CE Observational Science

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on behalf of the Cosmic Explorer Team

LSC wide call
Jan 21 2022

DCC G2200076

The Dawn report on CE Observational Science

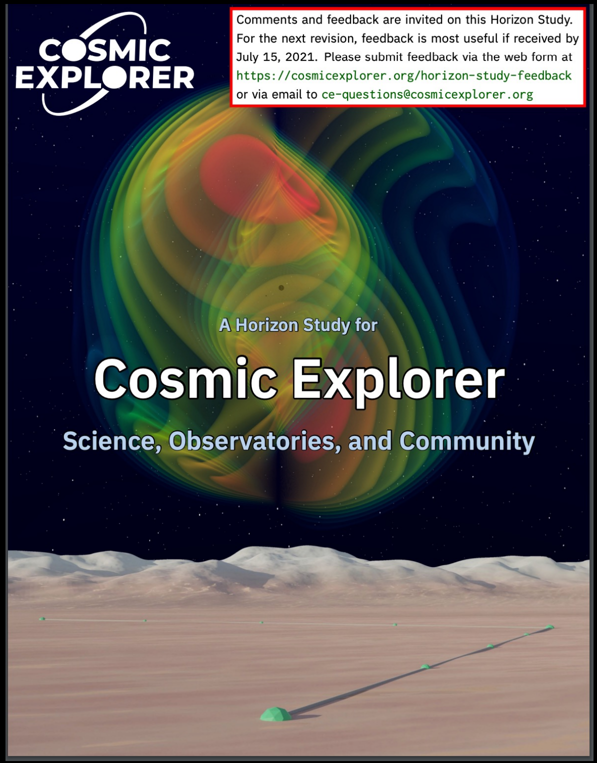
- Several scienstists who don't belong to the LVK were invited to provide their perspective on scientific potential of CE and 3G detectors, and related challenges
  - E. Berti, GW astrophysics (populations, tests of GR, …)
  - H. Peiris, Cosmology
  - P. Chandra, Radio
  - E. Troja, Gamma/X-ray observations
  - A. Steiner, Nuclear physics
  - W. Fong, OIR
  - K. Fang, Neutrinos (excited about prospects of SNe detection)
  - J. Greene, C. Miller, S. Smartt, A. Villar, panel discussion

Overall message

- The community *expects* GW observational science to be a central part of the astrophysics landscape in the 2030s
- This sentiment was also echoed in the Astro decadal
- Strong consensus that 3 or more sites are needed to maximize the science impact
- Given the large number of events, and cost of telescope time, more info should be given in GCNs to help prioritize
- Need to think carefully about construction/update schedules: the community doesn't have an appetite for a long upgrade gap.

3G science

- The scientific potential of CE has been discussed in the recently completed Cosmic Explorer Horizon Study (CEHS)
- The final draft can be read at https://cosmicexplorer.org/
- A corresponding document exists for [ET](ET) and papers exist for the high-frequency NEMO (OzGrav) concept



CEHS 2021

Cosmic Explorer Horizon Study

- The CE HS identifies key science outcomes that can be reached with 3G detectors
  - Black holes and neutron stars throughough cosmic time
  - Dynamics of dense matter & extreme environments
  - Extreme gravity & Fundamental Physics

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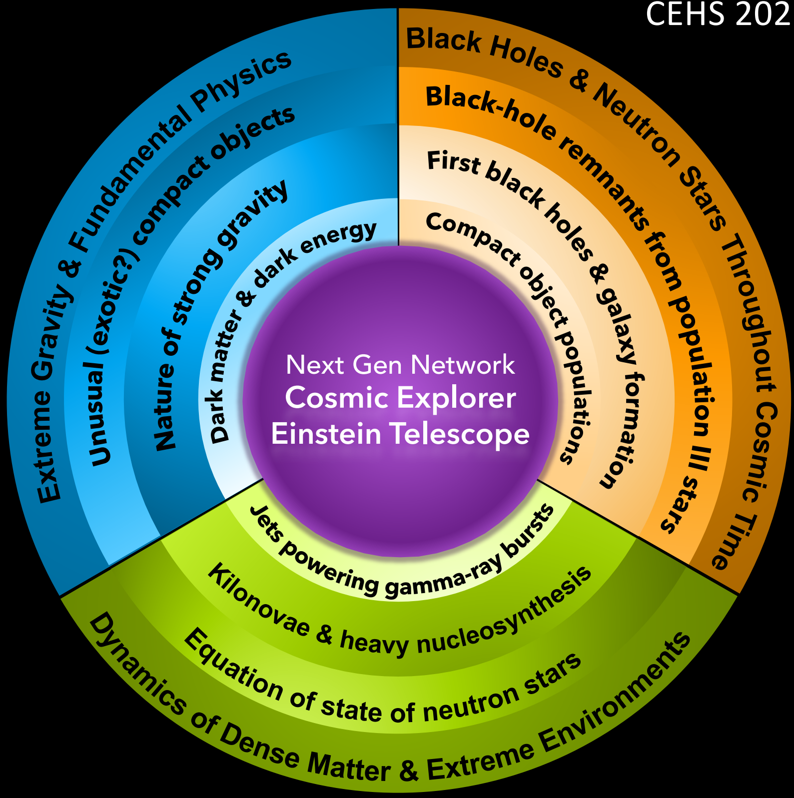
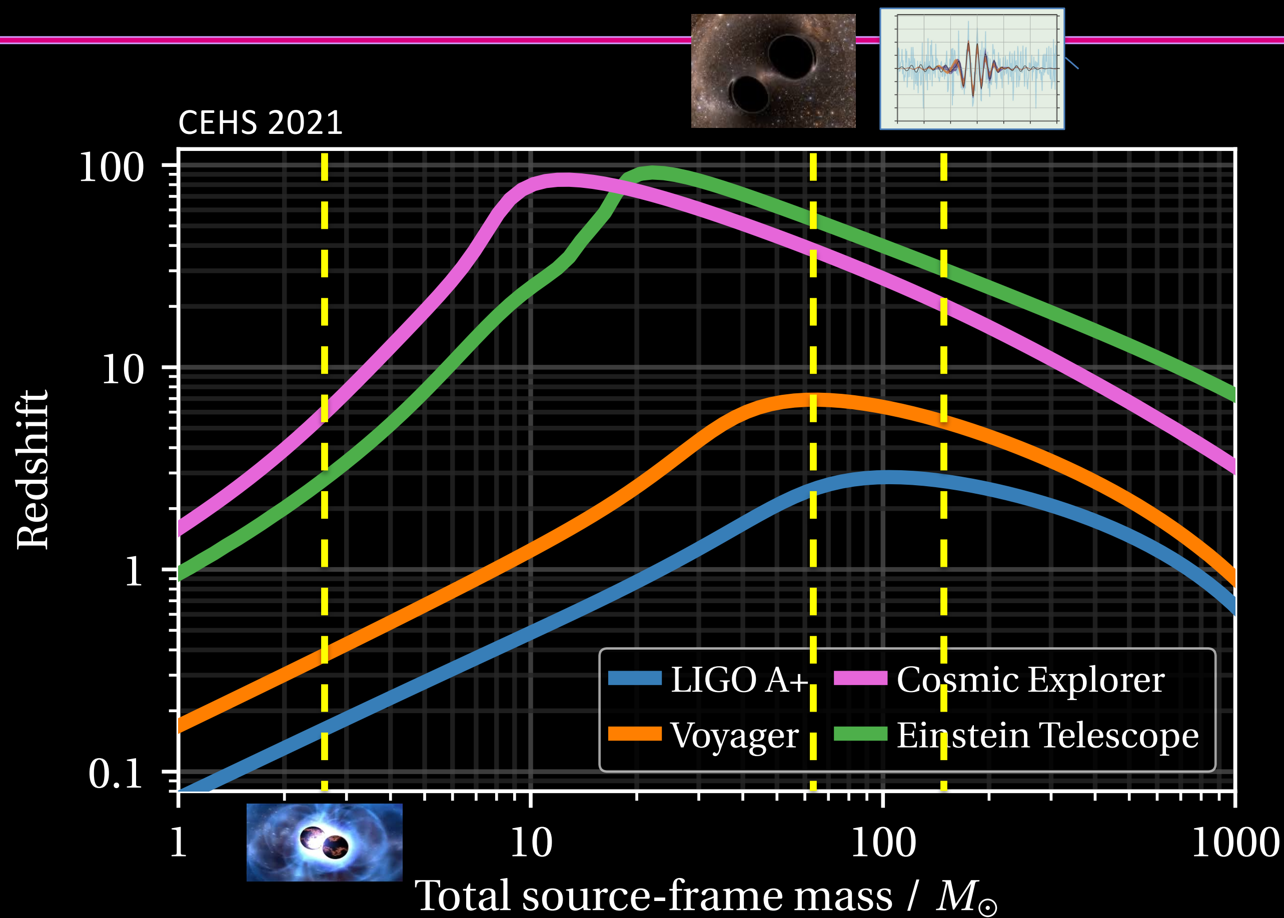
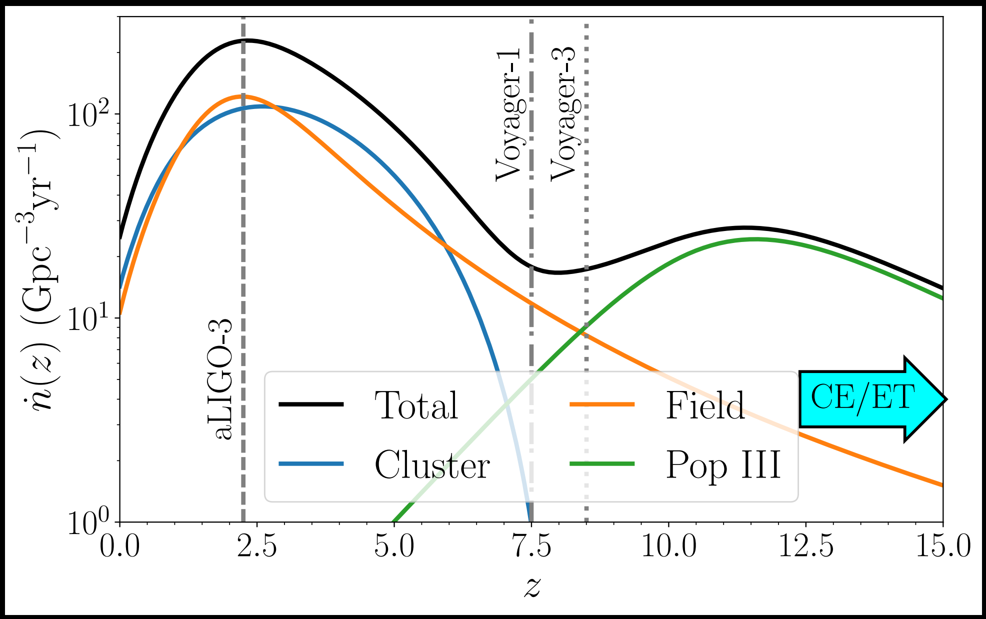


Listening to the Universe



Populations of binaries

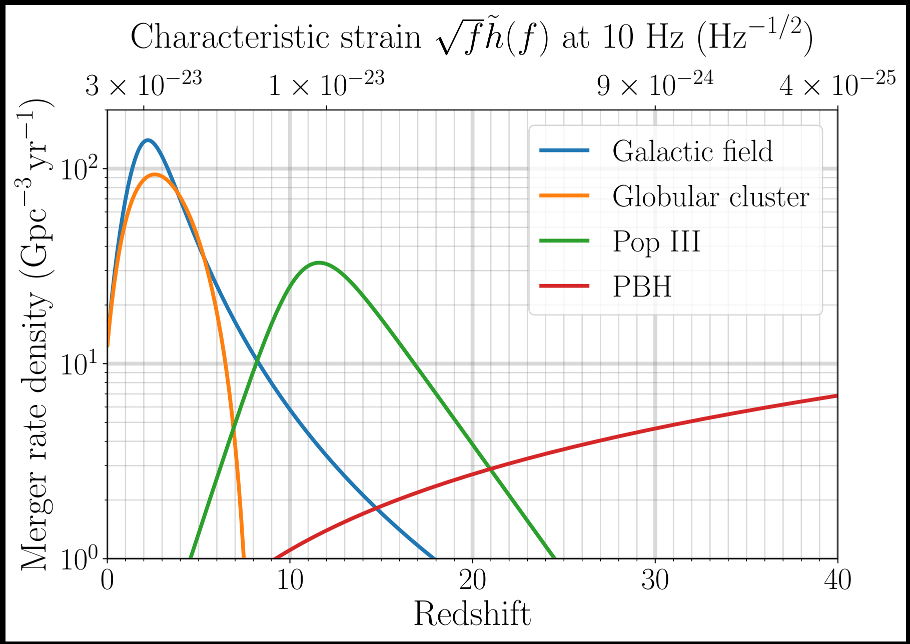


Ng+ ApJL 913 L5

- Can detect black holes from populations which are currently unaccessible
- "CE and ET will be probing the population before the peak of star formation. This gives lots of insight into metallicity, generations of stars (pop III), formation channels, etc. It teaches us about stellar formation and evolution in a unique and powerful way."
- It is important to have a network, to measure distance well, and hence source-frame mass

Detecting PBHs mergers

- Primordial black holes mergers might be recognizable because of
  - Mass and spins spectrum
  - Eccentricity at merger
  - Extemely high redshift
- Of these, the high redshift might be the most uncontroversial smoking gun



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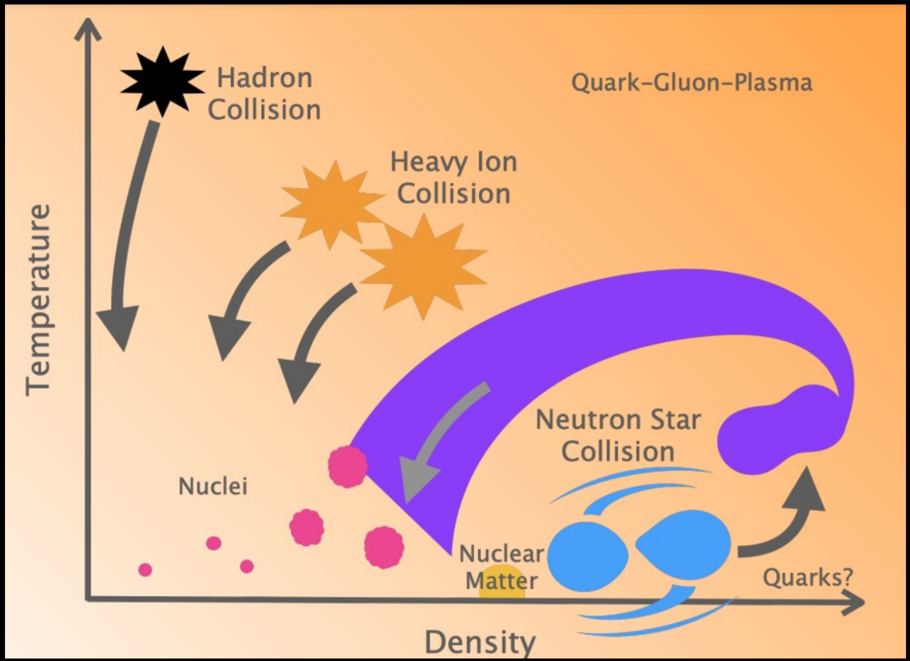
Neutron star physics

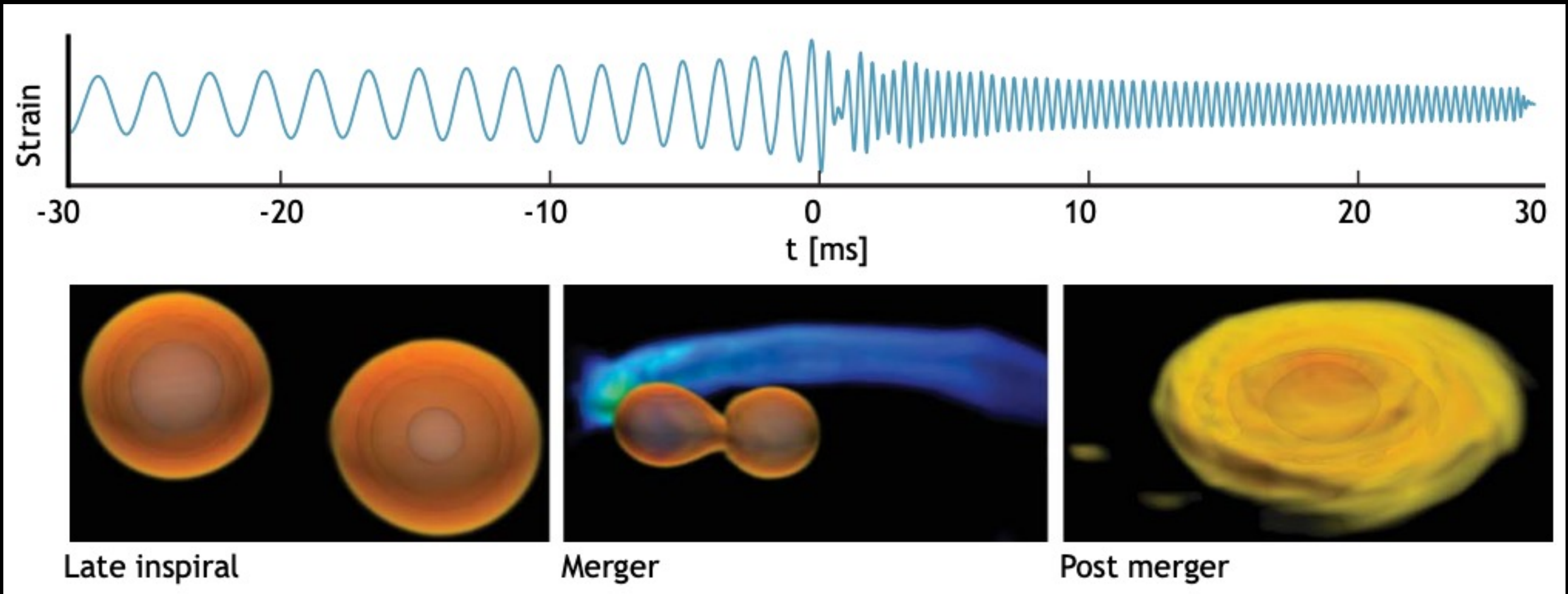
- Matter in neutron stars experiences the most extreme conditions in the visible universe
- Can explore regions of the QCD phase diagram which are not accessible at Earth
  - Determine internal structure of neutron star
  - Equation of state
- “It is clear that gravitational waves can provide insights into nuclear physics which are probably inaccessible otherwise"

CEHS 2021



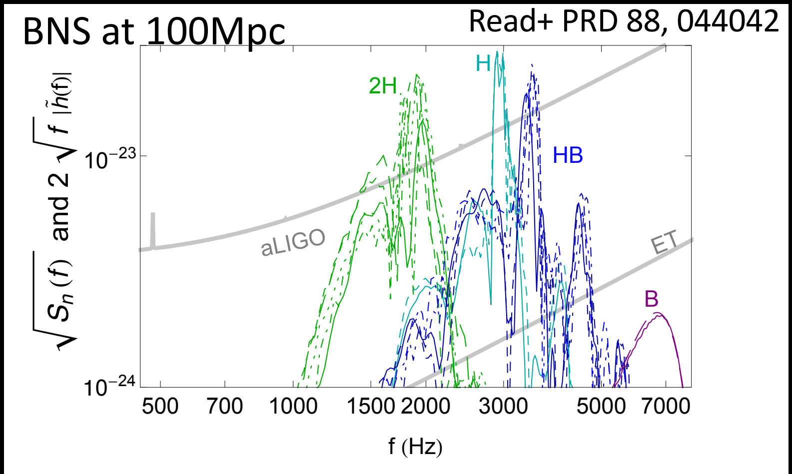
Binary neutron stars

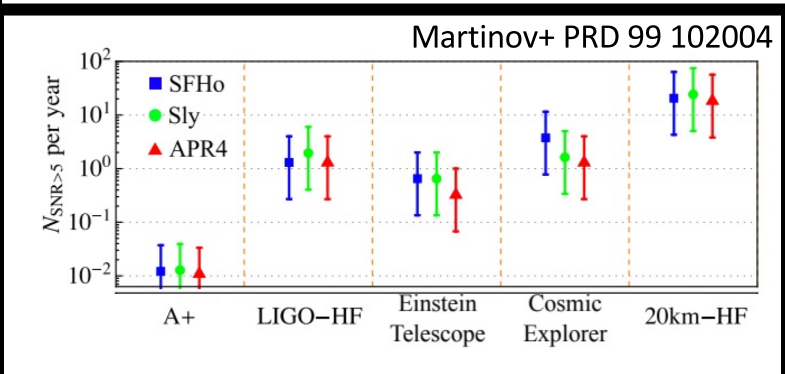
Credit: T. Dietrich



Binary neutron stars - Equation of state

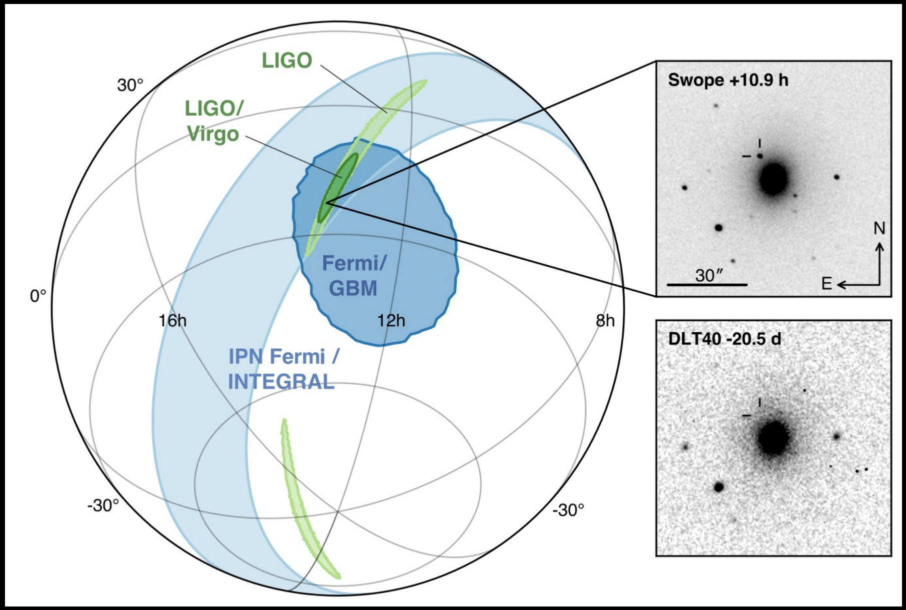
- Advanced detectors will start measuring the equation of state of neutron stars
  - Most likely from the inspiral phase
  - With a bit of luck, hints of postmerger physics
- 3G detectors will easily measure the EOS from both inspiral and post-inspiral





Multimessenger astrophysics - now

- Multiple DAWN panelist have stressed the fundamental significance of GW170817
  - Detection at all frequencies, from gamma rays to radio waves
  - Proved BNS are progenitors of (at least some) short gamma ray bursts
  - Proved BNS produce kilonovae emission, and heavy metals
  - Allowed for a measurement of the local Hubble parameter

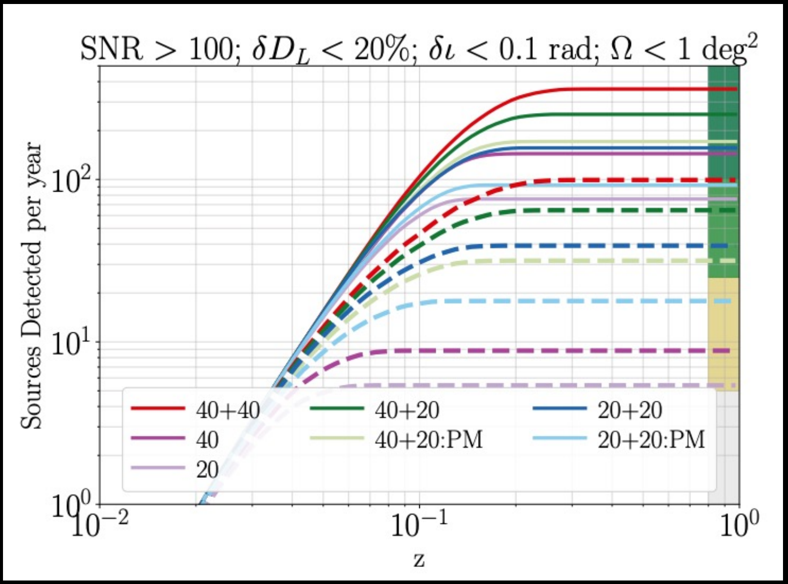


LVC and friends, ApJL, 848:L12, 2017

Multimessenger astrophysics - 3G

- With a network of 3G detectors we will be able to access hundreds of well-characterized BNSs per year
  - For many of them, the source can be localized even *before* the merger happens
  - Variety of system parameters, their effect on the EM emission and its energetics
  - Cosmology
- "CE provides an exciting opportunity to detect NSNS mergers to z~5 and beyond, allowing us to explore the optical/IR counterpart science drivers as a function of cosmic time."

CEHS 2021



Some of the challenges

- The DAWN meeting highlighted many challenges that our community needs to address to maximize the scientific promise of 3G detectors
  - High SNRs require very accurate waveforms (PE, TGR)
  - Even more so when matter is involved (BNS, NSBH, SNe modeling)
  - Population analyses will need to deal with large number of sources; overlaps
  - Algorithms cost scaling with N_events and SNR
  - Need to produce fast, reliable and small sky localization, including aux information (masses or probability of being bright)
  - Reliable detection of unmodeled sources, CWs, stochastic background

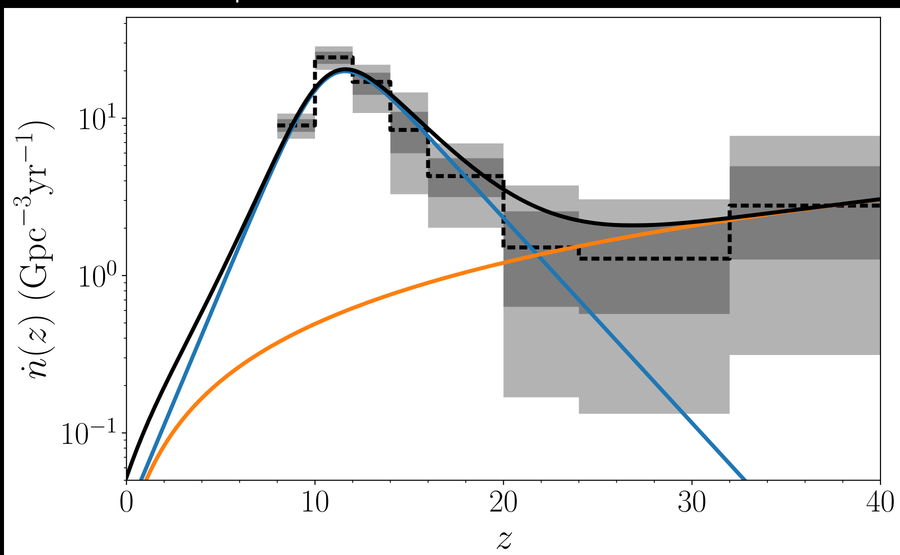
Why you should get involved

- Virtually all of these challenges will *already* be encountered by the LSC in the coming science runs, just less acute
  - R&D will pay off even before 3G detectors are online
- For early career scientists especially, you have the chance to help shaping and sharpening the science case of detectors that will be online when *your* students graduate
- Get involved! Can join the CE consortium, talk to me if you have questions
- But first, please endorse the DAWN report, strong support from the community is a must to get CE online!

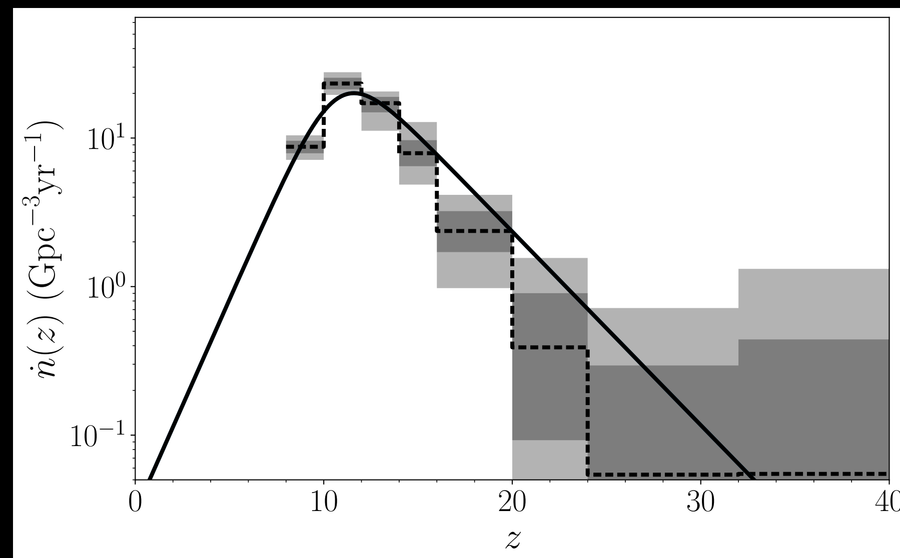
backups

Detecting PBHs mergers

$N_{PBH} = 1/8\ N_{Pop\ III}$

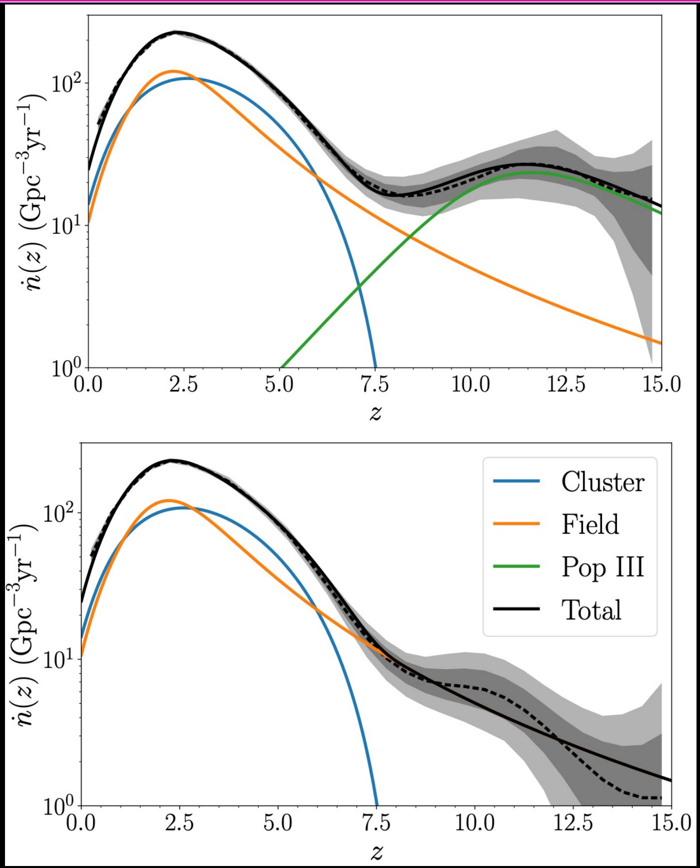


$N_{PBH} = 0$

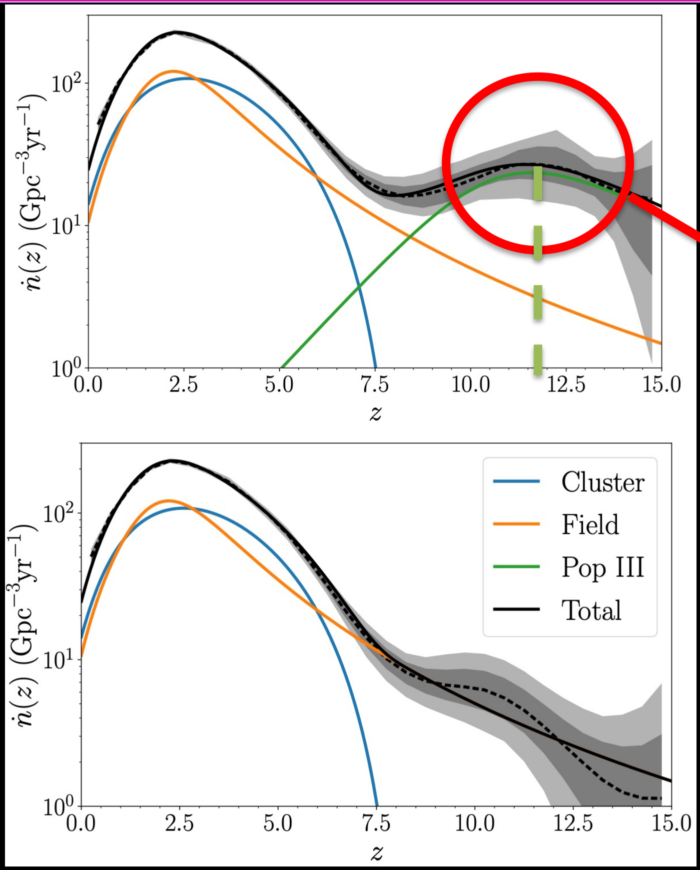


Ng+ in prep

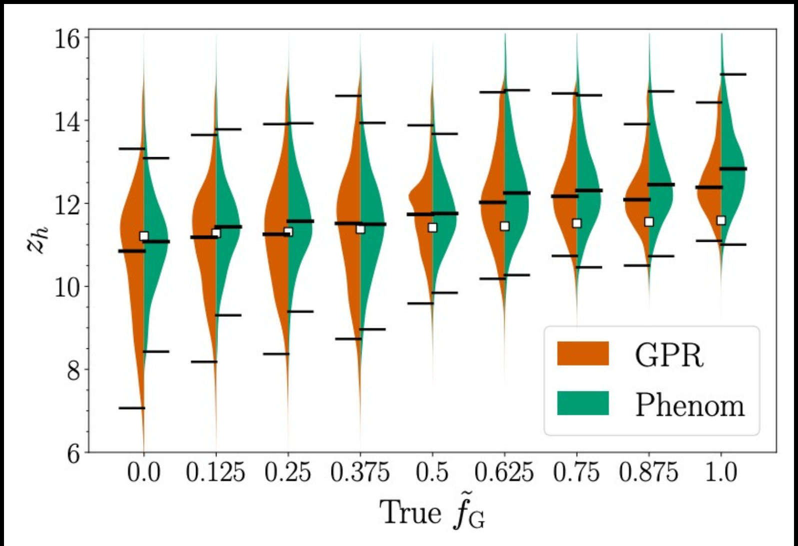
Detecting Pop III BH mergers



Detecting Pop III BH mergers



Can measure the location of high-z peak with a few months worth of data and no modeling!

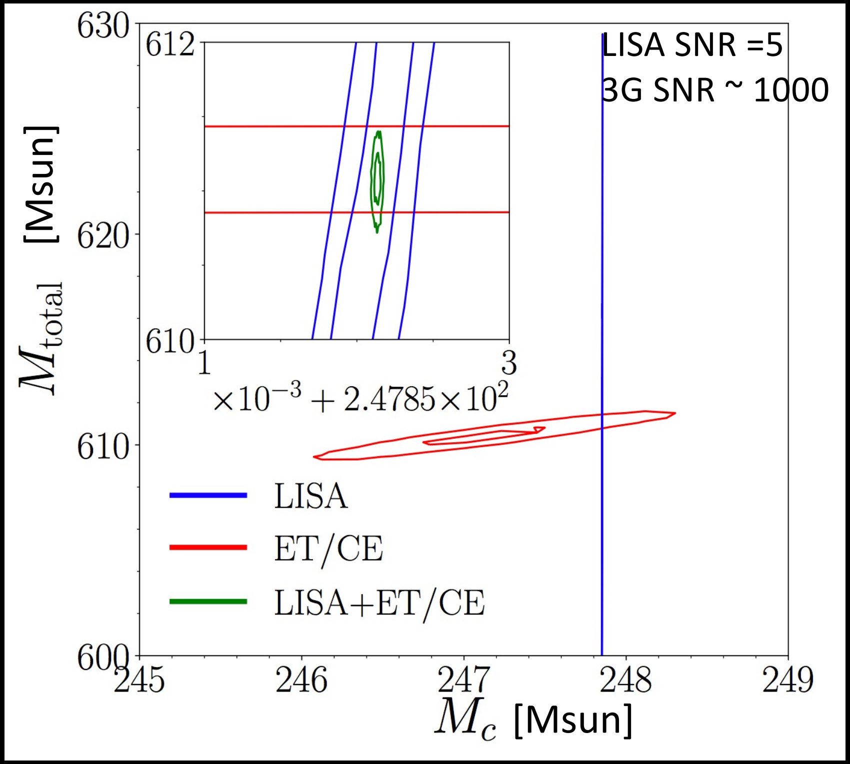


Ng+ ApJL 913 L5

Multibanding

- LISA can observe heavy BBH and intermediate-mass BBH
- Some of those signals will also be visible from the ground (years later)
- Complementary information! (Sesana PRL 116, 231102; Vitale PRL 117, 051102; Barausse+ PRL 116, 241104)
- For nearby IMBH, LISA might provide Mchirp info, but not for z>~0.3

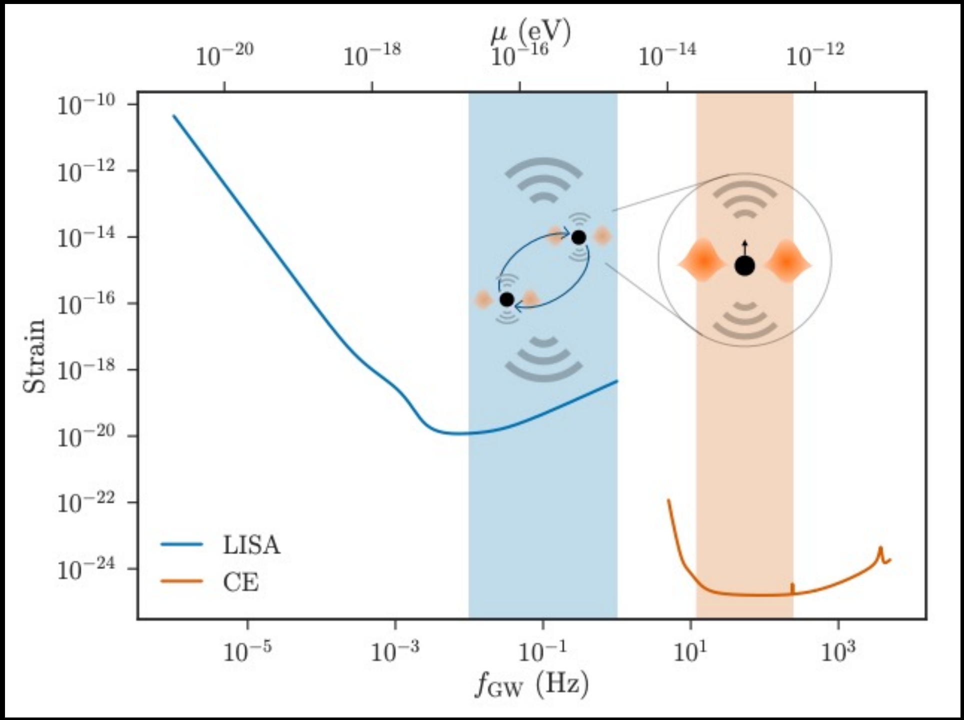
Cutler+, 1903.04069



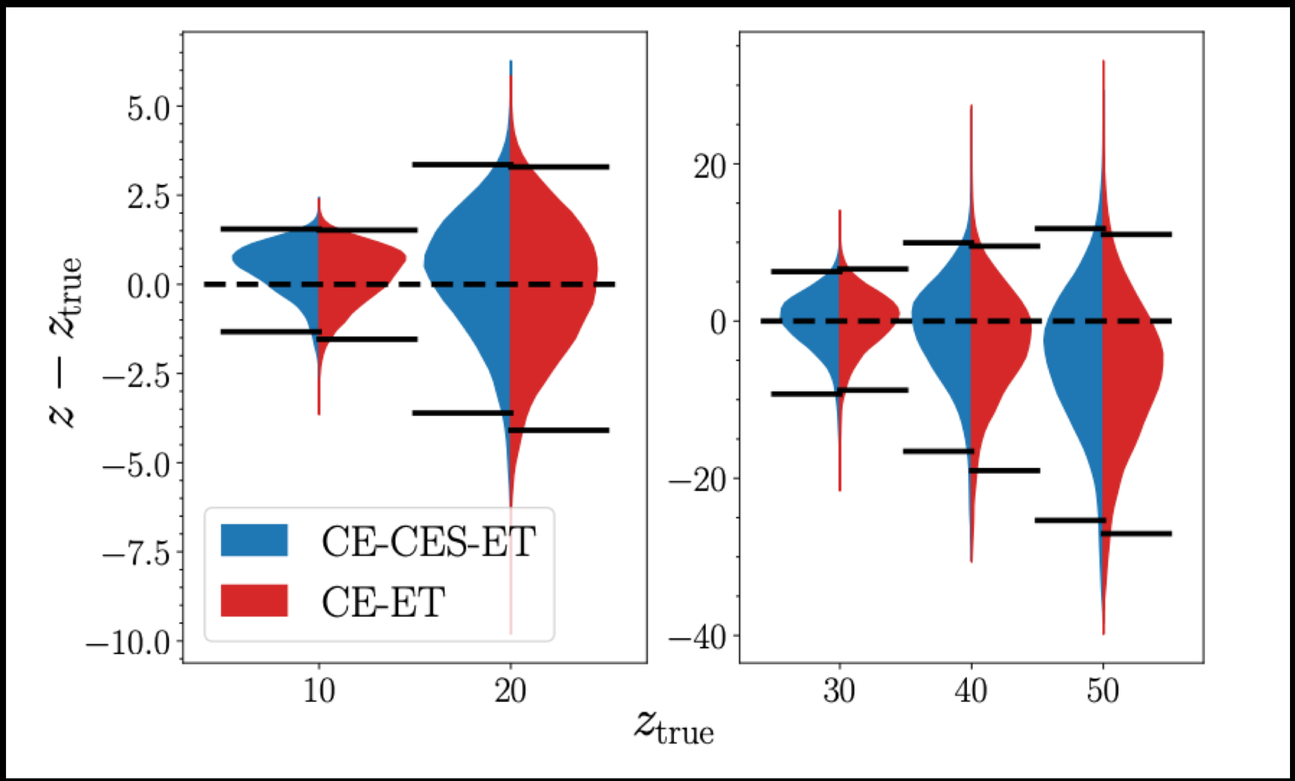
Multibanding

Ng+ PRD 102, 083020

- Black holes will form clouds of ultralight bosons (if such particles exist)
  - The bosons cloud emits nearly monochromatic GWs
- LISA could detect the GWs from the inspiral while 3G detectors could *simultaneously* detect the GWs from the axion clouds



Pinning down a single PBH

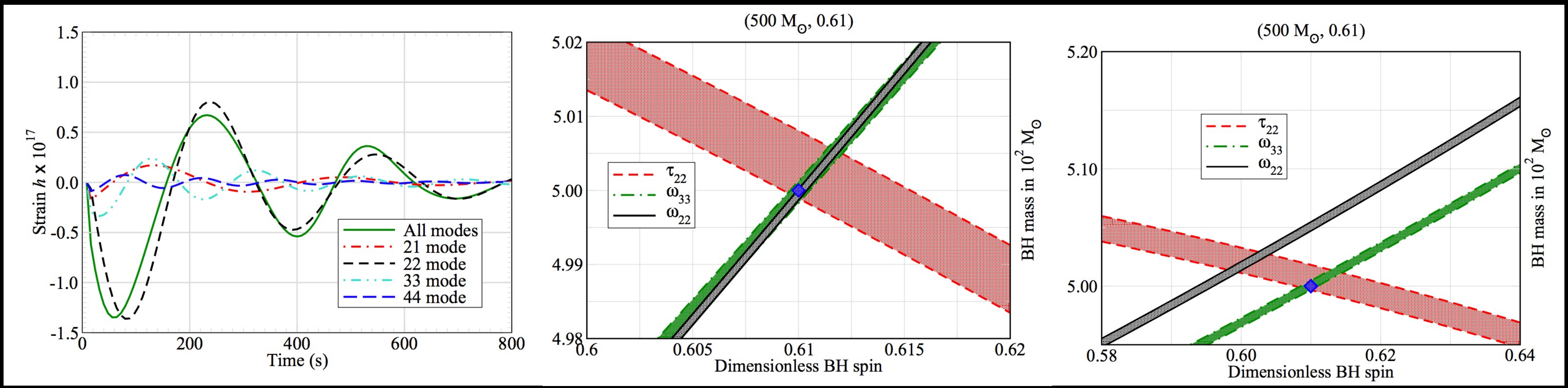


Ng+, 2108.07276

Ringdown tests

- Ringdown modes only depend on final BH mass and spins (in general relativity)
- If one can measure more than 2 of the ringdown parameters (dumping times, frequencies) then the others can be used for consistency checks

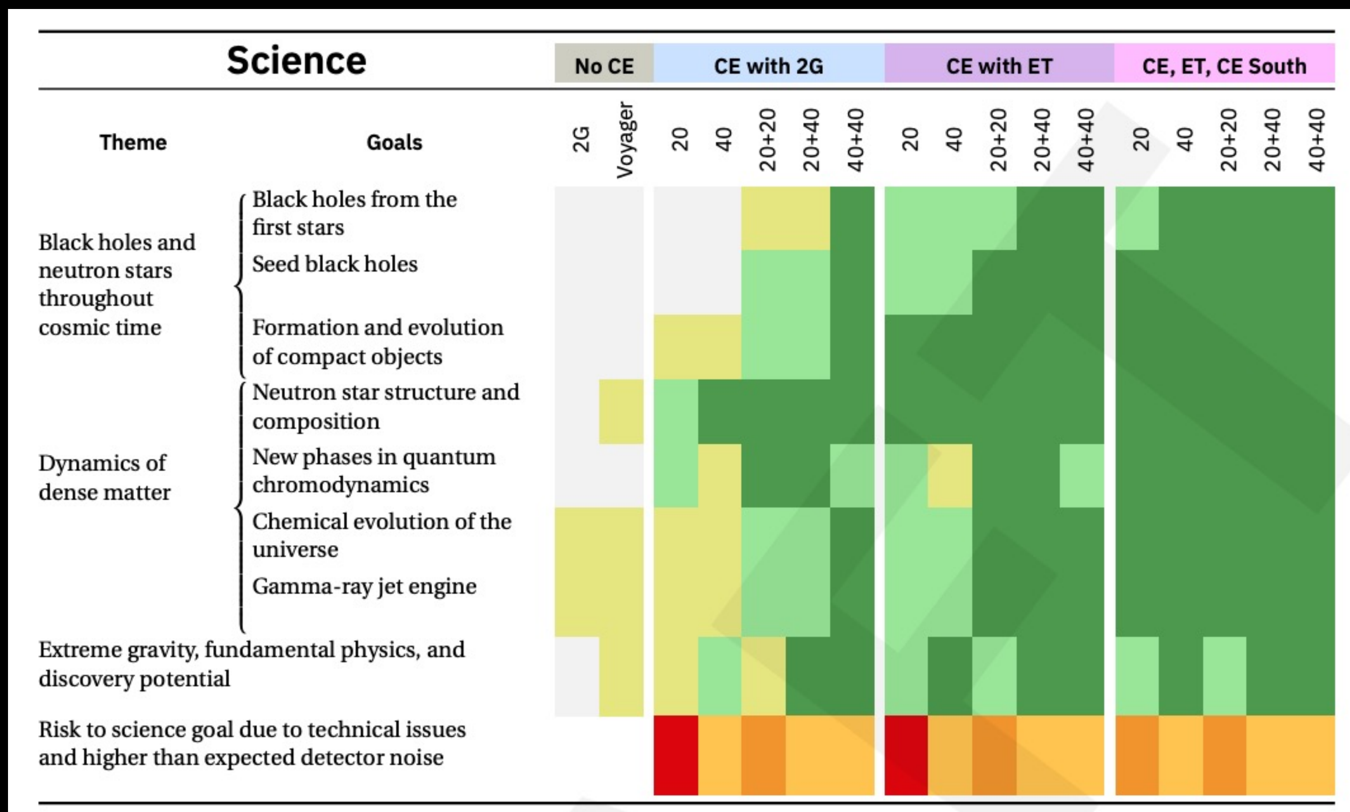
Gossan+, 1111.5819



Trade study

- The composition of the 3G network is not finalized
- The Horizon Study contain an analysis of various configurations and tradeoffs
  - Are 40Km necessary or are 20Km enough?
  - Are two 20Km – 20Km better than one 40Km?
  - Can previous-generation detectors help?
  - What science goals can be pursued with only one detector?

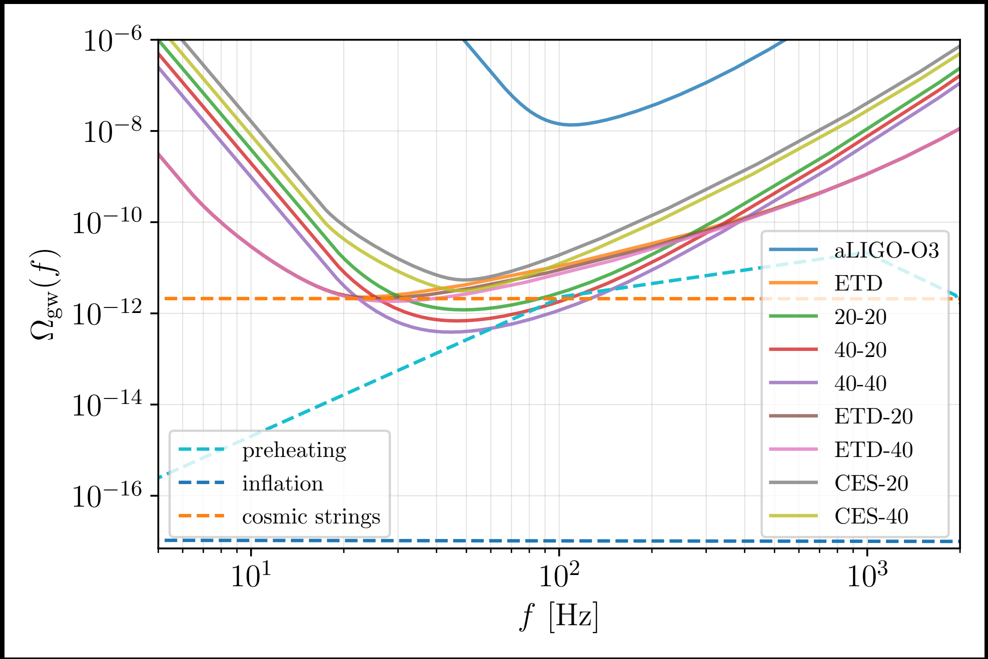
Trade study



CEHS 2021; also Borhanian+ in prep

Stochastic background

CEHS 2021

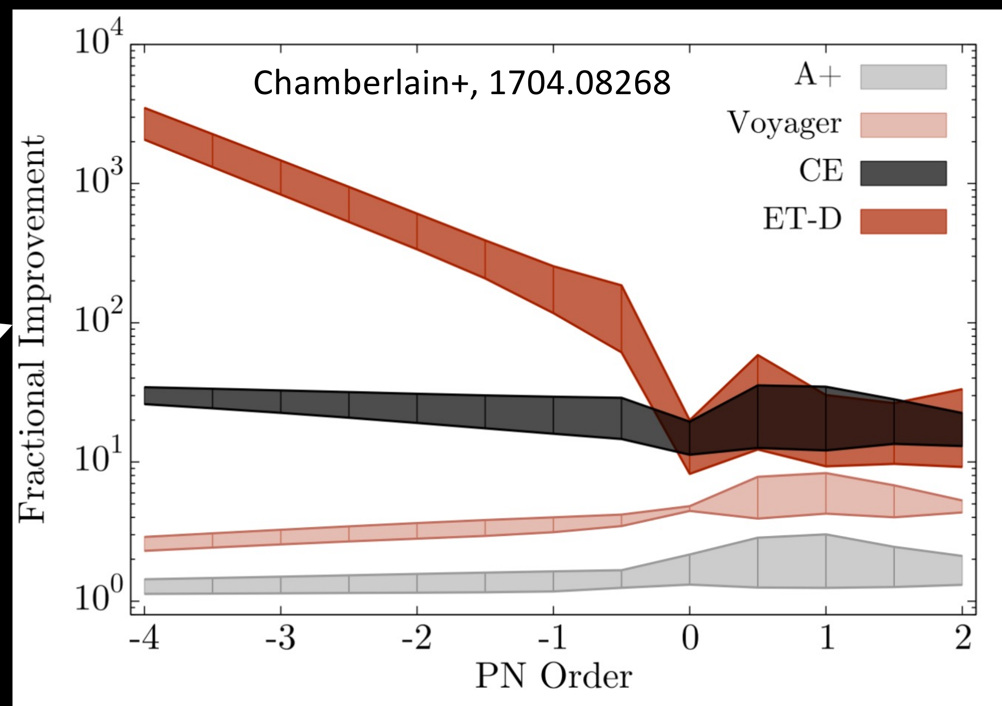


- In a network with ET or with another CE, Cosmic Explorer can contribute to searches for a stochastic background
  - Challenging for slor-roll inflation; cosmic strings and preheating also shown
- You can download these curves at dcc.cosmicexplorer.org/CE-P2100003/public

Tests of general relativity

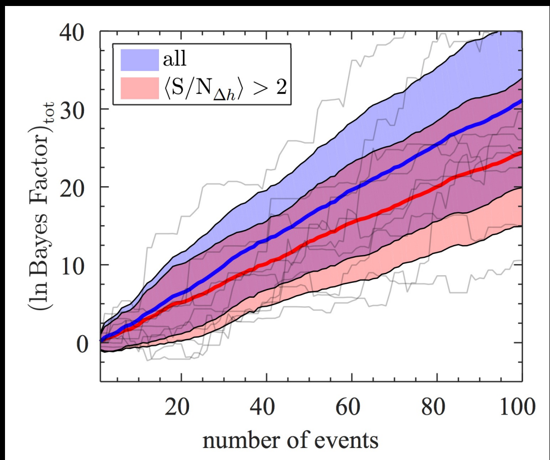
- Larger SNR and better low frequency will yield dramatic improvements
- Also, precise ringdown tests, memory effect, propagation tests, more!

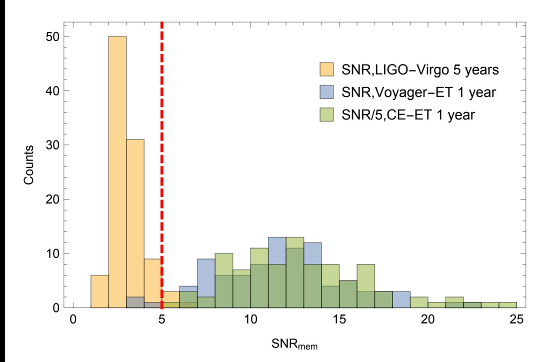
$$\frac{\text{Uncertainty w/ detector X}}{\text{Uncertainty w/ aLIGO}}$$



Memory

Lasky+, PRL 117, 061102





Yang+, 1803.02429

- Very challenging to detect with advanced detectors
- Lasky+ showed that one might make a statistical detection given >>1 sources
  - Somewhat optimistic assumptions
- Yang+ focuses on 3G and quantifies SNR in the memory phase

Axions and all that

- Axions are proposed ultralight bosons that can extend the standard model and could be viable dark-matter candidates
$$10^{-19} \lesssim \mu/\mathrm{eV} \lesssim 10^{-11}$$
- If an ultralight boson exists, they will spontaneously form clouds around spinning black holes
- These clouds will emit potentially detectable gravitational waves, providing evidence for a new particle
  - Nearly monocromatic GWs
- We can perform direct searches using known black holes

Golden BBH events

- A GW150914-like event will have SNR~2000 in a Cosmic Explorer facility.
- How well can we do?

Precision for a few key parameters for GW150914

Mass ratio q	$0.84^{+0.14}_{-0.21}$
Effective inspiral spin parameter $\chi_{\rm eff}$	$-0.03^{+0.14}_{-0.15}$
Luminosity distance $D_{\rm L}/{\rm Mpc}$	440^{+140}_{-180}

LVC 1602.03840

Golden BBH events

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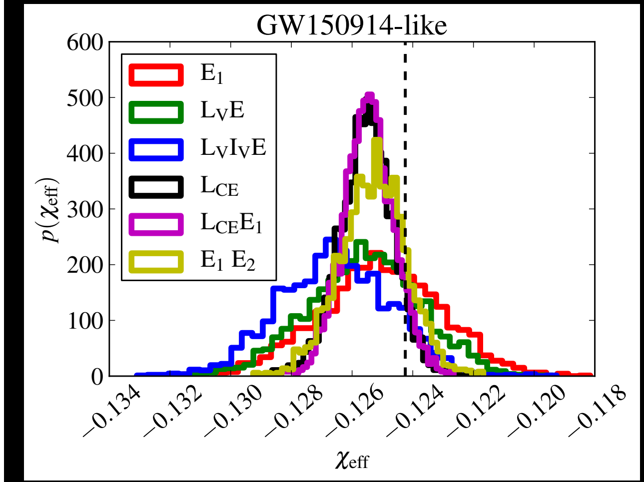
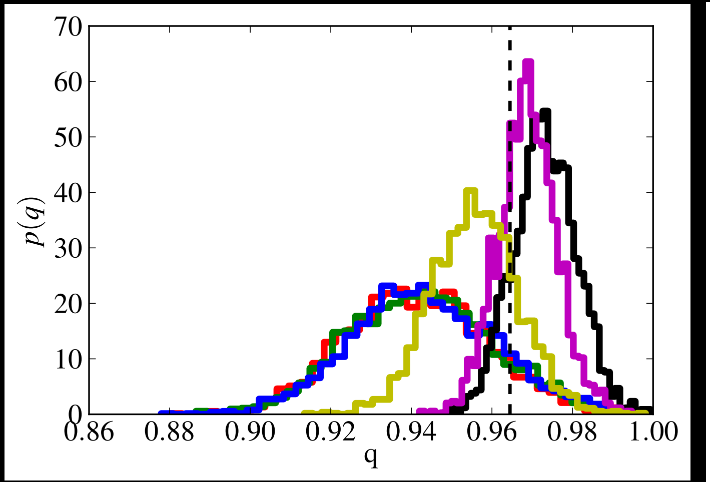
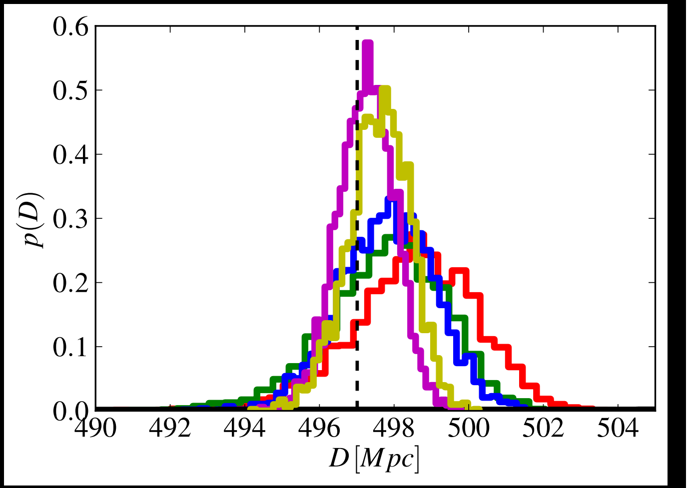
- How well can we do?



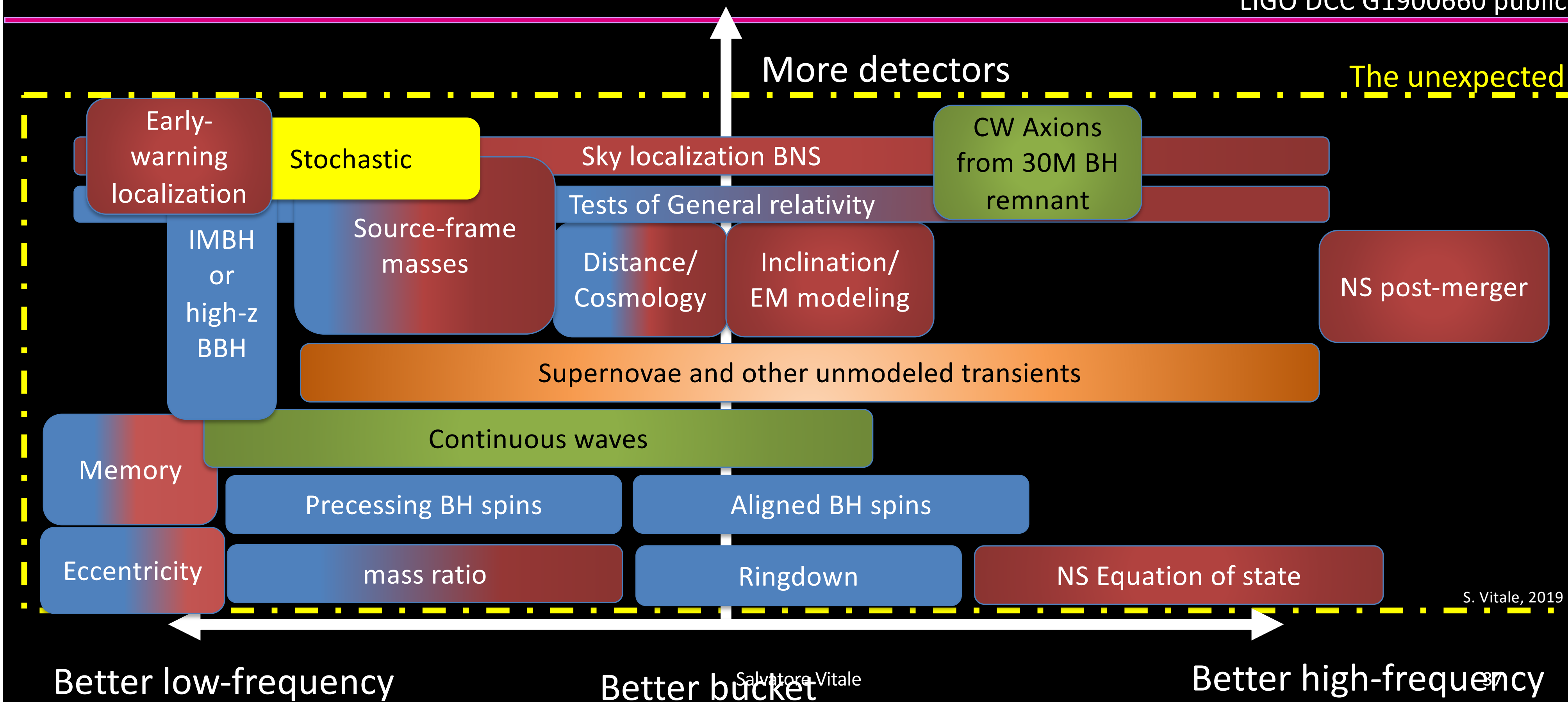




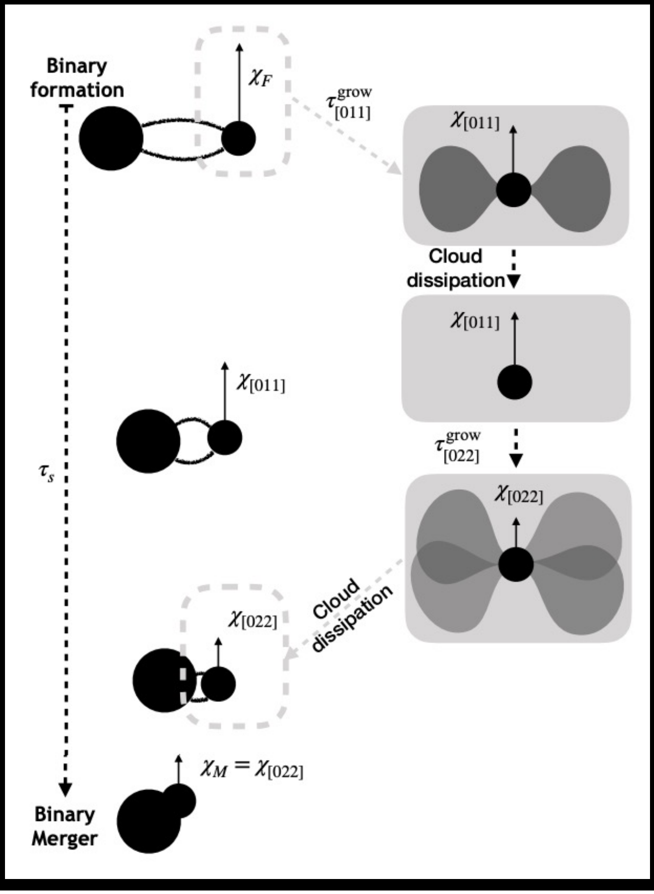
Vitale, Whittle, PRD 98, 024029

Low/High frequency - Network size trade off

LIGO DCC G1900660 public



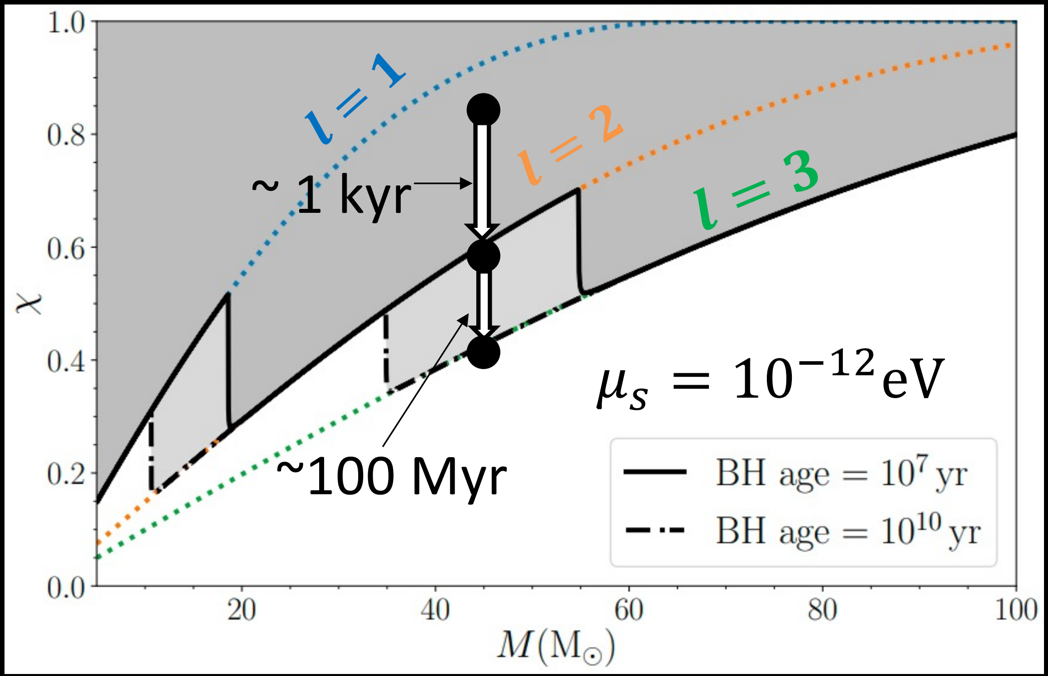
Axions and black hole spins



Ng+ 1908.02312, 2007.12793, 2011.06010

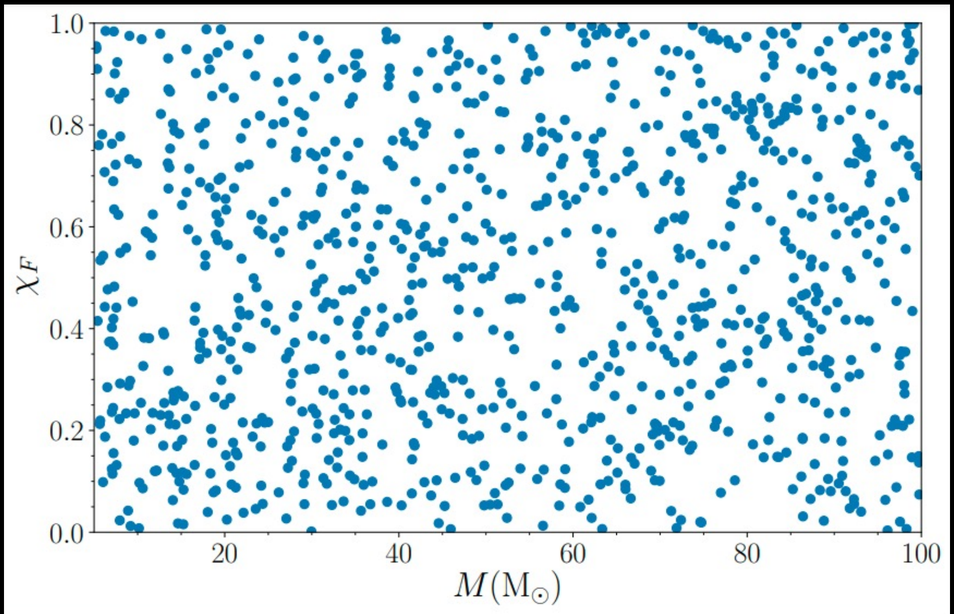
Observational signature

- If boson exist, black holes of appropriate mass **must have small spins**
  - Boson cloud has removed spin (Arvanitaki+, PRD 95 043001 , 91 084011)
  - Also a few % of mass loss
- E.g., $45 M_\odot$ can only reach $l = m = 3$ mode if its age is 10 billion years



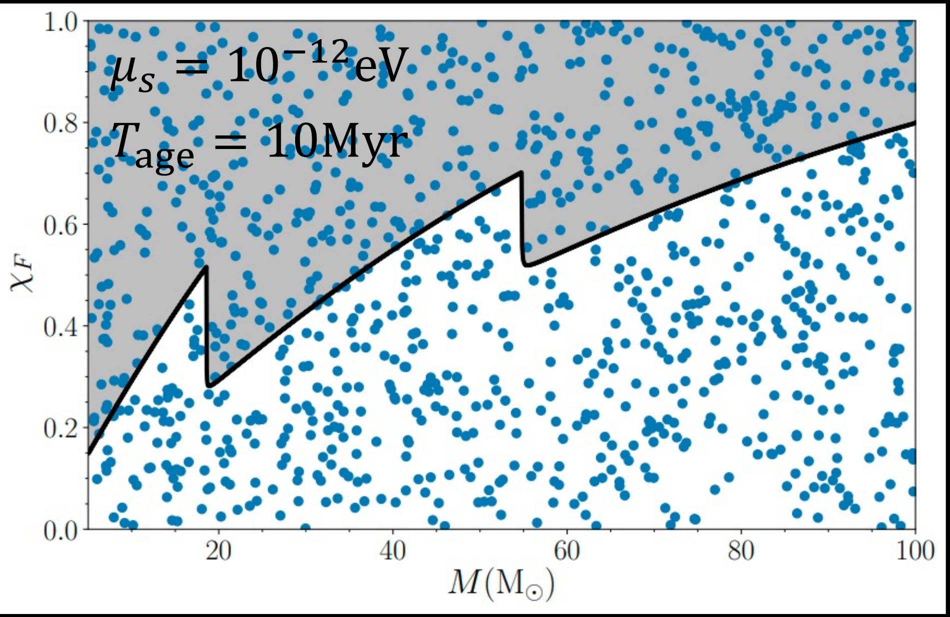
Signature in the BH population

- BH spins at formation χ_F
  - E.g. uniform in mass and spin



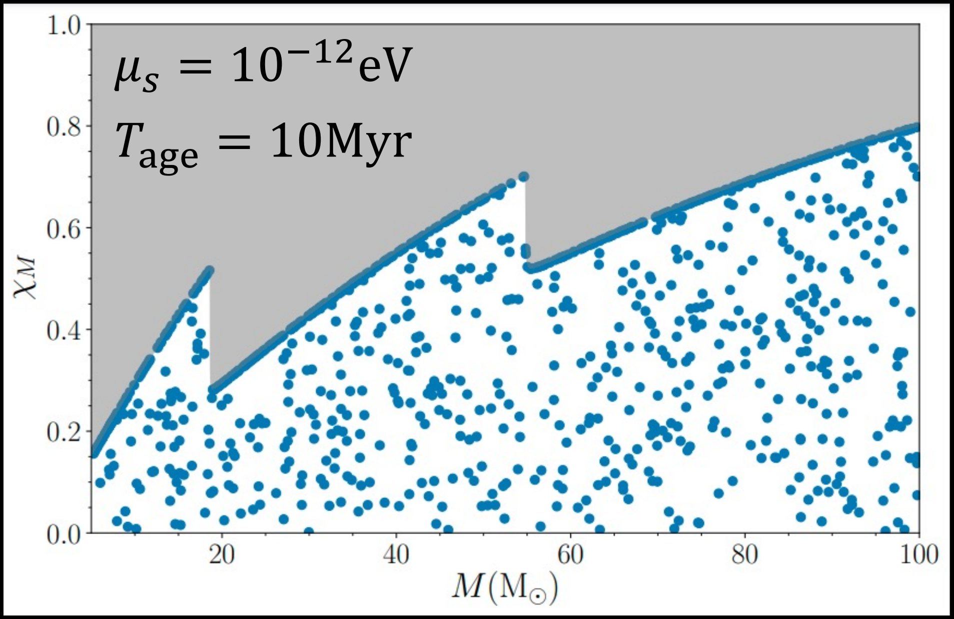
Signature in the BH population

- BH spins at formation χ_F
  - E.g. uniform in mass and spin
- Bosons carve an exclusion region in the mass/spin plane
  - Depends on black hole mass and age



Signature in the BH population

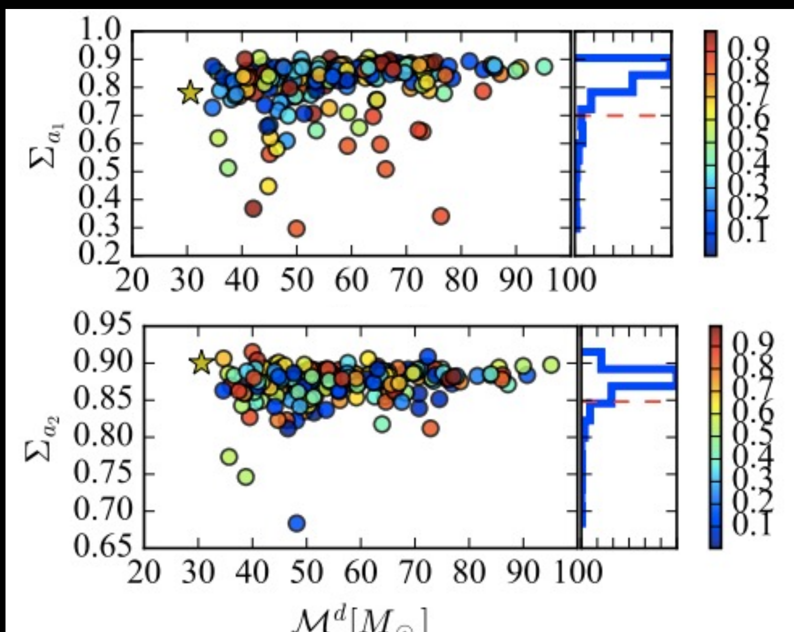
- BH spins at formation χ_F
  - E.g. uniform in mass and spin
- Bosons carve an exclusion region in the mass/spin plane
  - Depends on black hole mass and age
- Detected population should have small spins and follow critical curve



BBH Spins

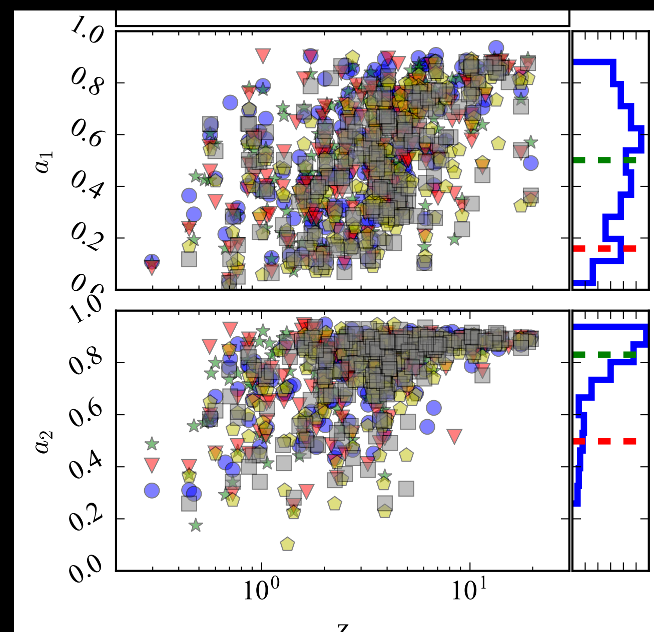
- Due to larger SNR and isotropic orbital orientation, 3G will get much better spin estimation than 2G

2G



Vitale+, PRD 95 064053

3G



Vitale & Evans PRD 95 064052

Post-merger optimization

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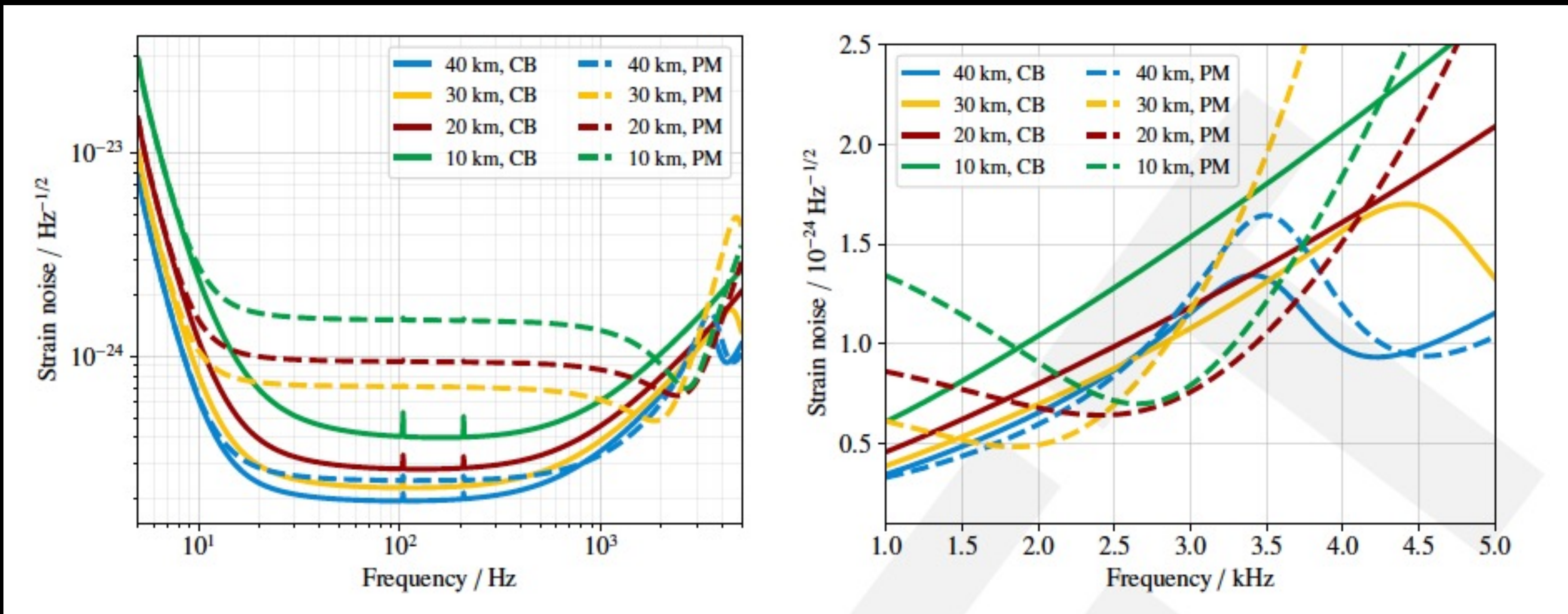
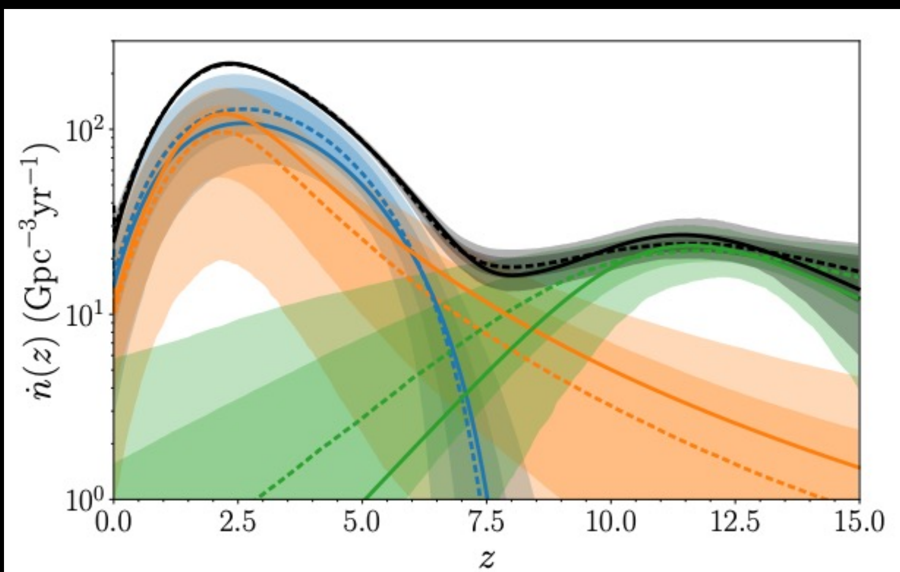
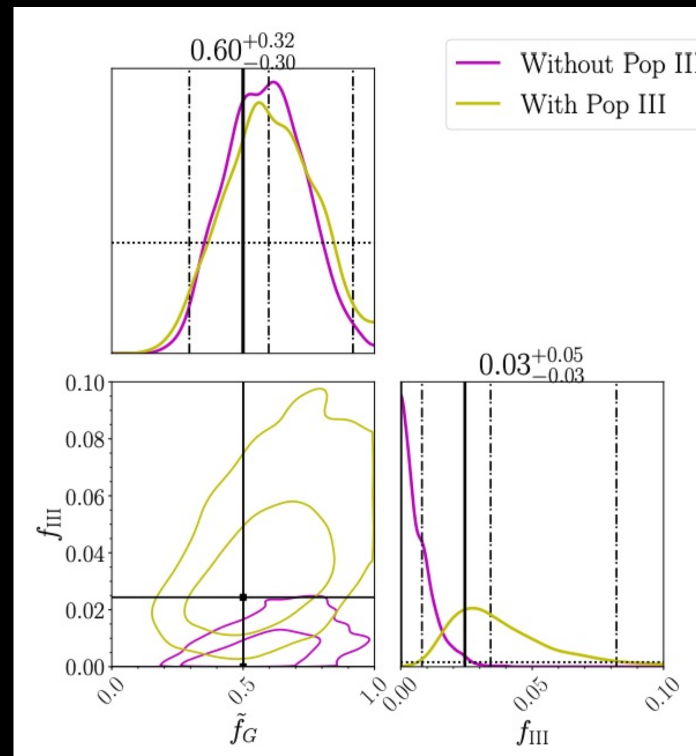
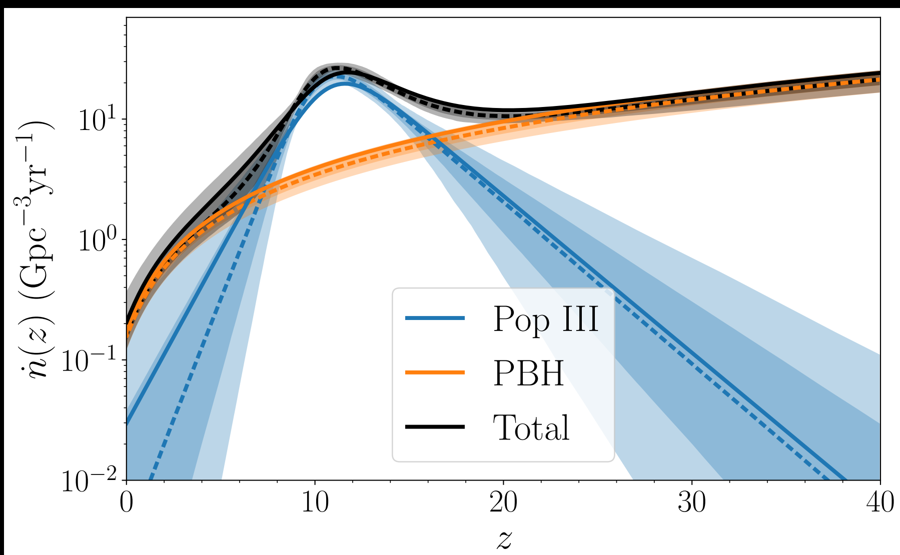


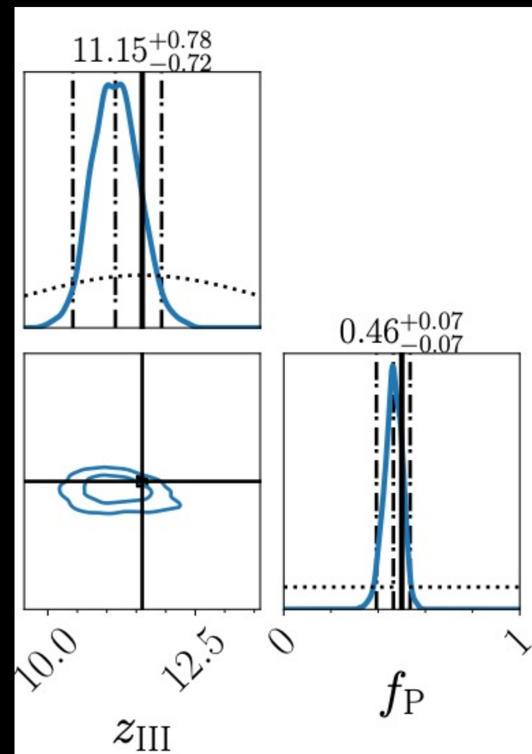
Measuring Pop III fraction





Measuring PBH fraction





Listening to the Universe

CEHS 2021