Northwestern
CIERA
CENTER FOR INTERDISCIPLINARY EXPLORATION AND RESEARCH IN ASTROPHYSICS

The Gravitational-Wave Messenger

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APS April 2024

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NHFP
NASA Hubble Fellowship Program

Image: Ed Seidel (AEI) and Werner Benger (ZIB, AEI)

Outline

- Current detectors
  - What we’ve learned
  - What we cannot learn
- Cosmic Explorer
  - Design concept
  - Science case
  - Timeline
- Multimessenger synergies

CE Horizon Study
Evans + (inc SB) 2109.09882

CE MPSAC ngGW White Paper
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CE Trade Study
Gupta+ (inc SB) 2307.10421

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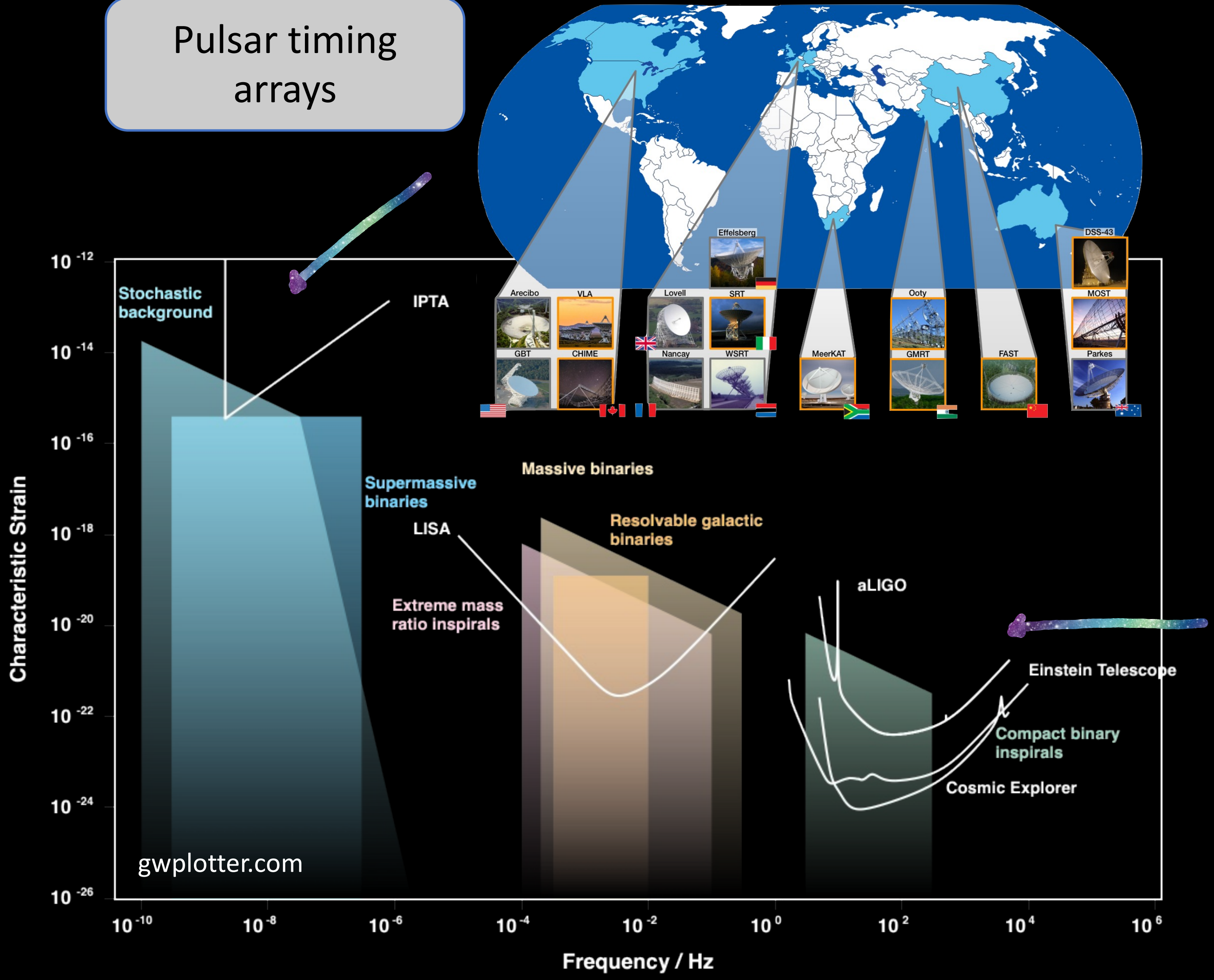
More Cosmic Explorer at April APS

This afternoon in D10.00002 - *Beyond O4: What lies ahead for Terrestrial Gravitational-Wave Detectors*, Stefan Ballmer

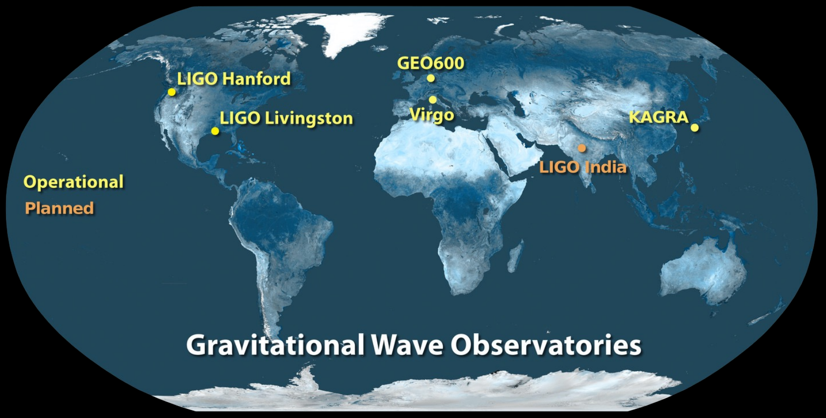
Saturday afternoon in S10.00002 - *Cosmic Explorer: Pushing the gravitational-wave frontier across astronomy, physics, and cosmology*, Alessandra Corsi

Our observational landscape

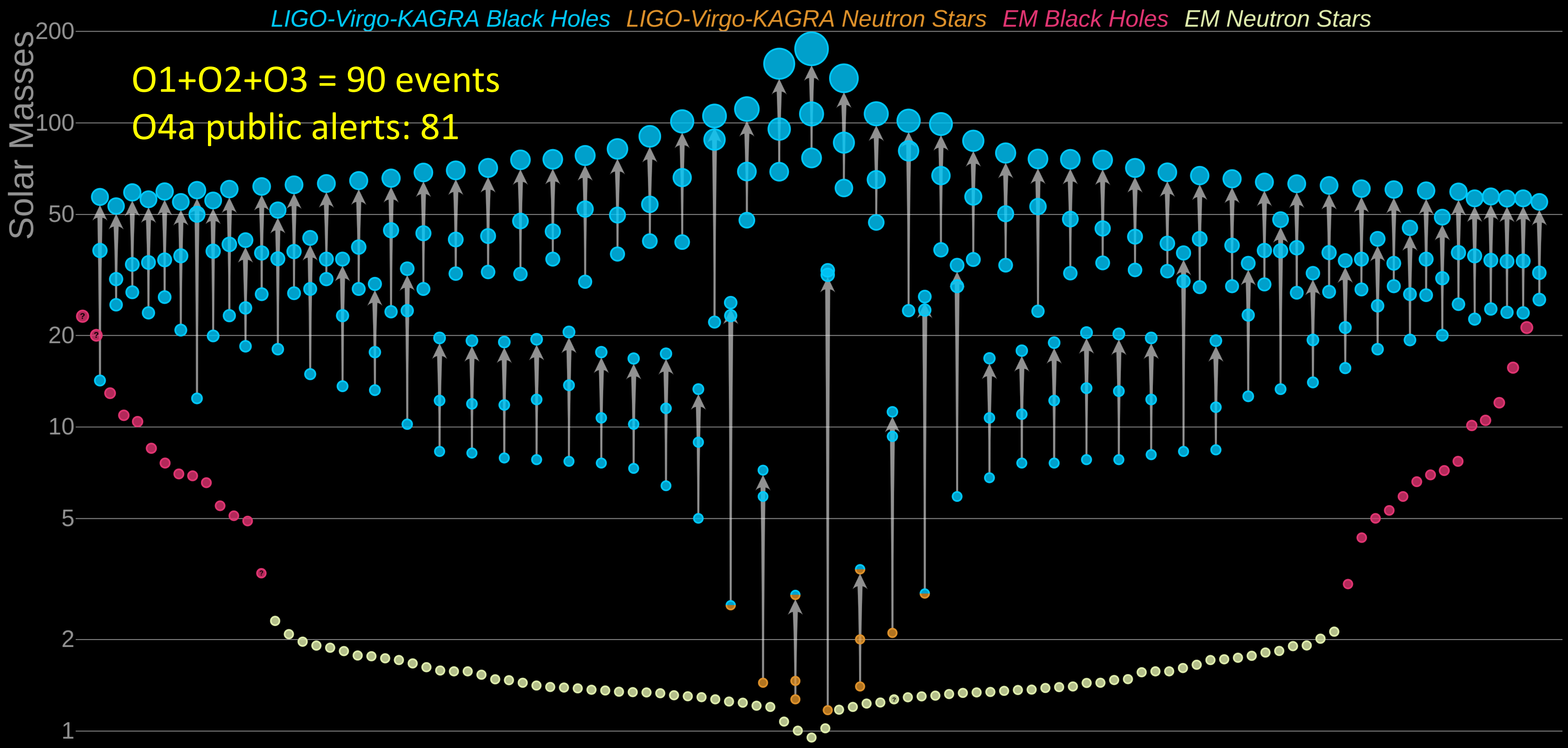
Pulsar timing arrays



Ground-based interferometers



Masses in the Stellar Graveyard

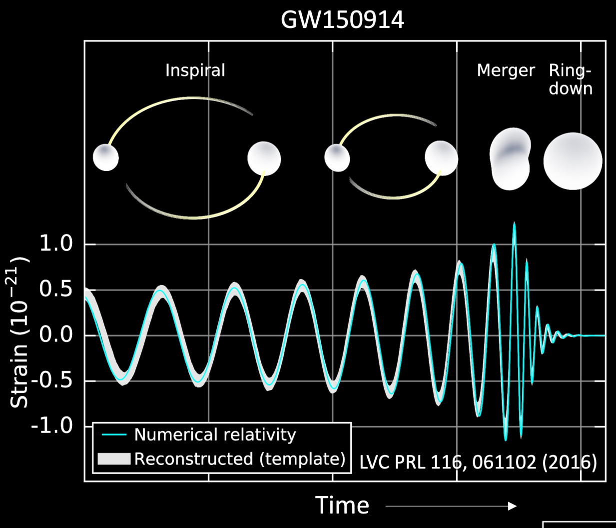


LIGO-Virgo-KAGRA | Aaron Geller | Northwestern

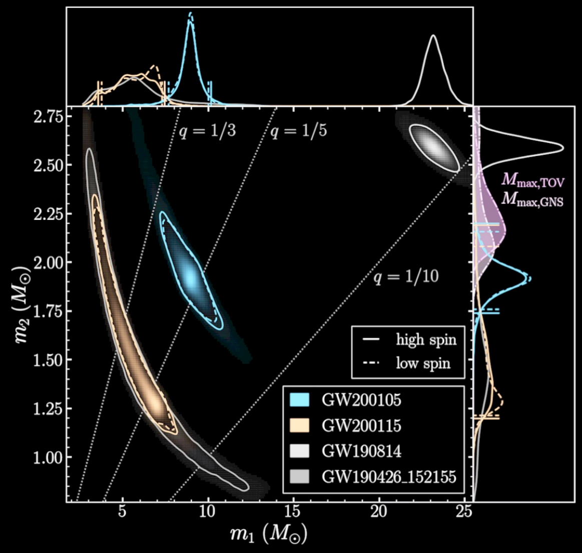
What we've learned

The gravitational-wave data obtained by the LIGO-Virgo-Kagra collaboration since 2015 has taught us that:

1. **Compact object binaries** that merge within a Hubble time exist in the Universe
2. Neutron stars and black holes in binaries have masses spanning the range $\sim 1 - 100\ M_\odot$
3. The spins (angular momenta) of the component compact objects in these binaries are small
4. Binary neutron star mergers are the progenitors of some short gamma-ray bursts and an astrophysical site of heavy-element nucleosynthesis
5. The fraction of the total energy density of the universe contributed by gravitational waves is $\Omega_{\mathrm{GW}} \leq 5.8\times10^{-9}$



LVK ApJL 915, L5 (2021)



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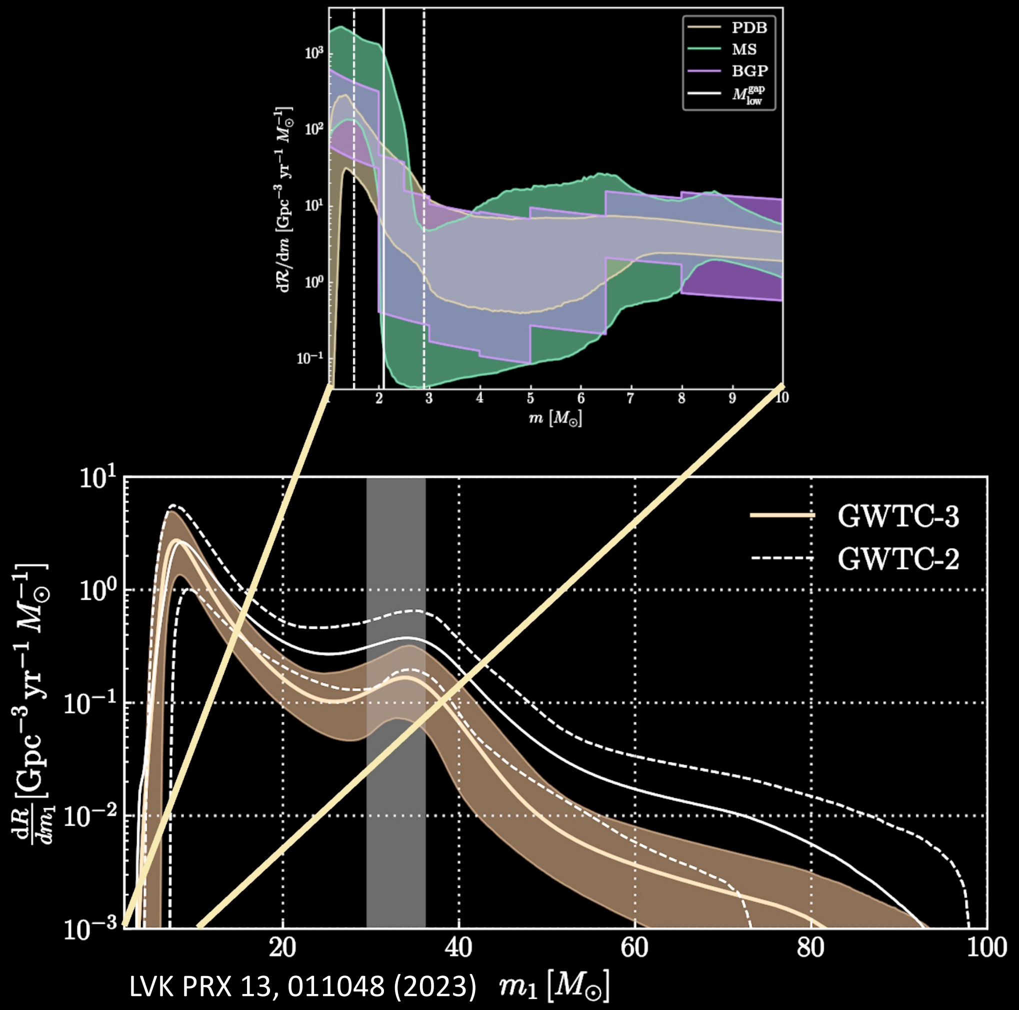

LVK PRX 13, 011048 (2023)

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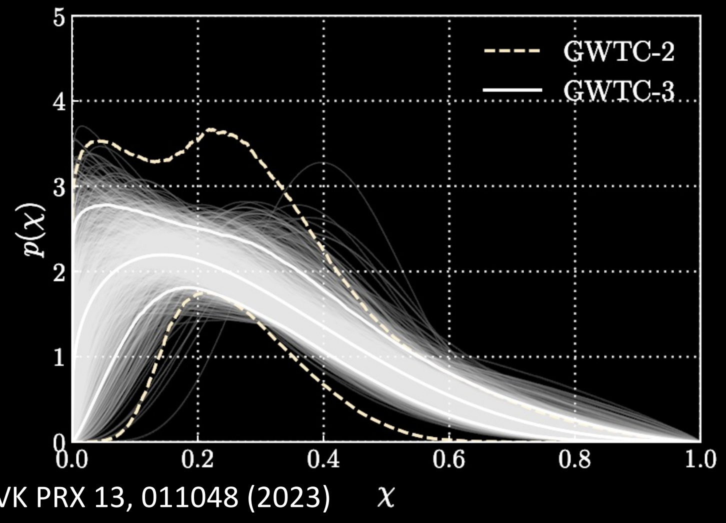
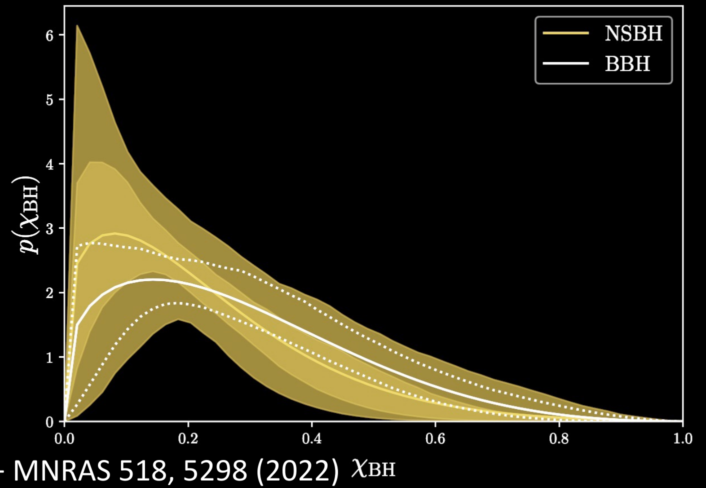
Binary black hole spin magnitude



LVK PRX 13, 011048 (2023)

Neutron star-black hole spin magnitude



SB+ MNRAS 518, 5298 (2022)

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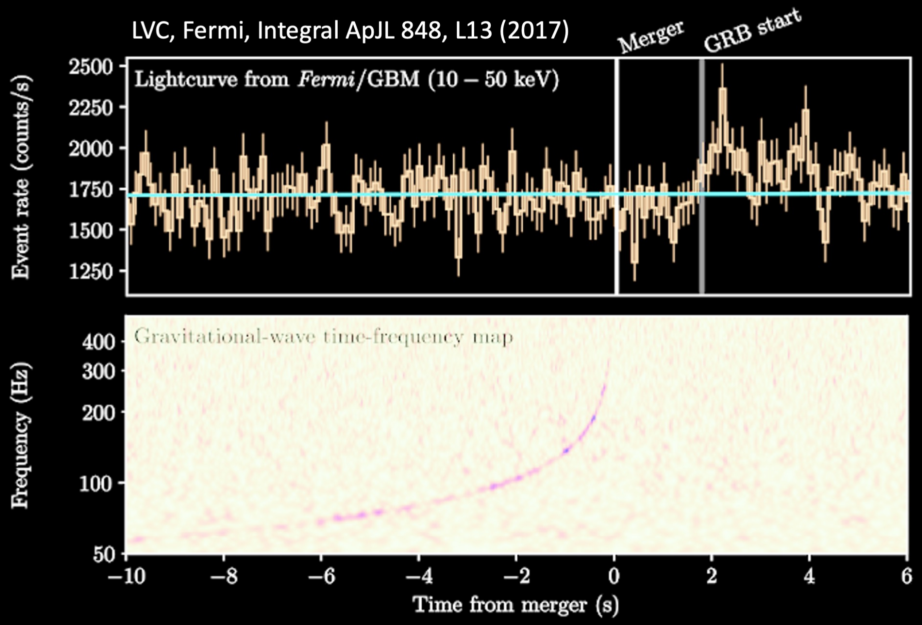
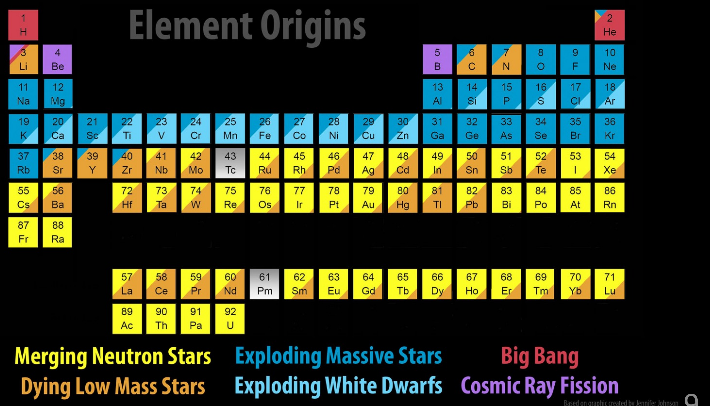
LVC, Fermi, Integral ApJL 848, L13 (2017)





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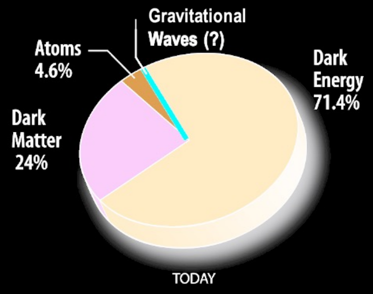
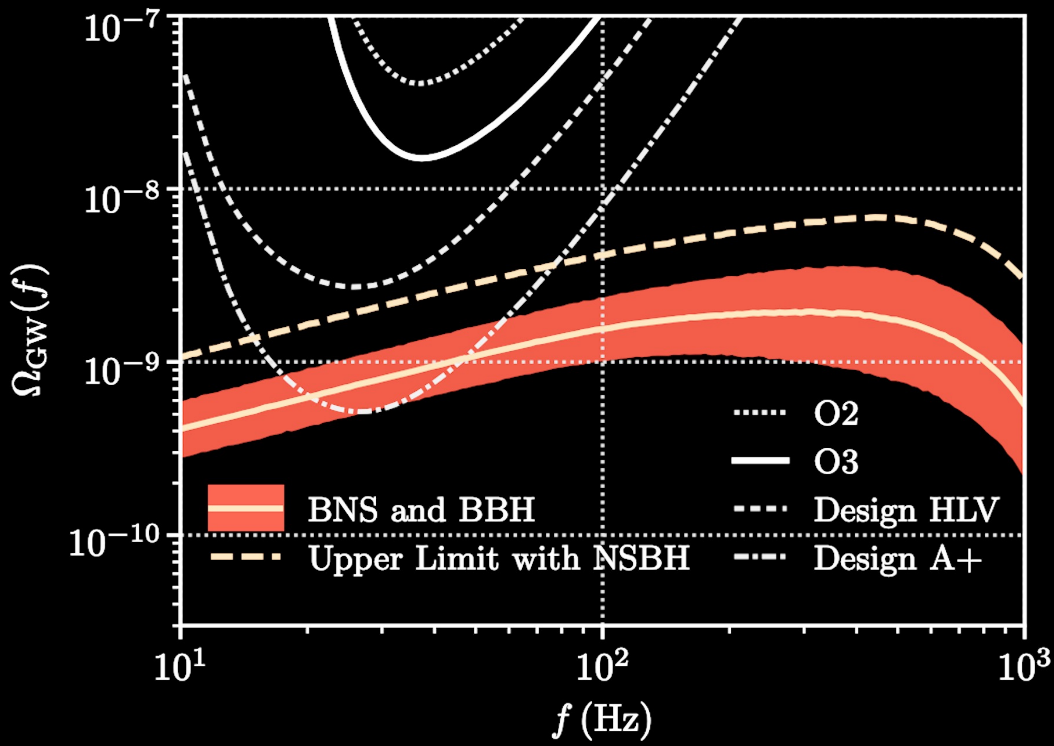
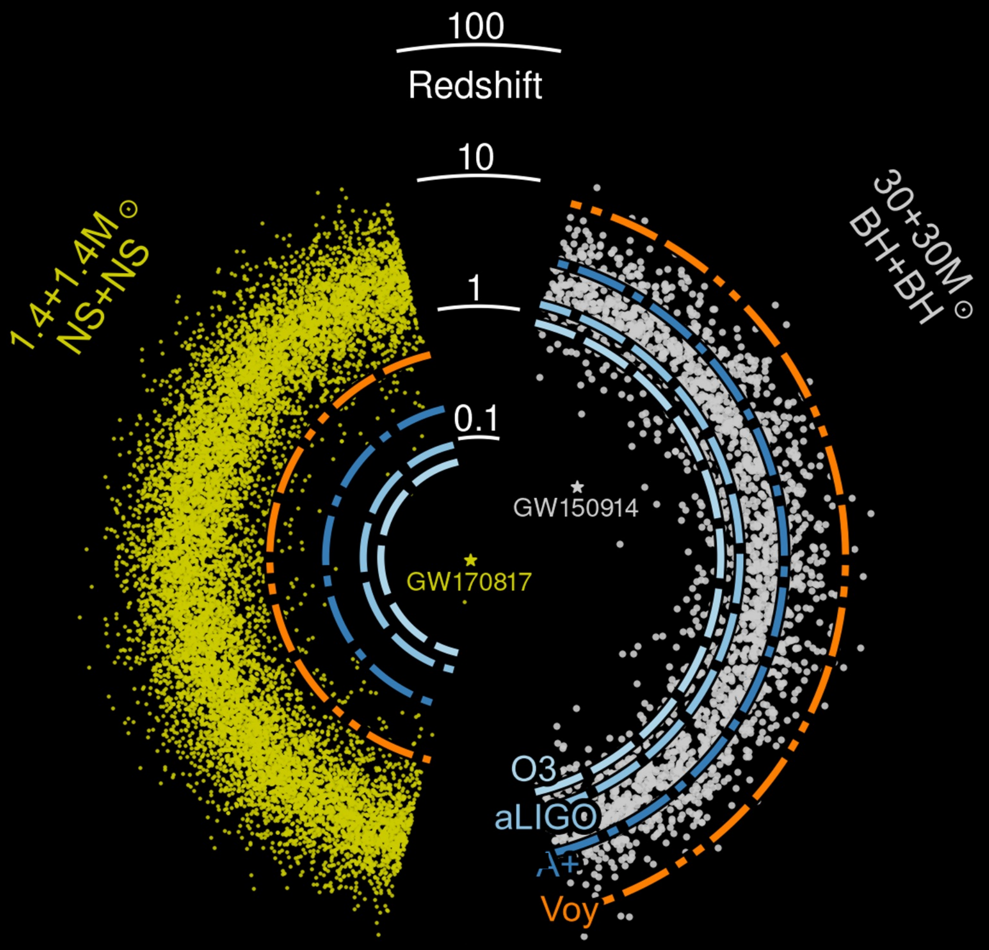


LVK PRD 104, 022004 (2021)



What we can’t learn… *yet*

- Binary neutron star mergers beyond cosmic noon
- Precision measurements of the neutron star equation of state
- Binary neutron star postmerger signal
- Binary mergers including Population III and primordial black holes
- Gravitational-wave memory effect
- Cosmological stochastic gravitational-wave backgrounds



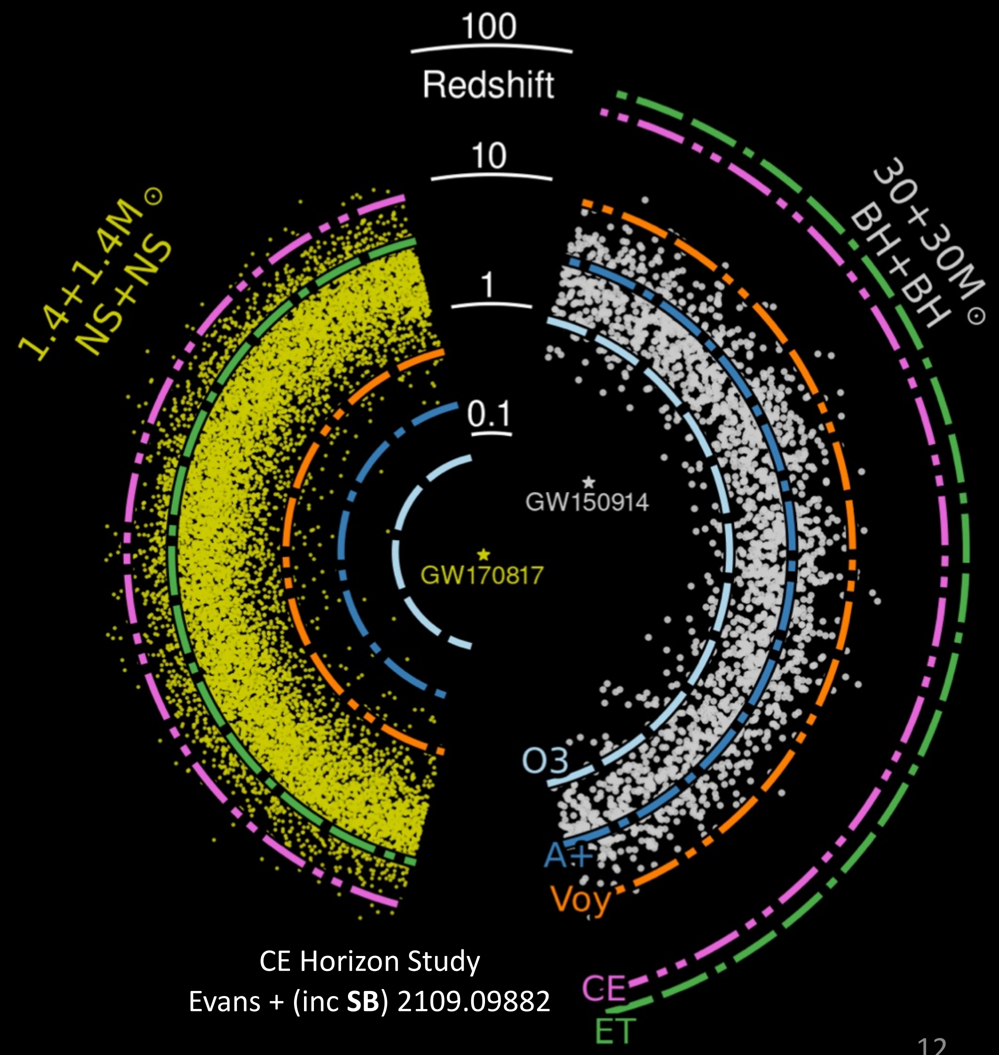
The next generation

COSMIC EXPLORER

US-based concept planned for the late 2030s

Einstein Telescope

European concept with triangular design



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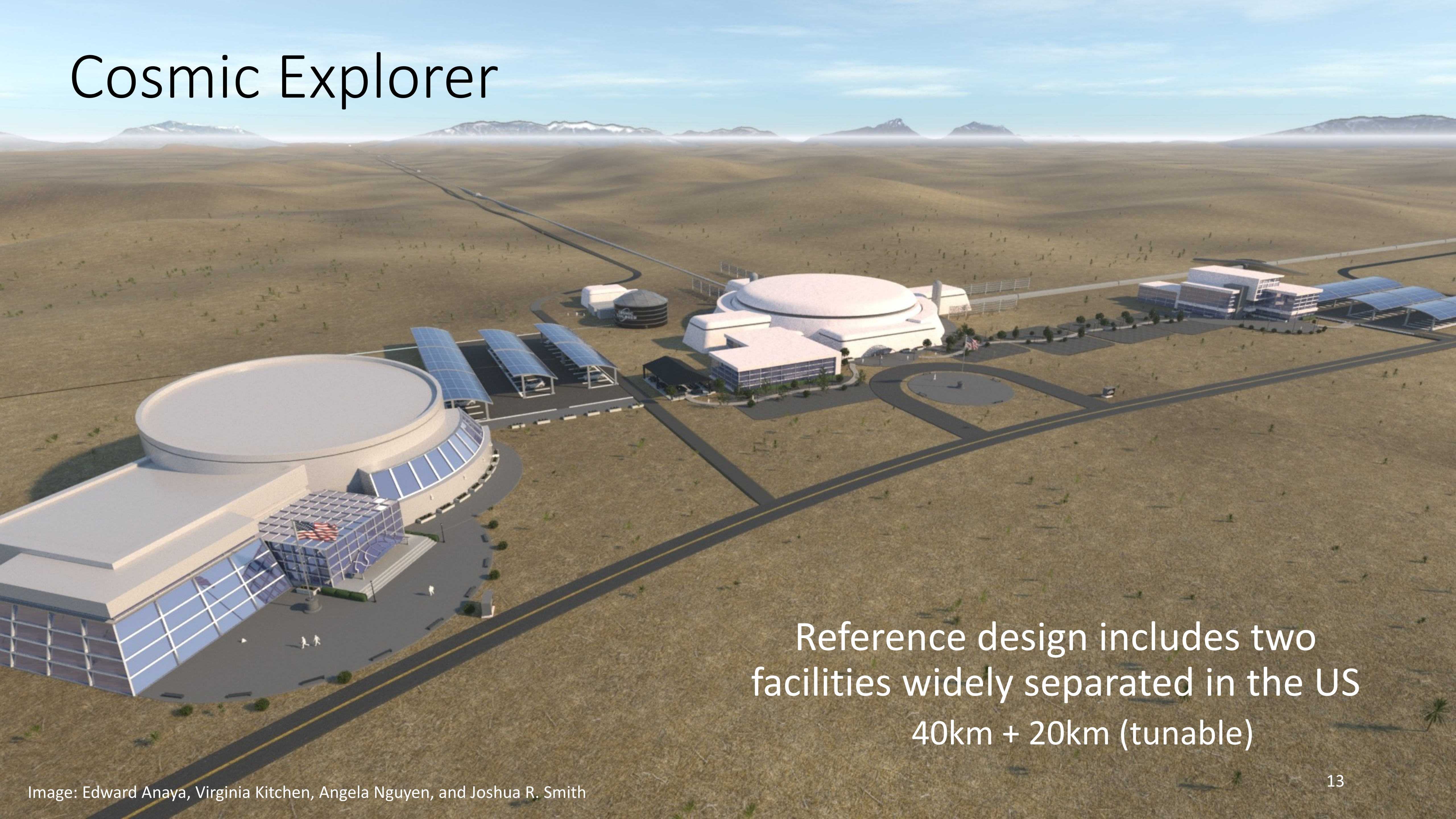
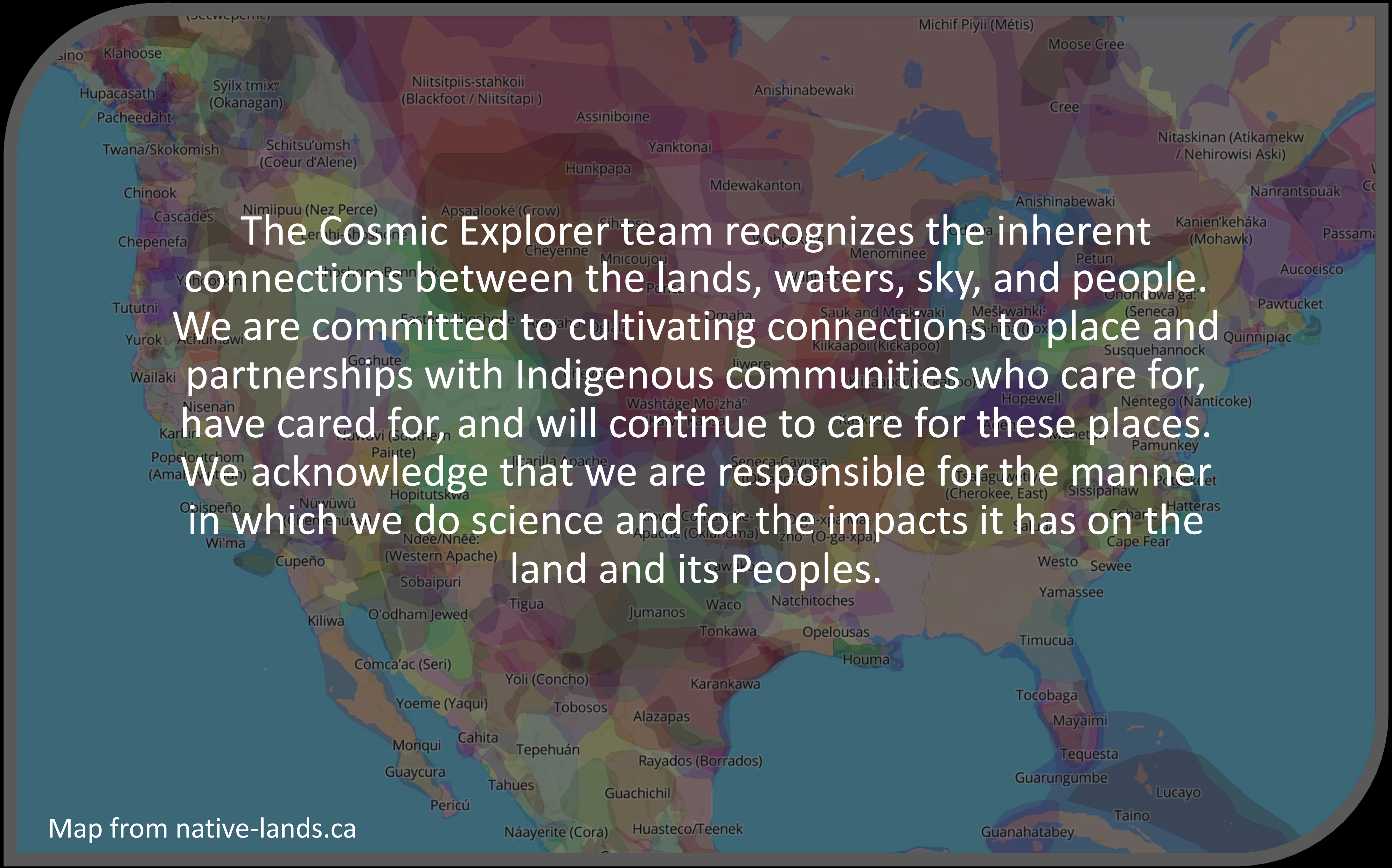
Cosmic Explorer



Reference design includes two facilities widely separated in the US

40km + 20km (tunable)

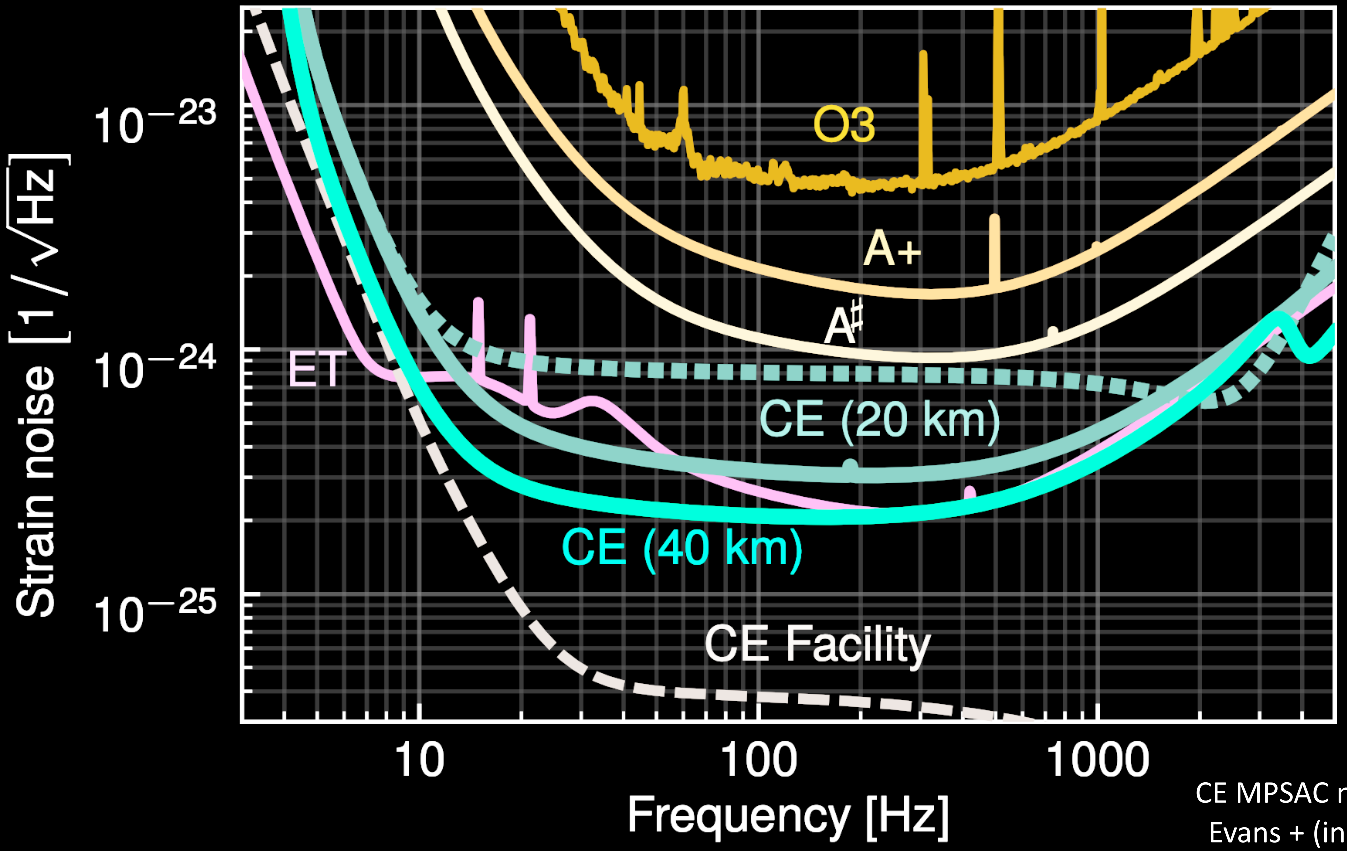
Image: Edward Anaya, Virginia Kitchen, Angela Nguyen, and Joshua R. Smith



The Cosmic Explorer team recognizes the inherent connections between the lands, waters, sky, and people. We are committed to cultivating connections to place and partnerships with Indigenous communities who care for, have cared for, and will continue to care for these places. We acknowledge that we are responsible for the manner in which we do science and for the impacts it has on the land and its Peoples.

Map from native-lands.ca

Order of magnitude improvement in strain sensitivity over current detectors



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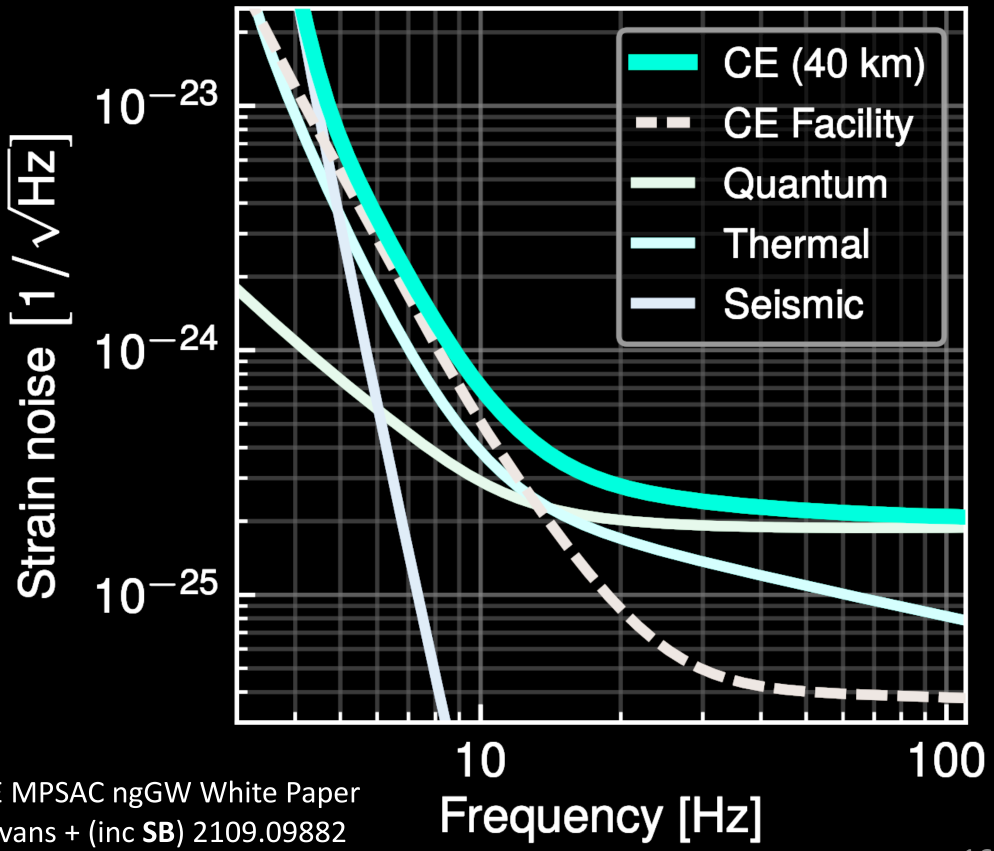
Equivalent to an order of magnitude increase in the diameter of a telescope

Design concept

- Dual-recycled Fabry-Perot Michelson Interferometer
- Order of magnitude longer arms
- Quantum sensing
- Improved low-frequency isolation

Design parameter	A+	A$^{\sharp}$	CE
Arm length	4 km	4 km	20 km, 40 km
Arm power	750 kW	1.5 MW	1.5 MW
Squeezing level	6 dB	10 dB	10 dB
Test mass mass	40 kg	100 kg	320 kg
Test mass coatings	A+	A+/2	A+
Suspension length	1.6 m	1.6 m	4 m
Newtonian mitigation	0 dB	6 dB	20 dB



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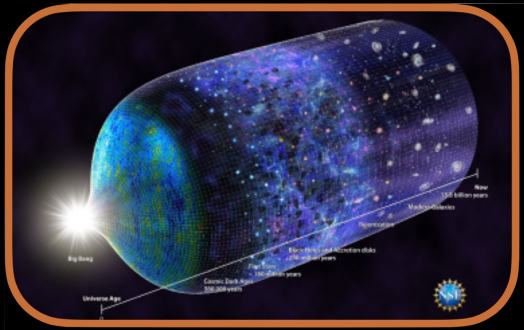
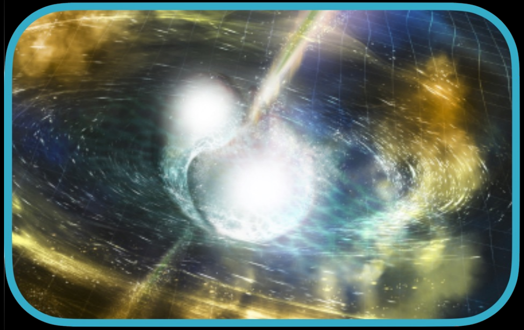
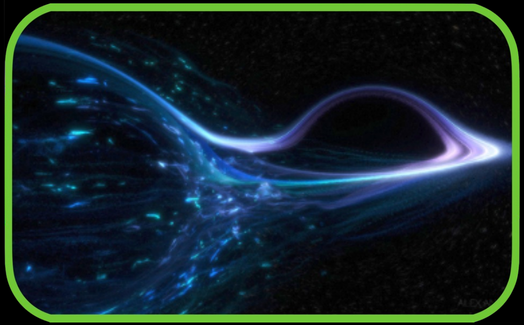
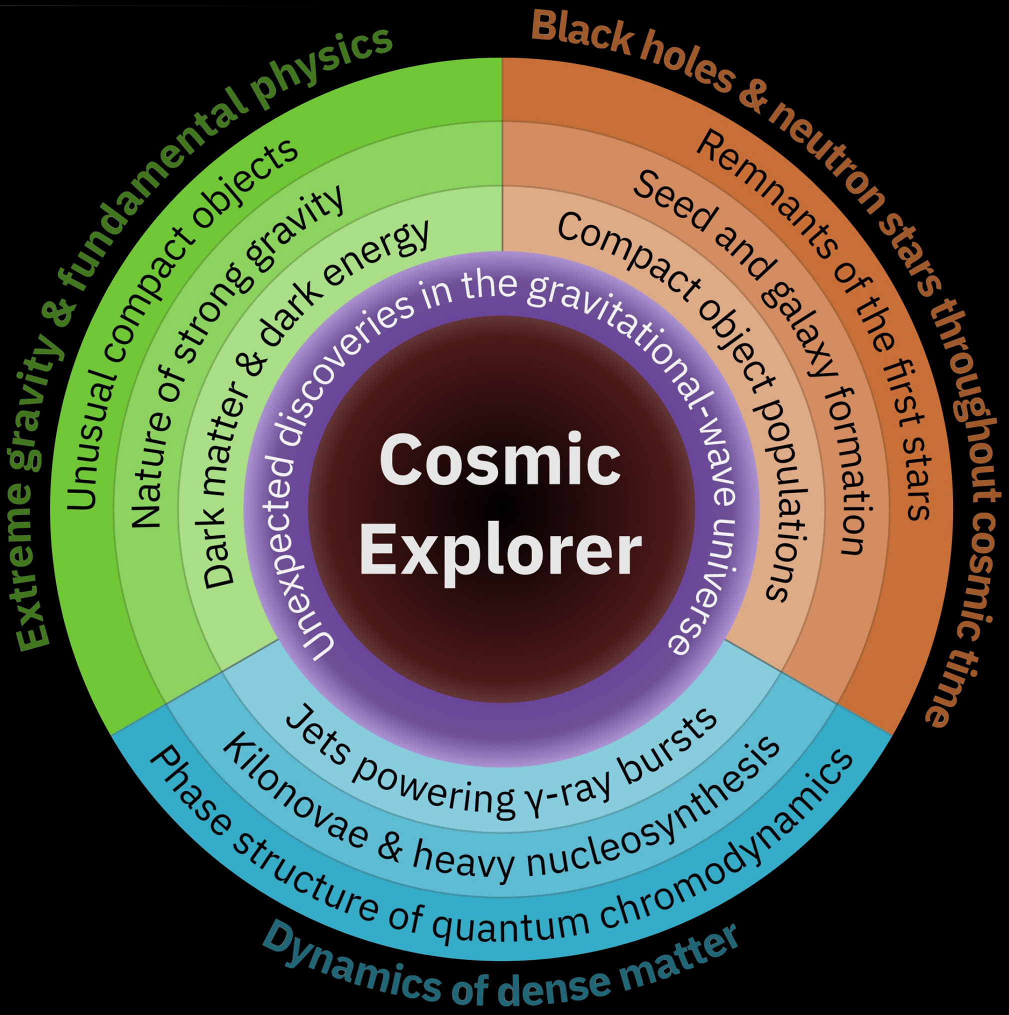
Key science objectives



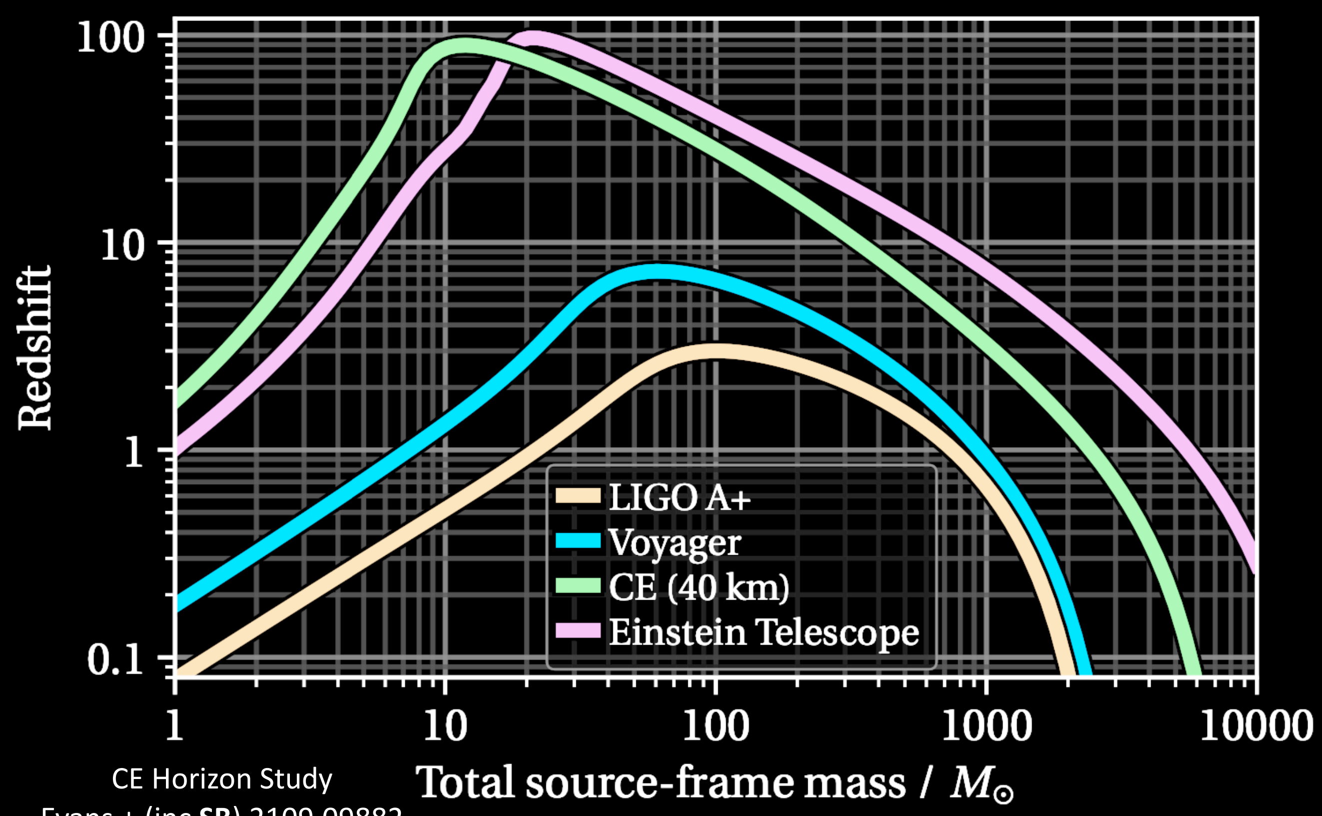






Black holes and neutron stars through cosmic time

- Evolution of the merger rate as a function of redshift
- Remnants of the first stars
- Seeds of supermassive black holes, hierarchical growth
- Smoking-gun distinction of primordial black holes



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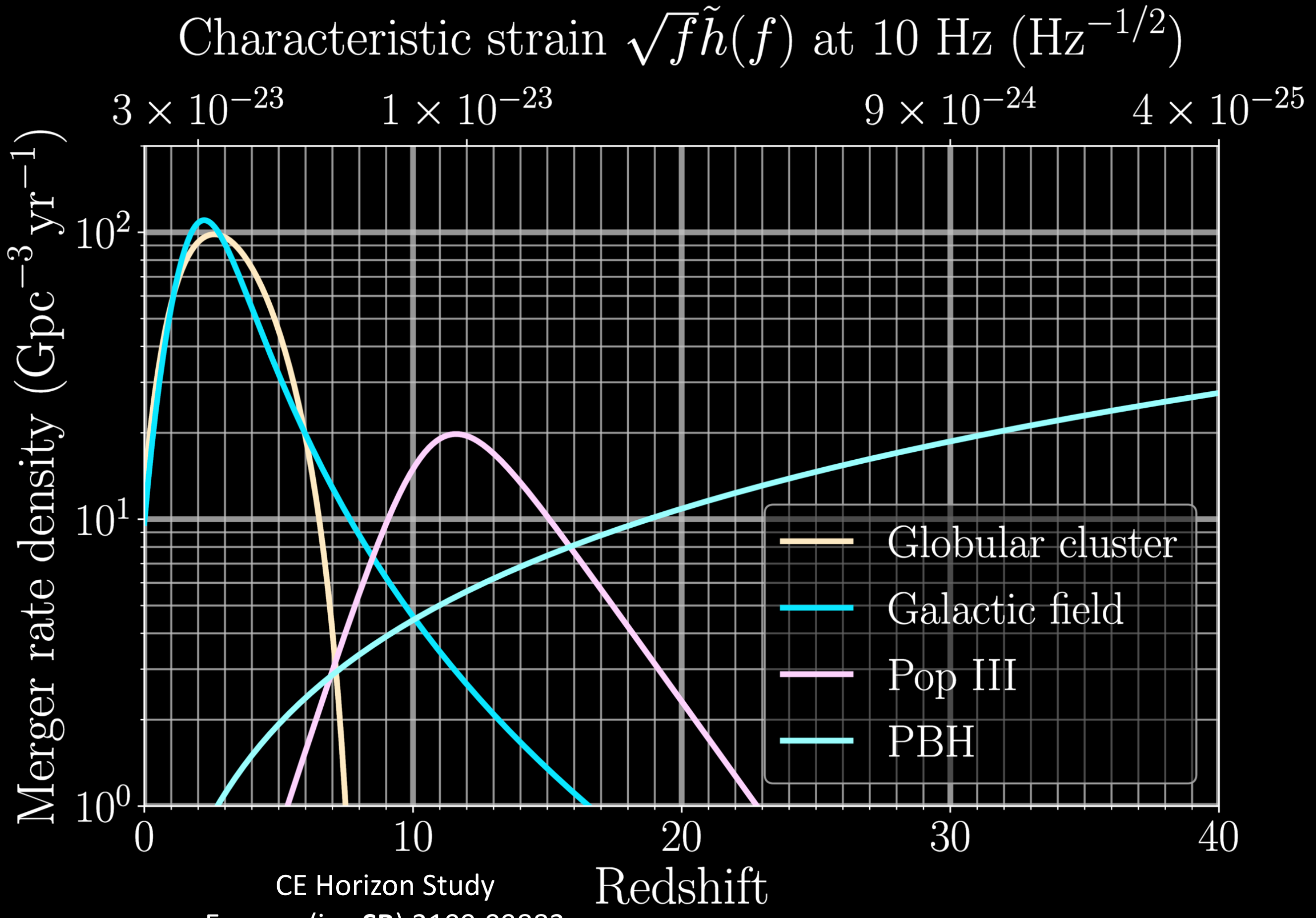

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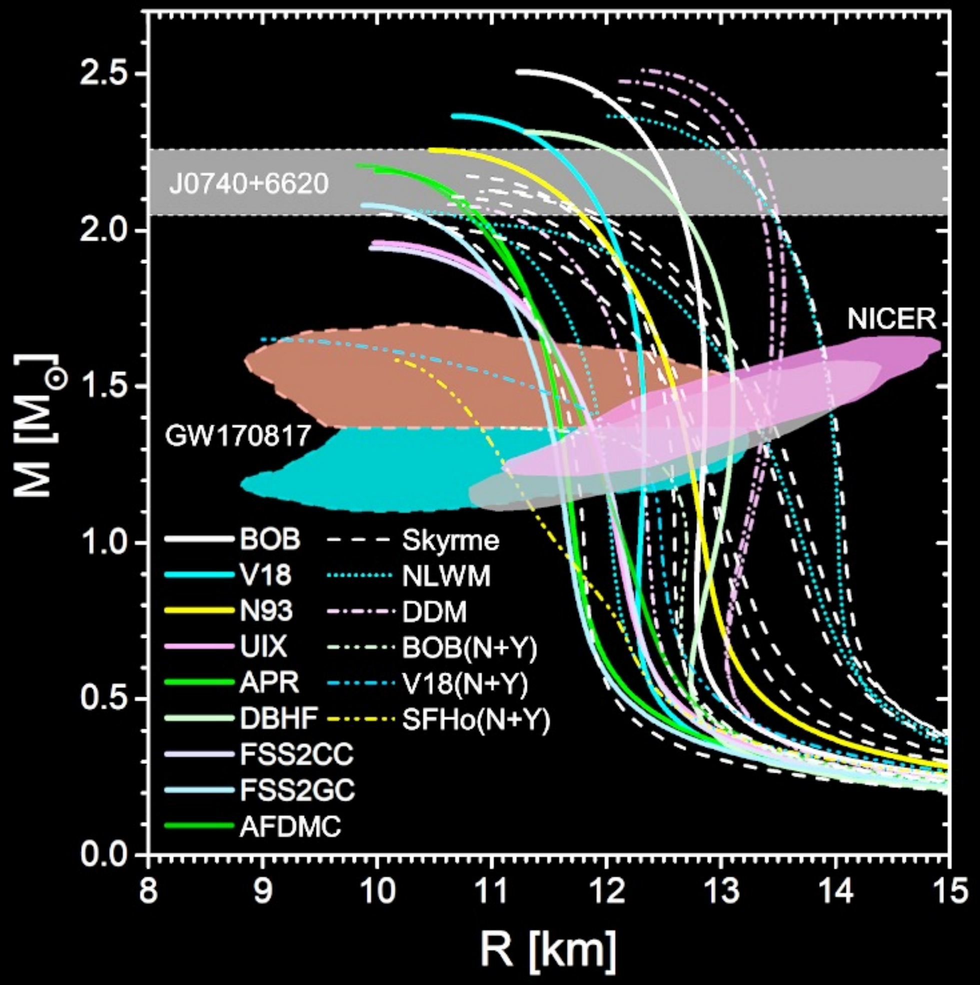
Dynamics of Dense Matter

- 10m NS radius errors on the population level
- Detection of BNS postmerger signal yearly
- Detection of continuous GWs from known accreting NSs and millisecond pulsars
- Detection of one supernova from within the Milky Way or its satellites over a 50-year lifetime

Burgio+ PrPNP 120, 103879 (2021)



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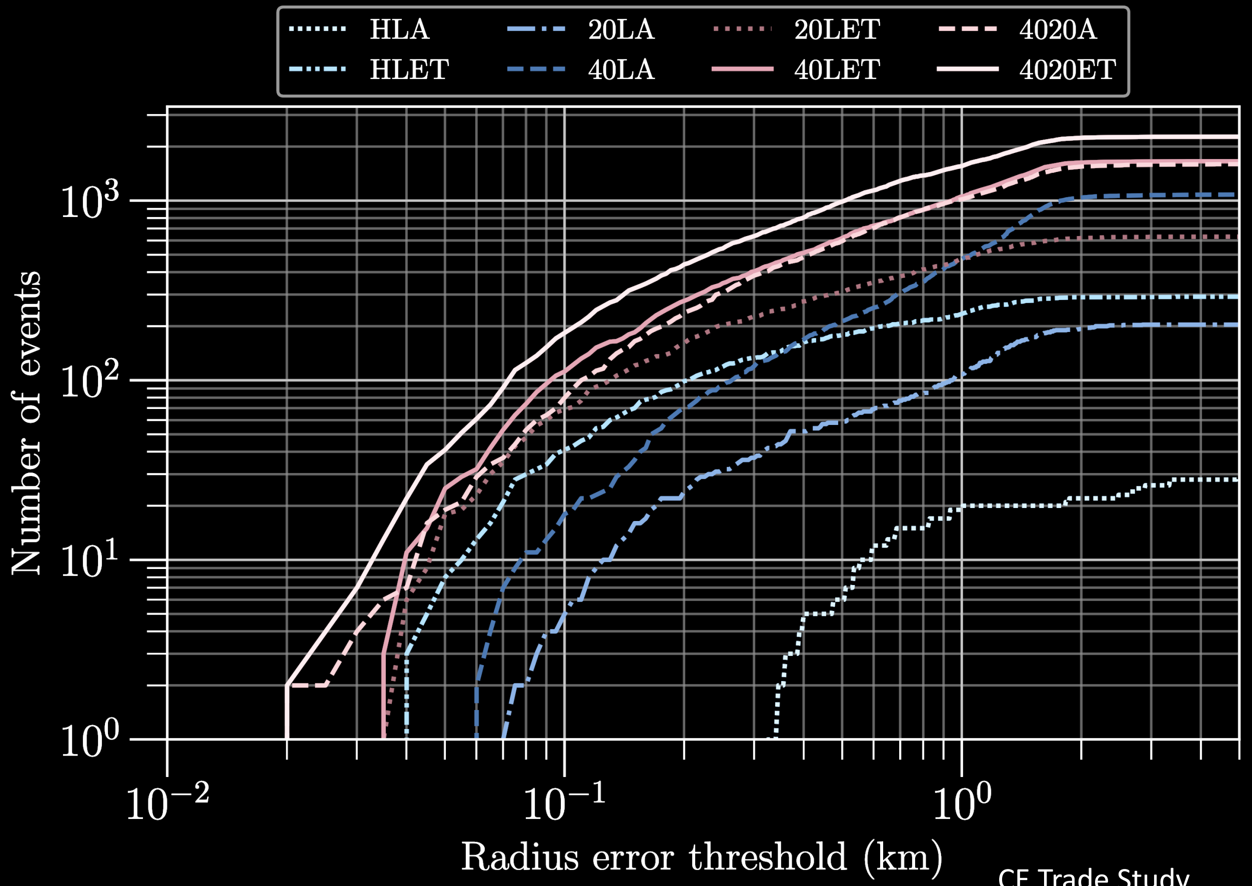
20km CE is critical!



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Gupta+ (inc **SB**) 2307.10421

Multimessenger Astrophysics

- At least one 40km CE → 100x higher BNS detection rate
- BNS redshift reach of $z \approx 2$
  - Map the progenitors of short gamma-ray bursts
  - Measure time delays
- With at least 2 XG detectors:
  - Tens of signals localized to < 1 deg^2
  - Thousands to < 10 deg^2
  - Few – tens < 10 deg^2 5 mins before merger

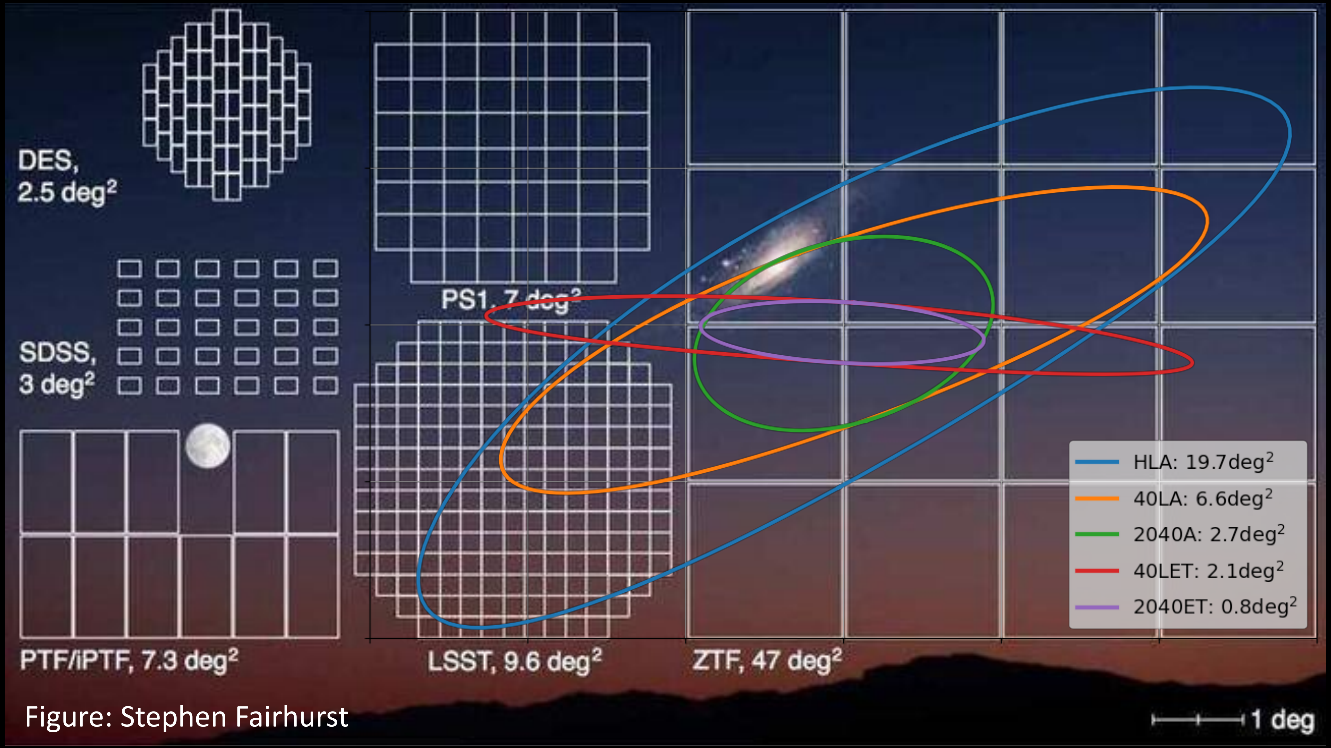
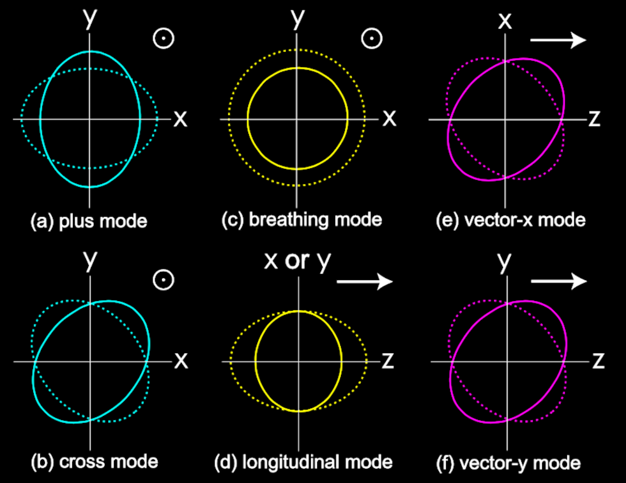
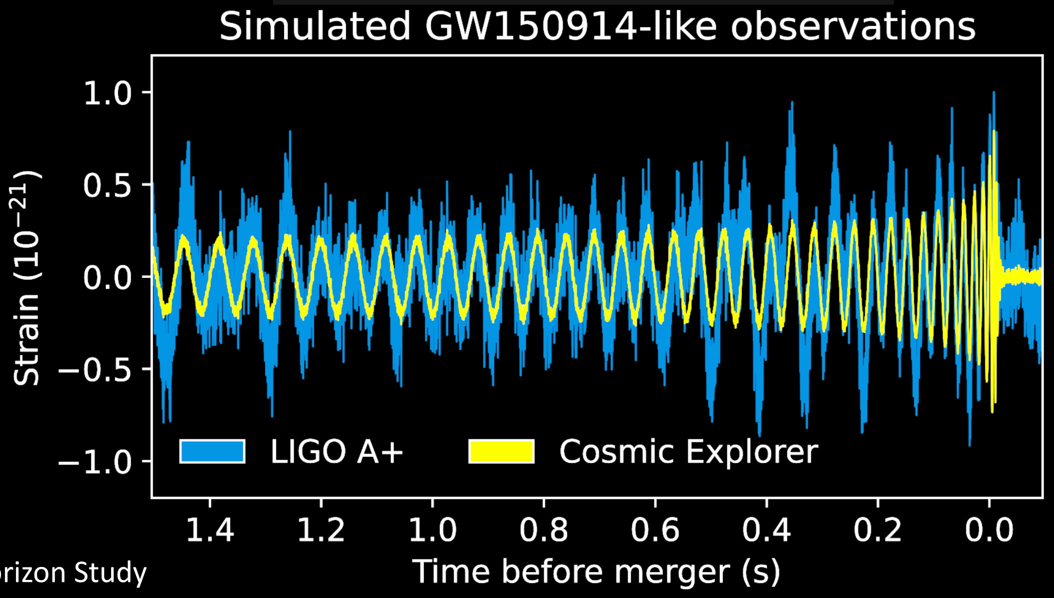


Figure: Stephen Fairhurst

Extreme Gravity and Fundamental Physics

- Tests of General Relativity
  - Parameterized deviations
  - Ringdown tests of no-hair theorem
  - Memory effect
  - Beyond-GR polarizations
  - Graviton mass
- Cosmology
  - Expansion rate of the universe using standard sirens
  - Constraints on ΛCDM and dark energy EoS using NS EoS





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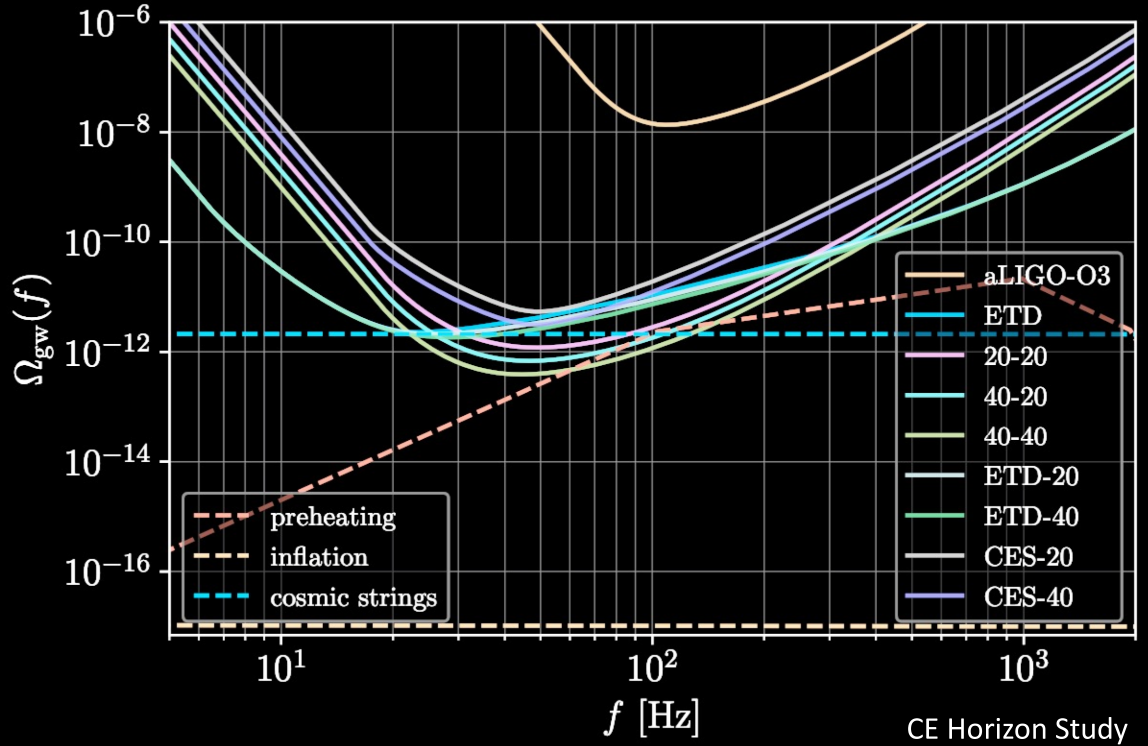
Beyond the Standard Model

- Exotic compact objects
  - Black hole mimickers
  - Boson clouds around black holes
  - Neutron stars with dark matter interiors
- Primordial stochastic gravitational-wave backgrounds
  - Cosmic strings
  - First-order phase transitions
  - Explosive particle production via preheating



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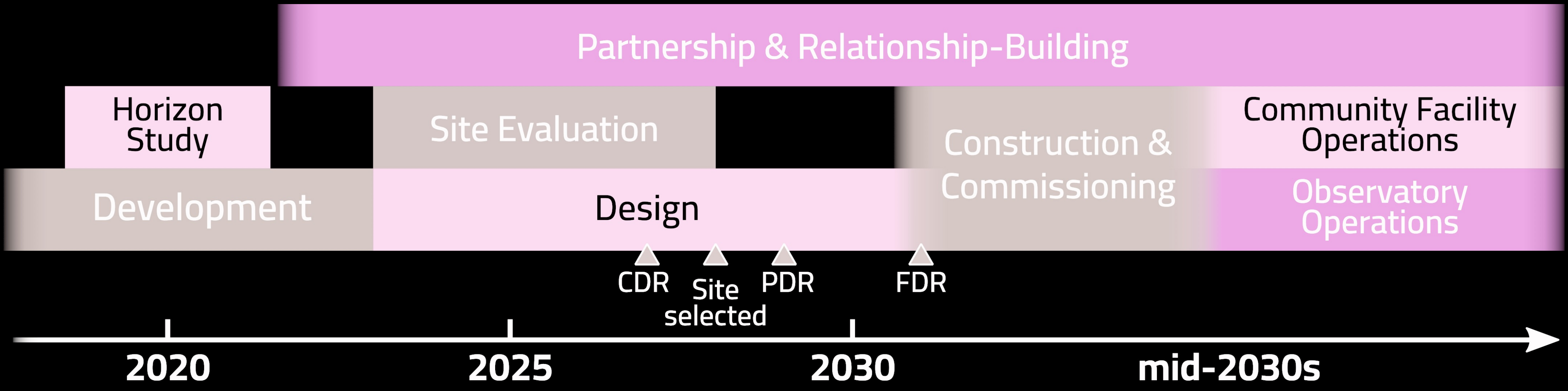
Evans + (inc **SB,** plot) 2109.09882

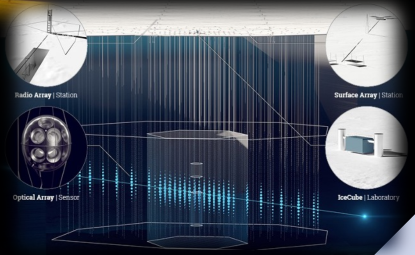
Cosmic Explorer timeline



NSF MPS ngGW subcommittee report emphasized the extraordinary discovery potential of a Cosmic Explorer 40km detector while at the same time carrying the lowest technical risk

See session S10.00002 on Saturday afternoon

Multimessenger synergies

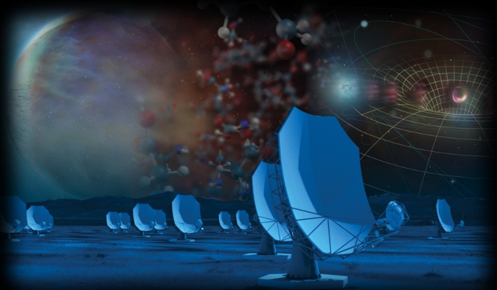


Neutrino:
DUNE, NKM3Net, IceCube Gen2

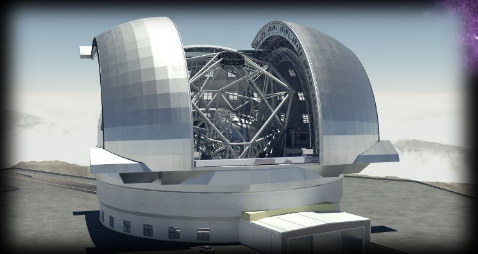
Radio:
ng VLA, SKA

X-ray/Gamma-ray:
Einstein Probe, Athena, THESEUS, HERMES

Optical/IR:
Nancy Grace Roman, ELTs, VRO LSST





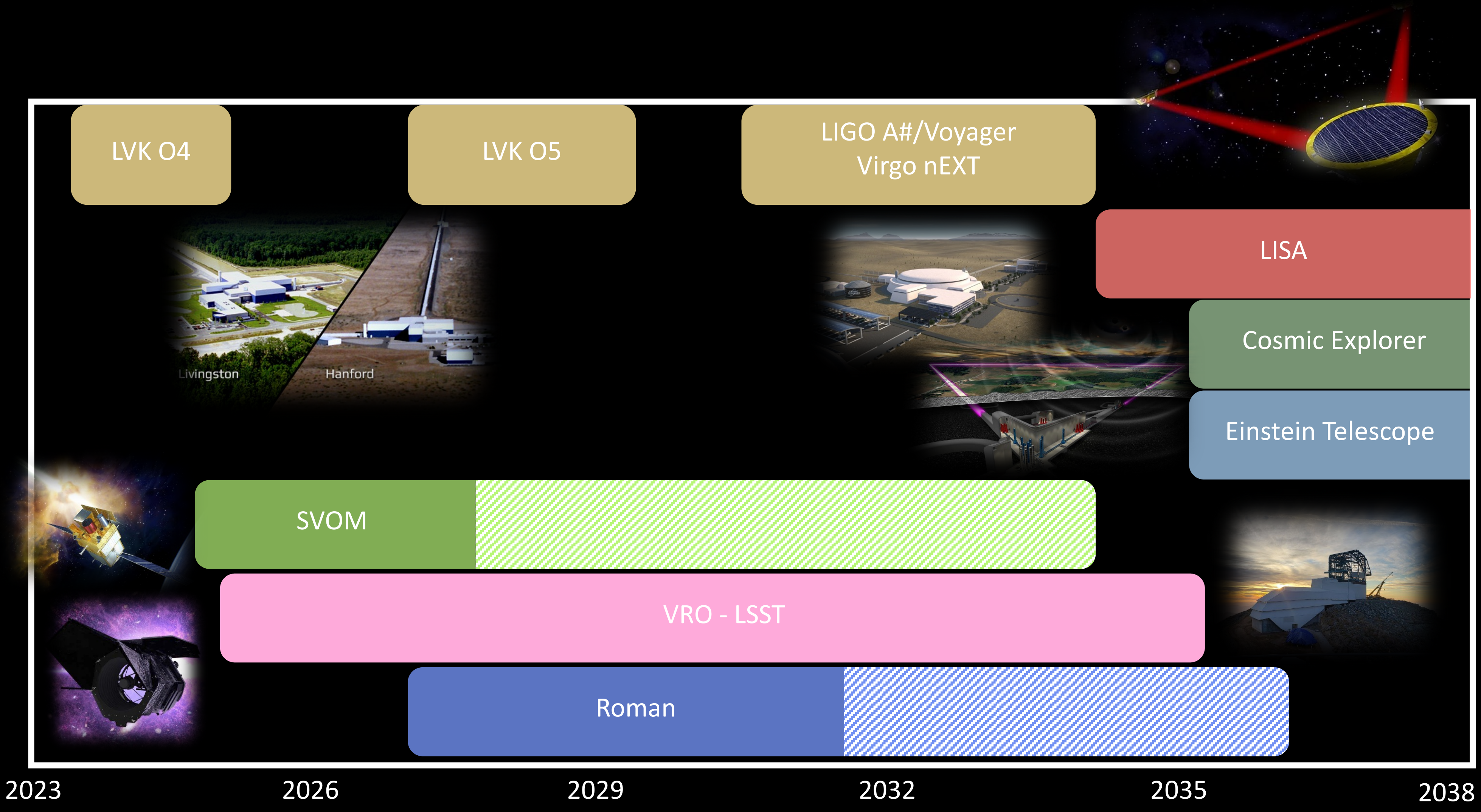


Conclusion

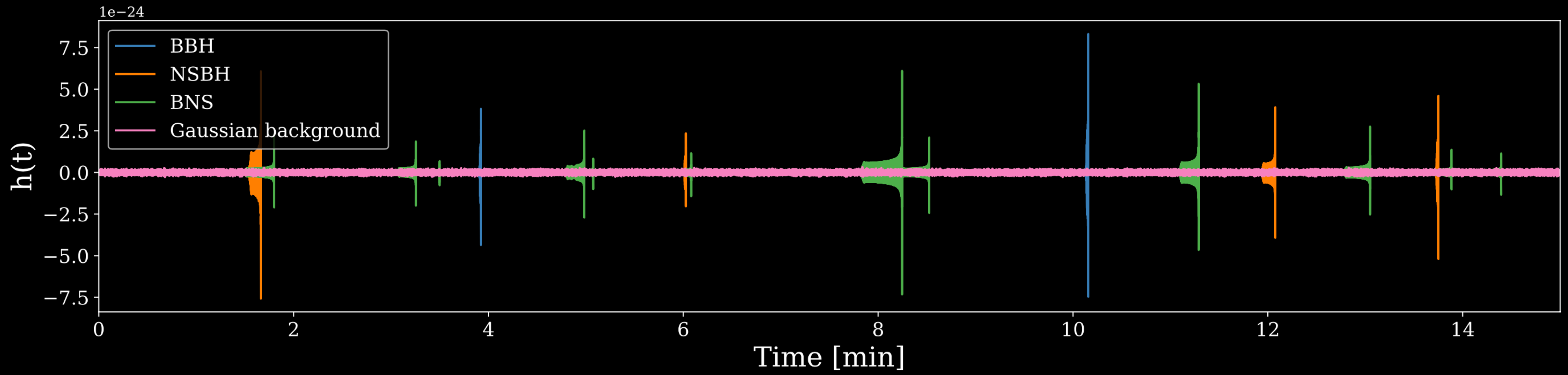
- Deeper, wider, sharper
  - Black holes and neutron stars through cosmic time
  - Dynamics of Dense Matter and Multimessenger Astrophysics
  - Extreme Gravity and Fundamental Physics
  - Discovery potential

Image: Evan Hall (MIT), Nils Fischer, Harald Pfeiffer, Alessandra Buonanno (Max Planck Institute for Gravitational Physics), SXS Collaboration

Backup


LVK O4
LVK O5
LIGO A#/Voyager
Virgo nEXT
LISA
Cosmic Explorer
Einstein Telescope
Livingston
Hanford
SVOM
VRO - LSST
Roman
2023
2026
2029
2032
2035
2038

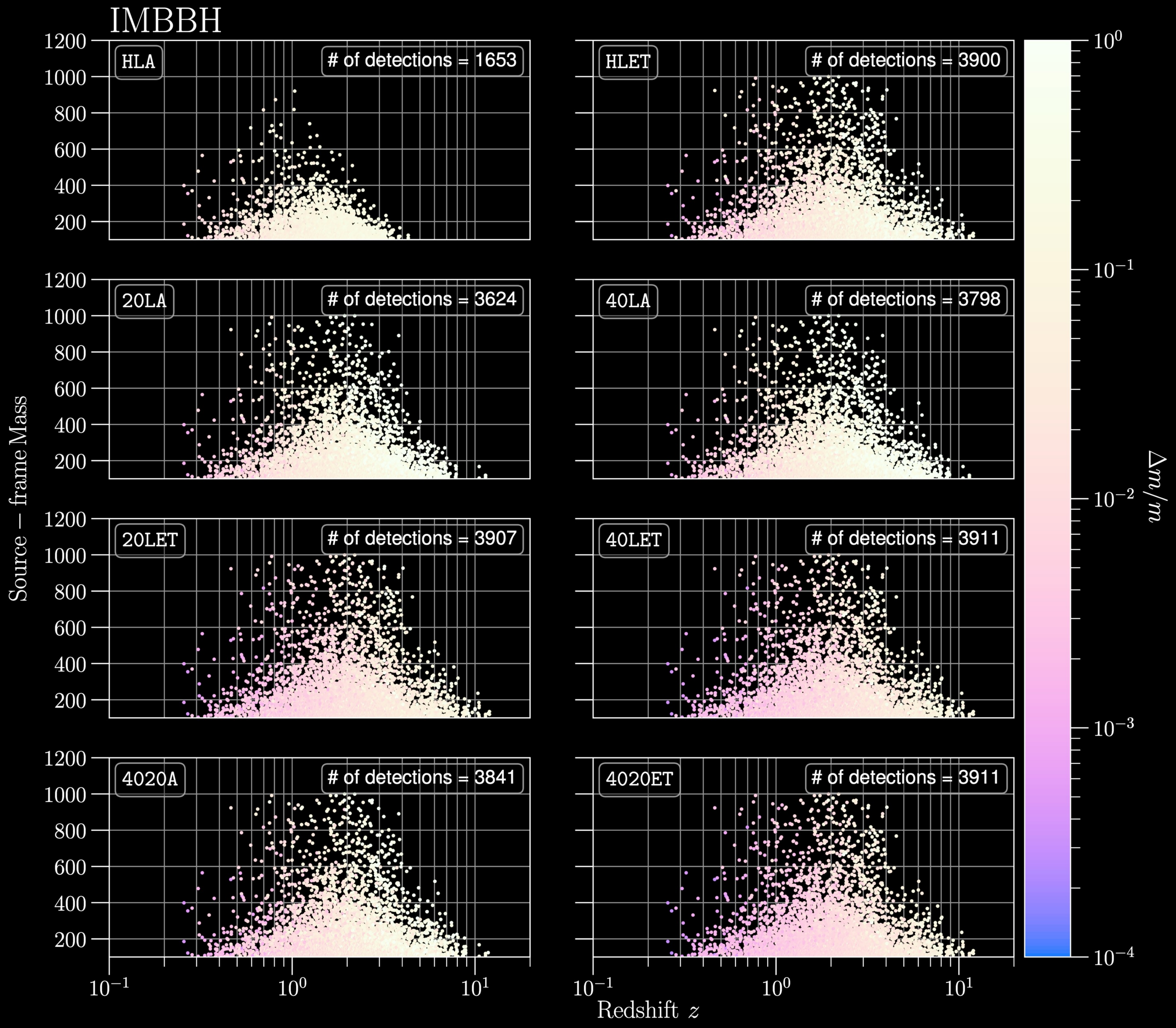
Next-generation data analysis



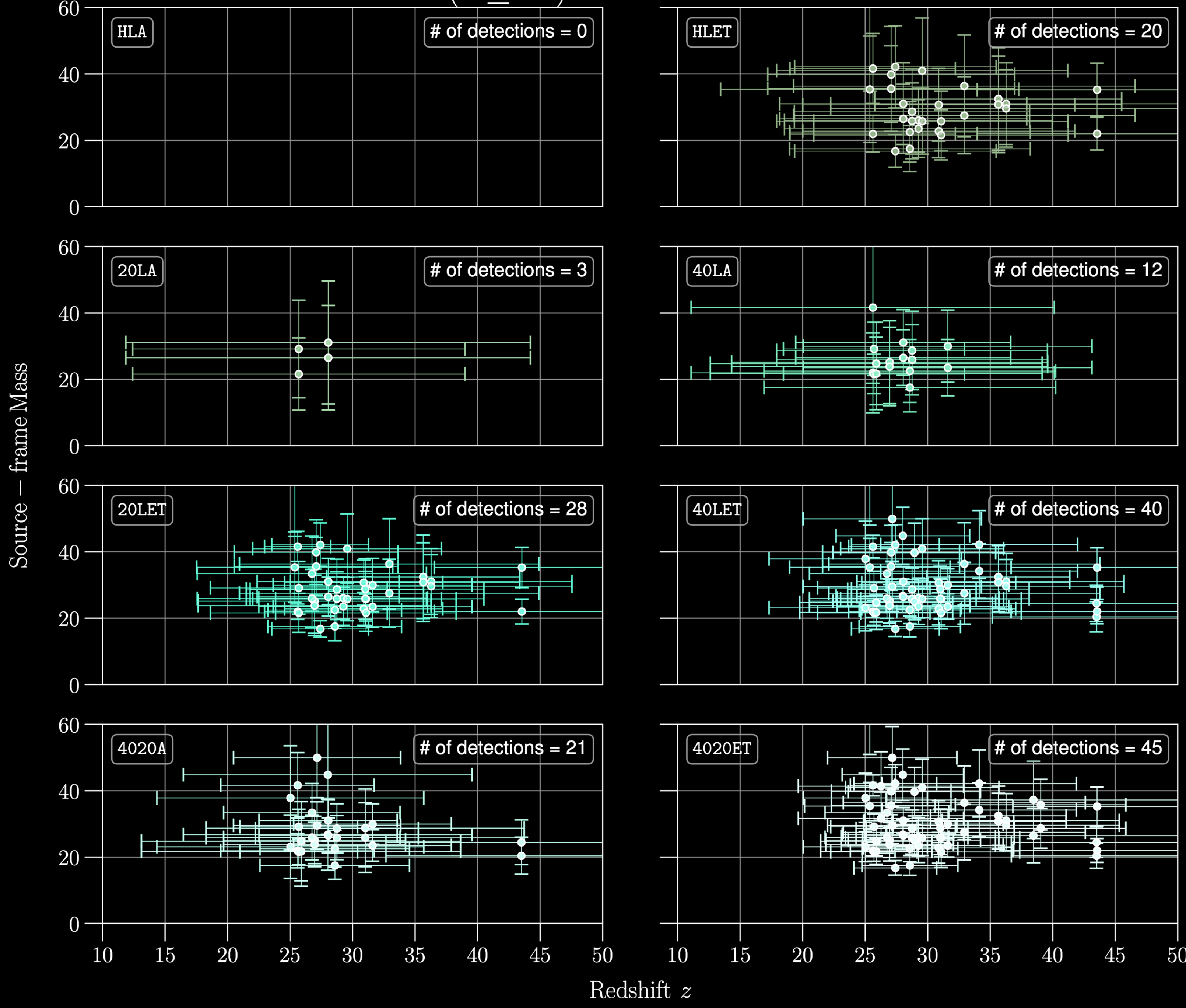
Bias in inferred binary parameters from overlapping signals?

Scalability of population inference techniques to thousands of events?

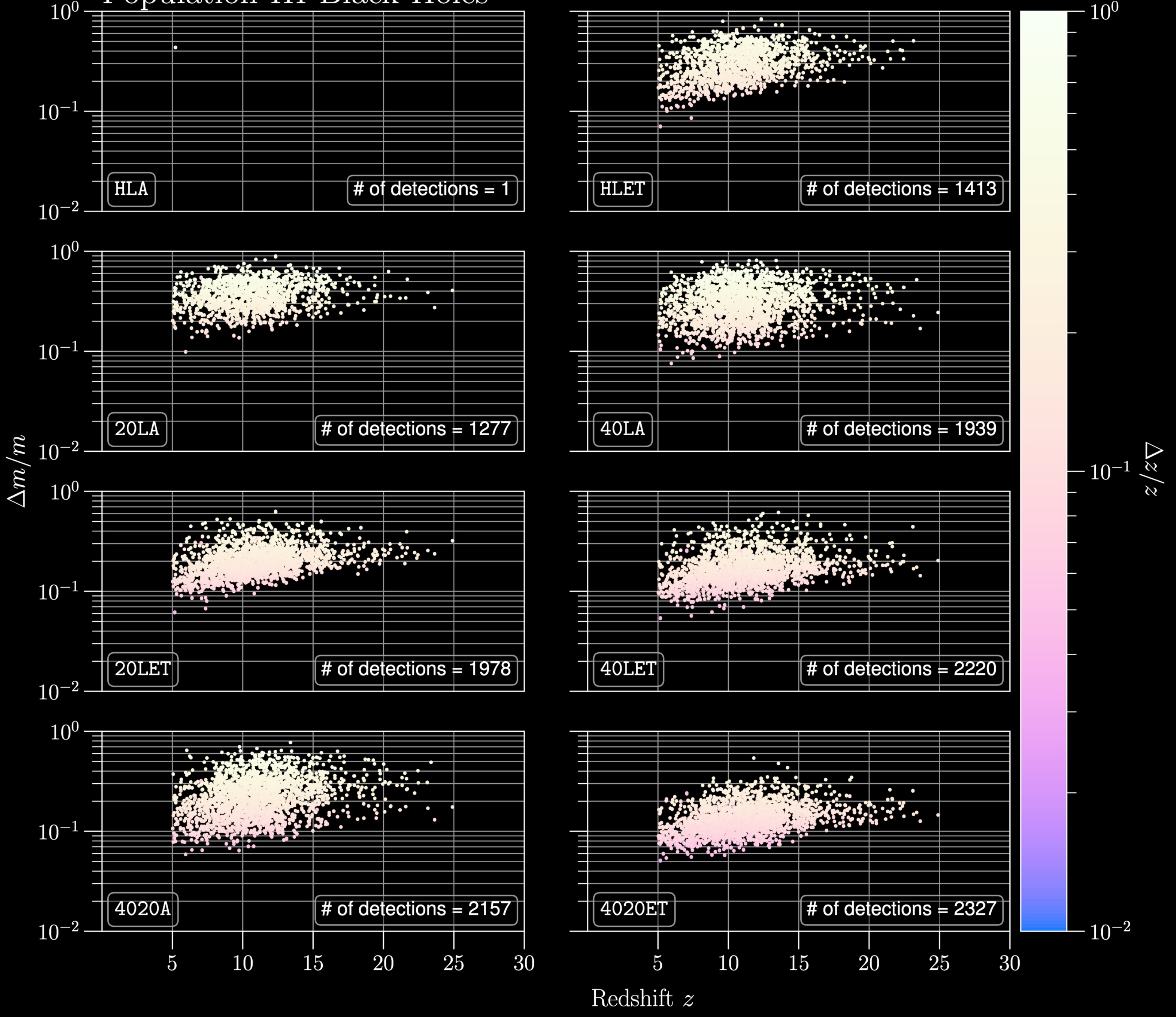
Separation of astrophysical foreground and cosmological background?


IMBBH
HLA
# of detections = 1653
HLET
# of detections = 3900
20LA
# of detections = 3624
40LA
# of detections = 3798
20LET
# of detections = 3907
40LET
# of detections = 3911
4020A
# of detections = 3841
4020ET
# of detections = 3911
Source − frame Mass
Redshift z
Δm/m

Primordial Black Holes ($z \geq 25$)



Population III Black Holes



Boson cloud reach