UNIVERSITY OF BIRMINGHAM | GRAVITATIONAL WAVE ASTRONOMY

LECTURE 3: OBSERVATIONS & MMA (PROSPECTS)

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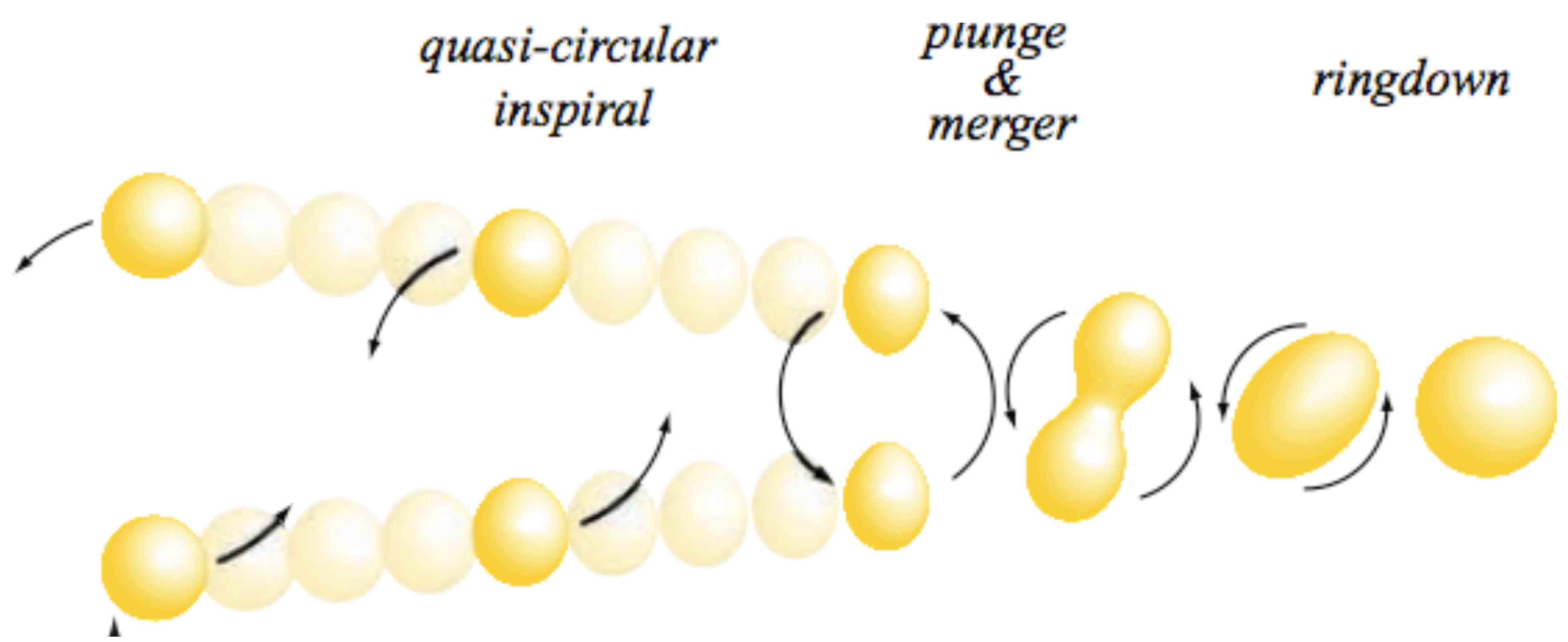
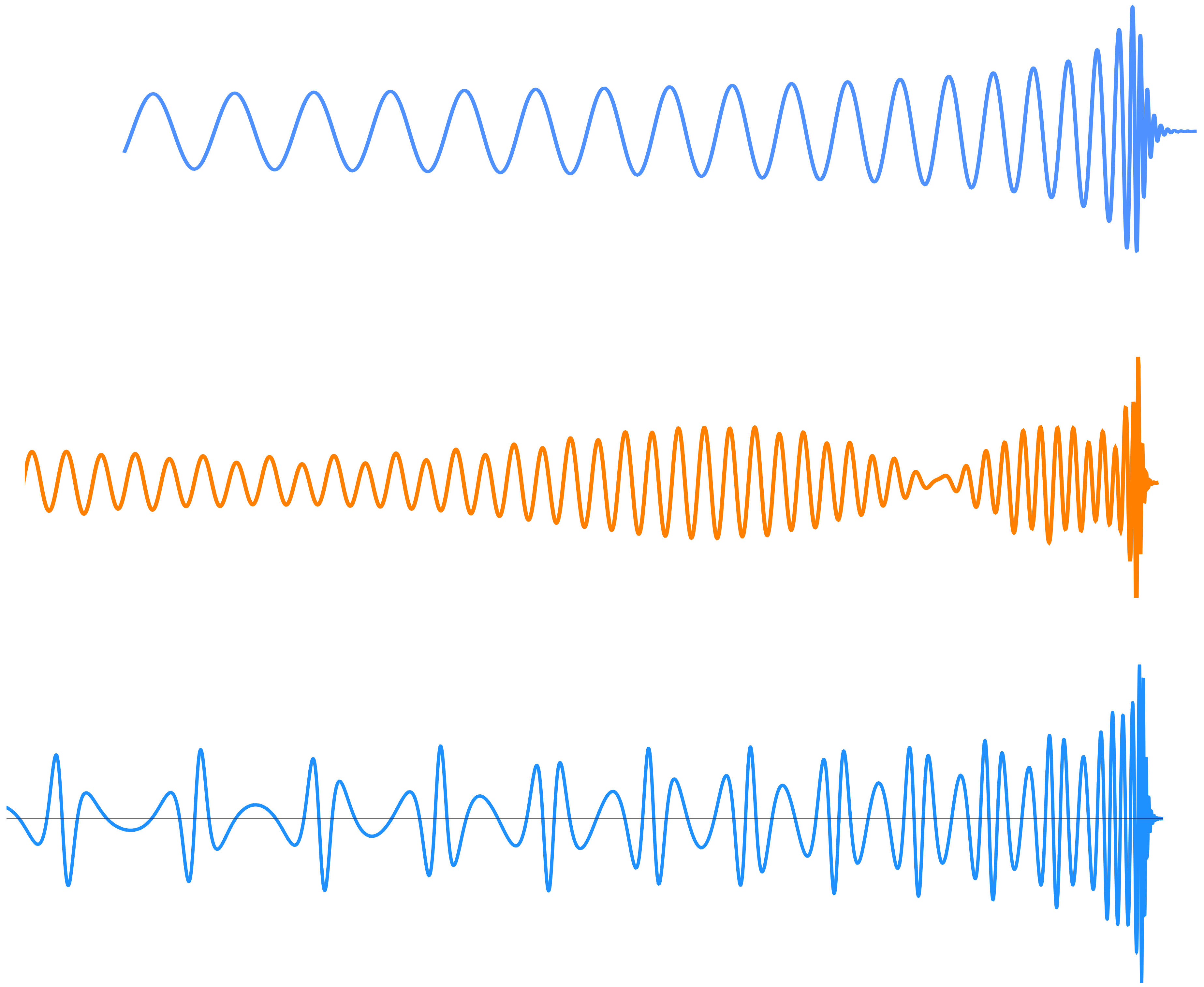
ISCRA 2024

SUMMARY LECTURE 2

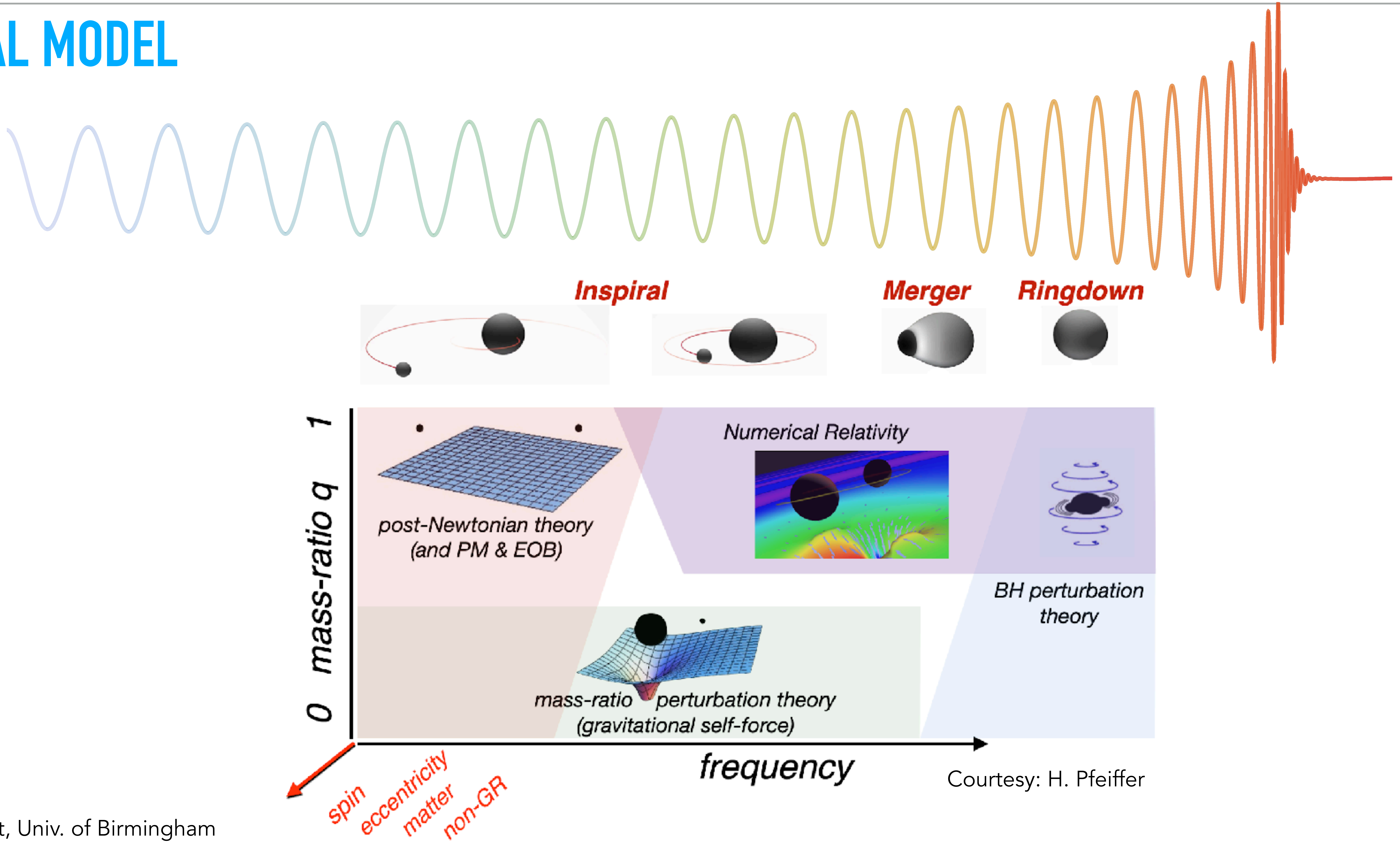
- **Network** of kilometre-scale GW detectors: LIGO, Virgo, KAGRA
  - Sensitive to GWs with frequencies between 20-2000Hz
  - Compact binaries with total mass of $1 - \mathcal{O}(\mathrm{a\,few}100)\,\mathrm{M}_\odot$



- Data analysis for compact binaries:
  - Optimal search = **matched filter**
  - **Bayesian inference** to extract binary parameters: masses, spins, source location, orientation, etc.
  - Assumption: **Noise** is Gaussian and stationary — not necessarily true
  - Requirement: **Signal model** — "tutti frutti" approach to modelling compact binaries
    - Analytical perturbation theory (inspiral & ringdown), numerical relativity



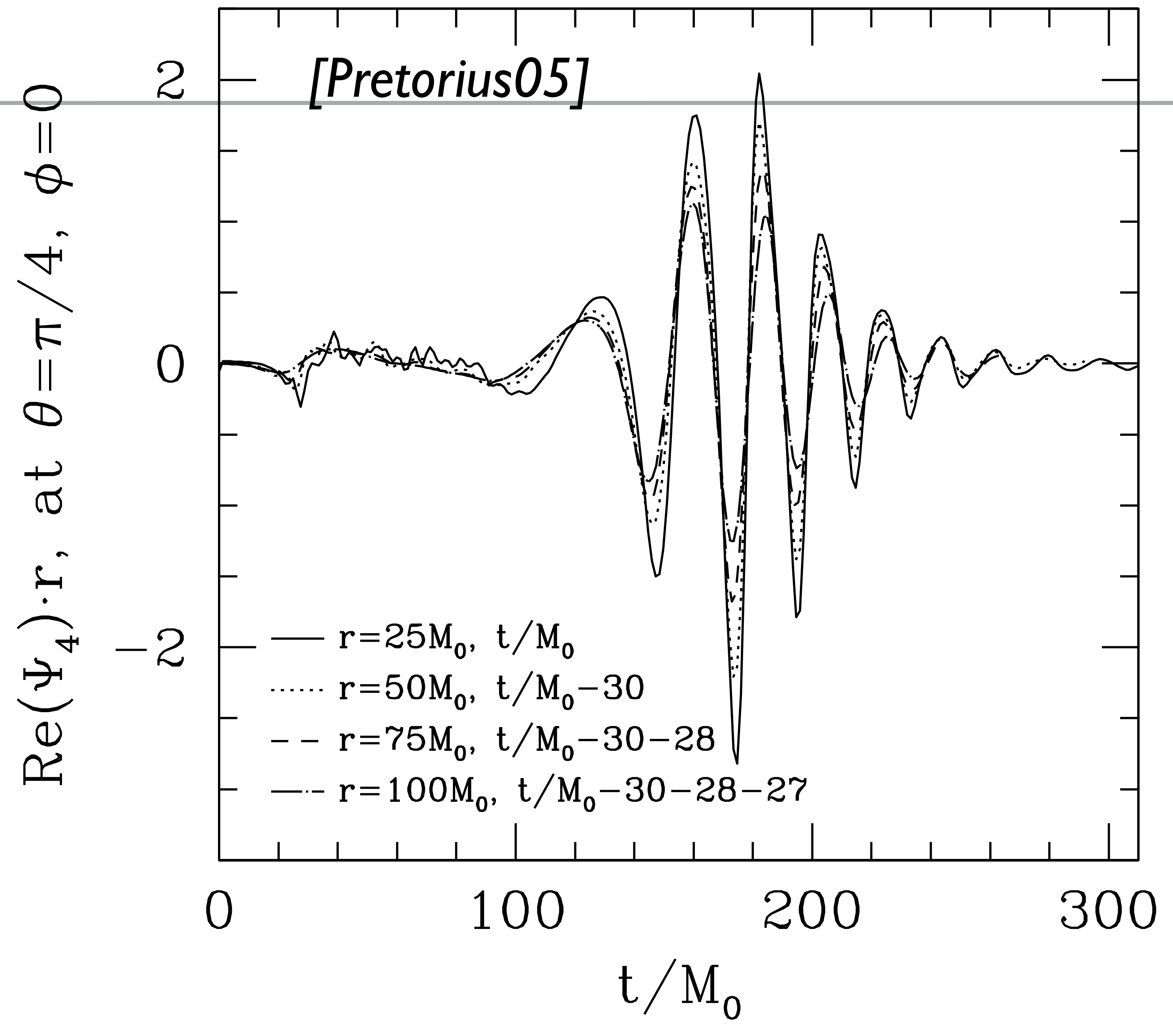
SIGNAL MODEL

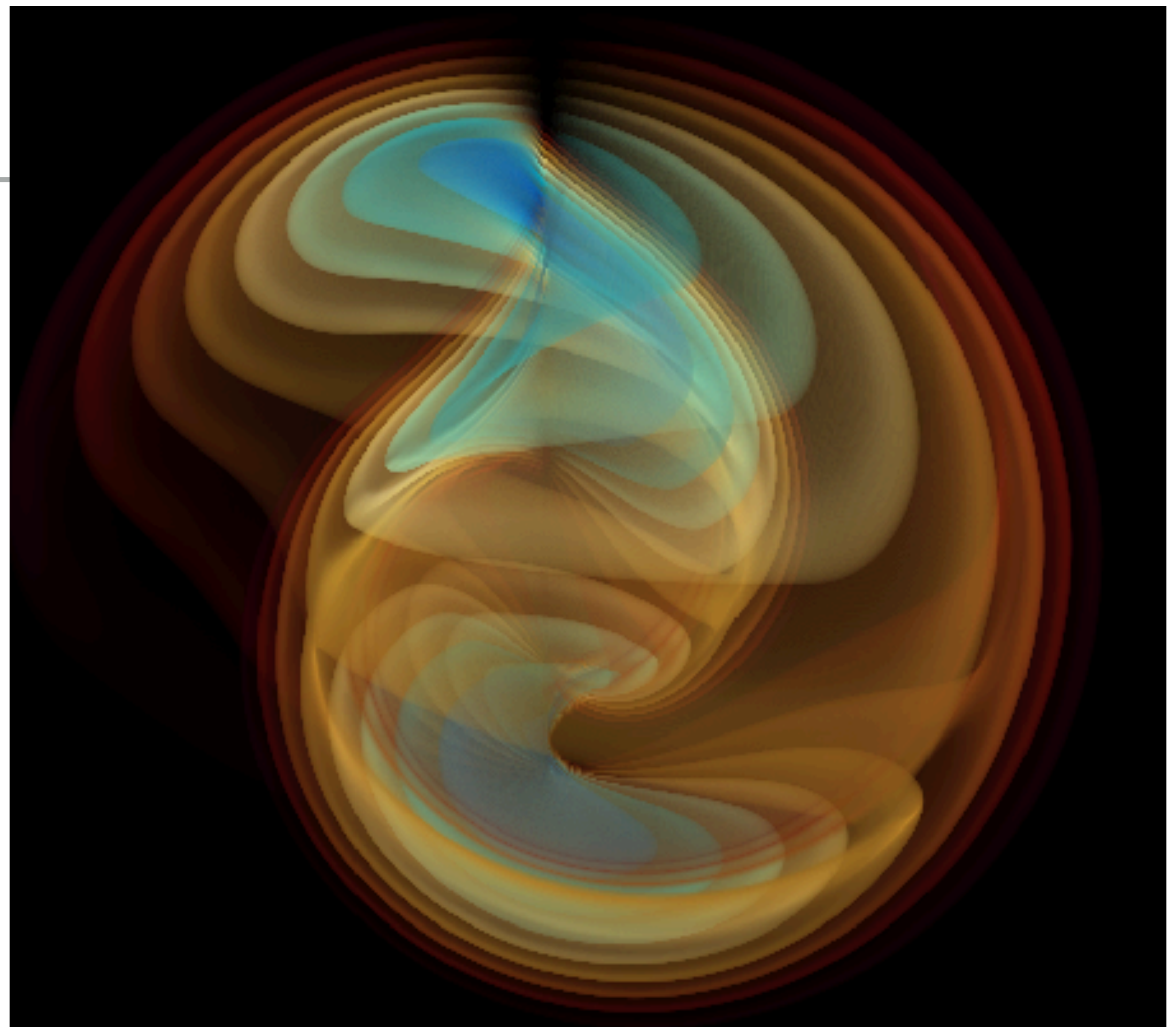


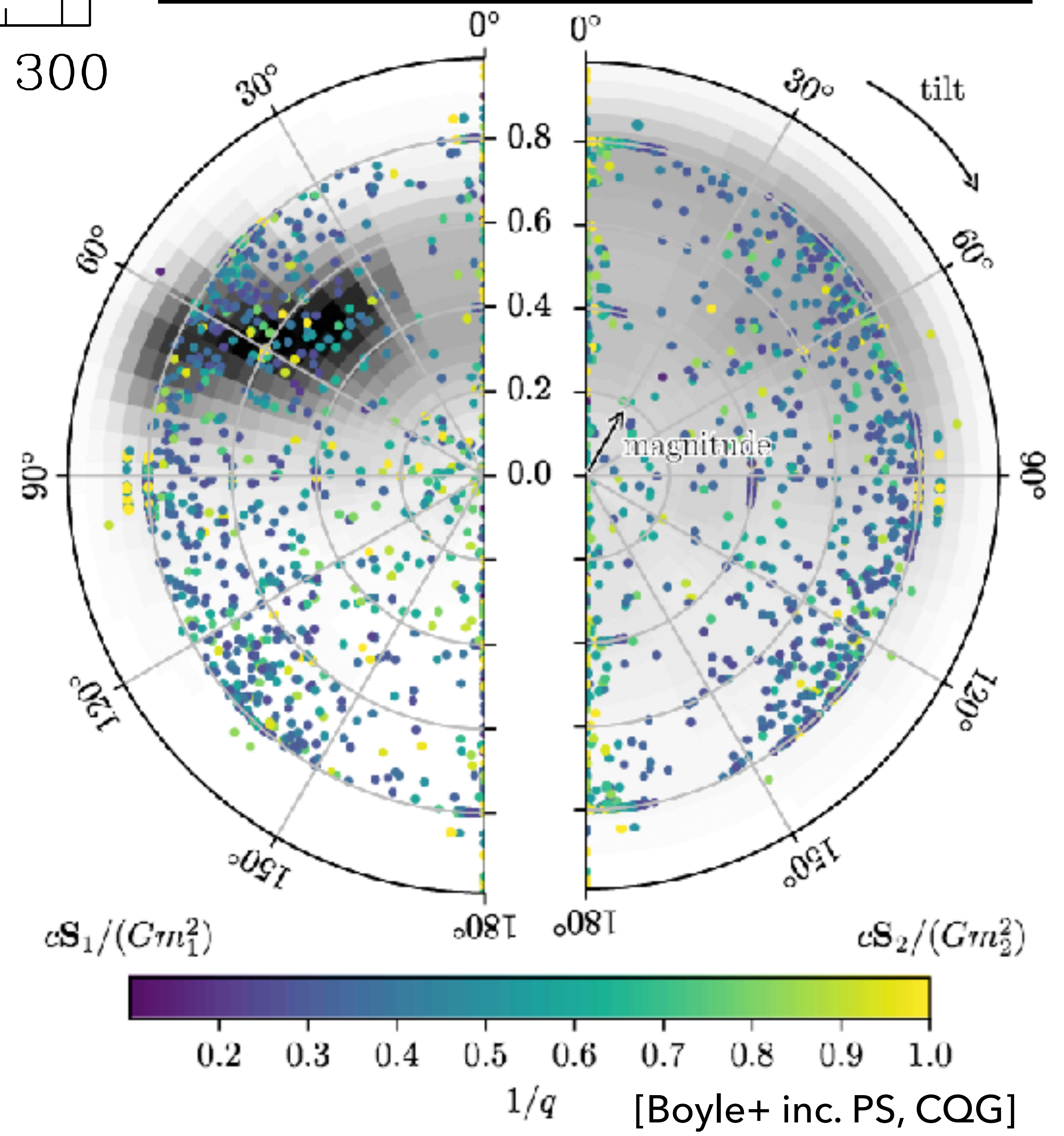
Courtesy: H. Pfeiffer

NUMERICAL RELATIVITY (NR)

- Only few analytic solutions to Einstein field equations known
  - **No analytic solutions to the general-relativistic two-body problem**
  - NR is a key ingredient to understanding GW observations!
- Breakthrough in 2005 *[Pretorius, Baker+, Campanelli+]*:
  - First stable binary evolutions
  - Extraction of the GW signal
  - Computationally expensive
  - Time consuming
- Many challenges remain!




Credit: G. Pratten/Einstein Toolkit



[Boyle+ inc. PS, CQG]

Reformulate the Einstein field equations (EFE) as initial value problem (IVP)

Prove existence of a well-posed initial value problem

Numerically suitable reformulation of the EFE

“good” coordinates (gauge choices)

Initial data

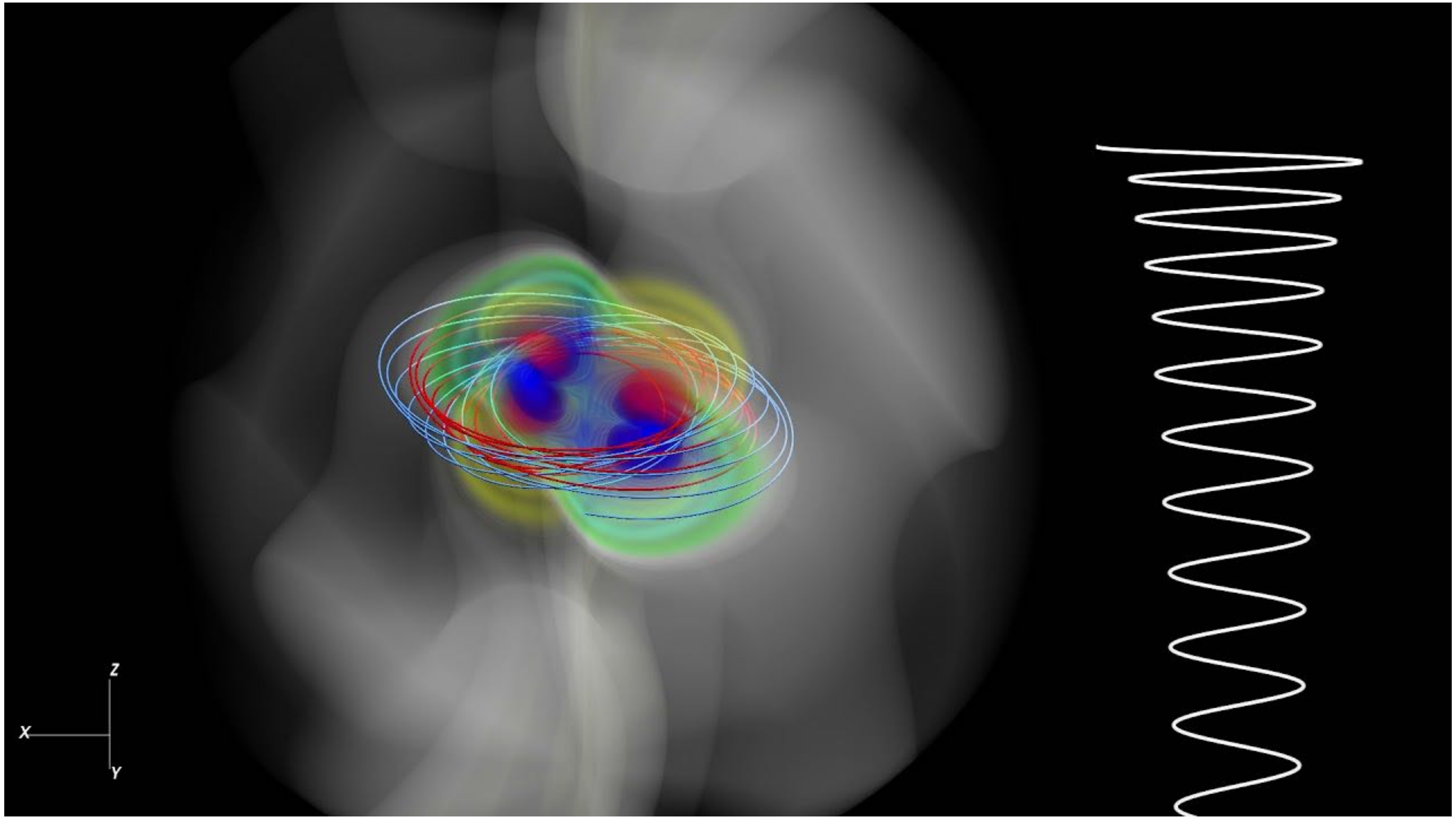
Deal with singularities

“Find” the black hole horizons

Extract gravitational waves

NUMERICAL RELATIVITY (NR)

- Open-source NR codes: Einstein Toolkit, NRpy+
- Recommended literature: Baumgarte & Shapiro, Numerical Relativity (Cambridge University Press)



[Credit: UIB]

INSPIRAL-MERGER-RINGDOWN WAVEFORM MODELS CHEATSHEET

	Phenom	EOB	NR Surrogates
Domain	FD & TD	TD (&FD)	TD
Physics	Precession Higher modes Some tides	Precession Higher modes Some tides Eccentricity (AS)	Precession Higher modes Eccentricity (NS)
Efficiency	Fast	Medium to slow	Slow
Accuracy	Good	Good	Best
Caveats	Systematics due to approximations & missing physics	Systematics due to approximations & missing physics	Only for massive BBH (can be hybridised) Limited parameter space

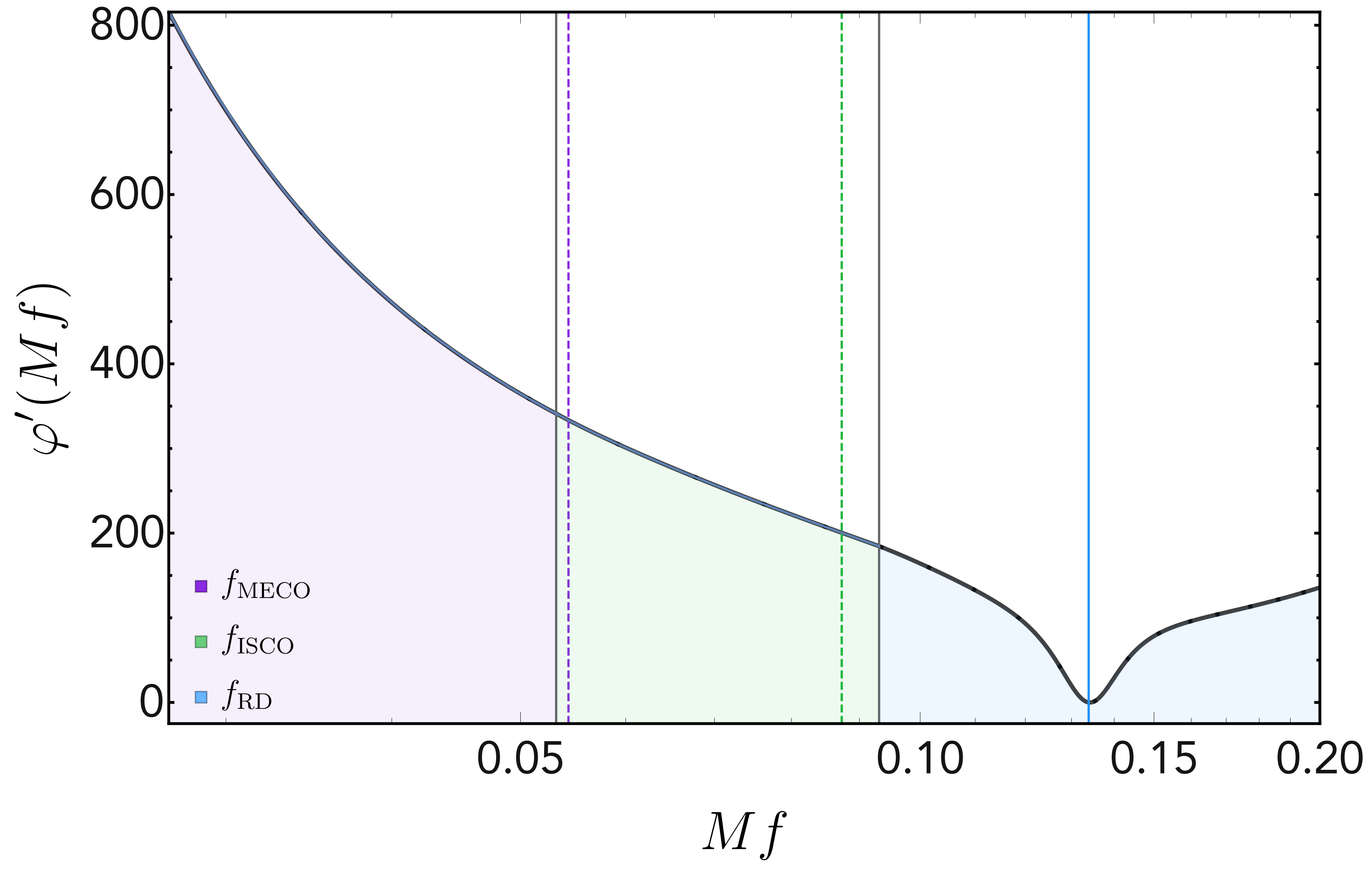
PHENOMENOLOGICAL WAVEFORM MODELS

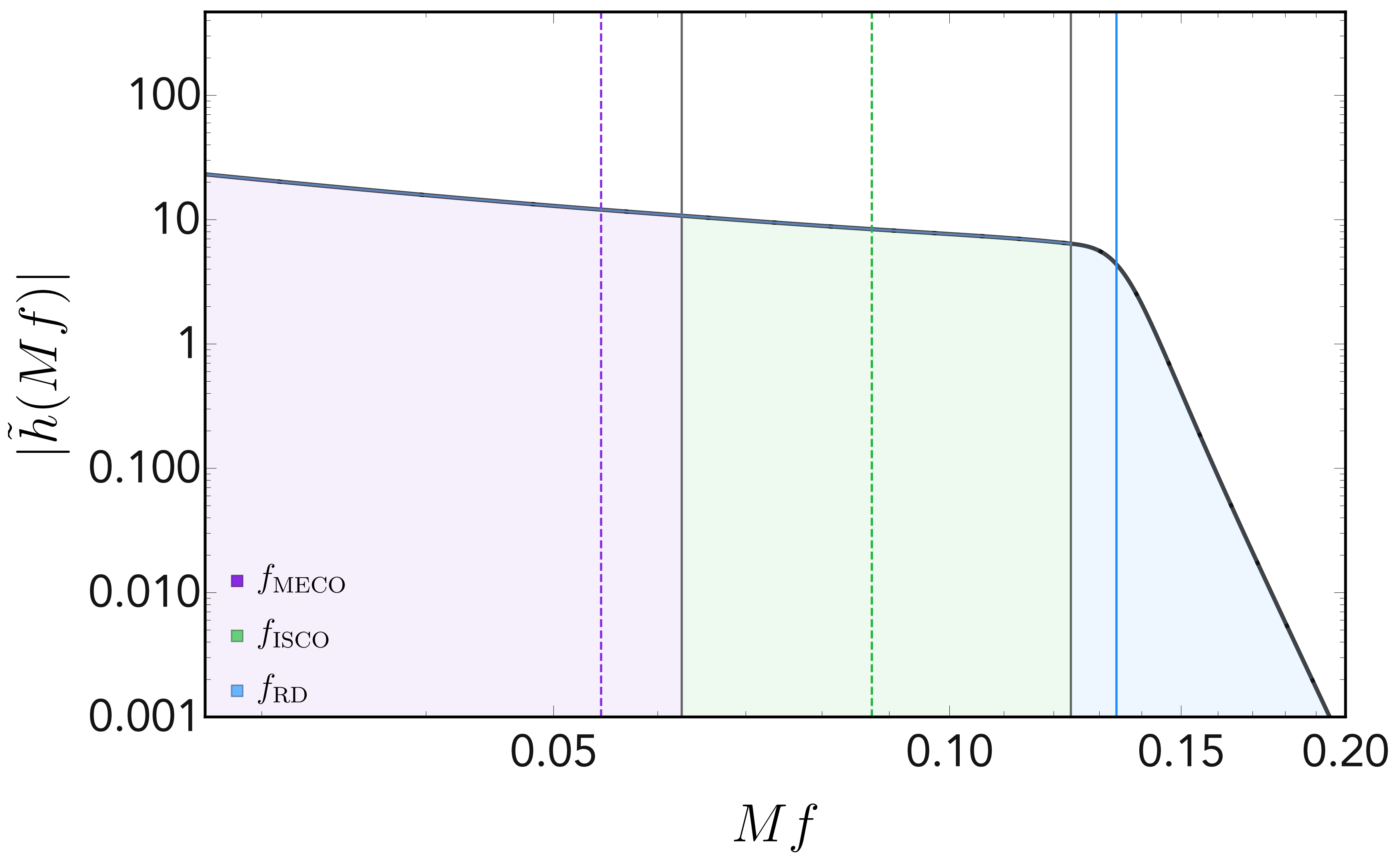
- Closed-form expressions utilising analytical & numerical inputs
- Analytical information from PN/EOB + pseudo terms
- NR calibration in the strong-field regime
- 3 regimes: inspiral, intermediate, merger-ringdown

amplitude — phase

$$\tilde{h}_{\ell m}(f) = \tilde{A}_{\ell m}(f) e^{-i\tilde{\phi}_{\ell m}(f)}$$

mode-by-mode

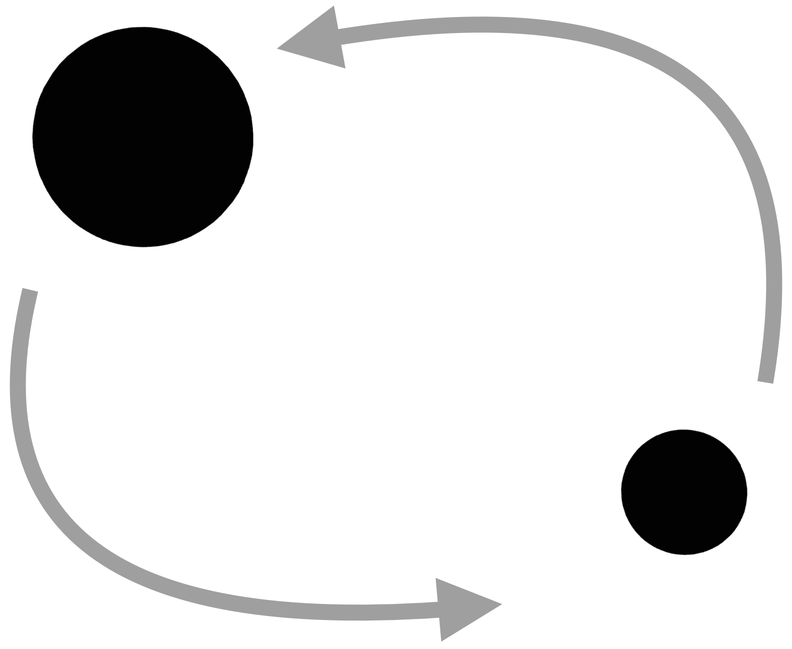




[Ajith+, Santamaria+, Husa+, Khan+, Hannam+, PS+, Pratten+, Garcia-Quiros+, Hamilton+, Estelles+]

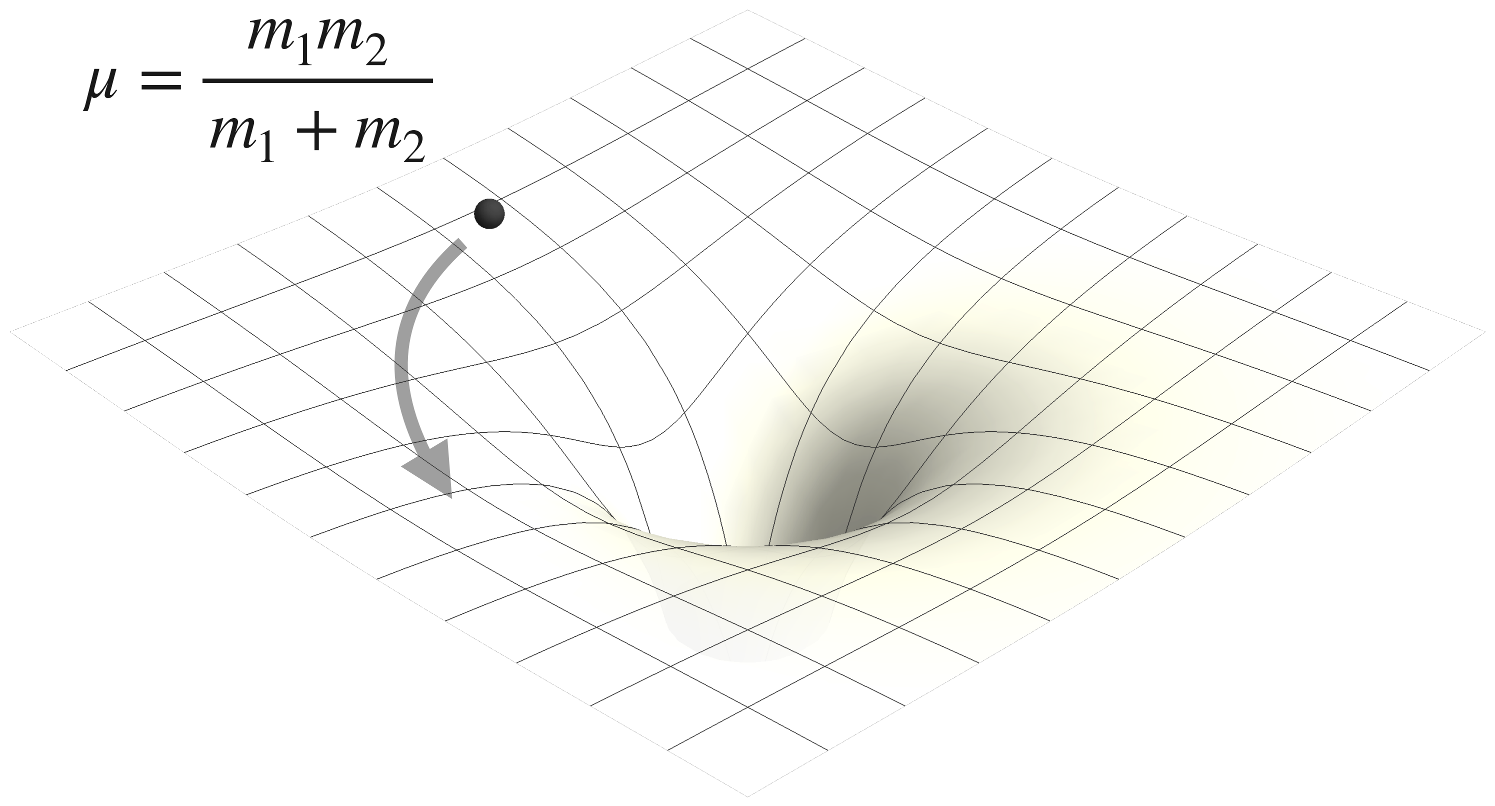
EFFECTIVE-ONE-BODY

- Two-body dynamics replaced by particle with reduced mass moving in effective metric:



EOB Mapping

$$H_{\text{real}}^{\text{EOB}} = M\sqrt{1 + 2\nu\left(\frac{H_{\text{eff}}^{\nu}}{\mu} - 1\right)}$$



- Equations of motions:

$$\dot{\mathbf{r}} = (A/B)^{1/2}\,\partial_{\mathbf{p}_{\mathbf{r}_*}}\hat{H}_{\text{EOB}} \qquad \dot{p}_{r_*} = -(A/B)^{1/2}\,\partial_r \hat{H}_{\text{EOB}}$$

$$\dot{\varphi} = \partial_{p_\varphi}\hat{H}_{\text{EOB}} \qquad \dot{p_\varphi} = \hat{\mathcal{F}}_\varphi$$

NR calibration

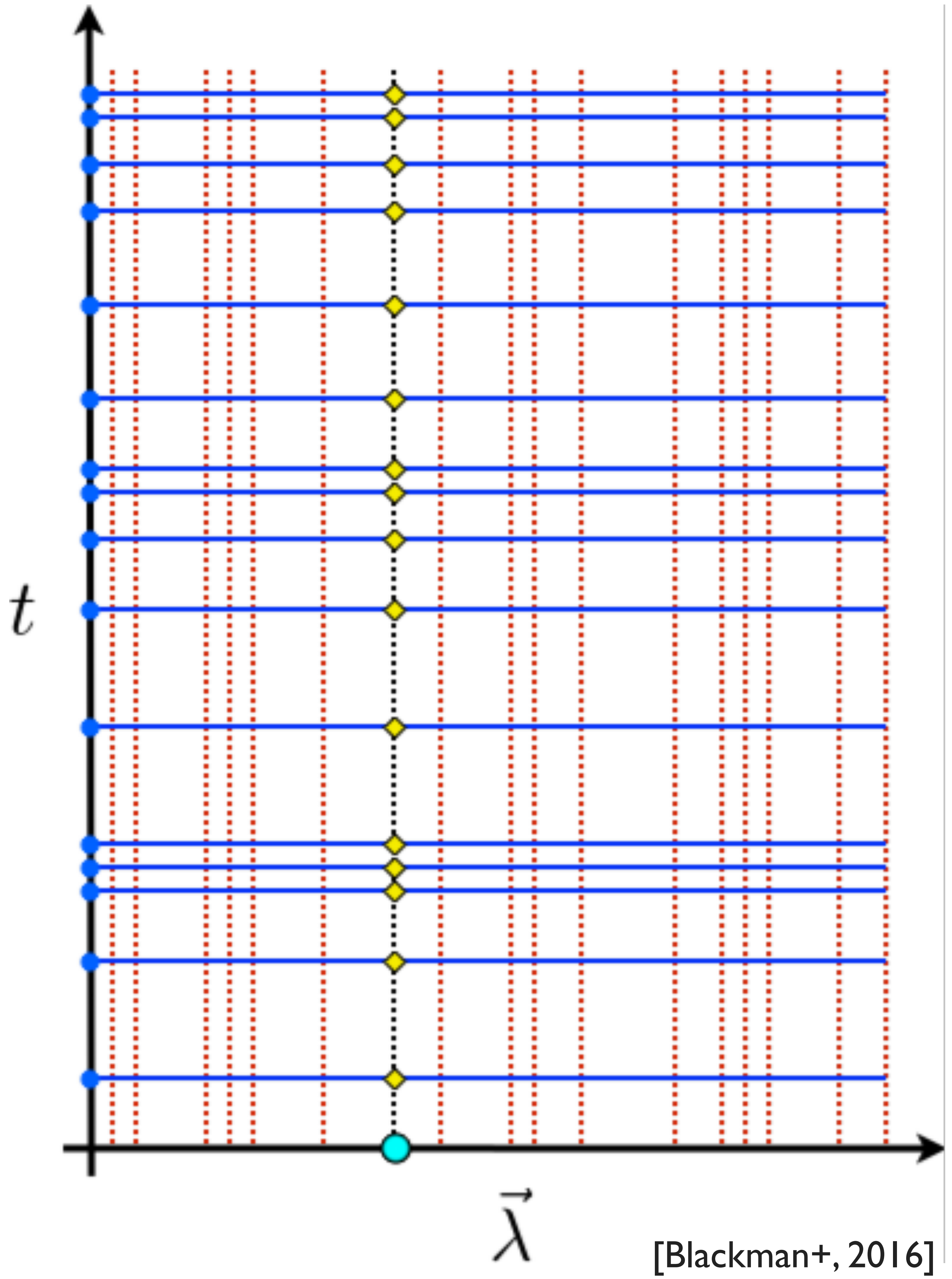
- Factorised waveform:

$$h_{\ell m}^{\text{EOB}} = \theta\left(t_m - t\right) h_{\ell m}^{\text{insplunge}}(t) + \theta\left(t - t_m\right) h_{\ell m}^{\text{ringdown}}(t)$$

[Credit: G. Pratten]

NUMERICAL RELATIVITY SURROGATES

- NR simulations are computationally expensive
  - Limited coverage of the full binary parameter space
- Are pure NR-based waveform models achievable, i.e. no analytic approximations?
  - NR surrogate models *[Canizares+ ,Field+, Blackman+, Varma+]*
  - Continuous interpolation between discrete waveforms *[Field+, Galley+]*
  - 5D precessing NR surrogate around GW150914:
    - ~270 NR simulations spanning ~20 orbits *[Blackman inc. PS+]*
  - 7D precessing NR surrogate between mass ratios 1-4 and spins ≤ 0.8
    - ~1528 NR simulations *[Boyle+ inc. PS]*

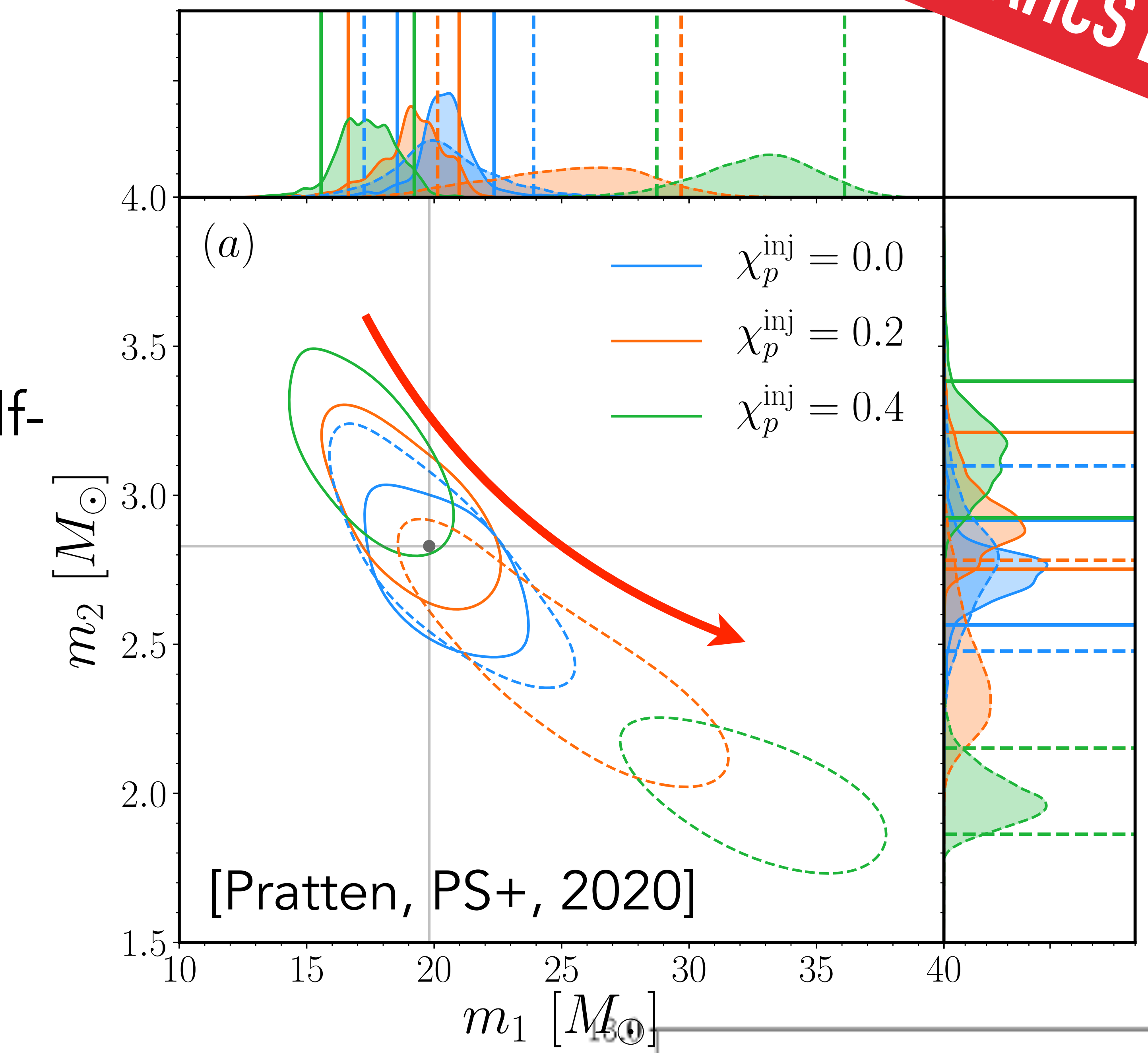


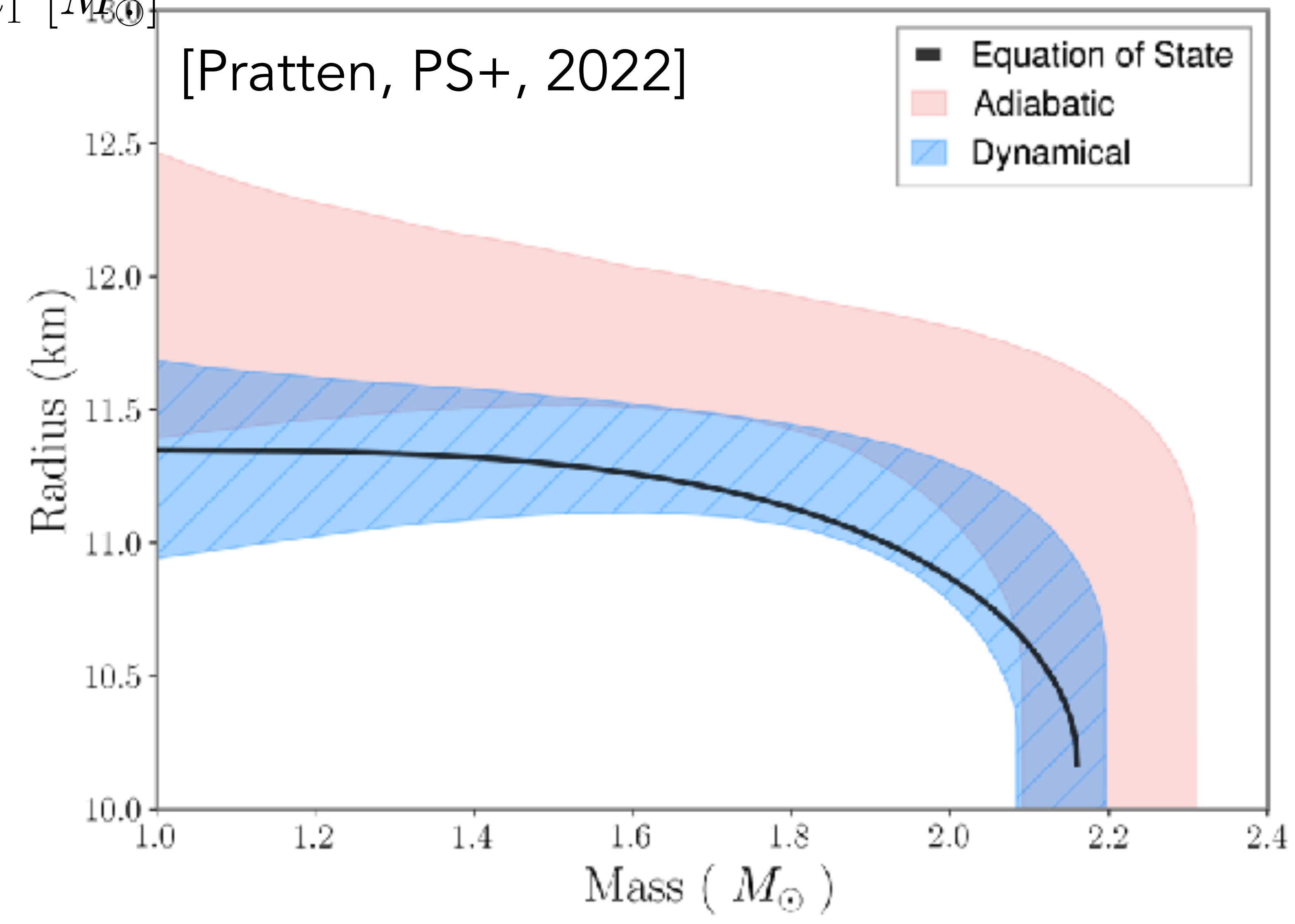
[Blackman+, 2016]

WHAT PHYSICS IS INCLUDED?

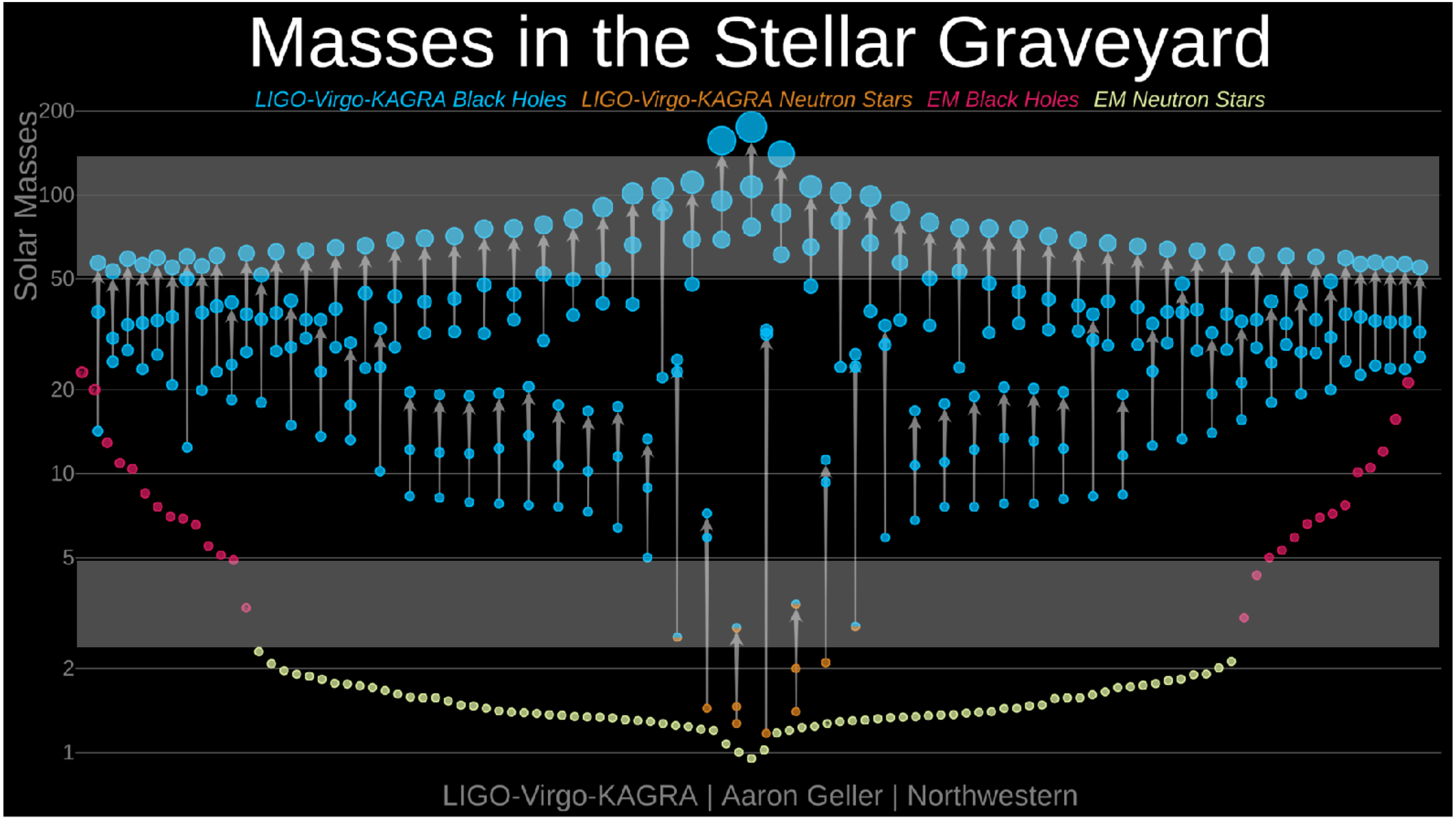
BEWARE OF SYSTEMATICS DUE TO MISSING PHYSICS!

- BBH models: Highly accurate for circular binaries with aligned spins
  - Including higher order multipoles
  - Verified up to moderate mass ratios + additional gravitational self-force information
  - Lack of simulations with large spins & long inspirals
  - Some eccentricity (lots of ongoing work & recent progress)
- Precessing BBH: modelled only approximately
  - Little to no calibration to NR
- BNS: low-order analytic f-mode tides + some calibration to NR simulations
  - No complete model including post-merger
- NSBH: no precession; no complete model including post-merger





MULTIMESSENGER ASTROPHYSICS WITH GRAVITATIONAL WAVES



Upper mass gap

Lower mass gap

SOME HIGHLIGHTS (A PERSONAL SELECTION)

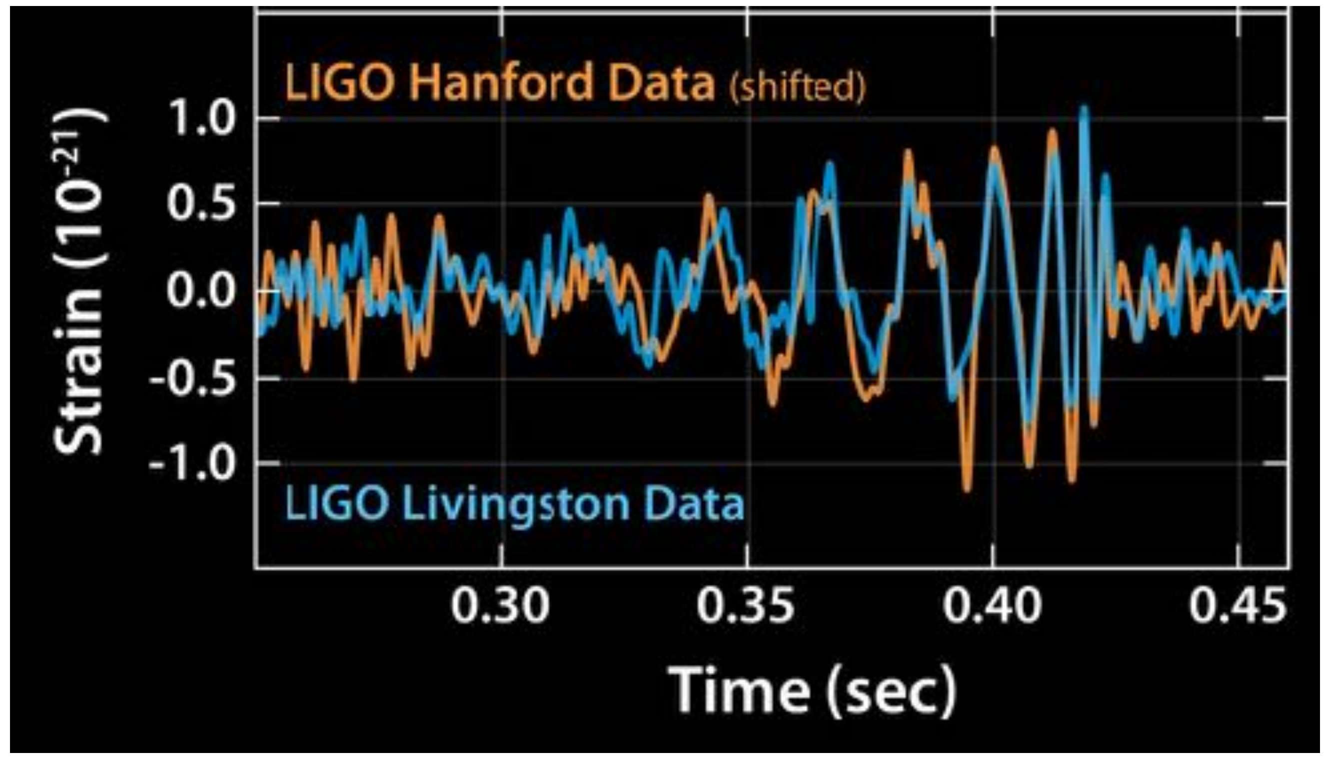
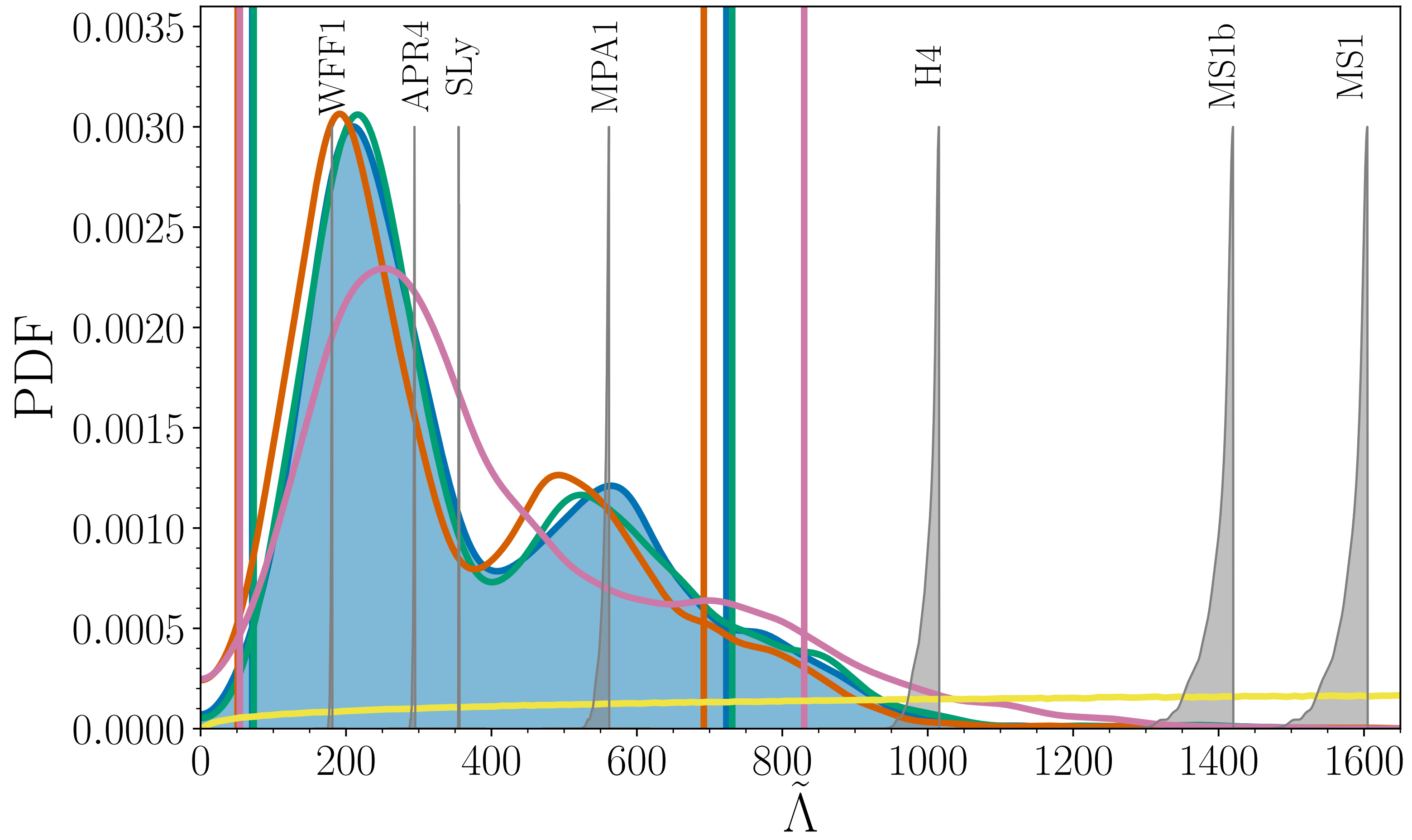
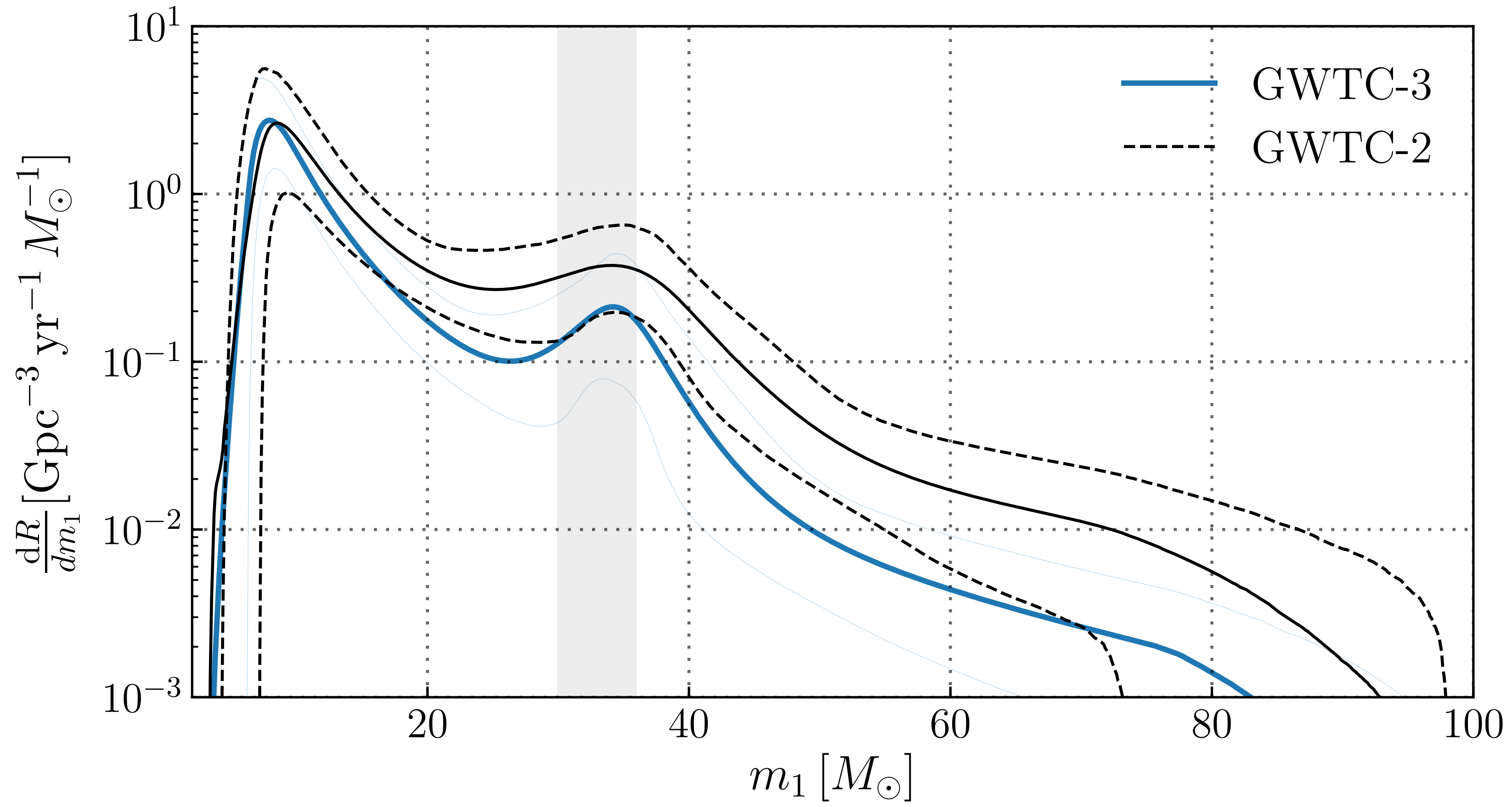


Image Credit: Caltech/MIT/LIGO Lab.

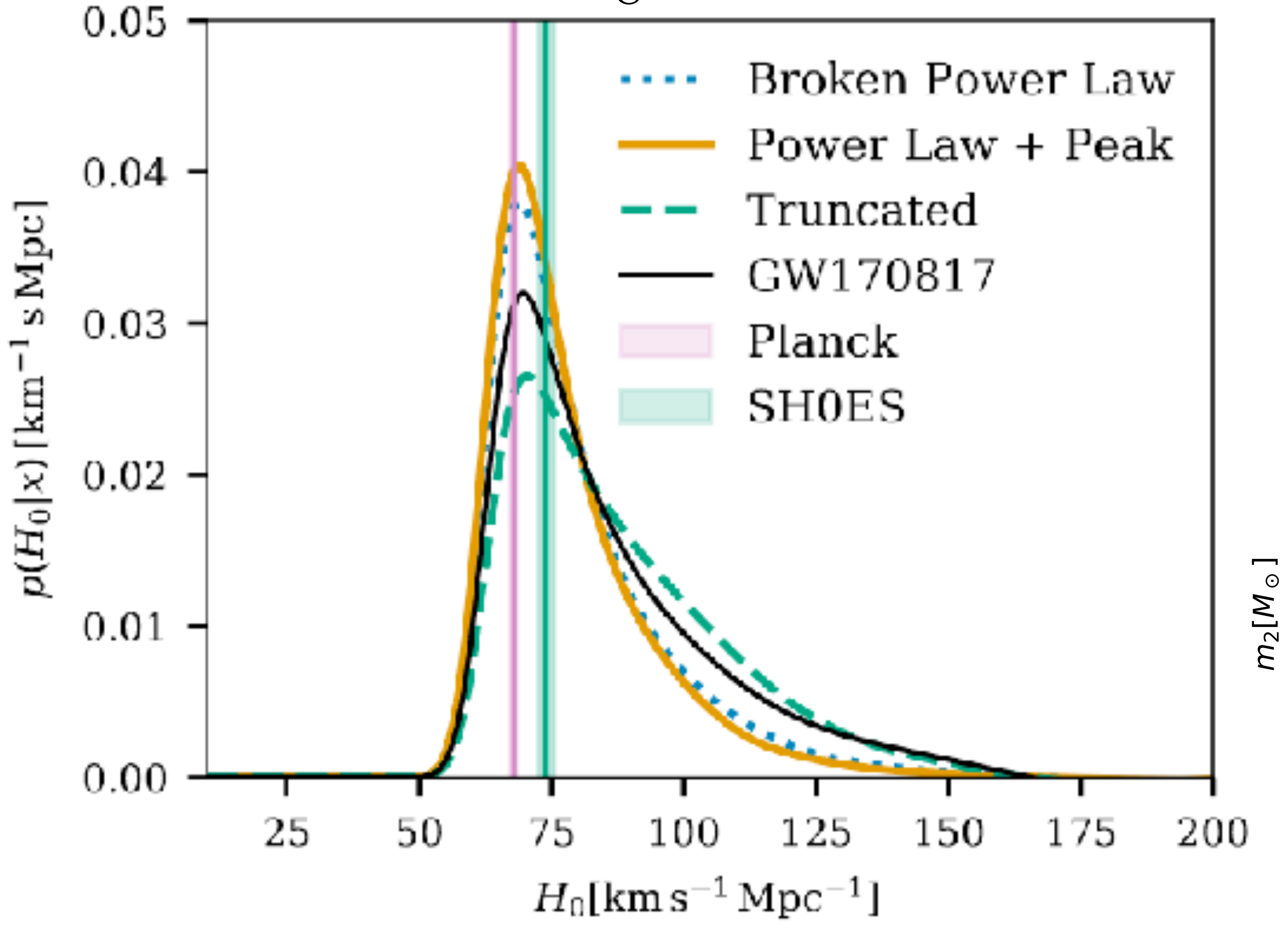


[LVC, PRX 9, 031040 (2019)]

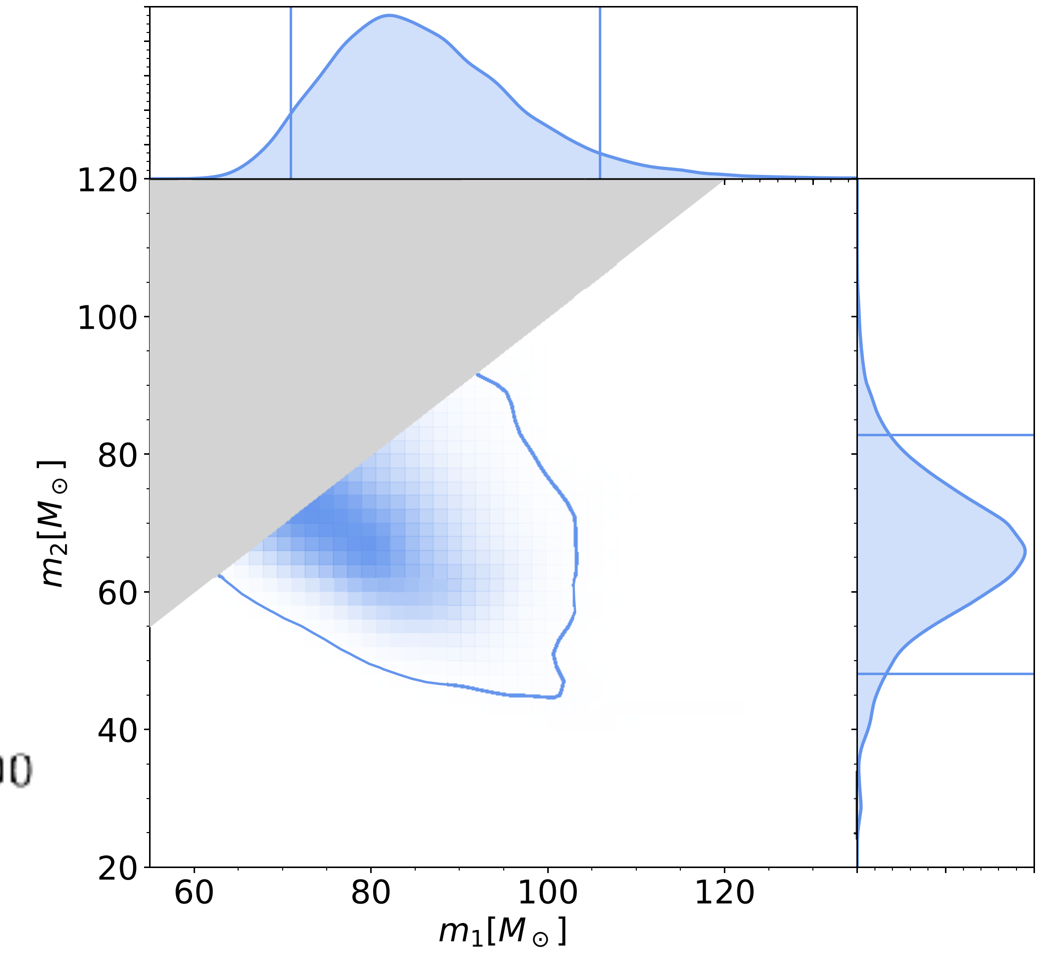


[LVK, arXiv 2111.03634 (2021)]

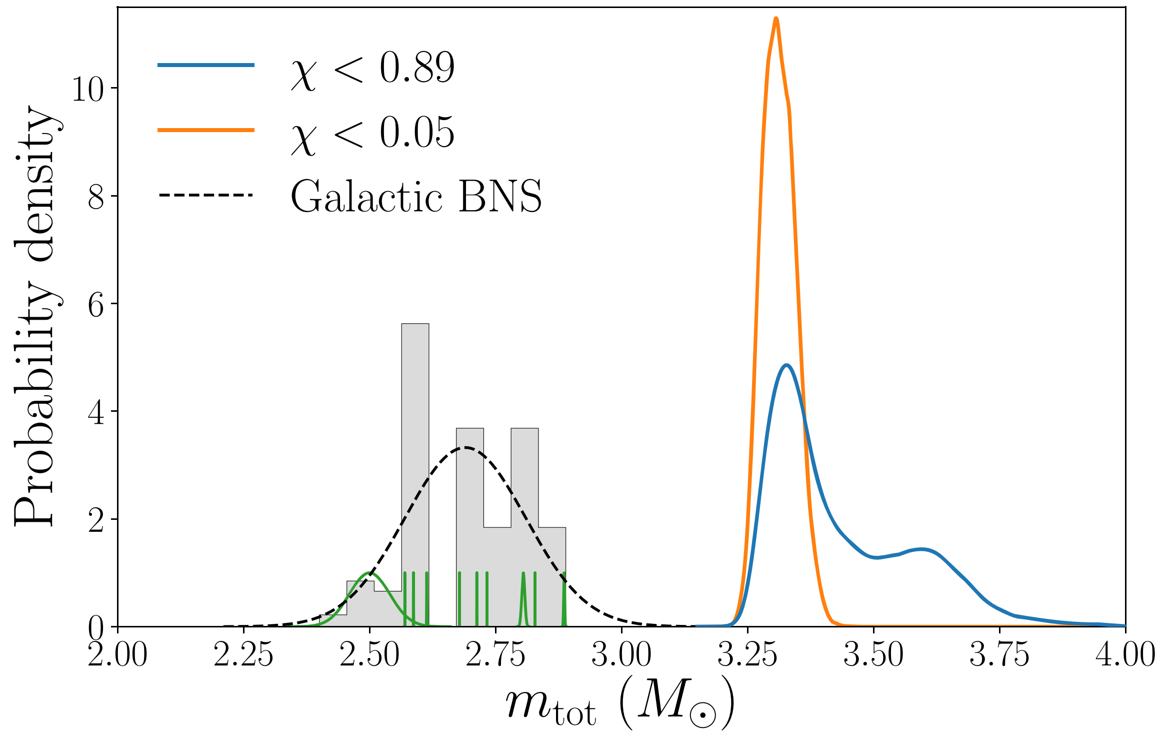
$$H_0 = 68^{+12}_{-8}\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$$



[LVK, arXiv:2111.03604]

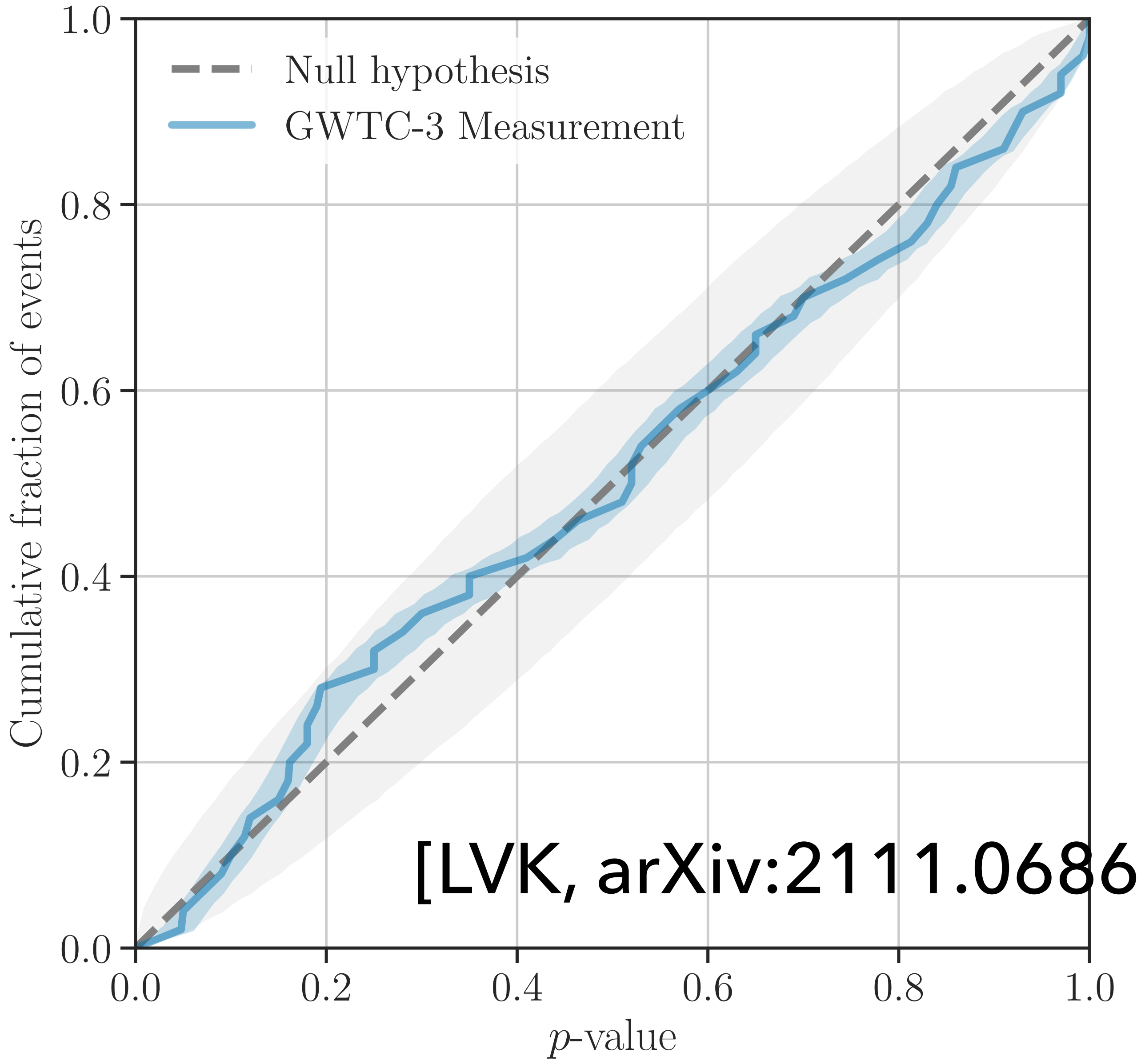


[LVK, PRL 125, 101102 (2020)]



[LVK, ApJ L 892:L3 (2020)]

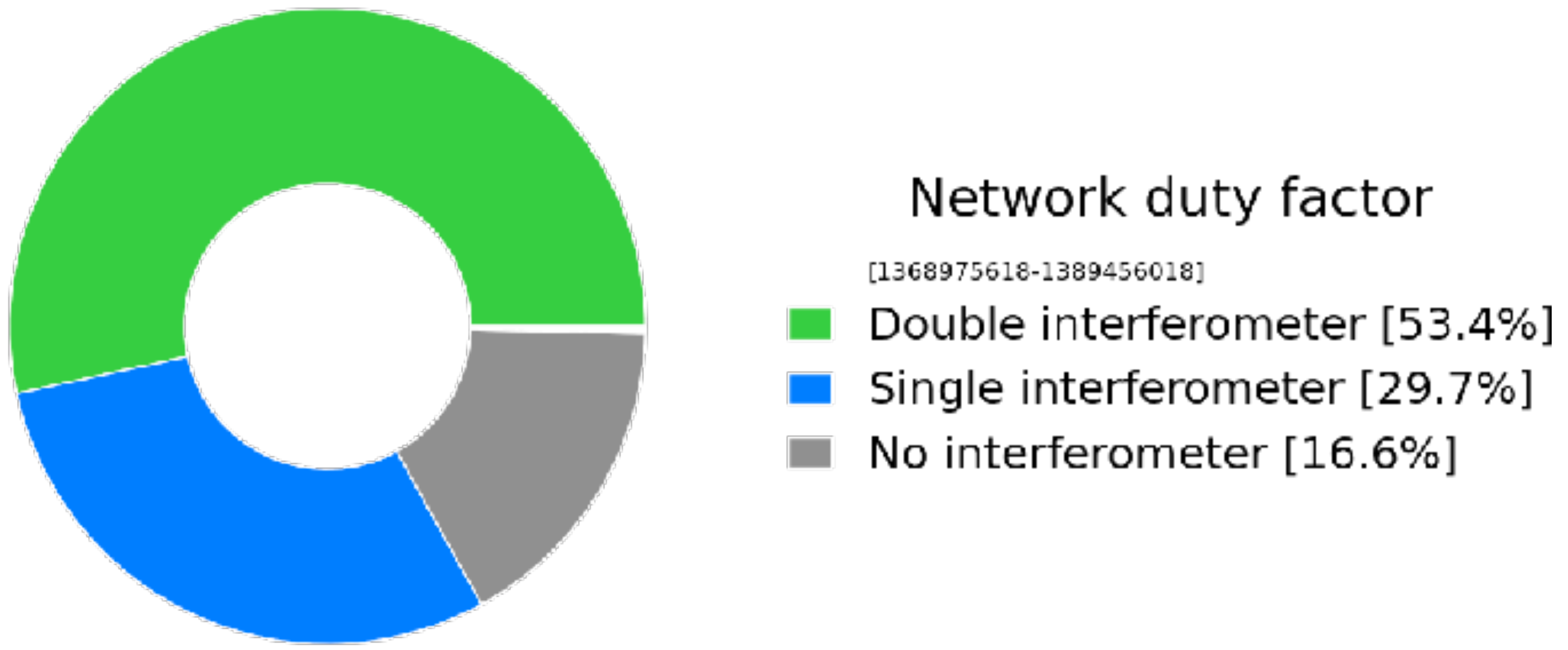
$$m_g \leq 1.27 \times 10^{-23}\,\mathrm{eV/c^2}$$

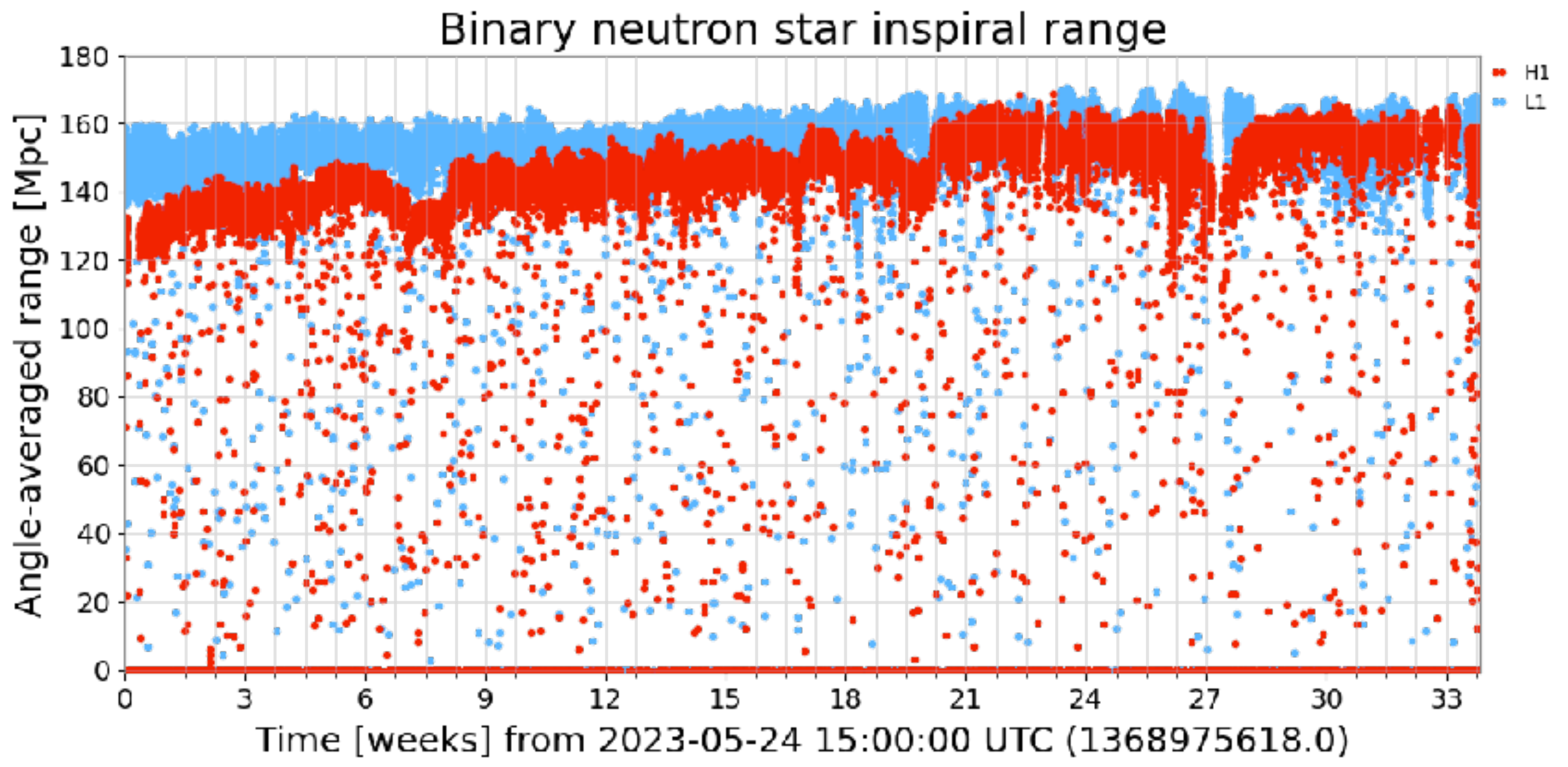


[LVK, arXiv:2111.06861]

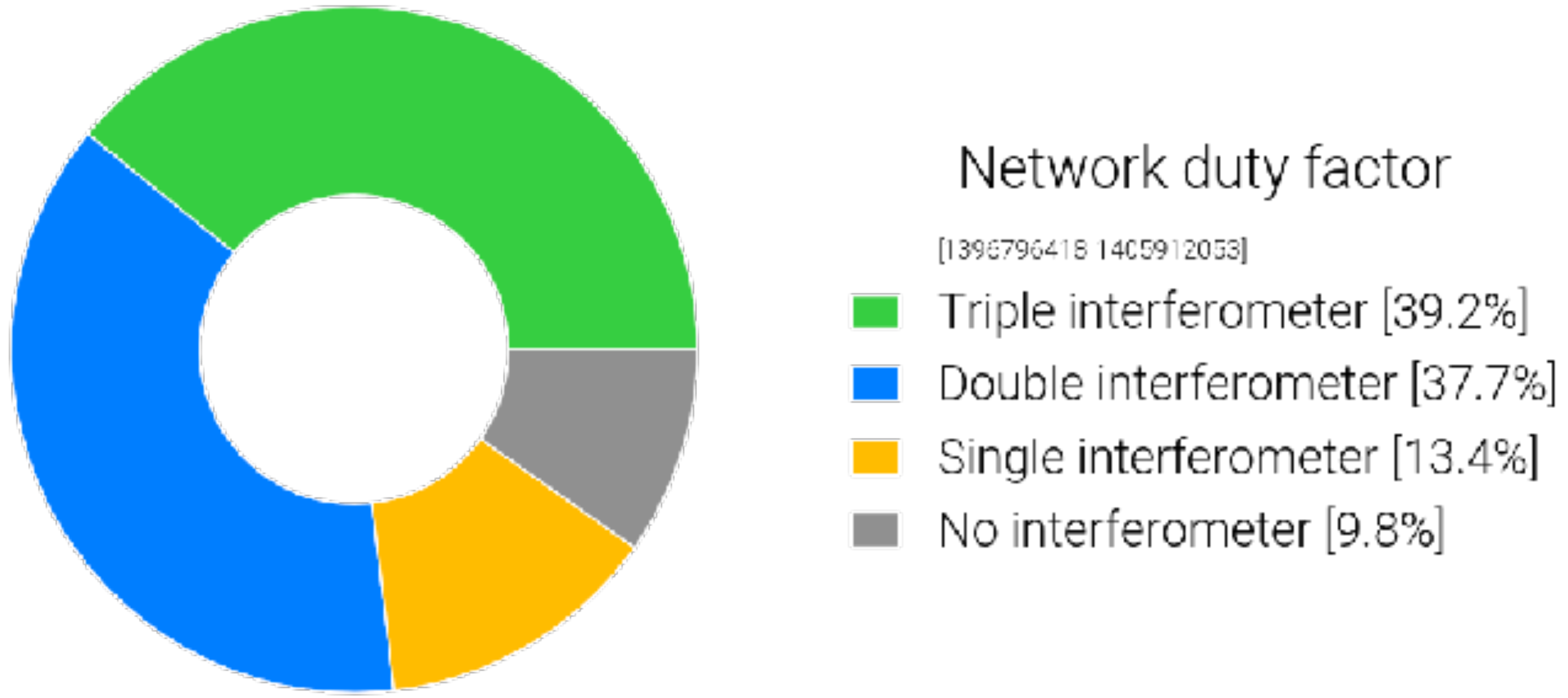
FOURTH OBSERVING RUN

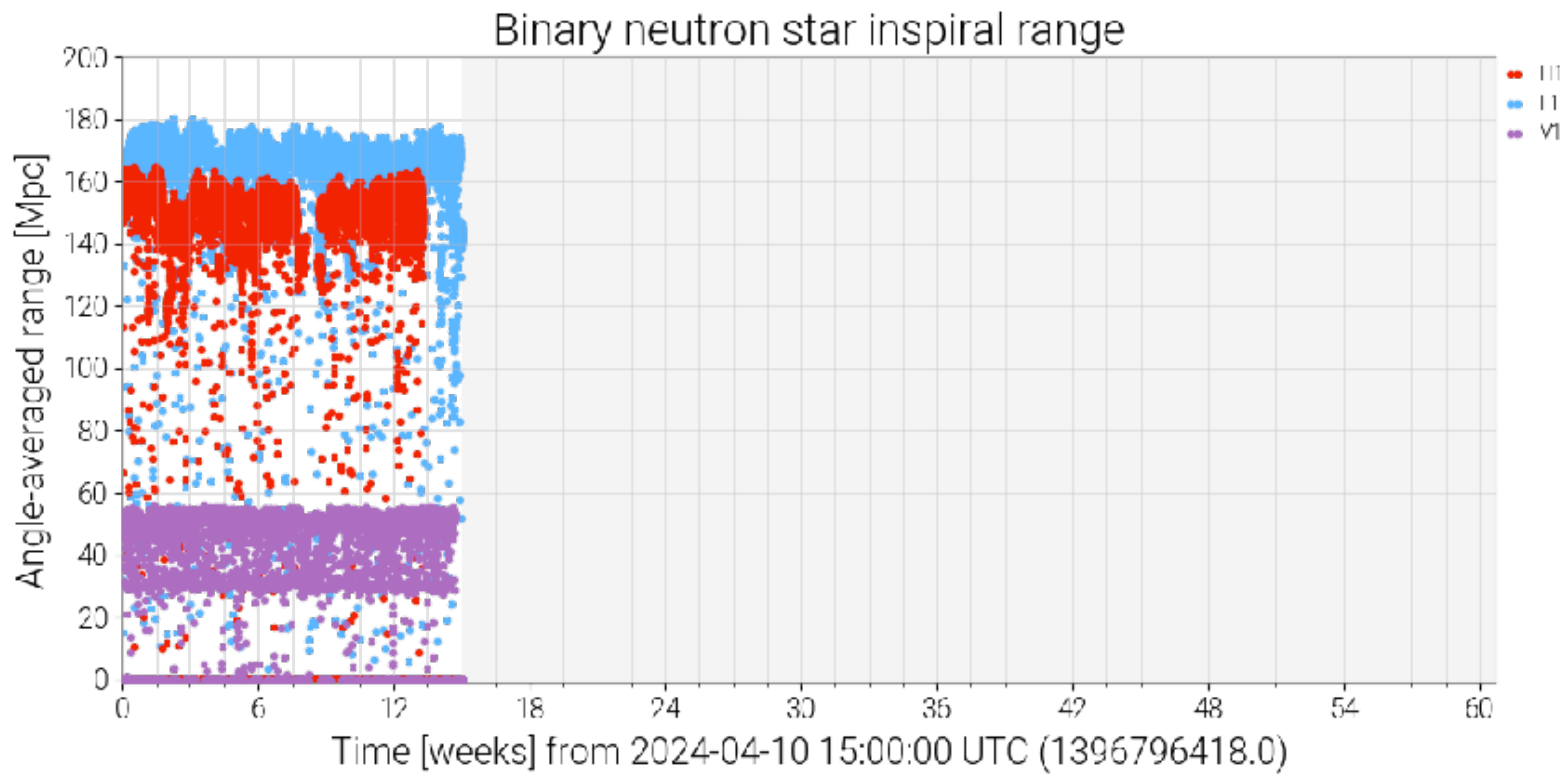
- O4a: May 24, 2023 - January 16, 2024
- Duty cycle: H1 (68%), L1(69%)





- O4b: April 10, 2024 - June 9, 2025
- Duty cycle: H1(54%), L1(74%), V1(79%)

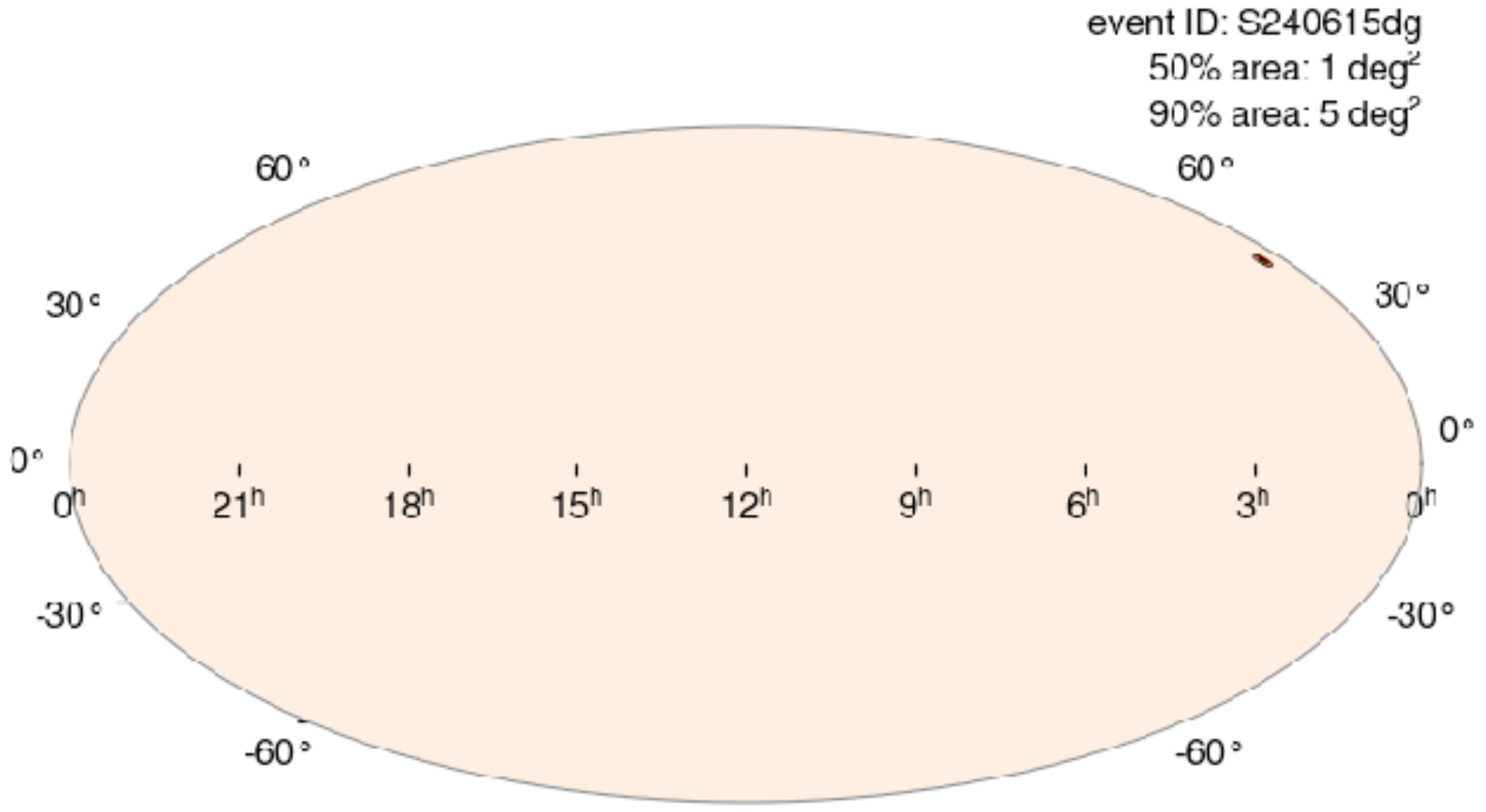


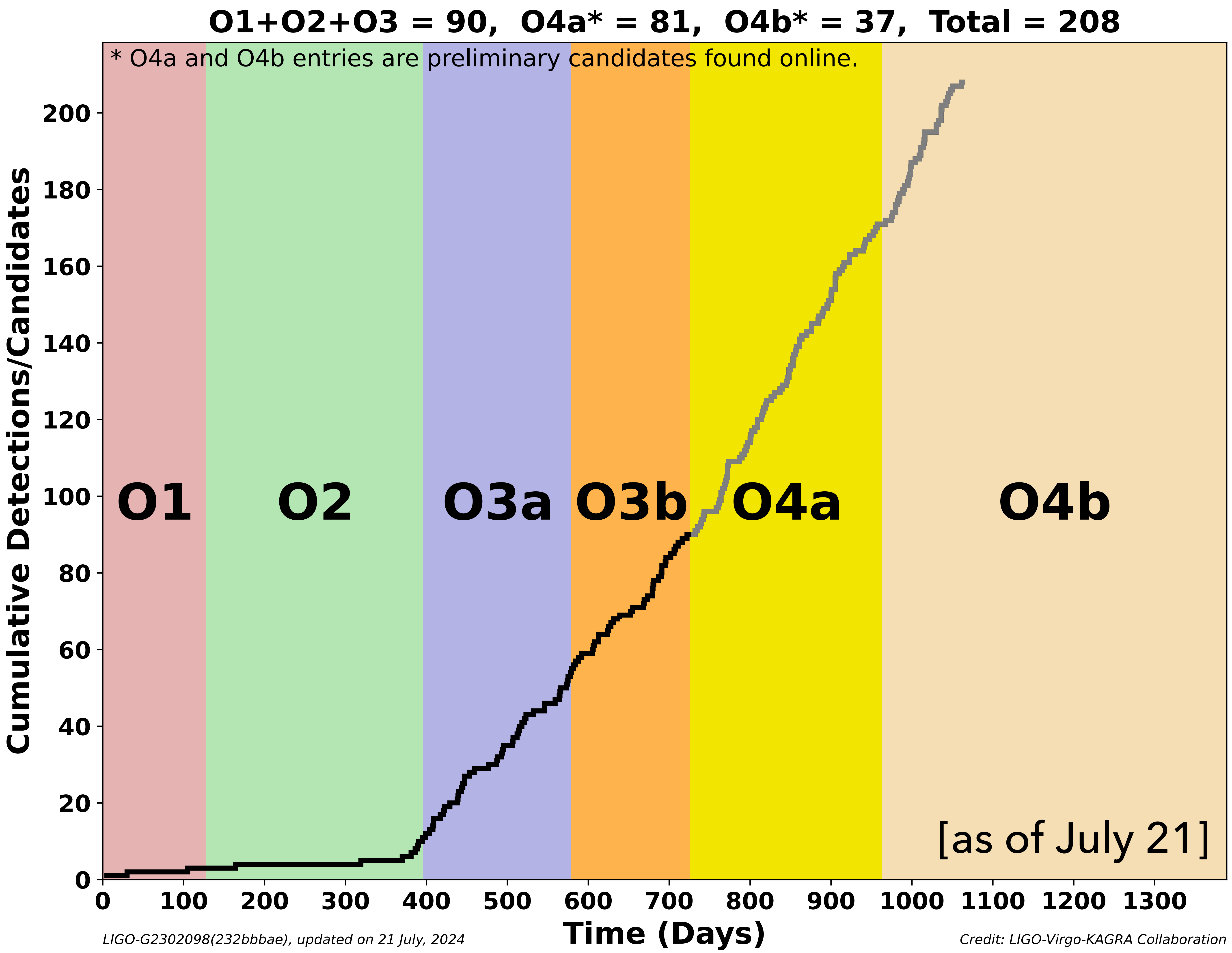


https://gwosc.org/detector_status

FOURTH OBSERVING RUN

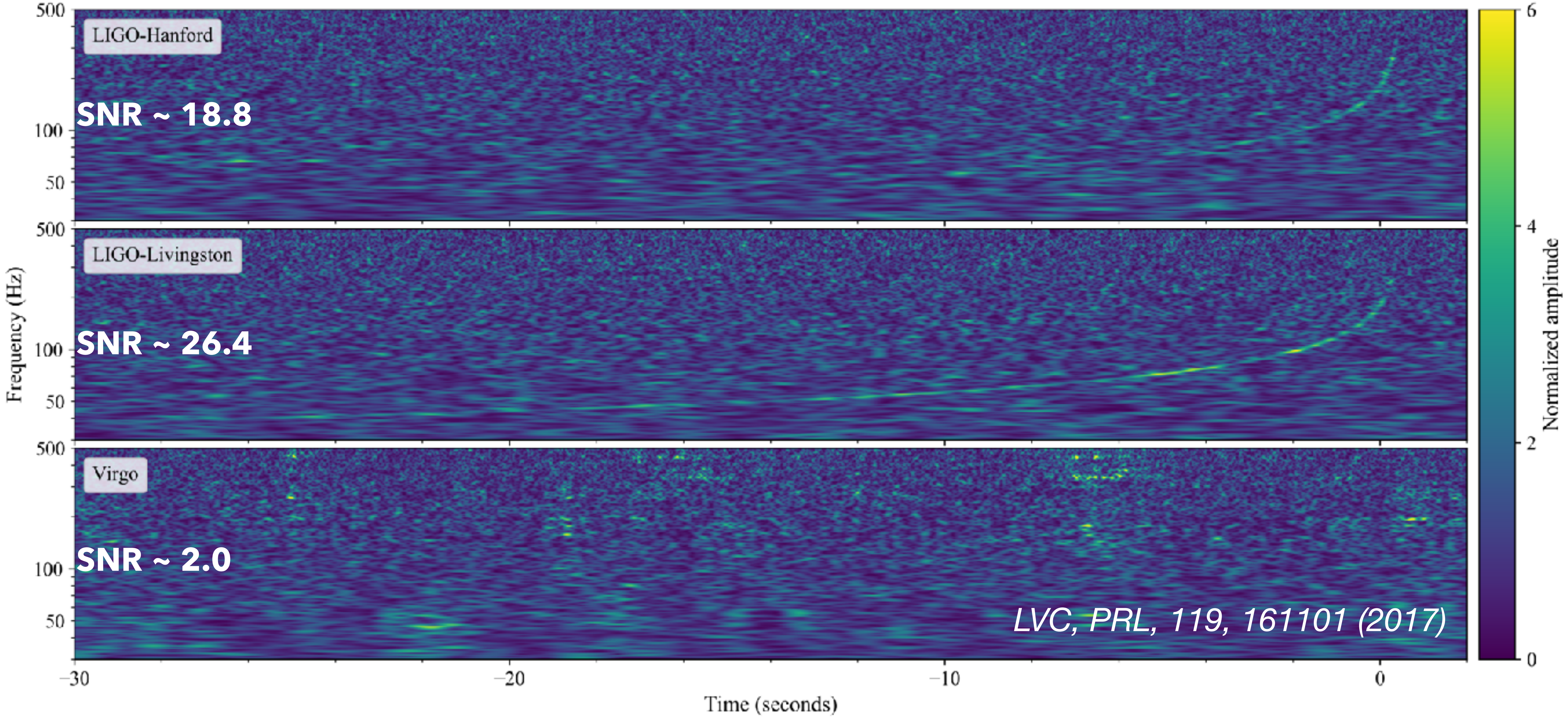
- As of July 25th @ 11.00 CEST:
  - **118 significant detection candidates**
  - 2175 low-significance detection candidates
- Binary detection rate:
  - **~3 events per week**
- Public alerts now also for
  - Low-significance triggers
  - Early warning
  - Automatically issued within ~30s





GW170817

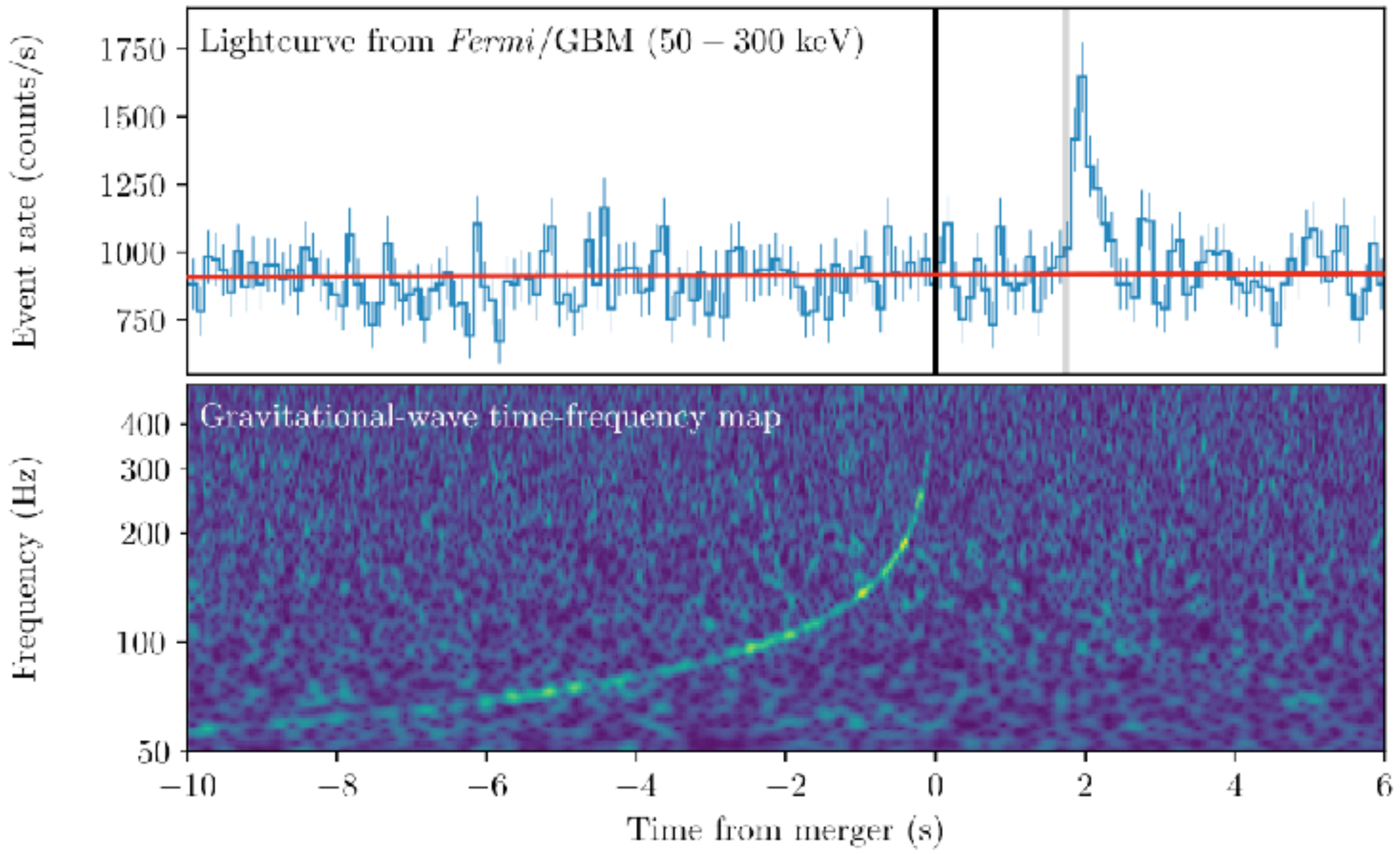
- On August 17th 2017 at 12:41:04 UTC (14:41), LIGO detected GWs from a **binary neutron star** inspiral: GW170817

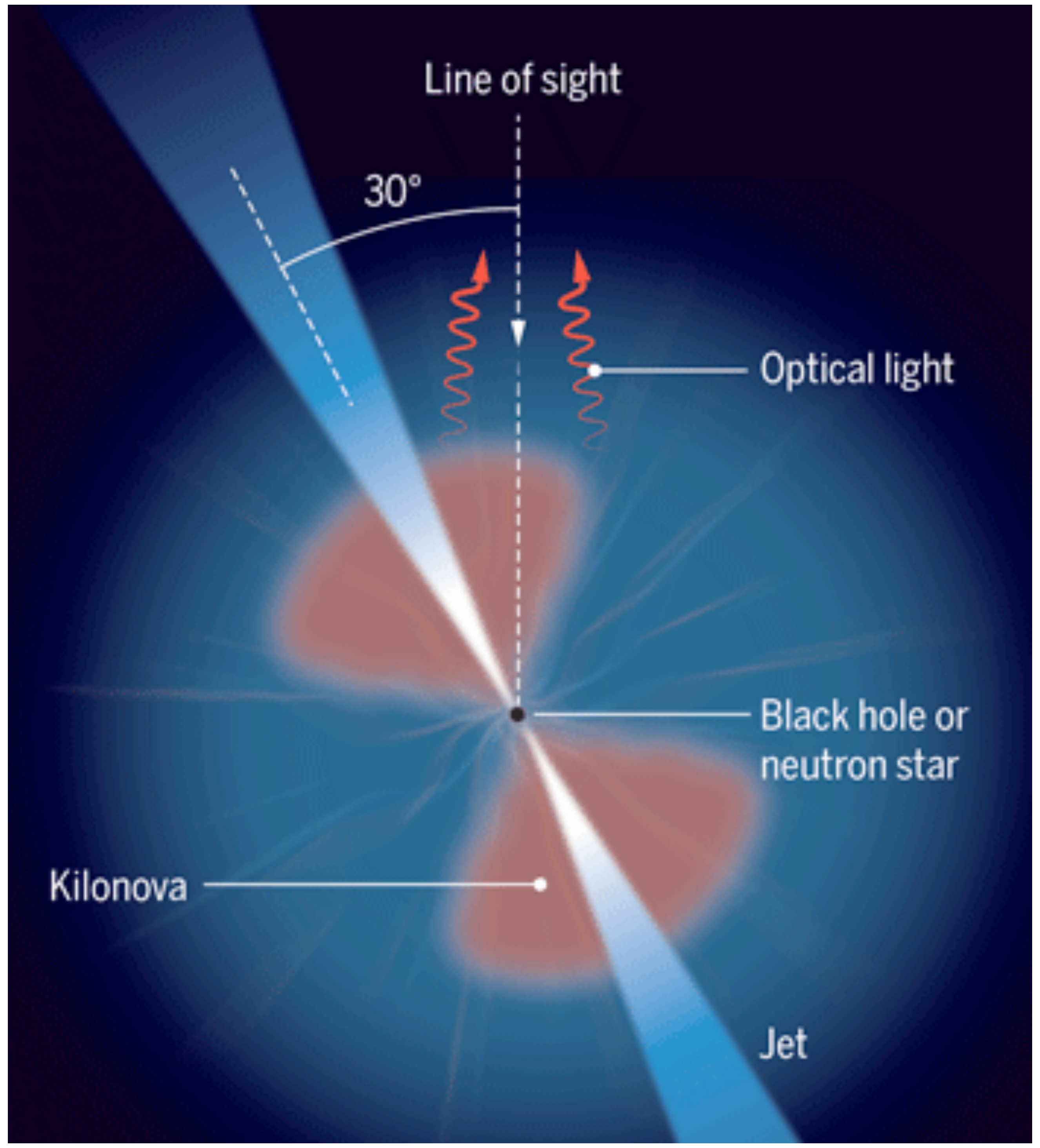


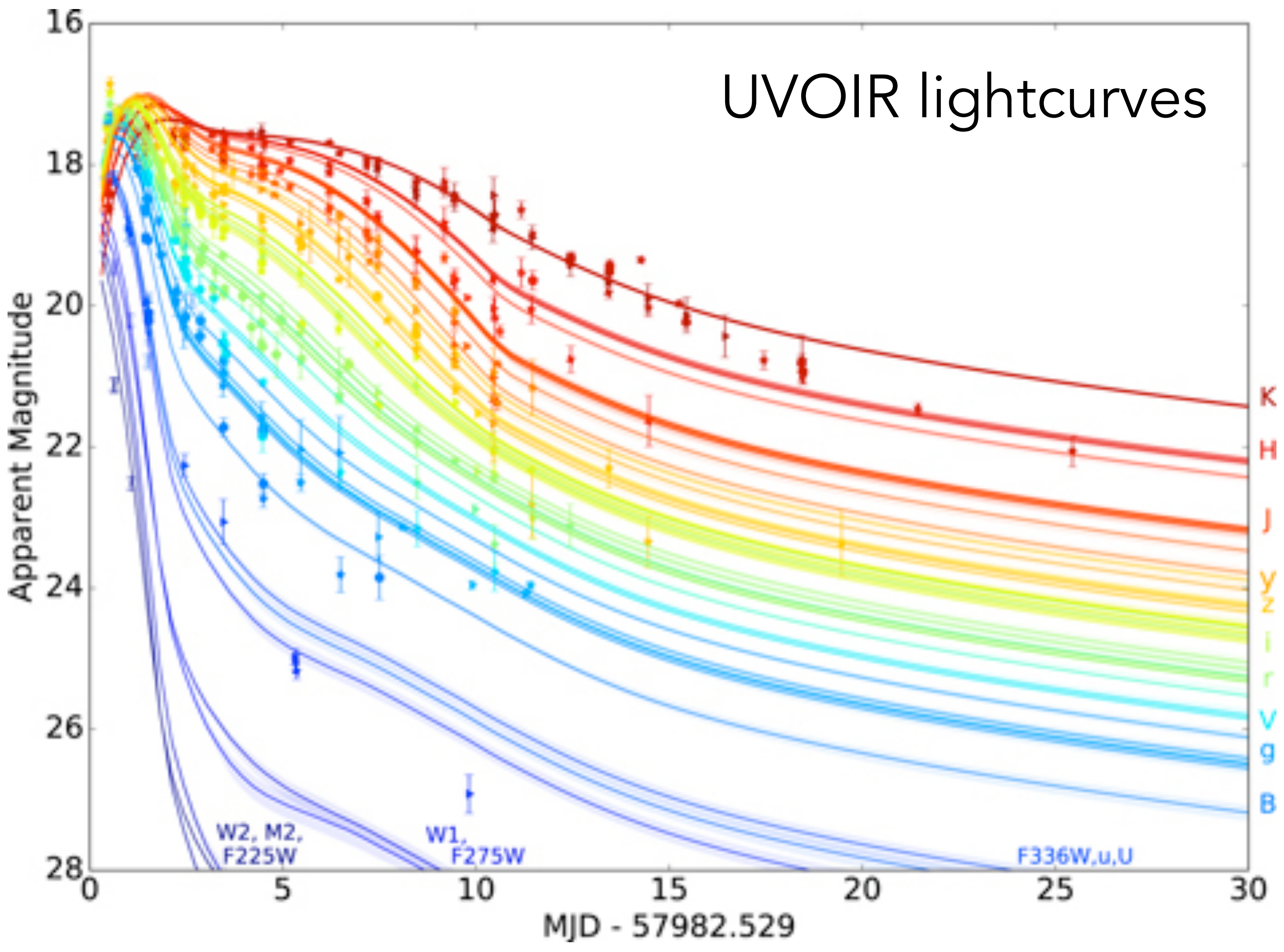
A new way of probing the structure of neutron stars!

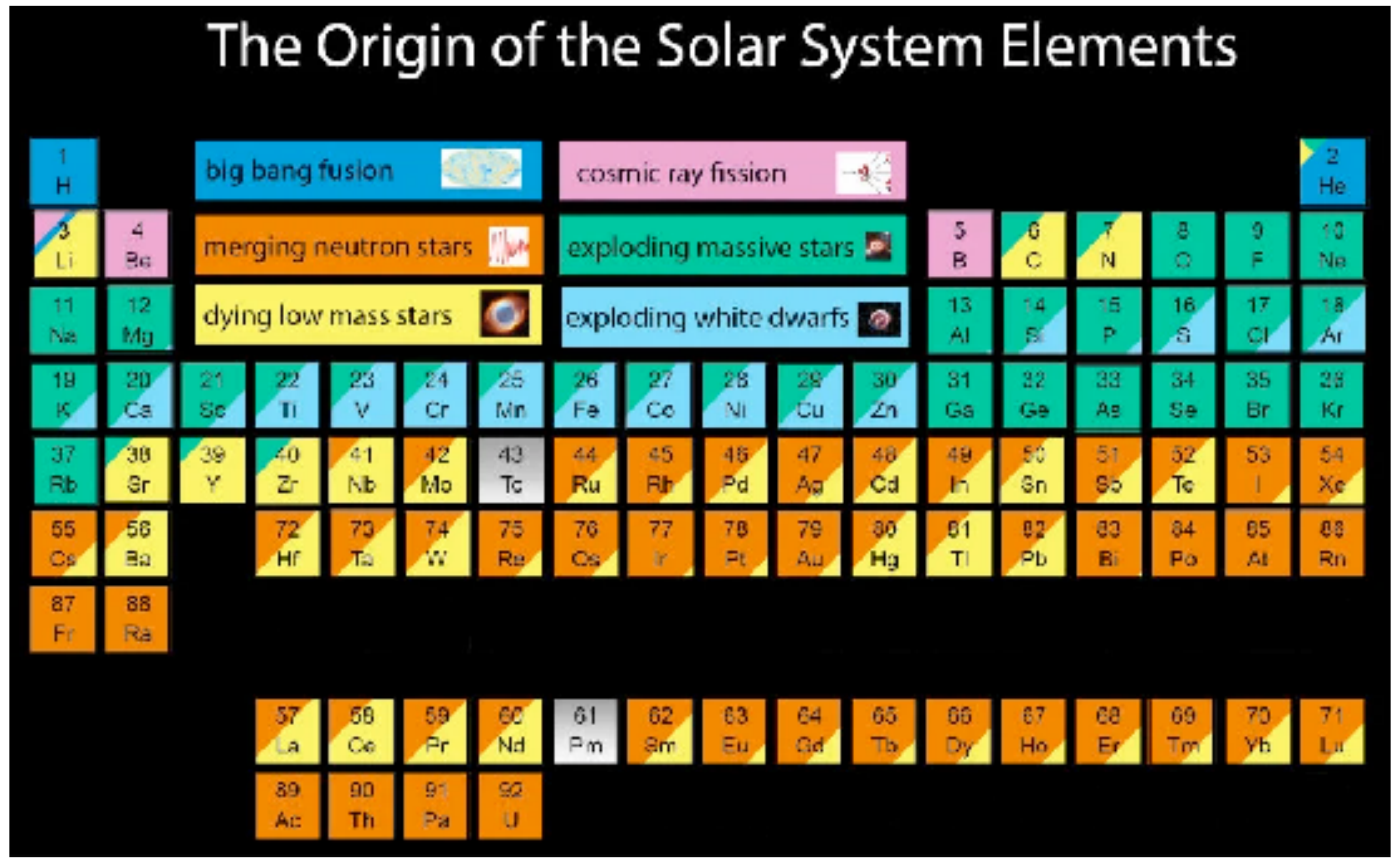
A GW MULTI-MESSENGER EVENT

- Coincident discovery of a short GRB by Fermi
- Observation across the entire EM spectrum



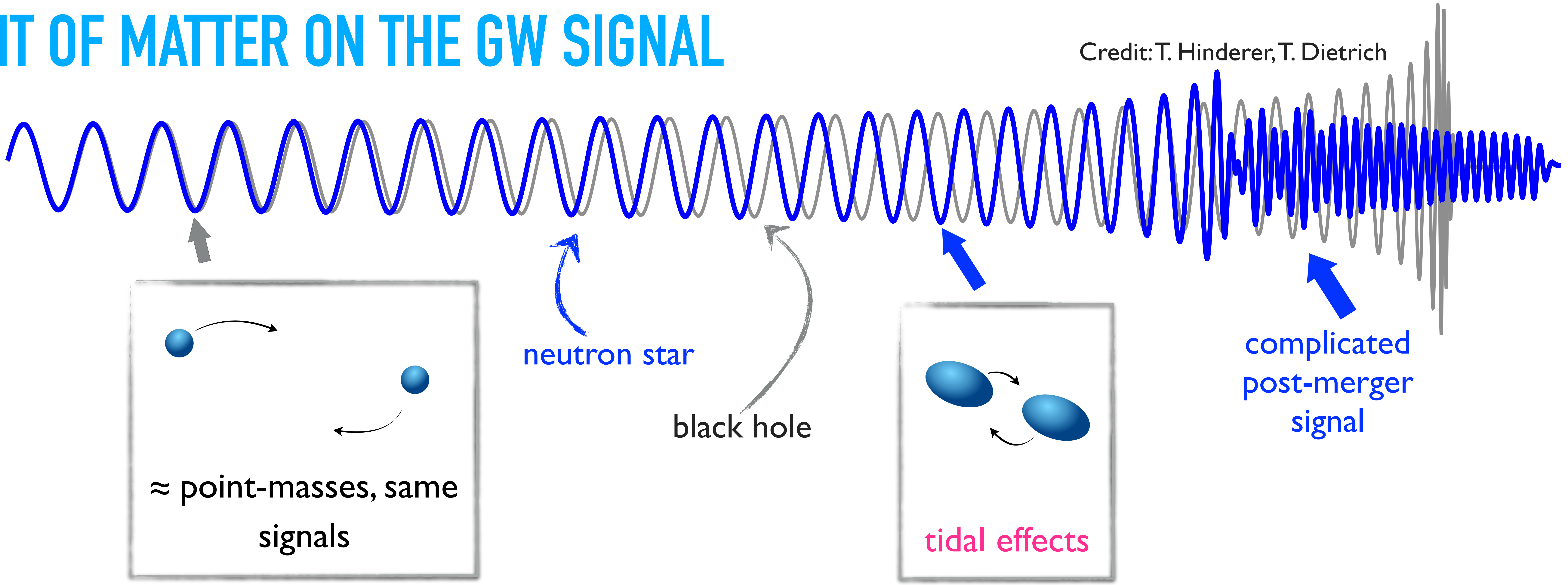






[Credit: LVK, Jennifer Johnson/NASA, Villar+]

IMPRINT OF MATTER ON THE GW SIGNAL



+ tidal excitation of internal oscillation modes

Some energy used to deform the NS

Moving tidal bulges produce GWs

$$\dot{E}_{\rm GW} \sim \left[\frac{d^3}{dt^3}\left(Q_{\rm orbit} + Q_{\rm NS}\right)\right]^2$$

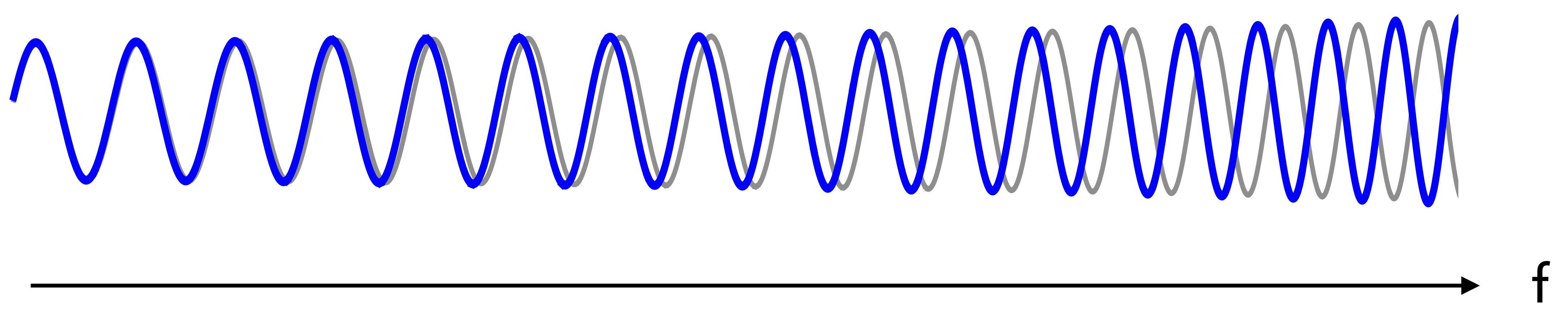
Tidally induced quadrupole moment

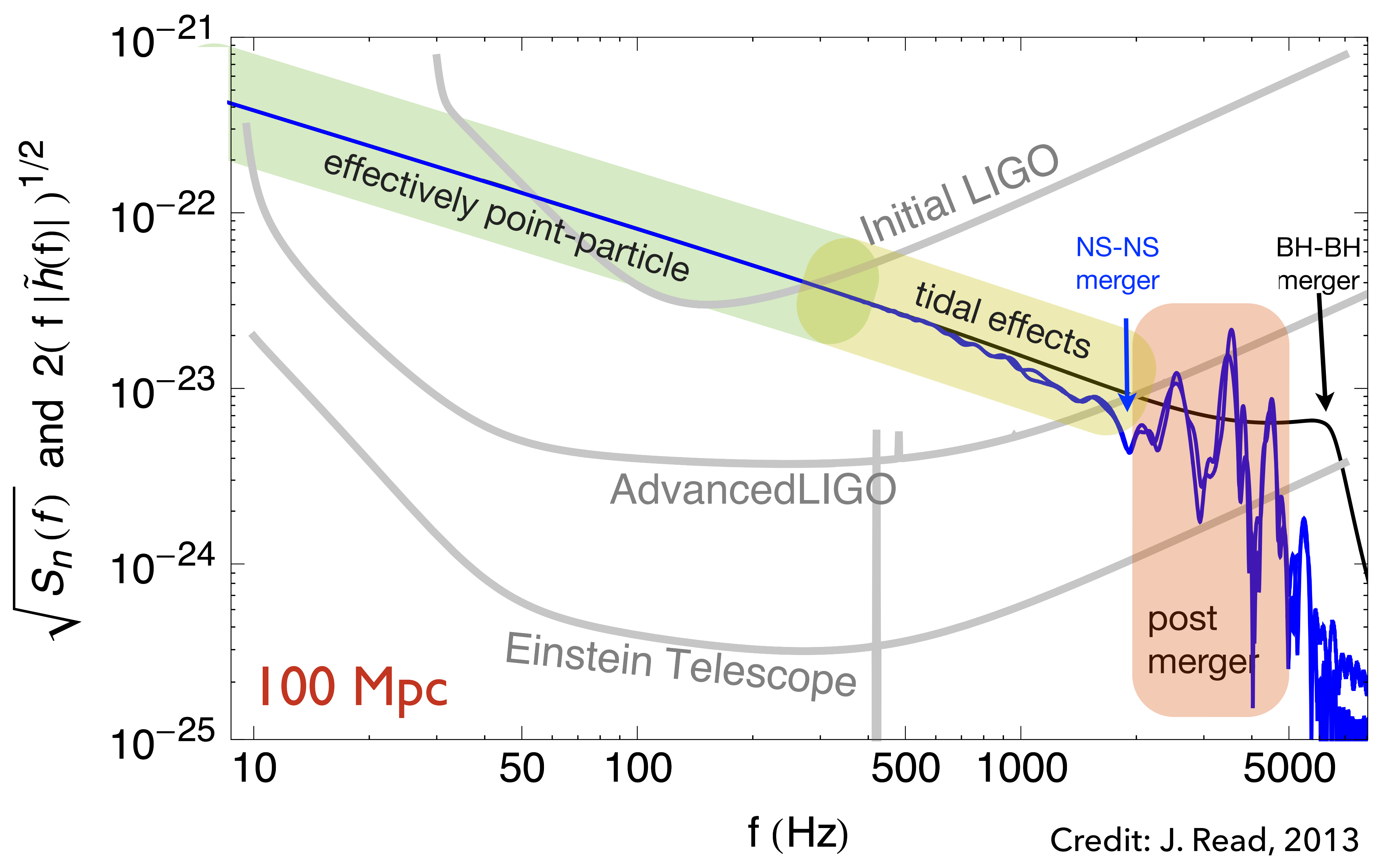
tidal deformability

$$Q_{ij}^{(\ell)} = -\lambda_\ell \mathcal{E}_{ij}^{(\ell)}$$

EFFECT ON THE GRAVITATIONAL WAVE

- Energy goes into deforming the neutron stars
- Enhances GW emission relative to black holes
- Leading-order effect at 5PN: builds up a clean dephasing from ~400Hz





- Leading-order phase contribution characterised by weighted combination:

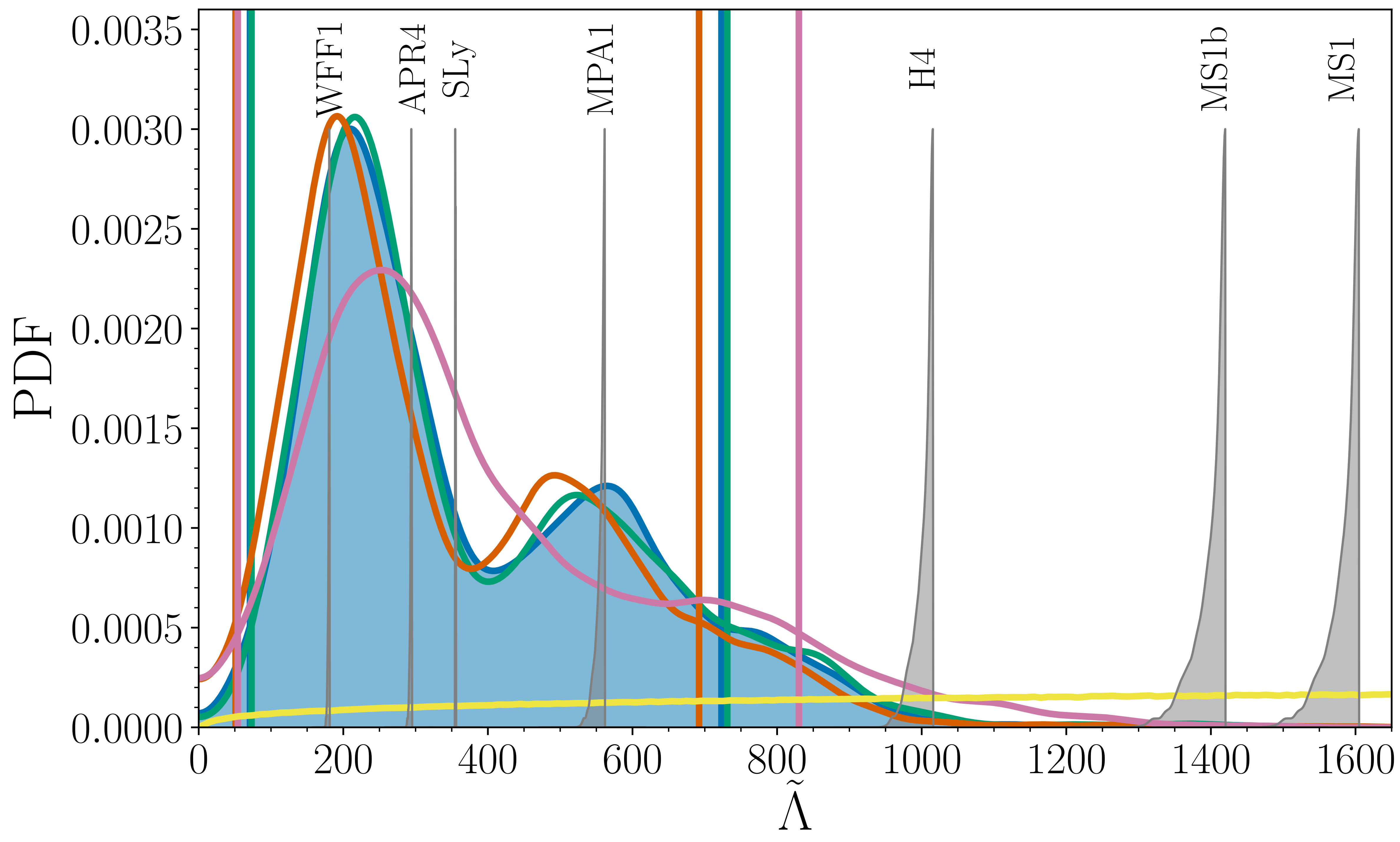
$$\tilde{\Lambda} = \frac{16}{13}\frac{(m_1+12m_2)m_1^4\Lambda_1 + (m_2+12m_1)m_2^4\Lambda_2}{(m_1+m_2)^5}$$

[Flanagan&Hinderer, Favata, Wade]

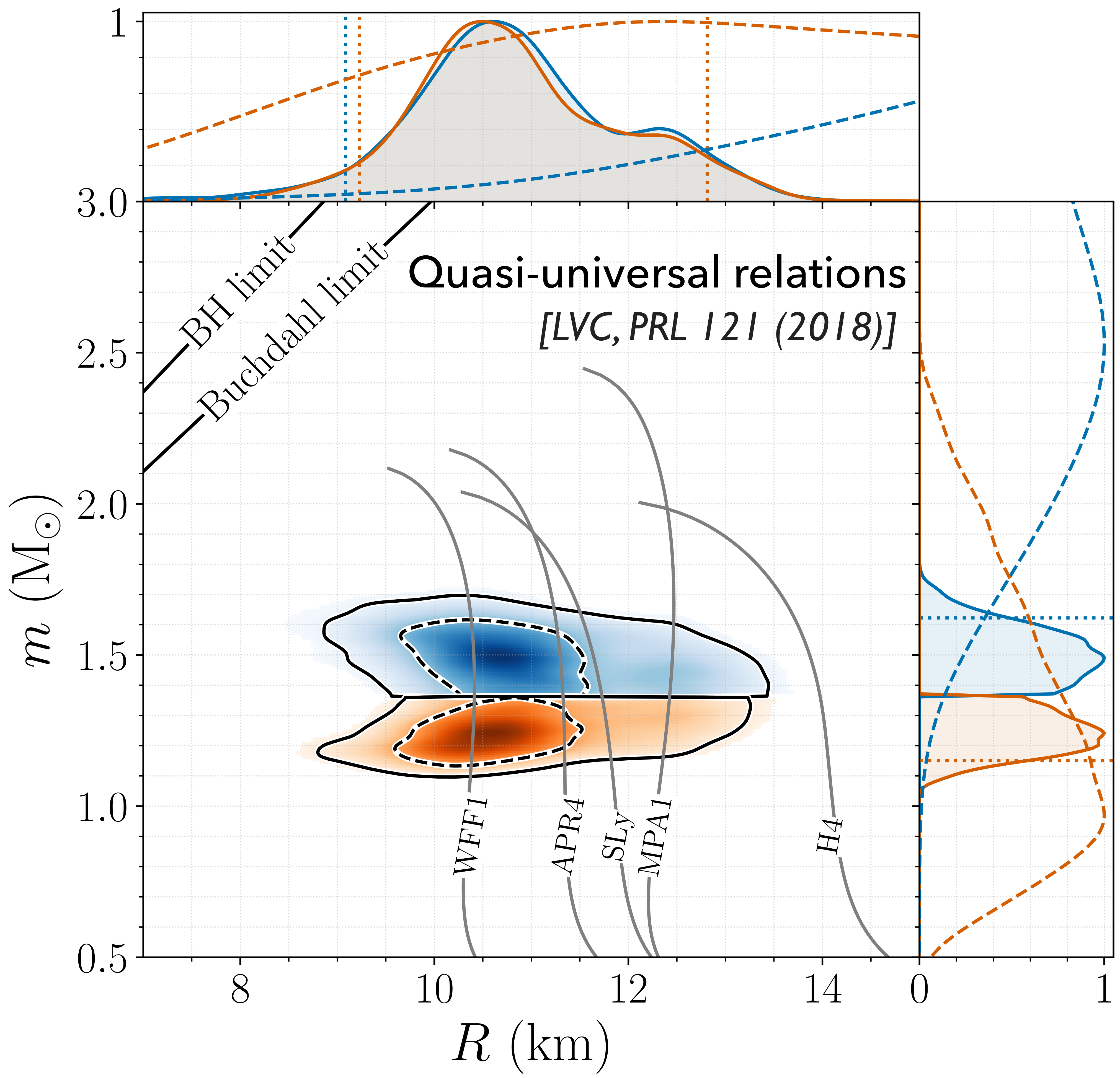
best measured tidal parameter — tells us about the equation of state

EOS CONSTRAINTS FROM GW170817

[LVC - Abbott et al., PRX (9) 2019]



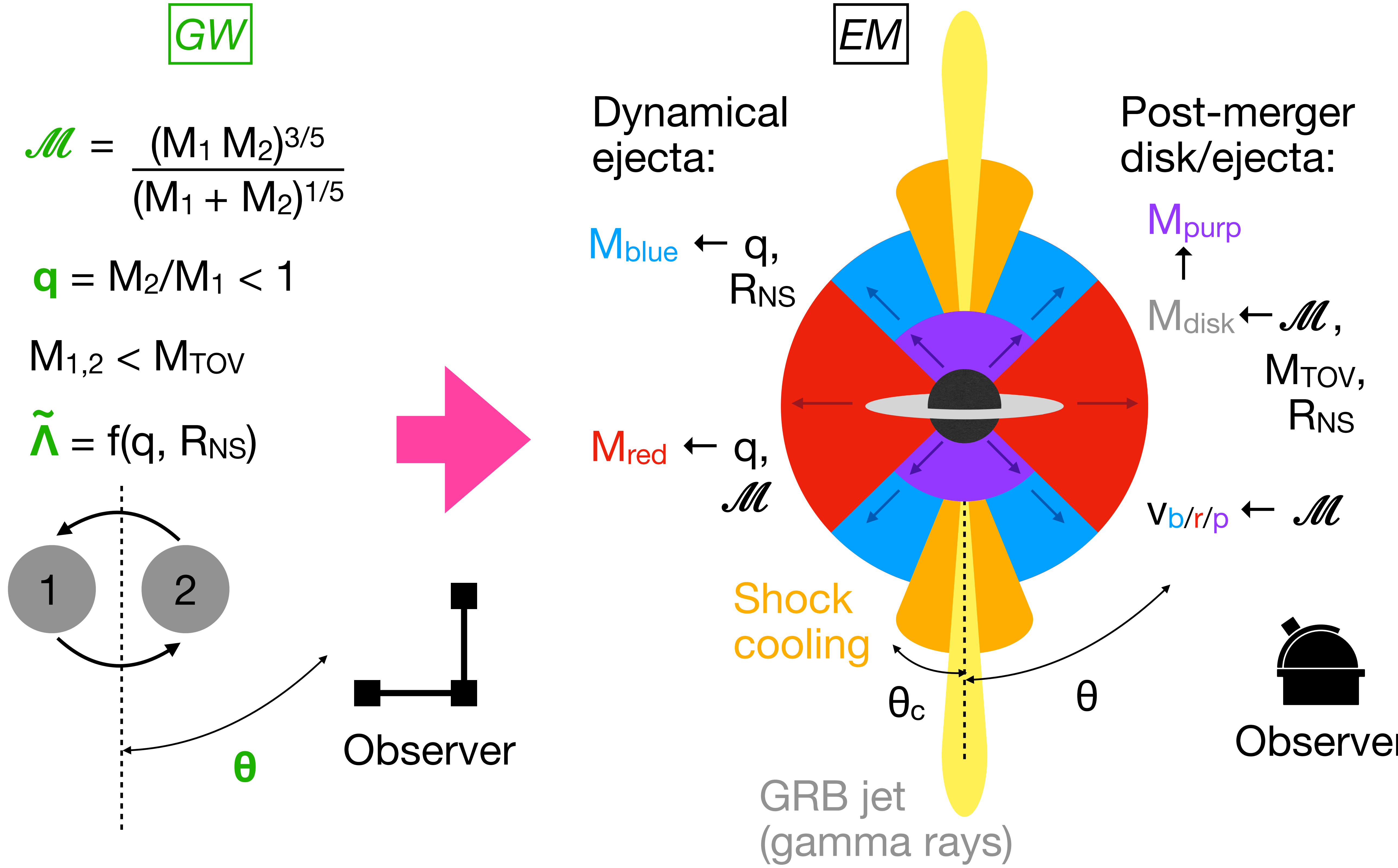
$$\Lambda_{1.4} \lesssim 800$$
$$R_{1.4} \lesssim 13.5\,\mathrm{km}$$

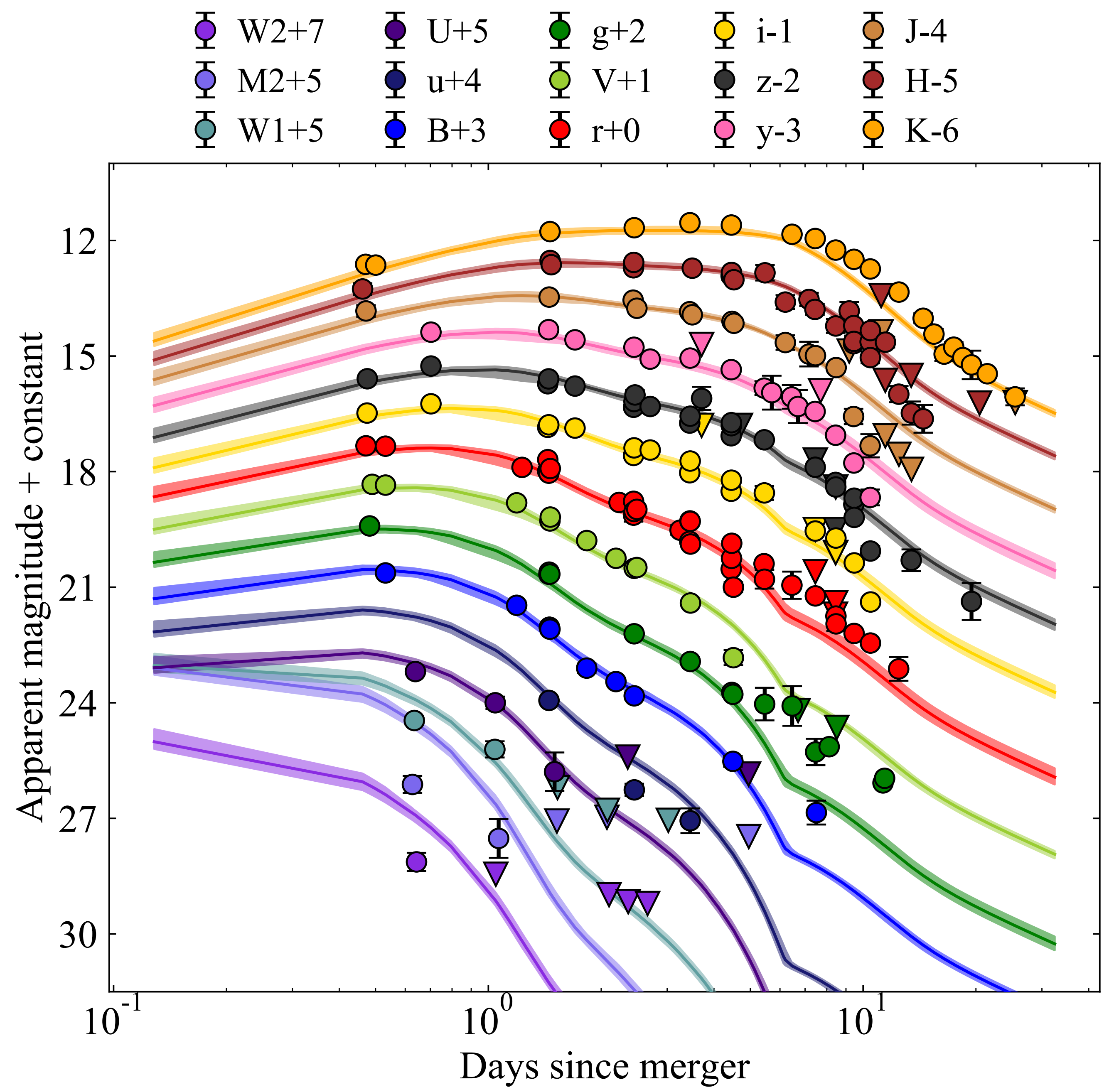


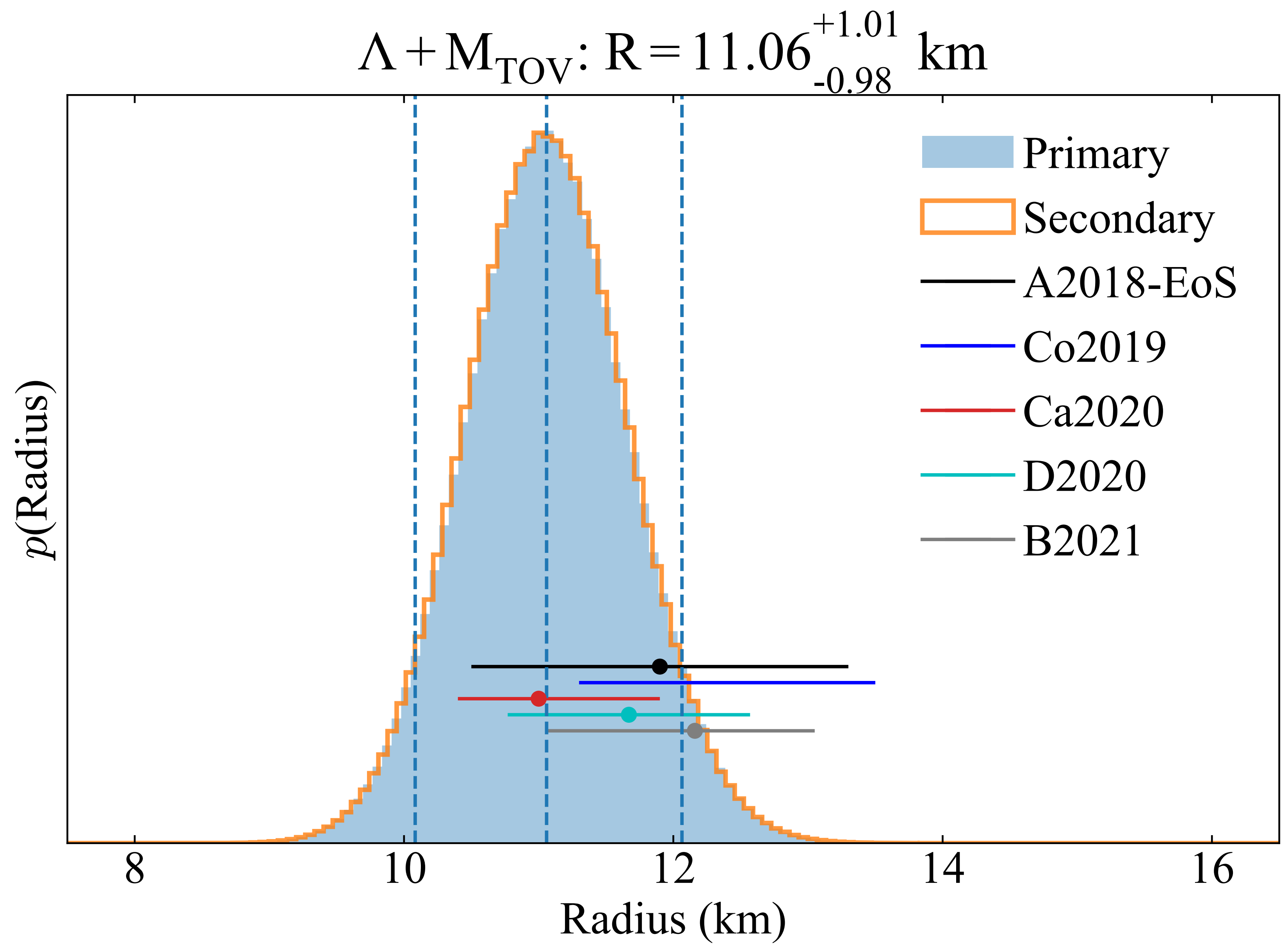
$$\Lambda_{1.4} \lesssim 190^{+390}_{-120}$$
$$R_1 = 11.9^{+1.4}_{-1.4}\,\mathrm{km}$$
$$R_2 = 11.9^{+1.4}_{-1.4}\,\mathrm{km}$$

EOS CONSTRAINTS FROM GW170817

- Using multi-messenger information to improve the constraint on the neutron star equation of state
- Prediction of kilonova light curve (forward modelling) & optimisation of follow-up strategies



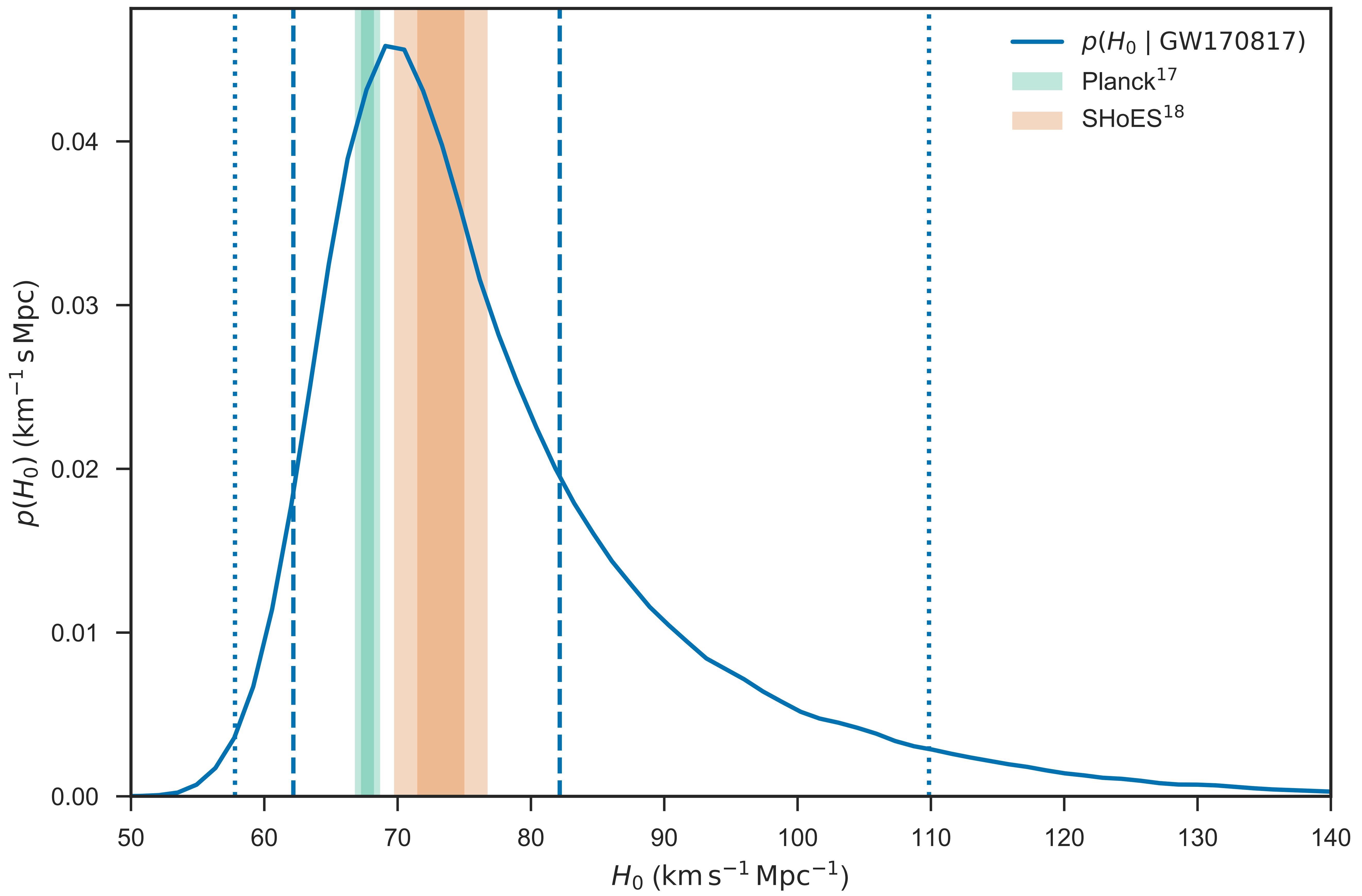




[Nicholl+, MNRAS 2021]

GW170817: A BRIGHT STANDARD SIREN

- GWs give the luminosity distance & inclination distributions
- EM identifies the host galaxy (sky position) from which we can determine the Hubble velocity distribution



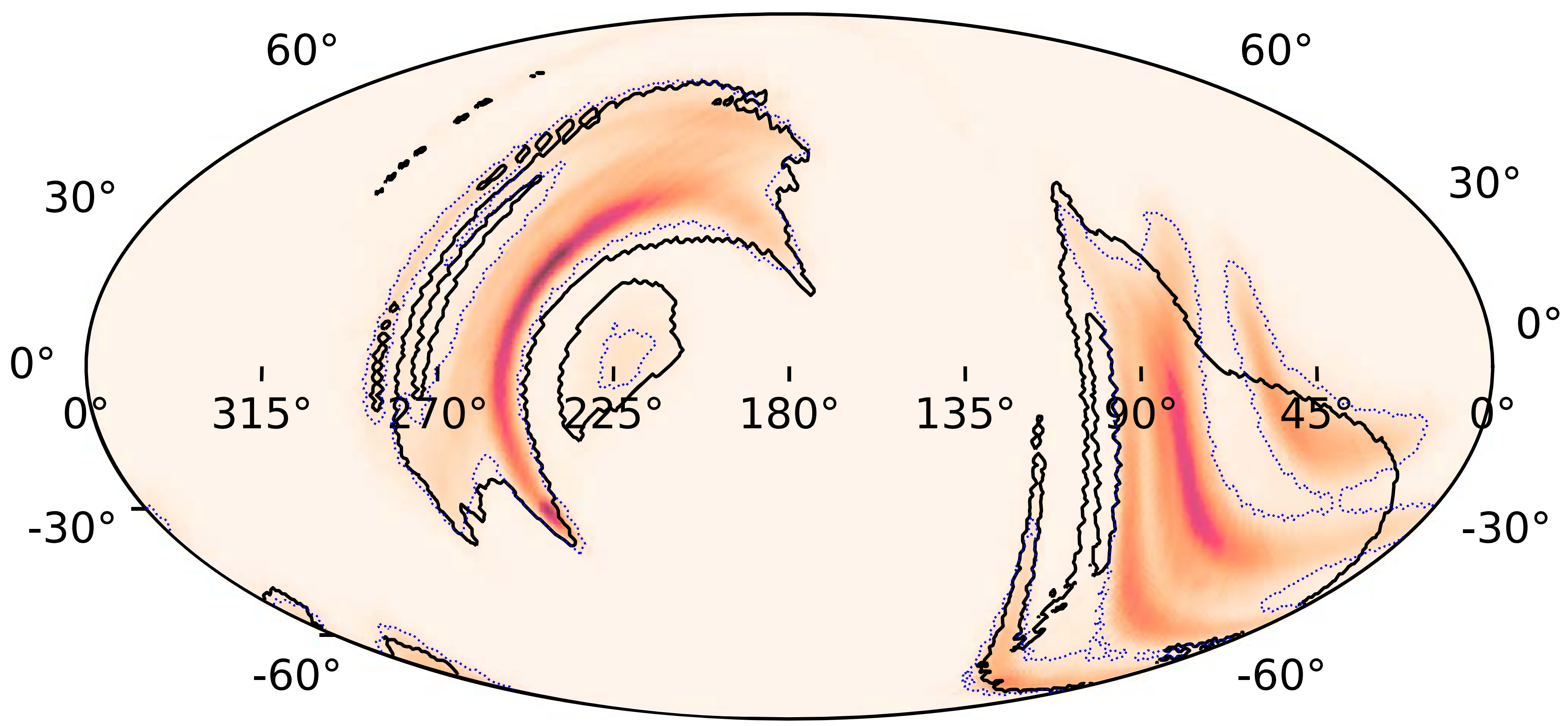
$$H_0 = 70.0^{+12.0}_{-8.0} \mathrm{km\,s^{-1}\,Mpc^{-1}}$$

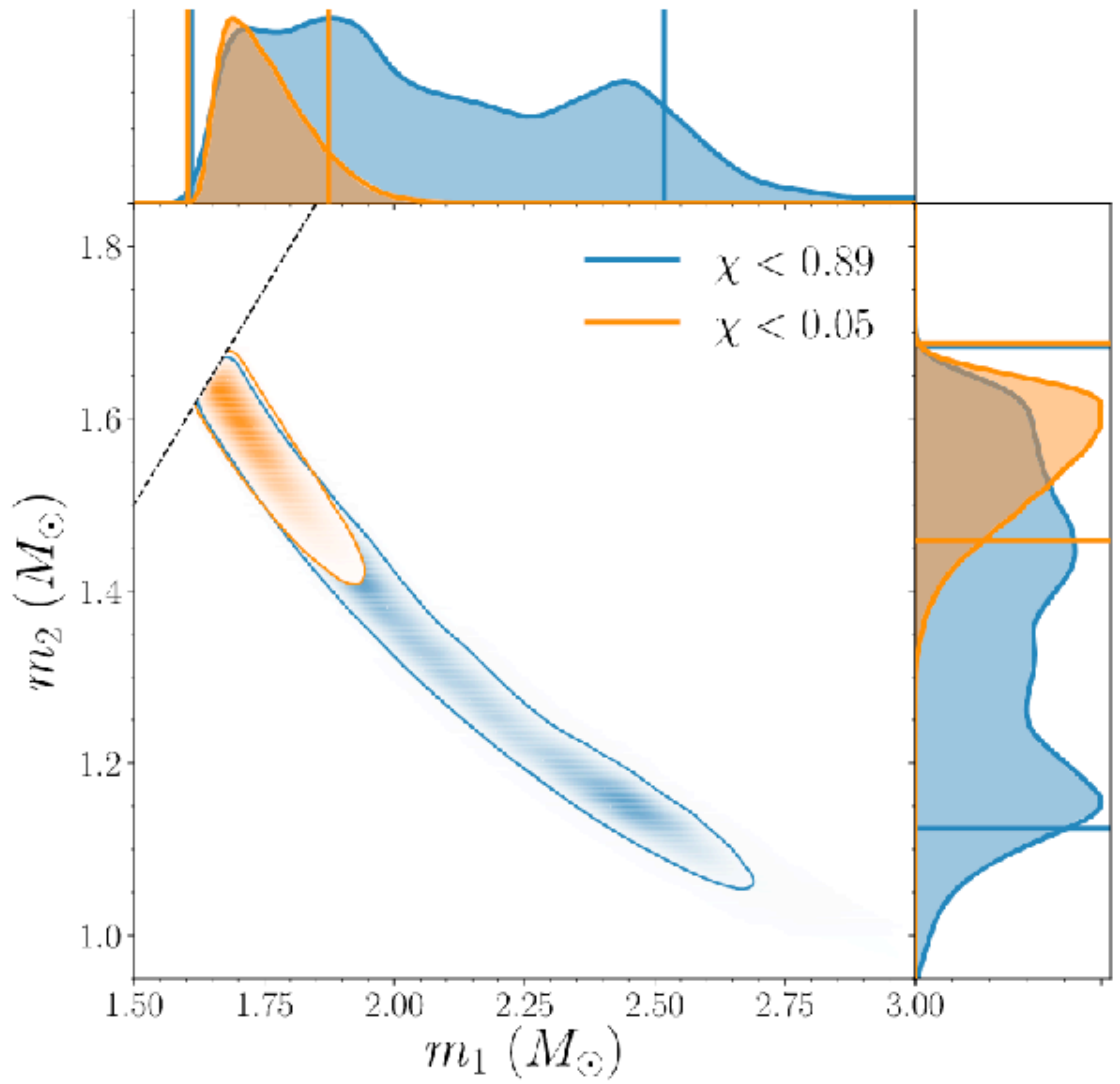
(at 68.3% CI)

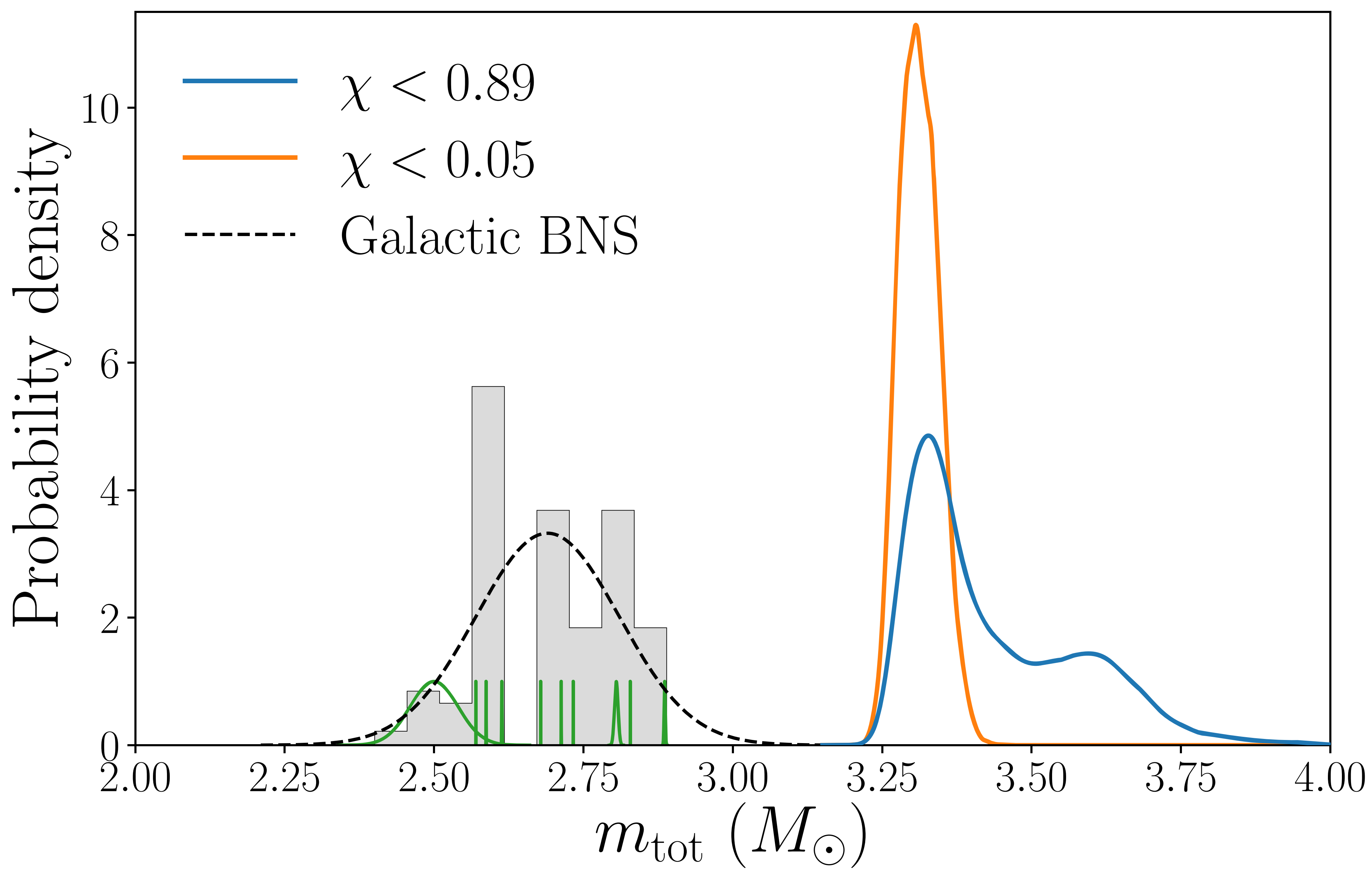
[LVC, Nature 551,85-88 (02 November 2017)]

GW190425

- BNS with SNR ~13 observed in LIGO Livingston in O3a
- Component masses consistent with neutron stars
- No improvement on EOS constraints (consistent but less constraining)



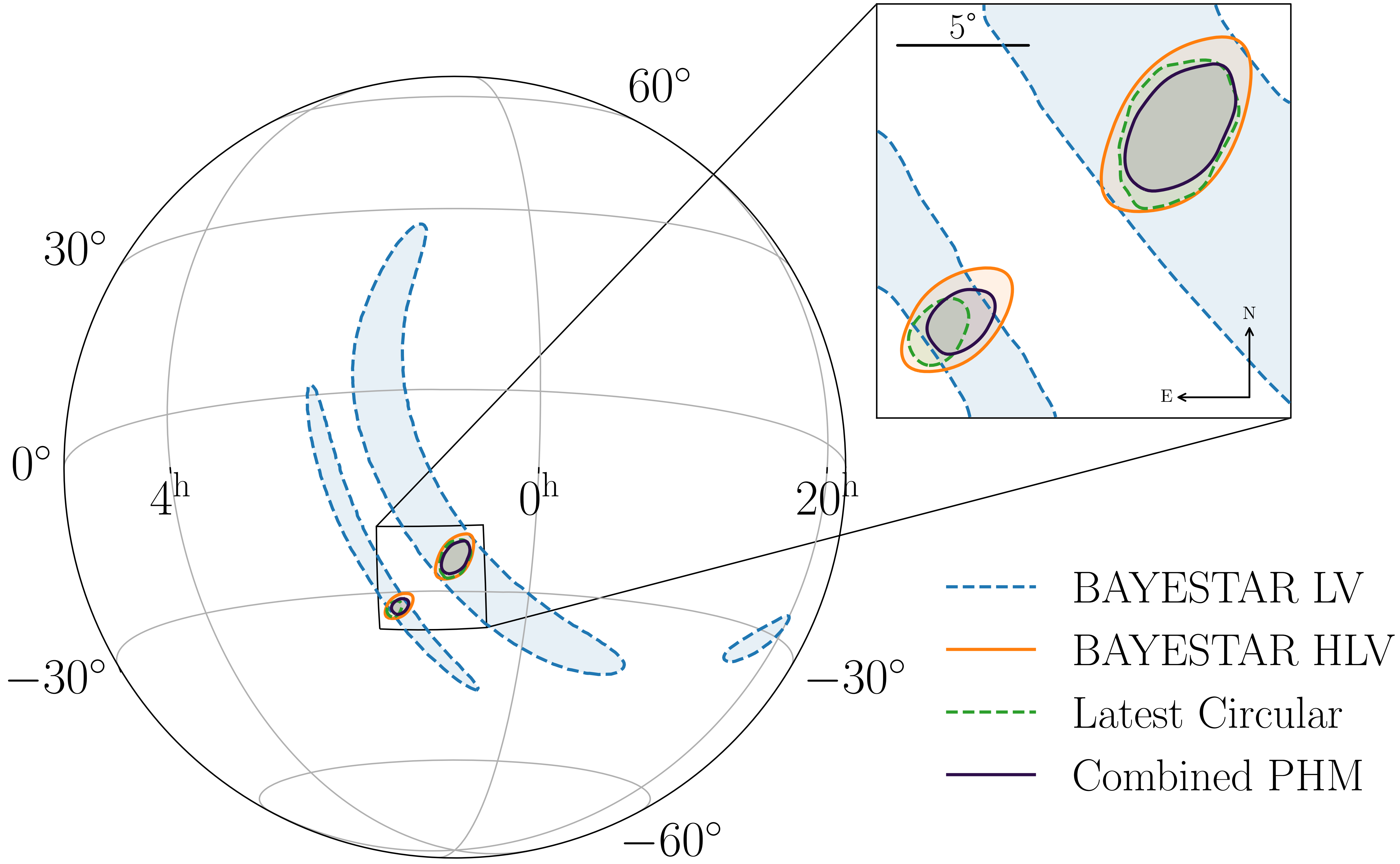




LVK, ApJ L 892:L3 2020

GW190814

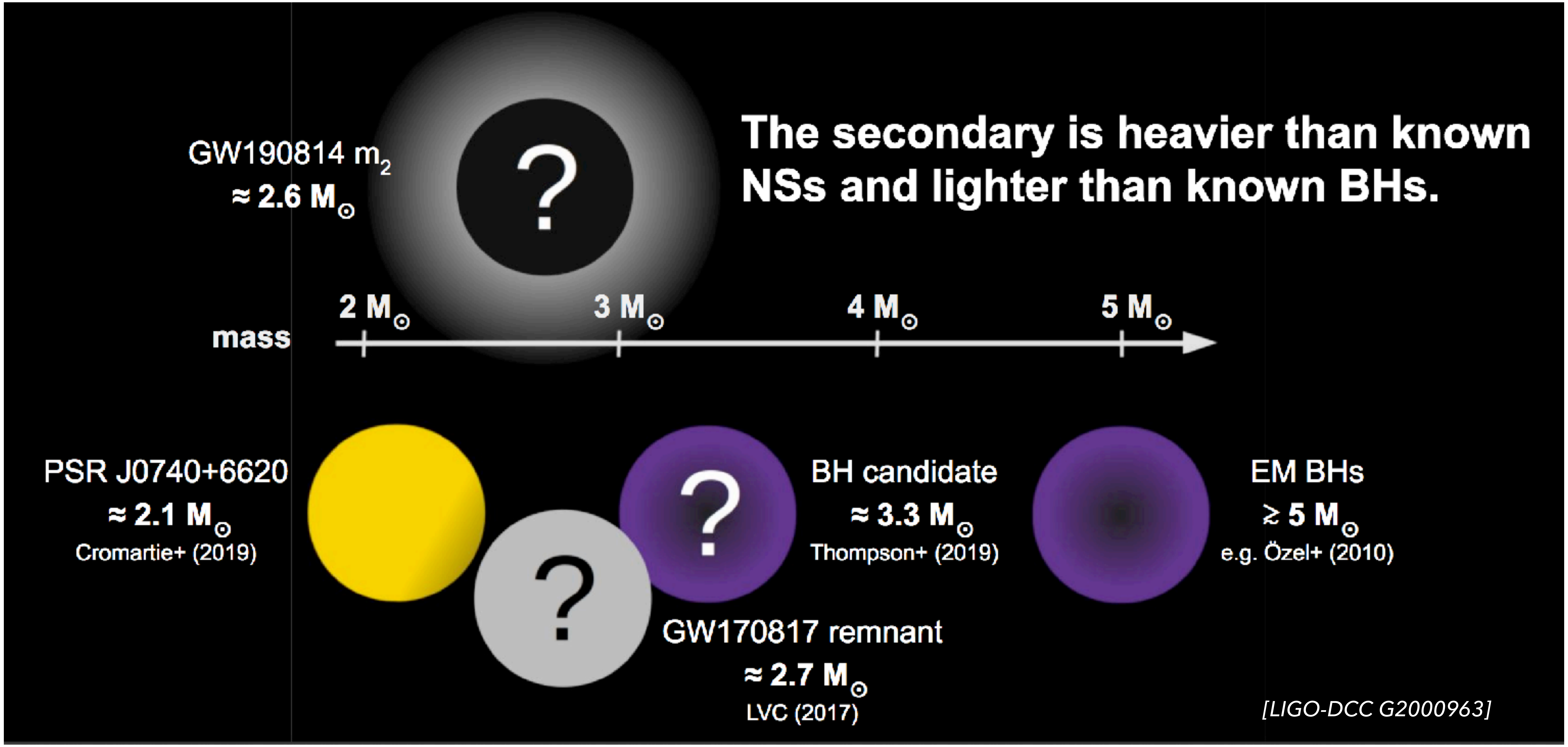
- Identified in low-latency by LIGO-Livingston & Virgo
- 3-detector SNR ~ 25
- Latest skyway (green) issued 13.5 hours after the detection



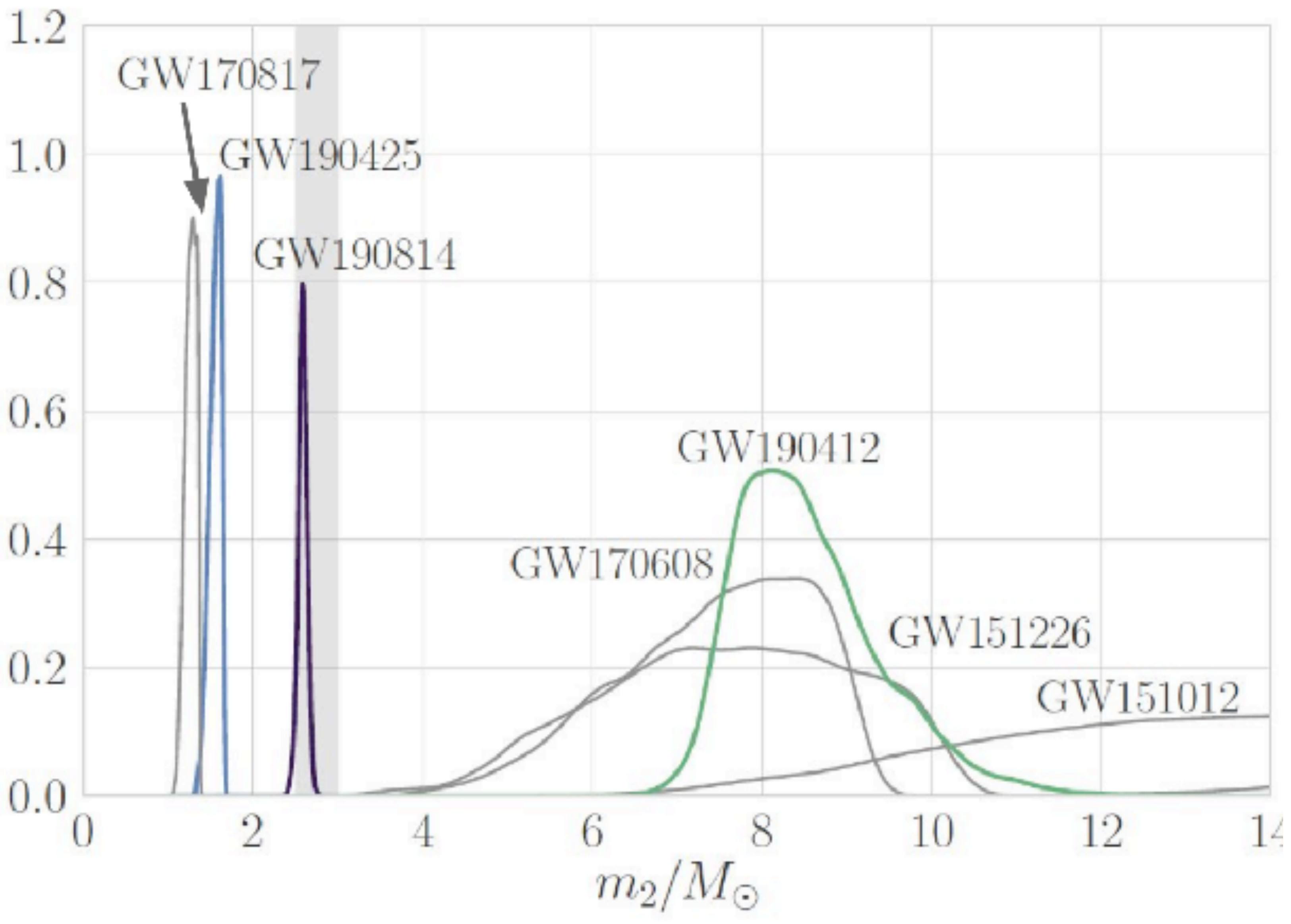
GW190814

[LVC, ApJL 896:L44 (2020)]

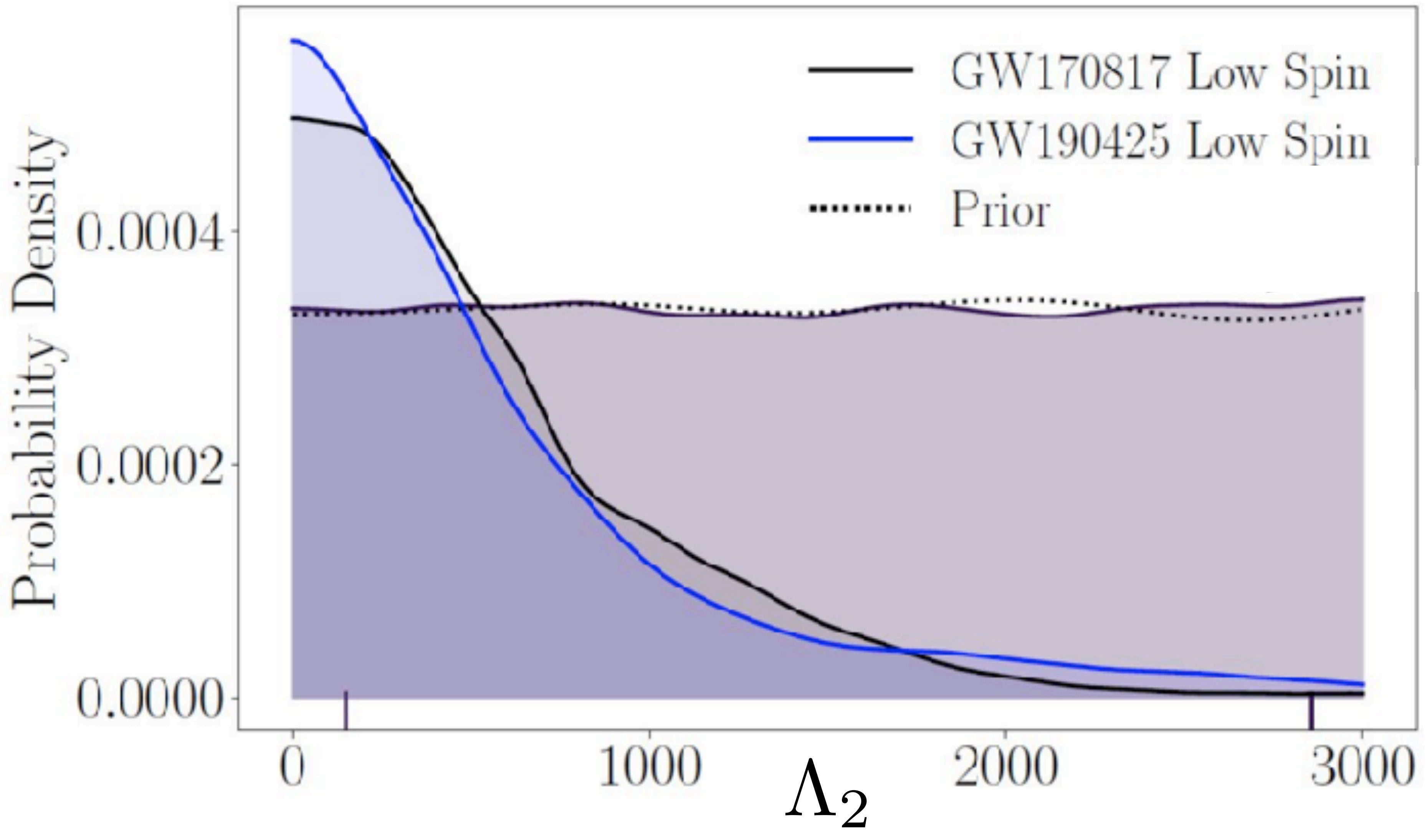
- A binary black hole or a neutron star — black hole binary?



GW190814 – WHAT IS THE NATURE OF THE SECONDARY?

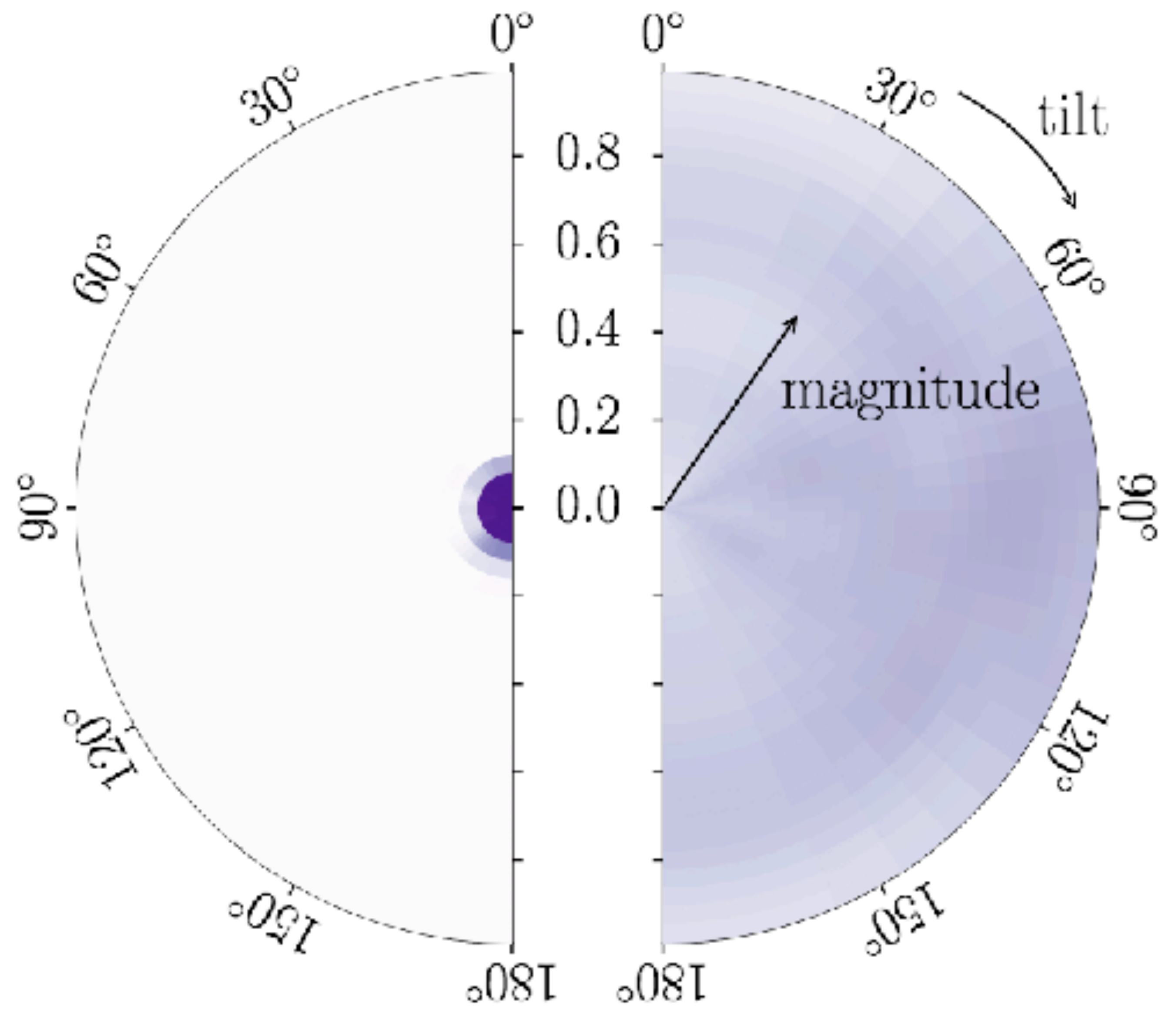


Difficult to reconcile with neutron star maximum mass constraints



No tidal information obtained

Asymmetric mass ratio suppresses tidal effects



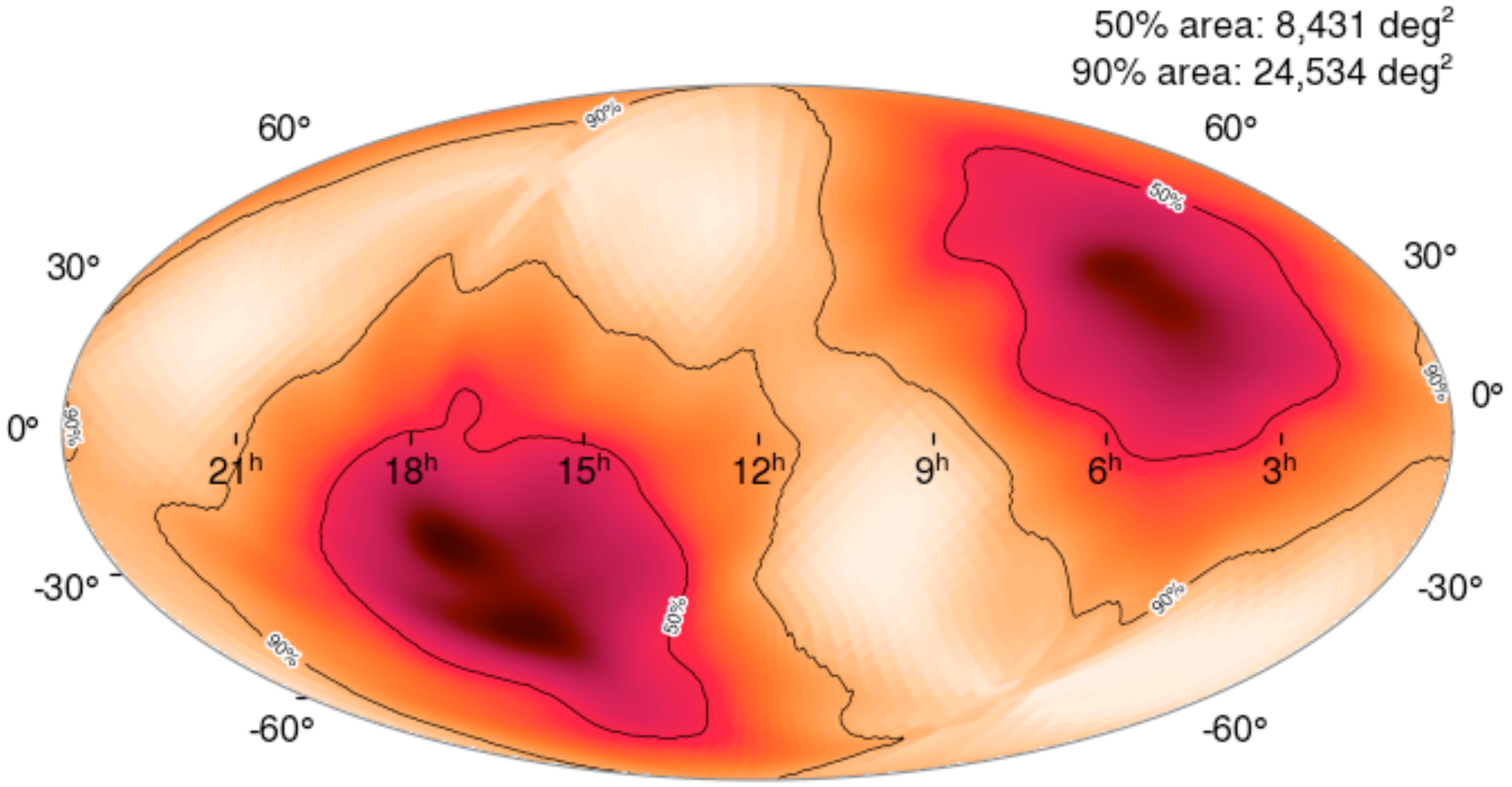
Low black hole spin makes tidal disruption unlikely

$$\delta\varphi_{\rm tidal} \propto -\frac{117}{16}\frac{q^4}{(1+q)^5}\frac{\Lambda_2}{X_1 X_2}x^{5/2} \times (\text{PN Corrections})\,;\; q \leq 1$$

[LIGO-DCC G2000963]

GW230529

- L1-only detection by 3 matched-filter searches with SNR ~ 11

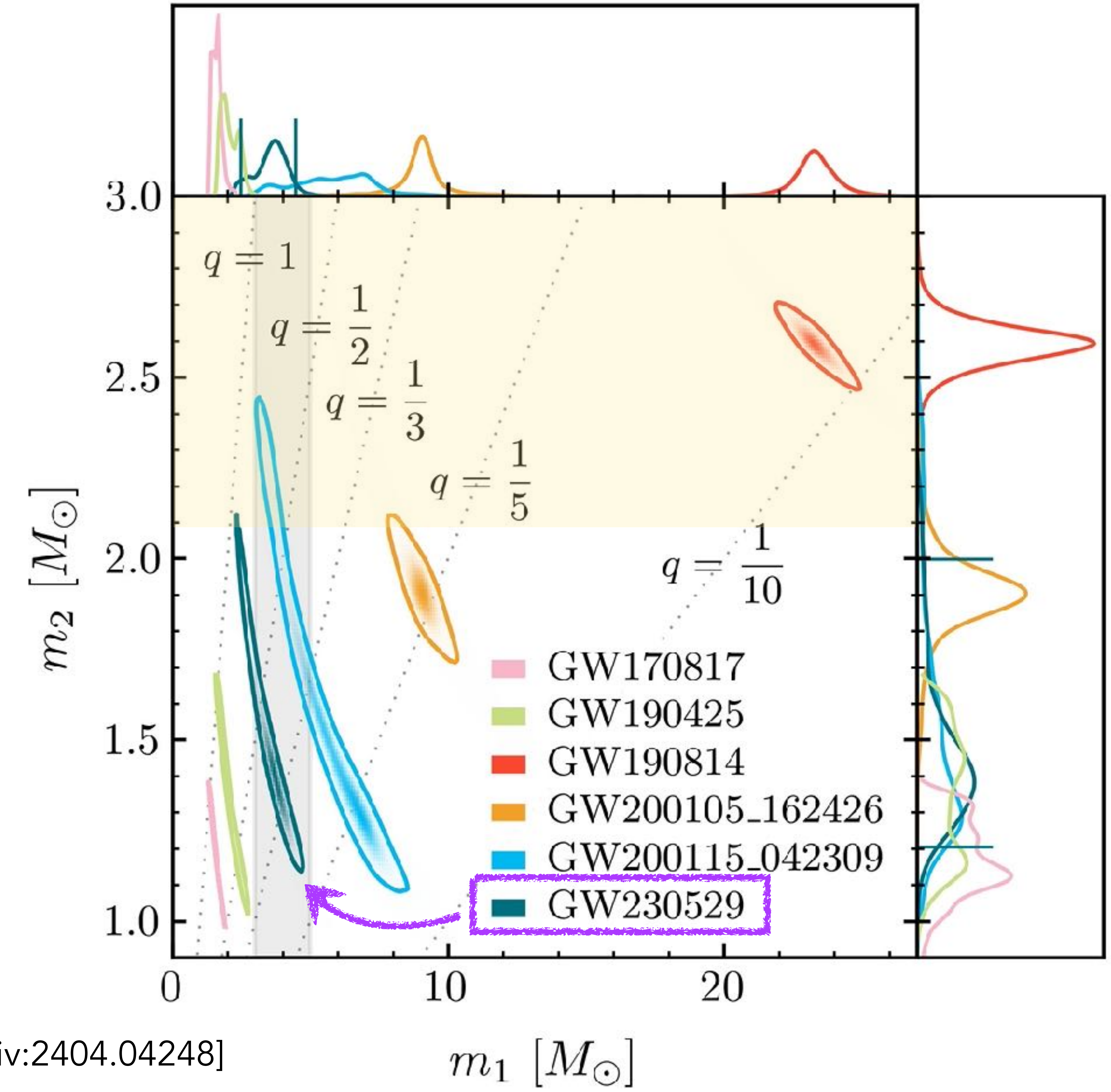


[LVK, arXiv:2404.04248]

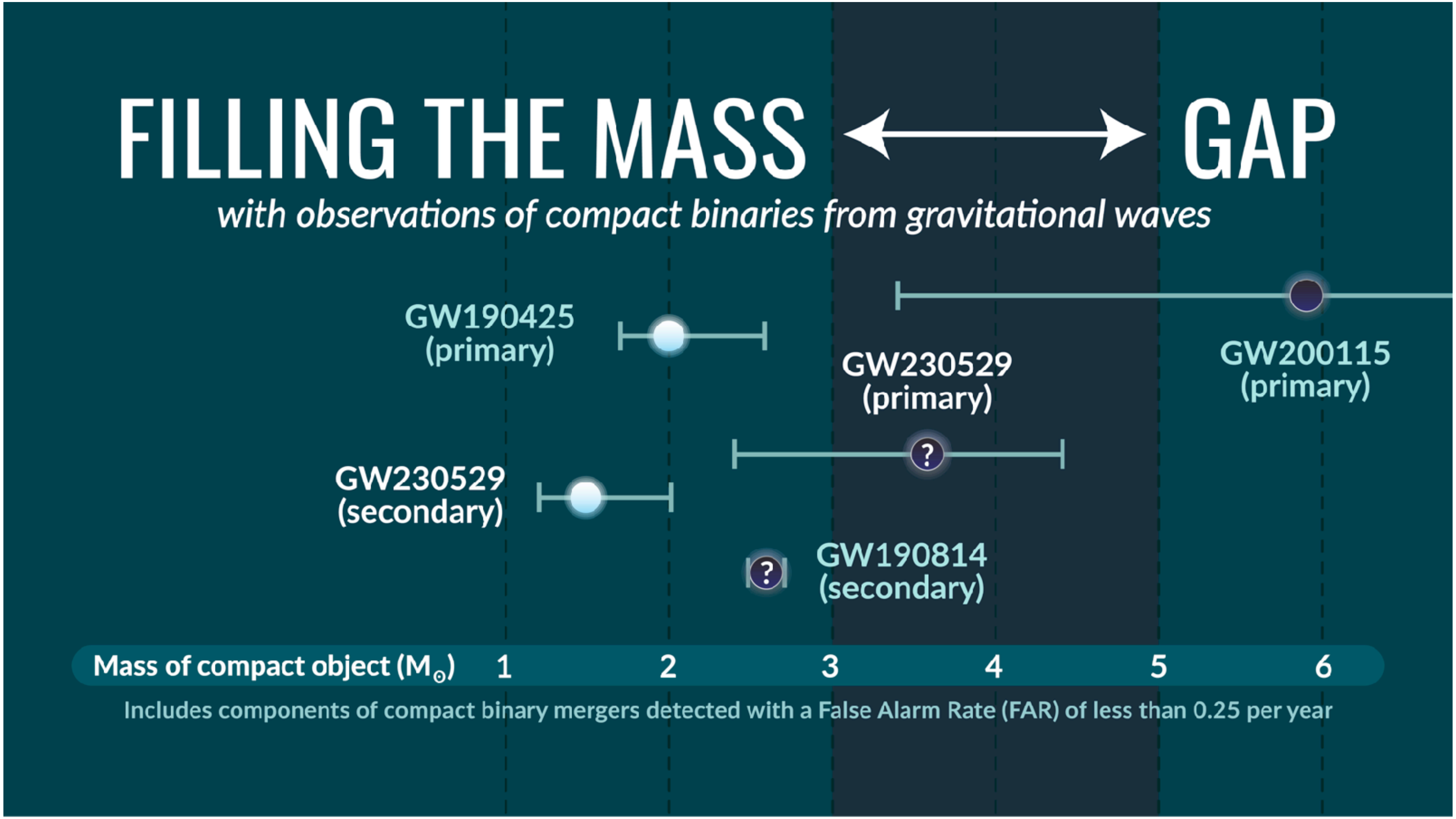
GW230529

- Primary mass $< 5M_\odot$ at 99% credibility
- Secondary mass consistent with a neutron star

Primary mass $m_1/M_\odot$	$3.6^{+0.8}_{-1.2}$
Secondary mass $m_2/M_\odot$	$1.4^{+0.6}_{-0.2}$
Mass ratio $q = m_2/m_1$	$0.39^{+0.41}_{-0.12}$
Total mass $M/M_\odot$	$5.1^{+0.6}_{-0.6}$
Chirp mass $\mathcal{M}/M_\odot$	$1.94^{+0.04}_{-0.04}$
Detector-frame chirp mass $(1+z)\mathcal{M}/M_\odot$	$2.026^{+0.002}_{-0.002}$
Primary spin magnitude χ_1	$0.44^{+0.40}_{-0.37}$
Effective inspiral-spin parameter $\chi_{\rm eff}$	$-0.10^{+0.12}_{-0.17}$
Effective precessing-spin parameter $\chi_{\rm p}$	$0.40^{+0.39}_{-0.30}$
Luminosity distance $D_{\rm L}/{\rm Mpc}$	201^{+102}_{-96}
Source redshift z	$0.04^{+0.02}_{-0.02}$



[LVK, arXiv:2404.04248]



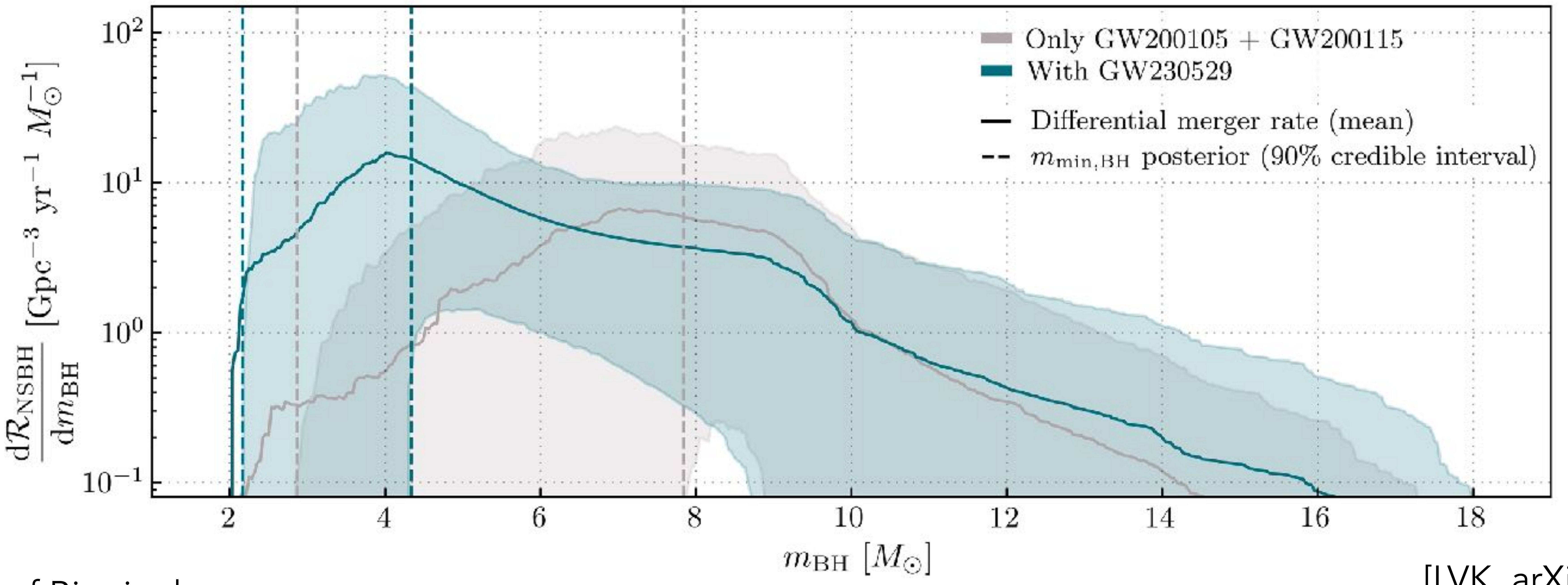
[Image credit: S. Galaudage/Observatoire de la Côte d’Azur]

GW230529: BLACK HOLES OR NEUTRON STARS?

- Source most likely an NSBH after accounting for uncertainties in population models and EOS constraints

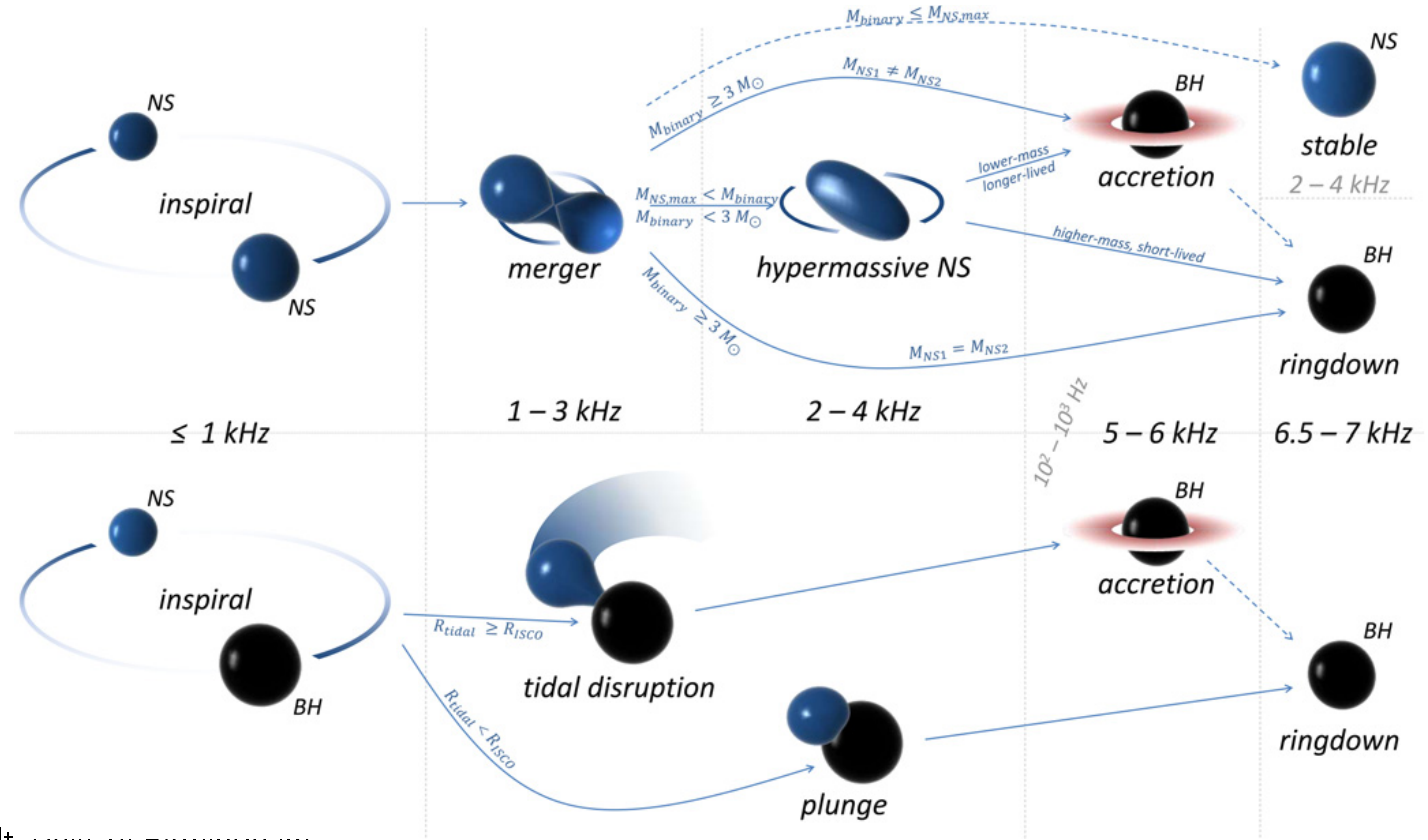
	$\chi_1, \chi_2 \leq 0.99$	$\chi_1, \chi_2 \leq 0.05$	Power law + Dip + Break
$P(m_1$ is NS)	$(2.9 \pm 0.4)\%$	$< 0.1\%$	$(8.8 \pm 2.8)\%$
$P(m_2$ is NS)	$(96.1 \pm 0.4)\%$	$> 99.9\%$	$(98.4 \pm 1.3)\%$

- Assuming an NSBH, the minimum black hole mass in NSBH is lower than previously inferred: $\sim 6M_\odot \rightarrow \sim 3.4M_\odot$



[LVK, arXiv:2404.04248]

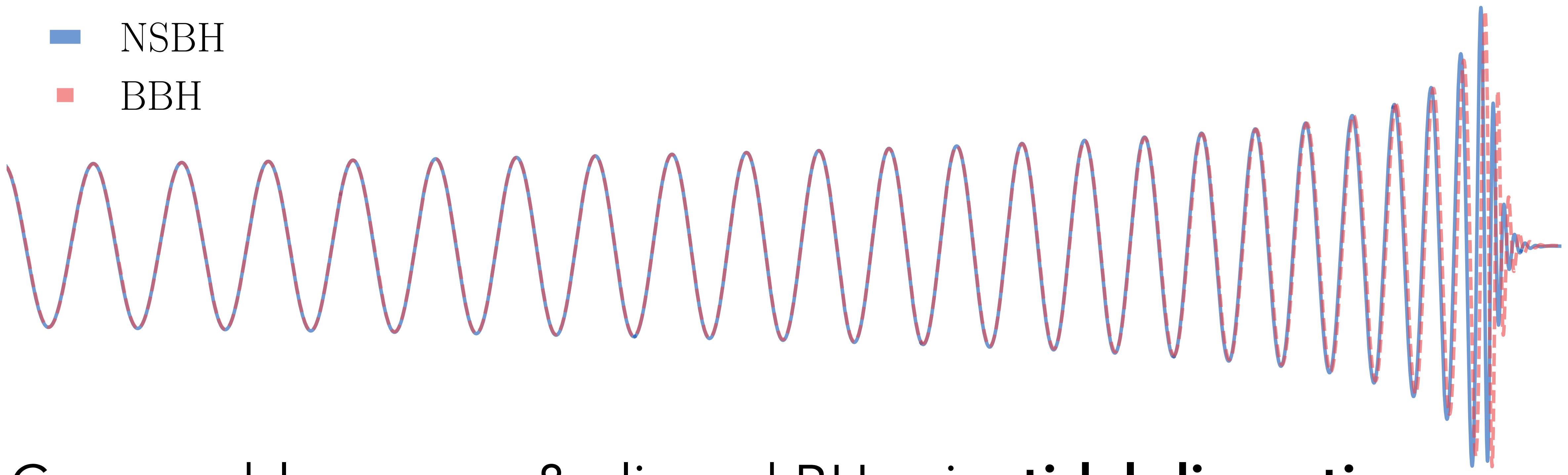
WHAT ABOUT MATTER SIGNATURES?



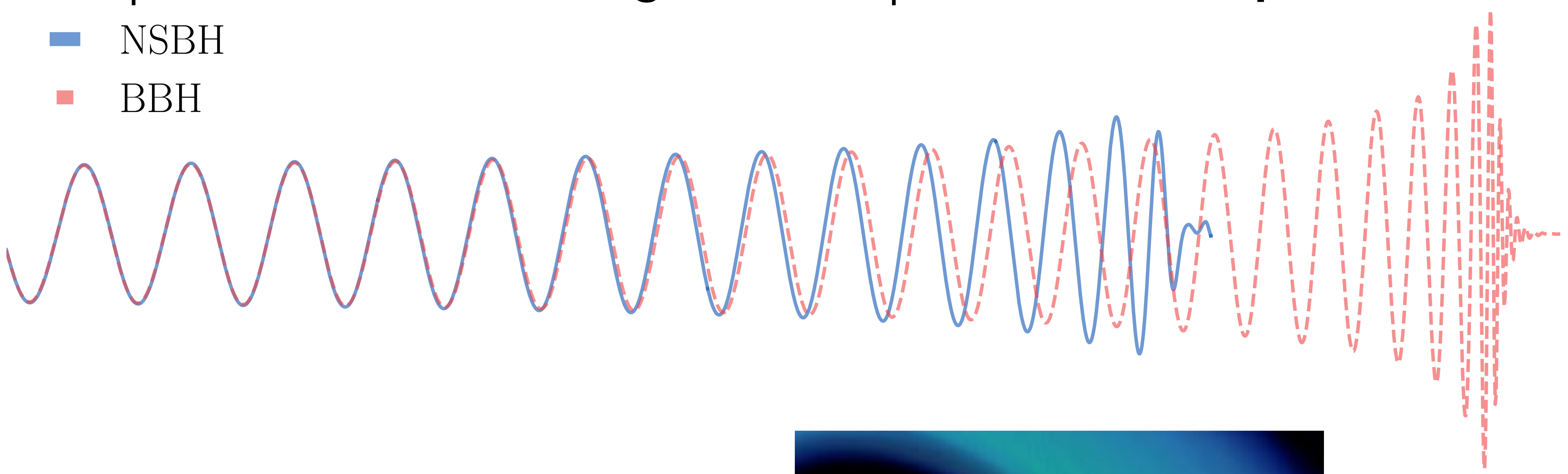
[Bartos+ 2019]

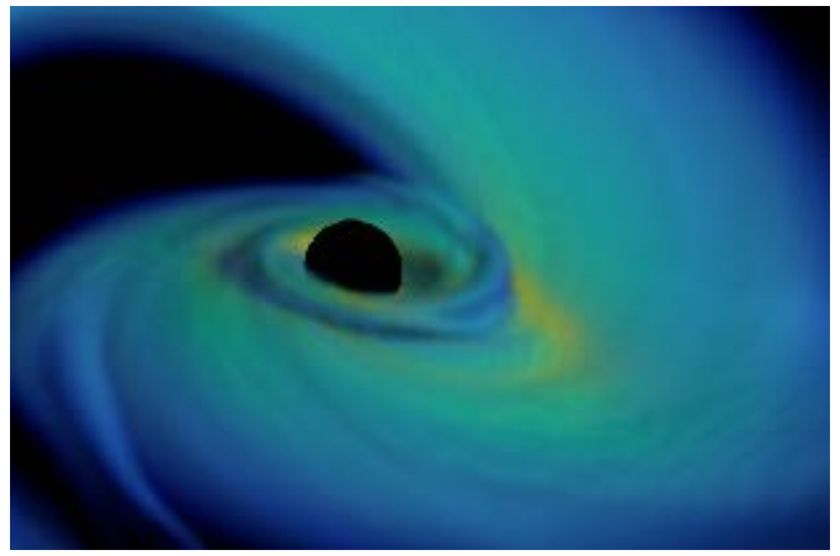
WHAT ABOUT MATTER SIGNATURES?

- Unequal masses & anti-aligned BH spin: indistinguishable from BBH

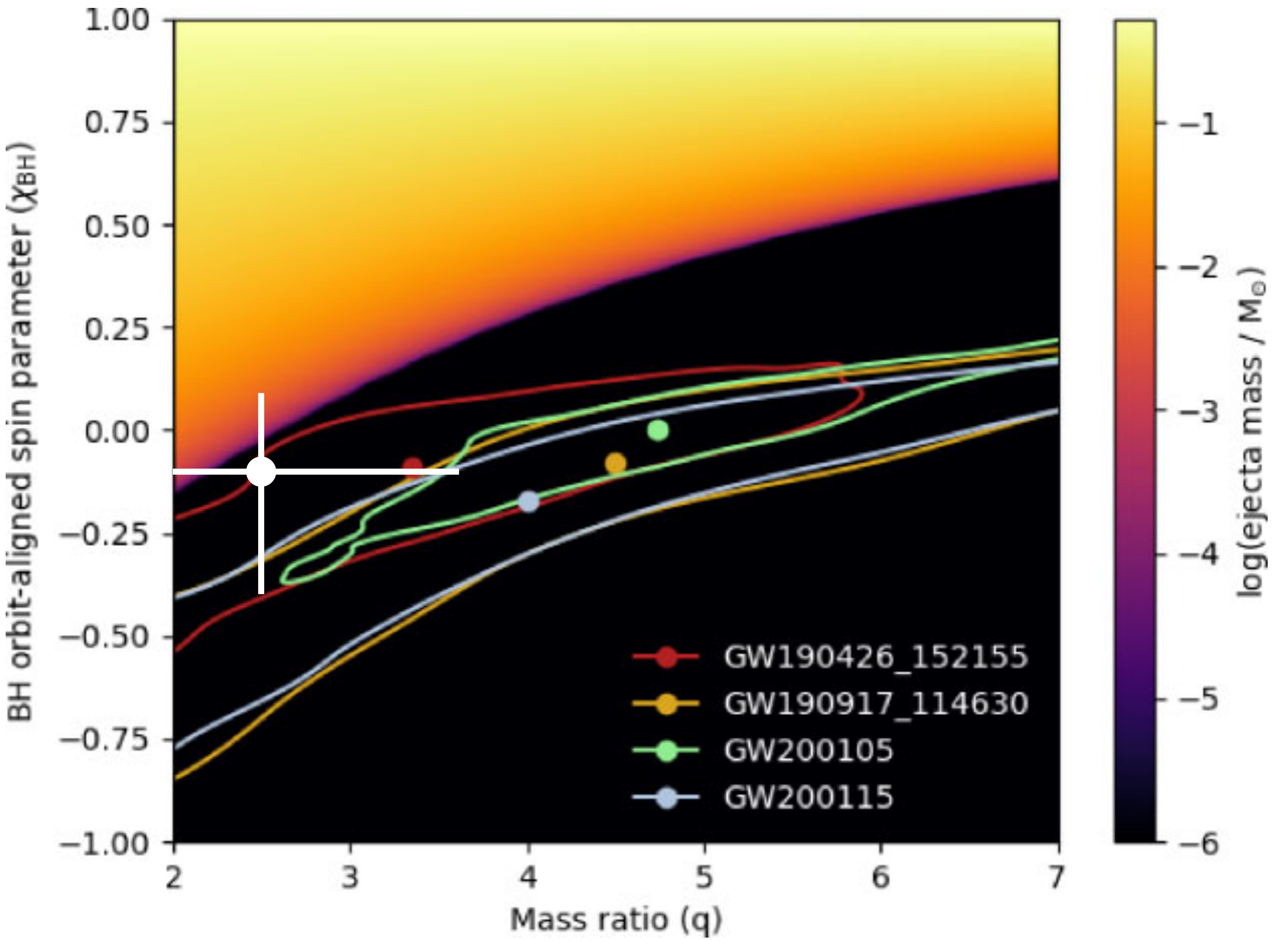


- Comparable masses & aligned BH spin: **tidal disruption**





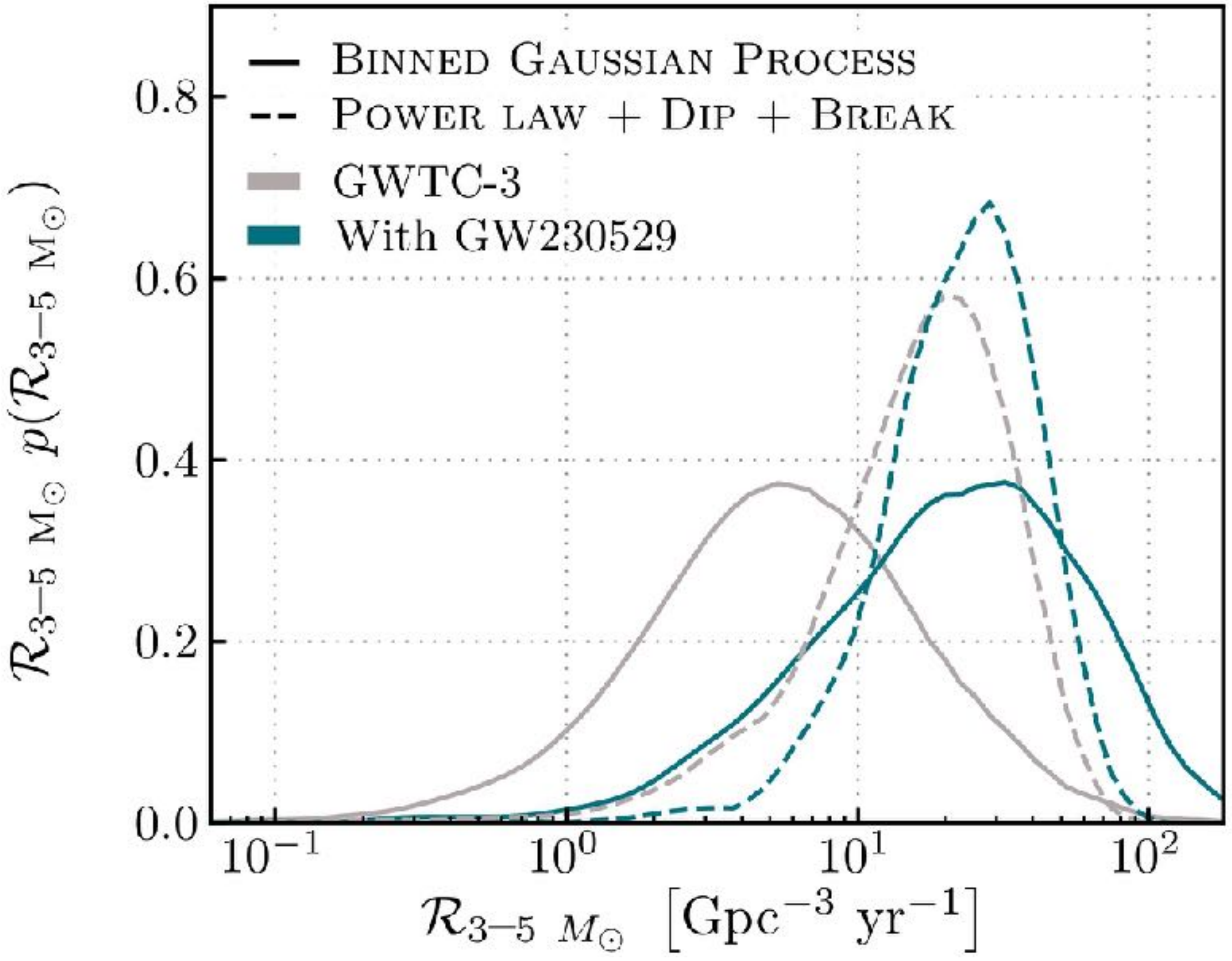
[Gompertz+, inc. PS; Fourcart+]



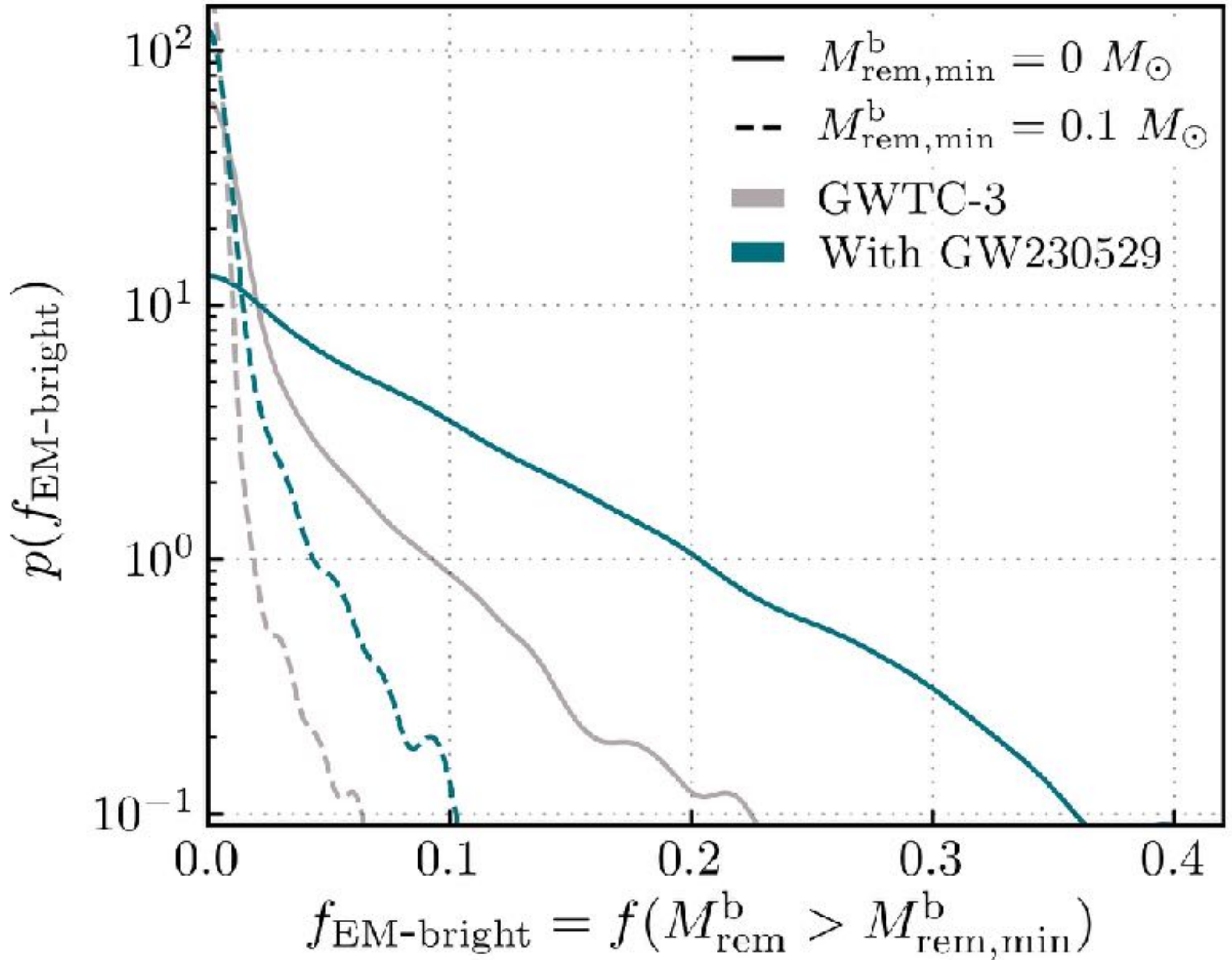
Disruption probability: 0.1 with $M_{\rm rem} \leq 0.052 M_{\odot}$ at 99% credibility

GW230529: RATES & EM PROSPECTS

- (Provisional) Update of local NSBH merger rate: $30 - 200\,\mathrm{Gpc^{-3}yr^{-1}}$ (note after O3: $18 - 44\,\mathrm{Gpc^{-3}yr^{-1}}$)



GW230529 increases the inferred lower mass gap merger rate!

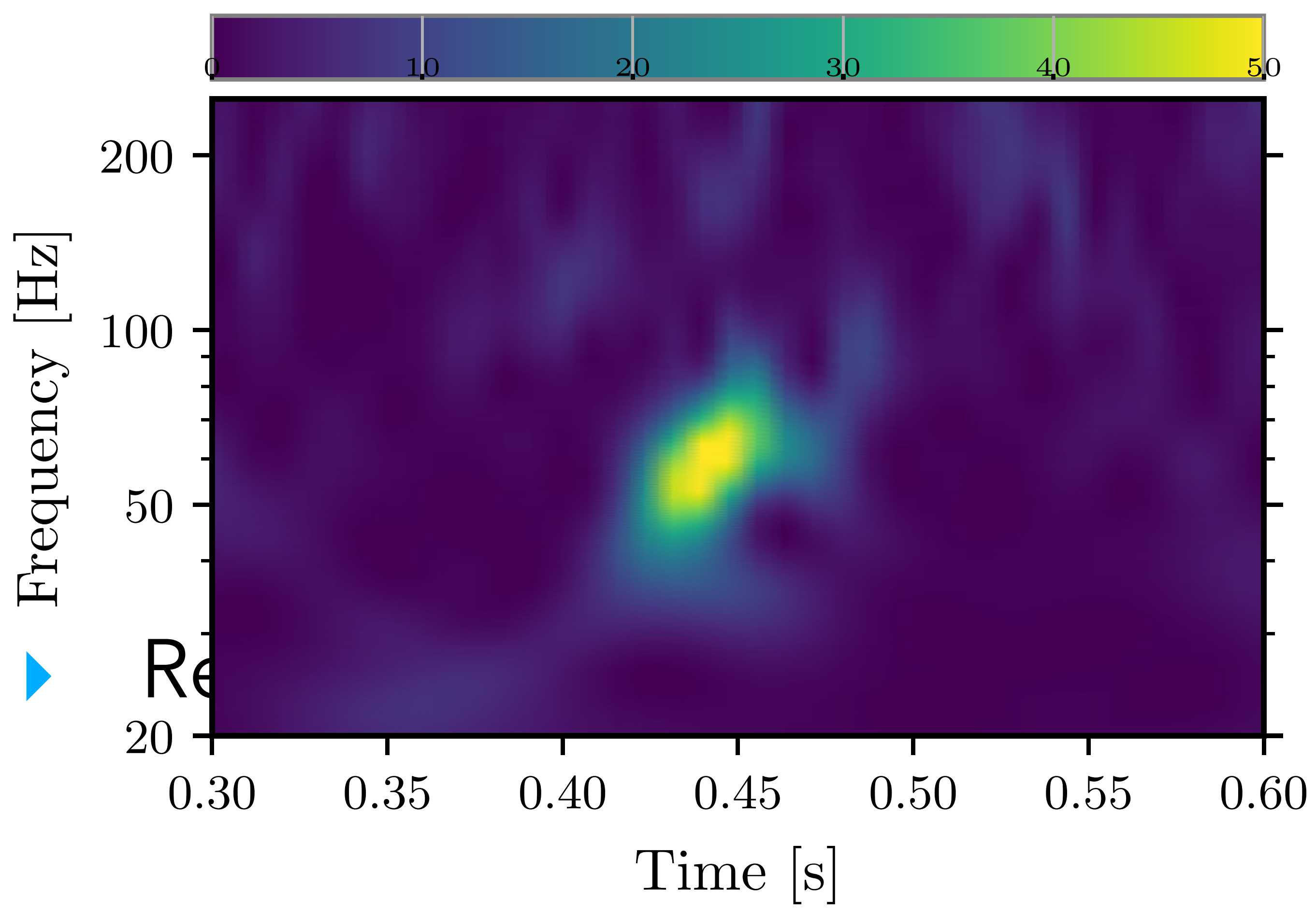


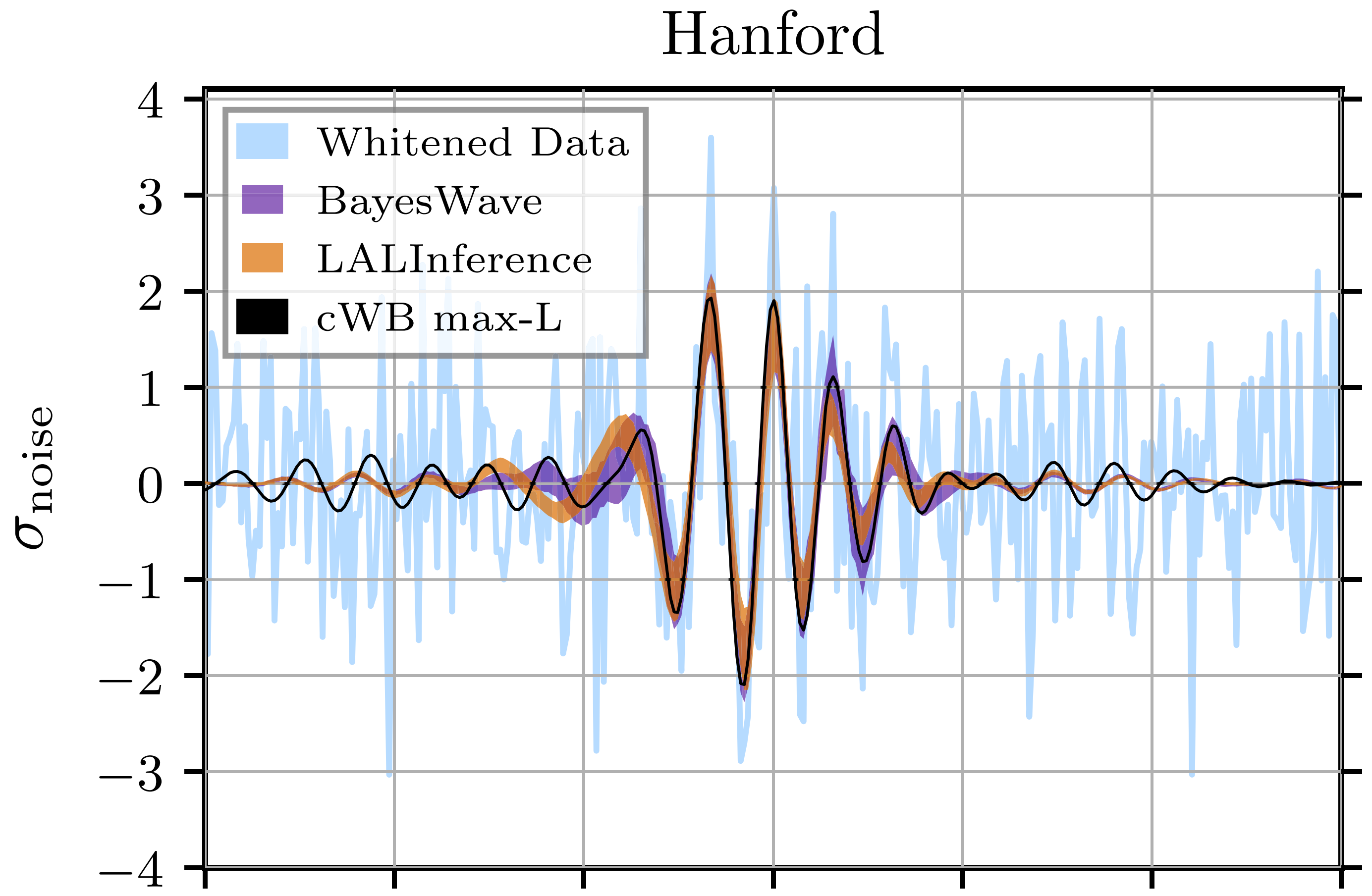
GW230529 increases the inferred fraction of NSBHs with EM counterparts!

[LVK, arXiv:2404.04248]

GW190521

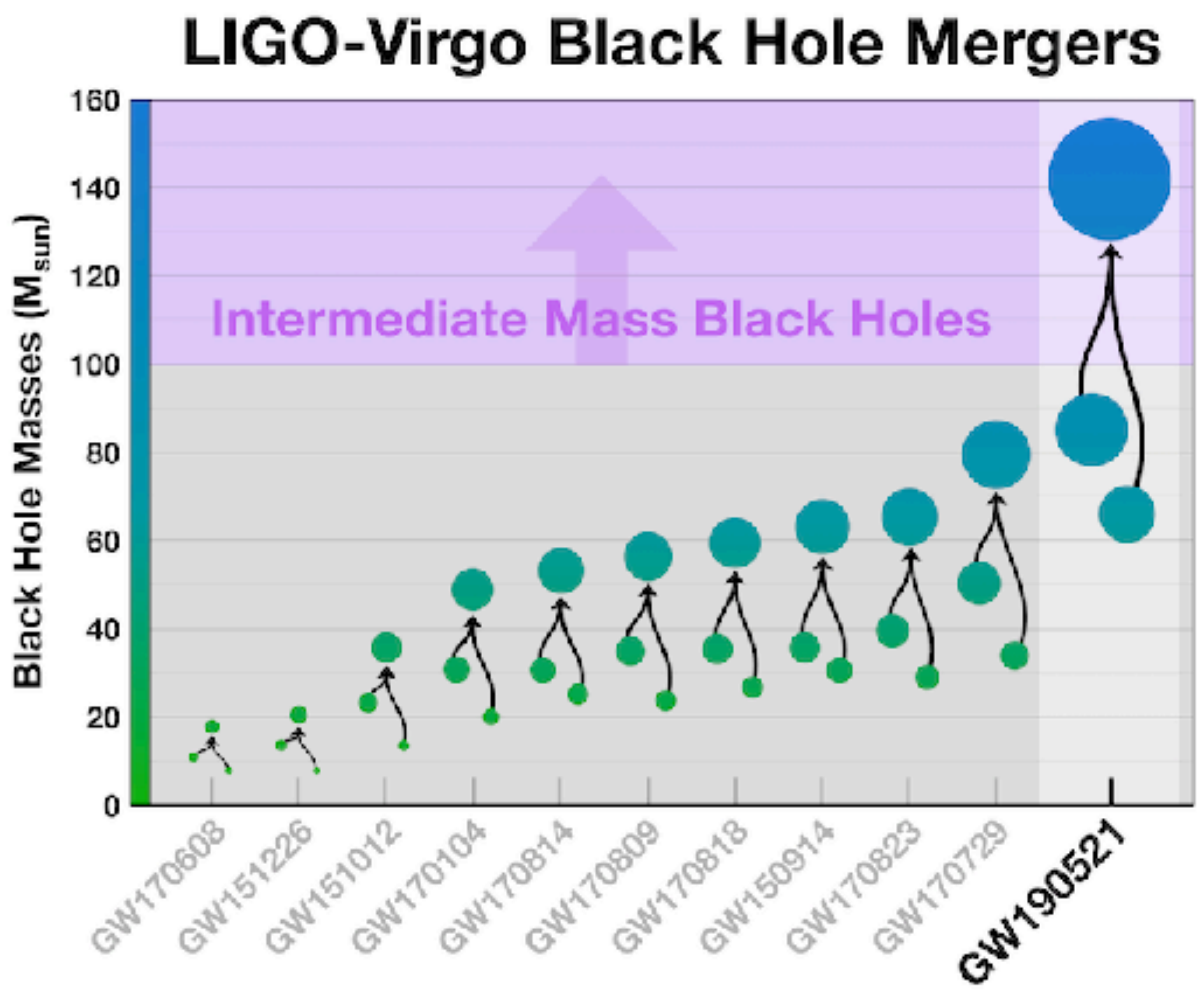
- Very massive binary black hole: $m_1 = 85^{+21}_{-14} M_\odot$ $\quad m_2 = 66^{+17}_{-16} M_\odot$

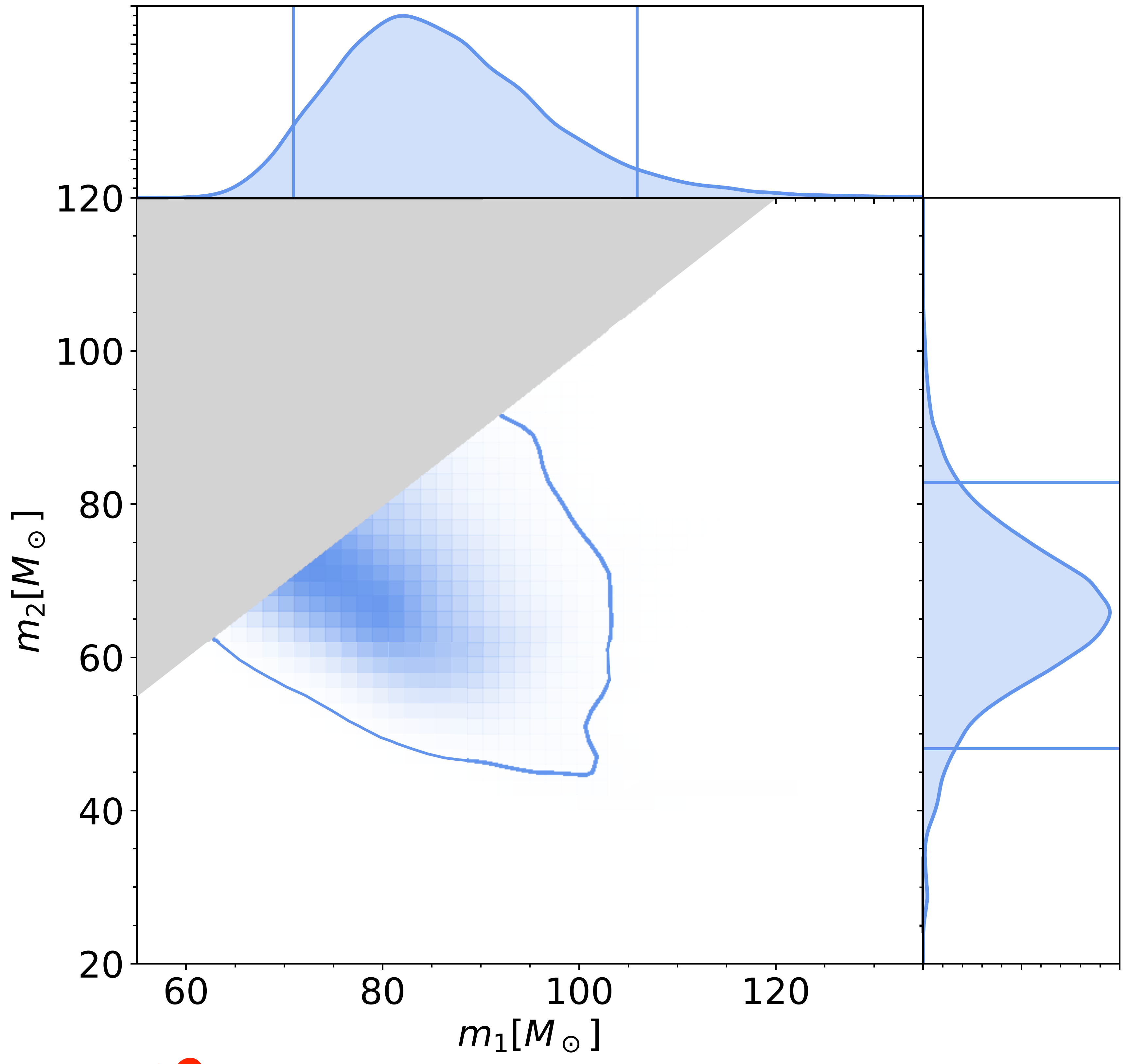




- Re

$$142^{+28}_{-16} M_\odot$$





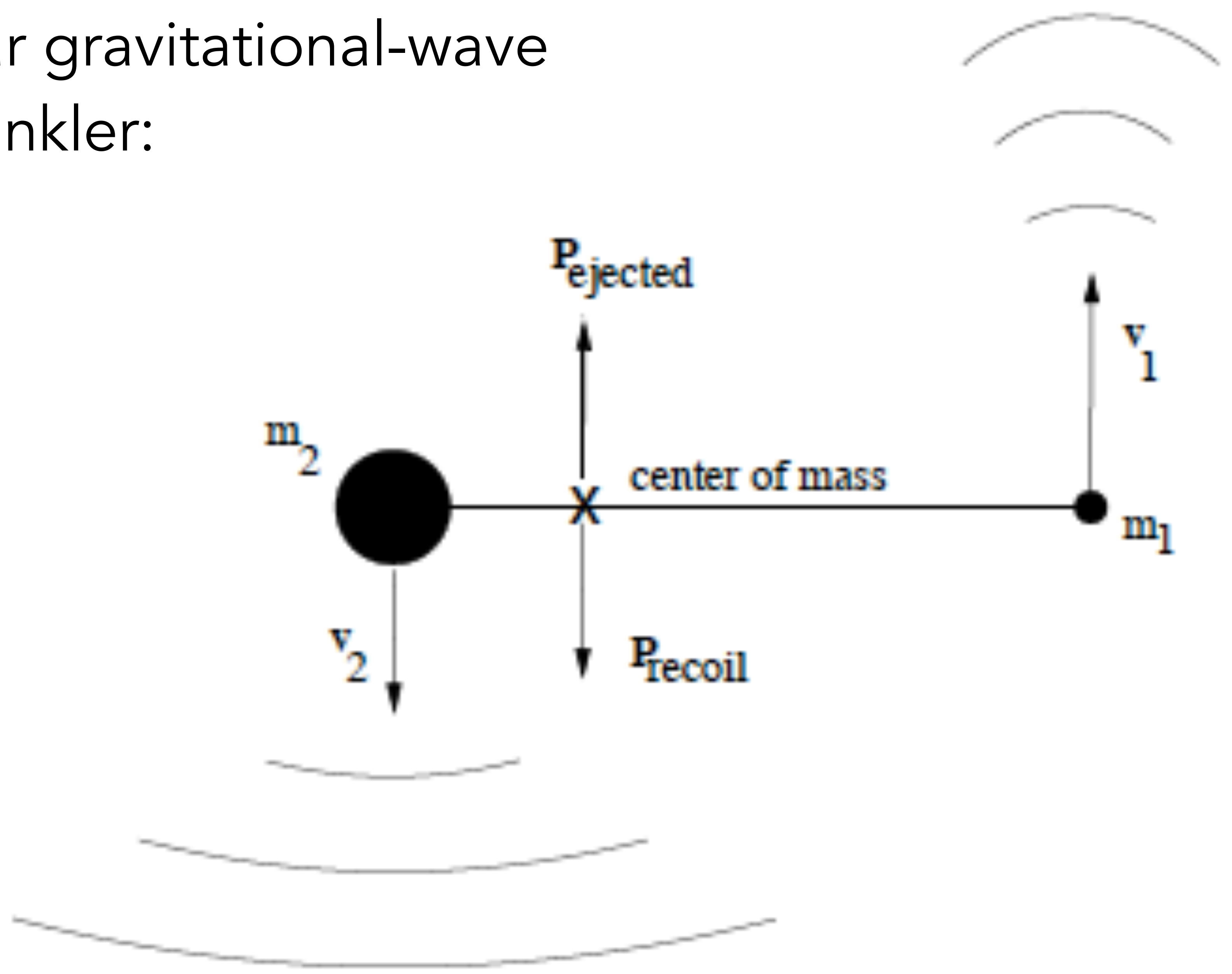
Intermediate mass black hole!

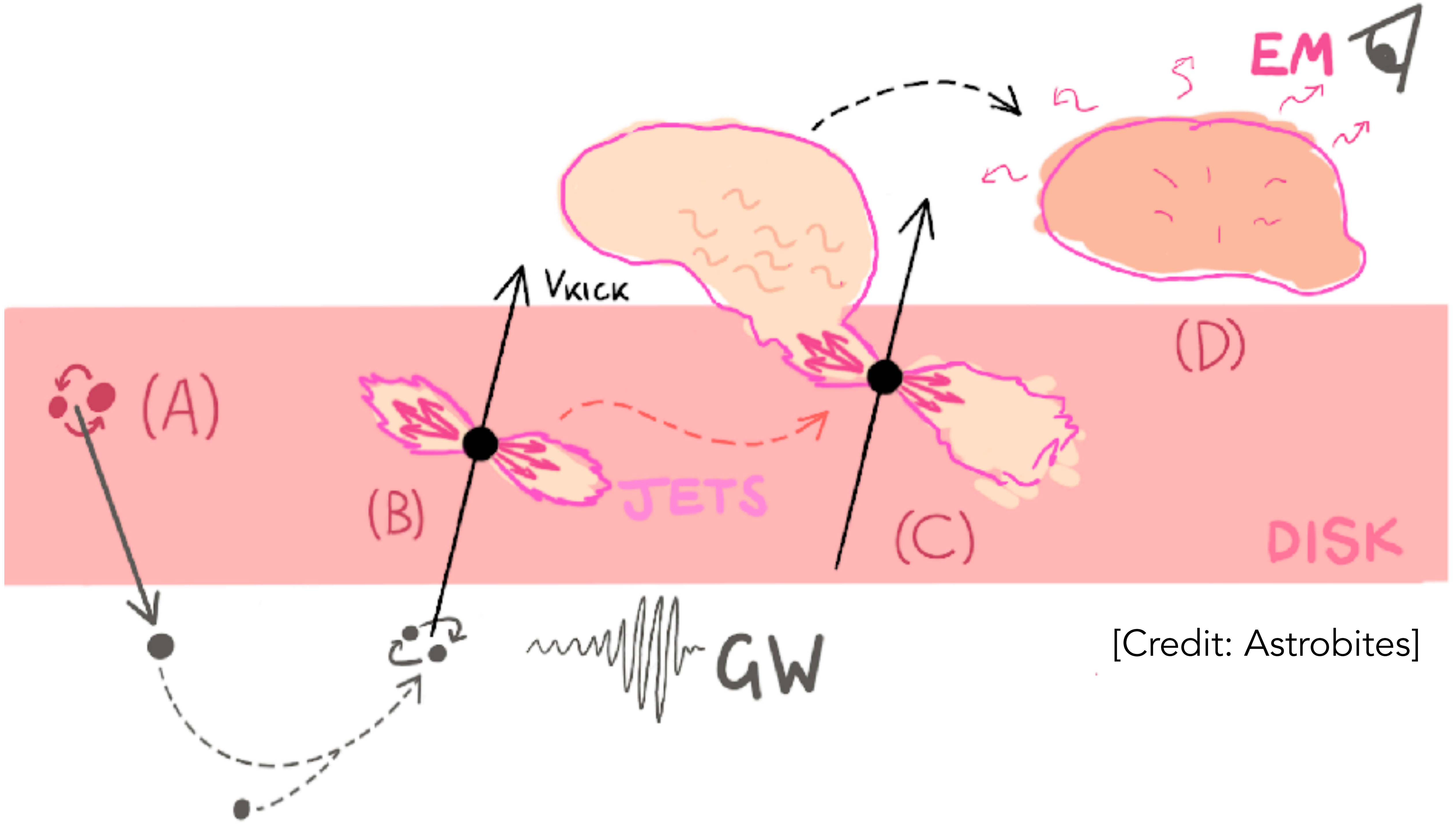
[LVC, Phys. Rev. Lett. 125, 101102 (2020)]

EM BRIGHT BBH?

- Mergers surrounded by gas (e.g. in AGN disks) can create counterparts
  - Interacting shocks, mini-disk interactions, accretion onto remnant black hole & jet formation (see e.g. Murase+ 2016, Bartos+2016, McKernan+ 2019, Rodriguez-Ramirez+ 2023, etc)
- Claim of EM counterpart to GW190521 by [Graham+, PRL 2020]
  - Redshift measurement

Your gravitational-wave sprinkler:

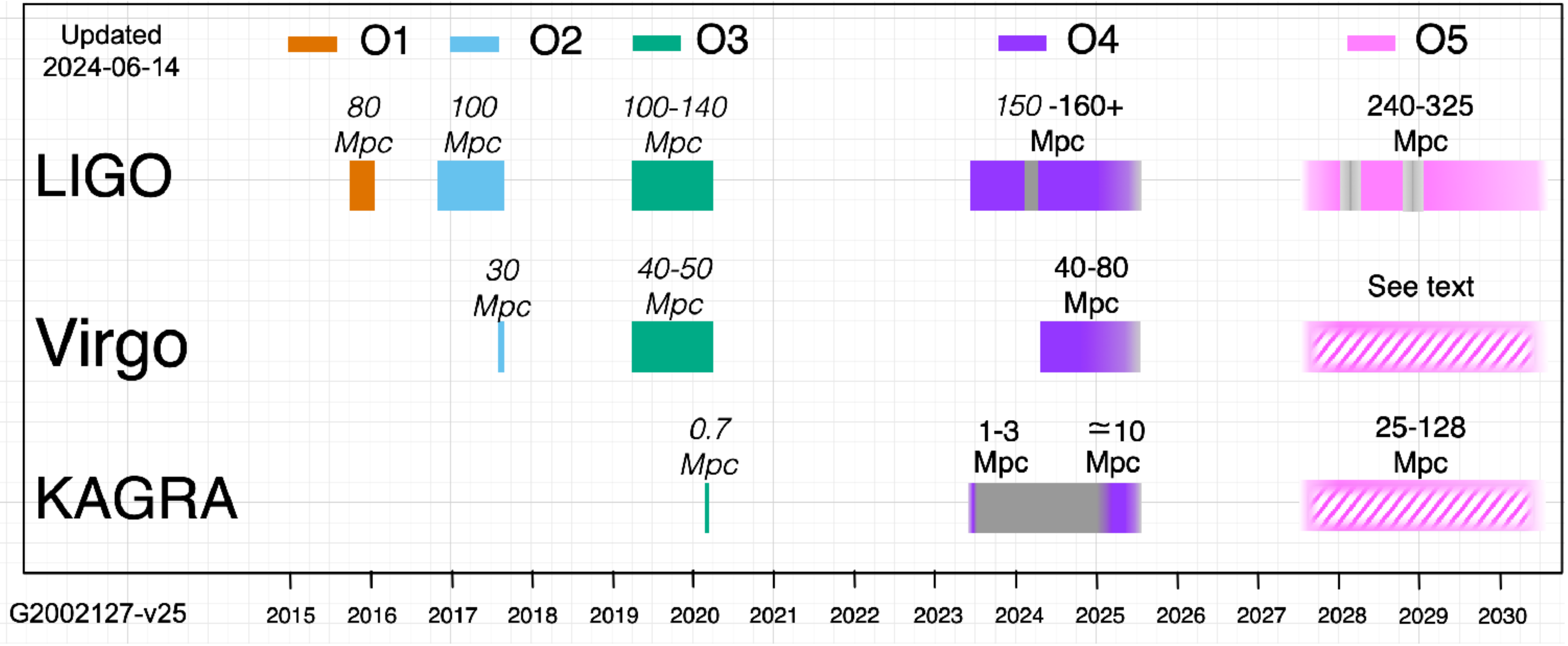




[Credit: Astrobites]

RUN EXTENSION & O5

- O4 extended until June 9th, 2025



See https://observing.docs.ligo.org/plan/

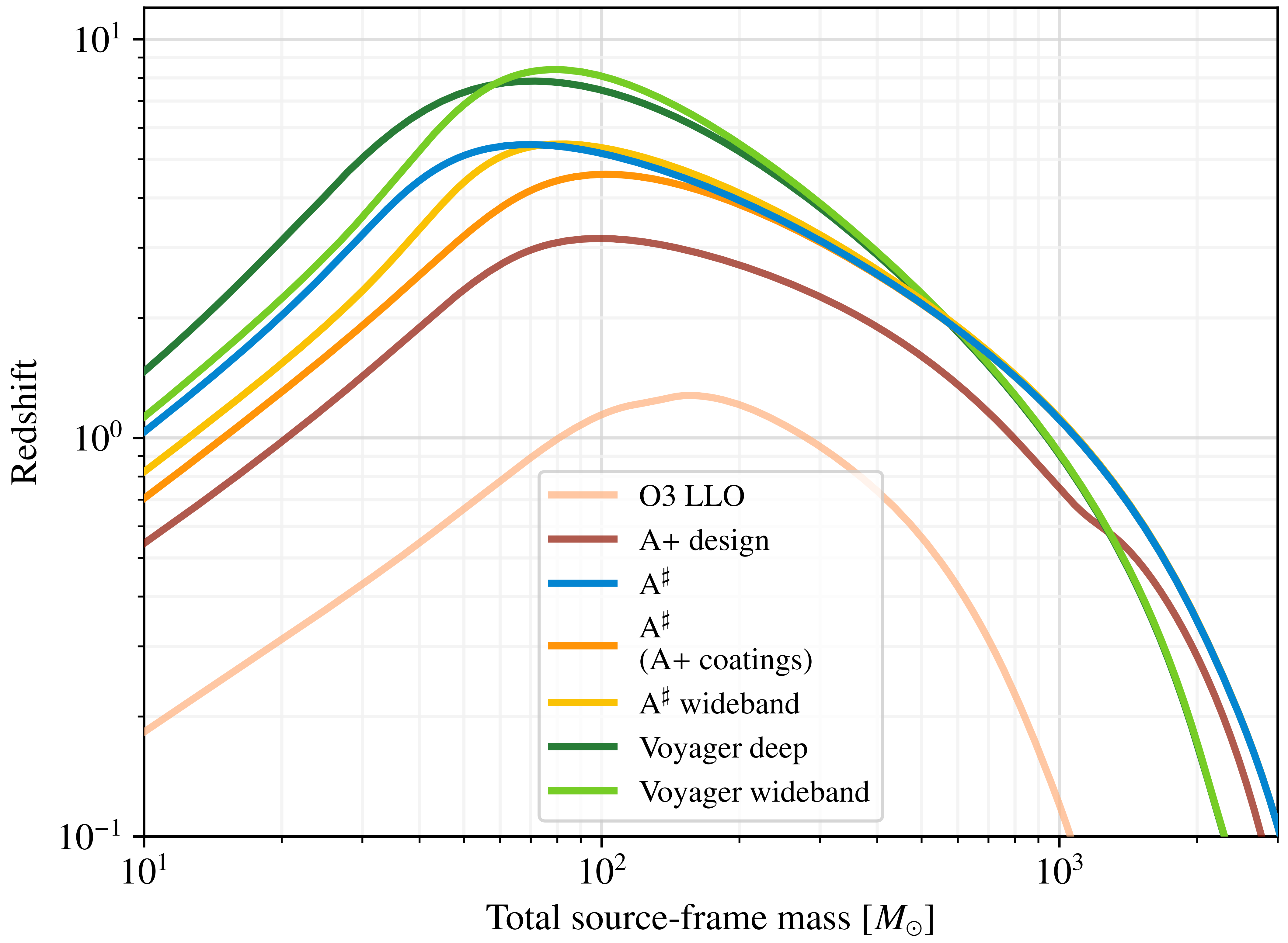
Virgo target sensitivity and entry date for O5 are currently being assessed

LIGO/VIRGO UPGRADES?

- **A#** — a possible targeted upgrade to the existing LIGO facilities (see https://dcc.ligo.org/LIGO-T2200287/public)
  - A **factor of 2 improvement in sensitivity** (larger test masses, improved seismic isolation & mirror coatings, higher laser power, etc.)
  - Similar upgrade proposal for Virgo (V_nEXT)

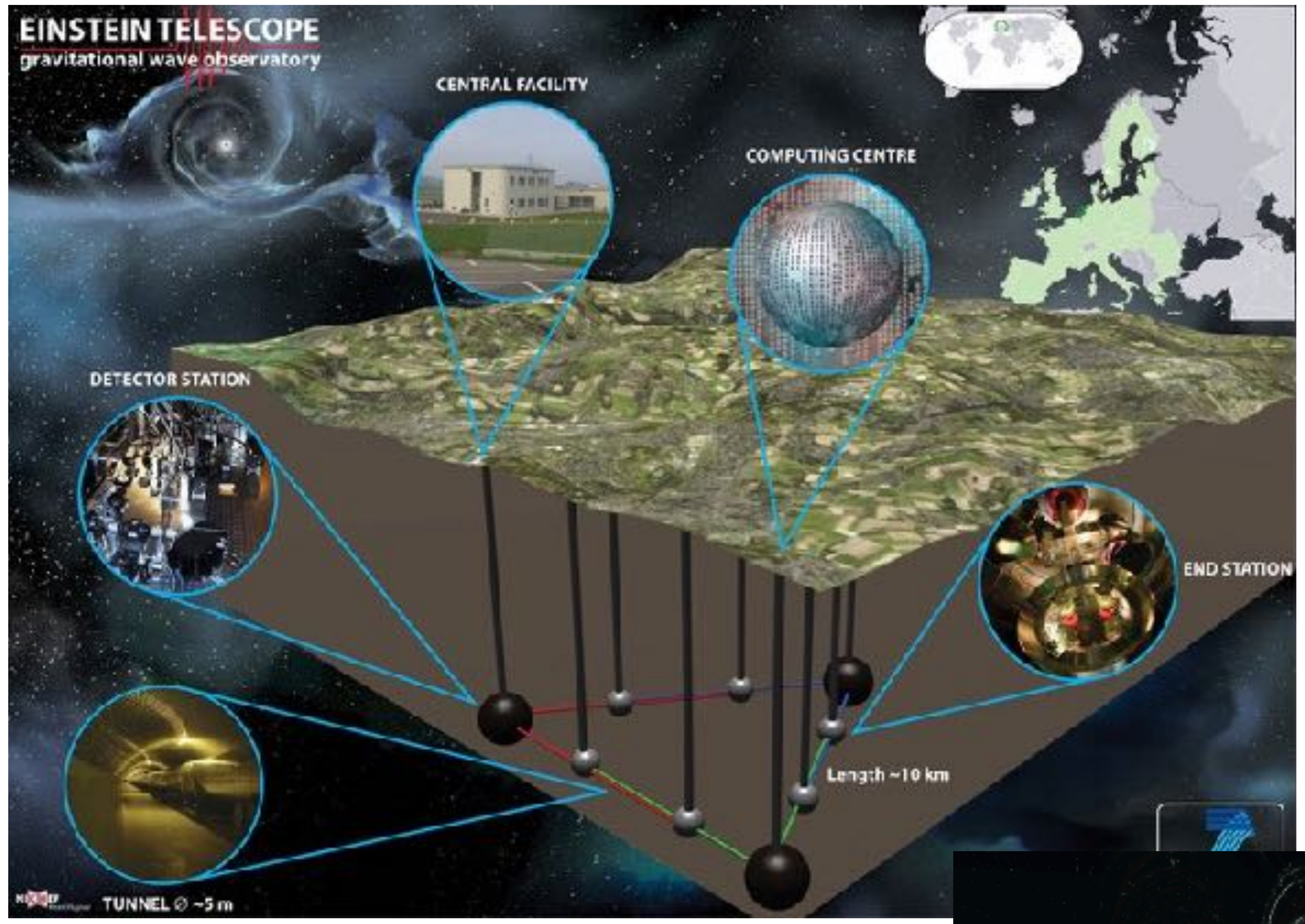
Configuration	Range [Mpc] BNS	Range [Mpc] BBH	t_{early}[min]	z_{max}	Post-Merger $\rho_{\text{pm}}^{(10)}$	Post-Merger $\rho_{\text{pm}}^{(\text{max})}$
O3 LLO	130	1200	0.3	1.3	0.4	0.6
July 2022 LLO	120	1200	0.5	1.5	0.3	0.5
A+	350	2600	2.7	3.2	1.4	2.0
A+ Wideband	290	2300	3.7	3.5	2.2	2.6
$A^\sharp$	600	3700	6.2	5.4	2.7	3.7
$A^\sharp$ (A+ coatings)	440	3000	6.1	4.6	2.7	3.4
$A^\sharp$ Wideband	490	3300	6.8	5.5	4.8	5.6
$A^\sharp$ Wideband (A+ coatings)	400	2900	6.7	4.7	4.8	5.5

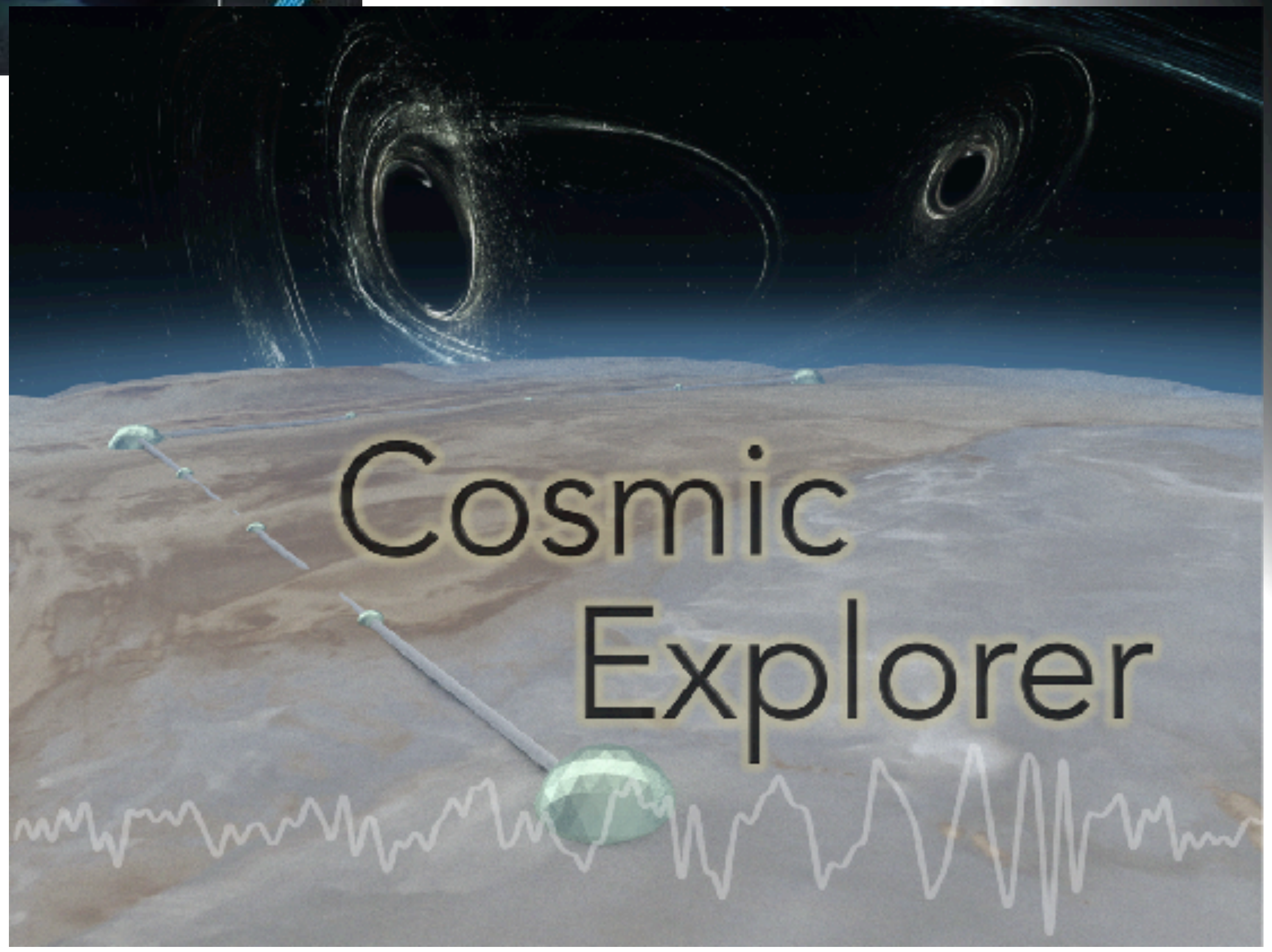
Estimated time before merger of an optimally-oriented BNS with $1.4 + 1.4\,M_\odot$ at $z = 0.03$ such SNR ≥ 8 in a given detector

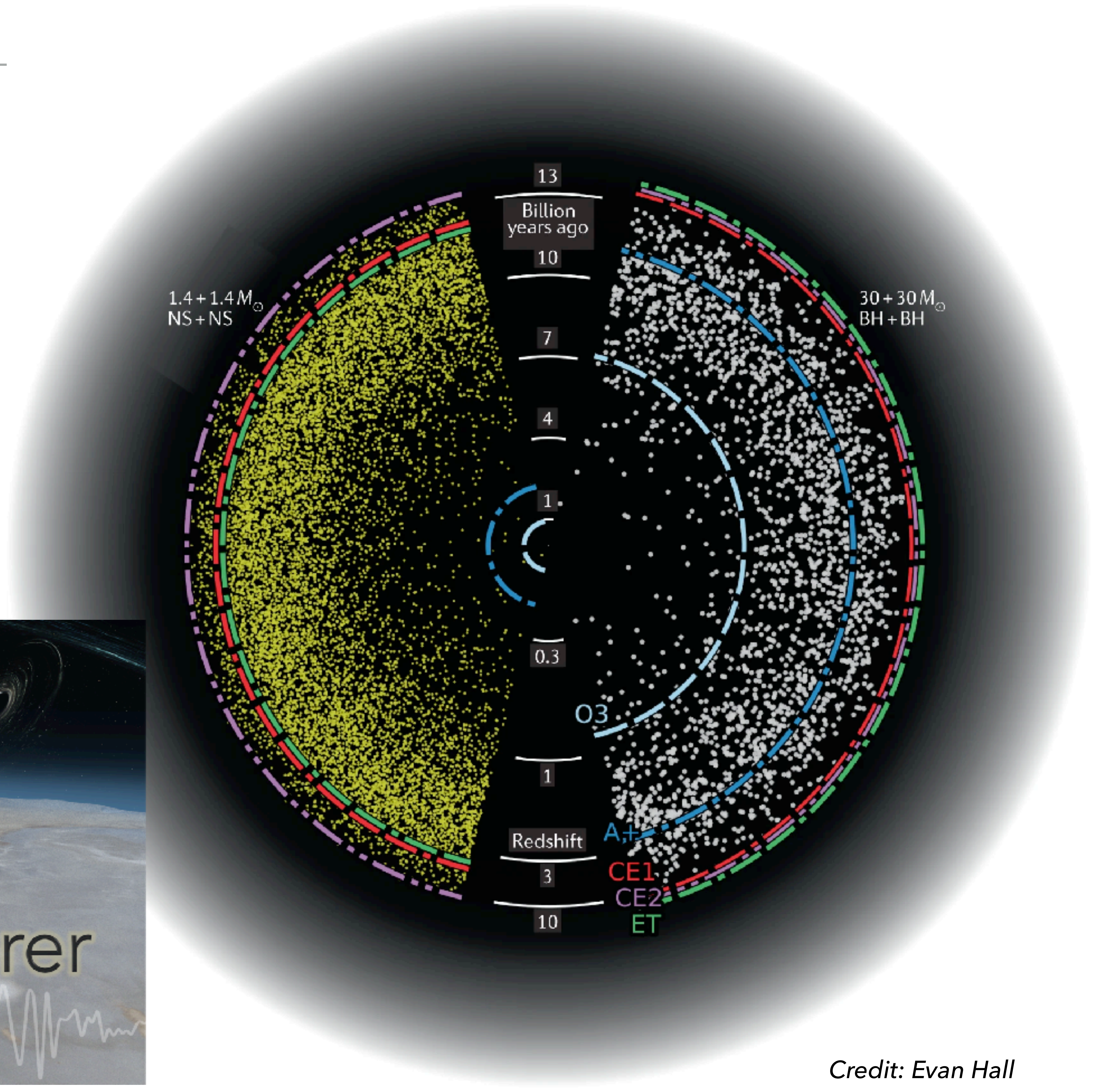


Configuration	Annual Detections BNS	Annual Detections NSBH	Annual Detections BBH
A+	69^{+138}_{-48}	291^{+291}_{-148}	1440^{+572}_{-412}
$A^\sharp$	364^{+717}_{-244}	1526^{+1517}_{-762}	6131^{+2132}_{-1739}
$A^\sharp$ (A+ coatings)	138^{+274}_{-94}	630^{+627}_{-317}	2902^{+1149}_{-826}
$A^\sharp$ Wideband	177^{+350}_{-120}	909^{+905}_{-455}	3937^{+1557}_{-1118}

THE NEXT GENERATION



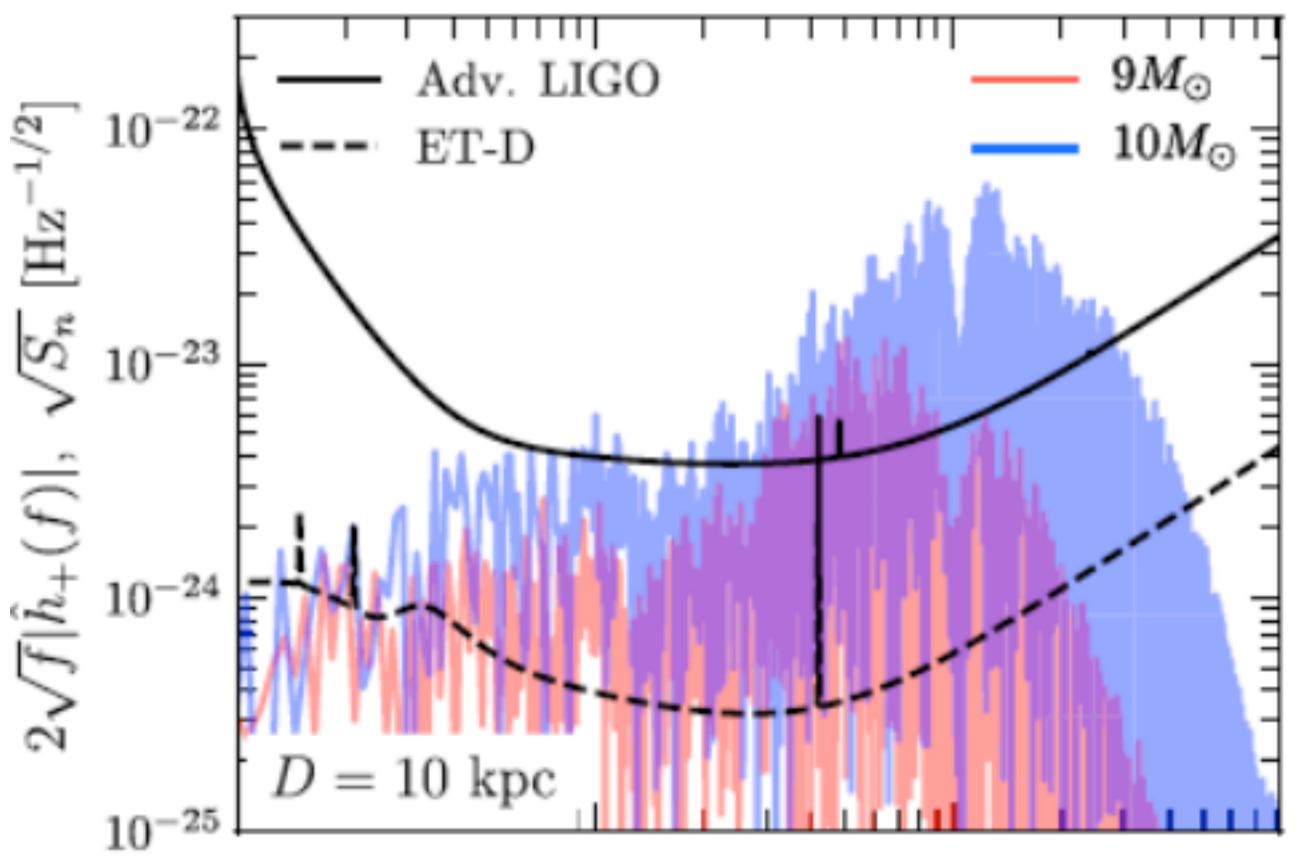




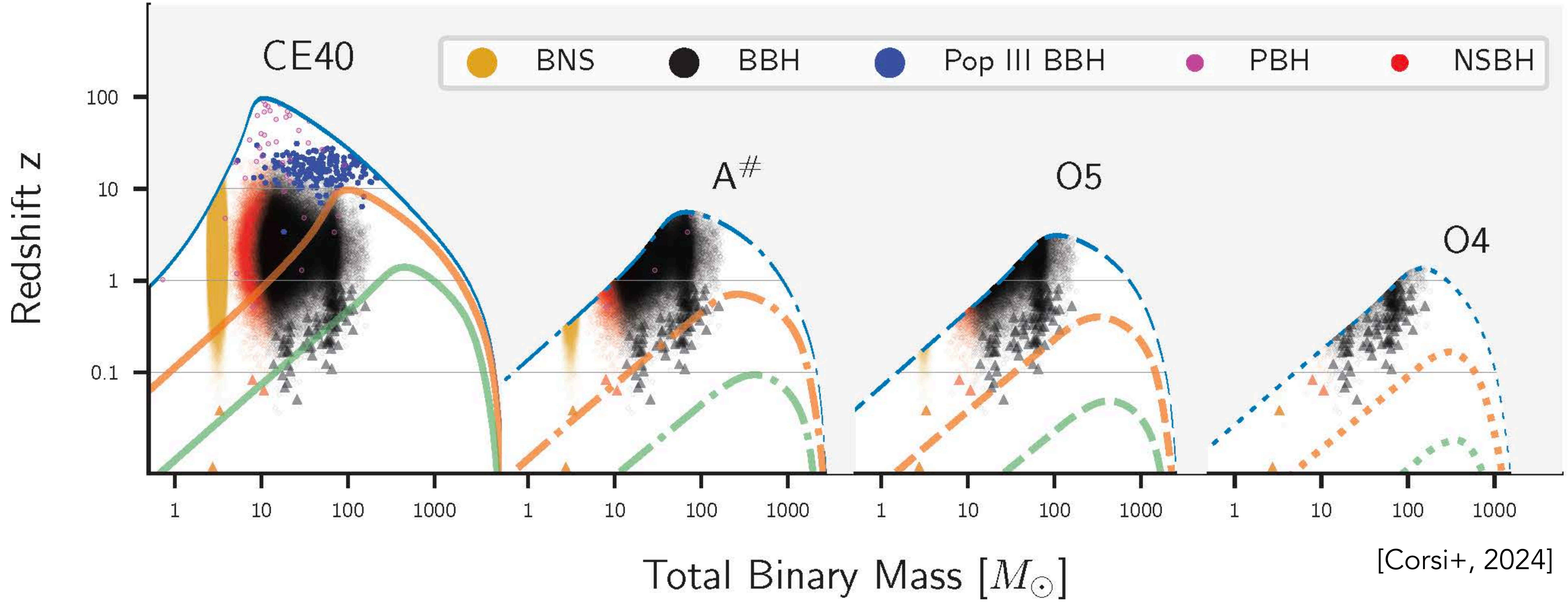
Credit: Evan Hall

THE NEXT GENERATION

- Detection rate: 10^5 - 10^6 BBH events per year; 10^5 BNS events per year
- New GW & MMA sources!
  - Access to the BNS poster merger phase
  - Possibility for discovering GWs from CCSNe & isolated neutron stars



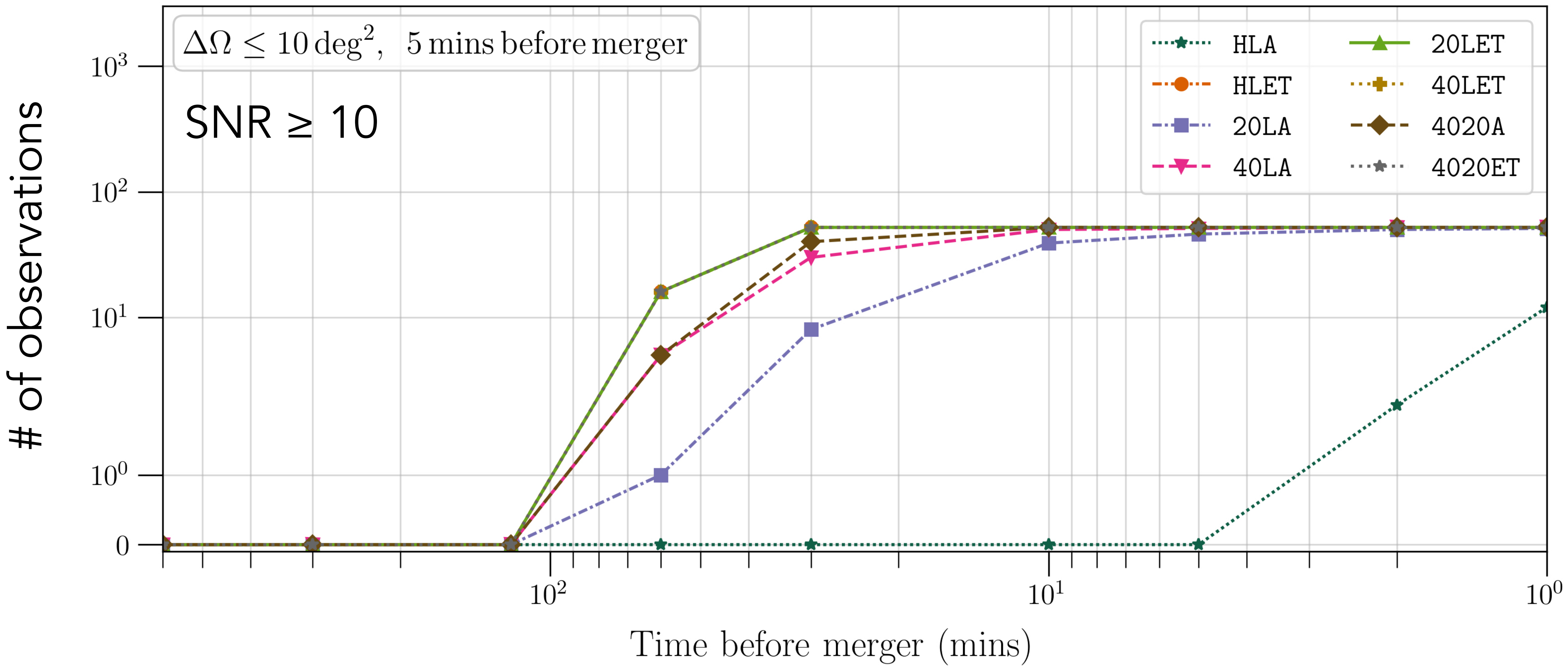
[Radice+, 2019]

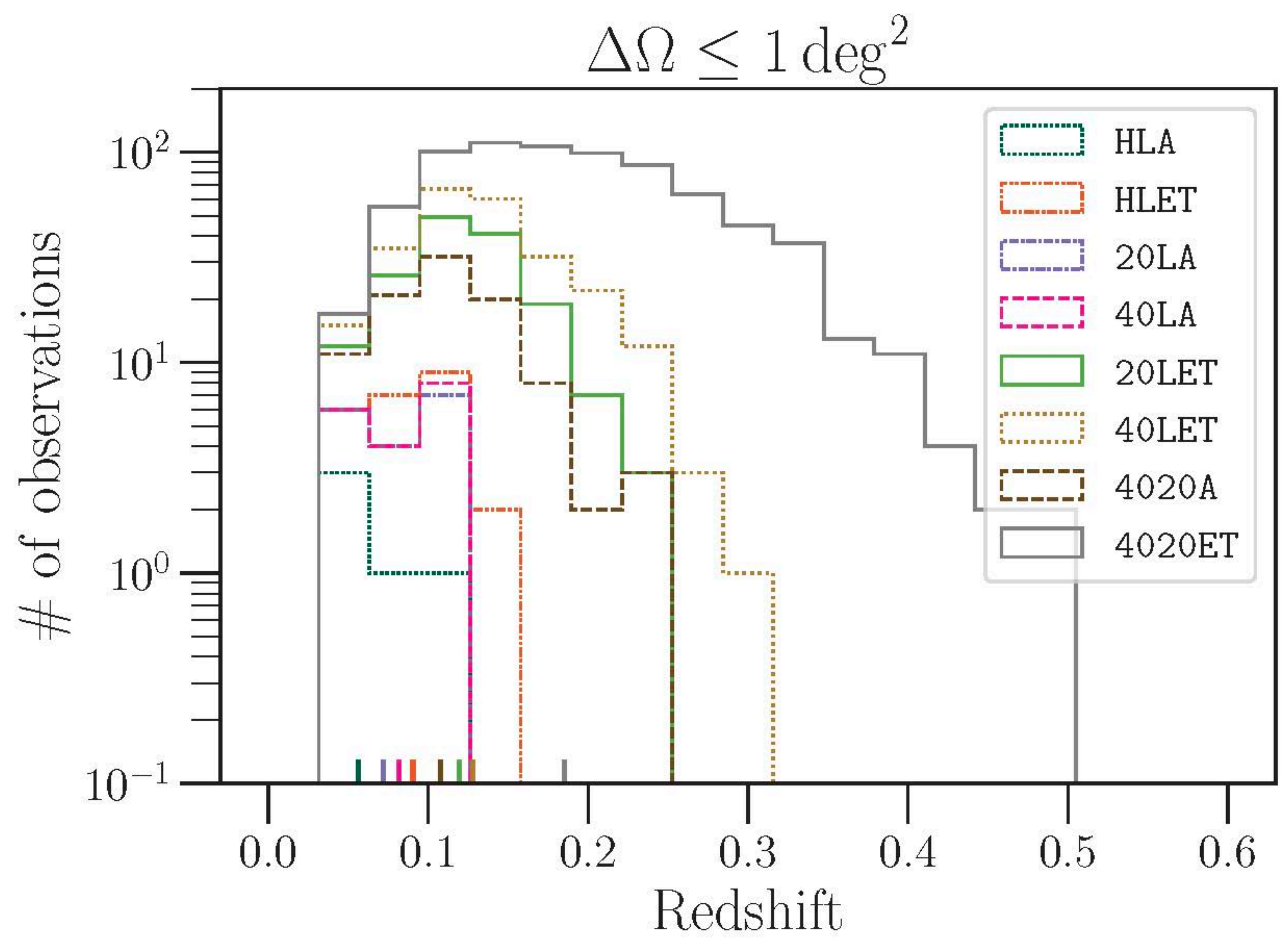


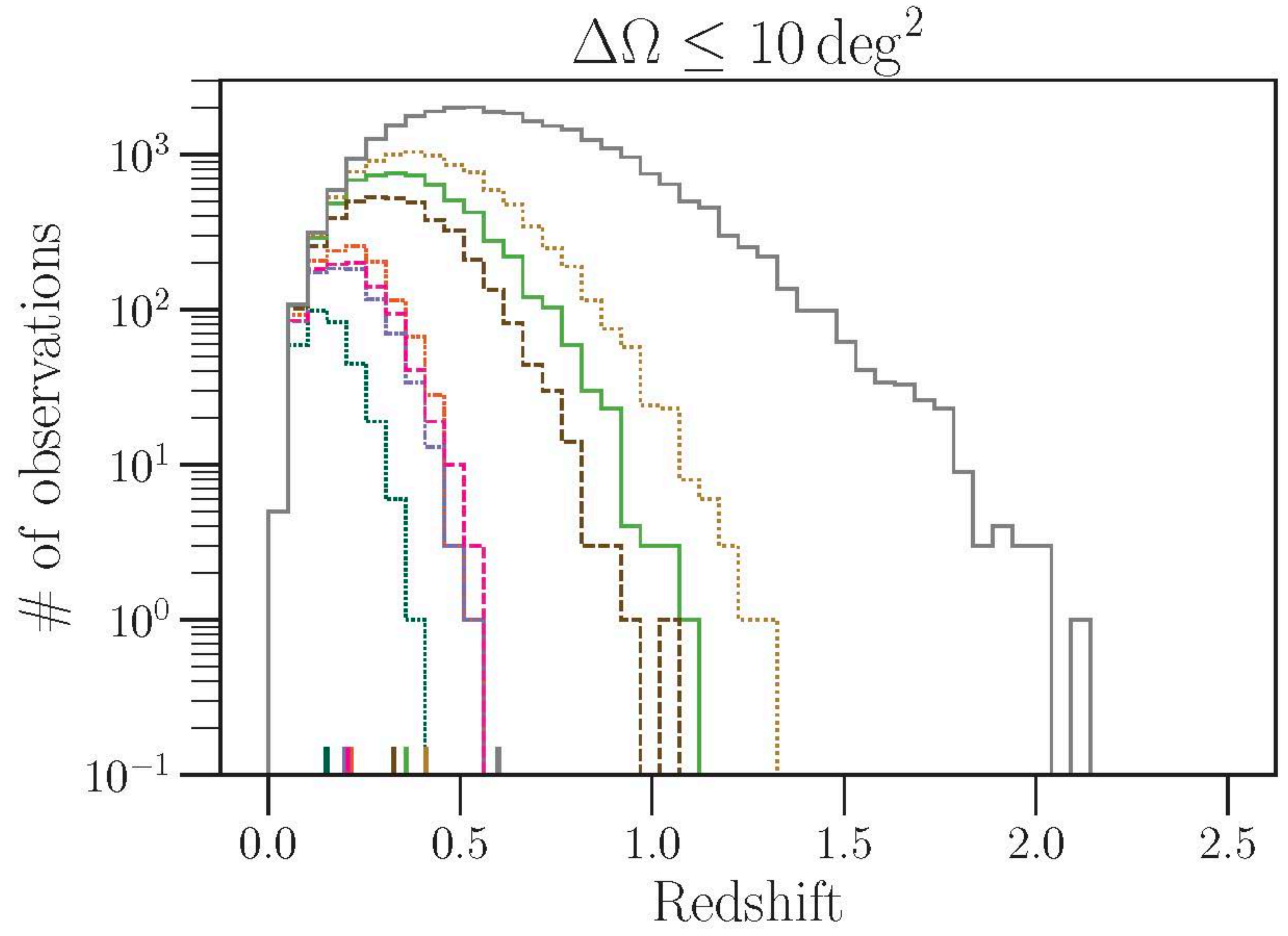
[Corsi+, 2024]

THE NEXT GENERATION

- 20/40: cosmic explorer with 20/40 km long arms
- ET: triangular Einstein telescope with 10km long arms
- H/L/A: Hanford, Livingston, Aundha with A# sensitivity
- Assumed BNS rate: $320\,\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$
- Observation time: 1 year
- Minimum frequency: 5 Hz







[Corsi+ 2024 & Gupta+ 2023]

LISA: DISCOVERING GWS IN SPACE

- Sensitivity range: 0.1mHz - 1Hz
- Access to new sources:
    - Galactic double white dwarfs
    - Supermassive black hole binaries
    - Extreme mass ratio inspirals
    - TDEs

$$f_0 \sim \frac{1}{4\pi}\left(\frac{3M}{R^3}\right)^{1/2} \sim 1\mathrm{kHz}\left(\frac{10M_\odot}{M}\right)$$