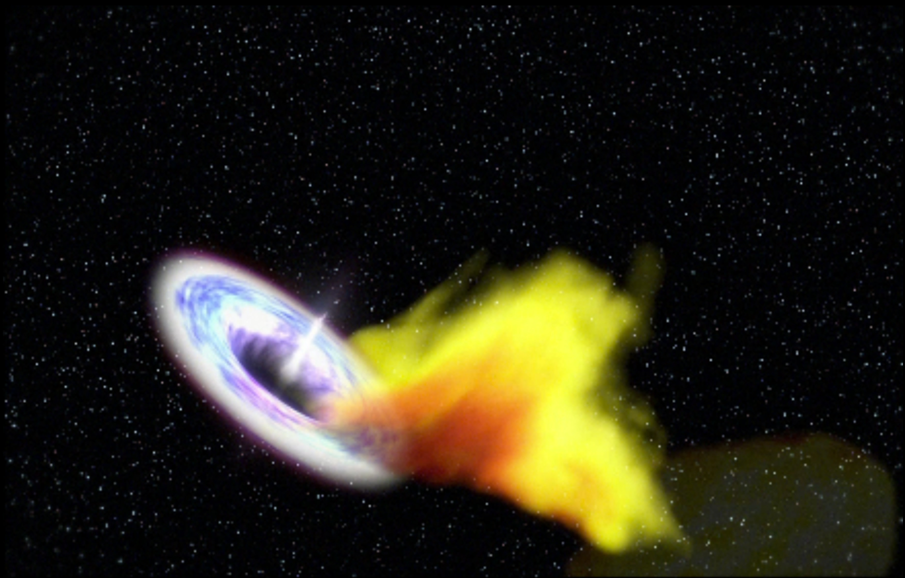
A Radio View of the Birth of a Relativistic Jet from a Tidal Disruption Event



Video credit: NASA/Goddard Space Flight Center/CI Lab

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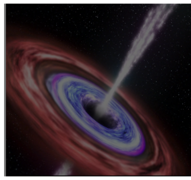
Tidal Disruption Events and AGN Outbursts Workshop

Madrid
June 26, 2012

E. Berger, A. Soderberg, R. Sari, A. Loeb, R. Narayan, D. Frail, G. Petitpas, A. Brunthaler, R. Chornock, J. Carpenter, G. Pooley, K. Mooley, S. Kulkarni, R. Margutti, D. Fox, E. Nakar, N. Patel, M. Bietenholz, M. Rupen



A Radio View of the Birth of a Relativistic Jet

- Brief overview of discovery of GRB110328A / Sw 1644+57

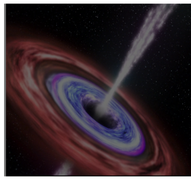
  - Rees
  - Krolik & Piran
  - Giannios & Metzger
  - Ramirez-Ruiz & Rosswog
  - Strubbe
  - Lodato, Rossi

  theoretical predictions
  of jets / super Eddington
  outflows from tidal disruption

- Summary of Radio Observations

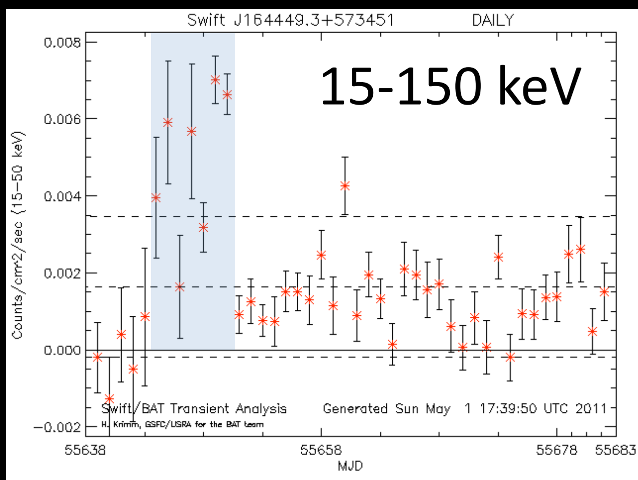
- Modeling the data
  - Evidence for Relativistic Outflow
  - Energy injection?
  - Density structure around (previously quiescent) black hole

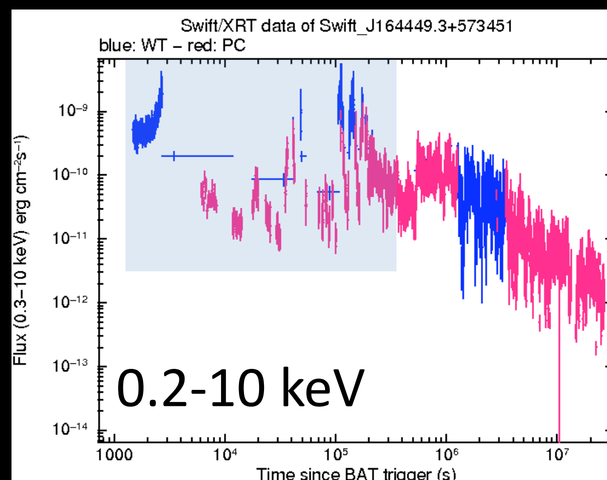
- Conclusions: Future/ongoing work

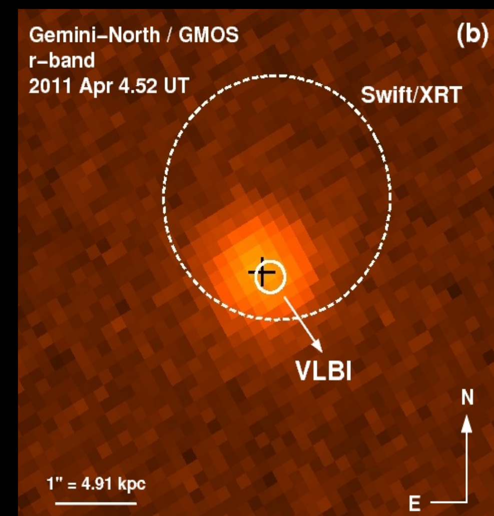


Sw1644+57: Overview

- *Swift* discovery on 2011 March 28.5 UT; multiple triggers; emission on 3/25
- Long-lived X-ray source; $L \propto t^{-5/3}$ at >10 days; beaming of 0.1 rad; extinction



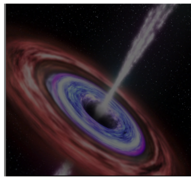




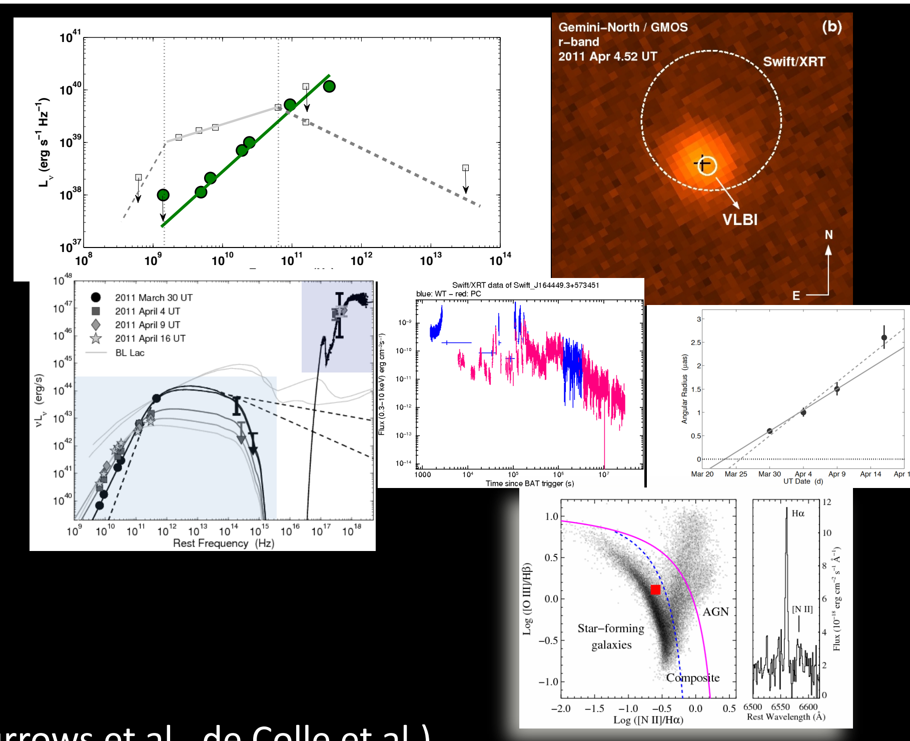
<u>Early radio observations</u> *(Zauderer et al. 2011, Nature, 476, 425)*:

- Linked the γ-ray/X-ray transient to the nucleus of a galaxy at $z = 0.354$
- Demonstrated a relativistic outflow (equipartition, interstellar scintillation)
- Tied the outflow formation time to the onset of γ-ray emission

Interpretation: tidal disruption of a star by a ~ few × 10^6 $M_\odot$ SMBH



Sw1644+57: Progenitor Possibilities



Non-TDE:

(1) Long GRB with Nuclear Origin ?

- spectral information unusual
- coincidence with nucleus of inactive galaxy
- Early gamma-ray/X-ray flares and long-lived X-ray emission inconsistent
- only mildly relativistic

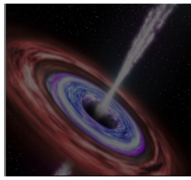
(2) AGN / Blazar

- typical lifetimes of ~million years
- spectral diagnostics
- no prior signatures in X-ray or radio

TDE variations:

- million solar mass black hole disrupting a star (e.g. Burrows et al., de Colle et al.)
- Less massive BH disrupting a white dwarf (e.g. Piran)
- Variations in BH spin or mass (e.g. Kesden, Gultekin)
- Precession of jet (e.g. N. Stone)
- Eccentricity of disrupted star (Hayasake)
- Deeply plunging (Cannizzo, Troja, Lodato)
- ???

Facts: Radio emission consistent with synchrotron emission, mildly relativistic, evolution inconsistent with single injection event, small measured polarization

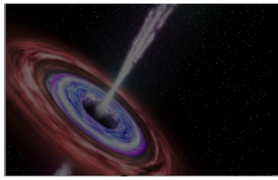


Summary of Radio Observations

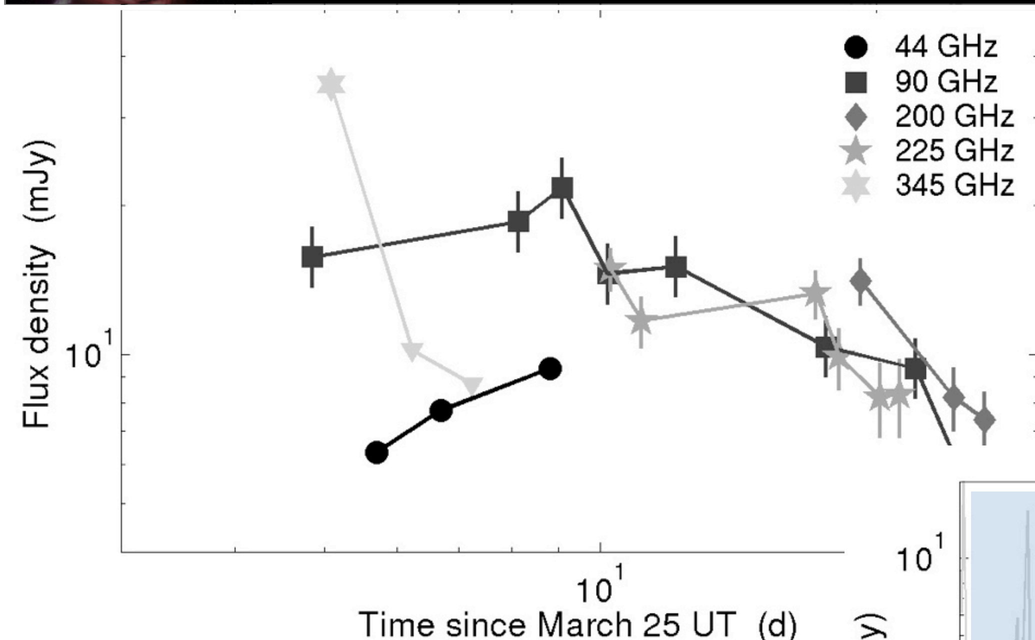
- Frequencies from 1.4 – 345 GHz
  - EVLA (L, C, X, K, Ka and Q bands)
  - VLBI (K band)
  - AMI-LA (15 GHz)
  - CARMA (95 GHz)
  - SMA (230, 345 GHz)

- Light curve sampled from 0.28 – 450 days since Swift trigger

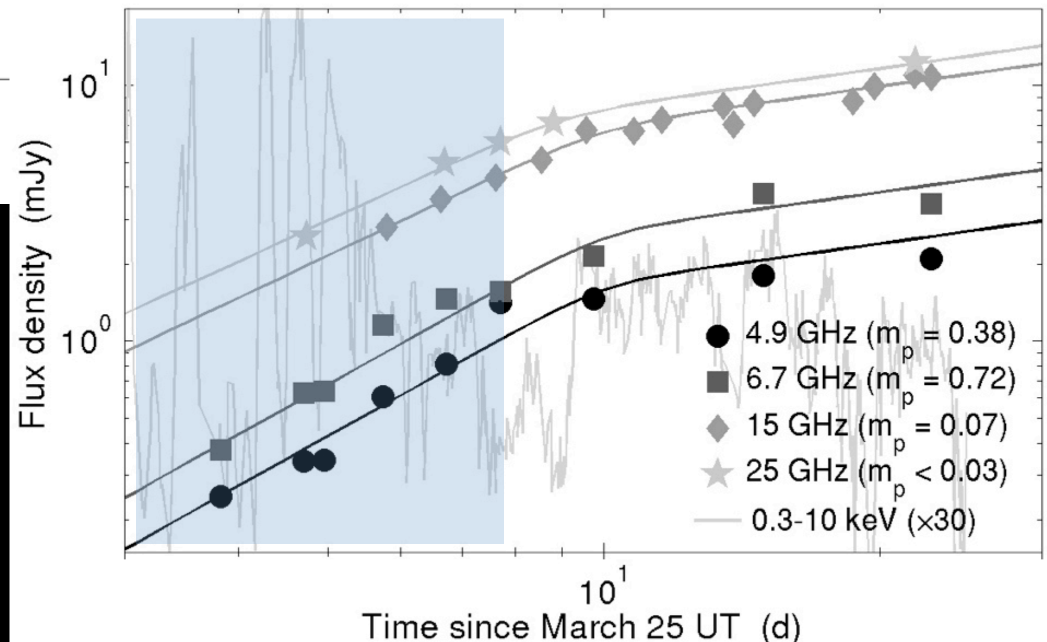
- Full polarization calibration with EVLA (2 GHz bandwidth – R. Perley et al.)



Sw1644+57: Early Light Curve

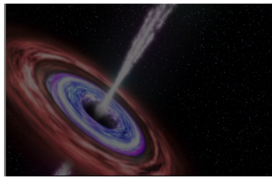


Large variations in X-rays are not accompanied by variations in radio



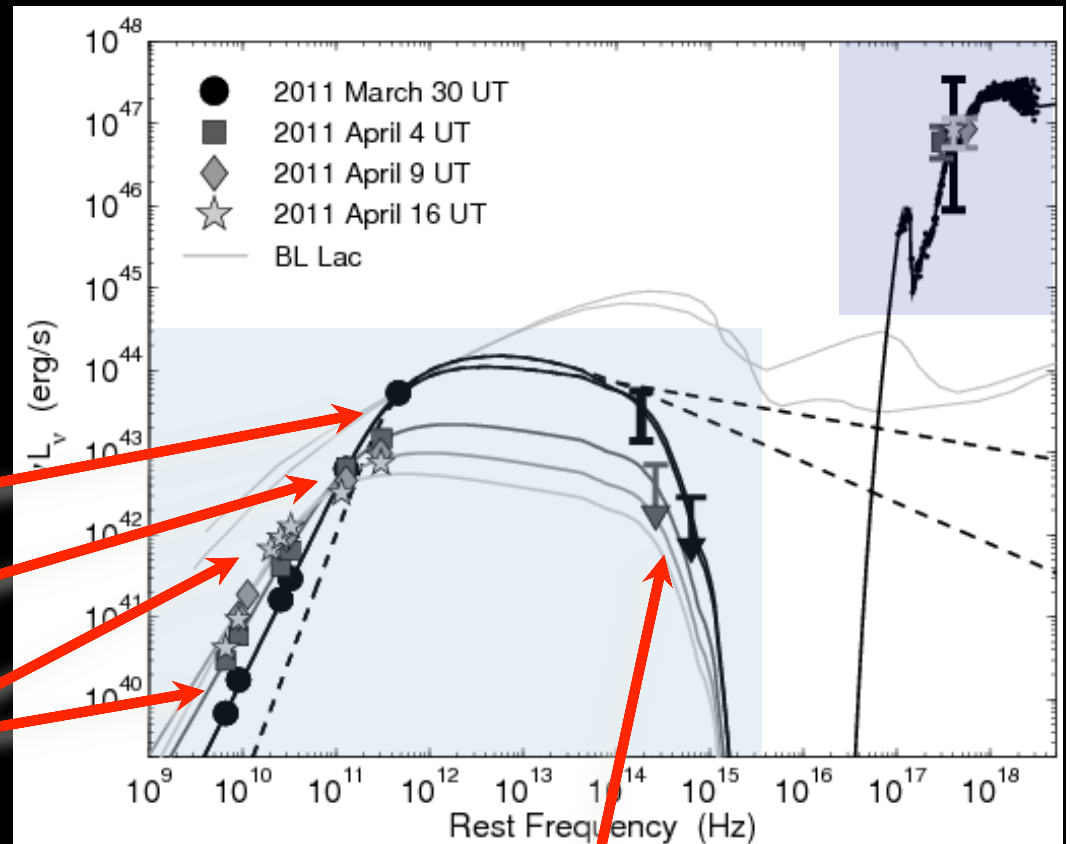
⇒ X-ray emission region distinct from radio emission region

Zauderer et al.



Sw1644+57: SED

- Radio spectrum ⇒ synchrotron
- No optical ⇒ $A_V > 3$ mag
- L_X exceeds L_{syn} by ~10^3



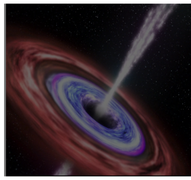
Zauderer et al.

SMA

CARMA

EVLA, Ryle,
OVRO 40-m

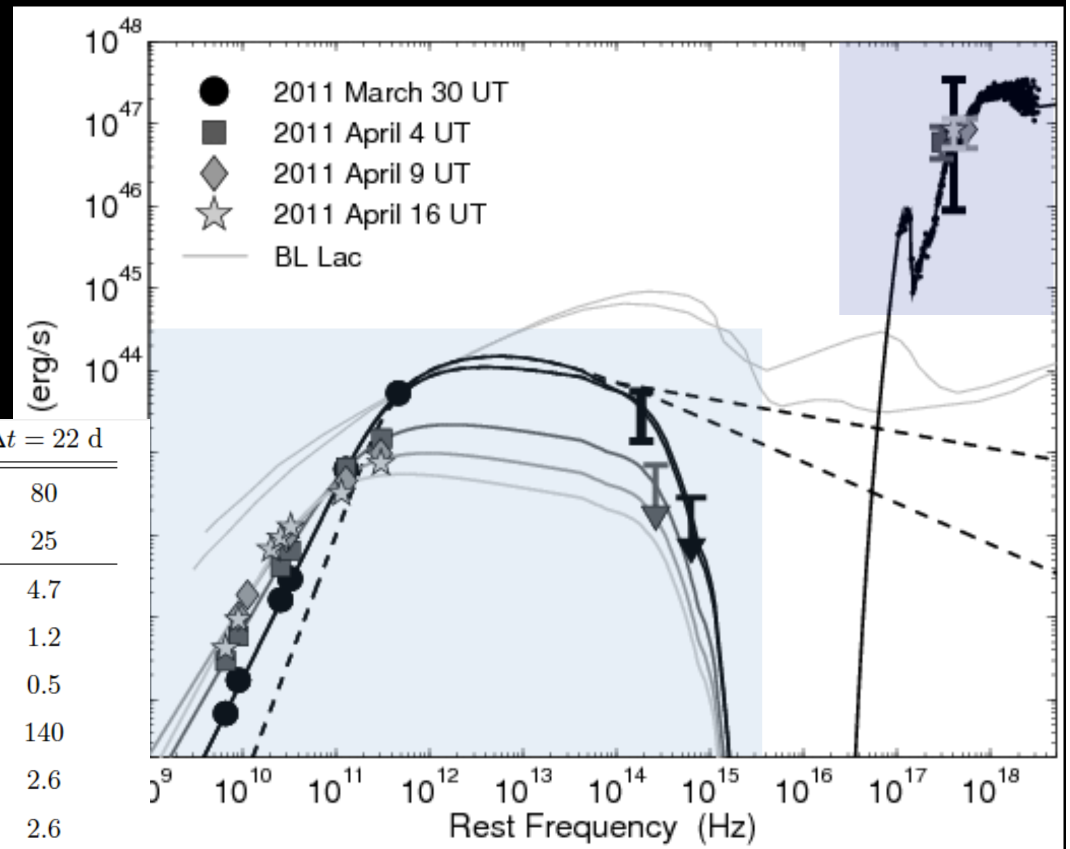
no optical / weak NIR



Sw1644+57: Synchrotron Modeling

Assumptions: peak freq = abs. freq
equipartition, spherical

Calculate: radius, Lorentz factor, magnetic field strength, electron number density, angular size



Zauderer et al.

Parameter	$\Delta t = 5$ d	$\Delta t = 10$ d	$\Delta t = 15$ d	$\Delta t = 22$ d
$\nu_a = \nu_p$ (GHz; rest-frame)	600	250	140	80
$F_{\nu,p}$ (mJy; rest-frame)	80	40	30	25
r (10^{16} cm)	1.0	1.7	2.6	4.7
Γ	1.2	1.2	1.1	1.2
β	0.5	0.5	0.5	0.5
γ_e	150	140	140	140
B (G)	17	8	4.6	2.6
N_e (10^{53})	1.0	1.1	1.5	2.6
n_e (10^4 cm^{-3})	2.4	0.5	0.2	0.06
$E_B = 10E_e$ (10^{50} erg)	1.4	1.5	1.9	2.9
θ_s (μas)	0.6	1.0	1.5	2.6

Table 2: Summary of relativistic model results for the four broad-band SEDs shown in Figure 2 of the main text. The top portion lists the observed synchrotron parameters, while the bottom portion lists the model fit results.

Sw1644+57: Radio Monitoring

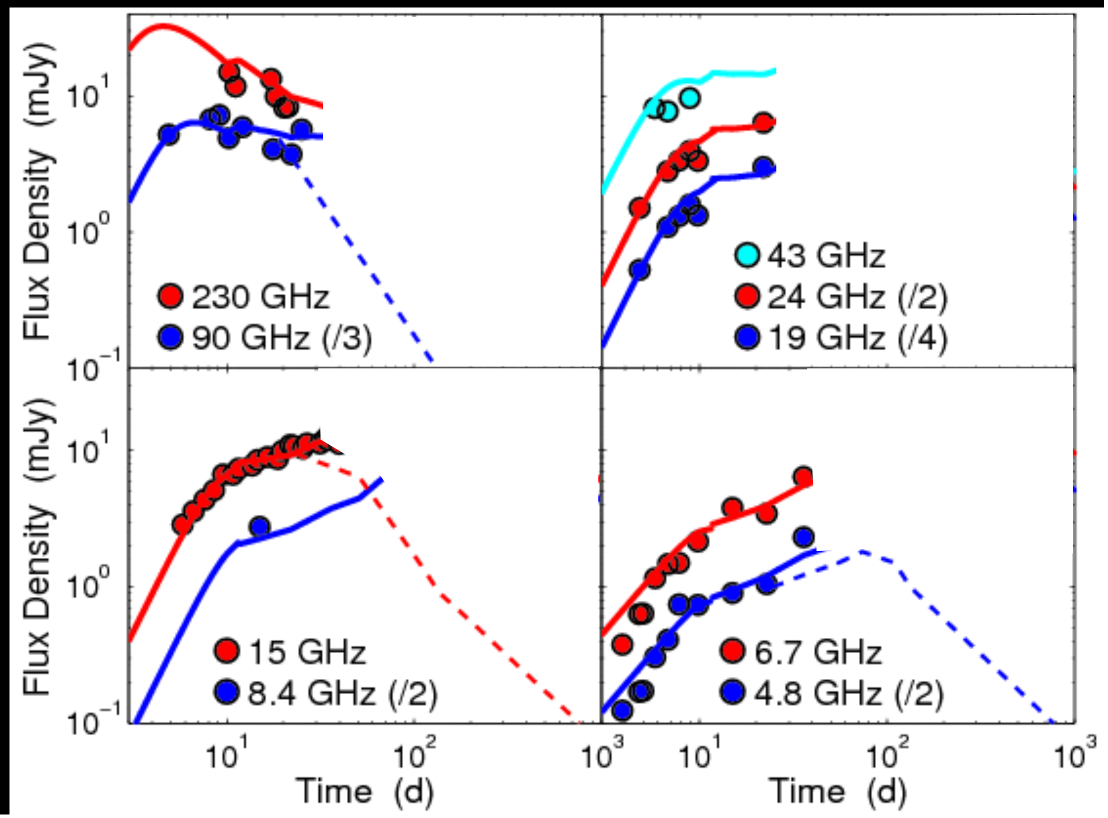
Long-term radio study provides several unique opportunities:

- Structure and evolution of a relativistic jet (flux, polarization, VLBI)
- Pristine environment of a (previously-dormant) SMBH

SMA
CARMA
EVLA
AMI-LA

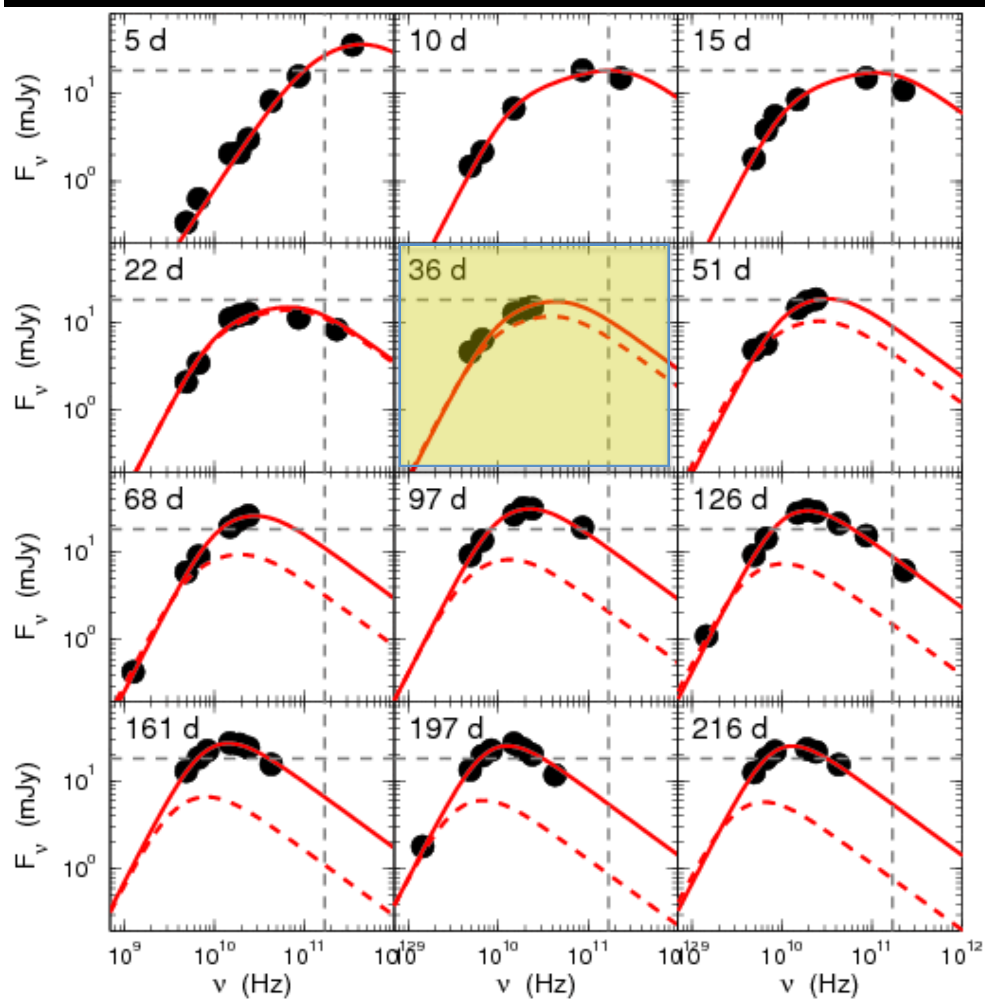
Observed radio evolution reveals much longer rise time and brighter emission than initially expected

⇒ <u>increase in *E*, *ρ*, both?</u>



Berger et al. ApJ (2012)

Sw1644+57: Synchrotron Modeling



No assumptions about hydrodynamics

Model each “snapshot” spectral energy distribution with a synchrotron model (cf GRBs)

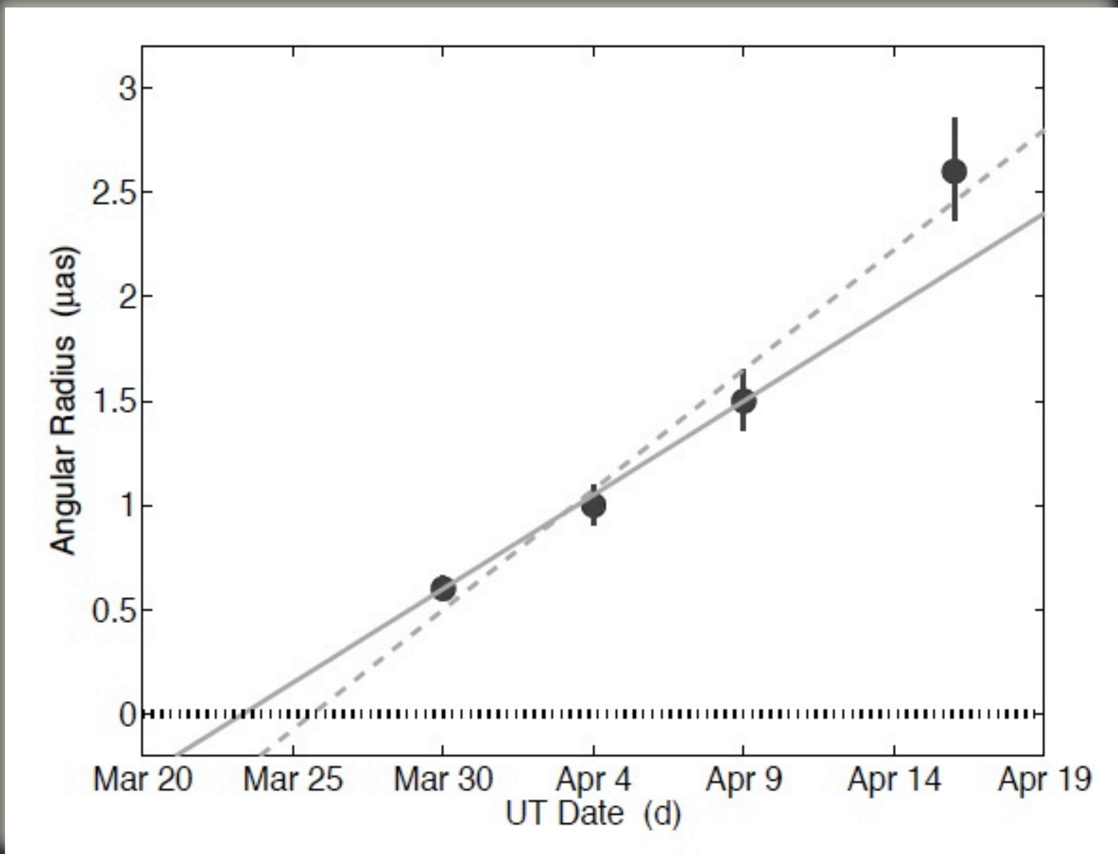
⇒ determine time evolution of *E, ρ, R, Γ*

no change in *E, ρ*

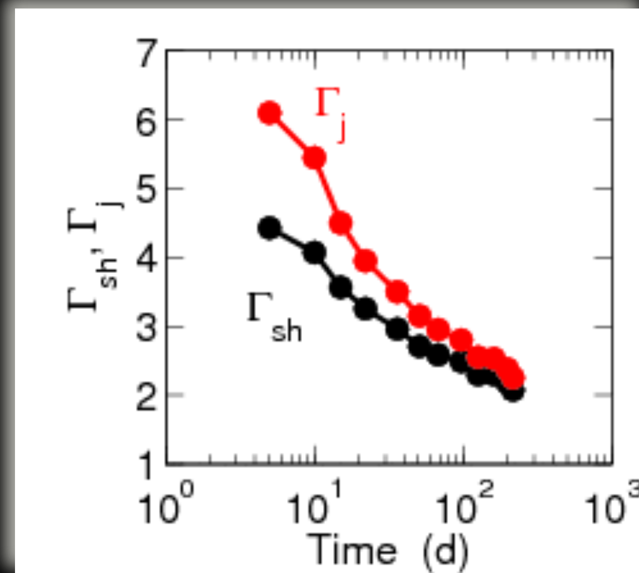
Berger et al. ApJ (2012)

Relativistic Expansion?

1. Modeling



Zauderer et al.



Berger et al. ApJ (2012)

Formation epoch: March 23-26

$$\theta_{\rm eq} \approx 110\, d_{\rm L,Mpc}^{-1/19}\, F_{\nu,{\rm p,mJy}}^{9/19}\, \nu_{\rm p,GHz}^{-1} \quad \mu as$$

Relativistic Expansion

2. Interstellar scintillation:

$$\nu_o \approx 10 \text{ GHz}$$

$$\theta_{F,0} \approx 1 \ \mu\text{as}$$

for $\nu > \nu_0$

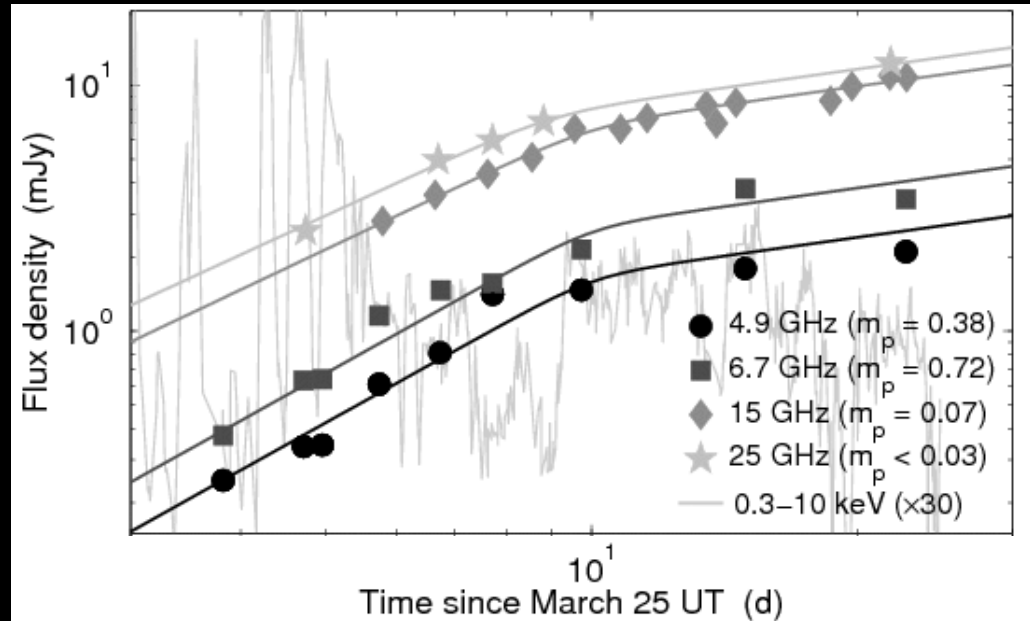
$$m_p \propto (\nu/\nu_0)^{-17/12} (\theta_s/\theta_{F,0})^{-7/6}$$

for $\nu < \nu_0$

$$m_p \propto (\nu/\nu_0)^{17/30} (\theta_s/\theta_r)^{-7/6}$$

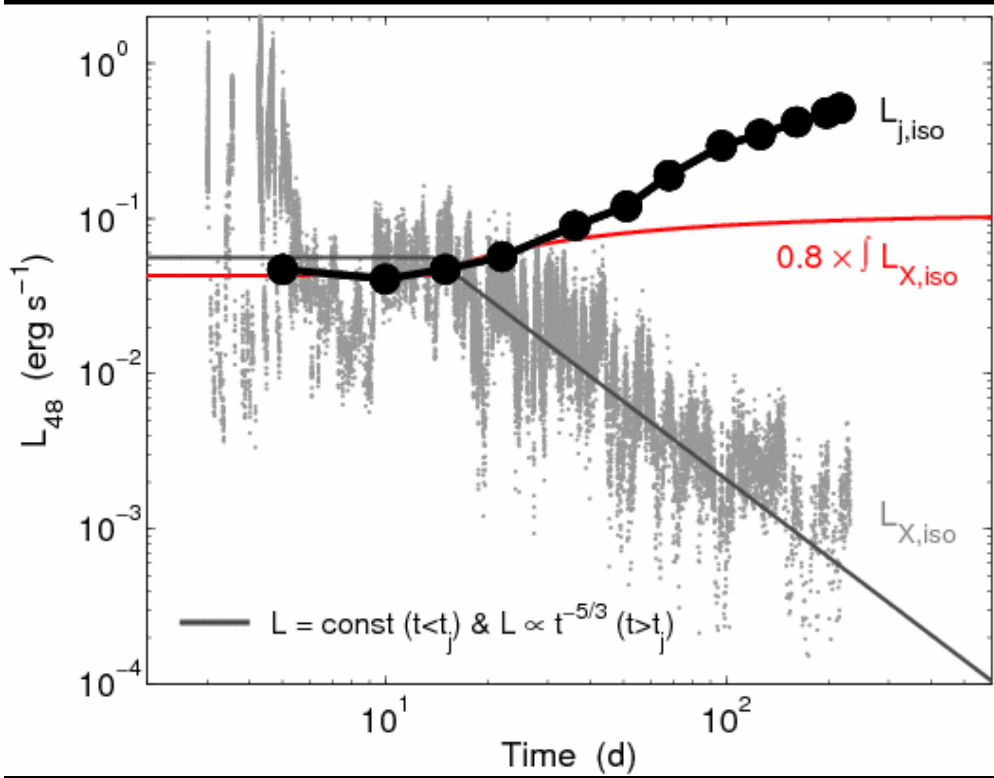
$$\theta_s \approx 5 \ \mu\text{as}$$

$$\Gamma \approx \text{few}$$



Zauderer et al.

Jet Energetics



Berger et al. ApJ (2012)

Is this ubiquitous for relativistic jets, Blandford-Znajek mechanism, GRBs?

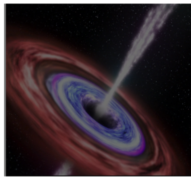
$$
\begin{aligned}
E_{\rm j,iso} &= \Delta t_j \times L_{\rm j,iso} \\
&\approx 10^6\,{\rm s} \times L_{\rm j,iso} \\
&\approx 5 \times 10^{53}\,{\rm erg\ at\ }200\,{\rm d}
\end{aligned}
$$

The increase in jet energy cannot be explained by on-going injection from the accreting SMBH

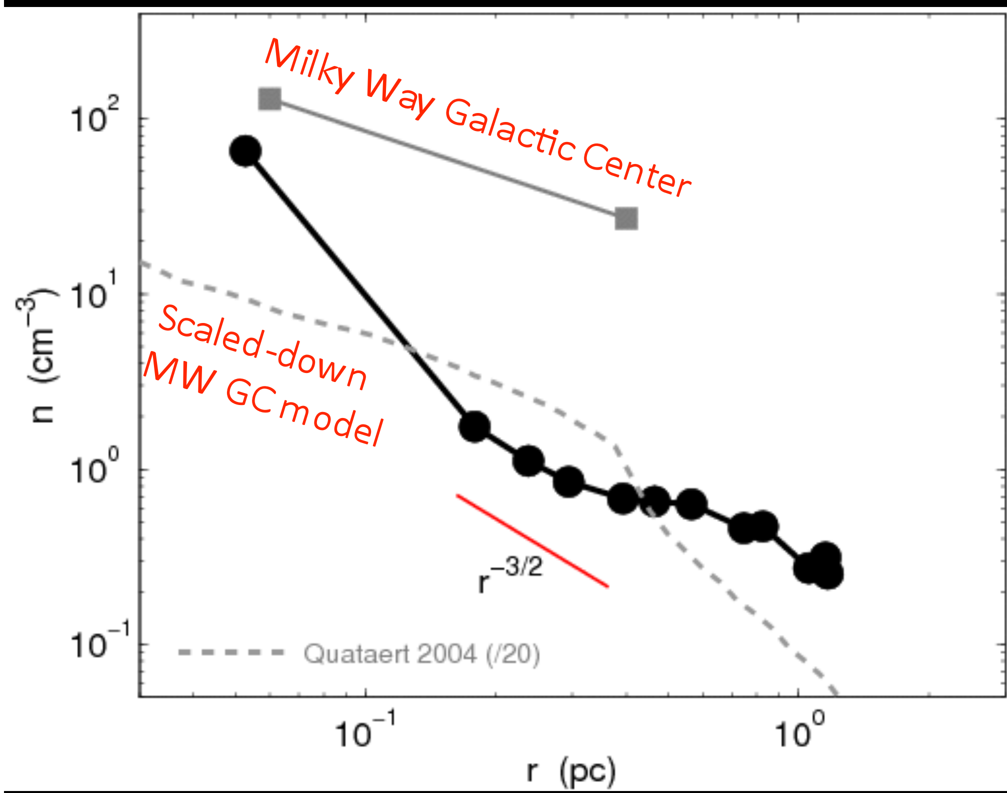
(as seen in X-rays w/ $L \propto t^{-5/3}$).

Instead, relativistic jet launched w/ a distribution of Lorentz factors explains the increase in *E* and evolution of *R*

$$E_{\rm j}(>\Gamma_{\rm j}) \propto \Gamma_{\rm j}^{-2.5}$$



Parsec-Scale Environment



Berger et al. ApJ (2012)

Radial profile is roughly $\rho \propto R^{-3/2}$

Lower density relative to Galactic Center indicative of lower SFR?

The density profile around a dormant SMBH at z = 0.354 measured with better spatial resolution than for the Milky Way Galactic Center

Conclusions
Ongoing & Future Work

- Continued monitoring to track the energy scale and density profile
  - UPDATE: Last epoch 1.4 – 15 GHz, consistent with predictions
- Polarization at 5-45 GHz (% and angle – magnitude and varia[illegible]me?)
  - UPDATE: polarization ~ a few percent
- VLBI monitoring to resolve the outflow and/or measure proper motion
  - UPDATE: not yet resolved (as of ~1 month ago)
- The long-term appearance of off-axis events; predictions for future radio searches
  - UPDATE: 2 more TDE candidates in 2011….when do jets form?

Guy Pooley

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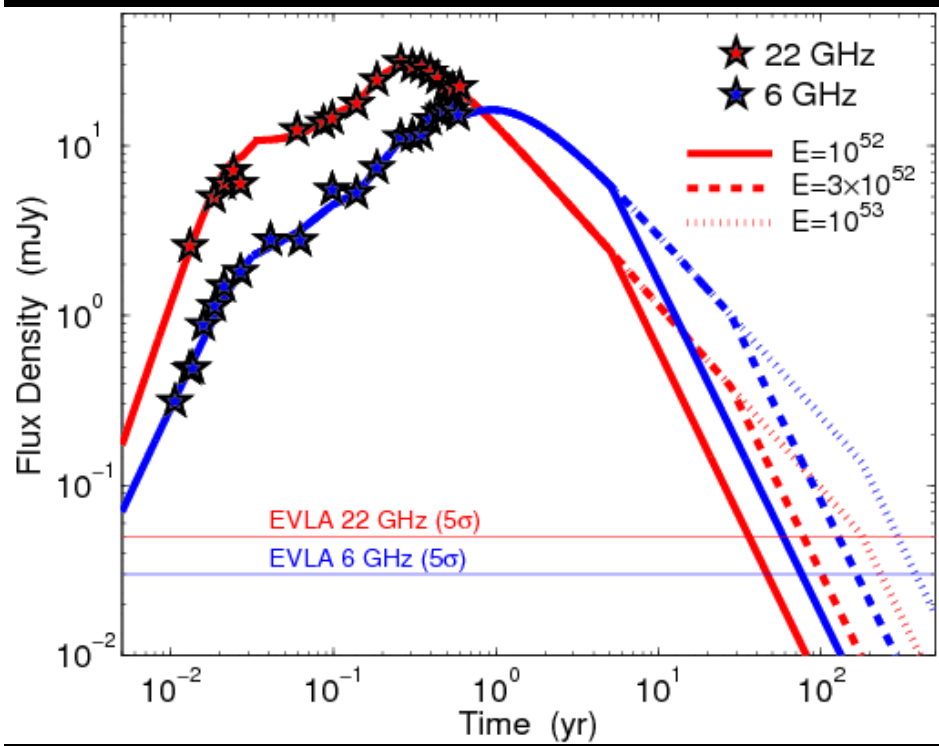
Our group, led by Bietenholz, Brunthaler

Early observations also by G. Bower et al.

VLBI

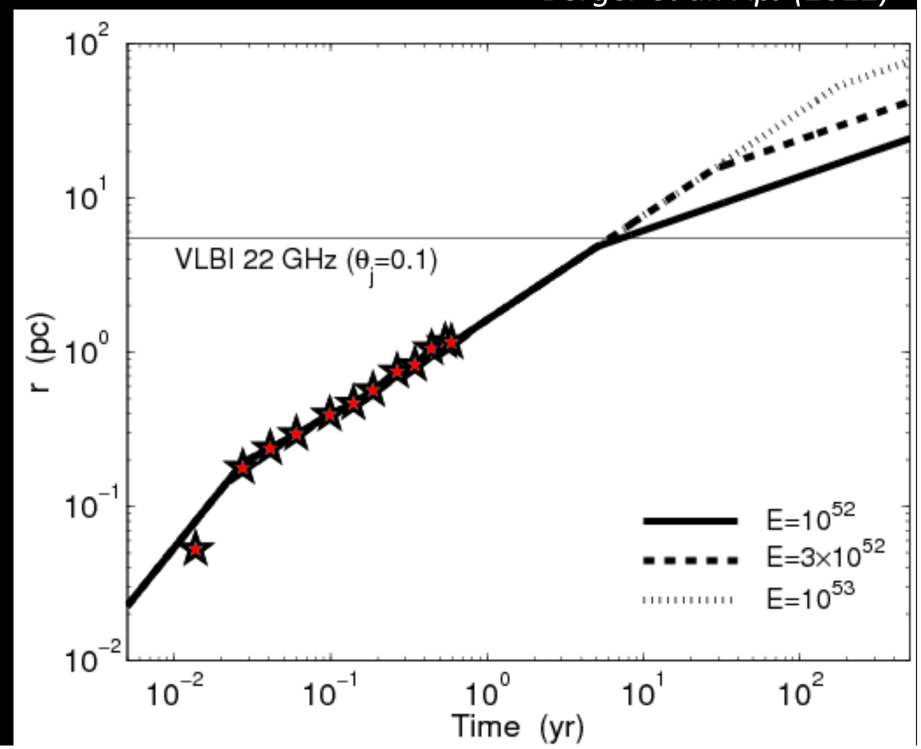


Berger et al. ApJ (2012)

Depending on total E_j, the radio emission will remain detectable with EVLA for ~100-500 years

Radio source will be resolvable with VLBI in ~3-5 years if stays collimated; ~1-2 years if it spreads

Berger et al. ApJ (2012)



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- Polarization at 5-45 GHz (% and angle – magnitude and variation with time?)
  - UPDATE: radio linear polarization detected ~ a few %
- The long-term appearance of off-axis events; pred searches
  - UPDATE: 2 more TDE candidates in 2011….whe m?

Work in prep. with R. Shcherbakov & R. Sari

Consistent with limits of 2.1% by Wiersema et al.

Conclusions
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Gezari et al. (L. Chomiuk)
Cenko et al.
van Velzen et al.

Gracias