ET Key Science

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Next Gen GW Gathering,
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obvious ET-CE synergies on observational Science :

- building together a compelling Science Case

The GWIC 3G Science Case Team Consortium, 3G Science Case

(coordinated by Sathya, Vuk, contributors from both US and EU communities, several parts used for the Astro2020 decadal survey)

Science Case for the Einstein Telescope

(coordinated by MM, 1912.02622, JCAP 2020)

A summary of the Science of 3G

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

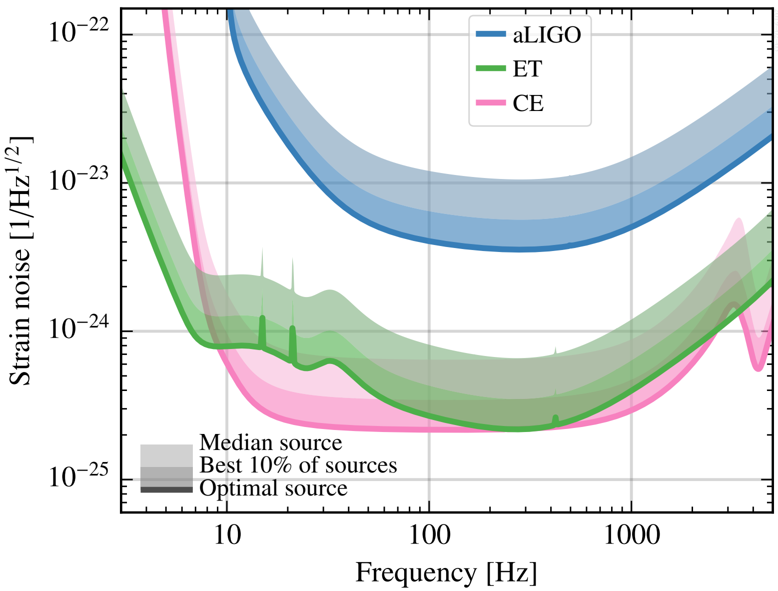
- Dark matter
  - primordial BHs
  - axion clouds, dark matter accreting on compact objects

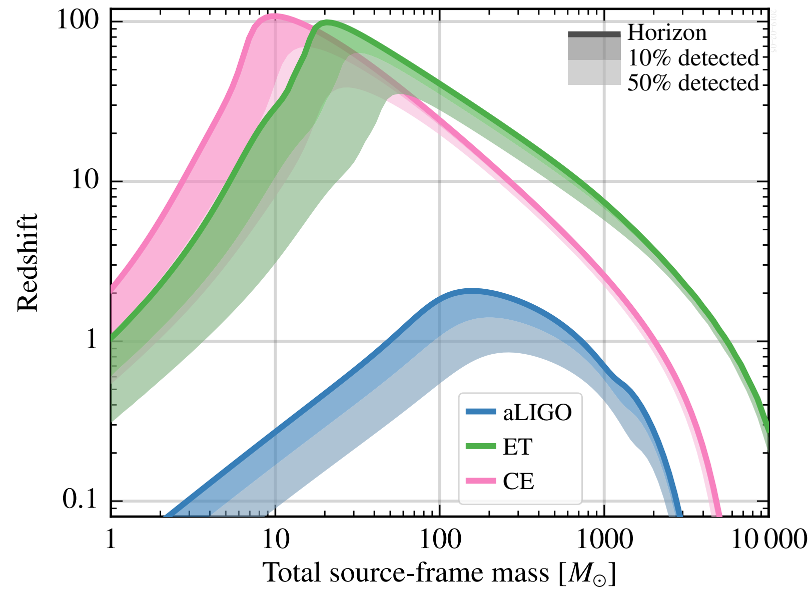
- Dark energy and modifications of gravity on cosmological scales
  - DE equation of state
  - modified GW propagation

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

... and we should not forget that ET/CE will be `discovery machines’

Expect the unexpected!





3G Science book, and Astro2020, Sathyaprakash et al 2019

- BBH to z ≈ 20

  10^6 BBH/yr

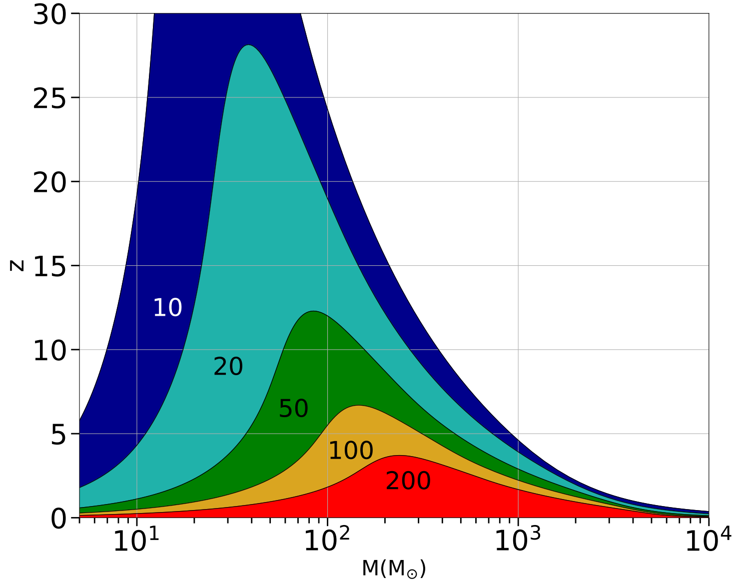
  masses up to 10^3 $M_\odot$

- BNS to z ≈ 2

  10^5 BNS/yr

  (15-50/yr with counterpart)

- high SNR



SNR for ET+CE+CE, courtesy Colpi and Mangiagli

The combination of

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

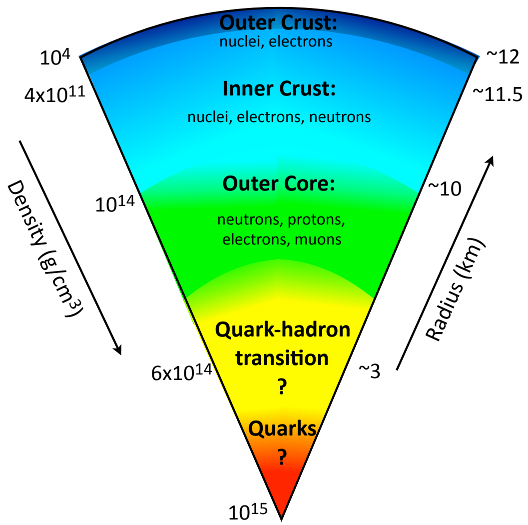
will provide a wealth of data that have the potential of triggering revolutions in astrophysics, cosmology and fundamental physics

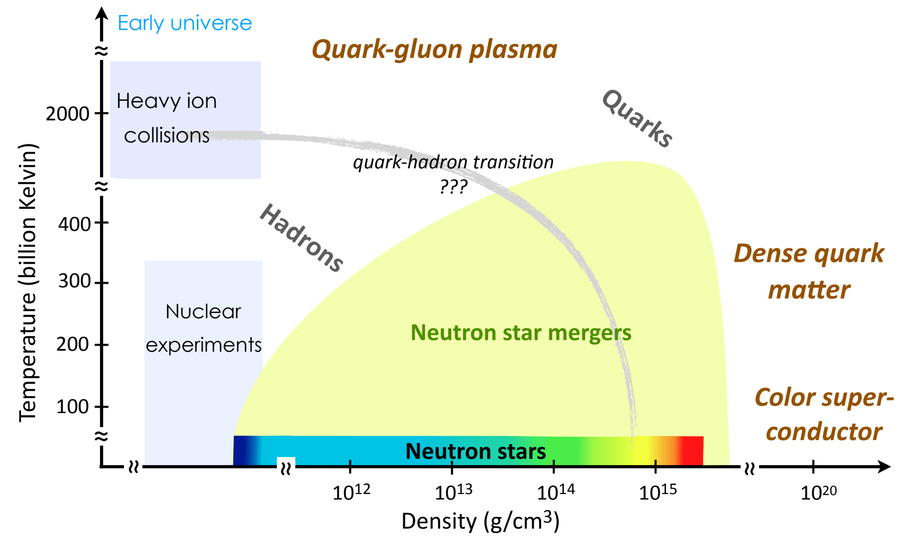
Astrophysics with BBH

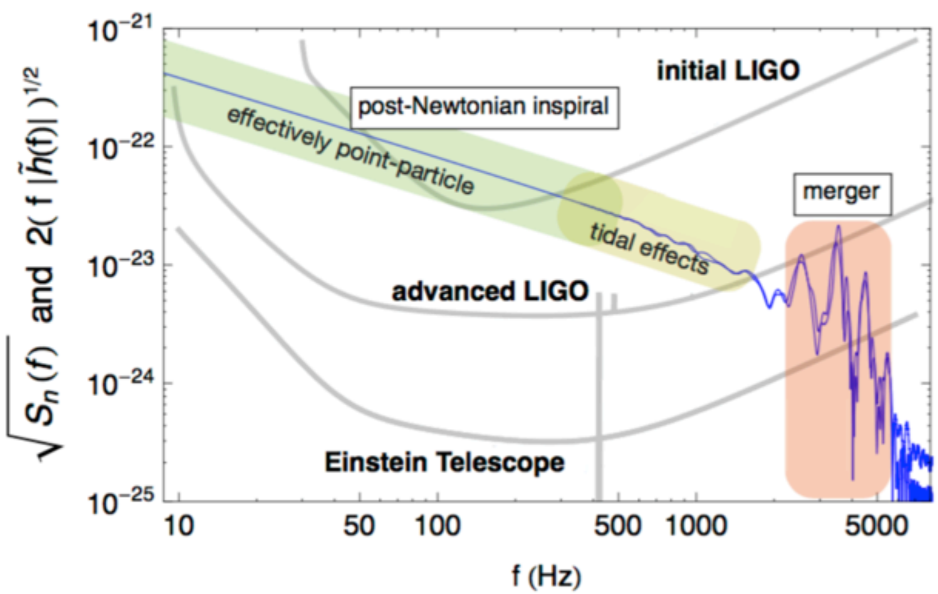
ET/CE will uncover the full population of coalescing stellar BBH since the end of the cosmological dark ages

- 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



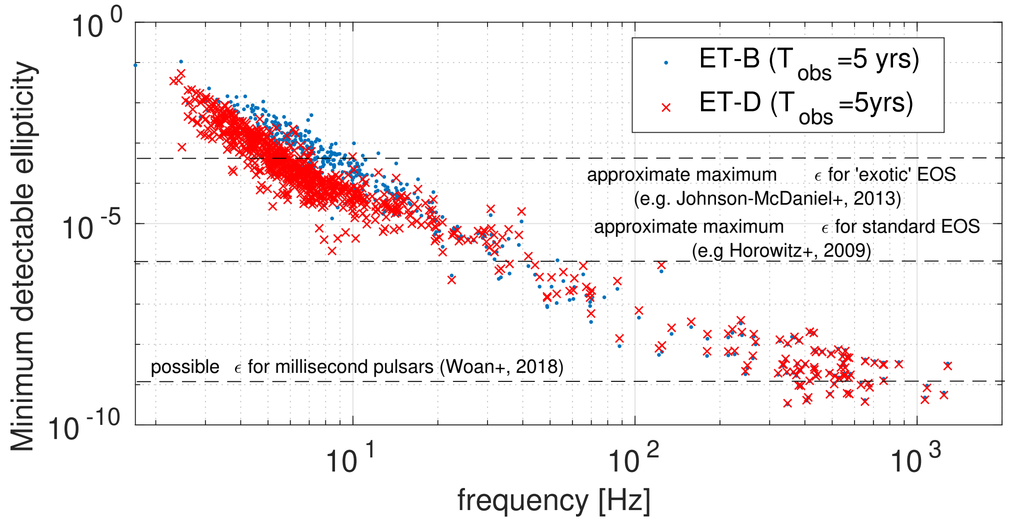




BNS merger @100 Mpc

(adapted from J. Read)

Continuous GWs from isolated NS

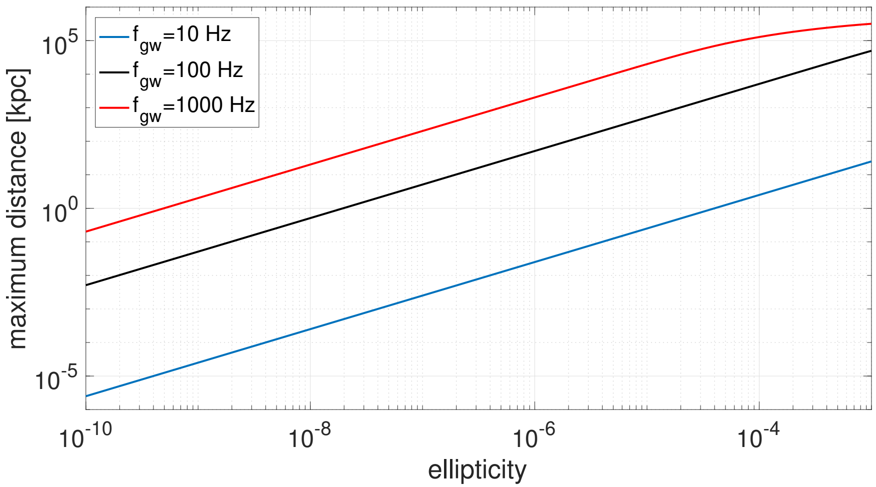


Minimum detectable ellipticity for known pulsars

depends on the internal structure and EoS at high density

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 !!



Multi-messenger astronomy

- main aims: formation, evolution and multi-messenger emission mechanism of neutron stars (kilonovae, short GRBs)

  star formation history, chemical evolution of the Universe

- Low z:

  higher SNR → constrains on EOS (from info progenitors and remnant)

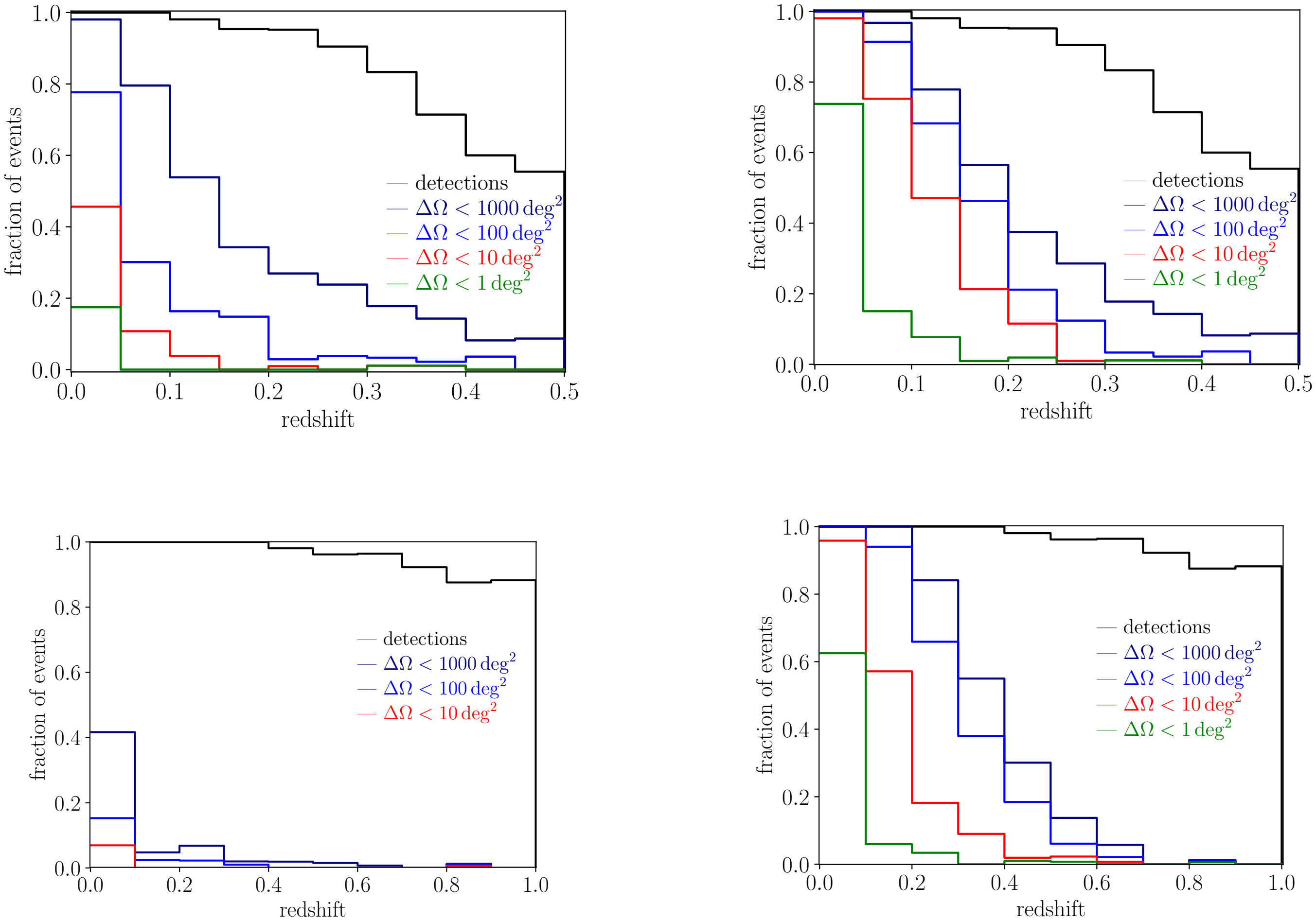
  Golden sample of detection with localization < 1 deg^2

  → possibility to detect the kilonova with the second generation instruments of ELT such as MOSAIC

- High-z: benefits in operating with high-energy satellites able to localize GRBs (large sample of detection for cosmology, GRB emission mechanism, jet physics)

  e.g. THESEUS is expected to detect 20-40 short GRB/yr within 1’ – 5’

with ET alone: at low z, large benefit from operating with 2G



BNS

BBH

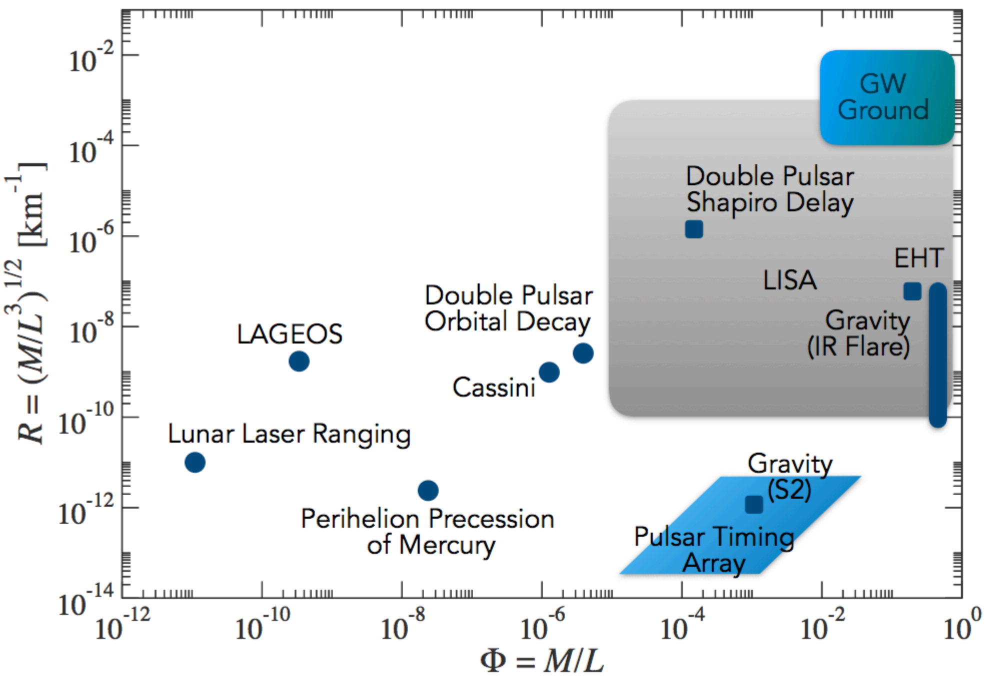
ET

ET+2G

results by M. Branchesi, S. Grimm, J. Harms, in the ET Science Case paper

Fundamental physics/ cosmology

scales probed by gravity experiments



from Sathyaprakash et al.
Astro2020, 1903.09221

BH quasinormal modes and Exotic Compact Objects

several proposal for exotic compact objects:
(boson stars, stars made of dark matter particles...)
are distinguishable because of the QNM

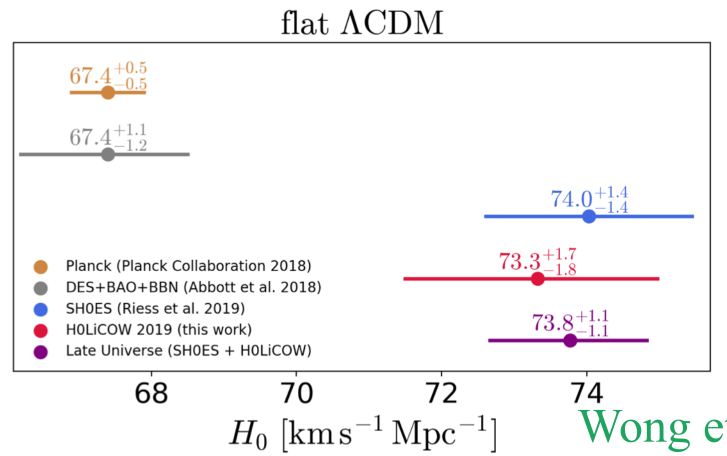
more speculative: quantum gravity effect near the BH horizon?
(Hawking information paradox, firewalls, etc.)

echos:

$$\tau_{\rm echo} \simeq \frac{R_S}{c} \log(R_S/\ell_{\rm Pl})$$

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

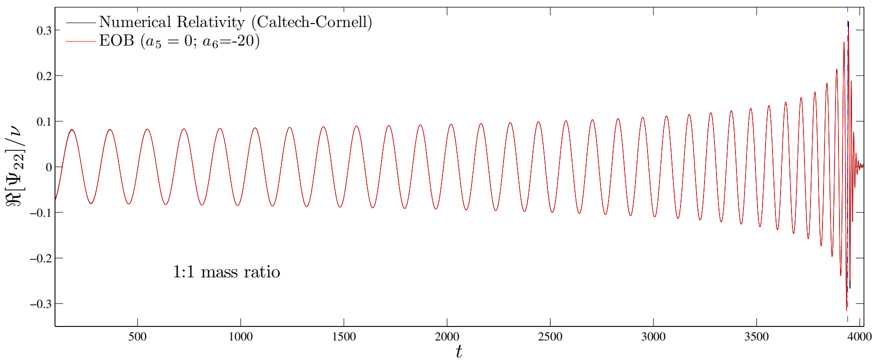
w_{DE},
modified GW propagation

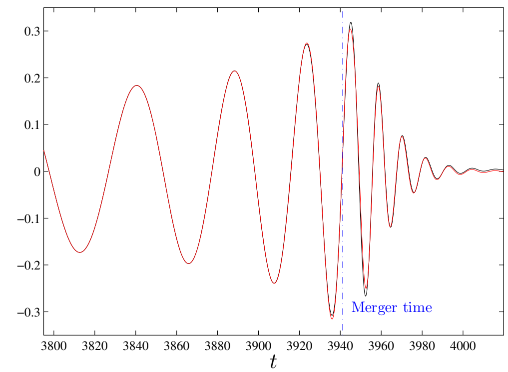
Ideas for the future: developing in more technical detail the science for 3G

- theoretical ideas usually apply equally well to ET and CE

- (loose) form of coordination for people working on predictions/forecasts?
  - eg sensitivity curves, network configurations,
  - repository of useful works
  - questions for the community at large (what is important/urgent to address?)

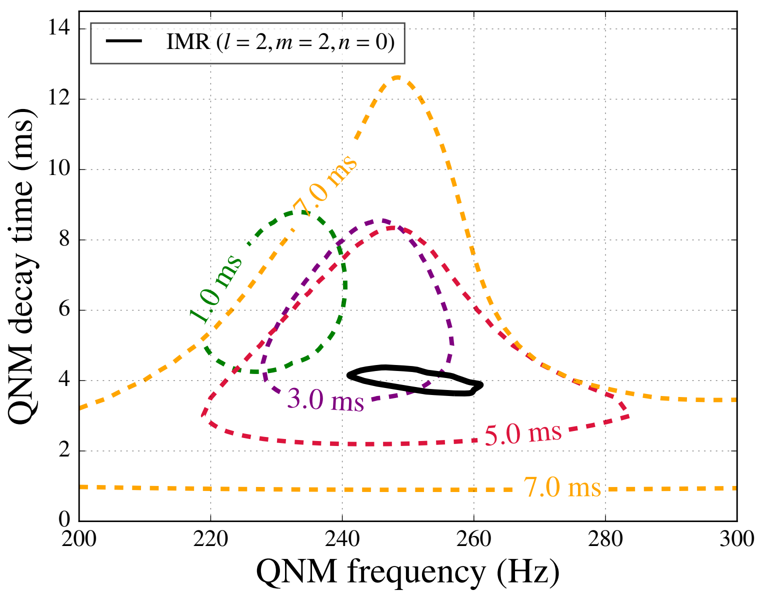
bkup slides

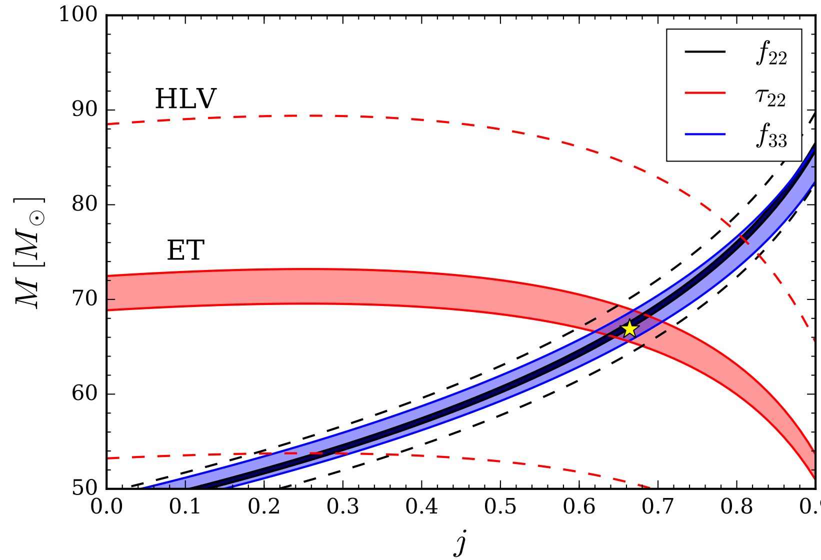




From GW150914:

at ET:





consistent with GR, but we cannot say much more

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

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

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

in terms of $\delta(z)$:

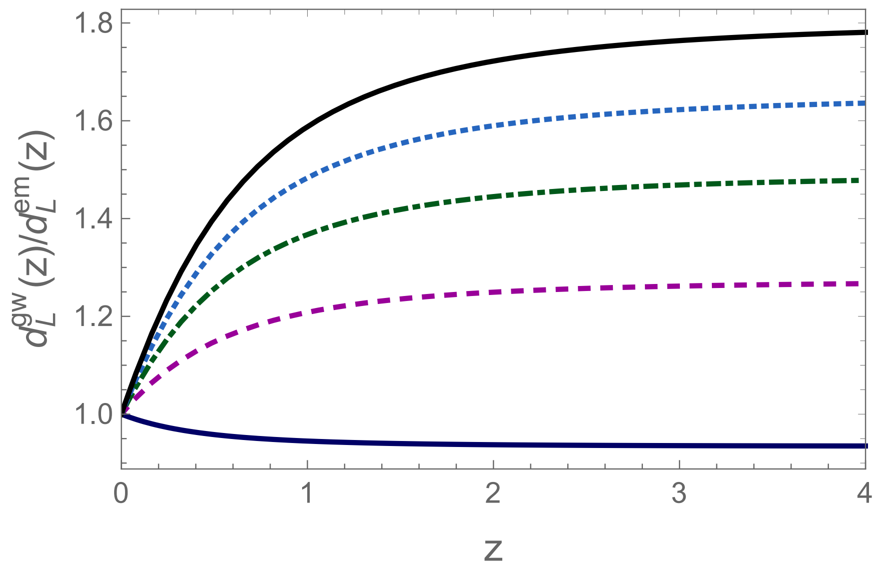
$$d_L^{\rm gw}(z) = d_L^{\rm em}(z) \exp\left\{ - \int_0^z \frac{dz'}{1+z'}\,\delta(z') \right\}$$

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

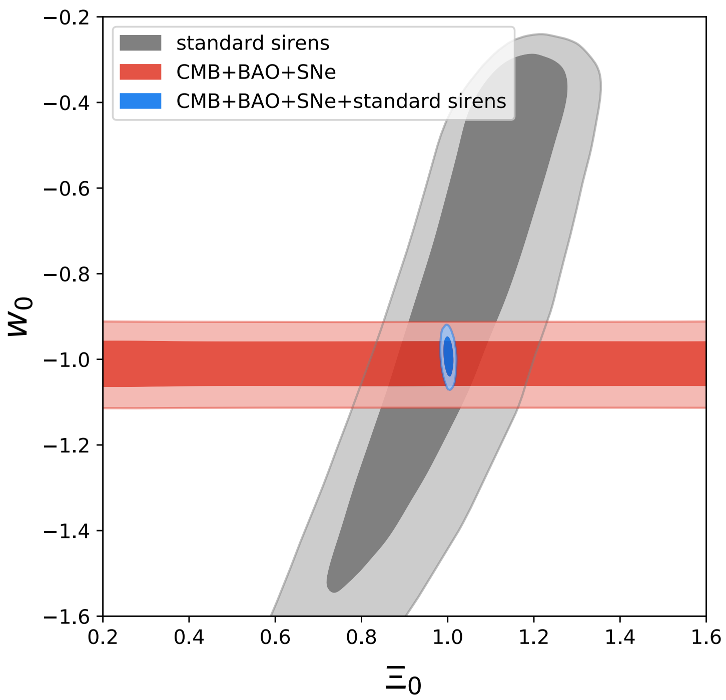
parametrizing extension of the DE sector:

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

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)