Science with the Einstein Telescope

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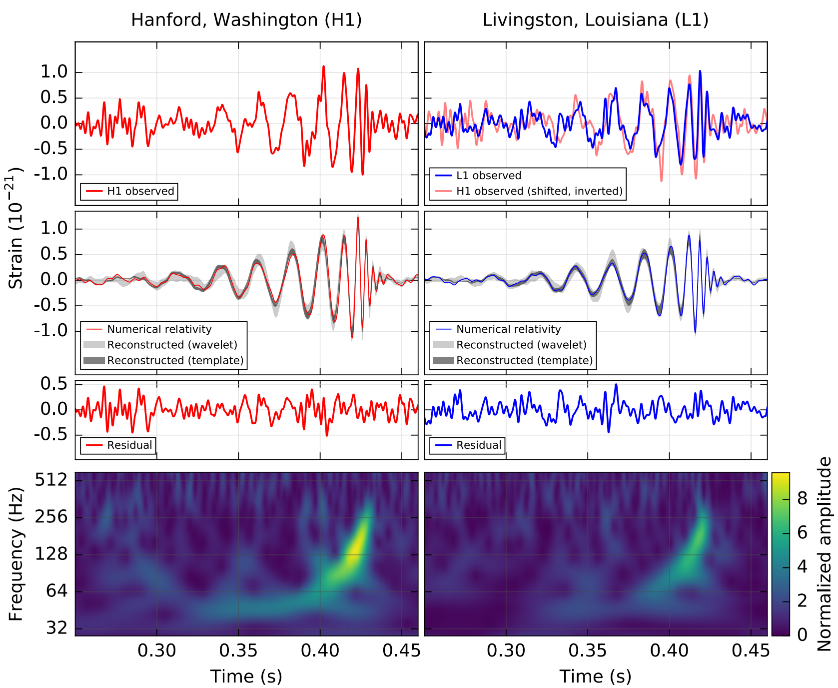
Advanced LIGO/Virgo have truly opened a new window on the Universe

First detection of a BH-BH coalescence, September 14, 2015



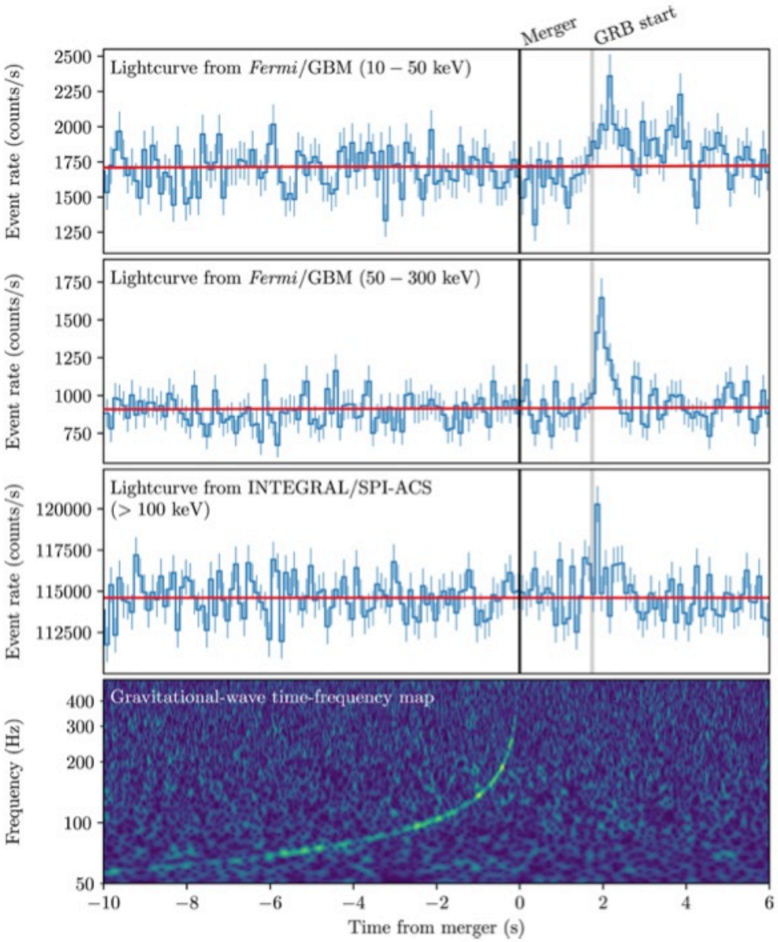
parameter estimation from matched filtering:

primary BH mass	$36^{+5}_{-4}\,M_\odot$
secondary BH mass	$29^{+4}_{-4}\,M_\odot$
final BH mass	$62^{+4}_{-4}\,M_\odot$
final BH spin $\hat{a} \equiv Jc/(GM^2)$	$0.67^{+0.05}_{-0.07}$
luminosity distance	410^{+160}_{-180} Mpc
source redshift	$0.09^{+0.03}_{-0.04}$

3 solar masses radiated in GWs in a few ms !!

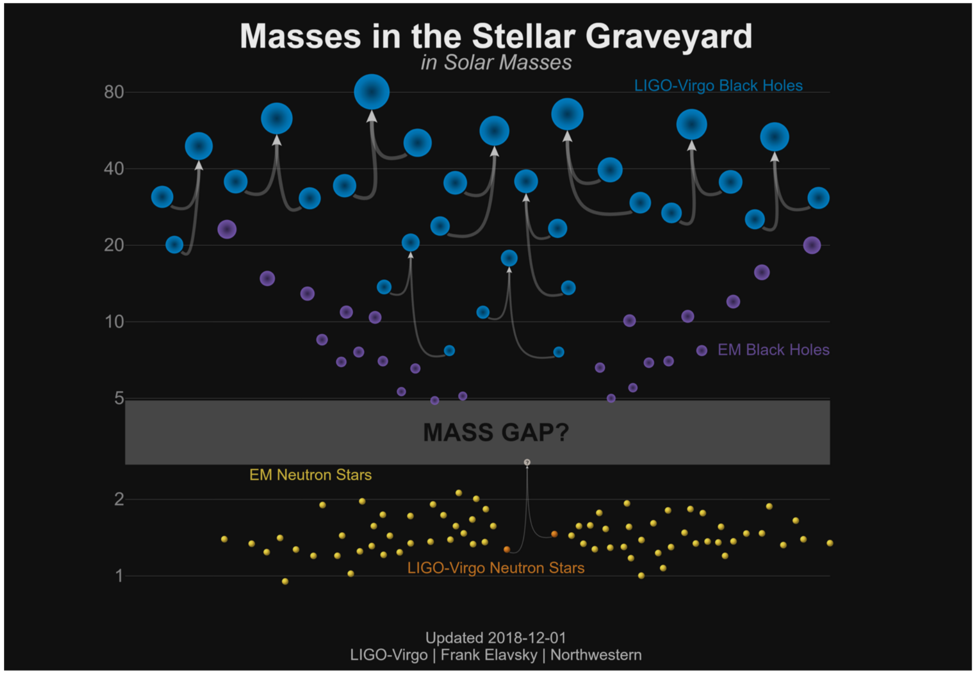
Weiss, Barish, Thorne, Nobel Prize 2017

Another milestone was the first NS-NS binary



- coincidence with a short GRB detected by Fermi-GBM and INTEGRAL
- triple coincidence (in a Virgo blind spot) $\rightarrow$ sky localization
- detection and follow-up of the counterpart in all wavelengths!
- $m_1 = (1.36 - 1.60) M_\odot$,
  $m_2 = (1.17 - 1.36) M_\odot$,
  $d_L = 40.4 \pm 3.4\,\mathrm{Mpc} \quad (z \simeq 0.01)$

- LIGO/Virgo detections in O1/O2



farthest BH-BH detection at z=0.48

- during O3, detections are becoming a routine (1/week) +NS-NS, NS-BH

What we have learned ?

Astrophysics

- GW170817 solved the long-standing problem of the origin of (at least some) short GRB
- NS-NS mergers are a site for the formation of some of the heaviest elements through r-process nucleosynthesis
- BH-BH binaries exist and merge within the age of the Universe
- discovered a new population of stellar-mass BHs, much heavier than those detected through X-ray binaries

Cosmology/fundamental physics

- speed of GWs equal to speed of light (1:10^{15})

- first measurement of the Hubble constant with GWs

- the tail of the waveform of GW150914 consistent with the prediction from General Relativity for the quasi-normal modes of the final BH

- deviations from GR (graviton mass, post-Newtonian coefficients, modified dispersion relations, etc.) could be tested and bounded

Still, 2G detectors lack the sensitivity to make really stringent tests of fundamental physics/cosmology

We have opened a new window:

3G detectors ground-based detectors (ET, CE)
and the space interferometer LISA
will look deeply into this window

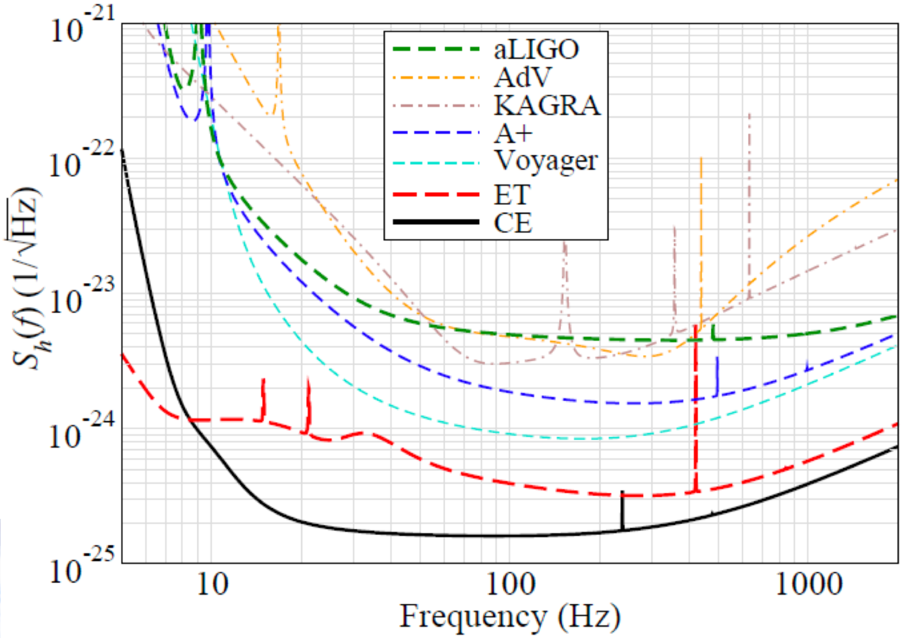
We will focus on the science that can be done with ET

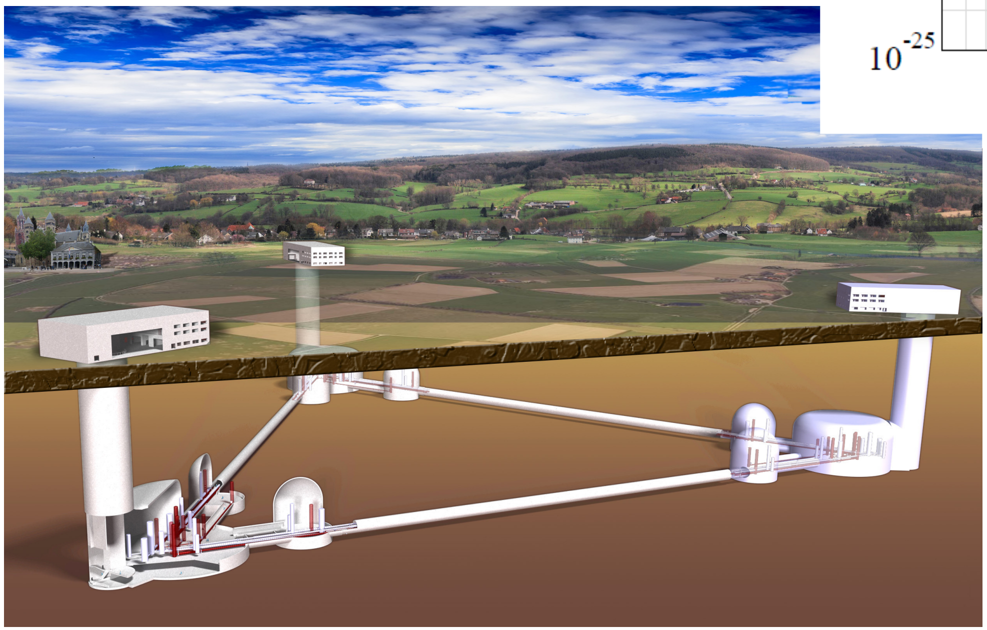
based on
MM et al “Science Case for the Einstein Telescope”, 1912.02622

see also Sathyaprakash et al. ``Scientific Objectives of Einstein Telescope” 1206.0331
and 3G Science Book, in preparation

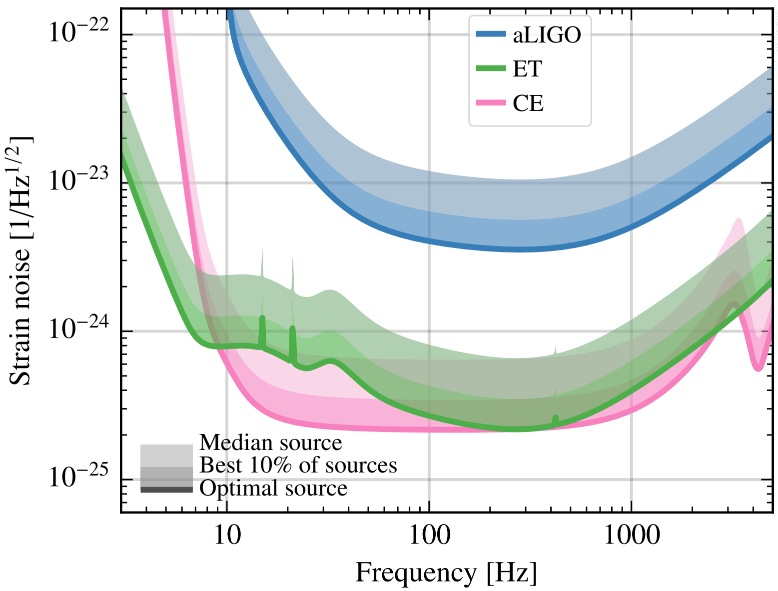
Einstein Telescope: the concept

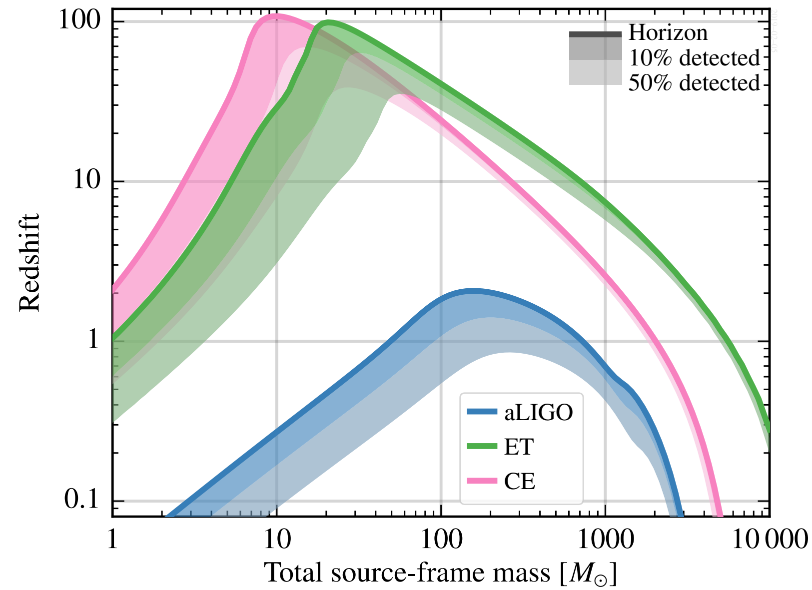
- Triangular shape
- Arms: 3 → 10 km
- Underground
- Cryogenic
- increase laser power
- Xylophone
- ...





c.a. 2035? submission to ESFRI roadmap ongoing





Sathyaprakash et al 2019

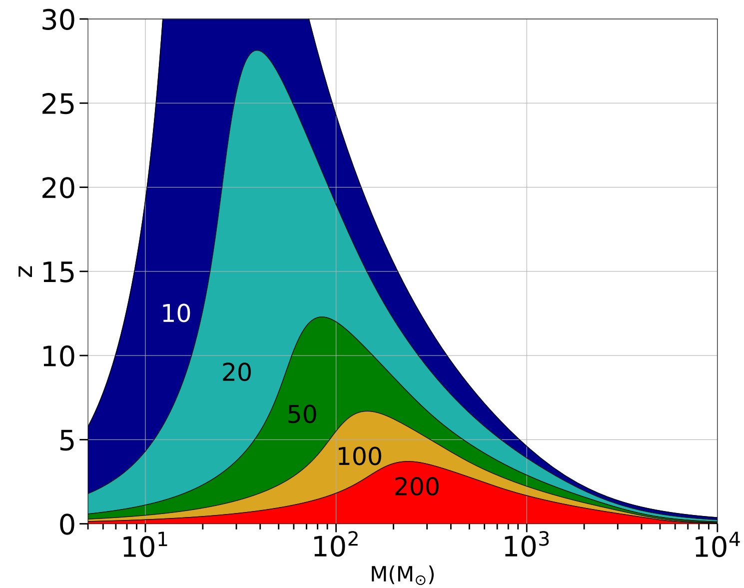
- BBH to z ≈ 20

  10^6 BBH/yr

  masses up to 10^3 $M_\odot$
- BNS to z ≈ 2

  10^5 BNS/yr

  (15-50/yr with counterpart)
- high SNR



courtesy Colpi and Mangiagli

The combination of

- distances and masses explored
- number of detections
- detections with very high SNR

will provide a wealth of data that have the potential of triggering revolutions in astrophysics, cosmology and fundamental physics

A summary of the Science of ET

Astrophysics

- Black hole properties
  - origin (stellar vs. primordial)
  - evolution, demography
- Neutron star properties
  - interior structure (QCD at ultra-high densities, exotic states of matter)
  - demography
- Multi-messenger astronomy
  - joint GW/EM observations (GRB, kilonova,...)
  - multiband GW detection (LISA)
  - neutrinos
- Detection of new astrophysical sources
  - core collapse supernovae
  - isolated neutron stars
  - stochastic background of astrophysical origin.

Fundamental physics and cosmology

- The nature of compact objects
  - near-horizon physics
  - tests of no-hair theorem
  - exotic compact objects

- Tests of General Relativity
  - post-Newtonian expansion
  - strong field regime

- Dark matter
  - primordial BHs
  - axion clouds, dark matter accreting on compact objects

- Dark energy and modifications of gravity on cosmological scales
  - DE equation of state
  - modified GW propagation

- Stochastic backgrounds of cosmological origin and connections with high-energy physics
  - inflation
  - phase transitions
  - cosmic strings
  - ...

... and we should not forget that ET will be a `discovery machine'

Expect the unexpected!

Astrophysics with BBH

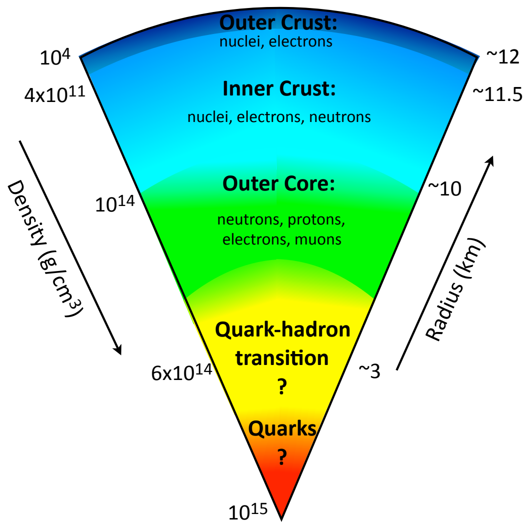
ET will uncover the full population of coalescing stellar BBH since the end of the cosmological dark ages

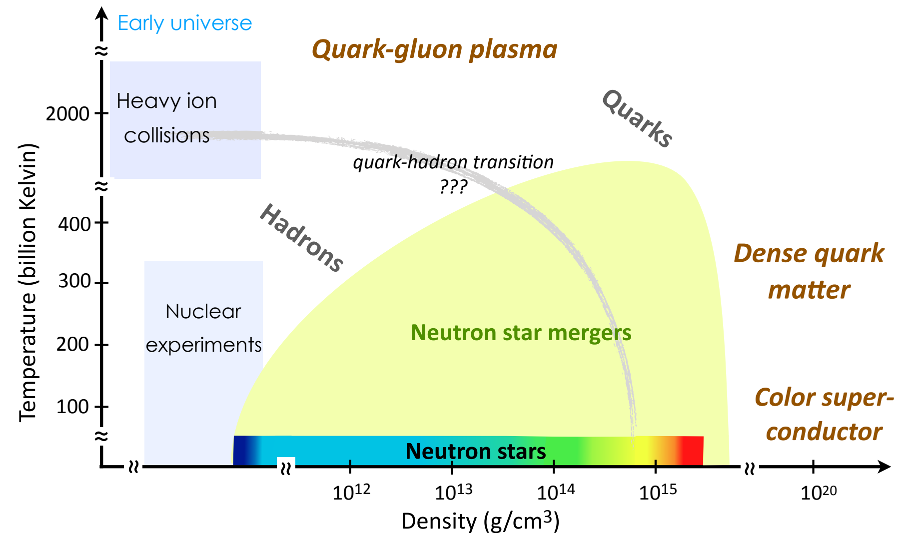
(a single BBH has a peak luminosity higher than the integrated em luminosity of the observable Universe!)

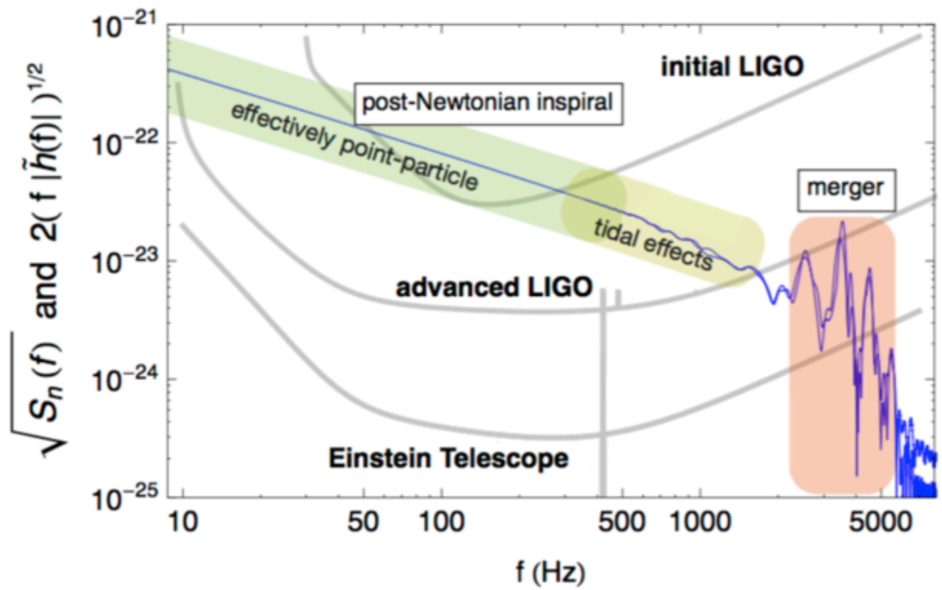
- contribute to uncover the star-formation history of the Universe
- disentangle stellar origin from primordial BH
  - compare redshift dependence with SFR determined electromagnetically
  - PBH should trace the distribution of DM rather than of baryons

    the large number of detections will allow cross-correlations
  - any stellar-mass BBH at $z > 10$ will be primordial
- discover seed BHs with $M=O(10^3)\ M_\odot$

QCD with neutron stars



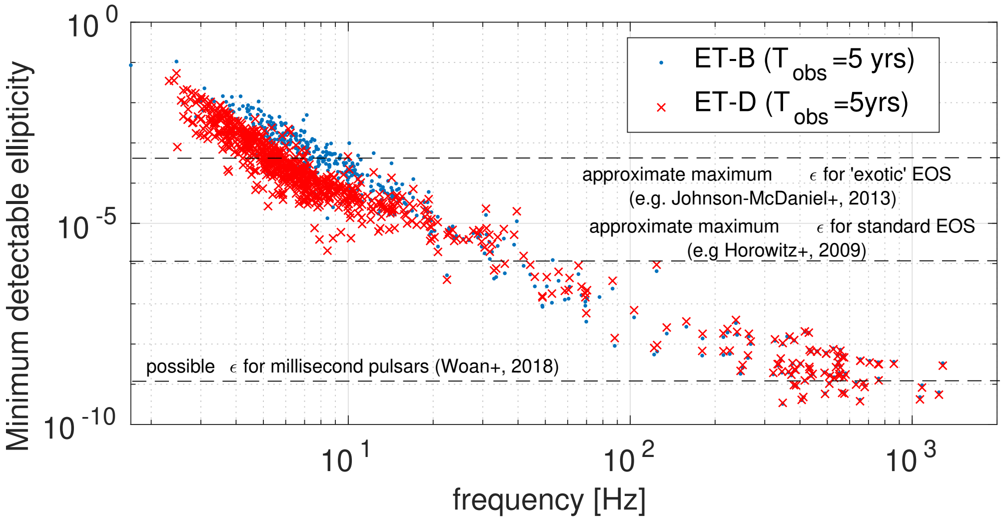




BNS merger @100 Mpc

(adapted from J. Read)

Continuous GWs from isolated NS

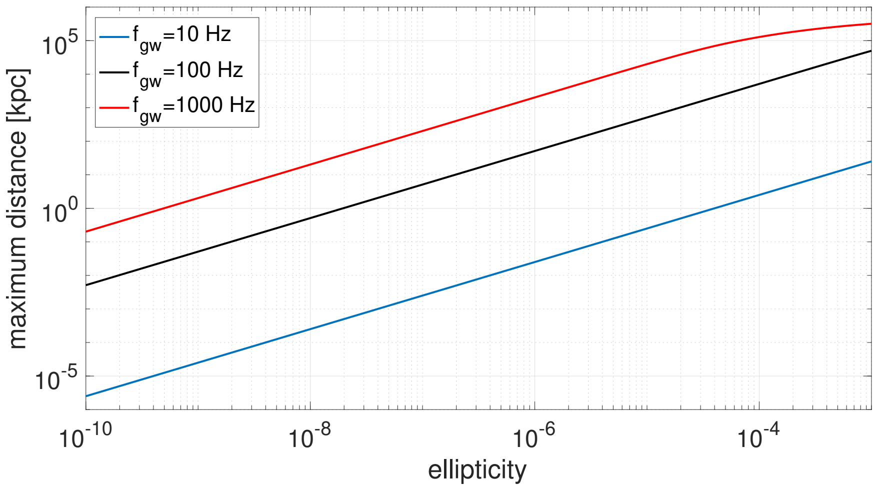


Minimum detectable ellipticity for known pulsars

depends on the internal structure and EoS at high dnesity

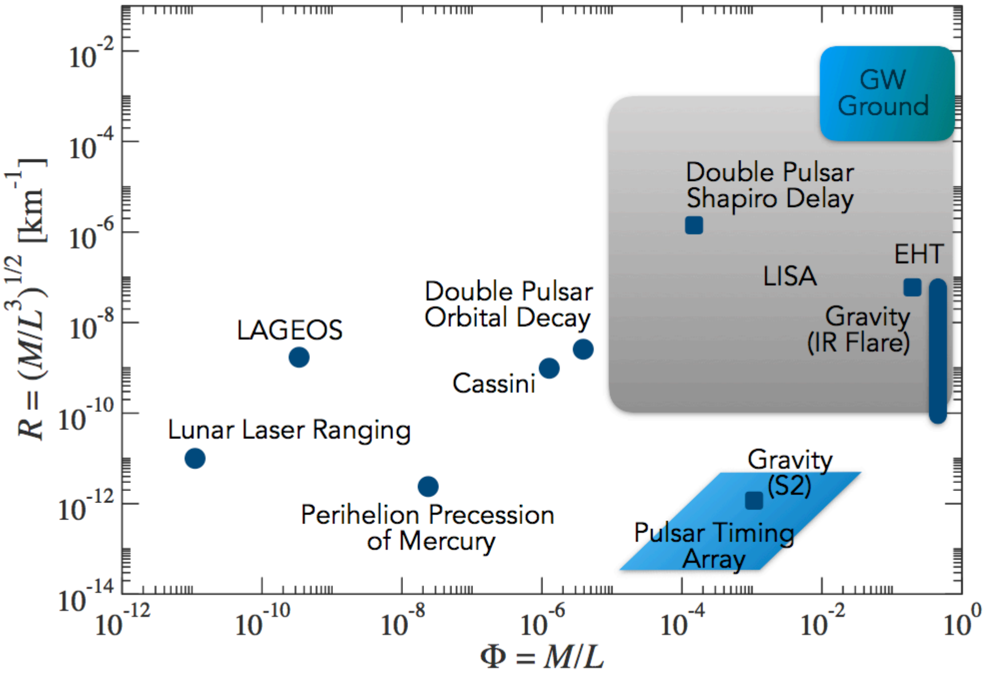
detecting GWs due to $\varepsilon = 10^{-7}$ means that we detect the effect of a ``mountain'' on a NS with height

$10^{-7} * 10$ km=1 mm !!



Fundamental physics/ cosmology

scales probed by gravity experiments



from Sathyaprakash et al.
1903.09221

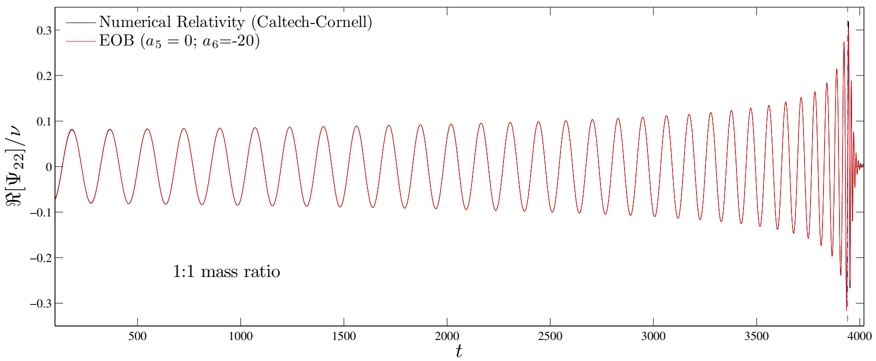
BH quasinormal modes and Exotic Compact Objects

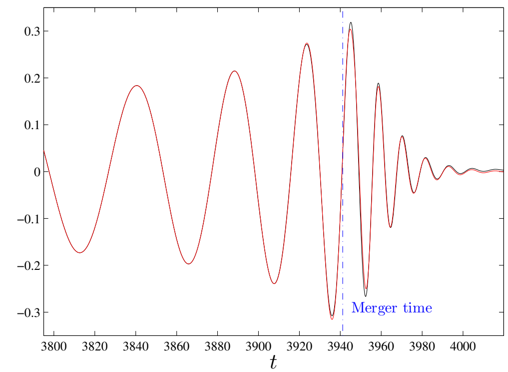
BH have QNM: they represent the elasticity of space-time in a regime of strong gravity

GR predicts their frequency and damping time as a function of mass and spin

classic works since the 50s: Regge-Wheeler, Chandrasekhar, Teukolsky...

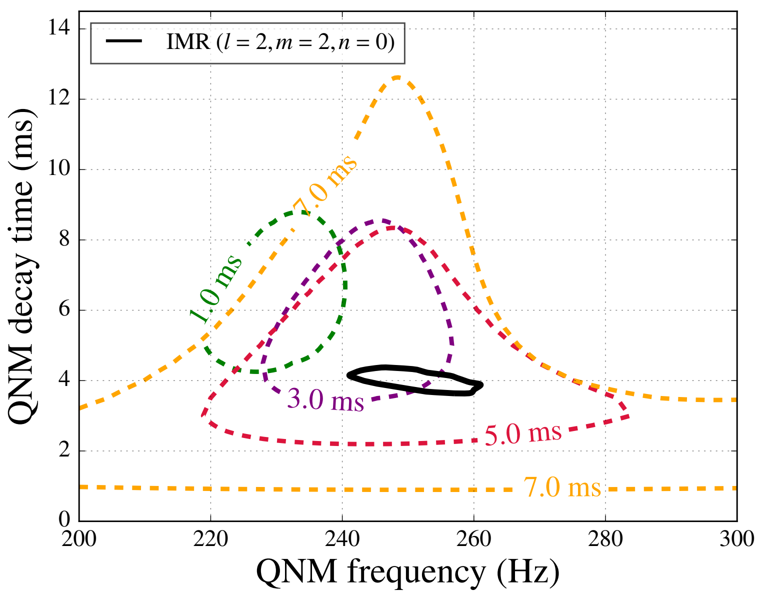
several proposal for ECOs (boson stars, stars made of DM particles...) are distinguishable because of the QNM

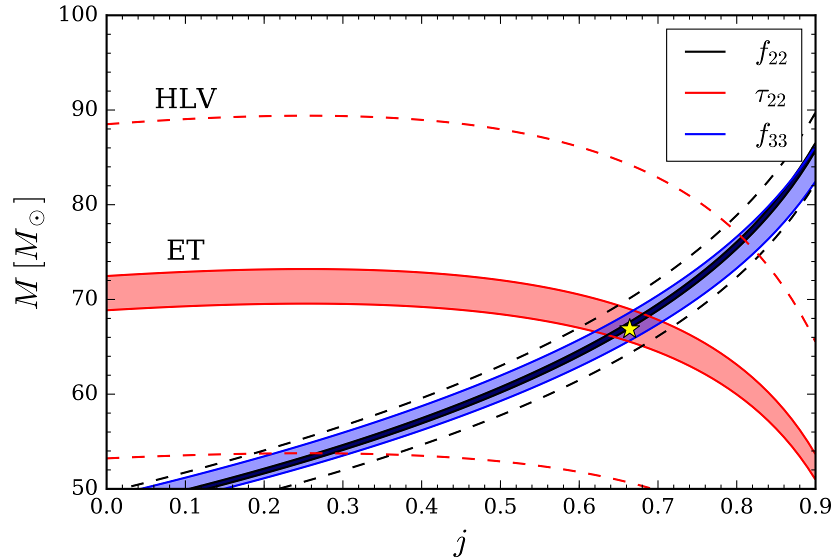




From GW150914:

at ET:

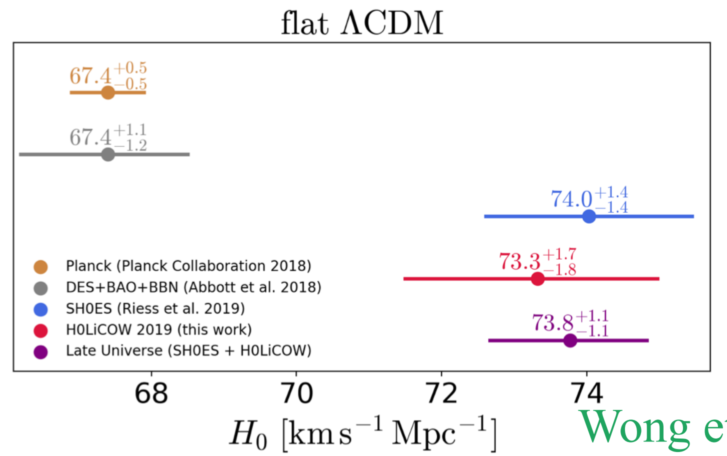




consistent with GR, but we cannot say much more

Cosmology and DE with ET

- Observational tensions, in particular early- vs late-Universe probes of H_0



Wong et al., H0LiCOW 2019

- Conceptual perplexities raised by a cosmological constant technically unnatural value, coincidence problem

good observational and theoretical reasons for testing ΛCDM and, especially, present and future data good enough to test it

Need to modify GR on cosmological scales?

Where to look for a non-trivial DE sector?

background evolution

deviations in w_{DE} from -1 bounded at (3-7)%

scalar perturbations

from growth of structures and lensing, bounds at the (7-10)% level

tensor perturbations (gravitational waves)

a new window on the Universe, that we have just opened

GWs from coalescing binaries provide an absolute measurement of the distance to the source. In flat space:

$$h_+(t) = \frac{4}{r}\,\frac{1+\cos^2\iota}{2}\left(\frac{GM_c}{c^2}\right)^{5/3}\left(\frac{\pi f}{c}\right)^{2/3}\cos\Phi(t)$$

$$h_\times(t) = \frac{4}{r}\cos\iota\left(\frac{GM_c}{c^2}\right)^{5/3}\left(\frac{\pi f}{c}\right)^{2/3}\sin\Phi(t)$$

$$\Phi(t) = 2\pi\int dt\, f(t)$$

$$\dot{f} = \frac{96}{5}\pi^{8/3}\left(\frac{GM_c}{c^3}\right)^{5/3} f^{11/3}$$

$$M_c = \frac{(m_1 m_2)^{3/5}}{(m_1+m_2)^{1/5}}$$

measure r without the need of calibration ("standard sirens")

(Schutz 1986)

For coalescing binaries at cosmological distances

$$\frac{1}{r} \to \frac{1}{d_L}\,, \qquad \mathcal{F} \equiv \frac{\mathcal{L}}{4\pi d_L^2} \qquad m_i \to m_i(1+z)$$

$$d_L(z) = \frac{1+z}{H_0} \int_0^z \frac{d\tilde{z}}{\sqrt{\Omega_M(1+\tilde{z})^3 + \rho_{\rm DE}(\tilde{z})/\rho_0}}$$

$$\Omega_M = \frac{\rho_M(t_0)}{\rho_0}, \quad \rho_0 = \frac{3H_0^2}{8\pi G}$$

- need an independent determination of z
  (electromagnetic counterpart, statistical methods)

- low z: Hubble law, $d_L \simeq H_0^{-1} z$
- moderate z: access $\Omega_M, \rho_{\rm DE}(z)$

Low-z important for the tension in H_0:

Planck 2018+BAO+SNe: $H_0 = 68.34 \pm 0.83$

local measurements (Riess et al) $H_0 = 74.22 \pm 1.82$

4.4σ discrepancy (5.3σ adding H0LiCOW):
indication for deviation from ΛCDM?

LIGO/Virgo measurement of H_0 from GW170817:

$$H_0 = 70.0^{+12.0}_{-8.0} \qquad (z \simeq 0.01)$$

O(50-100) standard sirens at advanced LIGO/Virgo needed to arbitrate the discrepancy

Moderate z: access $\rho_{DE}(z)$ and test ΛCDM against modified gravity

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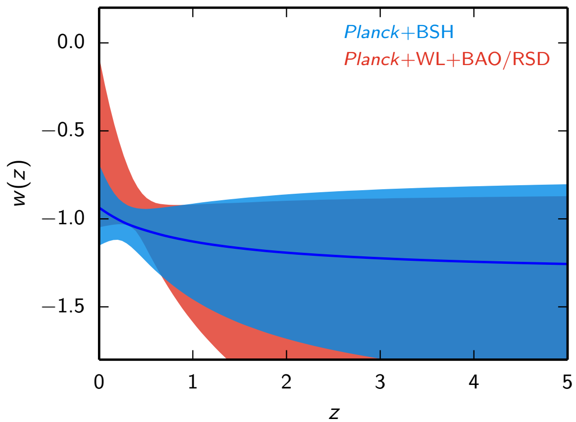
$$p_{\rm DE}(z) = w_{\rm DE}(z)\rho_{\rm DE}(z) \quad \Longrightarrow \quad \frac{\rho_{\rm DE}(z)}{\rho_0} = \Omega_{\rm DE} \exp\left\{3\int_0^z \frac{d\tilde z}{1+\tilde z}\left[1+w_{\rm DE}(\tilde z)\right]\right\}$$

Reconstructing the full function $w_{DE}(z)$ from the cosmological data gives a large error.
Better use a parametrization:

$$w_{\rm DE}(z) = w_0 + \frac{z}{1+z} w_a$$



Planck XIV 2015
(Dark-energy paper)

Planck 2018+BAO+SNe:

w_0 only: $\quad w_0 = -1.0281 \pm 0.031$

(w_0, w_a) : $\quad w_0 = -0.961 \pm 0.077$

$$w_a = -0.28^{+0.31}_{-0.27}$$

Several studies of forecasts for w_{DE} at ET

Sathyaprakash, Schutz, Van Den Broeck 2009; Zhao, Van Den Broeck, Baskaran, Li 2011; Taylor and Gair 2012; Camera and Nishizawa 2013; Cai and Yang 2016; Belgacem, Dirian, Foffa, MM 2017,2018

typical assumptions:

- $O(10^3)$ BNS with em counterpart over 3 yr
- BNS distributed uniformly in comoving volume for $0<z<2$, or using a fit to the rate evolution
- generate a catalog of detections assuming a sensitivity curve for ET and SNR>8
- assume a fiducial cosmological model (ΛCDM) for $d_L(z)$
- scatter the data according to the error $\Delta d_L(z)$
- run a MCMC (or Fisher matrix) and use priors from CMB, BAO, SNe to reduce degeneracies between cosmological parameters

Result: not a significant improvement on w_{DE} compared with what we already know from CMB+BAO+SNe

A potentially more interesting observable?
Modified GW propagation

Belgacem, Dirian, Foffa, MM
1712.08108 ,1805.08731
Belgacem, Dirian, Finke, Foffa, MM
1907.02047, 2001.07619
Belgacem et al, LISA CosWG, 1907.0148?

in GR : $$\tilde{h}''_A + 2\mathcal{H}\tilde{h}'_A + k^2\tilde{h}_A = 0$$

$$\tilde{h}_A(\eta, \mathbf{k}) = \frac{1}{a(\eta)}\tilde{\chi}_A(\eta, \mathbf{k})$$

$$\tilde{\chi}''_A + \left(k^2 - a''/a\right)\tilde{\chi}_A = 0$$

inside the horizon $a''/a \ll k^2$, so $\tilde{\chi}''_A + k^2\tilde{\chi}_A = 0$

1. GWs propagate at the speed of light
2. $h_A \propto 1/a$ For coalescing binaries this gives $h_A \propto 1/d_L(z)$

In several modified gravity models:

$$\tilde{h}''_A + 2\mathcal{H}[1-\delta(\eta)]\tilde{h}'_A + k^2\tilde{h}_A = 0$$

This is completely generic in modified gravity:

(Belgacem et al., LISA CosmoWG, JCAP 2019)

- non-local modifications of gravity
- DGP
- scalar-tensor theories (Brans-Dicke, Horndeski, DHOST,..)
- bigravity

$$\tilde{h}''_A + 2\mathcal{H}[1-\delta(\eta)]\tilde{h}'_A + k^2\tilde{h}_A = 0$$

$$\tilde{h}_A(\eta,\mathbf{k}) = \frac{1}{\tilde{a}(\eta)}\tilde{\chi}_A(\eta,\mathbf{k}) \qquad \frac{\tilde{a}'}{\tilde{a}} = \mathcal{H}[1-\delta(\eta)]$$

$$\tilde{\chi}''_A + (k^2 - \tilde{a}''/\tilde{a})\tilde{\chi}_A = 0$$

and again inside the horizon $\tilde{a}''/\tilde{a} \ll k^2$

1. $c_{GW} = c$ ok with GW170817

2. $\tilde{h}_A \propto 1/\tilde{a}$

the ``GW luminosity distance" is different from the standard (electromagnetic) luminosity distance !

in terms of $\delta(z)$:

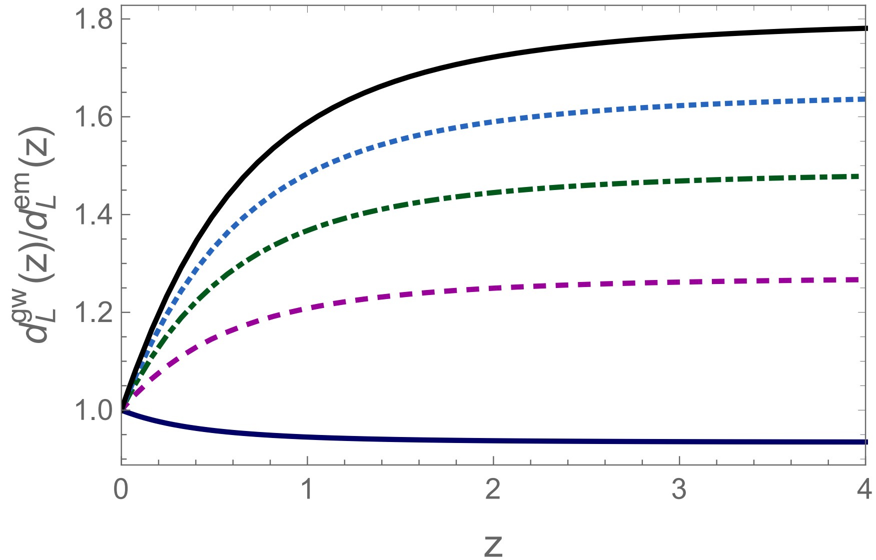
$$d_L^{\rm gw}(z) = d_L^{\rm em}(z) \exp\left\{ -\int_0^z \frac{dz'}{1+z'}\,\delta(z') \right\}$$

prediction of nonlocal gravity

(long term project

in the MM group)

80% effect at z>1 !!!



a general parametrization of modified GW propagation

Belgacem, Dirian, Foffa, MM
PRD 2018, 1805.08731

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

e.g. for the RT model in the best case $\Xi_0 \simeq 1.8\,, \quad n \simeq 1.9$

However, the parametrization is very natural, and indeed we find (LISA CosmoWG) that it fits the result of (almost) all modified gravity models

parametrizing extension of the DE sector:

background: (w_0, w_a); scalar pert: (Σ, μ) ; tensor pert: (Ξ_0, n)

for standard sirens, the most important parameters are w_0, Ξ_0

The observation of GW170817 already gives a limit modified GW propagation

Belgacem et al 2018

at low z:

$$\frac{d_L^{\rm gw}(z)}{d_L^{\rm em}(z)} = e^{-\int_0^z \frac{dz'}{1+z'}\,\delta(z')} \simeq 1 - z\delta(0)$$

- comparing directly d^{em} for the host galaxy (obtained from surface brightness fluctuations):

$$\delta(0) = -7.8^{+9.7}_{-18.4}$$

- comparing the values of H_0 inferred from GW170817 with the Riess et al. value from standard candles:

$$\delta(0) = -5.1^{+20}_{-11}$$

with mock catalogs of GW/GRB detection at HLVKI

produced in Belgacem, Dirian, Foffa, Howell, MM, Regimbau, 2019

z	d_L^{gw} (Mpc)	Δd_L^{gw} (Mpc)	$\Delta d_L^{gw}/d_L^{gw}$	$\Delta\delta(0)$
0.029271	134.815	4.000	0.030	1.36
0.035195	157.475	5.636	0.036	1.30
0.060585	283.567	18.706	0.066	1.25
0.066283	316.373	14.509	0.046	0.84
0.071053	327.381	20.085	0.061	1.00
0.071730	342.952	16.957	0.049	0.83
0.076180	341.595	22.360	0.065	0.99
0.081819	418.469	30.238	0.072	1.00
0.088698	396.734	25.757	0.065	0.84
0.091869	402.590	34.170	0.085	1.03
0.094237	406.423	31.472	0.077	0.93
0.095288	432.996	36.423	0.084	0.99
0.099956	491.071	31.721	0.065	0.75
0.102531	461.627	36.858	0.080	0.88
0.114869	626.939	43.010	0.068	0.68

Table 6. The events in a given realization of the mock catalog of joint GW-GRB detections for the HLVKI network, over 10 yr of simulated data. The 'measured' luminosity distance is obtained from the redshift assuming ΛCDM as fiducial model, and scattering randomly the fiducial values of $d_L^{gw}(z)$

the prediction of nonlocal gravity can be detected with 9 BNS with counterpart!

with mock catalogs of GW/GRB detection at ET/THESEUS

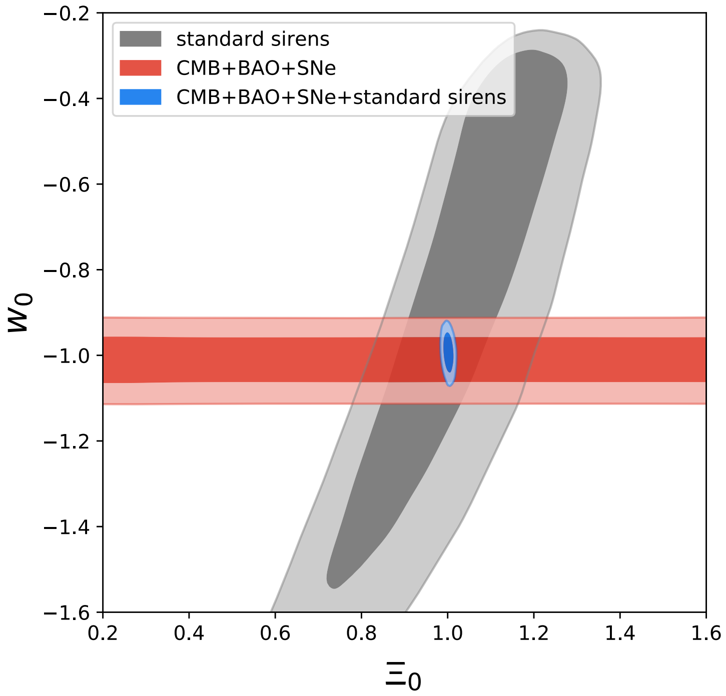
(in 10 yr of data)

redshift bin	number of joint GW-GRB events	mean redshift	mean $\Delta d_L^{gw}/d_L^{gw}$	$\Delta\Xi_0$
(0 , 0.1)	4	0.07108	0.00868	0.11
(0.1 , 0.2)	24	0.15001	0.01784	0.09
(0.2 , 0.3)	24	0.24043	0.02558	0.09
(0.3 , 0.4)	27	0.35355	0.03529	0.09
(0.4 , 0.5)	28	0.44966	0.04843	0.10
(0.5 , 0.6)	9	0.53785	0.05646	0.10
(0.6 , 0.7)	14	0.64540	0.05329	0.09
(0.7 , 0.8)	13	0.73793	0.05493	0.09
(0.8 , 0.9)	8	0.85497	0.06413	0.10
(0.9 , 1.0)	4	0.93702	0.06257	0.09
(1.0 , 1.1)	6	1.05334	0.06494	0.09
(1.1 , 1.2)	3	1.15162	0.06749	0.09
(1.2 , 1.3)	1	1.25943	0.07373	0.10
(1.3 , 1.4)	–	–	–	–
(1.4 , 1.5)	2	1.45375	0.07851	0.10
(1.5 , 1.6)	1	1.58407	0.07577	0.09
(1.6 , 1.7)	1	1.62843	0.07947	0.10

the prediction of nonlocal gravity can be detected with a single BNS with counterpart!

Forecasts for DE with ET from full MCMC

Belgacem, Dirian, Foffa, MM 2018



	$\Delta\, w_0$	$\Delta\, \Xi_0$
CMB+BAO+SNe+ET	0.032	0.008

ET can detect O(100-300) BNS with counterpart over a few years

Ξ_0 can be measured to better than 1%

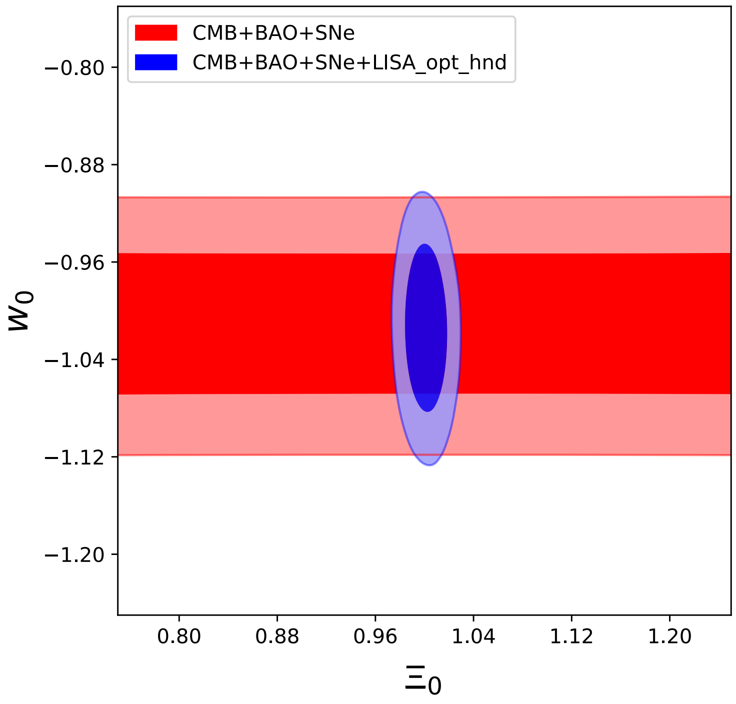
Forecasts for LISA

Belgacem et al LISA CosmoWG 2019

using supermassive BH binaries,

$\Delta\Xi_0$ =(1-4)%, Δw_0 =4.5%

(depending on formation scenarios for SMBH binaries)



Predictions for Ξ_0 from nonlocal gravity

- at the background level and for scalar perturbations, deviations from GR are bounded at the level (5-10)%

- one would expect similar deviations in the tensor sector
- instead, nonblocal gravity is a viable model where deviations can be 80% !

$\Longrightarrow$ GWs could become the best experiments for studying dark energy

Thank you!

Nonlocal IR modifications of gravity

a generic denomination for models in which the fundamental theory is local but non-local terms, relevant in the IR, emerge at some effective level

Example: DGP model (Dvali,Gabadadze, Porrati 2000)

$$S = \frac{1}{2} M_{(5)}^3 \int d^5X \sqrt{-G} R(G) + \frac{1}{2} M_{(4)}^2 \int d^4x \sqrt{-g} R(g)$$

linearizing over flat space $h_{\mu\nu}(x,y) = e^{-y\sqrt{-\Box}} h_{\mu\nu}(x)$

the resulting effective 4-dime theory (at the linearized level) is governed by (Dvali, Gabadadze, Shifman 2002)

$$\left(1 + \frac{m}{\sqrt{-\Box}}\right) G_{\mu\nu} = 8\pi G\, T_{\mu\nu}$$

example of how can emerge a nonlocal term, relevant in the IR, and associated to a mass scale

The quantum effective action is nonlocal and gauge-invariant (or diff-invariant) mass terms can be obtained with nonlocal operators

eg massive electrodynamics

Dvali 2006

$$\Gamma = -\frac{1}{4}\int d^4x \left(F_{\mu\nu}F^{\mu\nu} - m_\gamma^2 F_{\mu\nu}\frac{1}{\Box}F^{\mu\nu} \right)$$

in the gauge $\partial_\mu A^\mu = 0$ we have $\frac{1}{4} m_\gamma^2 F_{\mu\nu}\frac{1}{\Box}F^{\mu\nu} = \frac{1}{2} m_\gamma^2 A_\mu A^\mu$

it is a nonlocal but gauge-invariant photon mass term!

equivalently, $\left(1 - \frac{m_\gamma^2}{\Box}\right)\partial_\mu F^{\mu\nu} = 0 \quad \rightarrow \quad \begin{cases} \partial_\mu A^\mu = 0 \\ (\Box - m_\gamma^2) A^\mu = 0 \end{cases}$

- Numerical results on the gluon propagator from lattice QCD and OPE are reproduced by adding to the quantum effective action a term

$$\frac{m_g^2}{2}\mathrm{Tr}\int d^4x\, F_{\mu\nu}\frac{1}{\Box}F^{\mu\nu}$$

$$F_{\mu\nu} = F^a_{\mu\nu}T^a\,, \quad \Box^{ab} = D^{ac}_{\mu}D^{\mu,cb}\,, \quad D^{ab}_{\mu} = \delta^{ab}\partial_\mu - gf^{abc}A^c_\mu$$

(Boucaud et al 2001,Capri et al 2005,Dudal et al 2008)

it is a nonlocal but gauge invariant mass term for the gluons, generated dynamically by strong IR effects

Is it possible that a mass is dynamically generated in GR in the IR?

difficult non-perturbative question. Some hints:

- strong IR effects in de Sitter, especially for the conformal mode

  Antoniadis and Mottola 1991,1992; Tsmasis and Woodard 1995

- Euclidean lattice gravity suggests dynamical generation of a mass m, and a running of G_N

$$G(k^2) = G_N \left[1 + \left(\frac{m^2}{k^2} \right)^{\frac{1}{2\nu}} + \mathcal{O} \left(\frac{m^2}{k^2} \right)^{\frac{1}{\nu}} \right]$$

$\nu \approx 1/3$

Hamber 1999, .., 2017

- recent results based on causal dynamical triangulation find in the quantum effective action a mass for the conformal mode, just as in the model that we had previously postulated

  (Knorr and Saueressig PRL 2018)

- massive photon: can be described replacing

$$\partial_\mu F^{\mu\nu} = j^\nu \quad \to \quad \left(1 - \frac{m^2}{\Box}\right) \partial_\mu F^{\mu\nu} = j^\nu$$

(Dvali 2006)

- for gravity, a first guess for a massive deformation of GR could be

$$G_{\mu\nu} = 8\pi G T_{\mu\nu} \quad \to \quad \left(1 - \frac{m^2}{\Box_g}\right) G_{\mu\nu} = 8\pi G T_{\mu\nu}$$

(Arkani-Hamed, Dimopoulos, Dvali and Gabadadze 2002)

however this is not correct since $\nabla^\mu (\Box_g^{-1} G_{\mu\nu}) \neq 0$

we lose energy-momentum conservation

- to preserve energy-momentum conservation:

$$G_{\mu\nu} - m^2(\Box^{-1}G_{\mu\nu})^T = 8\pi G T_{\mu\nu}$$

(Jaccard,MM, Mitsou, 2013)

however, instabilities in the cosmological evolution

(Foffa,MM, Mitsou, 2013)

- $$G_{\mu\nu} - m^2(g_{\mu\nu}\Box^{-1}R)^T = 8\pi G T_{\mu\nu}$$

(MM 2013)

stable cosmological evolution ``RT model"

Extensive studies of the various possibilities have shown that it is the only known viable nonlocal model

- generates a dynamical DE and has stable cosmological perturbations in the scalar and tensor sectors

- fit CMB, BAO, SNe and structure formation data at a level statistically equivalent to ΛCDM

- passes solar system tests and bounds on time-variation of G

- predicts $c_{gw} = c$

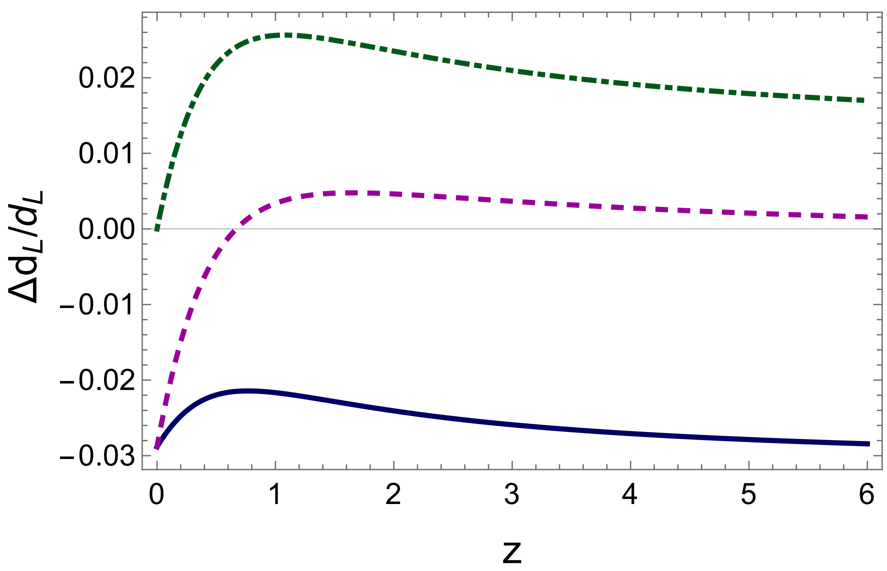
- predicts modified GW propagation

- implicit dependence on the number of efold during inflation through the initial conditions at ET and LISA this propagation effect dominates over that from the dark energy EoS !

recall that

$$d_L(z) = \frac{1+z}{H_0}\int_0^z \frac{d\tilde{z}}{\sqrt{\Omega_M(1+\tilde{z})^3 + \rho_{\rm DE}(\tilde{z})/\rho_0}}$$

(neglect radiation for standard sirens)



relative difference of e.m. luminosity distance RR-LCDM for the same values of Ω_M and H_0

relative difference with the respective best-fit parameters

relative difference of gw luminosity distance

Take-away message:

modified GW propagation can become a major science driver for 3G detectors and LISA

- it is specific to GW observations
- Ξ_0 can be measured with better accuracy than w_0
- there are phenomenologically viable models with large deviations from GR in the tensor sector

GW detectors could offer the best window on dark energy and modified gravity!