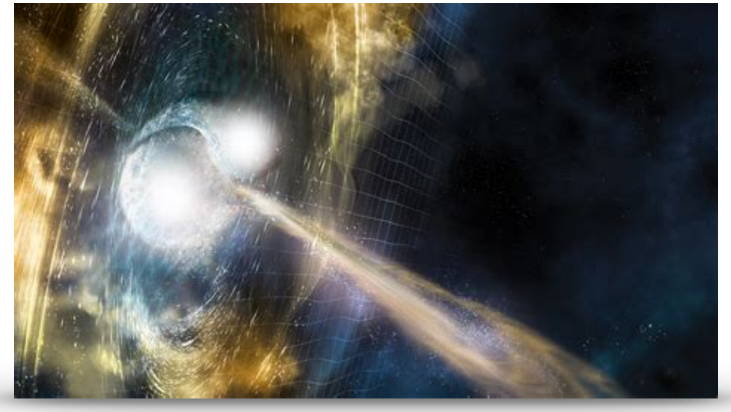
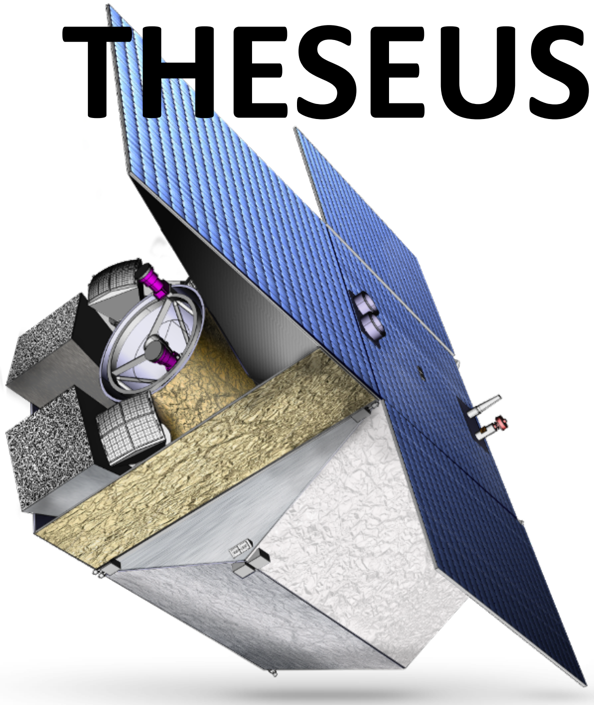
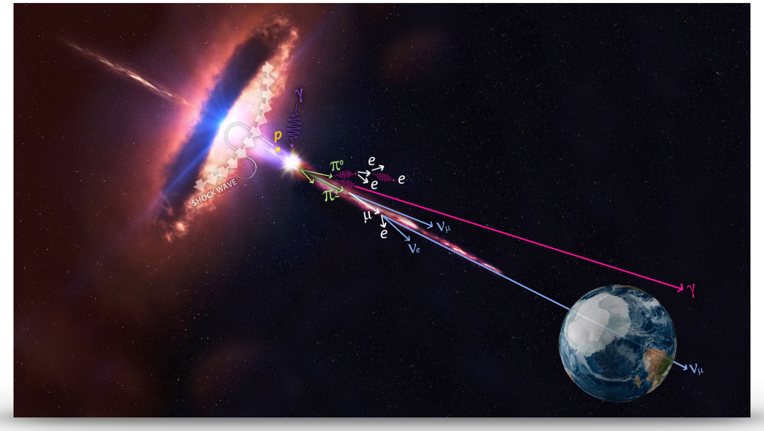
Multi-Messenger Astrophysics with THESEUS







Giulia Stratta (GU-Frankfurt, INAF)

On behalf of THESEUS Consortium

https://www.isdc.unige.ch/theseus/

RICAP24 - Frascati - 23-27 Sept 2024

Outline

- Current status on MMA and main challenges
- Future perspectives
- THESEUS and its role in multi-messenger astrophysics

The dawn of MMA

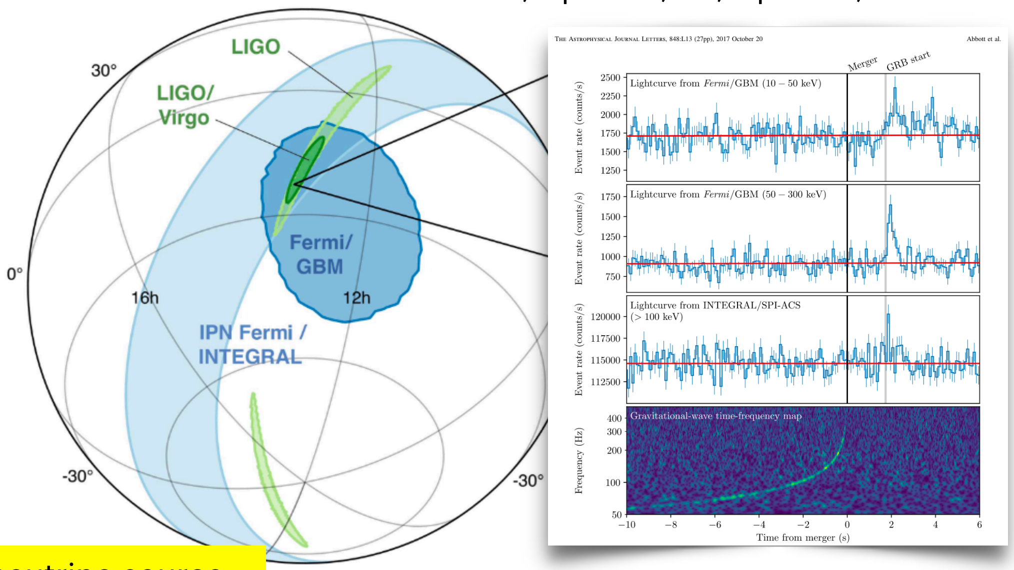
Sep 2015: first GW detection from BH-BH (Abbott+2016)

Aug 2017: first GW detection from NS-NS + **short GRB 170817** + first robust evidence of a kilonova (AT2017gfo) (e.g. Abbott+2017,Pian+2017)

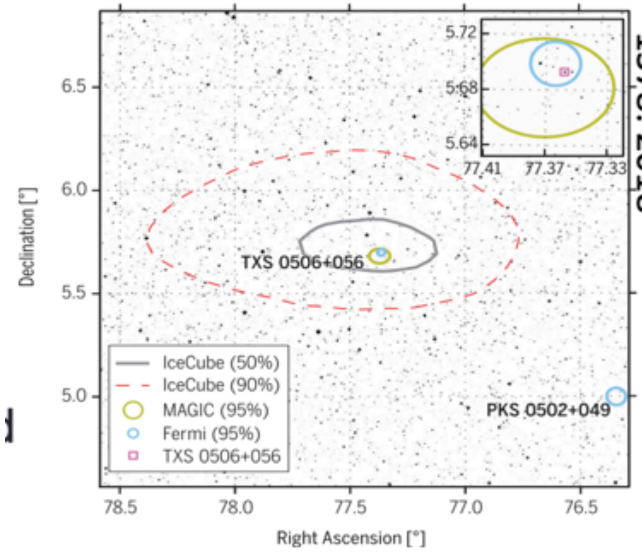
Sep 2017: IceCube ~300 TeV neutrino event spatially coincident with a **blazar** in active phase at z=0.34 (TXS 0506+056 , Artsen+2018)

From **2011-2020** IceCube data confirmed cosmic origin neutrino flux -> most significant gamma-ray sources: **AGN** NGC 1068 at 14.4 Mpc (Abbasi+2022) and two blazars (PKS1424+240 at unknown z, and GB6 J1542+6129 at z=0.5, e.g. Padovani+2022)

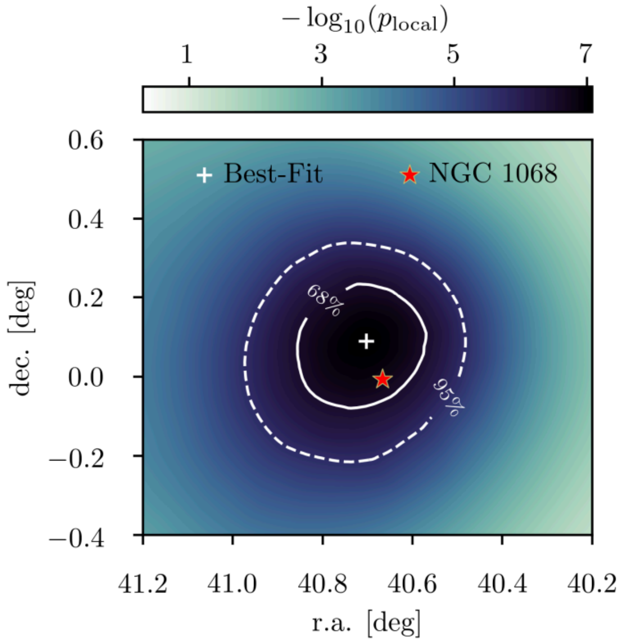
Abbott+2017, ApJ 848,L12; ApJ 848, L13



3rd identified neutrino source after our Sun and SN1987A in LMC



Aartsen et al. Science 361, 1378, 2018



The dawn of MMA

Abbott+2017, ApJ 848,L12; ApJ 848, L13

Sep 2015: first GW detection from BH-BH (Abbott+2016)

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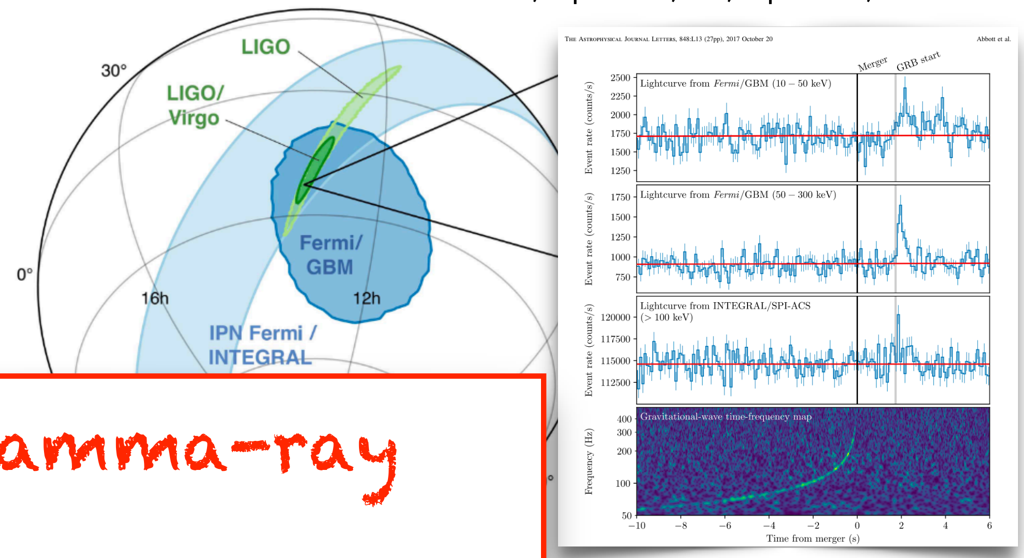
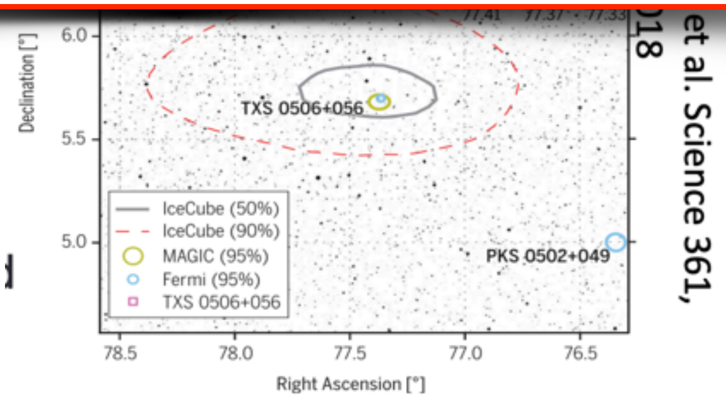
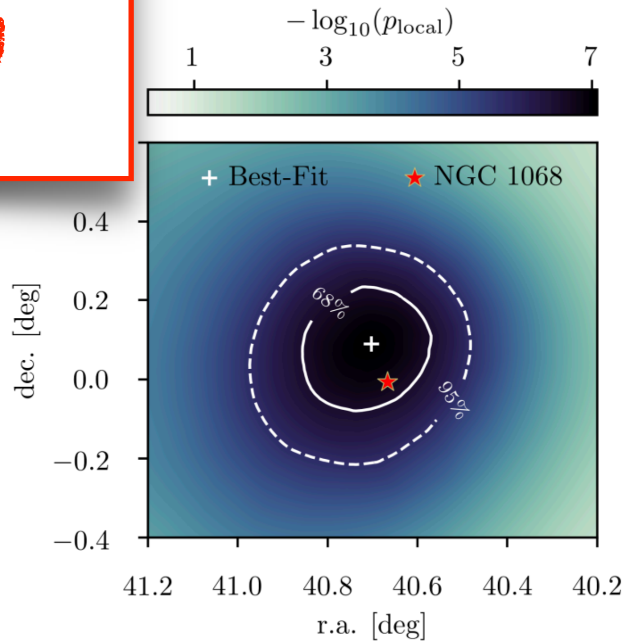
Sep 2017: IceCube ~30 spatially coincident wi phase at z=0.34 (TXS 0

MM sources are X/gamma-ray emitters
-> crucial role of high-energy missions in MMA

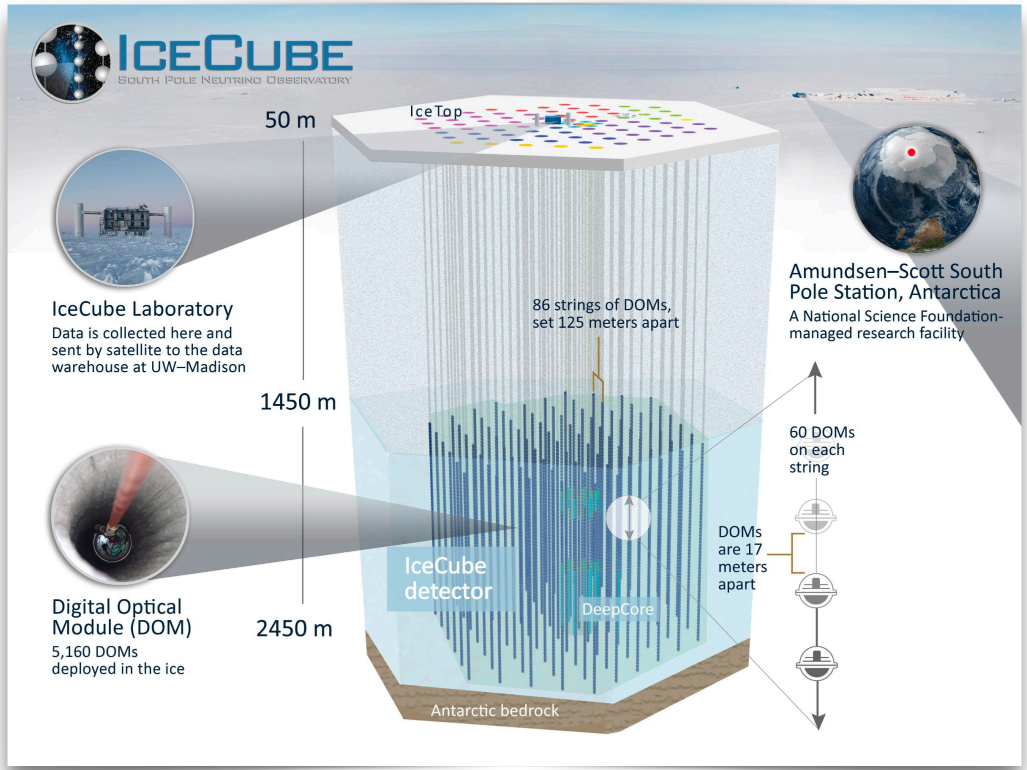
From **2011-2020** IceCube data confirmed cosmic origin neutrino flux -> most significant gamma-ray sources: **AGN** NGC 1068 at 14.4 Mpc (Abbasi+2022) and two blazars (PKS1424+240 at unknown z, and GB6 J1542+6129 at z=0.5, e.g. Padovani+2022)



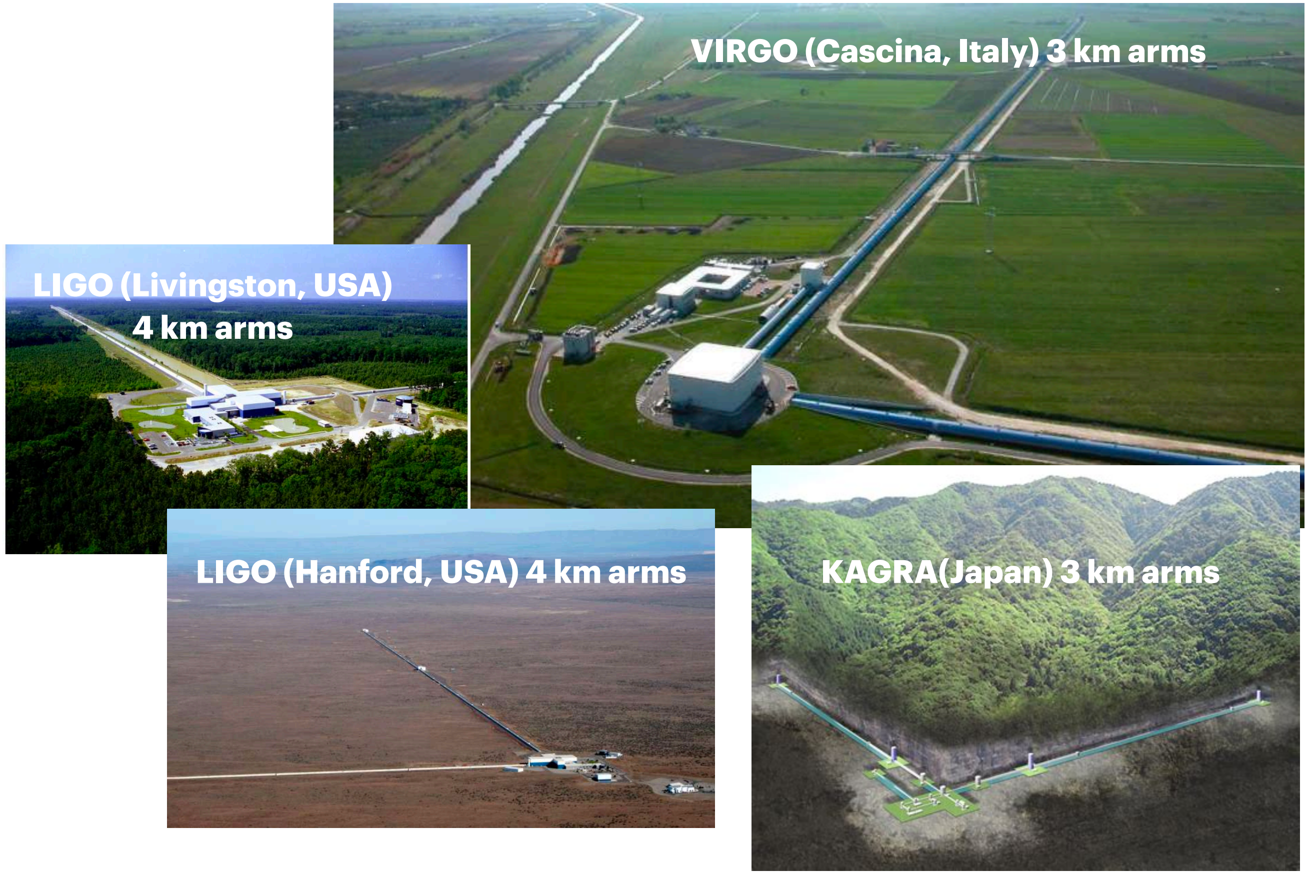




The current detectors



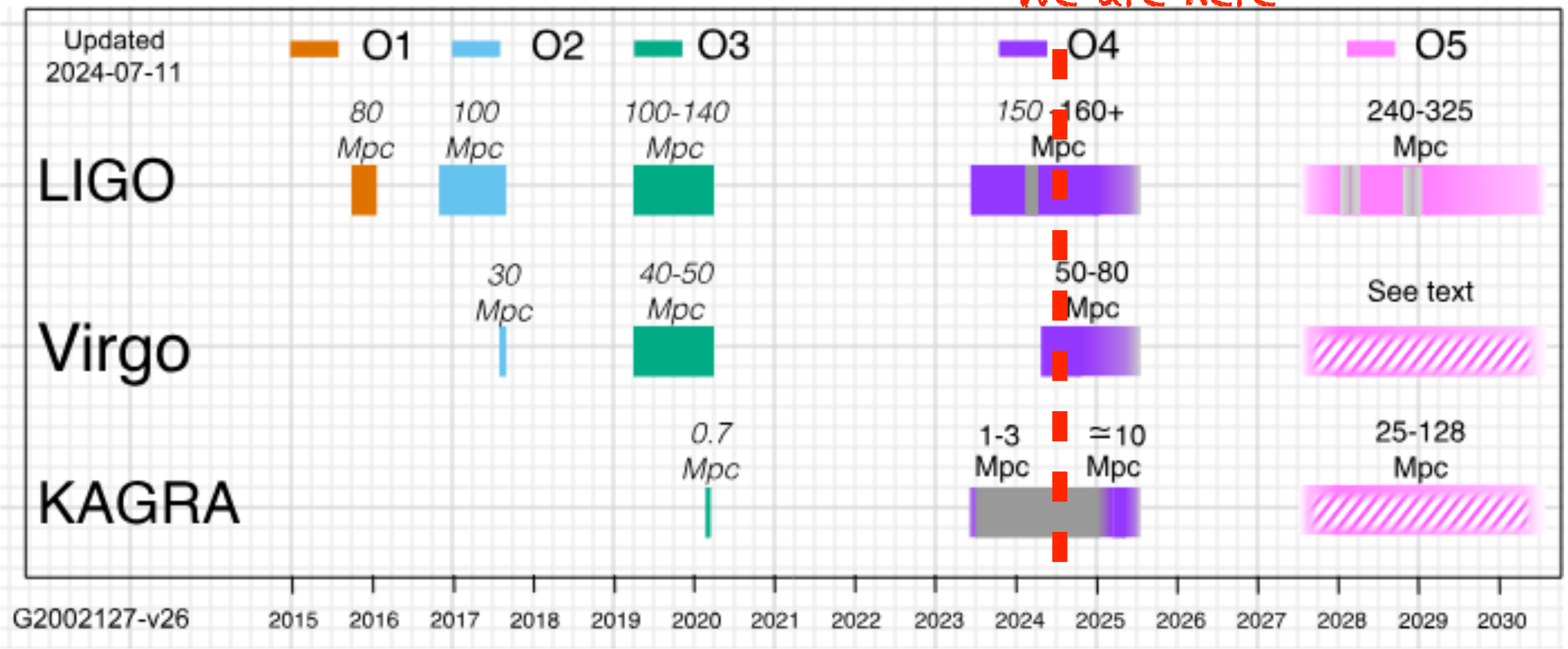
IceCube TeV-PeV neutrino telescope in the South Pole



The second generation gravitational wave interferometer network

Next future for GW observational runs

We are here



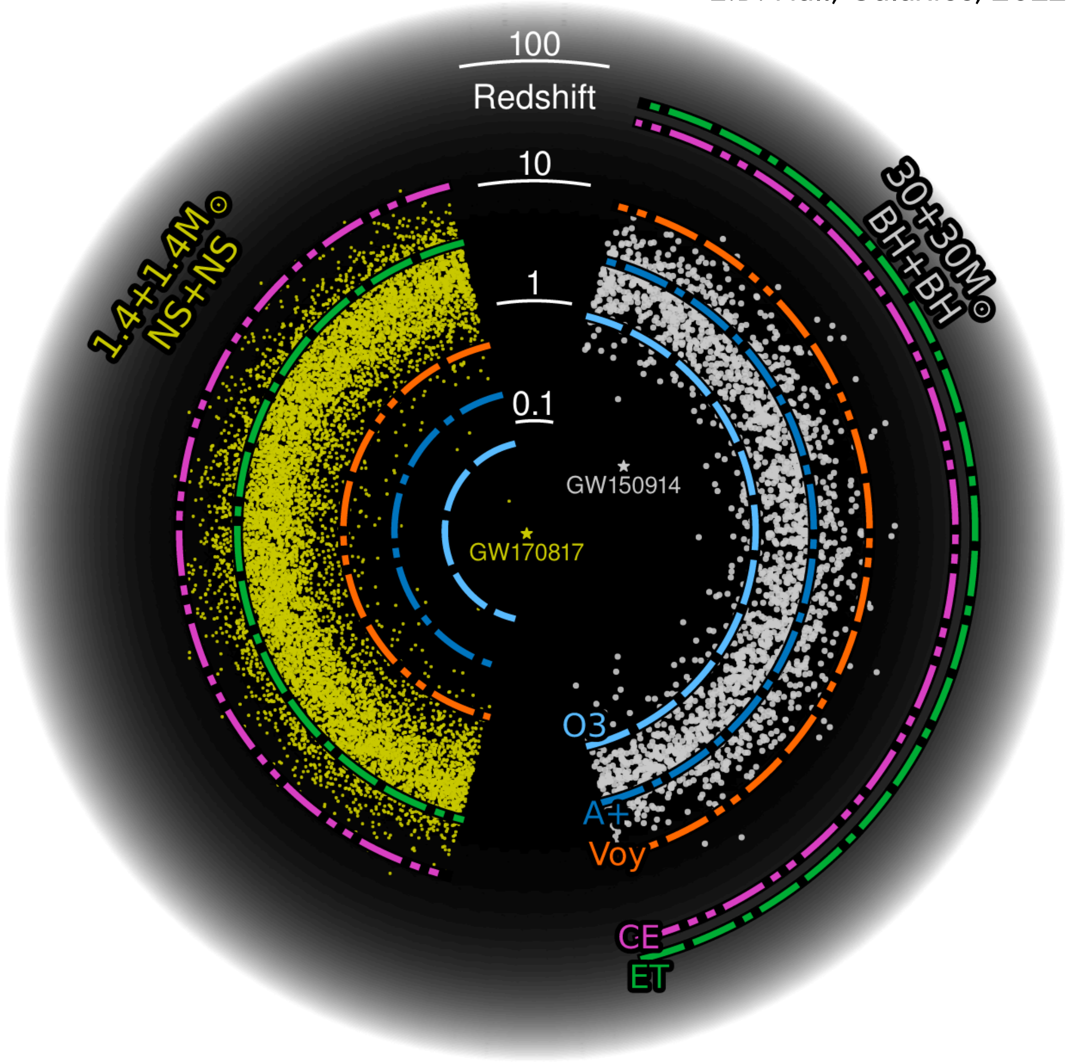
87% probability to detect at least 1 BNS during O4b

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

Challenges for GW source EM follow-up

E.D. Hall, Galaxies, 2022

1. Current detector sensitivity
-> low detection rate

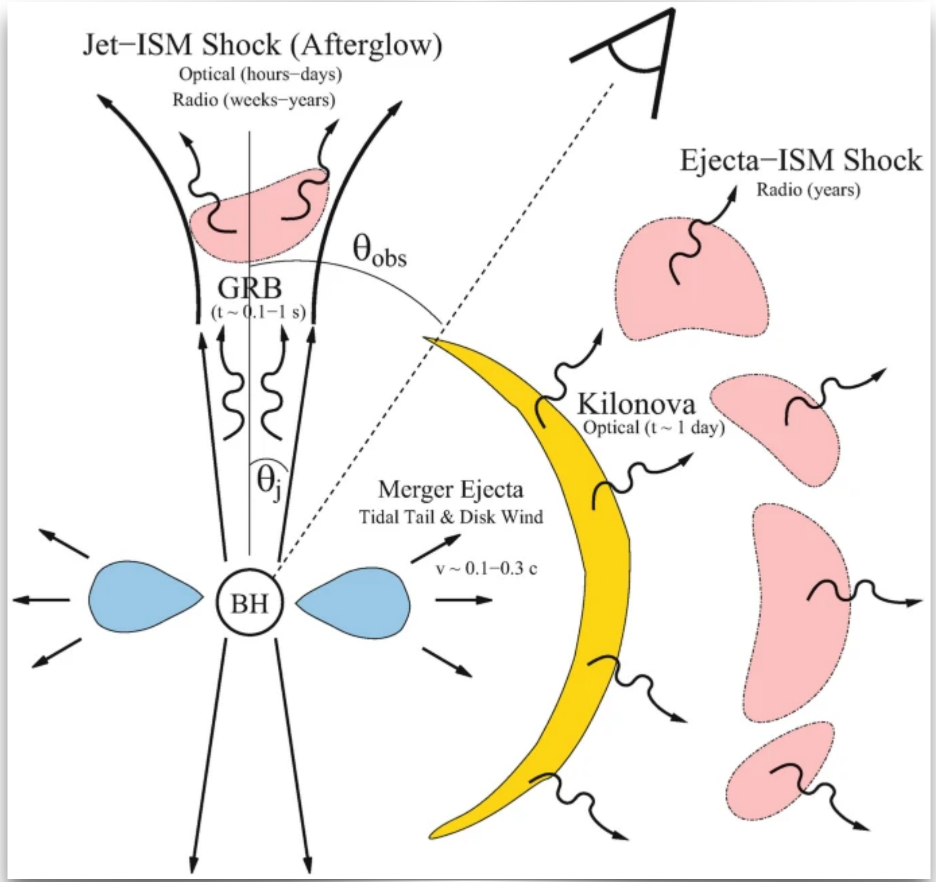


Challenges for GW source EM follow-up

1. Current detector sensitivity
-> low detection rate

2. Only a small fraction (~<1%) is face-on (i.e. GRB)
-> vast majority have optical counterpart

- Kilonova (opt/NIR): Isotropic but faint
- GRB (X/gamma-ray): bright but collimated



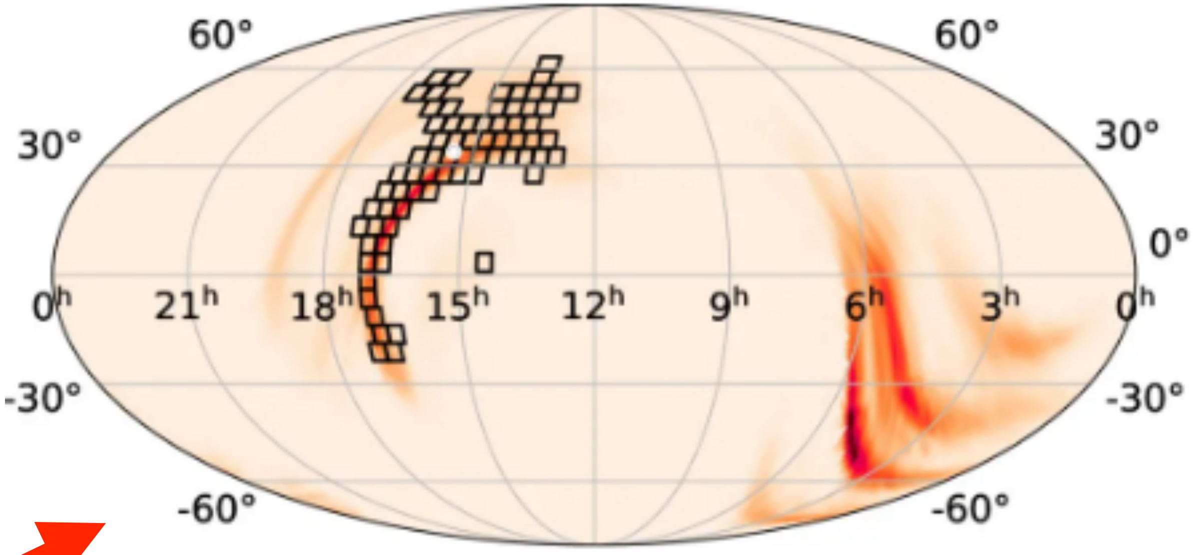
Expected EM counterparts from a BNS (Metzger & Berger 2012)

Challenges for GW source EM follow-up

1. Current detector sensitivity -> low detection rate

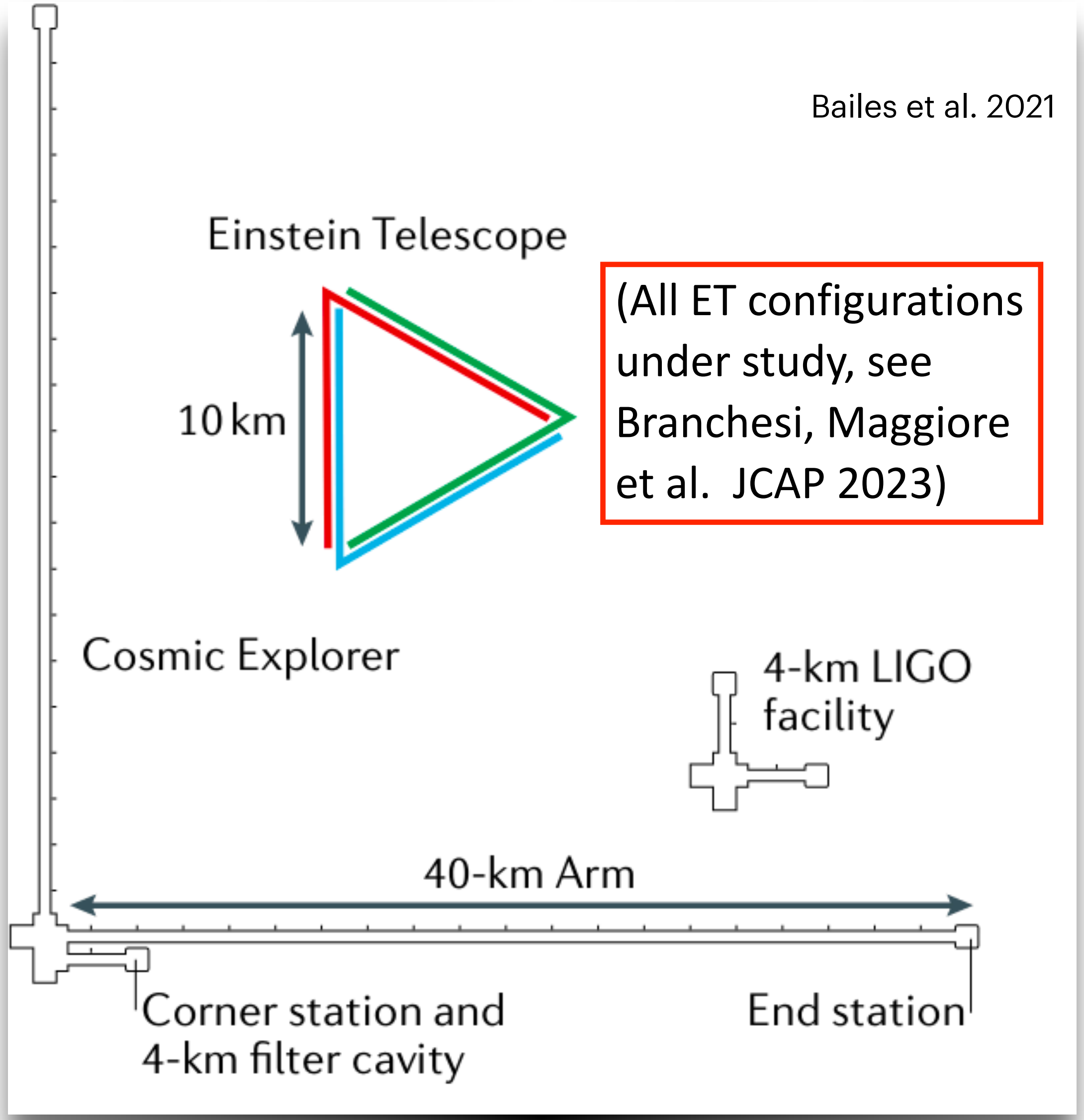
2. Only a small fraction (~<1%) is face-on (i.e. GRB) -> vast majority have optical counterpart

3. Poor sky localisation

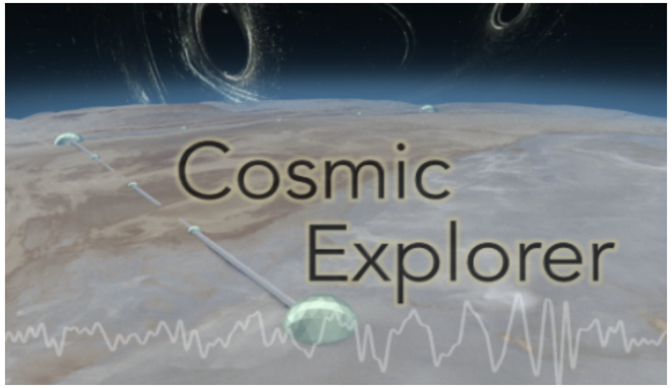


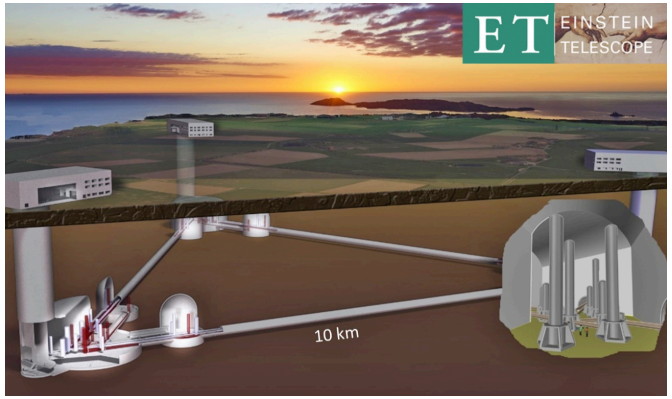
Skymap of the second BNS detected, GW190425

The next (3rd) generation GW detectors (>2035)



3G GW interferometer network by 2030s under study



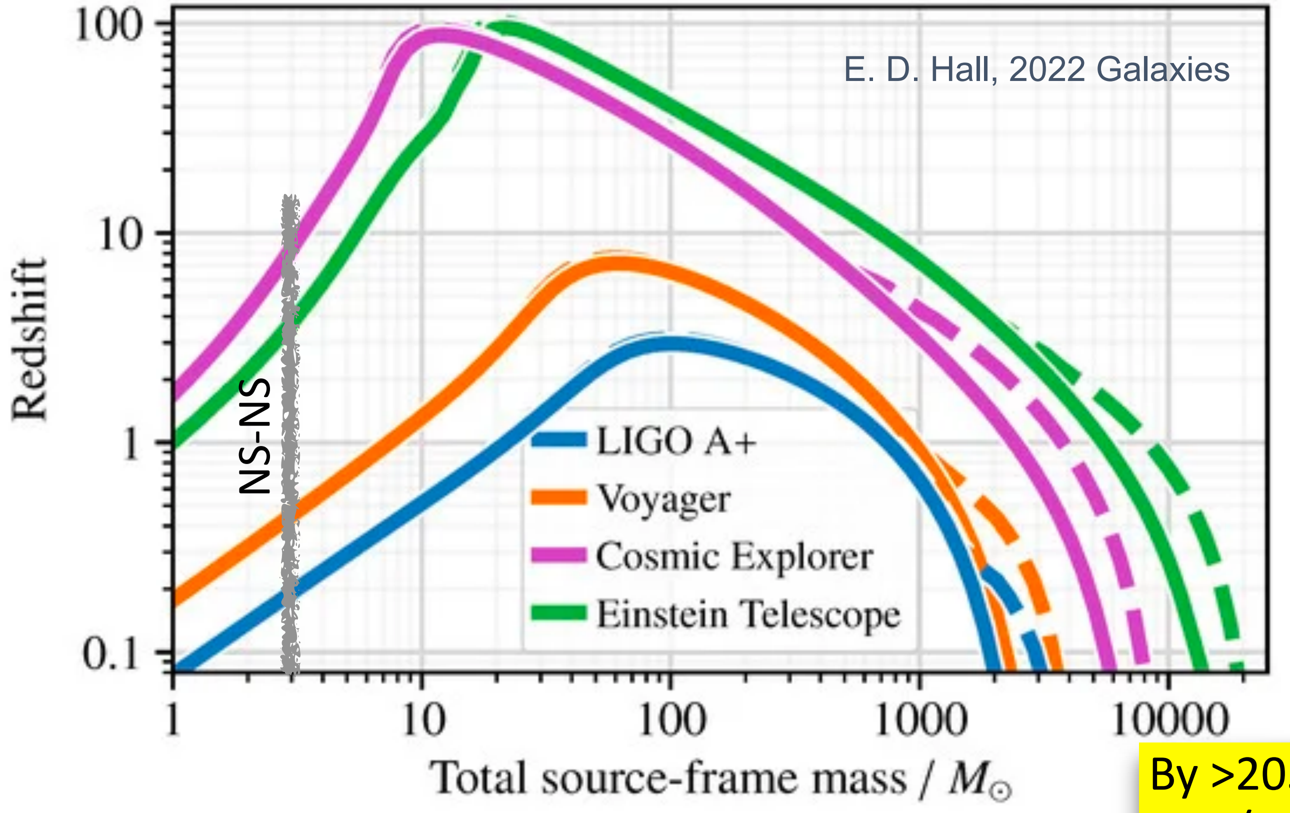


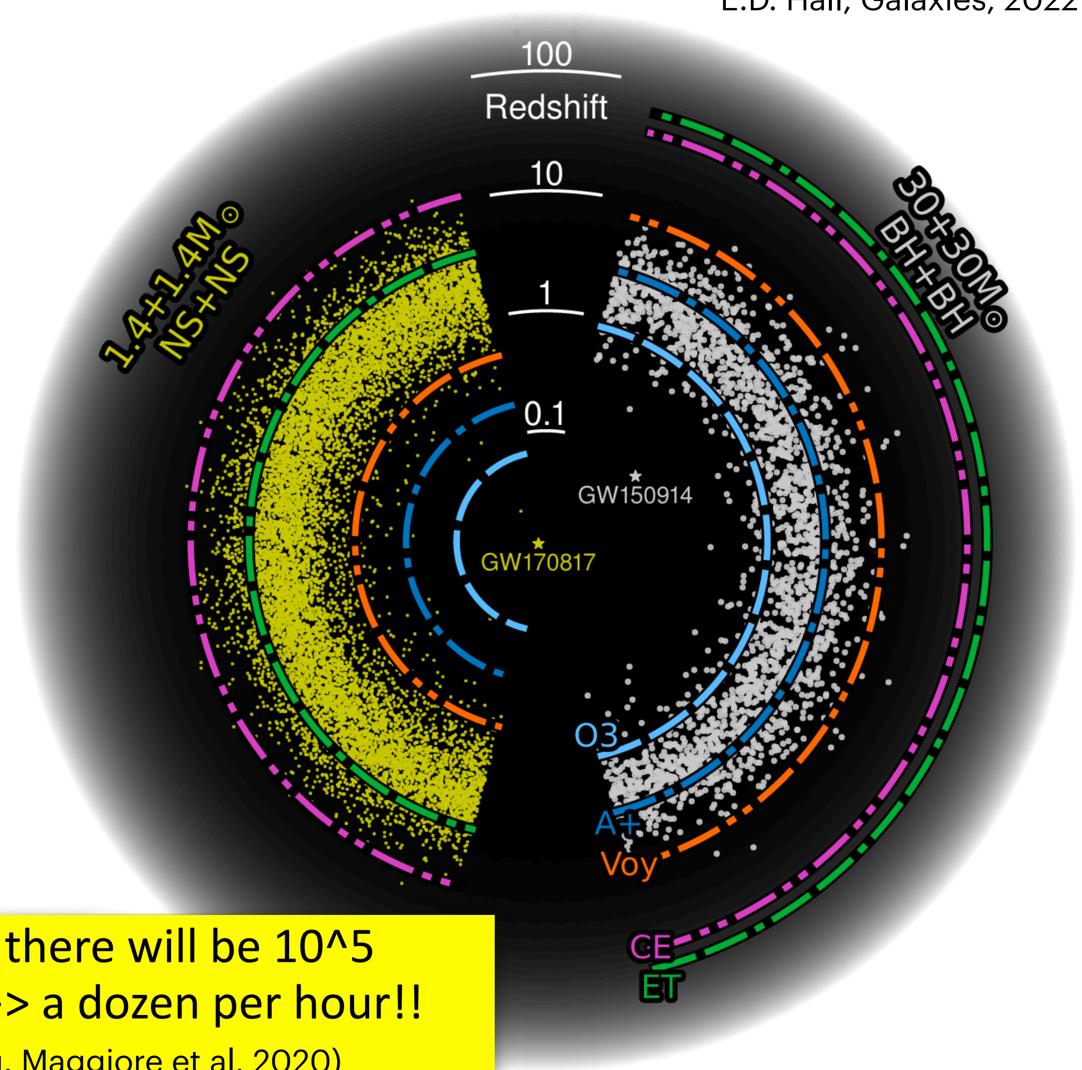
e.g. Maggiore et al. 2020

The next (3rd) generation GW detectors (>2035)

E.D. Hall, Galaxies, 2022

Highest cosmological redshift at which an equal-mass, compact binary coalescence could be detected with SNR=8





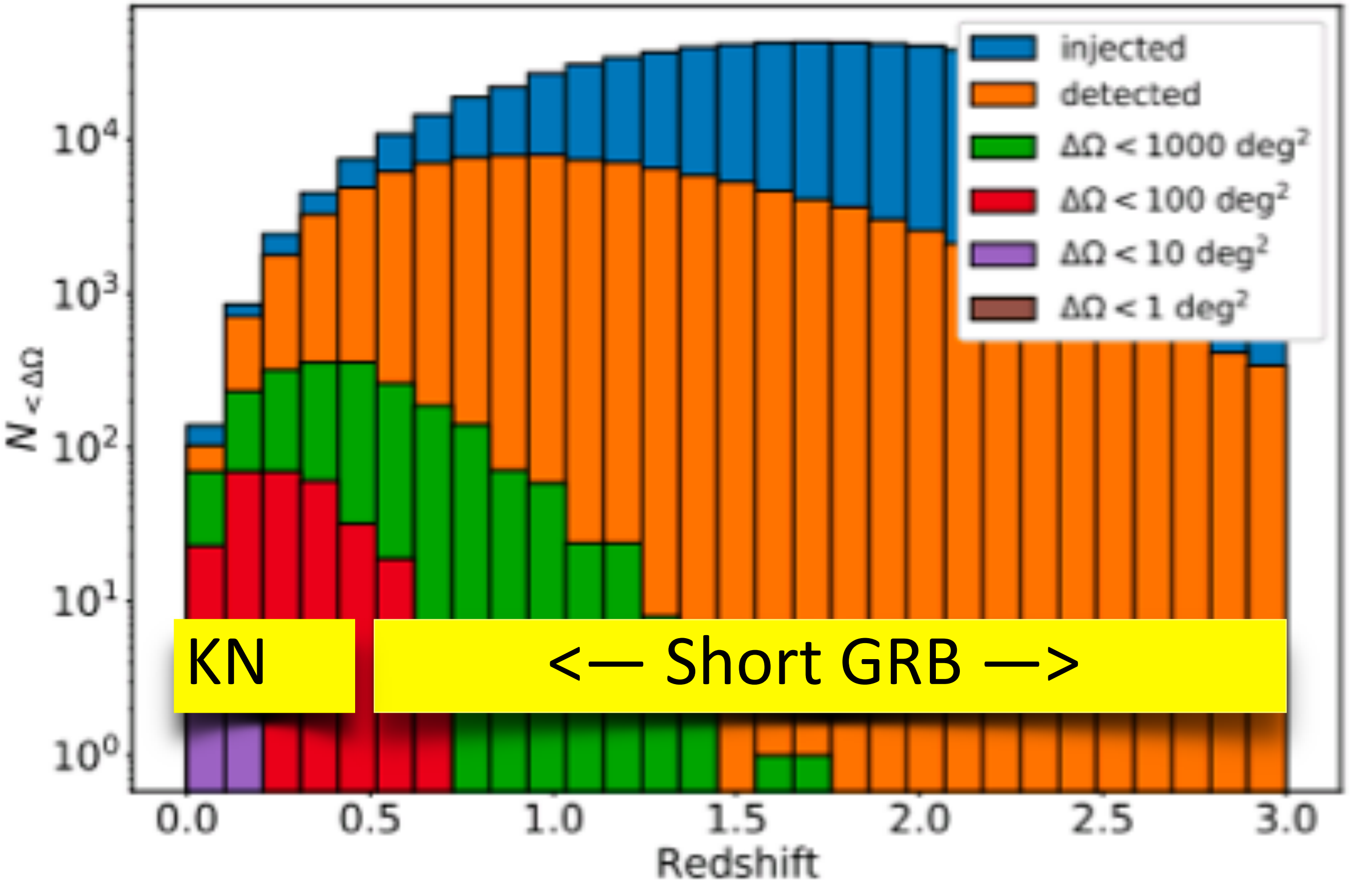
By >2035 there will be 10^5 BNS/yr —> a dozen per hour!!

(e.g. Maggiore et al. 2020)

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

GRB will be the only detectable EM counterpart for the vast majority of BNS

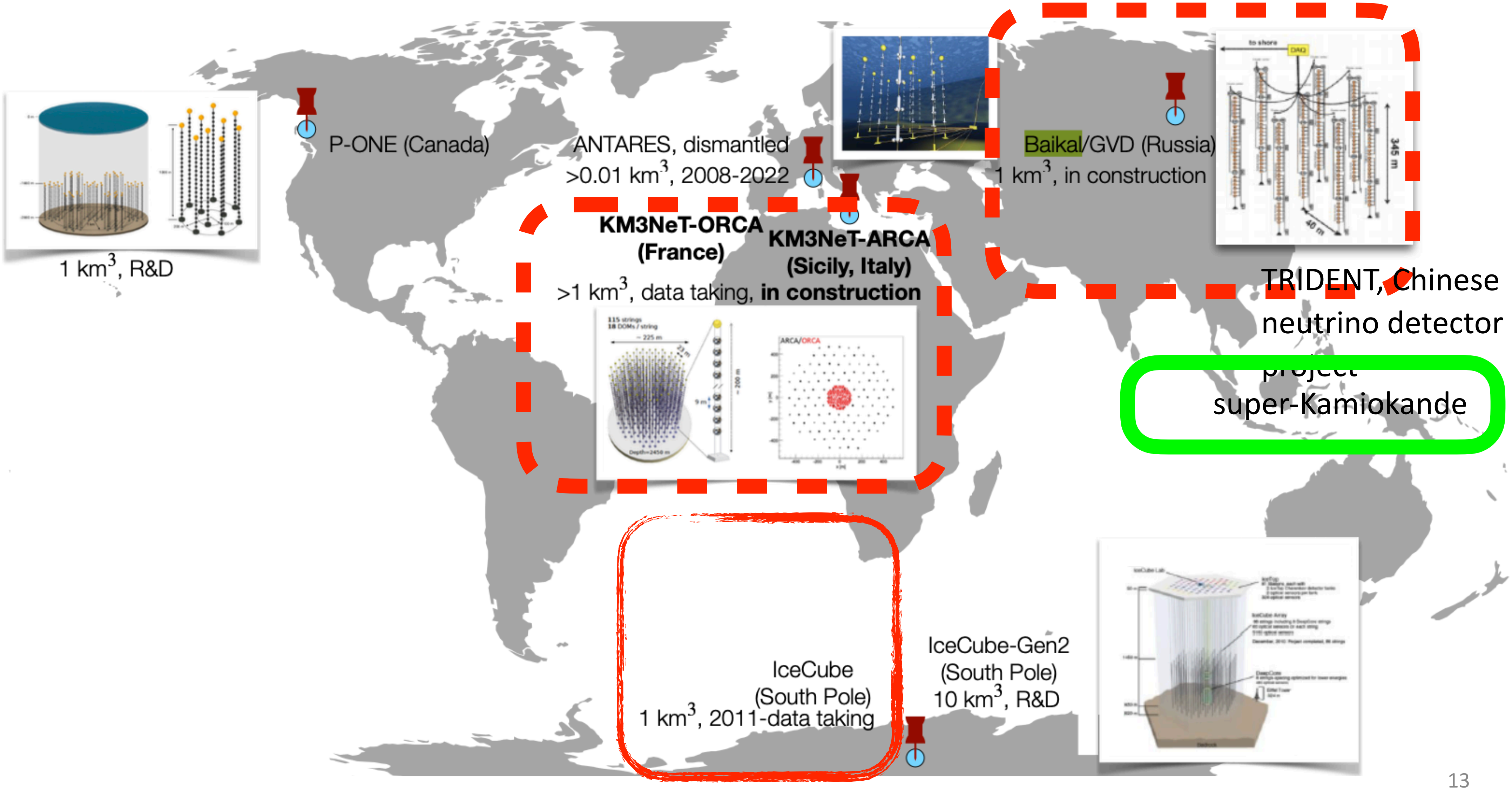
Sky localization capabilities of HE detectors is mandatory to allow MW follow-up campaigns



(a) Δ 10 km HFLF cryo.

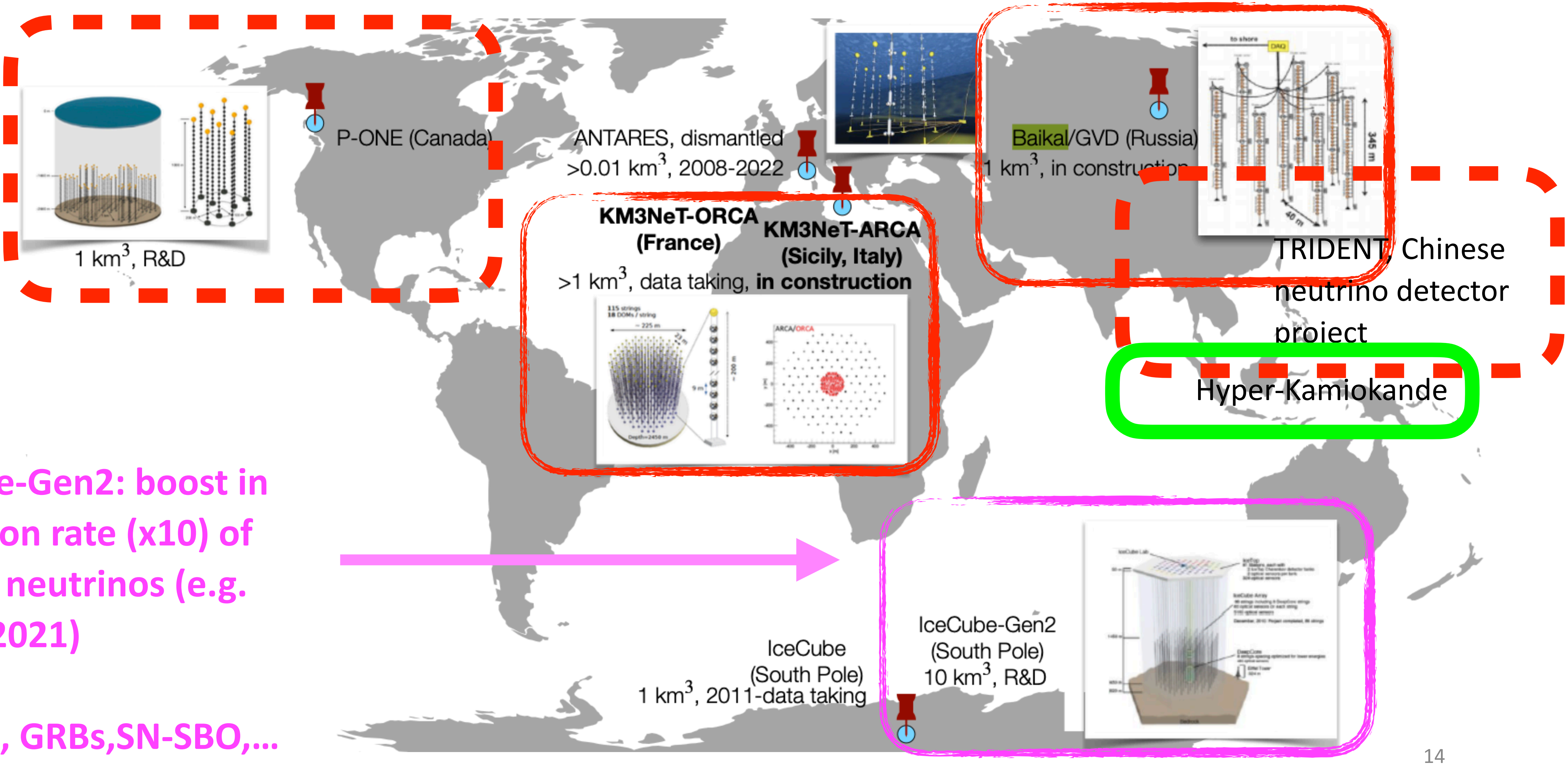
Branchesi, Maggiore et al. JCAP 2023

The growing neutrino detector network



Credit: adapted from A. Zegarelli

The growing neutrino detector network

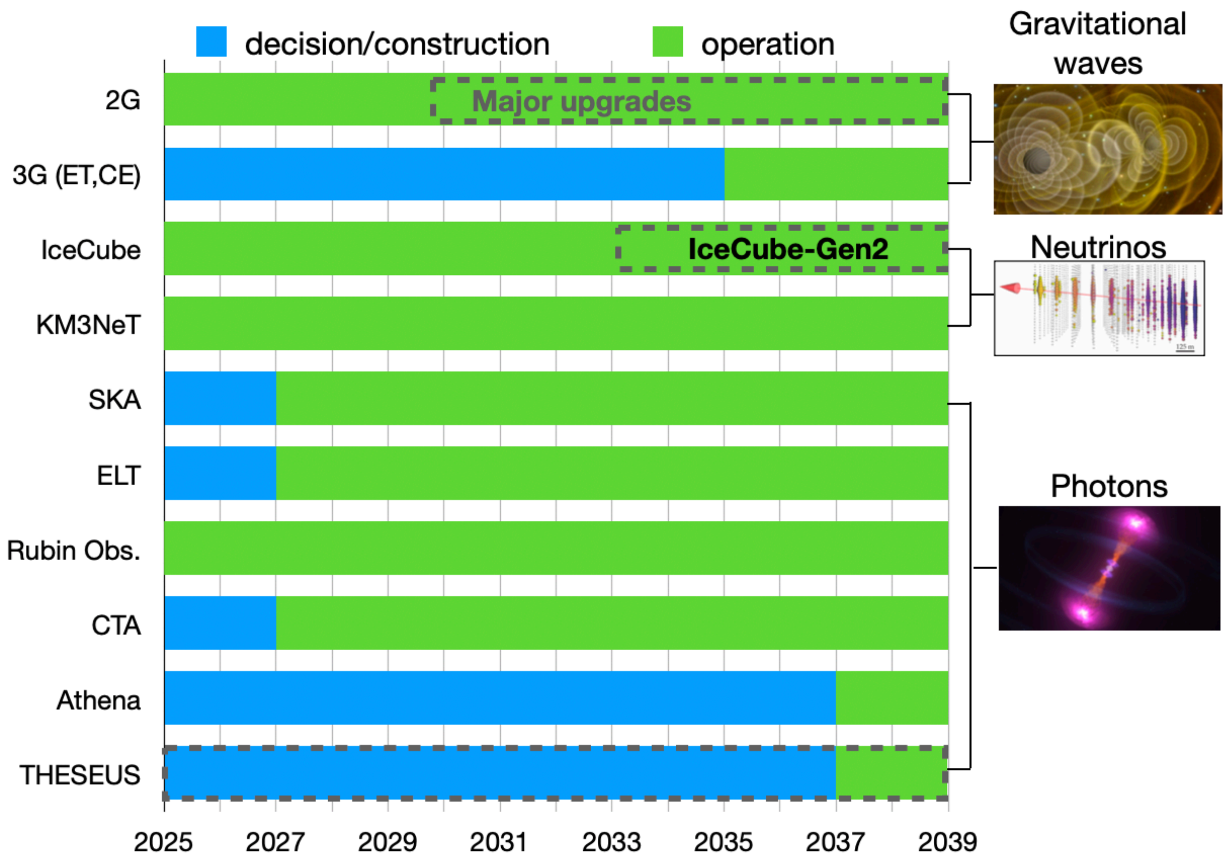


IceCube-Gen2: boost in detection rate (x10) of cosmic neutrinos (e.g. Clark+2021)

Blazars, GRBs,SN-SBO,…

Credit: adapted from A. Zegarelli

* **ESA M7 call 2021:**
  - **on end of 2023 THESEUS is Selected for Phase-A study (2024-Jun 2026)**
  - adoption 2028, **launch 2037**



Payload consortium: Italy, Germany, UK, France, Switzerland, Spain, Poland, Denmark, Belgium, Czech Republic, The Netherlands, Norway, Slovenia, Ireland (+ Hungary?)

Leads: L. Amati (INAF – OAS Bologna, Italy, lead proposer), A. Santangelo (Un. Tuebingen, D), P. O'Brien (Un. Leicester, UK), D. Gotz (CEA-Paris, France), E. Bozzo (Un. Genève, CH)

Amati et al. 2018 (Adv.Sp.Res., arXiv:1710.04638)
Stratta et al. 2018 (Adv.Sp.Res., arXiv:1712.08153)
Articles for SPIE 2020 and Exp..Astr. (all on arXiv)
http://www.isdc.unige.ch/theseus

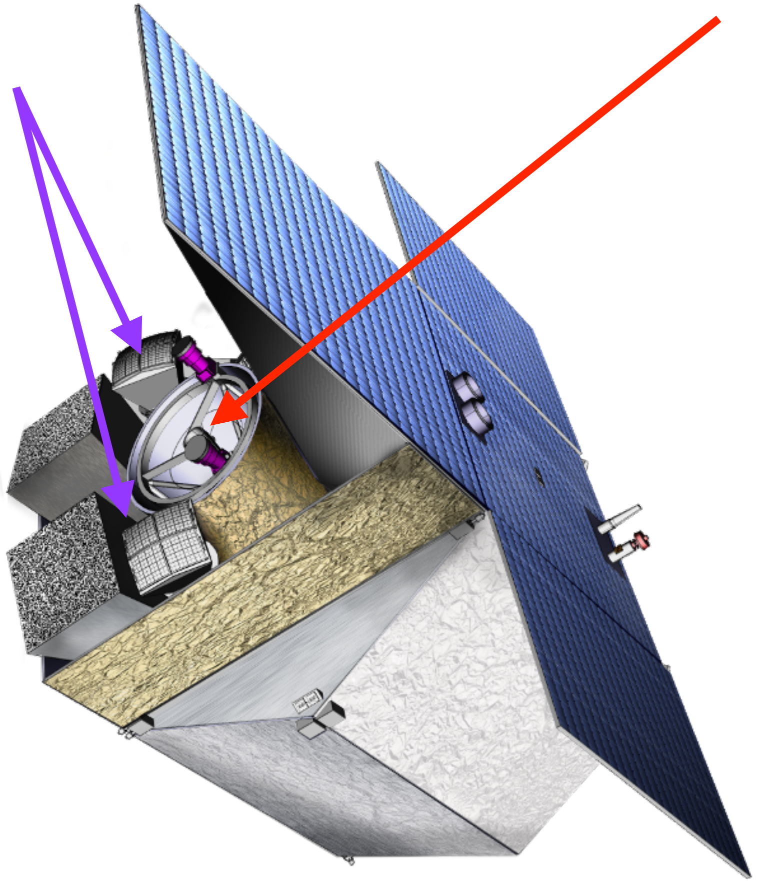
Experiment Astronomy, 2021, Volume 52, "Science with THESEUS"

theseus
TRANSIENT HIGH ENERGY SKY AND EARLY UNIVERSE SURVEYOR

X/gamma-rays Imaging Spectrometer (XGIS)

Soft X-ray Imager (SXI)

IR telescope (IRT)



Amati+2021 Exp.Astr., 52, 183

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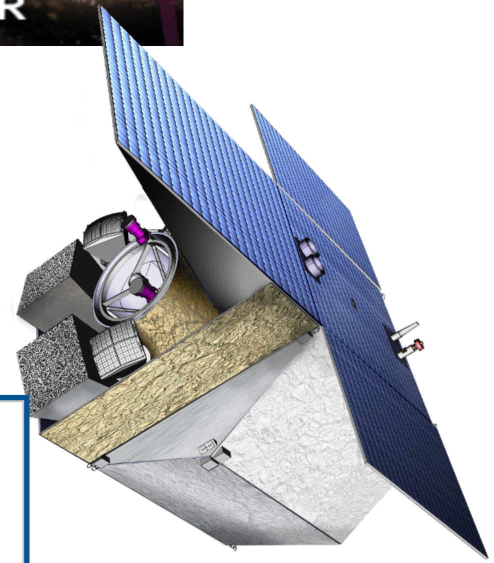
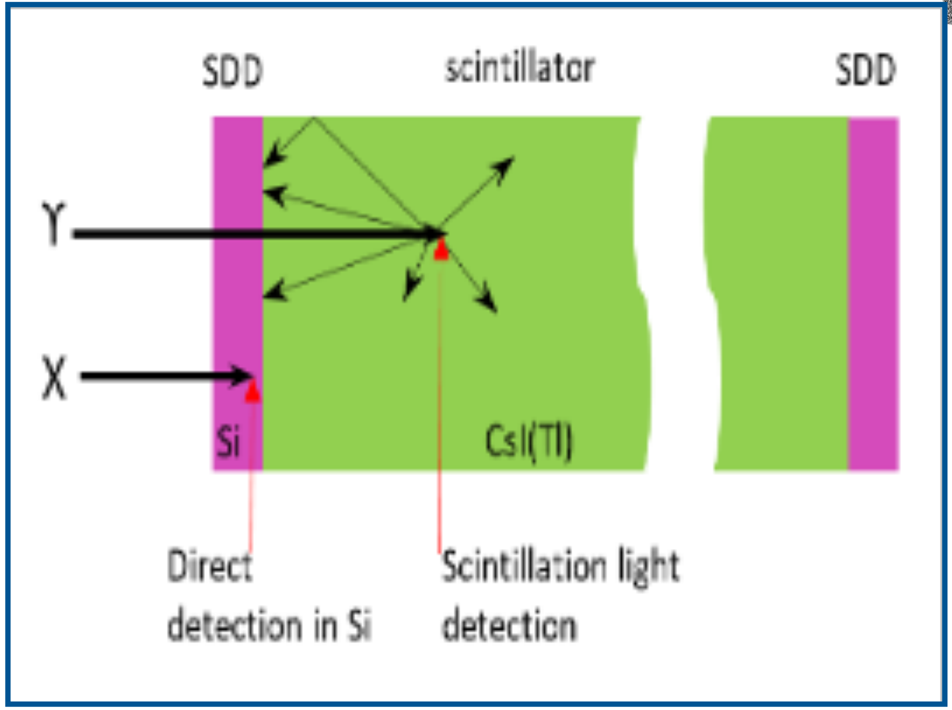
TRANSIENT HIGH ENERGY SKY AND EARLY UNIVERSE SURVEYOR



X/gamma-rays Imaging Spectrometer (XGIS)

- Si drift detector (2-30 keV) + scintillator (20 keV - 10 MeV)
- FoV (>20% efficiency):
  - 2-150 keV: 2 sr (177x77 deg^2)
  - >150 keV: up to 4 sr
- Positional accuracy (2-150 keV, 90% c.l.):
  - <7’ for 50% of triggered short GRBs;
  - <15’ for 90%



Amati+2021 Exp.Astr., 52, 183

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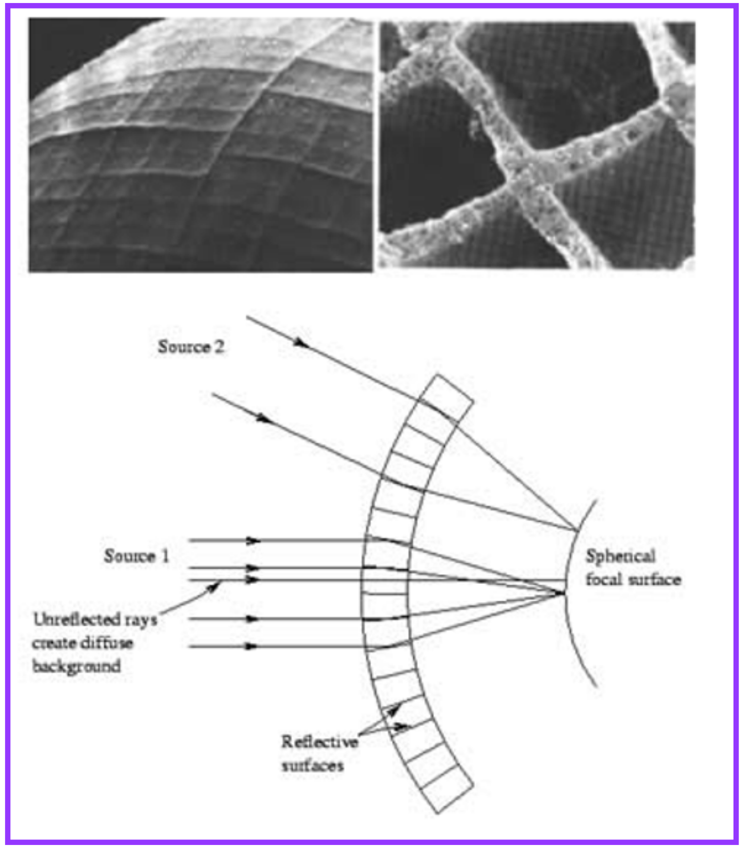
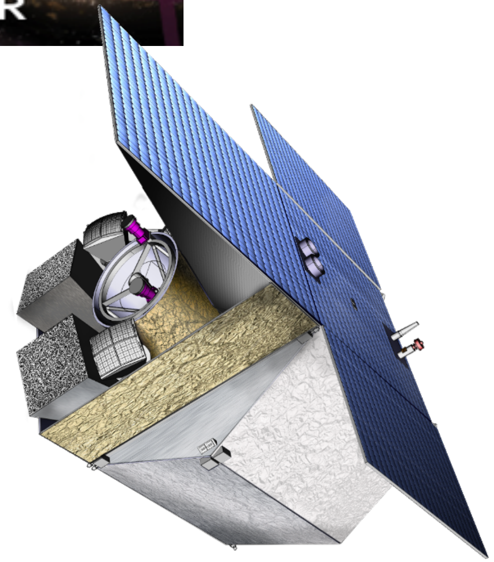
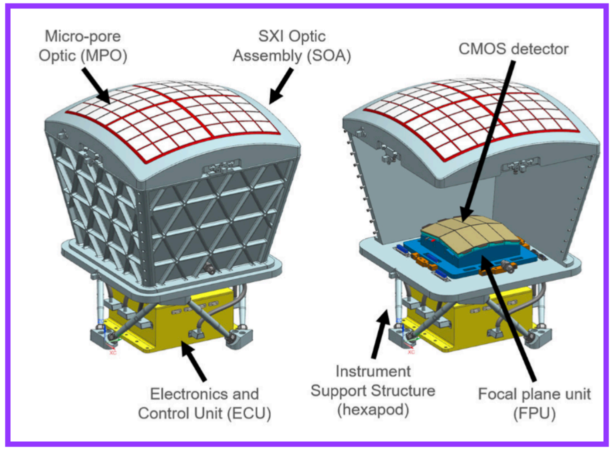
TRANSIENT HIGH ENERGY SKY AND EARLY UNIVERSE SURVEYOR



Soft X-ray Imager (SXI)

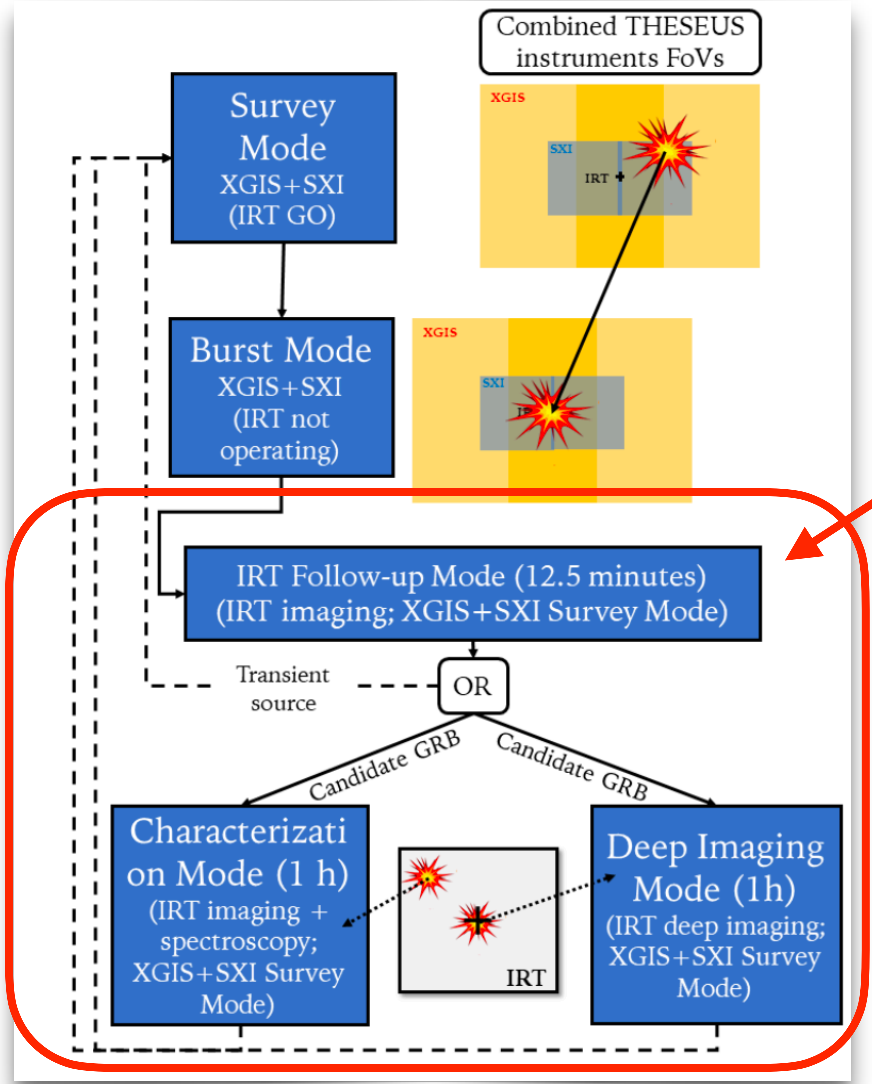
- Lobster eye telescope (0.3-5 keV)
- FoV: 0.5 sr (31x61 deg^2)
- Positional accuracy (99% c.l.): <2'





Amati+2021 Exp.Astr., 52, 183

THESEUS
TRANSIENT HIGH ENERGY SKY AND EARLY UNIVERSE SURVEYOR



Amati+2021 Exp.Astr., 52, 183

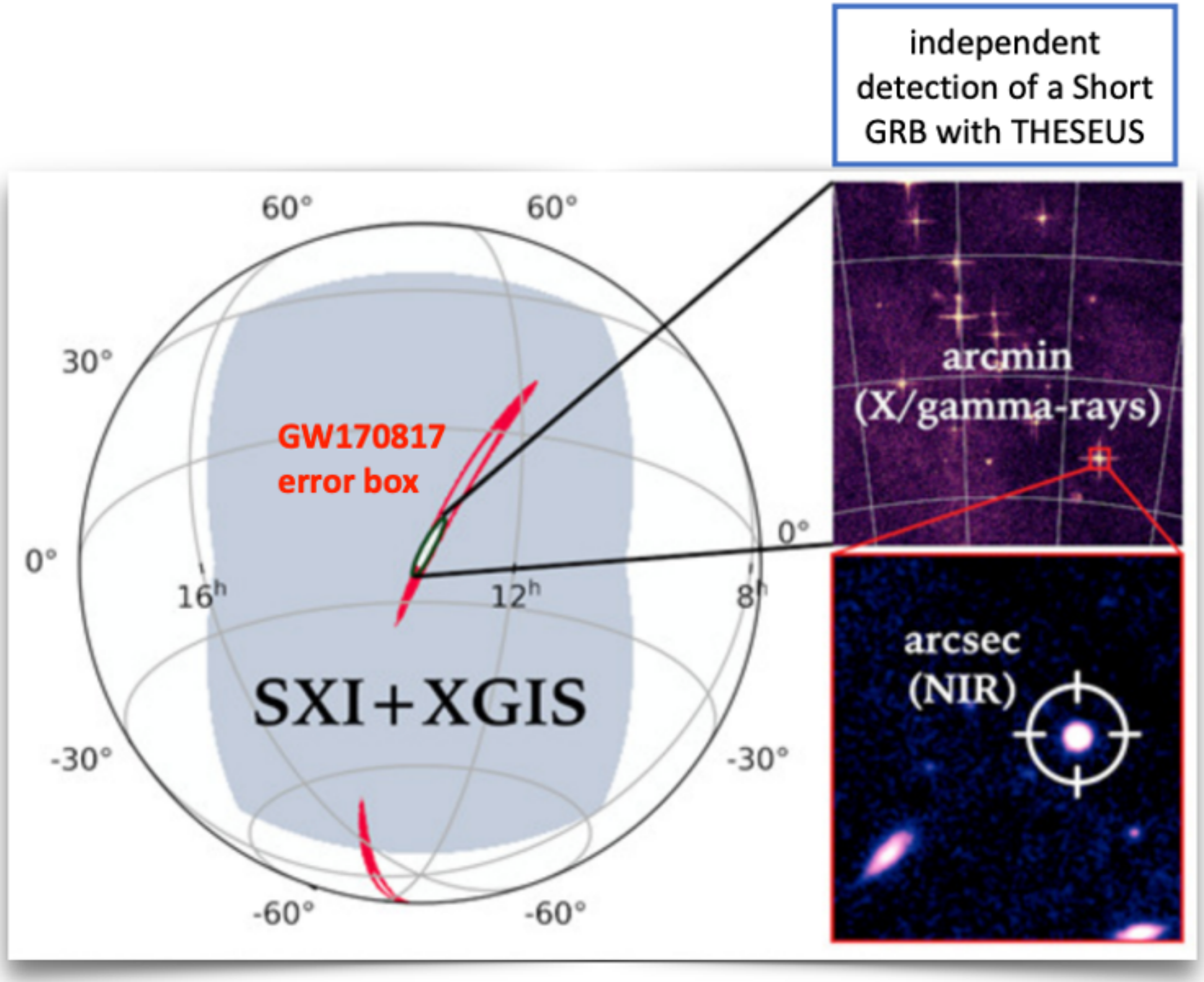
IRT will autonomously identify the GRB afterglow, compute and send coordinates on ground (<30")

IR telescope (IRT)

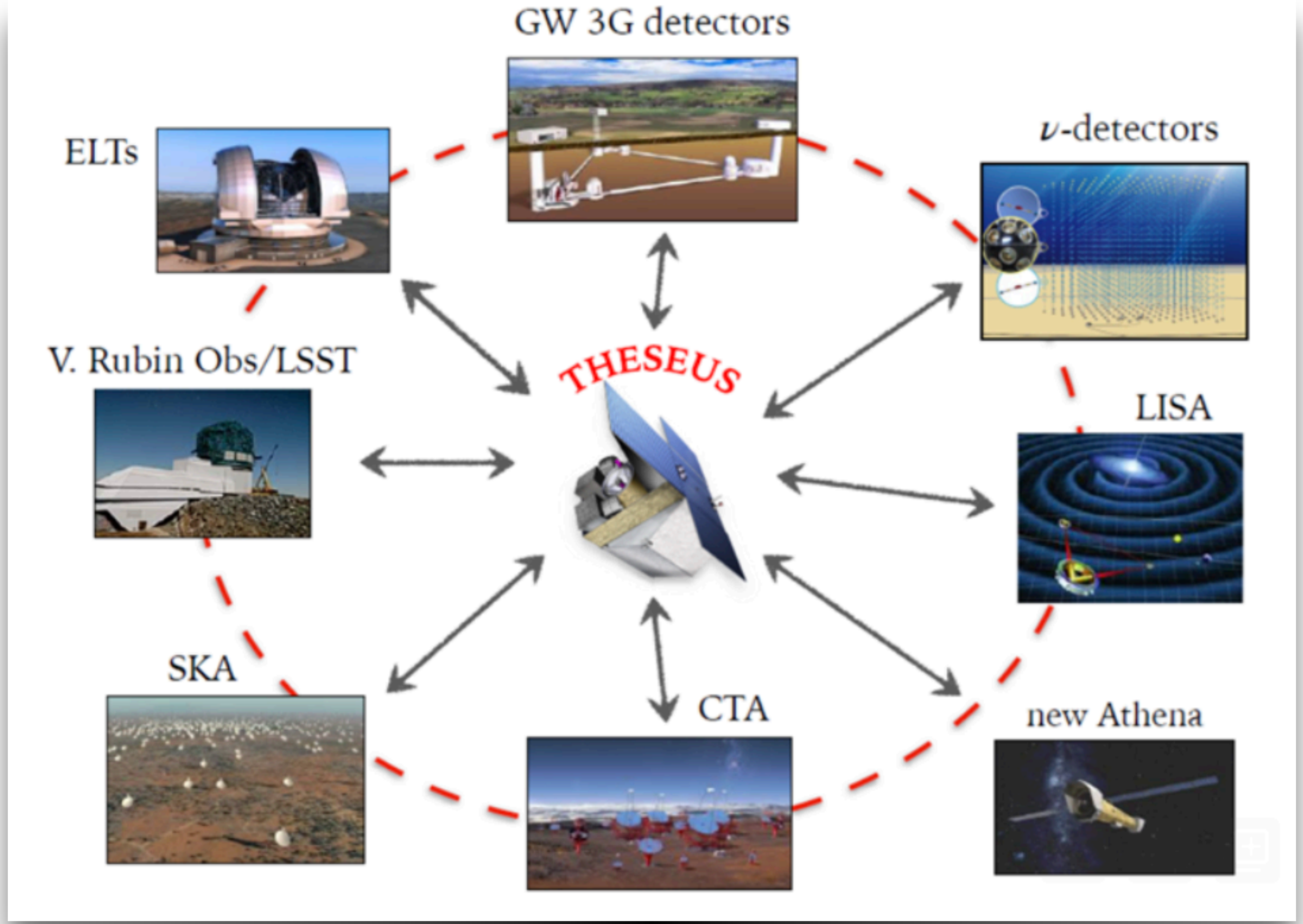
- 70 cm Korsch telescope
- Photometry:
  - FoV 15'x15'
  - 5 filters: I (20.9), Z (20.7), Y (20.4), J (20.7), H (20.8) for 150s and SNR=5
- Specroscopy:
  - FoV 2'x2'
  - R~400 resolution slit-less spectroscopy 0.8-1.6 micron

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.



Amati+2021 Exp.Astr., 52, 183
Ciolfi+2021 Exp Astr., 52, 245



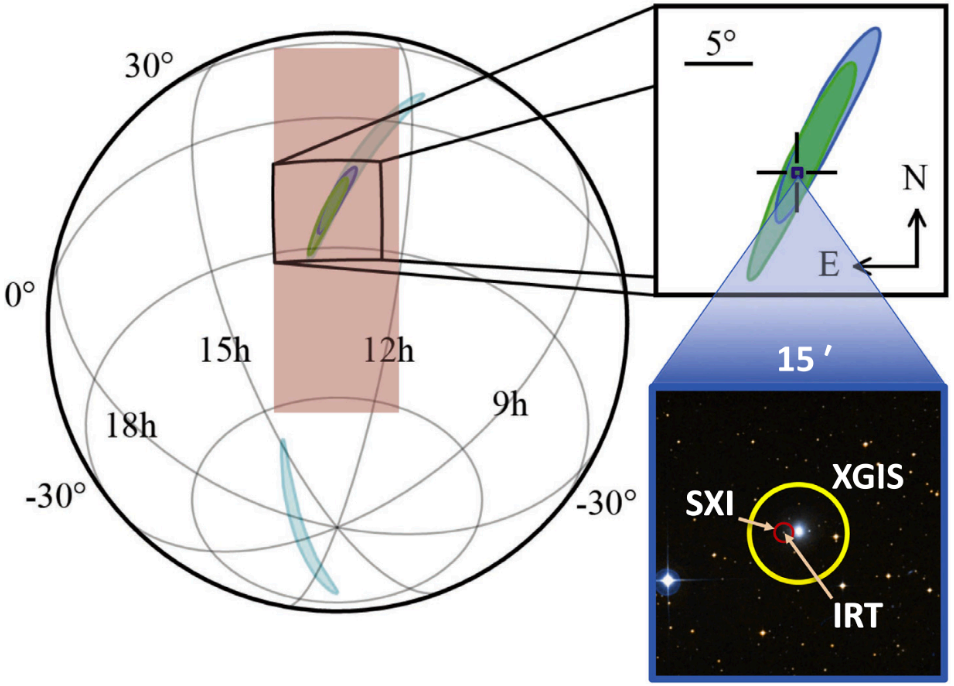
Rosati et al. 2021, Exp. Astr., 52, 407

Short GRBs with THESEUS

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]

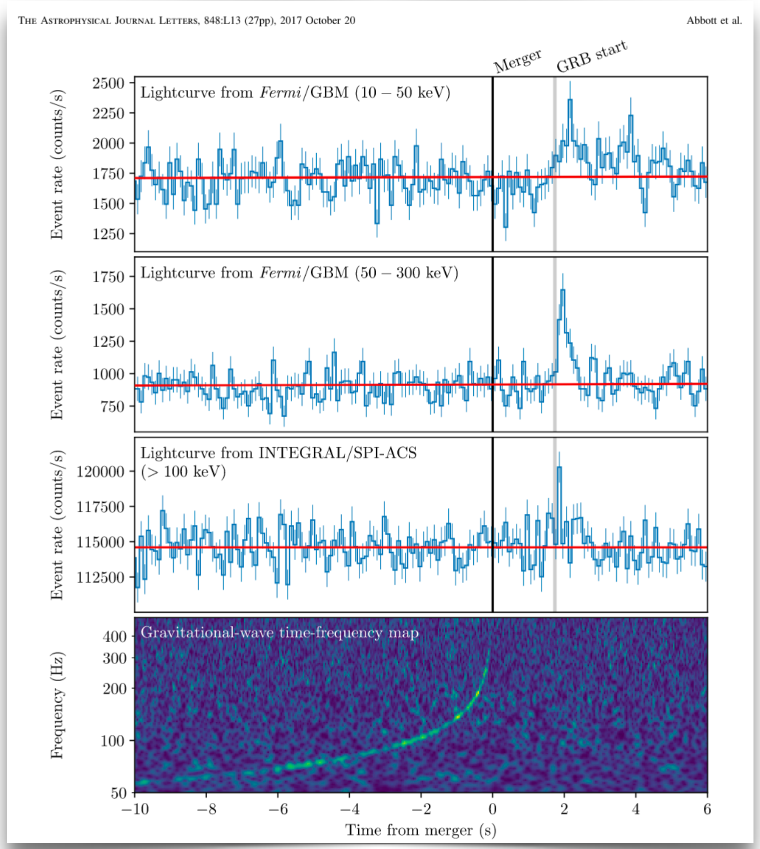
Based on most updated knowledge of GRB emission



-> O(100) BNS will be detected AND localized with THESEUS

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

Fundamental issues from short GRB+GW detections



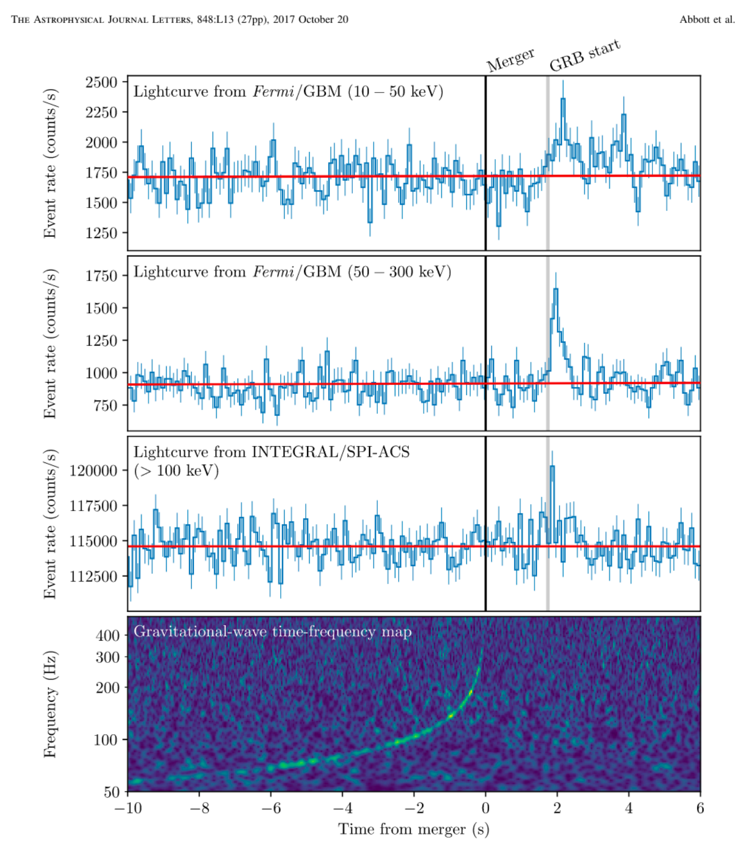
Fundamental issues from short GRB+GW detections

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)



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 in BNS and NS-BH?

What link with remnant nature and plateau/flare GRB features?

Conclusions

★ By >2035 the next generation GW detectors and neutrino detectors will be operative and high rate of MM sources is expected

★**Most plausible MM sources are X-ray/gamma-ray transients**

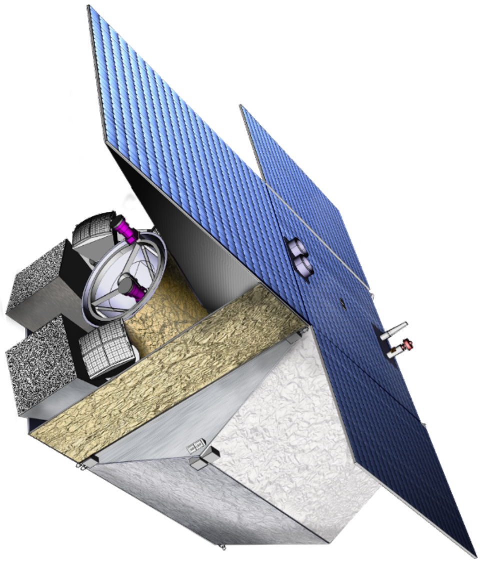
★HE Sky surveyors as **THESEUS** with good sky localization capabilities, will play a crucial role in independently detect and characterise MM sources and allow multi-band follow-up campaigns

Thank you!


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

Extra slides

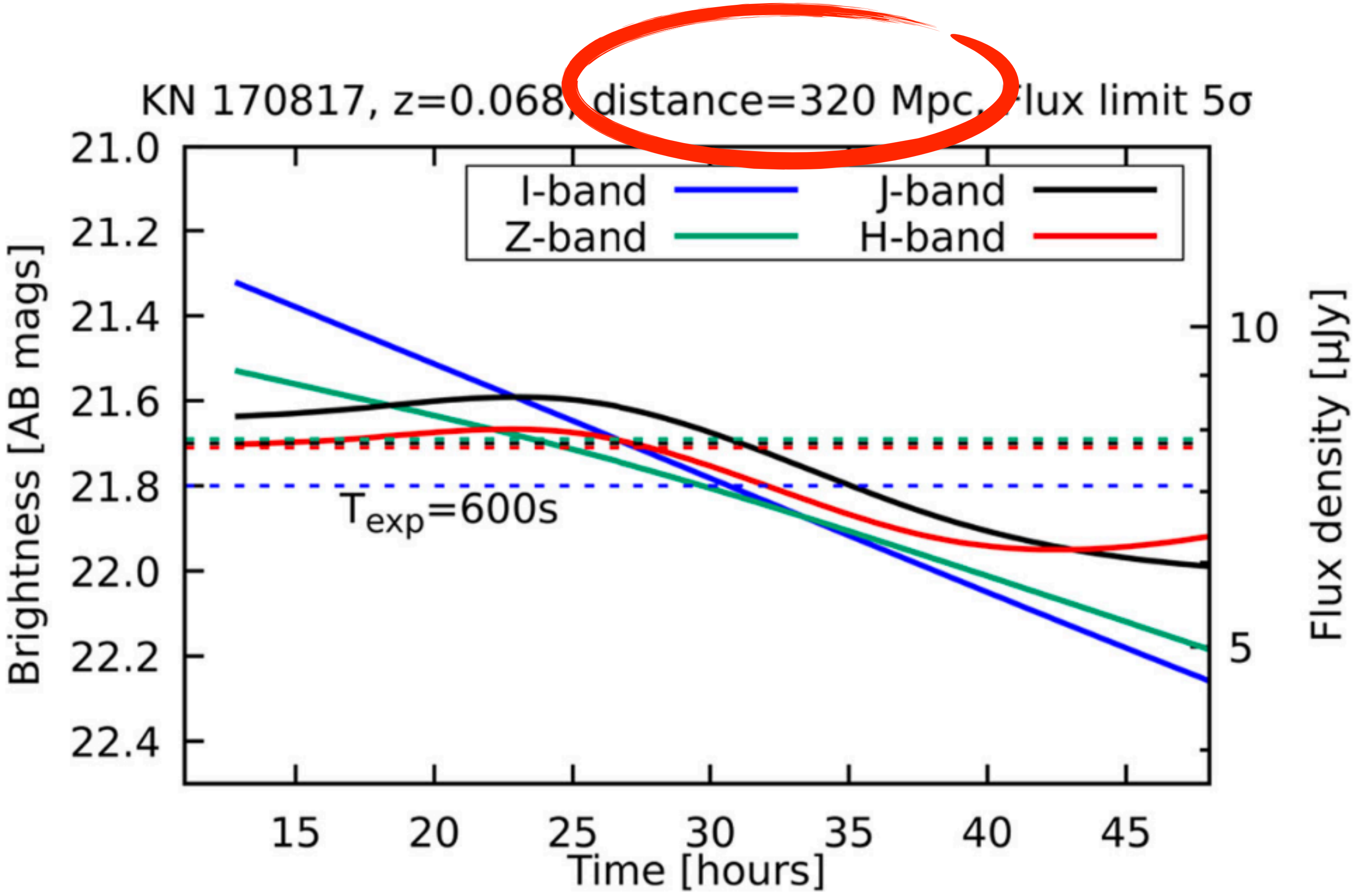
THESEUS broadcast time



THESEUS shall be able to distribute Burst/Transient alerts to ground observers (via the SDC) for

65% bursts	**<60’ -> goal <30’’**
95% bursts	**<90’ -> goal <20’**

Kilonova detection with THESEUS/IRT



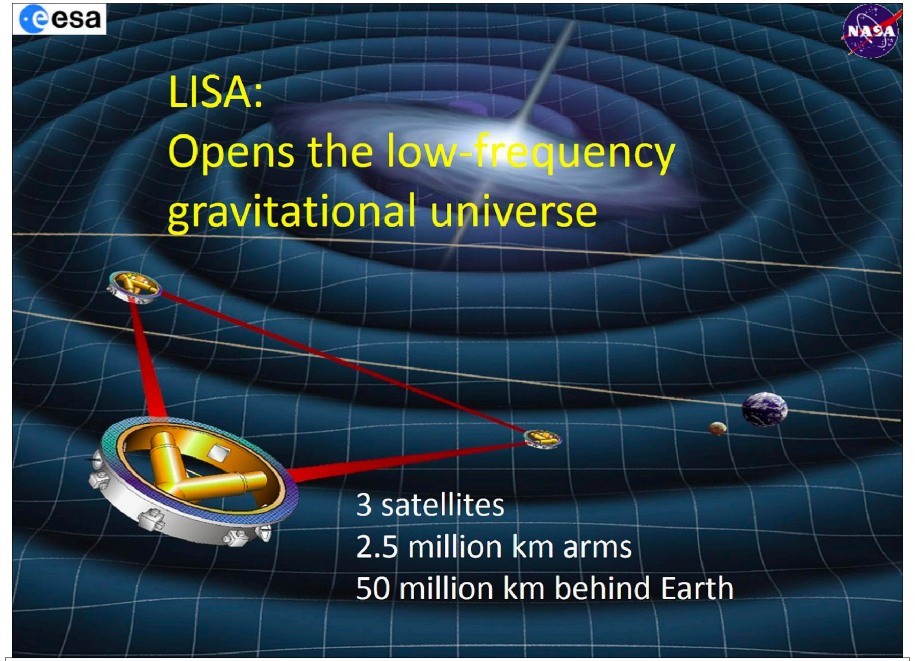
>2035:Laser Interferometer Space Antenna

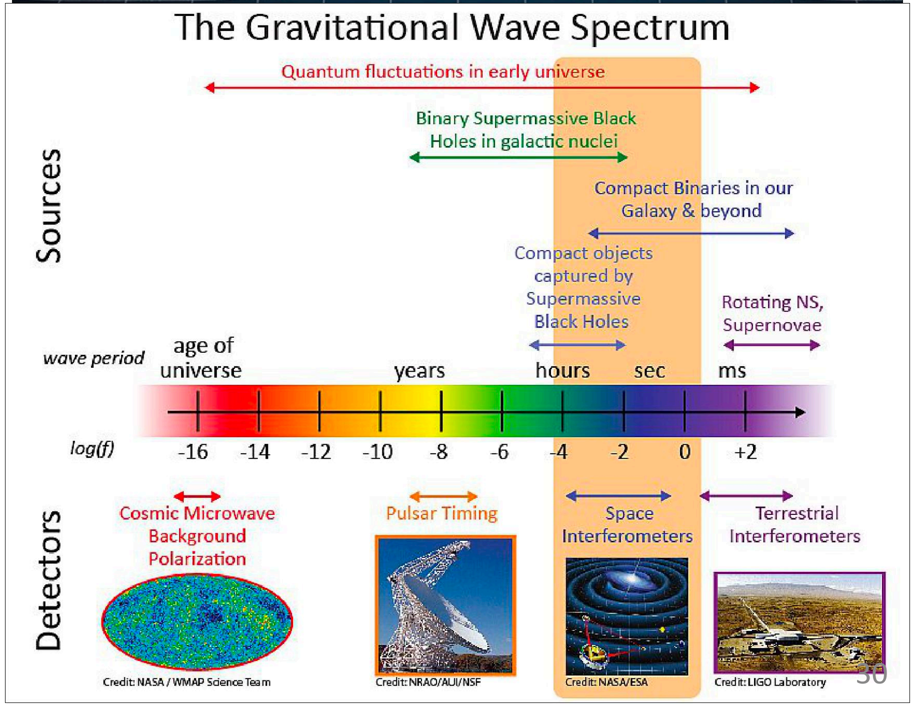
- Formally approved on 25 Jan 2024 by ESA Science Program Committee (construction authorzed - “adoption”)

- 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





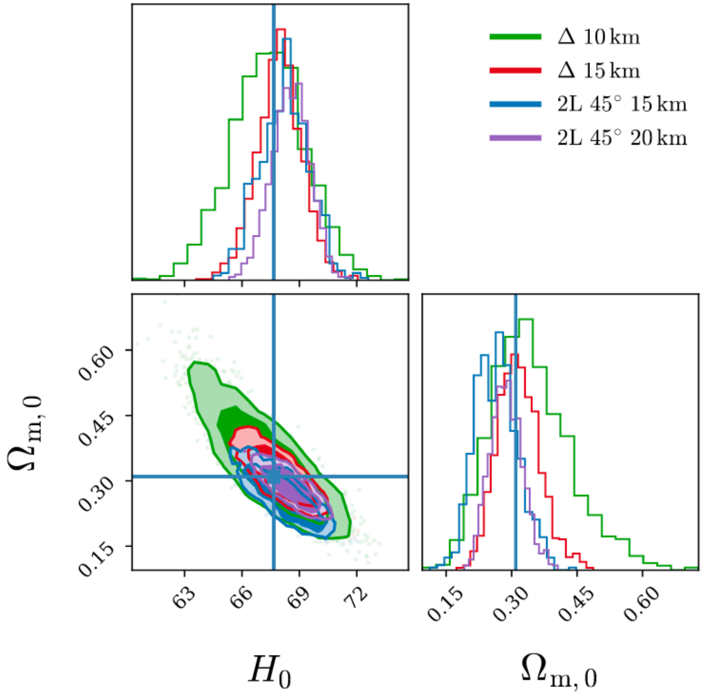


Figure 52. Reconstruction of the parameters H_0 and Ω_M in ΛCDM, from the joint GW+EM events obtained with ET+THESEUS in 5 yr of observations, for the different geometries of ET shown, all with their HFLF-cryo sensitivity.

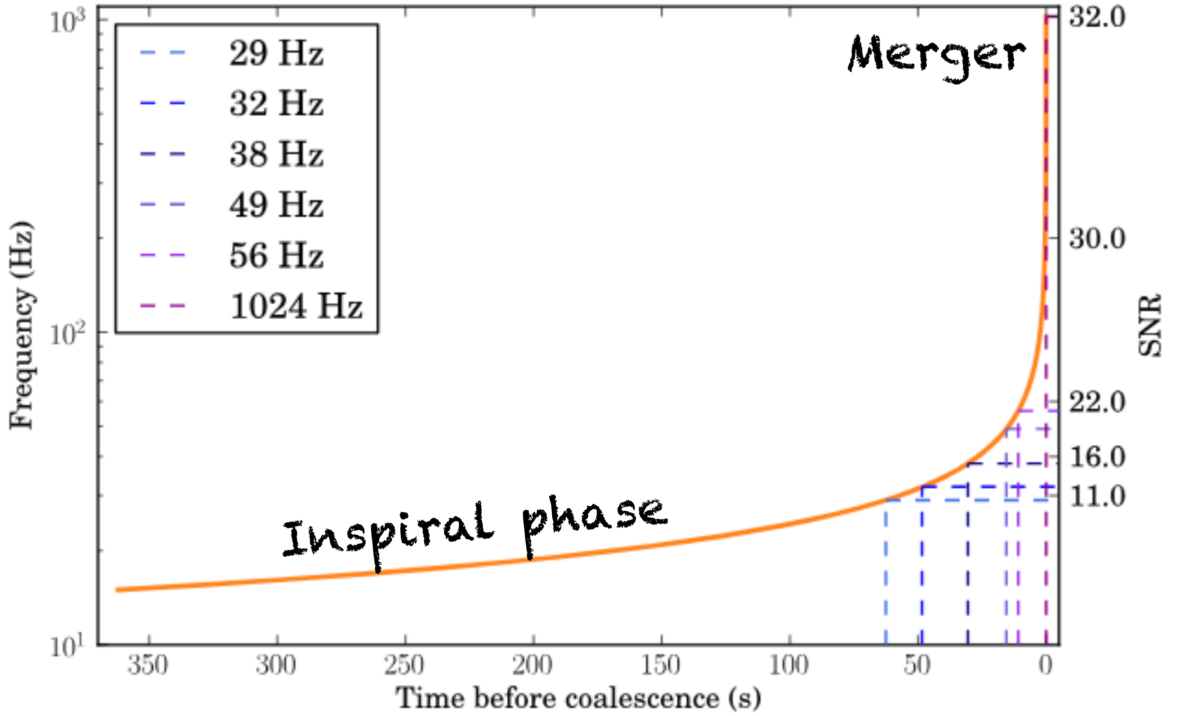
Configuration	$\Delta H_0/H_0$	$\Delta\Omega_M/\Omega_M$
Δ-10km	0.057	0.546
Δ-15km	0.035	0.290
2L-15km-45°	0.040	0.370
2L-20km-45°	0.029	0.276

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.

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	$\Delta\Omega_{90\%}$ [deg^2]	All orientation BNSs 30 min	All orientation BNSs 10 min	All orientation BNSs 1 min	BNSs with $\Theta_v < 15°$ 30 min	BNSs with $\Theta_v < 15°$ 10 min	BNSs with $\Theta_v < 15°$ 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

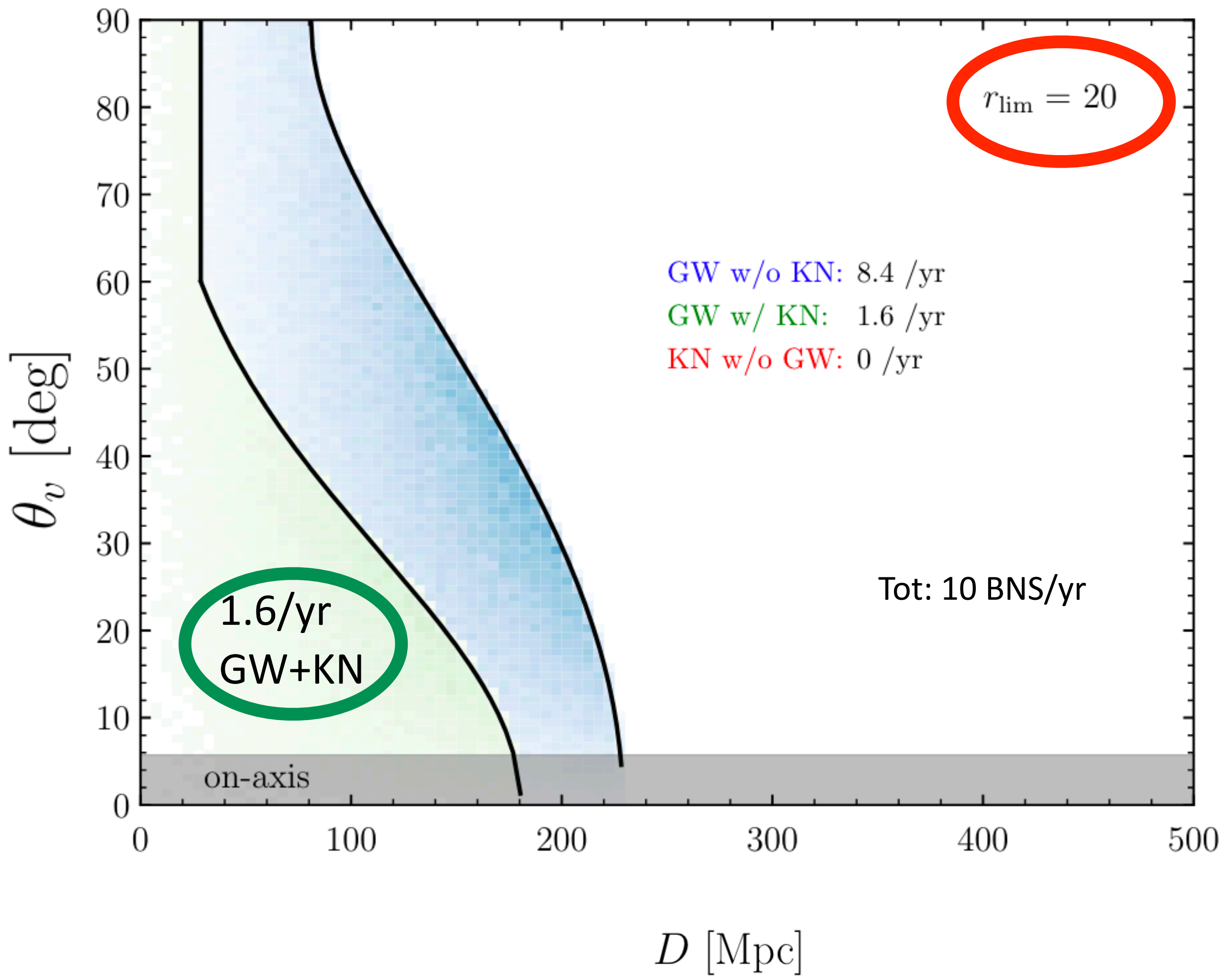
Number of BNS mergers per year detected (SNR ≥ 8) before the merger within z = 1.5 for the reference ET configuration

Joint GW+EM detection rates with KNe

- **GW+kilonovae ~ 2(8)/yr**
  - by assuming:
    - AT2017gfo-like kilonova
    - Survey with mag limit of r=20(22)mag
    - <u>10 BNS/yr</u>

(Mochkovitch et al. 2021)

Mochkovitch et al. 2021



Joint GW+EM detection rates for the next run O4

- **GW+kilonovae ~ 2(8)/yr**
  - by assuming:
    - AT2017gfo-like kilonova
    - Survey with mag limit of r=20(22)mag
    - <u>10 BNS/yr</u>

(Mochkovitch et al. 2021)