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)

Helvi Witek talk
Masha Okounkova talk

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

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

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 >=2, or by loop effects (tiny) of all spins

But!

Cosmological Effective Field Theories lead to new IR scale

$$E_{IR} \sim H$$

Physics responsible for Dark Energy may lead to effects at

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

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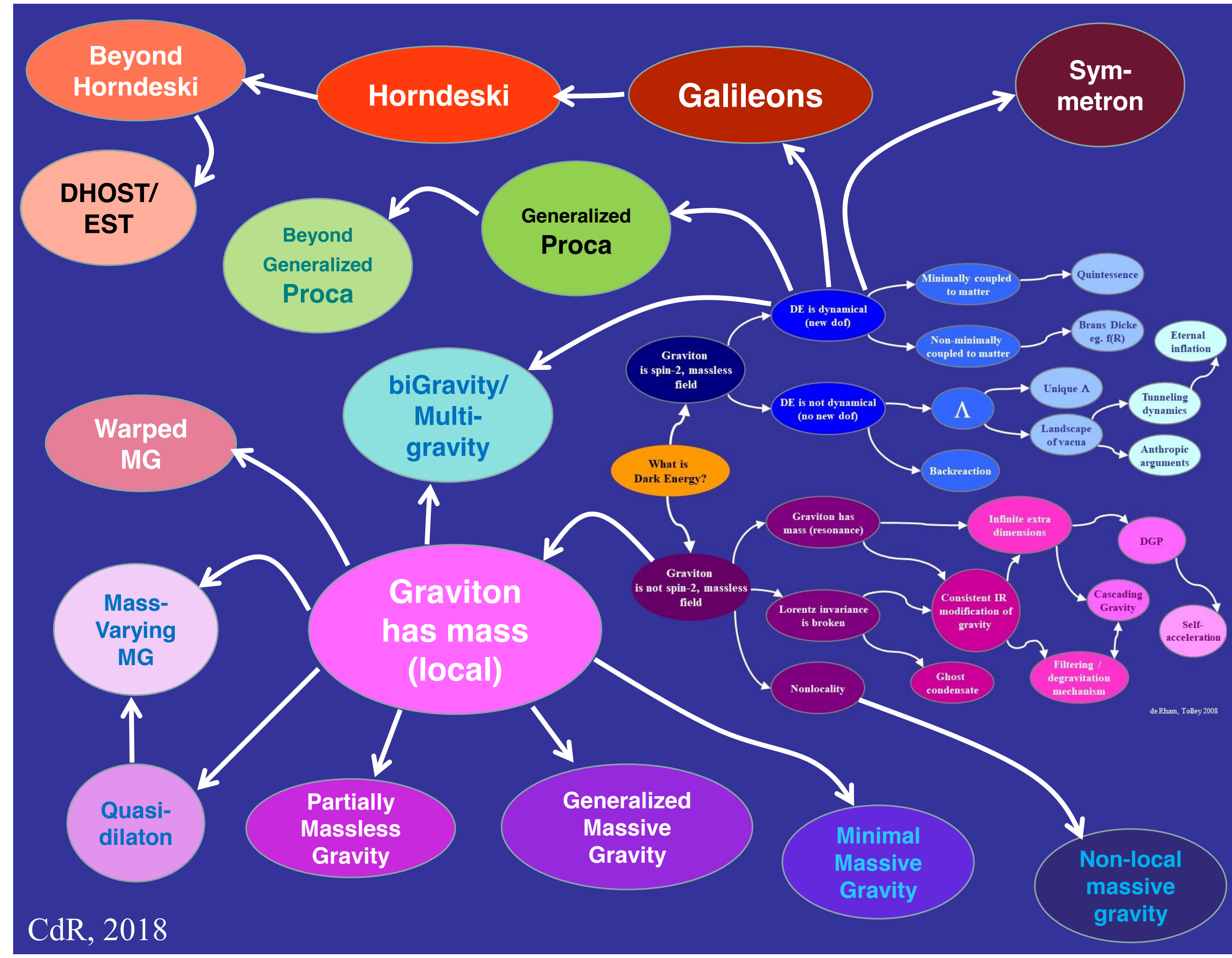
$$\Lambda_3 = (H^2 M)^{1/3} \sim 1000km$$

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

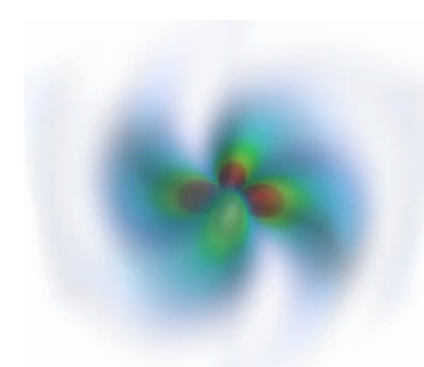


Additional gravitational wave polarizations, additional fifth forces, screening mechanisms

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

Tessa Baker talk
Giovanni Tambalo talk

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?

Testing modified gravity to explain DE

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

can be measured to an accuracy that reaches 1.1%

Model	$\Xi_0 - 1$	n
HS $f(R)$ gravity	$\frac{1}{2}f_{R0}$	$\frac{3(\tilde{n}+1)\Omega_m}{4-3\Omega_m}$
Designer $f(R)$ gravity	$-0.24\Omega_m^{0.76}B_0$	$3.1\Omega_m^{0.24}$
Jordan–Brans–Dicke	$\frac{1}{2}\delta\phi_0$	$\frac{3(\tilde{n}+1)\Omega_m}{4-3\Omega_m}$
Galileon cosmology	$\frac{\beta\phi_0}{2M_{\rm Pl}}$	$\frac{\dot{\phi}_0}{H_0\phi}$
$\alpha_M = \alpha_{M0}a^{\tilde{n}}$	$\frac{\alpha_{M0}}{2\tilde{n}}$	$\tilde{n}$
$\alpha_M = \alpha_{M0}\frac{\Omega_\Lambda(a)}{\Omega_\Lambda}$	$-\frac{\alpha_{M0}}{6\Omega_\Lambda}\ln\Omega_m$	$-\frac{3\Omega_\Lambda}{\ln\Omega_m}$
$\Omega = 1 + \Omega_+ a^{\tilde{n}}$	$\frac{1}{2}\Omega_+$	$\tilde{n}$
Minimal self-acceleration	$\lambda\left(\ln a_{acc} + \frac{C}{2}\chi_{acc}\right)$	$\frac{C/H_0-2}{\ln a_{acc}^2 - C\chi_{acc}}$

Belgacem,… Sakellariadou, **JCAP 1907 (2019) 024**

Tests of QG with GWs: gravitational wave luminosity distance

Can Quantum Gravity (QG) theories leave a signature in GWs?

- **NO**: any late-time QG corrections will be suppressed by the Planck scale

$$(\ell_{\rm Pl} H)^n \qquad n = 2, 3, \ldots . \qquad (\ell_{\rm Pl} H_0)^n \sim 10^{-60n}$$

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

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

$$h \propto \frac{1}{d_L^{\rm GW}}, \qquad d_L^{\rm GW} = d_L^{\rm EM}\left[1 + \varepsilon \left(\frac{d_L^{\rm EM}}{\ell_*}\right)^{\gamma - 1}\right], \qquad \gamma \neq 0$$

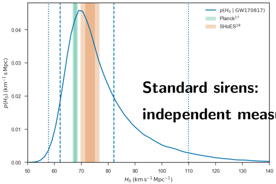
Only GFT, SF or LQG *could* generate a signal detectable with standard sirens

Calcagni, Kuroyanagi, Marsat, Sakellariadou, Tamanini, Tasinato, JCAP 1910 (2019) no.10, 012
Phys.Lett. B798 (2019) 135000

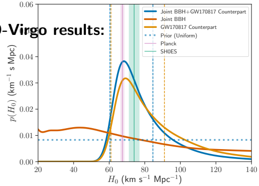
GWs → population of CBOs , beyond SM physics. , LSS

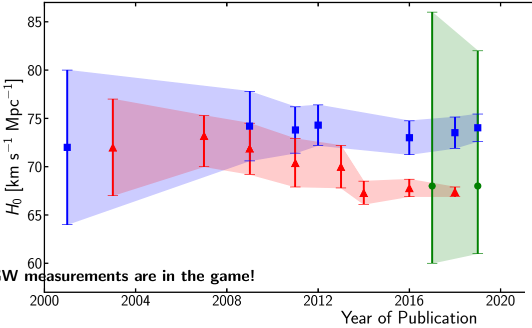
Talk by Alex Jenkins

O1-O2 LIGO-Virgo results:

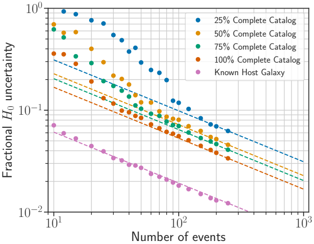


Standard sirens: independent measurement!





GW measurements are in the game!

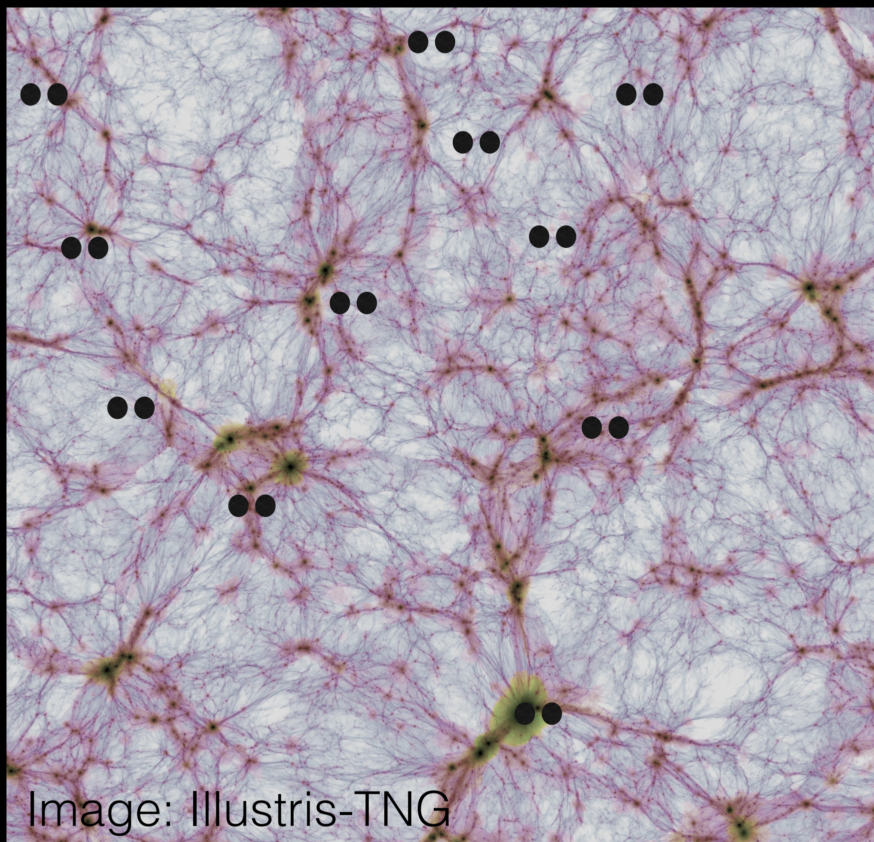


Only $\mathcal{O}(10)\times$ more sources without counterparts give similar precision.

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

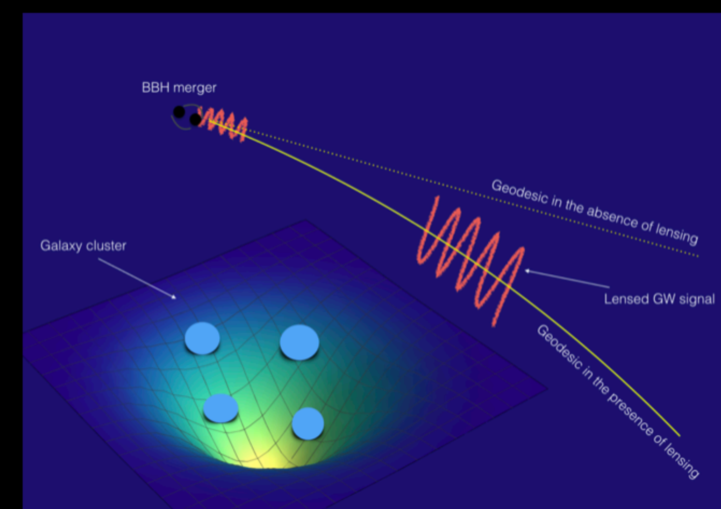
How GW Propagates

$$h''_{ij} + (2+\nu)\mathcal{H}h'_{ij} + (c_T^2 k^2 + a^2\mu^2)h_{ij} = a^2\Gamma\gamma_{ij}$$

Saltas et al. 2014, Nishizawa 2018

How matter density and metric perturbations are related

$$\nabla^2(\Phi + \Psi) = 8\pi G a^2 \rho_m \delta \qquad r(k,z) = \frac{1-\frac{\Phi}{\Psi}}{1+\frac{\Phi}{\Psi}}$$



Mukherjee, Wandelt, Silk
arXiv:1908.08950
arXiv:1908.08951

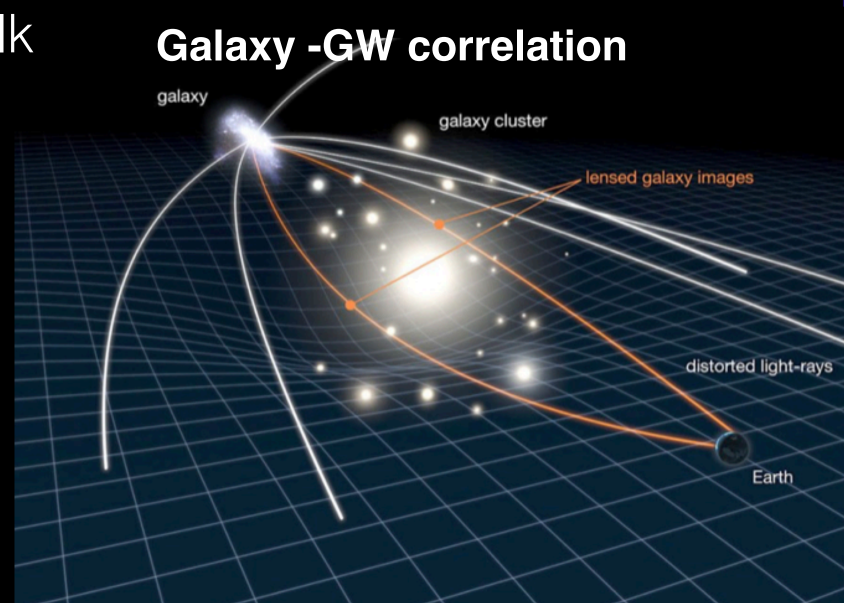
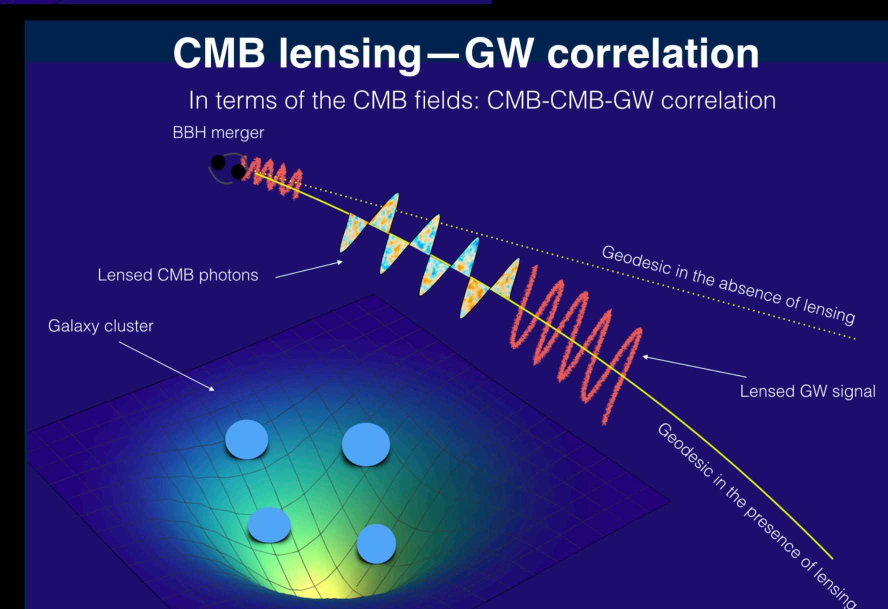
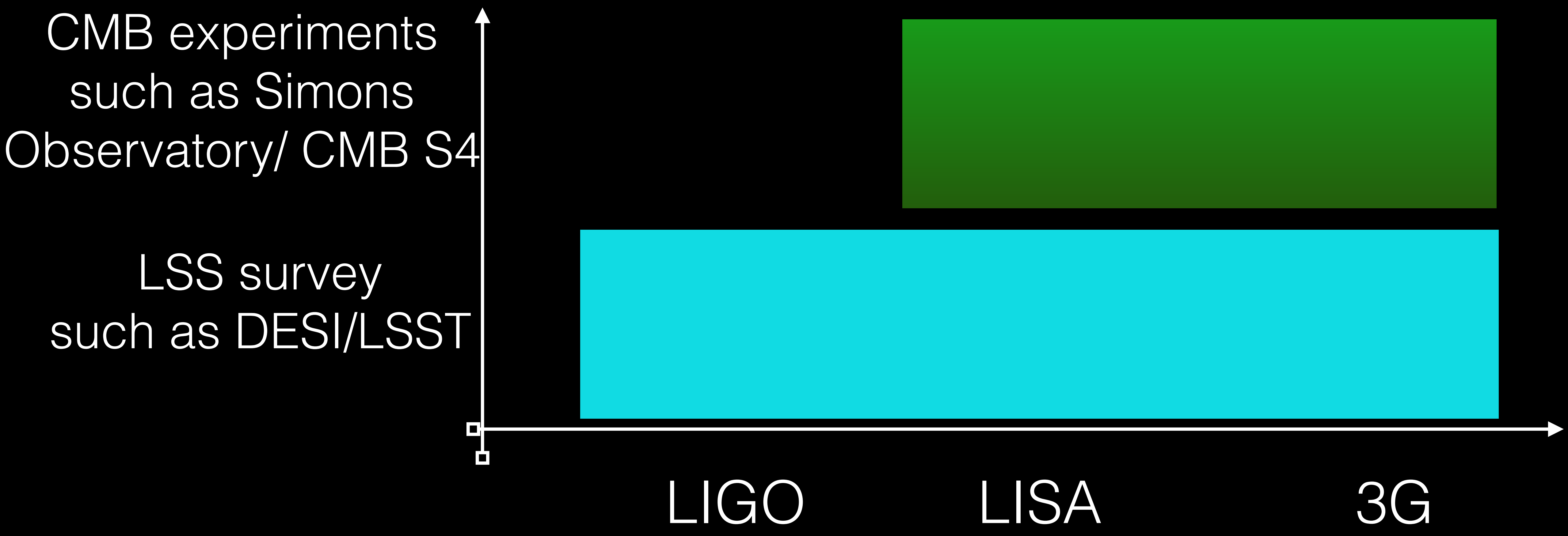


Image credit: NASA





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 ~ 10 msec. (But FRBs may be even better!)
     B. Weak lensing, look for brightness fluctuations. Typical rms ~ 1% for standard ΛCDM, 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, ε~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, $\Delta V \sim \mathcal{O}(10 - 100\,\mathrm{Mpc})^3$.

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

- Distinctive signature of H_0: violation of translation invariance

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

- Peculiar velocities give cute effect in redshift-space distortions of GW events, allow us to measure *H d* (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?