THESEUS role in Multi-Messenger Astrophysics

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

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

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

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

2030s: the golden era of MMA

Neutrino detector will improve sensitivity of \( \sim \mathcal{O}(10) \) → will collect high-statistics HE neutrino sample

See talk by M. Spurio at 16:20

Credit: U. Katz
2030s: the golden era of MMA

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

See next talk by M. Branchesi

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
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

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

THESEUS sky coverage:

SXI: 0.5 sr ~1600 deg²
XGIS: 2 sr <150 keV ~ 6400 deg²

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

XGIS+SXI: 12/yr (~40 in 3.45 yrs)

25% with IRT

redshift distribution of THESEUS/Short GRBs

See M. Branchesi next talk

NS-NS merger GW detection efficiency at each redshift

Joint GRB+GW detection
THESEUS short GRBs: joint GW detections

Aligned short GRBs

XGIS+SXI: 12/yr (~40 in 3.45 yrs)

46% with ET (~5-6/yr)

redshift distribution of THESEUS/Short GRBs +

NS-NS merger GW detection efficiency at each redshift

Joint GRB+GW detection

Credit: J. Harms, M. Branchesi, S. Grimm
THESEUS short GRBs: joint GW detections

XGIS+SXI: 12/yr (~40 in 3.45 yrs)

73% with ET+2CE
62% with ET+CE

~7 - 9 / yr

redshift distribution of THESEUS/Short GRBs

See M. Branchesi next talk

NS-NS merger GW detection efficiency at each redshift

Joint GRB+GW detection

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

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

Credit: O. Salafia
THESEUS short GRBs including off-axis viewing angles

- 83% with ET+2CE (~ 18 / yr)
- 76% with ET+CE (~ 16 / yr)
- 63% with ET (~ 13 / yr)

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

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

What is the nature of merger remnant and which connection with afterglow features?
A new independent measure of $H_0$

- 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 $H_0$ 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 $\sim$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 10 yrs 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 $z$ ($\sim 60\%$ aligned + $\sim 10\%$ misaligned) in 1 up to 4 years
- We find $\Delta H_0/H_0 \sim 1\%$ with $\sim 1$ yrs of synergies with ET+2CE or $\sim 4$ yrs with ET only

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

Short GRB 050724
Barthelmy et al. 2005 Nature

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

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

less collimated than prompt

→ 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 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

Detection significance for a sample of short GRB with EE

Short GRB X-ray plateau fluxes vs distance

figure by G. Oganiesyan
Kilonovae

- **Thermal emission** following a NS-NS/NS-BH merger powered by radiative decay of freshly formed, unstable 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
Other high-frequency GW sources

⭐ **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

<table>
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<th>Ultra long GRBs</th>
<th>Duration (T90,s)</th>
<th>Duration (Tx,s)</th>
<th>z</th>
<th>z_max prompt (XGIS)</th>
<th>z_max prompt (SXI)</th>
<th>z_max afterglow (SXI)</th>
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</tbody>
</table>

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

- 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
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.
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)

\[ E(\theta) = \frac{E_c}{1 + (\theta/\theta_c)^{5.5}} \]
\[ \Gamma(\theta) = 1 + \frac{\Gamma_c - 1}{1 + (\theta/\theta_c)^{3.5}} \]

\[ E_c = 2.51^{+7.49}_{-2.01} \times 10^{52} \text{ erg} \quad \Gamma_c = 251 \quad \theta_c = 3.4^\circ \]
\[ n = 5 \times 10^{-3} \text{ cm}^{-3} \quad p = 2.15 \quad \sqrt{\varepsilon_B} = 0.1 \]

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

Figure by Om Sharan Salafia

2G distance reach \(~<5^\circ\)
GRB 170817A distance \(~<10^\circ\)
GRB 170817A-like jet afterglows

Figure by Gavin Lamb