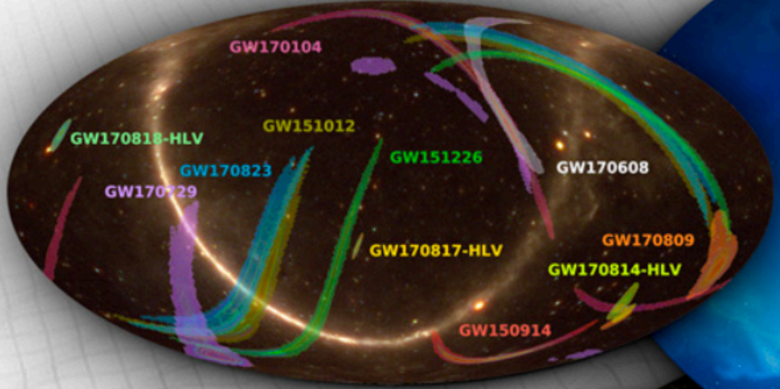


THESEUS role in Multi-Messenger Astrophysics

MMA is one of the three top Level Science Requirements of the THESEUS mission

See Assessment Study Report (aka "Yellow Book") on ESA wepages

new White Paper by **Ciolfi**, Stratta et al. 2021 in prep.

Giulia Stratta (INAF-OAS,INFN-Firenze)

Riccardo Ciolfi (INAF-OAP,INFN-Padova)

+ THESEUS Working Group 2

THESEUS Conference 23-26 March 2021

Outline

>2030: the golden era of MMA and the role of THESEUS

Expected NS-NS/NS-BH e.m. counterparts for THESEUS

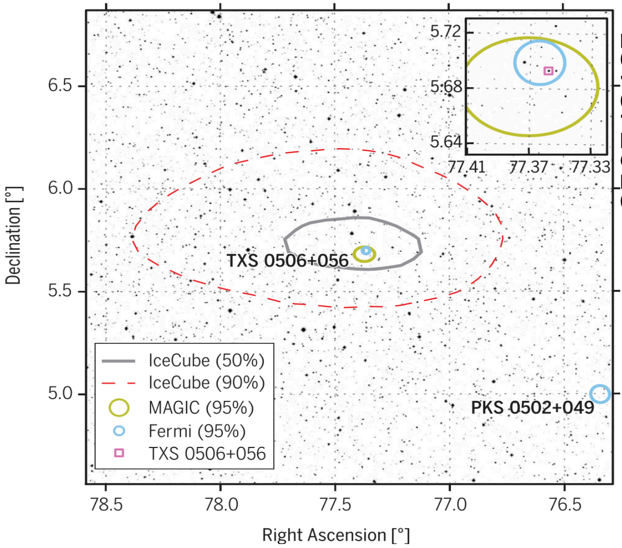
Other GW sources and neutrino sources for THESEUS

Conclusions

2020s: the dawn of multi-messenger astronomy

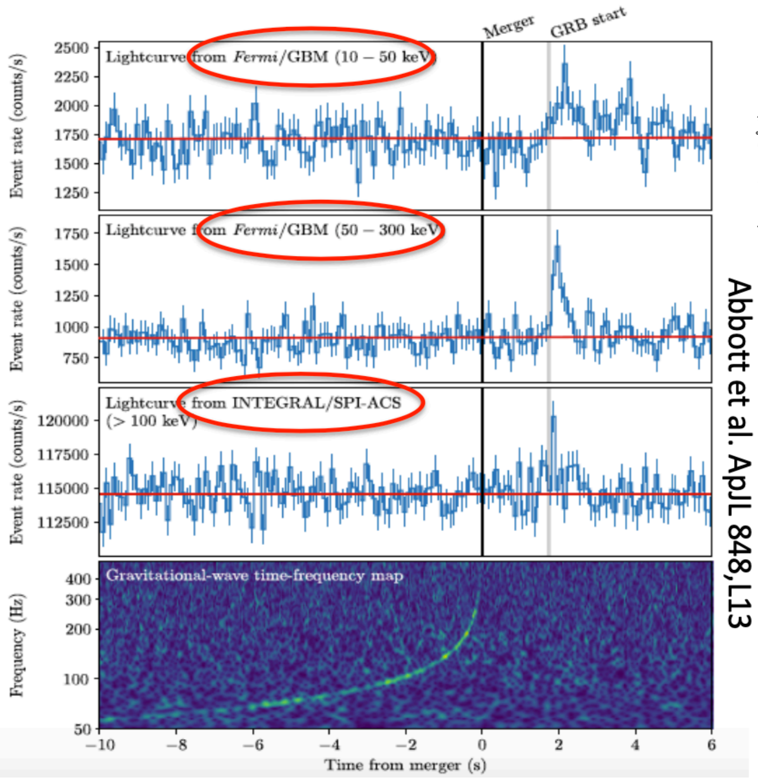
Recent breakthrough discoveries

22 September 2017: HE neutrino detection with IceCube was found spatially coincident with a γ-ray emitting blazar in active phase

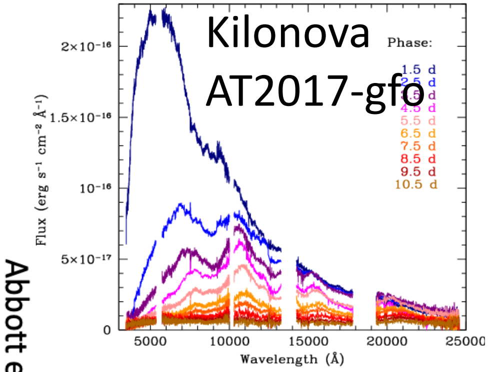


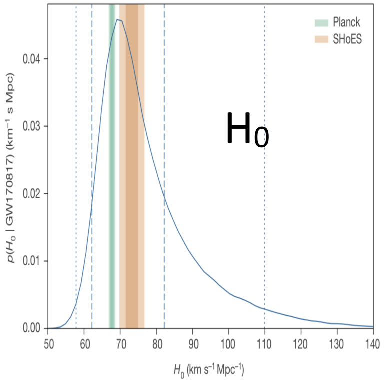
Aartsen et al. Science 361, 1378. 2018

17 August 2017: first joint GW+EM detection from a NS-NS merger (Abbott+2017, ApJL 848, L13)

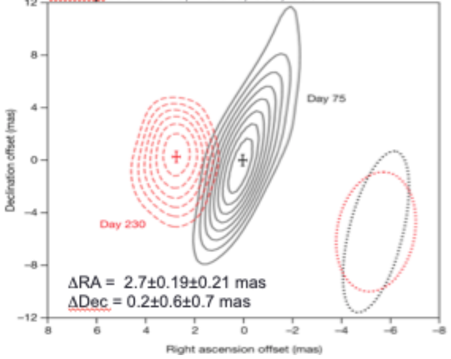


Abbott et al. ApJL 848,L13

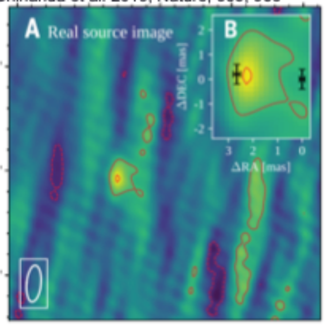




Mooley et al. 2018, Nature, 561, 355

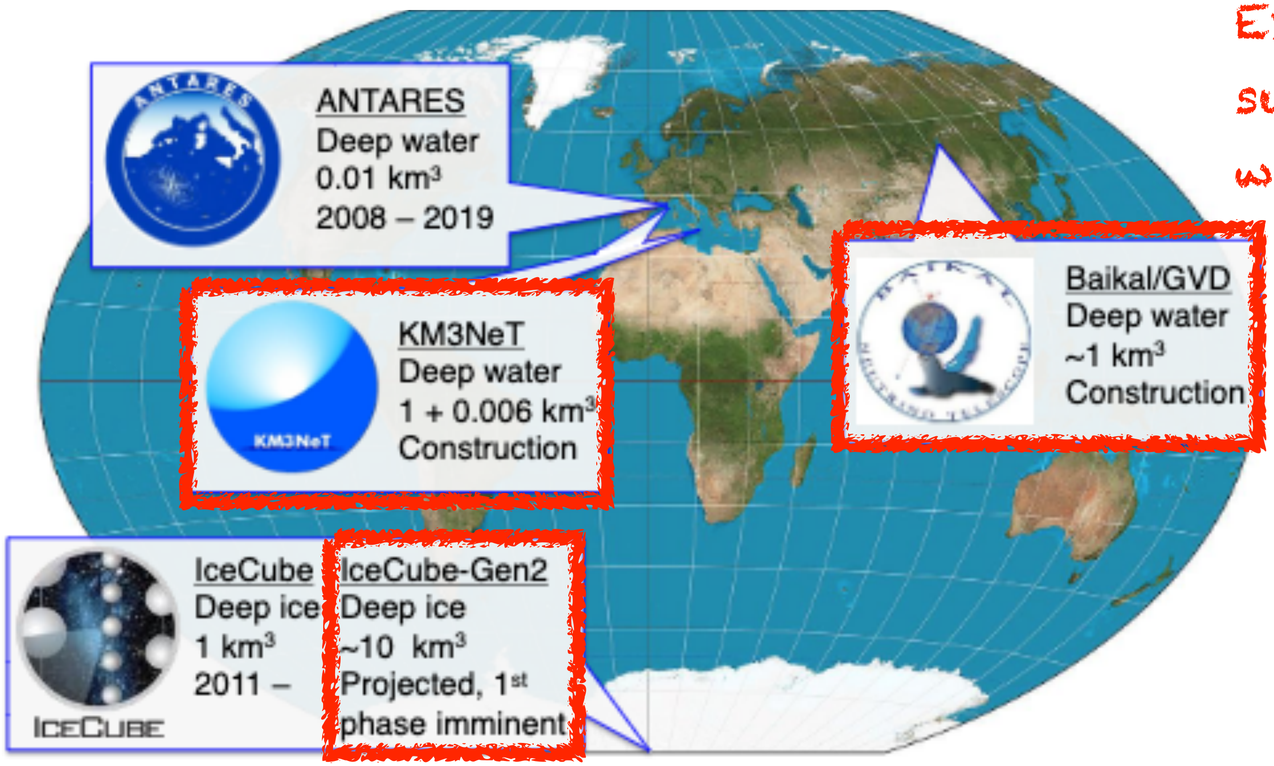


Ghirlanda et al. 2019, Nature, 363, 968



2030s: the golden era of MMA

See talk by M. Spurio at 16:20



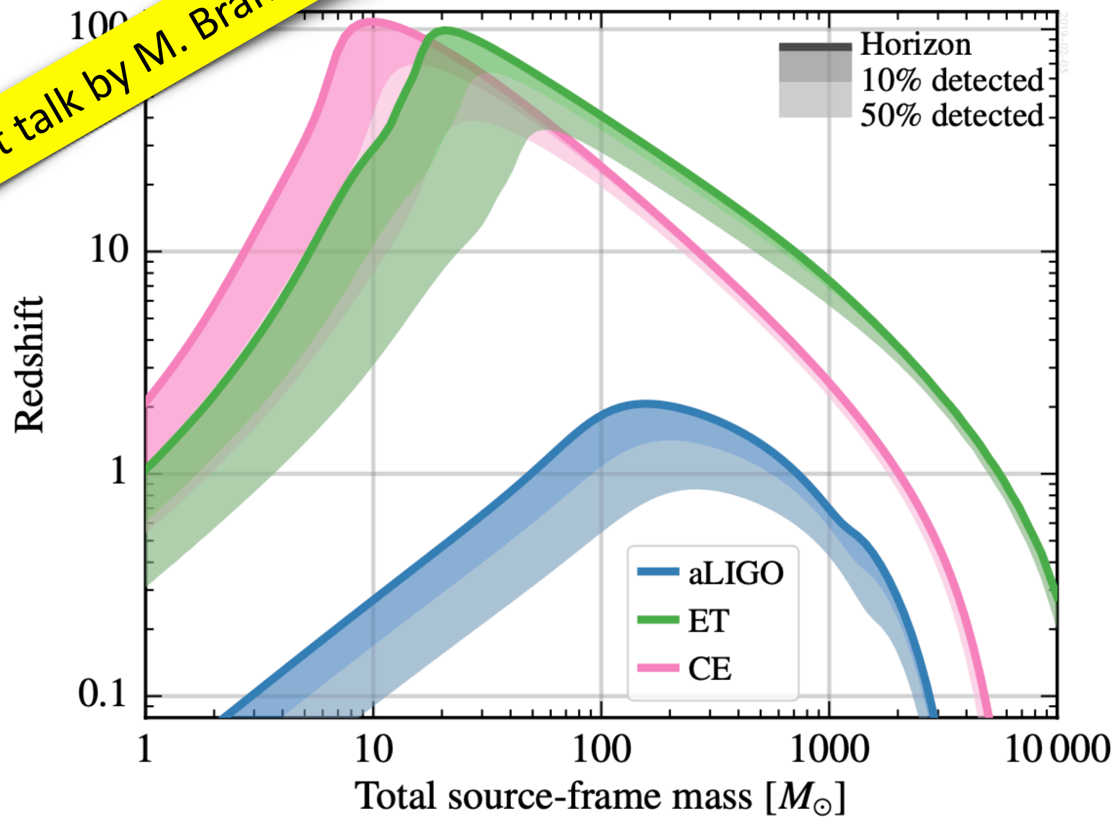
Expected superposition with THESEUS

Credit: U. Katz

Neutrino detector will improve sensitivity of ~O(10)
—> will collect high-statistics HE neutrino sample

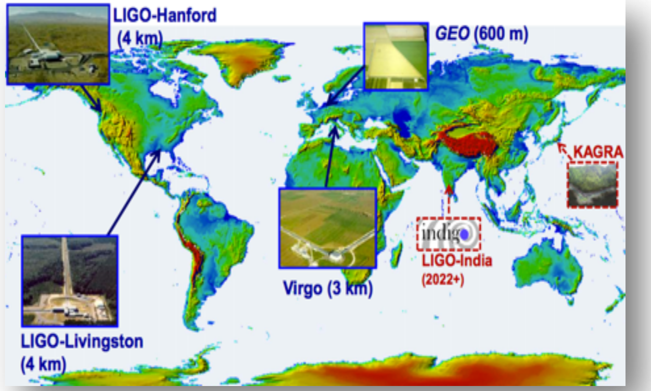
2030s: the golden era of MMA

See next talk by M. Branchesi

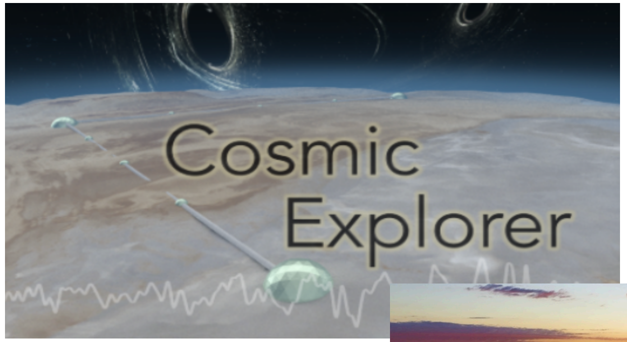


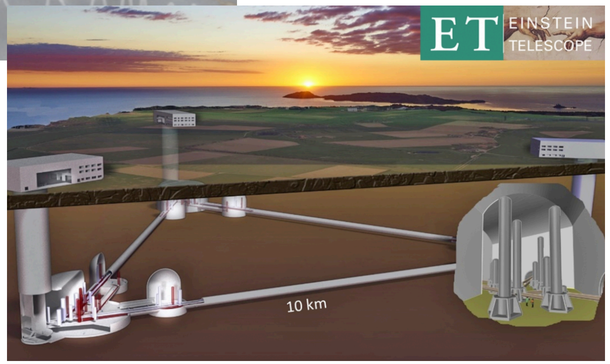
Sathyaprakash et al. arXiv:1903.09260

Next generation GW detectors will be O(10) more sensitive than 2G



2G GW interferometer network by 2025 with Virgo+ and A+





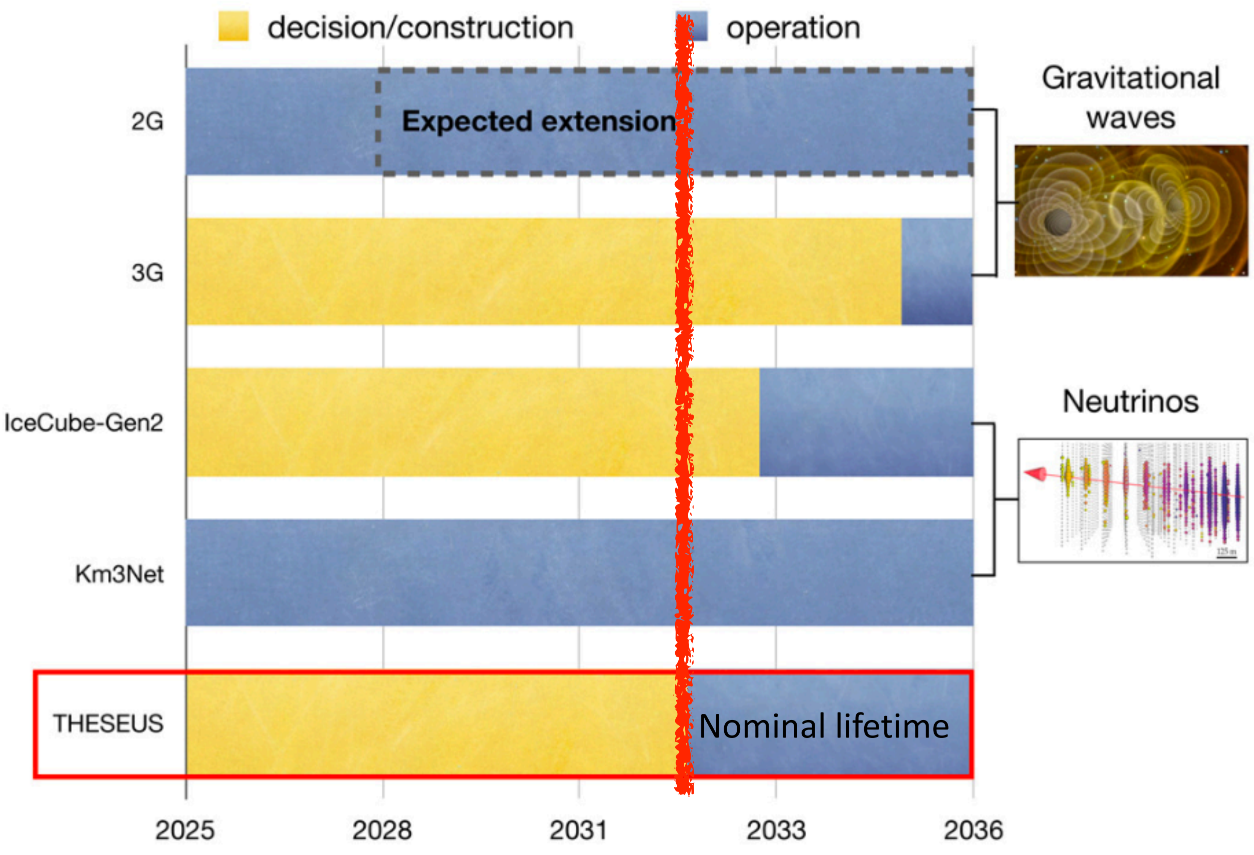
3G GW interferometer network by 2030s

2030s: the golden era of MMA

THESEUS expected launch epoch: 2032

Lifetime: 4 years

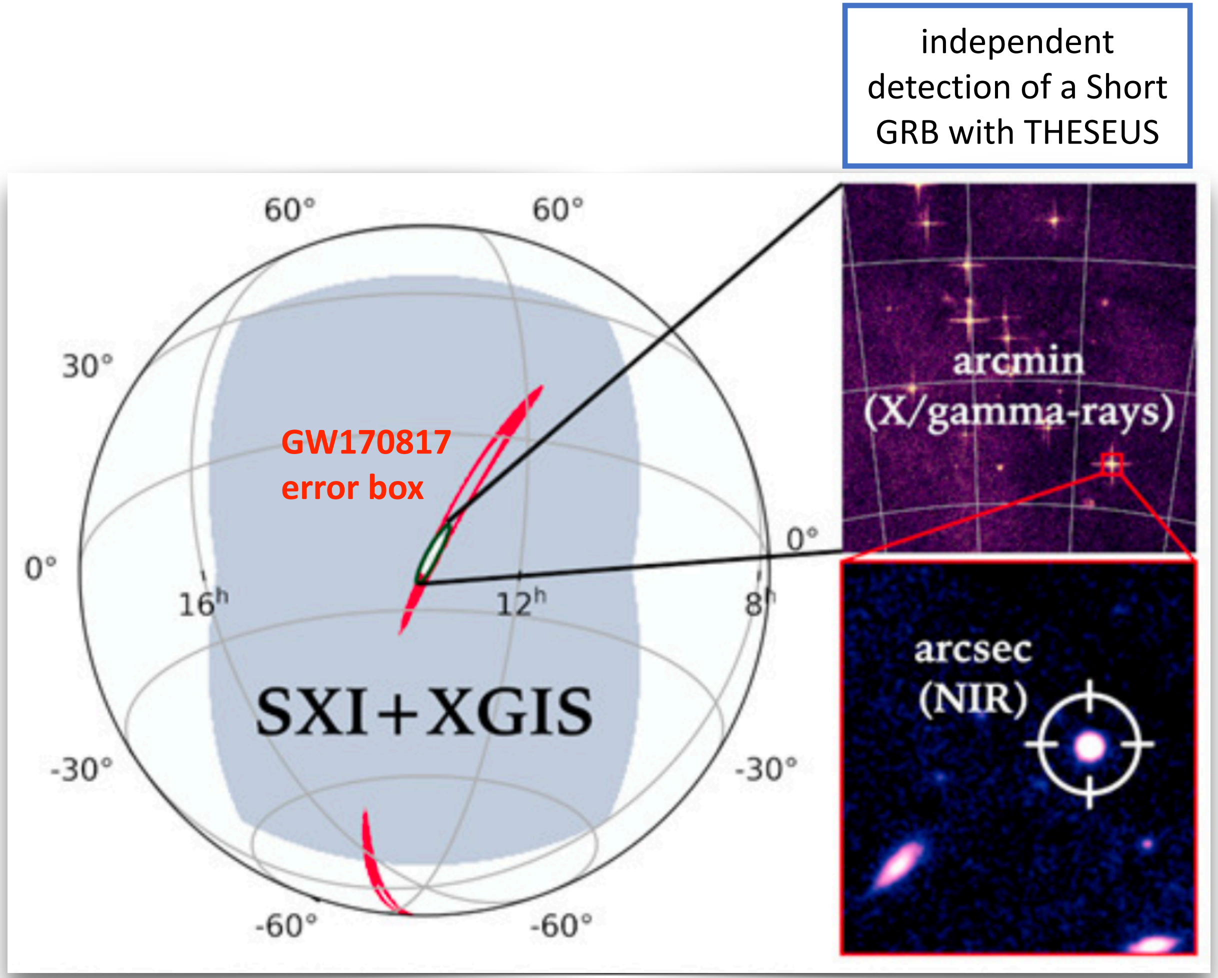
perfectly on time to operate in synergy with next generation GW and neutrino mission



THESEUS synergy with future GW and neutrino facilities, will allow for fundamental and transformational knowledge on multi-messenger sources

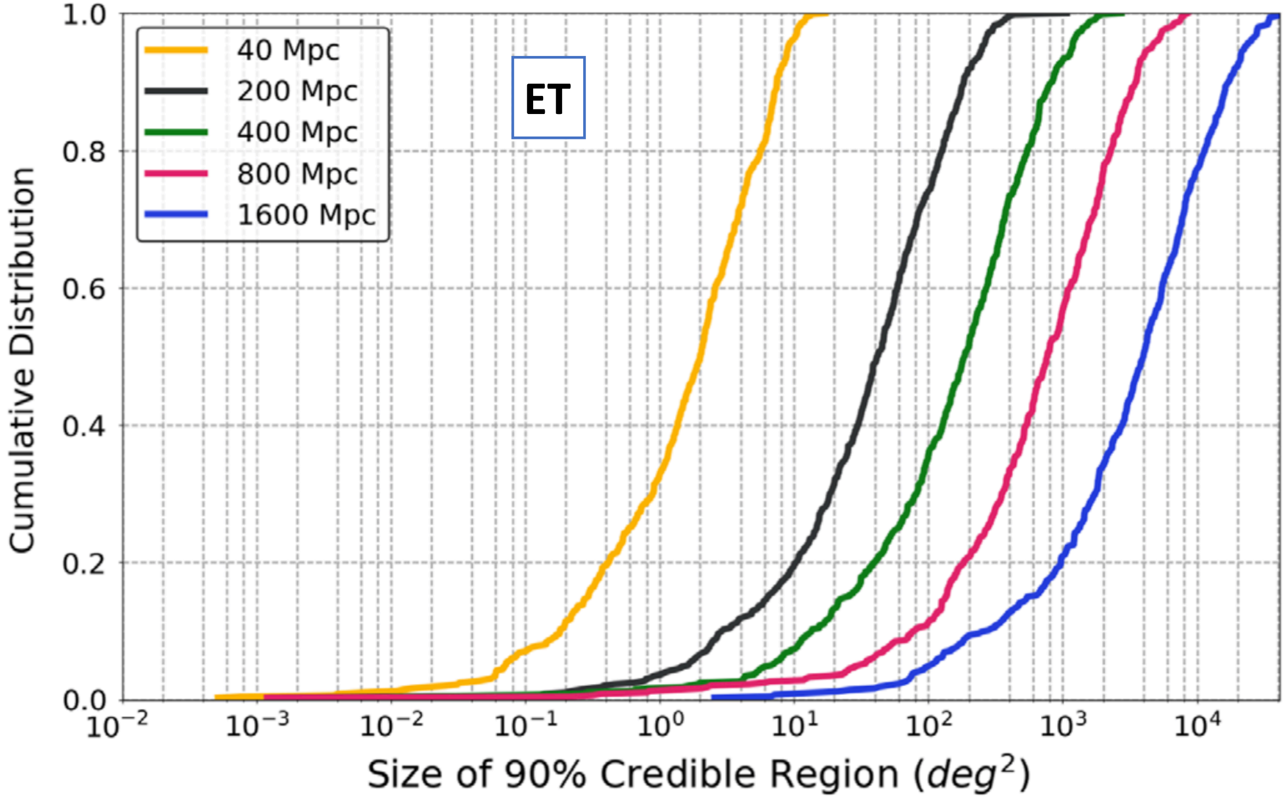
THESEUS role in MMA

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.



3G GW detector sky localization uncertainty

Chan+2018



NS-NS mergers

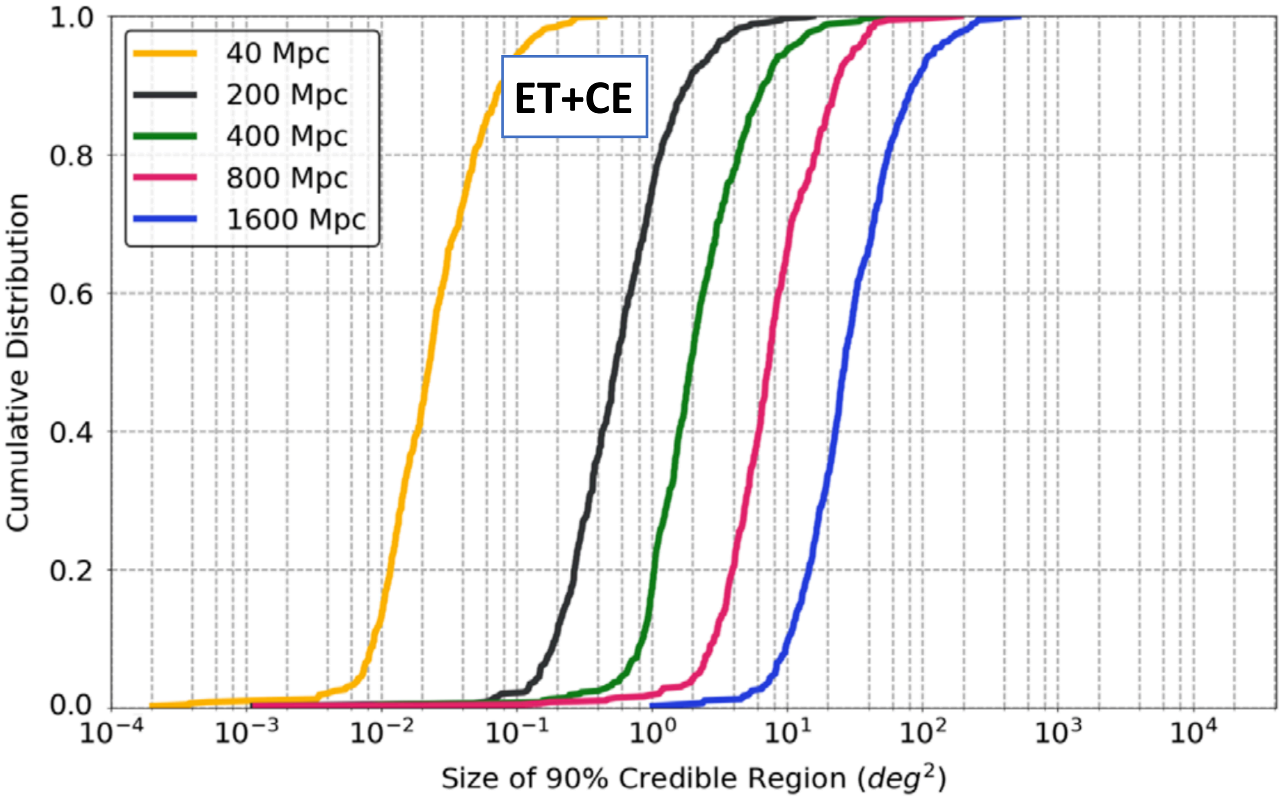
THESEUS sky coverage:

SXI: 0.5 sr ~1600 deg^2
XGIS: 2 sr <150 keV ~ 6400 deg^2

Large FoV are mandatory to allow MM observations during the 2030s

3G GW detector sky localization uncertainty

Chan+2018



NS-NS mergers

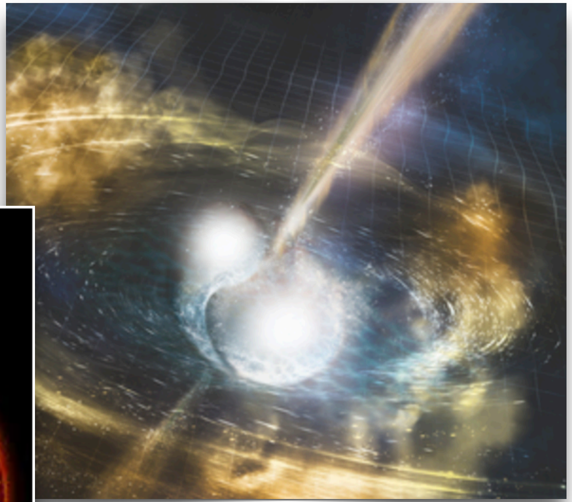
THESEUS sky coverage:

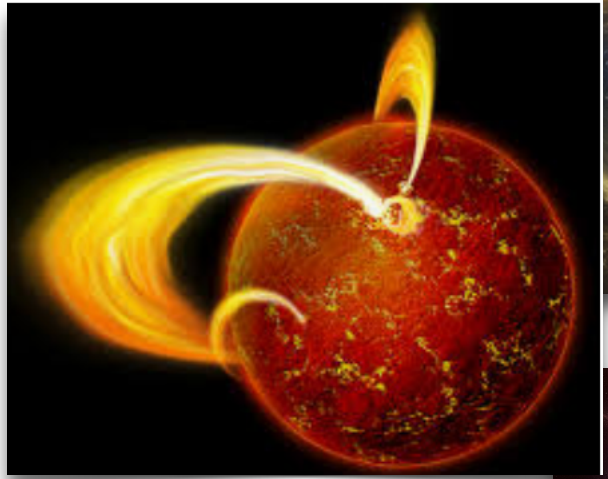
SXI: 0.5 sr ~1600 deg^2
XGIS: 2 sr <150 keV ~ 6400 deg^2

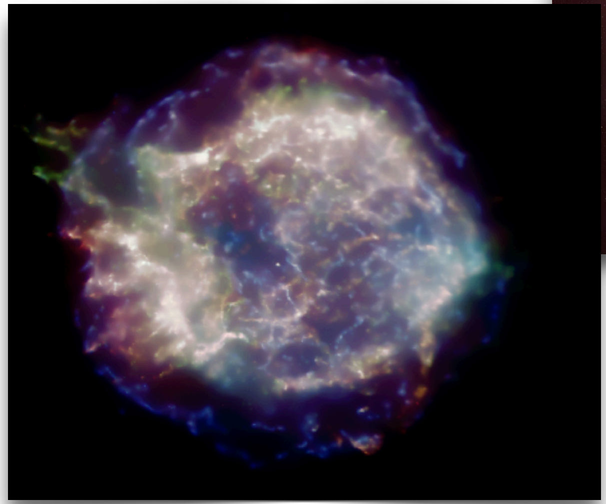
HE surveyors are the best instruments to pinpoint MMA sources

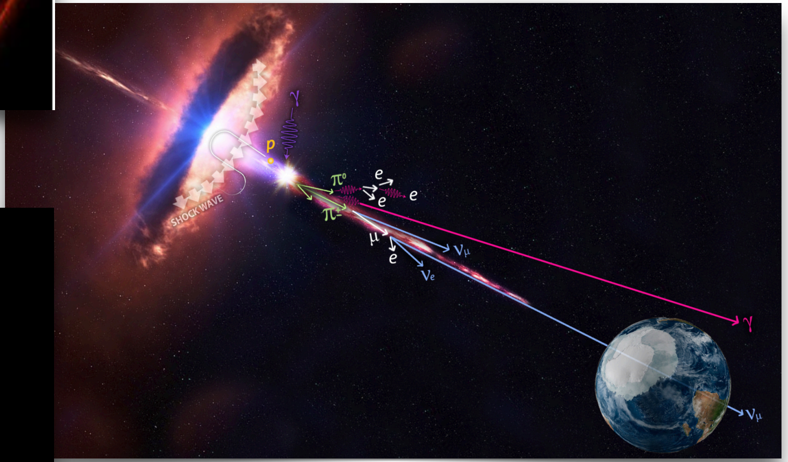
THESEUS MM targets

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









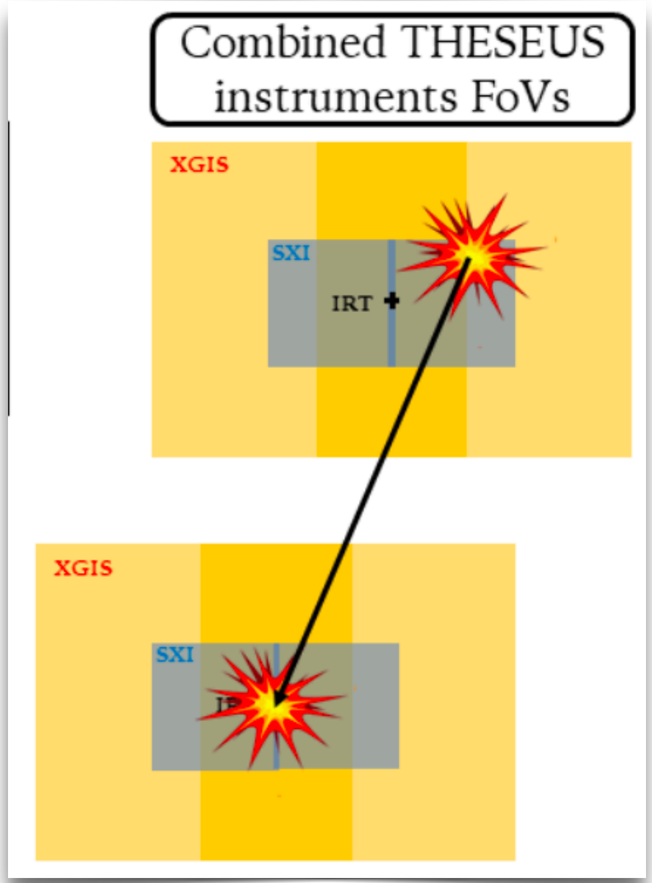
THESEUS short GRBs

✓THESEUS will detect and localize 12.0+/-1.9 short GRB per year with XGIS (2-150 keV) and SXI (0.3-5 keV)

✓These short GRB will be localized in the sky with an accuracy of:

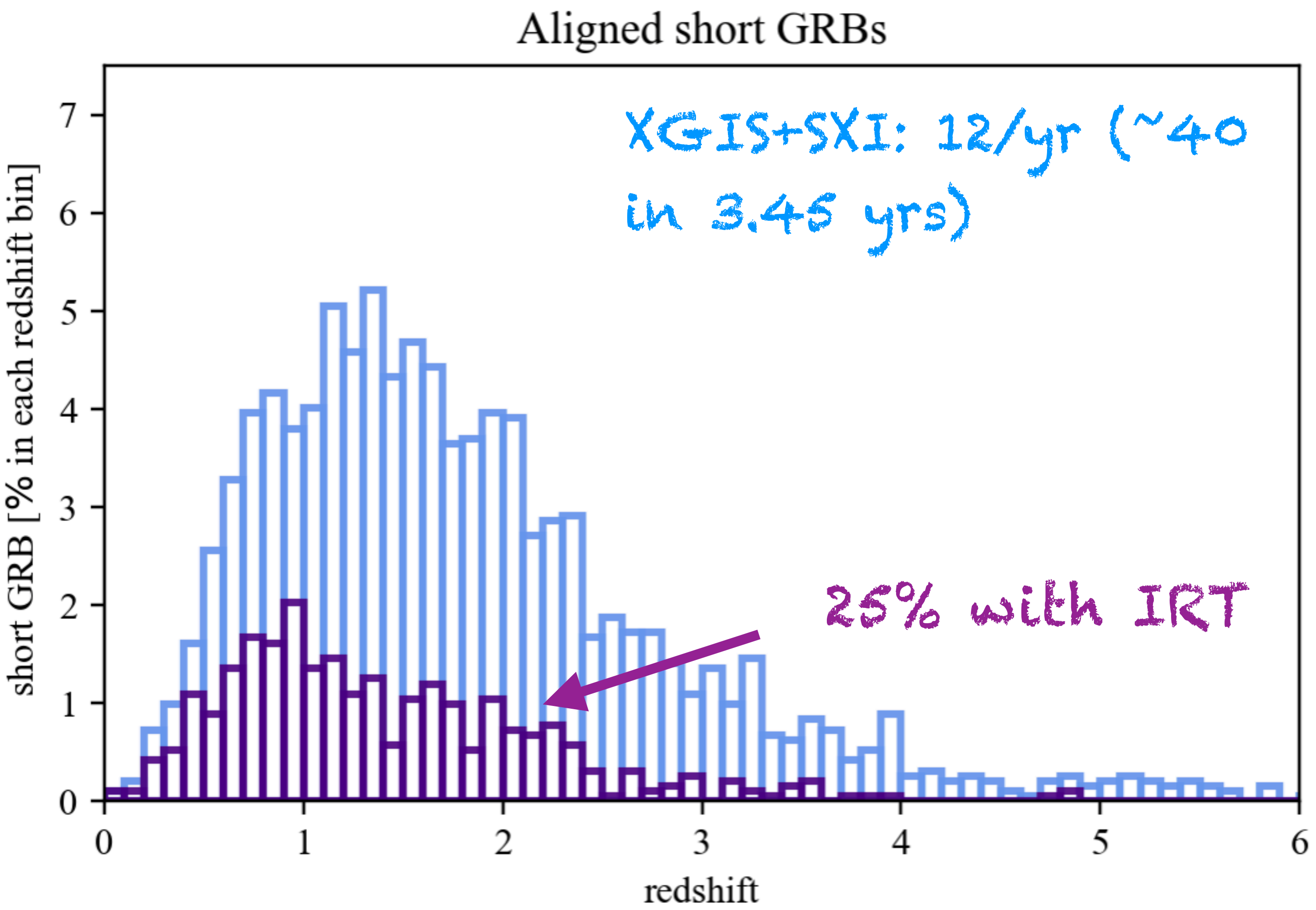
- better than 15’ (90%) and 7’ (50%) with XGIS
- better than 2’ with SXI (0.3-4 keV)

✓3.0 +/- 0.8 short GRB (25%) are expected to be detected per year also with the onboard IR telescope and localized down to the arcsecond level



Once a short GRB is detected, an automatic slew is initiated in order to place the transient within the IRT FoV. IRT will acquire a sequence of images in different filters

THESEUS short GRBs: joint GW detections



redshift distribution of THESEUS/Short GRBs

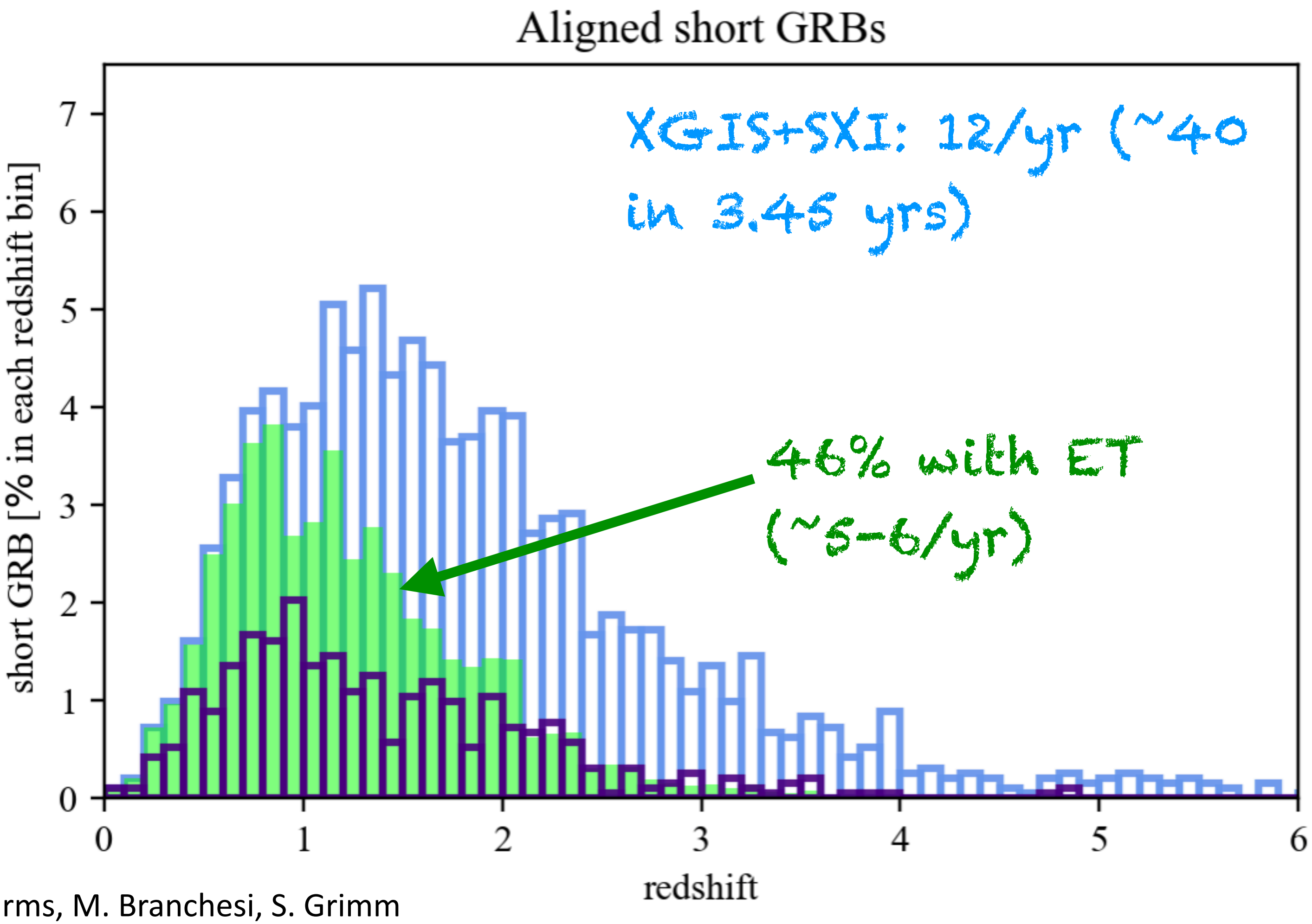
+

NS-NS merger GW detection efficiency at each redshift

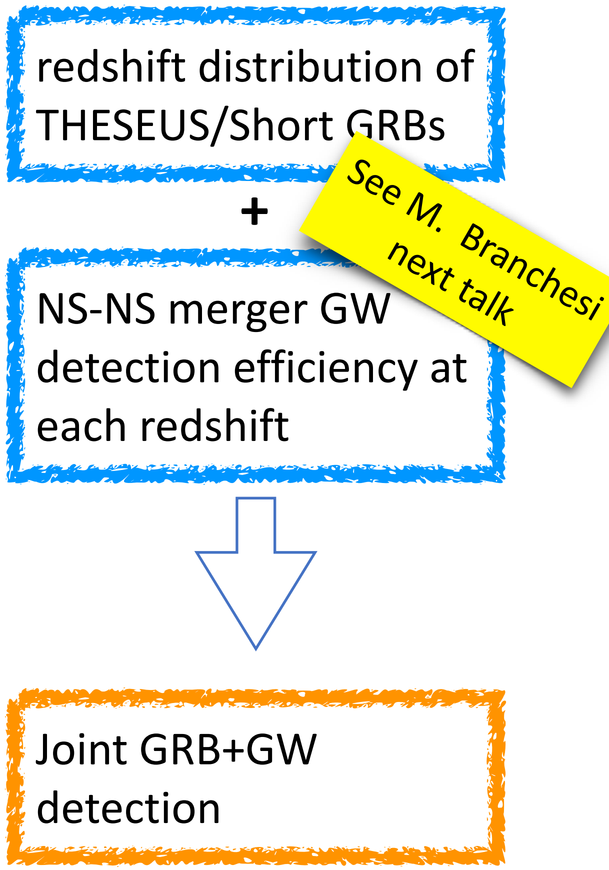
See M. Branchesi next talk

Joint GRB+GW detection

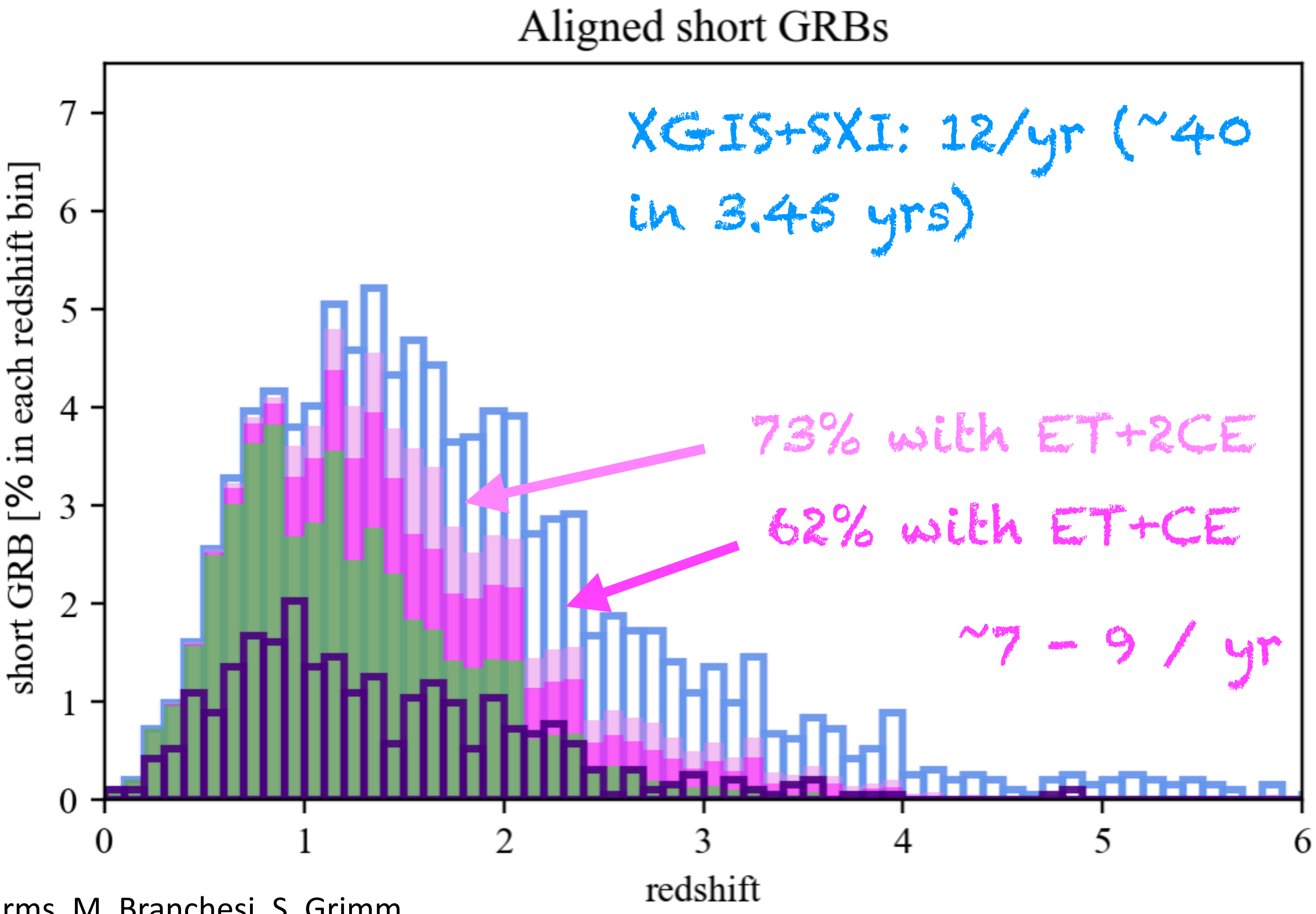
THESEUS short GRBs: joint GW detections



Credit: J. Harms, M. Branchesi, S. Grimm



THESEUS short GRBs: joint GW detections



Credit: J. Harms, M. Branchesi, S. Grimm

redshift distribution of THESEUS/Short GRBs

+

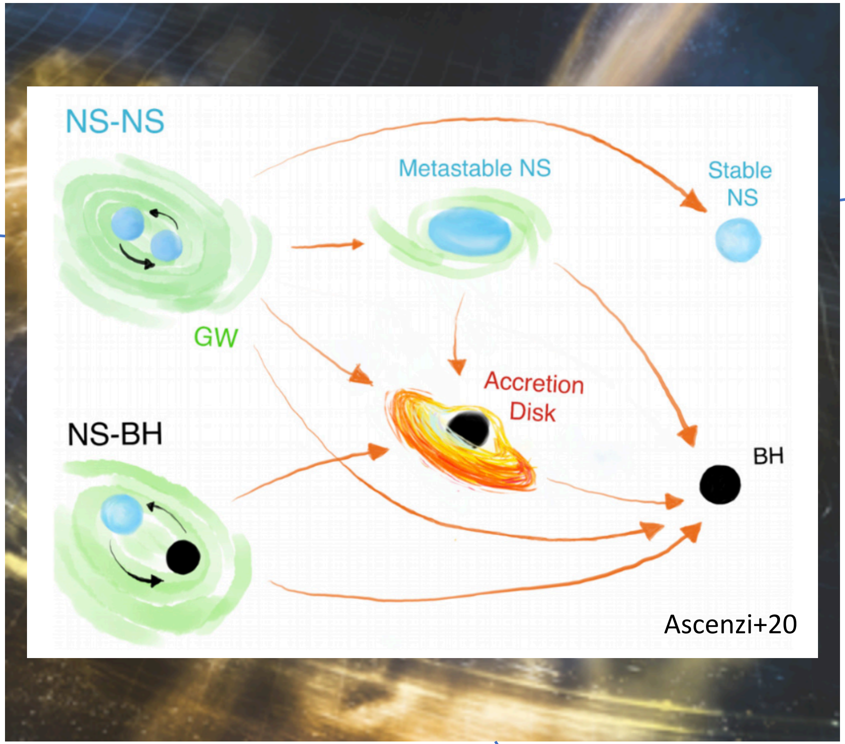
NS-NS merger GW detection efficiency at each redshift

See M. Branchesi next talk

Joint GRB+GW detection

Fundamental issues from short GRB+GW detections

What is the jet launching mechanism and its efficiency?

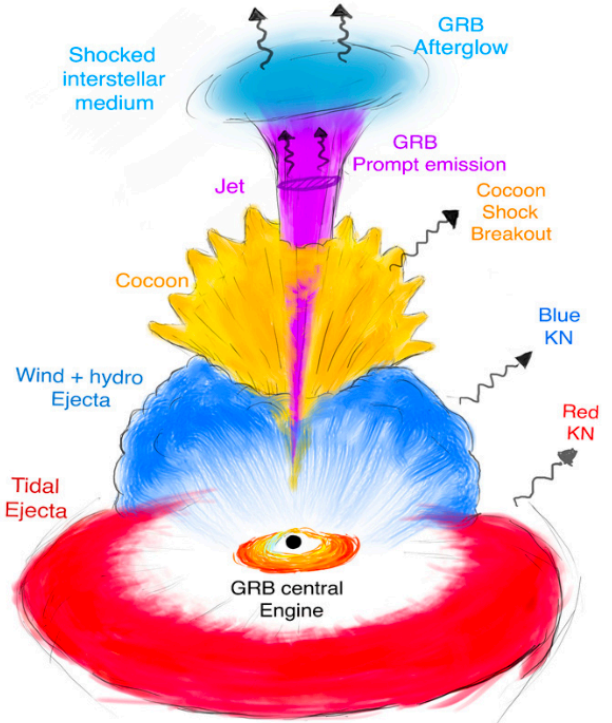


Are there any systematic differences between NS-BH and NS-NS jets?

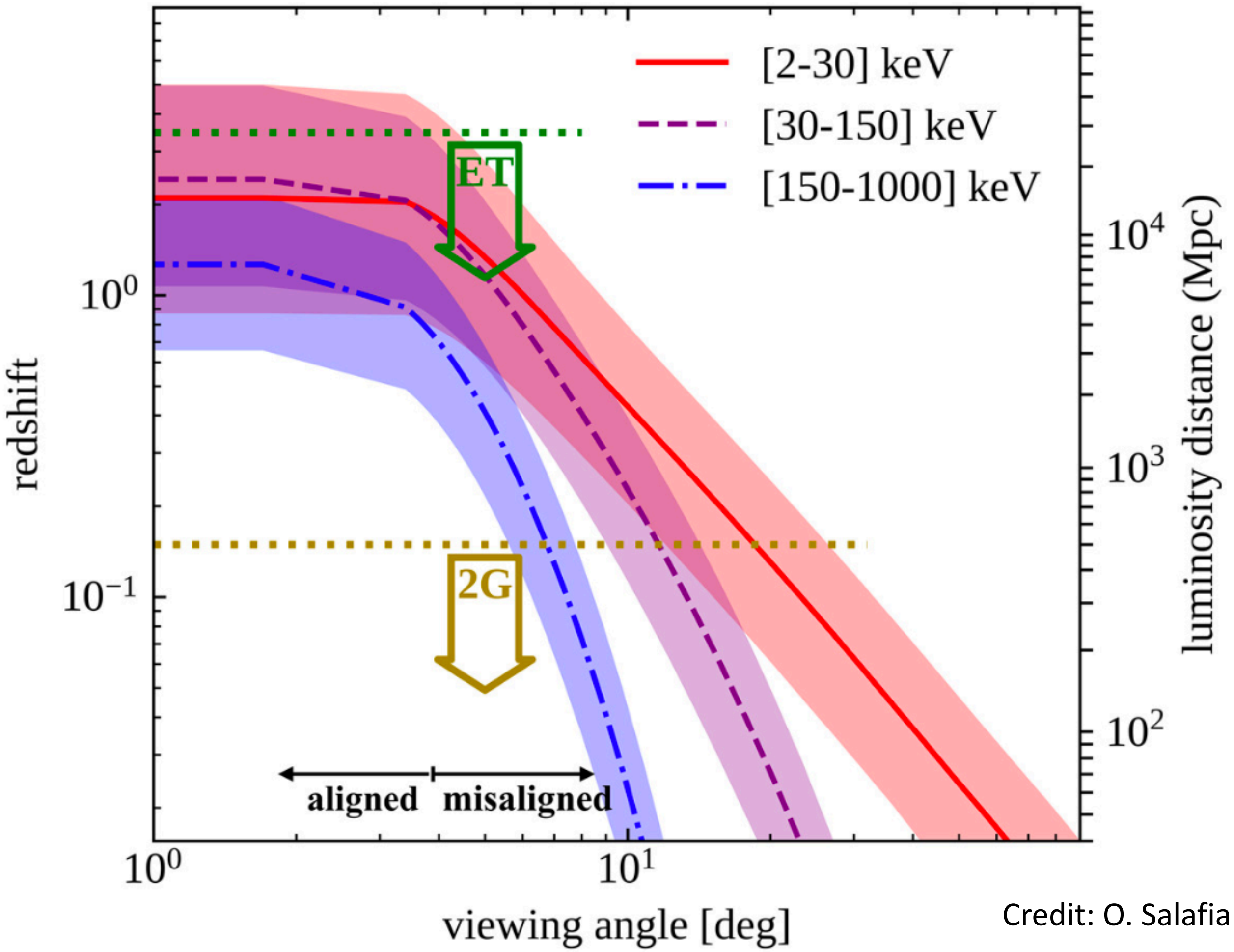
What is the nature of merger remnant and which connection with afterglow features?

THESEUS misaligned GRB detection capabilities

Ascenzi et al. 2020

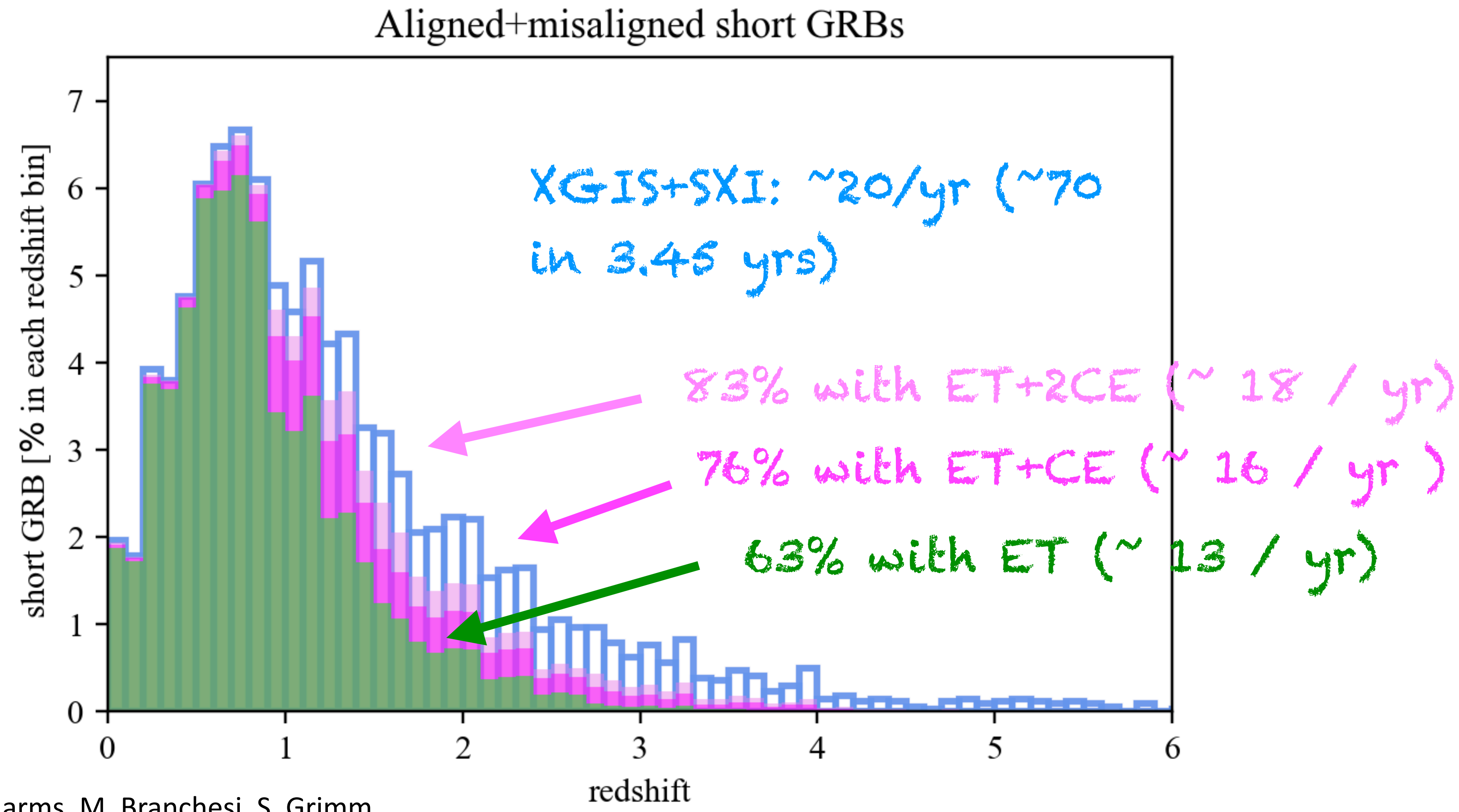


GRB 170817 associated with the NS-NS merger GW170817 was a misligned GRB



Credit: O. Salafia

THESEUS short GRBs including off-axis viewing angles

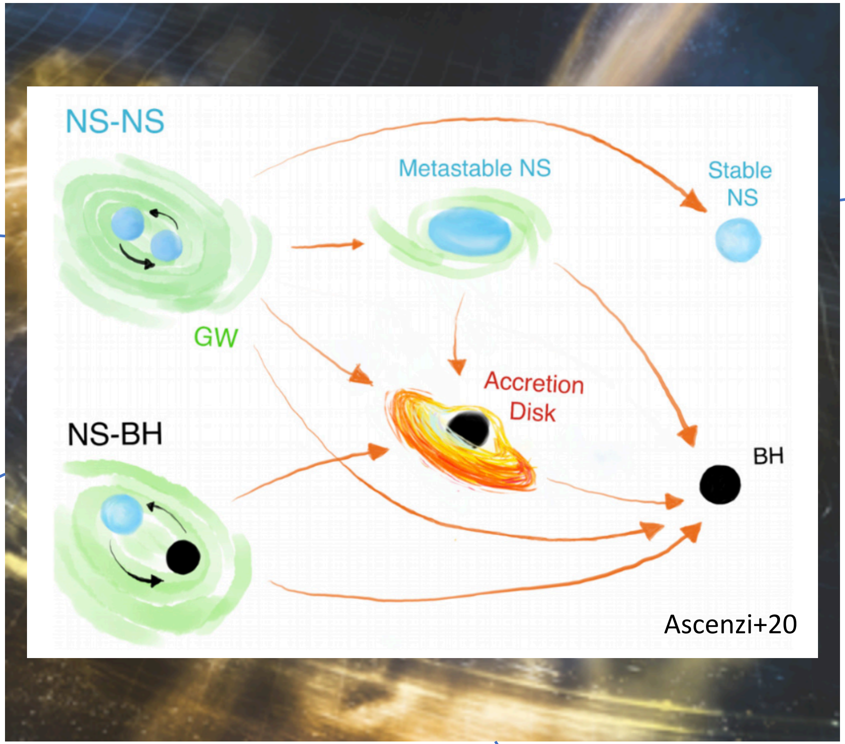


Credit: J. Harms, M. Branchesi, S. Grimm

Fundamental issues from short GRB+GW detections

What is the jet launching mechanism and its efficiency?

Do NS-NS/NS-BH jets have universal structure?



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

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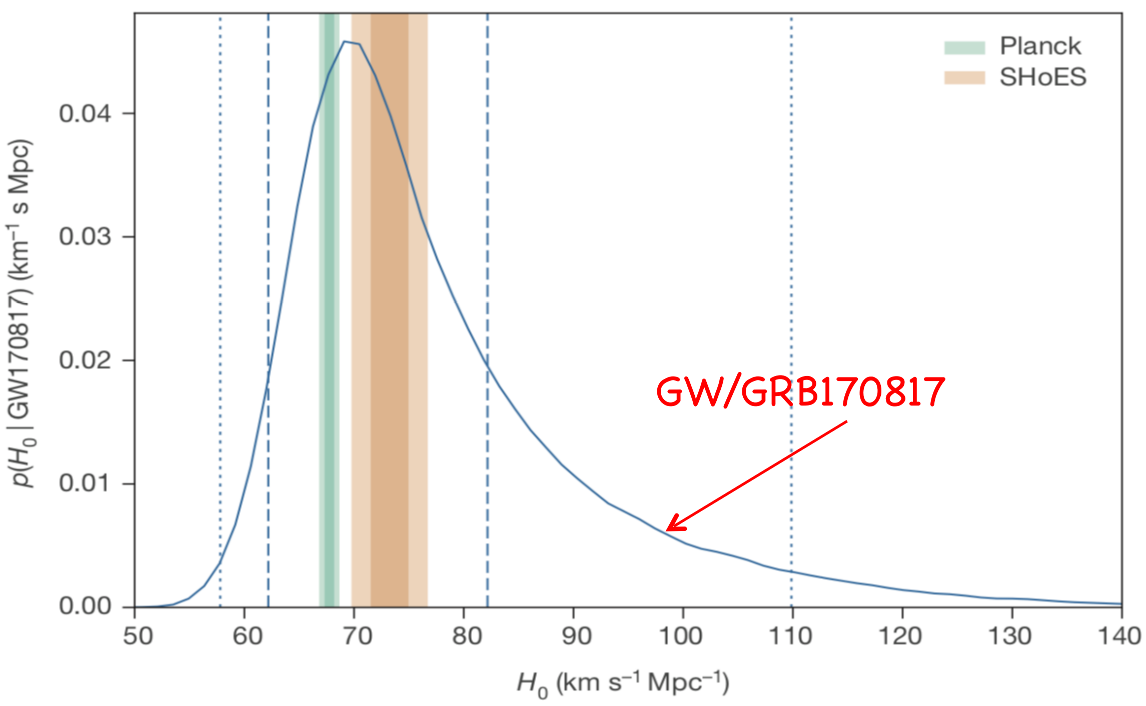
A new independent measure of H_0

LVC, Nature 2017, 551, 85

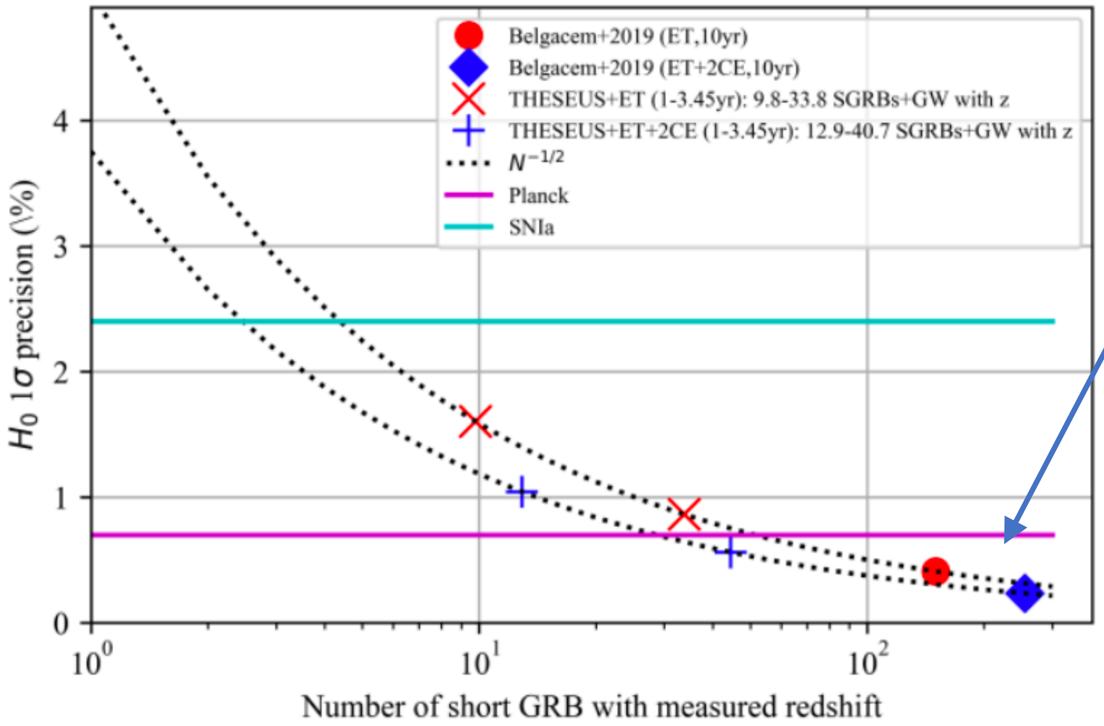


- The statistical significant sample of CBC that THESEUS will detect jointly with 3G interferometers can be used to measure the Hubble constant with high precision

- So far the first measure of H0 by combining GW luminosity distance and redshift, was obtained with GW170817 with poor accuracy (e.g. Abbott+17, Guidorzi+17, Hotokezaka+18)

- To solve the current tension ~1% precision level in required

A new independent measure of H_0



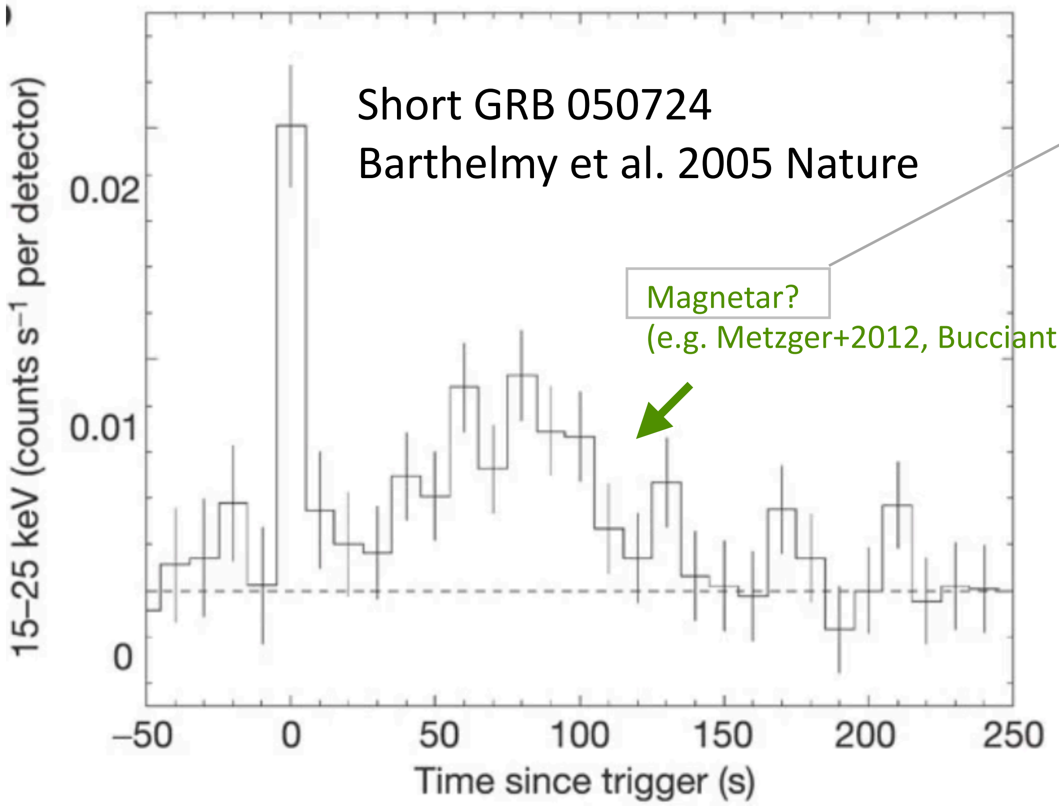
- We start from the predicted $\Delta H_0/H_0$ from **mock catalogs of NS-NS mergers and assuming 10yrs of observations of THESEUS+ET(+2CE)** (Belgacem et al. 2019)
- We rescaled $\Delta H_0/H_0$ to **expected values with joint GW+short GRB detection with measured z** (~ 60% aligned + ~10% misaligned) **in 1 up to 4 years**
- We find **$\Delta H_0/H_0$~1% with ~1 yrs of synergies with ET+2CE or ~4 yrs with ET only**

Related talk by L. Salmon

Possible further improvements:

- combining e.m.+GW data analysis (i.e. better constraints on off-axis angles & luminosity distance)
- adding potentially numerous “short GRB-less” X-ray transients from CBCs

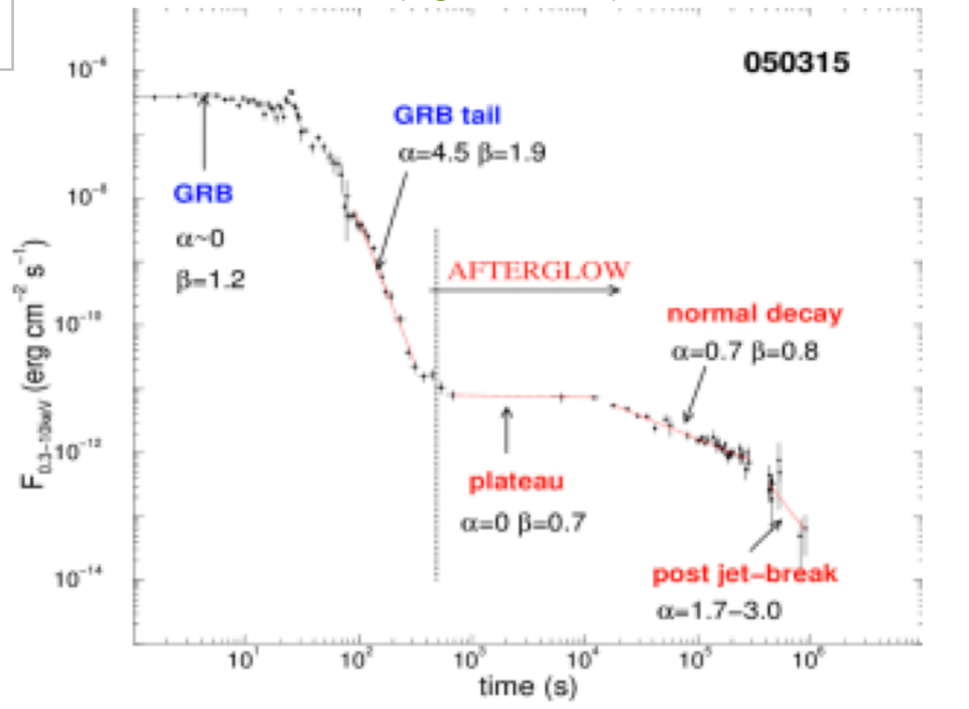
Additional science from joint short GRB + GW detections: the origin of short GRB “Extended Emission” and of X-ray plateaus



Magnetar?
(e.g. Metzger+2012, Bucciantini+2011)

less collimated than prompt

Magnetar? (e.g. Zhang&Mesazaros+2001)
HLE? (S. Ascenzi+20, G. Oganesyan+20)
Fallback on BH? (e.g. Kumar+08)



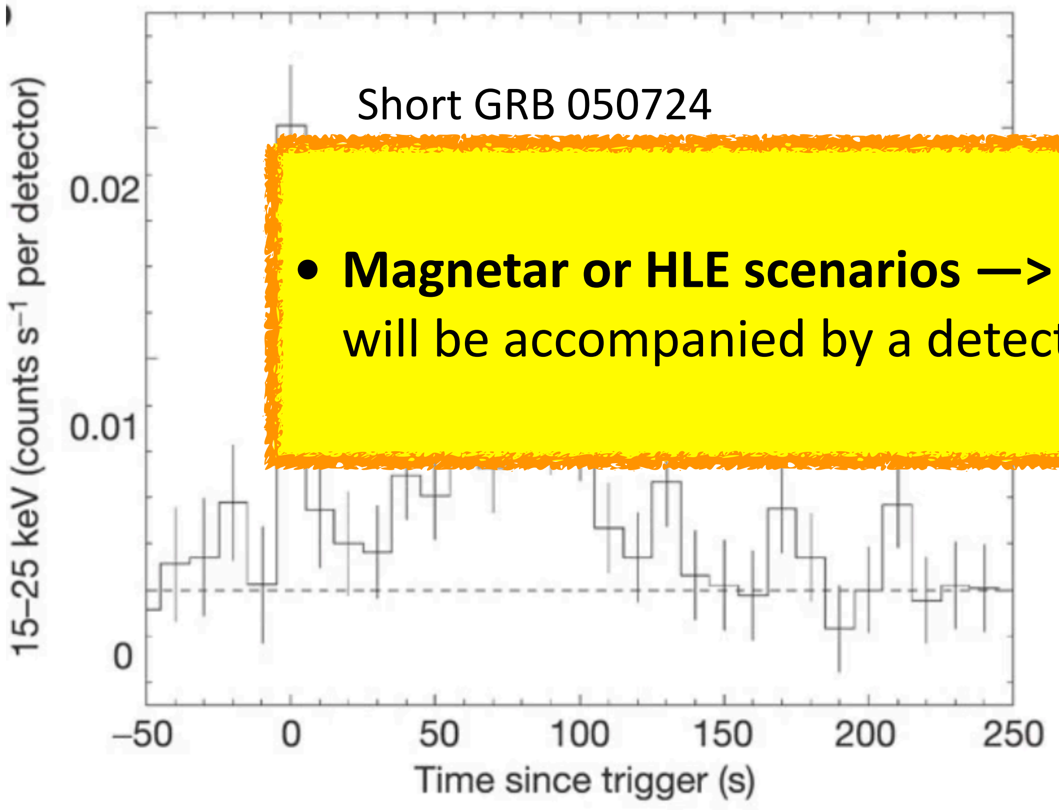
—> GW could contribute to the identification of a long-lived magnetar remnant

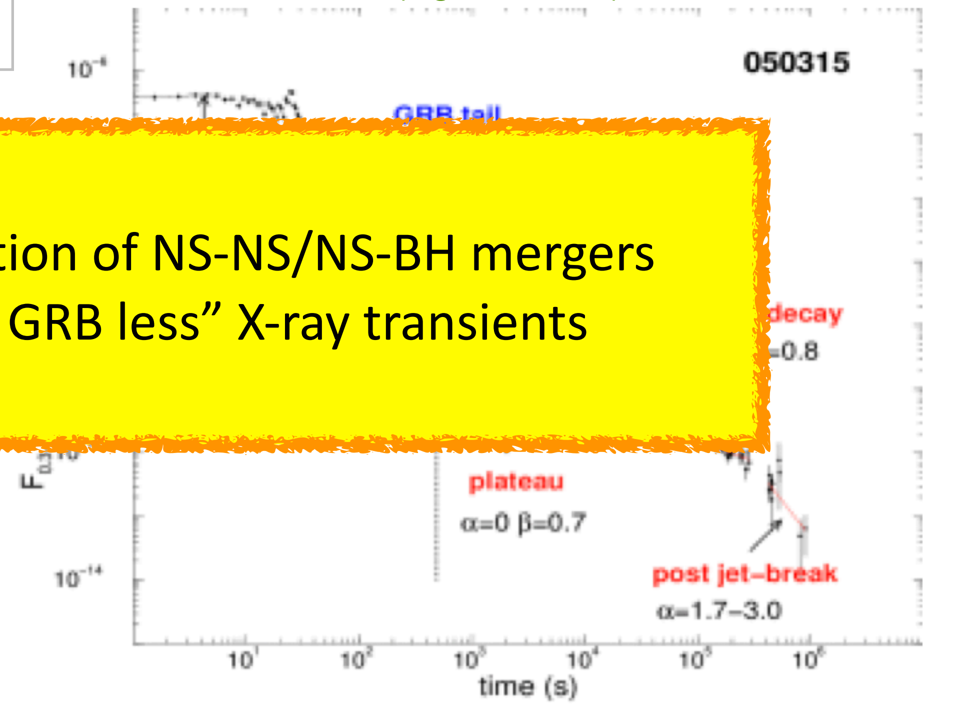
Additional science from joint short GRB + GW detections: the origin of short GRB “Extended Emission” and of X-ray plateaus

Magnetar? (e.g. Zhang&Mesazaros+2001)
HLE? (S. Ascenzi+20, G. Oganesyan+20)
Fallback on BH? (e.g. Kumar+08)

less collimated than prompt

Short GRB 050724



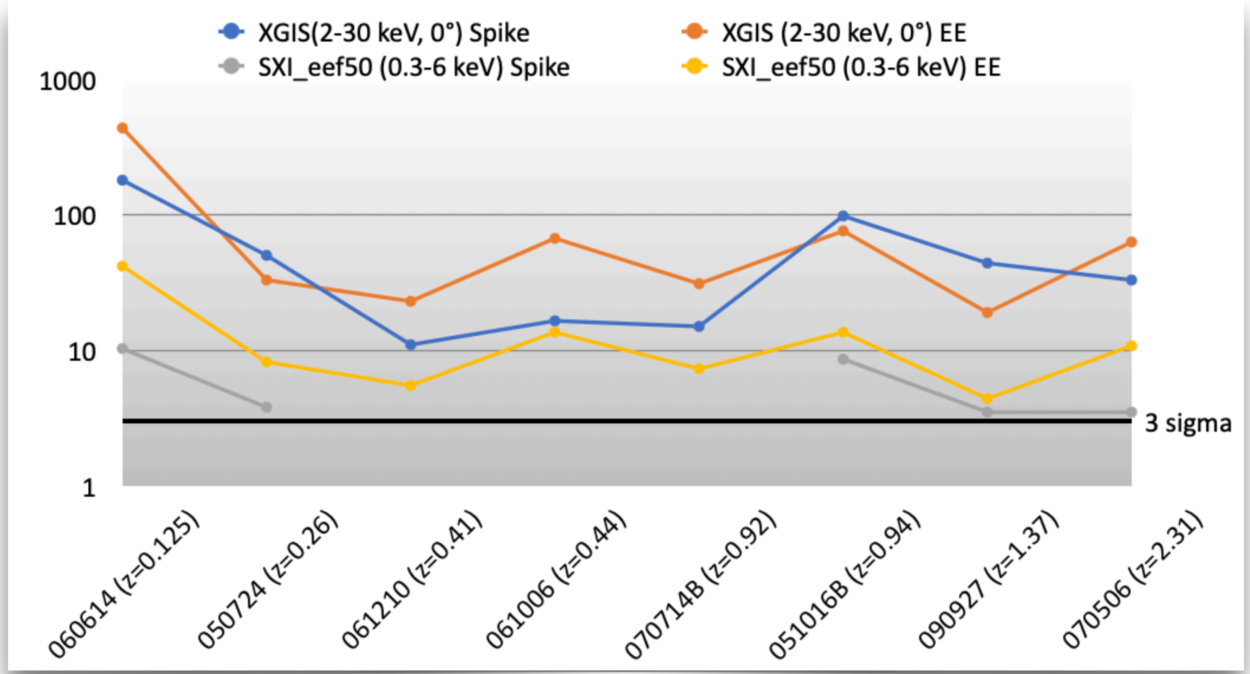


- **Magnetar or HLE scenarios —>** a large fraction of NS-NS/NS-BH mergers will be accompanied by a detectable “short GRB less” X-ray transients

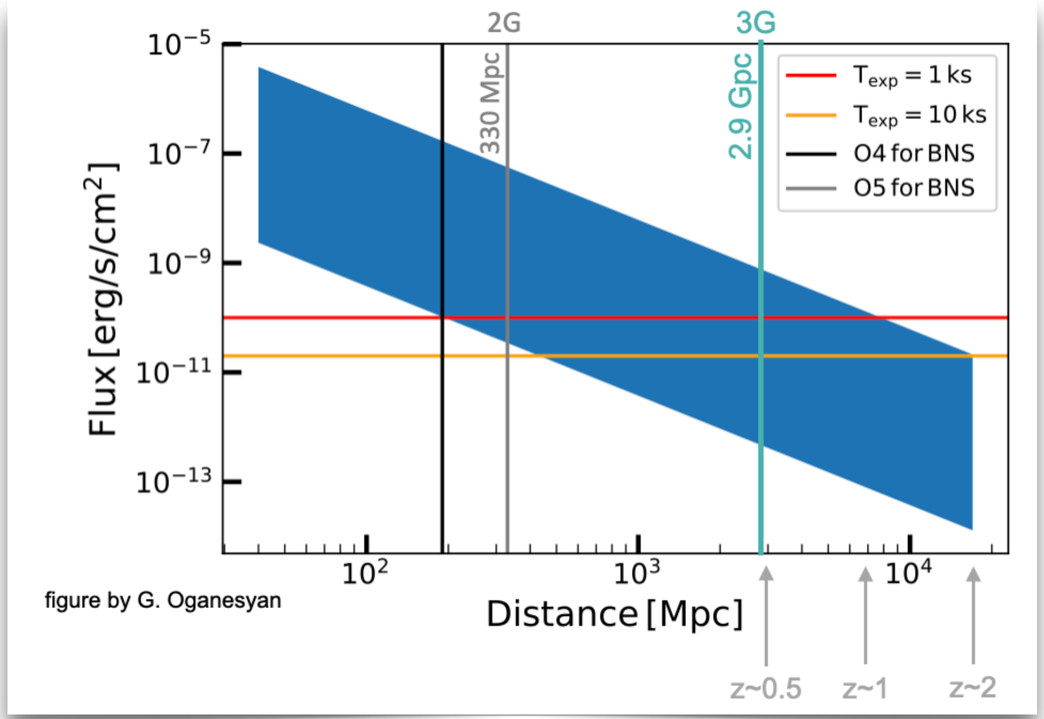
—> GW could contribute to the identification of a long-lived magnetar remnant

Additional science from joint short GRB + GW detections: the origin of short GRB "Extended Emission" and of X-ray plateaus

Detection significance for a sample of short GRB with EE



Short GRB X-ray plateau fluxes vs distance



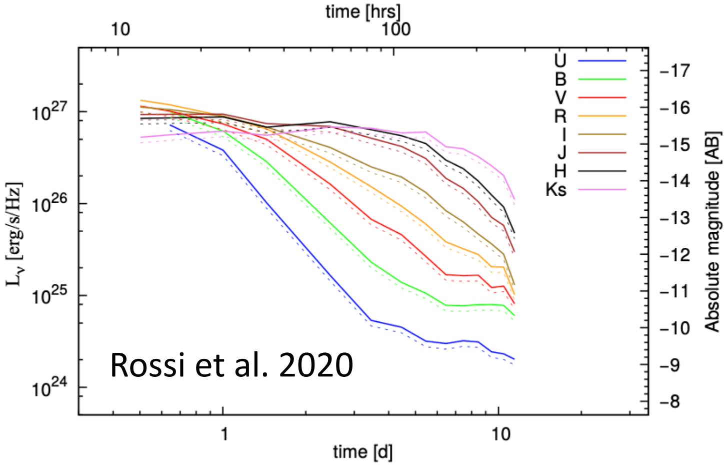
Kilonovae

✦**Thermal emission** following a NS-NS/NS-BH merger powered by radiactive decay of freshly formed, instable heavy nuclei

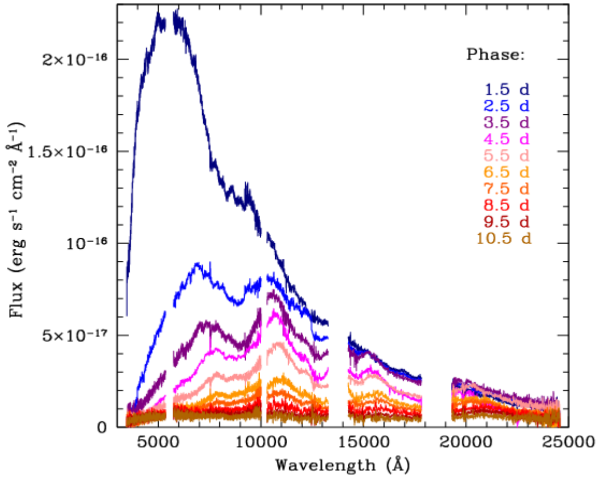
✦**AT2017gfo** is the best monitored kilonova so far associated with NS-NS merger source GW 170817

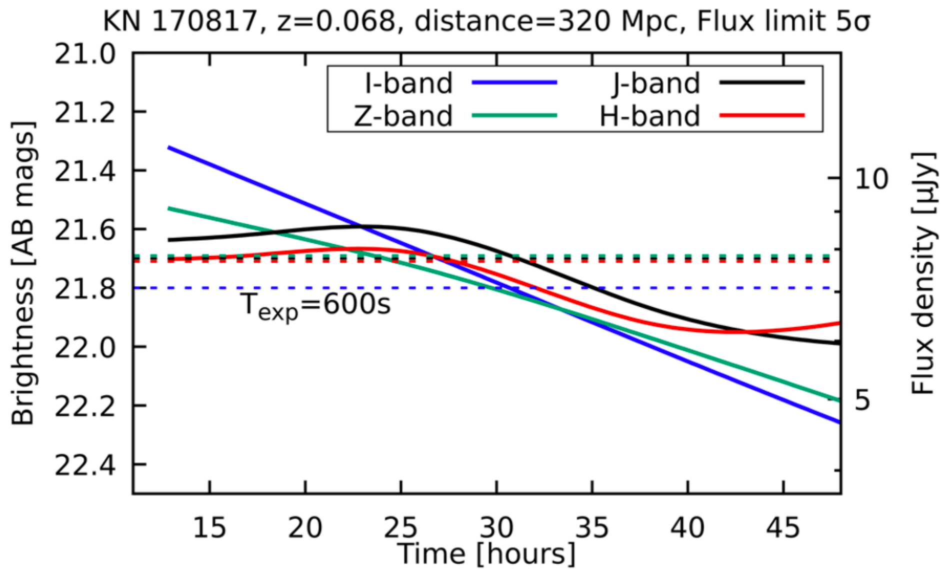
✦THESEUS/IRT can **detect** a kilonova AT2017gfo-like after a short GRB up to few x 100 Mpc

- Monitoring KN candidates localized by other facilities
- Discovery KN after a short GRB or an X-ray transient from long-lived magnetar



From Pian et al. 2017





Credit: E. Palazzi, A. Rossi (INAF-OAS)

Other high-frequency GW sources

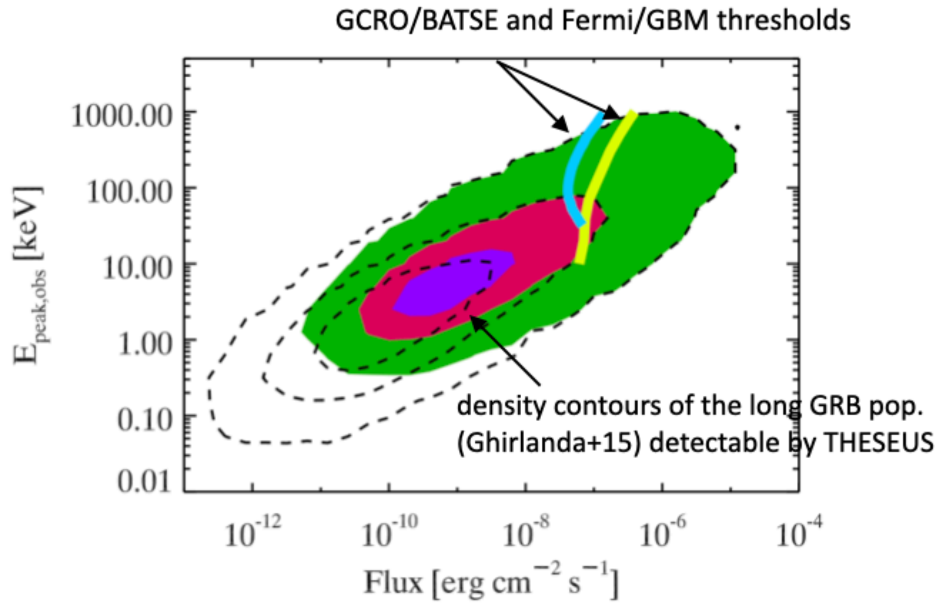
THESEUS WP Stratta+18

★ **CC-SNe** can emit GWs but their detectability is much more uncertain than for CBC sources

- Shock Break Out — See L. Izzo talk tomorrow
- Long GRB / Low Luminosity GRB / ultra-long GRB
- Promising GW signals may come from newly-formed compact object
  - In case of a newly-born long-lived magnetar, isotropic spin down powered transients can be detected in soft X-rays (e.g. Metzger+2014, Siegel+2016)

★ **magnetar instability phenomena** that can generate detectable GW in our Galaxy and possibly beyond (e.g., Corsi and Owen, 2011, Ciolfi et al., 2011)

- Soft Gamma Repeaters — See more during Session 7 tomorrow morning



Ultra long GRBs	Duration (T90,s)	Duration (Tx,s)	z	z_max prompt (XGIS)	z_max prompt (SXI)	z_max afterglow (SXI)
101225A	>2000	5300	0,847	-	1.5	0.1
111209A	25000	25400	0,677	0.4	>3	0.3
121027A	>6000	8000	1.77	1.7	>3	1.0
130925A	4500	10000	0.35	0.7	>3	0.6
170714A	420	16600	0,793	0.5	>3	0.4

Credit: B.Gendre, A.McCann

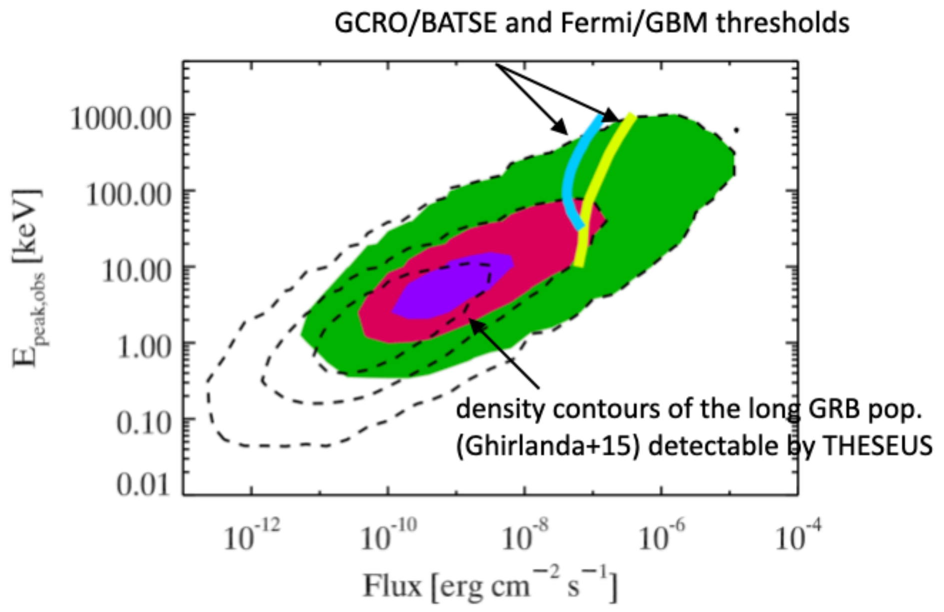
The role of THESEUS in Neutrino Astronomy

❋ HE ν are unique signature of accelerated hadrons at the source and allow to identify the most extreme accelerators in the Universe possibly originating UHCRs

$$p + \gamma \xrightarrow{\Delta^+} \begin{cases} p+\pi^0 \\ n+\pi^+ \end{cases} \longrightarrow \begin{cases} \pi^0 \longrightarrow \gamma+\gamma \\ n \longrightarrow p + e^- + \overline{\nu}_e \\ \pi^+ \longrightarrow \mu^+ + \nu_\mu \\ \mu^+ \longrightarrow e^+ + \nu_e + \overline{\nu}_\mu \end{cases}$$

❋ Among the best cosmological ν source targets for THESEUS there are:

- GRBs
- AGN
- star-forming galaxies (as calorimeters of ν sources)



❋ So far, no ν detections from GRBs —> constraints on energy transferred to baryons in the acceleration process and on the bulk jet Lorentz factor —> **soft/ faint GRBs may be more suitable targets**

THESEUS WP Stratta+18

External triggers

✤THESEUS is also designed to rapidly respond to triggers that are provided by other facilities

✤The time required to re-point THESEUS toward a specific direction is >4 hours after the trigger

✤ Number of external triggers defined as mission science requirement is: 3/month

Some examples of THESEUS external triggers

Neutrino alert:

- flaring AGNs
- starburst galaxies within ν

GW source alert:

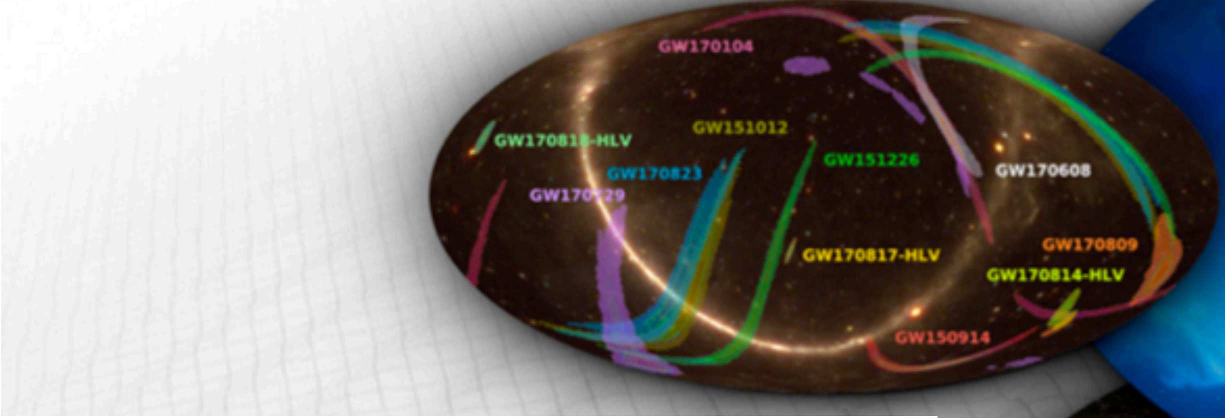
- kilonova candidate localized by other facilities

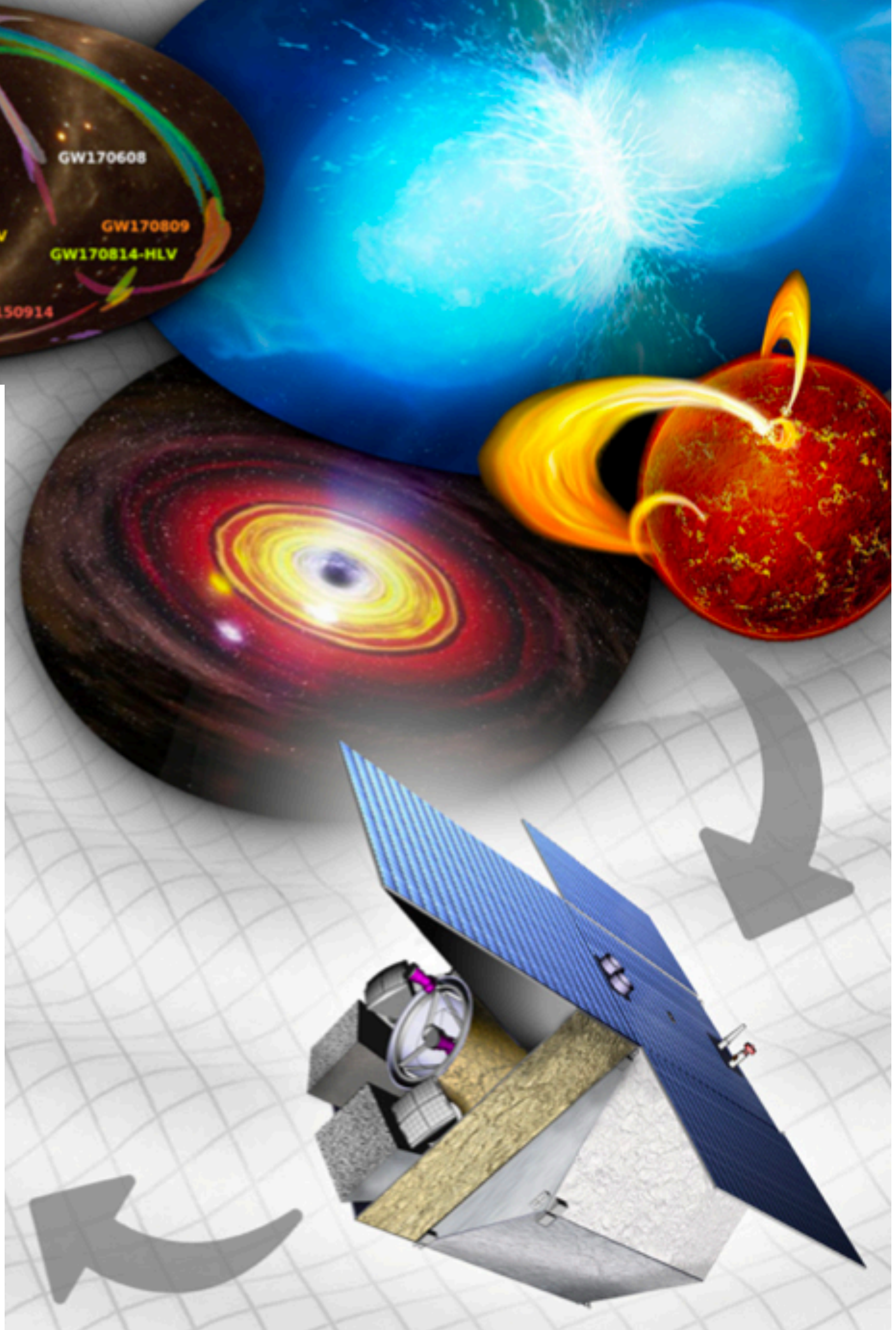
Conclusions

- **THESEUS** expected launch date on 2032 and lifetime of at least 4 years is **perfectely on time to work in synergy with next generation GW and neutrino detectors** which will provide high detection rates

- **THESEUS capabilities of independently detect the e.m. counterpart and characterize its nature** will be crucial for the identification of multi-messenger sources during the 2030s

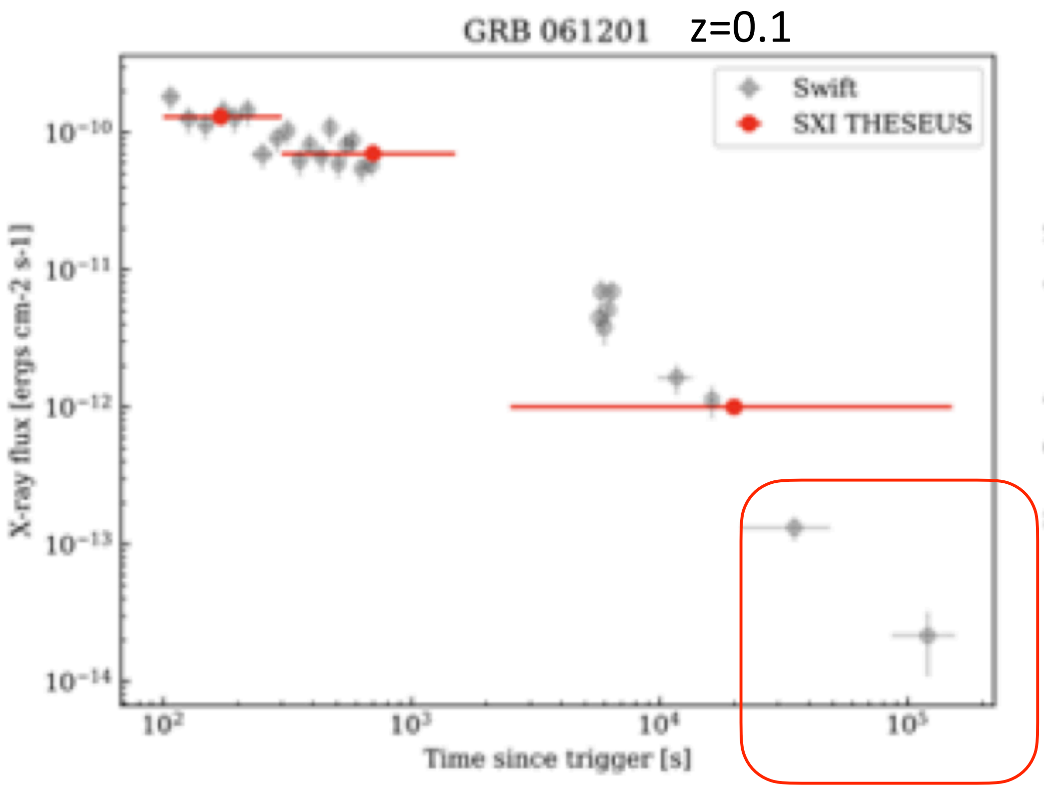
- **THESEUS accurate source sky localization capabilities will allow MW follow-up campaigns** with next generation facilities as ELT, Athena, SKA, CTA, etc. ultimately increasing the scientific output of each facility in the framework of multi-messenger astrophysics

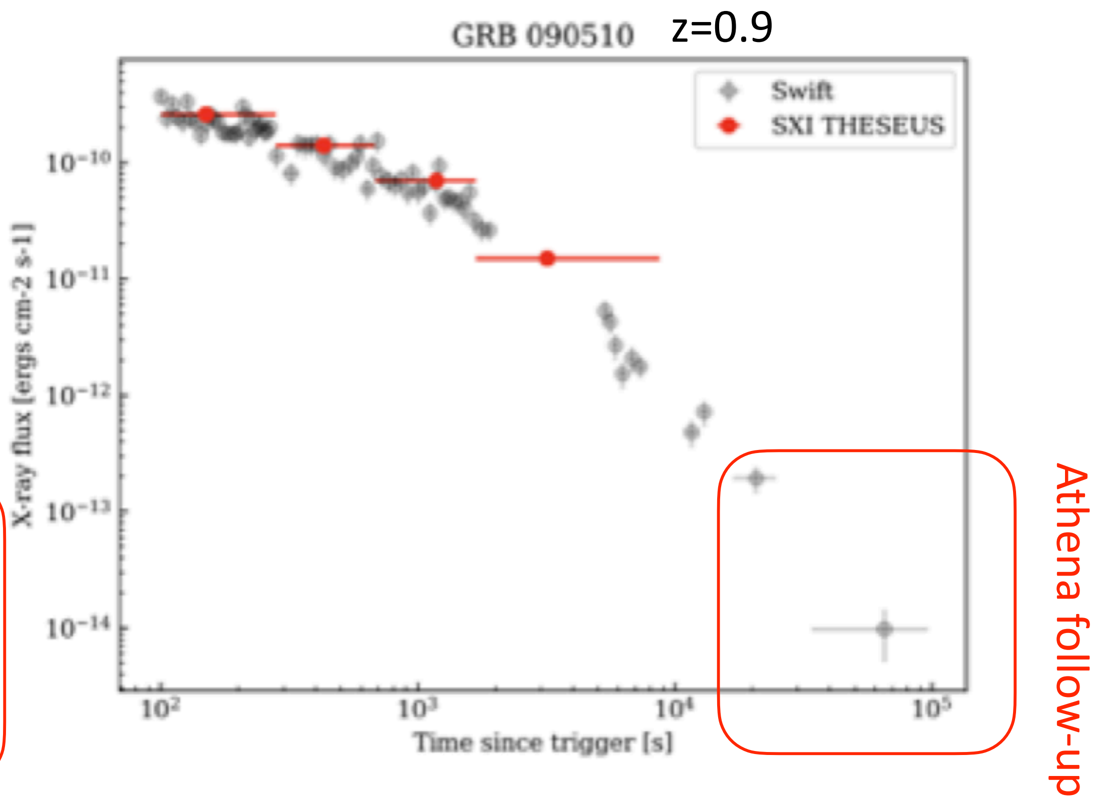

GW170104
GW151012
GW151226
GW170608
GW170823
GW170817-HLV
GW170809
GW170814-HLV
GW150914



Thank you!

Additional science from joint sort GRB + GW detections: the origin of short GRB "Extended Emission" and of X-ray plateaus





Credit: A. Martin-Carrillo

GRB 170817A-like jet afterglows

assuming Ghirlanda+2019 jet structure

(model Salafia+2019)

$$E(\theta) = \frac{E_c}{1+(\theta/\theta_c)^{5.5}}$$

$$\Gamma(\theta) = 1 + \frac{\Gamma_c - 1}{1+(\theta/\theta_c)^{3.5}}$$

$E_c = 2.51^{+7.49}_{-2.01} \times 10^{52}\,\mathrm{erg}$

$\Gamma_c = 251$

$\theta_c = 3.^{\circ}4$

$n = 5 \times 10^{-3}\,\mathrm{cm}^{-3}$

$p = 2.15$

$\sqrt{\varepsilon_B} = 0.1$

Predicted X-ray max flux as a function of the source distance and inclination angle

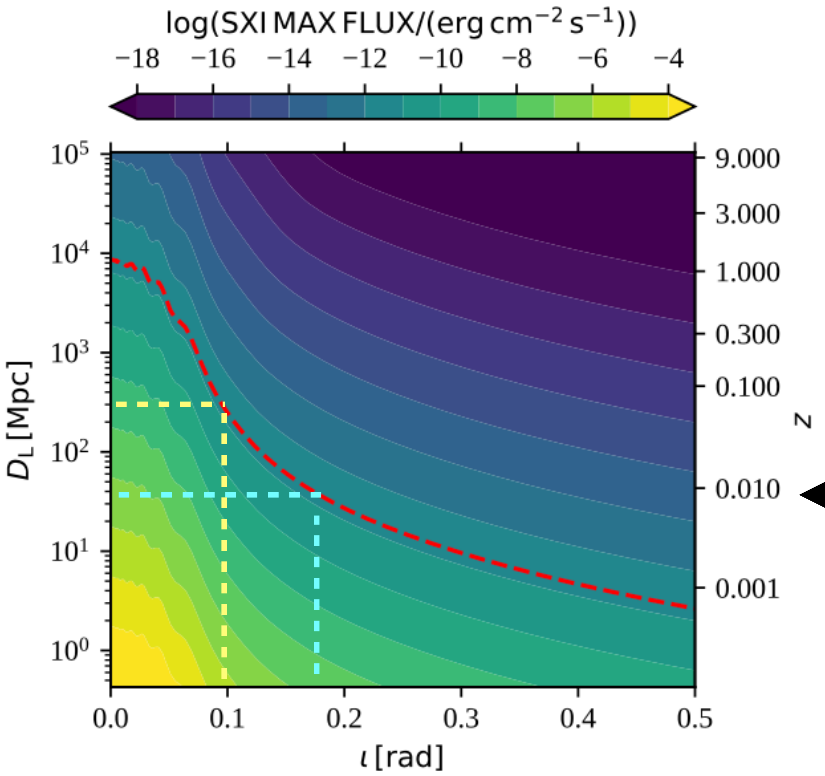


Figure by Om Sharan Salafia

← 2G distance reach ~<5°

← GRB 170817A distance ~< 10°

GRB 170817A-like jet afterglows

Figure by Gavin Lamb