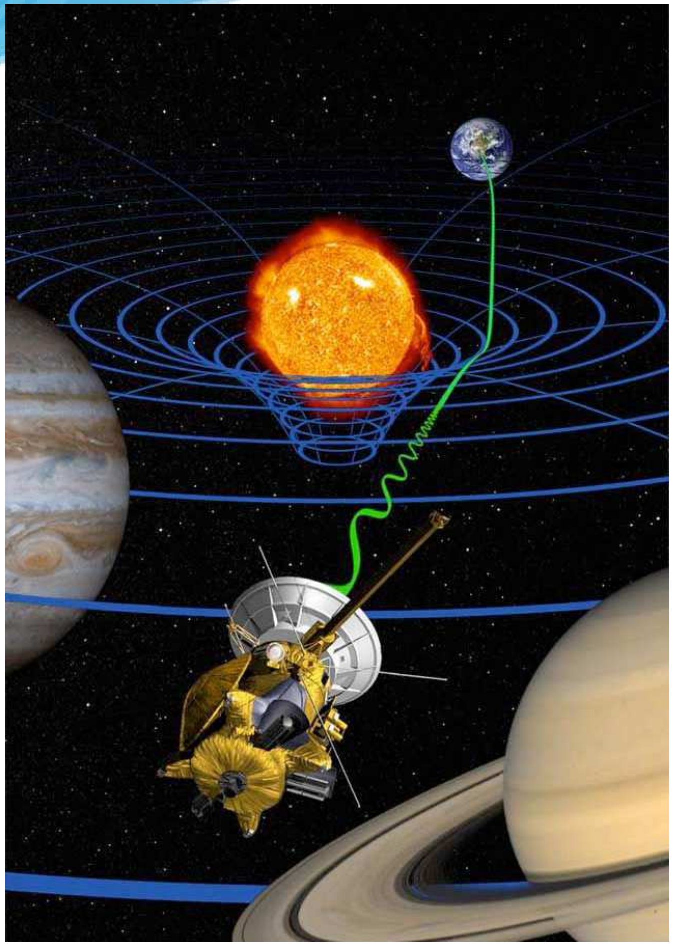
BUT

To have a successful field theory alternative to GR, one should

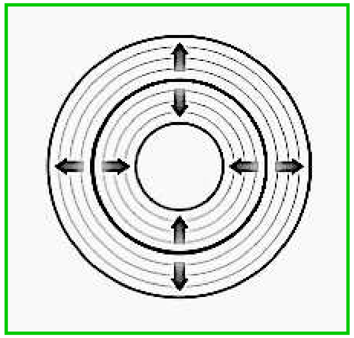
- Add or subtract *degrees of freedom*;
- *Propagation* through space (long-range/massless; short-range/massive);
- *Interactions* (coupling to other fields and themselves)

For GR we have gravitons which are massless, spin-2 and coupled to energy





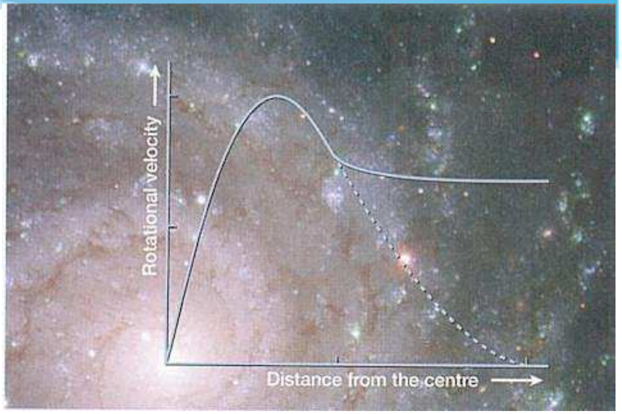
A scalar (spin-0) graviton would look different. It would distort the metric away from GR predictions, e.g. the curvature of the Solar System in a detectable way



Experiments and tests constrain the Brans-Dicke (linked to the coupling of the new dof) parameter to be $\omega > 40x10^3$

Example: MOND

1984: Milgrom noticed that DM was only needed in galaxy when the acceleration due to gravity falls below $a_0 \cong 10^{-8}$ cm/s^2. He proposed a *phenomenological* force law in which gravity falls off more slowly when it is weaker, i.e.



$$F \propto \begin{cases} 1/r^2 & a > a_0 \\ 1/r & a < a_0 \end{cases}$$

2004: Bekenstein introduced TeVeS, relativistic version of MOND, featuring the metric, a fixed-norm vector U_μ, a scalar field ϕ, and Lagrange multipliers η and λ

TeVeS vs GR

$$S = \frac{1}{16\pi G}\int d^4x\left(R + L_U + L_\phi\right)$$

where

$$L_U = \frac{1}{2}KF^{\mu\nu}F_{\mu\nu} + \lambda\left(g^{\mu\nu}U_\mu U_\nu + 1\right)$$

$$L_\phi = -\mu_0\eta\left[g^{\mu\nu} - U^\mu U^\nu\right]\partial_\mu\phi\,\partial_\nu\phi - V(\eta)$$

$$V(\eta) = \frac{3\mu_0}{128\pi l_B^2}\left[\eta\left(4 + 2\eta - 4\eta^2 + \eta^3\right) + 2\ln^2(\eta - 1)\right]$$

Variational Approach

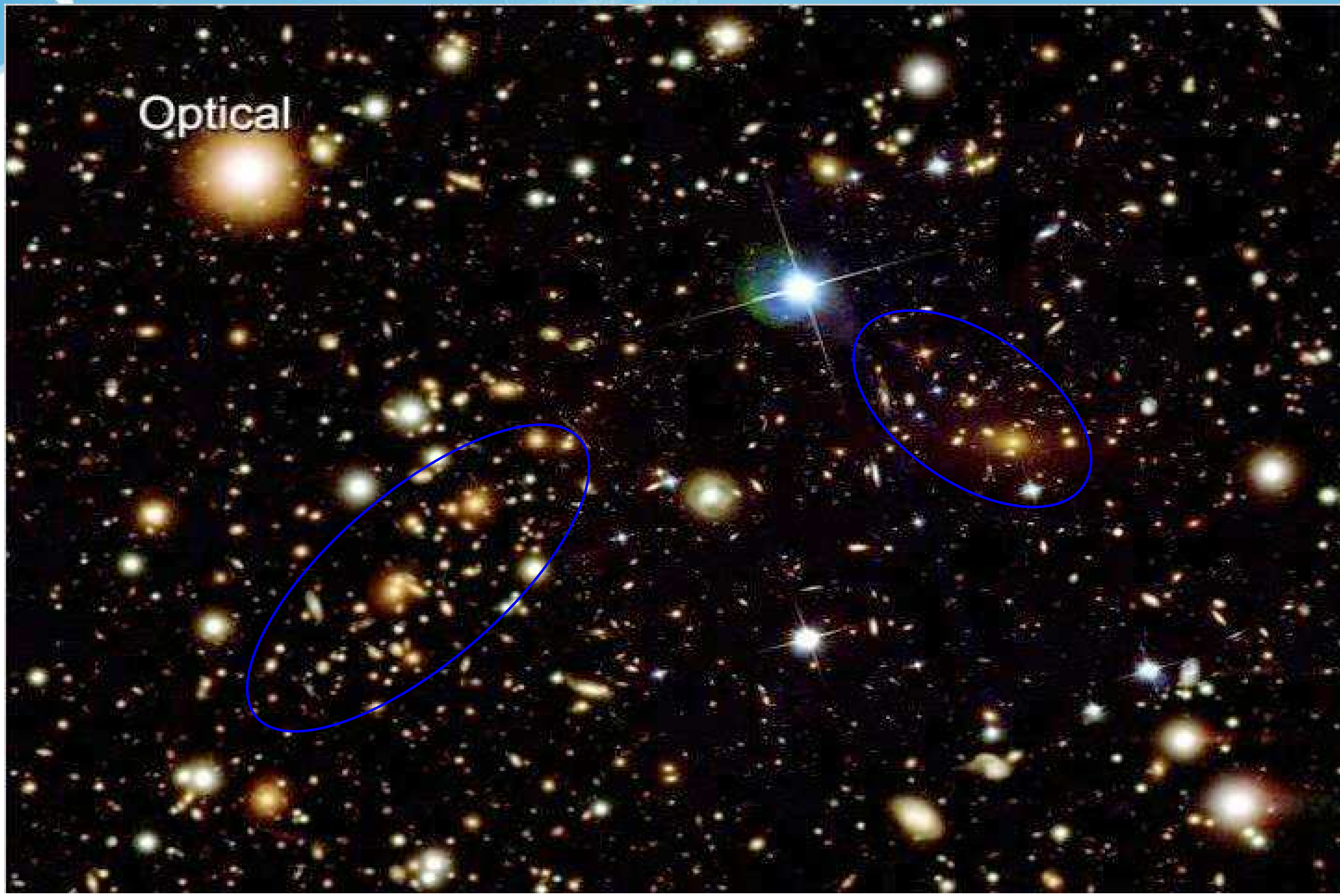
In classical field ths. *symmetries* and *conserved quantities* are essential

Conserved quantities are the integral counterparts of the Lagrangian symmetries

They are related to many fundamental quantities (energy, angular momentum, electric charge, etc.)

The Noether's Th. provides an explicit and algorithmic correspondence between Lagrangian symmetries and conserved quantities

The Bullet Cluster and Popper's spirit



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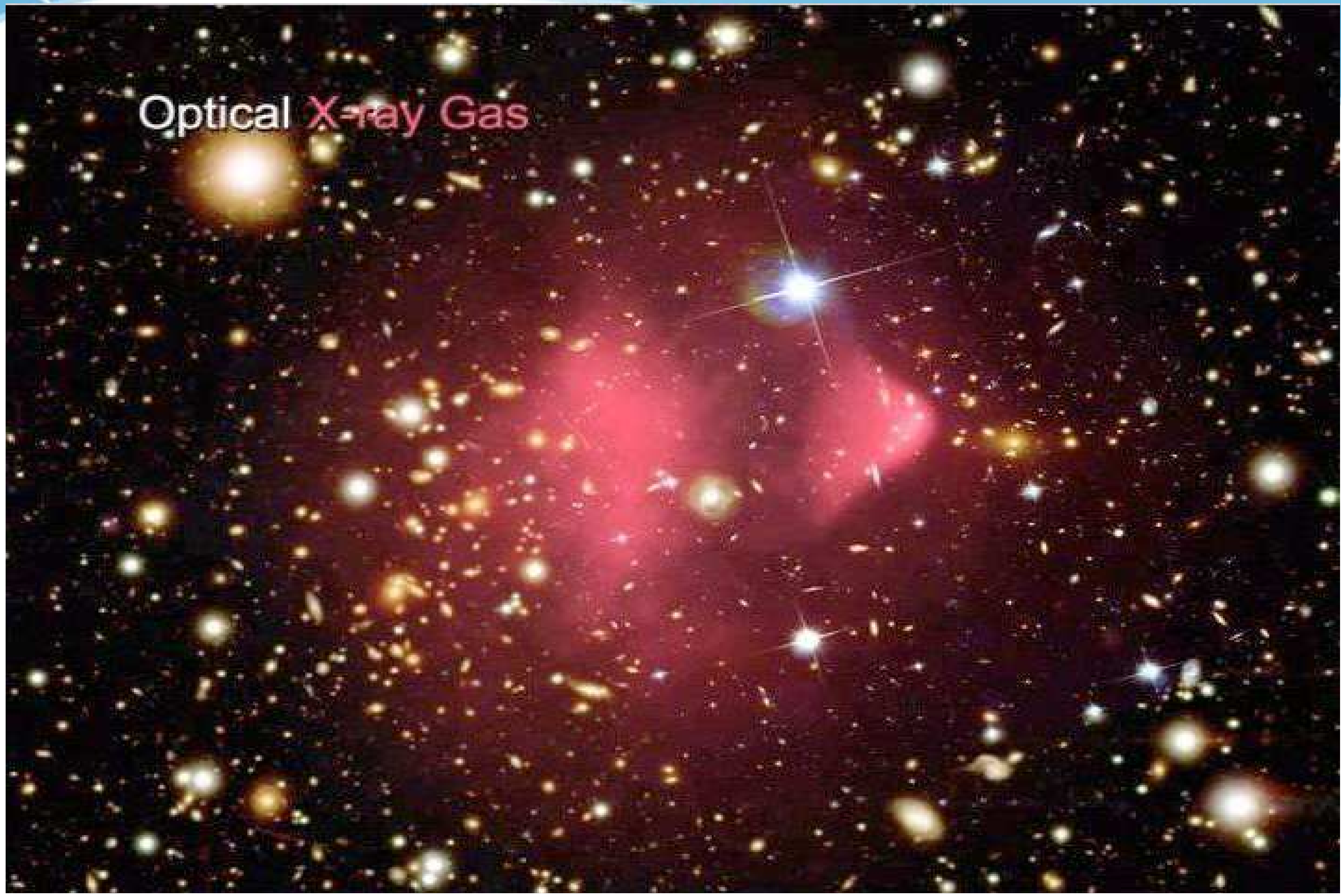

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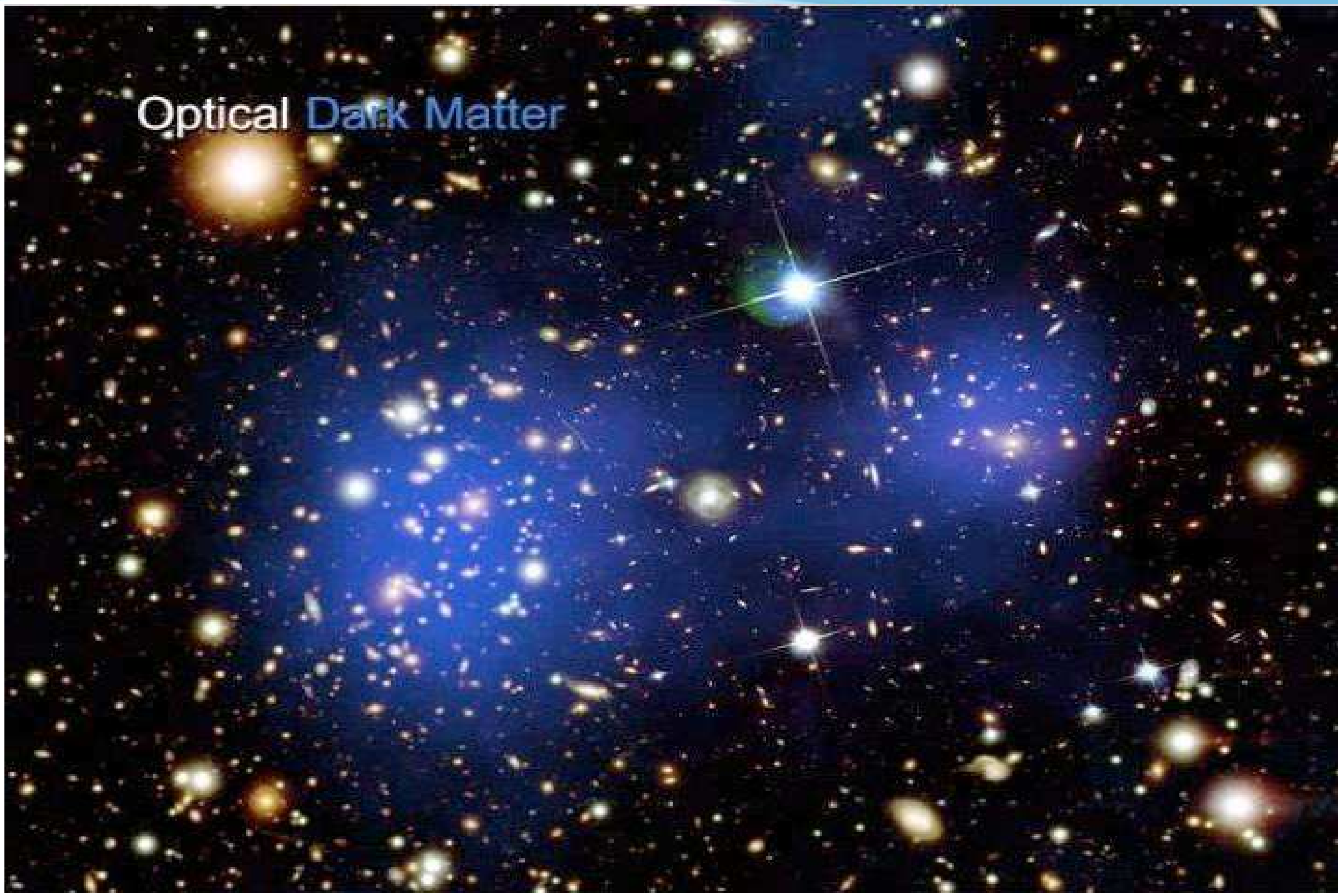

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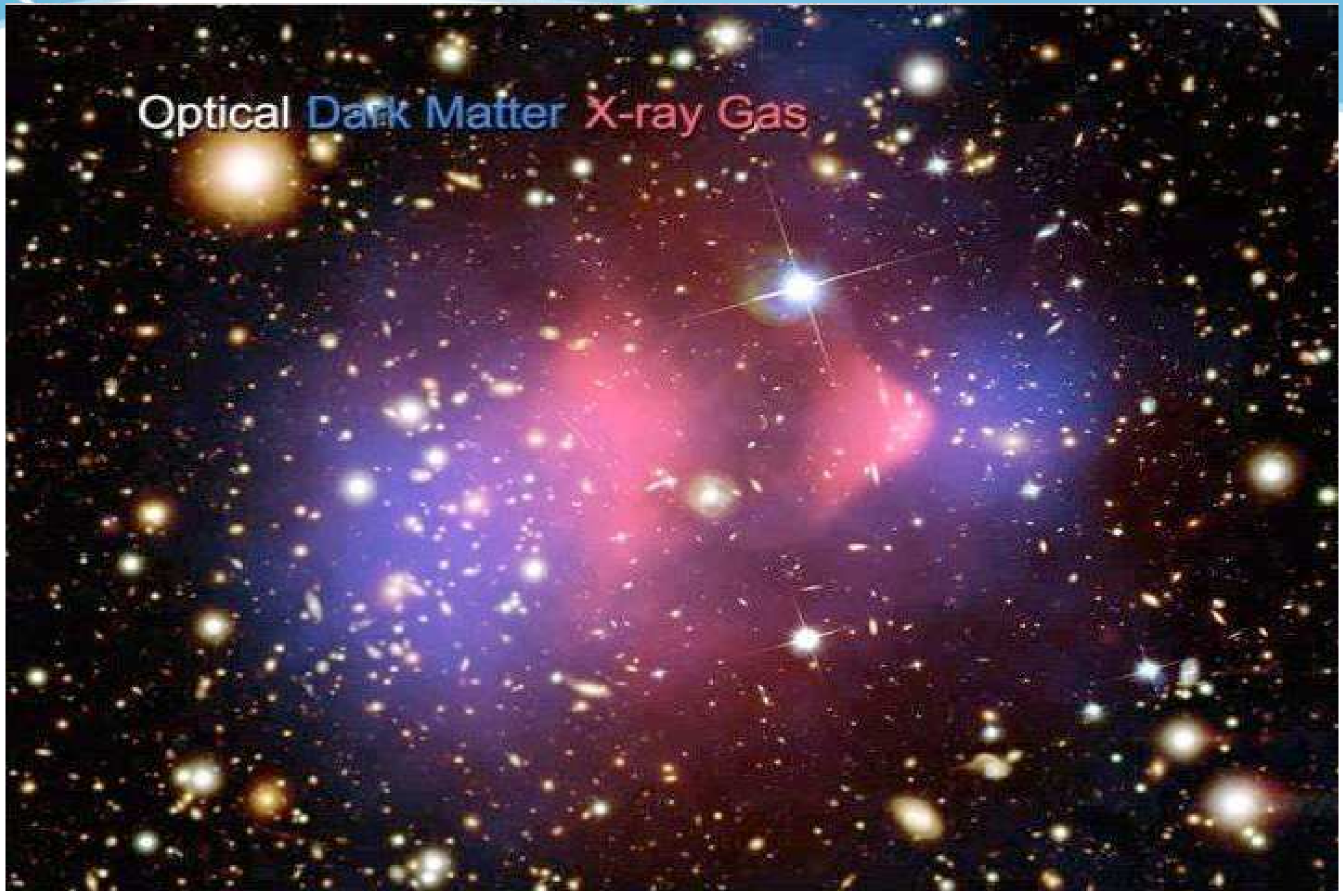
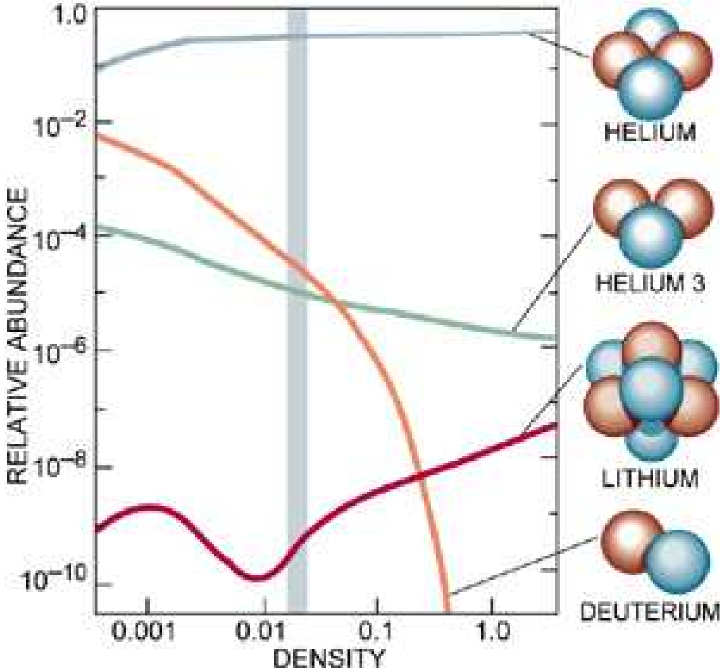


No escape: DM exists!

Getting rid of DE

Beware: *Big Bang Nucleosynthesis* (BBN) gives stringent constraints: 75% H, 25% He, traces of Li and D



BBN occurred when the universe was 1 minute old and its size was 10^{-9} its current size. This theory of light elements production in the early universe yields precise quantitative predictions for the mixture of these elements, that is, the primordial abundances

$\Rightarrow$ Deviation from GR must turn on rather late!

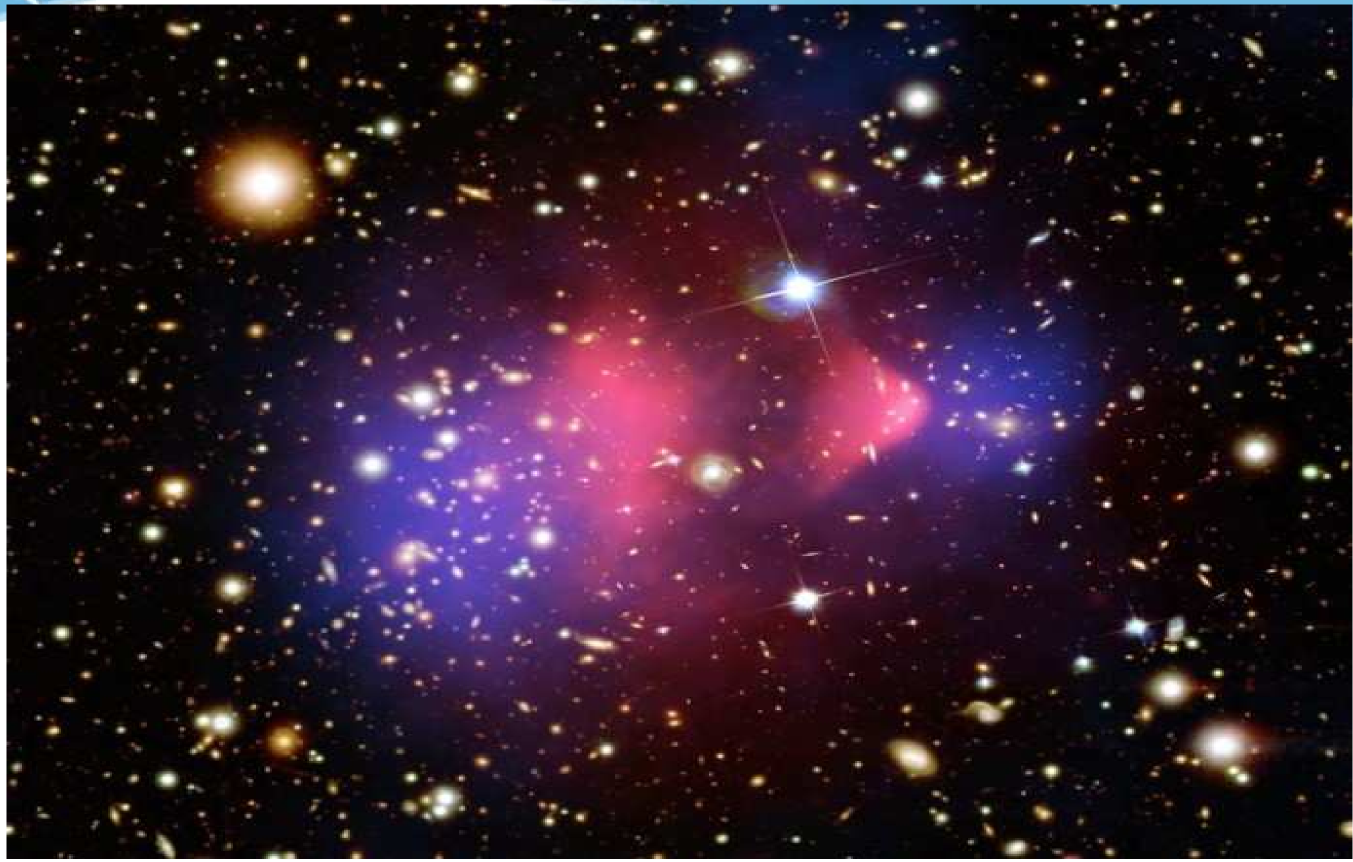
Possible Candidates

- Alternative theories of gravitation
- Vector Theories
- Generalized MOND (TeVeS)

- Cosmological constant Λ
- Quintessence $\phi(t, x^i) \approx \phi(t)$
- K-essence
- Chaplygin
- Cardiassians

- Branes-Walls
- Cosmic strings
- .....

Science is a collaborative effort between us and the universe. We propose ideas, the universe smacks down them...or occasionally agrees...



It’s a good system!

Facing the Future

- We can describe the constituents and patterns of our universe. But the description is at least weird. The next challenge is to move from *inventory* to *understanding*

- A new generation of experiments will provide crucial clues: satellites, laboratory experiments, large particle accelerators

- One century ago, Physics seemed almost settled, with only a few loose ends to figure out. What followed was a revolutionary upheaval. What is next for us?