Between observational results and new inference methods: developments in ground-based gravitational-wave science

Konstantin Leyde, 15/9/2026 @ CBPF

FLATIRON INSTITUTE

LIGO Scientific Collaboration

This talk is not on behalf of the LVK

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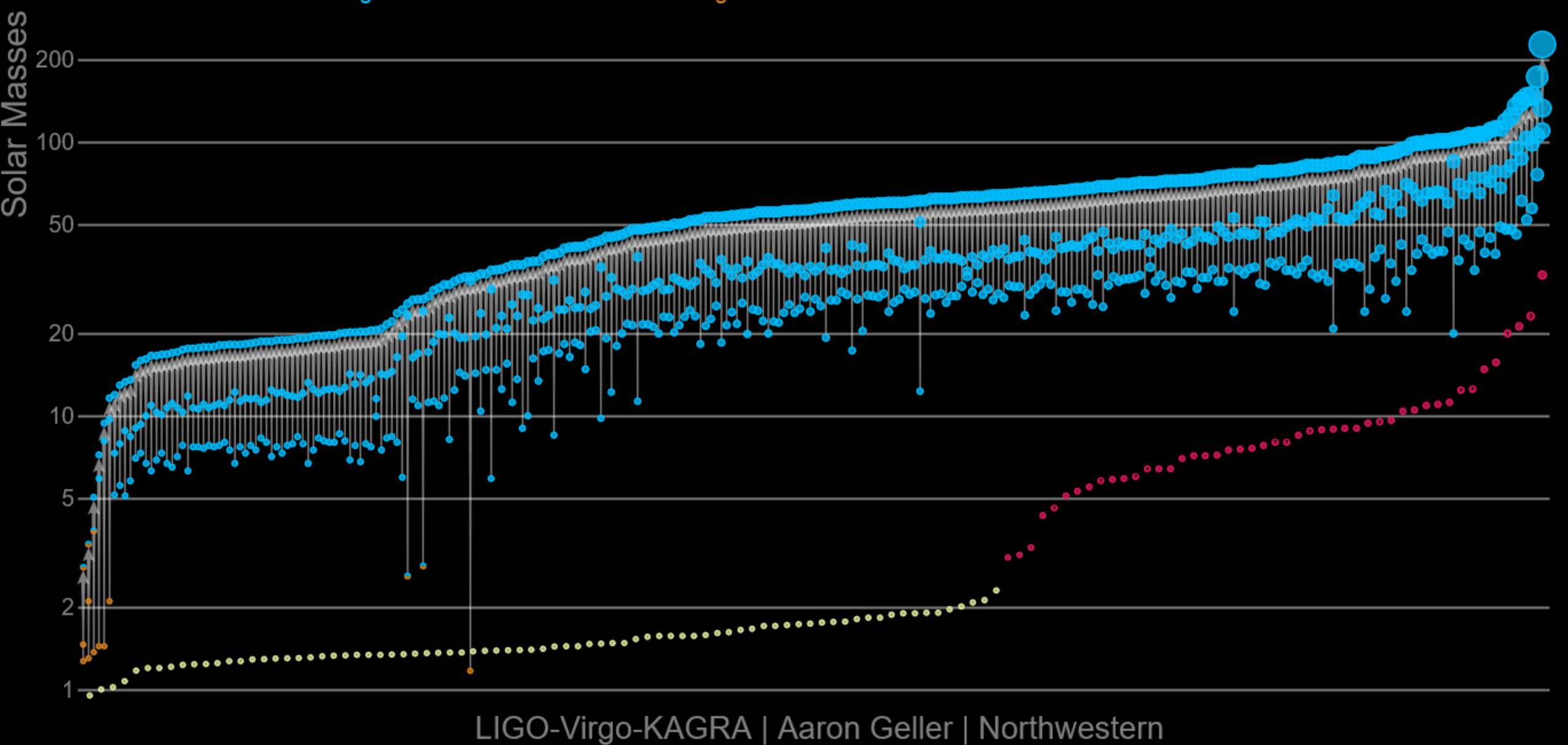
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Australian Consortium for Interferometric Gravitational Astronomy (ACIGA):
Australian National University, Charles Sturt University, Monash University, University of Adelaide, University of Melbourne, University of Western Australia

German/British Collaboration for the Detection of Gravitational Waves (GEO600):
Cardiff University, Leibniz Universität Hannover, Albert-Einstein Institut, Hannover, King's College London, Rutherford Appleton Laboratory,
University of Birmingham, University of Cambridge, University of Glasgow, University of Hamburg, University of Sheffield,
University of Southampton, University of Strathclyde, University of the West of Scotland

Masses in the Stellar Graveyard



Gravitational waves

- **Framework: General Relativity**
- **Definition**
  - **Perturbations of space-time**, i.e. gravitational field
- In vacuum ($T_{\mu\nu} = 0$): propagate at **speed of light**

Metric perturbations, aka GWs

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$$

Metric

Flat spacetime

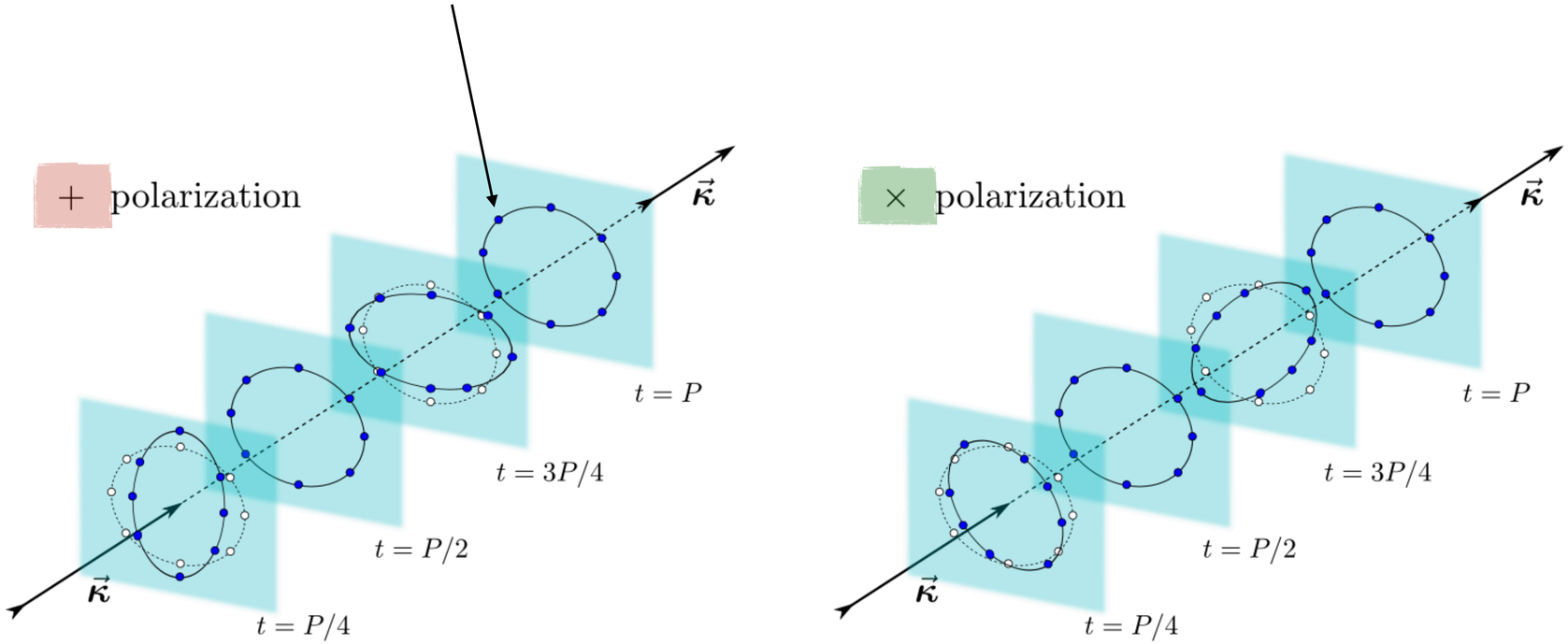
Linearize Einstein equations

$$\Box_{\text{flat}} \bar{h}_{\mu\nu} = -\frac{16\pi G}{c^4} T_{\mu\nu}$$

Observable effect (far from source)

- Effect on ring of **free-falling test particles**

Bishop and Rezzolla, 2016



- Experiments to **measure distance to high precision!**

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$$

$$h_{\mu\nu} = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & h_+ & h_\times & 0 \\ 0 & h_\times & -h_+ & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} \cos(2\pi f_{\rm GW}(t - z/c))$$

GW source terms

$$\Box_{\text{flat}}\,\bar{h}_{\mu\nu} = -\frac{16\pi G}{c^4}\,T_{\mu\nu}$$

$$h_{ij}^{\mathrm{TT}}(t,r) = \frac{2G}{c^4 r}\,\ddot{Q}_{ij}^{\mathrm{TT}}(t - r/c)$$

Quadrupole formula

Distance

$$Q_{ij} := \int \rho\left(x_i x_j - \tfrac{1}{3} r^2 \delta_{ij}\right) \mathrm{d}^3 x$$

Mass density

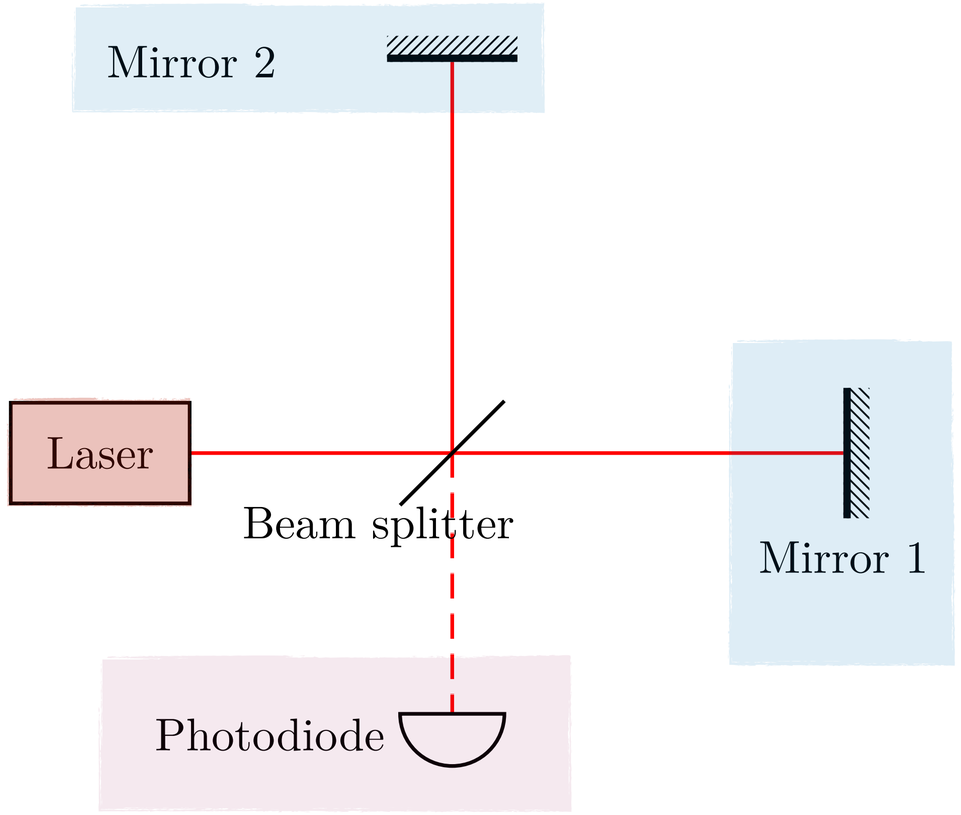
➡Need **high velocities, large masses**

➡**Sources: binaries of black holes or neutron stars**

- **Very weak at cosmological scales $\mathcal{O}(10^{-21})$, but falls of as $1/r$**

GW detection principle

- **Km-sized Michelson interferometer**
  - **Laser cavity** in each arm
  - **Free-falling mirrors** in two-dimensions, isolated from ground motion
  - **Mirror displacement** → **Interference pattern shift**
- **Detector output: $h(t)$ relative arm length time series**
- True instrument ∞-more complex



$$h \sim \frac{\Delta L}{L}$$

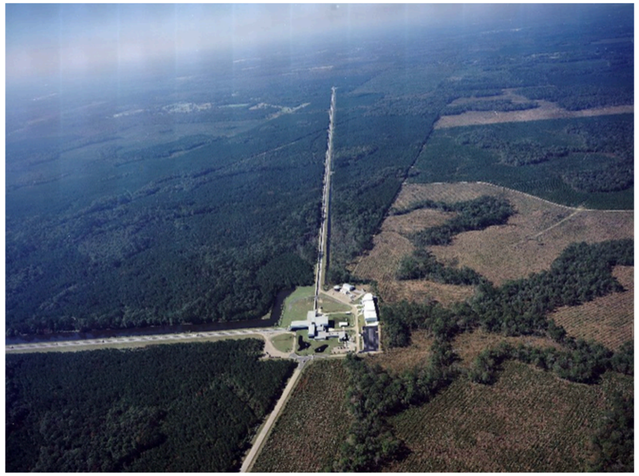
Length change

Arm length

Current ground-based detectors

- Four detectors
  - **LIGO** (2 USA)
  - **Virgo** (1 Italy)
  - **KAGRA** (1 Japan)
- Finished end 2025: **“O4c”-run**
- **Upgrades planned**

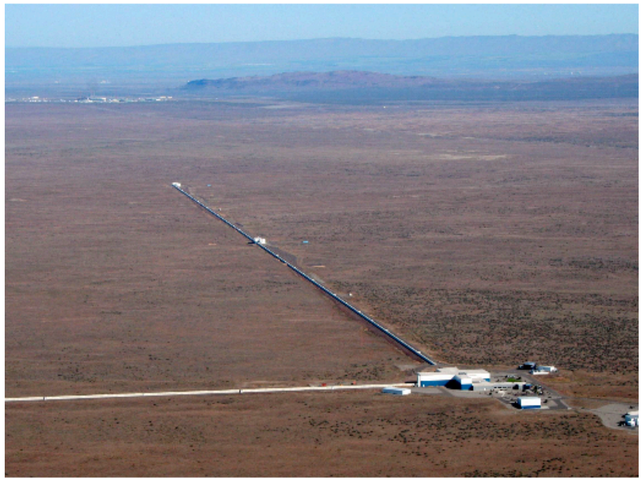
LIGO



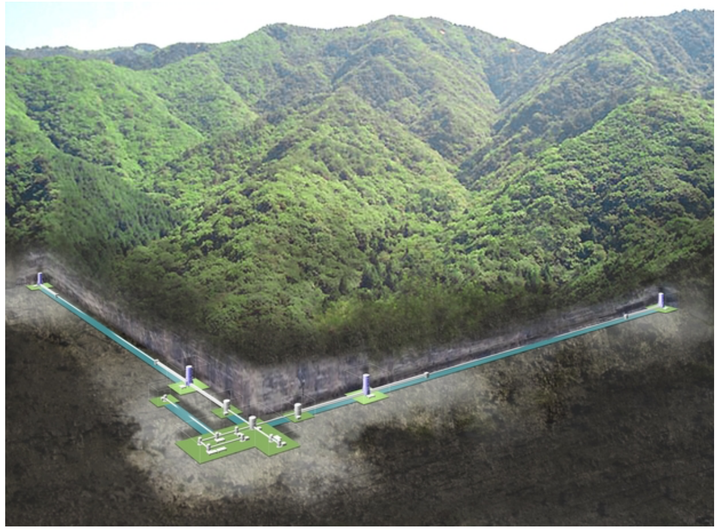
Virgo



LIGO

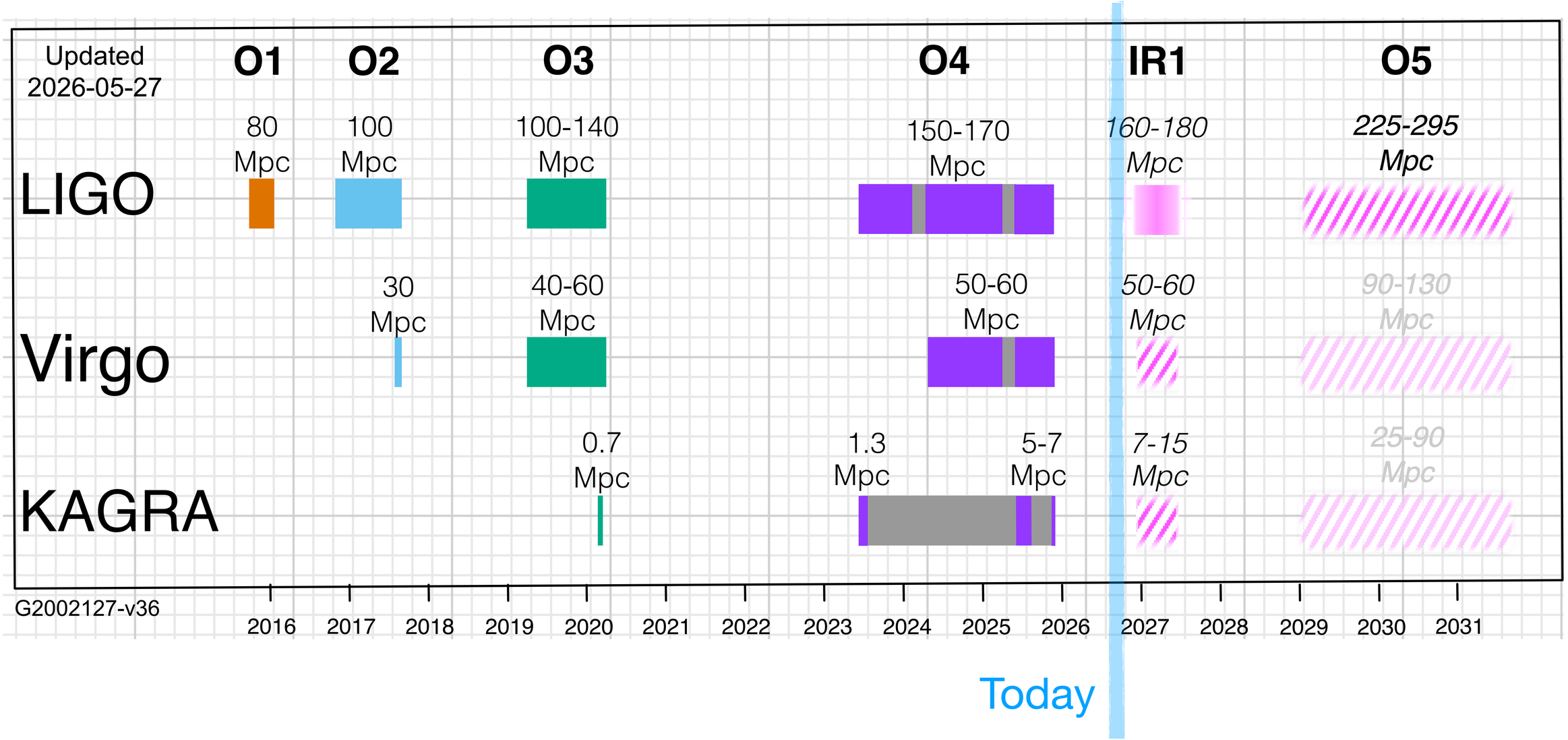


KAGRA



Capote et al. 2411.14607

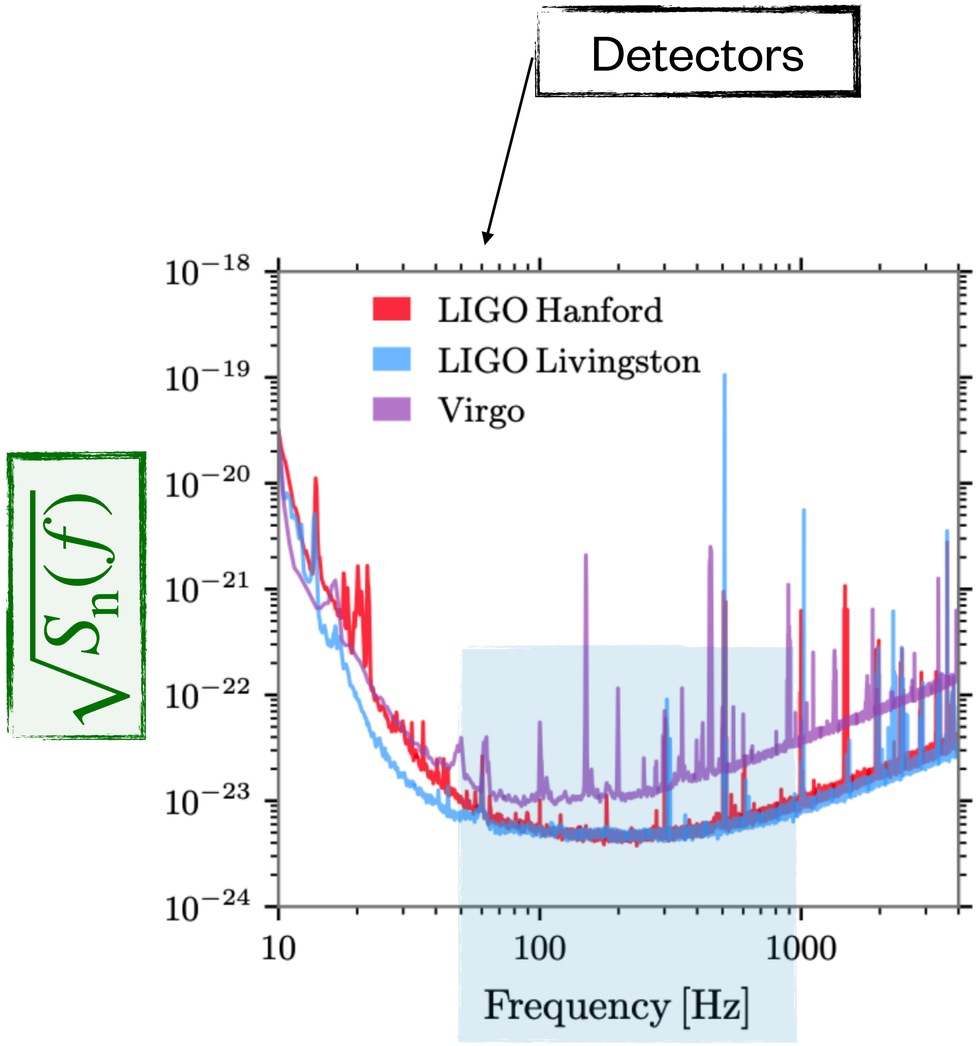
Observation runs



https://dcc.ligo.org/LIGO-G2002127/public

Detector noise properties

- **Noise properties**: most of data signal-free!
  - Work in **Fourier space**
  - $\langle n(f)n(f')\rangle = S_{\rm n}(f)\delta(f-f')$
- Estimate **noise PDF** $\mathbb{P}(n)$
  - **Model: Gaussian with short duration excess (“glitches”)**
  - Possible since sources are also short duration

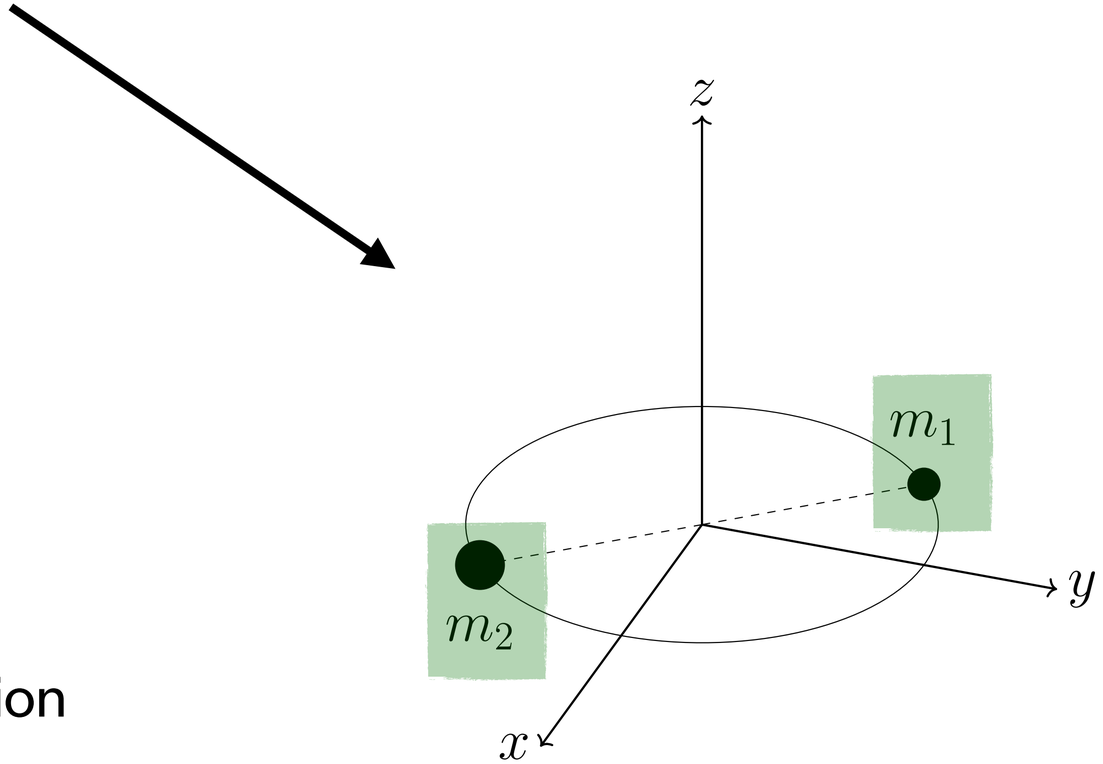


Gravitational wave sources

- **Sources with large** $h(f)$ at detector's most sensitive frequencies

$$h_{ij}^{\mathrm{TT}}(t,r) = \frac{2G}{c^4 r}\ddot{Q}_{ij}^{\mathrm{TT}}(t-r/c)$$

- **Compact binary mergers**
  - Black holes
  - Neutron stars
- **Potential: not yet observed**
  - Supernovae
  - Continuous waves
  - Tidal disruption events, head-on collision etc.



The gravitational-wave signal

$$h_{ij}^{\mathrm{TT}}(t,r) = \frac{2G}{c^4 r}\ddot{Q}_{ij}^{\mathrm{TT}}(t - r/c)$$

Distance

Chirp mass

$$\mathscr{M} = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}}$$

Mass-dependency in amplitude and phase

$$h_+(t) = \frac{4}{r}\left[\frac{G\mathscr{M}}{c^2}\right]^{5/3}\left[\frac{\pi f(t_{\mathrm{ret}})}{c}\right]^{2/3}\frac{1+\cos^2(\iota)}{2}\cos\left[2\phi(t_{\mathrm{ret}})\right]$$

Distance

GW frequency

Inclination

Distance measurement with GWs

$$h_{ij}^{\mathrm{TT}}(t,r) = \frac{2G}{c^4 r}\ddot{Q}_{ij}^{\mathrm{TT}}(t - r/c)$$

Distance

Distance measurement!

Mass-dependency in amplitude and phase

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GW frequency

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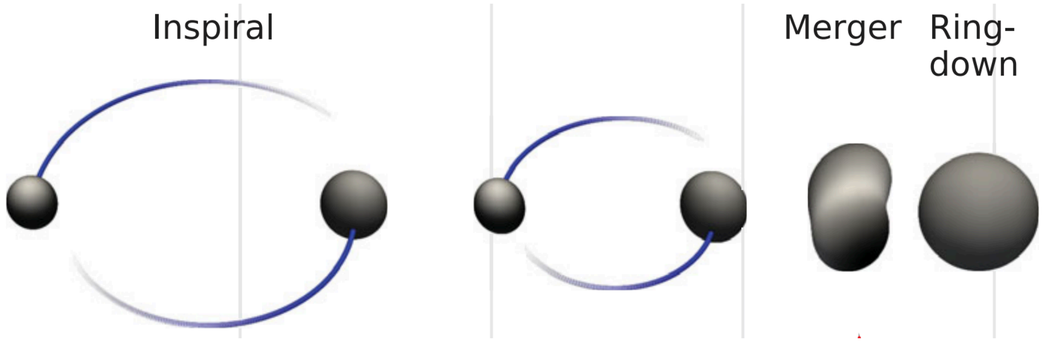
Compact binary mergers

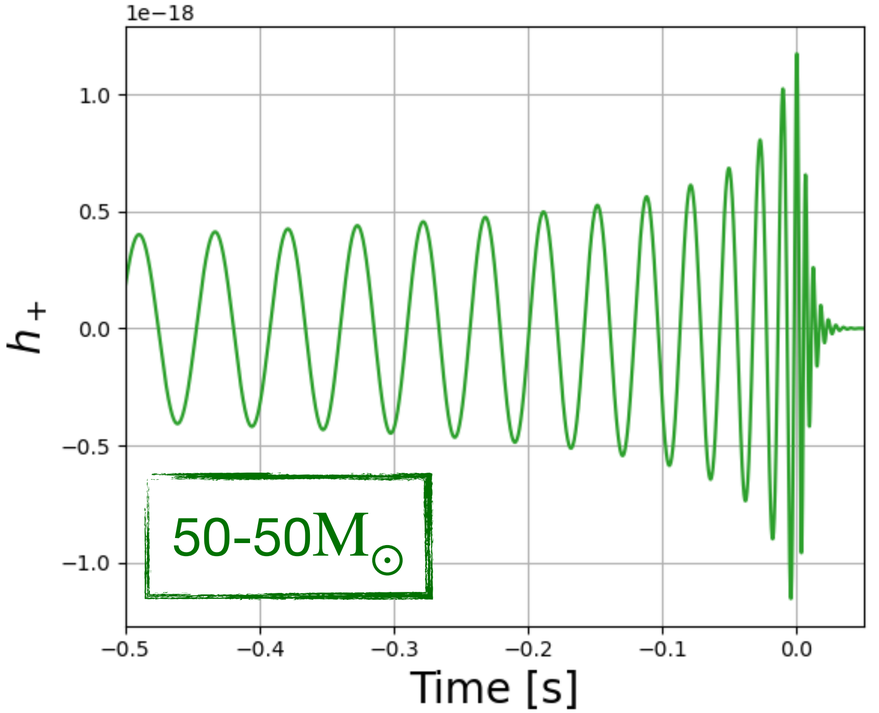
- Loss of energy and angular momentum through GW emission

  ➡ Binary separation shrinks

    ➡ Kepler: frequency increase

  ➡ Amplitude increase: *"Chirp"*





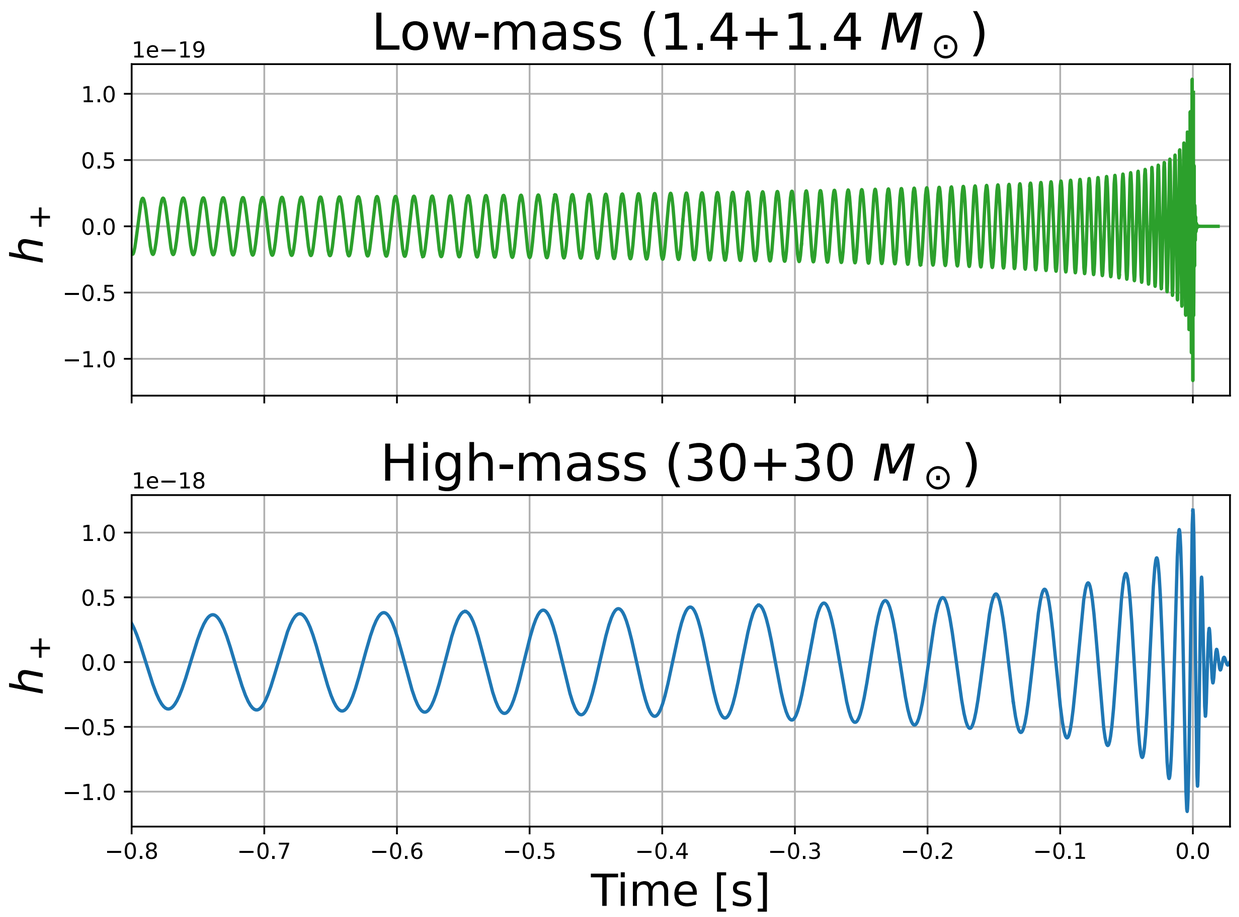
Chirp mass

$$\mathscr{M} = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}}$$

$$\dot{f} \propto \mathscr{M}^{5/3} f^{11/3}$$

Signal dependence on parameters

- Lighter signals
  - Merger at higher frequencies
  - Long duration (BNS up to minutes, BBH sub-second)
  - Low amplitude
- Spins induce beating pattern



1Mpc signal

Dedicated data analysis pipelines

A. **Detect short-duration binary signal** in noisy data

B. Estimate **astrophysical binary parameters**

C. Extract science from **populations of all binaries**

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GW parameters Noise

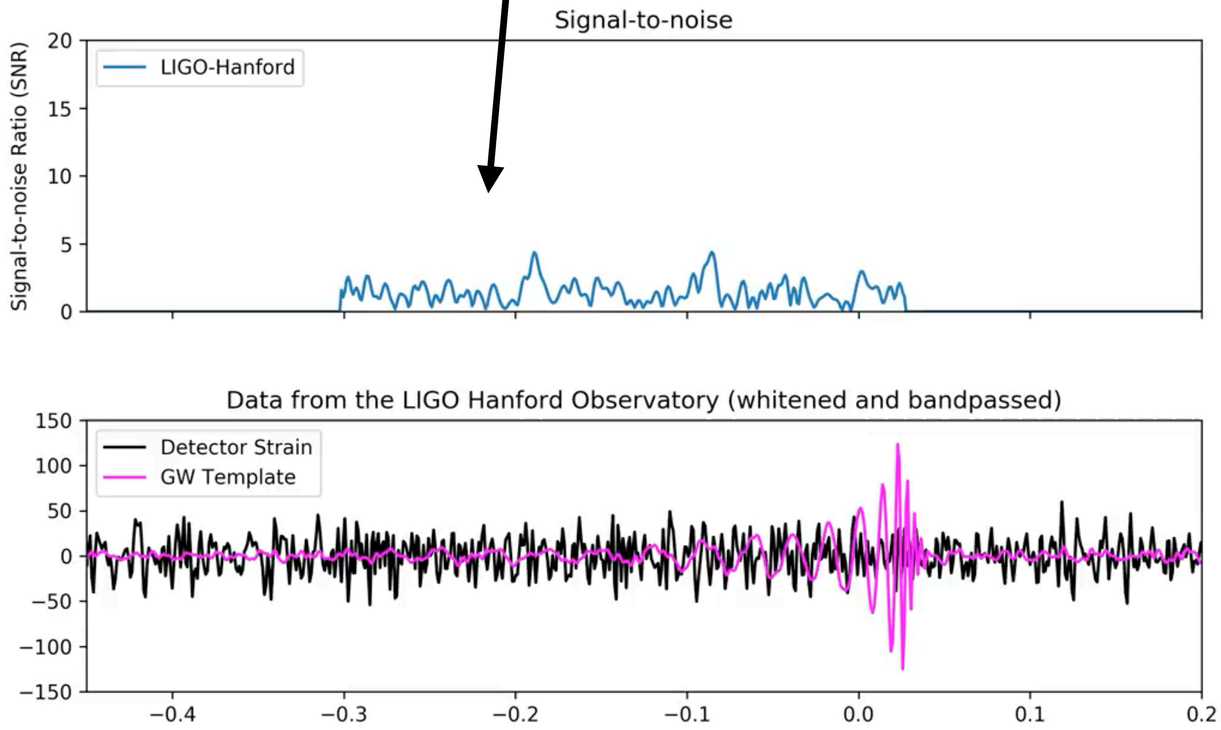
$$\mathscr{D} = s(\theta) + n$$

GW data Signal

(1) Modeled searches: *"Look for known signals"*

- **Find short-duration signals** in noisy data
  - **Signal + Noise model**
  - **Compute overlap**
  - **Binary parameters unknown**: **precompute dataset of signals, i.e. template bank**
- **Assess probability of data of astrophysical origin**
  - **Coincidence** in several detectors → **higher confidence**

$$\frac{\mathbb{P}(\text{Data}\,|\,\text{Signal + Noise})}{\mathbb{P}(\text{Data}\,|\,\text{Noise})}$$



(2) GW parameter estimation

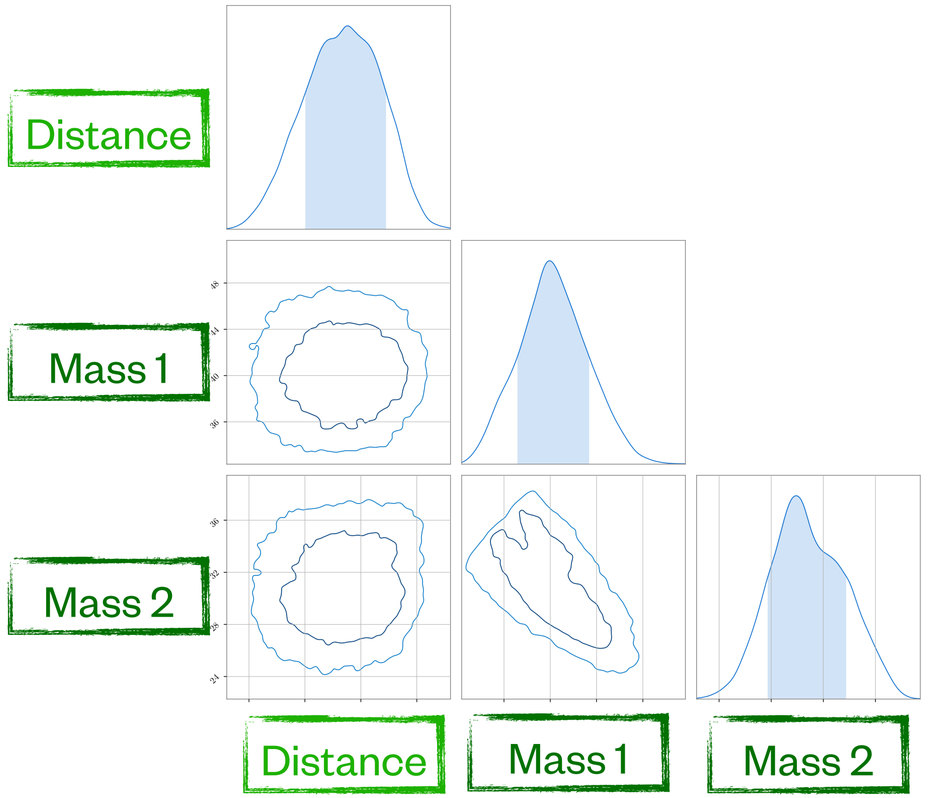
- **Characterize binary properties and uncertainties**
  - ~15D parameter space: masses, distance, spins, sky position, etc.

➡**Bayesian inference** approach

Signal

$$\mathscr{D} = s(\theta) + n$$

Data Noise



(2) GW parameter estimation

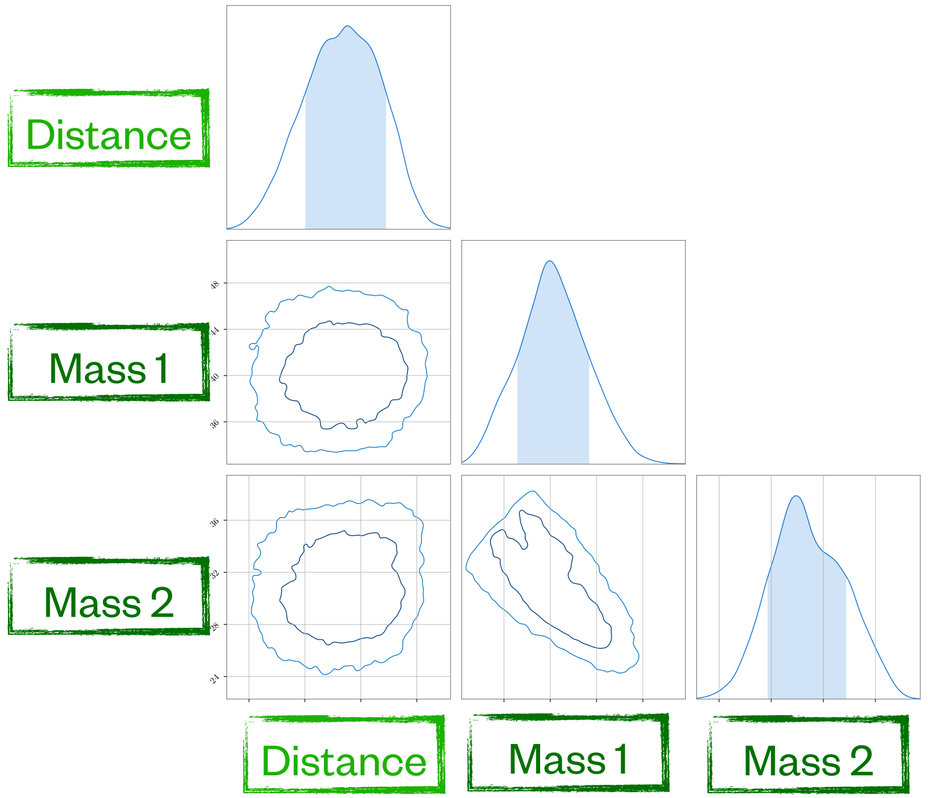
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  ➡**Bayesian inference** approach
  - **Likelihood:**
    - $\mathbb{P}(\mathscr{D} \mid \theta) = \mathbb{P}(\text{Residual noise} \mid \theta)$
    - Depends on **detector noise**
- **Outcome:** samples of binary parameters

Signal

$$\mathscr{D} = s(\theta) + n$$

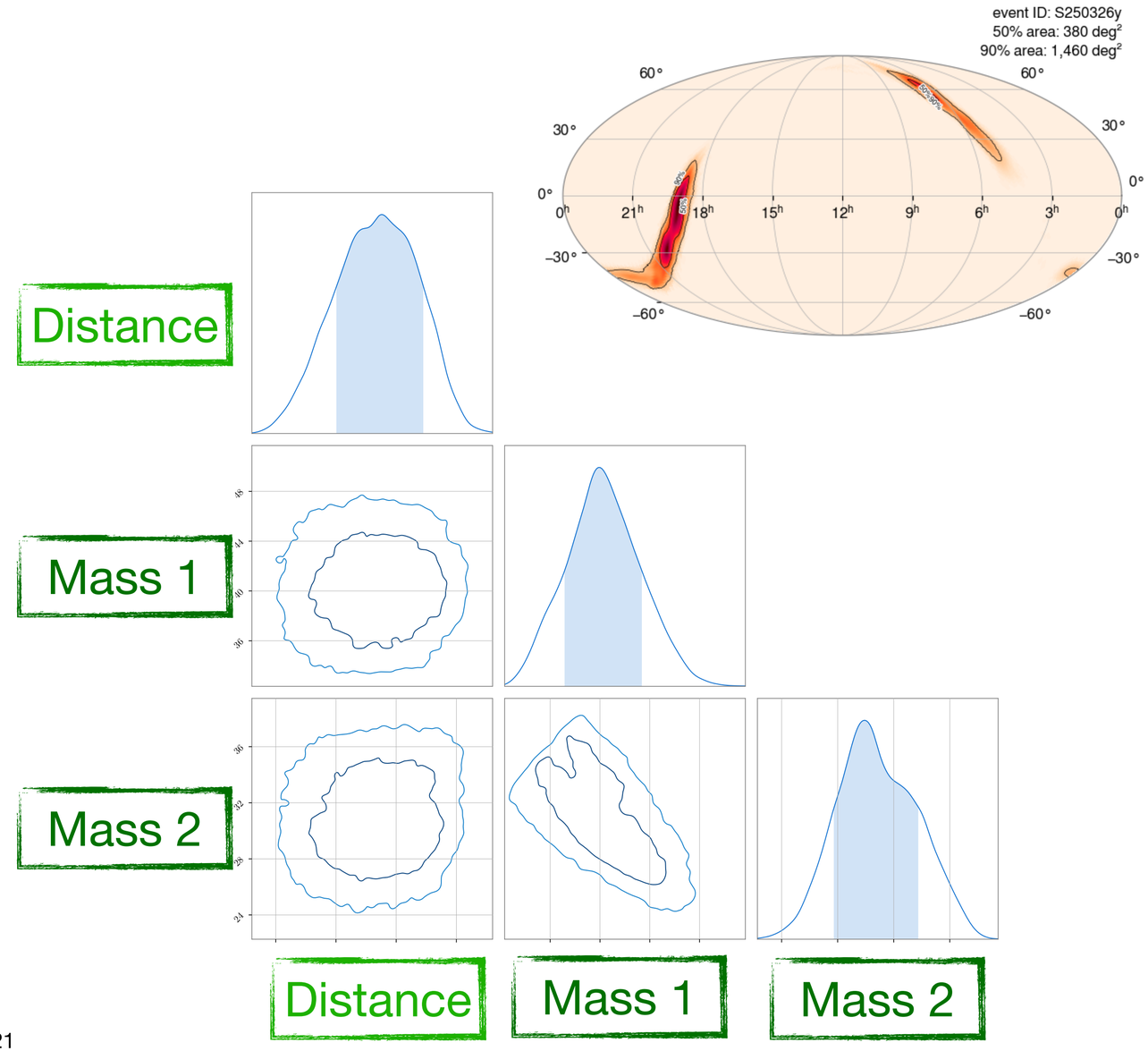
Data Noise



(2) Likelihood-based GW parameter inference

Ashton et al. 1811.02042

- **15 parameters; multi-modal posterior**
  - ➡ MCMC, nested sampling
  - ➡ **Hours for BBH, days for BNS**

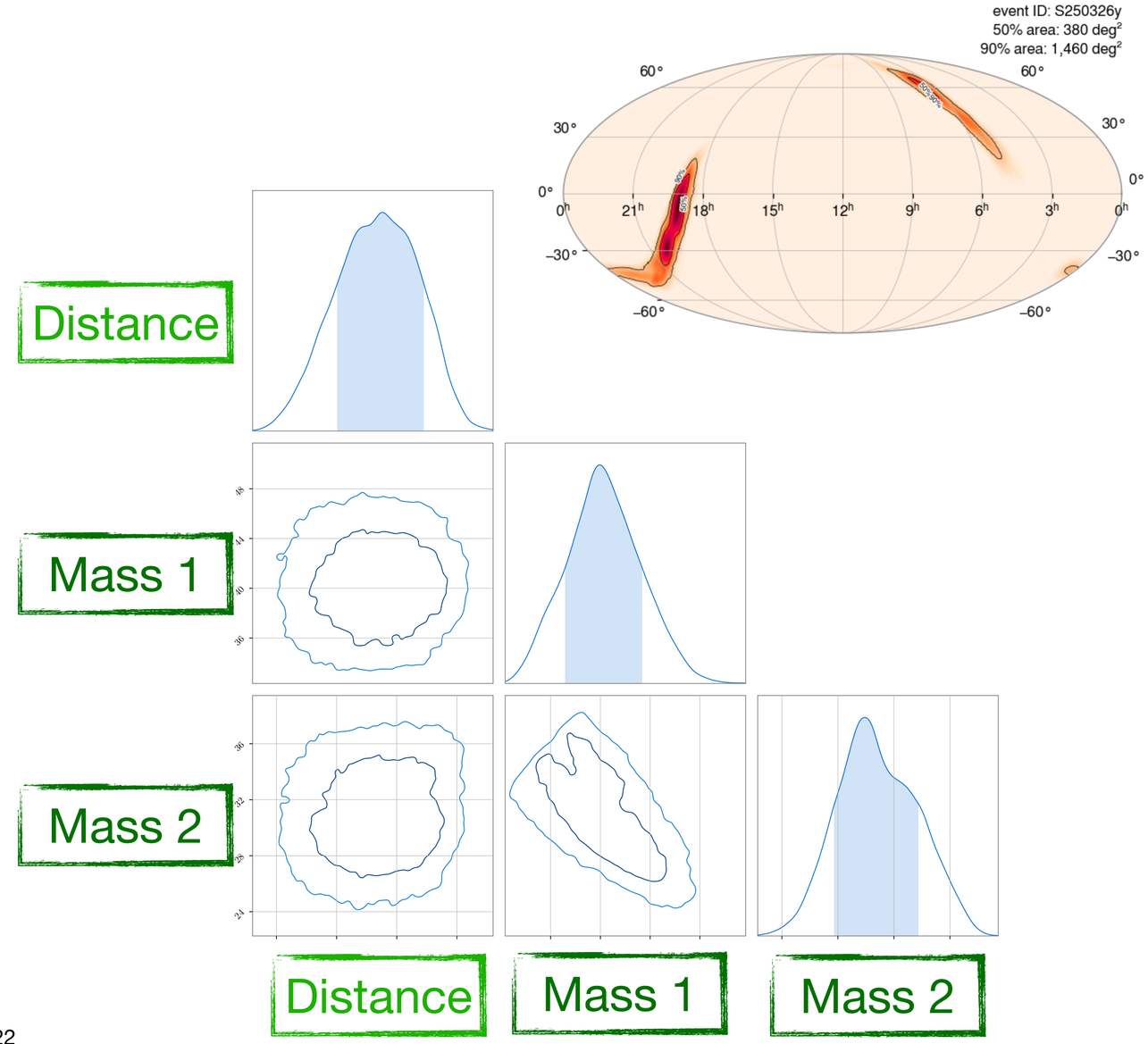


* Edwards et al. 2302.05329, Demasi et al. 2601.02336

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Ashton et al. 1811.02042

- **15 parameters; multi-modal posterior**
  - ➡ MCMC, nested sampling
  - ➡ **Hours for BBH, days for BNS**
- Alternatives
  - **Hamiltonian MC**, but most waveform models **not auto-differentiable***
  - **Simulation-based inference applications** (see later)
- Optimization
  - **Multi-banding, heterodyning**, etc.



* Edwards et al. 2302.05329, Demasi et al. 2601.02336

Dingo - binary neutron stars

Dax et al. 2407.09602

- Challenge:
  - Low mass → **long duration** signals
  - Potential EM → fast inference

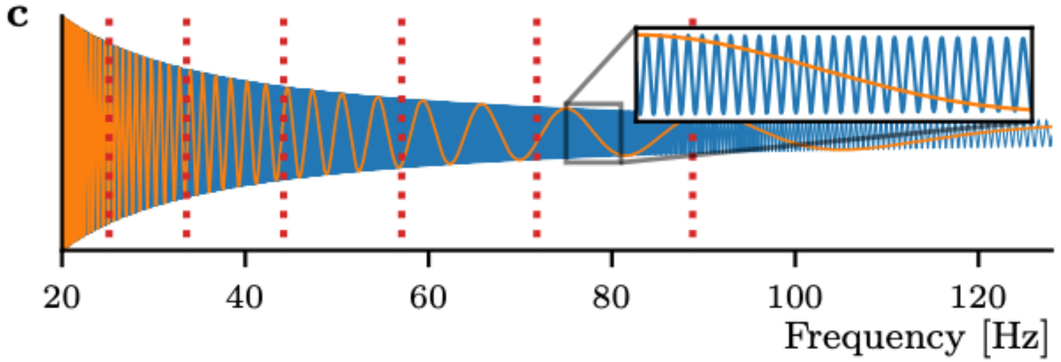
Dingo - binary neutron stars

Dax et al. 2407.09602

- Trick (1): **Data reduction**
  - **Divide out analytic signal evolution (heterodyning)**
  - **Adapt frequency bins to speed of frequency evolution, $\delta f \propto 1/\delta t$ (multi-banding)**

➡**Less frequency bins for same data content**

Full signal Simplified signal



$$\mathscr{D} \rightarrow \mathscr{D}_{\widetilde{\mathscr{M}}}$$

- Trick (2): **Importance-sampling**
  - Correct for eventual biases
- Trick (3): **Prior conditioning**
  - Reduce prior for localized posterior

Cornish 1007.4820, Zackay et al. 1806.08792
Vinciguerra et al. 1703.02062, García-Quirós et al. 2001.10897

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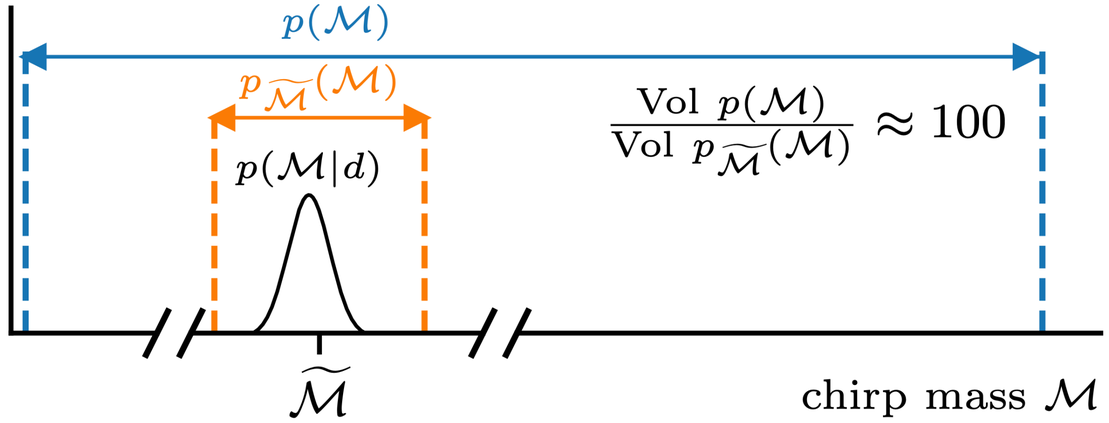
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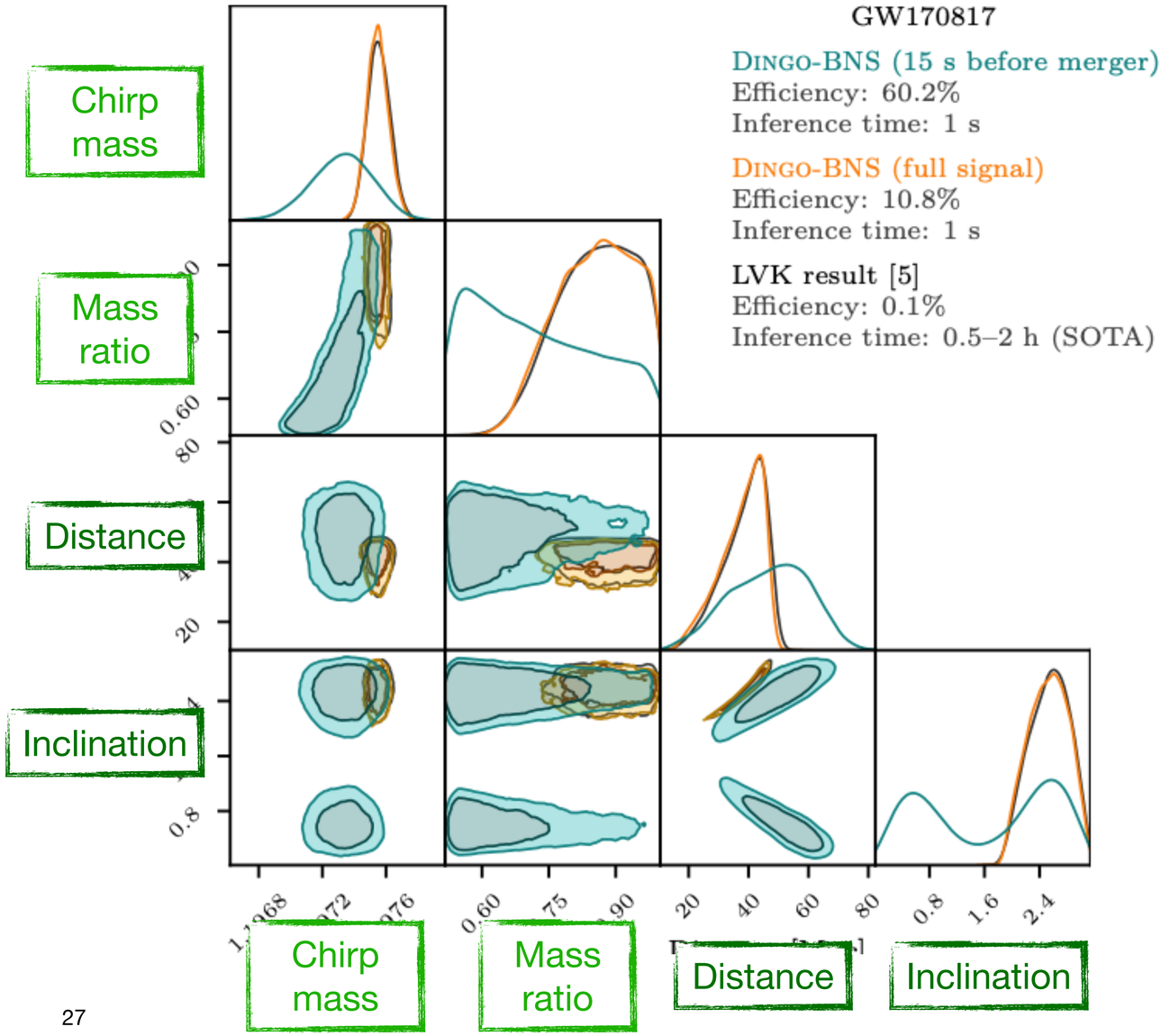


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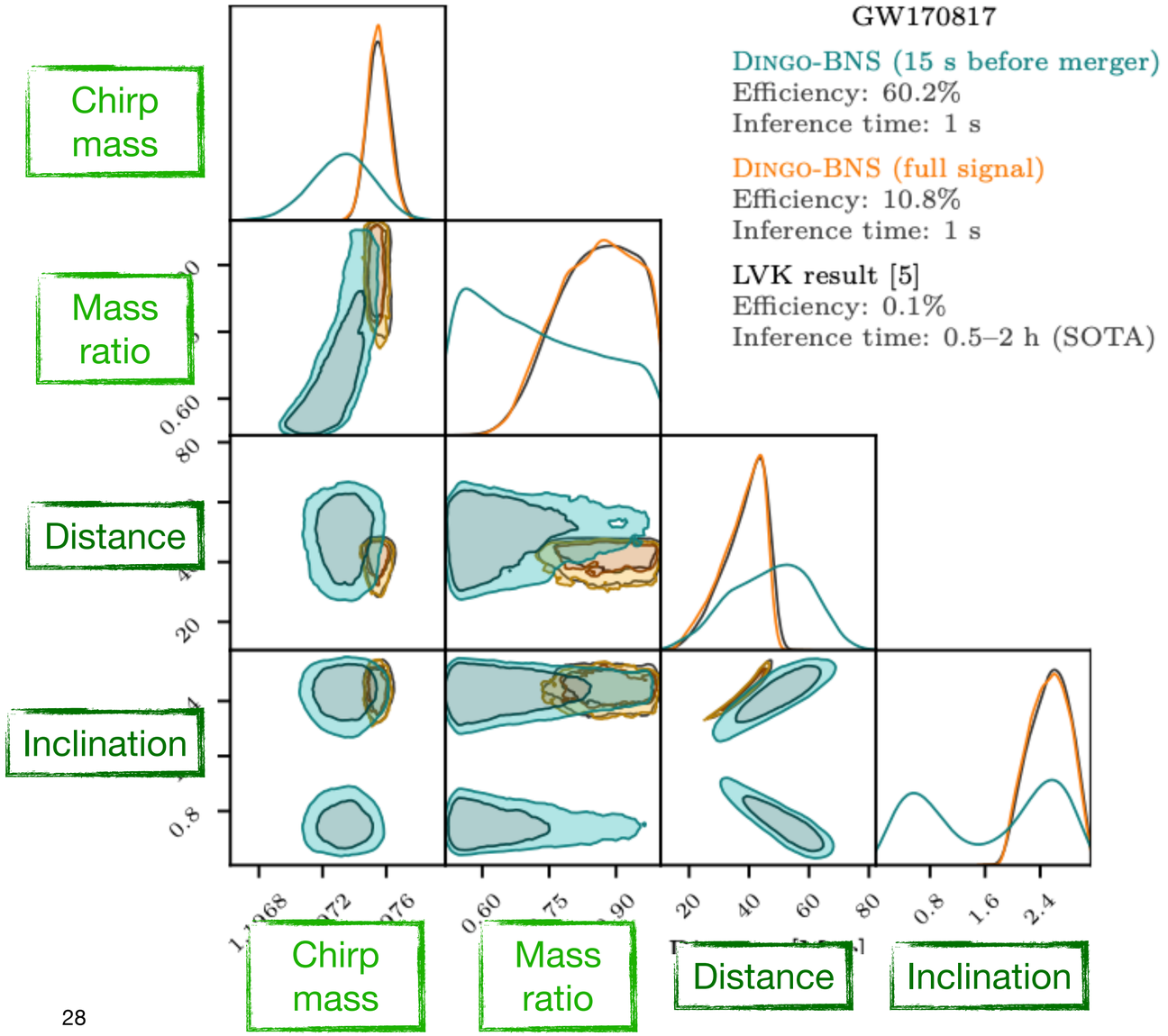
- **Results in ~1sec**
  - **Fast EM follow-up**
- Up to **1h duration**
  - **Future GW data**
- Fully simulation-based! No tractable noise likelihood needed
- Analyze incoming data
  - Pre-merger detection
- Challenges
  - Higher-order modes: no analytic reference signal



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(3) Population analyses

Questions

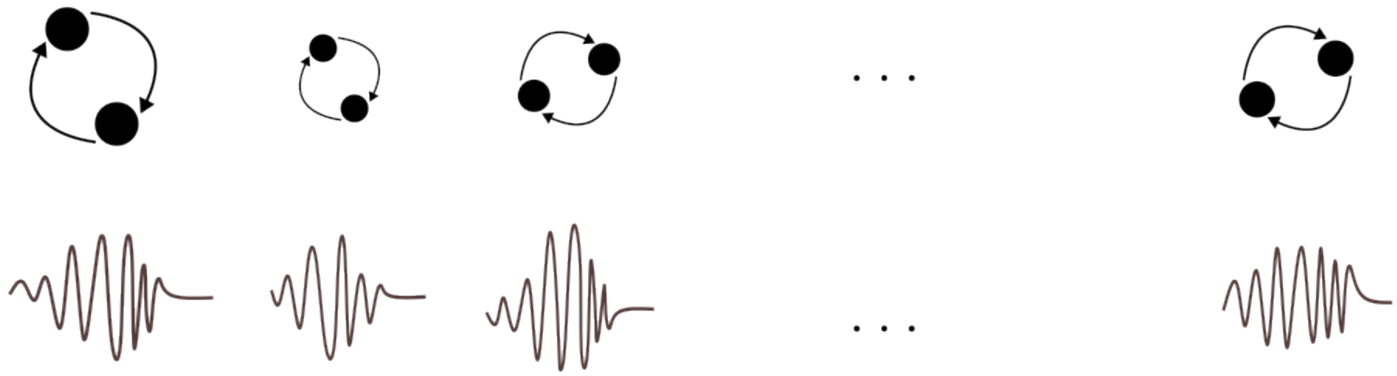
- Probe formation of black holes and neutron stars
- Test cosmological model
- Verify theory of gravity

$p(\Lambda \mid \text{Data})$ Hyperparameter posterior

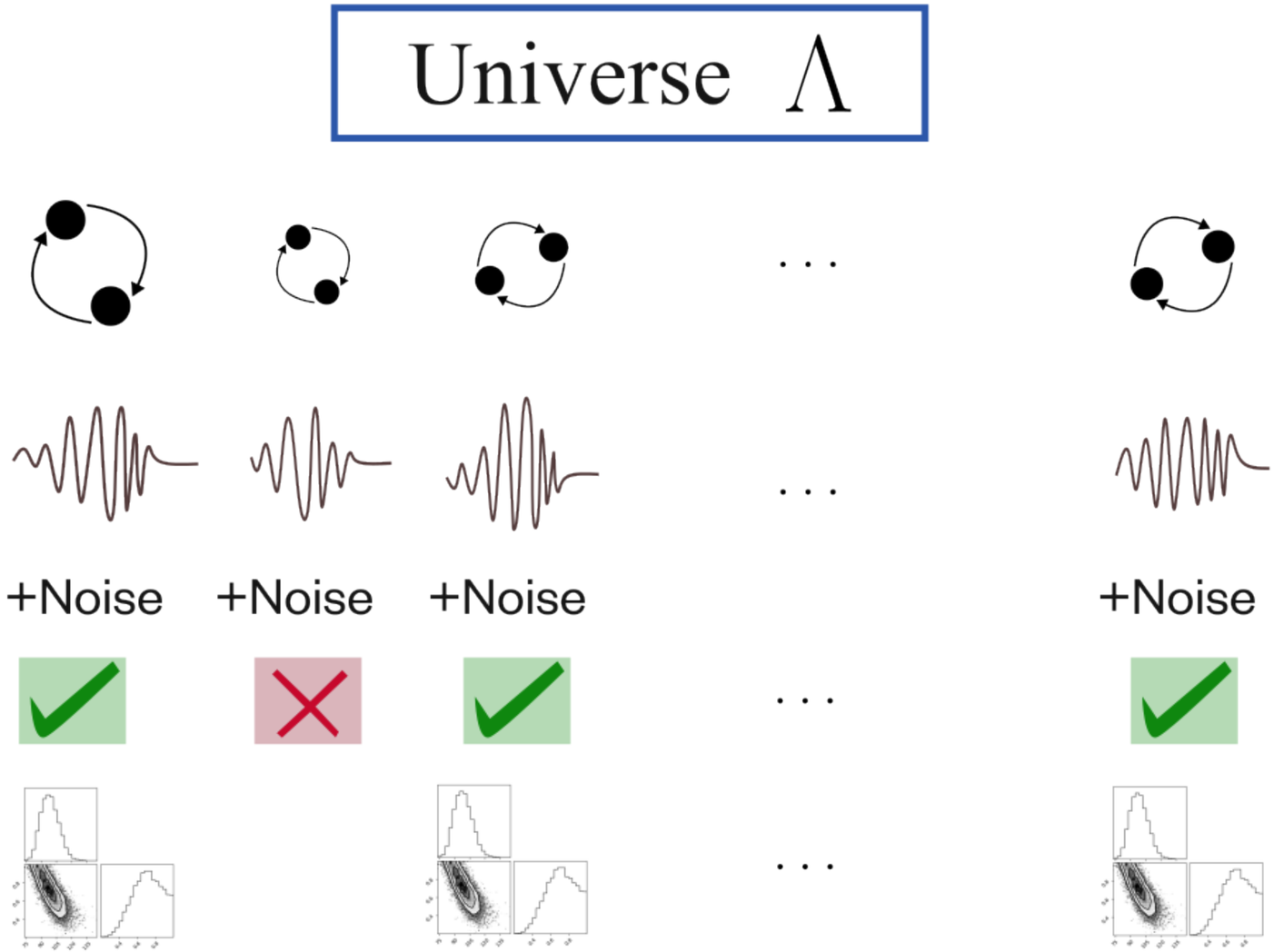
Vitale et al. 2007.05579

(3) Population analyses

Universe Λ



(3) Population analyses



Intermediate summary

A. **Searches:** detect short-duration binary signal in noisy data

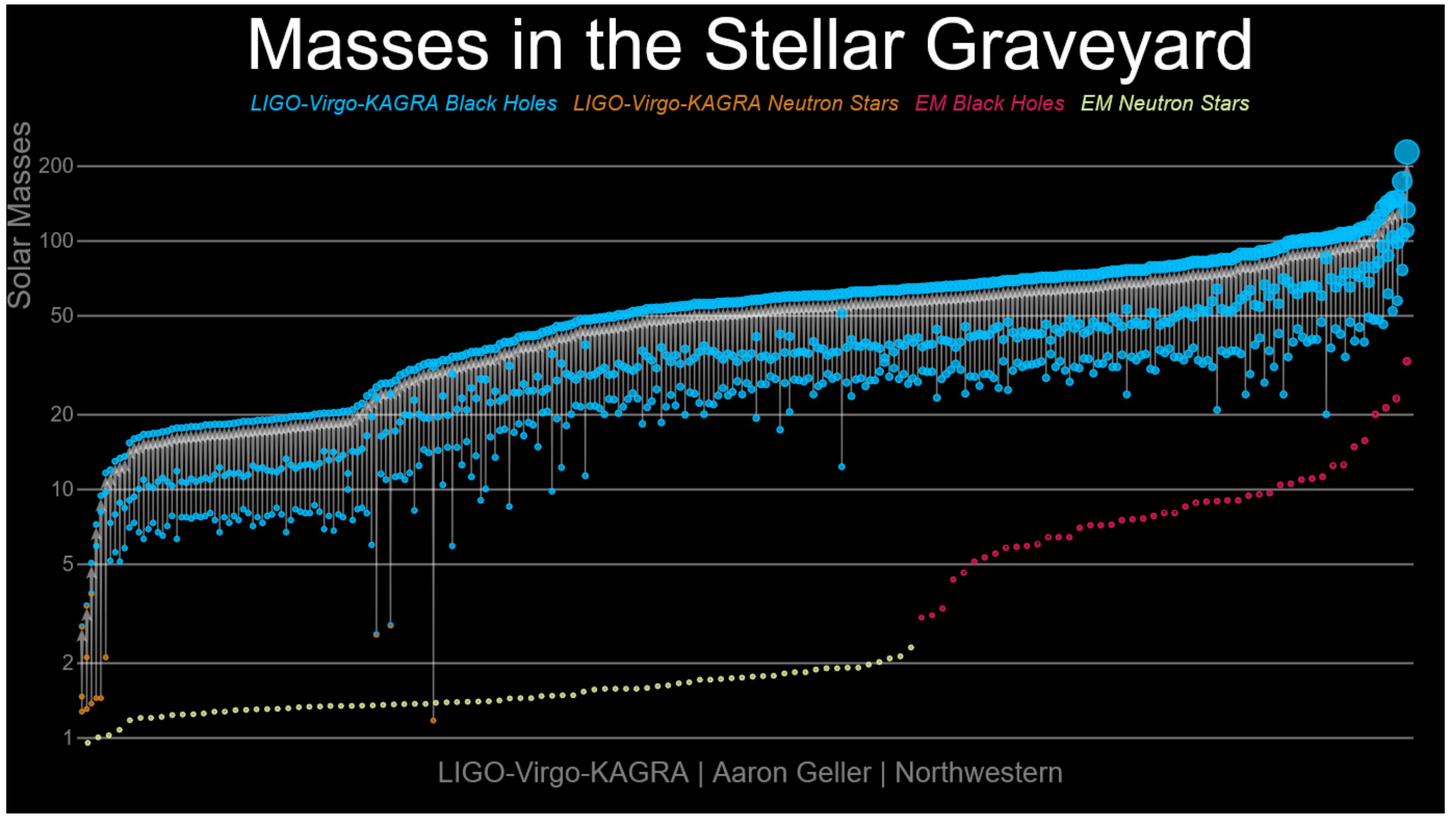
B. **Parameter estimation:** estimate astrophysical binary parameters

C. **Population analyses:** extract science from populations of all binaries

GWTC-5 Results

Latest data release: GWTC-5

- Release May 2025
- Cumulative catalog: 390 sources
- Update scientific results
  - Catalog paper
  - Rates and population
  - Cosmology
- Maximum redshift $O(1.3)$



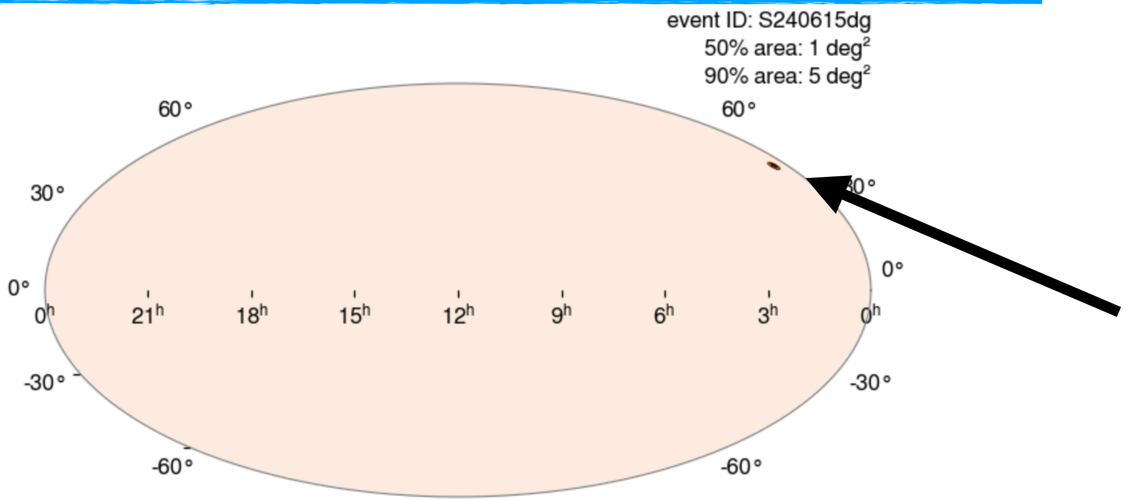
Abac et al. 2605.27223 - 27227

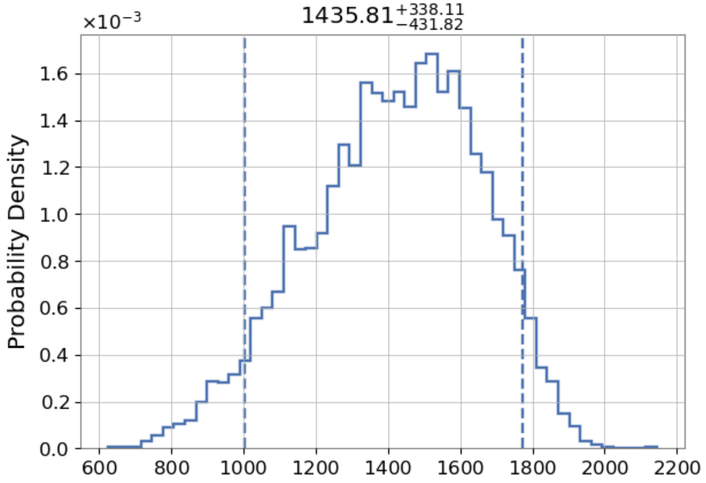
GWTC-5 Results (Single sources)

Best sky localization so far: GW240615_113620

Abac et al. 2605.27223

- O4b: LIGO + Virgo detectors
  - → Great for **triangulation**
  - 90% area: 5 deg^2
  - EM follow-up*, but no counterpart found
- For cosmology: GW + galaxy catalog?
  - Volume too large





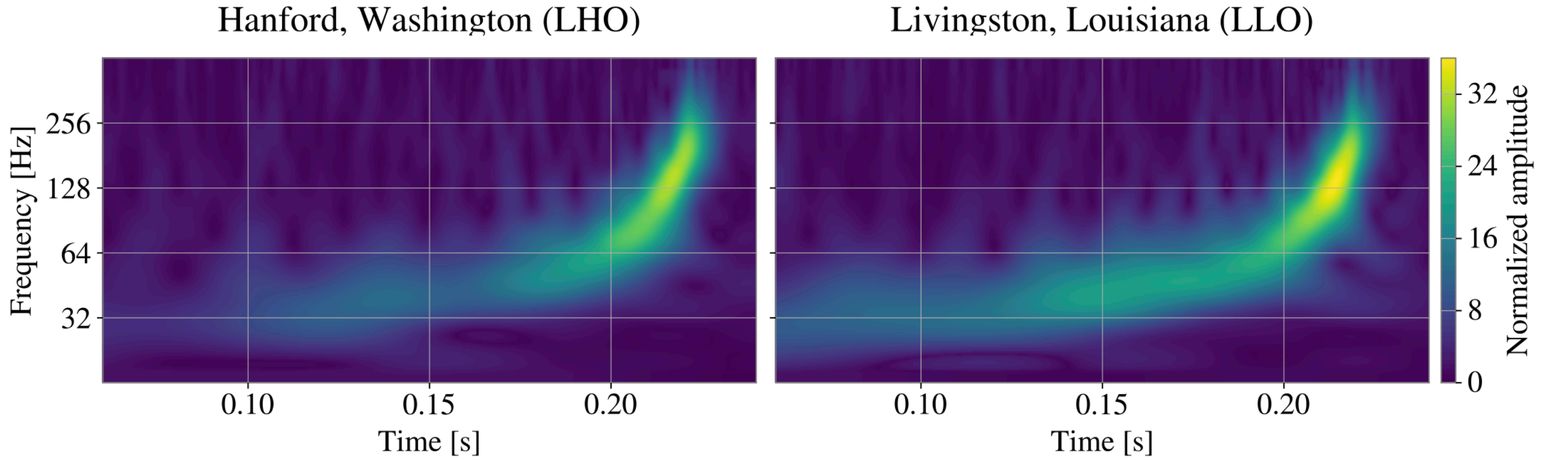
Distance [Mpc]

* Abe et al. 2607.19972

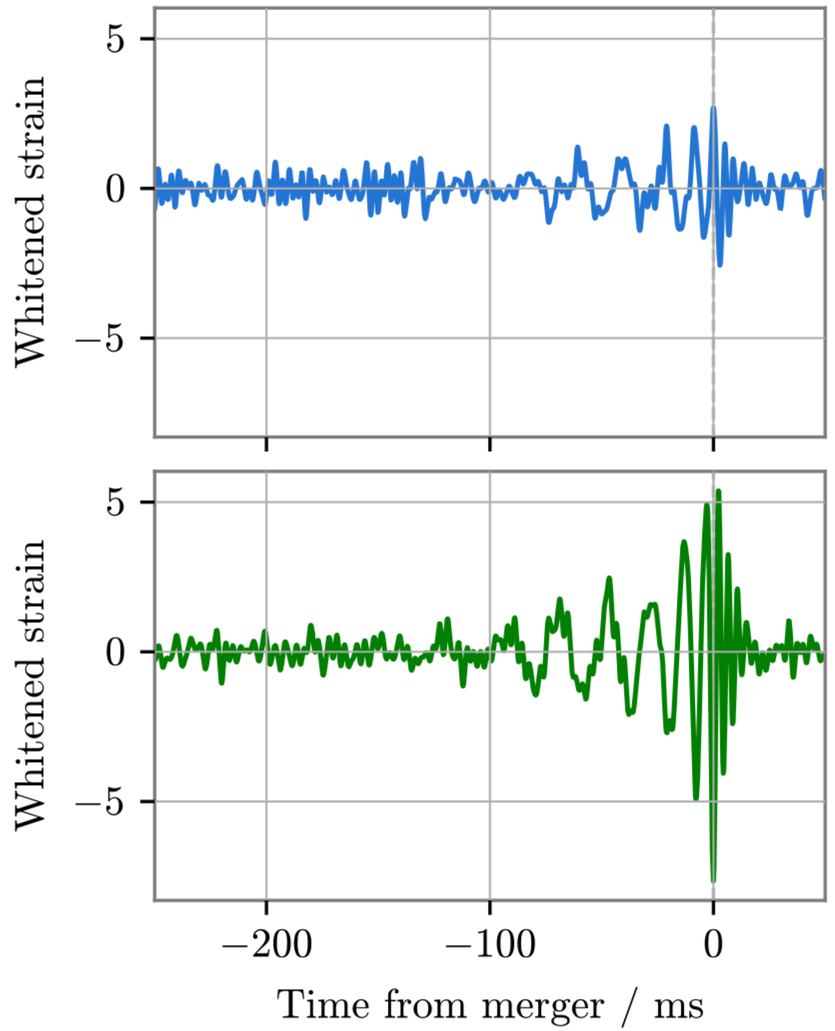
GW250114: loudest signal so far

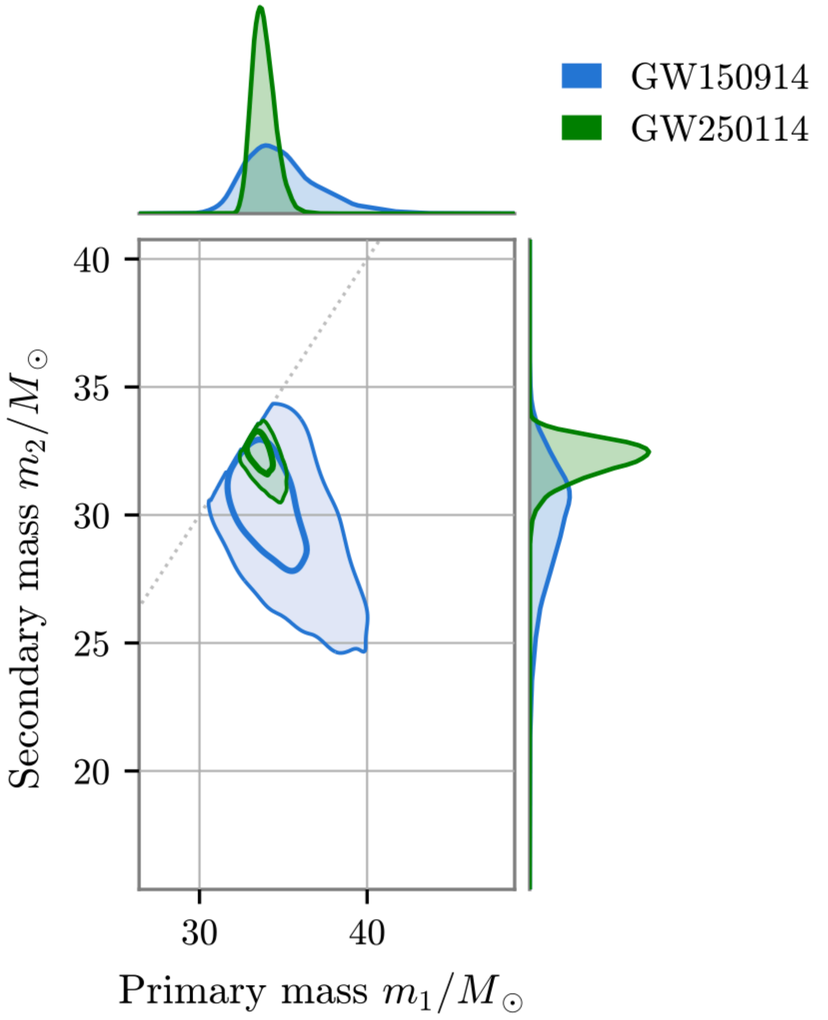
Abac et al. 2509.08054

- Highest SNR source so far (SNR ~ 80)
- **Masses** very similar to first detection
- Small spins, no evidence for eccentricity



$$m_1 = 33.6^{+1.2}_{-0.8}\, M_\odot \text{ and } m_2 = 32.2^{+0.8}_{-1.3}\, M_\odot$$





Berry and Williams 2609.03859

Tests of general relativity: GW250114

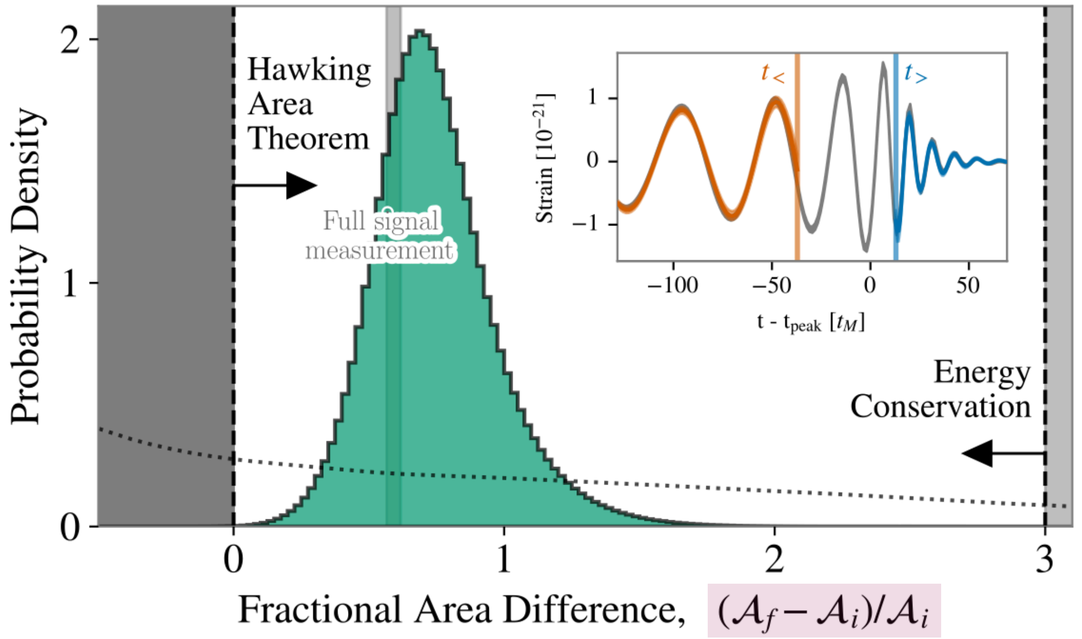
Abac et al. 2509.08054

- Highest SNR source so far (SNR ~ 80)
- Measured Kerr frequencies of remnant BH match theoretical expectations
- Divide signal in pre- and post-merger
  - Test whether **area** always increases

Area

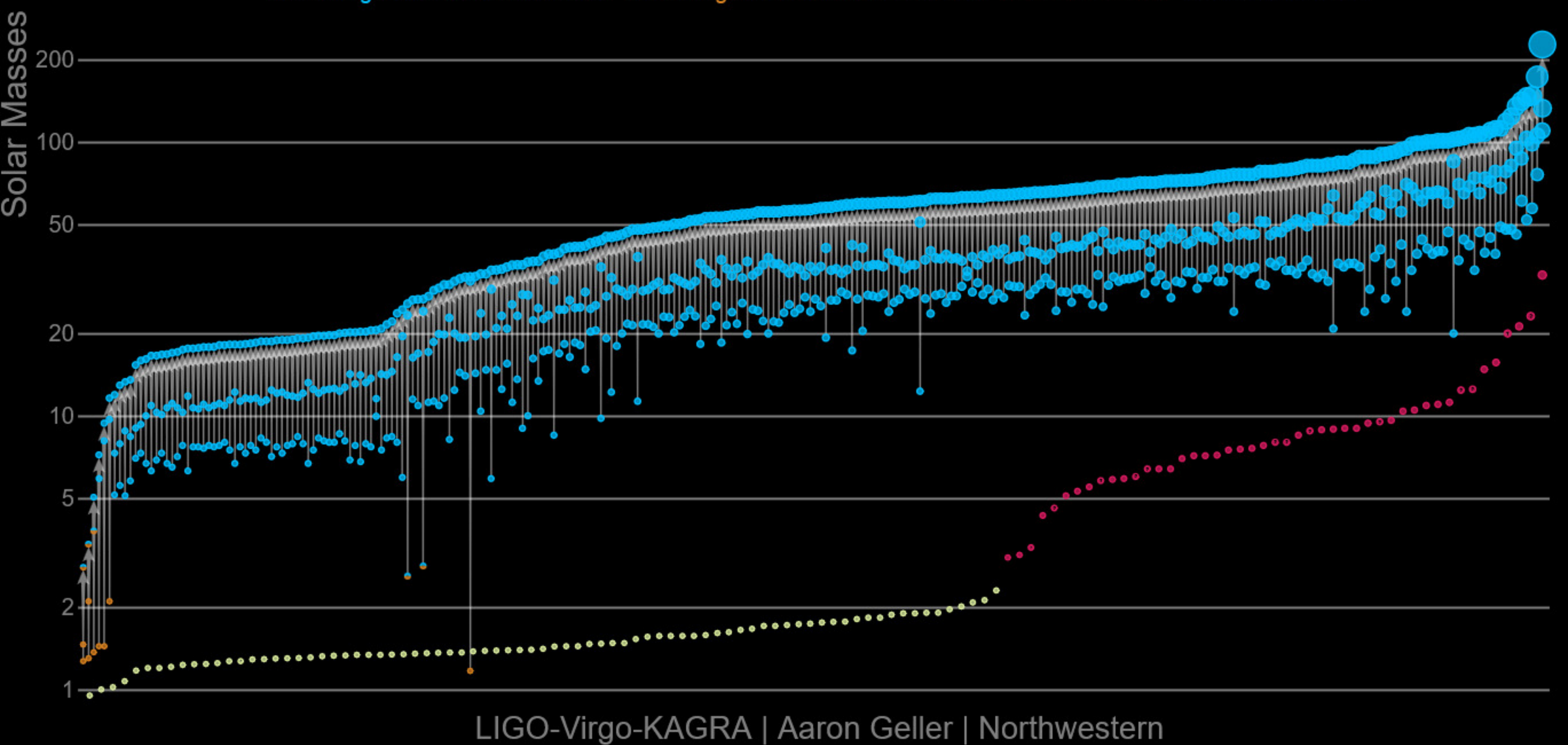
$$\mathcal{A}(m,\chi) = 8\pi\left(\frac{Gm}{c^2}\right)^2\left(1+\sqrt{1-\chi^2}\right)$$

Mass Spin

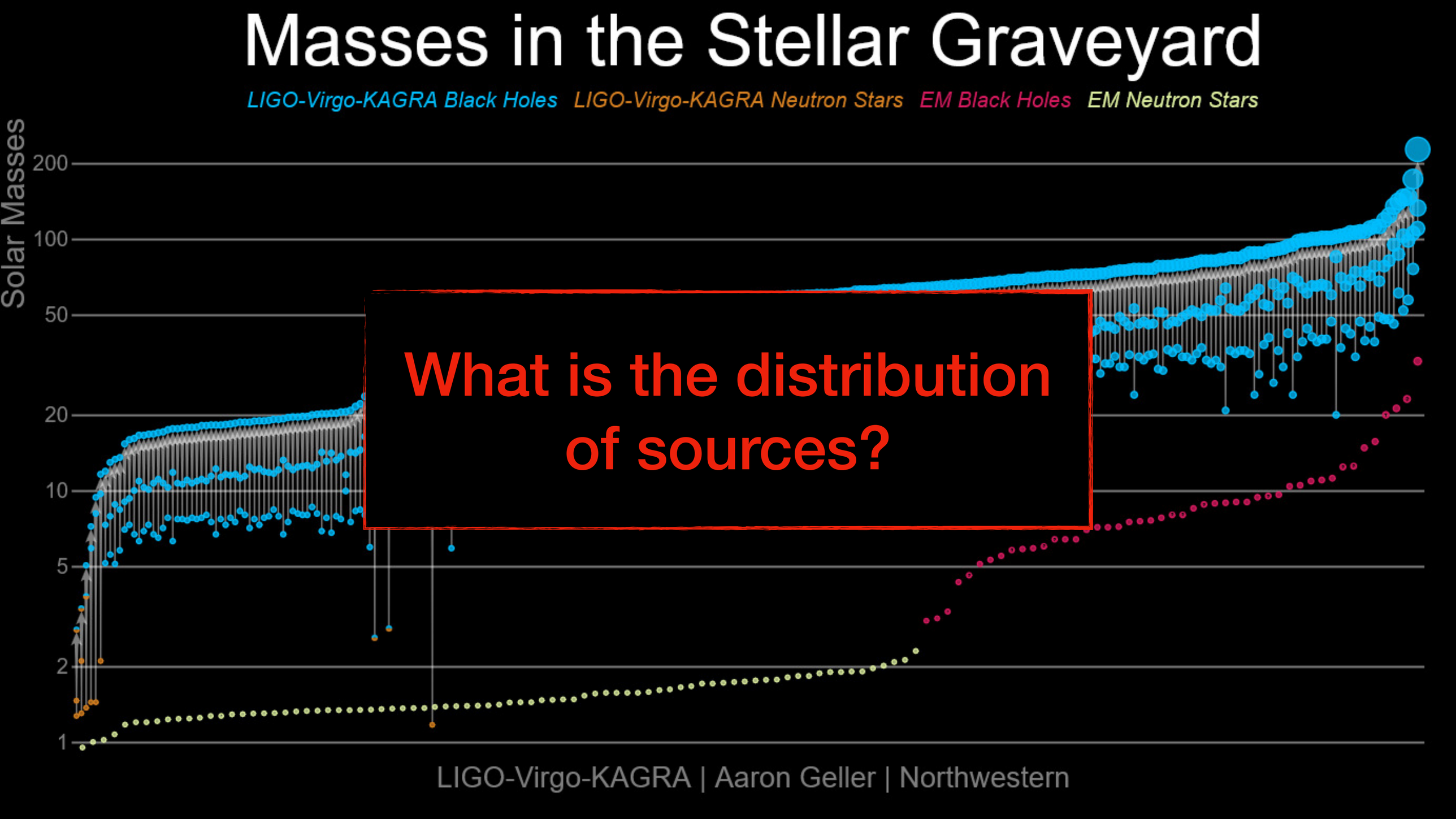


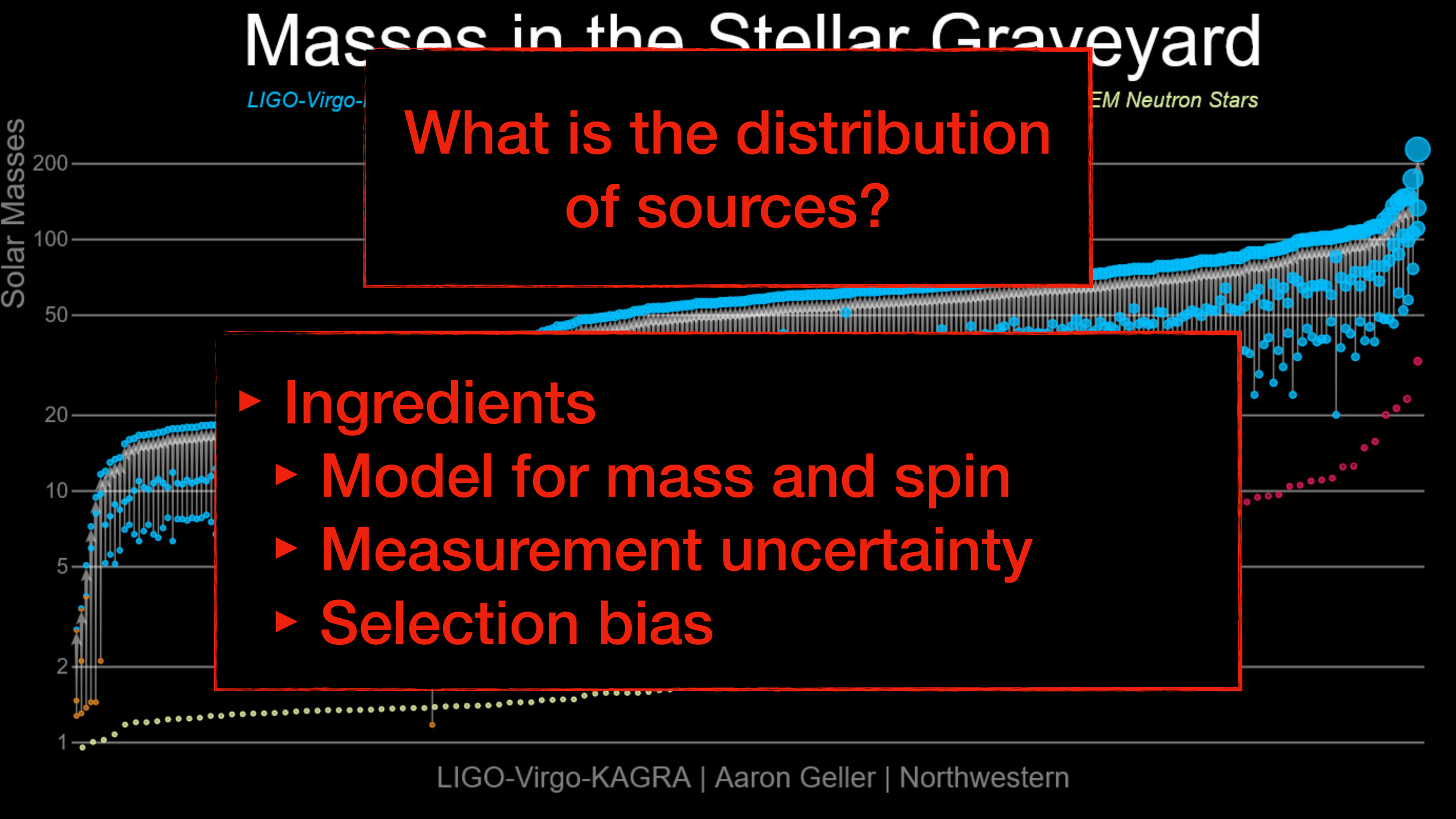
GWTC-5 Results (Population-level)

Masses in the Stellar Graveyard



Masses in the Stellar Graveyard

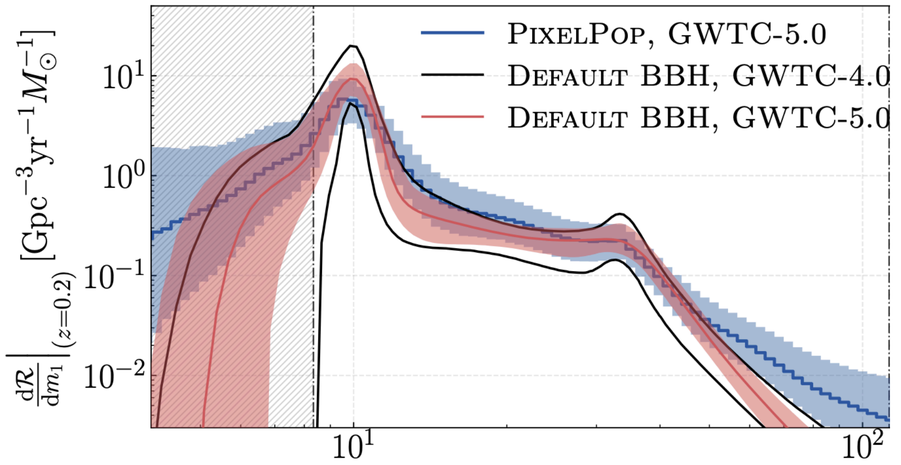



Masses in the Stellar Graveyard
LIGO-Virgo-
EM Neutron Stars
What is the distribution of sources?
Solar Masses
200
100
50
20
10
5
2
1
Ingredients
Model for mass and spin
Measurement uncertainty
Selection bias
LIGO-Virgo-KAGRA | Aaron Geller | Northwestern

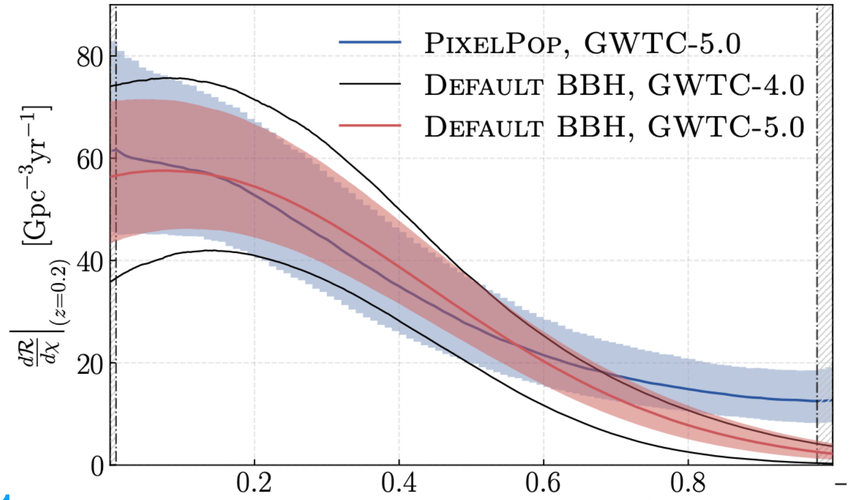
Rates and population results with GWTC-5

Abac et al. 2605.27226

- Two mass features:
  - $10M_\odot$ and $35M_\odot$
- Mostly low spin, but
  - evidence for high-mass high-spin/isotropic-spin correlation*
    → Hierarchical mergers?



Mass 1 [$M_\odot$]



Spin magnitude

* Cheng et al. 2605.25980, Hussein et al. 2605.24281, Guttman et al. 2607.22011

Gravitational-wave cosmology

Cosmology with gravitational waves

- Gravitational-wave propagation on an expanding background

1

$$r \to d_L$$

Luminosity distance

Hubble constant measurement with GWs

Taylor-expansion for $z \ll 1$

Redshift

Luminosity distance

$$d_L(z) \approx \frac{z}{H_0} \quad \Rightarrow \quad H_0 \approx \frac{z}{d_L}$$

??

GW

Current expansion rate of the Universe

Direct electromagnetic counterpart

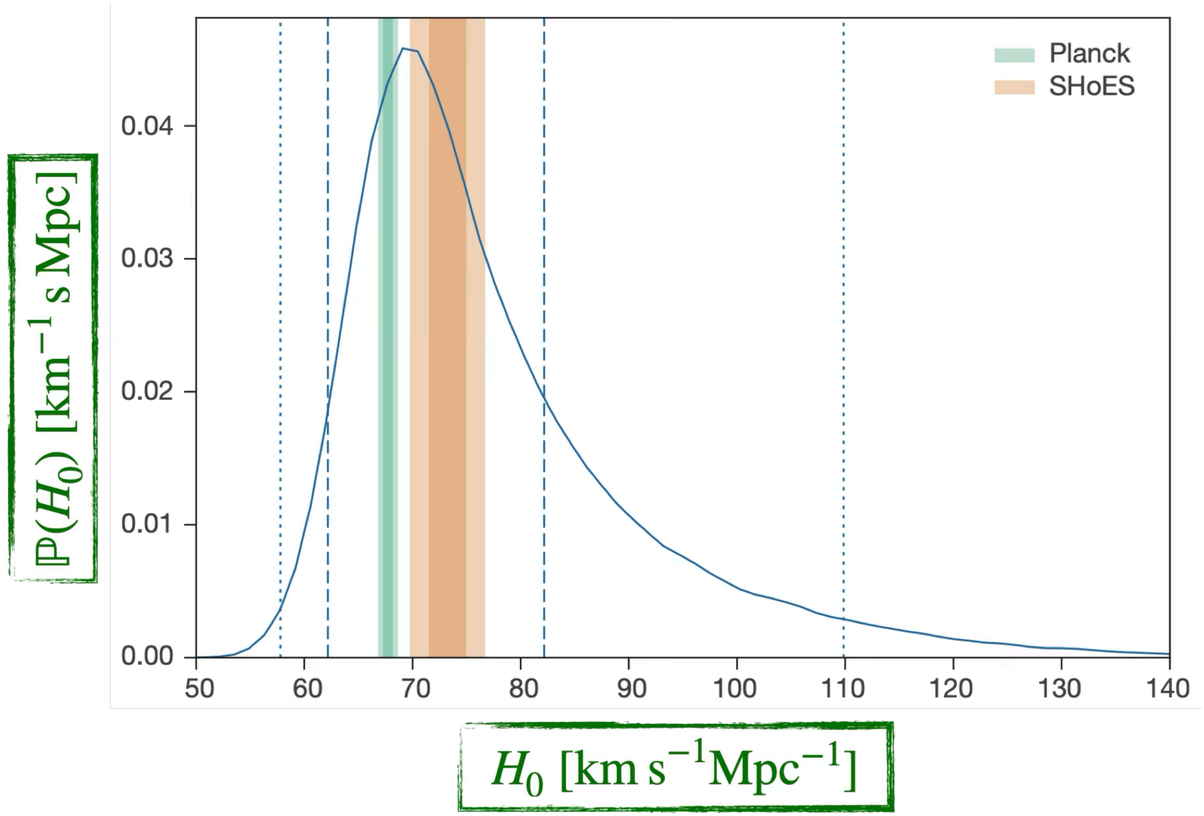
LIGO-Virgo+ 1710.05835

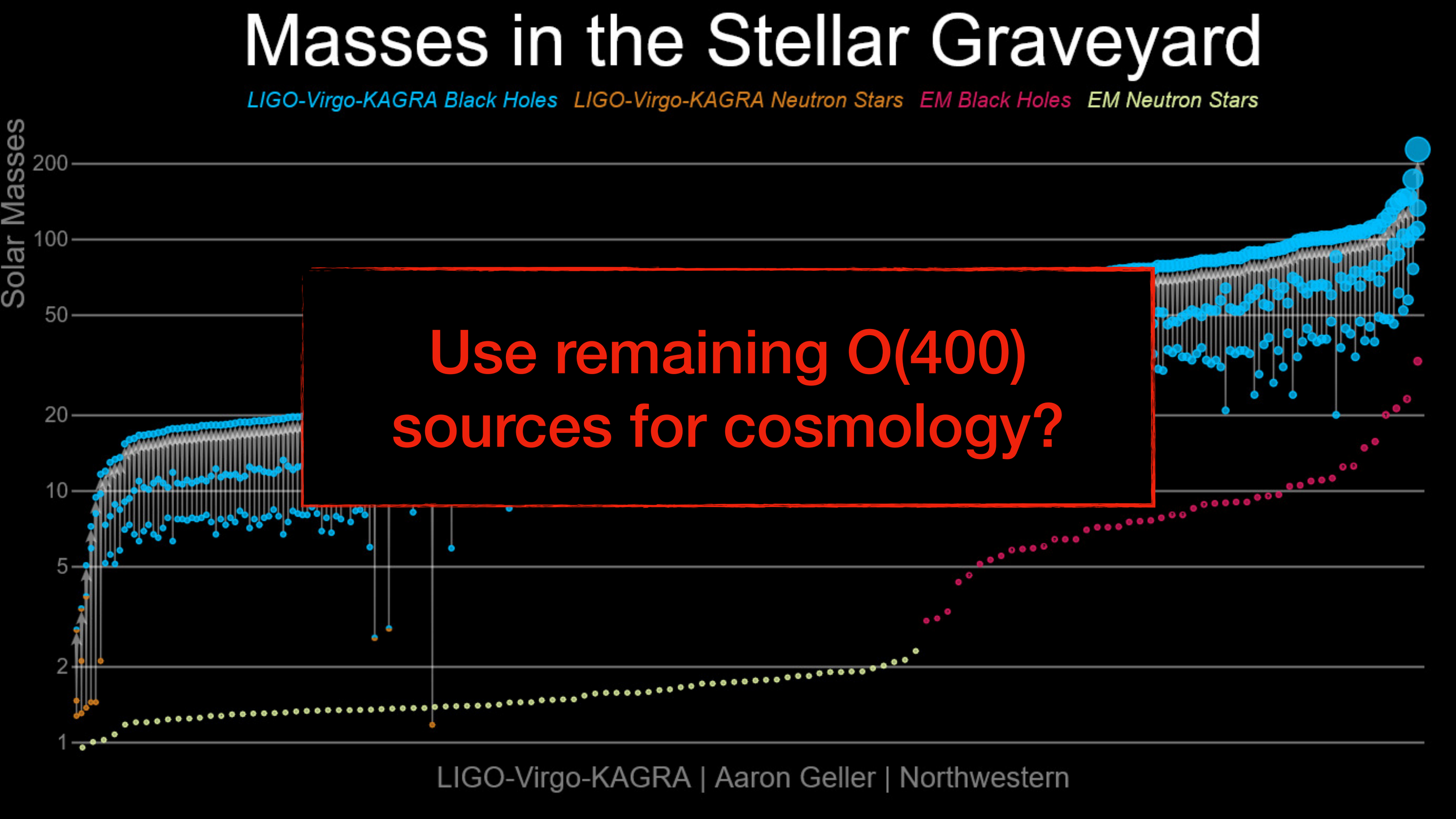
- One confident observation: GW170817
  - Follow-up observations -> Rapidly decaying counterpart -> Host galaxy identification
- Increasing observation evidence: very rare
  - -> How can the other BHs used for cosmology?

$$H_0 \approx \frac{z}{d_L}$$

z ← Host galaxy

d_L ← GW




Masses in the Stellar Graveyard
LIGO-Virgo-KAGRA Black Holes
LIGO-Virgo-KAGRA Neutron Stars
EM Black Holes
EM Neutron Stars
Solar Masses
200
100
50
20
10
5
2
1
Use remaining O(400) sources for cosmology?
LIGO-Virgo-KAGRA | Aaron Geller | Northwestern

Cosmology with gravitational waves

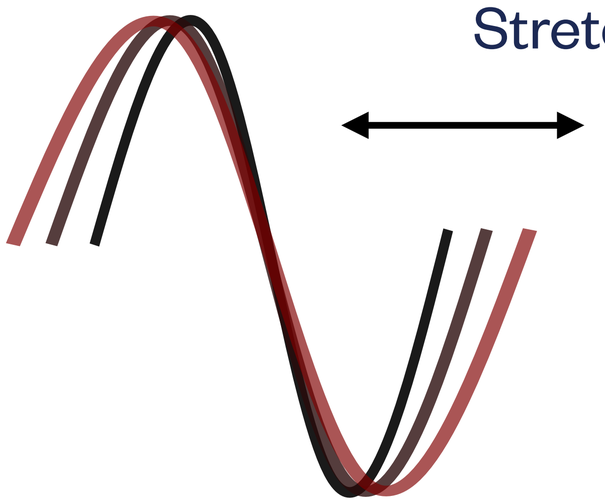
- Gravitational-wave propagation on an expanding background

1

$$r \to d_L$$

Luminosity distance

2



$$m_{\mathrm{d}} = (1+z)m_{\mathrm{s}}$$

Astrophysical mass

Redshift

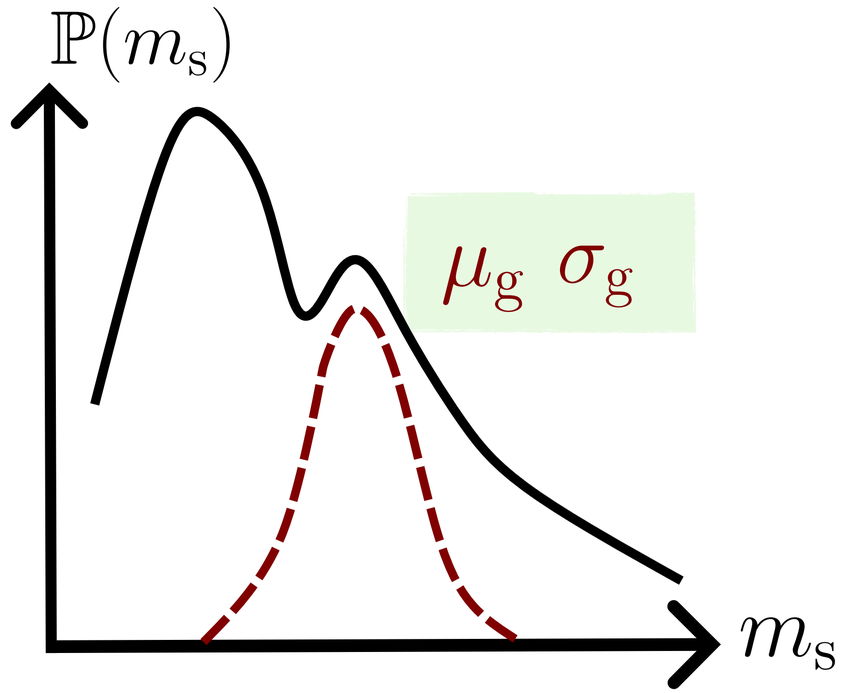
Spectral sirens

- Assume distribution of source-frame mass
- → **Statistical measurement** of z
- **Mass distribution not known** theoretically (both single-star and binary evolution)
  - Assume mass distribution, fit jointly
  - H_0, mass parameters

$$m_\mathrm{d} = (1+z)m_\mathrm{s}$$

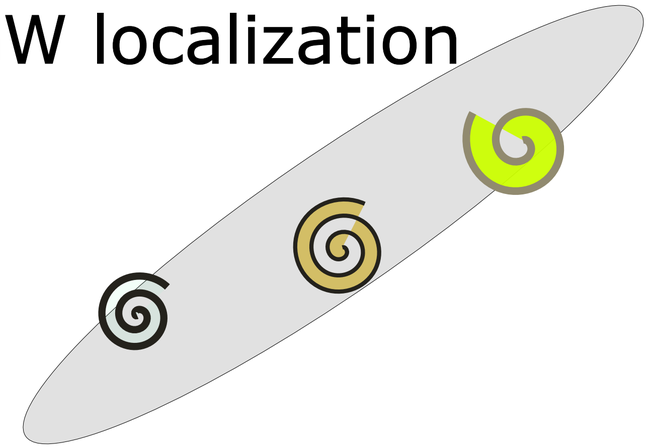
Astrophysical mass

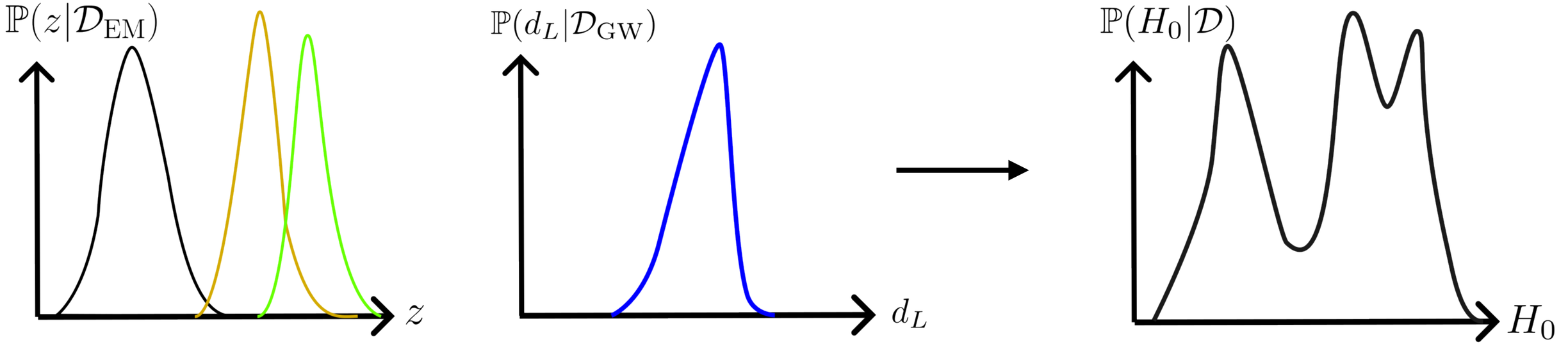
Redshift



Dark siren measurement

- **In addition**, to mass information, can use galaxy catalogs
- Potential host galaxies inform on redshift



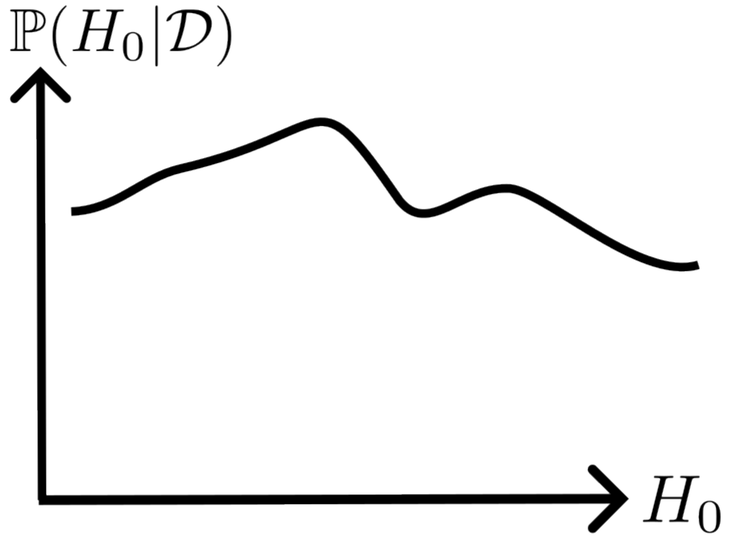


Mastrogiovanni et al. 2103.14663, 2305.10488,
Gray et al. 1908.06050, 2111.04629, 2308.02281

Reality for dark sirens

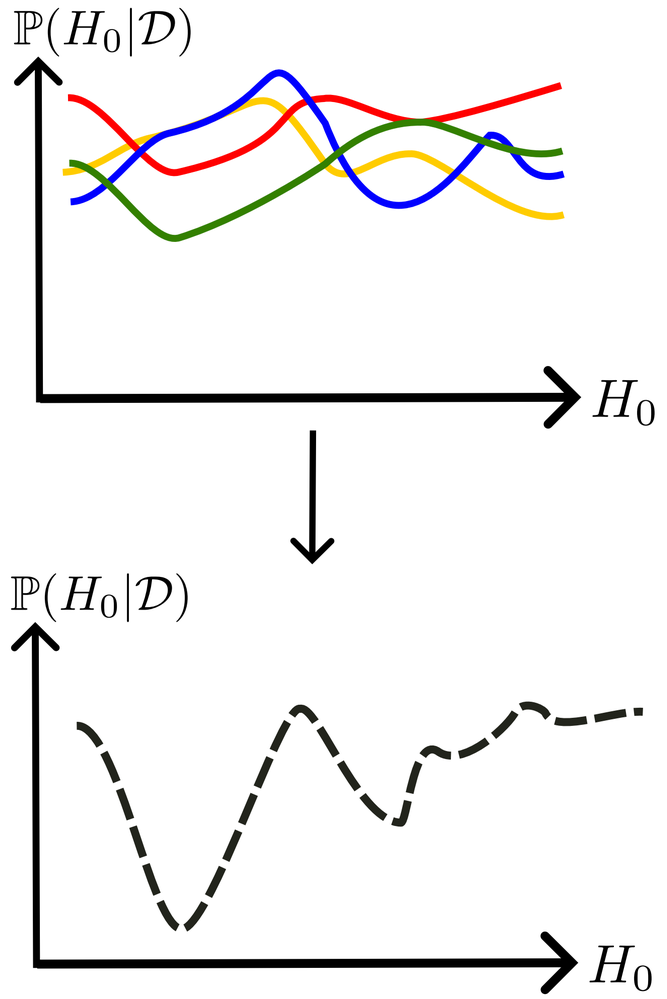
- Most GW events have large sky localization
- Many possible host galaxies
- One event relatively uninformative





Hierarchical Bayesian inference

- Combine the result for many events
- Multi-modal posterior localizes
- Measurement error $\sigma \propto 1/\sqrt{N}$ with N number of observed events*



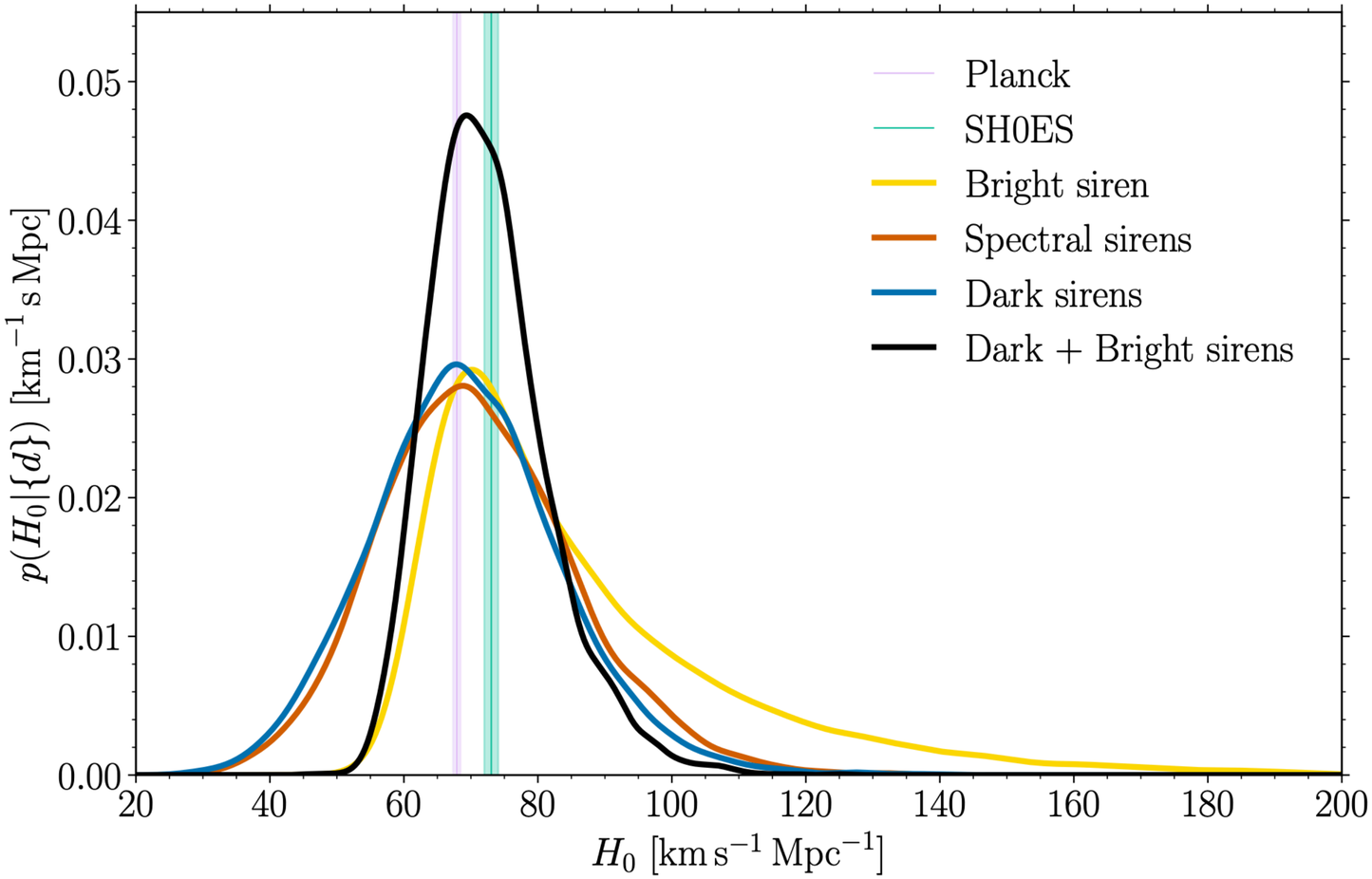
* Under some additional assumptions

Constraints on the cosmic expansion history with GWTC-5

Abac et al. 2605.27227

$$H_0 = 71.7^{+9.4}_{-7.5}\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$$

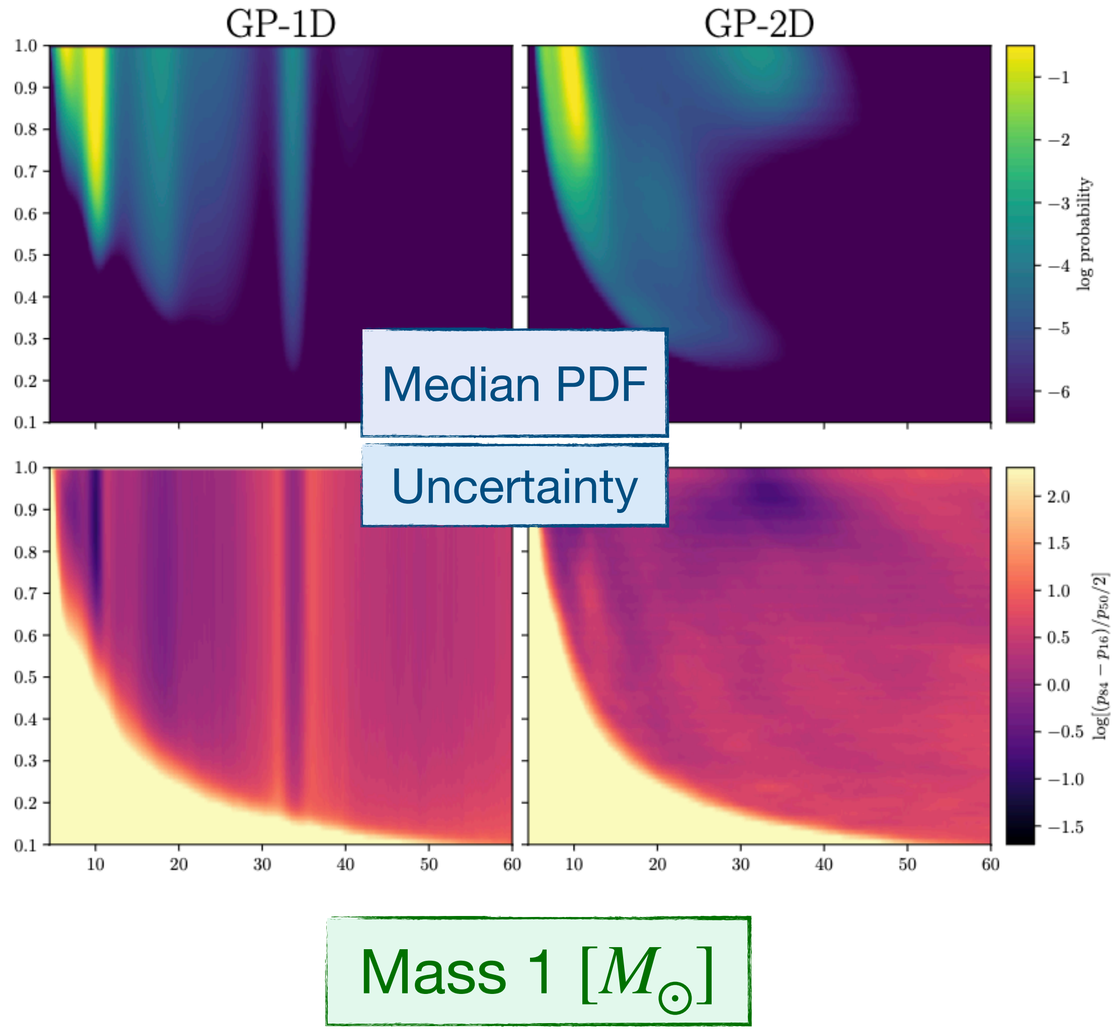
- Bright siren: GW170817
- Spectral sirens: use mass information alone
- Dark siren: uses the DES galaxy catalog
- First time all binary BHs as constraining as the bright siren
- 22% improvement over GWTC-4



Flexible mass distributions for GW cosmology

Leyde and Colangeli 2608.18281

- Currently: parametric mass distributions
- Gaussian process model for increased flexibility
- Cost: increased H_0 uncertainty, but more robust against mismodeling



$$h = 0.66^{+0.17}_{-0.20} \text{ and } h = 0.57^{+0.20}_{-0.15}$$

$h = H_0/[100\,\mathrm{km\,s^{-1}\,Mpc^{-1}}]$

Conclusions

- **GWTC-5** - O(400) sources
  - Loudest source, best localized source to date
  - **Evidence for overdensities/breaks at** $10M_\odot$ and $35M_\odot$
  - H_0 **measurement improvement of** $22\,\%$
  - What are the **sub-populations/formation channels** in the data?
- **Open methodological questions**
  - Optimal **cross-correlation techniques** for GW vs electromagnetic tracers
  - Full SBI results **without importance sampling**?
  - **Scaling of population inference** for large datasets?

Back-up slides

Simulation-based inference

- **Idea: posterior approximation**
  - Model parameters θ, data $\mathscr{D}$
  - **True posterior:** $\mathbb{P}(\theta \,|\, \mathscr{D})$
  - **Approximate model:** $\mathbb{Q}(\theta \,|\, \mathscr{D})$
- **Generative model with model parameters** w
  - $\mathbb{Q}(\theta \,|\, \mathscr{D}) \to \mathbb{Q}(\theta \,|\, \mathscr{D}, w)$
- **Optimize loss(w) s.t.** $\mathbb{Q} \approx \mathbb{P}$

Papamakarios and Murray 1605.06376, Lueckmann et al. 2017, Greenberg et al. 2019, Cranmer et al. 1911.01429

The loss

➡**Minimize distance($\mathbb{P}$,$\mathbb{Q}$)**

➡Example: **Kullback-Leibler**

$$\mathrm{KL}(\mathbb{P}, \mathbb{Q}) = \int \mathrm{d}\theta \, \mathbb{P} \log\left(\frac{\mathbb{P}}{\mathbb{Q}}\right)$$

$$\mathrm{KL}(\mathbb{P}, \mathbb{Q}) = 0 \quad \text{for } \mathbb{P} = \mathbb{Q}$$

$$\mathrm{KL}(\mathbb{P}, \mathbb{Q}) > 0 \quad \text{for } \mathbb{P} \neq \mathbb{Q}$$

- **Evaluation?** Avoid costly
  - **Integral over θ**
  - **Computation of $\mathbb{P}(\theta \,|\, \mathscr{D})$**

$$\text{Loss} = \mathbb{E}_{\mathbb{P}(\mathscr{D})}\left[\mathsf{KL}(\mathbb{P}, \mathbb{Q})\right]$$

$$= \ldots$$

Def. conditional probability

$$= -\,\mathbb{E}_{\mathbb{P}(\theta,\mathscr{D})} \log\left(\mathbb{Q}\right) + \#$$

$$\approx -\sum_{\theta,\mathscr{D}\sim\mathbb{P}(\theta,\mathscr{D})} \log\left(\mathbb{Q}\right) + \#$$

Dependent on w

Independent of w

- **Only forward model**

  ➡Generation of (parameter-data) pairs

  - **No appearance of $\mathbb{P}(\theta \mid \mathscr{D})$**

    ➡No explicit likelihood, *"likelihood-free"*

- **Require: evaluation of $\mathbb{Q}(\theta \mid \mathscr{D})$**

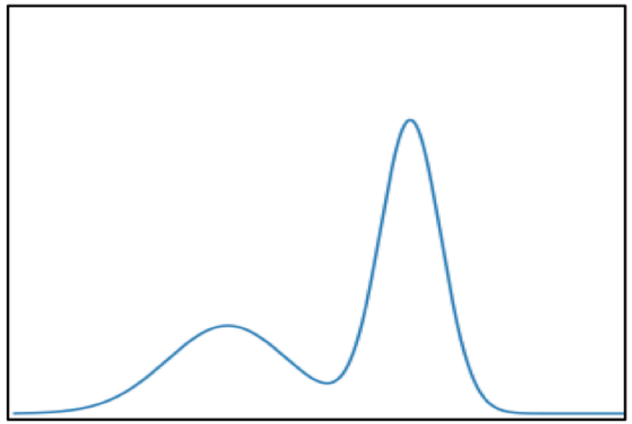
$$\text{Loss} \approx -\sum_{\theta,\mathscr{D}\sim\mathbb{P}(\theta,\mathscr{D})} \log\left(\mathbb{Q}\right)$$

Papamakarios and Murray 1605.06376, Lueckmann et al. 2017, Greenberg et al. 2019, Cranmer et al. 1911.01429

Normalizing flows

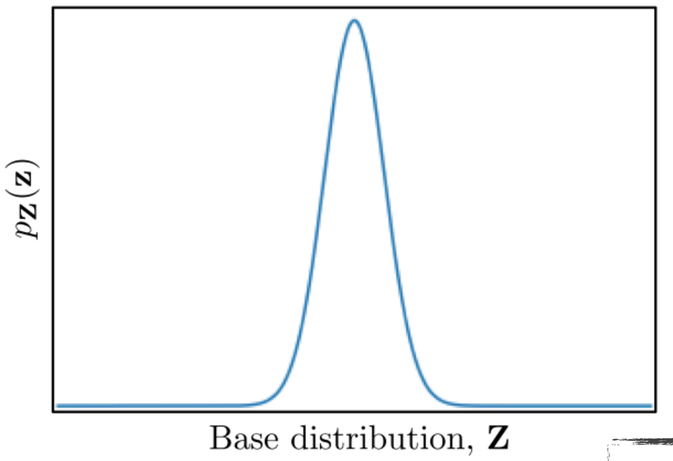
- **Generative model** from machine learning
- **Simple PDF via non-linear transformation to** $\mathbb{Q}(\theta \,|\, \mathscr{D})$
- **Transformation** g **data-dependent**

$\mathbb{Q}(\theta \,|\, \mathscr{D})$



θ

$\theta := g(Z, \text{data}; w)$



Embedding space

Tabak and Vanden-Eijnden 2010, Tabak and Turner 2013, Durkan et al. 2019, Kobyzev et al. 2019

$$
\begin{aligned}
\text{Loss} &= \mathbb{E}_{\mathbb{P}(\mathscr{D})}\left[\mathsf{KL}(\mathbb{P}\,||\,\mathbb{Q})\right] \\
&= \int \mathrm{d}\mathscr{D}\ \mathbb{P}(\mathscr{D})\mathsf{KL}(\mathbb{P}\,||\,\mathbb{Q}) \\
&= \int \mathrm{d}\mathscr{D}\ \mathbb{P}(\mathscr{D})\,\mathbb{P}(\theta\,|\,\mathscr{D})\log\left(\frac{\mathbb{P}}{\mathbb{Q}}\right) \\
&= \int \mathrm{d}\mathscr{D}\ \mathbb{P}(\theta,\mathscr{D})\log\left(\frac{\mathbb{P}}{\mathbb{Q}}\right)
\end{aligned}
$$

Loss of group equivarient posterior

2111.13139

$$\mathcal{L}_{\text{GNPE}} = \mathbb{E}_{p(\theta)}\mathbb{E}_{p(x|\theta)}\mathbb{E}_{p(\hat{g}|\theta)}\left[-\log q\left(\theta|T_{\hat{g}^{-1}}x, \hat{g}\right)\right]$$

Compact binary mergers

- **Intrinsic properties: masses, spins**
- **Extrinsic properties: sky position, distance, inclination, reference time, reference phase, etc.**
- Computational cost division:
  - **Intrinsic: costly, extrinsic: cheap**
- **Signal model ~understood: different waveform models**
  - **Computing 1 signal:** $\mathcal{O}(10^{-4} - 1)$ **sec**

