

Gravitational Waves - Part II

Sascha Husa `sascha.husa@csic.es`

Hands-on session:

- download the tutorials from
https://github.com/hectorestelles/gw_data_tutorials/tree/main
- follow the README instructions to setup the environment
- Includes download of a PE results file from
https://drive.google.com/file/d/1T3teGgI-TmjOKGQYaC2ilx_w2-6VWSFj/view?usp=drive_link) - this is big, do it now!

So what about machine learning?

- Can be applied to forward and inverse problem:
 - **Forward: Waveform modelling:**
 - develop a formula to produce a waveform from given input parameters.
 - Formula can be a neural network.
 - **Inverse: Simulation-based searches & inference:**
 - Search: Fit a formula (e.g. neural network) that can distinguish astrophysical events from noise to a large set of simulated data
 - Inference: same for inferring the parameters of the signal - mass, spins, ...
 - **We are currently all busy digesting the incorporation of LLM models for software engineering.**
- Typical trade-off for both forward and inverse problems
 - Speed
 - Accuracy
 - Parameter space coverage
 - **There are no silver bullets.**

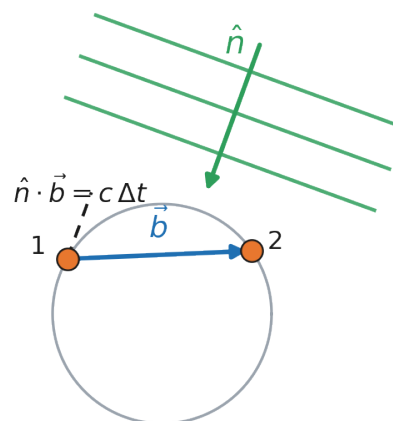
Sky localisation: triangulation & beyond

- **Timing triangulation:** a delay between two sites confines the source to a sky ring; three sites → intersecting rings → one or two patches.
- **Timing precision:** set by SNR ρ and bandwidth σ_f .
- **Amplitudes & phases:** antenna patterns differ per detector, so relative amplitudes and phases add direction and partly reconstruct both polarisations.
- **Coherence:** one waveform must fit all detectors at once - delays, amplitudes and phases together.
- **Detector motion:** Earth's rotation helps long signals; LISA's 1 AU orbit imprints Doppler, amplitude and polarisation modulation.
- **Waveform structure:** higher harmonics, precession and eccentricity pin down inclination and polarisation, shrinking the patch.

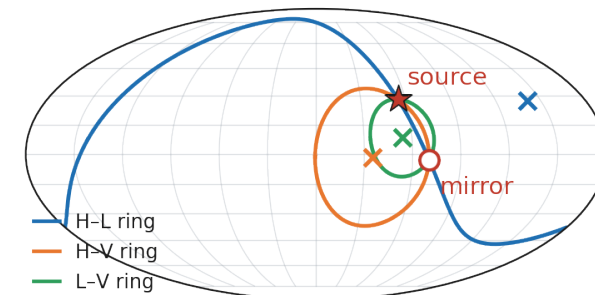
TIMING TRIANGULATION

$$\Delta t \simeq \frac{\hat{n} \cdot \vec{b}}{c} \implies \text{one ring on the sky per baseline}$$

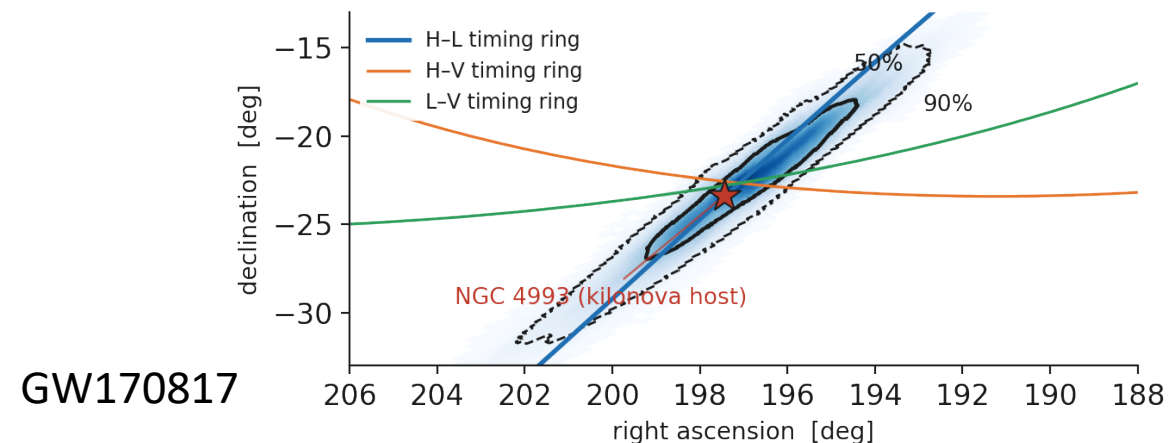
$$\sigma_t \sim \frac{1}{2\pi \rho \sigma_f} \quad (\rho = \text{SNR}, \quad \sigma_f = \text{effective bandwidth})$$



one ring per pair — H(anford), L(ivingston), V(irgo); x: baseline axis

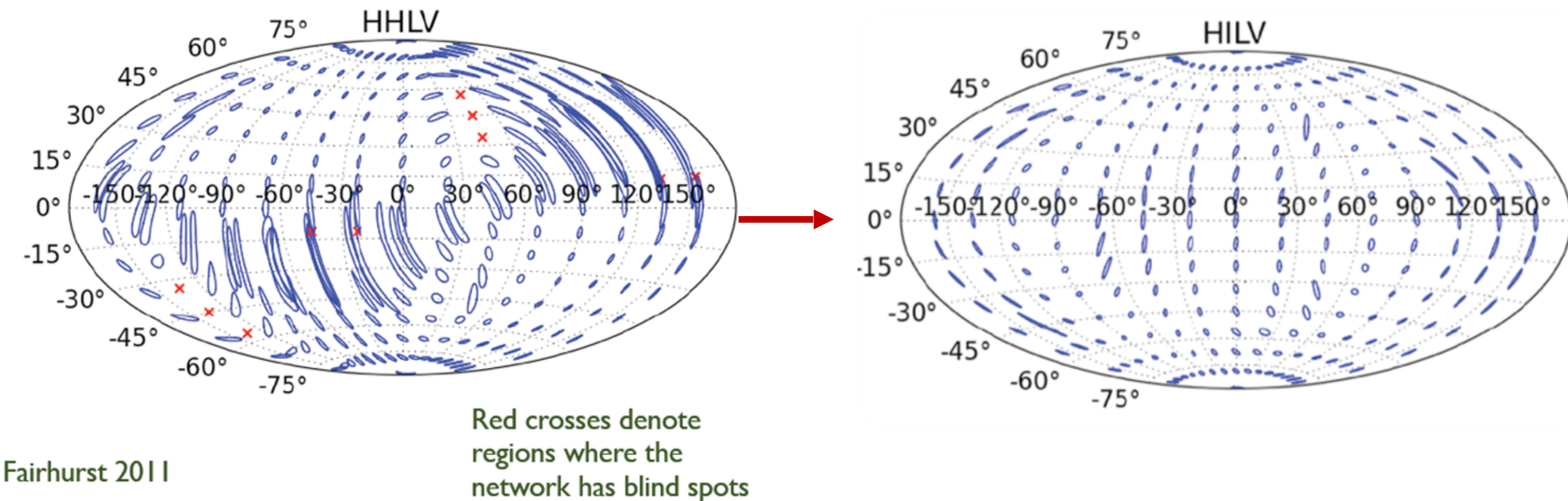


Each ring is a circle of angular radius $\vartheta = \arccos(c\Delta t/|b|)$ about its baseline axis (x): maximal delay → a point at the x; zero delay → a great circle. The oval shapes are map distortion.



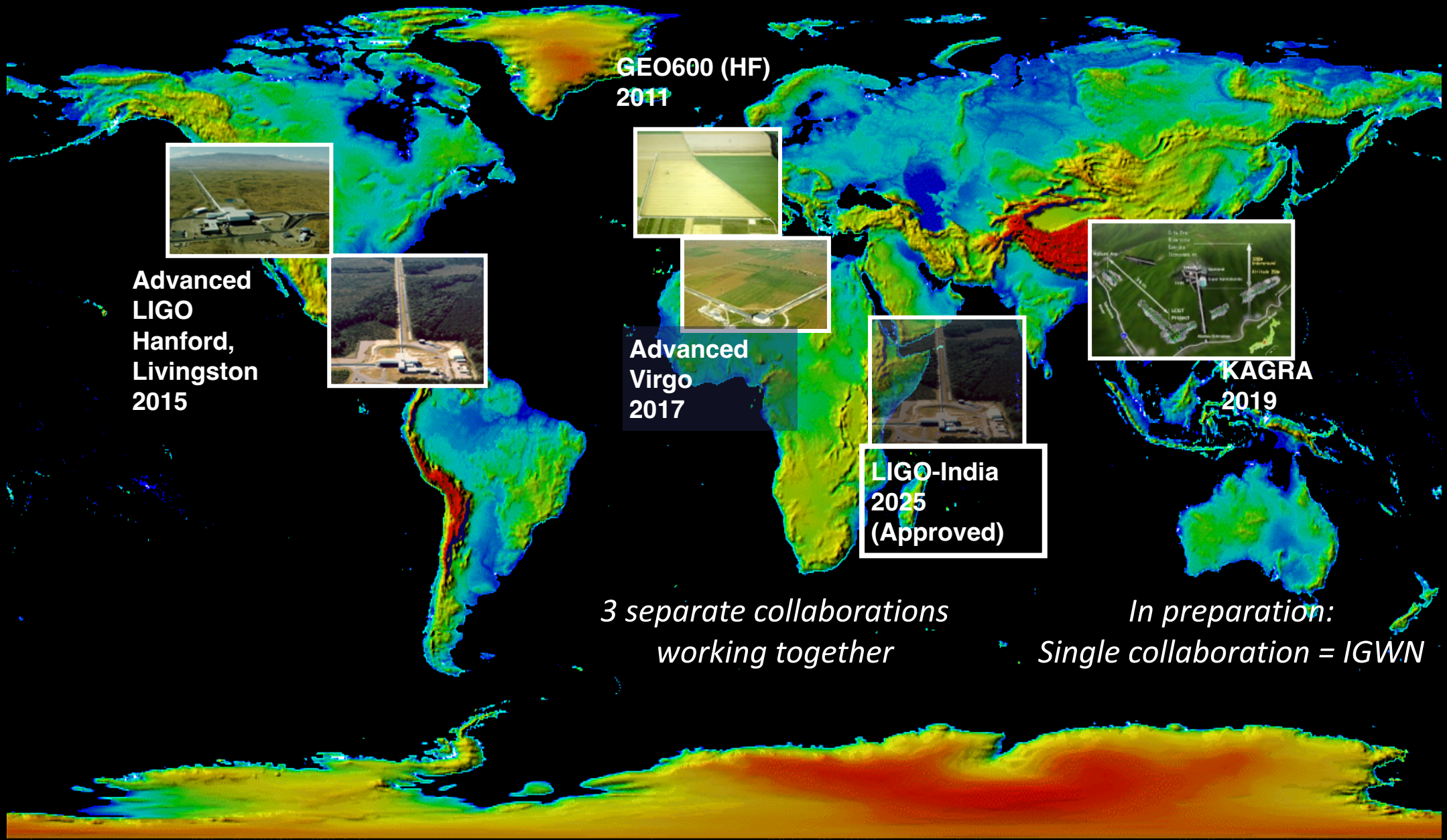
Detector networks: sky resolution

Much better sky location -> locate counterparts! e.g. addition LIGO India (instead of 2nd Hanford detector):



Fairhurst 2011

The growing network of advanced GW detectors



LIGO-Virgo-KAGRA Collaboration

LIGO.org

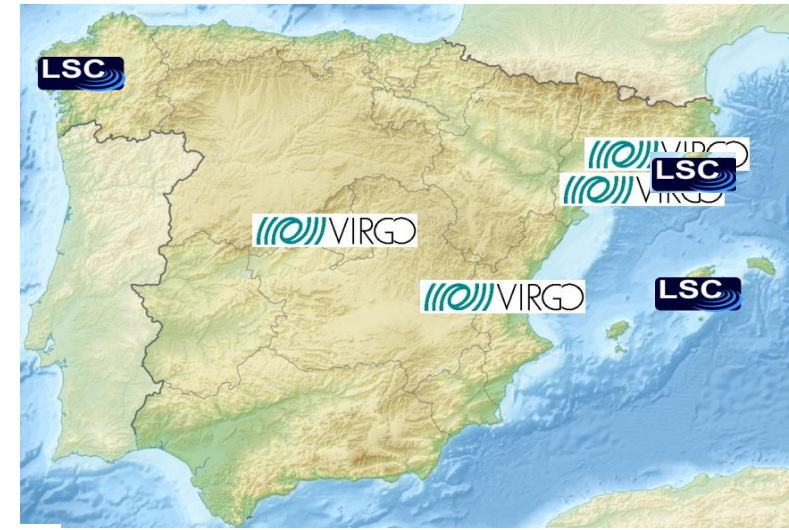
roster.ligo.org

LIGO Scientific Collaboration (LSC)

143 groups ~ 1495 members ~ 1008 authors ~ 714 FTEs

Virgo

36 groups ~ 140 institutions ~ 800 members ~ 450 authors



MOUs of individual groups with GEO, LIGO or Virgo. GEO is part of LIGO.

MOUs between collaborations.



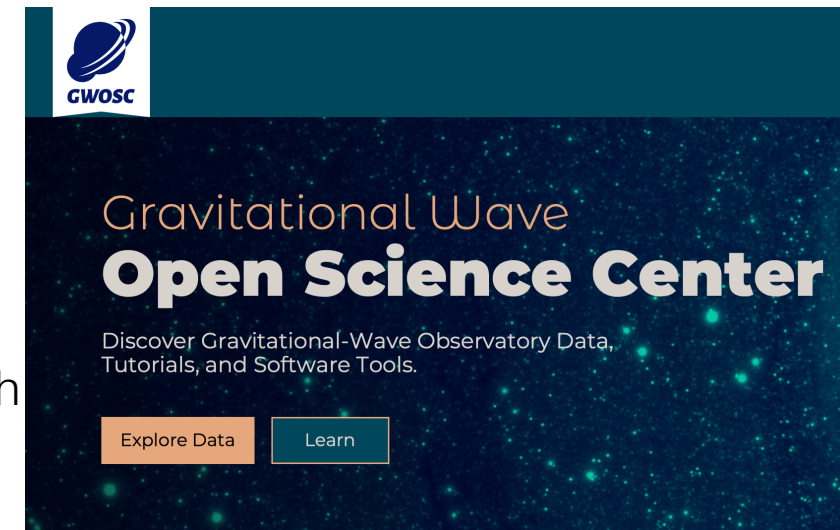
Transitioning to IGWN: International Gravitational Waves Observatory Network - www.igwn.org

Coordination effort initially aimed at jointly discussing computing policy, management, and architecture issues of LVK.

- Software “backbone”: conda - gitlab - LALSuite - pyCBC - Bilby - mattermost - high throughput computing | HTCondor - OSG

Open Science: open code + open data + community updates

- **Community updates:** ligo.org | www.virgo-gw.eu | gwcenter.icrr.u-tokyo.ac.jp
 - LIGO magazine: www.ligo.org/magazine; **science summaries.**
- **Public alerts:** GraceDB - <https://gracedb.ligo.org/superevents/public/O4/>
 - <https://rtd.igwn.org/projects/userguide>
 - Webinars, town hall meetings, detector updates, alerts, ...
- **Open source code:** LIGO algorithms C library + many python packages + ...
 - Code is reviewed + open source before the analysis
 - All results and papers are reviewed separately
- **Open data**
 - https://dcc.ligo.org/public/0009/M1000066/029/Data_Management_Plan-v29.pdf
 - Gravitational Wave Open Science Center at <https://gwosc.org>
 - Public detector logbooks
 - arXiv:2605.27090 : “Open Data from LIGO, Virgo, and KAGRA through Second Part of the Fourth Observing Run”
 - Annual Open Data Workshops, documentation + codes via GWOSC
 - <https://ask.igwn.org> - GW community forum



Low-latency analysis and public alerts

For details, see the LVK Public Alerts User Guide, <https://emfollow.docs.ligo.org/userguide/>

Analysis Pipelines

*Matched
Filter*

*Excess
Power*

*Machine
Learning*

CBC

(Compact Binary
Coalescence)

GstLAL
MBTA
PyCBC Live
SPIIR

cWB
(BBH tuned)

Aframe

Burst

(Unmodeled
Signal)

cWB (generic)

MLy

Plus: RapidPE-RIFT and Bilby rapid CBC parameter estimation
RAVEN search for coincident EM and GW events

Information Provided

Sky Loc.

Classification

Properties

✓
BAYESTAR

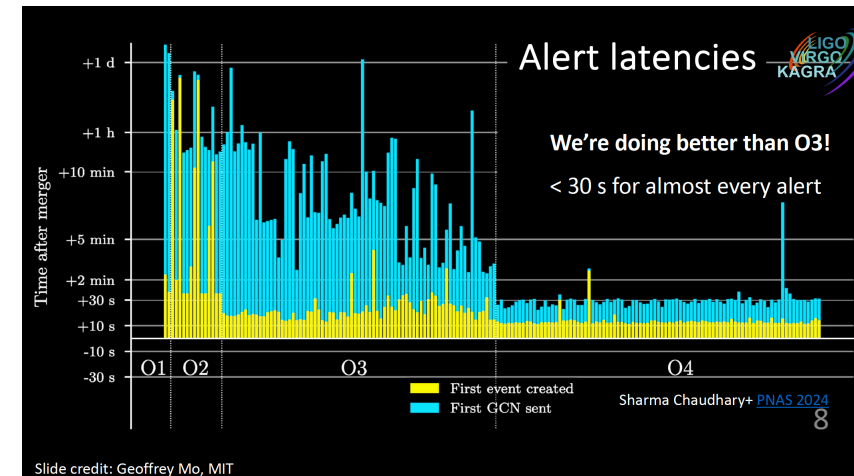
%

BNS
NSBH
BBH
Terr.

%

HasNS
HasRemnant
HasMassGap
HasSSM

Binned chirp mass



Signal Type

LIGO/Virgo/KAGRA Public Alerts

- More details about public alerts are provided in the [LIGO/Virgo/KAGRA Alerts User Guide](#).
- Retractions are marked in **red**. Retraction means that the candidate was manually vetted and is no longer considered a candidate of interest.
- Less-significant events are marked in **grey**, and are not manually vetted. Consult the [LVK Alerts User Guide](#) for more information on significance in O4.
- Less-significant events are not shown by default. Press "Show All Public Events" to show significant and less-significant events.

O4 Significant Detection Candidates: **254** (283 Total - 29 Retracted)

O4 Low Significance Detection Candidates: **5136** (Total)

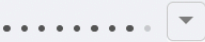
12 of these 29 retractions were Early-Warning triggers without full bandwidth confirmation

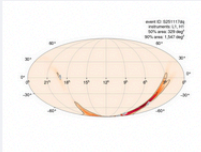
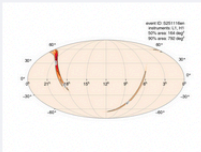
Show All Public Events

<https://gracedb.ligo.org/superevents/public>

Page 1 of 19. [next](#) [last](#) »

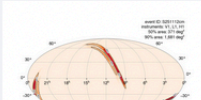
SORT: EVENT ID (A-Z) ▾



Event ID	Possible Source (Probability)	Significant	UTC	GCN	Location	FAR	Comments
S251117dq	BBH (>99%)	Yes	Nov. 17, 2025 21:38:33 UTC	GCN Circular Query Notices VOE		1 per 5.4005e+06 years	
S251116en	BBH (>99%)	Yes	Nov. 16, 2025 23:22:21 UTC	GCN Circular Query Notices VOE		1 per 24271 years	

Two significance thresholds

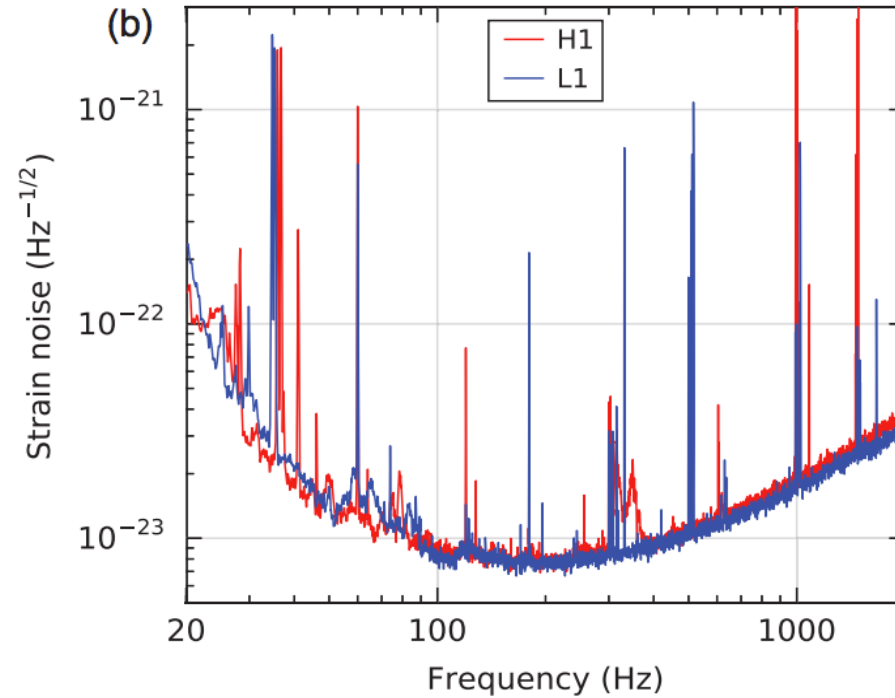
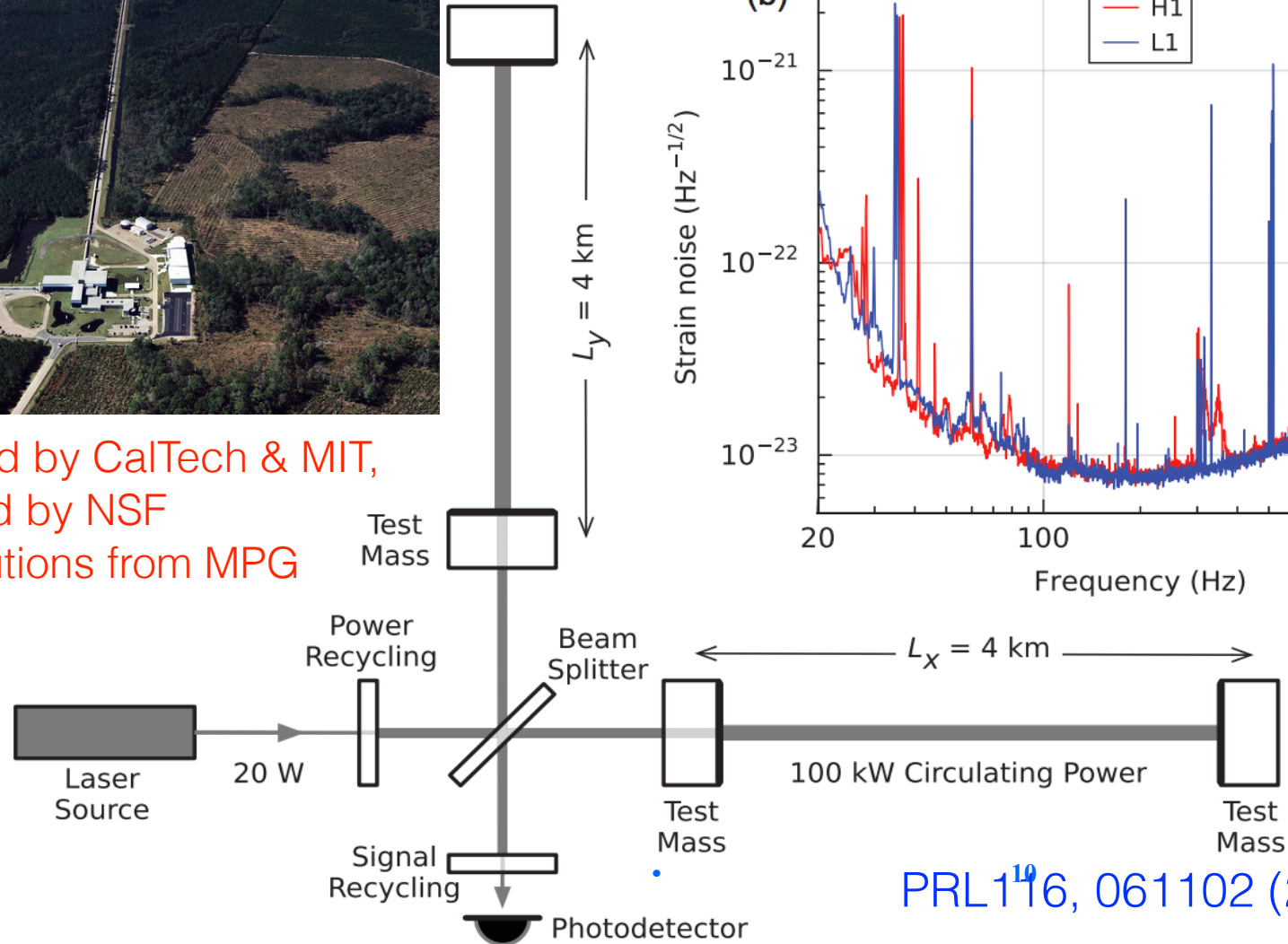
Early-Warning trigger without full bandwidth confirmation

S251115g	BBH (>99%)	Yes	Nov. 12, 2025 15:18:45 UTC	GCN Circular Query Notices VOE		1 per 6.2098 years	
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Detect GWs: measure strain $(\Delta L/L) < 10^{-21}$



operated by CalTech & MIT,
financed by NSF
contributions from MPG
and UK

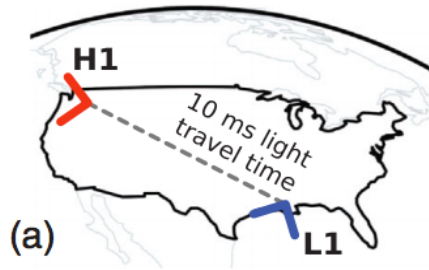


PRL116, 061102 (2016)

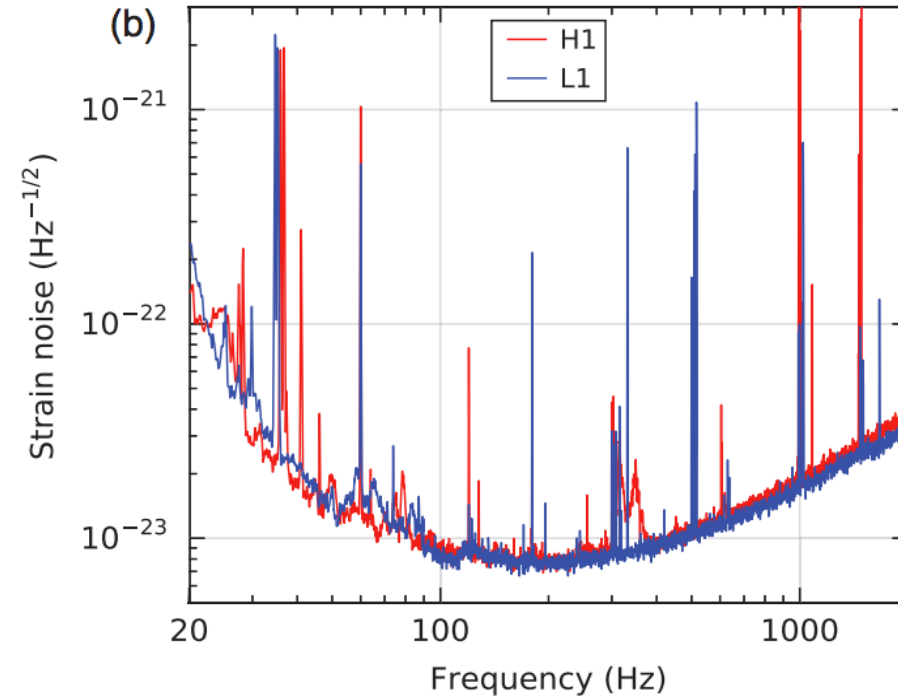
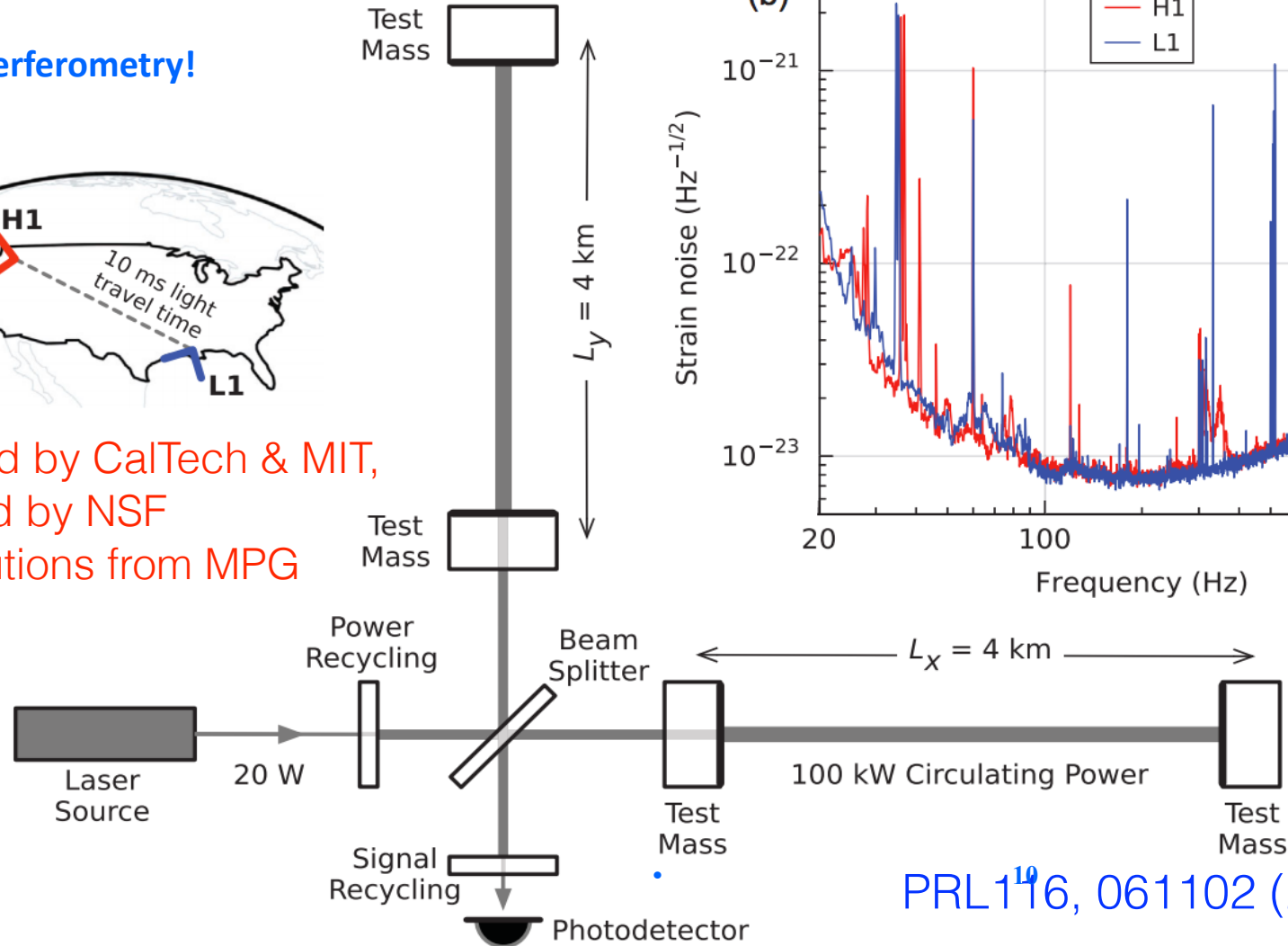


Detect GWs: measure strain $(\Delta L/L) < 10^{-21}$

Laser interferometry!

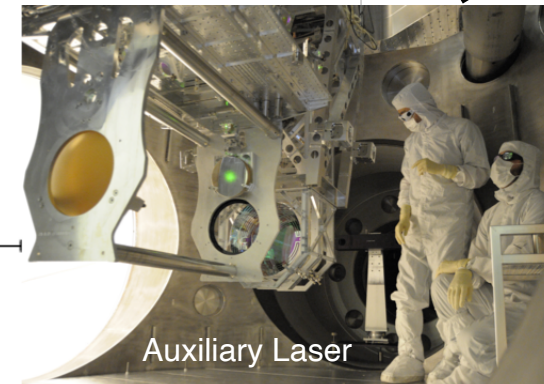
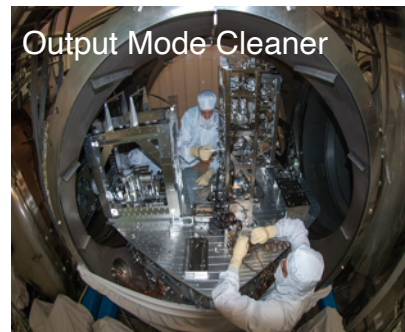
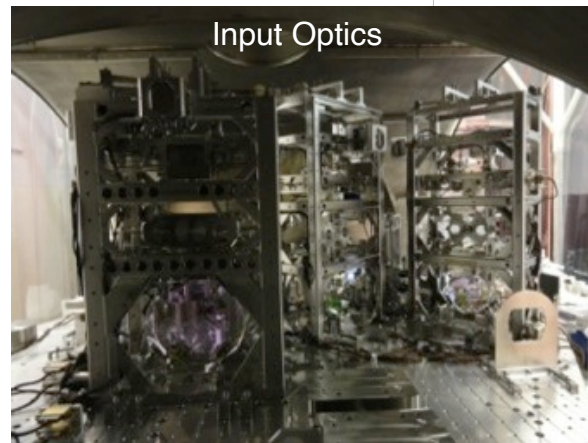
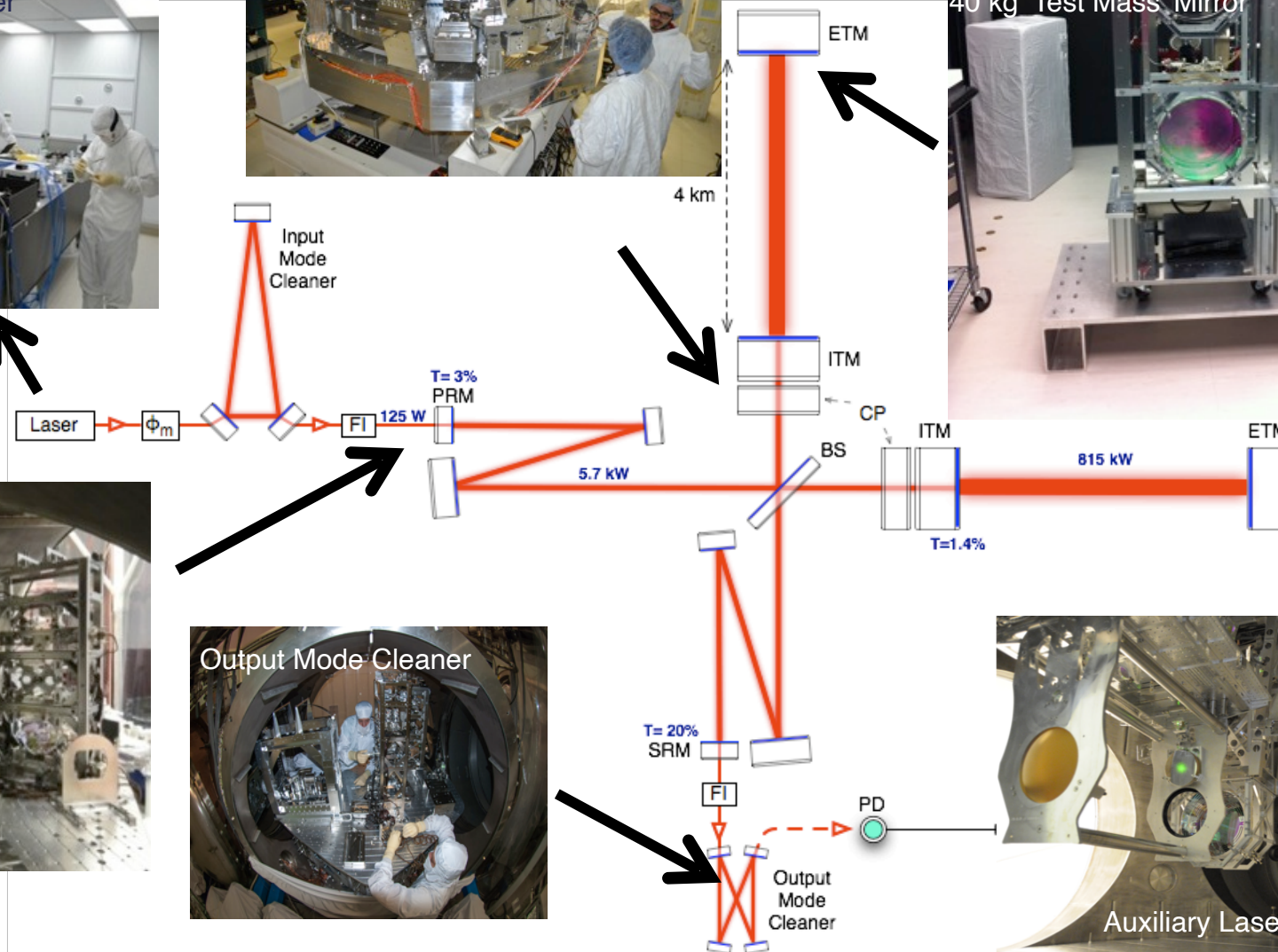
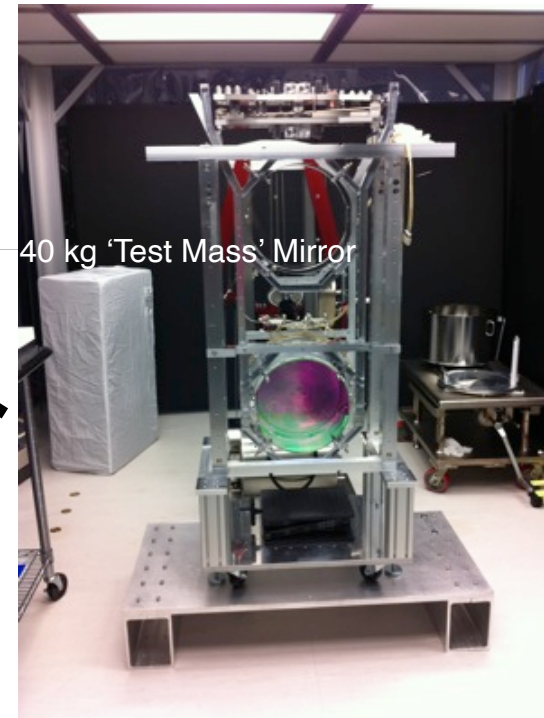


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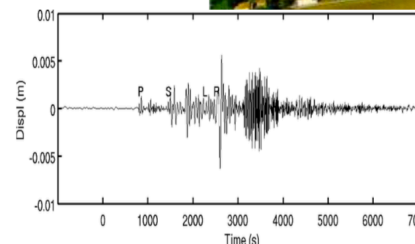
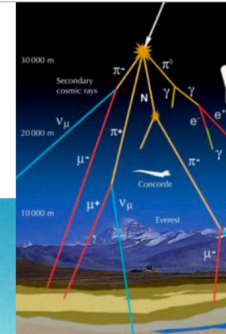
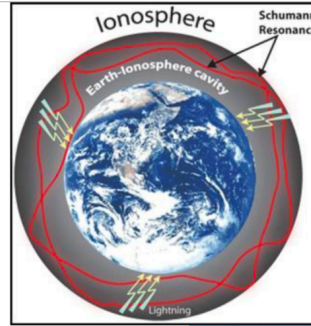
PRL1¹⁰6, 061102 (2016)

Advanced LIGO

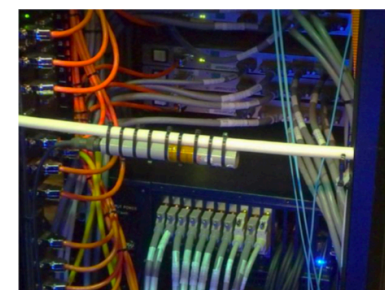
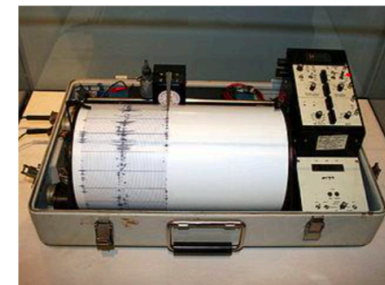
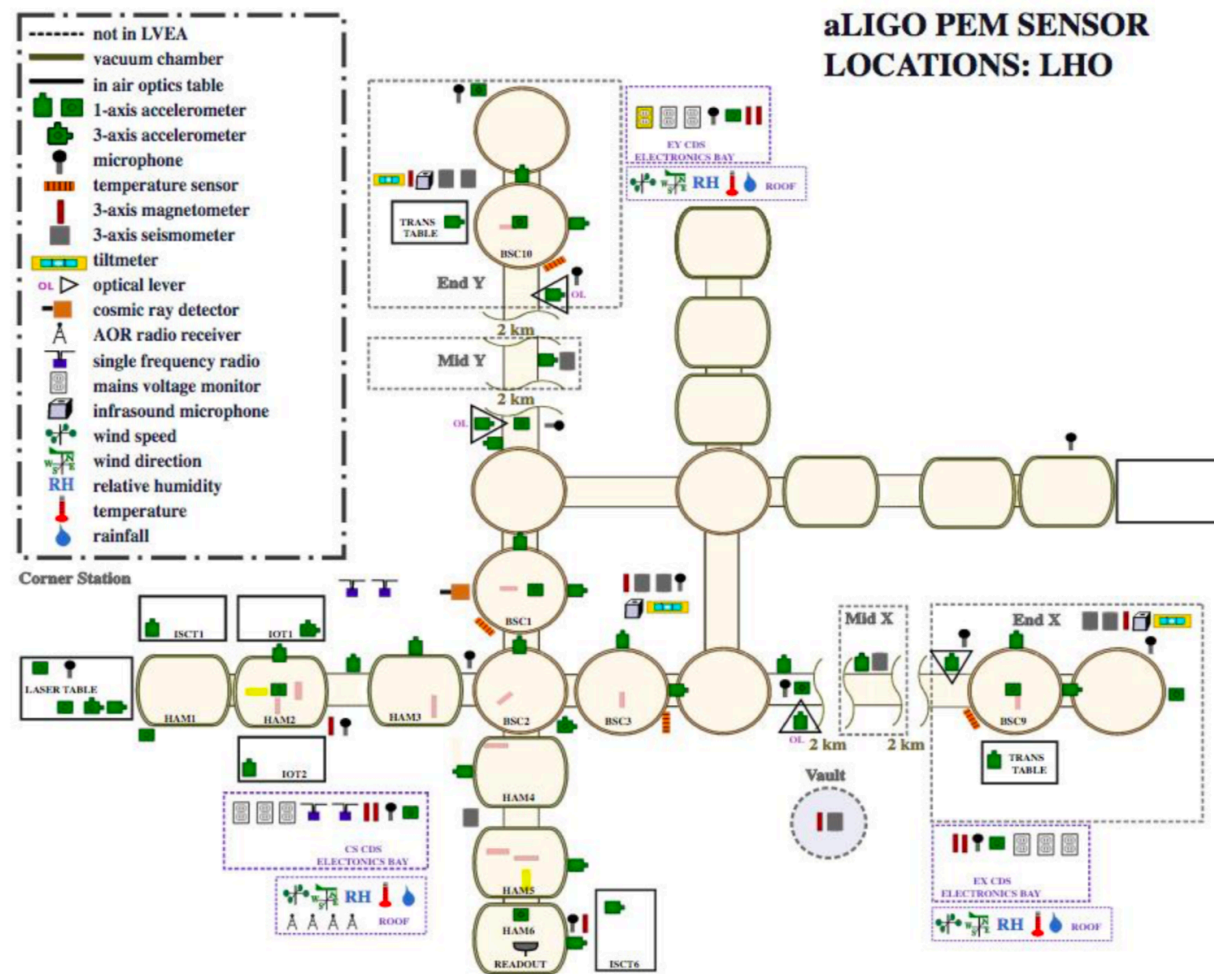


Environmental noise sources

- wind,
- earthquakes,
- storms,
- geomagnetic fields,
- cosmic rays,
- density fluctuations in the ground and the atmosphere.



Environmental Monitoring

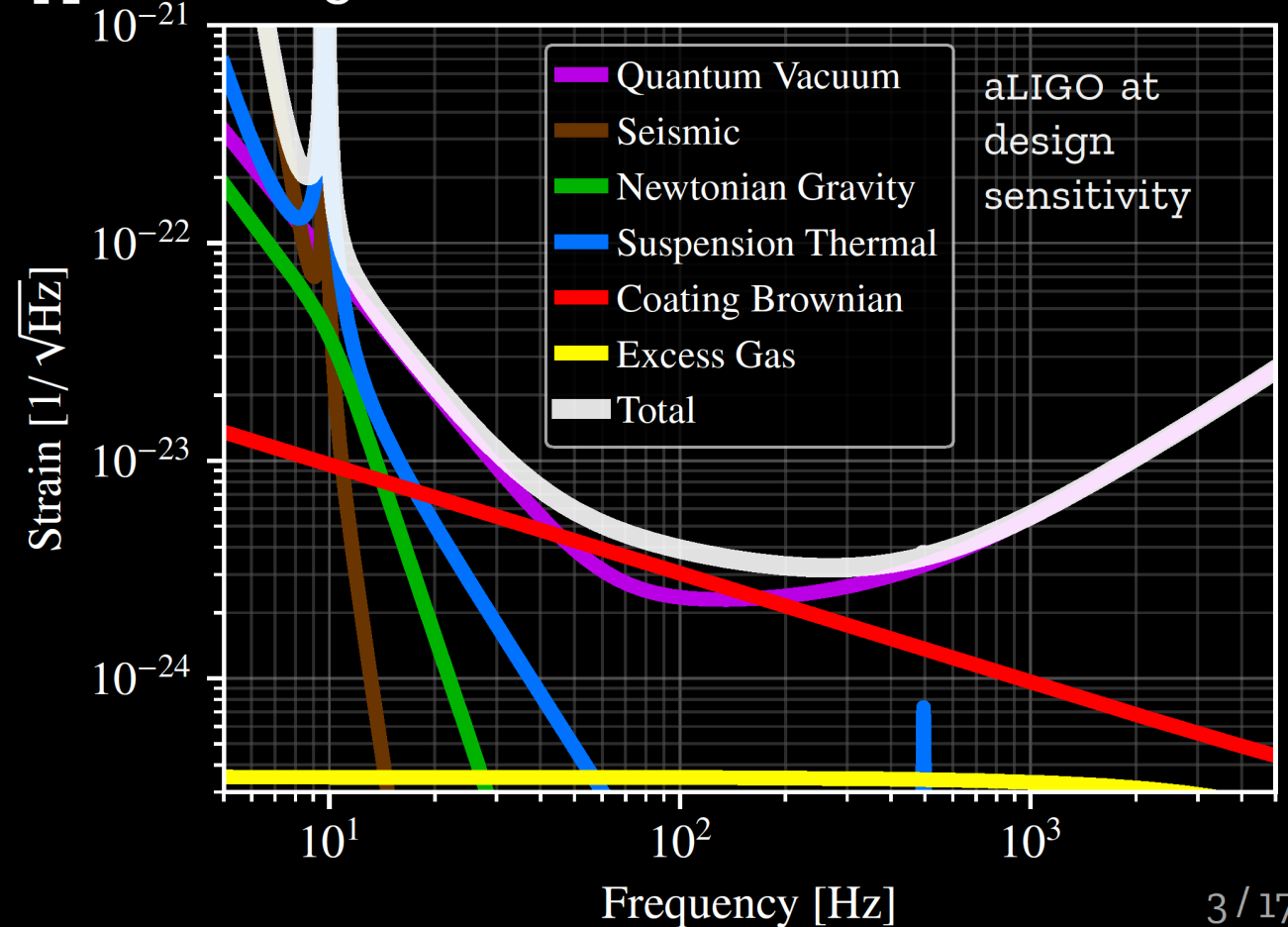


1000s of environmental channels are being monitored:
Microphones, magnetometers, seismometers, temperature,

What Limits LIGO-Virgo-KAGRA Sensitivity?

- Quantum noise – statistical nature of light – but we can use “squeezed states”
 - Reduce phase uncertainty at the cost of amplitude uncertainty.
- Thermal noise – Brownian noise – dominates in a middle region
- Seismic noise, direct and via changing gravitational attraction – at low frequencies
- These noise sources don’t grow with the arm length, but the signal does: **Length matters.**
- Technical issues - alignment, electronics, acoustics, etc limit us before we reach these design goals.
- Glitches: non-Gaussian instrumental transients.

Typical budget of fundamental noises

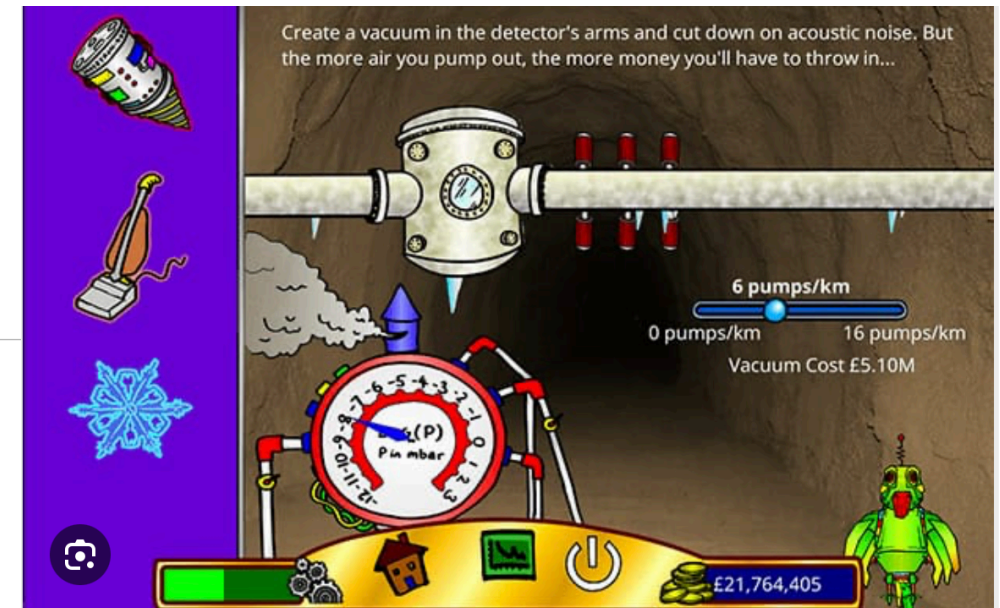
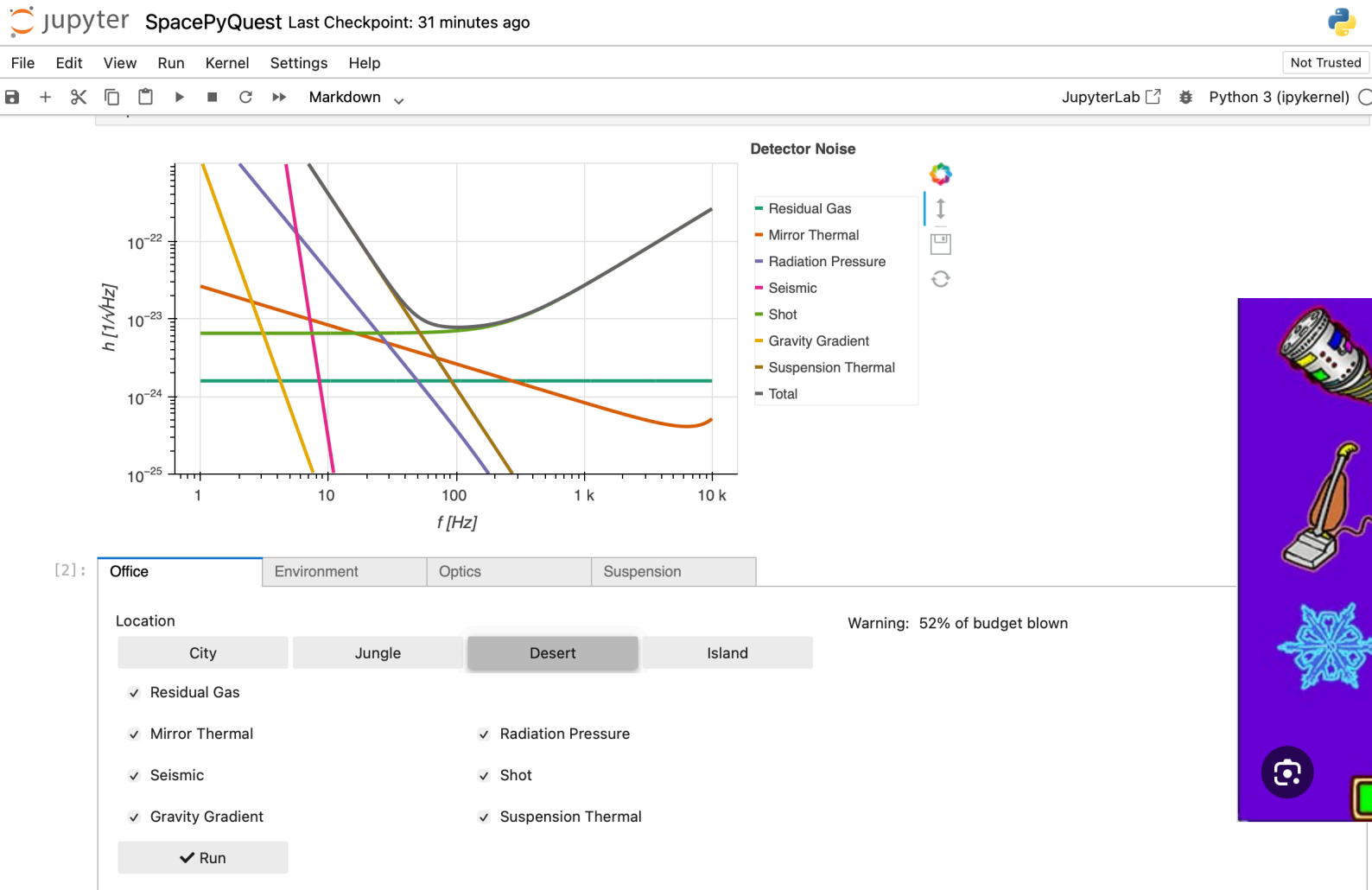


Exercise: Play Space Time Quest

<https://www.laserlabs.org/spacetimequest.php>
<https://github.com/gwoptics/SpacePyQuest>

Design a GW detector
In a Jupyter notebook
or a flashy game interface.

Minimize the noise,
maximise detection,
But keep on budget.



Advanced LIGO noise budget in O4

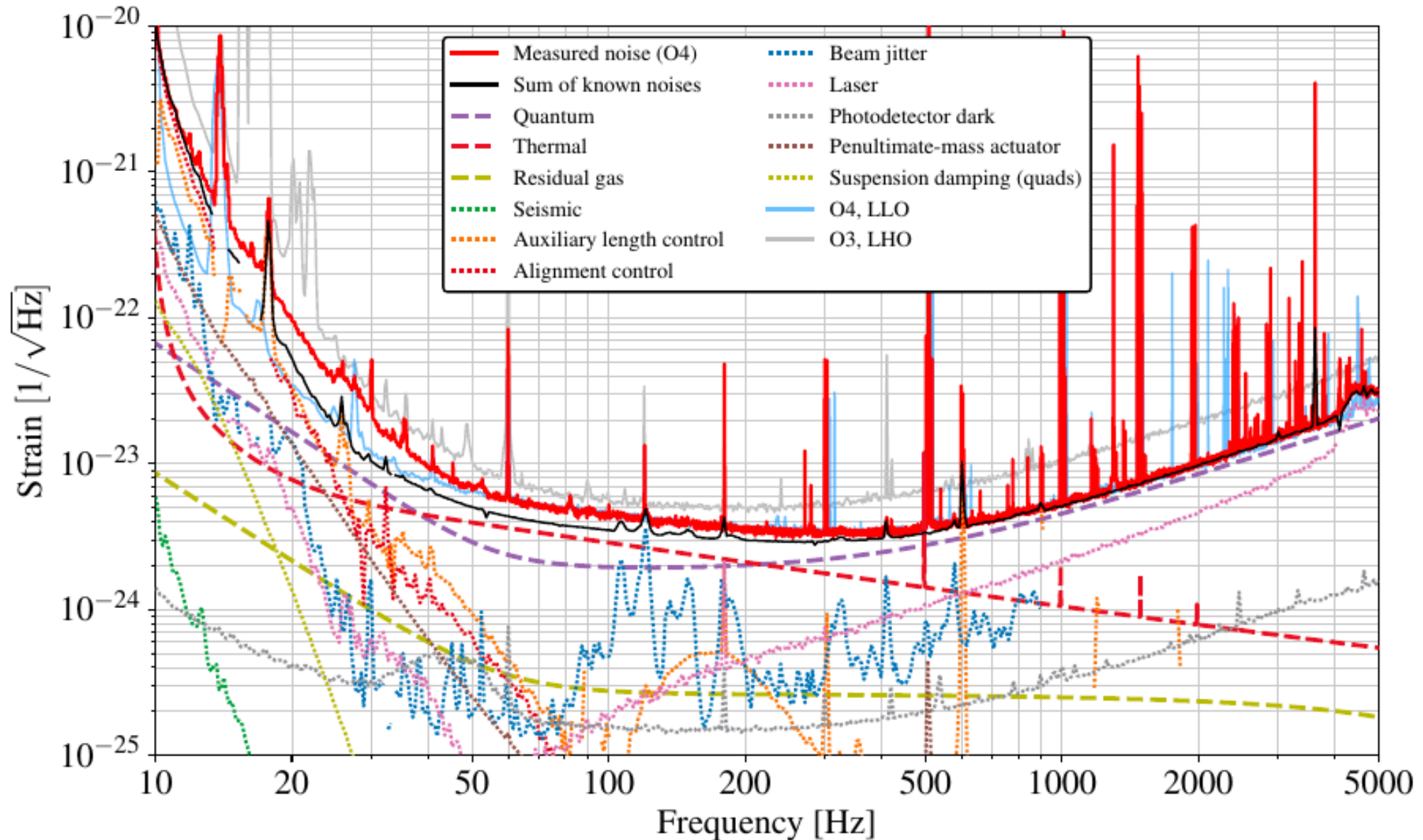
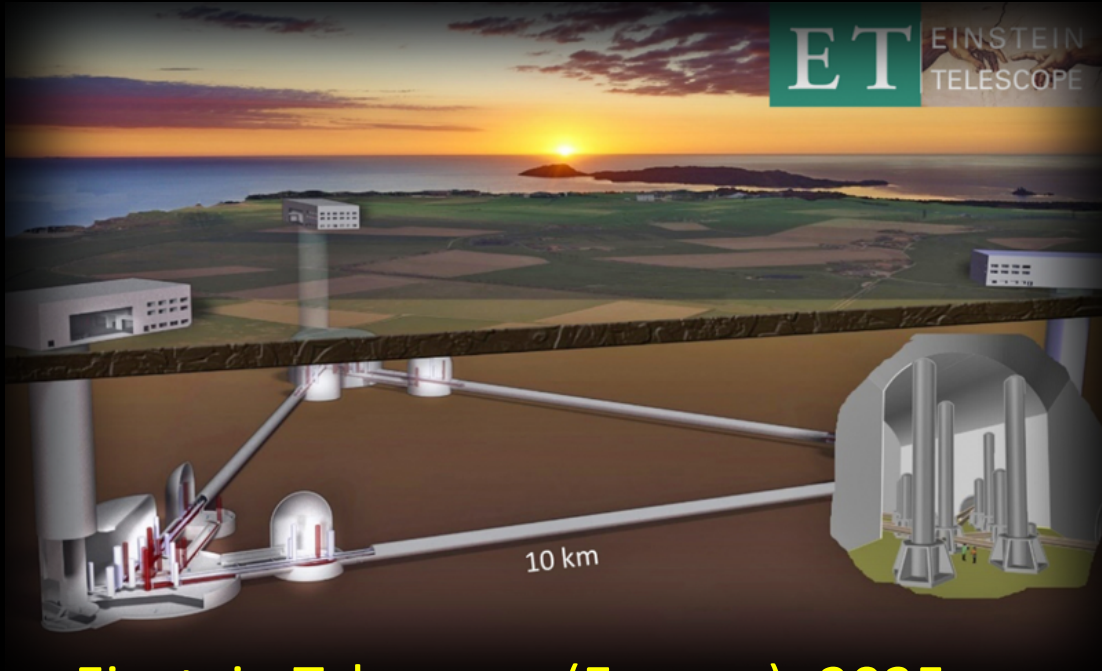


Figure from: Capote et al, [arXiv:2411.14607](https://arxiv.org/abs/2411.14607), “Advanced LIGO detector performance in the fourth observing run”

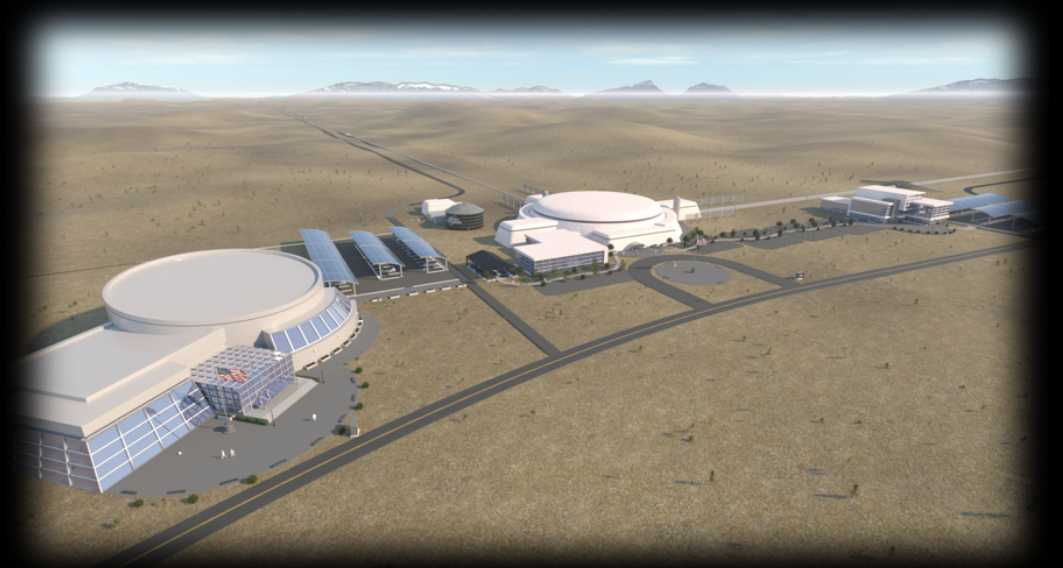
The future on the ground: KAGRA + LIGO-India + ET + Cosmic Explorer

- KAGRA observing in O5 in 2029+
- New facilities in 2030+, 2035+ - jointly with LISA.

LIGO-India: 2030+



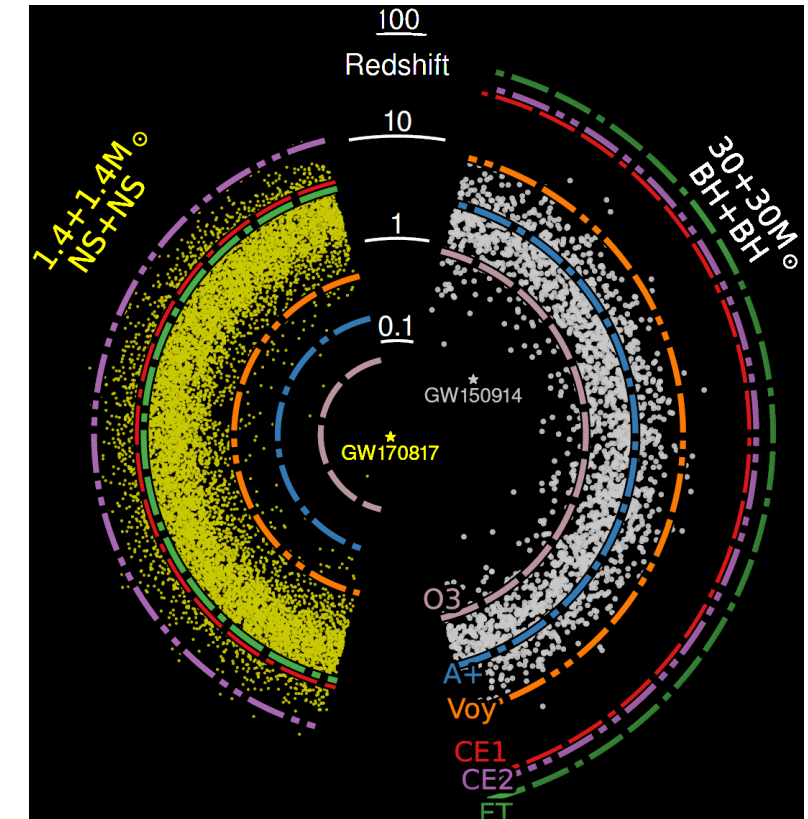
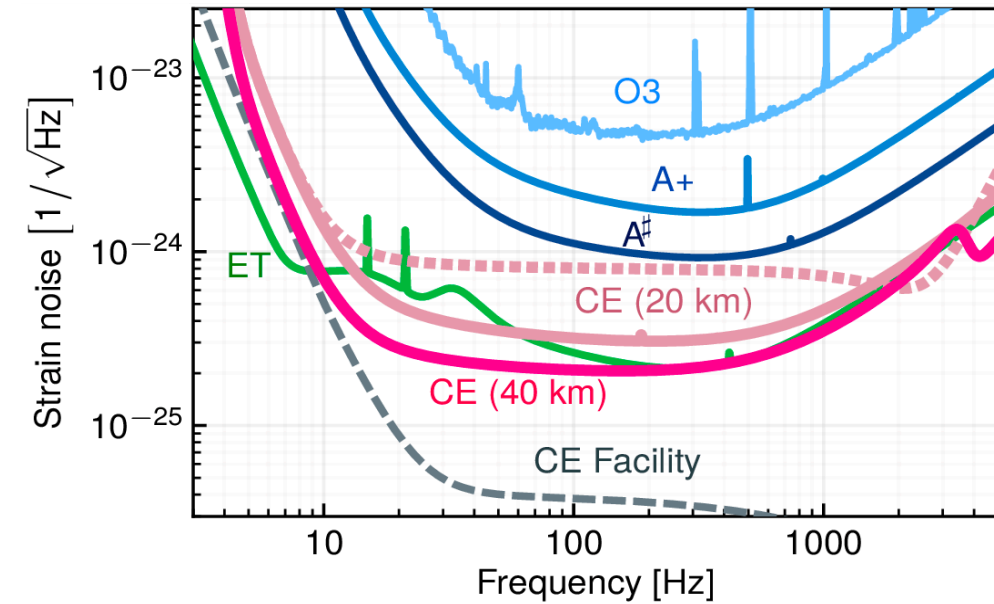
Einstein Telescope (Europe): 2035+



Cosmic Explorer (USA): 2035+

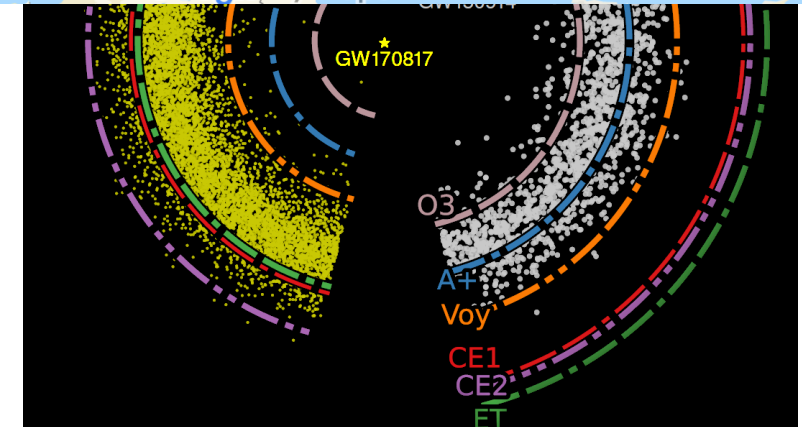
The Next Generation

- **3G:** Triangle or two Ls - underground for Einstein Telescope. Two widely separated, L-shaped surface facilities in the US, CE40 and CE20 for Cosmic Explorer
- **Low Frequency Sensitivity**
 - Longer signals (early warning);
 - Sensitive to higher masses
- **“Bucket” Sensitivity**
 - Greater reach. Higher SNR
- **High Frequency Sensitivity**
 - Sensitivity to merger and post-merger signals
 - Sensitivity to Supernovae
- New challenges (long-waveforms, overlapping signals, non-stationary noise)
- 3G observatories will detect **thousands of signals every day**
 - weak signals, loud mergers
 - BNS, NSBH, BBH, SN bursts, CW, ...
- 3G detectors enable a ~complete census of BNS and BBH mergers



The Next Generation

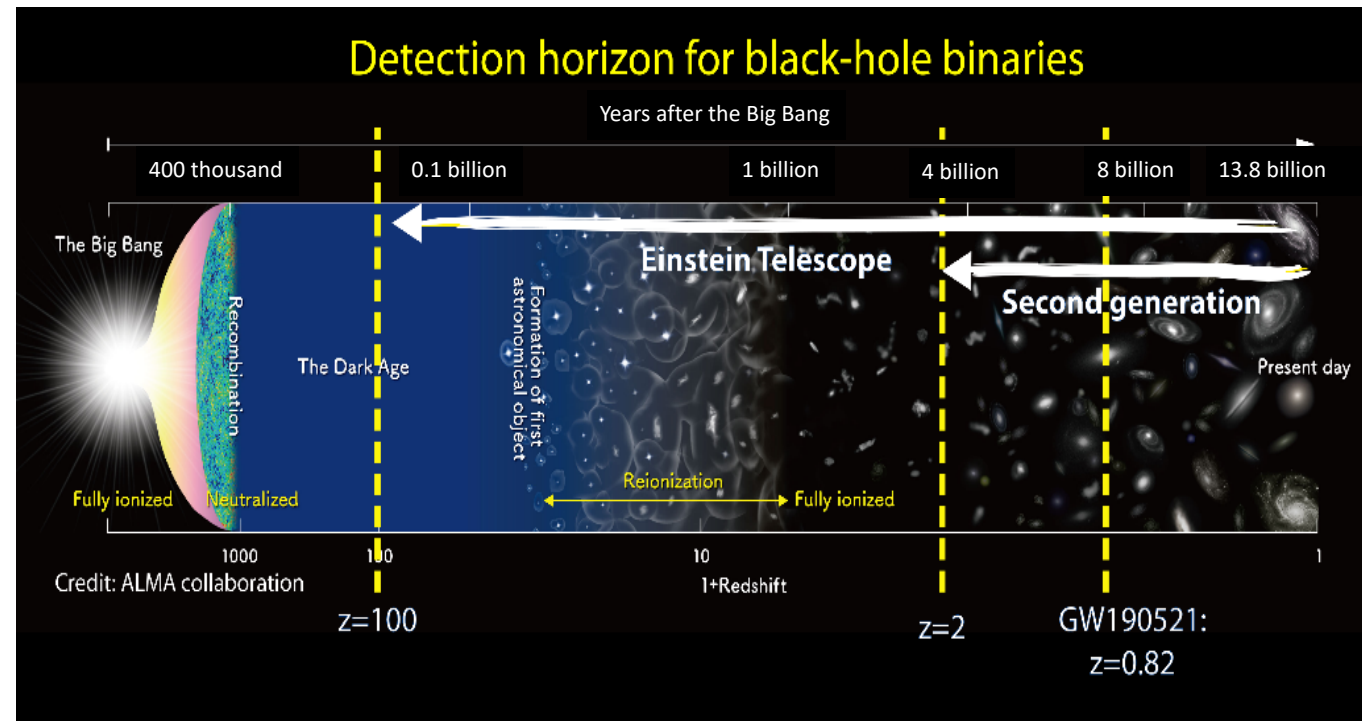
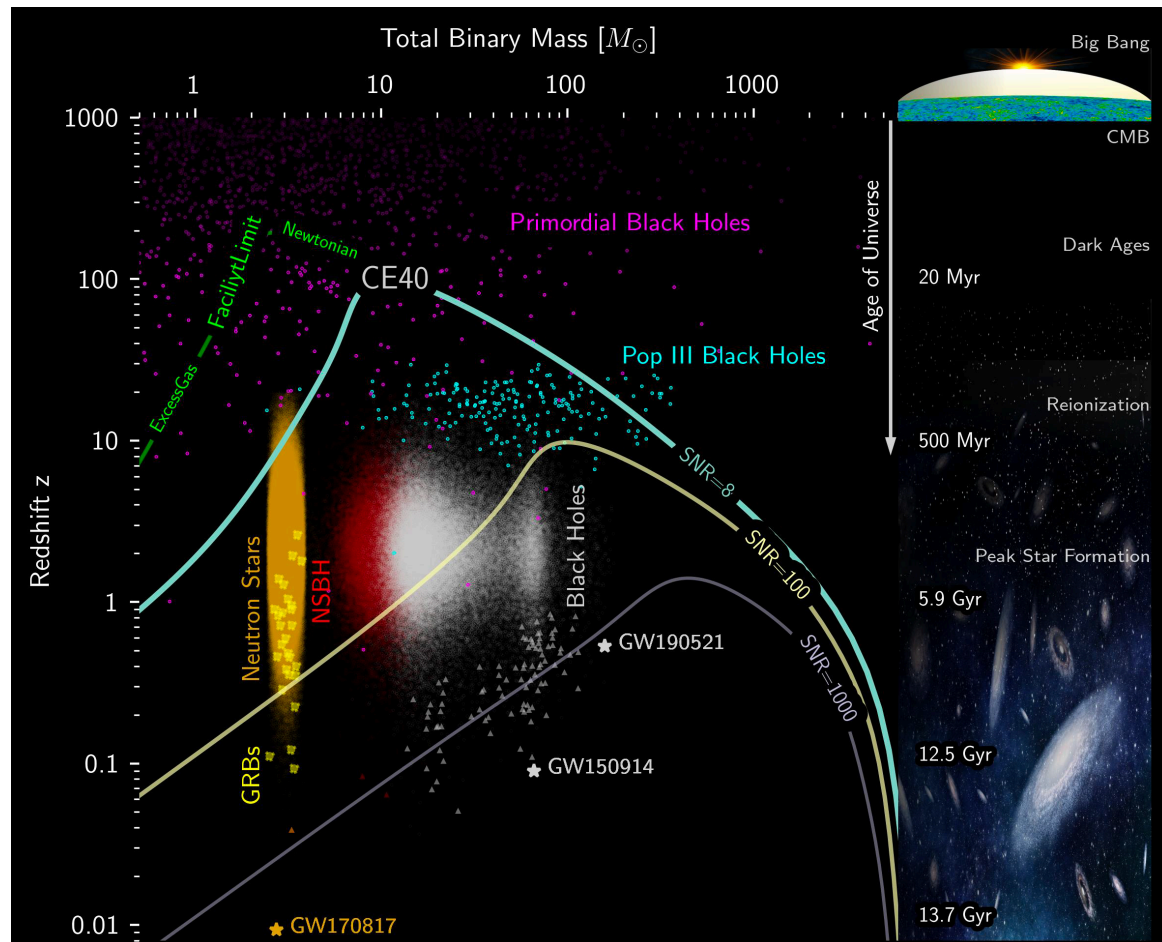
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The next generation

ET/CE will be discovery machines:

- ET/CE will explore almost the entire Universe listening the gravitational waves emitted by black hole, back to the dark ages after the Big Bang



ET/CE will be a precision measurement observatories:

- ET/CE will detect, with high SNR, hundreds of thousands coalescences of binary systems of Neutron Stars per year, revealing the most intimate structure of the nuclear matter in their nuclei
- Robust statistics on GRB+BNS merger association, and how that correlates with orientation & distance .
- BNS signals will be in band and detectable for O(100s) of seconds to several hours.
- Advanced warning for EM follow-up.

Gravitational wave detection with spacecraft: LISA

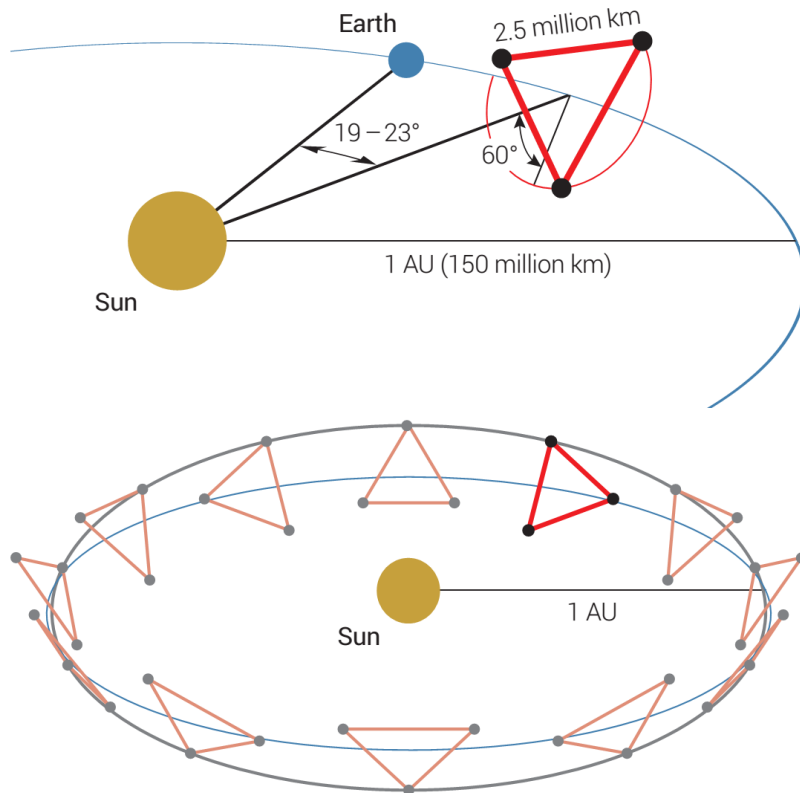
No seismic noise => can go to lower frequencies!

ESA-led mission scheduled for launch in ~2035

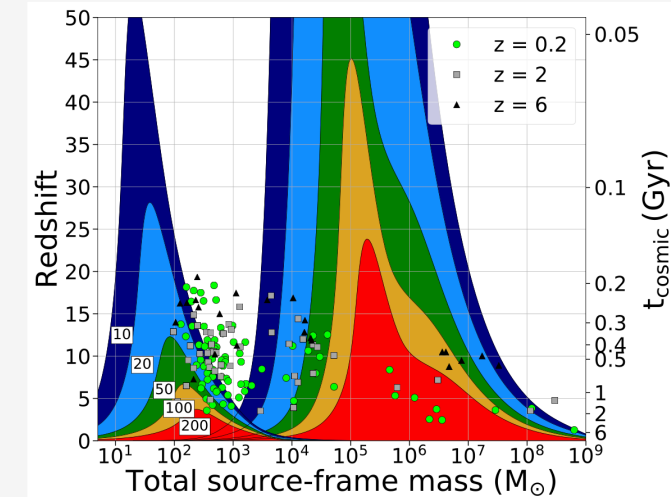
Forms two independent Michelson-like interferometric channels plus a “null” channel - remember TDI channels A, E, T.

2 Chinese projects:
Geocentric TianQuin
Taiji ~ LISA-like

**Data dominated by signal, many signals overlapping.
Analysis: global fit to all signals+noise.**



BBH MERGERS IN 3G AND LISA



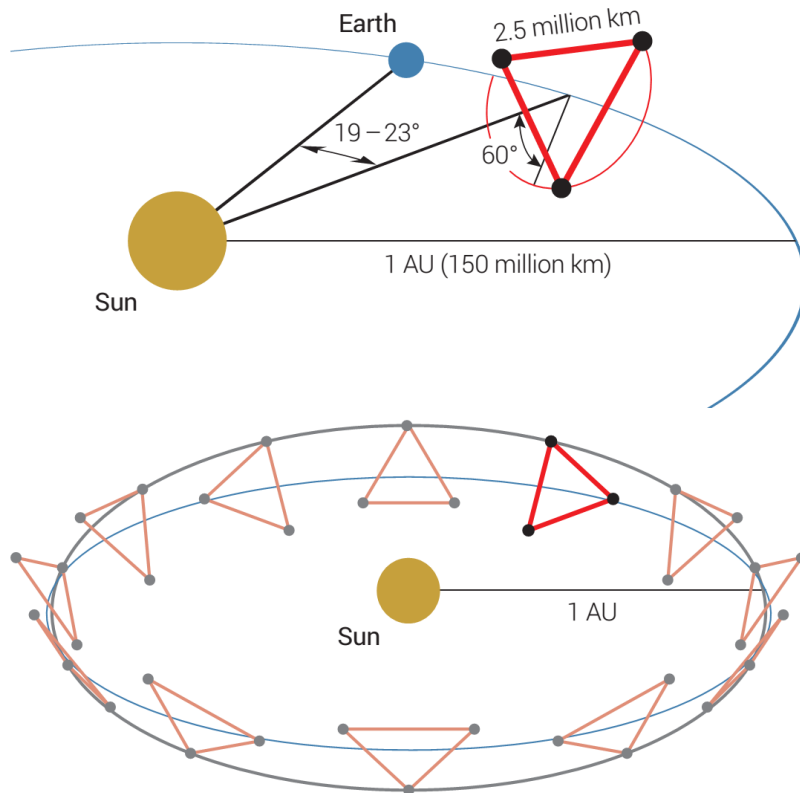
Gravitational wave detection with spacecraft: LISA

No seismic noise => can go to lower frequencies! How does going to lower frequency impacts the type of sources?

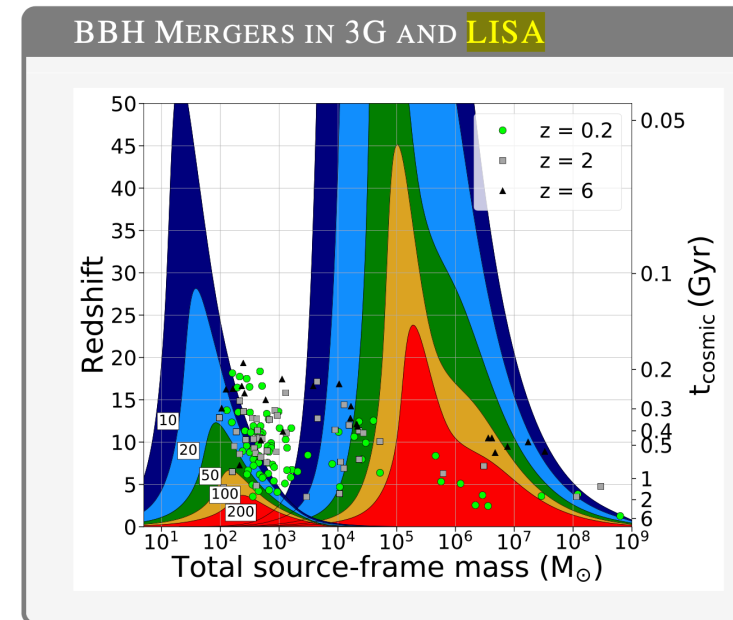
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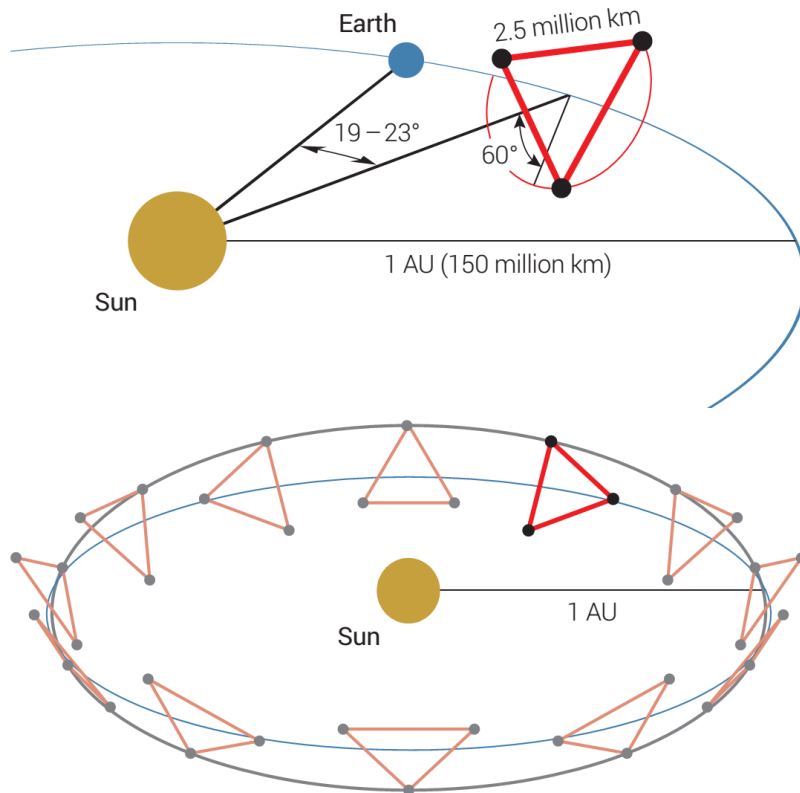
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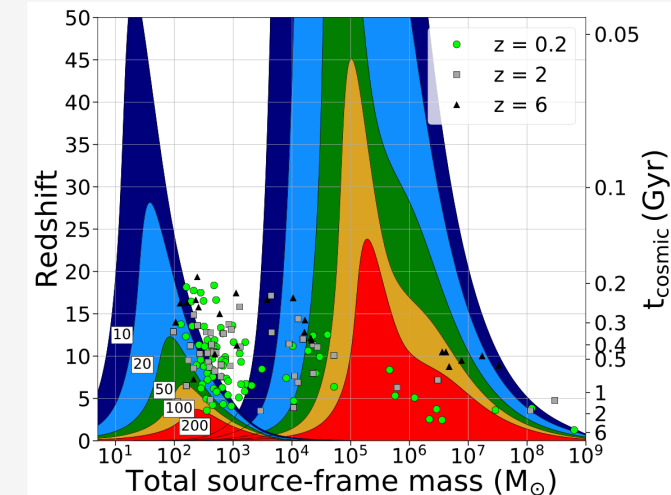


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~milliHertz sources:

- Supermassive BH binaries
- Intermediate mass BHs
- Extreme mass ratio inspirals (maps spacetime near BH)
- Galactic compact binaries
- Stochastic GW background?

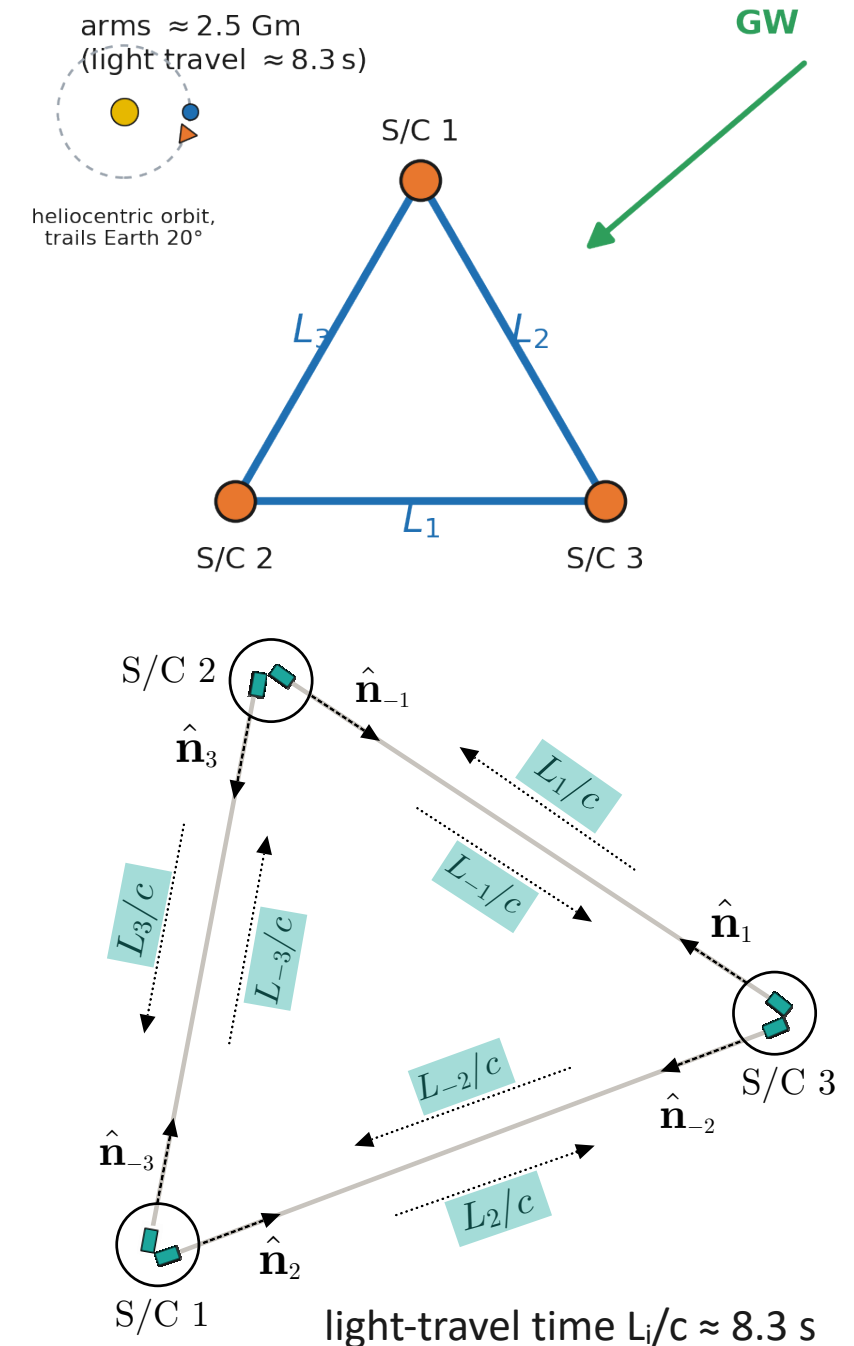
BBH MERGERS IN 3G AND LISA



Why LISA needs time-delay interferometry (TDI)



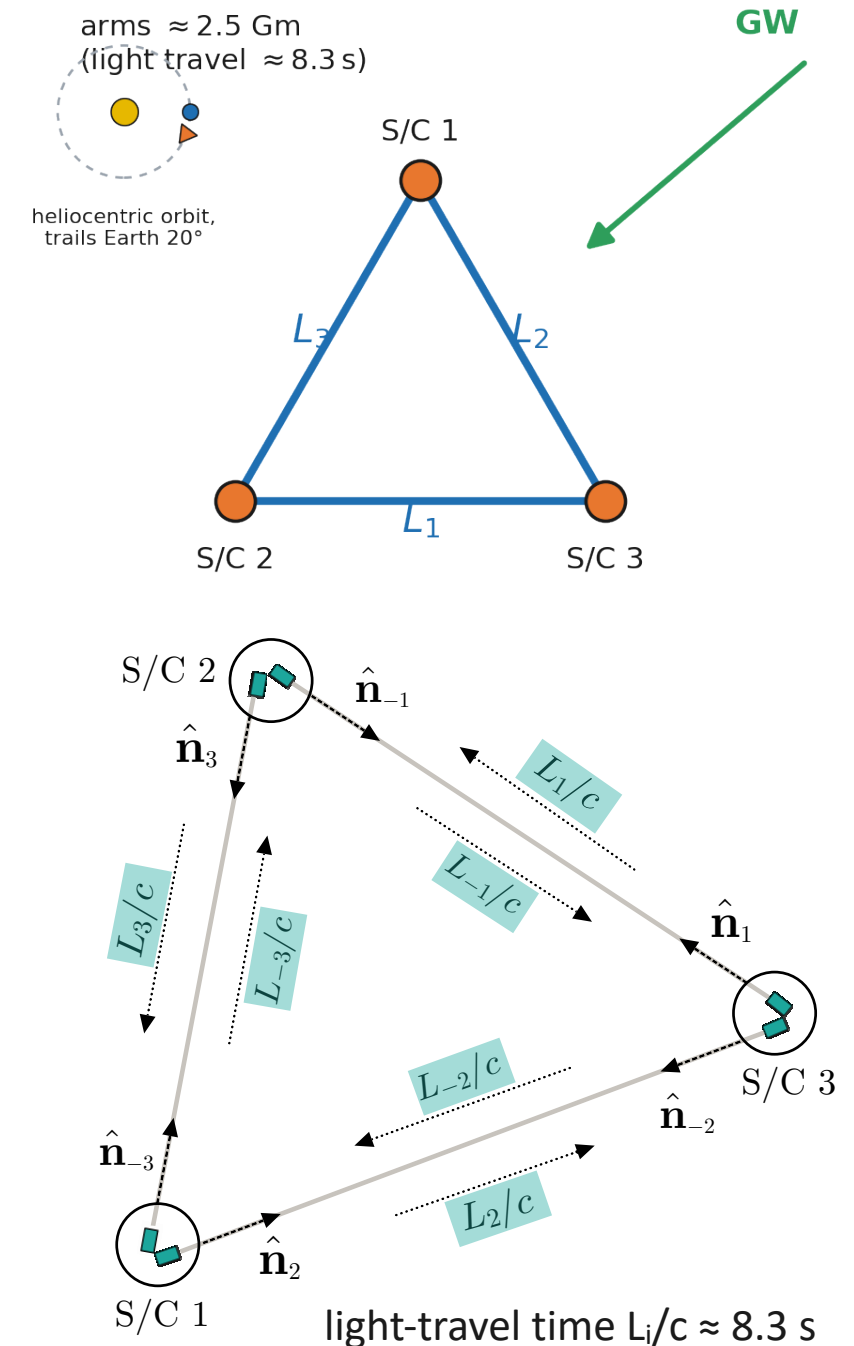
- **A triangle in space** - three drag-free spacecraft, 2.5 Gm apart, on a heliocentric orbit trailing Earth by 20°.
- **One-way links** - after 2.5 Gm only a few 100 picowatts arrive, so beams cannot be reflected: each spacecraft phase-locks the outgoing light against the incoming laser light.
- **Unequal, drifting arms** - the triangle rotates and 'breathes': arm lengths differ at the ~1% level and drift by up to ~10 m/s.
- **Laser noise dominates** - even cavity-stabilized lasers fluctuate several orders of magnitude above the GW signal.
- **The way out** - TDI: synthesize an equal-path interferometer in post-processing, from the recorded data streams.



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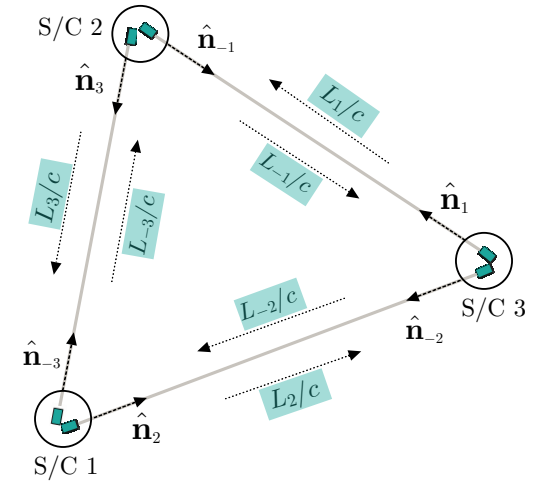


TDI CHANNELS (SLIDE ADAPTED FROM JORGE VALENCIA)

© CBCs & Current ground-based detectors:



$$h(t) = F_+(\text{sky}, \psi) h_+(t) + F_\times(\text{sky}, \psi) h_\times(t) \text{ Ready for DA}$$



TDI CHANNELS (SLIDE ADAPTED FROM JORGE VALENCIA)

- ◎ **CBCs & Current ground-based detectors:**

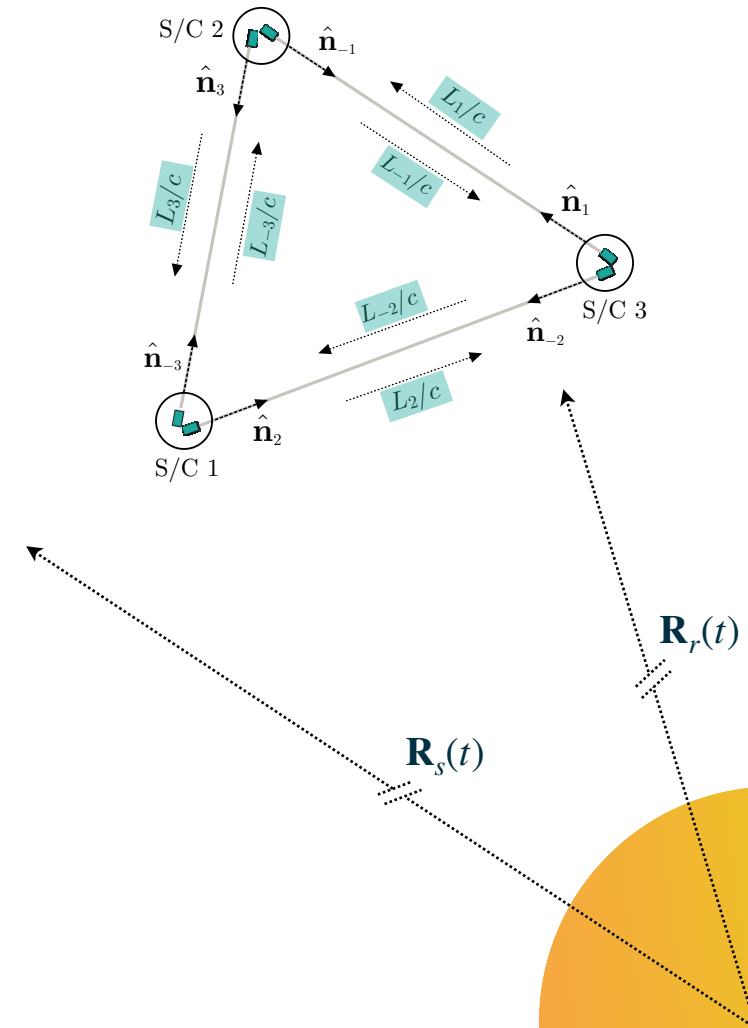


$$h(t) = F_+(\text{sky}, \psi) h_+(t) + F_\times(\text{sky}, \psi) h_\times(t) \text{ Ready for DA}$$

- ◎ **LISA:** The relative laser frequency shifts between spacecraft are related to the GW polarizations as:

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TDI CHANNELS (SLIDE ADAPTED FROM JORGE VALENCIA)

- ◎ **CBCs & Current ground-based detectors:**

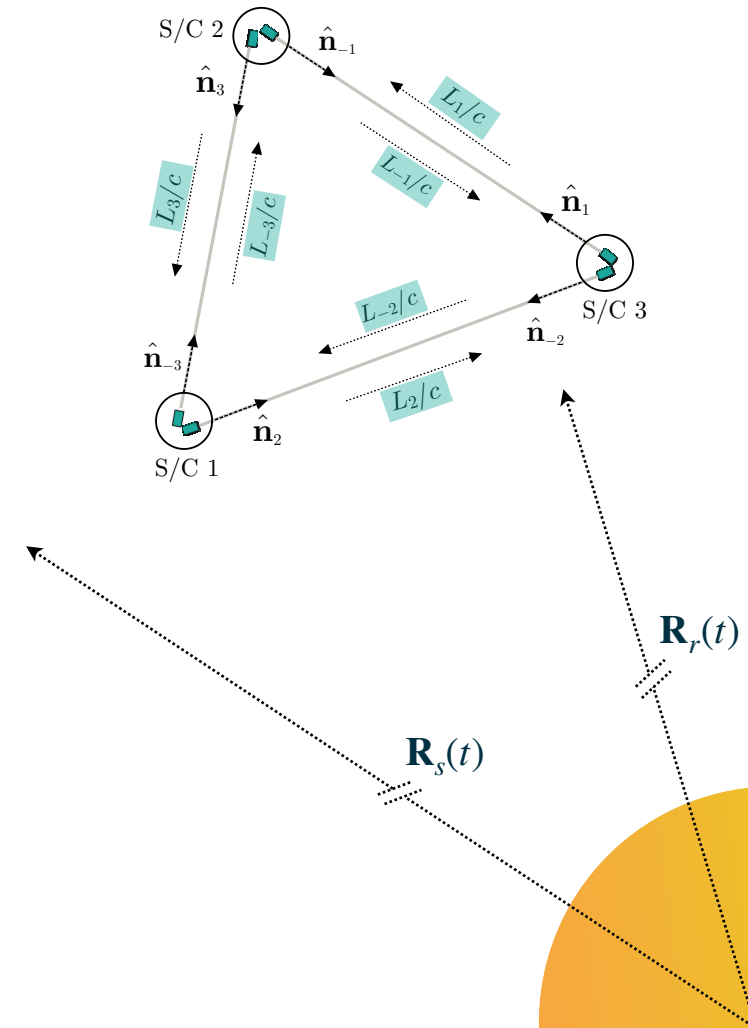


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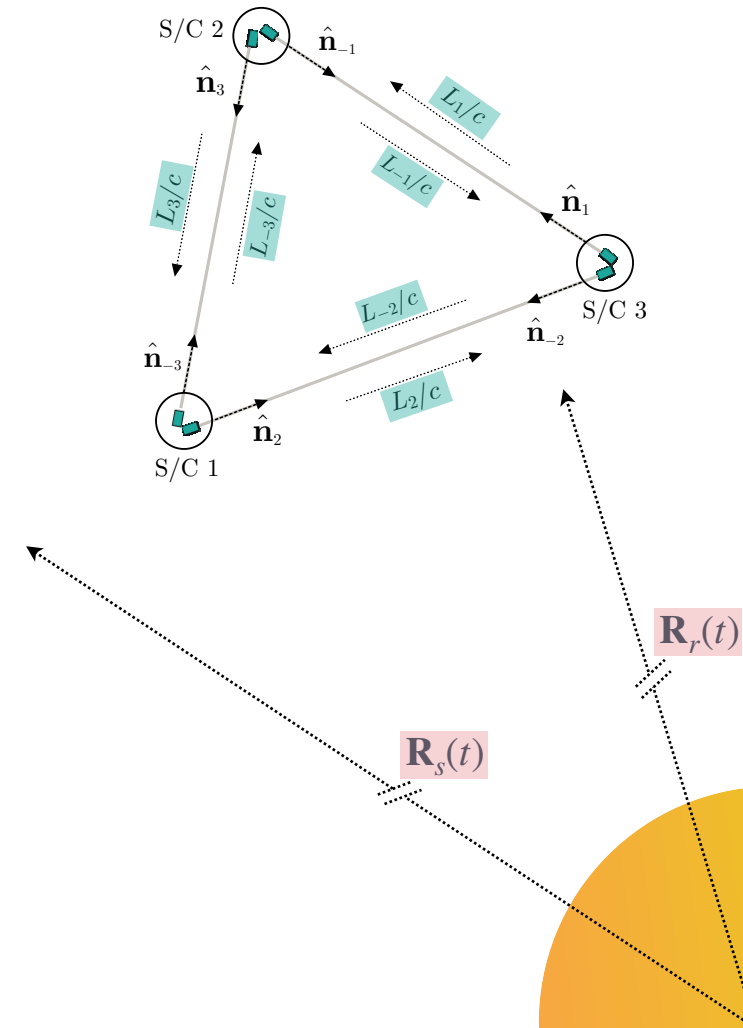
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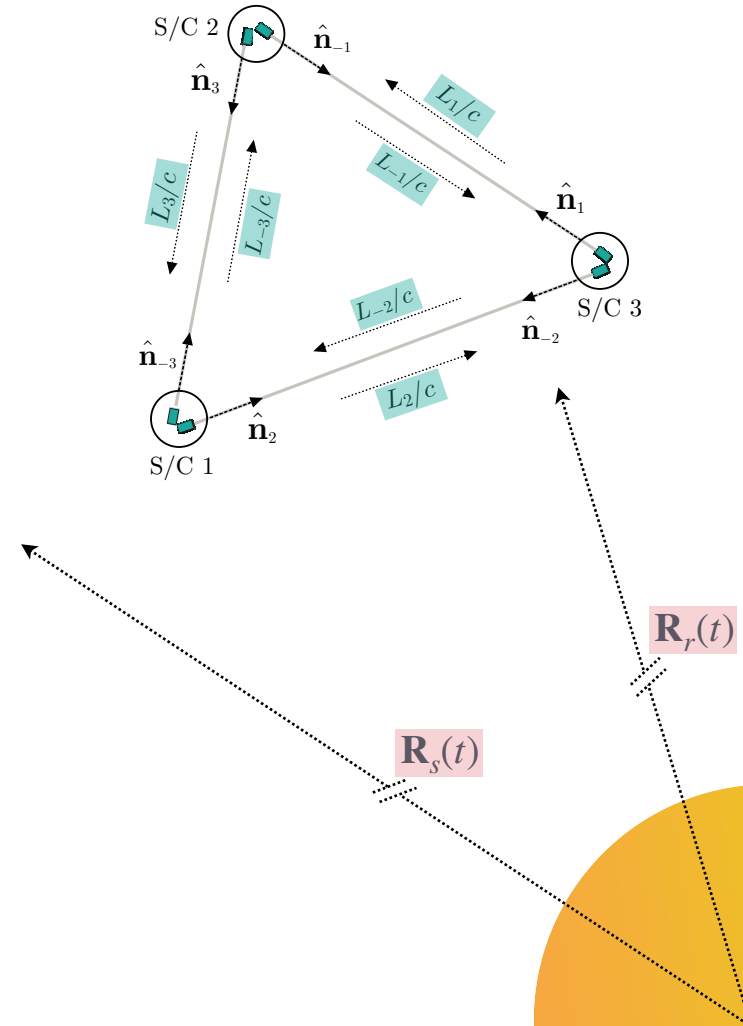
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$$\begin{aligned} X_{1,5}(t) &= y_{1-32}(t - L_{-2} - L_2 - L_3) \\ &\quad - y_{1-32}(t - L_3) \\ &\quad + y_{231}(t - L_2 - L_{-2}) \\ &\quad - y_{231}(t) \\ &\quad + y_{123}(t - L_{-2}) \\ &\quad - y_{123}(t - L_{-2} - L_{-3} - L_3) \\ &\quad + y_{3-21}(t) \\ &\quad - y_{3-21}(t - L_{-3} - L_3), \end{aligned}$$

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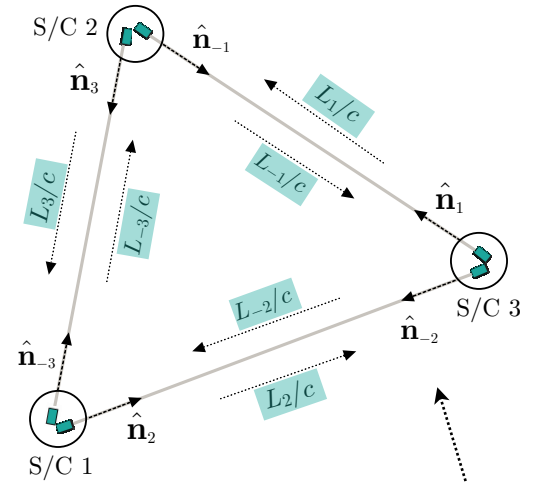
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Ready for DA

$$\begin{aligned} A(t) &= \frac{1}{\sqrt{2}}[Z(t) - X(t)], \\ E(t) &= \frac{1}{\sqrt{6}}[X(t) - 2Y(t) + Z(t)], \\ T(t) &= \frac{1}{\sqrt{3}}[X(t) + Y(t) + Z(t)]. \end{aligned}$$

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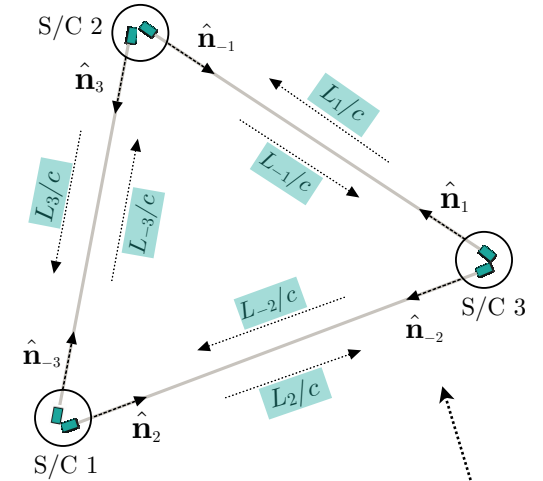
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Inter-spacecraft delay

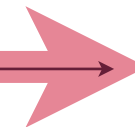
CBC delay

$$H_l(t) = F_l^+(t; \text{sky}, \psi) h_+(t) + F_l^\times(t; \text{sky}, \psi) h_\times(t)$$



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$\mathbf{R}_r(t)$

CORRESPONDENCE BETWEEN TDI AND DERIVATIVES



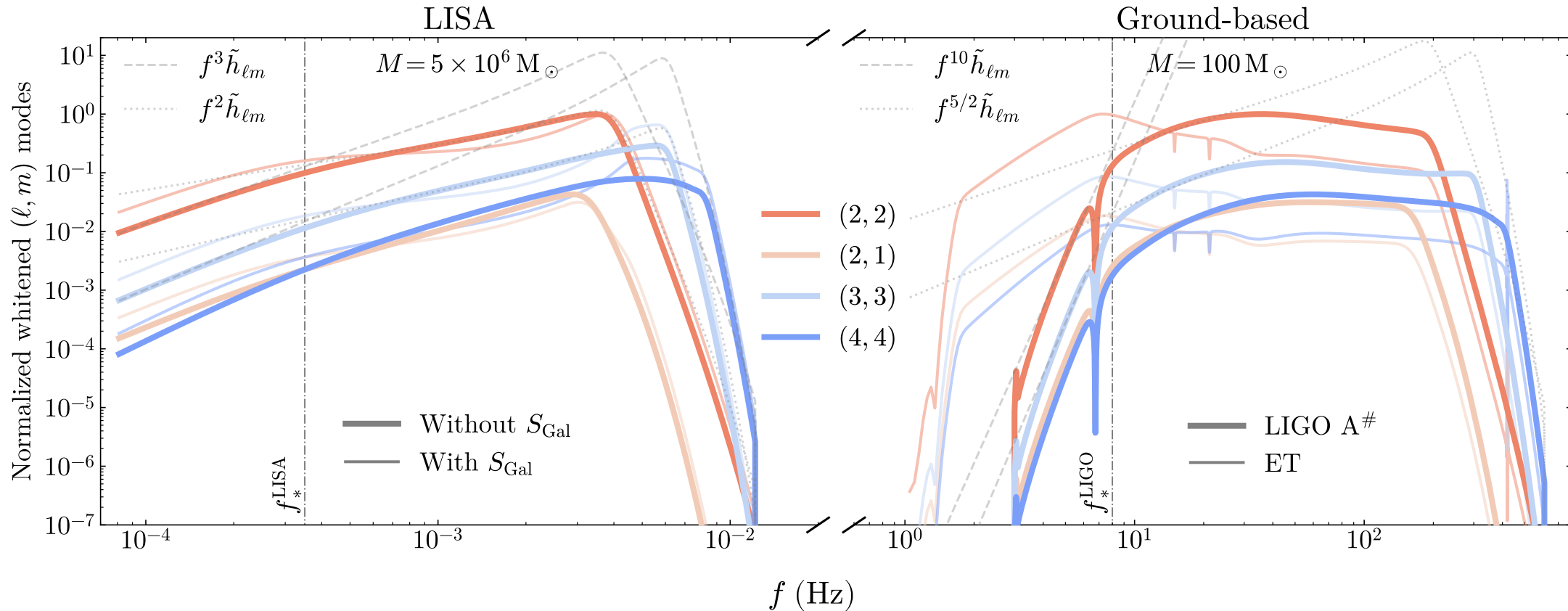
The laser frequency shifts between spacecraft are related to the time **derivatives** of the strain as:

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Finite difference scheme

$t - \delta_s(t) \quad \tau \quad t - \delta_r(t)$

$\approx \dot{H}(\tau)$



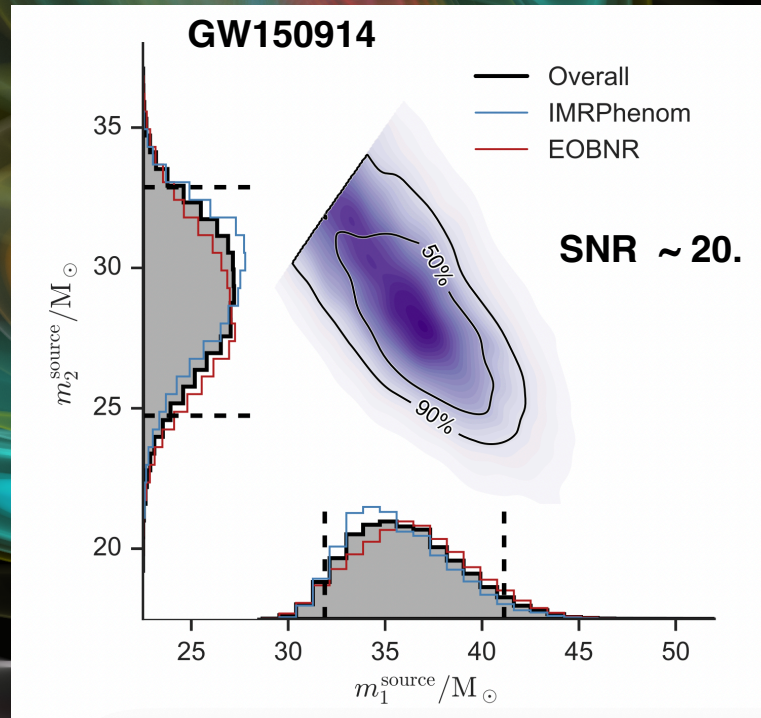
The challenge of waveform modelling for CBC

Describe the GW signal for astrophysically plausible parameter space of coalescing compact objects - accurate enough for Bayesian inference.

BH binaries described by 9 intrinsic parameters: mass ratio (1), spins (6), eccentricity (2).

Further complications:

- NS microphysics!
- Environmental effects, e.g. accretion disks
- exotic physics & “beyond GR”
- Extreme mass ratios (EMRIs) require special techniques
- **Model other messengers!**



Bayesian inference is expensive!

Cost of data analysis determined by cost of waveform evaluation!

Waveform models need to be accurate, fast, robust.

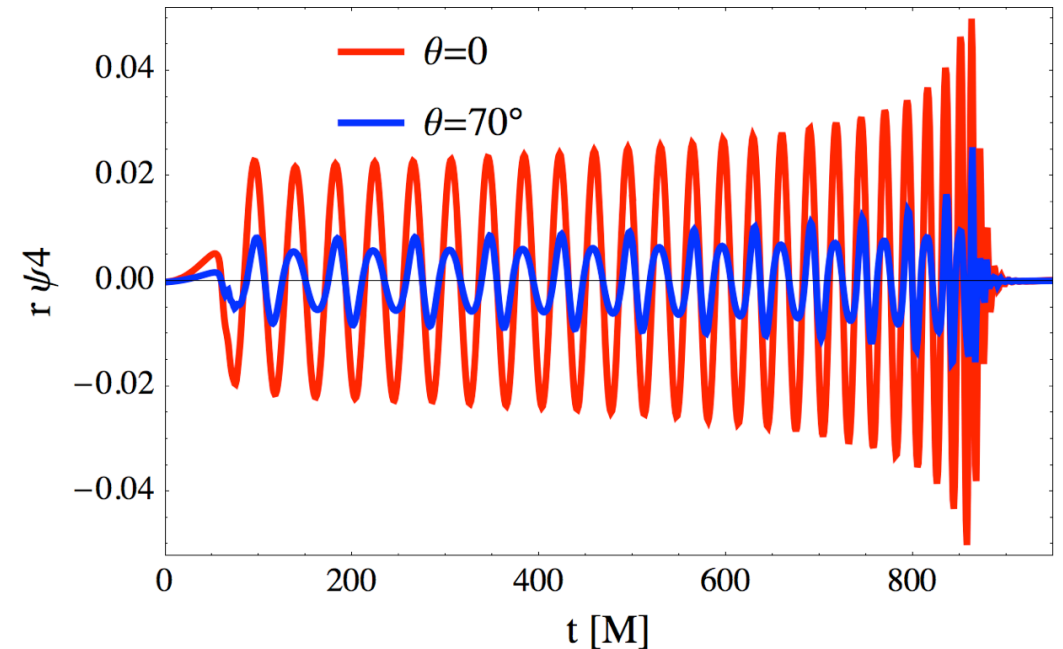
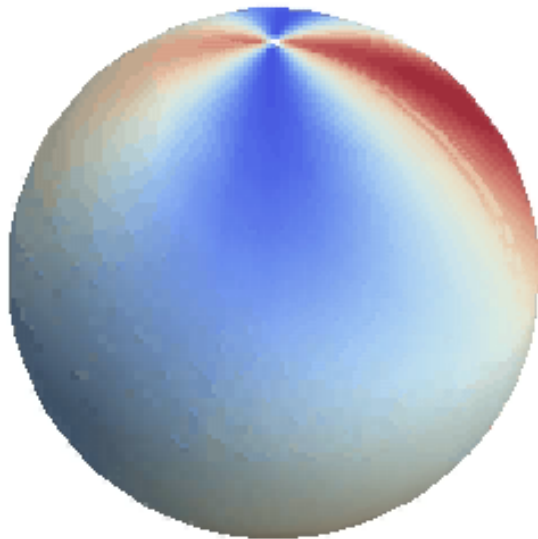
Spherical harmonic decomposition

For information compression:

$$h(t, r, \theta, \phi) = \frac{1}{r} \sum_{\ell=2, m=-\ell}^{\ell_{max}, \ell} h_{\ell m}(t) Y_{\ell m}(\theta, \phi)$$

How many spherical harmonics
do we have to include?

Currently typically include 22, 21, 33, 44, often also 32, 55. We will need further modes for LISA, 3G.



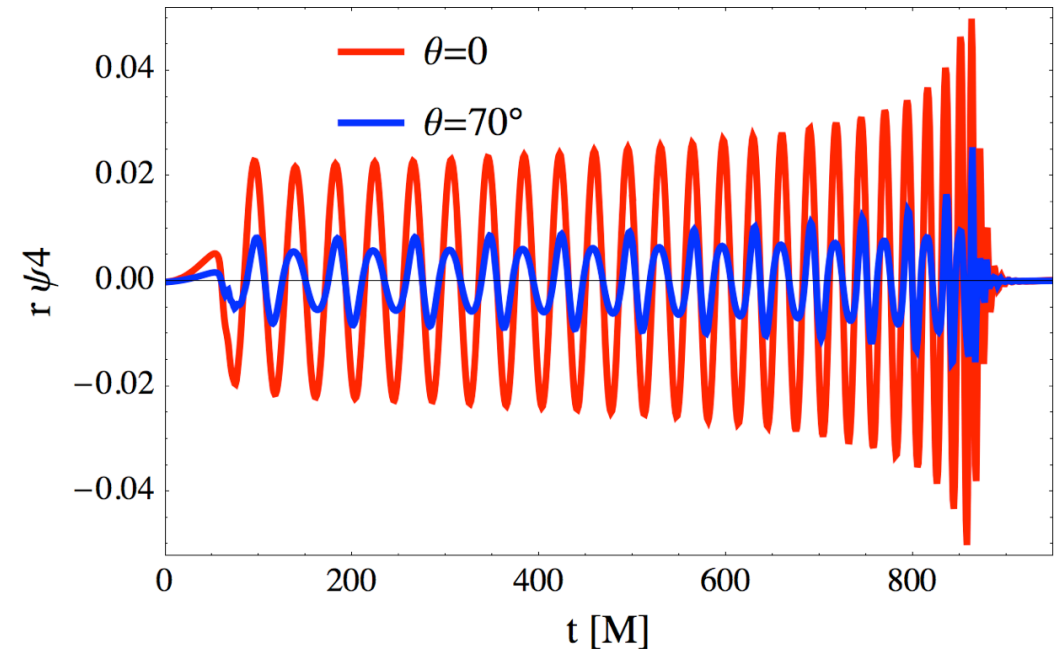
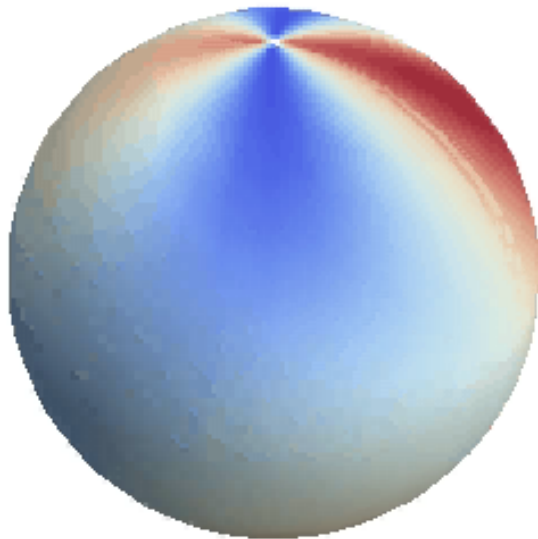
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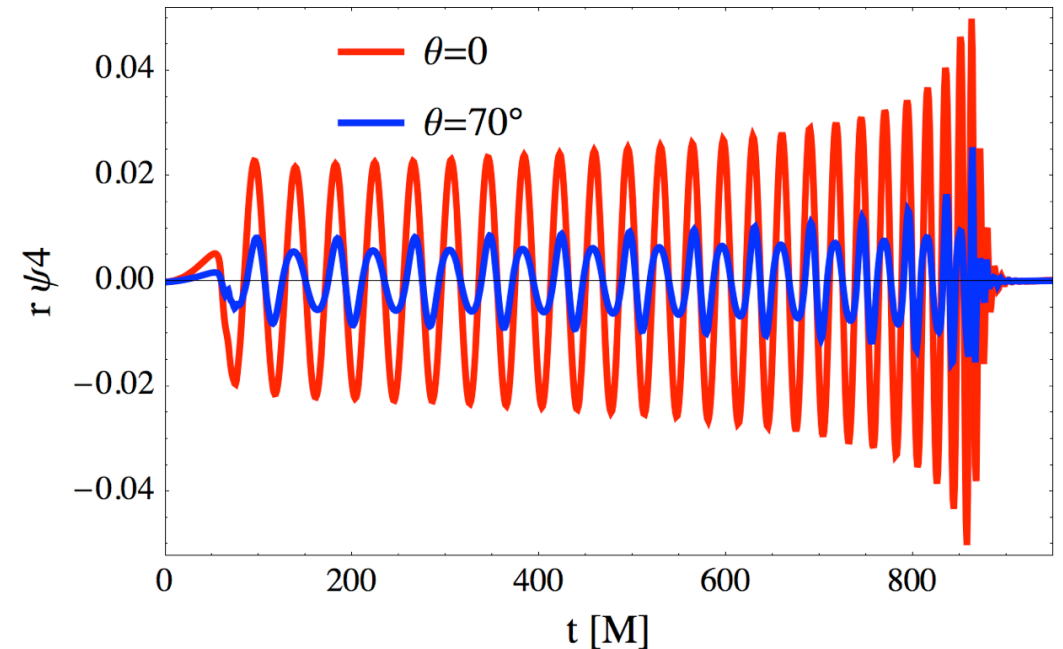
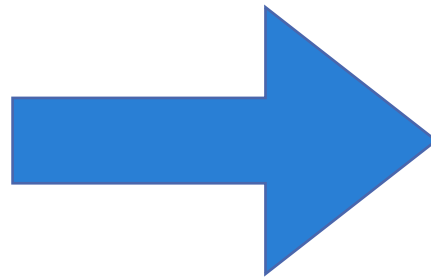
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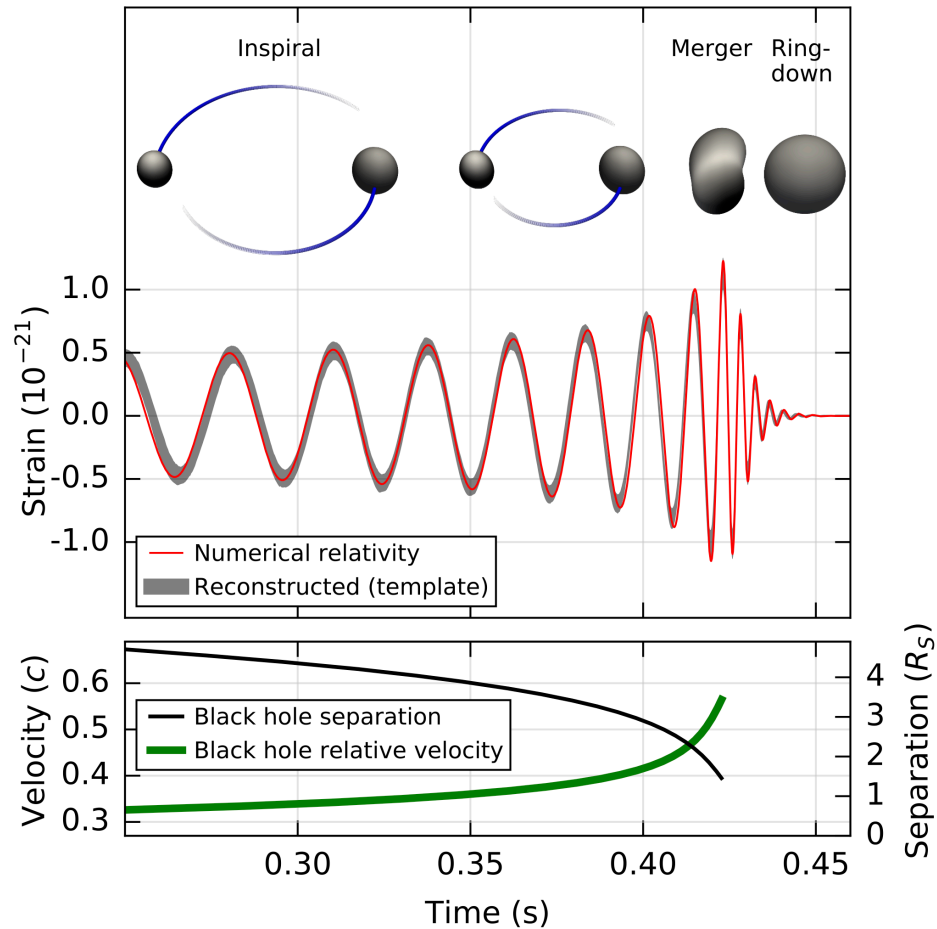
Techniques to solve Einstein's equations

- **Exact solutions:** typically only in the presence of high degree of symmetry. May not be stable!
- **Perturbative approaches:**
 - Post-Newtonian perturbation theory: Series in v/c
 - Good overview/reference text: Lluc Blanchet, Living Review Relativity.
 - Post-Minkowski perturbation theory: Series in G
 - Self-force perturbation theory: Series in mass ratio.
- **Numerical Relativity:** discretise and solve numerically, small parameter is grid spacing, not a physical parameter. Error bars!

Which ones to use:

Often a combination of all of the above.

Need perturbative approaches + numerical relativity



Inspiral: Post-Newtonian expansion in v/c
breaks down for the last orbits

State of the art: mostly $(v/c)^7$

Quasi-normal-mode ringdown

Described by BH perturbation theory.

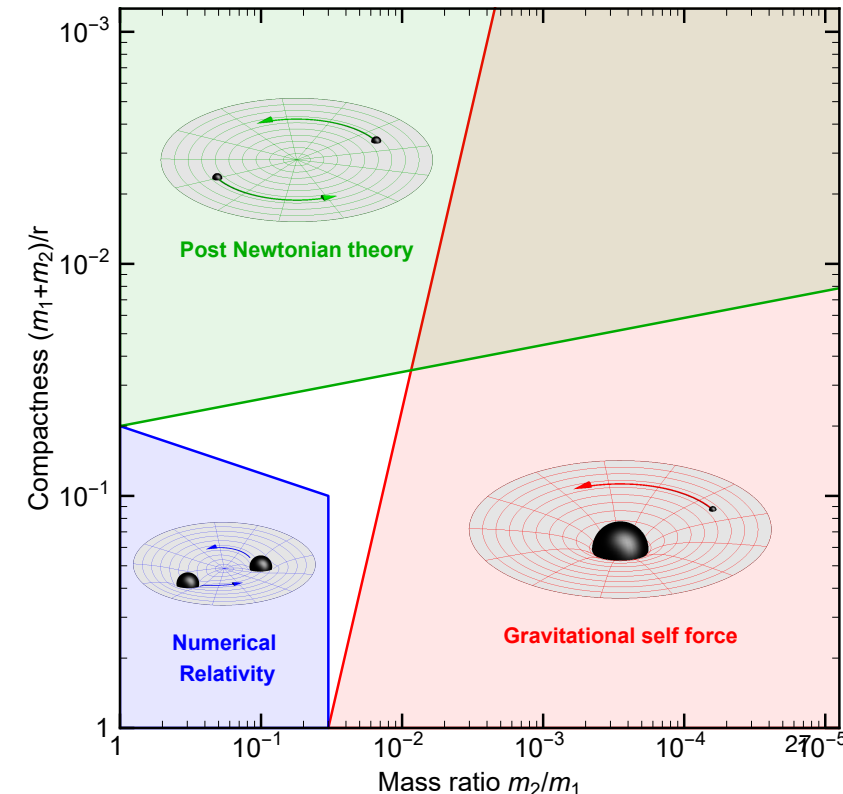
“Quasi” because of energy loss $\Rightarrow$ damped signal with complex frequency.

Self-force Expansion in mass ratio

State of the art: recent breakthrough for second order.

$$T_{\text{coalescence}} \approx \eta^{-1} f_{\text{initial}}^{-8/3} M \quad \eta = \frac{m_1 m_2}{(m_1 + m_2)^2}$$

Covering low frequencies with numerical simulations is very expensive.



CBC Phenomenology: Spin effects

- **Leading order PN spin effect: spin-orbit**

$$H_{SO} = 2 \frac{\vec{S}_{\text{eff}} \cdot \vec{L}}{r^3} \quad \text{Repulsive for aligned spins.} \quad \dot{S} = -2 \frac{\vec{S}_{\text{eff}} \times \vec{L}}{r^3}$$

- **Spins orthogonal to orbital plane: plane preserved.**

- 3-dimensional parameter space: dominant “average” spin

$$\chi_{eff} = \frac{\vec{S}_1 \cdot \hat{L}/m_2 + \vec{S}_2 \cdot \hat{L}/m_1}{m_1 + m_2} \quad \text{measure ok}$$

- subdominant: spin difference

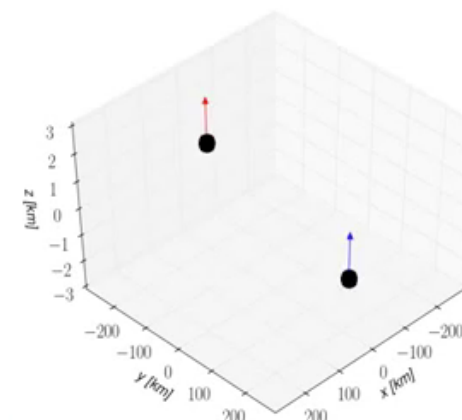
not yet

- **Spin components in orbital plane: precession**

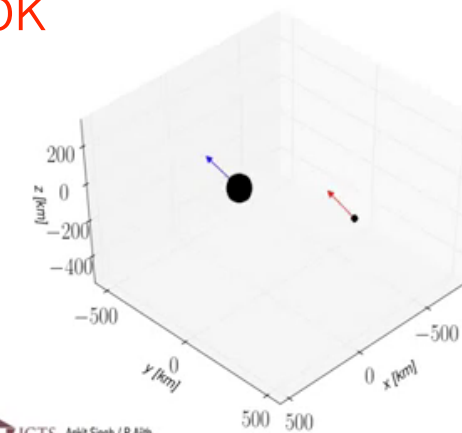
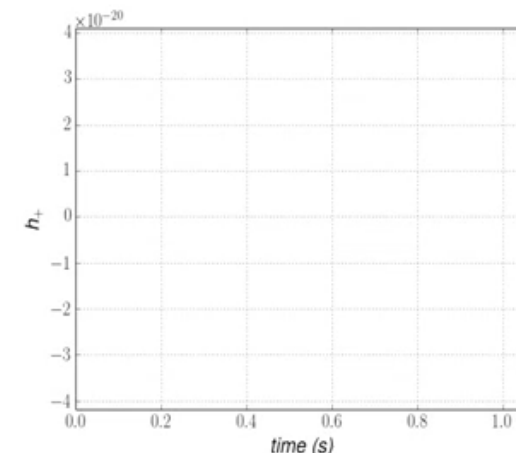
7 dimensions (9 with eccentricity)

- Dominant precession effective spin [Hannam+ PRL 2013, Schmidt+ PRD2014]

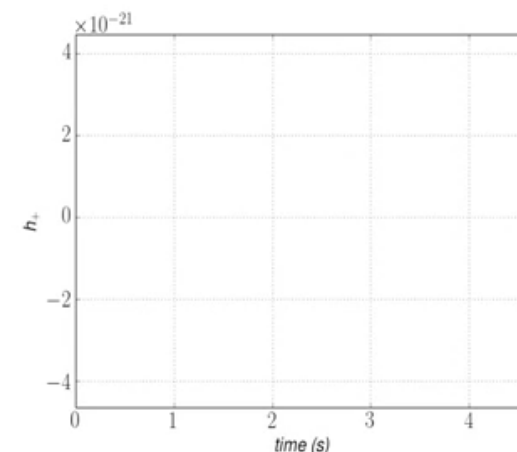
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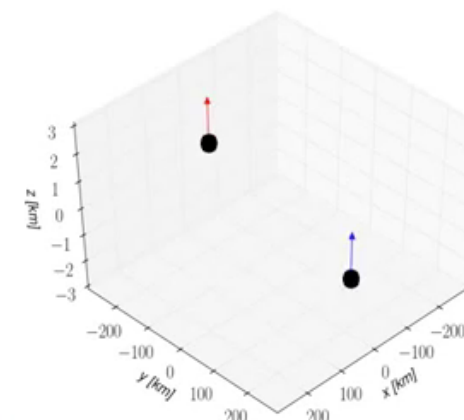
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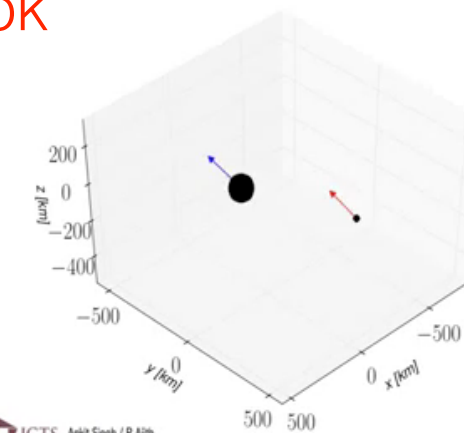
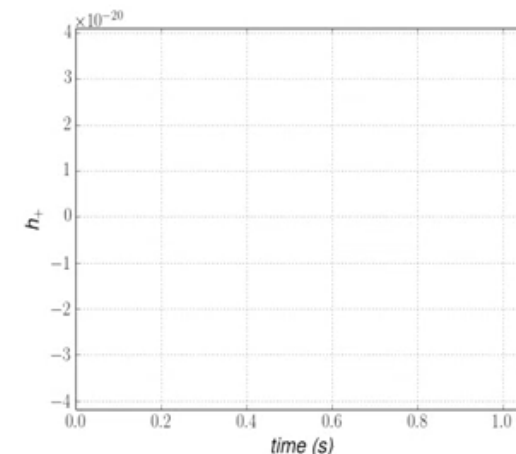
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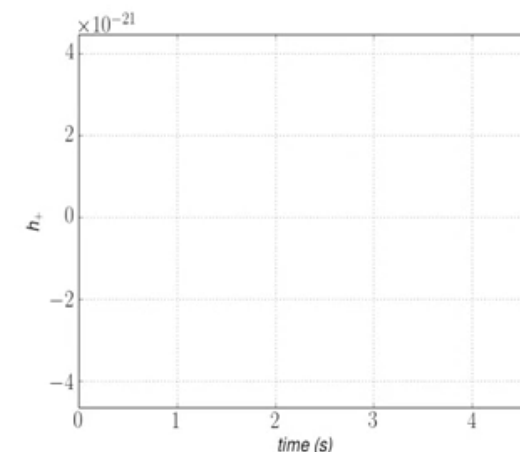
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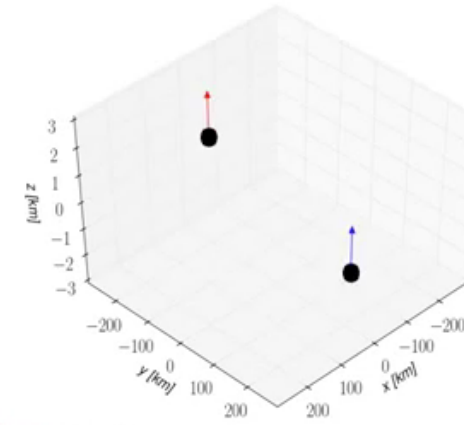
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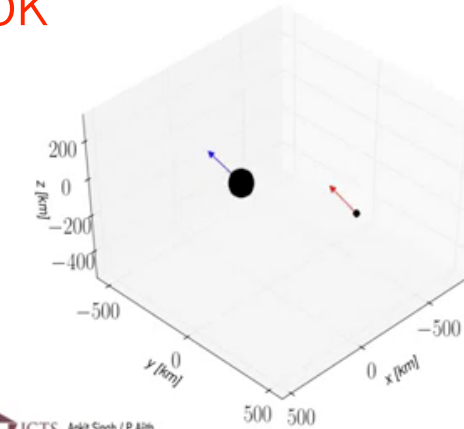
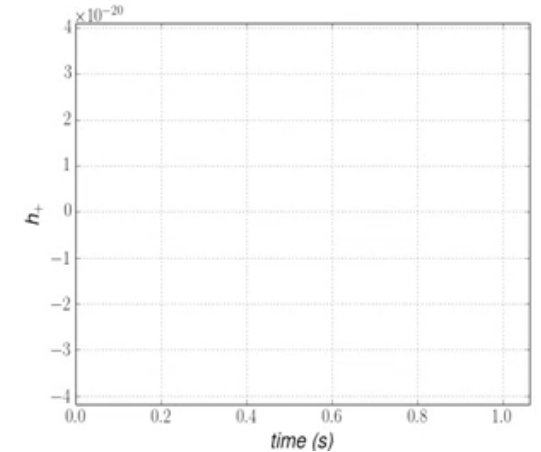
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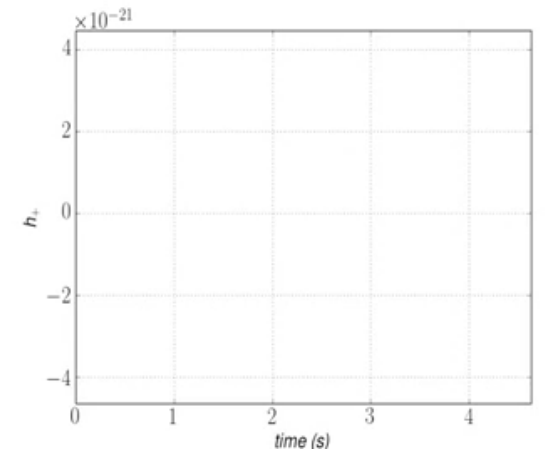
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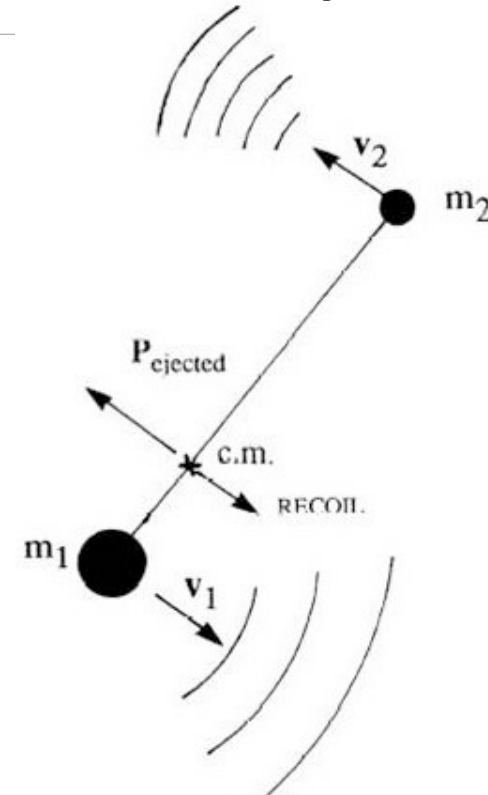


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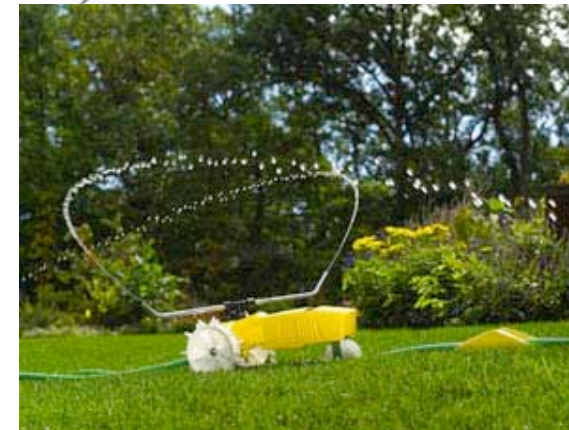


Recoil from merging binaries: need numerical relativity for accurate prediction

- For unequal BHs in a binary, GW emission is asymmetrical and produces a recoil of the final black hole - like a lawn sprinkler would move if the water intensity is asymmetric.
- Recoil from precessing BHs can eject remnant from host galaxy.



Strongest effect:
asymmetry between
22 and 2-2 spherical
harmonics:
out-of-plane
kicks for precessing
binaries.

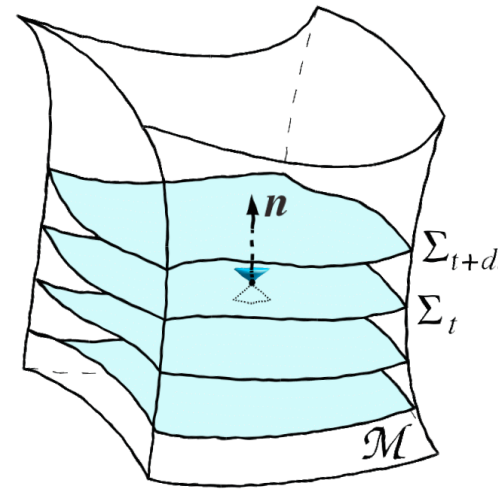


Numerical Relativity

$$G_{ab} = \frac{8\pi G}{c^4} T_{ab} \quad \text{--- starting 1950's --->}$$

IBM 7090: first installation
in December 1959

ANNALS OF PHYSICS: **29**, 304–331 (1964)



Choquet-Bruhat proves
well-posedness of harmonic
formulation.



The Two-Body Problem in Geometrodynamics

SUSAN G. HAHN

International Business Machines Corporation, New York, New York

AND

RICHARD W. LINDQUIST

Adelphi University, Garden City, New York



Numerical relativity is hard:

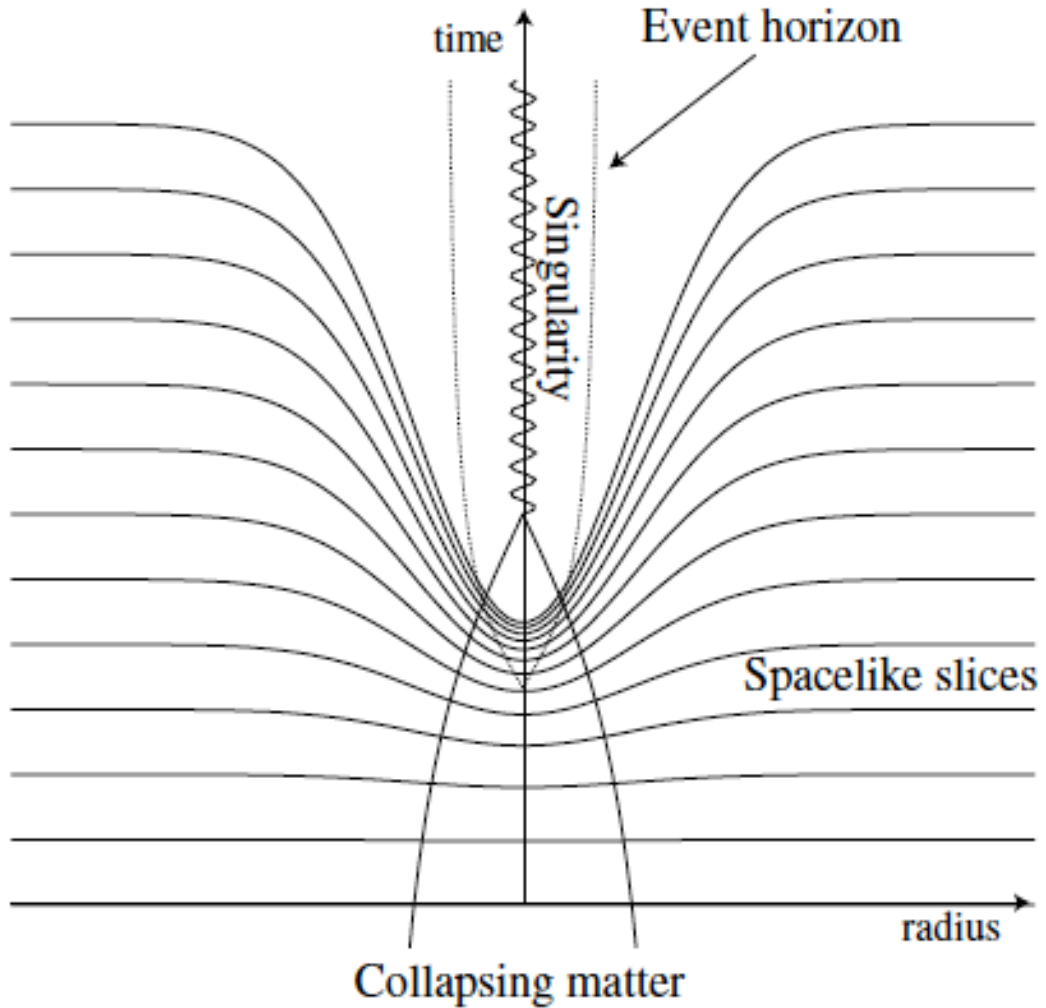
- complex equations without natural IVP,
- need to solve and preserve nasty constraints,
- find suitable coordinate gauge.

Weber bar GW searches:

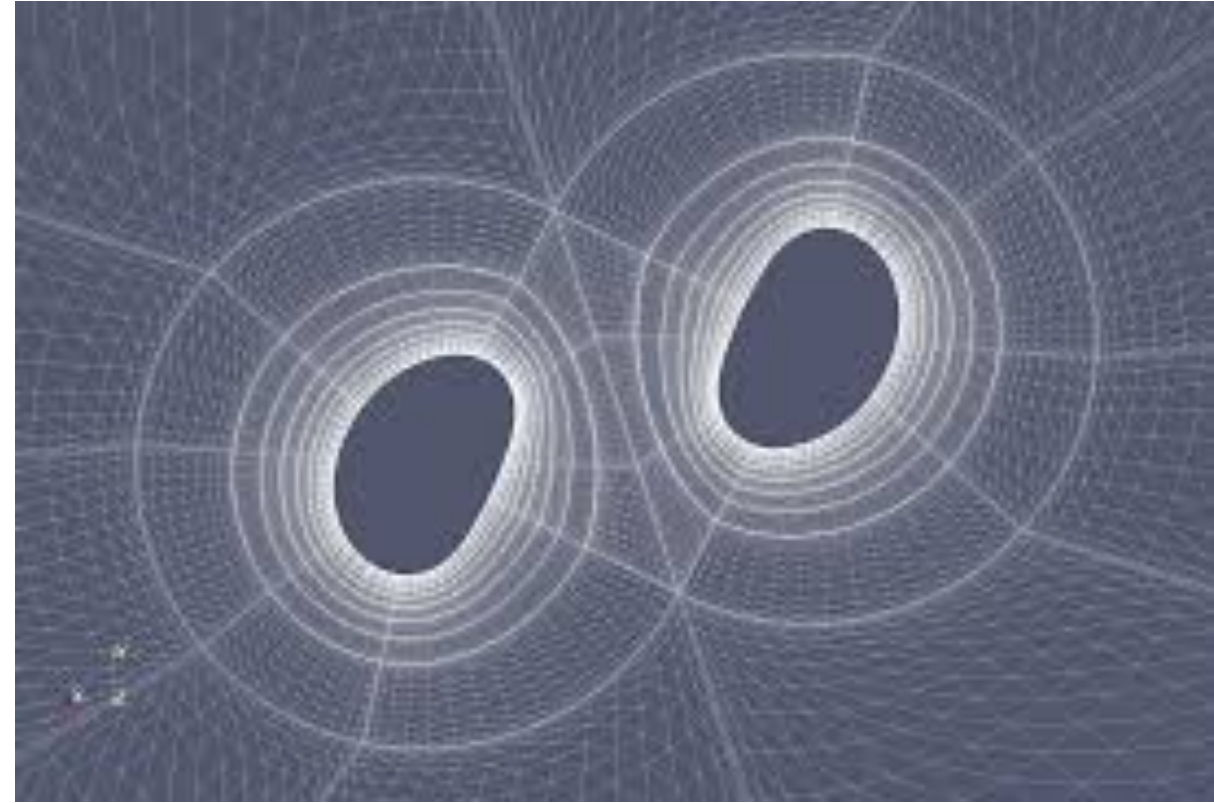
- J. Weber PRL 1967,
“GW observation can’t
be completely ruled out”.
- J. Weber PRL 1968,
“... which may
be gravitational radiation”

How do current NR codes work? - black hole treatment

“moving puncture codes” - temporal excision



Spatial excision closely inside AH



How do current NR codes work? - black hole treatment

“moving puncture codes” - temporal excision

- Several independent codes, including public.
- Small groups; Also: “Einstein Toolkit”, GRChombo.
- Coord. singularity inside AH
 - high order FD
 - High flexibility + robustness
- BSSNOK, Z4c+ “puncture lapse”
 - Typical: second order in space
 - (A)MR regions communicate via buffer points
- Simple mesh refinement geometry
 - Spatial and temporal mesh refinement
 - Communicate between meshes with buffer points
- Dual coordinates unstable for BBH with BSSN

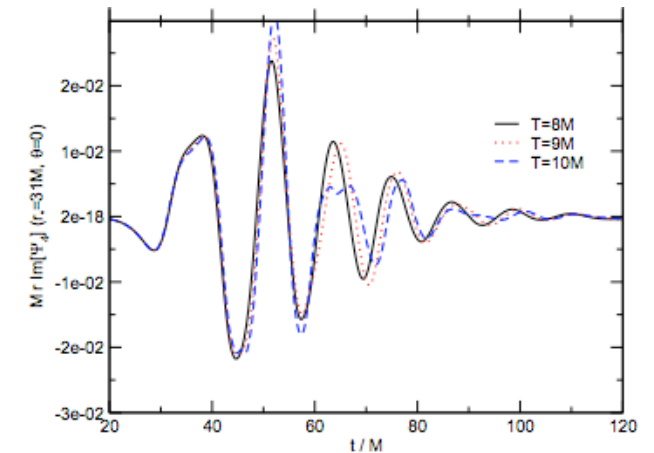
Spatial excision closely inside AH

- SpEC + BAMPS, new: public SpECTRE
- SXS: 1 large collaboration
- Excision surface - is hard to control.
 - Smooth solution - pseudospectral
 - Feedback system for AH location, less robust?
- Generalised harmonic formulation
 - First order reduction
 - Information exchange via characteristic fields
 - Complex domain decomposition
 - Communicate between grids by exchanging characteristic information (1st order formulation)
- Dual coordinates to evolve in co-rotating frame, factor out BH motion for better accuracy.

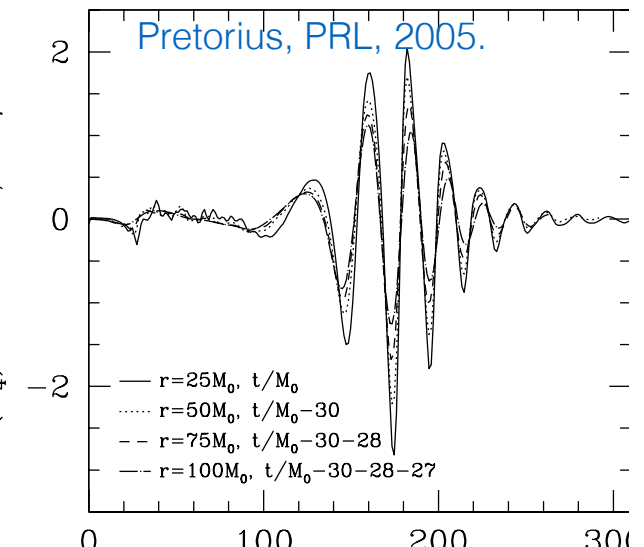
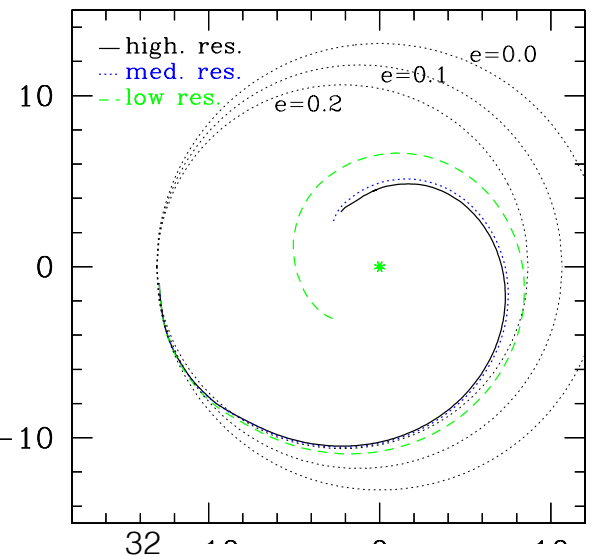
Numerical evolutions of black holes - a “holy grail” problem until 2005

- “Typing things up” required major improvements in the understanding of the Einstein equations.
 - 1992: LIGO project founded.
 - 1993: Choptuik - critical collapse (PRL 1993)
 - 1994-1998: BBH Grand Challenge fails to provide waveforms
 - 2002: First LIGO run & energy loss in equal mass merger $\sim 3\%$ (Lazarus).
 - Will NR have much to contribute to GW detection?
 - Expected binary masses small - SNR dominated by inspiral $\rightarrow$ use PN!

[Baker+. PRD65 124012]



- **First orbit + GWs: Pretorius PRL 2005**
- Surprise breakthrough after 4 decades of unstable formulations.
- $\Rightarrow$ Gold-rush of improved methods and results, first in NR, then data analysis.
- **Detection of first GW with inspiral-merger-ringdown waveform models 10 years later.**



Status: numerical relativity for BBH

- Methods studies (convergence, impact of gauge parameters, ...) very expensive!

• What can be done:

- few simulations ~ 100s of orbits
- routine simulations of ~ 10 orbits
- systematic exploration up to mass ratio 18, [Planas+, PRD (2024)] 12, 124028] short simulations of higher mass ratios (RIT)
- high spins with non-conformally flat data (SXS, RIT).

- Catalogues: SXS (SpEC), Maya, RIT, BAM - need more WFs, minimise time for new NR methods to impact WF models.

• Small selection of new codes and methods:

- GPUs start to become mainstream, e.g. CarpetX for Einstein Toolkit (but: cores/GPU?)
- GR-Athena++ - block based AMR instead of Berger-Oliger
- Public pseudo spectral (discontinuous Galerkin) code from SXS: Spectre

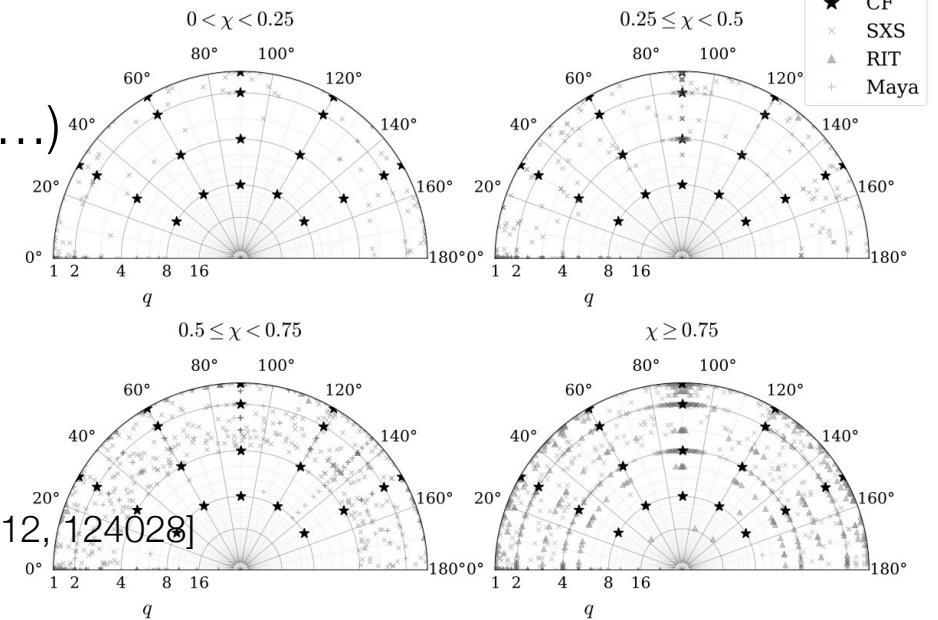


FIG. 16. Comparison between the parameters of the new BBH simulations presented here (CF) and the existing BBH simulations in the SXS, RIT and Maya catalogues. The *Top left* spin disk shows simulations with spin on the larger black hole $0 < \chi < 0.25$, *Top right* $0.25 \leq \chi < 0.5$, *Bottom left* $0.5 \leq \chi < 0.75$ and *Bottom right* $\chi \geq 0.75$. The radius of each disk shows the mass ratio of the binary and the orientation shows the spin tilt angle of the larger black hole. Spin tilt angles of 90° means that the spin vector lies in the binary's orbital plane.

Cardiff group, arXiv:2303.05419

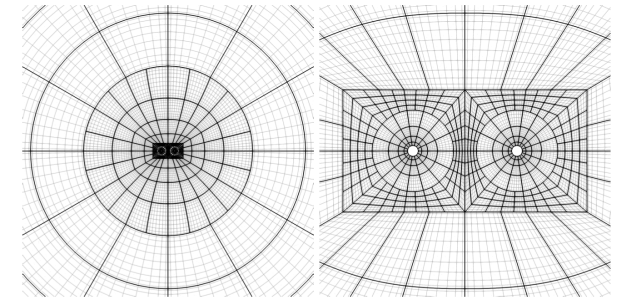


Figure 8. An illustration of the computational grid used during the inspiral. We make use of two excision regions, each region lying inside a black hole's apparent horizon. Each excision is surrounded by a spherical shell partitioned into six deformed cubes as in figure 2. Each spherical shell is then surrounded by another shell of six deformed cubes that transition to a cubical boundary. Then the two cubes themselves are surrounded by a transitional envelope which becomes spherical. *Left*: The transitional envelope. *Right*: A close-up of the domain structure around the excisions. The center of each excision is offset from the center of the cube.

SpECTRE (SXS), arXiv:2410.00265

Can we get the waveform models we want/need?

- Cross-pollination and competing ideas:
 - EOB (SEOBNR, TEOBResumS), IMRPhenom, ROM/surrogates!
 - Development of main “current” model families has become part of the LVK, based on **NRDA meeting series** and **Ninja-project**.
 - “Theoretical development”, (open source) code implementation, testing, review, maintenance & interpretation of parameter estimation results.
- Address trade-offs in different ways - 3 main strategies with [different emphasis](#).
- **effective one body (EOB)** - [analytical methods to compute waves from dynamics](#)
 - model energy + flux/wave amplitude of a particle in effective metric => integrate ODEs numerically.
 - Slow - need a fast model of the phenomenological EOB model, or fast PE, e.g. with ML
- **“surrogate models”** - [algorithms to interpolate large parameter spaces](#)
 - Fast evaluation of EOB or NR data directly.
- **IMRPhenom models** - [model waveform directly](#) - current generation IMRPhenomX* / IMRPhenomT*
 - piecewise closed form - **extreme compression of information**, fastest, parallelizable - GPUs!
used by LIGO-Virgo for all events to date.



Waveform systematics in GWTC-4.0

Models used in parameter estimation

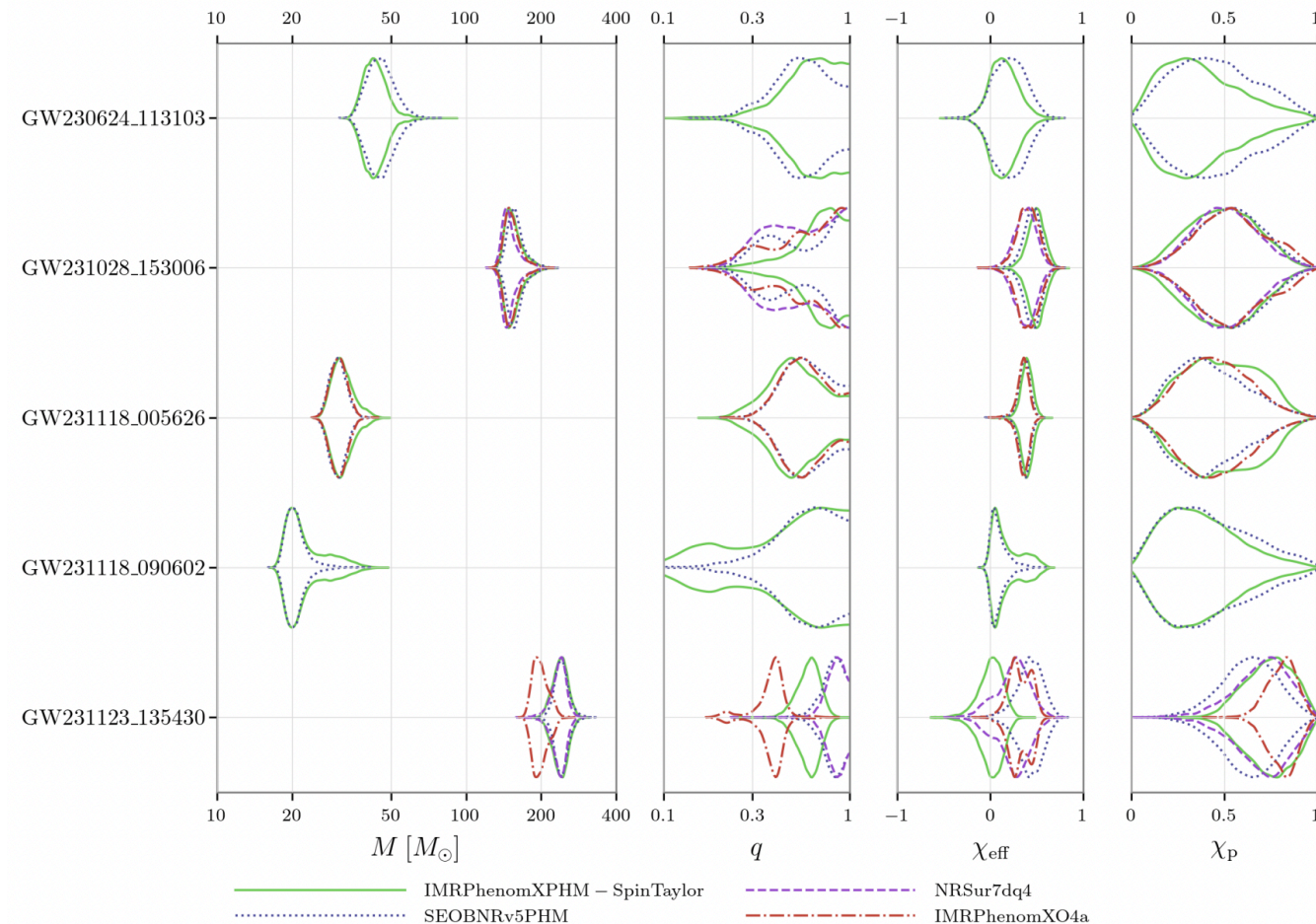
- Frequency domain: IMRPhenomXPHM-SpinTaylor, IMRPhenomXPNR, generalisations to NS.
- Time domain: SEOBNRv5PHM, NRSur7dq4 (within applicability), IMRPhenomTPHM.

Overall picture

- Most events show **consistent results across models**

But differences emerge when:

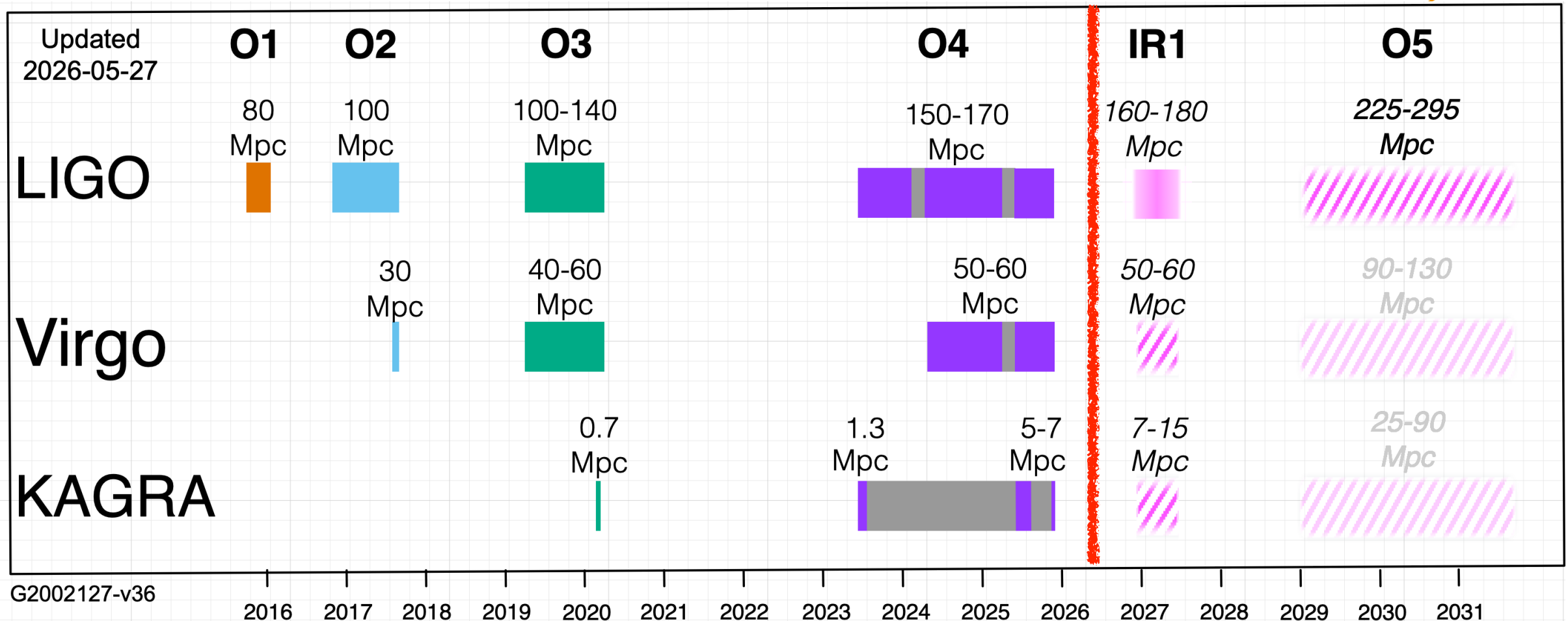
- **High total mass** → merger–ringdown dominated signals
- **Unequal masses / high spins** → limited calibration
- **High SNR** → statistical errors shrink, systematics dominate



Source: GWTC-4.0 Results ([arxiv:2508.18081](https://arxiv.org/abs/2508.18081))

Slide adapted from
Héctor Estellés

Observing runs:

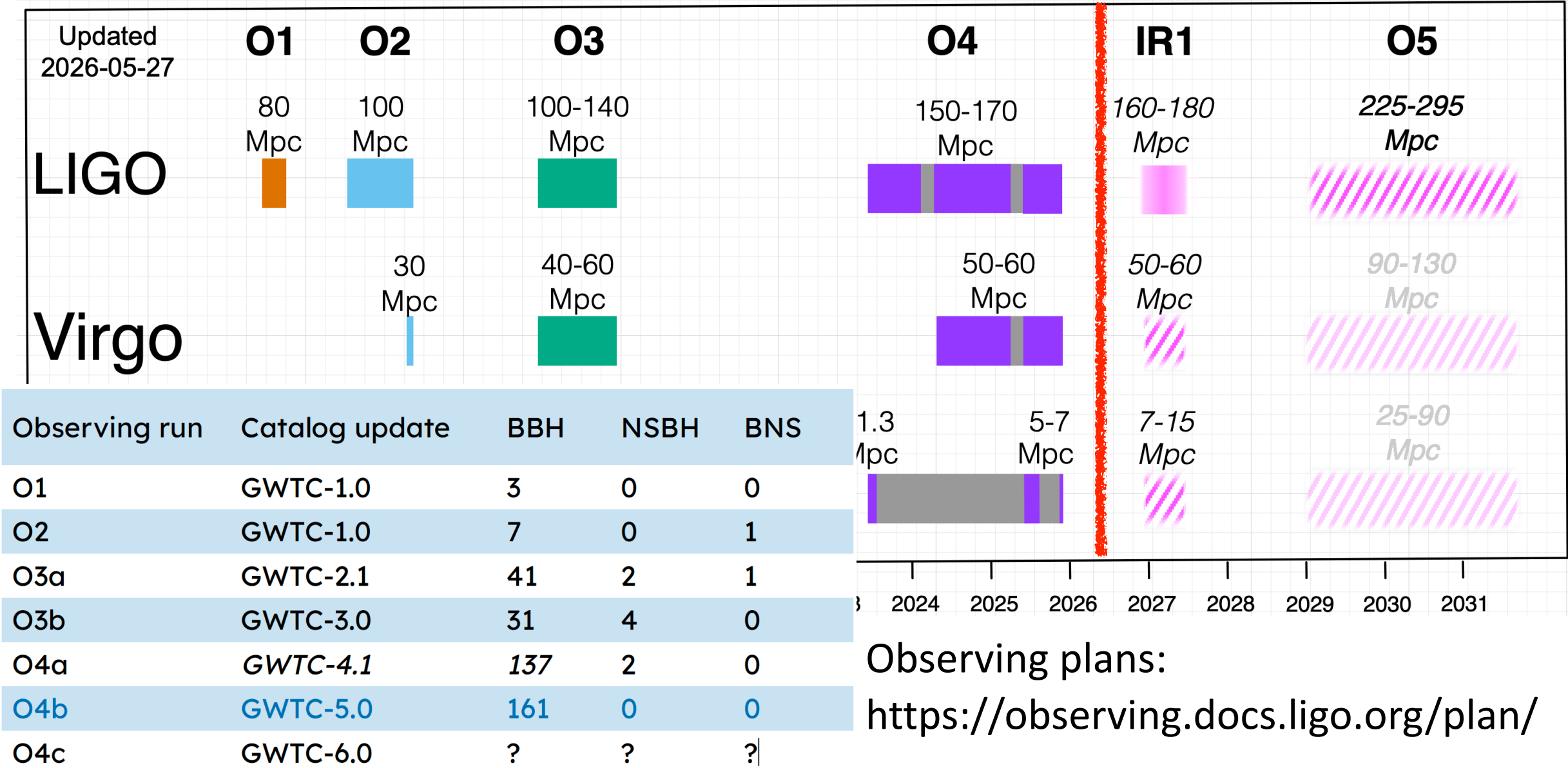


Observing plans:

[LIGO-Virgo-KAGRA observing scenarios: LRR23,3 \(2020\)](https://observing.docs.ligo.org/plan/)

<https://observing.docs.ligo.org/plan/>

Observing runs:



The O4 Observing Run

- Plotted: binary neutron star (BNS) range [for signal-to-noise ratio 8, averaged over inclinations and sky locations]

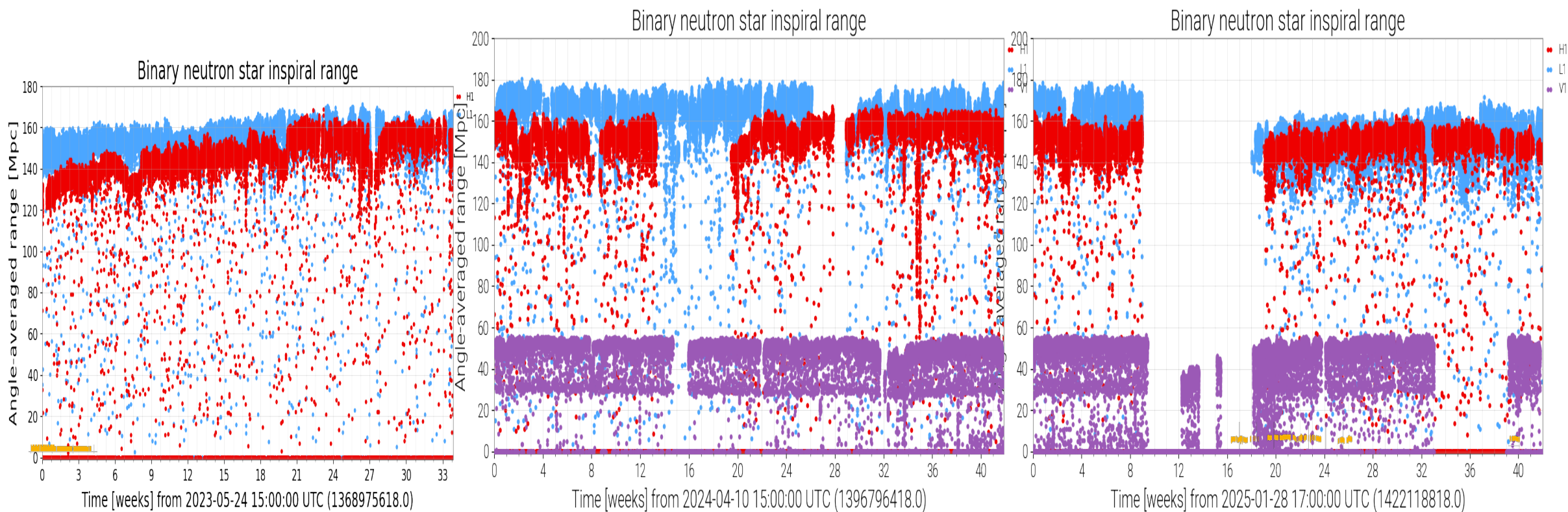
• LIGO Livingston LIGO Hanford Virgo KAGRA

O4a: May 24th 2023- January 16th 2024

O4b: April 10th 2024- January 23rd 2025

O4c: January 24th 2025- November 18th 2025

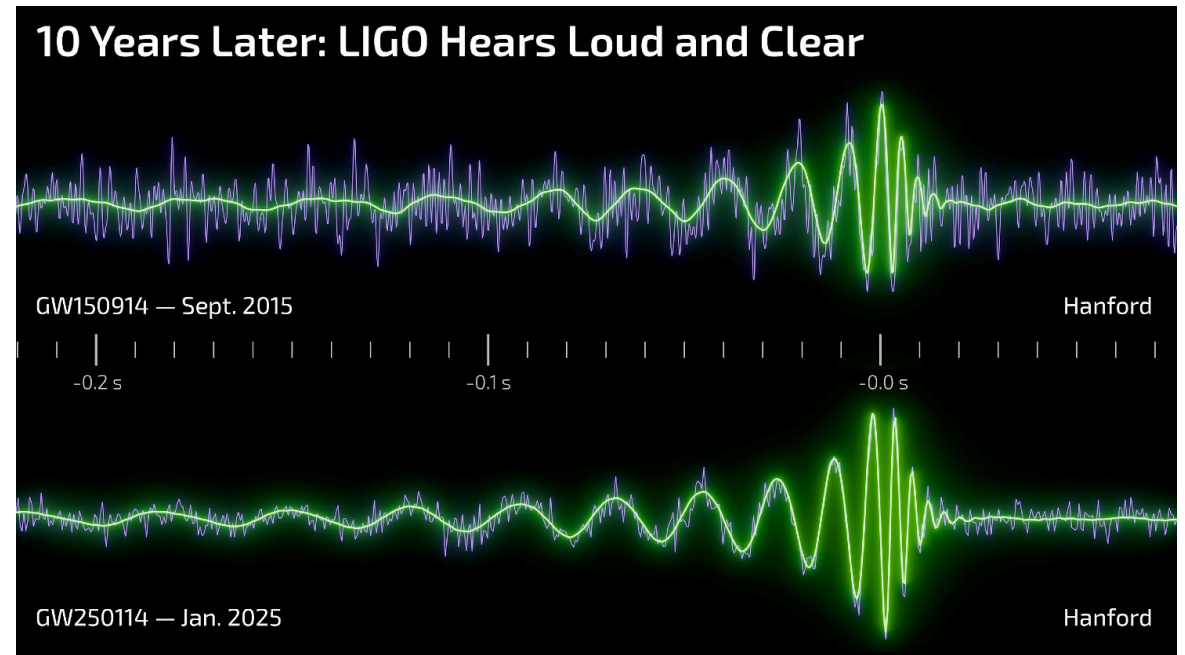
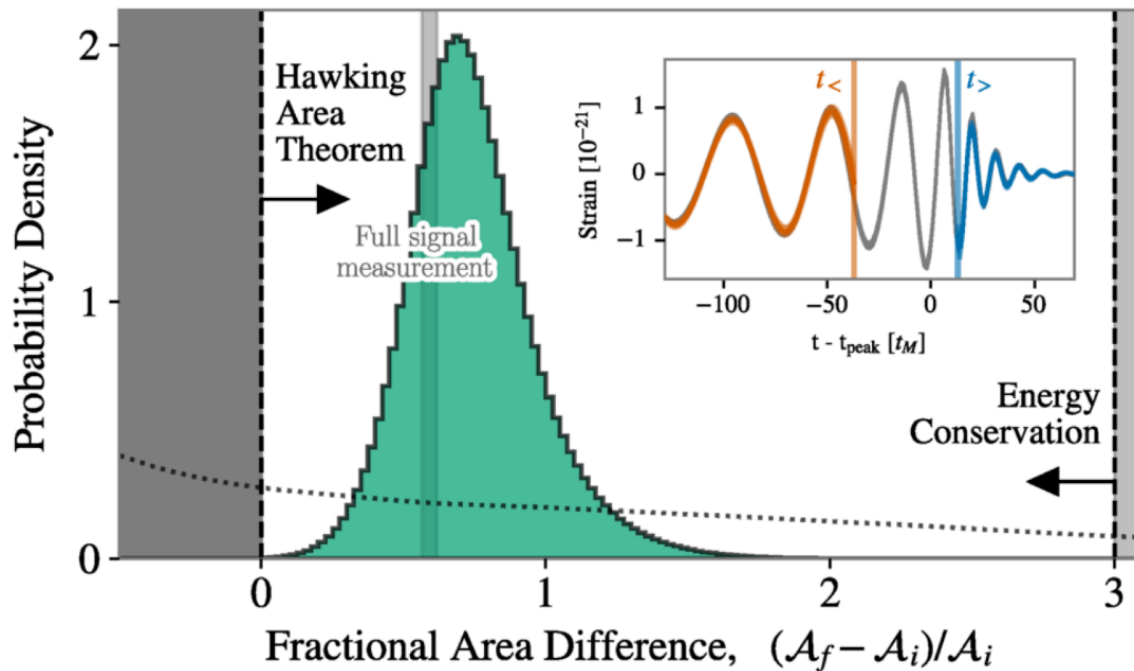
- O4 break for maintenance and enhancement work
+ Engineering Run 16 (ER16) was from Jan 16 to April 10, 2024.
- 2nd Maintenance break from 1 April 2025 to **11 June 2025**



GW250114:

LVK, PRL, 135, 111405 (2025)

- The loudest signal so far (SNR ~ 80) [O4b detection]. GW signal and source properties almost identical to GW150914 but over 3x louder
- GW250114 shows that **Hawking was right, too!**
remnant event horizon area > sum of progenitor areas with 3–5 σ significance



The Gravitational Wave Transient Catalogs (GWTC)

- **Cumulative catalogs** of GW transient events detected by the **LIGO-Virgo-KAGRA** (LVK) network.
- Each version includes **all previous events plus new detections / re-analyses**.

Versioning:

GWTC-<major>.<minor>

- **Major number**->adds new observing run data (O1, O2, O3a, O3b, O4a, ...)
- **Minor number**-> updates within the same run (e.g, re-analysis or expanded candidate list).

Slide adapted from
Héctor Estellés

Most recent: **GWTC-5.0**: Adds new sources from the O4b observing run (search arXiv for GWTC-5.0).

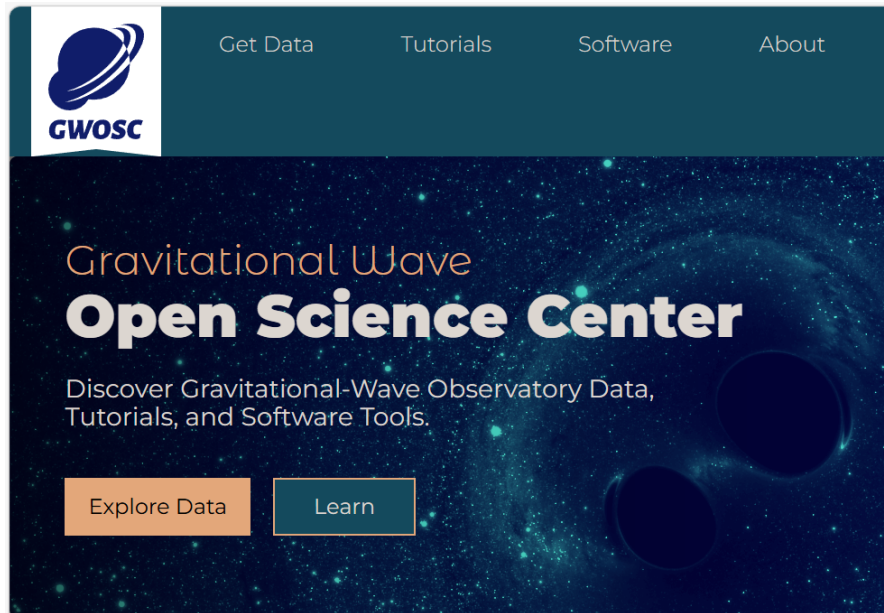
Since GWTC-4.0 we follow a standard focus issue scheme, which bundles several papers:

- **Introduction: Description of the runs, data, detector status, ...**
- **Methods: How the data were analysed**
- **Results: Searches** (list of candidates with astrophysical probability) + **PE**: posterior distributions for confidently detected sources.
- **Population Properties** of Merging Compact Binaries
- **Cosmology**: Constraints on the Cosmic Expansion Rate
- **Tests of GR**
- **Separate**: special events papers.

Public access: available via [Gravitational-Wave Open Science Center \(GWOSC\)](#)

Latest online catalogs and data releases

<https://gwosc.org/>



Event Catalog

The Gravitational-wave Transient Catalog (GWTC) is a cumulative set of events detected by LIGO, Virgo, and KAGRA.

O4a: **Strain data and GWTC-4.0 catalog** released on **August 26, 2025**

O4b: **Strain data and GWTC-5.0 catalog** released on **May 26, 2026**

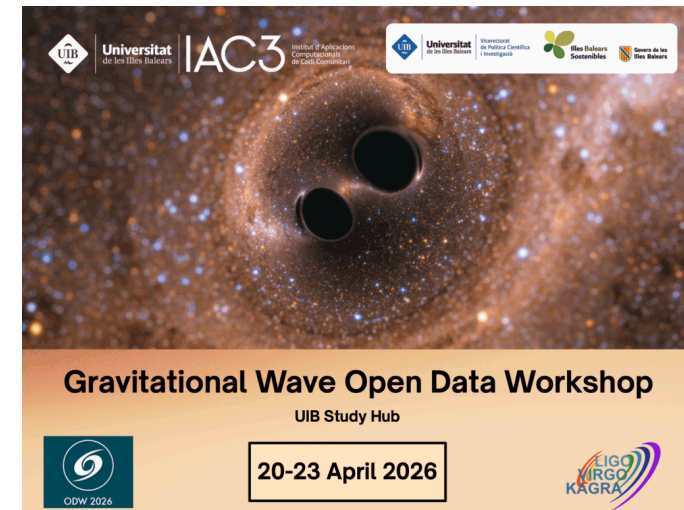
O4c: Strain data and catalog to be released on **December 16, 2026**

<https://dcc.ligo.org/M2300059/public>

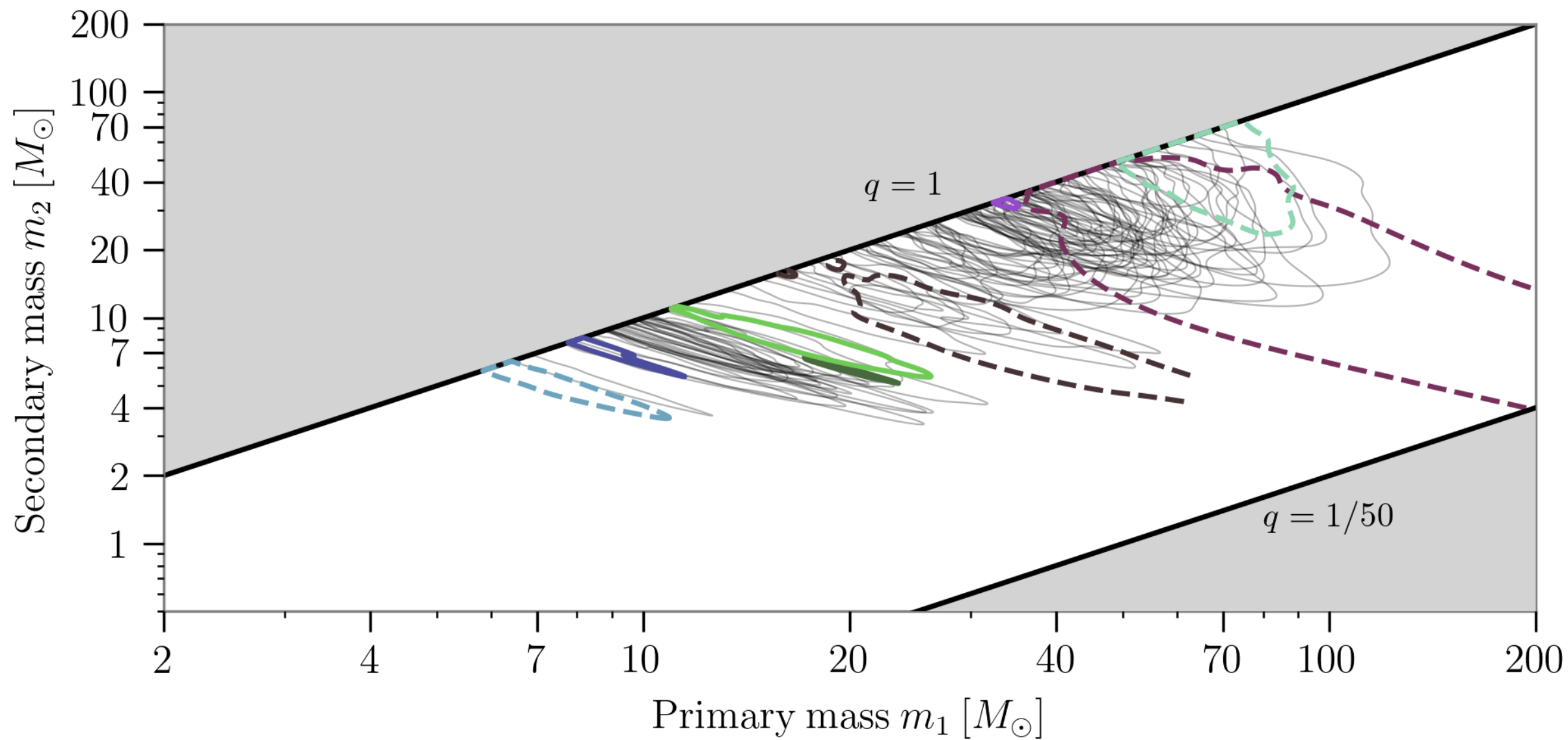
Last event open to all: <https://gwosc.org/workshops/>



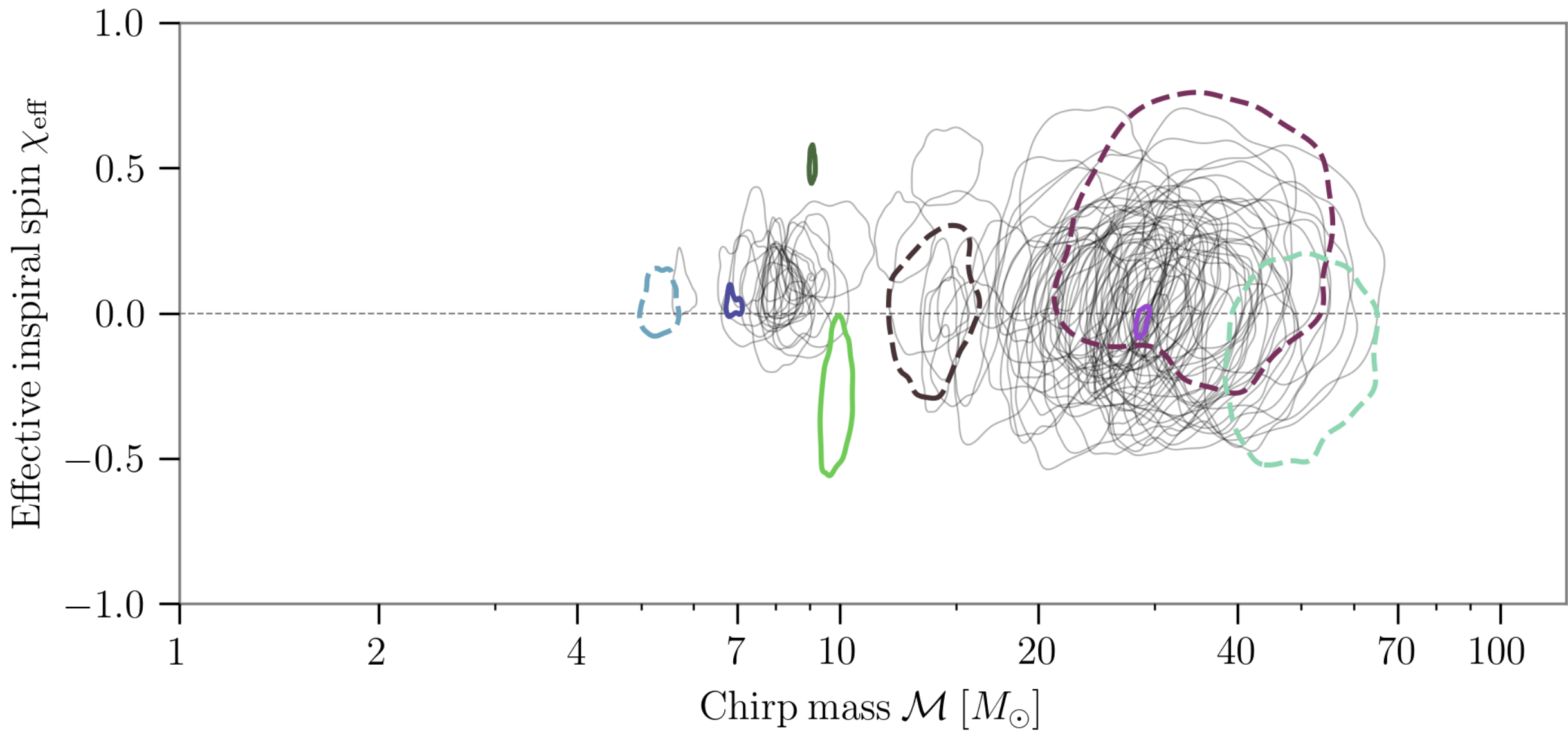
... plus tutorials, software, and materials from past workshops

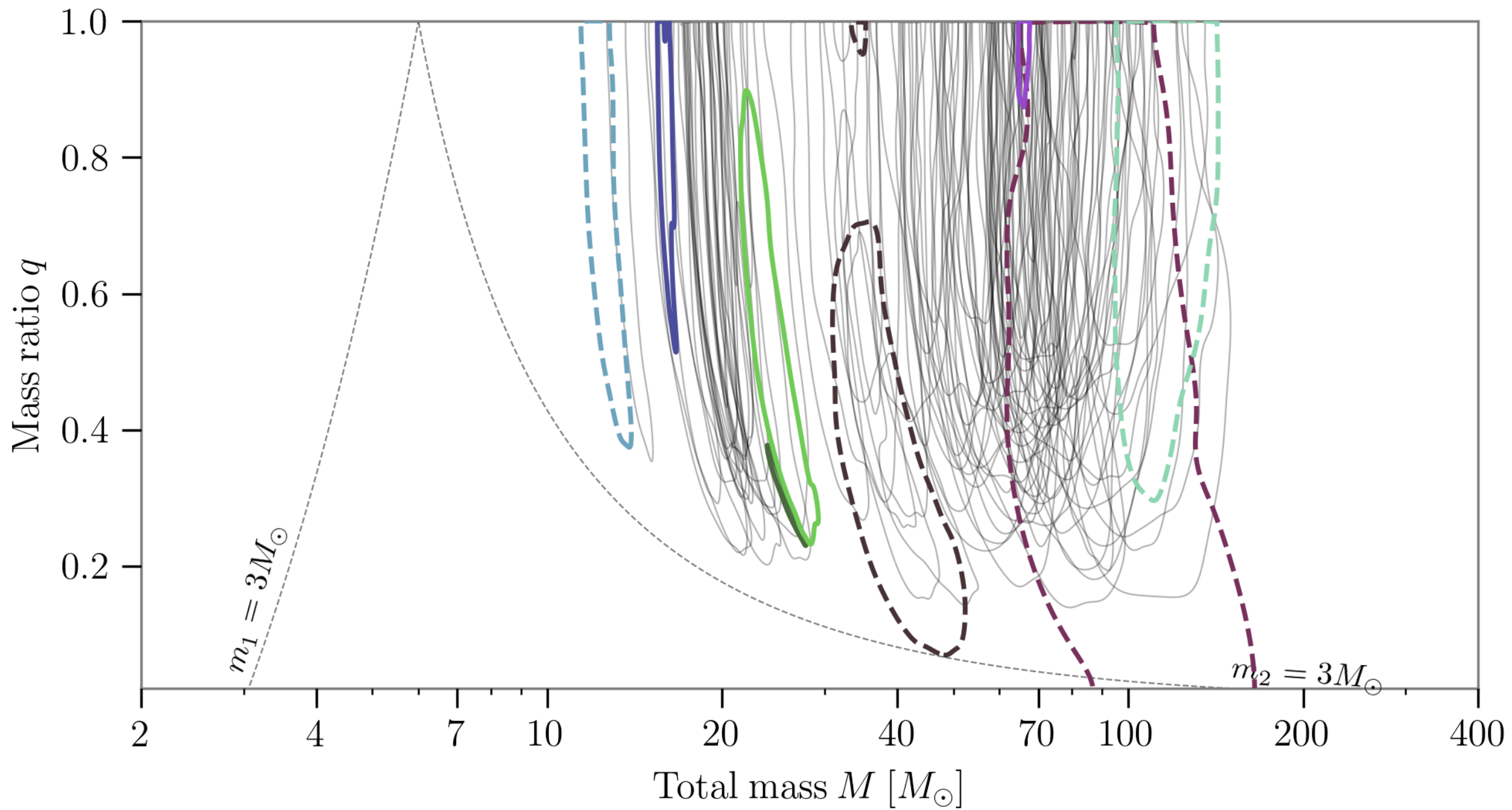


-- GW240507_041632	— GW241011_233834	— GW241110_124123	- - GW241230_233618
— GW240925_005809	- - GW241109_115924	- - GW241116_151753	— GW250114_082203

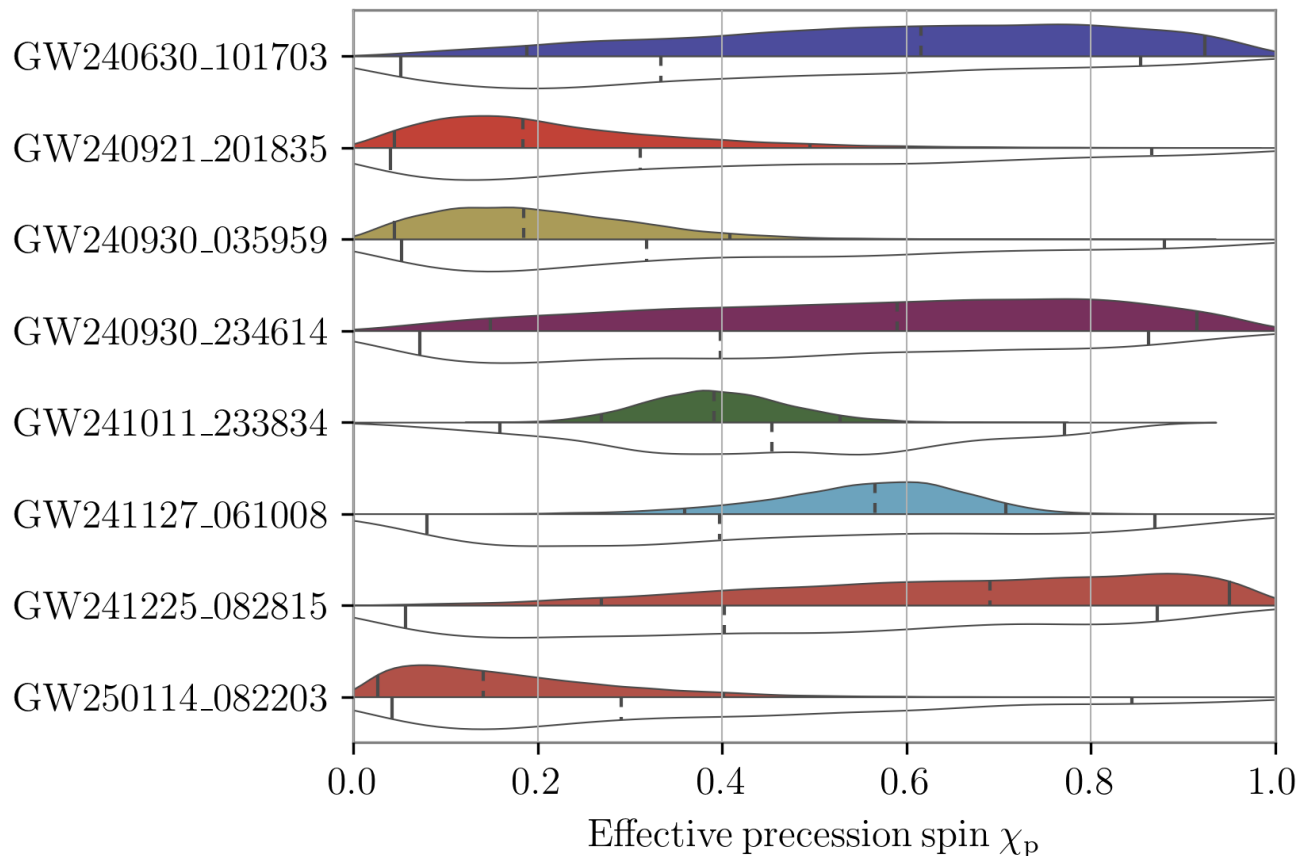


GW240507_041632 GW241011_233834 GW241110_124123 GW241230_233618
GW240925_005809 GW241109_115924 GW241116_151753 GW250114_082203

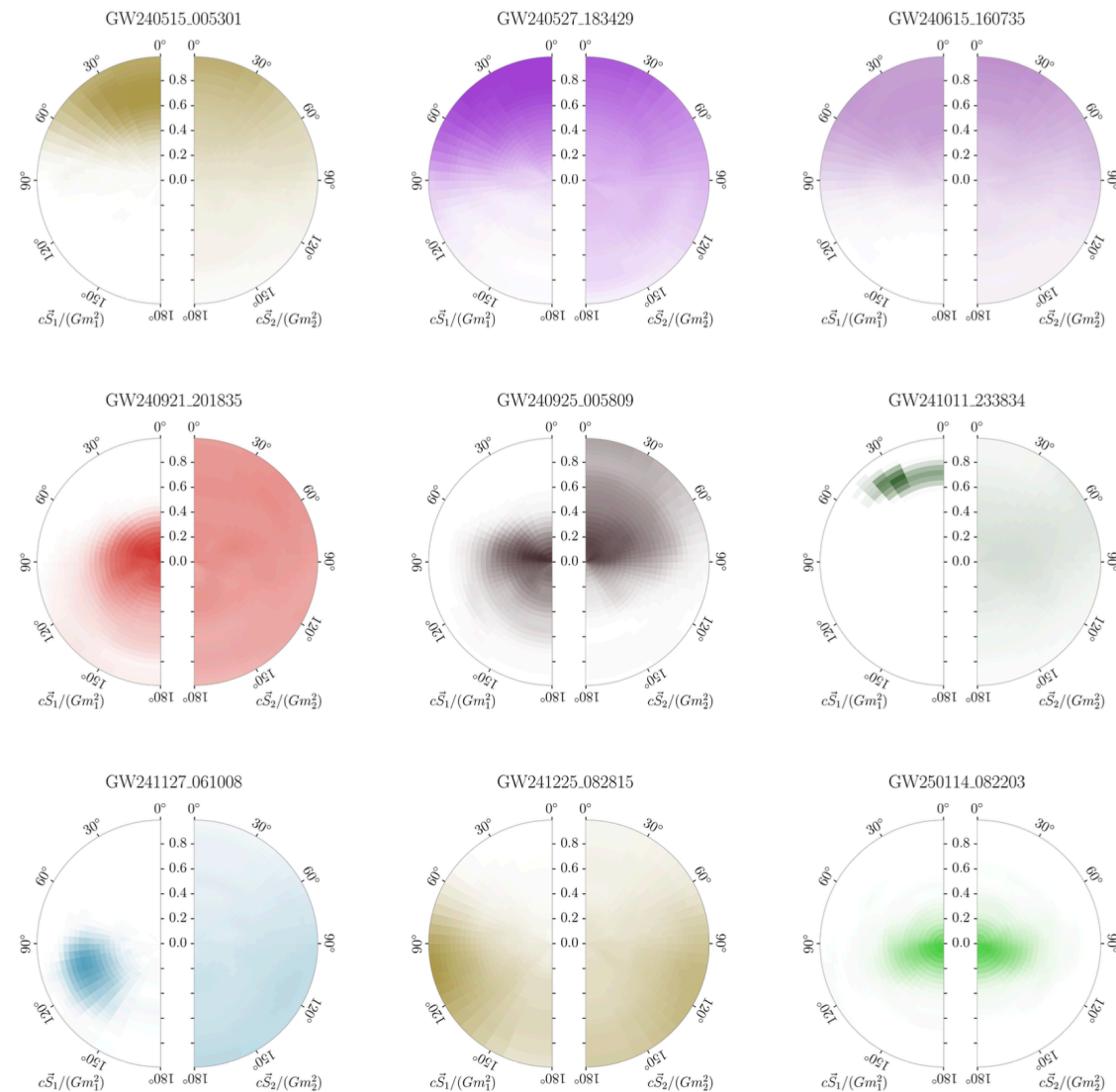




Spin precession

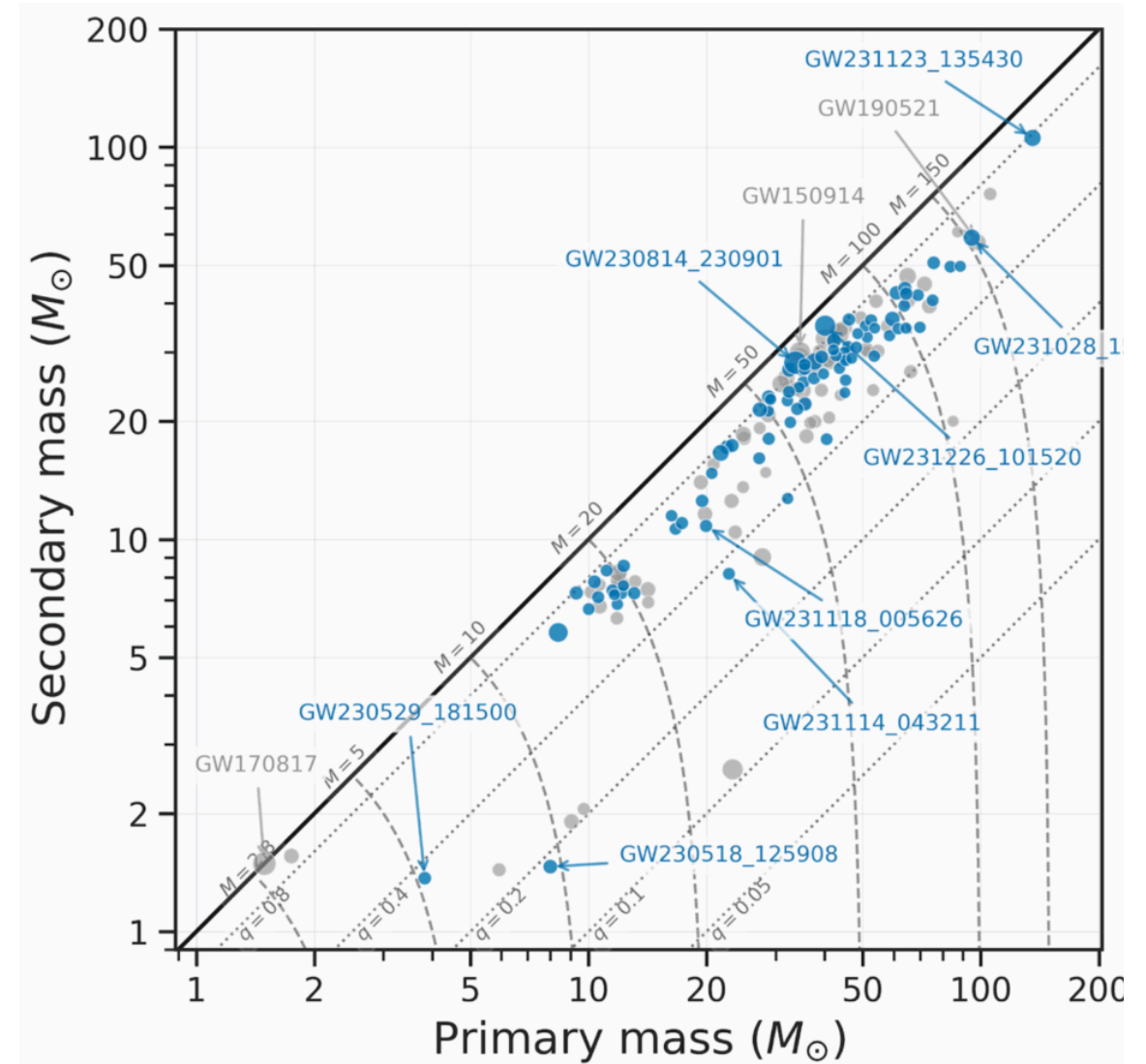


Average in-plane spin magnitude: posterior vs. effective prior.



CBC Populations

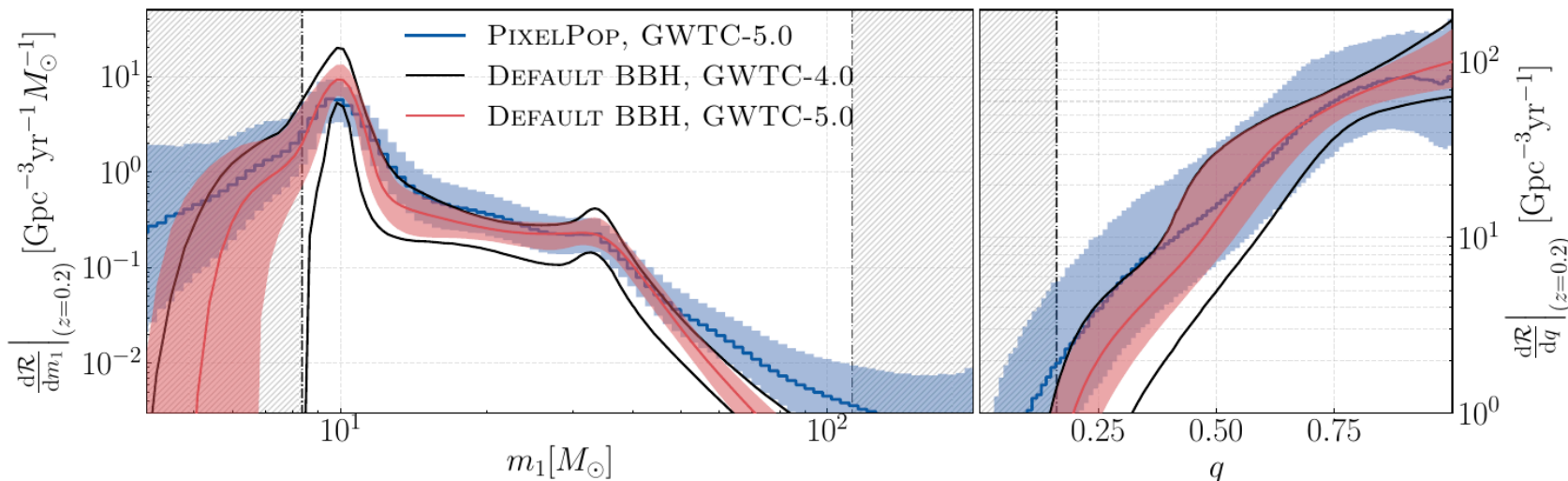
- There's something going on!
- Understanding the populations is a primary astrophysical goal!
- Population inference
compare population models across all observations.
- Take care of all bias effects!



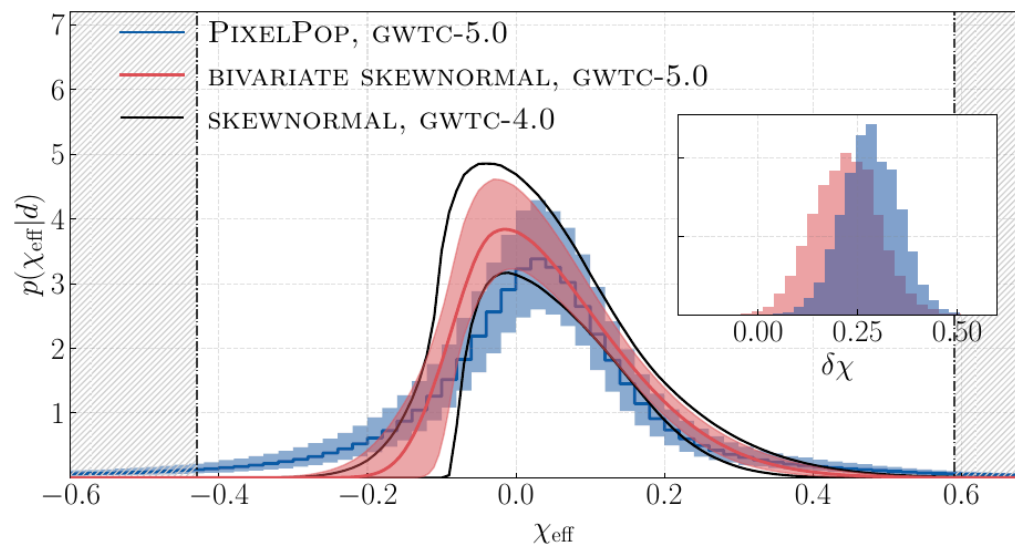
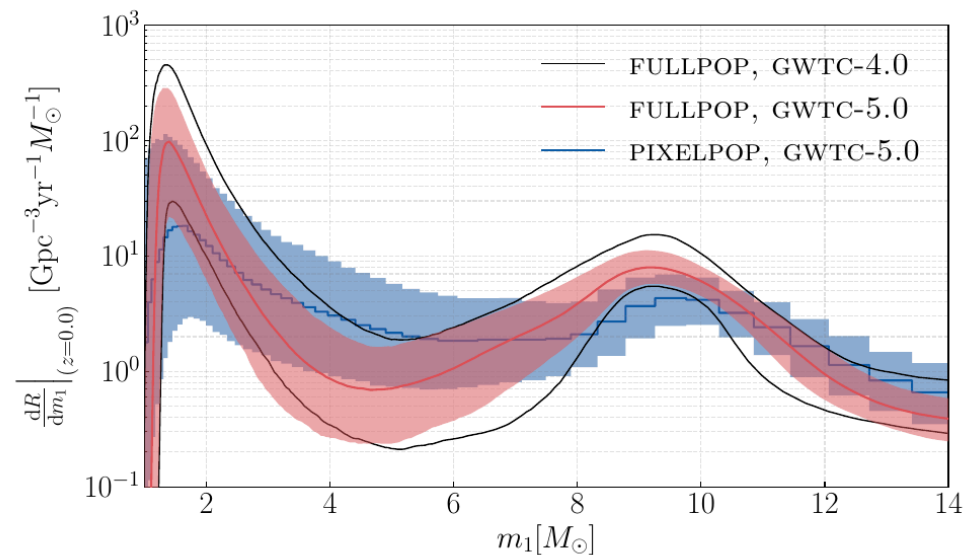
GWTC-5.0: The astrophysical population

Abac et al, [arXiv:2605.27226](https://arxiv.org/abs/2605.27226)

Infer the population of black hole/neutron star mergers from GW observations



- Fit both **strongly parametrized** and **weakly parametrized [PixelPop]** models.
- Growing evidence for multiple sub-populations of black hole binaries.
- Rule out “mass gap” between 3 and 5 $M_\odot$.
- Rates for BBH between 2.5 – 200 $M_\odot$ updated to 27.5–49.4 $\text{Gpc}^{-3} \text{yr}^{-1}$
- $R = 5.1\text{--}154.7 \text{ Gpc}^{-3} \text{yr}^{-1}$ for BNS
- $R = 6.7\text{--}32.8 \text{ Gpc}^{-3} \text{yr}^{-1}$ for NSBH
- Possible evidence of a population of hierarchical mergers

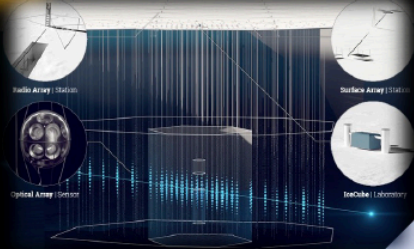


- Black hole spins are predominantly non-extremal with 85% belonging to a small spin population ($\chi < 0.25$)
- Spins preferentially aligned, rather than misaligned, with orbital angular momentum

Multimessenger synergies

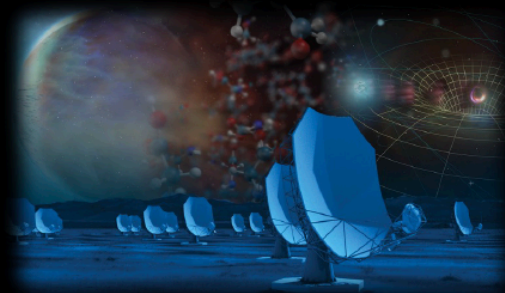


Galactic core-collapse supernova



Neutrino:
DUNE, NKM3Net,
IceCube Gen2

Radio:
ng VLA, SKA



Elliptical, single,
rapidly-rotating
neutron stars



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

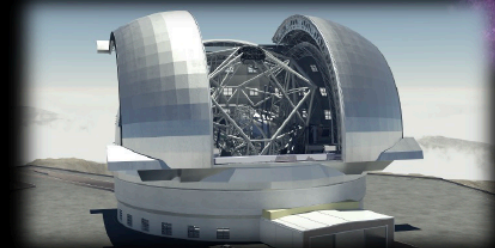
Optical/IR:
Nancy Grace
Roman, ELTs, VRO
LSST



Kilonova, GRB
afterglow



Gamma-ray bursts from
neutron star mergers

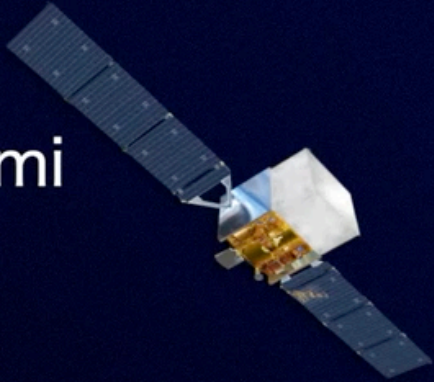


GRB 170817A - GW170817:

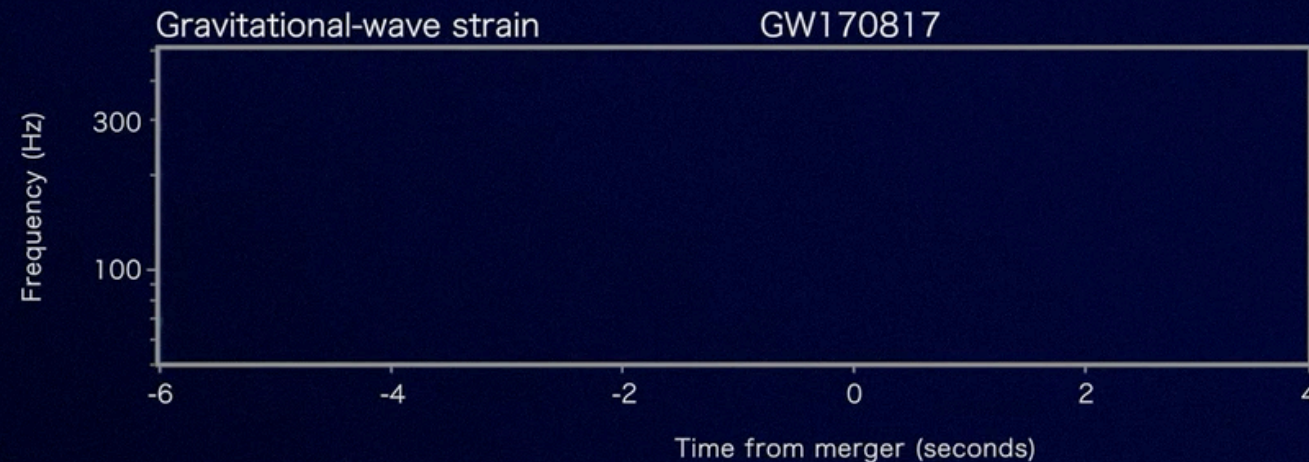
Coincident Detection with Gravitational Waves and Gamma Rays.

LIGO and Virgo and partners made first detection of gravitational waves and light produced by colliding neutron stars

Fermi



LIGO

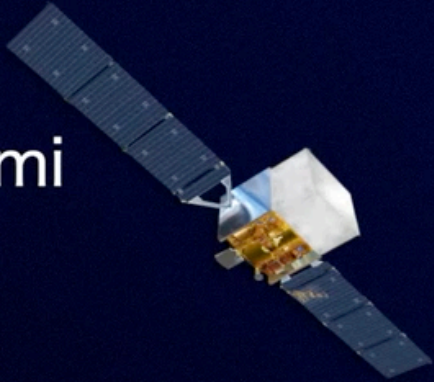


GRB 170817A - GW170817:

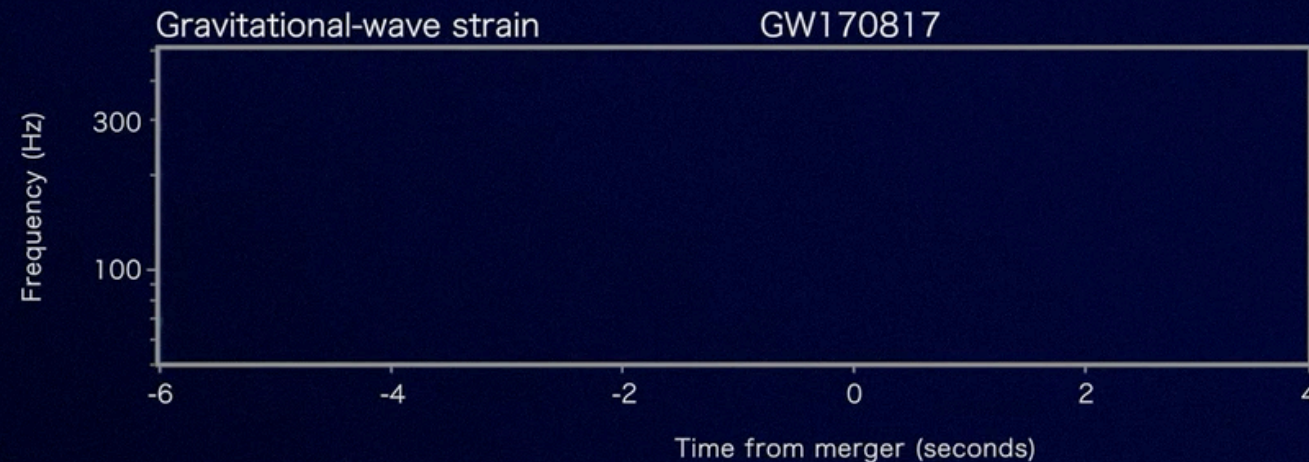
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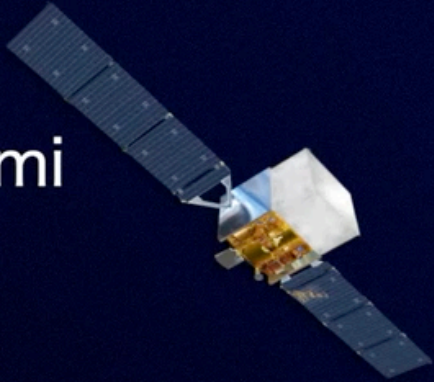


GRB 170817A - GW170817:

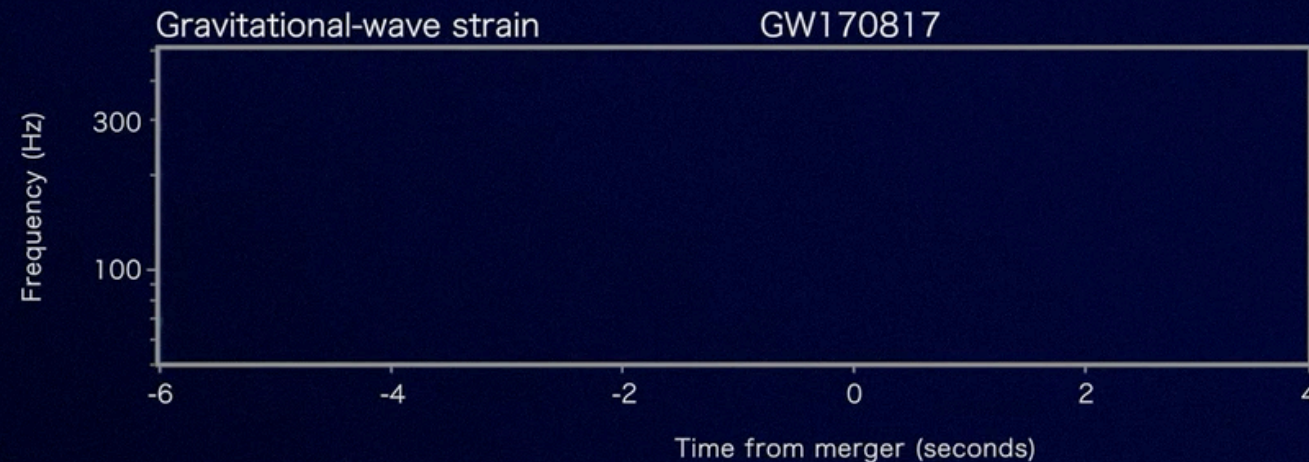
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Fermi

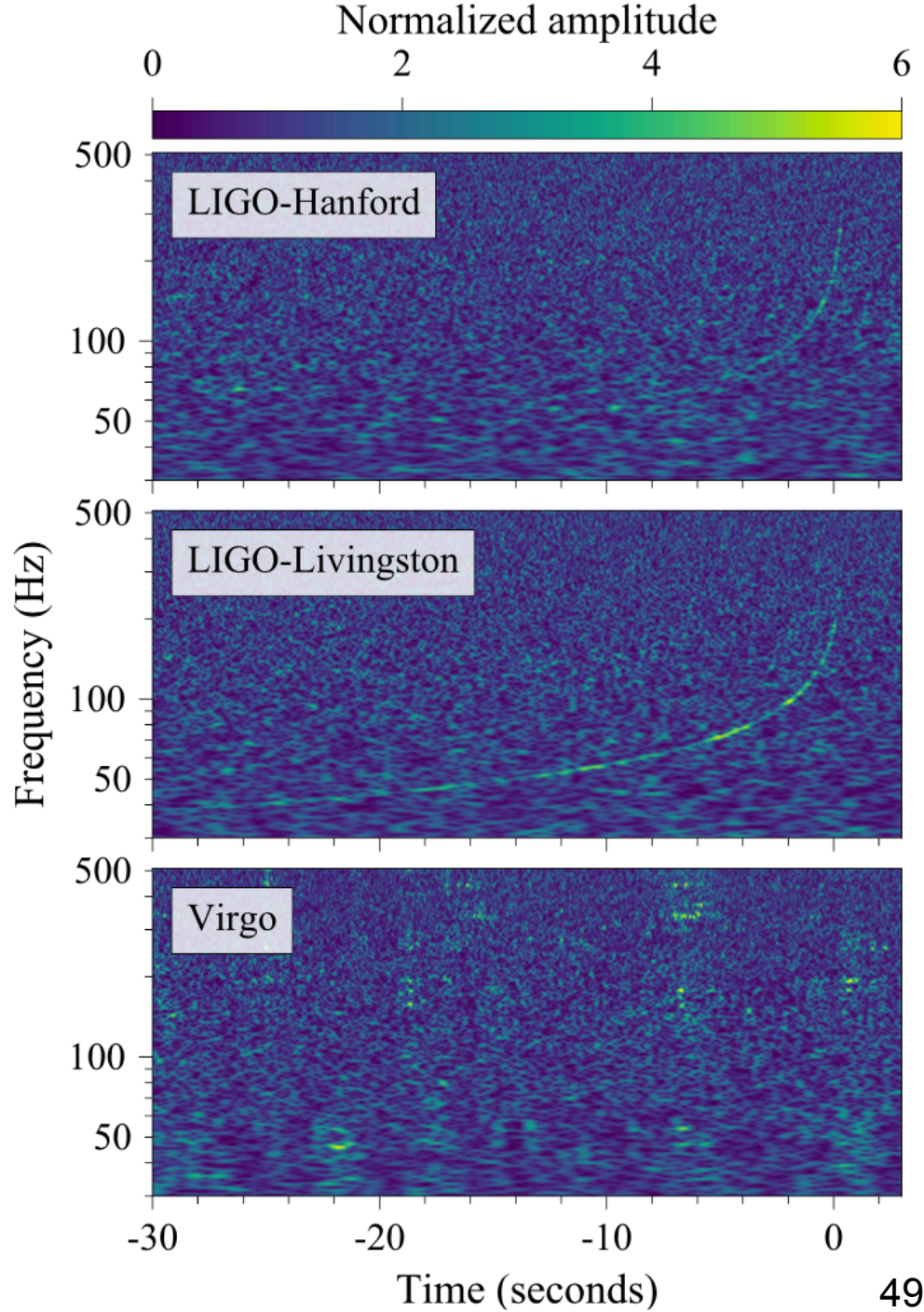
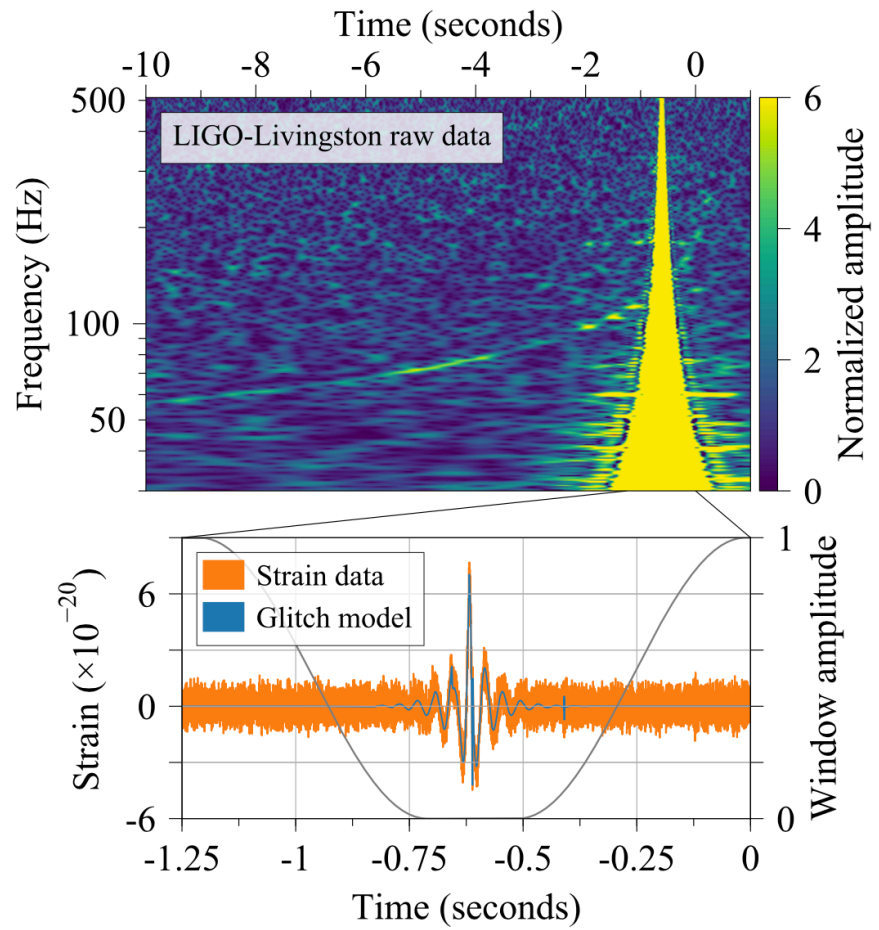


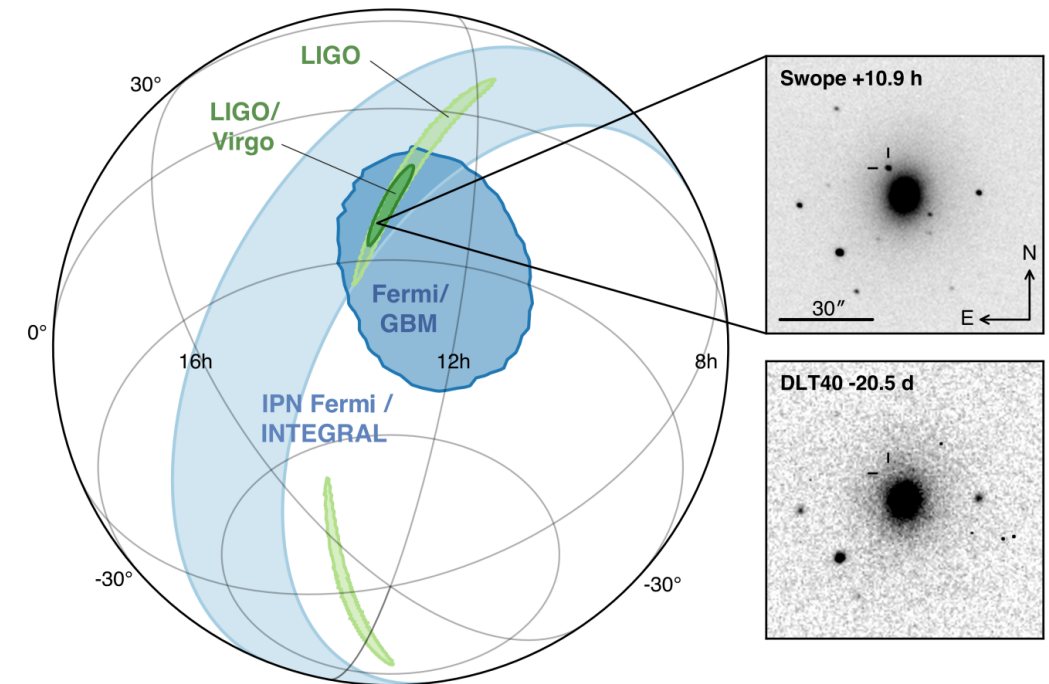
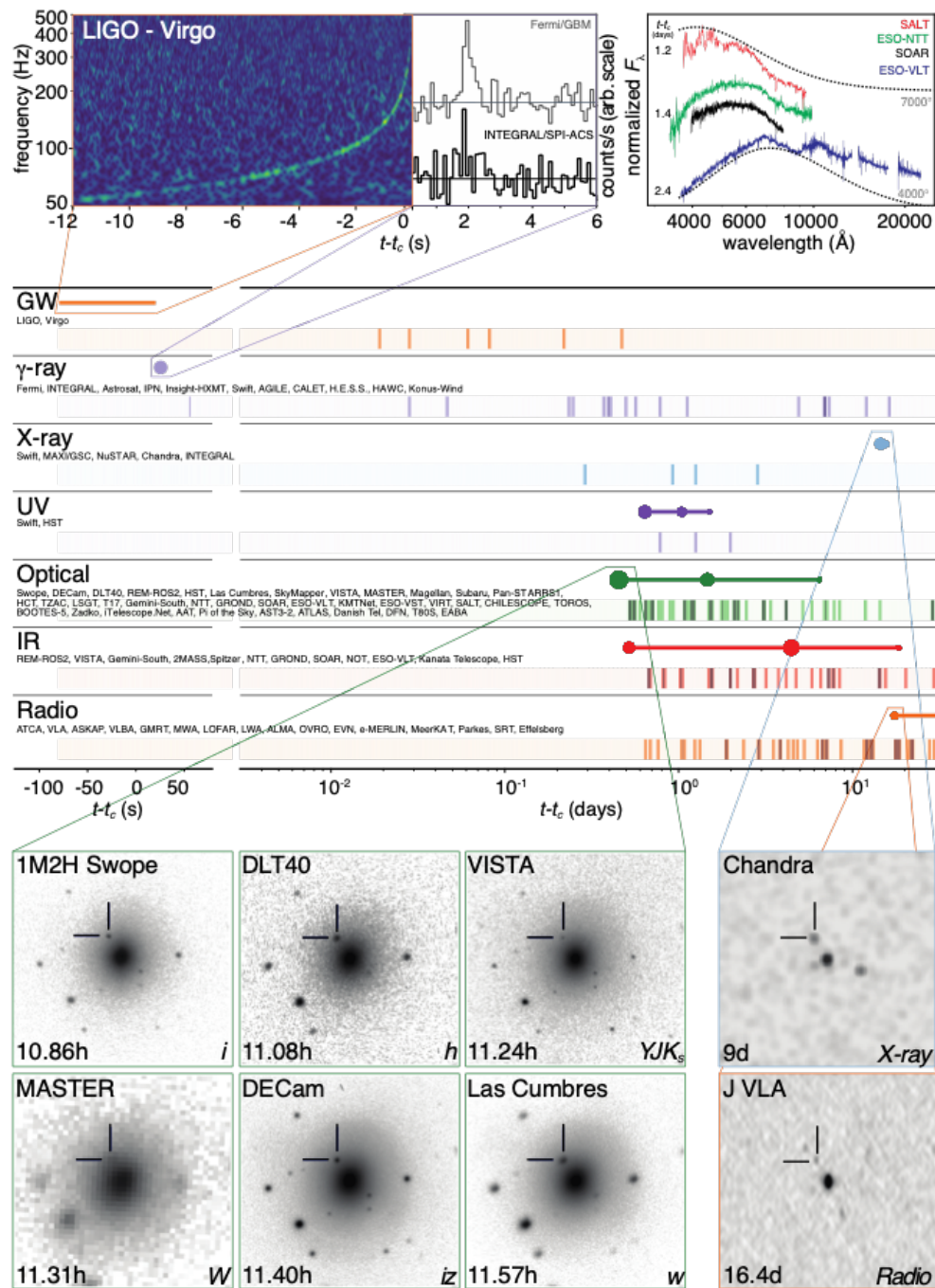
LIGO



• GW170817 •

PRL 119, 161101 (2017)





“Multi-Messenger Observations of a Binary Neutron Star Merger”

B. Abbott et al., ApJL 848 (2017) L12

59-page “letter” (!)

More than 3000 authors, ~70 collaborations

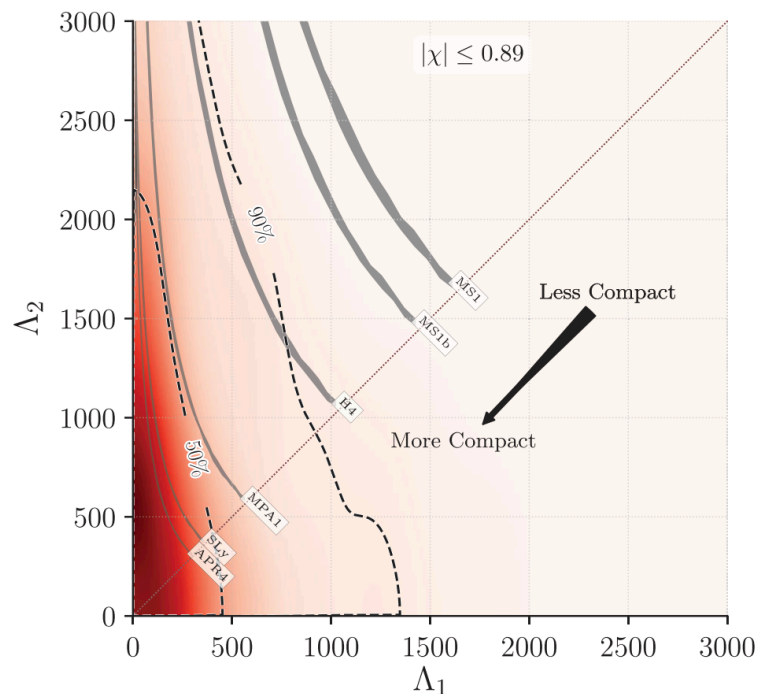
There have been important contributions from the Spanish groups that are part of INTEGRAL, AGILE, Fermi-LAT, DES, Vinrouge, Master, ePESSTO, TOROS, Red Global BOOTES, VLT, HAWK, Chandra, Gemini, Pierre Auger, ANTARES, EURO VLBI, among others.

Tidal effects encoded in **Love numbers**: 5th order Post-Newtonian effect phase due to quadrupole deformation of neutron stars, depends on EOS:

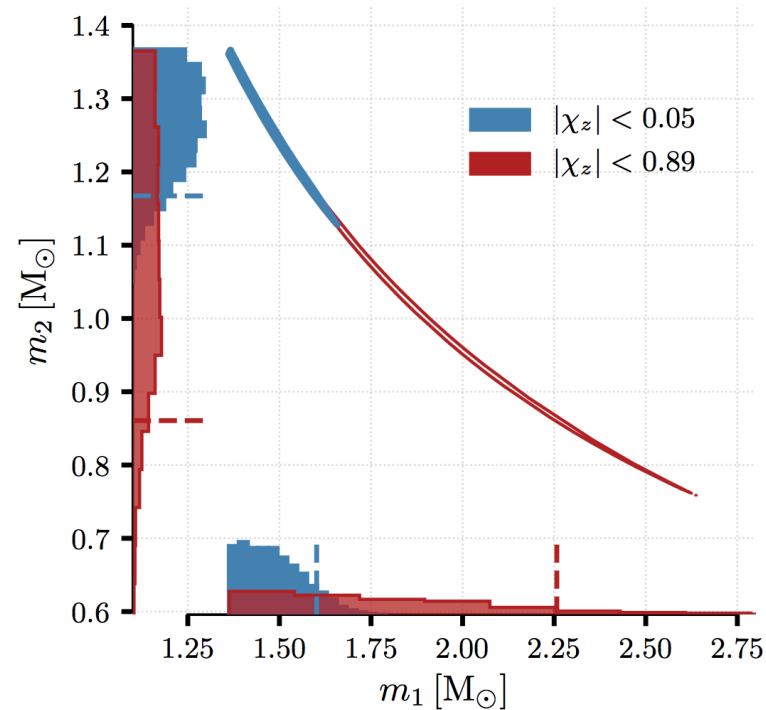
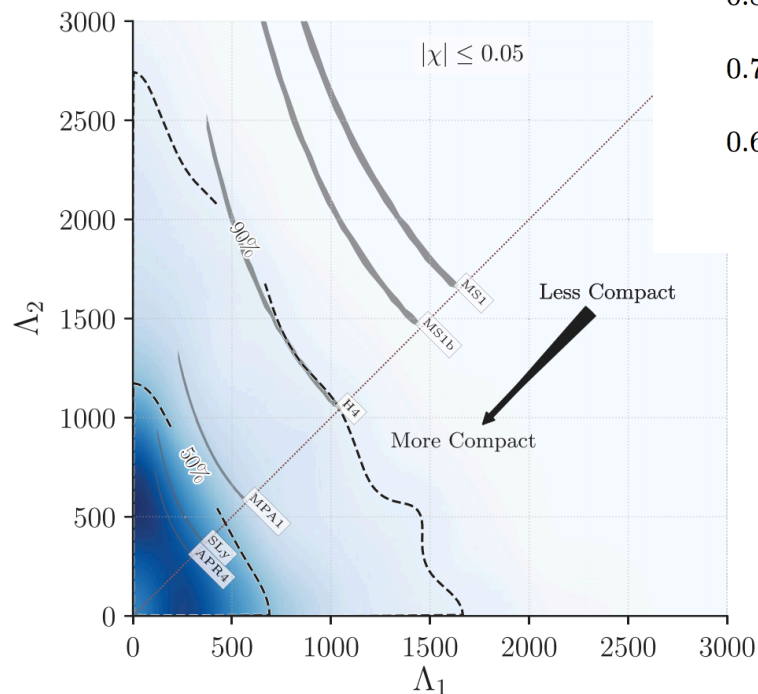
$$\delta\Psi = -\frac{9}{16} \frac{v^5}{\mu M^4} \left[\left(11 \frac{m_2}{m_1} + \frac{M}{m_1} \right) \lambda_1 + 1 \leftrightarrow 2 \right]$$

Preliminary results exclude large neutron stars.

high spin prior



Low spin prior



Binary Neutron Star Collisions Are the Foundries of Heavy Elements

Element Origins

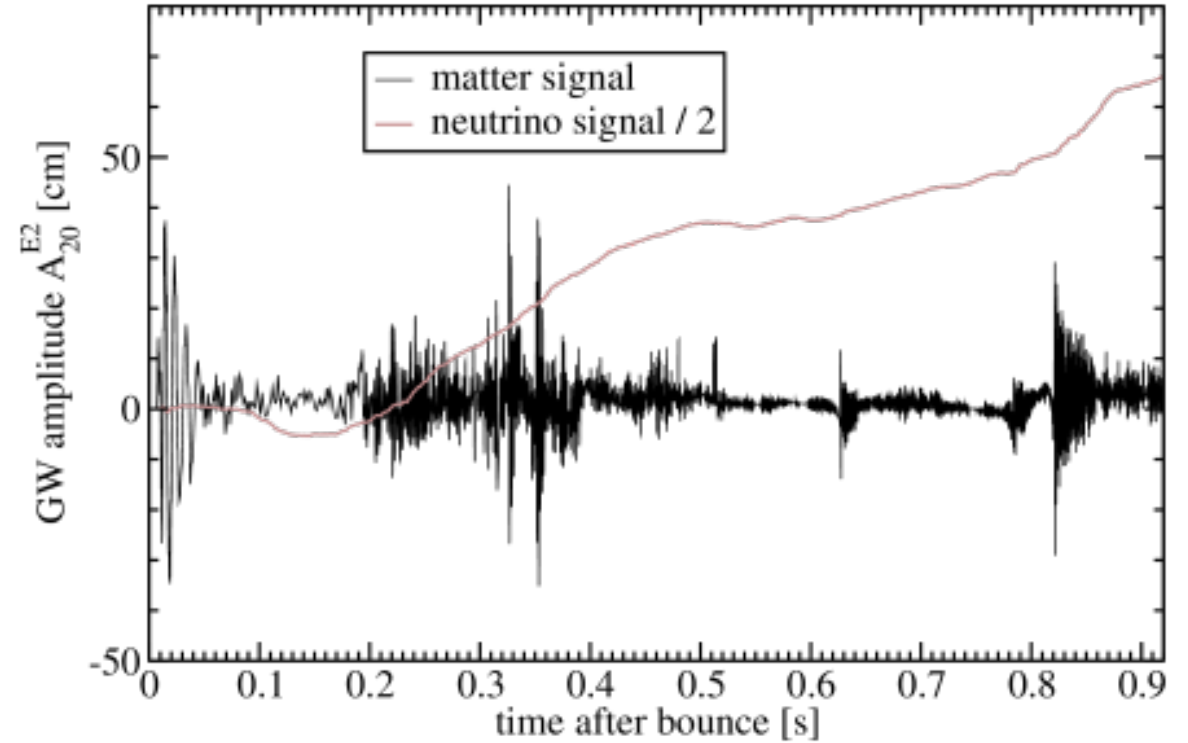
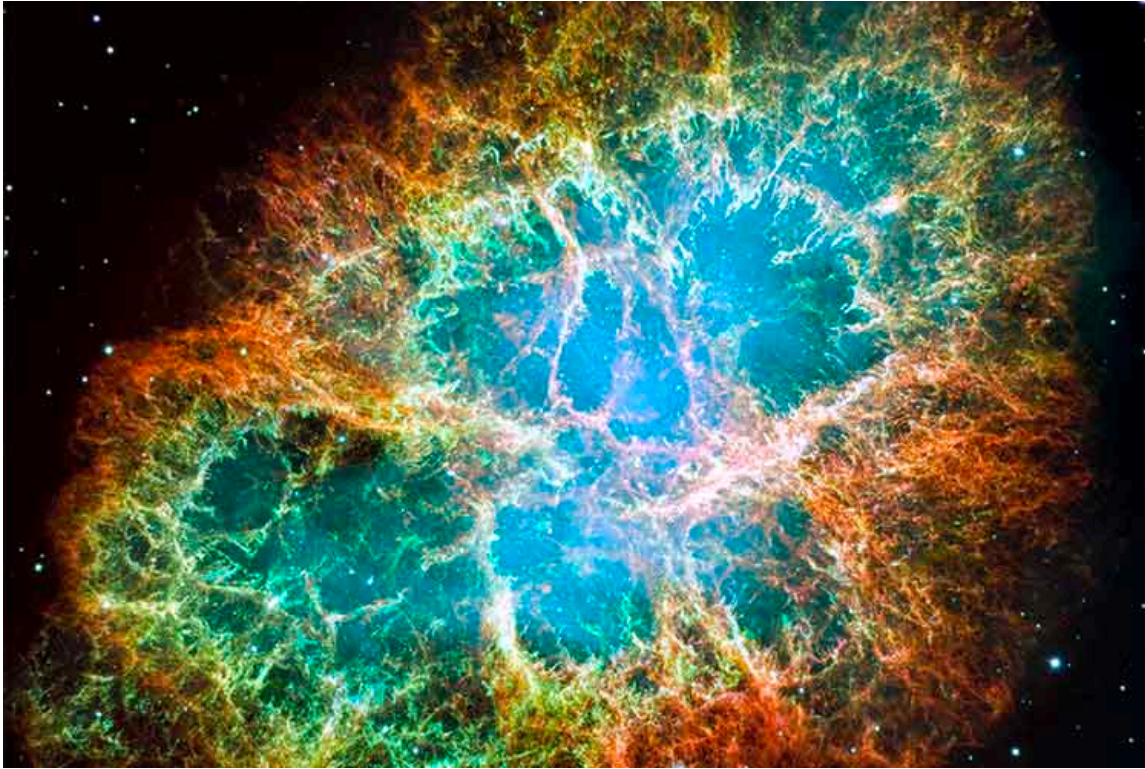
1 H																	2 He	
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne	
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar	
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr	
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe	
55 Cs	56 Ba			72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra																	
		57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu		
		89 Ac	90 Th	91 Pa	92 U													

Merging Neutron Stars
Dying Low Mass Stars

Exploding Massive Stars
Exploding White Dwarfs

Big Bang
Cosmic Ray Fission

Based on graphic created by Jennifer Johnson



Beyond Binary Mergers

Core collapse supernovae

- A galactic supernova is the ultimate multi-messenger prize
- GW emission encodes the internal dynamics of the supernova
- Detector range beyond the galaxy is limited, depending on explosion mechanism, so keep your fingers crossed
 - Rate $\sim 1/\text{century}$.

neutron star merger

neutron star merger

neutron star merger