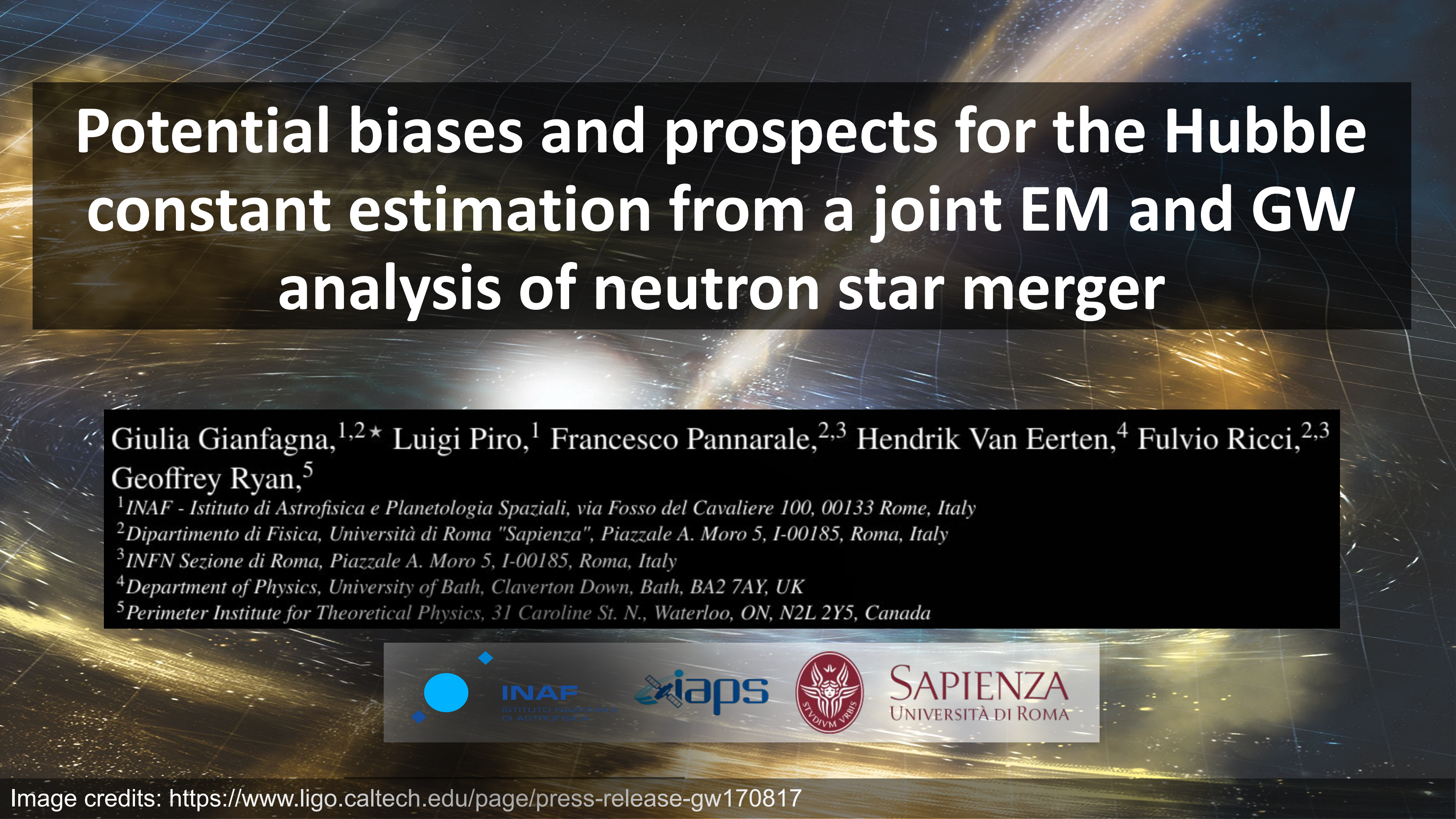

Potential biases and prospects for the Hubble constant estimation from a joint EM and GW analysis of neutron star merger

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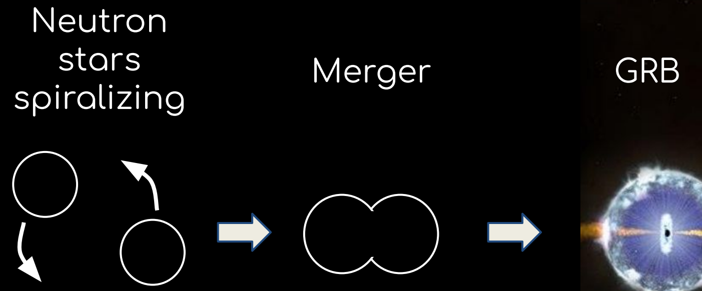
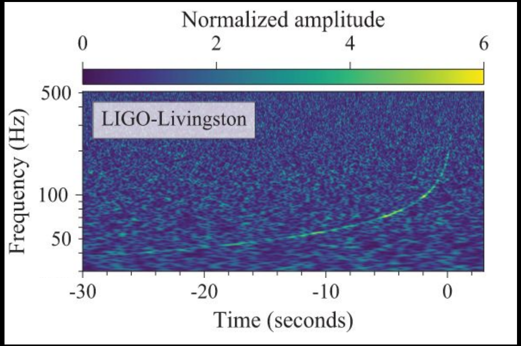
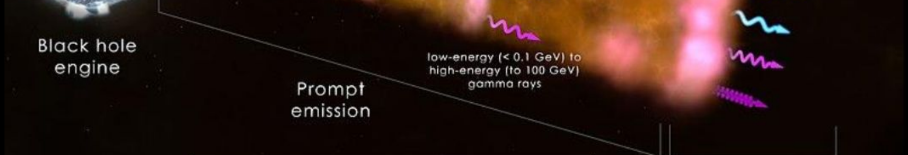
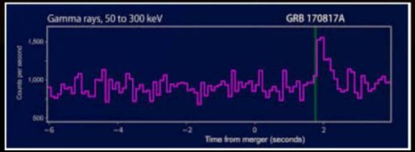
GW170817 and GRB 170817A



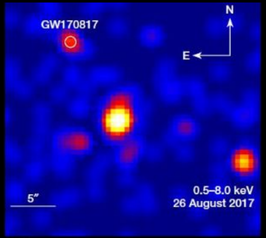


Gravitational Wave, *Abbott et al, 2017*

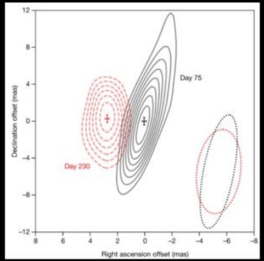




Fermi and INTEGRAL



Chandra observations
Troja et al, 2017



VLBI at 4.5 GHz
Mooley et al, 2017

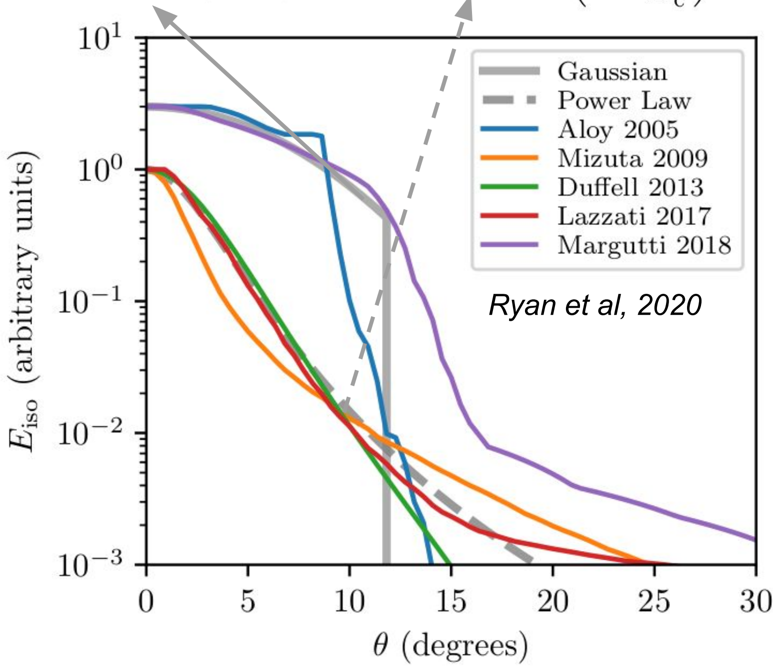
GW170817 afterglow modeling

Gaussian jet:

$$E(\theta) = E_0 \exp\left(-\frac{\theta^2}{2\theta_c^2}\right)$$

Power law jet:

$$E(\theta) = E_0 \left(1 + \frac{\theta^2}{b\theta_c^2}\right)^{-b/2}$$



Ryan et al, 2020

- Model: **`afterglowpy`** (*Ryan et al, 2020*)

θ_V	Jet orientation
θ_c	Opening angle of the jet
E_0	Isotropic equivalent energy
n_0	homogeneous circumburst medium number density
θ_W	Jet total width
p	power-law slope of the electron population
ϵ_e	fraction of post-shock internal energy in the accelerated electron population
ϵ_B	fraction of post-shock internal energy in magnetic field
b	power law index (only for power law jet)
d_L	luminosity distance

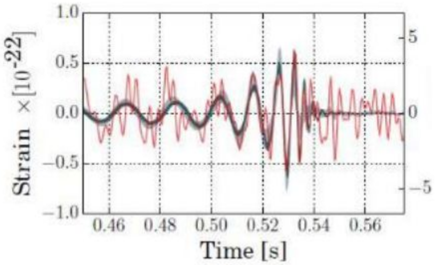
GW modeling

Intrinsic	1	$\mathcal{M}$	Chirp mass	or	m_1	Mass 1
	2	q	Mass ratio		m_2	Mass 2
	3	a_1	Spin amplitude 1			
	4	a_2	Spin amplitude 2			
	5	θ_1	Tilt angle between the spin 1 and the orbital angular momentum			
	6	θ_2	Tilt angle between the spin 2 and the orbital angular momentum			
	7	$\phi_{1,2}$	Azimuthal angle between the spin vectors			
	8	ϕ_{jl}	Azimuthal angle between total angular momentum and orbital angular momentum			
Extrinsic	9	d_L	Luminosity distance			
	10	DEC	Declination	FIXED to NGC 4993		
	11	RA	Right ascension			
	12	$\cos(\theta_{JN})$	Cosine of the inclination angle	or	θ_{JN}	Inclination angle
	13	ψ	Polarization angle			
	14	ϕ	Phase			
	15	Λ_1	Tidal deformability parameters of the primary neutron star	or	$\tilde{\Lambda}$	Dimensionless tidal parameters
	16	Λ_2	Tidal deformability parameters of the secondary neutron star		$\delta\tilde{\Lambda}$	

EM+GW parameters

$$m_1 \geq m_2$$

$$\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}}$$



+ 10 calibration parameters for each detector

$$\tilde{\Lambda} = \frac{16}{13}\frac{(m_1 + 12m_2)m_1^4\Lambda_1 + (m_2 + 12m_1)m_2^4\Lambda_2}{(m_1 + m_2)^5}$$

GW+EM joint fit and H_0 estimation

Bayes theorem Posterior = $\frac{\text{Likelihood x Prior}}{\text{Evidence}}$

Likelihood = EM Likelihood x GW Likelihood

Gaussian distributions

3 sets of parameters:

1. GW-only
2. EM-only
3. **GW+EM: θv and $\boxed{d_L}$**

Only from general theory of relativity

NO distance ladders involved !

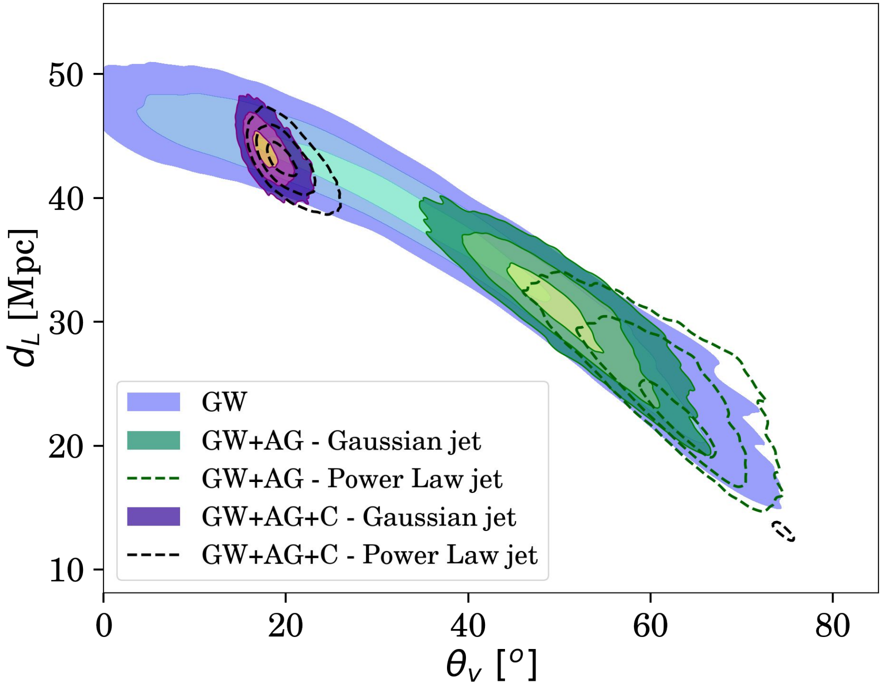
In the local Universe

$$v_H = c\,z = \boxed{H_0}\,D_L$$

Local Hubble flow velocity, at the position of GW170817 (*Abbott et al, 2017*):

$$v_H = 3017 \pm 166\ \mathrm{km\ s^{-1}}$$

d_L - θv degeneracy



Gianfagna et al, 2023, submitted, arXiv:2309.17073

- Far source
- Binary orbit facing Earth

=

- Close source
- Highly inclined

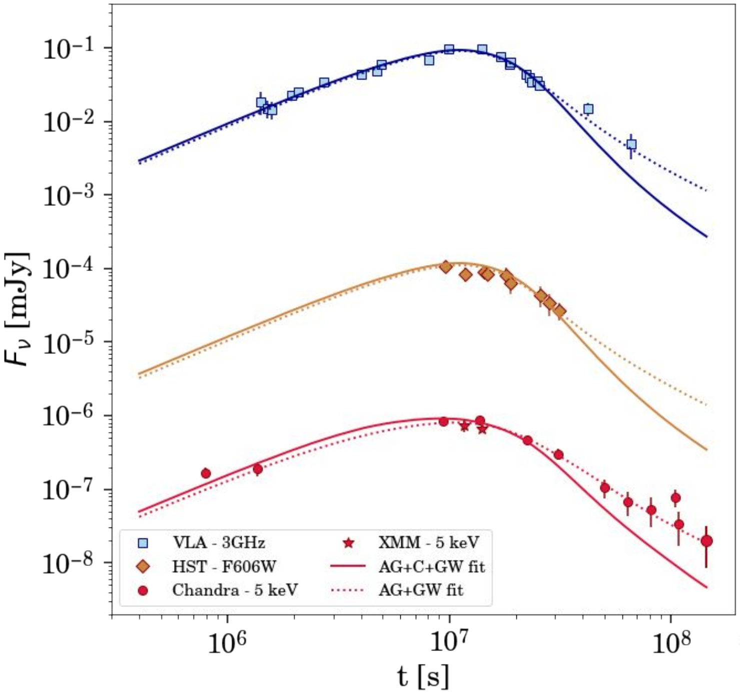
GW-only: $H_0 = 77^{+21}_{-10}\,\mathrm{km\,s^{-1}Mpc^{-1}}$

How to break this degeneracy?

EM dataset: **Afterglow (AG)** light curve

=> GW+AG fit

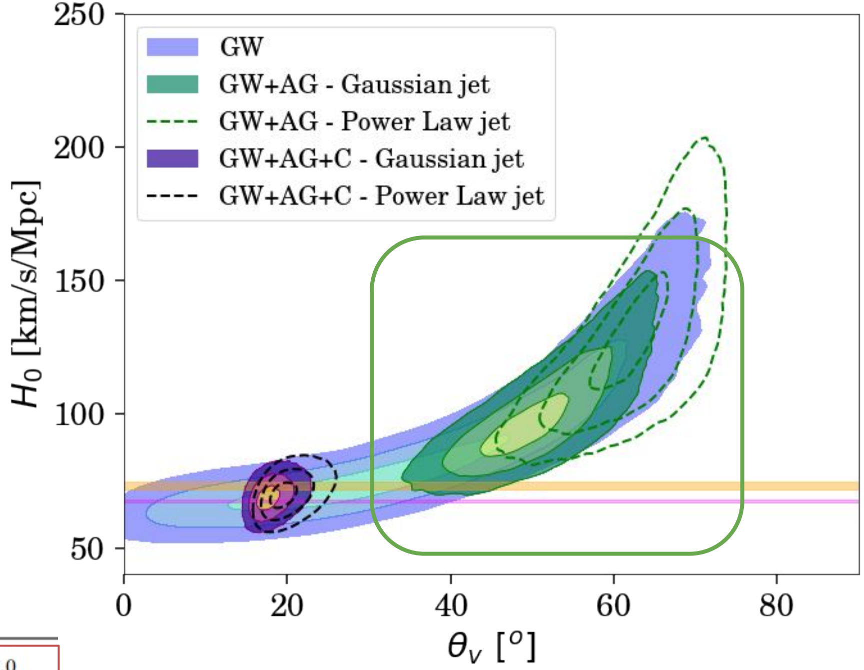
GW+AG analysis



Afterglow light curve

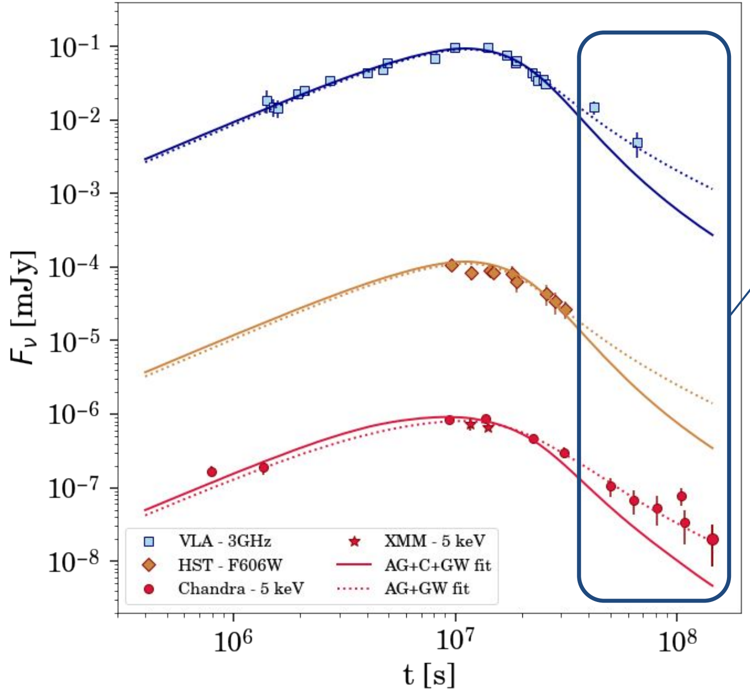
Observations in X-rays, optical and radio bands

$d_{\rm L}$ [Mpc]	$31.3^{+3.0}_{-3.6}$
$\theta_{\rm v}$ [deg]	50^{+5}_{-5}
$\theta_{\rm JN}$ [deg]	130^{+5}_{-5}



$$H_0 = 96^{+13}_{-10}\ \mathrm{km\ s^{-1}Mpc^{-1}}$$

Why is the afterglow not enough?



Excess in the flux at late times?

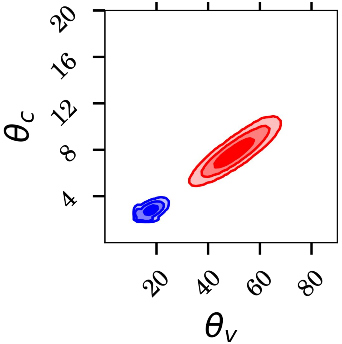
+

There are other degeneracies (proper of the light curve modeling) that influence:

$\boldsymbol{\theta v}$ (viewing angle)

$\boldsymbol{d_L}$ (luminosity distance)

H_0 (Hubble constant)

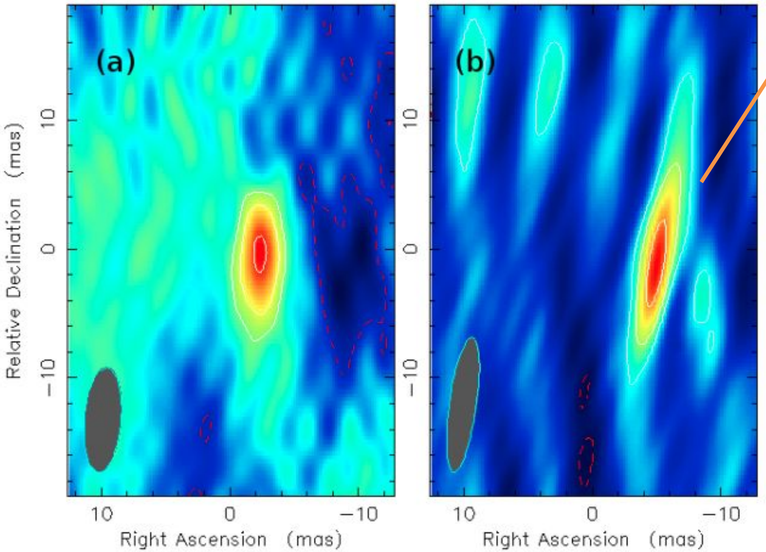


$\boldsymbol{\theta c}$: jet opening angle

GW+AG+C (Centroid) analysis

Centroid motion of the relativistic jet

Radio Observations taken with VLBI (Very Long Baseline Interferometry)

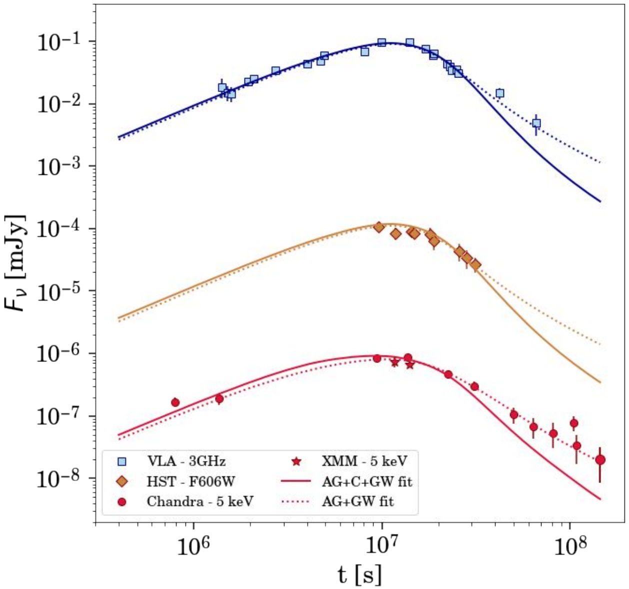


75 days

230 days

movement of the order of mas

Mooley et al, 2018

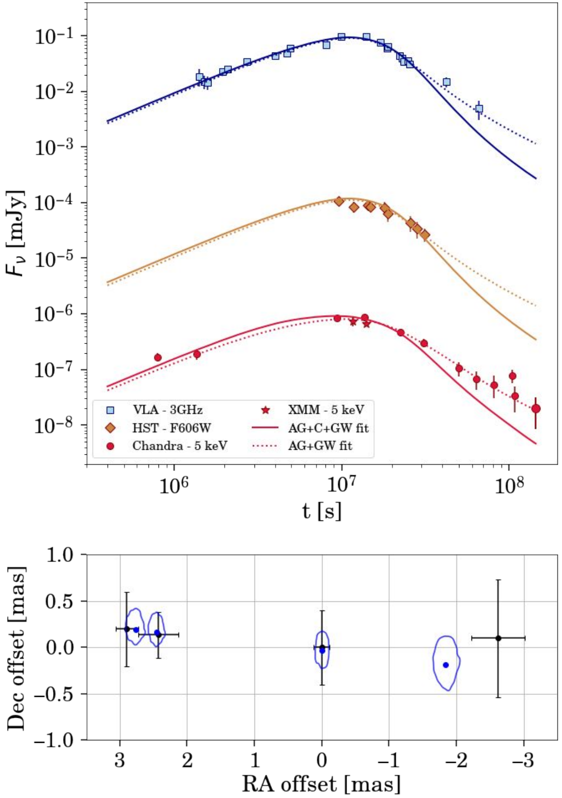


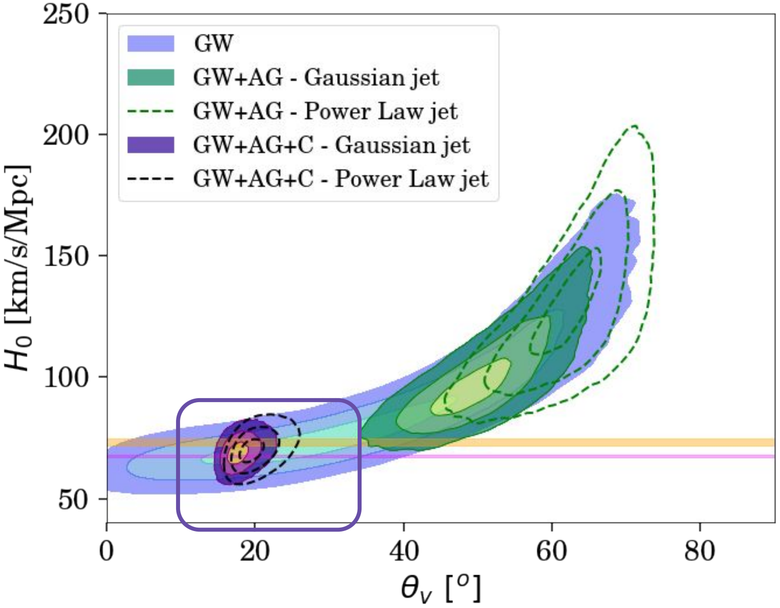
Afterglow light curve

Observations in X-rays, optical and radio bands

GW+AG+C: the Hubble constant

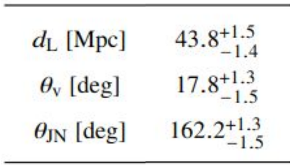
Gianfagna et al, 2023, submitted, arXiv:2309.17073





Afterglow shrinks the degeneracy

Afterglow and centroid break it!



d_{L} [Mpc]	$43.8^{+1.5}_{-1.4}$
θ_{v} [deg]	$17.8^{+1.3}_{-1.5}$
θ_{JN} [deg]	$162.2^{+1.3}_{-1.5}$

H0 results:

GW:

$$77^{+21}_{-10}\ \mathrm{km\ s^{-1} Mpc^{-1}}$$

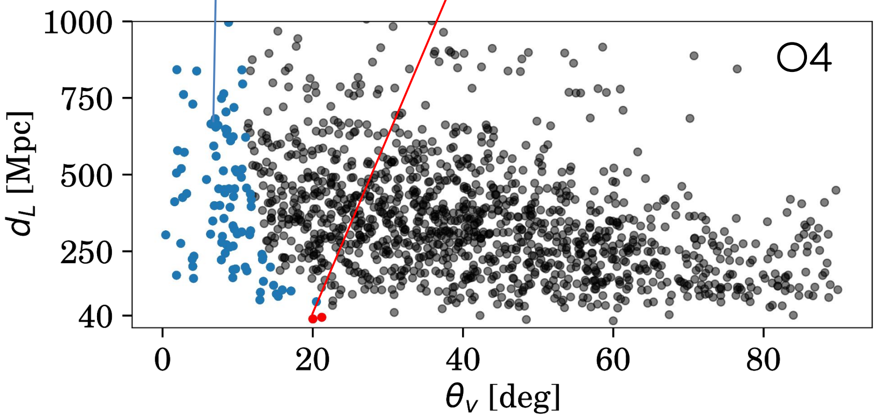
GW+AG+C:

$$68.9^{+4.4}_{-4.3}\ \mathrm{km\ s^{-1} Mpc^{-1}}$$

How likely is a new centroid measurement?

Flux > Sensitivity

Flux > sensitivity
Offset > resolution



GW simulations of binary neutron star mergers (*Petrov et al, 2022*)

θv

d_L

We generate the afterglow light curve and centroid motion

Considering VLBI sensitivity and resolution		GW rates	GW+AG rates	GW+AG+C rates
O4	2023-2025	$36^{+49}_{-22}\mathrm{yr}^{-1}$	$2^{+3}_{-1}\mathrm{yr}^{-1}$	$0.05^{+0.07}_{-0.03}\mathrm{yr}^{-1}$

Same for O5!

Conclusions

Binary neutron star mergers are interesting events in:

- ASTROPHYSICS:
  - Information about the **geometry** of the event and on the **relativistic jet theory**.

- COSMOLOGY: estimation of **H_0**, independently from any distance ladder:
  - GW-only fit: 20% error on **H_0**, because of d_L - θv degeneracy;
  - GW+AG fit: cut the tails of the degeneracy, but H_0 is high;
  - GW+AG+C fit: degeneracy broken and acceptable H_0. The **uncertainty** on H_0 is still **large** (~4 km/s/Mpc), with respect to the *Planck* and SH0ES measurements (~1 km/s/Mpc);
  - **The more the number of counterparts, the more robust is H_0.**

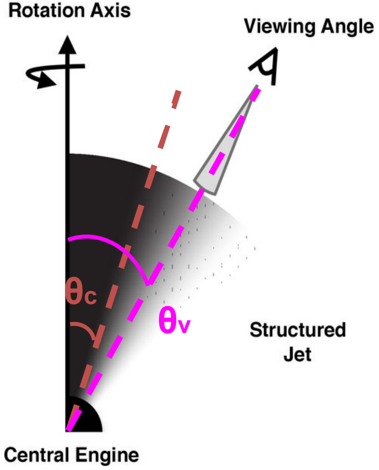
THANK YOU for your attention!

Backup slides

Previous work

Gianfagna et al, 2023, MNRAS

θ_c and θ_v are correlated



Fixed d_L

EM fit:

Further the event → Worse the degeneracy

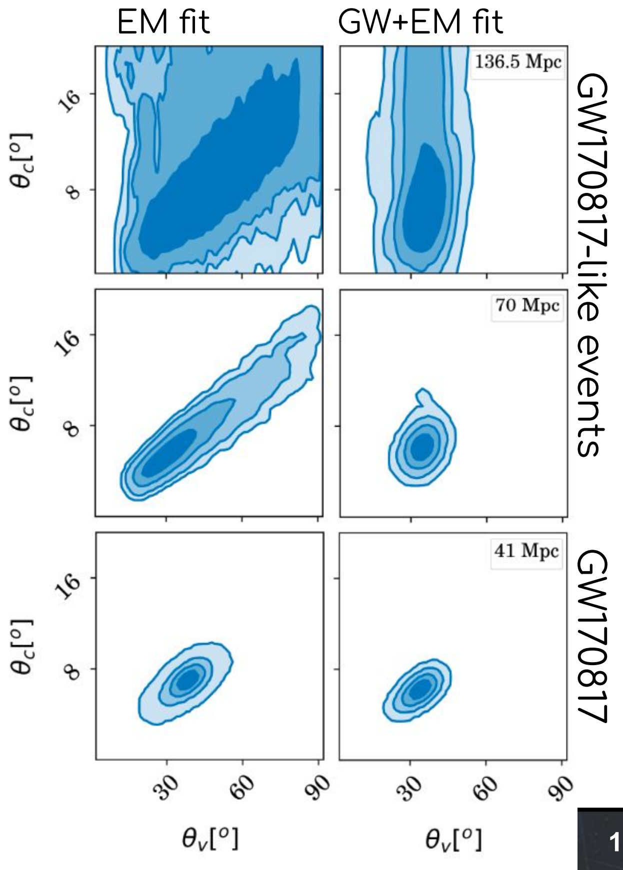
(@ 136.5 Mpc the two angles unconstrained above 1σ).

GW+EM fit:

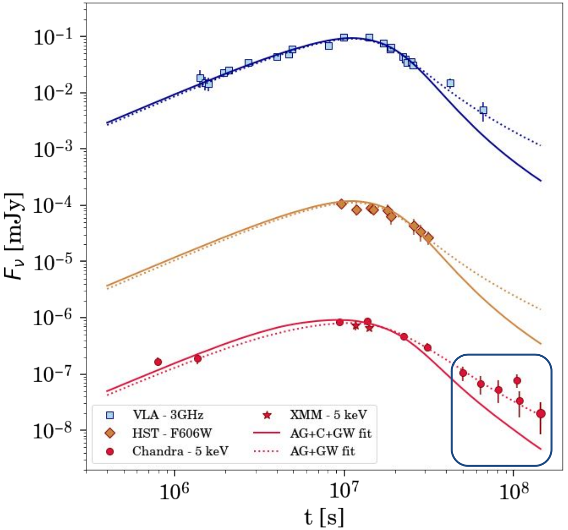
GW acts on θv → large distance: θc unconstrained above $1\ \sigma$.

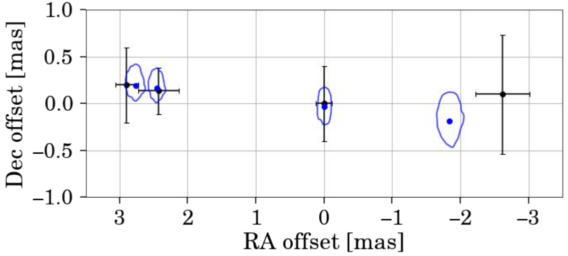
70 Mpc: EM dataset can constrain better these angles. Still a strong degeneracy, broken by the GW.

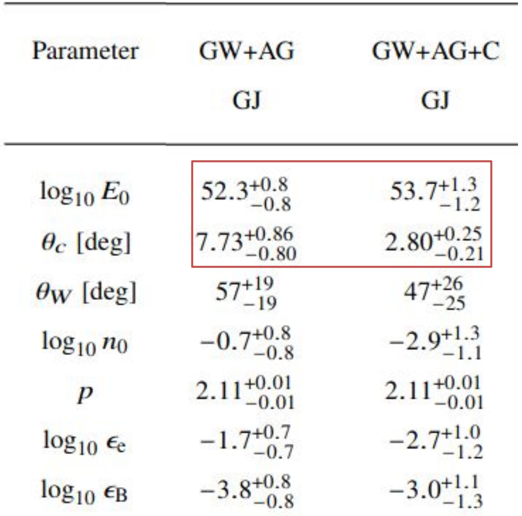
41 Mpc: angles already very well constrained, (well sampled light curve), GW domain ease the degeneracy.



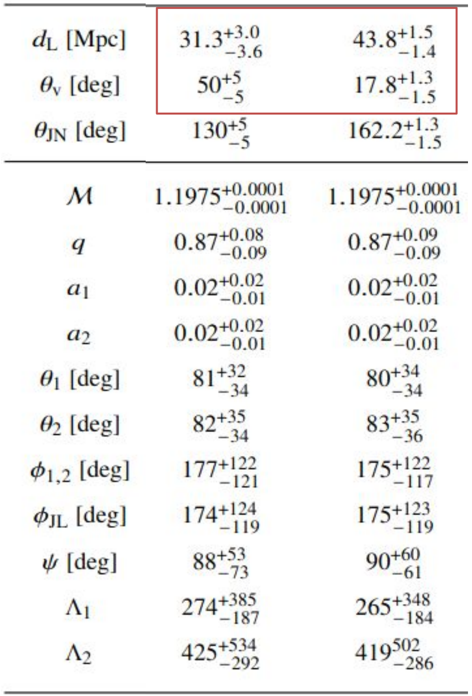
Gaussian jet fit







Parameter	GW+AG GJ	GW+AG+C GJ
$\log_{10} E_0$	$52.3^{+0.8}_{-0.8}$	$53.7^{+1.3}_{-1.2}$
θ_c [deg]	$7.73^{+0.86}_{-0.80}$	$2.80^{+0.25}_{-0.21}$
θ_W [deg]	57^{+19}_{-19}	47^{+26}_{-25}
$\log_{10} n_0$	$-0.7^{+0.8}_{-0.8}$	$-2.9^{+1.3}_{-1.1}$
p	$2.11^{+0.01}_{-0.01}$	$2.11^{+0.01}_{-0.01}$
$\log_{10} \epsilon_e$	$-1.7^{+0.7}_{-0.7}$	$-2.7^{+1.0}_{-1.2}$
$\log_{10} \epsilon_B$	$-3.8^{+0.8}_{-0.8}$	$-3.0^{+1.1}_{-1.3}$

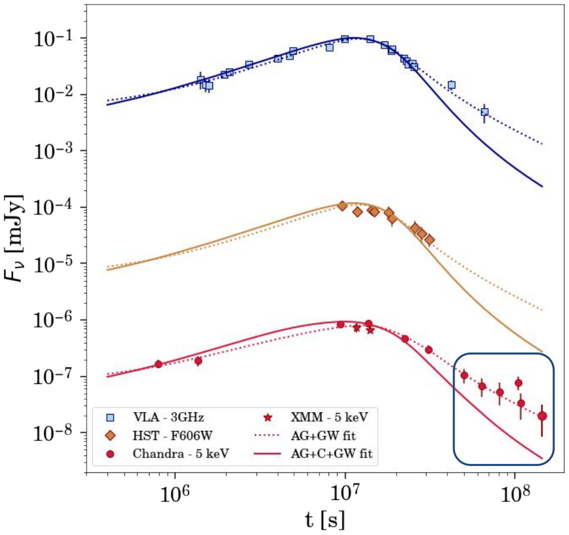


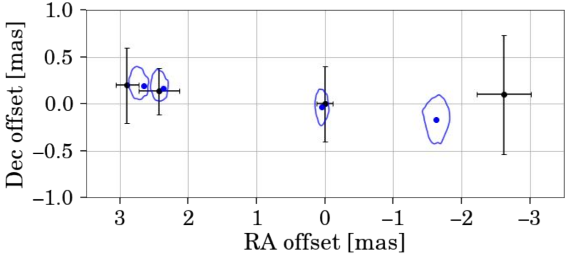
d_L [Mpc]	$31.3^{+3.0}_{-3.6}$	$43.8^{+1.5}_{-1.4}$
θ_v [deg]	50^{+5}_{-5}	$17.8^{+1.3}_{-1.5}$
θ_{JN} [deg]	130^{+5}_{-5}	$162.2^{+1.3}_{-1.5}$
$\mathcal{M}$	$1.1975^{+0.0001}_{-0.0001}$	$1.1975^{+0.0001}_{-0.0001}$
q	$0.87^{+0.08}_{-0.09}$	$0.87^{+0.09}_{-0.09}$
a_1	$0.02^{+0.02}_{-0.01}$	$0.02^{+0.02}_{-0.01}$
a_2	$0.02^{+0.02}_{-0.01}$	$0.02^{+0.02}_{-0.01}$
θ_1 [deg]	81^{+32}_{-34}	80^{+34}_{-34}
θ_2 [deg]	82^{+35}_{-34}	83^{+35}_{-36}
$\phi_{1,2}$ [deg]	177^{+122}_{-121}	175^{+122}_{-117}
ϕ_{JL} [deg]	174^{+124}_{-119}	175^{+123}_{-119}
ψ [deg]	88^{+53}_{-73}	90^{+60}_{-61}
Λ_1	274^{+385}_{-187}	265^{+348}_{-184}
Λ_2	425^{+534}_{-292}	419^{502}_{-286}

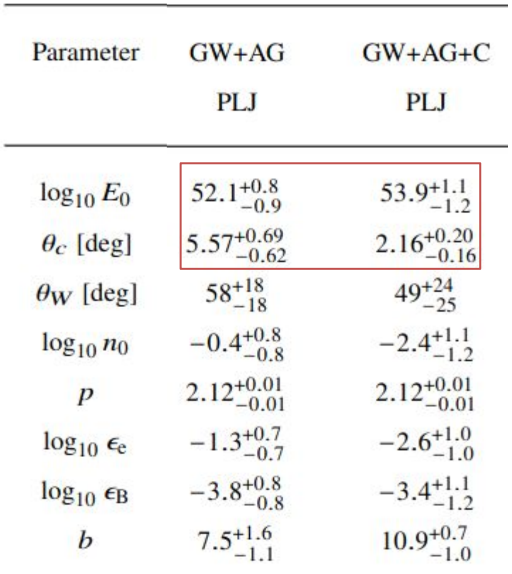
GW+AG
- Large θ_v
- Broader profile
- Less energy on the jet axis

GW+AG+C
- Small θ_v
- Highly collimated jet
- Large energy on the jet axis

Power law jet fit



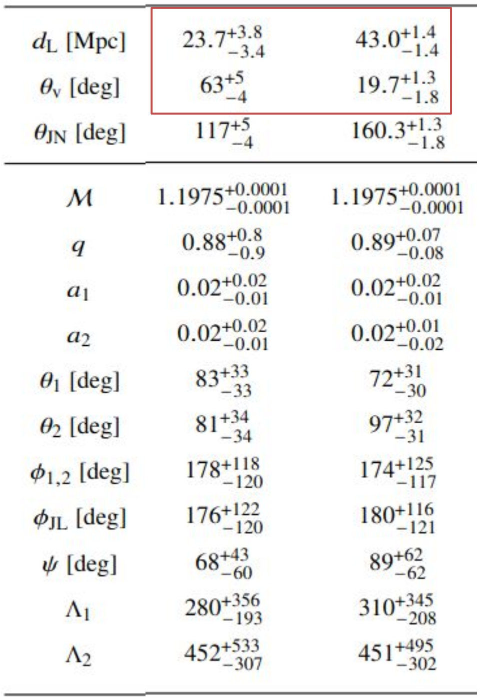




Parameter	GW+AG PLJ	GW+AG+C PLJ
$\log_{10} E_0$	$52.1^{+0.8}_{-0.9}$	$53.9^{+1.1}_{-1.2}$
θ_c [deg]	$5.57^{+0.69}_{-0.62}$	$2.16^{+0.20}_{-0.16}$
θ_W [deg]	58^{+18}_{-18}	49^{+24}_{-25}
$\log_{10} n_0$	$-0.4^{+0.8}_{-0.8}$	$-2.4^{+1.1}_{-1.2}$
p	$2.12^{+0.01}_{-0.01}$	$2.12^{+0.01}_{-0.01}$
$\log_{10} \epsilon_e$	$-1.3^{+0.7}_{-0.7}$	$-2.6^{+1.0}_{-1.0}$
$\log_{10} \epsilon_B$	$-3.8^{+0.8}_{-0.8}$	$-3.4^{+1.1}_{-1.2}$
b	$7.5^{+1.6}_{-1.1}$	$10.9^{+0.7}_{-1.0}$

GW+AG
- Large θ_v
- Broader profile
- Less energy on the jet axis

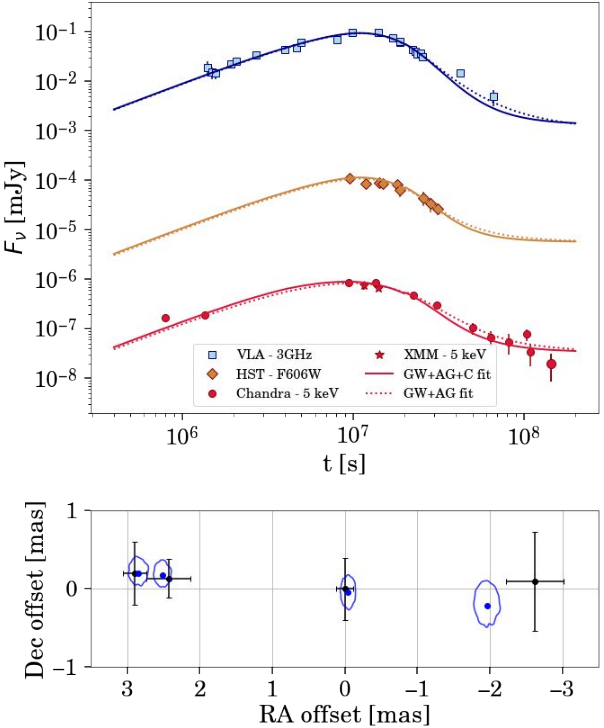
GW+AG+C
- Small θ_v
- Highly collimated jet
- Large energy on the jet axis

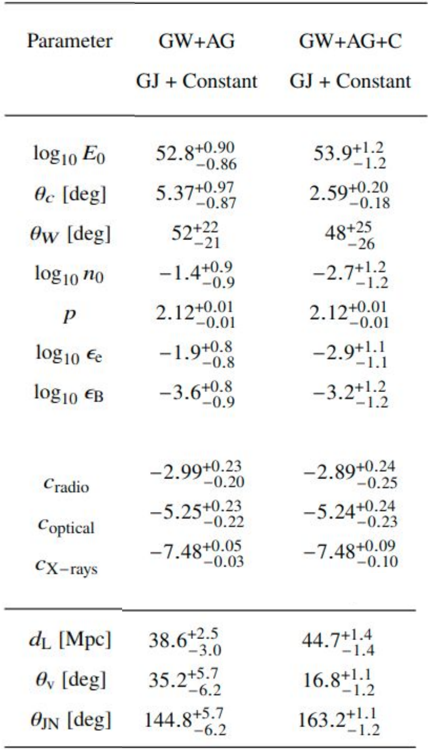


d_L [Mpc]	$23.7^{+3.8}_{-3.4}$	$43.0^{+1.4}_{-1.4}$
θ_v [deg]	63^{+5}_{-4}	$19.7^{+1.3}_{-1.8}$
θ_{JN} [deg]	117^{+5}_{-4}	$160.3^{+1.3}_{-1.8}$
$\mathcal{M}$	$1.1975^{+0.0001}_{-0.0001}$	$1.1975^{+0.0001}_{-0.0001}$
q	$0.88^{+0.8}_{-0.9}$	$0.89^{+0.07}_{-0.08}$
a_1	$0.02^{+0.02}_{-0.01}$	$0.02^{+0.02}_{-0.01}$
a_2	$0.02^{+0.02}_{-0.01}$	$0.02^{+0.01}_{-0.02}$
θ_1 [deg]	83^{+33}_{-33}	72^{+31}_{-30}
θ_2 [deg]	81^{+34}_{-34}	97^{+32}_{-31}
$\phi_{1,2}$ [deg]	178^{+118}_{-120}	174^{+125}_{-117}
ϕ_{JL} [deg]	176^{+122}_{-120}	180^{+116}_{-121}
ψ [deg]	68^{+43}_{-60}	89^{+62}_{-62}
Λ_1	280^{+356}_{-193}	310^{+345}_{-208}
Λ_2	452^{+533}_{-307}	451^{+495}_{-302}

Same as Gaussian jet !

Gaussian jet with constant component

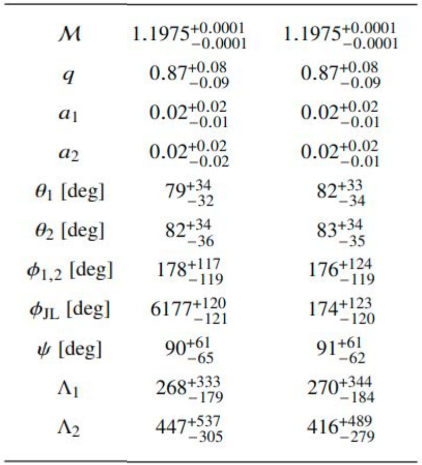




Parameter	GW+AG	GW+AG+C
	GJ + Constant	GJ + Constant
$\log_{10} E_0$	$52.8^{+0.90}_{-0.86}$	$53.9^{+1.2}_{-1.2}$
θ_c [deg]	$5.37^{+0.97}_{-0.87}$	$2.59^{+0.20}_{-0.18}$
θ_W [deg]	52^{+22}_{-21}	48^{+25}_{-26}
$\log_{10} n_0$	$-1.4^{+0.9}_{-0.9}$	$-2.7^{+1.2}_{-1.2}$
p	$2.12^{+0.01}_{-0.01}$	$2.12^{+0.01}_{-0.01}$
$\log_{10} \epsilon_e$	$-1.9^{+0.8}_{-0.8}$	$-2.9^{+1.1}_{-1.1}$
$\log_{10} \epsilon_B$	$-3.6^{+0.8}_{-0.9}$	$-3.2^{+1.2}_{-1.2}$
$c_{\rm radio}$	$-2.99^{+0.23}_{-0.20}$	$-2.89^{+0.24}_{-0.25}$
$c_{\rm optical}$	$-5.25^{+0.23}_{-0.22}$	$-5.24^{+0.24}_{-0.23}$
$c_{\rm X-rays}$	$-7.48^{+0.05}_{-0.03}$	$-7.48^{+0.09}_{-0.10}$
d_L [Mpc]	$38.6^{+2.5}_{-3.0}$	$44.7^{+1.4}_{-1.4}$
θ_v [deg]	$35.2^{+5.7}_{-6.2}$	$16.8^{+1.1}_{-1.2}$
θ_{JN} [deg]	$144.8^{+5.7}_{-6.2}$	$163.2^{+1.1}_{-1.2}$

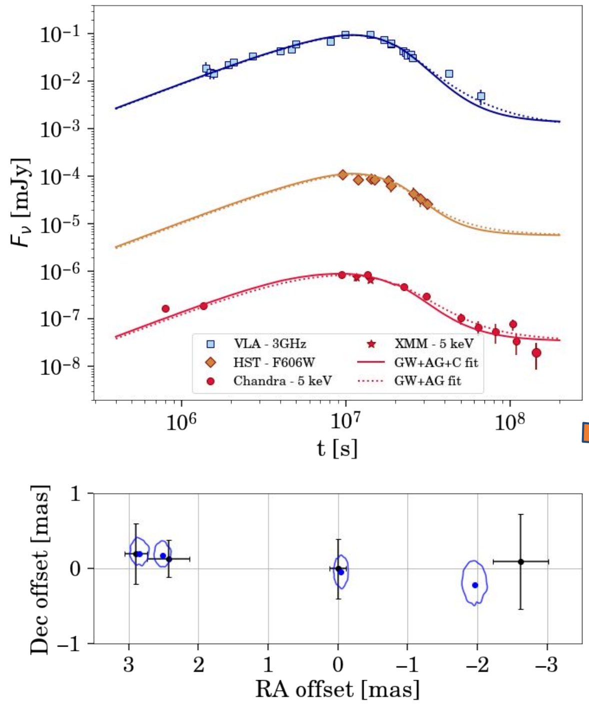
Constant flux component at late time of the type:

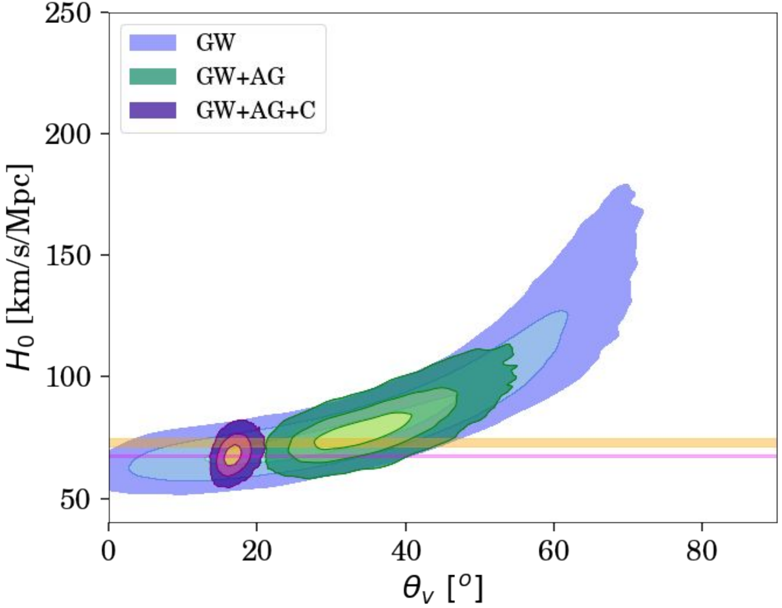
$$F_\nu = F_{\nu,\rm agpy} + 10^c$$



$\mathcal{M}$	$1.1975^{+0.0001}_{-0.0001}$	$1.1975^{+0.0001}_{-0.0001}$
q	$0.87^{+0.08}_{-0.09}$	$0.87^{+0.08}_{-0.09}$
a_1	$0.02^{+0.02}_{-0.01}$	$0.02^{+0.02}_{-0.01}$
a_2	$0.02^{+0.02}_{-0.02}$	$0.02^{+0.02}_{-0.01}$
θ_1 [deg]	79^{+34}_{-32}	82^{+33}_{-34}
θ_2 [deg]	82^{+34}_{-36}	83^{+34}_{-35}
$\phi_{1,2}$ [deg]	178^{+117}_{-119}	176^{+124}_{-119}
ϕ_{JL} [deg]	6177^{+120}_{-121}	174^{+123}_{-120}
ψ [deg]	90^{+61}_{-65}	91^{+61}_{-62}
Λ_1	268^{+333}_{-179}	270^{+344}_{-184}
Λ_2	447^{+537}_{-305}	416^{+489}_{-279}

Including a constant flux component at late times





Adding a constant flux component at late times shifts H0 of GW+AG fit

	GW+AG	GW+AG+C
d_{L} [Mpc]	$38.6^{+2.5}_{-3.0}$	$44.7^{+1.4}_{-1.4}$
θ_{v} [deg]	$35.2^{+5.7}_{-6.2}$	$16.8^{+1.1}_{-1.2}$
θ_{JN} [deg]	$144.8^{+5.7}_{-6.2}$	$163.2^{+1.1}_{-1.2}$

H0 results:

GW:

$$77^{+21}_{-10}\ \mathrm{km\ s^{-1}Mpc^{-1}}$$

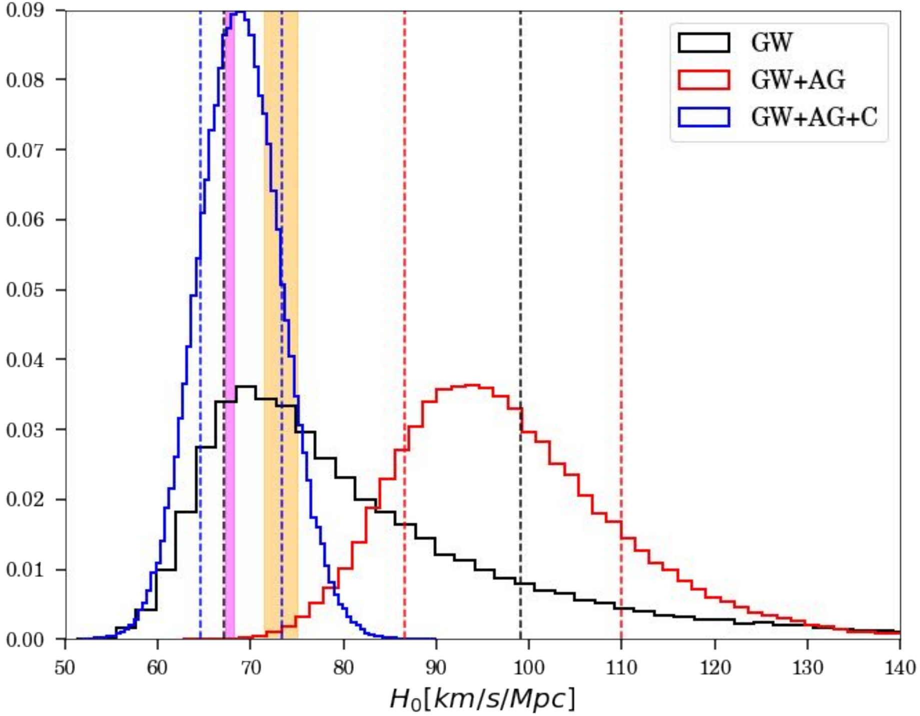
GW+AG+C:

$$67.8^{+4.3}_{-4.2}\ \mathrm{km\ s^{-1}Mpc^{-1}}$$

GW+AG:

$$78.5^{+7.9}_{-6.4}\ \mathrm{km\ s^{-1}Mpc^{-1}}$$

H_0 posterior



H_0 results for Gaussian jet:

GW: 77^{+21}_{-10} km s^{-1}Mpc^{-1}

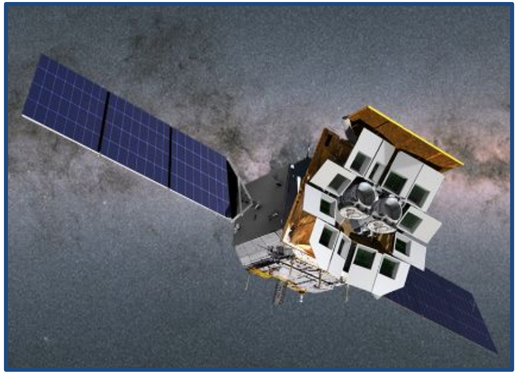
GW+AG+C: $68.9^{+4.4}_{-4.3}$ km s^{-1}Mpc^{-1}

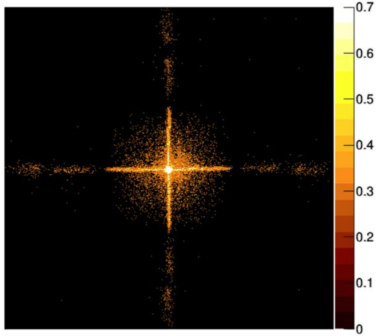
GW+AG: 96^{+13}_{-10} km s^{-1}Mpc^{-1}

Planck: 67.4 ± 0.5 km s^{-1}Mpc^{-1}

SH0ES: 74.0 ± 1.4 km s^{-1}Mpc^{-1}

Einstein Probe





Mission of the **Chinese Academy of Sciences (CAS)** dedicated to discover **high-energy transients and monitor variable objects**.

Launch: end 2023. Lifetime of 3 years. Einstein Probe website.

2 telescopes on board:

- **WXT**: **very large instantaneous field-of-view** (3600 square degrees) achieved by using established technology of novel **lobster-eye optics**. Unprecedentedly **high sensitivity** with respect to previous and existing X-ray all-sky monitors (eROSITA and XMM-Newton). Bandpass: **0.5-4.0 keV**.

- **FXT**: X-ray focusing telescope (Wolter-I) with a larger effective area to perform **follow-up characterization**. It has a **narrow field of view** (60 arcmin in diameter) and a source localization error of 5-15 arcsec (90% c.l.) depending on the source strength. **Bandpass: 0.5-10 keV**.