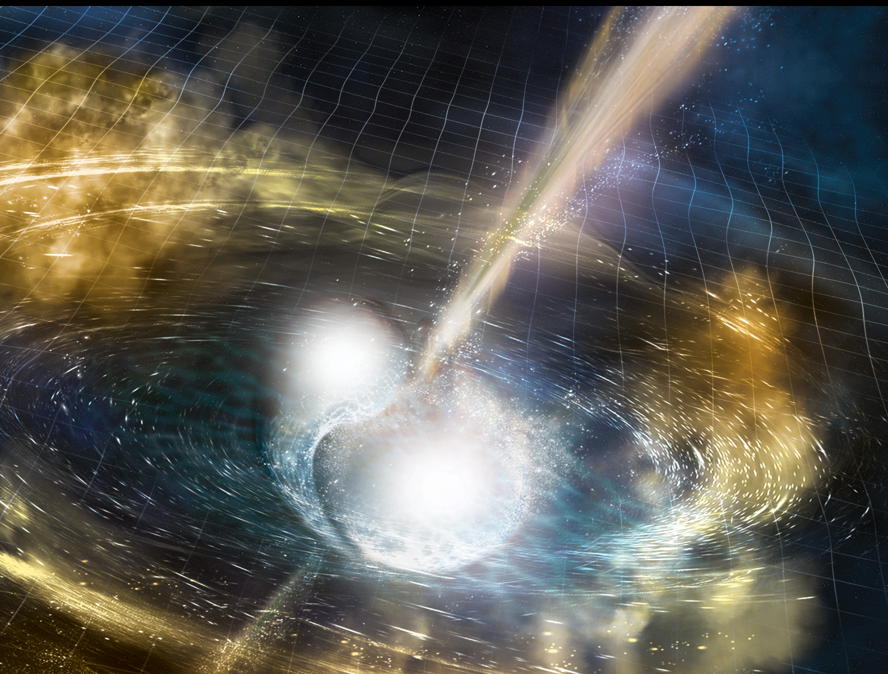
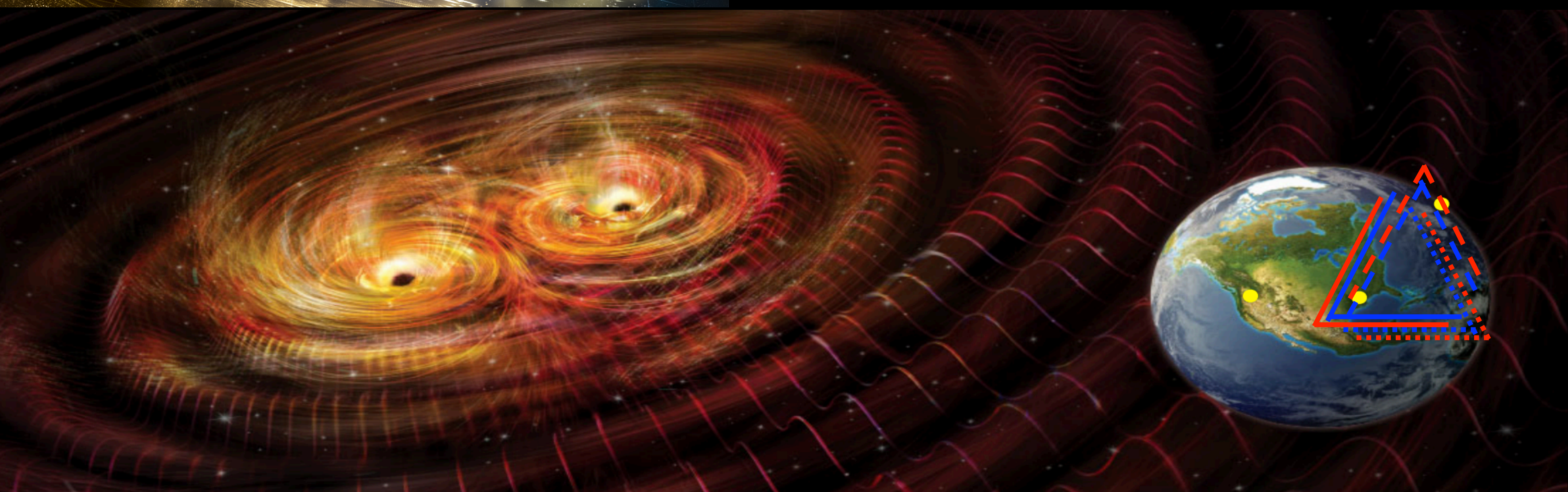
# The future of multi-messenger transient astronomy




*M. Branchesi*

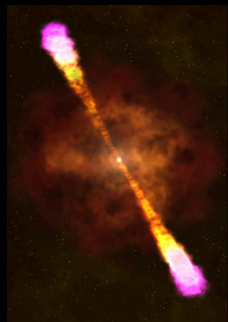
*Gran Sasso Science Institute*

*INFN/LNGS and INAF*

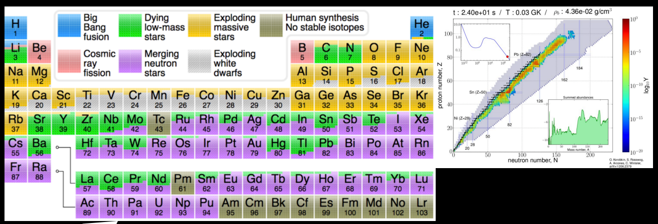



# Radioactively powered transients

## Relativistic astrophysics

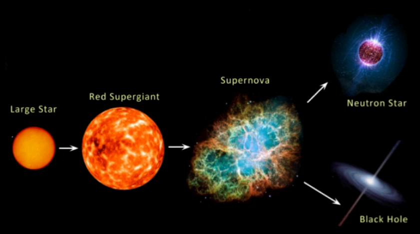


## Nucleosynthesis and enrichment of the Universe

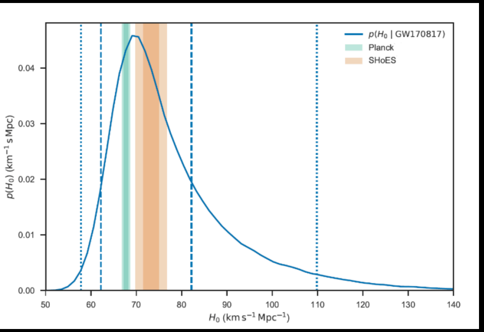




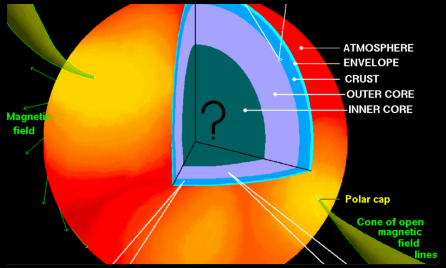
## Compact object formation and evolution




## Cosmology

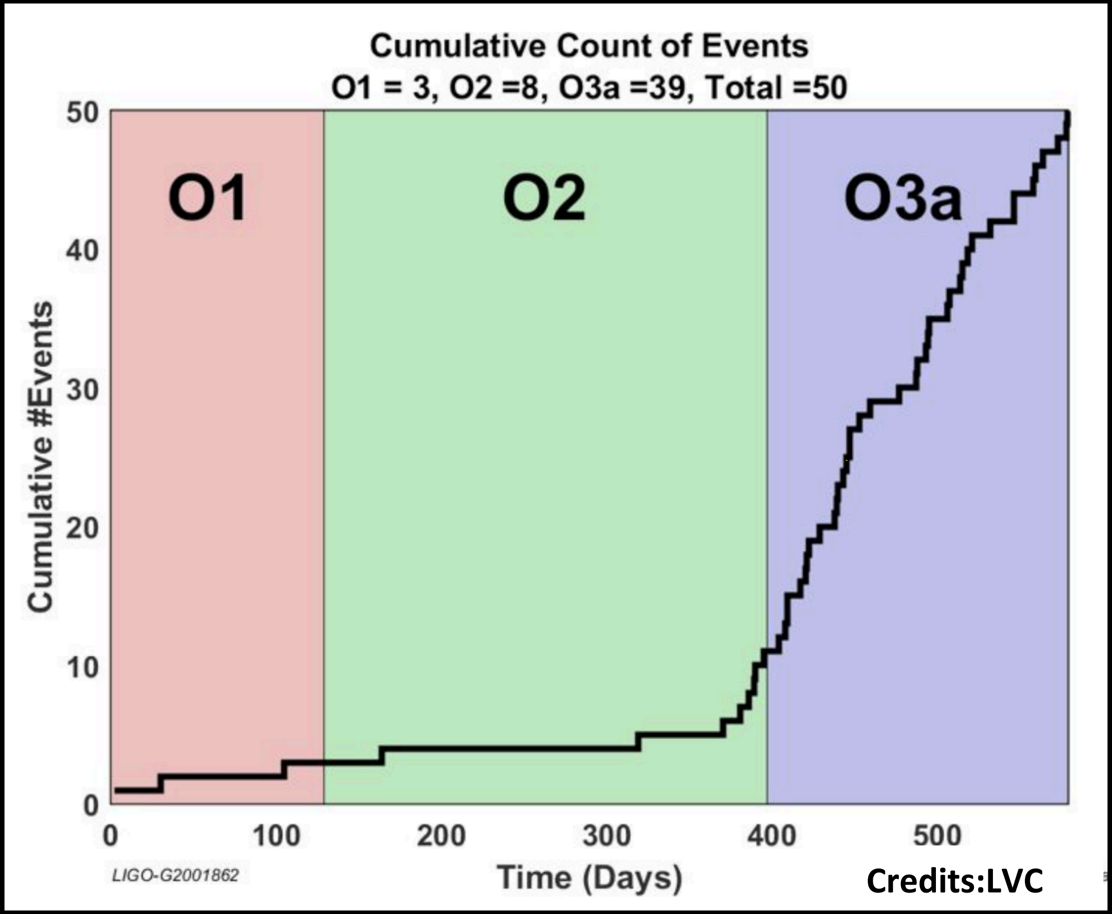



## Nuclear matter physics



*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%)

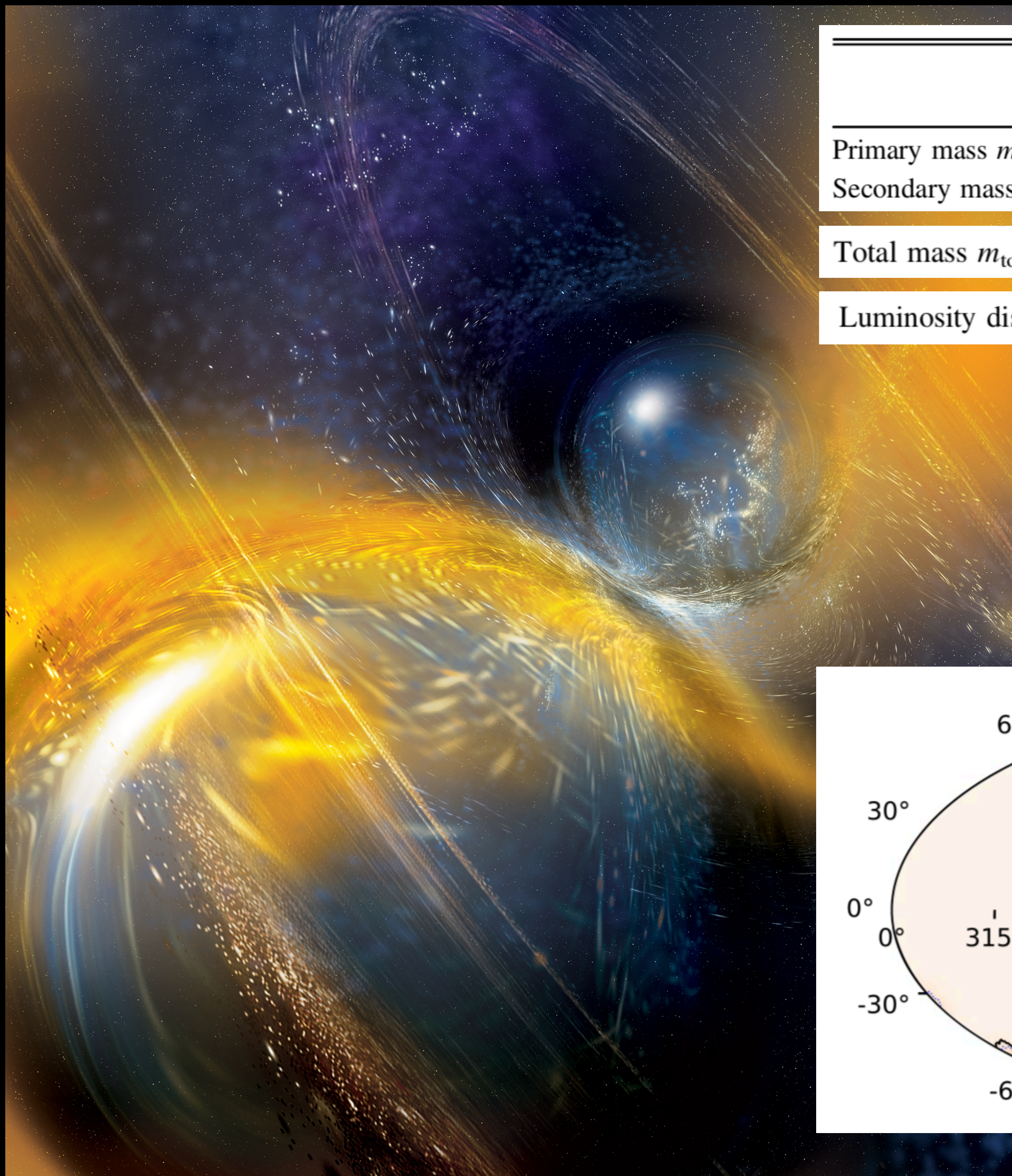
**26 candidate events** low-latecy reported in GCN alerts

**+**

**13 candidate events** offline analysis

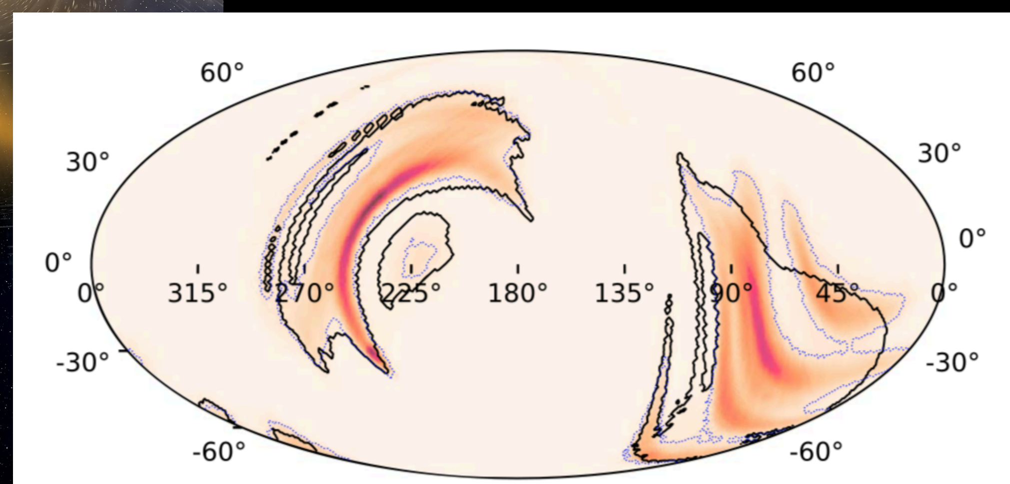
**O1, O2, O3 → 50 candidate GW events**

# 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 |

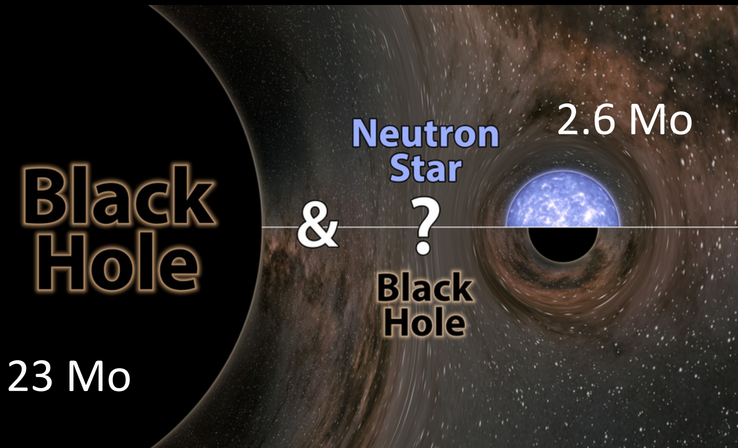
NO firm EM counterpart! ☹




Sky localization of 8284 deg$^2$

Abbott et al. 2020, ApJL, 892

# GW190814

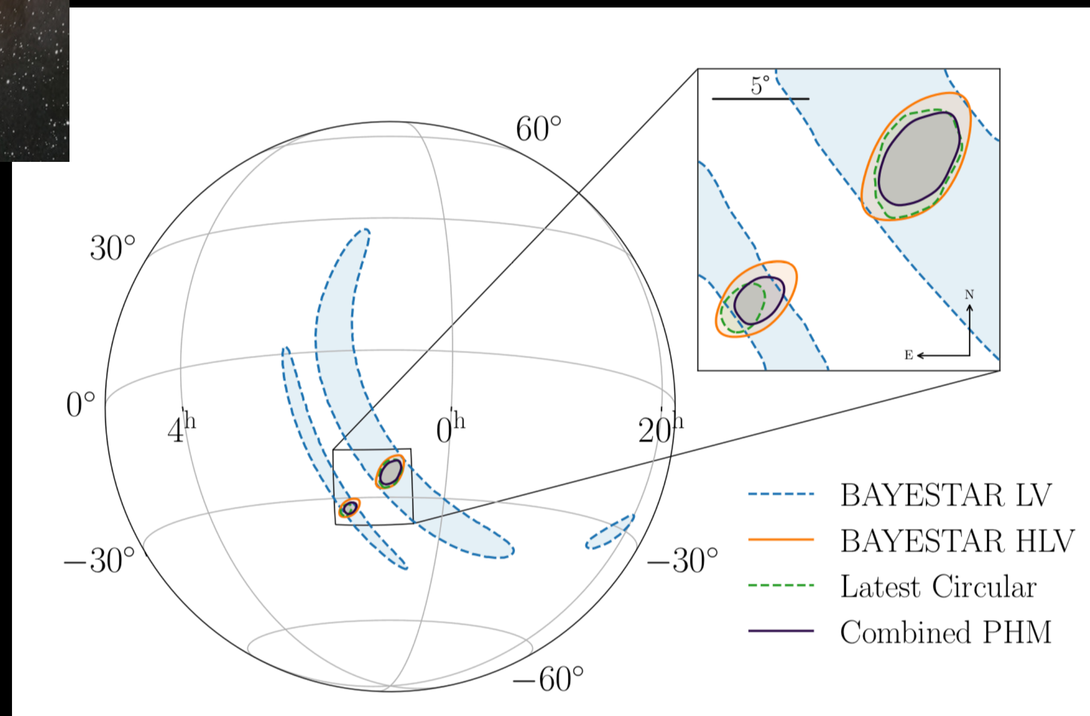



- NO EM counterpart

→ *Consistent with both BBH and NSBH scenarios*

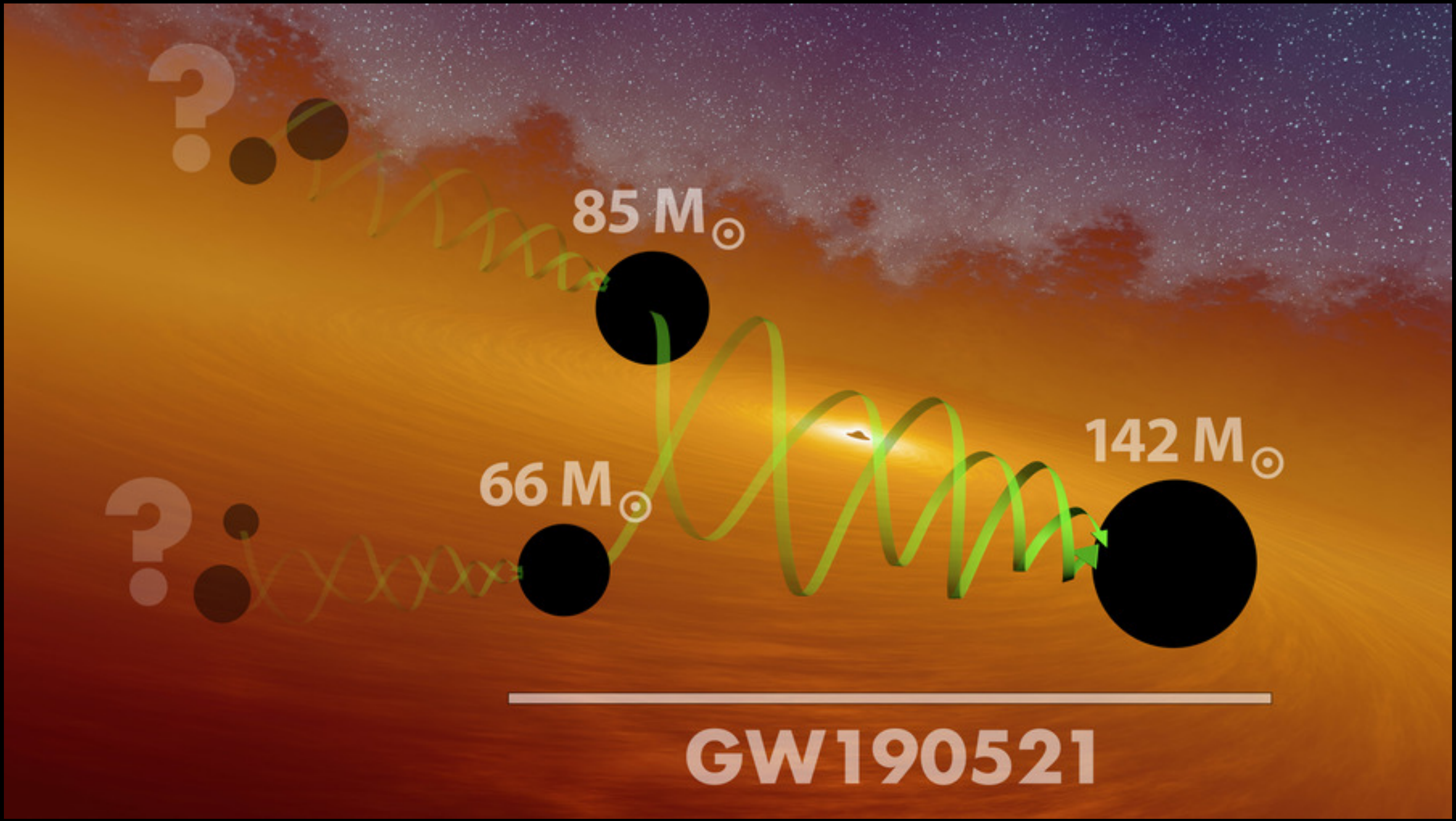
→ *In the NSBH, observation results can be explained by the large mass ratio*

Abbott et al. 2020, ApJL, 896




Sky localization of 18.5 deg$^2$

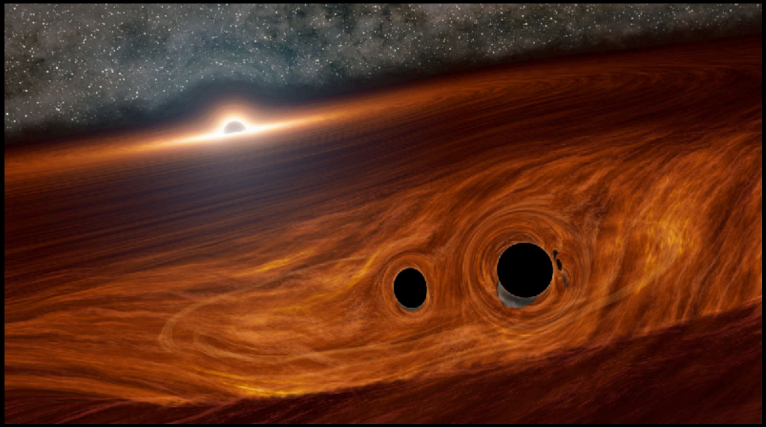
Luminosity distance 235 Mpc



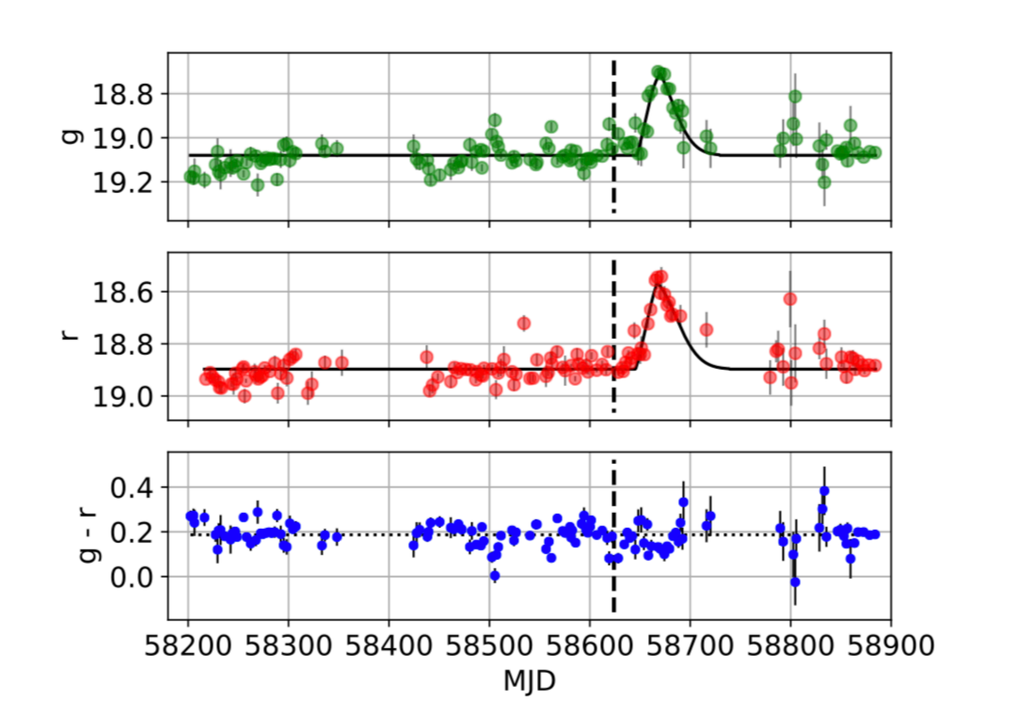

credit: LIGO/Caltech/MIT/R. Hurt (IPAC)

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(!?)

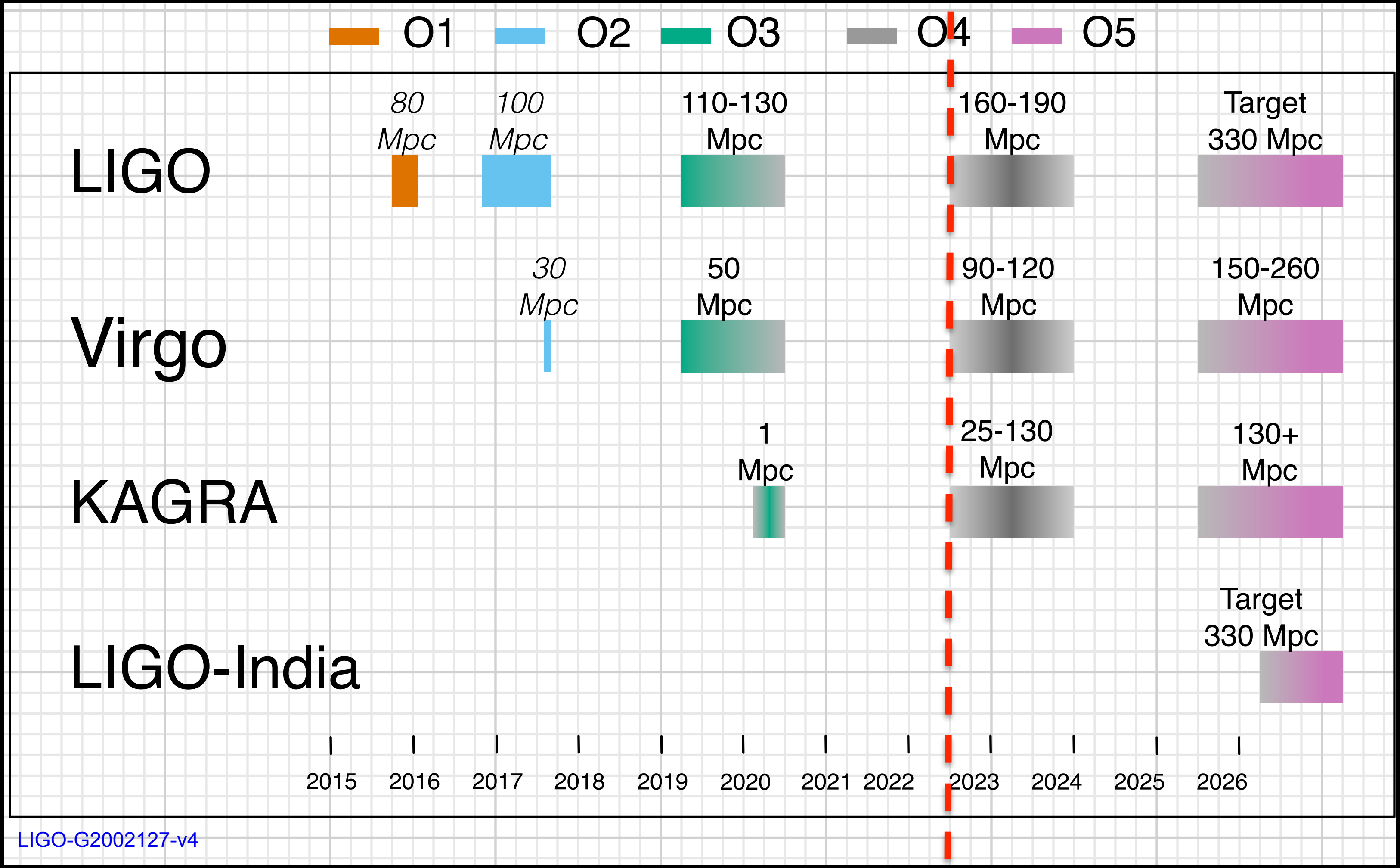
- EM flare close to AGN

~ 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.)

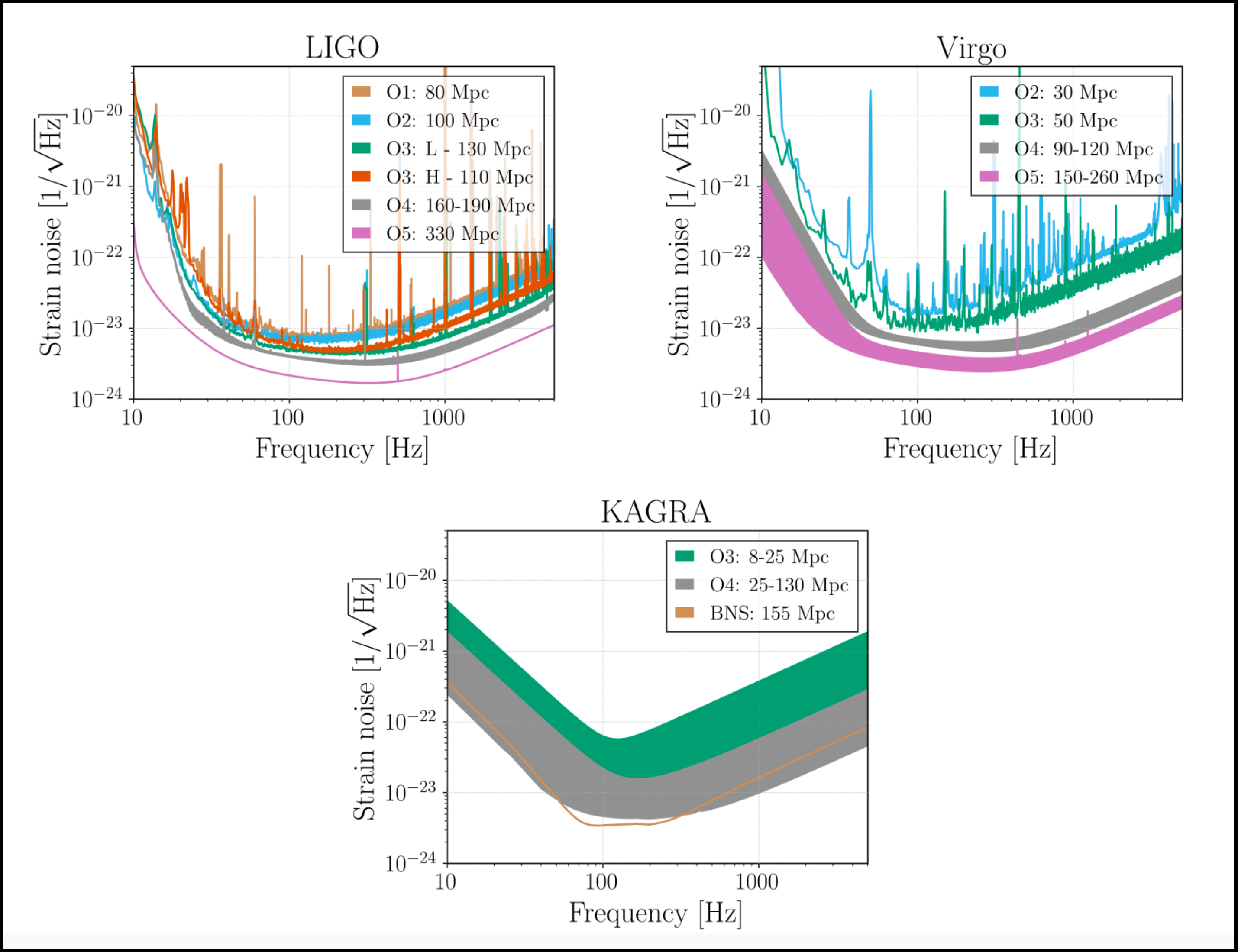
# Next observating runs

# *Observing run timeline and BNS sensitivity evolution*



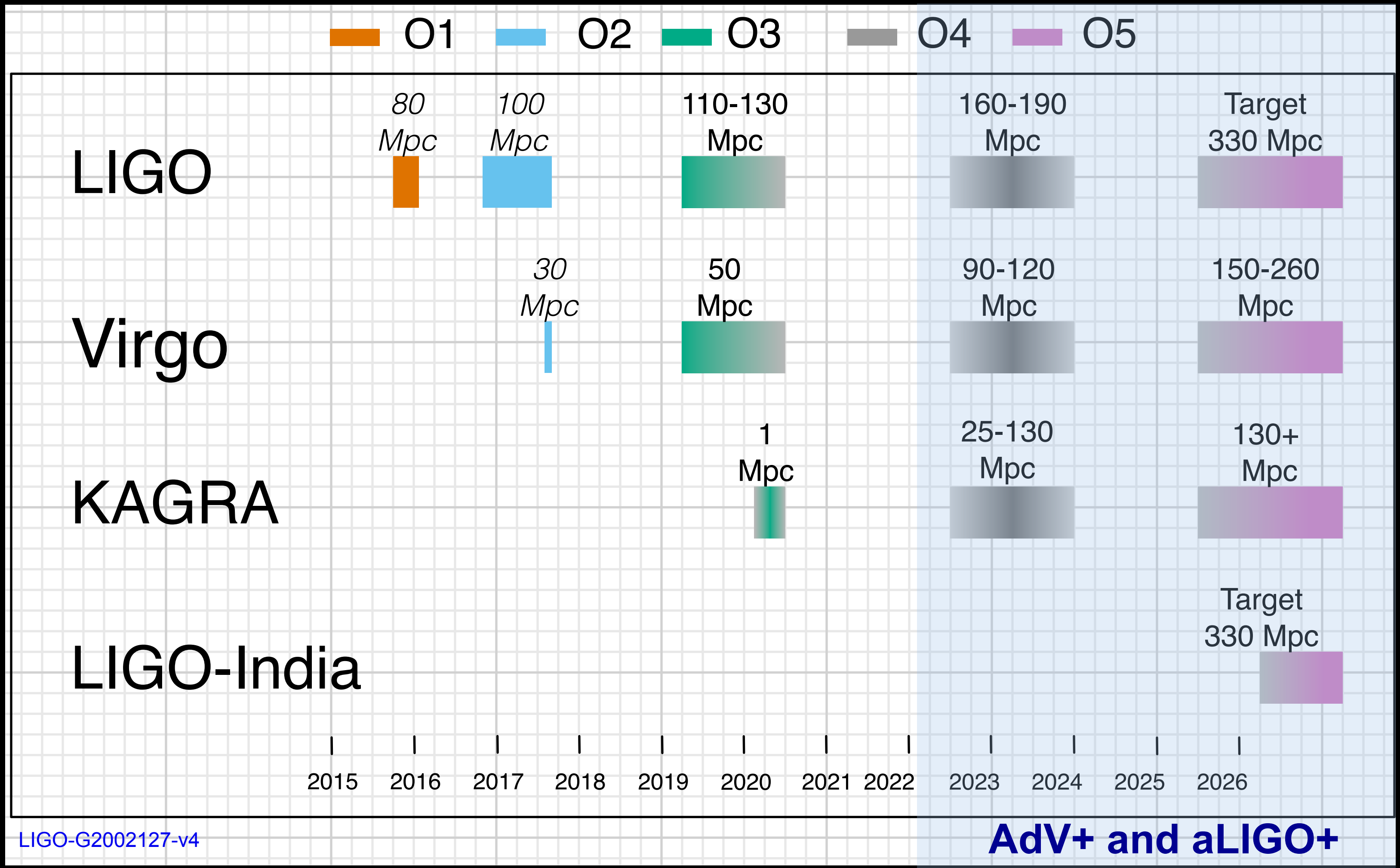

Starting of 04 not before June 2022

# *Strain sensitivities as a function of frequency*




Abbott et al. 2020, LRR

# *Observing run timeline and BNS sensitivity evolution*




Abbott et al. 2020, LRR

O4 volume = 3*O3 volume
O5 volume = 15*O3 volume

# O4 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

# 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

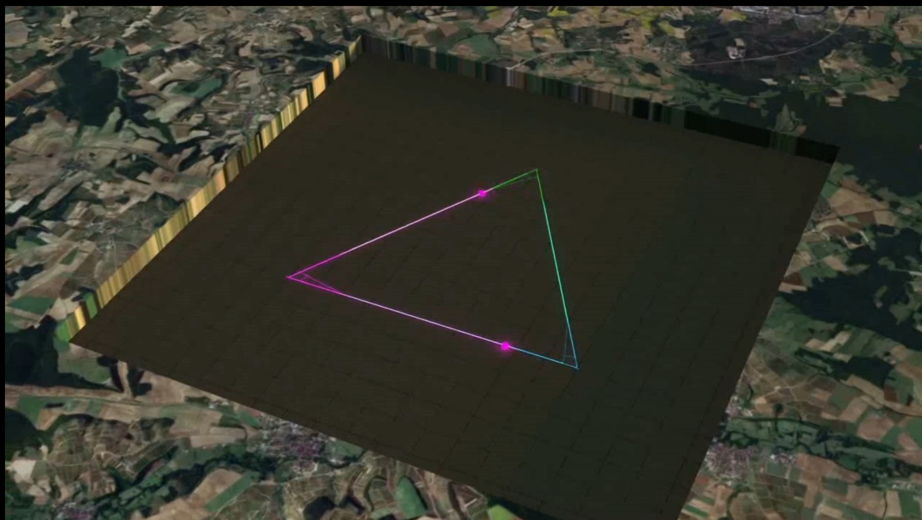
Detection: SNR > 4 in at least two detectors and network SNR > 12

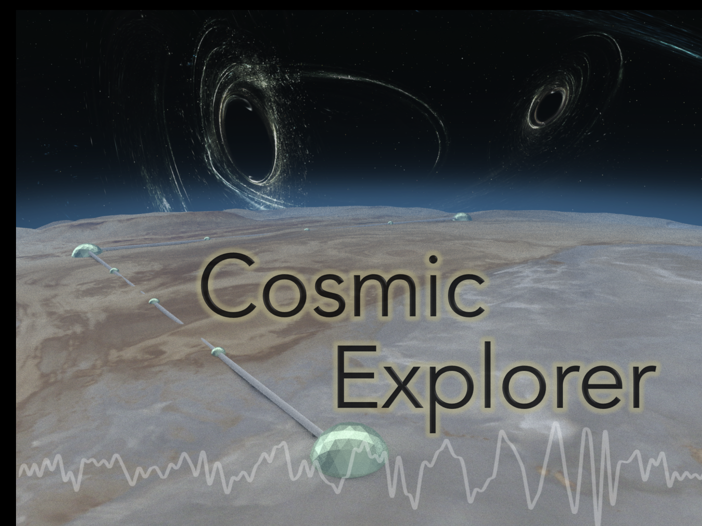
| Observation Run | Network | Expected BNS Detections | Expected NSBH Detections | Expected BBH Detections |
|---|---|---|---|---|
| O3 | HLV | $1^{+12}_{-1}$ | $0^{+19}_{-0}$ | $17^{+22}_{-11}$ |
| O4 | HLVK | $10^{+52}_{-10}$ | $1^{+91}_{-1}$ | $79^{+89}_{-44}$ |

Abbott et al. 2020, LRR

# The future of GW and Multimessenger astronomy

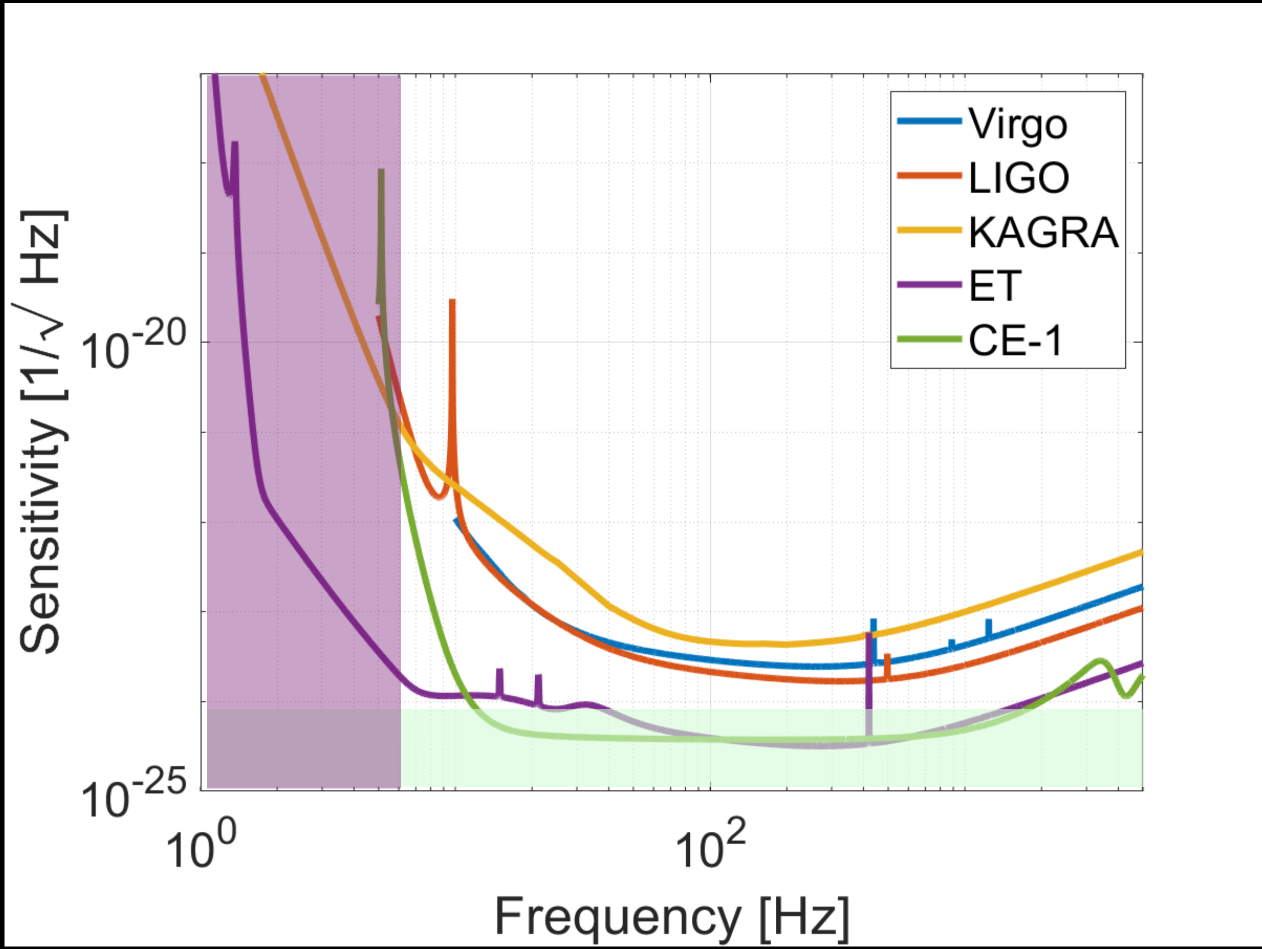
Einstein Telescope: the European 3G GW observatory concept






Cosmic Explorer: 40km
L shaped detector

# EXPECTED SENSITIVITY

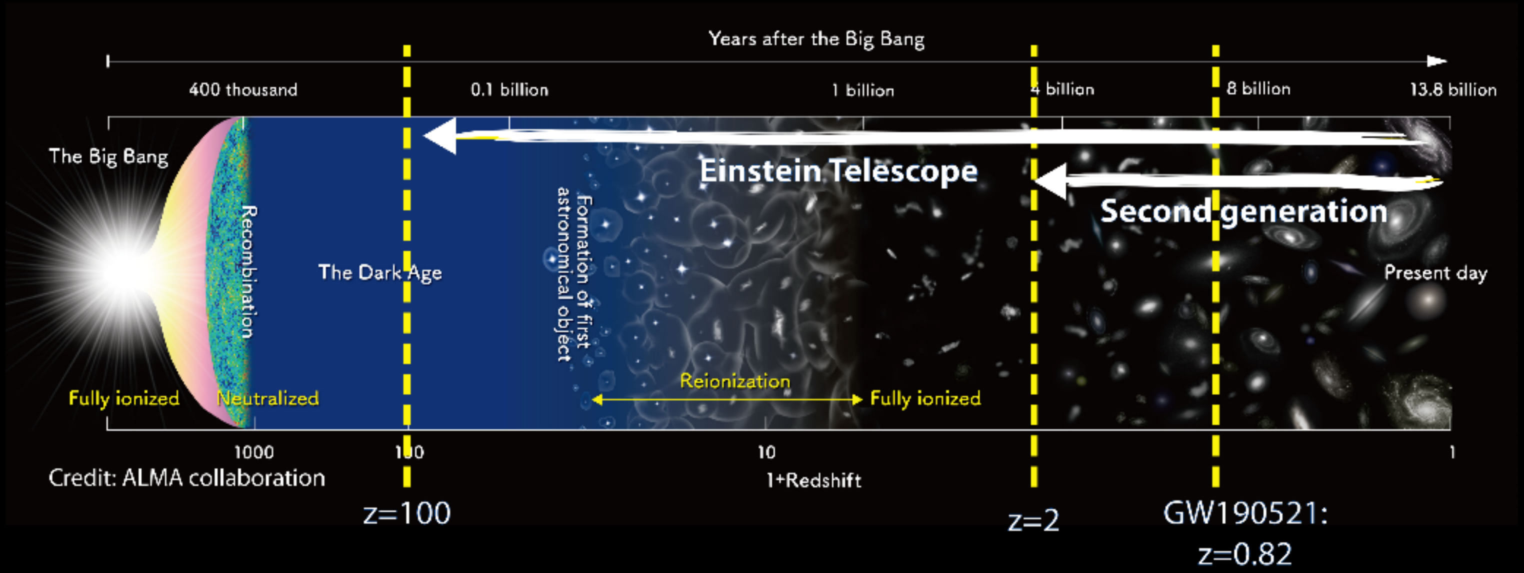


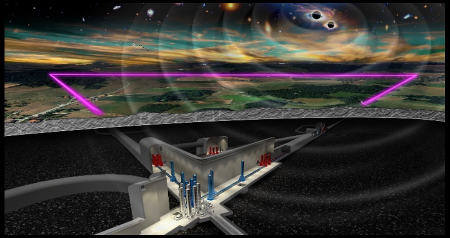

- Factor 10 better  (x1000 Volume) than 2G detectors
- Wide frequency, with special attention to low frequency (few Hz)

The ET sensitivity will make it possible:

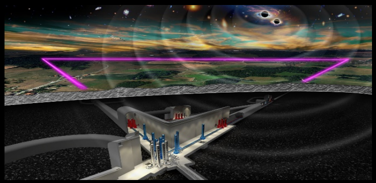
- Large distances back to the EARLY UNIVERSE

Detection horizon for black-hole binaries



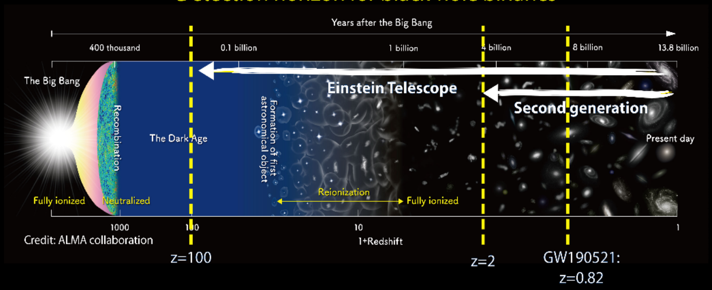



# The ET sensitivity will make it possible:

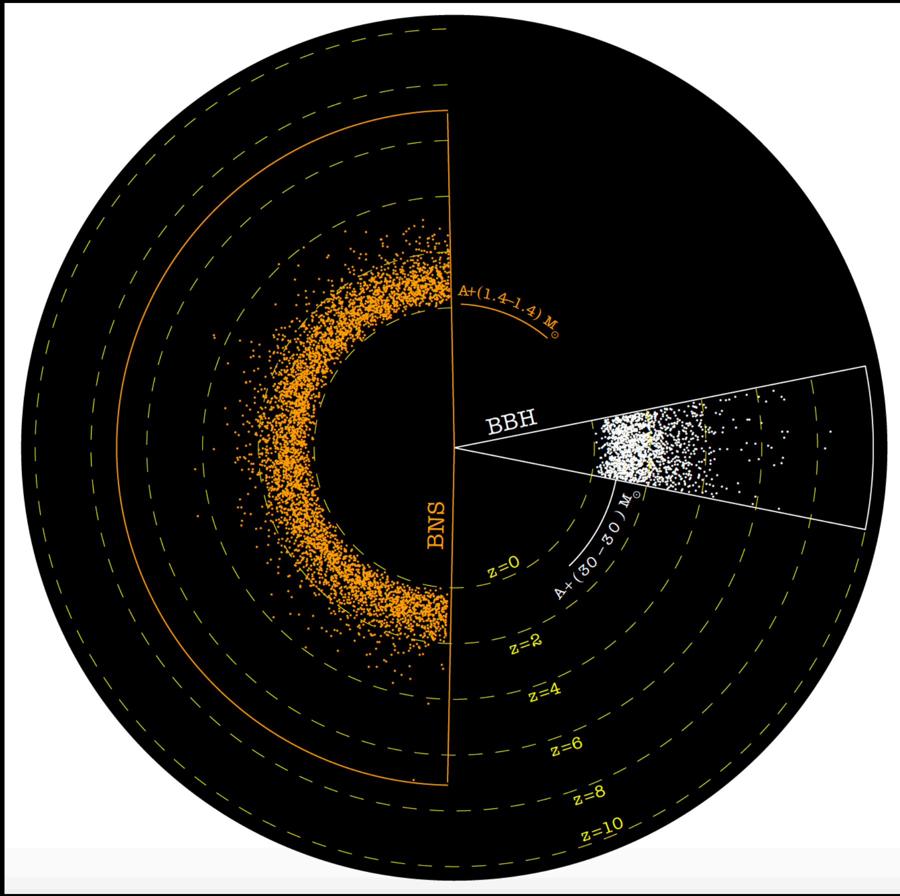


- Large distances back to the EARLY UNIVERSE

Detection horizon for black-hole binaries

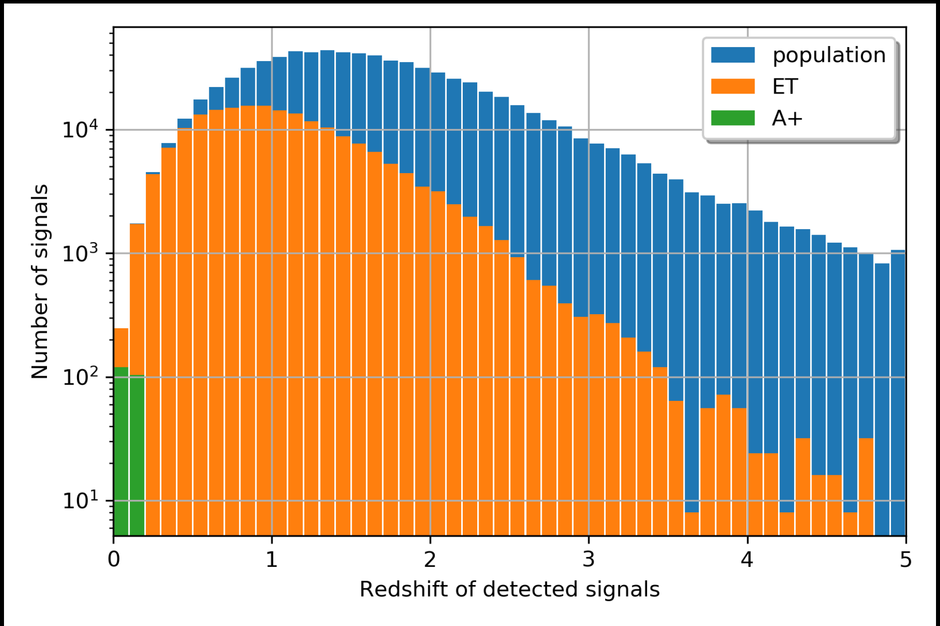



- POPULATION:
  increase number of detections

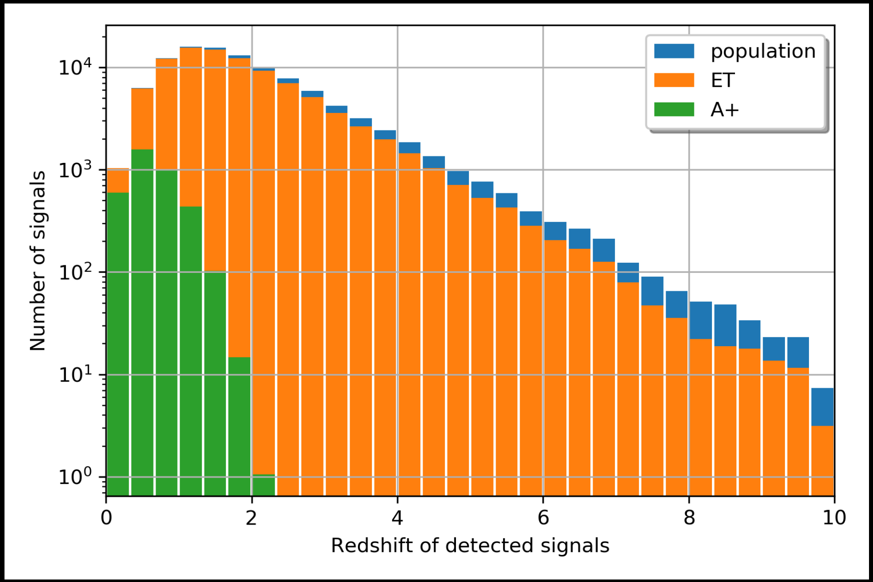


# COMPACT OBJECT BINARY POPULATIONS

## BINARY NEUTRON-STAR MERGERS




## BINARY BLACK-HOLE MERGERS

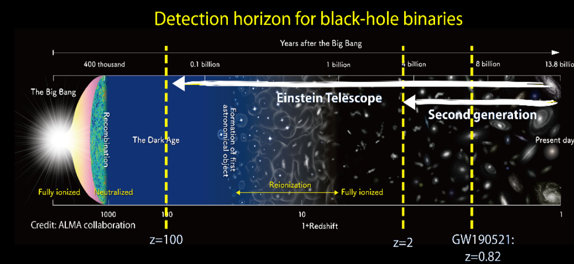



Sampling **astrophysical populations** of binary system of compact objects along the cosmic history of the Universe

$10^5$ BNS detections per year

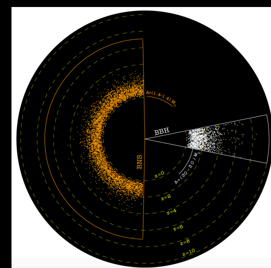
$10^5$ BBH detections per year

## The ET sensitivity will make it possible:

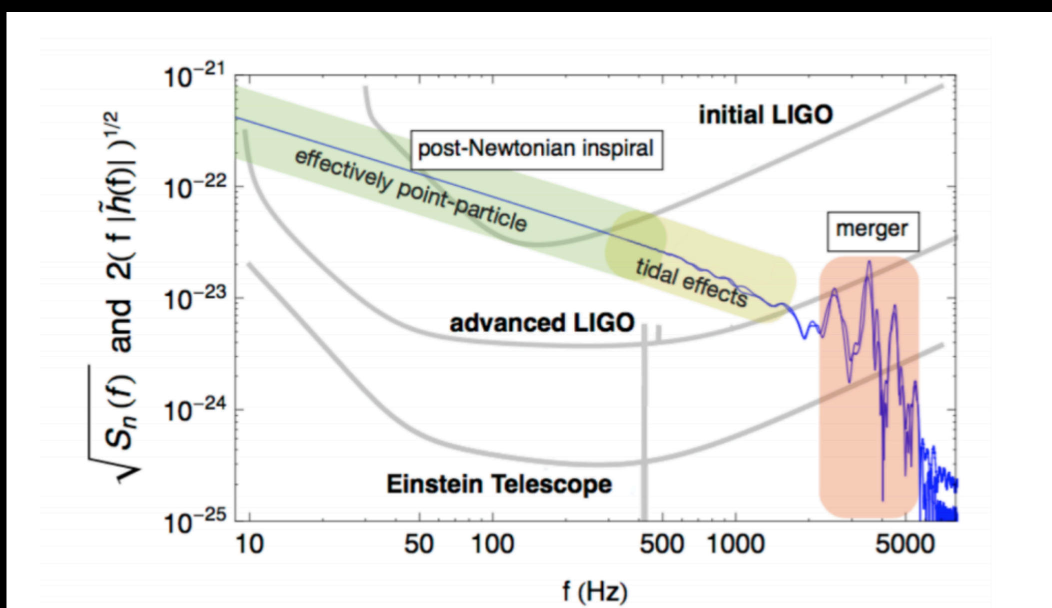



- EARLY UNIVERSE

- POPULATION




- PRECISE GW ASTRONOMY: exceptional parameter estimation accuracy for very high SNR events

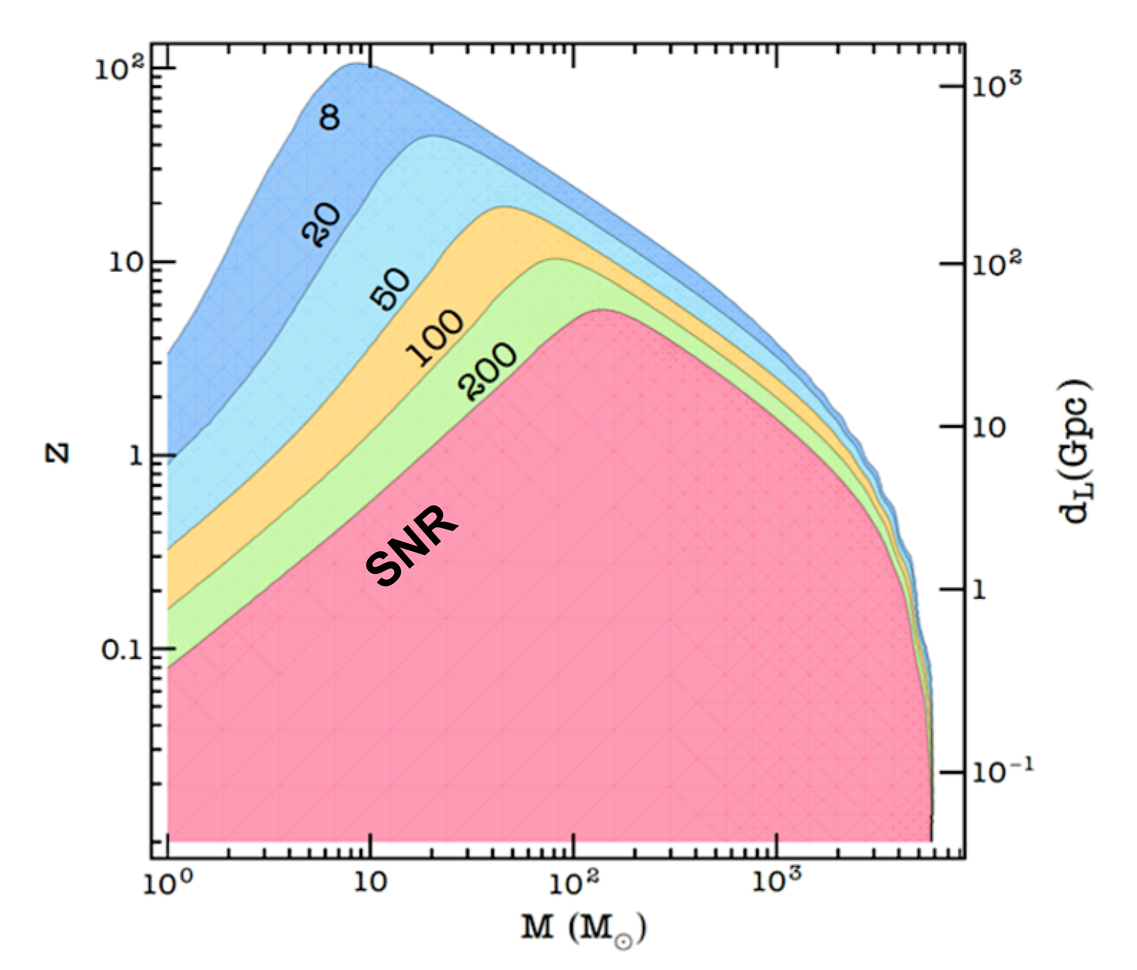


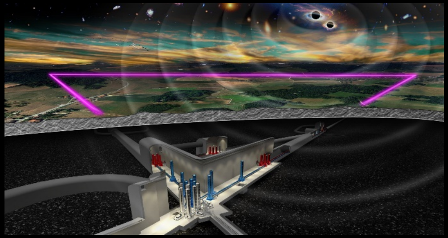

Remote Universe

Nearby Universe

The ET wide frequency band will make it possible:

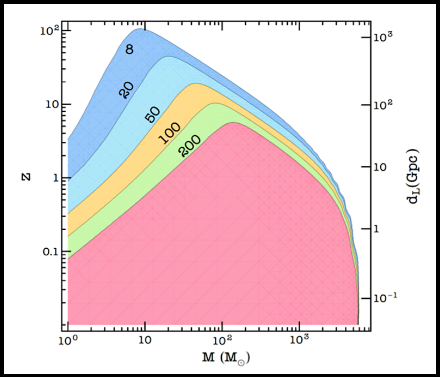
- Access UNEXPLORED MASS up to $10^3$ Mo



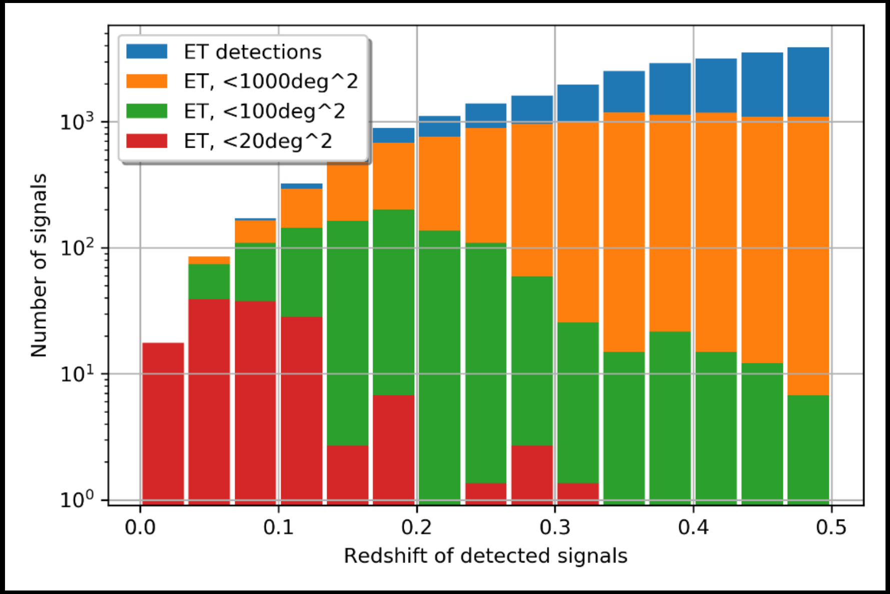



# The ET wide frequency band will make it possible:

- Access UNEXPLORED MASS up to $10^3$ Mo

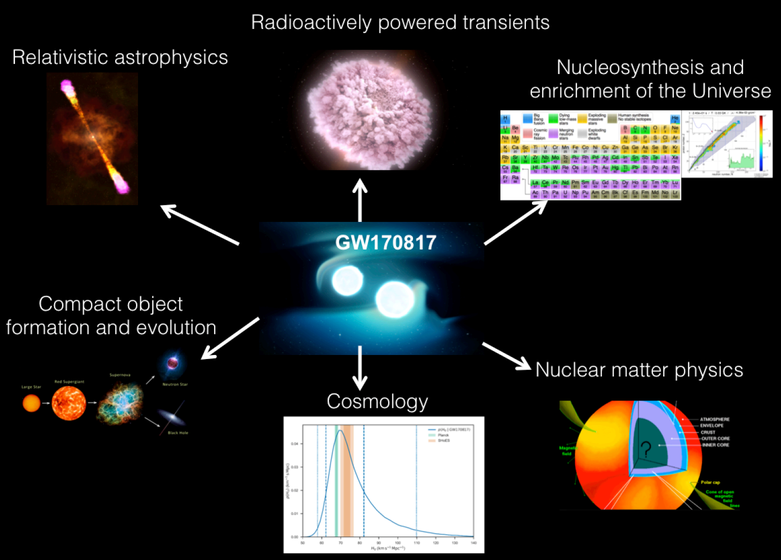



- ET sky-localization capabilities




BNS simulation

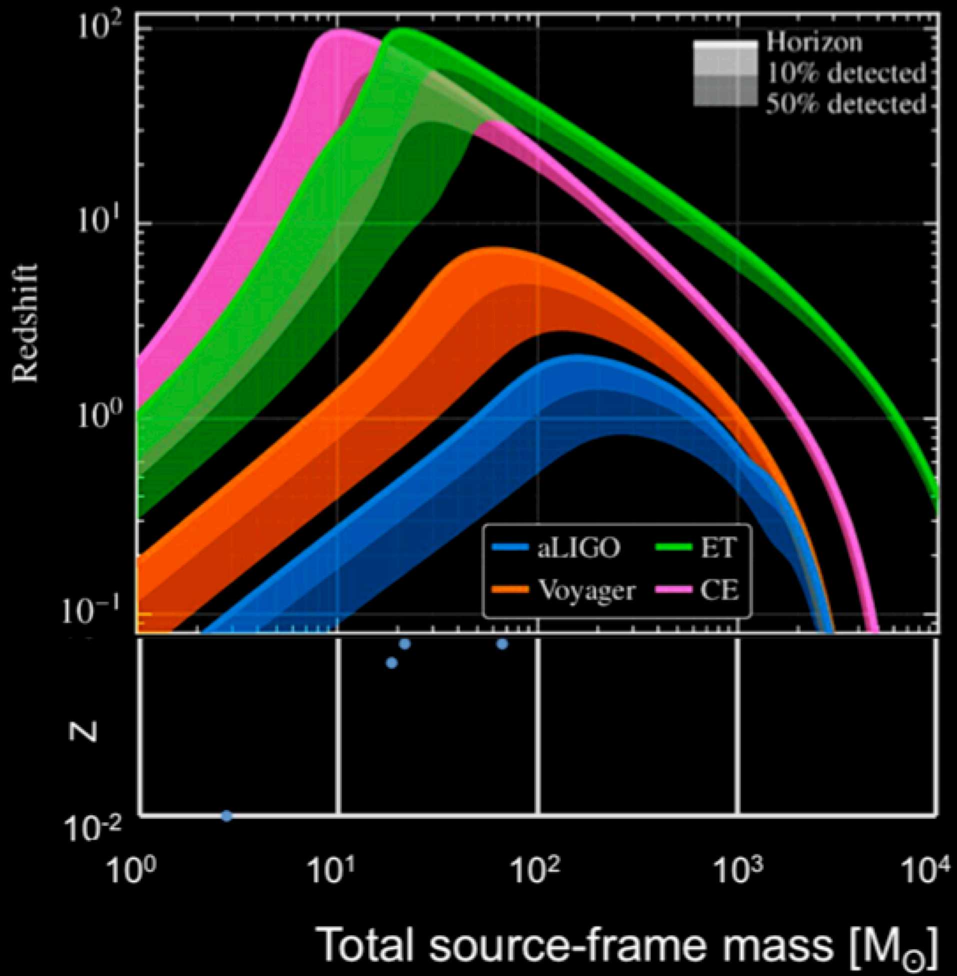
See M. Maggiore talk for ET science case




ET science case in Maggiore et al. 2020

*Multi-messenger in the ET era*

# Binary systems of Compact Objects




**Kilonova/GW - EOS constraints**

**Kilonova/GW - Nucleosynthesis**

**GRBs – BNS/NSBH merger up to high z**

**Relativistic jet properties**

**Jet-less/jet GRBs**

**GRB/stable NS remnant**

**Link to Star Formation History**

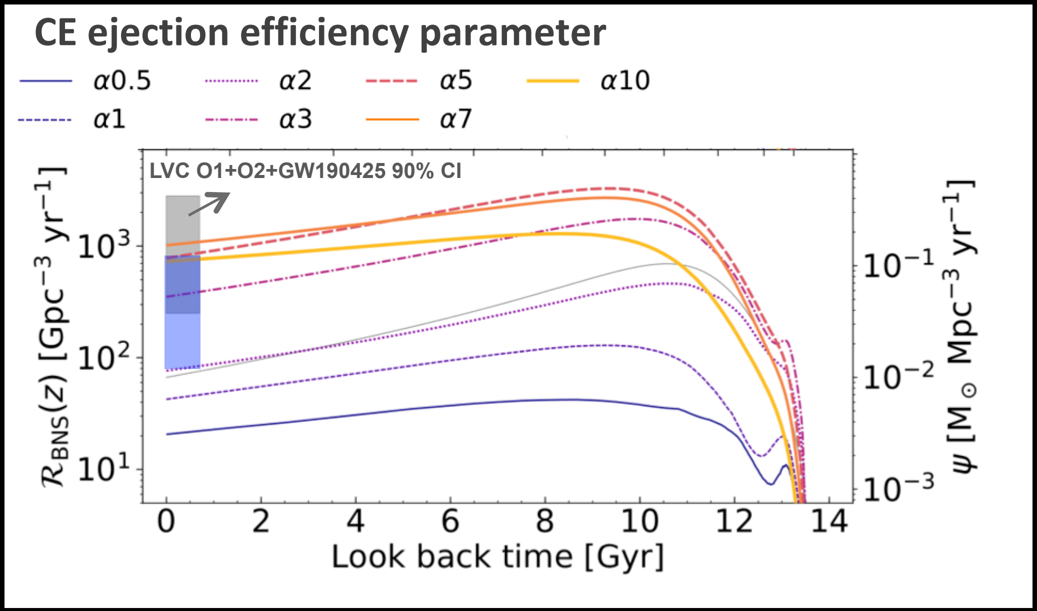
**Emission mechanism**

**Cosmology**

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

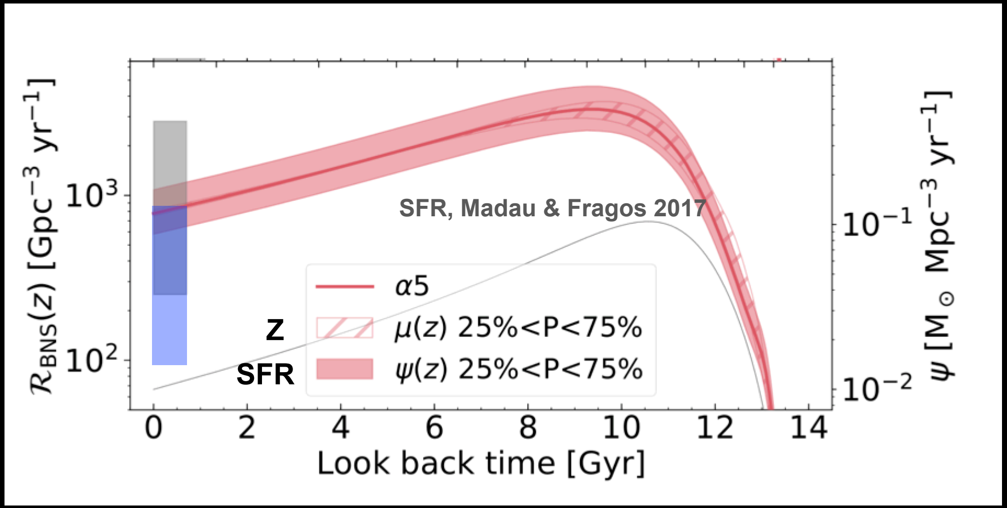
# ET detection capabilities

Astrophysical simulations for BNS from population synthesis code



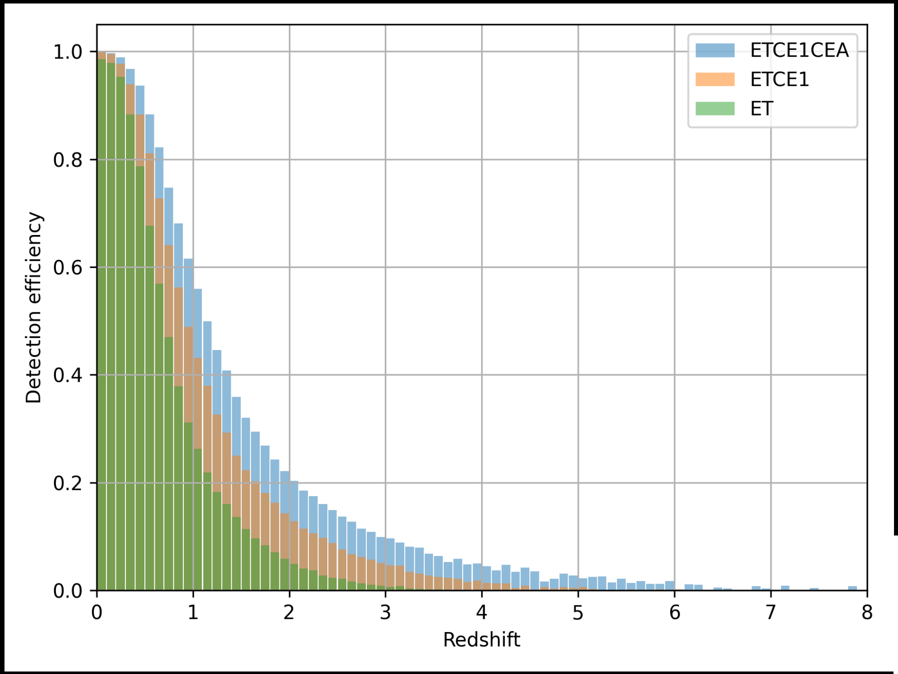

MERGER RATE EVOLUTION
impact of common envelop

MERGER RATE EVOLUTION
impact of SFR and metallicity uncertainty



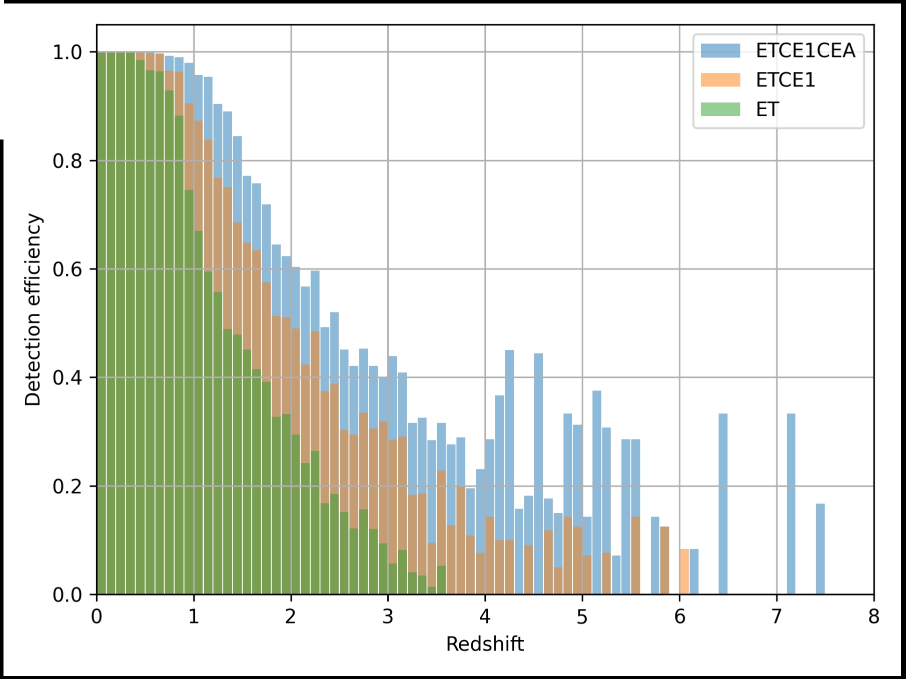

**Santoliquido et al. 2021, MNRAS**

# ET DETECTION EFFICIENCY



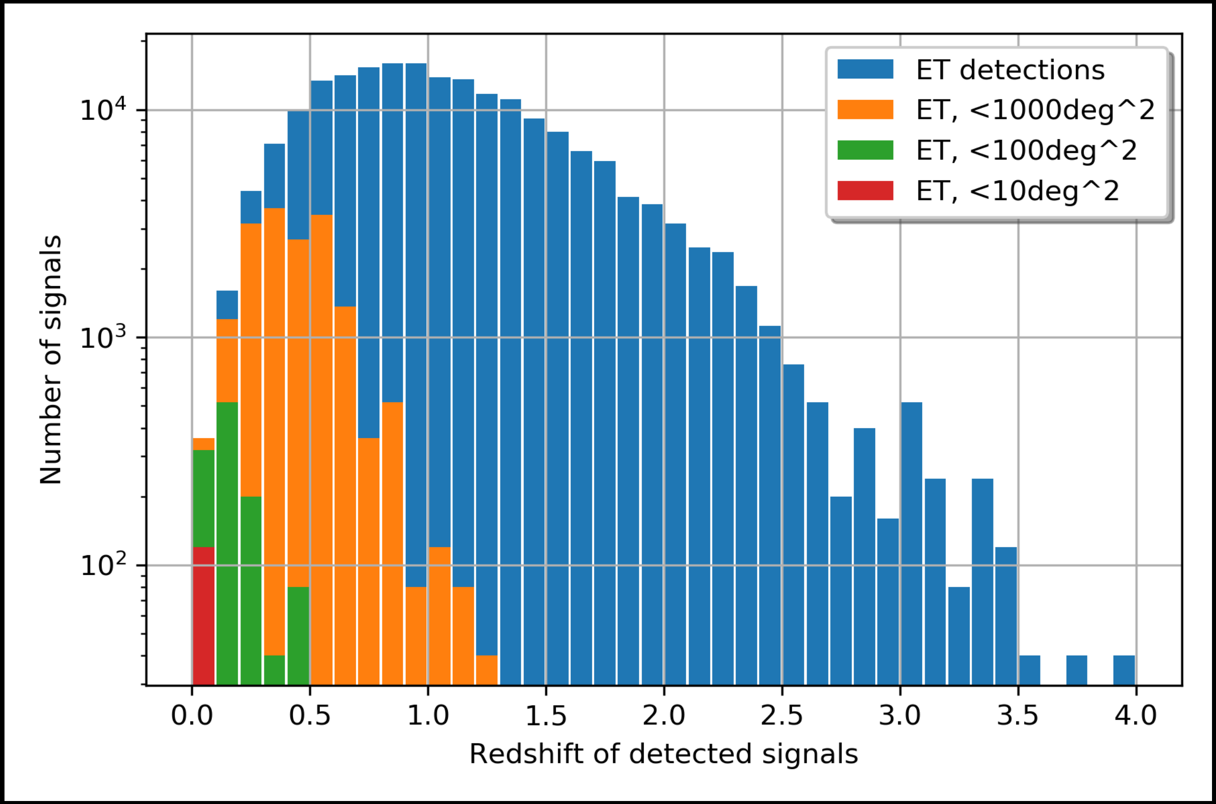

ALL ORIENTATION

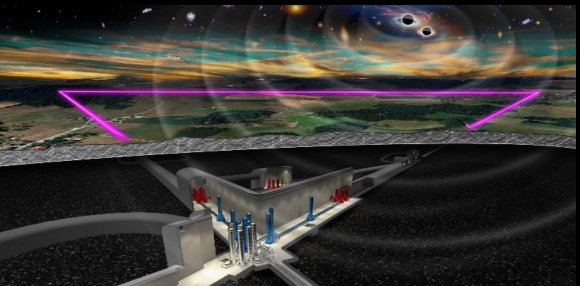
Viewing angle < 10 deg



# EINSTEIN TELESCOPE DETECTION/SKY LOCALIZATION

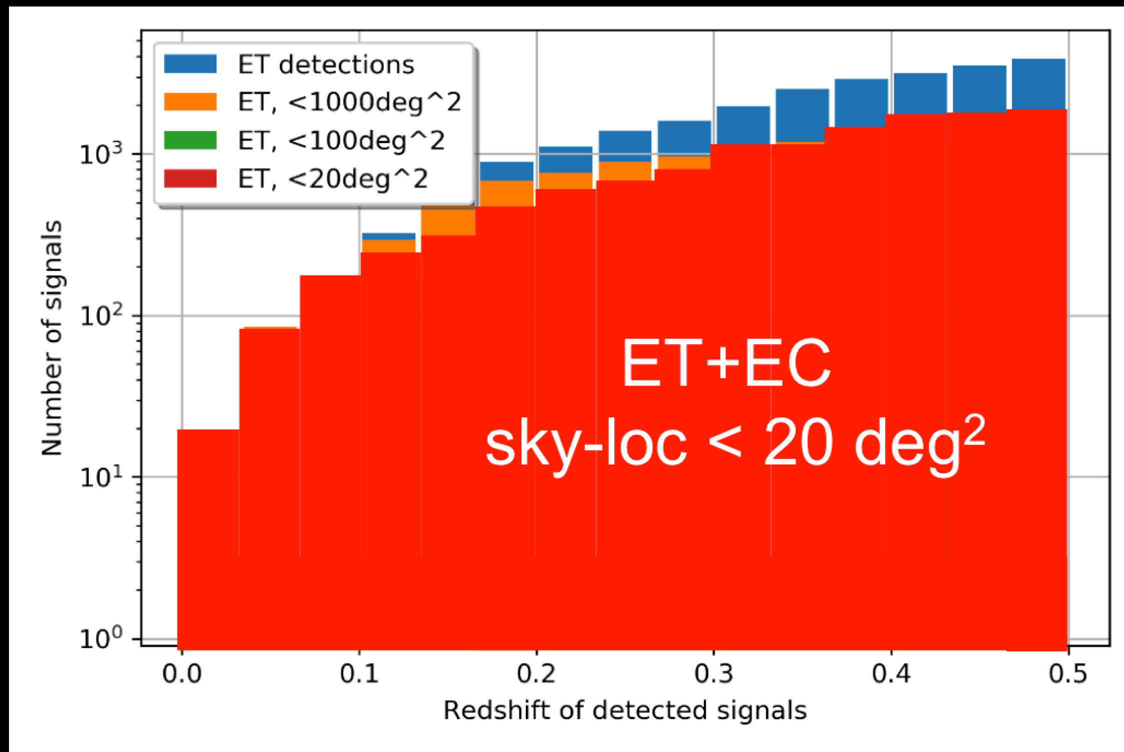
## BINARY NEUTRON-STAR LOCALIZATION

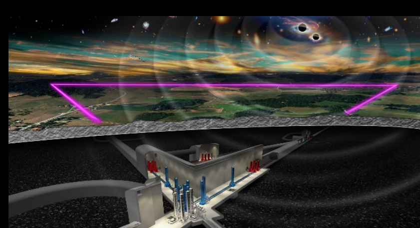


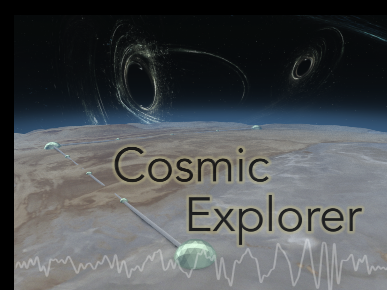



1 year of observations

# ET sky-localization capabilities
# Network sky-localization capabilities

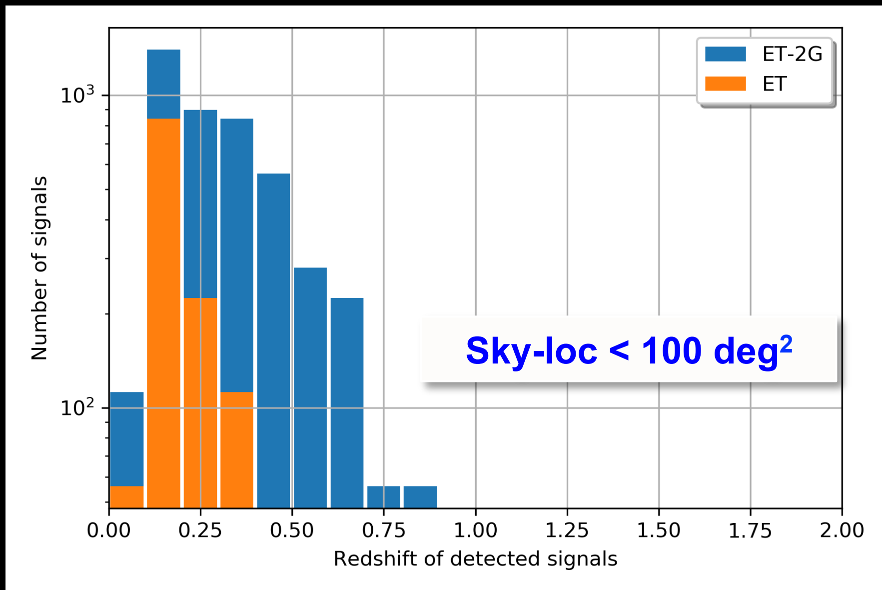


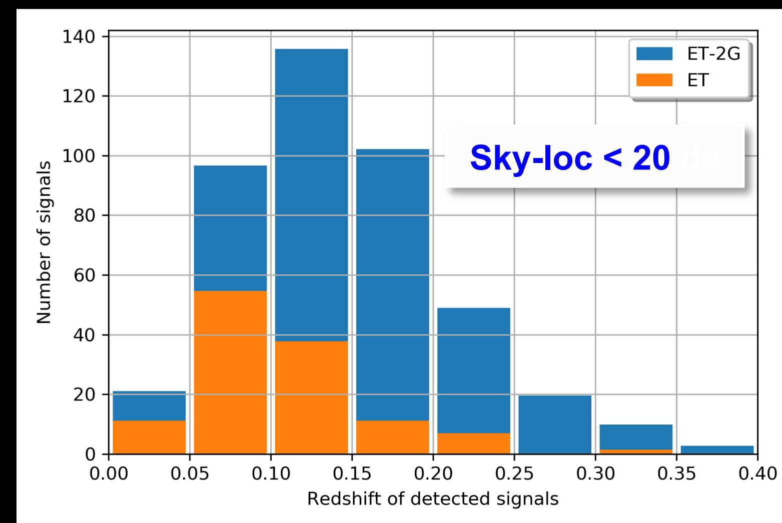


# **ET+ 2G detector network** (Virgo+, LIGO-H+, LIGO-L+, LIGO-India, KAGRA)

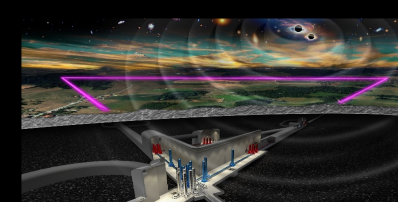
Number of detected BNS



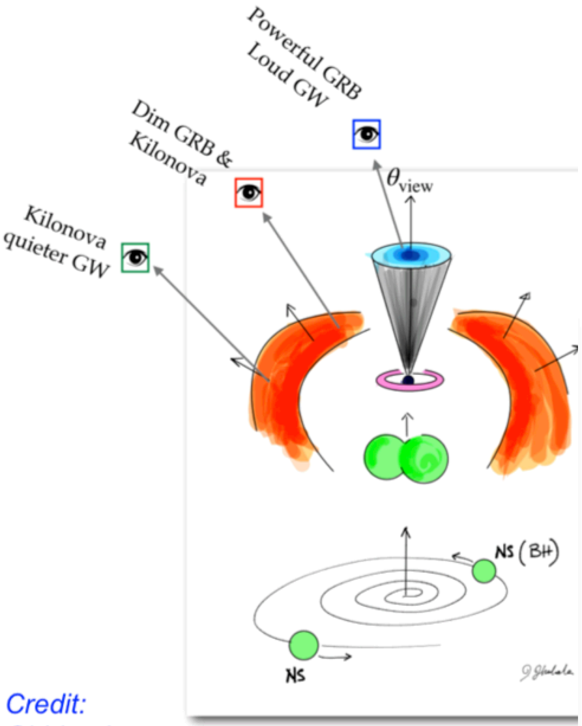

Redshift



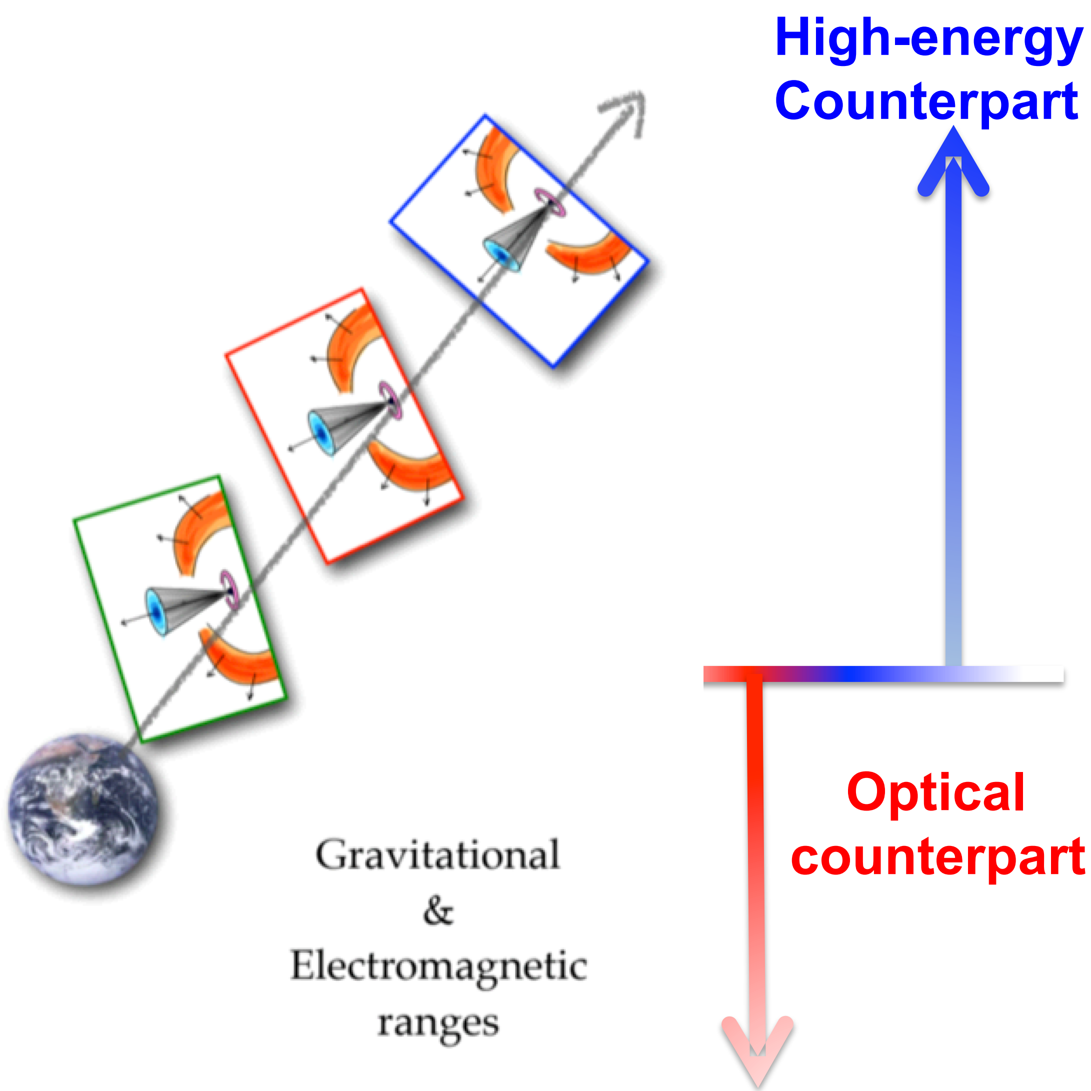

Operating with 2G detector network
improves the ET sky-localization capability
up to a redshift of about 0.6 (3.5 Gpc)



SEARCH PHASE: two regimes **nearby Universe** and **remote Universe**



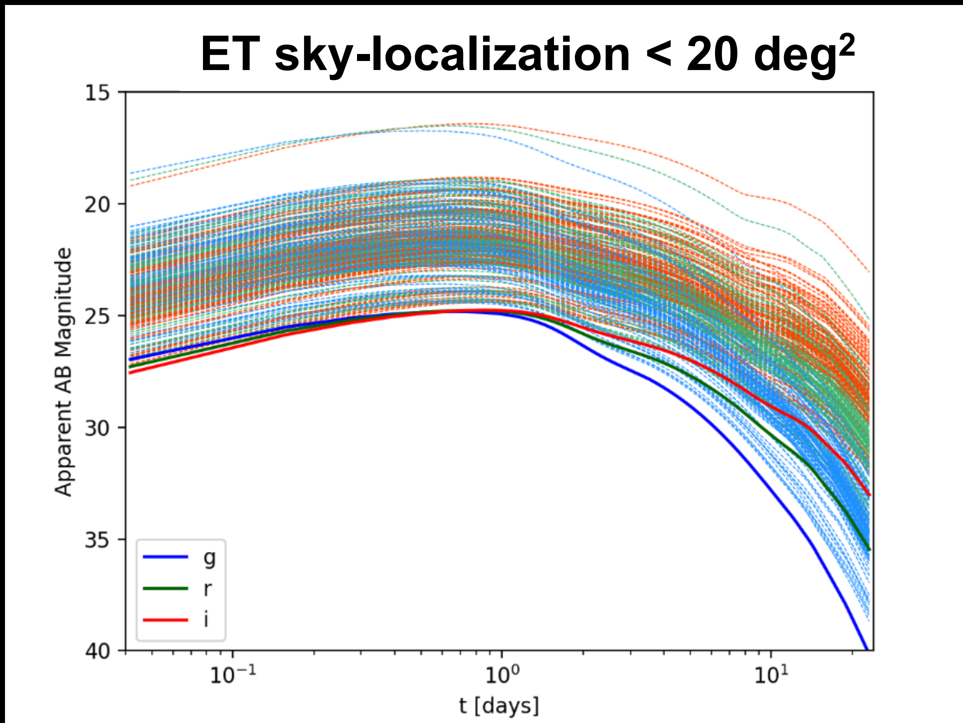

*Credit: Ghirlanda*



# THERMAL EMISSION - KILONOVAE

KILONOVA PHYSICS, NUCLEOSYNTHESIS, NUCLEAR PHYISCS and COSMOLOGY

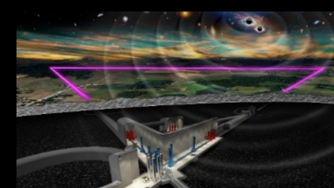
# ET+Vera Rubin synergy




Credits: Loffredo

VERA RUBIN OBSERVATORY ToO:

- three epochs of 600s observations in two filters
- detection efficiency is larger than 99% up to z=0.3



| | Joint ET/VRO detections per year | Fraction of VRO telescope time |
|---|---|---|
| ET | 60 | 6% |
| ET+2G | 170 | 17% |

**COSMOLOGY:** Hubble constant measurement from GW standard sirens with sub-percent precision!

# CHARACTERIZATION PHASE: spectroscopy and deep observations

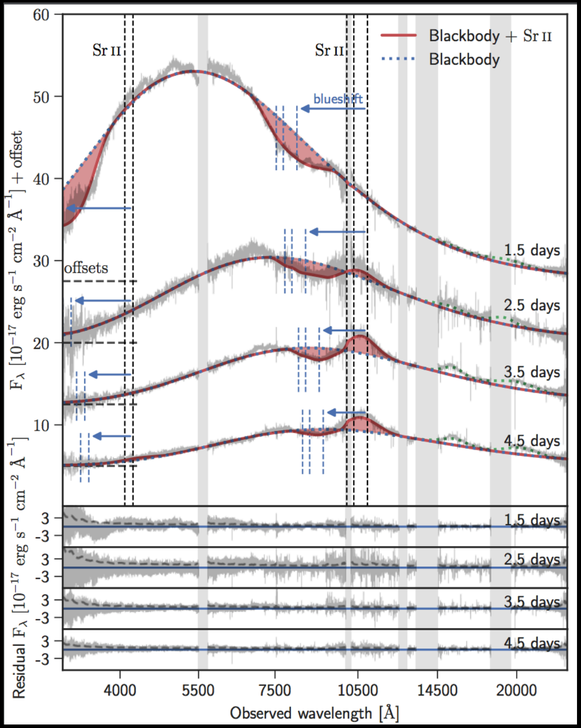
## HOST GALAXY REDSHIFT

- Spectroscopic surveys (WAVES, DESI, MSE) will measure the z for several milions of galaxies

## TRANSIENT SPECTRA and DEEP FOLLOW-UP

- VLT, JWST, TMT, ELT

Several tens of transients are expected to be completely characterized




Watson, D. et al. 2019 Nature

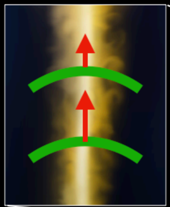
# HIGH-ENERGY

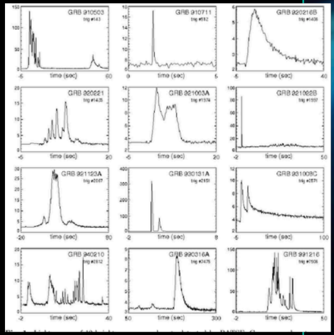
## RELATIVISTIC JET PHYSICS,
## GRB EMISSION MECHANISMS,
## COSMOLOGY and MODIFIED GRAVITY

Prompt emission phase:

Energy range: keV-MeV

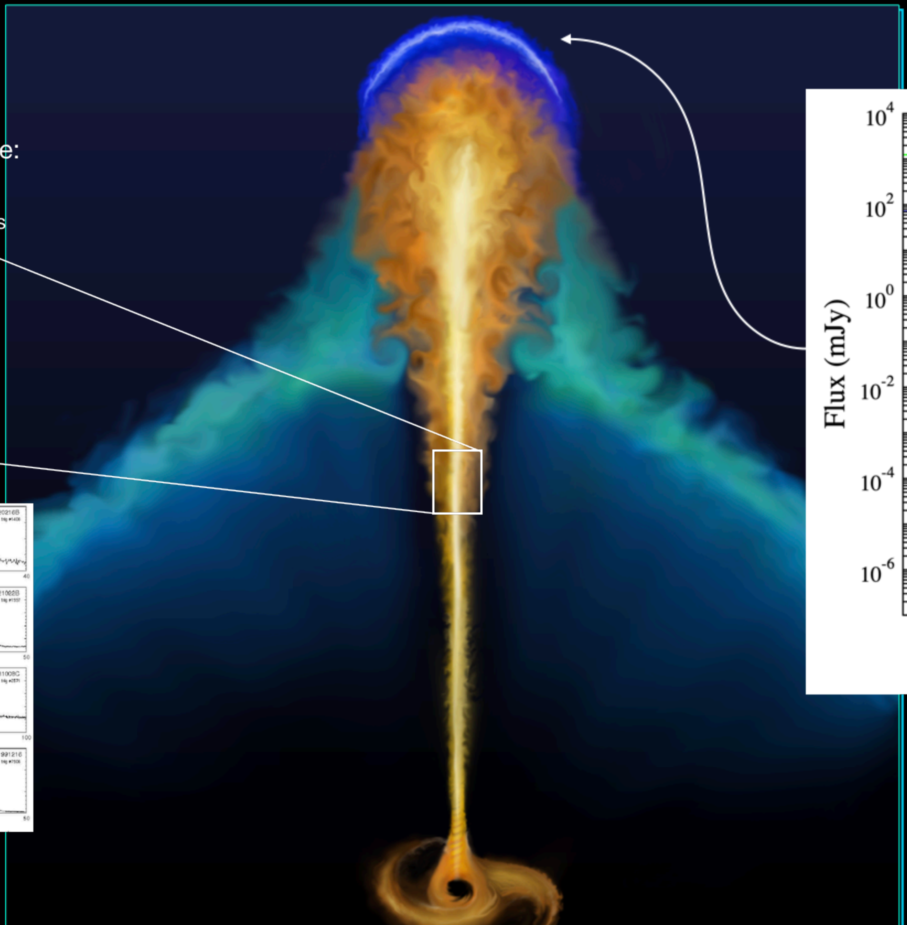
Variability time-scales: ms-s





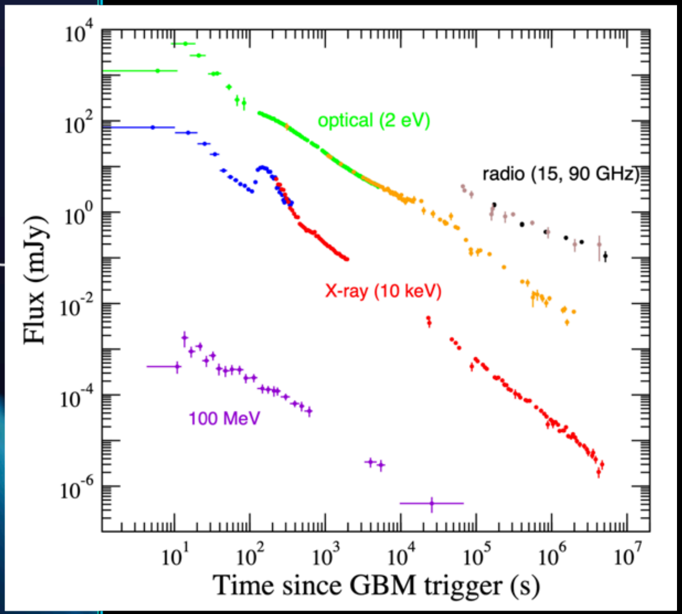
Shemi & Piran (1990)

Rees & Meszaros (1994)



Credit: Ronchini

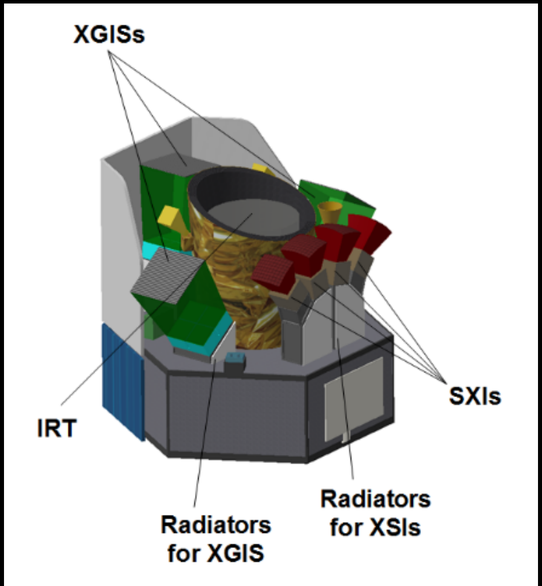
Afterglow phase




From Panaitescu et al (2013)

- 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 MISSION CONCEPT




Amati et al. 2018

See L. Amati talk

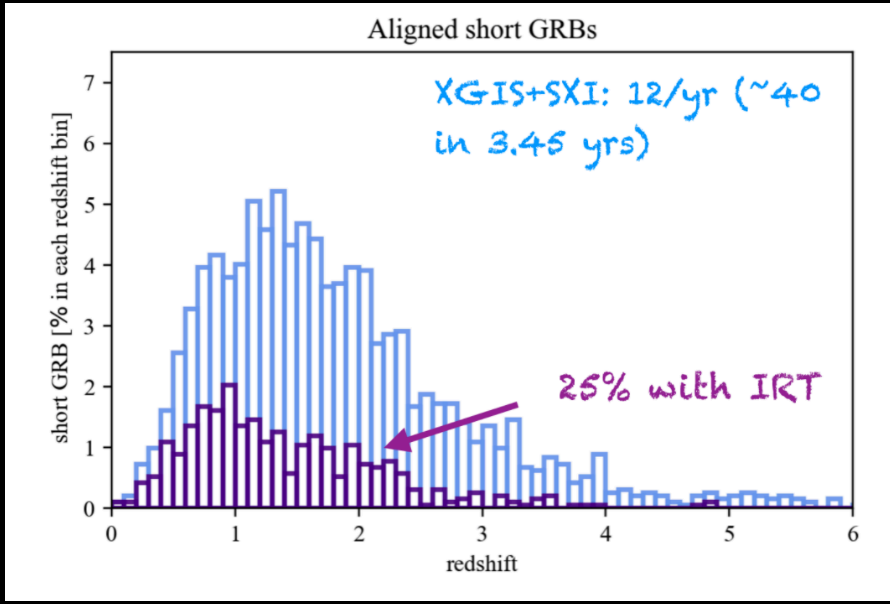
**Soft X-ray Imagers (SXI)**
- **0.3-5 keV**
- FoV ~ 0.5 sr
- Location accuracy ~ 0.5’-1’

**X-Gamma-ray Imager Spectrometer (XGIS)**
- **2 keV – 10 MeV**
- FoV ~ 2 for 2-150 keV band and > 4 sr for > 150 keV band sr
- 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

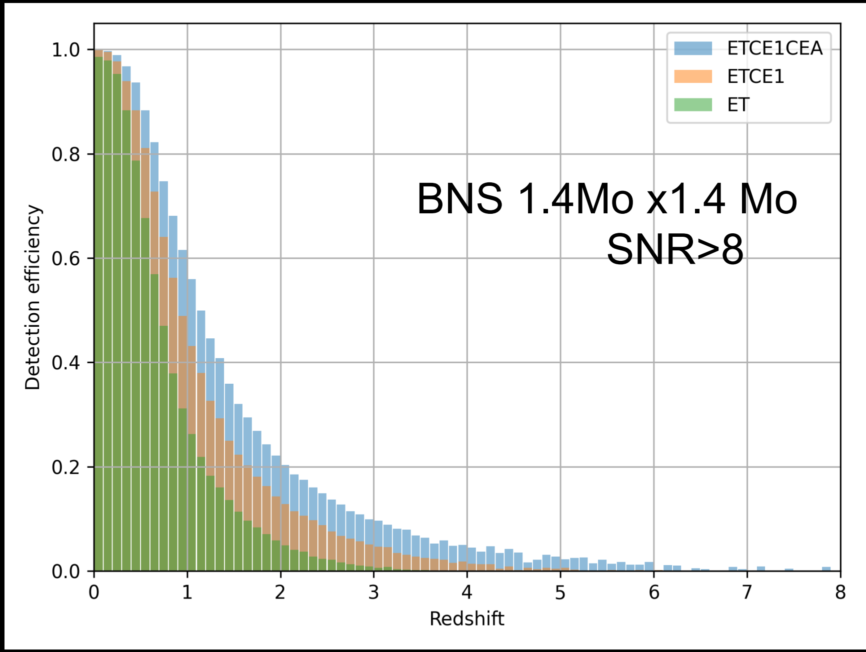
# COMBINED DETECTION EFFICIENCY

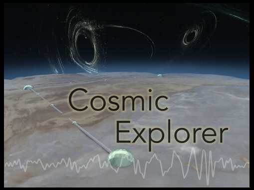



On-axis short GRB detection rate of THESEUS di 12/yr within 1' – 5'
about 25% is expected to be detected also with IRT with arcsec loc

+

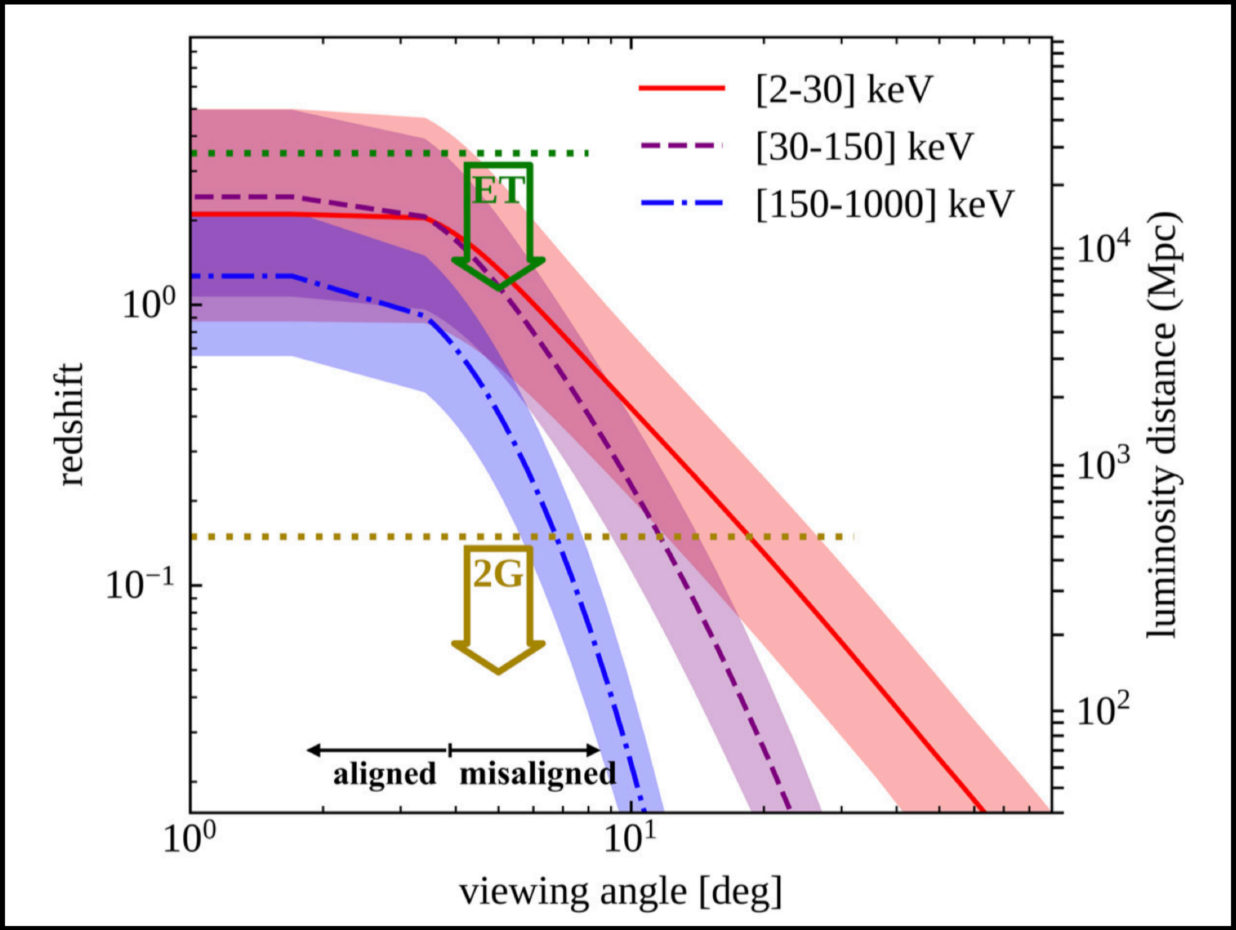
ET, ET+CE, ET+CE+CE



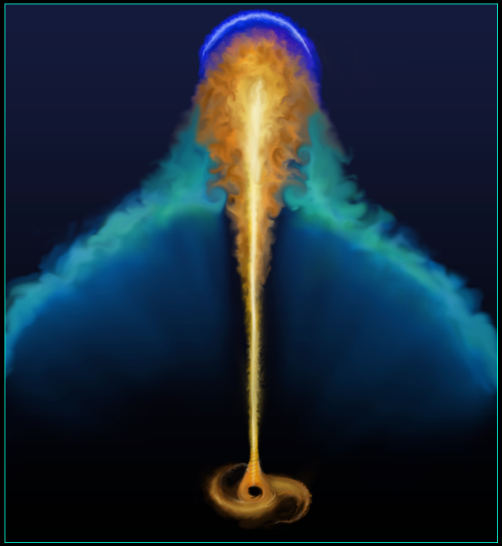

ET EINSTEIN TELESCOPE

# Considering off-axis GW/GRB detections….

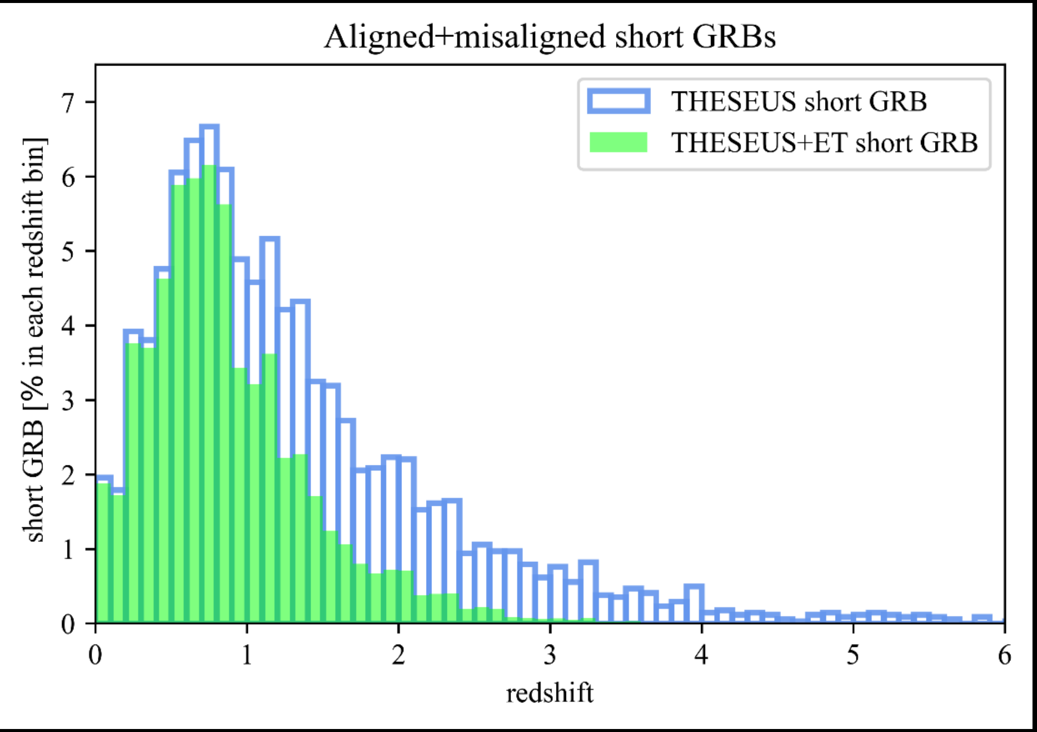



THESEUS/XGIS detectable distance versus viewing angle.

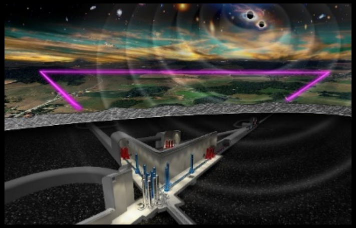
# ET+THESEUS synergy



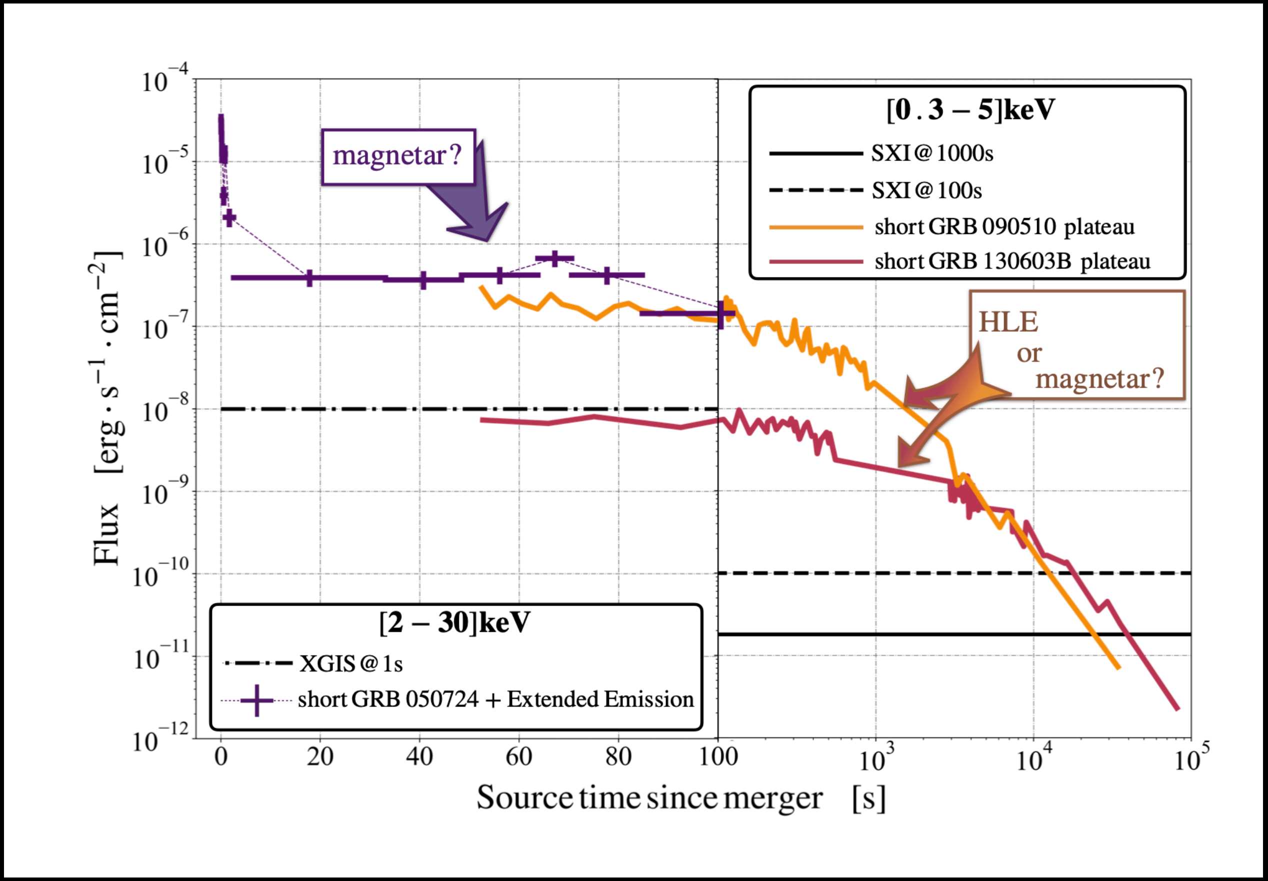
Credits: Ronchini




**THESEUS-ET joint detections**
**13 per year**

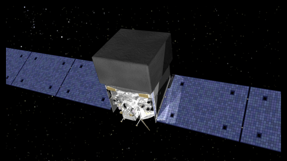


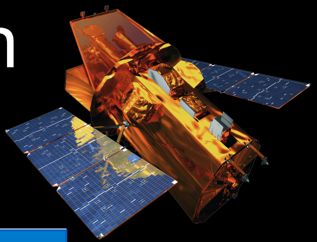
Adding GRB EXTENDED EMISSION, PLATEAU (magnetar or high latitude emission) and SPIN-DOWN POWERED EMISSION.




**THESEUS-ET joint detections about 100 per year**

# Preliminary results for prompt emission joint detections by other instruments






| Instrument | Joint/Total EM | Joint detections |
|---|---|---|
| Fermi GBM | 89% | 40 |
| BAT | 88% | 10 |
| GECAM | 81% | 160 |
| HERMES | 87% | 90 |
| SVOM GRM | 86% | 20 |
| EP | 87% | 3 |
| TAP-GTM | 86% | 40 |

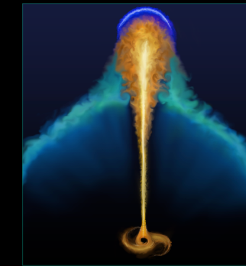
PRELIMINARY

Ronchini S + GSSI group

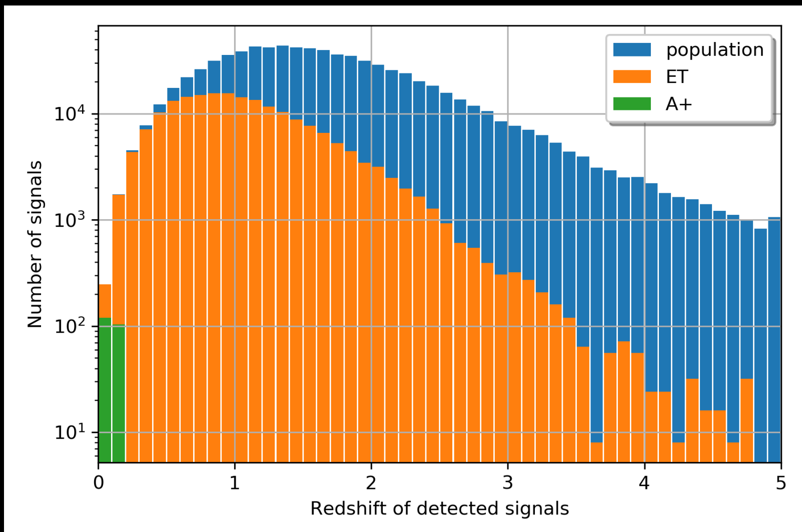
exploring transients and variability in the dynamic X-ray Universe
Einstein Probe

Transient Astrophysics Probe (TAP)

# Cosmology and dark energy with ET



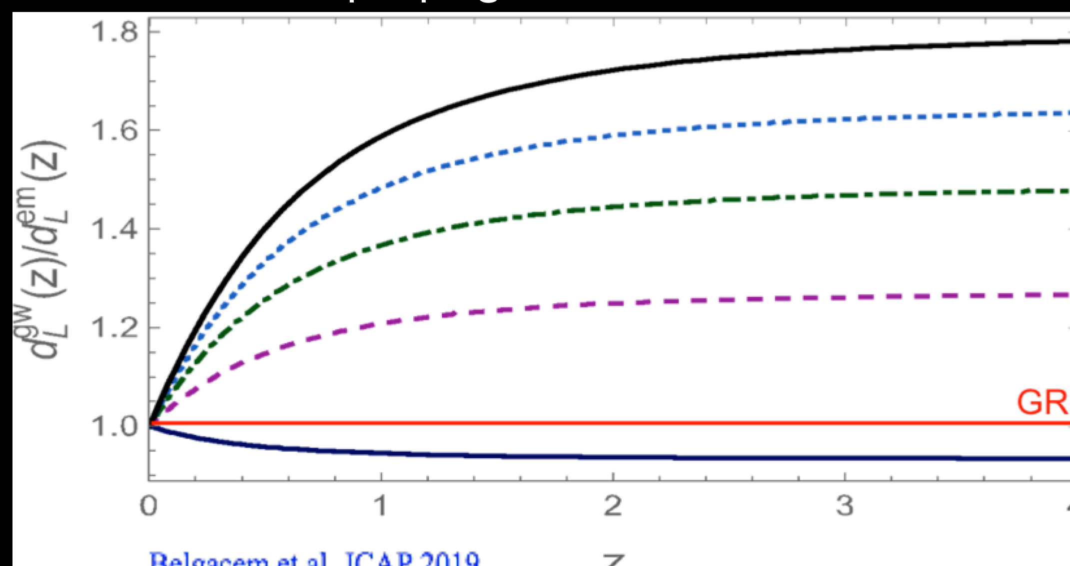
BINARY NEUTRON-STAR MERGERS




**High-redshift**

**Cosmology and dark energy with ET**

Modified GW propagation




See M. Maggiore talk for ET science case


Euclid
ATHENA
THE ASTROPHYSICS OF THE HOT AND ENERGETIC UNIVERSE
HOW DOES ORDINARY MATTER ASSEMBLE INTO THE LARGE SCALE STRUCTURES THAT WE SEE TODAY?
HOW DO BLACK HOLES GROW AND SHAPE THE UNIVERSE?
Europe's next generation X-RAY OBSERVATORY
GECAM
Nancy Roman
Transient Astrophysics Probe (TAP)
AMEGO
ALL-SKY MEDIUM ENERGY GAMMA-RAY OBSERVATORY
theseus
TRANSIENT HIGH ENERGY SKY AND EARLY UNIVERSE SURVEYOR
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cta
cherenkov telescope array
SKA
SQUARE KILOMETRE ARRAY
LIGO INDIA
Rubin Observatory
ELT
Cosmic Explorer
ICECUBE GEN2
KM3NeT
Hyper-Kamiokande