Einstein Telescope and synergies with THESEUS

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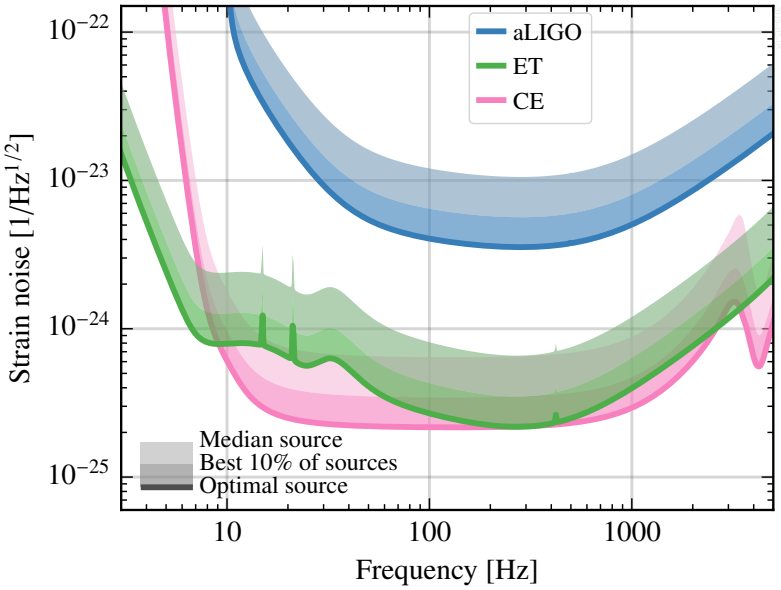
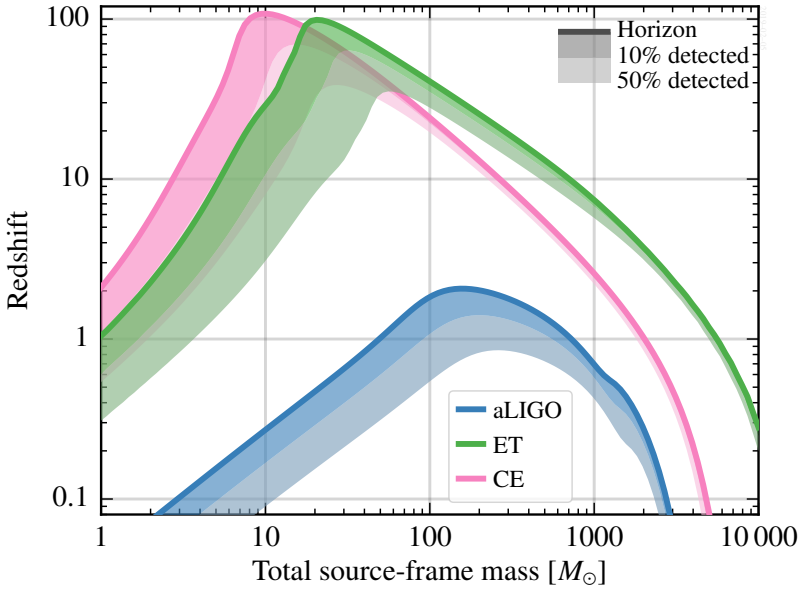
Einstein Telescope: motivations

2G detectors (adv LIGO/Virgo) have opened a new window on the Universe

Thanks to an order of magnitude better sensitivity and a wider frequency,

3G detectors (ET, CE) will allow us to address a huge number of key issues related to astrophysics, fundamental physics and cosmology





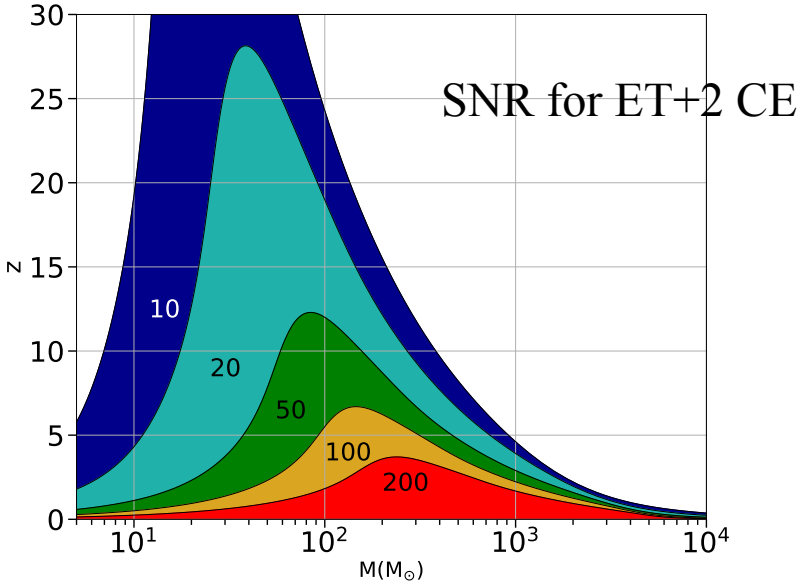
- BBH to z ≈ 20

  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



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

for more detail,
MM et al
"Science Case for the Einstein Telescope",
JCAP 2020, 1912.02622

- 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)
- 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

  DE equation of state, modified GW propagation

- Stochastic backgrounds

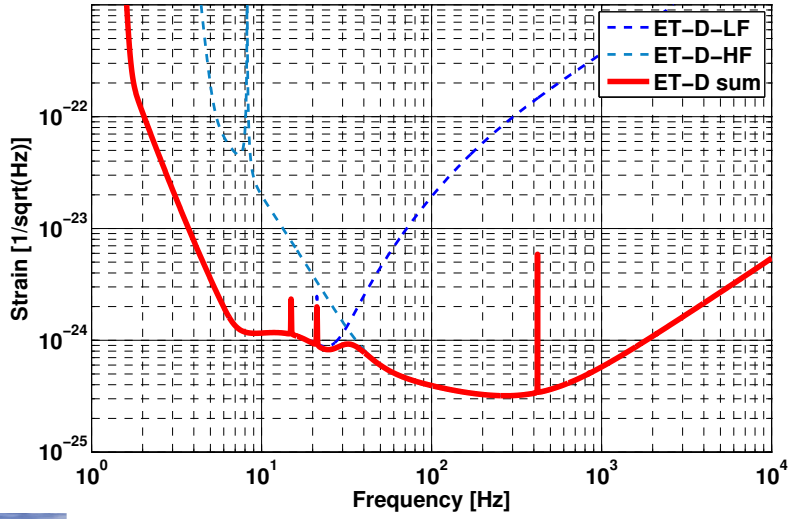
  inflation, phase transitions, cosmic strings, ...

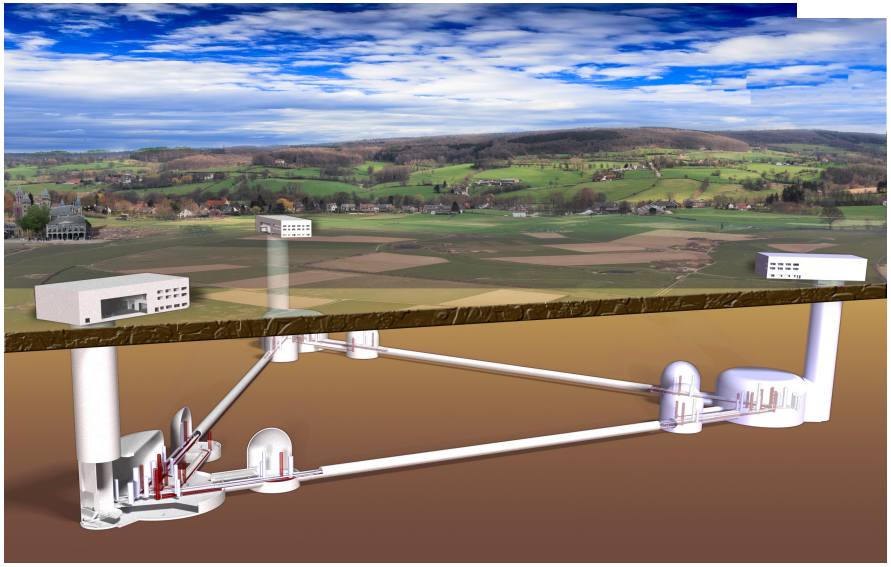
... and we should not forget that ET will be a `discovery machine'

Expect the unexpected!

ET: the concept

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





Two remaining candidate sites:

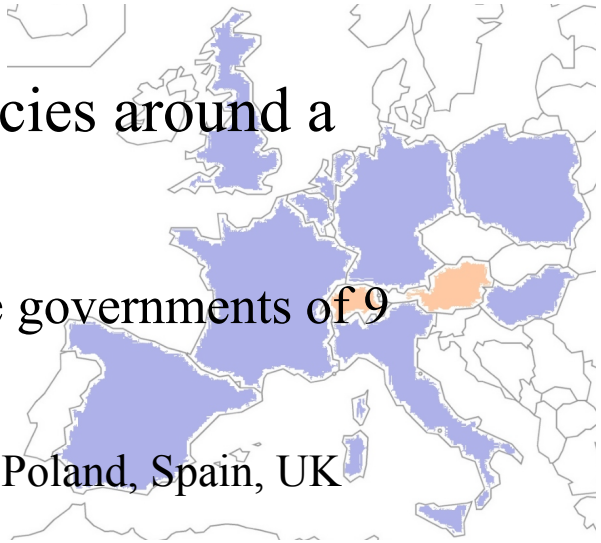
- Sos Enattos mine in Sardinia
- the Meuse-Rhine border region between the Netherlands, Belgium and Germany

ET status

- ET activities in the last year focused on:
  - Preparation and submission of the ET-ESFRI proposal
  - Characterisation of the two sites candidate to host the ET infrastructure

- ET-ESFRI proposal is ready
  - We updated the ET Research Infrastructure design, the ET science document and the ET cost book

- Large organisation effort to coagulate the agencies around a common project
  - ESFRI proposal is at the level of governments
  - Currently we submitted our draft proposal to the governments of 9 European countries
    - Italy (Leading country)
    - Belgium, France, Germany, Hungary, Netherlands, Poland, Spain, UK (Perspective countries)
    - Institutions of other 2 countries (Austria and Switzerland) have expressed interest to contribute



Synergies with THESEUS: astrophysics

- Relativistic astrophysics and short GRBs

  on axis/off axis prompt and afterglow,

  GW or THESEUS triggered

- X-ray transients powered by NS merger remnant

- nucleosynthesis and kilonovae

- SNe

Synergies with THESEUS: Cosmology

- GW detections of coalescing binaries measure d_L

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

need an independent determination of z

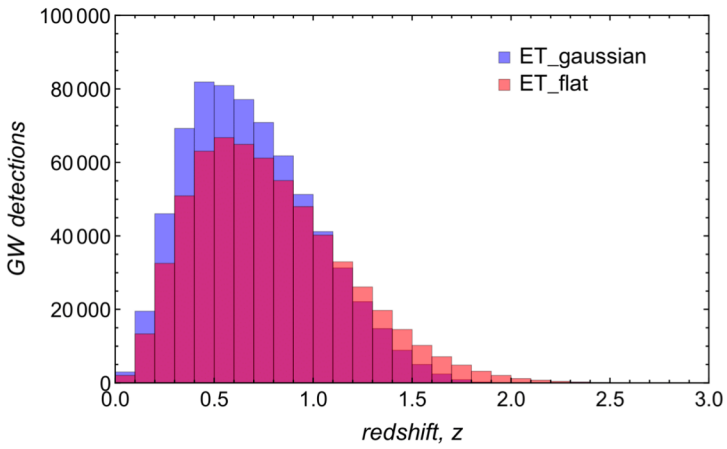
- low z: $d_L \simeq H_0^{-1} z$ H_0 tension
- moderate z: dark energy
  modified GW propagation

Activities in this direction:

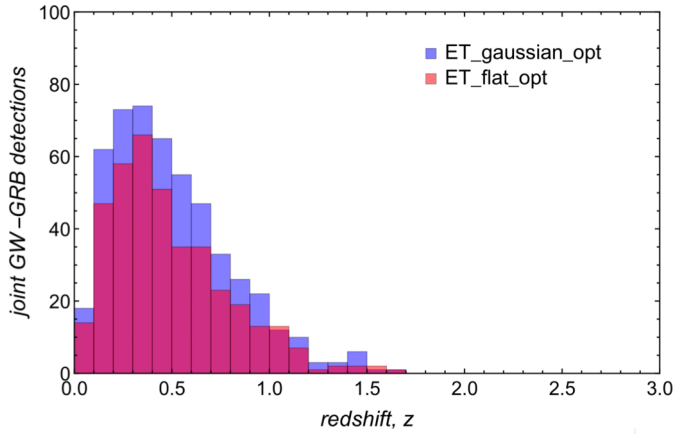
study of coincidence between THESEUS and ET or ET+2CE

Stratta, Amati, Ciolfi, Vinciguerra, 1802.01677

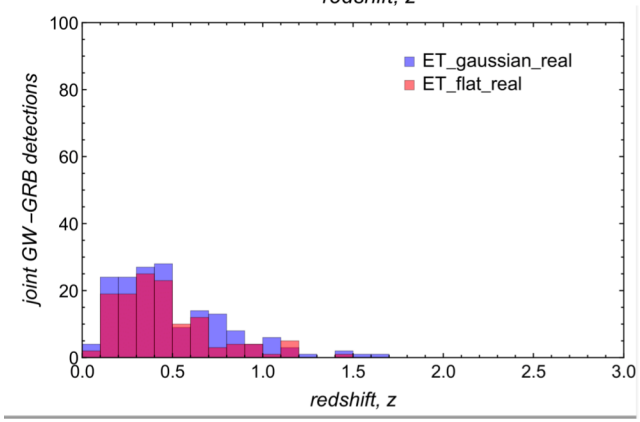
Belgacem, Dirian, Foffa, Howell, MM, Regimbau, 1907.01487



generated 10 yr of
simulated data to have statistics
(from Belgacem et al)



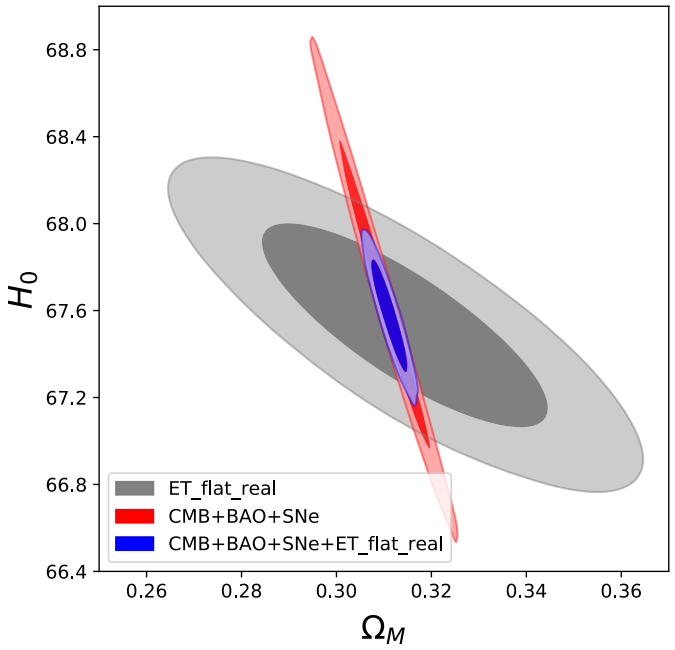
optimistic:
all events detected
by XGIS have
measured z

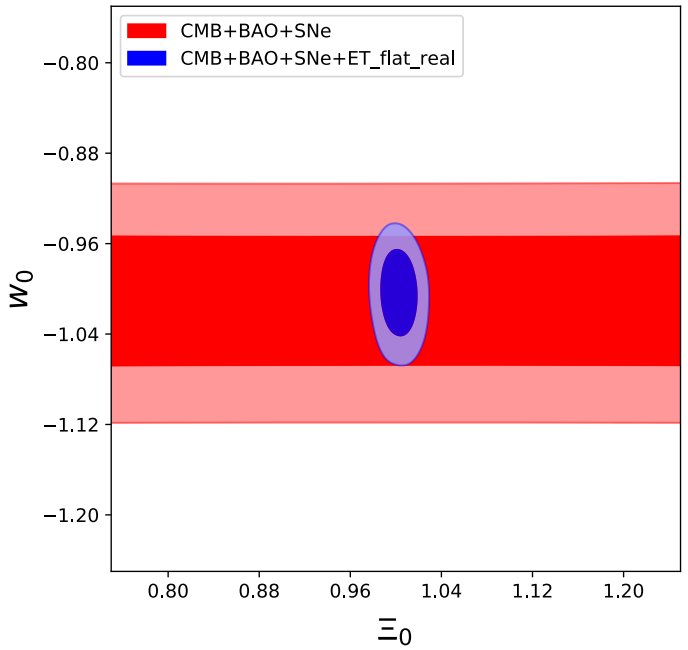


realistic:
1/3 of the events
have measured z

applications to H_0, w_0 and modified GW propagation (Ξ_0)

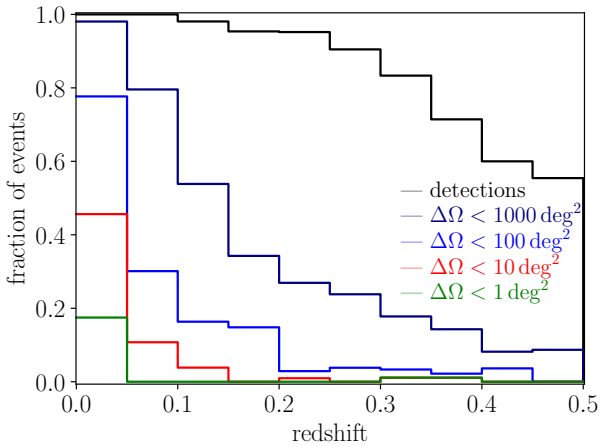
(Belgacem et al)

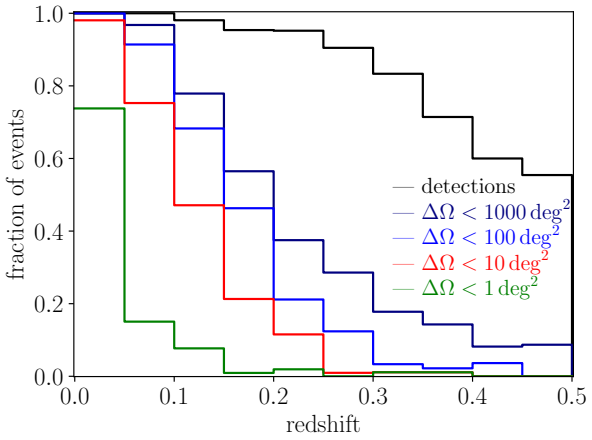




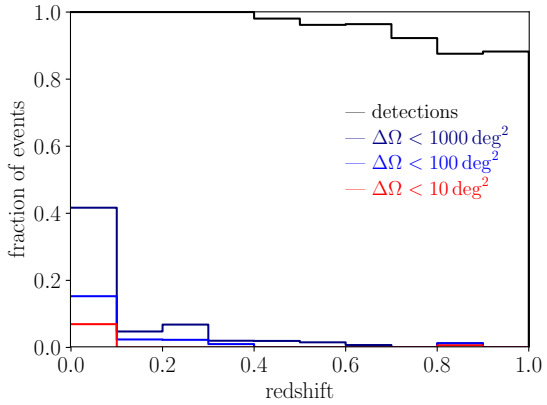
$\Delta H_0/H_0 = 0.7\%$

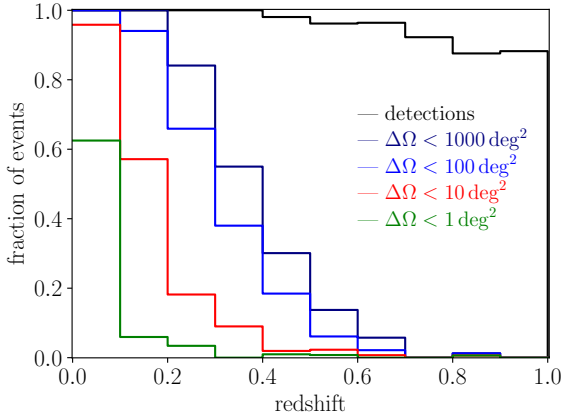
Angular resolution of the GW network is a crucial factor





BNS





BBH

ET

ET+2G

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

thank you!

bkup slides

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

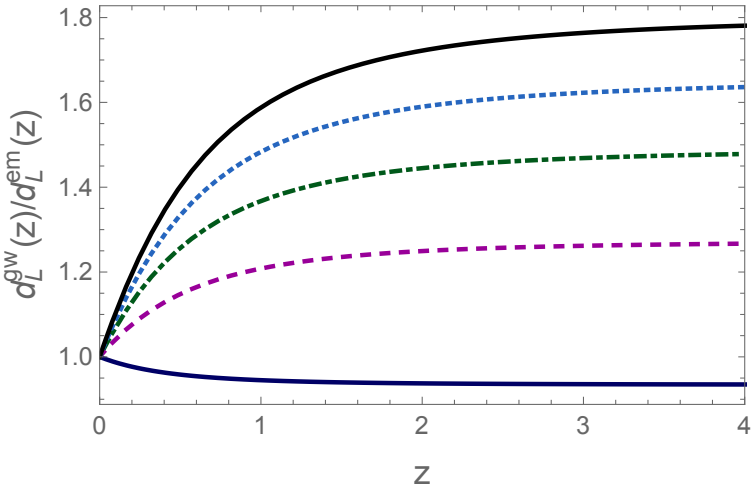
the ``GW luminosity distance'' is different from the standard (electromagnetic) luminosity distance !

in terms of δ(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 !!!

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



Astrophysics with BBH

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

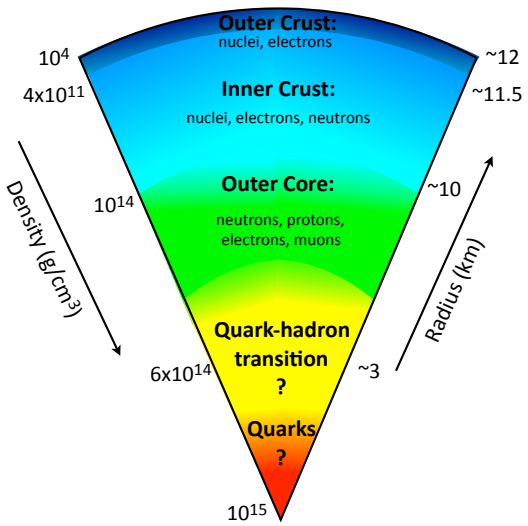
(a single BBH has a peak luminosity higher than the integrated em luminosity of the observable Universe!)

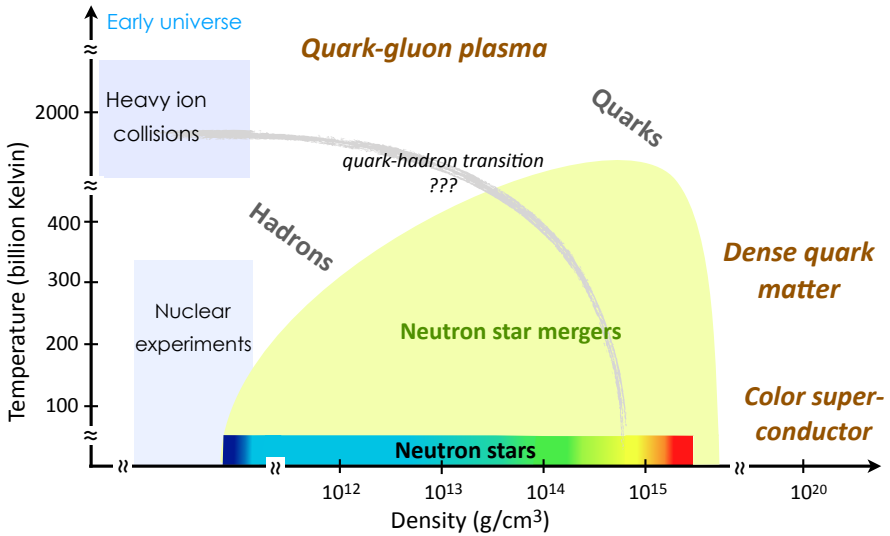
- contribute to uncover the star-formation history of the Universe

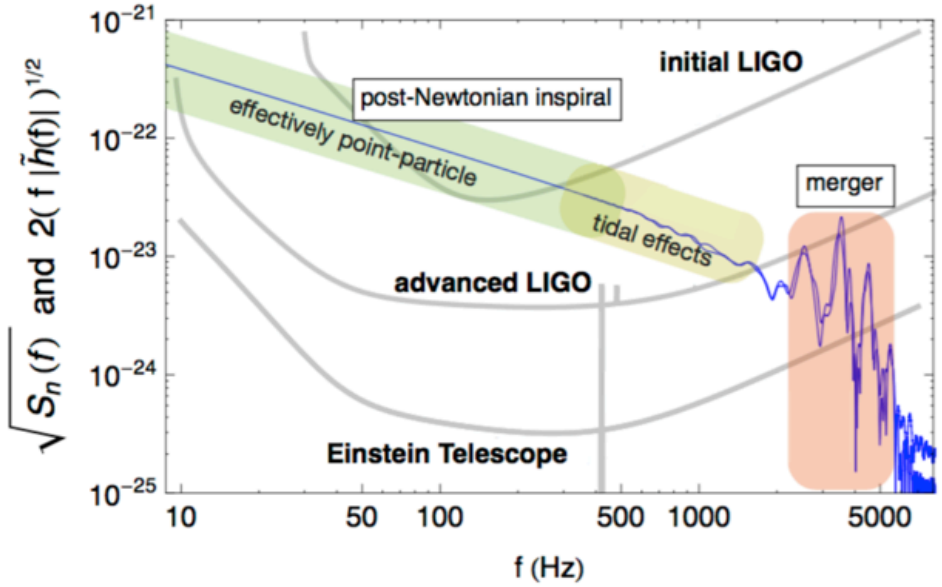
- disentangle stellar origin from primordial BH
  - compare redshift dependence with SFR determined electromagnetically
  - PBH should trace the distribution of DM rather than of baryons
    the large number of detections will allow cross-correlations
  - any stellar-mass BBH at $z > 10$ will be primordial

- discover seed BHs with $M=O(10^3)\ M_\odot$

QCD with neutron stars



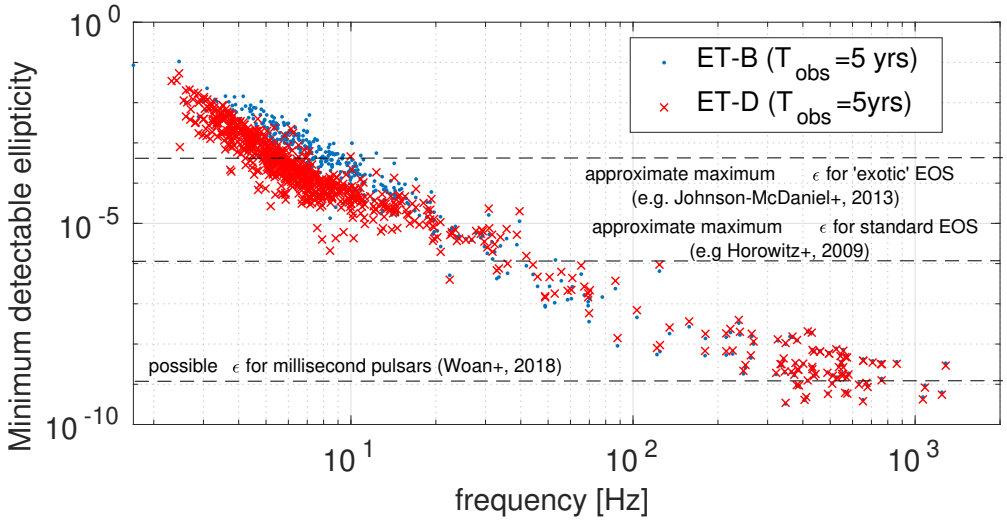




BNS merger @100 Mpc

(adapted from J. Read)

Continuous GWs from isolated NS

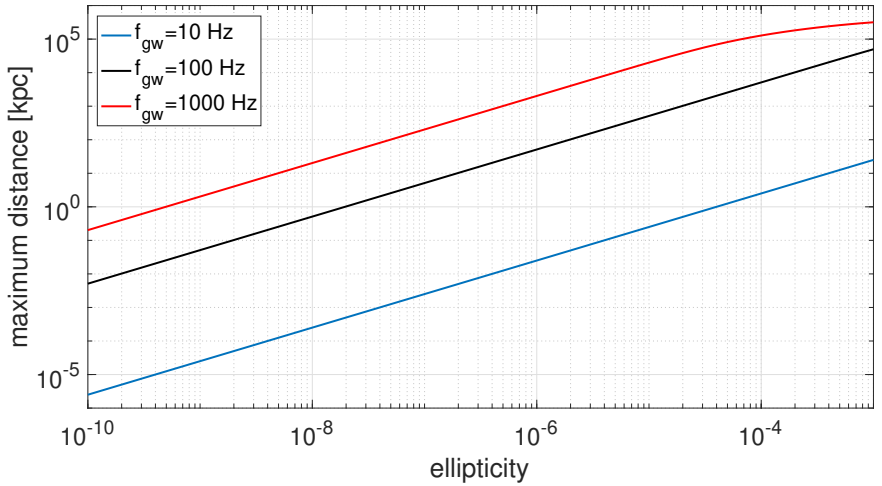


Minimum detectable ellipticity for known pulsars

depends on the internal structure and EoS at high dnesity

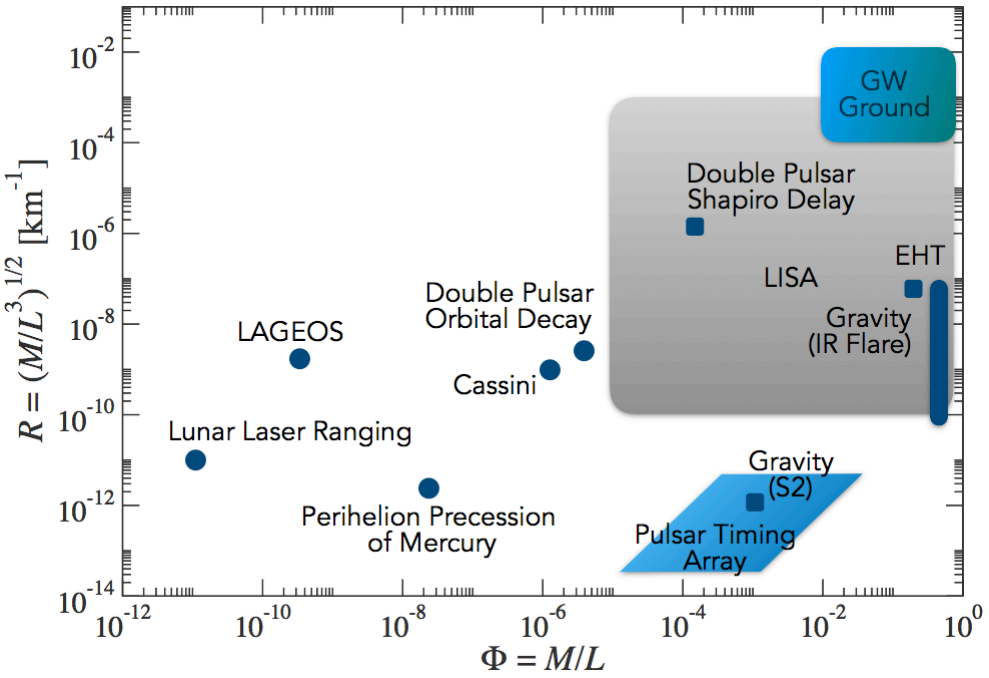
detecting GWs due to $\varepsilon = 10^{-7}$ means that we detect the effect of a ``mountain'' on a NS with height

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



Fundamental physics/ cosmology

scales probed by gravity experiments



from Sathyaprakash et al. 1903.09221

BH quasinormal modes and Exotic Compact Objects

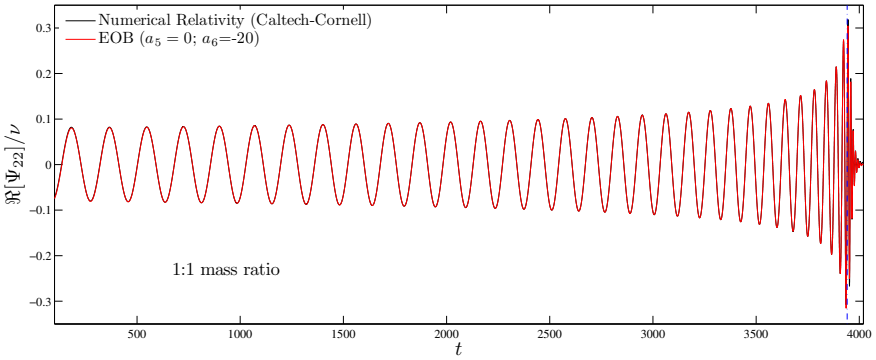
BH have QNM: they represent the elasticity of space-time

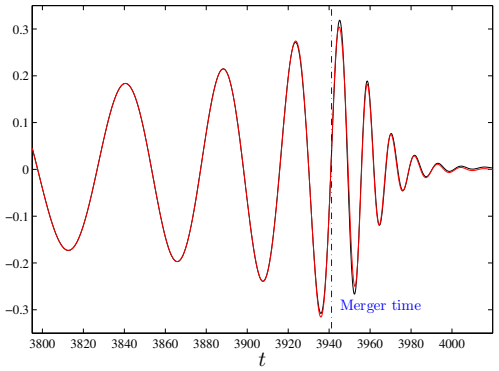
in a regime of strong gravity

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

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

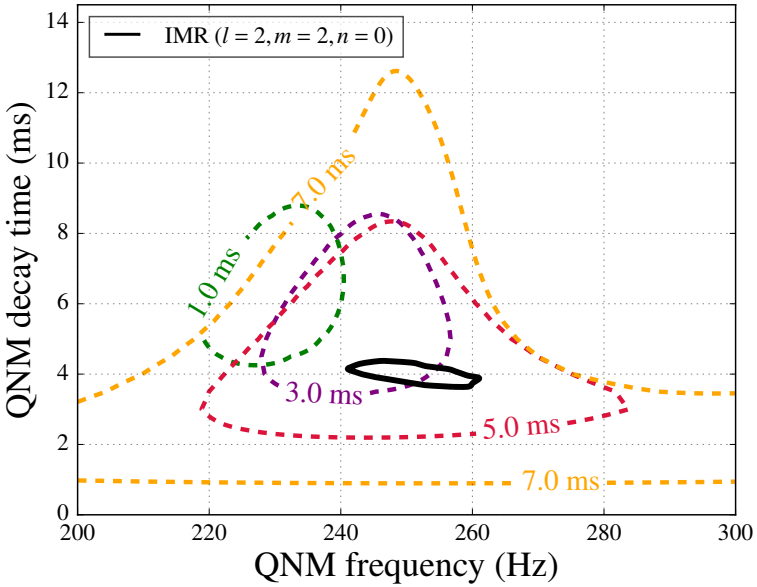
several proposal for ECOs (boson stars, stars made of DM particles...) are distinguishable because of the QNM

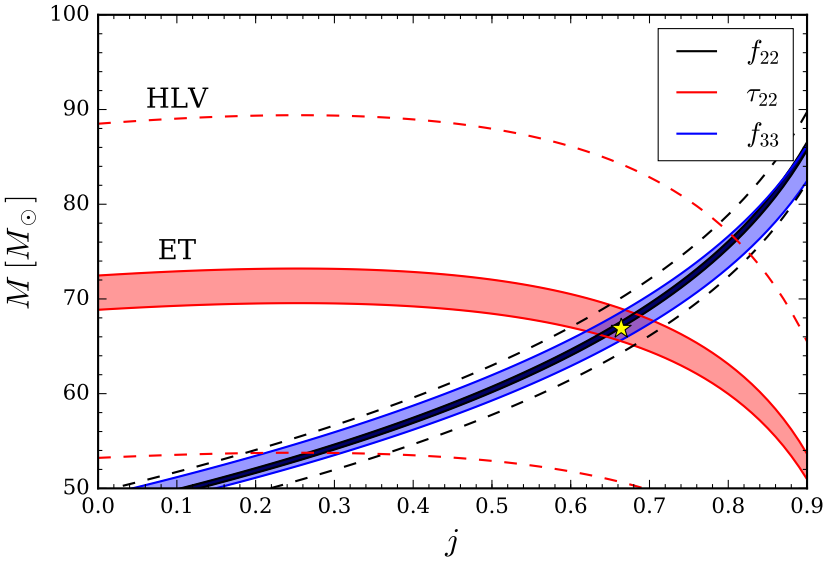




From GW150914:

at ET:





consistent with GR, but we
cannot say much more