The Science Case for the Einstein Telescope

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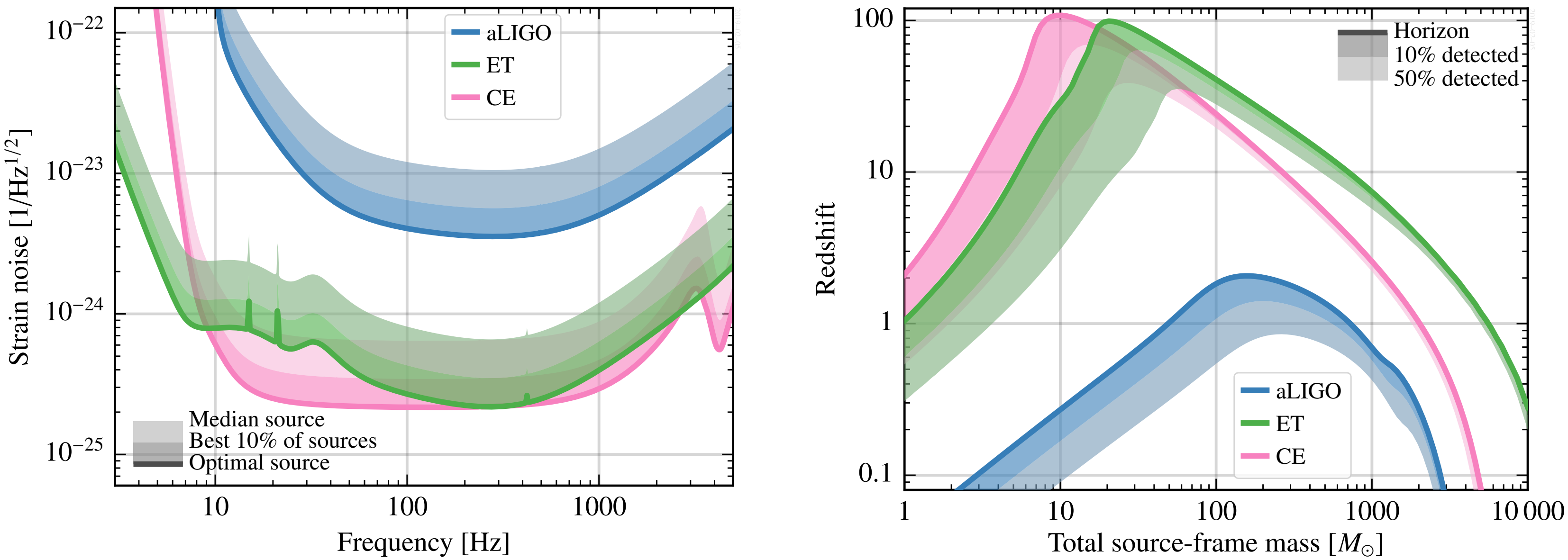
2G detectors have opened a new window:
3G detectors ground-based detectors (ET, CE)
will look deeply into this window

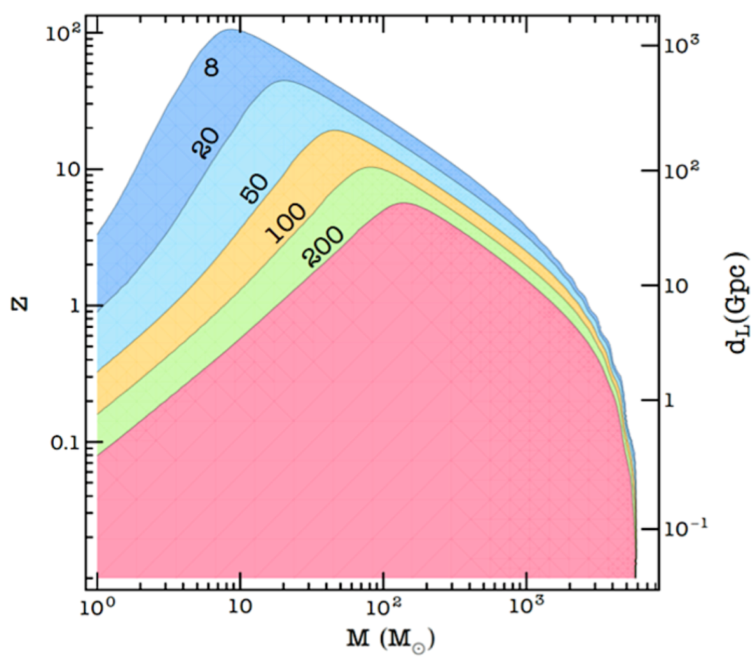
We will focus on the science that can be done with ET

based on
MM et al "Science Case for the Einstein Telescope", JCAP, 1912.02622



Evans and Hall 2019

- BBH up to z ≈ 50 !!
  10^6 BBH/yr
  masses up to 10^3 $M_\odot$
- BNS to z ≈ 2 10^5 BNS/yr
  (possibly O(10-100/yr)
  with counterpart)
- high SNR



Detection distance of BBHs

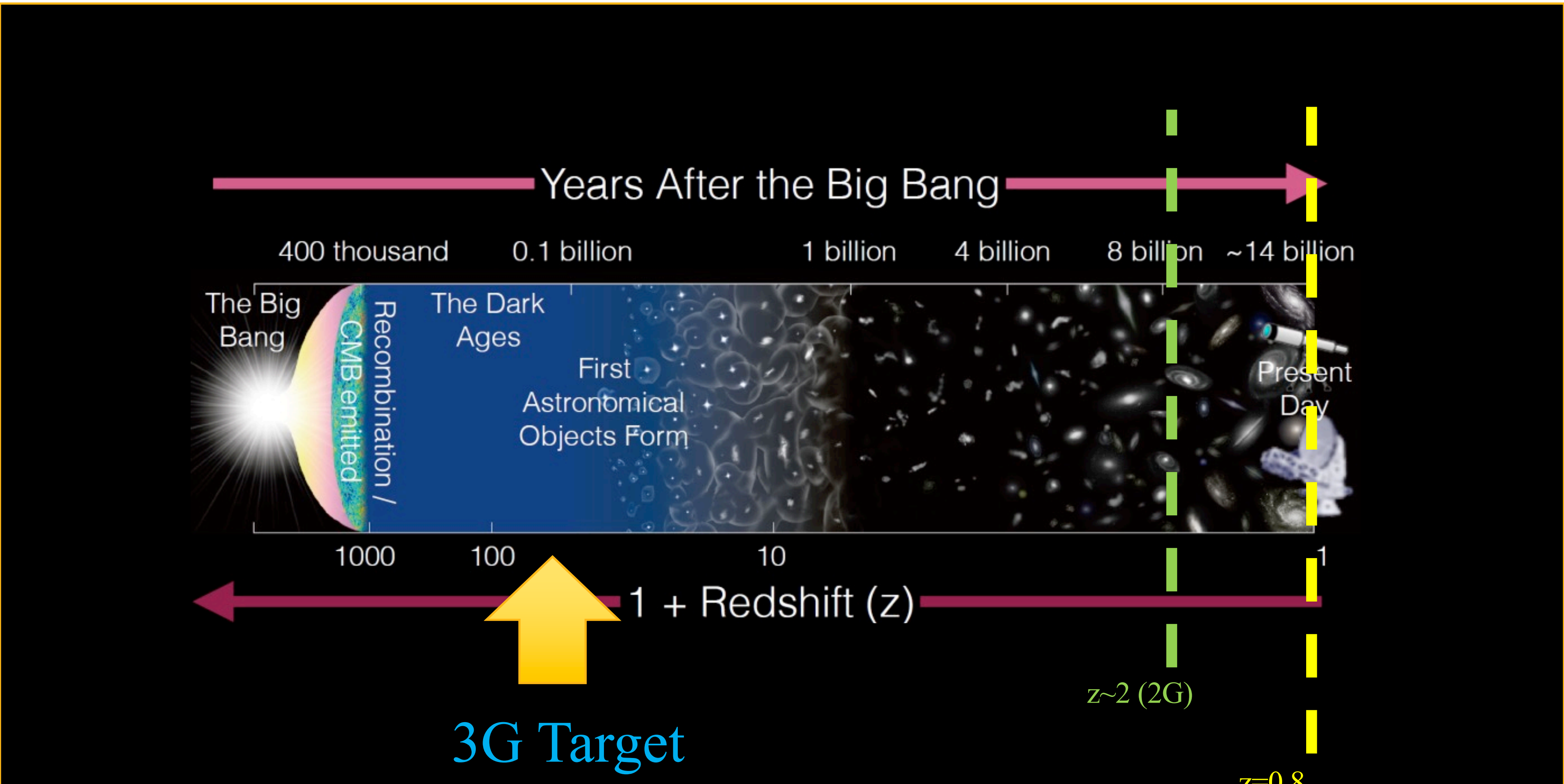


Image credit: NAOJ/ALMA http://alma.mtk.nao.ac.jp/

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
  - demography, equation of state
- 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

- testing the nature of gravity
  - perturbative regime

    inspiral phase of BBH, post-Newtonian expansion
  - strong field regime

    physics near BH horizon

    exotic compact objects

- QCD

  interior structure of neutron stars probe:
  - QCD at ultra-high temperatures and densities
  - exotic states of matter

- Dark matter/new particles
  - primordial BHs
  - axions, 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!

In the following, we elaborate just on some
`selected highlights'
focusing on high-risk/high gain

1. The nature of Gravity

BHs are one of the most extraordinary predictions of GR

(e.g. $10M_{\odot}$ concentrated in 30 km)

but, how can we be sure that the compact objects observed by LIGO/Virgo are the BHs predicted by GR?

- can we `quantify' the existence of horizons?
- can we test the existence of Exotic Compact Objects?

no shortage of proposals in the literature:

boson stars (self-gravitating fundamental fields)

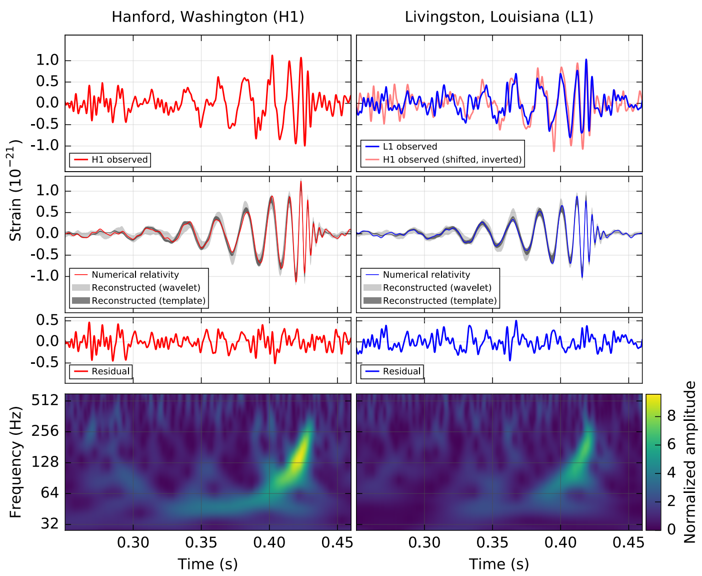
firewalls, fuzzballs... (quantum effects near the horizon motivated by the Hawking information loss problem):

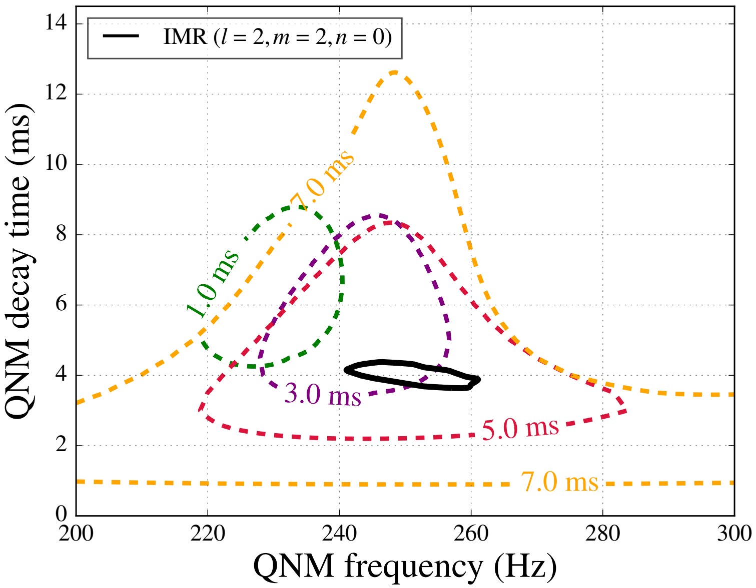
BH quasi-normal modes (QNM)

the elasticity of space-time in the regime of strong gravity!

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

classic chapter of GR: Regge-Wheeler, Chandrasekhar, Teukolsky...

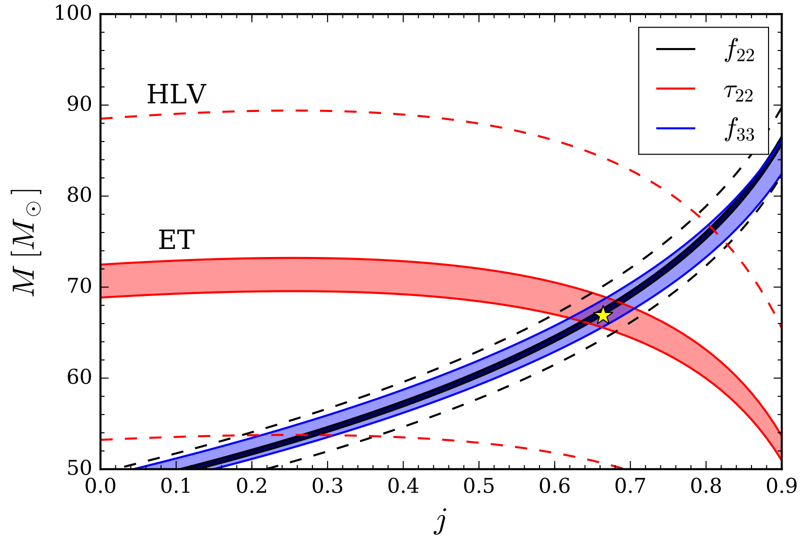




already observed in GW150914 (LVC)

consistent with GR, but we cannot say much more

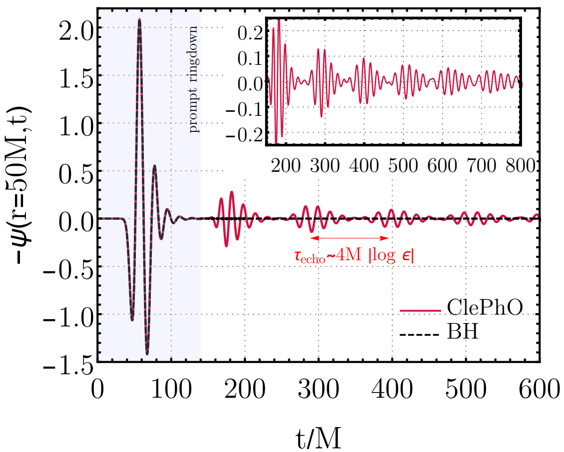
BH quasi-normal modes at ET



3G Science Book, adapted from Brito, Buonanno, Raymond 2018

- accurate BH spectroscopy already from single events
- 10^4-10^5 events/yr with detectable ringdown
- 20-50 events/yr with detectable higher modes

Echoes from Exotic Compact Object



Cardoso, Franzin, Pani 2016

$$\tau_{\rm echo} = (2R_S/c)\log(R_S/\ell_{\rm new\ physics})$$

even possible to have signals from the Planck scale. Eg:

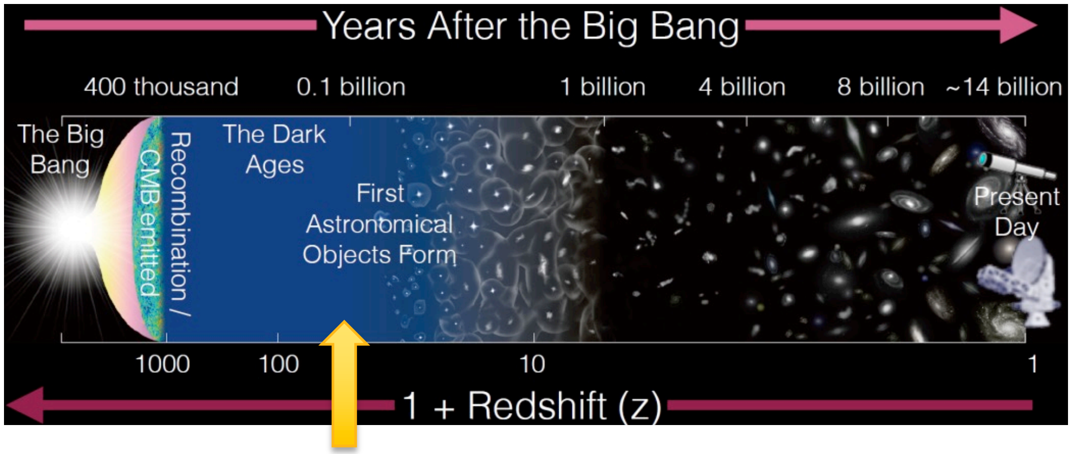
$$\ell_{\rm new\ physics} = \ell_{\rm Pl}, \quad M = 60M_{\odot} \to \tau_{\rm echo} \simeq 50\,{\rm ms}$$

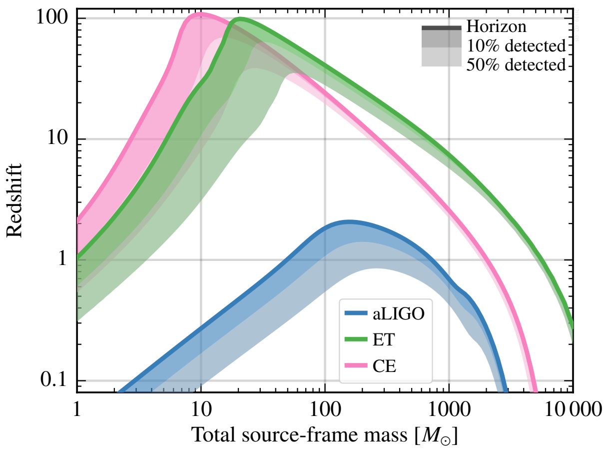
- quite different from accelerator physics, where the Planck scale is unreachable

- detecting echoes might require SNR=O(100) in the ringdown phase, achievable only with 3G detectors (ET, CE)

2. The origin of BHs: astrophysical vs primordial

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





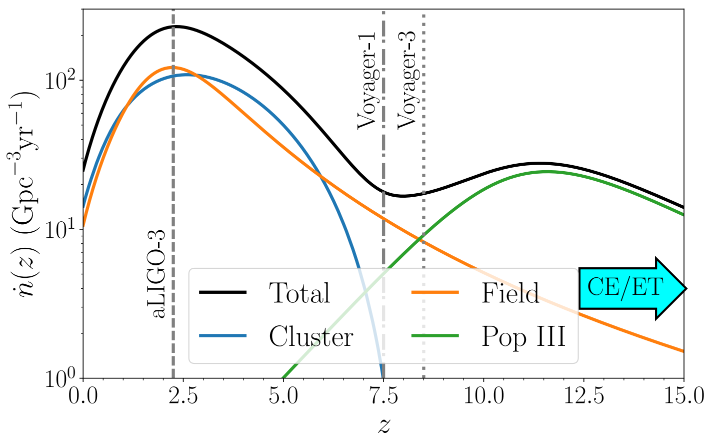
BHs can also be generated by the collapse of large over-densities in the early Universe (PBHs) → window on inflationary scales

PBHs might also contribute to dark matter

Disentangle astrophysical from primordial BH

- the PBH merger rate increases with redshift, up to $z = O(10^3)$

BHs from Pop III stars peak at $z \simeq 12$ and could form binaries (and merge) up to $z \simeq 25\text{-}30$ (conservatively)



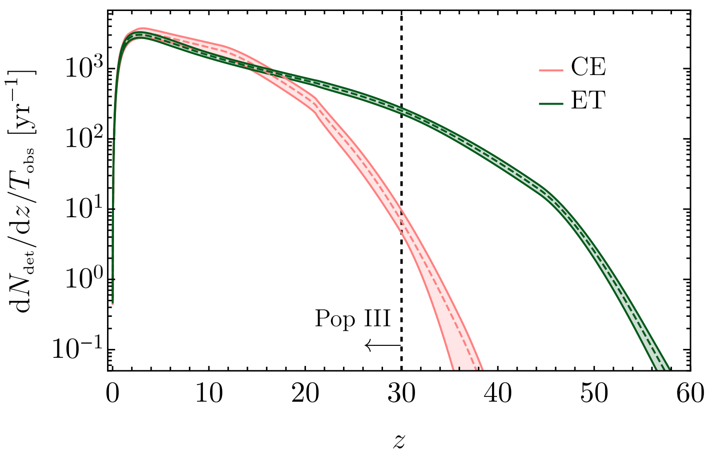
(Ng et al 2012.09876)

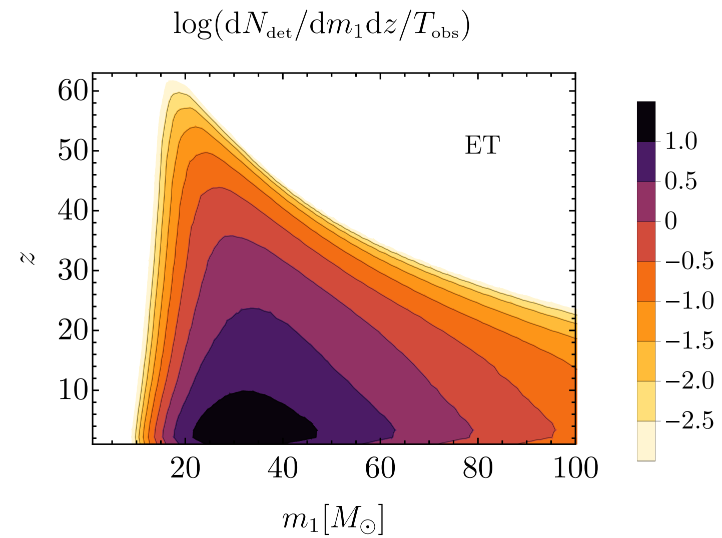
Any BBH merger at z>30 (very conservatively) will be of primordial origin

ET can reach z~ 50 !

predictions for ET/CE, using a mixed astrophysical/primordial population model that fit best the GWTC-2 catalog

(De Luca et al 2102.03809)





$$N_{det}^{ET}(z > 30) = 1315^{+305}_{-168}\,\mathrm{yr}^{-1}\,, \qquad N_{det}^{CE}(z > 30) = 12^{+22}_{-11}\,\mathrm{yr}^{-1}$$

difference between ET and CE due to the better ET sensitivity at low frequencies

Note: accurate measurement of z is also needed !

More ways of disentangling astrophysical from primordial BHs

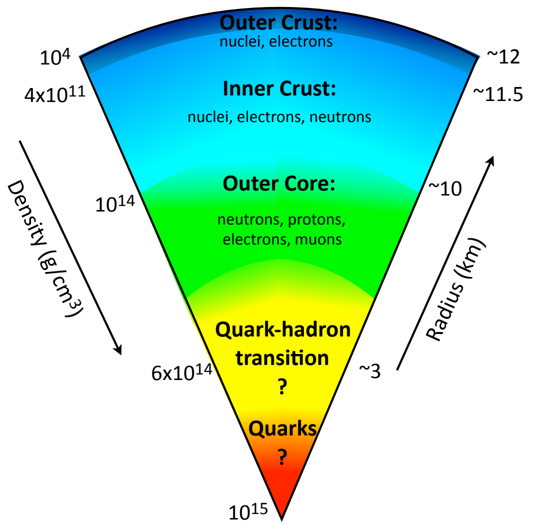
– PBH should trace the distribution of DM rather than of baryons

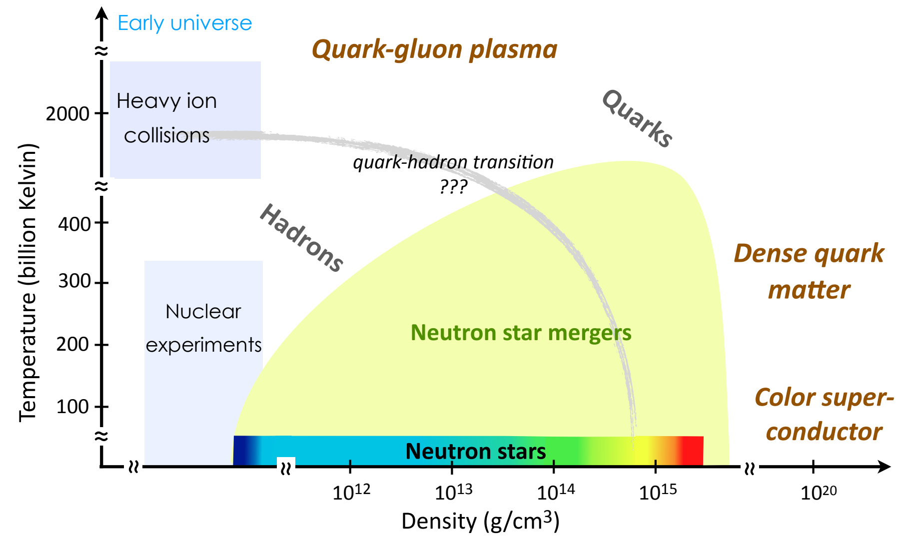
  the large number of detections will allow cross-correlations

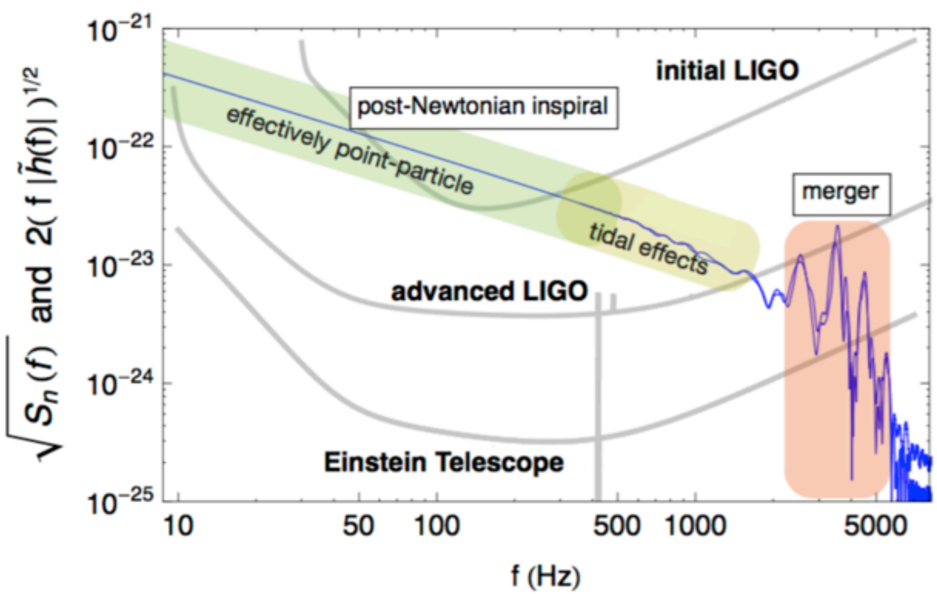
– predictions for the distributions of spins, masses, eccentricity (need robust predictions!)

– subsolar mass BHs

3. QCD with neutron stars







BNS merger @100 Mpc
(adapted from J. Read)

4. GWs as probes of cosmology

GWs from coalescing binaries provide an absolute measurement of the luminosity distance to the source

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

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

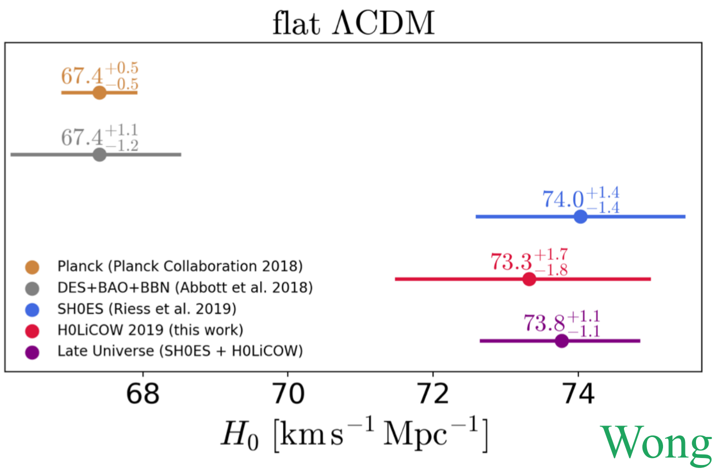
- need an independent determination of z

  (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: measuring H_0

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



Wong et al., H0LiCOW 2019

O(50-100) standard sirens at 2G needed to arbitrate the discrepancy

already solved by the time of 3G detectors? (possible, but not sure, no counterpart in O3)

depending on the network of electromagnetic facilities at the time of ET, ET can detect O(10-100) BNS with counterpart per year

At higher z, accessible only to 3G detectors or LISA, we access the redshift evolution of the dark energy density

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

Several studies of forecasts for w_{DE} at ET

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, 1907.01487

Modified GW propagation

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

In all theories that modify GR on cosmological scales:

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

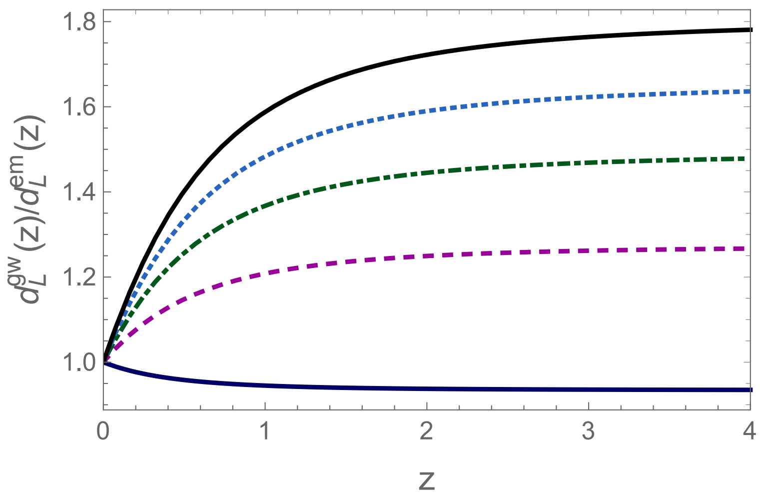
This affects the propagation of GWs across cosmological distances

The net effect is that the quantity extracted from GW observations is a `GW luminosity distance'

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

- 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, in a viable model (non-local gravity) the deviations at the redshifts explored by ET can reach 80% !



Belgacem, Dirian, Finke, Foffa, MM , 2020

$\Longrightarrow$ 3G detectors could be the best experiments for studying dark energy

5. Dark matter, new fundamental fields

Several DM candidates can be studied (only?) by ET

- primordial BHs
  - BBH at $z \sim 10\text{-}50$,
  - masses down to (0.1-1) $M_\odot$
  - correlation with Large Scale Structures

- DM particles captured in NS/BH
  - DM core in NS, drag in binary systems

Ultralight particles

particles with m ~ 10^{-20}-10^{-10} eV have Compton wavelength of order of the Schwartzschild radius of BHs with masses billions $M_\odot$ to a few $M_\odot$

10^{-22}-10^{-10} eV : lower range → viable DM candidates
upper range → QCD axions
ultralight axions from string theory possibly covering the whole range

because of a super-radiance instability, they extract energy from rotating BHs and form a long-lived Bose condensate rotating with the BH

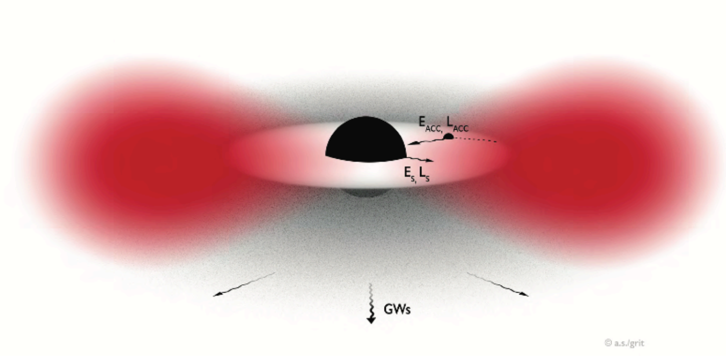


figure: Brito, Cardoso, Pani 2014

- monochromatic GW signals from BHs   Arvanitaki et al 2009,...

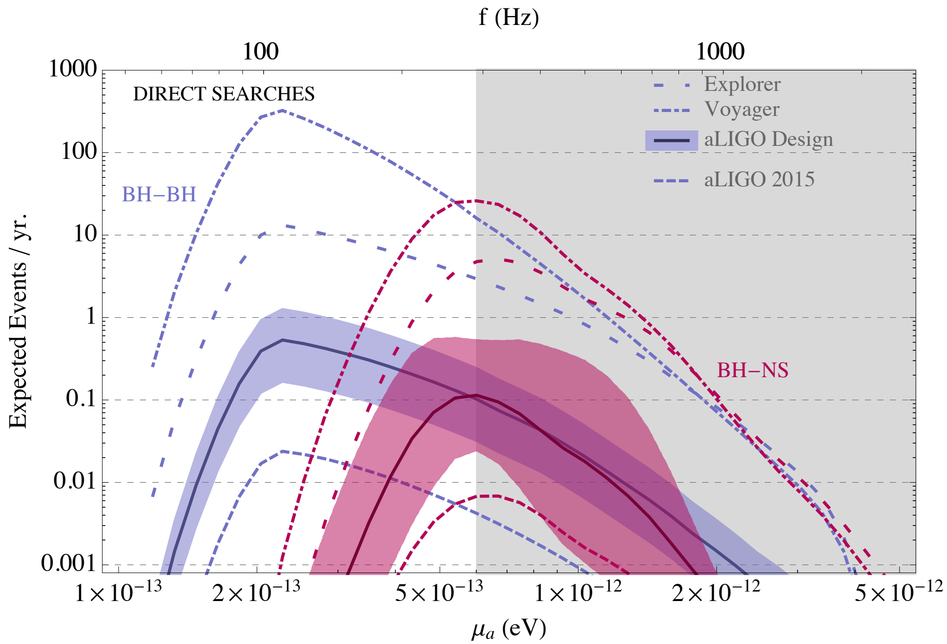


fig from Arvanitaki et al 2016

- affects the dynamics of BBHs   Baumann, Chia, Porto 2018

6. Stochastic GW backgrounds

GWs can carry uncorrupted information from the very earliest moments after the big bang and corresponding high-energy physics

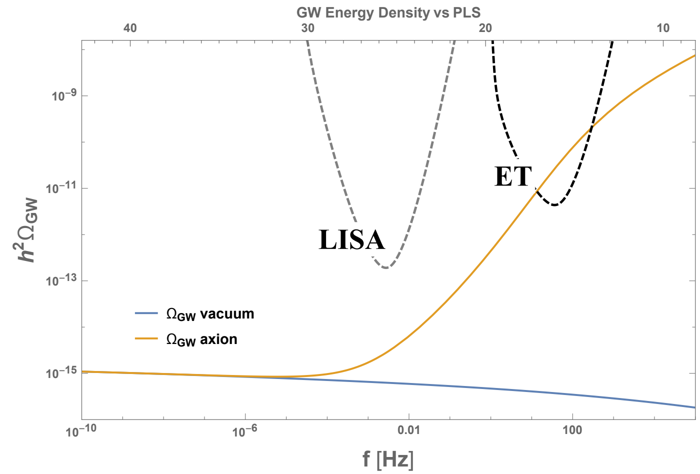
- photons decouple from primordial plasma when

  $z \simeq 1090, \quad T \simeq 0.26 \text{ eV}$

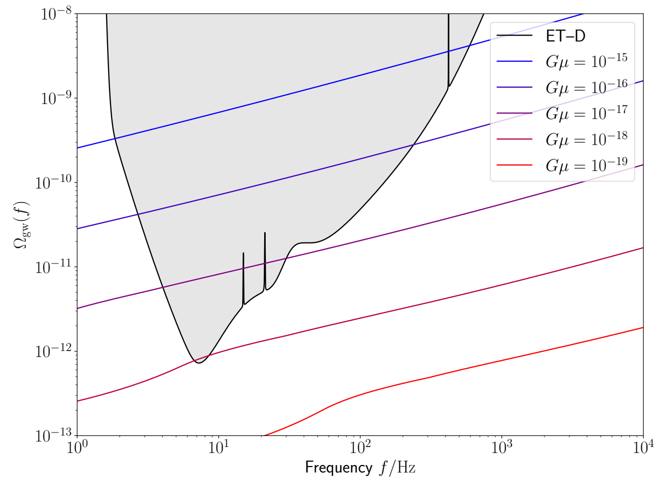
  CMB gives a snapshot of the Universe at this epoch

- neutrinos decouple at $T \simeq \text{MeV}$

- GWs are already decoupled below the Planck scale, 10^{19} GeV vacuum fluctuations from slow-roll inflation too small, but other inflation-related mechanisms can produce detectable signals



- cosmic strings
- 1st order phase transitions at T ~10^7-10^{10} GeV
- anisotropies, multipole expansion



ET has an exciting and broad science program, ranging from astrophysics to cosmology and fundamental physical

Thank you!

Multi-messenger astronomy

- formation, evolution and multi-messenger emission mechanism of BNS (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

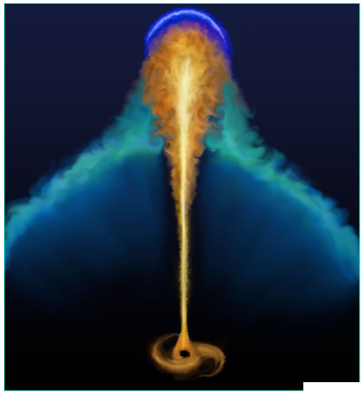
→ possibility to detect the kilonova with the second generation instruments of ELT such as MOSAIC

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

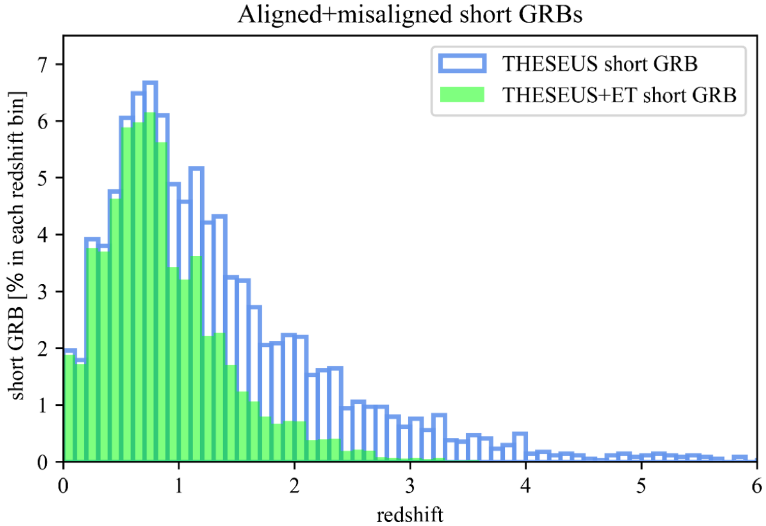
e.g. THESEUS for short GRB, O(10/yr) on-axis, several tens off-axis

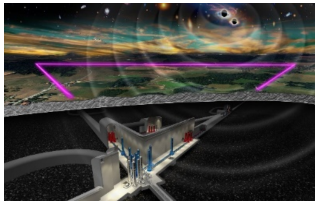
Multi-messenger observations

SEARCH PHASE – HIGH ENERGY SATELLITES



- Gamma-Ray Burst detectable up to high z
- Sensitive wide field of view hard-soft X-ray instruments (such as the Vera Rubin Observatory, SVOM, Einstein Probe, the mission concept THESEUS or AMEGO)
  observe in survey mode → no necessity to interrupt other observations
- Good sky localization to drive a prompt EM follow-up





THESEUS-ET joint detections
13 per year

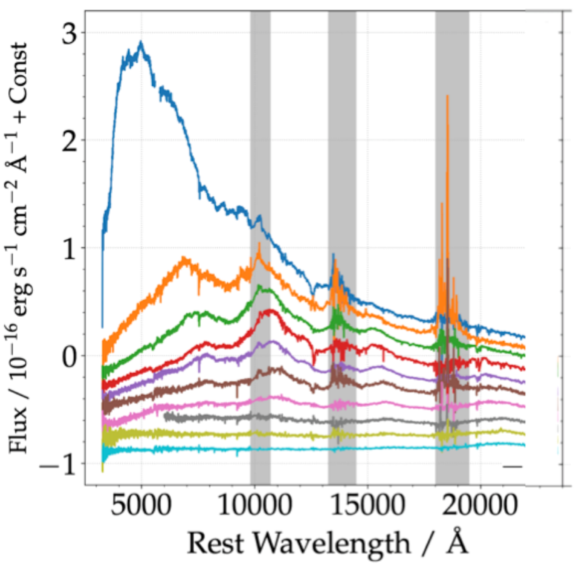
Low-z:

SEARCH PHASE IN THE OPTICAL BAND

VERA RUBIN OBSERVATORY FOLLOW-UP:

- three epochs of 600s observations in two filters
- detection efficiency is larger than 99% up to z=0.3

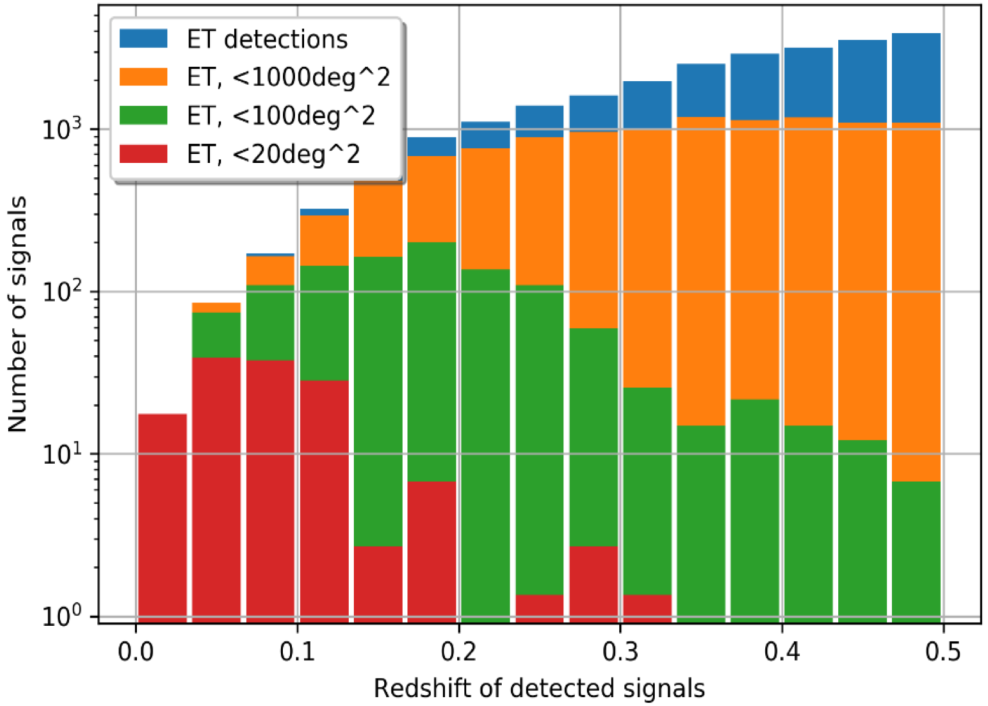
CHARACTERIZATION PHASE IN THE OPTICAL BAND



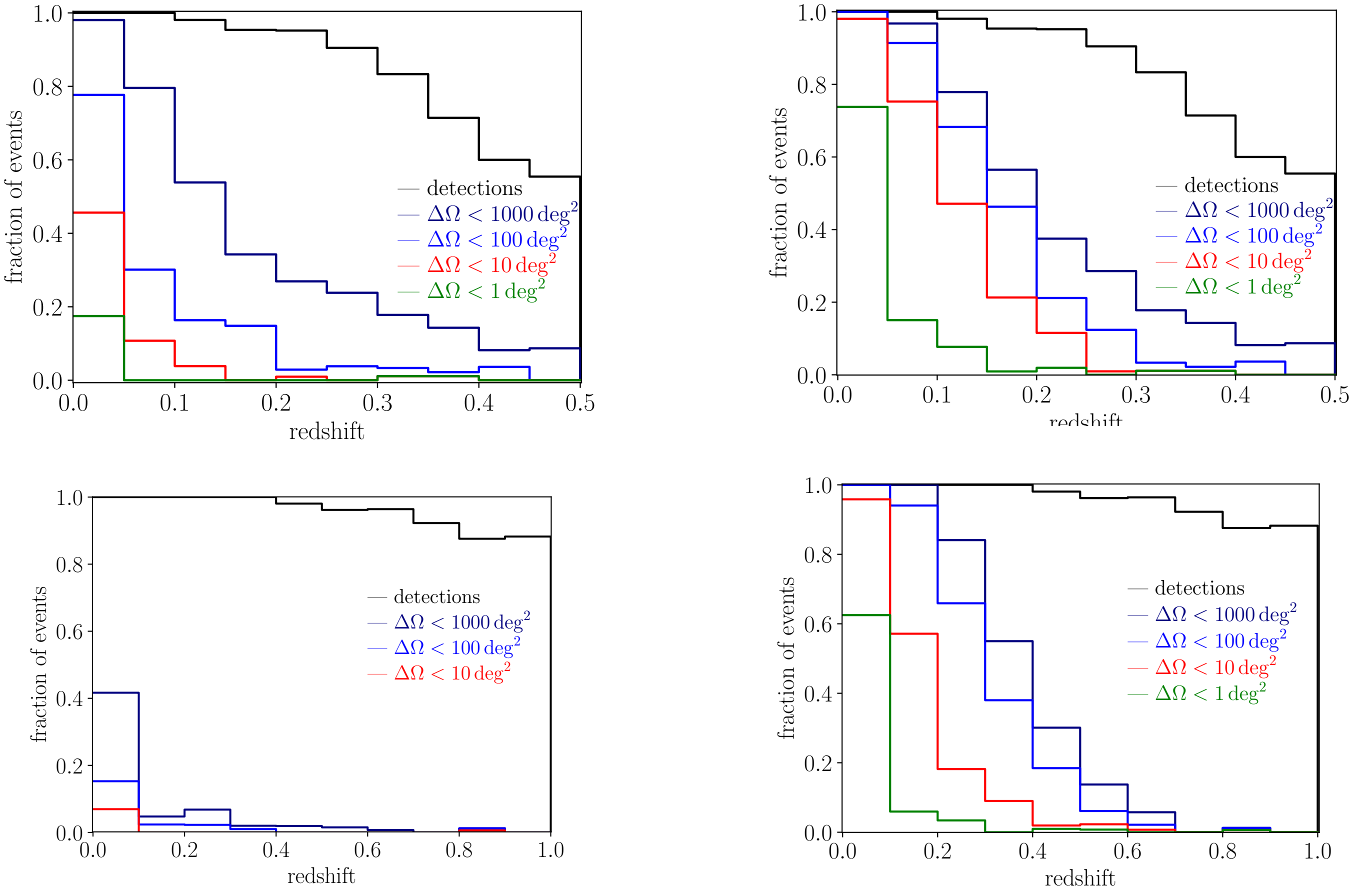
- Larger telescope, such as JWST, TMT, ELT

Several tens to hundreds events/yr can be identified and characterized

BINARY NEUTRON-STAR LOCALIZATION



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



BNS

BBH

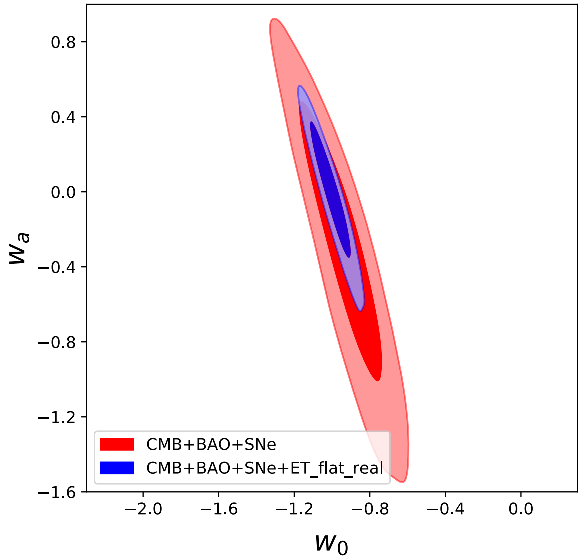
ET

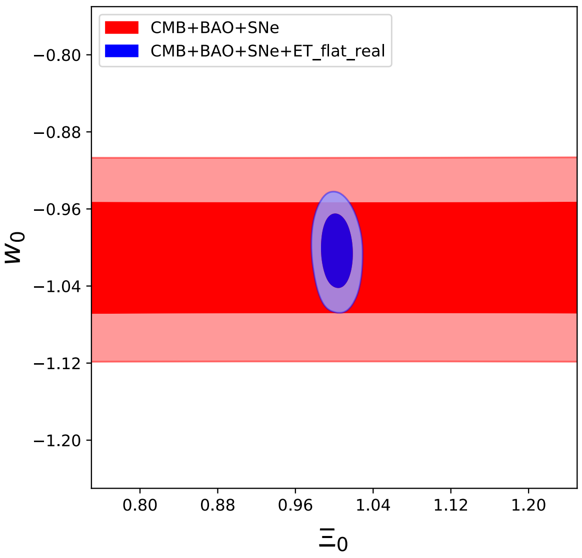
ET+2G

Forecasts for DE with ET

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

assuming coincidences with a GRB detectors
such as THESEUS





	$\Delta\, w_0$	$\Delta\, \Xi_0$
CMB+BAO+SNe+ET	0.026	0.010

Ξ_0 can be measured to 1%