Fundamental Physics and Cosmology with the Einstein Telescope

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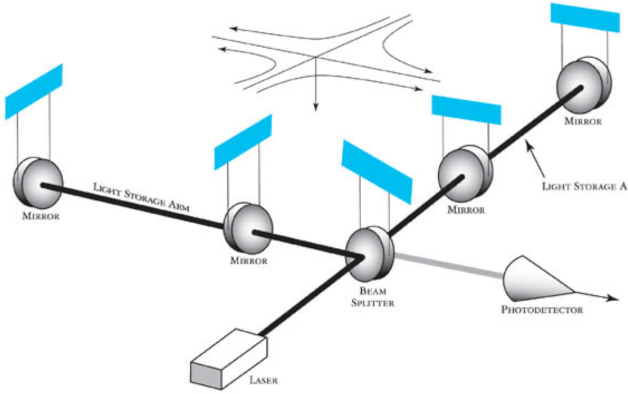
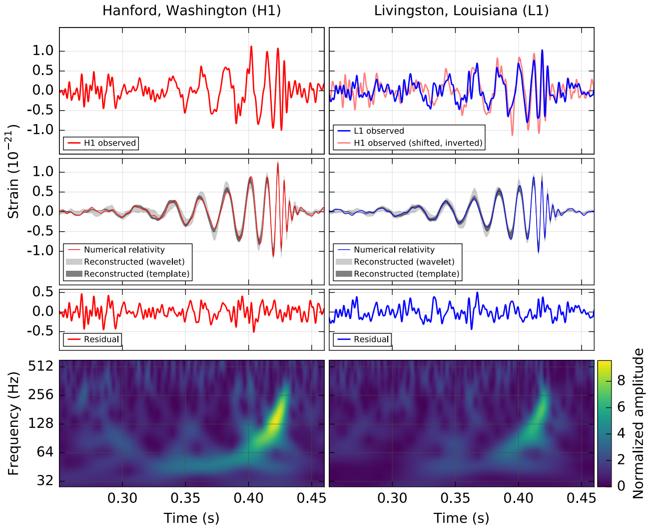
GWSC
GRAVITATIONAL
WAVE
SCIENCE
CENTER

Exploring the Universe with gravitational waves

- first direct detection of GWs in 2015 after 50+ yr of developments



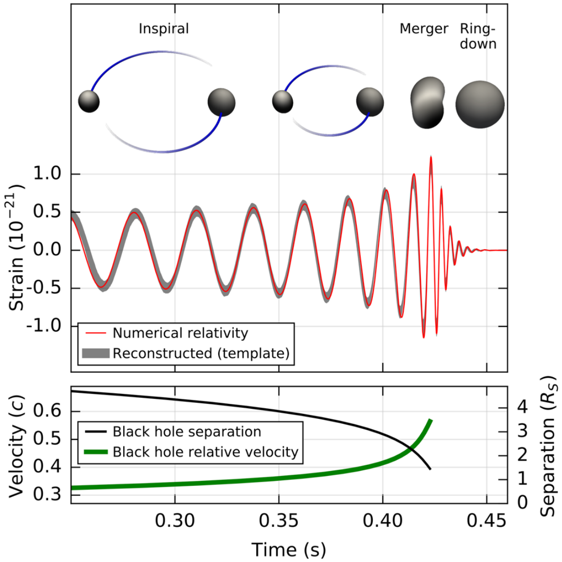
First detection of a BH-BH coalescence, Sept. 14, 2015



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	$0.09^{+0.03}_{-0.04}$

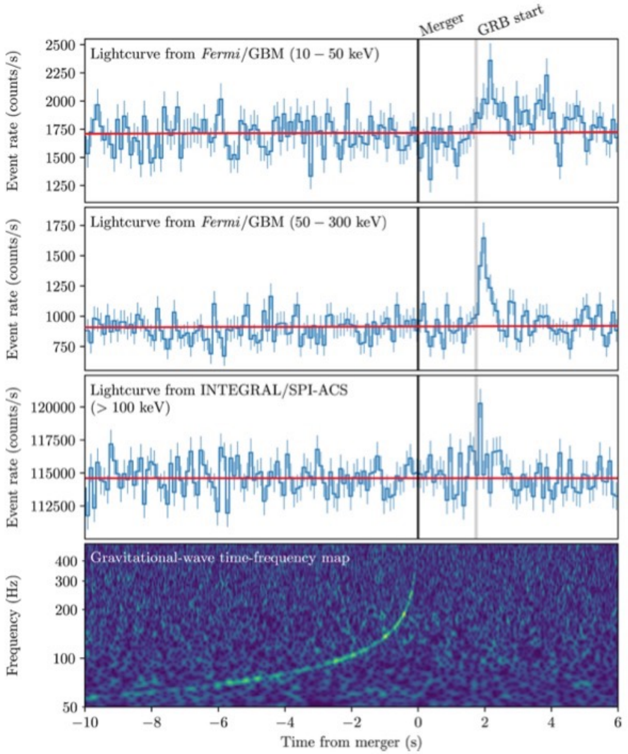
3 solar masses radiated in GWs in a few ms !!



v/c ~ 0.4 at merger !

Nobel Prize 2017

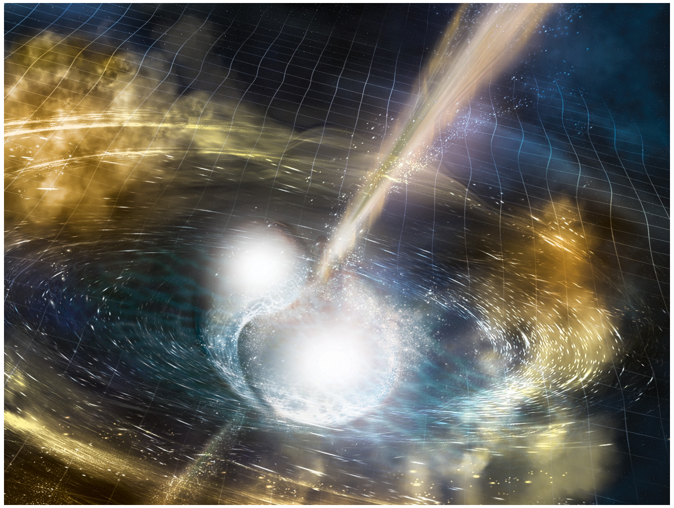
Another milestone was the first NS-NS binary, GW170817

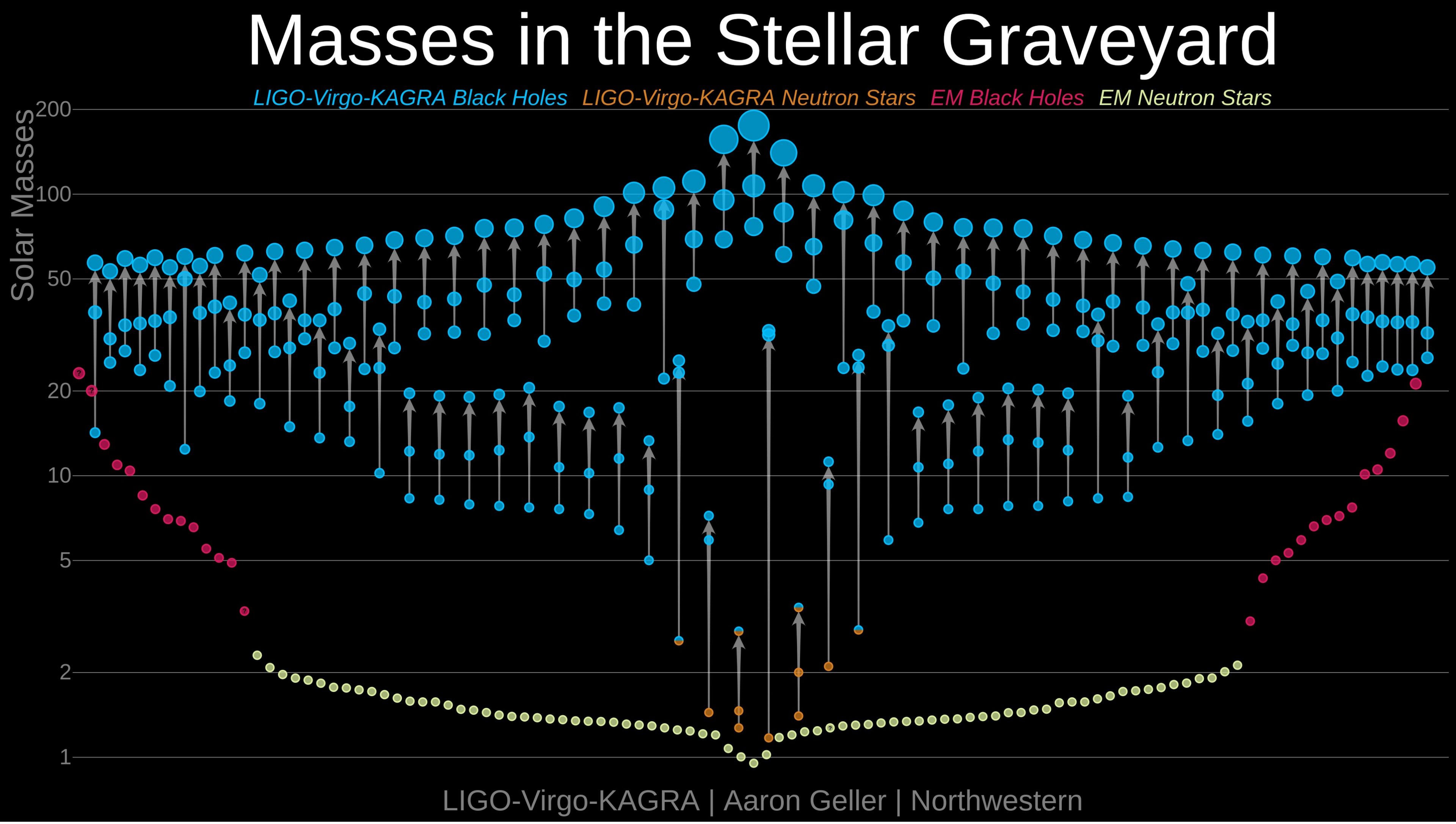


Observed in coincidence with a GRB

detection and follow-up of the counterpart in all wavelengths of the EM spectrum

⇒ multi-messenger astronomy





After 3 observing runs, about 90 BBHs, 2 BNS and 2 NS-BH
During O3, detections made every few days

What have we learned ? Some highlights:

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

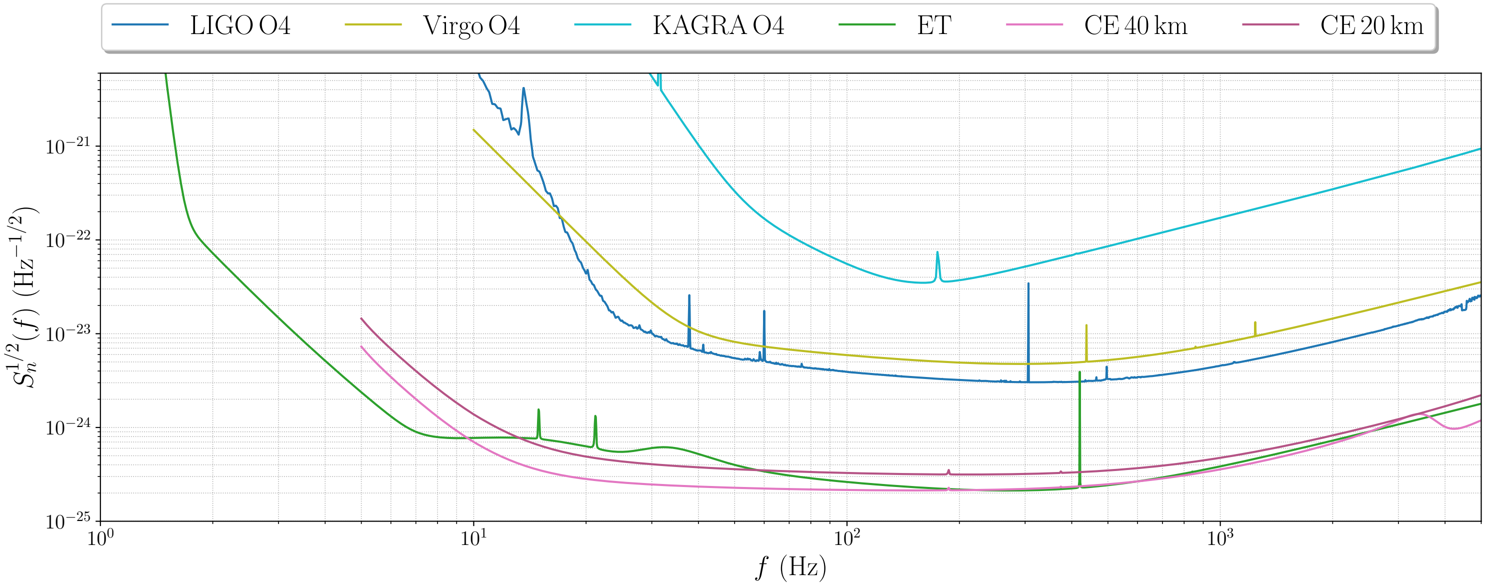
2G detectors have opened a new window

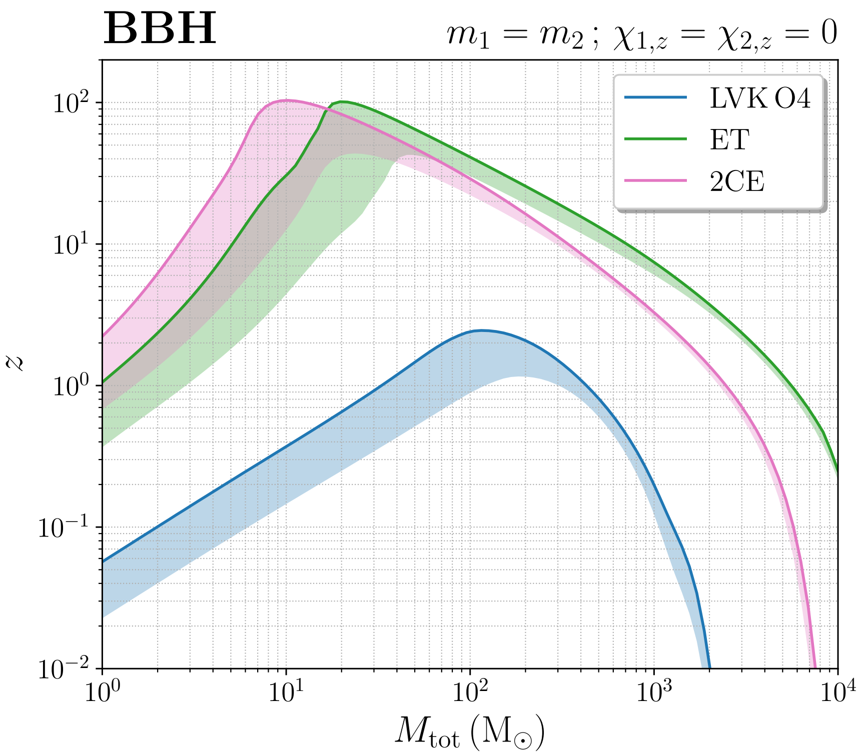
3G ground-based detectors (ET, CE) will look deeply into this window

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 (written for the ESFRI RoadMap)
- Iacovelli, Mancarella, Foffa, MM, ApJ, 2207.02771
- M. Branchesi, MM et al, JCAP, 2303.15923 (the "Science-CoBA" paper)

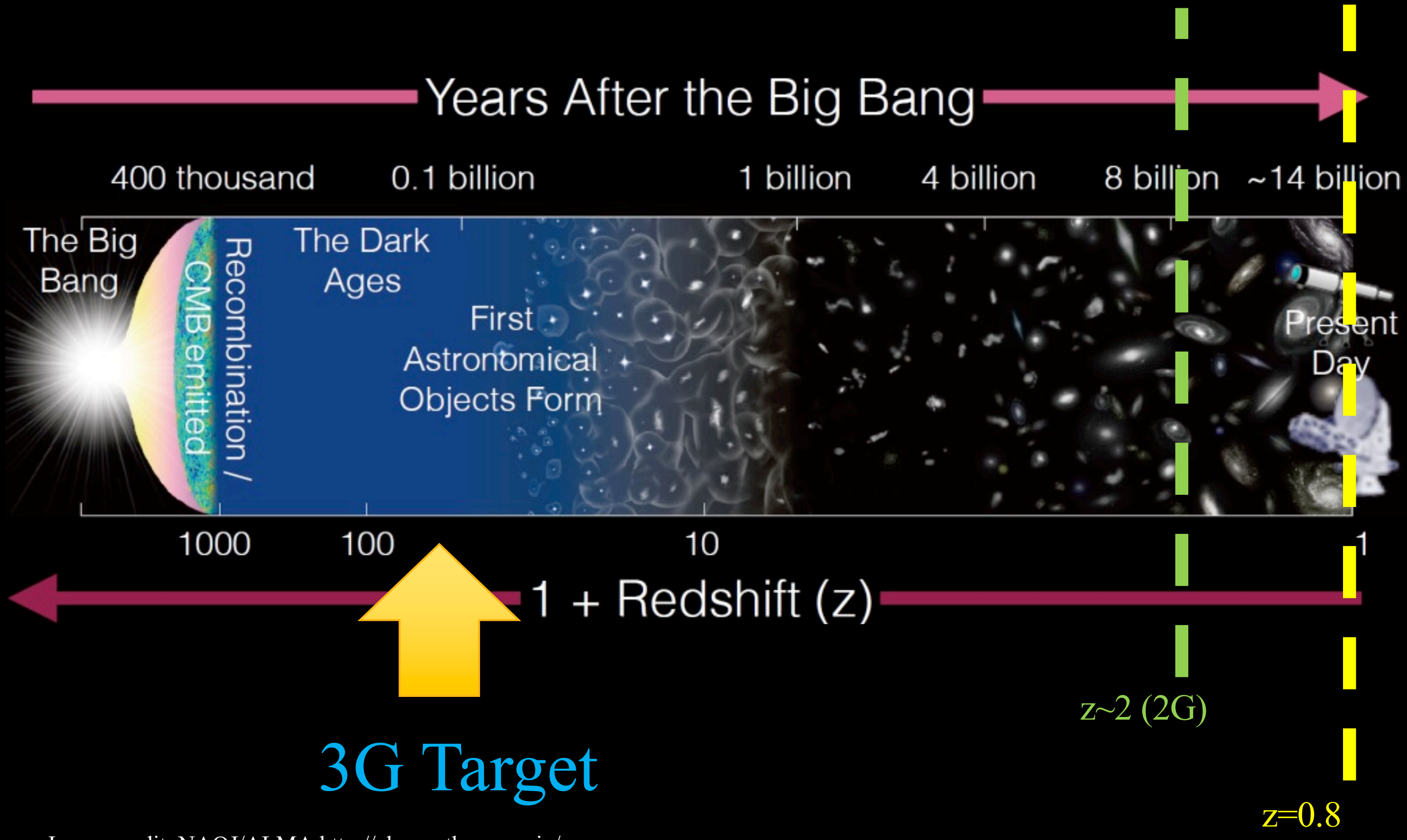




BBH up to z=O(50-100) !!

BNS up to z ~ 3

Detection distance of BBHs



z~2 (2G)

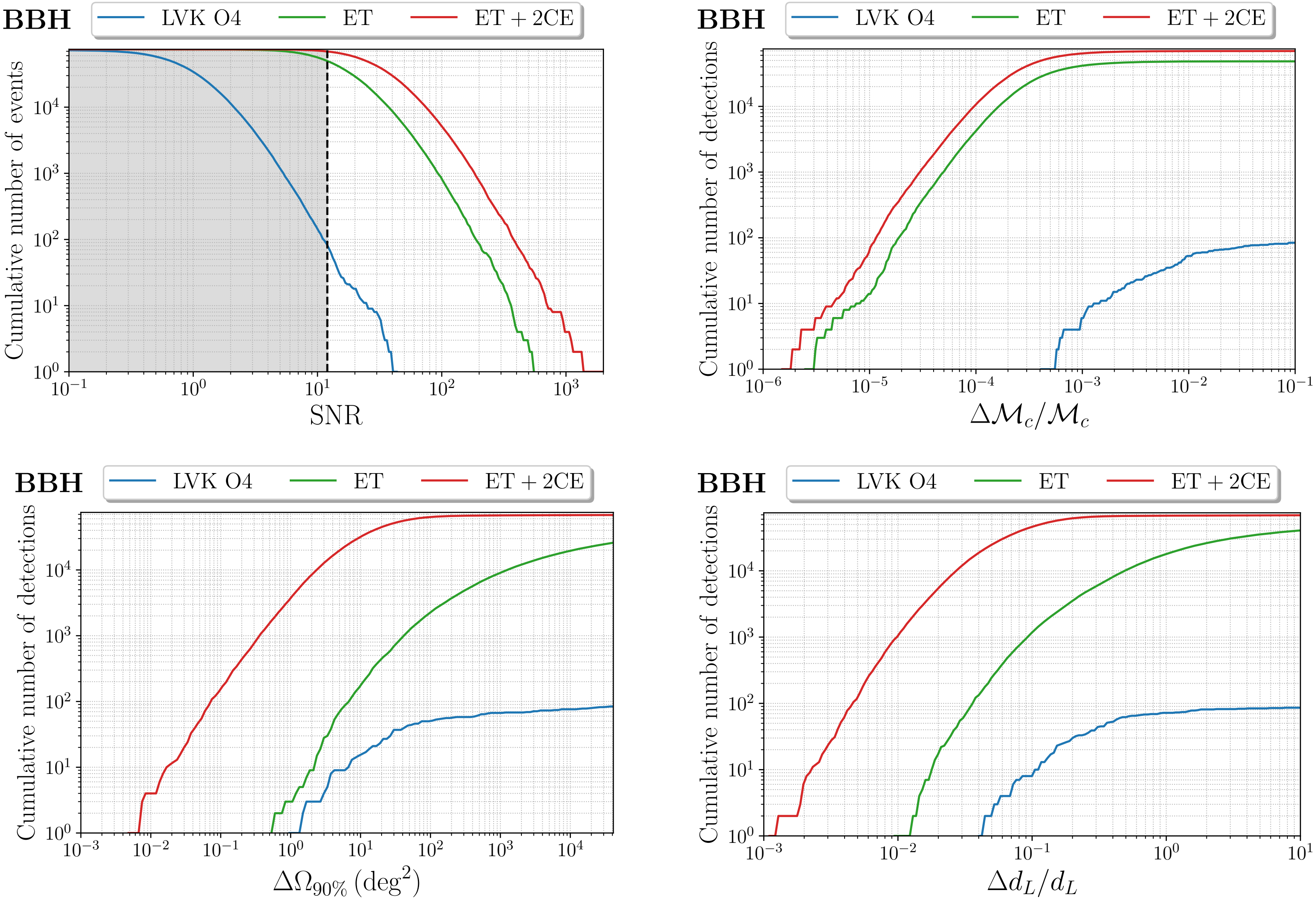
3G Target

z=0.8

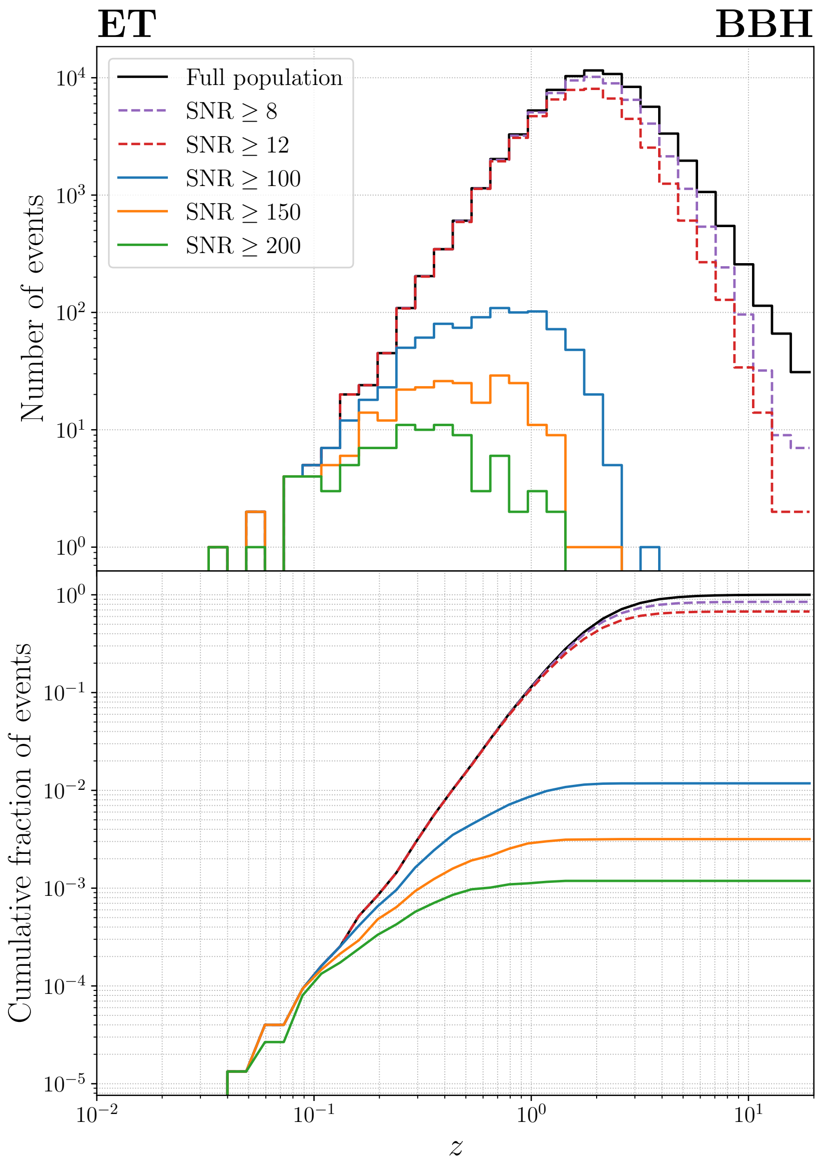
Image credit: NAOJ/ALMA http://alma.mtk.nao.ac.jp/

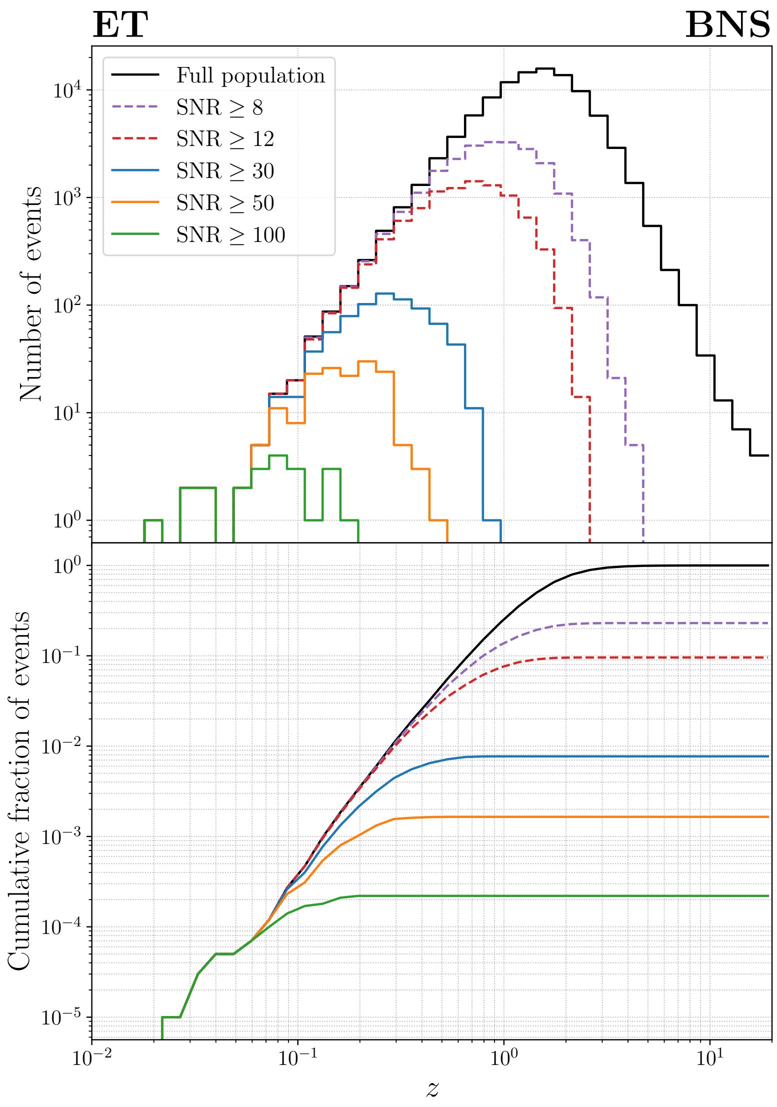
SNR distribution and examples of parameter reconstruction (BBH)

Iacovelli et al. 2022

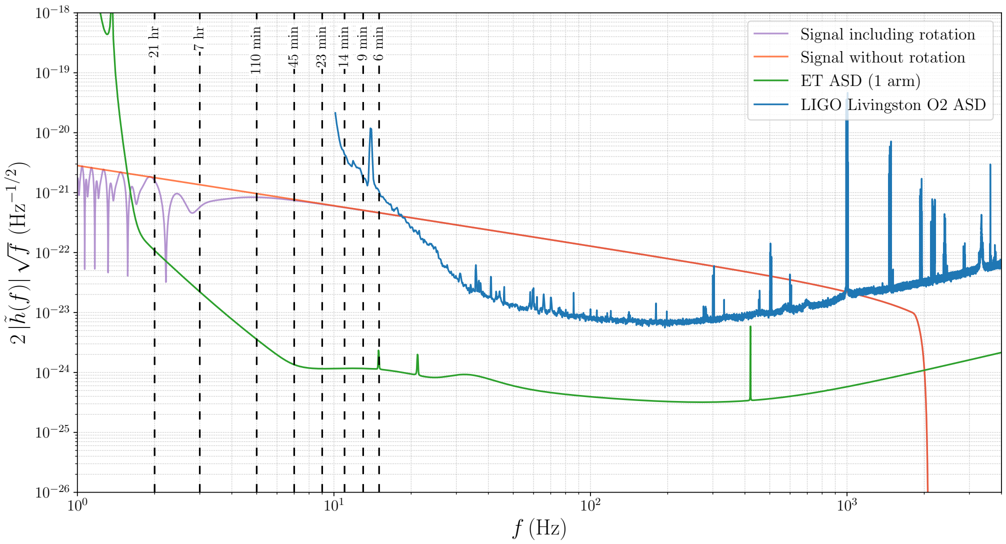


`golden events’



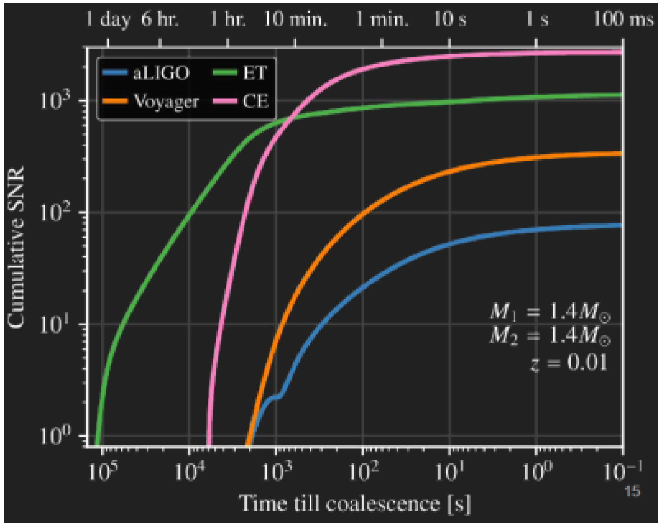


GW170817 at LVC-O2 and at ET



If we are able to cumulate enough SNR before the merging phase, we can trigger e.m. observations before the emission of photons

Keyword: low frequency sensitivity



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)

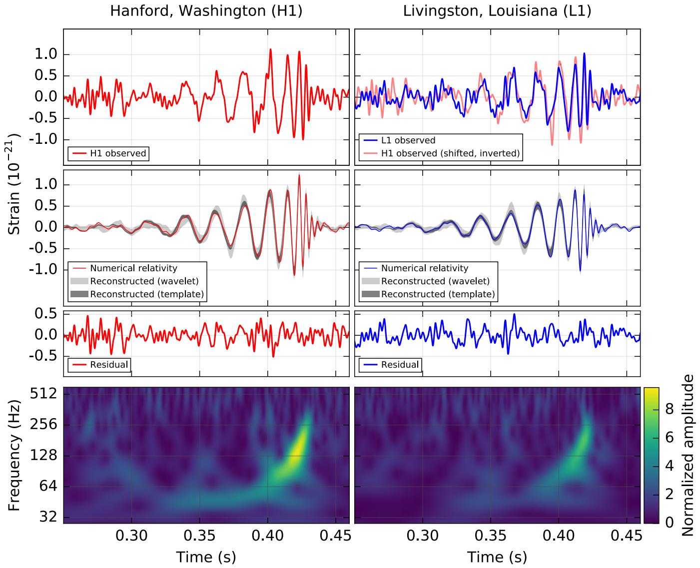
firewalls, fuzzballs... (quantum effects near the horizon motivated by the Hawking information loss problem):

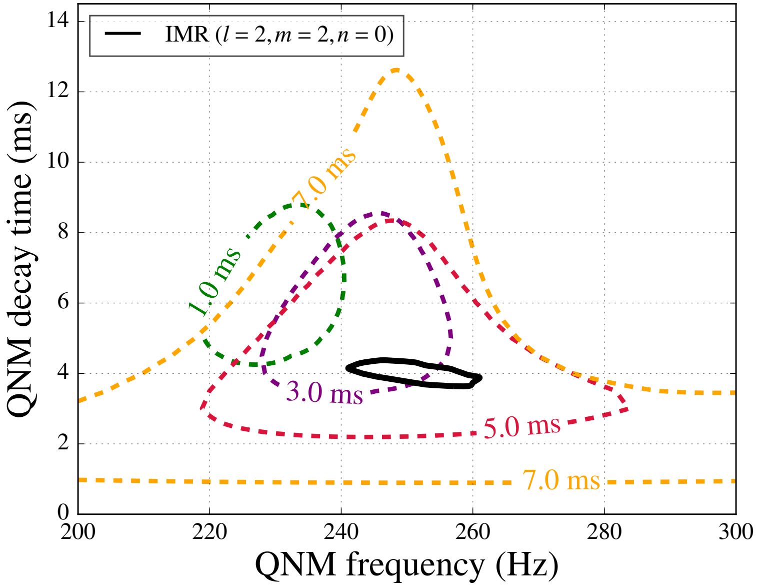
BH quasi-normal modes (QNM)

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...

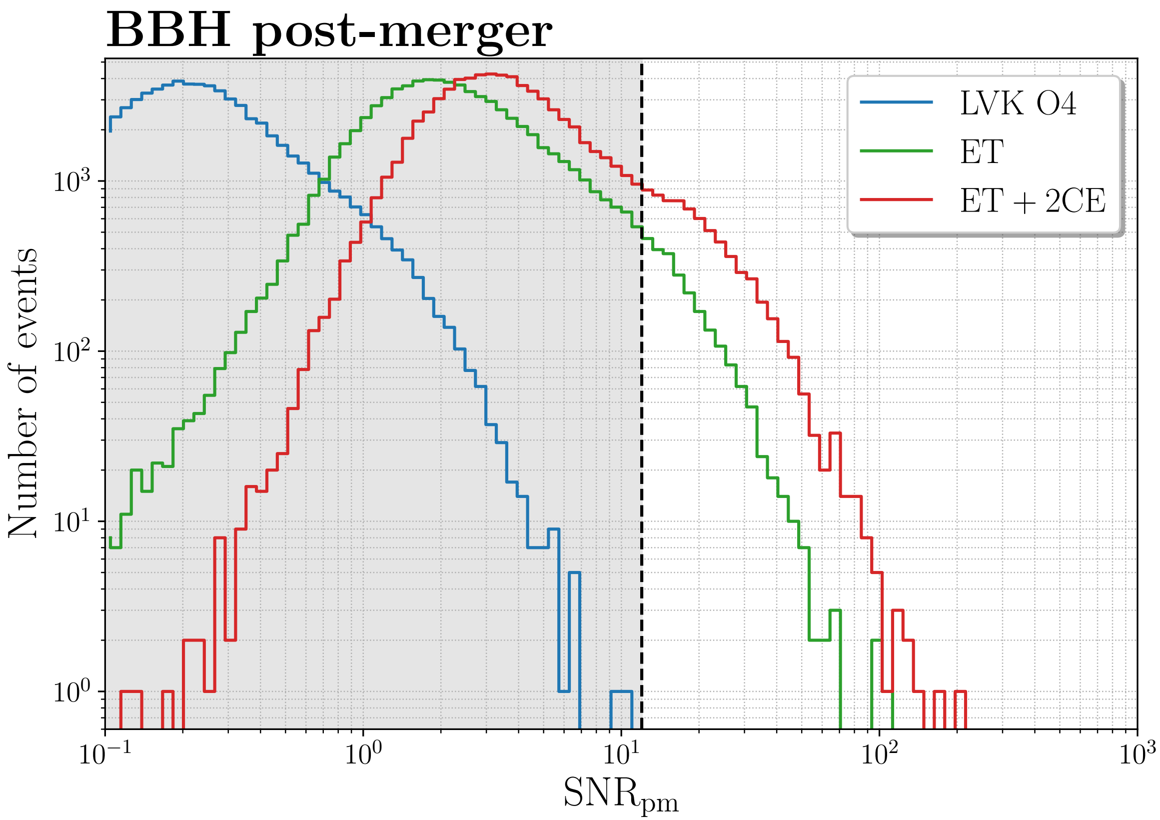




already observed in GW150914 (LVC)

consistent with GR, but we cannot say much more

BBH post-merger at ET

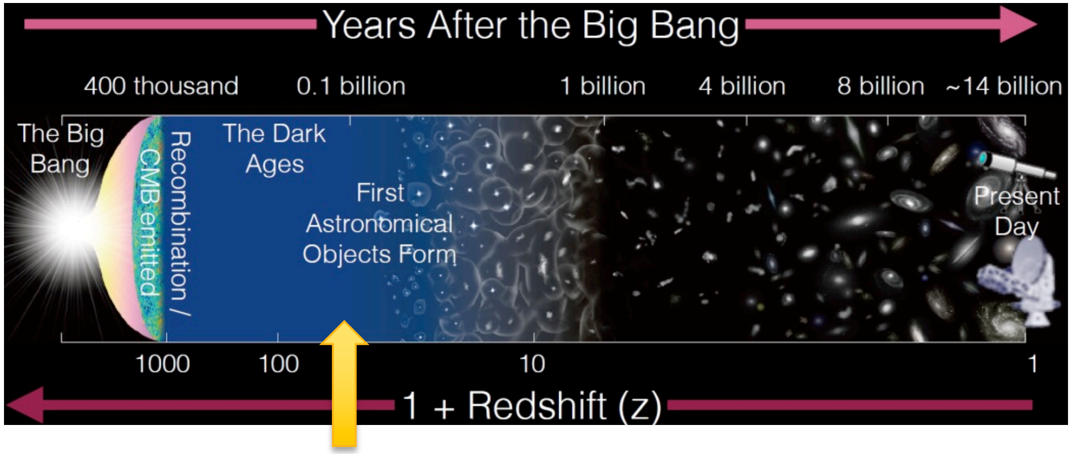


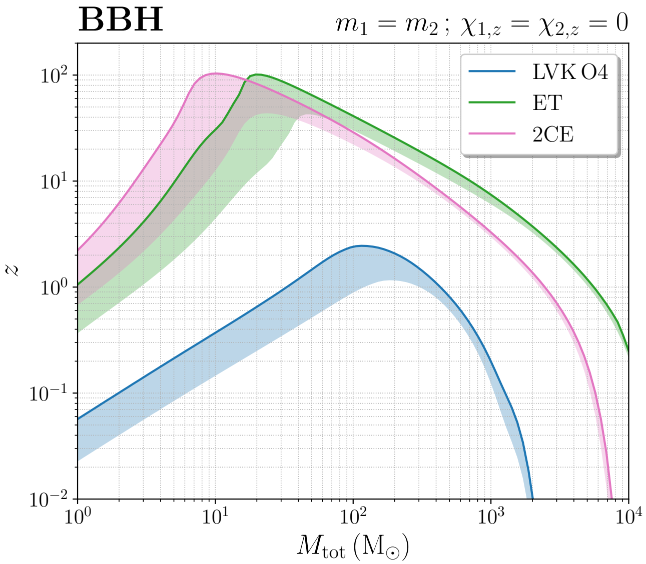
Iacovelli et al. 2022

- accurate BH spectroscopy already from single events
- 10^3 events/yr with detectable ringdown
- 20-50 events/yr with detectable higher multipoles or overtones

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

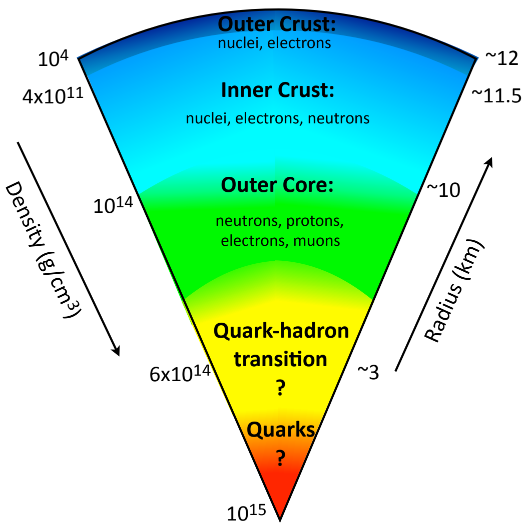
- the PBH merger rate increases with redshift, up to $z = O(10^3)$

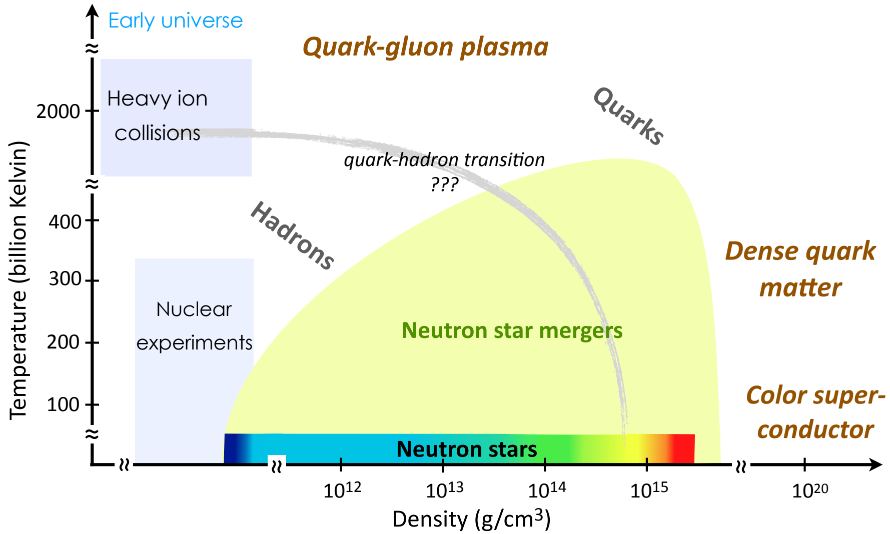
Any BBH merger at $z>30$ (very conservatively) will be of primordial origin. ET can reach $z \sim 50$-100 !!

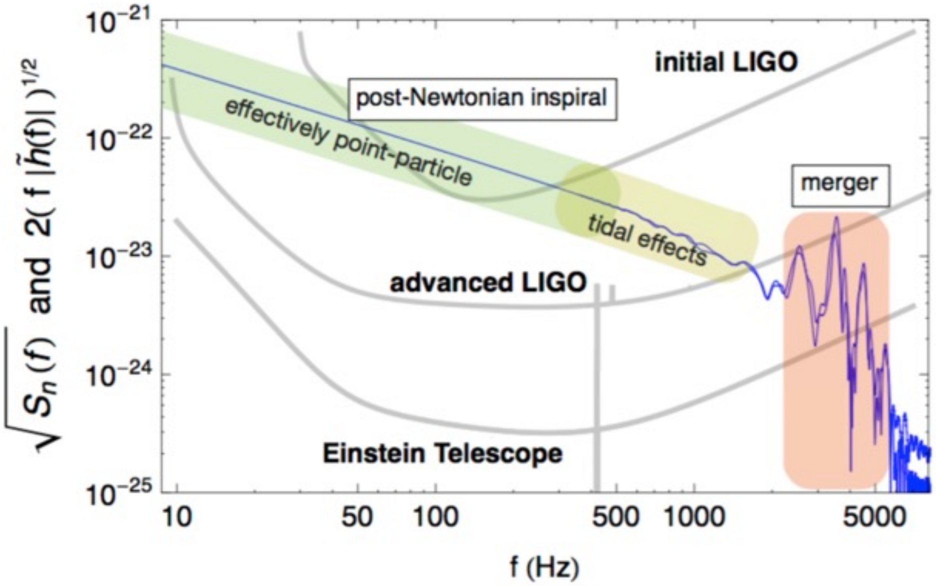
Accurate measurement of z is also needed (Ng et al 2108.07276)

- subsolar mass BH must be primordial

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

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

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

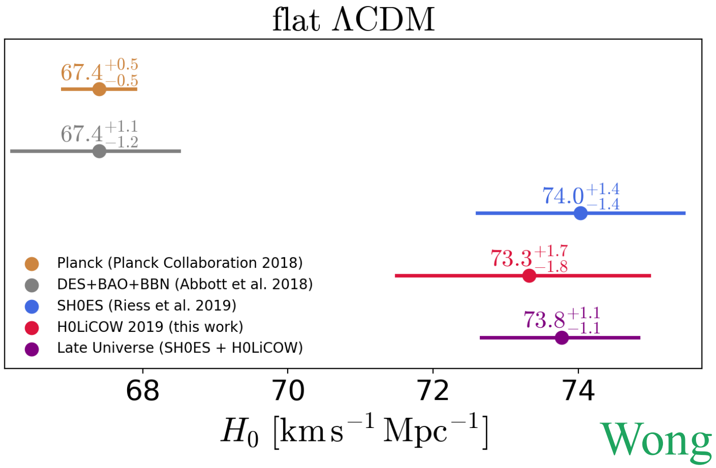
- need an independent determination of z

  (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 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

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

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:

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

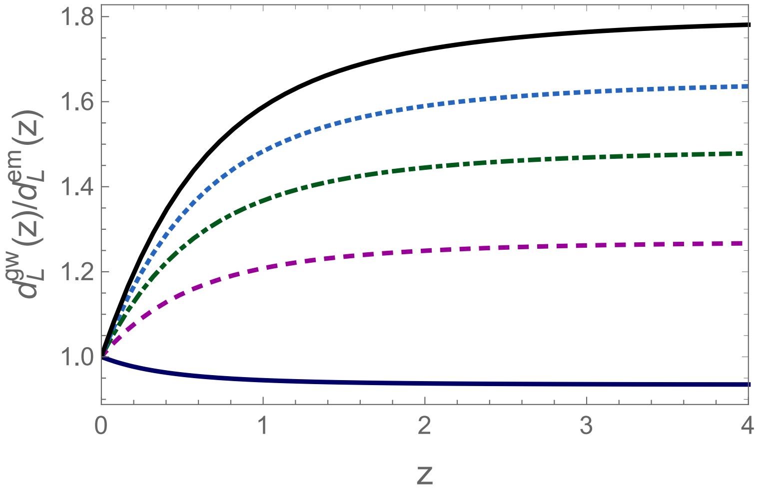
This affects the propagation of GWs across cosmological distances

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

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

- 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 $z \sim 30\text{-}100$,
  - 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 ~ 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

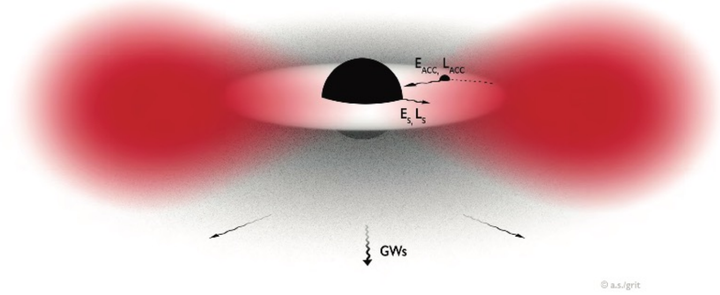


figure: Brito, Cardoso, Pani 2014

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

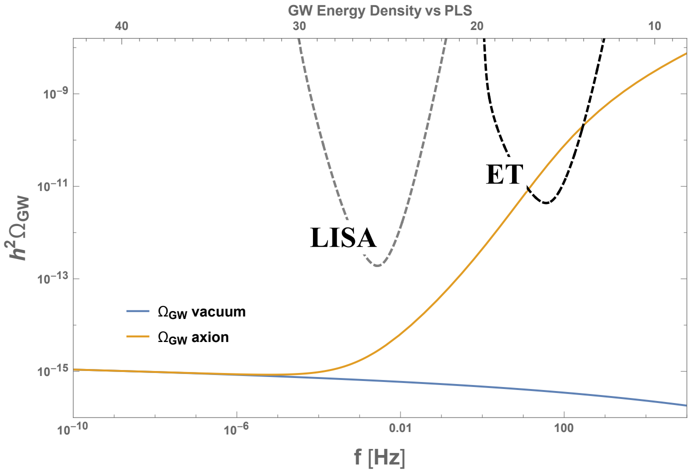
  $z \simeq 1090, \quad T \simeq 0.26$ eV

  CMB gives a snapshot of the Universe at this epoch

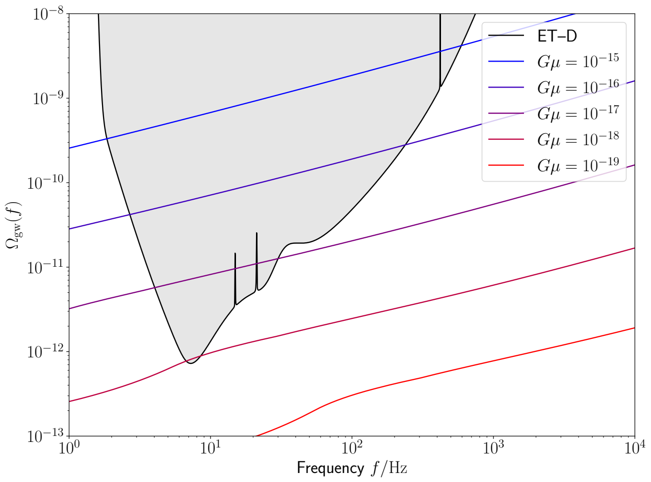
- neutrinos decouple at $T \simeq$ MeV

- GWs are already decoupled below the Planck scale, 10^{19} GeV

ET improves the sensitivity to stochastic backgrounds by 2-3 orders of magnitude compared to LIGO/Virgo 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

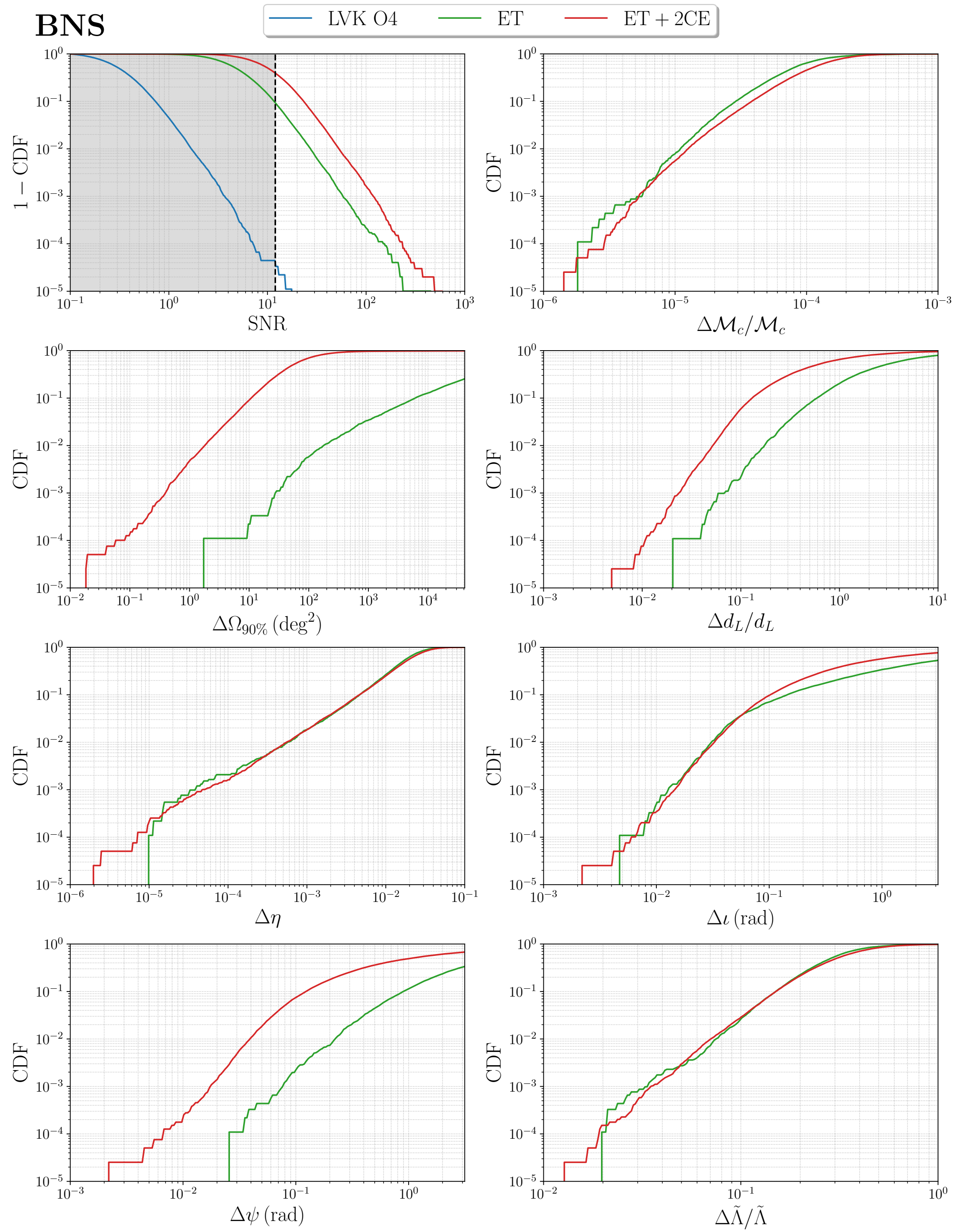


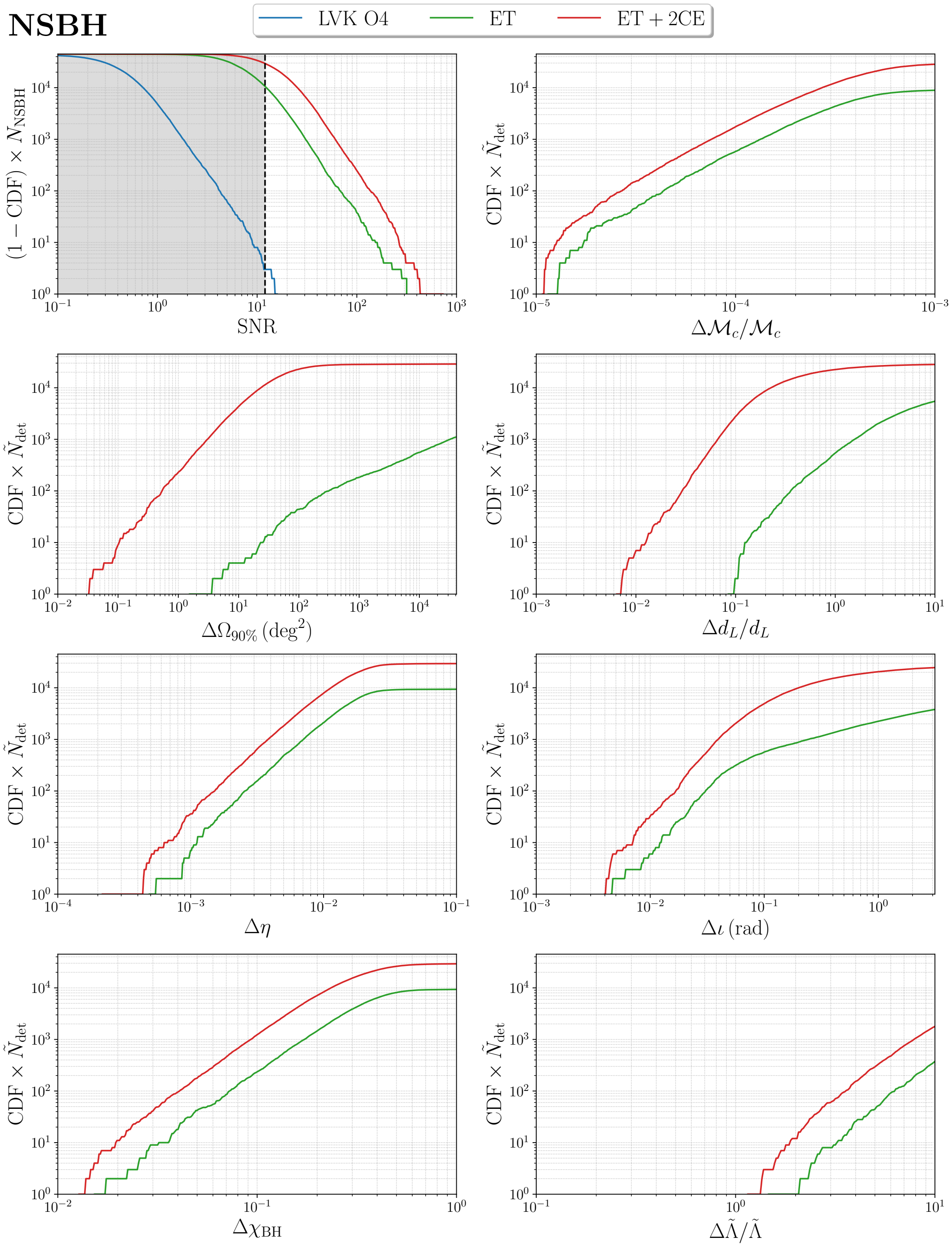
Take-away messages

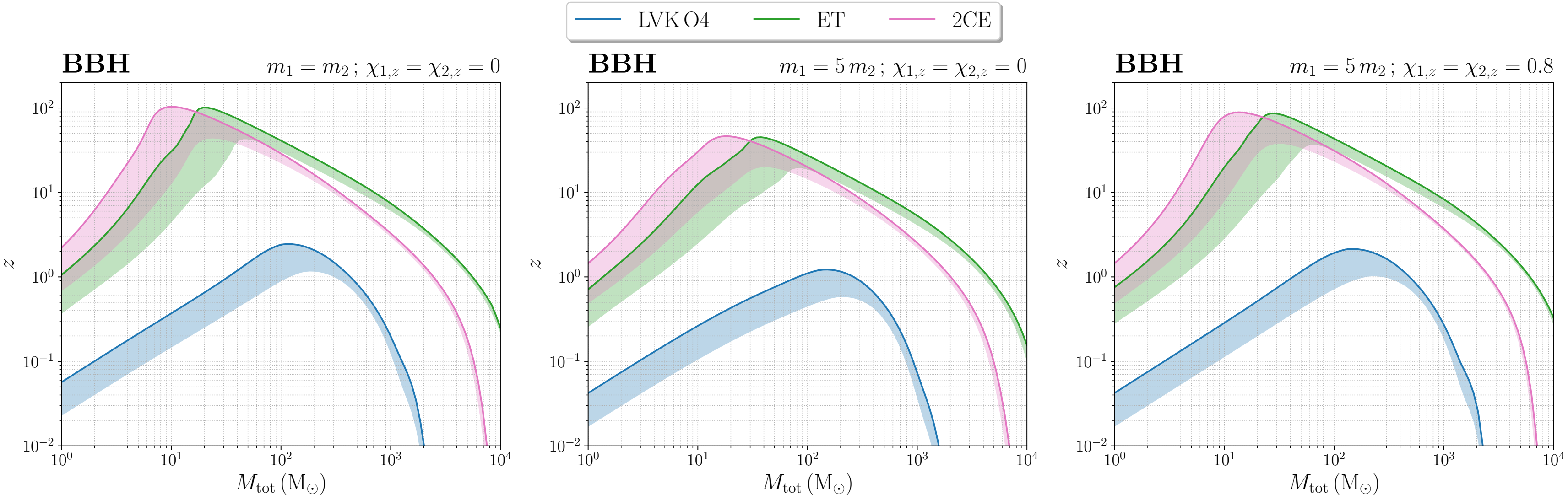
ET has an exciting and broad science program, ranging from astrophysics to cosmology and fundamental physical

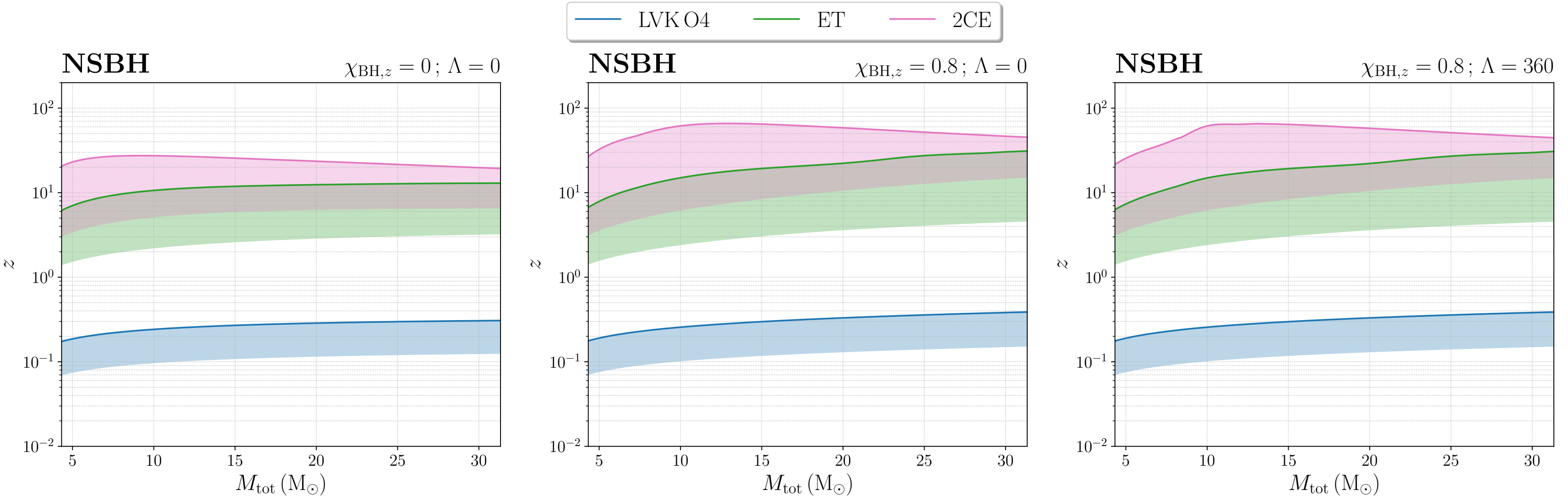
Thank you!

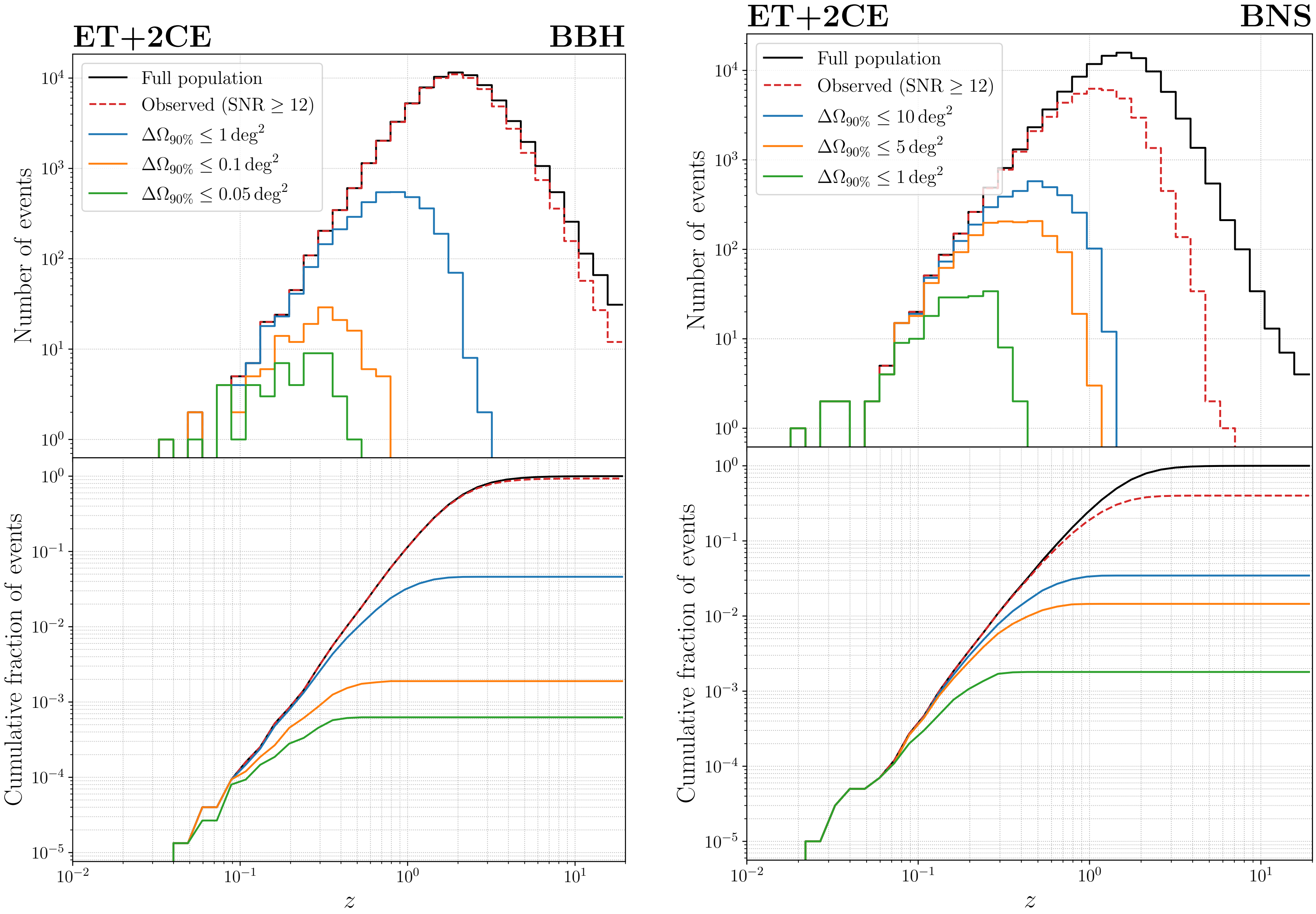
bkup slides


BNS
LVK O4
ET
ET + 2CE
1 − CDF
SNR
CDF
$\Delta\mathcal{M}_c/\mathcal{M}_c$
$\Delta\Omega_{90\%}$ (deg^2)
$\Delta d_L/d_L$
$\Delta\eta$
$\Delta\iota$ (rad)
$\Delta\psi$ (rad)
$\Delta\tilde{\Lambda}/\tilde{\Lambda}$

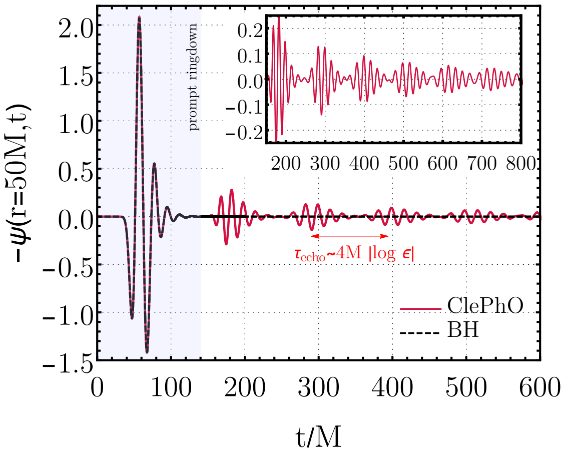

NSBH
LVK O4
ET
ET + 2CE
$(1 - \mathrm{CDF}) \times N_{\mathrm{NSBH}}$
SNR
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
$\mathrm{CDF} \times \tilde{N}_{\mathrm{det}}$
$\Delta\mathcal{M}_c/\mathcal{M}_c$
10^{-5}
10^{-4}
10^{-3}
$\Delta\Omega_{90\%}\,(\mathrm{deg}^2)$
10^{-2}
$\Delta d_L/d_L$
$\Delta\eta$
$\Delta\iota\,(\mathrm{rad})$
$\Delta\chi_{\mathrm{BH}}$
$\Delta\tilde{\Lambda}/\tilde{\Lambda}$


LVK O4
ET
2CE
BBH
$m_1 = m_2\,;\ \chi_{1,z} = \chi_{2,z} = 0$
BBH
$m_1 = 5\,m_2\,;\ \chi_{1,z} = \chi_{2,z} = 0$
BBH
$m_1 = 5\,m_2\,;\ \chi_{1,z} = \chi_{2,z} = 0.8$
z
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
$M_{\rm tot}\ ({\rm M}_\odot)$


LVK O4
ET
2CE
NSBH
$\chi_{{\rm BH},z} = 0\,;\ \Lambda = 0$
NSBH
$\chi_{{\rm BH},z} = 0.8\,;\ \Lambda = 0$
NSBH
$\chi_{{\rm BH},z} = 0.8\,;\ \Lambda = 360$
z
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
5
10
15
20
25
30
$M_{\rm tot}\ ({\rm M}_\odot)$


ET+2CE
BBH
Full population
Observed (SNR $\geq$ 12)
$\Delta\Omega_{90\%} \leq 1\,\mathrm{deg}^2$
$\Delta\Omega_{90\%} \leq 0.1\,\mathrm{deg}^2$
$\Delta\Omega_{90\%} \leq 0.05\,\mathrm{deg}^2$
Number of events
10^0
10^1
10^2
10^3
10^4
Cumulative fraction of events
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^0
10^{-2}
10^{-1}
10^0
10^1
z
ET+2CE
BNS
Full population
Observed (SNR $\geq$ 12)
$\Delta\Omega_{90\%} \leq 10\,\mathrm{deg}^2$
$\Delta\Omega_{90\%} \leq 5\,\mathrm{deg}^2$
$\Delta\Omega_{90\%} \leq 1\,\mathrm{deg}^2$
Number of events
10^0
10^1
10^2
10^3
10^4
Cumulative fraction of events
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^0
10^{-2}
10^{-1}
10^0
10^1
z

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:

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

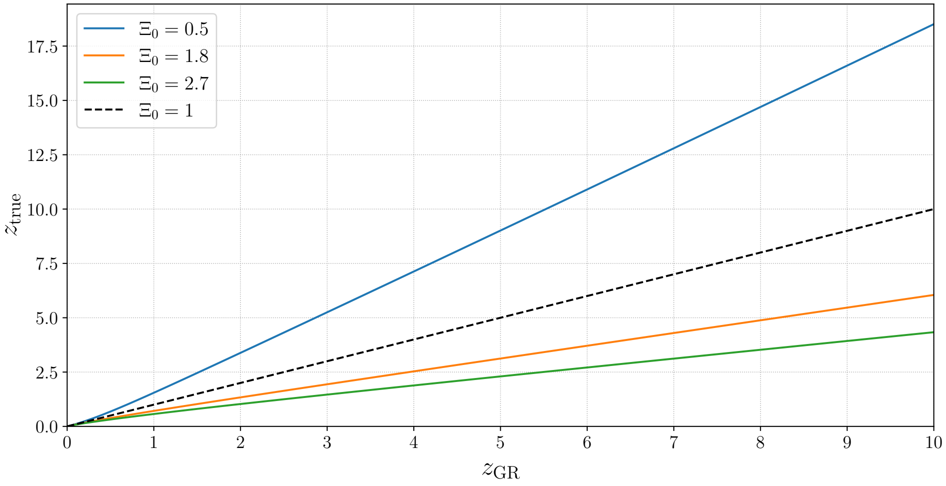
- quite different from accelerator physics, where the Planck scale is unreachable

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

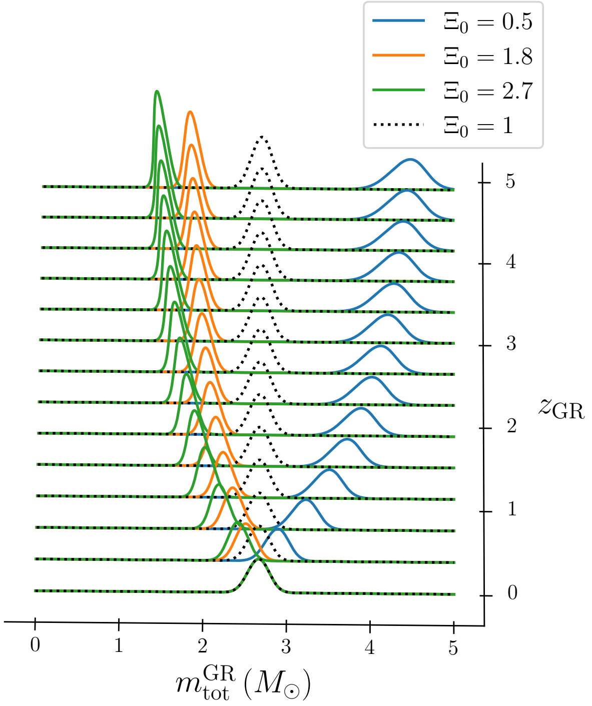
Example: BNS mass function at ET

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

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



Finke, Foffa, Iacovelli, MM, Mancarella 2021



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

see Ronchini et al 2022 for comprehensive studies of MMO with ET