Modern Cosmology : Puzzles and Thoughts

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COSMOFondue

Introduction

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- How does inflation work ?

- Dark matter ?

- Dark energy?

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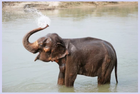

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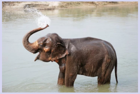

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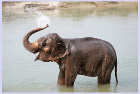

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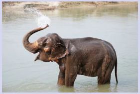

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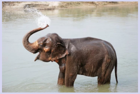

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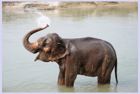

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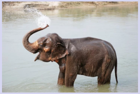

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- Gravitational waves, the scale of inflation ?

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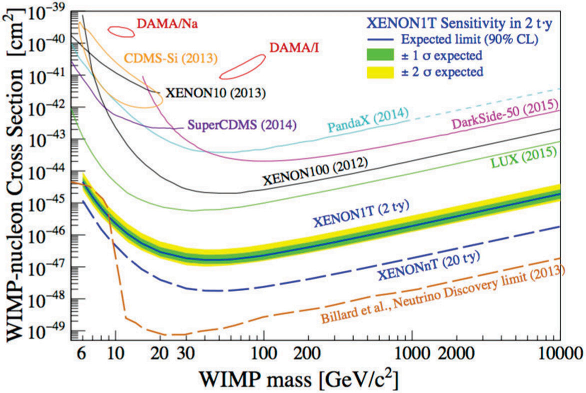

XENON1T collab. (2016)

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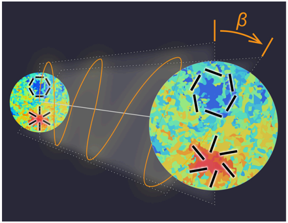

$\beta = 0.341 \pm 0.094$
Eskilt & Komatsu 2022

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

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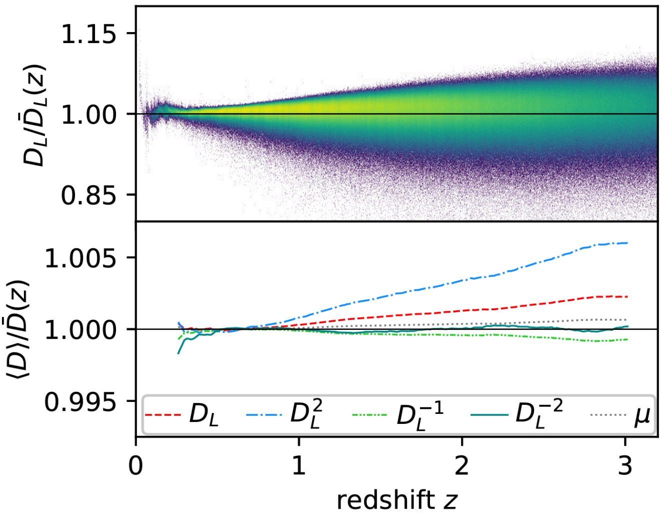
- What about the coincidence problem

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?
- Baryon asymmetry?
- 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 intrinsic curvature (Israel junction conditions, Deruelle & Mukhanov, 1995)

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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 to about $M_P/E_{inf}^2(T_r/T_0)$ by today.
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

$$
\begin{aligned}
H_{inf}^{-1}\frac{a_0}{a_r} &\simeq 10\mathrm{cm}\left(\frac{10^{16}\mathrm{GeV}}{E_{inf}}\right)^2\frac{T_r}{10^{16}\mathrm{GeV}} \\
&\simeq 10^{16}\mathrm{cm}\left(\frac{1\mathrm{GeV}}{E_{inf}}\right)^2\frac{T_r}{1\mathrm{GeV}} \simeq 0.001\mathrm{pc}\left(\frac{1\mathrm{GeV}}{E_{inf}}\right)^2\frac{T_r}{1\mathrm{GeV}}\,.
\end{aligned}
$$

In most models of inflation this scale is irrelevant for LSS.

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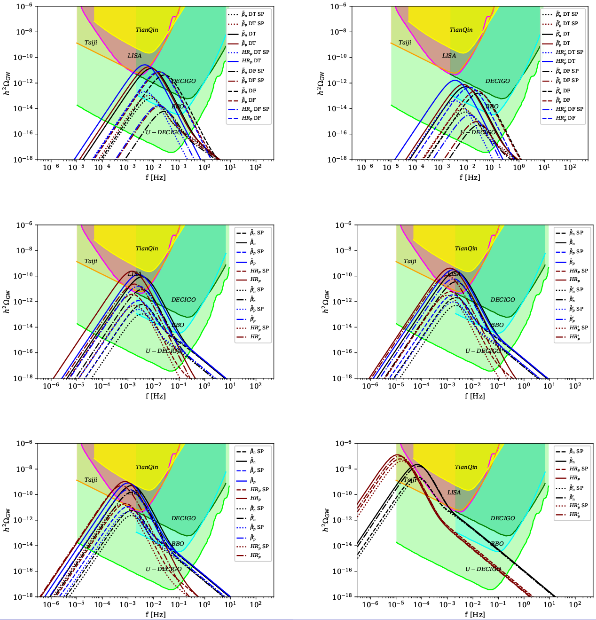
  - The bubbles, the turbulent plasma and the magnetic fields generate (chiral) gravitational waves.



From
Wang, Huang & Zhang
2003.08892

Cosmic magnetic fields

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- Could a dipole component in these fields generate the requested fields in voids?

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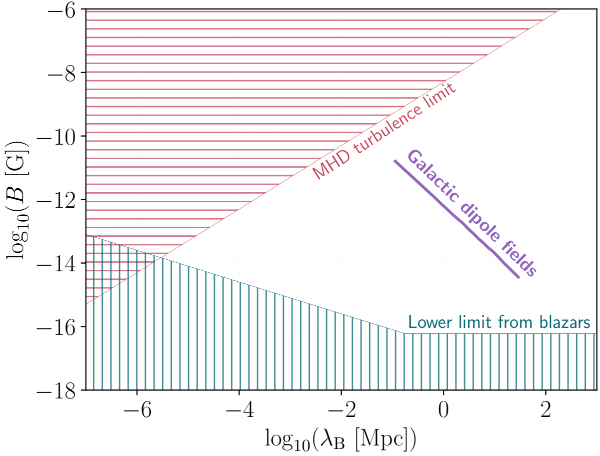

From
Garg, RD, Schober
2505.14774

Stochastic GW backgound

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- Already 2nd order scalar perturbations generate GWs ($\rightarrow$ poster by Stylianos Papadopoulos).

Stochastic GW backgound

STOCHASTIC BACKGROUND SOURCES AND DETECTOR SENSITIVITIES

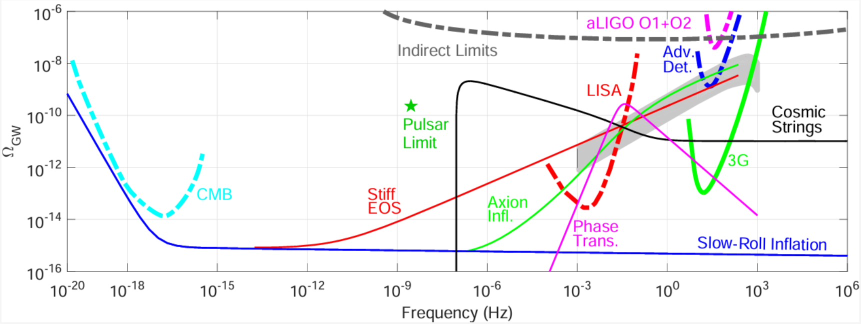

Figure 4.2: Stochastic GW background for several proposed model spectra in comparison with past measurements (Advanced LIGO upper limit [249], constraints based on the big bang nucleosynthesis and cosmic microwave background (CMB) observations, low-l CMB observations, and pulsar timing [250]), and future 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. $N_{\rm eff} = 2.99 \pm 0.34$ is in perfect agreement with the theoretically expected value for 1 photon and 3 species of neutrinos, $N_{\rm eff} = 3.046$. (from Planck 2018).

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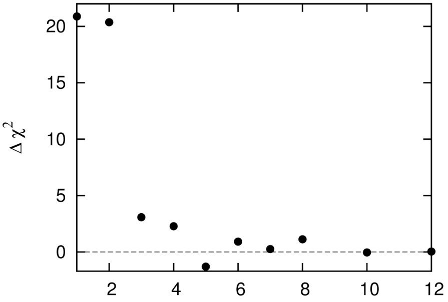

$\Delta\chi^2$ as a function of $\ell^{(\nu)}_{\rm max}$

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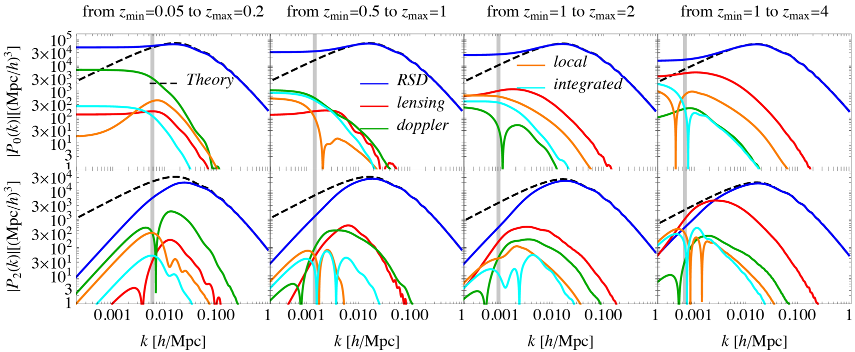
- Observations are made on our background lightcone.
- We cannot observe a $\{t = \text{const.}\}$ hypersurface and therefore not a power spectrum.
- For small scales this is irrelevant but the more we go to cosmological scales the more it becomes important.



(From Castorina & Di Dio 2106.08857)

Weak lensing

Lensing describes the deflection of photon geodesics on their way from a source into our antennas $\mathbf{n} \to \mathbf{n}'$.

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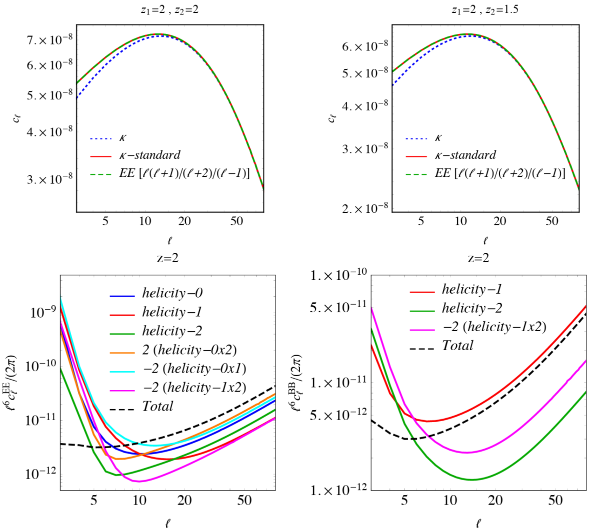
Differences

- 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)

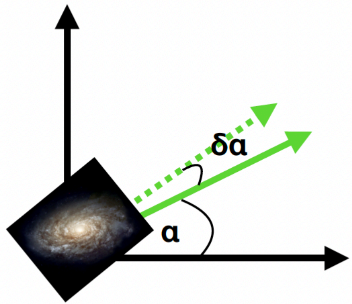
(From Fanizza, Di Dio, RD & Marozzi 2201.11552)

Measuring shear via galaxy rotation

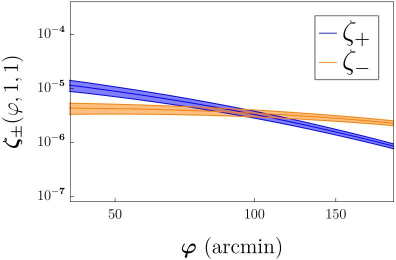
Galaxies are usually quite elliptical.
If you shear an ellipse whose principle axes are not aligned with the principle axes of the shear map, this induces not only a change in the ellipticity but also a rotation.
With respect to arbitrary parallel transported axes $(\mathbf{e}_1, \mathbf{e}_2)$, shear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

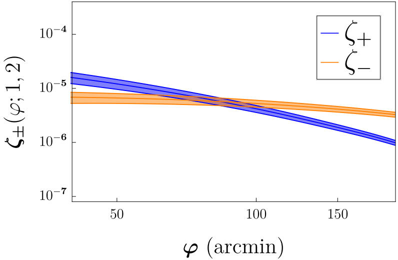
$$\delta\alpha = \frac{\varepsilon^2}{2 - \varepsilon^2} \left(\gamma_2 \cos 2\alpha - \gamma_1 \sin 2\alpha\right) .$$

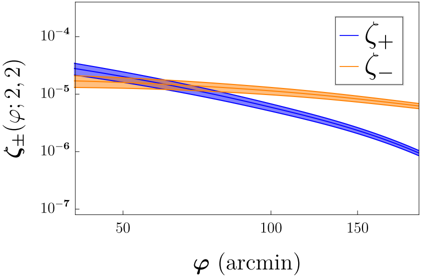
Here $0 \leq \varepsilon \leq 1$ is the ellipticity of the galaxy. (Note that $\delta\alpha = 0$ if the principle axes are aligned, i.e. $\alpha = 0$ (or π) and $\gamma_2 = 0$ or $\alpha = \pi/4$ (or $5\pi/4$) and $\gamma_1 = 0$.)



Results with SKA 2







SNR ~ 45
For a conservative SNR
of 10^{-3} per galaxy.

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

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- 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.