Cosmology at the Crossroads: Puzzles and Perspectives

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Introduction

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- Dark matter ?

- Dark energy?

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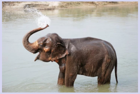

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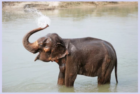

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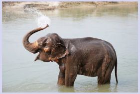

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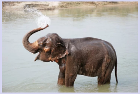

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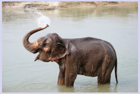

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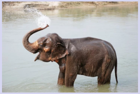

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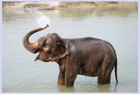

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- Gravitational waves, the scale of inflation ?

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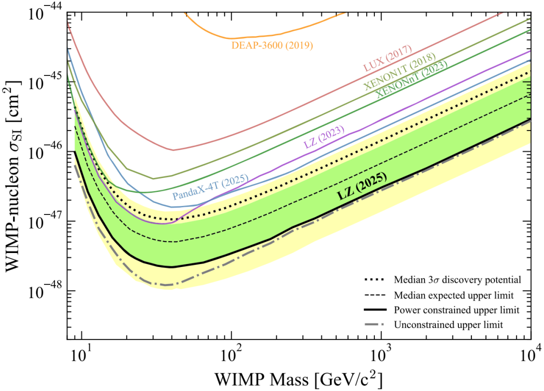

LUX-ZEPLIN coll. (2025)

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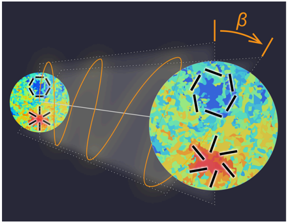

$\beta = 0.341 \pm 0.094$
Eskilt & Komatsu 2022

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- How is it interacting with ordinary matter or with dark energy (apart from gravity) ?

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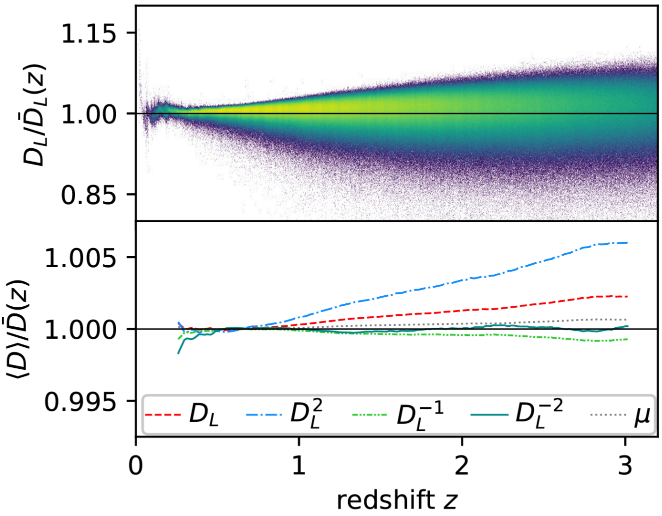
- How important is clustering of dark energy?
- What about the coincidence problem? Backreaction?

Clustering does not affect the distance redshift relation significantly



(From Adamek et al. 1812.04336)

More puzzles

But there are also other important wide open questions:

- What is the physics of reheating? Does it lead to observational relicts?
- How does the baryon asymmetry originate?
- Phase transitions
- Cosmic magnetic fields
- Gravitational wave background, is the pulsar timing array signal cosmological?
- How can we observe the neutrino background ?
- Galaxy formation

Reheating

On large cosmological scales ($>$ Mpc) reheating can probably be regarded as instantaneous and fluctuations from inflation can simply be matched to the radiation era by requiring continuity of the metric and the extrinsic curvature (Israel junction conditions, Deruelle & Mukhanov, 1995)

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- This depends on the detailed model of reheating $\Rightarrow$ Contains information on very high energy physics.
- If reheating is accompanied by a first order phase transition it can lead to a very high frequency gravitation wave background.
- During a phase of extremely slow roll, fluctuations are strongly amplified, these may lead to the formation of primordial black holes and via 2nd order fluctuations to a GW background.

Reheating: Some numbers

$H_{inf}^{-1} \simeq M_P/E_{inf}^2 \sim$ the smallest scale on which quantum fluctuations are amplified.
This scale has grown by today to about $M_P/E_{inf}^2(T_{\rm reheat}/T_0)$.

It is useful to put in some numbers:

$10^{16}\text{GeV} \sim (0.2 \times 10^{-29}\text{cm})^{-1}$. [1=200MeV fm]

The scale H_{inf}^{-1} redshifted to today is about

$$H_{inf}^{-1}\frac{a_0}{a_{\rm reheat}} \simeq 10^2{\rm cm}\left(\frac{10^{16}{\rm GeV}}{E_{inf}}\right)^2\frac{T_{\rm reheat}}{10^{16}{\rm GeV}}$$
$$\simeq 10^{18}{\rm cm}\left(\frac{1{\rm GeV}}{E_{inf}}\right)^2\frac{T_{\rm reheat}}{1{\rm GeV}} \simeq 0.3{\rm pc}\left(\frac{1{\rm GeV}}{E_{inf}}\right)^2\frac{T_{\rm reheat}}{1{\rm GeV}}\,.$$

In most models of inflation this scale is irrelevant for LSS.
But is may determine the frequency of GWs or primordial black holes generated during reheating.

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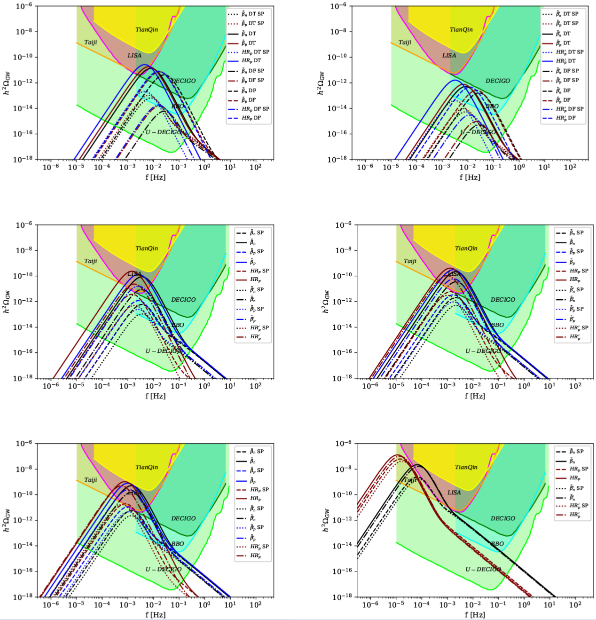
  - A slight enhancement of the parity violating terms can lead to chiral magnetic fields and baryon asymmetry (both are related the the Chern-Simons number of the electroweak sector).
  - The bubbles, the turbulent plasma and the magnetic fields generate (chiral) gravitational waves.

Gravitational waves from phase transitions



From
Wang, Huang & Zhang
2003.08892

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- But these fields are not expected to be transported out into the voids by MHD processes.

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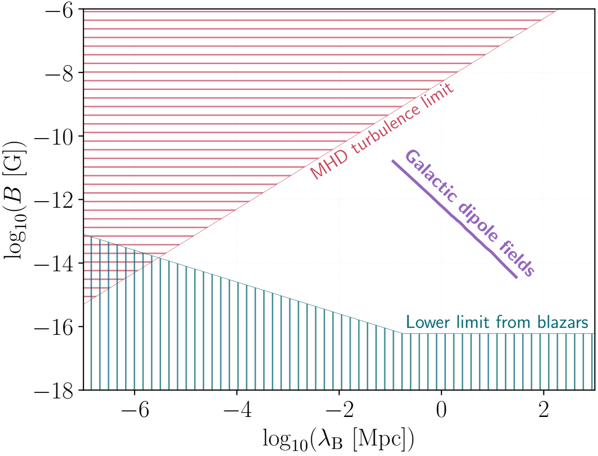

From
Garg, RD, Schober
2505.14774

Stochastic GW backgound

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- Also 2nd order scalar perturbations generate GWs

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STOCHASTIC BACKGROUND SOURCES AND DETECTOR SENSITIVITIES

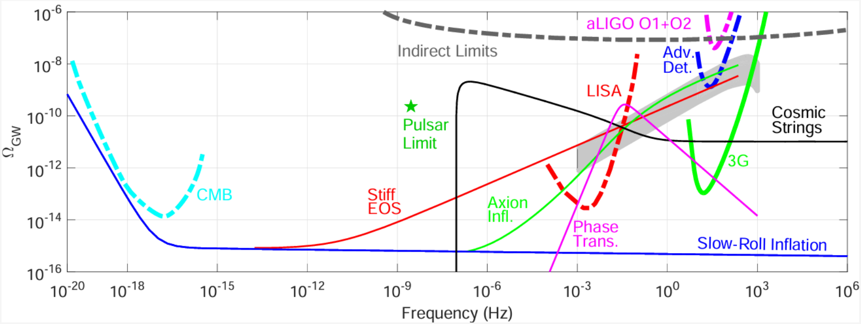

Figure 4.2: Stochastic GW background for several proposed model spectra in comparison with past measurements (Advanced LIGO upper limit [249], constraints based on the big bang nucleosynthesis and cosmic microwave background (CMB) observations, low-l CMB observations, and pulsar timing [250]), and future expected sensitivities [251], (the final sensitivity of Advanced LIGO [252], Cosmic Explorer [90], and LISA, all assuming 1 year of exposure [253, 254]). The gray band denotes the expected amplitude of the background due to the cosmic population of compact binary mergers, based on the observed coalescieng binary systems [255].

(From Kalogera et al. 2111.06990)

Neutrinos : Have we already detected the cosmic neutrino background?

- Number of relativistic degrees of freedom after $e^{\pm}$ annihilation. $N_{\rm eff} = 2.99 \pm 0.34$ (from Planck 1807.06209) is in perfect agreement with the theoretically expected value for 1 photon and 3 species of neutrinos, $N_{\rm eff} = 3.044$.

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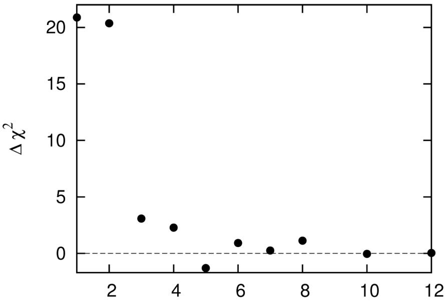

$\Delta\chi^2$ as a function of $\ell_{\rm max}^{(\nu)}$

(From Sellentin & RD. 1412.6427 using Planck 2013 data)

Galaxy formation

- Can we learn e.g. about dark matter from galaxy formation ?
- Are the high z galaxies discovered with JWST a problem for ΛCDM ?
- If there are galaxies at $z > 13$ why did reionization only happen at $z \simeq 6$?
- When did the large central BHs in galaxies form ?

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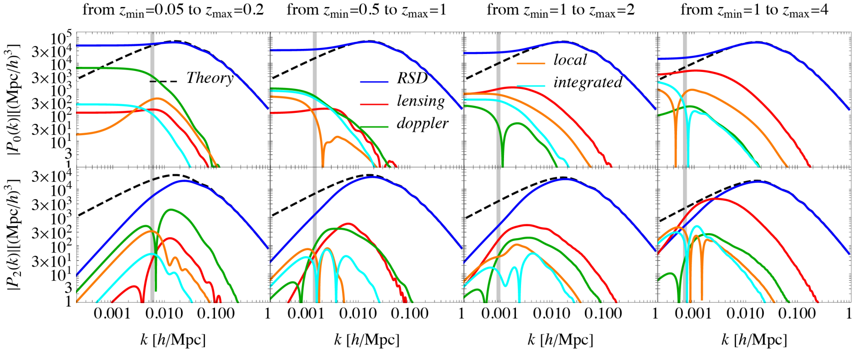
- Observations are made on our background lightcone.
- We cannot observe a $\{t = \text{const.}\}$ hypersurface and therefore not a power spectrum (i.e. Fourier transform of a spatial correlation function).
- For small scales this is irrelevant but the more we go to cosmological scales the more it becomes important.



(From Castorina & Di Dio 2106.08857, using the Yamamoto estimator for $P(k)$)

Weak lensing

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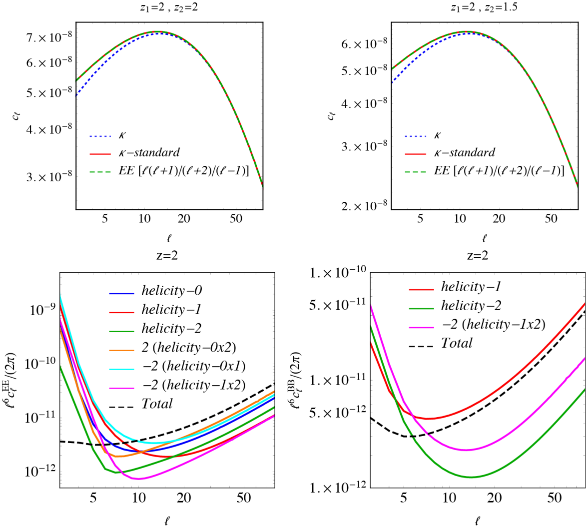
Differences

- At first order in perturbation theory there is no rotation.
- The B-component of shear and the rotation have different spectra
- Convergence and the E-component of shear have different spectra (on large scales).

Weak lensing



scalar pert.

tensor pert.
(r=0.1)

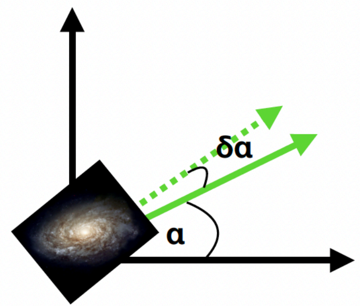
(From Fanizza, Di Dio, RD & Marozzi 2201.11552)

Measuring shear via galaxy rotation

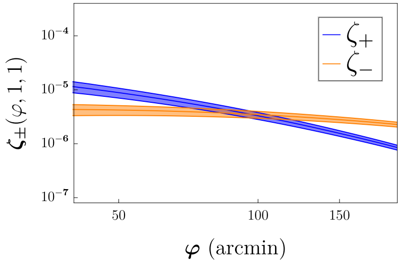
Galaxies are usually quite elliptical.
If you shear an ellipse whose principle axes are not aligned with the principle axes of the shear map, this induces not only a change in the ellipticity but also a rotation.
With respect to arbitrary parallel transported axes $(\mathbf{e}_1, \mathbf{e}_2)$, shear rotates the original orientation α of, say, the semi-major axis into $\alpha + \delta\alpha$ where (at first order in γ)

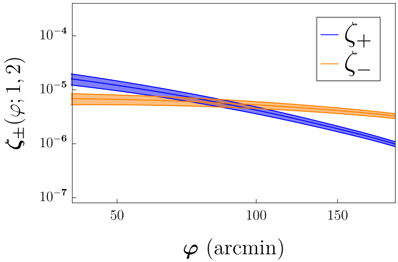
$$\delta\alpha = \frac{\varepsilon^2}{2 - \varepsilon^2} \left(\gamma_2 \cos 2\alpha - \gamma_1 \sin 2\alpha\right) .$$

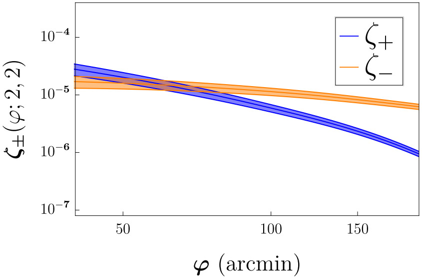
Here $0 \leq \varepsilon \leq 1$ is the ellipticity of the galaxy. (Note that $\delta\alpha = 0$ if the principle axes are aligned, i.e. $\alpha = 0$ (or π) and $\gamma_2 = 0$ or $\alpha = \pi/4$ (or $5\pi/4$) and $\gamma_1 = 0$.)



Results with SKA 2







$SNR \sim 45$
For a conservative SNR
of 10^{-3} per galaxy.

J. Francfort, RD, & G. Cusin (2022)

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- Apart from the '3 elephants' there are reheating, baryon asymmetry, stochastic GW background, cosmic magnetic fields and more.
- We must be careful when analysing our observations. Better observations need more care concerning systematics and theoretical analysis
- It is important to develop new, independent cosmological observables that have different systematics.