Cosmology: Discussion Session

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"Gravitational Wave Probes of Fundamental Physics", EuCAPT, 13 November 2019
In principle GWs test general EFT (e.g. Chern-Simons, Gauss-Bonnet etc)

\[ S = M_{\text{Planck}}^2 \int d^4 x \sqrt{-g} \left[ \frac{1}{2} R + \frac{a}{\Lambda^2} R^2 + \frac{b}{\Lambda^2} R_{\mu\nu}^2 + \cdots + \frac{c}{\Lambda^4} R_{abcd} R^{cd}_{\epsilon f} R^{efab}_{\epsilon} + \cdots + \mathcal{L}_{\text{matter}} \right] \]

+ \Lambda^2 \left( \frac{\phi}{\Lambda} \right)^a \left( \frac{\nabla}{\Lambda} \right)^b \left( \frac{\text{Riemann}}{\Lambda^2} \right)^c

In practice tough, scales needed for sizeable effect typically unrealistic

e.g. propagation of GW only modified at tree level by massive higher spins \( s \geq 2 \), or by loop effects (tiny) of all spins

But!

Cosmological Effective Field Theories lead to new IR scale

\[ E_{\text{IR}} \sim H \]

Physics responsible for Dark Energy may lead to effects at

\[ \Lambda_N \sim \left( H^{N-1} M \right)^{\frac{1}{N}} \]
\( \Lambda_N \sim (H^{N-1}M)^{\frac{1}{N}} \)

\( \Lambda_3 = (H^2 M)^{1/3} \sim 1000 km \)

\( \Lambda_2 = (HM)^{1/2} \sim 1 \) micron

Additional gravitational wave polarizations, additional fifth forces, screening mechanisms

Already strong constraints on special case - decay of graviton, speed of gravity/light constraints, coherent production of scalars which backreact

Understanding nonlinear region very challenging - need numerical + better approximation/analytic understanding
Models not well parameterized by post-Newtonian etc
Strong gravity regime poorly understood

Can all dark energy models with intermediate scale physics ruled out?
can be measured to an accuracy that reaches 1.1%

\[
\frac{d_L^{gw}(a)}{d_L^{em}(a)} = \Xi_0 + a^n(1 - \Xi_0)
\]

<table>
<thead>
<tr>
<th>Model</th>
<th>$\Xi_0 - 1$</th>
<th>$n$</th>
</tr>
</thead>
<tbody>
<tr>
<td>HS $f(R)$ gravity</td>
<td>$\frac{1}{2} f_R 0$</td>
<td>$\frac{3(\tilde{n} + 1)\Omega_m}{4 - 3\Omega_m}$</td>
</tr>
<tr>
<td>Designer $f(R)$ gravity</td>
<td>$-0.24\Omega_m^{0.76} B_0$</td>
<td>$3.1H_0^{0.24}$</td>
</tr>
<tr>
<td>Jordan–Brans–Dicke</td>
<td>$\frac{1}{2} \delta \phi 0$</td>
<td>$\frac{3(\tilde{n} + 1)\Omega_m}{4 - 3\Omega_m}$</td>
</tr>
<tr>
<td>Galileon cosmology</td>
<td>$\frac{\beta \phi_0}{\Omega_m}$</td>
<td>$\frac{\phi_0}{\Omega_m}$</td>
</tr>
<tr>
<td>$\alpha_M = \alpha_M 0 \tilde{a}$</td>
<td>$\frac{\alpha_M 0}{2\tilde{a}}$</td>
<td>$\tilde{n}$</td>
</tr>
<tr>
<td>$\alpha_M = \alpha_M 0 \frac{\Omega_{\Lambda}(a)}{\Omega_{\Lambda}}$</td>
<td>$-\frac{\alpha_M 0}{3\Omega_{\Lambda}} \ln \Omega_m$</td>
<td>$\frac{3\Omega_{\Lambda}}{\ln \Omega_m}$</td>
</tr>
<tr>
<td>$\Omega = 1 + \Omega_+ \tilde{a}$</td>
<td>$\frac{1}{2} \Omega_+$</td>
<td>$\tilde{n}$</td>
</tr>
<tr>
<td>Minimal self-acceleration</td>
<td>$\lambda (\ln \alpha_{acc} + \frac{C}{2} \chi_{acc})$</td>
<td>$\frac{C/H_0 - 2}{\ln \alpha_{acc} - C \chi_{acc}}$</td>
</tr>
</tbody>
</table>
Can Quantum Gravity (QG) theories leave a signature in GWs?

- **NO**: any late-time QG corrections will be suppressed by the Planck scale
  \[(\ell_{Pl}H)^n \quad n = 2, 3, \ldots \quad (\ell_{Pl}H_0)^n \sim 10^{-60n}\]

- **Nonperturbative effects beyond the simple dimensional argument**

  If there is a third scale \(L \gg \ell_{Pl}\) then QC \(\sim \ell_{Pl}^a H^b L^c\) with \(a - b + c = 0\)
  and NOT all these exponents are small

  \[
h \propto \frac{1}{d_{GW}^L}, \quad d_{GW}^L = d_{EM}^L \left[1 + \varepsilon \left(\frac{d_{EM}^L}{\ell_{\ast}}\right)^{\gamma-1}\right], \quad \gamma \neq 0.
\]

Only GFT, SF or LQG could generate a signal detectable with standard sirens

**Calcagni, Kuroyanagi, Marsat, Sakellariadou, Tamanini, Tasinato**, JCAP 1910 (2019) no.10, 012
GWs population of CBOs, beyond SM physics., LSS

Talk by Alex Jenkins
Standard sirens: independent measurement!

O1-O2 LIGO-Virgo results:

GW measurements are in the game!

Only $\mathcal{O}(10) \times$ more sources without counterparts give similar precision.

Clustering will improve prospects: by a factor of 2.5?

Number and nature of sources will dictate relative contribution of “dark” sirens.
Cosmology with GW beyond H0

A probe to the alternative theories of gravity

How GW Propagates
\[ h_{ij}'' + (2 + \nu) \mathcal{H} h_{ij}' + \left( \frac{c_T^2 k^2}{a^2} + a^2 \mu^2 \right) h_{ij} = a^2 \Gamma \gamma_i. \]

Saltas et al. 2014, Nishizawa 2018

How matter density and metric perturbations are related
\[ \nabla^2 (\Phi + \Psi) = 8\pi G a^2 \rho_m \delta \]
\[ r(k, z) = \frac{1 - \frac{\Phi}{\Psi}}{1 + \frac{\Phi}{\Psi}} \]

Mukherjee, Wandelt, Silk
arXiv:1908.08950
arXiv:1908.08951

Image credit: NASA
CMB experiments such as Simons Observatory/ CMB S4
LSS survey such as DESI/LSST

Wide range of masses
Wide GW frequency
Up to high redshift

- Concordant trajectory between electromagnetic waves and gravitational waves
- A probe to the alternative theories of gravity
- Breaking the degeneracy between lensing and other effects.
- Measurement of the lensing signal from GW strain for different frequencies
- Testing the equivalence principle
Lensing & GW’s

• GW std sirens might be useful as lensing sources, especially for alternative DM models that produce excess structure on tiny scales (e.g. axion miniclusters, ultra-compact minihalos, PBH’s)

• 3 wavelength regimes:
  1. \( \lambda \gg GM/c^2 \): grav lensing is negligible
  2. \( \lambda \sim GM/c^2 \): wave lensing, strong frequency dependence
  3. \( \lambda \ll GM/c^2 \): geometric optics, frequency independent.
    A. Strong lensing: multiple images, sensitive to dense concentrations. LIGO sources are appealing, since they are coherent, so we can measure time delays \( \sim 10 \) msec. (But FRBs may be even better!)
    B. Weak lensing, look for brightness fluctuations. Typical rms \( \sim 1\% \) for standard \( \Lambda \)CDM, so this will be difficult to detect via excess variance. Better approach might be cross-correlation, figure-of-merit is noise power spectrum \( \varepsilon^2/\bar{n} \). For type Ia SNe, \( \varepsilon \sim 5\%-10\% \), so many GW events are needed in order to be competitive.
**$H_0$ without counterparts**

- Standard method (e.g. Schutz) is equivalent to cross-correlation in limit of weak correlations ($\xi \ll 1$). Current LIGO is in this limit since localization errors are large, $\Delta V \sim \mathcal{O}(10 - 100 \text{ Mpc})^3$.

- In this regime, density fluctuations are nearly Gaussian distributed, so 2-pt functions contain all information $\rightarrow$ cross-correlation analysis should be nearly *optimal*.

- Distinctive signature of $H_0$: violation of translation invariance

- Cross-correlation takes the form
  \[
  \langle n^*_{GW}(\vec{k}_1)n_{gal}(\vec{k}_2) \rangle = (2\pi)^3 P_c(k_1)\delta_D(\vec{k}_1 - \vec{k}_2),
  \]
  where
  \[
  P_c(k) = \bar{n}_{GW}\bar{n}_{gal}P(k) + f_{gal}\bar{n}_{GW}
  \]

- Peculiar velocities give cute effect in redshift-space distortions of GW events, allow us to measure $Hd$ (in principle)
Questions/Thoughts

• Can we test the Lambda CDM model with GWs data independently of CMB?
• Can we test the thermal history of the universe (i.e, phase transitions) through GWs data?
• Model independent constraints on the theory of gravity from GW observations
• Can we rule out all dark energy models with intermediate scale physics? are there other constraints from GWs on cosmological EFTs?
• Can we understand the nature of dark matter from GW observations?
• Will a GW measurement (of H0) ever be as competitive as conventional measurements?
• Expansion history using GW sources.
• Will we be able to address galaxy catalogue systematics well enough to confidently report and accurate H0 measurement without counterparts?
• Will we know the NS physics well enough to measure H0 using GW sources alone?
• Can we rely on BBH population properties for cosmography?
• Can GW sources be used as calibrators of the distance ladder? If so, at what redshift?
• Cosmography or testing gravity with standard sirens?
• In what other ways can we use standard sirens?
• Can GW detectors improve their absolute calibration from ~ few % to < 1%?
• Combining the measurements from strong gravity regime and GW propagation.
• Is there any hope to probe high frequency primordial GW signal?
• Inference of the Hubble parameter from the GW sources without EM counterparts.
• Possibility of measuring the additional polarization of GW signal?
• Peculiar velocity corrections to the BNS, BH-NS sources
• Cosmology using the stochastic GW background
• Is it worthwhile to probe very high frequency regime (e.g. > 10^4 Hz) where there are no astrophysical sources, so any signal means novel physics?