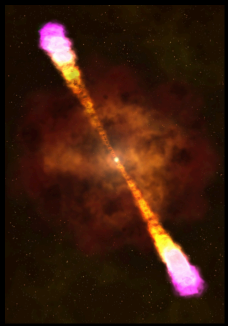
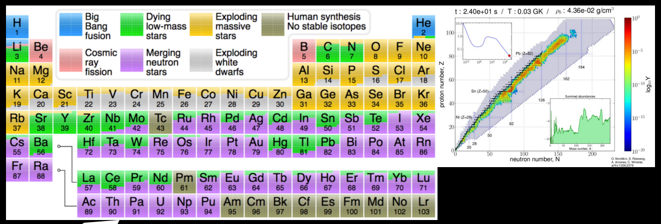
Radioactively powered transients

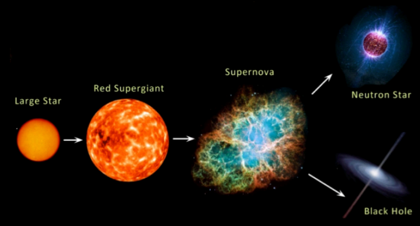
Relativistic astrophysics



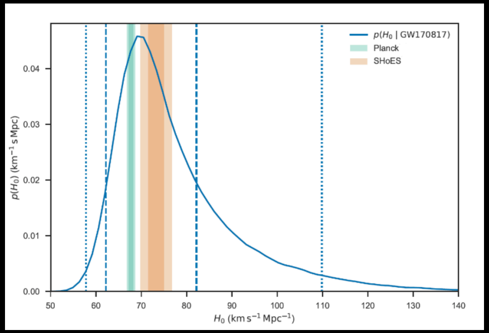
Nucleosynthesis and enrichment of the Universe



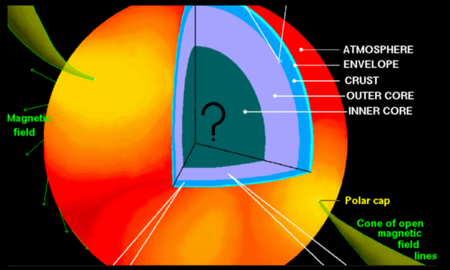
Compact object formation and evolution



Cosmology

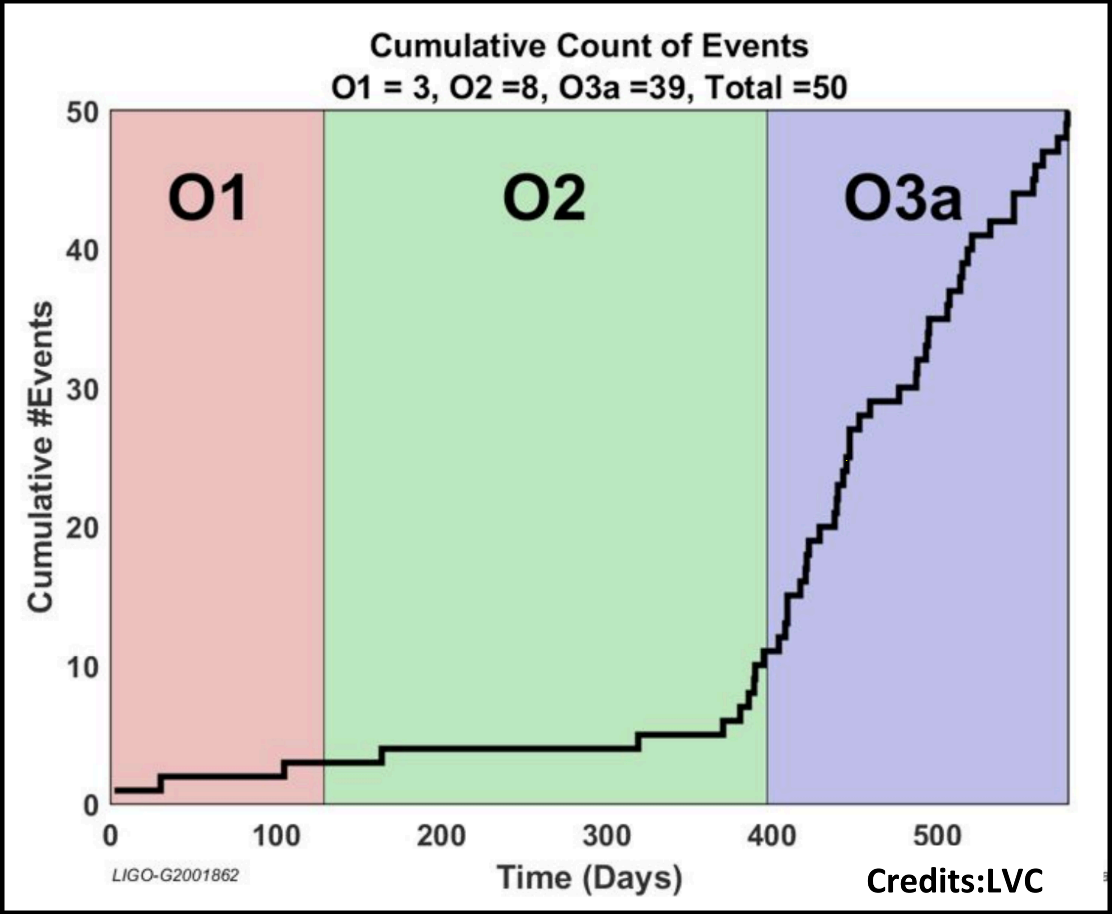


Nuclear matter physics



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

O3a Event Rate



LVC Catalog paper, arXiv: 2010.14527

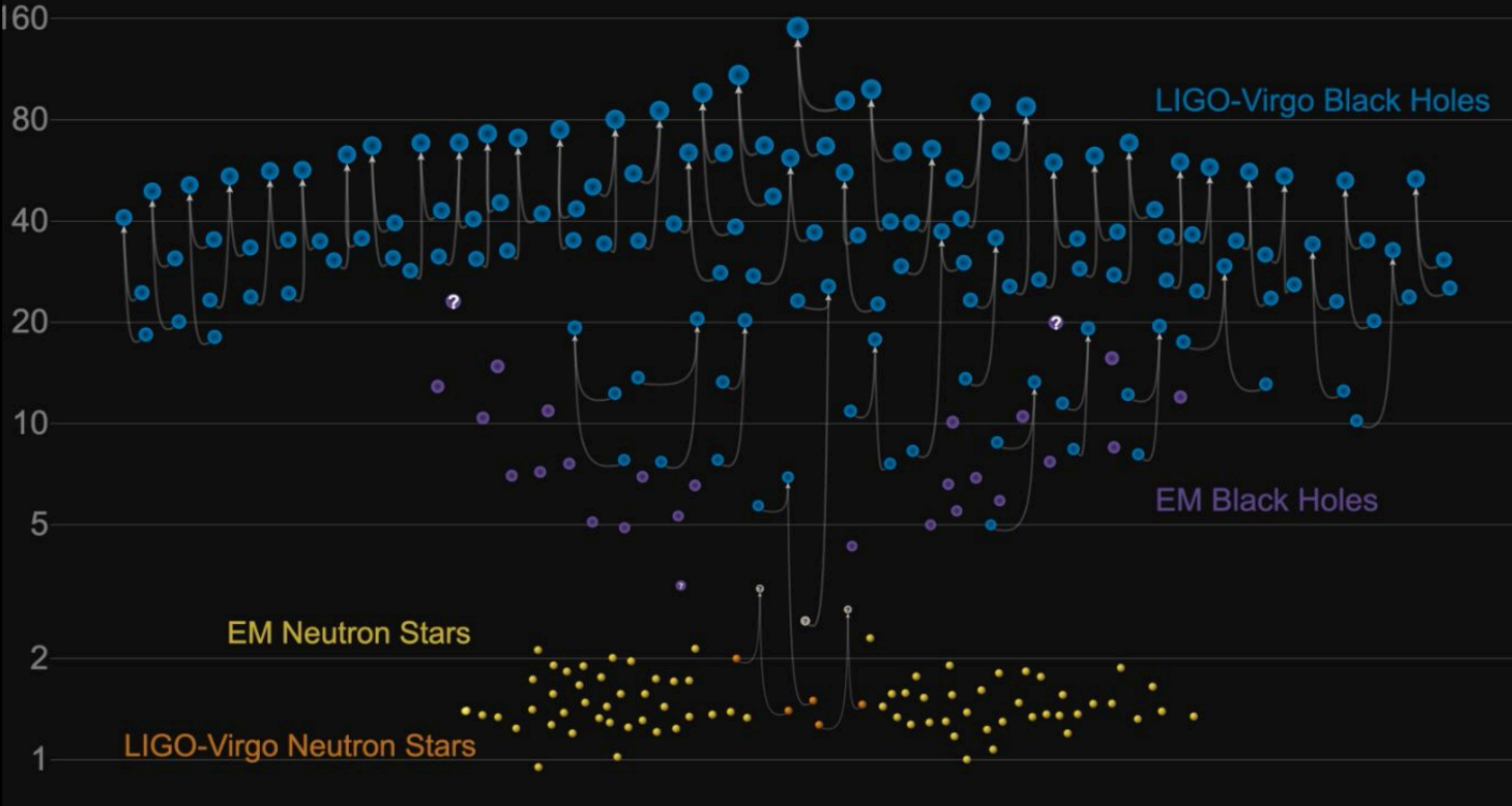
39 candidate GW events in ~26 weeks of O3a (FAR 2 per year → contamination fraction of less than 10%)

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

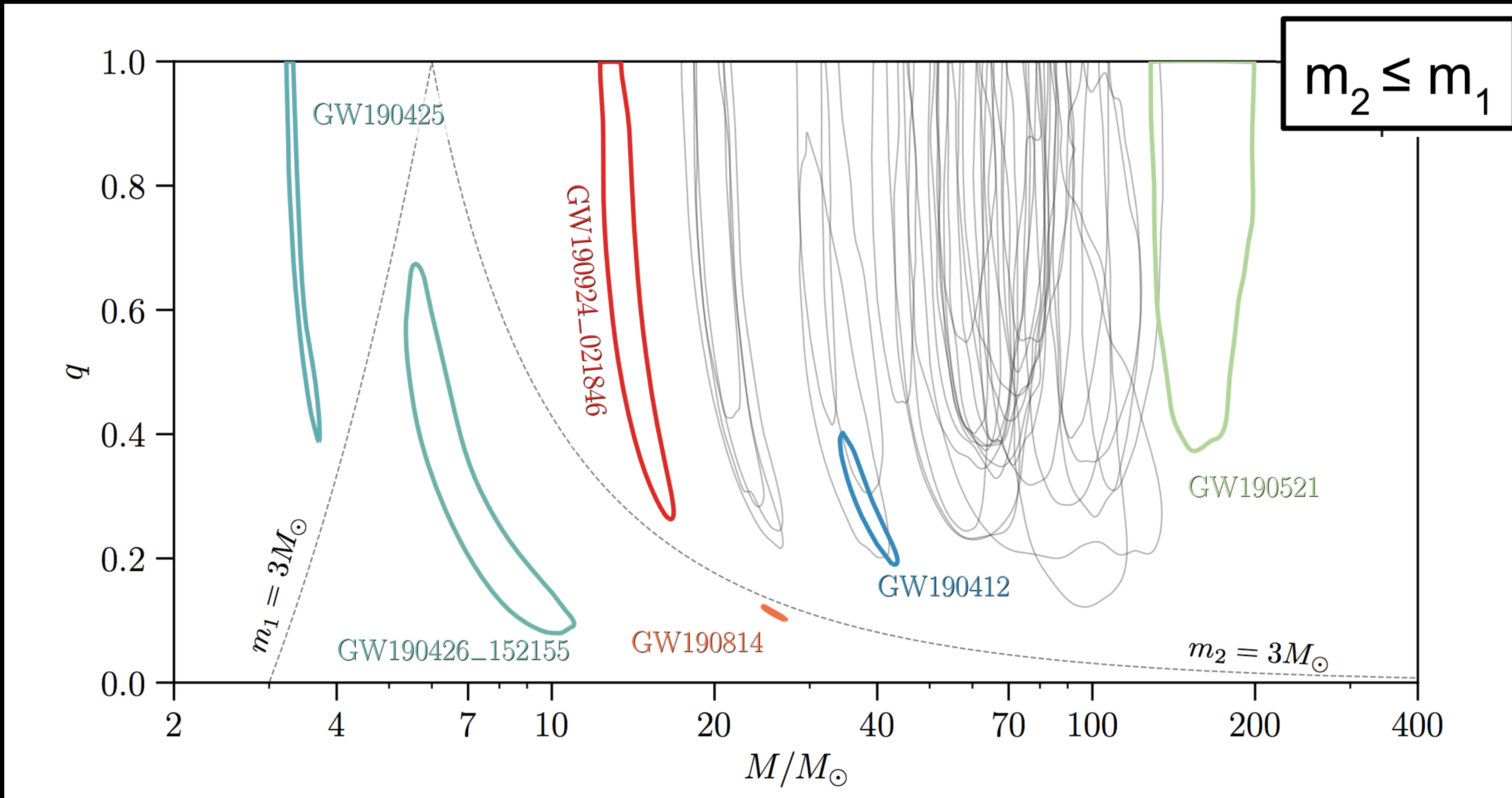
in Solar Masses



O3a

LIGO-Virgo | Frank Elavsky, Aaron Geller | Northwestern

TOTAL MASS vs MASS RATIO

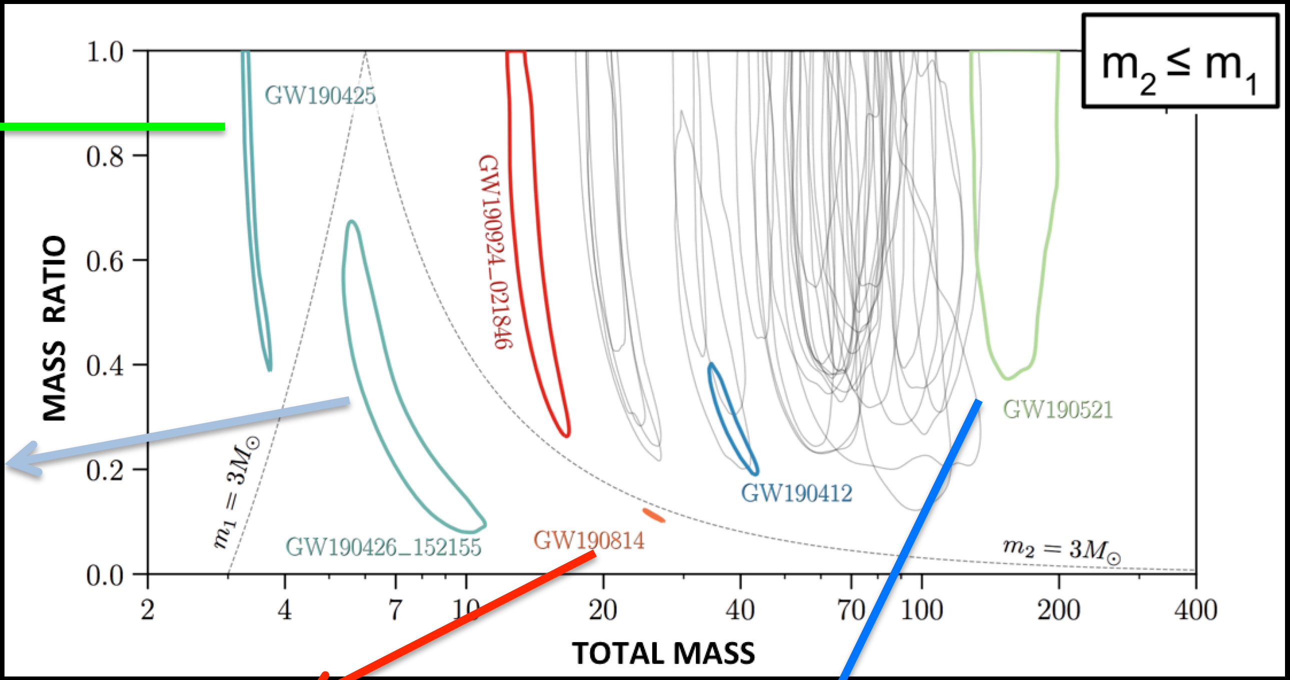


LVC Catalog paper, arXiv: 2010.14527

Notable candidate events

GW190425:
m1 and m2 < 3 Mo
Consistent with BNS

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

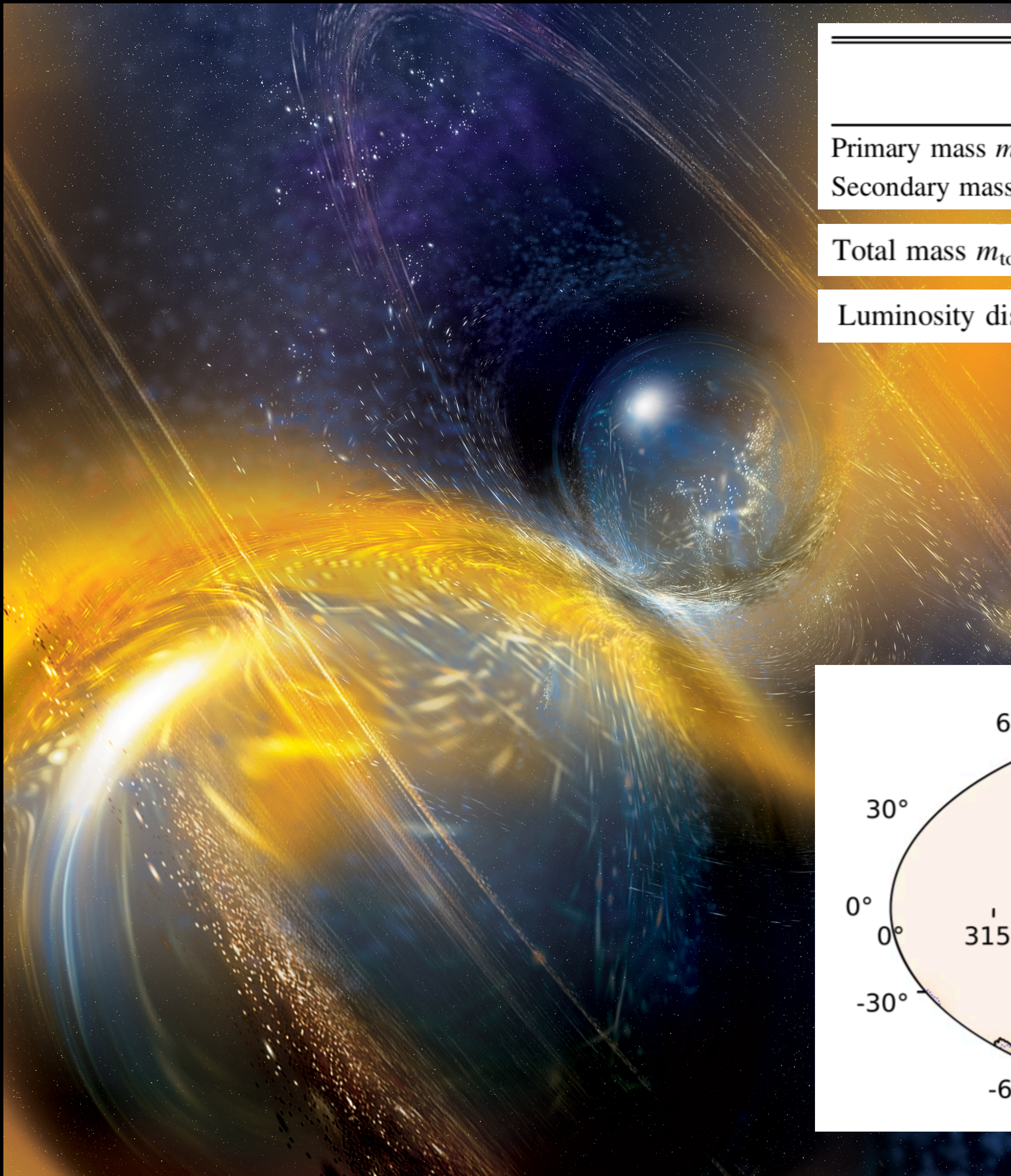


GW190814: m2 < 3Mo
NSBH or BBH?

GW190521:
most massive component BHs
→ intermediate massive BH

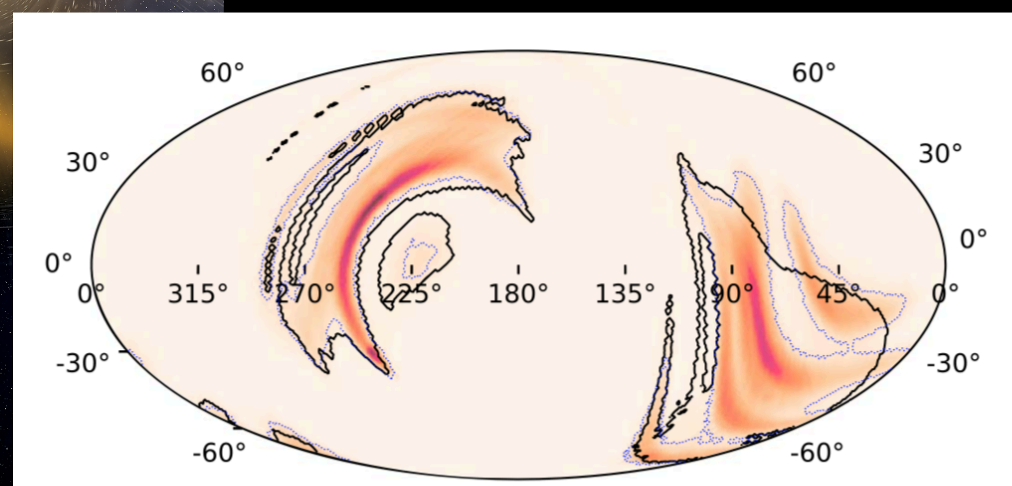
LVC Catalog paper, arXiv: 2010.14527

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

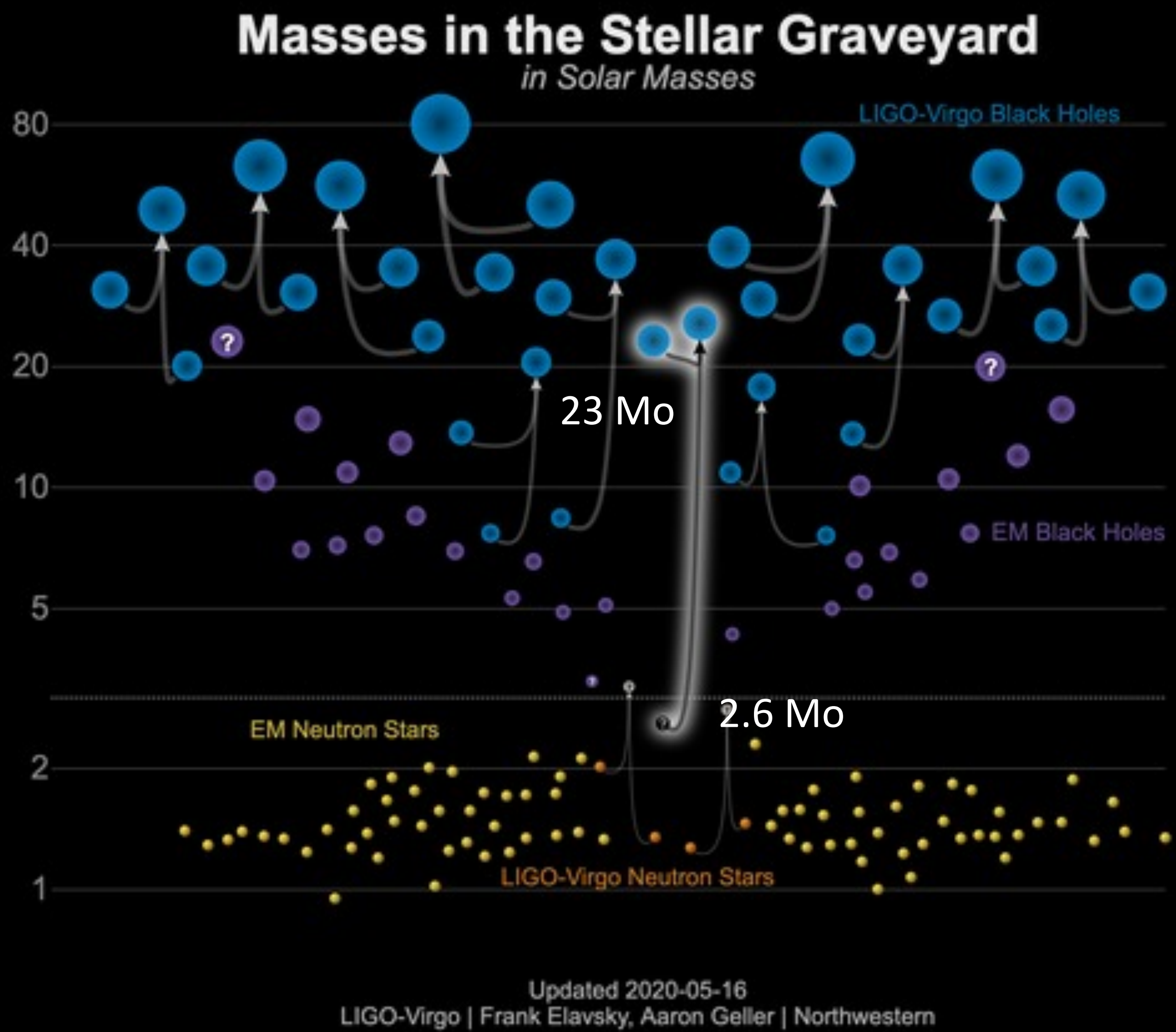
NO firm EM counterpart! ☹



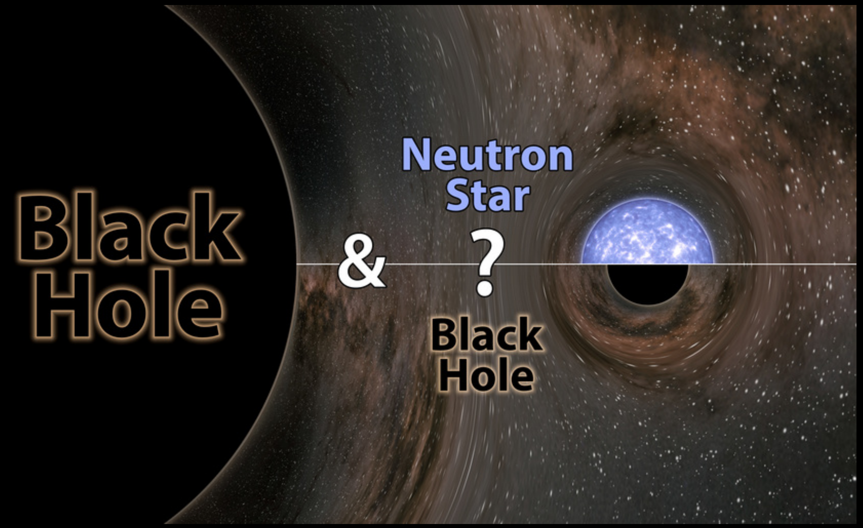
Sky localization of 8284 deg^2

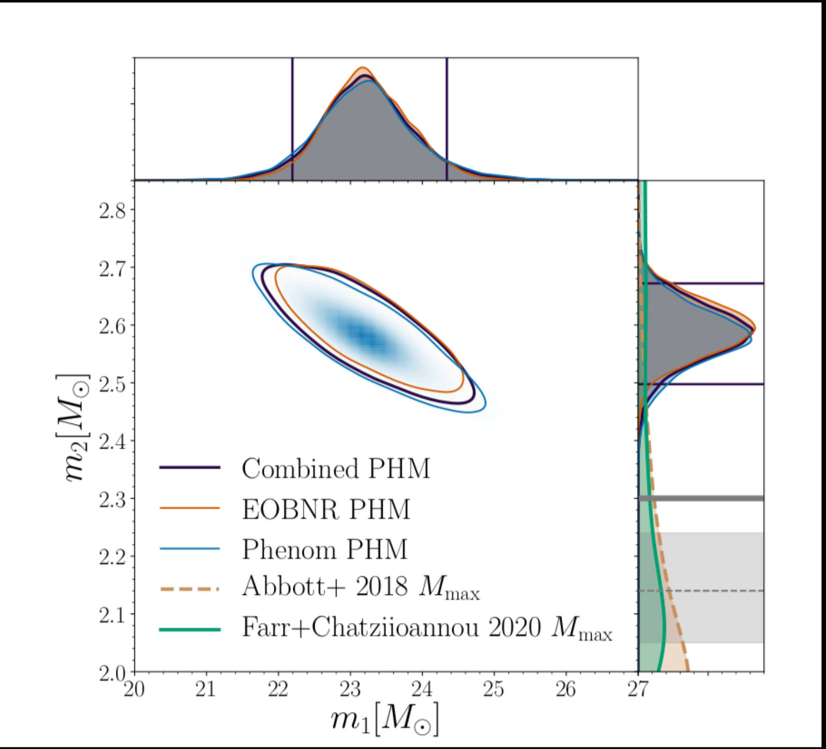
Abbott et al. 2020, ApJL, 892

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



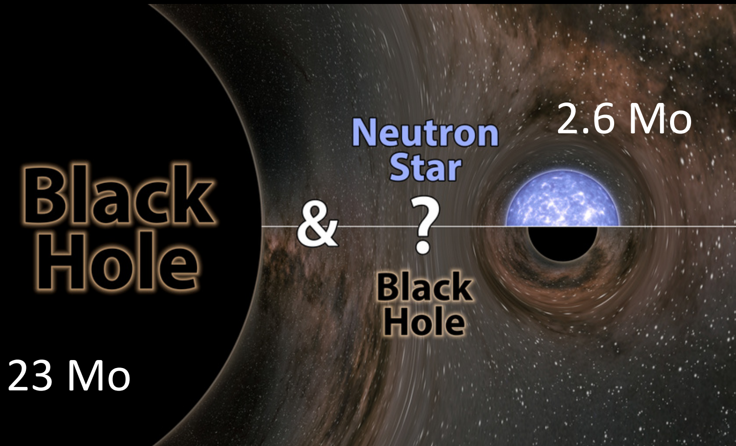
GW190814





	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

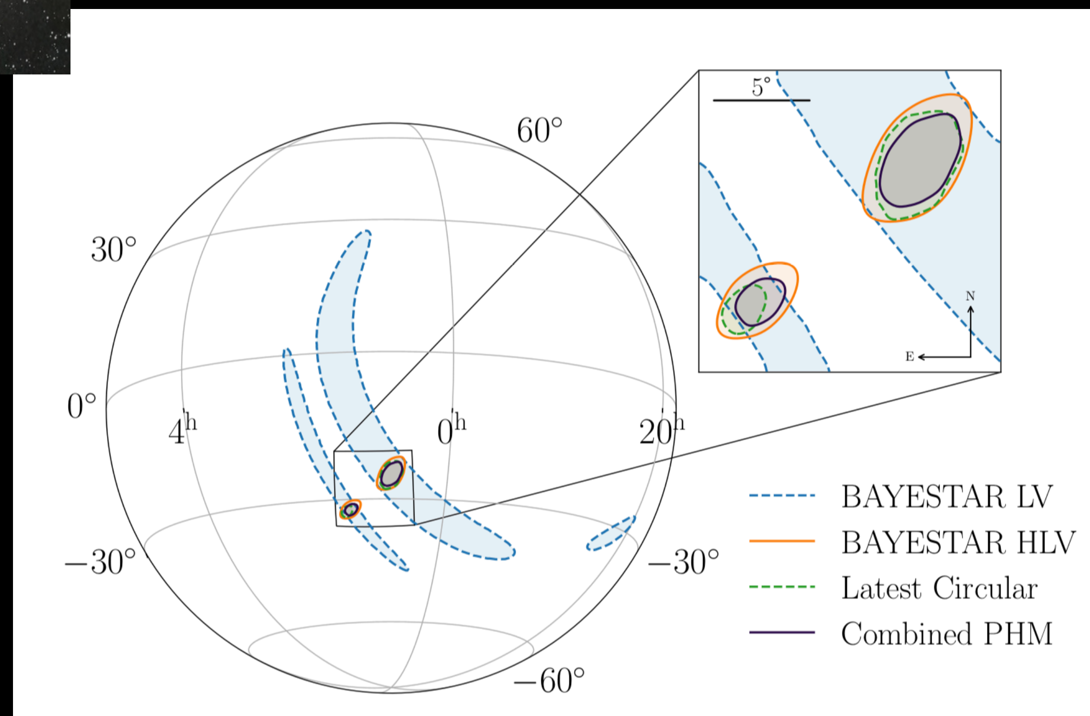


Abbott et al. 2020, ApJL, 896

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

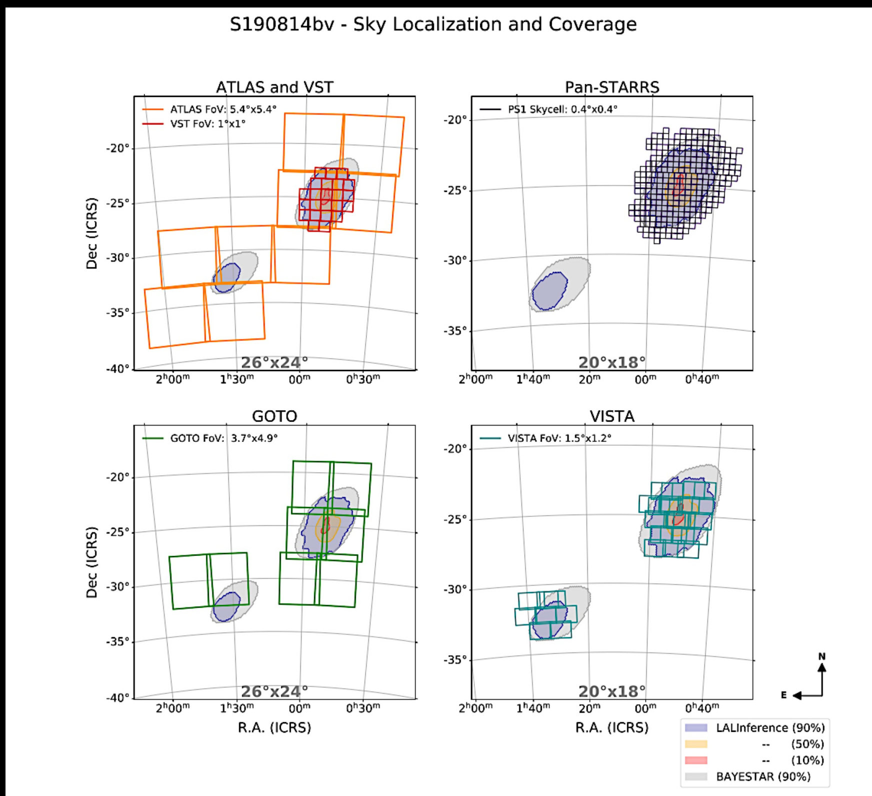
→ Consistent with both BBH and NSBH scenarios

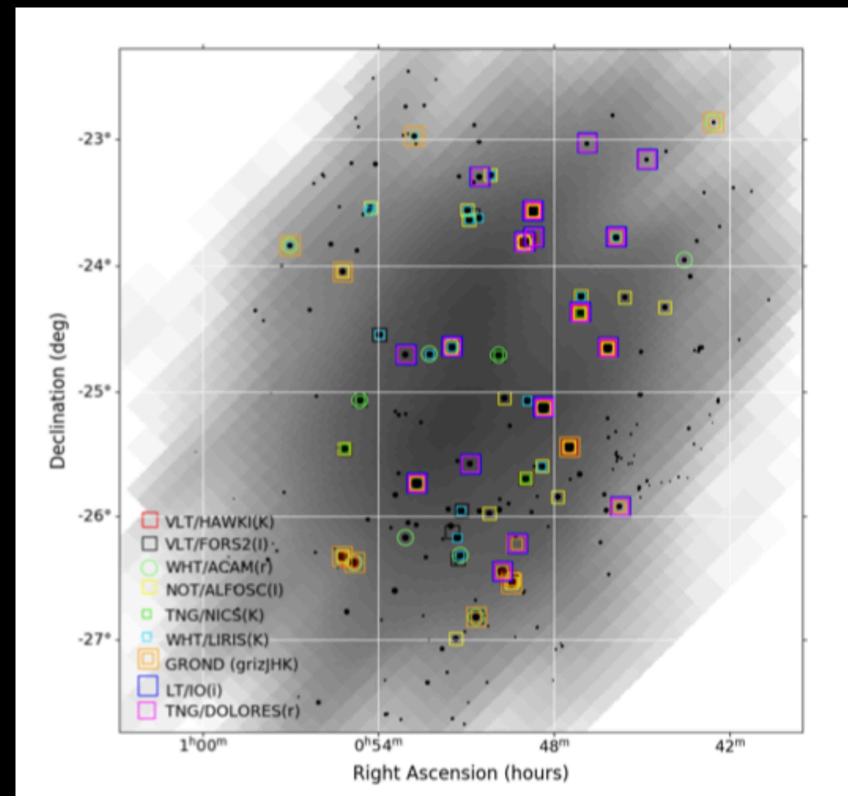
→ In the NSBH, observation results can be explained by the large mass ratio



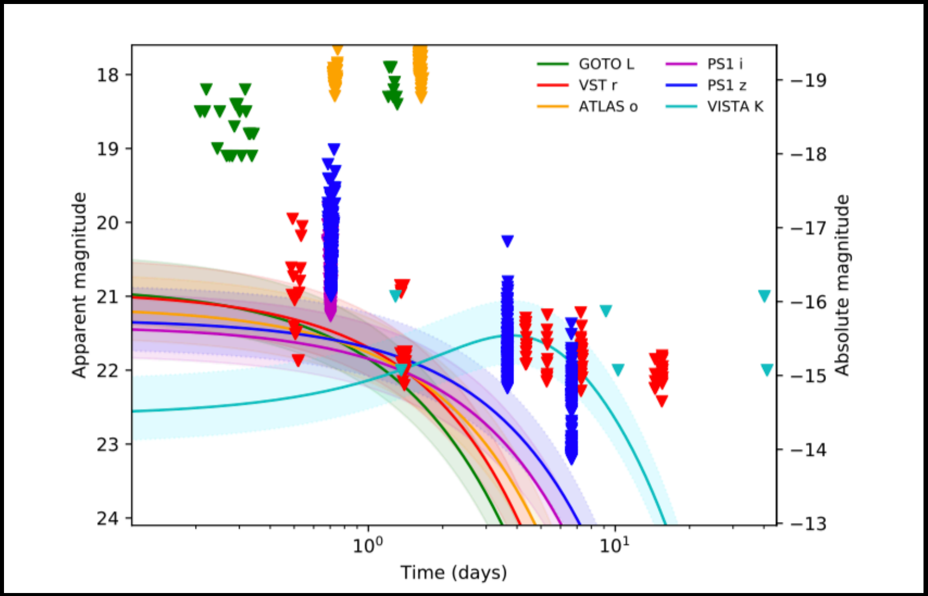
Sky localization of 18.5 deg^2

Optical counterpart search



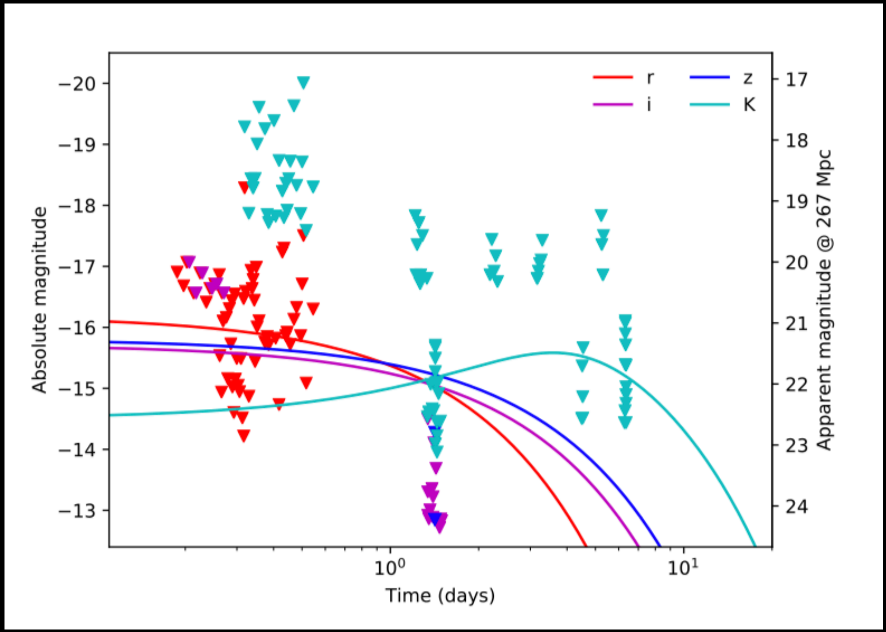


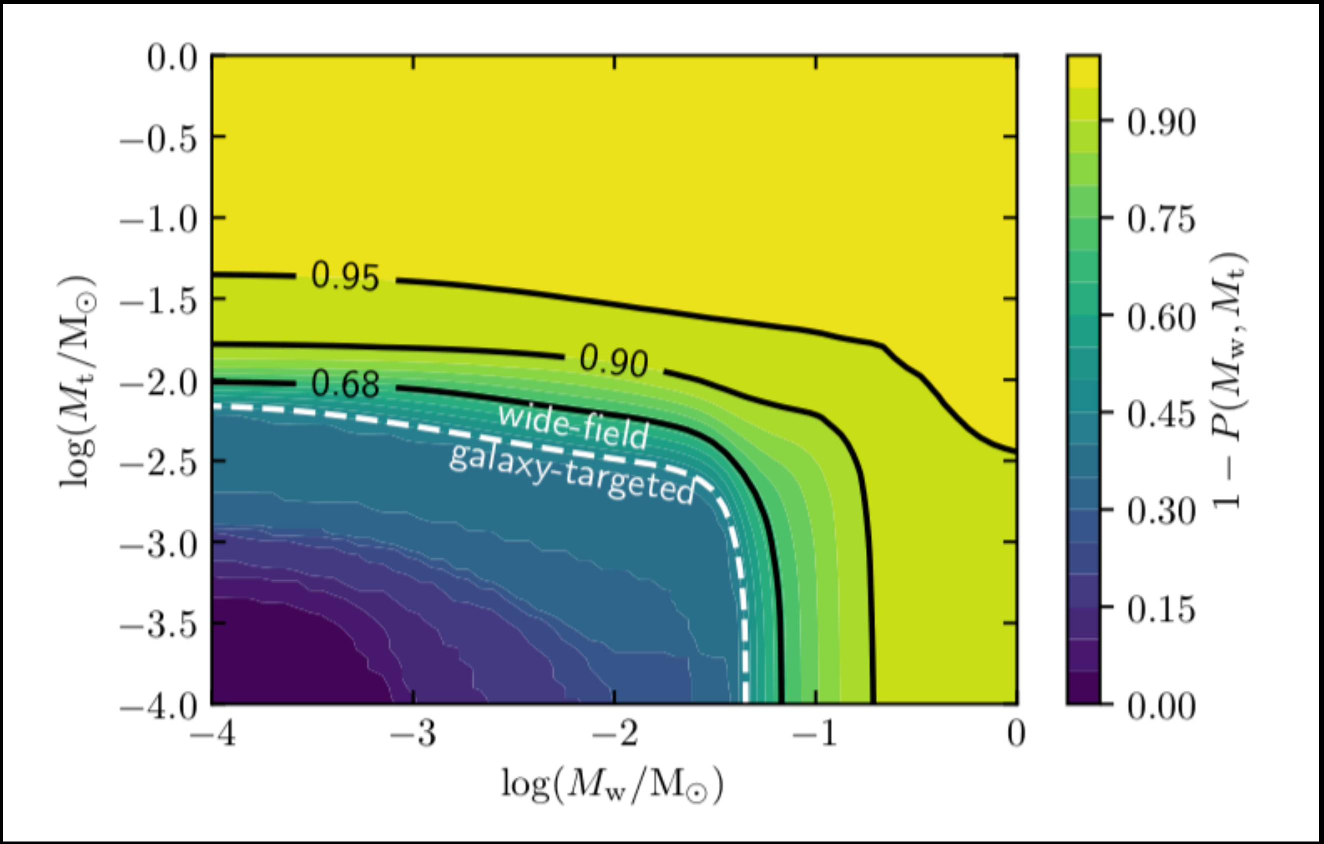
Ackley et al. 2020, A&A



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

Galaxy targeted upper limits →





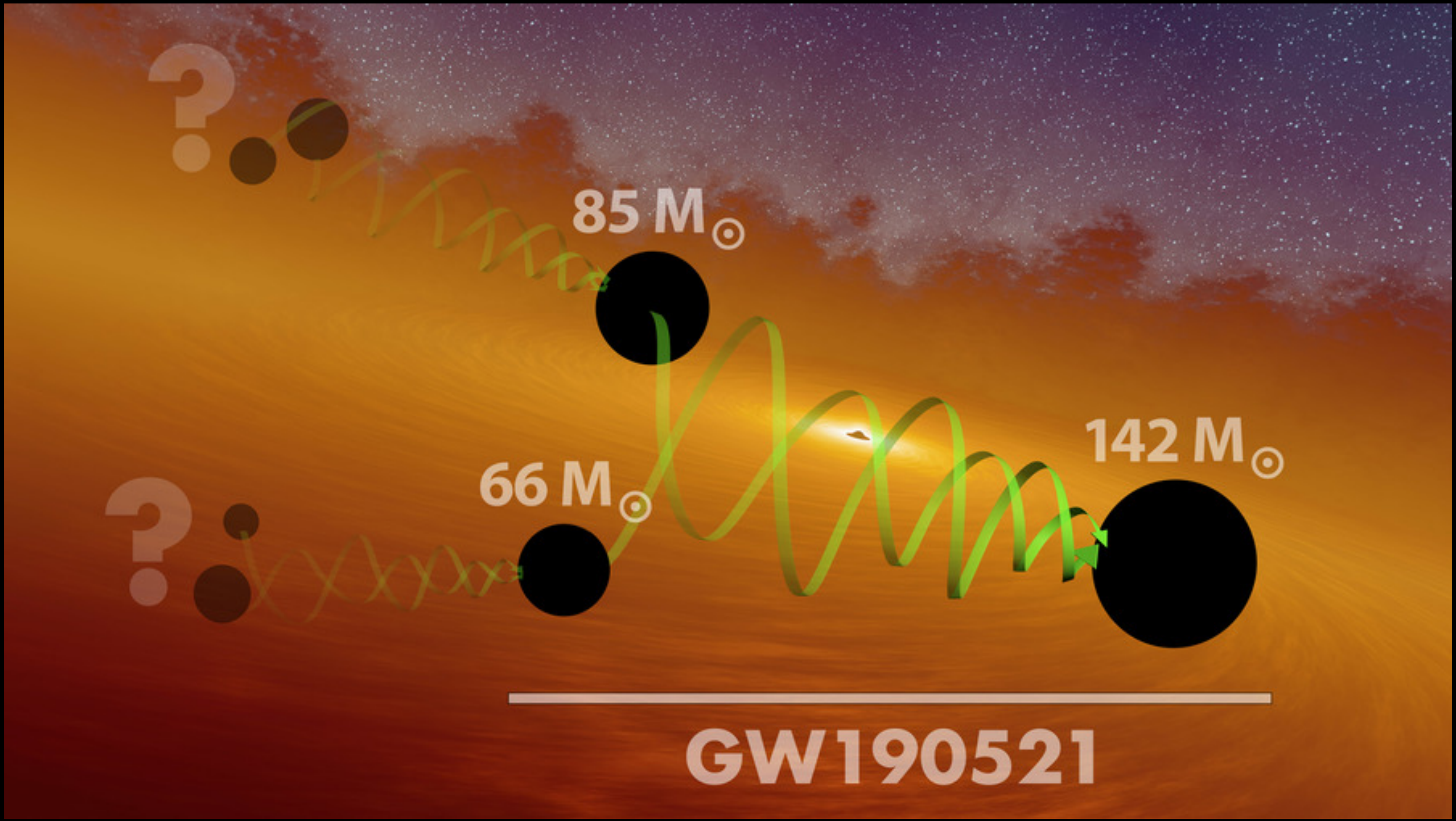
Observations allow us to exclude a KN with large ejecta mass M > 0.1 M_0 to a high (> 90%) confidence

Ackley et al. 2020, A&A

GW190521

The birth of a intermediate massive black-hole!

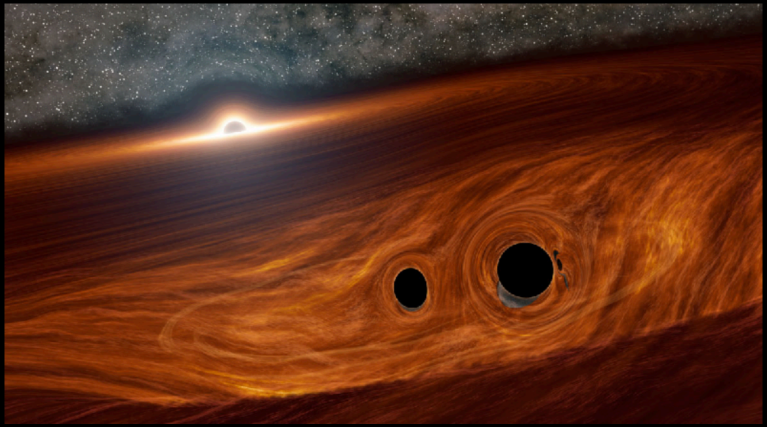
Credit: Mark Myers, ARC Centre of Excellence for Gravitational Wave Discovery (OzGrav)



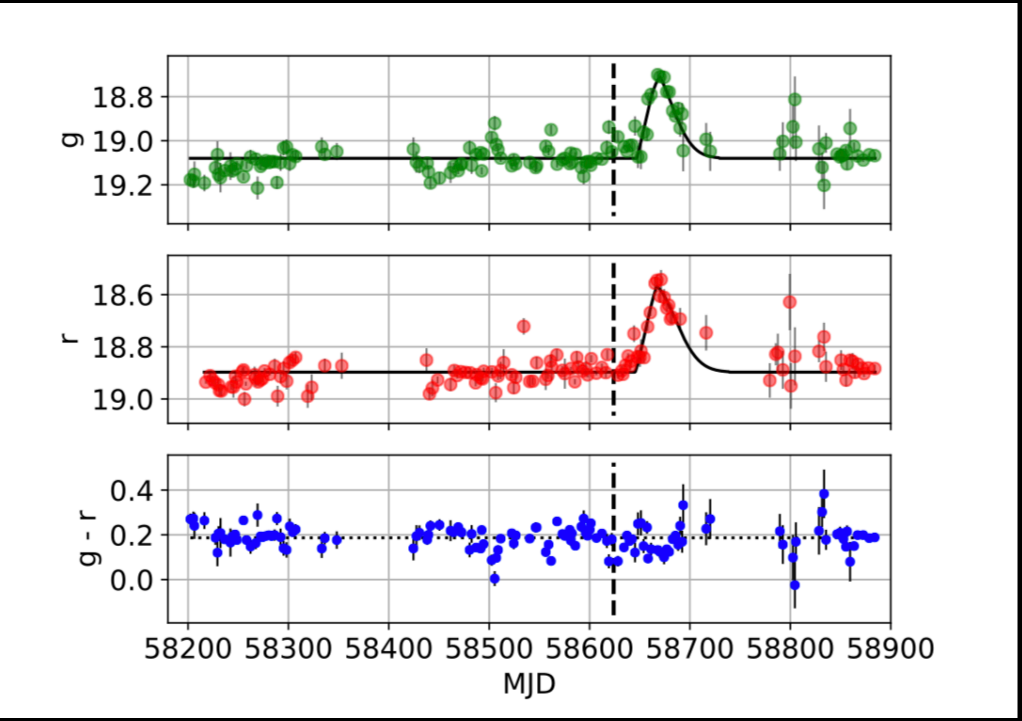
credit: LIGO/Caltech/MIT/R. Hurt (IPAC)

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

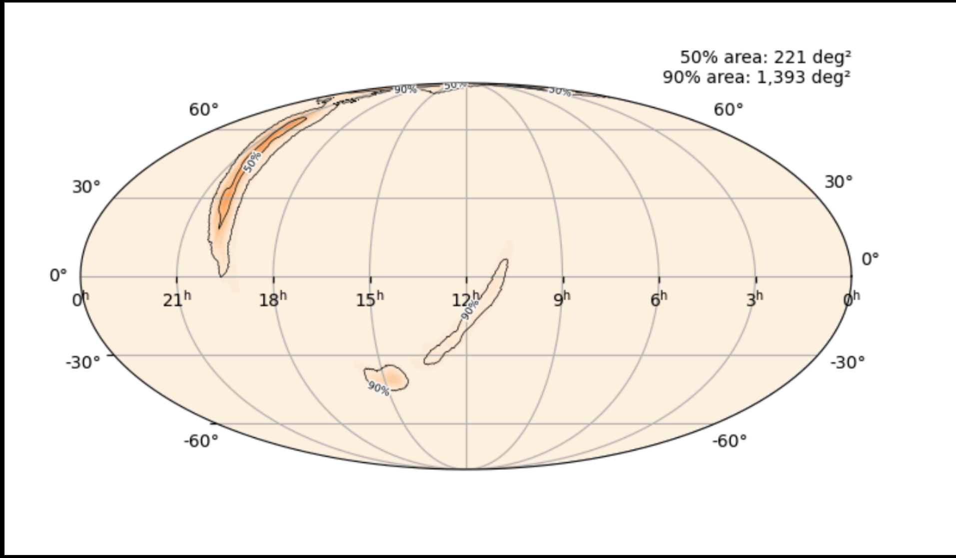
Event	m_1 $(M_\odot)$	m_2 $(M_\odot)$	$\chi_{\rm eff}$	$D_{\rm L}$ (Gpc)	z	SNR
GW190426_152155	$5.7^{+4.0}_{-2.3}$	$1.5^{+0.8}_{-0.5}$	$-0.03^{+0.33}_{-0.30}$	$0.38^{+0.19}_{-0.16}$	$0.08^{+0.04}_{-0.03}$	$8.7^{+0.5}_{-0.6}$

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

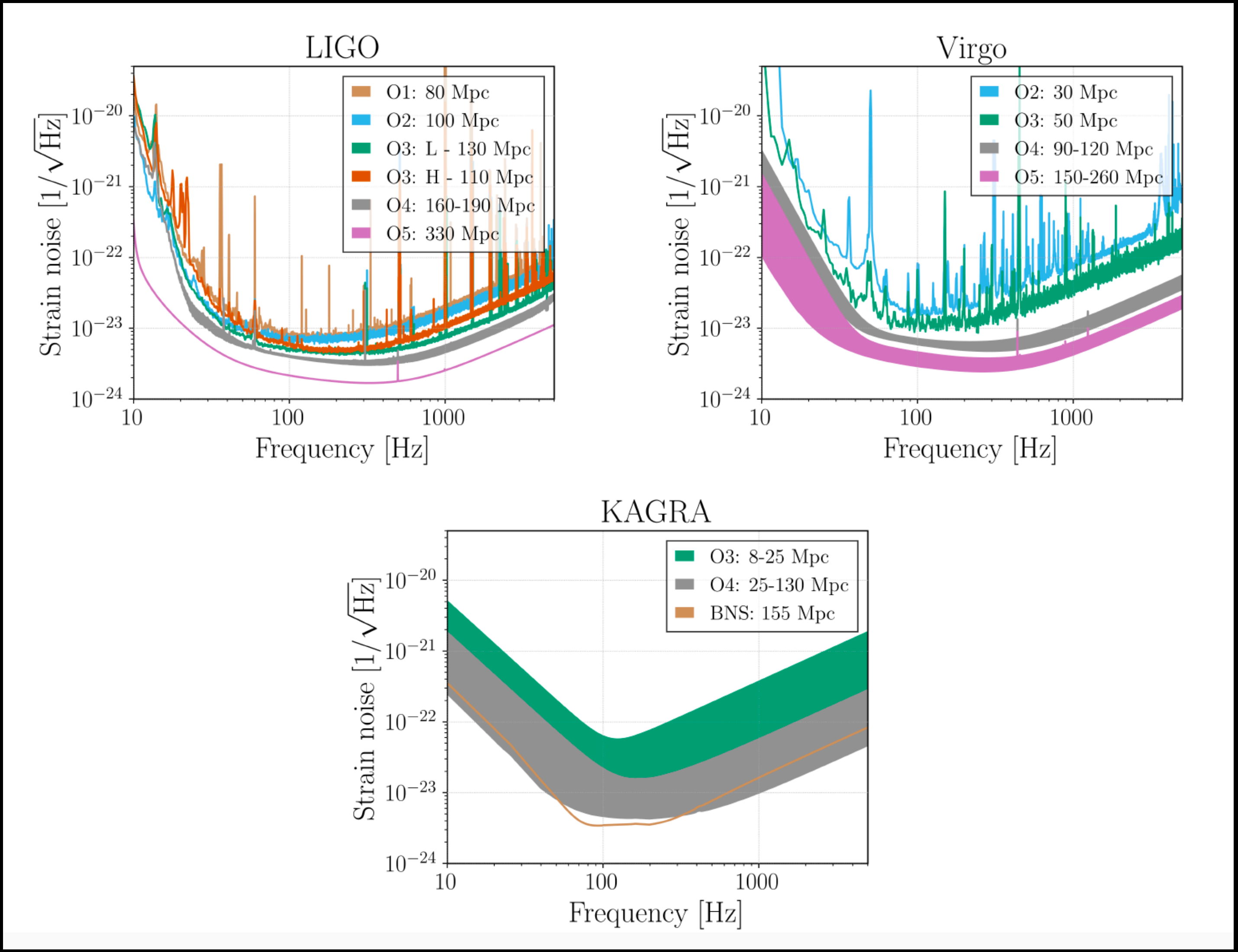
NSBH?



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

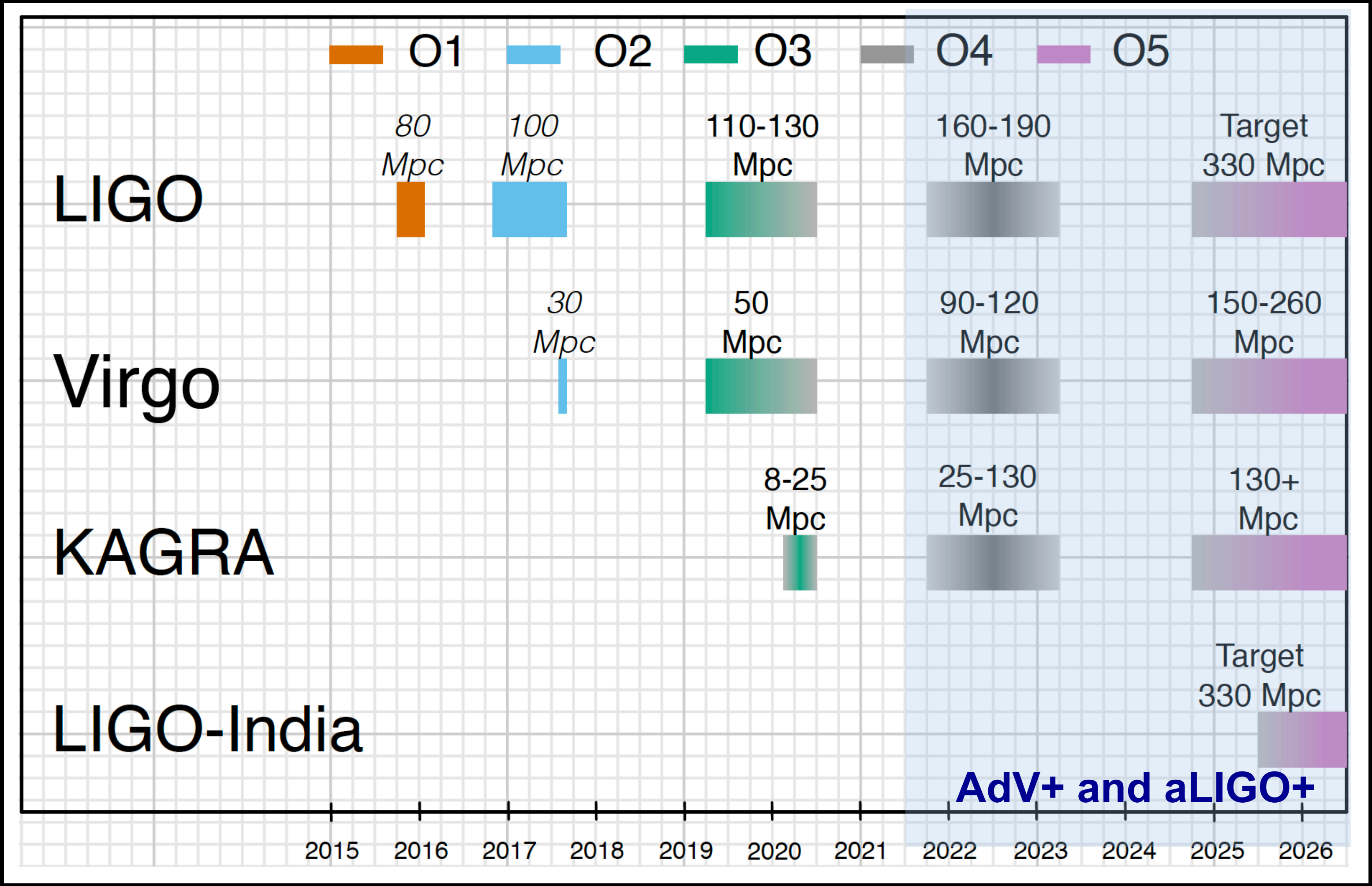
Next observative runs

Strain sensitivities as a function of frequency



Abbott et al. 2020, LRR

Observing run timeline and BNS sensitivity evolution

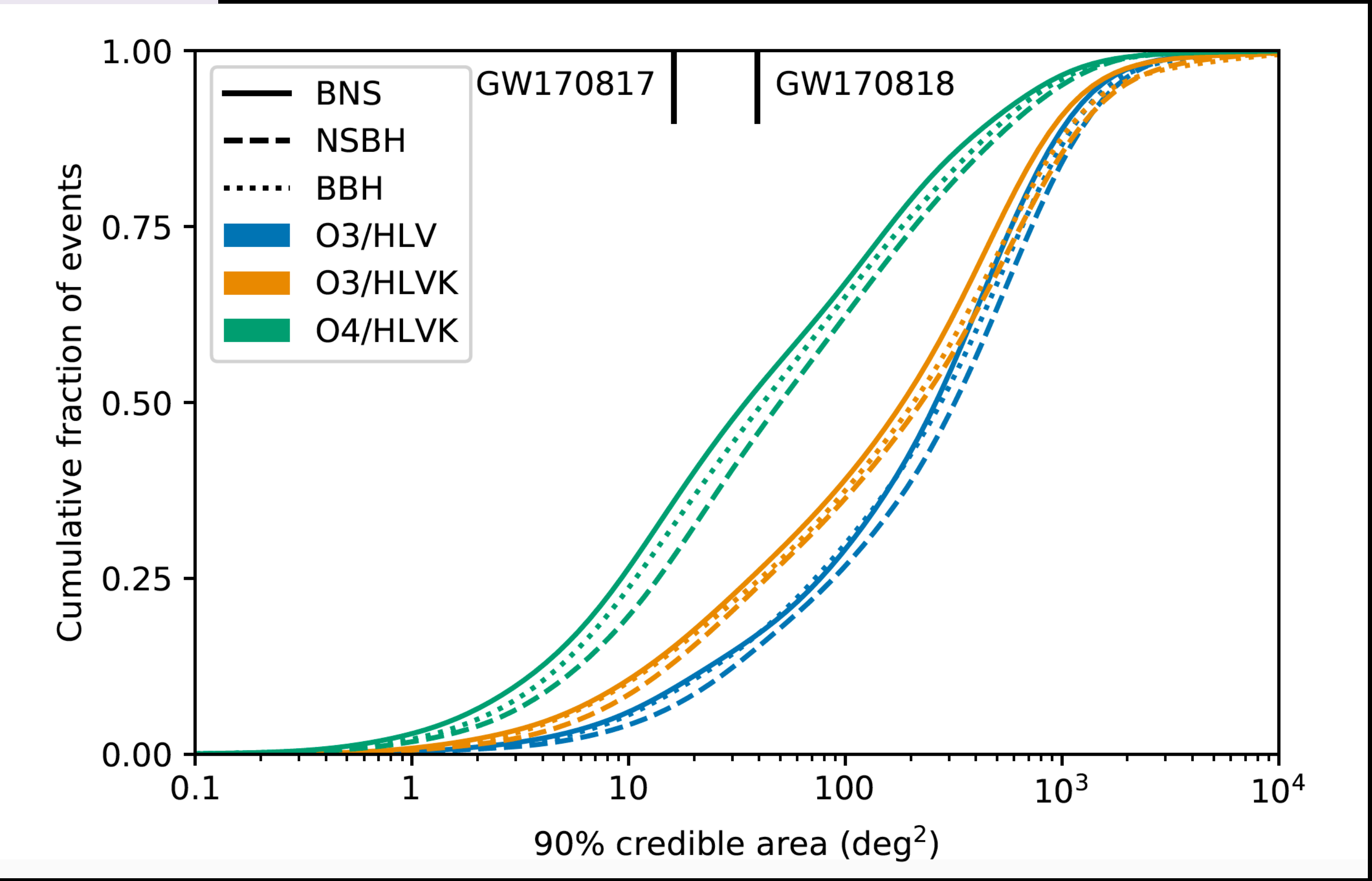


O5 volume = 15*O3 volume

Abbott et al. 2020, LRR

GW sky localization for CBC

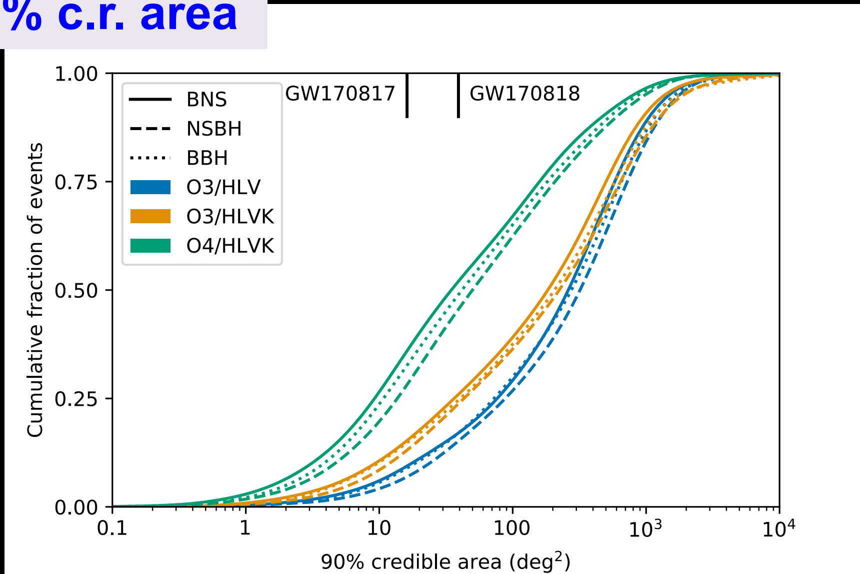
90% c.r. area



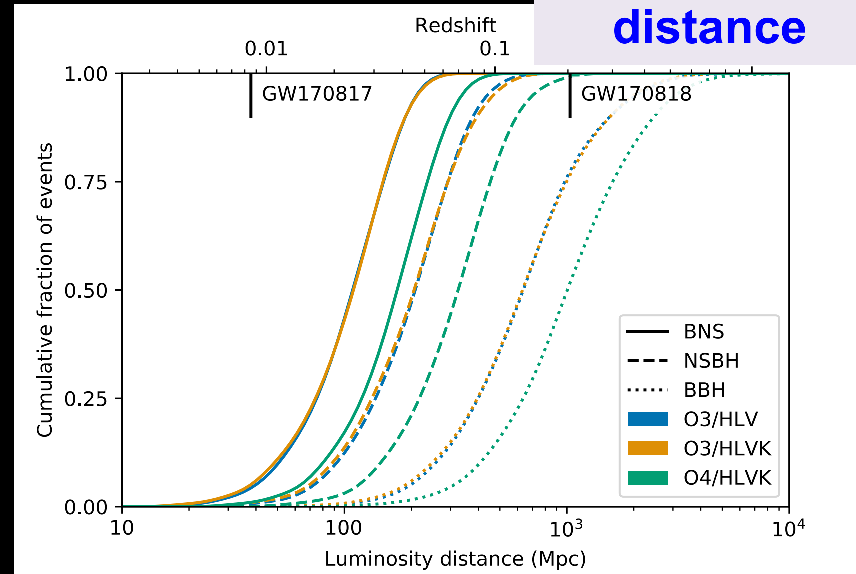
Abbott et al. 2020, LRR

GW sky localization for CBC

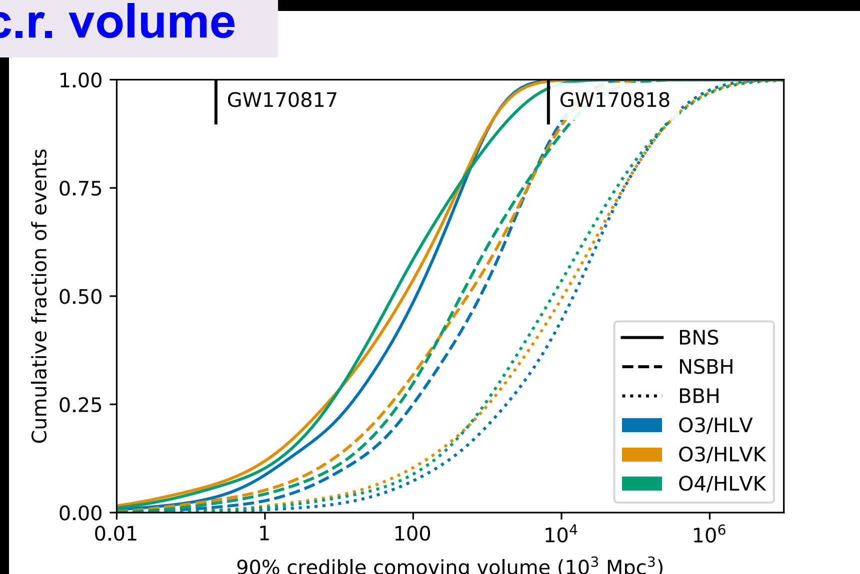
90% c.r. area



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}

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

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}

Abbott et al. 2020, LRR

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}

Abbott et al. 2020, LRR

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

0.6 per year | **20 per year**

	BNS	BBH
O3a	1	36

Six months
About network **SNR > 8**

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

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

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

O1, O2, O3 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}	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

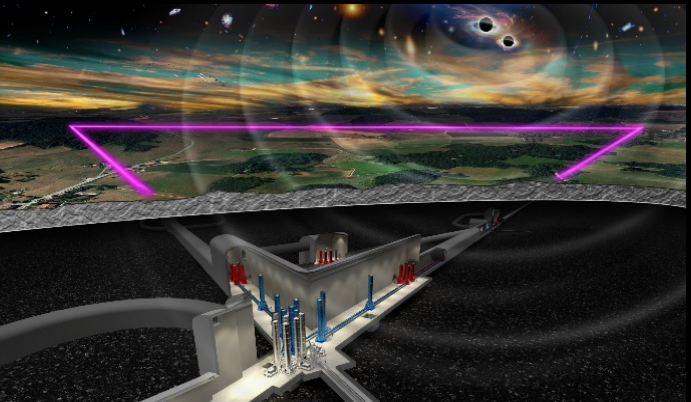
3G detector

The European 3G idea

ET EINSTEIN TELESCOPE

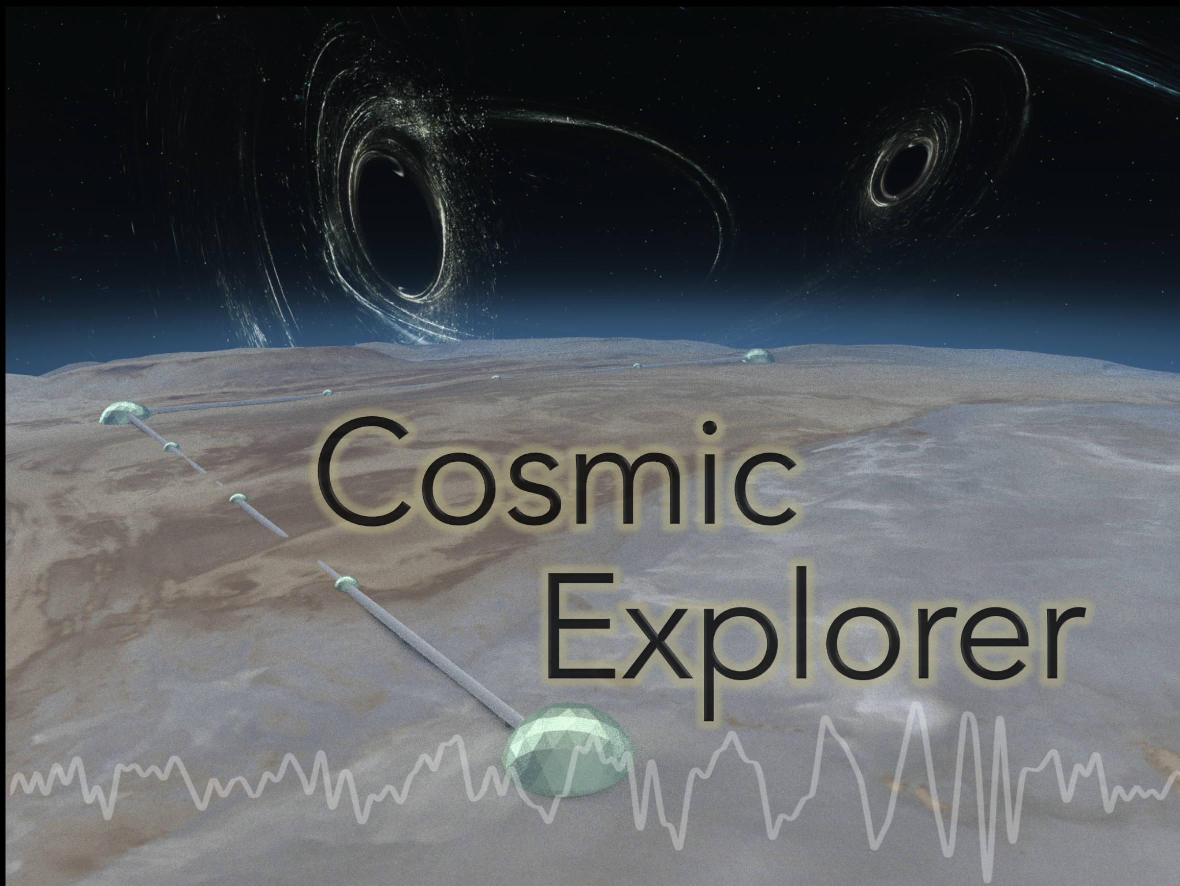
Europe we developed the idea of a 3G GW observatory

- 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

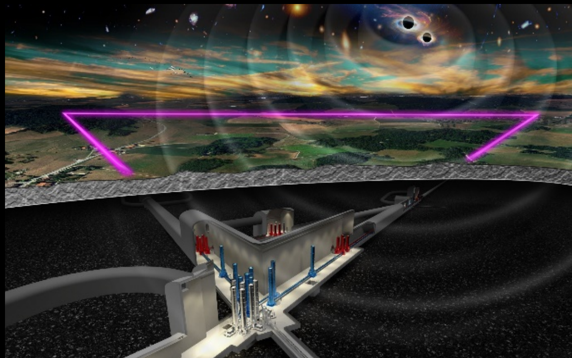


Recently submitted ESFRI proposal

3G effort worldwide

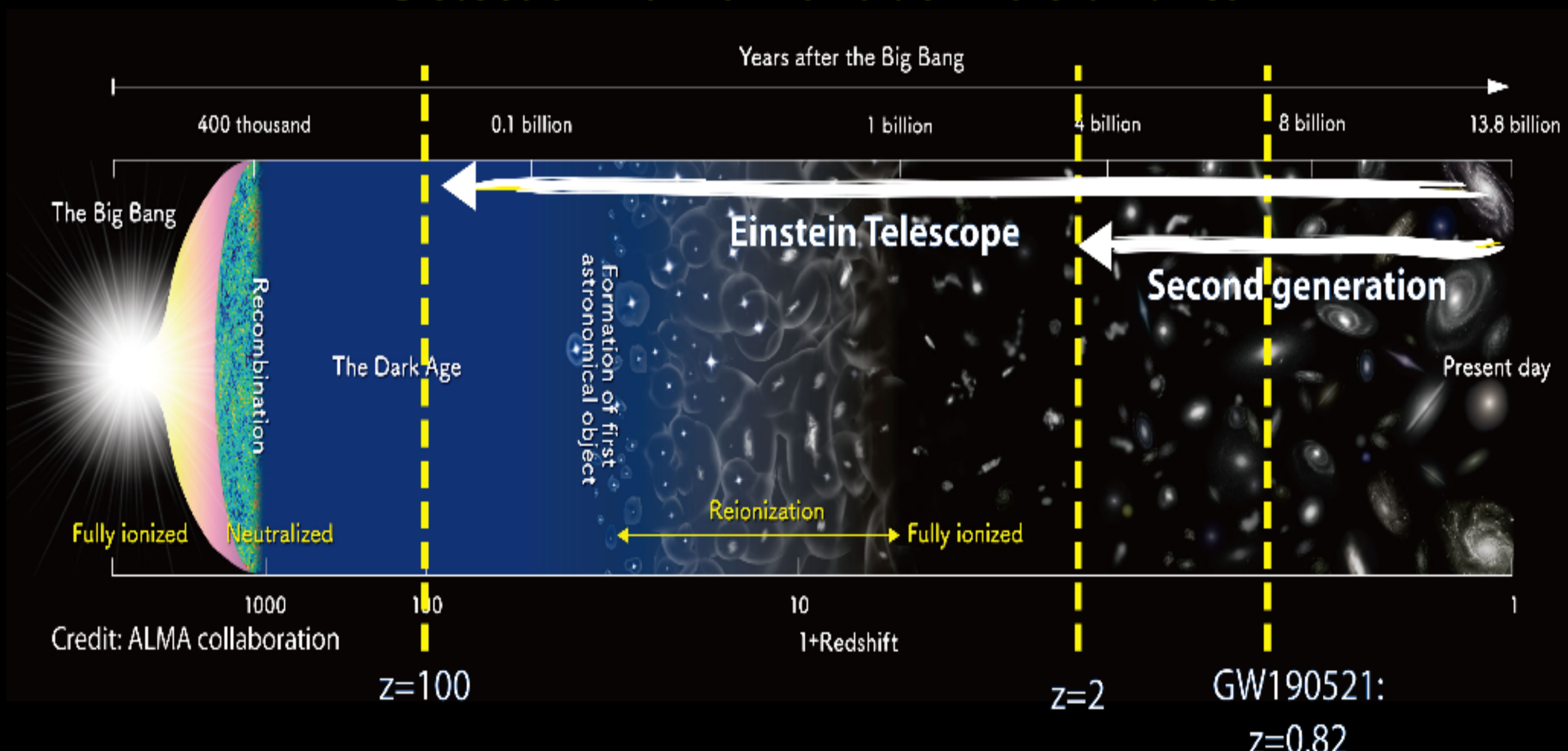


NSF funded in 2018 the Conceptual Design Study of a 3G facility: Cosmic Explorer: 40km – L shaped detector



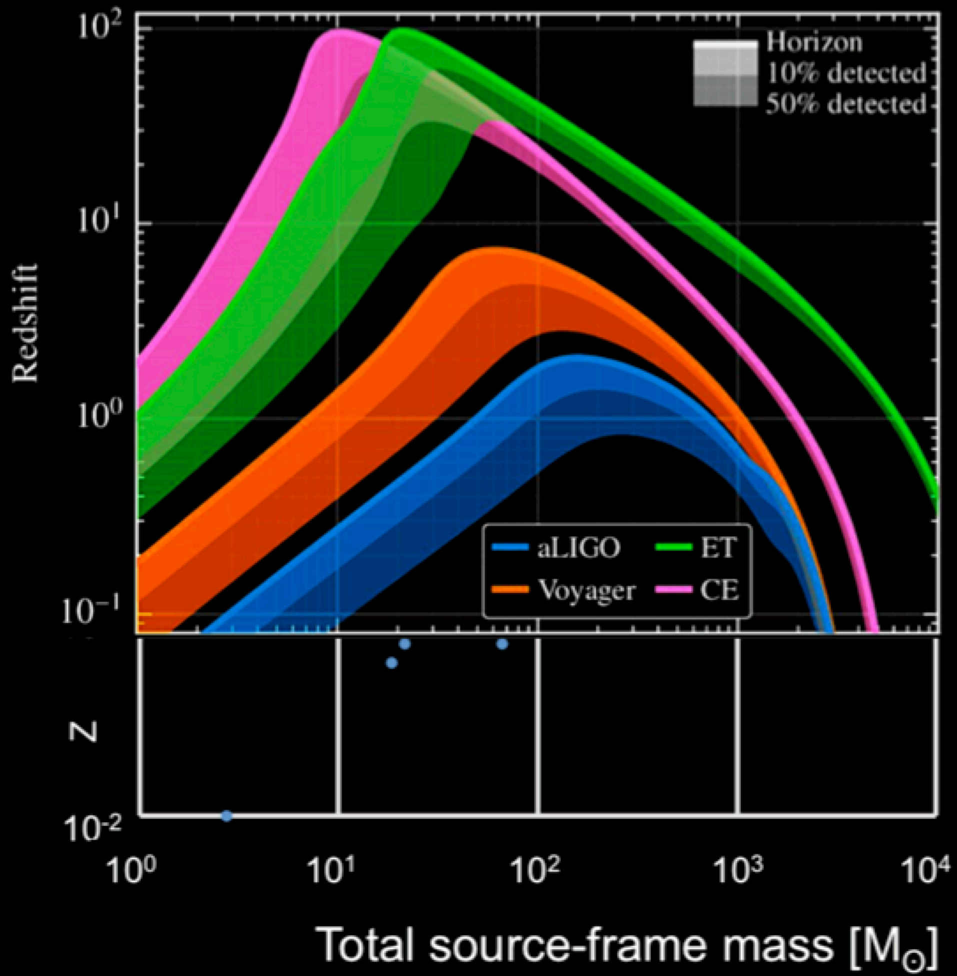
Einstein Telescope

Detection horizon for black-hole binaries



What ET and future EM observatories can do?

Binary systems of Compact Objects



Kilonova/GW - EOS constrains

Kilonova/GW - Nucleosysthesis

GRBs – BNS/NSBH merger up to high z

Relativistic jet properties

Jet-less/jet GRBs

GRB/stable NS remnant

Link to Star Formation History

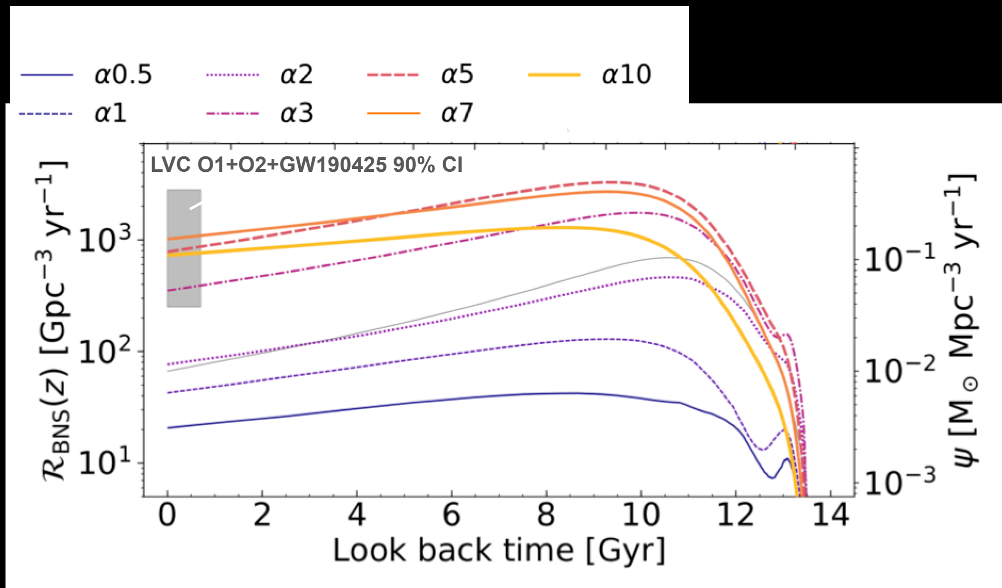
Emission mechanism

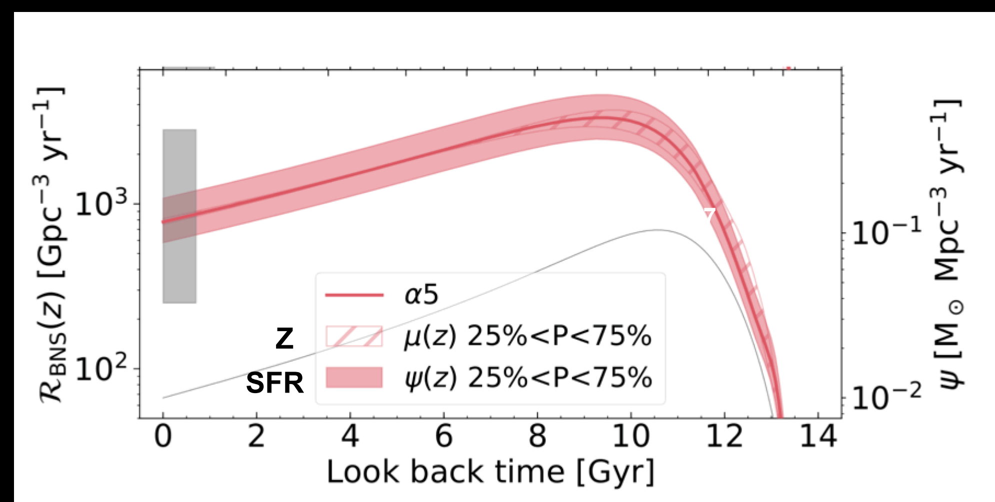
Cosmology

- Study BNS/NSBH/BBH along the cosmic history
- Large increase of detatction rate
- Better parameter estimation

ET capabilities

Astrophysical simulations for BNS from population synthesys code

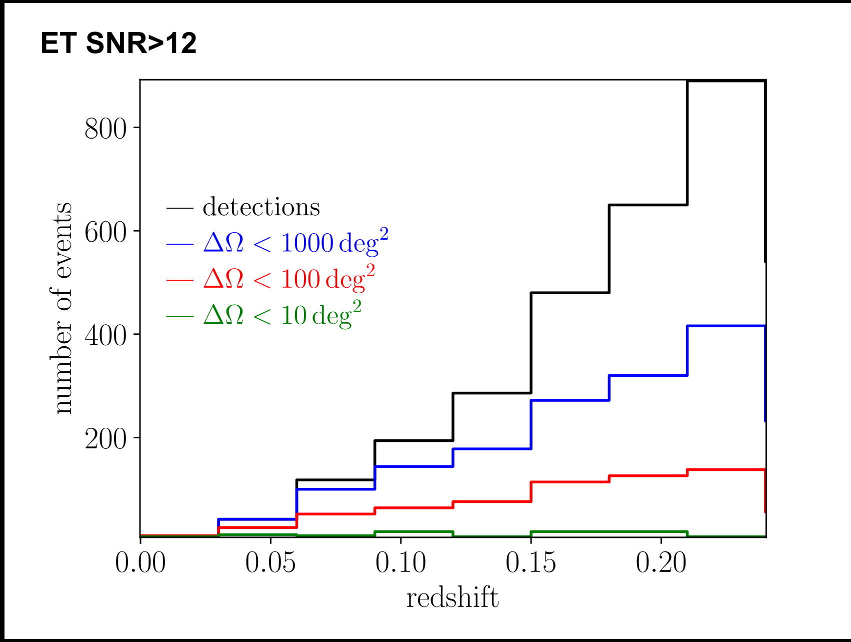




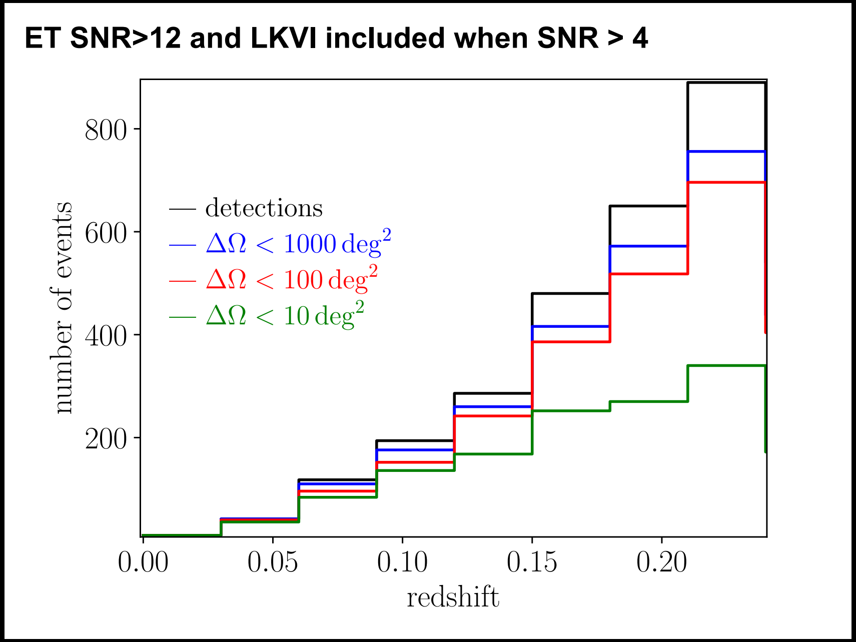
Santoliquido et al. 2020,

EINSTEIN TELESCOPE DETECTION/SKY LOCALIZATION up to z=0.26

ET



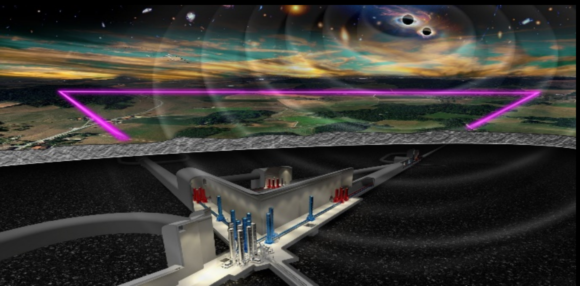
ET+LIGO/Virgo/KAGRA/LIGOindia



1 year of observations

Up to z=0.26

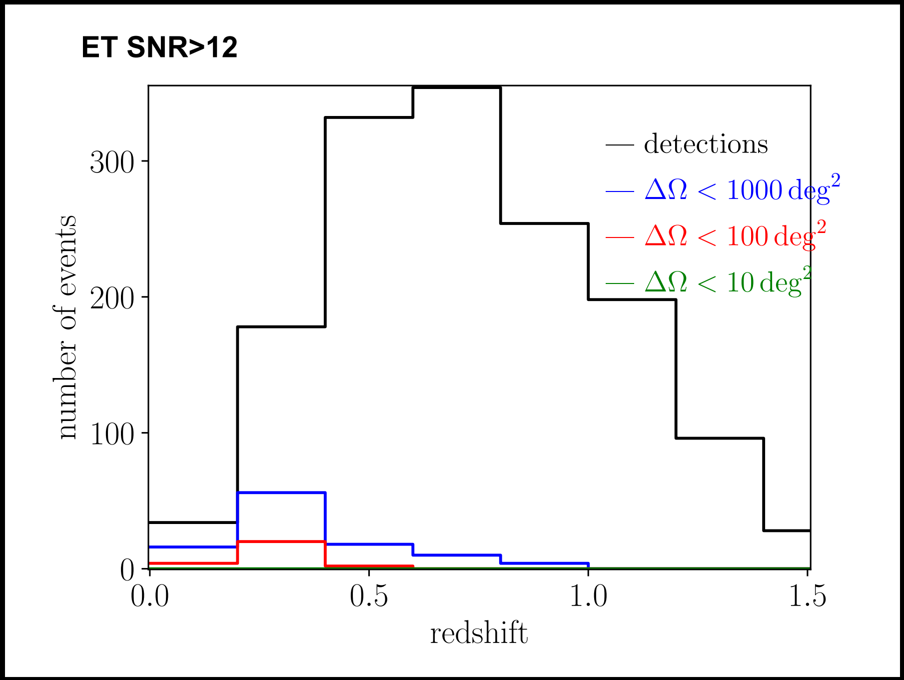
- Among ~4000 mergers per year detected 3210 per year
- For ET 104 per year have sky loc < 10 sq. degrees
- For ET+LVKI 1468 per year have sky loc < 10 sq. degrees
- For ET+LVKI 284 per year have sky loc < 1 sq. degrees



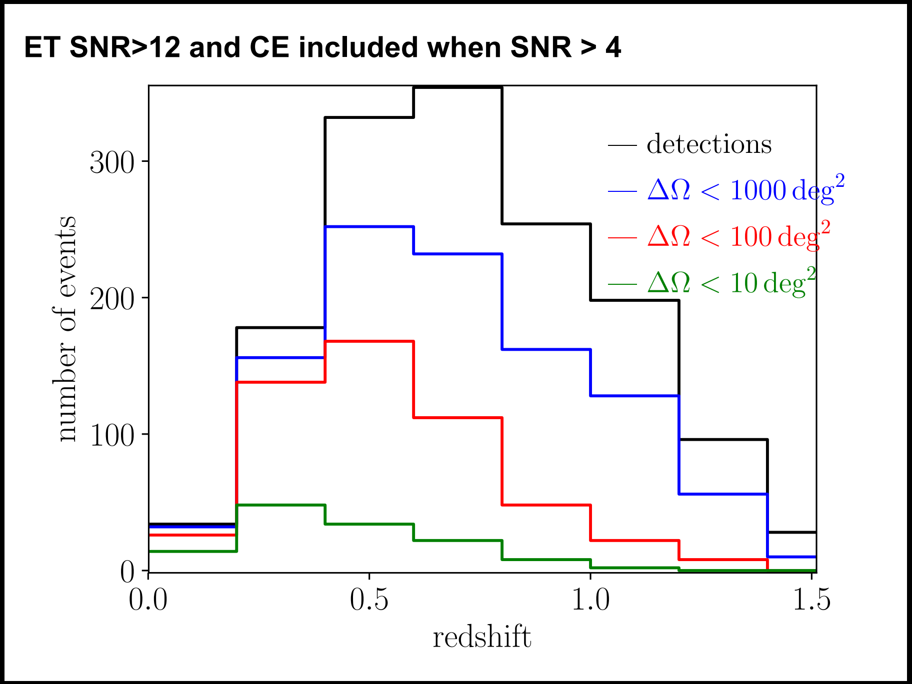
Prelimiary results by Stefan Grimm, GSSI

EINSTEIN TELESCOPEDETECTION/SKY LOCALIZATION up to z=1.8

ET



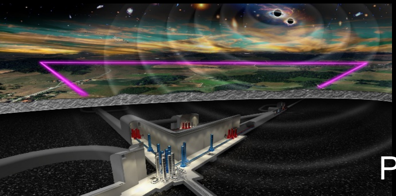
ET+CE



1 week of observations

- Among ~10^4 mergers per week up to z=1.8 detected 1492
- For ET+ CE 128 per week have sky loc < 10 sq. degrees

At z larger than 0.2 sky-localization from GRBs!



Prelimiary results by Stefan Grimm, GSSI

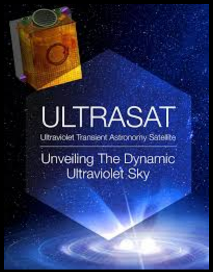
Sensitivity (in terms of observable distances) and sky-localization capabilties of ET determine the observatories able to effectively operate in synergy with ET

- ET as single detector median BNS localization of 100 deg^2 at a distance of ≤ 200 Mpc
- operating with a network of five 2G detectors similar localization up to about 1 Gpc
- going to larger distances the ET localization larger than $10^3 - 10^4$ deg^2 for the majority of the sources

These localizations require large FoV instruments

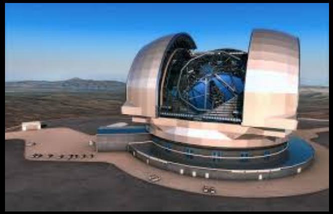
SKA SQUARE KILOMETRE ARRAY

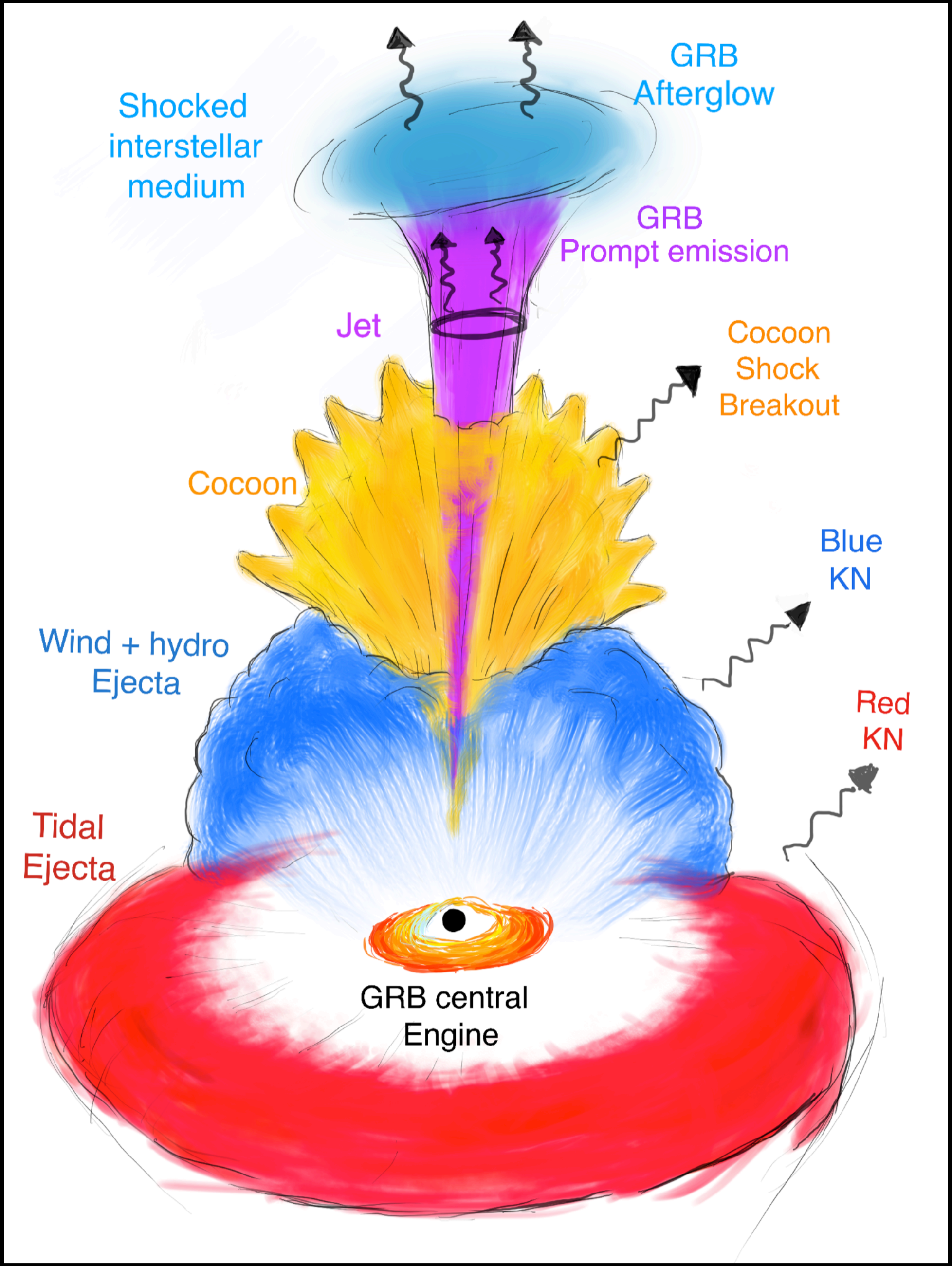
Rubin Observatory



HERMES SP

and follow-up observations to characterize the nature of the counterpart





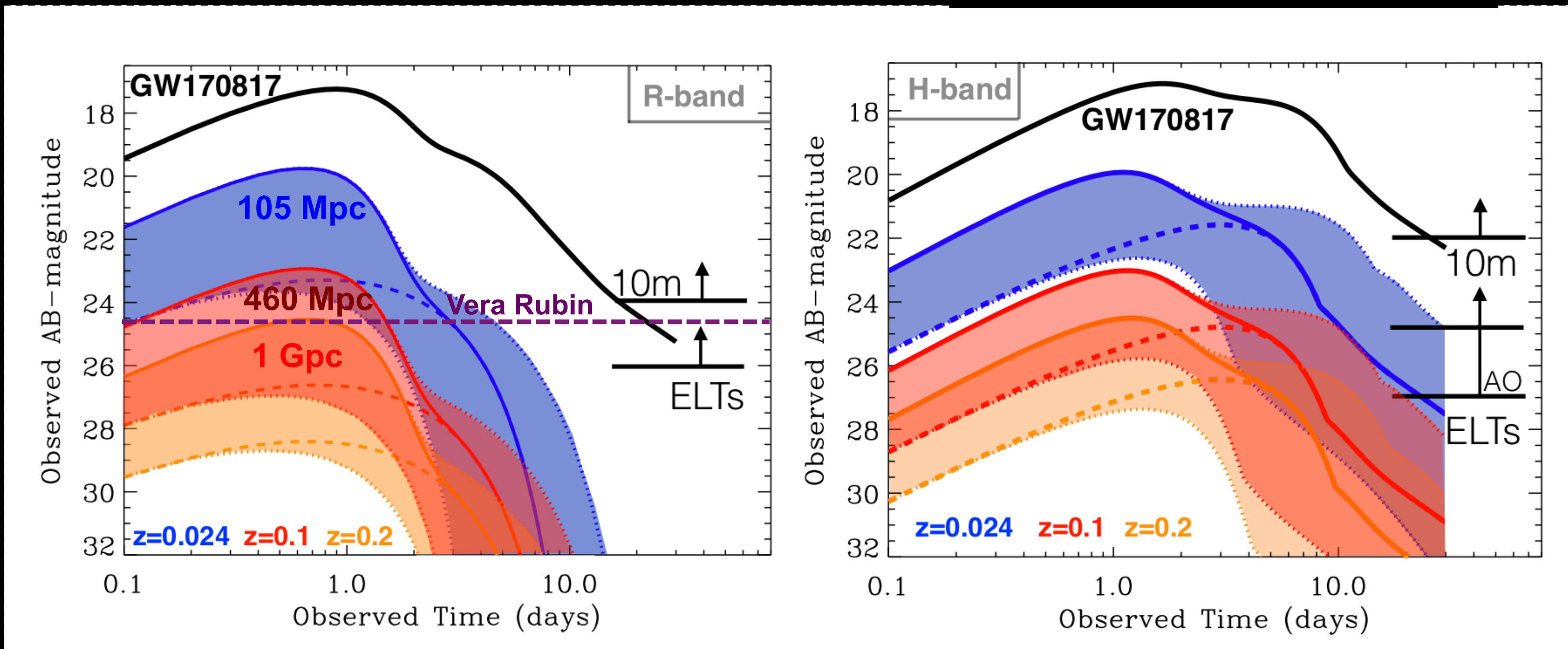
Thermal and non thermal emission components associated with BNS and NSBH merger

Ascenzi et al. 2020 arXiv:2011.04001

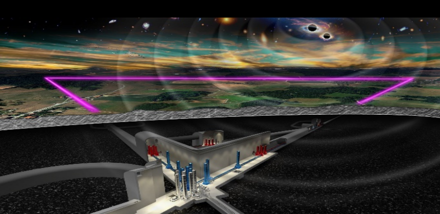
THERMAL EMISSION - KILONOVAE

OPTICAL BAND

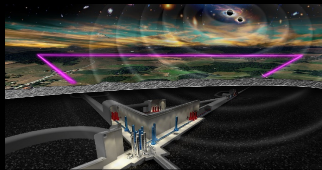
Adapted from Chornock+ 2019



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



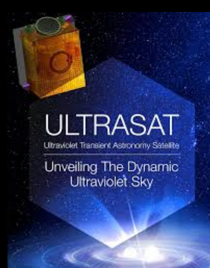
Joint detections for ET limited by optical instruments capabilities!!



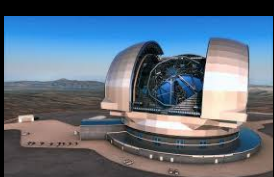
- The Vera C. Rubin Observatory survey able to detect kilonova emission up to 800 Mpc
- BNS mergers detectable in this volume are of order 10^3 per year
- A few hundred kilonova are expected to be in the Rubin Observatory surveyed field

→ For the majority of these sources, the GW localization by ET will make it difficult to identify the optical counterpart among many contaminants

→ Joint GW/kilonova detections (of order of several tens) becomes possible considering ET+2G



Promising UV wide-FoV detector



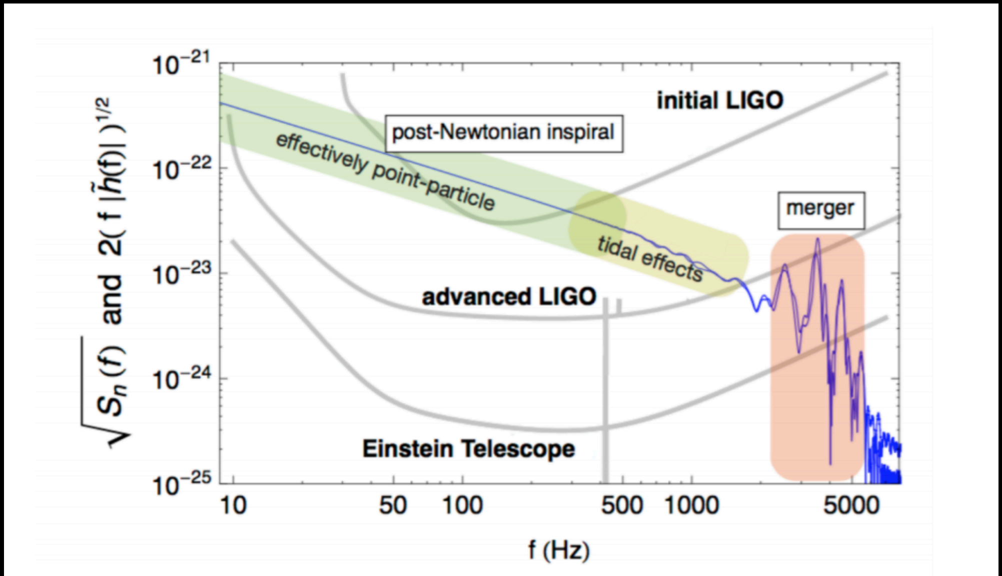
The 39-m E-ELT able to observe the kilonova up to z ~ 0.5 photometrically, and up to z ~ 0.3 spectroscopically

JOINT GW/KILONOVAE

Limited to near Universe

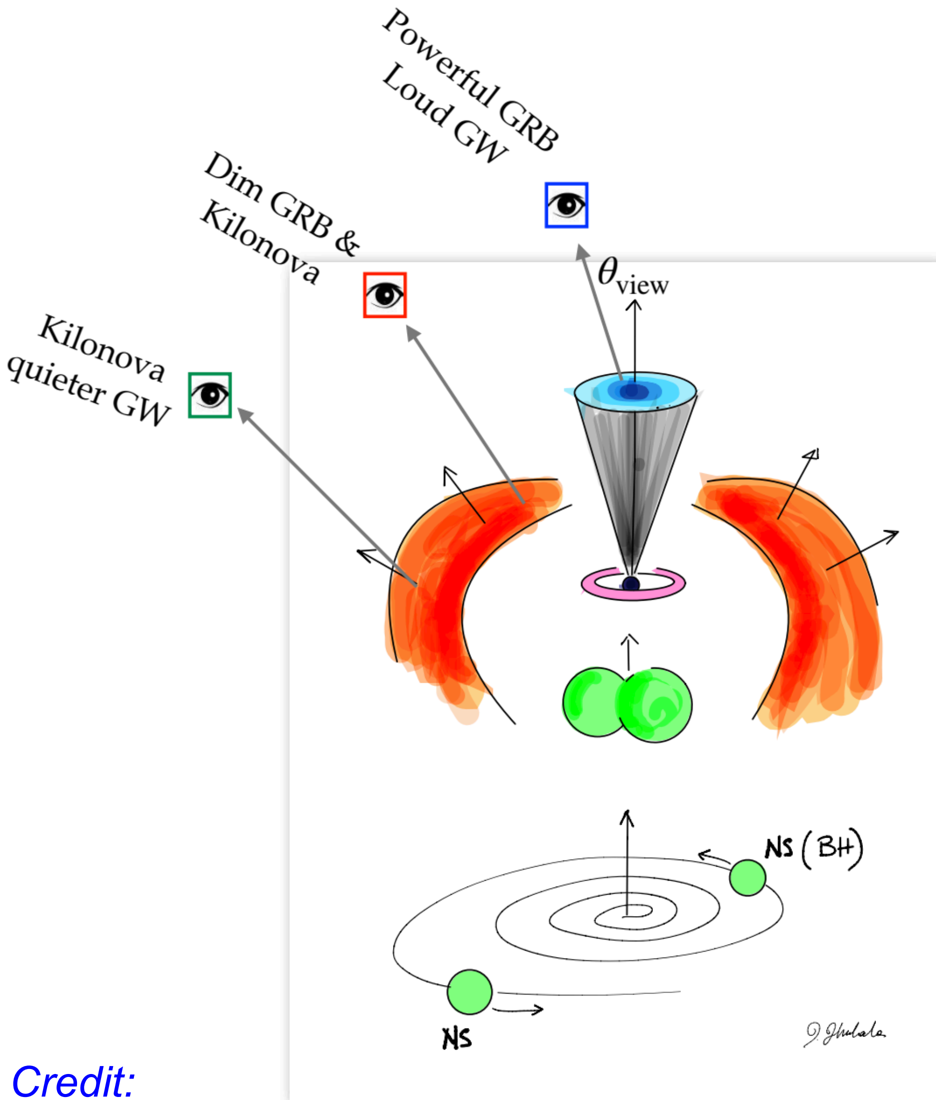
Strong benefit of the higher sensitivity of ET with respect to 2G detectors
→ better precision of PE for the progenitor system and the merger remnant

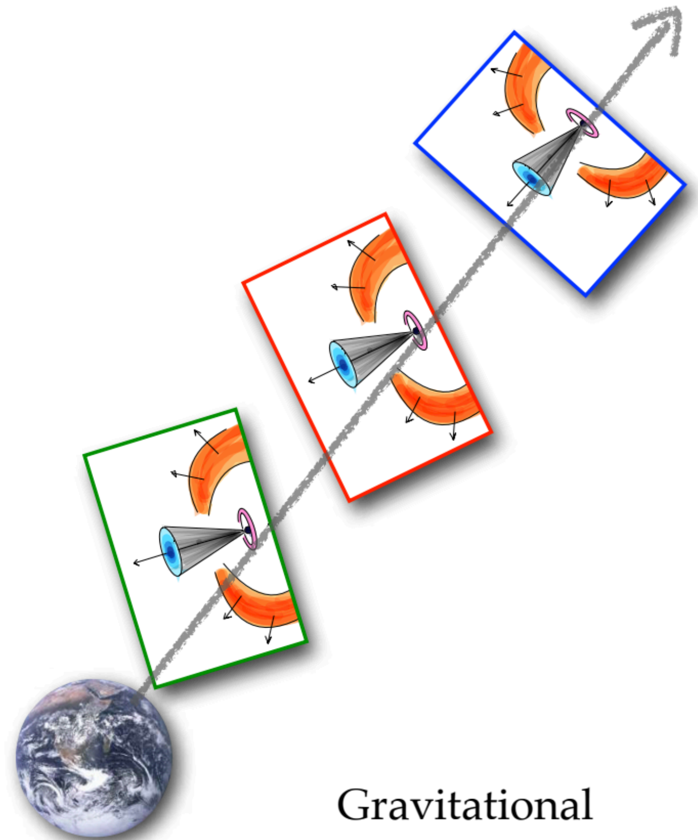
unprecedent opportunity to understand the unveil of state of neutron stars



3G Science case WP

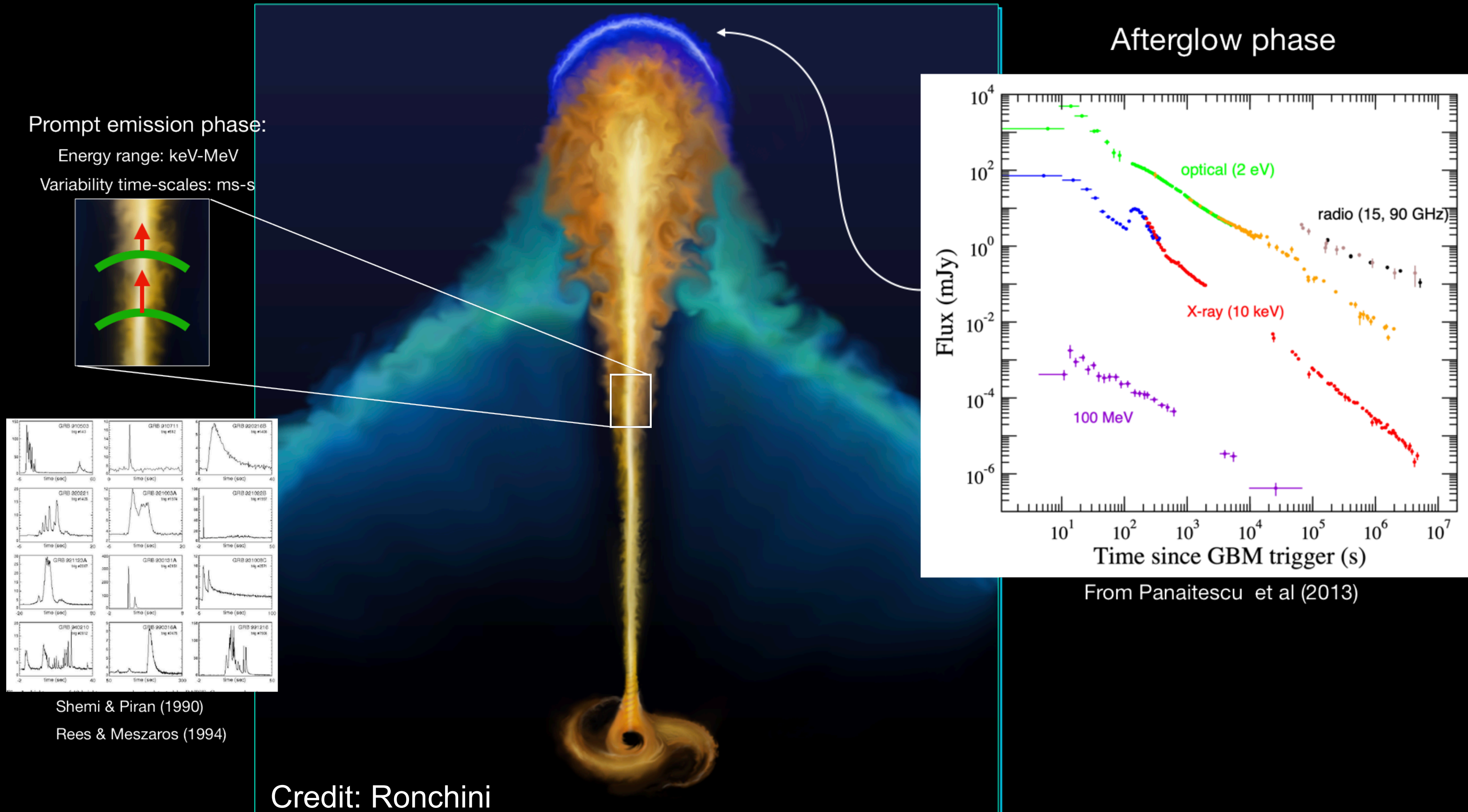
WHY HIGH-ENERGY?





Gravitational
&
Electromagnetic
ranges

Credit:
Ghirlanda



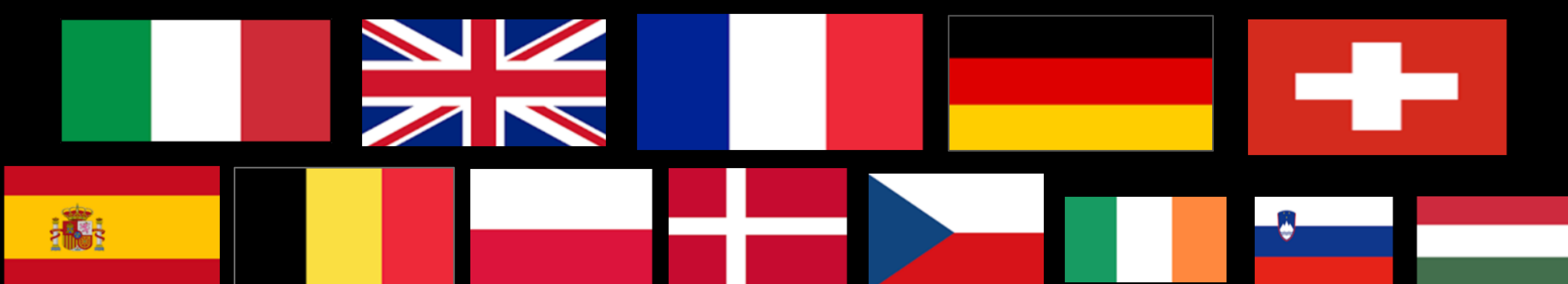
- GRB detectable up to high z
- Small number of contaminants
- Promising wide FoV hard-soft Xray instruments
- Good sky localization to drive a prompt EM follow-up

theseus

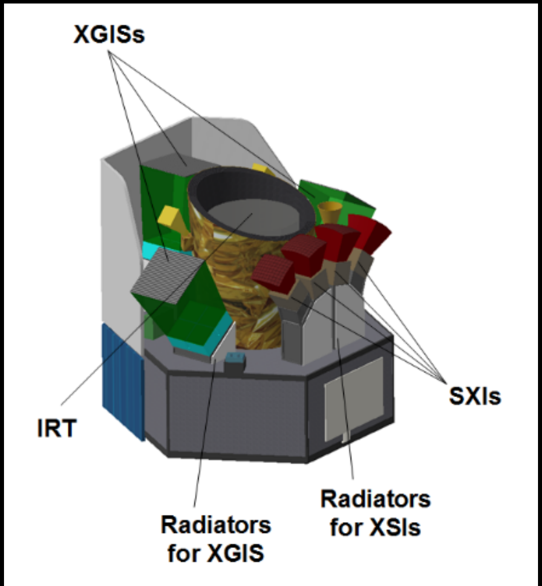
TRANSIENT HIGH ENERGY SKY AND EARLY UNIVERSE SURVEYOR

May 2018: THESEUS selected within ESA Cosmic Vision science programme as midium class mission concept for study with SPICA and EnVision Venus

Final decision 2021
IF SELECTED LAUNCH 2032!



THESEUS MISSION CONCEPT →a unique combination of instruments:



Amati et al. 2018

Soft X-ray Imagers (SXI)

- 4 Lobster-eye telescopes
- **0.3-5 keV**
- FoV ~ 0.5 sr
- Location accuracy ~ 0.5'-1'

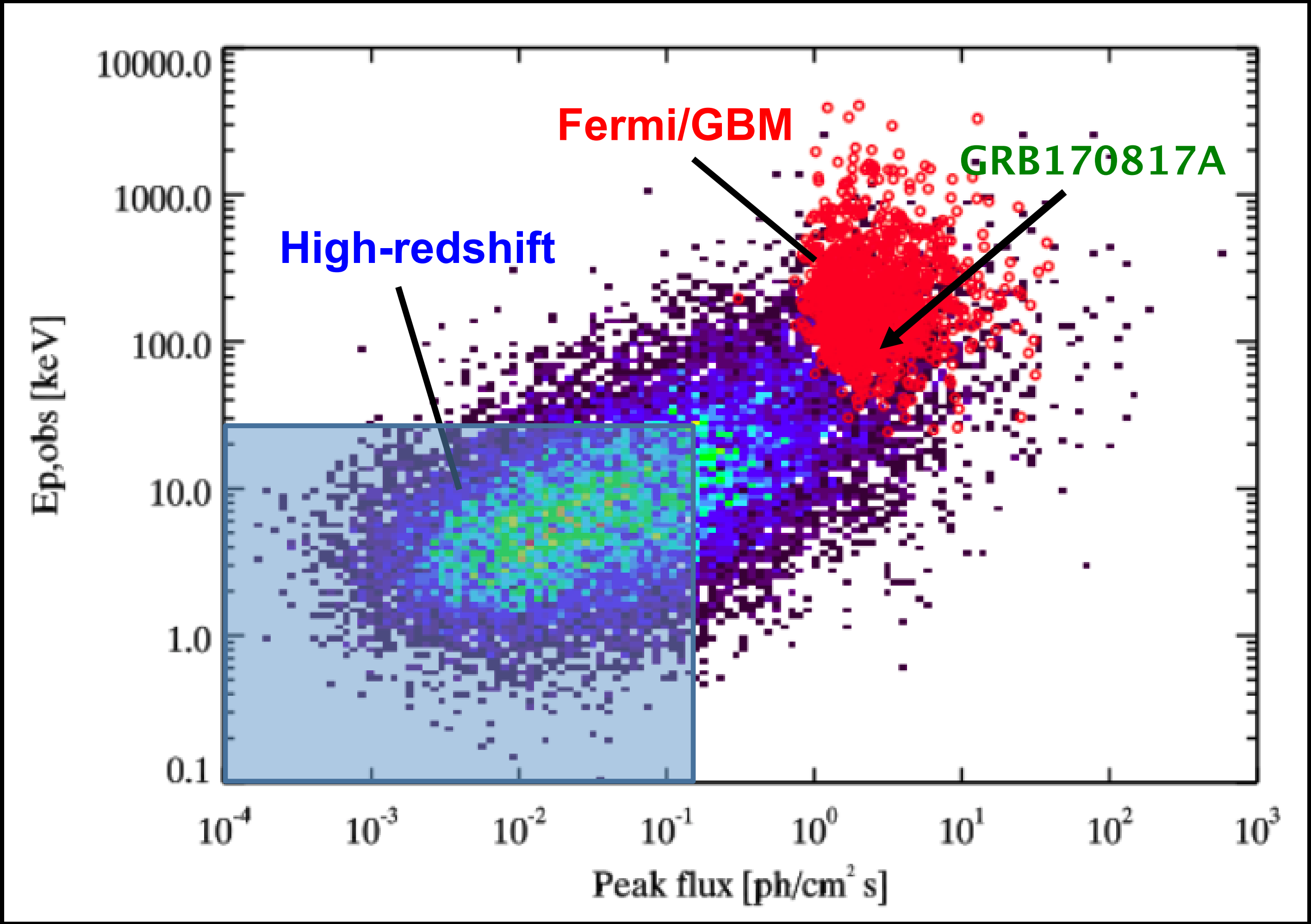
X-Gamma-ray Imager Spectrometer (XGIS)

- 3 Coded mask telescopes + X(Si) – Gamma(CsI) ray cameras
- **2 keV – 10 MeV**
- FoV ~ 2 for 2-150 keV band and > 4 sr for > 150 keV band sr (overlapping SXI)
- Location accuracy ~ 5'

- **InfraRed Telescope (IRT)**
  - 0.7mt class telescope
  - 0.7-1.8 mm (IZYJH)
  - FoV: 15'x15'
  - Imaging (H=20.8;150 s) and high resolution spectroscopy (H=17.5;1800s) capabilities (→ redshift)

- **BROAD FIELD OF VIEW (more than 1sr) with ACCURATE LOCALIZATION (down to 0.5'-1' in the X-rays)**
- **LARGE SPECTRAL COVERAGE from 0.3 keV up to several MeV**
- **an on-board prompt (few minutes) follow-up with a 0.7 m CLASS IR TELESCOPE** with both imaging and spectroscopic capabilities

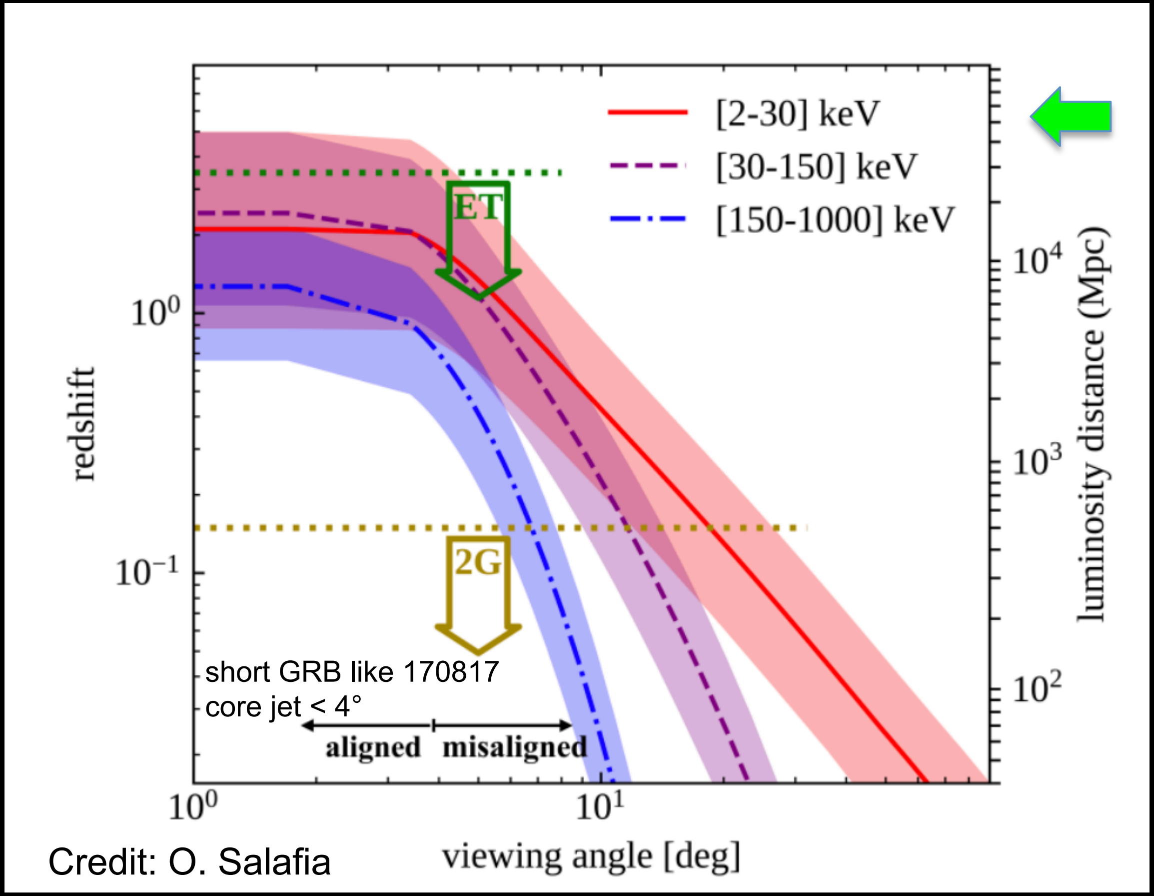
THESEUS will detect all types of GRBs (long, short/hard, weak/soft, high-redshift) and localize them from a few arcmin down to arcsec and measure the redshift for a large fraction of them



THESEUS will detect between one and two orders of magnitude more GRBs at any redshift, and most notably in the high-redshift regime (z>6)

THESEUS in Multi-Messeger context

On-axis short GRB detection rate of THESEUS di 12/yr within 1' – 5'
about 25% is expected to be detected also with IRT with arcsec loc

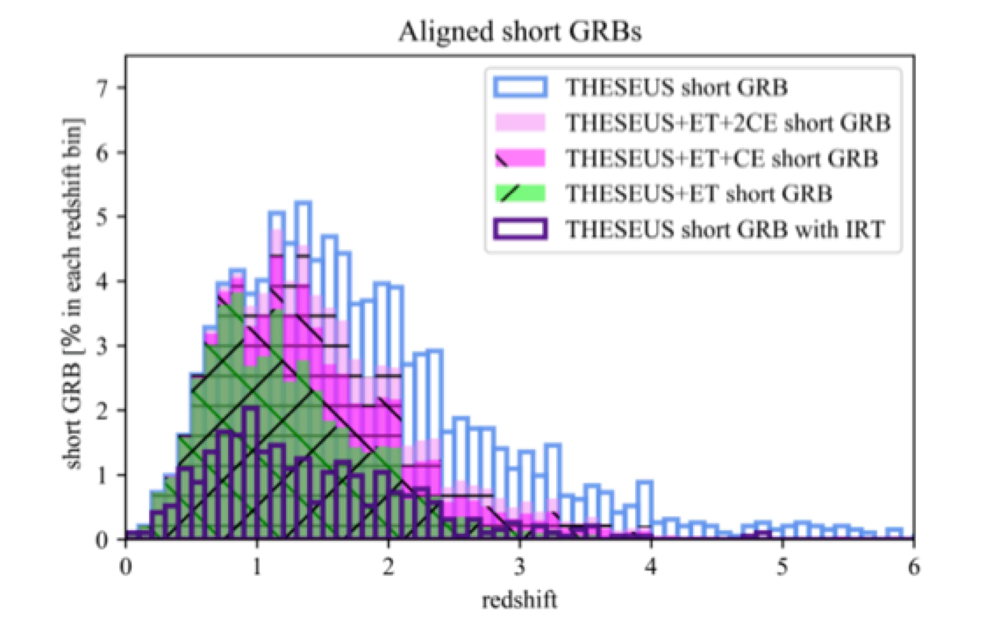


Maximum THESEUS/XGIS detectable distance versus viewing angle.

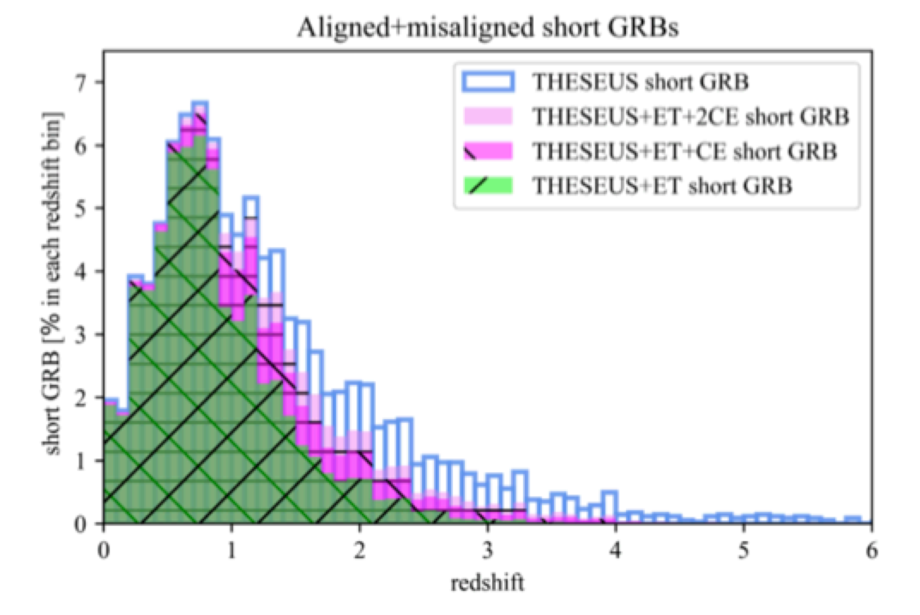
At the typical ET range for BNS (330 Mpc)

→ THESEUS can detect a GRB up to a viewing angle of ~20-40°, potentially increasing the event rate by a factor of >20-100 the on-axis rate

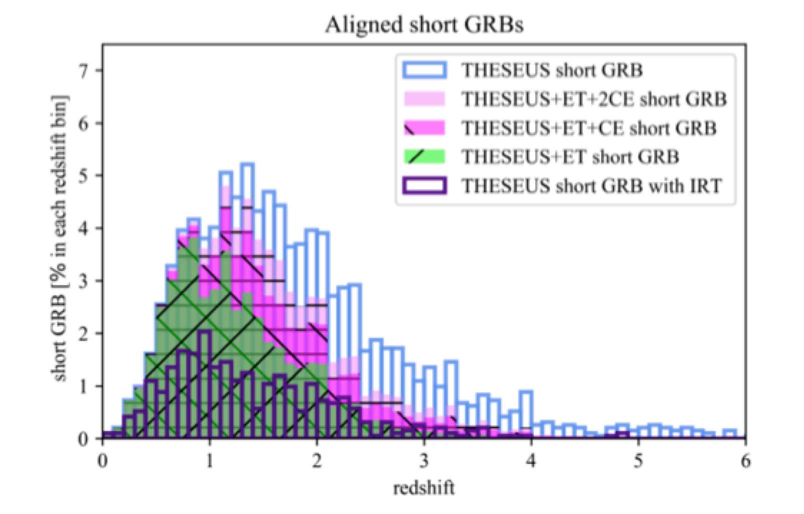
THESEUS in Multi-Messeger context

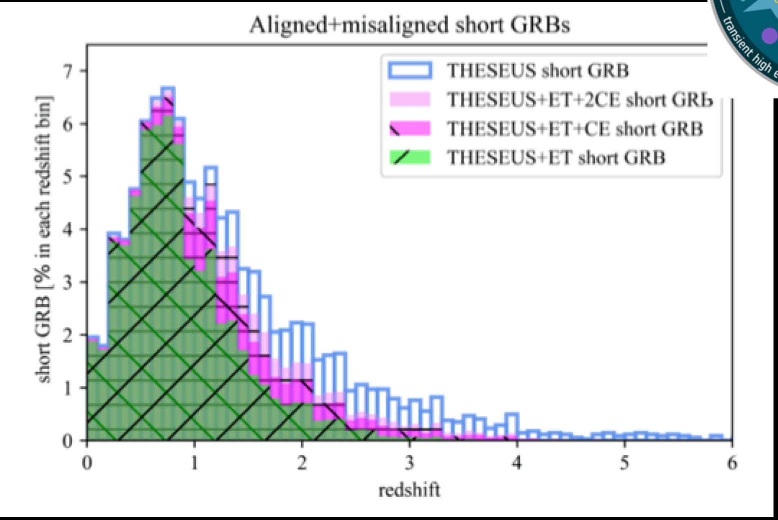


Credit THESEUS Yellow Book



THESEUS in Multi-Messeger context





Preliminary

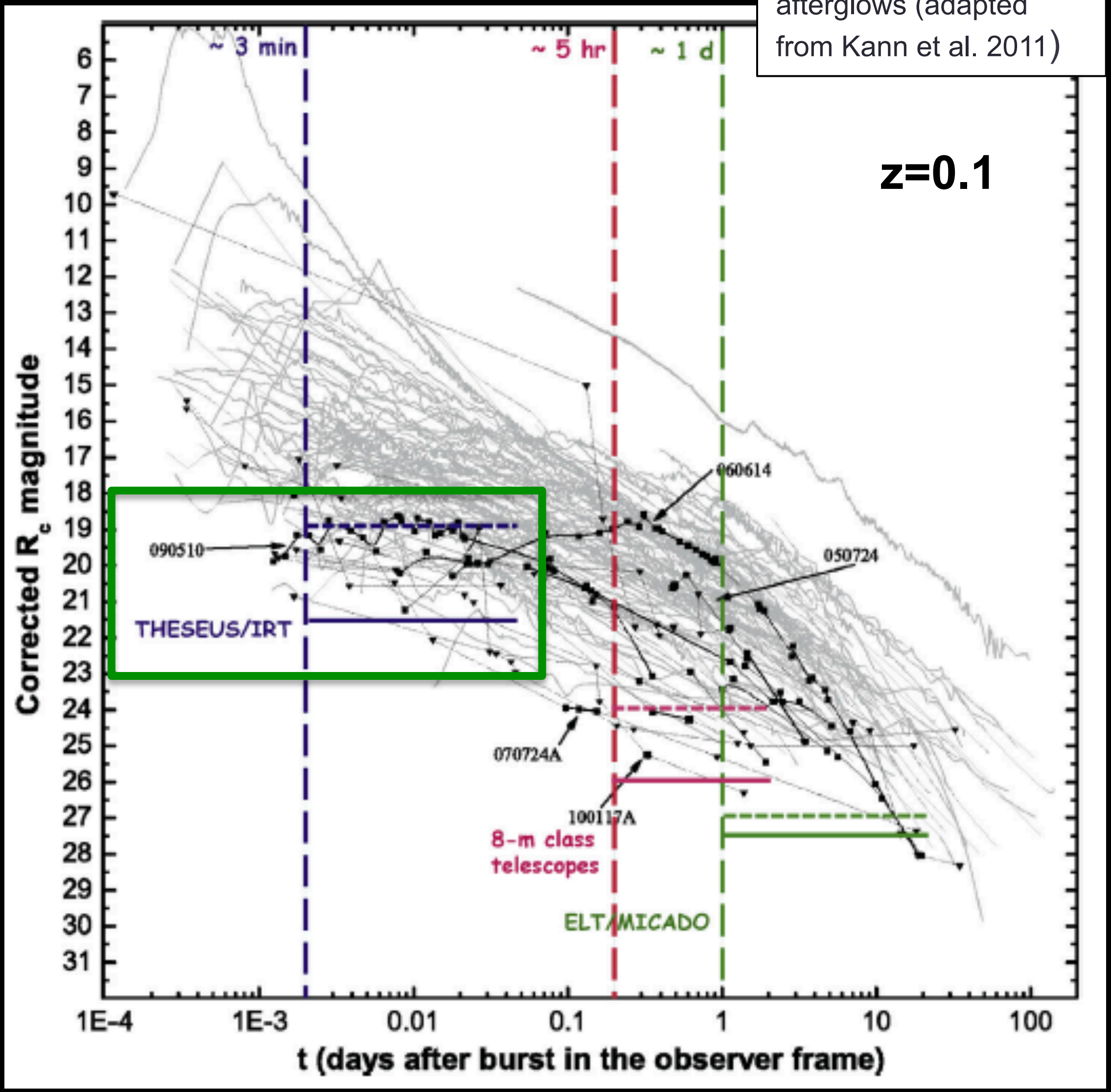
GW detectors	THESEUS+GW detectors plausible joint observation time	aligned short GRB+GW detections	aligned & misaligned short GRB+GW detections
2G network z<0.107 (500 Mpc)	3.45 yr	~0.04	1.8
ET	1 yr (3.45 yr)	5.6 (19.2)	13 (46)
ET+CE	1 yr (3.45 yr)	7.4 (25.7)	16 (55)
ET+2CE	1 yr (3.45 yr)	8.7 (30.1)	18 (61)

Credit THESEUS Yellow Book

Optical afterglow detection with THESEUS/IRT

Stratta et al. 2018

R-band light curves of long and short GRB afterglows (adapted from Kann et al. 2011)



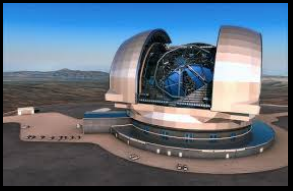
IR Telescope will provide:

- arcsec localizations
- redshift measures
- luminosity estimates

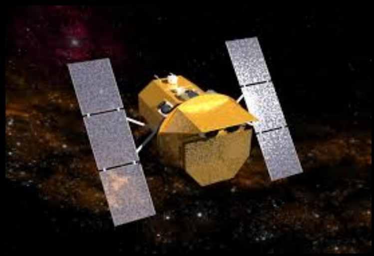
These information will be used to optimise follow-up high S/N spectroscopy

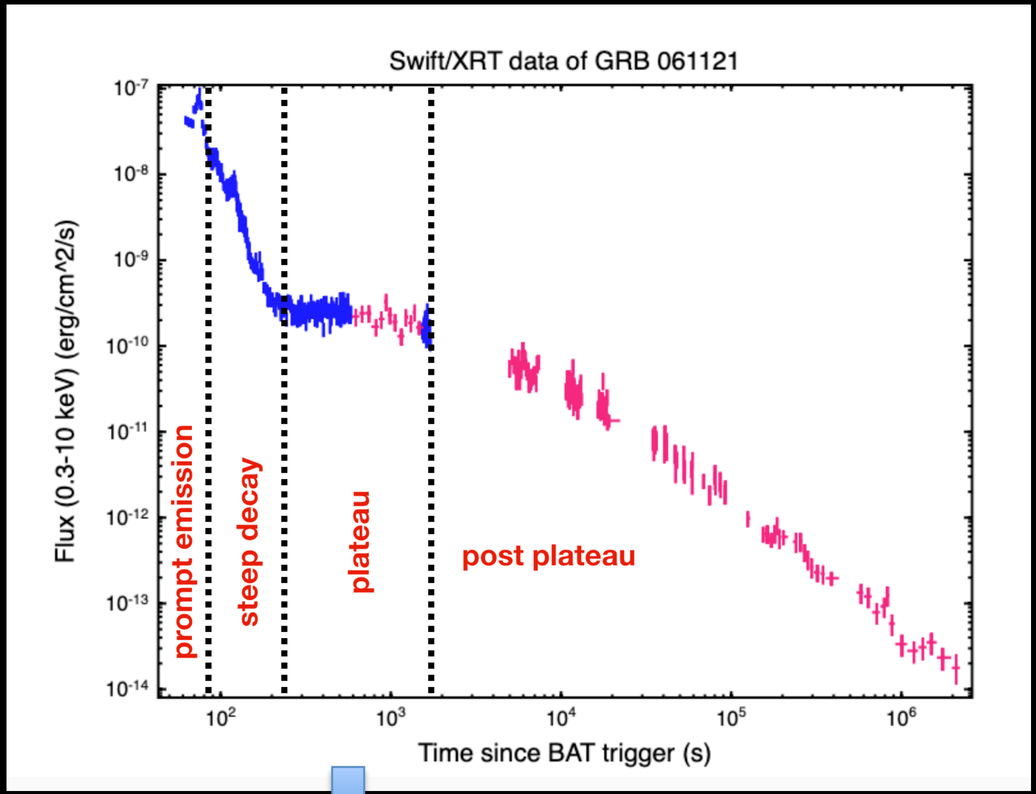
VLT 8 m

ELT 39 m

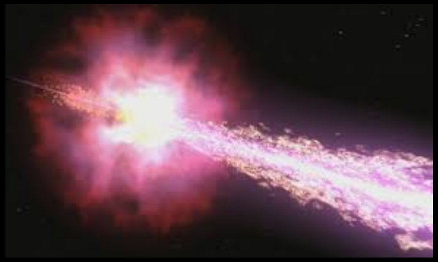


OTHER PROMISING HIGH-ENERGY COUNTERPARTS for SXI (0.5- 5 KeV sky loc < 1-2'

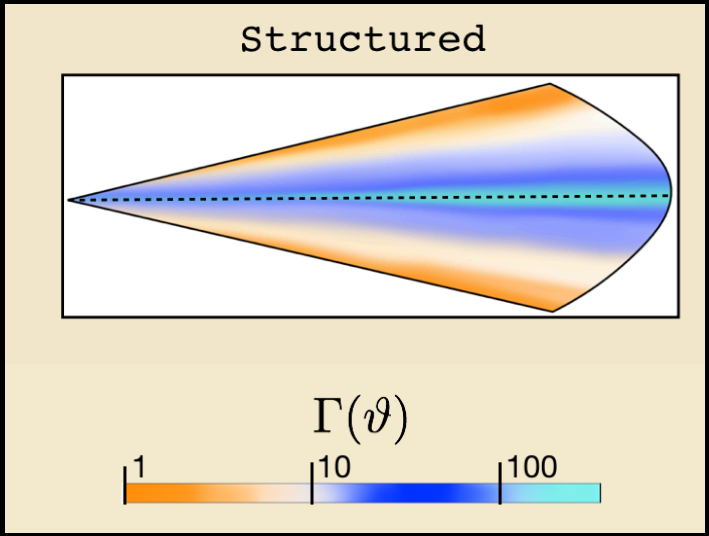


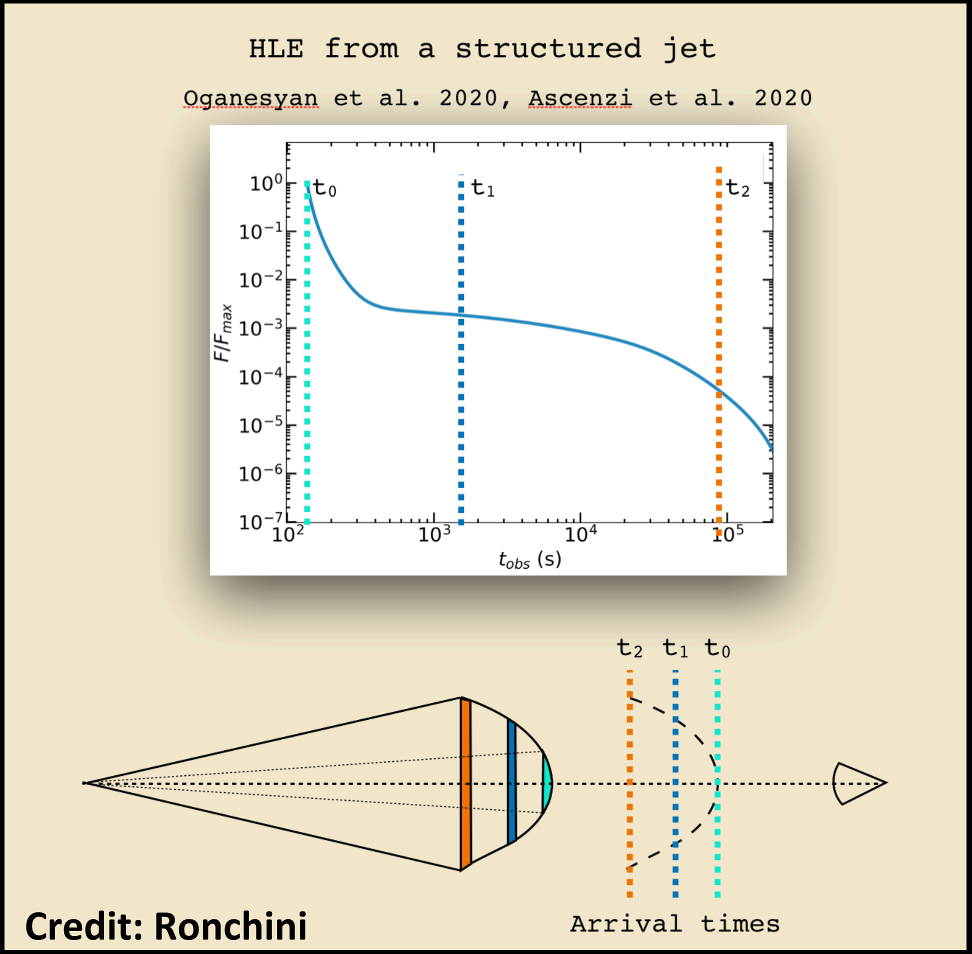


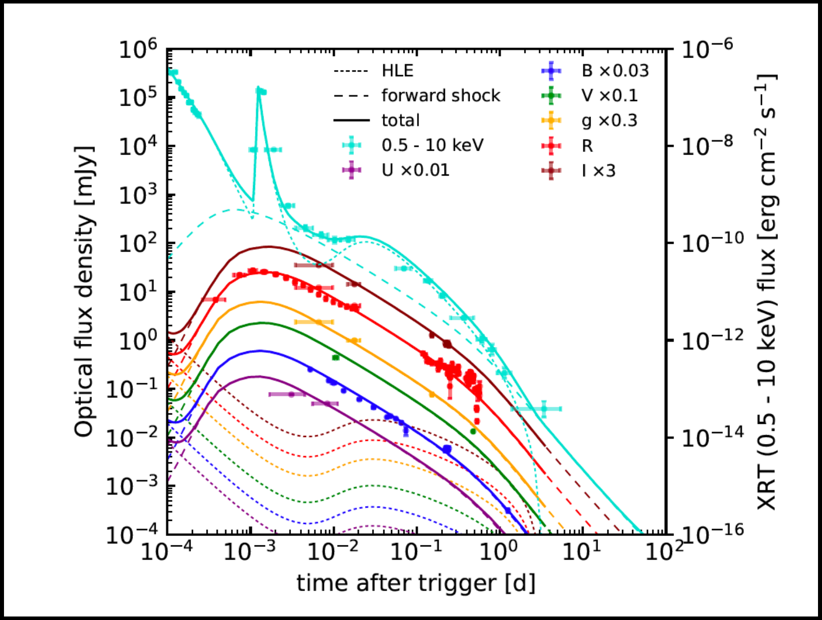
Magnetar? or High latitude emission from structured jet?



GRB X-ray plateaus explained by structured jets

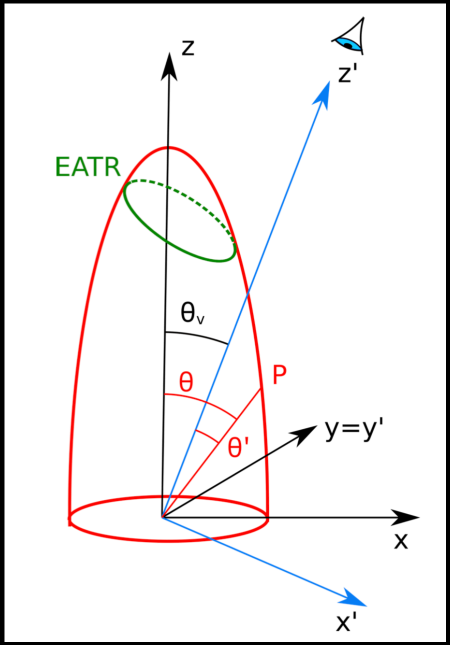


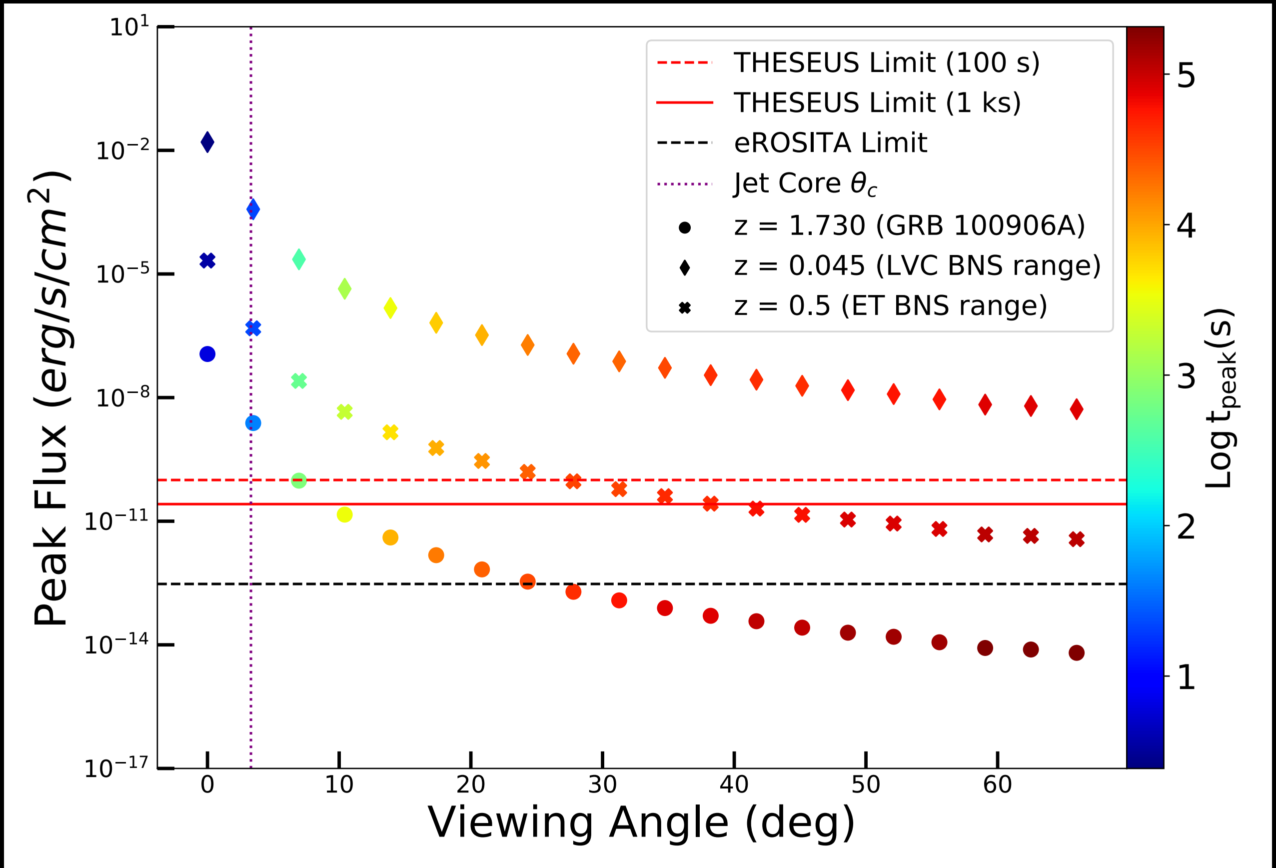




Oganesyan et al. 2020 ApJ

What happen off-axis?

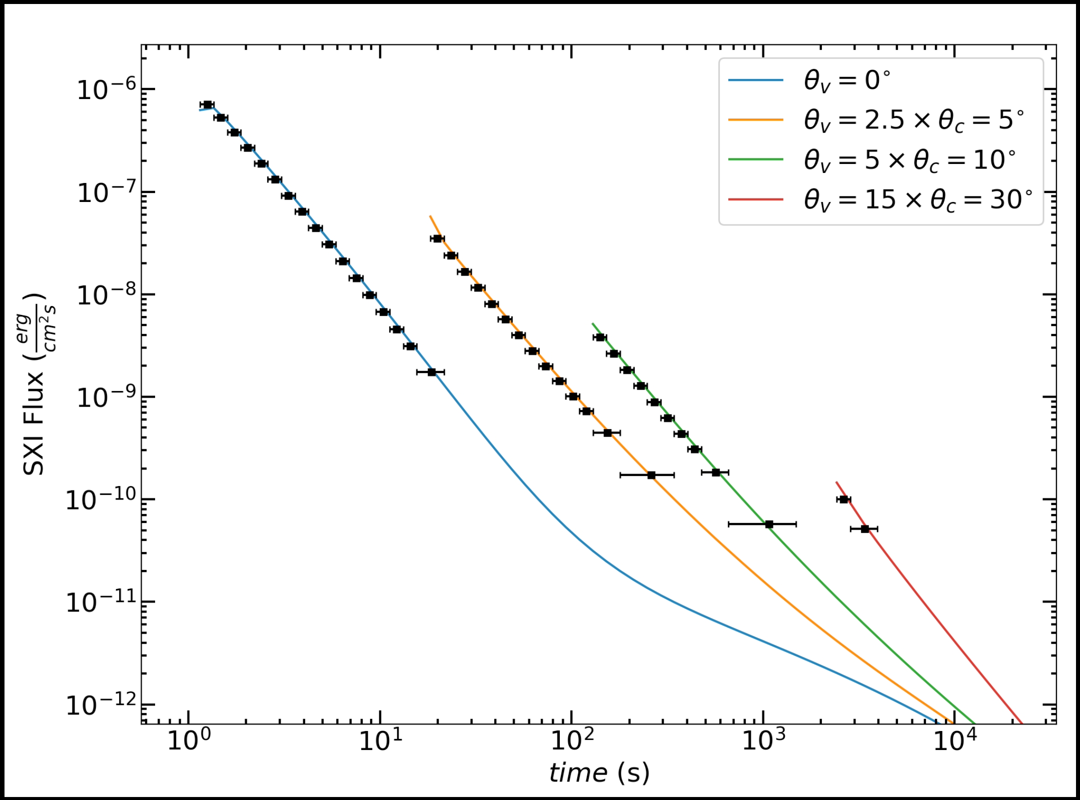


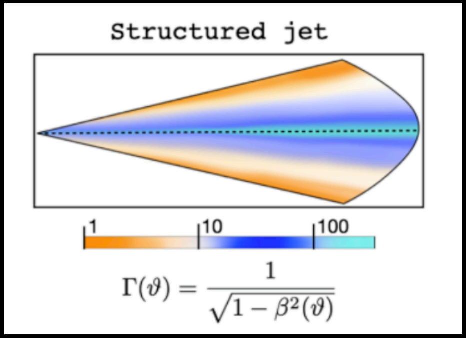


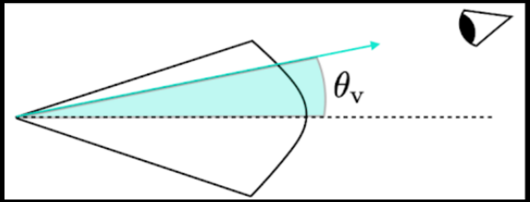
Ascenzi et al. 2020 A&A

Promising X-ray couterparts!

Off-axis X-ray emission from short GRBs observed by SXI



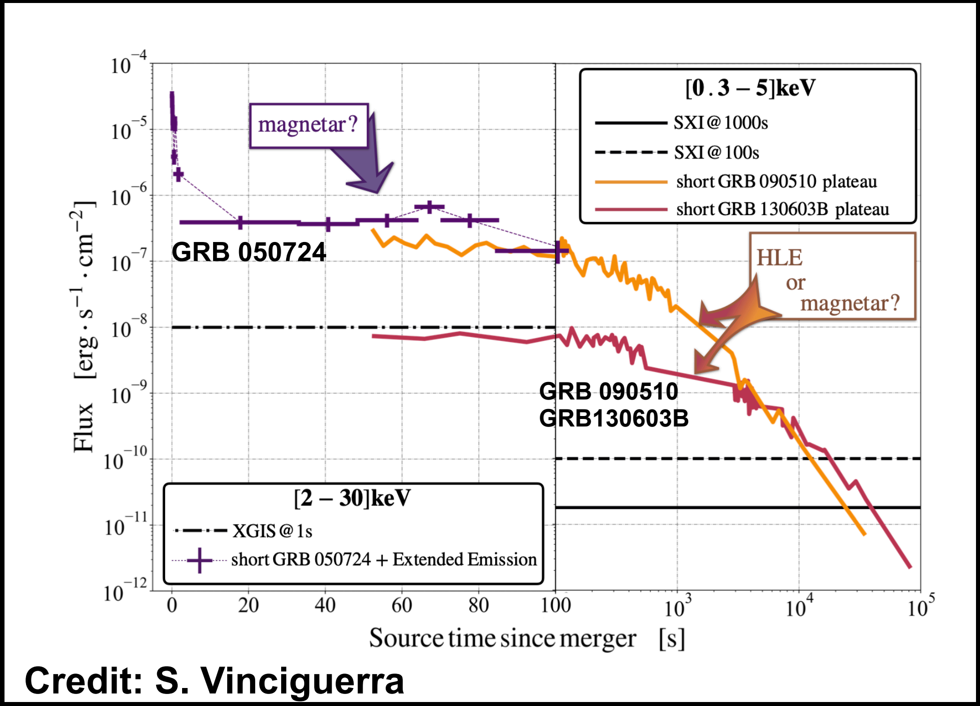




GRB 140903A placed at z=0.5
0.5-10 keV lightcurves

Credit: Ronchini, Ascenzi, Oganesyan

A large fraction of short GRB show an EXTENDED EMISSION during the prompt phase a softer and prolonged emission lasting a few tens up to hundreds of second



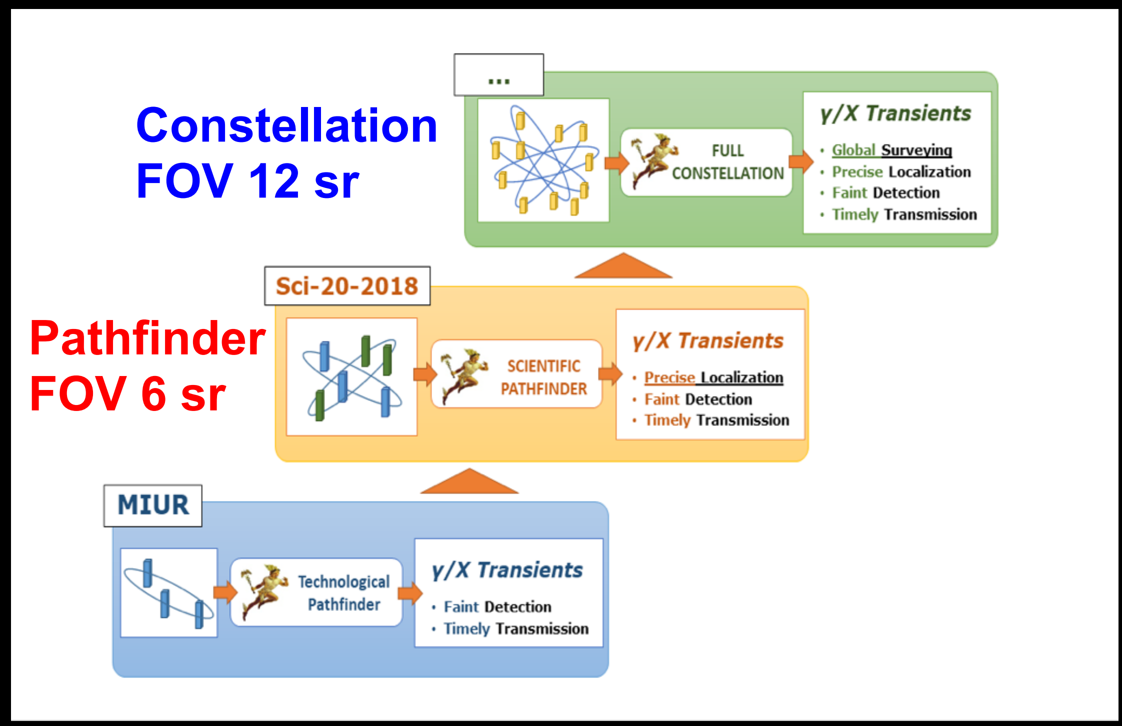
X-ray light curves showing Extended Emission (EE) and plateaus

- Very uncertain fraction of short GRB with EE and degree of collimation
- Assuming 50% and a cone semi-aperture angle of 20°
  → about 100 joint EE+GW detections for 3G detectors

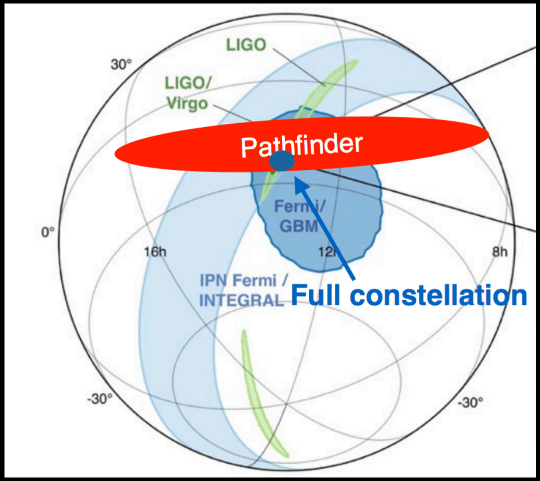
Credit THESEUS Yellow Book in prep

HERMES constellation of cubesat

- From a few to hundreds detectors single
- Collecting area ≥50cm^2, total collecting area ≥1m^2
- Energy range 3-10 - 300-1000 keV
- Temporal resolution a few hundred ns



Credit: Fiore, Nava, Ghirlanda

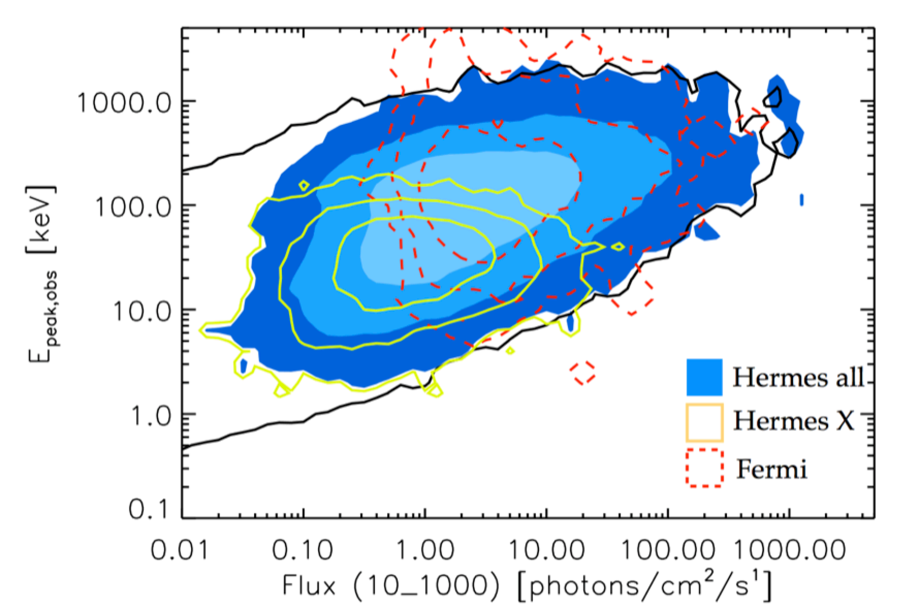


SKY LOCALIZATION

Pathfinder → σPos ~ 2.4 deg

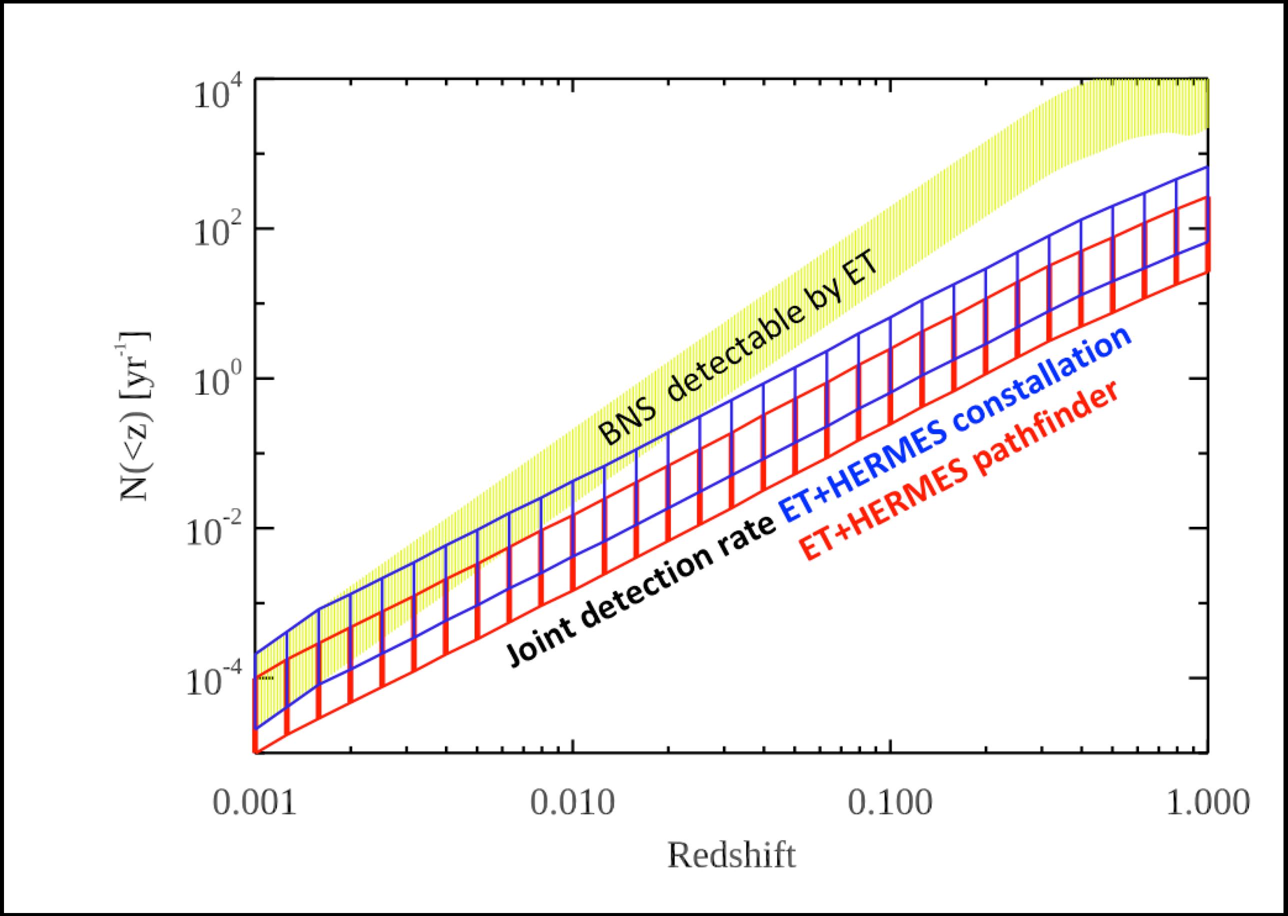
Constellations → σPos ~ 15 arcmin

HERMES GRB detection capabilities



Pathhfinder: launch 2022, ASI provided

- Short GRB Population Based on Ghirlanda et al. 2016
- BNS detectable rate from GWTC-2, LVC 2020 taking into account ET detection efficiency
- Assumed that all BNS produce a jet
- It considers short GRB observed off-axis



Credit: Ghirlanda

Next decades multi-messenger observatories