

# Binary black hole mergers so far...

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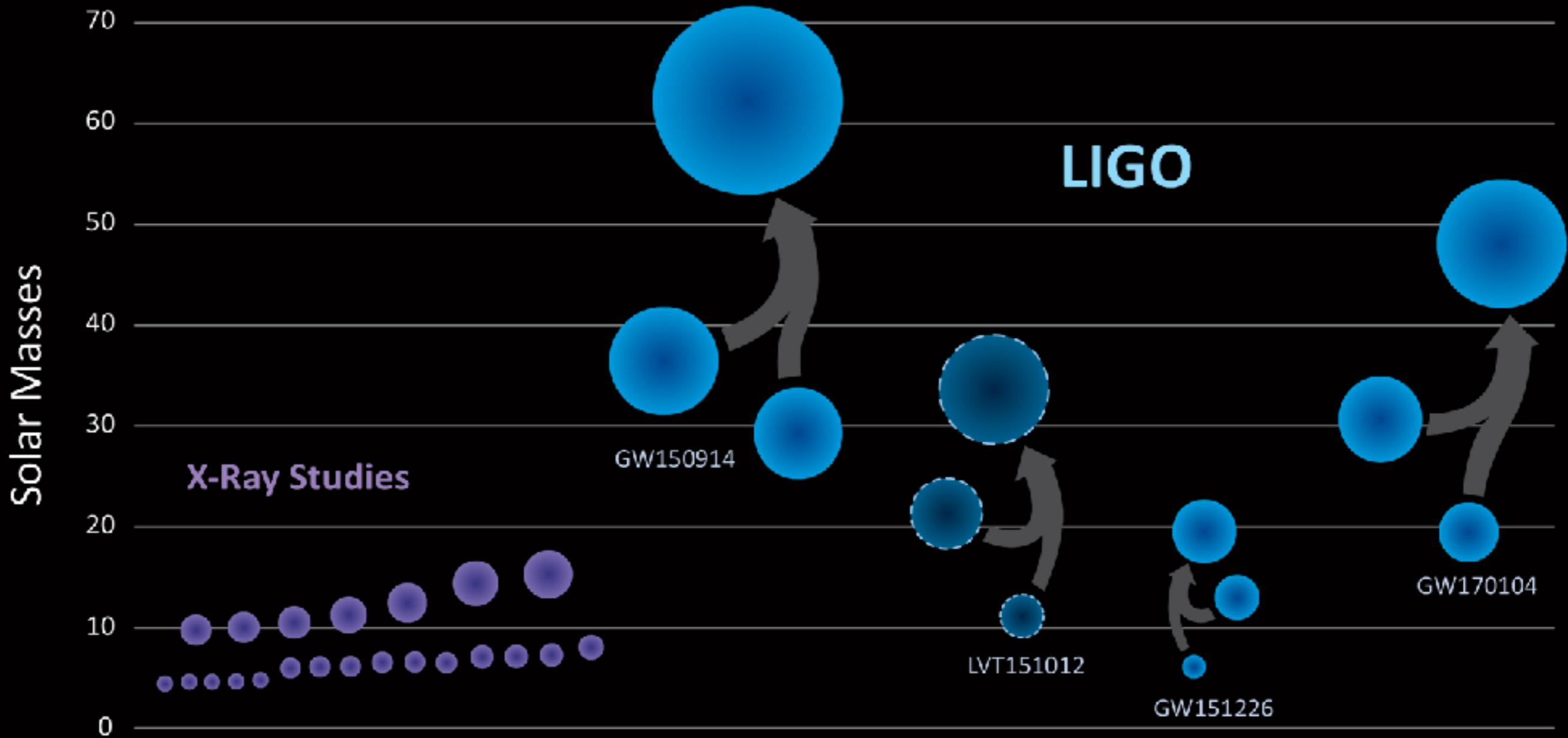
*New Frontiers in Gravitational Wave Astrophysics - Roma, 19 June 2017*

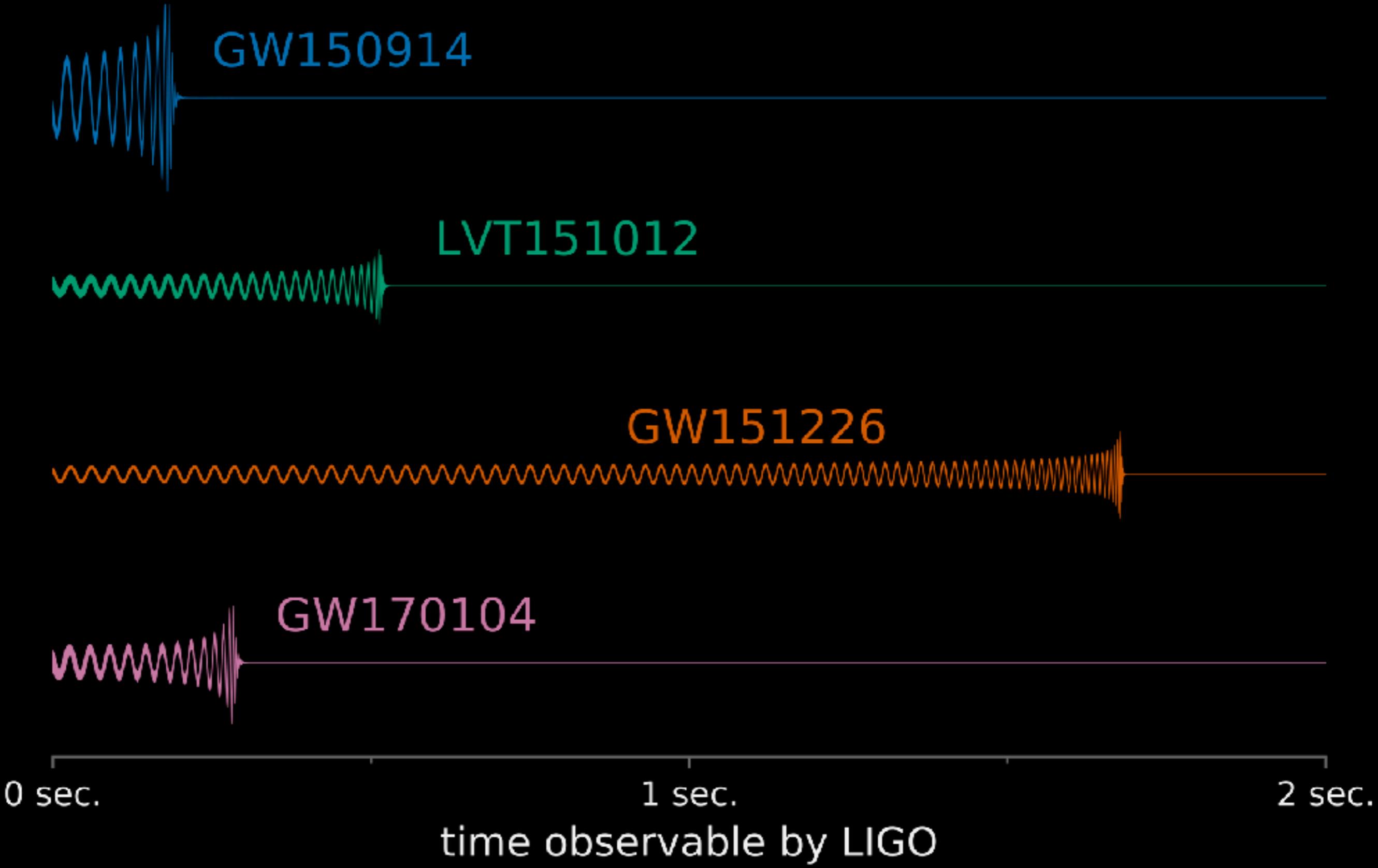
## References

- GW150914:** PRL 116 (2016), 061102, arXiv:1602.03837
- GW151226:** PRL 116 (2016), 241103, arXiv:1606.04855
- GW150914 tests of GR:** PRL 116 (2016), 221101, arXiv:1602.03841
- GW150914 physical properties:** PRL 116 (2016), 241102, arXiv:1602.03840
- O1 BBH summary:** PRX 6 (2016) 041015, arXiv:1606.04856
- O1 BNS/NSBH limits:** ApJ 832 (2016), L21, arXiv:1607.07456
- O1 background limits:** PRL 118 (2017), 121101 arXiv:1612.02029
- GW170104:** PRL 118 (2017), 221101, arXiv:1706.01812



LIGO-G1701147



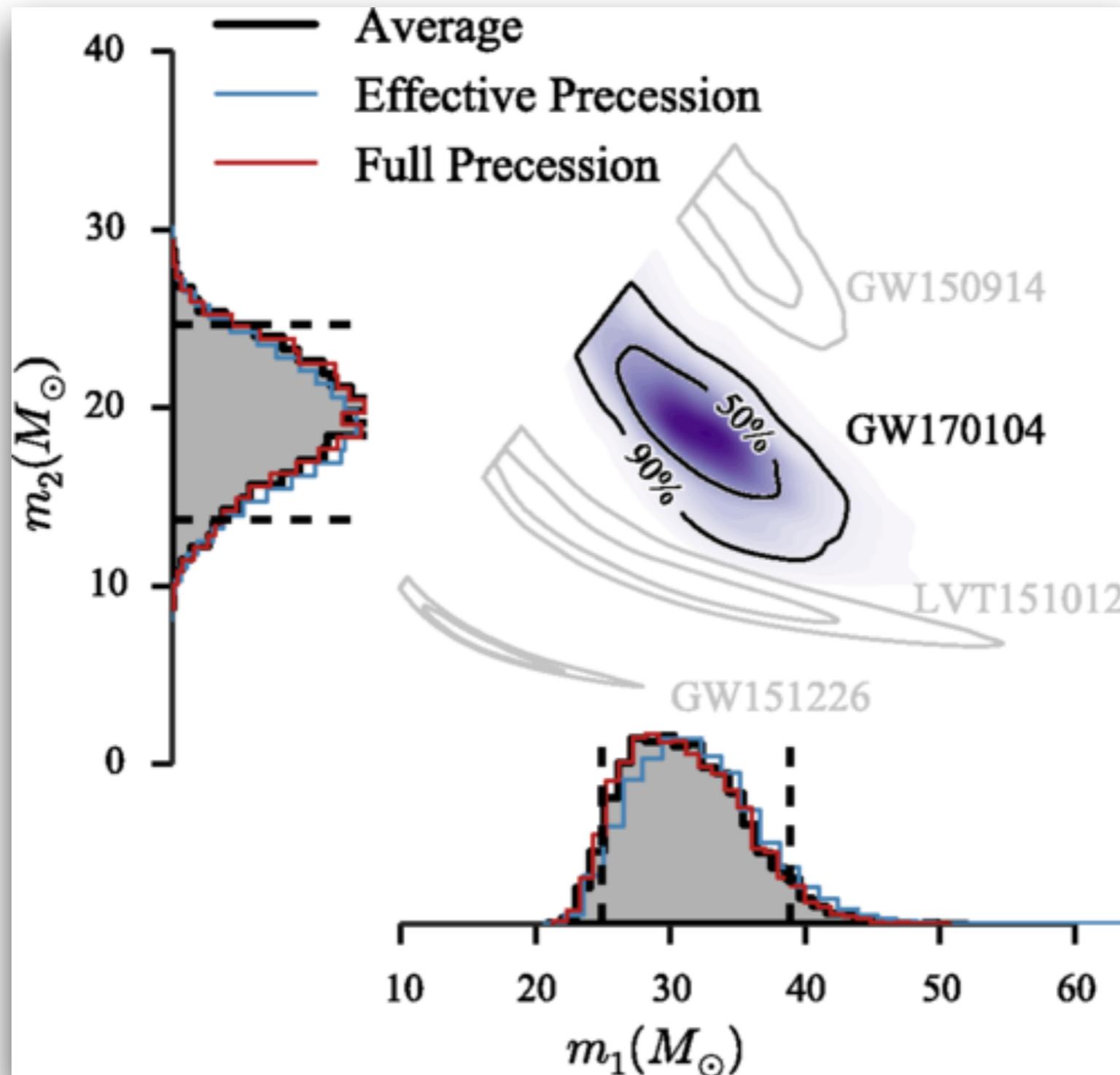


A new (abundant)  
population

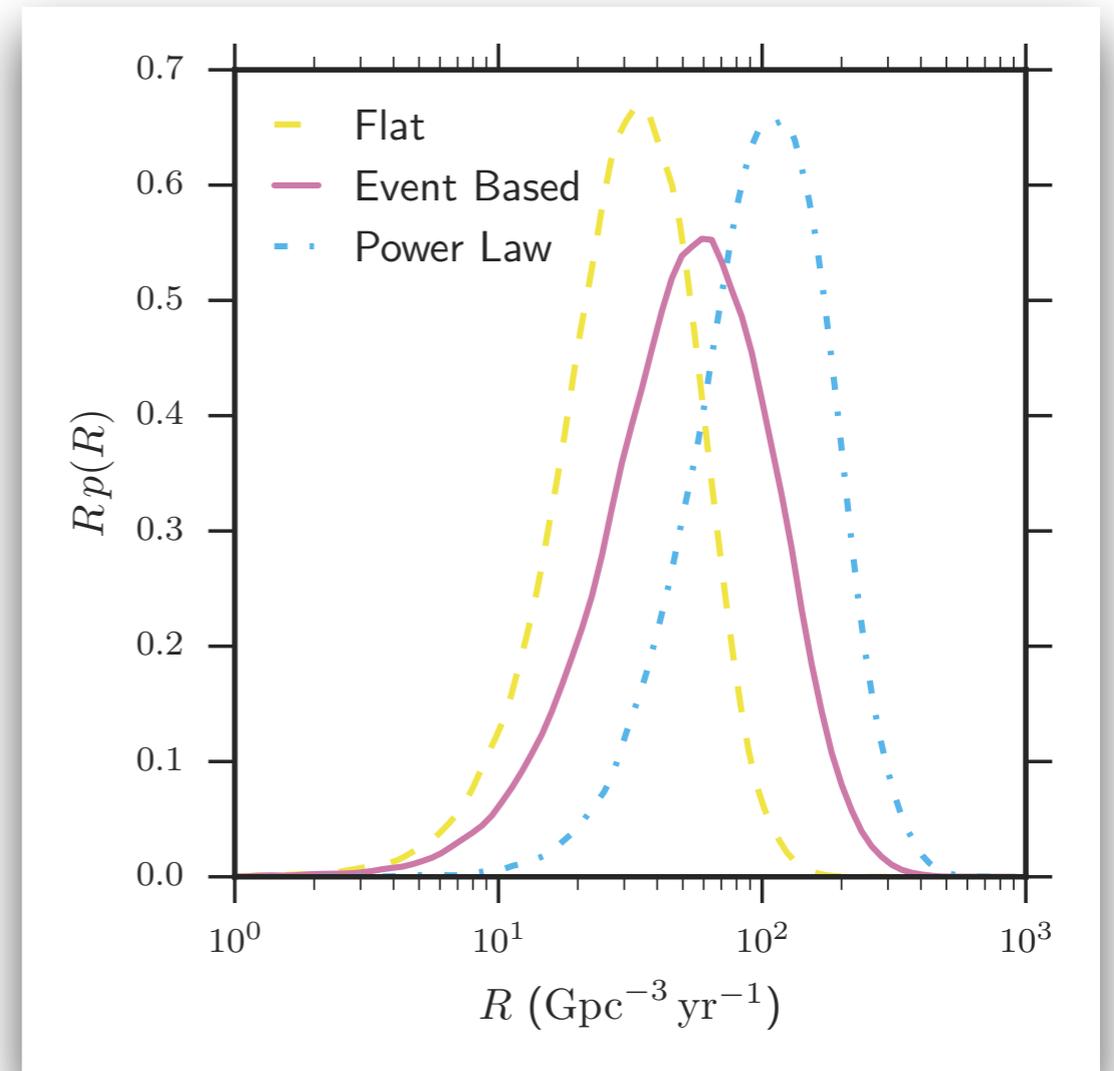
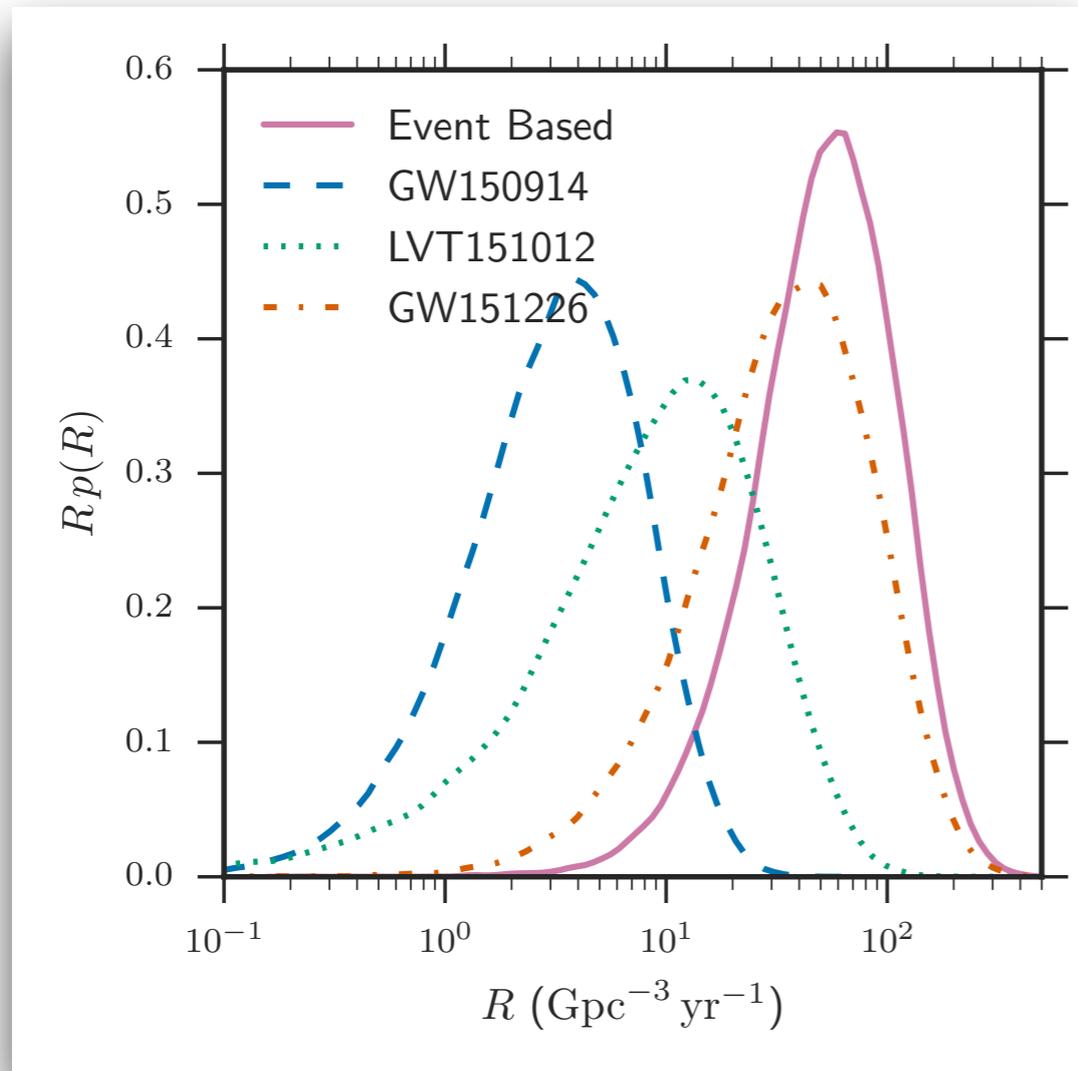
# A new population

- Masses
- Rates
- Spins

# Masses

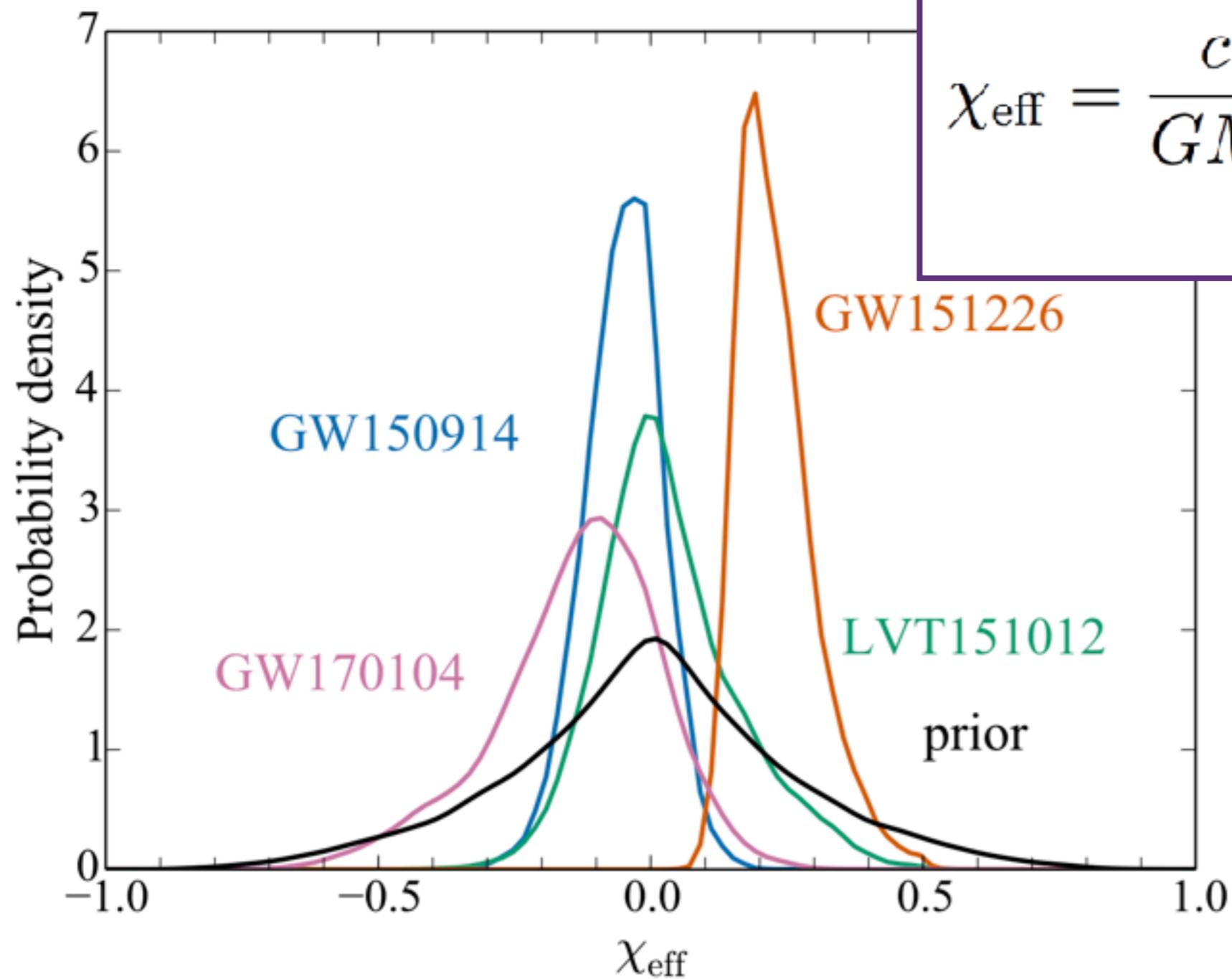


# Rates



9 - 240  $\text{Gpc}^{-3} \text{yr}^{-1}$   $\longrightarrow$  12 - 213  $\text{Gpc}^{-3} \text{yr}^{-1}$

# Spins



$$\chi_{\text{eff}} = \frac{c}{GM} \left( \frac{\vec{S}_1}{m_1} + \frac{\vec{S}_2}{m_2} \right) \cdot \frac{\vec{L}}{|\vec{L}|}$$

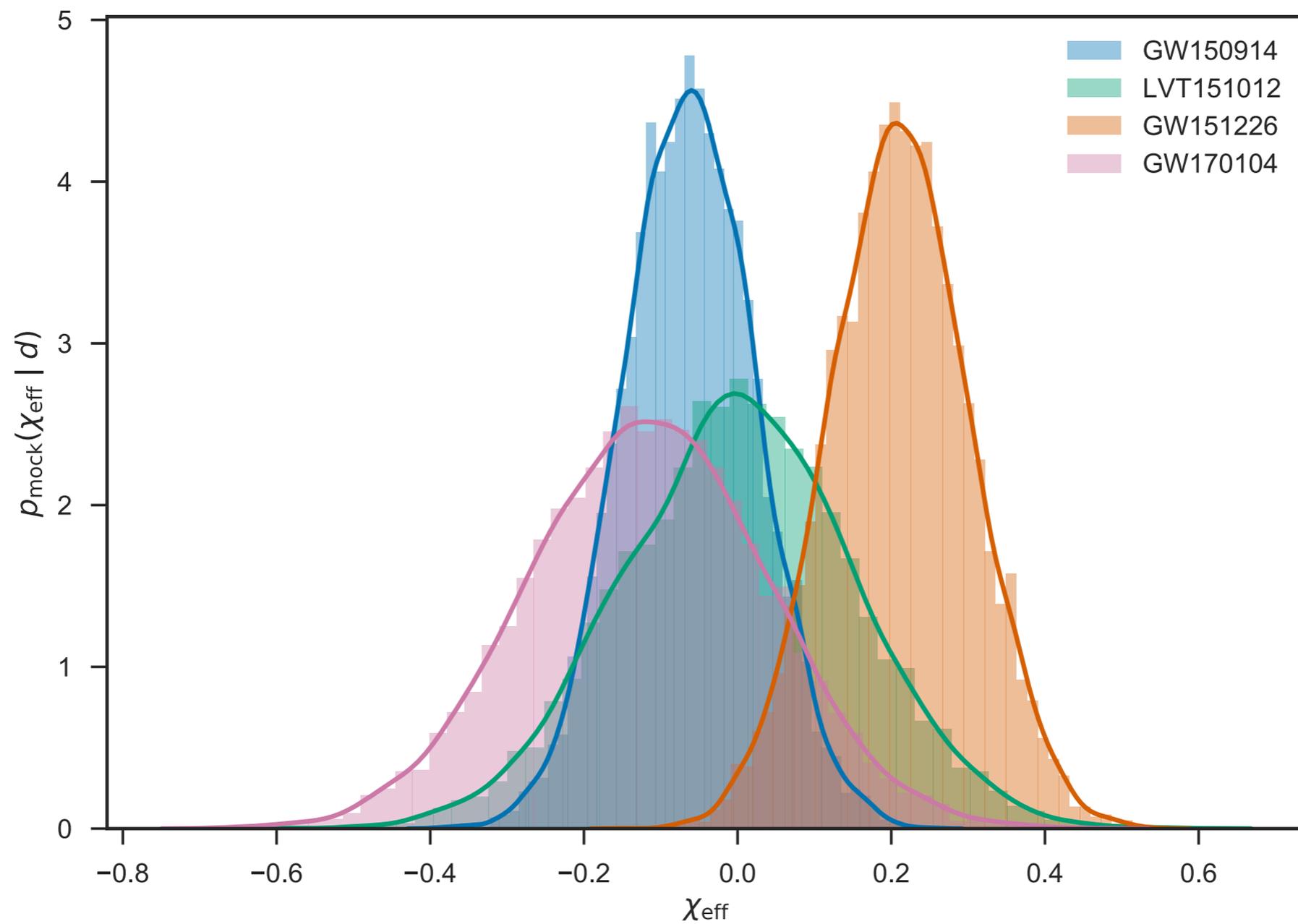
# Aligned vs isotropic BH spin distribution of the population

significance  
isotropic vs aligned

Events	$\sigma_{I/A}$ “Low”	$\sigma_{I/A}$ “Flat”	$\sigma_{I/A}$ “High”
GW150914 and GW151226	1.3	2.2	3.7
All O1 events	1.7	2.7	4.4
All O1 events and GW170104	<b>2.4</b>	3.6	5.4

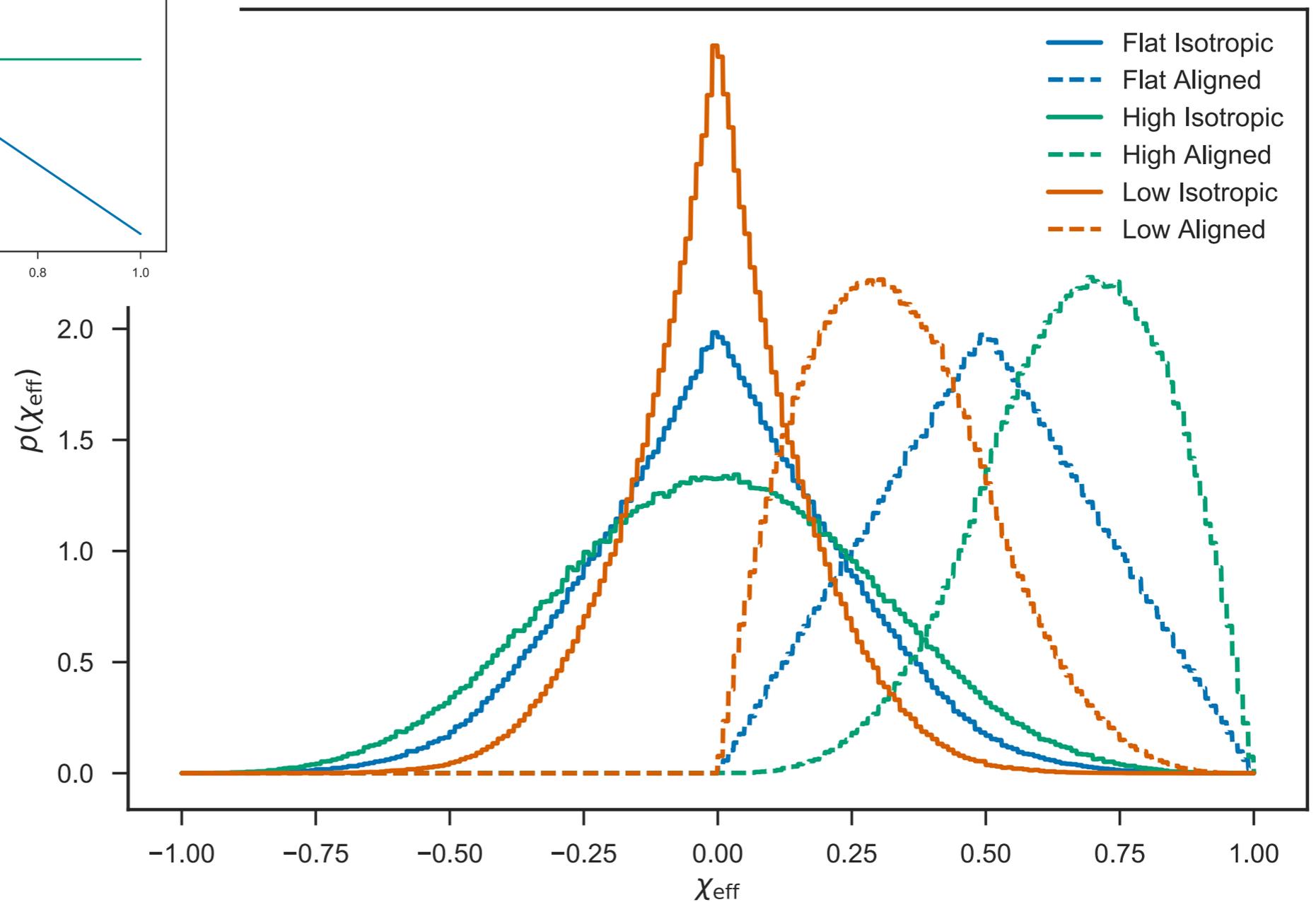
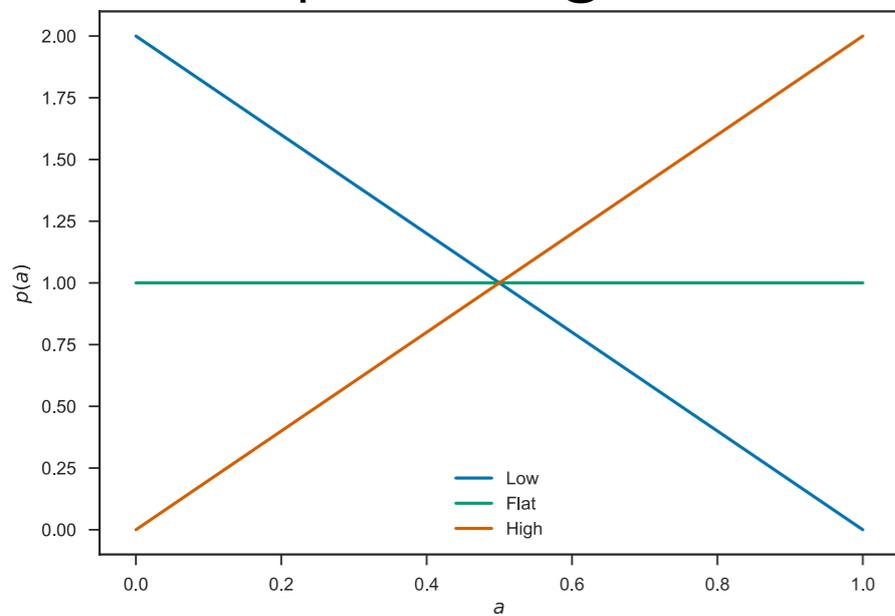
- Data favour isotropic spin distribution or low spins
- During O3 this will be confirmed or overturned at (likely)  $> 5\sigma$

# Approximate posteriors



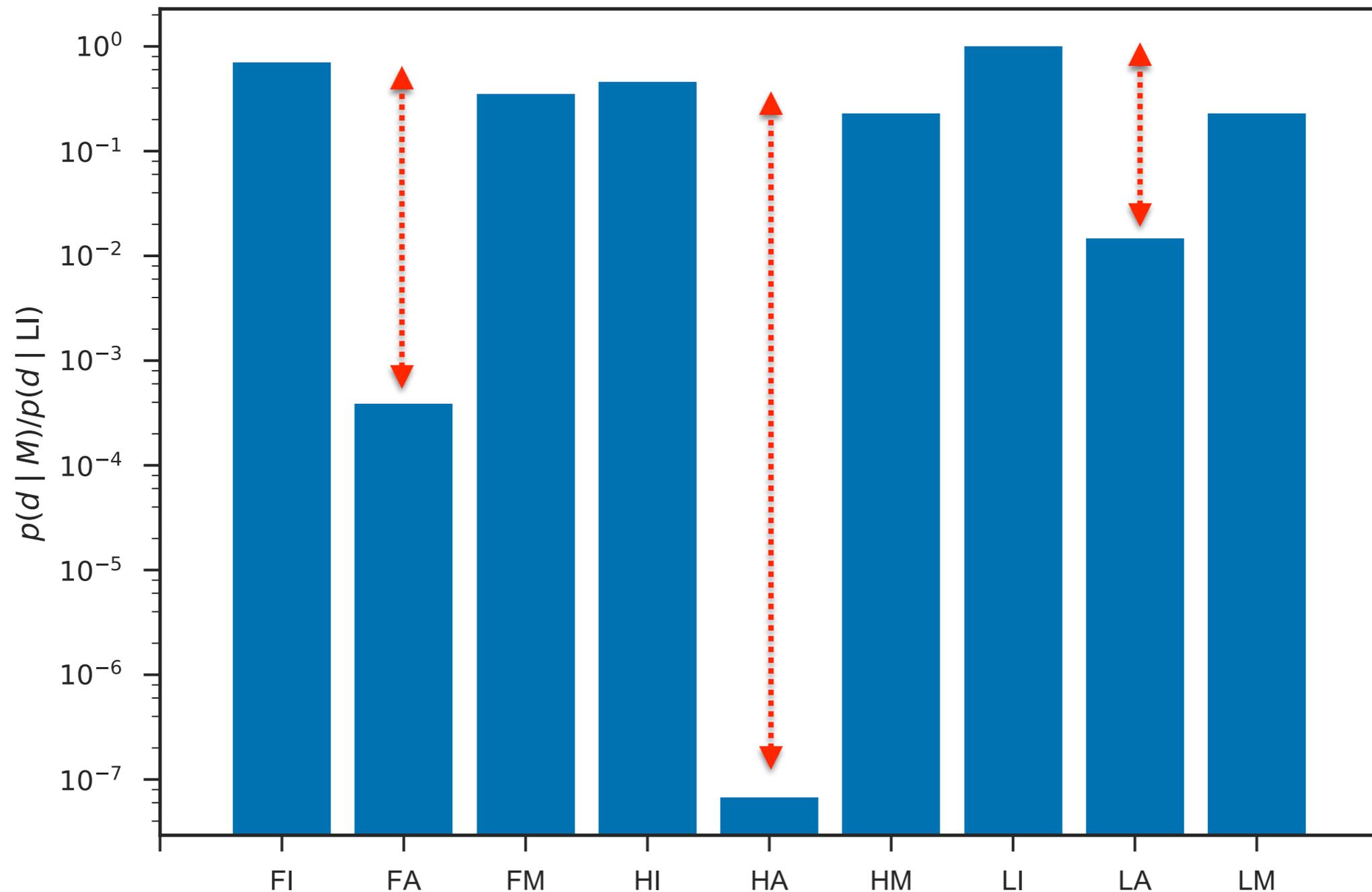
# 6 models of $\chi_{\text{eff}}$

Spin magnitude + either aligned or isotropically orientated spins



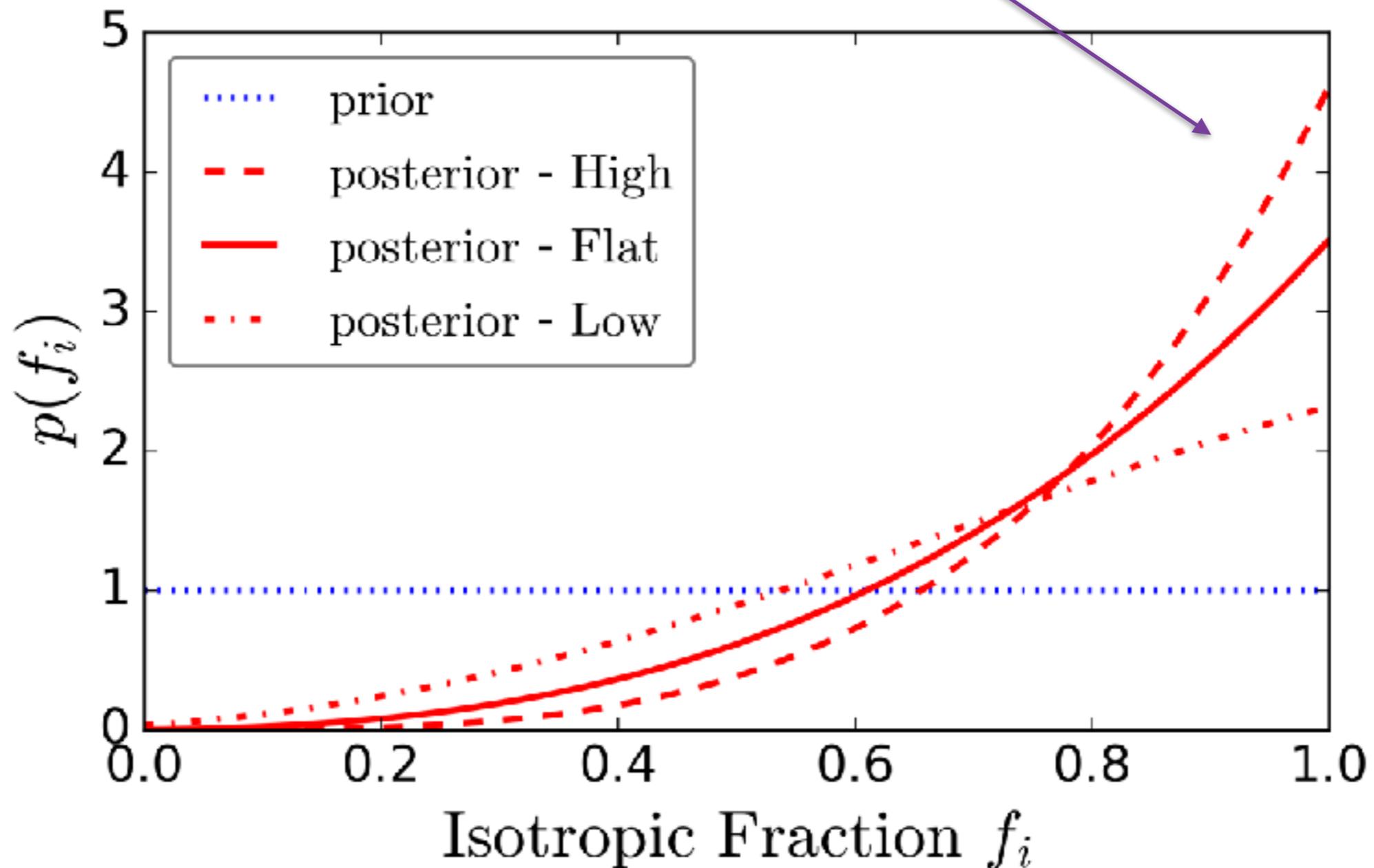
# Odds ratios

data always disfavour aligned vs isotropic distribution

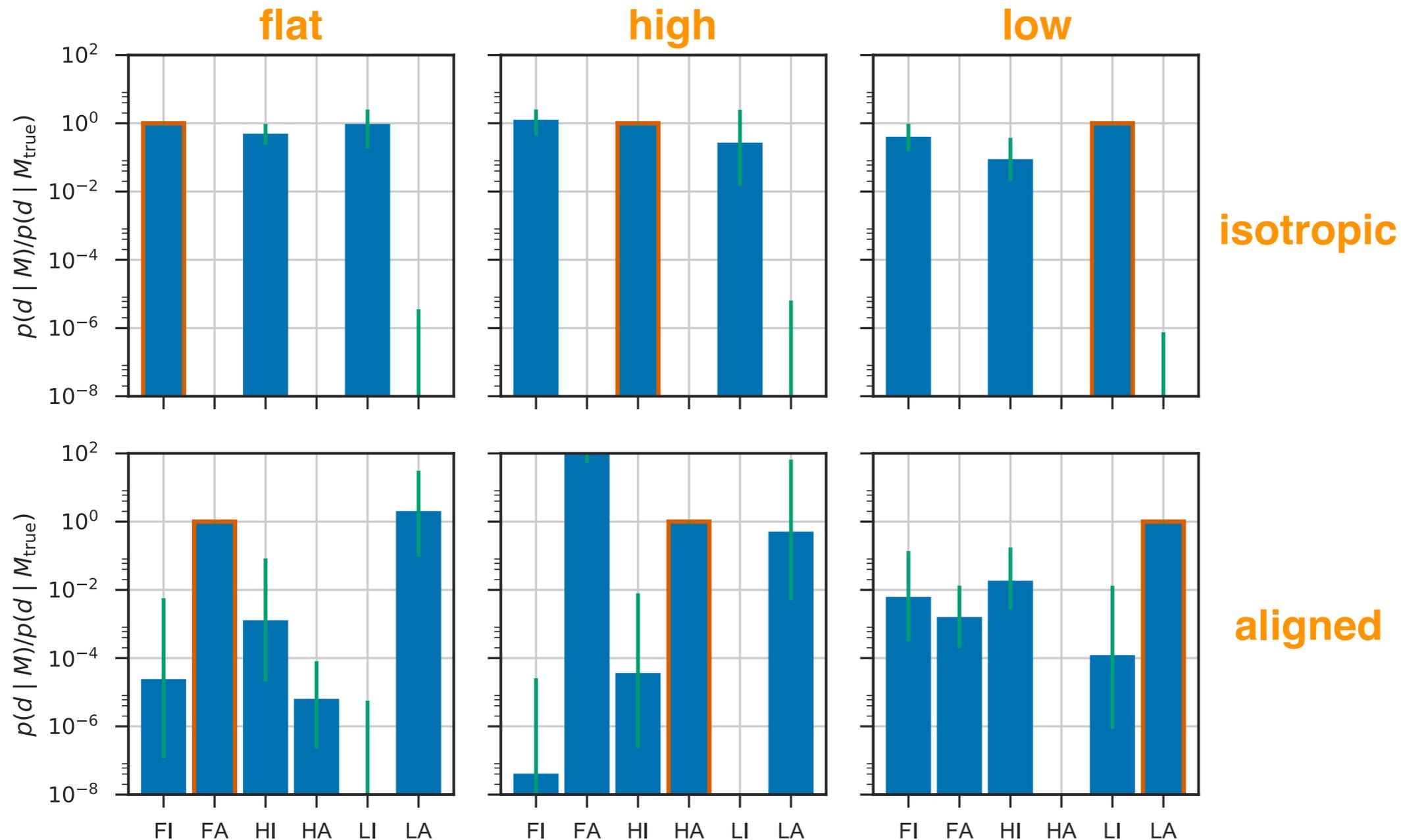


# Mixture model

peak always at 100% isotropic fraction



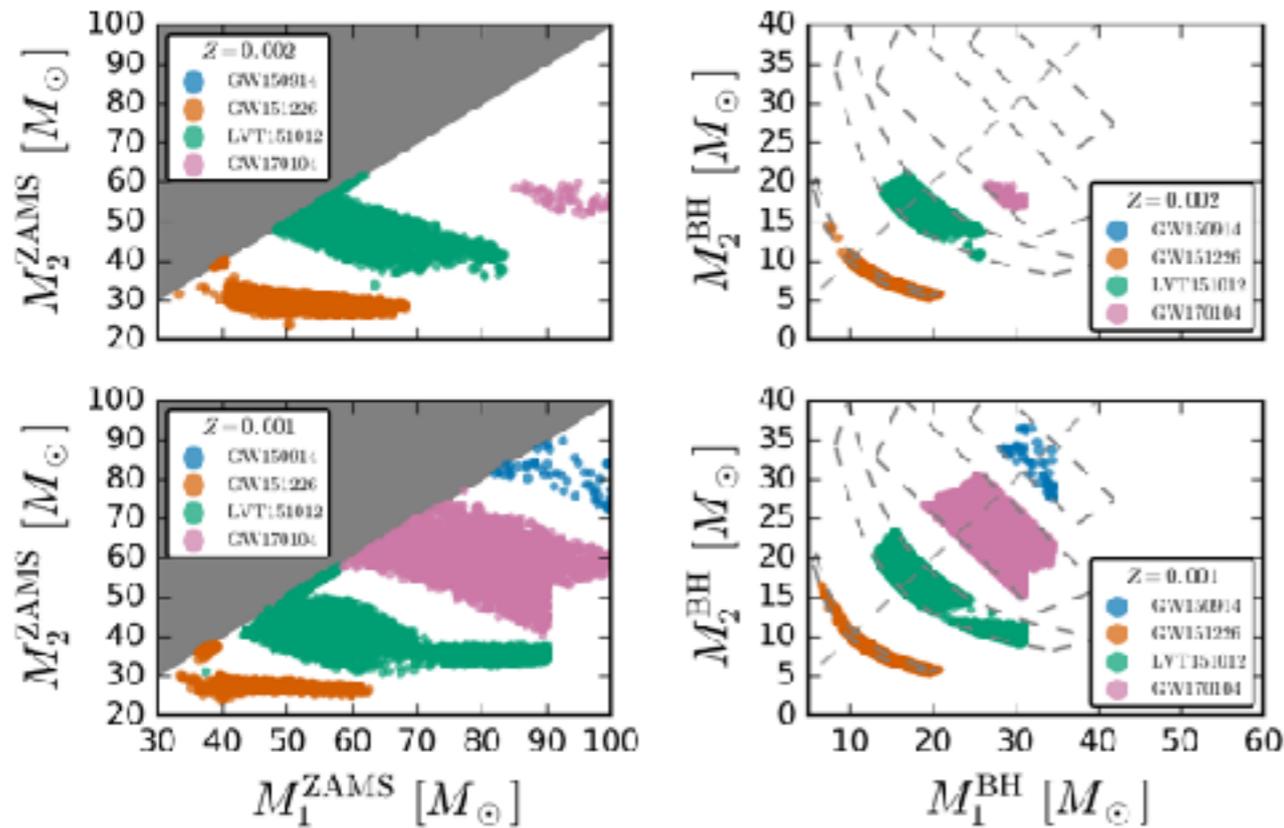
# GW150914, GW151226, GW170104, LVT151012 + 10 detections drawn from **orange** population



- Median significance between most favoured aligned and most favoured isotropic model is at least  $2.4\sigma$
- But, in general, significance is  $> 5\sigma$

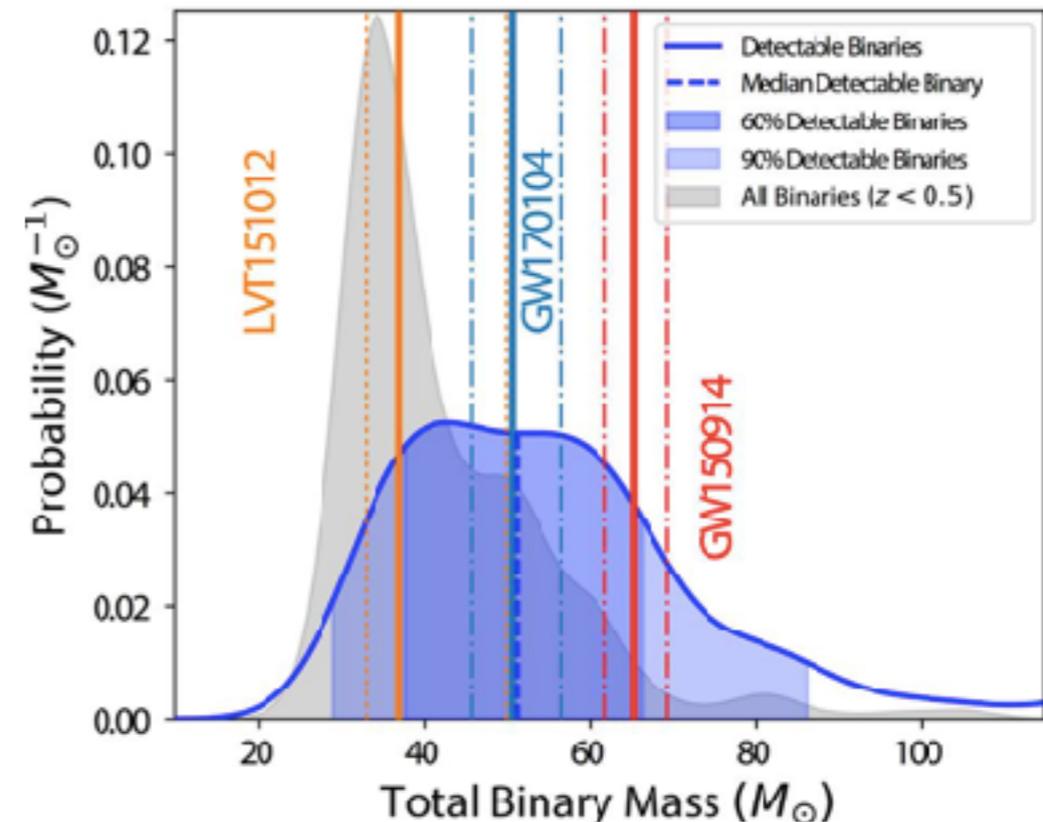
# Formation channels?

Isolated binary evolution



Stevenson et al,  
Nature Comm. 8, 14906 (2017)

Dynamical evolution

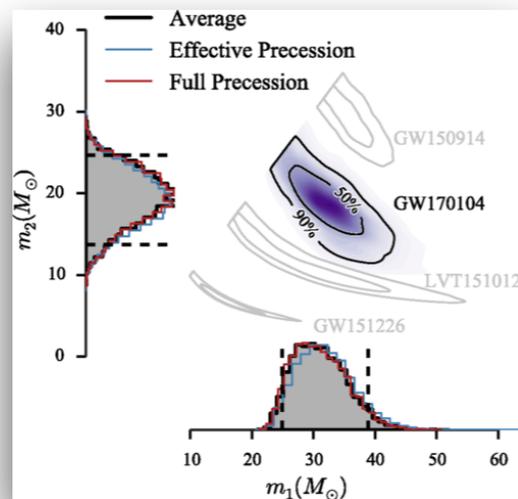


Rodriguez, Zevin, Pankow, Kalogera  
& Rasio, ApJ 832, L2, 2016

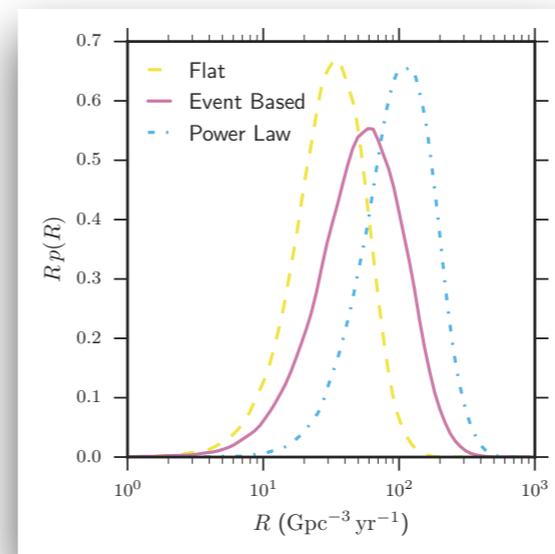
... other more exotic ?

# Any viable formation scenario needs to explain 3 main properties

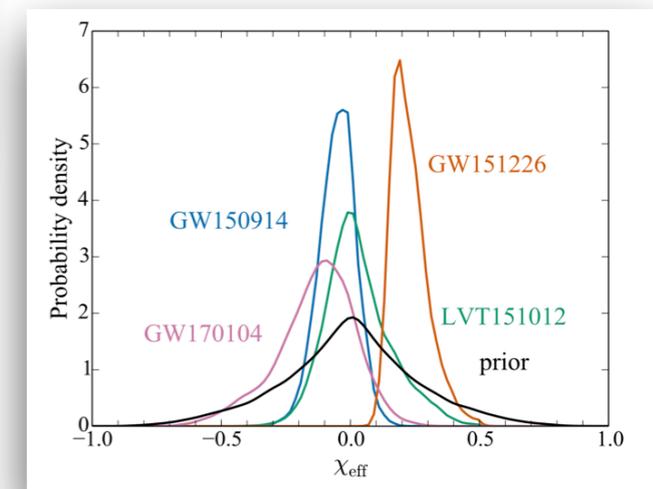
- Masses



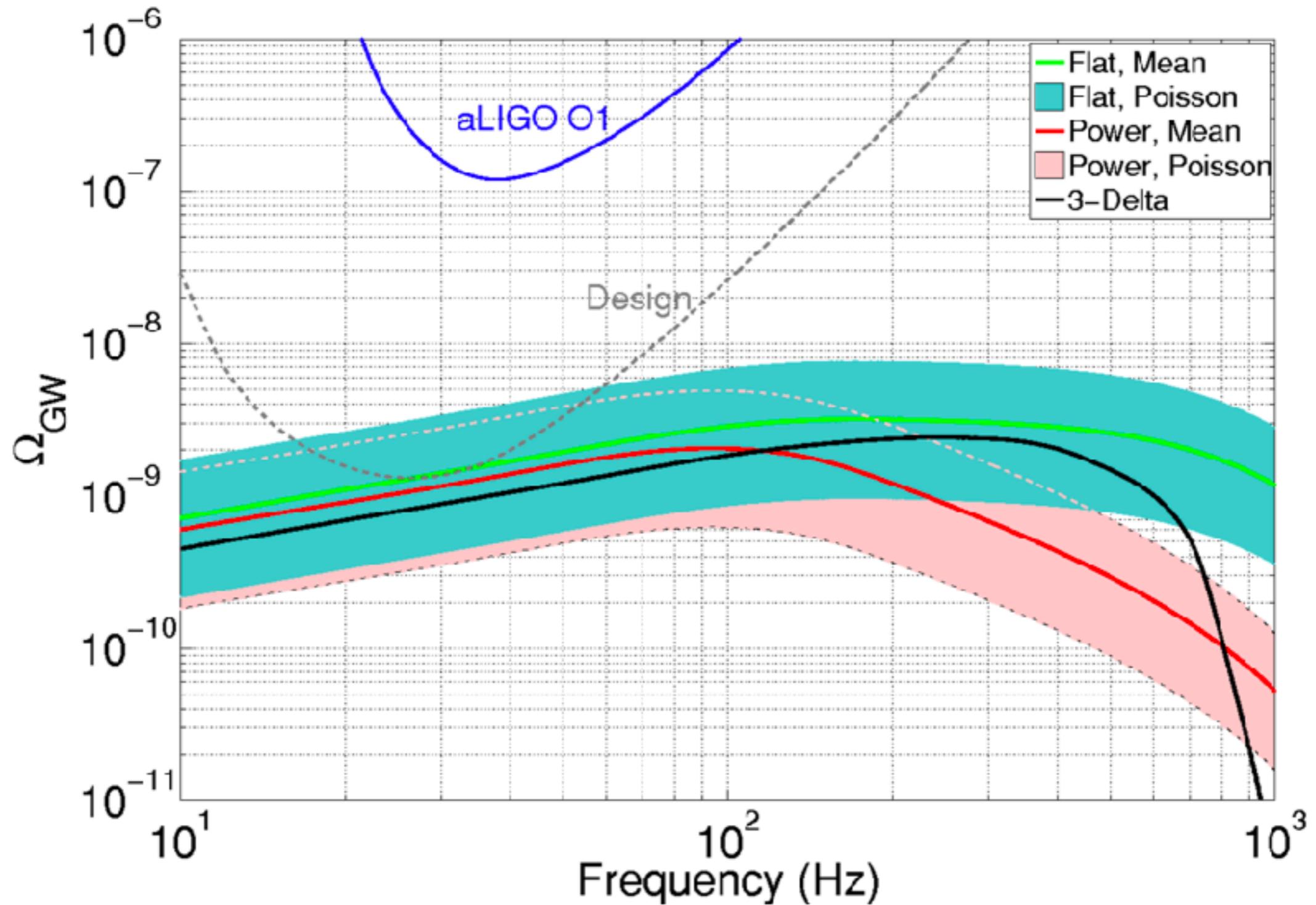
- Rate: 12 - 213  $\text{Gpc}^{-3} \text{yr}^{-1}$



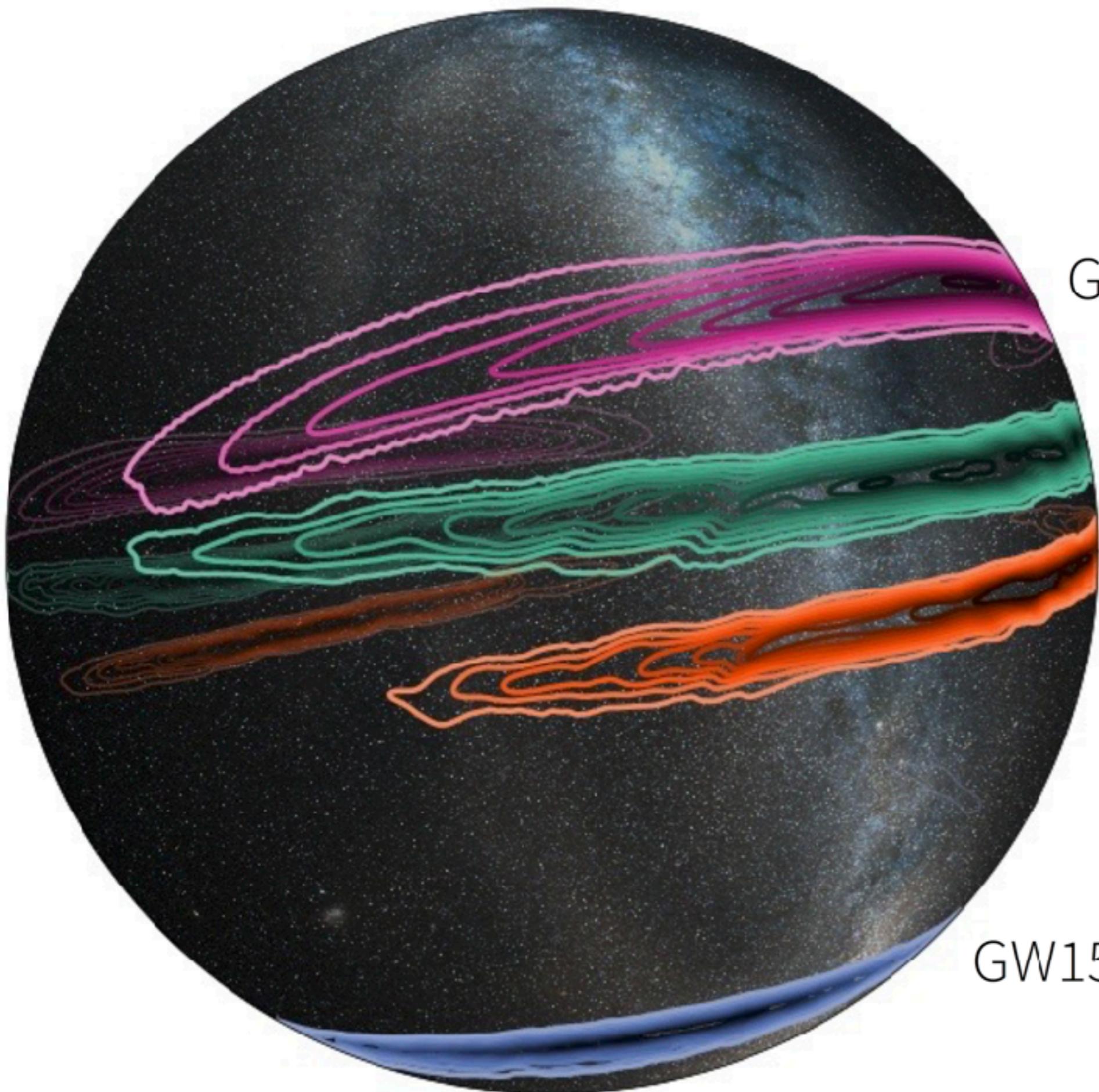
- Isotropic spin distribution or low spin magnitude



# BBH foreground



# Localising BBH mergers



1200 deg<sup>2</sup> (90%)

GW170104

1600 deg<sup>2</sup> (90%)

LVT151012

GW151226

850 deg<sup>2</sup> (90%)

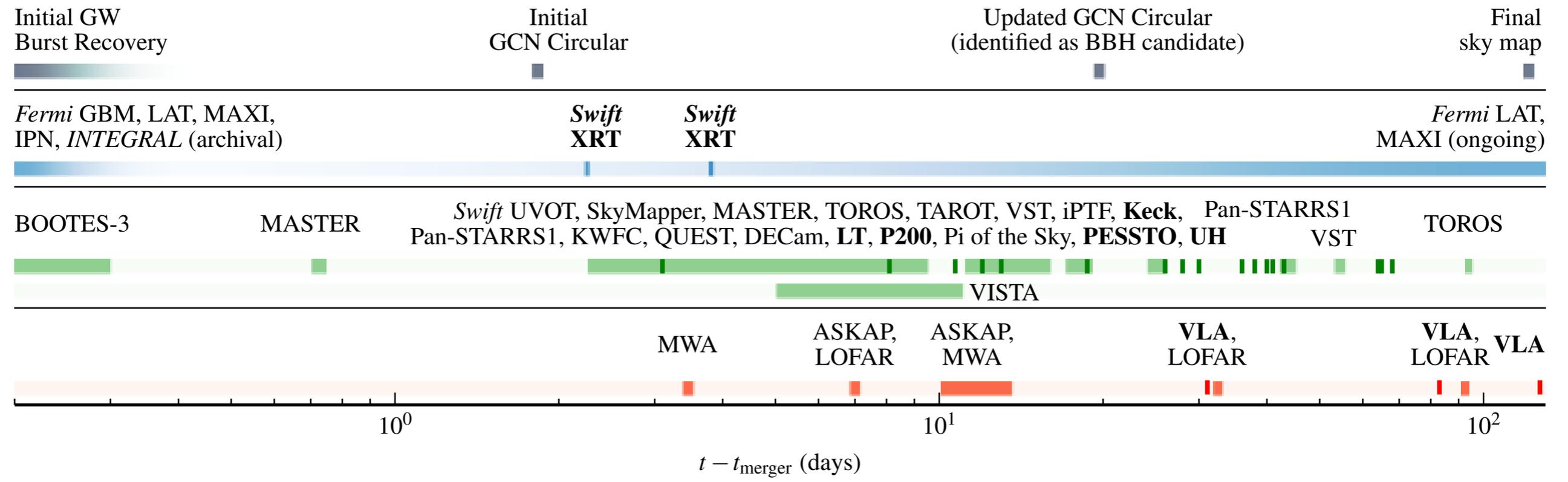
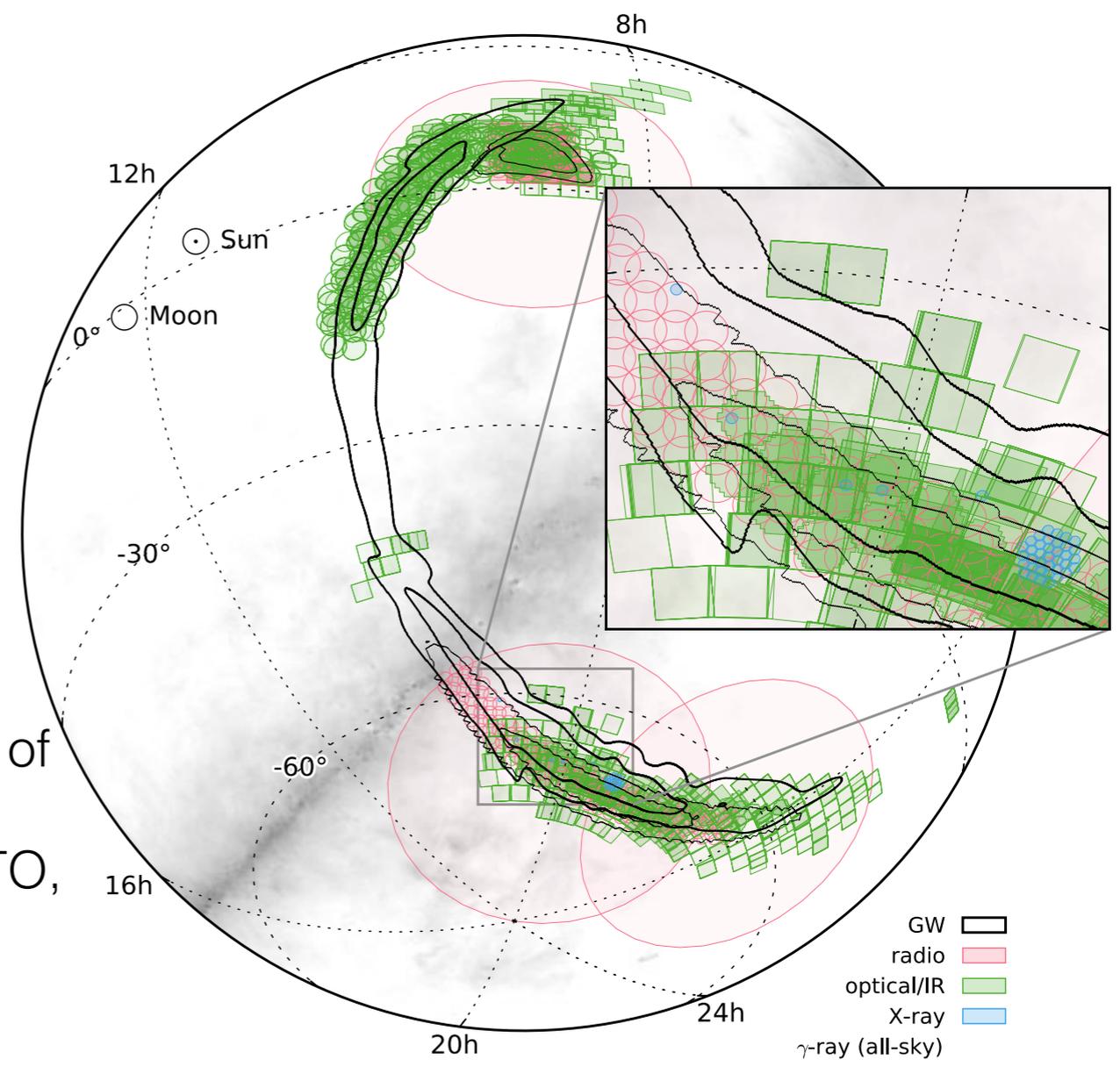
GW150914

230 deg<sup>2</sup> (90%)

# LOCALIZATION AND BROADBAND FOLLOW-UP OF THE GRAVITATIONAL-WAVE TRANSIENT GW150914

25 observing teams

ASKAP, LOFAR, MWA, Fermi/GBM, Fermi/LAT, INTEGRAL, IPN, Swift, MAXI, BOOTES, MASTER, Pi of the Sky, DES/DECam, INAF/GRAWITA, iPTF, J-GEM/KWFC, La Silla-QUEST, Liverpool Telescope, PESSTO, Pan-STARRS, SkyMapper, TAROT, Zadko, TOROS, VISTA

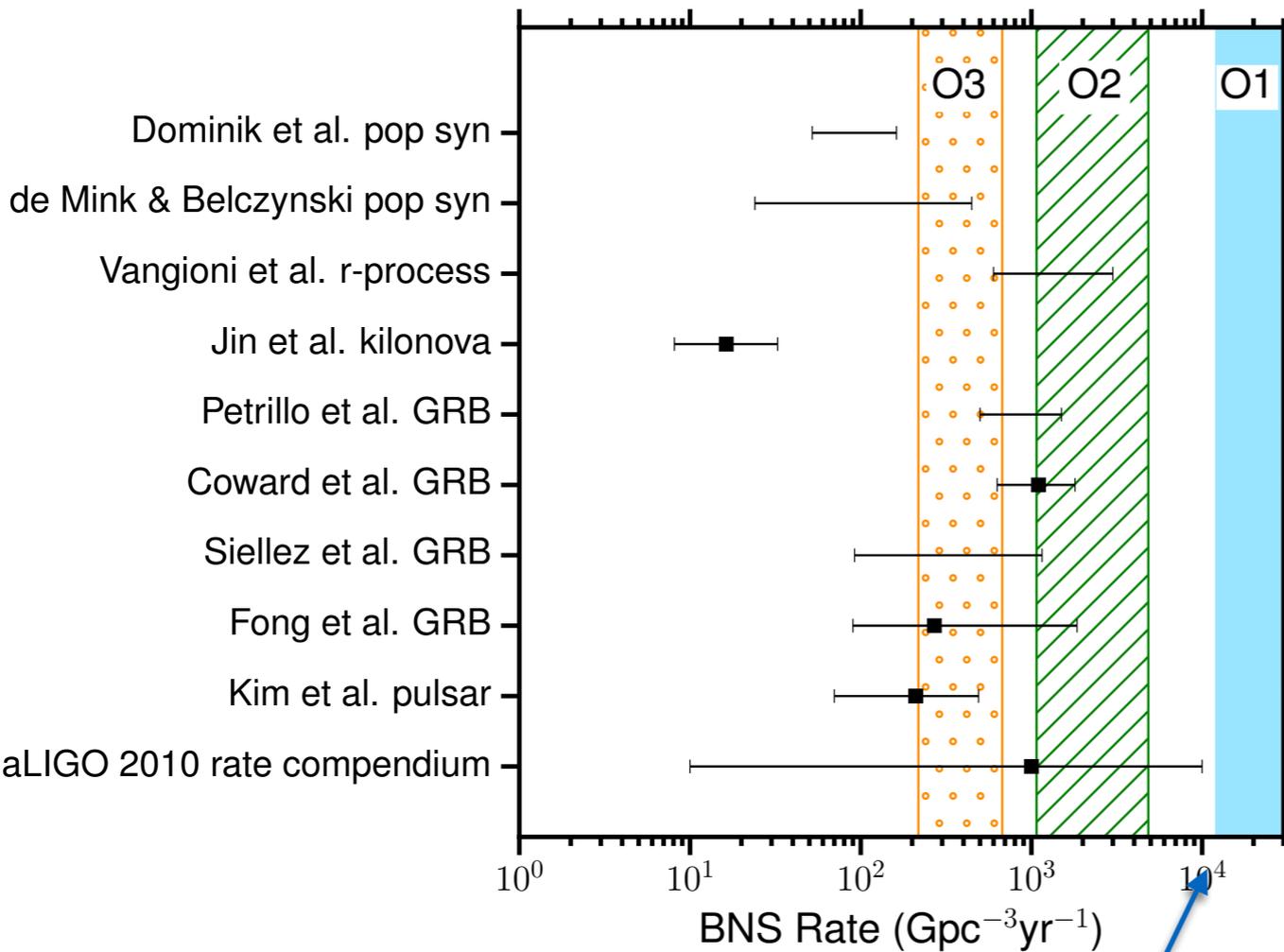


Binary neutron stars and  
black hole-neutron stars

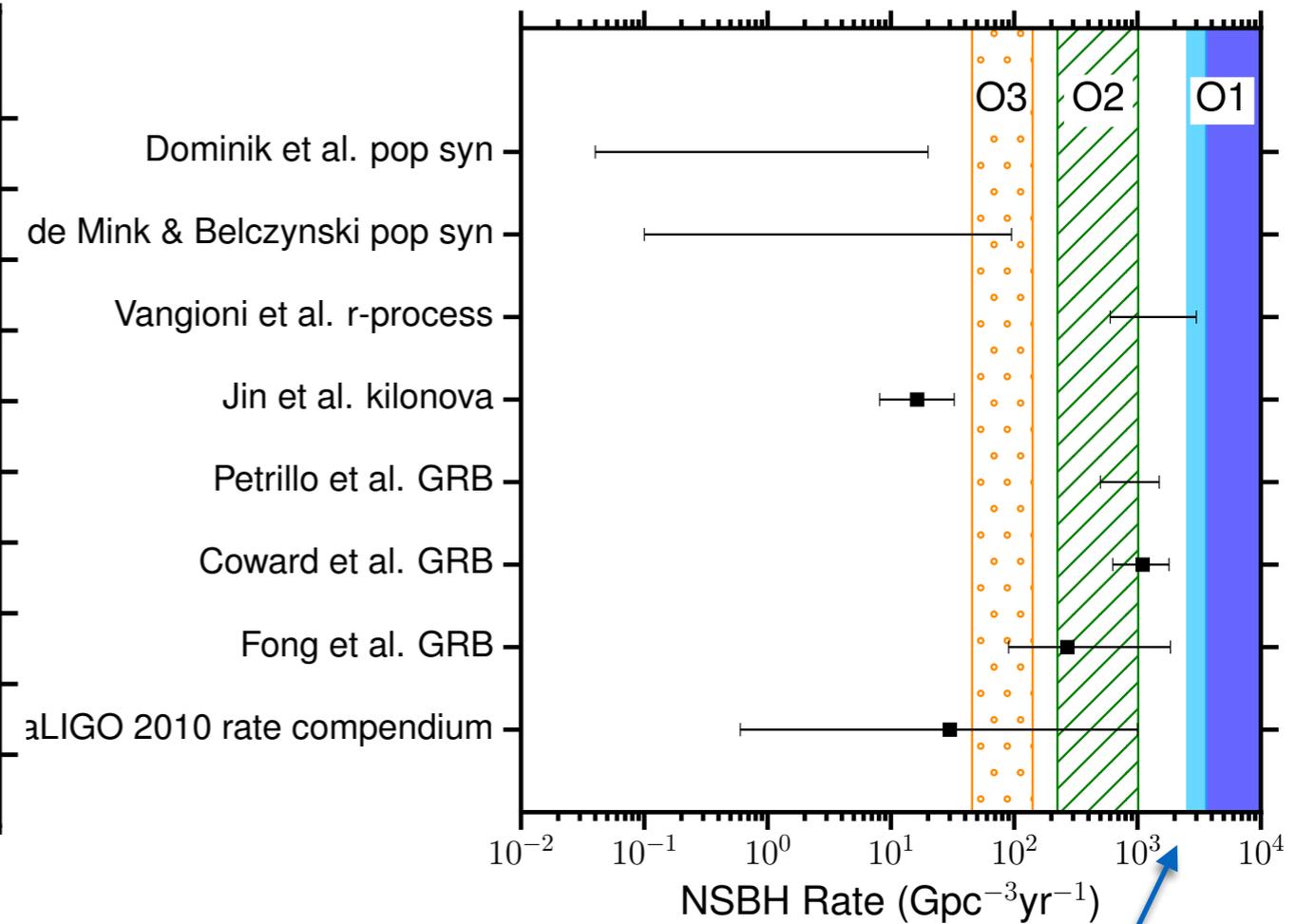
# Limits on merger rates

binary neutron stars

neutron star - black hole

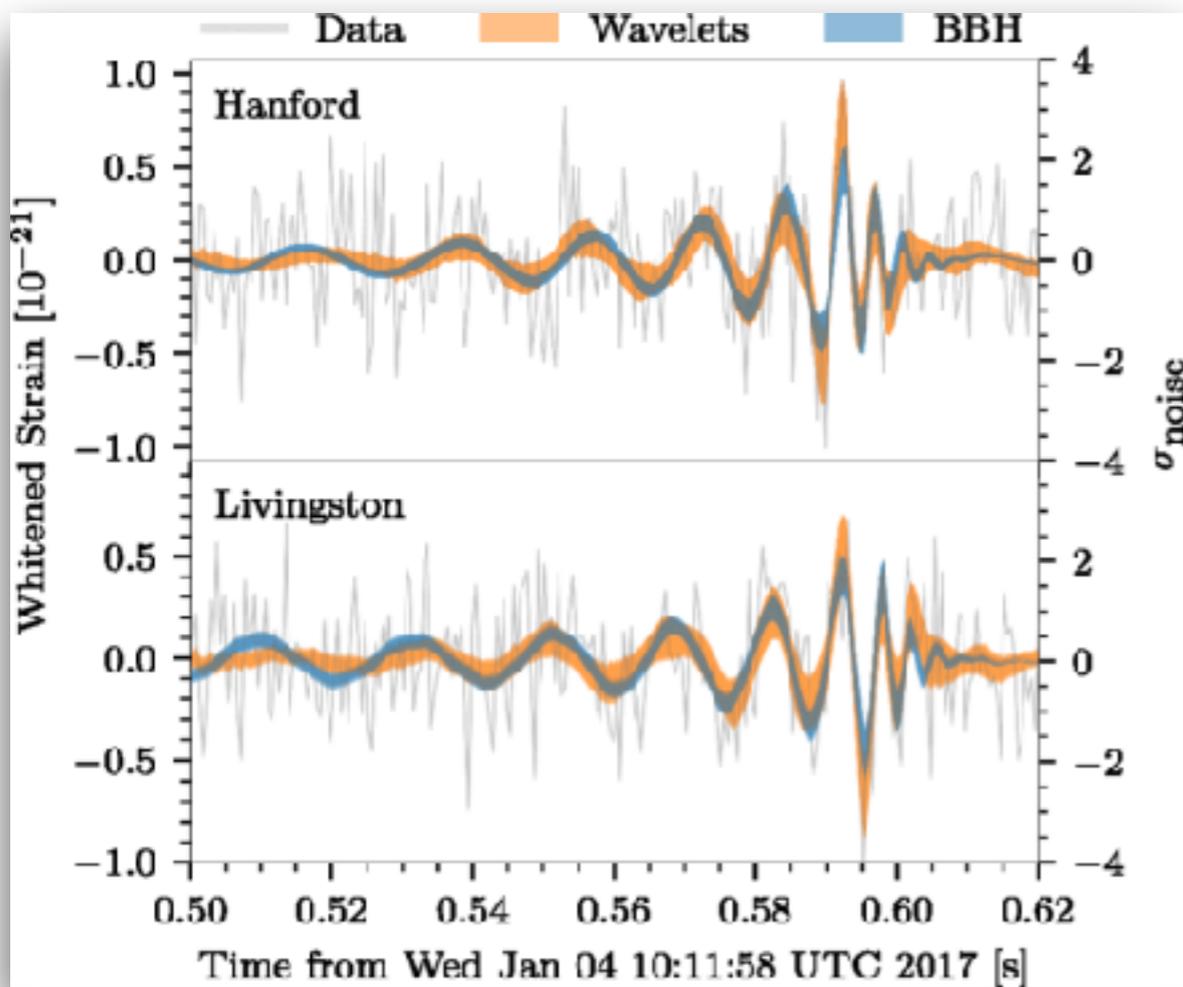


$1.2 \times 10^4 \text{ Gpc}^{-3} \text{ yr}^{-1}$  (90%)



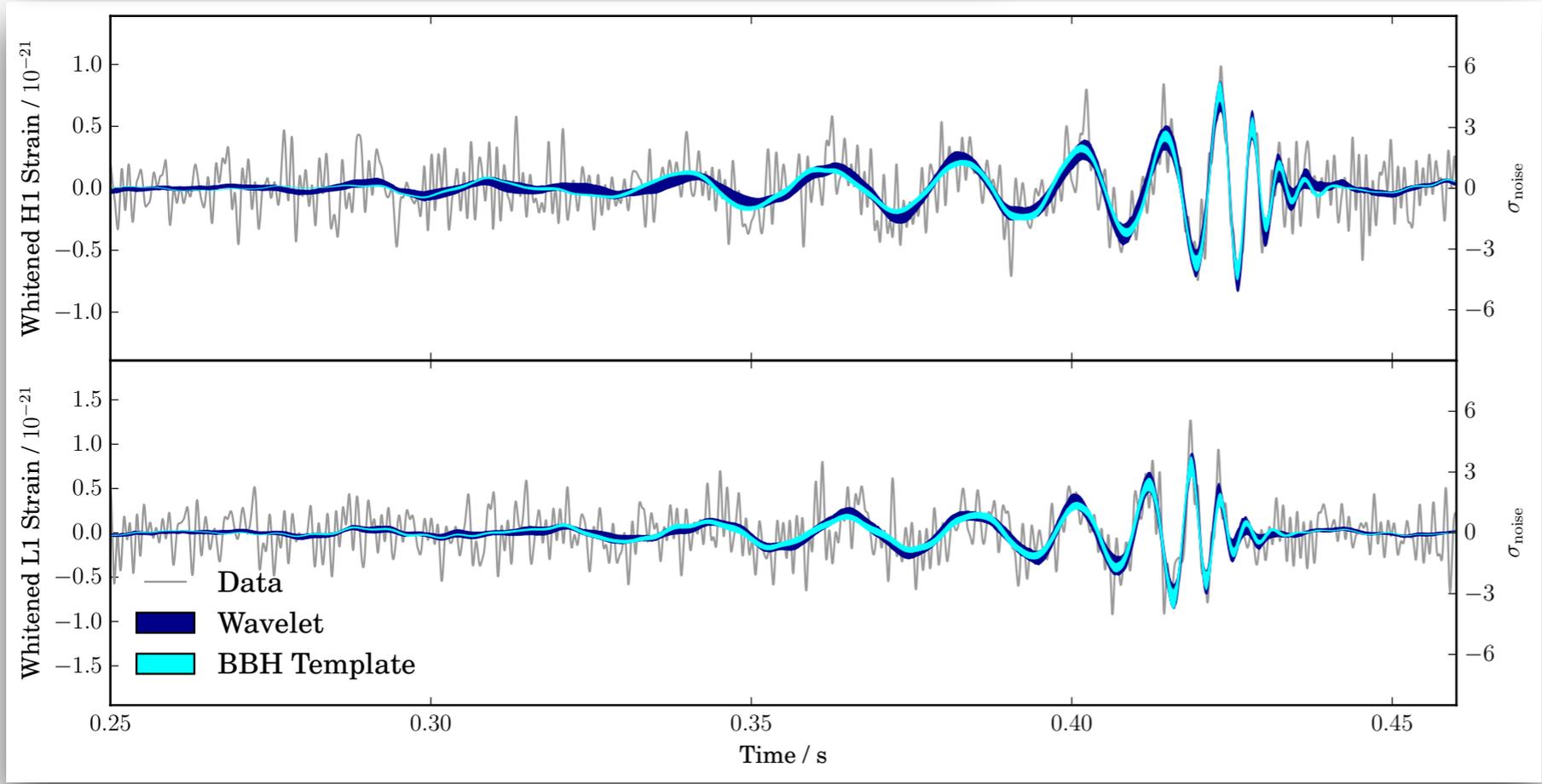
$3.6 \times 10^3 \text{ Gpc}^{-3} \text{ yr}^{-1}$  (90%)

Really binary black  
holes?

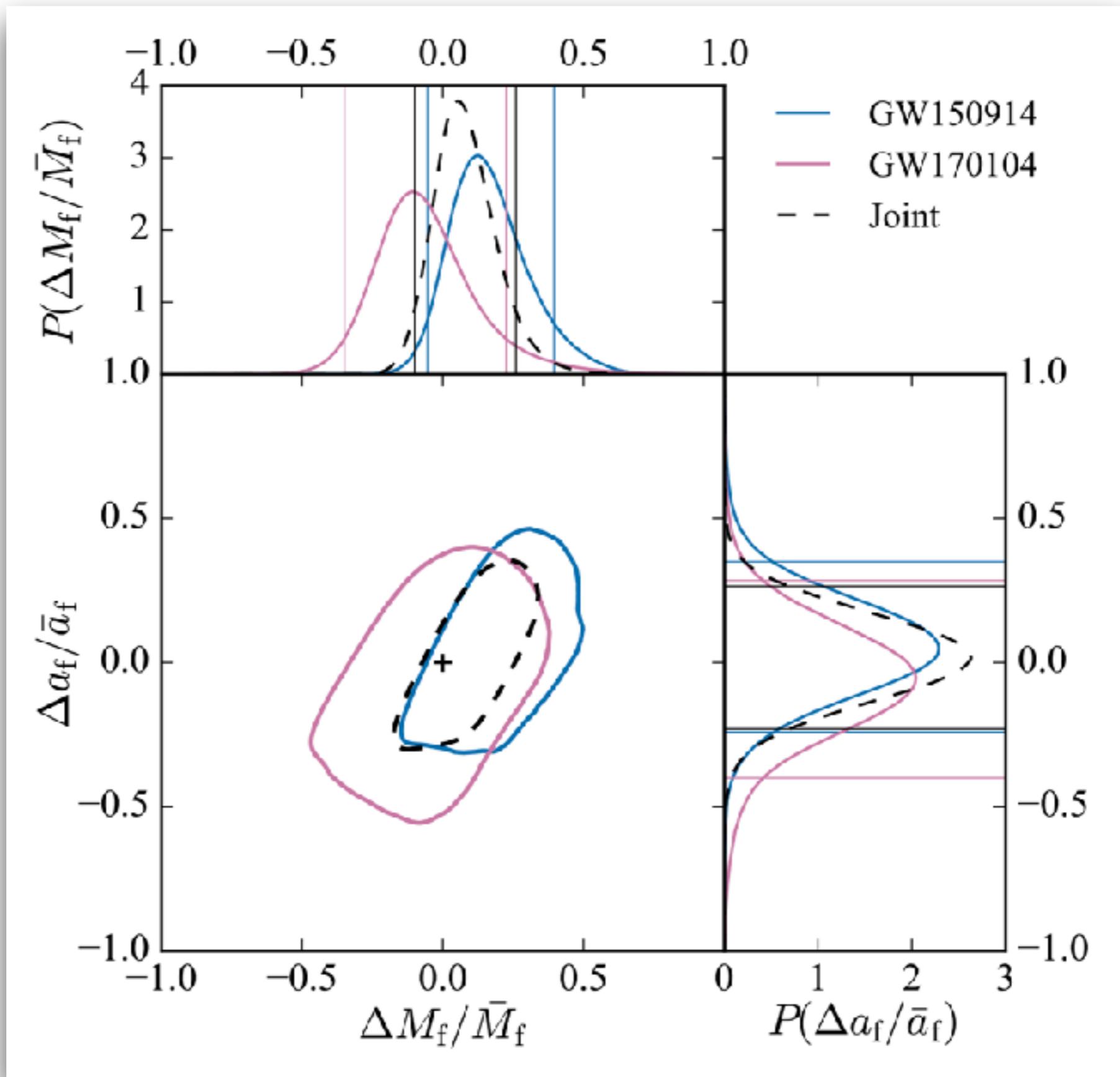


GW170104

modelled vs un-  
modelled waveform  
reconstruction



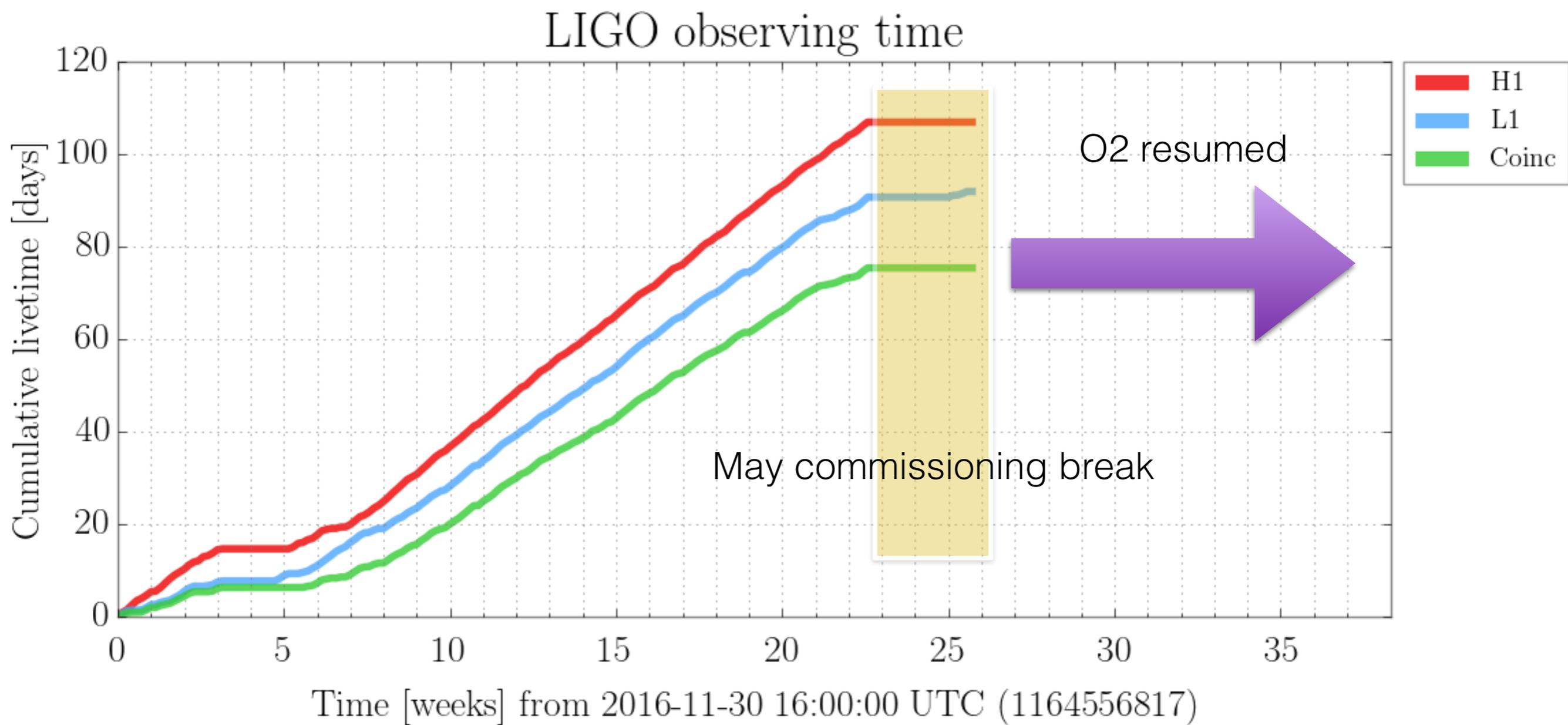
GW150914



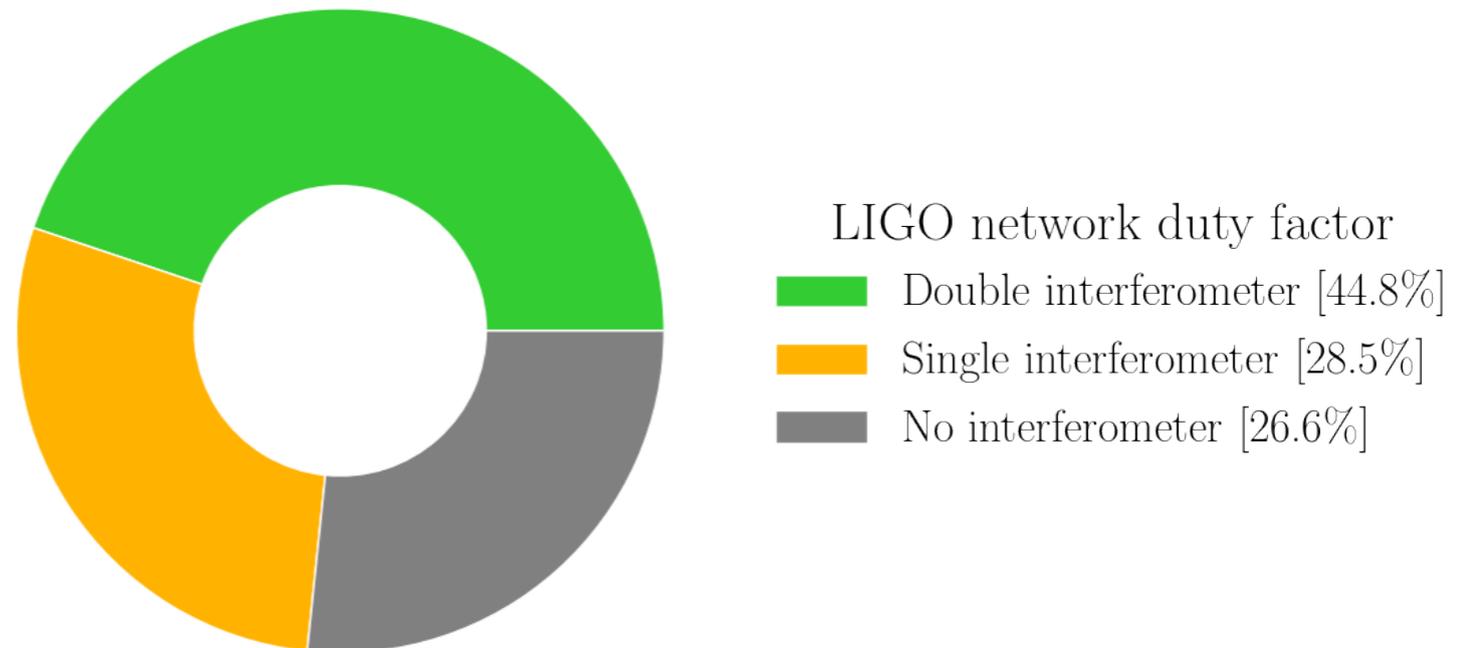
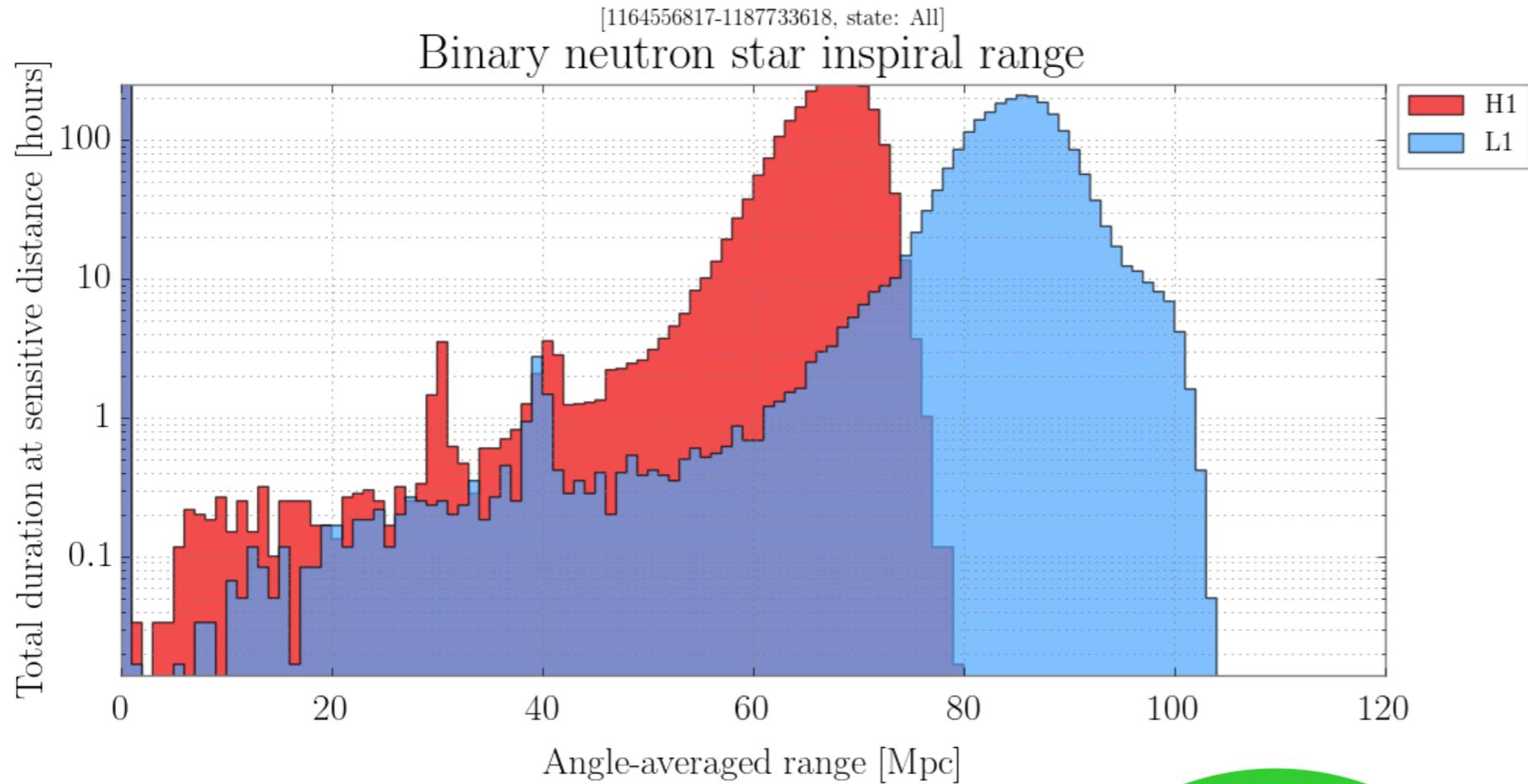
(technical details in A. Ghosh et al, arXiv:0704.06784)

O2 is ongoing

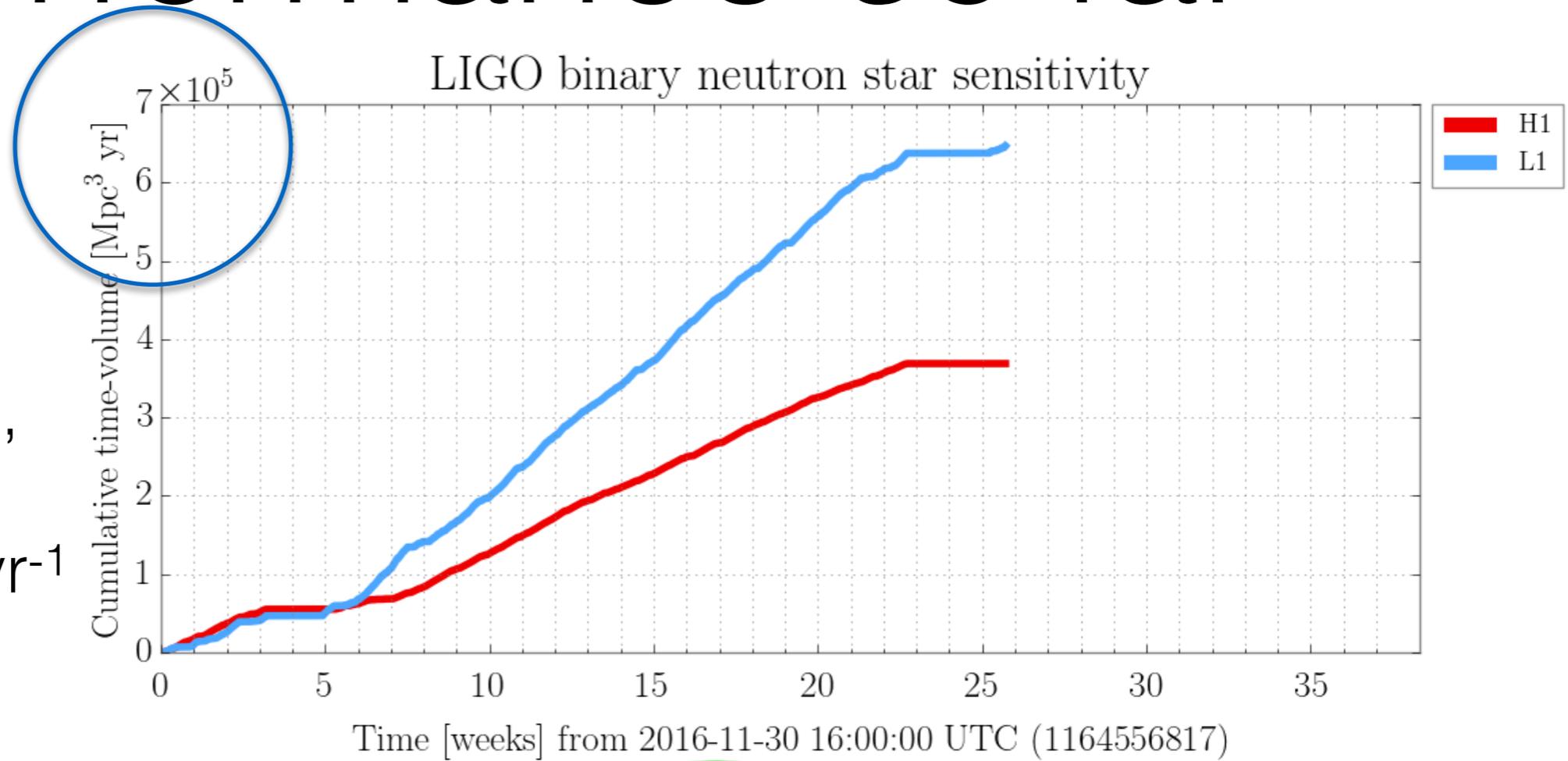
# O2 livetime



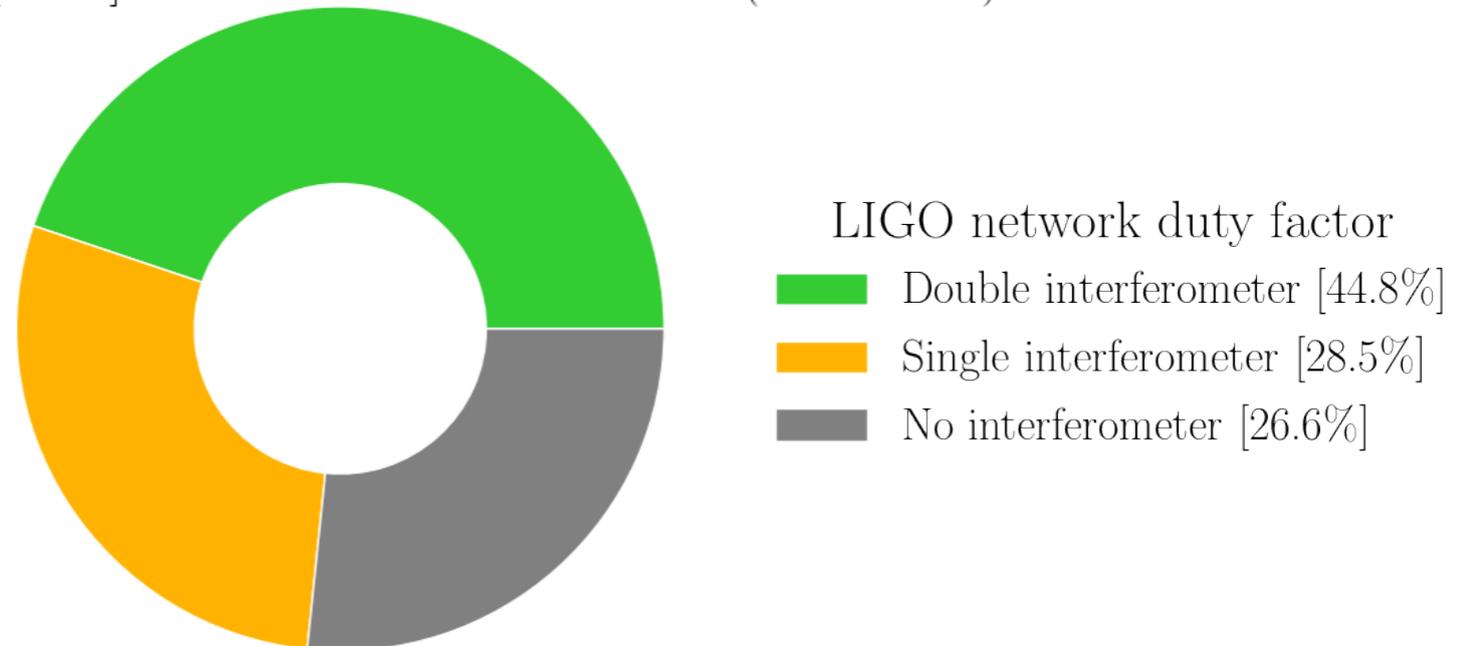
# Performance so far



# Performance so far



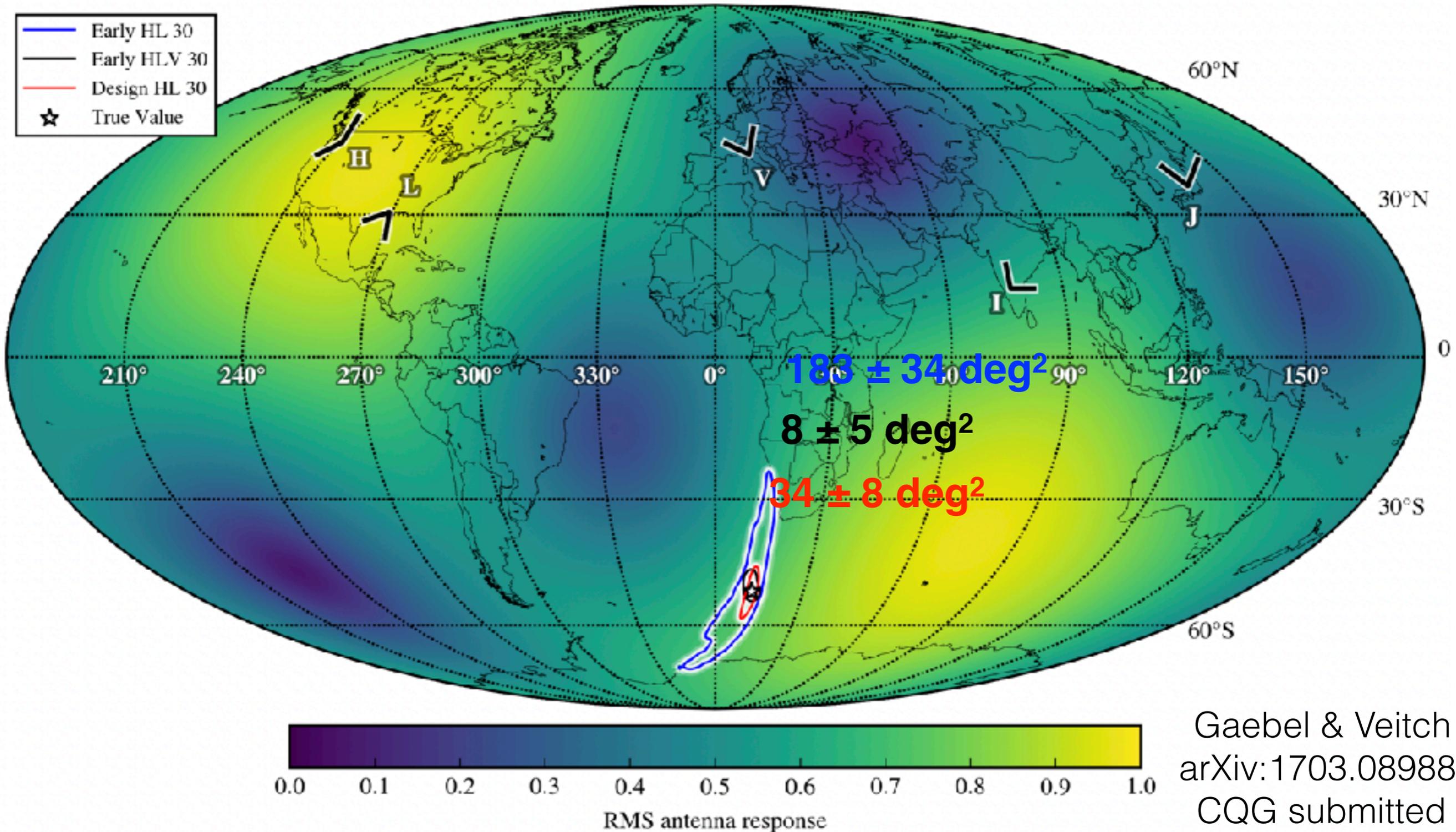
For comparison,  
upper limit:  
 $1.2 \times 10^{-5} \text{ Mpc}^{-3} \text{ yr}^{-1}$

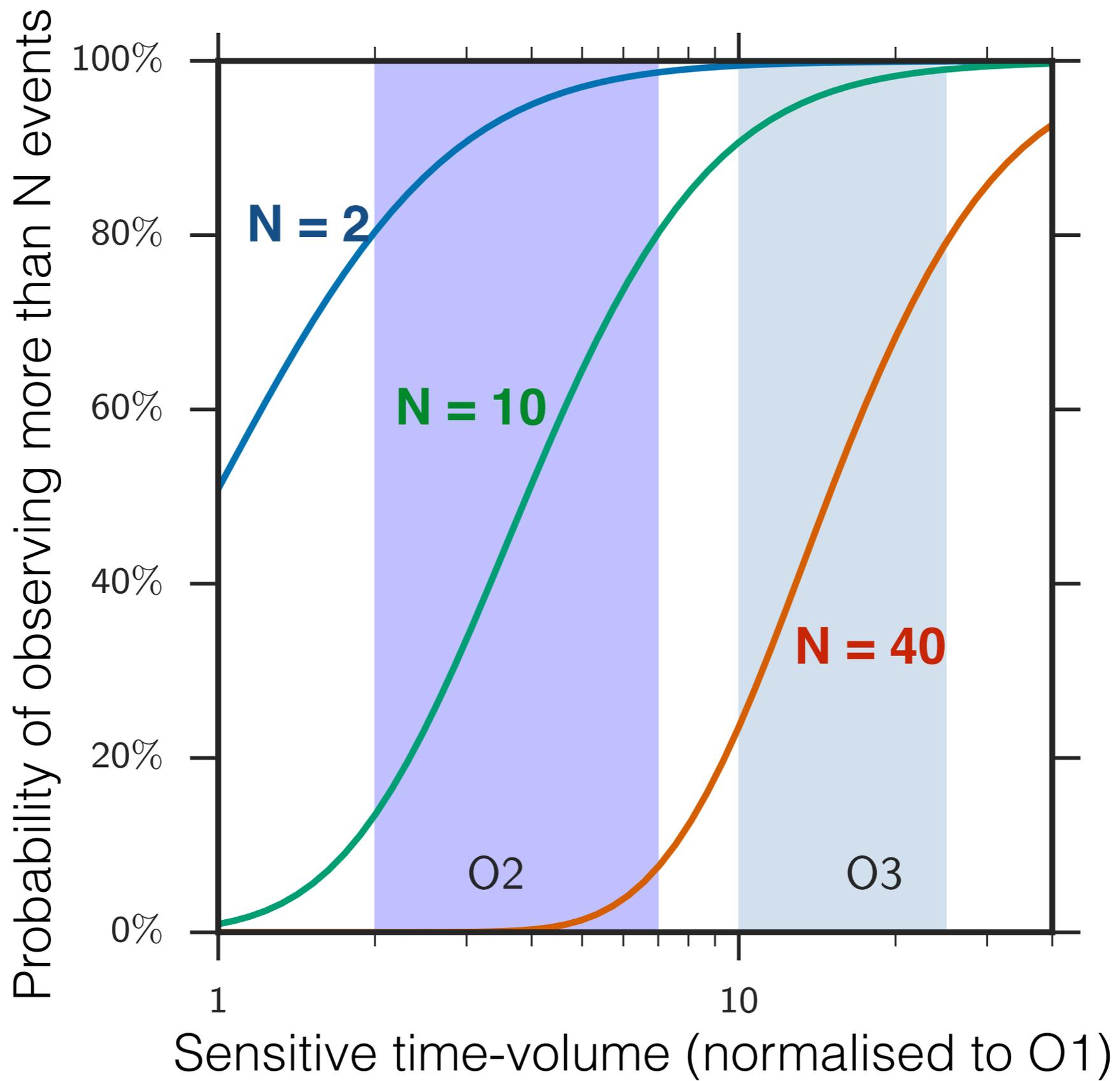


**Virgo is coming on-line now**



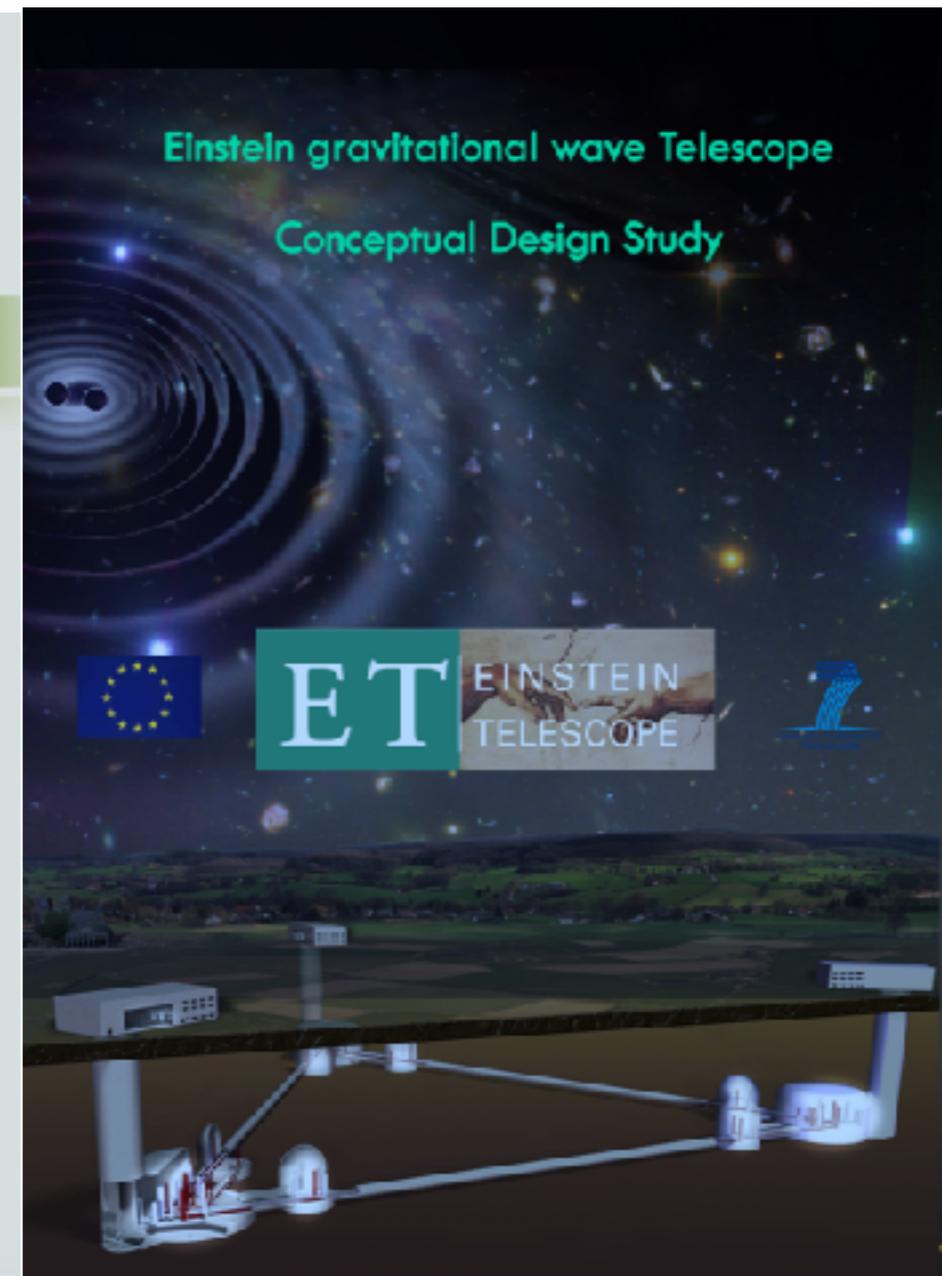
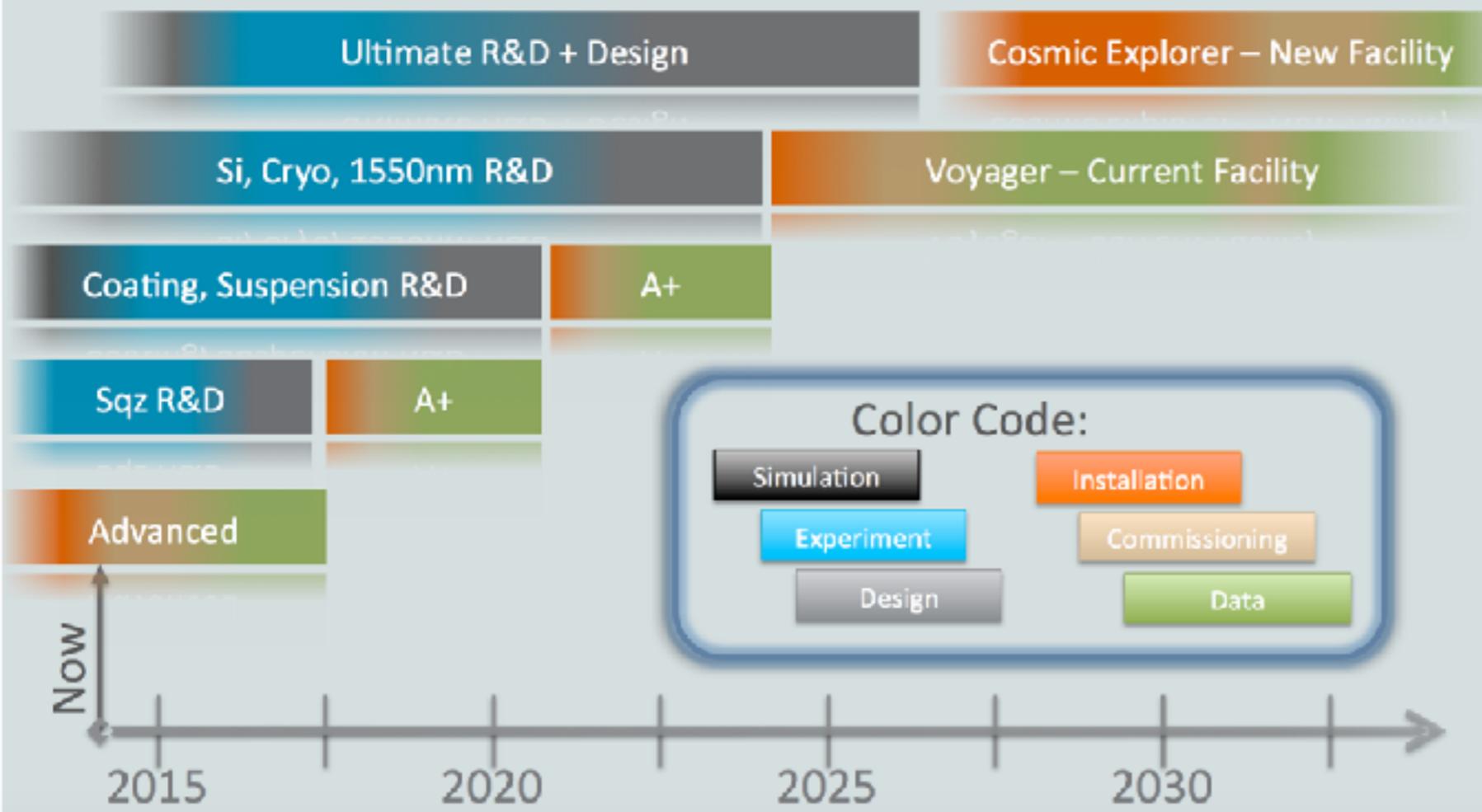
# Sky resolution





The future

# LIGO Upgrade Timeline



one BBH coalescence every 15 minutes!