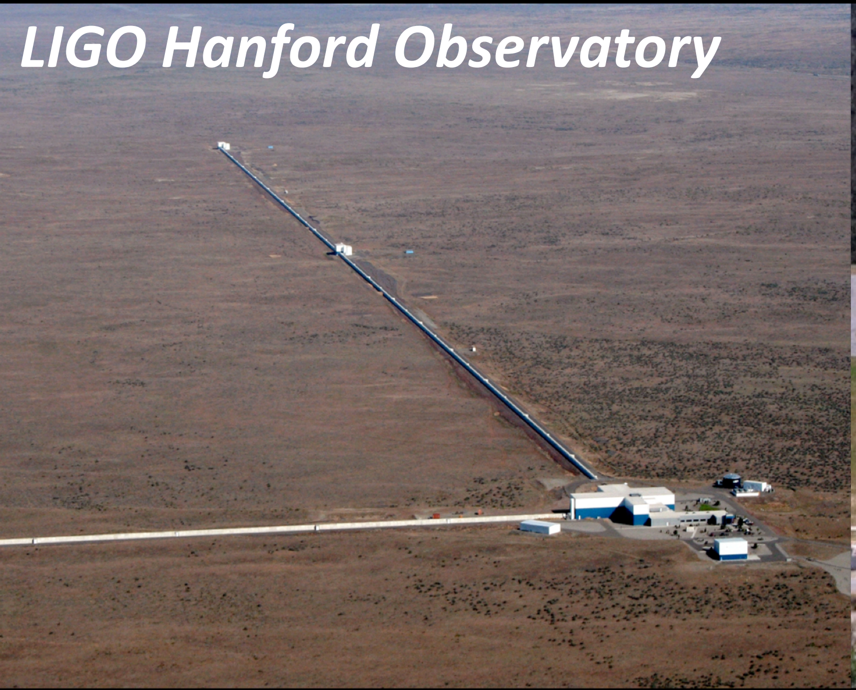
Compact binaries throughout cosmic history

Salvatore Vitale

Gravitational Waves Beyond the Boxes II
Perimeter institute
April 7 2022

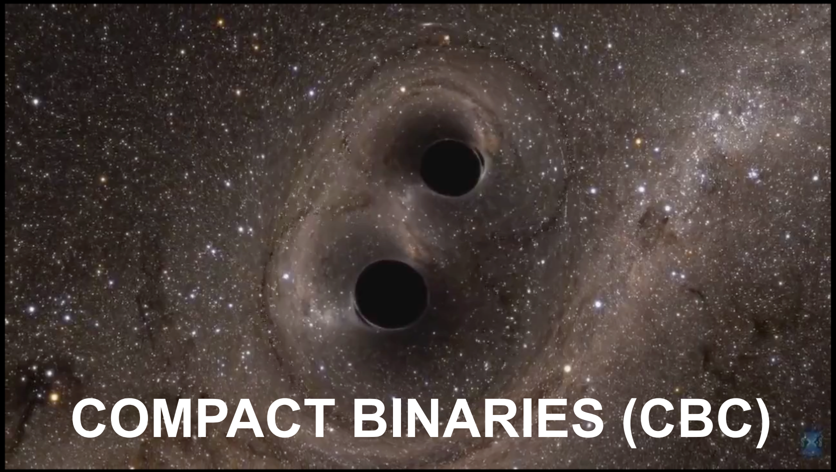
Ground based gravitational-wave detectors



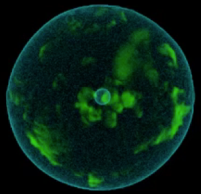
What’s can we detect?

TRANSIENT

Credits:
SXS collaboration

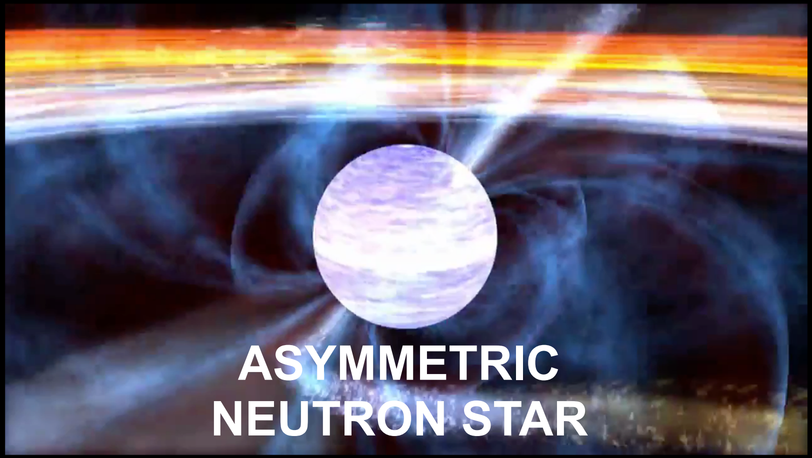


43.76 ms



BURSTS
Core collapse Supernovae

PERSISTENT



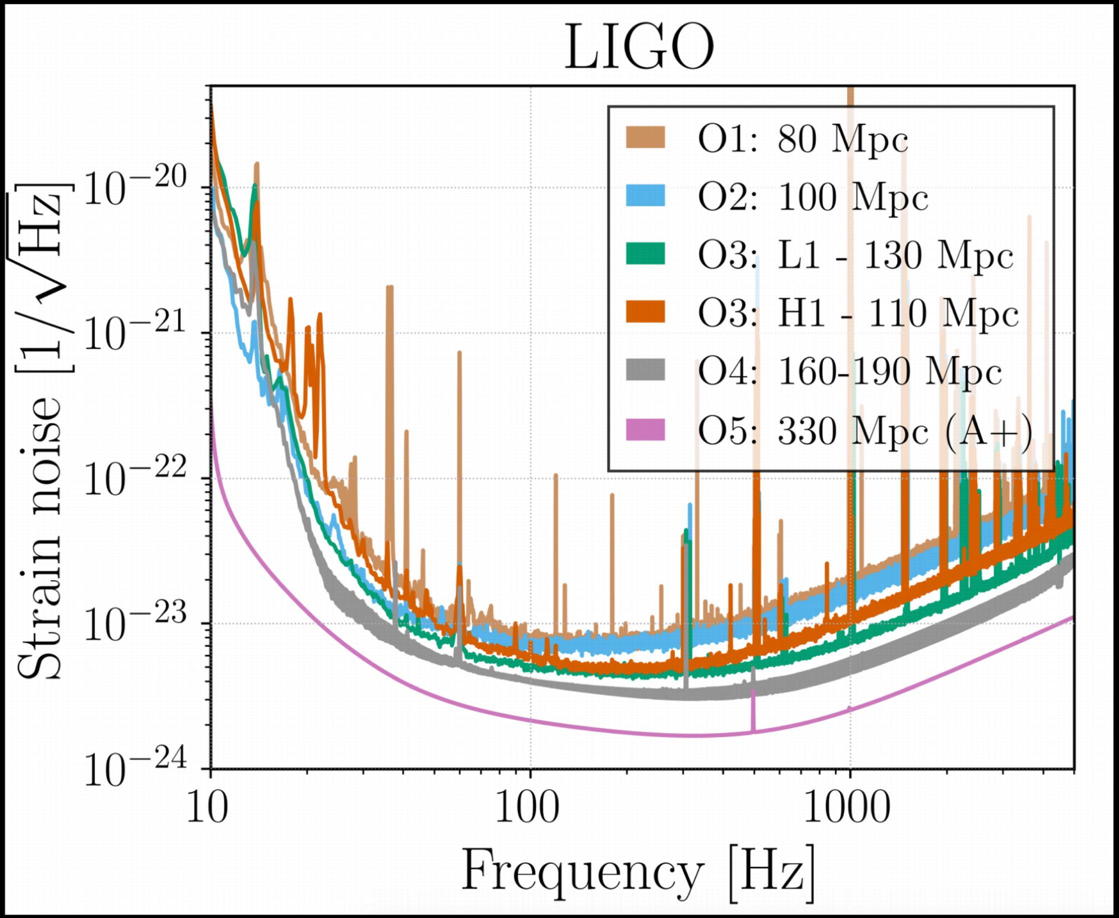
MATCH FILTER

UNMODELED

Where are we?

Worse

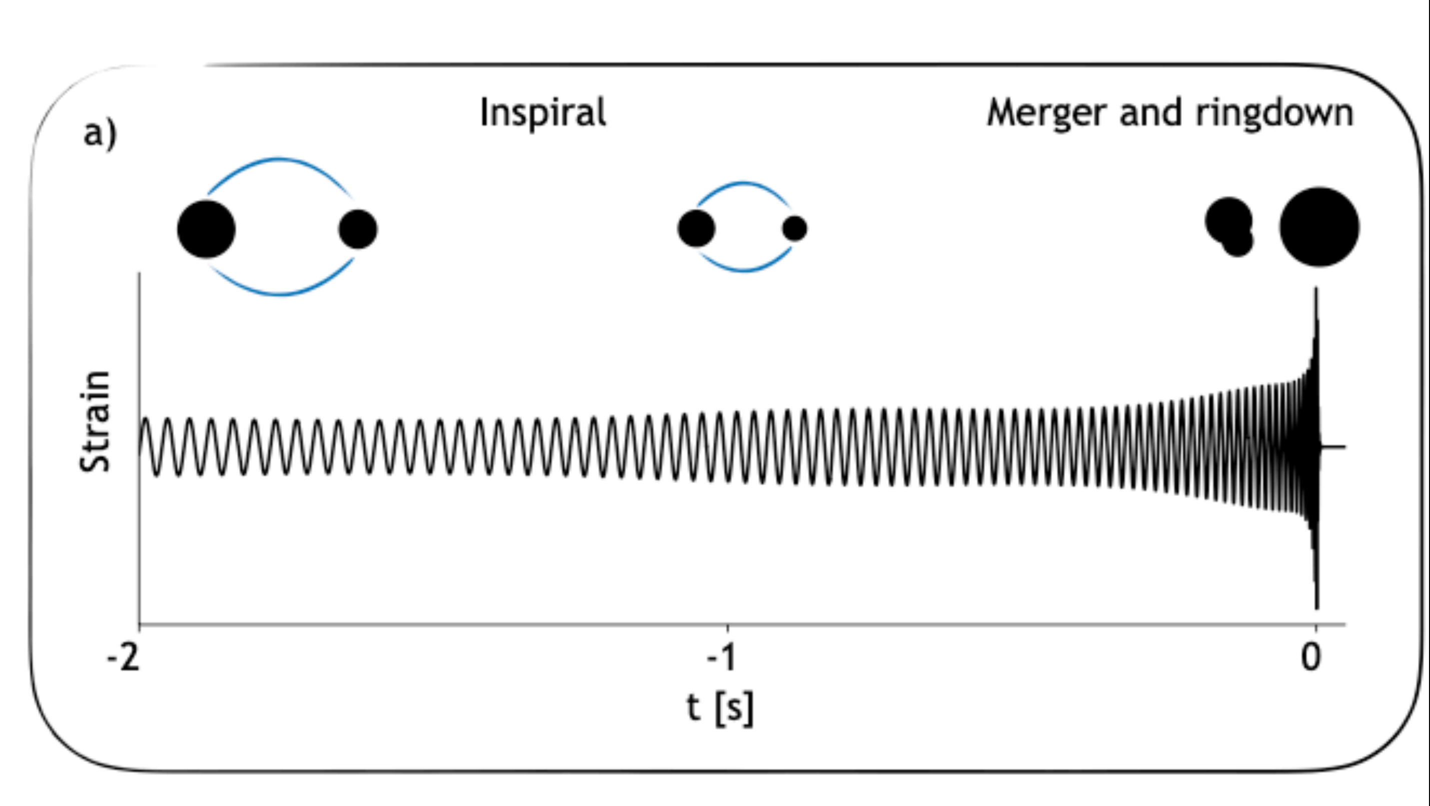
Better



LVC LRR 21 3

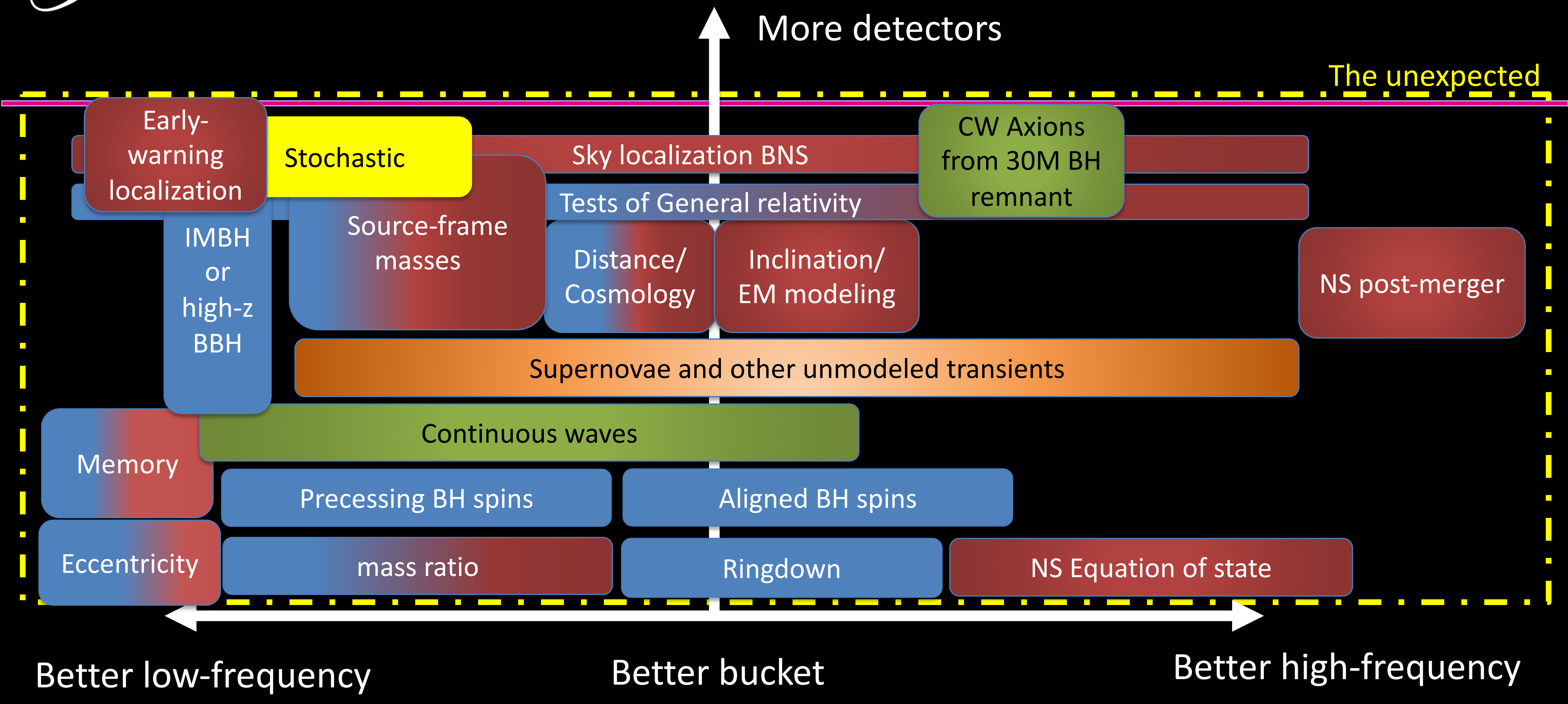
- Advanced LIGO detectors have run since 2015 (with Virgo since 2017)
- Three observing runs
- The third observing run lasted roughly one year

Compact binary anatomy

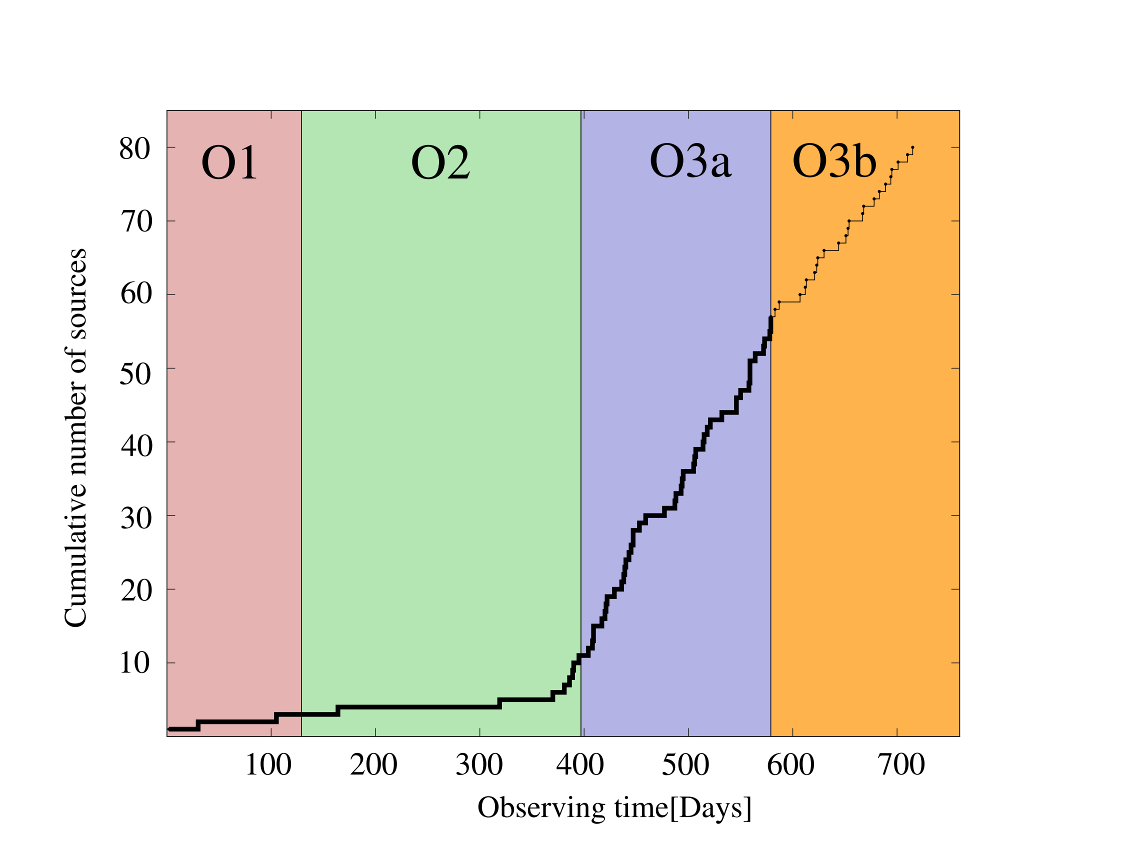


Vitale, Science 372, 6546

- Duration/Merger frequency: total mass, spins
- Phasing: chirp mass, mass ratio, spins
- Overall amplitude: distance, orbital inclination
- Amplitude modulation: spins angles
- Merger-ringdown: nature of the compact objects


More detectors
The unexpected
Early-warning localization
Stochastic
Sky localization BNS
CW Axions from 30M BH remnant
Tests of General relativity
Source-frame masses
IMBH or high-z BBH
Distance/ Cosmology
Inclination/ EM modeling
NS post-merger
Supernovae and other unmodeled transients
Continuous waves
Memory
Precessing BH spins
Aligned BH spins
Eccentricity
mass ratio
Ringdown
NS Equation of state
Better low-frequency
Better bucket
Better high-frequency

Where are we?

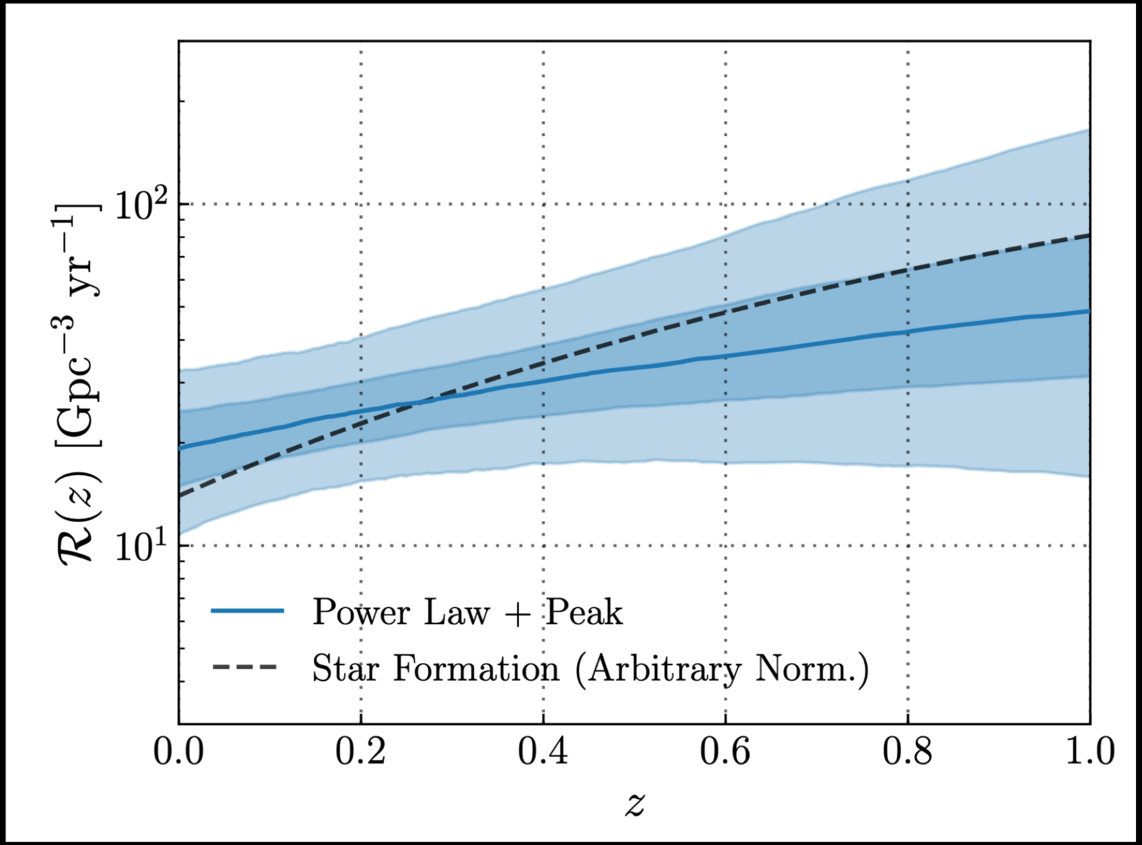


SV, Science 372, 6546, adapted from LVC public document G1901322

- Advanced LIGO detectors have run since 2015 (with Virgo since 2017)
- Three observing runs
- The third observing run lasted roughly one year
  - 56 candidate events made public (one per week!)
  - Two neutron star black hole mergers (LVK 2106.15163)
  - Tens of binary black holes!
  - LVC catalogs paper online: 2010.14527, 2010.14529, 2010.14533

Where are we?

- Even at design sensitivity, current detectors will be limited to
  - Local universe
  - ~100-200 sources (mostly BBH) per year
  - Low to moderate signal-to-noise ratio
  - Limited number of sources with EM counterparts



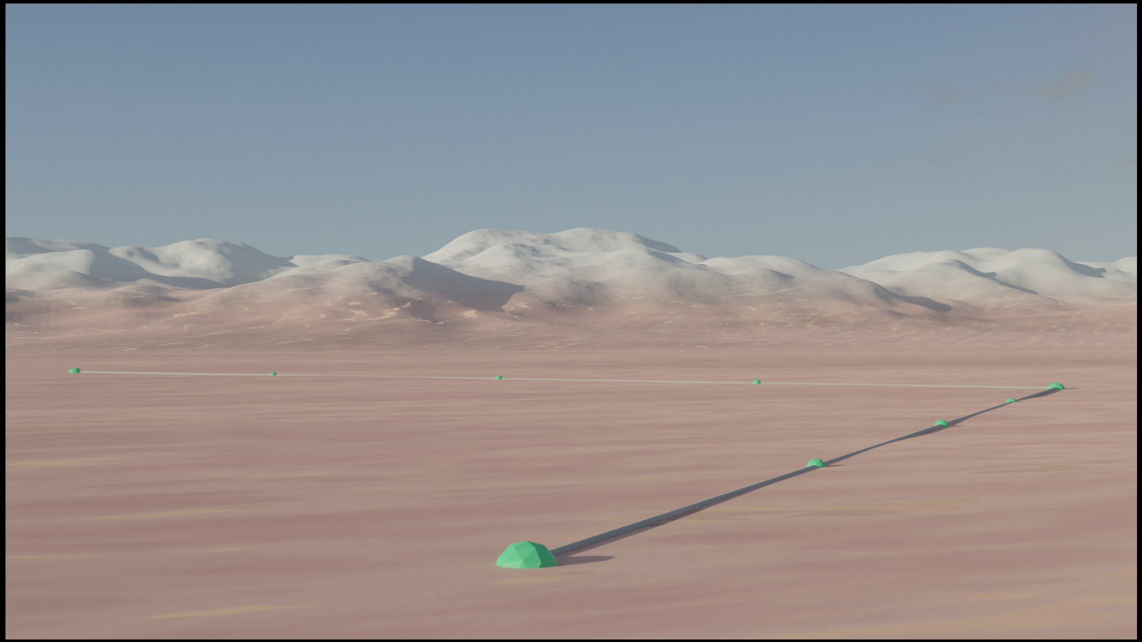
LVK ApJL 913 L7

Next-generation (NG) detectors

- To gain access to sources across the universe new facilities are required
- NG detectors
  - Strain sensitivity 10x better than advanced detectors
  - Detect black hole binaries at large redshifts
  - High signal-to-noise ratios
  - Many 100K sources per year
- Targeting operation in the second half of 2030s

Cosmic Explorer

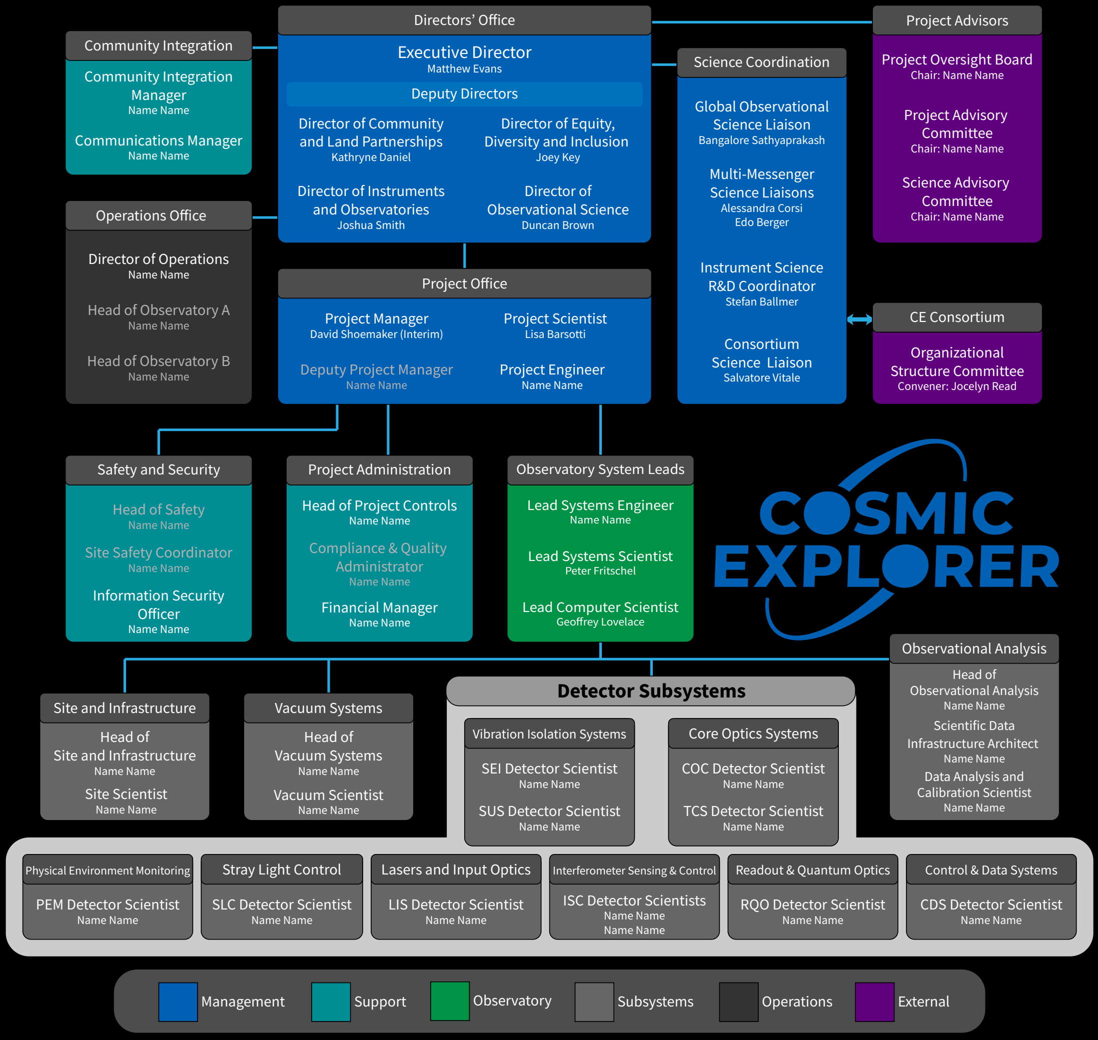
- Next Generation gravitational-wave observatories
  - based on current LIGO concepts: 10x longer, 10x more sensitive
- Two L-shaped sites, one 20km on-a-side, other 40km
  - Significant impact on Indigenous lands; consideration of this central to our planning
- Observatories with ~50-year lifetime housing a progression of detectors
- Likely to fully explore GW observation capability in this band
- ~$2B
- ~2035



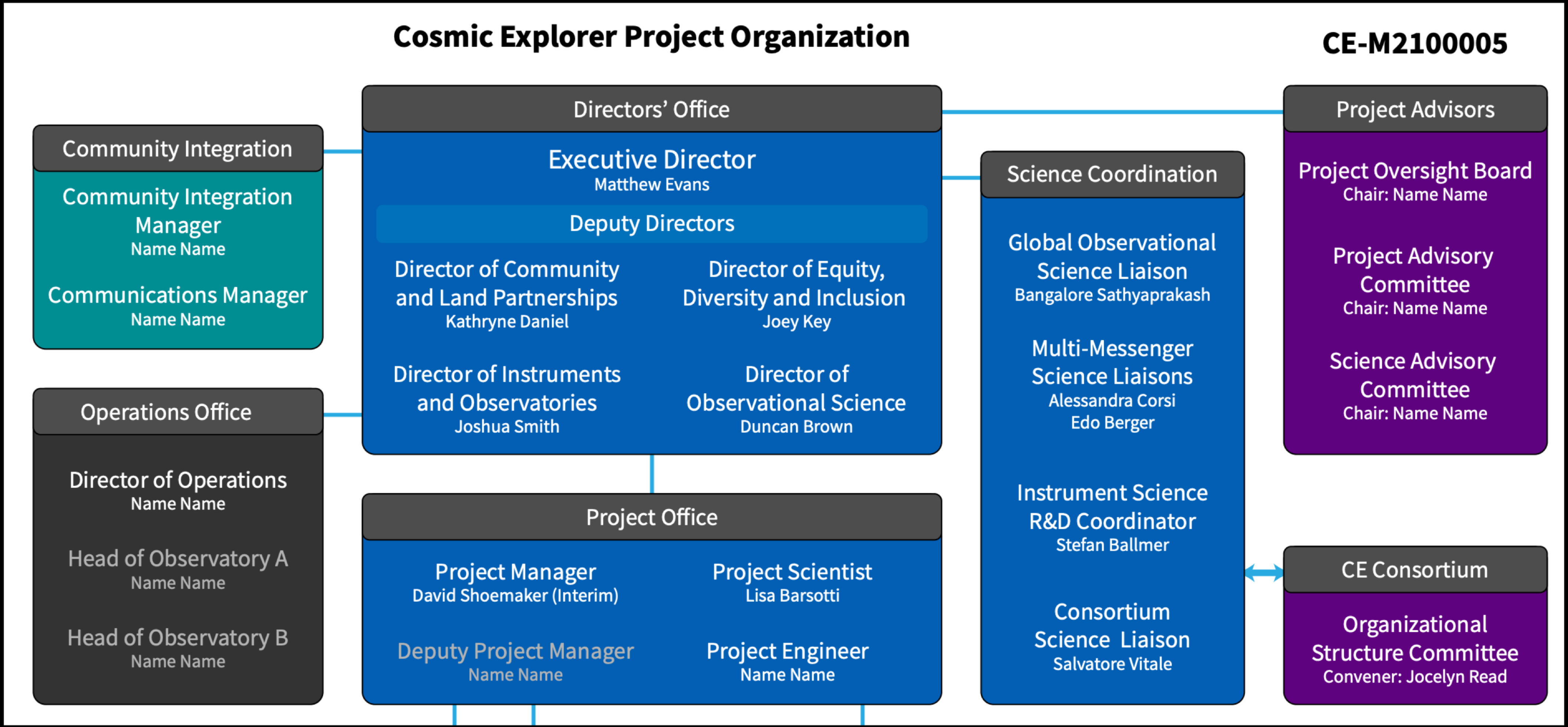
Who is CE currently?

- CEHS team (NSF funded 2019-2021, ~$3M)
    - Institutions (and faculty PIs):
        - MIT (M. Evans (overall PI), S. Vitale)
        - Cal State Fullerton (G. Lovelace, J. Read, J. Smith)
        - Penn State (B.S. Sathyaprakash)
        - Syracuse University (S. Ballmer, D. Brown)
        - Caltech (Y. Chen, R. Adhikari)
    - Postdocs, students
        - ~5 postdocs, ~10 students
    - Professional scientists/engineers
        - Matrixed from LIGO Lab + consultants for civil and vacuum engineering
- Organization: Pivoting from collaborative effort to project structure
    - Currently populating with volunteers, seeking funding for Conceptual Design phase (MREFC)
    - External to project: CE Consortium with ~378 scientists

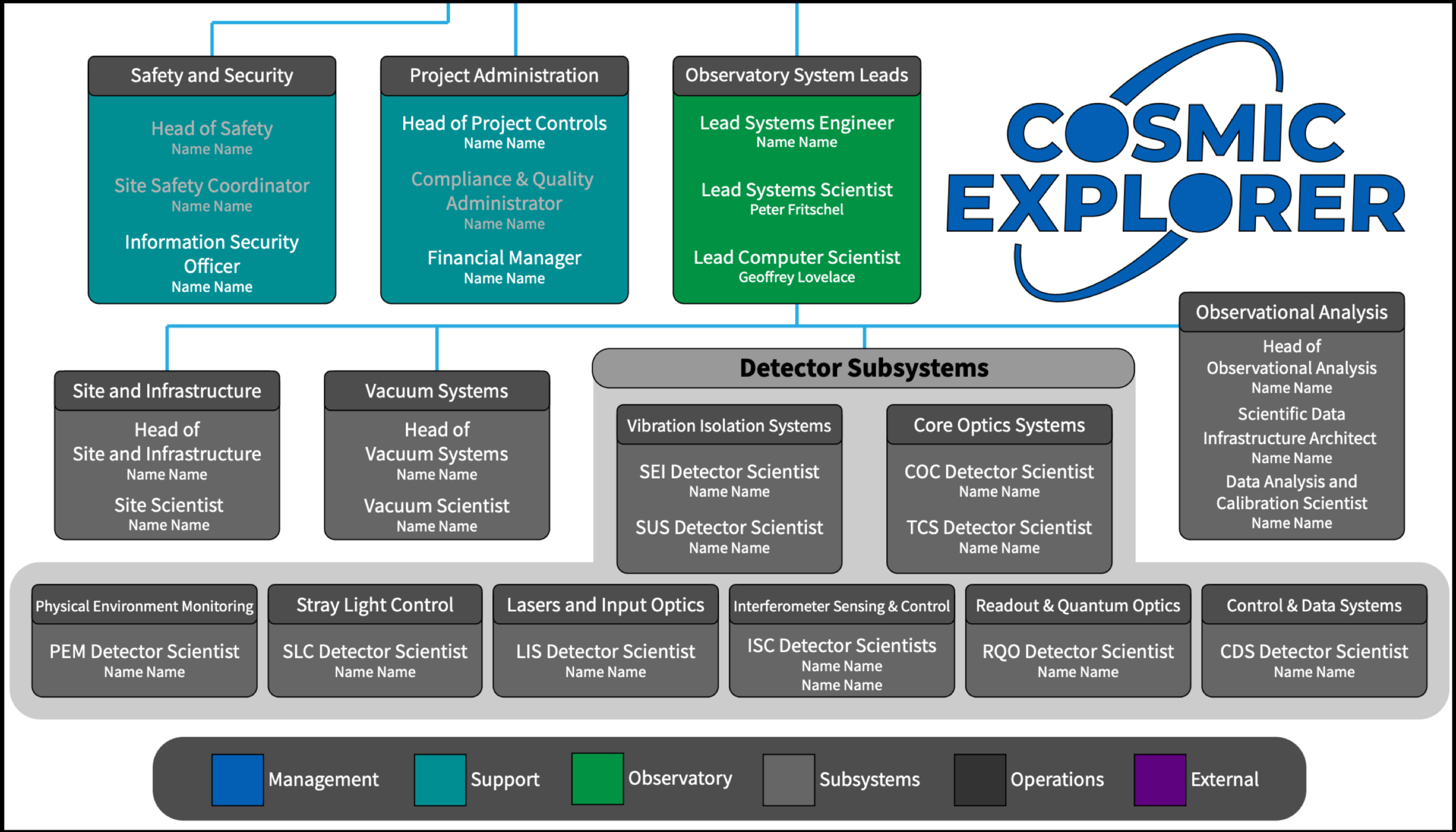
Toward a CE project



Toward a CE project



Toward a CE project



CE Science calls

- We are holding monthly calls where you can present your NG-related work
- https://cosmicexplorer.org/sciencecalls.html

The Cosmic Explorer Science calls

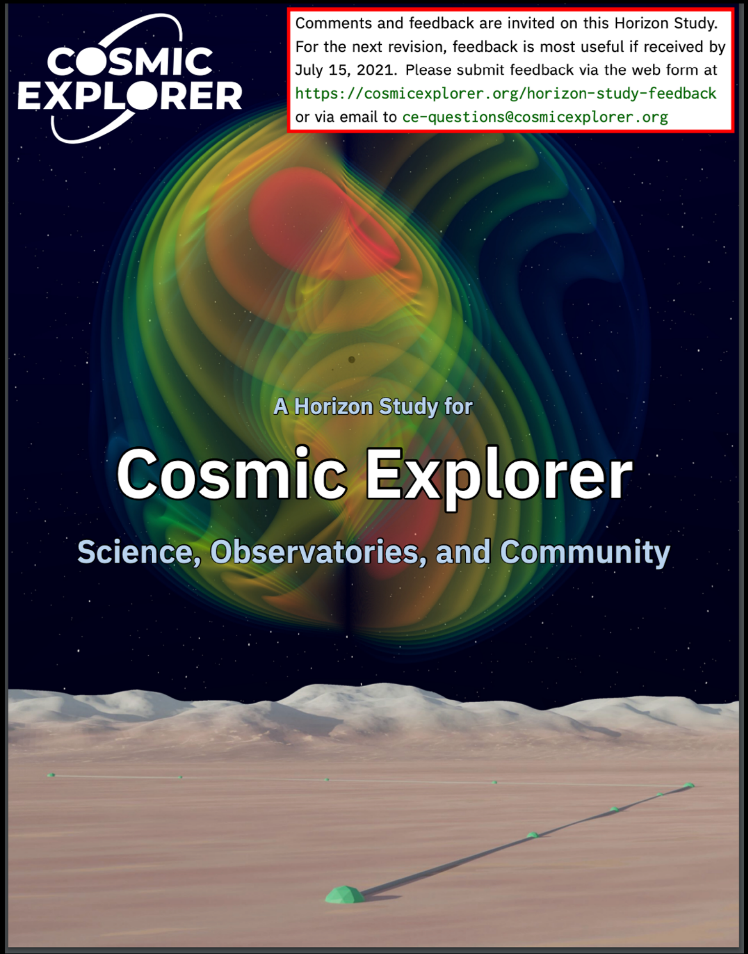
The Cosmic Explorer Consortium holds monthly calls, a venue where we can share and discuss work relevant to the science case of Cosmic Explorer. We hope to cover all of the multiple facets that make third-generation science so exciting. We will thus discuss research on a broad range of topics, from nuclear physics, to multimessenger astrophysics, fundamental physics, computational challenges for third-generation datasets.

These calls are open to anyone in the Consortium. In fact, please feel free to share this email with colleagues who might be interested, and invite them to join the Consortium!

You can use this Google form (no Google account required) to propose a talk (usually 24+5m). We will get back to you ASAP after we receive your request.

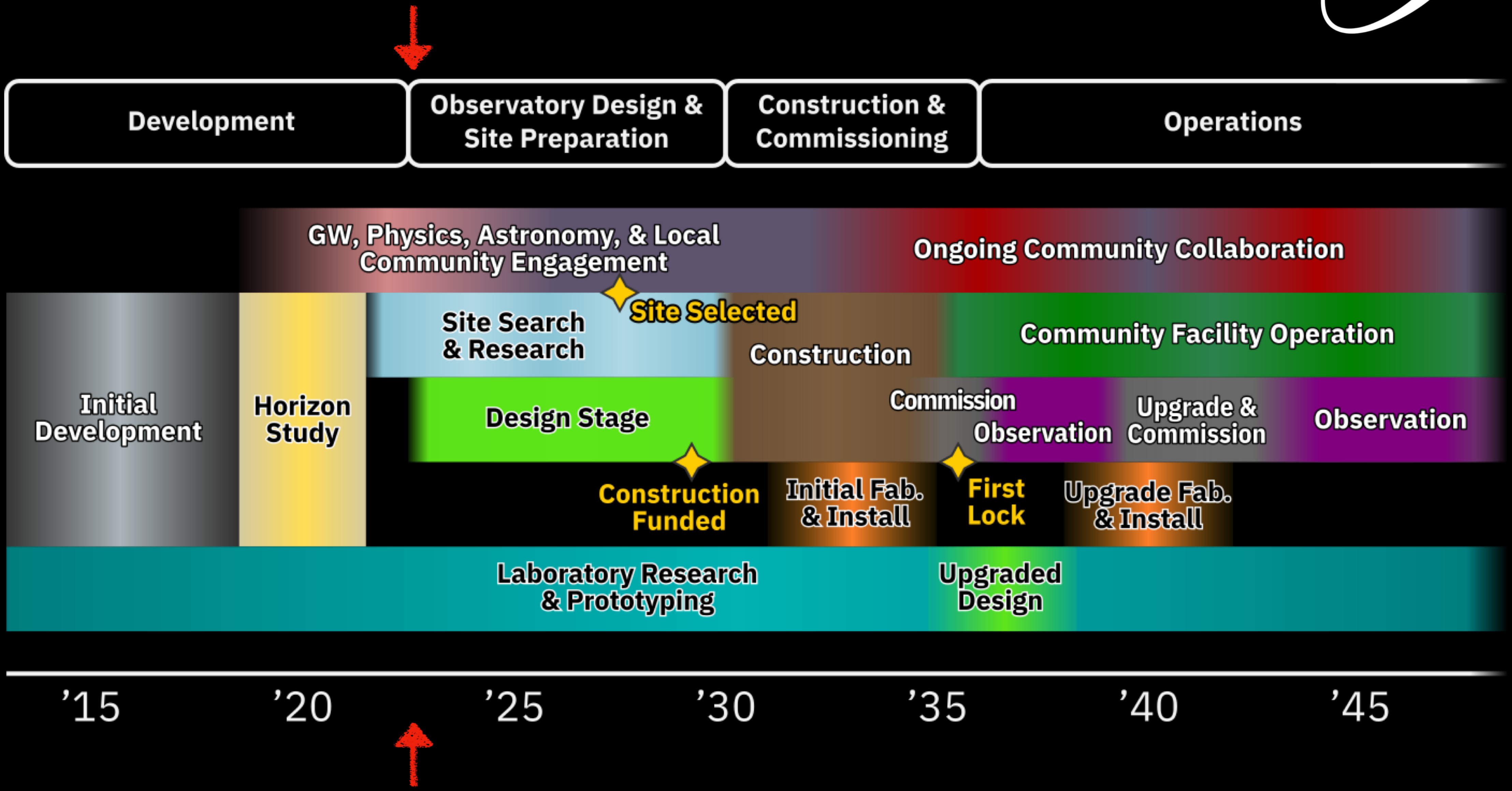
Cosmic Explorer Horizon Study

- NSF funded an Horizon Study (CEHS) to explore design options and scientific potential of ground-based next-generation detectors in the US
- The final draft can be read at https://cosmicexplorer.org/



CEHS 2021

Cosmic Explorer Notional Timeline (see CEHS)



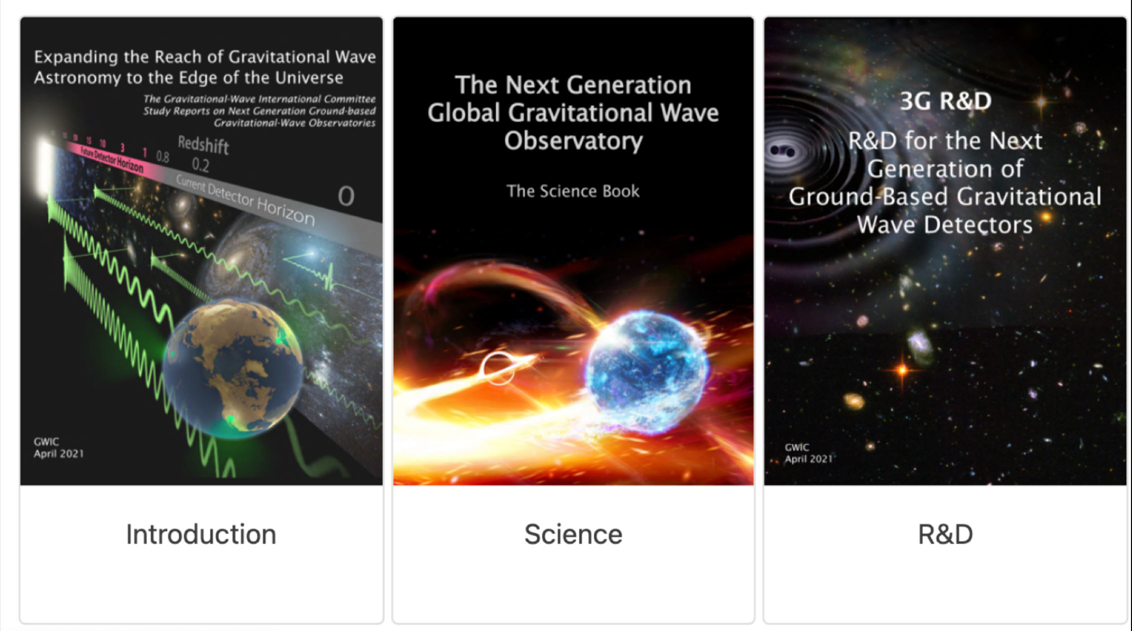
‹#›

Currently seeking support for Conceptual Design

- Conceptual Design scale: 3 years
  - Principal cost elements: preparing PEP (professional project staff), Engineering studies (vacuum systems, civil construction), Site identification and acquisition planning
  - Detector R&D but intention that this be pursued by small proposals to NSF
- Preliminary and Final Design scale: 4 years
  - Currently preparing unsolicited proposal to fund the Conceptual Design
  - NSF program officer not yet seeking a centralized project proposal, but clearly on-board with the idea of CE and in the process of learning how major facilities are funded at NSF
- Private funds
  - In discussion with institutions; anticipate leadership at MIT
  - Working to grow our institutional connections and support network

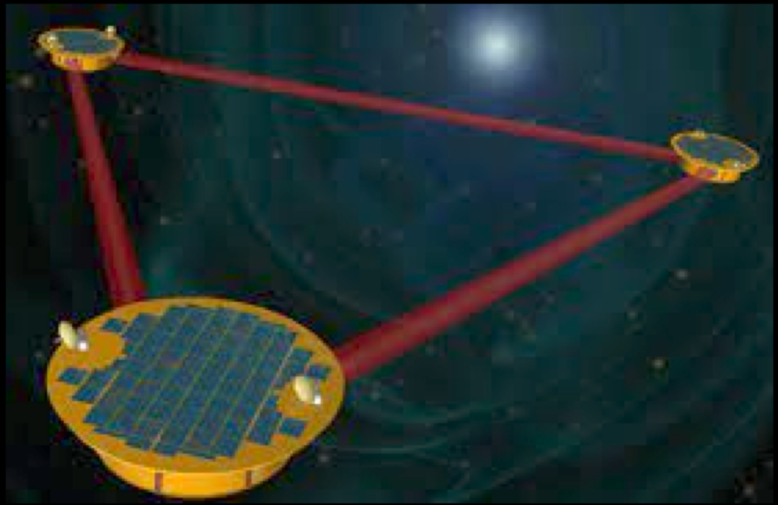
The Gravitational Wave International Committee and NG

- To get the most out of NG detectors, a network is required
- The GWIC has formed a committees focusing on NG R&D, science, and global coordination
- Read more here: gwic.ligo.org/3Gsubcomm/
- Dozens of useful documents and links (includes Cosmic Explorer Horizon Study, Einstein Telescope Design report)



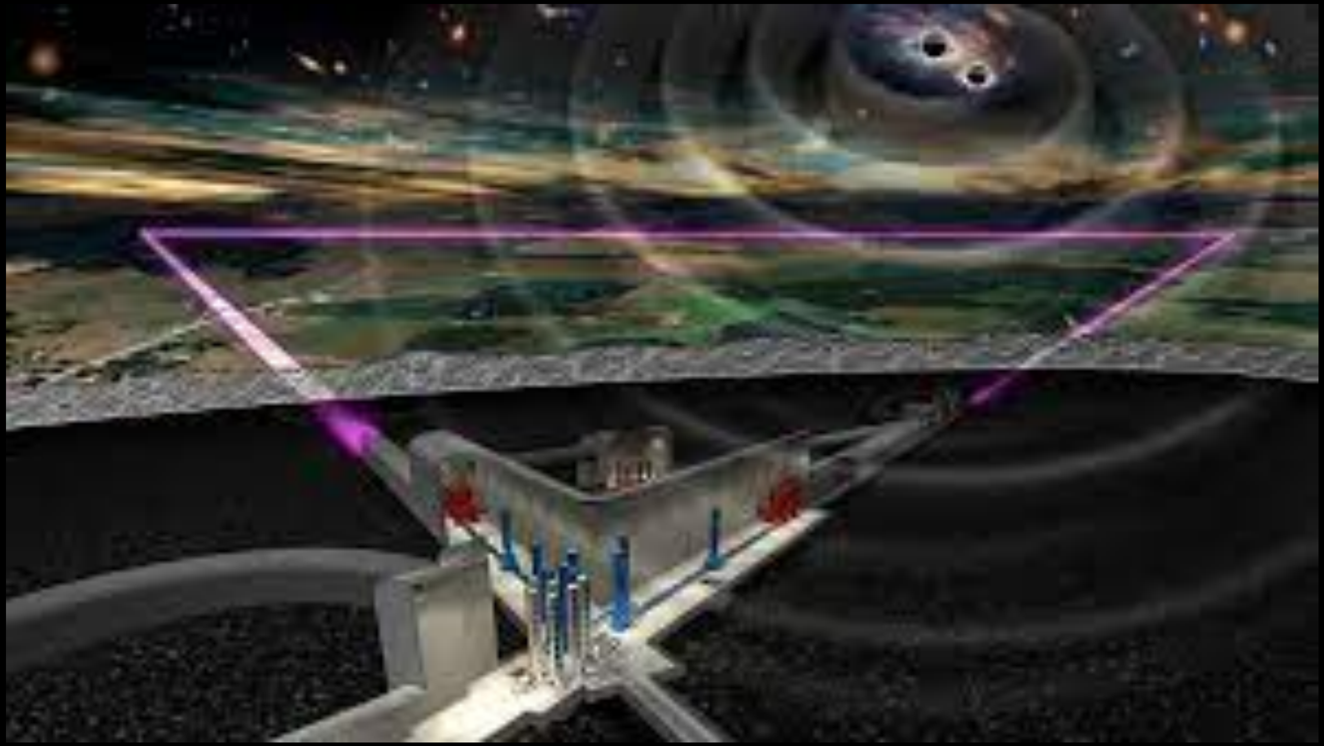
CE in the International Context

- Laser Interferometer Space Antenna (LISA)
  - An ESA-led space observatory with a small NASA contribution
  - Expected to be launched in 2034 and take data concurrently with CE and ET
  - Similar efforts also in China (two space observatories)
- Neutron-star Extreme Matter Observatory (NEMO)
  - An Australian observatory but a smaller observatory focussed on specific science
  - Aspire to build a 20km CE-like detector in the future



Einstein Telescope

- A proposed next-generation ground-based gravitational-wave detector
- Triangular-shaped, 10 Km arms
- Underground to access low (~Hz) frequency
- Mature design, design report published in 2011
  - Technically challenging (underground cryogenic multiple interferometers)
- Recently included in the European Strategic Forum for Research Infrastructures (ESFRI) roadmap!

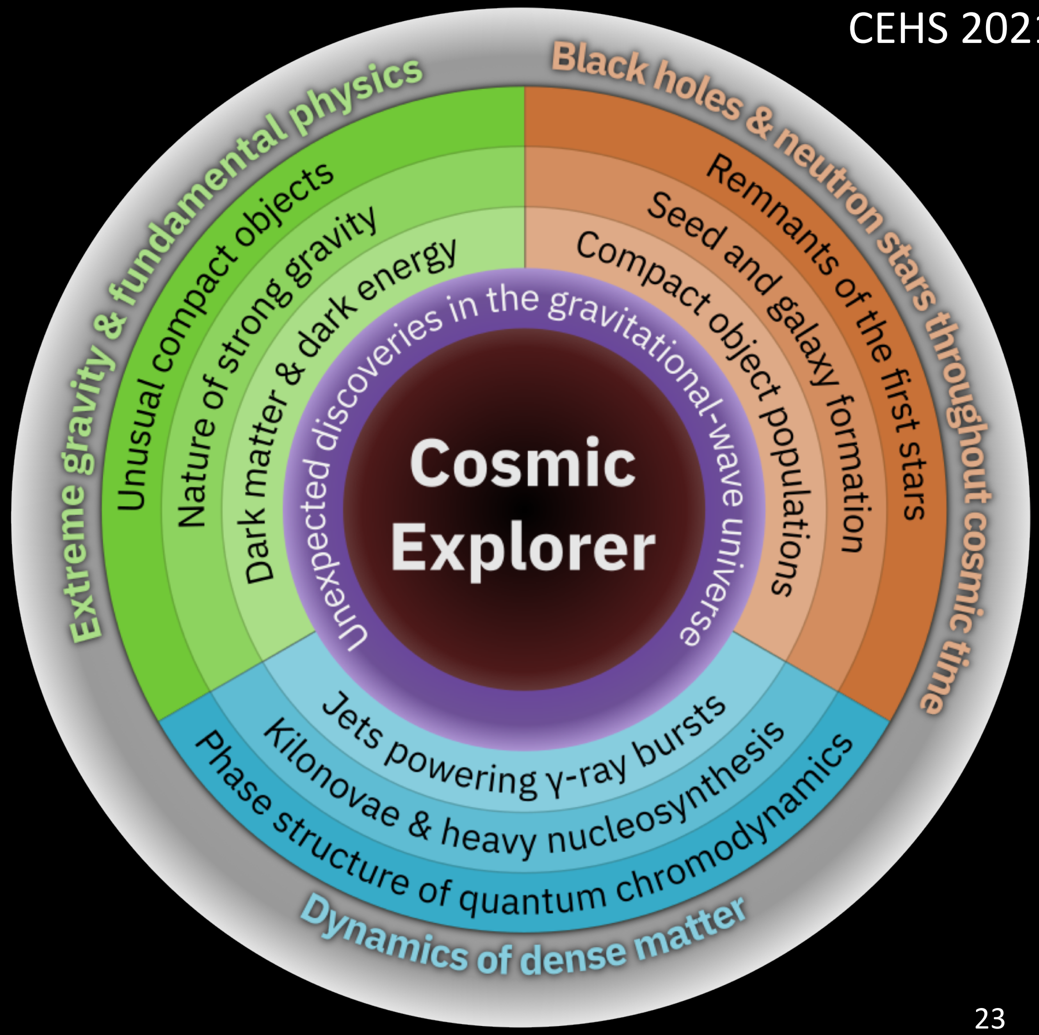


Credit: NIKHEF

Cosmic Explorer Horizon Study

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

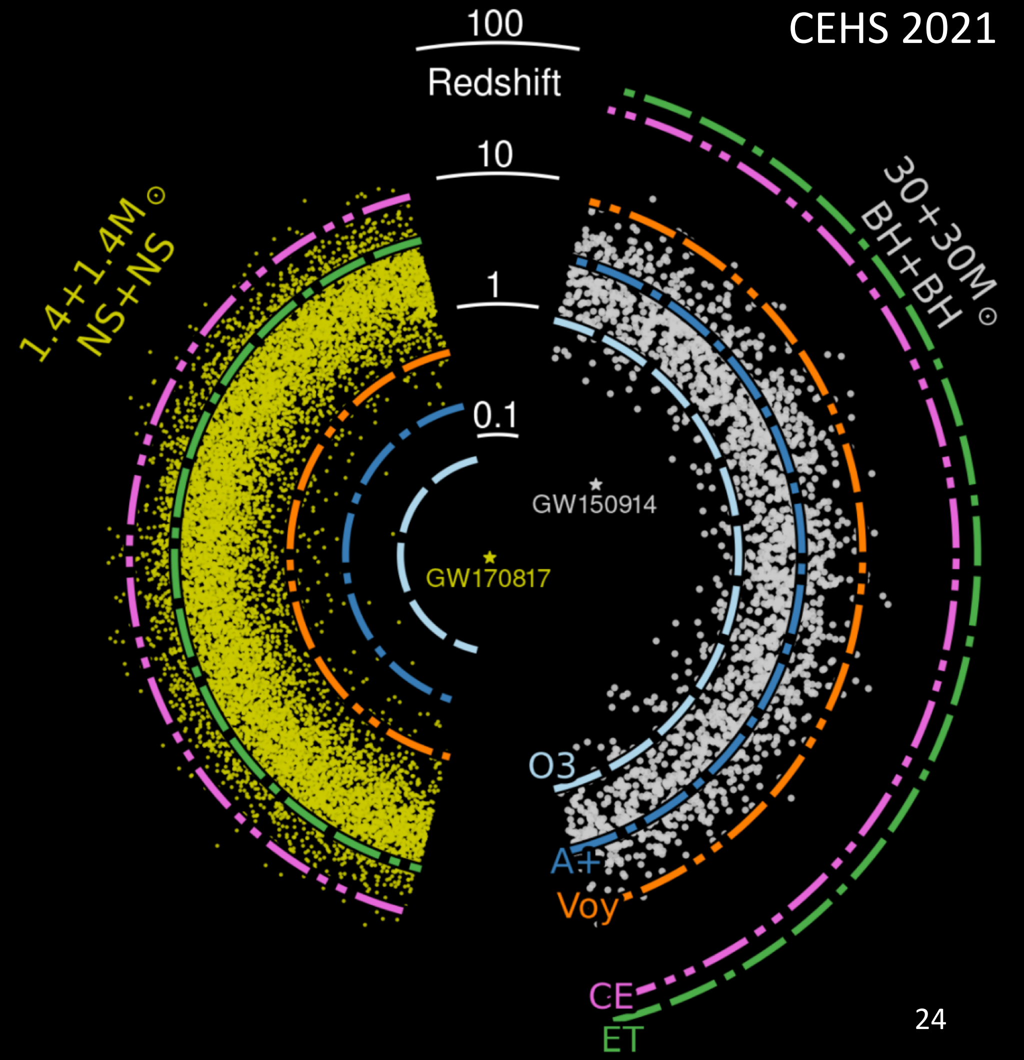
CEHS 2021



Cosmic Explorer Horizon Study

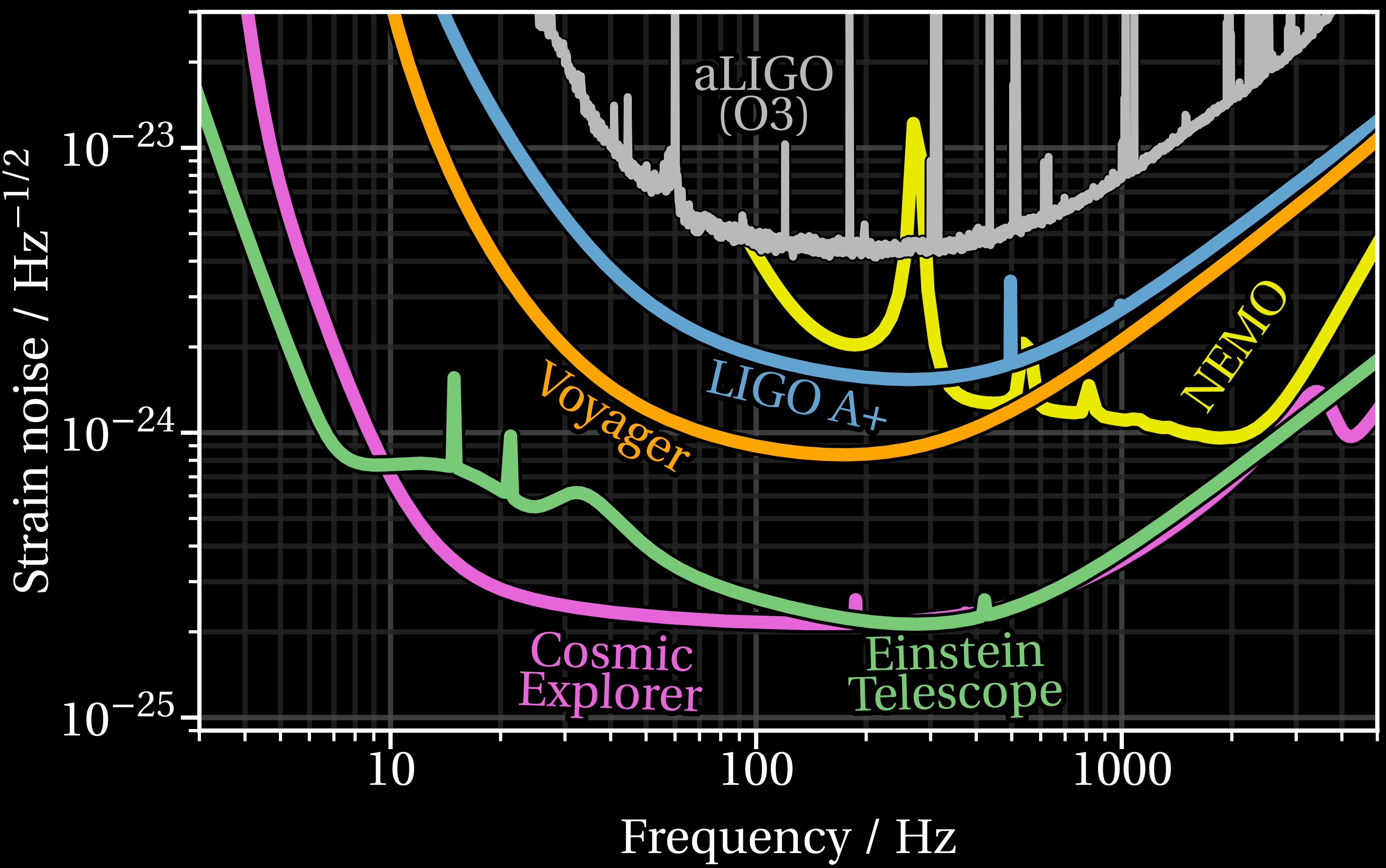
- The CE HS identifies key science outcomes that can be reached with NG detectors
  - Black holes and neutron stars throughough cosmic time
  - Dynamics of dense matter & extreme environments
  - Extreme gravity & Fundamental Physics

CEHS 2021

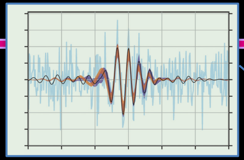


Detector sensitivity

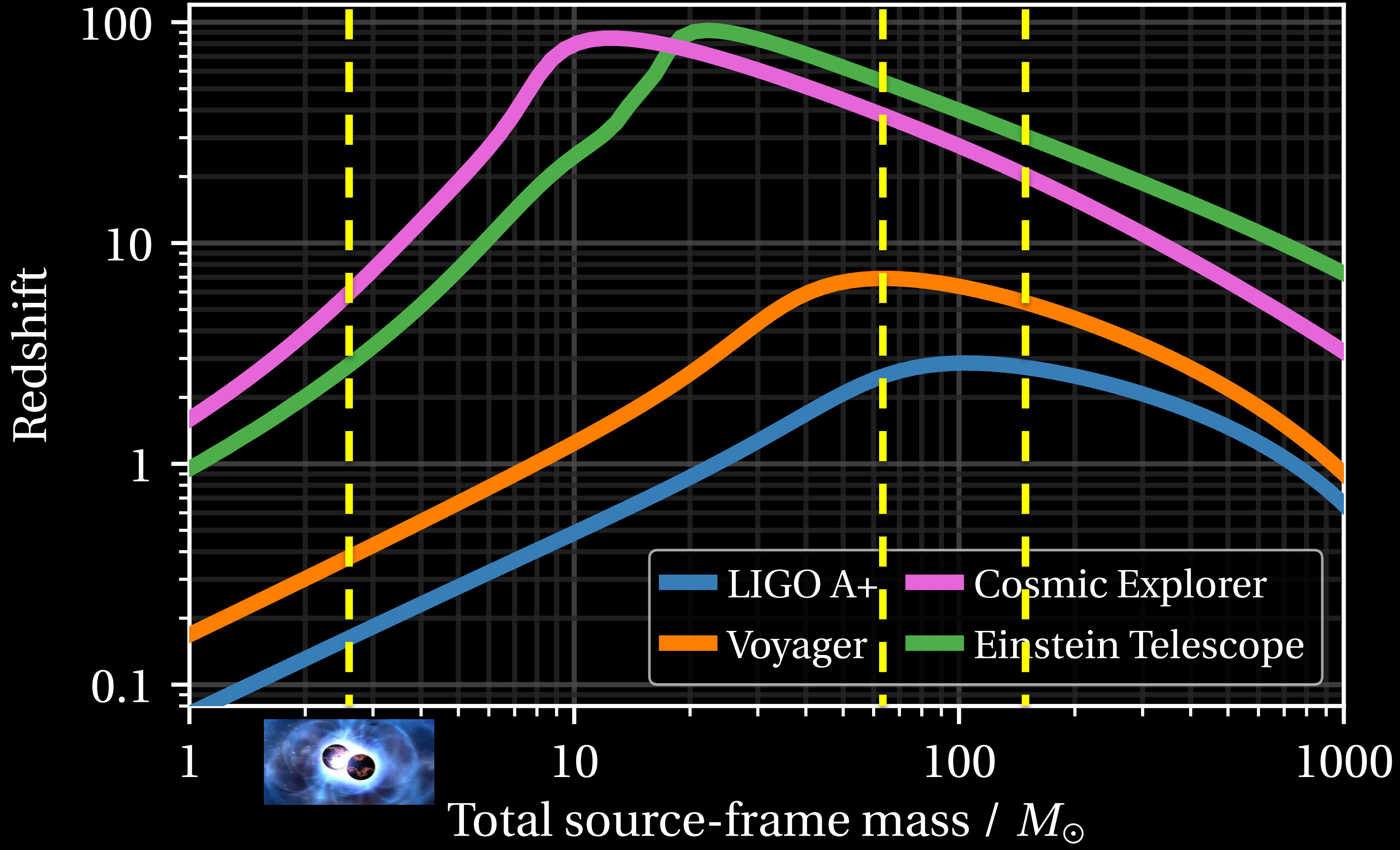
CEHS 2021



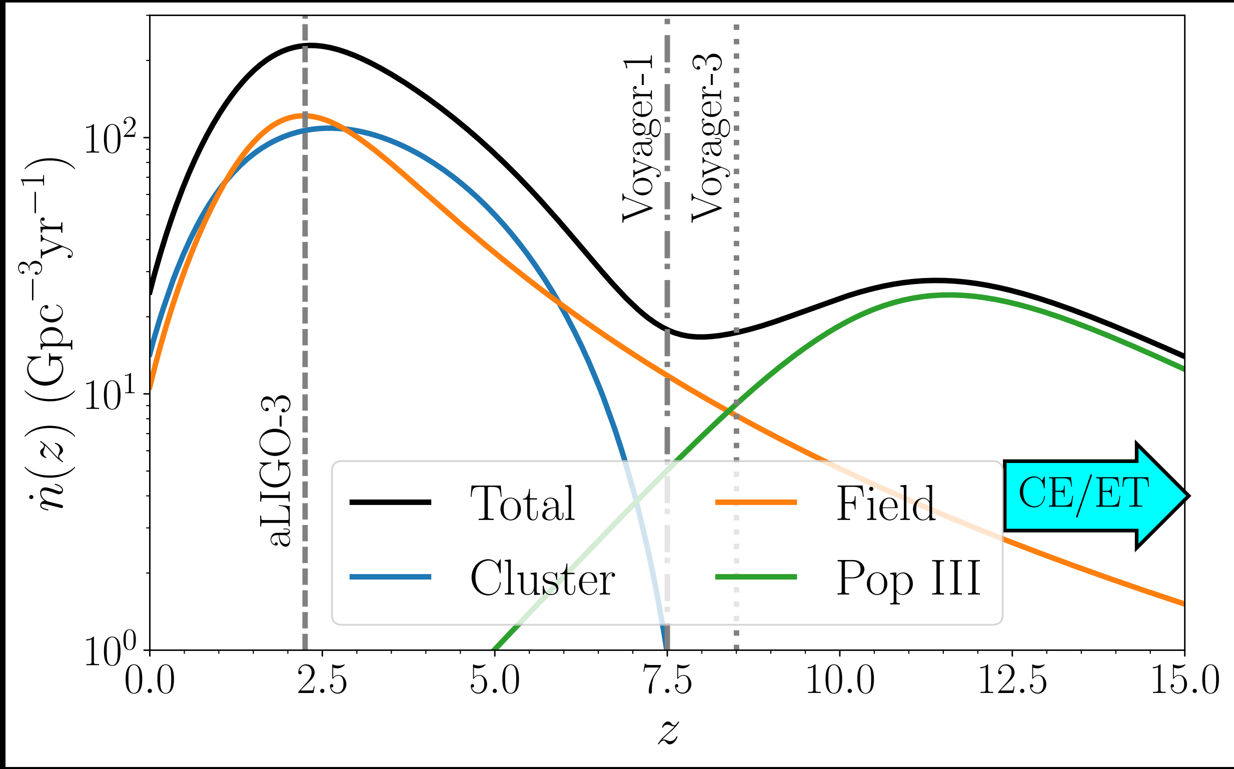
Listening to the Universe



CEHS 2021



Astrophysical populations of binaries

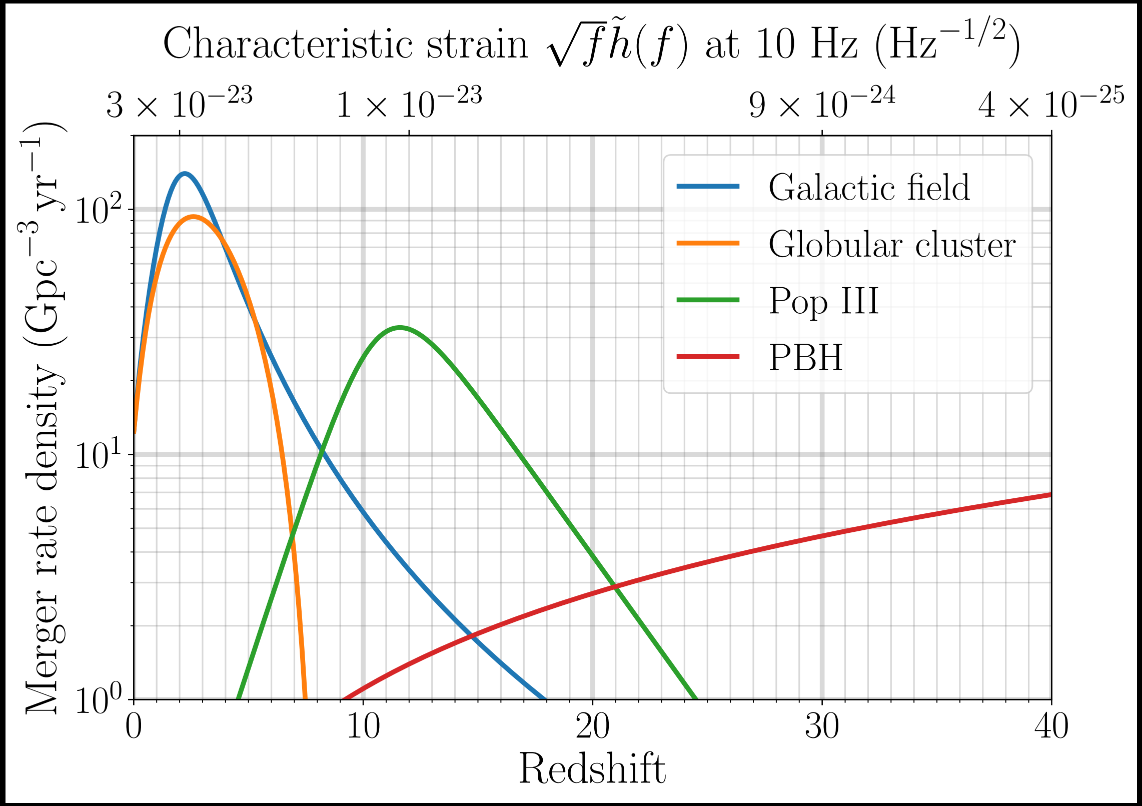


Ng+ ApJL 913 L5

- Can detect black holes from astrophysical populations which are currently unaccessible
- It is important to have a network, to measure distance well, and hence source-frame mass

Primordial black holes

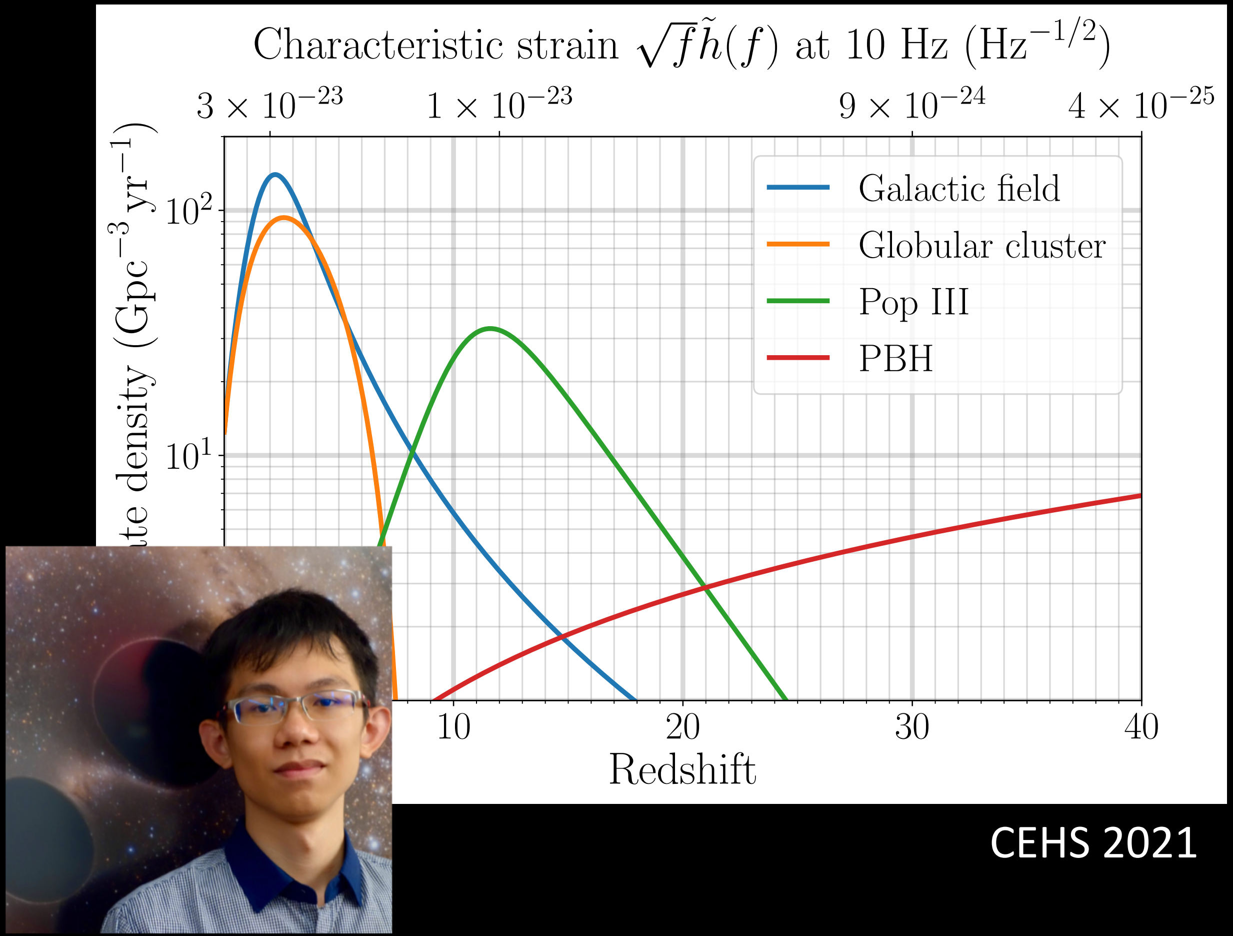
- If they exist, primordial black holes (PBHs) are expected to have had a higher merger rate in the past
- Redshifts of tens
- Detecting PBHs would be extremely consequential



CEHS 2021

Primordial black holes

- If they exist, primordial black holes (PBHs) are expected to have had a higher merger rate in the past
- Redshifts of tens
- Detecting PBHs would be extremely consequential
- A lof of what I will report on is work of MIT student Ken Ng



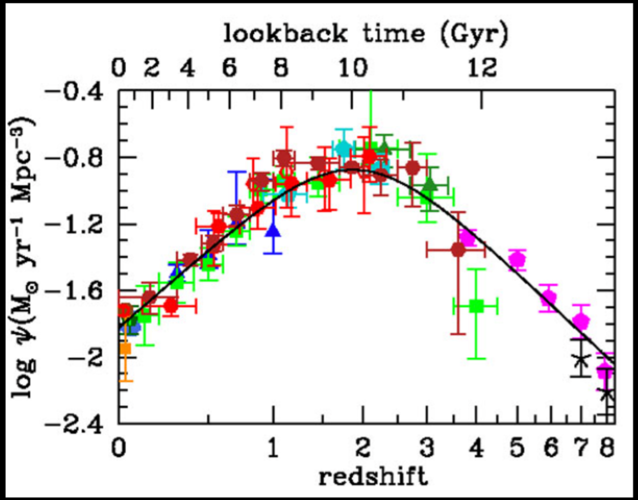
CEHS 2021

ASTROPHYSICAL BLACK HOLES

Star formation rate

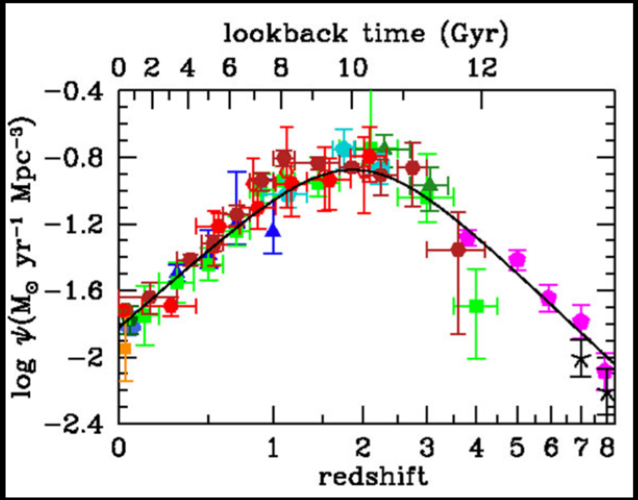
- We can reasonably expect that the *formation* rate of astrophysical black holes follows the star formation rate (SFR)

Madau Dickinson 1403.0007



Star formation rate

- We can reasonably expect that the *formation* rate of astrophysical black holes follows the star formation rate (SFR)
- But "one never measures mass, one measures luminosity. Everyone then adopts the same unproven assumptions." (Carlos Frenk, about measuring astrophysical masses)



SFR and all that

- Assume that the BBH merger rate is only affected by a (metallicity dependent) SFR and a time delay distribution (TDD)

$$\mathcal{R}_m(z_m) = \int_{z_m}^{\infty} dz_f \frac{dt_f}{dz_f} \mathcal{R}_f(z_f) p(t_m | t_f, \lambda)$$

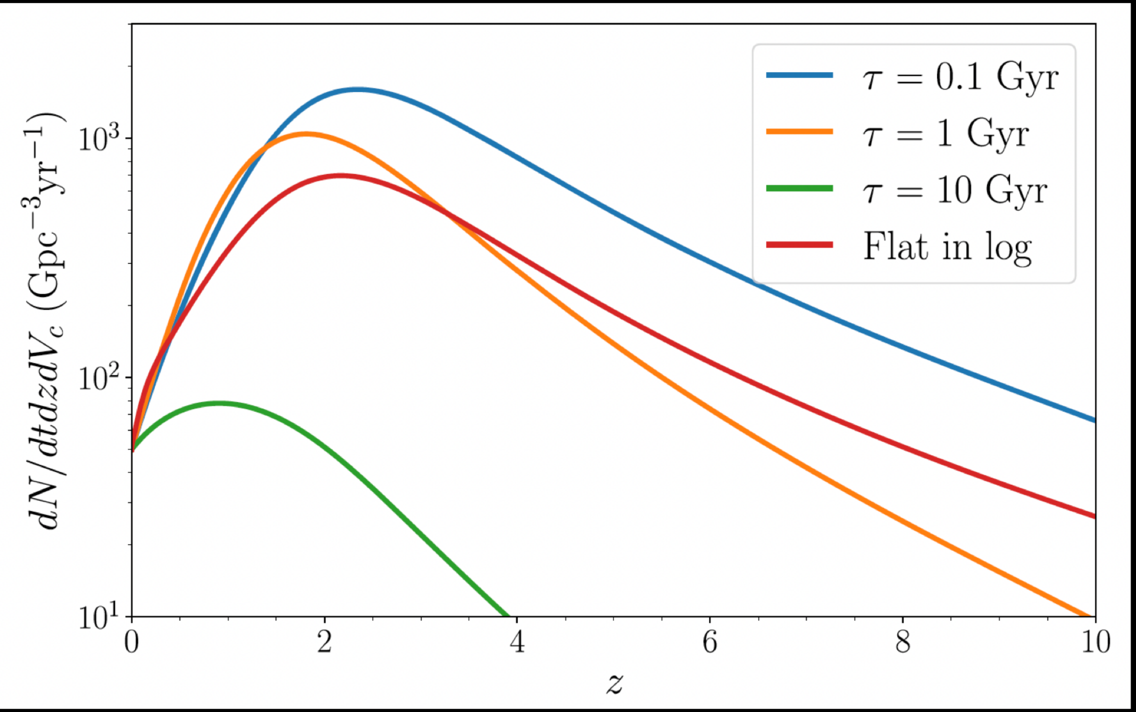
$$\mathcal{R}_f(z_f) \equiv \frac{dN_{\rm form}}{dV_{\rm C}\, dt_f} \propto \eta(z_f)\psi(z_f)$$

- In reality, things are more complicated and the merger rate might also depend on intrinsic properties (e.g. masses); various channels will contribute, etc
  - Straightfoward to extend analysis to account for this
- Can we use detected BBHs to measure SFR and TDD?

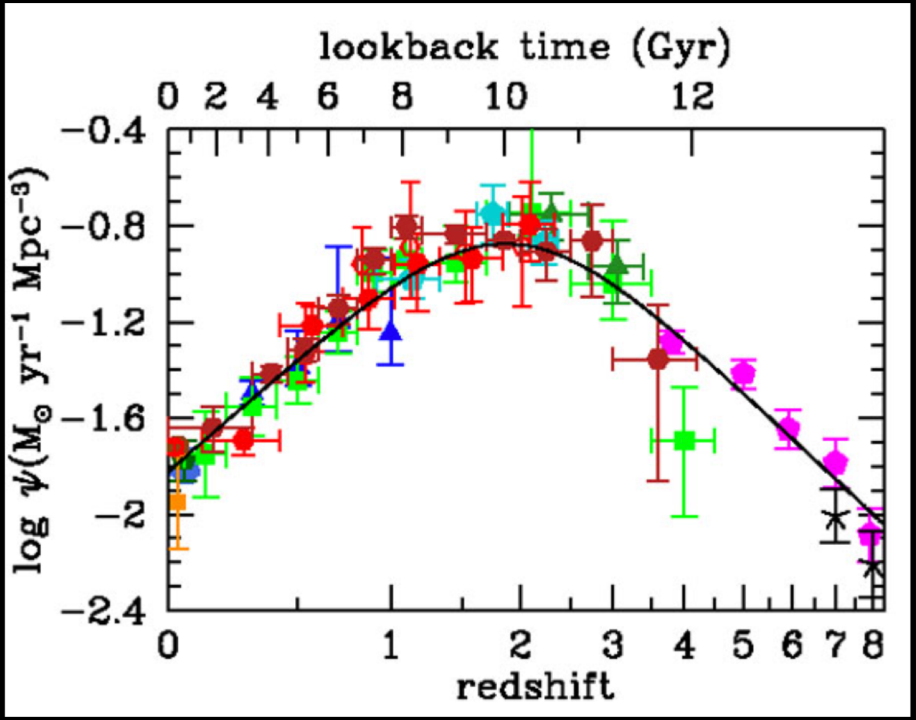
From SFR to merger rate

For a given formation rate, the true merger rate will depend on the time delay distribution

Madau Dickinson 1403.0007

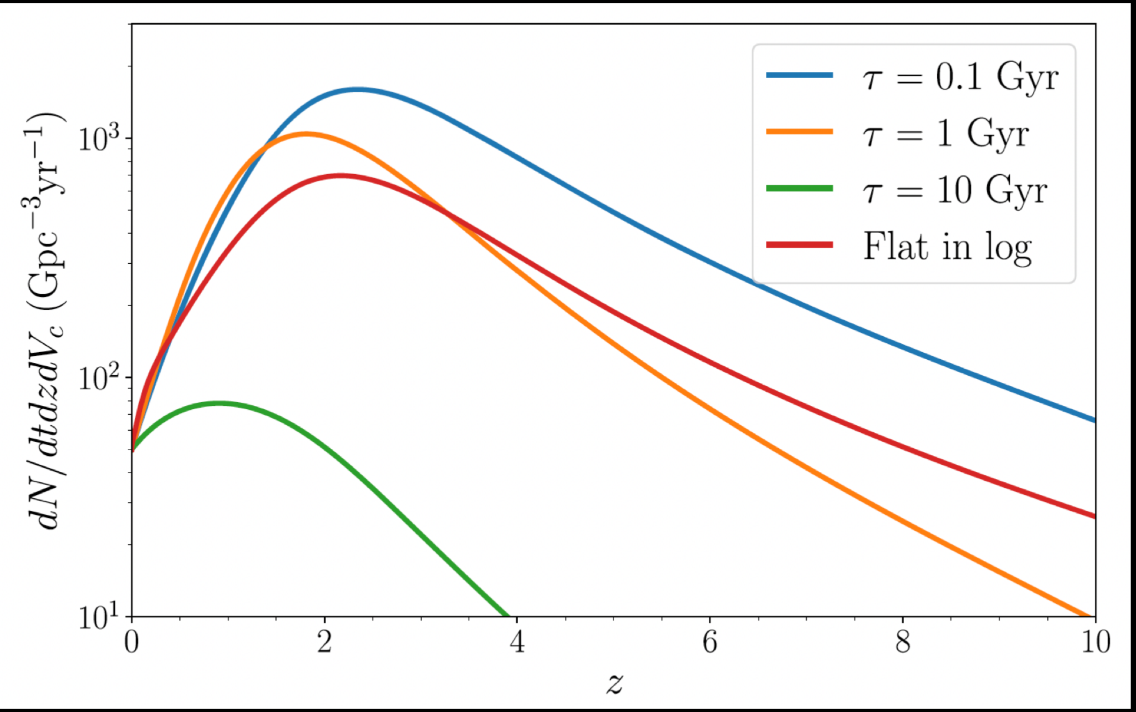


Vitale+ 1808.00901

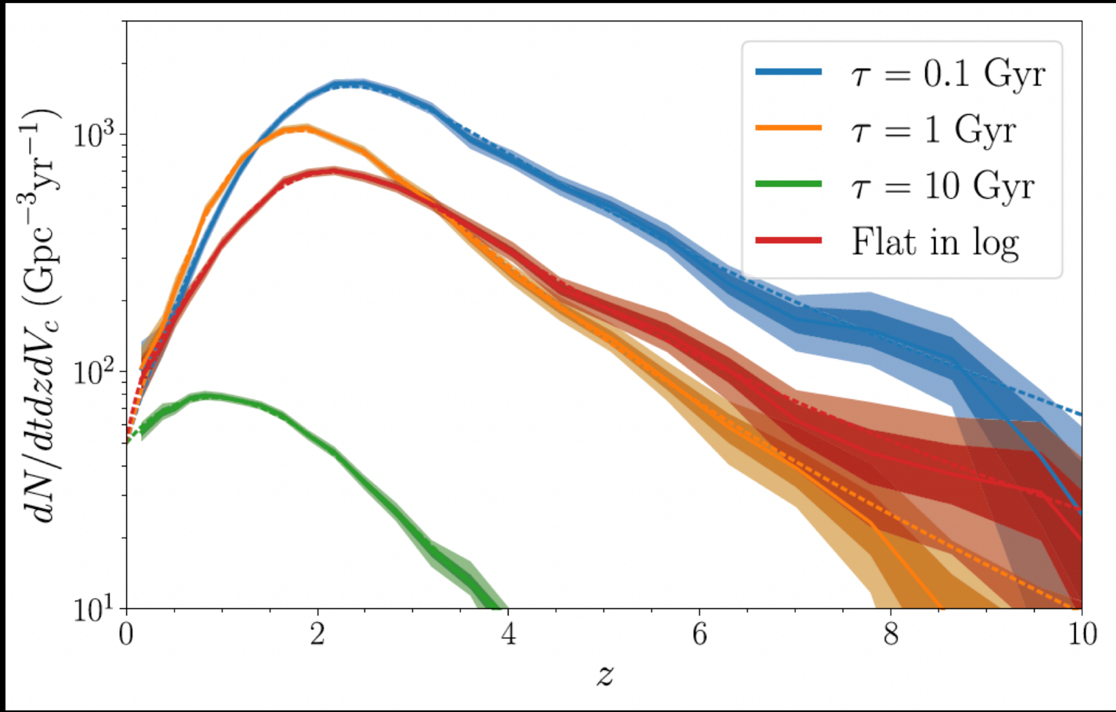


Unmodeled inference

For a given formation rate, the true merger rate will depend on the time delay distribution



With an **unmodeled** approach, one can measure the total merger rate and see where it peaks

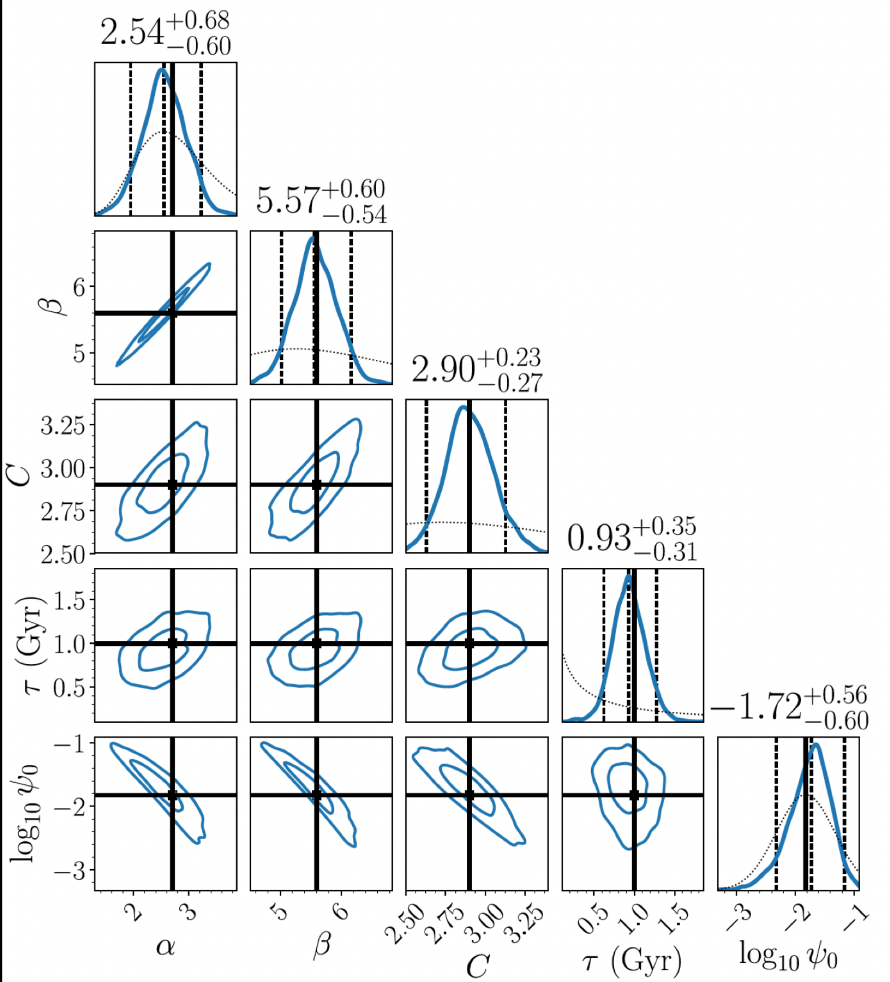


Measuring SFR and TDD

- With a model for the SFR and the TDT, once can measure their parameters

$$\psi_{\rm MD}(z) = \psi_0 \frac{(1+z)^\alpha}{1 + \left(\frac{1+z}{C}\right)^\beta}$$

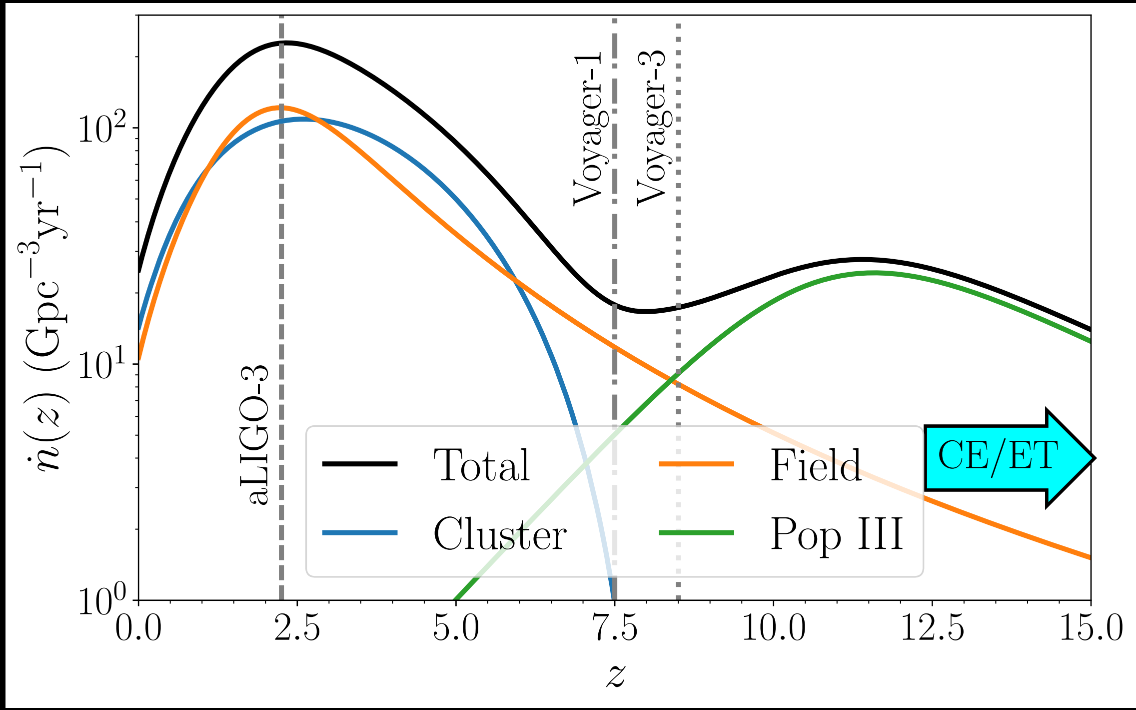
$$p(t_m|t_f,\tau) = \frac{1}{\tau}\exp\left\{\left[-\frac{(t_f - t_m)}{\tau}\right]\right\}$$



- Caveats: results as good as your model!

Allowing for multiple populations

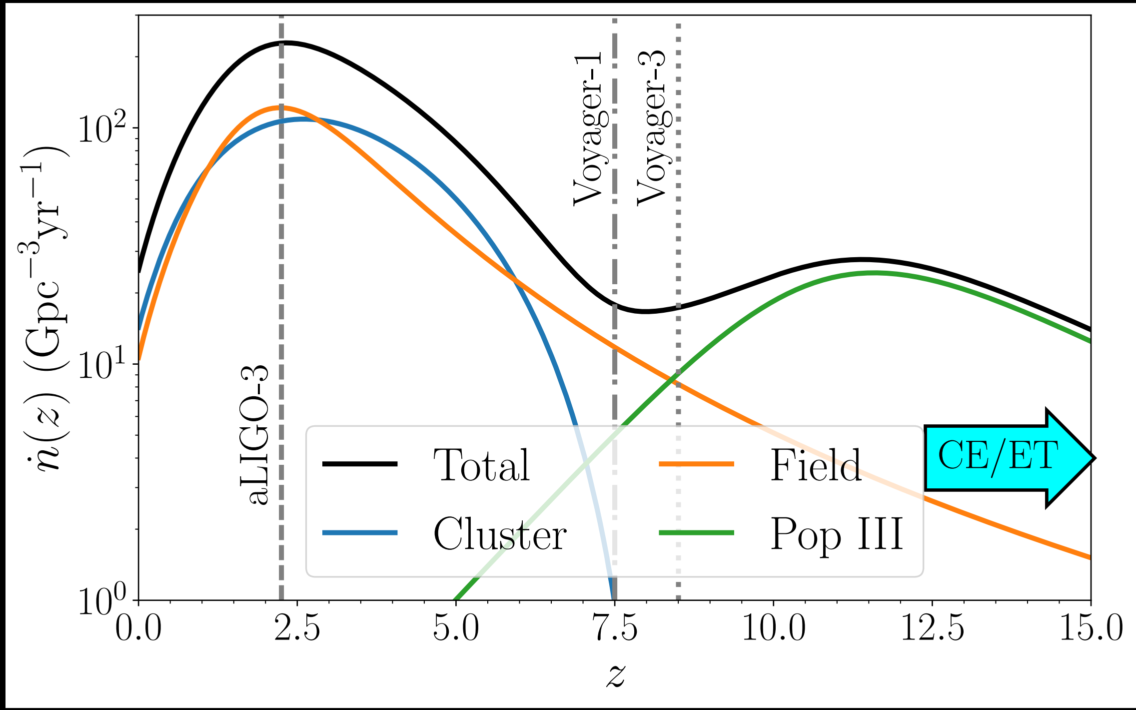
- In Ng+ 2012.09876 we allowed for multiple astrophysical populations
  - "Local" field and dynamical channels
  - High-z mergers from Pop III leftovers
- Assumed **two months** worth of detections
- 2 CE + 1 ET



Ng+ ApJL 913 L5

Immediate questions

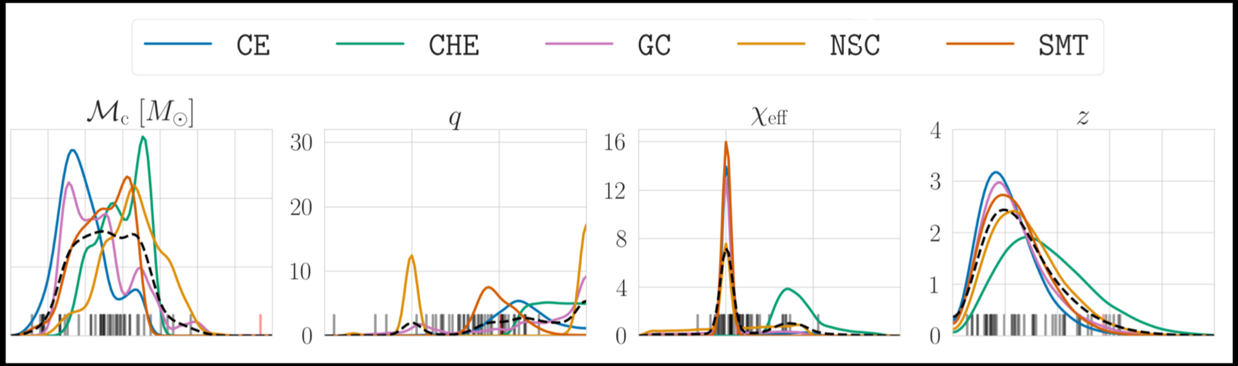
- Can we measure the properties of each channel separately?
- Can we measure the branching ratios between channels?
- Can we show that Pop III BHs exist and when their rate peaked?



Models, models, models!

- To characterize individual channels we need a way of labeling black holes
- The ideal world scenario:
  - Population synthesis gives us predictions we trust for the mass and spin and eccentricity and redshift of each channel as a function of redshift

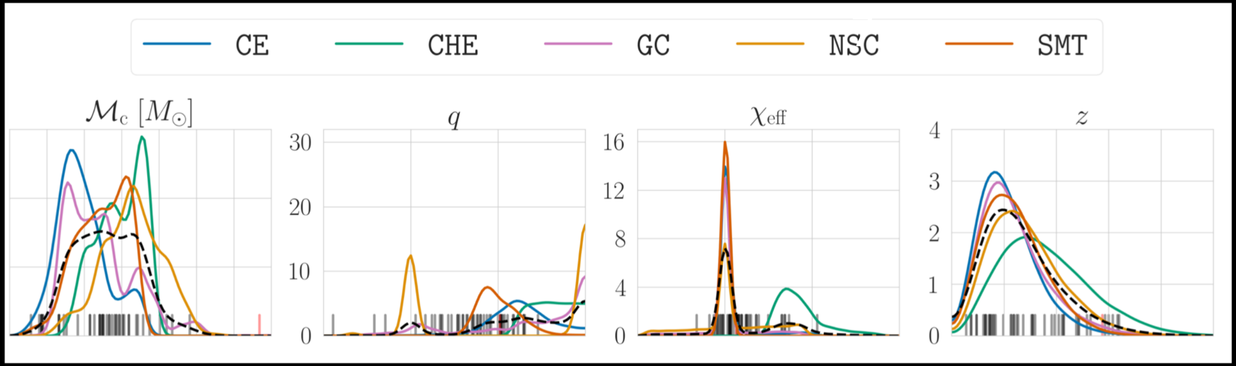
Zevin+,2011.1005



Models, models, models!

- To characterize individual channels we need a way of labeling black holes
- The world were we live:
  - Population synthesis gives us predictions which are highly uncertain locally, and even more so for Pop III
- Use as little modeling as possible
  - Redshifts!

Zevin+,2011.1005



Modeled inference

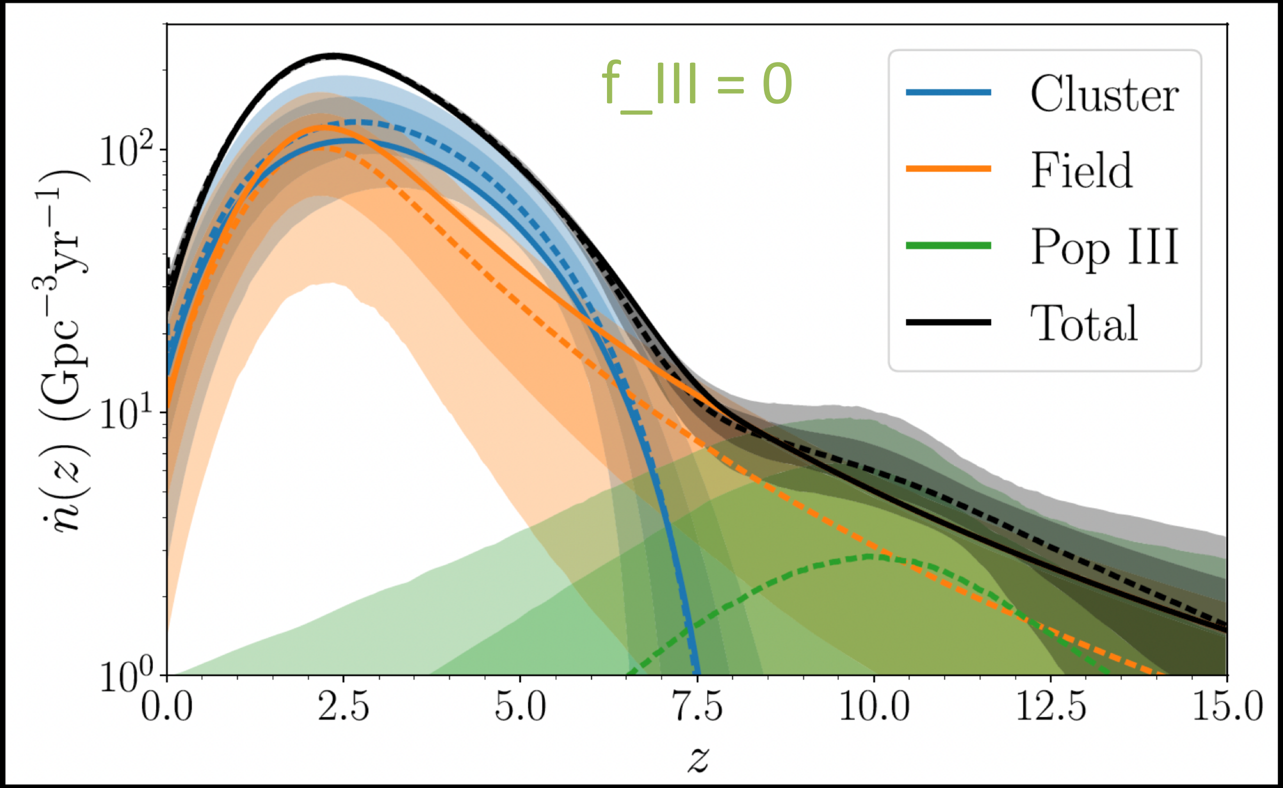
- Take predictions on redshift evolution of various channels, and use them as a parametrized template
- E.g. for Pop III

$$\dot{n}_{\rm III}(z|a_{\rm III}, b_{\rm III}, z_{\rm III}) \propto \frac{e^{a_{\rm III}(z-z_{\rm III})}}{b_{\rm III} + a_{\rm III}e^{(a_{\rm III}+b_{\rm III})(z-z_{\rm III})}}$$

Modeled inference

- Take predictions on redshift evolution of various channels, and use them as a parametrized template
- E.g. for Pop III

$$\dot{n}_{\rm III}(z|a_{\rm III}, b_{\rm III}, z_{\rm III}) \propto \frac{e^{a_{\rm III}(z-z_{\rm III})}}{b_{\rm III} + a_{\rm III}e^{(a_{\rm III}+b_{\rm III})(z-z_{\rm III})}}$$

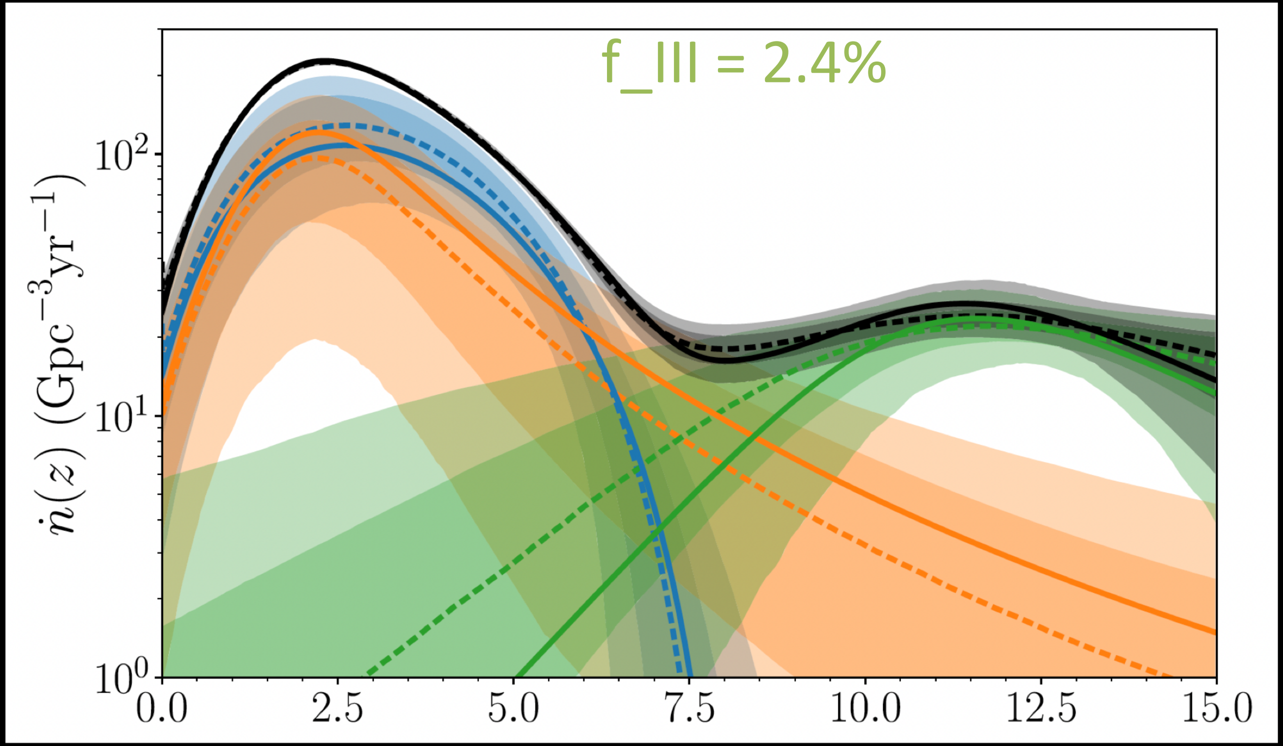


COSMIC EXPLORER

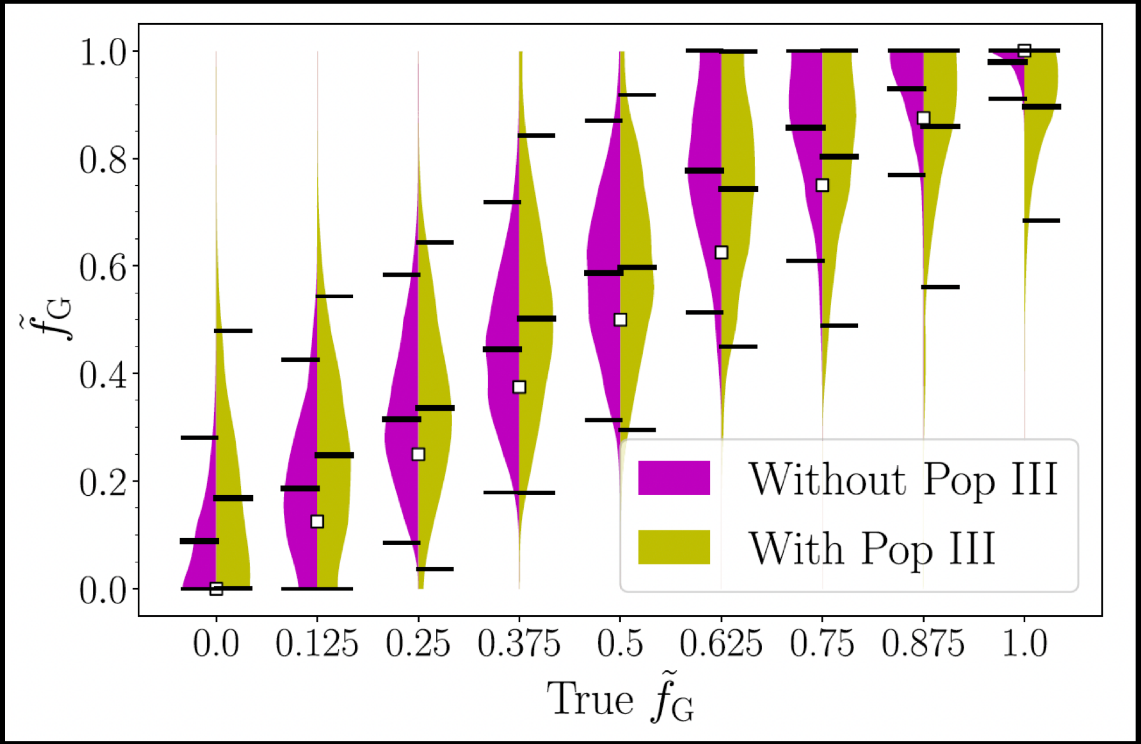
Modeled inference

- Take predictions on redshift evolution of various channels, and use them as a parametrized template
- E.g. for Pop III

$$\dot{n}_{\rm III}(z|a_{\rm III}, b_{\rm III}, z_{\rm III}) \propto \frac{e^{a_{\rm III}(z-z_{\rm III})}}{b_{\rm III} + a_{\rm III}e^{(a_{\rm III}+b_{\rm III})(z-z_{\rm III})}}$$

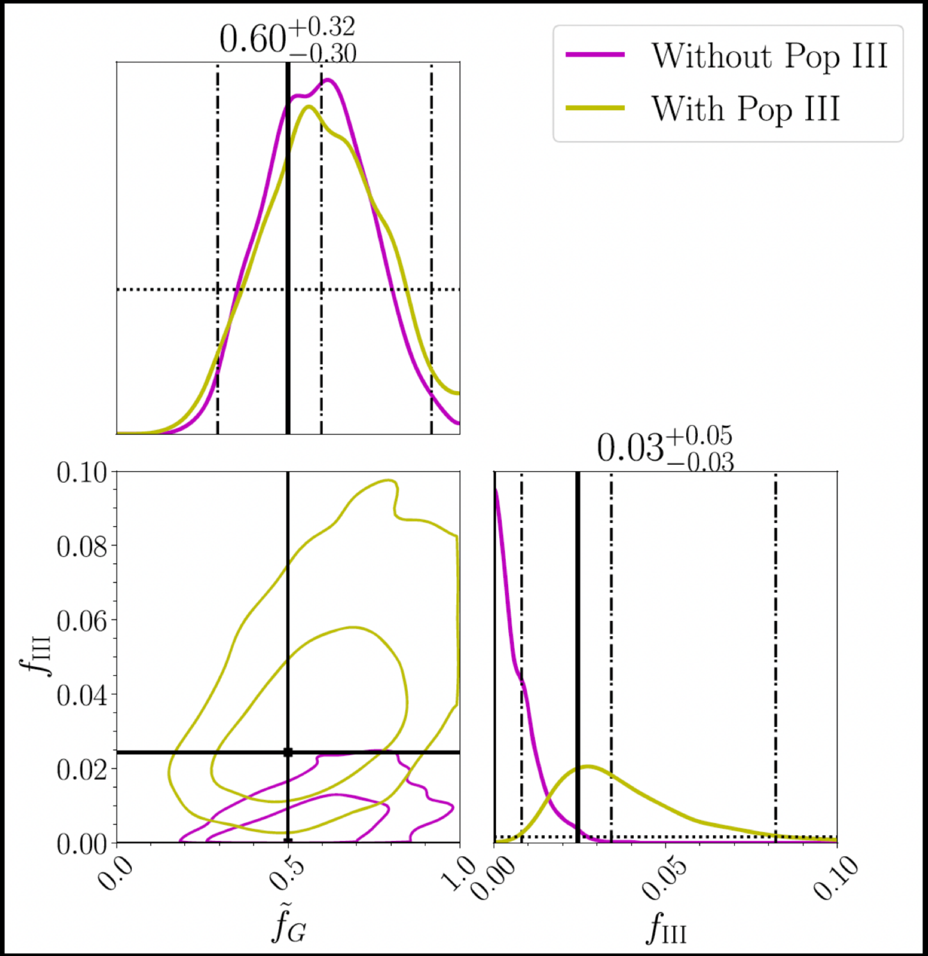


Branching ratios

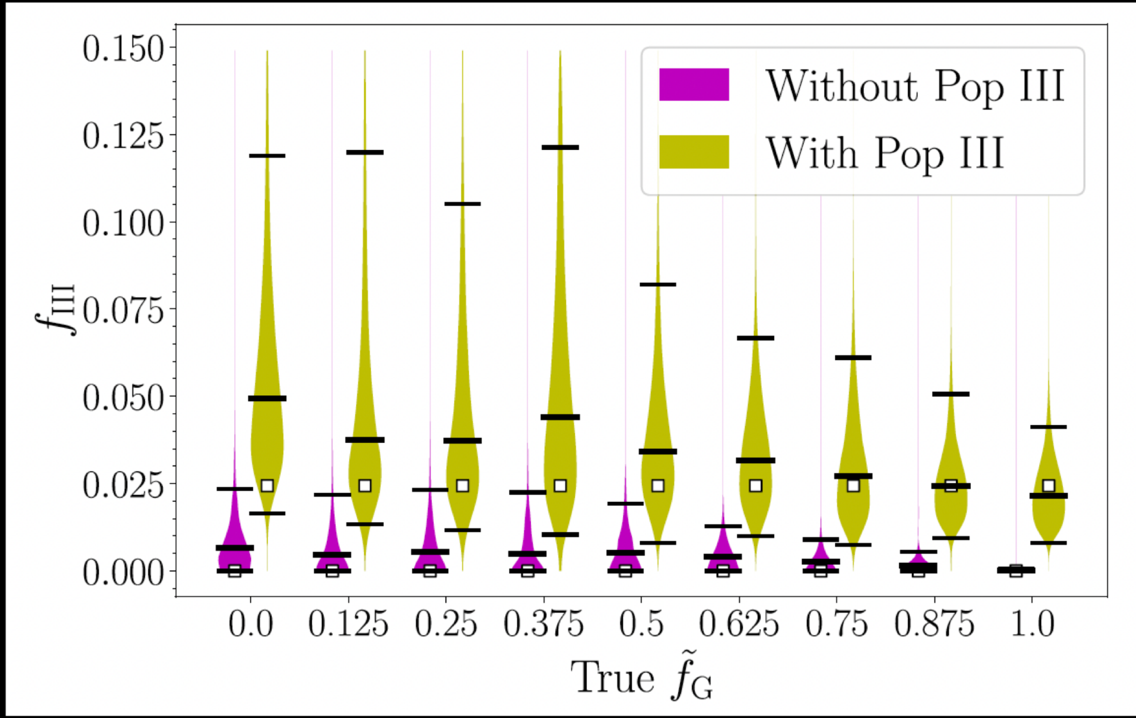


- The ratio between the two local channels can be measured with an uncertainty of ~0.4
- This is with two months of data, uncertainty reduced with more time and more sophisticated population modeling
- Results based on IMRp_v2, HM will help a lot (more on this later)

Are there Pop III mergers?

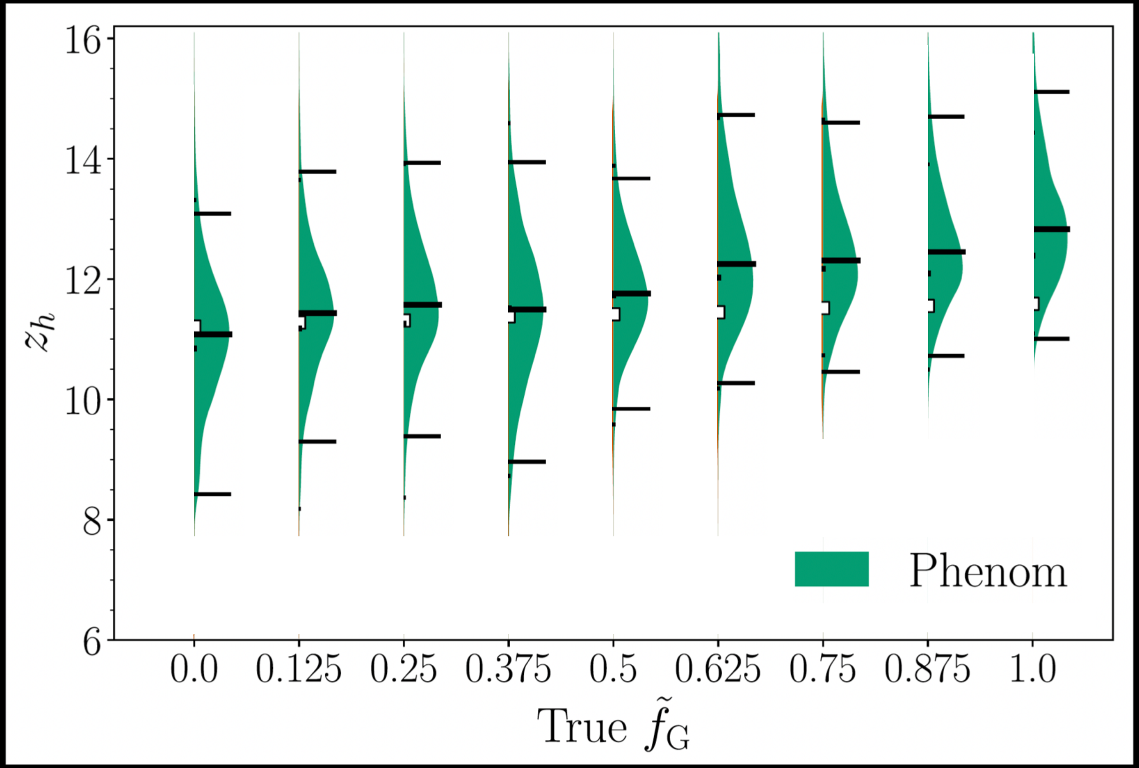


Assumes cluster and field have same rate



O Brother, Where Art Thou?

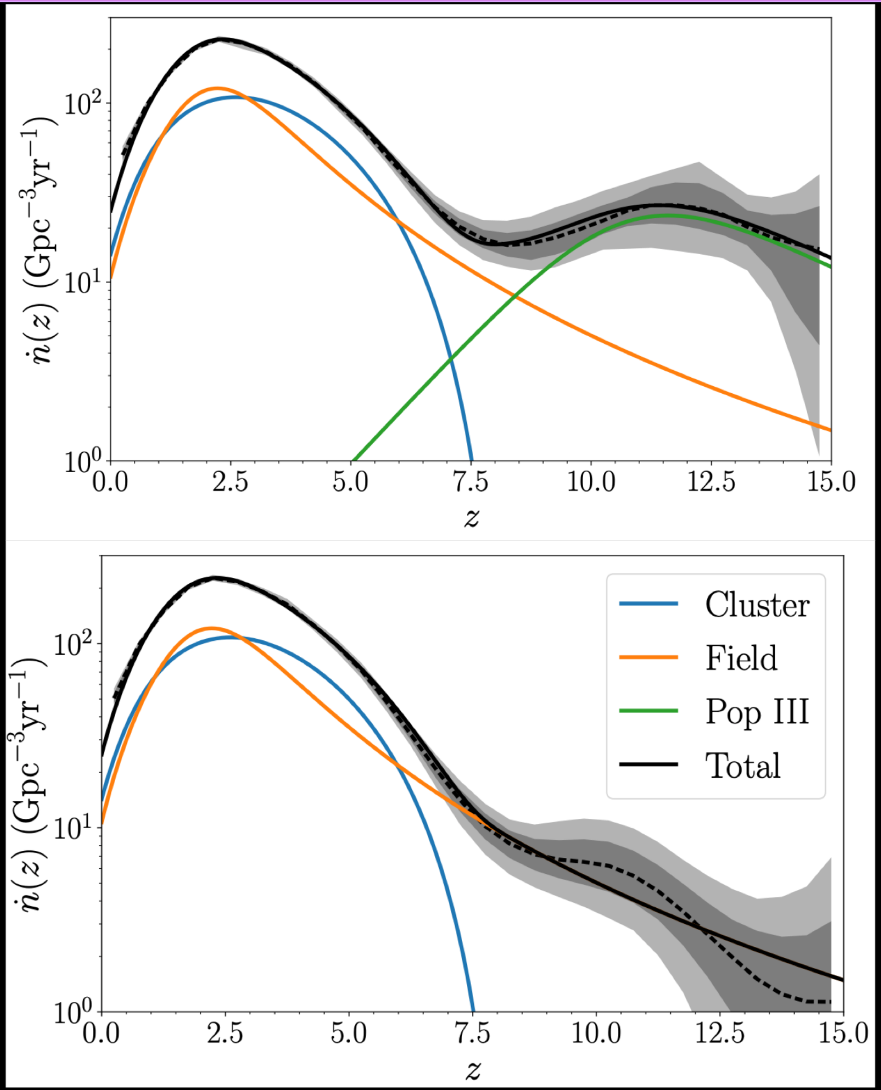
- We can measure the peak of the Pop III mergers easily as one of the model parameters



An unmodeled approach

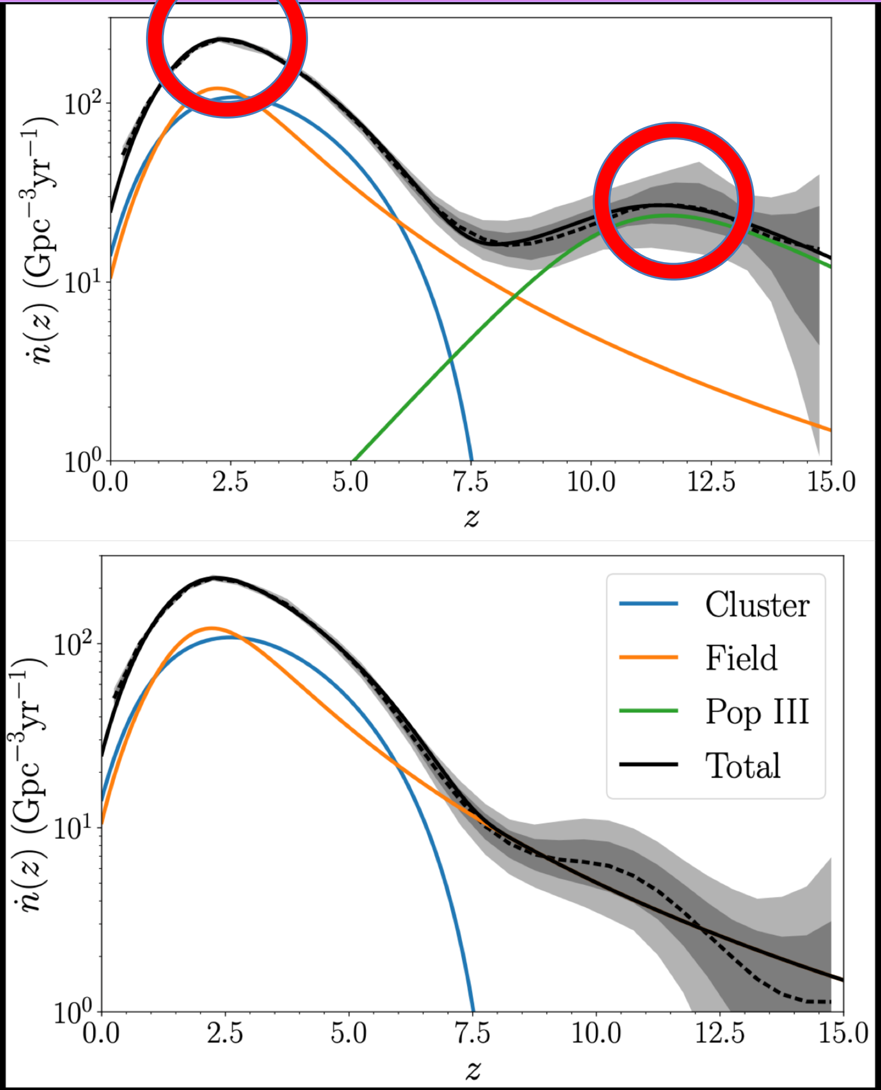
- What can be done if we really don’t trust **any** information coming from theory or population synthesis?
- Just measure the **total** merger rate, without trying to label the black holes

An unmoded approach



- What can be done if we really don't trust **any** information coming from theory or population synthesis?
- Just measure the **total** merger rate, without trying to label the black holes
- Use gaussian process to infer the total merger rate

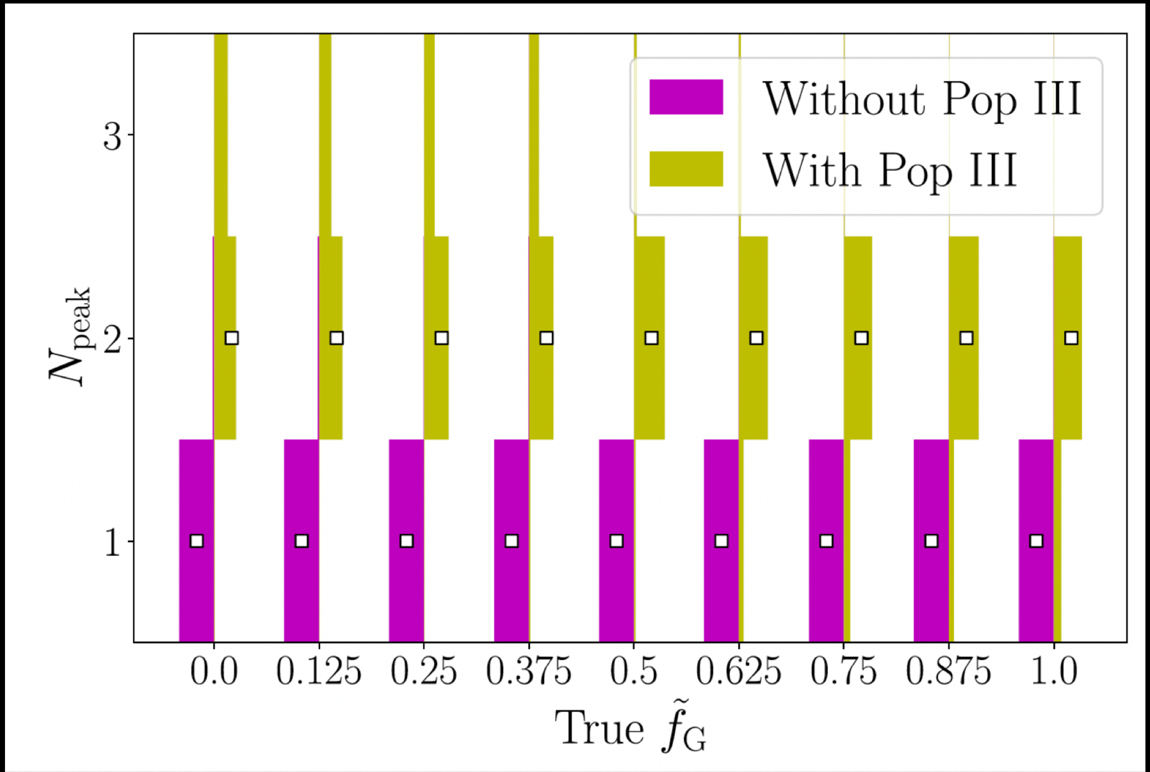
An unmodeled approach



- Use a simple algorithm to find stationary points of the total merger rate

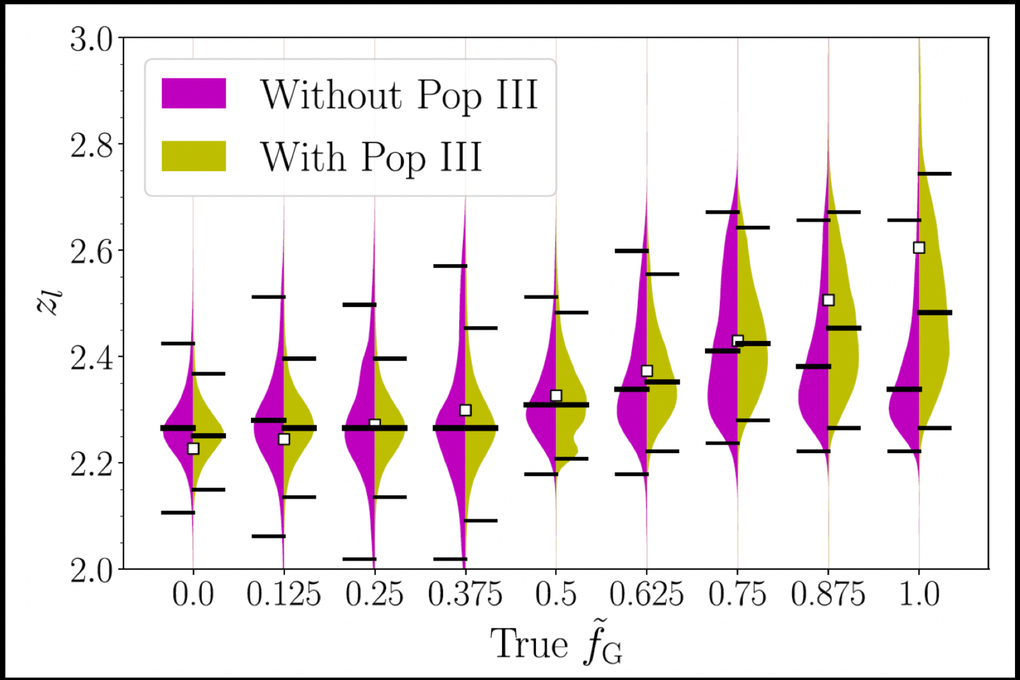
How many peaks

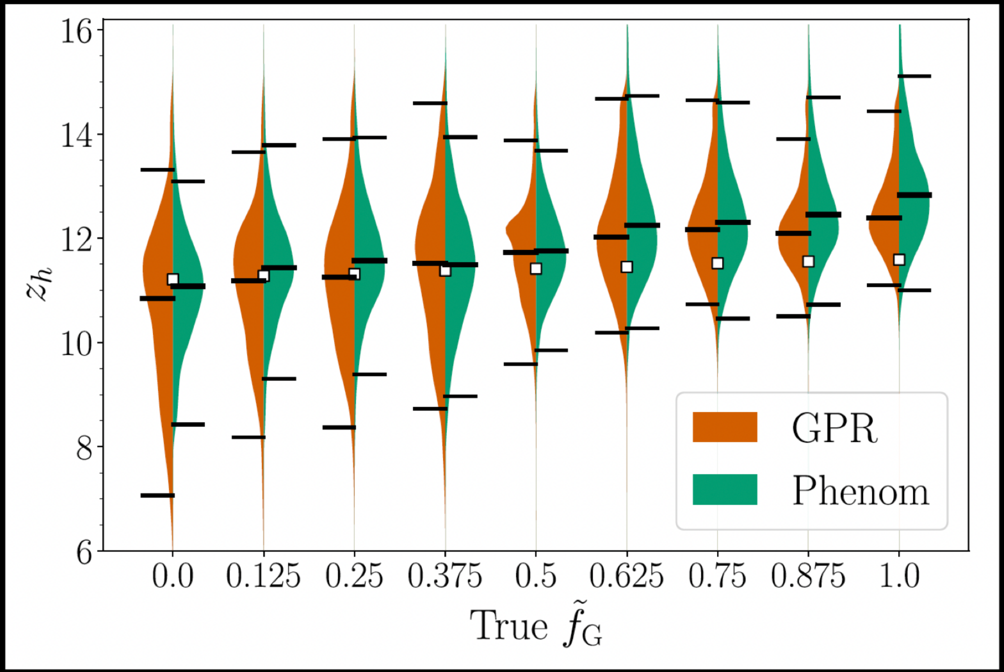
- Can we find out that there is an high-redshift peak?
- Yes!



O Brother, Where Art Thou?

- Can also measure the redshift of the nearby and far away redshift

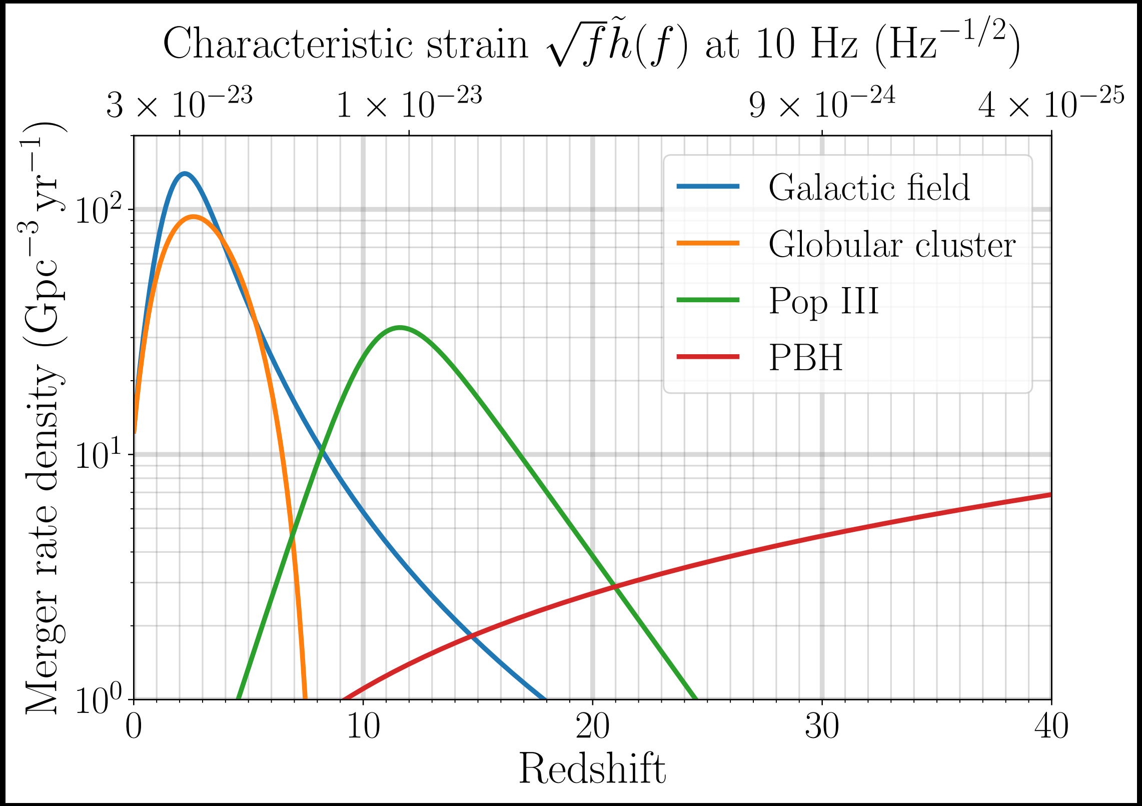




PRIMORDIAL BLACK HOLES

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 seems like the most uncontroversial tracer

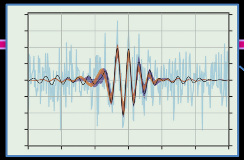


CEHS 2021

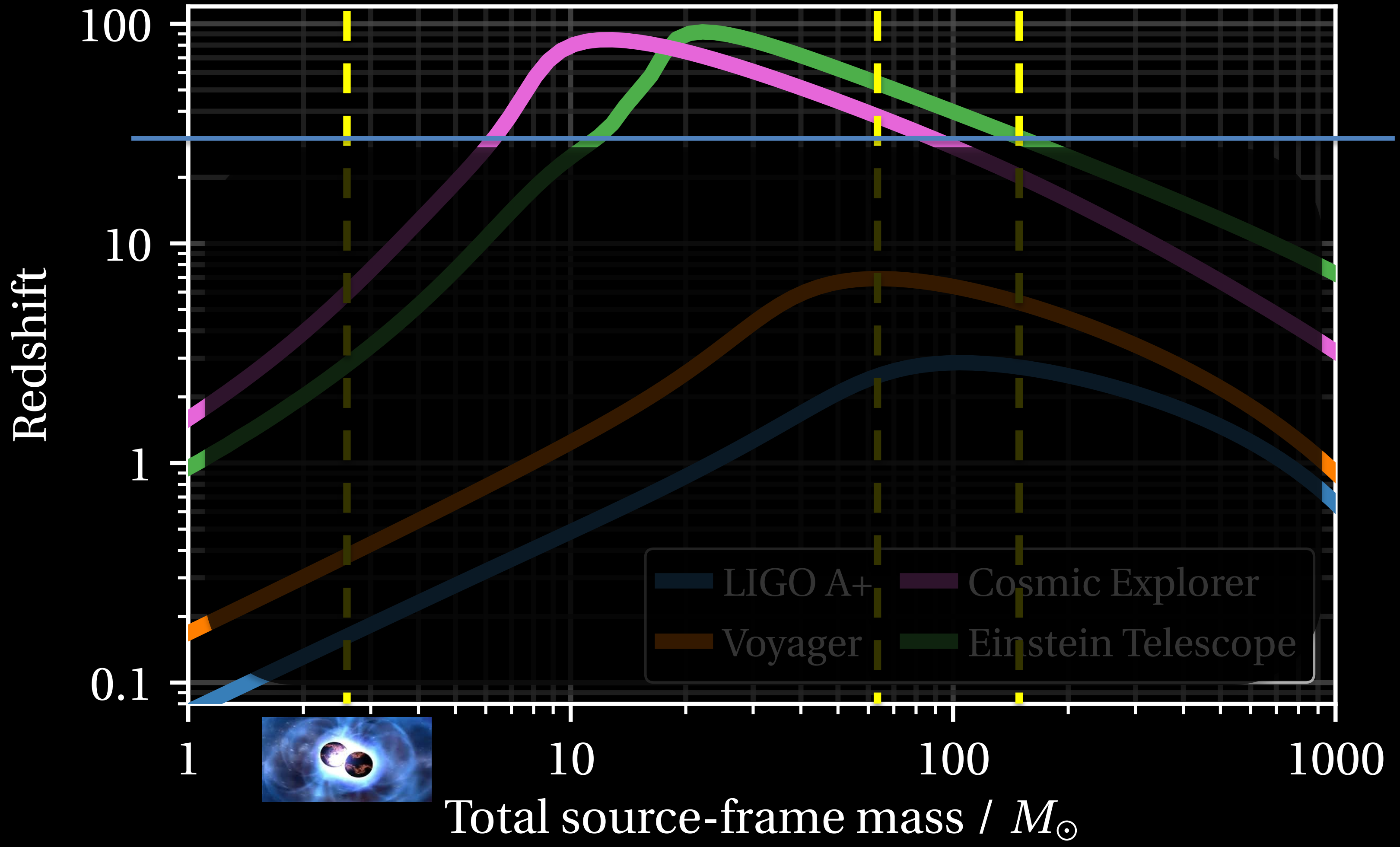
The smoking gun

- If NG detectors can observe a BBHs at redshift larger than say 30, the it’s going to be made of PBHs!

Listening to the Universe



CEHS 2021



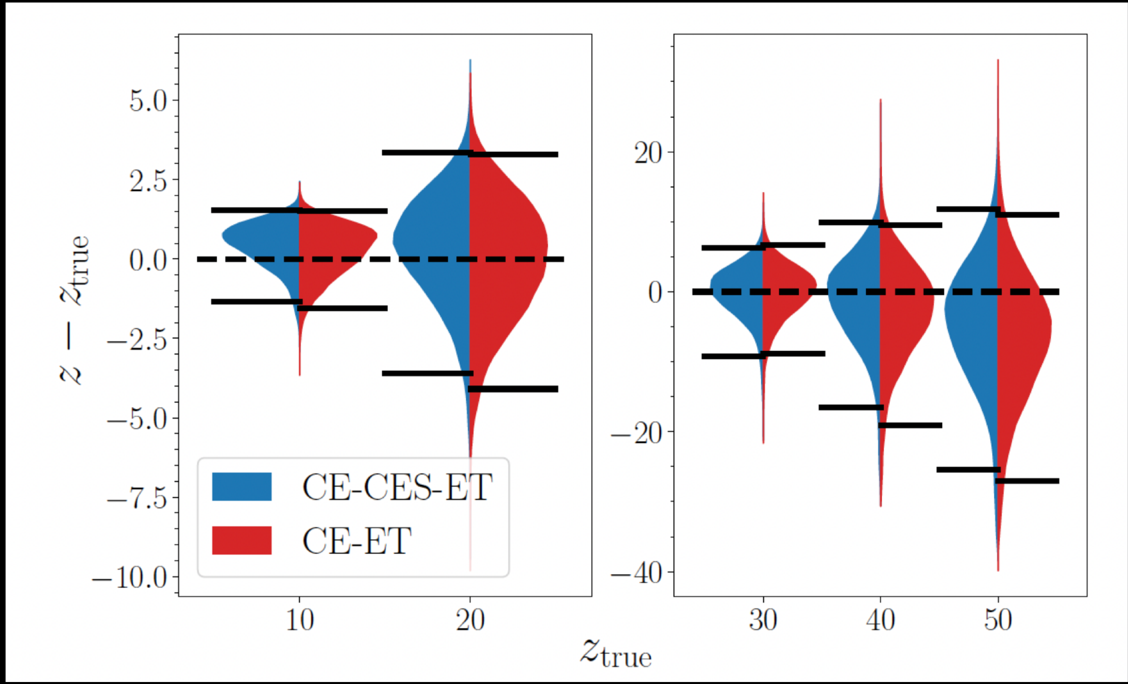
The smoking gun

- If NG detectors can observe a BBHs at redshift larger than say 30, the it's going to be made of PBHs!
- But being able to *detect* something at z >30 does not imply being able to *measure* its redshift to be that large
- We don't measure distance/redshift that well!

Pinning down a single PBBH

- Can NG networks prove with certainty that a merger happened above some z_critical?
- Not really. The best system we found for z_crit=30 has M_tot=40Msun, q=1, iota=pi/3 and ``only" 97% of the posterior lies at z>30

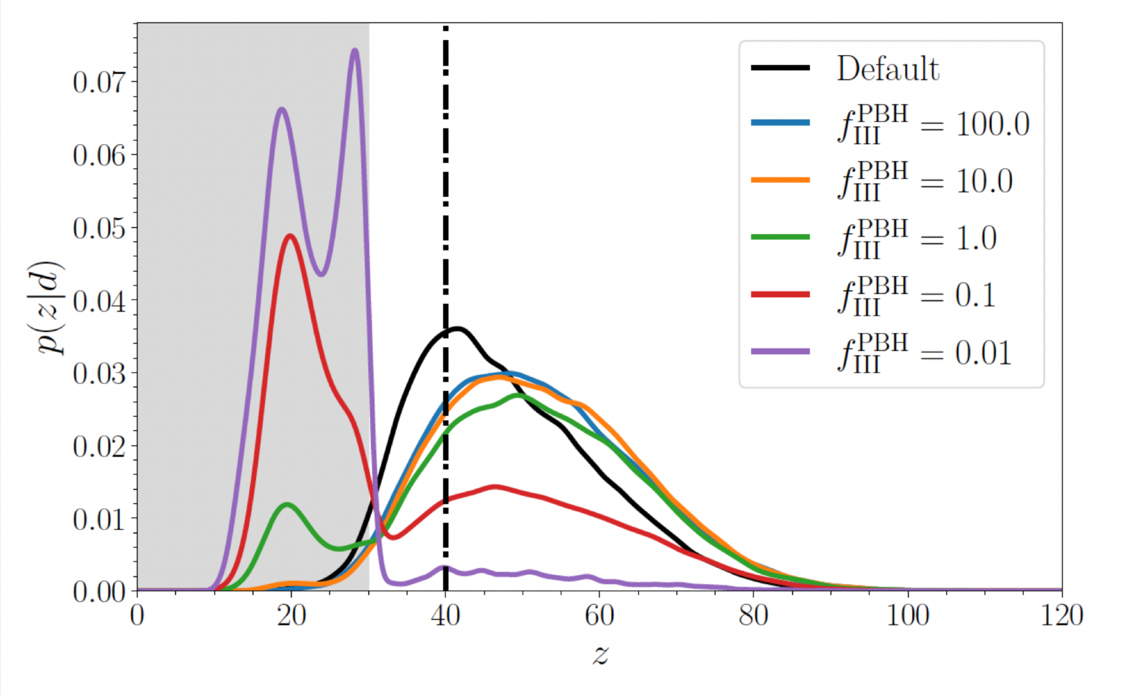
Ng+, 2108.07276



But which prior?

- We also found that priors play a decisive role
- The result in the previous slide used a uniform in comoving volume/time prior
- But one should also use prior information about the relative aboundance of Pop III and PBH mergers
- How much you believe *this* BBH is primordial strongly depends on how many BBHs you believe are primordial

Ng+, 2108.07276



What about the other parameters?

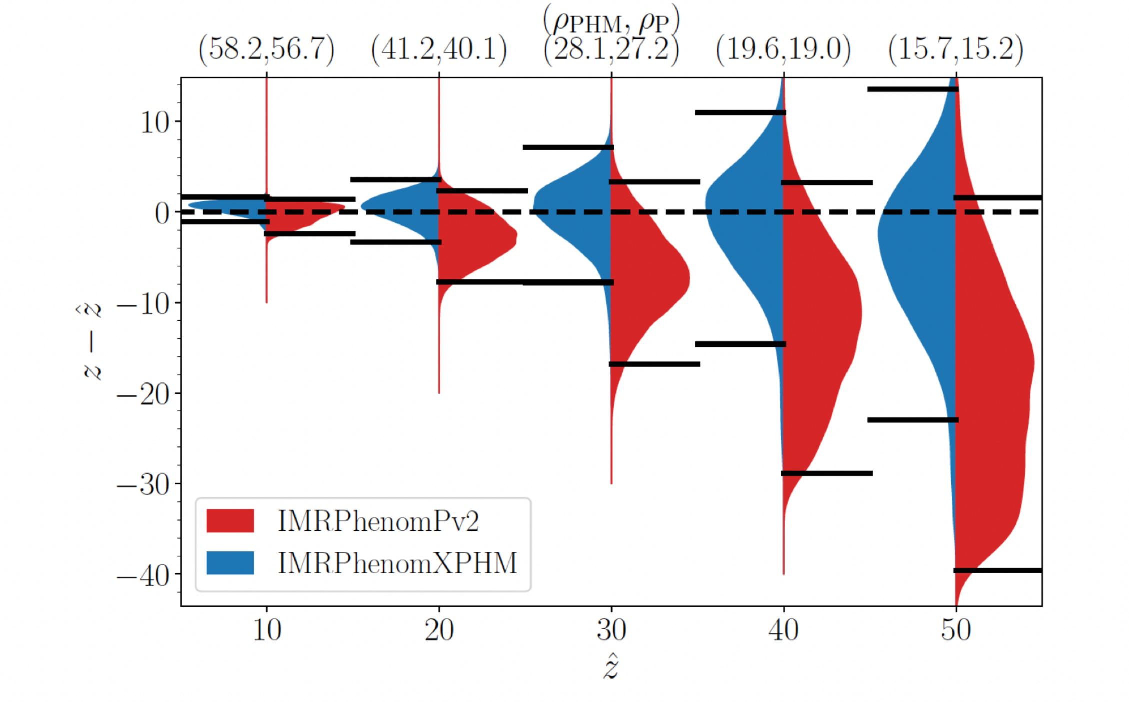


FIG. 4. Redshift measurements for sources with $(\hat{M}_{\mathrm{tot}}, \hat{q}, \hat{\iota}) = (40 M_{\odot}, 1, 30^{\circ})$ at $\hat{z} = 10, 20, 30, 40$ and 50. We offset the

- Currently wrapping up extensive parameter estimation study for BBHs at large redshift
- Focus on impact of higher order modes and their relation with other parameters
- Offsets in figure *not* due to waveform systematics
- HOMs buy up to a factor of ~2 in redshift estimation

Ng+, imminent

What about the other parameters?

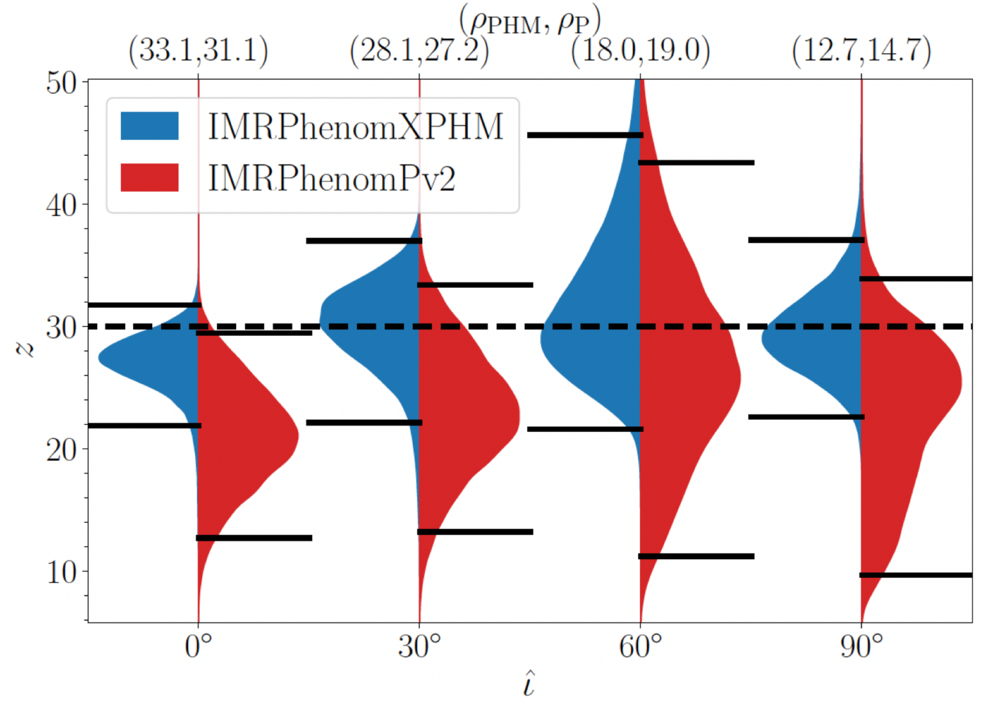


FIG. 1. Posteriors of redshift for sources with $(\hat{M}_{\rm tot}, \hat{z}, \hat{q}) = (40M_\odot, 30, 1)$ at $\hat{\iota} = 0°, 30°, 60°$ and $90°$, obtained with HoM (blue, IMRPhenomXPHM) and without HoM (red, IMRPhenomPv2).

- Inclination significanty impacts amout of HOMs
- Non linear trend
  - First one wins because more HOMs break redshift/inclination degeneracy
  - Then one loses because SNR is decreasing

What about the other parameters?

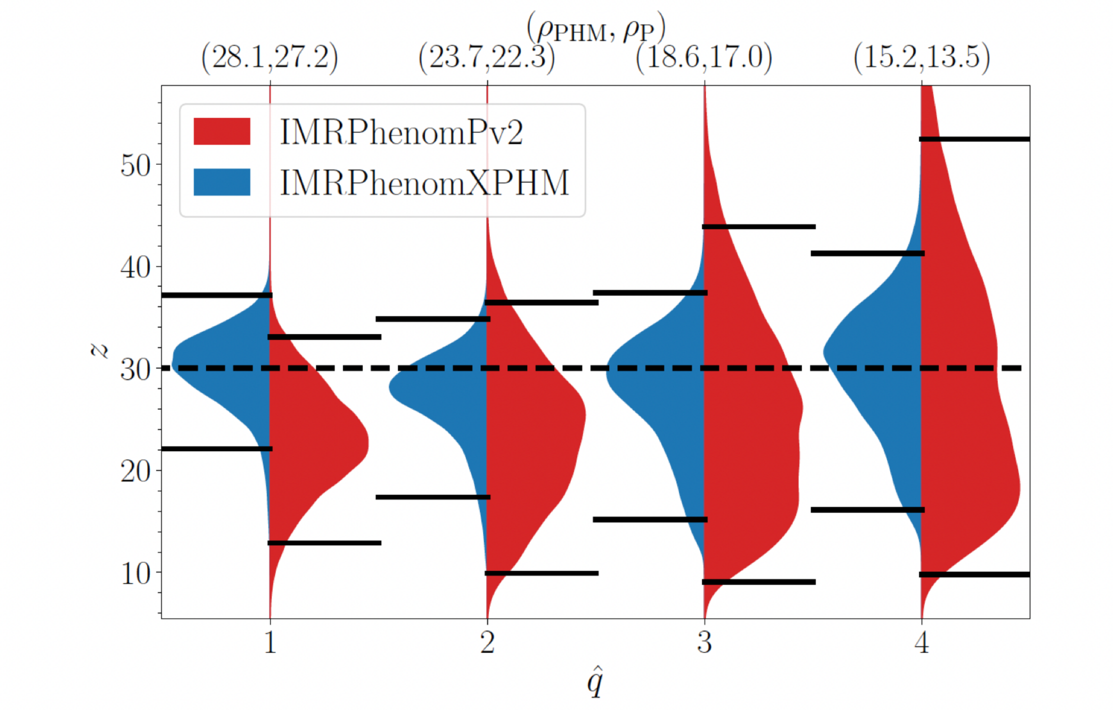
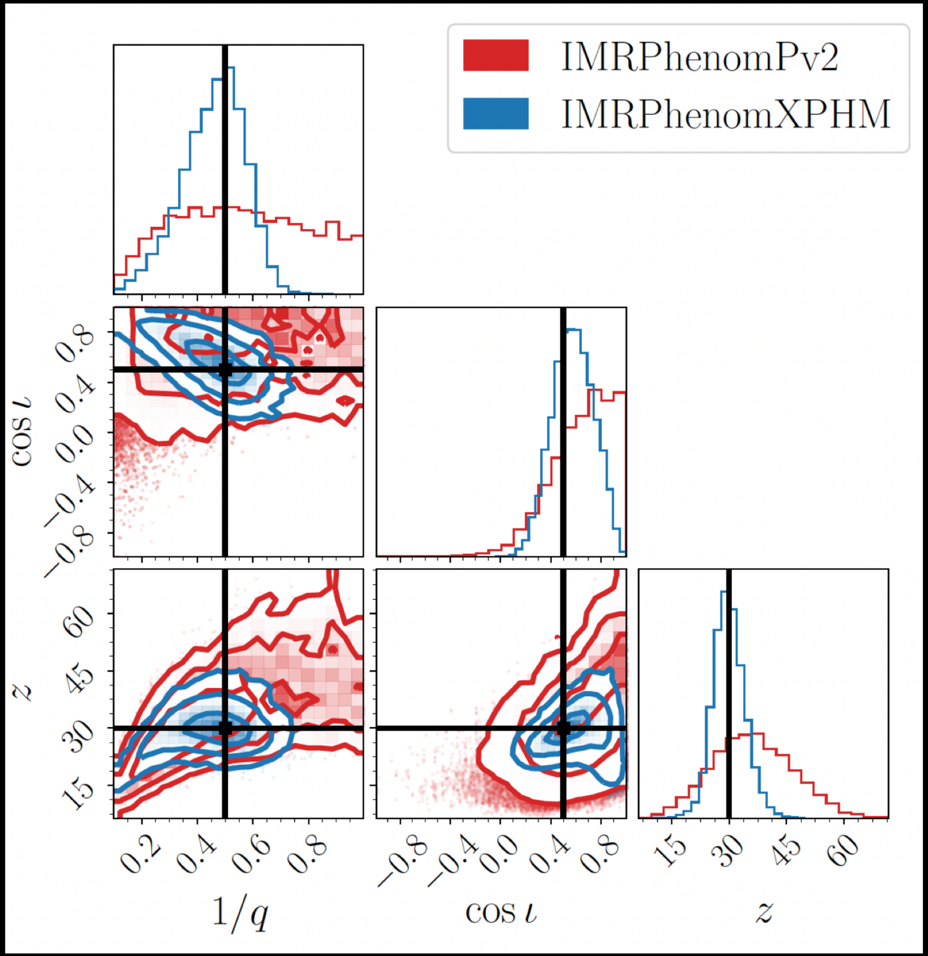


FIG. 2. Redshift measurements for sources with $(\hat{M}_{\rm tot}, \hat{z}, \hat{\iota}) = (40M_\odot, 30, 30^\circ)$ at $\hat{q} = 1, 2, 3$ and 4. The format is the same

- Mass ratio also impact the amount of HOMs
- Non linear trend
  - First one wins because more HOMs break redshift/inclination degeneracy
  - Then one loses because SNR is decreasing

New correlations



- The fact that the mass ratio enters in different ways in different harmonics creates an interesting q/iota correlation

M=40Msun

Can we show PBHs have zero spin?

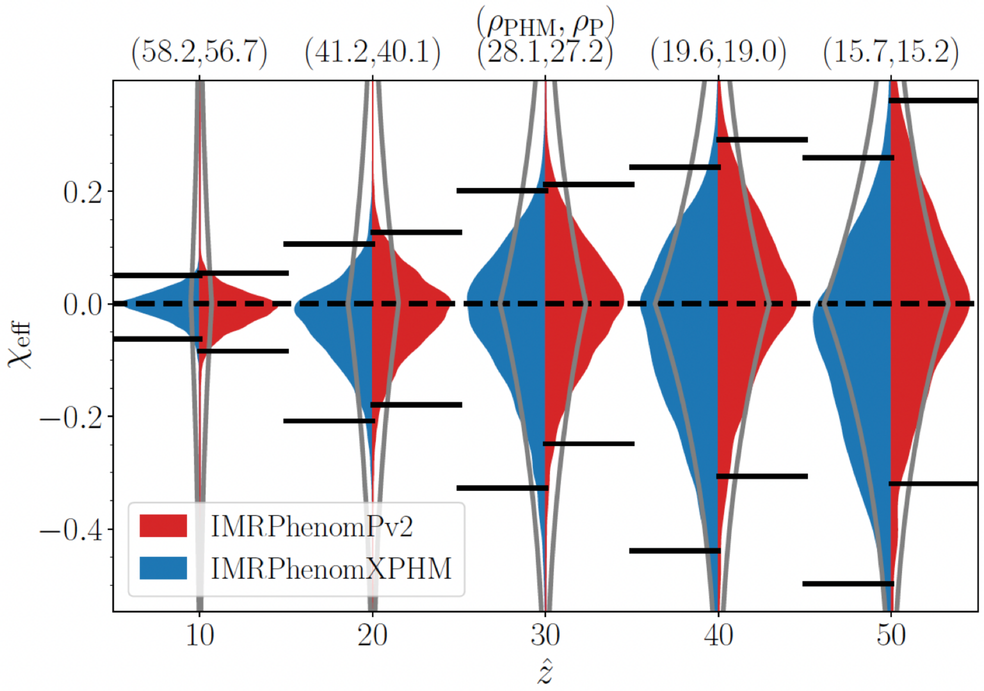


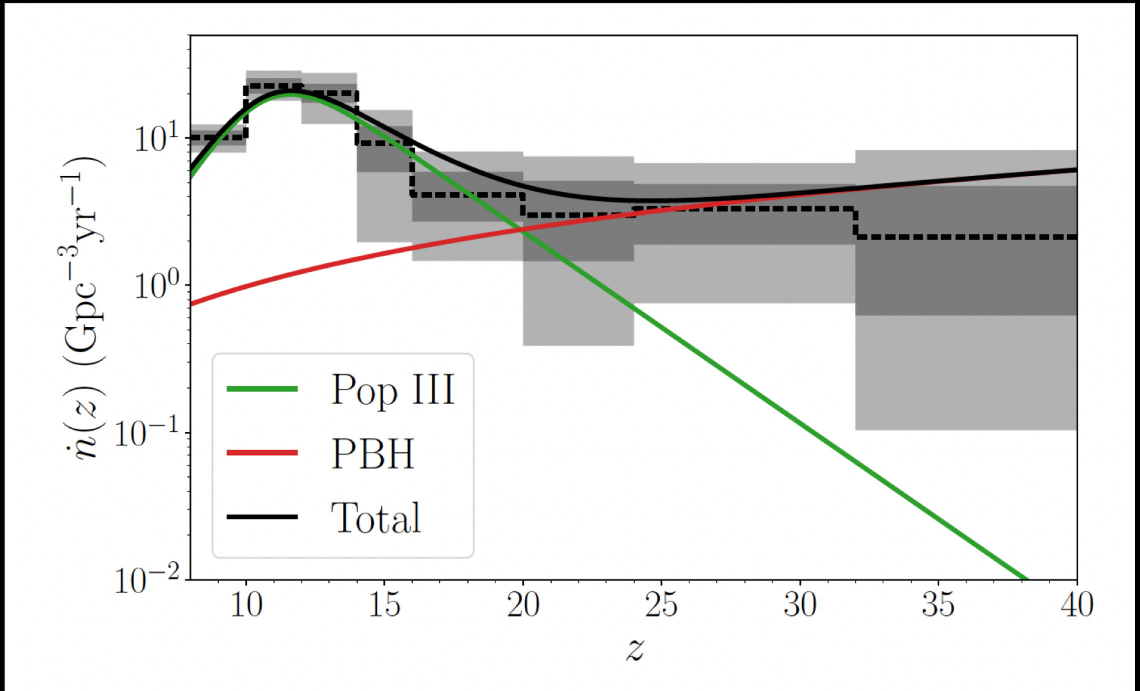
FIG. 8. Posteriors of effective spin for zero-spin sources with $(\hat{M}_{\rm tot}, \hat{q}, \hat{\iota}) = (40M_\odot, 1, 30^\circ)$ at $\hat{z} = 10, 20, 30, 40$ and 50,

- PBHs are expected to be created with zero spin
- Possibly acquire some spin by accretion as smaller redshifts
- For redshifts above 30, 90% credible intervals are broad

Gotta catch 'em all

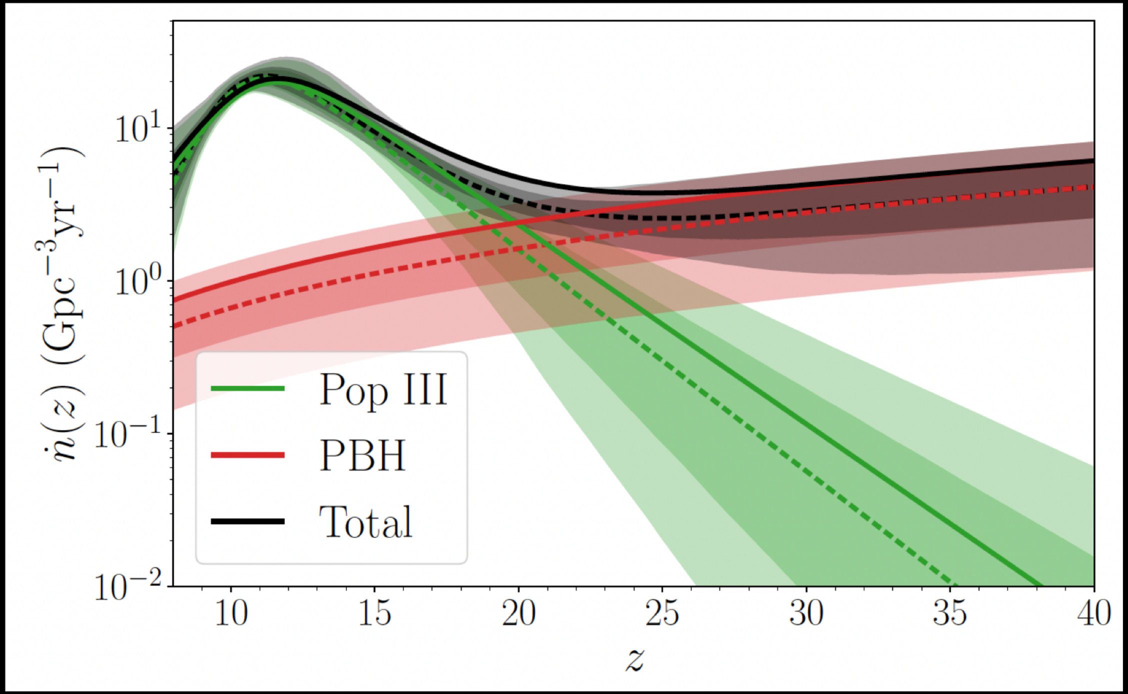
- Put away the “exceptional event paper” and go after the population
- Can we find evidence of something past the peak of mergers from Pop III?
- Looking into Ng+ in prep

Ng+, imminent



Gotta catch 'em all

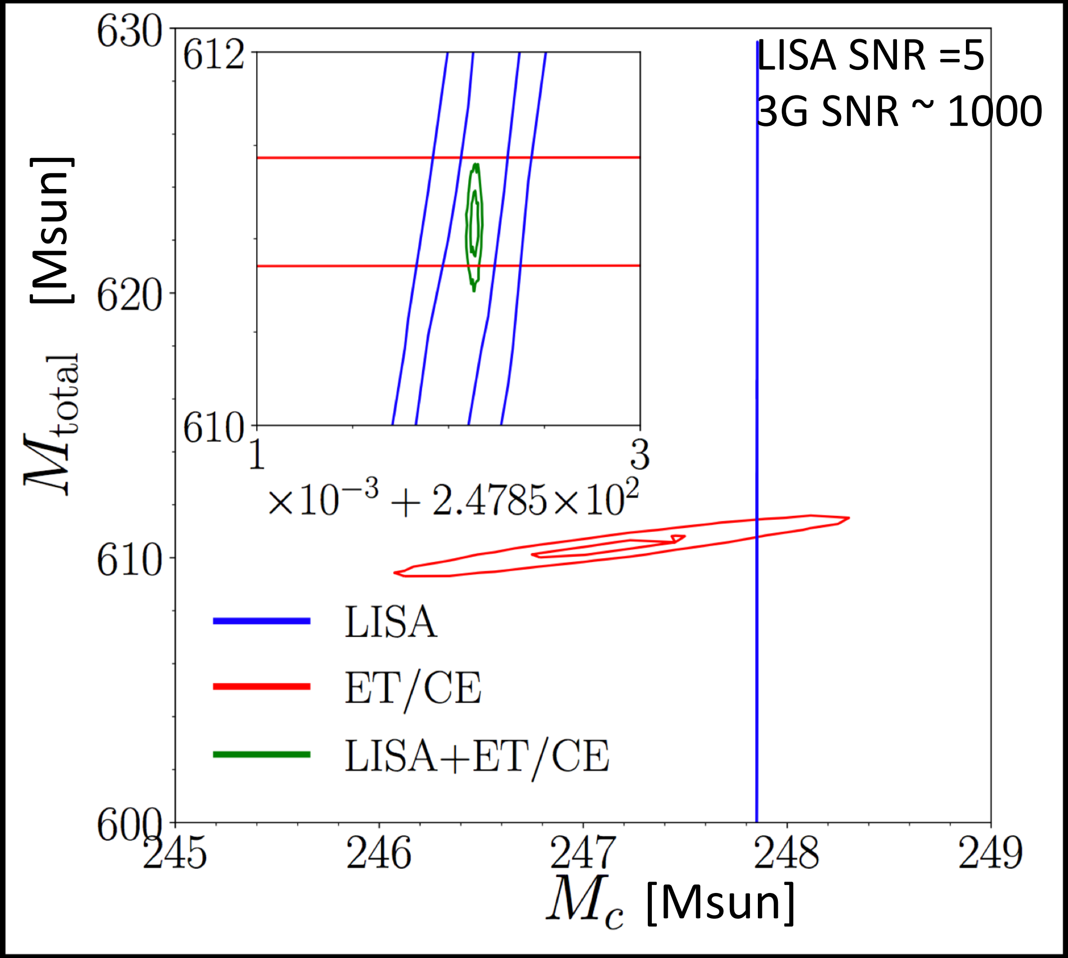
- Put away the "exceptional event paper" and go after the population
- Can we find evidence of something past the peak of mergers from Pop III?
- Looking into Ng+ in prep



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

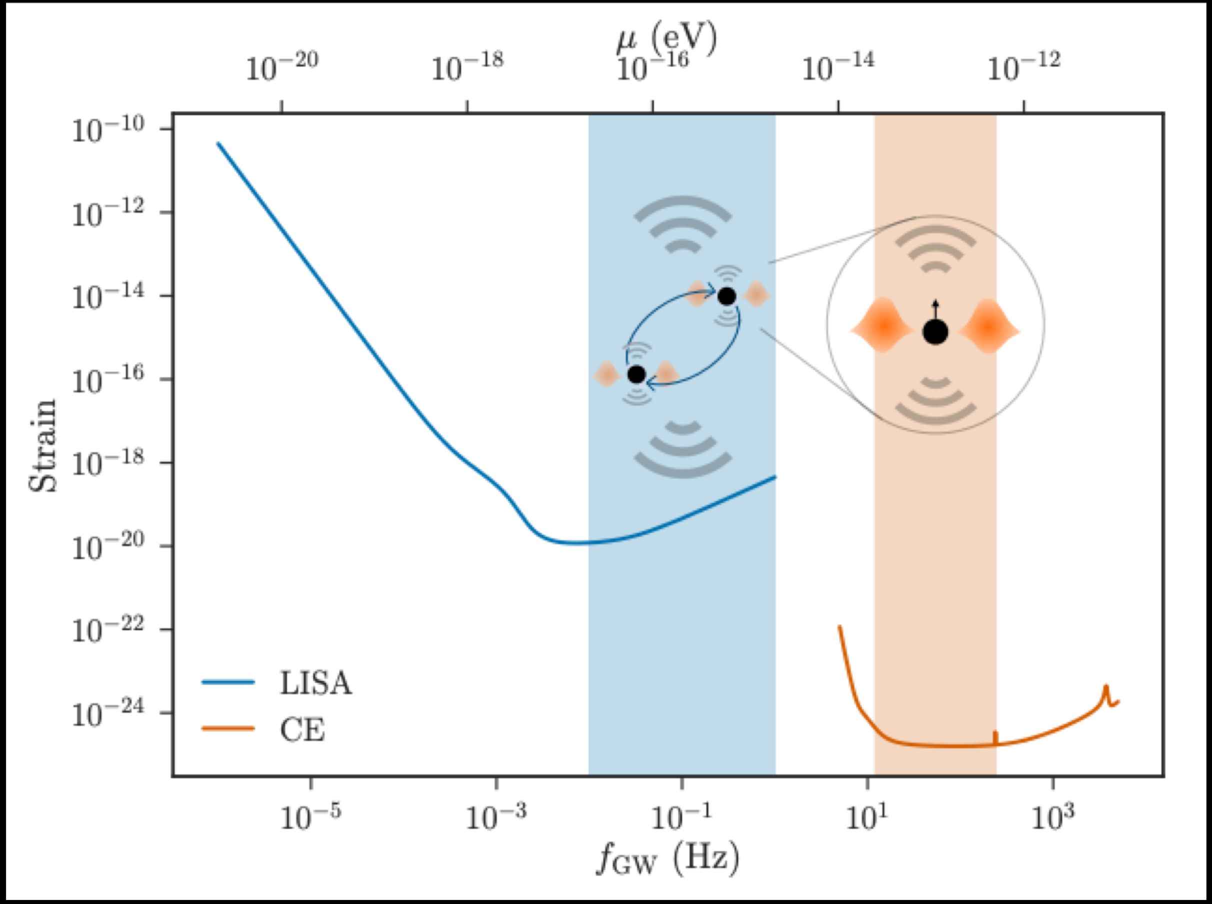
Cutler+, 1903.04069



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



Conclusions

- Advanced detectors will explore the local universe ($z \sim 1$)
- A new generation is required to detect sources everywhere in the universe
  - Characterization of BH masses and spins, formation channels, evolution,…
  - Thousands of neutron stars, EOS, cosmology,...
  - Precise tests of general relativity
  - Access to sources throughout cosmic history
- Get involved! Numerous opportunities to play role in CE and ET