Hubble constant estimation from GW and EM joint measures

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Vulcano Workshop 2024 - Frontier Objects in Astrophysics and Particle Physics

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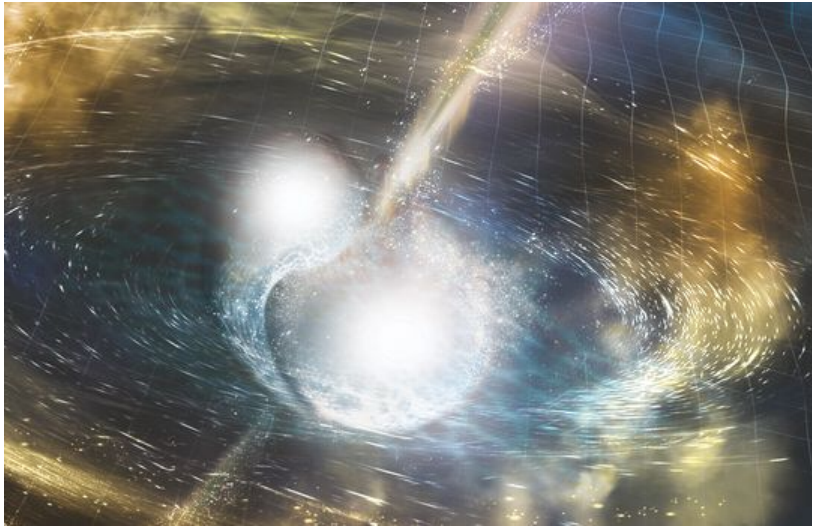
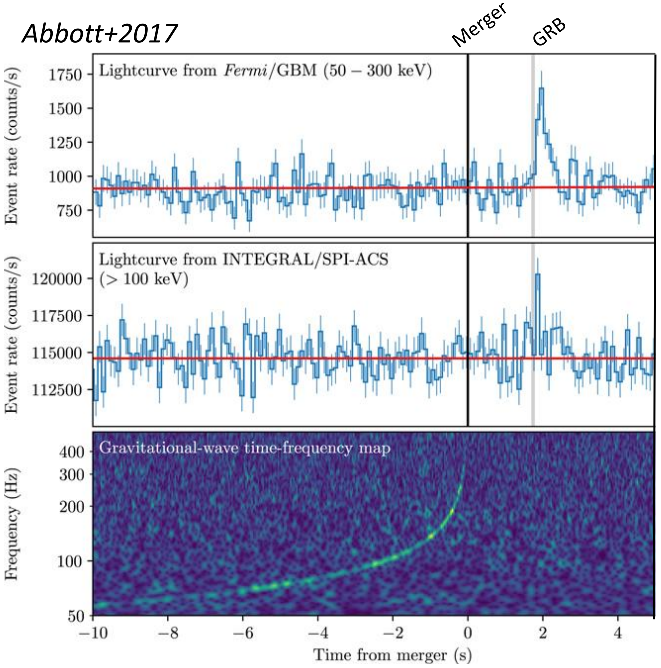
Outline

1. Introduction: binary neutron star mergers and GW170817
2. Methods: joint fit of gravitational waves (GW) and electromagnetic (EM) domains
3. GW170817: two types of analysis
4. GW170817: the estimation of the Hubble constant (H_0)
5. Future prospects
6. Conclusions



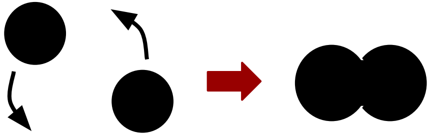
Binary neutron star (BNS) mergers: GW170817

Abbott+2017



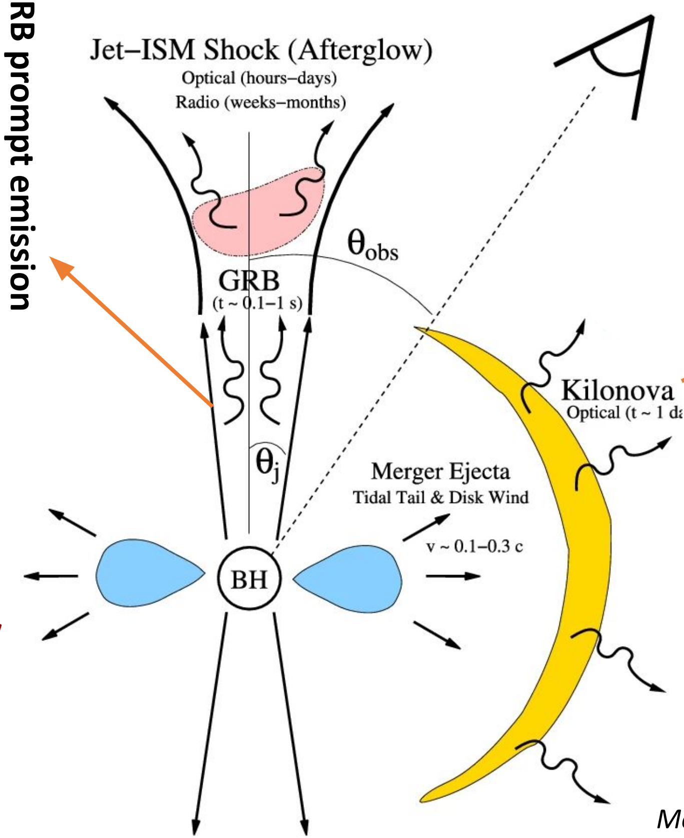
GRB prompt emission

Gravitational wave



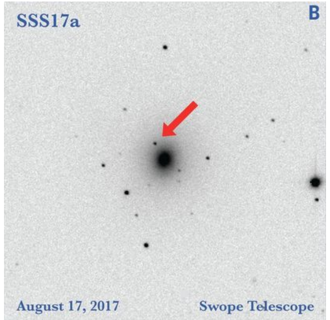
Neutron stars spiralizing

Merger



Metzger,Berger+2012

Optical (Swope)



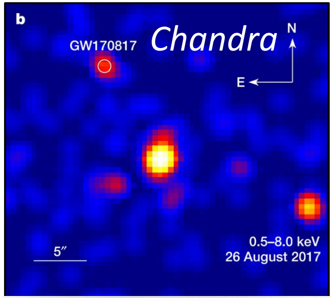
Coulter+2017

Kilonova

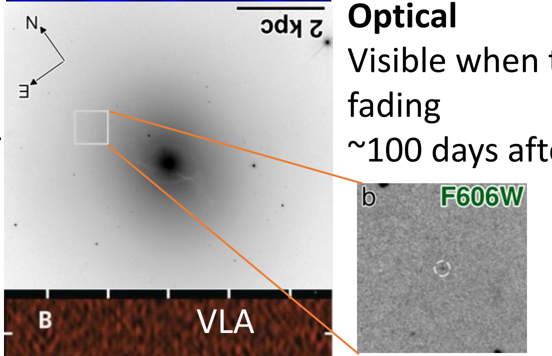
~11 hrs after the merger

Binary neutron star (BNS) mergers: GW170817

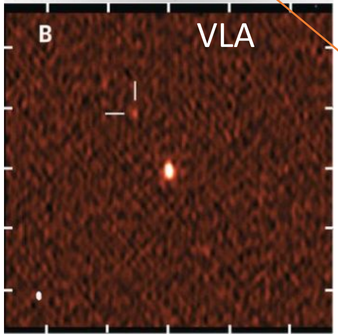
Troja+2017



Lyman+2018



Hallinan+2017

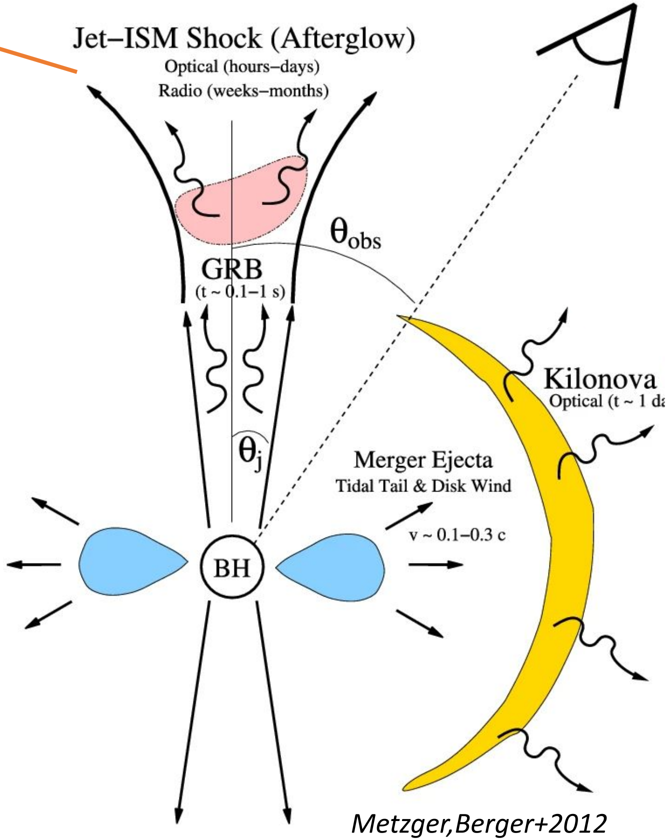


Afterglow:
Long lasting emission:

X-rays
9 days after the merger

Optical
Visible when the kilonova started fading
~100 days after the merger

Radio
16 days after the merger



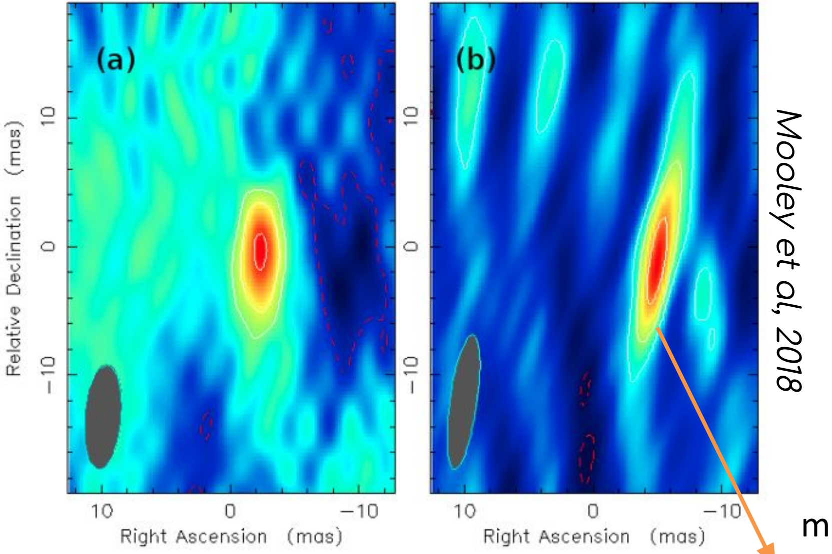
Metzger,Berger+2012

GW170817 observations

Centroid motion of the relativistic jet

Radio Observations taken with VLBI (Very Long Baseline Interferometry)

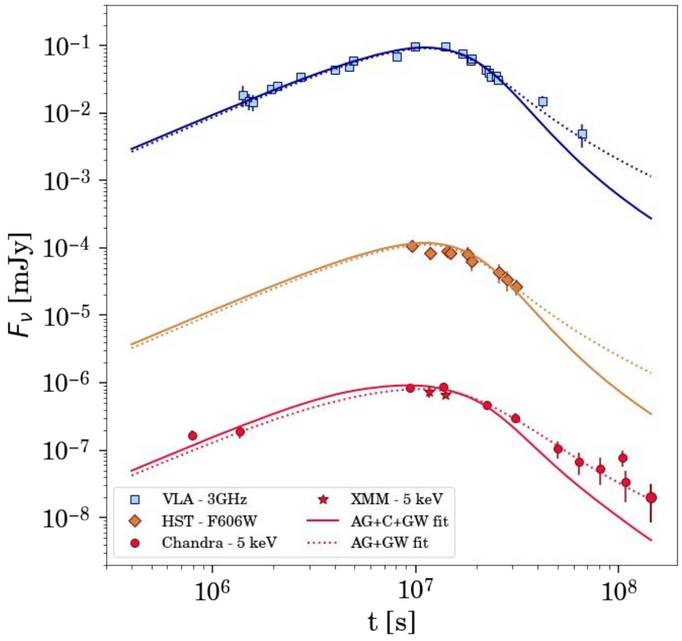
@ 75, 206, 230 days



75 days

230 days

movement of the order of mas



Afterglow light curve

Observations in X-rays, optical and radio bands

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GW170817 jet type

Power law jet:

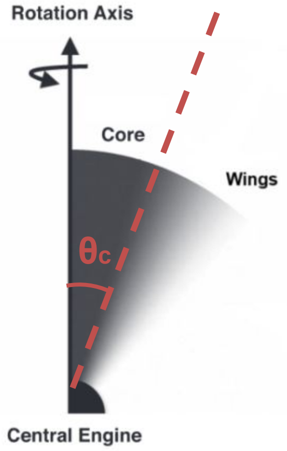
$$E(\theta) = E_0 \left(1 + \frac{\theta^2}{b\theta_c^2}\right)^{-b/2}$$

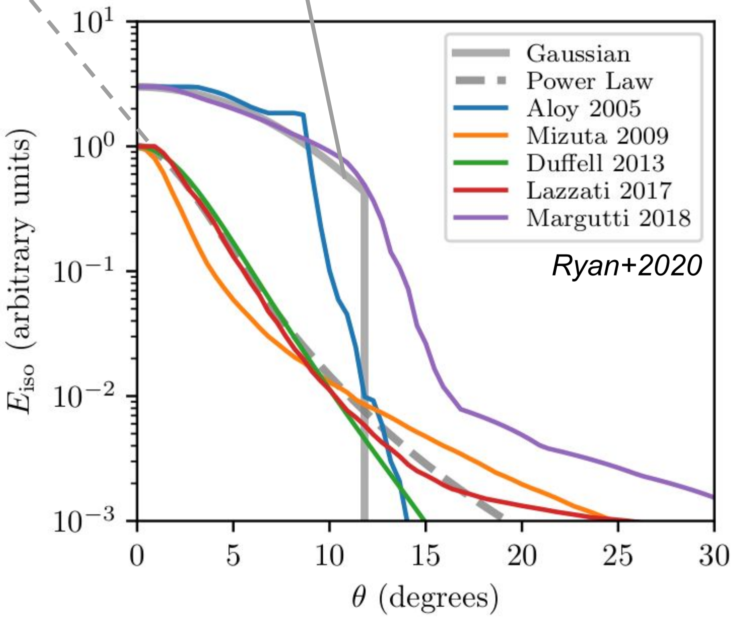
Gaussian jet:

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

Scenario i: Uniform Top-hat Jet

Scenario ii: Structured Jet





GW and afterglow modelling

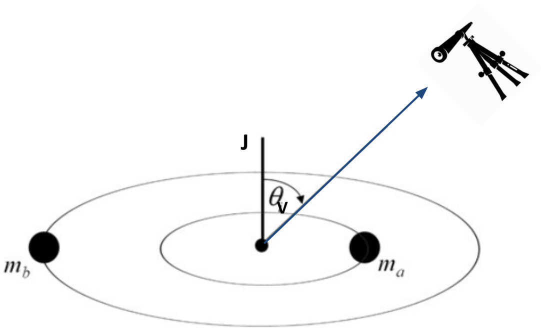
A novel approach to asses these problems is a joint analysis of GW and EM domains:

Afterglow

Synchrotron parameters

Energetics

Geometry:
Jet core angle,
Viewing angle/Inclination — θv
Luminosity distance — d_L



Gravitational Waves

Intrinsic parameters
NS Masses, spins and tidal parameters

Extrinsic parameters
RA, Dec
Inclination
Luminosity distance

Shared parameters!

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Joint fit and H_0 estimation

Bayes theorem

$$\text{Posterior} = \frac{\text{Likelihood} \times \text{Prior}}{\text{Evidence}}$$

Likelihood = EM Likelihood x GW Likelihood

Gaussian distributions

3 sets of parameters:

1. GW-only
2. EM-only
3. **GW+EM: θv and d_L**

Only from general theory of relativity

NO distance ladders involved !

In the local Universe

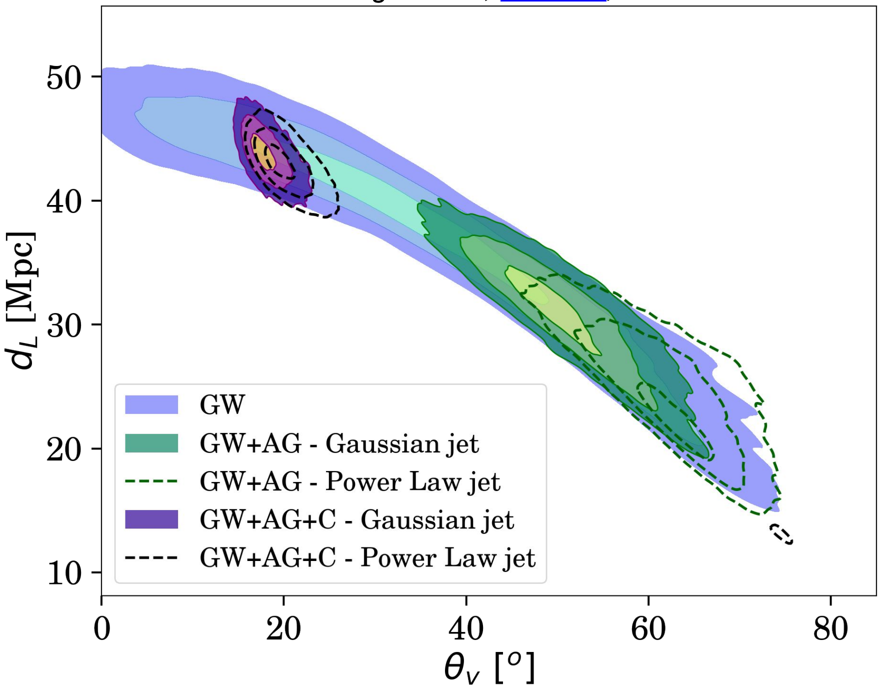
$$v_H = cz = H_0 D_L$$

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

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

The need for a joint analysis: d_L - θ_v degeneracy

Gianfagna et al, MNRAS, 2024



- 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?

With an independent dataset:

Afterglow

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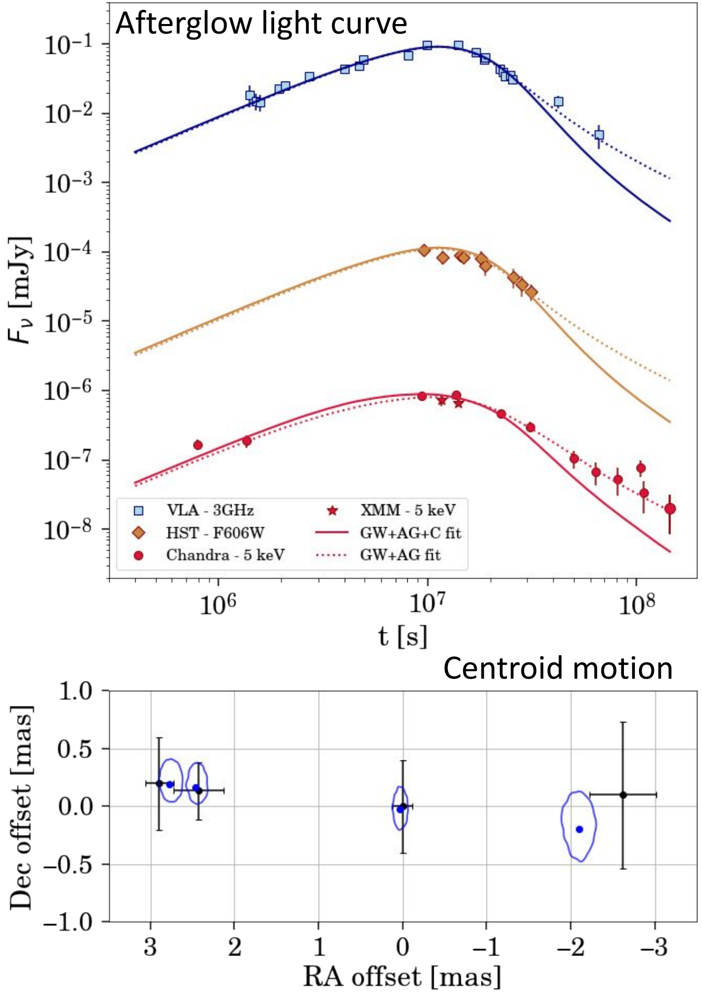


Two kinds of analysis

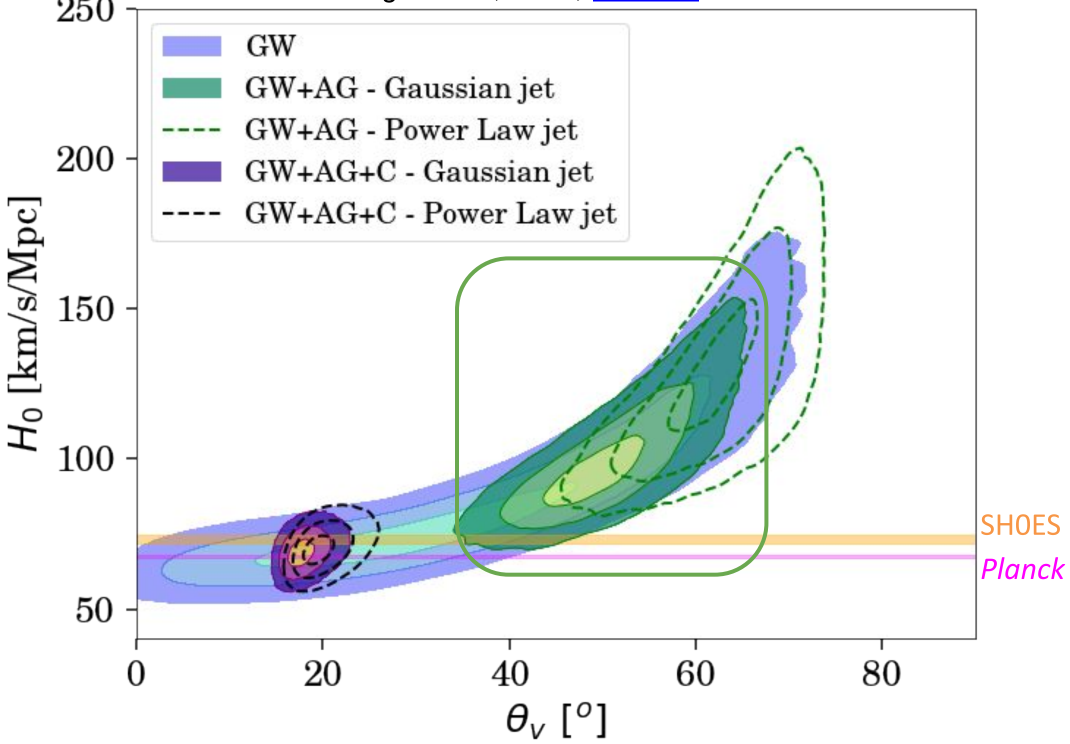
1. GW and Afterglow light curve (**GW+AG**):
   a. Wider jet
   b. Less energy on the jet axis

2. GW, afterglow light curve and centroid motion (**GW+AG+C**):
   a. Collimated jet
   b. Energetic

Parameter	GW-only	GW + AG GJ	GW+AG + C GJ
$\log_{10}E_0$	–	$52.31^{+0.82}_{-0.80}$	$54.50^{+0.28}_{-0.33}$
θ_c [°]	–	$7.73^{+0.86}_{-0.80}$	$2.85^{+0.24}_{-0.20}$

GW+AG: the Hubble constant

Gianfagna et al, 2024, MNRAS



Problem of the flux excess at late times

d_L [Mpc]	$31.3^{+3.0}_{-3.6}$
θ_v [deg]	50^{+5}_{-5}

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

$H_0 = 77^{+21}_{-10}$ km s^{-1}Mpc^{-1}

20% error

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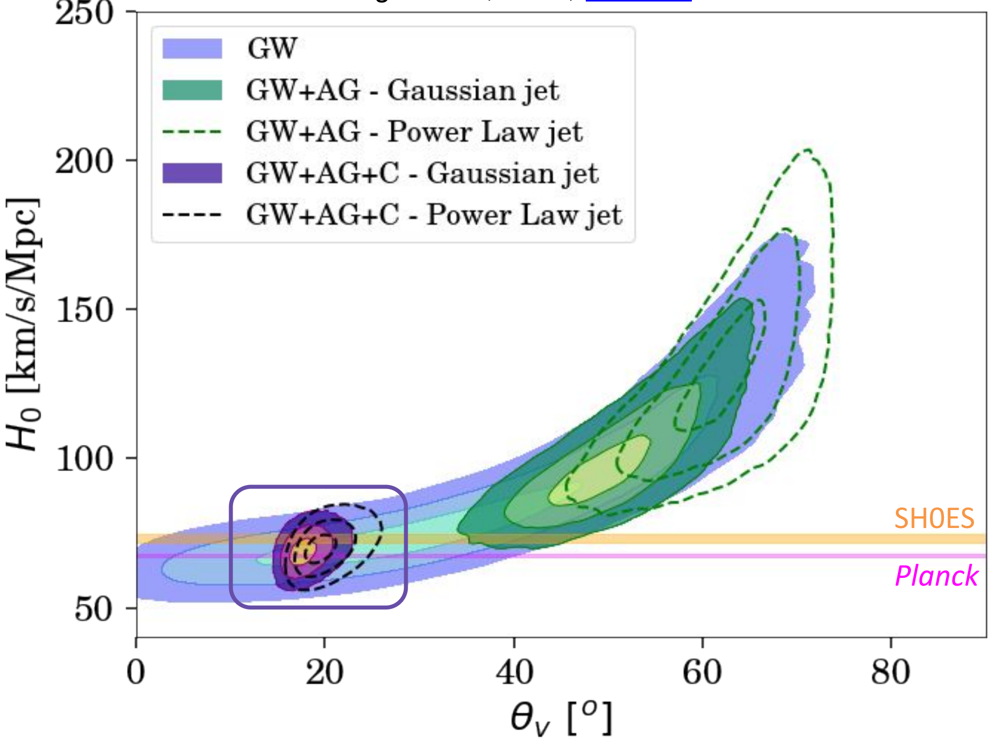
GW+AG+C: The Hubble constant

Gianfagna et al, 2024, MNRAS



Afterglow and centroid **break** the degeneracy!

$H_0 = 77^{+21}_{-10}$ km s^{-1}Mpc^{-1}

$H_0 = 69.0^{+4.4}_{-4.3}$ km s^{-1}Mpc^{-1}

Seems to prefer *Planck* H_0

3x more precise than GW

d_L [Mpc]	$43.7^{+1.4}_{-1.4}$
θ_v [deg]	$18.2^{+1.2}_{-1.5}$

How likely is a new centroid measurement?

GW simulations of binary neutron star mergers (*Petrov et al, 2022*) → θ_v, d_L → Generate the afterglow light curve and centroid motion

Considering VLBI sensitivity (24 uJy) and resolution (1.5 mas)

H_0 uncertainty:

		GW rates	GW+AG+C rates (4 km/s/Mpc)	GW+AG rates (10 km/s/Mpc)
O5	~ 2027	$180^{+220}_{-100}\,\mathrm{yr}^{-1}$	$0.2^{+0.2}_{-0.1}\,\mathrm{yr}^{-1}$	$10^{+13}_{-6}\,\mathrm{yr}^{-1}$

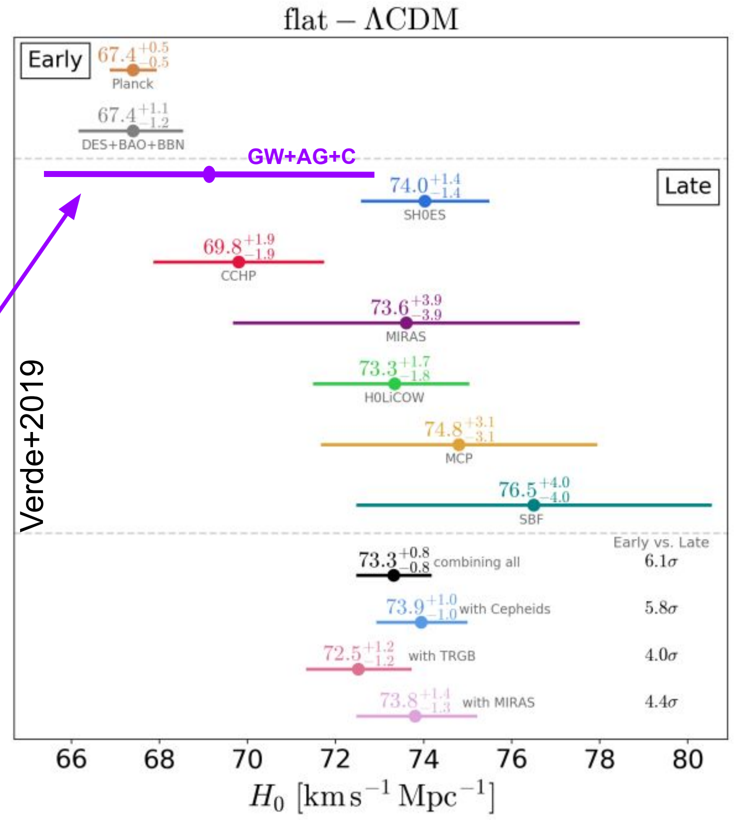
~10 events per year in **O5**.

At the end of O5 we could be able to reach the **SH0ES** sensitivity of **1.5 km/s/Mpc**

Conclusions

From GW and afterglow emission from **binary neutron star mergers**, we can estimate the Hubble constant, independently from any distance ladder:

- ***θv–d$_L$* degeneracy:** plays a crucial role in its estimation;
- Considering the complete dataset, the **uncertainty** on H_0 is still **large** (~4 km/s/Mpc), with respect to the *Planck* and SH0ES measurements (< 1.5 km/s/Mpc);
- We need more events (~30) to get to the SH0ES precision.



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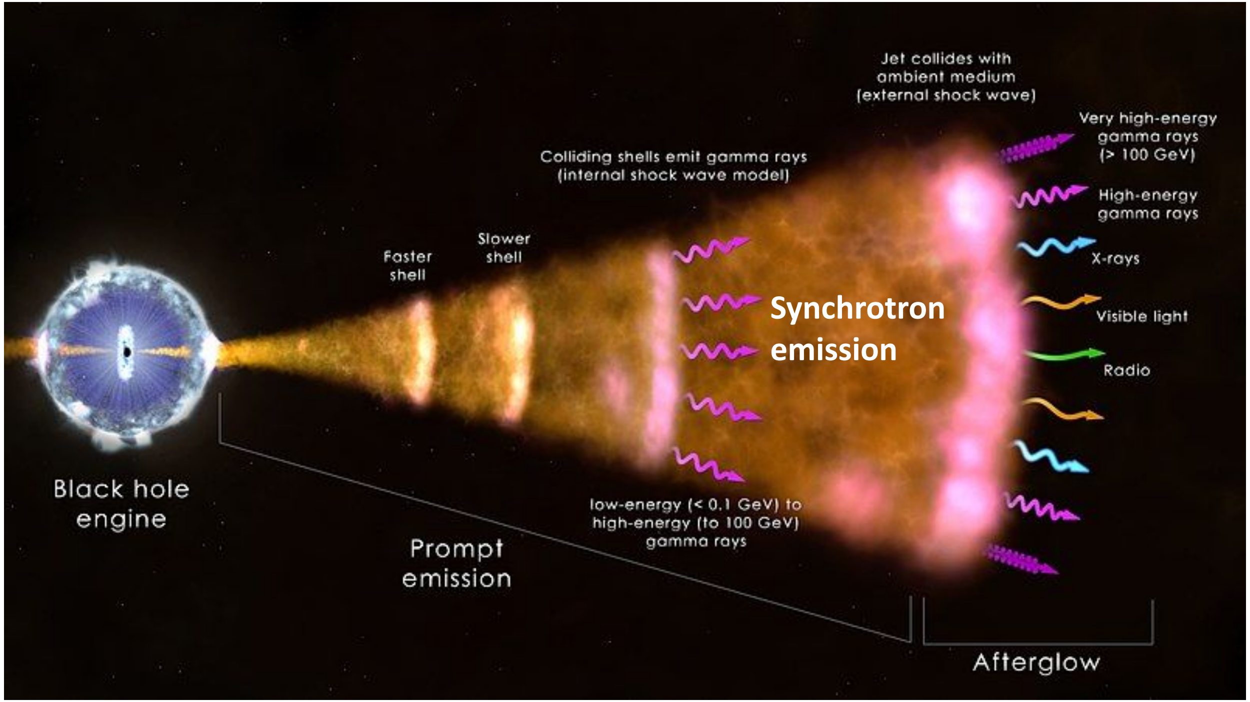
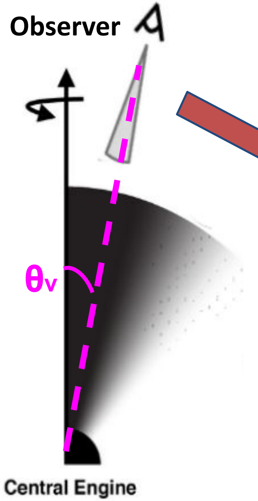
THANK YOU for your attention!

Backup slides

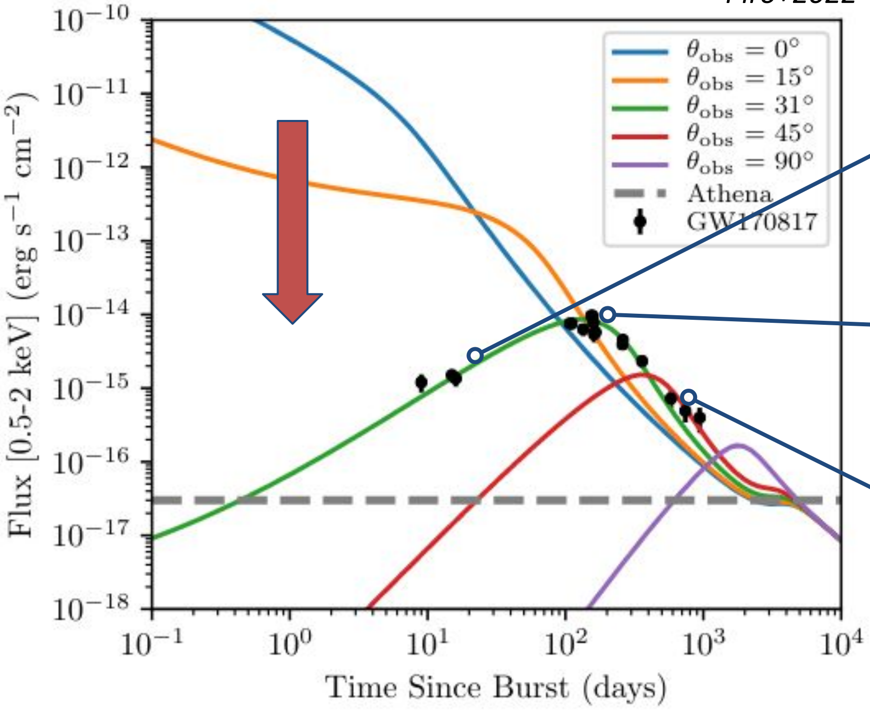
Gamma Ray Bursts (GRBs)

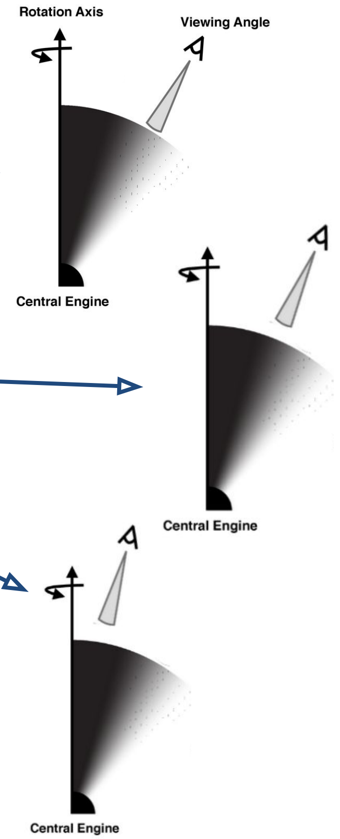


Off-axis observers



Piro+2022





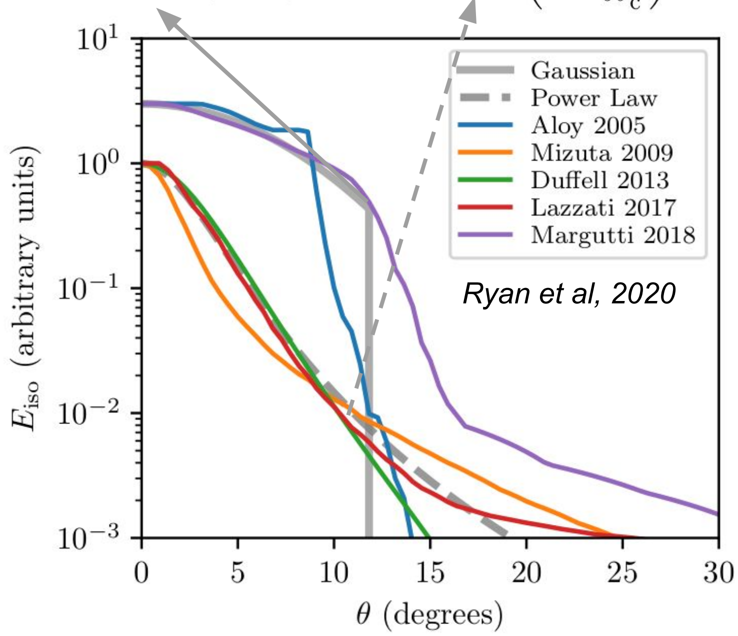
Afterglow modeling

Gaussian jet:

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

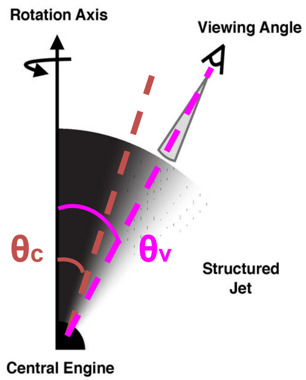
Power law jet:

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



Ryan et al, 2020

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

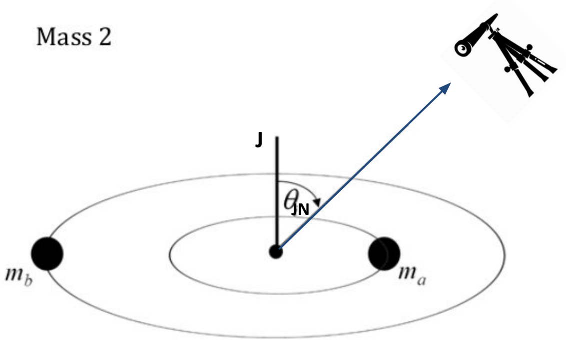


θ_V	Jet orientation
θ_c	Opening angle of the jet
E_0	Isotropic equivalent energy
n_0	homogeneous circumburst medium number density
θ_W	Jet total width
p	power-law slope of the electron population
ϵ_e	fraction of post-shock internal energy in the accelerated electron population
ϵ_B	fraction of post-shock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

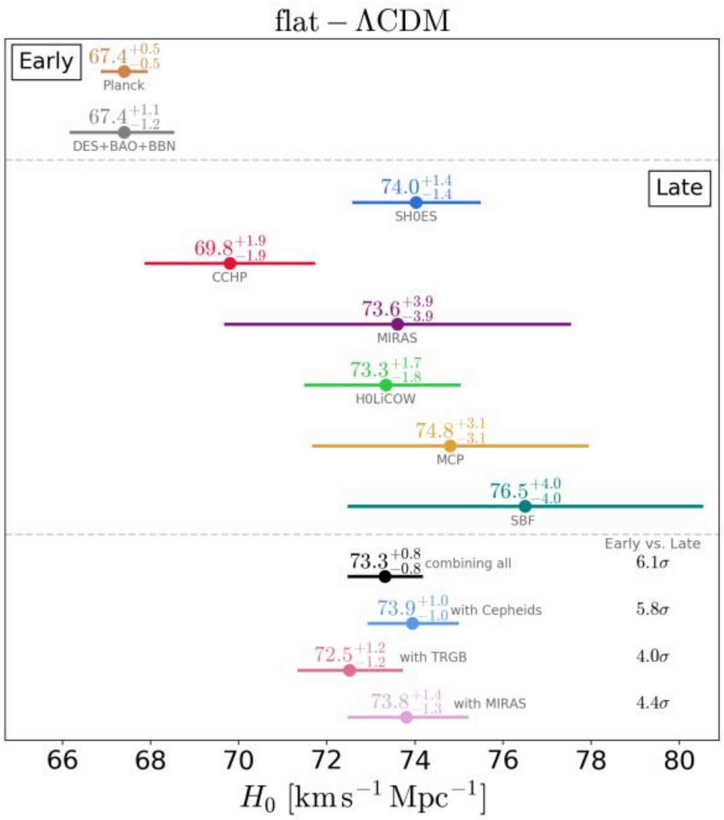
GW modeling

Group	#	Parameter	Description		Alternative	Alternative description
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		$\widetilde{\delta\Lambda}$	

EM+GW parameters (Luminosity distance, Inclination angle)



Hubble tension

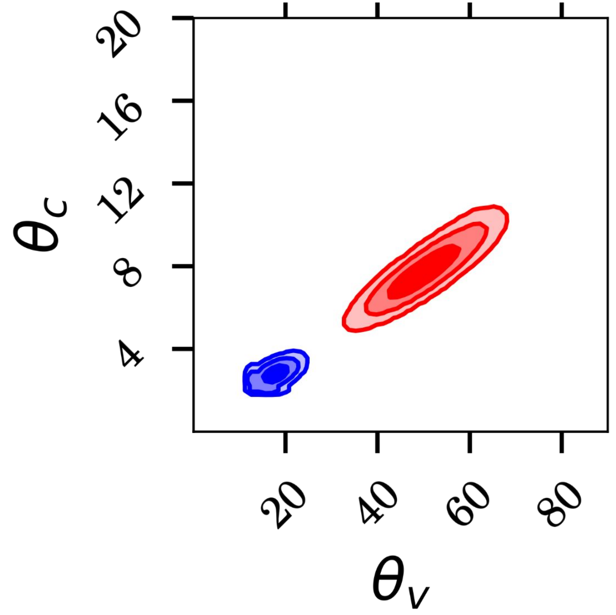


Verde+2019

~5 sigma **tension** between the **Hubble constant H_0** estimated with:

- Late time Universe (for example SH0ES);
- Early time Universe (for example *Planck*).

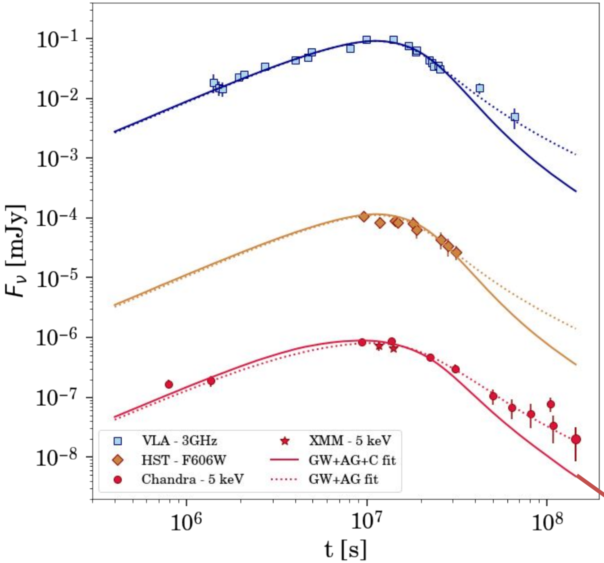
EM degeneracy



θc: jet opening angle
θv: viewing angle angle

GW+AG+C analysis
GW+AG analysis

GW+AG+C

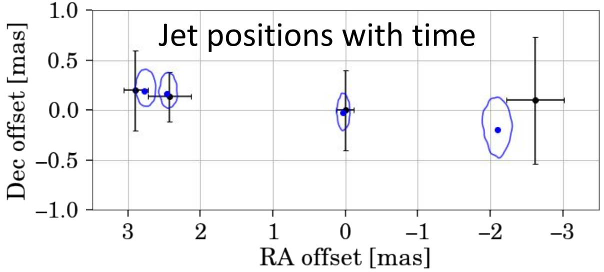


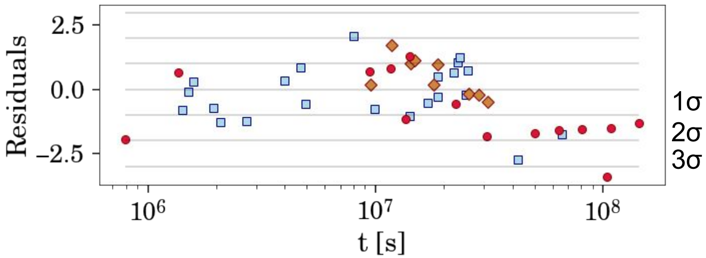
	GW+AG GJ	**GW+AG+C** GJ
θ_c [deg]	$7.73^{+0.86}_{-0.80}$	$2.85^{+0.24}_{-0.20}$
d_L [Mpc]	$31.3^{+3.0}_{-3.6}$	$43.7^{+1.4}_{-1.4}$
θ_v [deg]	$50.1^{+5.1}_{-5.4}$	$18.2^{+1.2}_{-1.5}$
θ_{JN} [deg]	$129.9^{+5.1}_{-5.4}$	$161.8^{+1.2}_{-1.5}$
	Wide jet	Collimated jet

EM degeneracy

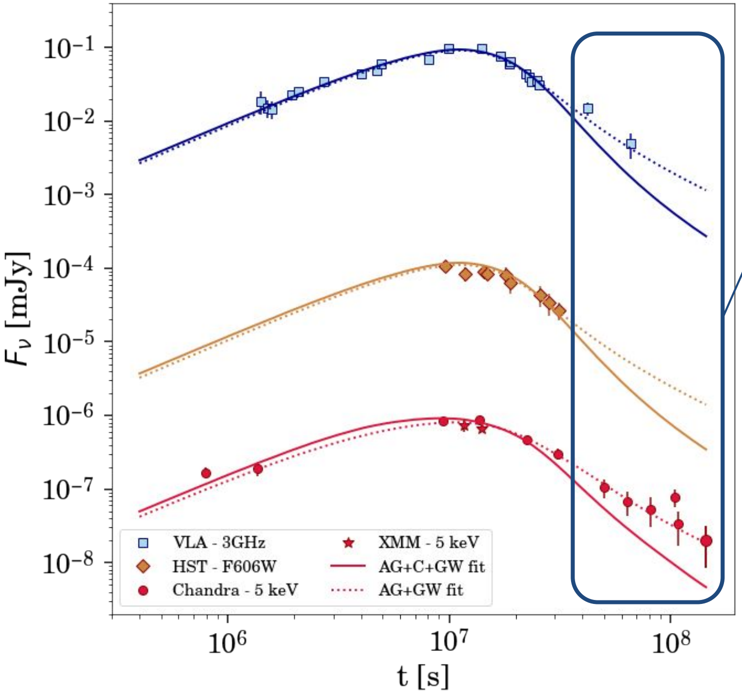
GW degeneracy

Jet features in agreement with population studies (θc in [3,6] deg).





Why are they so different?



Excess in the flux at late times?

+

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

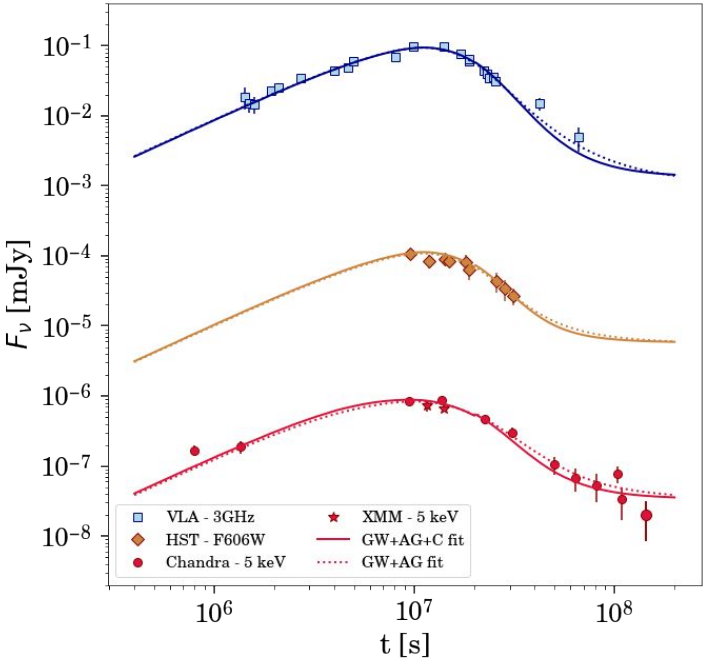
$\boldsymbol{\theta v}$ (viewing angle)

$\boldsymbol{d_L}$ (luminosity distance)

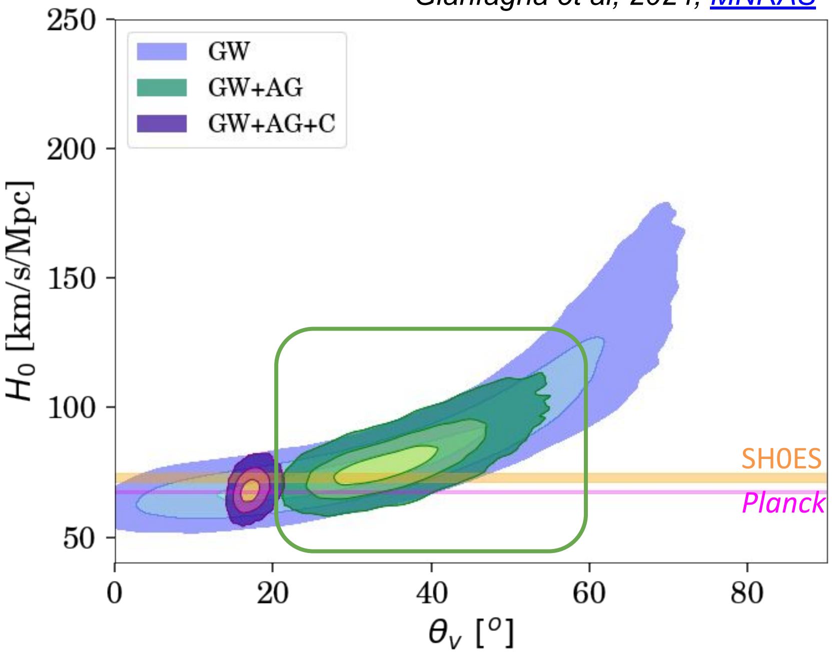
H0 (Hubble constant)

Centroid motion strongly constraints $\boldsymbol{\theta v}$!

Including a constant flux component at late times



Gianfagna et al, 2024, MNRAS



d_L [Mpc]	$38.6^{+2.5}_{-3.0}$
θ_v [deg]	$35.2^{+5.7}_{-6.2}$
θ_{JN} [deg]	$144.8^{+5.7}_{-6.2}$

$$H_0 = 78.5^{+7.9}_{-6.4}\ \mathrm{km\ s^{-1} Mpc^{-1}}$$

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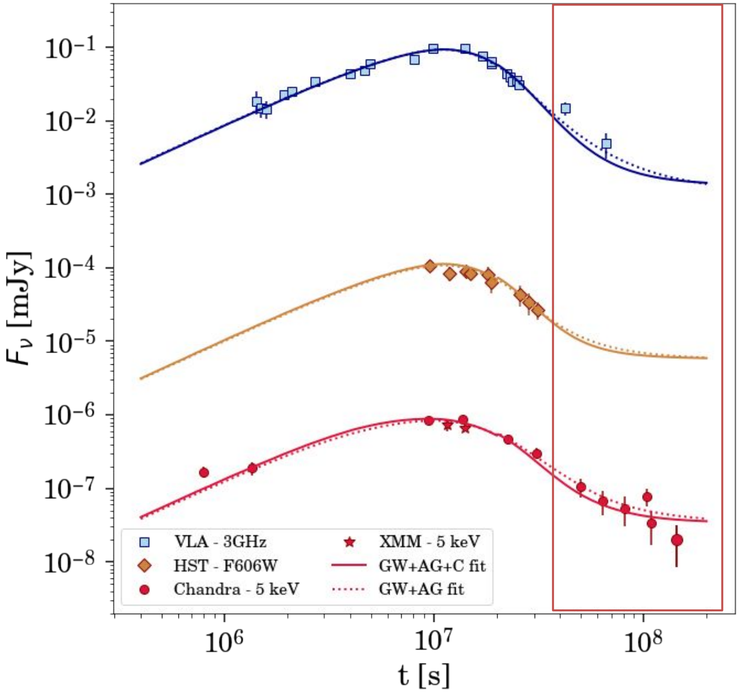
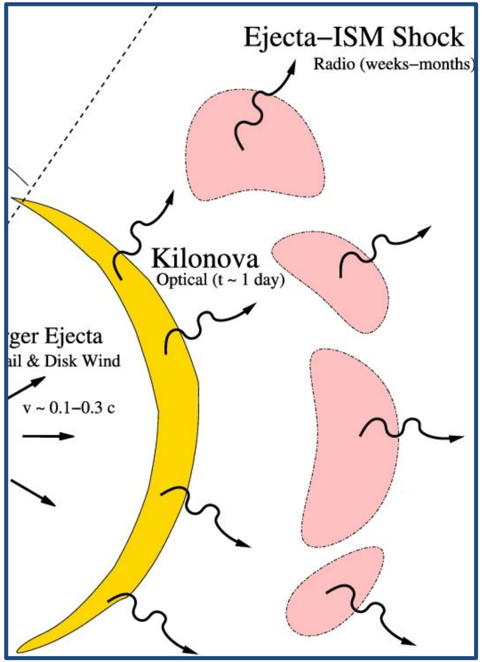
Kilonova afterglow



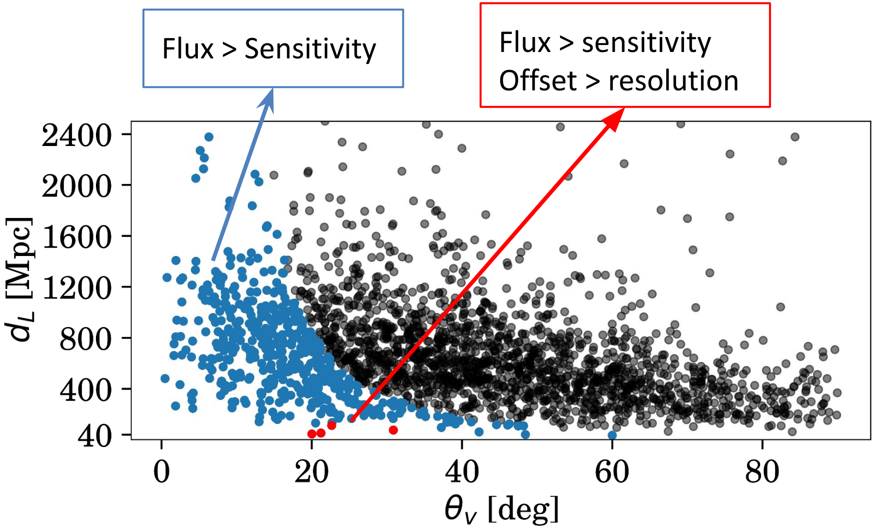
Kilonova afterglow?



	GW+AG	GW+AG+C
d_L [Mpc]	$38.6^{+2.5}_{-3.0}$	$44.3^{+1.4}_{-1.3}$
θ_v [deg]	$35.2^{+5.7}_{-6.2}$	$17.2^{+1.1}_{-1.2}$

Gives information about velocity and mass of the ejecta!

Future rates



GW simulations of binary neutron star mergers *Petrov+2022*

θv , d_L

Generate the afterglow light curve and centroid motion

Considering VLBI sensitivity (24 uJy) and resolution (1.5 mas)

		GW rates	GW+AG+C rates (H0 uncertainty: 4 km/s/Mpc)	GW+AG rates (H0 uncertainty: 10 km/s/Mpc)
O5	2027	$34^{+78}_{-25}\,\mathrm{yr}^{-1}$	$0.05^{+0.11}_{-0.03}\,\mathrm{yr}^{-1}$	$2.4^{+5.5}_{-1.8}\,\mathrm{yr}^{-1}$

~10 events per year in **O5**.

At the end of O5 we could be able to reach the **SH0ES** sensitivity of **1.5 km/s/Mpc**