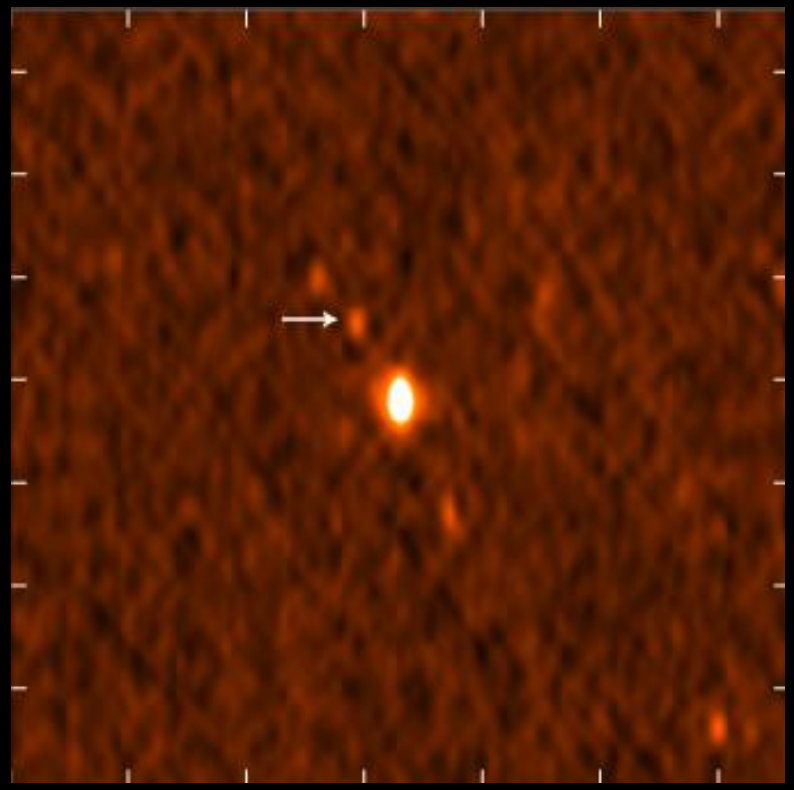
Radio Observations of GW170817



G. Hallinan, K. P. Mooley, E. Nakar, K. Hotokezaka, A. Corsi, M.M. Kasliwal, O. Gottlieb, D.L. Kaplan, D.A. Frail, S.T. Myers, T. Murphy, K. De, D. Dobie, J.R. Allison, K.W. Bannister, V. Bhalerao, P. Chandra, T.E. Clarke, S. Giacintucci, A.Y.Q. Ho, A. Horesh, N.E. Kassim, S. R. Kulkarni, E. Lenc, F. J. Lockman, C. Lynch, D. Nichols, S. Nissanke, N. Palliyaguru, W.M. Peters, T. Piran, J. Rana, E. M. Sadler, L.P. Singer, S. Bourke, A. Deller

E-mail: *gh@astro.caltech.edu*

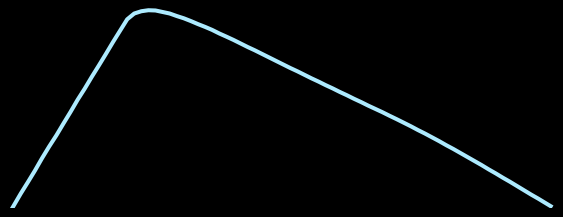
Caltech

GROWTH

Global Relay of Observatories Watching Transients Happen

Image credit: NASA's Goddard Space Flight Center/CI Lab

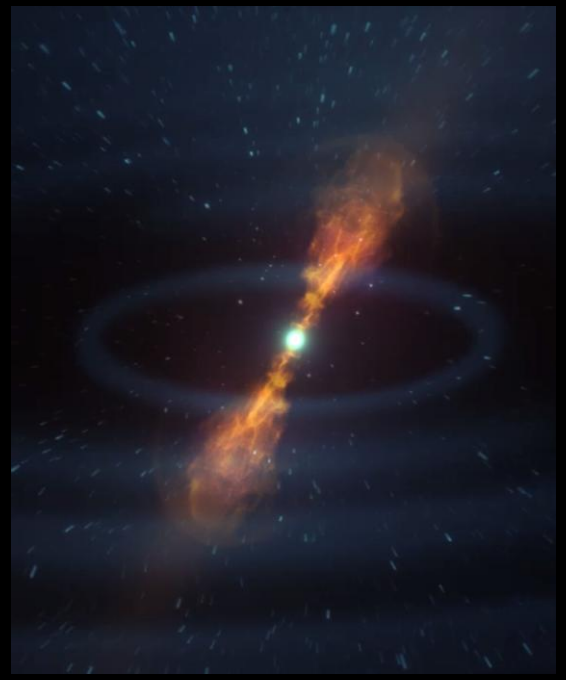
Dynamical Ejecta

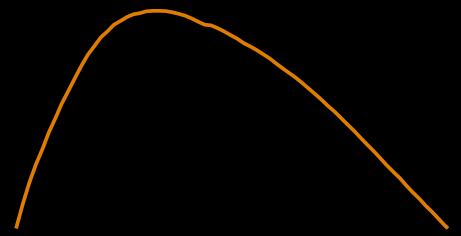


Months-Years

Nakar & Piran 2011
Hotokeza & Piran 2015

Relativistic Jet

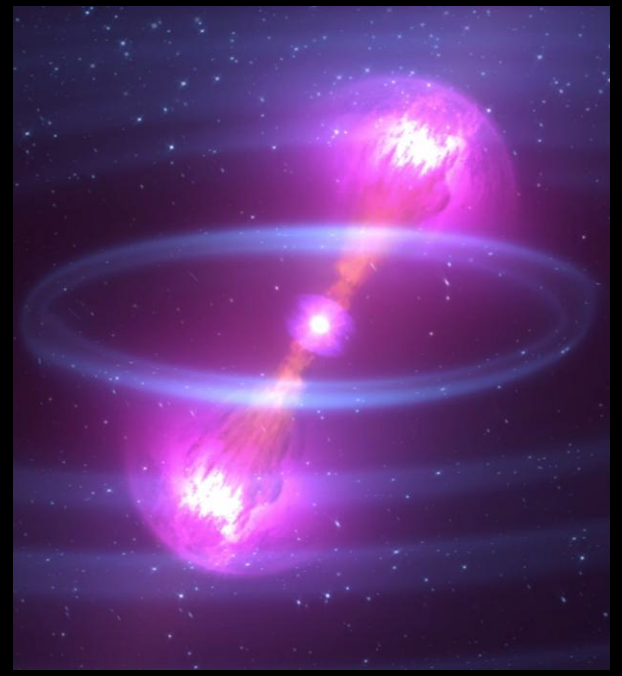


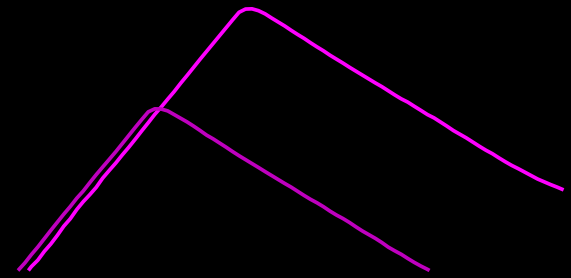


Days-Weeks

Granot et al. 2002

Cocoon

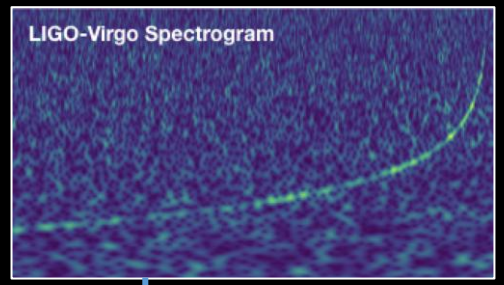




Weeks-Months

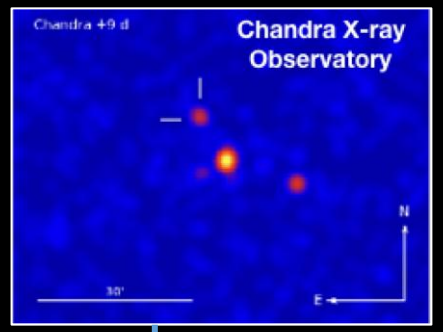
Gottlieb et al. 2018
Kasliwal et al. 2017
Lazzati et al. 2017

Gravitational waves
T = 0

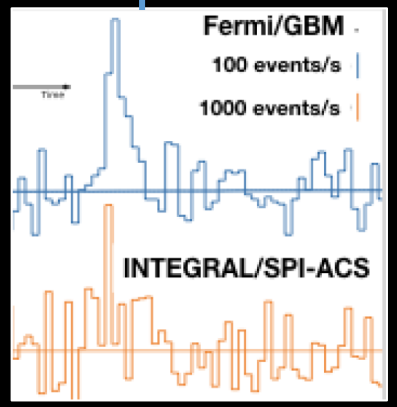


Near Infrared
T = 11h 36 minutes

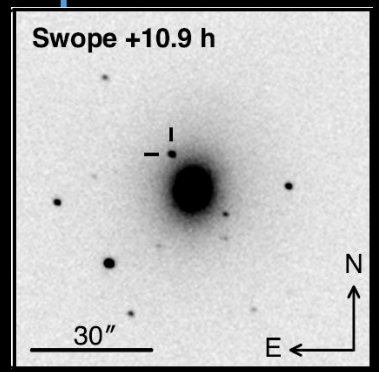
X-ray
T = 9 days



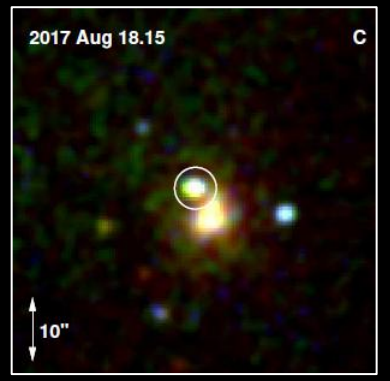
Radio?



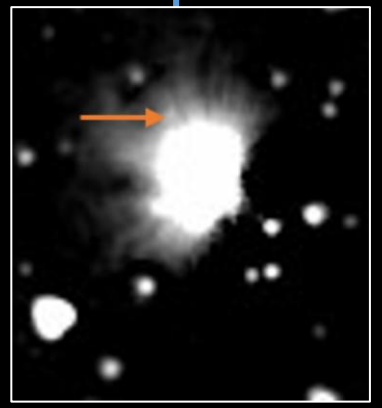
Gamma-rays
T = 1.7 seconds



Optical
T = 10h 52 minutes



Ultraviolet
T = 15 hours



Infrared
T = 43 days

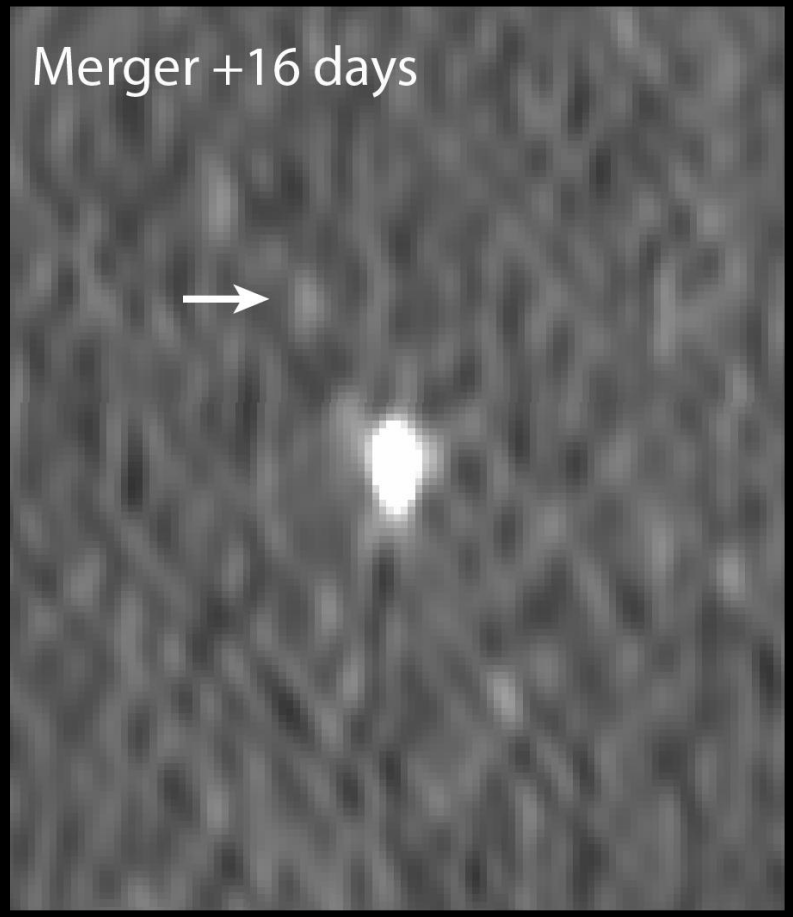
See full list of publications at www.kilonovae.org


The VLA
New Mexico


The GMRT
India

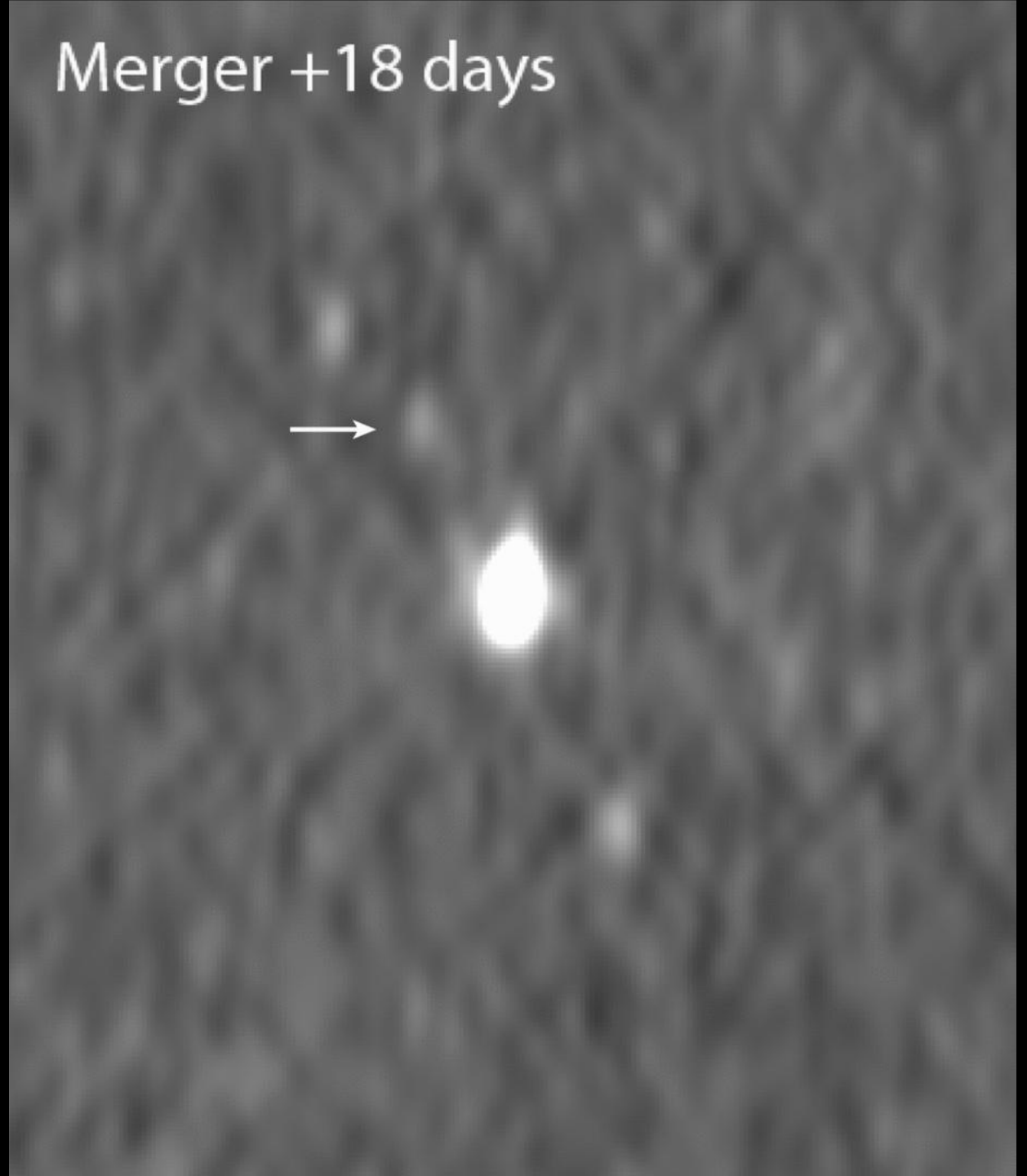

The ATCA
Australia

Discovery with the VLA

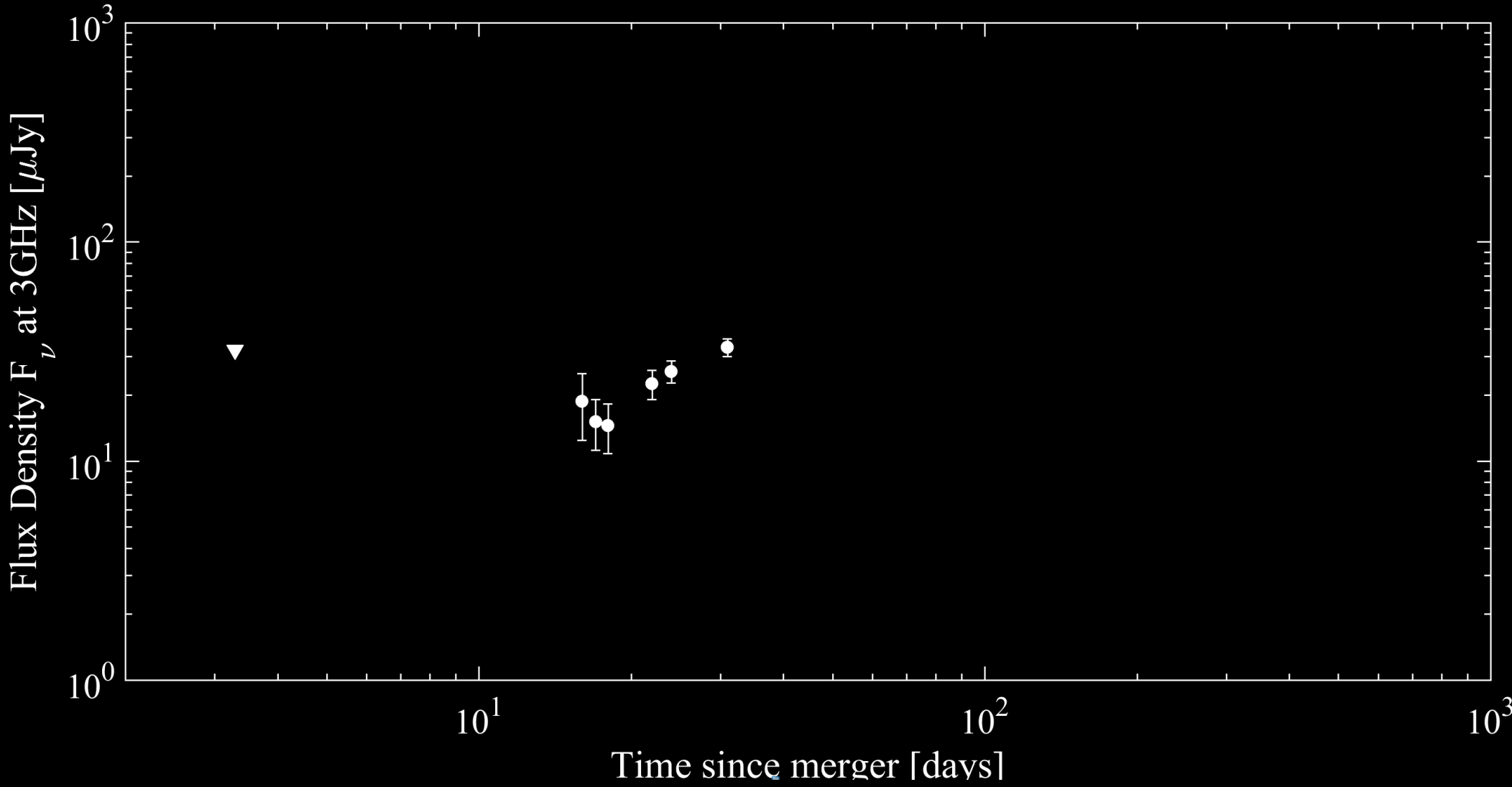


VLA observations from G. Hallinan, A. Corsi, *et al*., *Science* 10.1126/science.aap9855 (2017)

Gemini image from Kasliwal, et al., Science 10.1126/science.aap9455 (2017).


Merger +18 days

Light curve: Day 16 – Day 31



G. Hallinan, A. Corsi, *et al*., *Science* 10.1126/science.aap9855 (2017)

Modeling Light Curves

Modeling team consists of Udi Nakar, Kenta Hotokezaka, Tsvi Piran and Ore Gottlieb

Models use two numerical codes described in:

i) Soderberg, et. al. ApJ, 638, 930 (2006)

ii) Hotokezaka & Piran

Results consistent with BOXFIT

Models assume $\varepsilon_e = 0.1$ and $\varepsilon_B = 0.01$

Models assume $p \sim 2.2$ - consistent with X-ray data (Troja et al. 2017; Margutti et l. 2017; Haggard et al. 2017)

Models ruled out – On-Axis Jet

Isotropic equivalent luminosity of gamma-rays
= 4 × 10^{46} erg

Classical sGRB population (10^{49} – 10^{52} erg;
median = 2 × 10^{51} erg)

Low-luminosity on-axis jet would not escape
- Kasliwal et al. 2017

No early fading afterglow

Radio and X-ray light curve rising after a few days

Hallinan, Corsi et al. 2017, Alexander et al. 2017, Kim et al. 2017, Troja et al. 2017, Margutti et al. 2017, Evans et al. 2017, Haggard et al. 2017

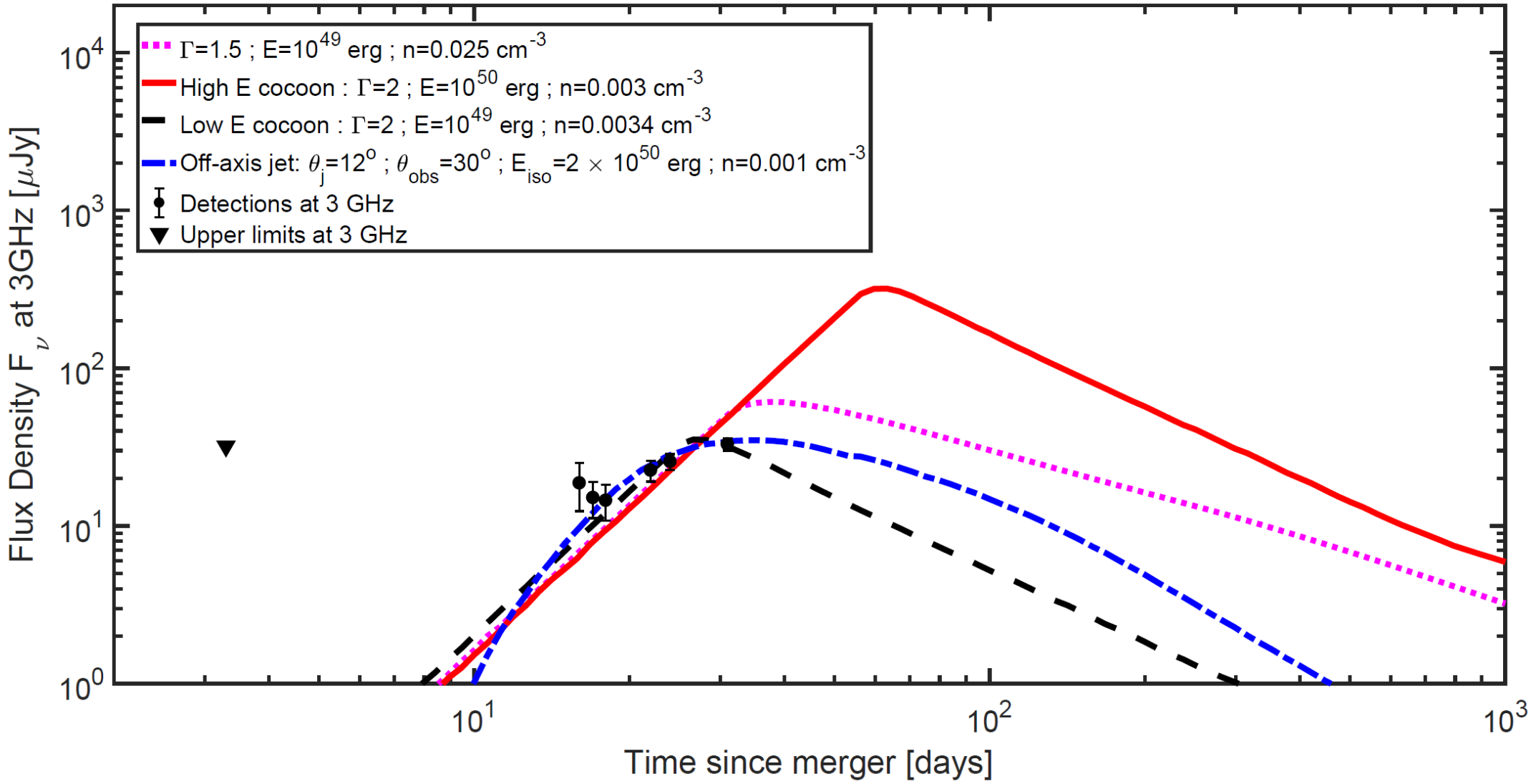
Models ruled out –Slightly Off-Axis Jet (<6 deg from jet)

Isotropic equivalent luminosity of gamma-rays
= 4×10^{46} erg

Classical sGRB population (10^{49} – 10^{52} erg;
median = 2×10^{51} erg)

See Gottlieb, Nakar, Piran & Hotokezaka 2017
Kasliwal et al. 2017
Margutti et al. 2017
Alexander et al. 2017
Bromberg et al. 2017
Burgess et al. 2017
Granot et al. 2017
(and many more!)
for detailed discussion

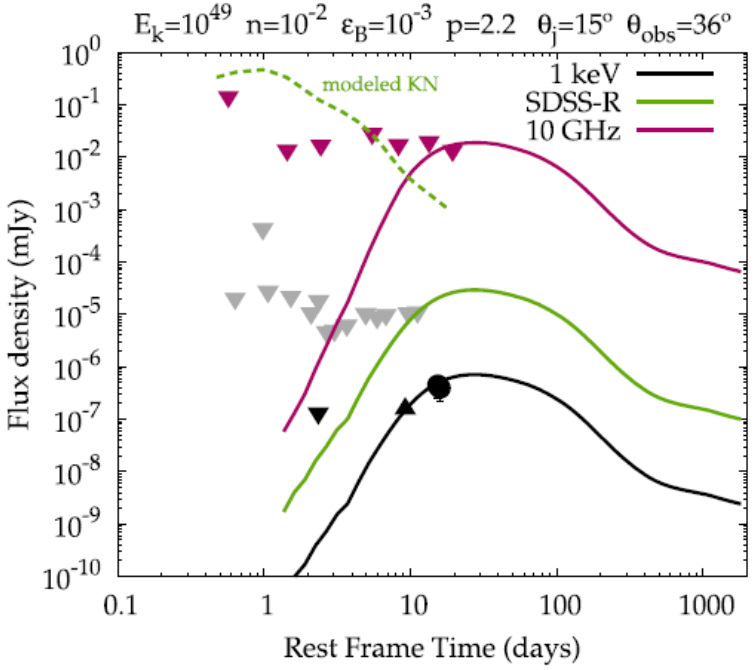
Models Consistent with Early Light Curve



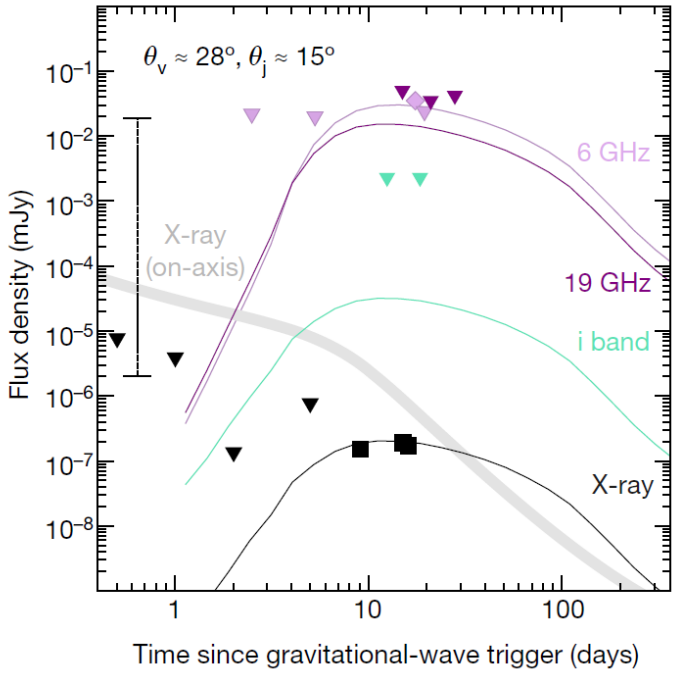
Low density environment ~ 10^{-4} – 10^{-2} cm^{-3}

G. Hallinan, A. Corsi, *et al.*, *Science* 10.1126/science.aap9855 (2017).

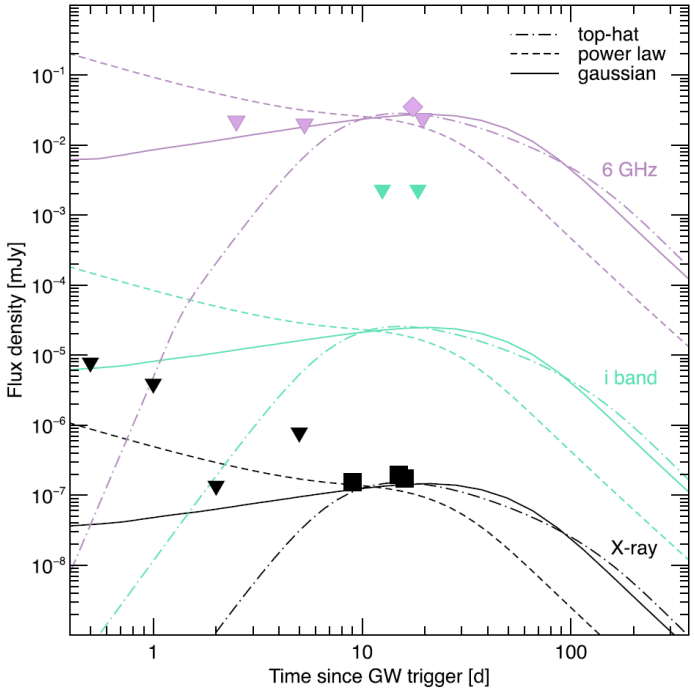
Models Consistent with Early Light Curve



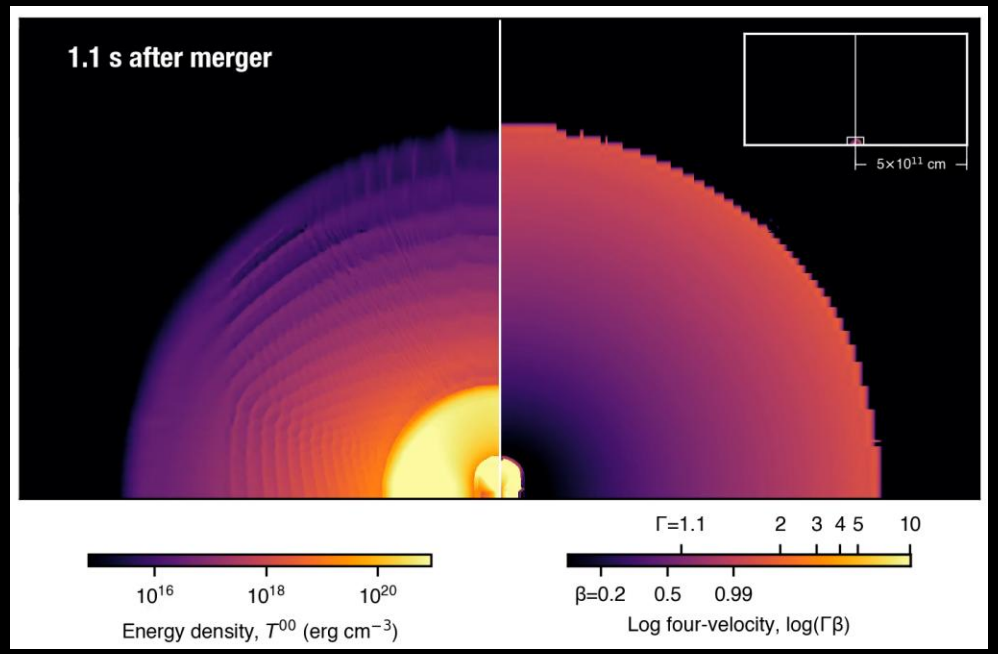
Margutti et al. 2017
Alexander et al. 2017

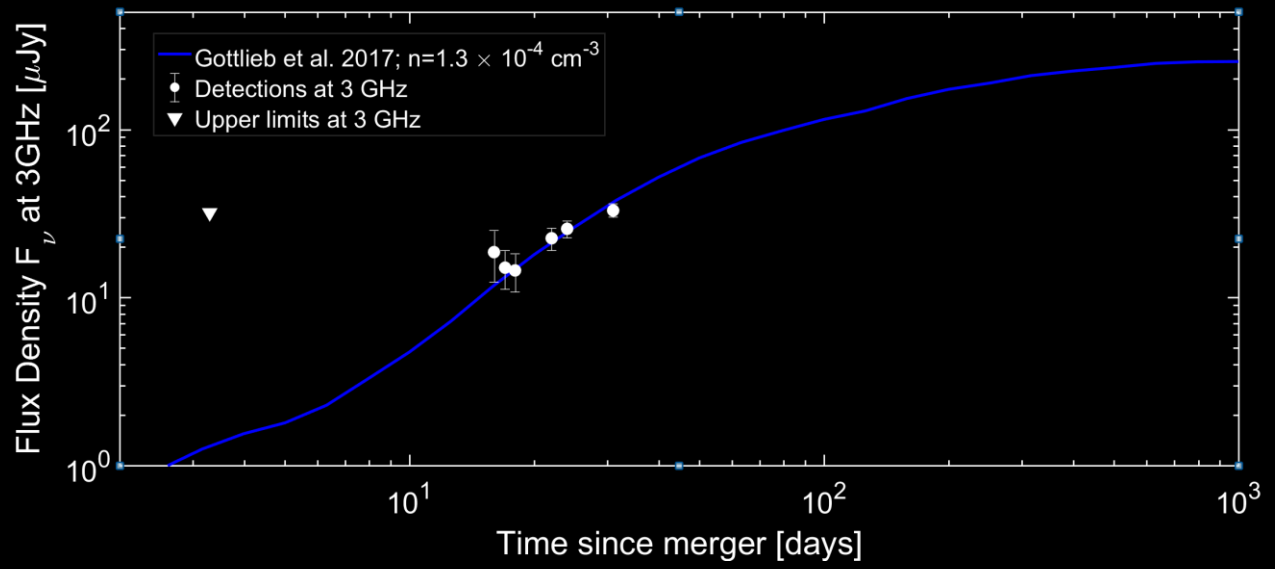


Troja et al. 2017



Troja et al. 2017





Gottlieb, Nakar, Piran & Hotokezaka 2017, Kasliwal et al. 2017
2-D simulation to explain the gamma-rays

Dynamical Ejecta

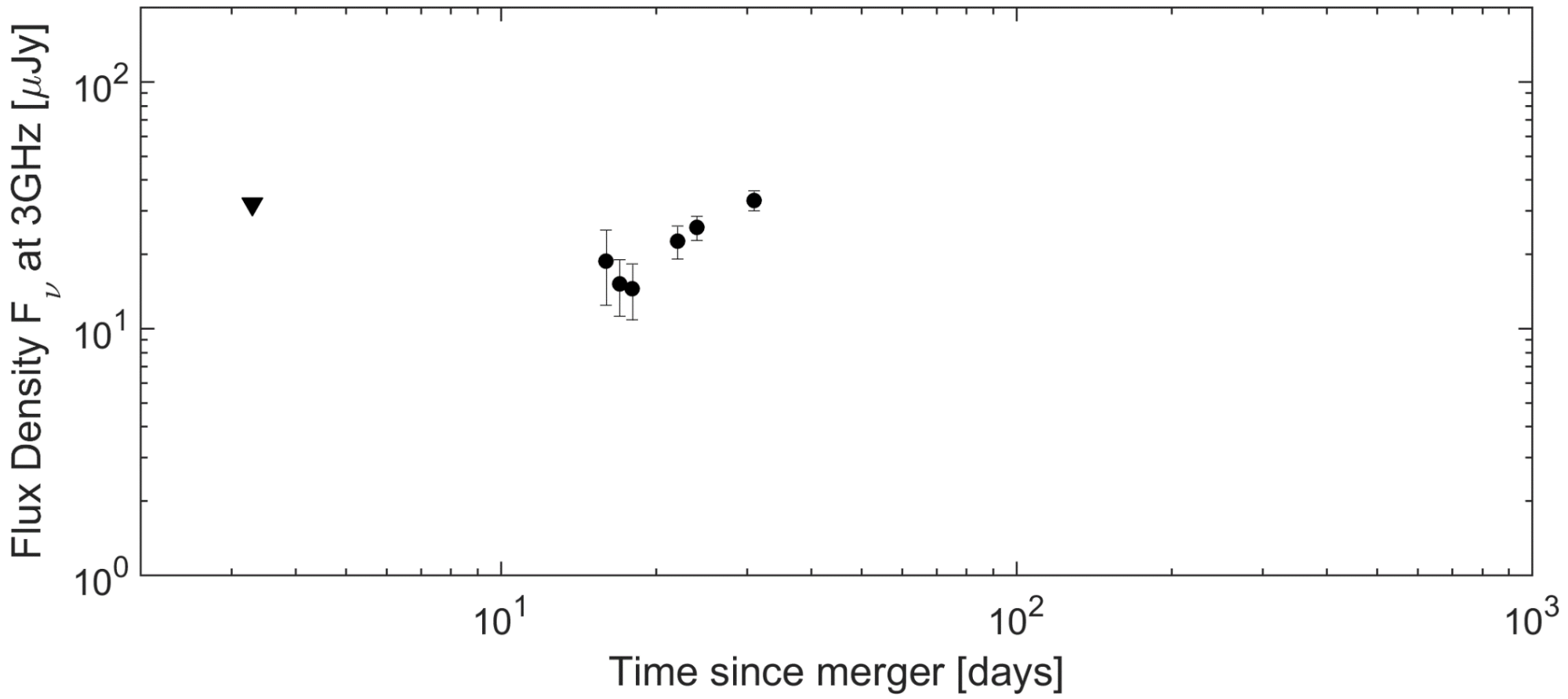
Relativistic Jet

Cocoon

i) Light curve at day 100 distinguishes ejecta morphology – collimated vs (quasi-)spherical

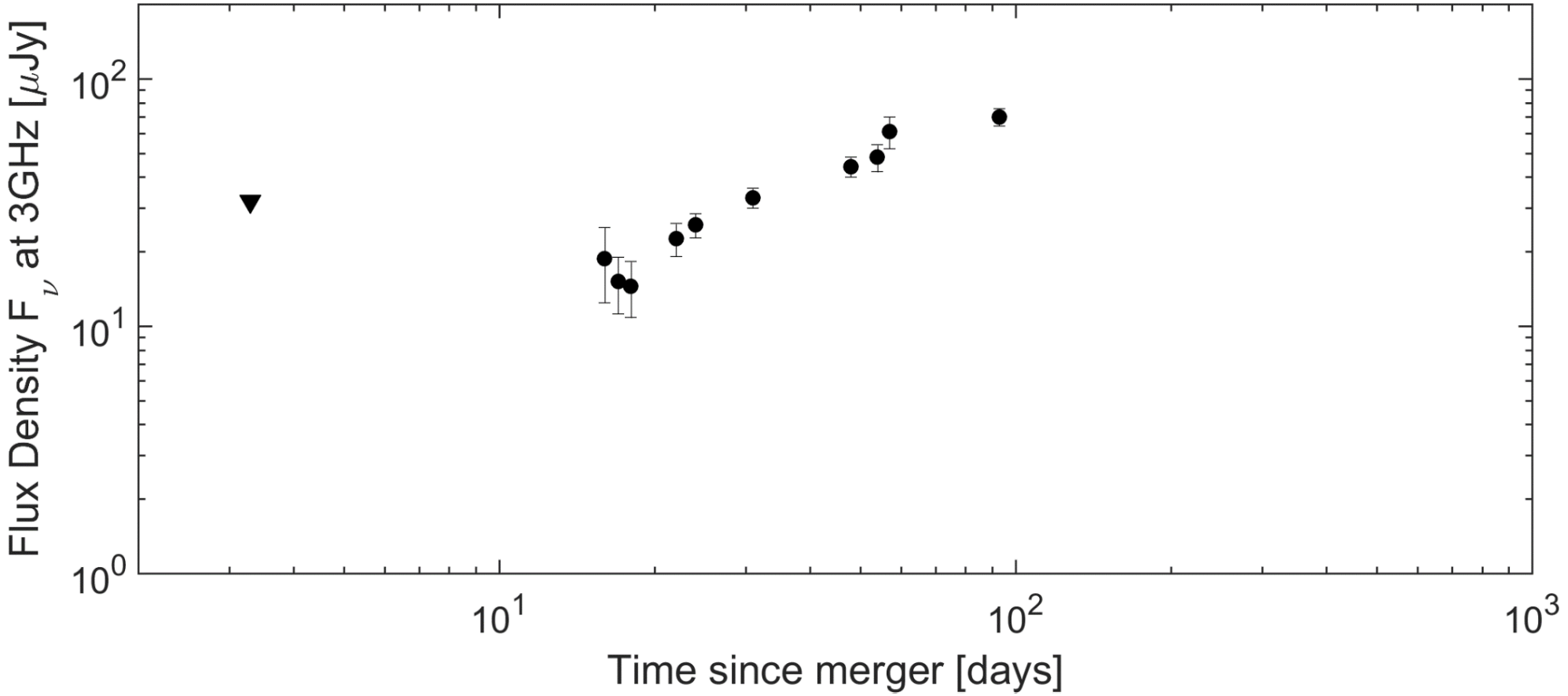
ii) Size distinguishes between dynamical ejecta tail and cocoon/jet

Light curve: Day 16 – Day 31

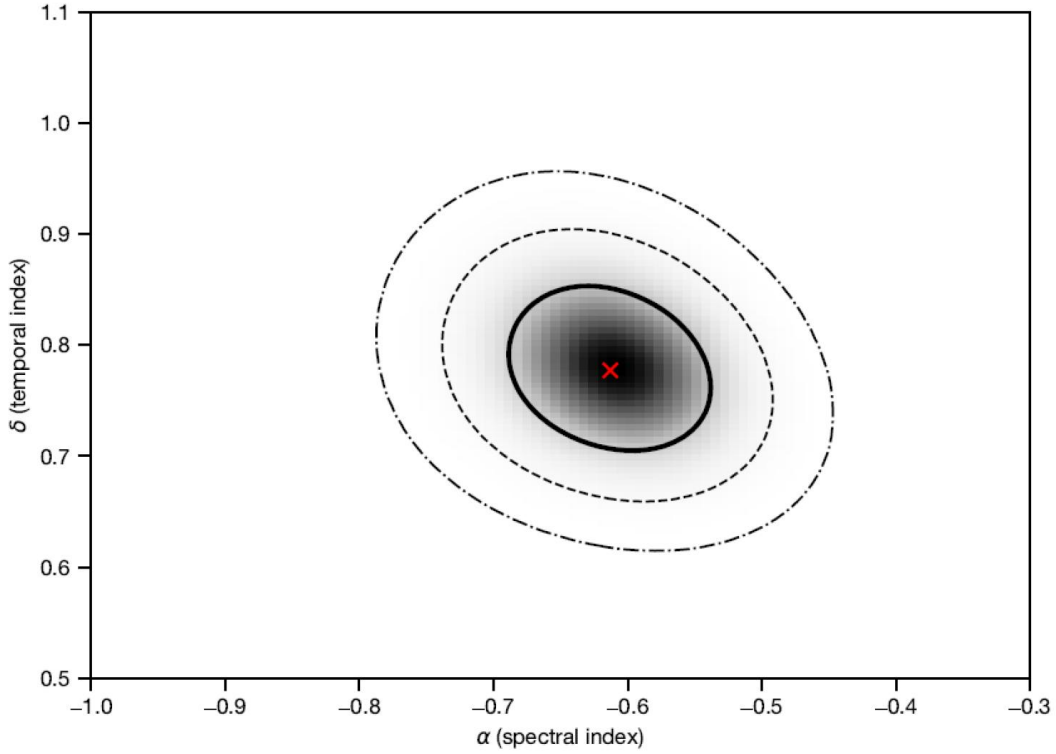


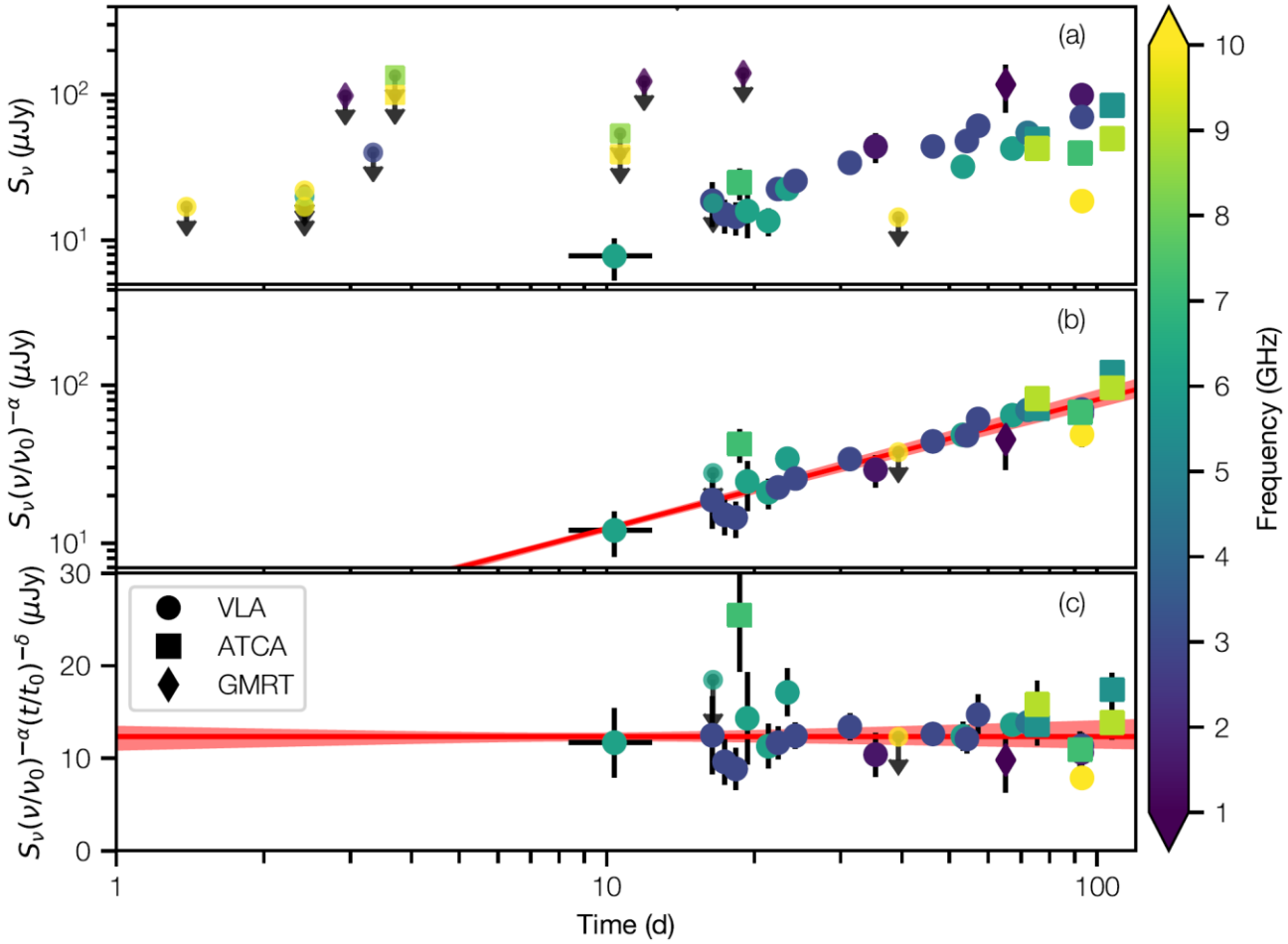
G. Hallinan, A. Corsi, *et al.*, *Science* 10.1126/science.aap9855 (2017)

Light curve: Day 16 – Day 93



Mooley et al. 2017 [arXiv:1711.11573]





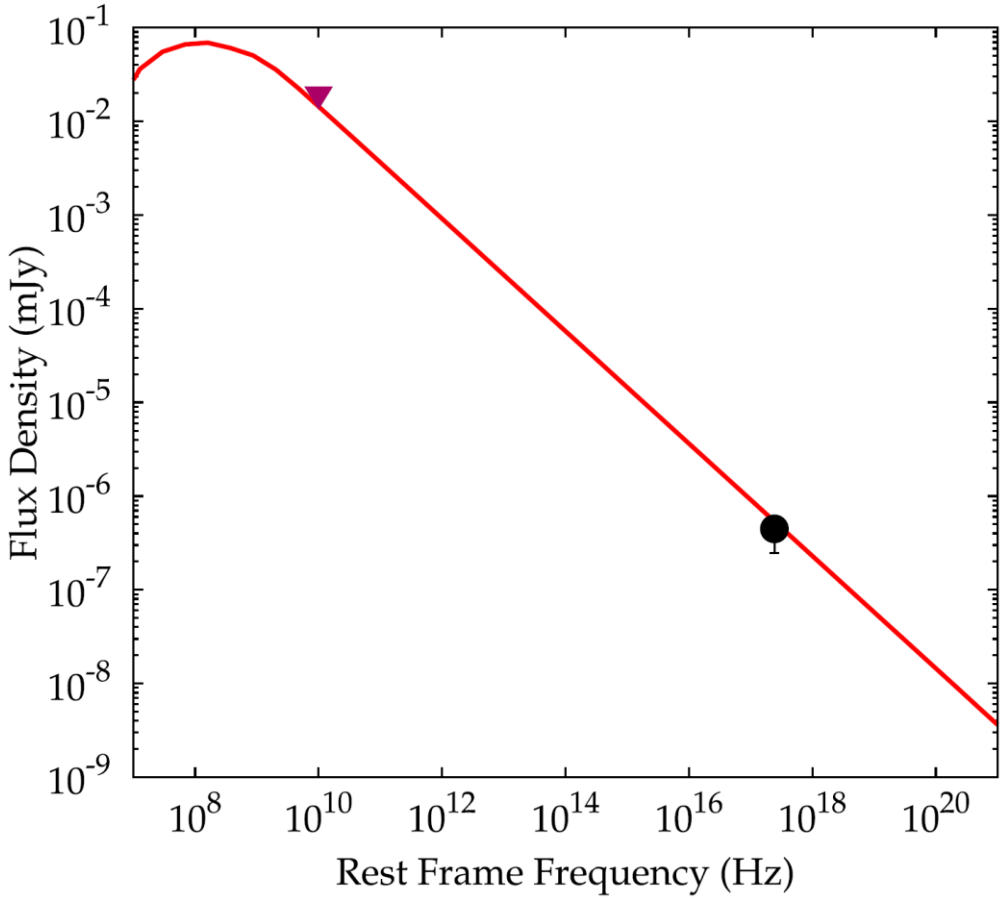
$S \propto \nu^{\alpha} t^{\delta}$ - Best joint fit to the data:

Spectral index α=-0.61+/- 0.05

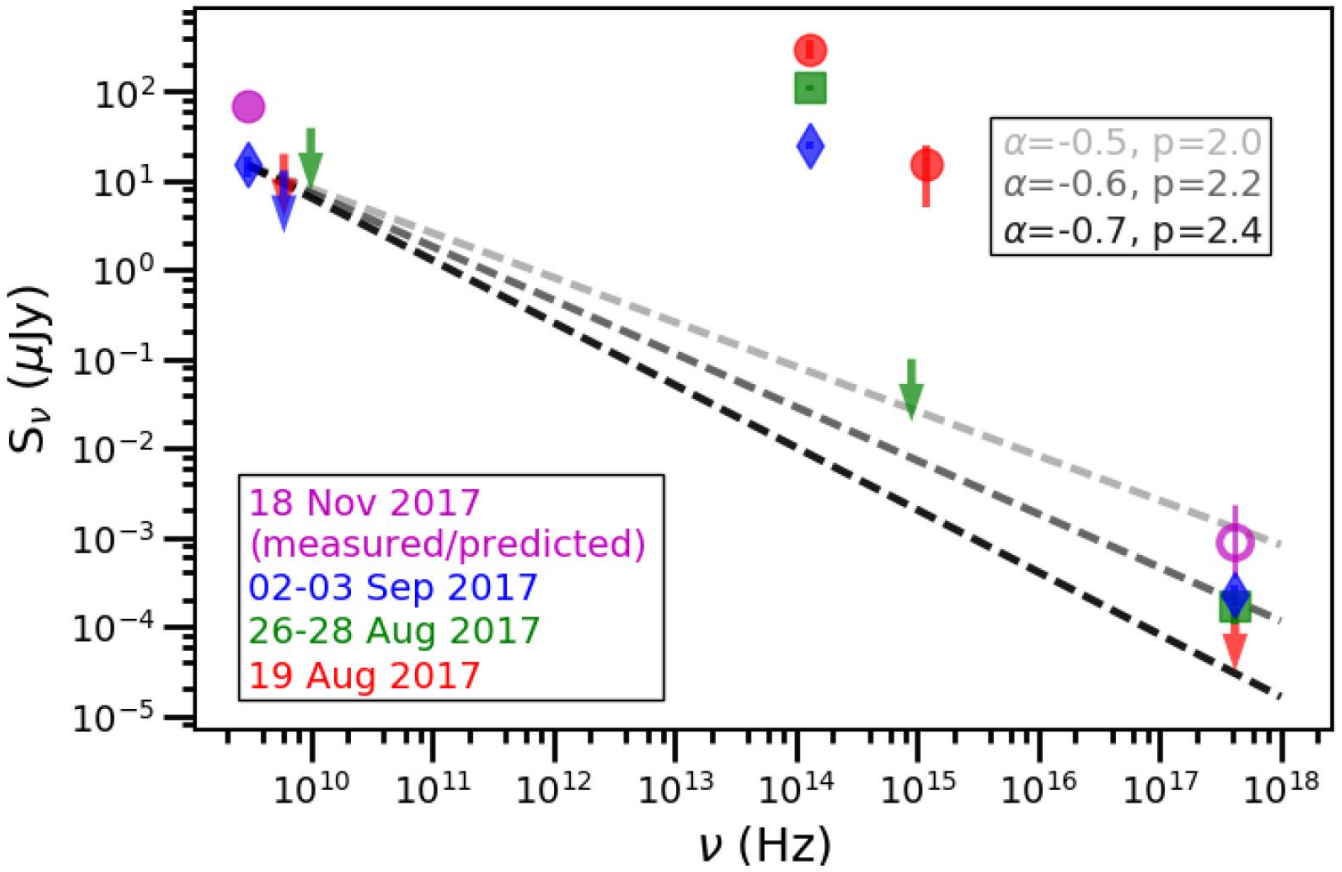
Temporal index δ=0.78+/0.05

Mooley et al. 2017 [arXiv:1711.11573]

Comparison with X-ray



Margutti et al. 2017

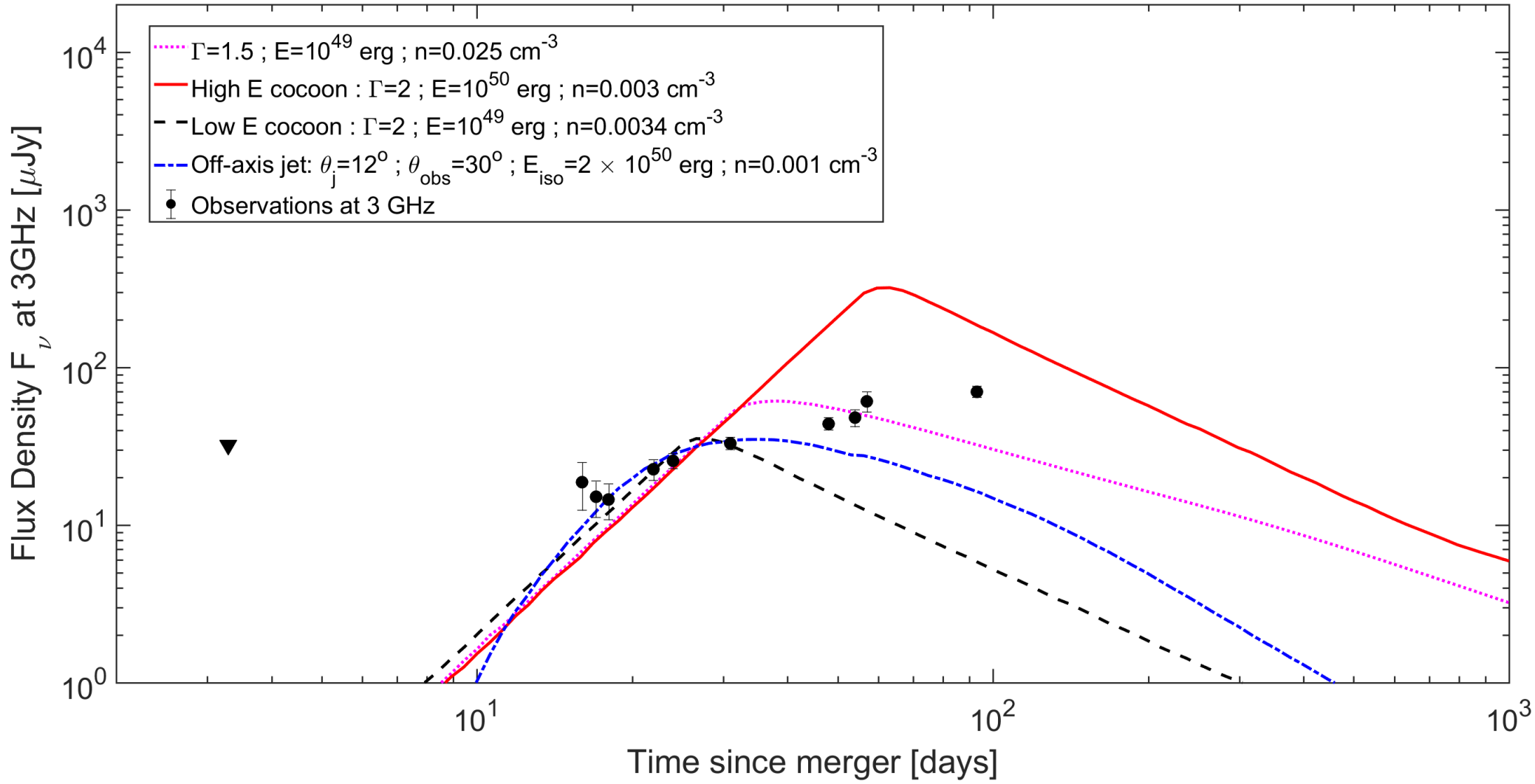


Mooley et al. 2017

Radio-only spectral index α=-0.61+/- 0.05

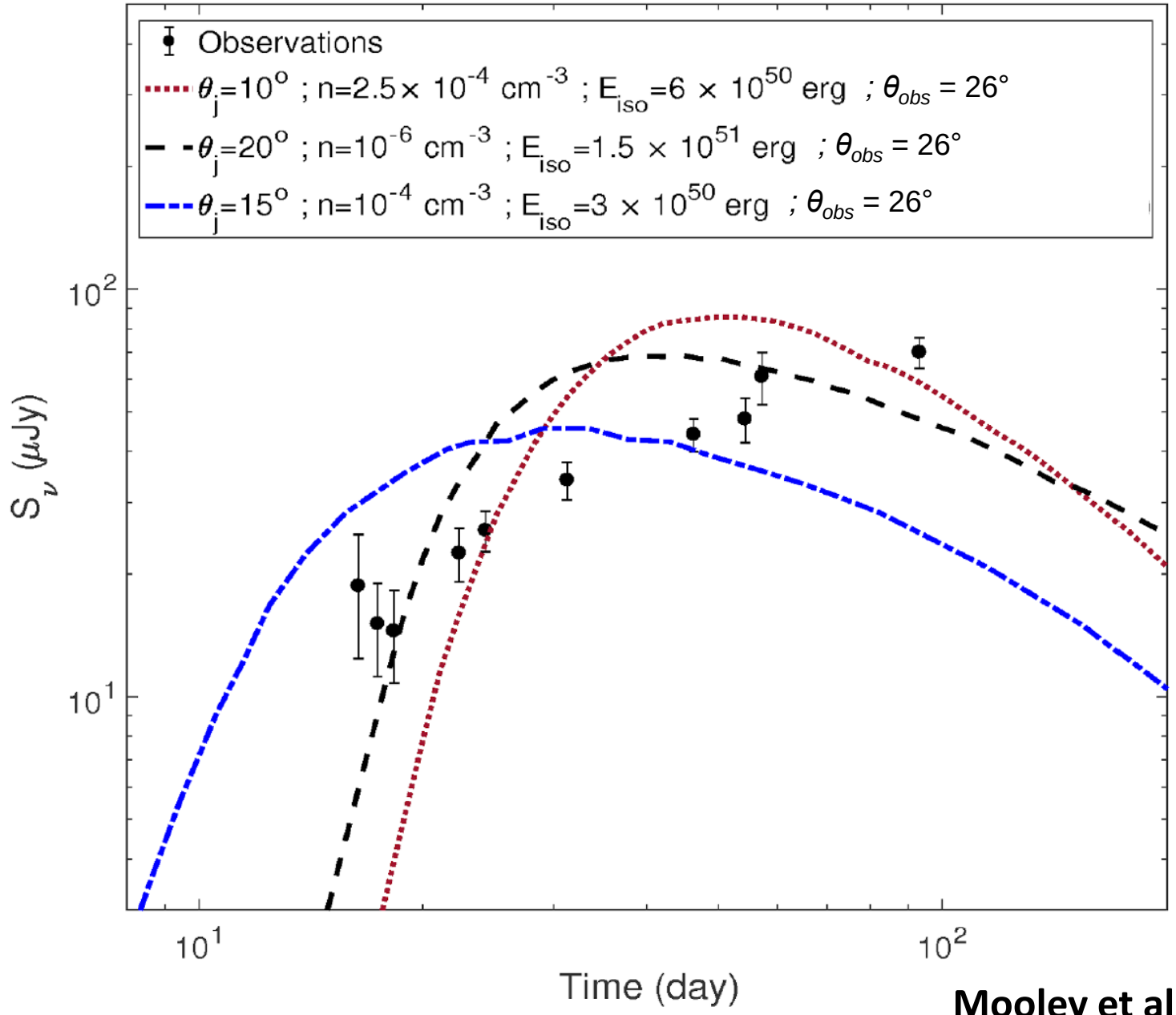
Radio and X-ray spectral index α=-0.60+/- 0.03

See also Troja et al. 2017; Hallinan et al. 2017; Alexander et al. 2017; Haggard et al. 2017



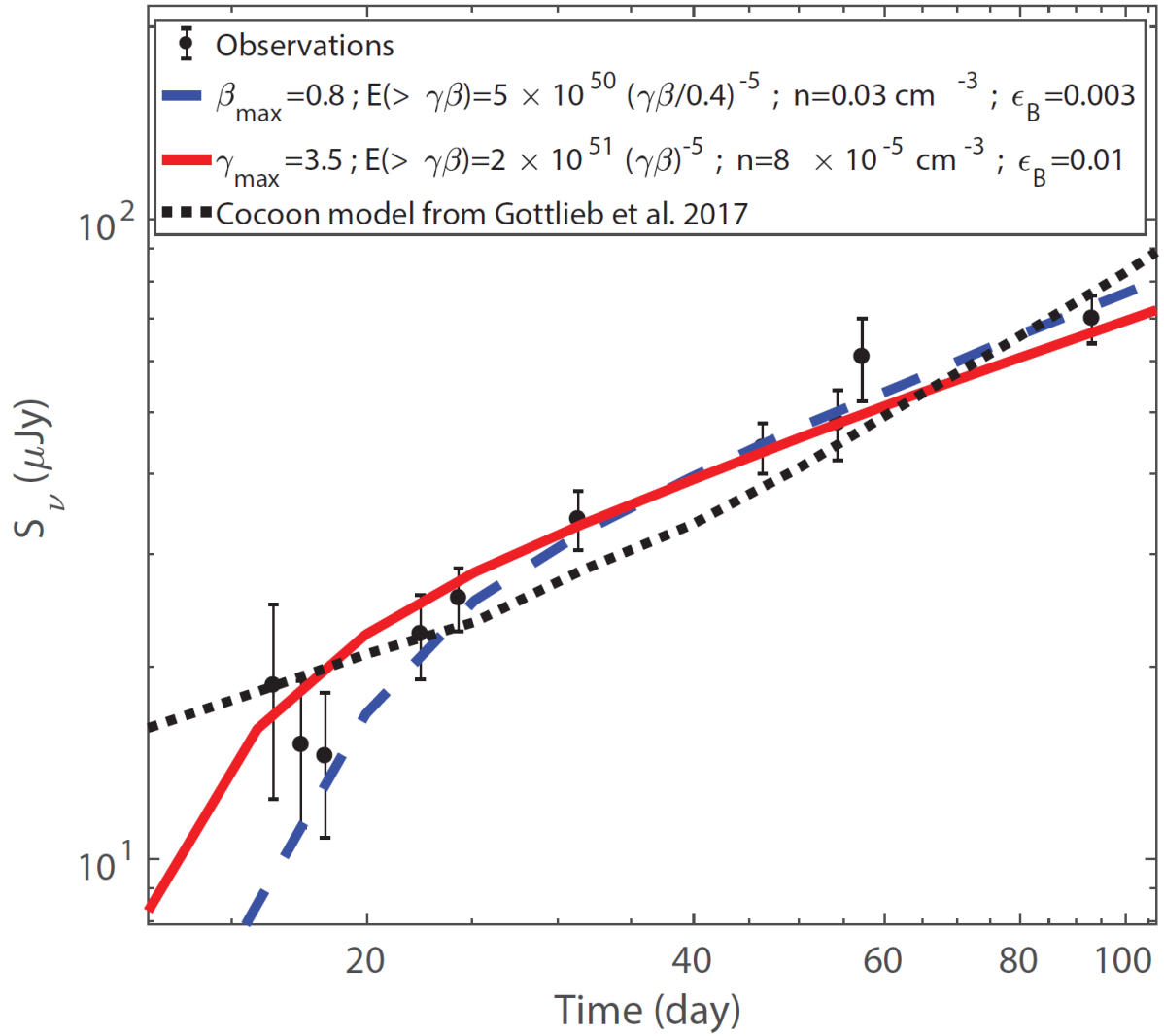
Mooley et al. 2017 [arXiv:1711.11573]

Model Ruled Out - Off-Axis Jet



Mooley et al. 2017 [arXiv:1711.11573]

Consistent Models



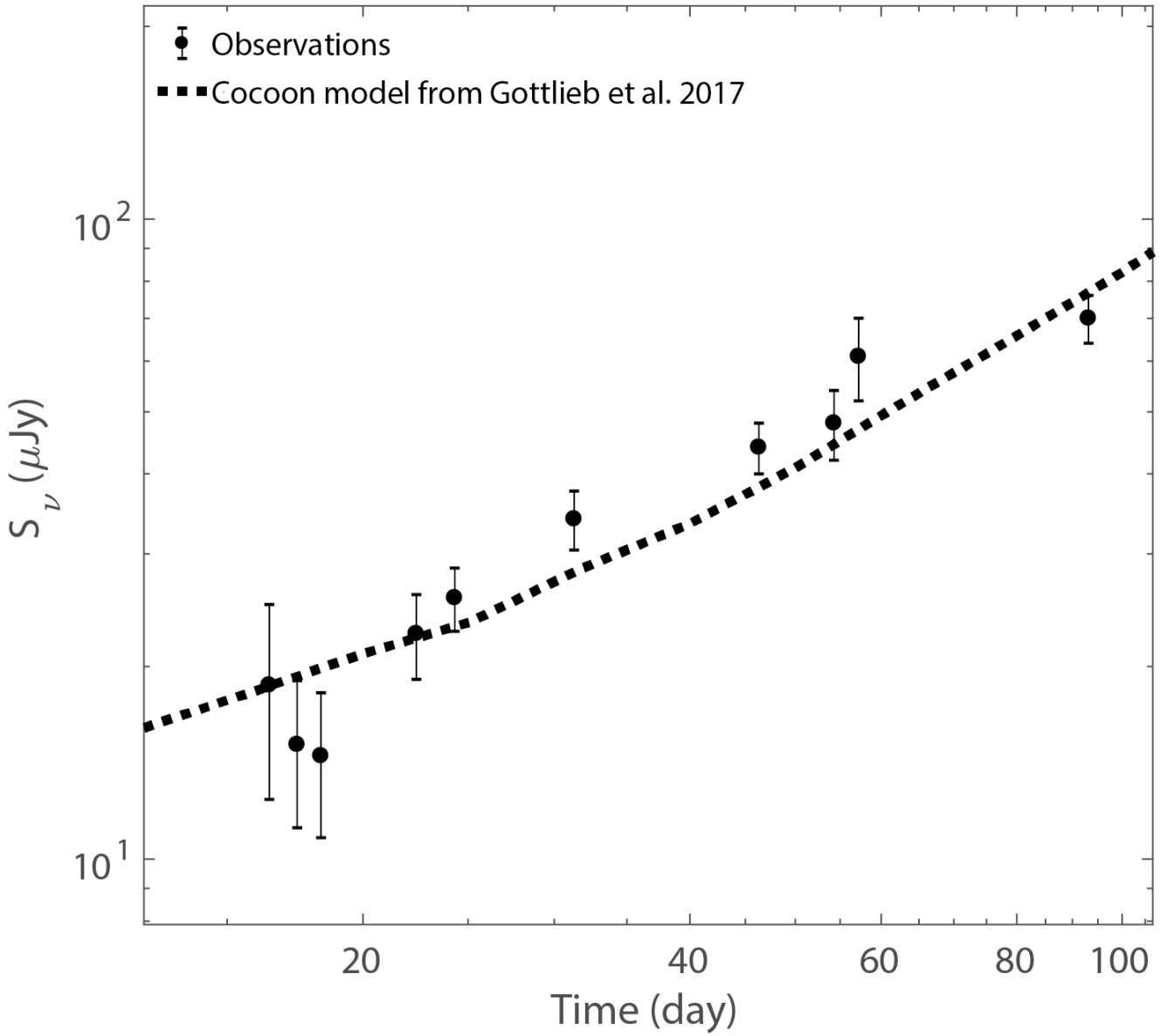
Can be modeled with a single one-dimensional velocity profile: $E(>\beta\gamma) \propto (\beta\gamma)^{-5}$

Indicates quasi-spherical outflow

More energy in the slower moving ejecta

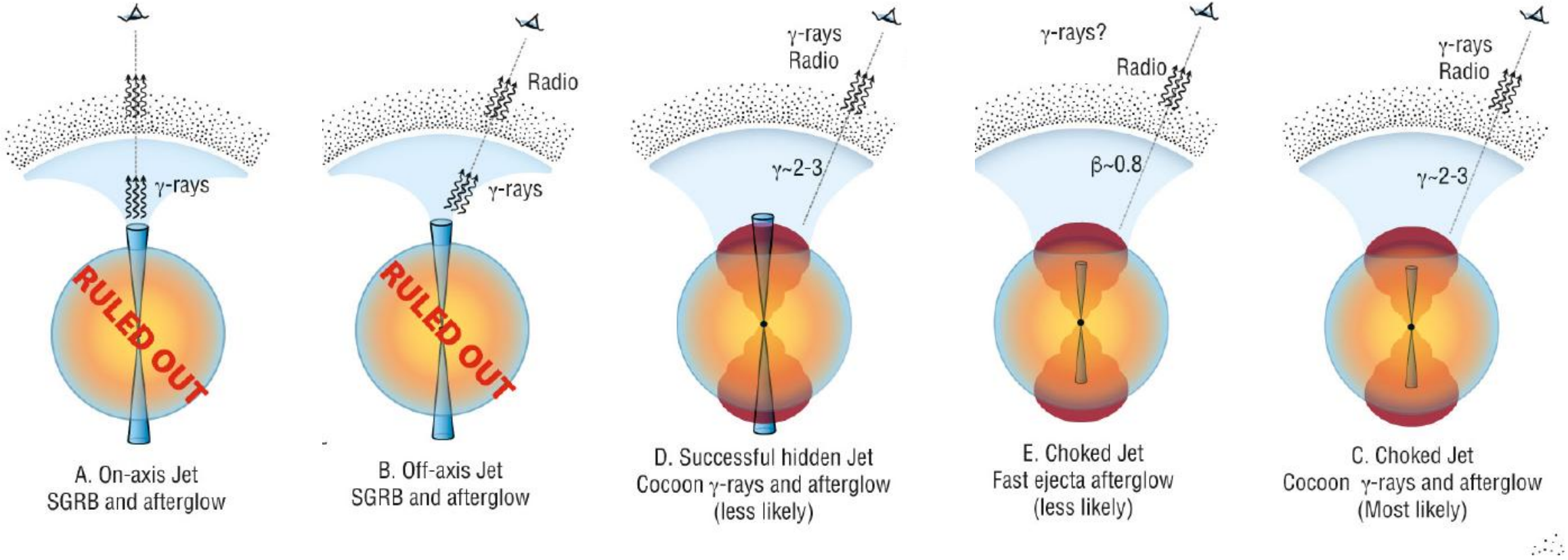
Mooley et al. 2017 [arXiv:1711.11573]

Consistent Models



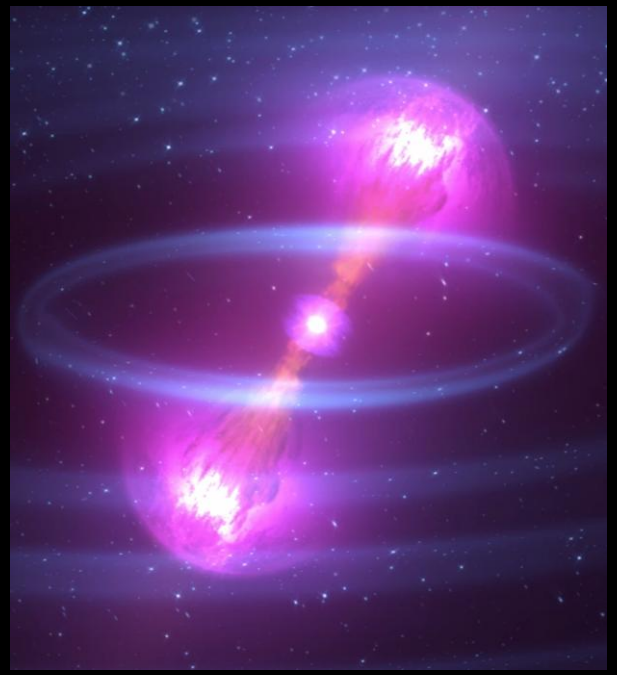
Ore et al. 2017; Mooley et al. 2017

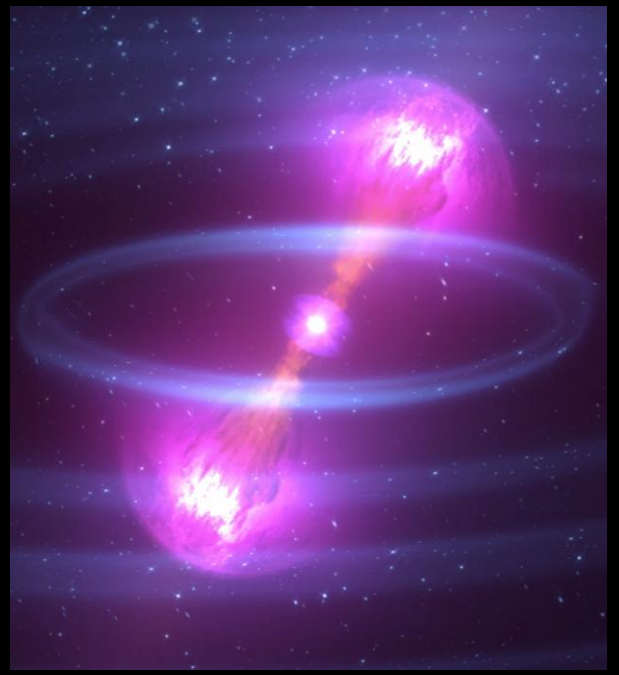
Source of Radio Emission



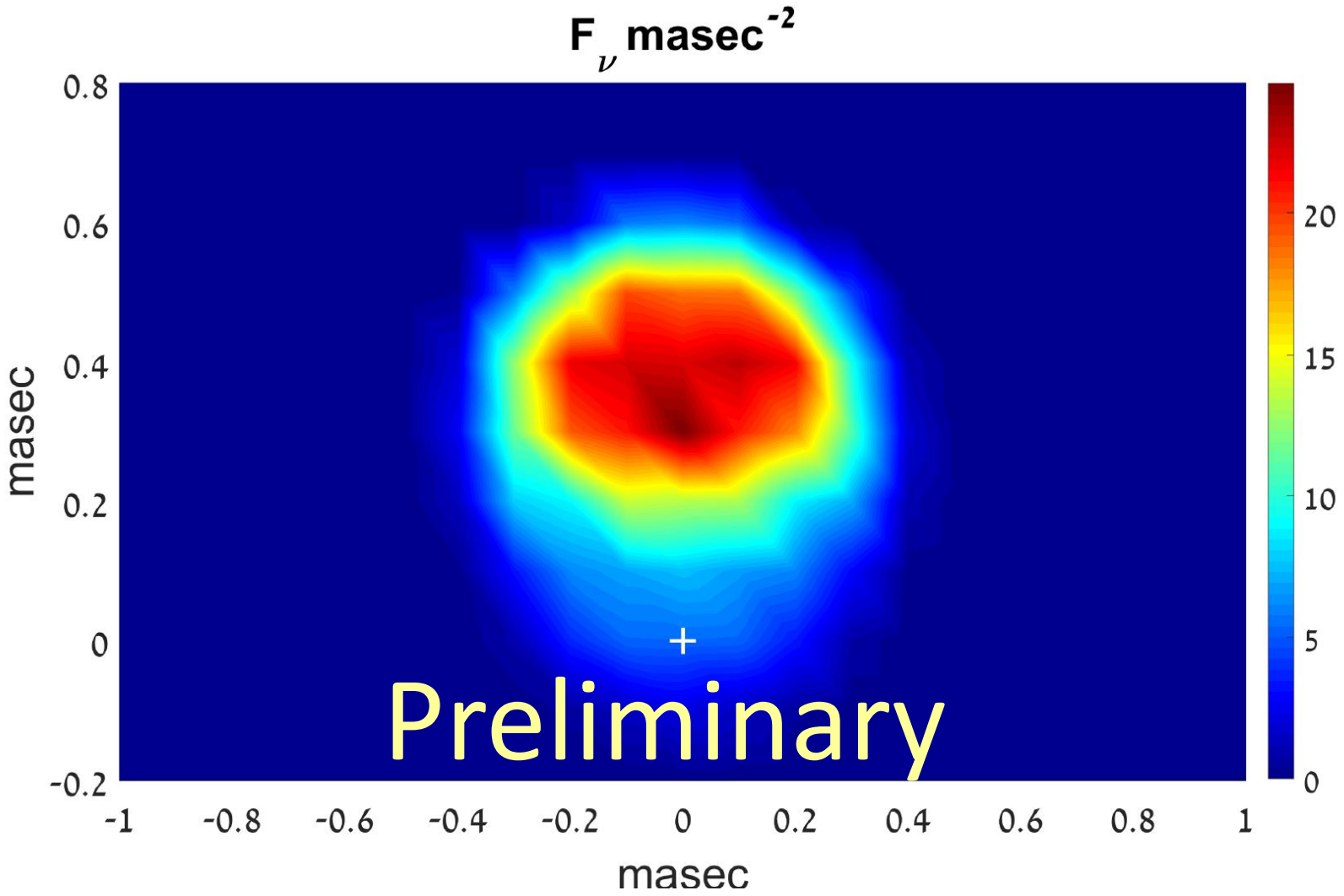
Going forward – size may distinguish between dynamical ejecta tail and mildly relativistic cocoon

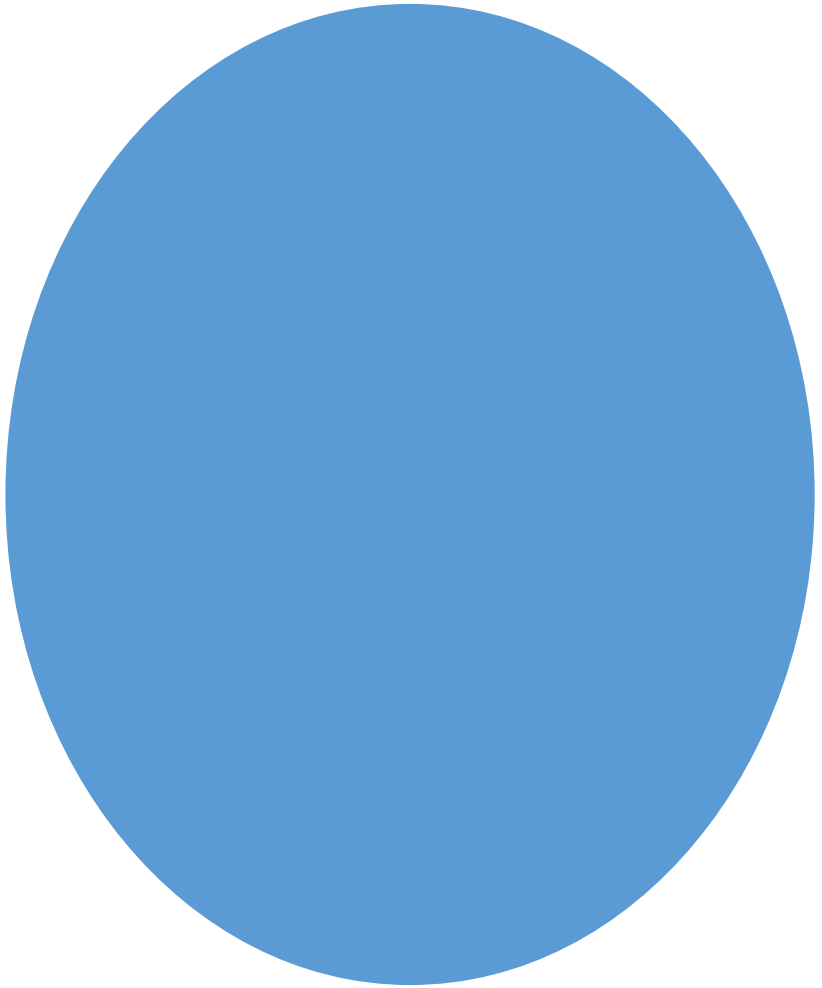

Owens Valley, California
Brewster, Washington
North Liberty, Iowa
Hancock, New Hampshire
Mauna Kea, Hawaii
Los Alamos, New Mexico
Kitt Peak, Arizona
Pie Town, New Mexico
Fort Davis, Texas
St. Croix, Virgin Islands



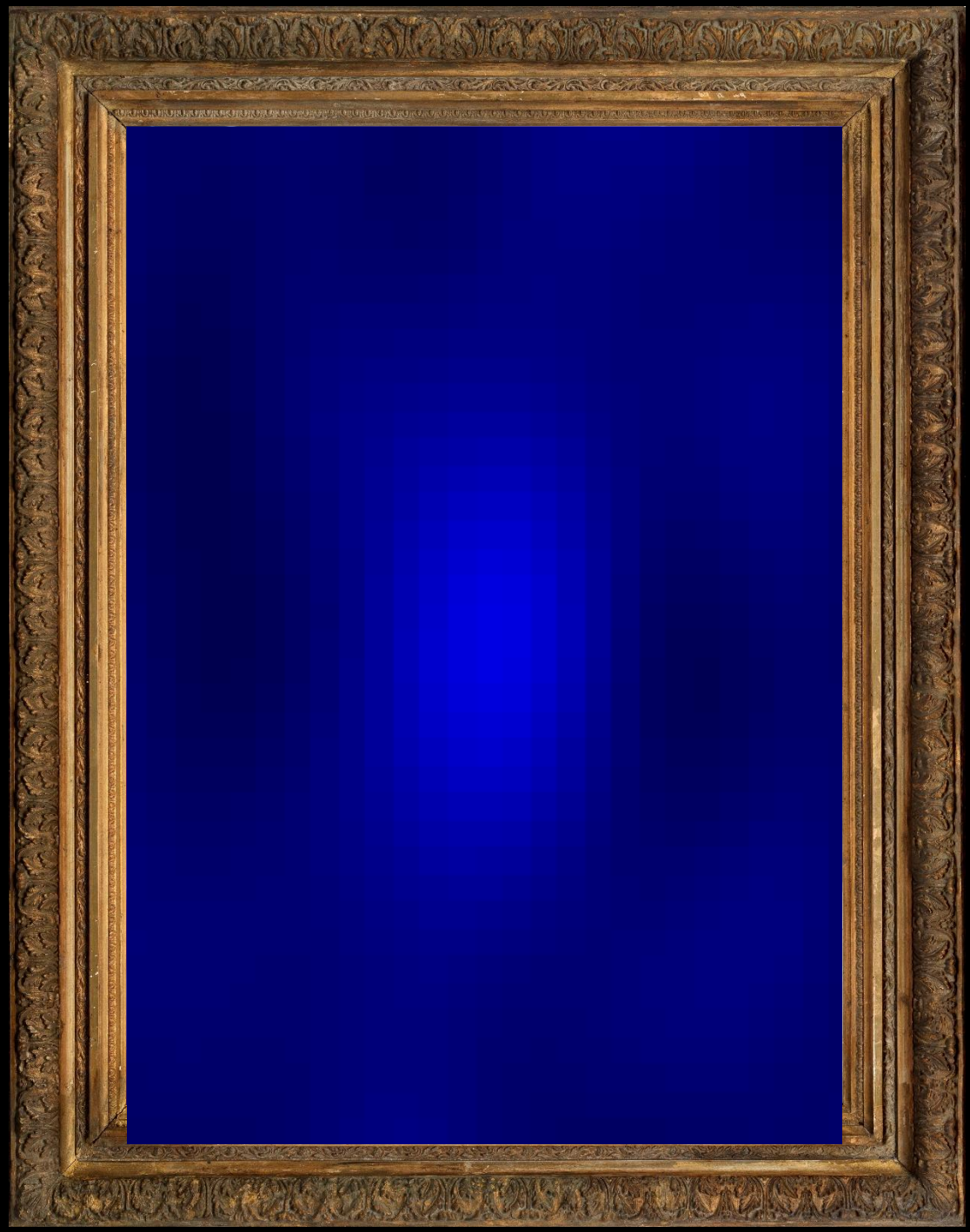


Gottlieb et al. in prep.





VLBI FWHM at 6 GHz ~ 1.4 mas



Summary

Radio observations of GW170817 are ongoing

Radio-only spectrum consistent with common origin for radio and X-ray

Light curve to date favors a quasi-spherical outflow

More energy in the slower moving ejecta $E(>\beta\gamma) \propto (\beta\gamma)^{-5}$

VLBI will possibly distinguish between cocoon and dynamical ejecta high velocity tail

Radio emission from the slower moving dynamical ejecta may take years to rise

Cocoon

Structured Jet