The Einstein Telescope: a next-generation gravitational wave detector in Europe

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GWSC GRAVITATIONAL WAVE SCIENCE CENTER

Gravitational waves from binary mergers

Gravity is a very weak force
- Observable signals require enormous energy

All confirmed GWs come from binary mergers
- Black hole + black hole (BBH)
- Neutron star + neutron star (BNS)
- Black hole + neutron star (BHNS/NSBH)

What do these signals look like?

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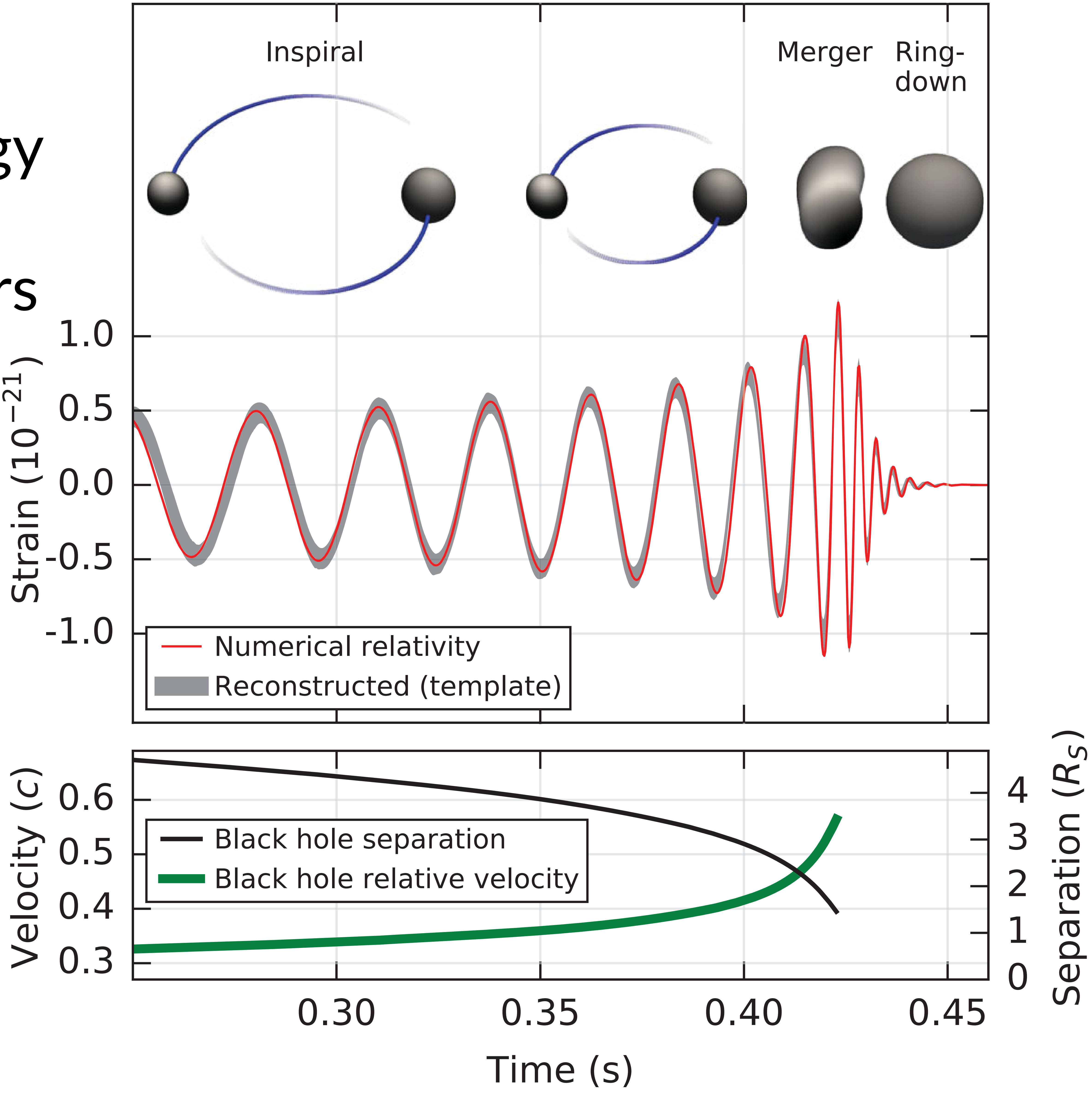
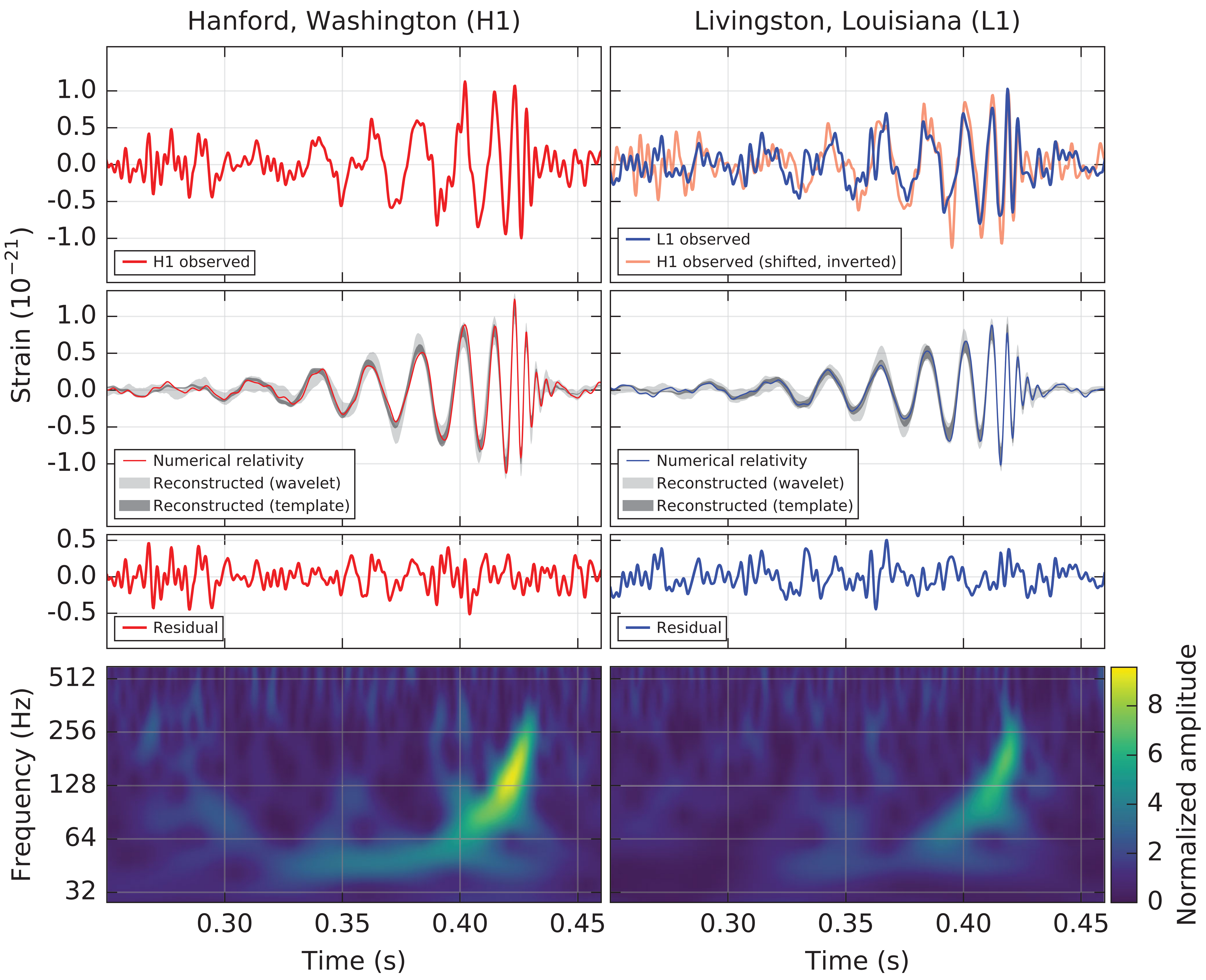
What do these signals look like?
- **Inspiral**: the compact objects approach
  - Growing signal strength
- **Merger**: the compact objects connect
  - Maximum signal strength, the "chirp"
- **Ringdown**: the produced object stabilises
  - Rapidly decaying signal strength



The first observation: GW150914

The first GW signal was observed on 14 September 2015
- Black hole 1: 36 solar masses
- Black hole 2: 29 solar masses
- Resulting BH: 62 solar masses



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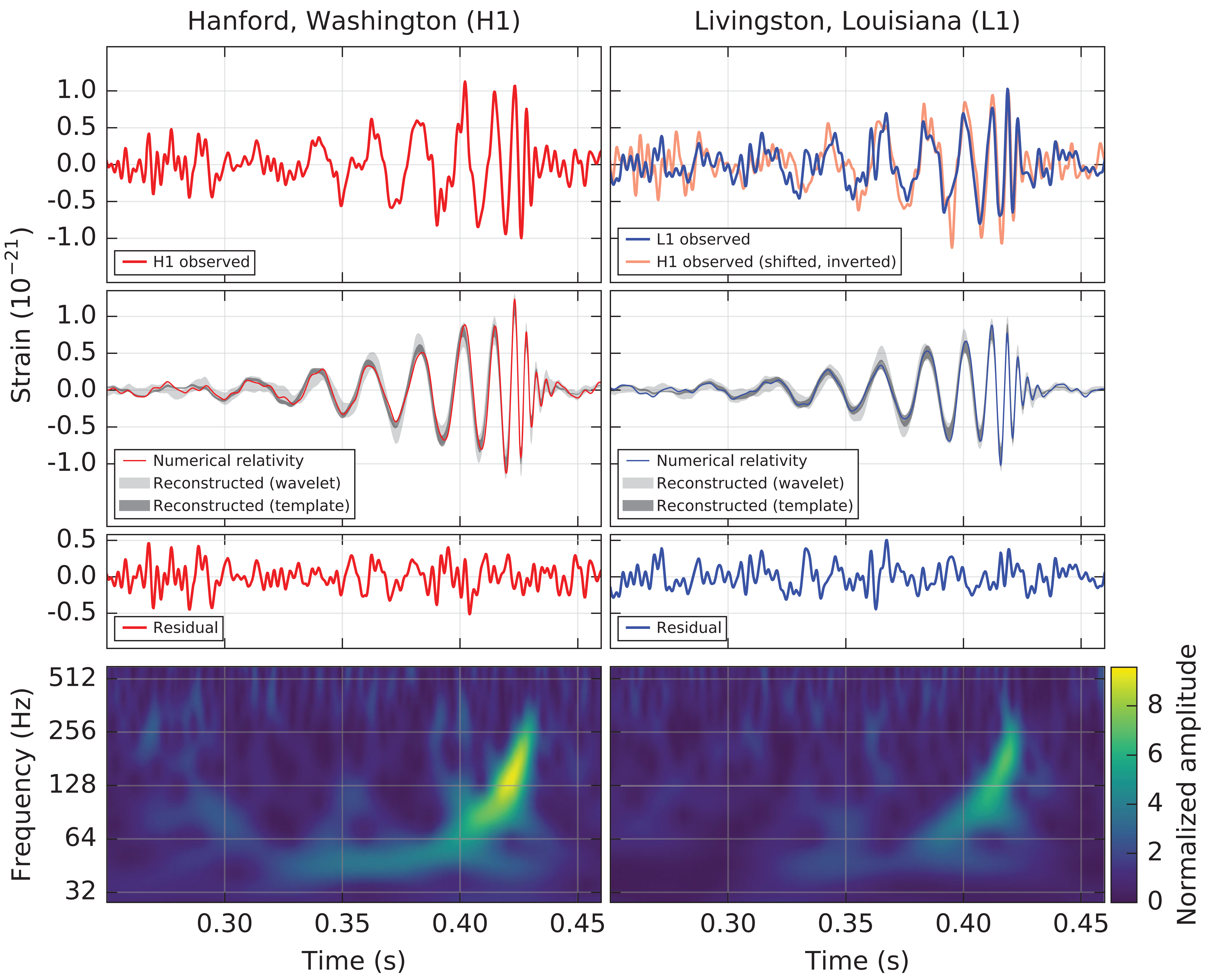
3 solar masses of energy radiated as GWs, within a few milliseconds!

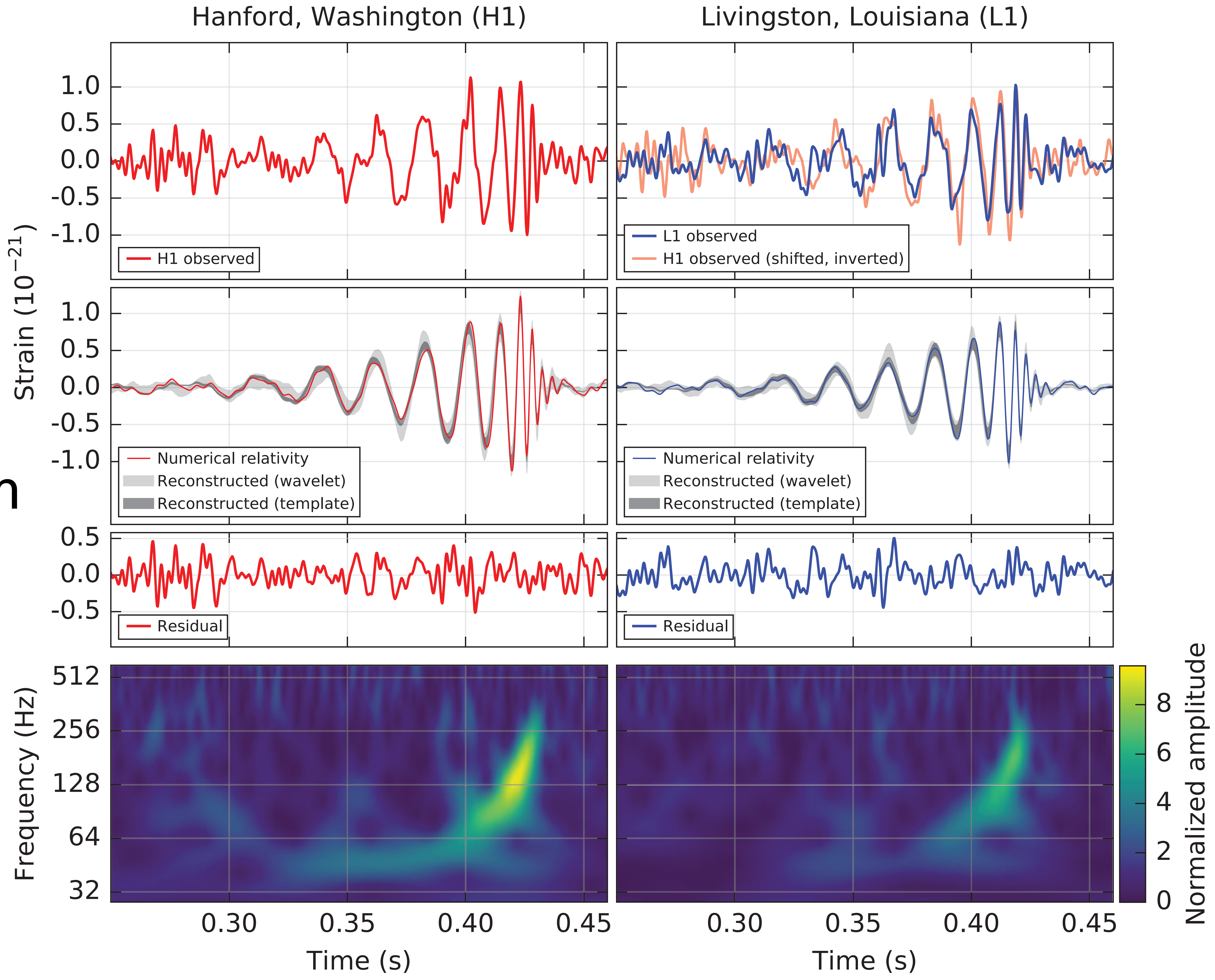
- For a brief moment, this source radiated more energy as GW than the entire Universe radiated in the visible spectrum



Strain and GW150914

Signals are space-time deformations
- Look in two different directions
- Measure the difference in the distance travelled by light

Result is the strain, $\sim \Delta L/L$
- GW150914 max strain: $1.0\text{x}10^{-21}$
- Earth-sun distance (AU): $1.5\text{x}10^{11}$ m



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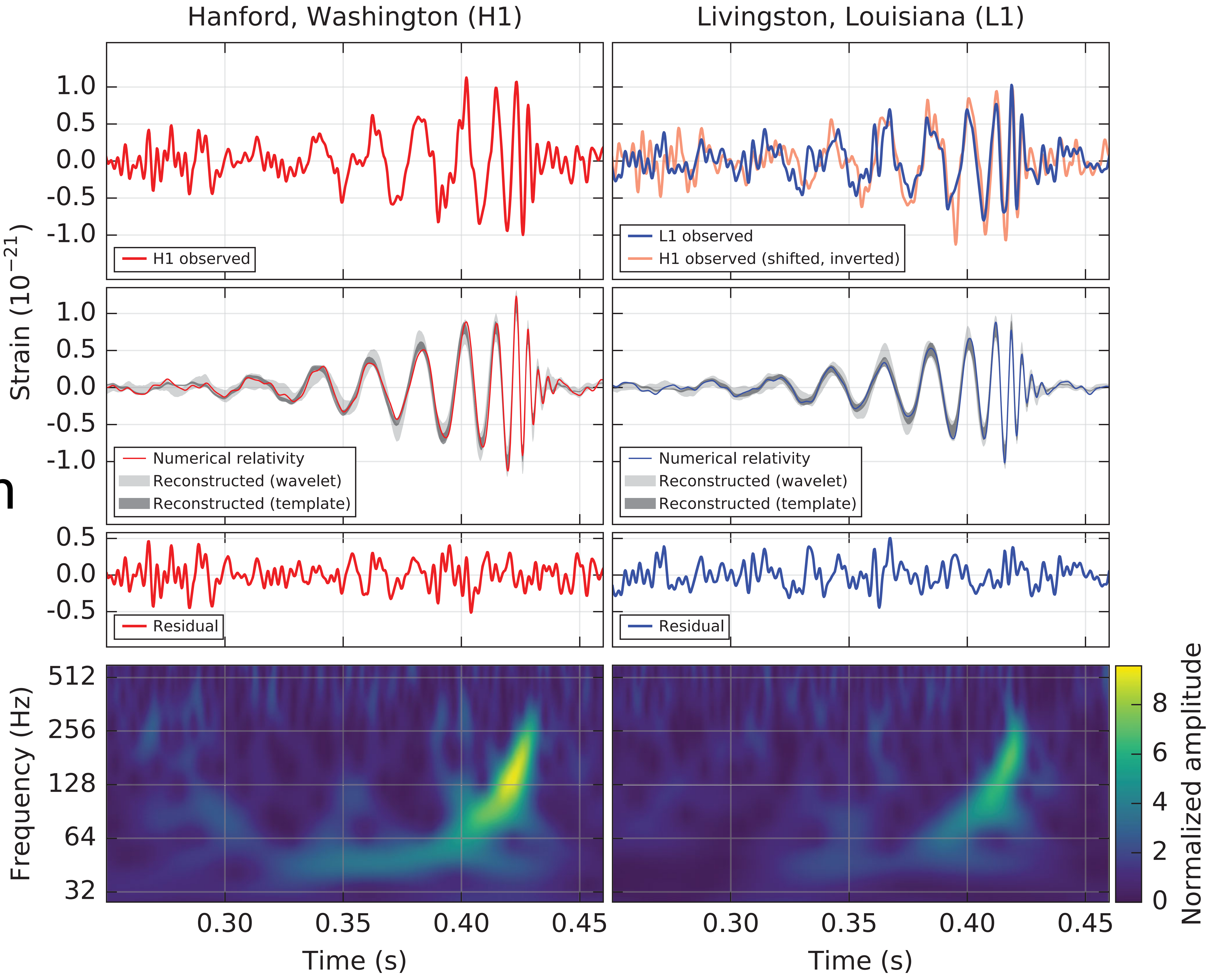
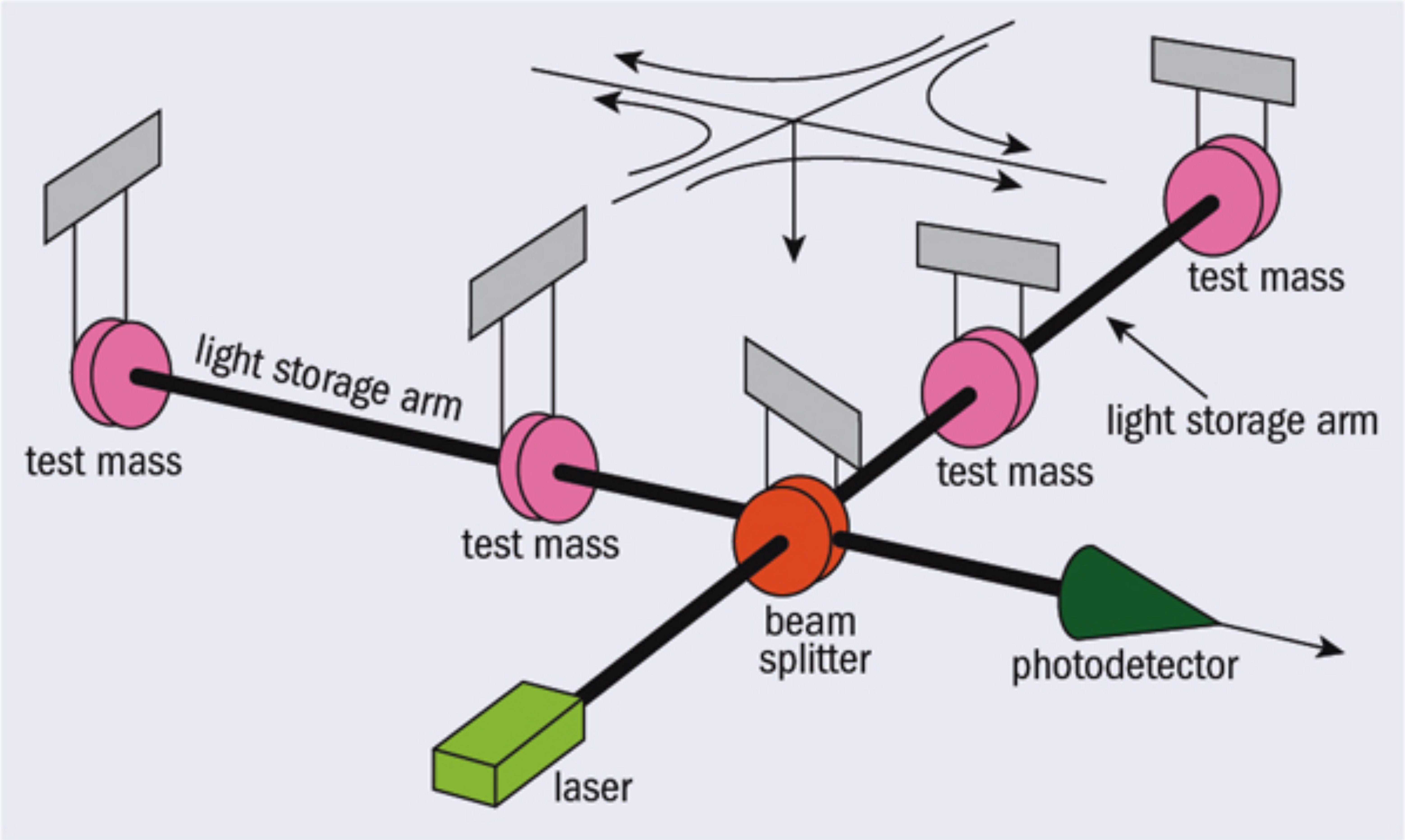
- Earth-sun distance (AU): $1.5\text{x}10^{11}$ m
- 10^{-21} strain on AU: $1.5\text{x}10^{-10}$ m
- Bohr radius: $0.5\text{x}10^{-10}$ m

3 solar masses of GW energy was observed by measuring a strain compatible with the AU length changing by 3 hydrogen radii!



Observing GW signals

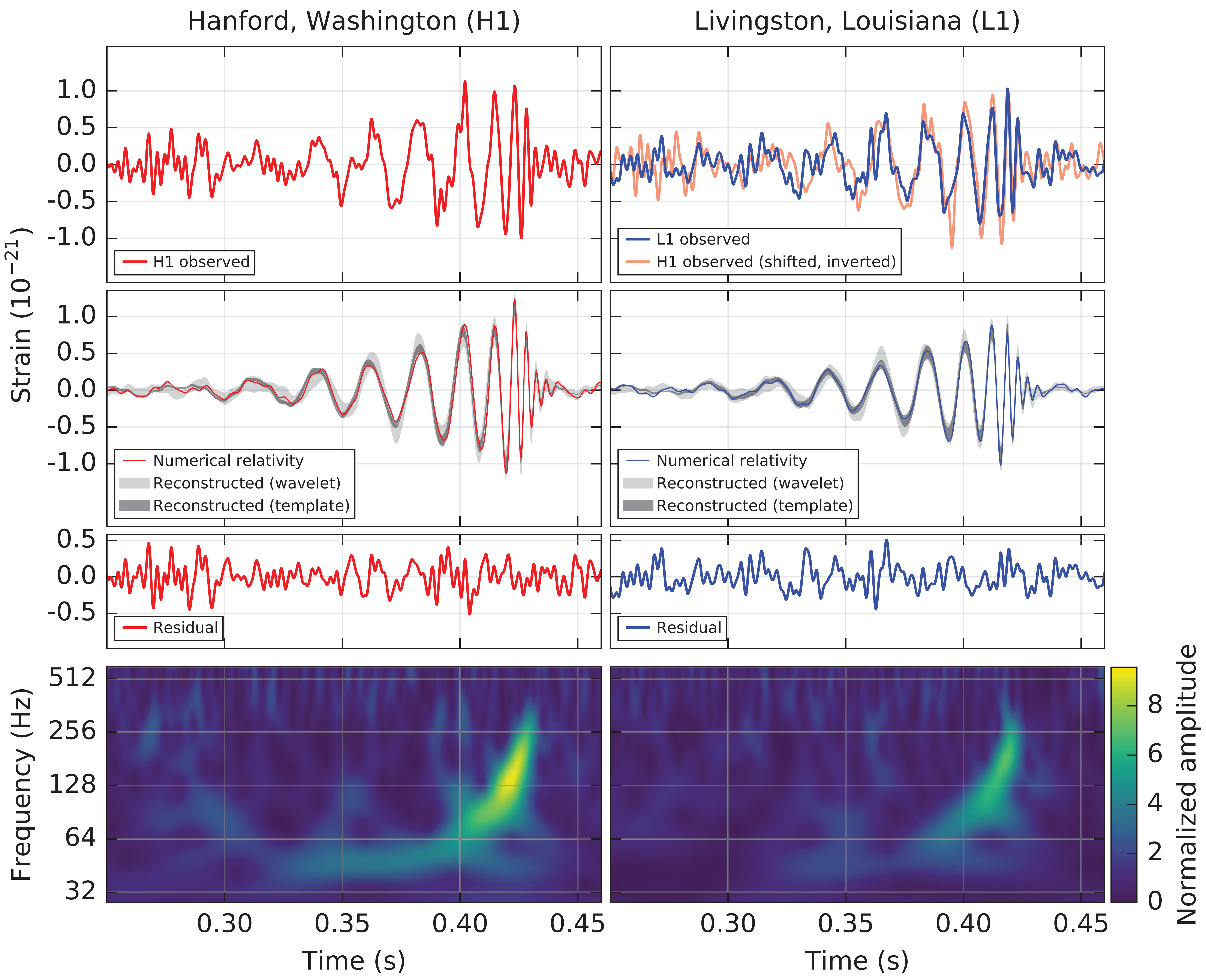
Measuring the strain so precisely requires extraordinary distance precision
- Laser interferometers are the way all GW signals have been observed to date
- Perturbations of the relative lengths of the two arms (strain) leads to interference



Extracting a GW signal

The interferometer strain is noisy
- Even the top panel here is after substantial data pre-processing

Extracting the middle panel relies on **matched filtering**



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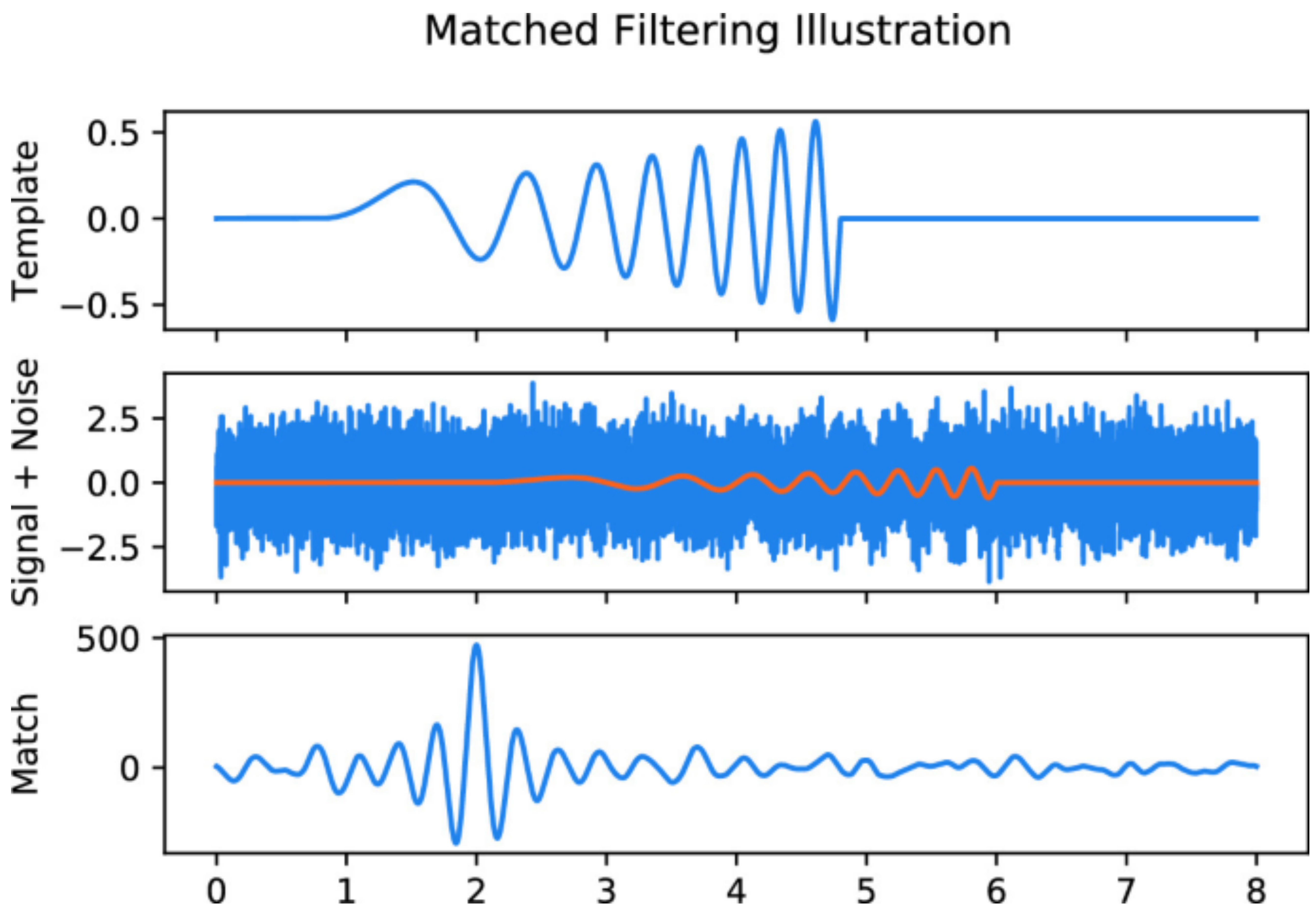
Extracting the middle panel relies on **matched filtering**
- Assume a given signal shape
- Slide the signal over the time series
- Calculate shape-to-data correlation

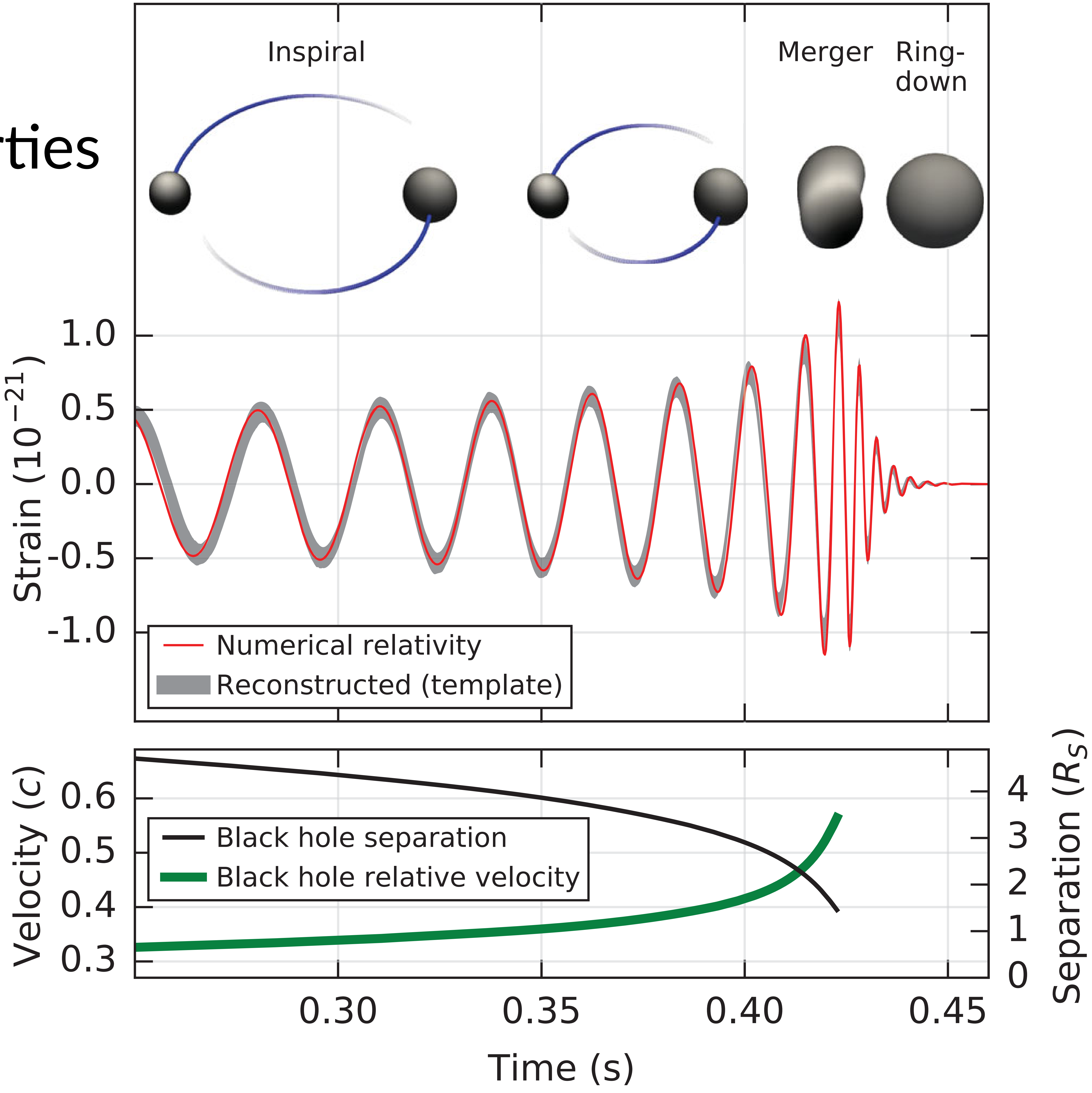
Mathematically proven to provide optimal signal extraction
- Assumes you have the right shape
- Repeat with **MANY** templates, pick the best correlation if multiple match



What information is in the template?

The template describes the full process
- **Inspiral** gives information about the properties of the two incident objects (mass, spin, etc)
- **Ringdown** gives information about the resulting object's properties

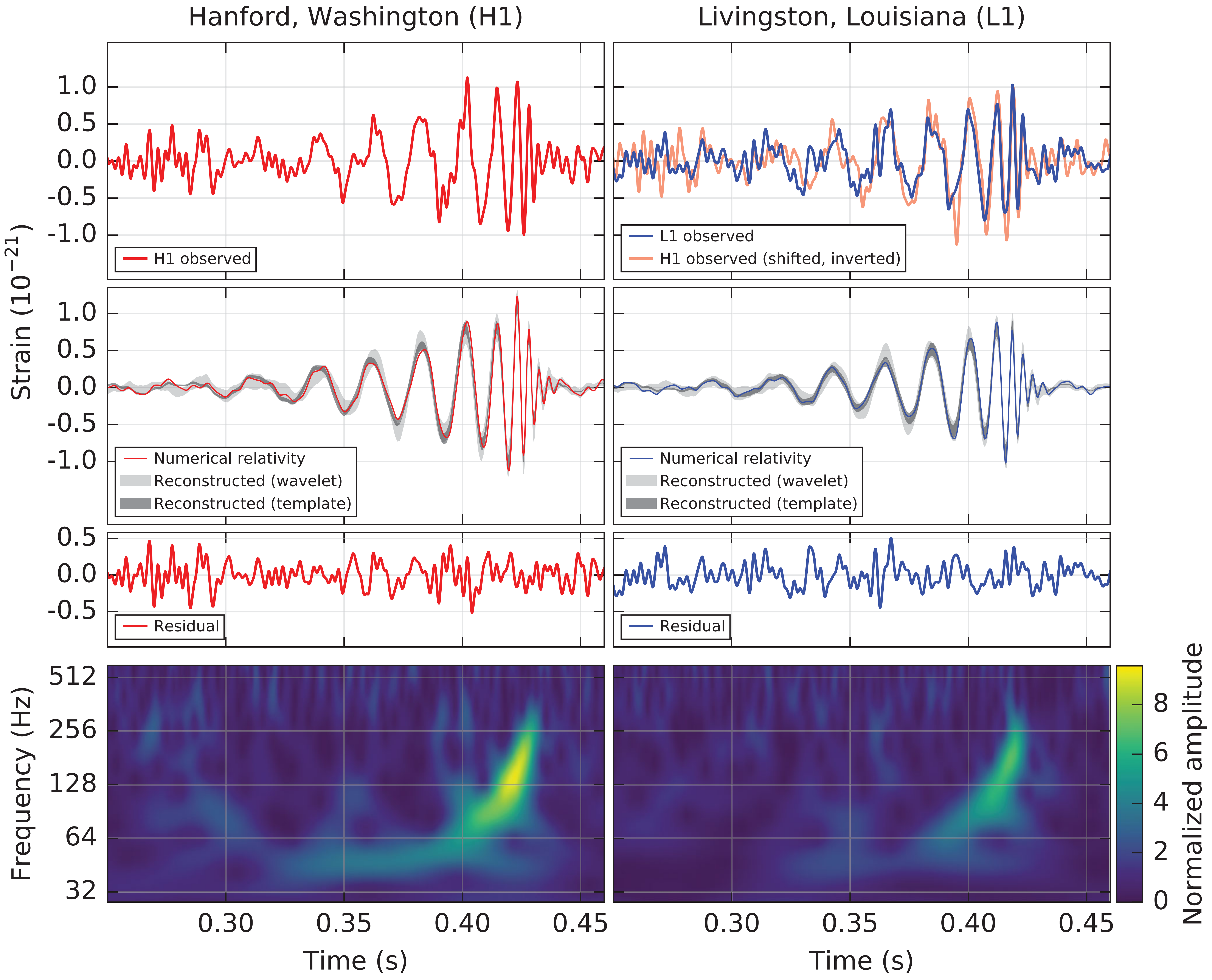
Ideally, we would use numerical relativity (NR) for all of the templates
- This is too expensive, as we need millions of templates for matched filtering
- Instead, rely on approximants for the "pattern bank", and can then refine with NR for the final signal characterisation
- Approximants work well enough for now



Networks of interferometers

GW detection is greatly enhanced through having multiple detectors
- First GW detection involved two LIGO interferometers

Benefits of multiple detectors:
- Increased signal sensitivity
  - Signal is present in both detectors
  - Noise should be uncorrelated



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Benefits of multiple detectors:
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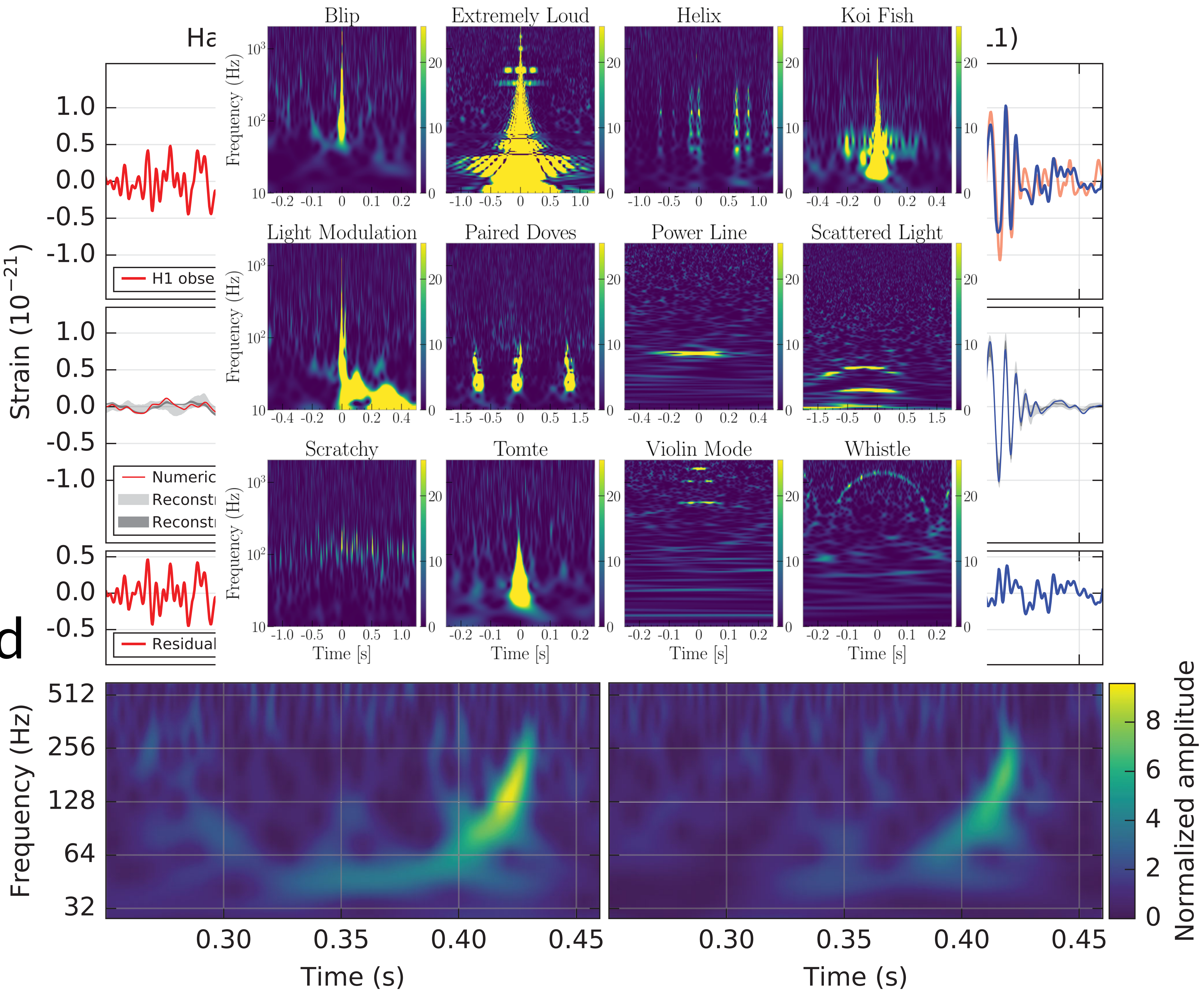
  - Noise should be uncorrelated
  - Background events/glitches should only be present in one detector
- Geometric acceptance effects
  - GW-detector alignment matters
- Sky localisation (more later)



LVK: the 2nd generation GW network

There are four 2nd-gen GW detectors
- Both LIGO started in 2015
- Virgo joined 2017, KAGRA 2020

All are laser interferometers
- LIGO: 4km arms, surface
- Virgo: 3km arms, surface
- KAGRA: 3km arms, underground, cryogenic mirrors

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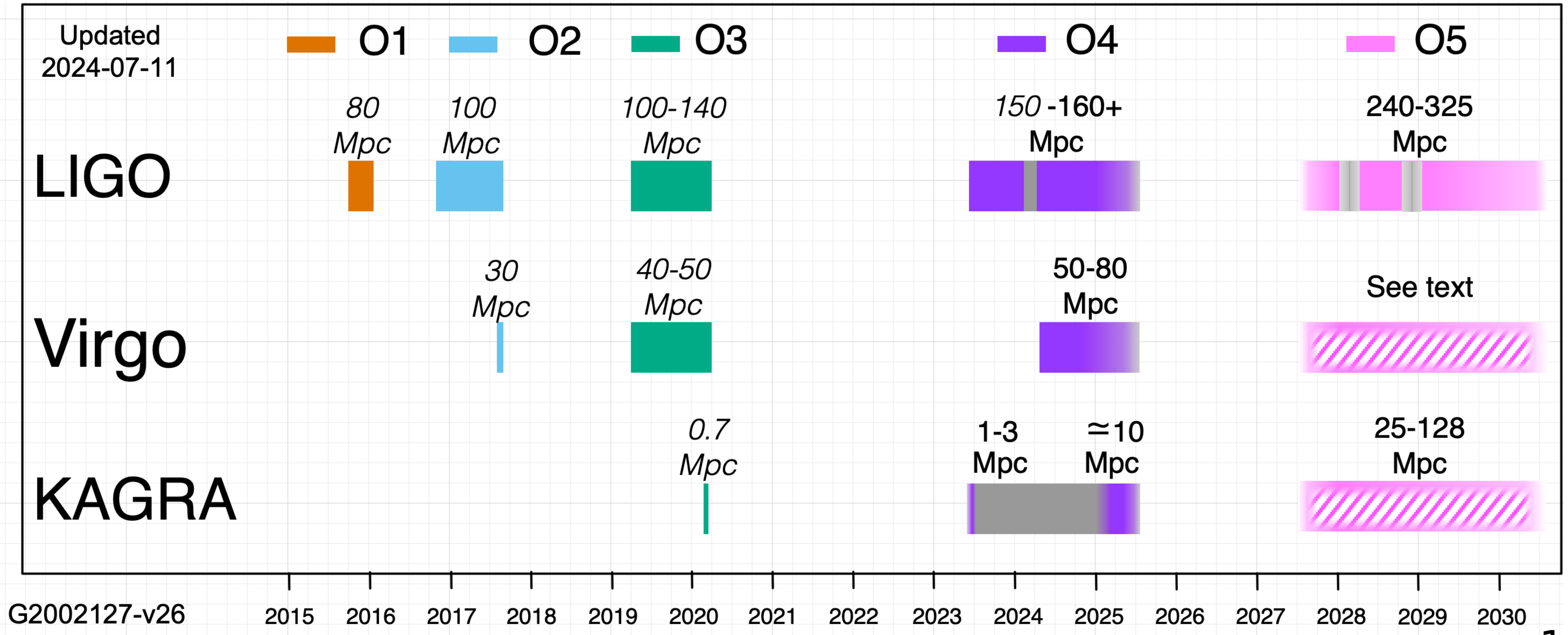
Three scientific collaborations, but also form a joint super-collaboration: LVK
- Data is live-streamed between sites
- Operate as a single network, jointly planning science runs (better sensitivity)

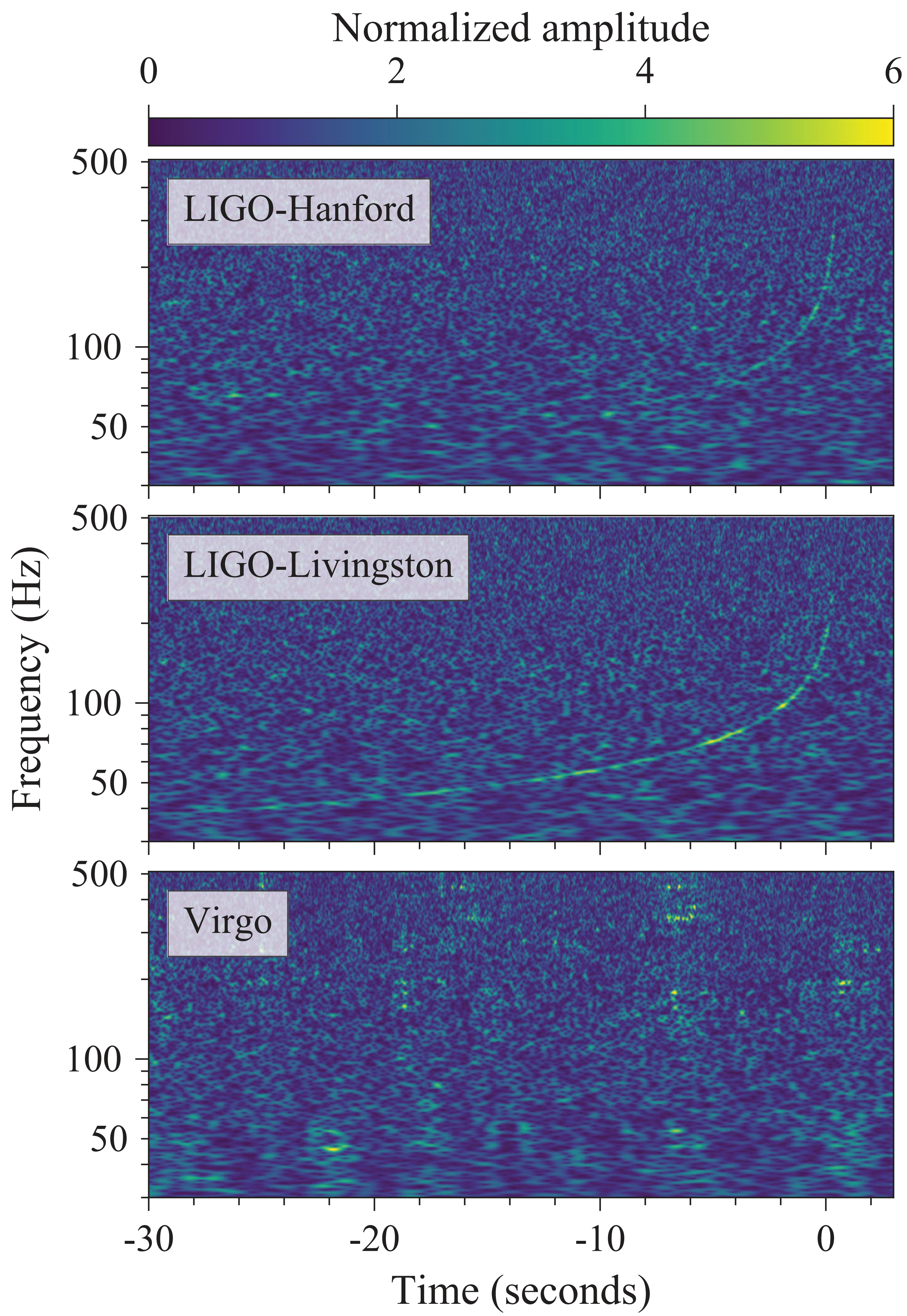


The importance of a network: GW170817

The second most famous GW event was a perfect example of the importance of detector networks
- Seen in both LIGO detectors, **but not in Virgo**
- Signal **was strong enough** to be seen in Virgo

Why was it missing in Virgo? Geometry!
- The event happened to be in the Virgo "blind zone"
- This is a narrow window; helped to identify where in the sky the GW signal came from
- More precise than if all three had seen the signal!

Sky localisation turned out to be very important



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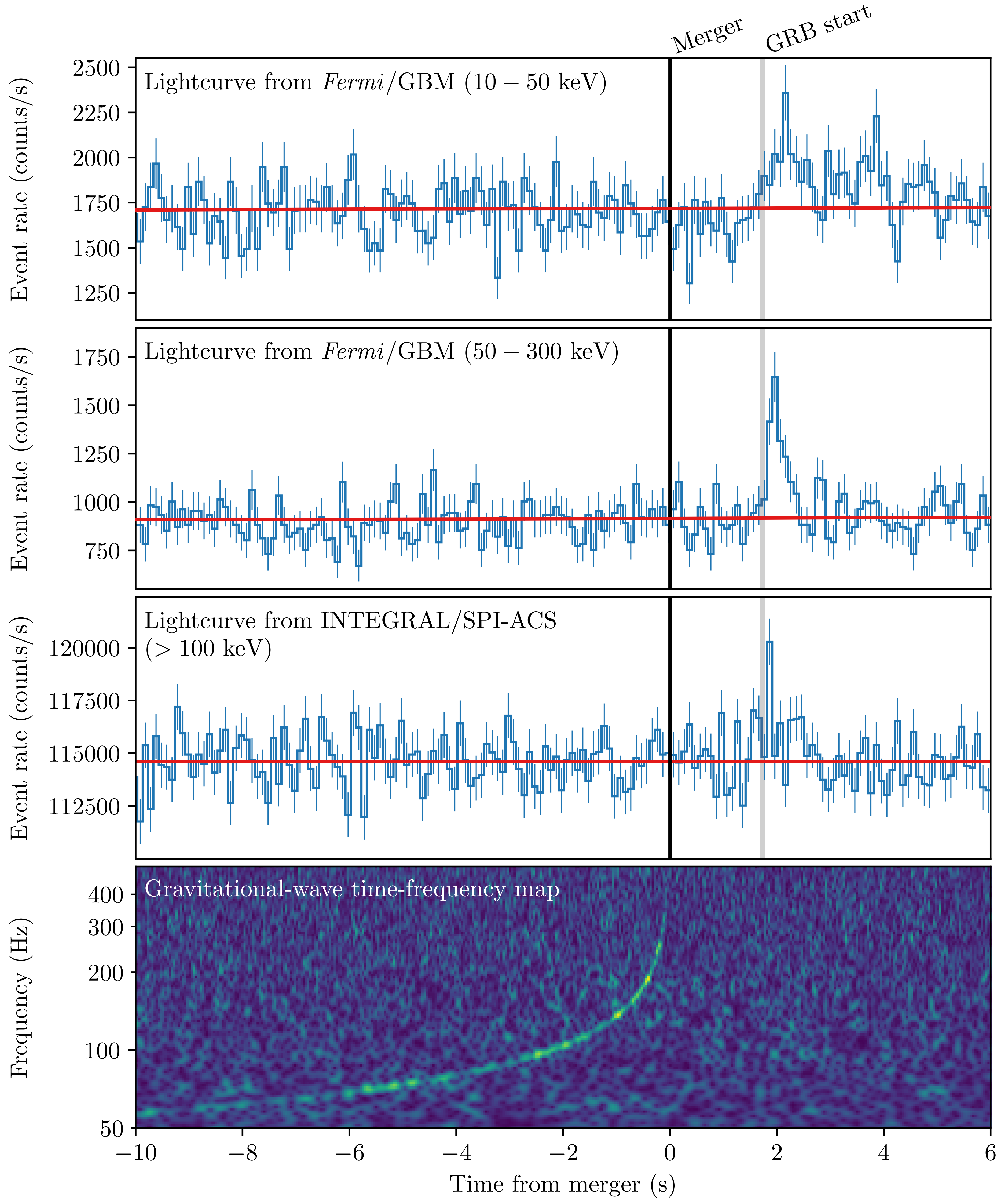
- First multi-messenger (MM) observation with GWs
- Correlated GW signal and gamma-ray burst (GRB)



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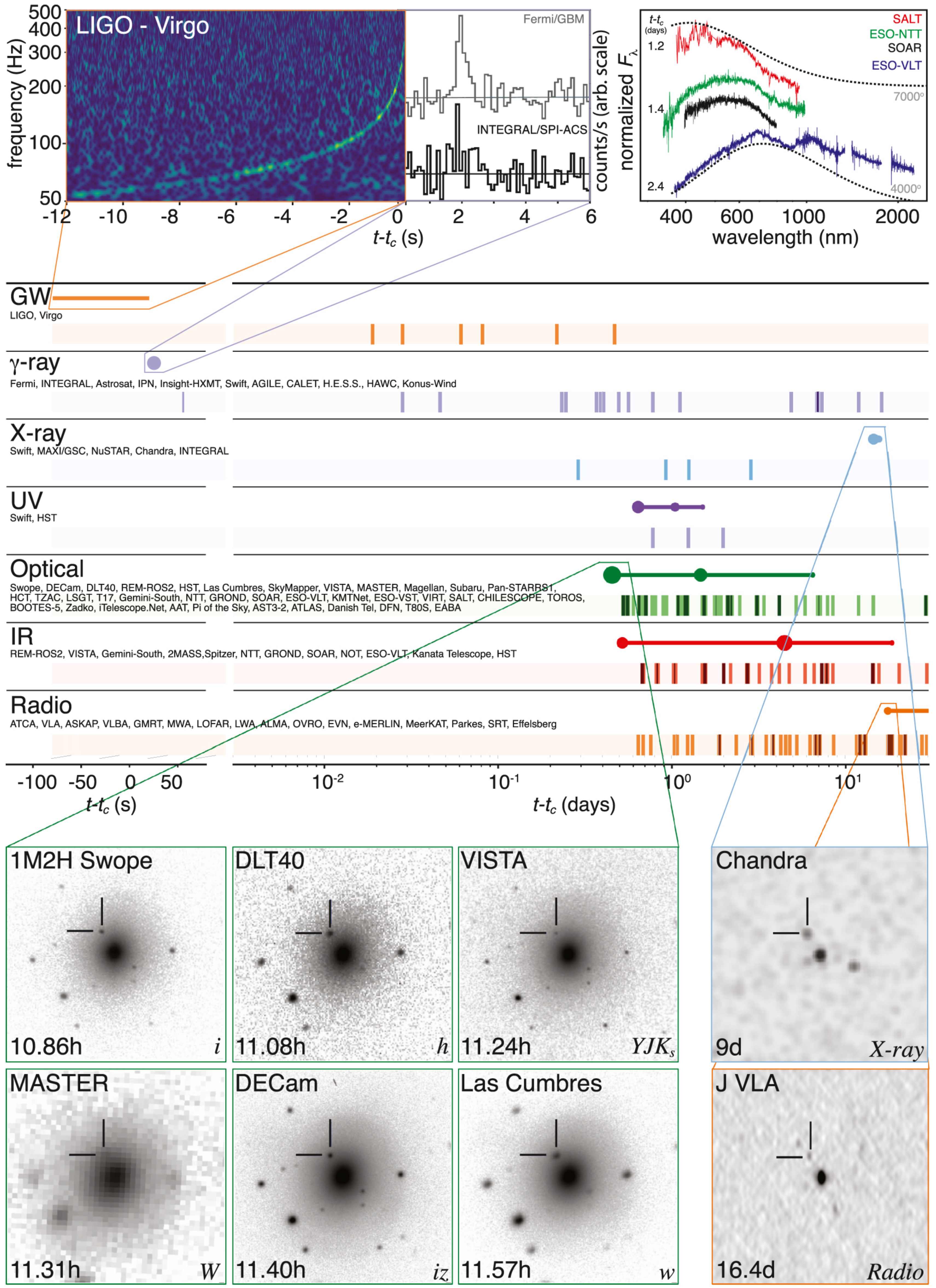
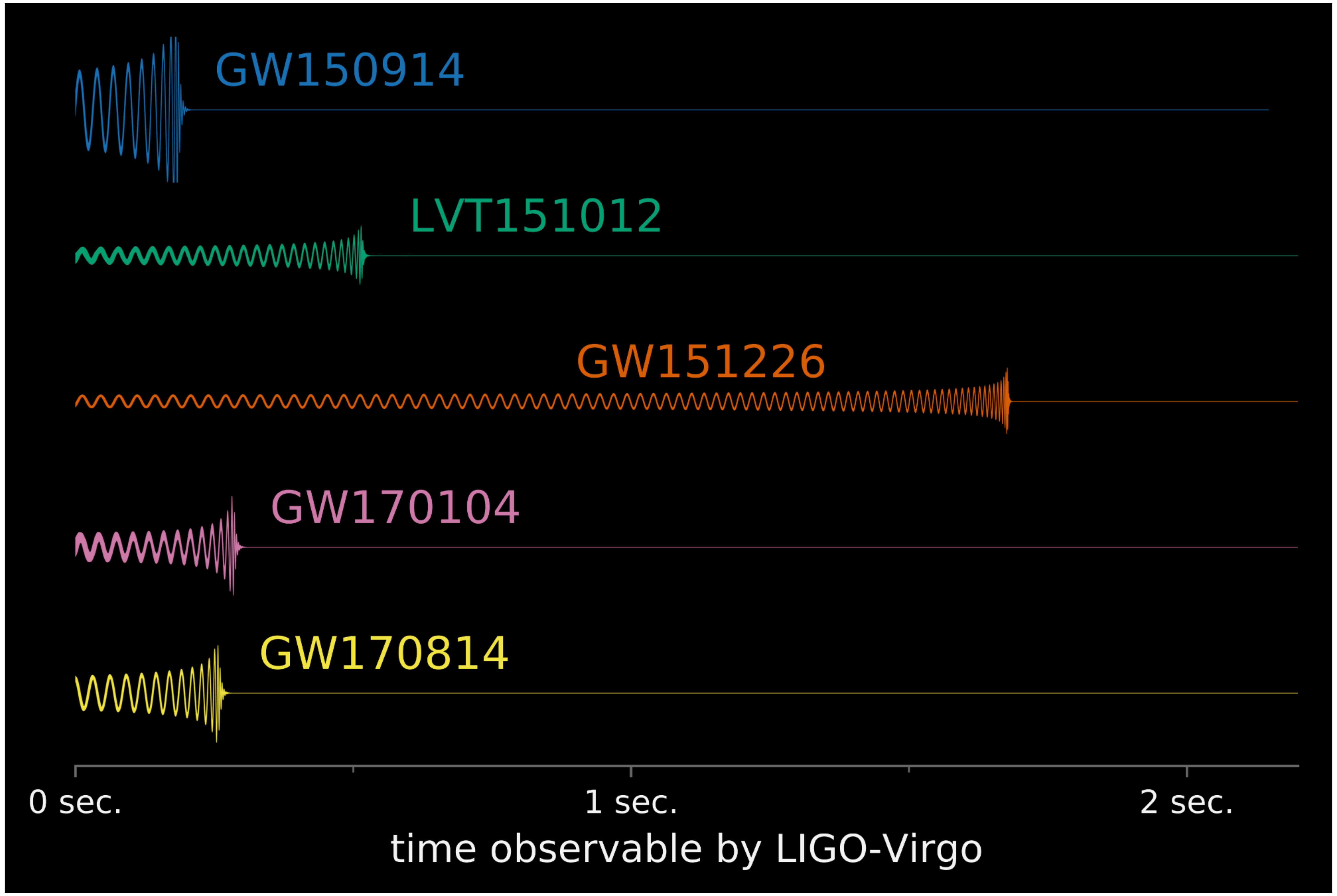
Led to a huge MM follow-up programme



Another key GW170817 feature

Beyond multi-messenger observations, GW170817 also looks different as a GW
- Previous GW signals lasted on the order of a second or less



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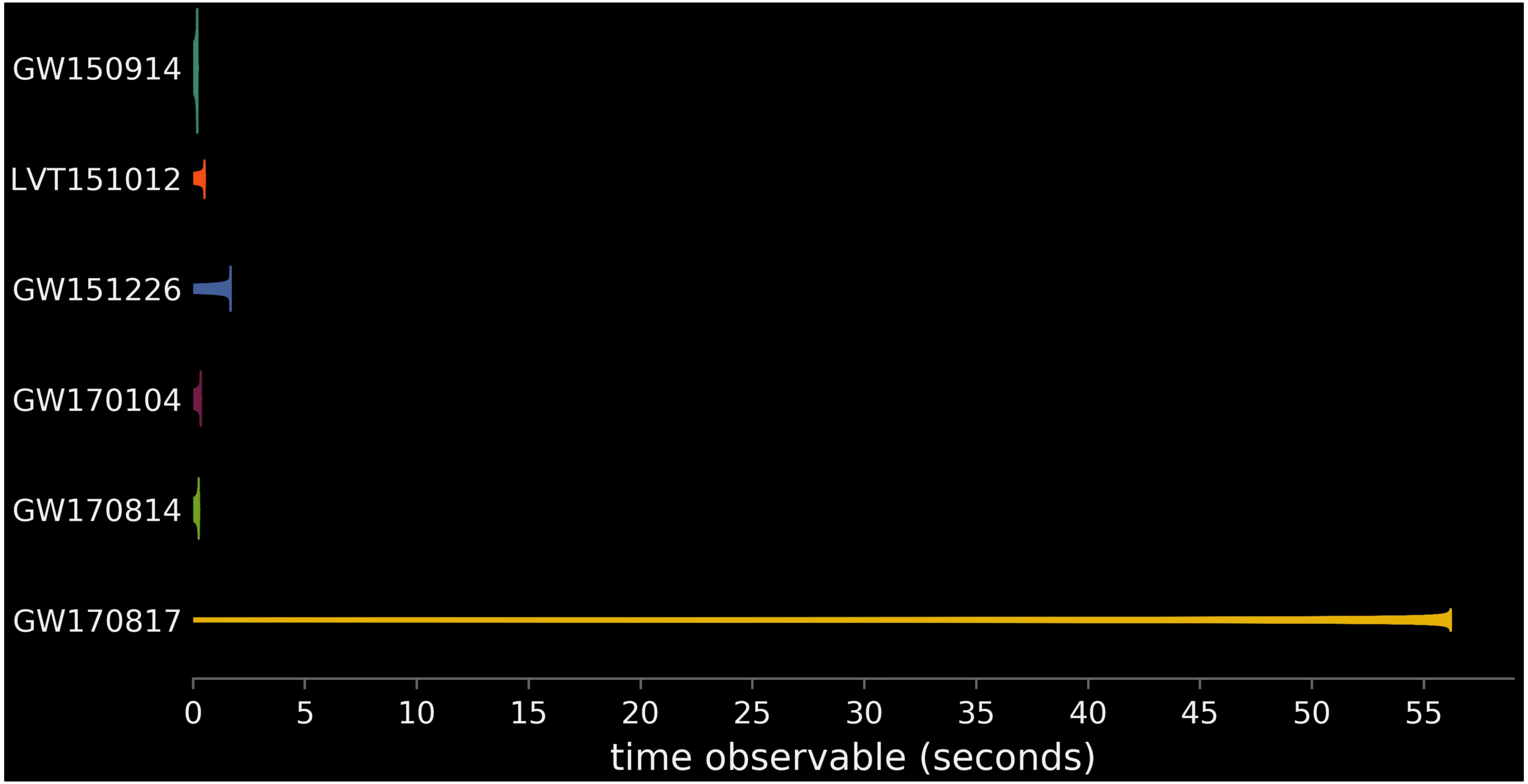

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What is going on?
- Previous signals were all BBH: binary black holes, with significant masses
- GW170817 is a BNS: binary neutron star, much lower mass
- Less massive = takes more time to coalesce (weaker gravitational interactions)

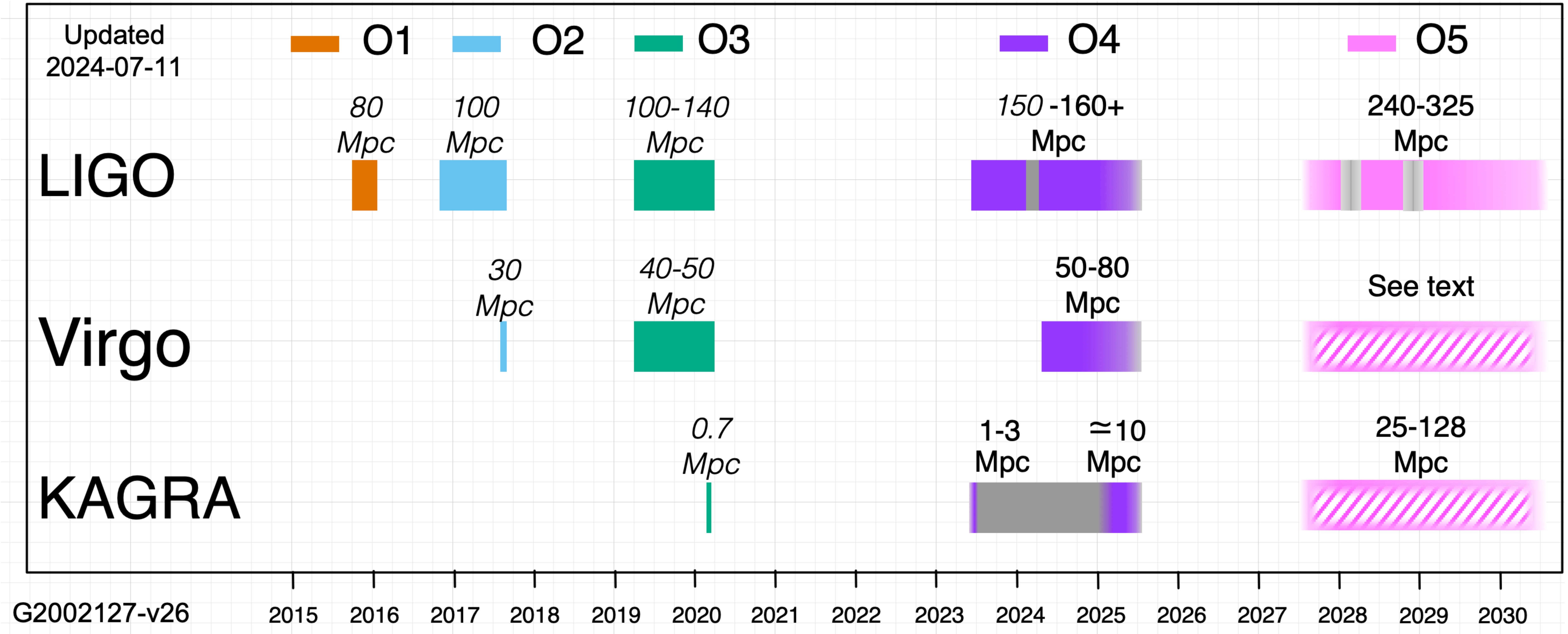
Multi-messenger observations confirm this first BNS as a kilonova source

Masses in the Stellar Graveyard

The future of 2nd gen GW detectors

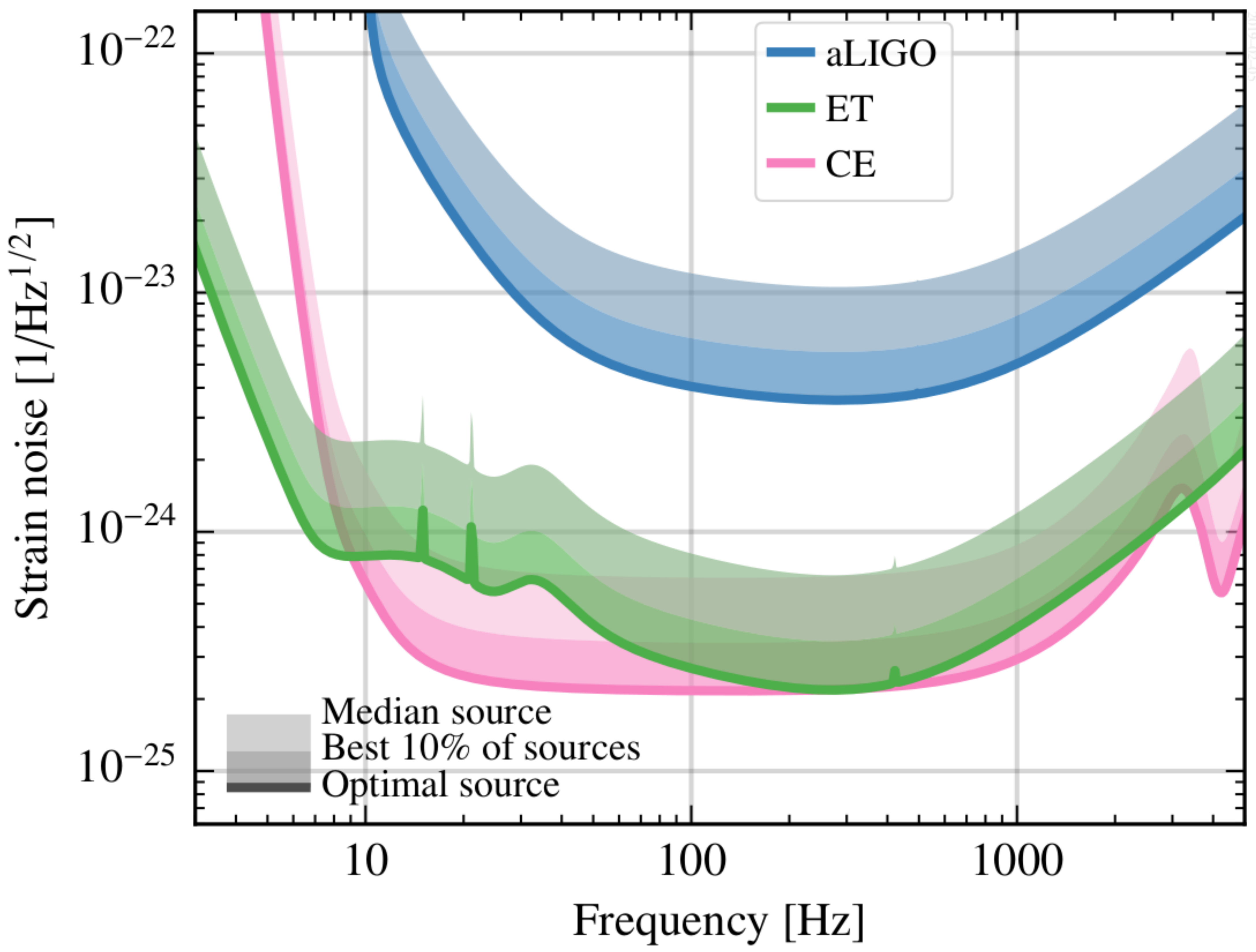
Up to the end of O3, LVK observed roughly 90 binary coalescence events
- Roughly one observation per week, with growing sensitivity

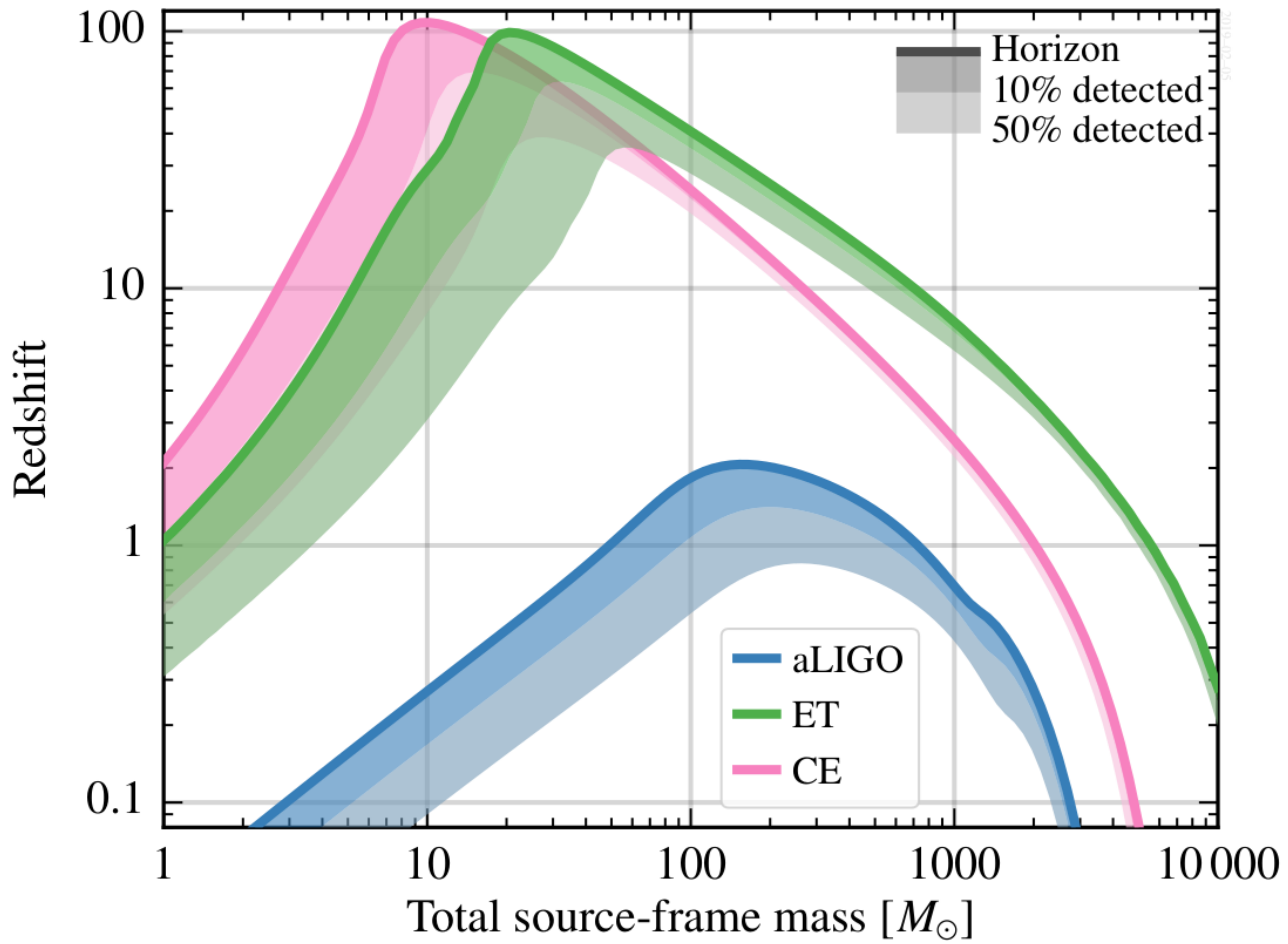
Upgrades are planned for the O5 run, and are being proposed for a potential O6
- Will increase sensitivity, but ultimately limited by the infrastructure



The 3rd generation GW detectors

Einstein Telescope (ET, Europe) and Cosmic Explorer (CE, USA) have been proposed
- Different configurations, but both dramatically improve on LIGO 2nd gen
- 10x increase in strain sensitivity = 10^3 increase in sensitive volume
- Extends reach in redshift (time) from the local to primordial Universe





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Cosmic Explorer: continue the current LIGO 2nd gen strategy
- A pair of laser interferometers: one with 20km arms, one with 40km arms
- Take advantage of the fact that there are large unoccupied deserts in the USA

Einstein Telescope: a new strategy, building on KAGRA as a pathfinder
- Roughly 250m underground to minimise noise and background sources
- Both high-frequency (classic) and low-frequency (cryogenic) interferometers
- A triangular configuration of 3 nested interferometers per frequency range
- Baseline is 10km arm length, but alternatives are under study (more on this later)

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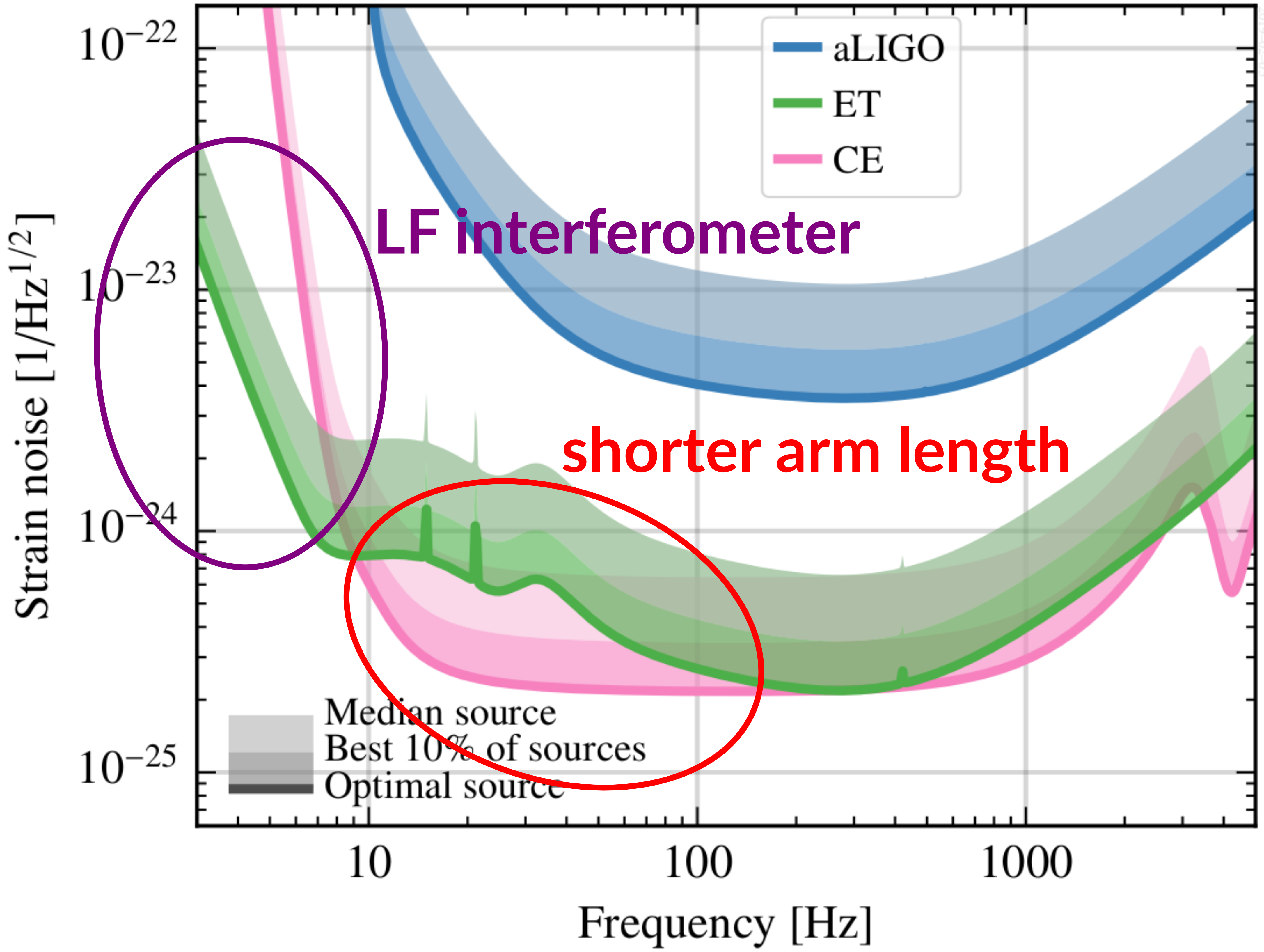

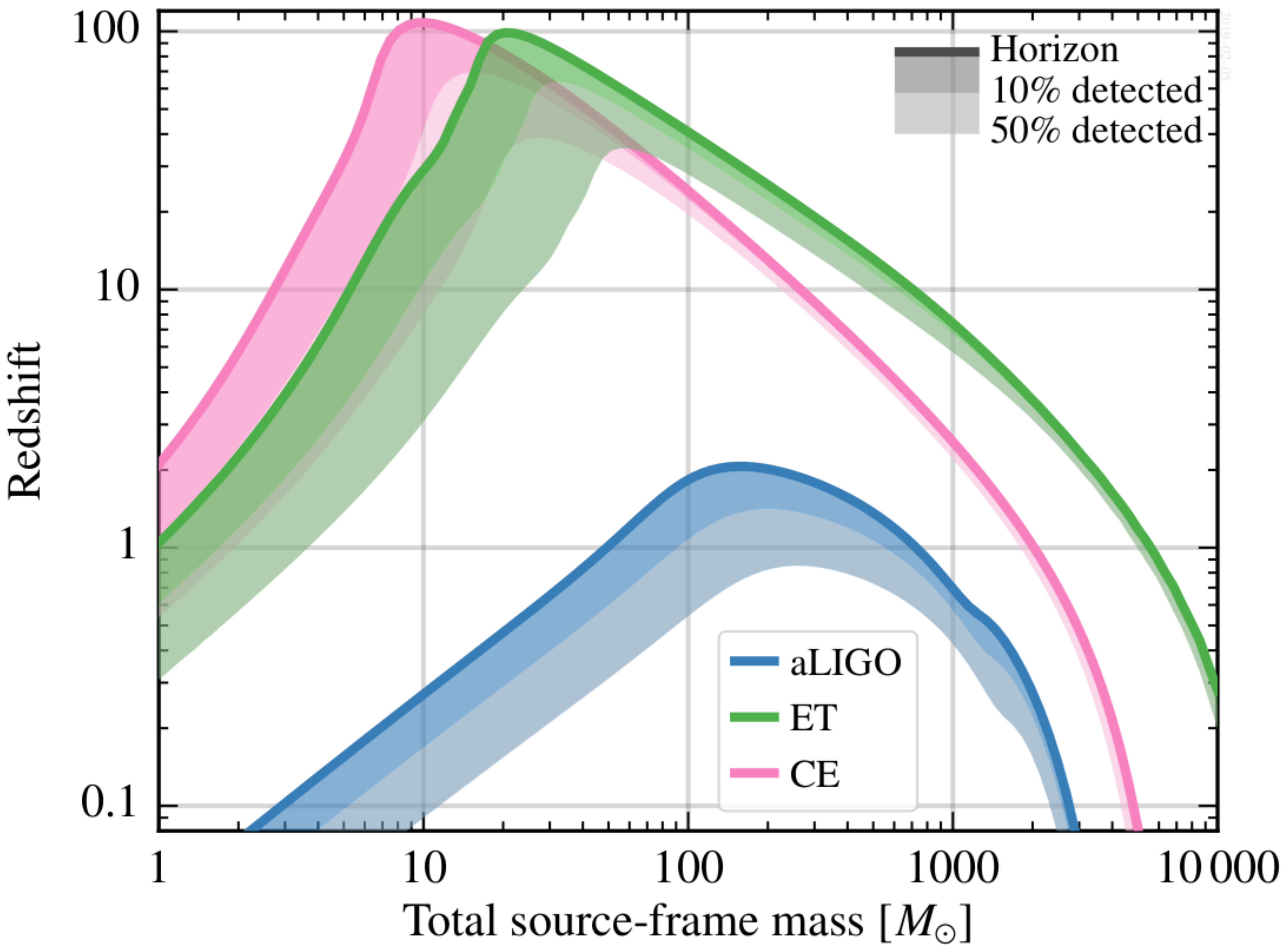

Implications of 3rd generation sensitivity

Einstein Telescope and Cosmic Explorer increase strain sensitivity by 10x
- 10x more SNR for a given signal at a given time
- Longer SNR integration time (wider freq. range)
- "Golden signals" can have SNR > 1000
- **Extreme precision on GW parameters!**

Sensitive volume grows by strain^3 = 10^3
- BNS/BBH not uniformly distributed in redshift

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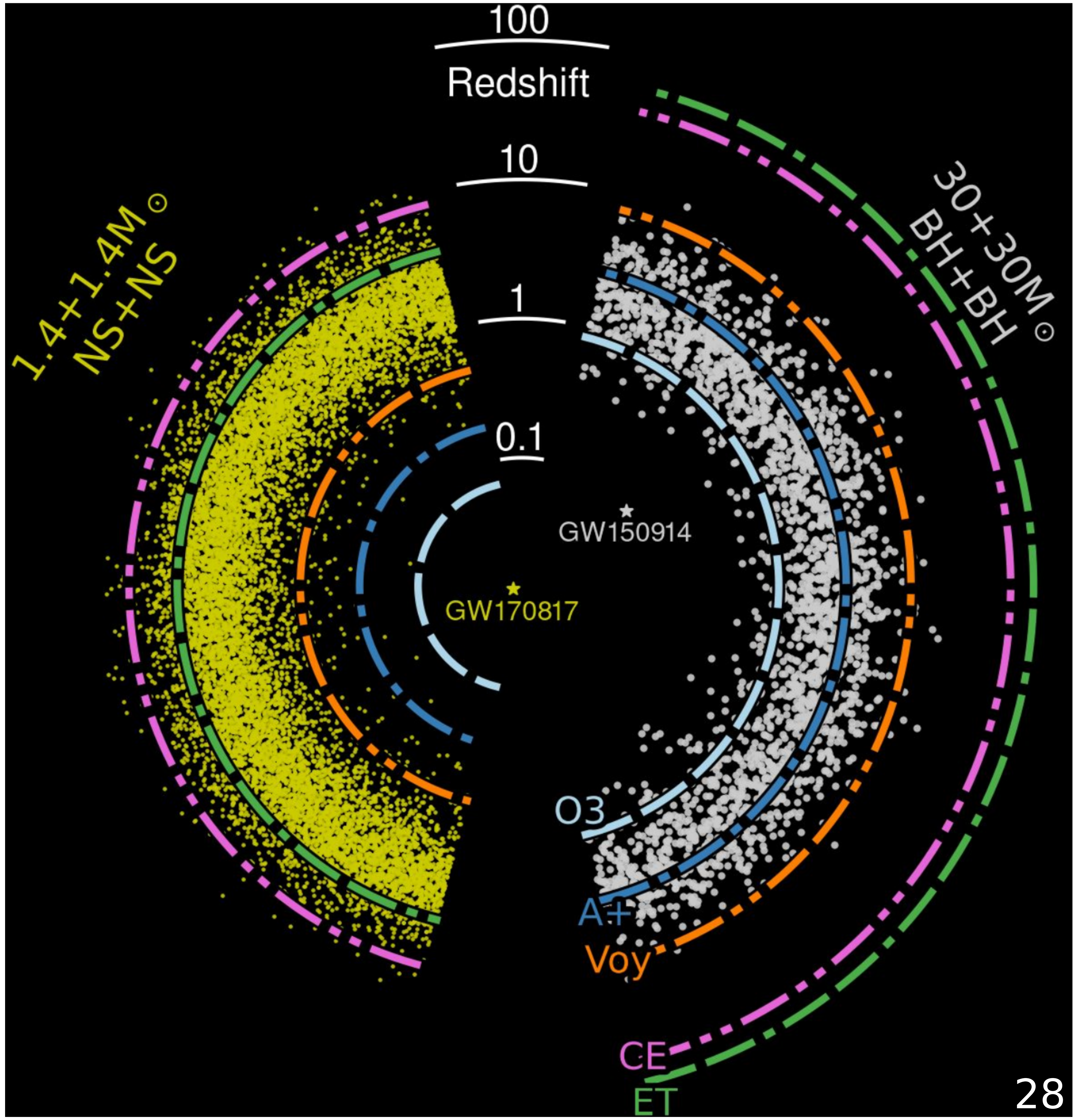


Sensitive volume grows by strain^3 = 10^3
- BNS/BBH not uniformly distributed in redshift
- 1 signal/week becomes 1/min: 10^4 increase
- ET sees large majority of BNS, CE even more
- Both see vast majority of non-primordial BBH
- **Huge increase in GW event rates and types**

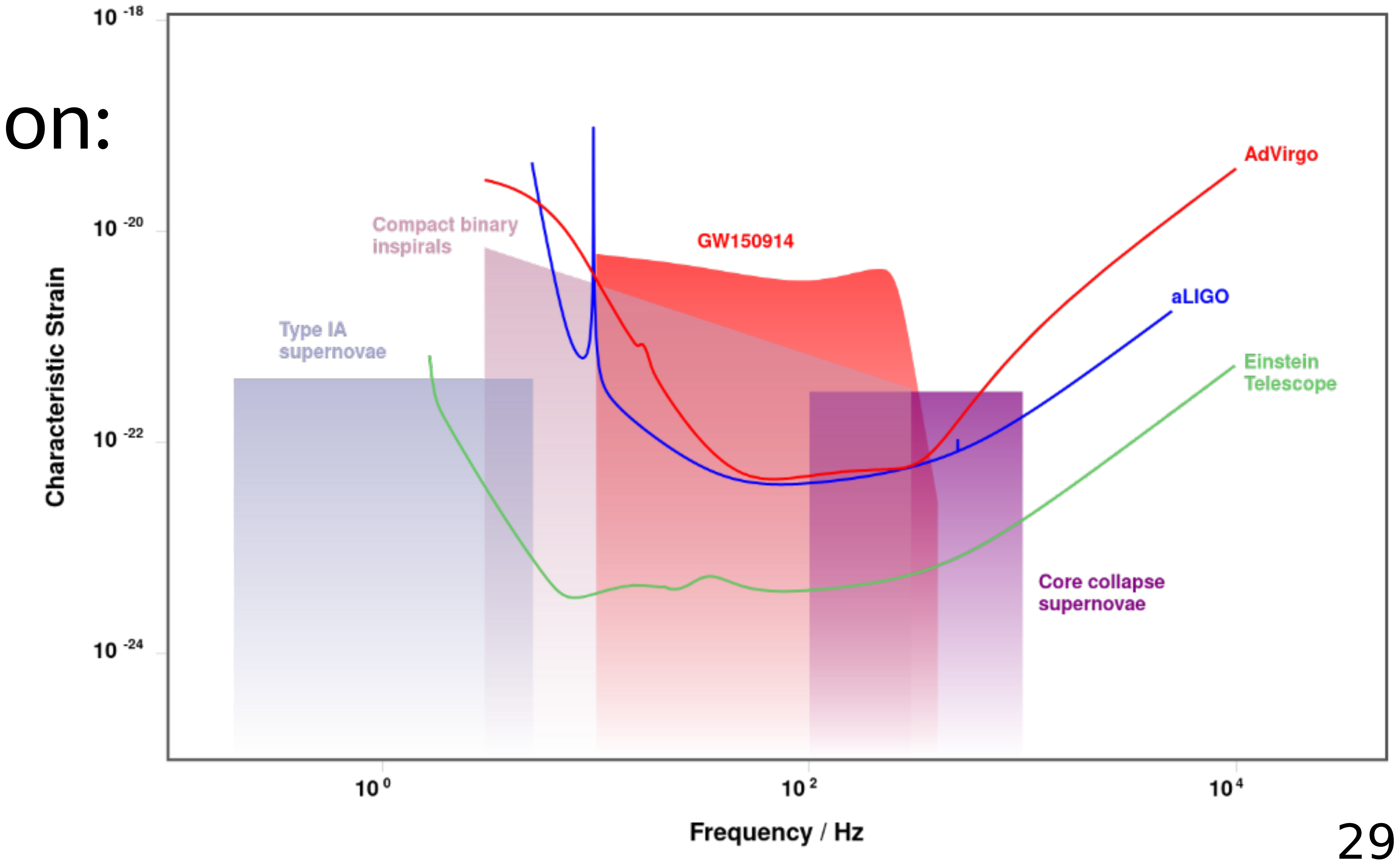
3rd gen GW gives both precision and discovery
- Similar to combining LEP+LHC in one device

The Einstein Telescope science case

Going forward, I will focus on ET over CE: ET studies are more advanced
- They have a very similar science case, and ideally will operate as a network

The entire science case is too extensive to cover; for more details see:
- ET science case for the ESFRI proposal: arXiv:1912.02622
- ET science case for different configurations: arXiv:2303.15923

I will present a particle-physics-biased selection:
- Neutron stars and QCD
- Multi-messenger astrophysics
- Supernovae and neutrinos
- Dark matter
- Dark energy
- Probing quantum gravity

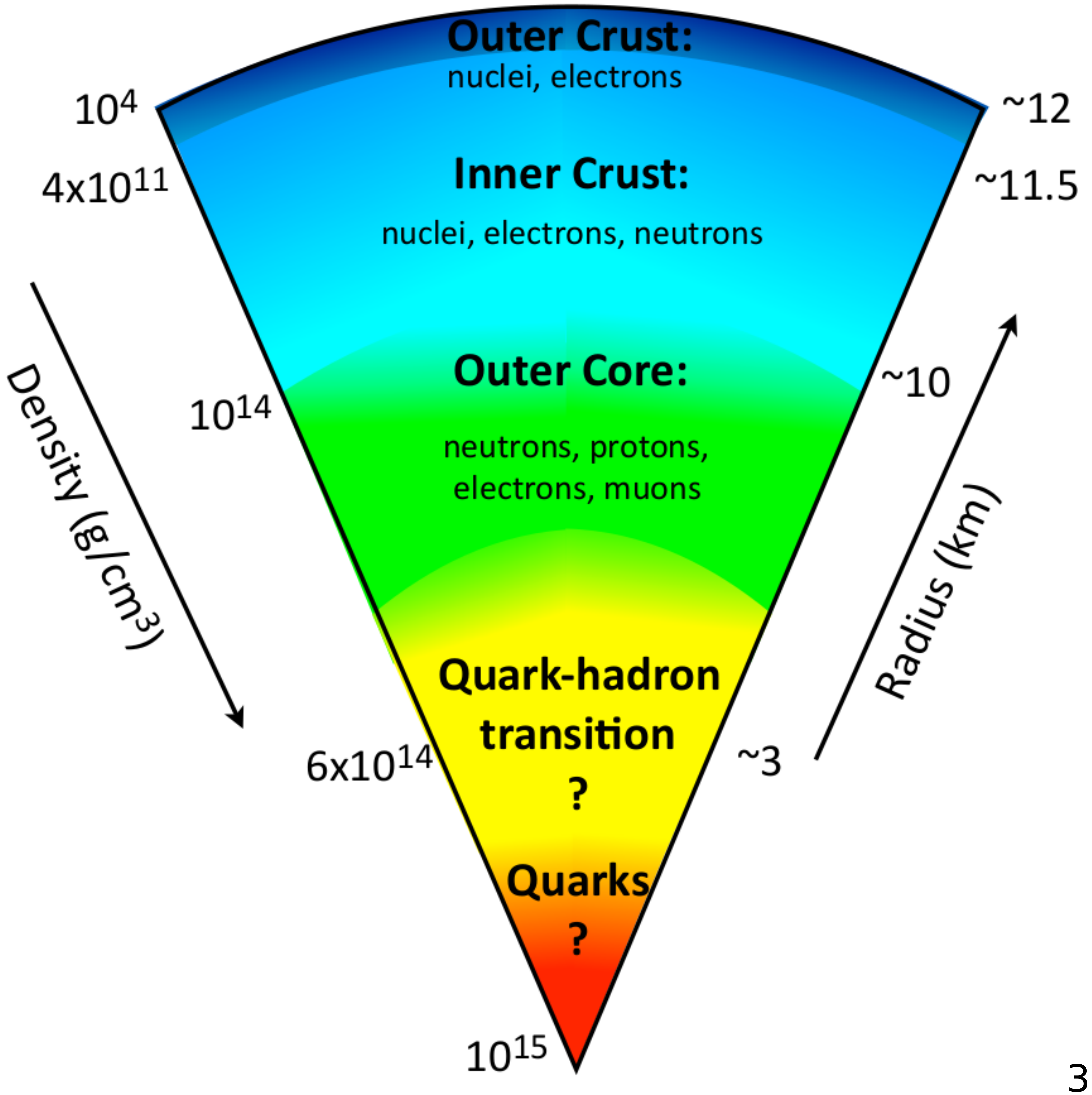


Neutron stars and QCD

Neutron stars are an excellent environment to study QCD in a new domain
- Low-temperature and high-density compared to nuclear or particle physics

The NS equation of state can be measured using gravitational waves
- Sensitivity to individual NS (pulsars)
- Alternatively, BNS in the early inspiral

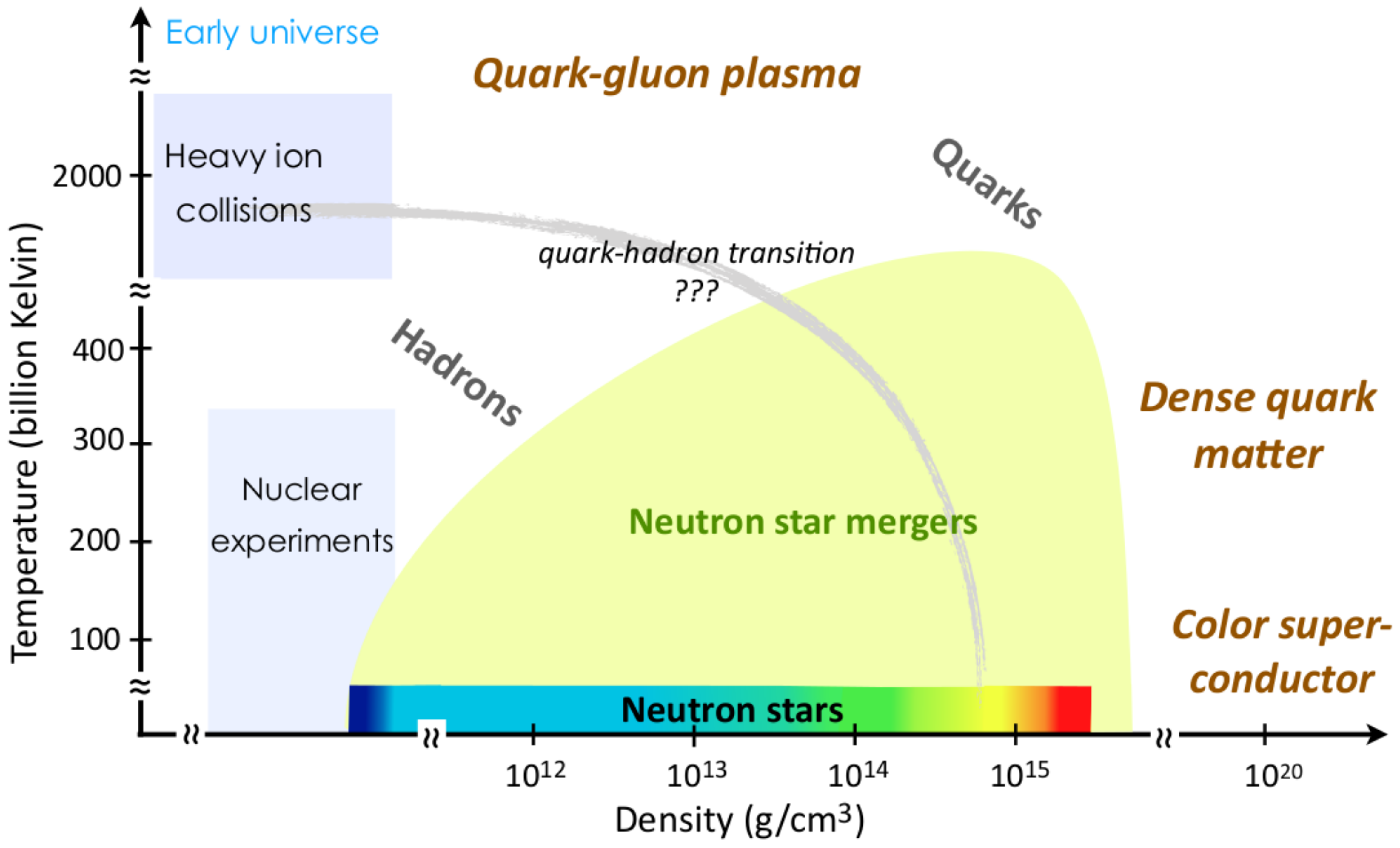
May provide evidence for deconfined quarks or exotic states of matter
- At least probes the quark-hadron transition at low temperature

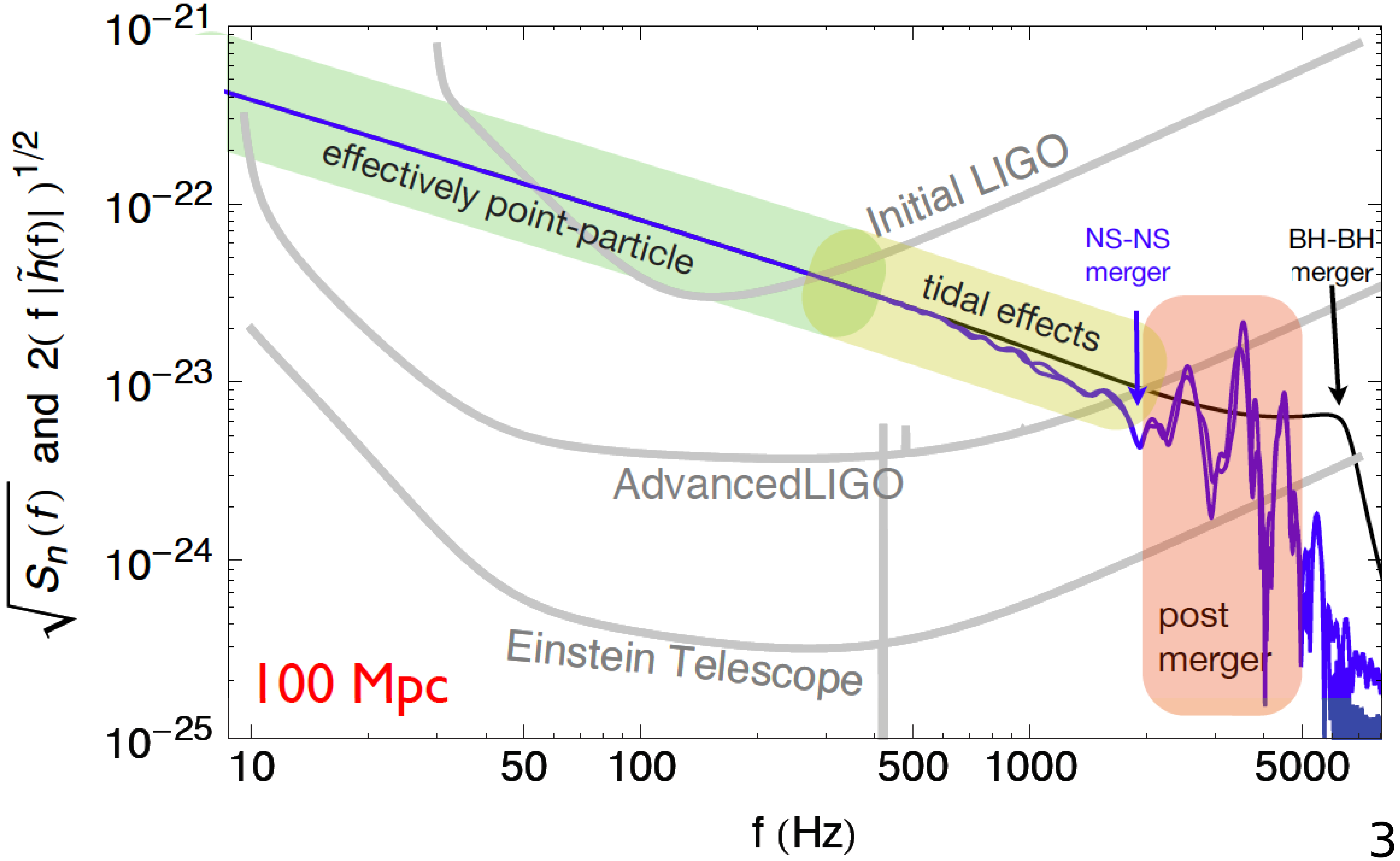


Binary neutron stars and QCD

Individual neutron stars are a great start, but cover a specific regime
- Much larger coverage by measuring the equation of state following BNS mergers

This is possible with ET: dramatically increased sensitivity to the BNS ringdown
- Covers complementary (temperature,density) space to other experiments
- May provide key insights into how the strong force behaves





Multi-messenger astrophysics

Multi-messenger and multi-band observations are key to understanding the details of the most energetic phenomena in the Universe
- GW170817 was the birth of MMA involving GW signals
- BNS neutron star coalescence, with a huge visible-spectrum follow-up effort

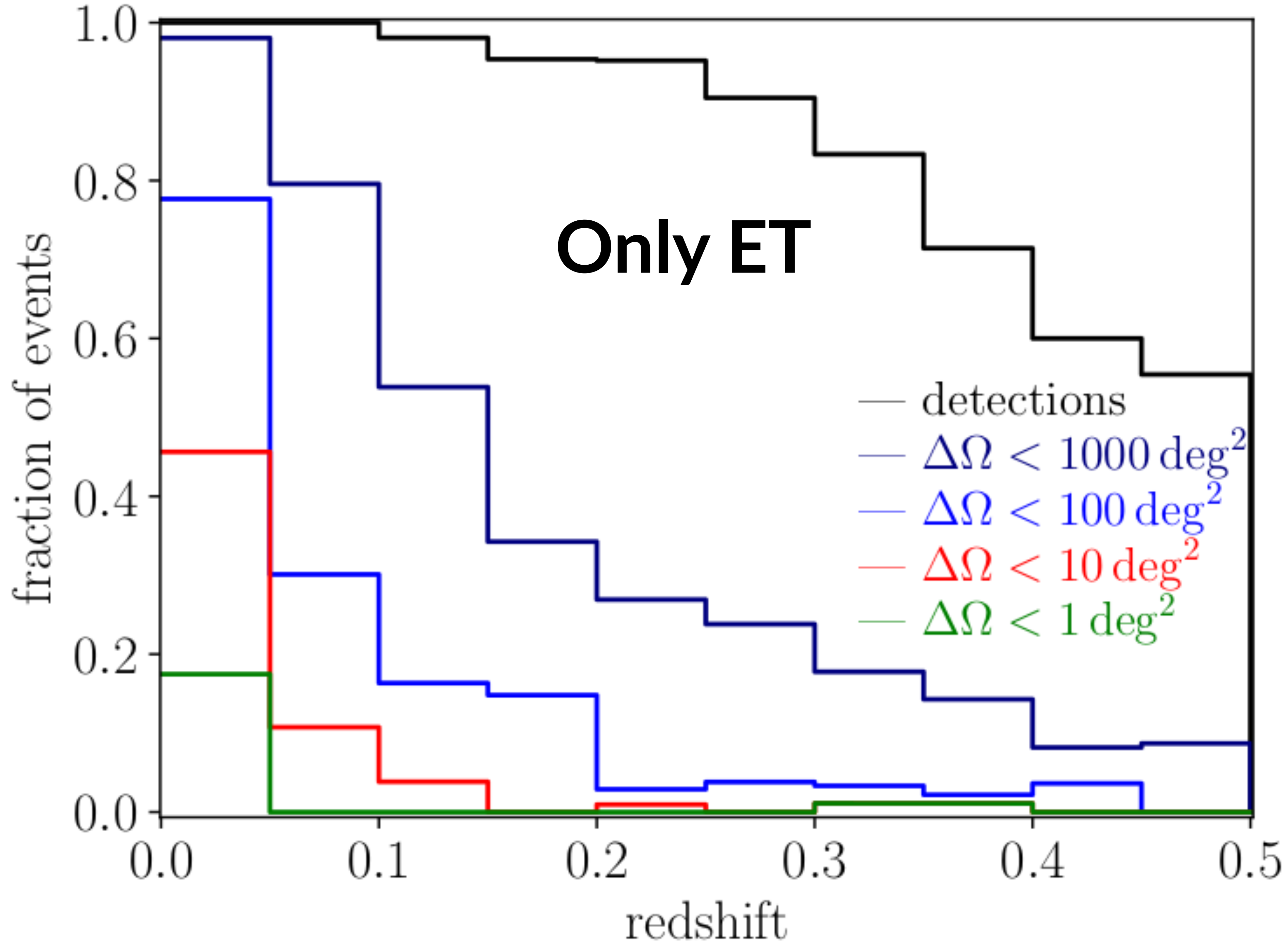
The GW coalescence event was seen to occur before the visible spectrum
- From second(s) before the GRB signals to week(s) before the radio signals

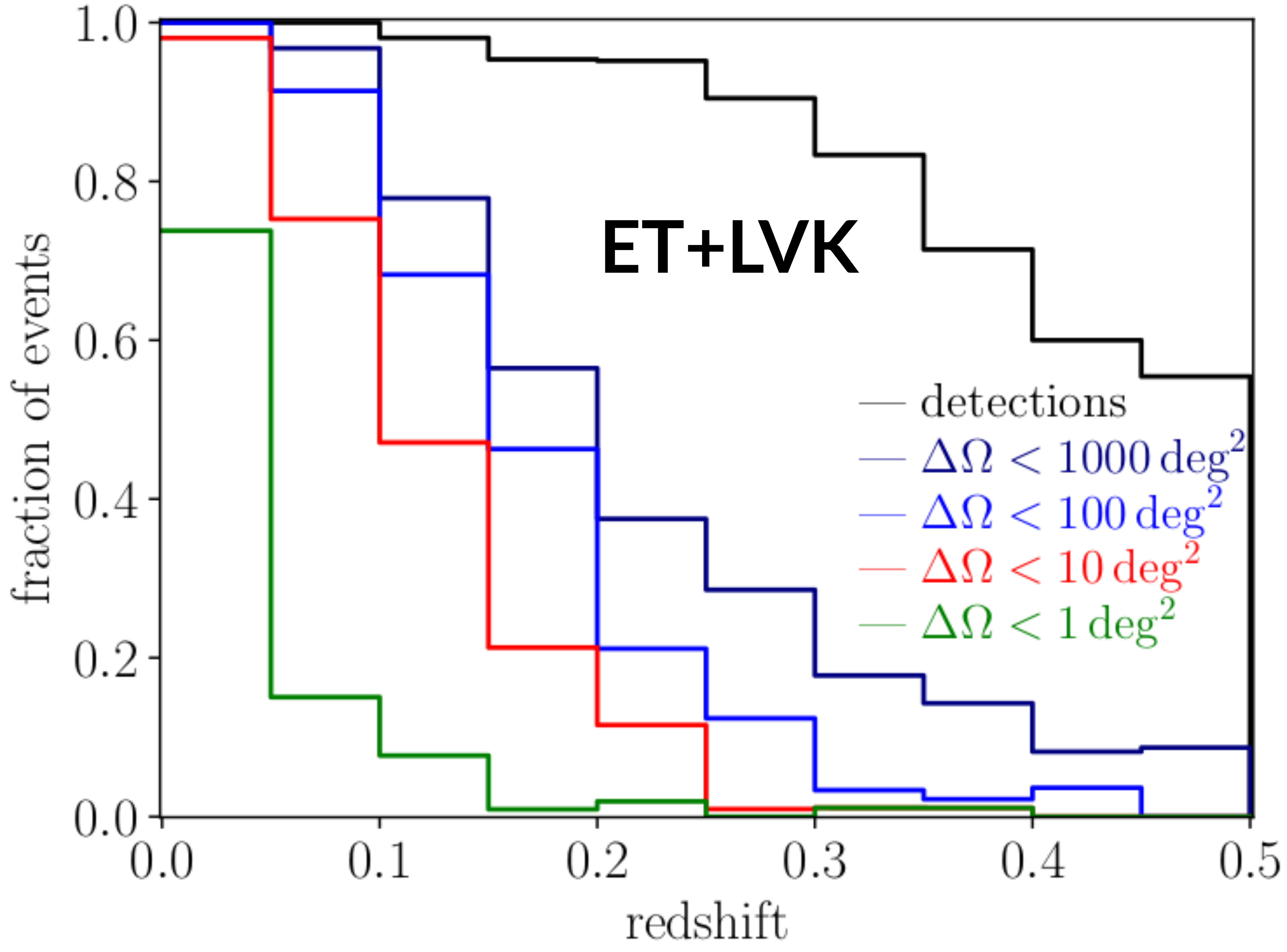
ET will revolutionise the potential for MMA with GW
- GW170817 was in-band for about a minute: not much time to react before GRB
- BNS signals can be in-band up to 24 hours at ET: **enables pre-merger detection**
- Optical telescopes can react/reorient to focus on signals matching their interests

MMA and sky localisation

ET enables pre-merger detection of MMA candidates, but sky localisation is harder
- Precise sky localisation is critical to supporting visible-spectrum follow-up
- GW detectors are full-sky surveys; GW networks are needed for triangular

ET is a network of three nested interferometers, so it can perform some localisation
- Physical distance is important; adding 2^{nd} gen LVK to ET really helps (CE even more)

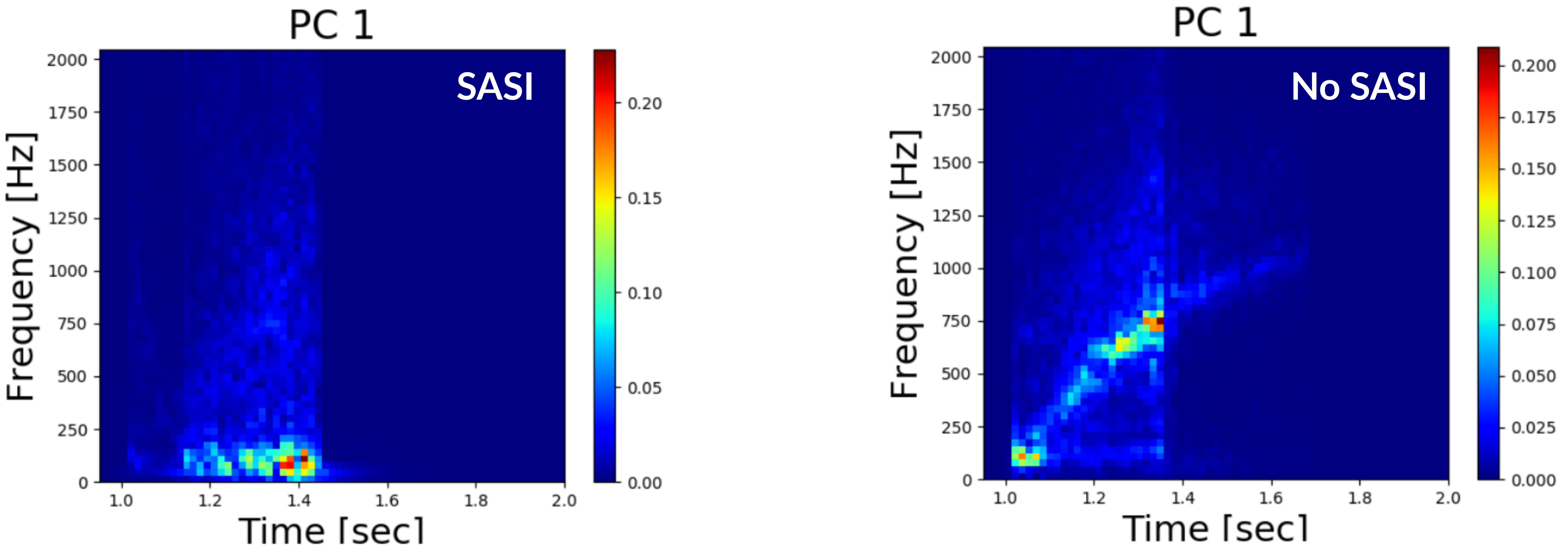




MMA and core collapse supernovae

MMA can also work the other way: core collapse supernovae are weak GW signals
- Neutrino flux can pinpoint such an occurrence, and be used to find the GW signal

The GW signal then provides unique access to the internal NS dynamics
- For example, confirm/reject the Standing Accretion Shock Instability (SASI) model



Dark matter: primordial black holes

Primordial black holes are BH formed in the very early Universe
- Concerns the time before the matter-dominated era, aka before stars exist

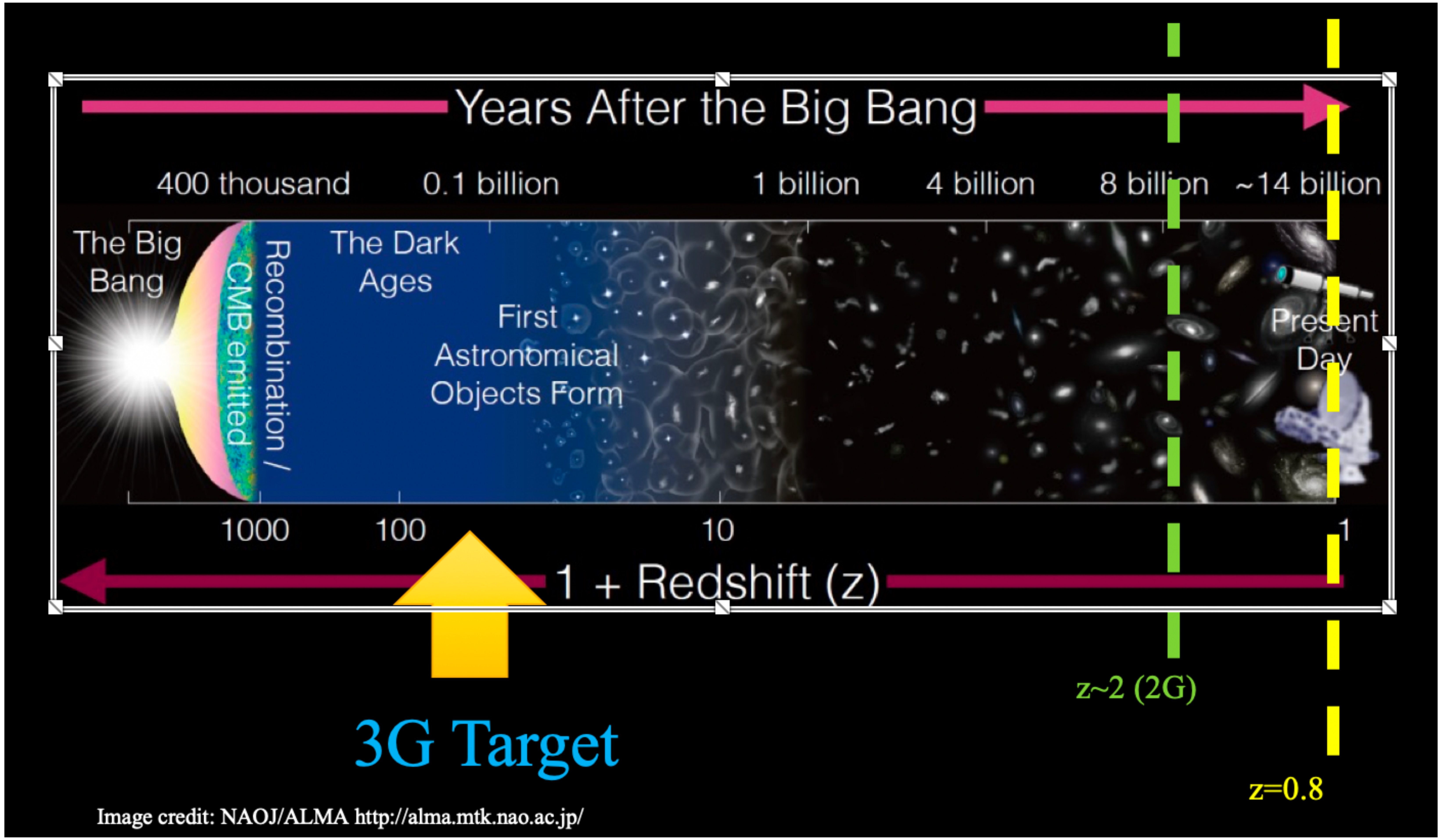
Such black holes are a direct collapse of local overdensities
- No stellar mass constraints, as they do not originate from stars
- May be very low mass to very high mass, and everything in between

Primordial black holes may explain part/all of the dark matter in the Universe
- Only gravitational interactions, and could produce the observed DM distribution
- Constraints on PBH vary significantly with mass and formation mechanism

If they exist, ET could provide the first clear evidence for primordial BHs

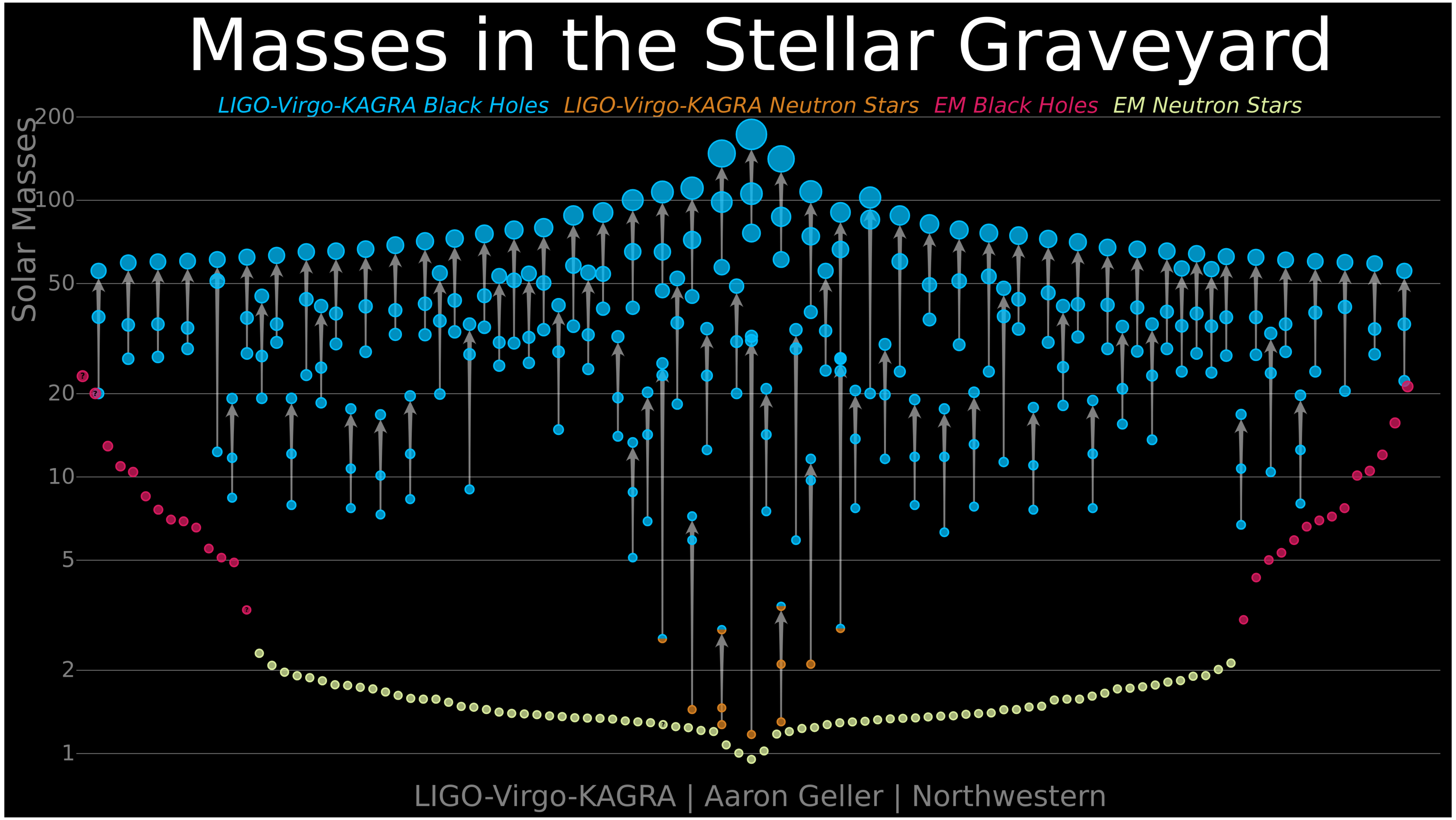
Primordial black holes at high redshift

ET is sensitive to BBH mergers from the era before astronomical objects formed
- Redshift 20 is roughly the point at which the first galaxies formed
- ET can probe up to redshift 100 in the best cases, redshift 30+ over a wide range



Primordial black holes at low mass

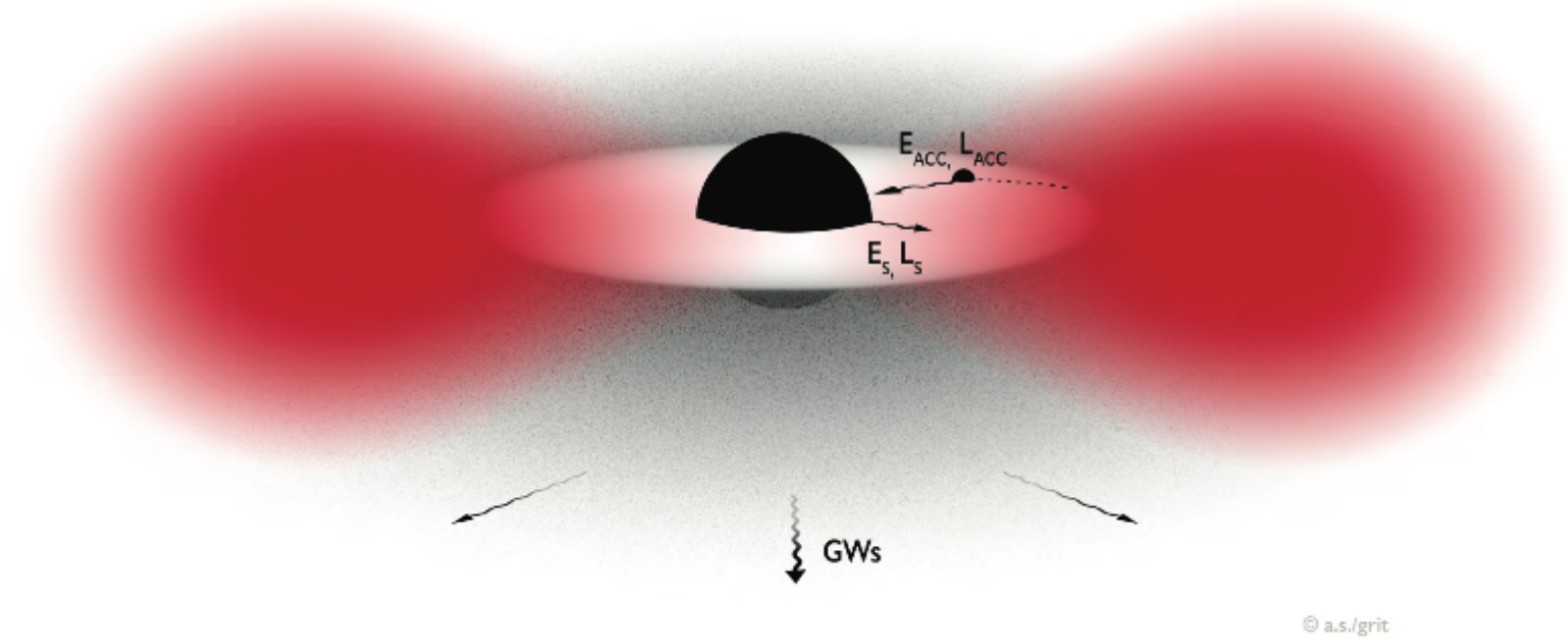
Stellar-origin black holes must consist of at least a few solar masses
- ET will have the sensitivity to probe sub-solar mass binary events
- Any evidence for such events would be a clear signal of primordial black holes



Dark matter beyond primordial black holes

Ultralight bosons are also a credible DM candidate, and can generate GW signals
- If the boson has a Compton wavelength comparable with Schwartzschild radius, then they can be produced around black holes via superradiance
- Boson mass 10^{-21} eV to 10^{-11} eV correspond to stellar mass to supermassive BHs
- Lower mass range compatible with DM, higher mass range with QCD axions

Can form Bose condensate clouds up to 10% of parent BH mass, rotating around BH



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More generally, DM may accumulate within neutron stars due to gravity
- The presence of a DM core would impact the NS equation of state
- May also impact how BNS mergers occur, if the DM interacts between NSs
- ET should be able to search for such effects in GW signals from NS and BNS

Dark energy and gravitational waves

GWs are arguably the best probe we have for directly studying dark energy
- Arguably beyond particle physics, but we search for some DE models at colliders

Gravitational waves measure the luminosity distance, d_L, to the signal
- The relation between d_L and the redshift, z, carries key cosmology information

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

Under ΛCDM, $\rho_{\rm DE}(z')/\rho_0 = \Omega_\Lambda$, which is a constant
- Population studies of gravitational waves will directly probe the ΛCDM model

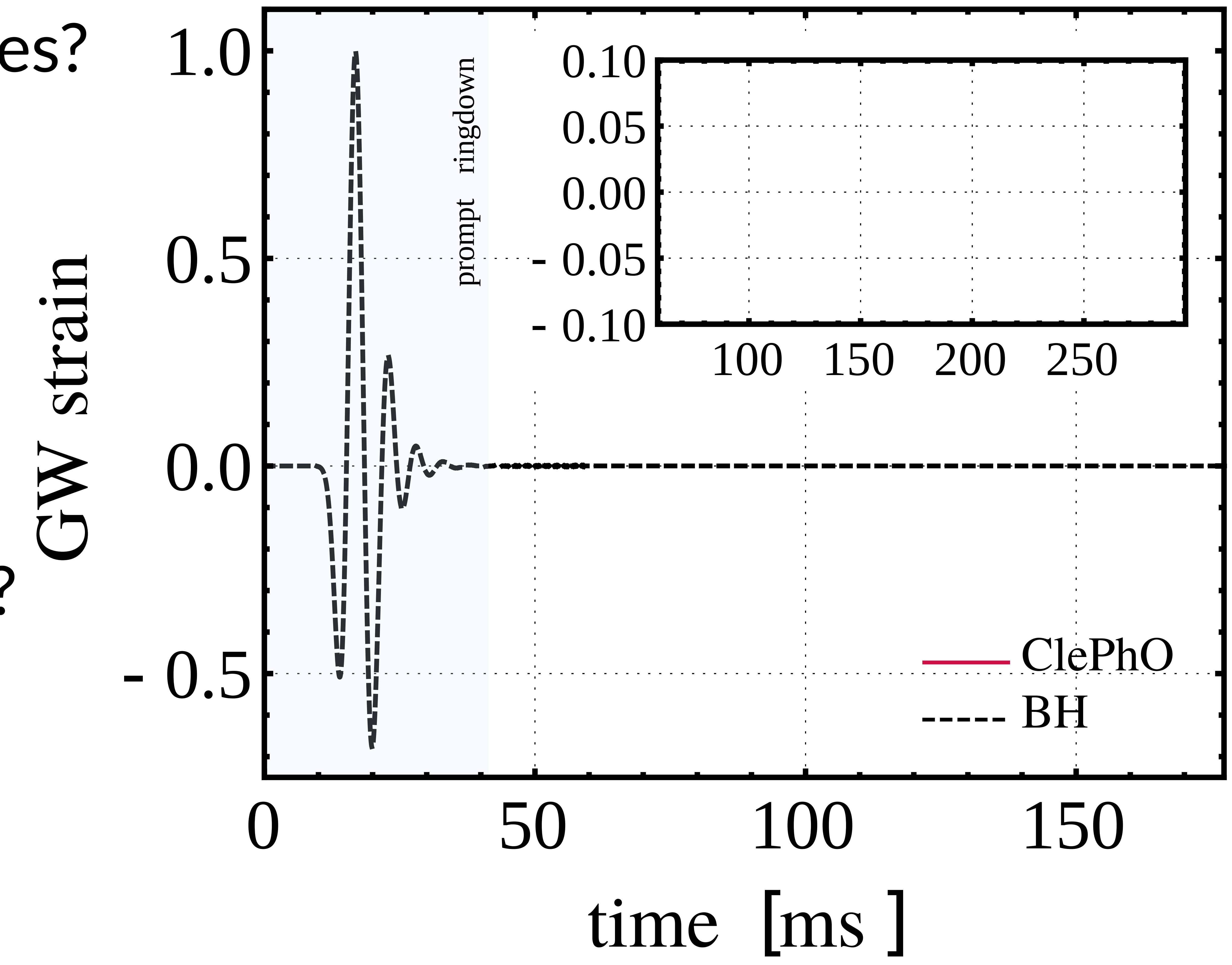
This task requires joint effort: d_L from GW, and z from the visible spectrum
- Must probe $z >> 1$, or else reduces to the Hubble law
- LVK is constrained to low redshift, while ET will probe high z in great detail

Echoes of quantum gravity

LVK have discovered ~90 BBH signals so far
- How do we know they are really black holes?

Black holes are very simple objects
- Trivial ringdown defined by mass and spin
- LVK has not yet had sufficient sensitivity to ringdown to confirm traditional BHs

What if they are instead some other object?
- Boson stars, dark matter stars, etc



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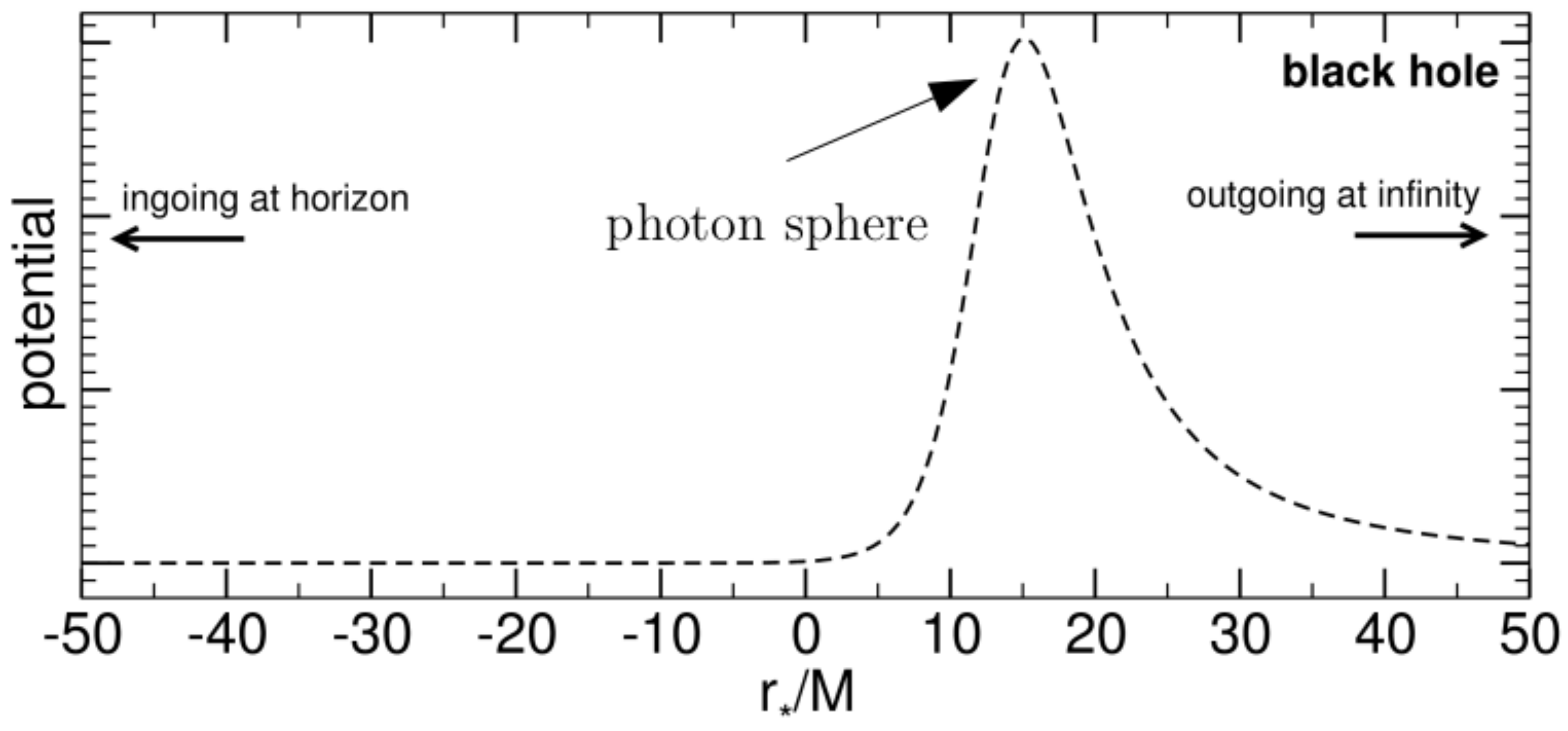
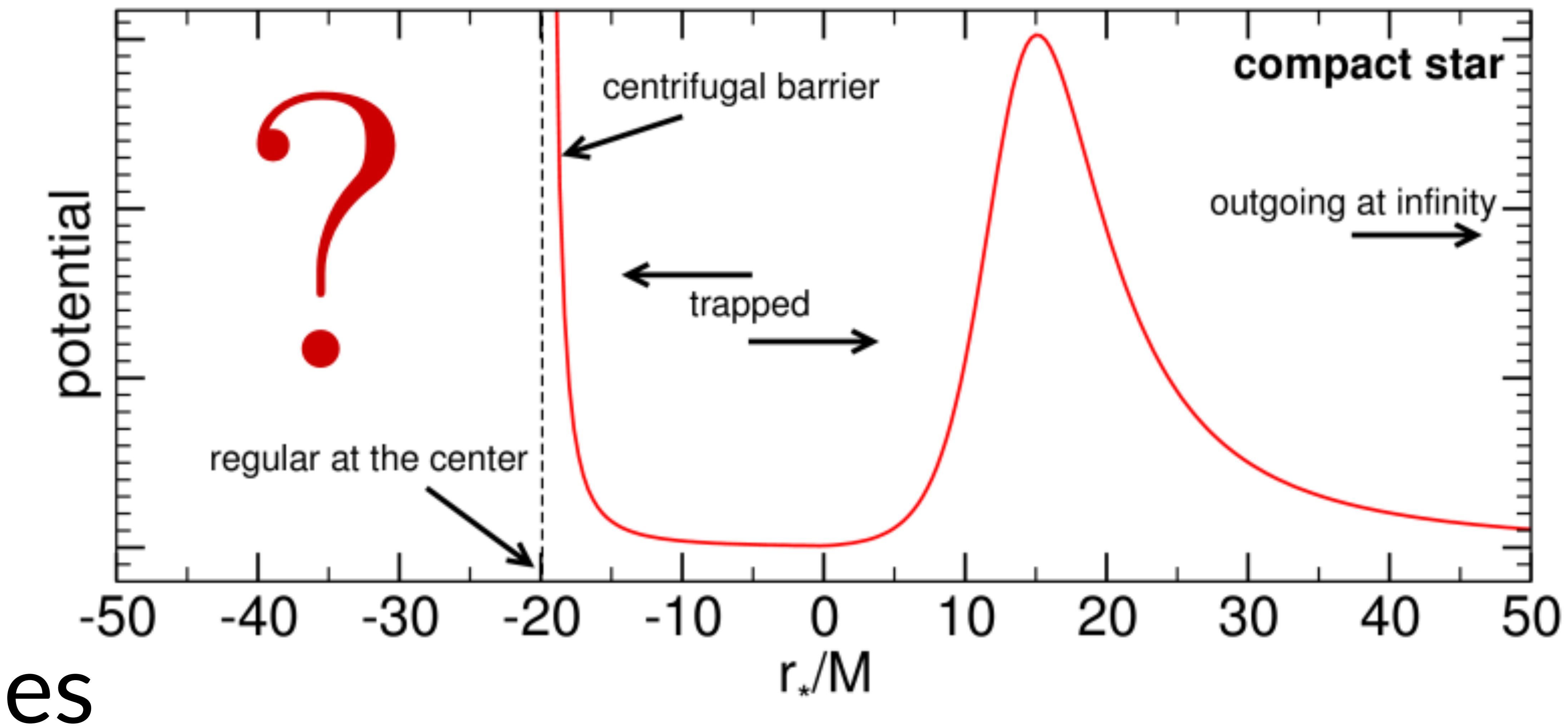
Black holes are very simple objects
- Trivial ringdown defined by mass and spin
- LVK has not yet had sufficient sensitivity to ringdown to confirm traditional BHs

What if they are instead some other object?
- Boson stars, dark matter stars, etc

Exotic compact objects (ECOs) may mimic BHs
- Can have a photon sphere preventing light escape, yet still have a surface underneath
- Provides a trapped region, causing signal echoes





Echoes of quantum gravity

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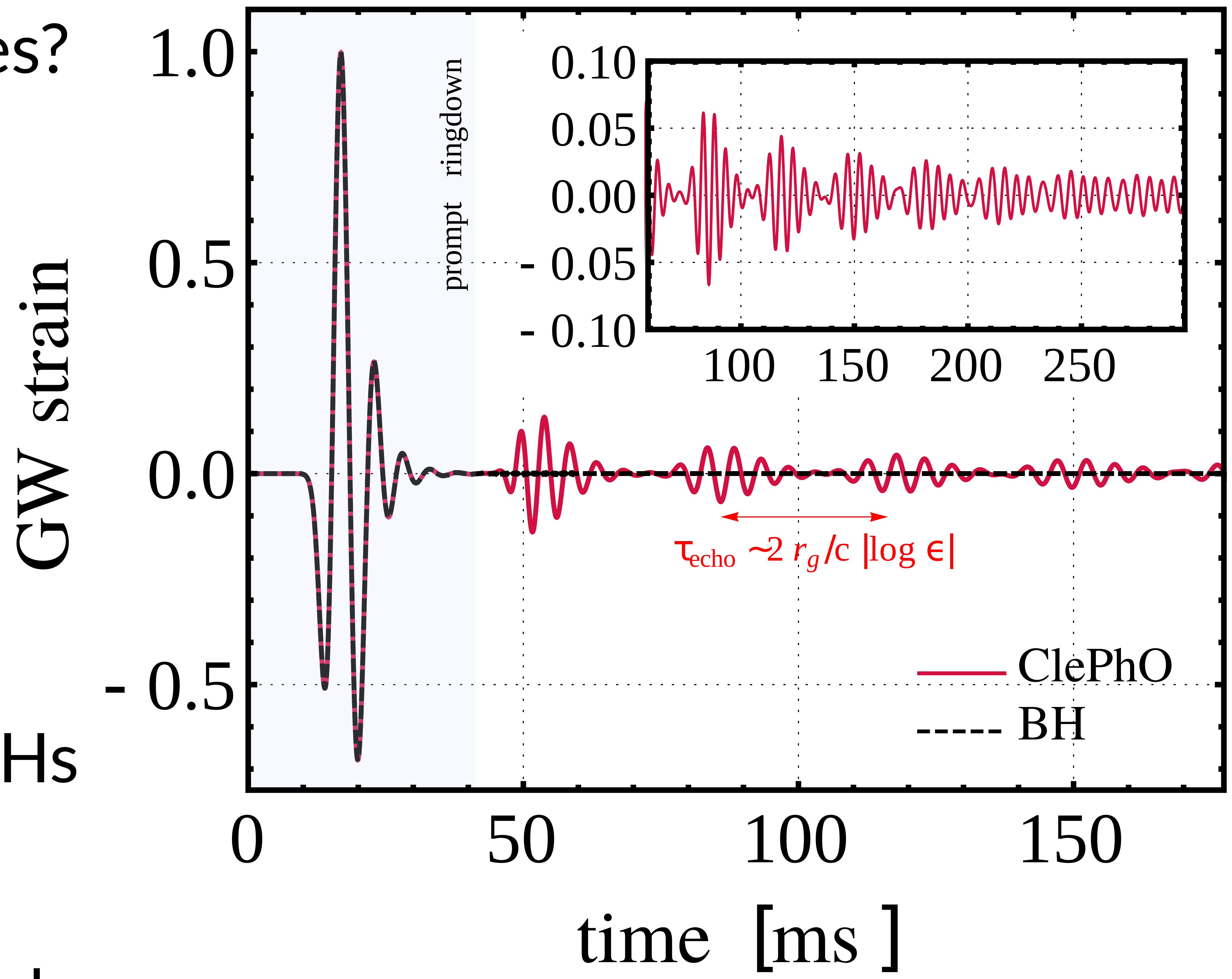

Echoes of quantum gravity

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Black
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- LVK
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> ***These tests could also in principle lead to surprises, such as revealing the existence of exotic compact objects, and could even carry observable imprints of quantum gravity effects. While the latter goals are more speculative, their impact would be revolutionary.***
> -- Science Case for the Einstein Telescope (2019)

What
- Boso

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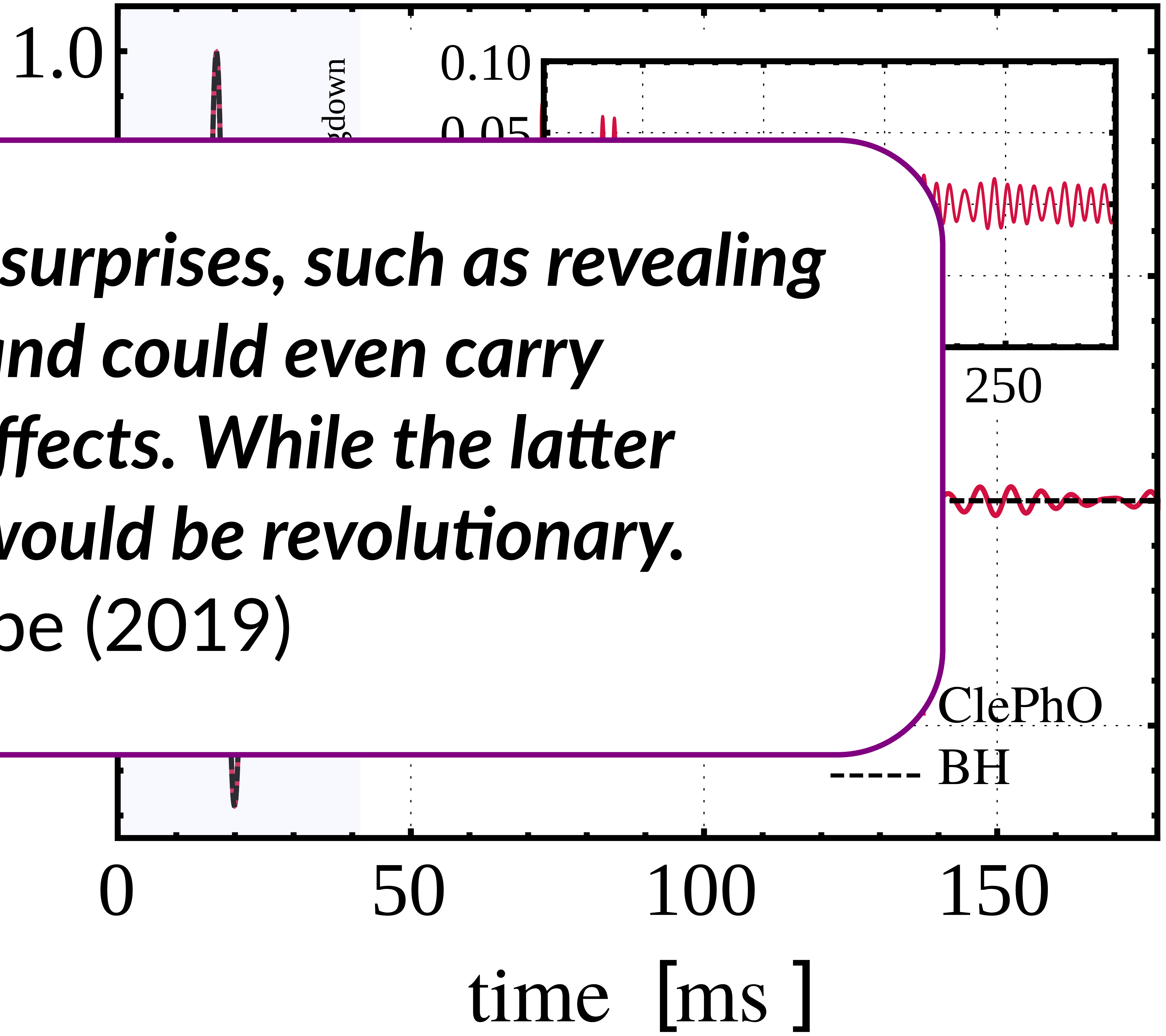

The Einstein Telescope science case

We have only seen a small fraction of the interesting possibilities with ET
- A selection biased towards particle physics interests

Some of the topics are "certain", while others are stretch goals
- Neutron stars and BNS mergers will give excellent information on QCD
- Multi-messenger astrophysics with GW will open a new window on the Universe
- Dark matter may or may not be visible, depending on what DM is
- Dark energy will be studied, testing the validity of the ΛCDM model
- Exotic compact objects may or may not exist, but they could probe quantum gravity

For more details on the science case, see:
- ET science case for the ESFRI proposal: arXiv:1912.02622
- ET science case for different configurations: arXiv:2303.15923

Status of the Einstein Telescope

The Einstein Telescope was submitted as an ESFRI proposal in 2020
- ESFRI = European Strategy Forum on Research Infrastructures

Approved and entered roadmap in 2021; largest ever approved proposal (2B EUR)
- ET Collaboration was formed in 2022; now >1500 people
- ET Organisation also formed in 2022; handle project management, legal, etc
- Analogy: ETO is CERN (LHC infrastructure), ET is ALICE/ATLAS/CMS/LHCb

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While the project is in the roadmap, that does not yet mean it is going to happen
- However, there are serious offers to host the site on the table
- 2023: Netherlands pledged 0.9B EUR if ET is built near Maastricht (BE/DE/NL)
- 2023: Italy pledged 0.35B EUR if ET is built in Sardinia, plus "political commitment"

The final configuration of the ET apparatus is also under discussion

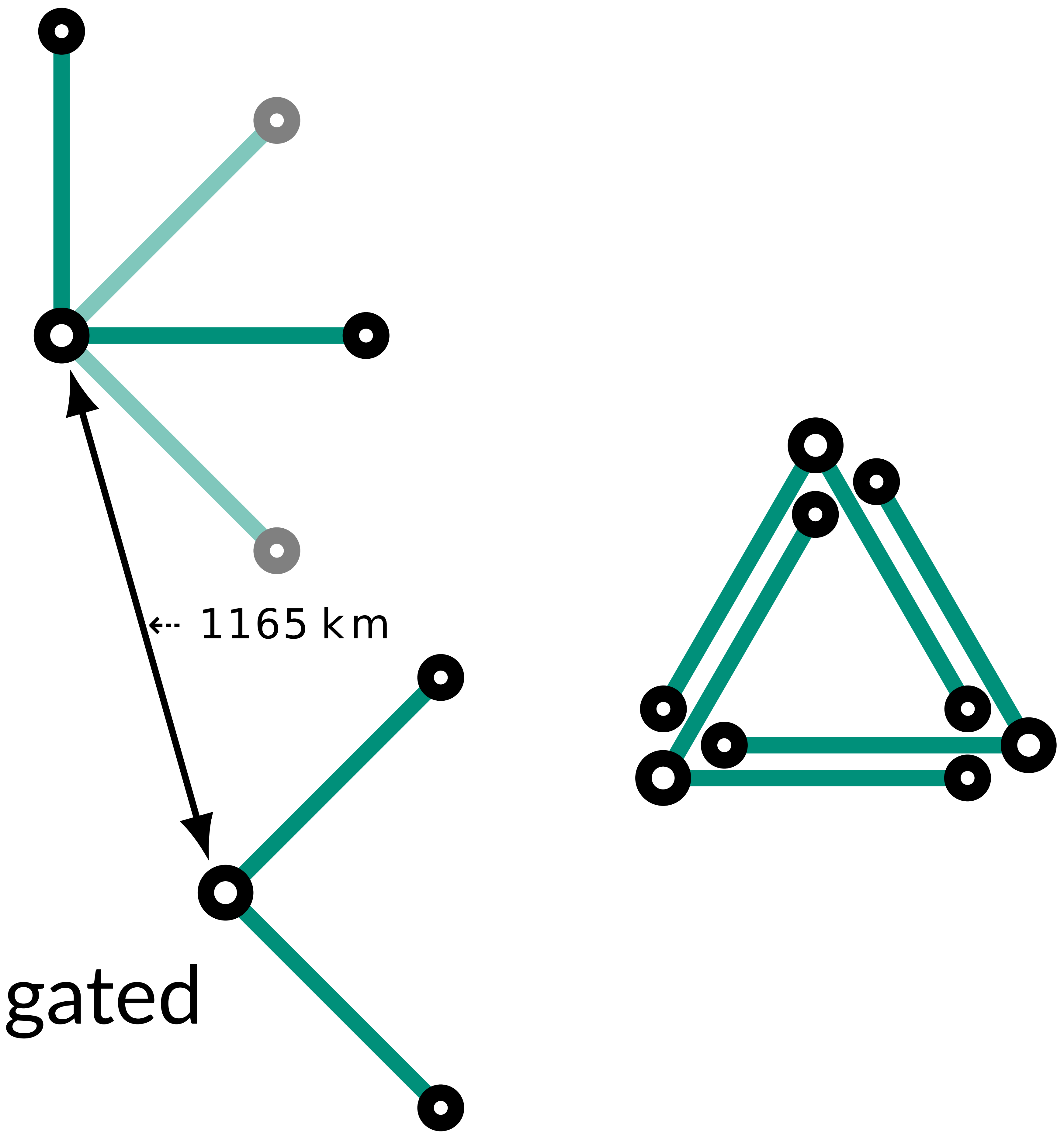
Einstein Telescope configurations

Everything I have shown uses the ESFRI configuration of ET
- One triangle, 10km arm length, both high-frequency and low-frequency systems

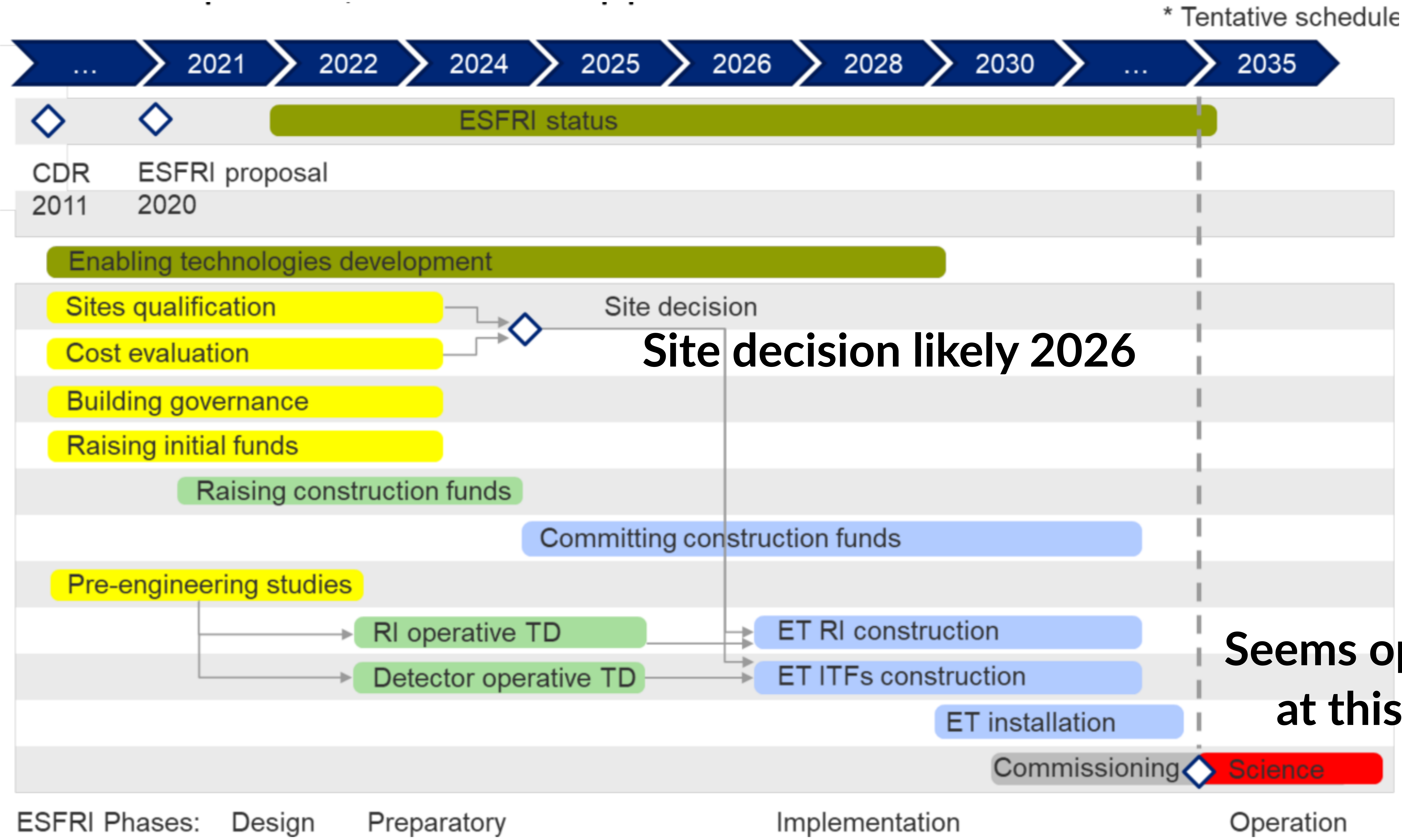
In 2023, conducted a comprehensive science study
- One triangle vs two L-shaped (like LIGO/CE)
- Arm lengths of 10km, 15km, or 20km
- Only high-frequency, or also with low-frequency

Message does not significantly change
- Two L-shaped similar/better in most but not all cases
- Increased arm length always helps
- Low-frequency is required for many science goals

The site and instrument feasibility is now being investigated
- Will lead into the site(s) selection process



Path toward ET (ESFRI 06/2021)



Site decision likely 2026

Seems optimistic at this point

The Swiss ET community

Currently, Swiss ET is a UniGe-led effort, but the community is growing
- Marcelle Soares-Santos joined UZH Jan 2024, is a LIGO member, plans to join ET
- EHTZ is hiring an experimental GW prof, should start Jan 2025

UniGe astronomy department
- Anastasios Fragkos, Corrine Charbonnel, Paul Laycock (staff)

UniGe theoretical physics department
- Antonio Riotto, Camille Bonvin, Michele Maggiore, Stefano Foffa (staff)

UniGe experimental physics department
- Steven Schramm

Others are very welcome to join!

UniGe investment in ET

Leadership roles in ET:

- Anastasios Fragkos:	CH rep. on Board of Scientific Representatives
- Antonio Riotto:	ET science division leader
- Michele Maggiore:	ET science board leader, ET executive board, ET ESFRI science lead, ET configuration science lead
- Paul Laycock:	ETO task leader
- Steven Schramm:	ET computing division leader

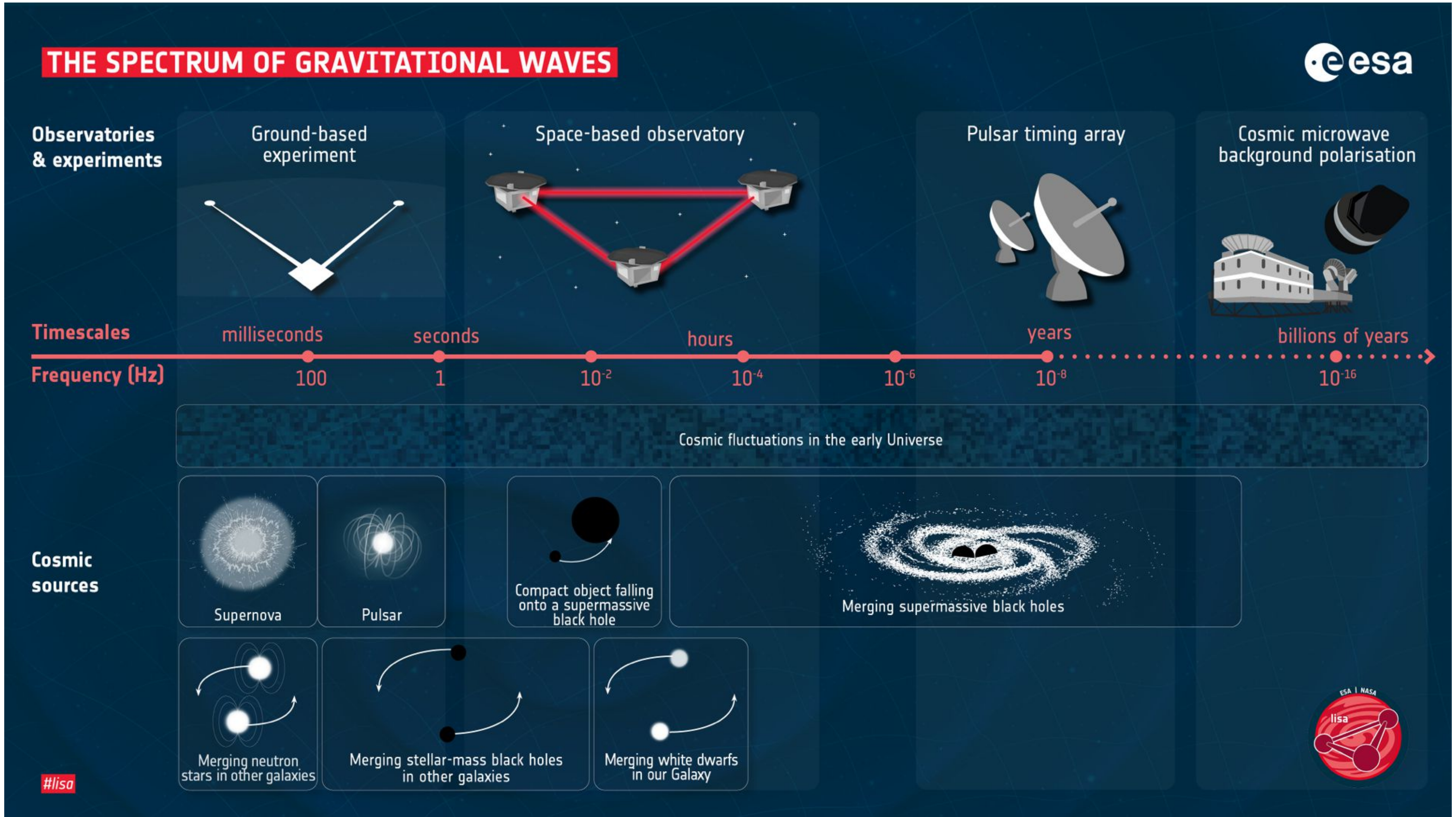
Institute investment:

- Created a cross-departmental centre on gravitational wave science
- DPT+DPNC+DASTRO+SecPhysique joint statement that solidfying leadership in ET is their single leading priority for next four years
  - Recognised and supported by the UNIGE rectorate
  - Creation of tenured professorships (one confirmed, second pending)

The future of GW science

The Einstein Telescope would be a part of the ground-based GW network
- This is only one piece of the picture of a larger network of GW observatories

The future of GW science is bound to change our understanding of the Universe



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