Compact radio emission indicates a structured jet produced by a binary NS merger

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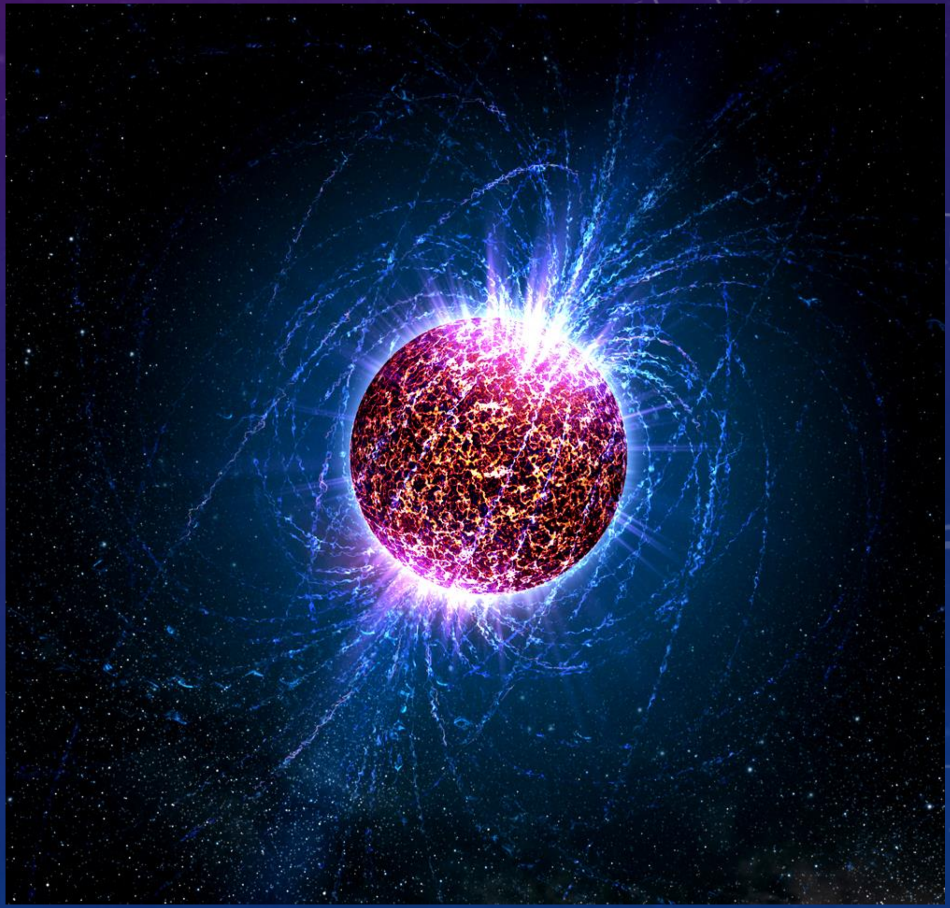
One sentence summary:

Size Measurement through worldwide radio telescope array proves that a relativistic jet successfully emerged from the NS merger GW170817.

GW170817: a merge of Neutron Stars

Neutron stars are really compact objects, originated from the core of a massive star.

They are small but really dense, formed by neutrons and slowly cooling down. They can be found in binary systems: after a long while, they can collide and merge.

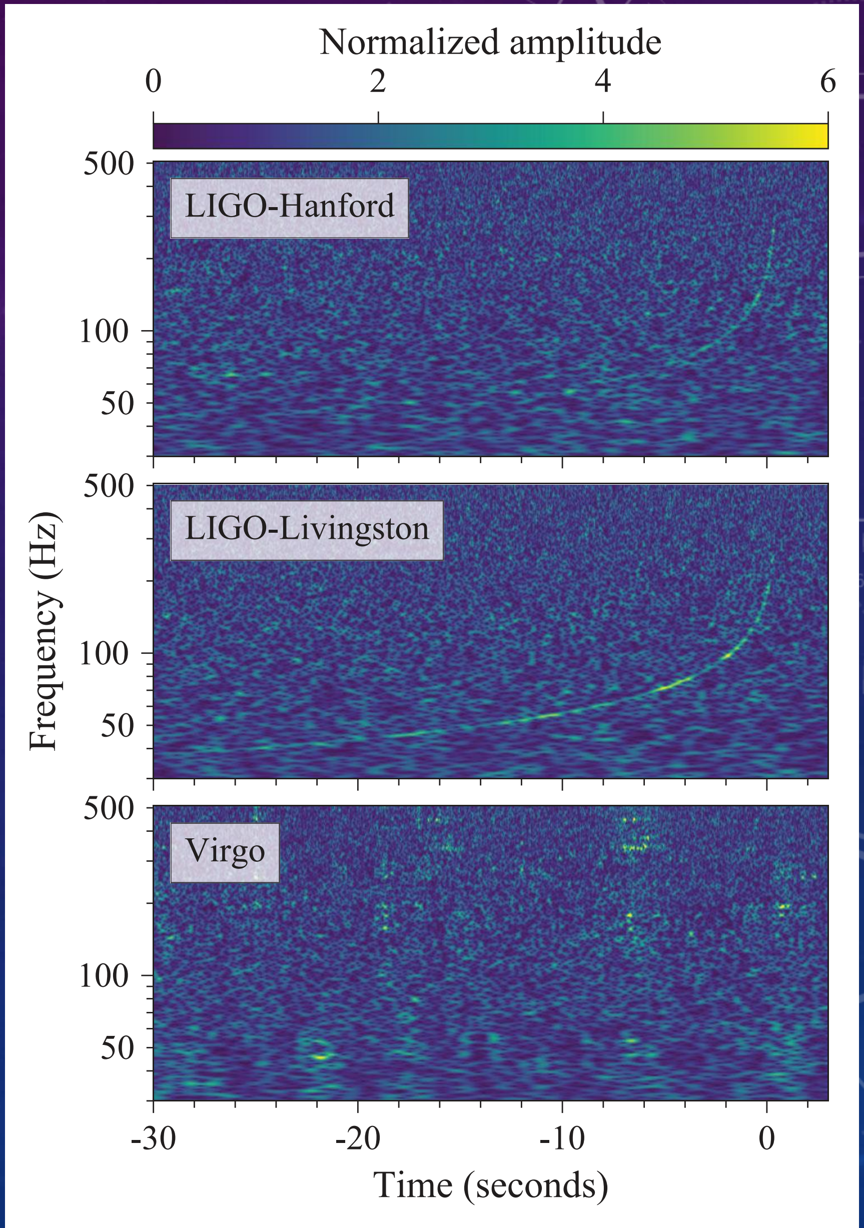


The 170817 merger was detected both through GW and EM waves.
After a short time a short GRB was detected, while in the following days we detected emission in X-rays and radio (GRB's afterglow).

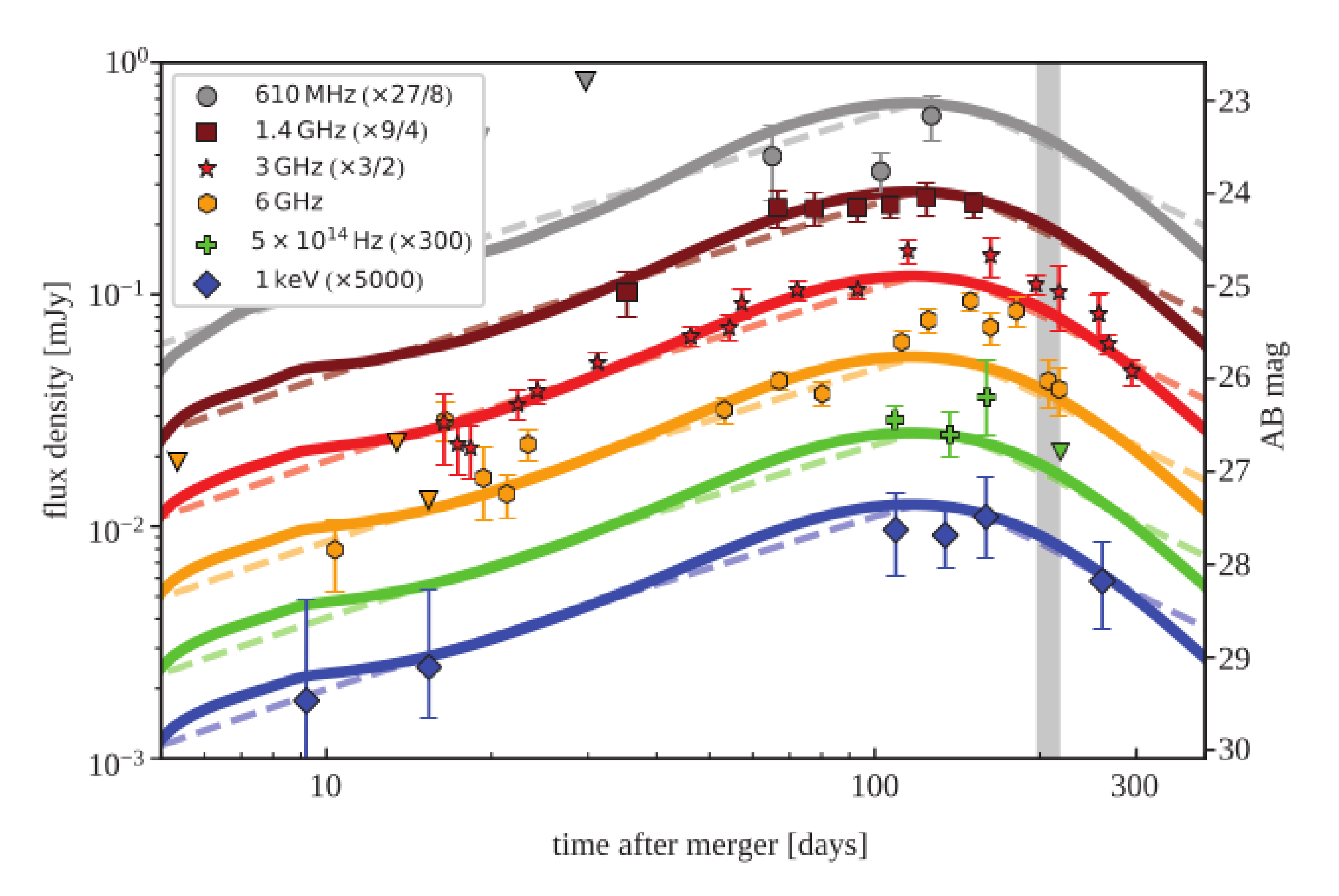
The flux in the optical, X-ray and radio increased with time, following:

$$F \propto t^{0,8}$$

After a peak the flux started decreasing.

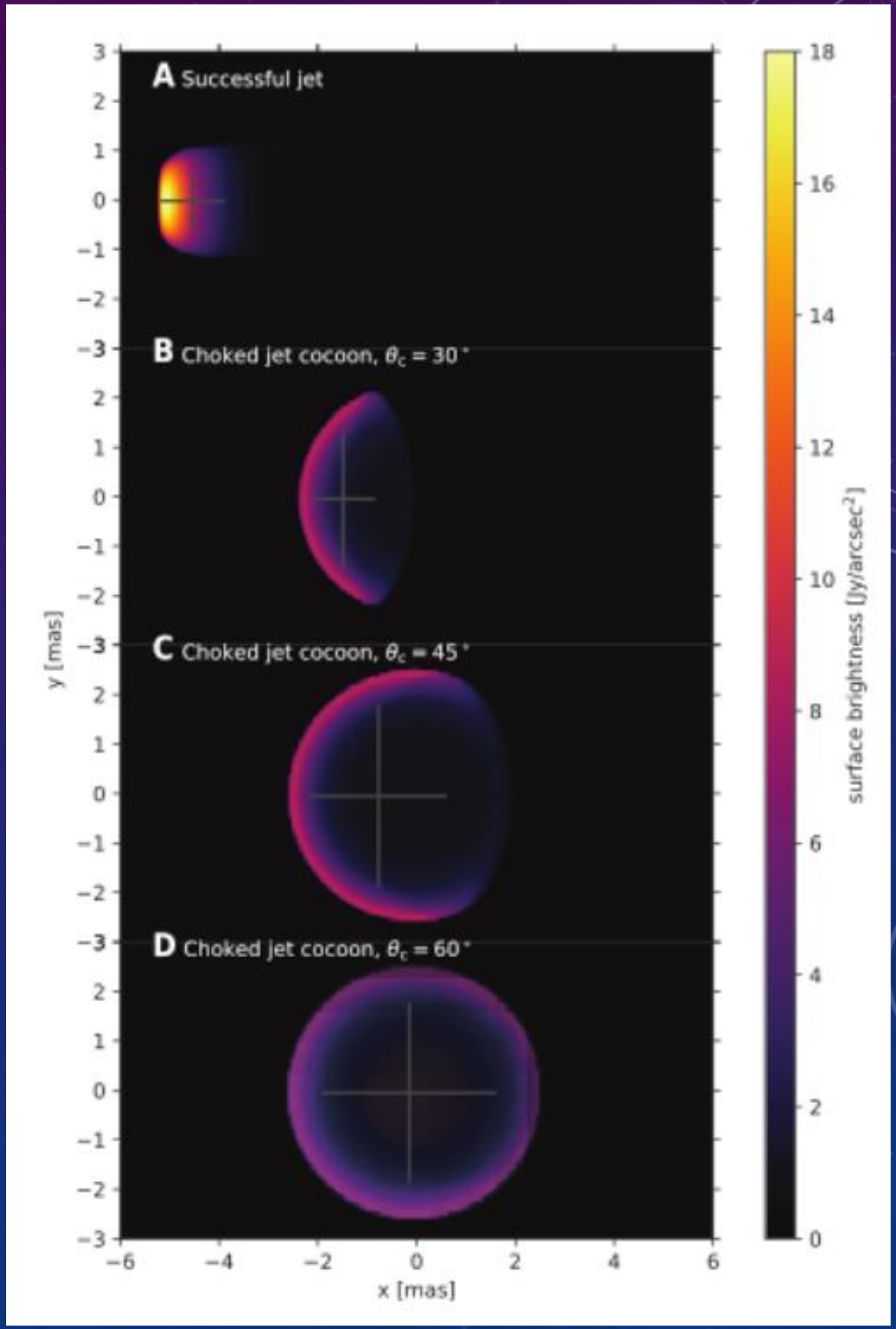


By LIGO Scientific Collaboration and Virgo



610 MHz (×27/8)
1.4 GHz (×9/4)
3 GHz (×3/2)
6 GHz
5 × 10^14 Hz (×300)
1 keV (×5000)
flux density [mJy]
AB mag
time after merger [days]

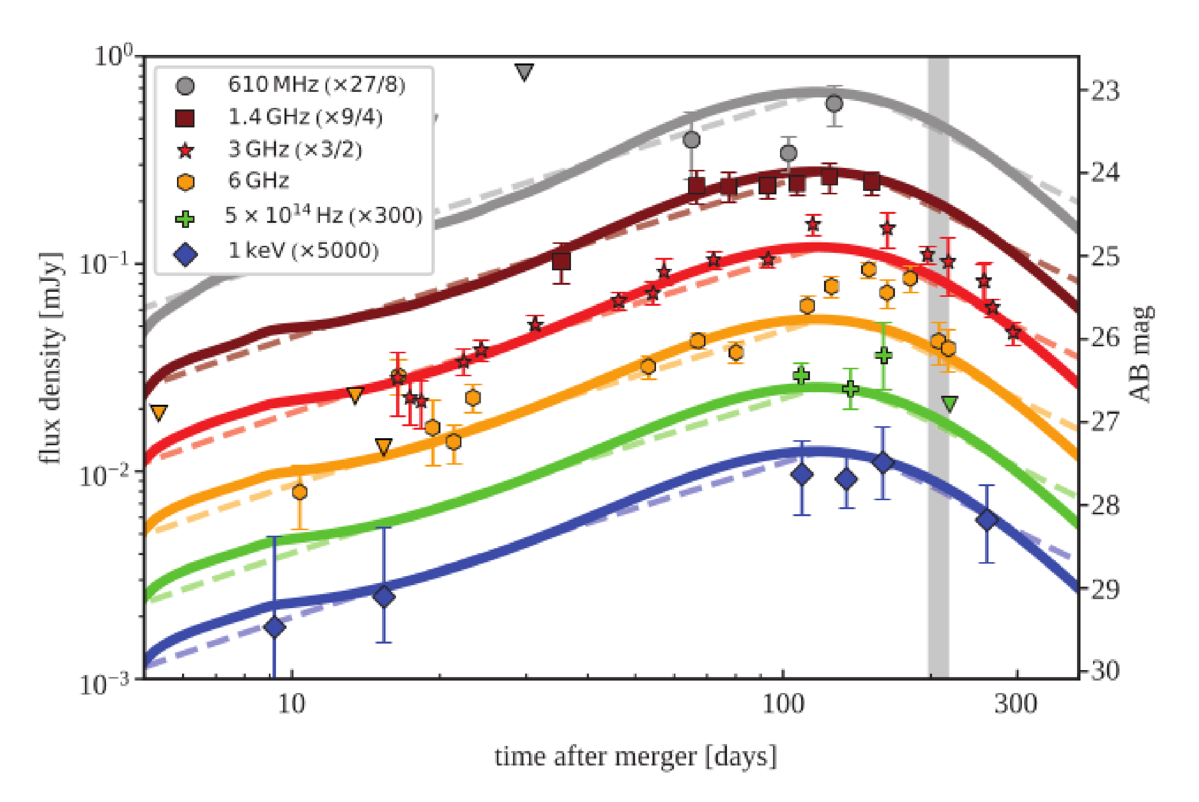
The long lived emission can be explained if we consider jet launched from the remnant of the merger. A jet can in general drill into the ejected material or be absorbed. In the first scenario, the jet develops an angular structure (successful jet), in the latter the ejecta gets hotter after absorbing the energy of the jet (Chocked jet cocoon).



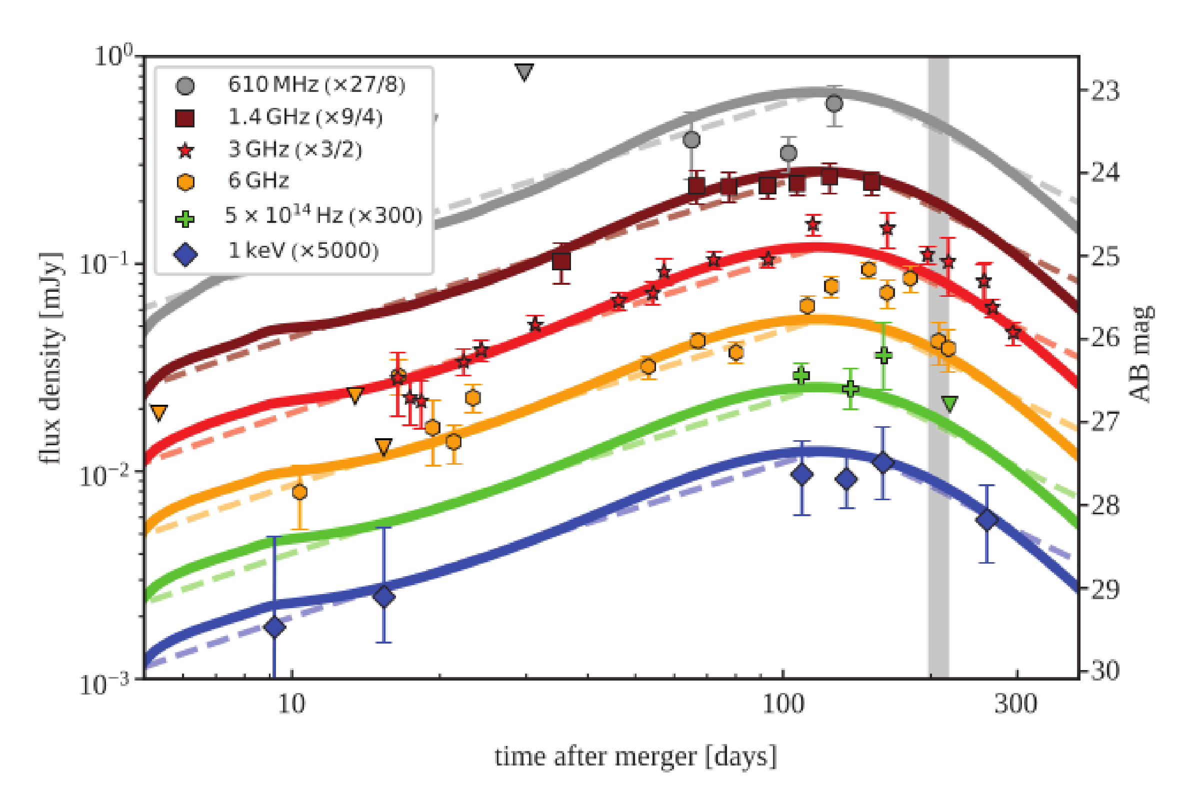
Can we find evidence in favour of one or the other model?

Light curve

All four models produce with reasonable parameters the observed light curve.

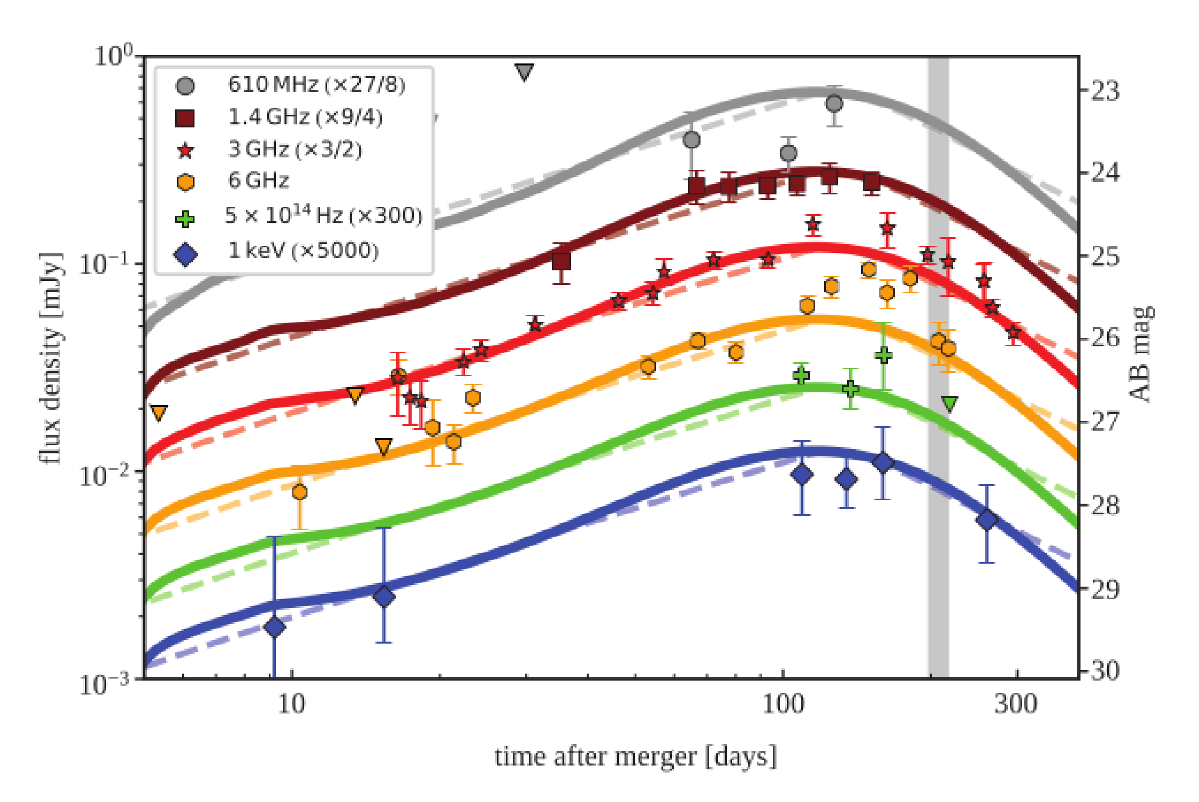


Solid lines describe a structured jet model, while the dashed ones are associated with the cocoon model.



To compute the expected light curve one needs to know the dynamics of the jet expansion and its interaction with ISM. Suppose our jet is axisymmetric and has a Lorentz factor Γ_0. Until jet elements move faster than sound in that medium, the dynamics of the jet depends only on Γ_0.

As they are slown down, they are more and more influenced by surrounding.



Dynamics for an isotropical outflow is different from the one of a jet: the ejecta in the outflow do not move all at the same velocity.

Fastest ejecta drives a shock in the ISM. Progressively, slower ejecta reach the ISM and contribute their energy to the shocked emission. The deceleration is then slower than a single shell model, where once the shell collides with the ISM immediately starts decelerating. The dynamics can be obtained by energy conservation.

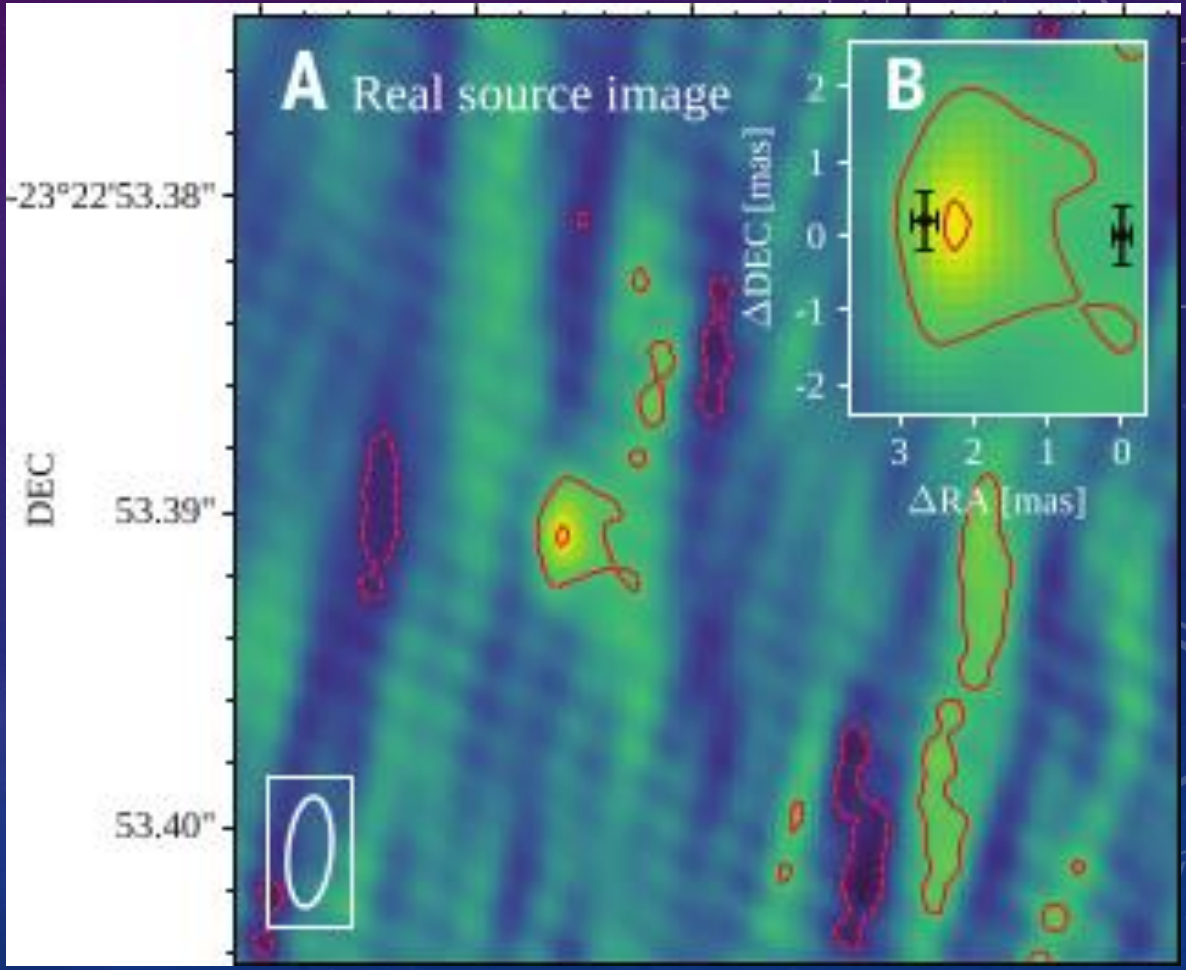
Displacement from merger location

The structured jet and the isotropic outflow are expected to have a different displacement from the detected source. An isotropic emission is also expected to be less collimated, thus having larger angular size.

https://spacetelescope.org/images/heic1717c/

Estimation of the source size

We start by putting an upper limit to the size of the source: due to low SNR, the flux density of the source can be easily overestimated. Fitting the data gathered we obtain that the source should be at most a circle of radius 2,9 mas.
Choosing a more reasonable value for the flux one obtains a radius of 1,3 mas.



One can try to calculate the odds of having a source of a fixed size once the flux peak is known, using Bayes' theorem. Modelling the source as an elliptical gaussian with axes on the N-S/E-W directions and calling s_x and s_y the half-lenght of said axis, the probability of obtaining the estimated values is given by:

$$P(s_x, s_y, F|F_P) = \frac{P(F_P|s_x, s_y, F)P(F), P(s_x, s_y)}{P(F_P)} \quad (1)$$

If one works out the result of the previous equation obtains that with a 90% confidence level sources with a size bigger than 2,5 mas are to be rejected, strongly suggesting that the structured jet is to be considered the preferred model.

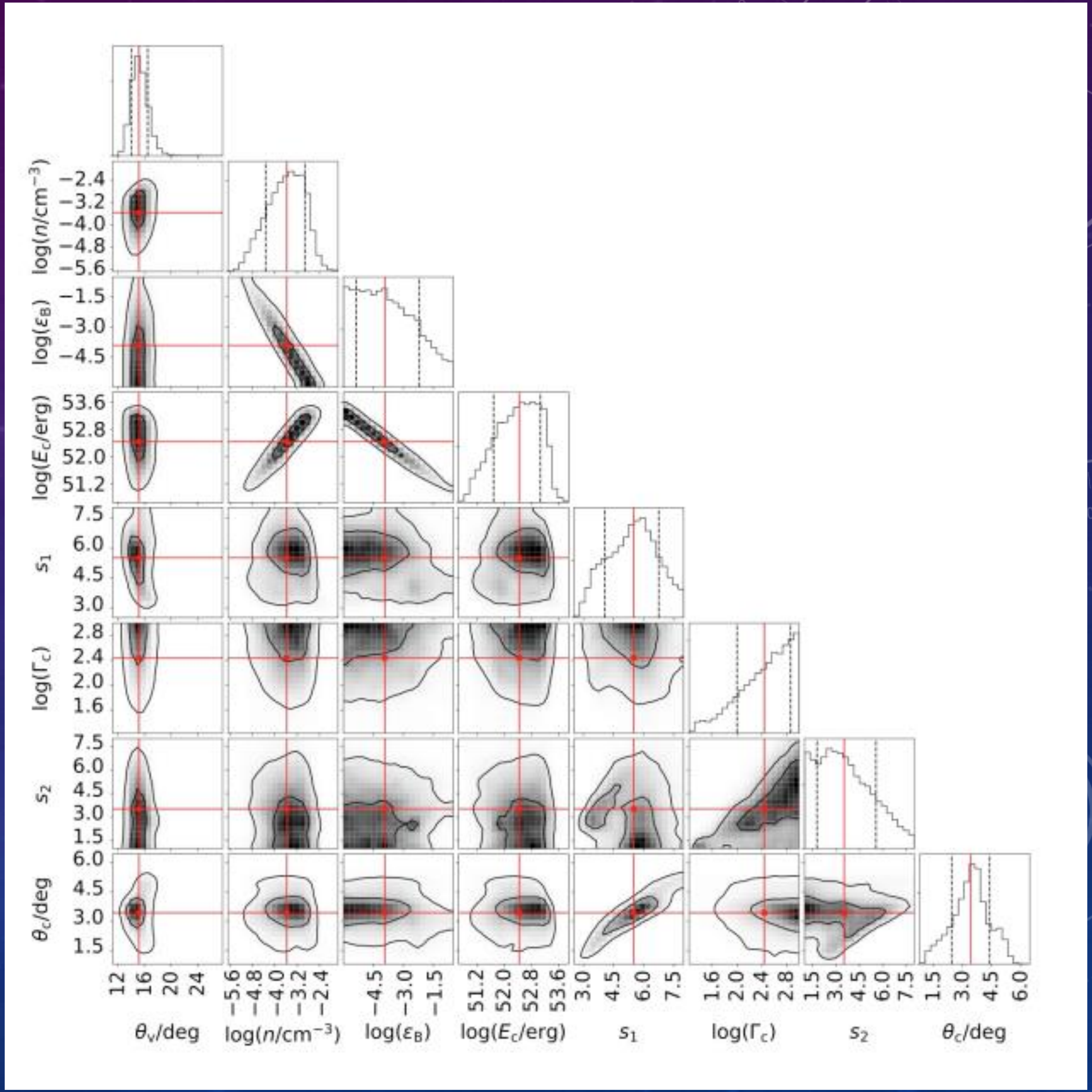
Jet parameters

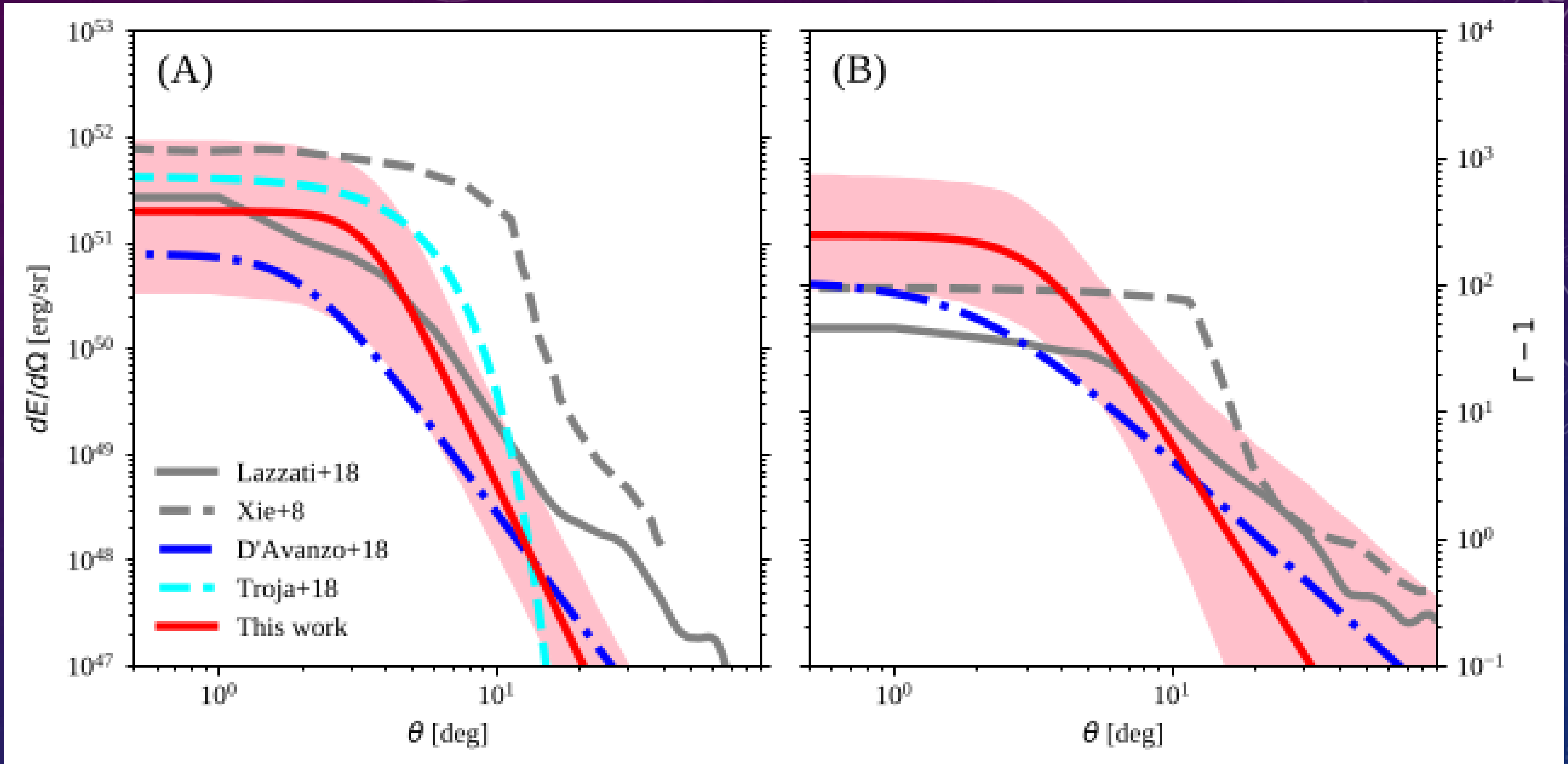
The data obtained for the jet can be fitted using a power law model. There are several free parameters, some of which can be obtained just by analyzing gathered datas, while some other are constrained by the model in order to avoid model degeneracy.

The results are interesting: several parameters show degeneracy (i.e. more than one combination of said parameters can give the right light curve) while some other are just constrained to be bigger or smaller than a constant.

Parameter	Best fitting value	One sigma range
$\mathrm{Log}(E_c/\mathrm{erg})$	52.4	(51.7, 53.0)
s_1	5.5	(4.1, 6.8)
$\mathrm{Log}(\Gamma_c)$	2.4	(2.0, 2.9)
s_2	3.5	(1.8, 5.6)
θ_c/deg	3.4	(2.4, 4.4)
$\mathrm{Log}(\varepsilon_B)$	-3.9	(-5.4, -2.2)
$\mathrm{Log}(n/\mathrm{cm}^{-3})$	-3.6	(-4.3, -2.9)
θ_v/deg	15	(14, 16.5)

Data obtained through fit procedures are in good agreement with data found in literature, strengthening the jet hypotesis.



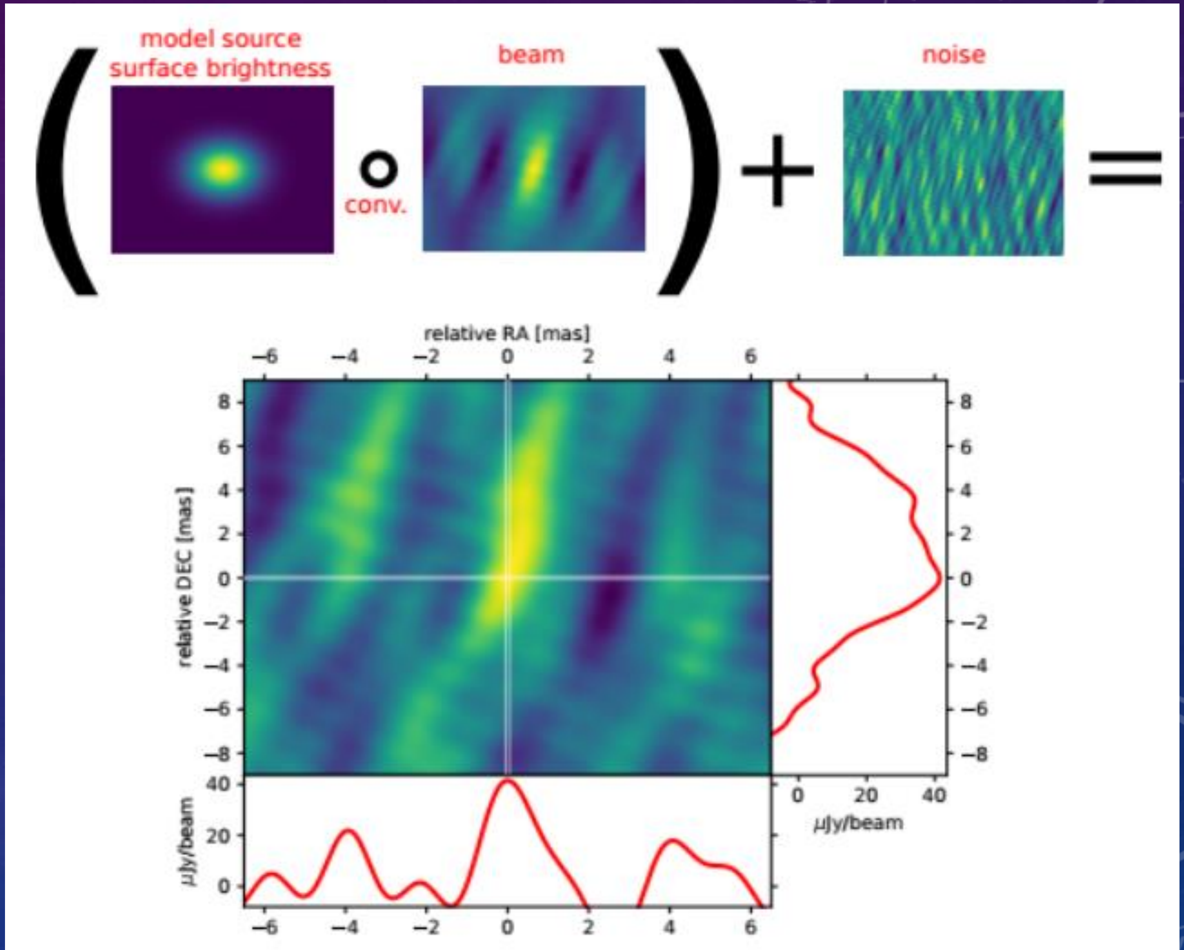


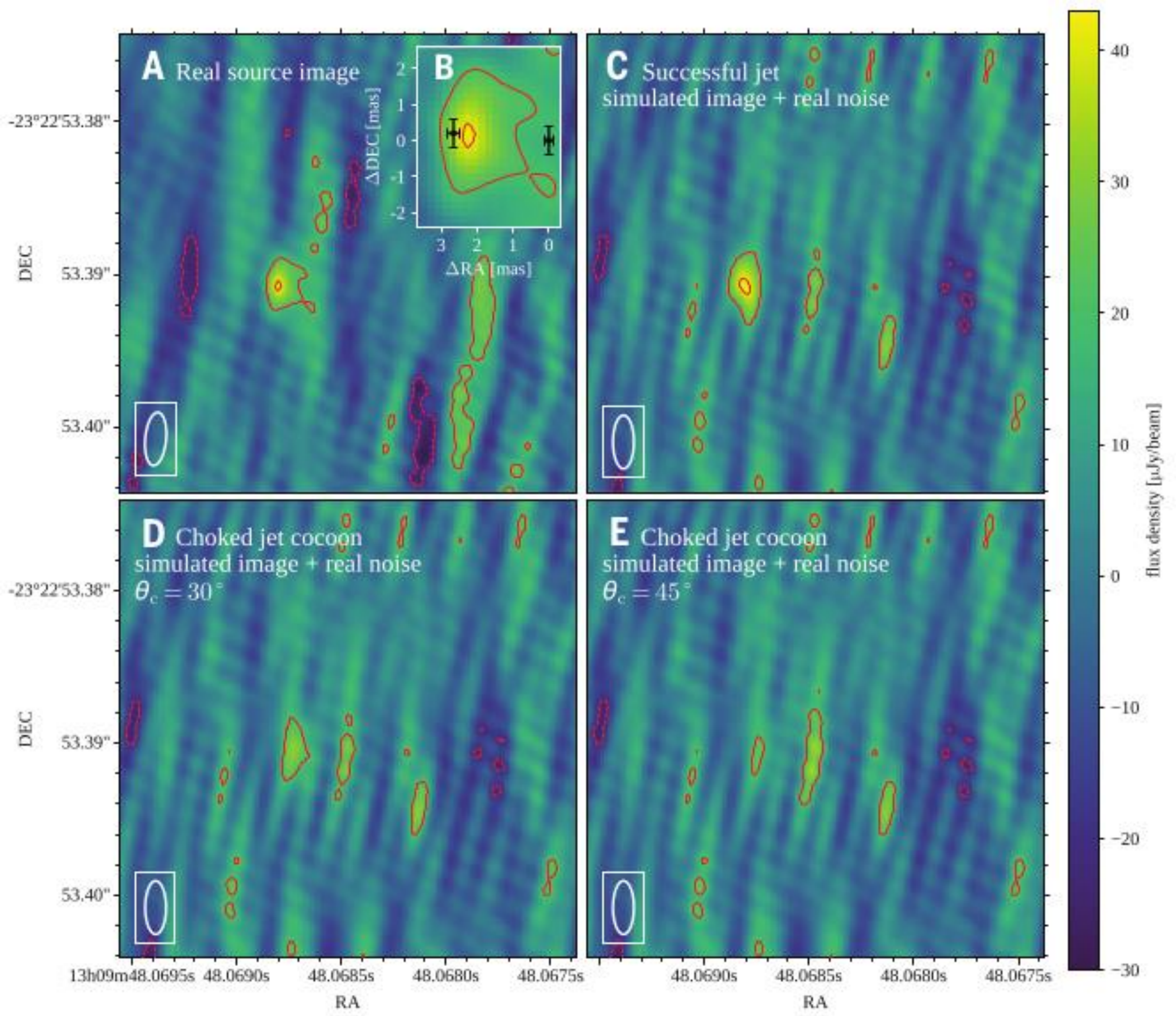
Comparison of the jet structure between numerical simulation and analytical structures from literature. Red: best fitting model, pink shaded region: 1σ error band

‘Visual’ Comparison

Comparing data with simulation of emission hints the presence of jets, instead of cocoon emission.
The authors of the paper described how they managed to simulate events: once they created a model, they generated data, computed the surface brightness for the image and added some real noiose.

Result are shown in the following page.

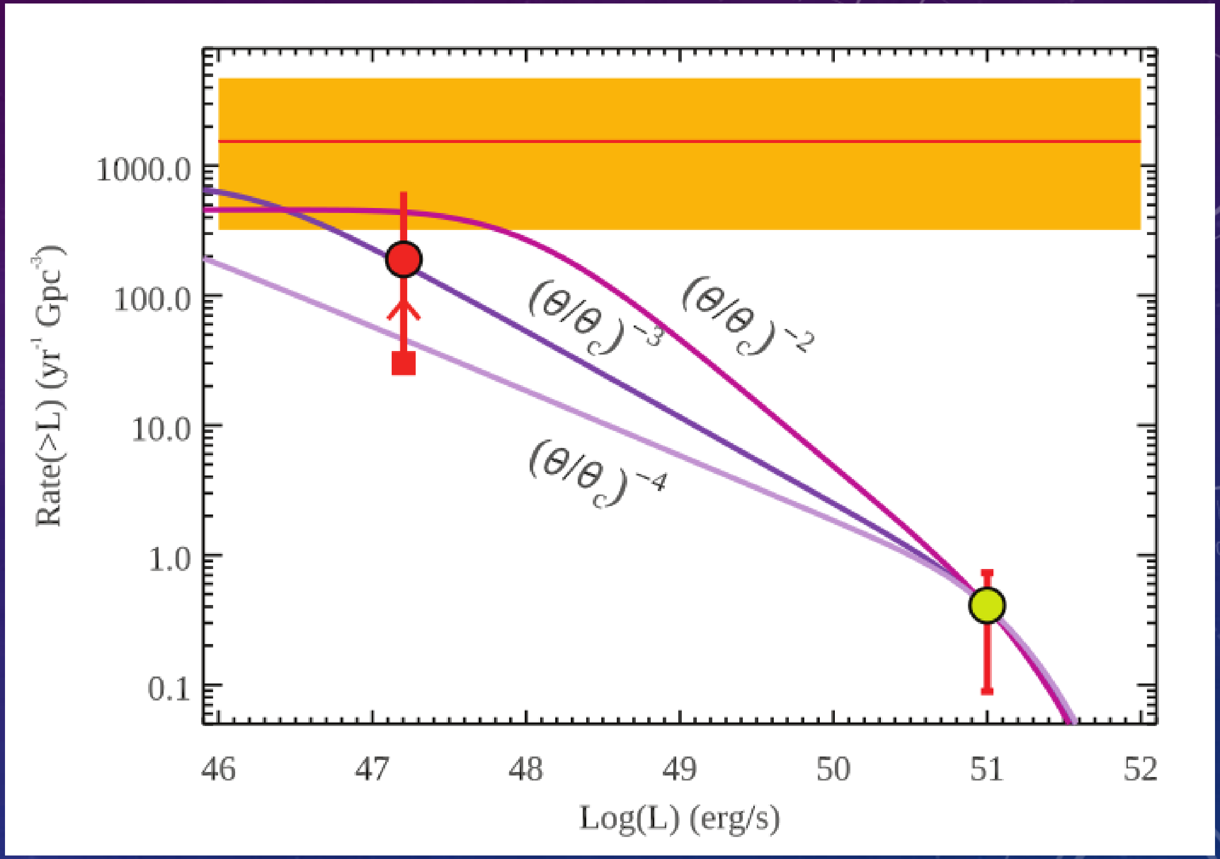




A Real source image
B
ΔDEC [mas]
ΔRA [mas]
C Successful jet
simulated image + real noise
D Choked jet cocoon
simulated image + real noise
$\theta_c = 30^\circ$
E Choked jet cocoon
simulated image + real noise
$\theta_c = 45^\circ$
-23°22'53.38"
53.39"
53.40"
DEC
13h09m48.0695s
48.0690s
48.0685s
48.0680s
48.0675s
RA
flux density [μJy/beam]
40
30
20
10
0
−10
−20
−30

GRB rate

It's also interesting to note that 170817 seemed to be a weak GRB compared to the standard short GRB. The emission was probably not produced by the core but by the sheath of the jet facing in our direction. However, if seen on-axis, GW 170817 would have been a lot more energetic (Isotropic energy > 10^{51} erg/s).



Rate of GRBs with isotropic equivalent luminosity > 10^51 – yellow filled symbol & exptected rate of short GRBs, similar to GRB170817 – solid red symbol. Lines show predictions for different jet structures (see α and how it's changing)

GRB rate

For a GRB whose luminosity function scales as a power-law, such as:

$$L(\theta_\nu) \propto (\theta_\nu/\theta_c)^{-\alpha}$$

It's relatively easy to obtain a plot like the one on the right.

It's comforting to note that the rate of GRBs as faint as GRB170817A is consistent with a jet model.