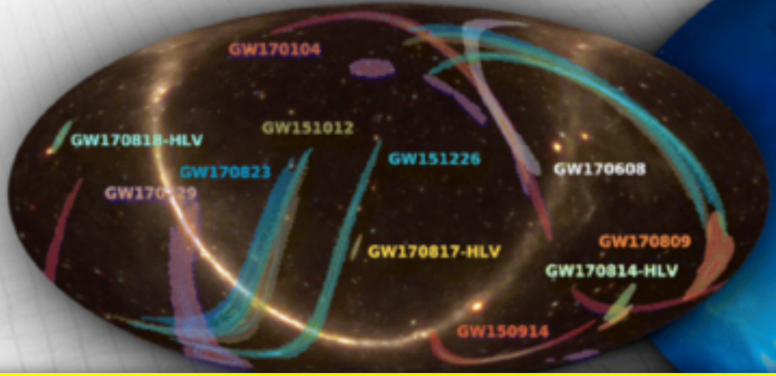
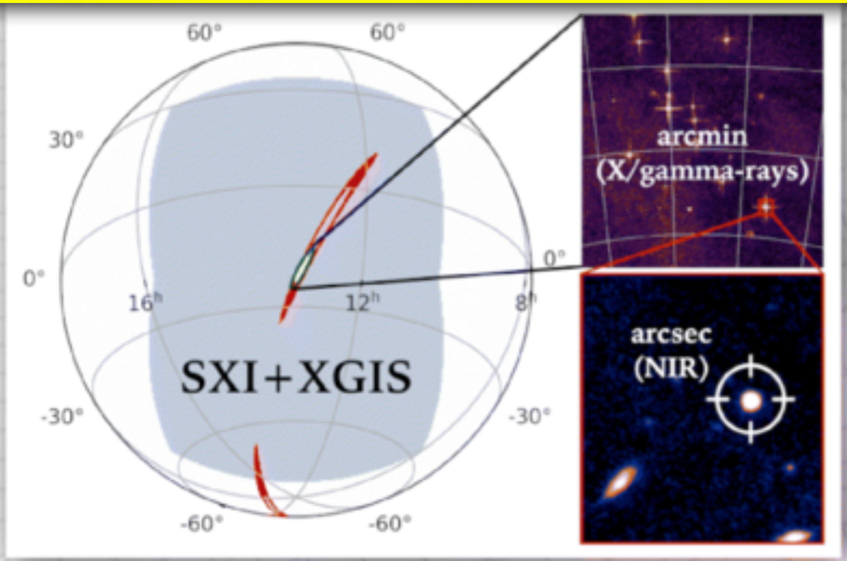
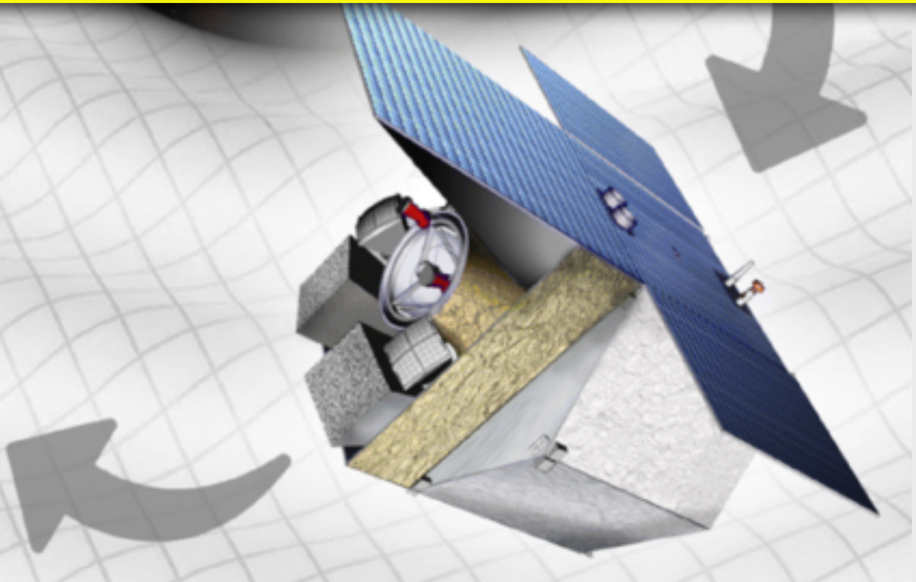


The mission project THESEUS in the Multi-Messenger Astronomy golden era

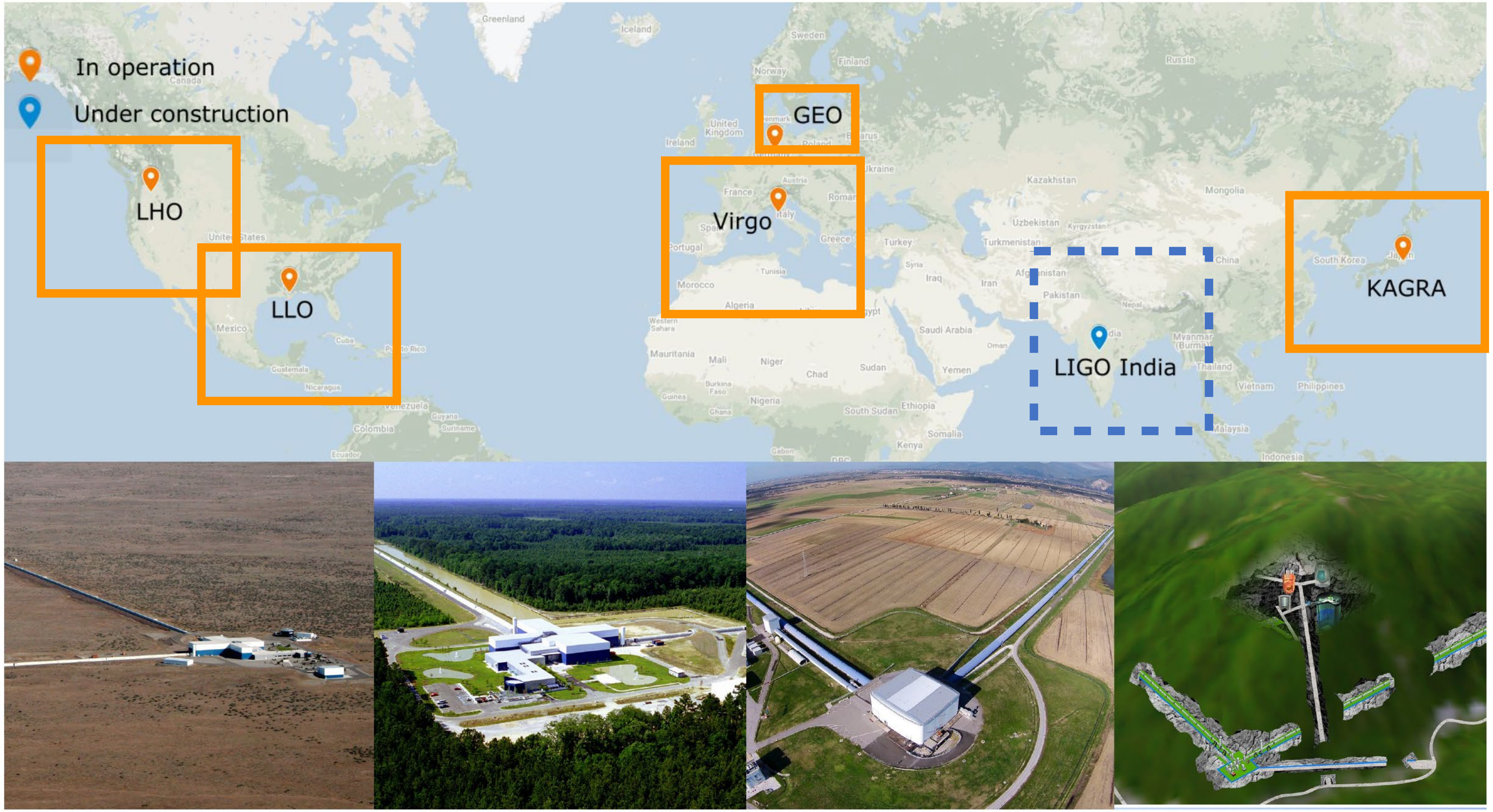
Giulia Stratta (GU-Frankfurt, INAF-IAPS,INAF-OAS,INFN-Roma)

17th Marcel Grossmann Meeting - 8-13 July 2024





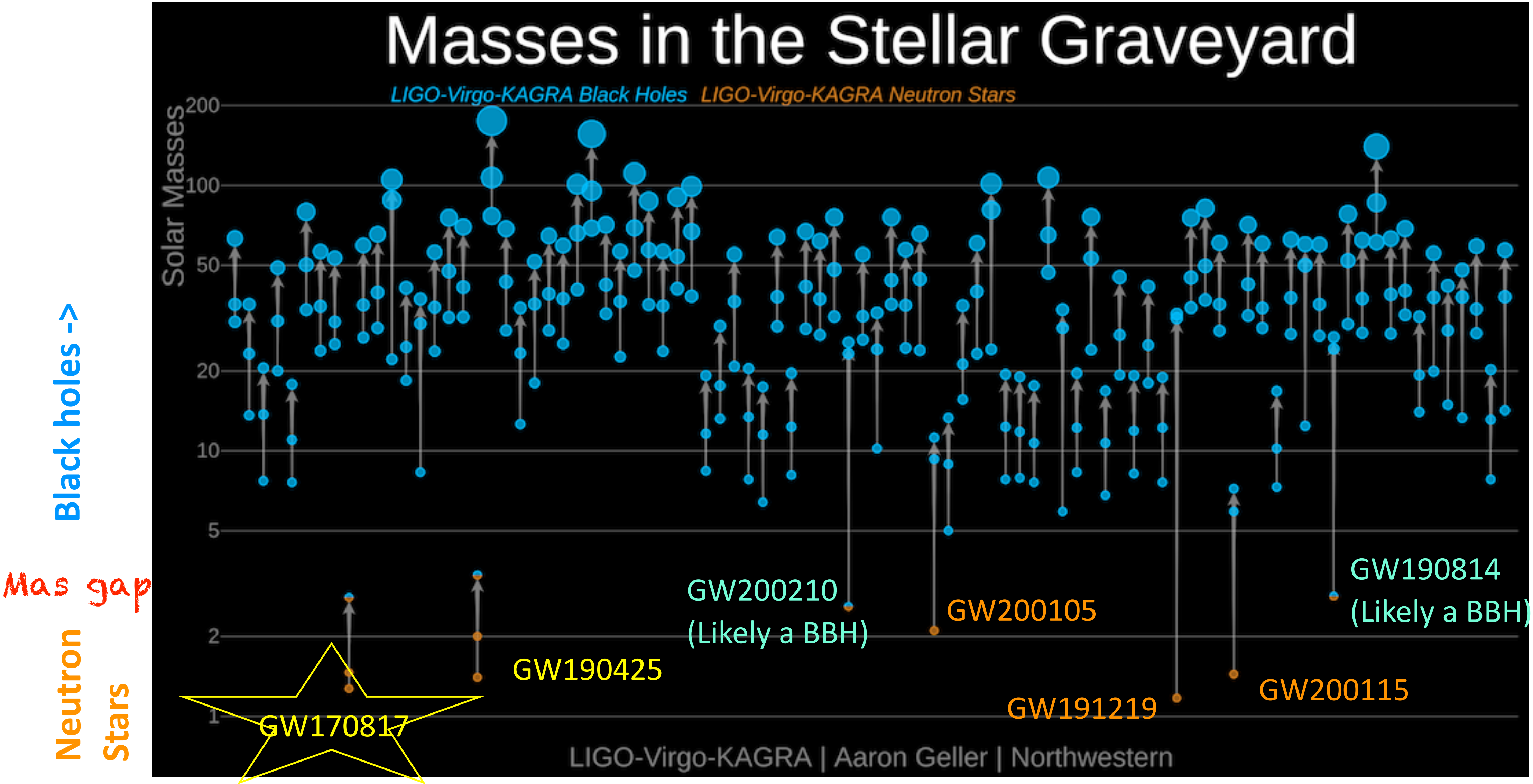
High-frequency 2G GW detector network



LIGO Aundha Observatory (LAO, aka LIGO-India)

Intent: join GWN as A+ (preferably A#) by the end of the 2020s

https://www.nsf.gov/mps/phy/nggw/present_ligo_india.pdf

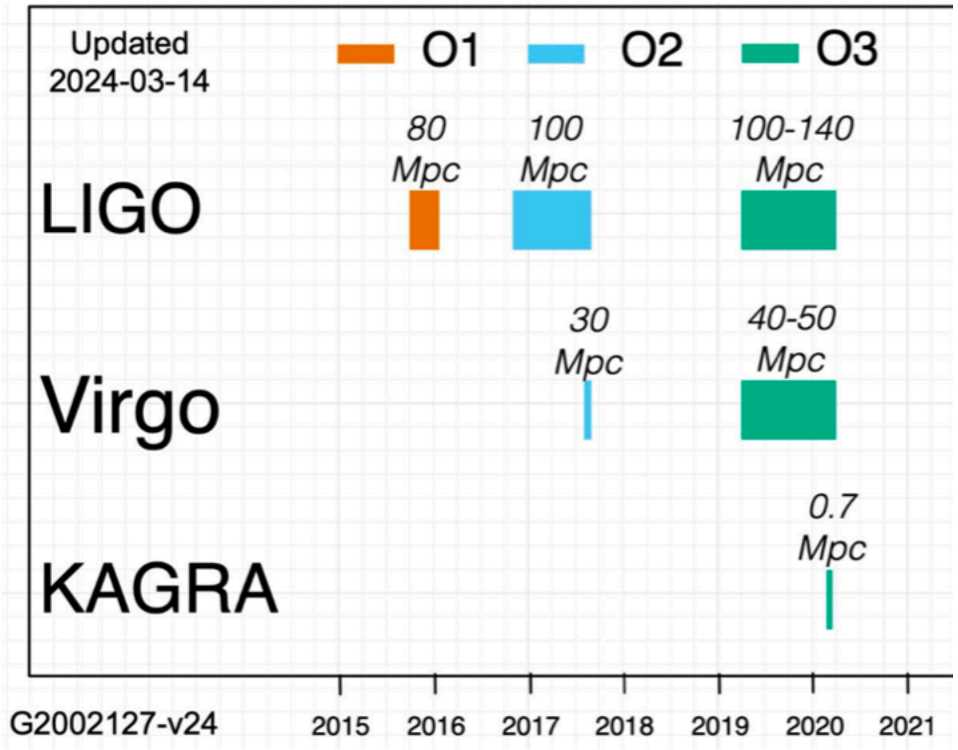


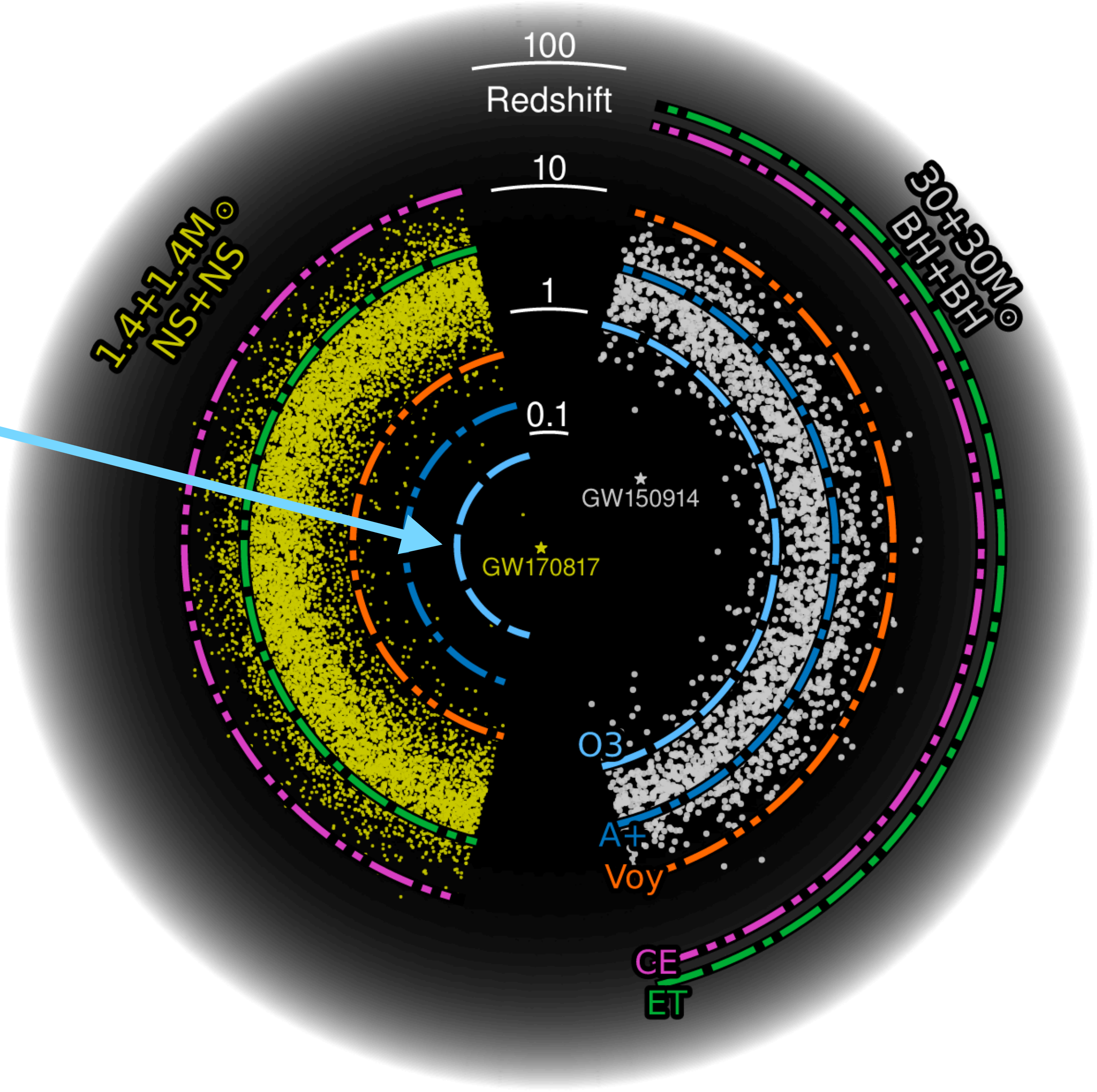
90 GW sources detected so far published in the first GW Transient Catalog (GWTC)

Last release: GWTC-3 2023, Phys.Rev. X,13

Interactive version: https://ligo.northwestern.edu/media/mass-plot/index.html

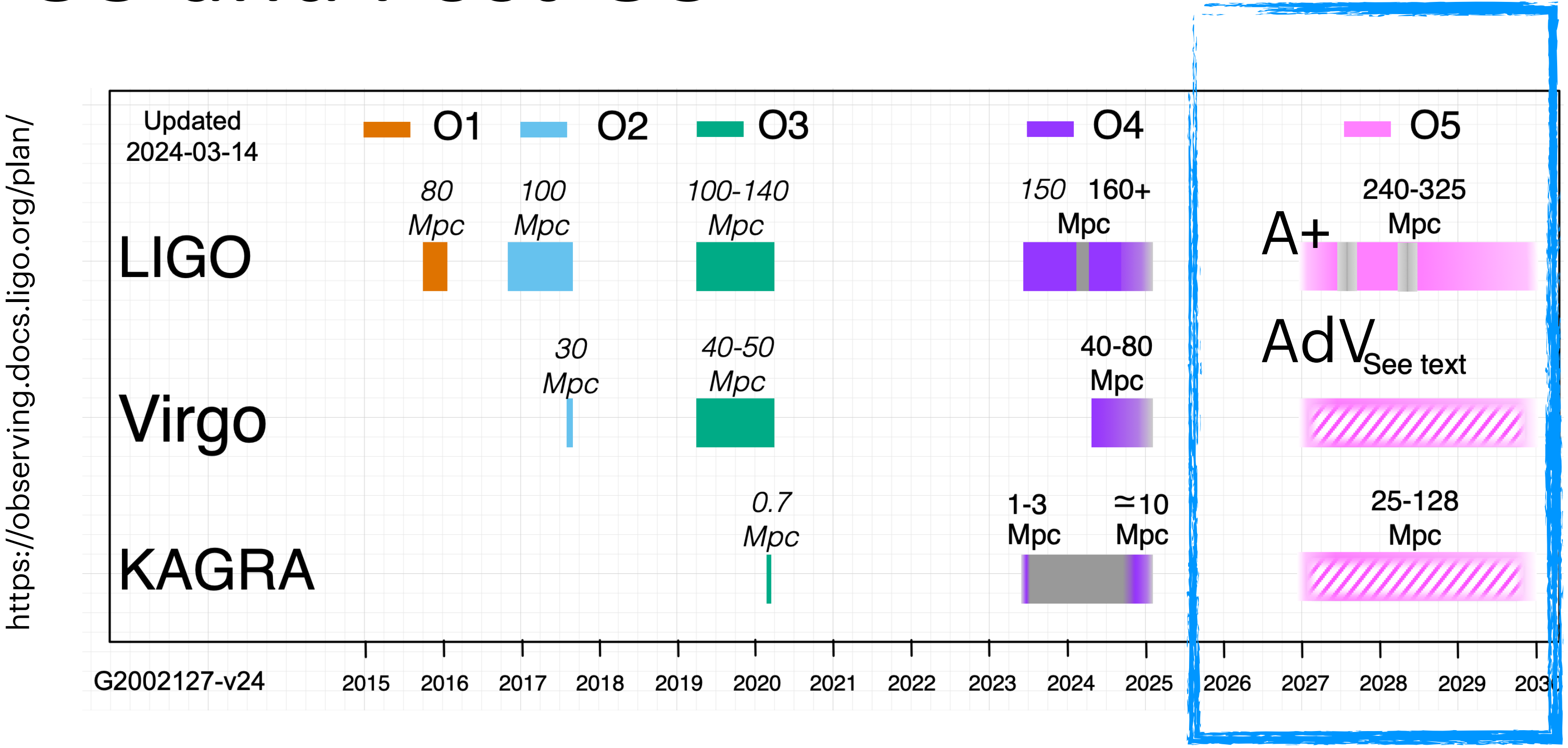
- 3 Observational runs completed
- Distance for BNS detection up to 140 Mpc





E.D. Hall, Galaxies, 2022

O5 and Post-O5



Post-O5

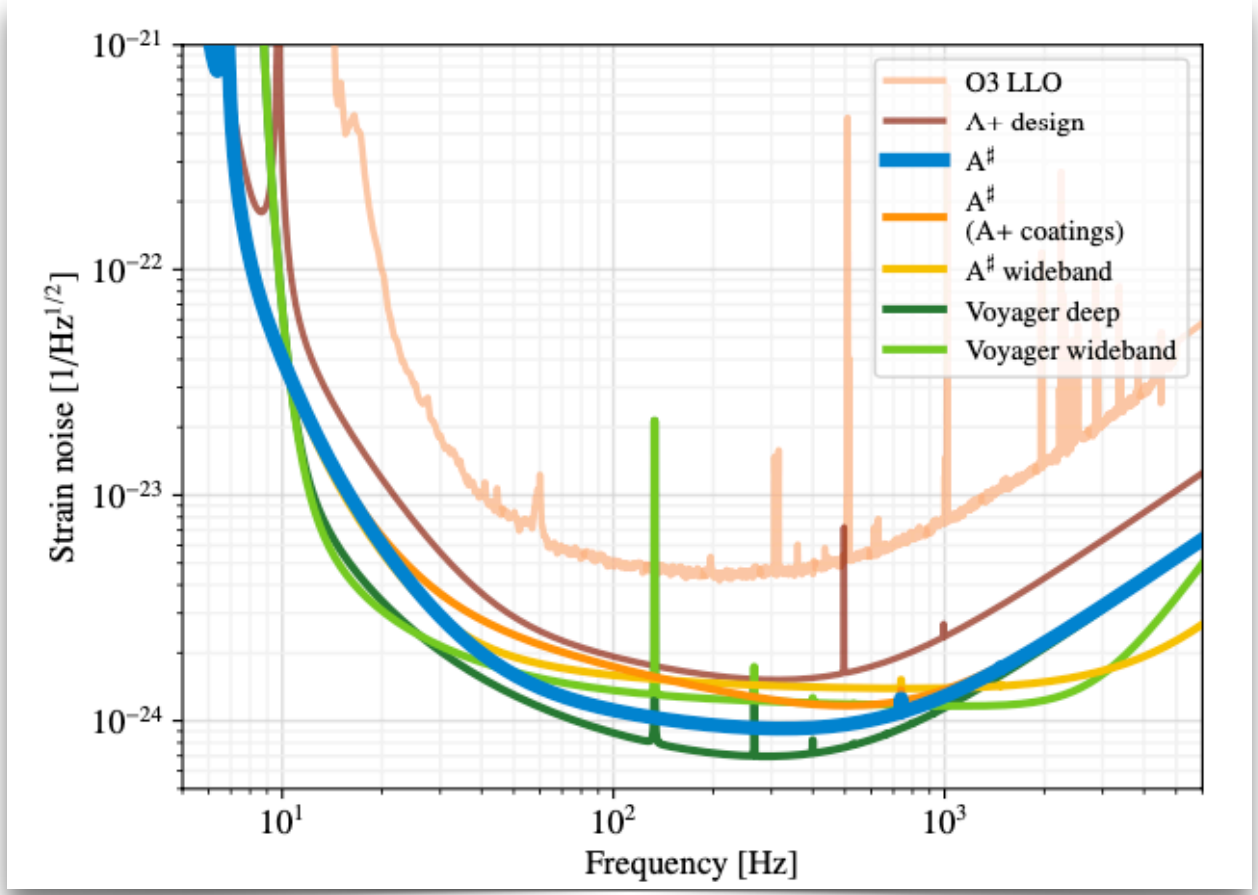
- A# — Series of recommended upgrades of LIGO detectors collectively known as A#
- Virgo_nEXT — detector sensitivity improvements in the whole detection band by roughly a factor two compared to O5

Early 2030s

- https://observing.docs.ligo.org/plan/ extension of O4b by a few months and starts of O5 by mid 2027
- **O5:** upgraded detectors will be **LIGO A+ and AdV+ (proposal by mid-2025)**
- **post-O5: 2.5 G** “bridge” to the 3rd generation

A#

Series of recommended upgrades of LIGO detectors collectively known as A#



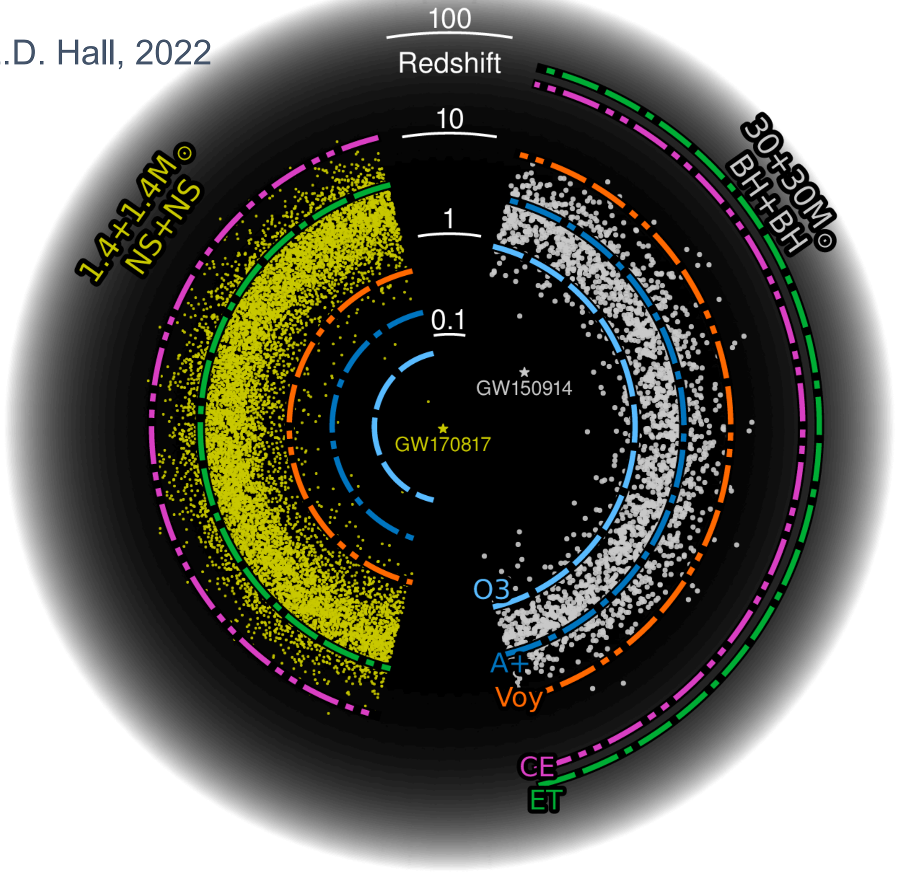
Configuration	Annual Detections BNS	NSBH	BBH
A+	135^{+172}_{-78}	24^{+34}_{-16}	740^{+940}_{-420}
A♯	630^{+790}_{-350}	100^{+128}_{-58}	2100^{+2600}_{-1100}
A♯ (A+ coatings)	260^{+320}_{-140}	45^{+60}_{-27}	1150^{+1450}_{-640}
A♯ Wideband (A+ coatings)	200^{+250}_{-110}	40^{+54}_{-25}	970^{+1220}_{-540}
Voyager Deep	1280^{+1610}_{-710}	190^{+240}_{-110}	3100^{+3900}_{-1700}
Voyager Wideband	730^{+920}_{-410}	129^{+165}_{-74}	2300^{+2900}_{-1300}

Table 5: Plausible range of number of detections in a calendar year observing run for each class of binary. Ranges are based on the central 90 % credible intervals on astrophysical rates from O3 [28].

https://dcc.ligo.org/public/0183/T2200287/002/T2200287v2_PO5report.pdf

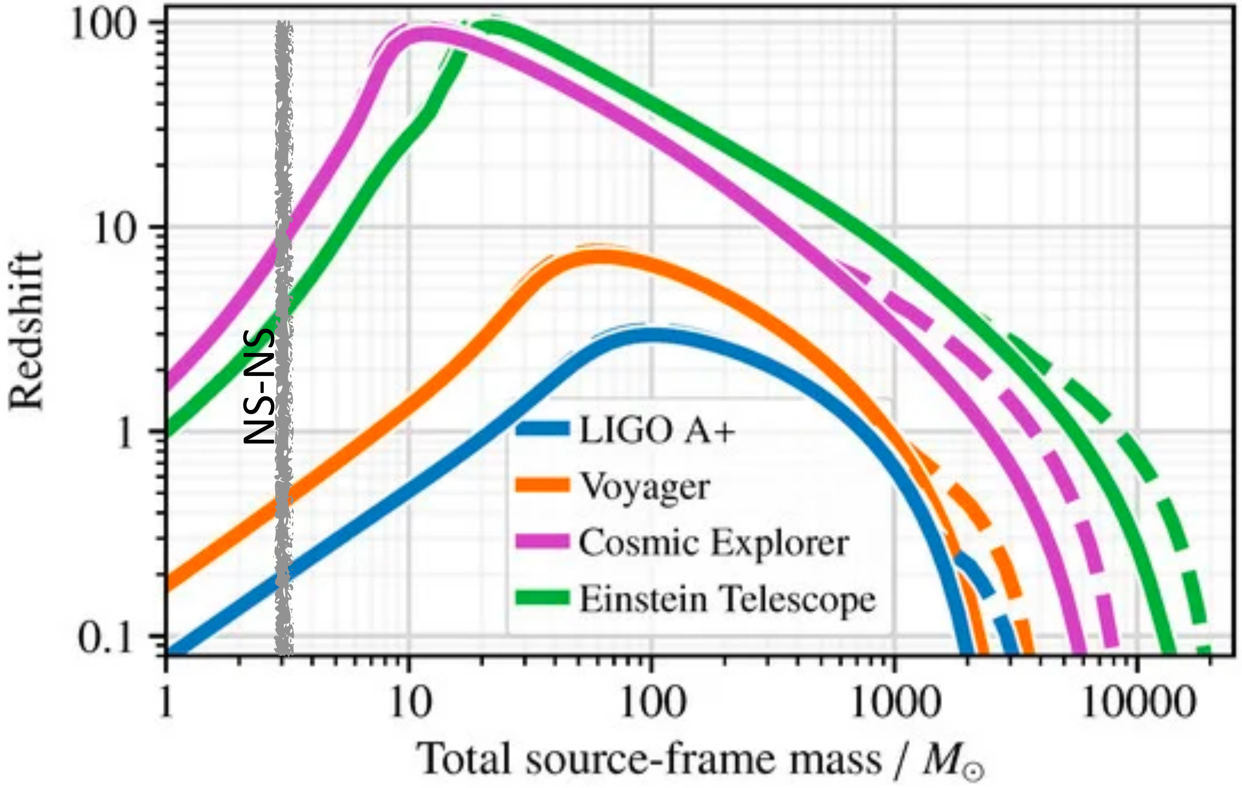
The next (3rd) generation GW detectors

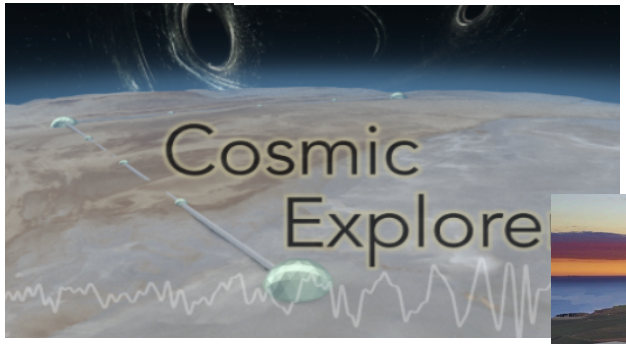
E.D. Hall, 2022

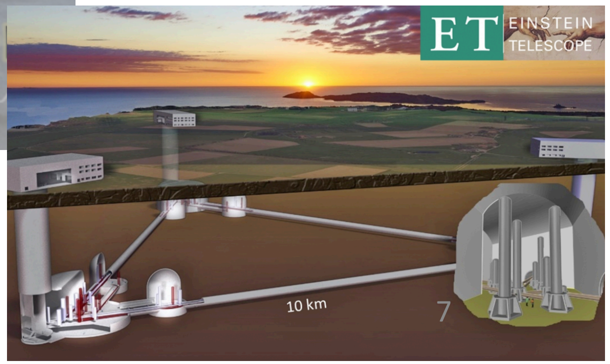


10^5 BNS/yr —> a dozen per hour!!

E. D. Hall, 2022 Galaxies





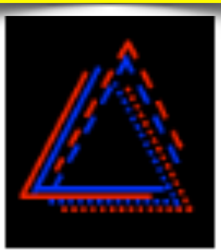


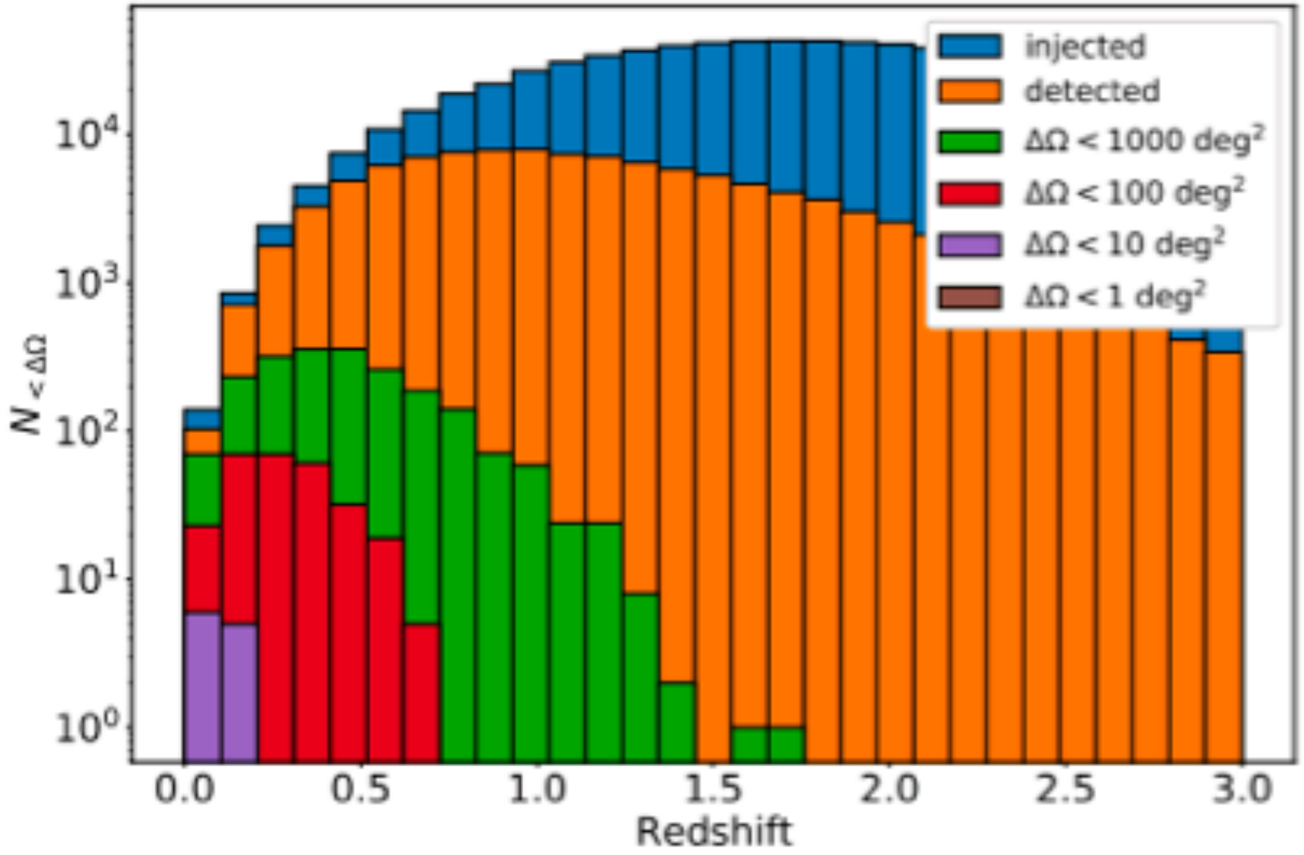
3G GW interferometer network by 2030s

ET sky localization capabilities (N_{BNS}/yr vs z)

triangular configuration

(Reference configuration)





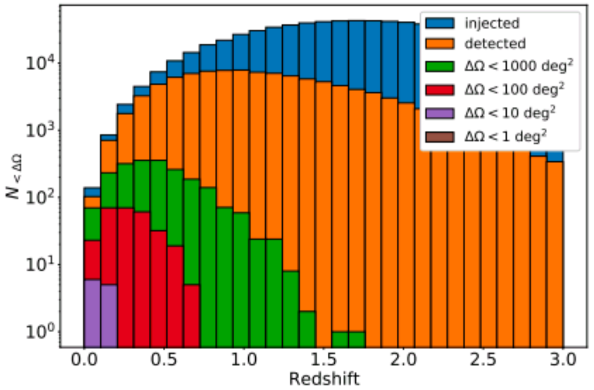
(a) Δ 10 km HFLF cryo.

Branchesi, Maggiore et al. JCAP 2023

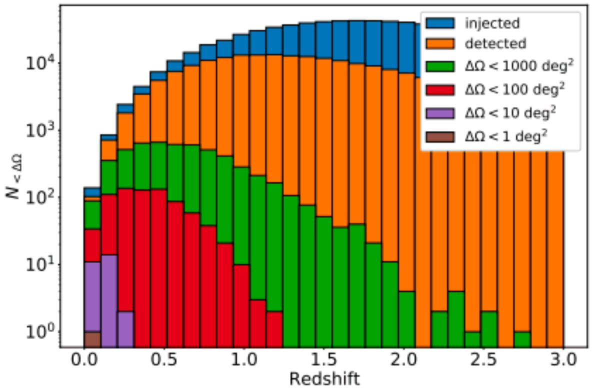
ET sky localization capabilities (N_{BNS}/yr vs z)

High- and Low- frequency config. | High-frequency config.

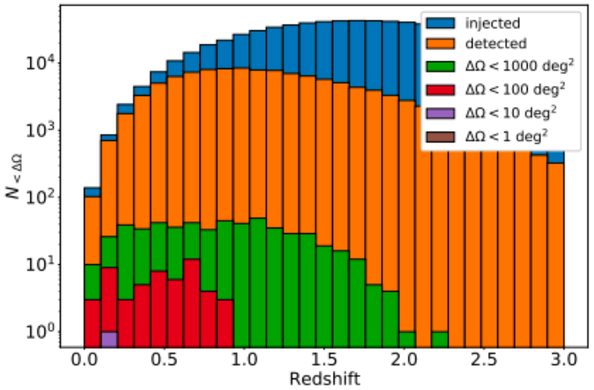
triangular configuration



(a) Δ 10 km HFLF cryo.

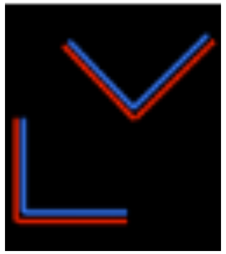


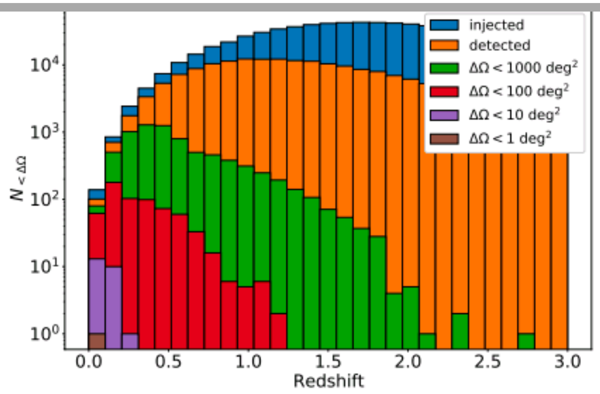
(b) Δ 15 km HFLF cryo.



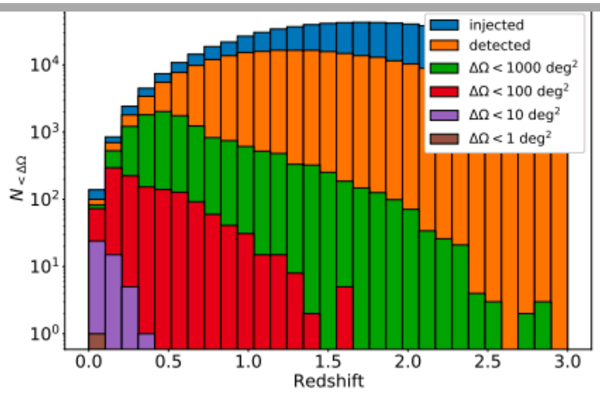
(c) Δ 15 km HF.

2 L-shape configuration

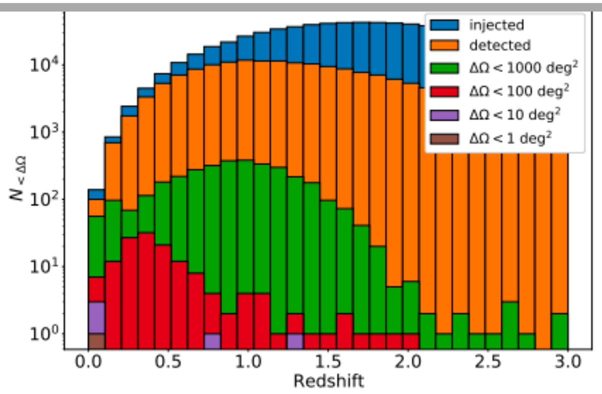




(d) 2L 15 km HFLF cryo.



(e) 2L 20 km HFLF cryo.



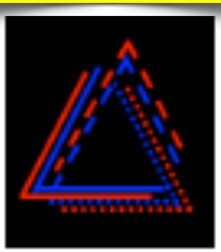
(f) 2L 20 km HF.

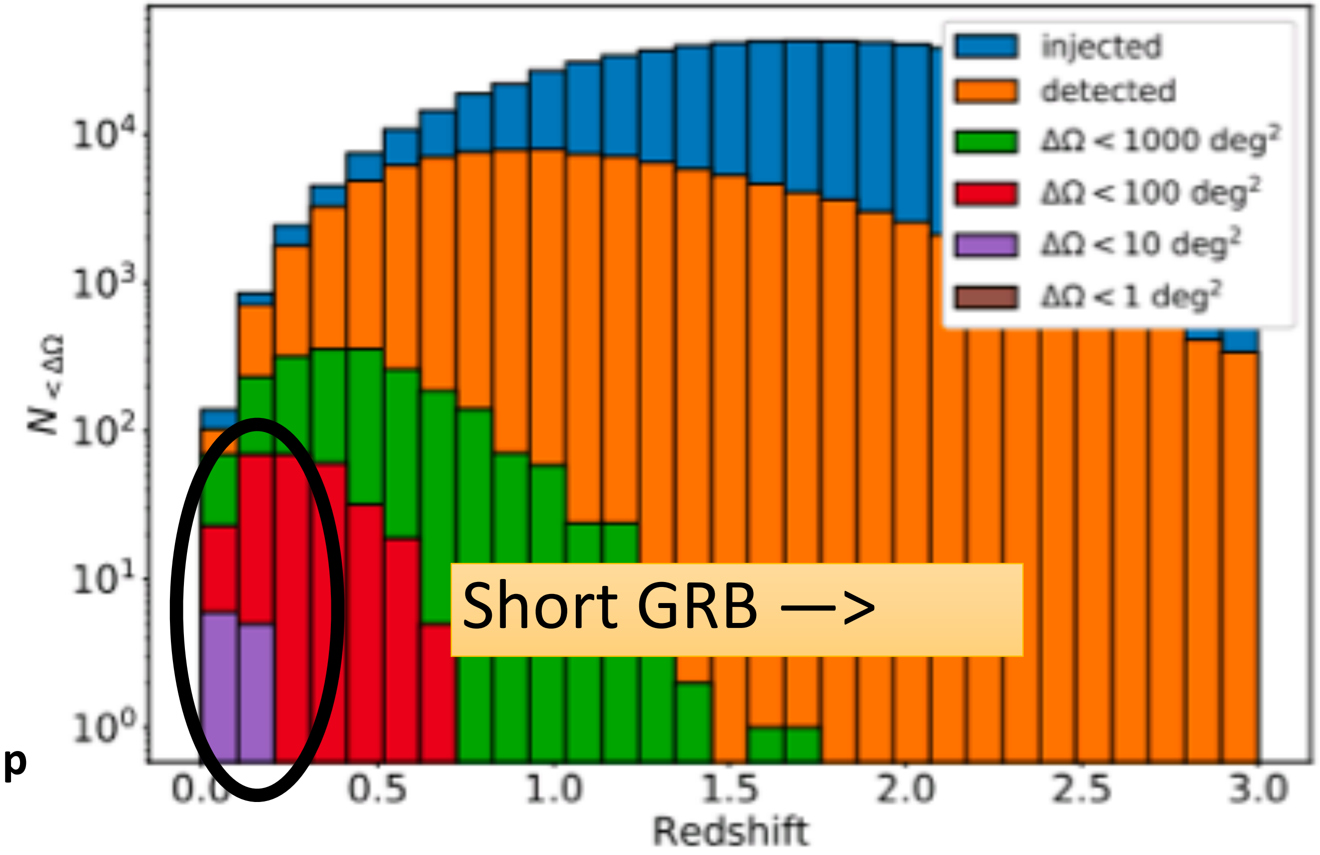
Branchesi, Maggiore et al. JCAP 2023

ET sky localization capabilities (N_{BNS}/yr vs z)

triangular configuration

(Reference configuration)



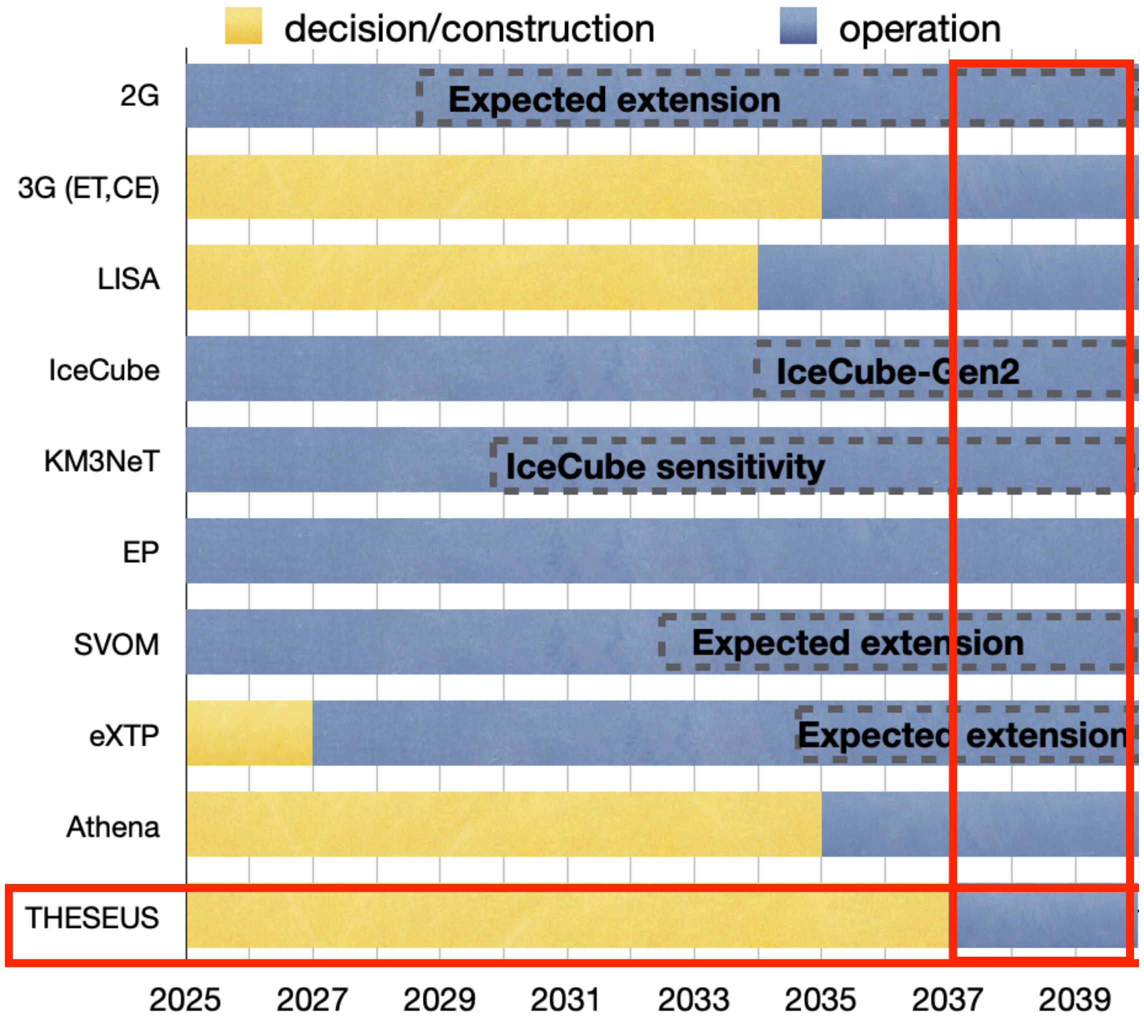


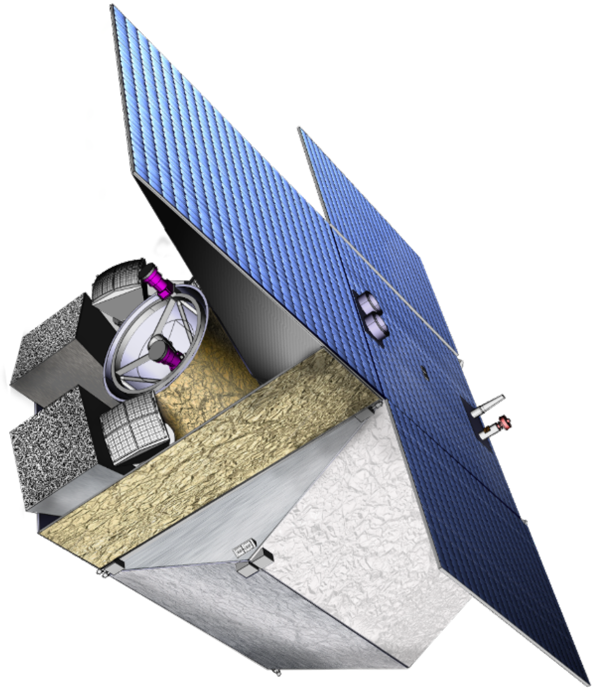
(a) Δ 10 km HFLF cryo.

Kilonova detections in optical surveys up to z<0.3-0.4

Branchesi, Maggiore et al. JCAP 2023

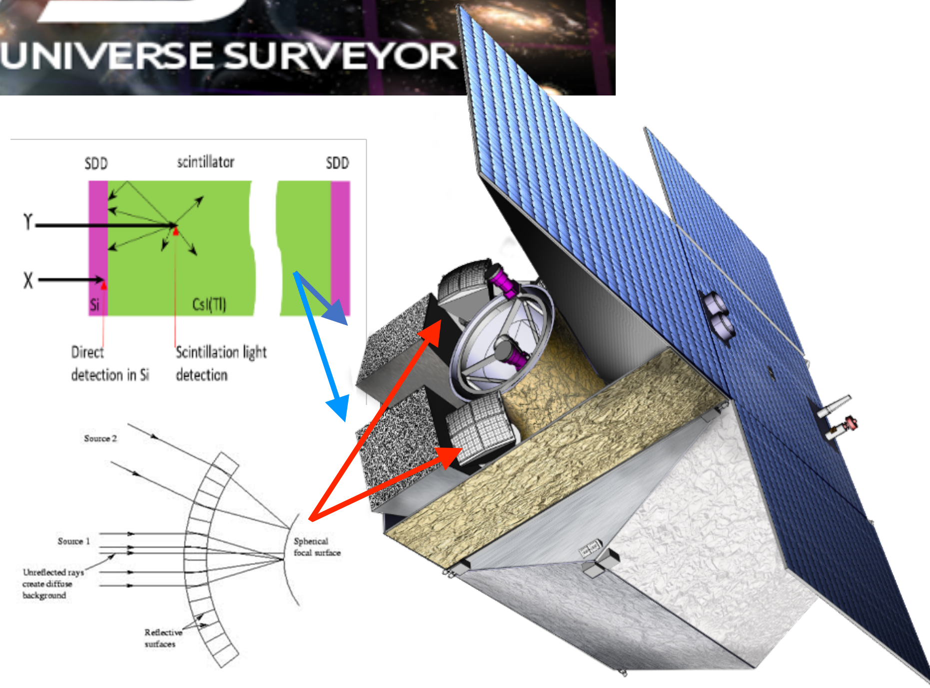
>2035s: the golden era of MMA





theseus

TRANSIENT HIGH ENERGY SKY AND EARLY UNIVERSE SURVEYOR



ESA M5 call 2018-2021: Selected for Phase-A study but not for Phase-B

ESA M7 call 2022: **Selected** for Phase 0 study

2023: **Selected** for Phase-A study (2024-2026)

M7 timeline: Phase-A (2024-2026), adoption 2028, launch 2037

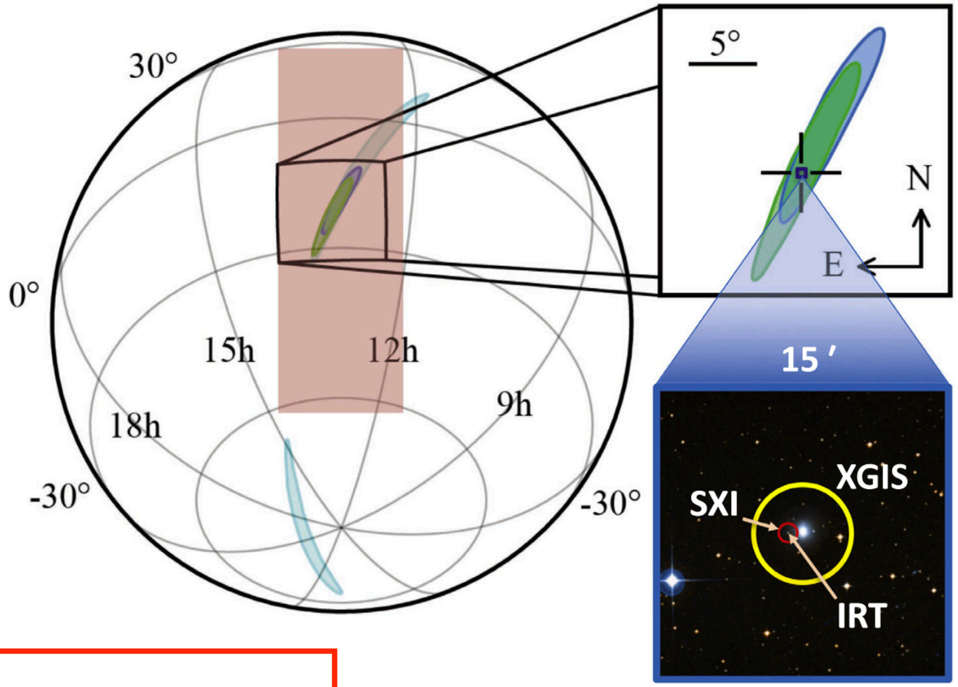
- XGIS (2 keV - 30 keV Si drift + 20 keV - 10 MeV CsI)
- SXI (0.3-5 keV) Lobster Eye telescope
- IR telescope 0.7m (I (20.9),Z (20.7),Y (20.4),J (20.7),H (20.8) for 150s and SNR=5)

SXI FoV	0.5 sr – 31 × 61 deg^2
XGIS FoV (≥20% efficiency)	2 sr (2–150 keV) – 117 × 77 deg^2 4 sr (≥150 keV)

SXI positional accuracy (0.3–5 keV, 99% c.l.)	≤2 arcmin
XGIS positional accuracy (2–150 keV, 90% c.l.)	≤7 arcmin (50% of triggered short GRBs) ≤15 arcmin (90% of triggered short GRBs)

Short GRBs with THESEUS

- Based on most updated knowledge of GRB emission, we predict several dozens of short GRBs with accurate sky localization with GW counterparts in 3.45 yrs with THESEUS



GW detectors	Total detections with XGIS and SXI
ET	70 [56 - 87]
ET+2 CE	87 [72 - 107]

+ 28/yr detections outside XGIS FoV

more including Extend Emission?

THESEUS Phase-II proposal document for ESA M7, based on Ronchini et al. 2022

Fundamental issues from short GRB+GW detections

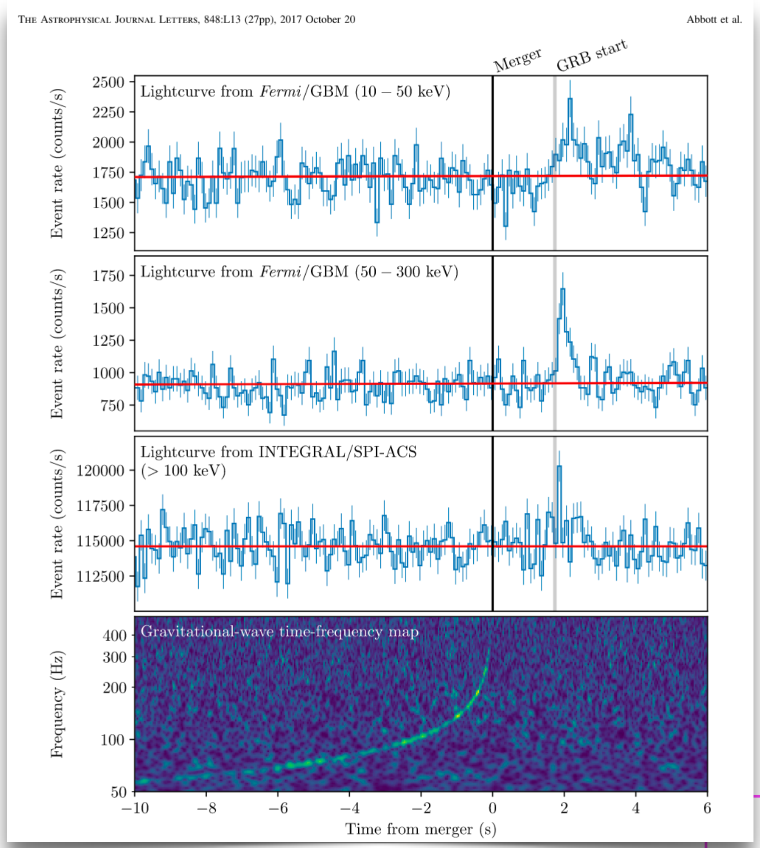
No follow-up with other facilities is required:

What is the jet launching mechanism and its efficiency?

Are there any systematic differences between NS-BH and NS-NS jets formation efficiencies?

What is the nature of merger remnant from NS-NS mergers and their link with burst prompt properties?

Fundamental physics (e.g. photon/GW propagation)



< few hours follow-up with other facilities required:

What is the Universe expansion rate (H0 measure)?

What role plays NS-NS/ NS-BH in Universe chemical enrichment of heavy elements?

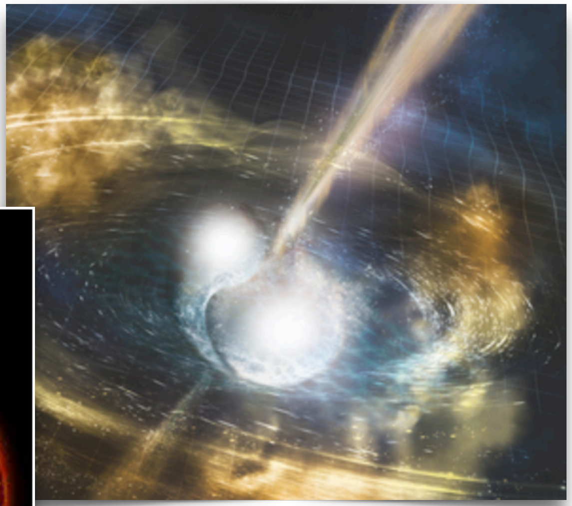
What is the jet structure?

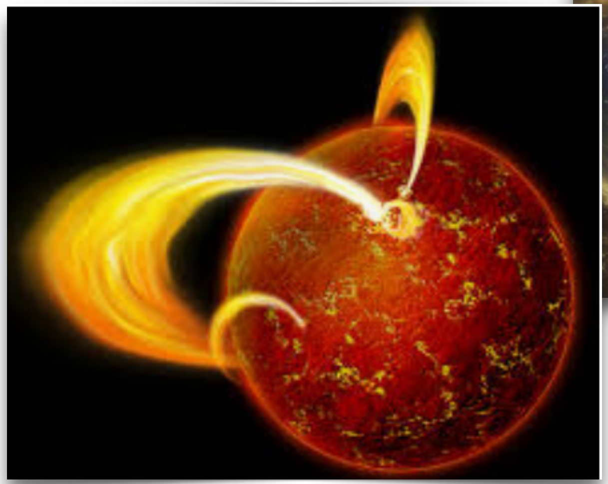
What link with remnant nature and plateau/flare features?

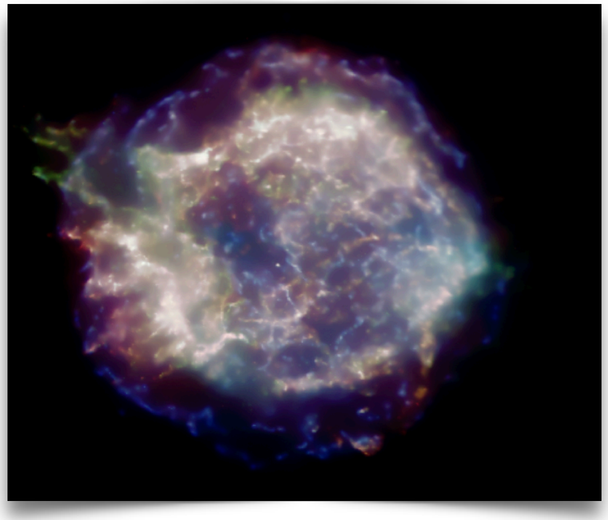
< 1 hours follow-up with other facilities required:

Multi-messenger sources

- Short GRBs ✓
- Core-collapsing stars
- Soft Gamma Repeaters
- AGNs
- Starburst galaxies
- Unexpected transients…



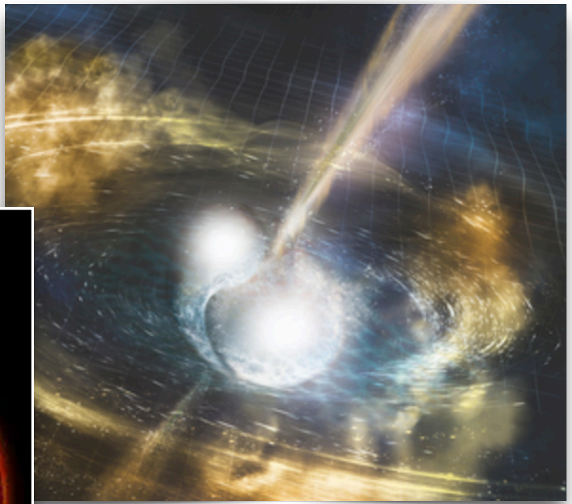


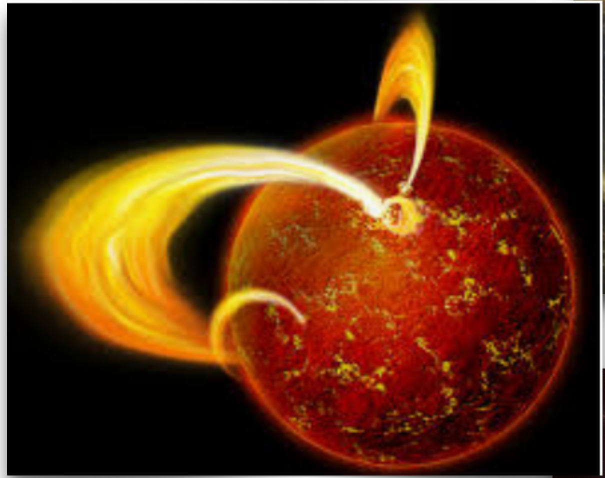


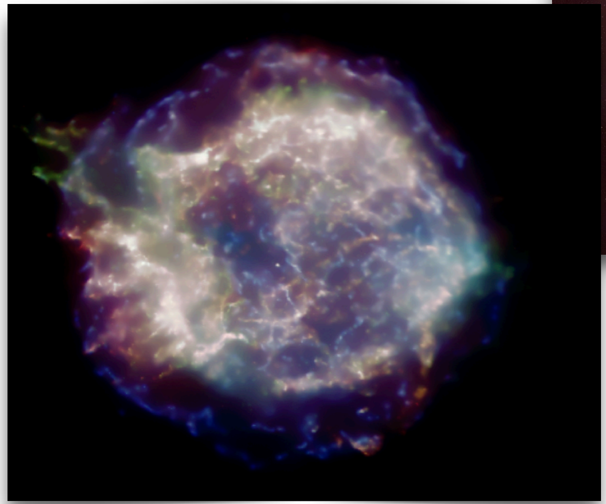
Multi-messenger sources

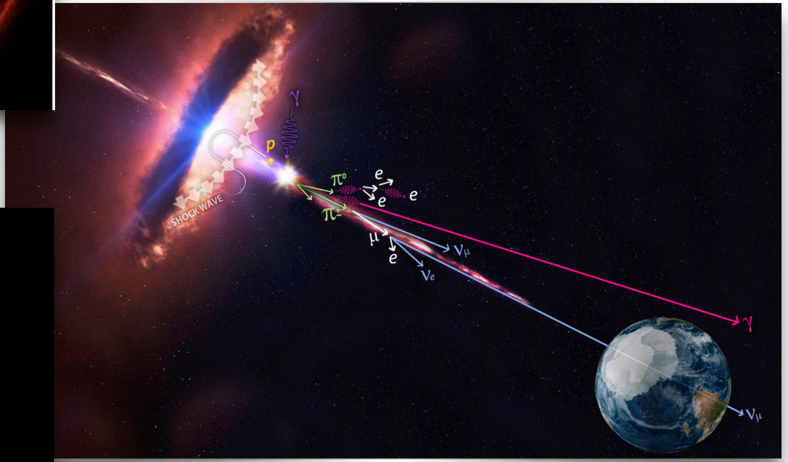
- Short GRBs ✓
- Core-collapsing stars
- Soft Gamma Repeaters
- AGNs ✓
- Starburst galaxies
- Unexpected transients…

Neutrino sources !



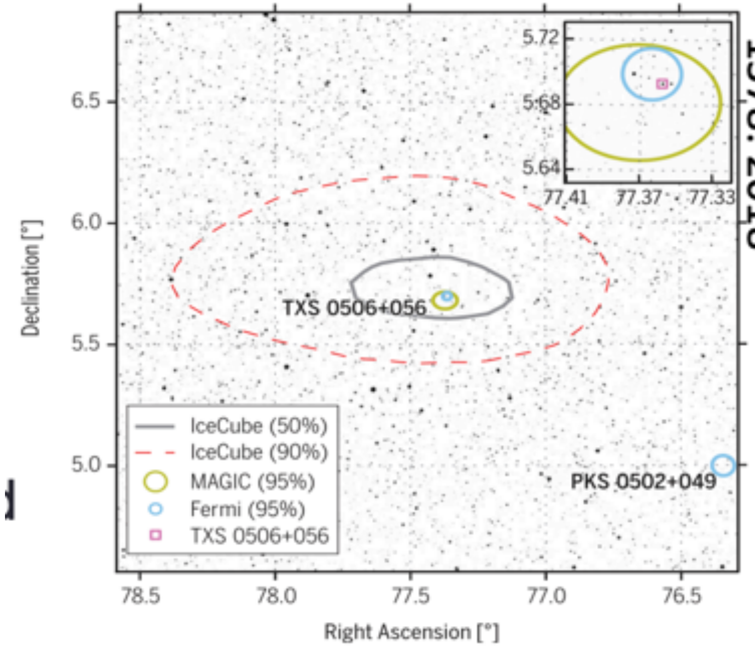




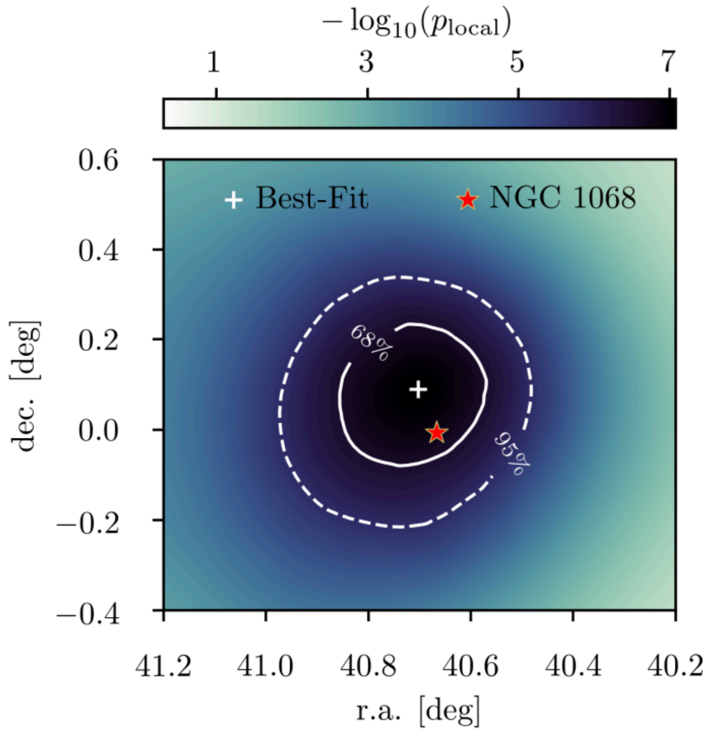


Cosmic neutrino sources detected so far

- **2013:** IceCube robust measure of cosmic neutrino flux but source composition is still to be disclosed
- **Sep 2017**: first IceCube neutrino event spatially coincident with a **blazar** in active phase at z=0.34 (TXS 0506+056 , Artsen+2018)
- From **2011-2020** IceCube data confirmed cosmic origin neutrino flux + another identification of TeV neutrinos from nearby **AGN** (NGC 1068, Abbasi+2022)

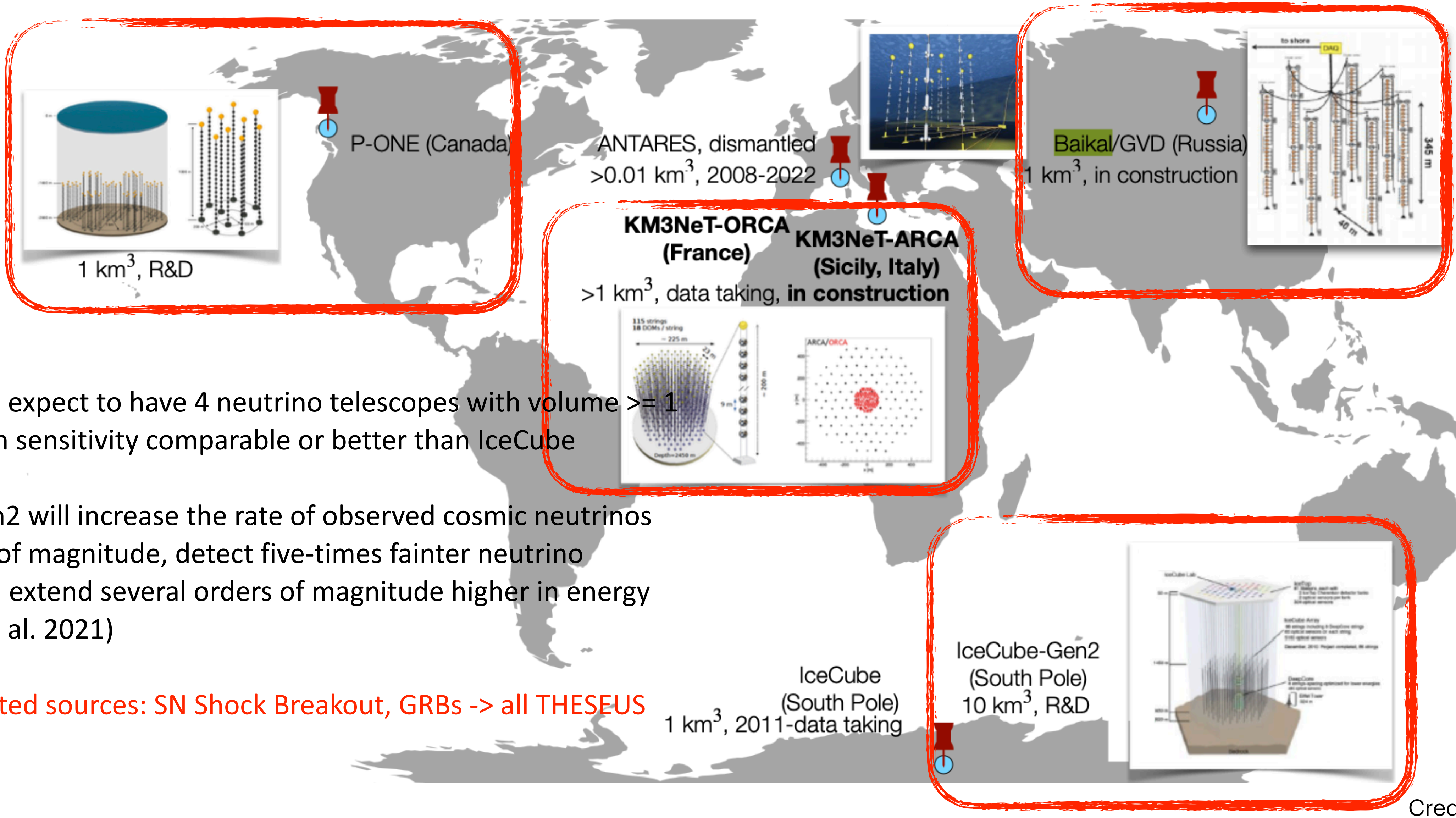


Aartsen et al. Science 361, 1378. 2018



Abbasi+2022

The growing neutrino detector network



By 2030s we expect to have 4 neutrino telescopes with volume >= 1 km^3 -> with sensitivity comparable or better than IceCube

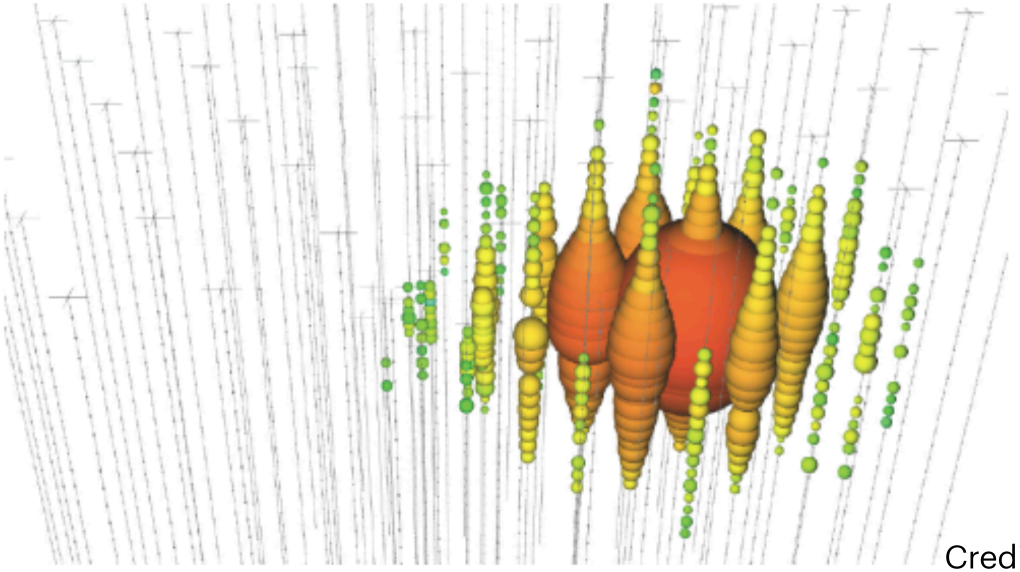
IceCube-Gen2 will increase the rate of observed cosmic neutrinos by an order of magnitude, detect five-times fainter neutrino sources, and extend several orders of magnitude higher in energy (e.c. Clark et al. 2021)

Other expected sources: SN Shock Breakout, GRBs -> all THESEUS targets!

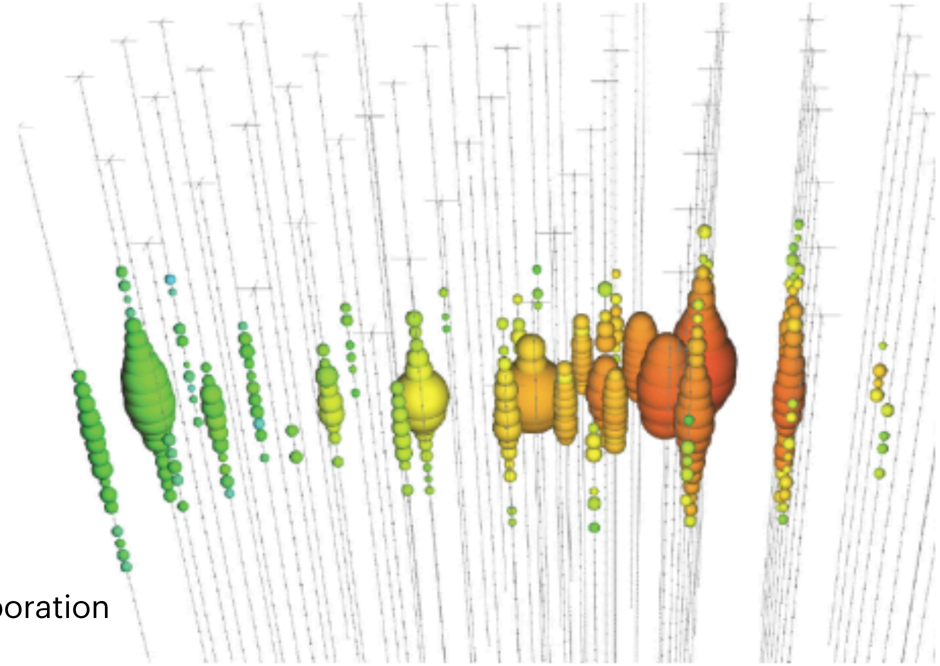
Credit: A. Zegarelli

Neutrino telescope sky localization accuracy

cascade-like event, typically from ν_e and most ν_τ -> sky localization accuracy of O(10) deg^2



track-like event, typically from ν_μ -> sky localization accuracy of O(0.1) deg^2

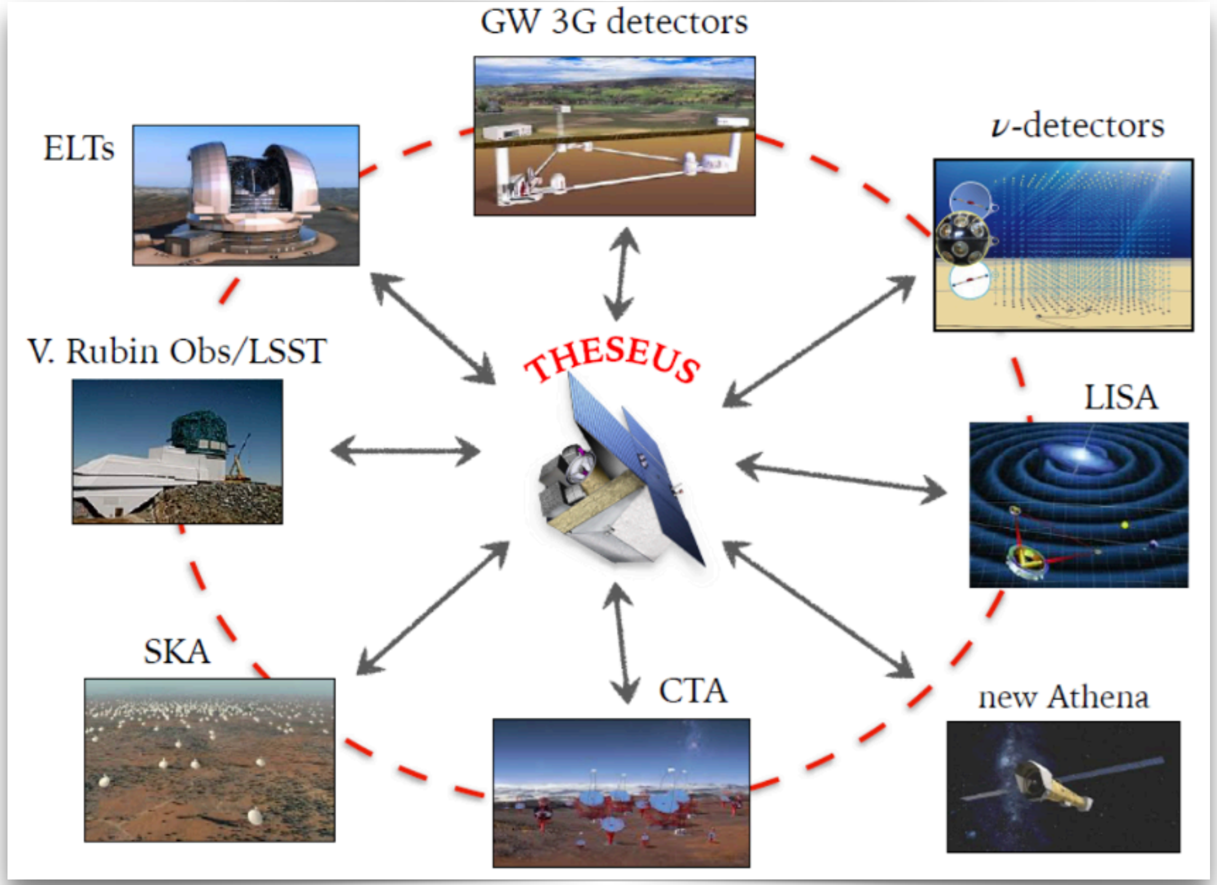


Credit: IceCube Collaboration

THESEUS will allow to detect simultaneous gamma/X-ray/NIR counterpart, refine sky localization down to arcmin/arcsec level of a large number of neutrino sources detected with IceCube-Gen2

The role of THESEUS in MMA

1. **Independent detection** of the electromagnetic counterpart of neutrino and/or GW —> increase statistical confidence of astrophysical nature of GW or ν event
2. **Autonomous source characterization** and identification (large spectral coverage of onboard instrumentations, from γ-rays to NIR)
3. **Accurate sky coordinate dissemination** —> follow-up campaigns with large facilities of 2030s as ELT, Athena, SKA,CTA, etc.



Summary

- ★ By >2035 the next generation GW detectors and neutrino detectors will be operative and high rate of MM sources is expected but with poor sky localization (especially for GW sources)
- ★ Most plausible MM sources are X-ray/gamma-ray transients
- ★ THESEUS ESA mission project main targets, as GRBs, AGN, blazars, Soft-Gamma-Repeaters, are potential GW and neutrino emitters
- ★ THESEUS + next generation neutrino and GW detectors -> transformational science in several fields (e.g. neutron star physics, cosmology, neutrino astronomy)


Thank you!
GW170104
GW151012
GW170818-HLV
GW151226
GW170608
GW170809
GW170814-HLV
GW150914
arcmin
(X/gamma-rays)
arcsec
(NIR)
SXI+XGIS
30°
0°
-30°
-60°
16h
12h
8h

Extra slides

THESEUS observational strategy

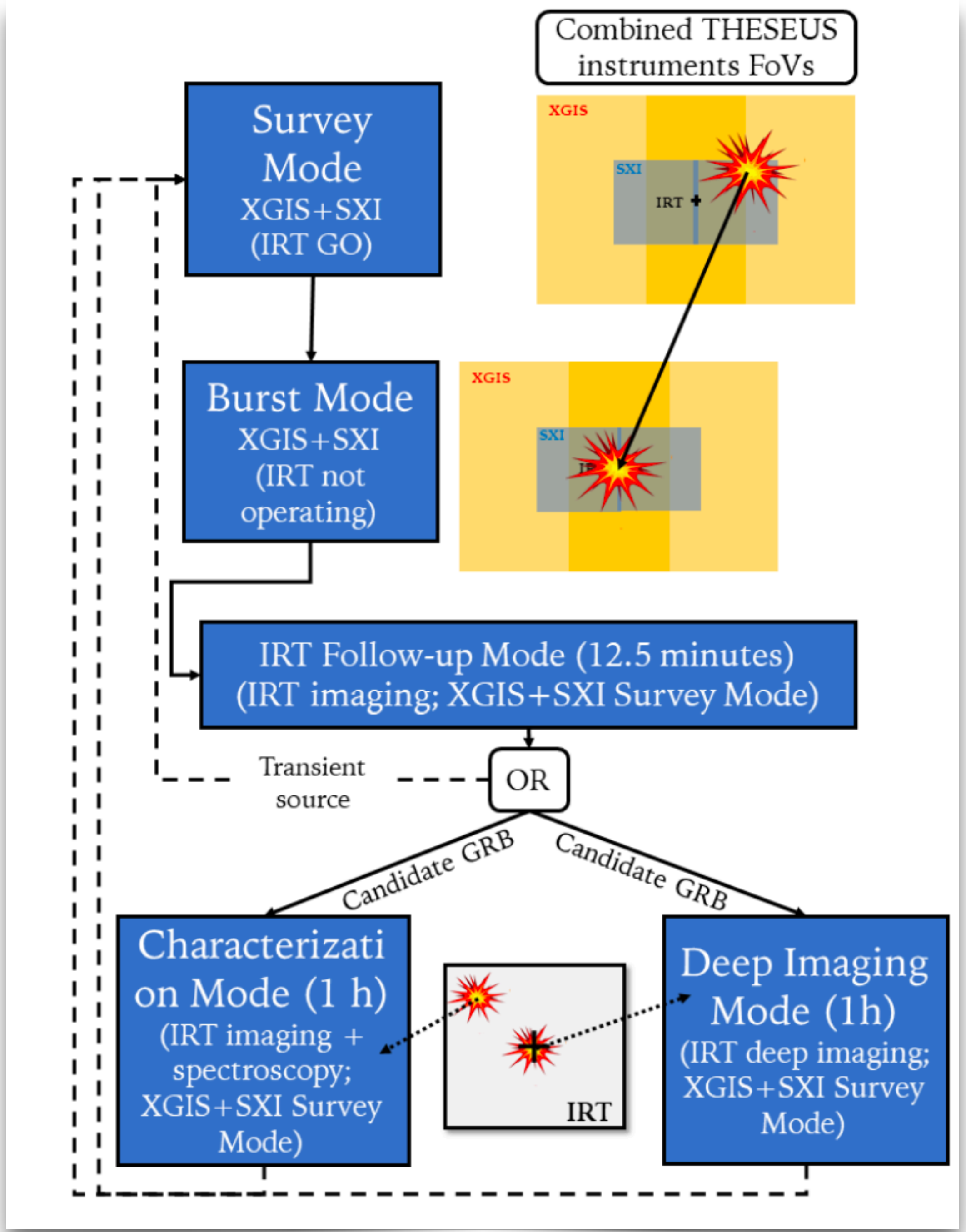
Once in the “Burst mode”, IRT will start to acquire images in different filters for a total of ~ 12 min (“Follow-up Mode”) aimed at:

(i) identifying the counterpart of the high-energy source,

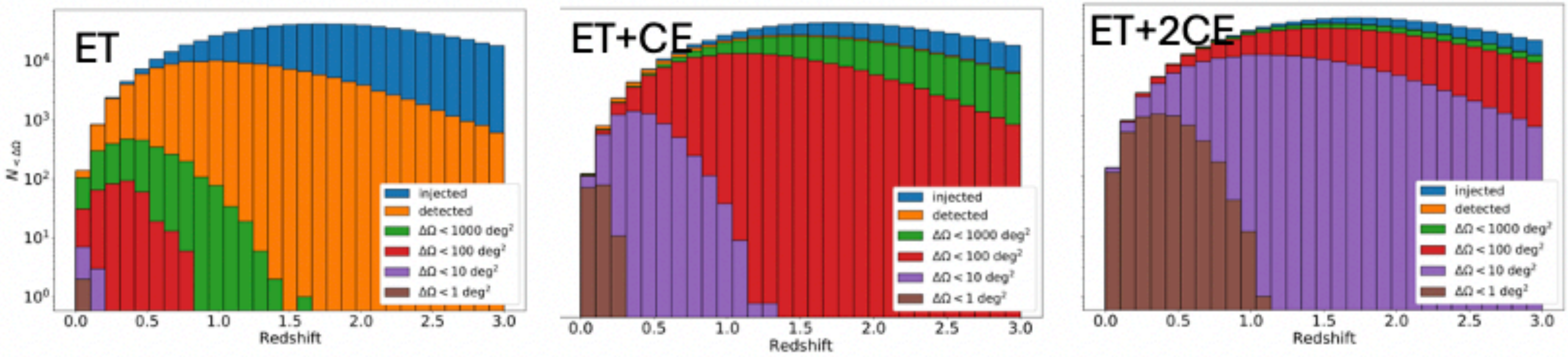
(ii) narrow down its localization to the arcsec accuracy,

(iii) provide a first indication of a possible high redshift event (z≥6)

The spacecraft will then enter either the “Characterization Mode” (deep images in different filters and spectra) or the “Deep Imaging Mode”



ET+CE sky localization capabilities



- ET: O(100) detections per year with sky-localization (90% c.r.) < 100 sq. deg
- ET+CE: O(1000) detections per year with sky-localization (90% c.r.) < 10 sq. deg
- ET+2CE: O(1000) detections per year with sky-localization (90% c.r.) < 1 sq. deg

Branchesi, Maggiore et al 2023, JCAP
Ronchini et al A&A. 2022

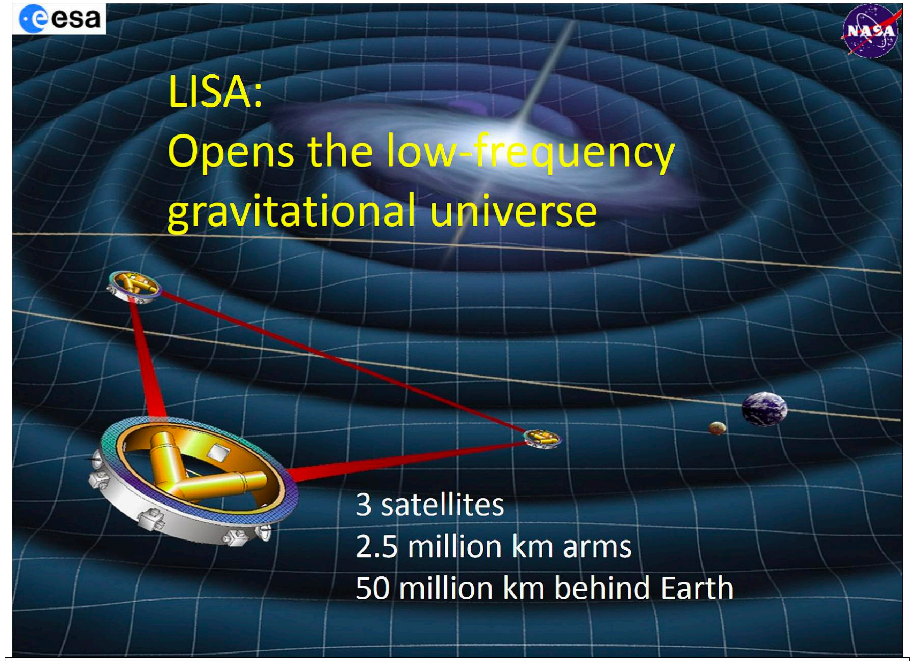
>2035:Laser Interferometer Space Antenna

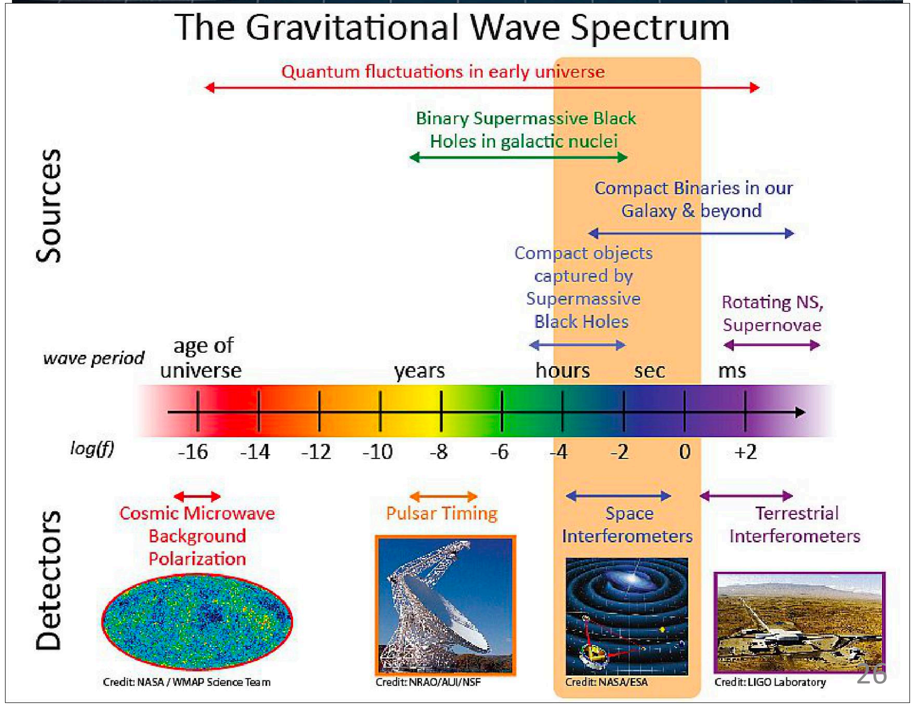
- Formally approved on 25 Jan 2024 by ESA Science Program Committee (construction authorzed - “adoption”)

- Space-based interferometers sensitive to low-frequency GW sources (~ 10^{-4} -1 Hz), e.g.:
  - **Ultra compact binaries**
  - **Extreme mass ratio binary mergers**
  - **Super massive BH binaries**
  - **NS-NS/NS-BH/BH-BH yrs before merger**

?

X-ray sources





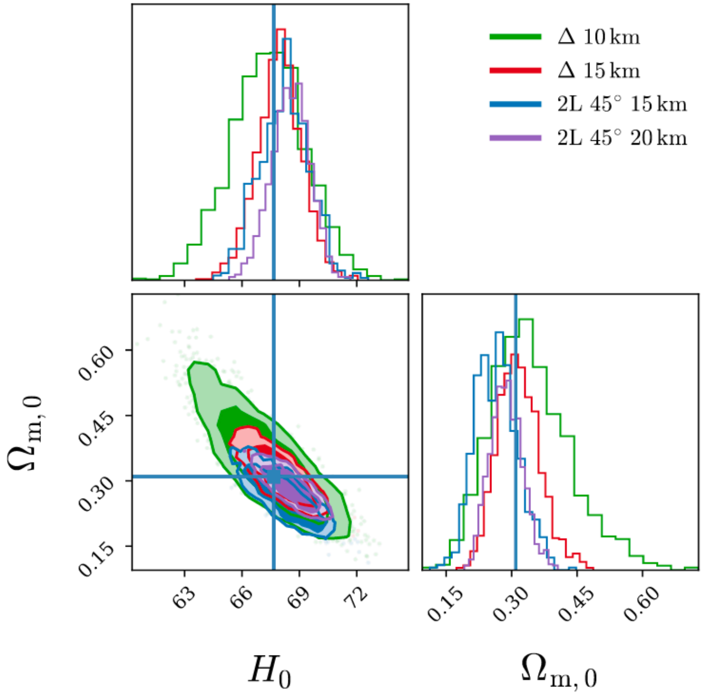
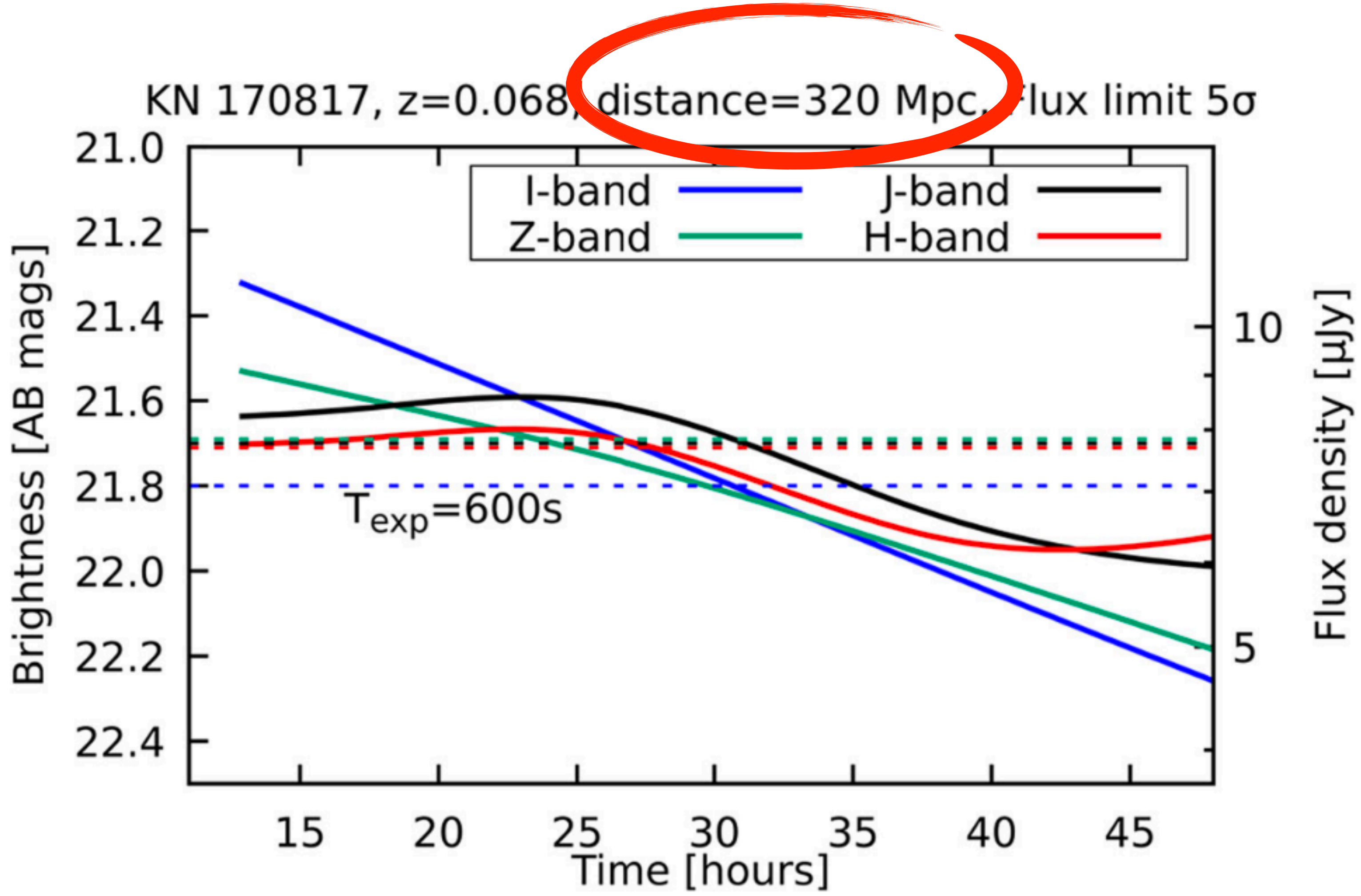


Figure 52. Reconstruction of the parameters H_0 and Ω_M in ΛCDM, from the joint GW+EM events obtained with ET+THESEUS in 5 yr of observations, for the different geometries of ET shown, all with their HFLF-cryo sensitivity.

Configuration	$\Delta H_0/H_0$	$\Delta\Omega_M/\Omega_M$
Δ-10km	0.057	0.546
Δ-15km	0.035	0.290
2L-15km-45°	0.040	0.370
2L-20km-45°	0.029	0.276

Table 28. Relative errors on H_0 and Ω_M in ΛCDM (median and symmetric 68% CI), from the joint GW+EM events obtained with ET+THESEUS, for the different geometries of ET shown, all with their HFLF-cryo sensitivity. We stress that no prior from electromagnetic observations, such as CMB+BAO+SNe, is used here; with such priors, the accuracy on H_0 becomes sub-percent.

Kilonova detection with THESEUS/IRT



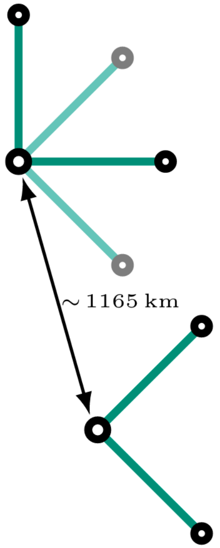
ET configurations under study

Reference configuration: triangular-shaped

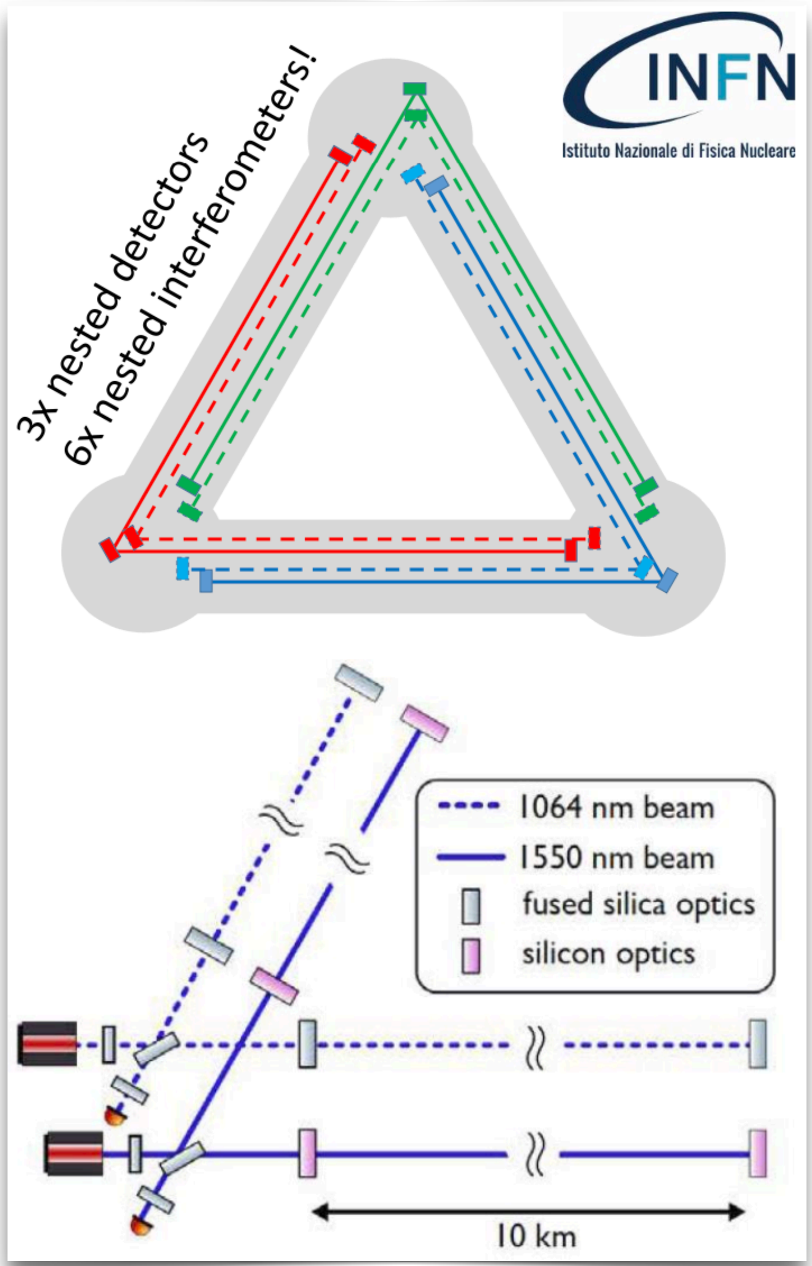
- 3 nested detectors of 10 km arms
- each detector made of a Low Frequency (cryogenic temperature) and High Frequency interferometer

Among possible alternative configuration:

- Triangular with 15 km arms, without LF
- 2L-shaped, each made of a Low and High frequency interferometer, of 15 or 20 km parallel or with relative orientation of 45° arms

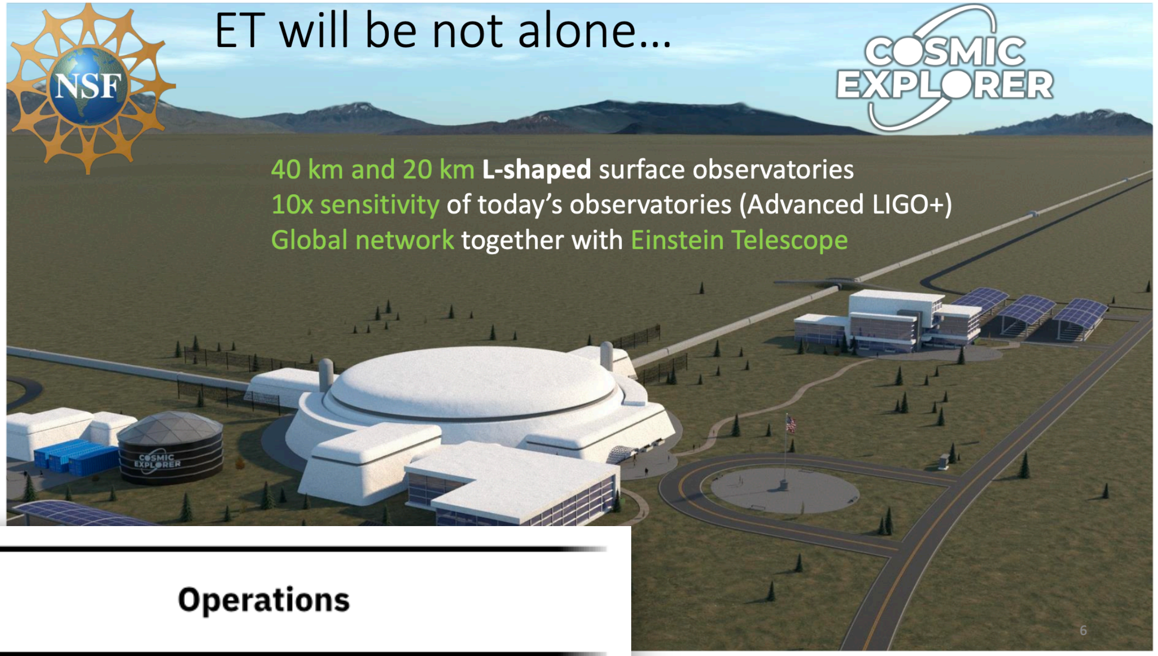


E.g. Branchesi, Maggiore et al. JCAP, 2023

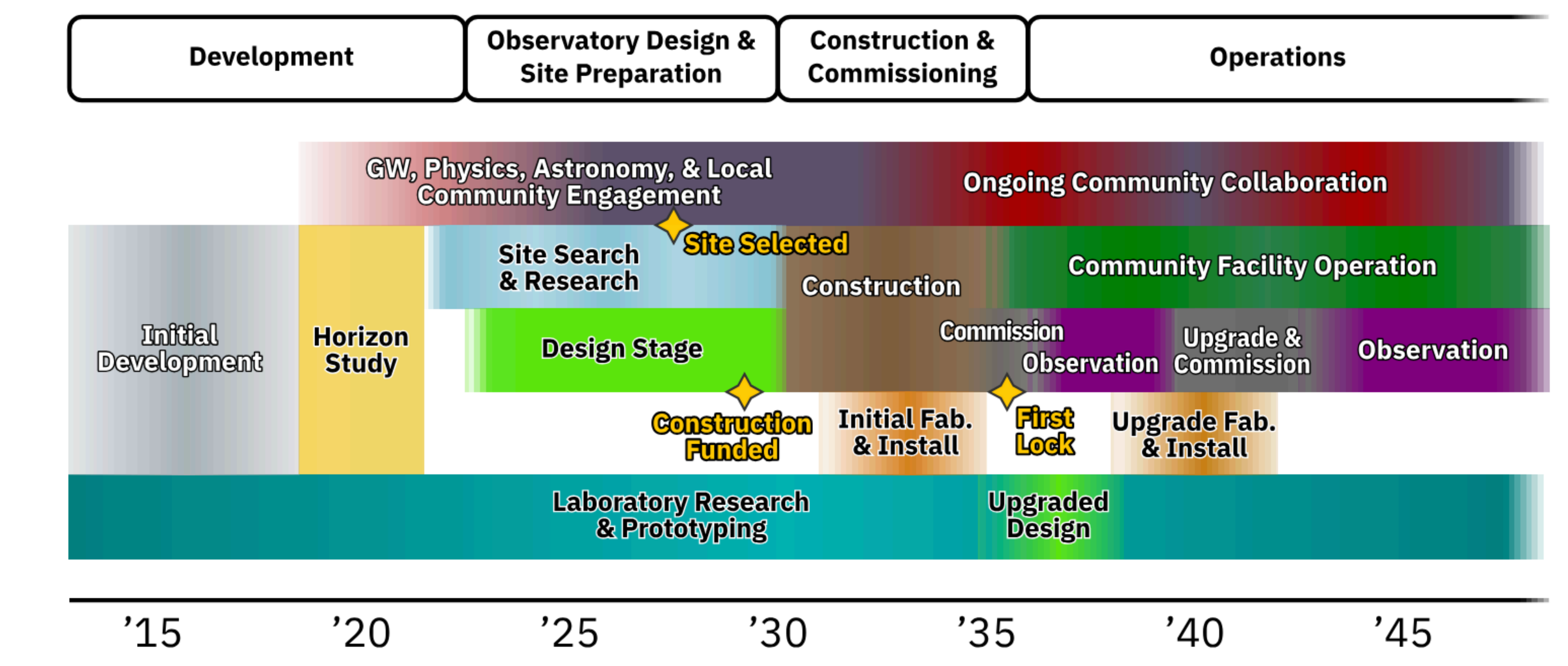


Credit: Naticchioni

Cosmic Explorer



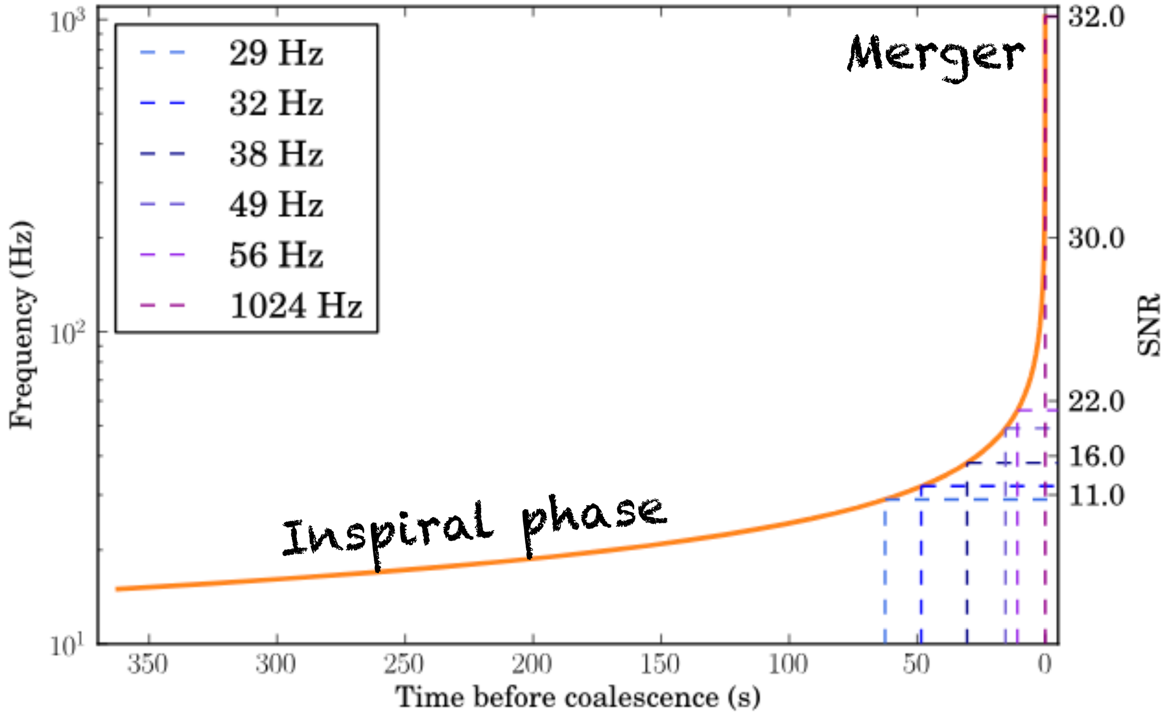
Cosmic Explorer Study https://arxiv.org/pdf/2109.09882



Early Warnings

- Compact binary merger bright signals can be detected at low GW frequencies before merger
- 3G GW detector have higher sensitivity at low frequencies and allow for ~min-hrs early warnings of most nearby BNS events

https://emfollow.docs.ligo.org/userguide/early_warning.html



The time evolution of the GW frequency and the cumulative SNR for a GW170817-like BNS system detected with Advanced LIGO

Early Warnings from ET

Full (HFLF cryo) sensitivity detectors

Configuration	$\Delta\Omega_{90\%}$	All orientation BNSs			BNSs with $\Theta_v < 15°$		
	[deg^2]	30 min	10 min	1 min	30 min	10 min	1 min
Δ10km	10	0	1	5	0	0	0
	100	10	39	113	2	8	20
	1000	85	293	819	10	34	132
	All detected	905	4343	23597	81	393	2312

Within THESEUS FoV

Branchesi, Maggiore et al. JCAP 2023

Number of BNS mergers per year detected (SNR ≥ 8) before the merger within z = 1.5 for the reference ET configuration