Gravitational-Waves O3 results

Séminaires du pôle A2C

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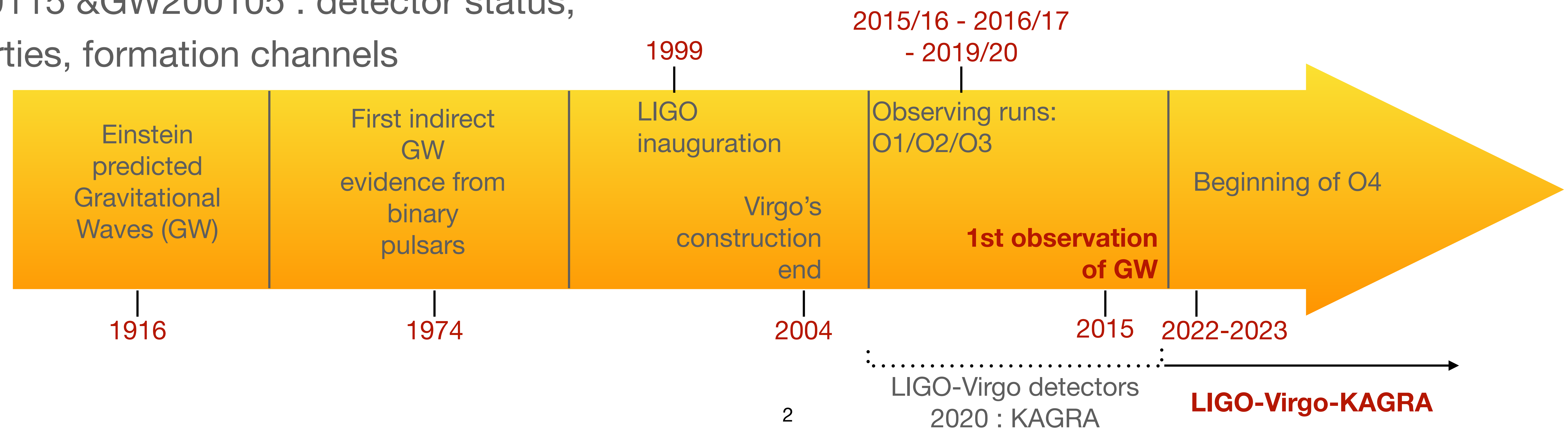
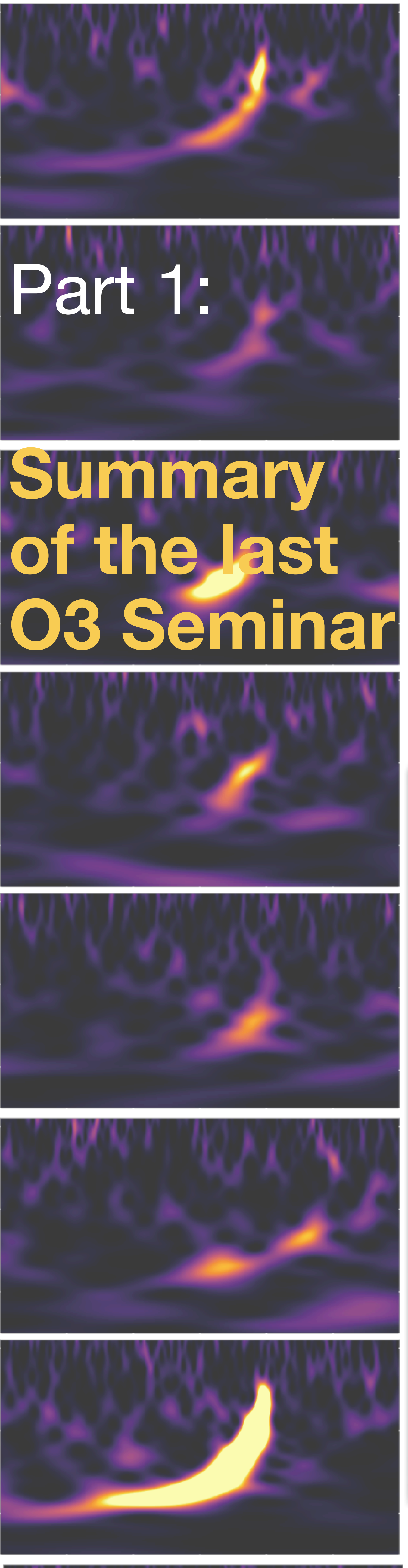
- Sub-Solar Mass Search
  - O3a results, implication for PBH
- Testing GR
  - Introduction, tests
- Burst search
  - All-Sky Search, Candidates, other searches

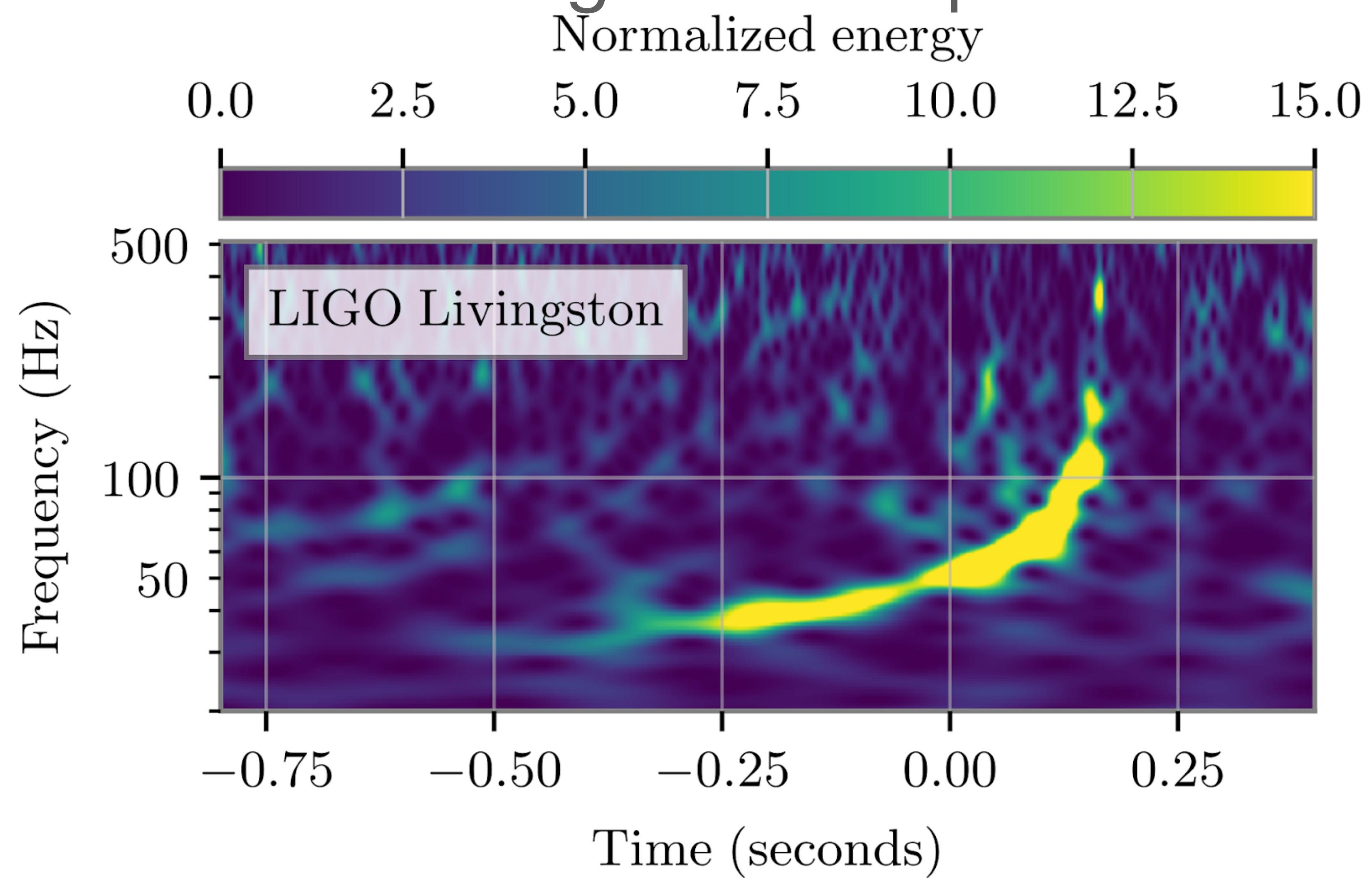




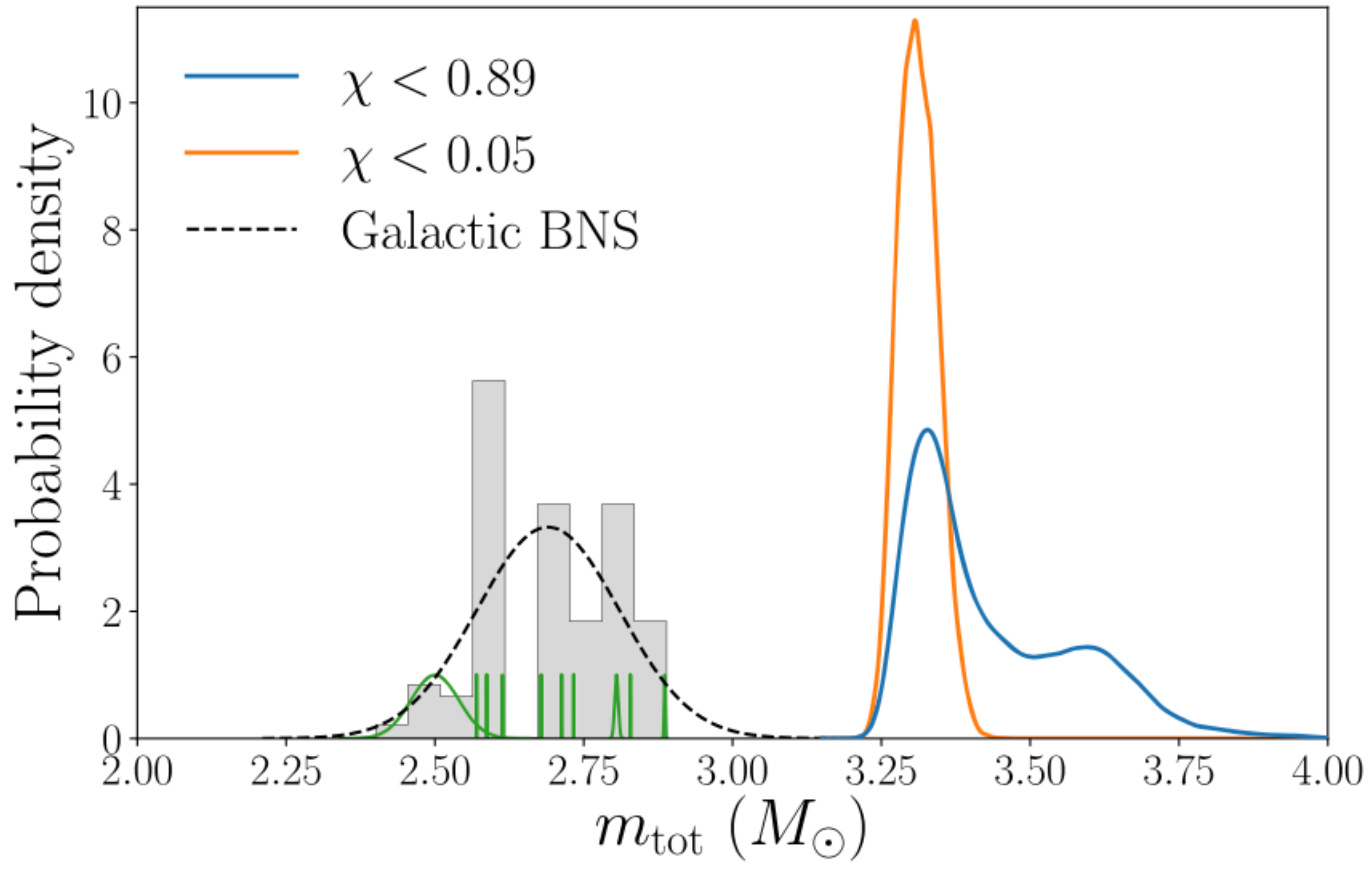
Part 1:

Summary of the last O3 Seminar

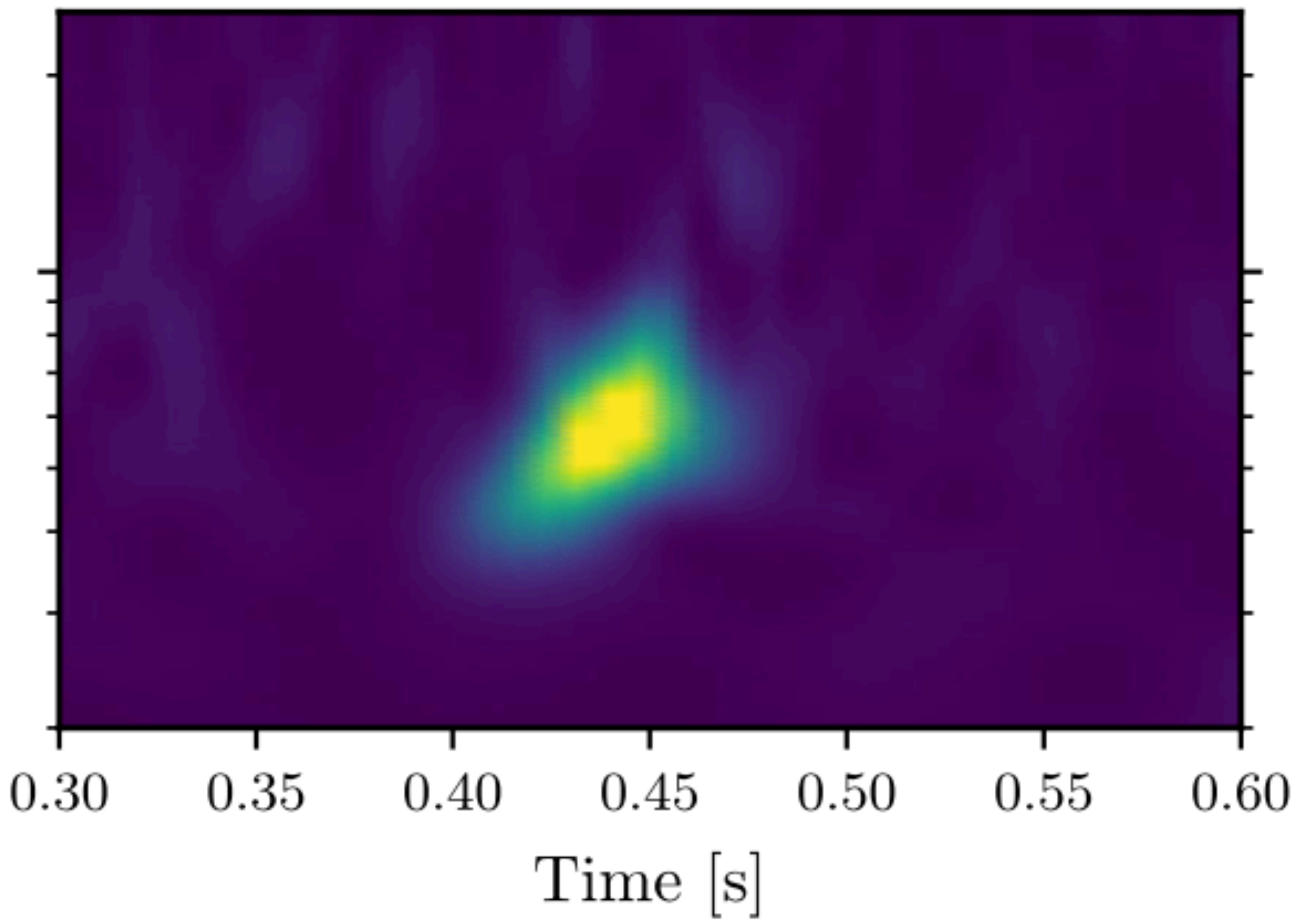
GW190412: a merger of unequal-mass BHs



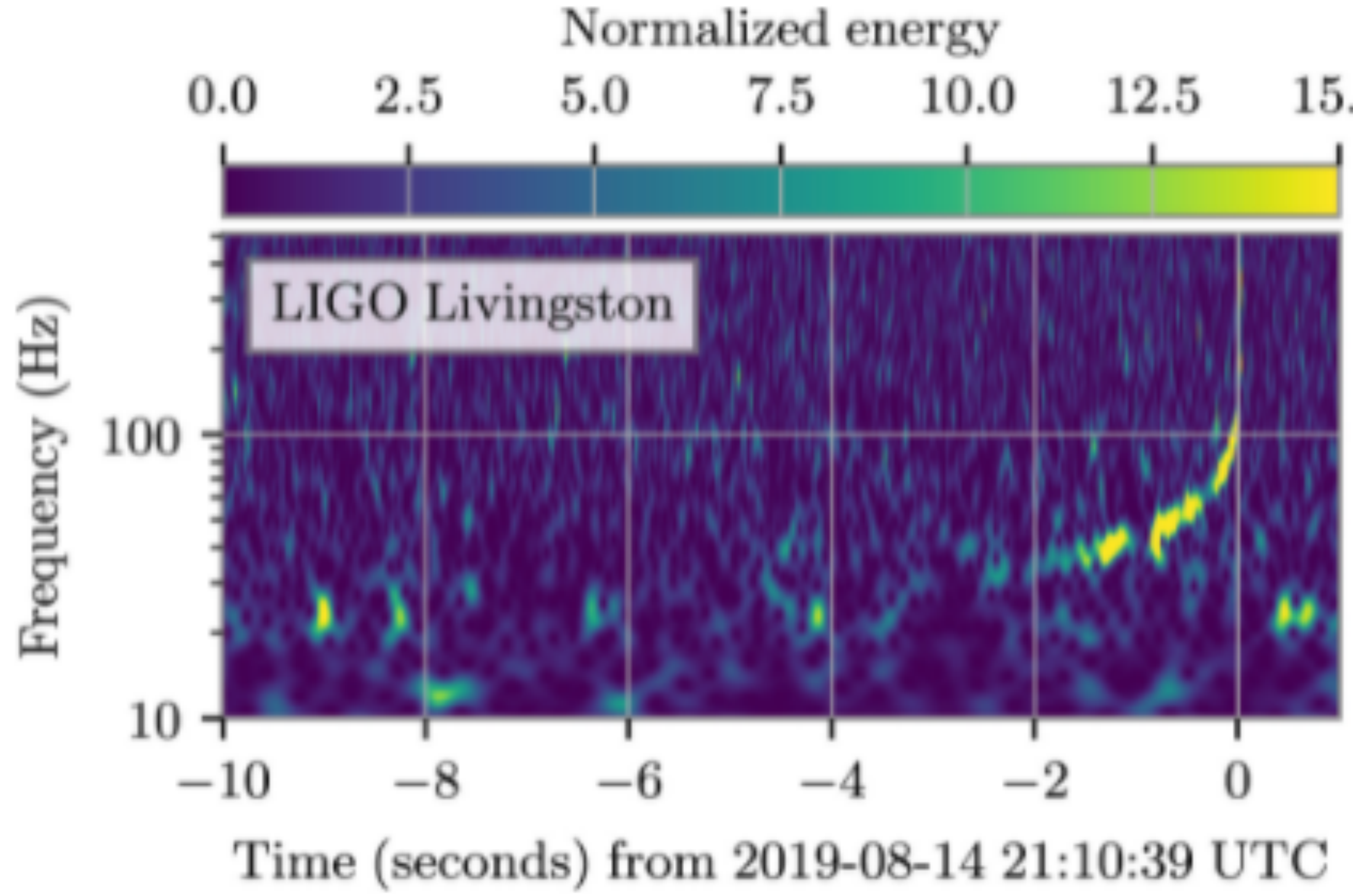
GW190425: a merger involving massive NSs



GW190521: a merger of remarkably massive BHs



GW190814: the first observed NSBH merger… maybe



Figures and title taken from Tito Dal Canton previous seminar

Introduction :
GW theory & GW ground-based detectors

CBC : Compact binary Coalescence, systems with neutron stars or black holes (BBH, BNS, NSBH)

PN : Post-Newtonian *approximation inspiral templates, waveform models of CBC.*

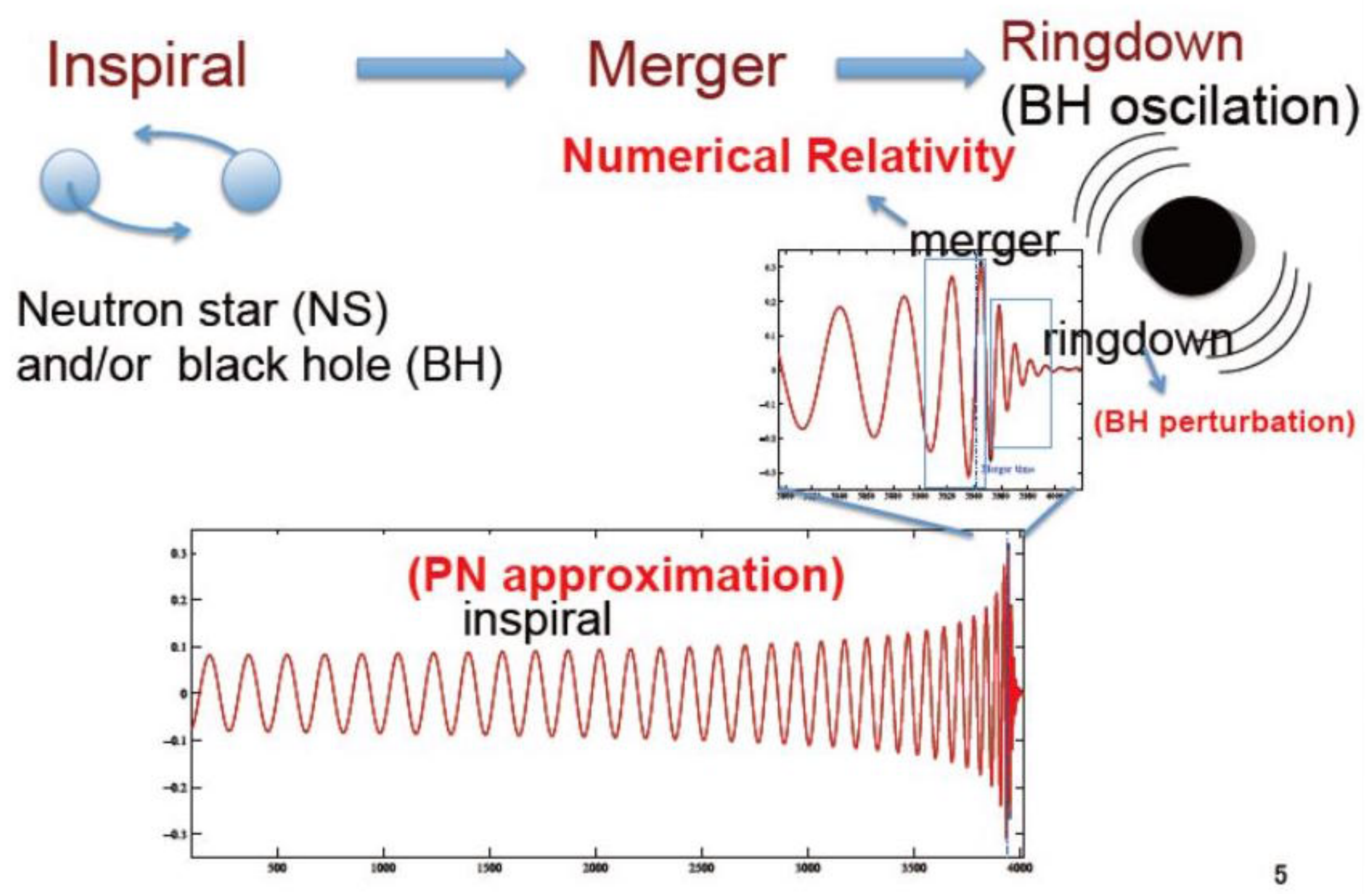


Fig1 : *Three stages of a GW event coming from CBC*

Fig2 : *LIGO (top right & bottom left), Virgo (bottom right)*

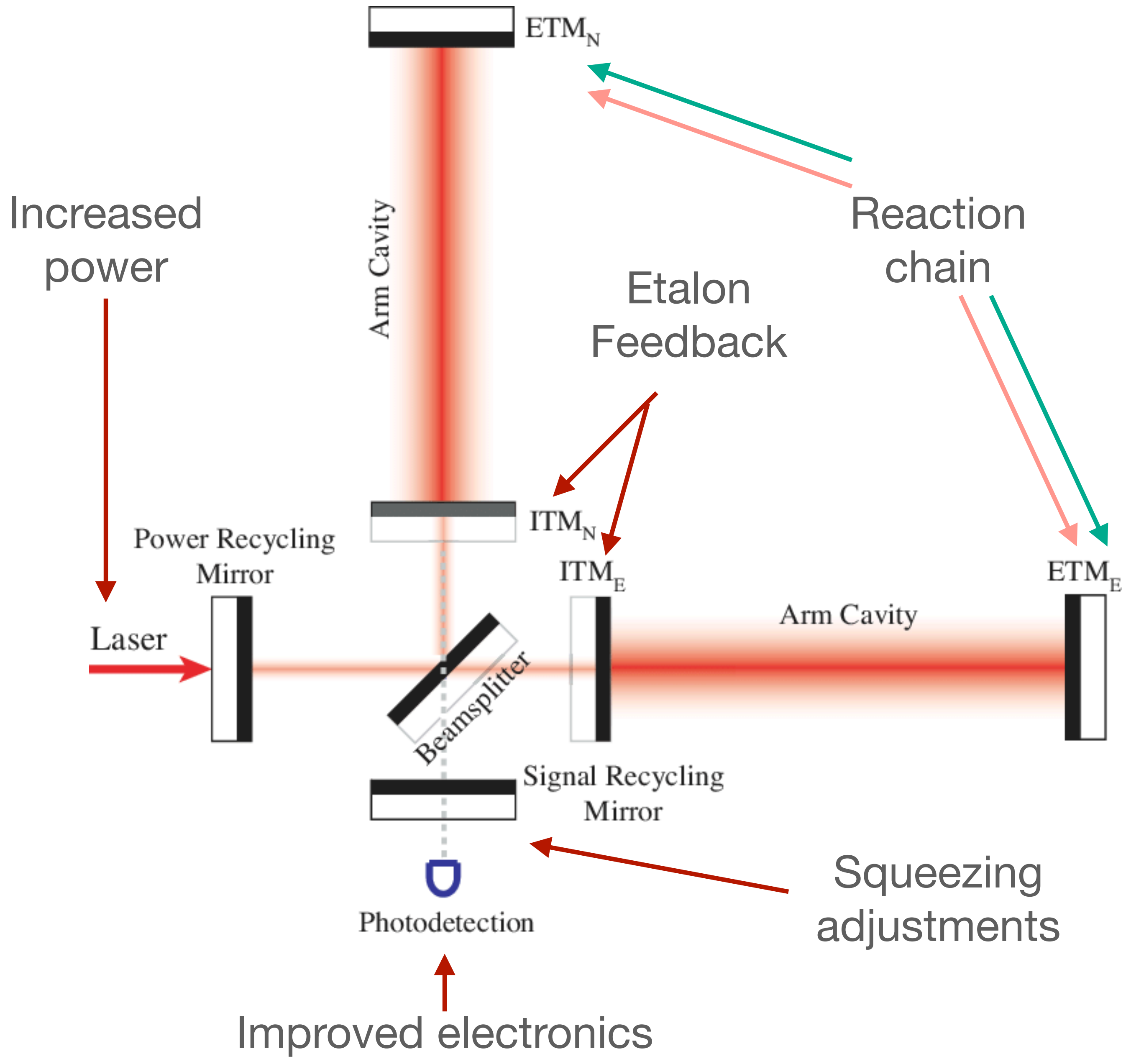
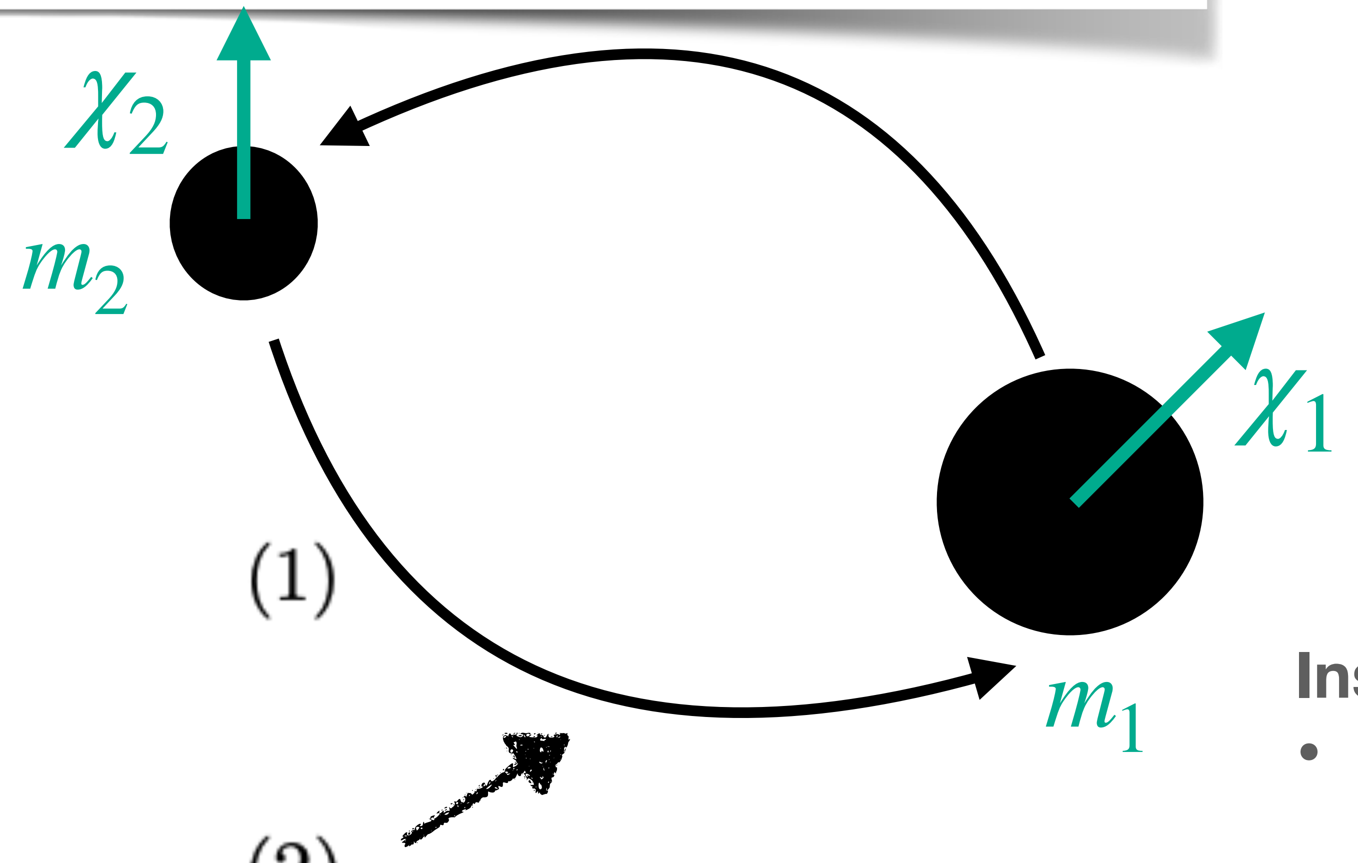


Fig3 : *Laser interferometer setup and O3 improvements*

- Some useful formula :



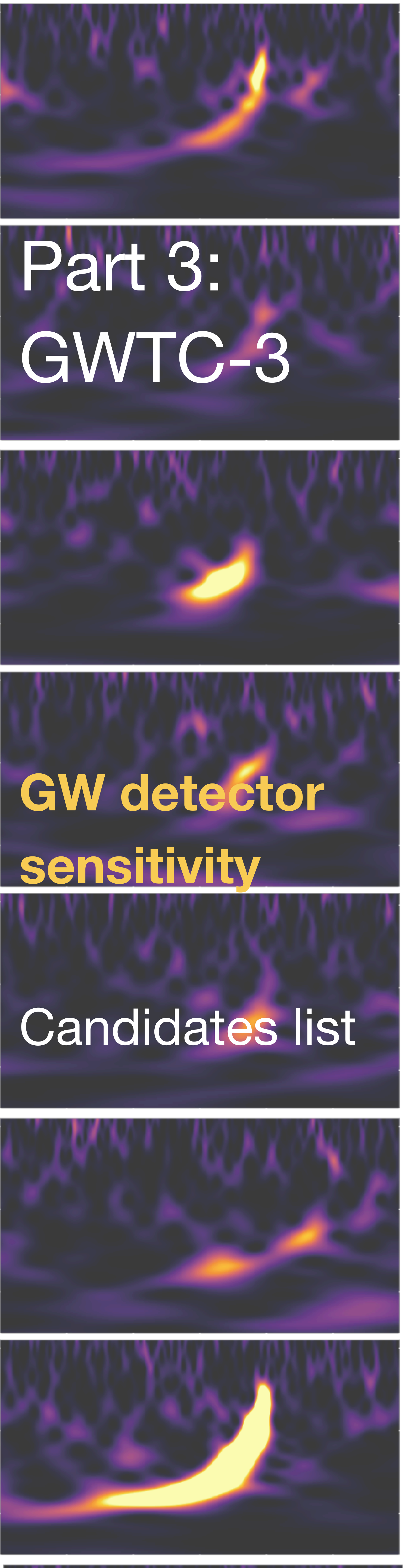
$$\mathcal{M} = (m_1 m_2)^{3/5}/(m_1 + m_2)^{1/5}\,. \qquad (1)$$

$$\chi_{\rm eff} = \frac{(m_1 \boldsymbol{\chi_1} + m_2 \boldsymbol{\chi_2}) \cdot \hat{\boldsymbol{L}}}{m_1 + m_2}, \qquad (2)$$

$$q = m_2/m_1 \qquad (3)$$

Instrument improvement during O3:
- Adjustment of in-vacuum squeezing for LIGO Hanford and Livingston
- Increase of laser power for Virgo

After October commissioning break:
- LIGO: reduction of scattered light noise; implementation of reaction-chain tracking …
- Virgo: Increased laser power; improved electronics …



GWTC-3 :

Detector sensitivity

Better sensitivity and a high duty cycle :
142 days with at least one detector observing

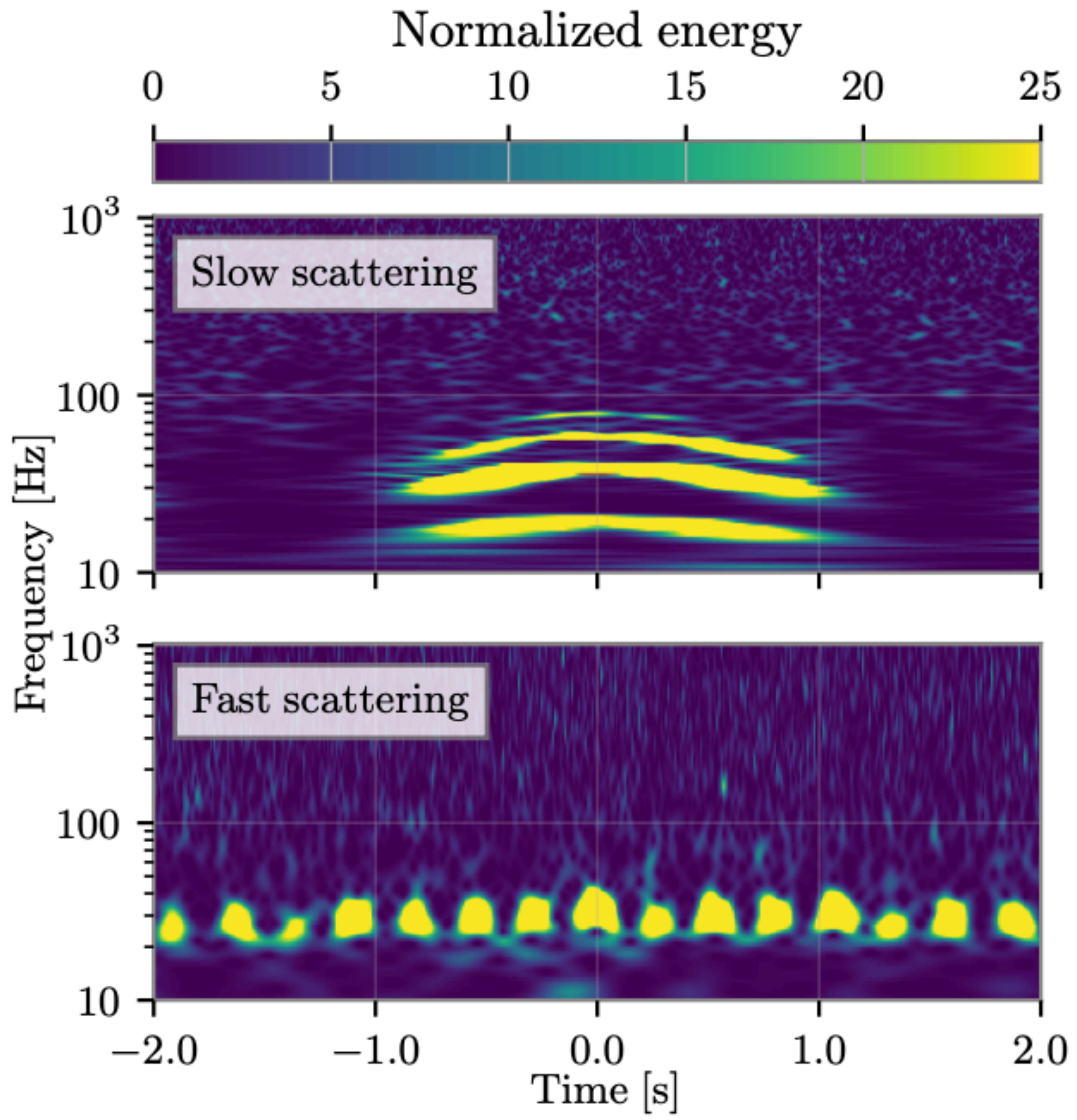


Fig4 : *Spectrograms of glitches caused by scattered-light* *

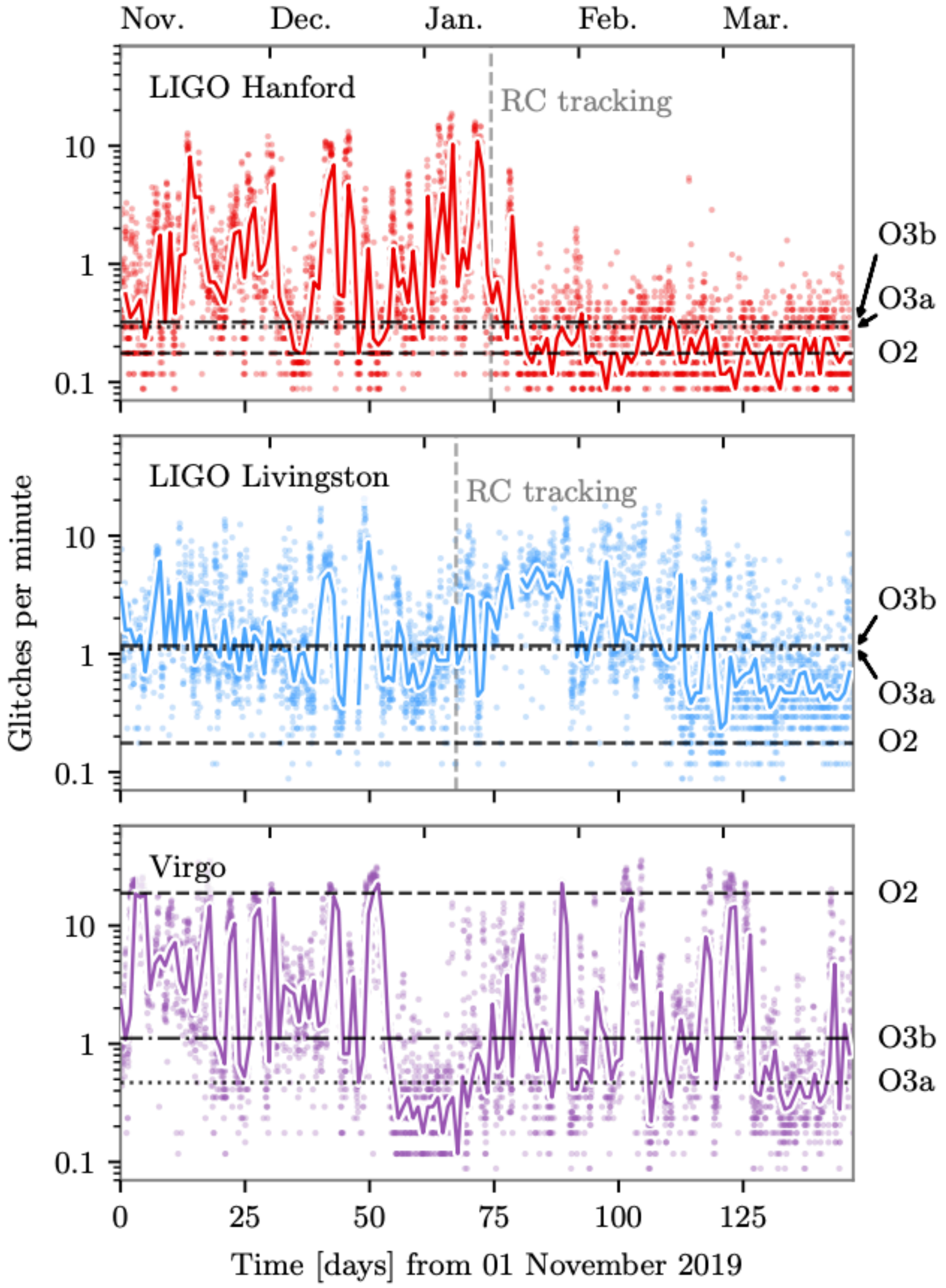


Fig5 : *Rate of single-interferometer glitches* *

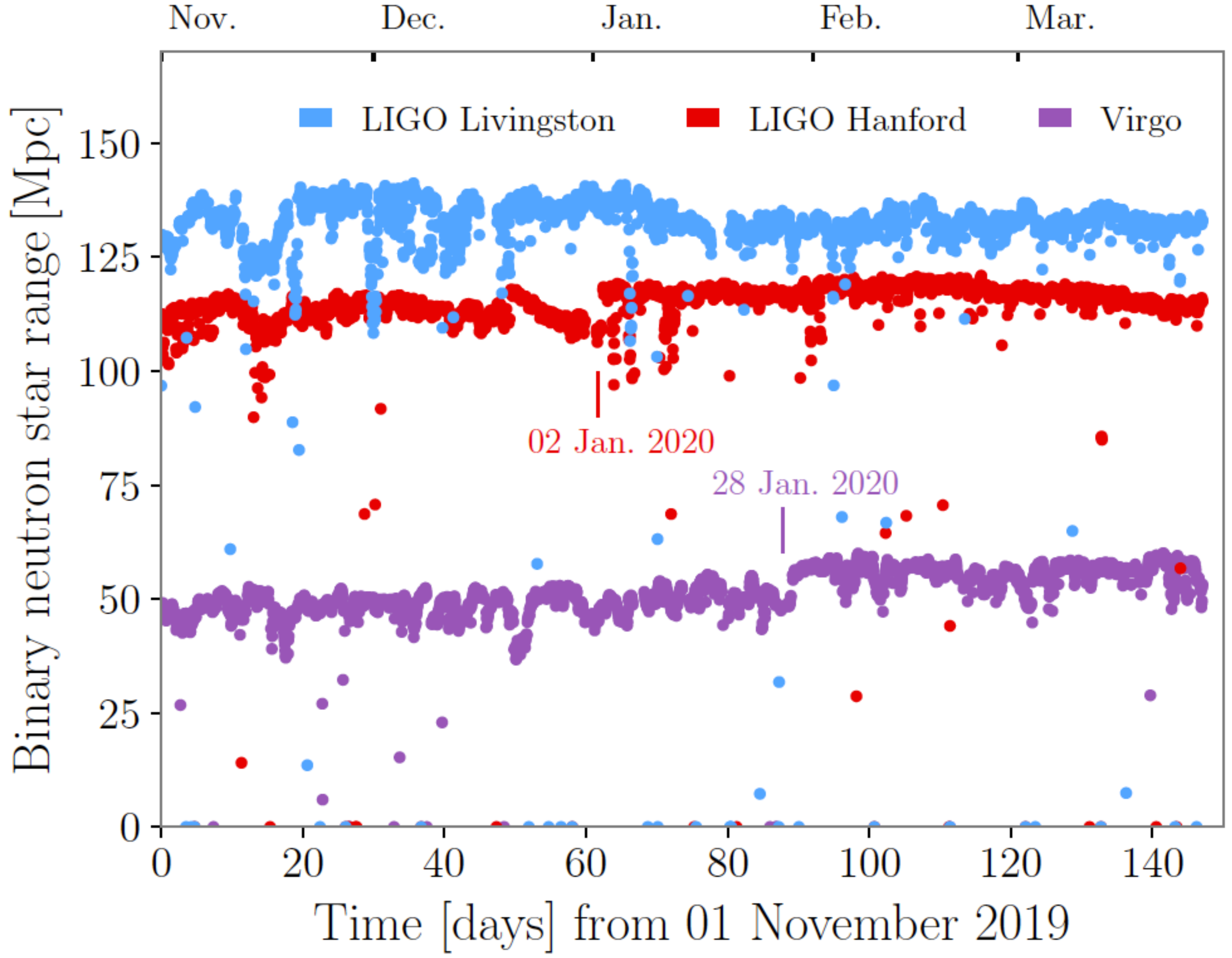
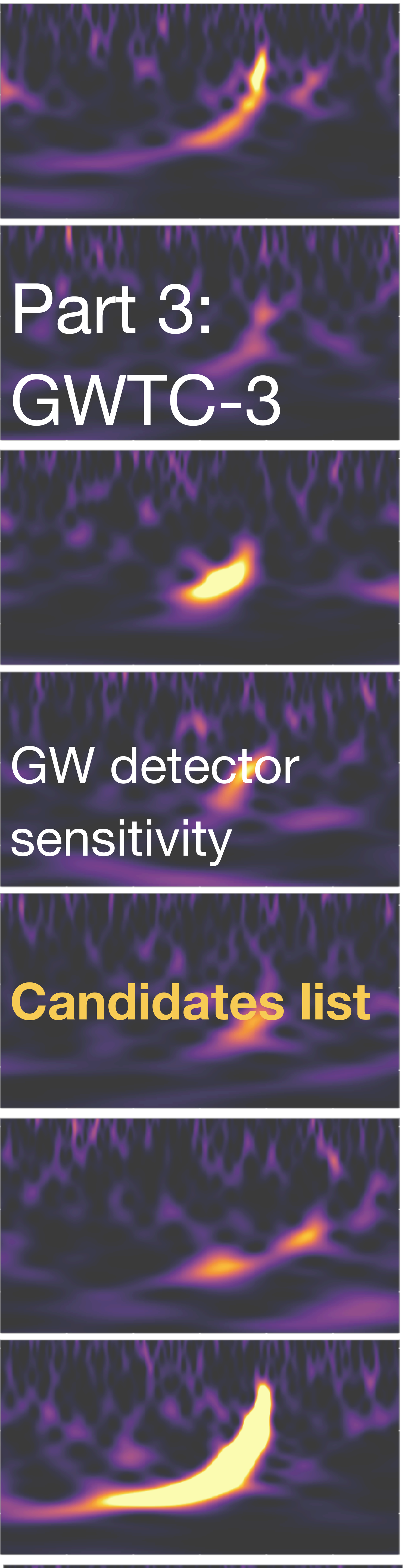


Fig6 : O3 *BNS inspiral range* *

Measure of detector sensitivity:
The binary neutron star range represents the distance a detector is able to detect a signal from a 1.4-1.4 solar mass binary

* Figures from https://arxiv.org/pdf/2111.03606.pdf



GWTC-3 :

Candidates

Procedure :

- Search method : Modeled searches (PyCBC GstLal, MBTA …) & Minimally modeled search (cWB) *
- Candidates events identification
- Validation by checking for evidence that they were caused by one or more detector noise artifacts following the same procedure as for previous catalogs
- Parameter estimation
- Main list (35 events): candidates with a probability of astrophysical origin (p-astro) > 0.5
- Marginal list** (7 events): p-astro < 0.5 but FAR < 2 per year

Likely instrumental artifacts :

Main list : 0
Marginal candidates list : 3

Glitch subtraction :

Applied on 8 events before source property analysis

** Searches are done on 2 timescales : low-latency & offline re-analysis*
***Marginal : Low-significance detections of possible signals*

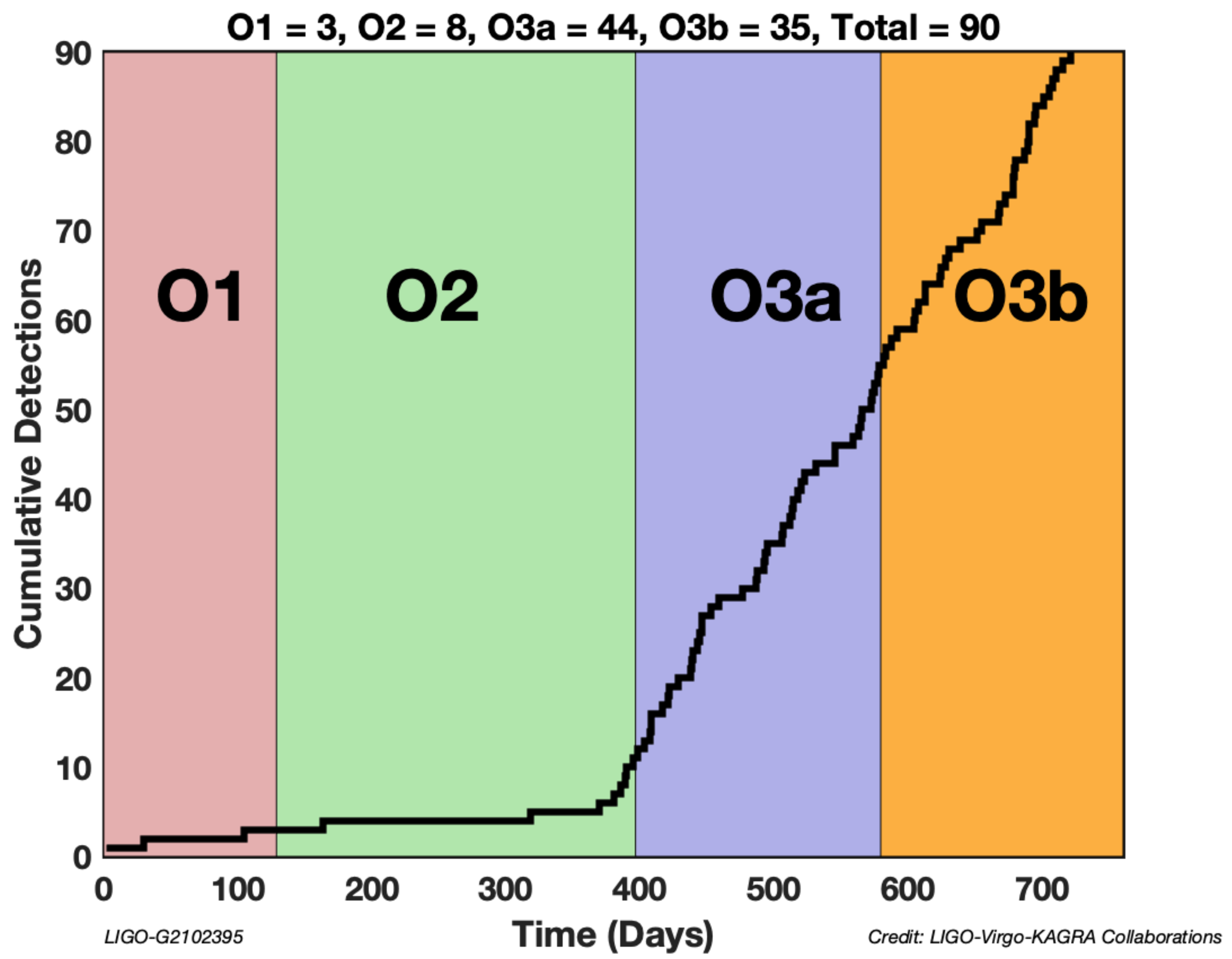
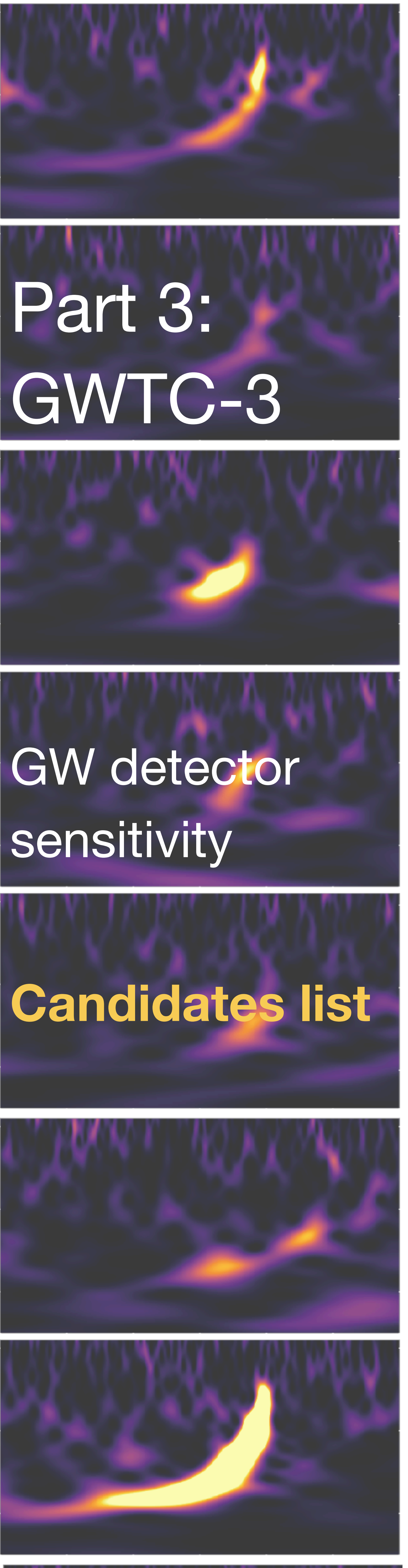


Fig7: *Cumulative detection from O1 to O3* (from https://www.ligo.org/science/Publication-O3bTGR/)

Significance estimation :

- False Alarm Rate (FAR) : how often do we expect noise to produce a trigger with the same ranking statistic as a candidate in question. No astrophysical information.
- Probability of astrophysical origin (p-astro) : foreground/background ranking statistics distributions comparison



GWTC-3 :

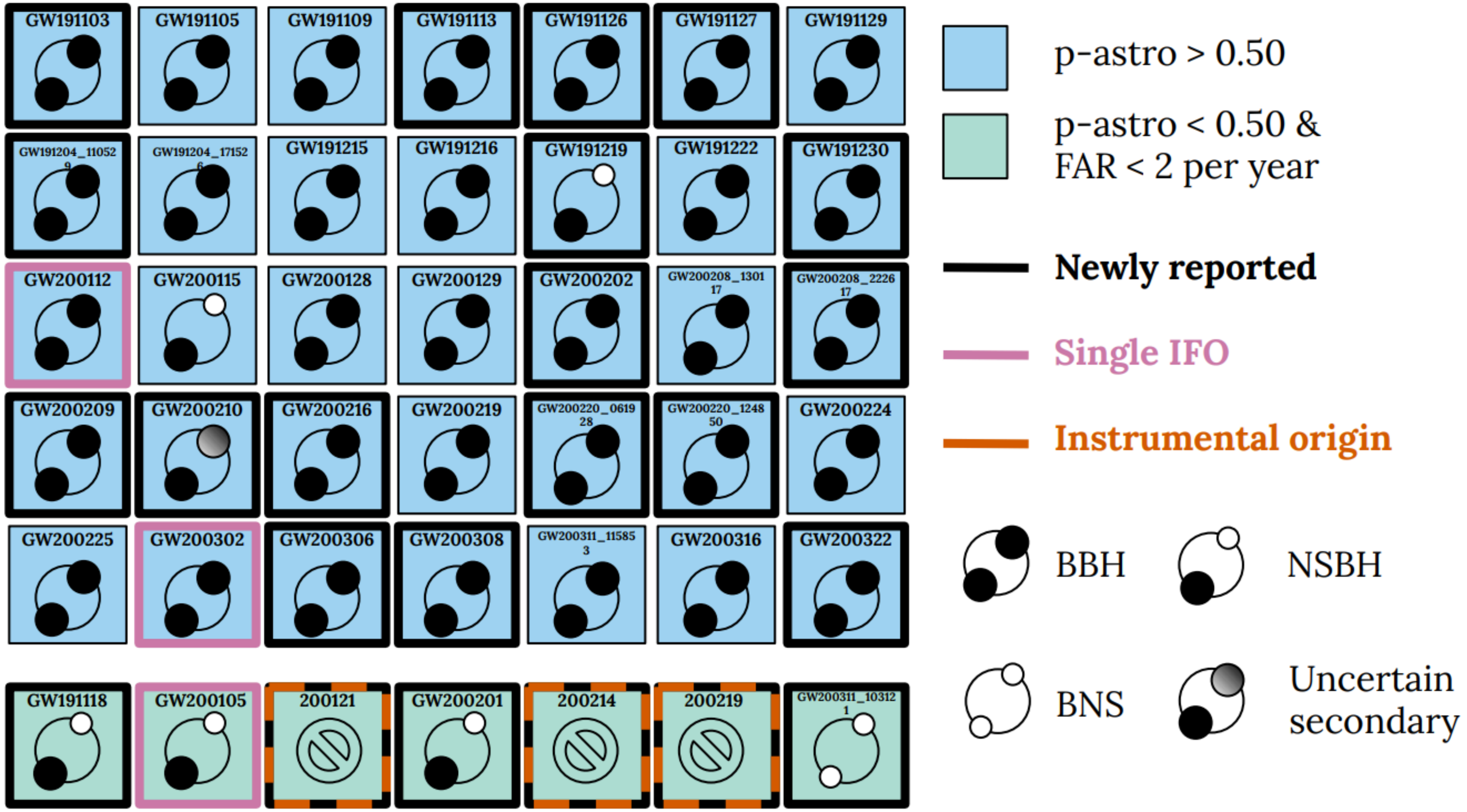
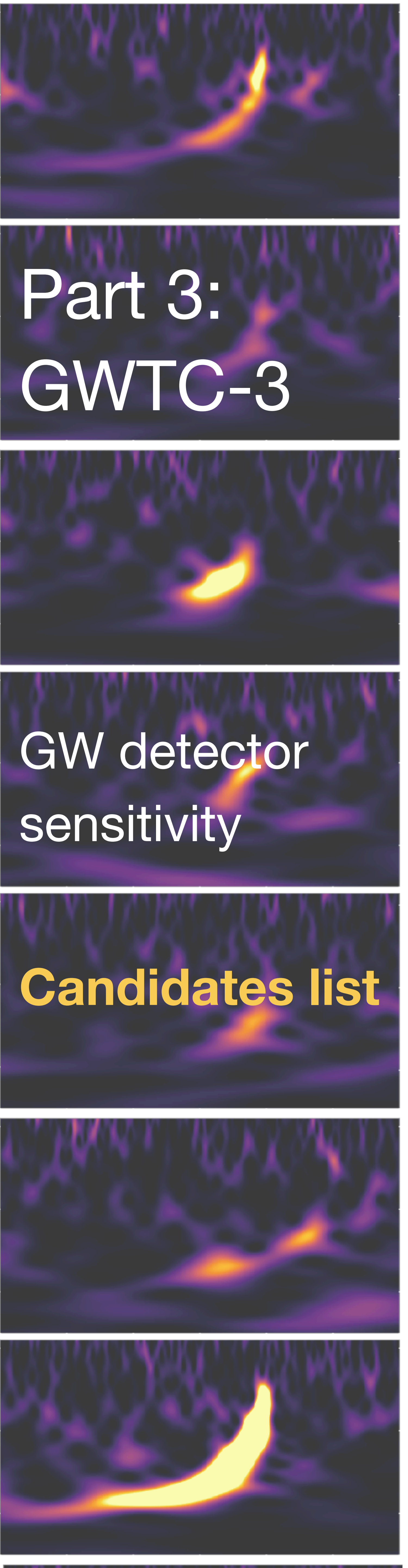


Fig8: *GW merger detections in O3b observing run*
(Figure made by Becca Ewing)



GWTC-3 :
Candidates properties

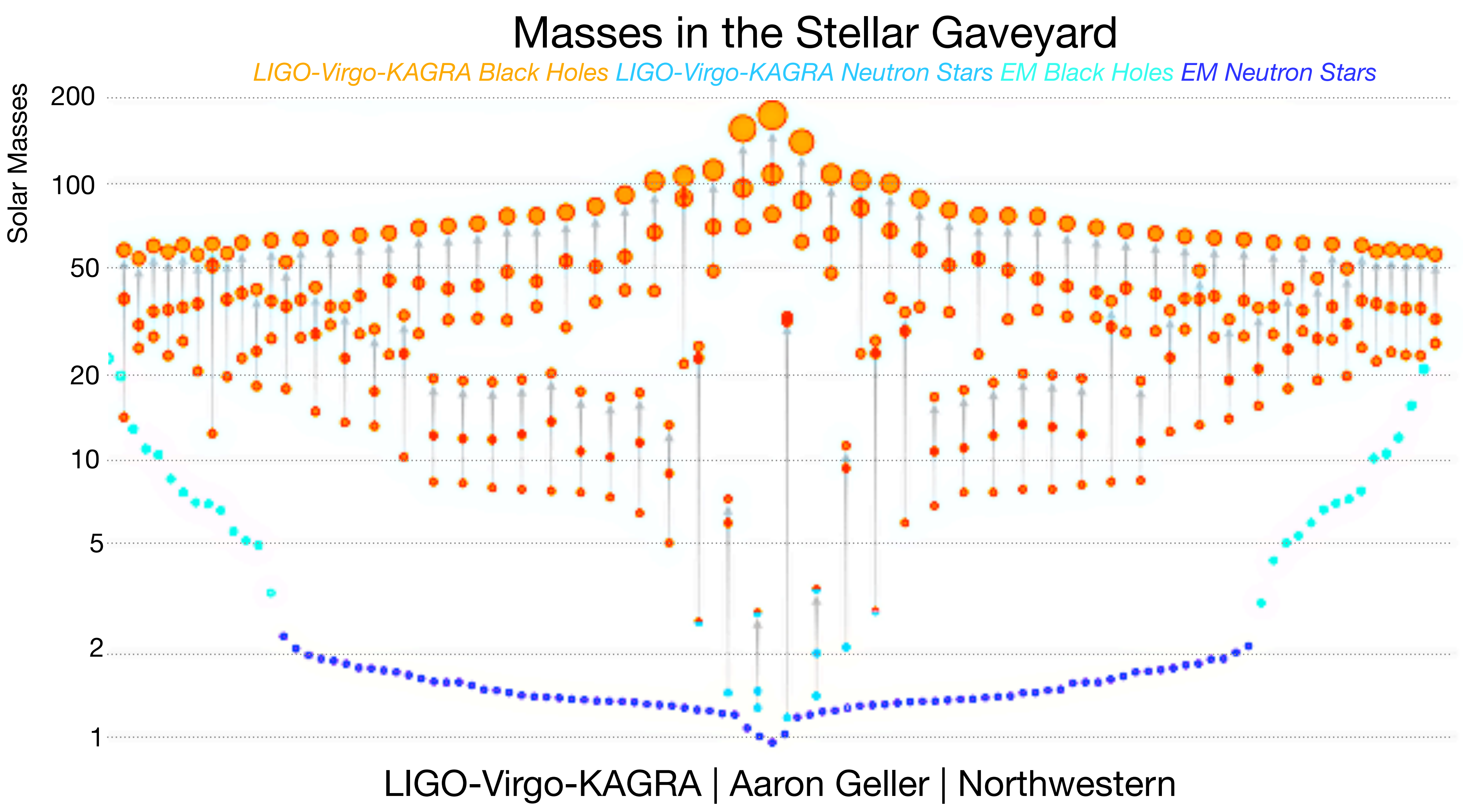


Fig9: *Graphic of masses of GW announced detections from O3b*

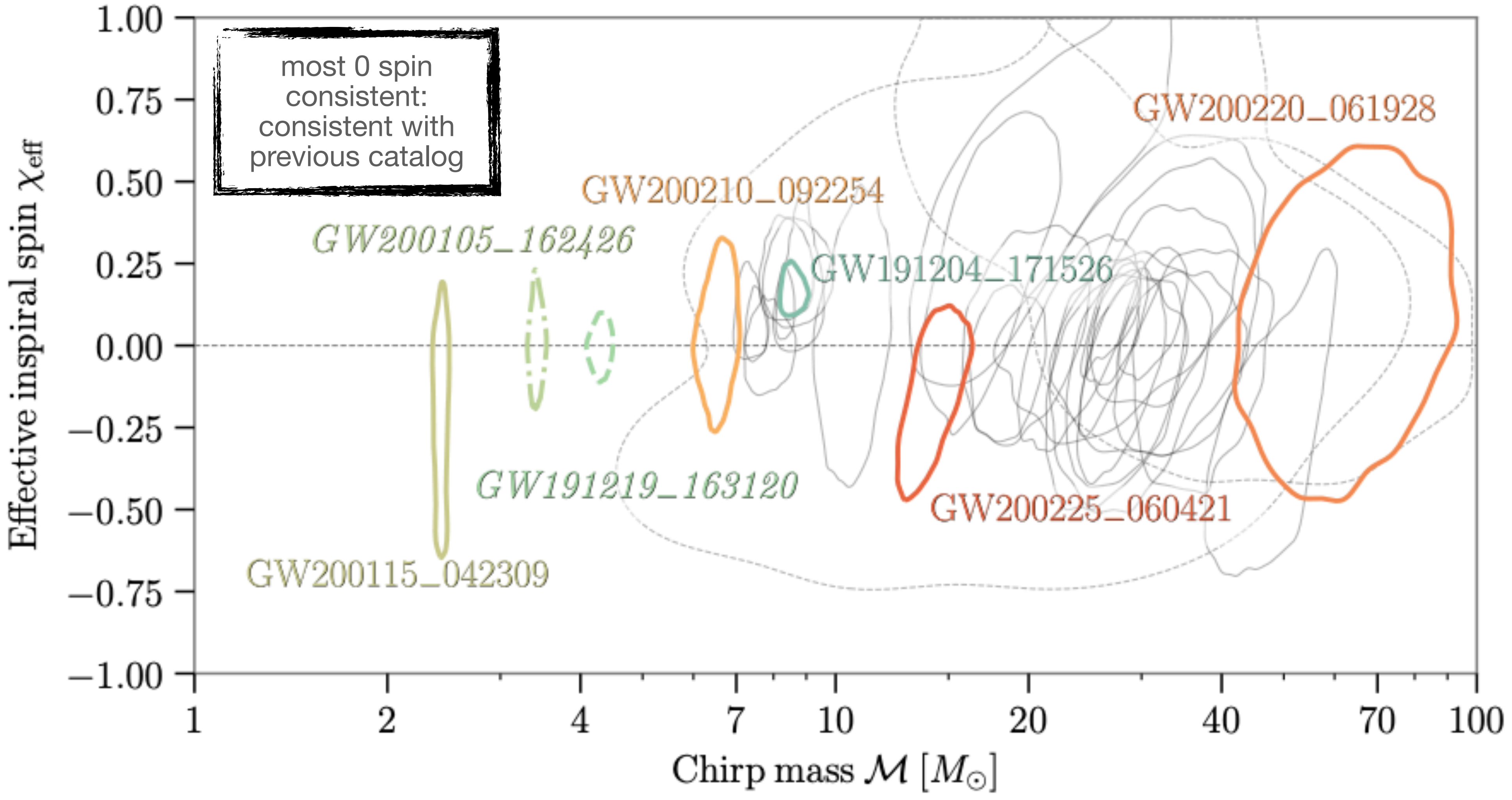


Fig11: *Credible-region contours in the plane of chirp mass M and effective inspiral spin χeff for O3b candidates with p-astro > 0.5 plus GW200105-162426 **

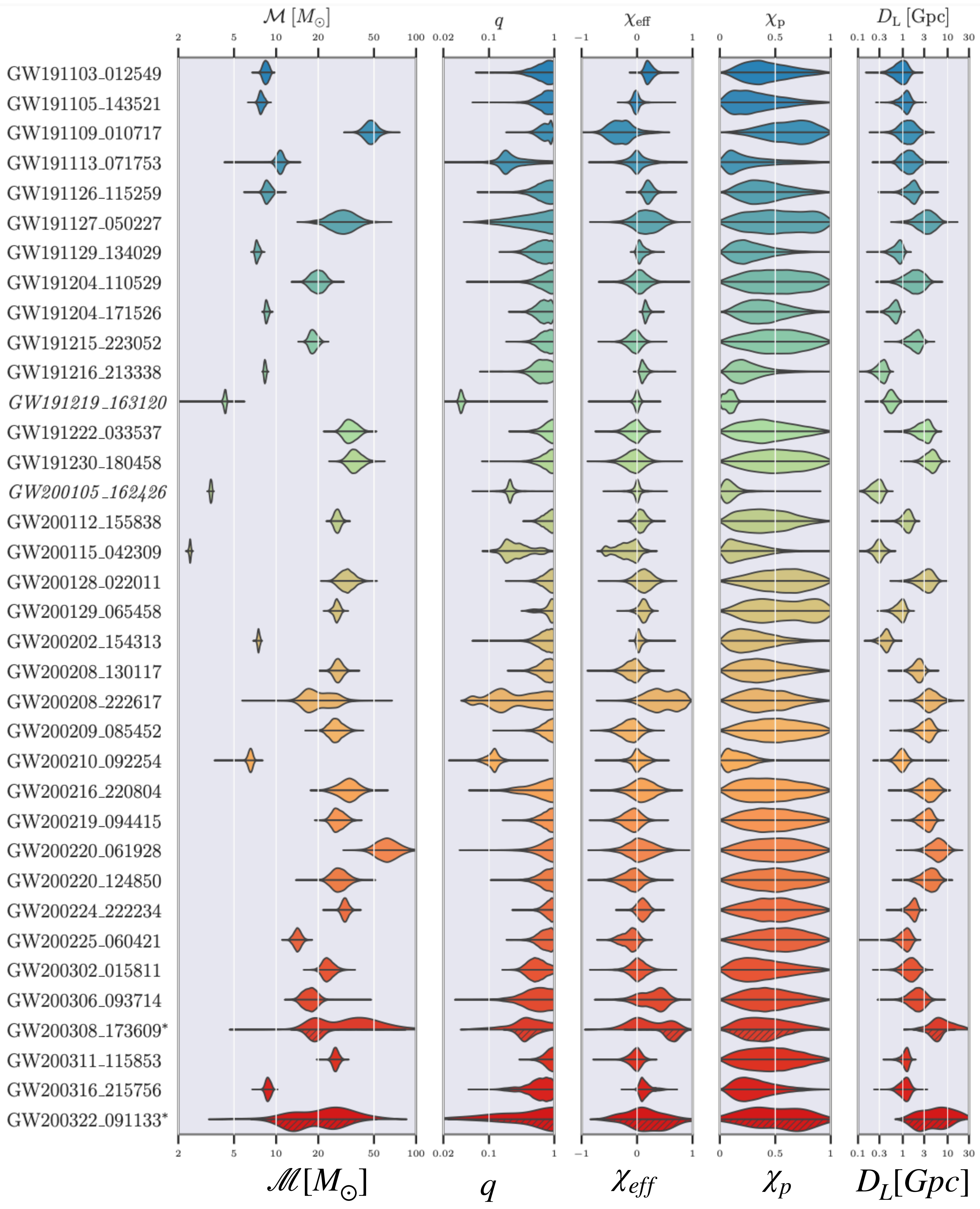


Fig10: *Marginal posterior distributions for the source properties for O3b **

* Figures from https://arxiv.org/pdf/2111.03606.pdf

GWTC-3 :

Summary

- Data releases : https://www.gw-openscience.org/GWTC-3/
- O3 : detector greatest performance to date.
- 35 O3b candidates with p-astro > 0.5, diverse range of masses and spins
- 1st confident NSBH detections

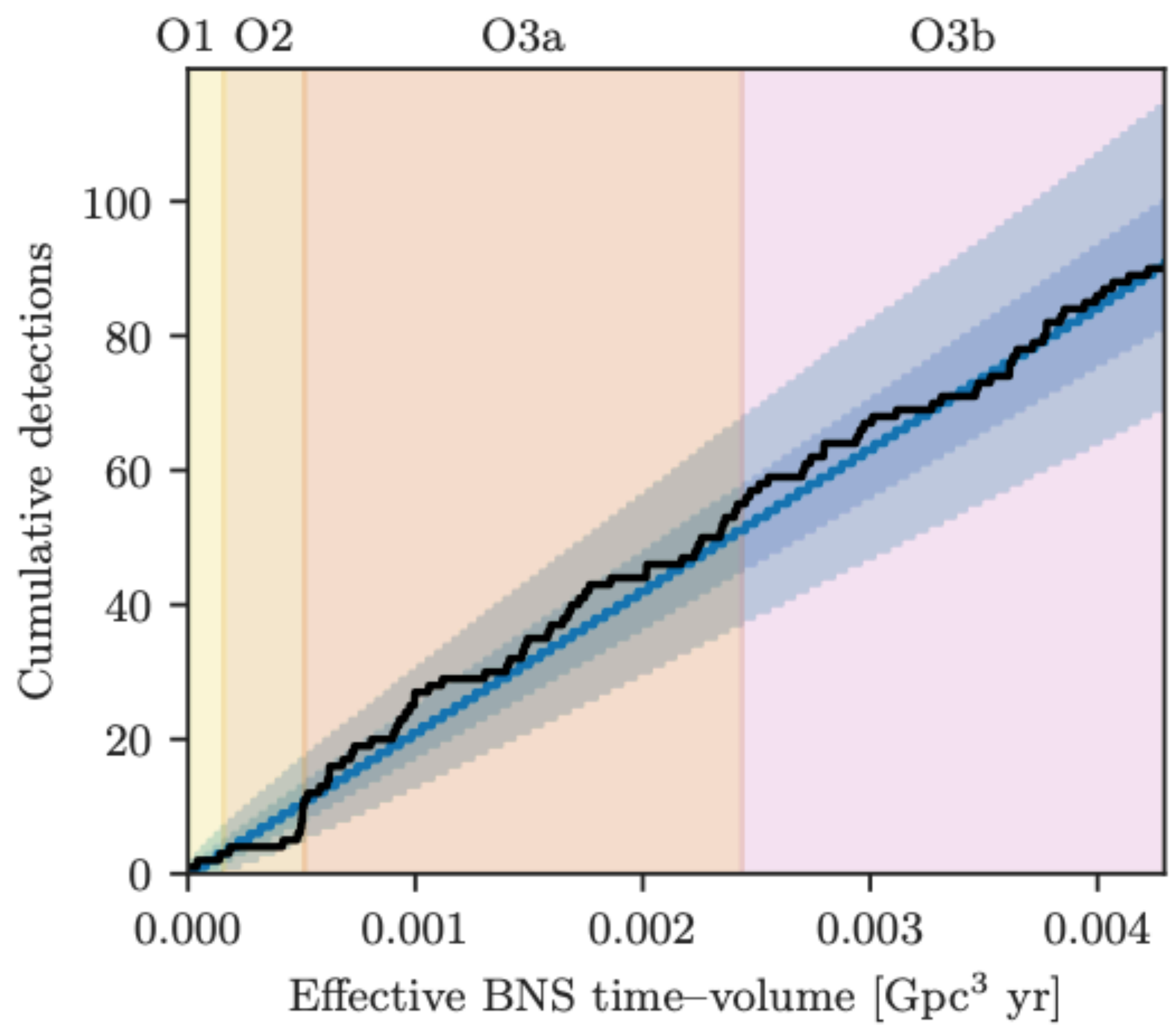


Fig12: *The number of CBC detection candidates with a probability of astrophysical origin pastro > 0.5 versus the detector network's effective surveyed time–volume for BNS coalescences* (from https://arxiv.org/pdf/2111.03606.pdf)

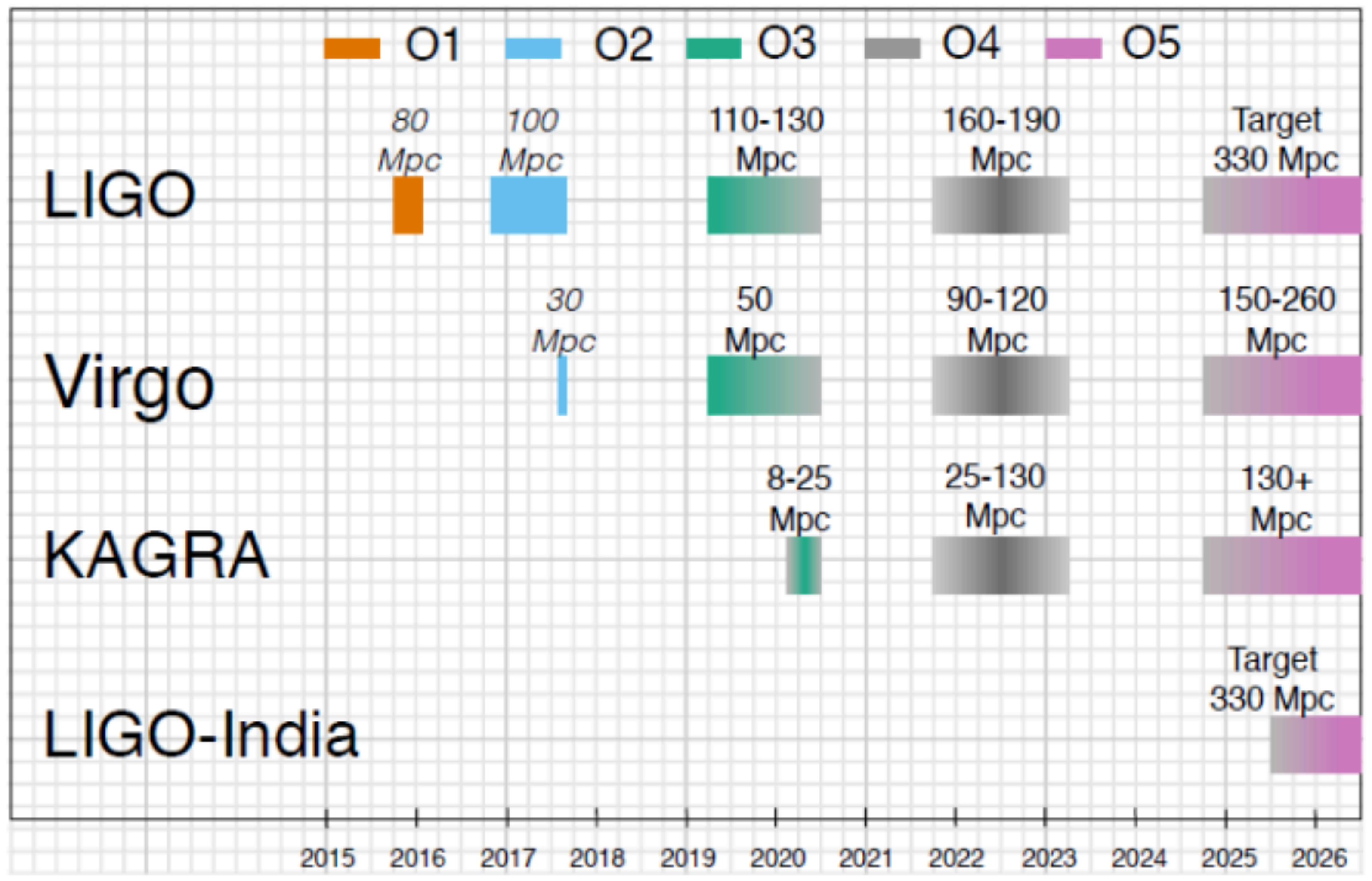


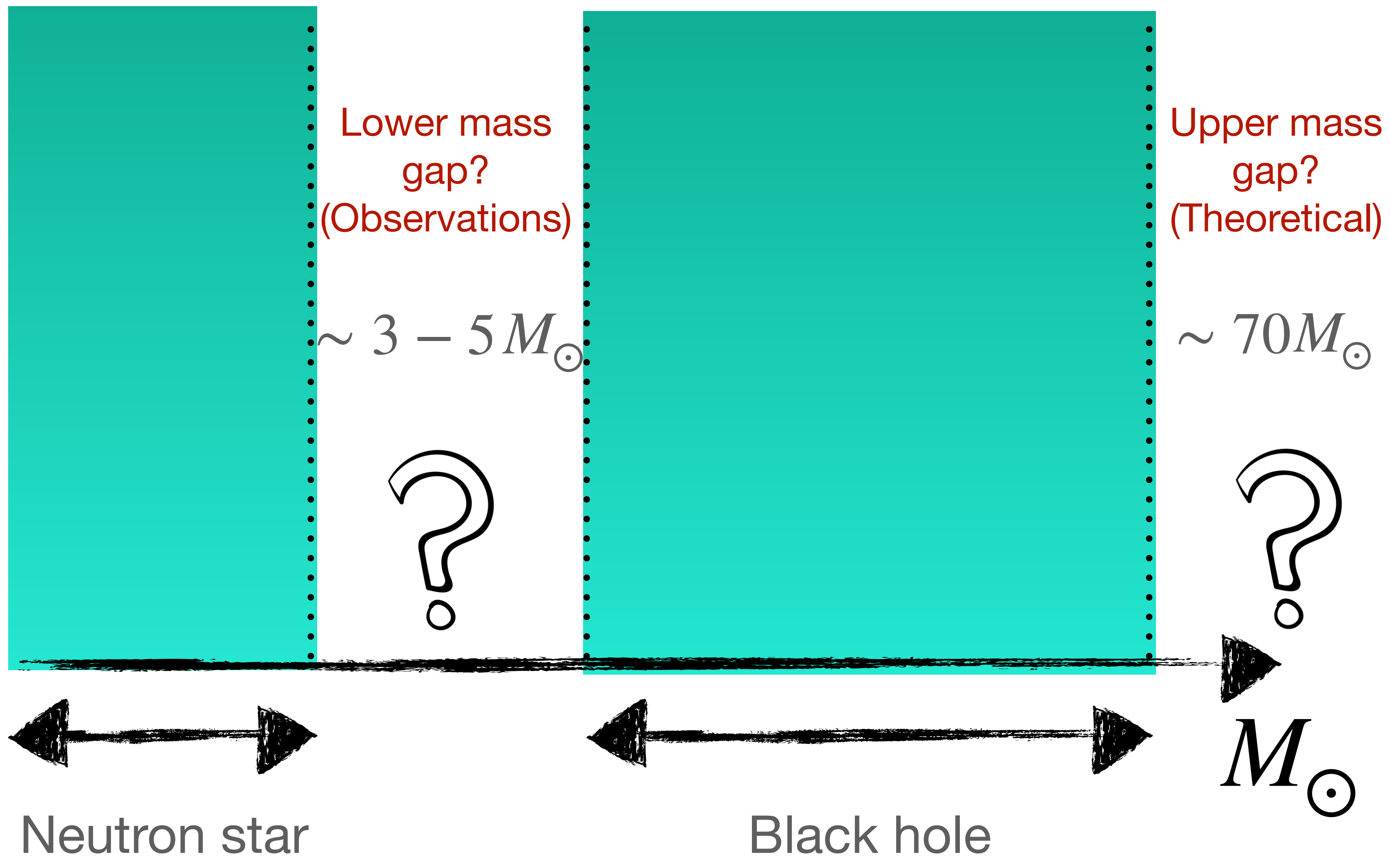
Fig13 : *Observing scenarios with targeted sensitivities* (from https://arxiv.org/pdf/2105.09247.pdf)

Astrophysical Populations

Introduction

Population properties of 76 compact binary mergers detected with gravitational waves below a false alarm rate of 1 per year through GWTC-3

- Masses, spins, distances of these events inferred from the GW signal
- Several mass models, 3 spins models, one distance model



Fundamental questions :

- Which types of mergers are we seeing? In terms of formation channels?
- How many are happening in the Universe ?
- What is the mass distribution of BH and NS ?

Astrophysical population

Fundamental questions

How many are happening in the Universe ?

➡ Study of the merger rate

Multiple models but consistent with the same results :

$$\mathcal{R}_{\text{total}} = 470^{+830}_{-300}\ \text{Gpc}^{-3}\text{yr}^{-1}$$

$$\mathcal{R}_{\text{BNS}} = 250^{+640}_{-200}\ \text{Gpc}^{-3}\text{yr}^{-1}$$

$$\mathcal{R}_{\text{NSBH}} = 170^{+150}_{-89}\ \text{Gpc}^{-3}\text{yr}^{-1}$$

$$\mathcal{R}_{\text{BBH}} = 22^{+9}_{-6}\ \text{Gpc}^{-3}\text{yr}^{-1}$$

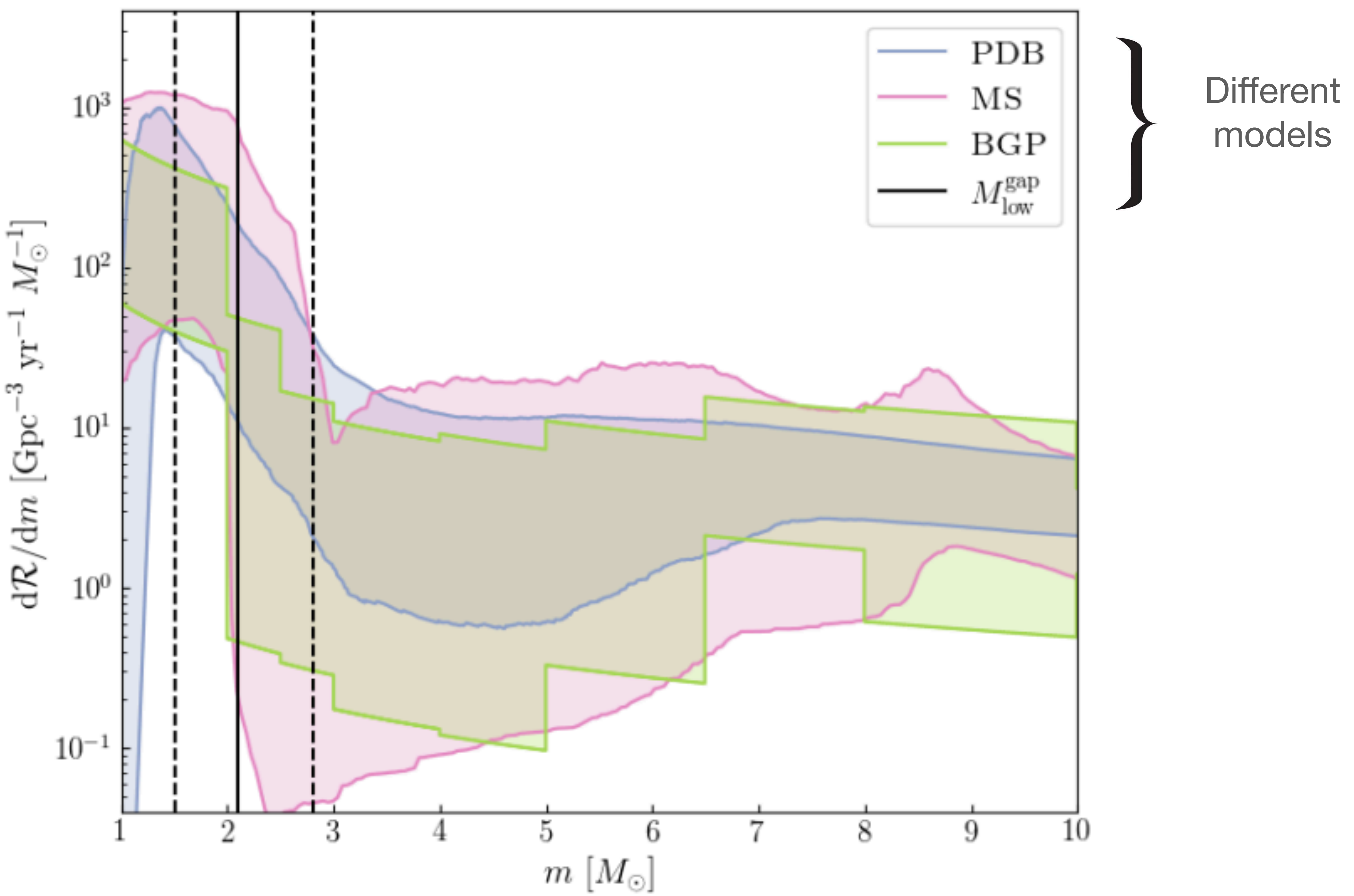


Fig14: *Differential merger rate as a function of component mass for the PDB, MS, and BGP model* (from https://arxiv.org/pdf/2111.03634.pdf)

Astrophysical population

BNS & NSBH Properties

GW190814 seems to be a BH

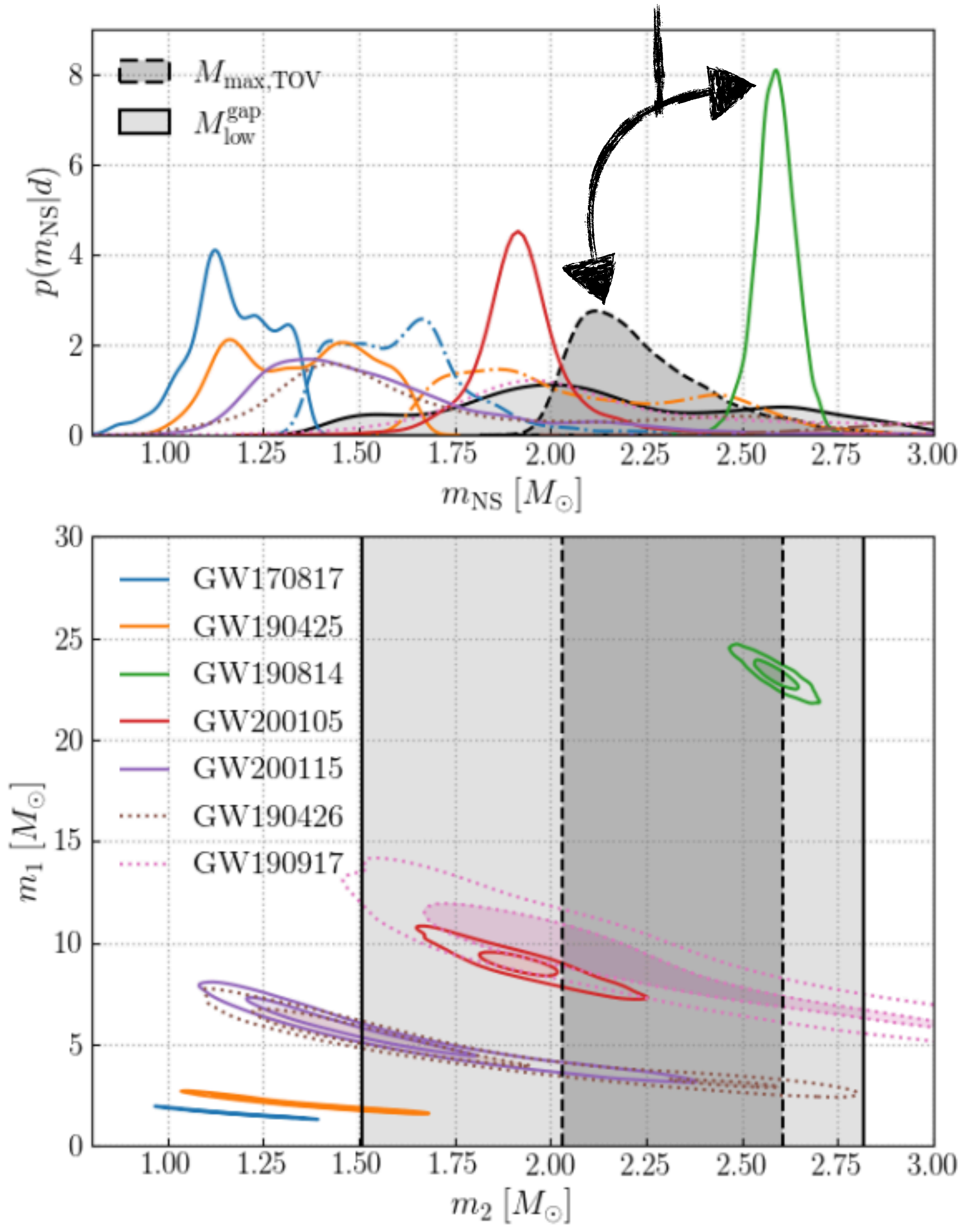


Fig15: *Masses for events with at least one candidate neutron* *

Maximum mass observed in the NS population : $m_{max} = 2.0^{+0.3}_{-0.2} M_\odot$

Consistent with the mass found with the equation of state & Galactic pulsars

Minimum NS mass in the gravitational wave population inferred to be $m_{min} = 1.2^{+0.1}_{-0.2} M_\odot$ in both the Power and Peak models.

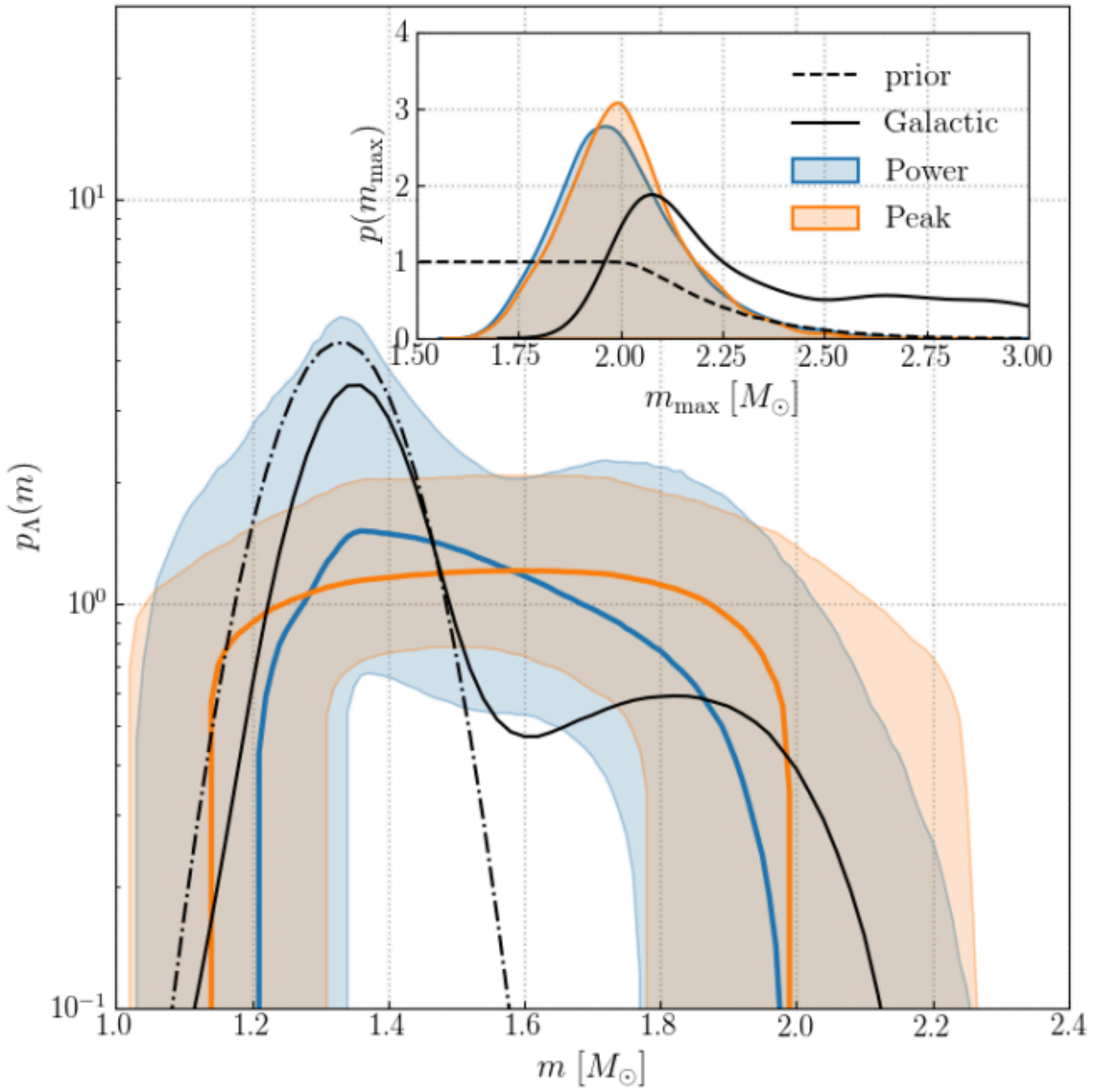


Fig16: *Inferred neutron star mass distribution* *

* Figures from https://arxiv.org/pdf/2111.03634.pdf

Astrophysical population

BBH Properties : Mass

PP-model used for all plots here

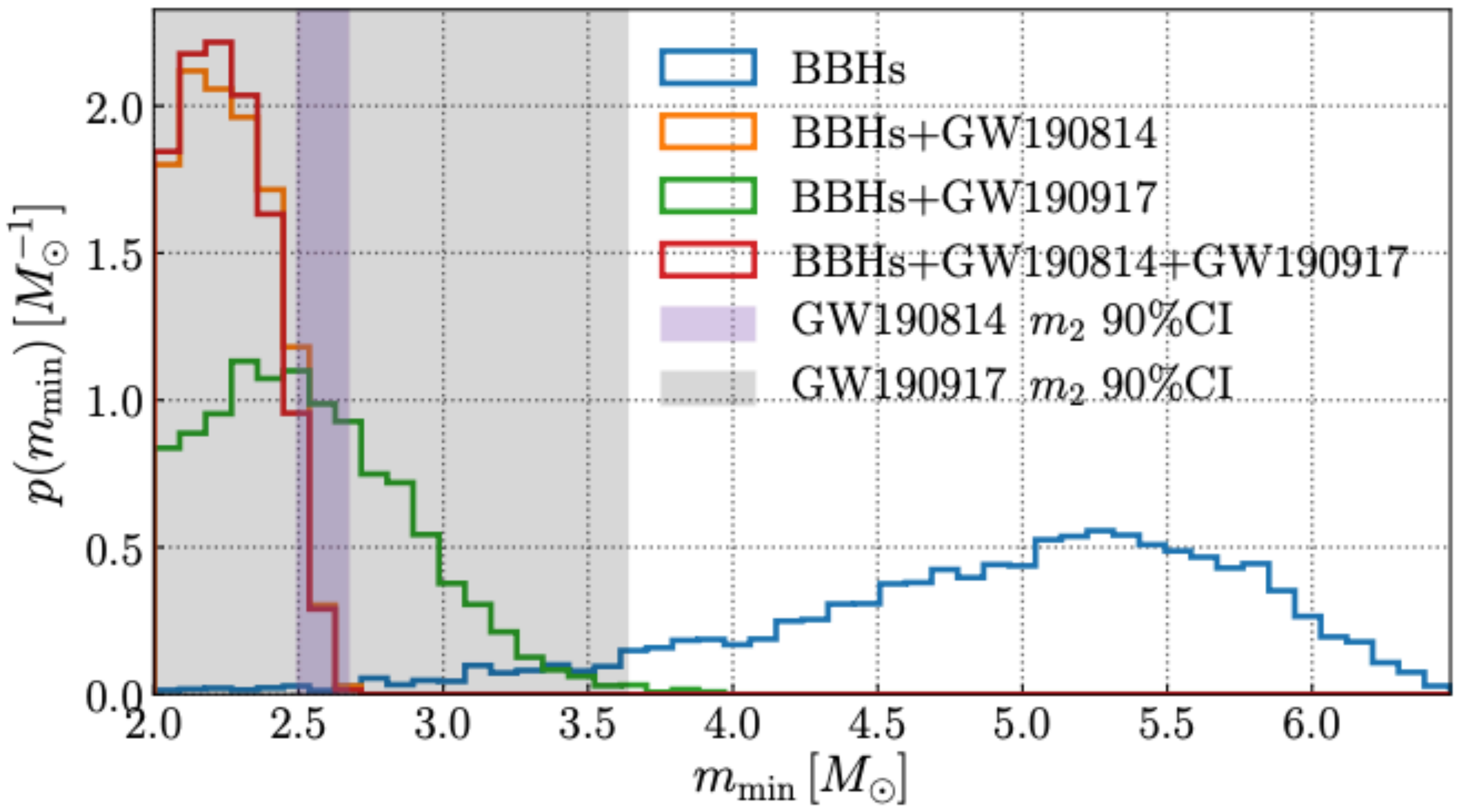


Fig17: *Posterior distribution on the minimum mass truncation hyper-parameter m_{min}* *

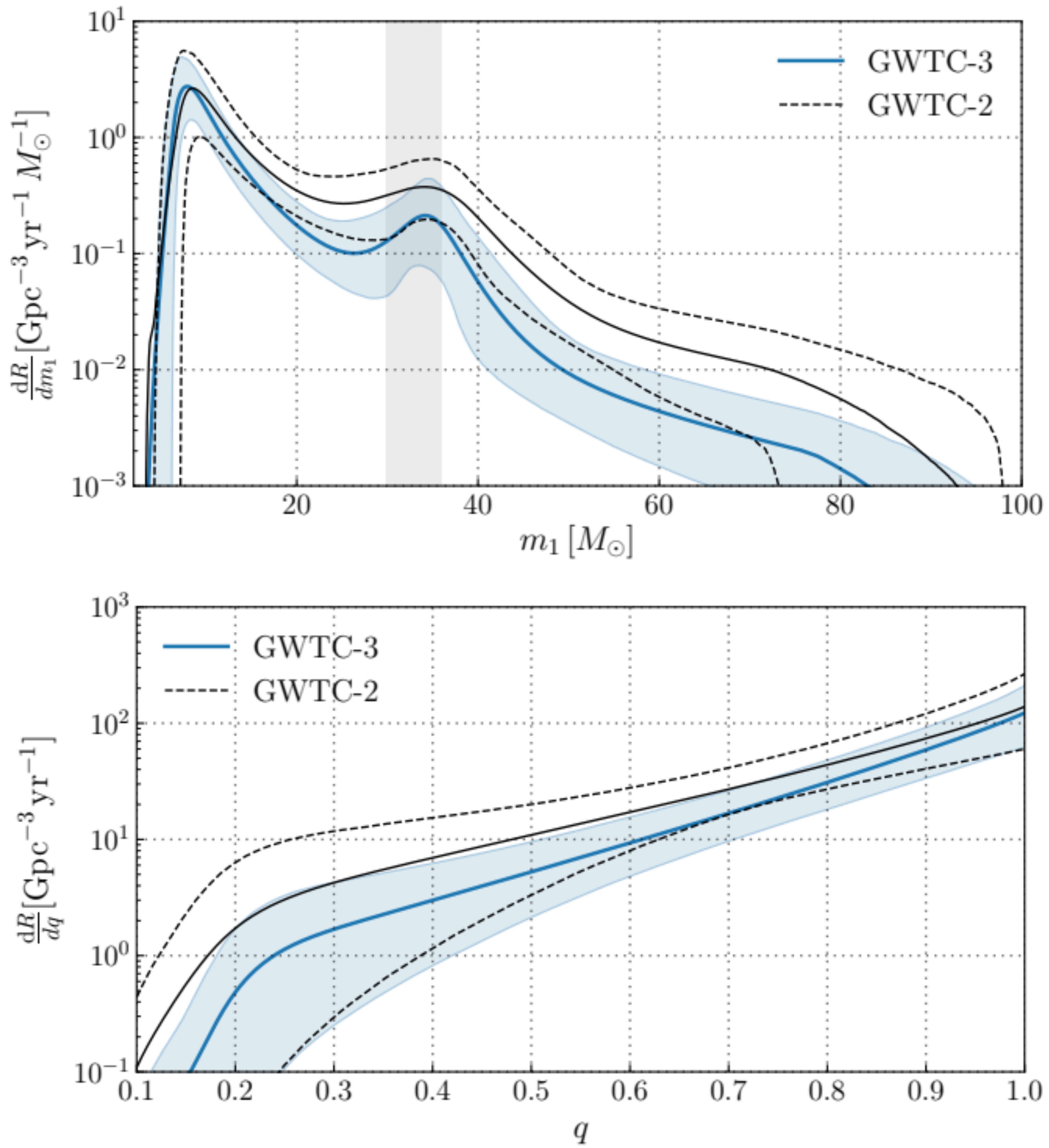


Fig18: *The astrophysical BBH primary mass (top) and mass ratio (bottom) distributions* *

Results consistent between GWTC-2 & GWTC-3

* Figures from https://arxiv.org/pdf/2111.03634.pdf

Astrophysical population

BBH Properties : Spins

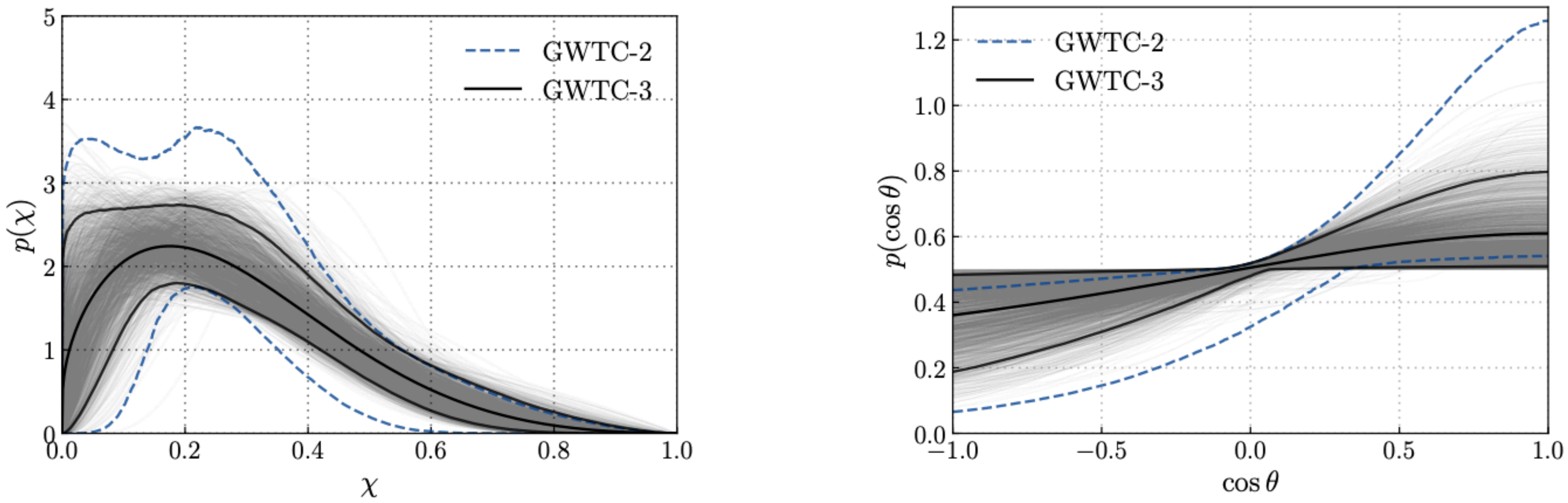


Fig19: *The distributions of component spin magnitudes χ (left) and spin-orbit misalignment angles θ (right) among binary black hole mergers* (from https://arxiv.org/pdf/2111.03634.pdf)

GWTC-3 : a broad or isotropic distribution of spin tilts.
GWTC-2 : consistent with tilts concentrated preferentially around cos θ = 1

Spin magnitude : small but non-zero (concentrate below $\chi_i < 0.4$)

Astrophysical population

BBH Properties : Merger rates & Redshift

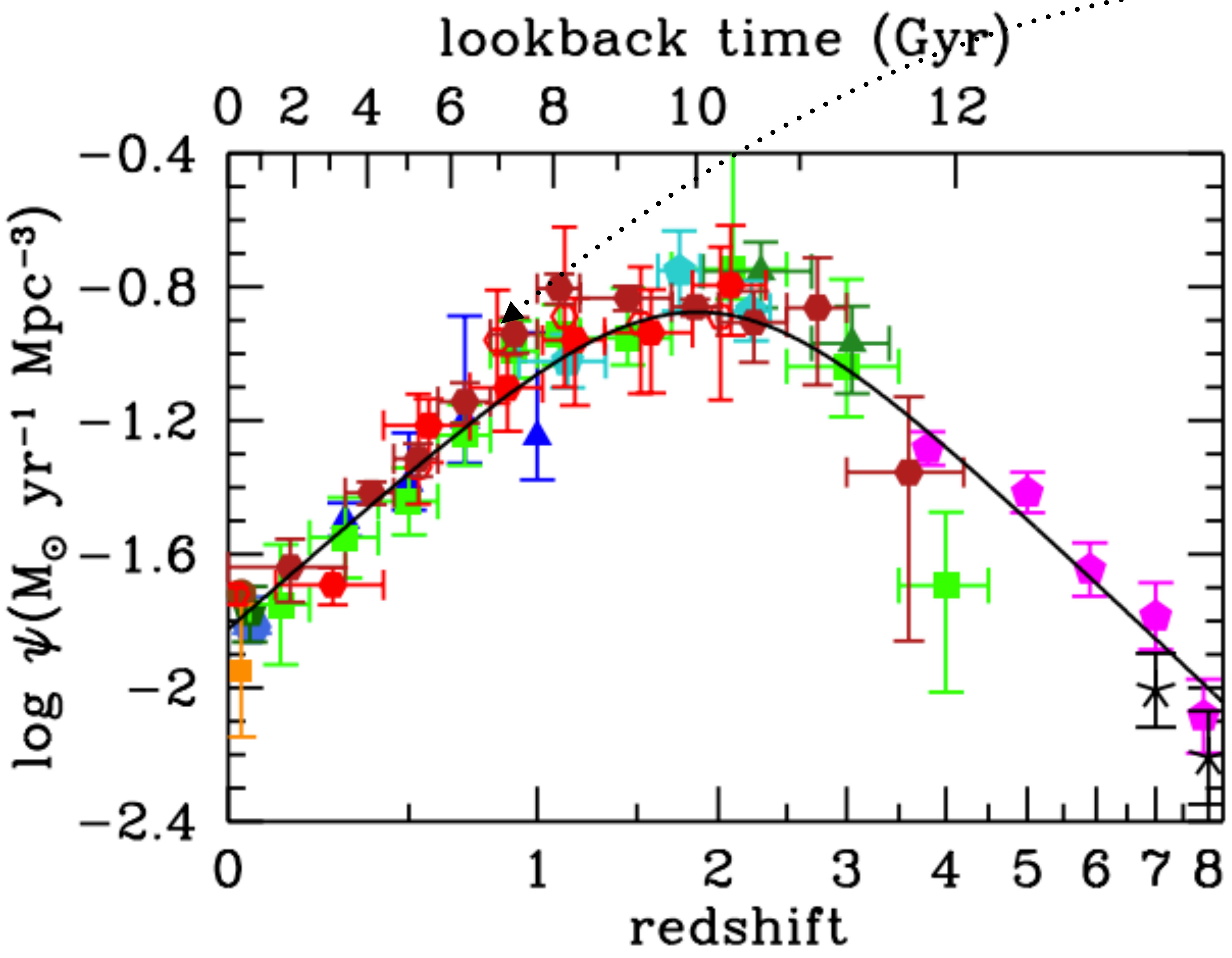


Fig20: *The history of cosmic star formation* (from https://arxiv.org/pdf/1403.0007.pdf)

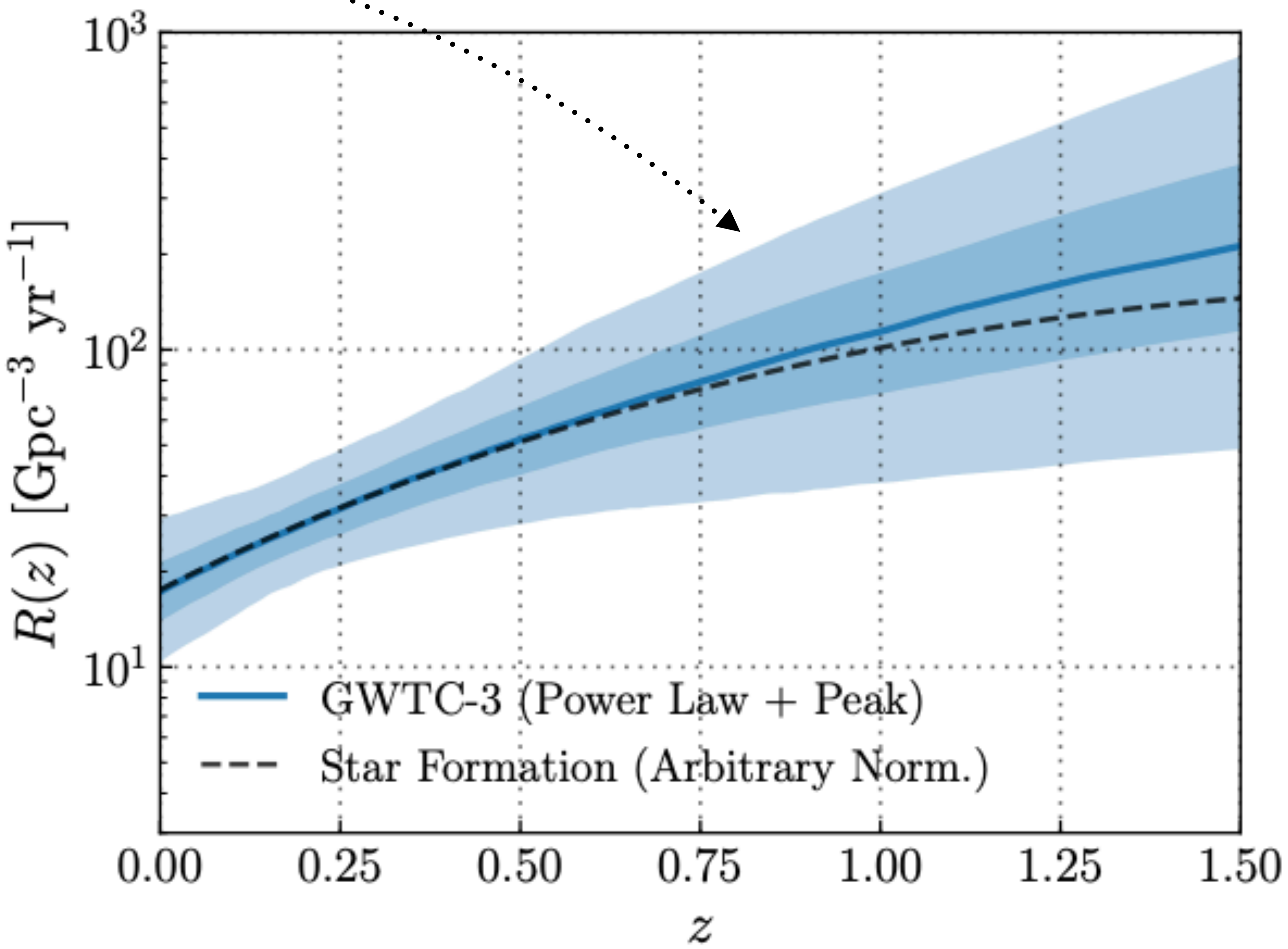
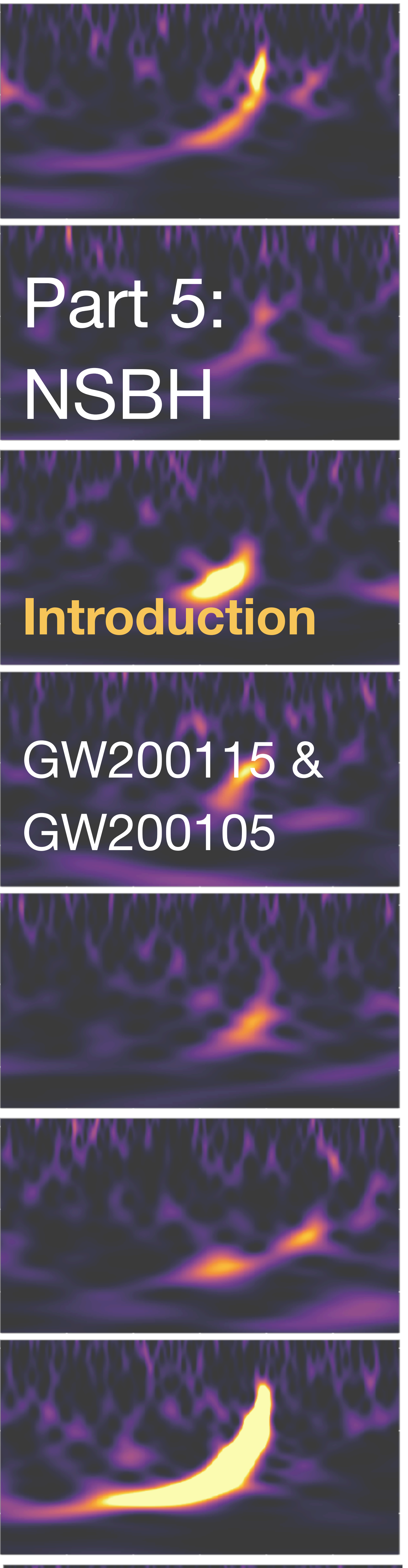


Fig21: *Constraints on the evolution of the BBH merger rate with redshift* (from https://arxiv.org/pdf/2111.03634.pdf)

- Merger rate density increases with redshift
- In most plausible formation scenarios : we do not expect R(z) to continue growing with arbitrarily high z. Instead, we anticipate that R(z) will reach a maximum beyond which it turns over and falls to zero. —> not observed yet, maybe with Einstein Telescope ?



Gravitational waves from NSBH coalescences

Introduction

January 2020 : First confident observations of NSBH !

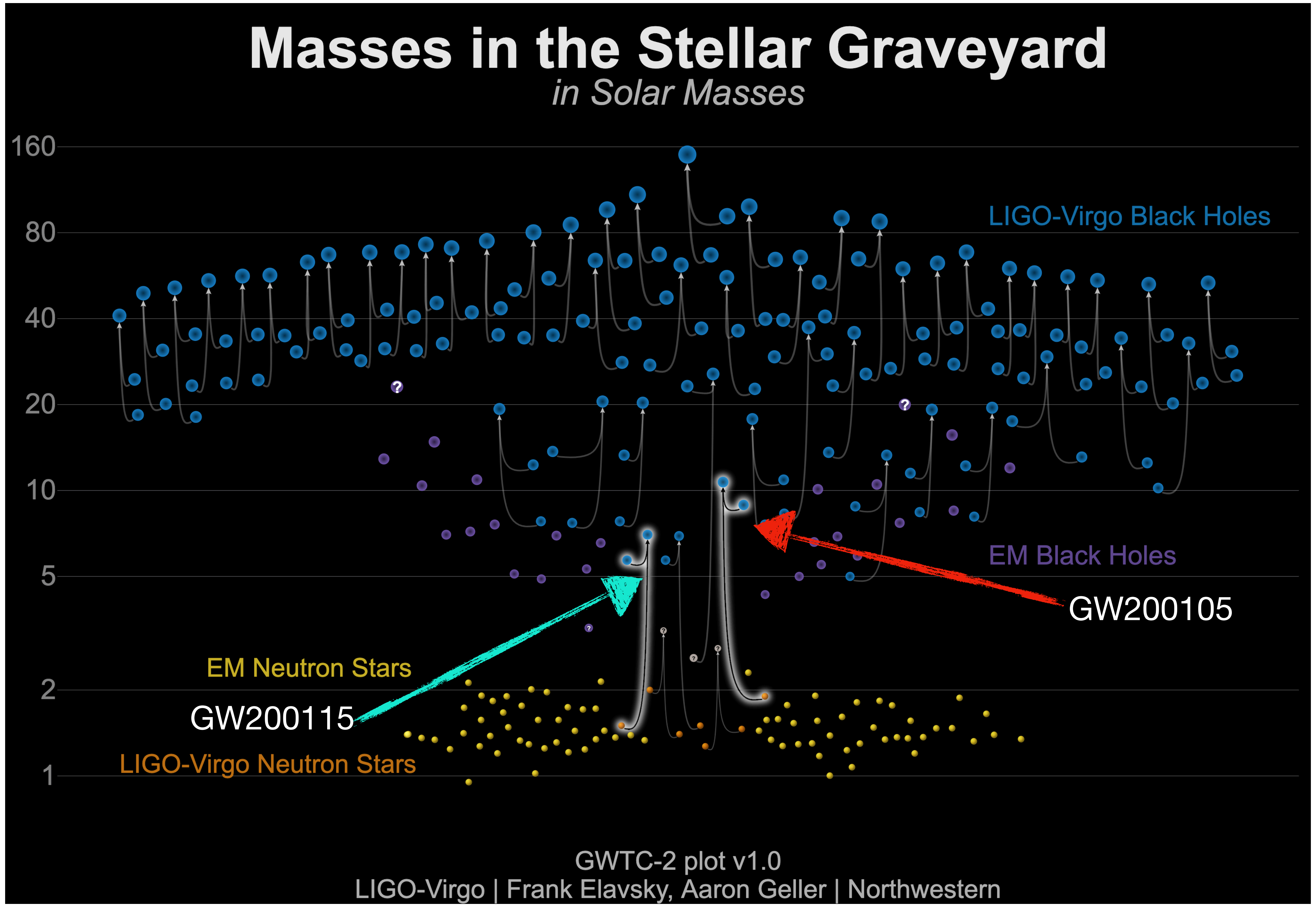
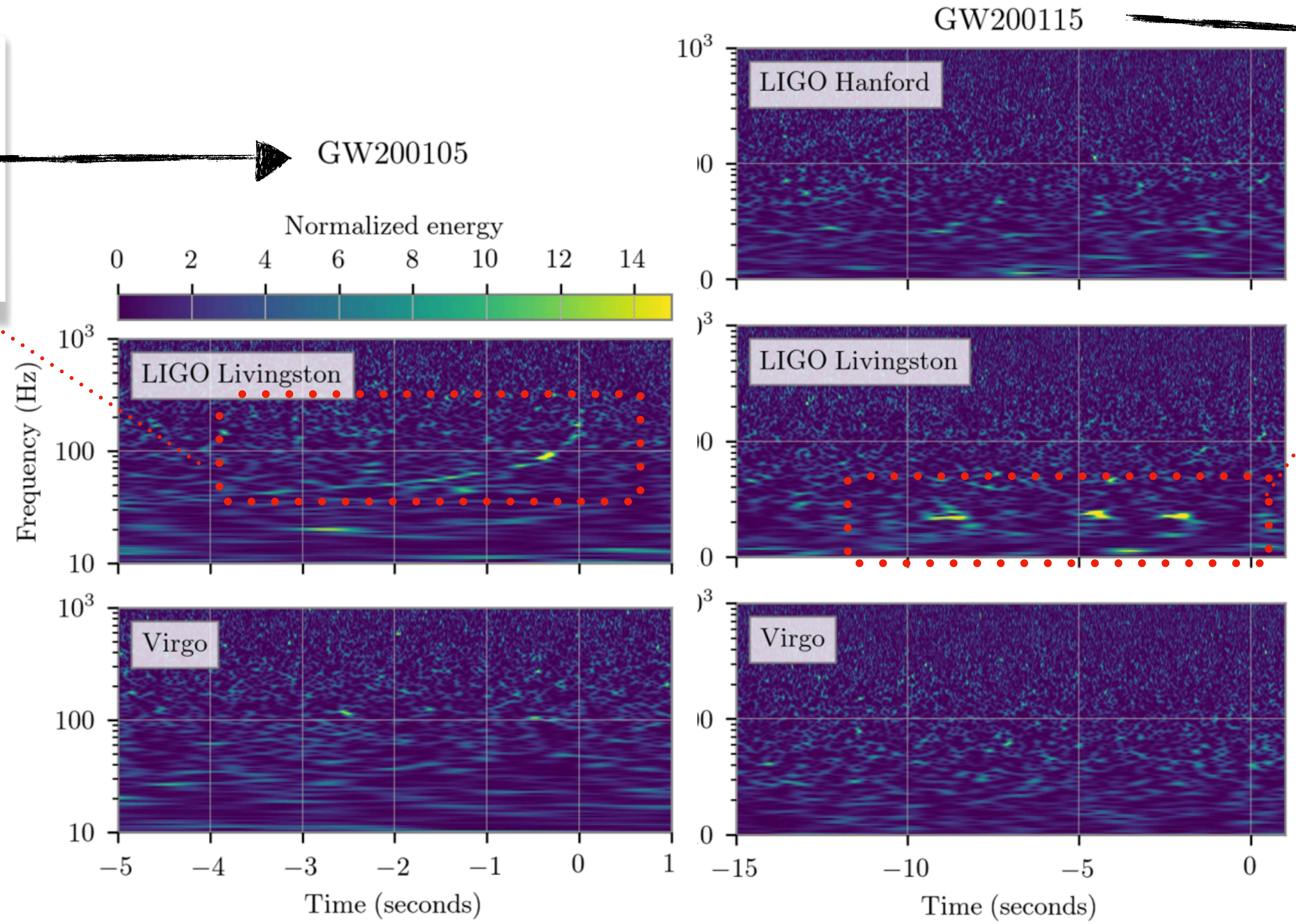


Fig22 : *Graphic of masses of GW announced detections from GWTC-2 catalog + NSBH*

Gravitational waves from NSBH coalescences

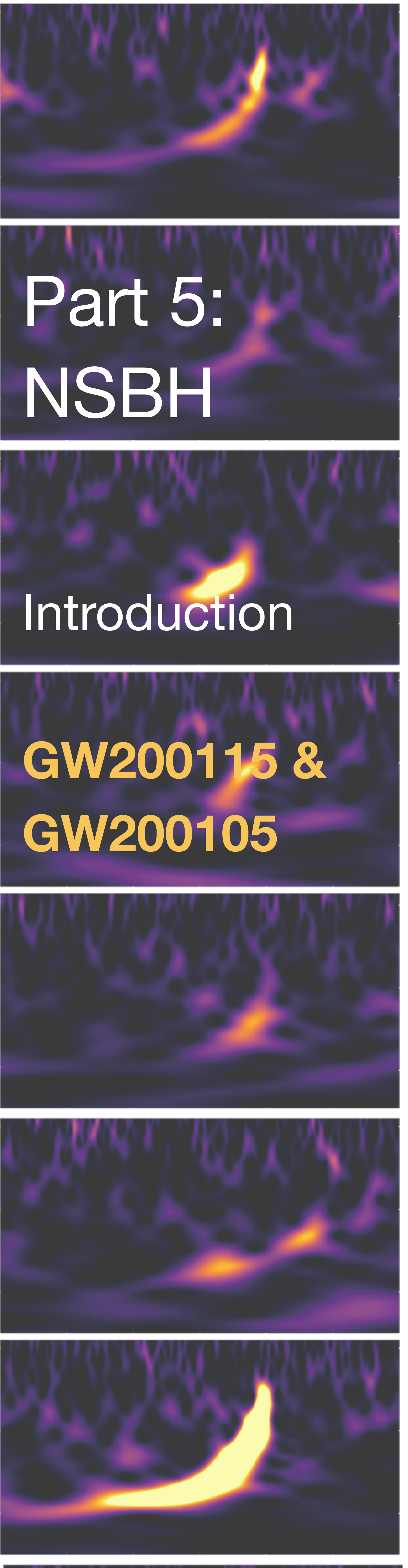
GW200115 & GW200105 detector status

- Only Livingston & Virgo were taking data
- Chirp visible in L1



- All the 3 detectors were taking data.
- Not loud enough in Virgo
- Noise in L1

Fig23: *Time–frequency representations of the data containing GW200105 (left column) and GW200115 (right column)* (from https://iopscience.iop.org/article/10.3847/2041-8213/ac082e/pdf)



Gravitational waves from NSBH coalescences

GW200115 & GW200105 significance status

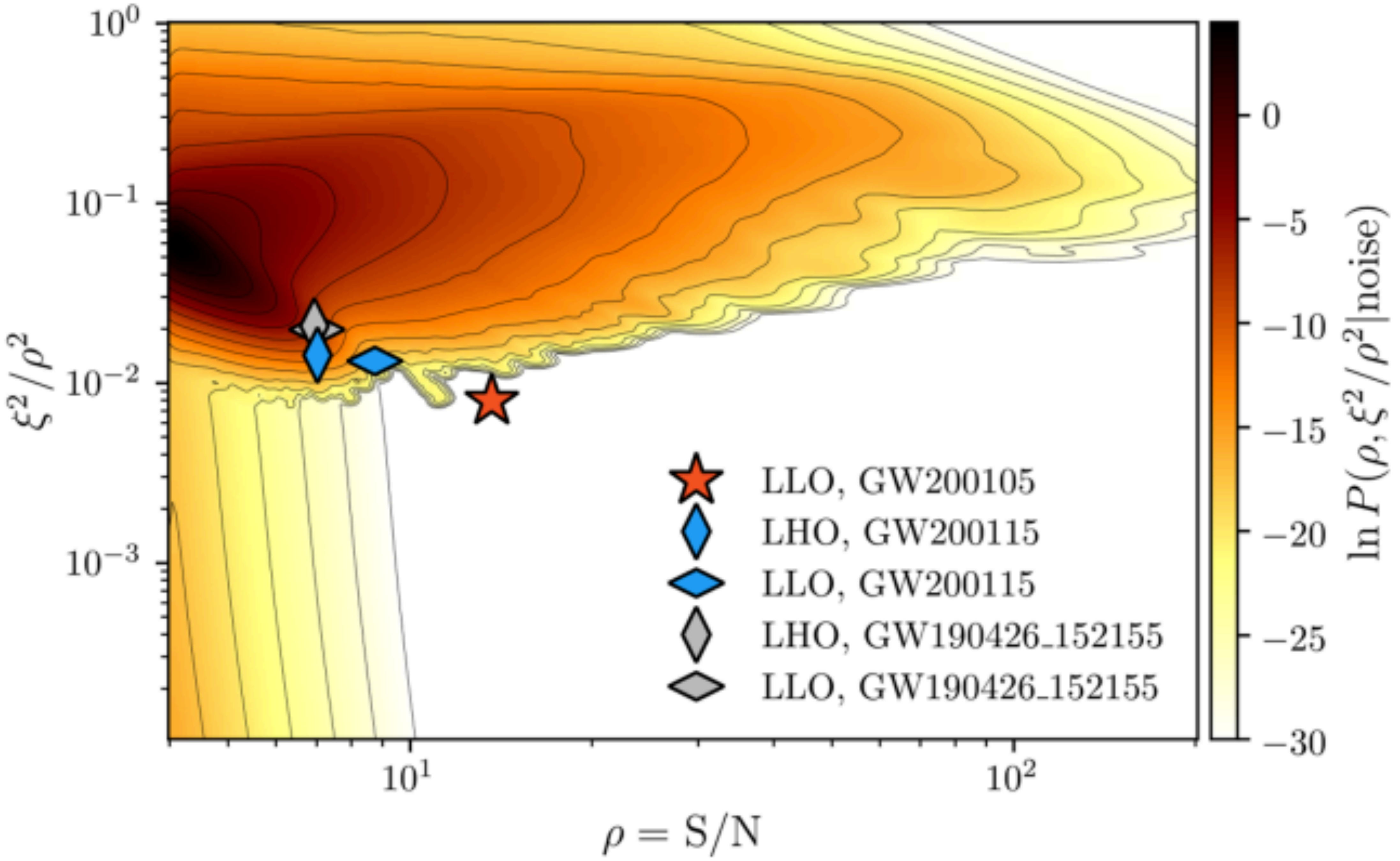


Fig24: *Colored shading shows the joint S/N–ξ^2 noise probability density function for LIGO Hanford (LHO), LIGO Livingston (LLO), and Virgo. For comparison, the marginal GW190426_152155 is also shown* (from https://iopscience.iop.org/article/10.3847/2041-8213/ac082e/pdf)

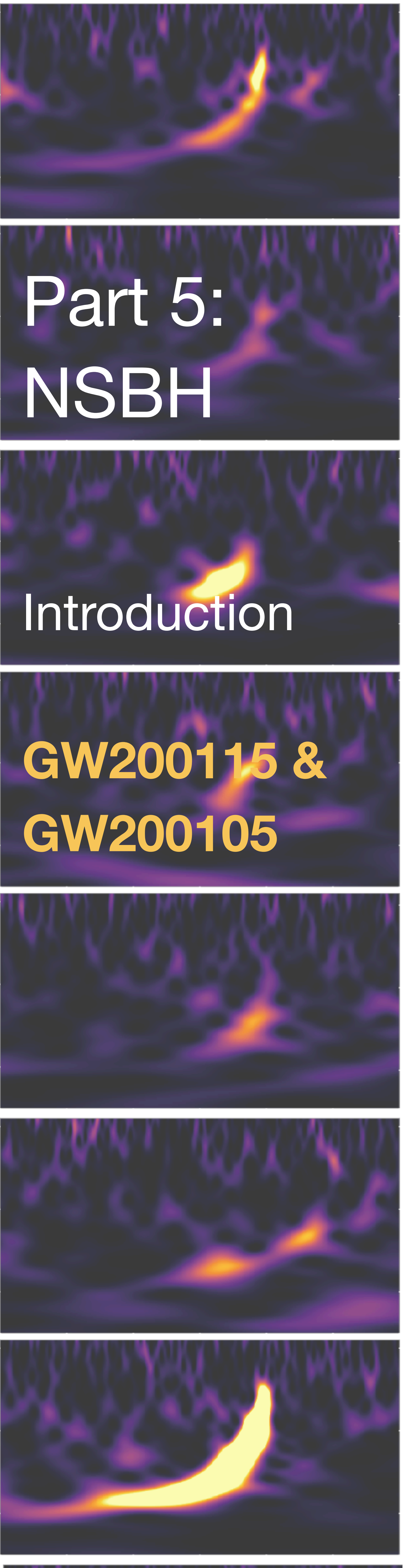
- Spectrograms do not always show the track of the signal (see previous slide).
- To detect a CBC we use matched-filtering methods but the SNR is not always enough to estimate the significance of a trigger so we also compute the χ^2 or auto correlation χ^2(y-axis of the plot)

GW200115 :

- Coincident event
- H1 & L1 do not stand individually

GW200105 :

- Single detector
- L1 SNR : 13.6
- In L1, Distinctly separate



Gravitational waves from NSBH coalescences

GW200115 & GW200105 skymaps

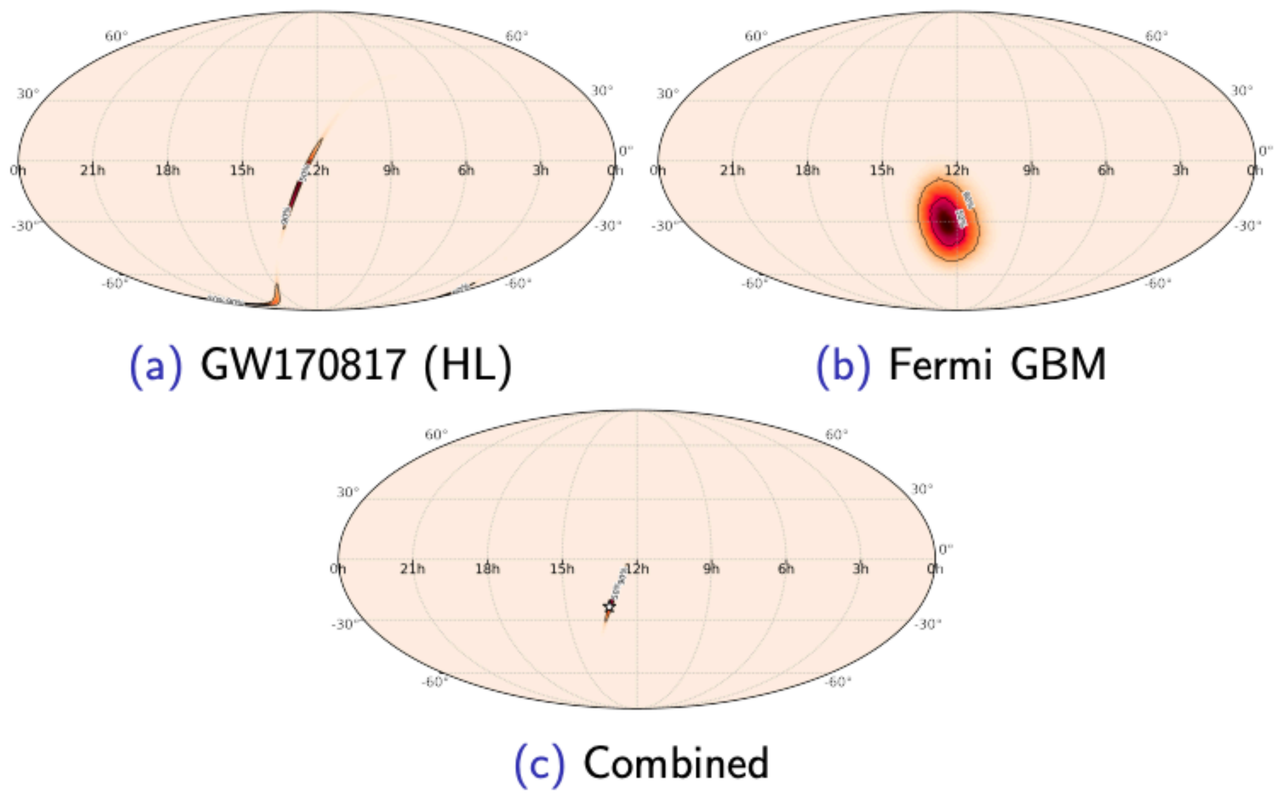


Fig26: *For comparison skymaps from GW170817*

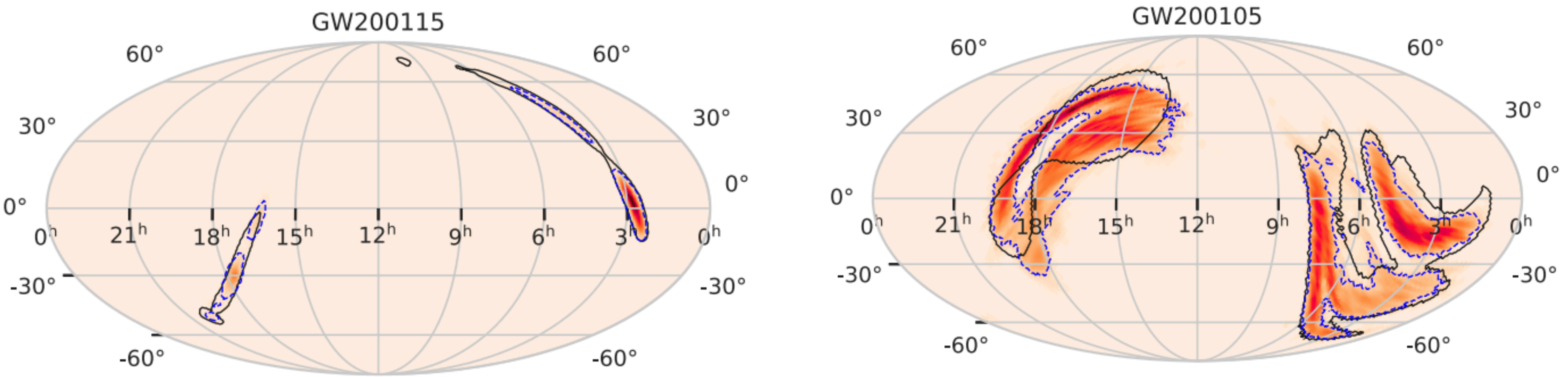


Fig25: *Sky localizations for GW200105 (top) and GW200115 (bottom)* (from https://iopscience.iop.org/article/10.3847/2041-8213/ac082e/pdf)

Sky localisation : 600 deg^2

No EM or neutrino counterpart

Sky localisation : 7200 deg^2 (large sky area arises due to the absence of data from LIGO Hanford)

Gravitational waves from NSBH coalescences

GW200115 & GW200105 source properties

* Figures from https://iopscience.iop.org/article/10.3847/2041-8213/ac082e/pdf

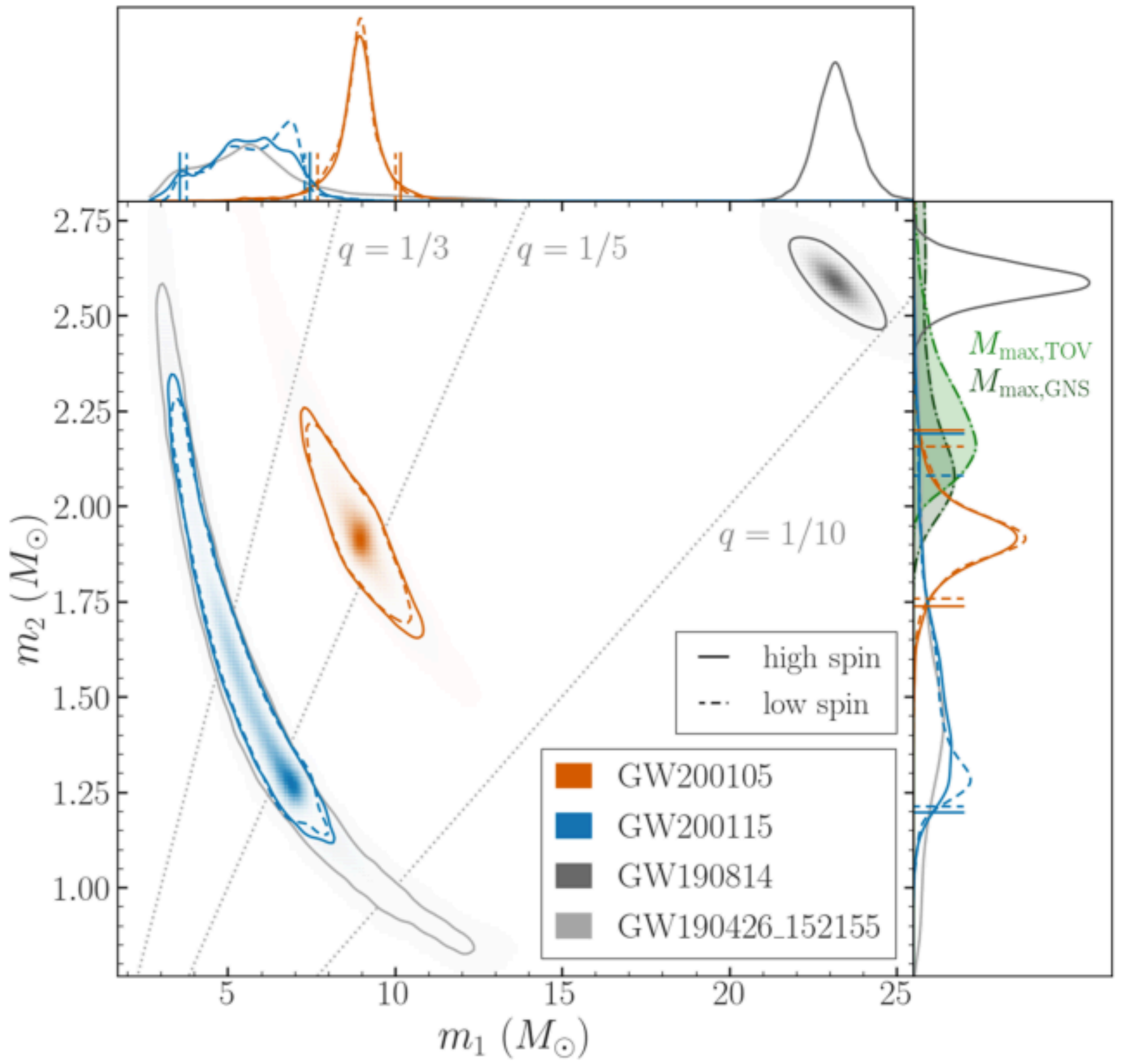


Fig27: *Component masses of GW200105 (red) and GW200115 (blue), represented by their two- and one-dimensional posterior distributions* *

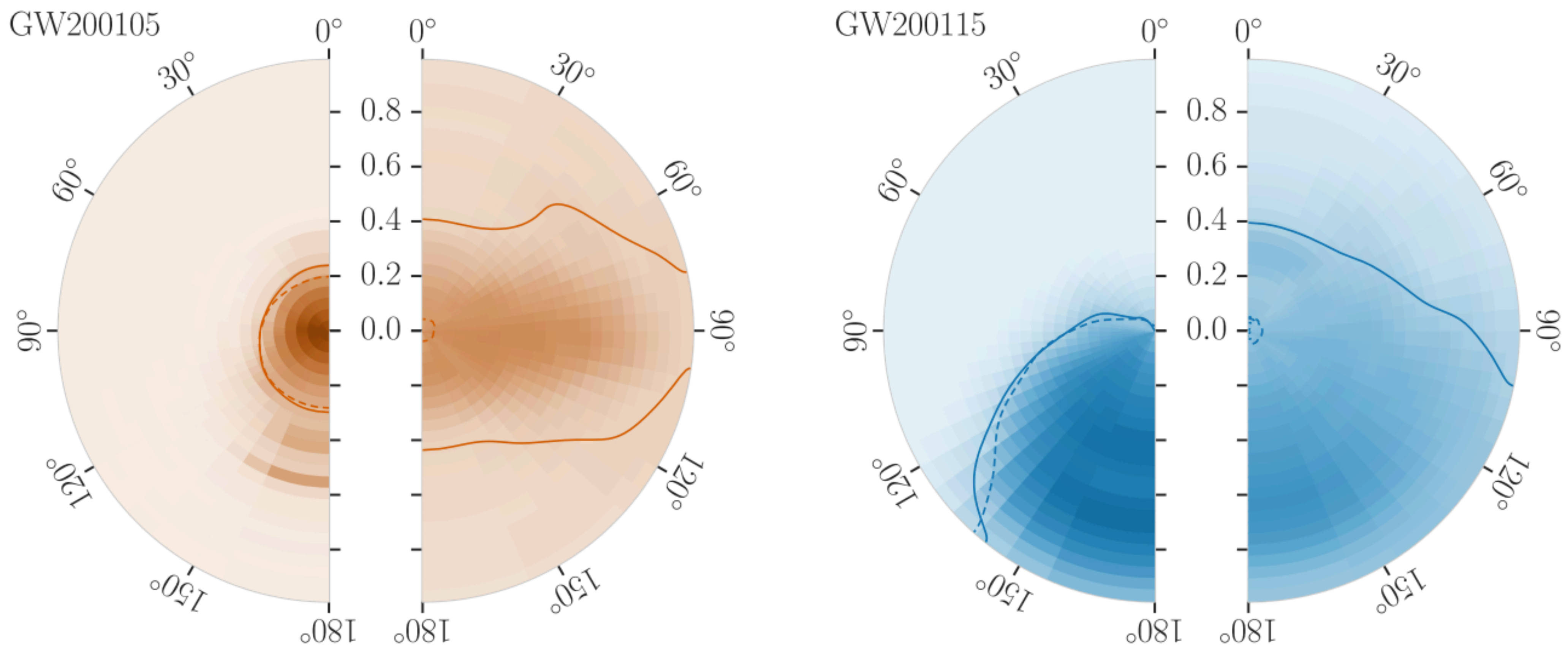


Fig28: *Two-dimensional posterior probability for the spin-tilt angle and spin magnitude for the primary objects (left hemispheres) and secondary objects (right hemispheres) for both events* *

	m1	m2
GW200105	$8.9^{+1.2}_{-1.5} M_\odot$	$1.9^{+0.3}_{-0.2} M_\odot$
GW200115	$5.7^{+1.8}_{-2.1} M_\odot$	$1.5^{+0.7}_{-0.3} M_\odot$

m2: Consistent with maximum NS mass

m1 : BH identified

GW200115 m1: 30% probability of falling in the mass gap

GW200105 :
Primary spin: $|\vec{\chi}_1^2| < 0.23$

Secondary spin: unconstrained

GW200115 :
Primary spin: $-0.19^{+0.24}_{-0.50}$

$P(\chi_{1,z} < 0) = 88\,\%$

Secondary spin: unconstrained

Part 5: NSBH

Introduction

GW200115 & GW200105

Gravitational waves from NSBH coalescences

GW200115 & GW200105: Nature of the secondary components

Investigations to establish the nature of the secondary objects :

- Tidal Deformability and Tidal Disruption
- Consistency of Component Masses with the NS Maximum Mass

Tidal deformability of NSs imprinted in the GW signal.
In contrast, BHs have zero tidal deformability.

Tidal deformability inference : Waveform models that include tides.

This measurement cannot establish the presence of NSs (Expected)

No EM counterpart detected for both events (Expected)

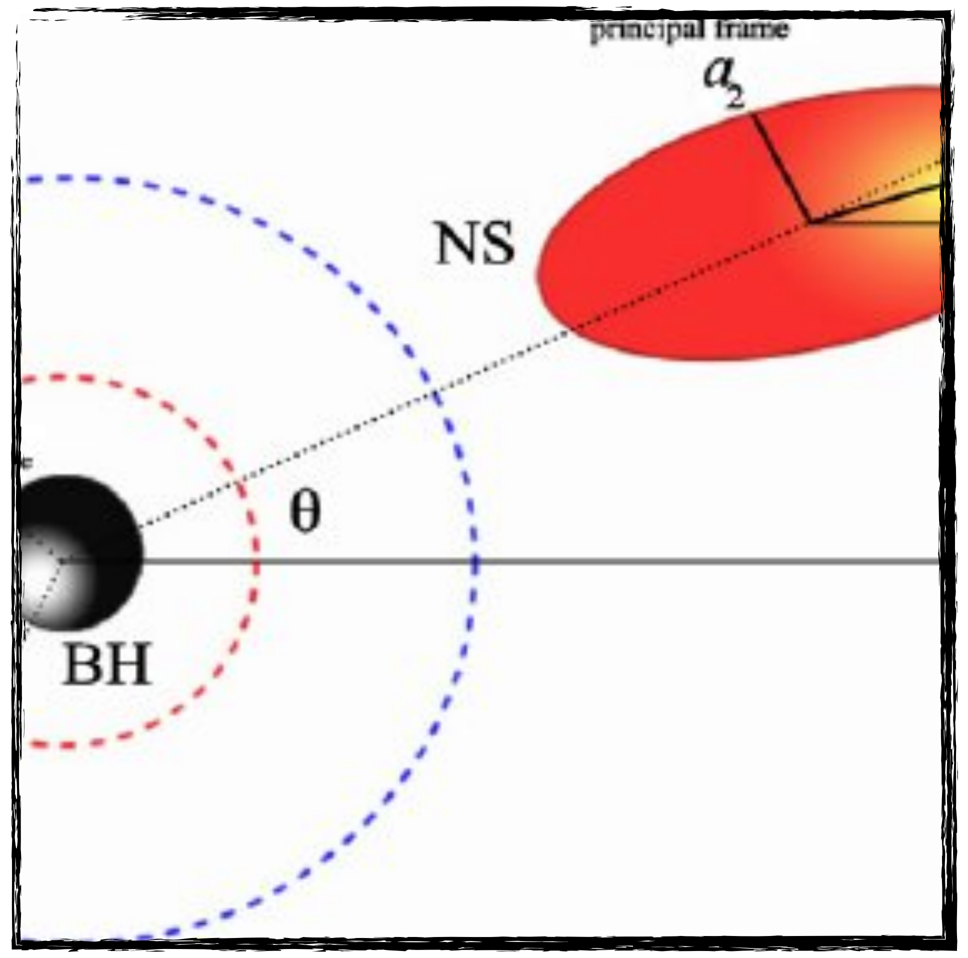


Fig29: *Tidal deformation for NS compared to BH*

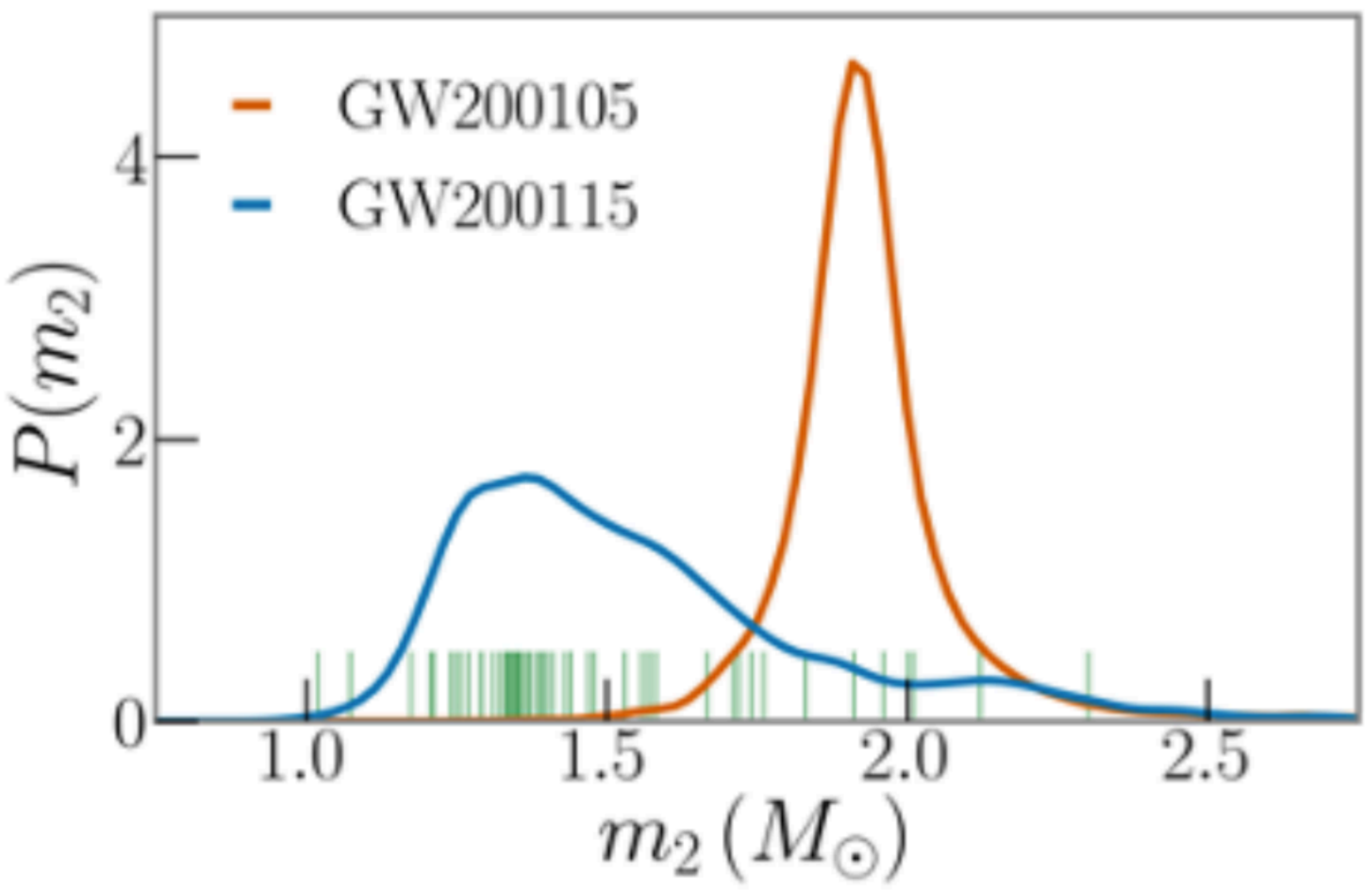


Fig30: *Estimation of the second object mass in comparison with the maximum mass*

Consistency with the maximum NS mass.
BUT does not exclude the possibility that the secondaries could be BHs or exotic compact objects (if such objects also exist within the NS mass range ie.PBH) .

Gravitational waves from NSBH coalescences

Conclusion

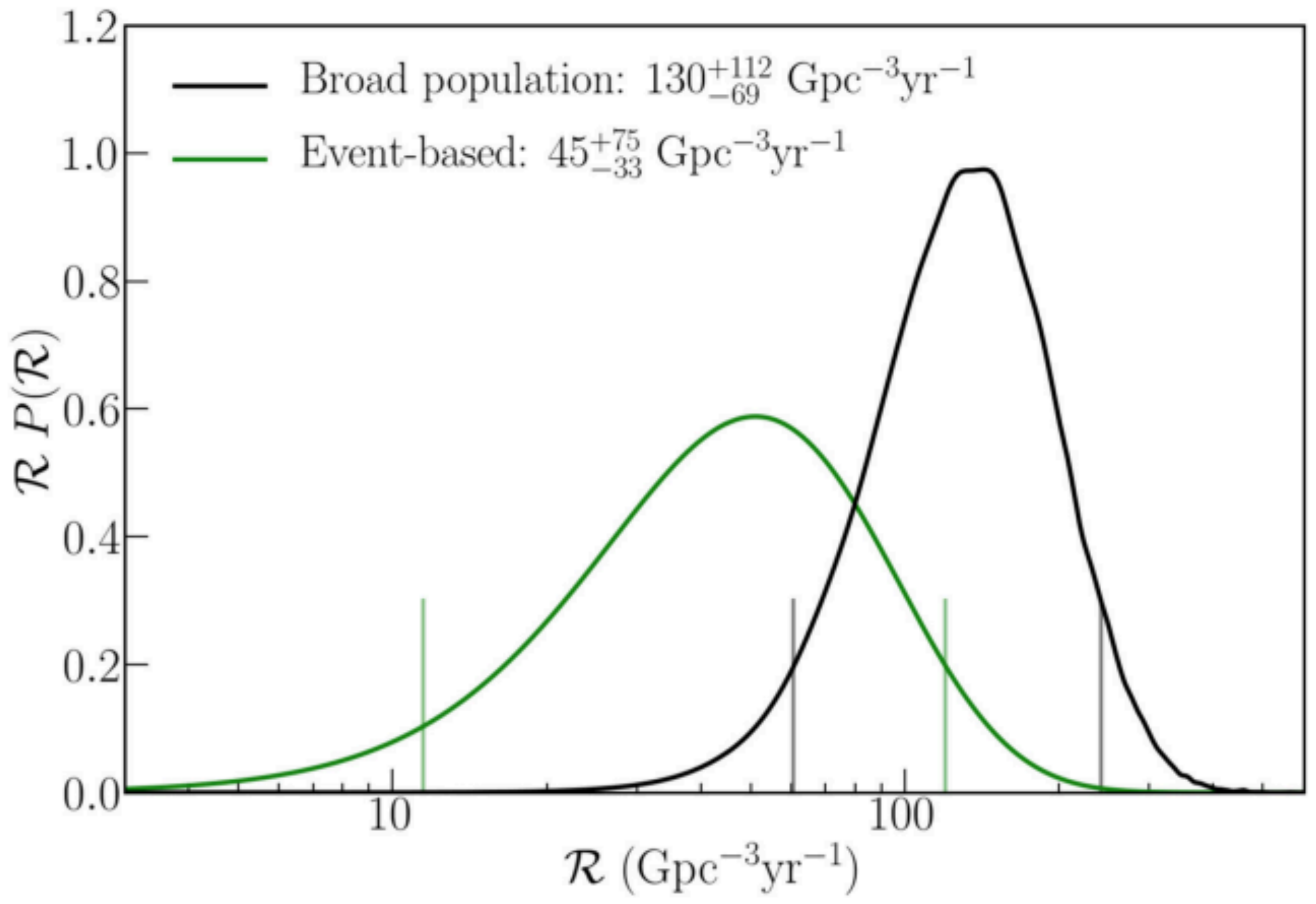


Fig31: *Inferred probability densities for the NSBH merger rate* (from https://iopscience.iop.org/article/10.3847/2041-8213/ac082e/pdf)

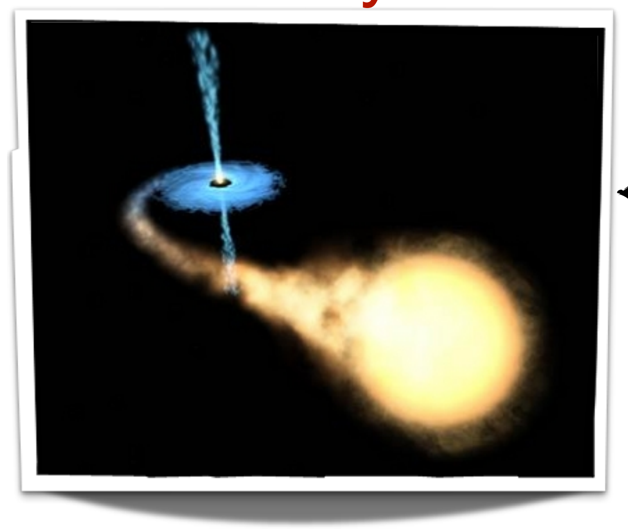
	BBH	BNS	NSBH
Merger rate $Gpc^{-3}yr^{-1}$	15-38	80-810	12-242

First robust detections of a black hole merging with a neutron star.

GW200105 ~1.9 and 9 $M_{\odot}$(two detectors)
GW200115 ~ 1.5 and 6 $M_{\odot}$ (three detectors)

Predicted rates of NSBH mergers in the local universe vary by orders of magnitude across the various formation channels.

Isolated binary evolution



Credit: European Space Agency, NASA, and Felix Mirabel

Merger rate : $Gpc^{-3}yr^{-1}$

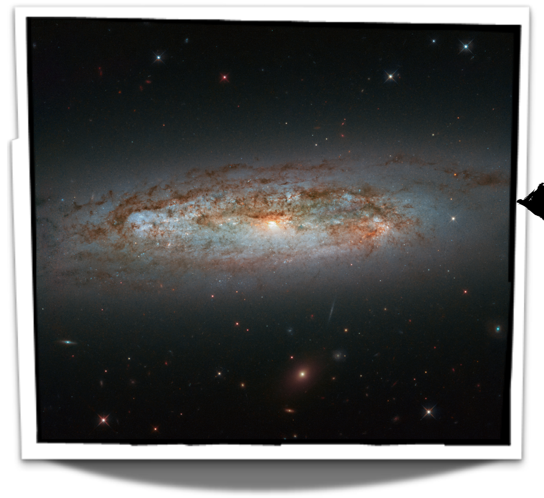
~0.1-800

~0.1-100

Young stars clusters

NGC 4755 Credit: ESO

Dynamical formation channels



Credit: ESA / NASA / Hubble / Rosario et al

AGN Disk

Merger rate : $Gpc^{-3}yr^{-1}$

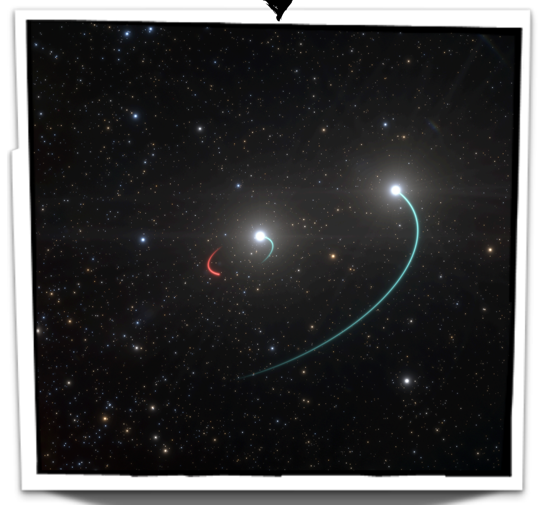
< 300

~0.01

~0.001-0.01

Credit: ESA / NASA / Hubble

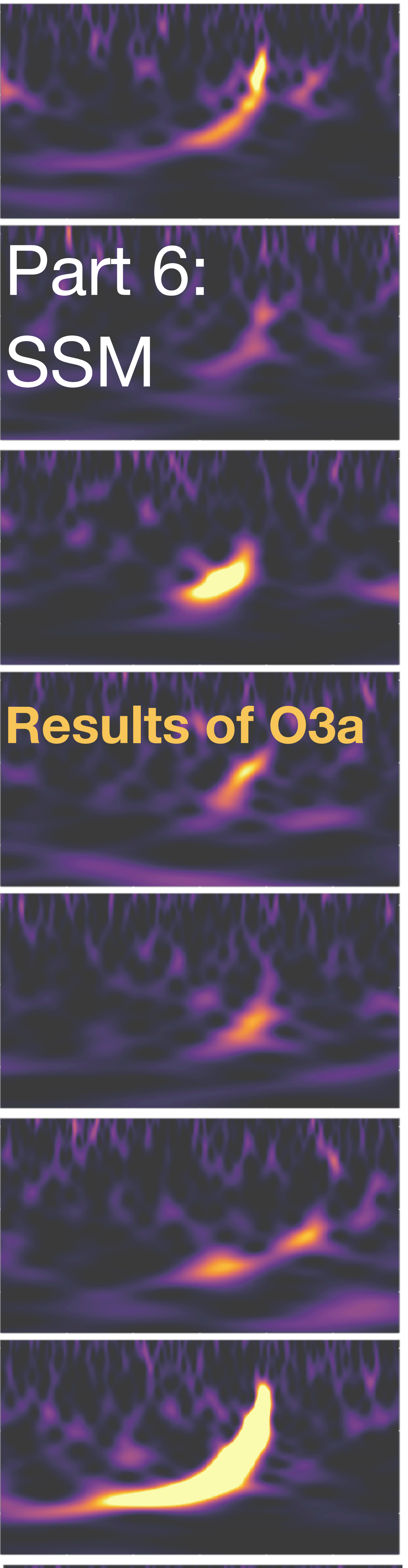
Globular clusters



Credit: ESO / L. Calçada

Hierarchical triples

Other NSBH detection: GW191219 but only found in offline (that's why it's not the « first » ..)



Sub-Solar Mass Search with O3a

PBH: Primordial Black Hole. A theoretical type of BH formed in the early Universe from the collapse of over denses regions of space

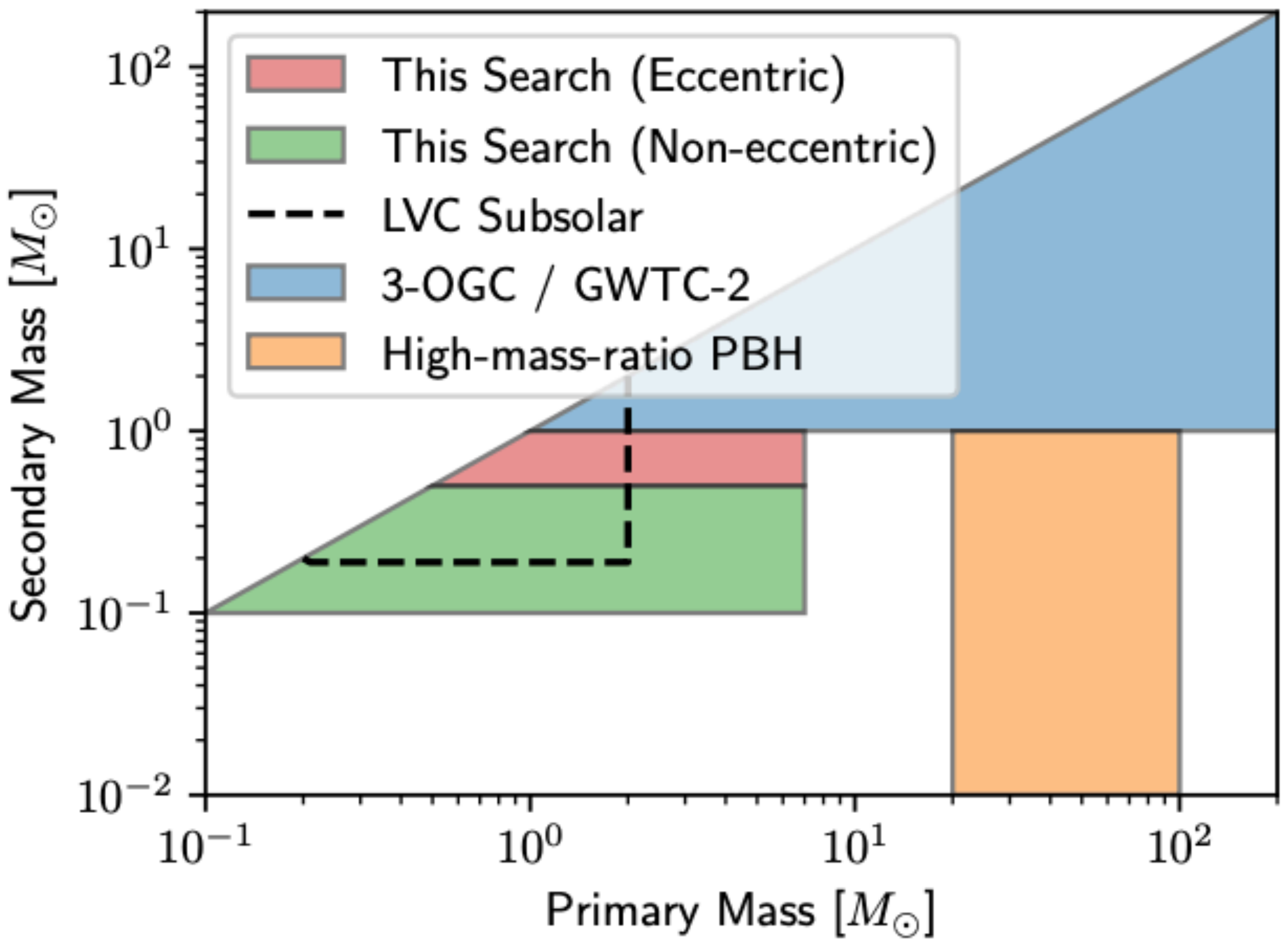


Fig32: *The regions searched by recent gravitational-wave analyses of the LIGO and Virgo data as a function of detectorframe primary and secondary mass.* *

GPS time	IFAR (yr)	$m_1/M_\odot$	$m_2/M_\odot$	e_{10}
1245411568.354	0.084	0.69	0.21	0.00
1242817372.434	0.079	0.86	0.11	0.00
1246418221.718	0.075	0.13	0.13	0.00
1252963276.322	0.062	1.05	0.52	0.28
1240000657.632	0.057	3.04	0.10	0.00

Table1: *The top 5 candidates in our search with the highest inverse false alarm rates (IFAR).* *

Consistent with a null observation

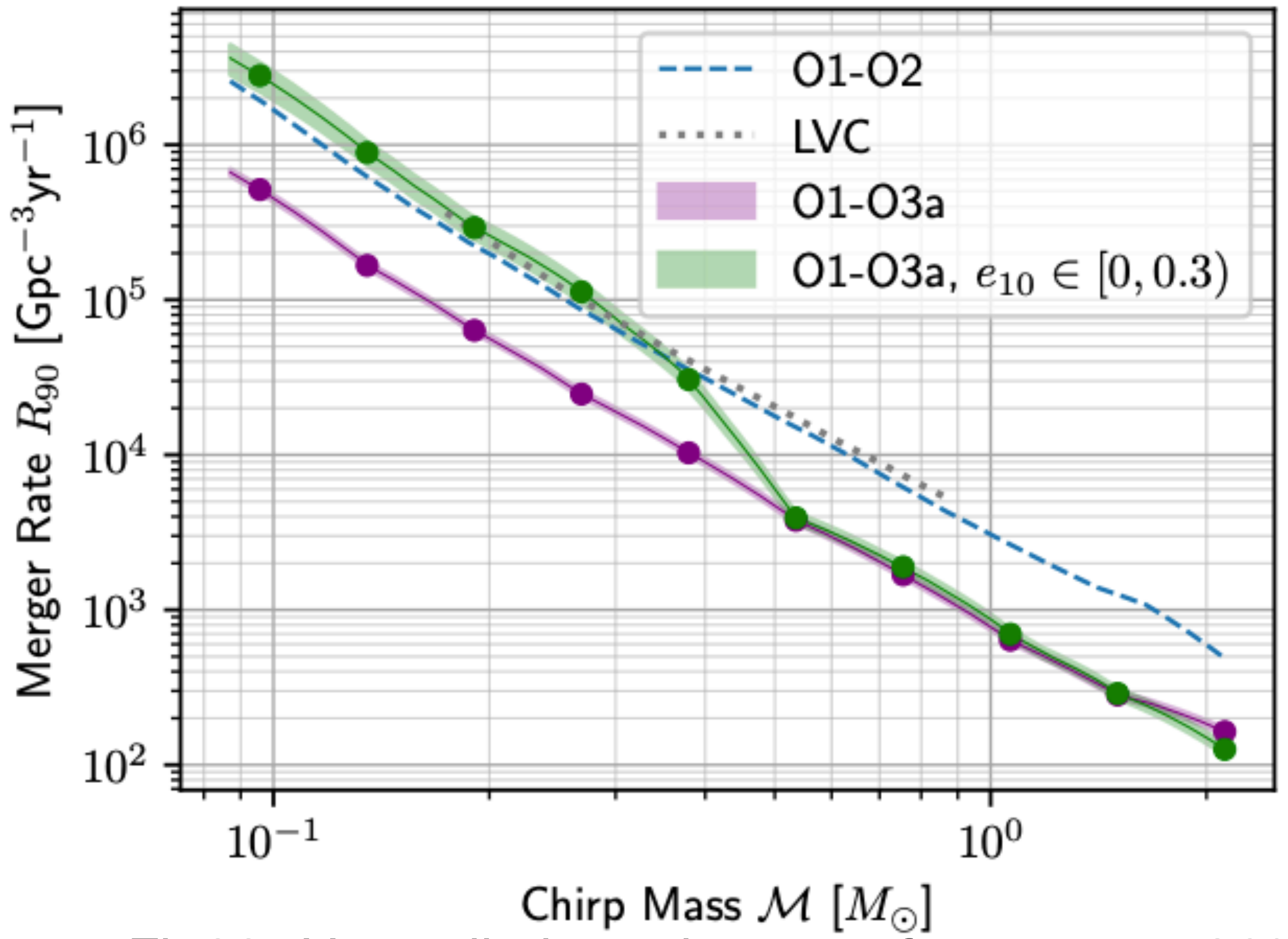


Fig33: *Upper limit on the rate of mergers at 90% confidence for the SSM search (purple)*

$$R_{90} = \frac{2.3}{VT}$$

where V is the estimated sensitive volume of the analysis assessed at the false alarm rate of the most significant observed candidate and T is the duration of the observation period.

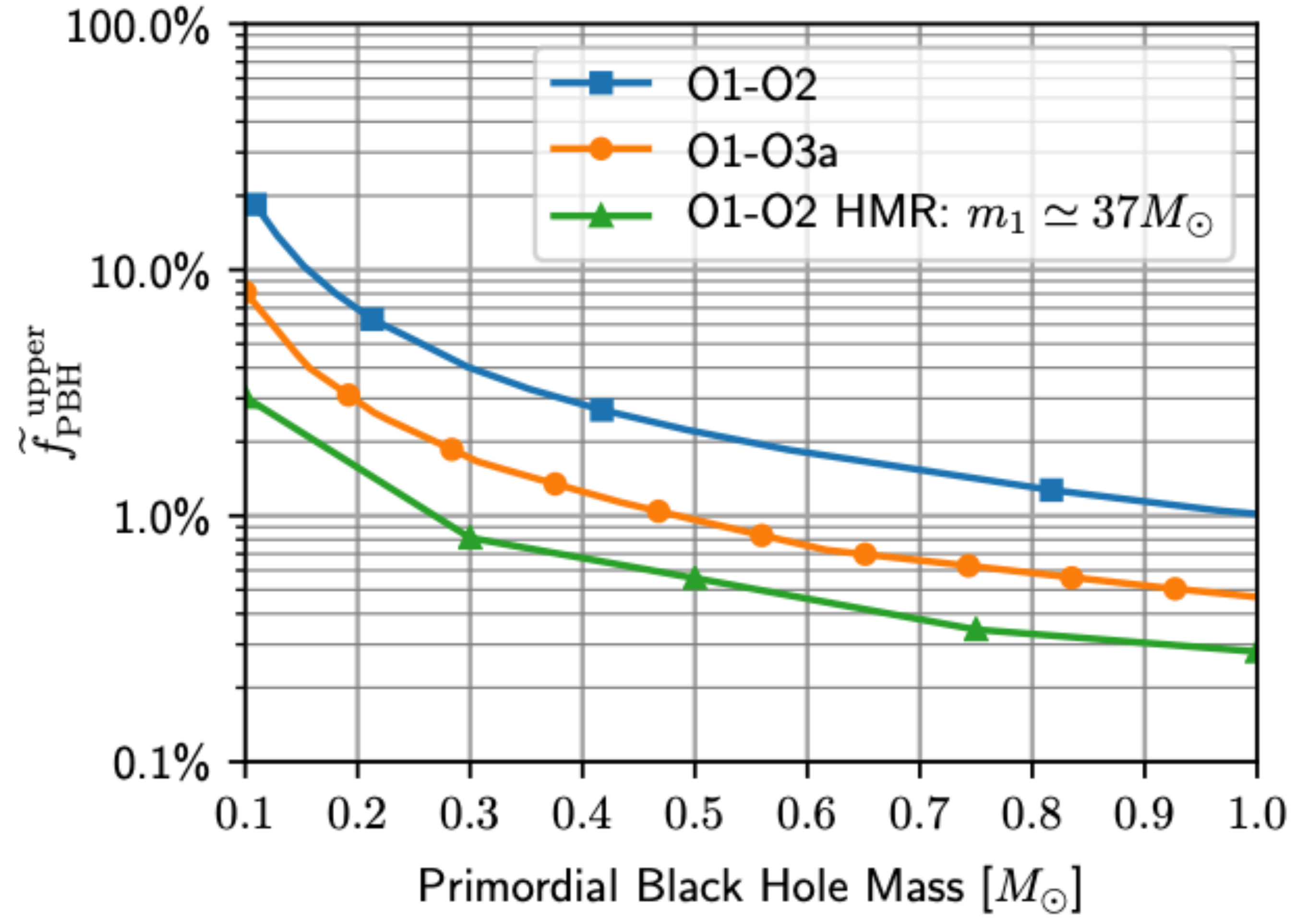


Fig34: *The upper limits on the effective fraction of the primordial black hole contribution to dark matter.* *

*Figures and Table from https://arxiv.org/pdf/2106.08979.pdf

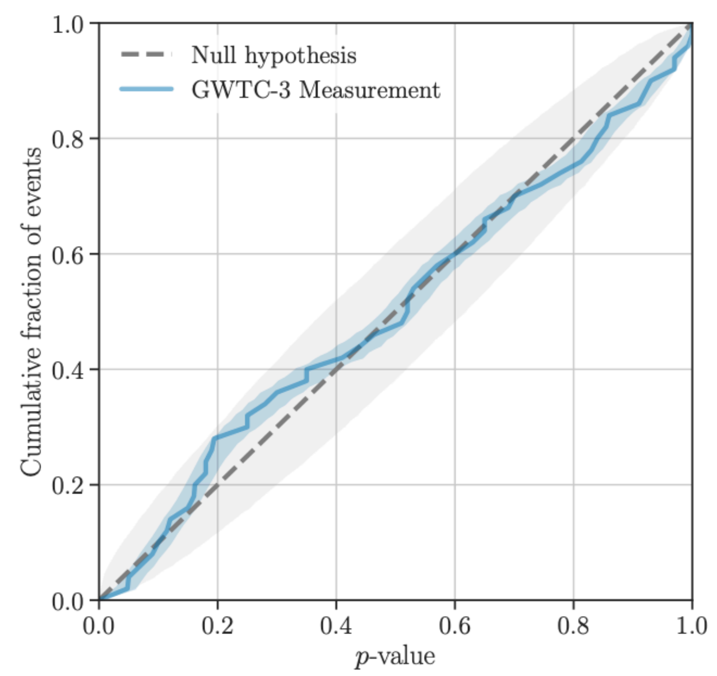
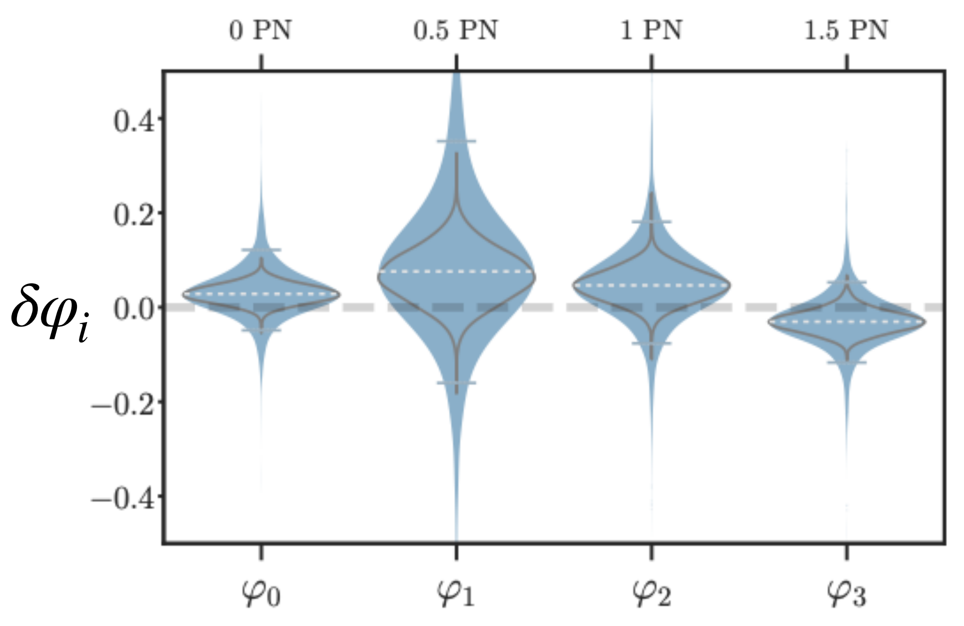
Test of General relativity

Introduction

- The model waveform is constructed using the predictions of General Relativity.
- Gravitational-wave sources offer us unique testbeds for probing strongfield, dynamical and nonlinear aspects of gravity
- Tests predictions of General Relativity by introducing small modifications to our currently available waveform models and compare the data with these "distorted" waveforms
- Three theory-agnostic tests (parameterized tests, inspiral-merger-ringdown consistency tests, and gravitational-wave propagation tests)

Tests : Examples

Event selection : 15 events
with IFAR > 1000 yr from O3b
Combined with events from GWTC-2, whenever possible

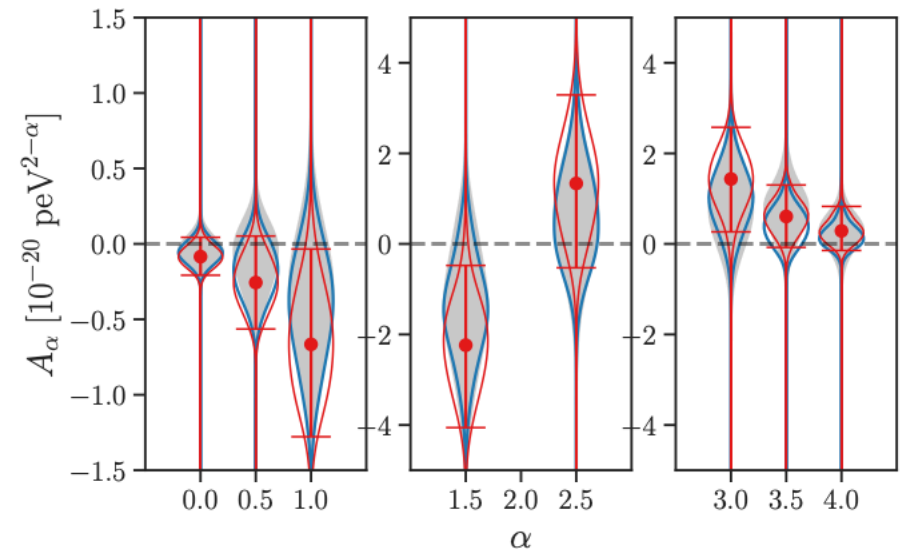
Tests	Question to answer	Description	Results
Residual Test	Are the residual consistent with detector noise?	Subtracts the best-fit GR waveform from the data and asks whether there is any statistically significant residual power.	 **No evidence for violation of GR**
Parametrized test	Is the inspiral phase consistent with GR ?	Inspiral can be treated perturbatively within the post-Newtonian framework. PN coefficients : measurable parameters of the waveform —> sensible consistency test of GR	 **No evidence for violation of GR**

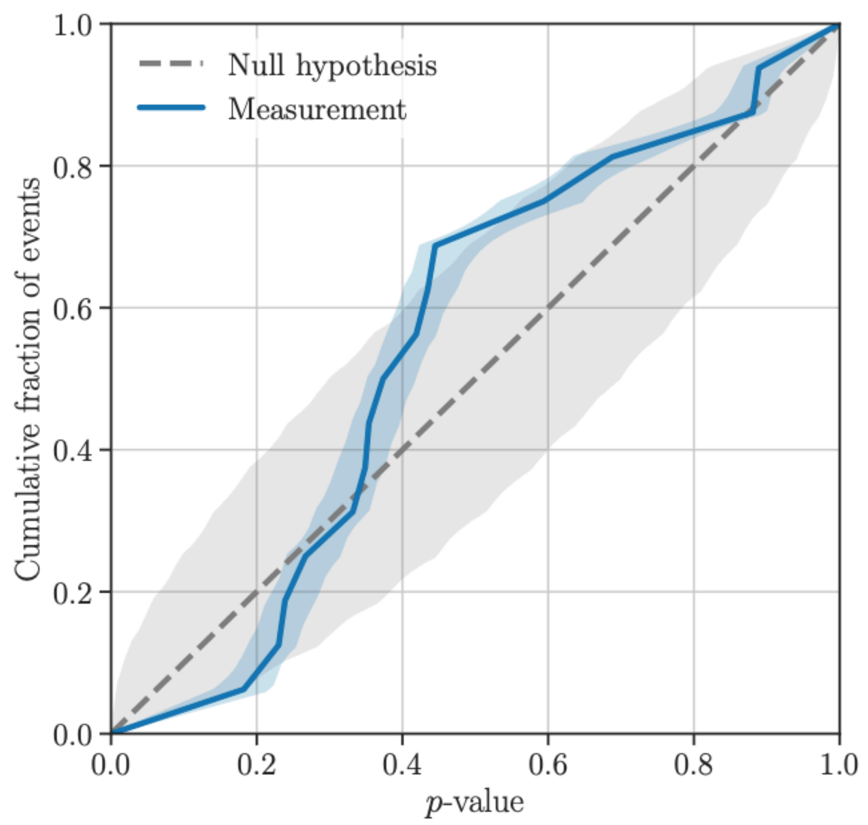
$$\varphi_{\mathrm{PN}}(f) = 2\pi f t_c - \varphi_c - \frac{\pi}{4} + \frac{3}{128\eta}\left(\pi \tilde{f}\right)^{-5/3} \sum_{i=0} \left[\varphi_i + \varphi_{i\,l} \log(\pi \tilde{f})\right] \left(\pi \tilde{f}\right)^{i/3}$$

Fig35-36: from https://arxiv.org/pdf/2112.06861.pdf

Tests : Examples

<table>
<tr><th>Tests</th><th>Question to answer</th><th>Description</th><th>Results</th></tr>
<tr><td>Modified dispersion</td><td>Modified theory predict dispersion of GW</td><td>Affect the morphology of the signal —> effective dephasing of the GW signal can be measured.
$E^2 = p^2c^2 + A_\alpha p^\alpha c^\alpha$
Different choices of α—> leads to a deviation in the GR phasing formula.

Mass of the graviton :
$m_g = \sqrt{A_0}/c^2$</td><td>

Improved bounds on graviton mass with respect to GWTC-2
$m_g < 1.27 \times 10^{-23} eV/c^2$</td></tr>
<tr><td>Test for GW echoes</td><td>If the merger remnant is not a classical BH but an exotic compact object without an event horizon but a reflective surface</td><td>Search for post-merger echoes in a morphology independent way.</td><td>

No evidence for echoes</td></tr>
</table>

Fig37-38: from https://arxiv.org/pdf/2112.06861.pdf

Testing GR : Summary

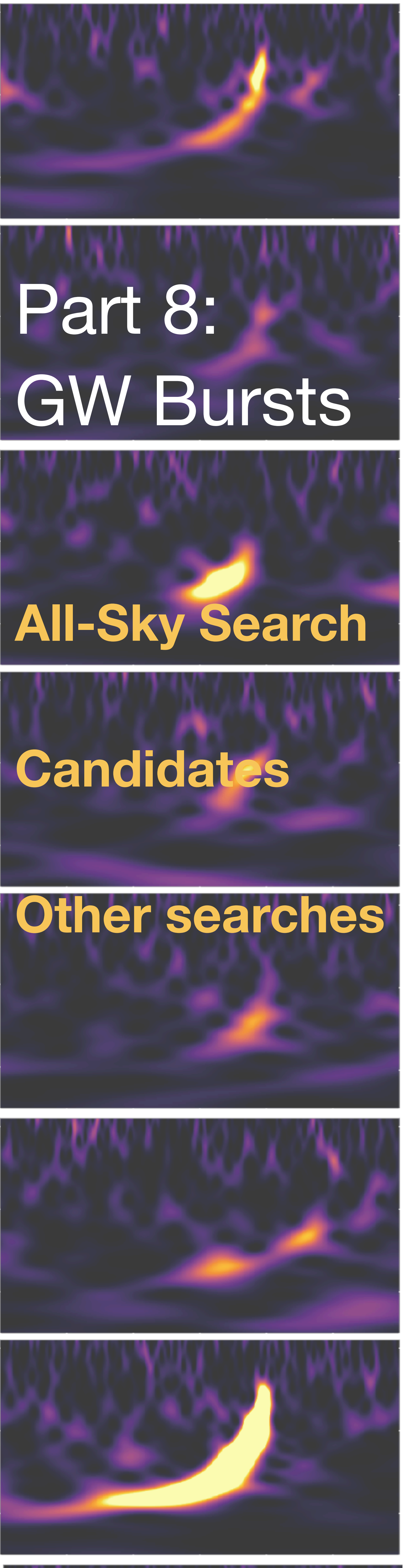
Many more tests of General Relativity have been done :

- Spin-induced quadrupole moment test
- GW polarizations test
- BH remnant test
- Ringdown test
- …

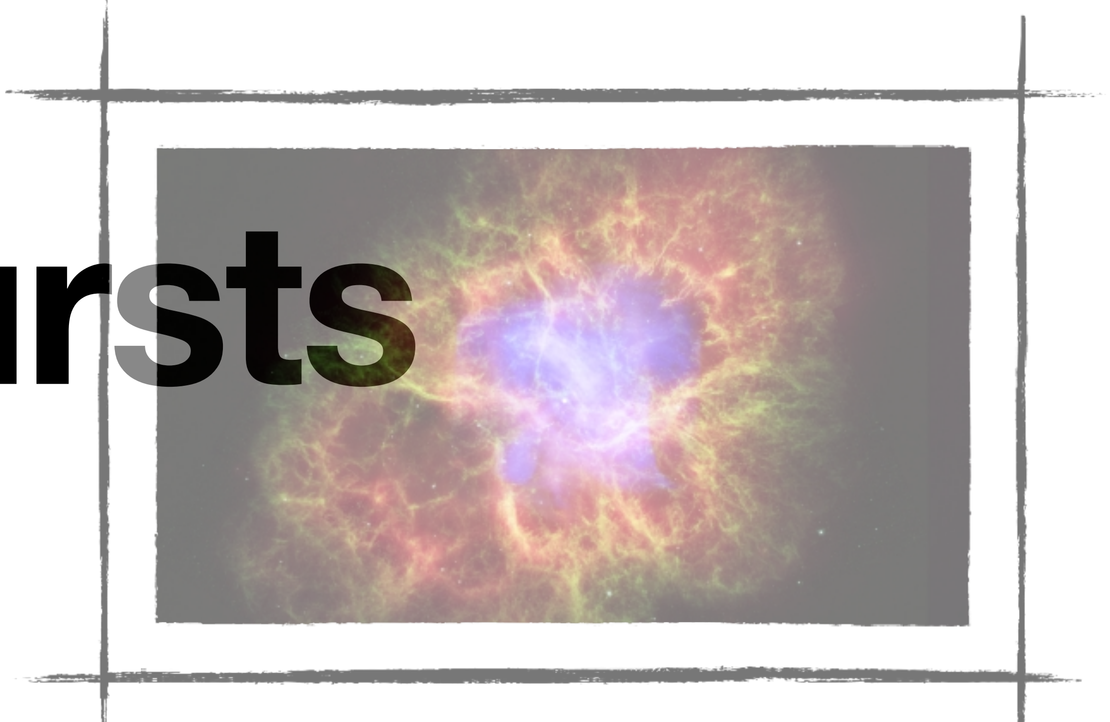
- Found no statistically significant evidences for any deviation from GR

- Update bounds on deformation parameters in the case of parametrized tests

- Testing GR is very hard, even if a deformation is found:
    - Is it really GR that is deformed ?
    - A problem in the data qualify models ?
    - Waveform not enough precise ?

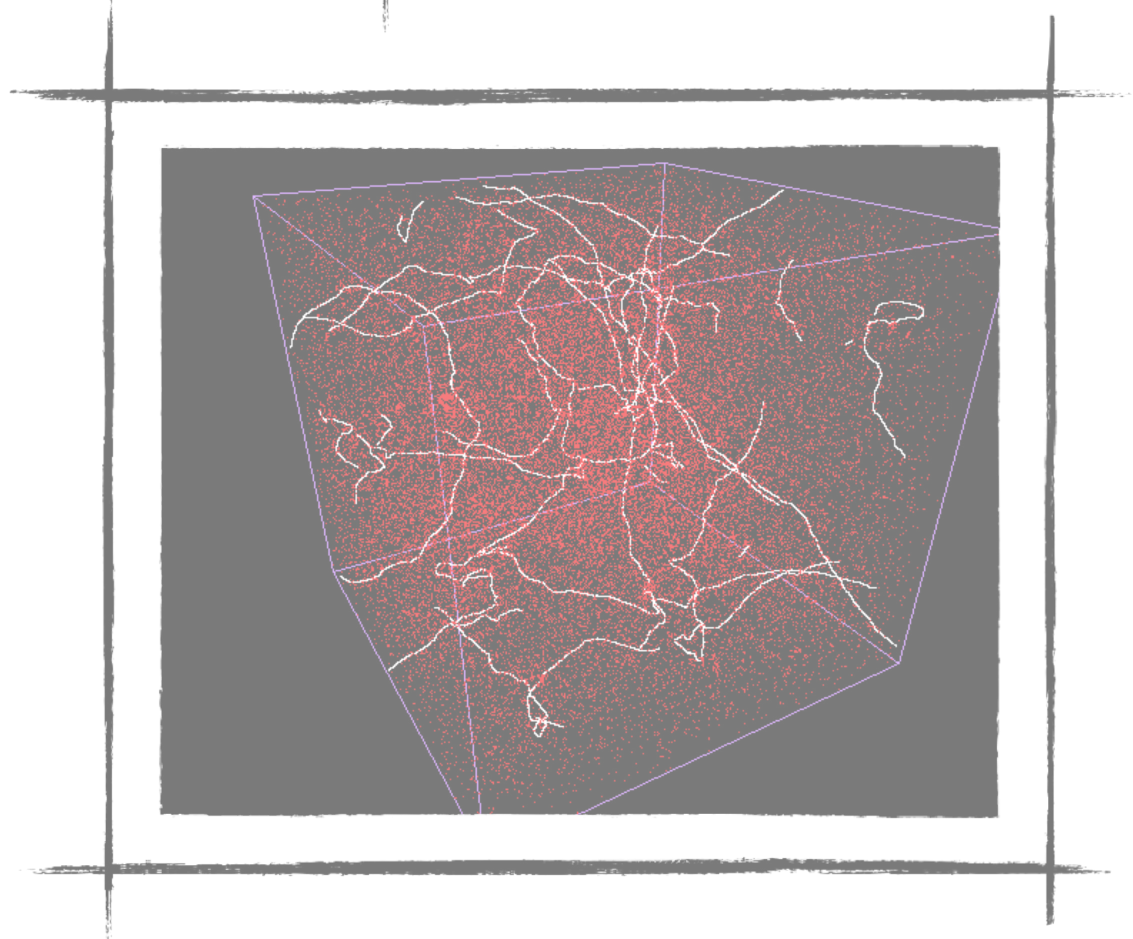


All-Sky Search for short GW Bursts



Introduction : All-Sky Search

- There are several plausible sources of short-duration GW transients (GW bursts) that have not yet been observed, such as core-collapse supernovae, neutron star excitations, non-linear memory effects, or cosmic string cusps and kinks
- All-sky search looks for signals arriving at any time from any sky direction : short-duration GW transients, up to a few seconds duration , and longer GW transients, up to $\sim 10^3$ s duration
- 2 independently developed search algorithms deployed: coherent WaveBurst (cWB) and BayesWave (BW).



Candidates

Three loudest candidates : statistical significance insufficient to exclude an instrumental origin.

Null result of this search : - Allows setting of rate density upper limits at an inverse false alarm rate threshold of 100 years

- Estimate sensitivity to certain classes of GW signals: CCSNe and isolated NS excitations.

Other searches …

Searches have also been done for many other objects such as continuous GWs and stochastic background —> Currently nothing found !

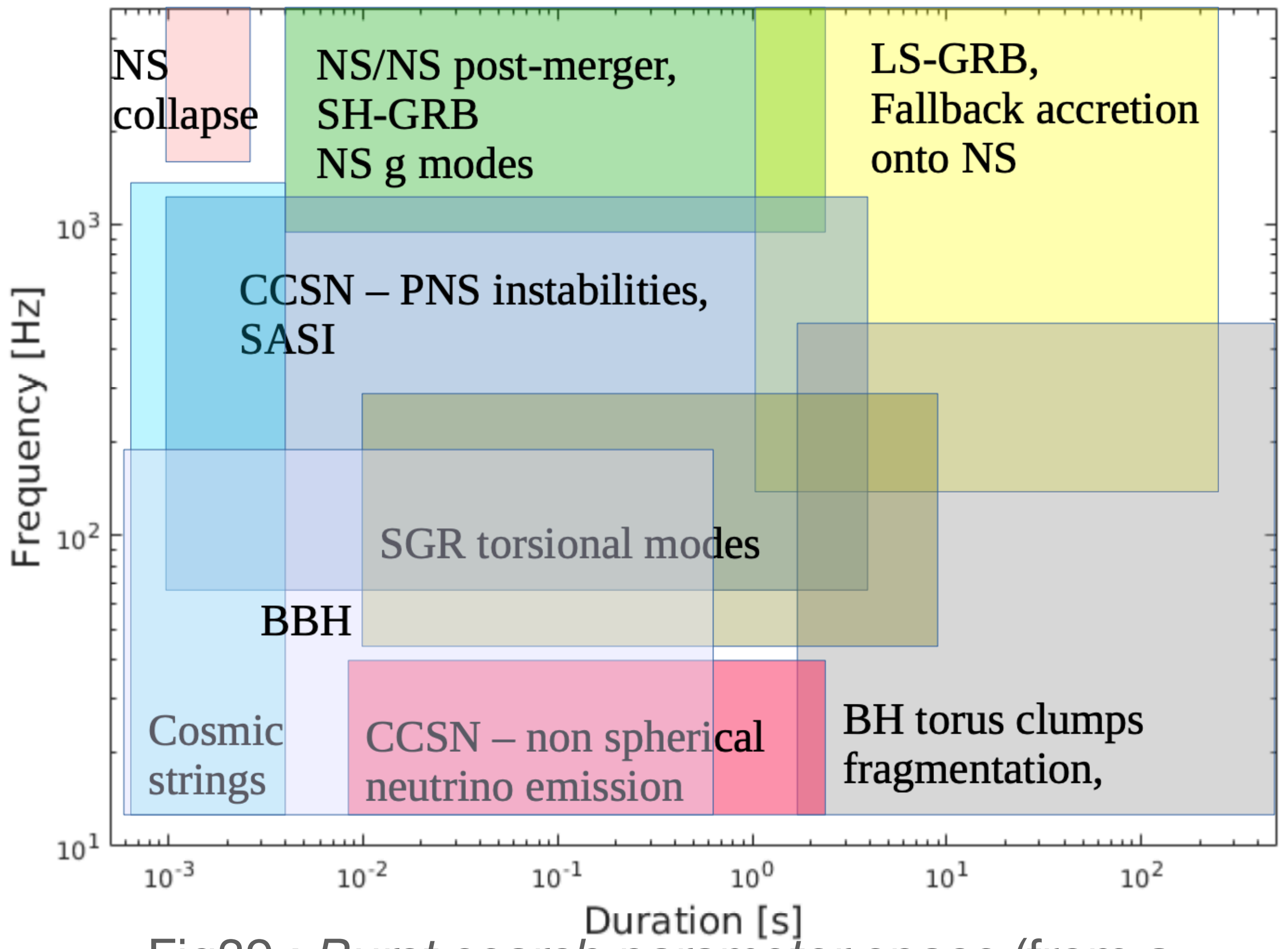


Fig39 : *Burst search parameter space* (from a presentation of Marie Anne Bizouard)

What happened since the last O3 seminar ?

Summary

- O3a : 44 new events (in GWTC-2.1) —> O3b 35 new events
- First robust NSBH detections
- No evidence for deviation of GR (same as previously)
- No exotic source found (Burst, continuous GW …) only CBC sources (same as previously)
- O3a sub-solar mass search : no SSM object found

- Forthcoming publications :
- O3b sub-solar mass search

Thank you !

Backup

Detector spectrum noise

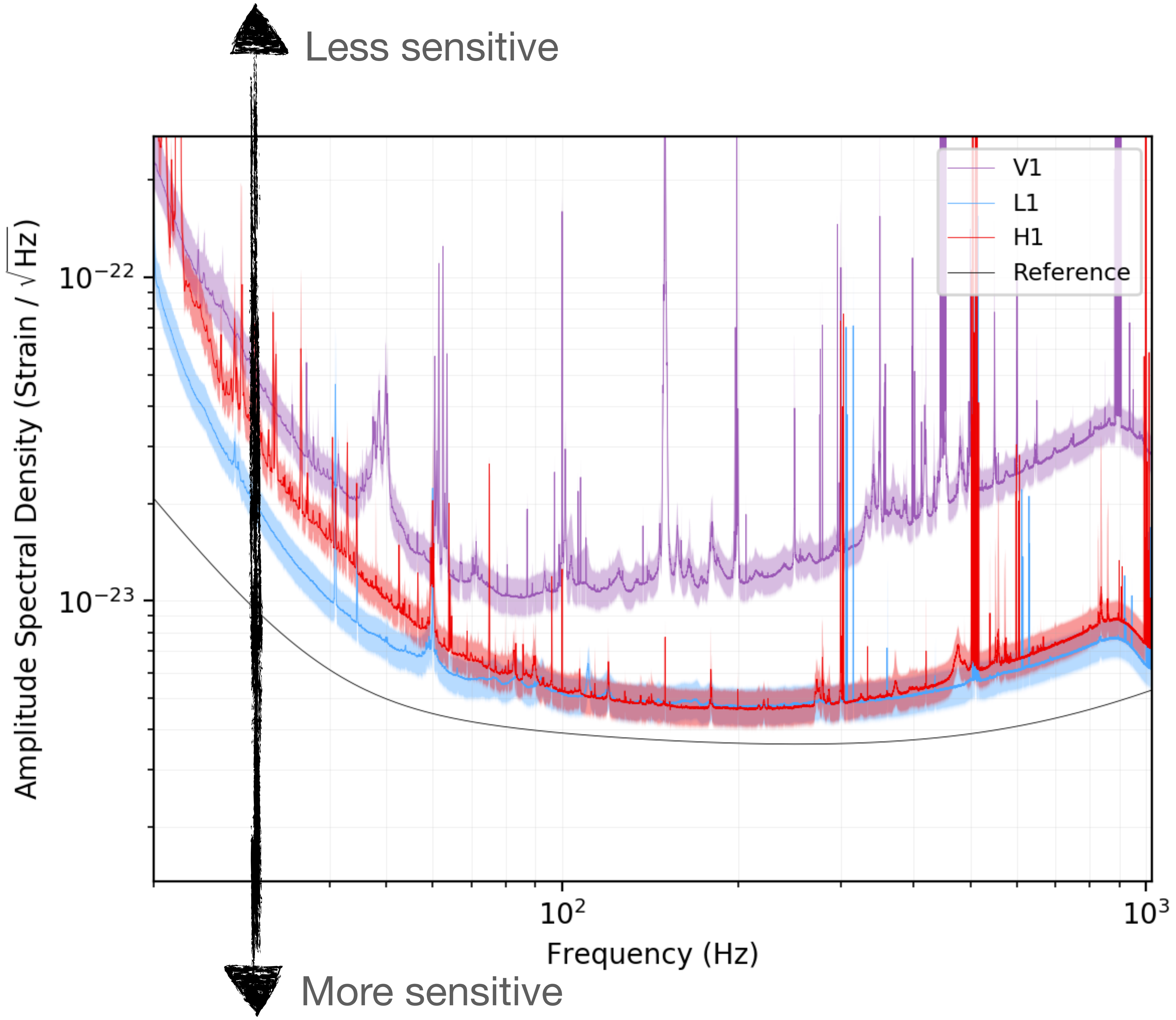


Fig5 : *Representative amplitude spectral density of the three interferometers' strain sensitivity*

Astrophysical population

To go further: Implication for Binary Black hole & Neutron stars formation

BH : The statistical distribution of BH source properties such as their mass, spin and redshift can be used to probe the astrophysics of BH binary formation and evolution:

PREDICTIONS :

Formation in globular clusters : the resulting BH mass distribution is generally predicted to peak at > 10 $M_\odot$. Large spin–orbit misalignment. Redshifts : $\kappa \lesssim 2$

Dynamical formation in young clusters : disfavored to explain the whole BH population at m ~ 10 $M_\odot$. large spin–orbit misalignment. Redshifts : $\kappa \lesssim 2$

Galactic nuclei : a BBH population with a much wider mass spectrum than both young and globular clusters. Large spin–orbit misalignment. Redshifts : $\kappa \sim 1$.

Near an AGN disk : a significant population of BBH mergers with a wide mass spectrum. Spin depends on several factors

Isolated binary evolution models : a peak near m ~ 10 $M_\odot$. Preferentially aligned spins

NS : One result from gravitational wave (GW) observations is tension with the strong preference for 1.35 $M_\odot$ mass objects which has been recovered in galactic BNS.

GW Burst : CCSN

P. Cerda-Duran et al, Astrophys.J. 779 (2013) L18

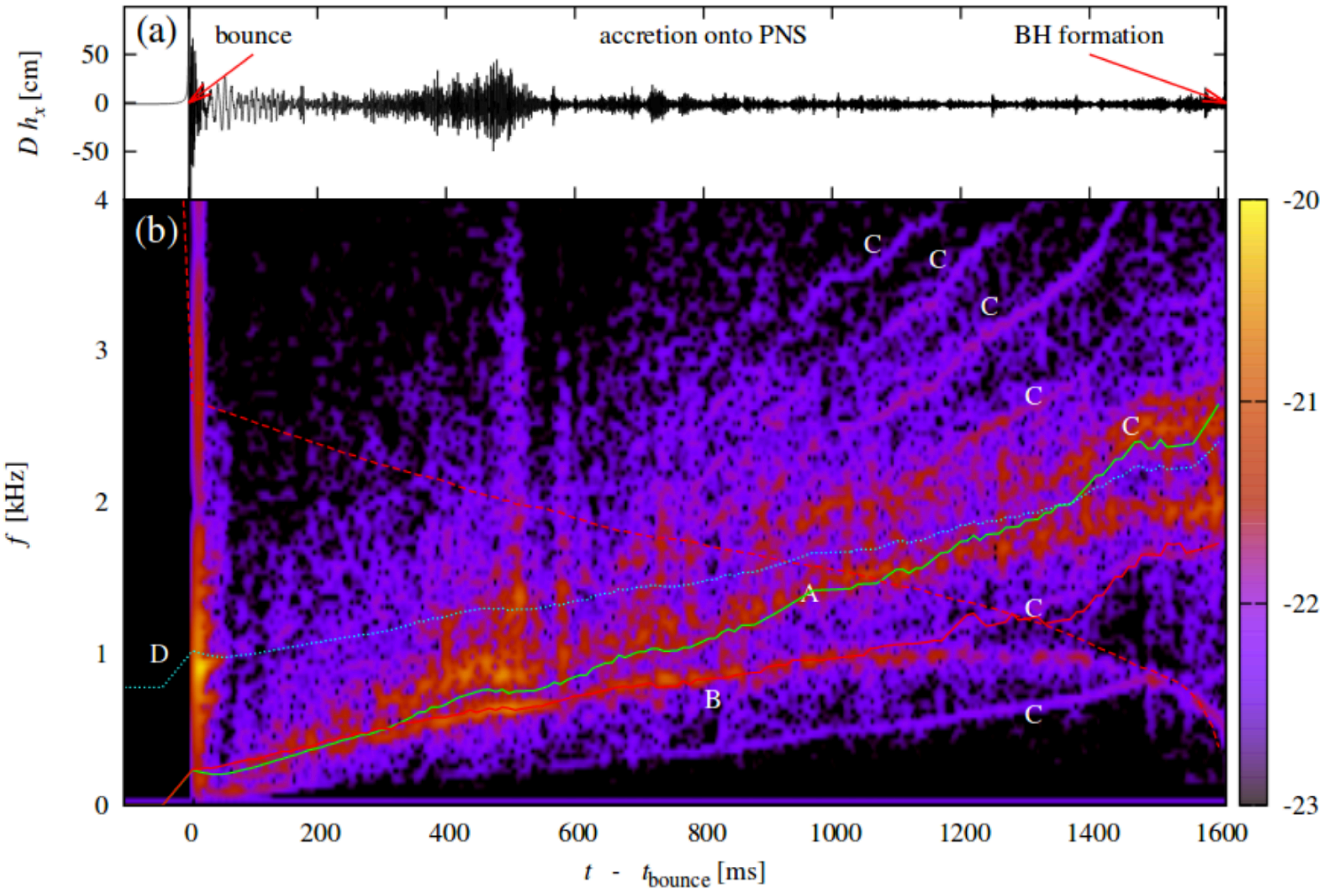


FIG. 3.— Waveform (a) and spectrogram (b) of the characteristic gravitational wave signal for the *fiducial model* at $D = 100$ kpc. We overplot estimates for the frequency evolution of g-modes at the surface of the PNS (solid-green line), g-modes in the cold inner core (solid-red line), quasi-radial mode (dashed-red line) and f-mode (dotted-blue line). Capital letters point to features described in the main text.

Morozova et al, Astrophys.J. 861 (2018) no.1, 10

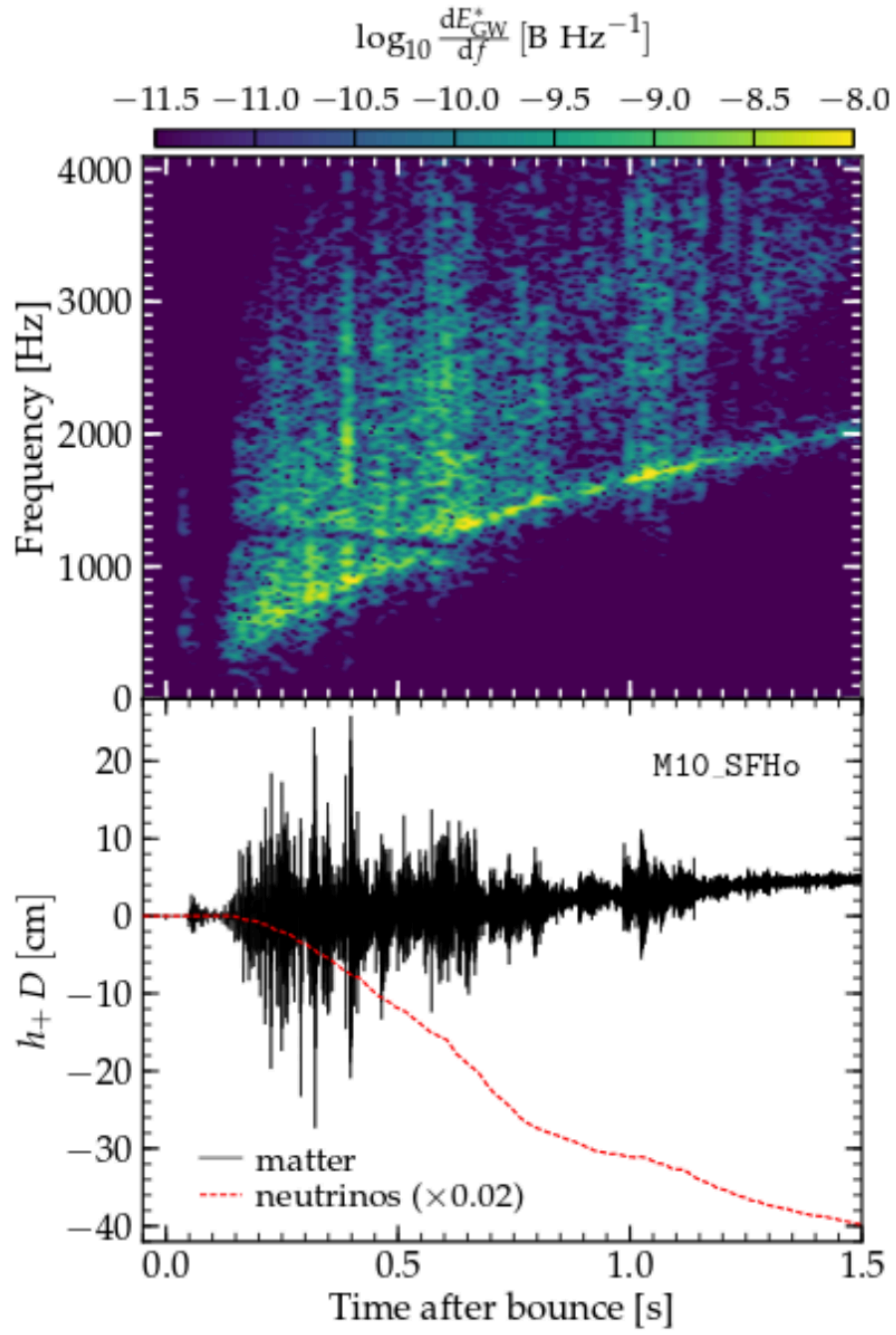


Figure 1. Spectrogram (top) and the corresponding waveform (bottom) of the GW signal from the model M10_SFHo.

GW200105-15