Conseil scientifique de l'IN2P3
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Introduction : physique et cosmologie

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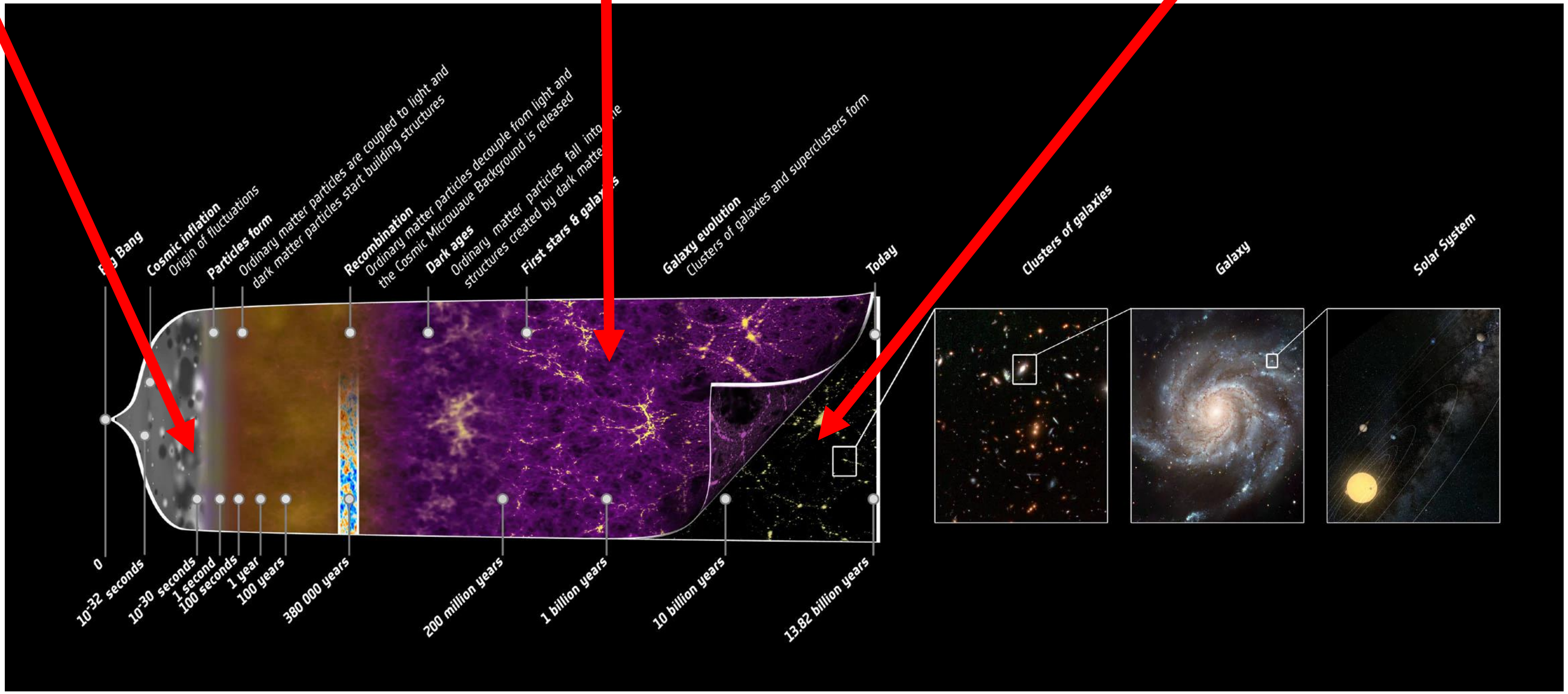
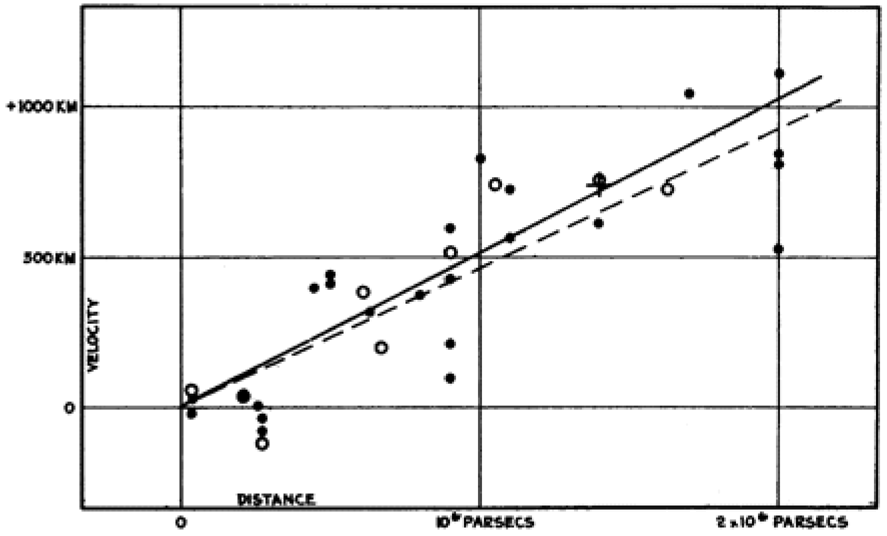
Cosmology: a wide range of energies and scales

Inflation:
the grand Unification scale?
10^{15} GeV

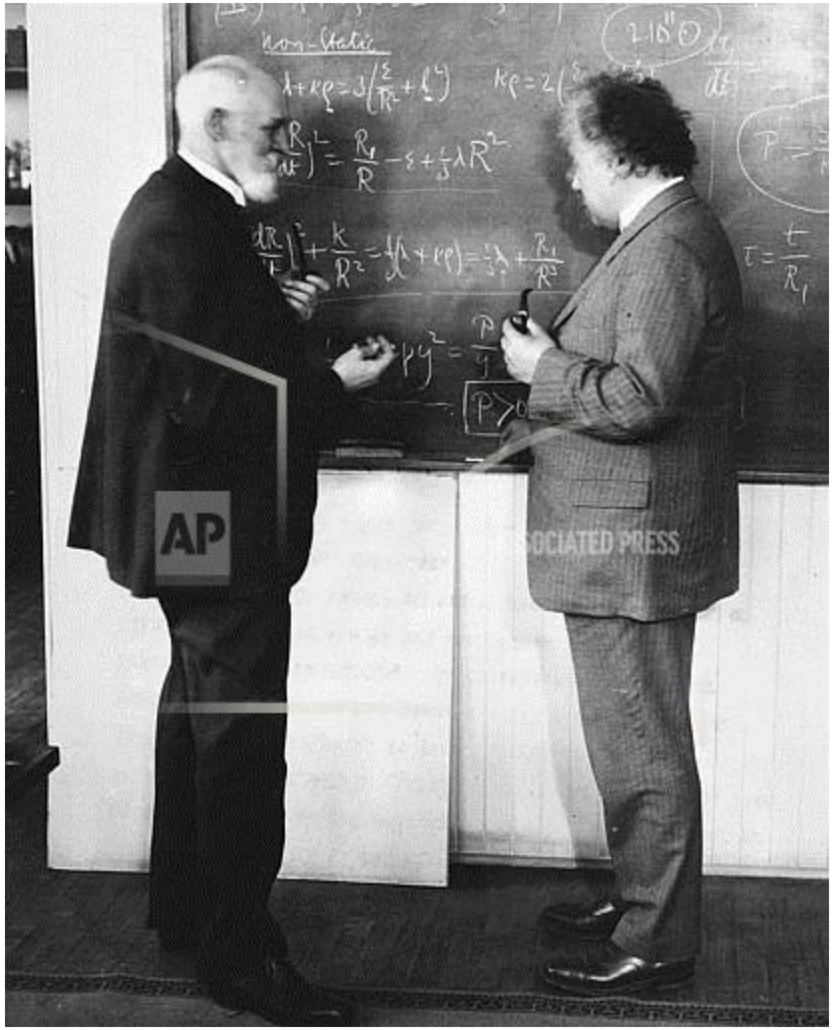
The dark ages: Sub-eV energies

The acceleration epoch:
the pico-eV era





The original
Hubble diagram



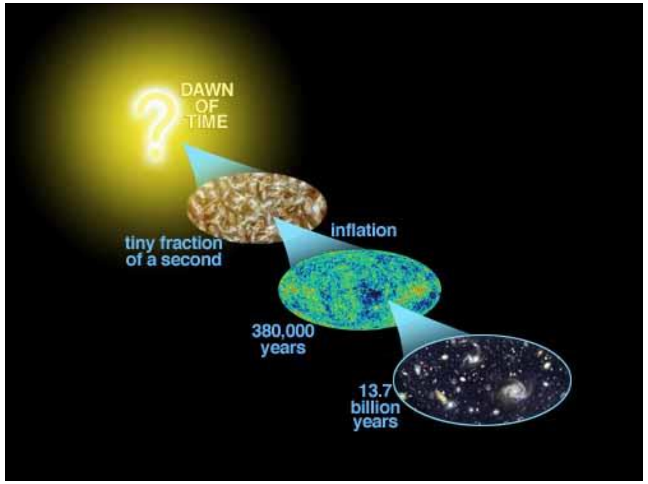
Einstein and de Sitter in Pasadena (1932) building the standard model of cosmology till 1998. The ***Einstein-de Sitter*** model ($\Omega_\Lambda = 0$)

On large scale, the Universe is homogeneous and isotropic (cosmological principle).

The Universe is not static: matter and radiation prevent it (Friedmann 1923).

Lifschitz (1946): In the expanding universe of the general relativity theory, the perturbations of most types decrease with time, thus showing no tendency to spontaneous increase. There also exist such perturbations which increase with time, but so slowly that they cannot produce large concentrations. Thus we can apparently conclude that gravitational instability is not the source of condensation of matter into separate nebulae.

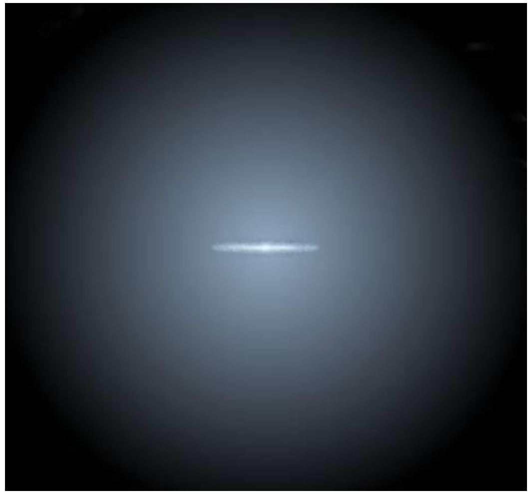
Two missing ingredients in 1946:



10^{-5}

- Cosmic Inflation setting the *initial fluctuations.* Also guarantees the isotropy of space on large scales via an era of *exponential expansion*. The initial fluctuations are ***quantum fluctuations***.

- Dark matter responsible for the potentials wells where baryonic matter aggregates and for a longer period of matter domination.



A galaxy embedded in its halo

For a long time, the role of the ***quantum vacuum*** in cosmology was neglected. It is now fundamental during inflation and possibly crucial for dark energy.

Everything happens as though the energy in vacuo would be different from zero. In order that absolute motion, i.e., motion relative to vacuum, may not be detected, we must associate a pressure $p = -\rho c^2$ to the density of energy ρc^2 of vacuum. This is essentially the meaning of the cosmical constant λ which corresponds to a negative density of vacuum according to $\rho_0 = \lambda c^2/4\pi G \cong 10^{-27}$ g/cm^3.[14]

Lemaitre (1934)

Close to present value:

10^{-29} g/cm^3

Pauli and Jordan (1928) following Lenz (1926) worry about the vacuum energy.

Although the "reality" of quantum fluctuations was ascertained by the detection of the Lamb shift (1s-2s):

$$\rho_\Lambda \sim \frac{m_e^4}{32\pi^2}$$

$$\delta E_n = \frac{2\alpha^4}{3}\frac{1}{n^3} < (\delta r)^2 >$$

Jittering of electrons due to quantum fluctuations

$$< (\delta r)^2 > = \frac{2\alpha}{\pi m^2}\int_0^\infty \frac{d\omega}{\omega}$$

$$\int_0^\infty \frac{d\omega}{\omega} = \int_{1/a_0}^m \frac{d\omega}{\omega} = \ln\frac{1}{\alpha}$$

The use of explicit cut-offs was later better understood in terms of renormalisation

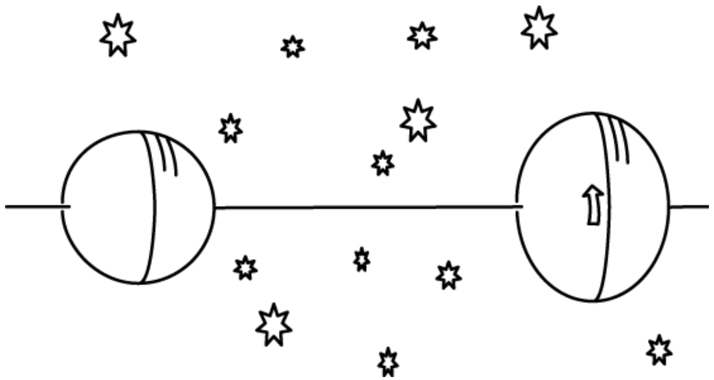
The ***vacuum energy*** contribution (or cosmological constant) was postulated as early as 1917 by Einstein and enters in the Einstein equation on par with matter.

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} T = 8\pi G_N (T_{\mu\nu} + T_{\mu\nu}^{\text{vac}})$$

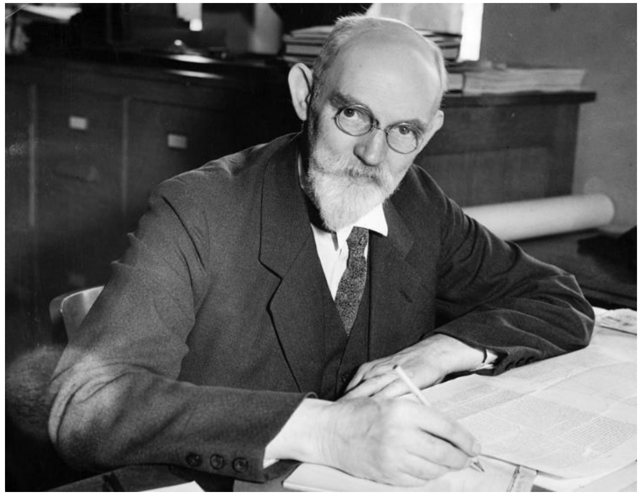
It immediately led to great confusion as it admits a solution with no matter and an ***accelerating expansion*** rate (de Sitter space-time 1919):

$$ds^2 = -dt^2 + a^2(t) d\vec{x}^2, \quad a(t) = e^{Ht}, \quad H^2 = 8\pi G_N V$$

Einstein did not like this solution because it violates « Mach's principle »: inertia (geometry) here is only due to matter there.



Does vacuum energy gravitate?

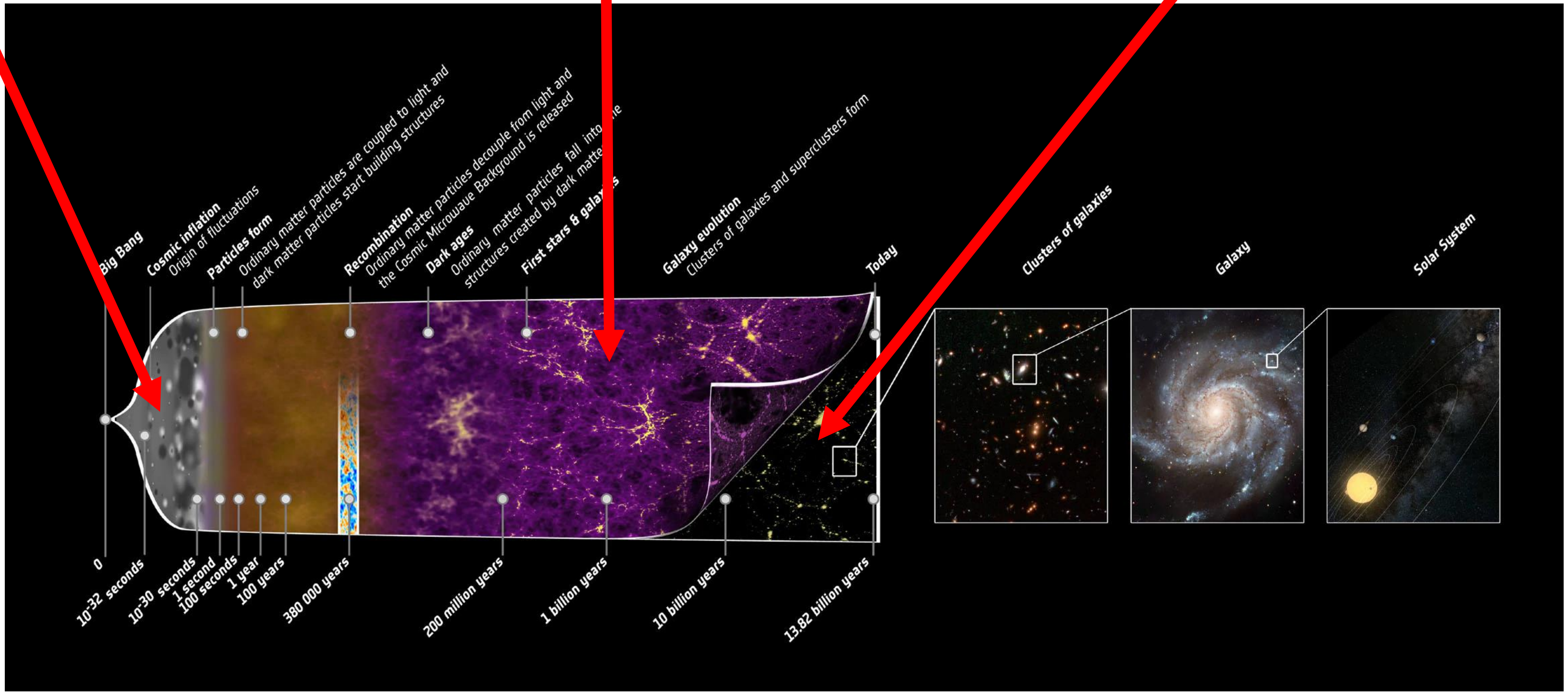


Cosmology: from de Sitter to de Sitter?

Inflation:
A first phase of accelerated expansion

The dark ages: The dark matter era

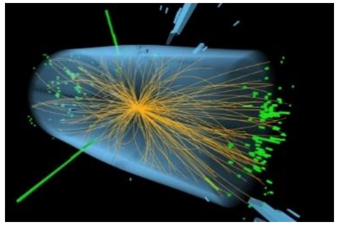
The acceleration epoch:
A second phase of acceleration



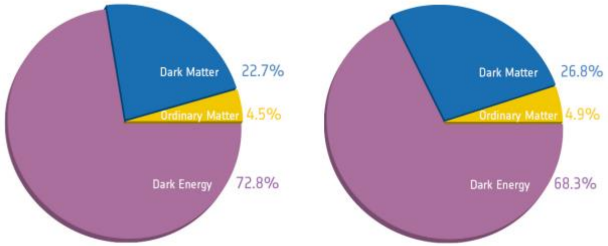
What is the Physics behind these phenomena?

- ***Inflation***: Inflation is close to a de Sitter phase but inflation must end. Cannot be pure vacuum and must be driven by something else.

- ***Dark matter***: For a long time, the best candidates were WIMPS (weakly interacting particles) . Now not so obvious. Looking for alternatives.



- ***Dark energy***: Could be driven by vacuum energy. Nobody knows how to calculate it from first principles. What makes it emerge so late in the Universe?



Before Planck After Planck

The ubiquitous scalar fields

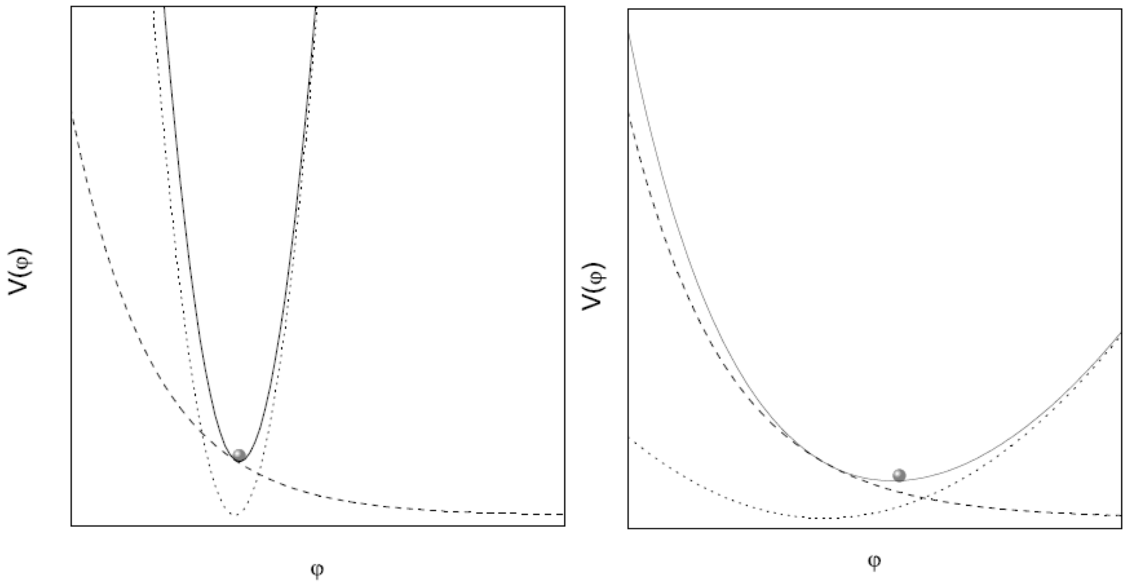
One of the most fundamental observations in cosmology is that ***the Universe is dynamical***, i.e. time dependent.

This realises a breaking of time translation invariance which must be spontaneous, i.e. we always assume that space-time respects local Poincare invariance.

Associated to this breaking is a ***Goldstone mode*** which can be realised as a scalar field.

$$t \to t + \xi(\vec{x}, t)$$

$$t \to t + t_0 \qquad\qquad \xi(\vec{x}, t) \to \xi(\vec{x}, t) - t_0$$



A general framework: ***Scalar-tensor*** *theories*

$$S = \int d^4x \sqrt{-g}\left(\frac{R}{16\pi G_N} - \frac{(\partial\phi)^2}{2} - V(\phi) + \mathcal{L}_m(\psi_i, \tilde{g}_{\mu\nu}\right)$$

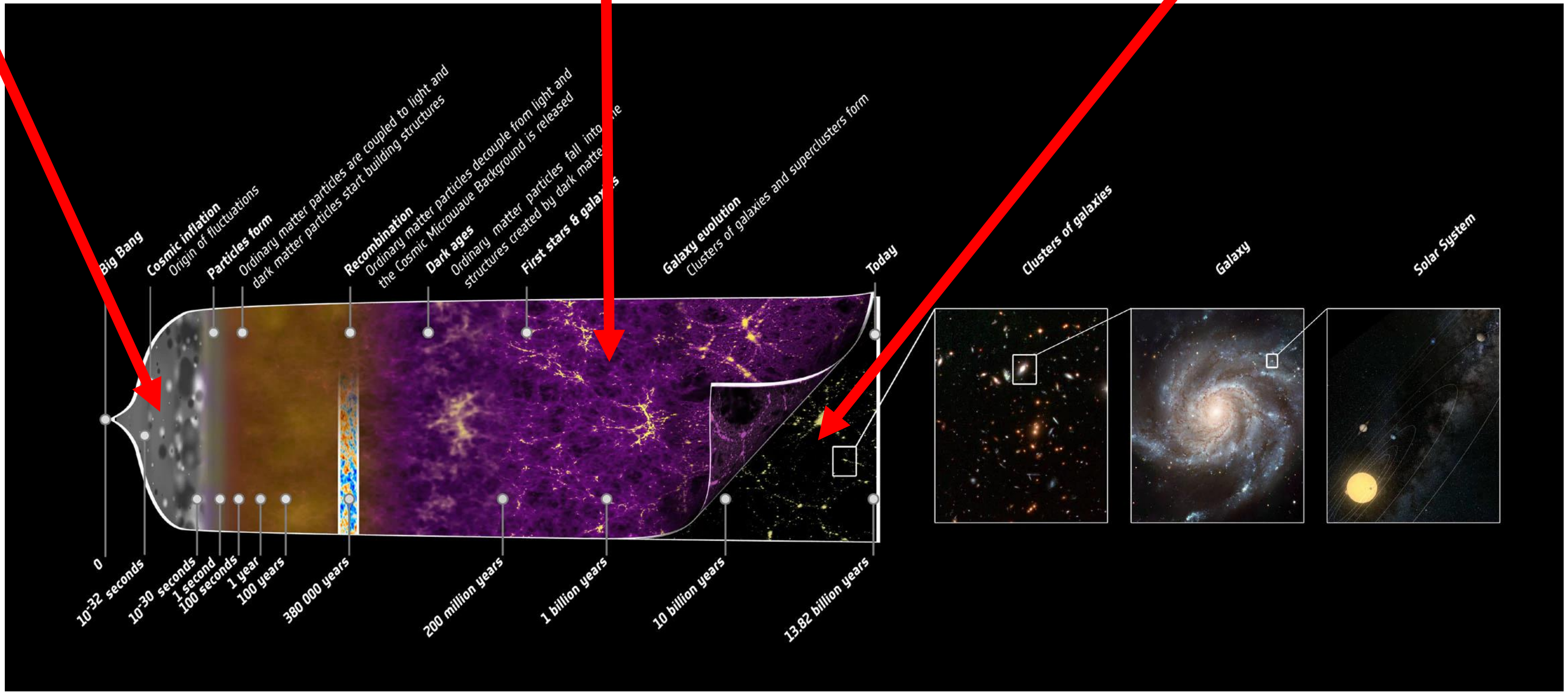
$$\tilde{g}_{\mu\nu} = A^2(\phi, X) g_{\mu\nu} + B^2(\phi, X)\partial_\mu\phi\partial_\nu\phi \qquad X = -\frac{(\partial\phi)^2}{2}$$

Cosmology: a landscape of (scalar) theories?

Inflation:
Primordial scalar field model?

The dark ages: WIMP or scalar dark matter?

The acceleration epoch:
Another scalar coupled to gravity?



INFLATION

Single field inflation is a triumph of effective field theory: all the observations can be described by a few numbers related to the derivative of the potential during inflation.

$$\epsilon = \frac{m_{\rm Pl}^2}{2}\left(\frac{V'}{V}\right)^2, \quad \eta = m_{\rm Pl}^2 \frac{V''}{V}$$

Quantum fluctuations of the inflaton and of the graviton have a power spectrum:

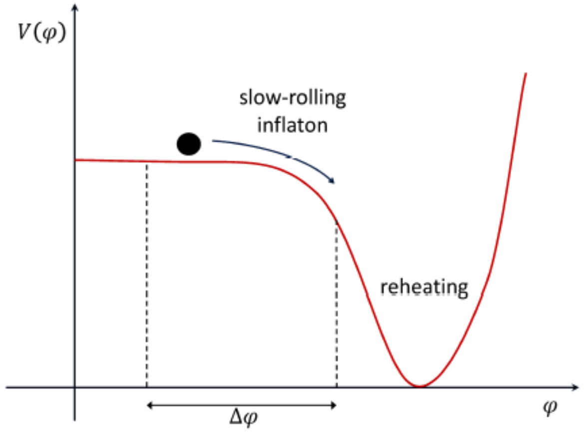
$$\mathcal{P}_\xi = A_s\left(\frac{k}{k_\star}\right)^{n_s-1} \qquad \mathcal{P}_t = A_T\left(\frac{k}{k_\star}\right)^{n_T}$$

The spectral indices are related to the slow roll parameters by:

$$n_s = 1 - 6\epsilon + 2\eta, \quad n_T = -2\epsilon$$

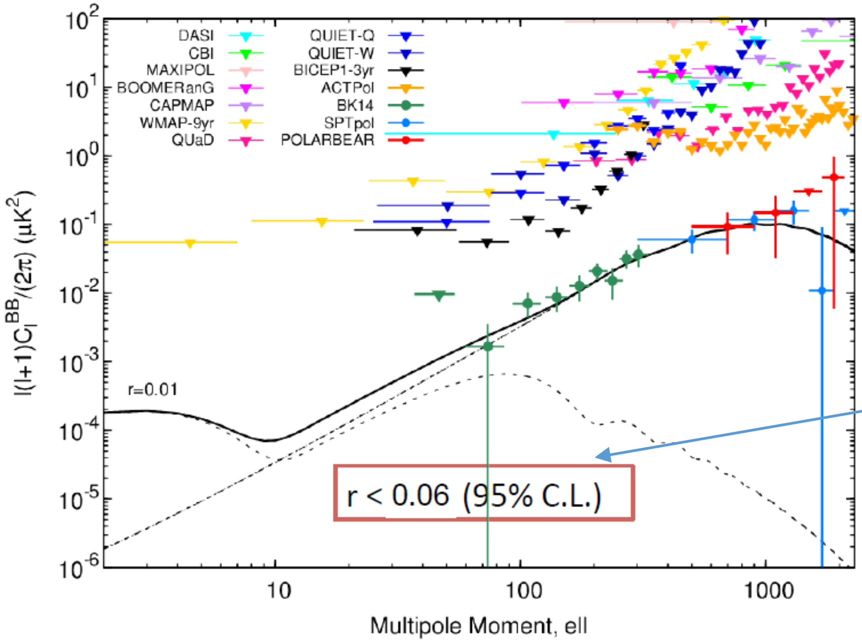
The tensor to scalar ratio is related to the tensor spectral index by the consistency relation:

$$r \equiv \frac{A_T}{A_S} = 16\epsilon = -8n_T$$

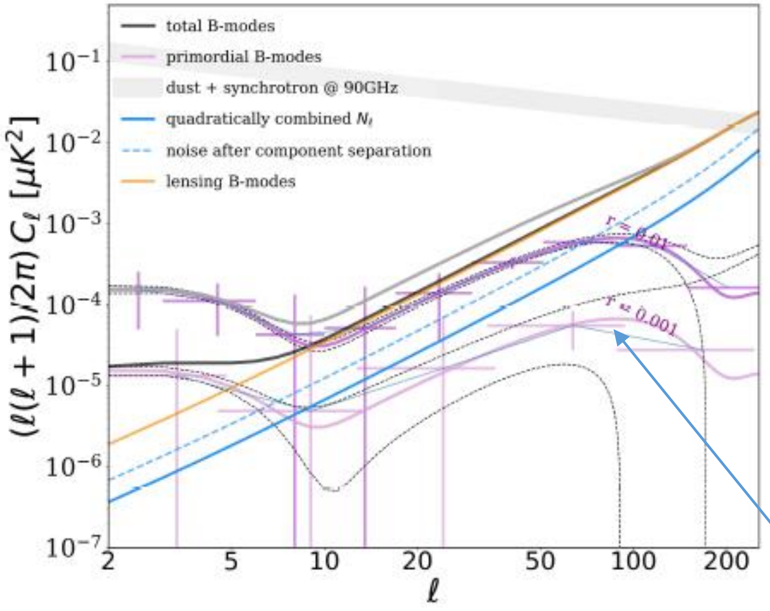


Small field inflationary model

Scalar perturbations already constrained by **Planck**, their tensorial nature is the goal of future experiments such as **Litebird.**



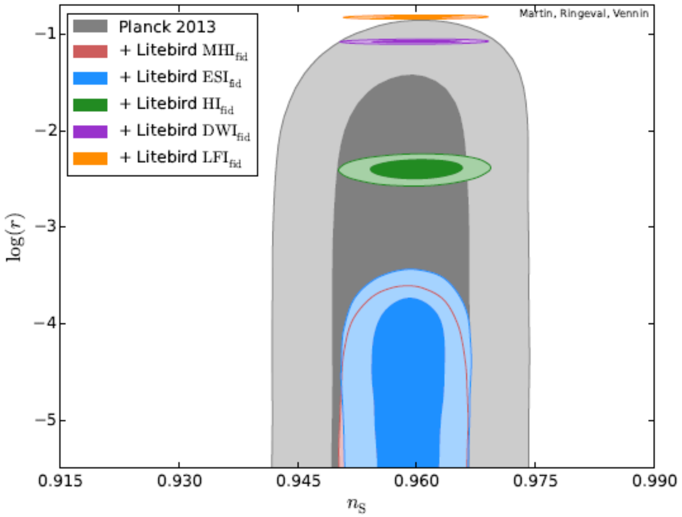
Current constraint



Litebird

Spectra for different values of r

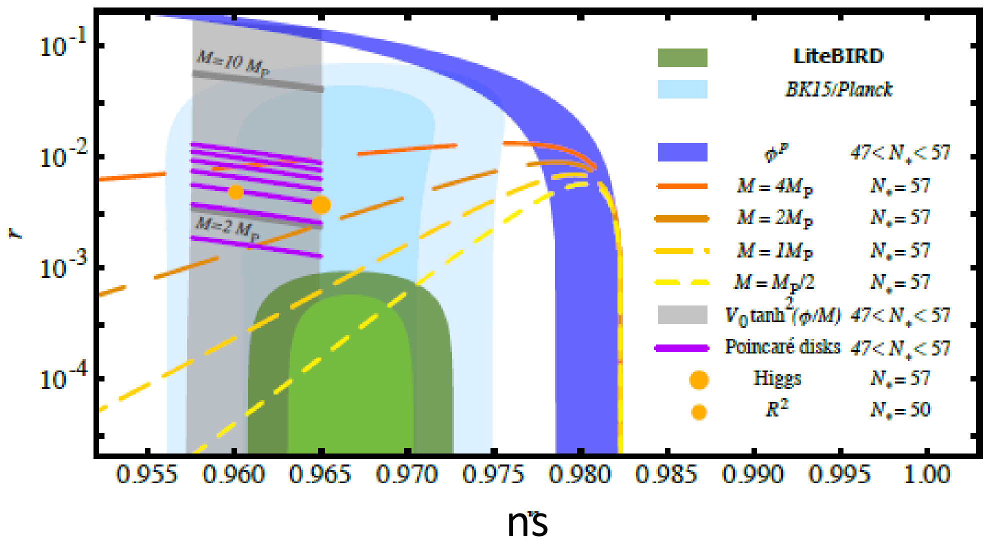
Future missions will analyse the B-modes of the Cosmic Microwave Background (CMB) polarisation whose source is the primordial generation of gravitational waves.



1407.4034

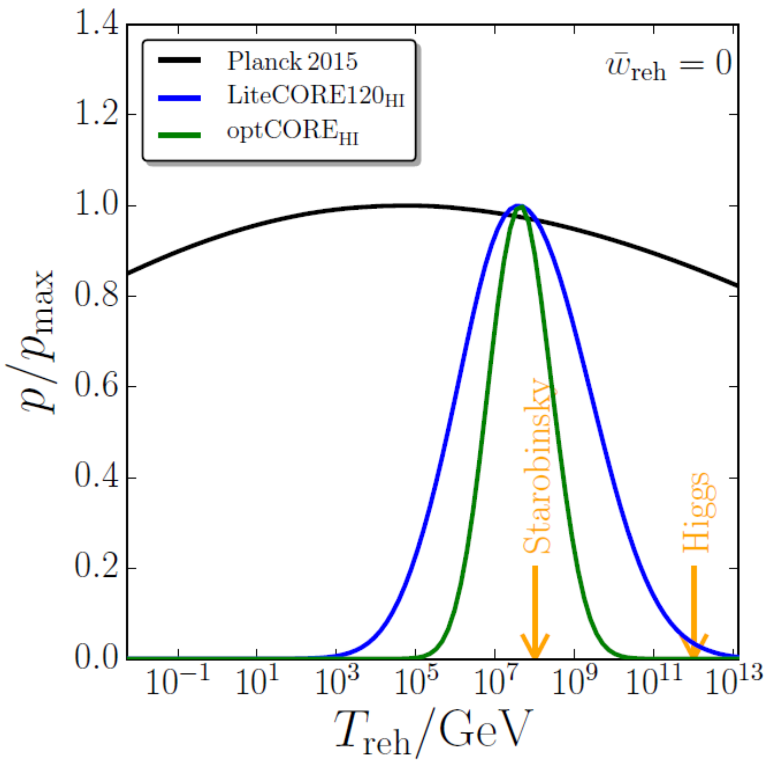
Fiducial model	Potential $V(\phi)/M^4$	Potential parameters
$\mathrm{LFI_{fid}}$	$(\phi/M_{\mathrm{Pl}})^2$	
$\mathrm{DWI_{fid}}$	$\left[(\phi/\phi_0)^2 - 1\right]^2$	$\phi_0/M_{\mathrm{Pl}} = 25$
$\mathrm{HI_{fid}}$	$\left[1 - \exp\left(-\sqrt{2/3}\phi/M_{\mathrm{Pl}}\right)\right]^2$	
$\mathrm{ESI_{fid}}$	$1 - \exp\left(-q\frac{\phi}{M_{\mathrm{Pl}}}\right)$	$q = 8$
$\mathrm{MHI_{fid}}$	$1 - \mathrm{sech}\,(\phi/\mu)$	$\mu/M_{\mathrm{Pl}} = 0.01$

Tight constraints on inflationary models will result



$$n_s = 1 - \frac{2}{N}, \quad r = \frac{12}{N^2}$$

N number of efolding between horizon crossing and the end of inflation



Martin-Vennin

Two natural candidates for the inflaton:

- The Higgs field
- The Universal size of string compactification (Starobinski model)

The analysis of the reheating temperature can also help distinguishing similar models.

They could be ruled out when objective r=0.001 achieved !

$$V(\phi) = V_0(1 - e^{-\sqrt{\frac{2}{3}}\frac{\phi}{m_{Pl}}})^2$$

The ***energy scale of inflation*** will be uncovered and also give access to the *reheating temperature*:

$$V^{1/4} = 6.1\ 10^{15}\ \mathrm{GeV}(\frac{r}{10^{-3}})^{1/2} \rightarrow \quad T_{reh}$$

Depends on the decay modes of the inflaton

$f_{NL} \leq 2(68\%)$ Perfect CMB experiment l<3000 for Polarisation and temperature.

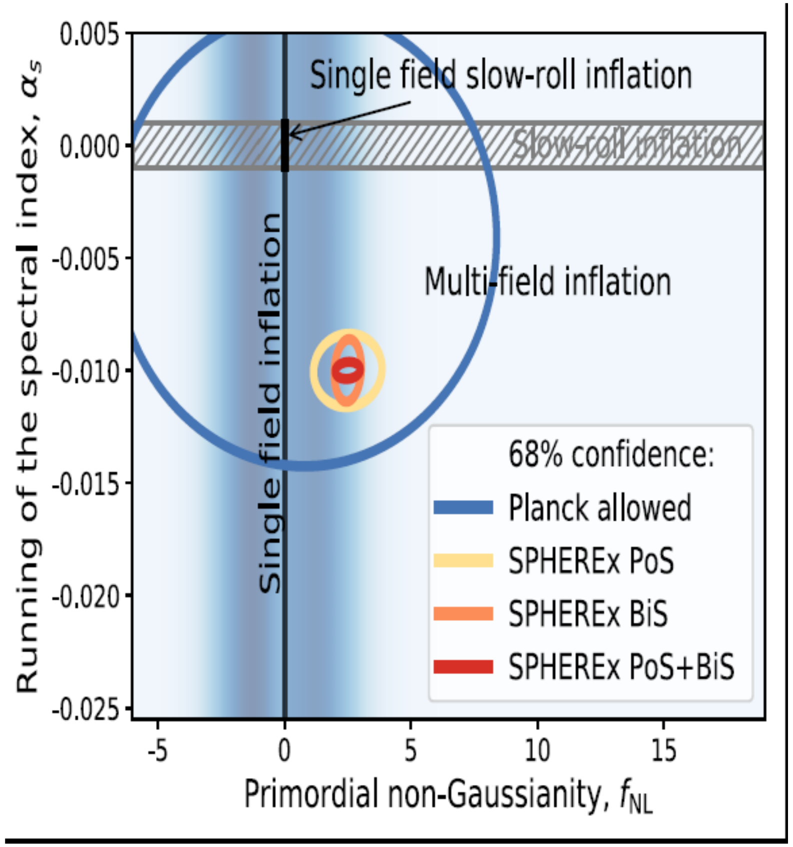
What happens if r is well below 0.001? Inflation could be multi-field.
Future surveys like sphere will discriminate $\Delta f_{NL} \approx 0.5$

$$r = -8n_T \sin^2 \Delta$$

Mixing between the inflaton and other fields.

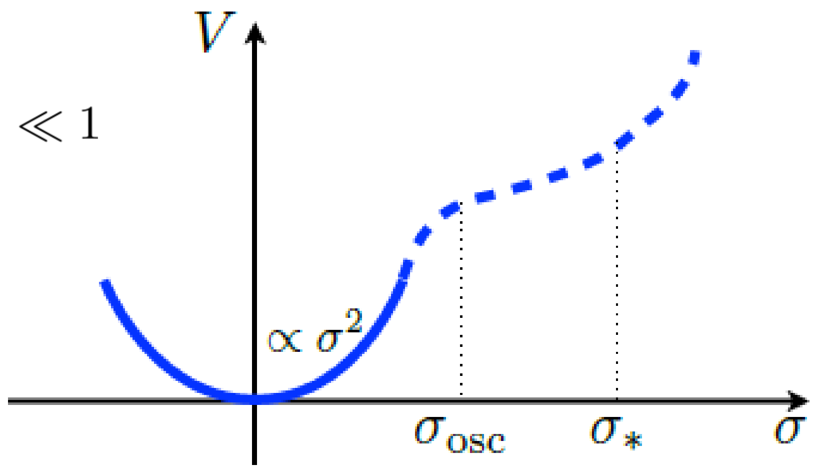
$$\xi = \Phi + f_{NL}\Phi^2$$

Non-Gaussianities



sphereX

Single field: $f_{NL} = \frac{5}{12}(n_s - 1) \ll 1$



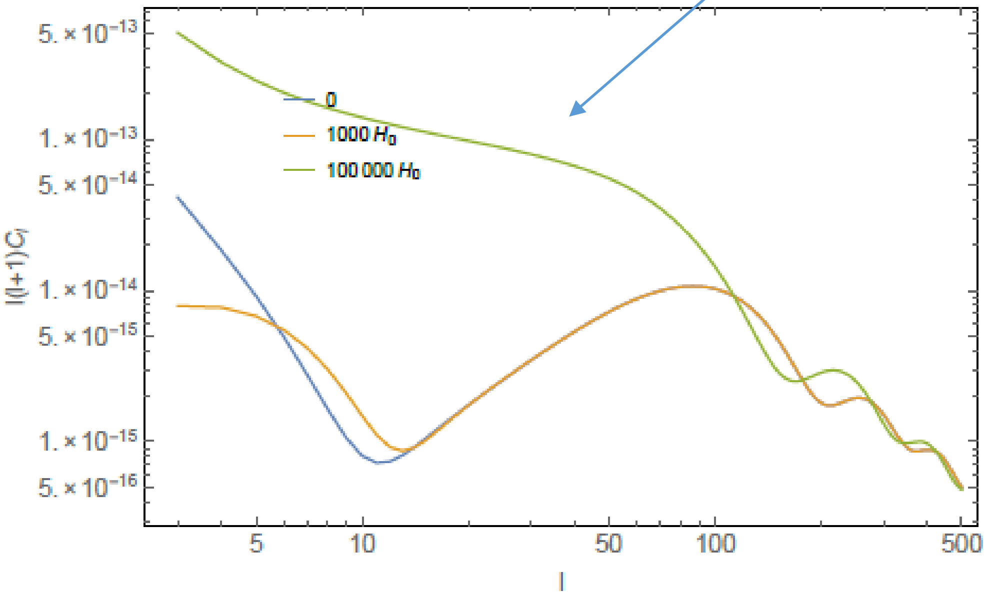
In the curvaton scenario, the inflaton generates the exponential expansion of the Universe whilst the curvaton slow-rolls and generates the primordial fluctuations.

Non-gaussianities feed a scale dependent bias in the galaxy matter spectrum on large scales.

$$f_{NL} = -\frac{5}{4}$$

When curvaton density dominates at the start of oscillations

Low l plateau on the BB spectrum due to a non-vanishing graviton mass.



1710.09818

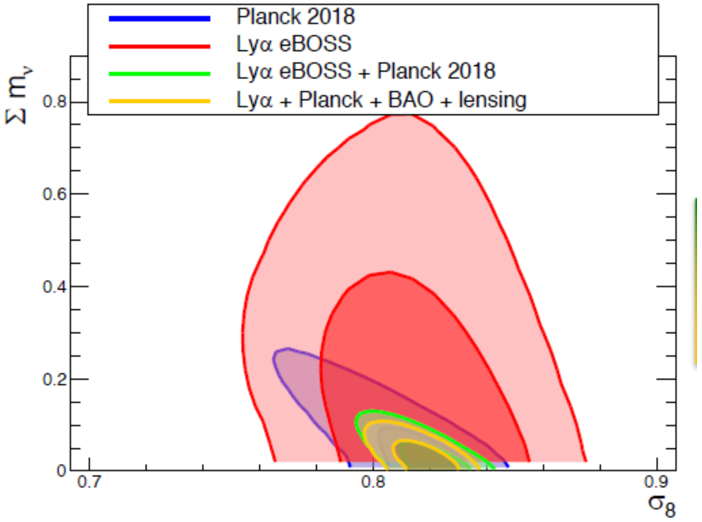
General Relativity could be incomplete and in fact gravitons could have a mass.

$m_g \leq 10^{-22}$ eV → $m_g \leq 10^{-30}$ eV

Current bound

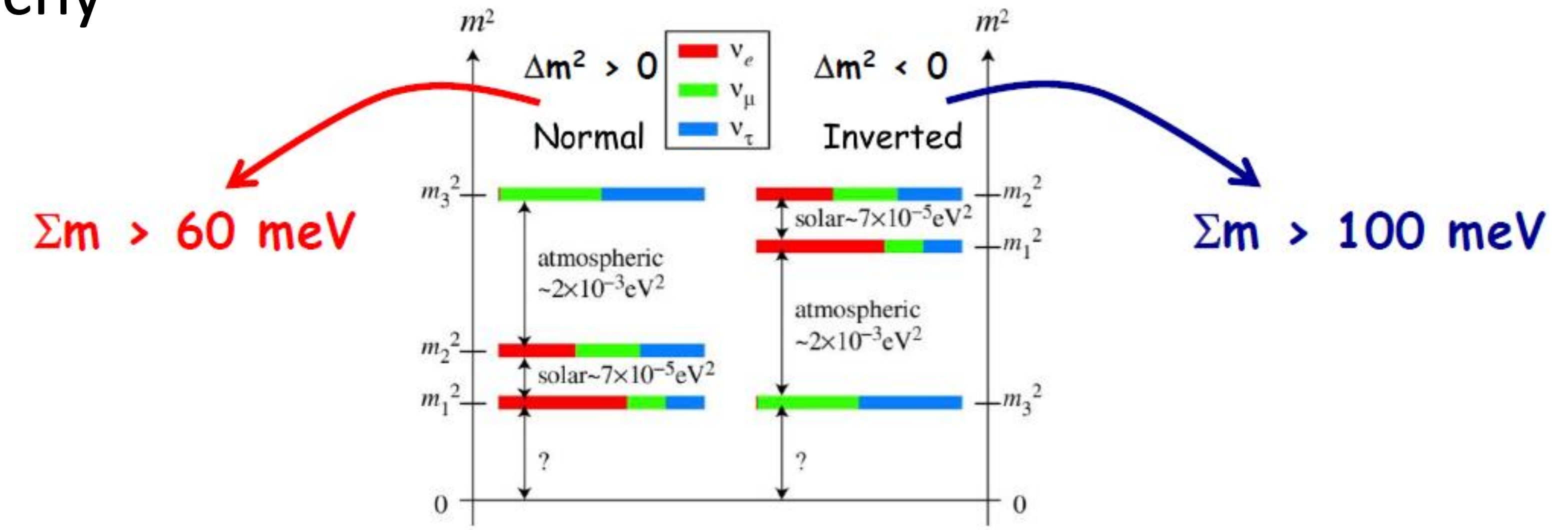
Litebird

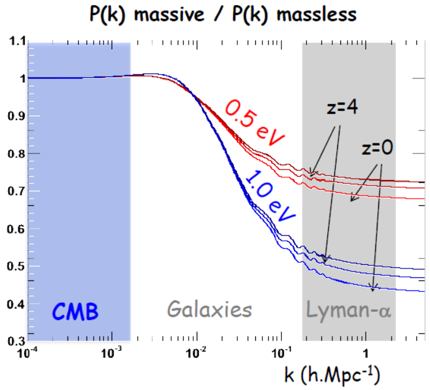
Neutrinos and their hierarchy



$$\sum_\nu m_\nu \leq 0.09 \text{ eV } (95\%)$$

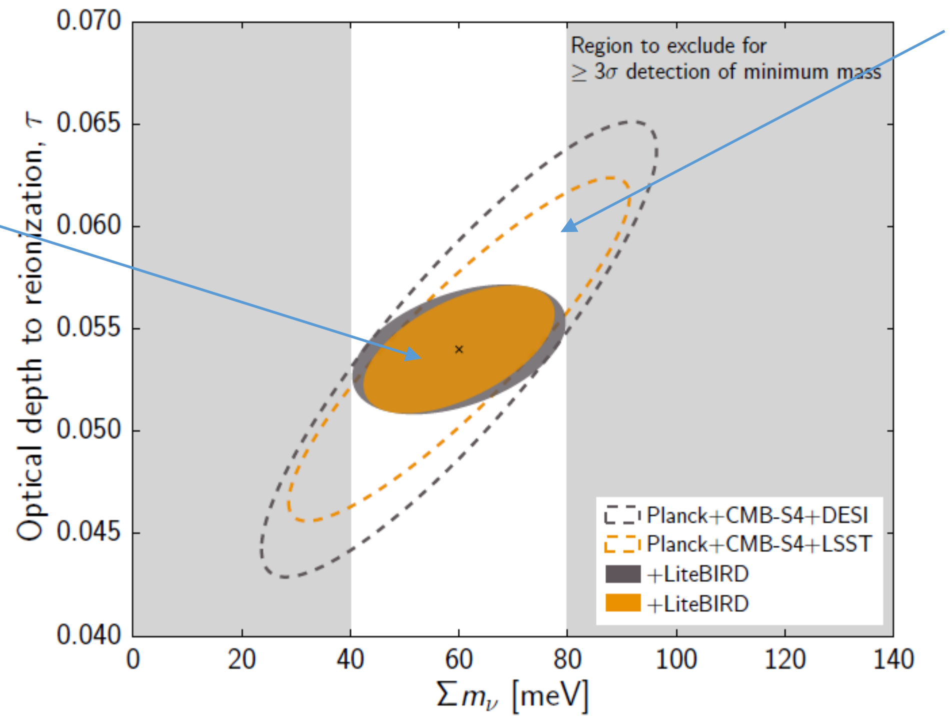
1911.09073





Reduction of power spectrum on small scales by free streaming

Reaching 20 meV uncertainty enough to distinguish between inverted and normal hierarchies



Better measurement of optical depth using EE spectrum

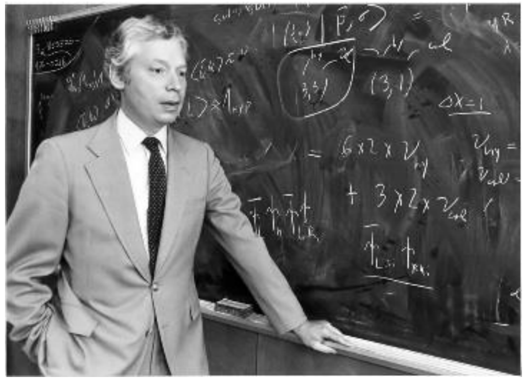
Synergy litebird-large scale structure

DARK ENERGY

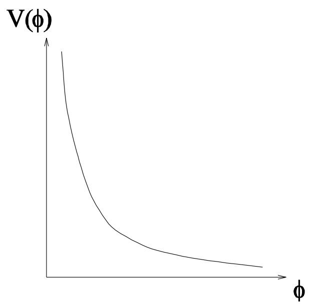
The dark energy scale is in the pico-eV range: apparent fine-tuning compared to standard model scales.

$$\delta\rho_\Lambda = M^4, \quad M \sim 100\mathrm{GeV}$$

Weinberg's theorem states that there is no non-fined tuned vacuum in a 4d quantum field theory respecting **Poincare invariance**.



Dynamical configurations



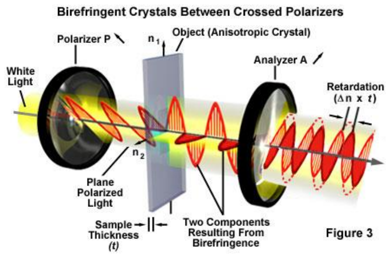
Scalar field rolling down its potential

Dark energy

Modified gravity

5=2+2+1

Massive graviton

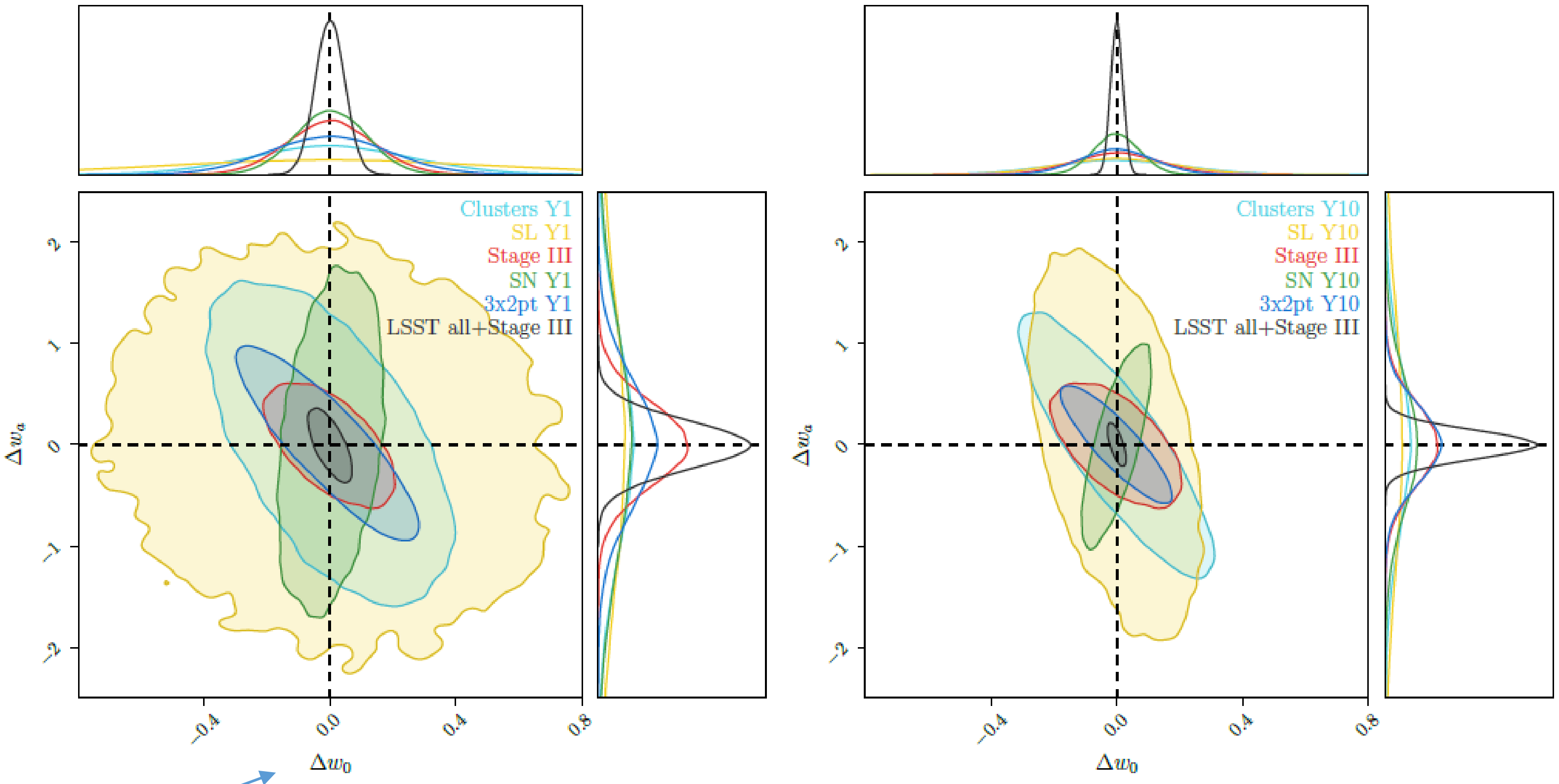


Scalar polarisation: can modify Newton's law and play the role of dark energy

Future large scale galaxy surveys will test the evolution of the ***background cosmology***.

$w = -1$ cosmological constant

$w \neq -1$ *dynamical dark energy*

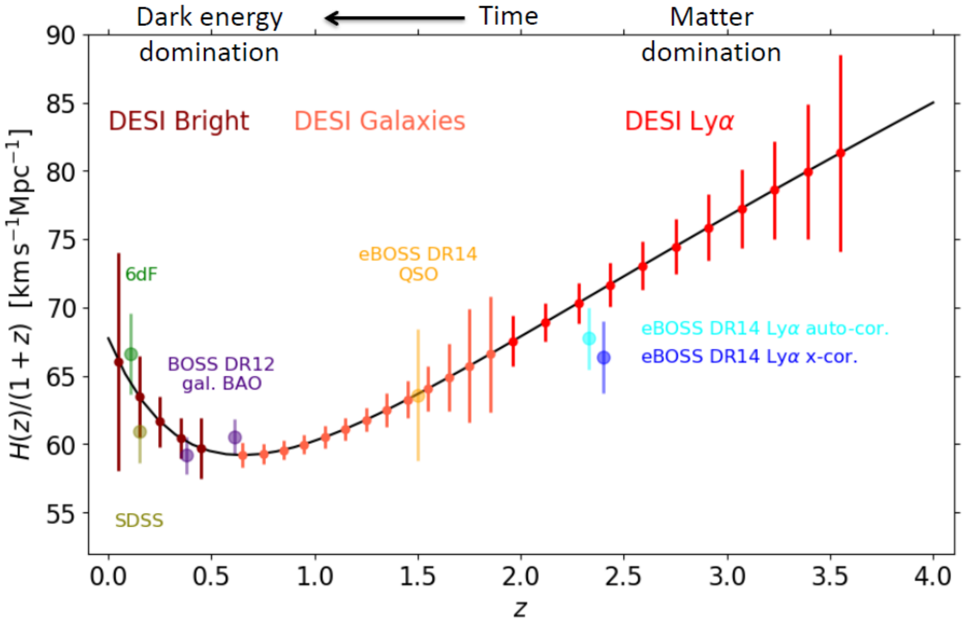


LSST collaboration

$$w = w_0 + w_a(1 - a)$$

2% level

The full redshift dependence of the Hubble rate up to z=3.5 will also be accessible.



Baryon Acoustic Oscillations (BAO)

Desi collaboration

Linked to ***Horndeski***:

$$\mathcal{L} = K(\phi, X) - G_3(\phi, X)D^2\phi + G_4(\phi, X)R + G_{4,X}((D^2\phi)^2 - (D_\mu D_\nu \phi)^2)$$
$$-\frac{1}{6}G_{5X}((D^2\phi)^3 - 3D^2\phi(D_\mu D_\nu\phi)^2 + 2D^\mu D_\alpha \phi D^\alpha D_\beta \phi D^\beta D_\mu \phi)$$

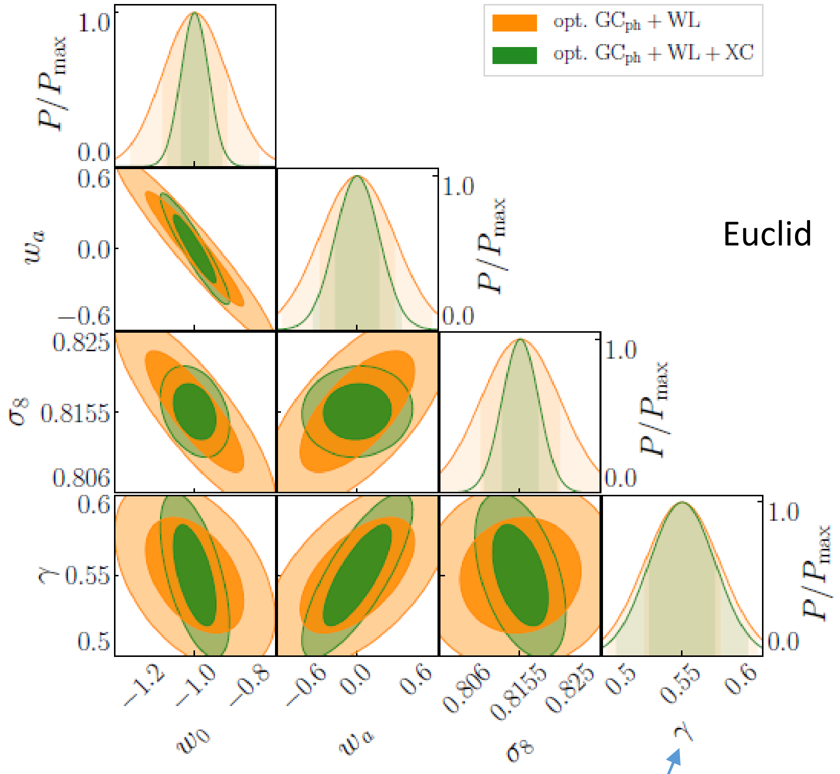
Almost most general scalar-tensor theory leading to dark energy.

The ***growth of structure*** could also be modified:

- Dynamical dark energy compares to L-CDM

$$\ddot{\delta} + 2H\dot{\delta} - \frac{3}{2}\Omega_m H^2 (1+\epsilon)\delta = 0$$

- Newton's constant could be dynamical and scale-dependent.



Euclid

The simplest parameterisation involves three constants, two for the background and one for perturbations.

$$(w_0, w_a), \quad \gamma$$

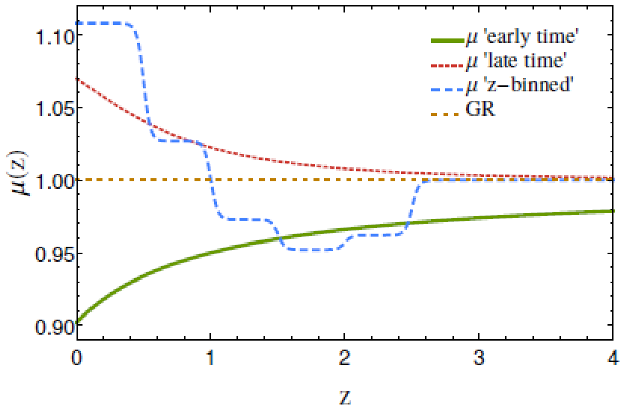
$$f = \frac{d\ln\delta}{d\ln a} \sim \Omega_m^{\gamma}$$

More sophisticated parameterisation of modified gravity: ***two Poisson equations.***

Newton's law

$$\vec{F} = -\vec{\nabla}\Phi$$

$$\Delta\Phi = 4\pi G_N a^2 \mu \rho_m \delta$$



For theories with one extra degree of freedom:

$$\mu(k,z) = \frac{\mu_0(z) + \mu_1(z)k^2}{\mu_2(z) + \mu_3(z)k^2}$$

Here no k dependence

Two ***Newtonian potentials***

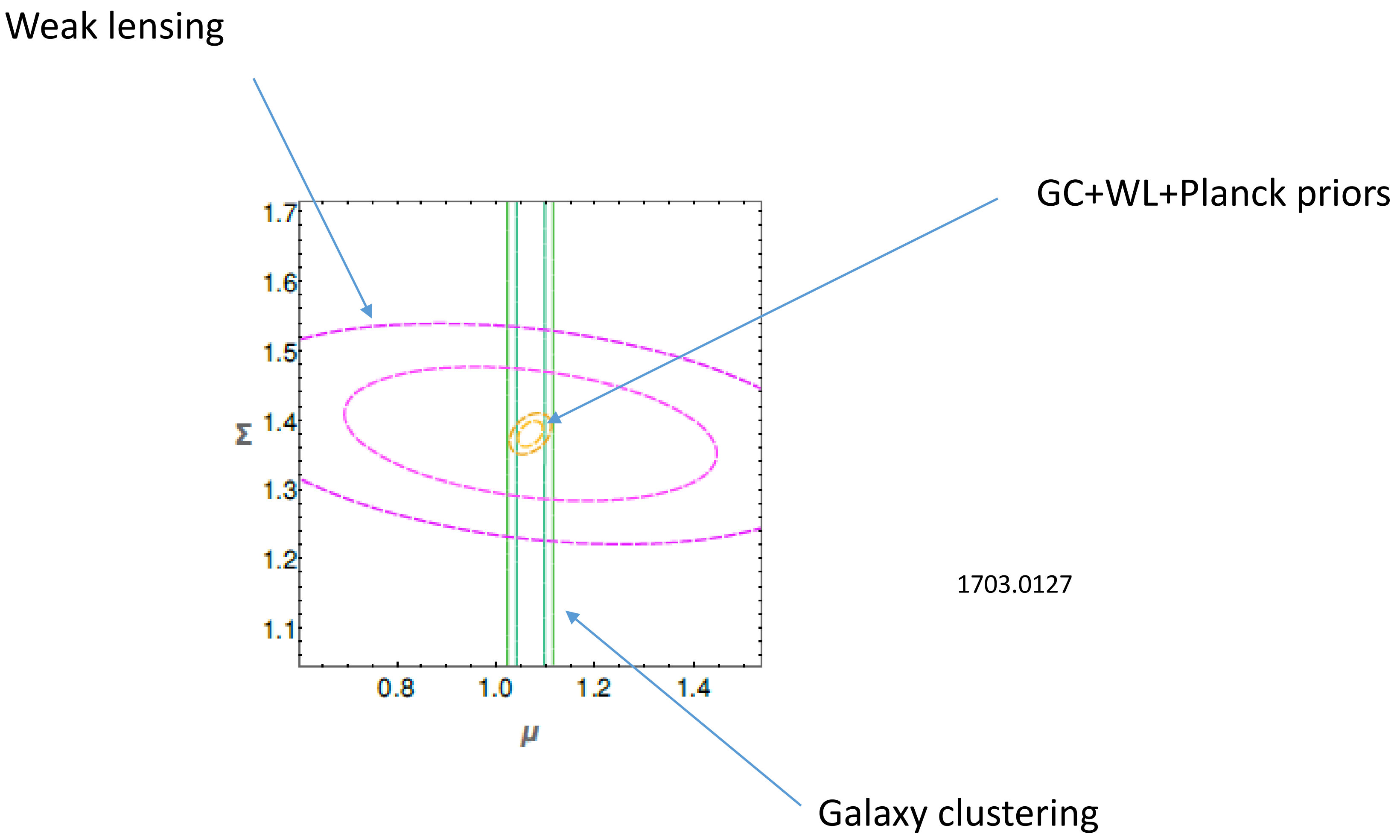
$$ds^2 = -(1+2\Phi)dt^2 + a^2(1-2\Psi)dx^2$$

$$\Phi_L = \frac{\Phi + \Psi}{2}$$

$$\vec{\alpha} = 2\int d\ell\ \vec{\nabla}_\perp \Phi_L$$

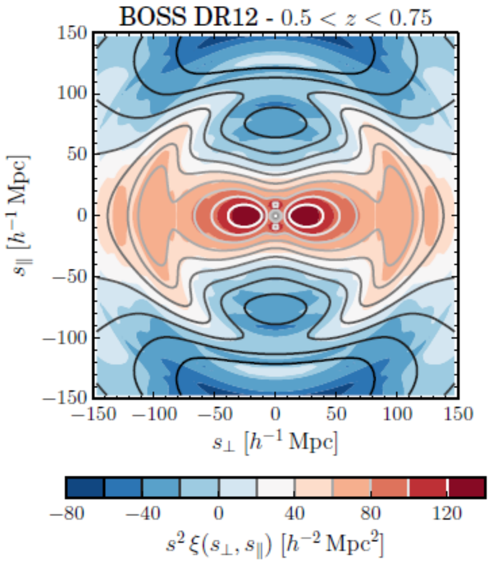
Deviation angle

$$\Delta\Phi_L = 4\pi G_N a^2 \Sigma \rho_m \delta$$


Weak lensing
GC+WL+Planck priors
Galaxy clustering
1.7
1.6
1.5
1.4
1.3
1.2
1.1
Σ
0.8
1.0
1.2
1.4
μ

1703.0127

Redshift Space distorsion will give access to the growth rate:



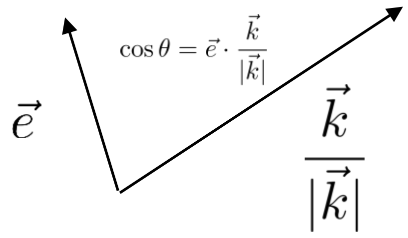
$$\vec{s} = \vec{x} + \frac{\vec{v}.\vec{x}}{H_0|\vec{x}|}\frac{\vec{x}}{|\vec{x}|}$$

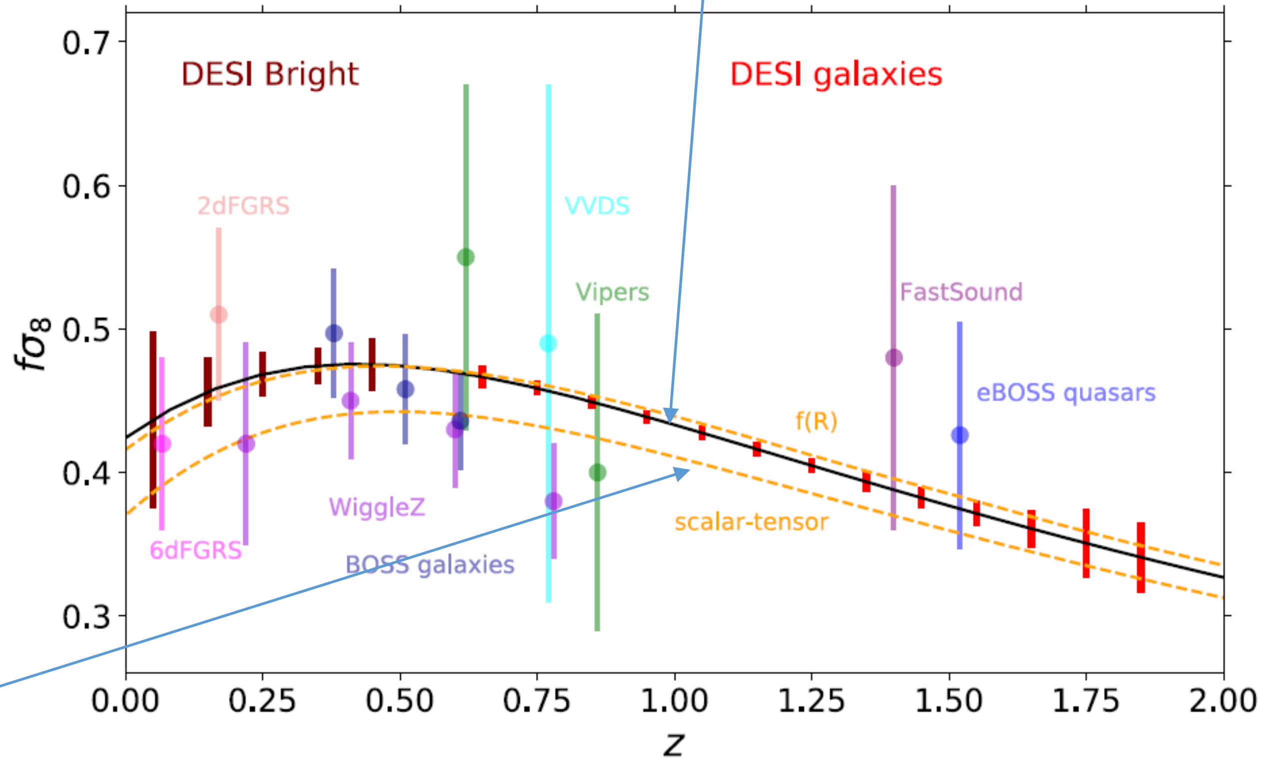
$$z_{\mathrm{obs}} = H_0 x + \frac{\vec{x}}{|\vec{x}|}.\vec{v}$$

Peculiar velocities

LCDM

$$\mathcal{P}_g \propto (1 + f\cos^2\theta)\mathcal{P}_{DM}$$



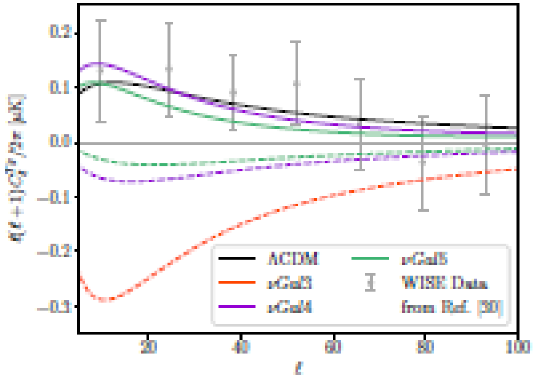


Constraint on some scalar-tensor models.

Desi collaboration

Gravitational Waves

Gravitational waves have already had a dramatic impact on dark energy models!



GW1708017: $|c_g^2 - 1| \leq 10^{-15}$

Simplest cases excluded cosmologically

$$\mathcal{L} = K(\phi, X) - G_3(\phi, X)D^2\phi + G_4(\phi, X)R + G_{4,X}((D^2\phi)^2 - (D_\mu D_\nu \phi)^2)$$
$$-\frac{1}{6}G_{5X}((D^2\phi)^3 - 3D^2\phi(D_\mu D_\nu\phi)^2 + 2D^\mu D_\alpha \phi D^\alpha D_\beta \phi D^\beta D_\mu \phi)$$

*The Great Massacre**

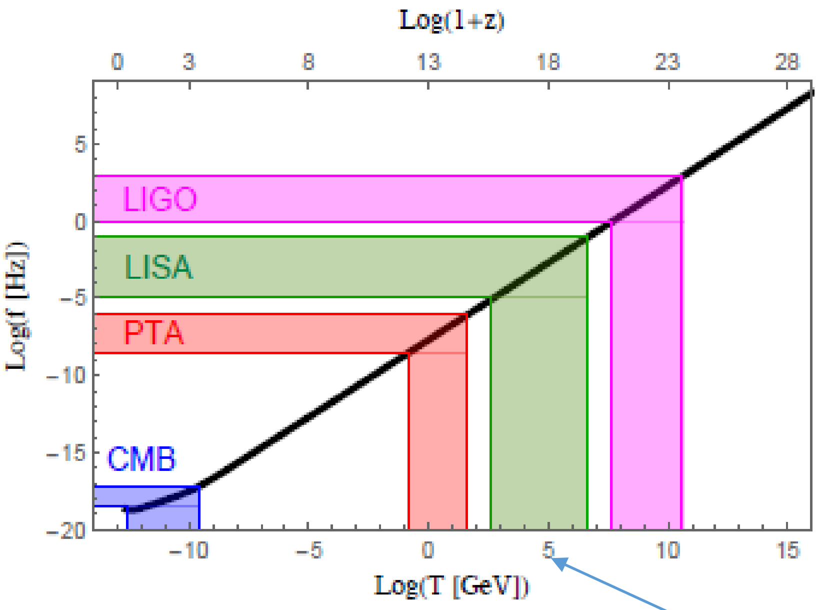
* Certain DHOST theories are unscathed

Distances (luminosity) will be tested up to a redshift of order 10: ***standard sirens.***

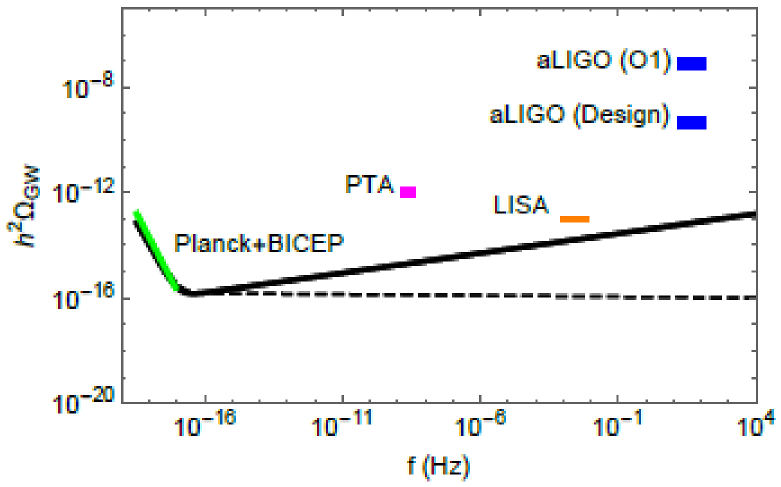
$$h_{GW} \propto \frac{1}{d_L(z)}$$

In addition, we investigate the measurement precision of cosmological parameters as a function of the number of observed LISA MBHB standard sirens, finding that 15 events will on average achieve a relative precision of 5% for H0, reducing to 3% and 2% with 25 and 40 events, respectively.

2010.09049



C. Caprini



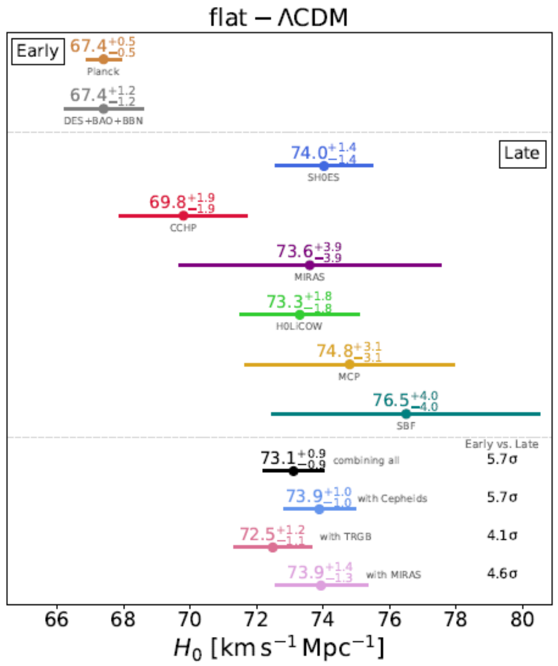
Would require a large and positive tensor spectra index.

Gravitational wave experiments will test high energy physics

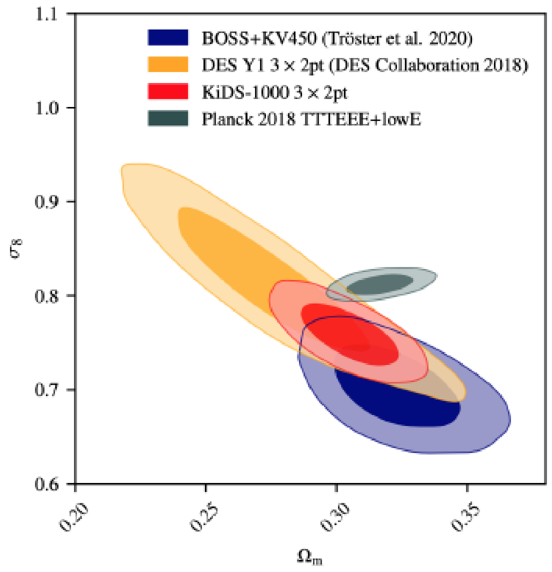
Typically not sensitive enough to the stochastic gravitational background from inflation. Need enhancement…

Cosmic strings? Phase transitions?

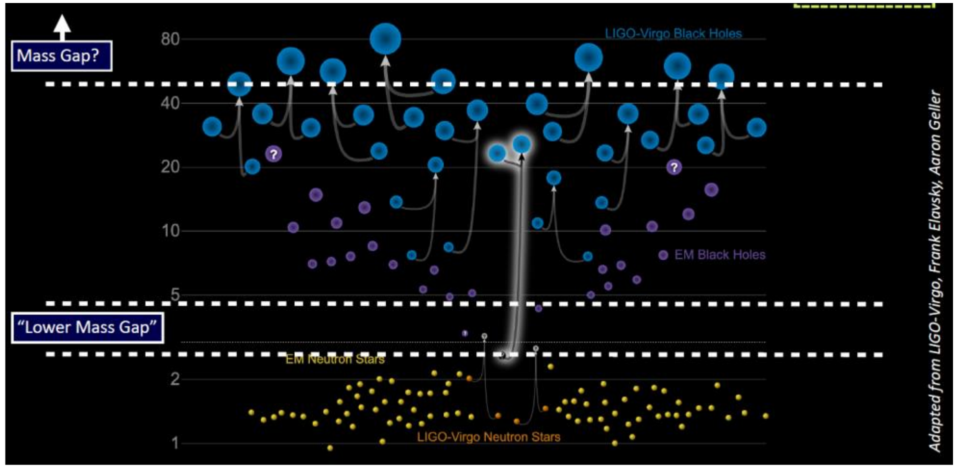
Is the future now?



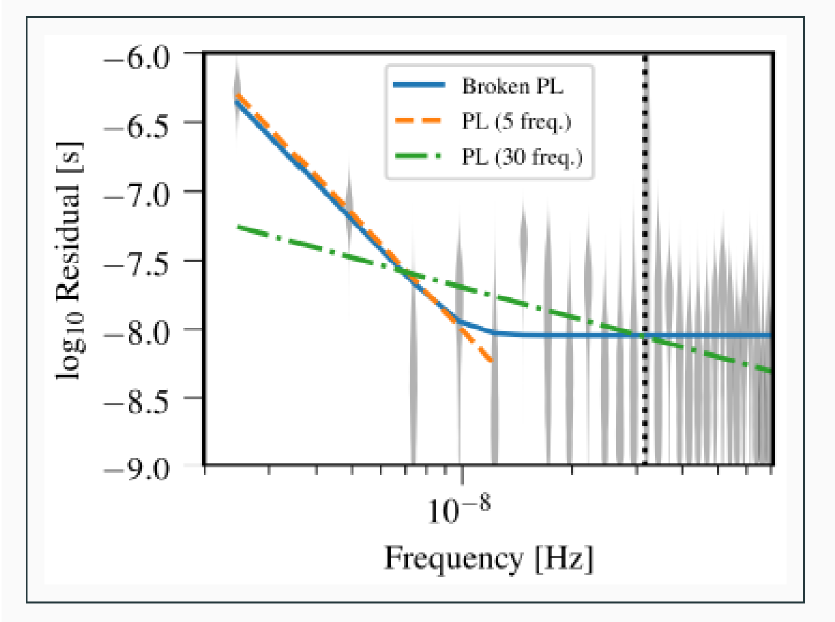
The local and cosmological Hubble constants differ: why?
A sign of early dark energy or time dependent Newton constant?



Planck and weak lensing experiments do not measure the same amount of matter. Could it be resolved in a dynamical background?



Recent observations of ***Black Holes in the mass gap***: a modification of gravity with an environmental Newton constant ?



Residual ***stochastic background*** measured by Nanograv: cosmic strings, primordial Black Holes, phase transitions?

Conclusions

In the next decade large scale galaxy survey, CMB and gravitational wave experiments should give indications on:

- Is inflation single-field? What is the energy scale of inflation?
- Is the Higgs field responsible for inflation?
- How much do neutrinos weigh?
- Is dark energy dynamical? Is there a modification of General Relativity at large scale?

They could also shed light on the current puzzles: the H0 tension etc…