Prospects for multi-messenger astronomy in O4 and O5

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Queen's University Belfast

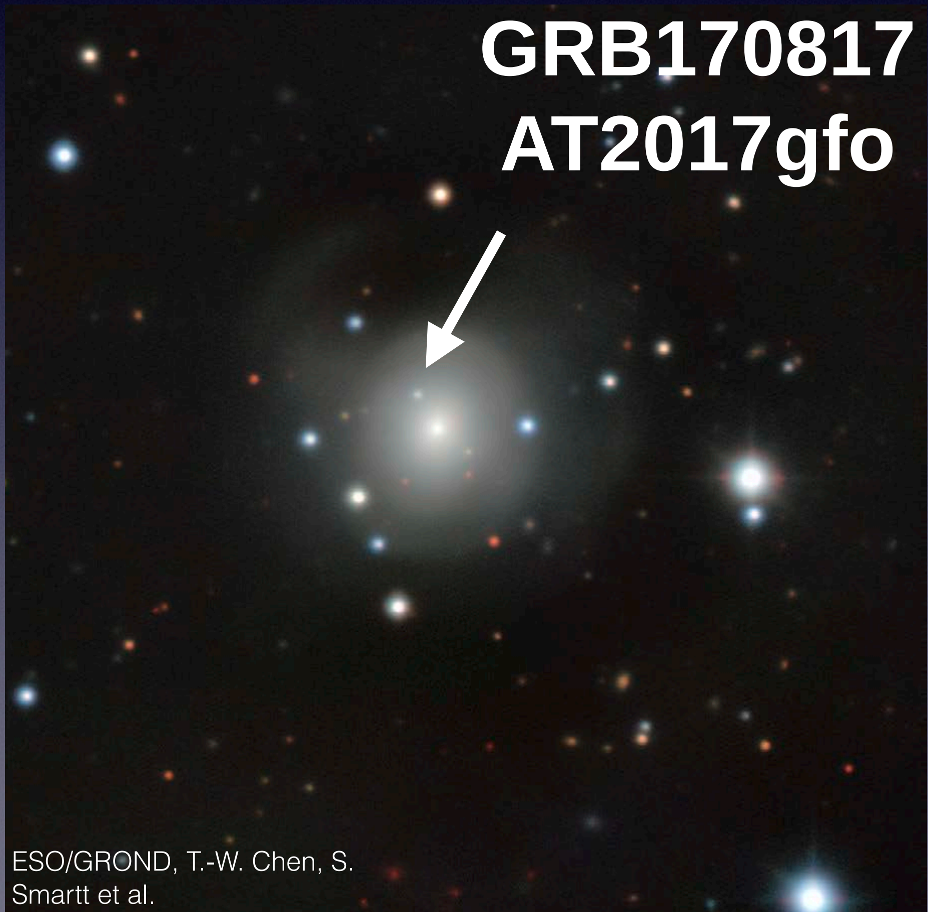
Overview

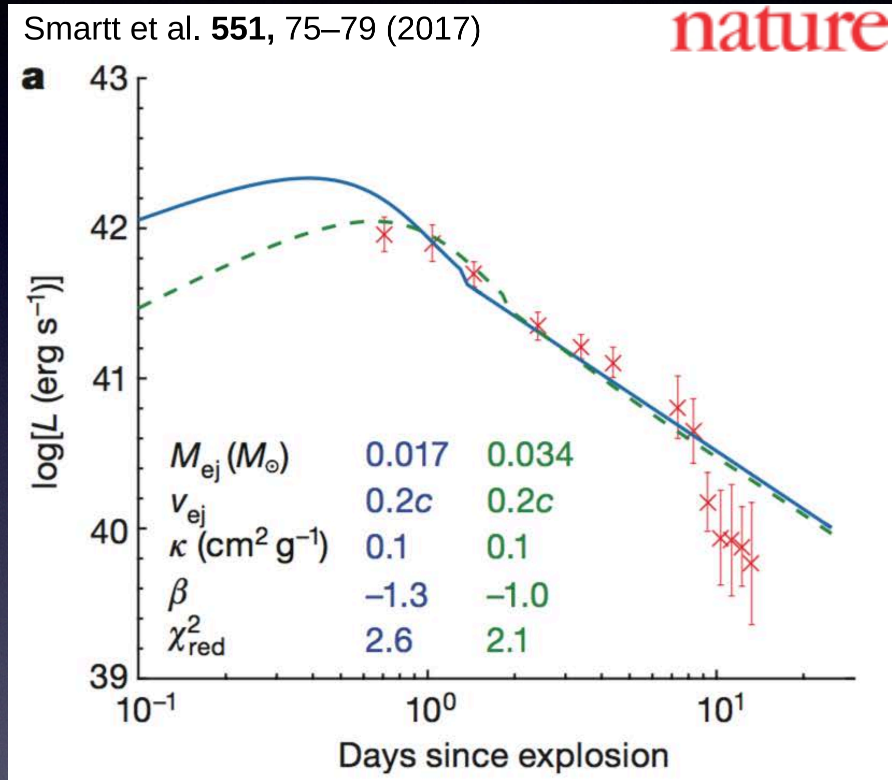
- The potential of multi-messenger astronomy has yet to be fully realised - one electromagnetic counterpart of a gravitational wave source
- What has happened since 2017 (O2 and O3 lessons learned)
- What we can expect in 2023 : multi-messenger astronomy focus
- Outlook for multi-messenger astronomy in the era of O5 (GW detectors reach optimal sensitivity) and the Rubin Observatory in 2025

O2 and O3 multi-messenger results and lessons learned

GW170817

GW170817
GRB170817
AT2017gfo

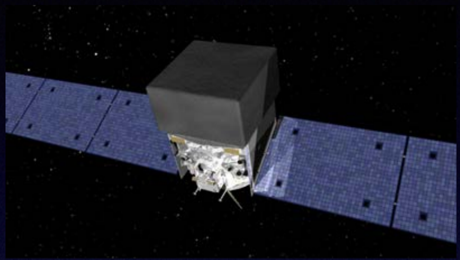




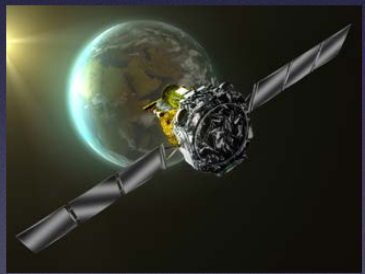
- UV, optical and NIR fading emission
- Radioactively heated, thermal emission
- About 1000 times brighter than a nova
- Kilonova (or macronova)

GW170817 and coincident short, weak GRB

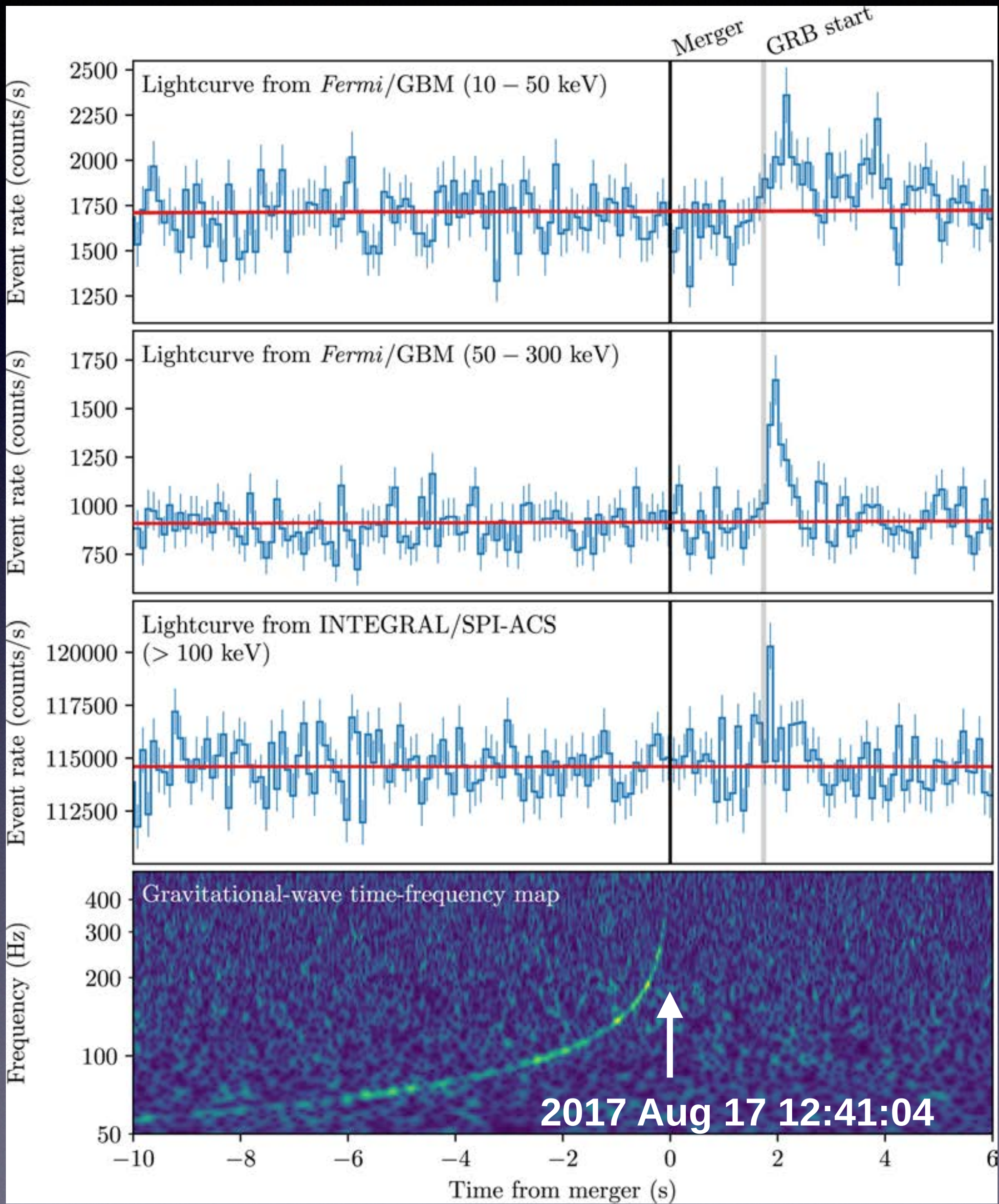
NASA's Fermi satellite



ESA's Integral satellite

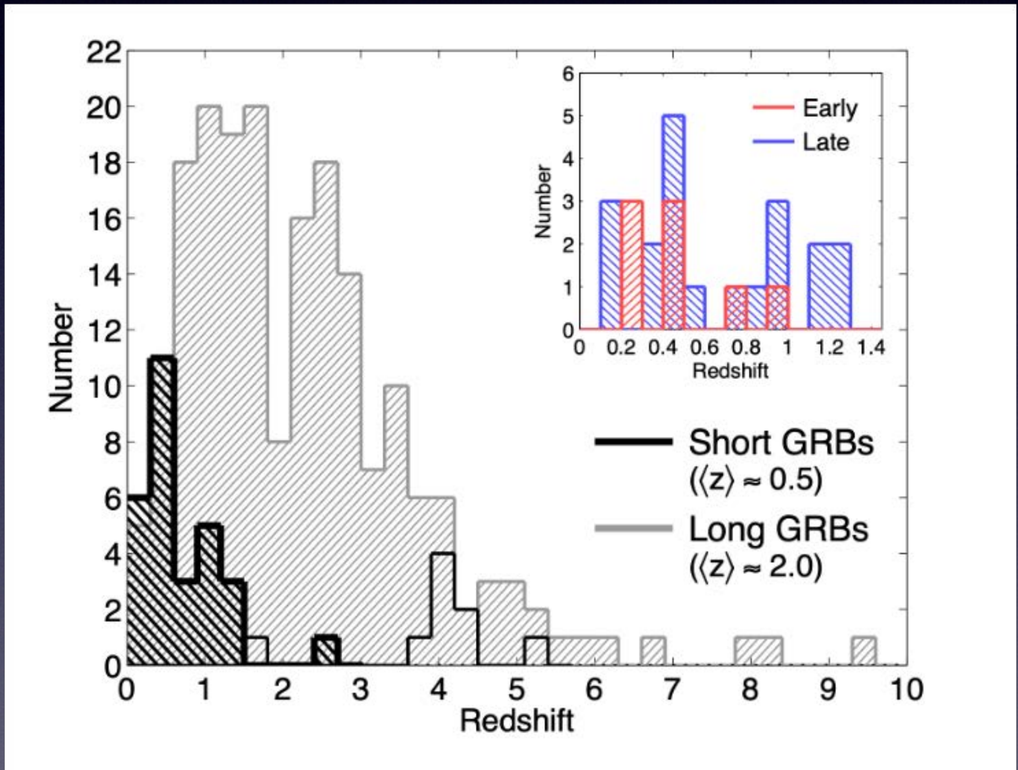


LIGO-Virgo



LIGO and Virgo, Fermi GBM, INTEGRAL collaborations 2017, ApJ, 848, 2

Gamma ray bursts



Berger 2014

Annual Rev. Astron. Atrophys.

- Nearly all short GRBs have been found at z > 0.1
- D > 400 Mpc
- GRB + GW expected to be low (1 in ~ 10, at most)
- Unlikely high energy will help in localisation in most cases
- Optical and near-infrared most likely wavelength regime
- UV (satellite) and radio (wide-field requirement) also possible

Post-covid timeline and the Rubin Observatory

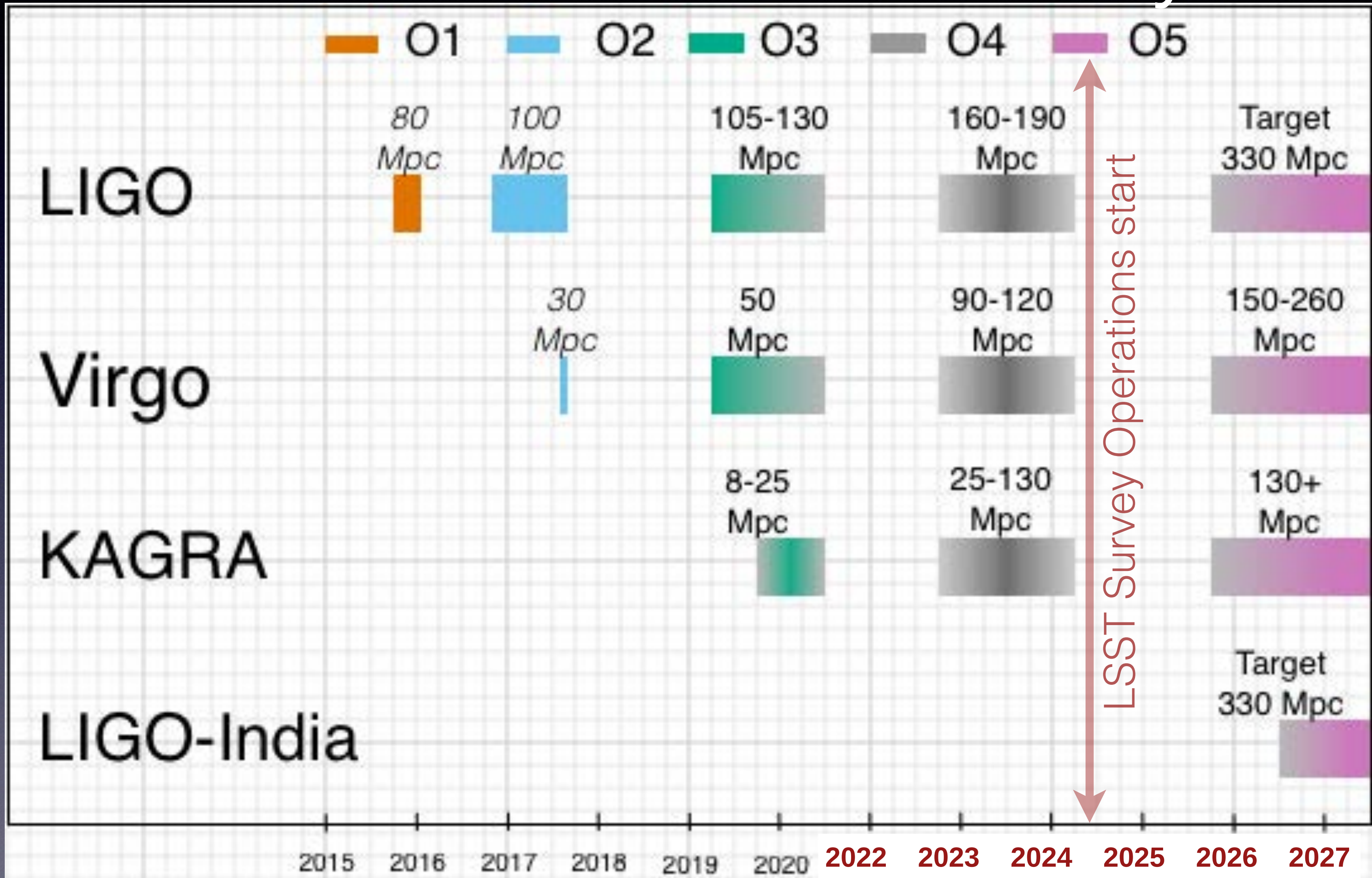
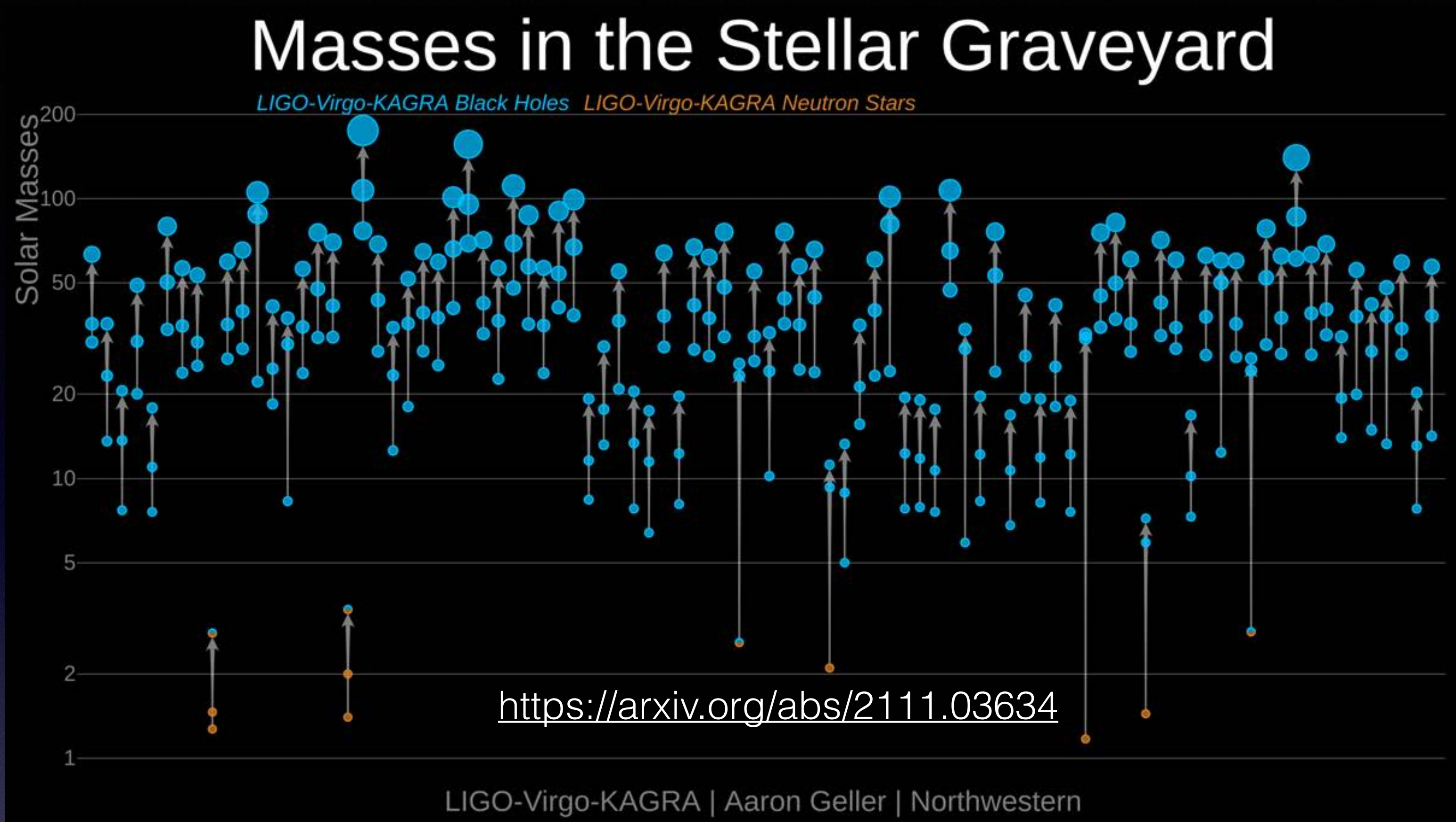


Image Credit : LIGO-Virgo-Kagra collaboration

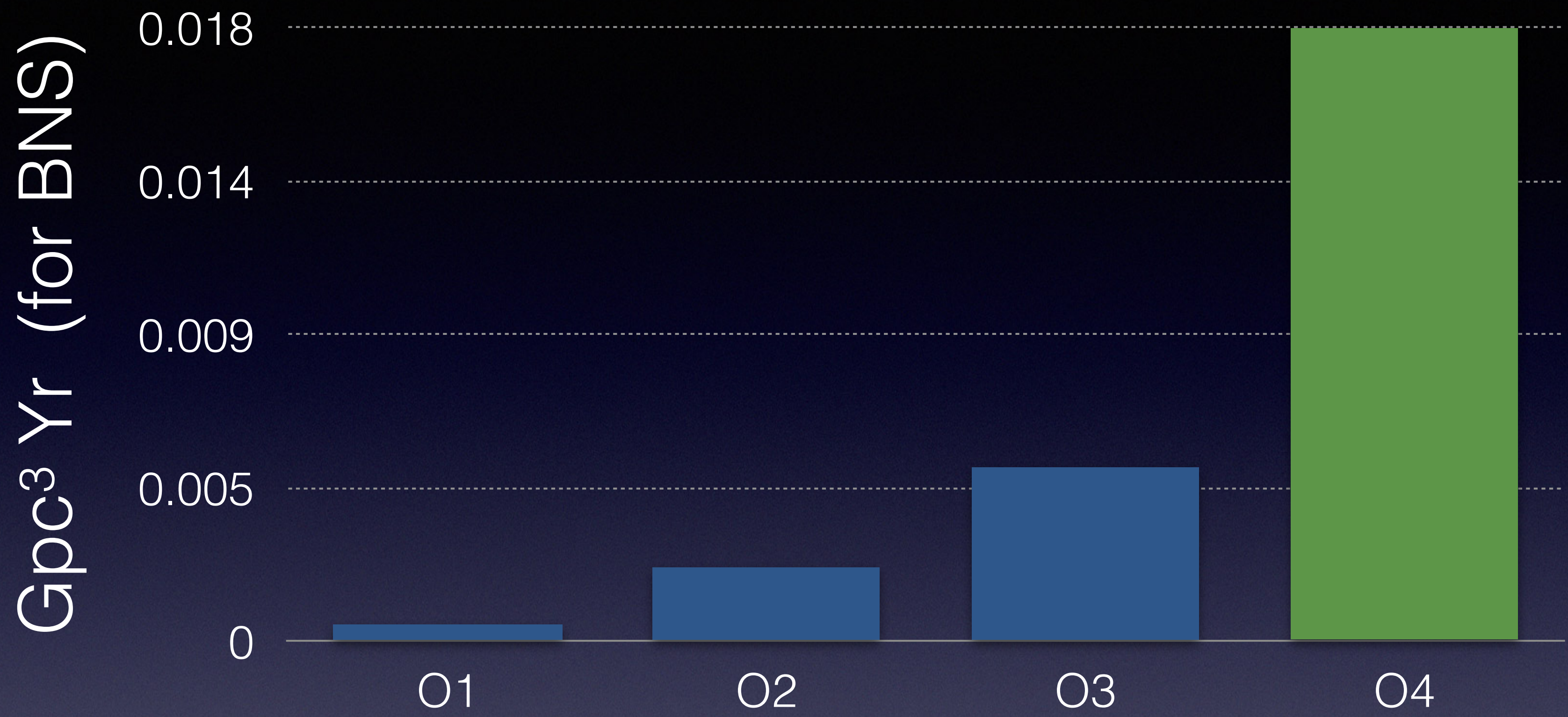


The LIGO Scientific Collaboration, the Virgo Collaboration the KAGRA Scientific Collaboration

$$N_{BNS} = R_{BNS}\frac{4\pi}{3}D_{\mathrm{BNS}}^{3}T_{\mathrm{up}}$$

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

Projected rates in O4



Note : Frostig et al 2022 predict ~10

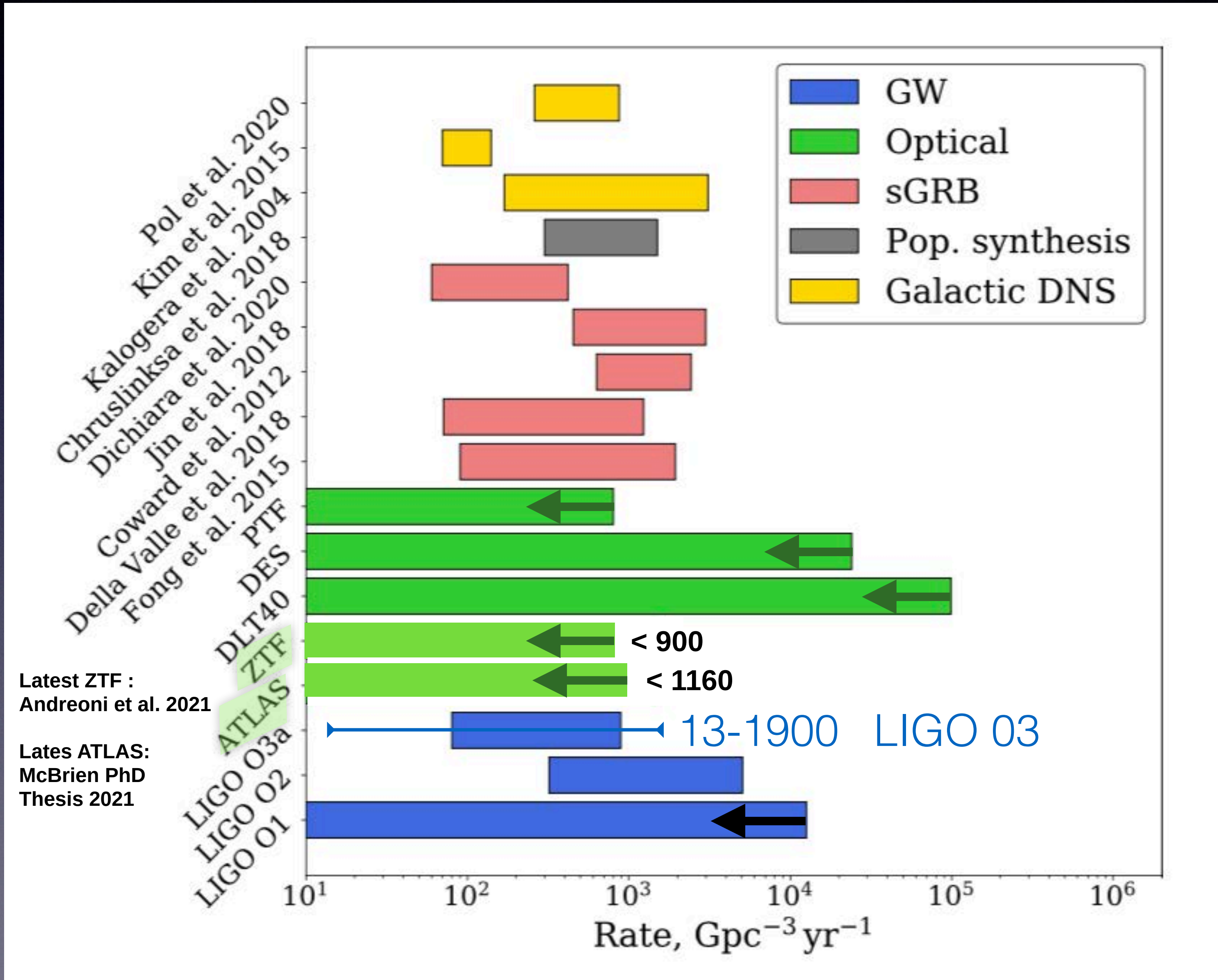
$$\text{Total BNS detections O1 + O2 + O3} \quad = 2$$

$$\text{Ratio of Gpc}^3 \text{ Yrs } \left(\frac{\text{O4}}{\text{O1 + O2 + O3}}\right) \quad = 2.31 \pm 1.09$$

$$\text{O4 projected : } N_{\text{BNS}} \quad = 5 \pm 2$$

$$\text{O4 projected : } N_{\text{EM}} \quad \sim 4 \pm 2$$

Kilonova and BNS merger rates



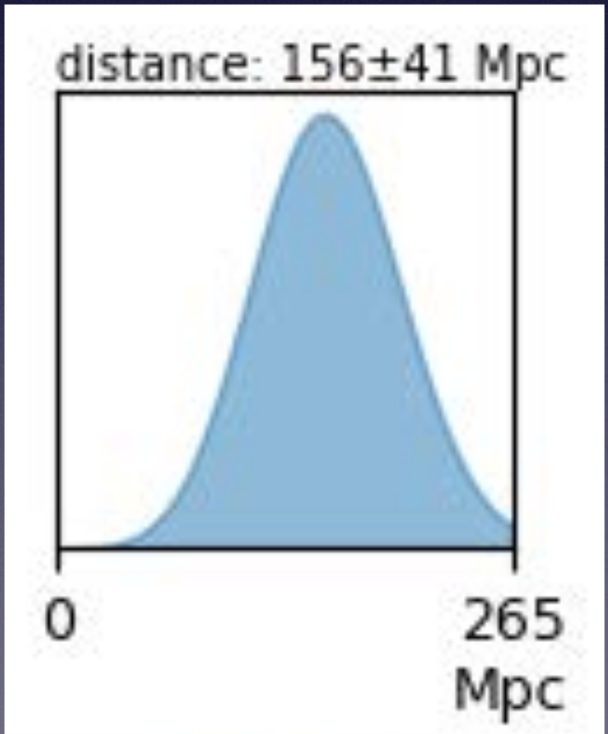
Let's take
LVK rate = 300 $\mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$
Factor ~3 uncertainty

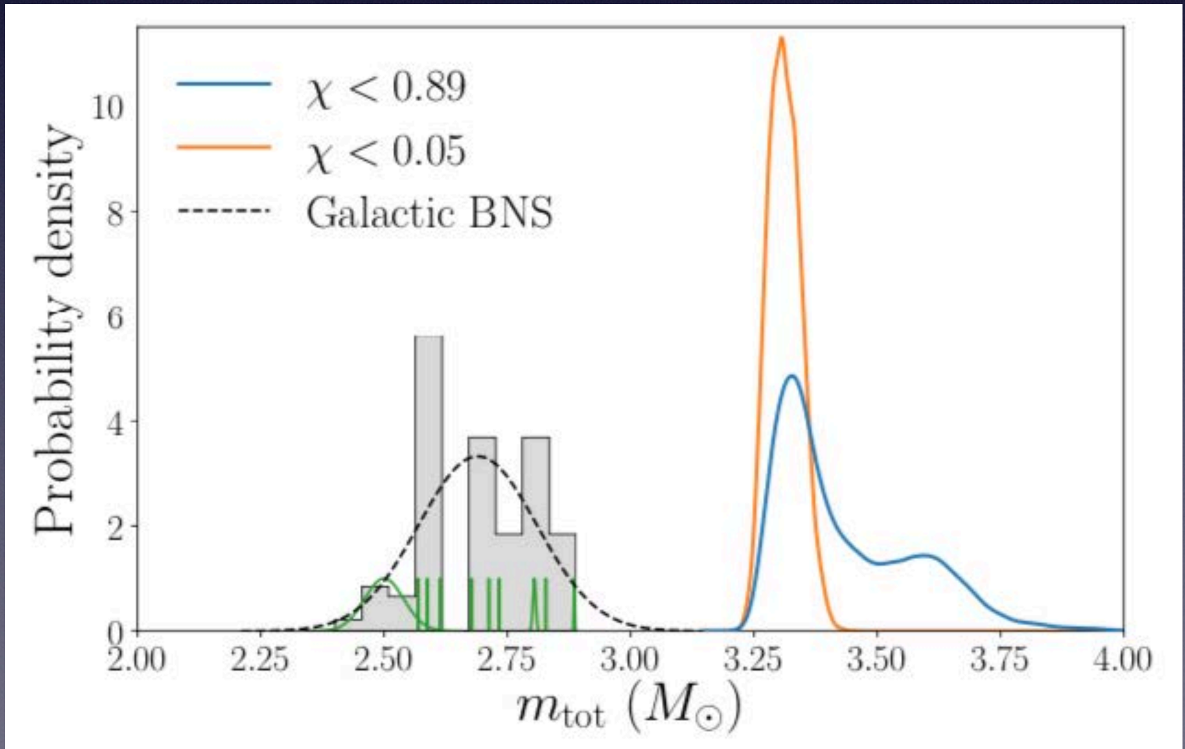
D	BNS per year	Comment
100 Mpc	1	GW170817 is once per decade event
175 Mpc	4 - 7	Most likely for O4 ?
300 Mpc	30	Game changing number : O5 + Rubin Observatory ToO

See Mandel & Broekgaarden 2022, LRR

GW190425: Binary NS merger

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



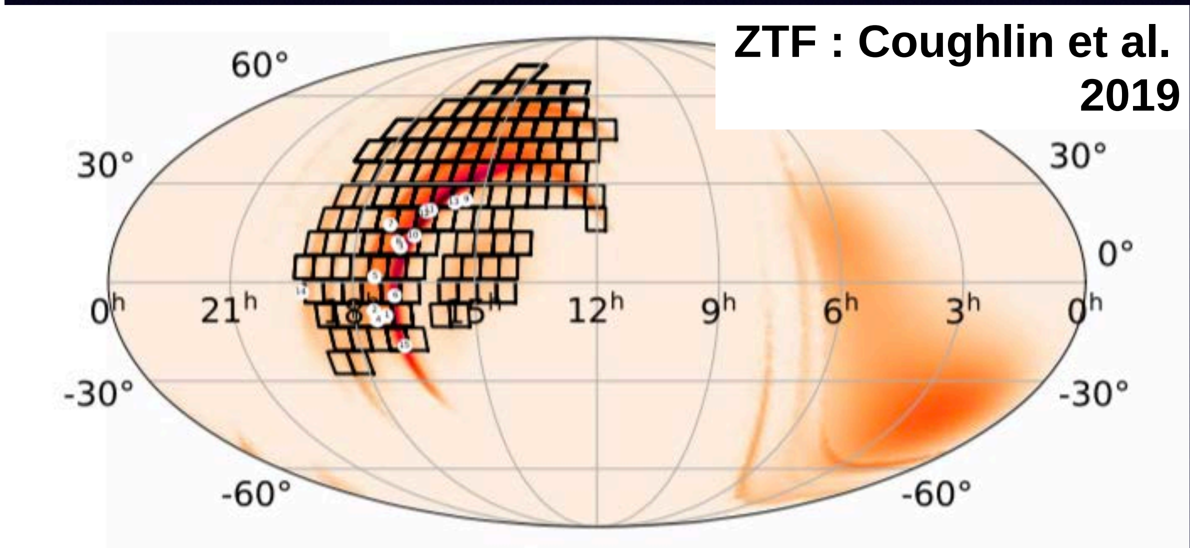


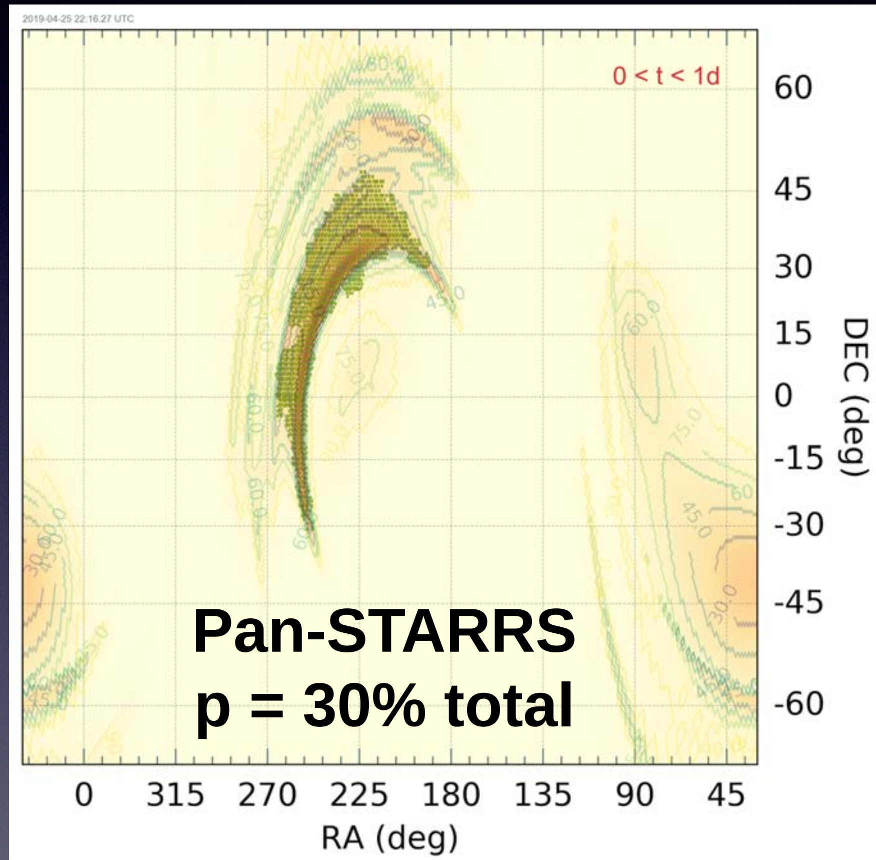
LIGO-Virgo Collaboration :Abbott et al. 2020

No EM counterpart for GW190425

90% area 7461 deg²

21% coverage of the final skymap





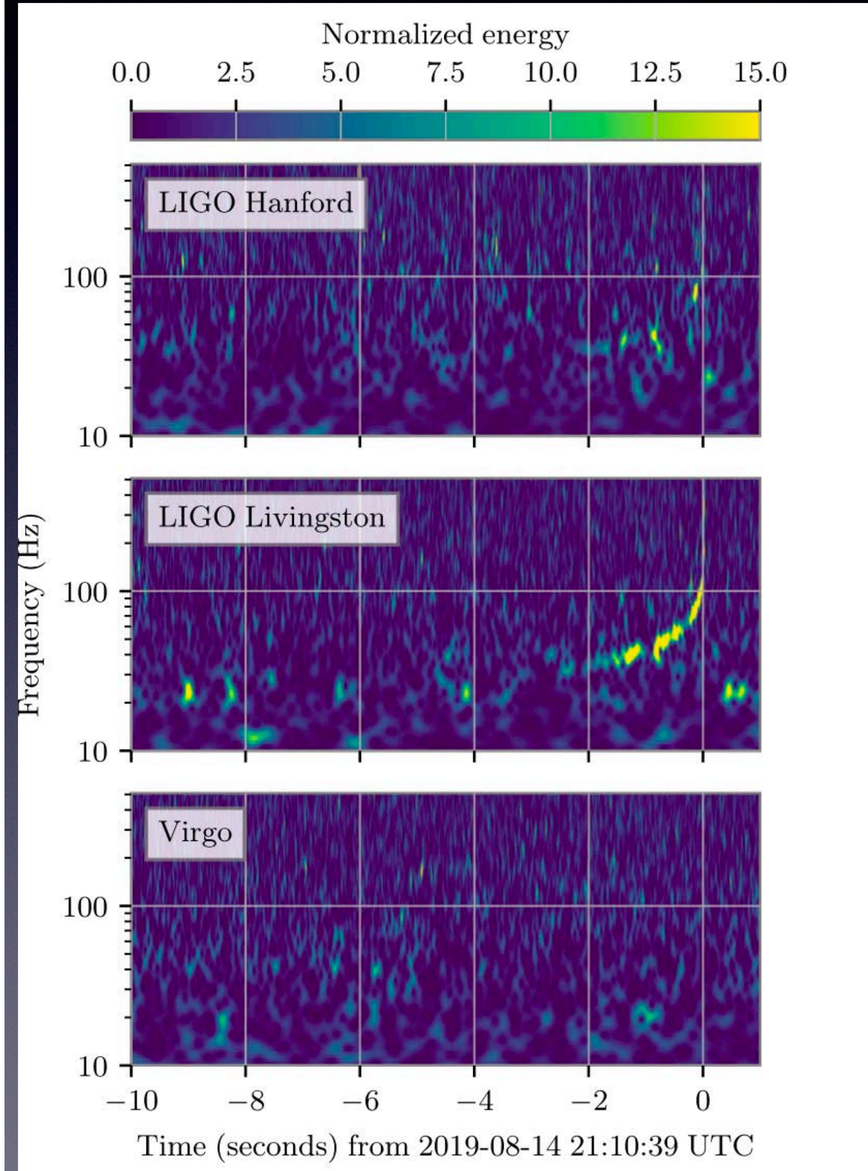
Livingstone - detection
Hanford - offline
Virgo - observing but non-detection

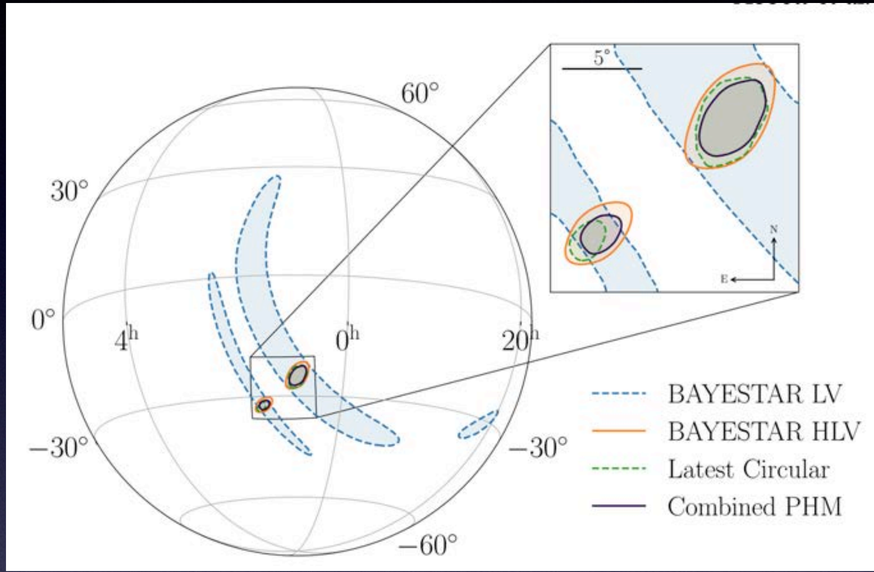
ZTF, Pan-STARRS, ATLAS covered ~30% of sky map. No detection

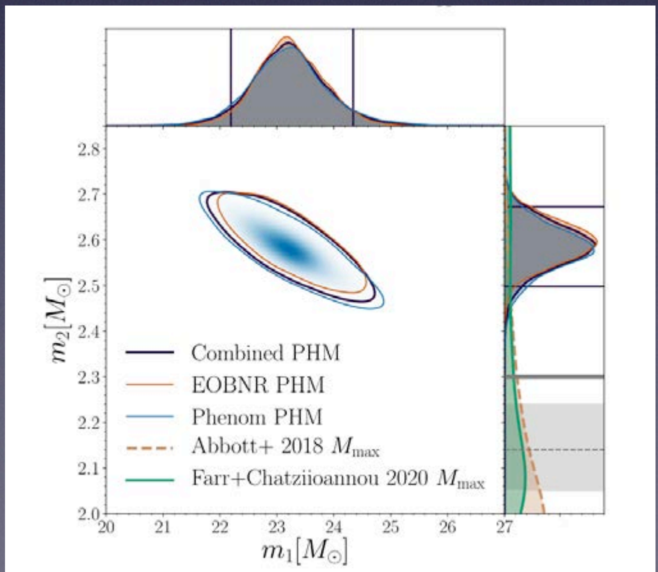
GW190814 : BH + NS ?

90% area 19 deg^2

200 < D < 280 Mpc







$M_1 = 23 \pm 1 M_\odot$

Black hole

$M_2 = 2.50 - 2.67 M_\odot$

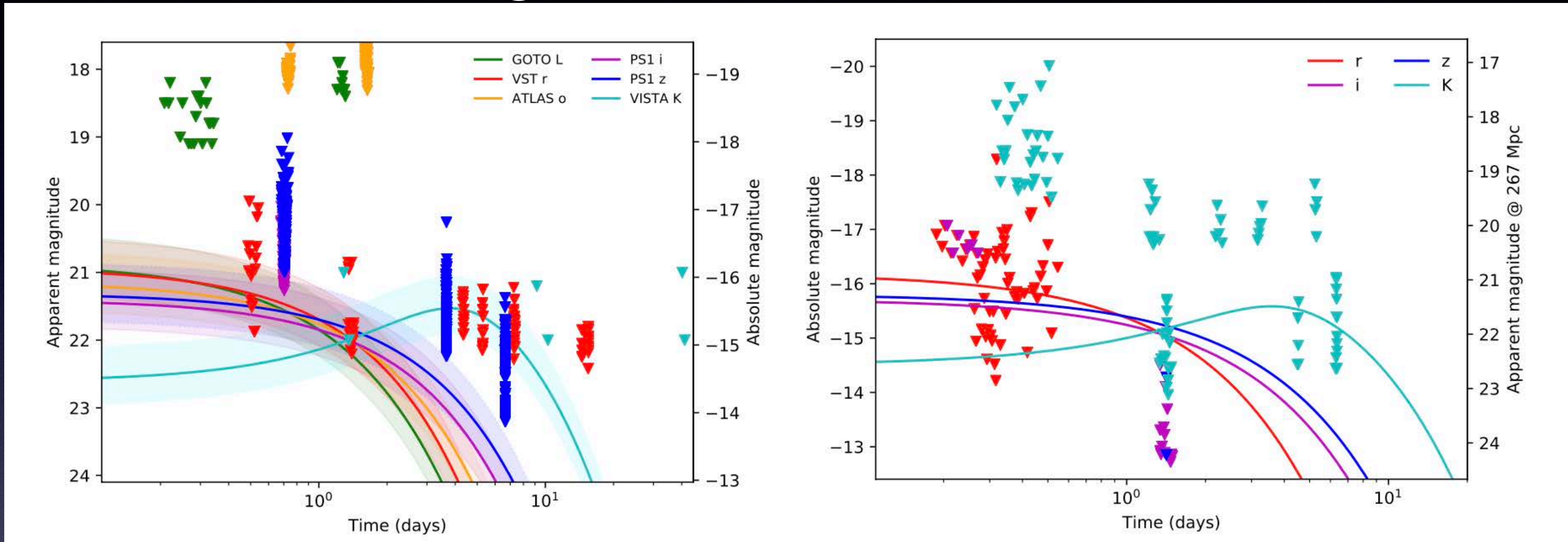
Neutron star or black hole ?

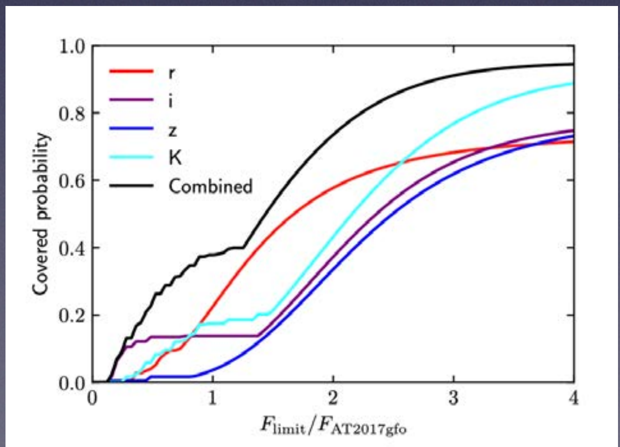
Abbott et al. 2020 ApJL, 896, 44

ENGRAVE search for a counterpart to GW190814

90% area 19 deg^2

ENGRAVE Collaboration, Ackley et al. 2020





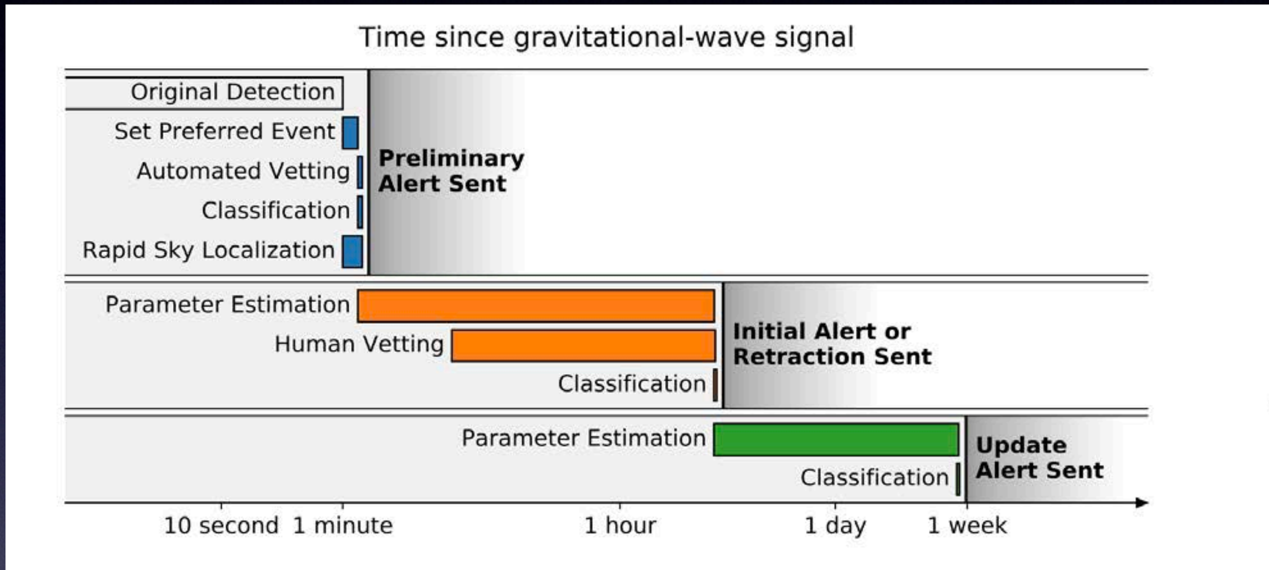
75 optical transients. Mostly ruled out due to :

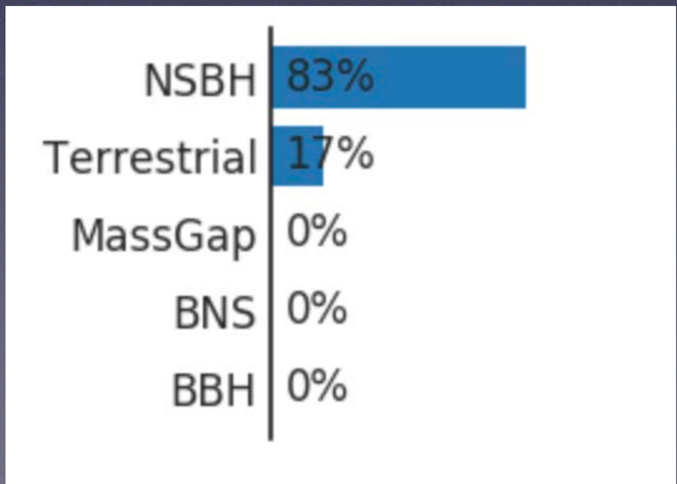
- pre-merger detections,
- spectrum of transient
- inconsistent host z,
- lightcurve which is SN like,
- likely nuclear or AGN activity,
- moving object

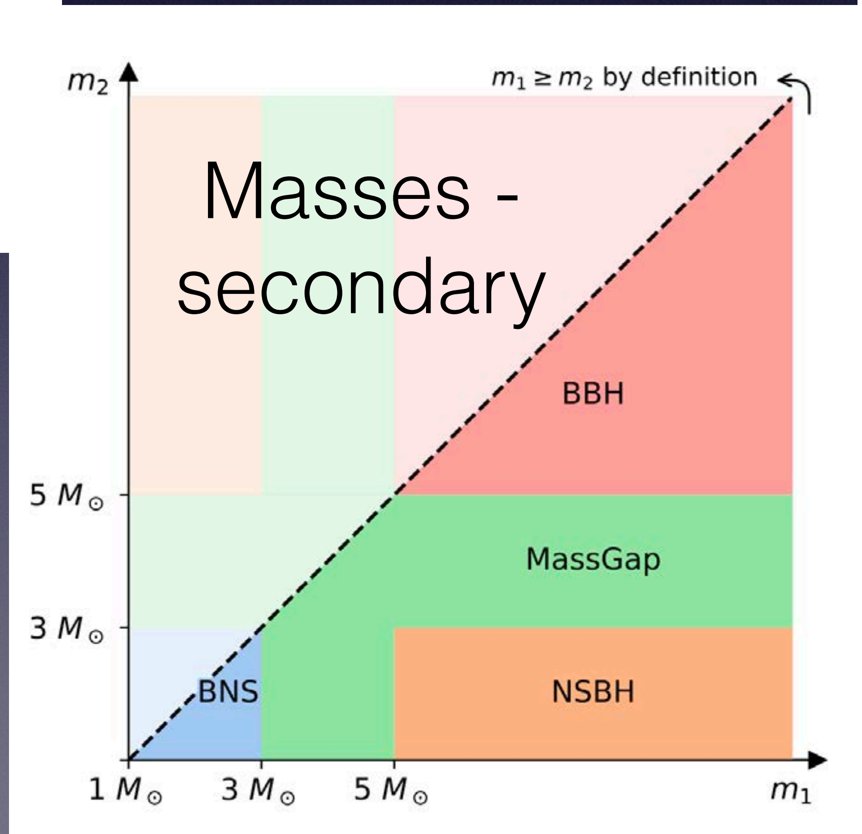
~ 10 faint sources lack enough information to rule out.

Other 4+8m sensitive limits : Gomez et al. 2019, Andreoni et al. 2020, Viera et al. 2020
ASKAP radio search : Dobie et al. (2019)

O3 lesson : Ensure changes to maps, p_astro sent promptly

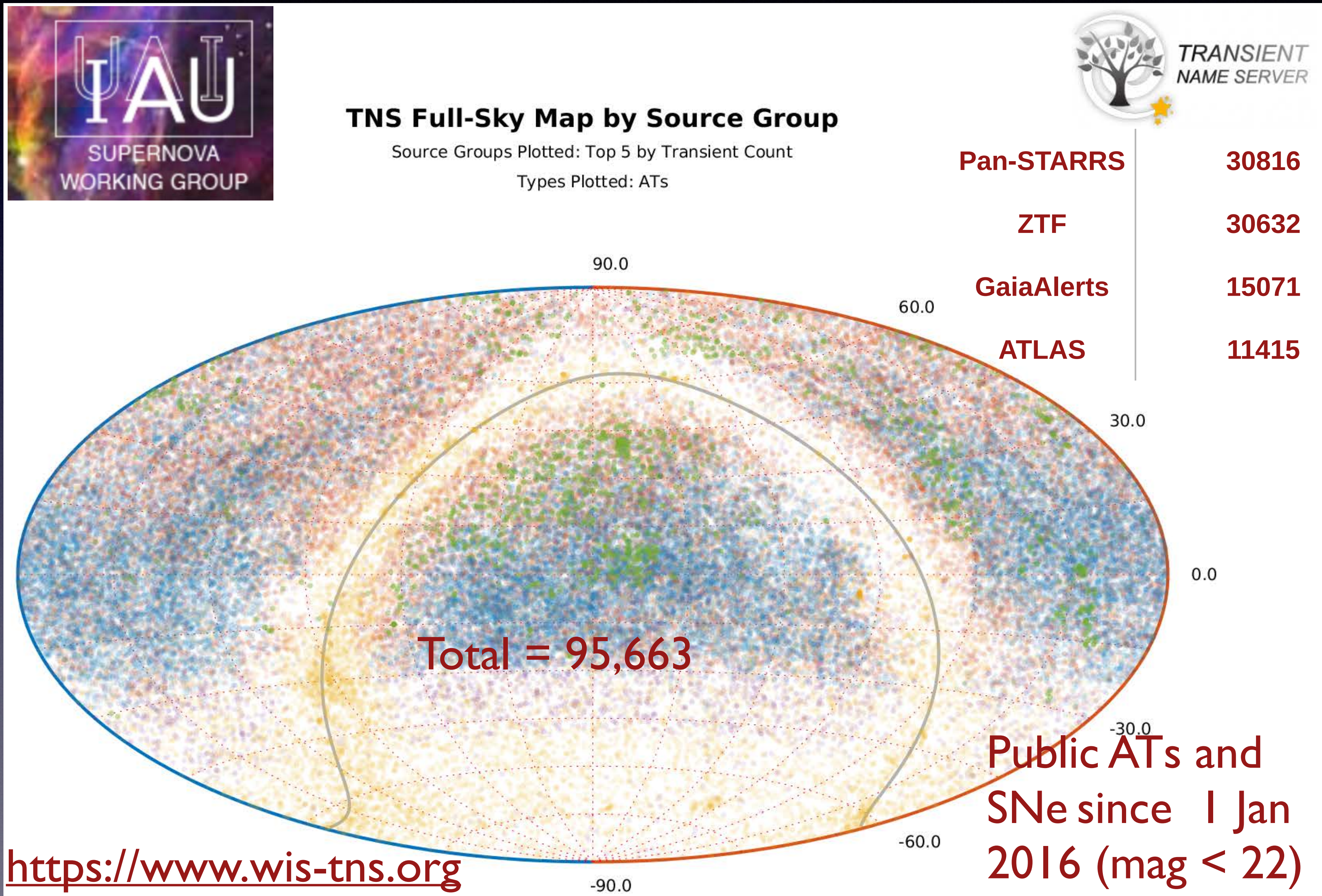






Current EM searches and and outlook for O4

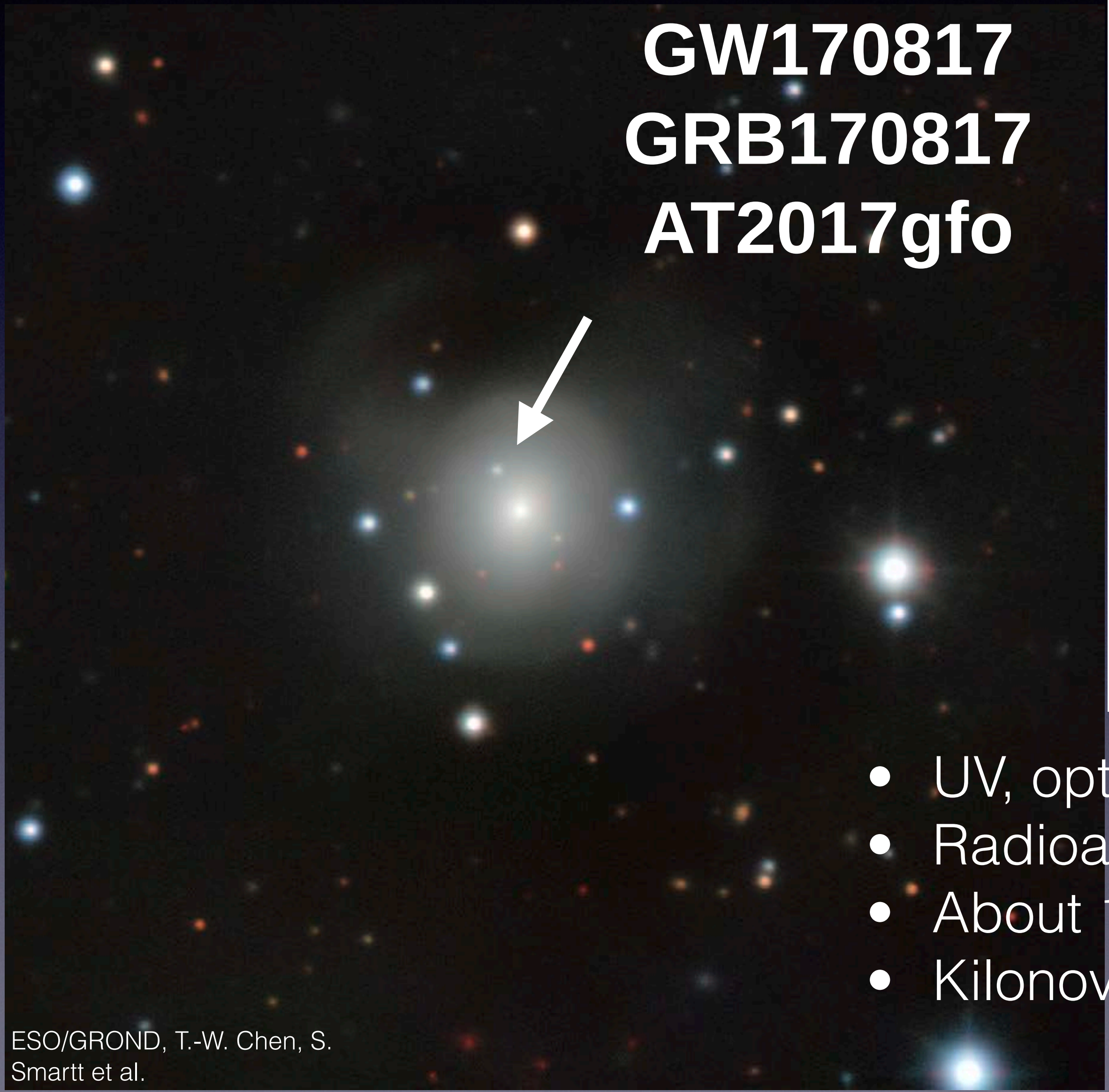
Optical kilonova searches with no GW

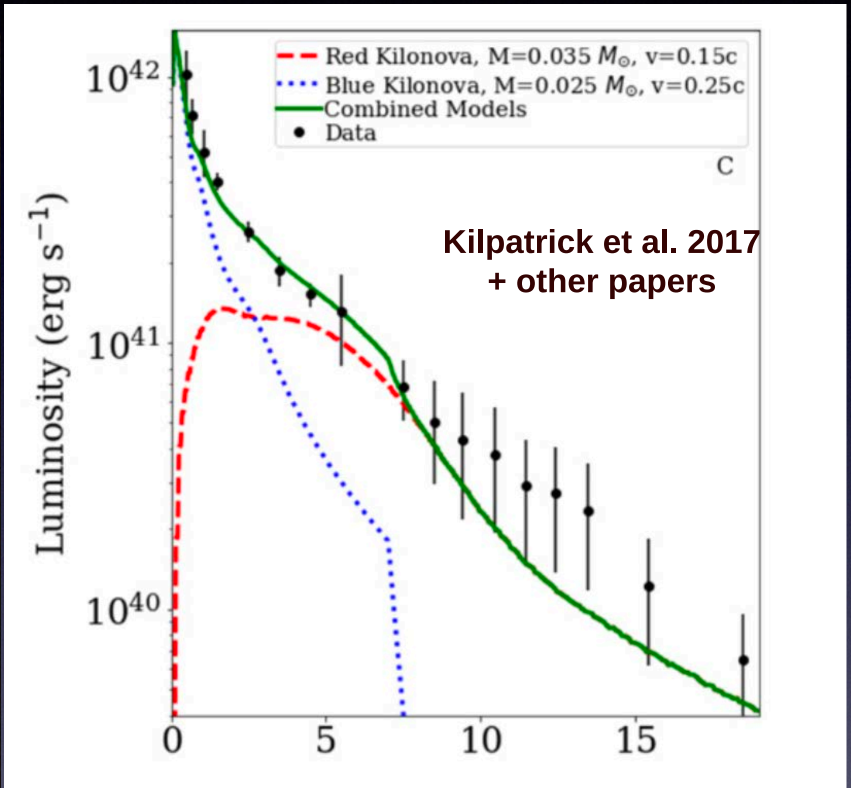


Indicative Distance ranges

Aperture	limiting mag	D 2017gfo	Examples
0.5m	19.5	100 Mpc	ATLAS, GOTO, MASTER
1m	20.5	150 Mpc	ZTF, Blackgem
2m	21.5	250 Mpc	PanSTARRS
4m	22.5	350 Mpc	DECam, CFHT
Rubin (6.5m)	23.5	600 Mpc	Rubin

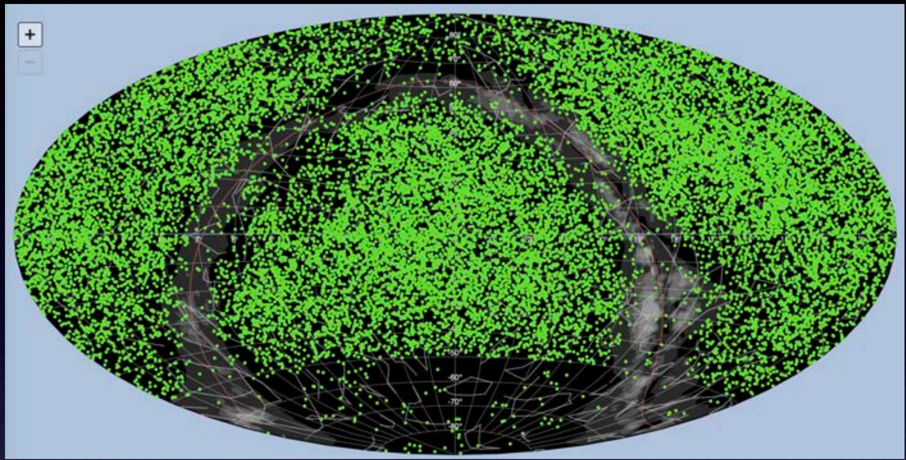
GW170817 : GRB and kilonova

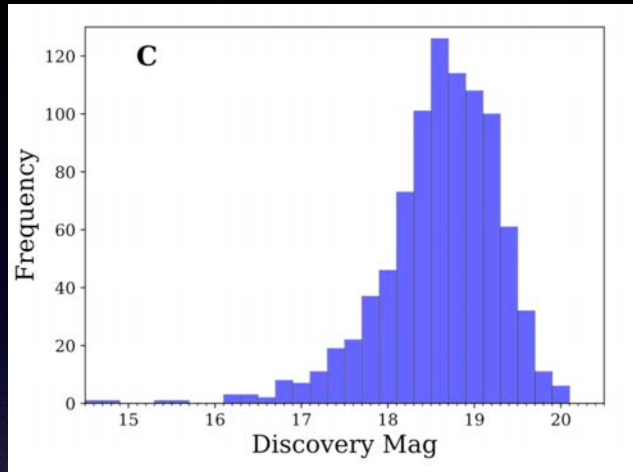




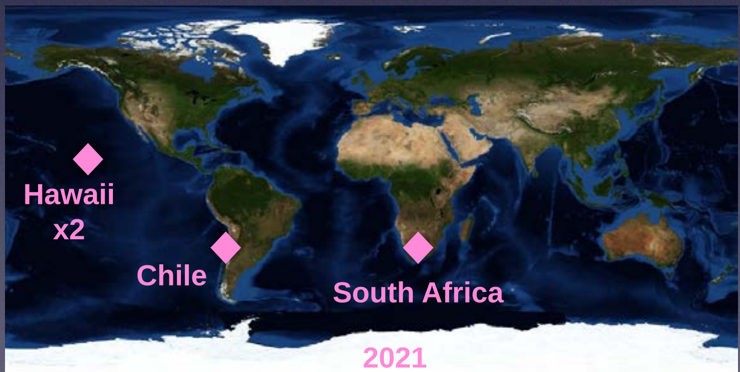
- UV, optical and NIR fading emission
- Radioactively heated, thermal emission
- About 1000 times brighter than a nova
- Kilonova (or macronova)

ATLAS - all sky every night





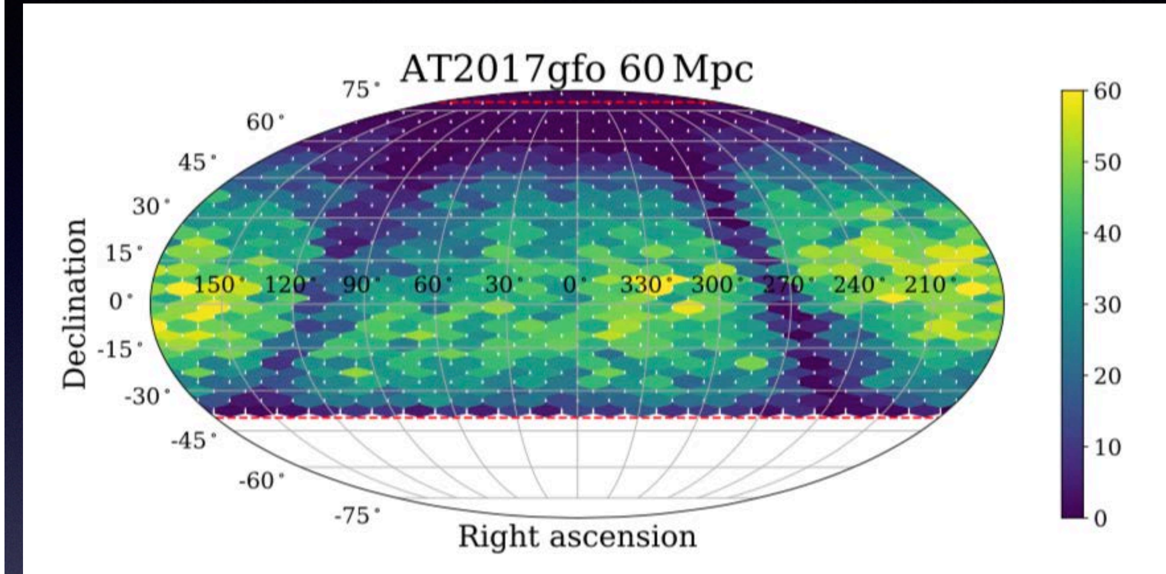
Tonry et al. 2018, Smith et al. 2020



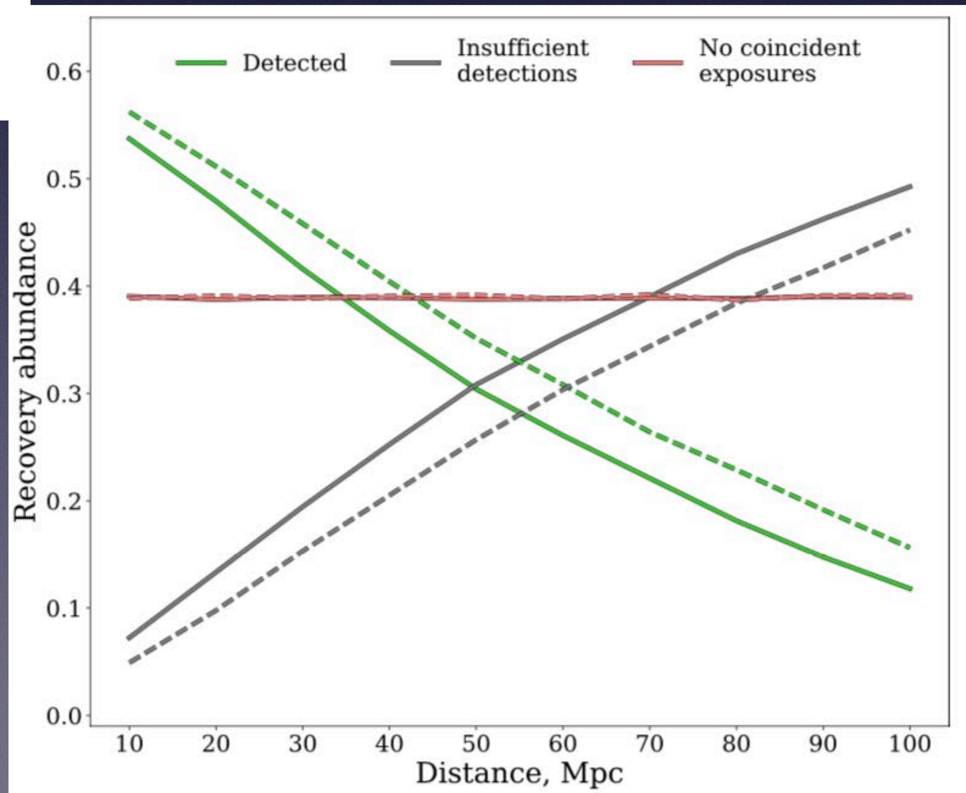
- 4 x 0.5m telescopes, 29 sq deg FOV each
- m < 19.5 (5 sigma)
- 4 x 30s : all-sky every night
- Chile + South Africa commissioned Feb 2022
- D_{KN} ~ 100 Mpc

Public data access, forced photometry at any point on sky - all data
https://fallingstar.com/

ATLAS recovery efficiency

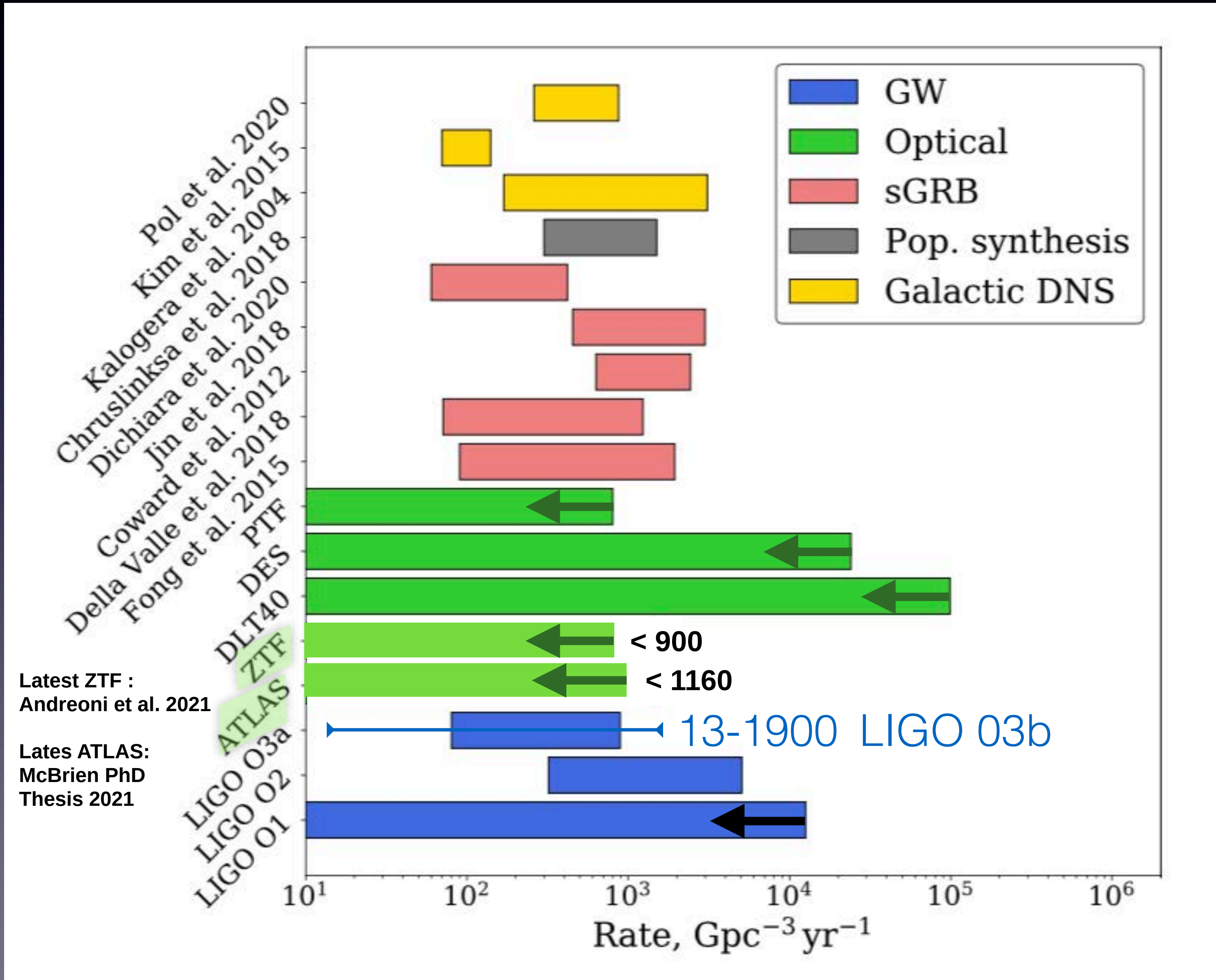


Recovery map at
a distance of 60Mpc



Reason for simulated
object not being recovered.
Our "Transient Server" software
requires 3 x 5σ detections

Kilonova and BNS merger rates



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See Mandel & Broekgaarden 2022, LRR

New developments for O4

Southern hemisphere :

- ATLAS all-sky capability - all sky, every night
- BlackGem likely to be available and working
- VISTA not formally offered but DDTs likely - wide-field infrared capability

Northern hemisphere :

- Pan-STARRS2 : now 2 x 1.8m, fully commissioned
- WINTER : 1m infra-red telescope with 1 sq deg (Frosting et al. 2022)
- GOTO : 0.4m telescopes with 100 sq degree combined (Steeghs et al. 2020)

BlackGem
Lead institute : Radboud Univ, NL

At La Silla, Chile
3 x 0.65m telescopes
Combined field of 8 sq deg
Equivalent sensitivity to ZTF
Dedicated to GW follow-up

https://astro.ru.nl/blackgem/

New developments and outlook for O5

Rubin Observatory and the "Legacy survey of space and time"

Projected (post-Covid) start of science operations: end of mid-2024

Simonyi Telescope in Spain 2019 (now on site)

Image Credit: Rubin Obs.

https://www.youtube.com/watch?v=NOaS8jzkTMI

Charles Simonyi telescope : 8.4m but really 6.5m effective aperture

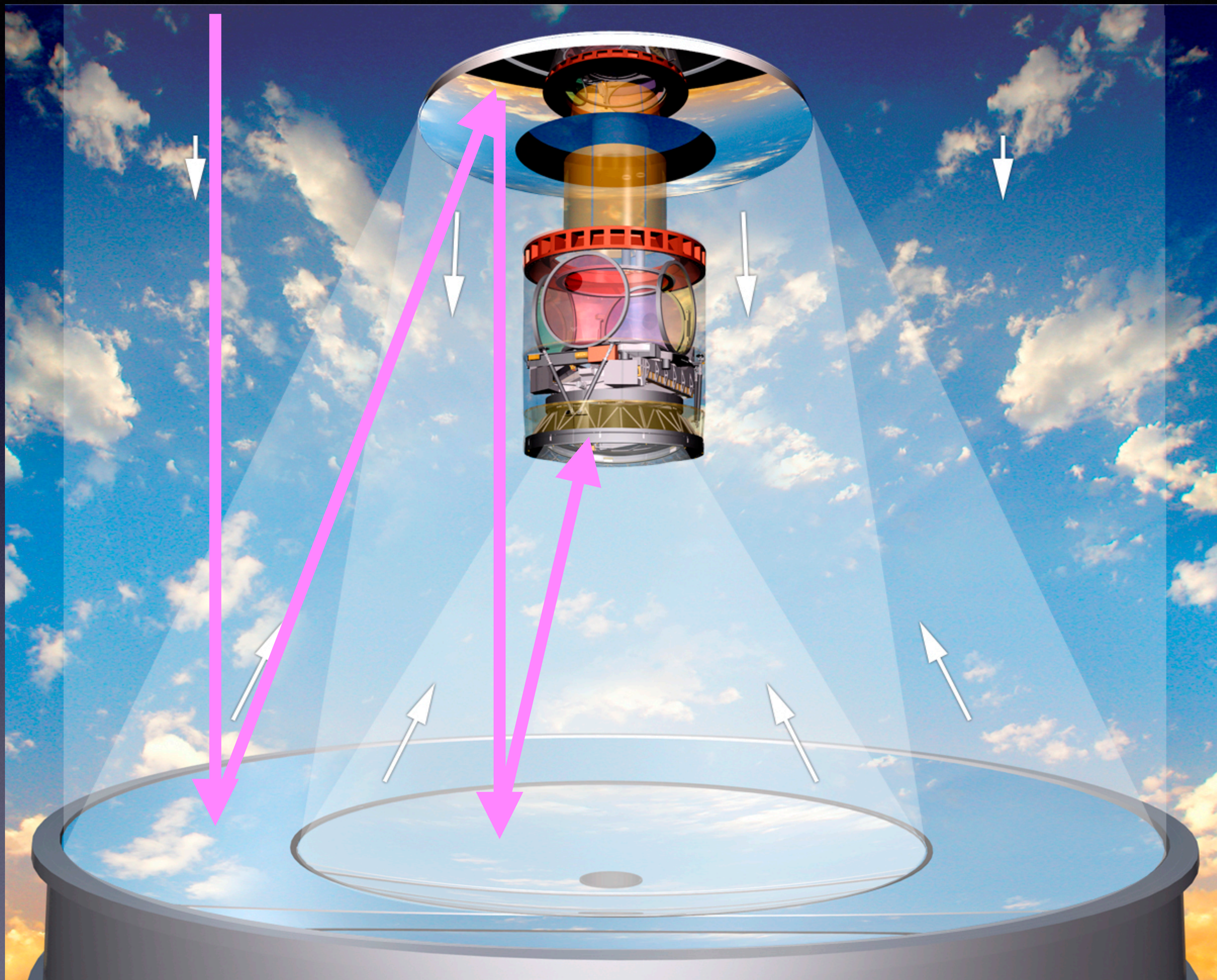


Image Credit: Rubin Obs.

8.4m primary, with 5.0m tertiary inset ⇒ 6.5m effective diameter of primary

Vera Rubin Observatory Camera 3.2 Gigapixels Constructed at SLAC,

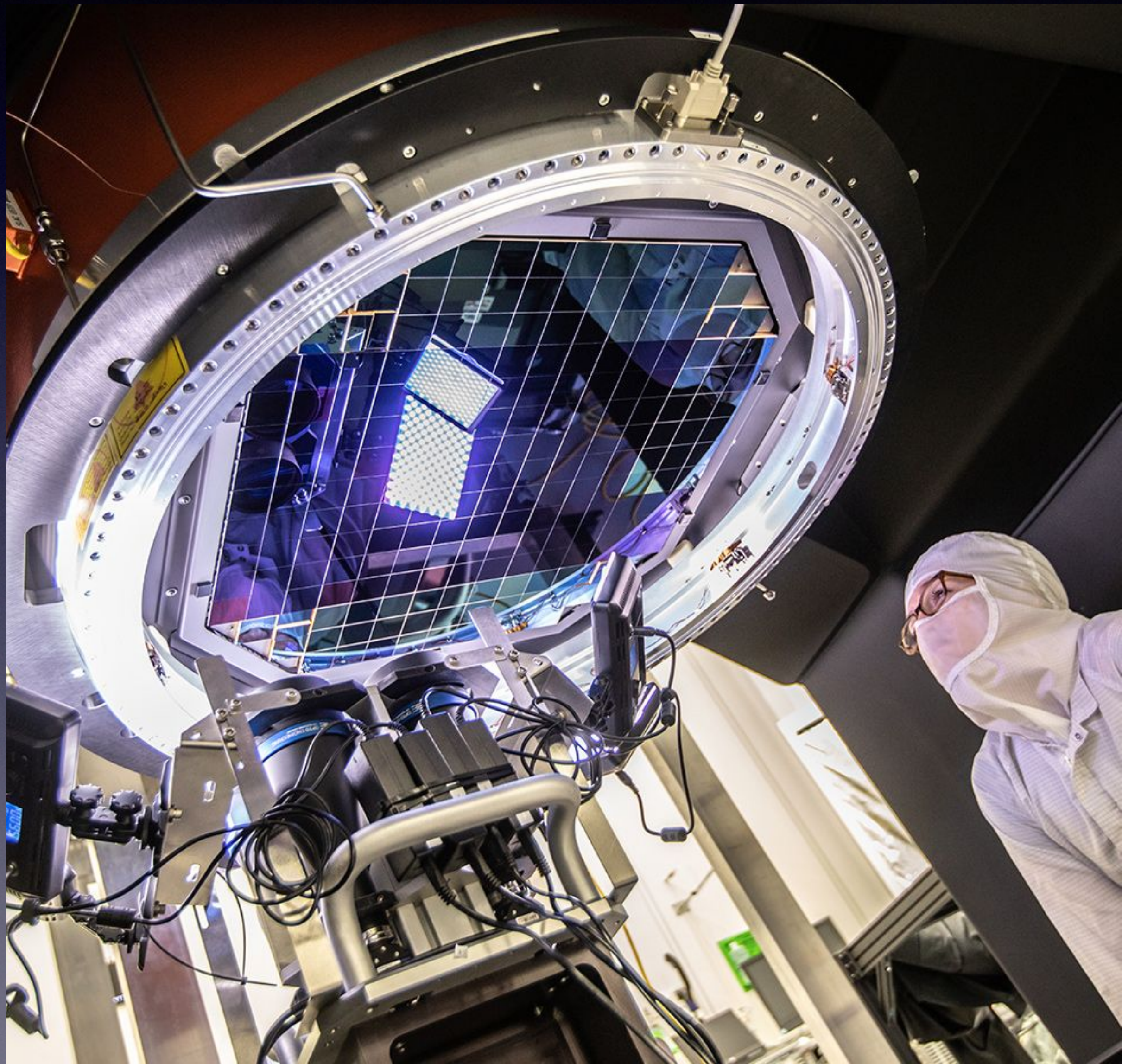
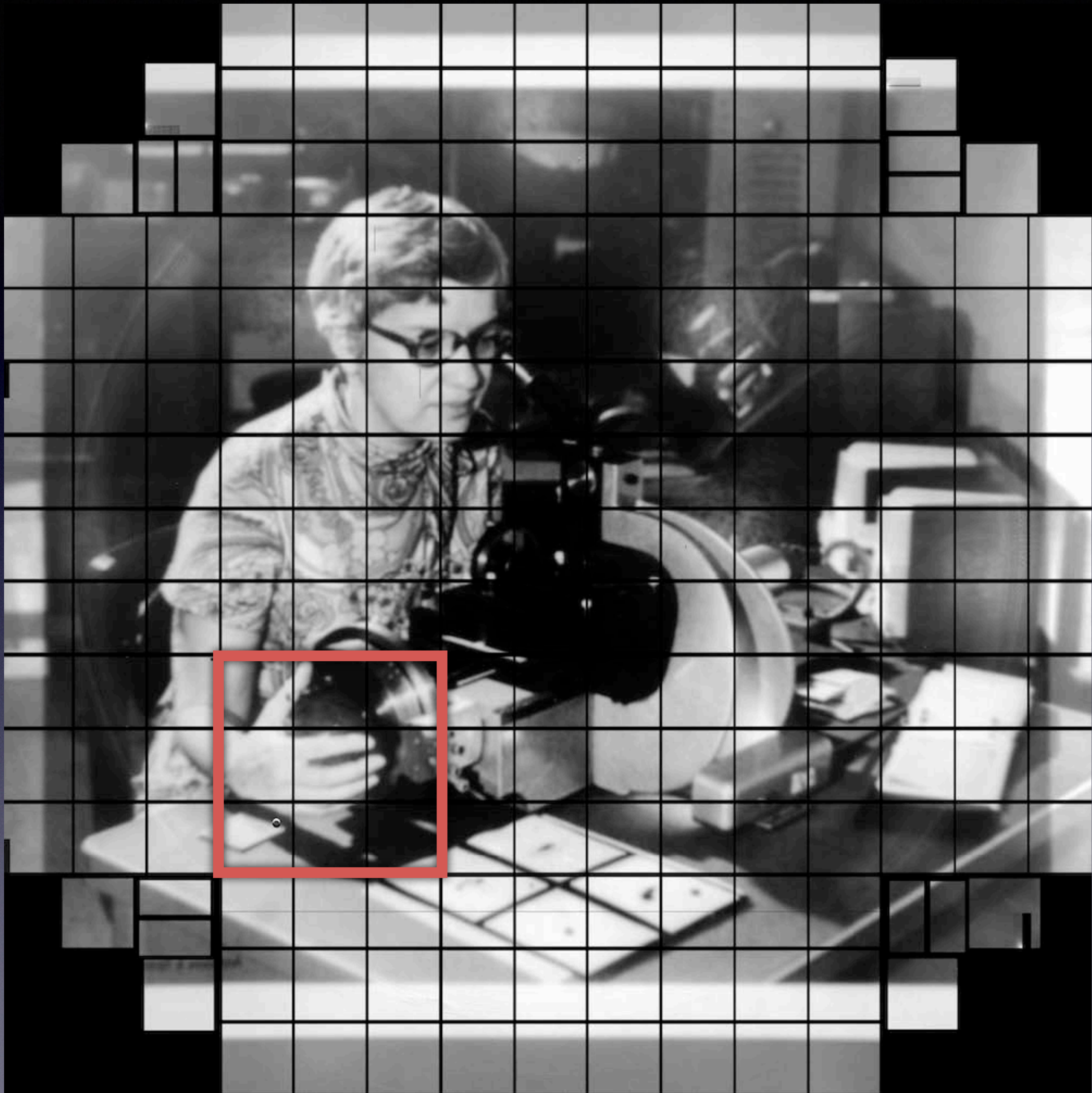


Image Credit:
J. Orrel/SLAC



3.2 Gigapixels
3 x 3 CCD “raft”
21 full rafts
198 CCDs

Ship to Chile
~mid 2022

Image Credit:
Rubin Camera
Team

Multi-colour and deep

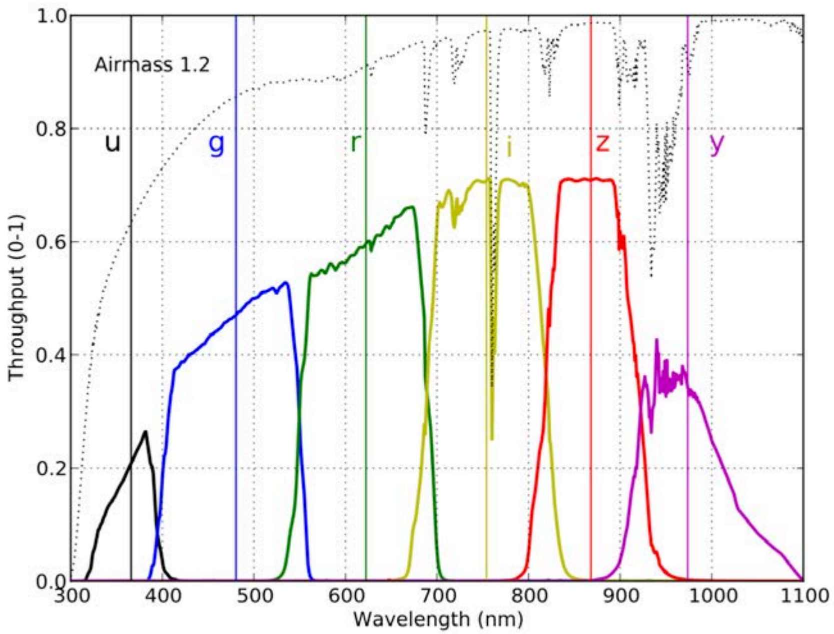


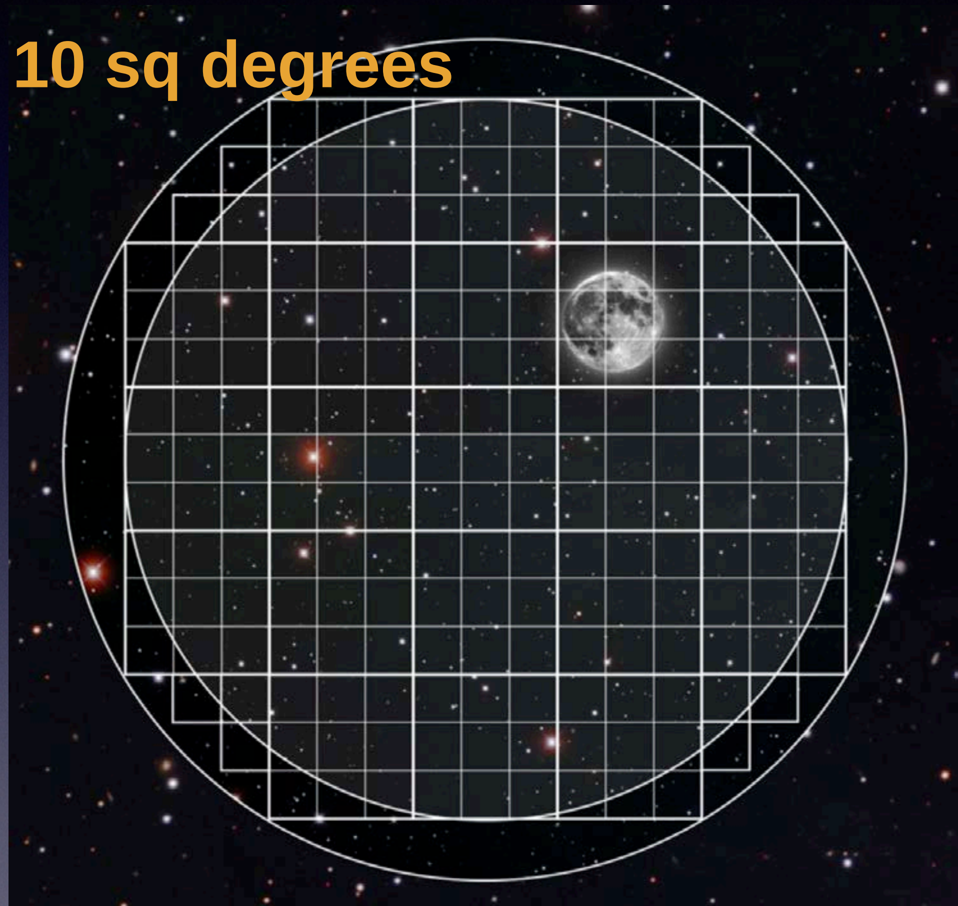
Figure 4. The LSST bandpasses. The vertical axis shows the total throughput. The computation includes the atmospheric transmission (assuming an airmass of 1.2, dotted line), optics, and the detector sensitivity.

	5σ single visit	10 yr depth
u	23.9	26.1
g	25.0	27.4
r	24.7	27.5
i	24.0	26.8
z	23.3	26.1
y	22.1	24.9

Ivezić et al: http://arxiv.org/pdf/0805.2366.pdf

Where to point and when ?

- Rubin Observatory
  - *8m telescope (6.5 m clear aperture) on Cerro Pachon, Chile*
  - *3.5 gigapixel camera, impressive detector quality*
  - *Real time alert stream and multi-colour deep image of the sky*



- Science ***Requirements***
  - *18,000 square degrees observed 825 times over 10 yrs*
  - *Multi-Colour deep image of southern sky*

Cadence problem :
Can do all southern, visible sky once per night : we need 2 visits and we have 6 filters
Average return time (in same filter) would be 2 x 6 = 12 days

Reference image of the sky essential

This is a gri colour image of the 3pi Steradian survey. Image quality is ~ 1 arcsec, with 0.256'' sampling over 30,000 square degrees or about 6 Petapixels (10^{12}) with over 100 epochs.

Examples : Pan-STARRS, DECAM and DECaLS

Covid, delays and the Rubin Observatory

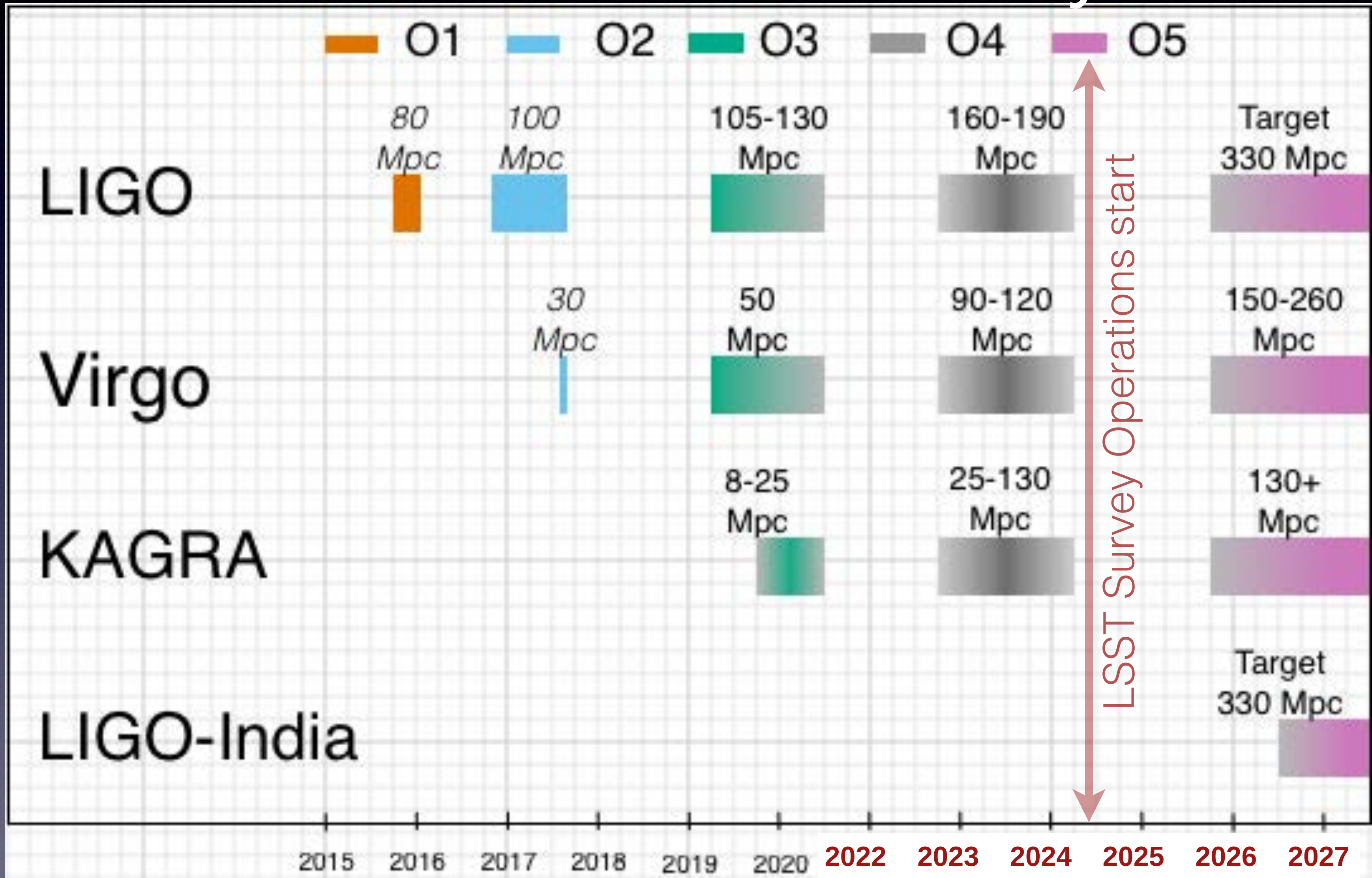
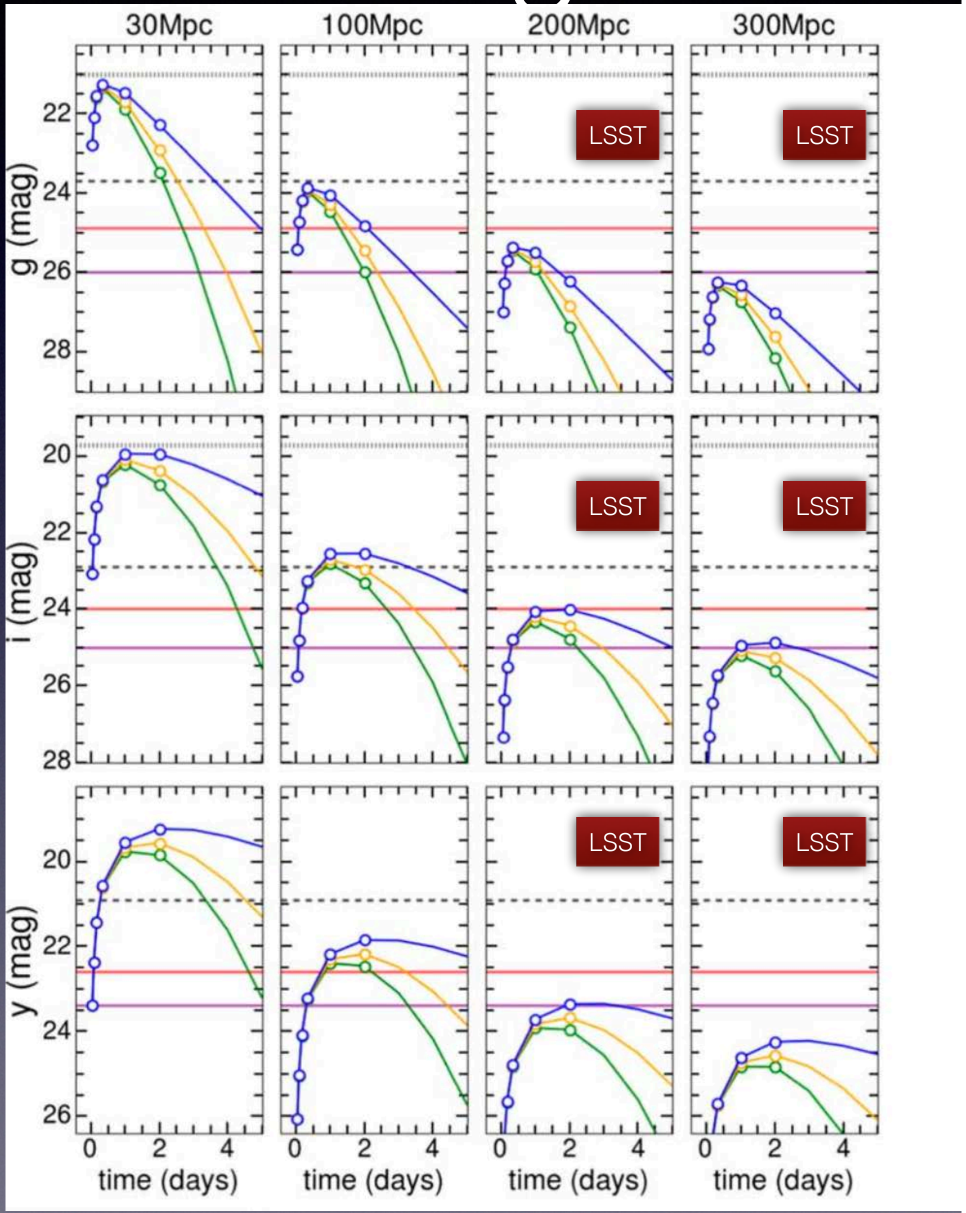


Image Credit : LIGO-Virgo-Kagra collaboration

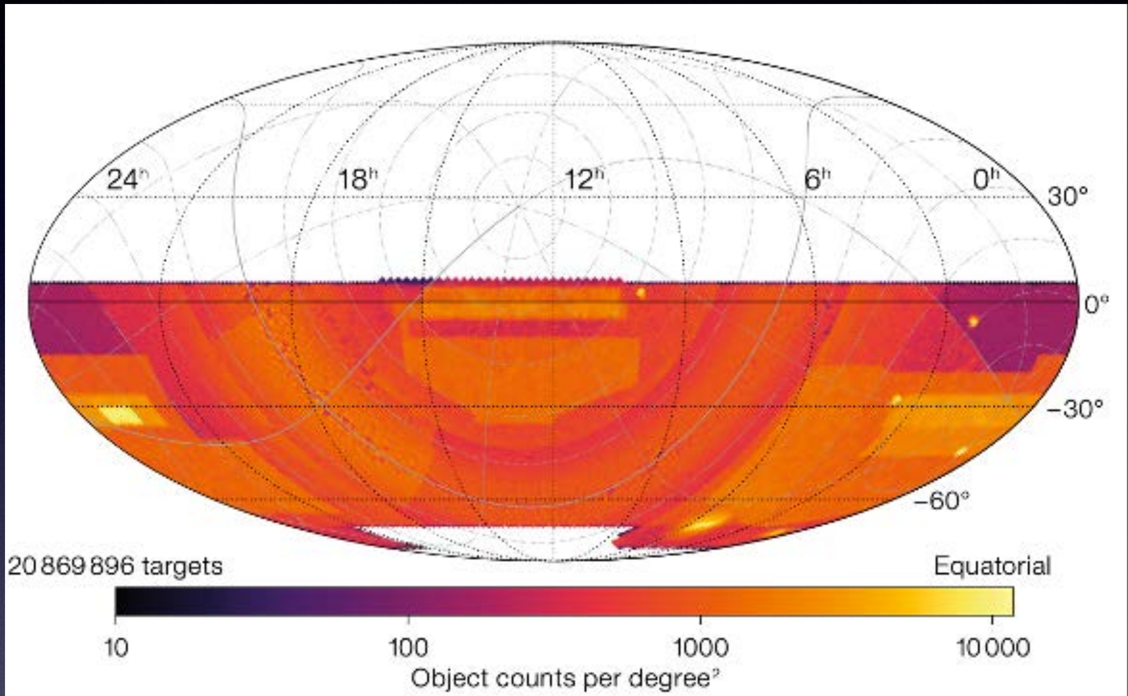
LSST: the next game changer ?

D	BNS per yr	Ligo-Virgo-Kagra Observing run	Comment
100 Mpc	1	O2 and O3	GW170817 is once per 10yr event
175 Mpc	4 - 7	O4	Most likely for O4 - (day light hours, moon)
300 Mpc	30	O5	Game changing number : O5 + Rubin Observatory ToO



Margutti & LSST TVS 2019; Andreoni et al. 2022

O5 - much more than Rubin



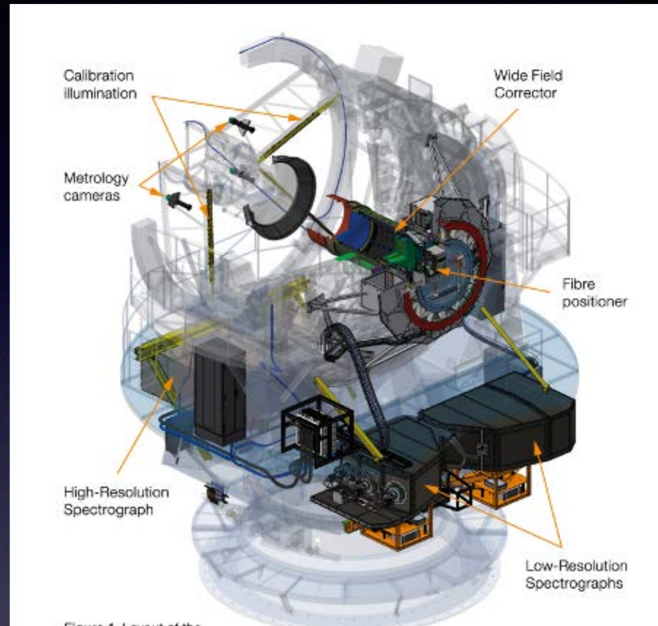


Figure 1. Layout of the different subsystems of 4MOST on the VISTA telescope.

- 4MOST + DESI Galaxy surveys - 20 - 50 million redshifts
- ULTRASAT - widefield UV surveyor (Israel-DESY-NASA; 2025)
- ESO NTT + SOXS : dedicated spectrometer
- James Web Space Telescope - near to mid infrared
- EUCLID : but now uncertain launch

Conclusions

The potential of multi-messenger astronomy has not yet been fully realised
One EM counterpart to a gravitational wave source to date

Reason - almost certainly rates are lower than previous expectations (small number statistics)

For O4 : expect $N < 10$ binary NS mergers, roughly half may have counterparts identified

EM astronomers : tremendous interest, large resources invested and waiting. Need detections.

The major change in this field of multi-messenger astronomy will be O5 and the Rubin Observatory in 2025 plus many other astronomy developments (>>10 BNS detections per yr)

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Rubin (6.5m)	23.5	600 Mpc	Rubin