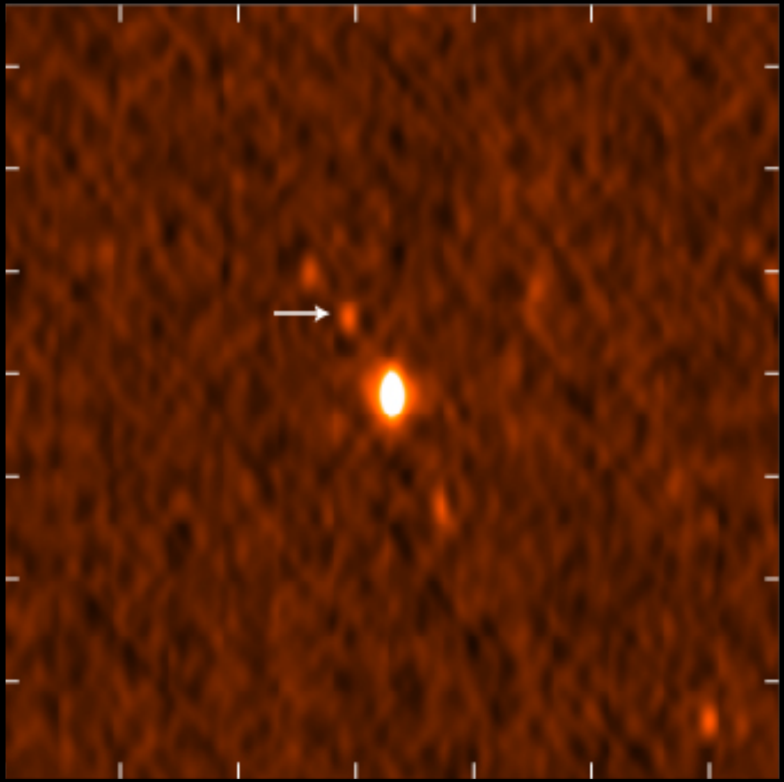
The Radio Afterglow of a Neutron Star Merger



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*

GROWTH

Global Relay of Observatories Watching Transients Happen

Caltech

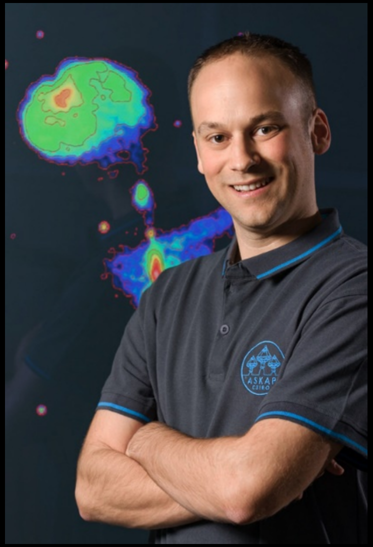
JAGWAR

Tara Murphy

David Kaplan

Dougal Dobie

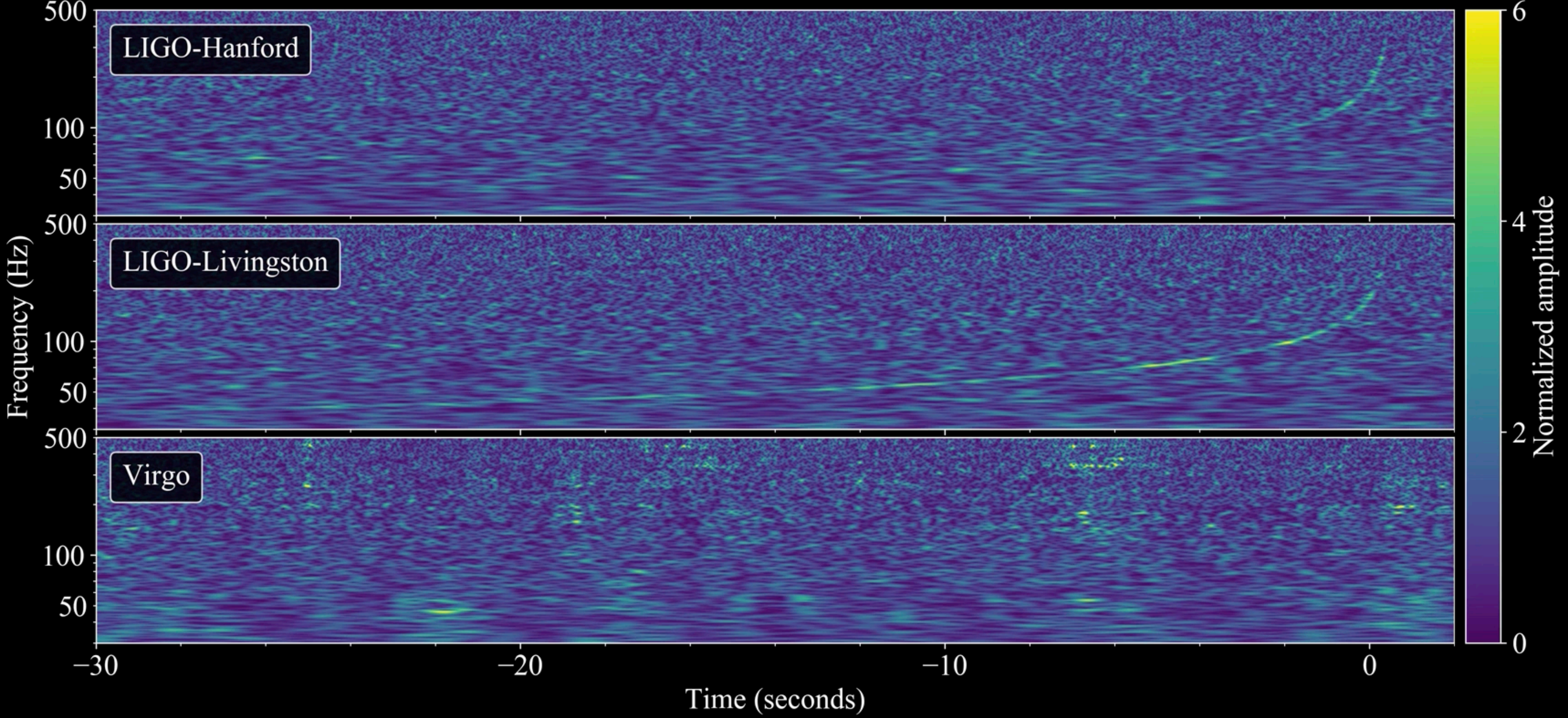
Elaine Sadler



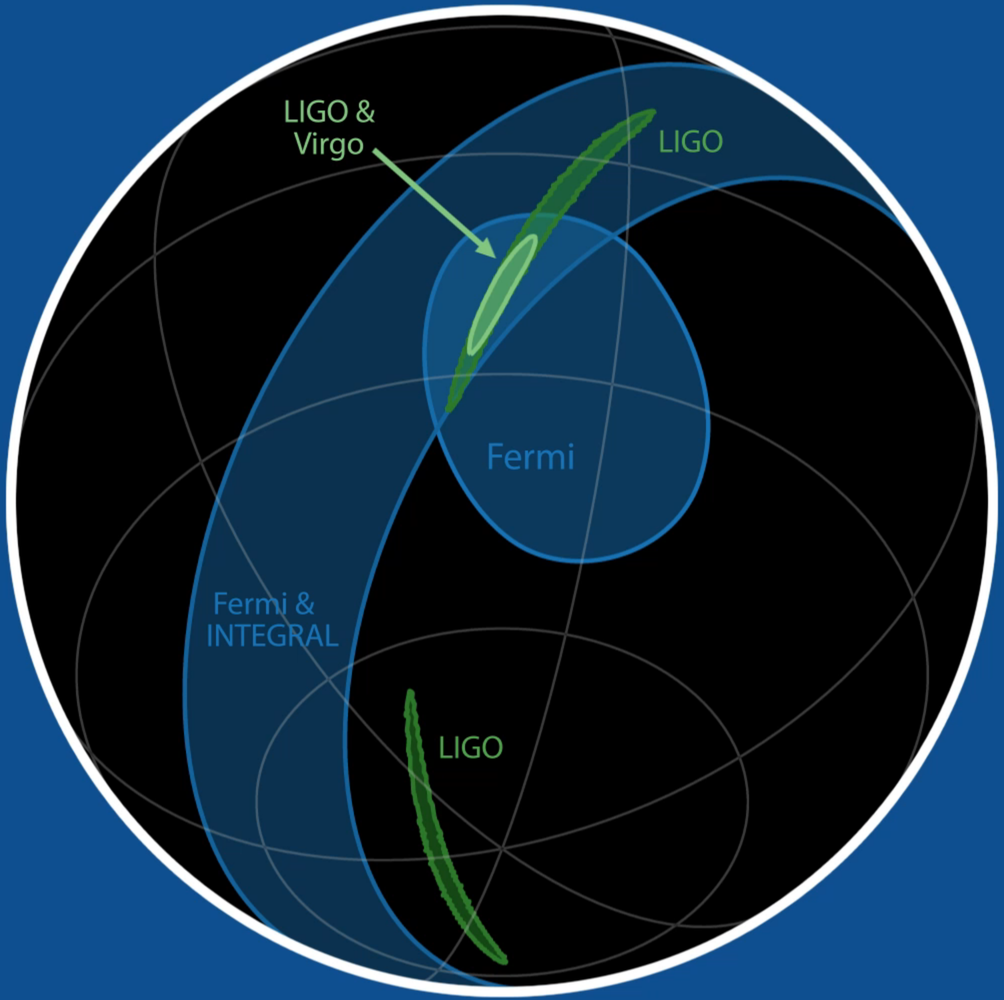
James Allison

Christene Lynch

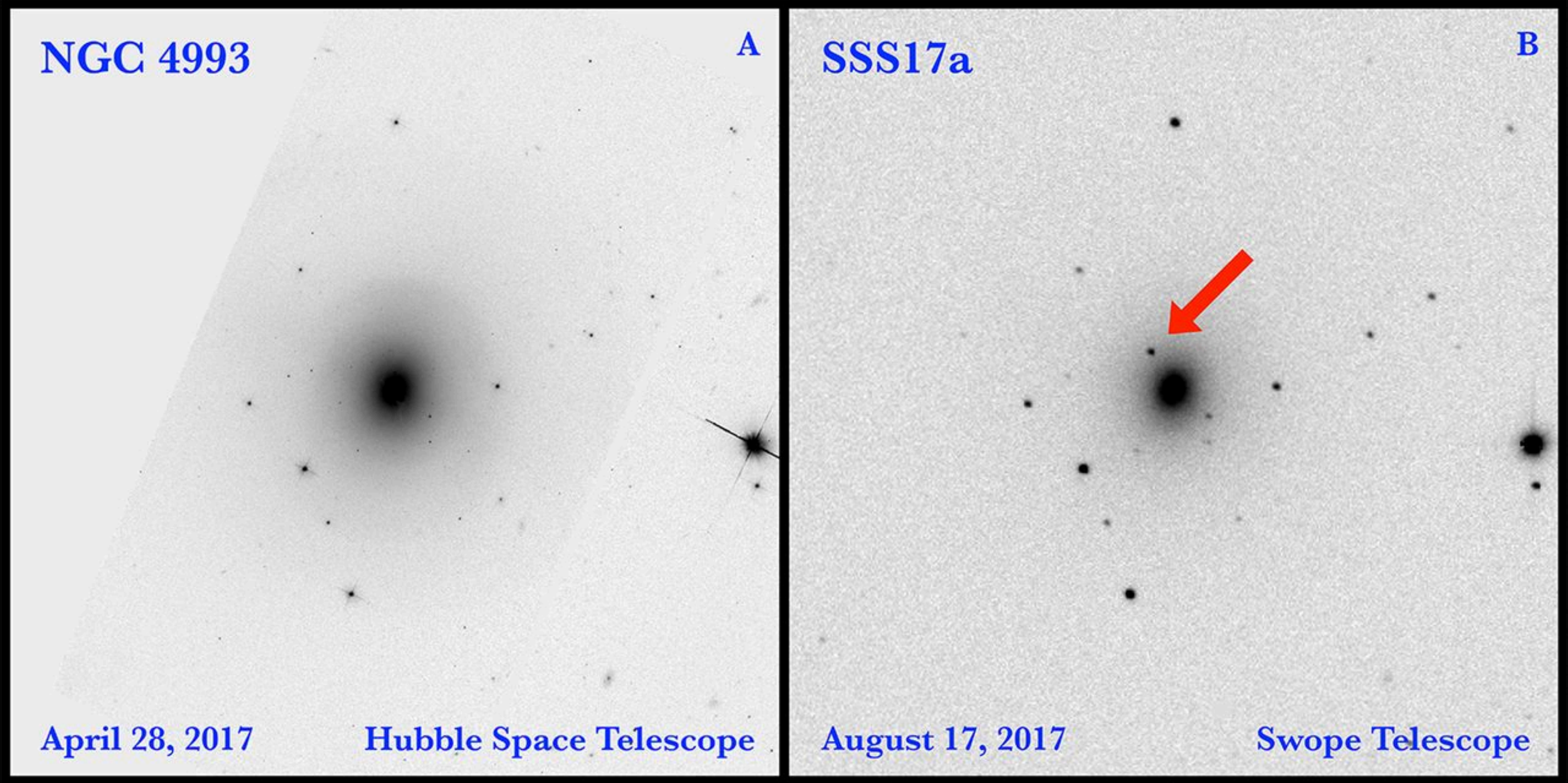
Emil Lenc



LIGO-Hanford
LIGO-Livingston
Virgo
Frequency (Hz)
500
100
50
Time (seconds)
−30
−20
−10
0
Normalized amplitude
6
4
2
0



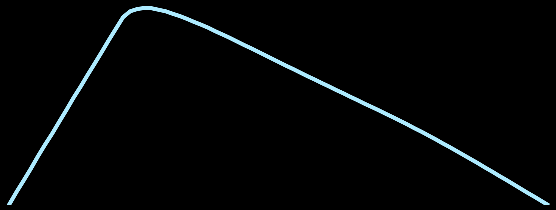
LIGO &
Virgo
LIGO
Fermi
Fermi &
INTEGRAL
LIGO



Coulter et al. 2017

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

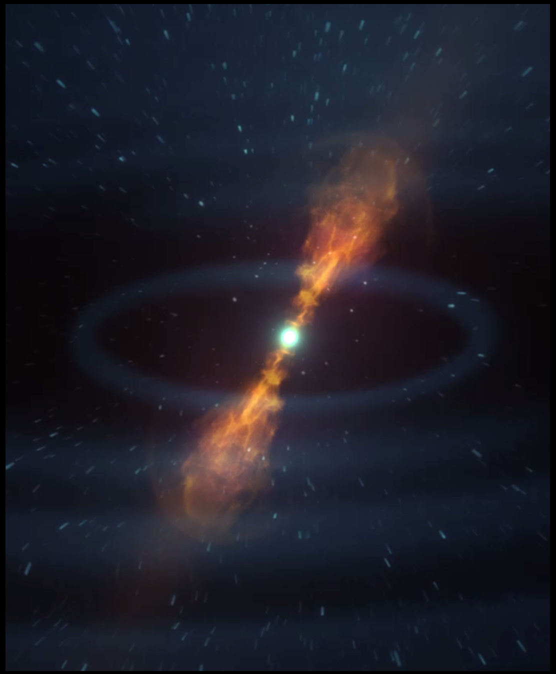
Dynamical Ejecta

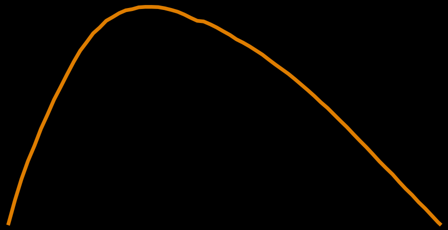


Months-Years

Nakar & Piran 2011
Hotokeza & Piran 2015

Relativistic Jet

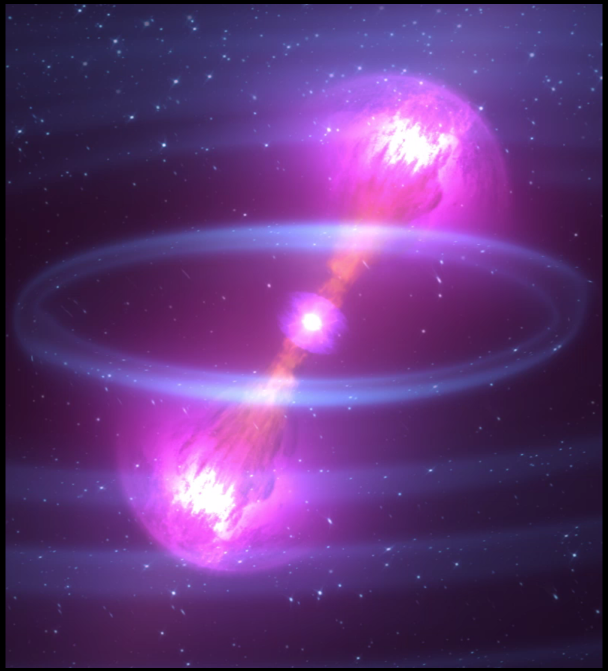


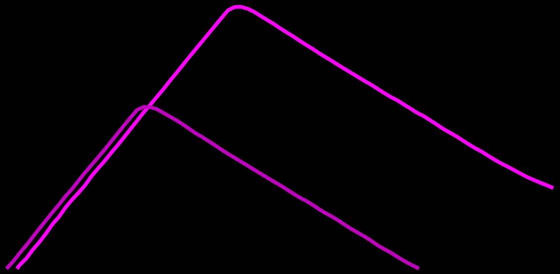


Days-Weeks

Granot et al. 2002

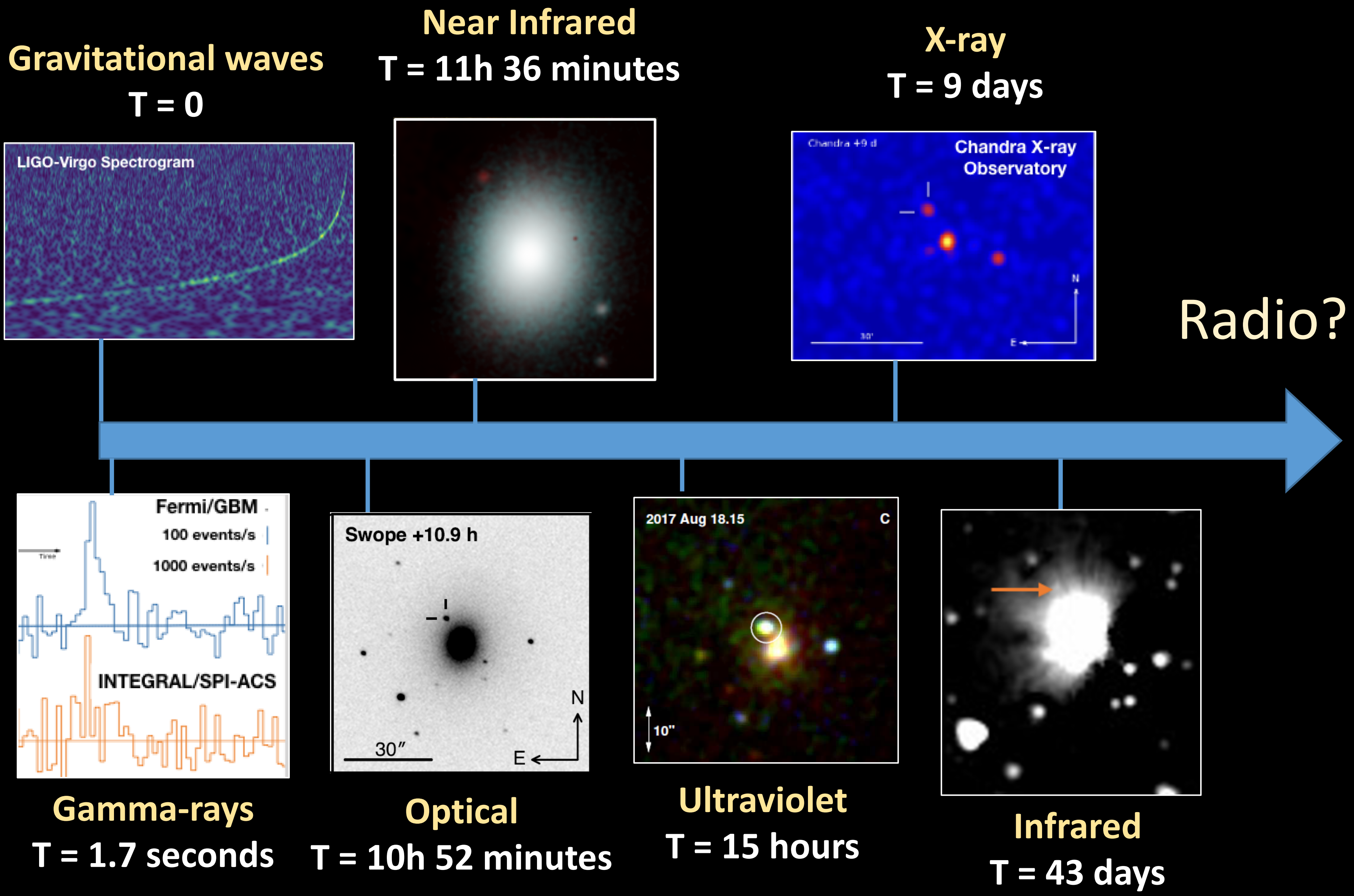
Cocoon





Weeks-Months

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



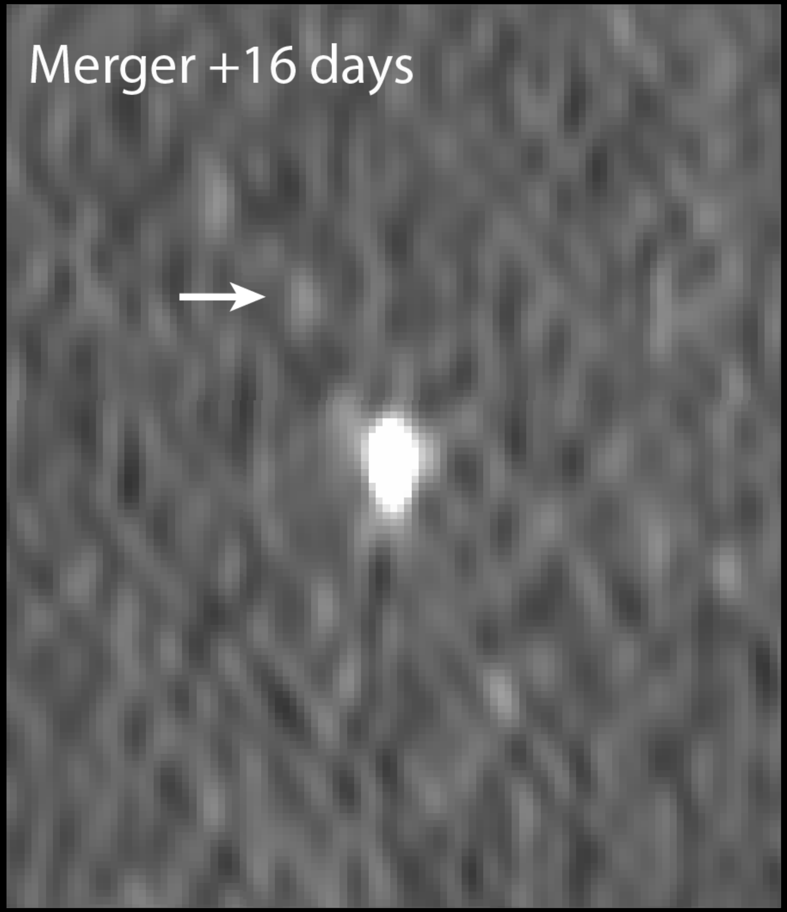
See full list of publications at www.kilonovae.org


The VLA
New Mexico


The GMRT
India


The ATCA
Australia

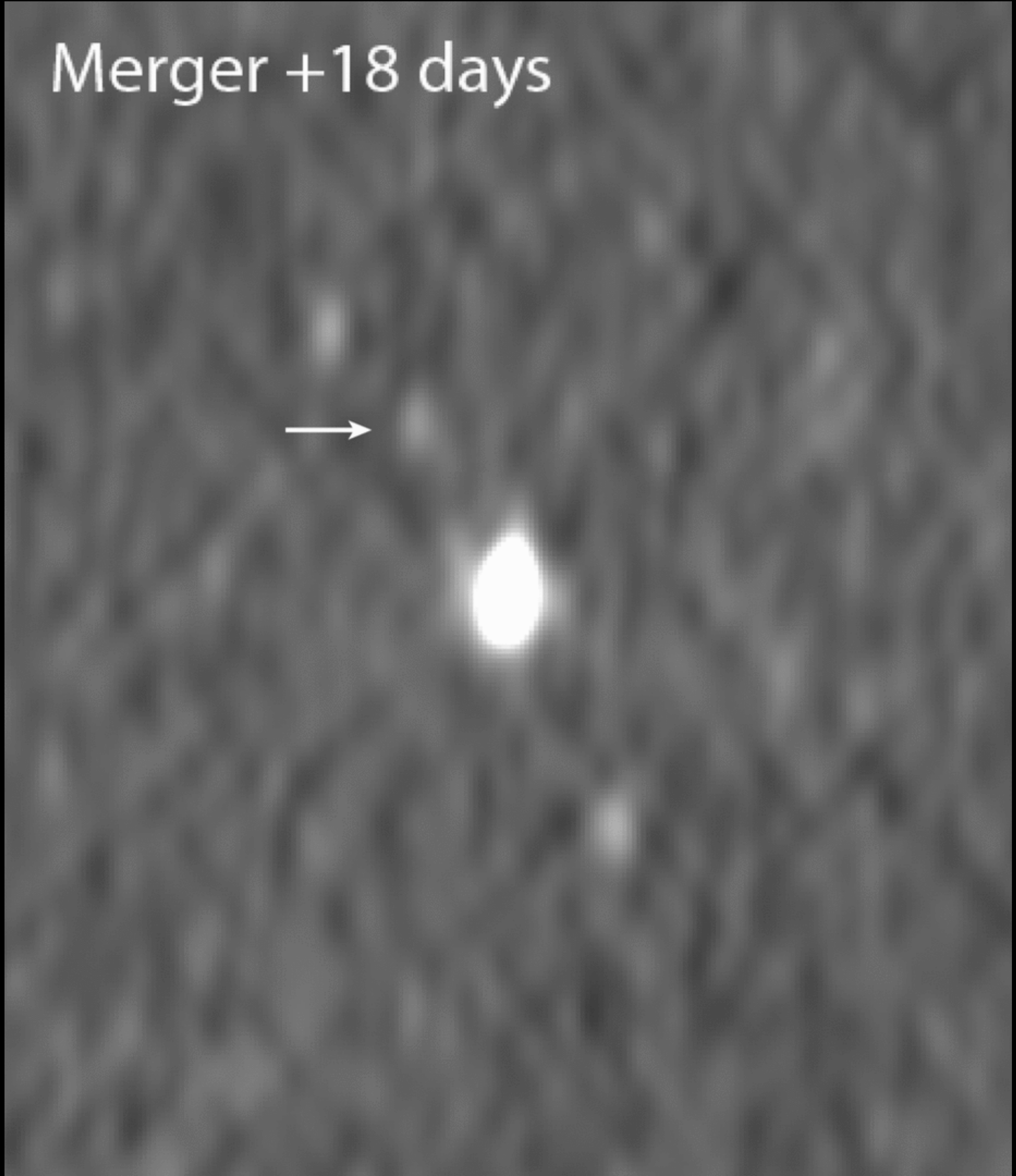
Discovery with the VLA



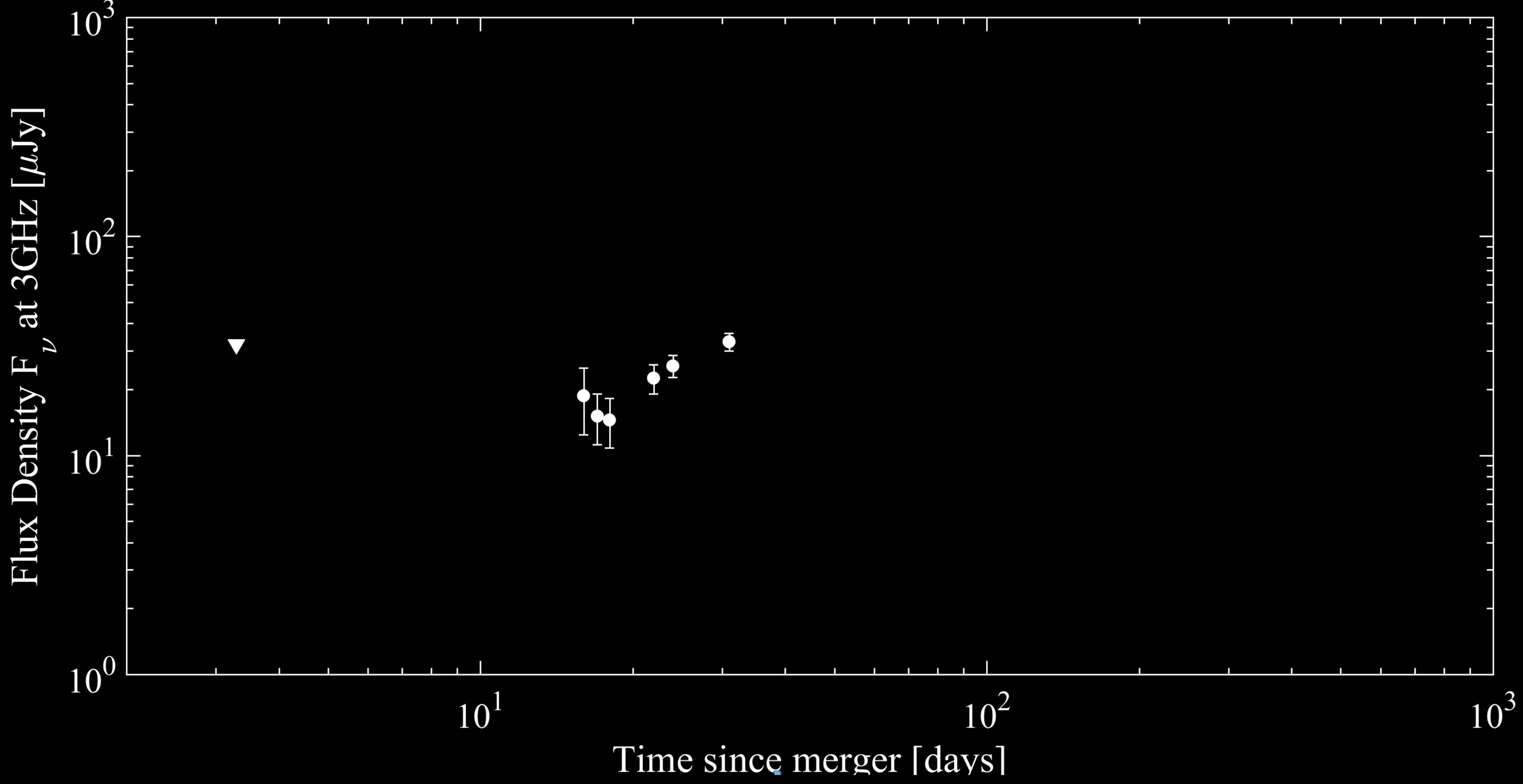
VLA observations from G. Hallinan, A. Corsi, *et al.*, *Science* 10.1126/science.aap9855 (2017)

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

Independently discovered with the VLA at 6 GHz – Alessandra Corsi
Confirmed with the ATCA – Tara Murphy et al.


Merger +18 days

Light curve at 3 GHz: 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)

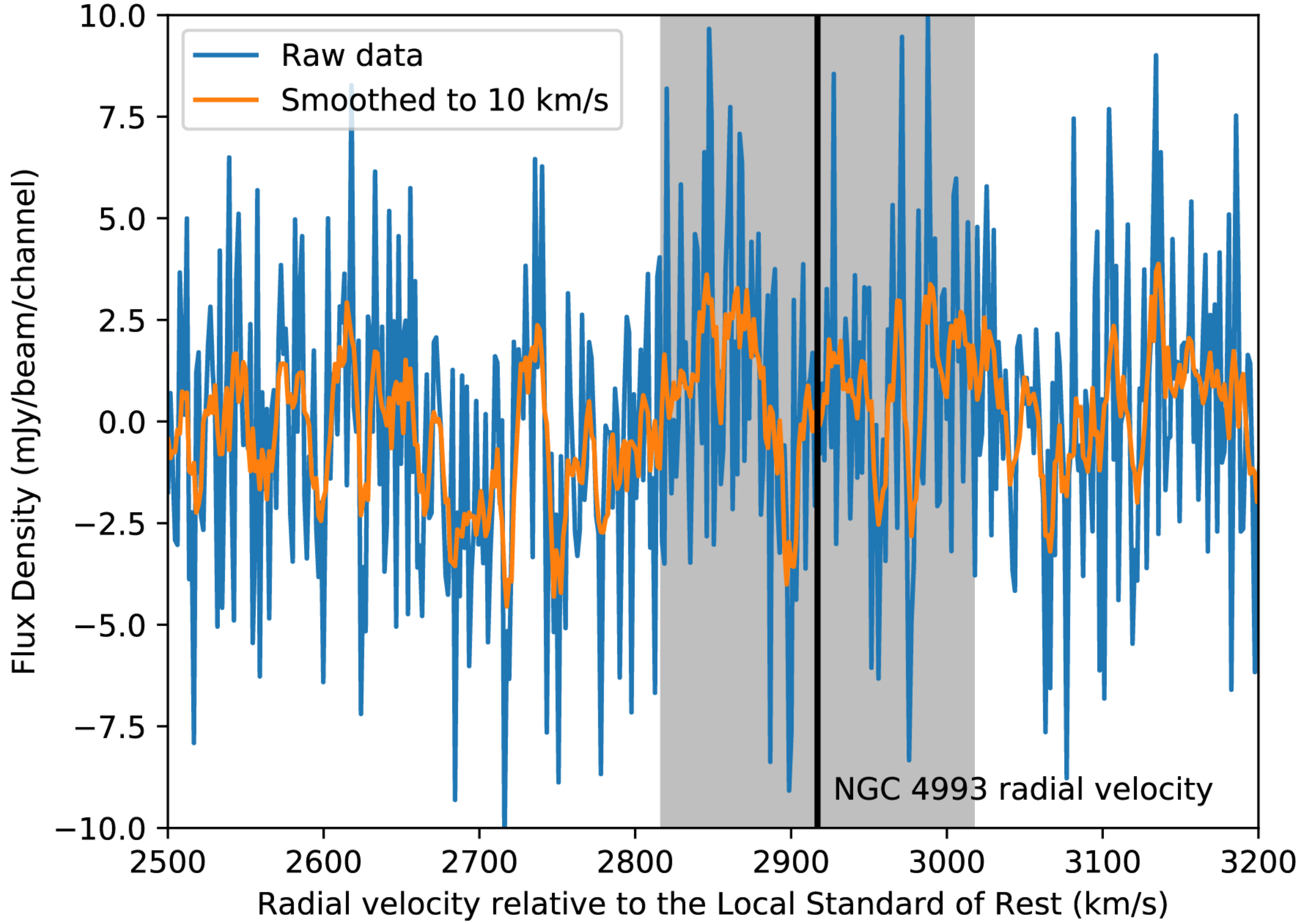
ii) Hotokezaka & Piran

Results consistent with BOXFIT

Models assume ε_e = 0.1 and ε_B = 0.01

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

Green Bank Telescope: 2017 September 11



Search for HI: The grey region spans a +/- 100 km s^{-1} velocity width that we used to estimate an upper limit on the neutral hydrogen mass.

M_{HI} of < 1 × 10^8 $M_\odot$ - Implied local number density $n_{H\,I}$ < 0.04 cm^{-3}

David Kaplan, Jay Lockman, James Allison, Elaine Sadler

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

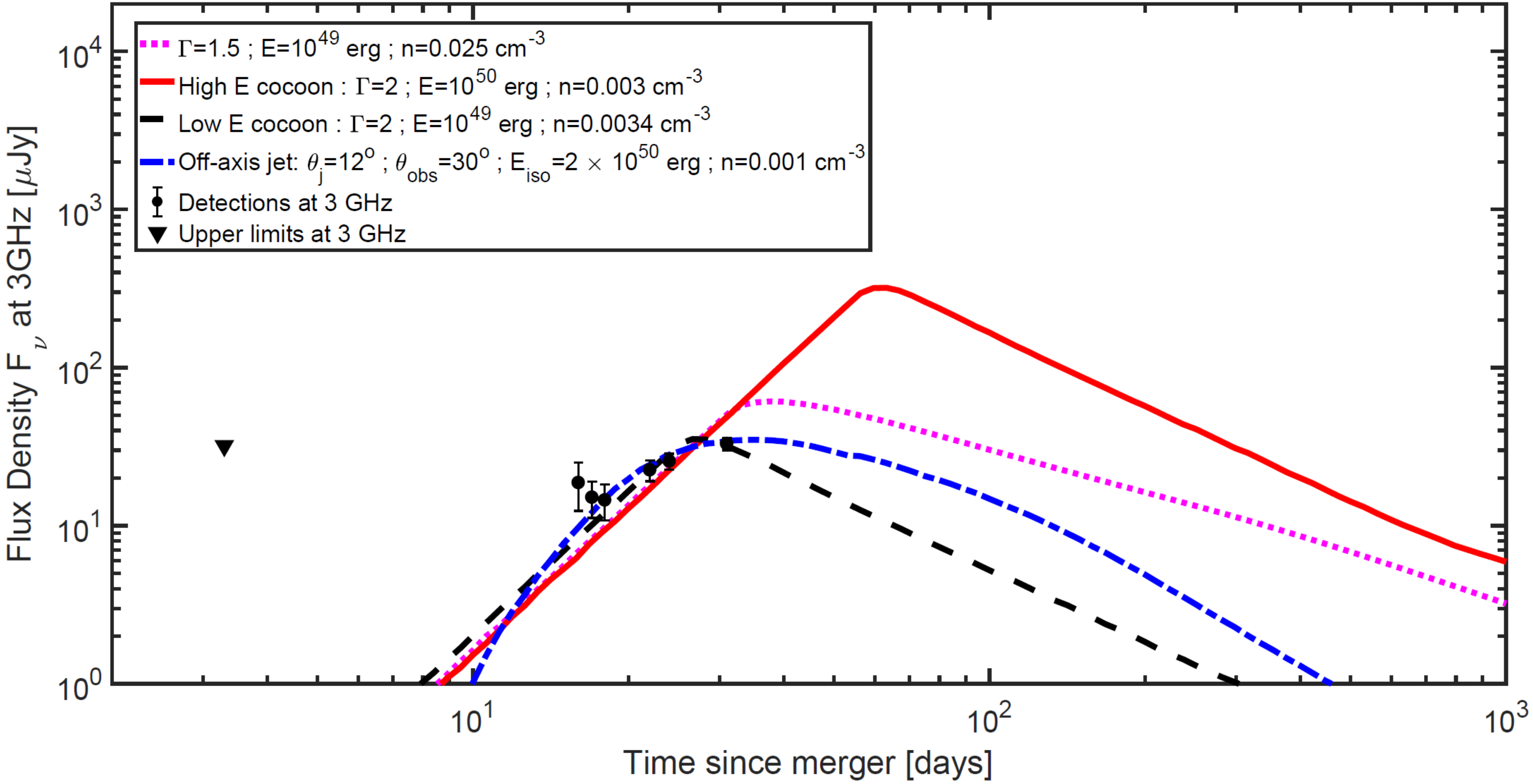
Radio and X-ray light curve rising after a few days

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)

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

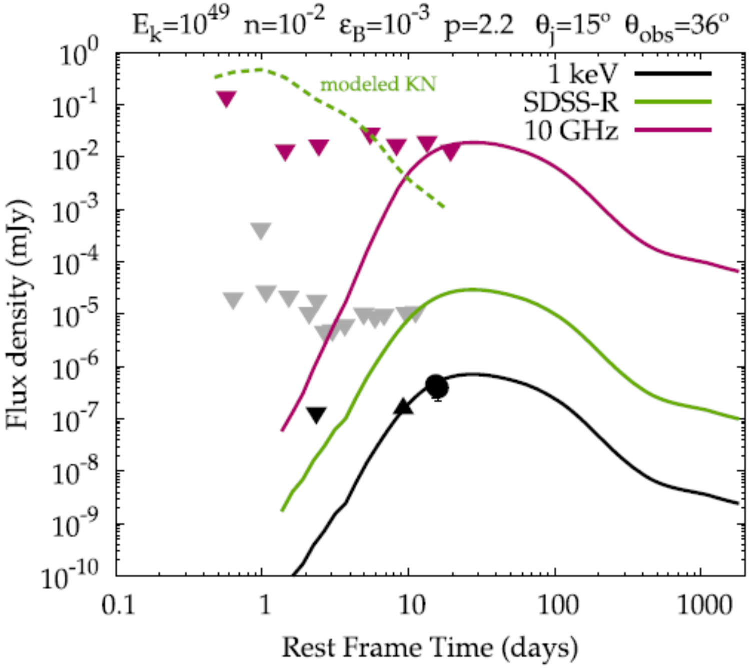
Models Consistent with Early Light Curve



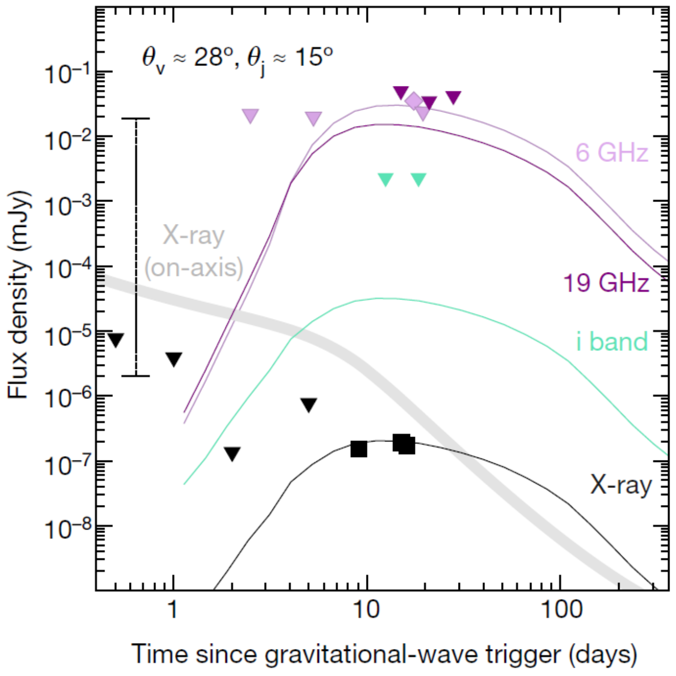
Low density environment ~ $10^{-4} – 10^{-2}$ cm^{-3}

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

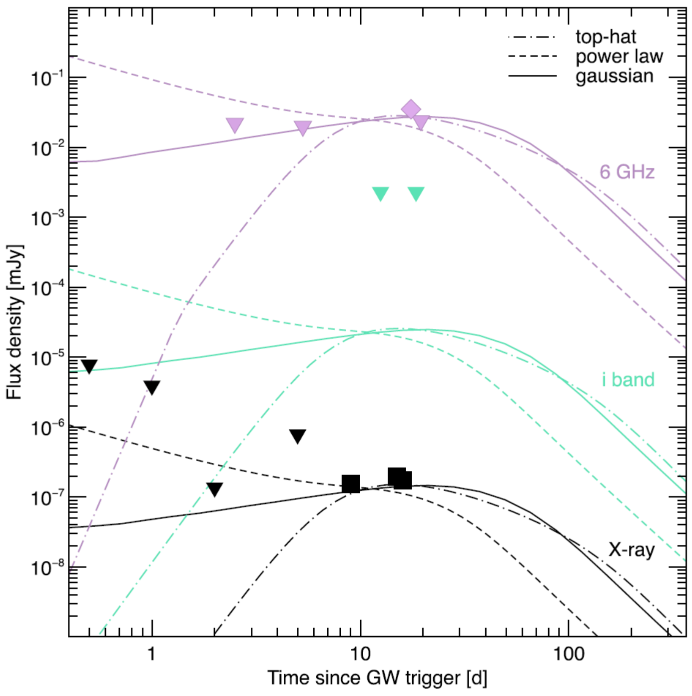
Models Consistent with Early Light Curve



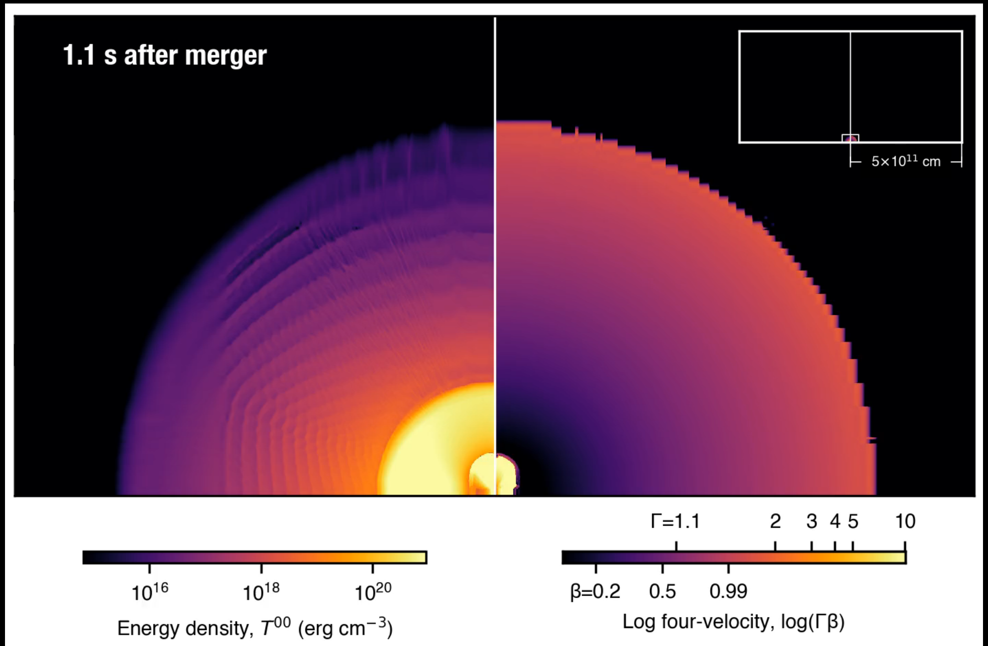
Margutti et al. 2017
Alexander et al. 2017

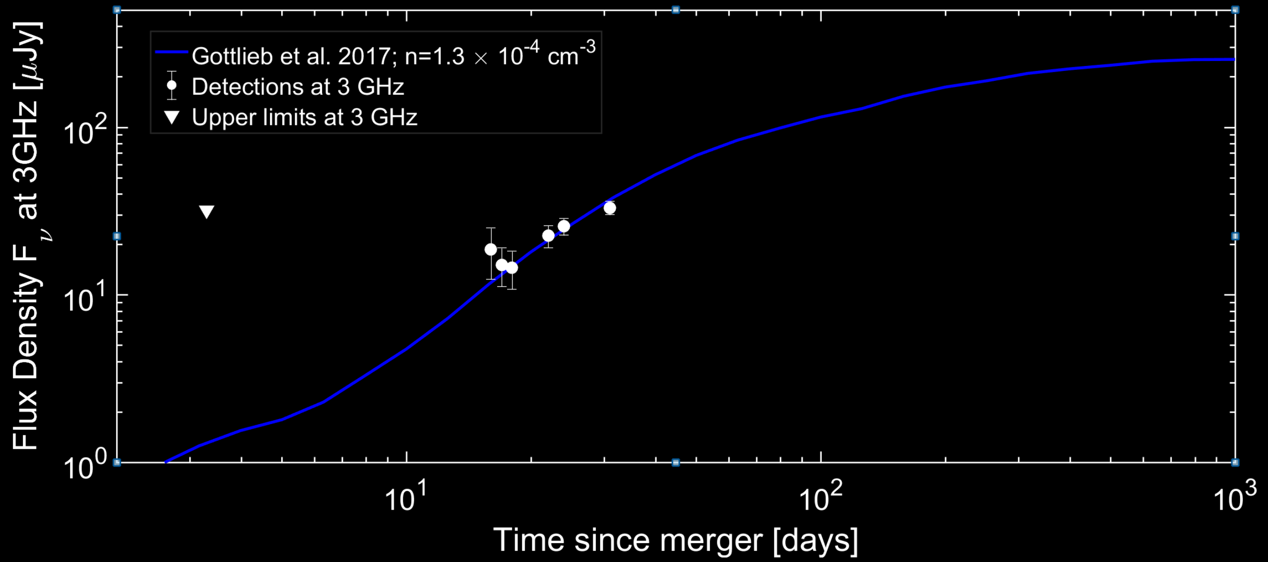


Troja et al. 2017



Troja et al. 2017





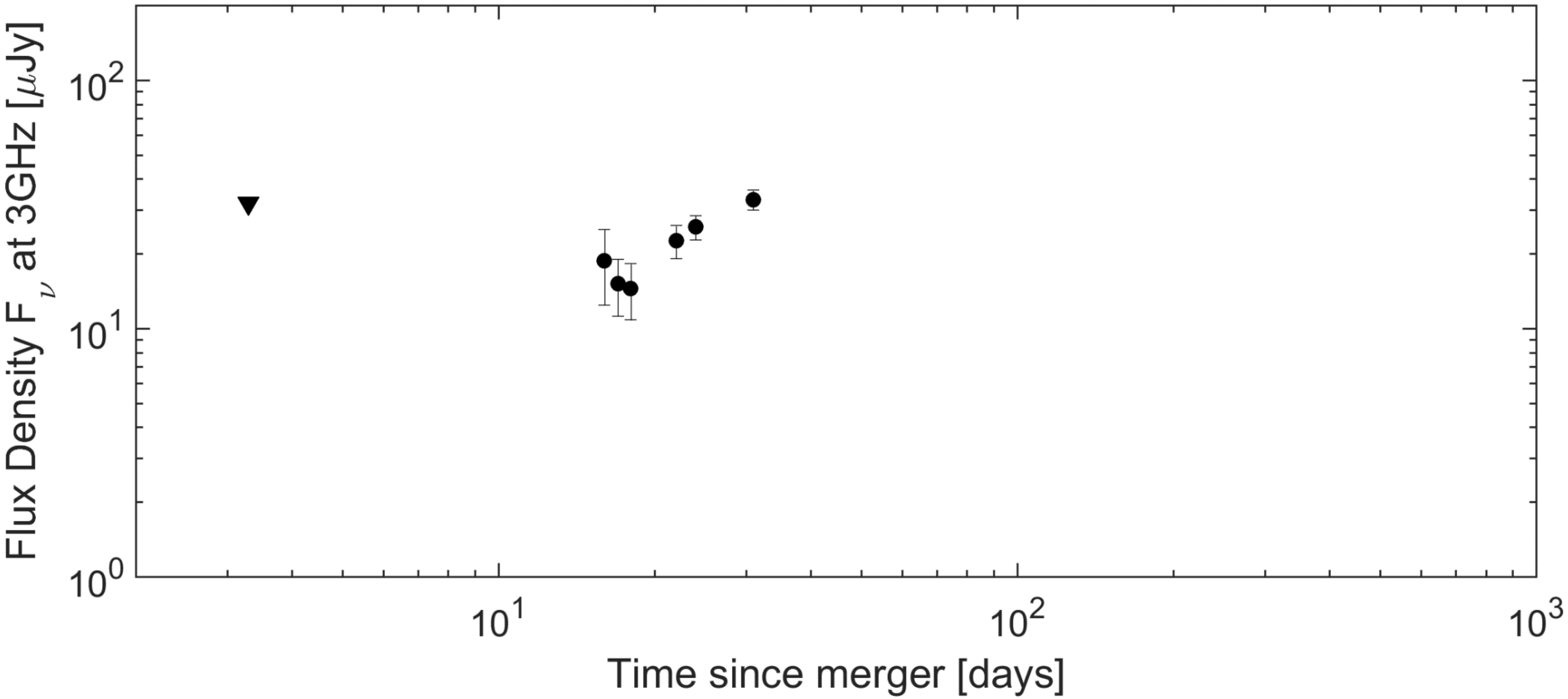
Gottlieb, Nakar, Piran & Hotokezaka 2017, Kasliwal et al. 2017
2-D simulation to explain the gamma-rays

Dynamical Ejecta | Relativistic Jet | Cocoon

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

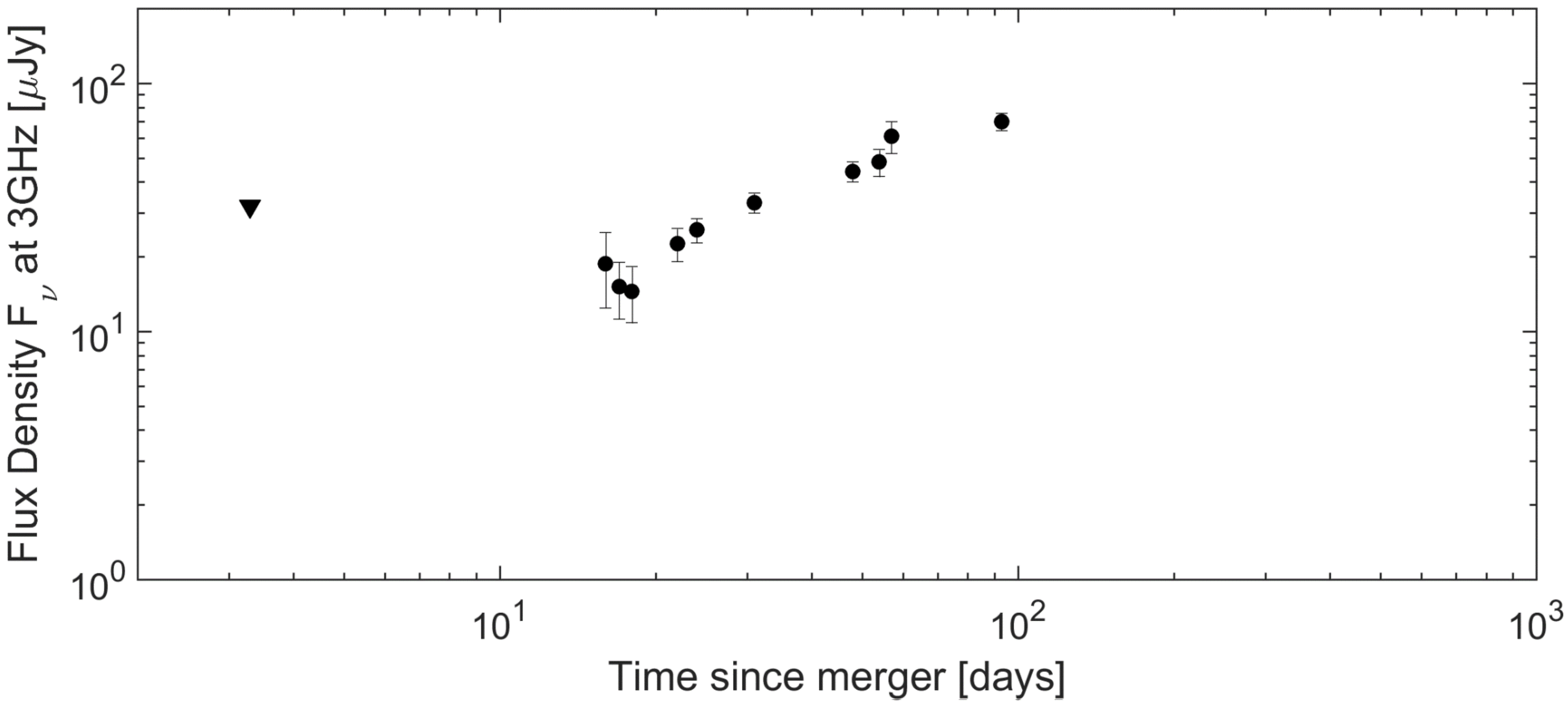
ii) Size distinguishes between dynamical ejecta tail and cocoon/jet

Light curve at 3 GHz: Day 16 – Day 31

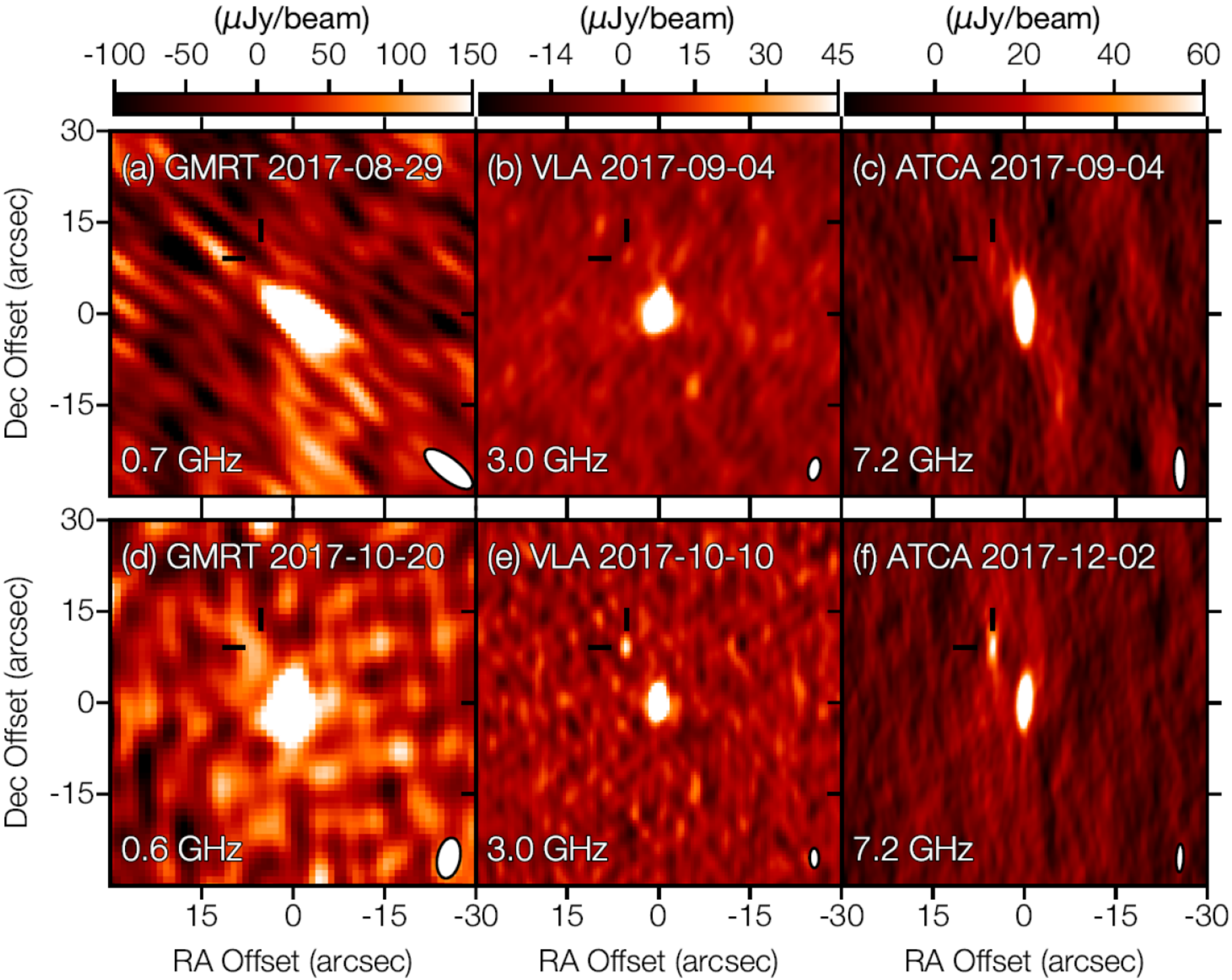


G. Hallinan, A. Corsi, *et al.*, *Science* 10.1126/science.aap9855 (2017)

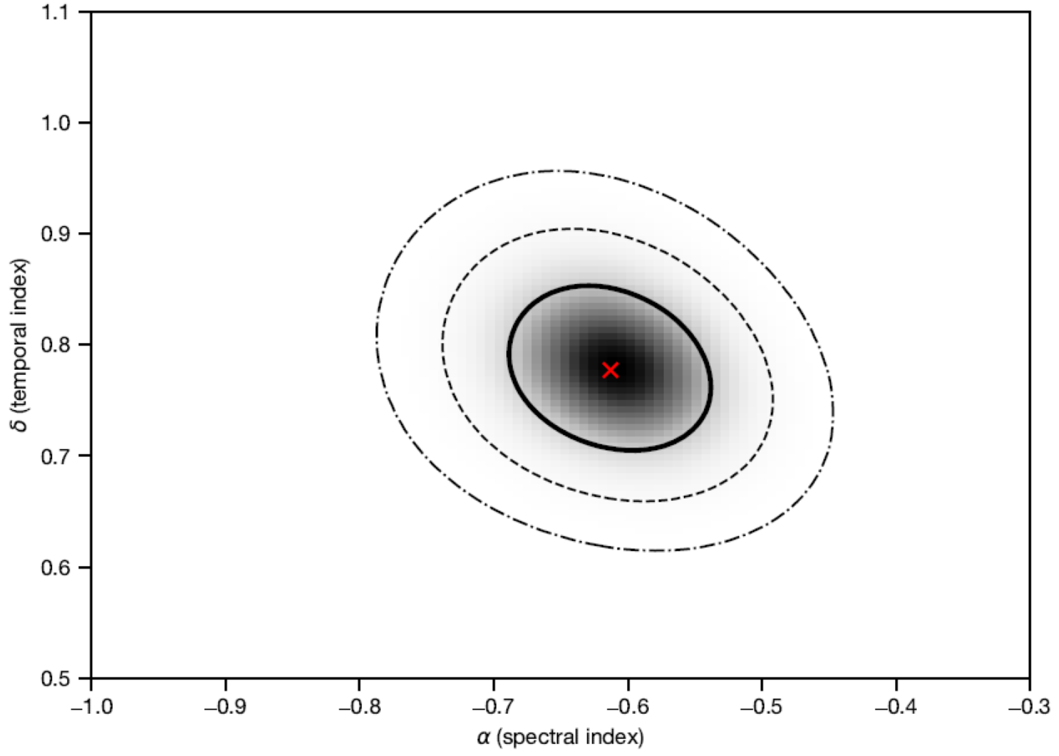
Light curve at 3 GHz: Day 16 – Day 93

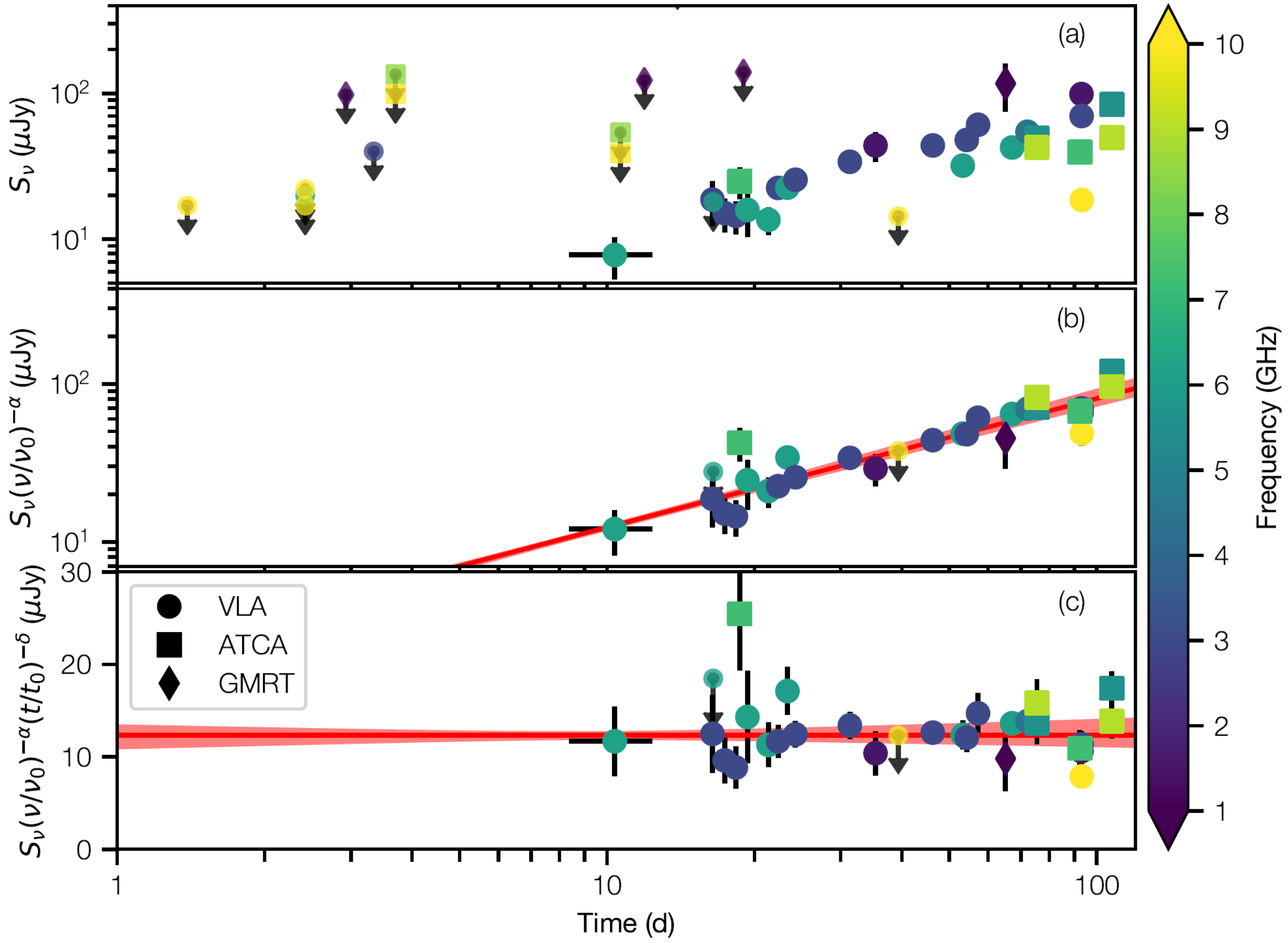


Mooley et al. 2017 [arXiv:1711.11573]



(μJy/beam)
-100 -50 0 50 100 150
(μJy/beam)
-14 0 15 30 45
(μJy/beam)
0 20 40 60
(a) GMRT 2017-08-29
0.7 GHz
(b) VLA 2017-09-04
3.0 GHz
(c) ATCA 2017-09-04
7.2 GHz
(d) GMRT 2017-10-20
0.6 GHz
(e) VLA 2017-10-10
3.0 GHz
(f) ATCA 2017-12-02
7.2 GHz
Dec Offset (arcsec)
30 15 0 -15
RA Offset (arcsec)
15 0 -15 -30



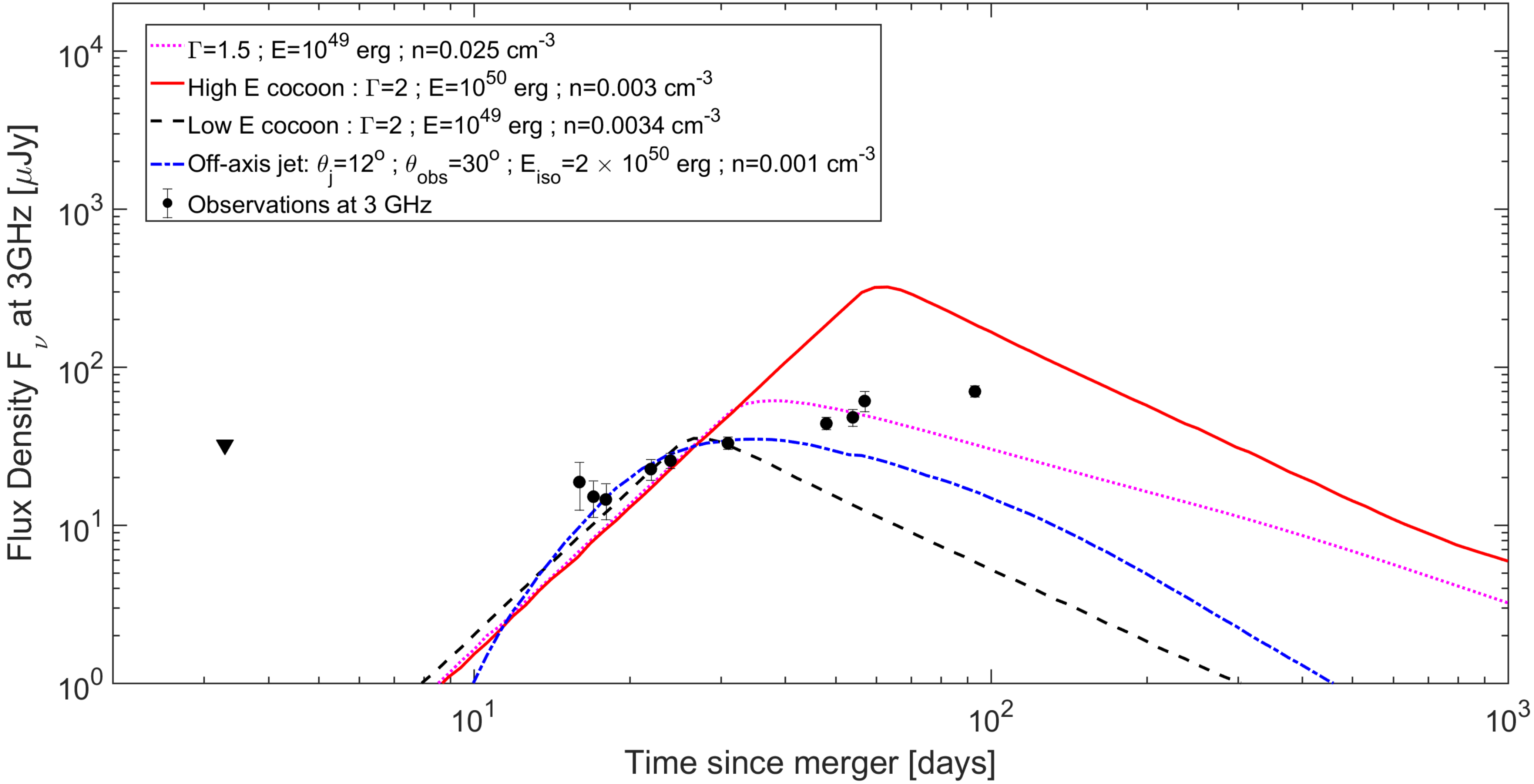


S ∝ $\nu^\alpha t^\delta$ - Best joint fit to the data:

Spectral index α=-0.61+/- 0.05

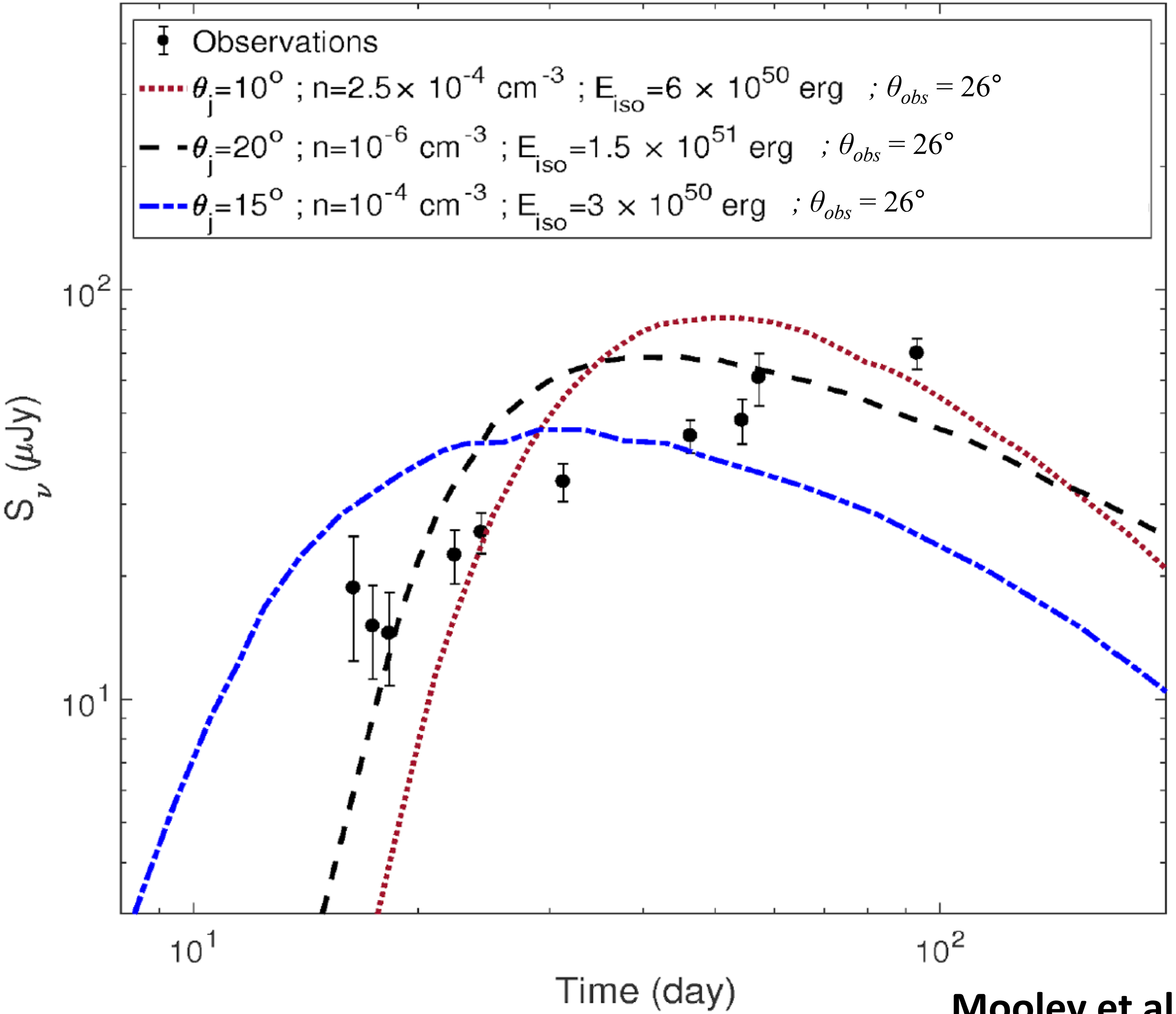
Temporal index δ=0.78+/0.05

Mooley et al. 2017 [arXiv:1711.11573]



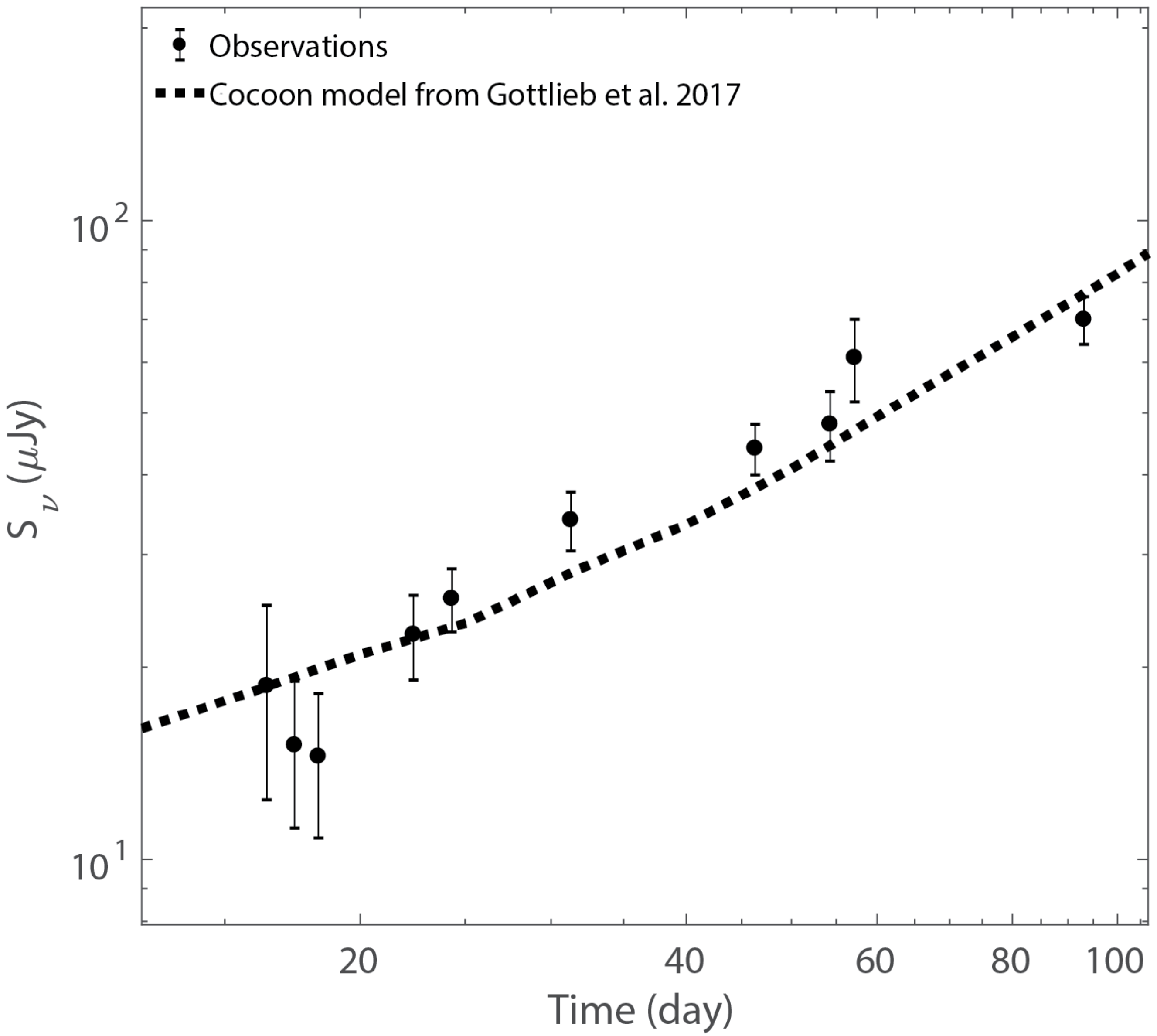
Mooley et al. 2017 [arXiv:1711.11573]

Model Ruled Out - Off-Axis Jet



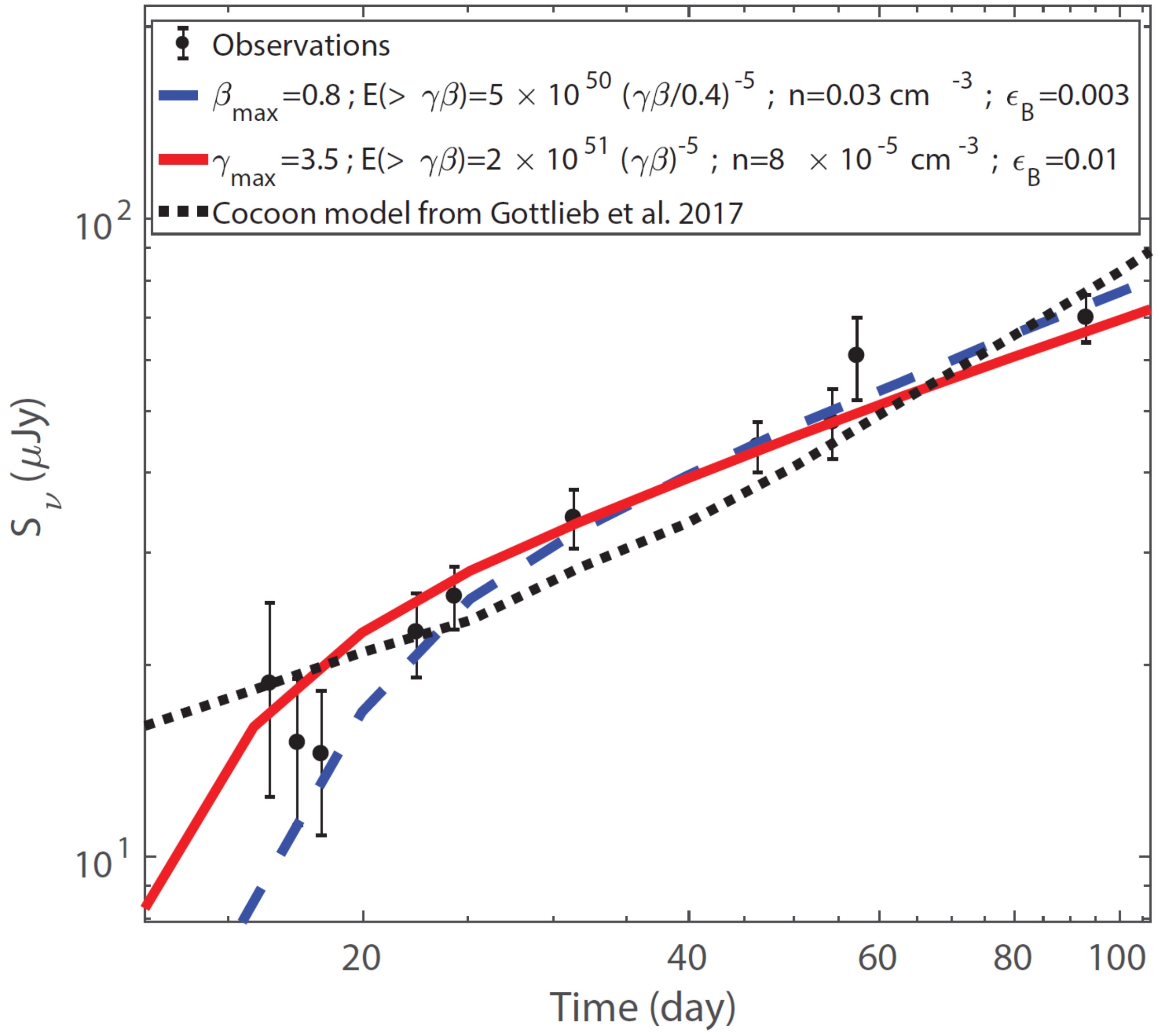
Mooley et al. 2017 [arXiv:1711.11573]

Consistent Models



Gottlieb et al. 2017; Mooley et al. 2017

Consistent Models



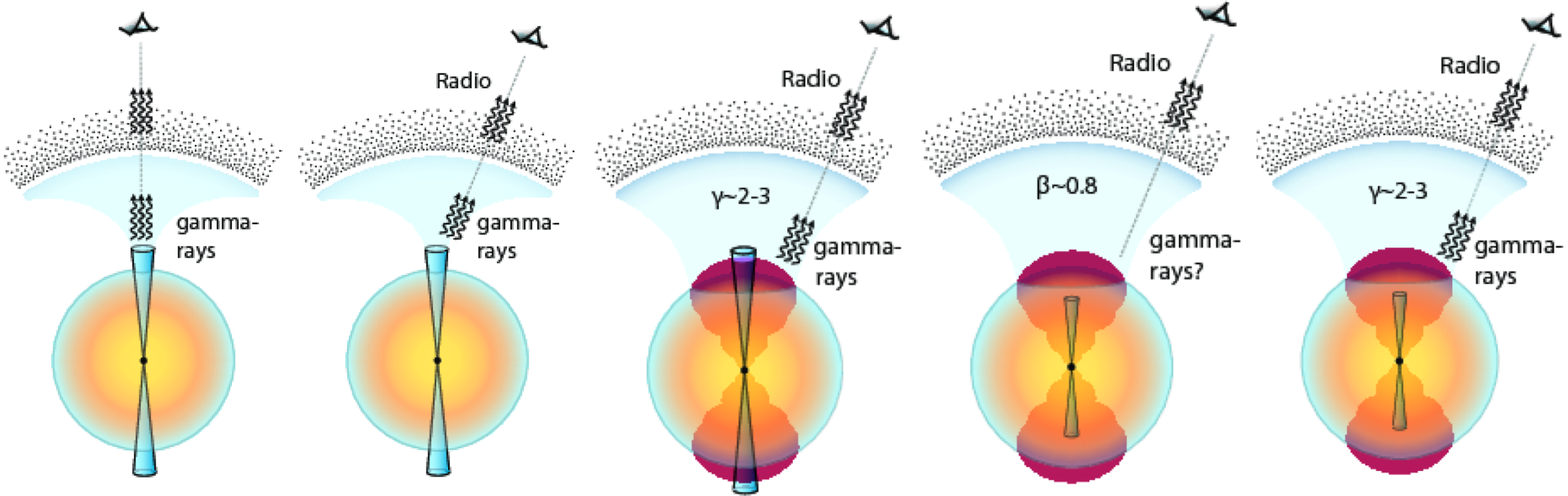
Can be modeled with a single one-dimensional velocity profile: $E(>\beta\gamma) \propto (\beta\gamma)^{-5}$

Indicates quasi-spherical outflow

More energy in the slower moving ejecta

Mooley et al. 2017 [arXiv:1711.11573]

Source of Radio Emission



A. On-axis Jet
SGRB and afterglow
(RULED OUT)

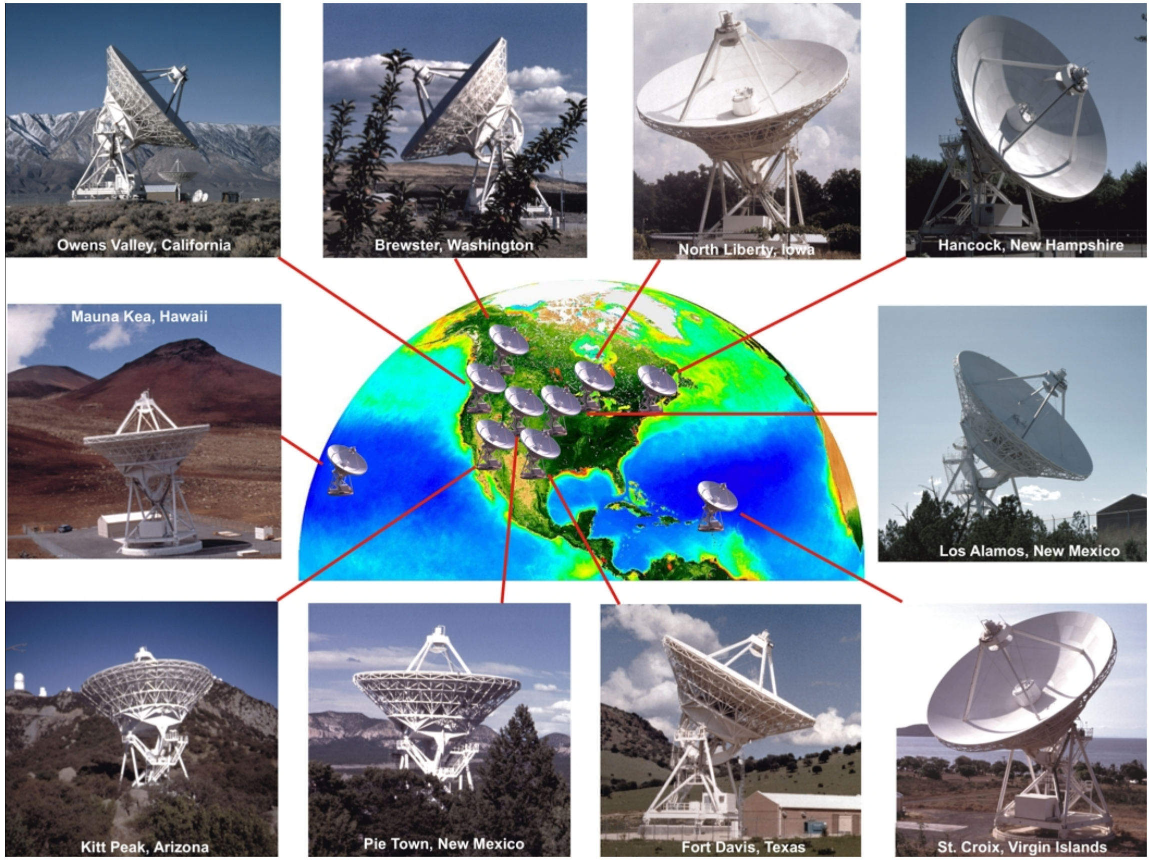
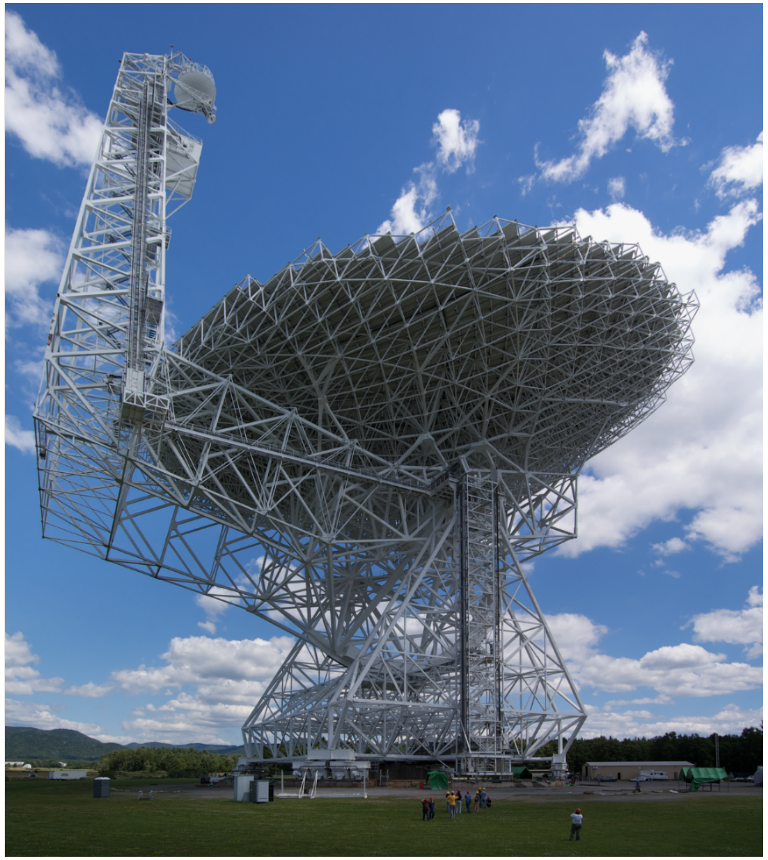
B. Off-axis Jet
SGRB and afterglow
(RULED OUT)

E. Successful hidden Jet
Cocoon gamma-rays
and afterglow
(Less likely)

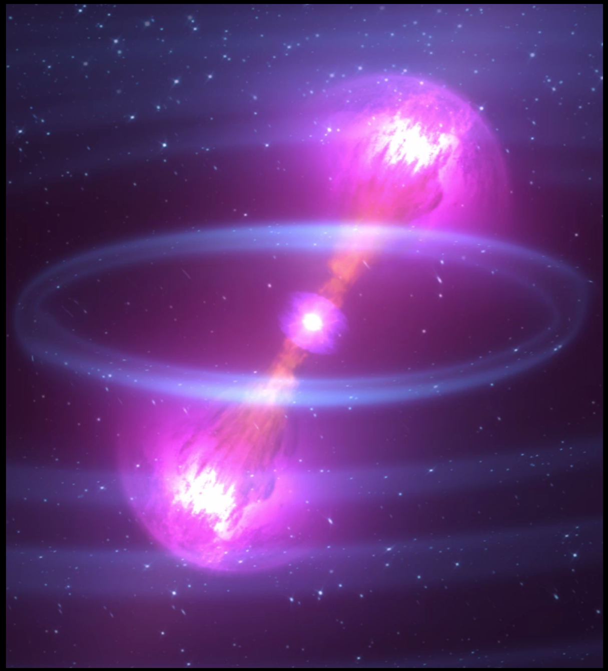
D. Choked Jet
Fast ejecta afterglow
(Less likely)

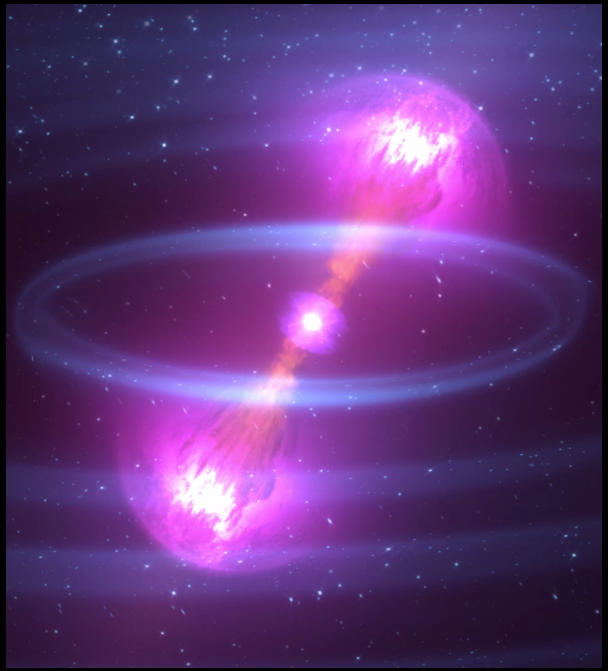
C. Choked Jet
Cocoon gamma-rays
and afterglow
(Most likely)

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

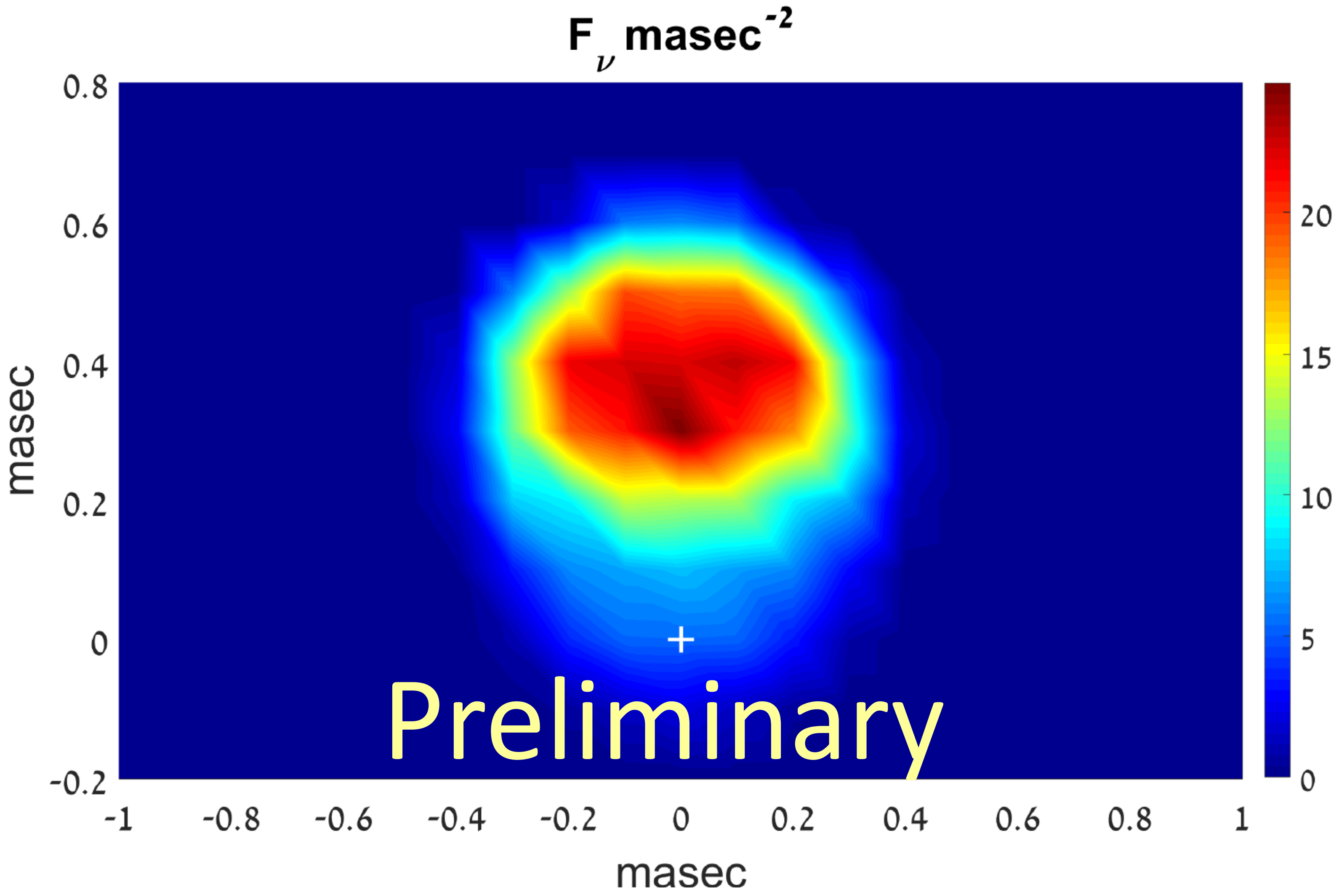

Owens Valley, California
Brewster, Washington
North Liberty, Iowa
Hancock, New Hampshire
Mauna Kea, Hawaii
Los Alamos, New Mexico
Kitt Peak, Arizona
Pie Town, New Mexico
Fort Davis, Texas
St. Croix, Virgin Islands


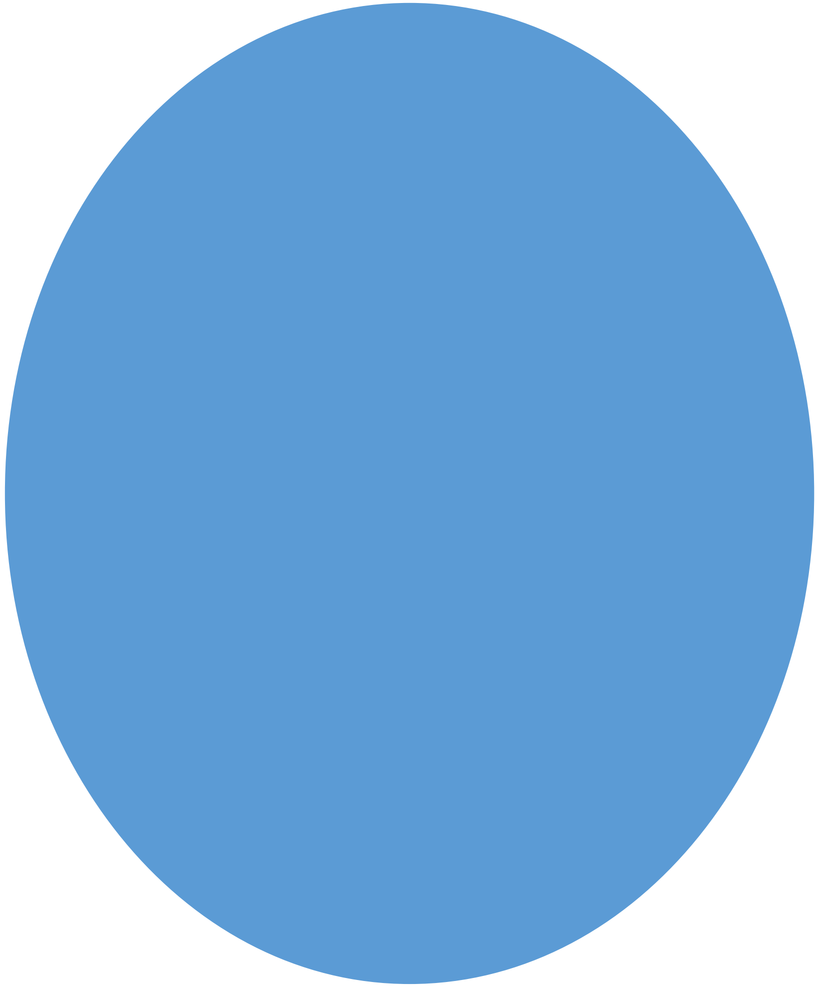




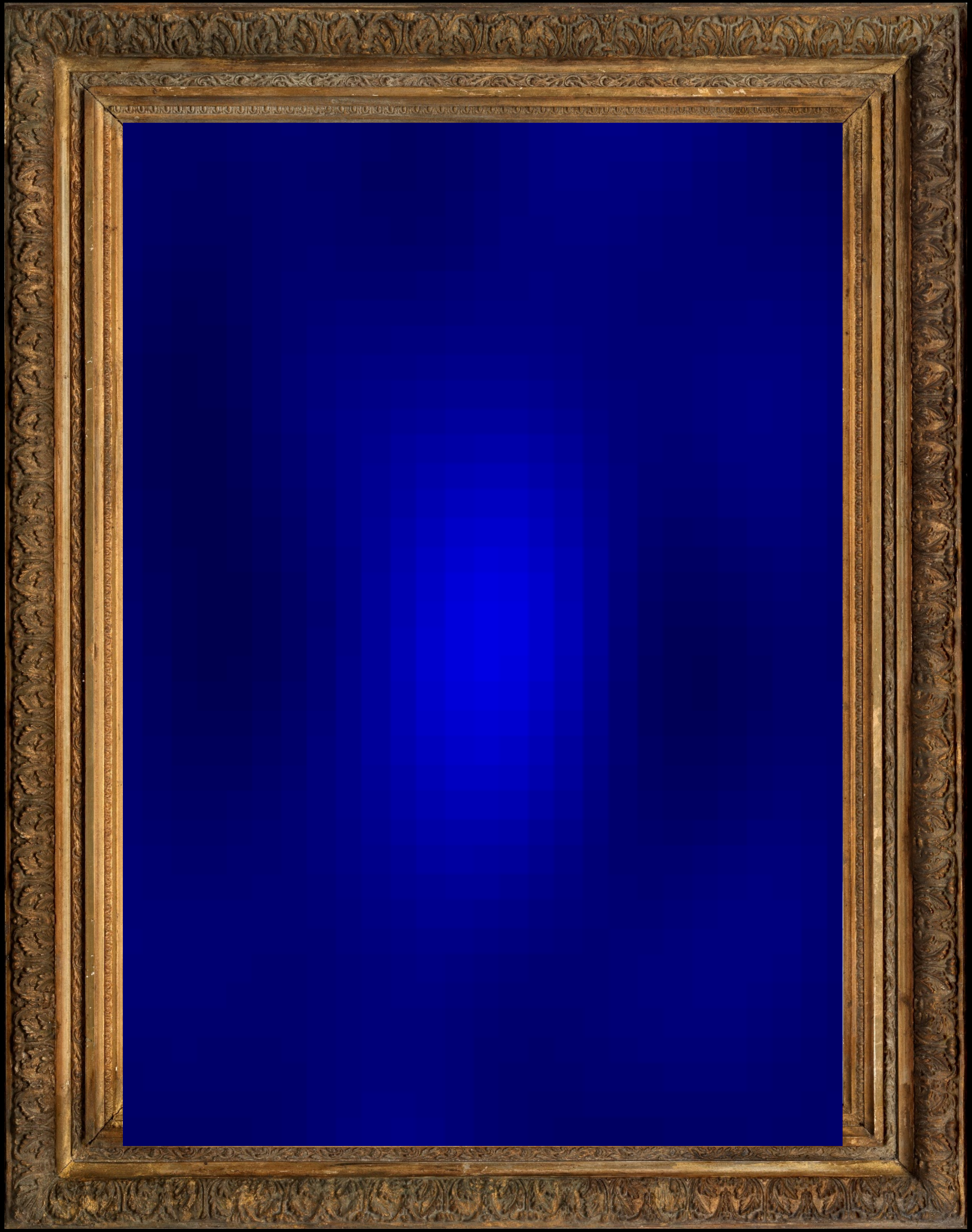


Gottlieb et al. in prep.





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 inconsistent with off-axis jet

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