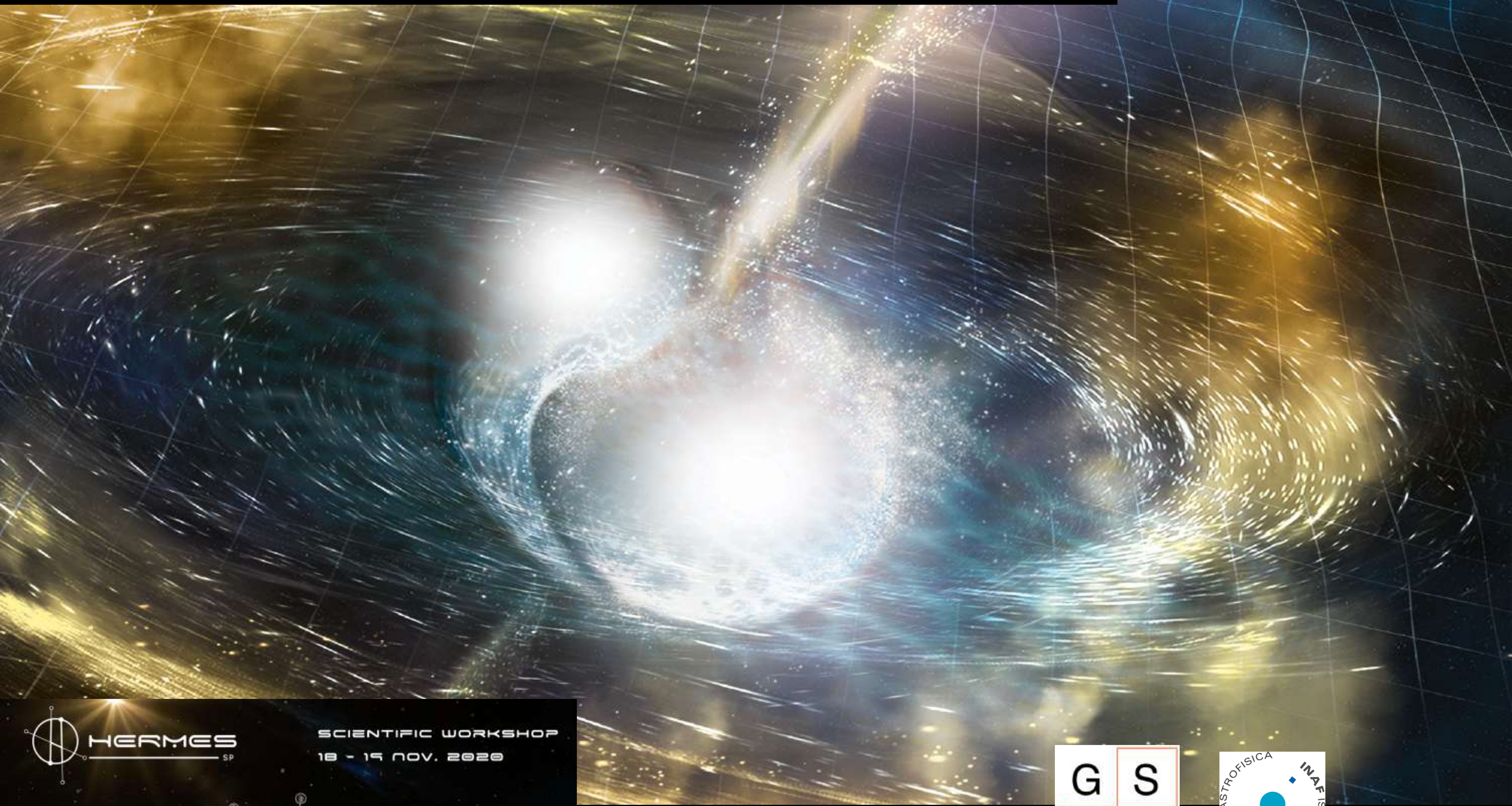
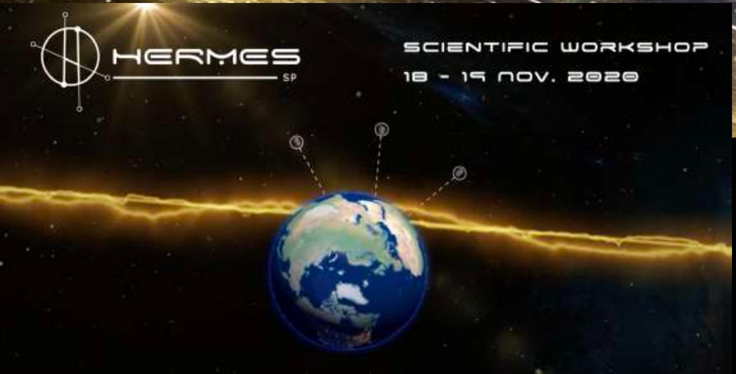
Gravitational-wave astronomy





M. Branchesi
Gran Sasso Science Institute
INFN/LNGS and INAF

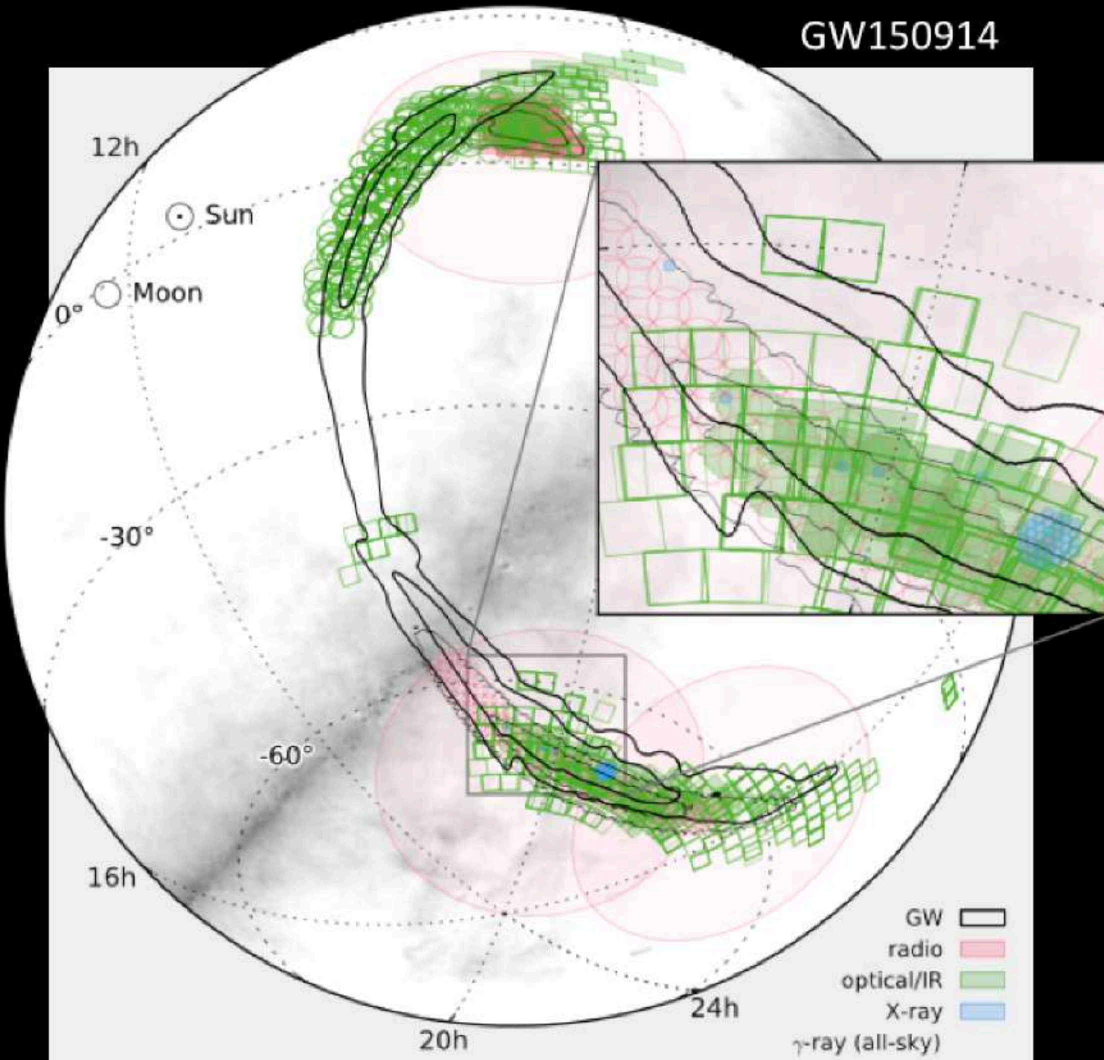
A new window into the Universe

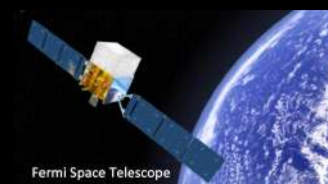
Credit: LIGO–Virgo

KAGRA, Japan

First run O1 of
the Advanced GW detectors

GW150914





- Weak transient gamma-ray signal detected by FERMI
- 0.4 s after the GW event, with FAP 0.0022 (2.9σ)

Connaughton et al. 2016, ApJL, 826, 6

Abbott et al. 2016, ApJL, 826, 13
Abbott et al. 2016, ApJS, 225, 8

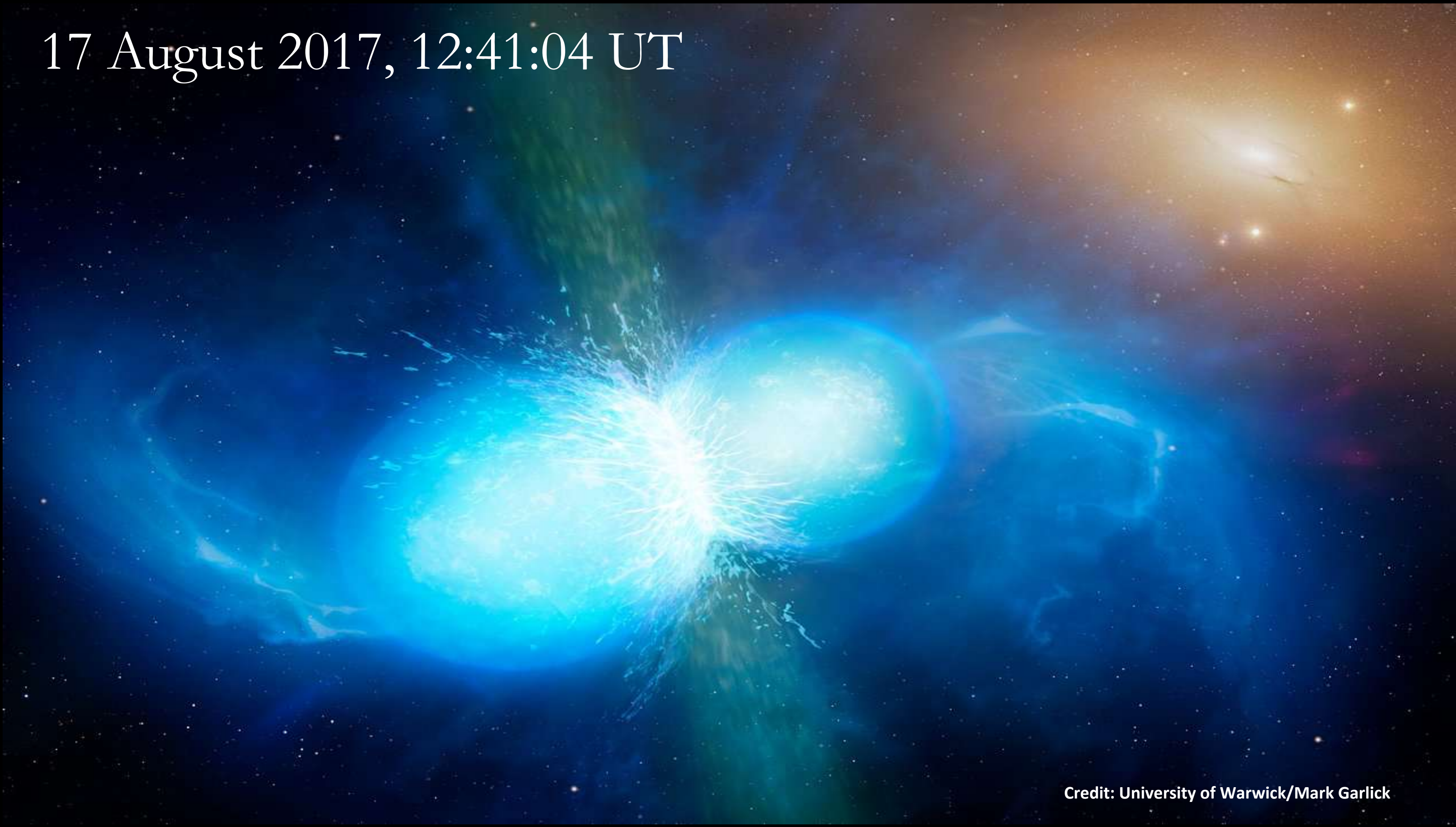
Second run O2


LIGO, Livingston, LA


LIGO, Hanford, WA

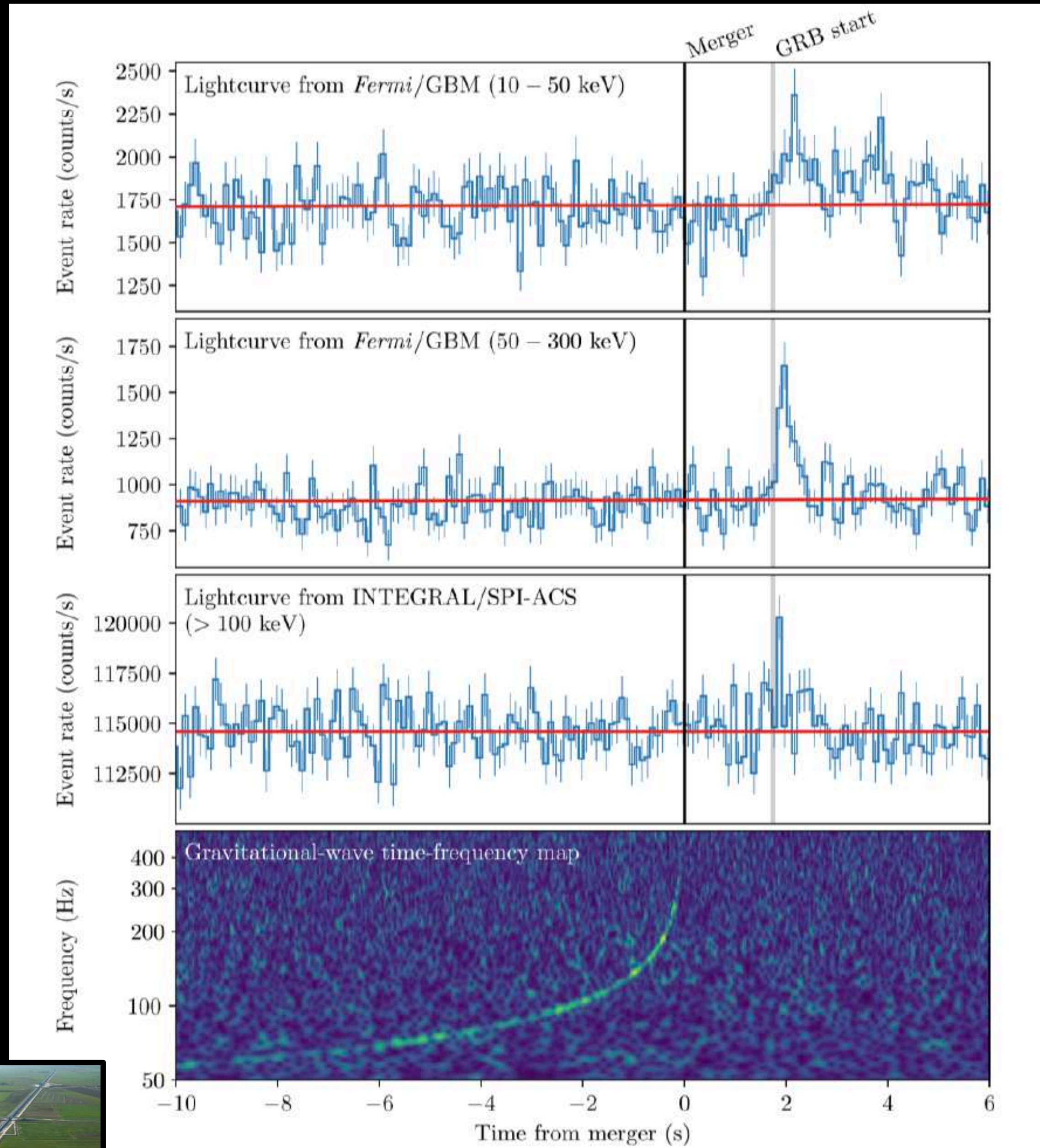

Virgo, Cascina, Italy

17 August 2017, 12:41:04 UT



Credit: University of Warwick/Mark Garlick

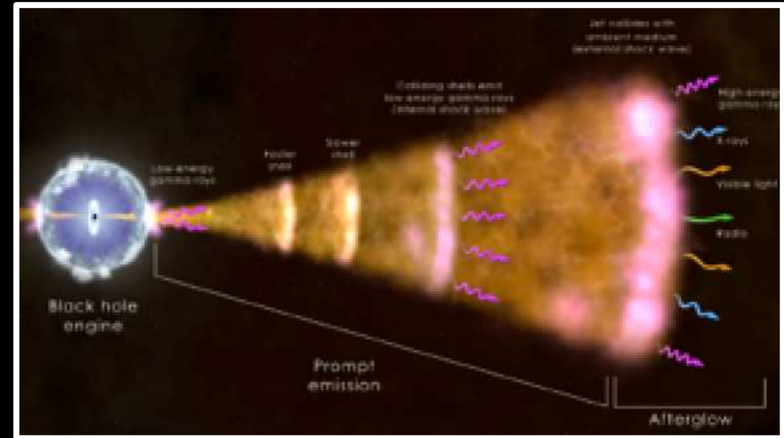

Fermi Space Telescope


Merger
GRB start
Lightcurve from Fermi/GBM (10 – 50 keV)
Event rate (counts/s)
2500
2250
2000
1750
1500
1250
Lightcurve from Fermi/GBM (50 – 300 keV)
Event rate (counts/s)
1750
1500
1250
1000
750
Lightcurve from INTEGRAL/SPI-ACS
(> 100 keV)
Event rate (counts/s)
120000
117500
115000
112500
Gravitational-wave time-frequency map
Frequency (Hz)
400
300
200
100
50
−10
−8
−6
−4
−2
0
2
4
6
Time from merger (s)

GW170817

NS merger

Short GRB

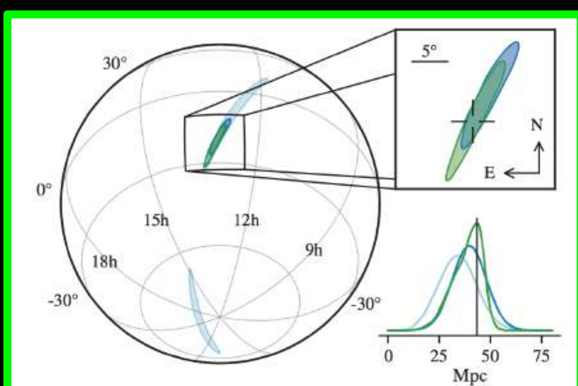


X-ray

Radio afterglow

t0 | 1.7s | +5.23hrs | +10.87 hrs | +9 days | +16 days

LHV sky localization



UV/Optical/NIR Kilonova

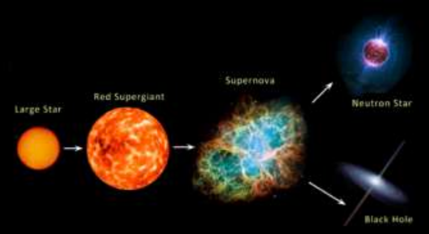
LVC + astronomers, ApJL, 848, L12

Radioactively powered transients

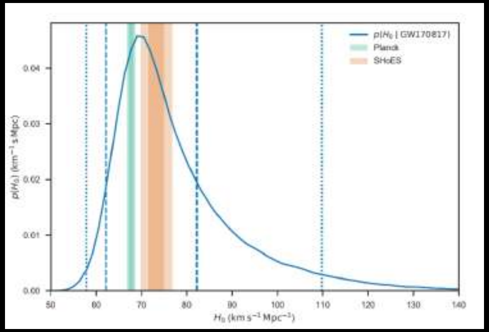
Relativistic astrophysics

Nucleosynthesis and enrichment of the Universe

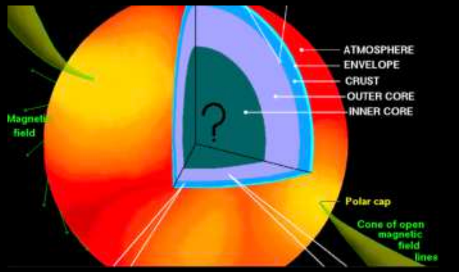
Compact object formation and evolution



Cosmology

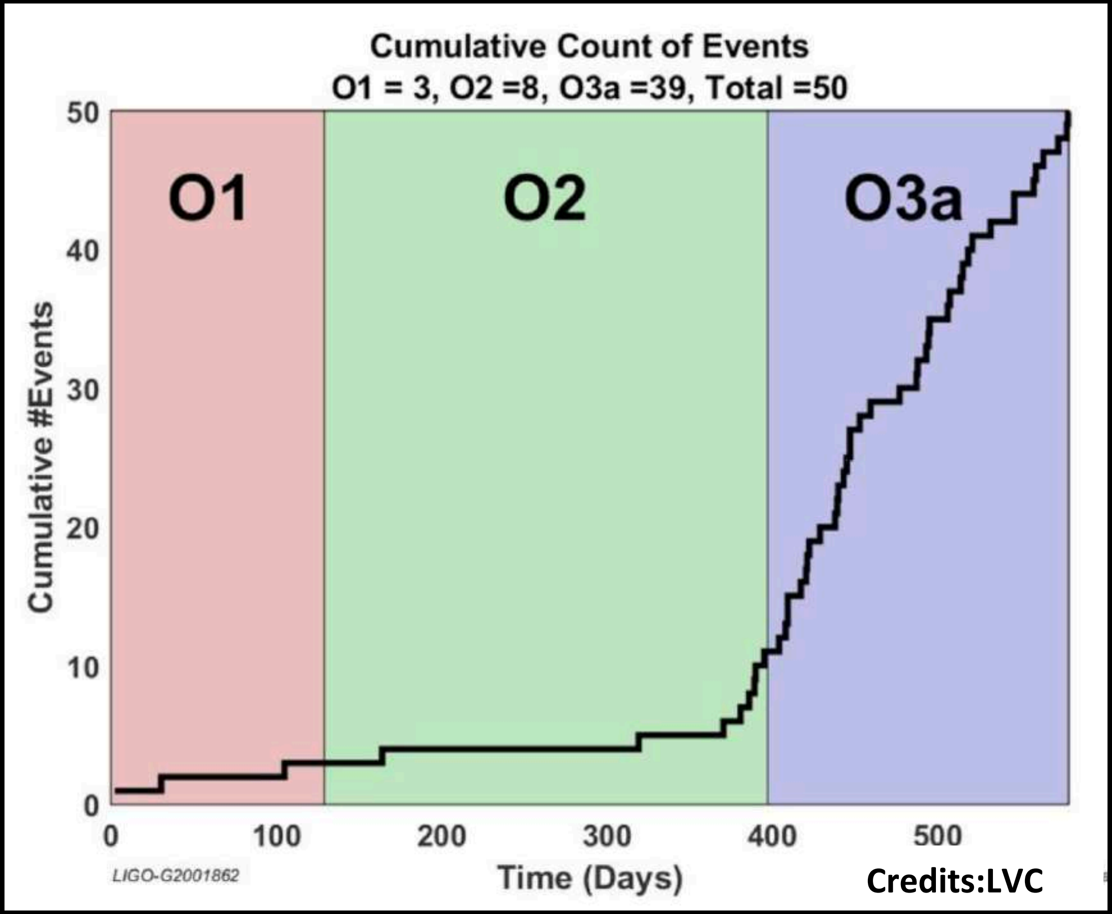


Nuclear matter physics



First run O1, second run O2, and half of third run O3a

O3a Event Rate



LVC Catalog paper, arXiv: 2010.14527

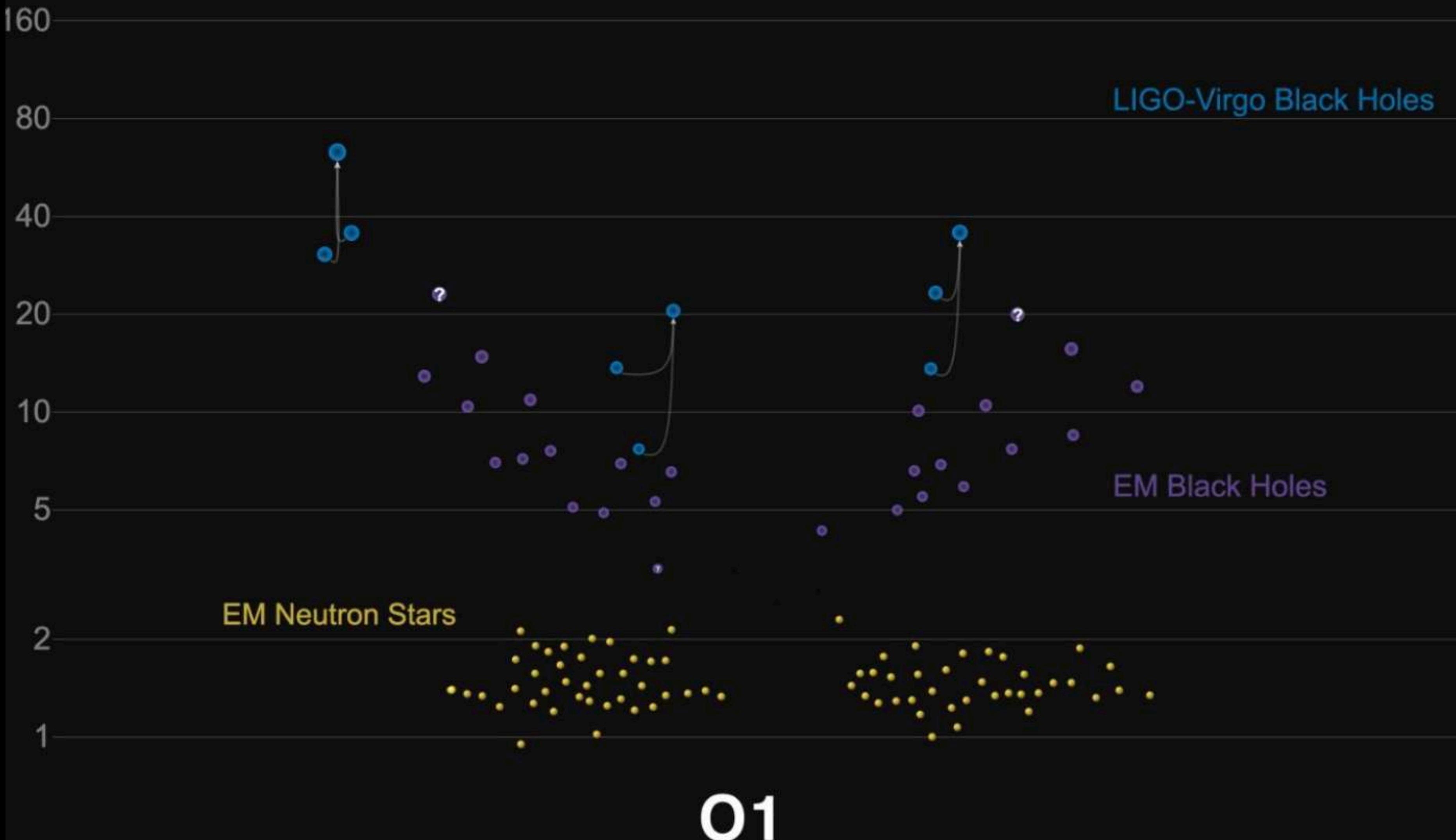
39 candidate GW events in ~26 weeks of O3a (FAR 2 per year → contamination fraction of less than 10%)

26 candidate events
low-latecy reported
in GCN alerts
+
13 candidate events
offline analysis

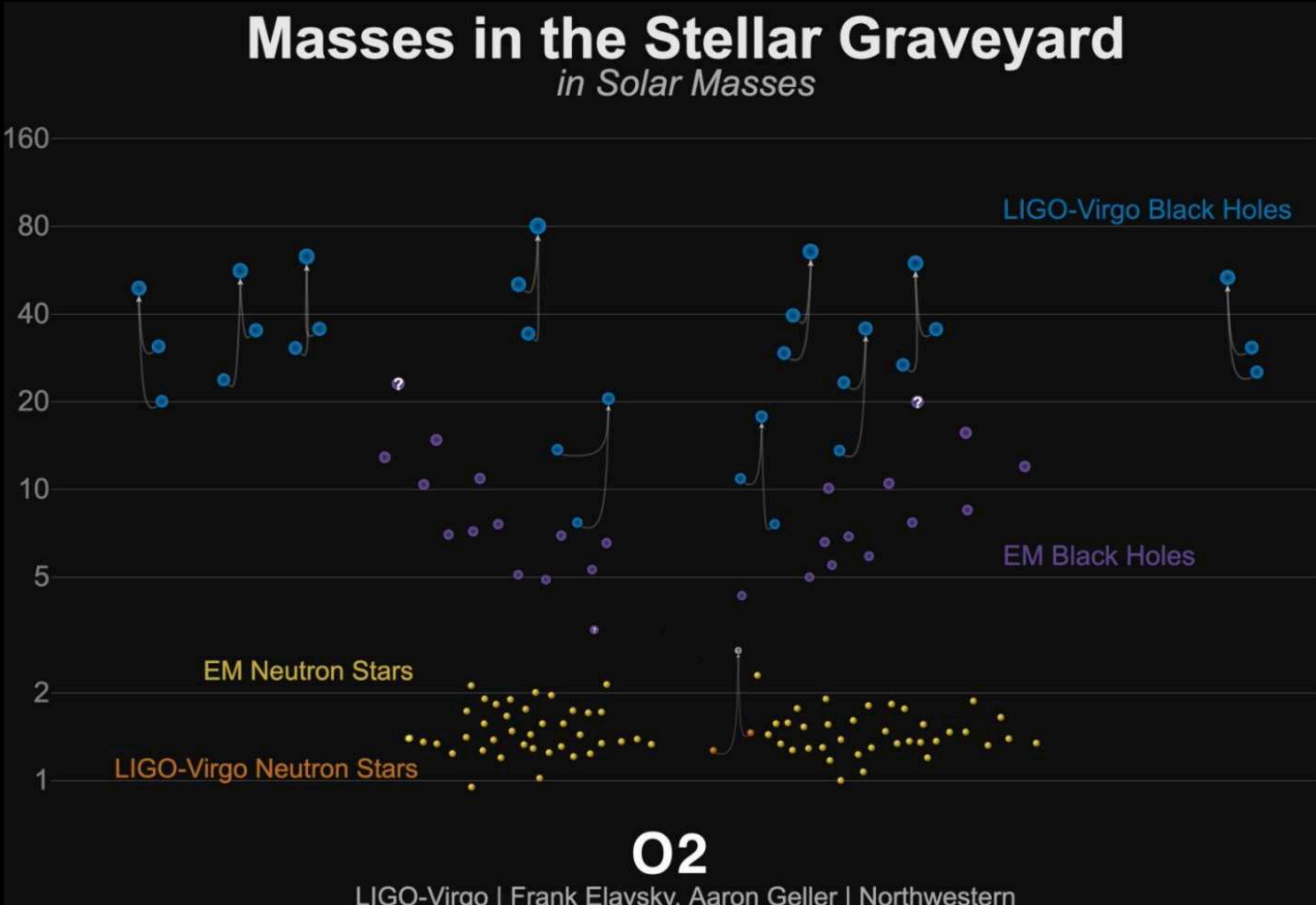
O1, O2, O3 → 50 candidate GW events

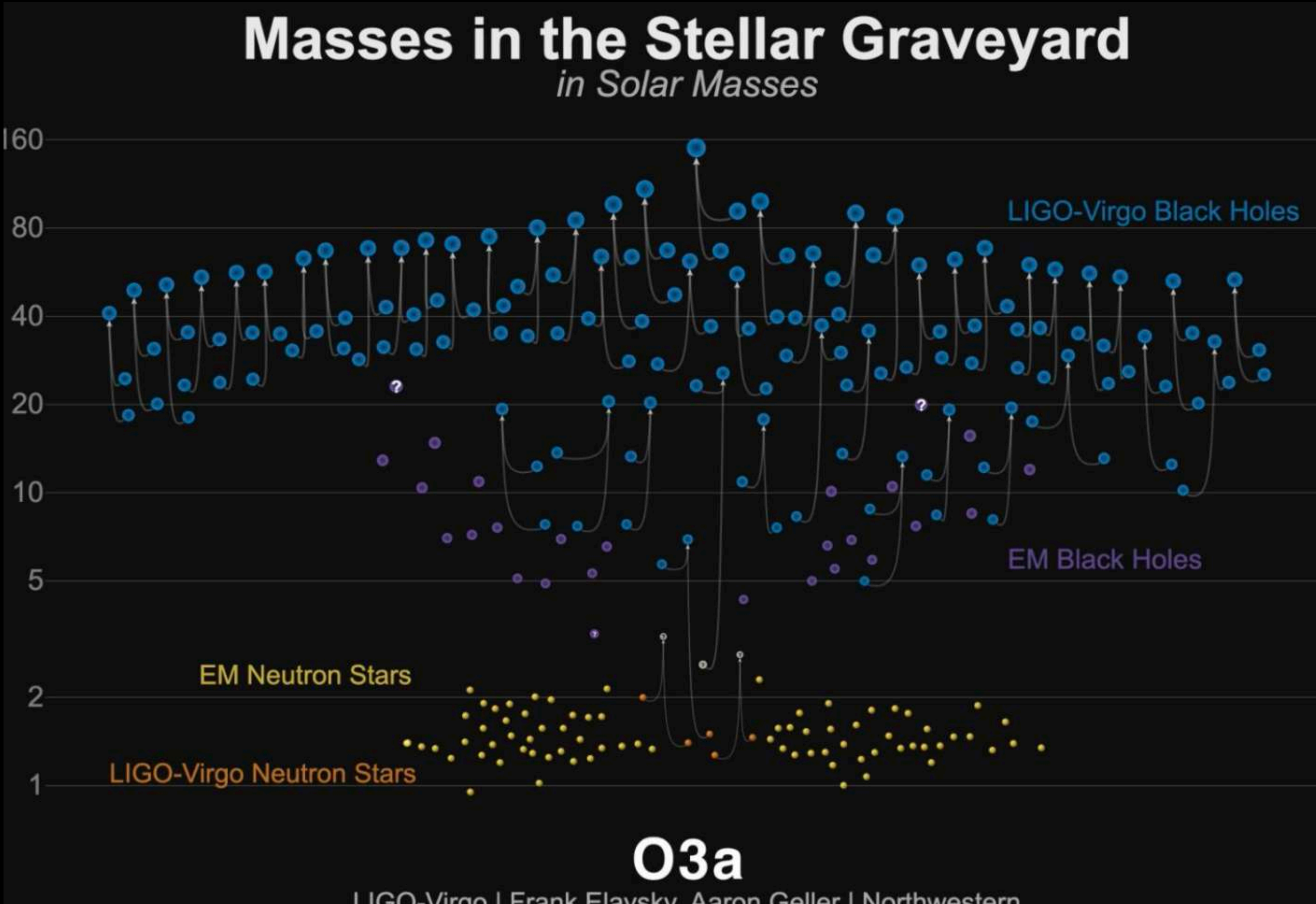
Masses in the Stellar Graveyard

in Solar Masses

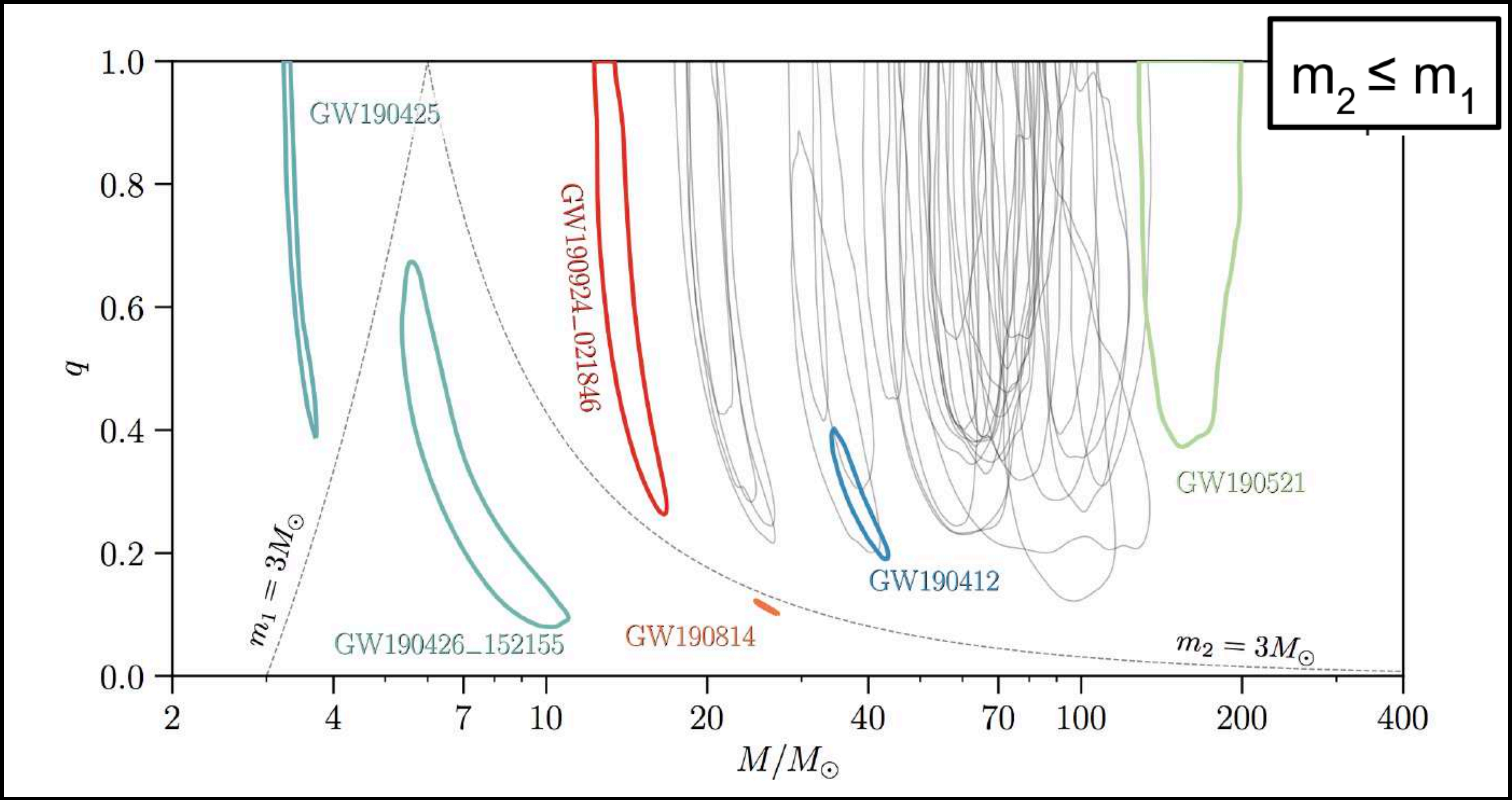


LIGO-Virgo | Frank Elavsky, Aaron Geller | Northwestern


Masses in the Stellar Graveyard
in Solar Masses
160
80
40
20
10
5
2
1
LIGO-Virgo Black Holes
EM Black Holes
EM Neutron Stars
LIGO-Virgo Neutron Stars
O2
LIGO-Virgo | Frank Elavsky, Aaron Geller | Northwestern


Masses in the Stellar Graveyard
in Solar Masses
160
80
40
20
10
5
2
1
LIGO-Virgo Black Holes
EM Black Holes
EM Neutron Stars
LIGO-Virgo Neutron Stars
O3a
LIGO-Virgo | Frank Elavsky, Aaron Geller | Northwestern

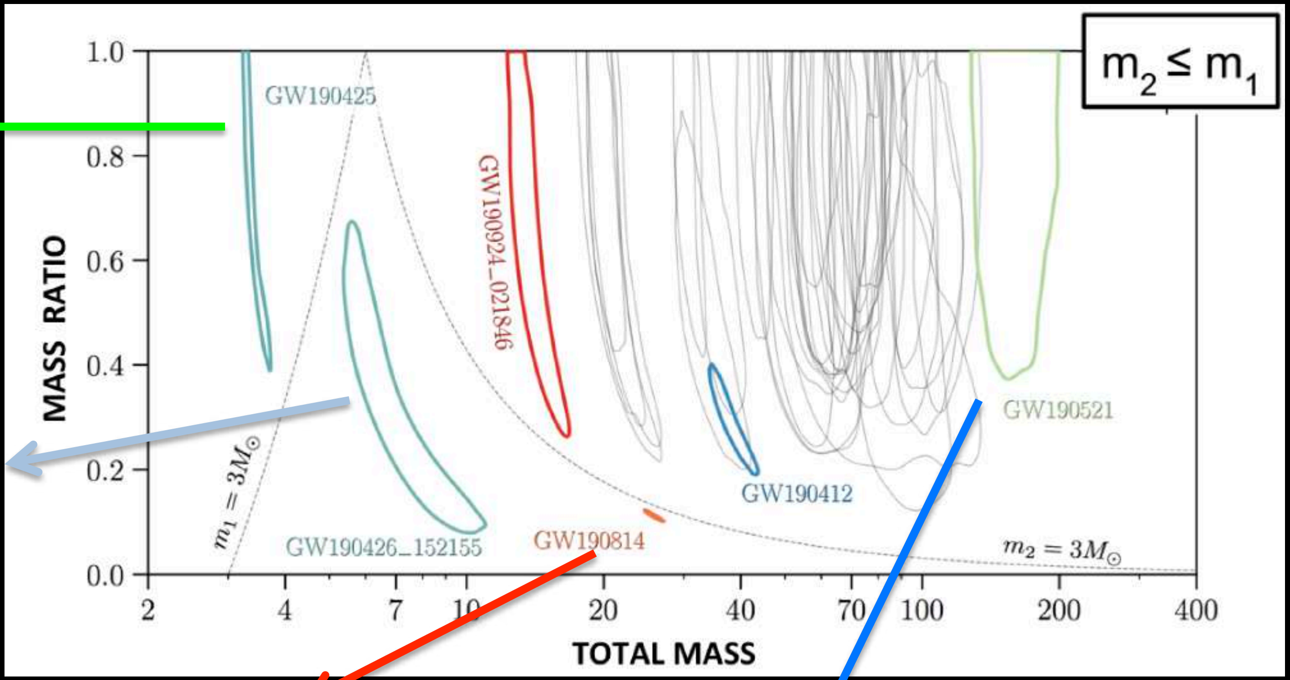
TOTAL MASS vs MASS RATIO



LVC Catalog paper, arXiv: 2010.14527

Notable candidate events

GW190425:
m1 and m2 < 3 Mo
Consistent with BNS



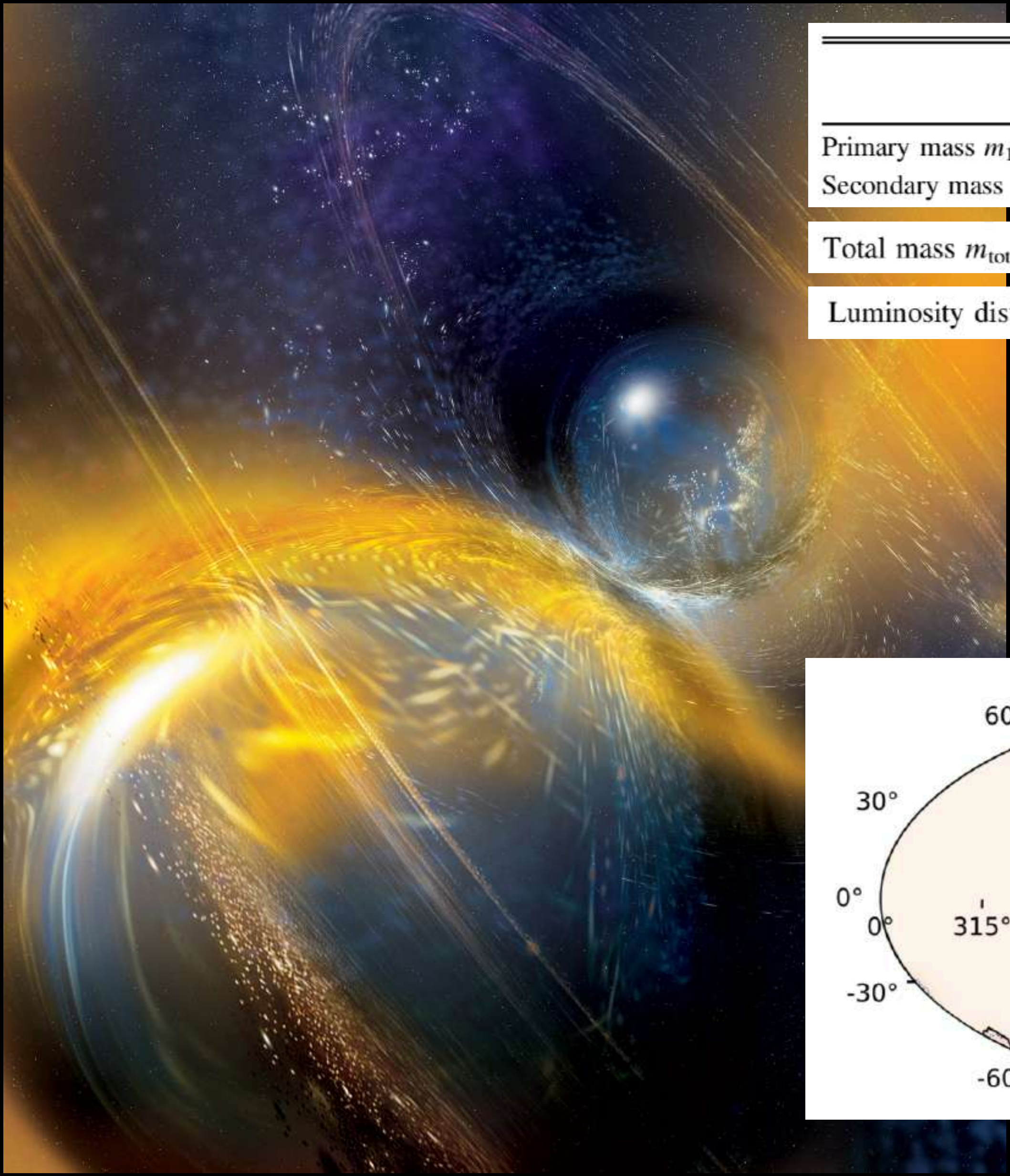
GW190426_152155:
Highest FAR event
m2 < 3Mo
Consistent with NSBH

GW190814: m2 < 3Mo
NSBH or BBH?

GW190521:
most massive component BHs
→ intermediate massive BH

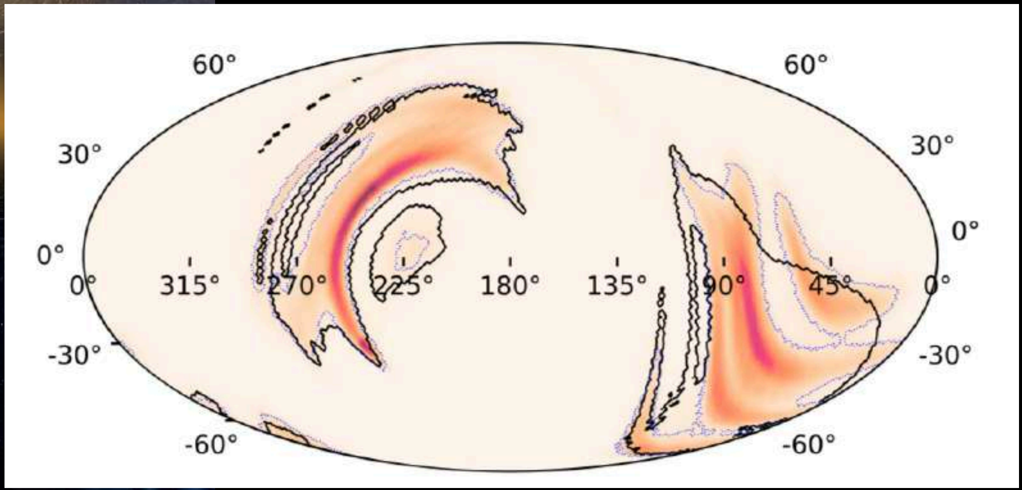
LVC Catalog paper, arXiv: 2010.14527

GW190425: another BNS detection!



	Low-spin Prior ($\chi < 0.05$)	High-spin Prior ($\chi < 0.89$)
Primary mass m_1	1.60–1.87 $M_\odot$	1.61–2.52 $M_\odot$
Secondary mass m_2	1.46–1.69 $M_\odot$	1.12–1.68 $M_\odot$
Total mass m_{tot}	$3.3^{+0.1}_{-0.1}$ $M_\odot$	$3.4^{+0.3}_{-0.1} M_\odot$
Luminosity distance D_L	159^{+69}_{-72} Mpc	159^{+69}_{-71} Mpc

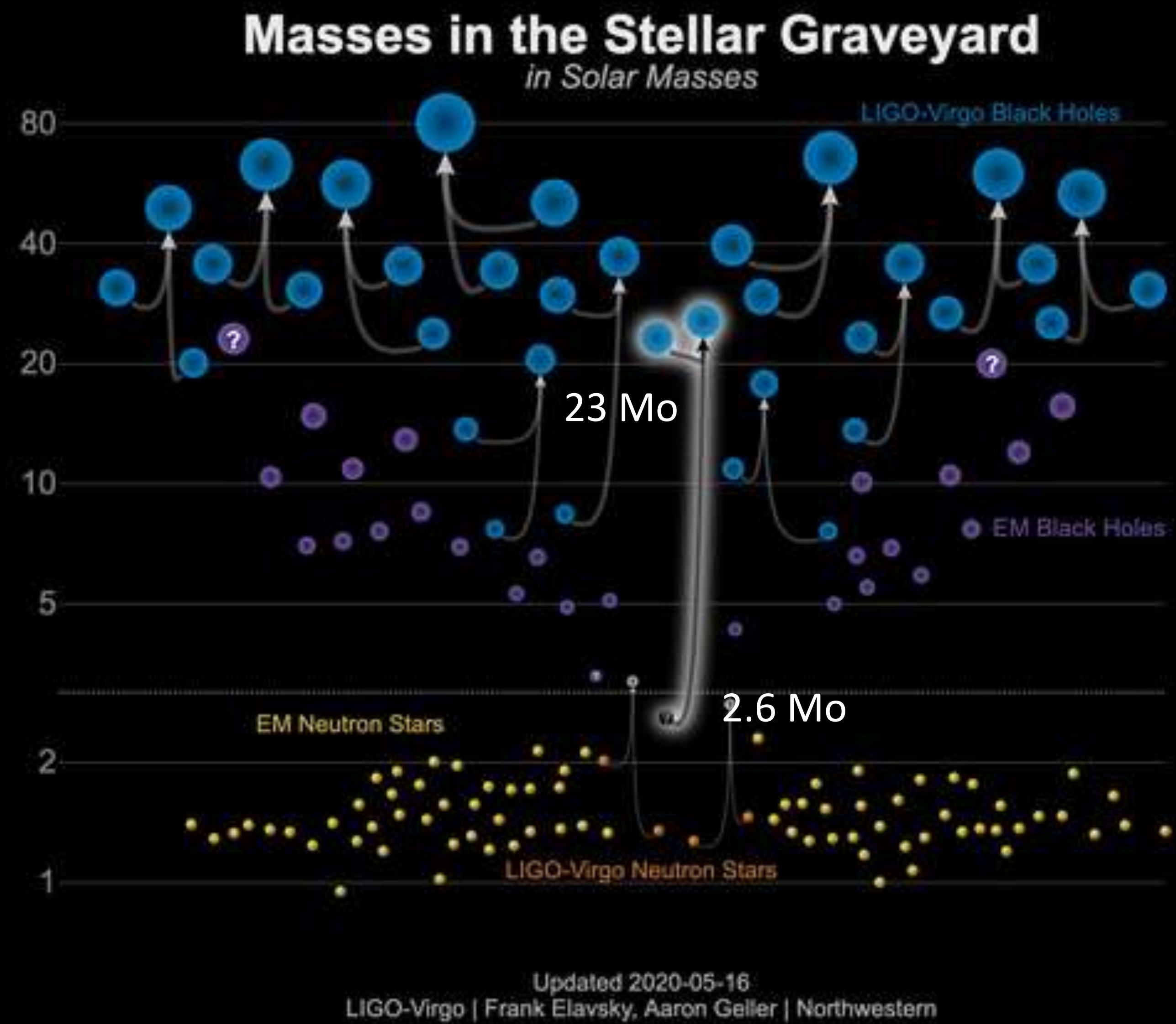
NO firm EM counterpart!



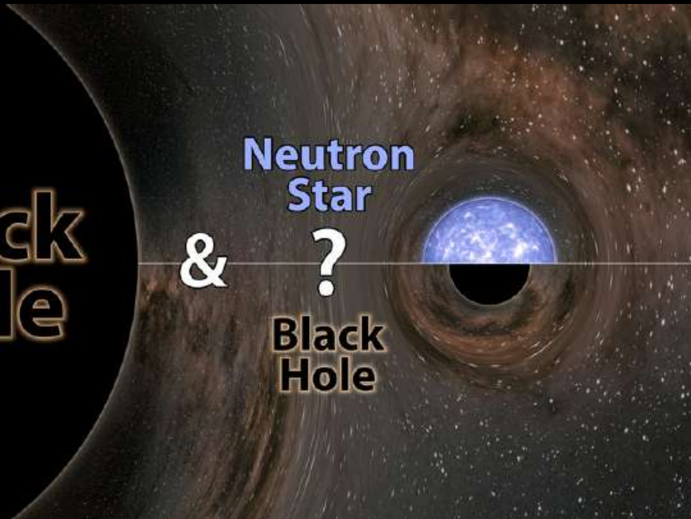
Sky localization of 8284 deg^2

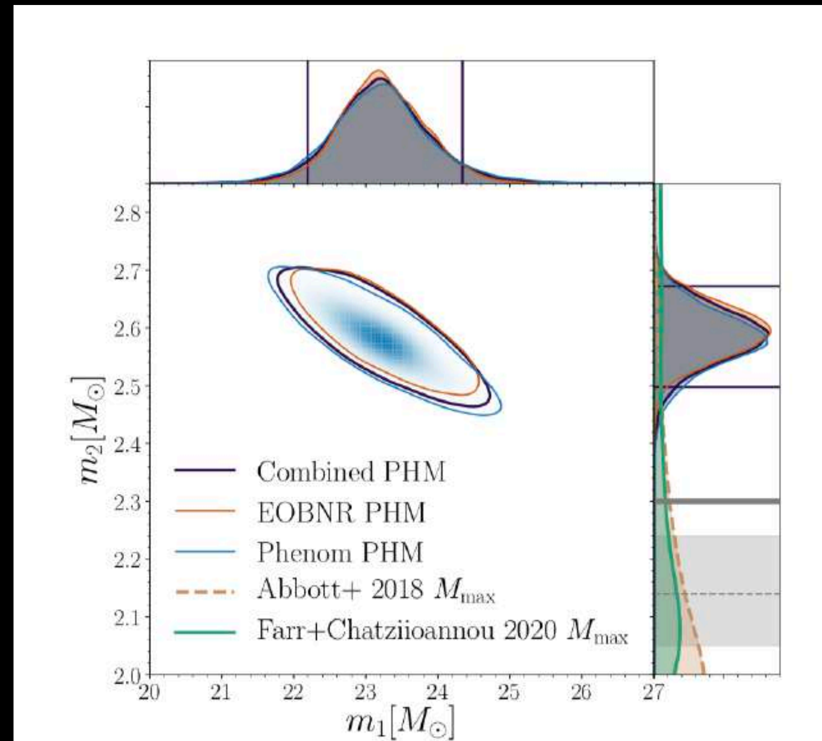
Abbott et al. 2020, ApJL, 892

GW190814: FIRST NS-BH or low-mass BBH?



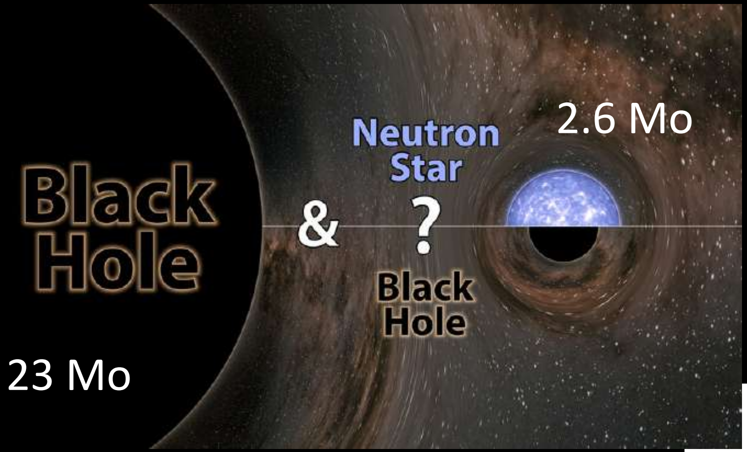
GW190814





	EOBNR PHM	Phenom PHM	Combined
Primary mass $m_1/M_\odot$	$23.2^{+1.0}_{-0.9}$	$23.2^{+1.3}_{-1.1}$	$23.2^{+1.1}_{-1.0}$
Secondary mass $m_2/M_\odot$	$2.59^{+0.08}_{-0.08}$	$2.58^{+0.09}_{-0.10}$	$2.59^{+0.08}_{-0.09}$
Luminosity distance D_L/Mpc	235^{+40}_{-45}	249^{+39}_{-43}	241^{+41}_{-45}
Source redshift z	$0.051^{+0.008}_{-0.009}$	$0.054^{+0.008}_{-0.009}$	$0.053^{+0.009}_{-0.010}$
Inclination angle Θ/rad	$0.9^{+0.3}_{-0.2}$	$0.8^{+0.2}_{-0.2}$	$0.8^{+0.3}_{-0.2}$

GW190814

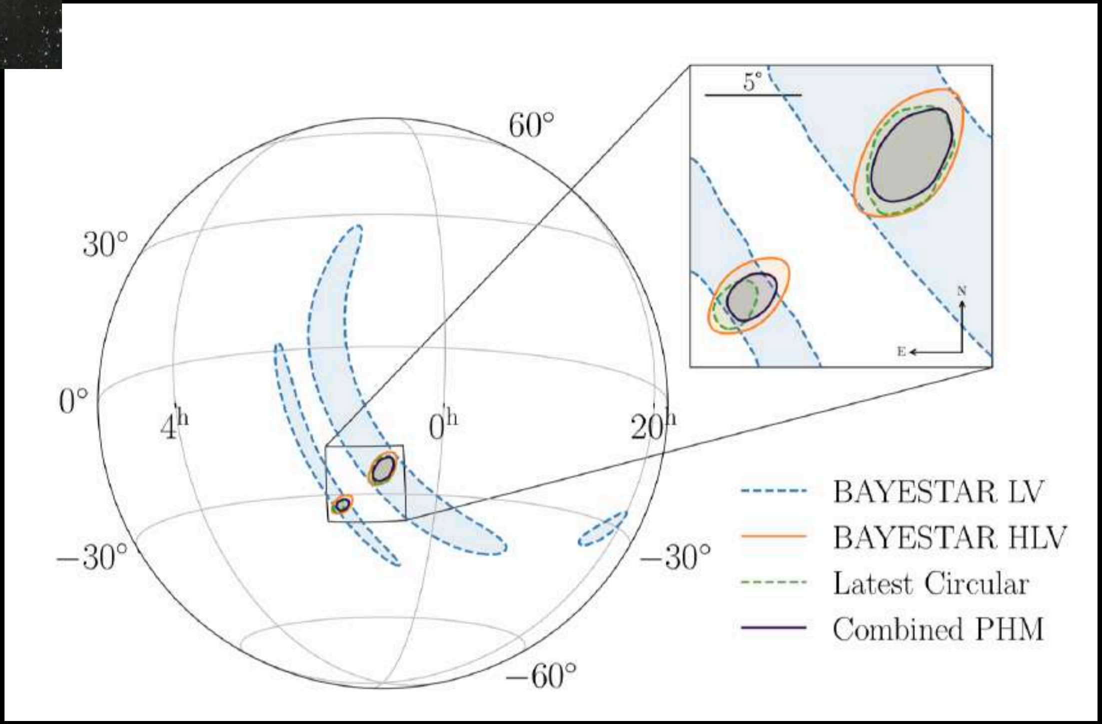


Abbott et al. 2020, ApJL, 896

- NO evidence of measurable tidal effects in the GW signal
- NO EM counterpart

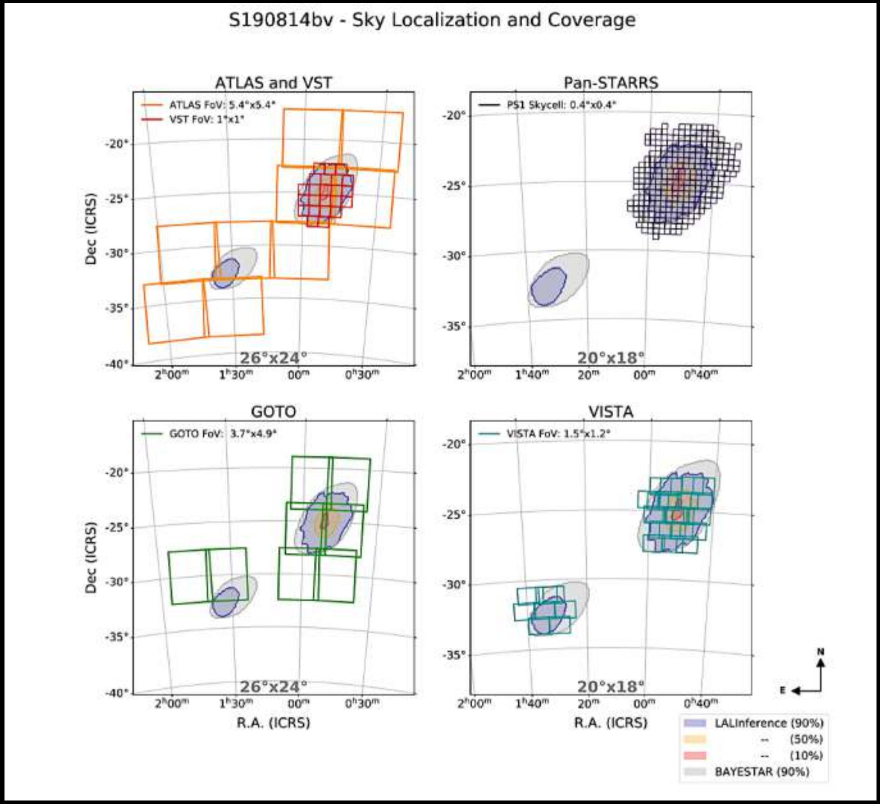
→ *Consistent with both BBH and NSBH scenarios*

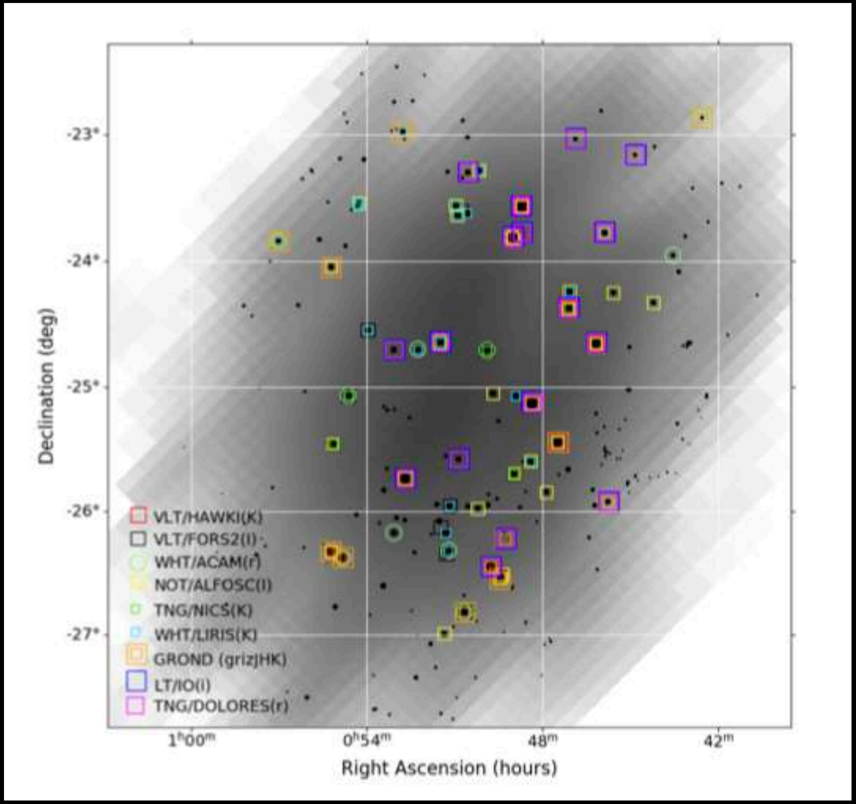
→ *In the NSBH, observation results can be explained by the large mass ratio*



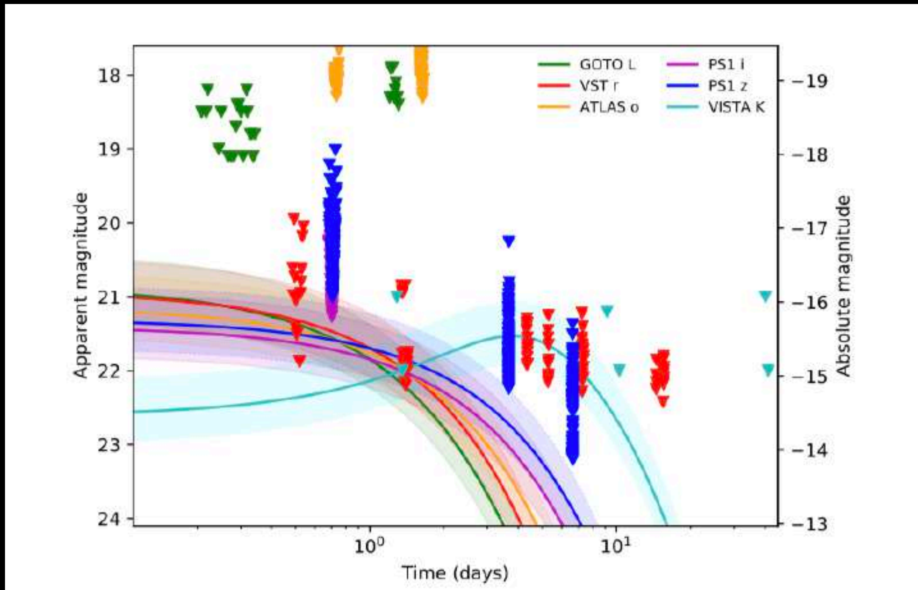
Sky localization of 18.5 deg^2

Optical counterpart search



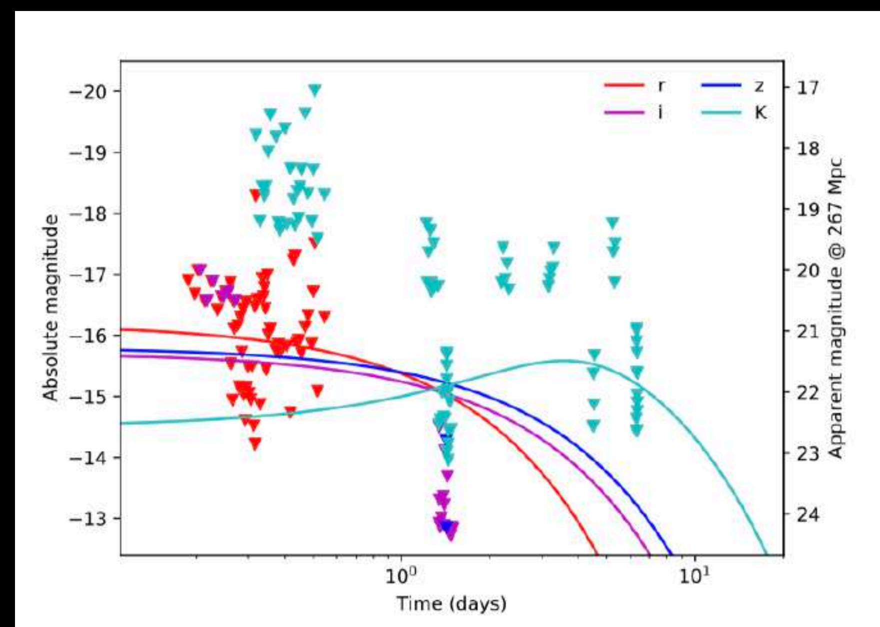


Ackley et al. 2020, A&A



→ Upper limits from the wide-field instrument follow-up campaign

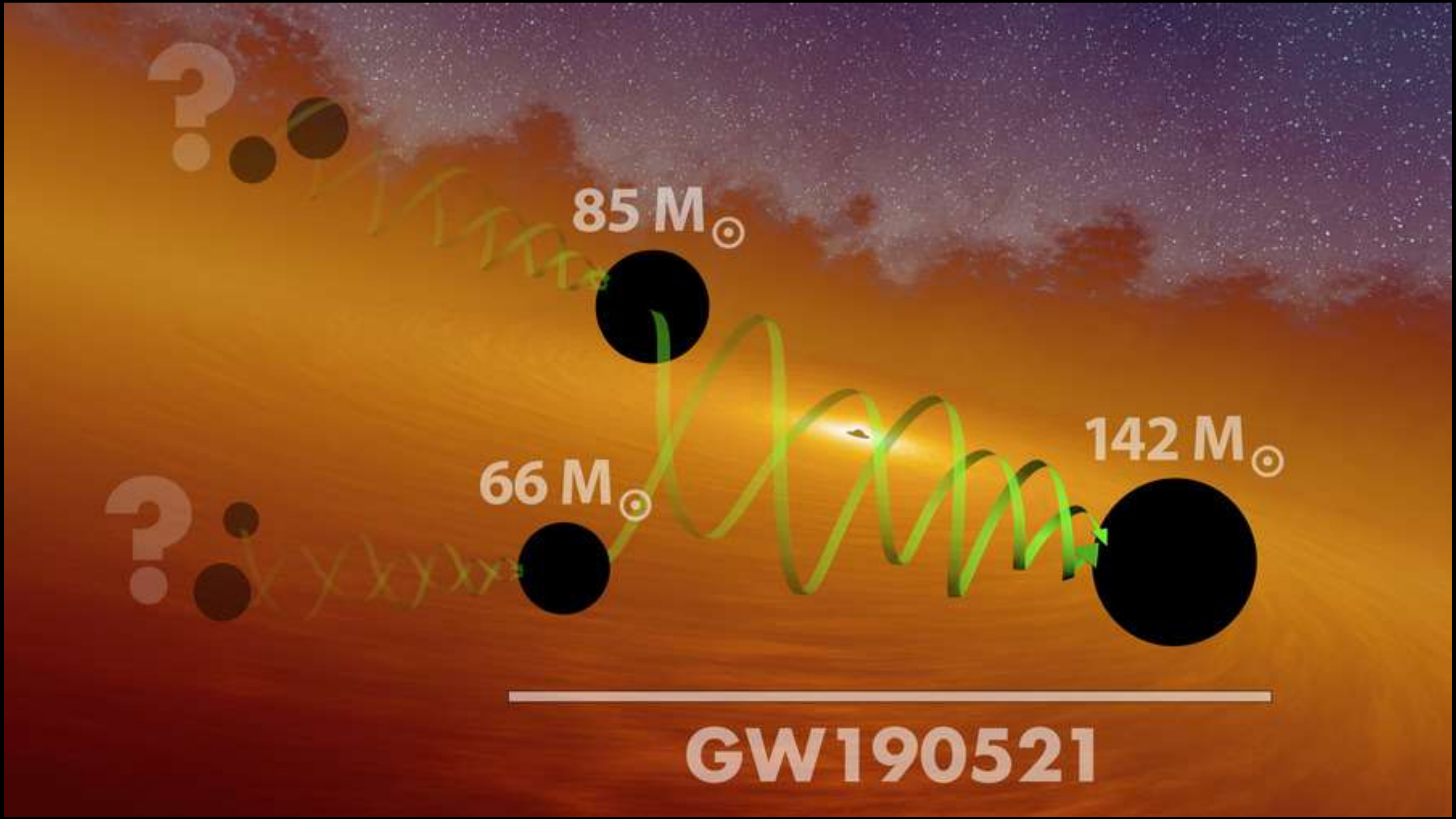
Galaxy targeted upper limits →



GW190521

The birth of a intermediate massive black-hole!

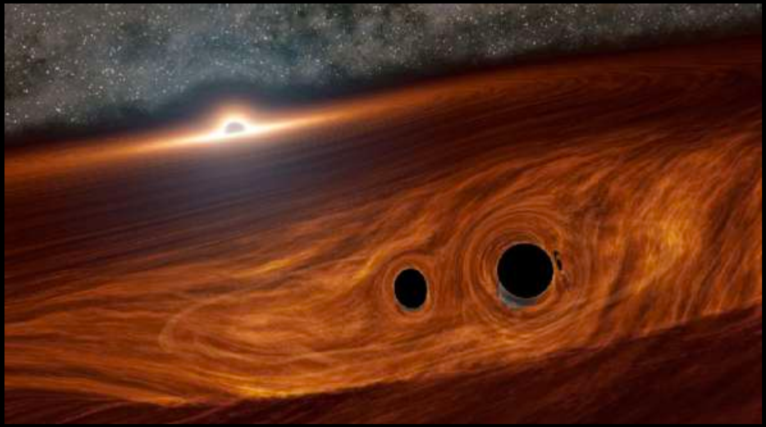
Credit: Mark Myers, ARC Centre of Excellence for Gravitational Wave Discovery (OzGrav)



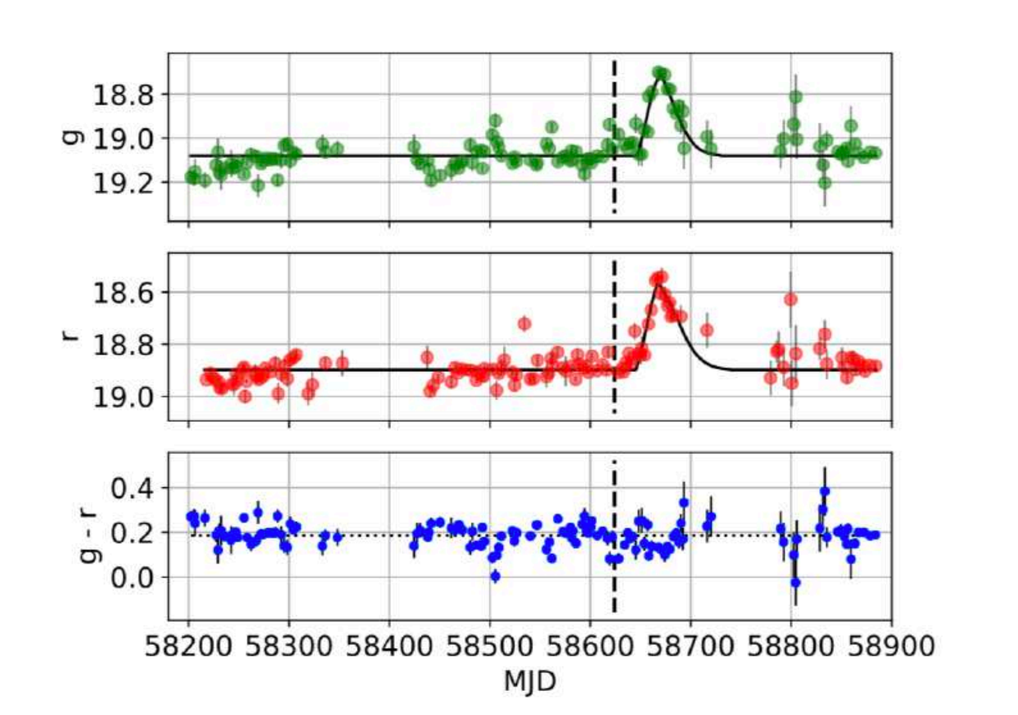
credit: LIGO/Caltech/MIT/R. Hurt (IPAC)

Abbott et al 2020, PRL, 125
Abbott et al 2020, APJ, 900

BBH in the accretion disk of a supermassive black hole?



Caltech/R. Hurt (IPAC)



Graham et al 2020, PRL 124

ZTF detected a candidate counterpart(!?)

- EM flare close to AGN

~ 34 days after the GW event

- consistent with expectations for a kicked BBH merger in the accretion disk AGN
- 765 deg^2 localization area
- ZTF observed 48% of the 765 deg^2 (90% c.r.)

GW190426_152155

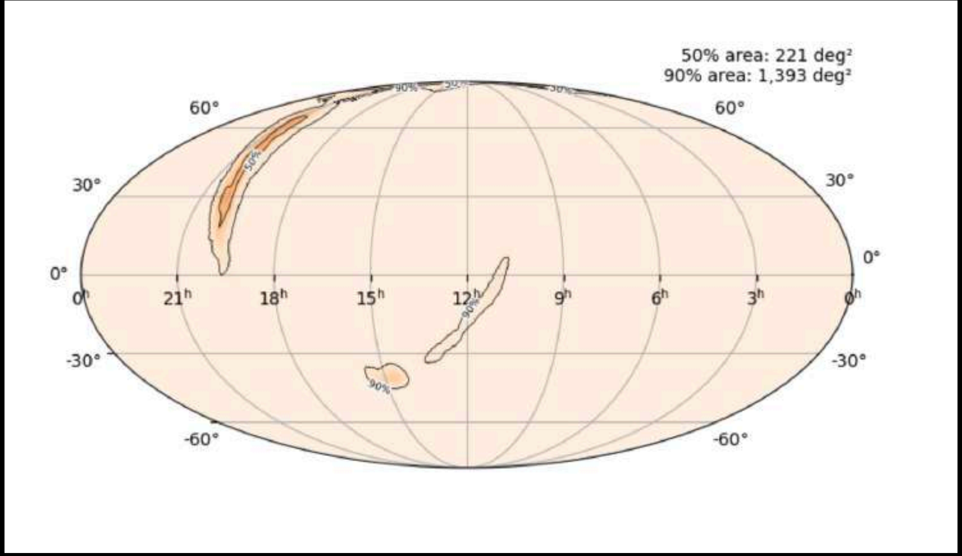
Event	m_1 $(M_\odot)$	m_2 $(M_\odot)$	$\chi_{\rm eff}$	$D_{\rm L}$ (Gpc)	z	SNR
GW190426_152155	$5.7^{+4.0}_{-2.3}$	$1.5^{+0.8}_{-0.5}$	$-0.03^{+0.33}_{-0.30}$	$0.38^{+0.19}_{-0.16}$	$0.08^{+0.04}_{-0.03}$	$8.7^{+0.5}_{-0.6}$

Highest FAR: 1.4 yr^{-1}

One of the most likely to be noise among the candidate event list

Data are uninformative about potential tidal effects

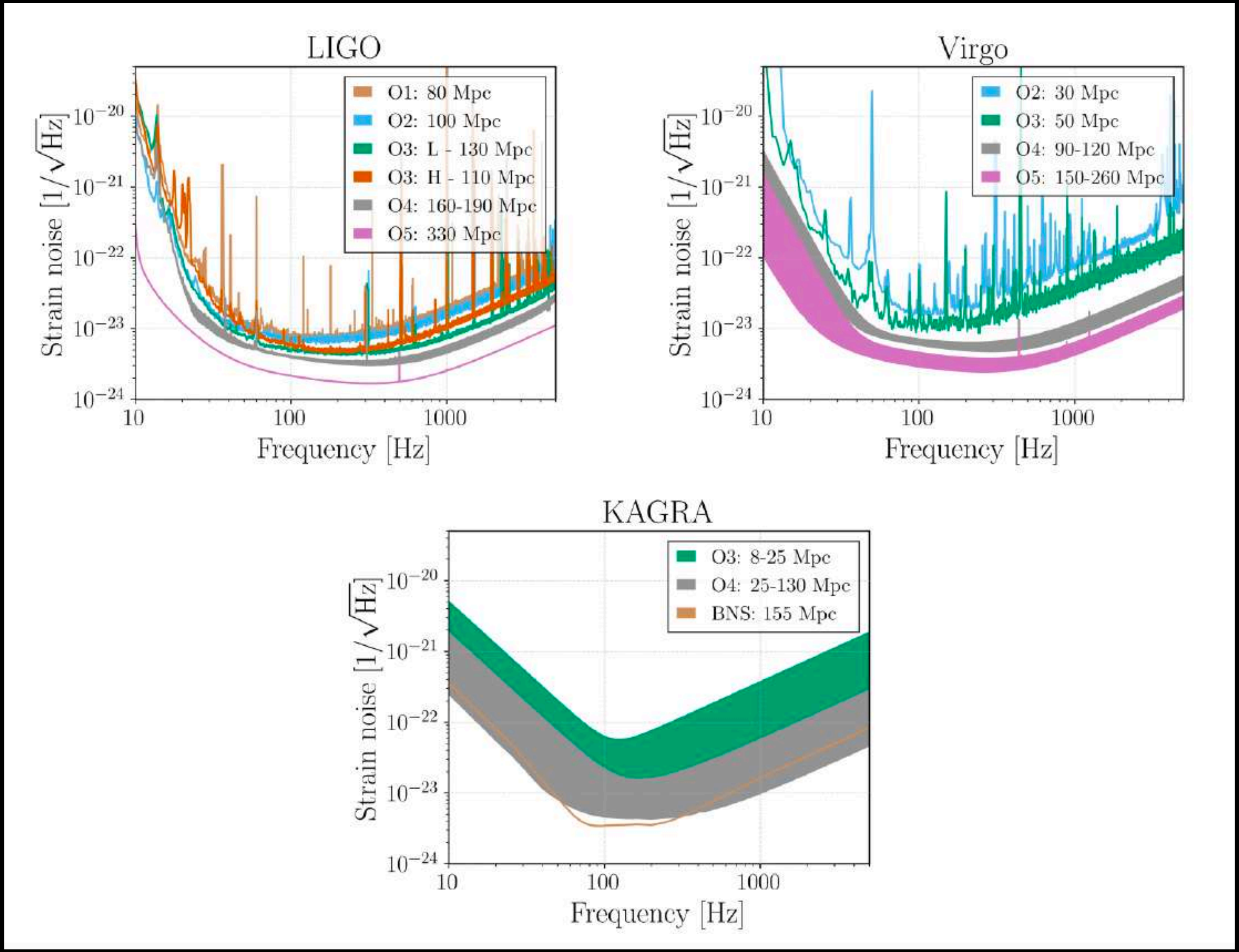
NSBH?



DL = 380 Mpc, 90% c.r. 1400 sq. degrees → NO EM counterpart

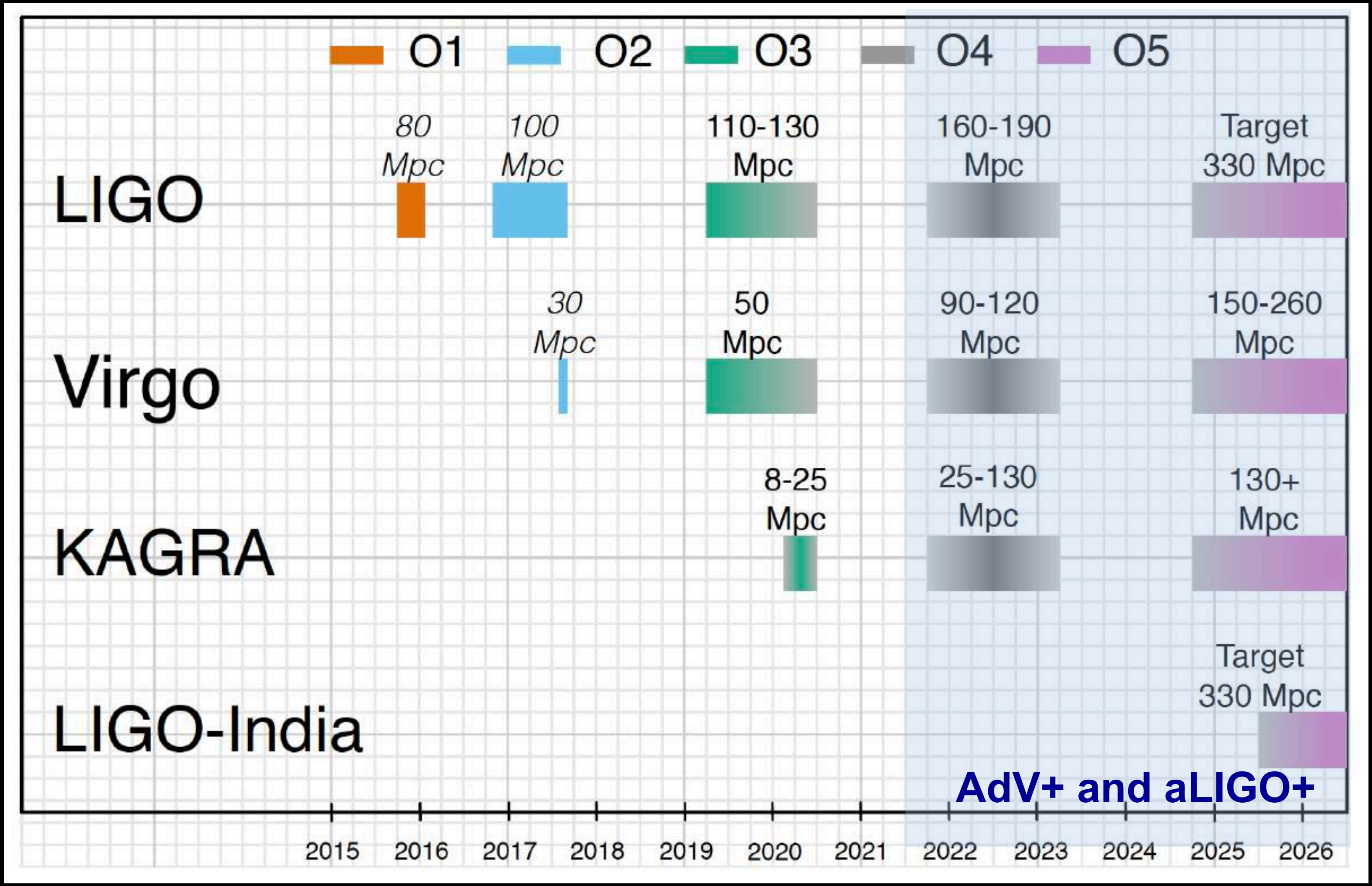
Next observative runs

Strain sensitivities as a function of frequency



Abbott et al. 2020, LRR

Observing run timeline and BNS sensitivity evolution



O5 volume = 15*O3 volume

Abbott et al. 2020, LRR

RANGES corresponding to the orientation-averaged spacetime volumes surveyed per unit detector time

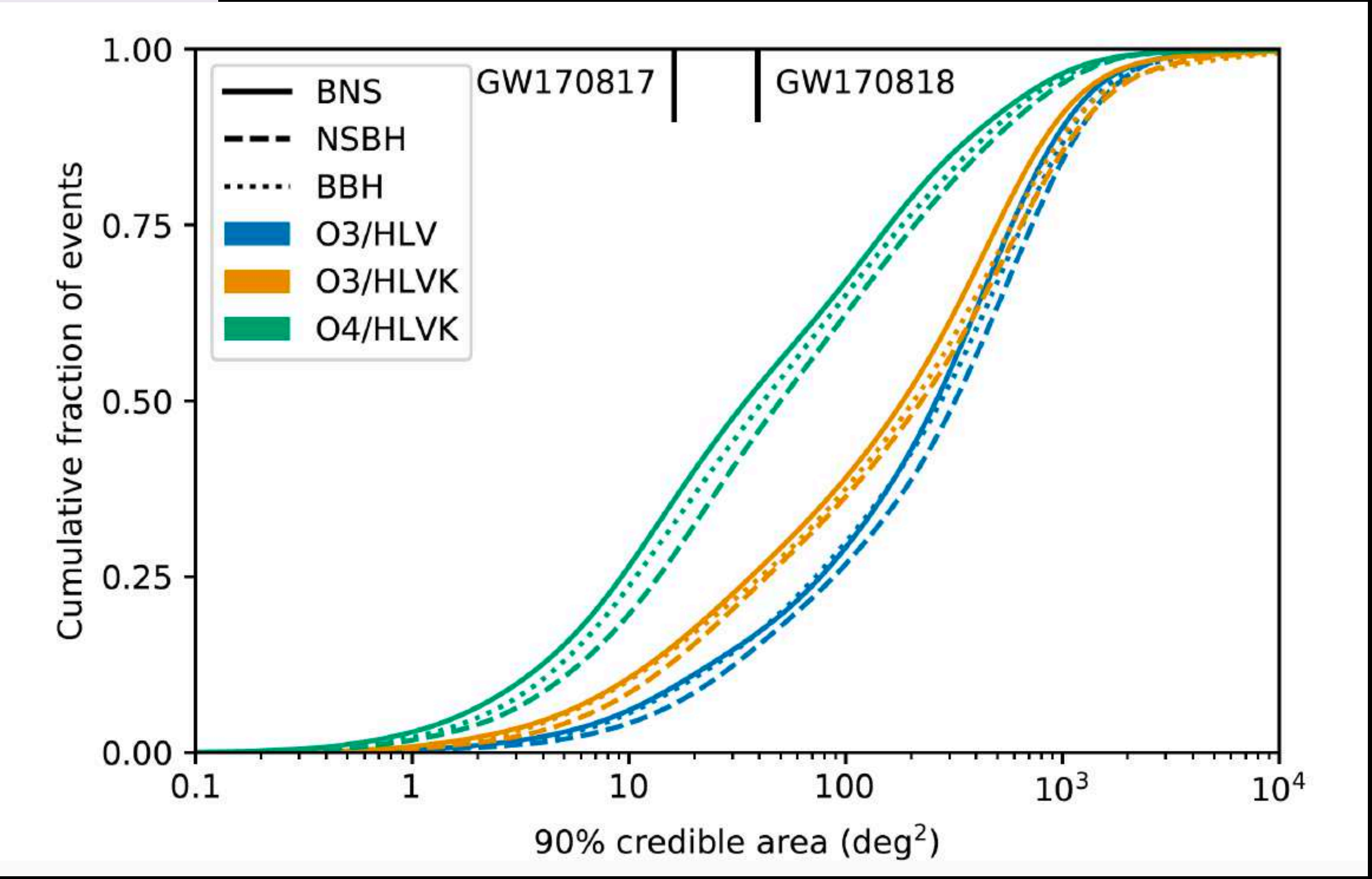
SNR = 8 in each detector

		O1	O2	O3	O4	O5
BNS Range (Mpc)	aLIGO	80	100	110 – 130	160 – 190	330
1.4 Mo+1.4 Mo	AdV	-	30	50	90 – 120	150 – 260
	KAGRA	-	-	8 – 25	25 – 130	130+
BBH Range (Mpc)	aLIGO	740	910	990 – 1200	1400 – 1600	2500
30 Mo+30 Mo	AdV	-	270	500	860 – 1100	1300 – 2100
	KAGRA	-	-	80 – 260	260 – 1200	1200+
NSBH Range (Mpc)	aLIGO	140	180	190 – 240	300 – 330	590
1.4 Mo+10 Mo	AdV	-	50	90	170 – 220	270 – 480
	KAGRA	-	-	15 – 45	45 – 290	290+
Burst Range (Mpc)	aLIGO	50	60	80 – 90	110 – 120	210
$[E_{GW} = 10^{-2} M_{\odot} c^2]$	AdV	-	25	35	65 – 80	100 – 155
	KAGRA	-	-	5 – 25	25 – 95	95+
Burst Range (kpc)	aLIGO	15	20	25 – 30	35 – 40	70
$[E_{GW} = 10^{-9} M_{\odot} c^2]$	AdV	-	10	10	20 – 25	35 – 50
	KAGRA	-	-	0 – 10	10 – 30	30+

Abbott et al. 2020, LRR

GW sky localization for CBC

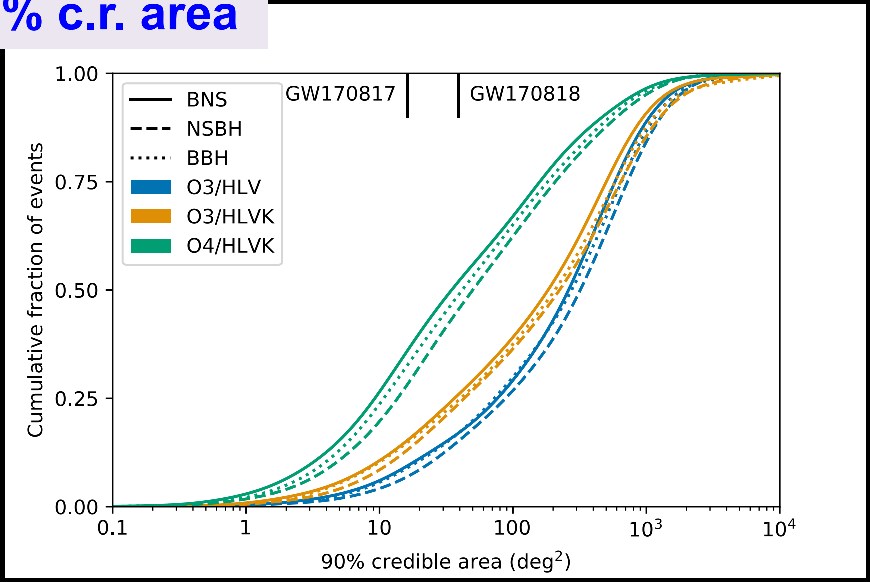
90% c.r. area



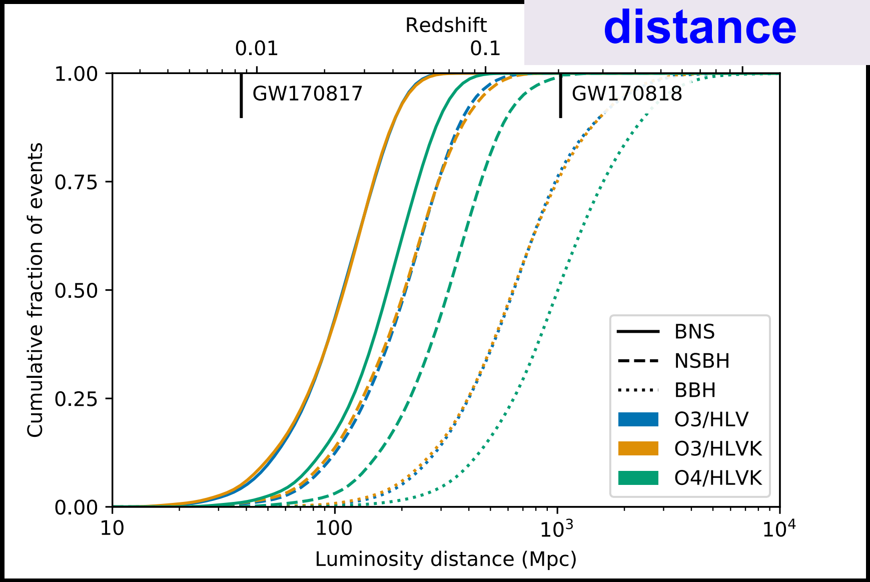
Abbott et al. 2020, LRR

GW sky localization for CBC

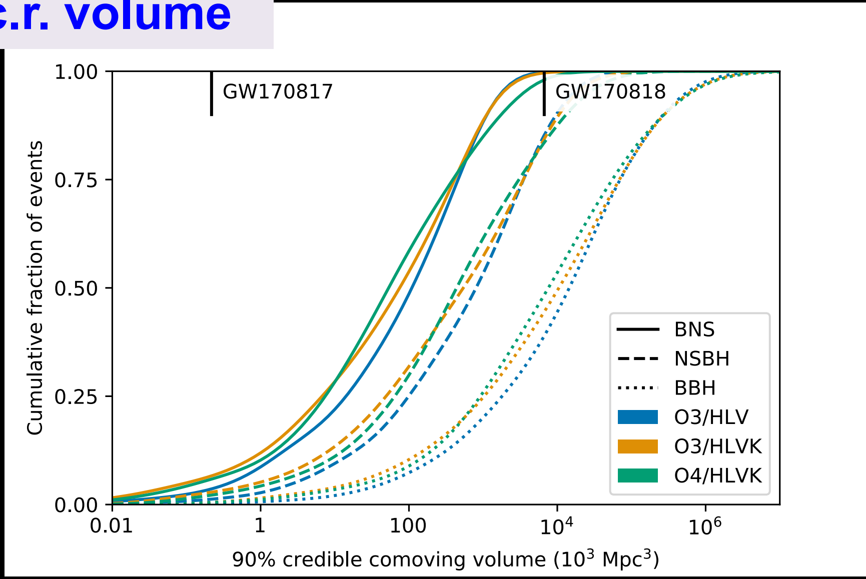
90% c.r. area



Luminosity distance



90% c.r. volume



Abbott et al. 2020, LRR

LOCALIZATION: sky-area and volume

Abbott et al. 2020, LRR

		BNS	NS-BH	BBH
		Area (deg^2) 90% c.r.	Area (deg^2) 90% c.r.	Area (deg^2) 90% c.r.
O3	HLV	270^{+34}_{-20}	330^{+24}_{-31}	280^{+30}_{-23}
O4	HLVK	33^{+5}_{-5}	50^{+8}_{-8}	41^{+7}_{-6}
		Comoving Volume (10^3 Mpc^3) 90% c.r.	Comoving Volume (10^3 Mpc^3) 90% c.r.	Comoving Volume (10^3 Mpc^3) 90% c.r.
O3	HLV	120^{+19}_{-24}	860^{+150}_{-150}	16000^{+2200}_{-2500}
O4	HLVK	52^{+10}_{-9}	430^{+100}_{-78}	7700^{+1500}_{-920}

Detection: SNR > 4 in at least two detectors and network SNR > 12

- O4 HLVK → median sky localization a few tens of square degrees
- 38-44% (12 - 16 %) BNS are expected to have a 90% credible region smaller than 20 deg^2 (5 deg^2)

O1, O2, O3 astrophysical Implications: merger rate

Population-level analyses of all-GWTC-2 reveals

- BBH merger rate $\mathcal{R}_{\rm BBH} = 23.9^{+14.9}_{-8.6}\,{\rm Gpc}^{-3}\,{\rm yr}^{-1}$
- BNS merger rate $\mathcal{R}_{\rm BNS} = 320^{+490}_{-240}\,{\rm Gpc}^{-3}\,{\rm yr}^{-1}$

LVC Populations paper, arXiv:2010.14533

- the BNS rate based on the two confident BNS detections: GW170817 and GW190425
- Assume a uniform BNS mass distribution between 1 Mo and 2.5 Mo with zero spins

O1, O2 Astrophysical rate → Detection rate

R_{BNS}= 110- 3840 Gpc^{-3} yr^{-1}

R_{NSBH}= 0.6 - 1000 Gpc^{-3} yr^{-1}

R_{BBH}= 25 - 109 Gpc^{-3} yr^{-1}

Abbott et al. 2020, LRR

EXPECTED NUMBER OF DETECTIONS FOR O3 and O4
detection counts per one-calendar-year observing run

Detection: SNR > 4 in at least two detectors and network SNR > 12

Observation Run	Network	Expected BNS Detections	Expected NSBH Detections	Expected BBH Detections
O3	HLV	1^{+12}_{-1}	0^{+19}_{-0}	17^{+22}_{-11}
O4	HLVK	10^{+52}_{-10}	1^{+91}_{-1}	79^{+89}_{-44}

LVC Populations paper, arXiv:2010.14533

R_{BNS}= 110- 3840 Gpc^{-3} yr^{-1}

R_{BBH}= 25 - 109 Gpc^{-3} yr^{-1}

O1, O2 Astrophysical rate

EXPECTED NUMBER OF DETECTIONS FOR O3 and O4
detection counts per one-calendar-year observing run

Observation Run	Network	Expected BNS Detections	Expected BBH Detections
O3	HLV	1^{+12}_{-1}	17^{+22}_{-11}
O4	HLVK	→ 10^{+52}_{-10}	100 79^{+89}_{-44}

Detection: SNR > 4 in at least two detectors and network SNR > 12
About FAR < 1/100 yr

Abbott et al. 2020, LRR

	BNS	BBH
O3a	1	36

About network SNR > 8

LVC Populations paper, arXiv:2010.14533

R_{BNS}= 80 - 810 Gpc^{-3} yr^{-1}

R_{BBH}= 15 - 39 Gpc^{-3} yr^{-1}

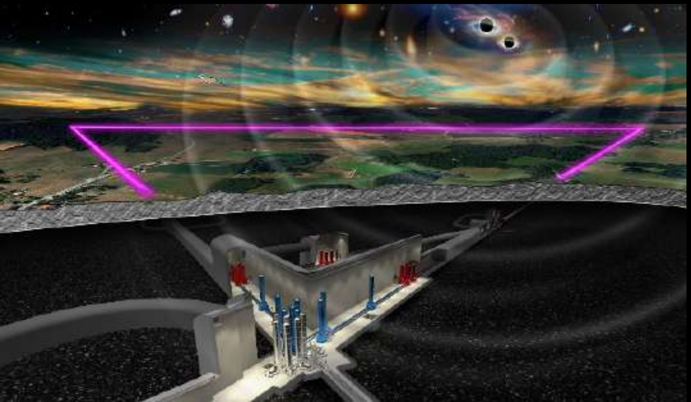
O1, O2, O3 Astrophysical rate

3G detector

The European 3G idea

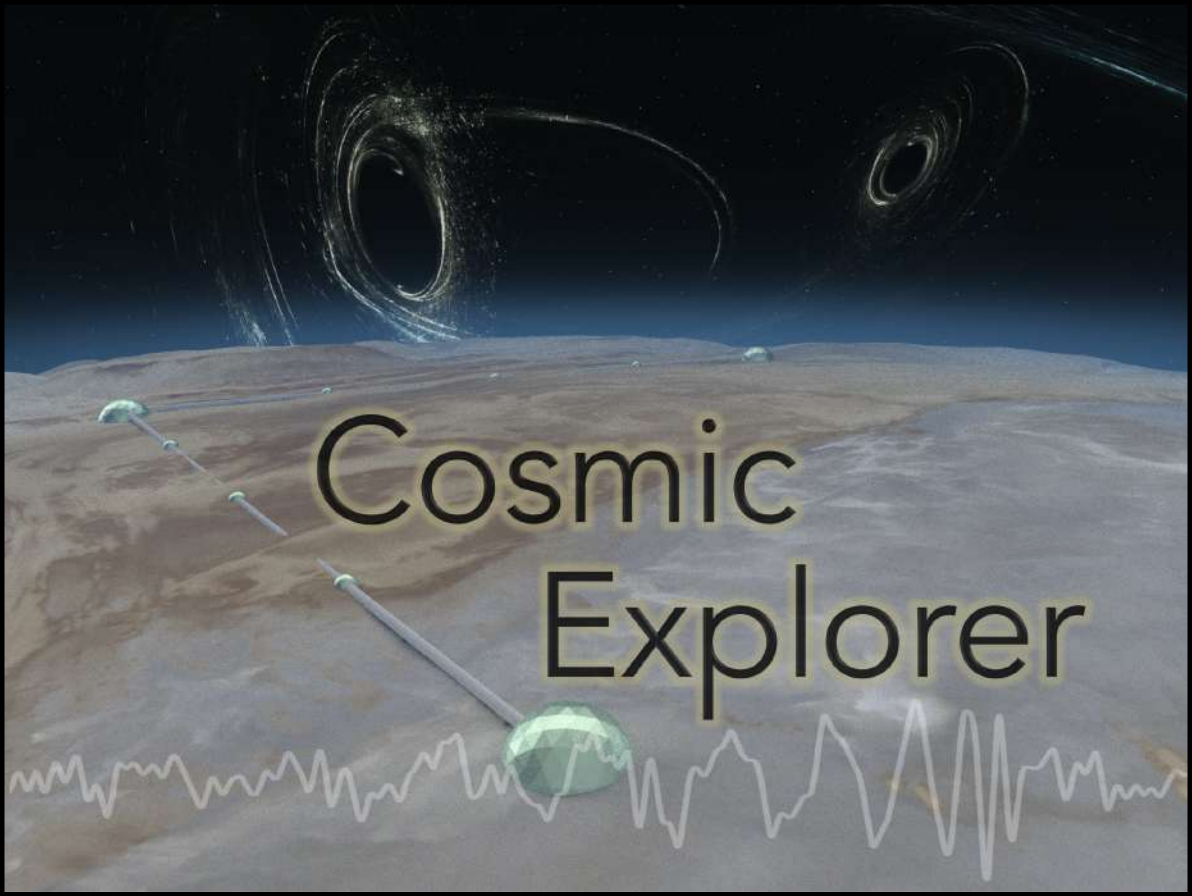
Europe we developed the idea of a 3G GW observatory

- Factor 10 better (x1000 Volume) than Advanced (2G) detectors
- Wide frequency, with special attention to low frequency (few HZ)
- Capable to work alone (but aiming to be in a 3G network)
- 50-years lifetime of the infrastructure

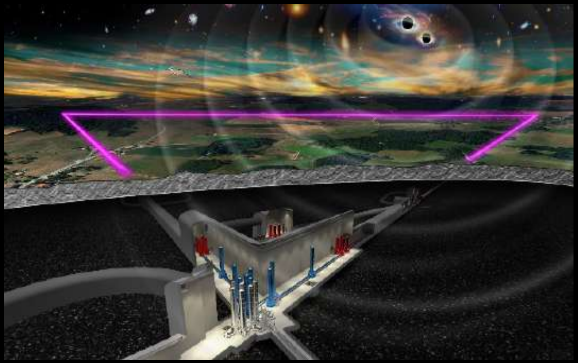


Recently submitted ESFRI proposal

3G effort worldwide

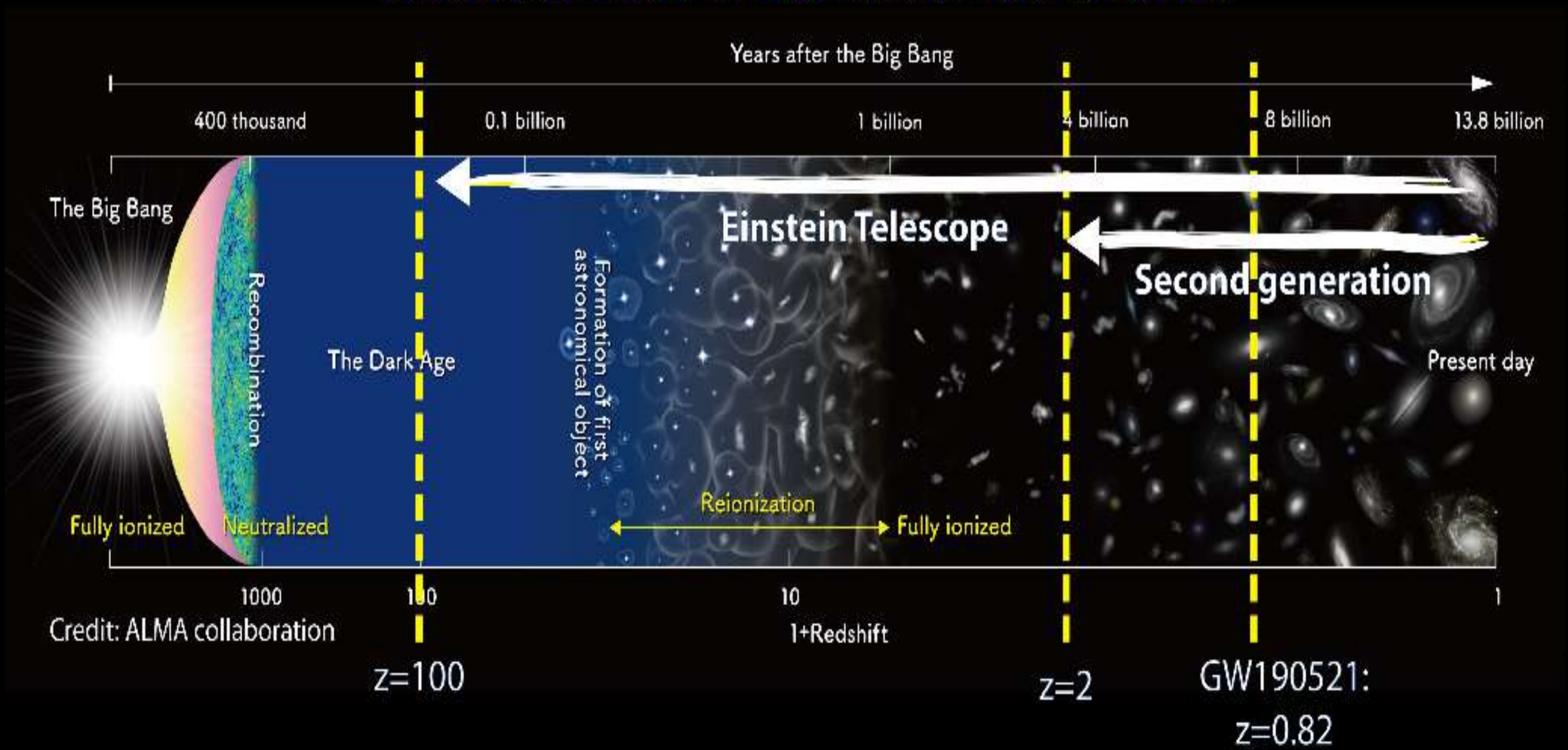


NSF funded in 2018 the Conceptual Design Study of a 3G facility: Cosmic Explorer: 40km – L shaped detector

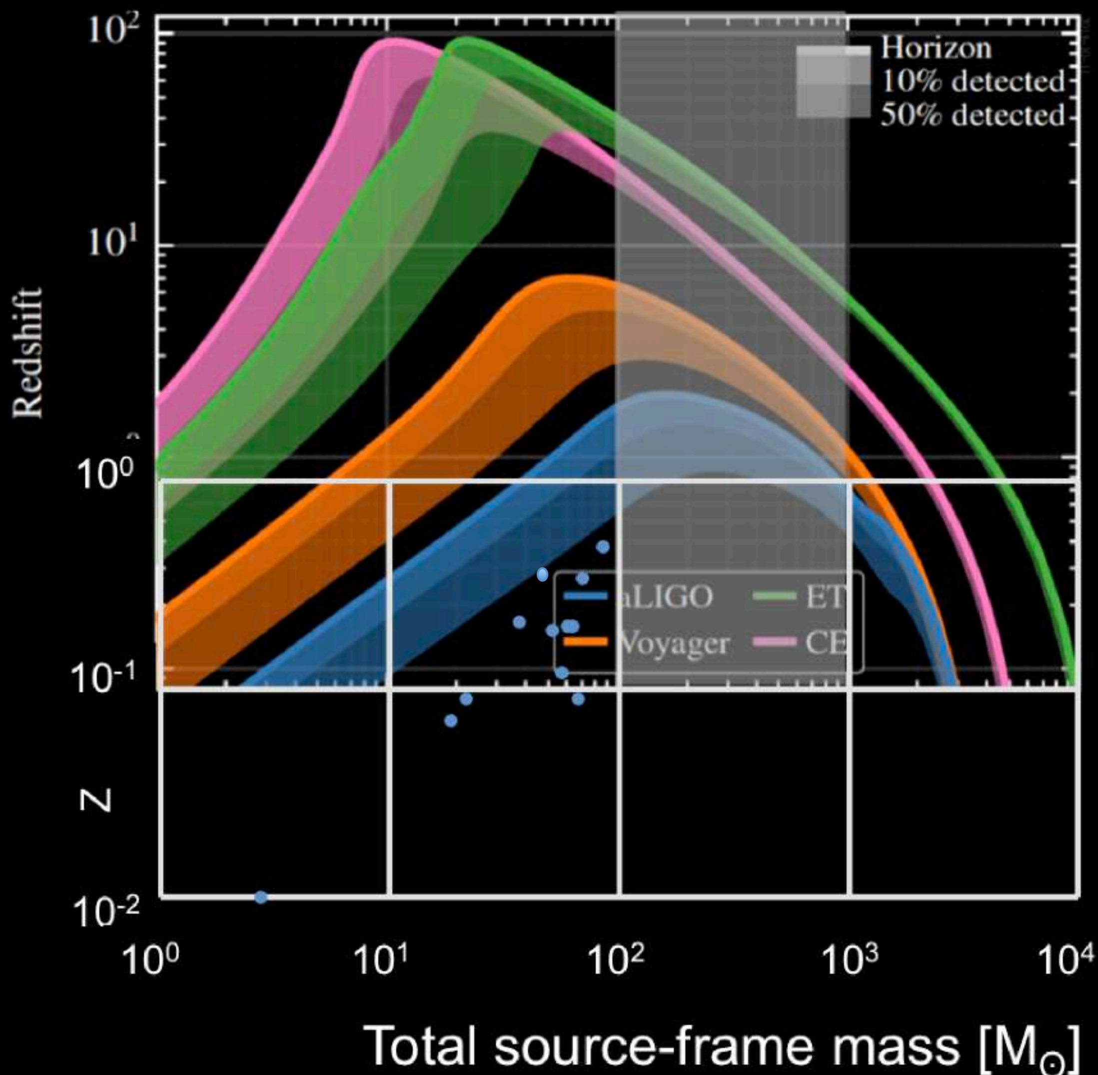


Einstein Telescope

Detection horizon for black-hole binaries



Binary systems of Compact Objects



Primordial BH?

BBHs from POP3 stars merger?

Imtermediate Massive BHs?

Link to Star Formation History

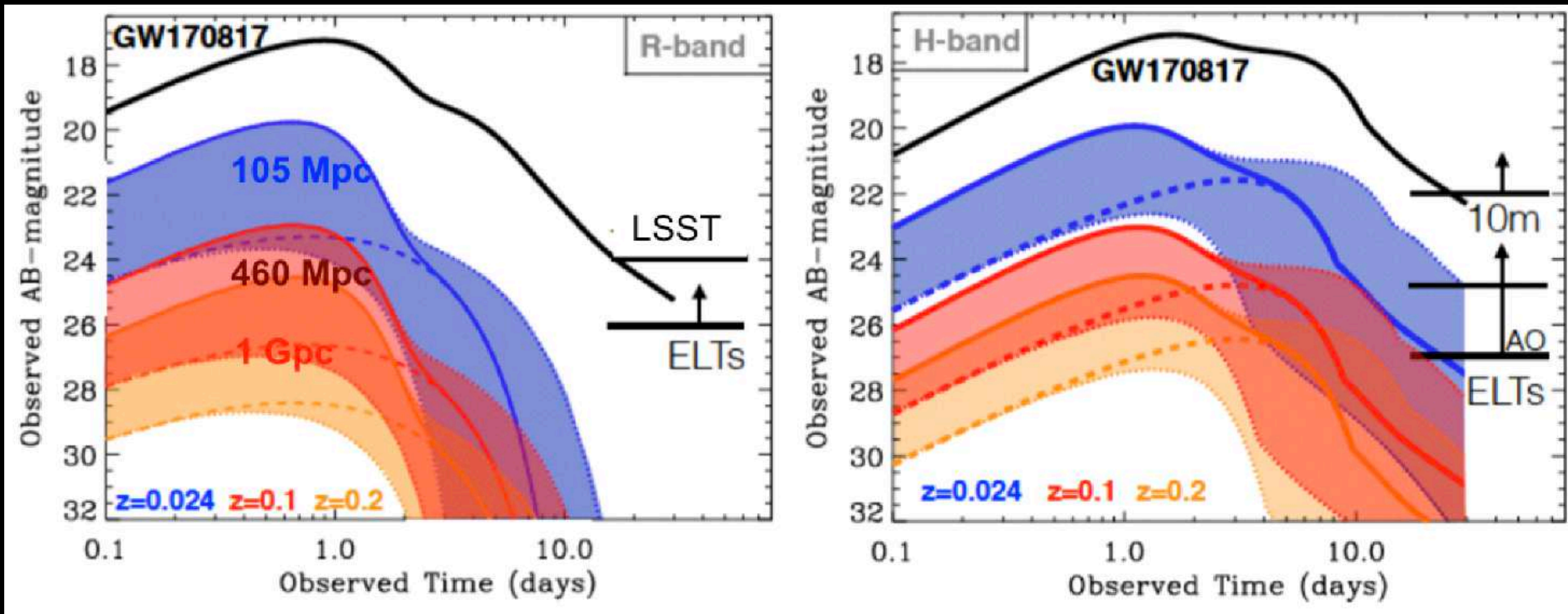
GRBs – BNS/NSBH merger high z?

About 10^5 NS-NS per year

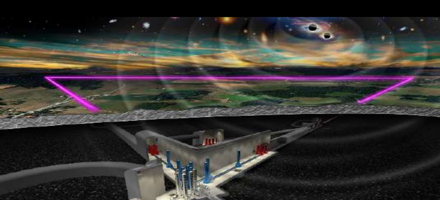
WHY HIGH-ENERGY?

OPTICAL BAND

Adapted from Chornock+ 2019



- Too faint counterpart
- Large sky-localization/many contaminants

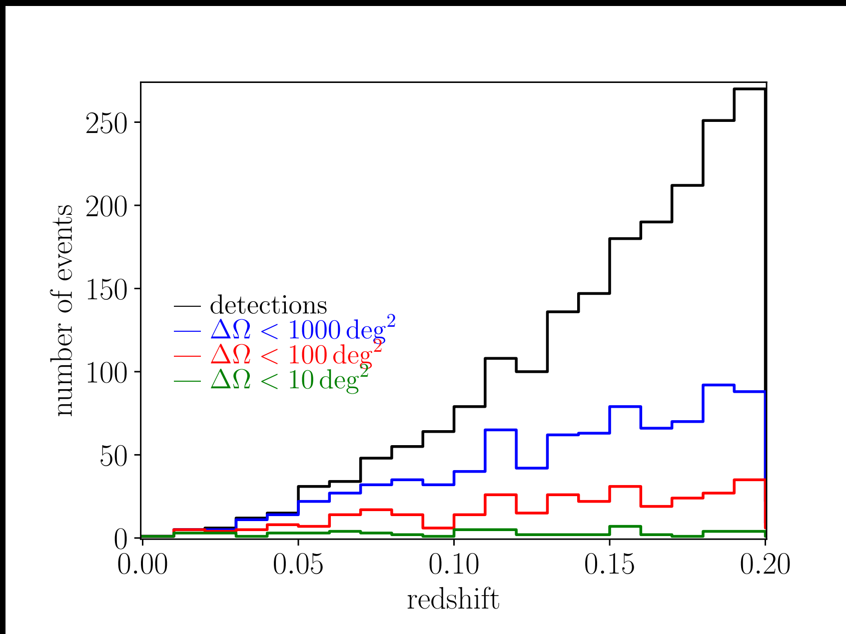


Rubin Observatory

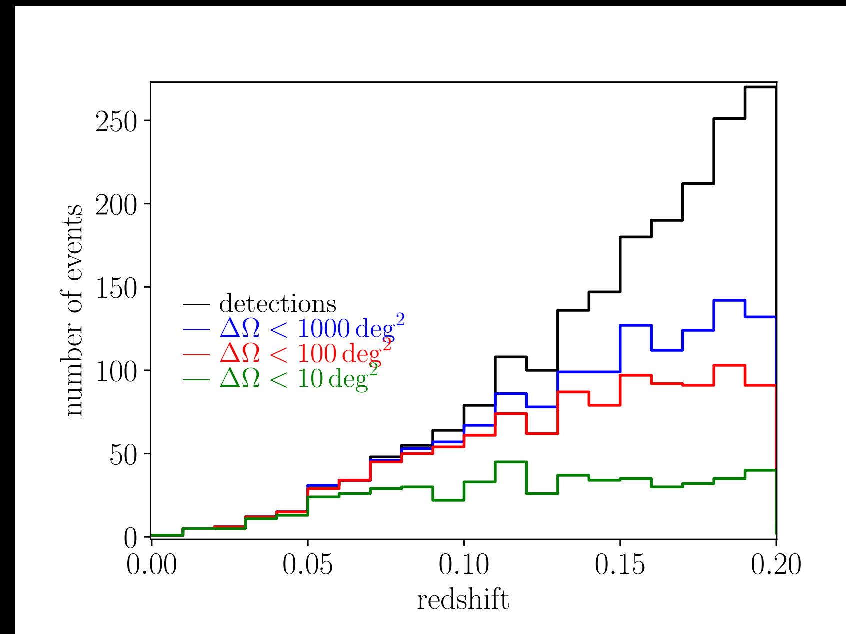
Joint detections for ET limited by optical instruments capabilities!!

EINSTEIN TELESCOPE SKY LOCALIZATION

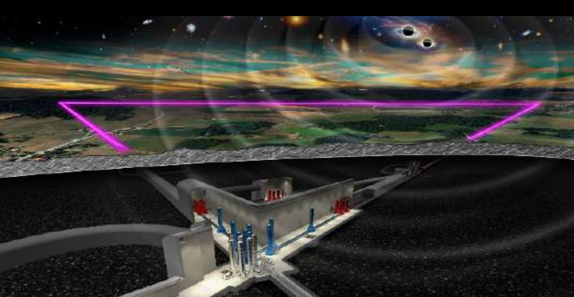
ET



ET+LIGO/Virgo/KAGRA/LIGOindia



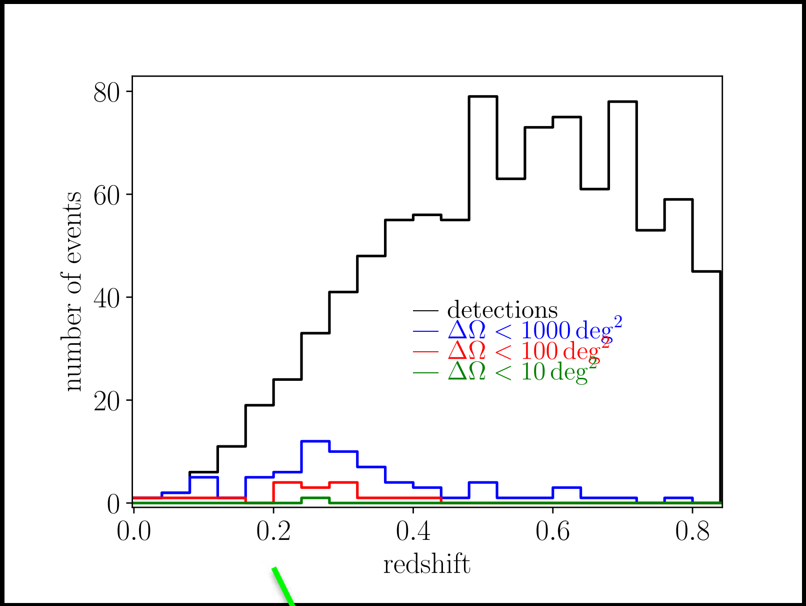
1 year of observations



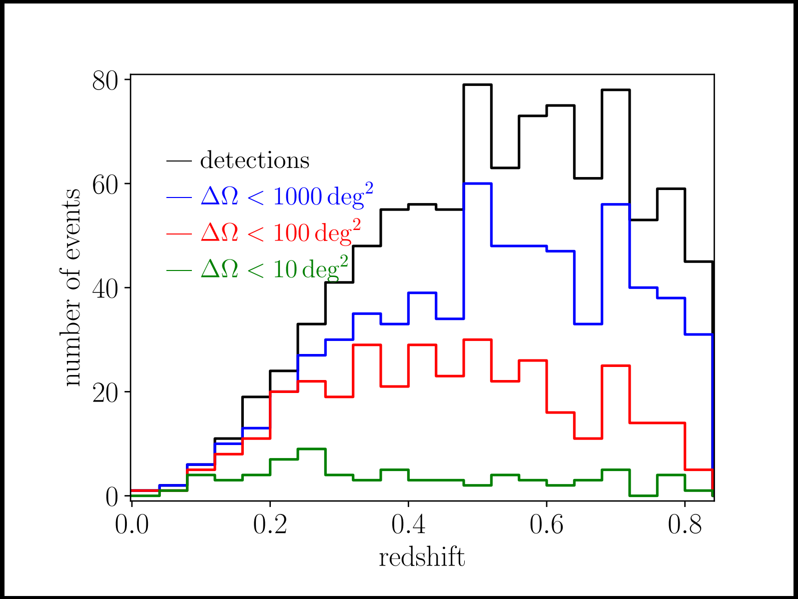
Prelimiary results by Stefan Grimm, GSSI

EINSTEIN TELESCOPE SKY LOCALIZATION

ET

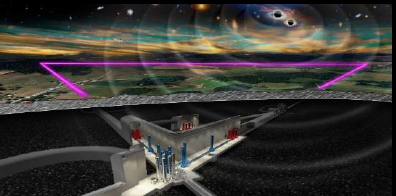


ET+CE



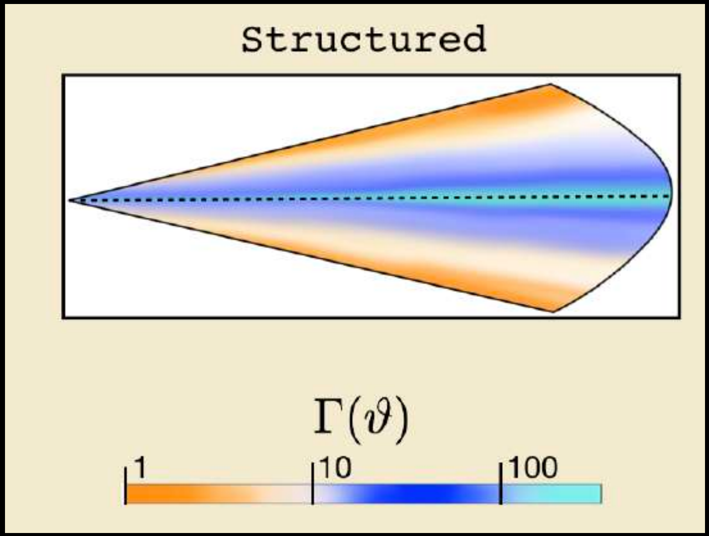
1 week of observations

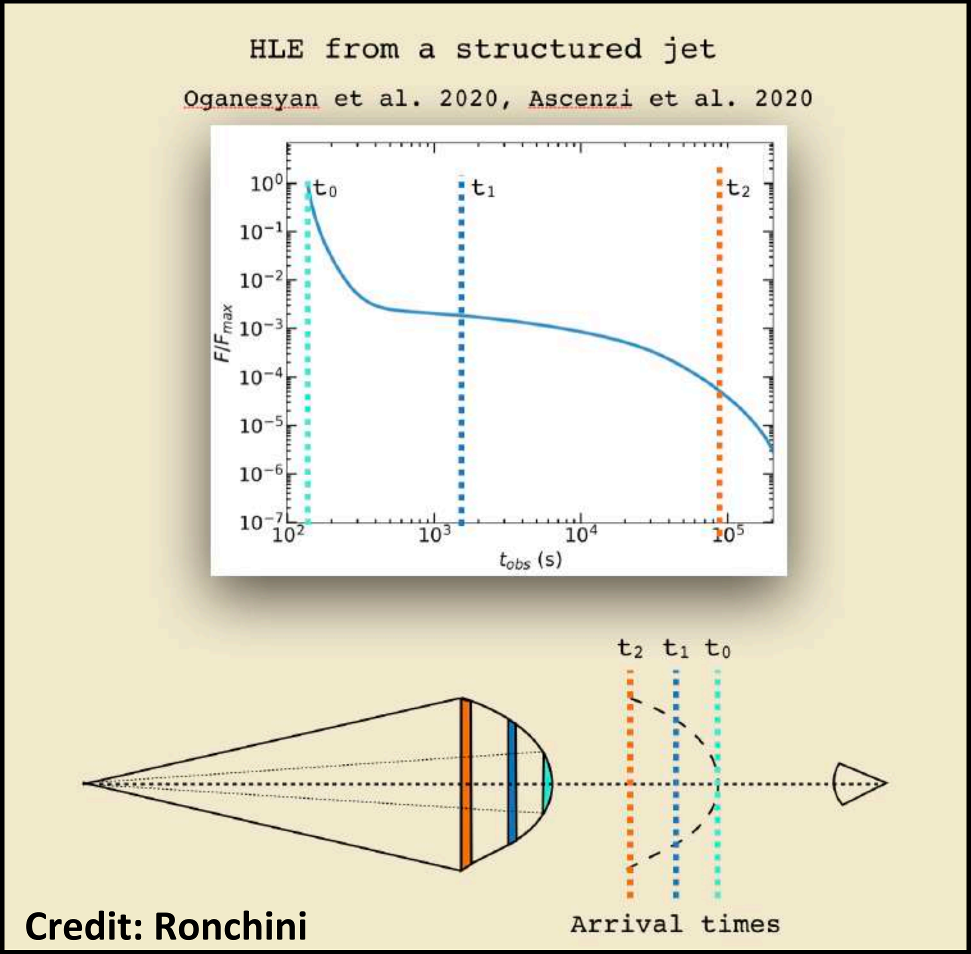
At z larger than 0.2 sky-localization from GRBs!

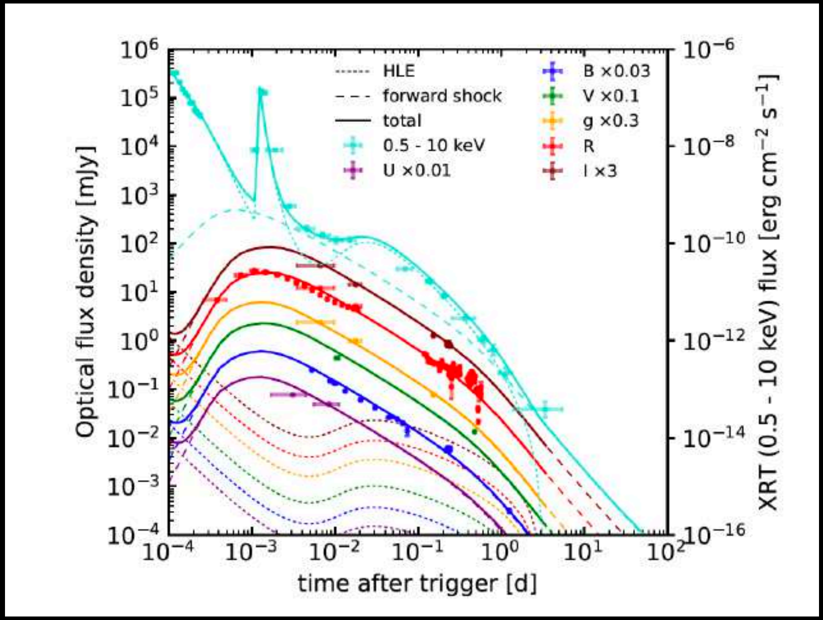


Prelimiary results by Stefan Grimm, GSSI

GRB X-ray plateaus explained by structured jets

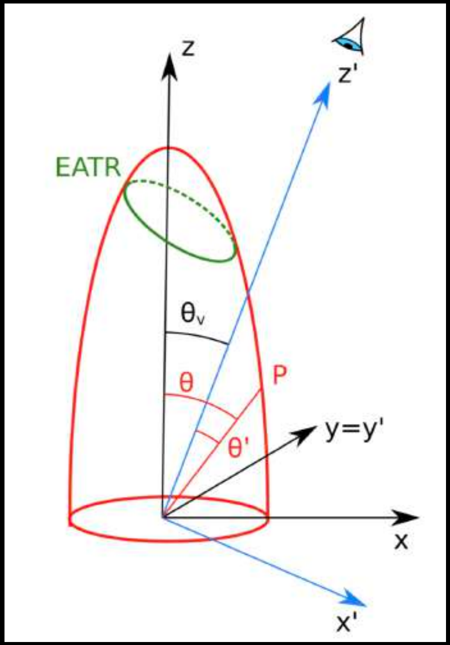


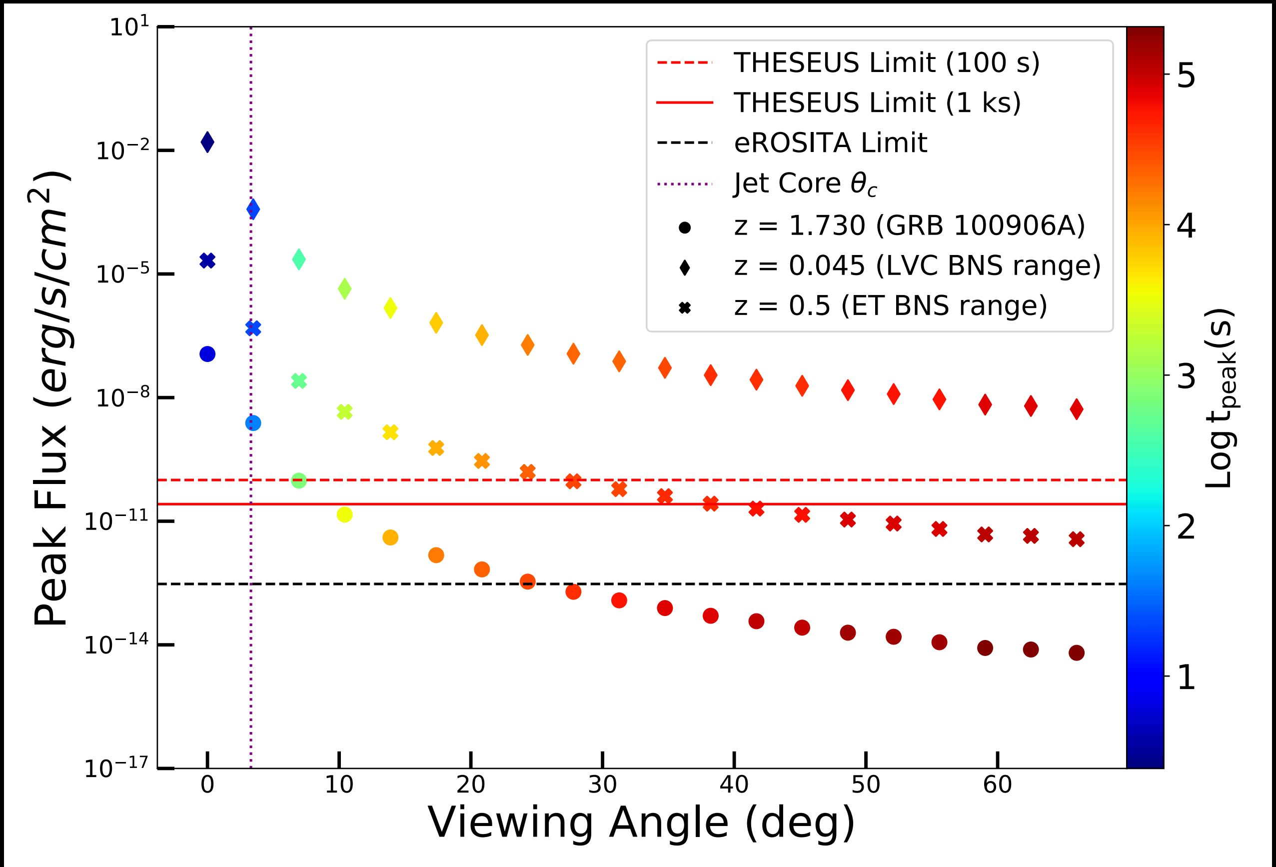




Oganesyan et al. 2020 ApJ

What happen off-axis?





Ascenzi et al. 2020 A&A

Promising X-ray couterparts!

Next decades multi-messenger observatories