Has Dark Energy gotten even weirder?

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SCIENCE CAFE
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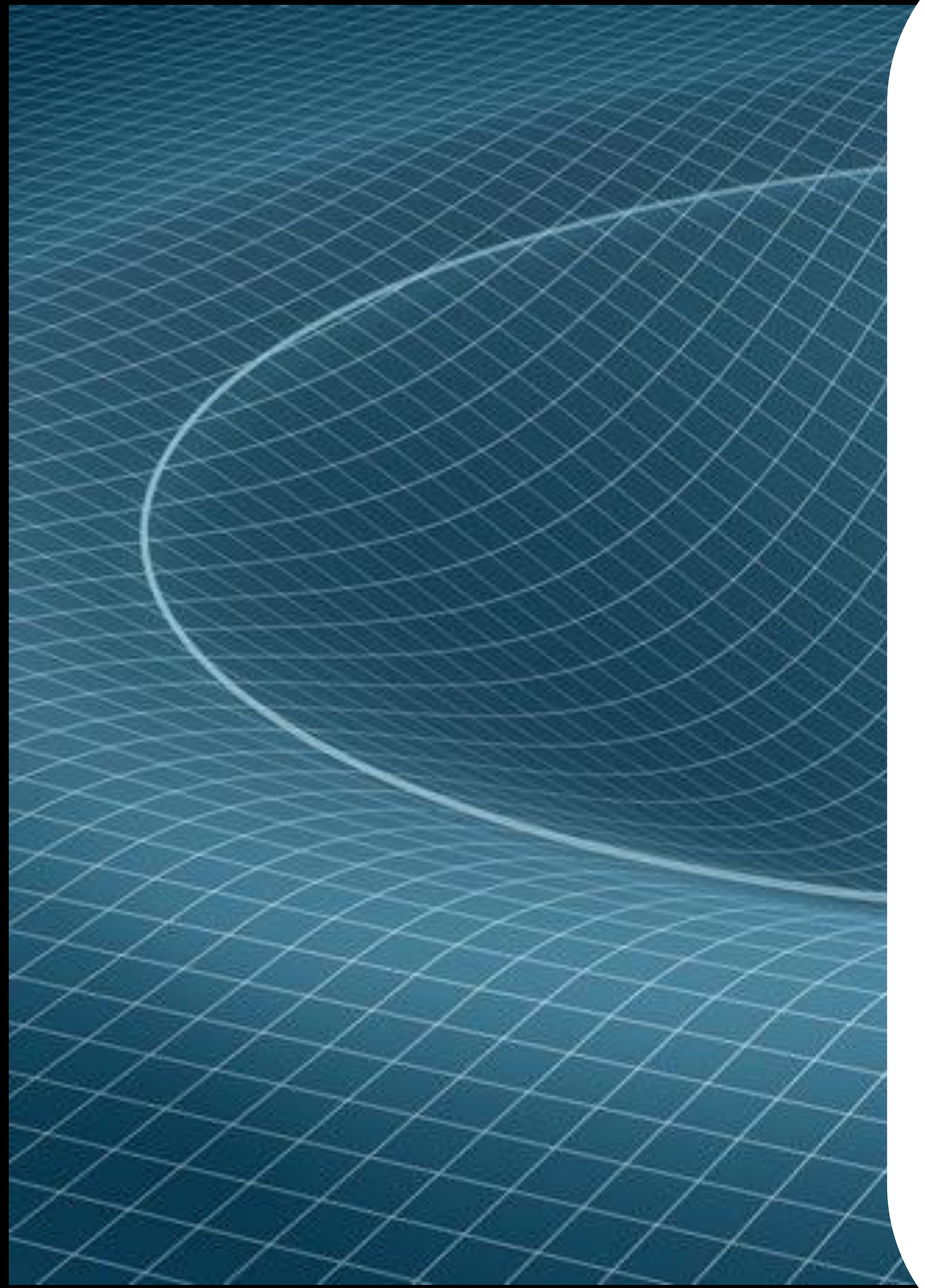
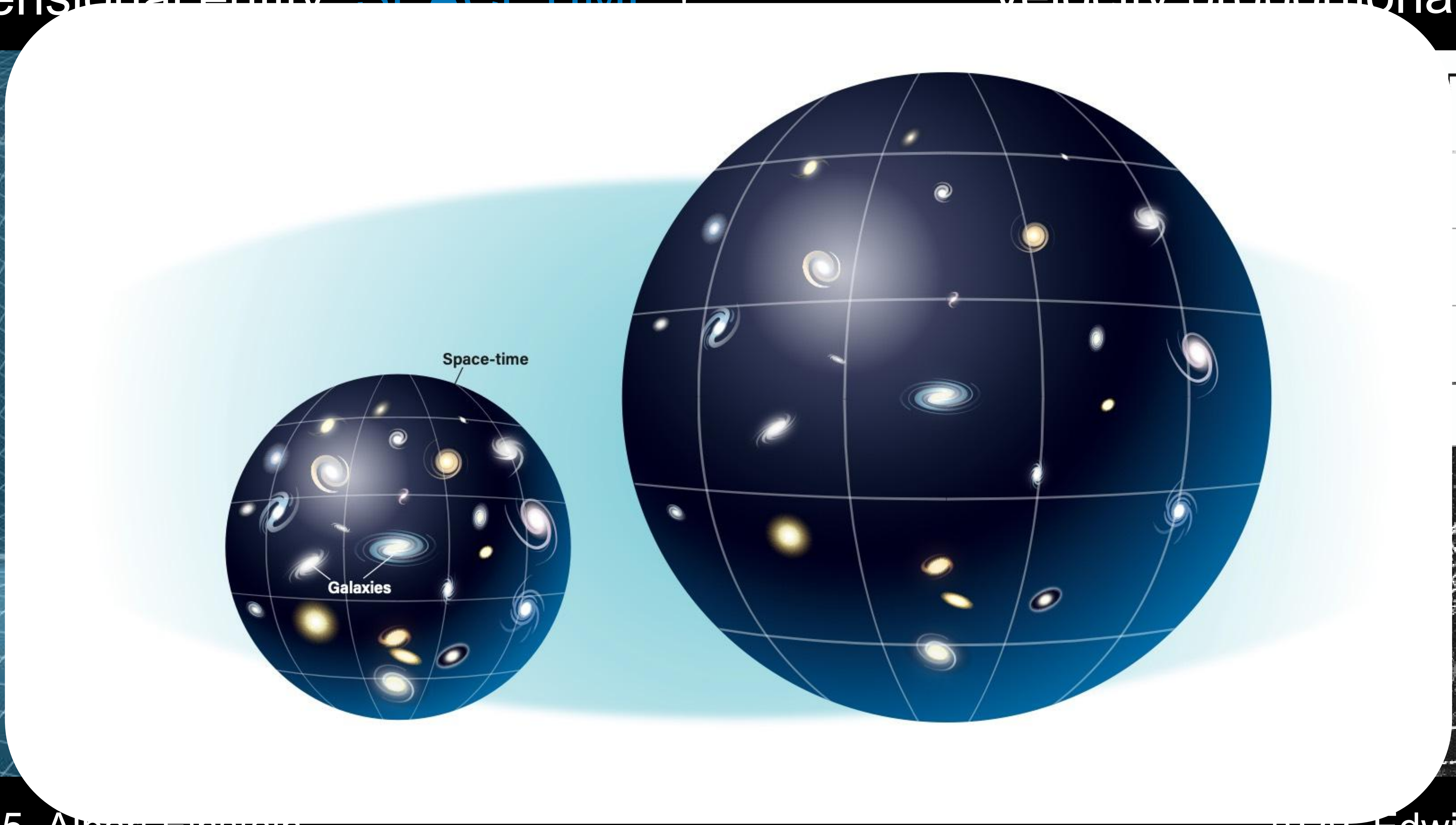
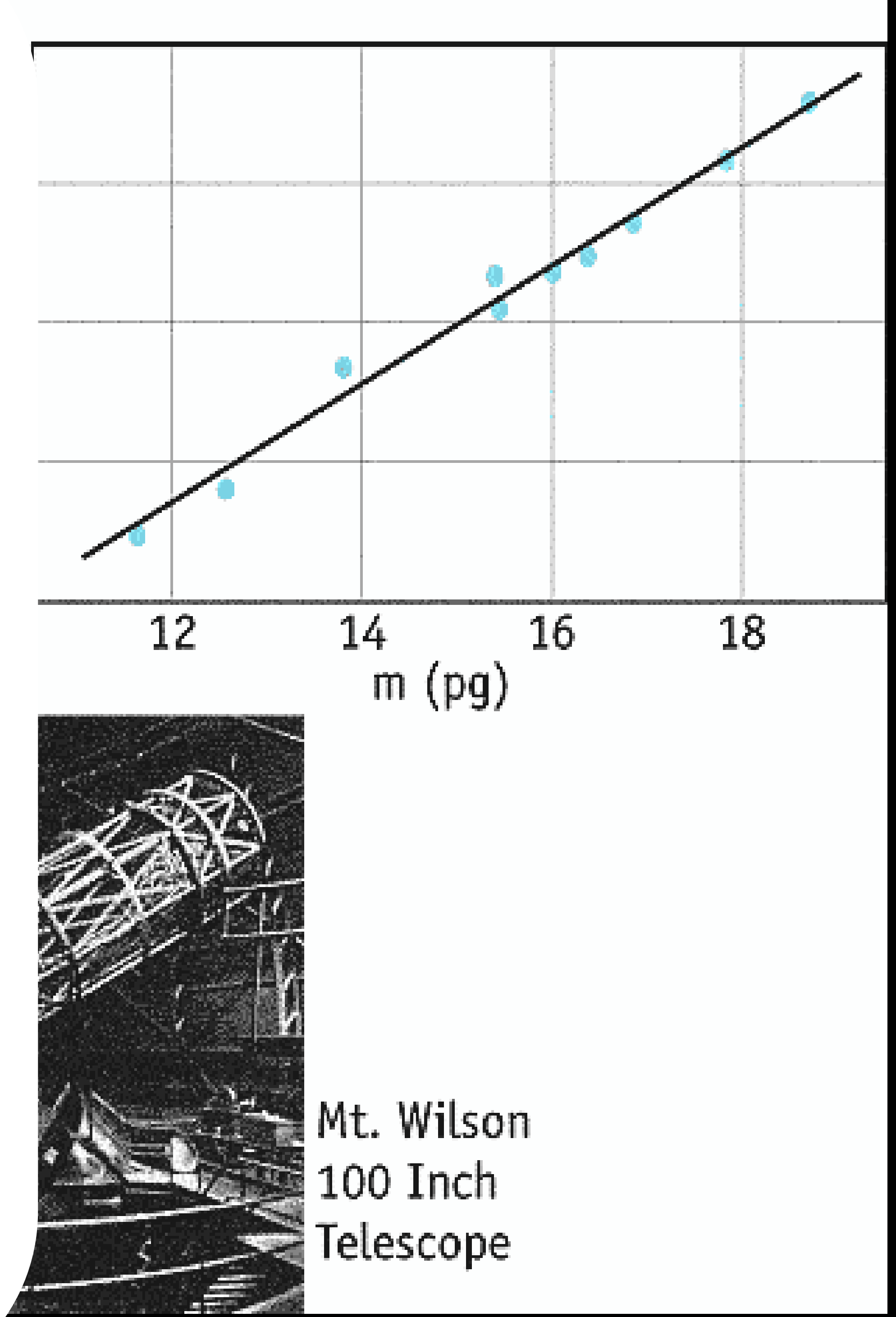
Physical Cosmology

A theory of gravity that ties time and space into a dynamical 4-dimensional entity: SPACETIME !

Distant galaxies recede from us with a velocity proportional to their distance !



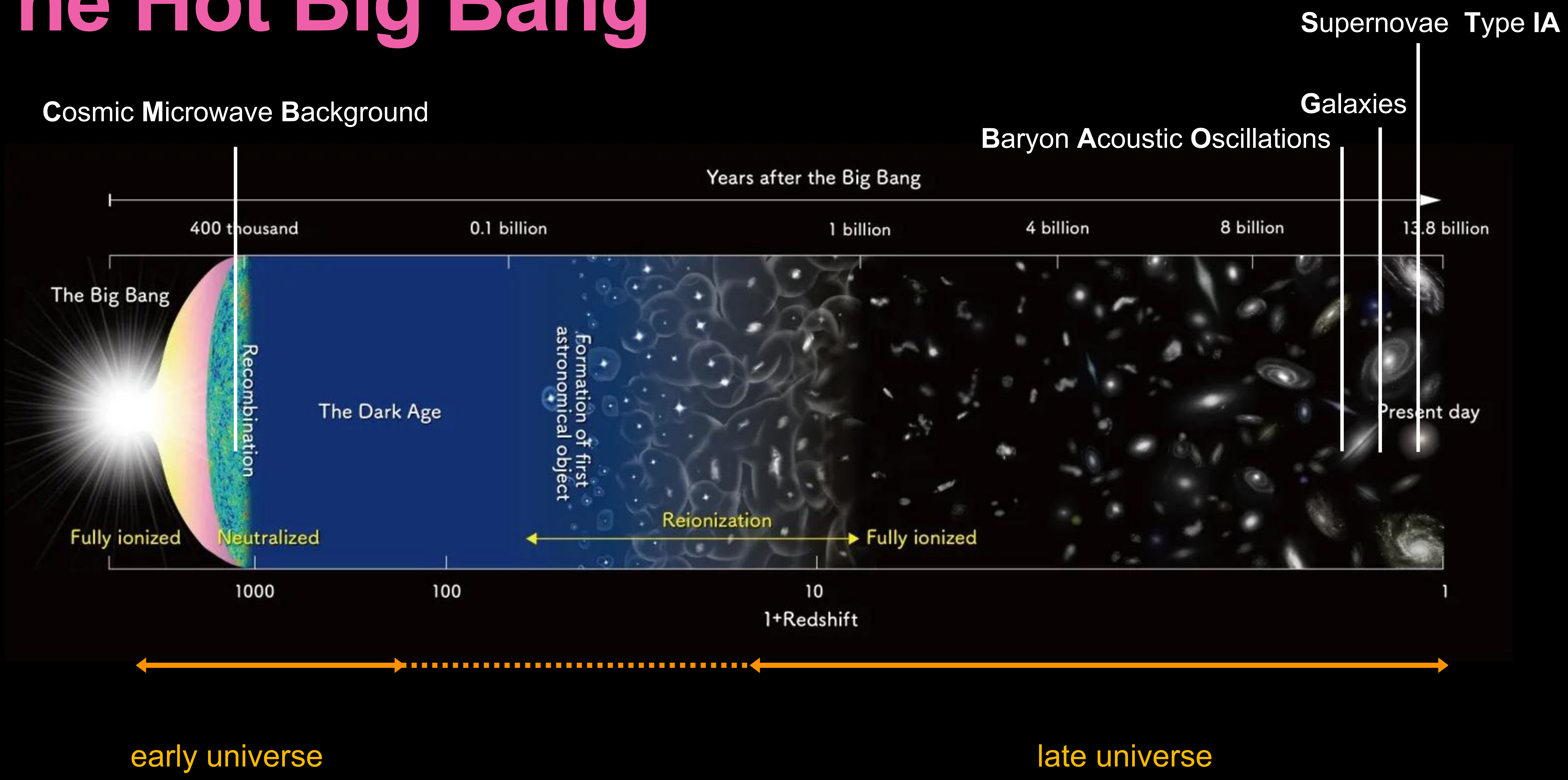




1915, Albert Einstein

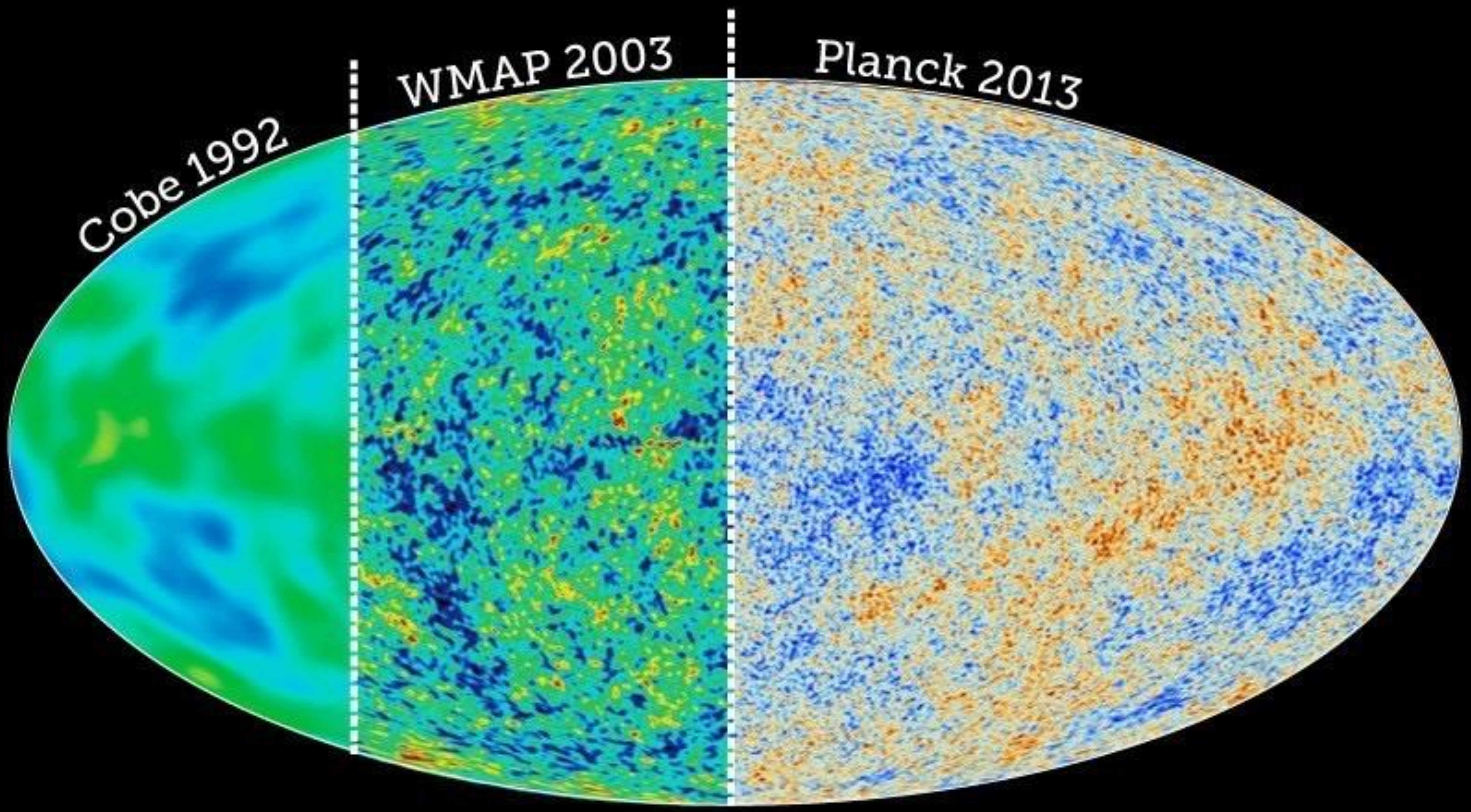
1929, Edwin Hubble

The Hot Big Bang

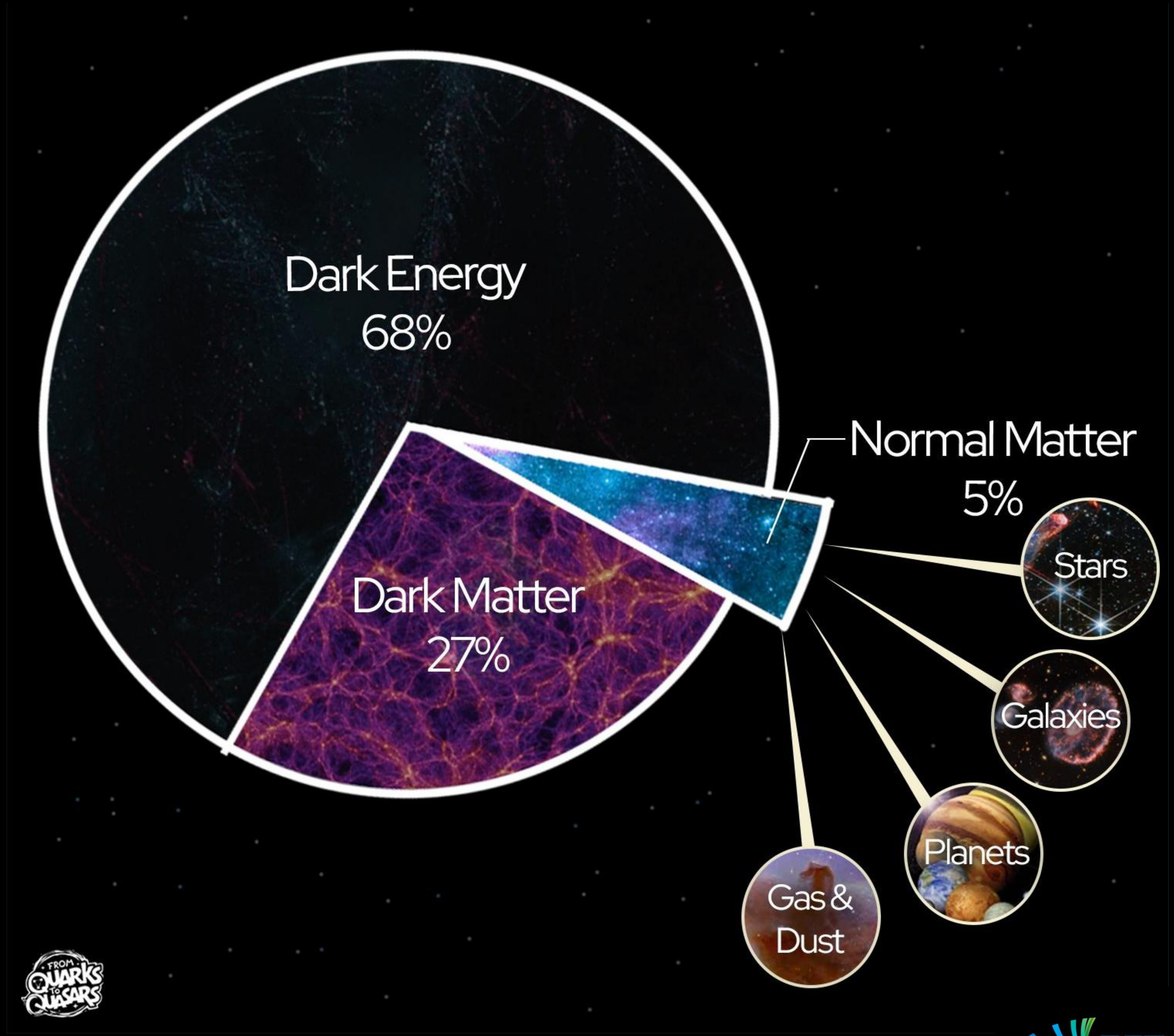


Credit: NAOJ

The Cosmic Microwave Background



The Standard Model of Cosmology



Very close to spatially flat.

Following the laws of gravity as formulated by Einstein, i.e. General Relativity.

Dark Energy: sourcing the speeding up of the expansion, started some billion years ago; experimentally established with SNe in 1998

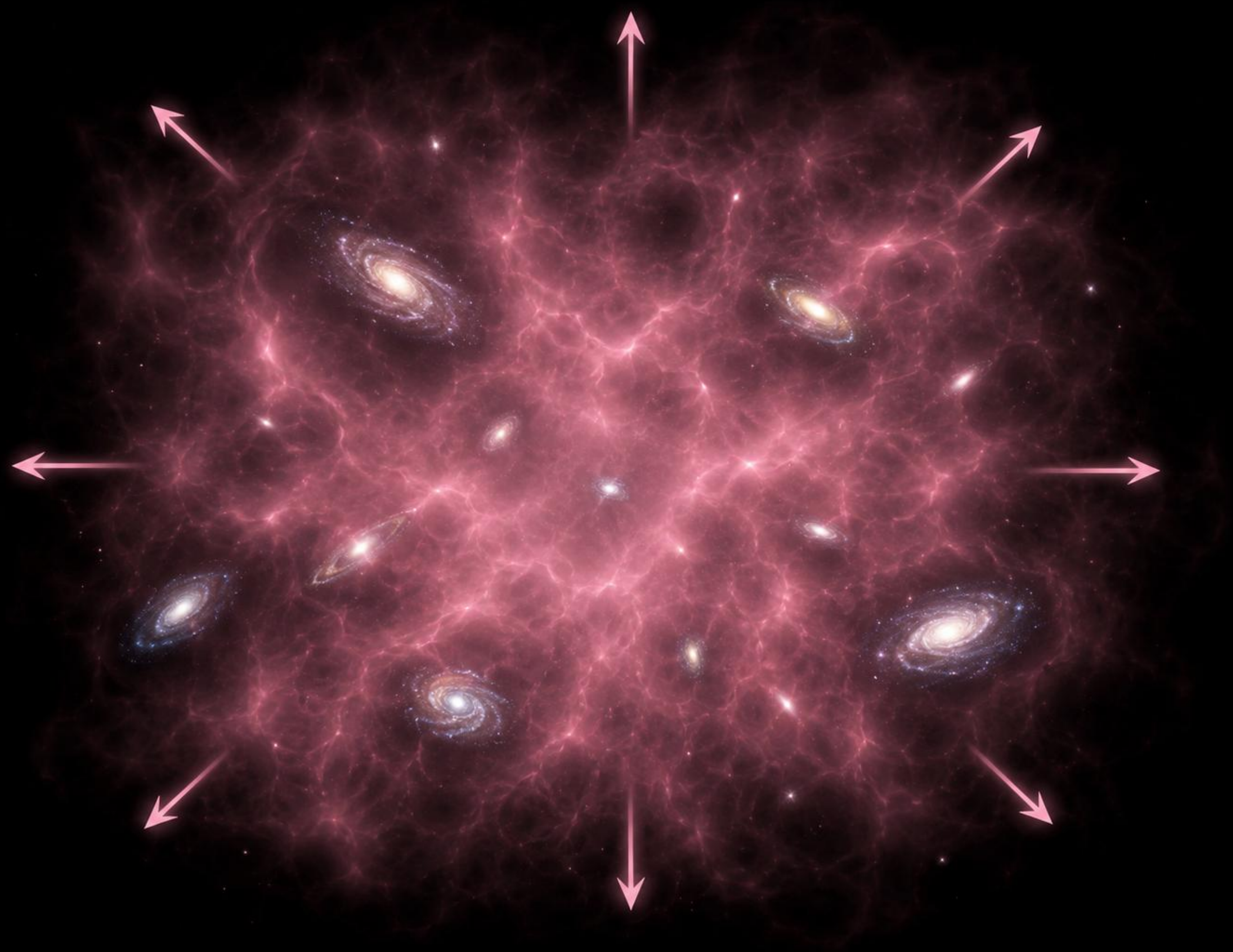
Dark Matter: providing the gravitational pull that is needed to form all the structure that we observe around us.

EFTCAMB

CMB ANALYZER: Let us play a game!

courtesy of Stan Verhoeve

What is Dark Energy ??



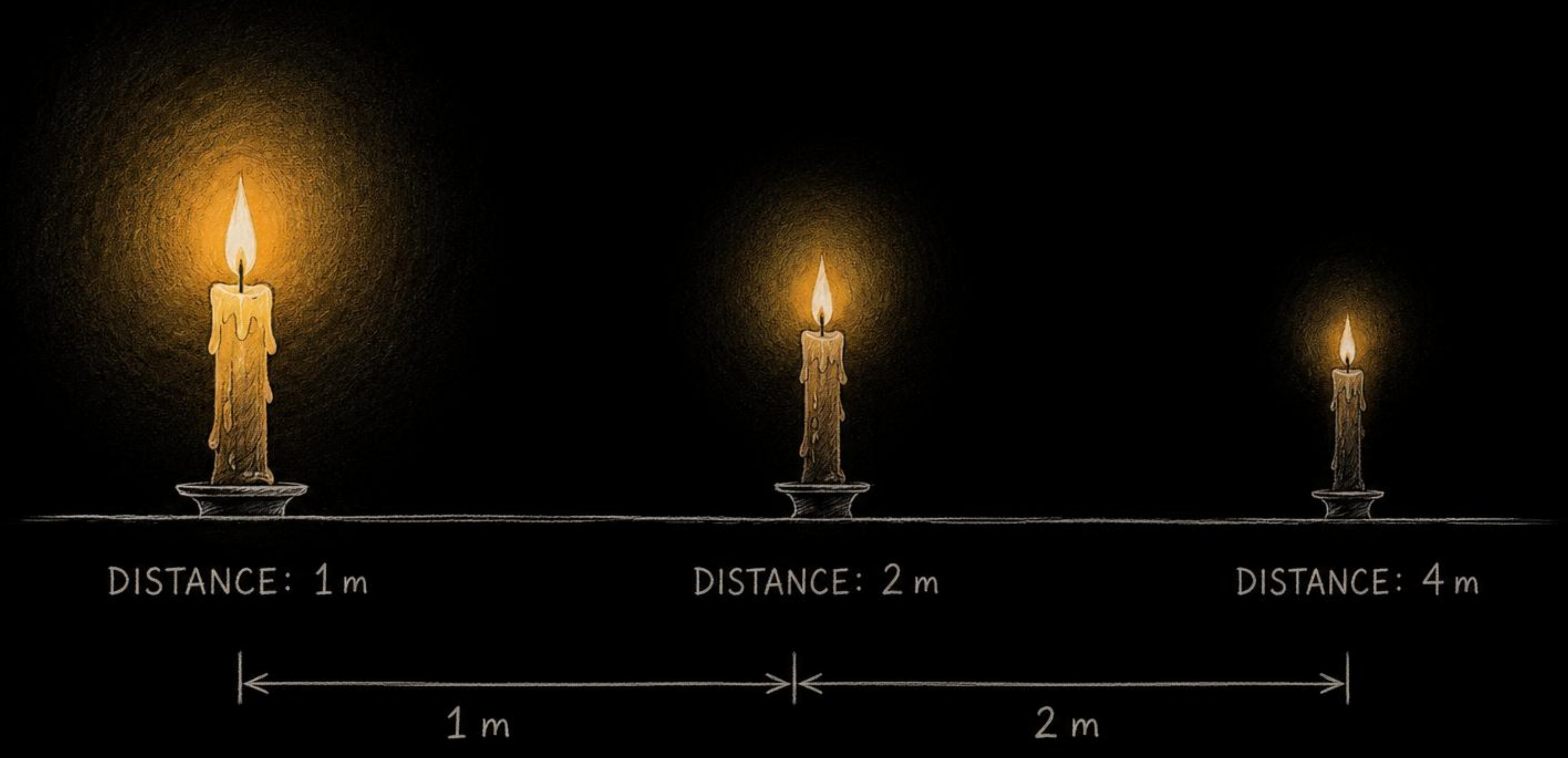
The name Dark Energy was conceived in 1998 by cosmologist Michael Turner to indicate the mysterious source of **cosmic acceleration** discovered that year.

Why this name? Because it behaves like a kind of **energy** spread throughout space which is **dark** in the sense that we cannot see it, we do not know what it is, but we definitely detect its effect on the dynamics of the Universe.

While earlier measurements of galaxies and comparisons with cosmological simulations had already hinted at the effect, **compelling evidence for cosmic acceleration came in 1998 from observations of Type Ia Supernovae, used as standard candles**.

Supernova Cosmology Project & High-z Supernova Search Team (Nobel Prize 2011)

Supernovae Type Ia



The further the SNIa, the dimmer it appears. But by how much exactly?

This is where the information on the expansion is encoded! In more technical terms we write:

$$d_L(z) \propto \int_0^z \frac{dz'}{H(z')}$$

where H(z) is the expansion rate of the Universe.

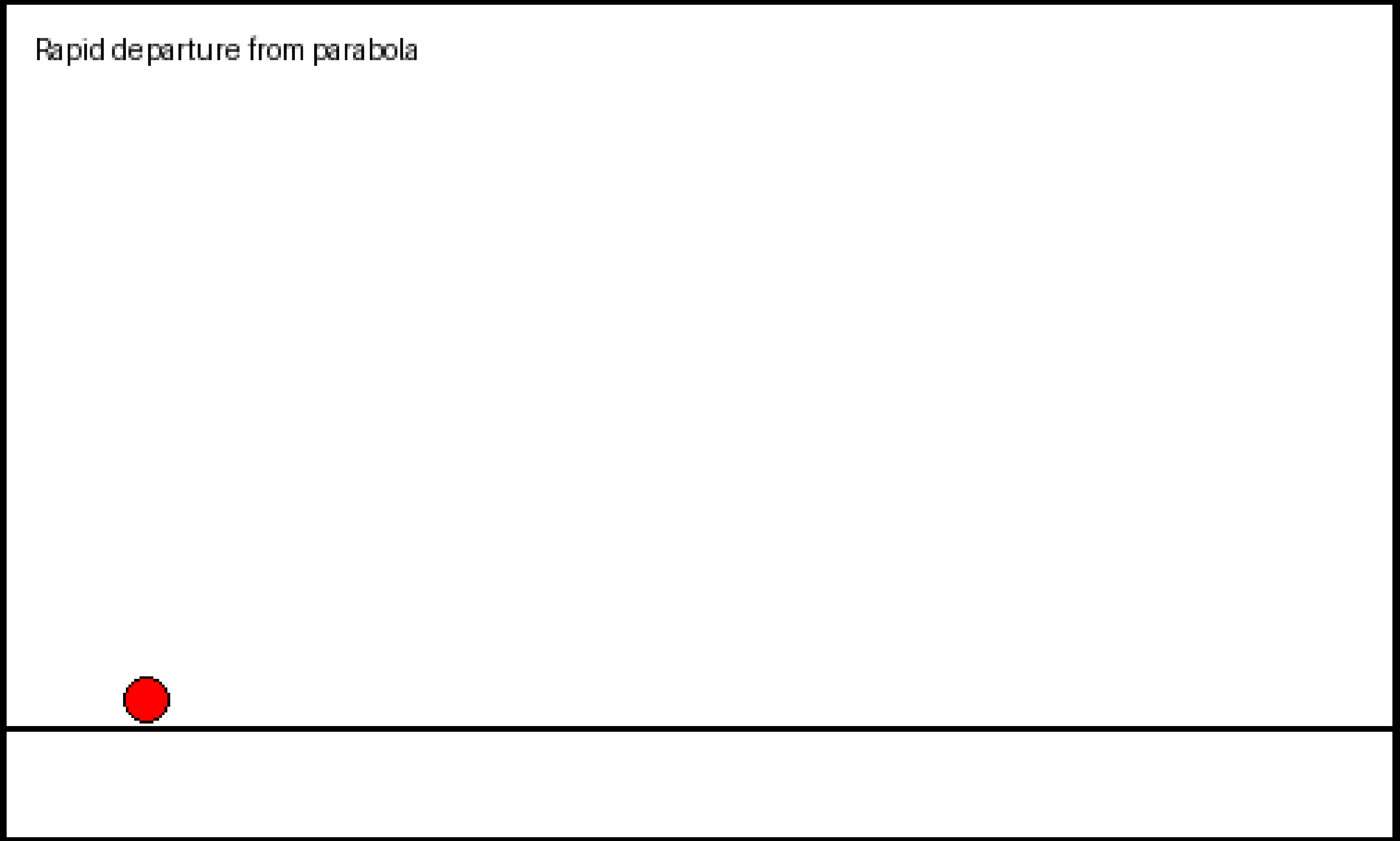
Accelerating Universe ??

This is counterintuitive!

In fact, after the Big Bang, the Universe initially expanded at a gradually slower rate - something we naturally expect because the gravitational pull of matter acts to slow down the expansion.

About 5 billion years ago, the expansion of the universe stopped slowing down and began accelerating.Imagine throwing a ball upward: normally gravity makes it slow down over time. But now imagine the ball speeding up instead.

That’s roughly what happened to the universe — instead of gravity gradually slowing the cosmic expansion, some unknown component of the universe began driving the expansion faster and faster.



Profiling Dark Energy

What do we know about Dark Energy?

- It is by far the dominant component of the Universe nowadays.
- It was negligible in the past.
- It speeds up the expansion of the Universe.
- It is everywhere, homogeneously distributed
- It is everlasting.

The cosmological constant

Empty space is not truly empty!

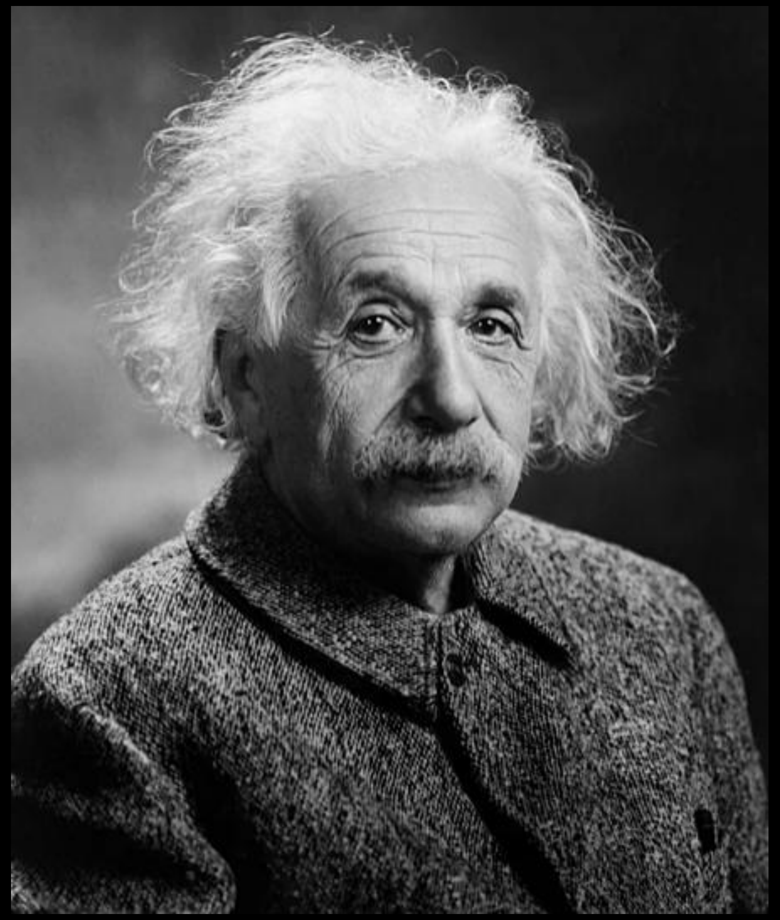
We prefer to call it **vacuum**, it comes with an (enormous) energy which we can detect gravitationally and has a constant energy density.

$$\Lambda_{\text{theory}} \equiv \Lambda_{\text{const}} + \Lambda_{\text{vacuum}}$$

Small problem:

$$\Lambda_{\text{theory}} \gg \Lambda_{\text{measured}}$$

Hendrik Casimir


Albert Einstein

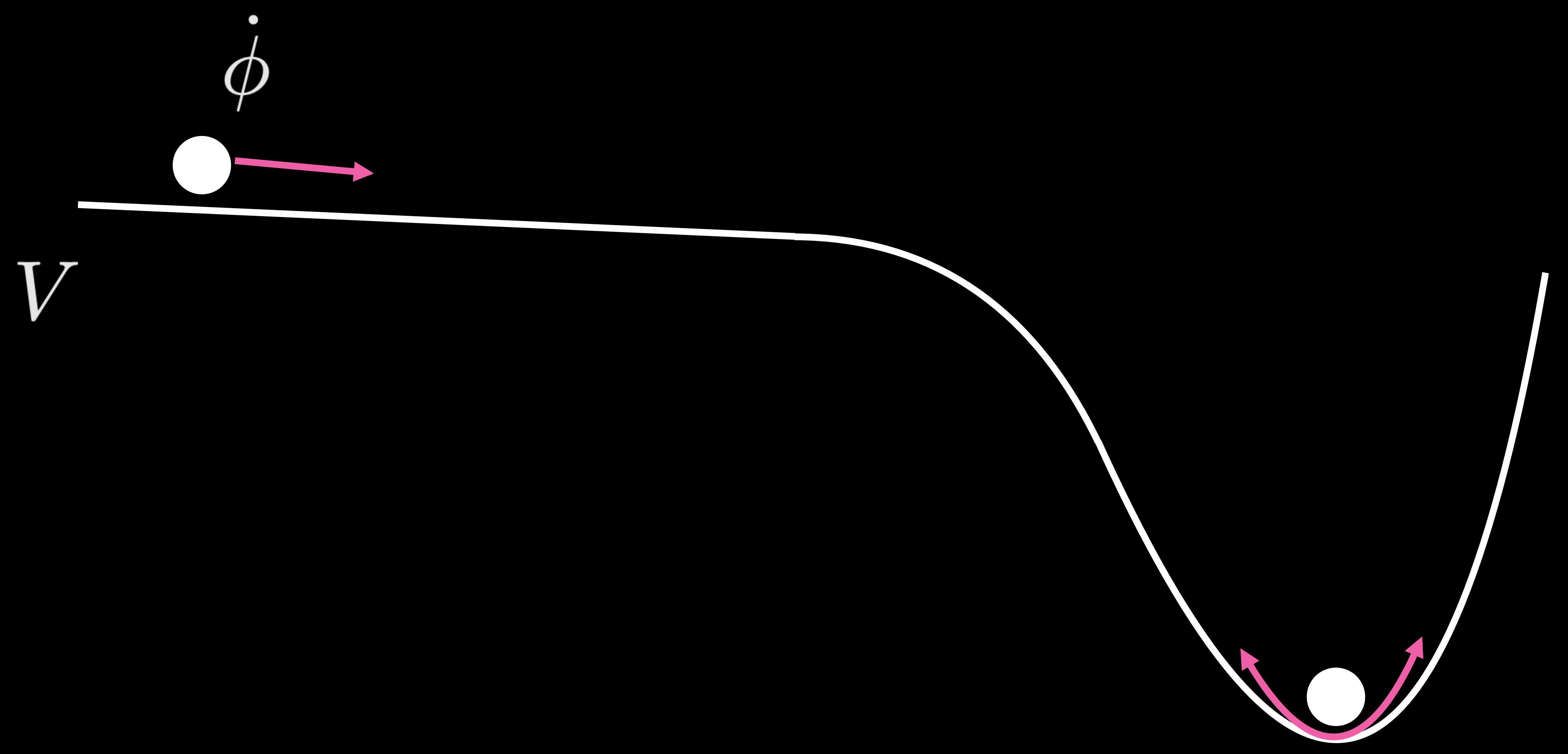
Alternatives I

The next simplest option is a **scalar field**, $\phi(t, \vec{x})$ i.e. a function which at any given time takes a specific value at each point in space.

In Cosmology we like to add scalar fields because they respect the symmetries of our Universe.

QUINTESSENCE: a slowly rolling scalar field

$$\mathcal{L} = \frac{\dot{\phi}}{2} - V(\phi)$$

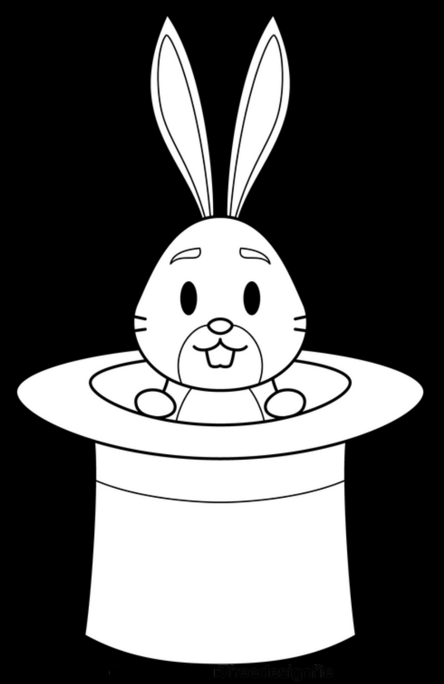


Alternatives II

A pillar of the standard model of Cosmology, which we used to interpret the data, is the theory of General Relativity. Could we have gone wrong there?

Weinberg-Deser theorem: A Lorentz invariant theory of a massless spin-2 particle must be General Relativity.

But, there's virtually no limit to a physicist's creativity !



Do we need a spin-2? yes, we do!

Can't the spin-2 have a mass? may be

Can we have anything more than the spin-2? yes…

Can we work in more that 4D ? yes!

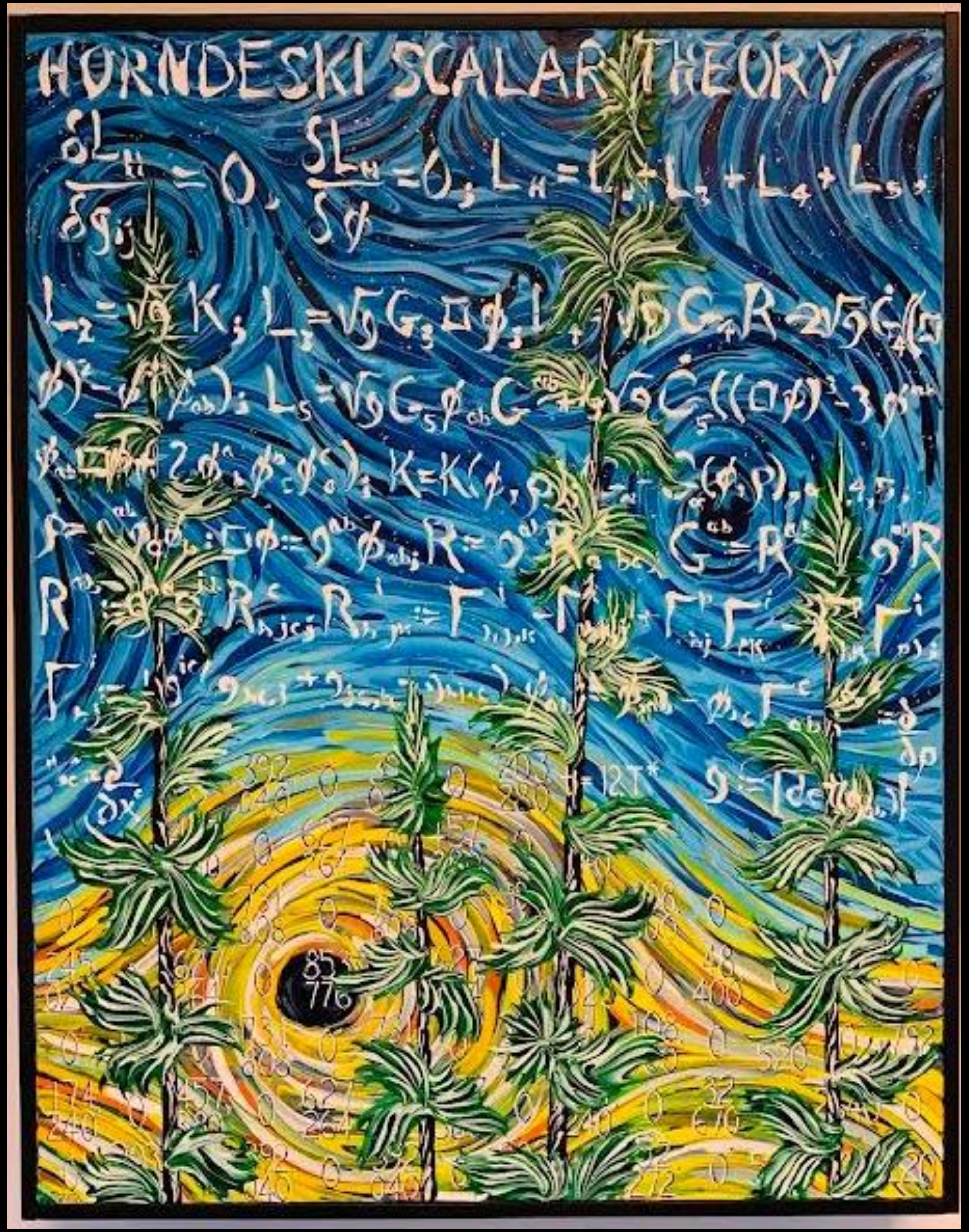
Alternatives

With an **Effective Field Theory** point of view, most of these models can be described as standard General Relativity plus a scalar field.

Generalized Galileons

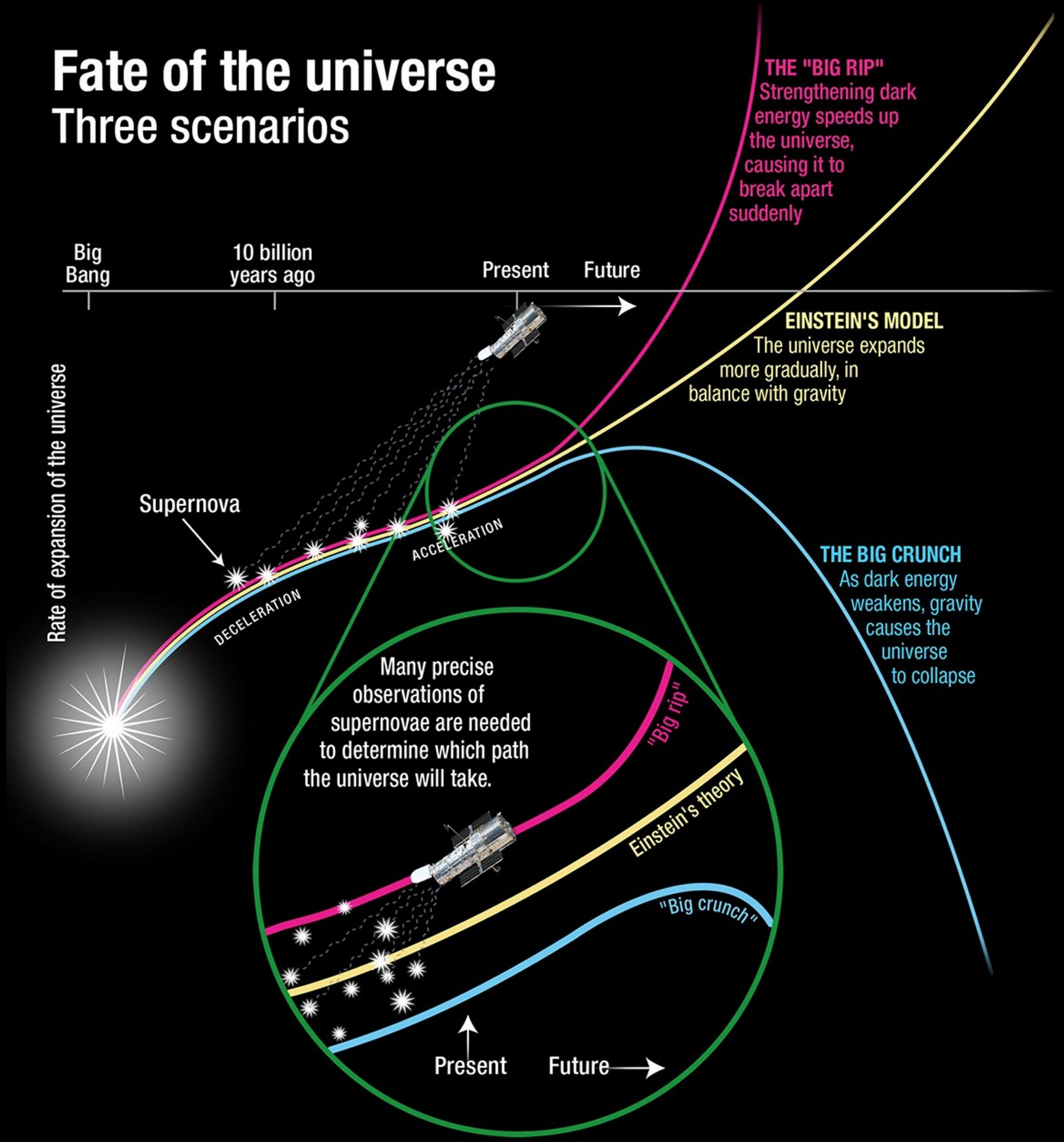
$$
\begin{aligned}
\mathcal{L}_2 &= K(\phi, X), \\
\mathcal{L}_3 &= -G_3(\phi, X)\Box\phi, \\
\mathcal{L}_4 &= G_4(\phi, X)\, R + G_{4,X}\left[(\Box\phi)^2 - (\nabla_\mu\nabla_\nu\phi)\,(\nabla^\mu\nabla^\nu\phi)\right], \\
\mathcal{L}_5 &= G_5(\phi, X)\, G_{\mu\nu}\,(\nabla^\mu\nabla^\nu\phi) - \frac{1}{6}\, G_{5,X}\left[(\Box\phi)^3 - 3(\Box\phi)\,(\nabla_\mu\nabla_\nu\phi)\,(\nabla^\mu\nabla^\nu\phi)\right. \\
&\quad \left. +2(\nabla^\mu\nabla_\alpha\phi)\,(\nabla^\alpha\nabla_\beta\phi)\,(\nabla^\beta\nabla_\mu\phi)\right]
\end{aligned}
$$

A. Nicolis, R. Rattazzi and E. Trincherini, Phys. Rev. D79, 064036 (2009).
C. Deffayet, G. Esposito-Farese and A. Vikman, Phys. Rev. D79, 084003 (2009).
G. W. Horndeski, Int. J. Theor. Phys. 10.



'Horndeski Scalar Theory, Past, Present and Future', by Gregory Horndeski

The Fate of the Universe



Can we learn more?

Yes!

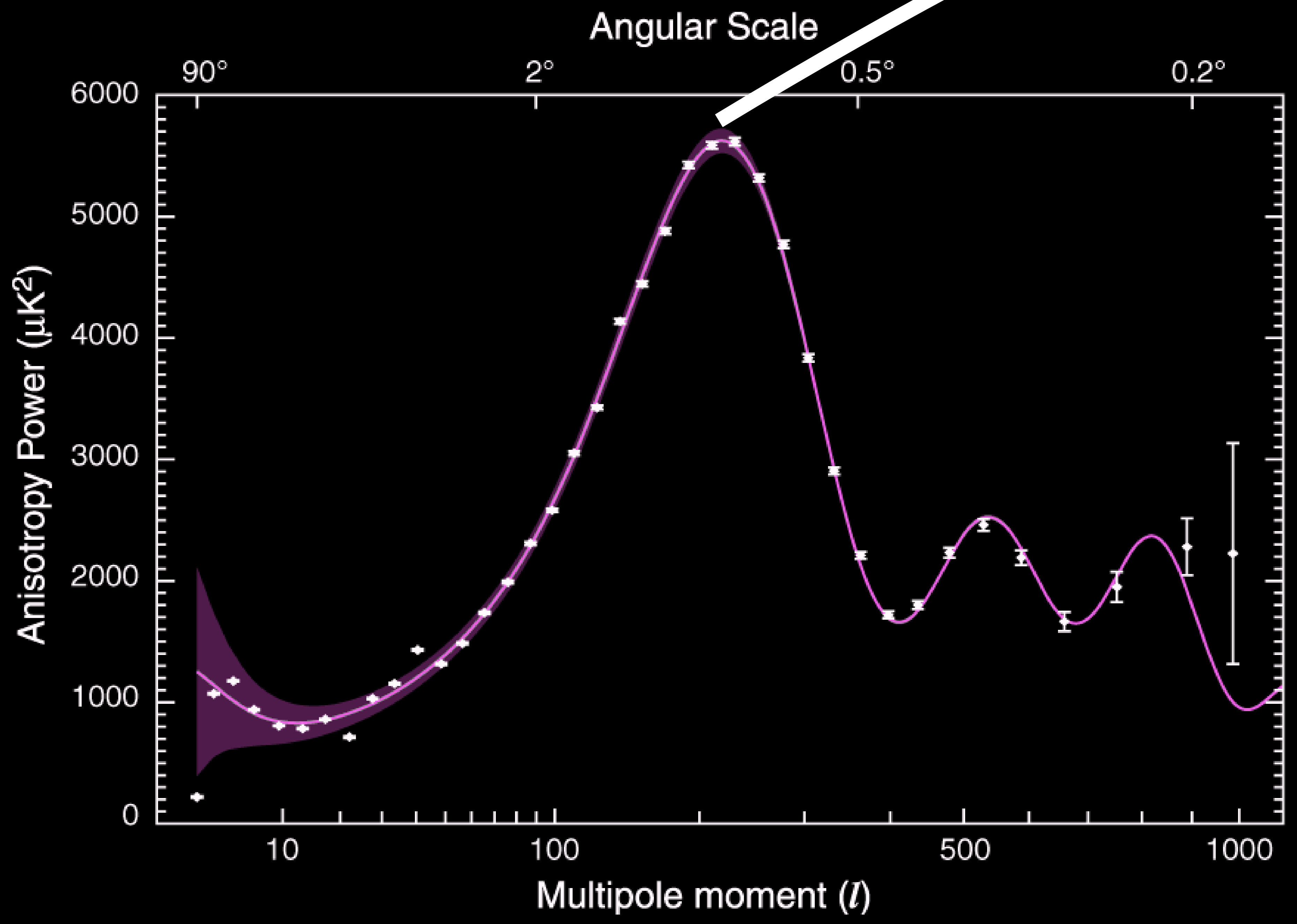
The so-called Stage IV Galaxy and Weak Lensing Surveys are unfolding and they are designed to shed light on the nature of dark energy (and dark matter) !

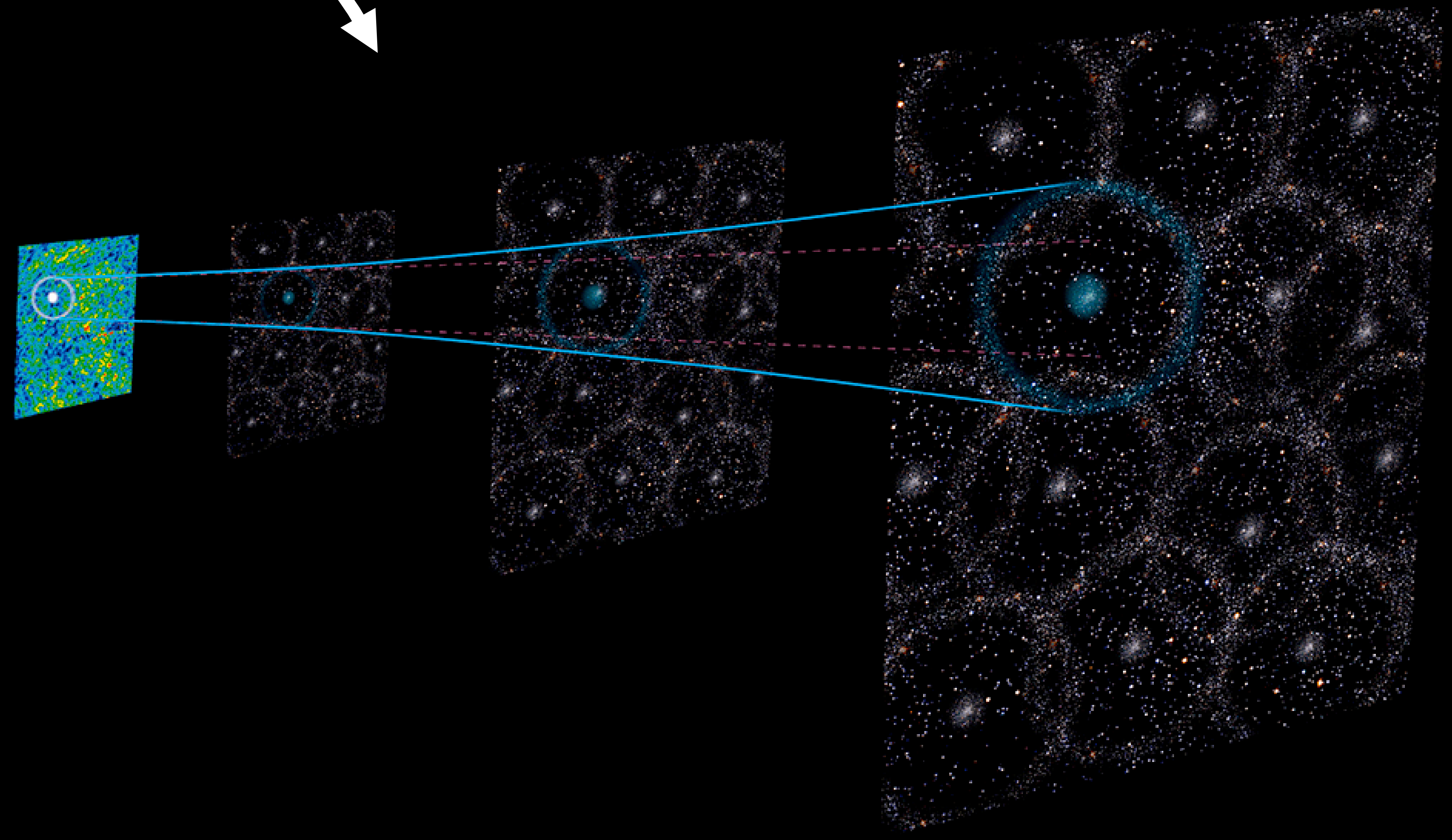
In fact the Galaxy Survey being carried out by DESI has delivered some interesting results and created quite some buzz!

Baryon Acoustic Oscillations

The primordial, hot plasma of photons and baryons undergoes oscillations due to the interplay of pull from gravity and push from pressure. These freeze at the moment the CMB photons are released (~ when we take the picture of the CMB).

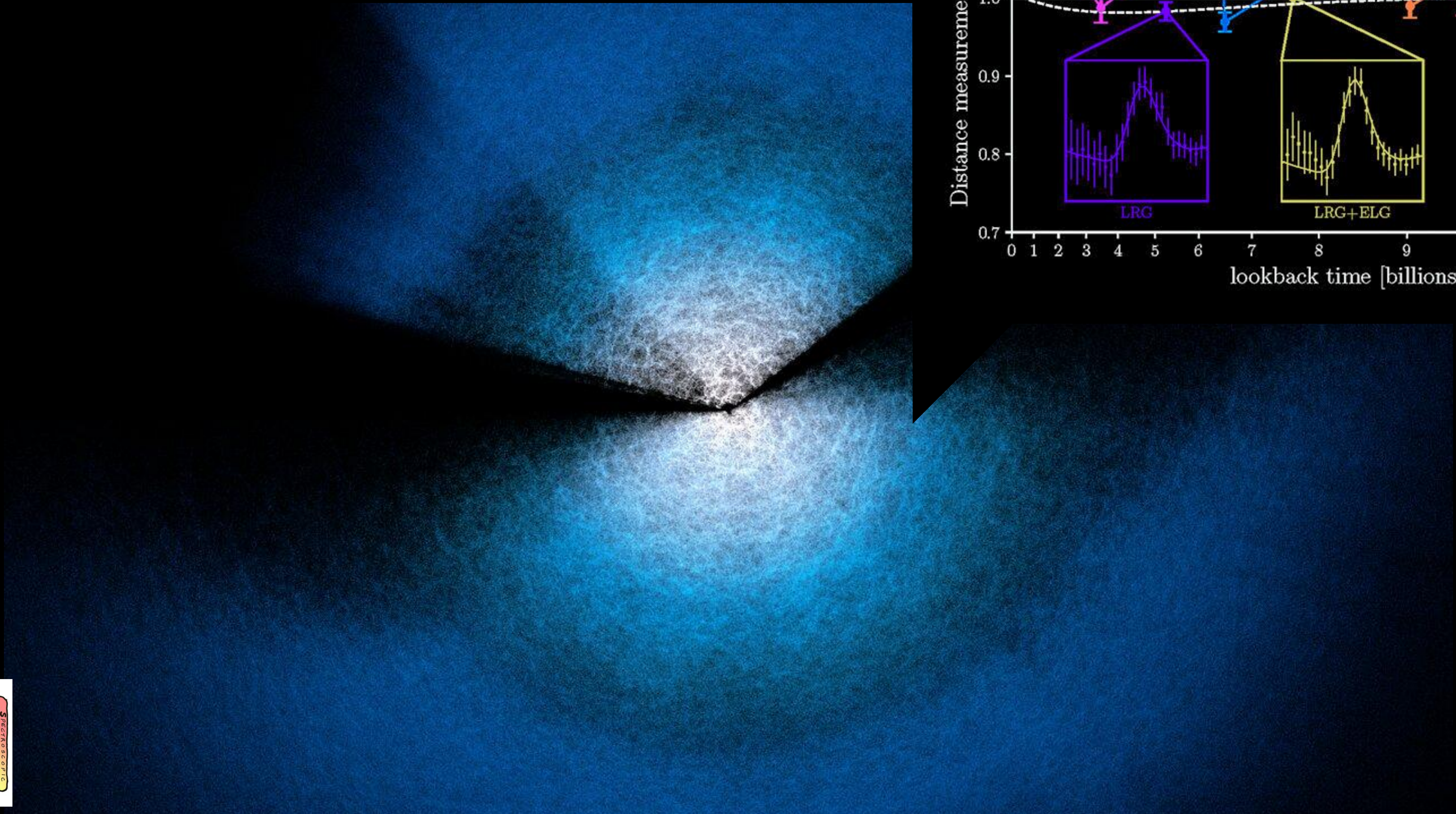
We see them in the power spectrum, in particular the first peak, but also in the distribution of matter. In the latter case they show up as a **PREFERRED CLUSTERING SCALE** which expands along with the Universe.

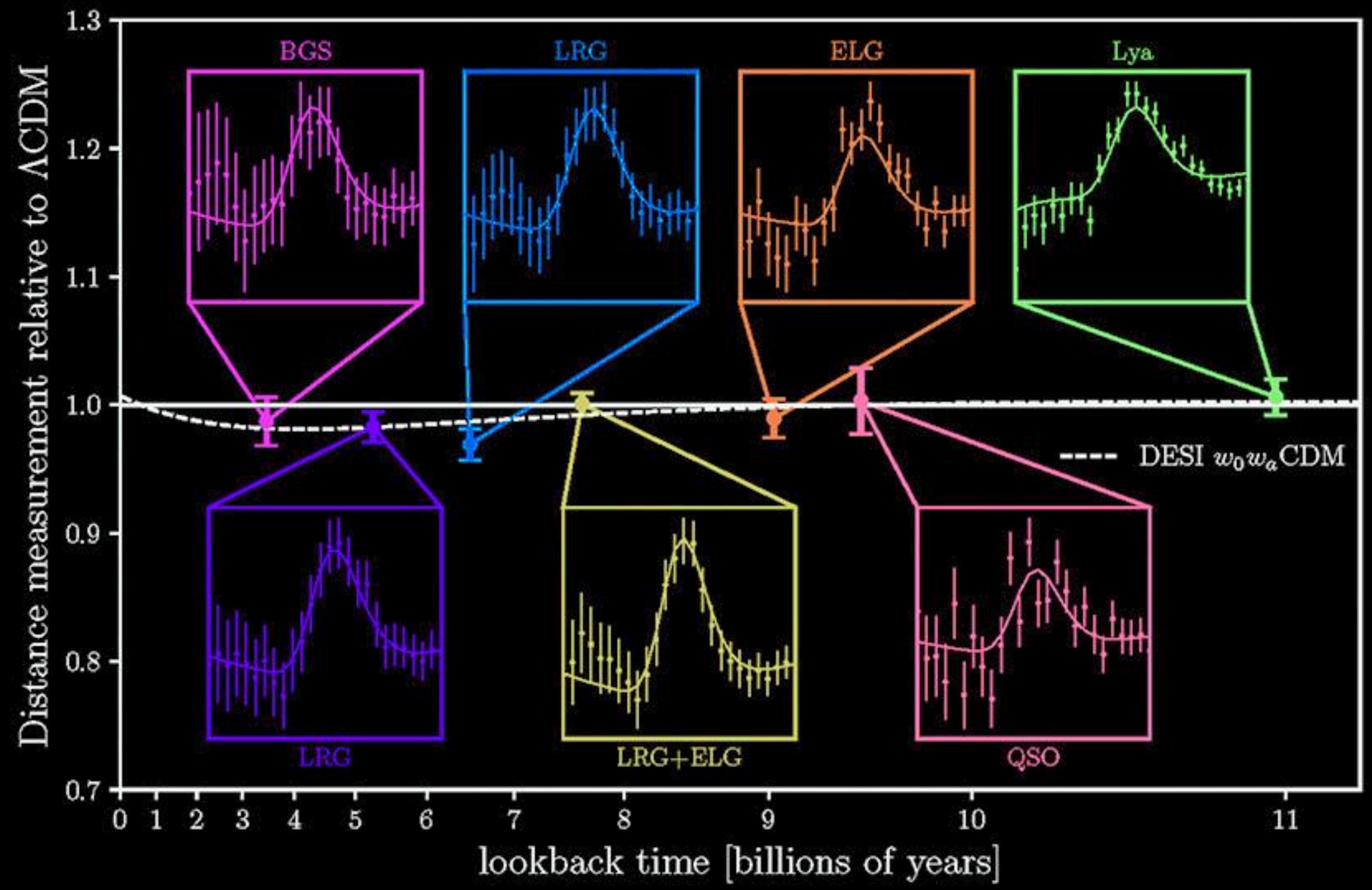




DESI's results

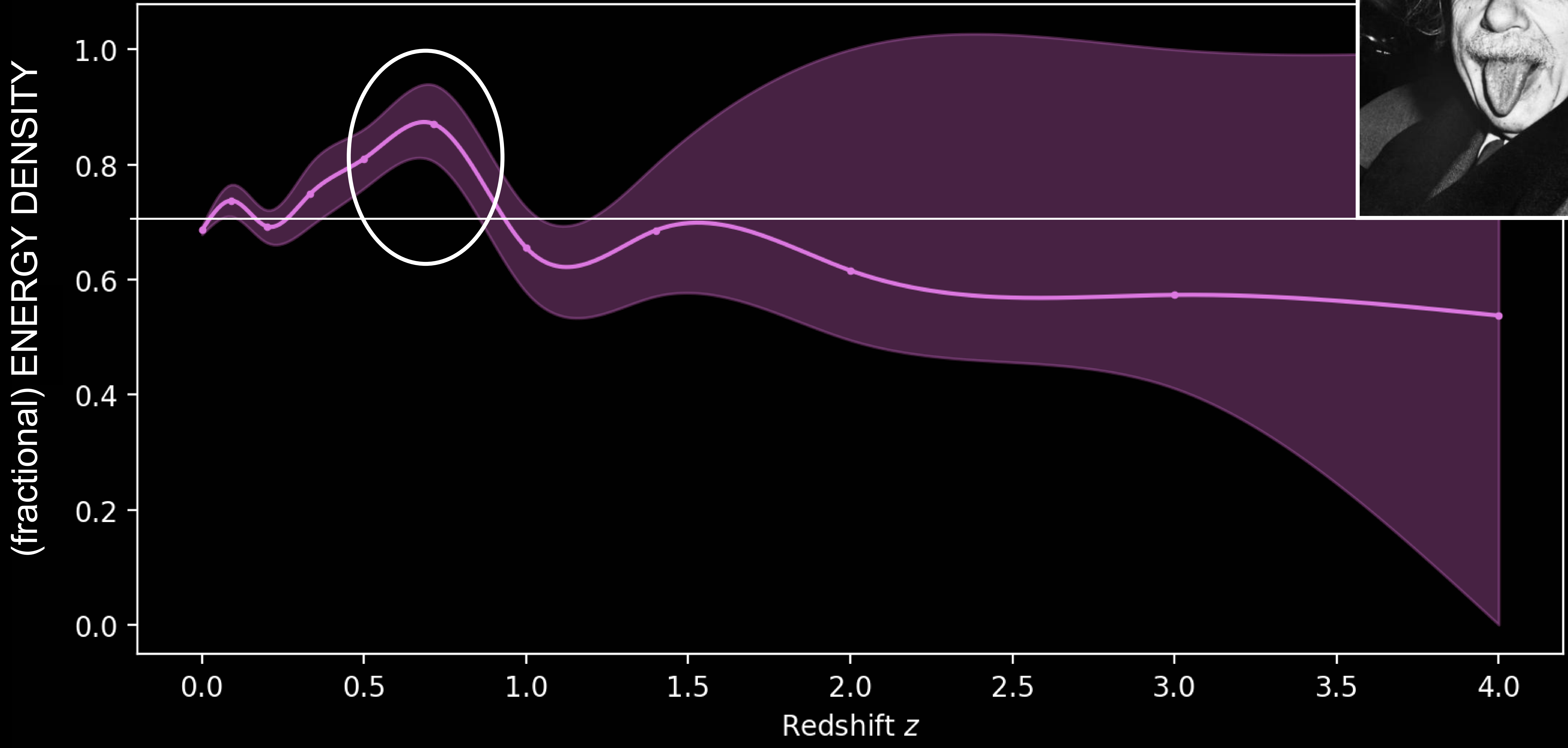
The **D**ark **E**nergy **S**pectroscopic Instrument is measuring precise (angular) position and redshift (~distance) of nearly 40 millions of galaxies and quasars.

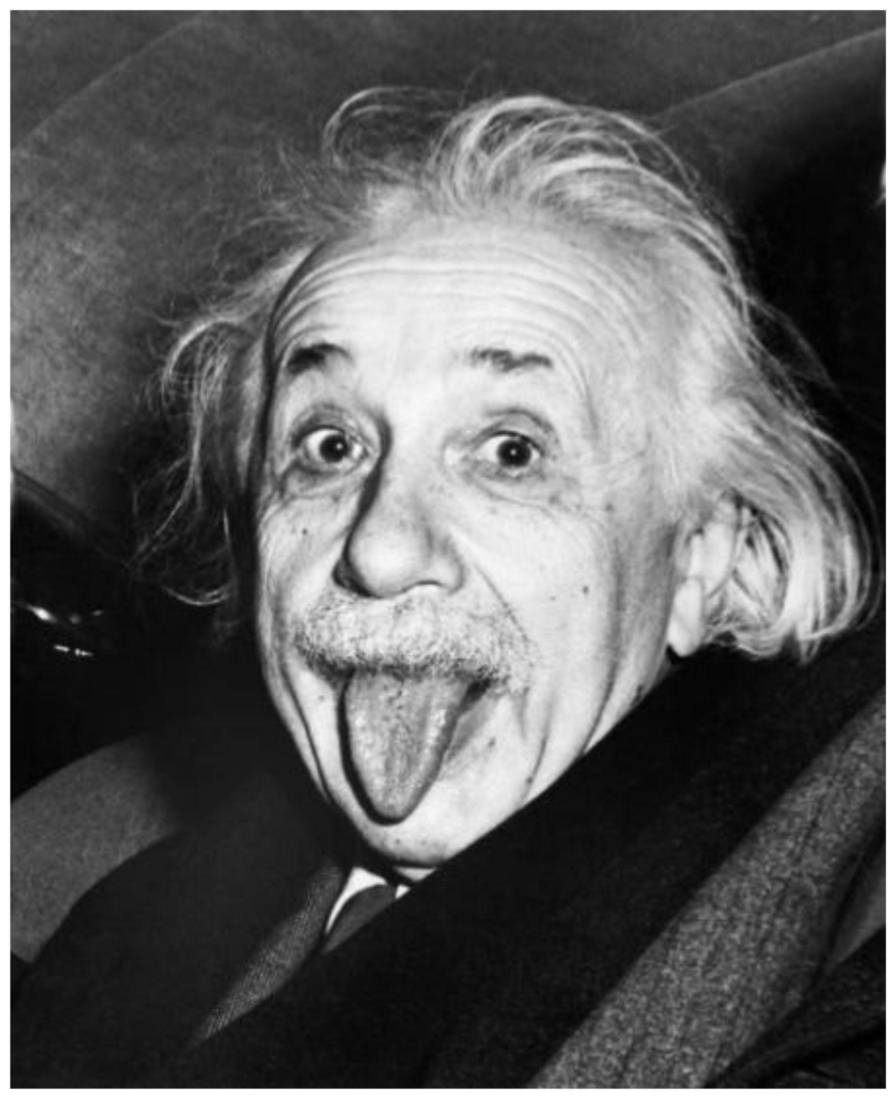




Credit: DESI Collaboration

Dark Energy after DESI



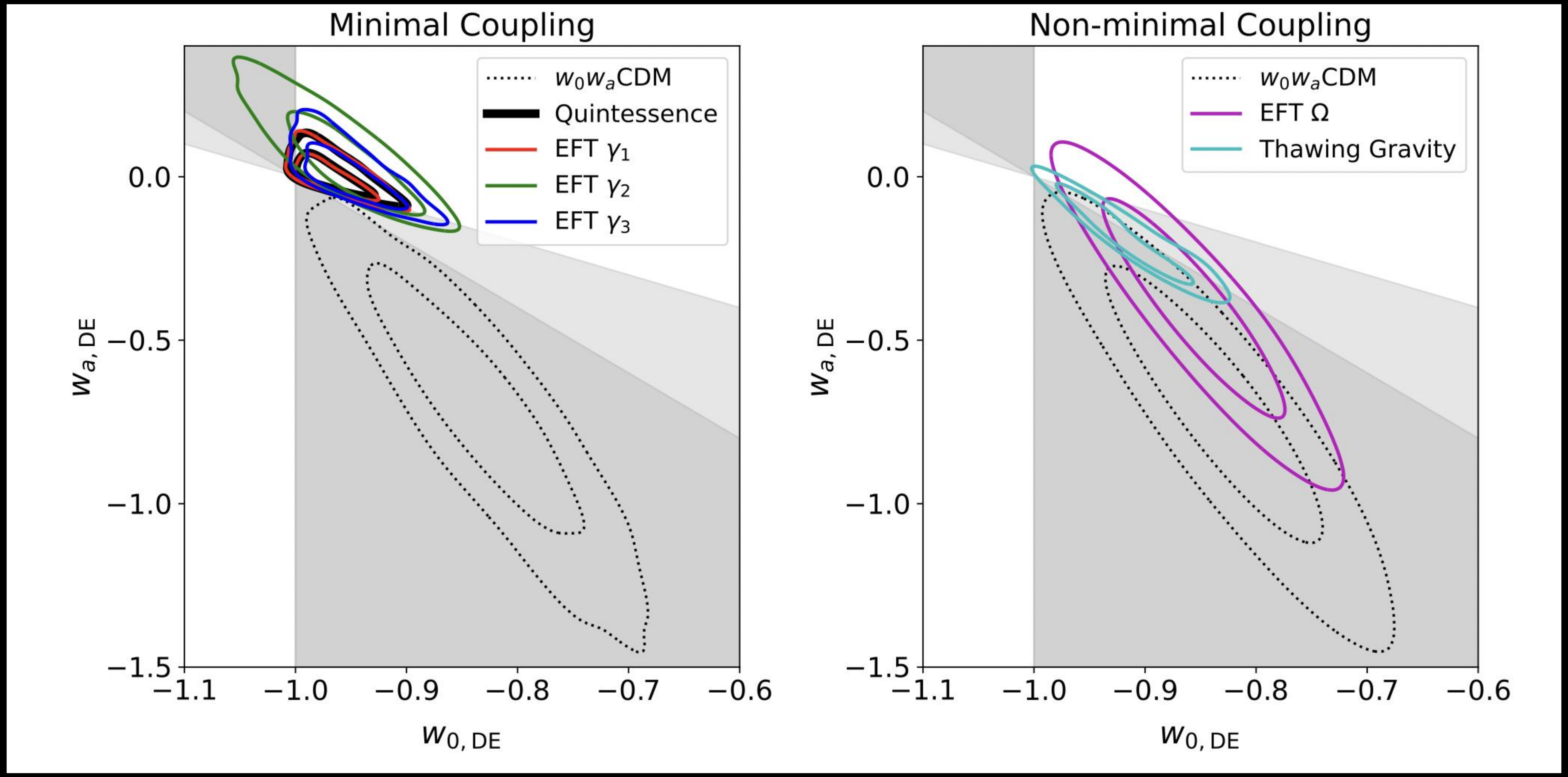


courtesy of Maria Luisa Gallavotti

Any ideas?

Out of all models, which one could give us such a behavior?

We asked ourselves that question, and were able to identify a key feature required by these data: a **non-minimal coupling** with gravity,

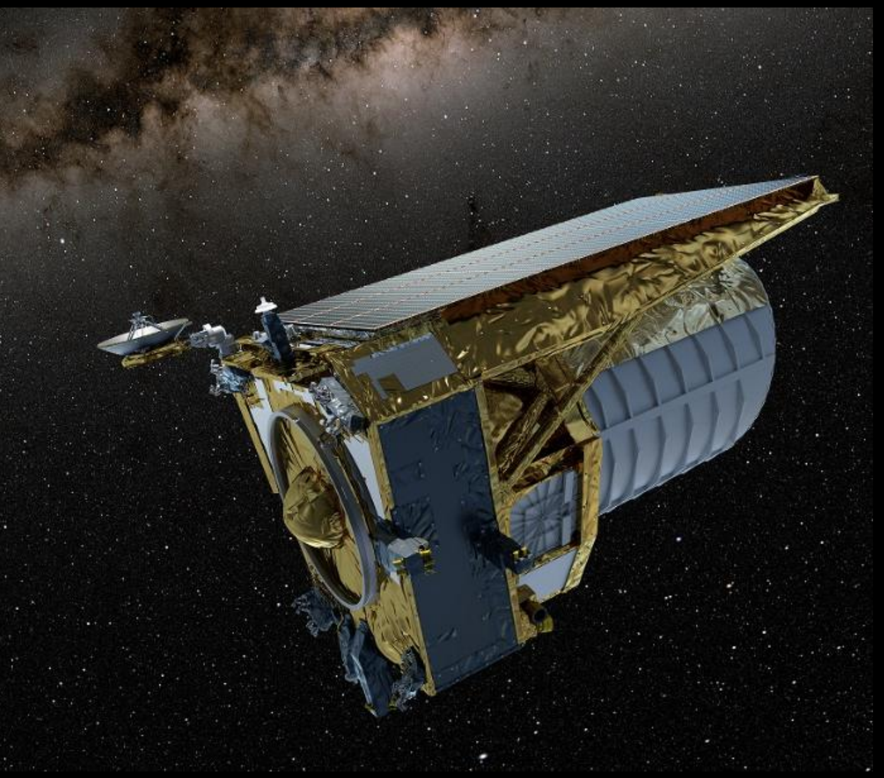


Thawing Gravity

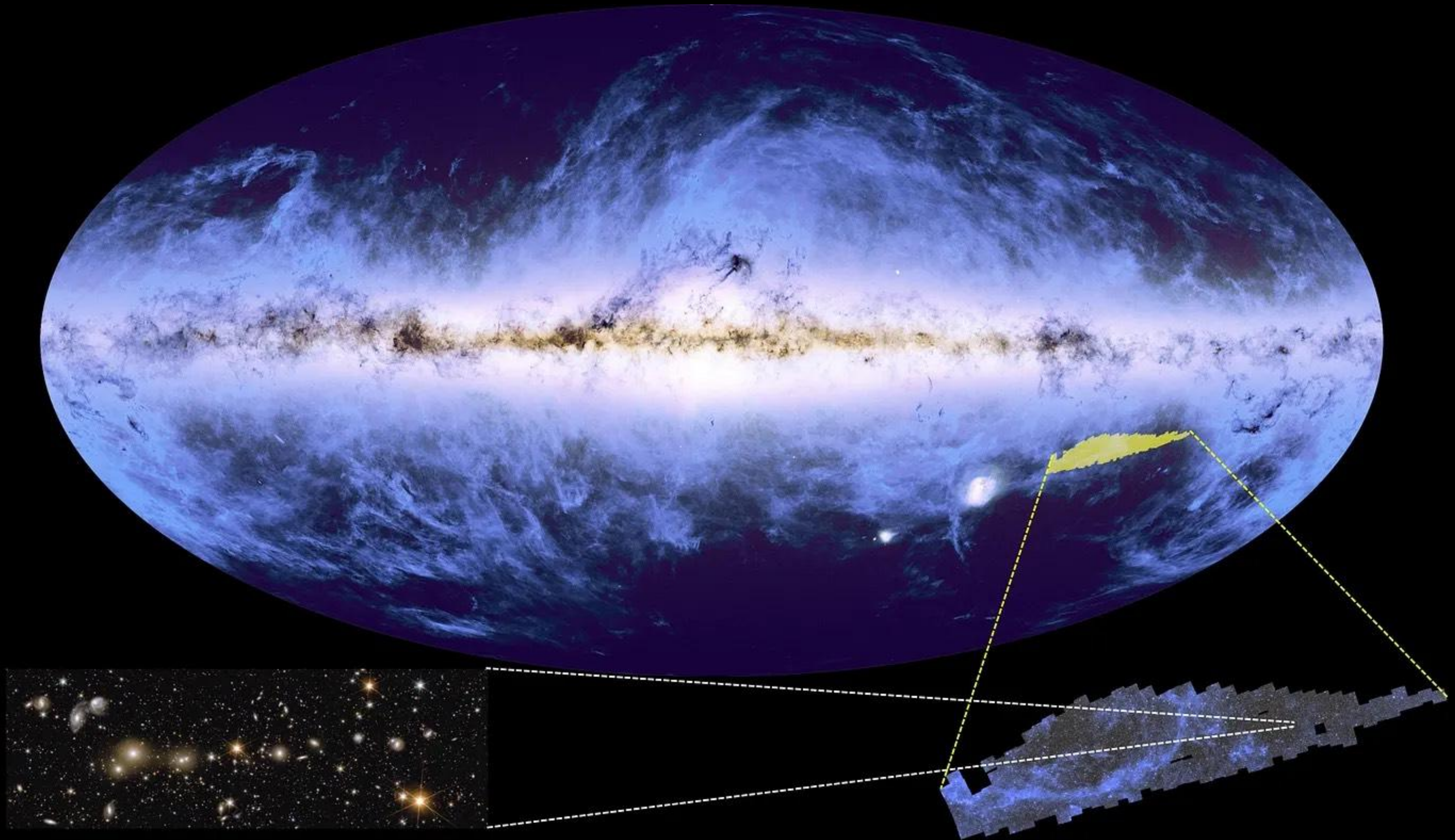
$$L = \frac{M_p^2}{2}\left[1 - \xi(\phi/M_p)^2\right] R + X - V_0 e^{-\lambda\phi/M_p}$$

Alternative models lead to a different rate for the **formation of structure** and different prescriptions for **gravitational lensing**. These are the **core cosmology probes of Euclid**!

Next comes Euclid!



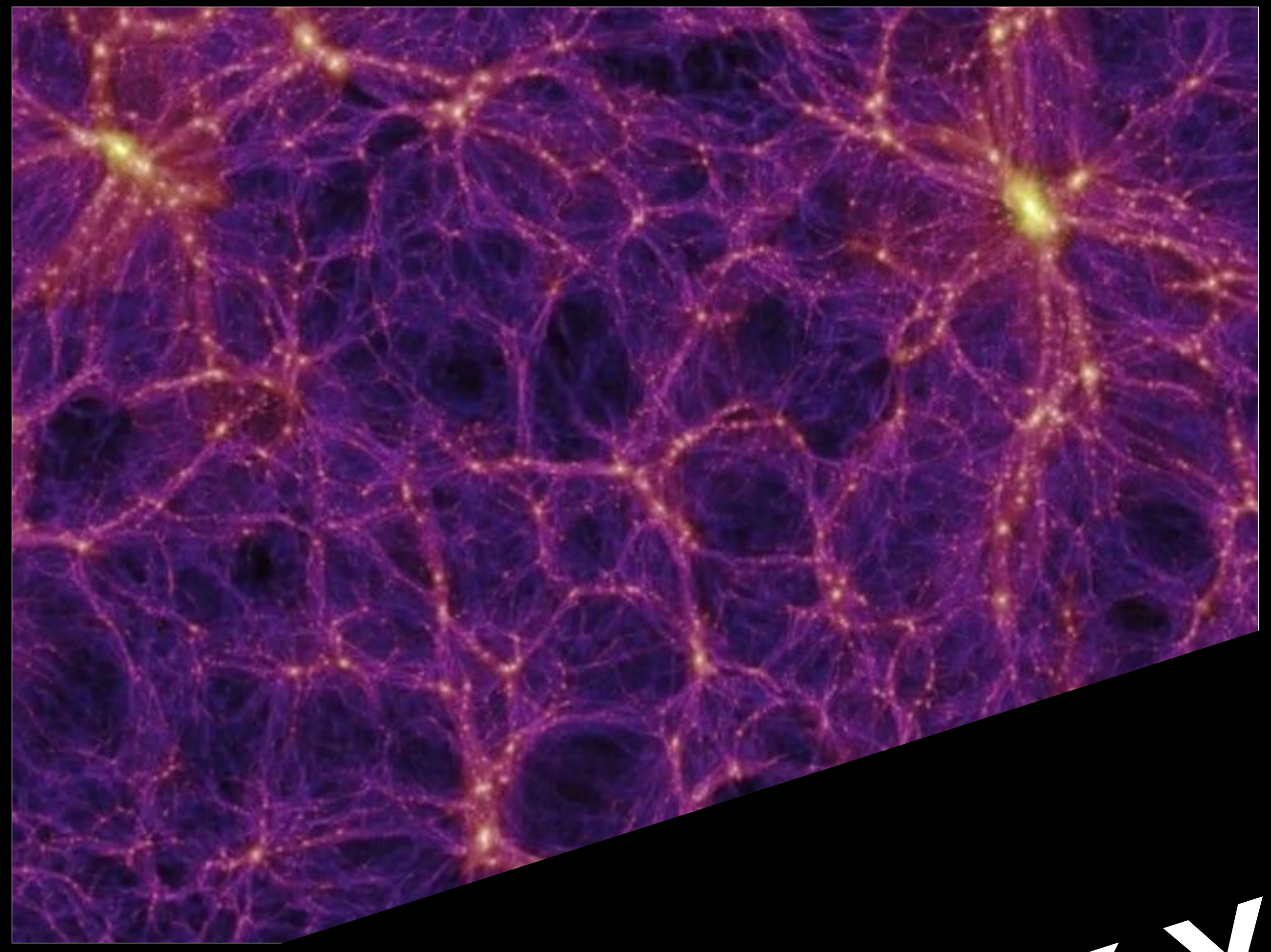
14,000 deg^2 — shape and photometry for 10^9 galaxies — spectroscopy for 10^7 galaxies

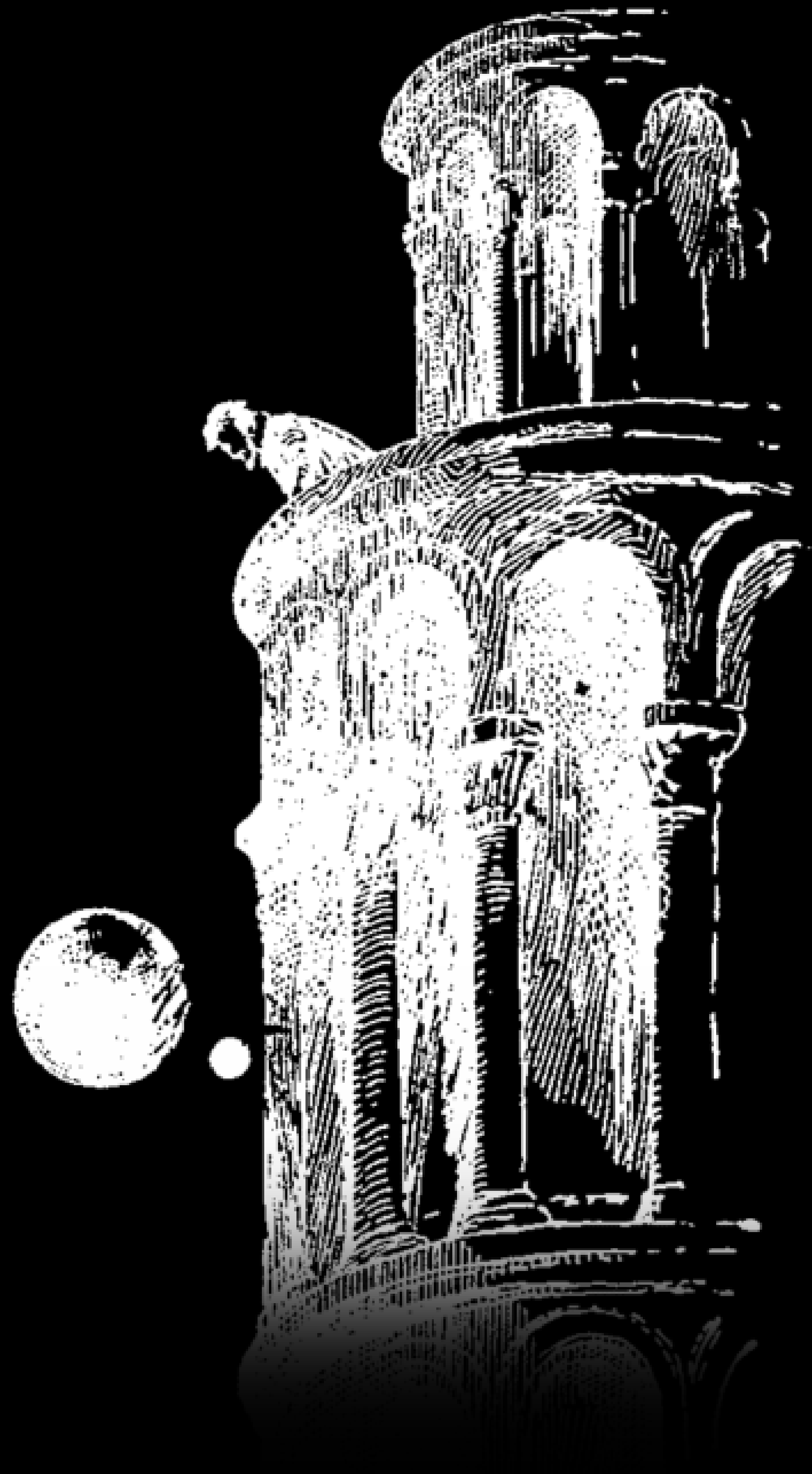


Credit:ESA/Euclid/Euclid Consortium/NASA; ESA/Gaia/DPAC; ESA/Planck Collaboration; Processing: J.-C. Cuillandre, E. Bertin, G. Anselmi; Composition: E. Siegel

PLAYING BALL IN THE UNIVERSE WITH EUCLID

By comparing how galaxies form and cluster, and how light is deflected by massive structure we can shed light on Dark Energy and the nature of gravity on cosmological scales.





THANK YOU FOR YOUR ATTENTION !

Sta 2027!