

Cosmology and fundamental physics with future GW experiments

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Astrophysics Workshop

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2G detectors have opened a new window:

3G ground-based detectors (ET, CE)

and space-borne detectors (LISA)

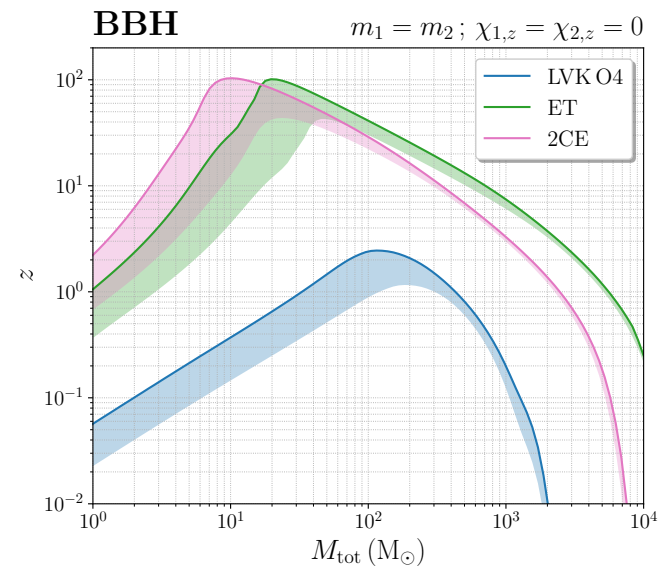
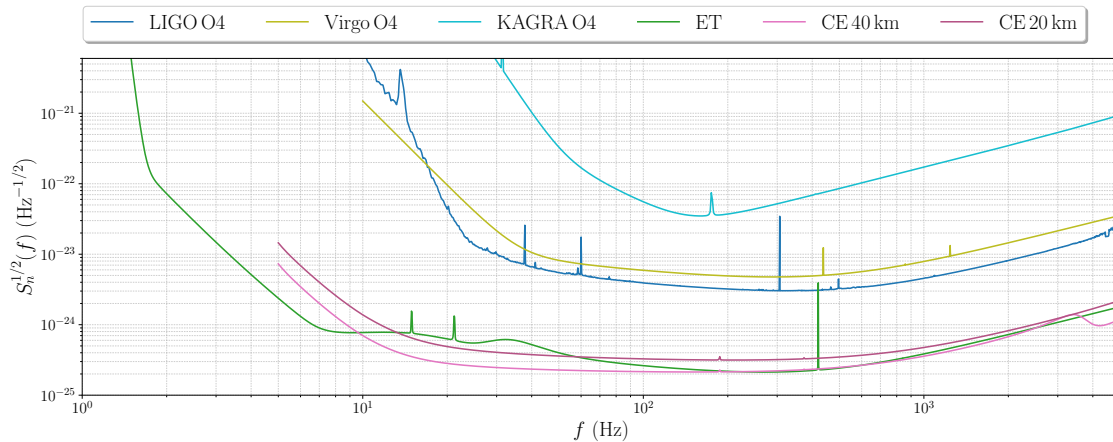
will look deeply into this window

Ground-based: ET, CE

MM et al “Science Case for the Einstein Telescope”,
1912.02622, JCAP (written for the ESFRI RoadMap)

Iacovelli, Mancarella, Foffa, Maggiore, 2207.02771, ApJ

for MMO see Ronchini et al, 2204.01746, Astron. Astrophys.



BBH up to $z=0(50-100)$!!
BNS up to $z \sim 3$

Detection distance of BBHs

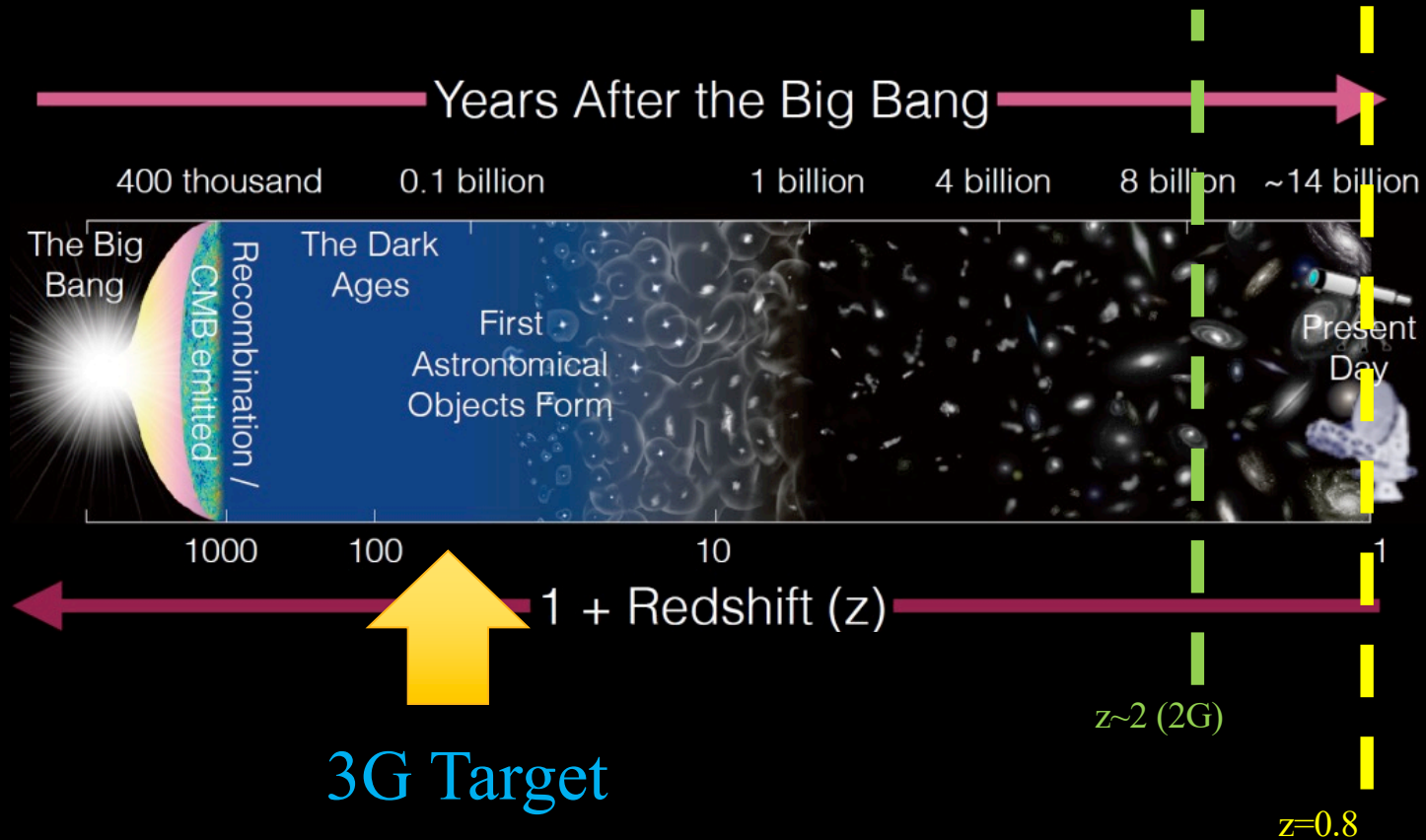
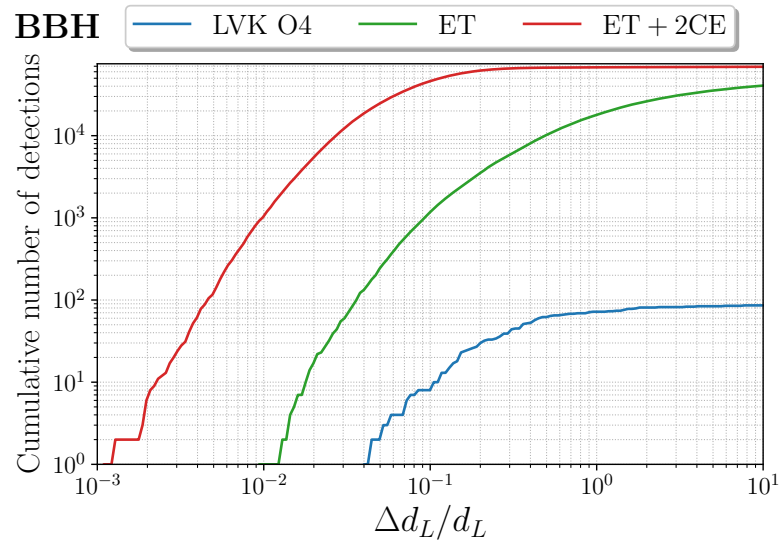
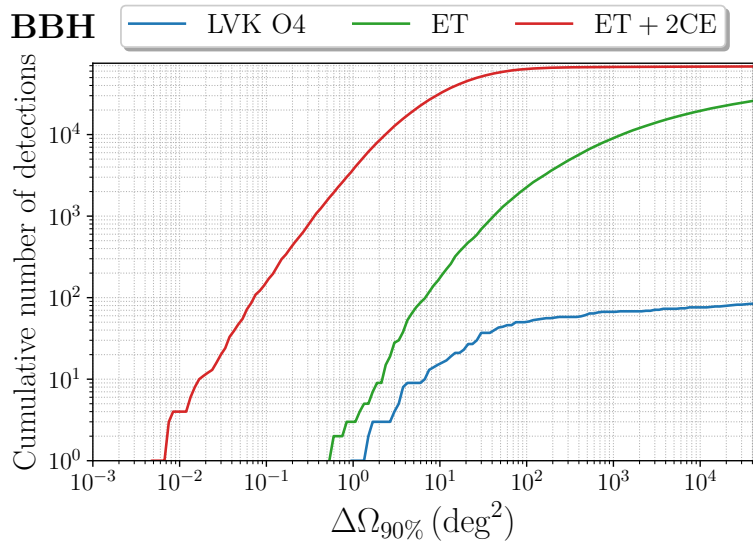
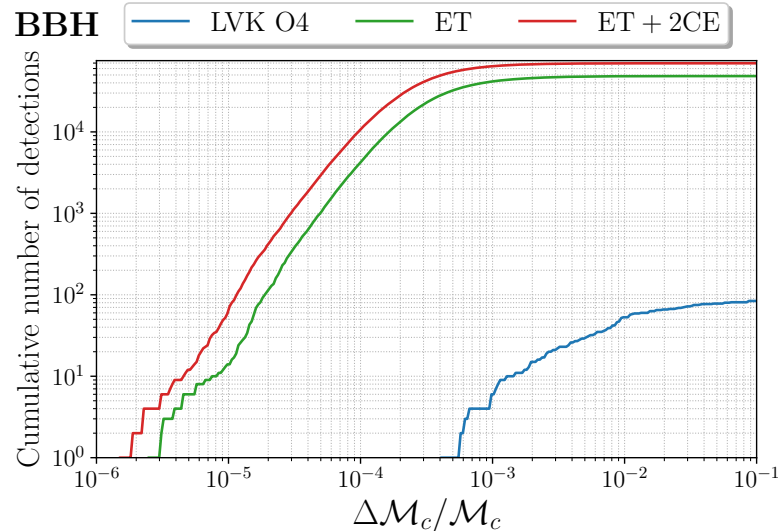
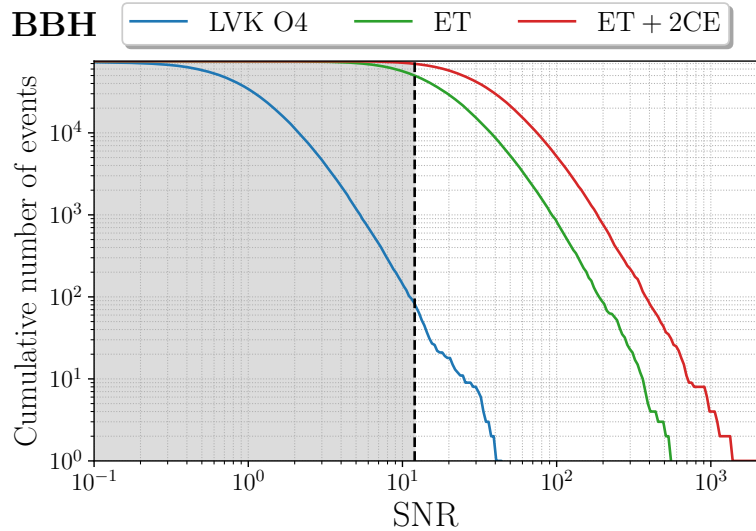


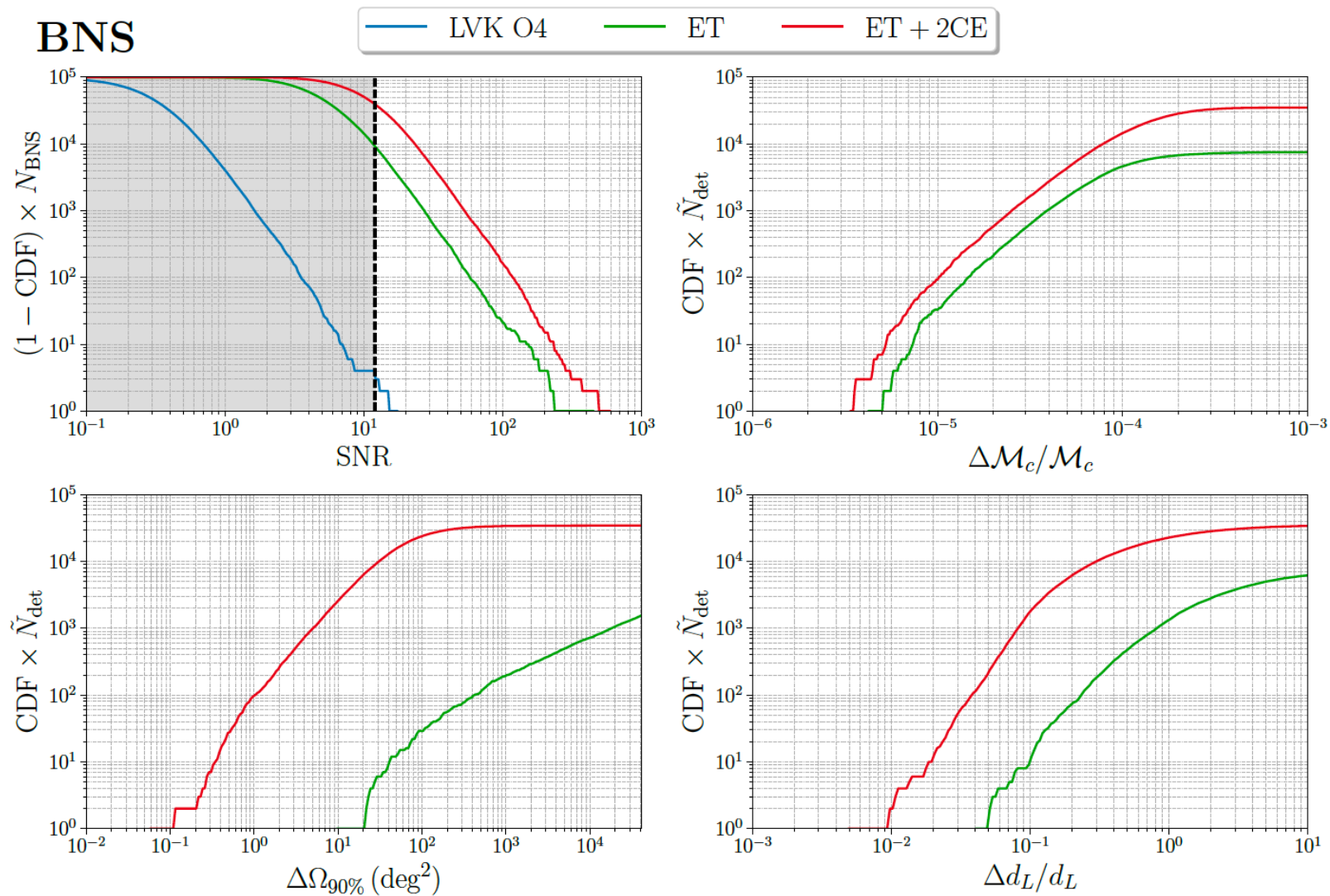
Image credit: NAOJ/ALMA <http://alma.mtk.nao.ac.jp/>

SNR distribution and examples of parameter reconstruction (BBH)

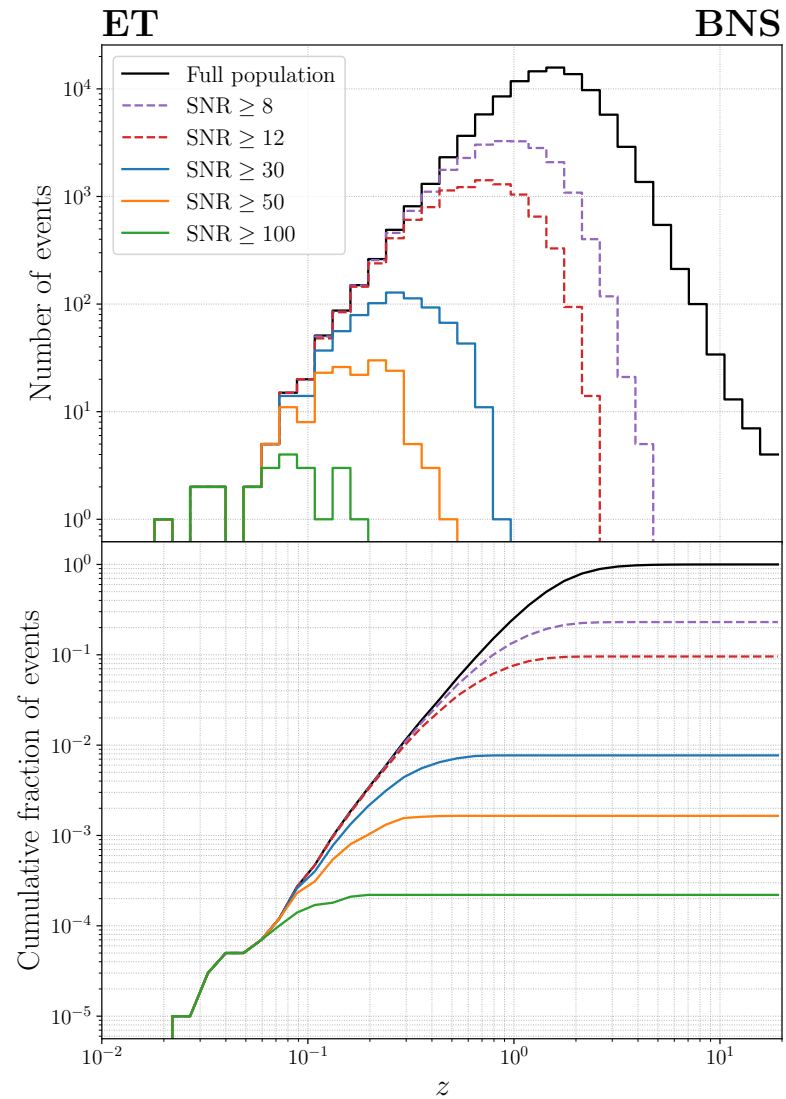
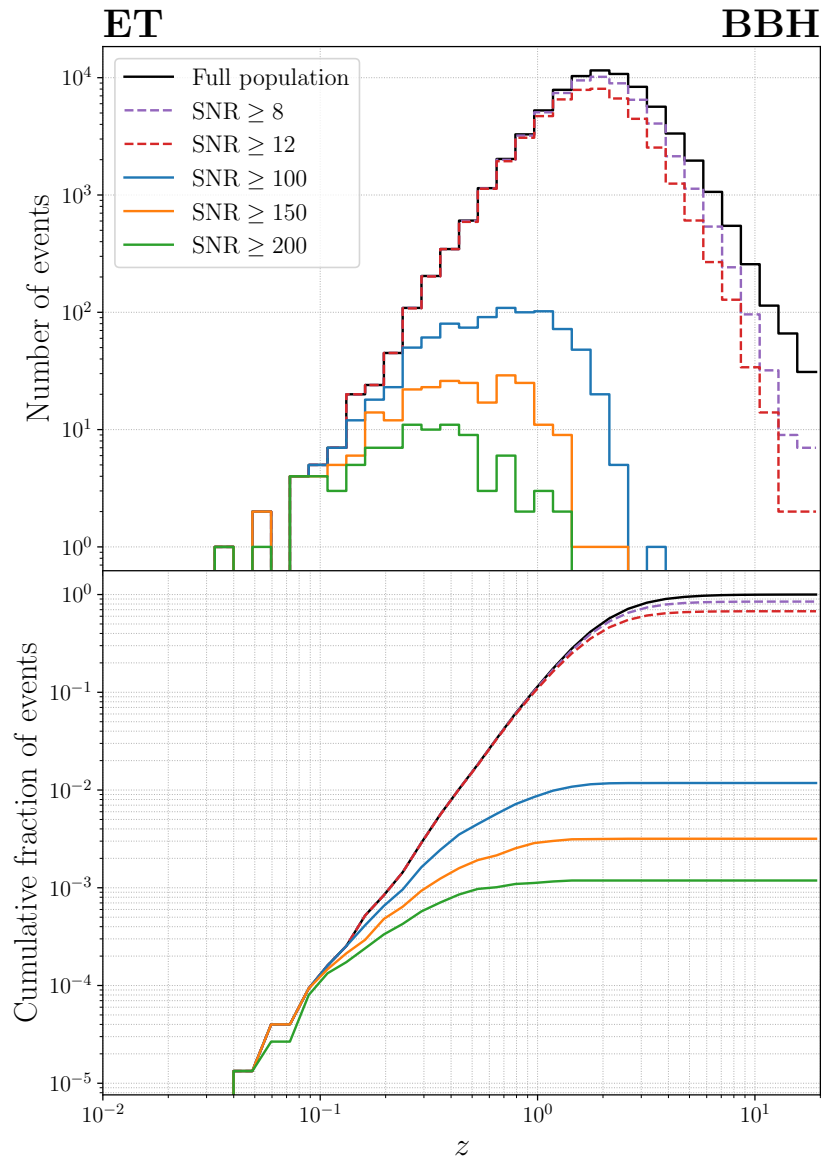
Iacovelli et al. 2022



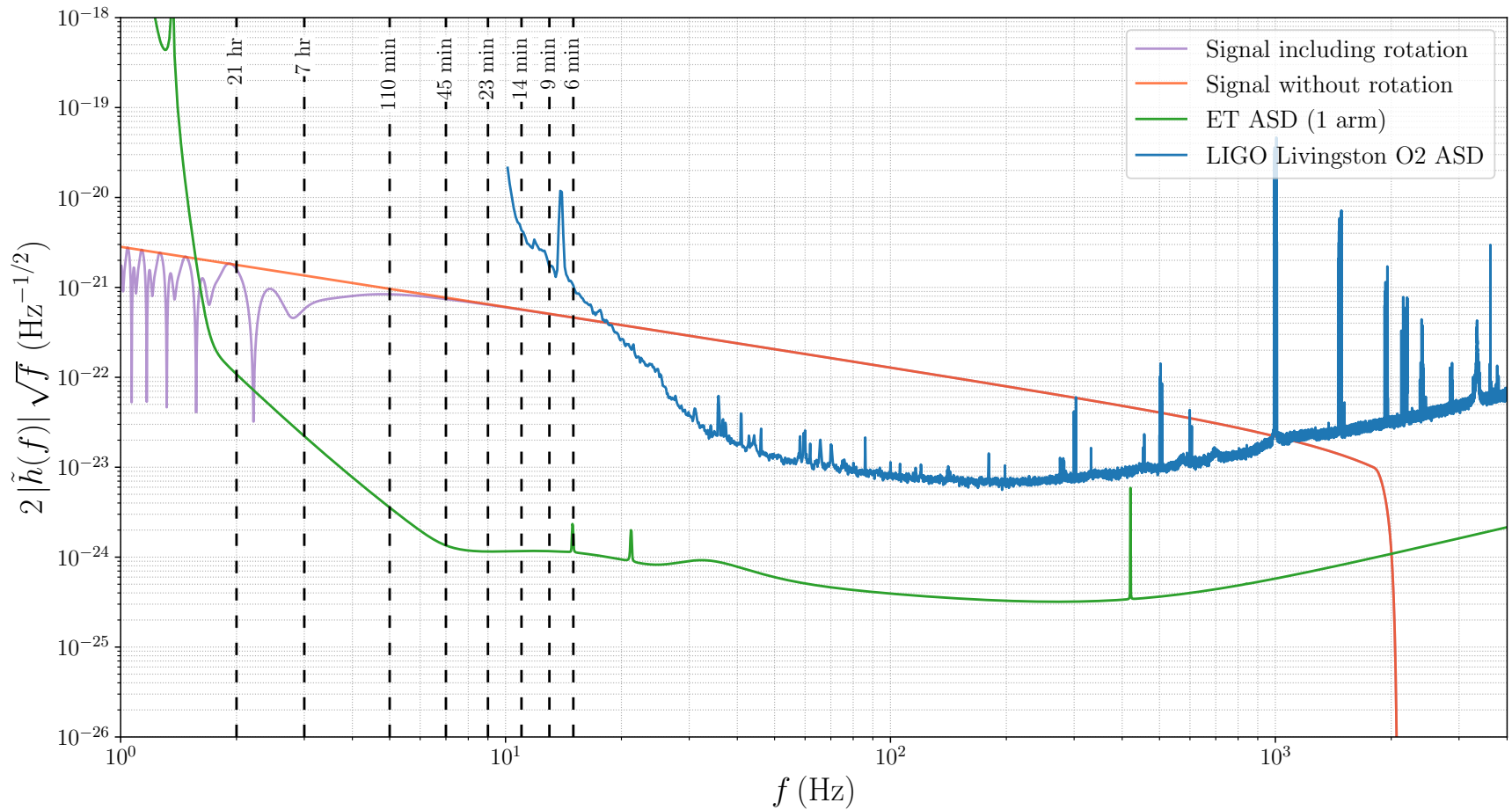
parameter reconstruction (BNS)



'golden events'



GW170817 at LVC-O2 and at ET



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'

1. The nature of Gravity

BHs are one of the most extraordinary predictions of GR

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

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)

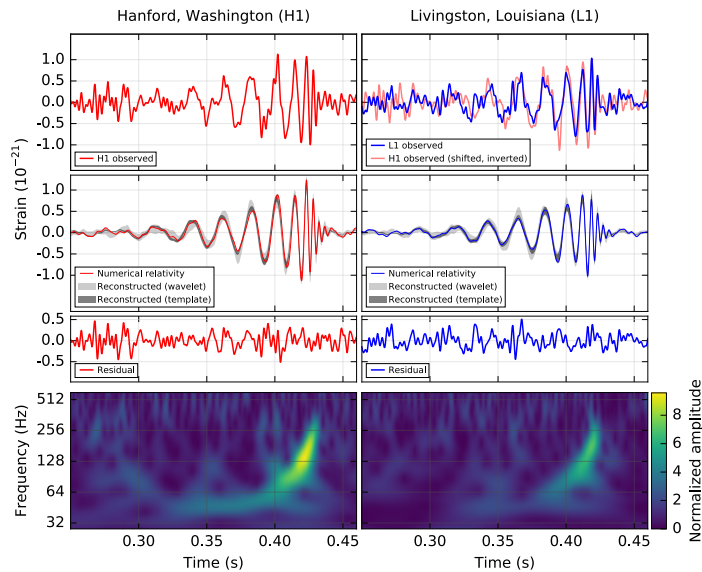
firewalls, fuzzballs... (quantum effects near the horizon motivated by the Hawking information loss problem):

BH quasi-normal modes (QNM)

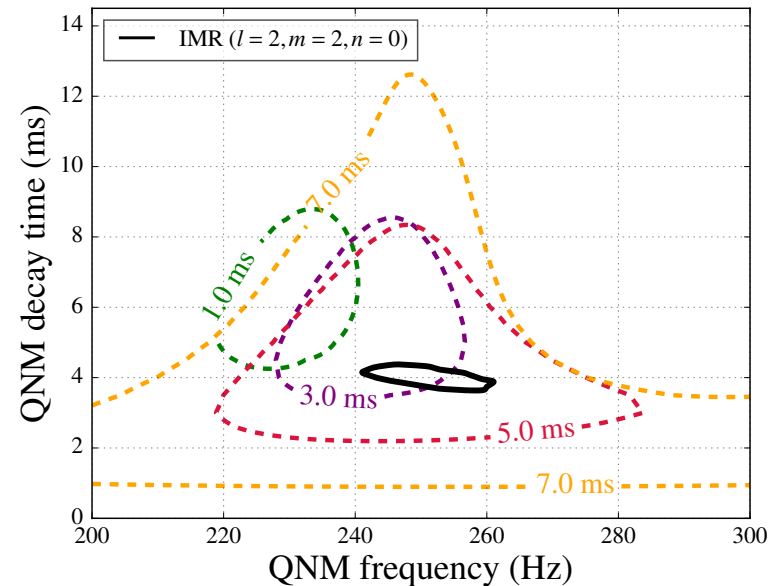
the elasticity of space-time in the regime of strong gravity!

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

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

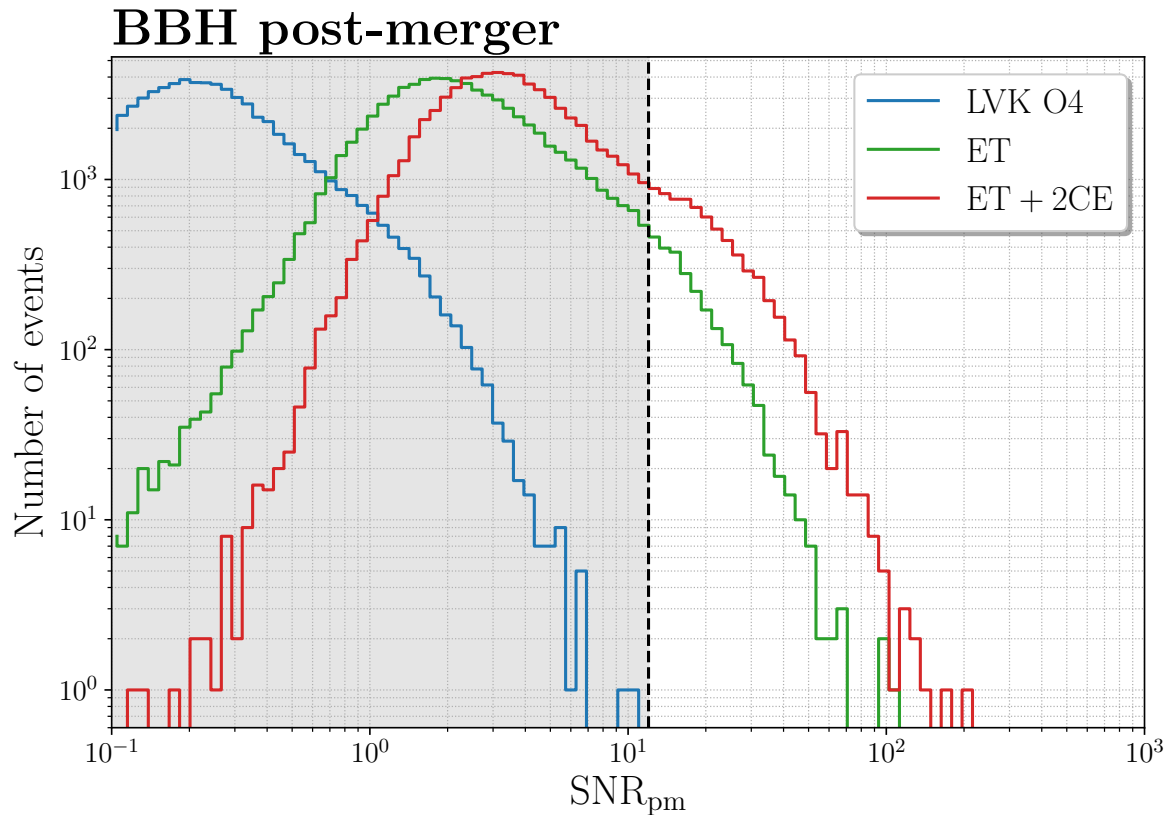


already observed in GW150914 (LVC)



consistent with GR, but we cannot say much more

BBH post-merger at ET

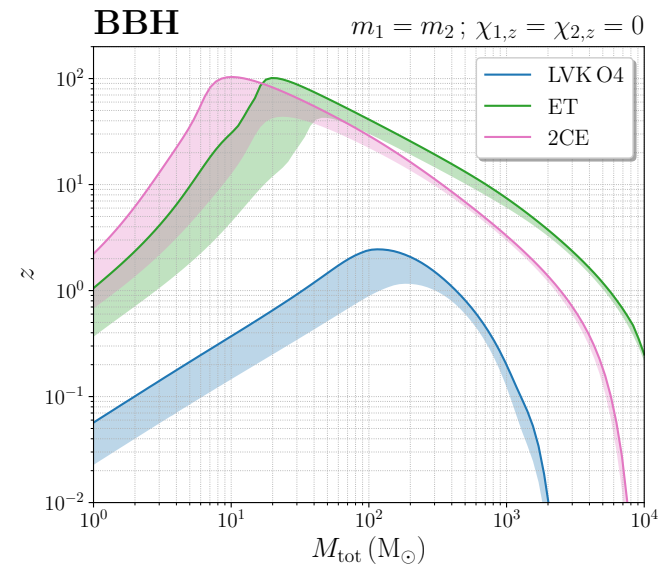
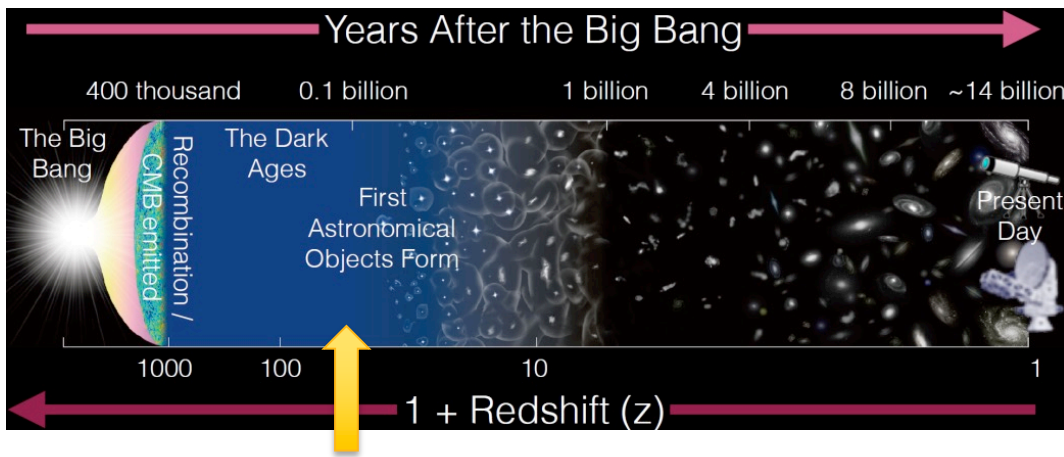


Iacovelli et al. 2022

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

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



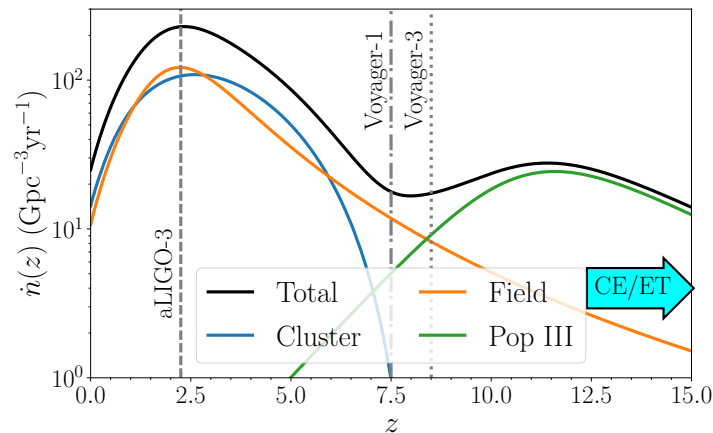
BHs can also be generated by the collapse of large over-densities in the early Universe (PBHs) \rightarrow window on inflationary scales

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 $z \approx 12$ and could form binaries (and merge) up to $z \approx 25-30$ (conservatively)



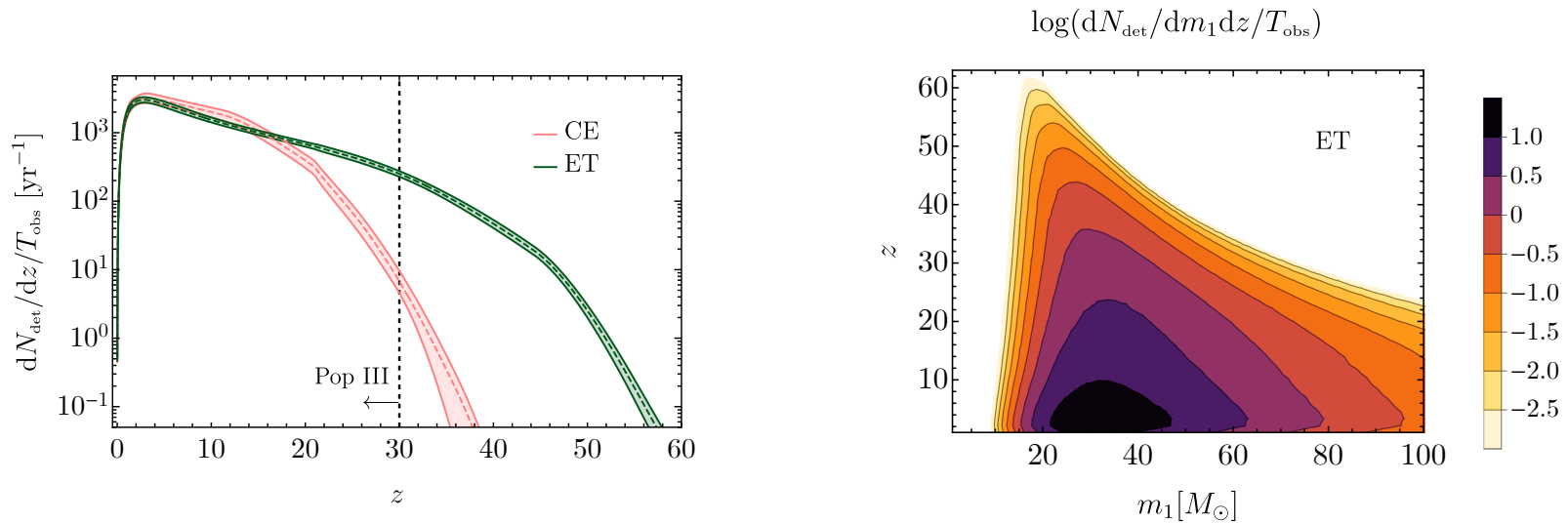
(Ng et al 2012.09876)

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

ET can reach $z \sim 50-100$!!

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

(De Luca et al 2102.03809)



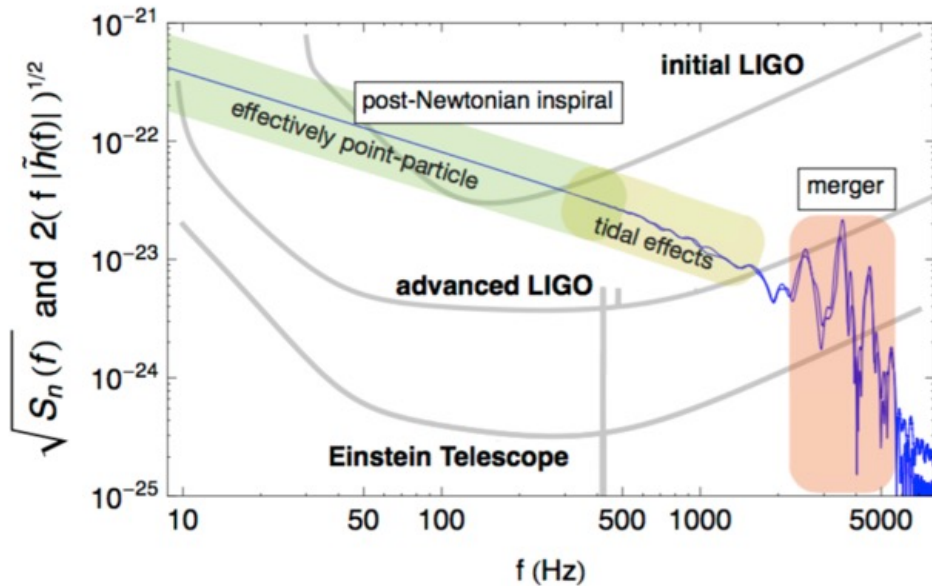
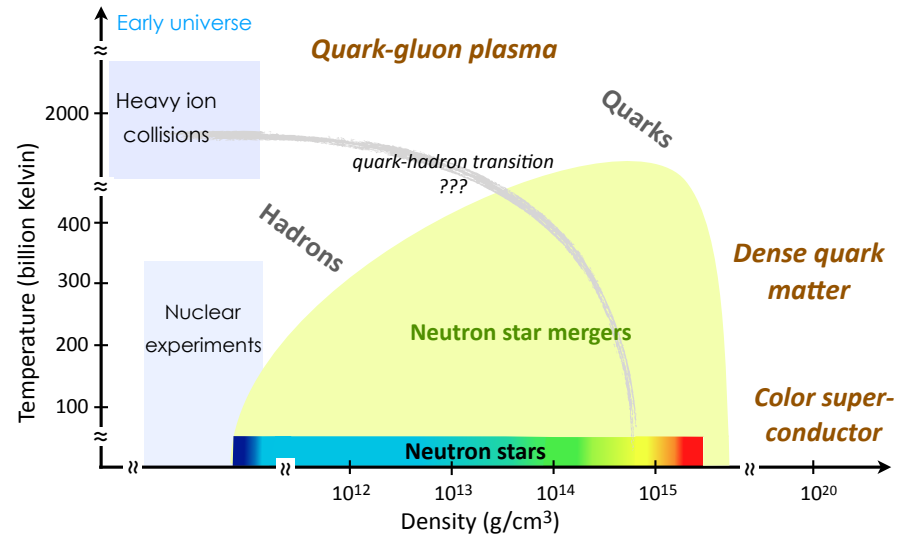
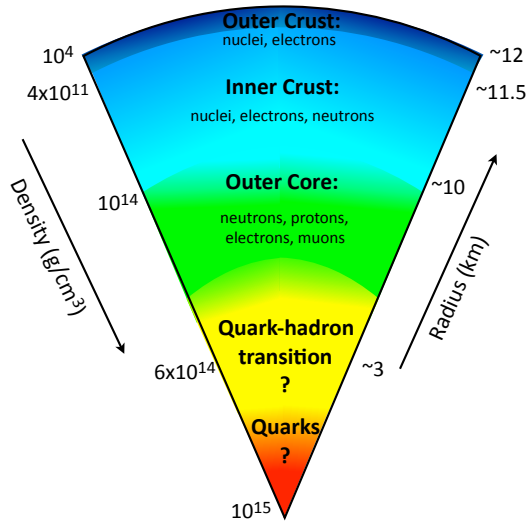
$$N_{\text{det}}^{\text{ET}}(z > 30) = 1315_{-168}^{+305} \text{ yr}^{-1},$$

$$N_{\text{det}}^{\text{CE}}(z > 30) = 12_{-11}^{+22} \text{ yr}^{-1}$$

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

Accurate measurement of z is also needed ! (Ng et al 2108.07276)

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

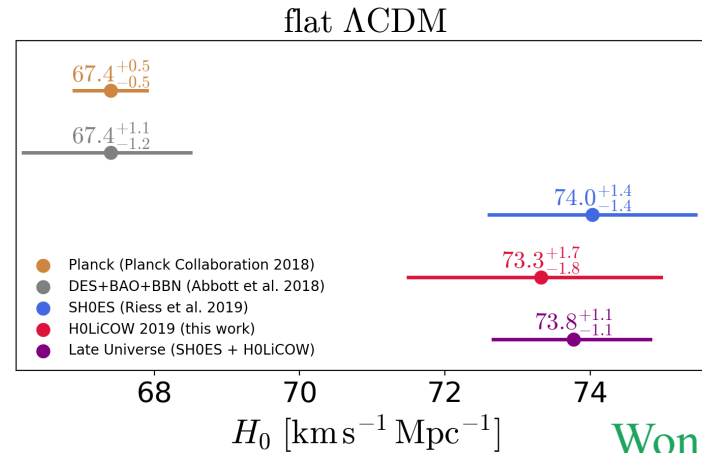
$$d_L(z) = \frac{1+z}{H_0} \int_0^z \frac{d\tilde{z}}{\sqrt{\Omega_M(1+\tilde{z})^3 + \rho_{\text{DE}}(\tilde{z})/\rho_0}}$$

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

- need an independent determination of z
(electromagnetic counterpart, statistical methods)
- low z : Hubble law, $d_L \simeq H_0^{-1} z$
- moderate z : access $\Omega_M, \rho_{\text{DE}}(z)$

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 several tens 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

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

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:

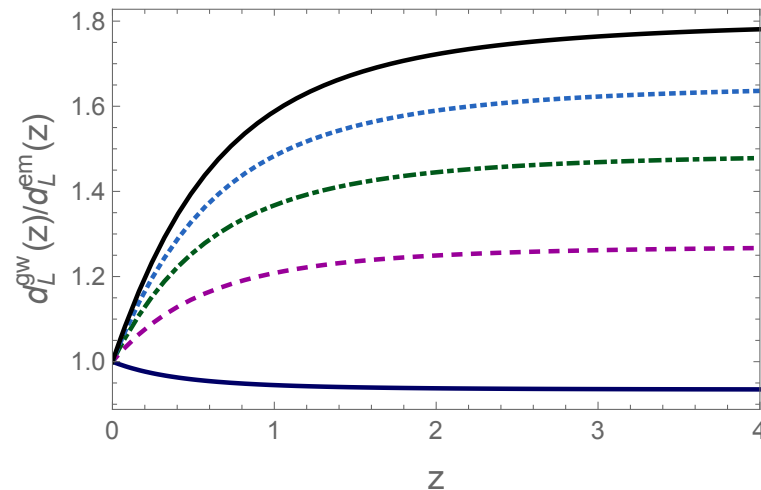
$$\tilde{h}''_A + 2\mathcal{H}[1 - \delta(\eta)]\tilde{h}'_A + k^2\tilde{h}_A = 0$$

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'

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

- 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% !



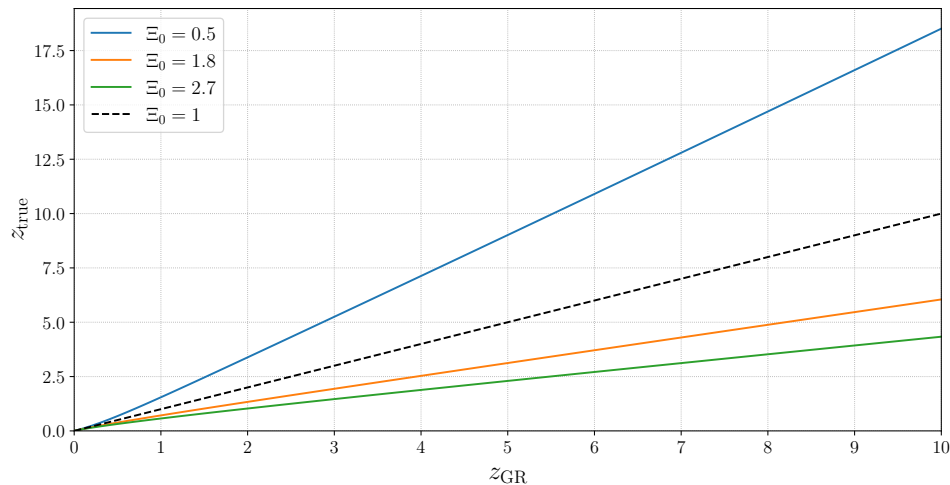
Belgacem, Dirian, Finke, Foffa, MM , 2020

⇒ 3G detectors could be the best experiments for studying dark energy

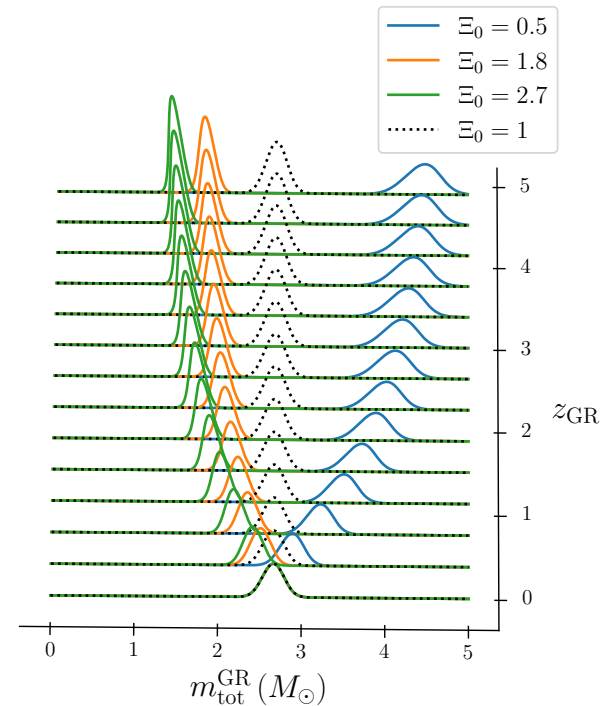
Example: BNS mass function at ET

GW detectors measure the combination $m_{\text{det}} = (1 + z)m$

and do not measure directly z but $d_L \Rightarrow$ here cosmology enters



Finke, Foffa, Iacovelli, MM, Mancarella 2021



5. Dark matter, new fundamental fields

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

- primordial BHs
 - BBH at $z \sim 30-100$,
 - 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 $m \sim 10^{-20}$ - 10^{-10} eV have Compton wavelength of order of the Schwarzschild radius of BHs with masses billions M_{\odot} to a few M_{\odot}

10^{-22} - 10^{-10} eV : lower range \rightarrow viable DM candidates

upper range \rightarrow 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

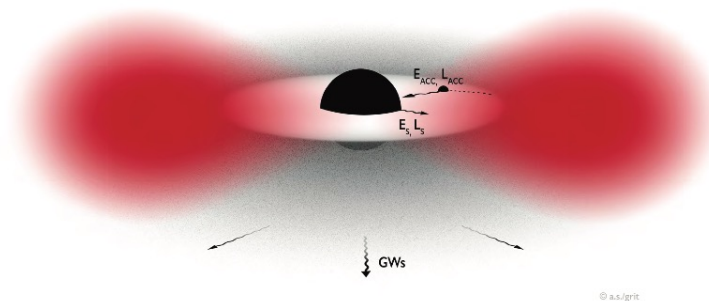


figure: Brito, Cardoso, Pani 2014

6. Stochastic GW backgrounds

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

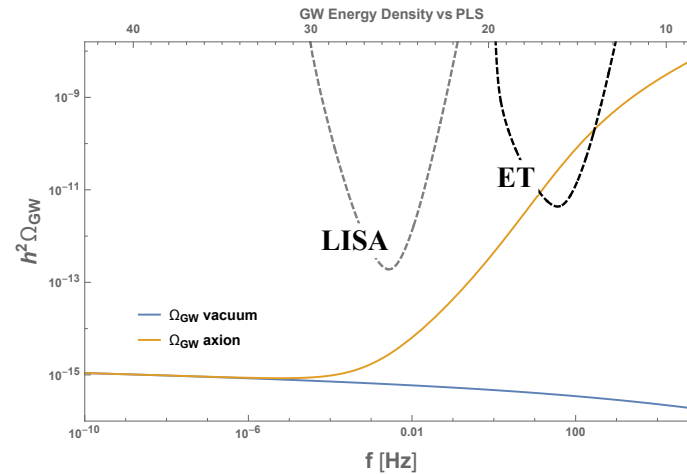
- photons decouple from primordial plasma when

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

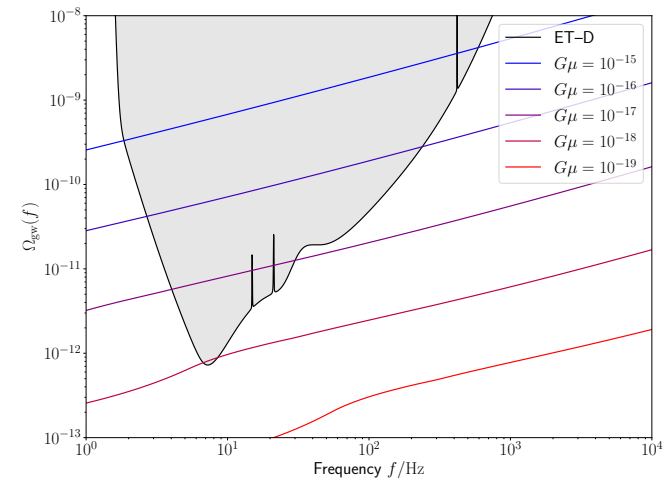
CMB gives a snapshot of the Universe at this epoch

- 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 $T \sim 10^7 - 10^{10}$ GeV
- anisotropies, multipole expansion



Cosmology and fundamental physics with LISA

Fundamental physics with LISA, 2205.01597, Liv. Rev. Rel.
Cosmology with LISA, 2204.05434

Massive Binary Black Holes (MBBHs)

- a few to several tens of events/yr at $z \simeq 1-8$ (but possibly up to 15-20)
(main uncertainties: heavy vs light seeds, delay time)
- Localization and early warning Mangiagli et al 2006.12515, PRD
at $z=1$, a MBHB with $M_{\text{tot}}=3*10^5 M_{\odot}$ can be localized to
 10^2 deg^2 (1 deg^2) at 1 month (1 hr) before merger
at merger, sky localization $< 10^{-1} \text{ deg}^2$ for all masses
- $\Delta d_L/d_L < 10\%$ at $z < 3$

If MBBHs evolve in gas-rich environment, EM radiation can be produced before or after the merger

- pre-merger emission across all wavelengths, detectable if the pre-merger localization is good
- X-ray emission in post-merger

'Dark sirens' at LISA

statistical methods (eg correlation with galaxy catalogs)

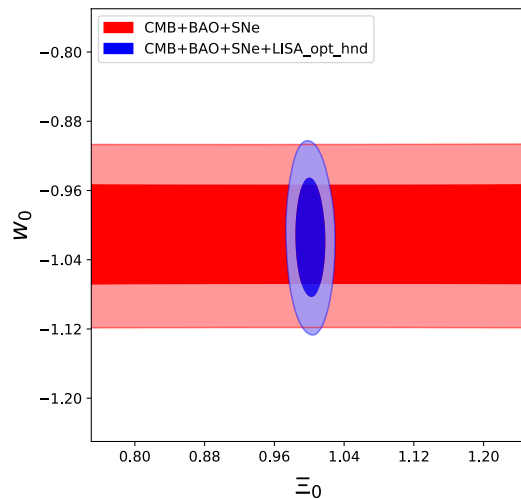
- stellar-origin BBH. LISA sees them in the early inspiral.
Because of their low masses, are detectable only at $z \lesssim 0.1$
possibly 10-100 events detectable by LISA, but large uncertainties

they also allow for multi-band astronomy with ET !

- EMRI ($0.5 \lesssim z \lesssim 2$)
a few to several tens events sufficiently well localized to provide useful cosmological information

Forecasts for cosmology at LISA

- H_0 measured at a few percent by MBBH, EMRI and SOBBH, possibly below 1% combining the results
- also w_0 at few % level
- very interesting results for modified GW propagation



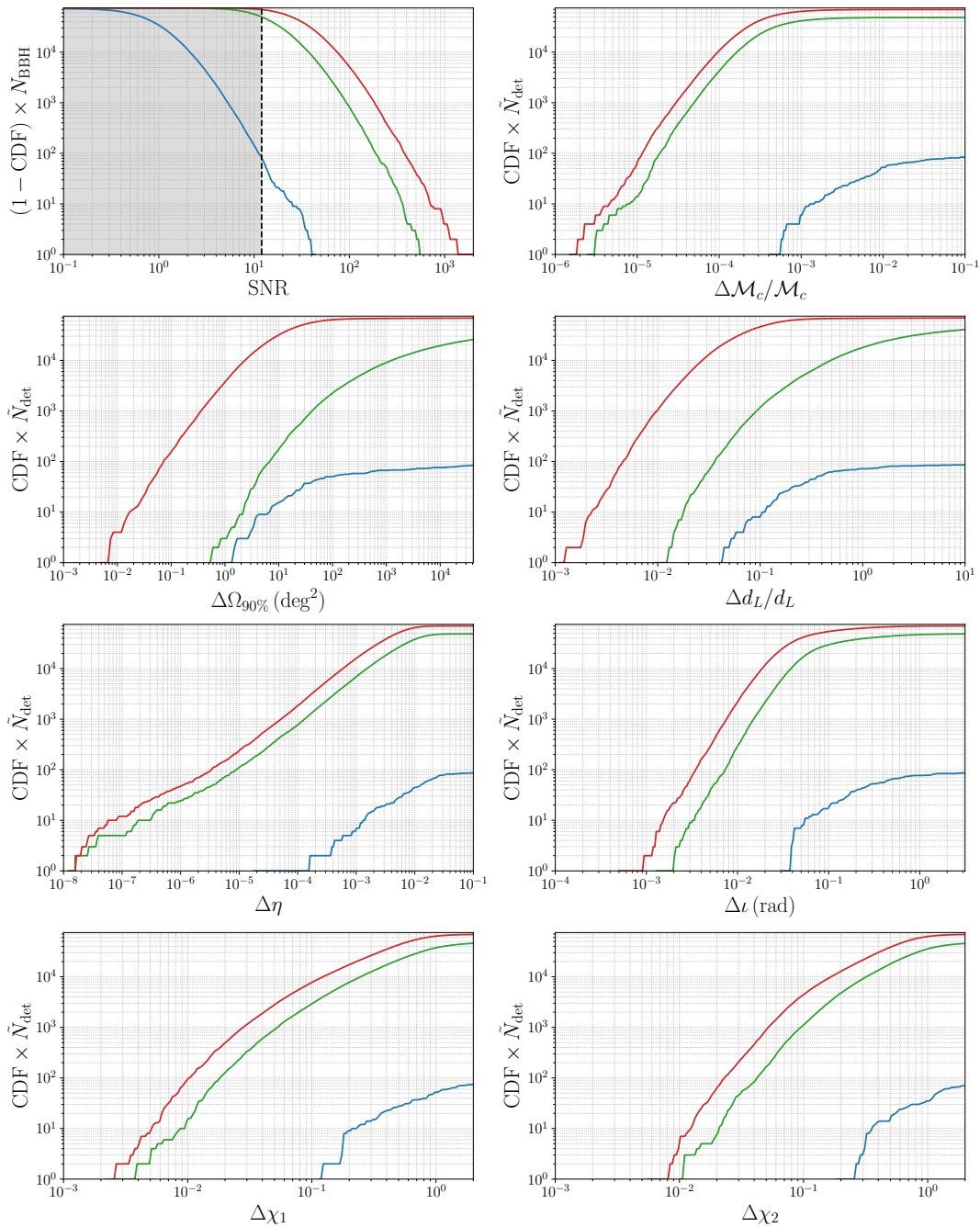
Belgacem et al, LISA CosmoWG,
1906.01593, JCAP

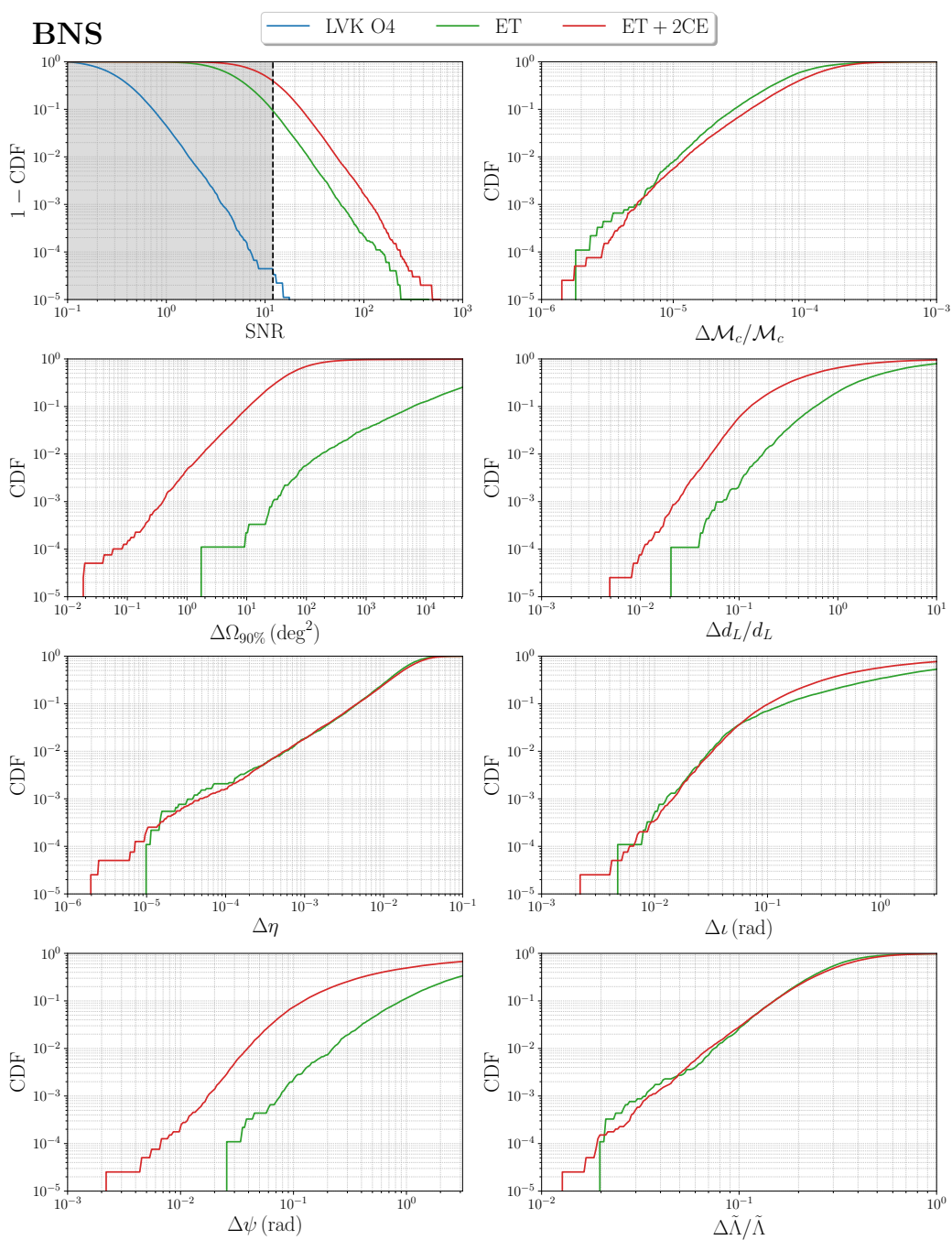
Thank you

bkup slides

BBH

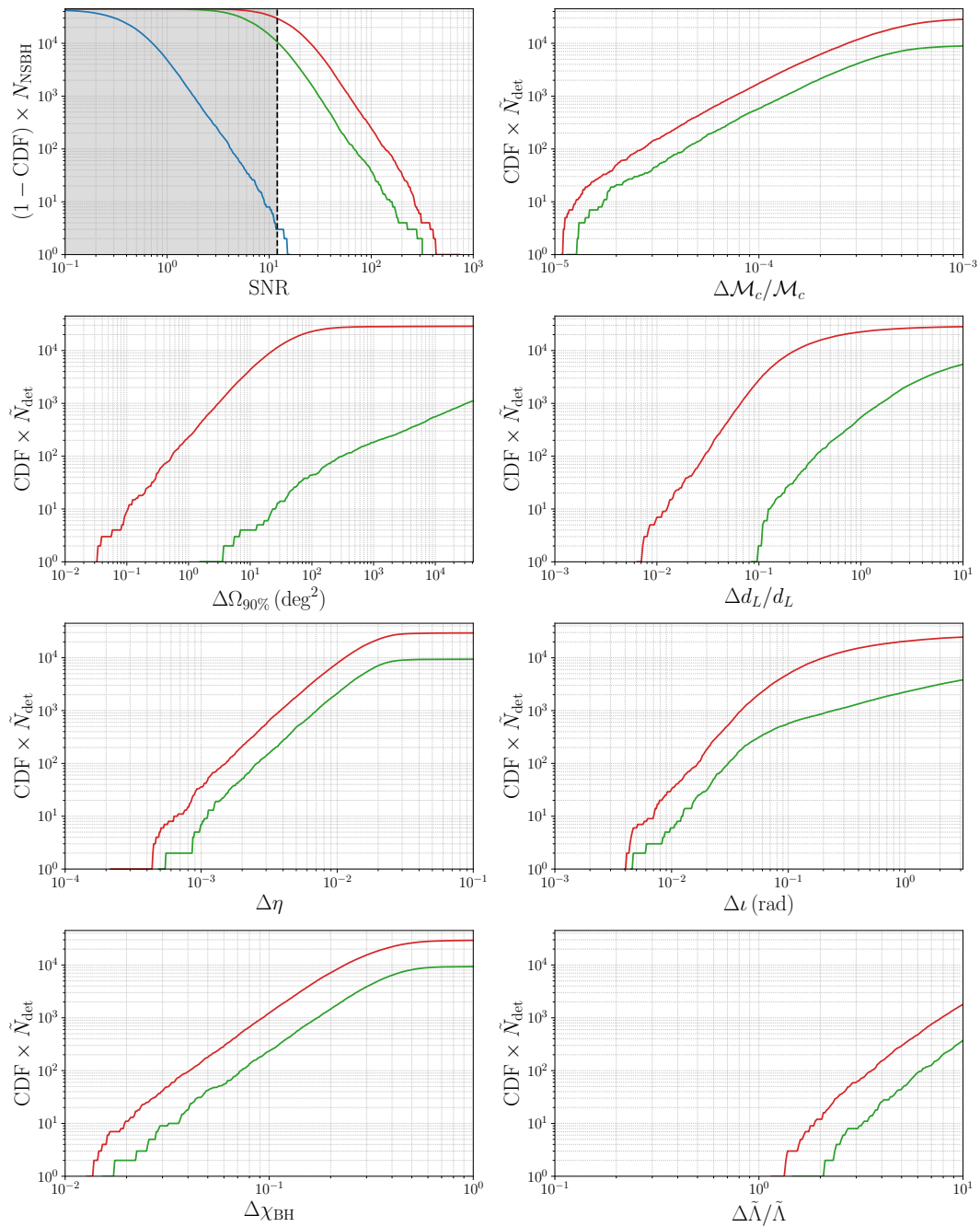
— LVK O4 — ET — ET + 2CE

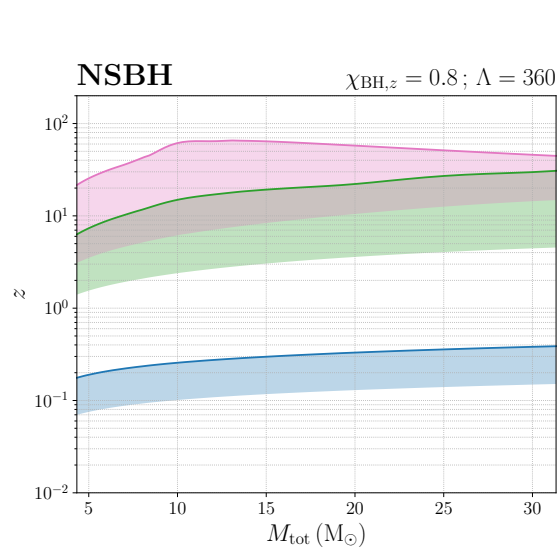
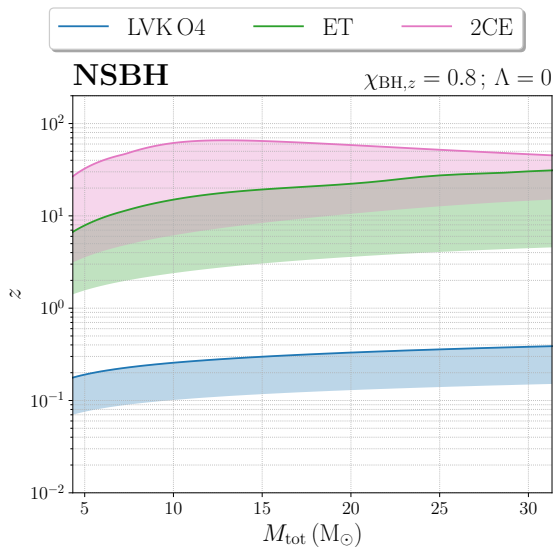
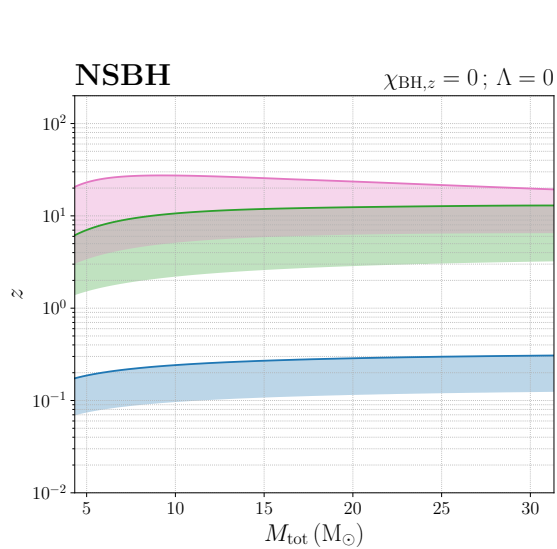
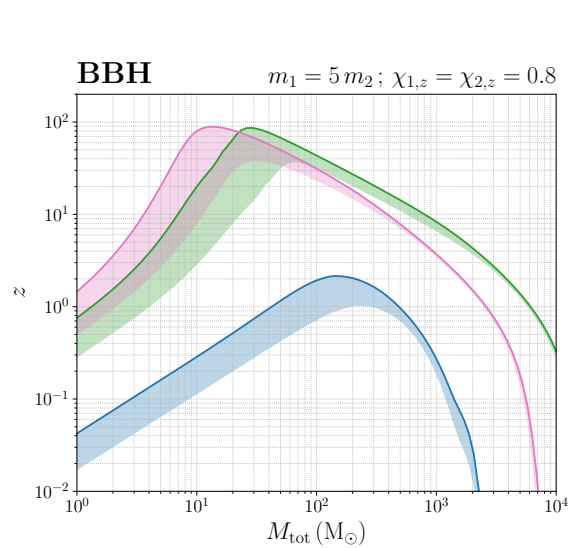
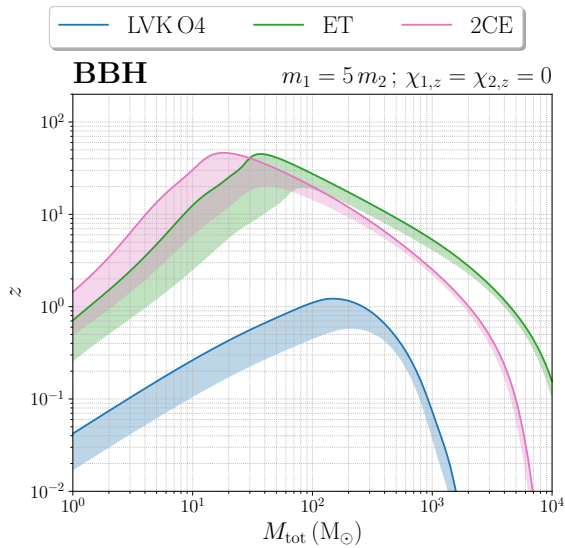
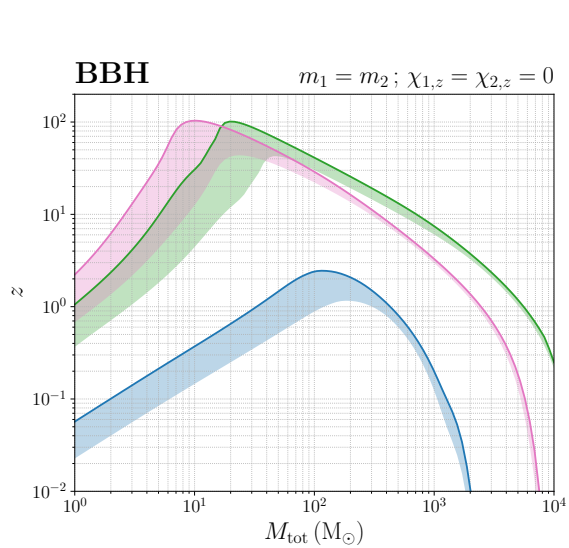


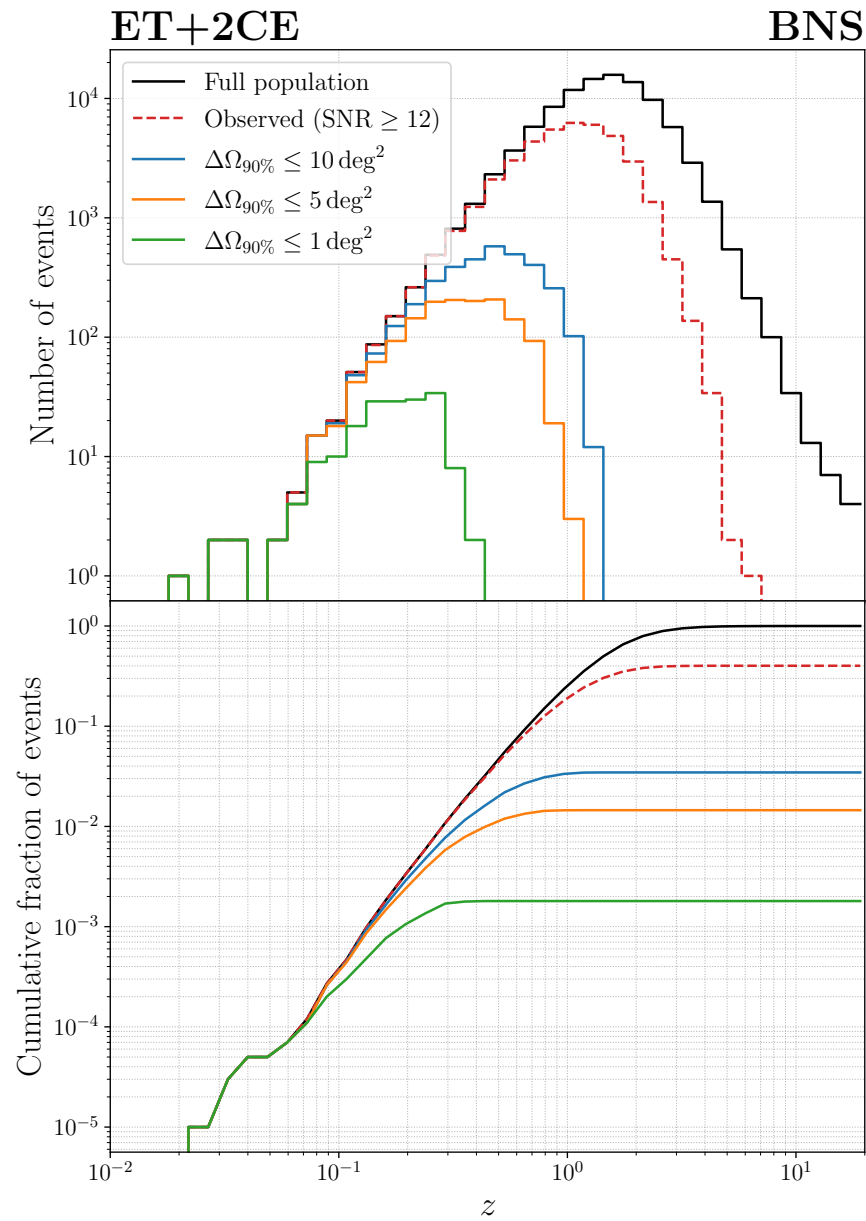
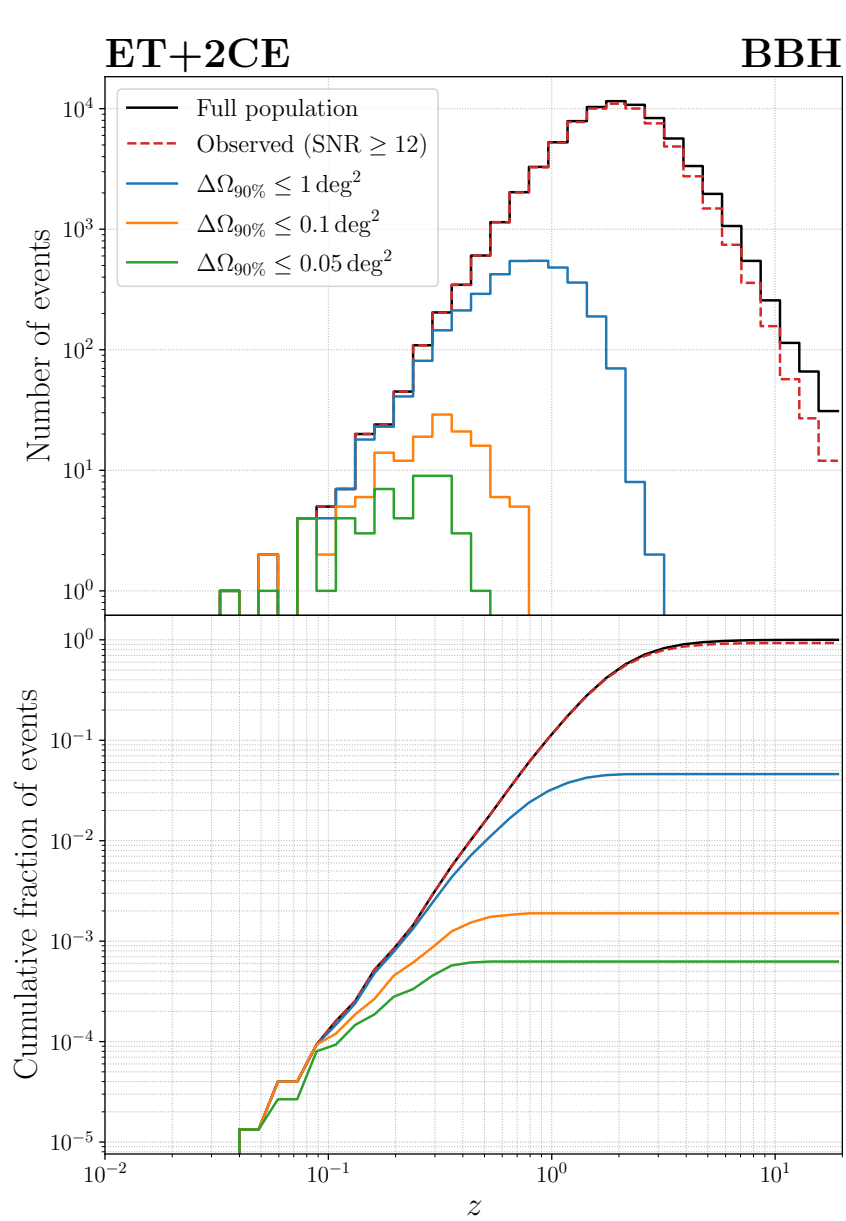


NSBH

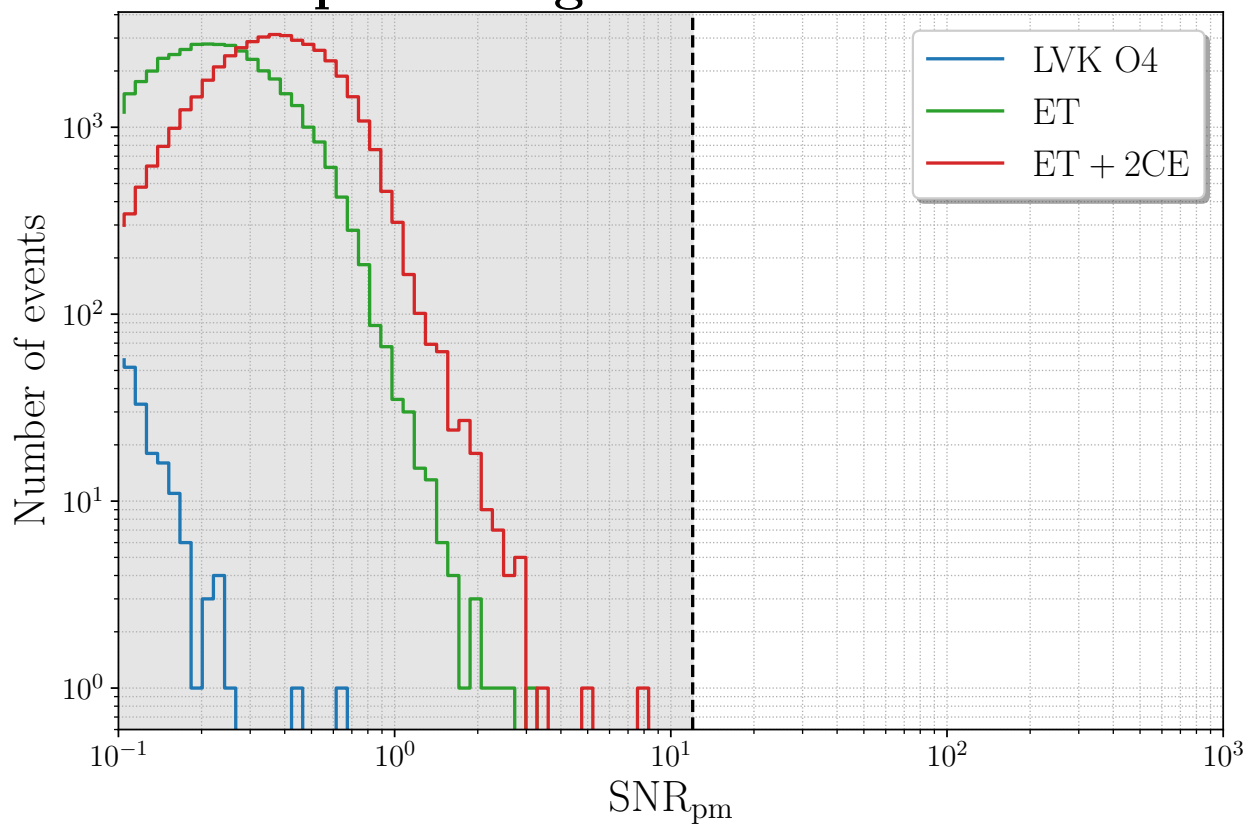
— LVK O4 — ET — ET + 2CE



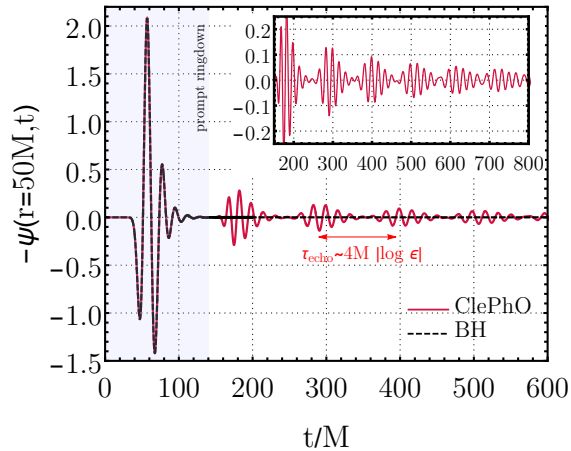




NSBH post-merger



Echoes from Exotic Compact Object



Cardoso, Franzin, Pani 2016

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

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

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

- 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)