Future prospects for UV to near-infrared data for kilonovae

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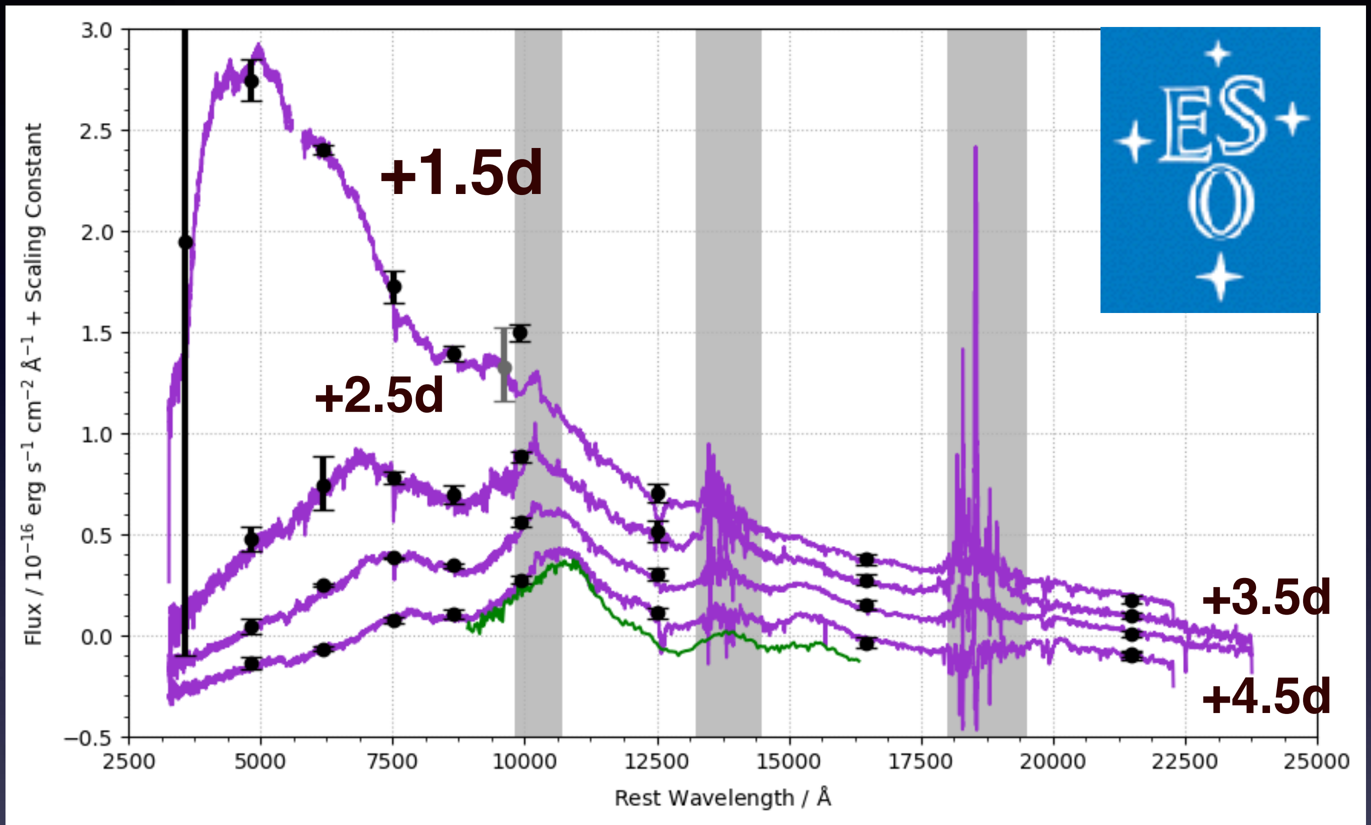
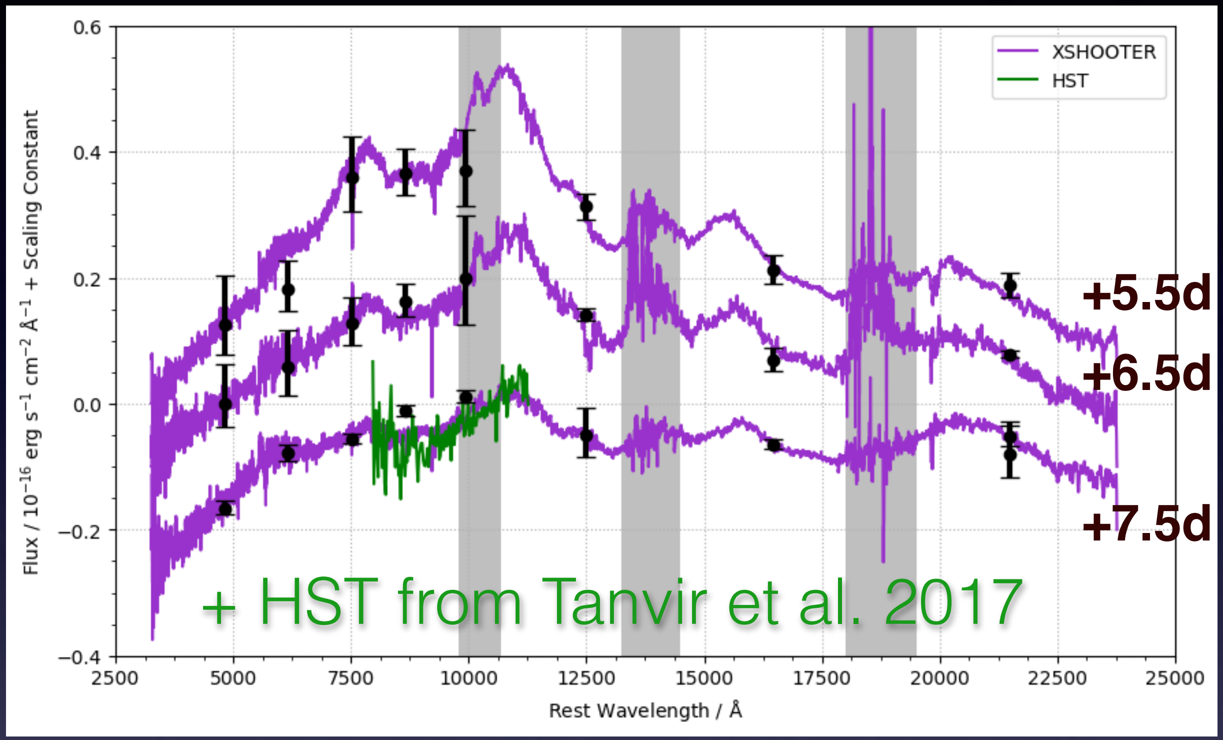
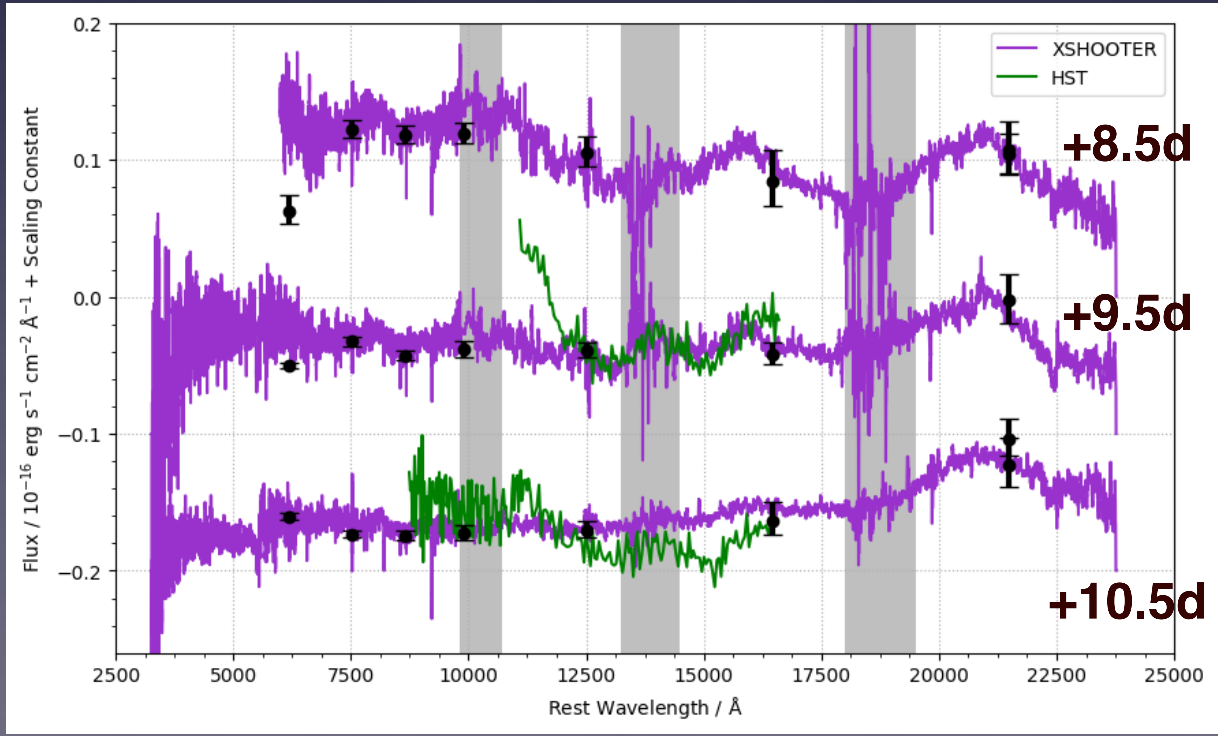
AT2017gfo : X-shooter + VLT







10 well calibrated X-shooter spectra
Original data from :
Pian et al. 2017
Smartt et al. 2017
Recalibration discussed in Gillanders et al. 2021
Data available on ENGRAVE website link

http://www.engrave-eso.org/

Overview

- The potential of multi-messenger astronomy has yet to be fully realised - one electromagnetic counterpart of a gravitational wave source

- What has happened since 2017 :

    1. Kilonovae discoveries enabled with GW signals = 1
    2. Kilonovae discovered with wide-field surveys = 0
    3. Kilonovae discovered with nearby GRBs = 2

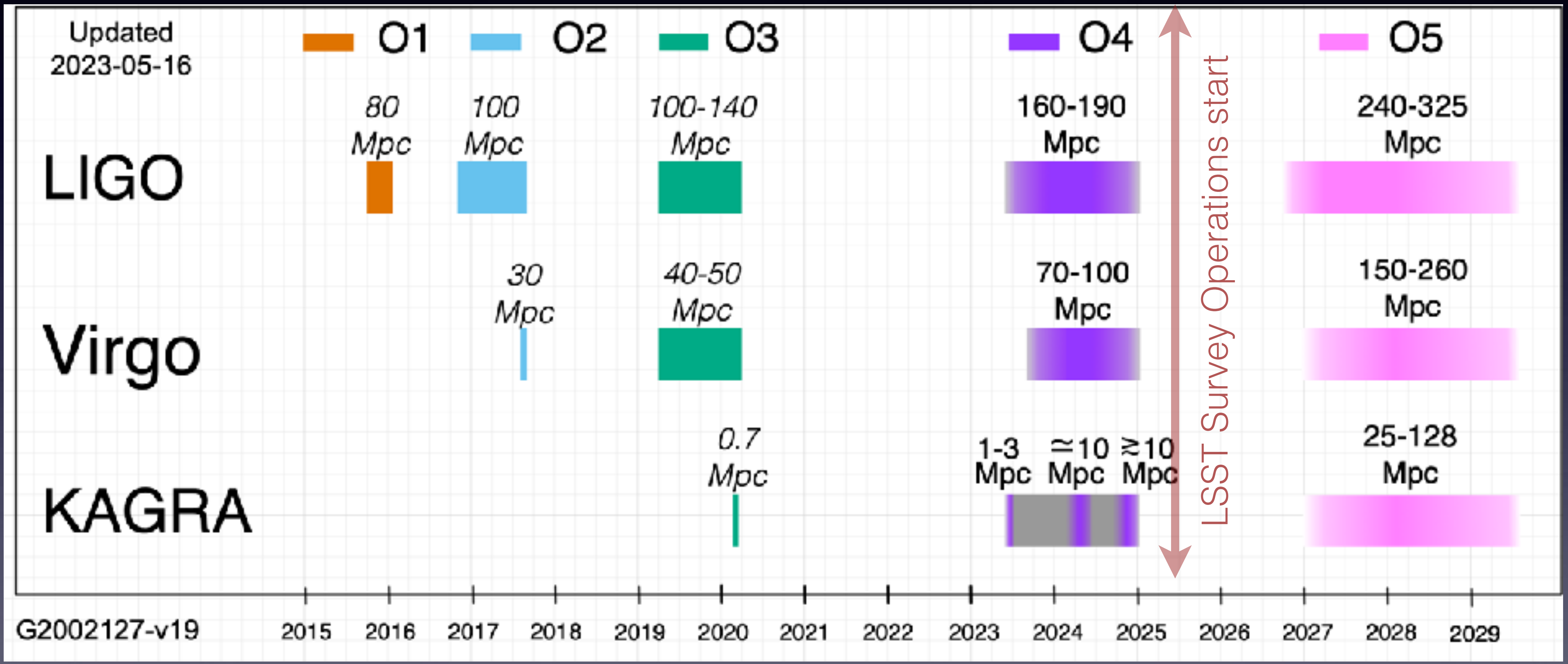
- Conclusion : discoveries likely limited by the natural BNS merger rate, not instrumentation or project effort

- Outlook for multi-messenger astronomy in the era of O5 (GW detectors reach optimal sensitivity) and the Rubin Observatory in 2025

LIGO - Virgo Gravitational wave detectors

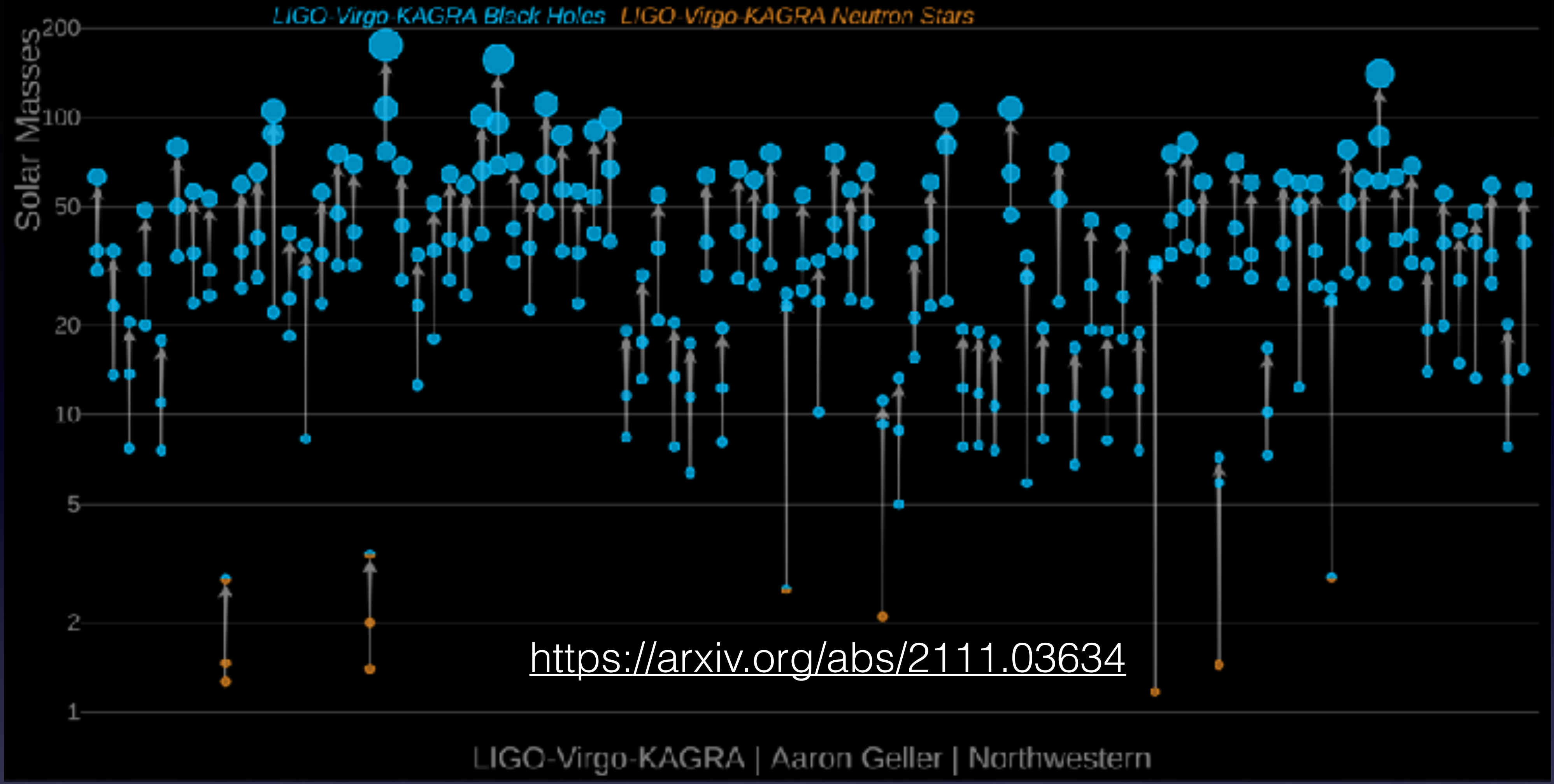
O1 : 4 months 2015-16
O2 : 9 months 2016-17
O3 : 12 months 2019-20
O4 : 18-20 months, started June 2023

LVK timeline (updated Aug 2023)



IGWN Observing Plans
https://observing.docs.ligo.org/plan/
Update : 15th Aug 2023

Masses in the Stellar Graveyard



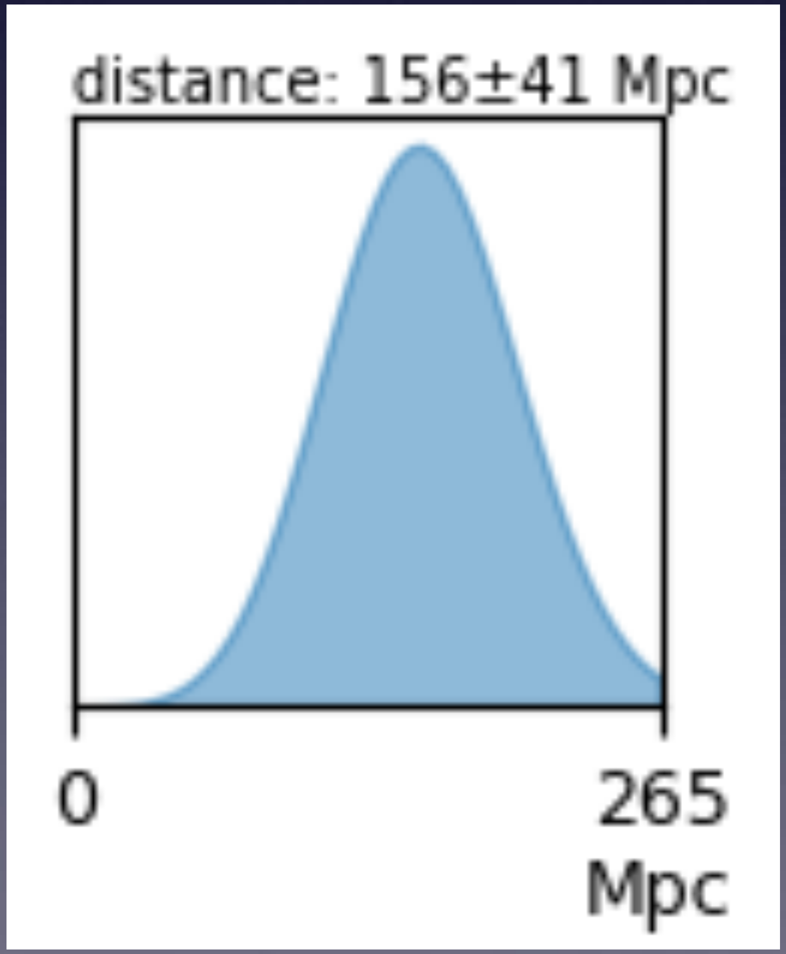
The LIGO Scientific Collaboration, the Virgo Collaboration the KAGRA Scientific Collaboration

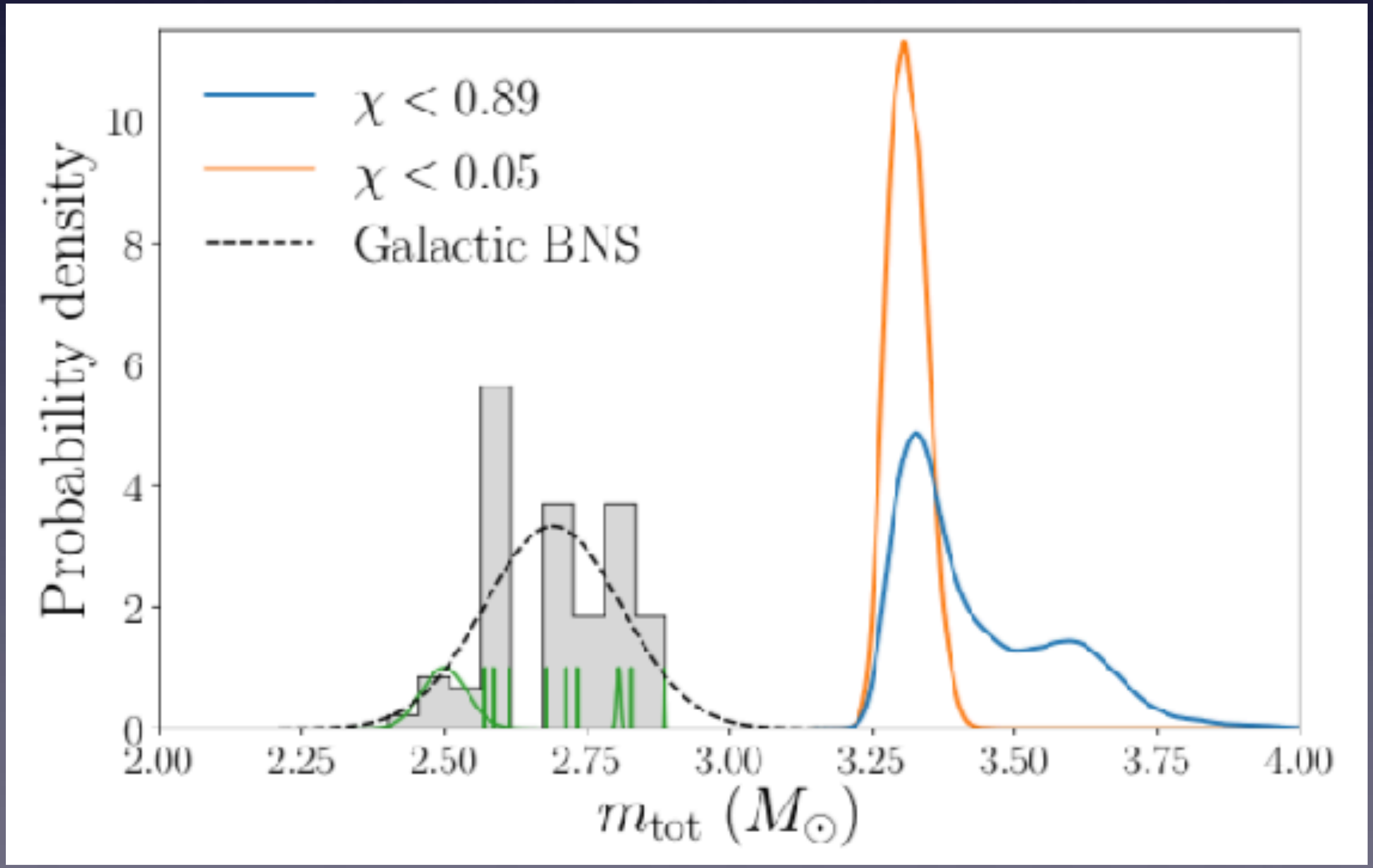
$$N_{BNS} = R_{BNS}\left(\frac{4\pi}{3}D_{\rm BNS}^{3}\right)T_{\rm up}$$

$$D_{\rm gain} > \left(\frac{T_{\rm down}}{T_{\rm up}} + 1\right)^{1/3}$$

GW190425: Binary NS merger

During O3 :
One high significance Binary NS merger in April 2019
$D \simeq 150\,\mathrm{Mpc}$

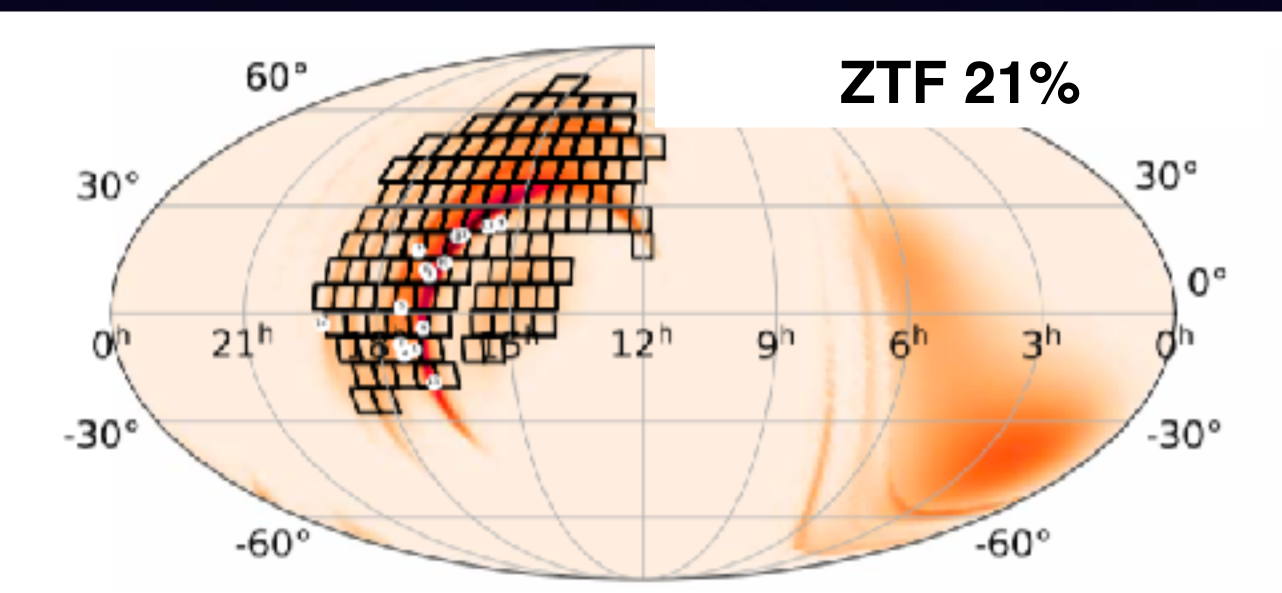




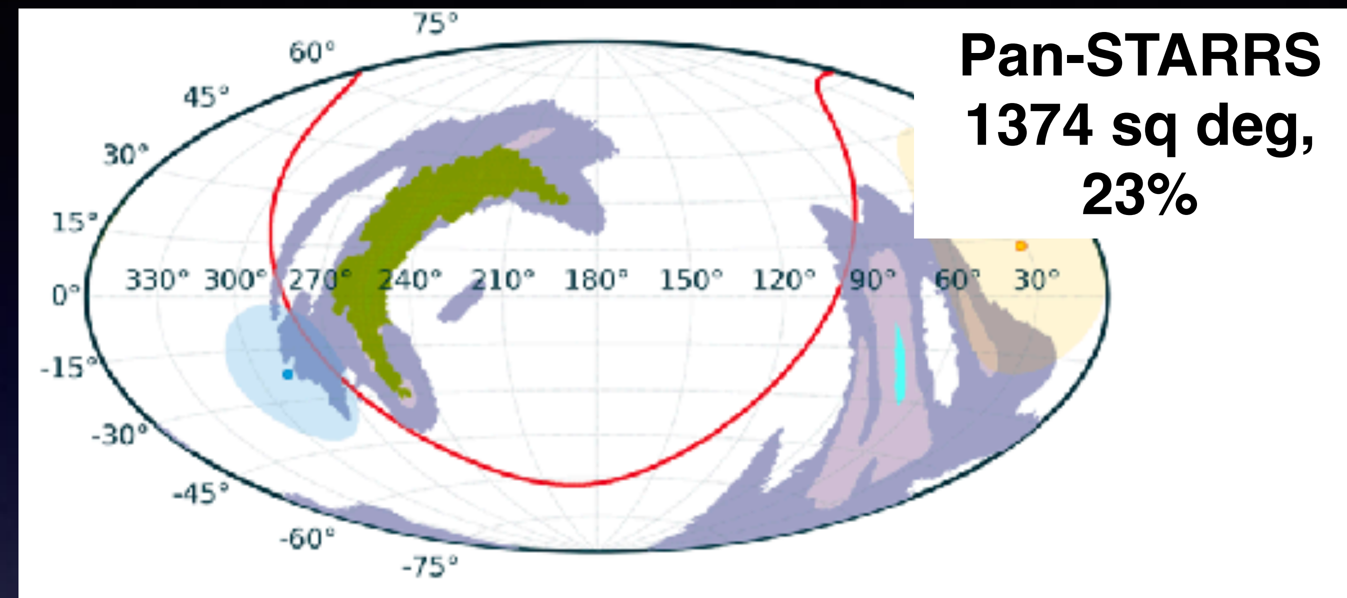
LIGO-Virgo Collaboration : Abbott et al. 2020

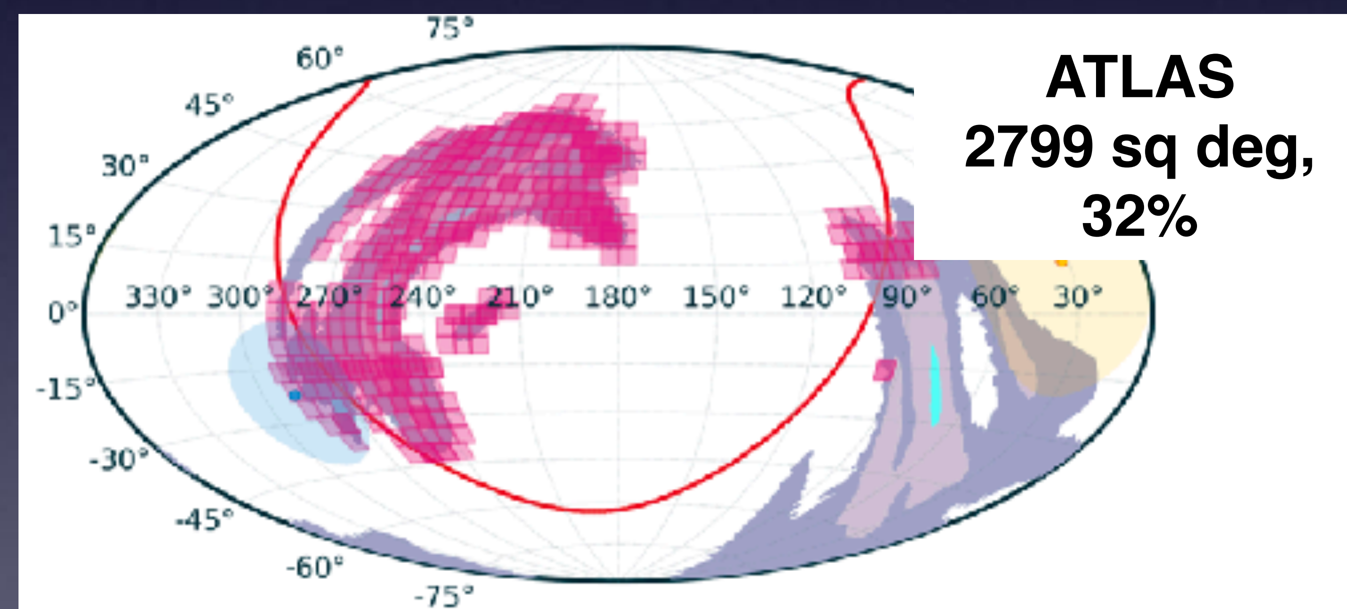
No EM counterpart for GW190425

90% area was 7461 deg^2



ZTF : Coughlin et al. 2019



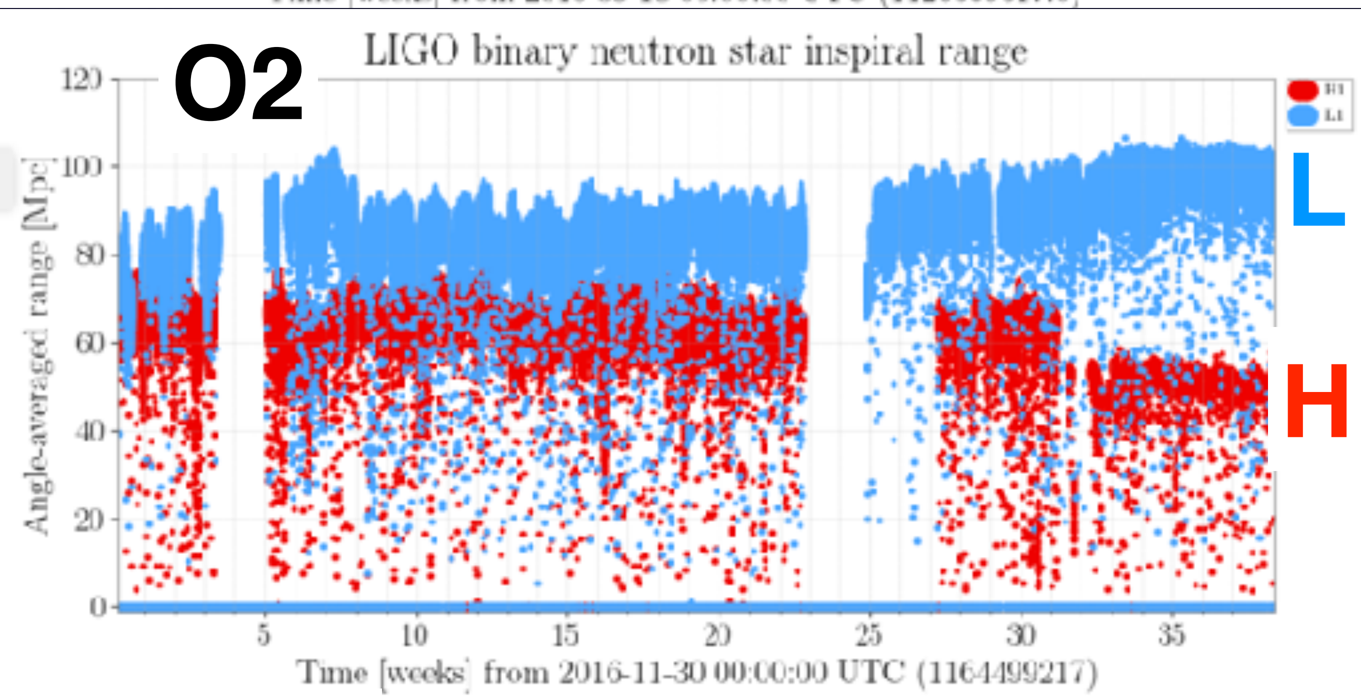


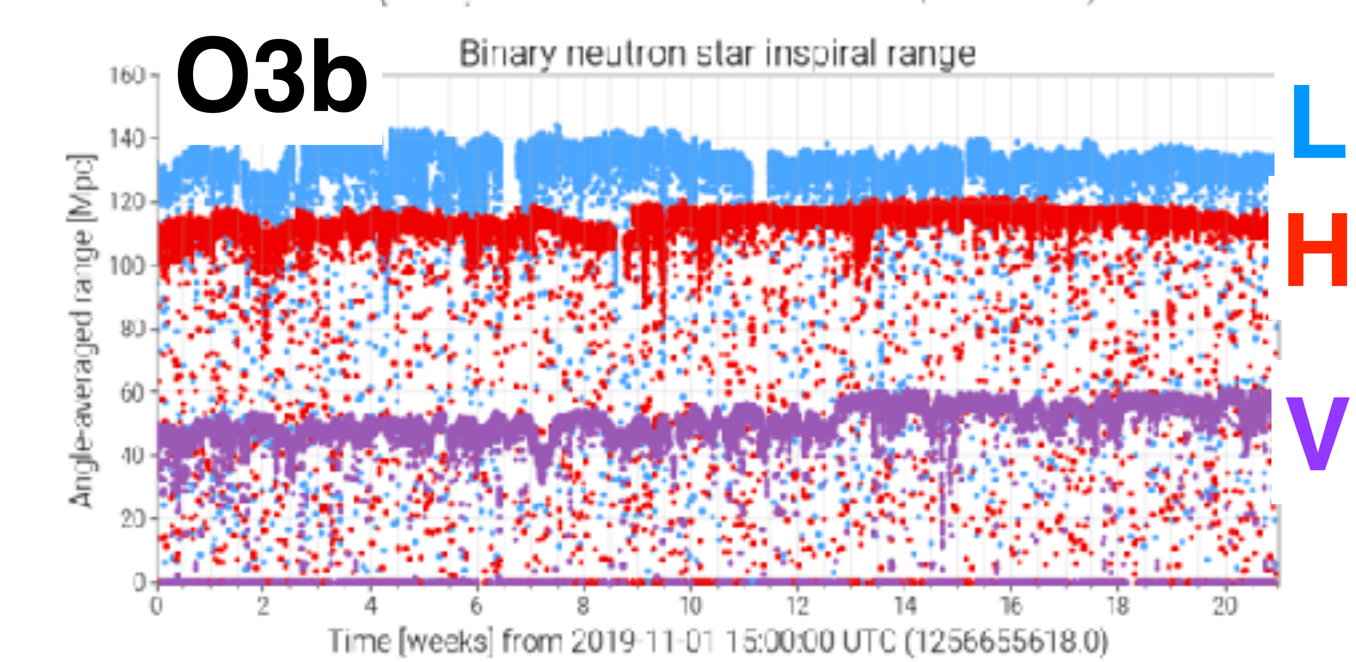
Smartt et al. 2023, in prep.

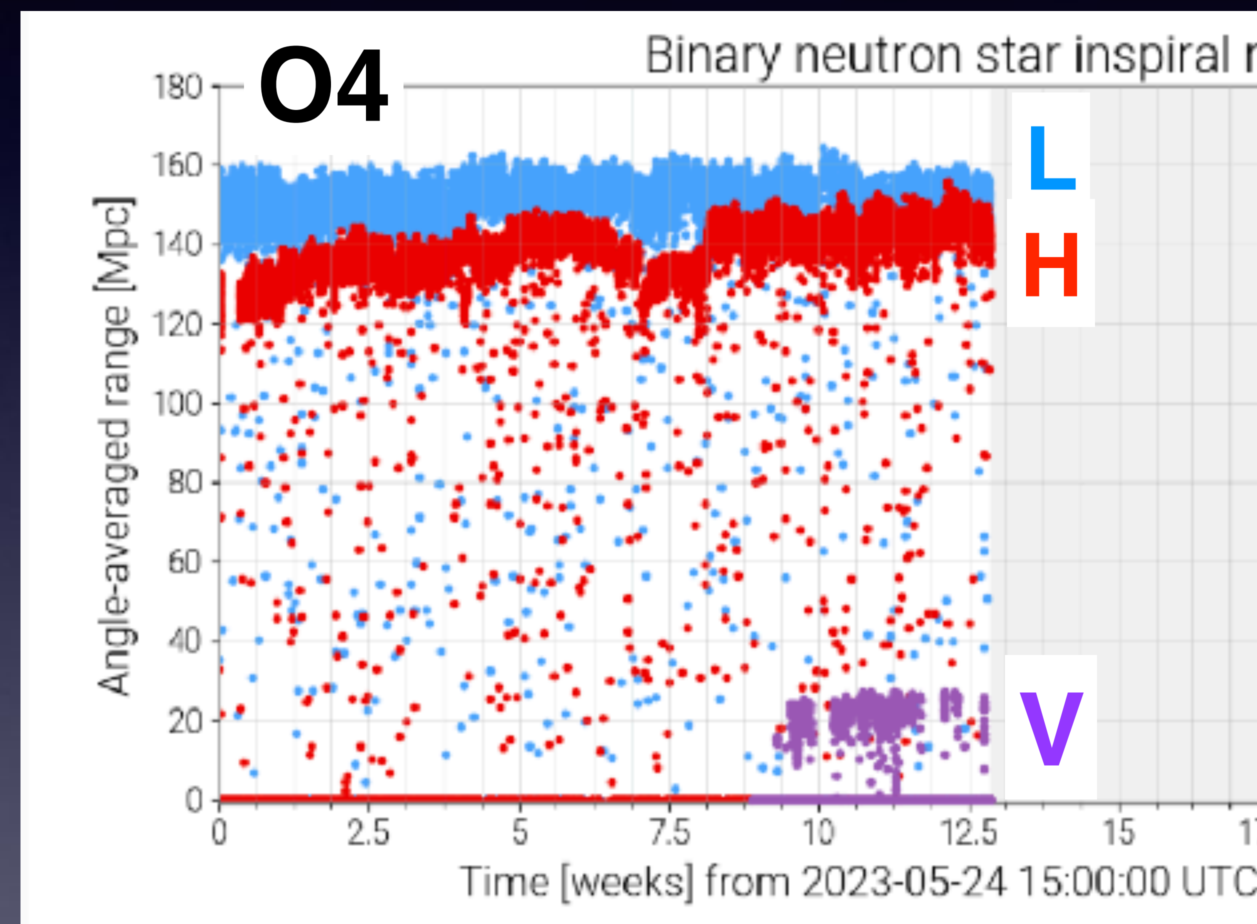
Livingstone - detection
Hanford - offline
Virgo - observing but non-detection

1. Kilonovae from GW triggers - prospects for the rest of O4

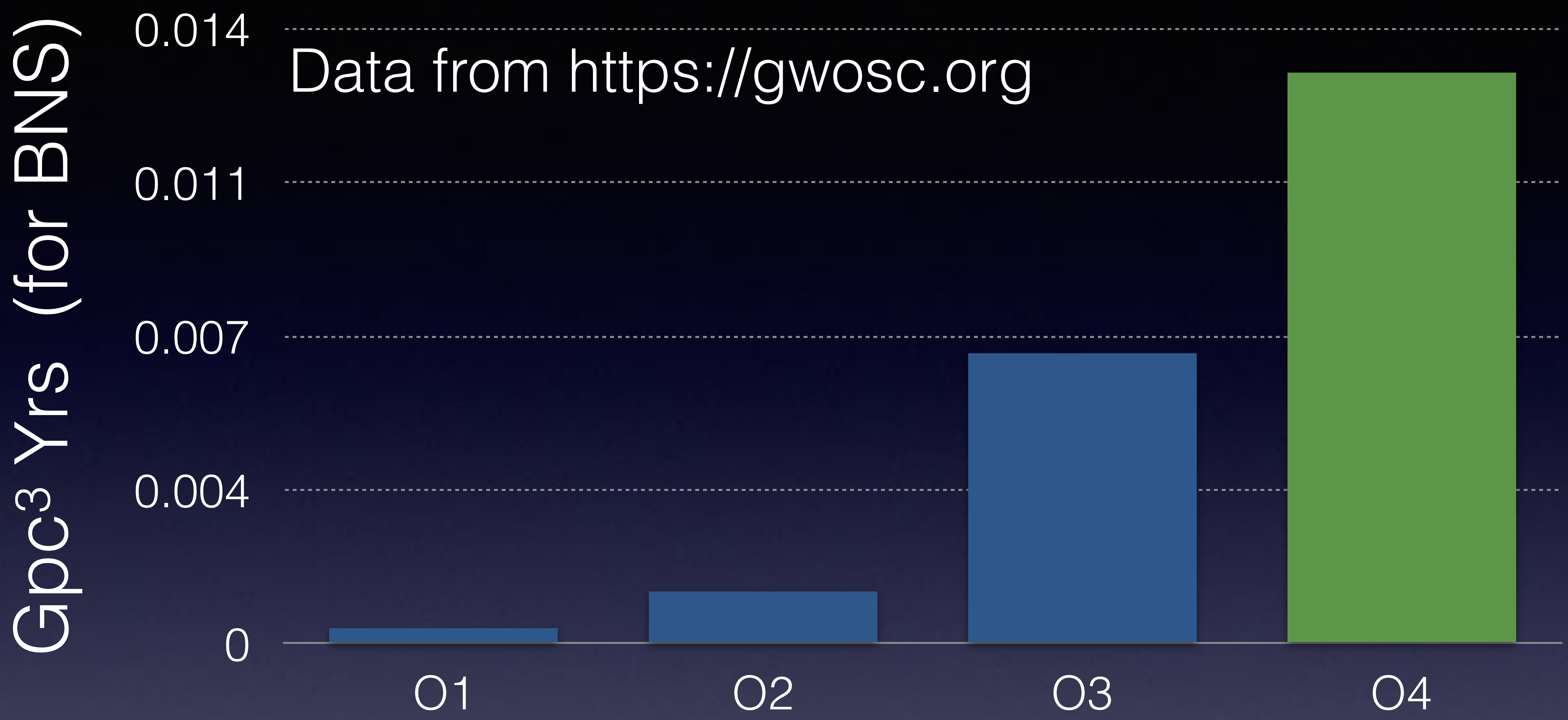
Data from https://gwosc.org







Projected BNS rates in O4



Note : Frostig et al. (2022) predicted ~10 BNS mergers in O4

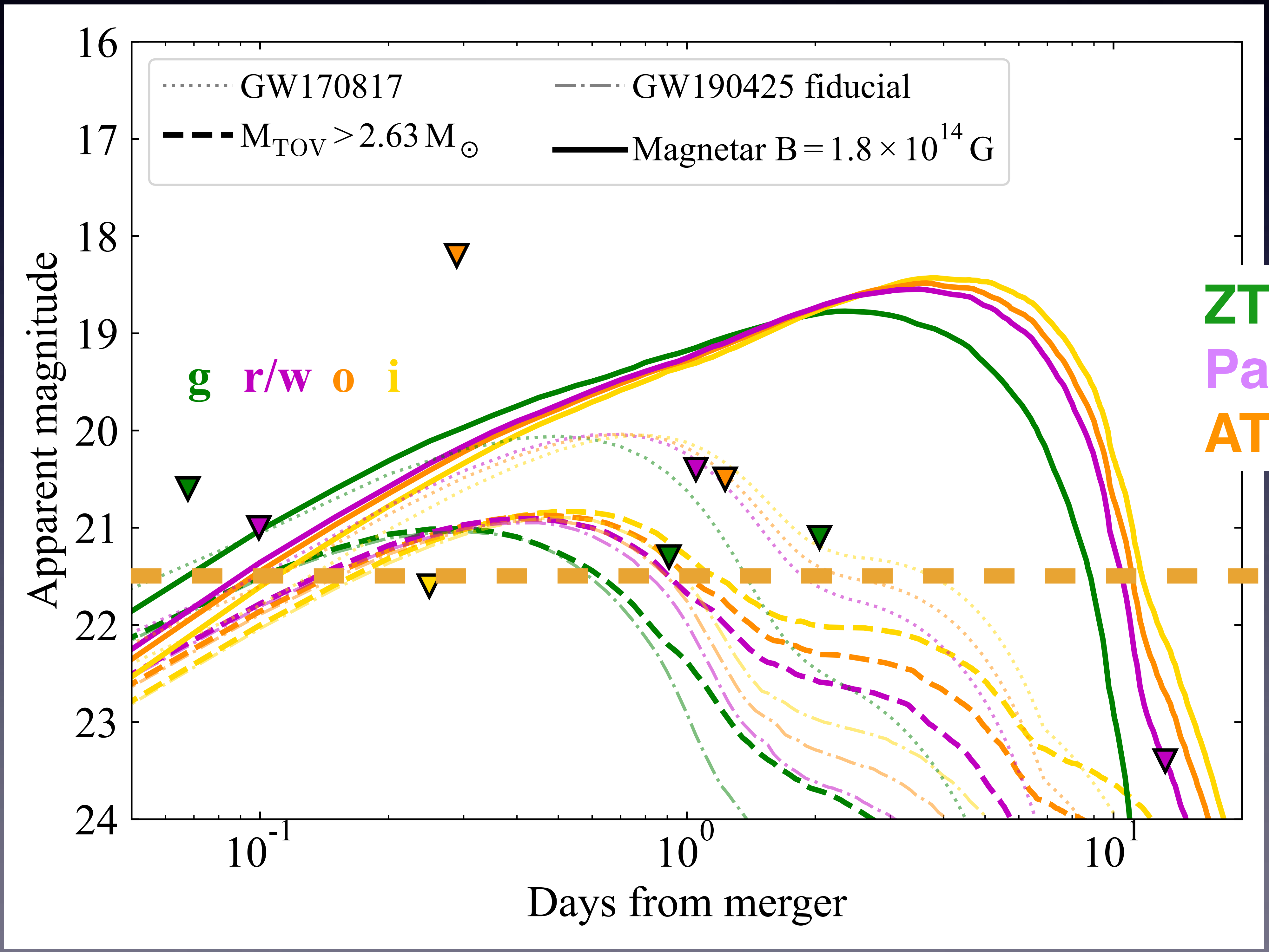
$$\text{Total BNS detections O1 + O2 + O3} \quad = 2$$

$$\text{Ratio of Gpc}^3\text{ Yrs } \left(\frac{\text{O4}}{\text{O1 + O2 + O3}}\right) \quad = 1.6$$

$$\text{O4 projected : } N_{\text{BNS}} \quad = 3 \pm 2$$

$$\text{O4 projected : } N_{\text{EM}} \quad \sim 2 \pm 2$$

Typical kilonova light curves and limits at 150Mpc



GW190425

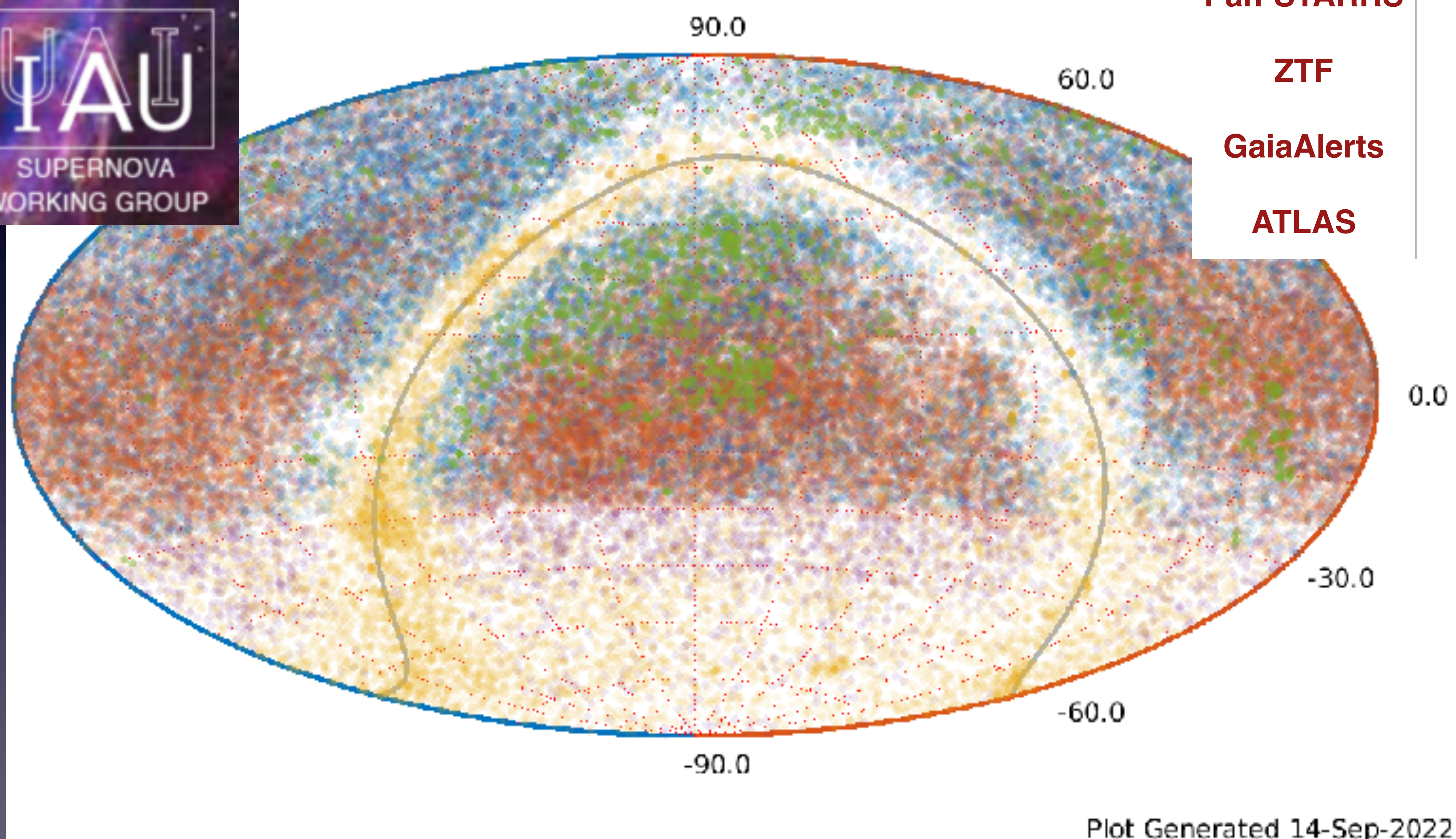
ZTF *g, r*
Pan-STARRS *w, i*
ATLAS *o*

$m = 21.5$

2. Kilonovae from wide-field surveys - results and prospects

Kilonova with no GW trigger ?

Pan-STARRS	38834
ZTF	41924
GaiaAlerts	17263
ATLAS	16023

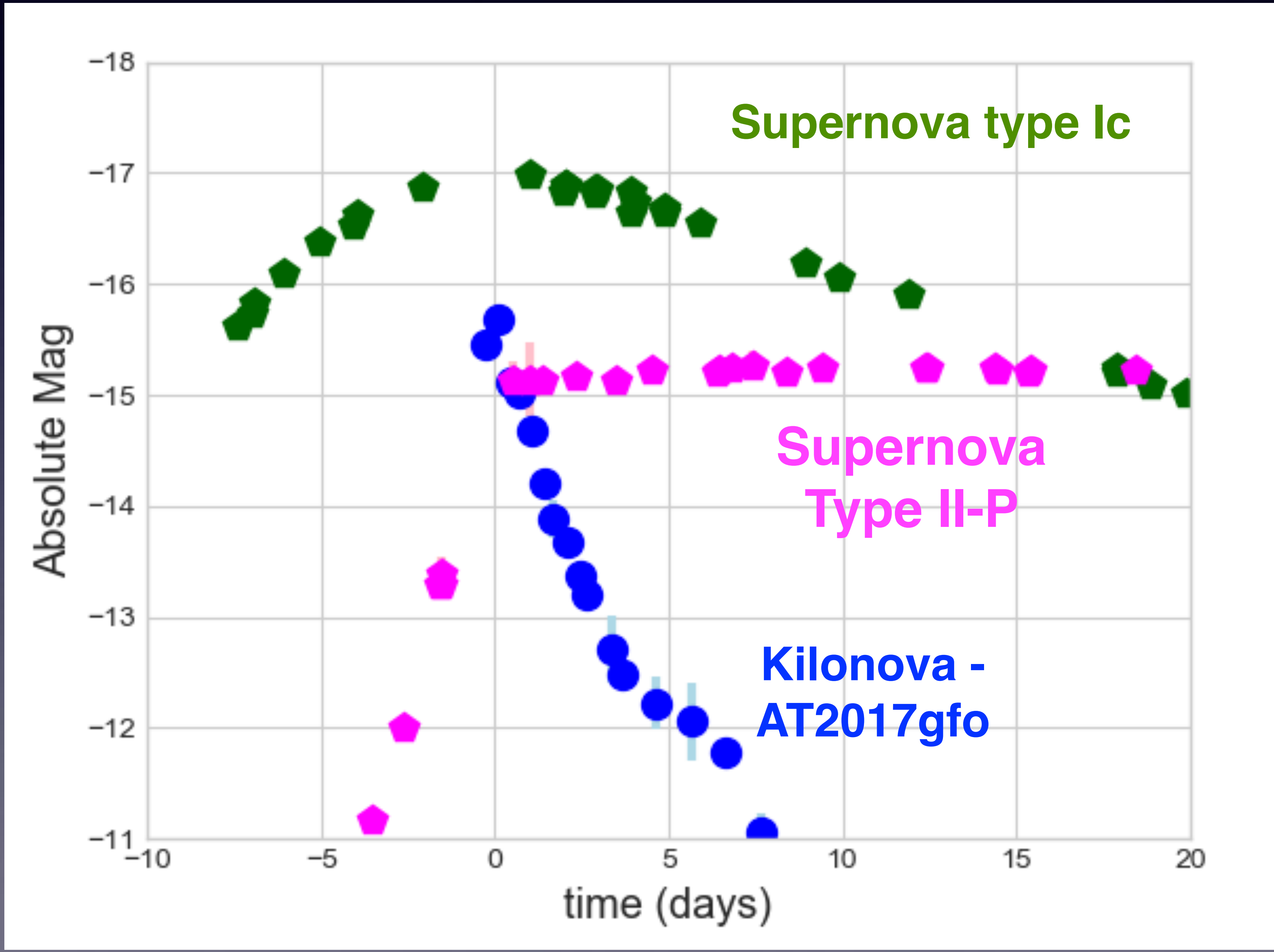


Total = 122,734

Public ATs and SNe since 1 Jan 2016 (mag < 22)

https://www.wis-tns.org

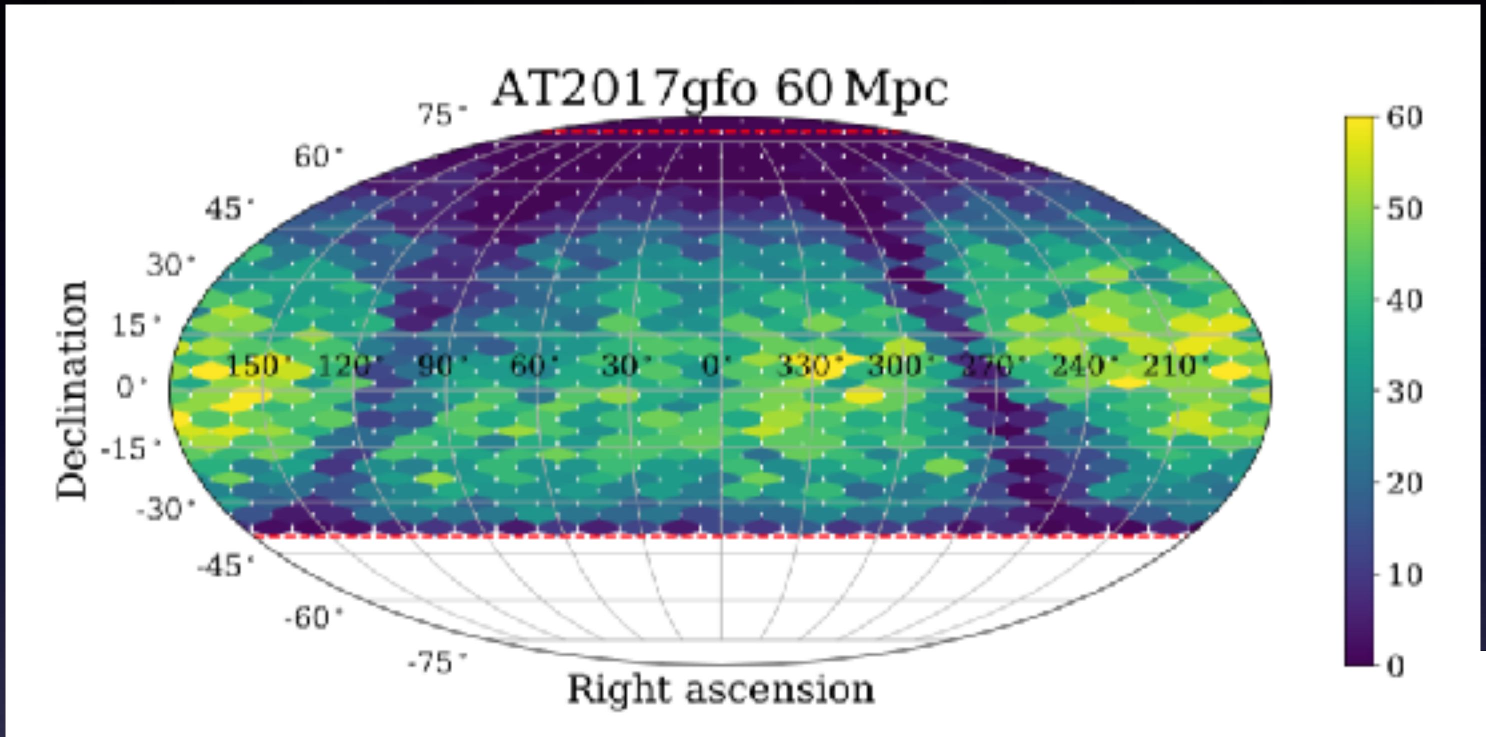
AT2017gfo : quite bright, but fast decline



Comparison
r-band mags

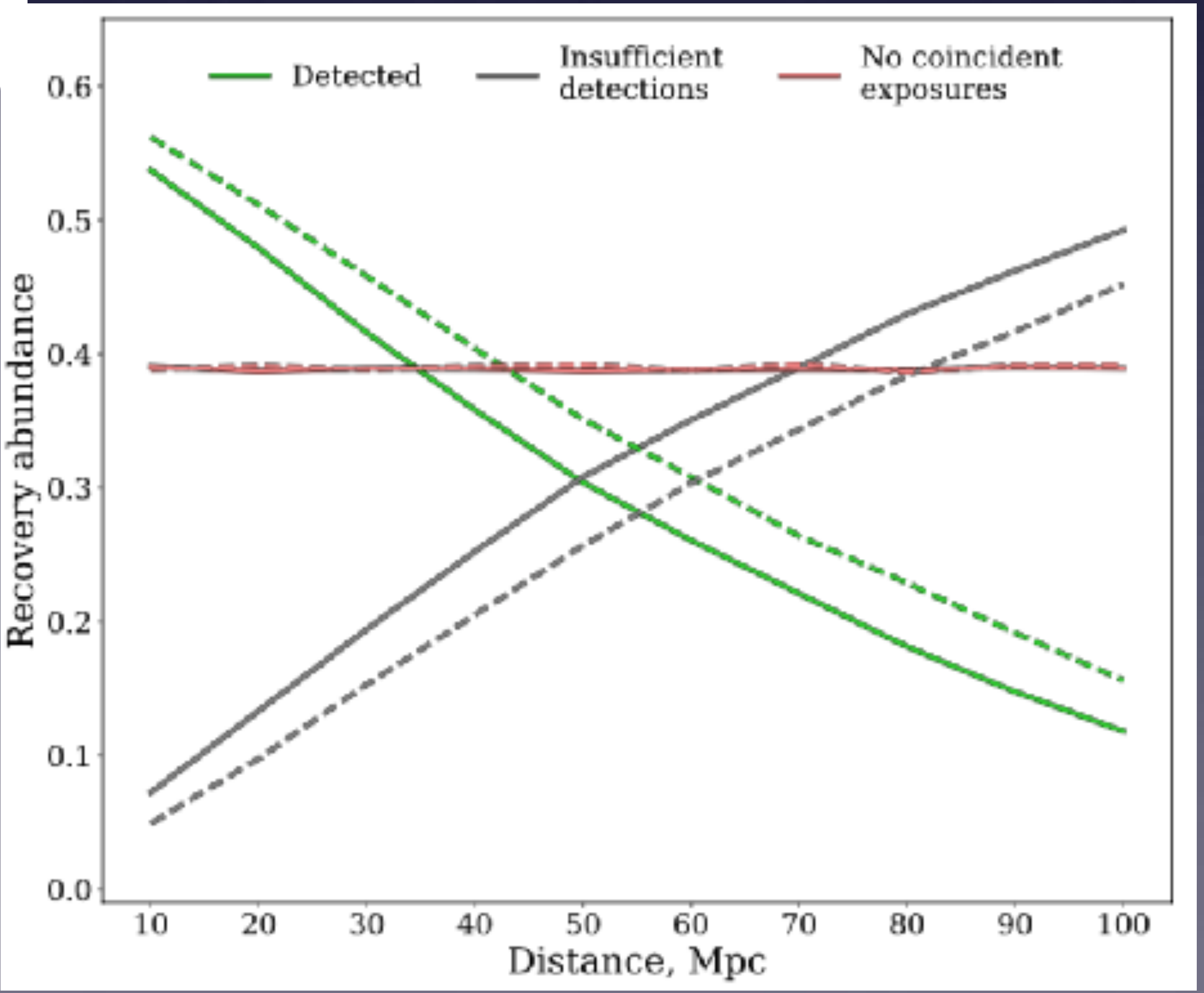
time = 0 set
to peak epoch

ATLAS recovery efficiency



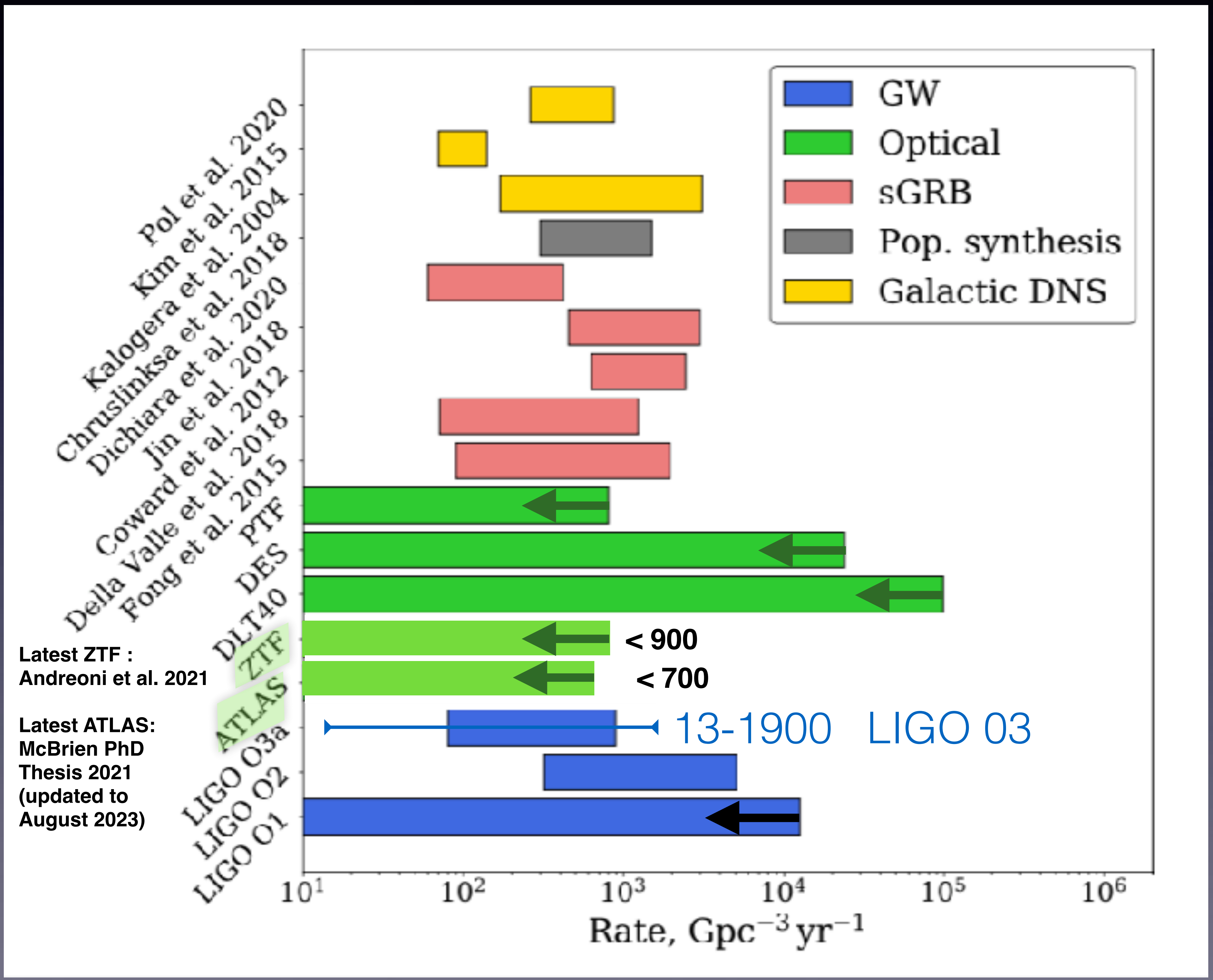
- Recovery map within a distance of 60Mpc
- ATLAS Transient Server: requires 3 x 5σ detections

Reason for simulated :object not being recovered :



Also see ZTF , Andreoni et al. 2021

Kilonova and BNS merger rates



Let's take
LVK rate = 300 Gpc^{-3} yr^{-1}
Factor ~3 uncertainty

D	BNS per year	Comment
100 Mpc	1	GW170817 is once per decade event
175 Mpc	4 - 7	Most likely for O4 ?
300 Mpc	30	Game changing number : O5 + Rubin Observatory ToO

See Mandel & Broekgaarden 2022, LRR

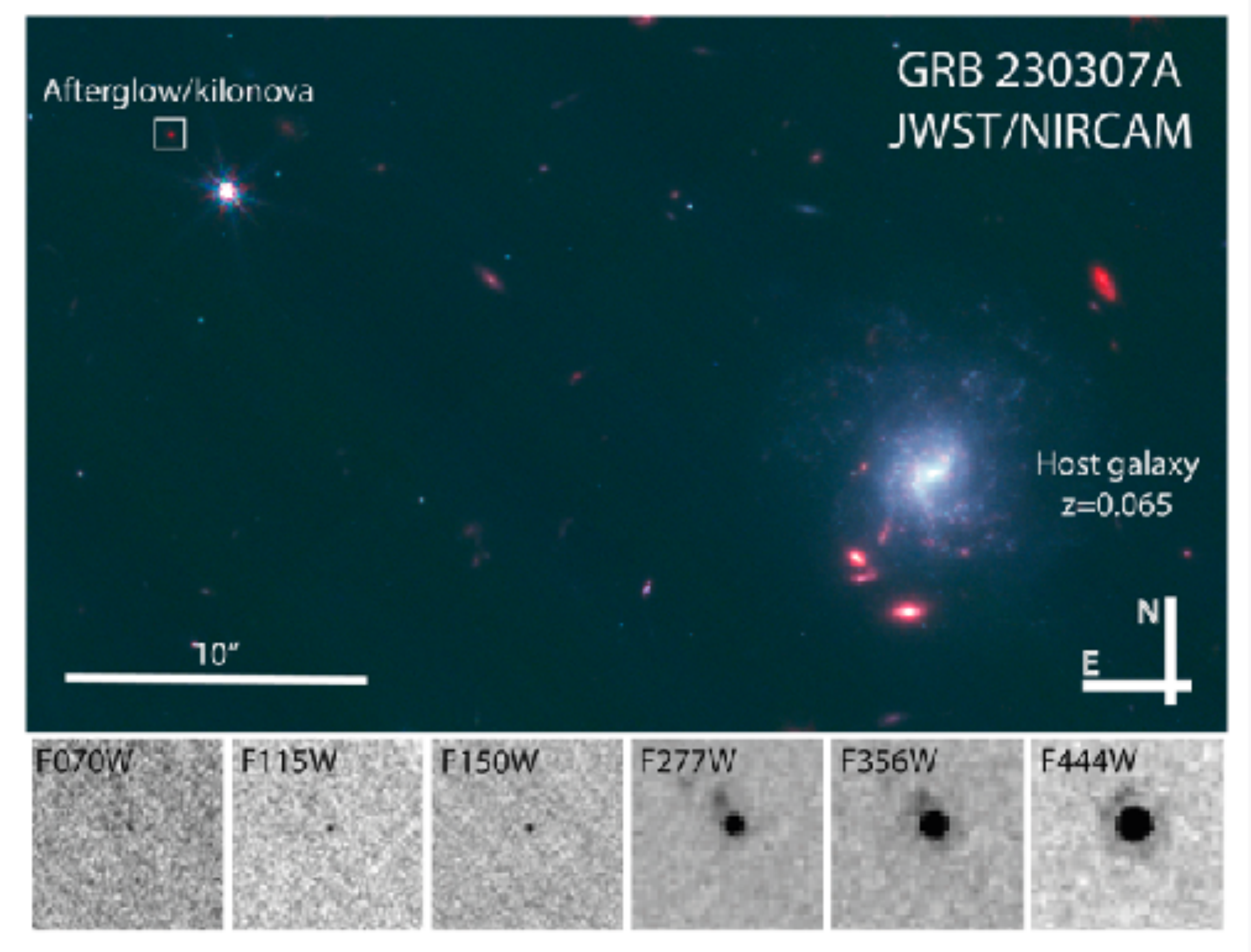
Prospects in wide-field surveys

- No detections of a kilonova signature in any wide-field survey
- Typically sensitive to D < 100-200 Mpc
- LIGO-Virgo efficiency is ~90%, during observing runs
- LIGO-Virgo equivalent 10 yr uptime is ~30%
- Recovery efficiency of wide-field surveys needs to be 20 - 30% at D < 100Mpc
- **Ongoing, continual wide-field surveys are competitive discovery engines for D < 100Mpc.**
- **Discovery rates will be low**

Fulton, Smartt et al. 2023 in prep

3. Kilonovae from GRB triggers

Probably biggest surprise

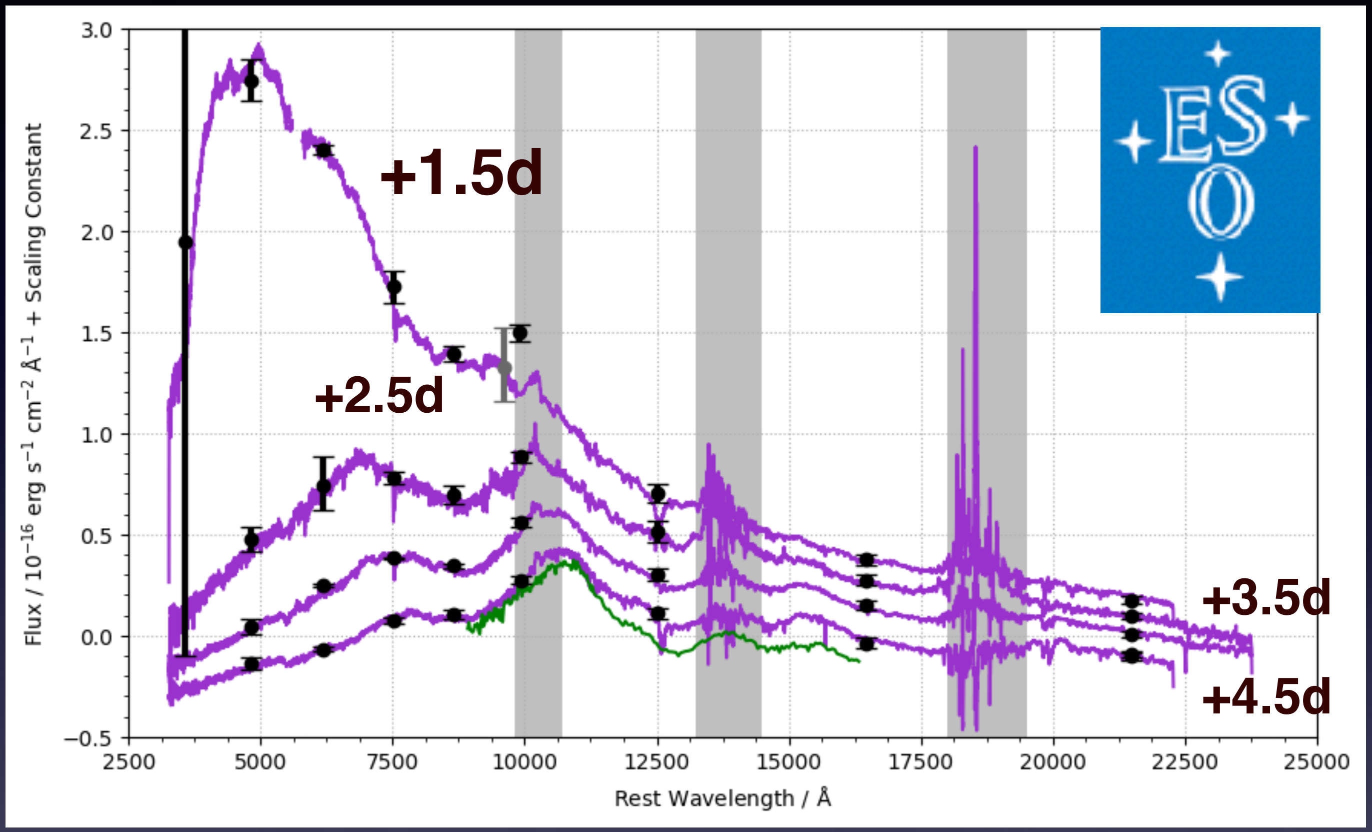


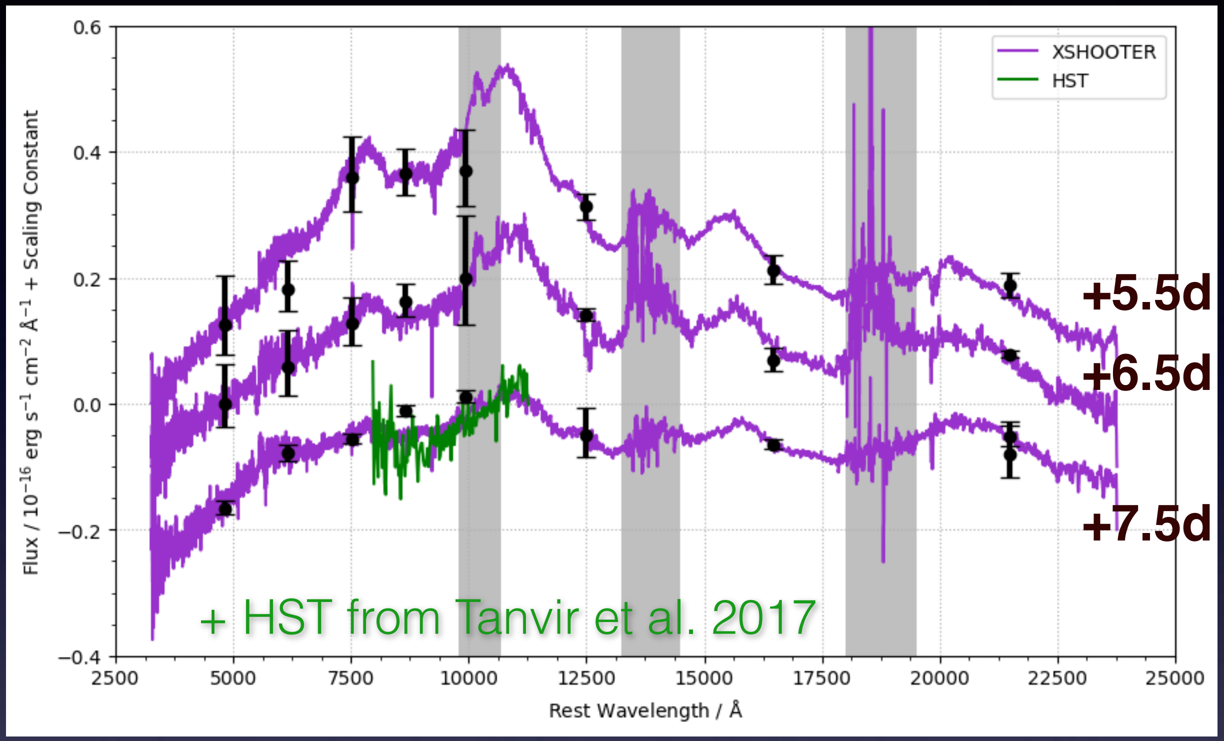
Levan et al. 2023
Gillanders et al. 2023
Yang et al. 2023

- Two detections of a kilonova signature in the afterglow of 2 longish GRBs
- GRB230307A : z = 0.0646 (280 Mpc)
- GRB211211A : z = 0.0763 (350 Mpc)
- Rate estimate extremely low : $R_{merger} \sim 0.01$ Gpc^{-3} yr^{-1}
- **But 2 discoveries since 2021**

Data quality for future kilonovae

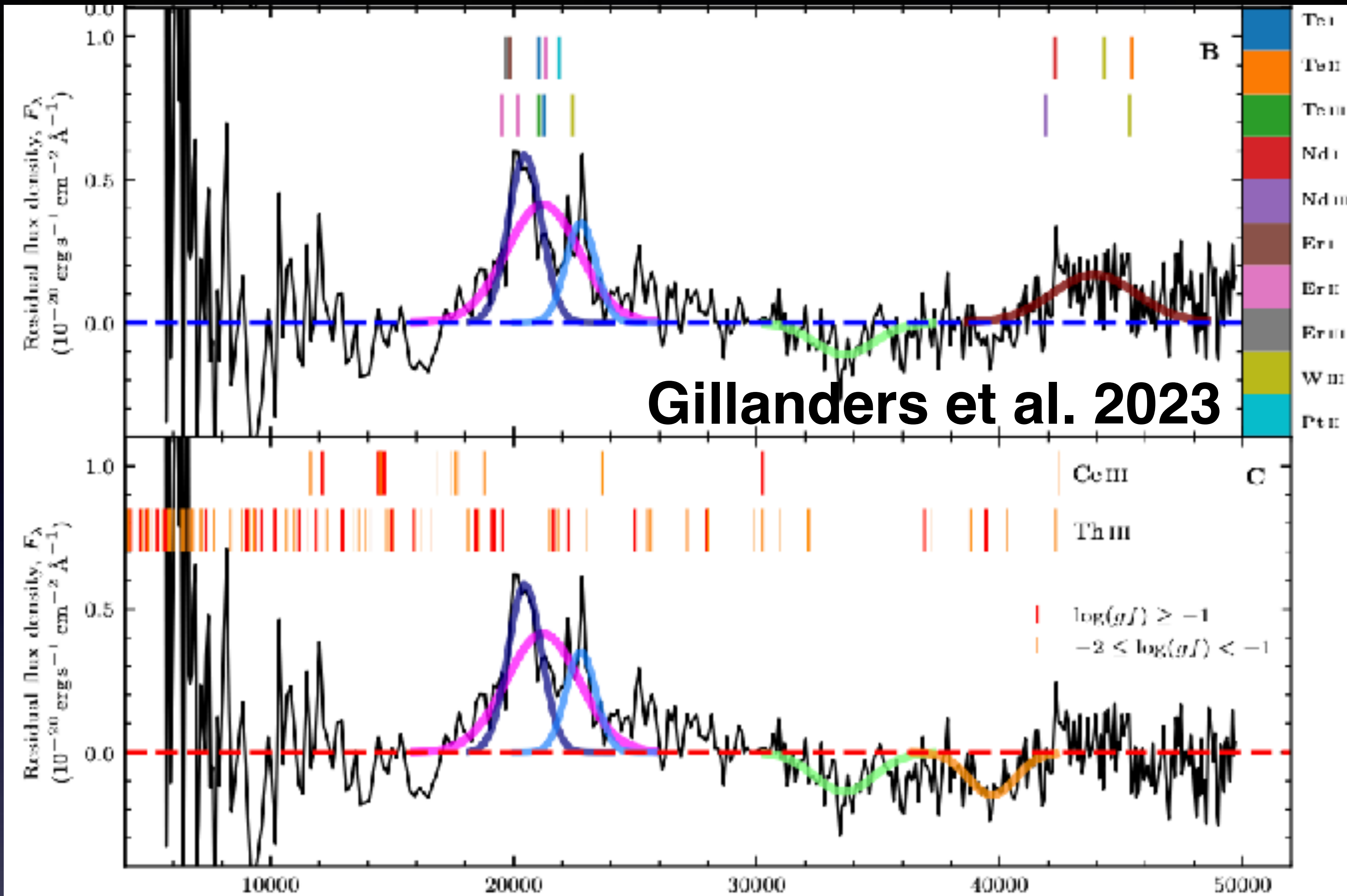
10 well calibrated X-shooter spectra
Smartt et al. 2017
Pian et al. 2017
Gillanders et al. 2021

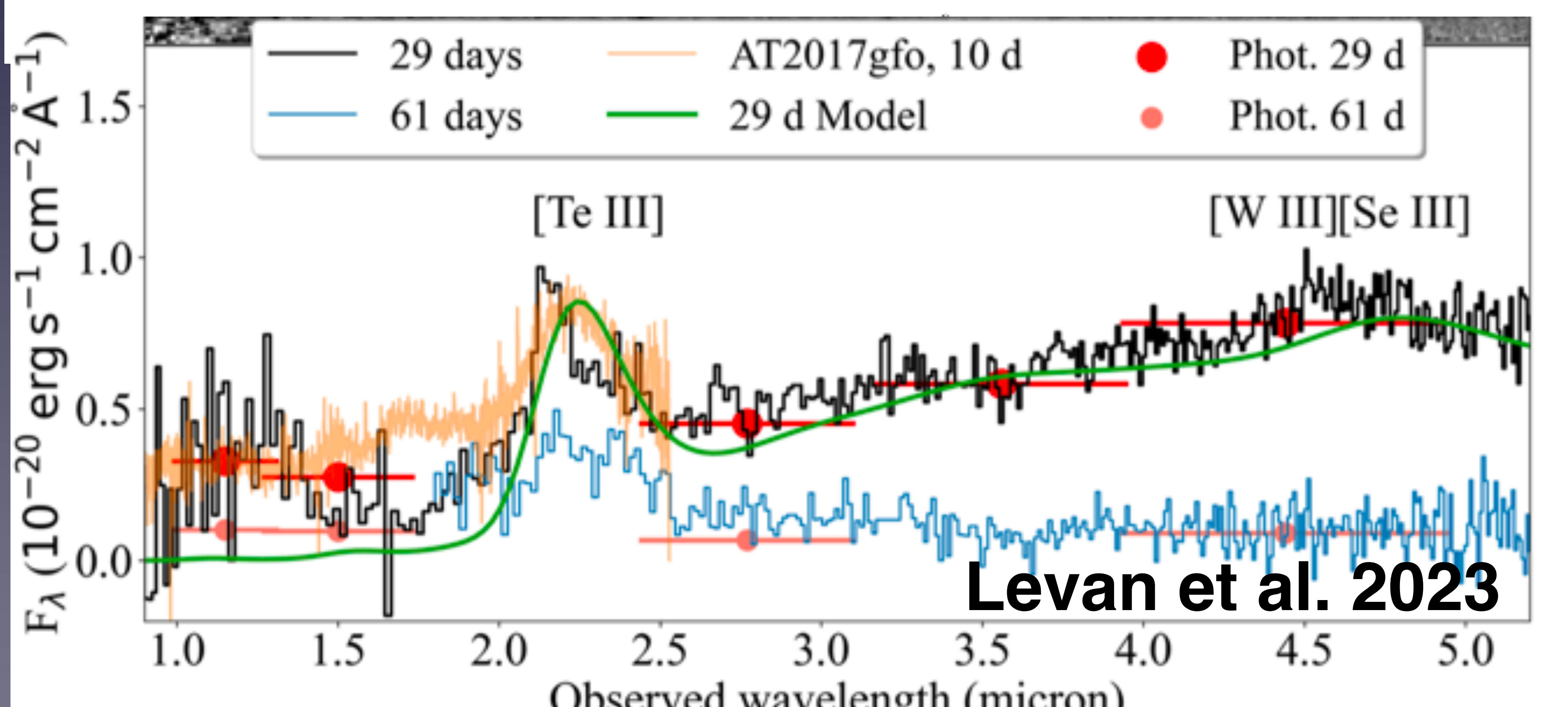




D = 120 Mpc
Can reach AT2017gfo (r=22) at +4 days with 6hrs X-shooter
S/N ~25 at a binned resolution of 1000 km/s

http://www.engrave-eso.org/

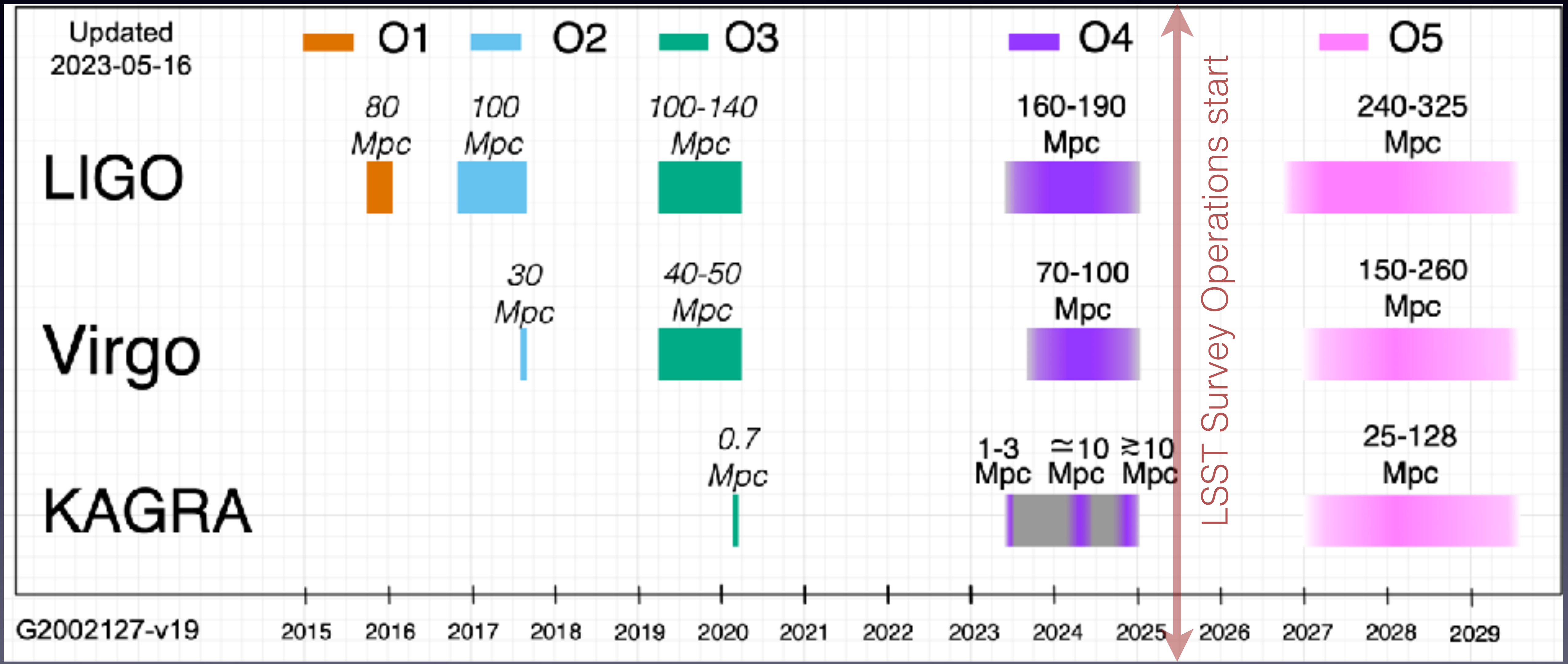




Beyond +4 days, JWST will be the instrument for D > 100 Mpc targets.

Multiple approved programmes

Prospects for O5



IGWN Observing Plans
https://observing.docs.ligo.org/plan/
Update : 15th Aug 2023

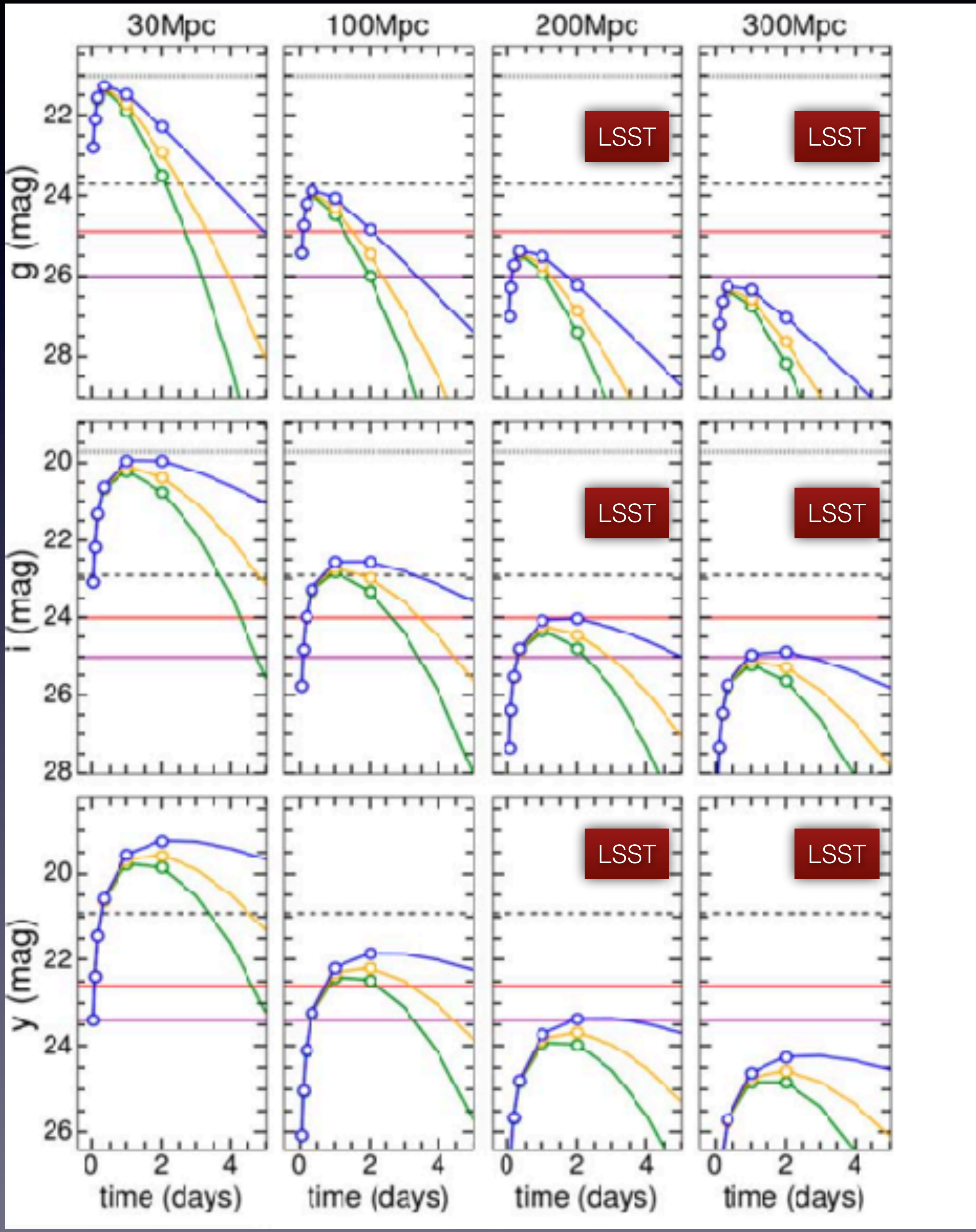
Rubin Observatory and the "Legacy Survey of Space and Time"

6m aperture, 10 square degree survey facility
Start of science operations: mid-2025

LSST: the next game changer

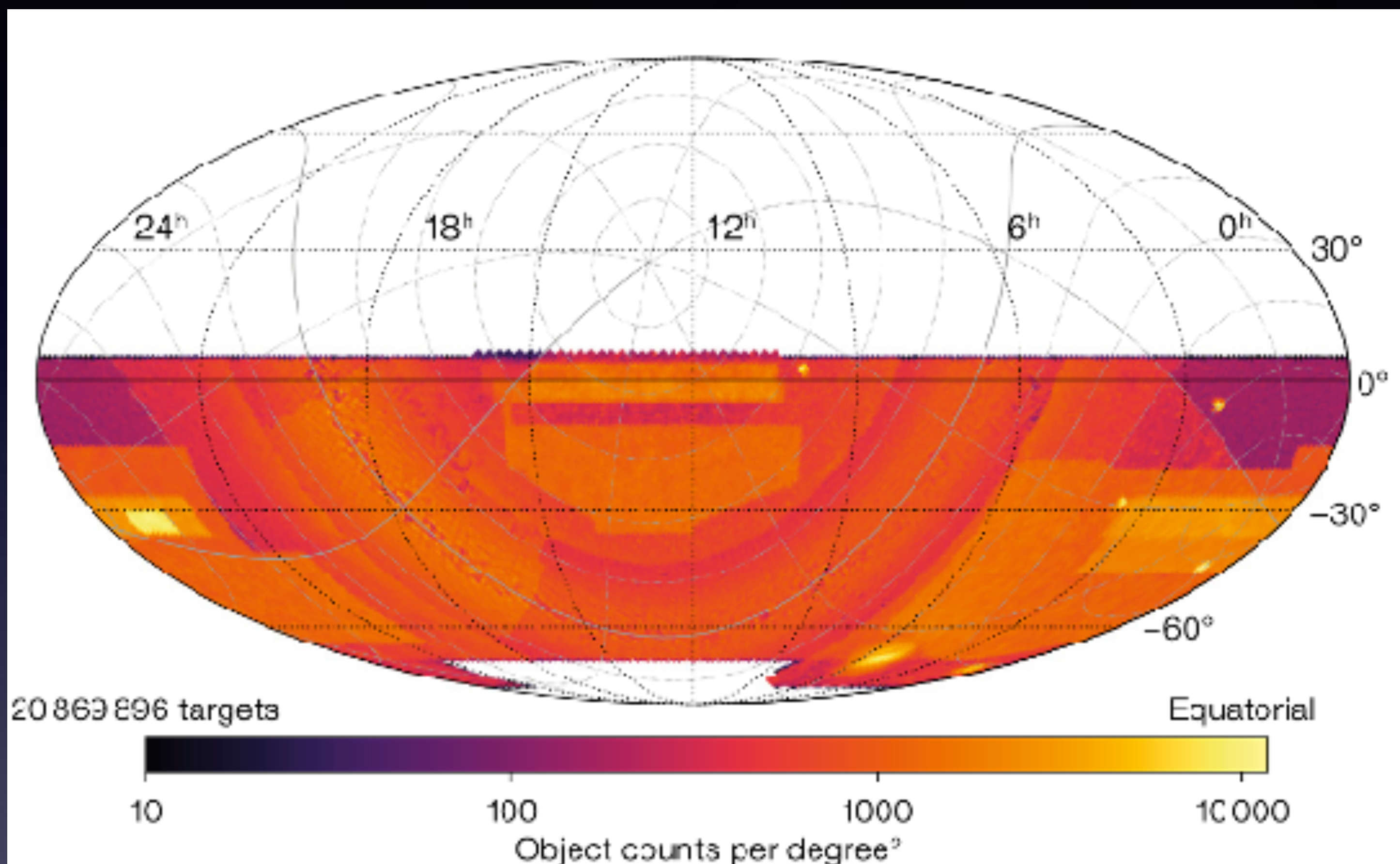
D	BNS per yr	Ligo-Virgo-Kagra Observing run	Comment
100 Mpc	1	O2 and O3	GW170817 is once per 10yr event
160 Mpc	1 - 5	O4	Most likely for O4 - (but day light hours, moon)
300 Mpc	~30	O5	Game changing number : O5 + Rubin Observatory ToO

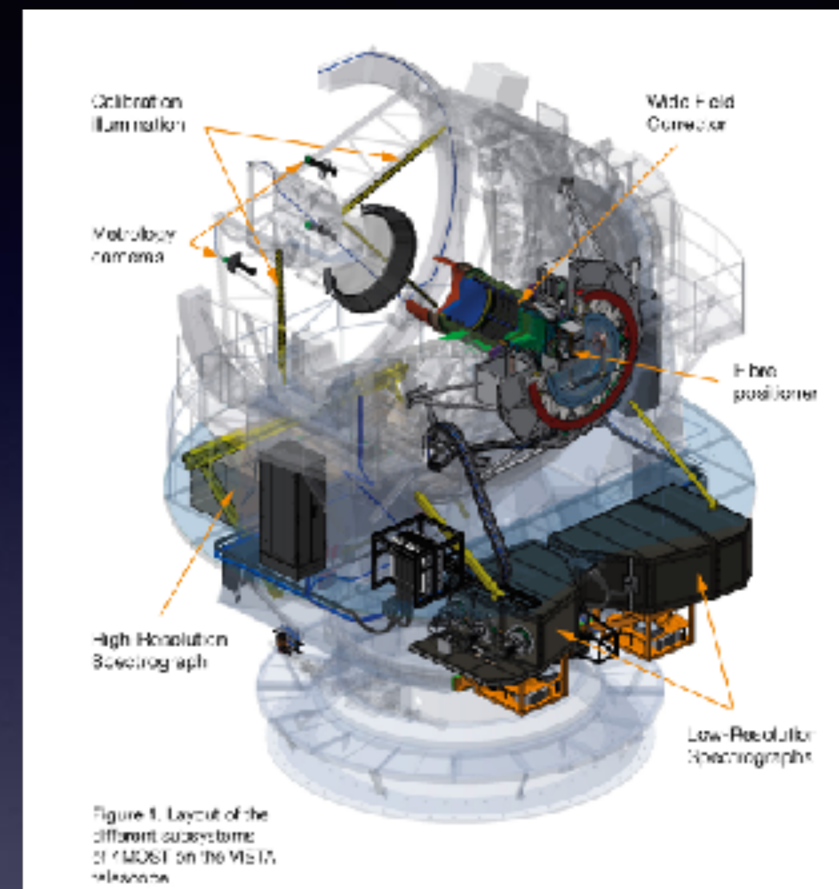
Assuming
LVK rate = 300 Gpc^{-3} yr^{-1}



Margutti & LSST TVS 2019; Andreoni et al. 2022

O5 - much more than Rubin





- 4MOST + DESI Galaxy surveys - 20 - 50 million redshifts
- EUCLID : high resolution host galaxies
- ULTRASAT - widefield UV surveyor (Israel-DESY-NASA; 2025)
- ESO NTT + SOXS : dedicated spectrometer
- James Webb Space Telescope - near to mid infrared

Conclusions

1. Kilonovae discoveries enabled with GW signals = 1
2. Kilonovae discovered with wide-field surveys = 0
3. Kilonovae discovered with nearby GRBs = 2

- Discoveries likely limited by the natural BNS merger rate, not instrumentation or project effort
- Likely numbers in O4 (now to end of 2024): $N_{\rm BNS} = 3 \pm 2$
- Prospects of data equivalent to AT2017gfo : reasonable to good
- Likely not all the LIGO-Virgo-Kagra BNS will have kilonovae detected

- O5 (GW detectors reach optimal sensitivity) and the Rubin Observatory is the only chance of large numbers (few x 10 per yr) but not until 2027+