THE DISCOVERY OF THE BIRTH OF A RELATIVISTIC JET FROM A TIDAL DISRUPTION EVENT

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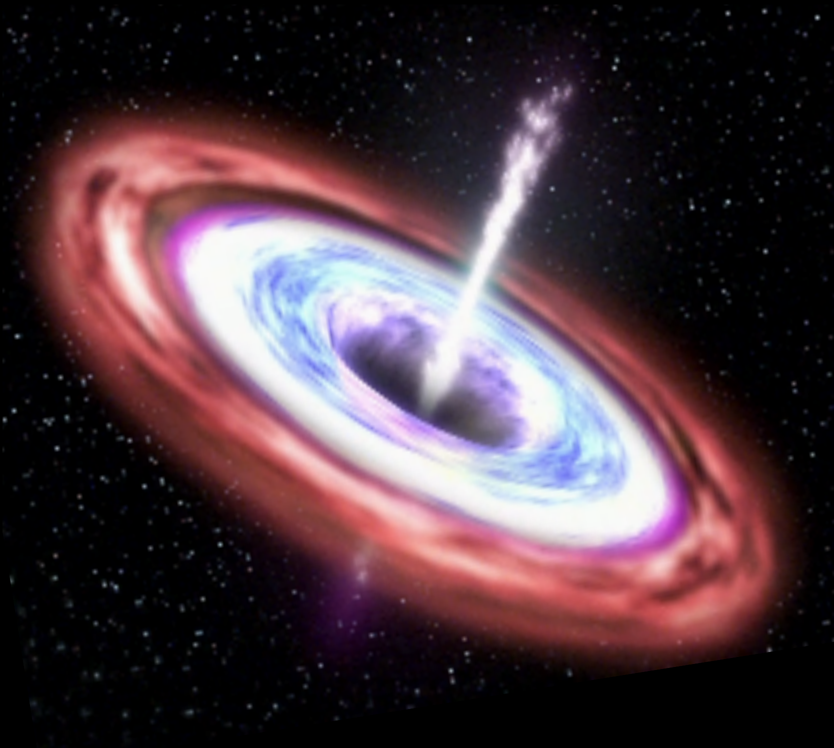
E. Berger, A. Soderberg, R. Sari, A. Loeb, R. Narayan, D. Frail, G. Petitpas, A. Brunthaler, R. Chornock, J. Carpenter, G. Pooley, K. Mooley, S. Kulkarni, R. Margutti, D. Fox, E. Nakar, N. Patel, M. Bietenholz, M. Rupen

Tidal Disruption Events:
A Change in Paradigm



Bower et al. X-ray selected TDEs: 10% launch jets?

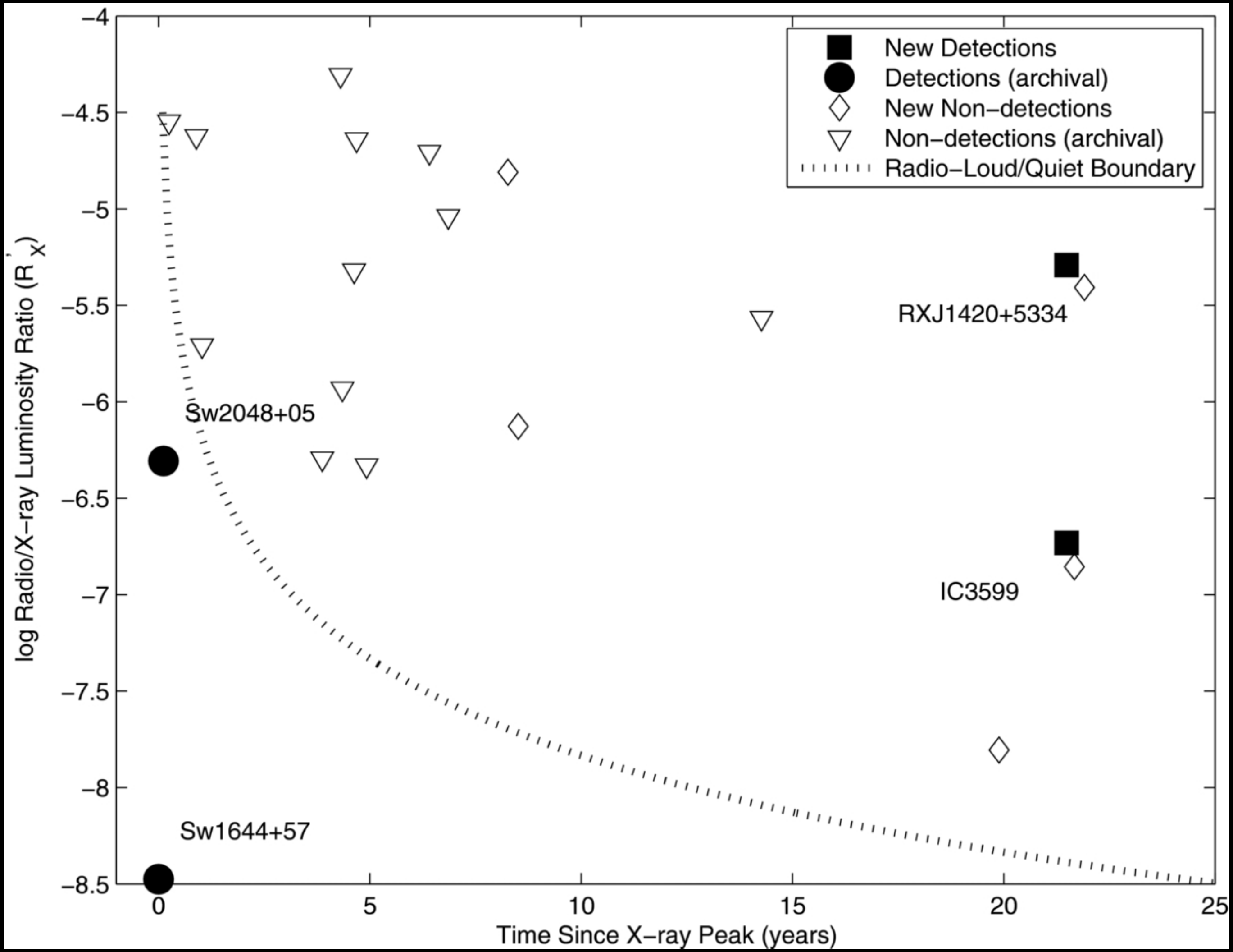
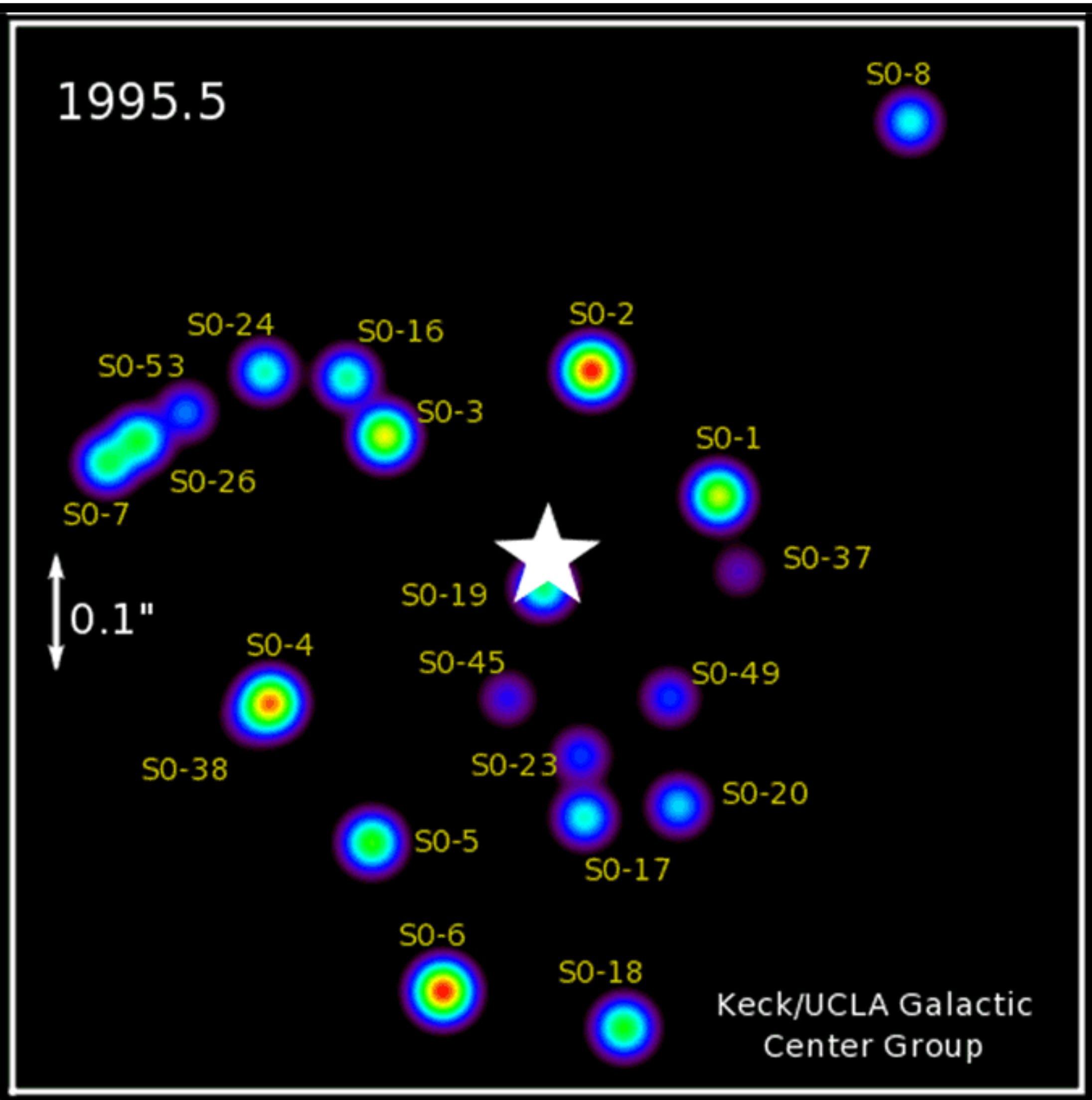


Figure 4 from Late-time Radio Emission from X-Ray-selected Tidal Disruption Events
Geoffrey C. Bower et al. 2013 ApJ 763 84 doi

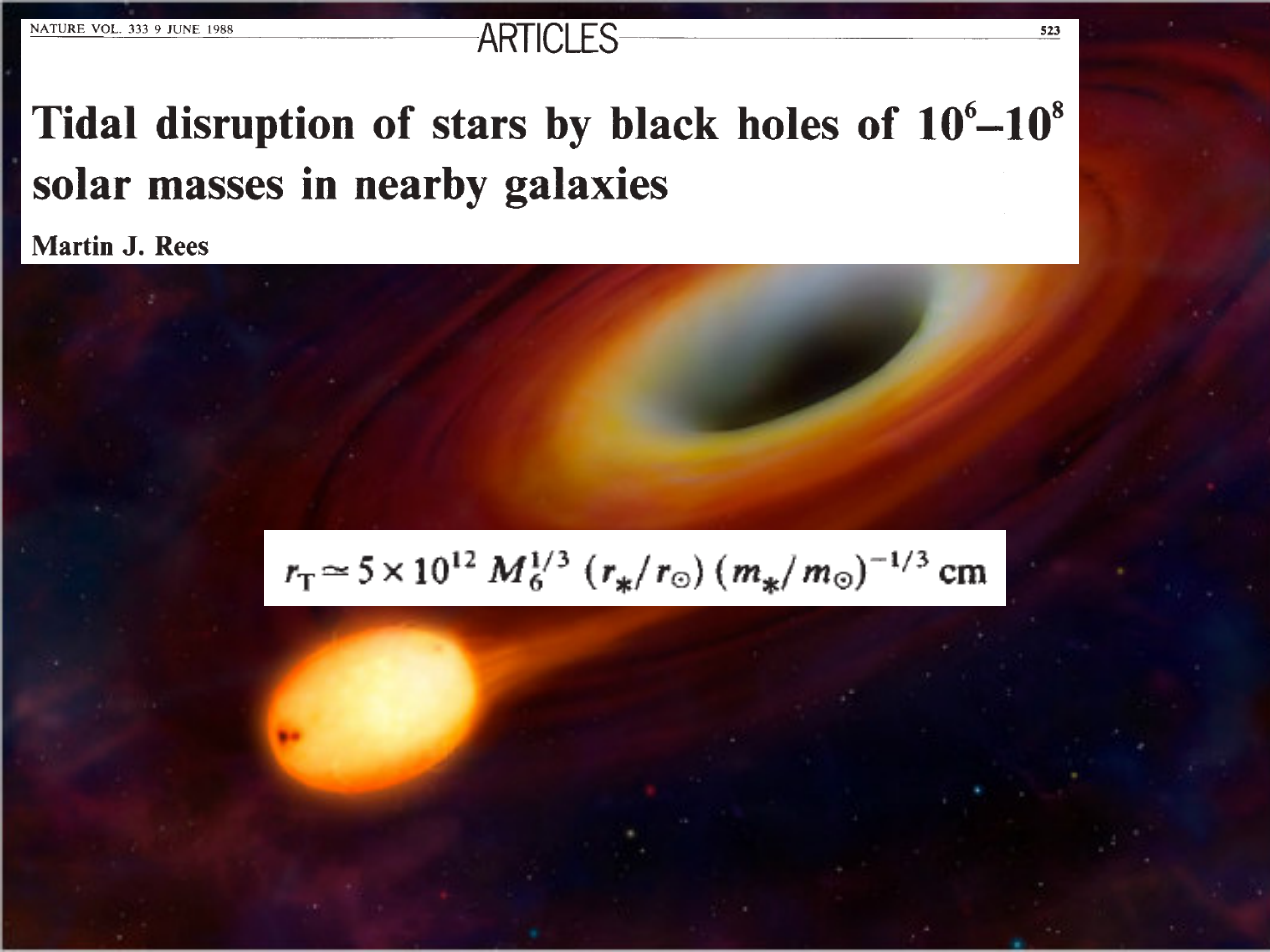
TDE Background



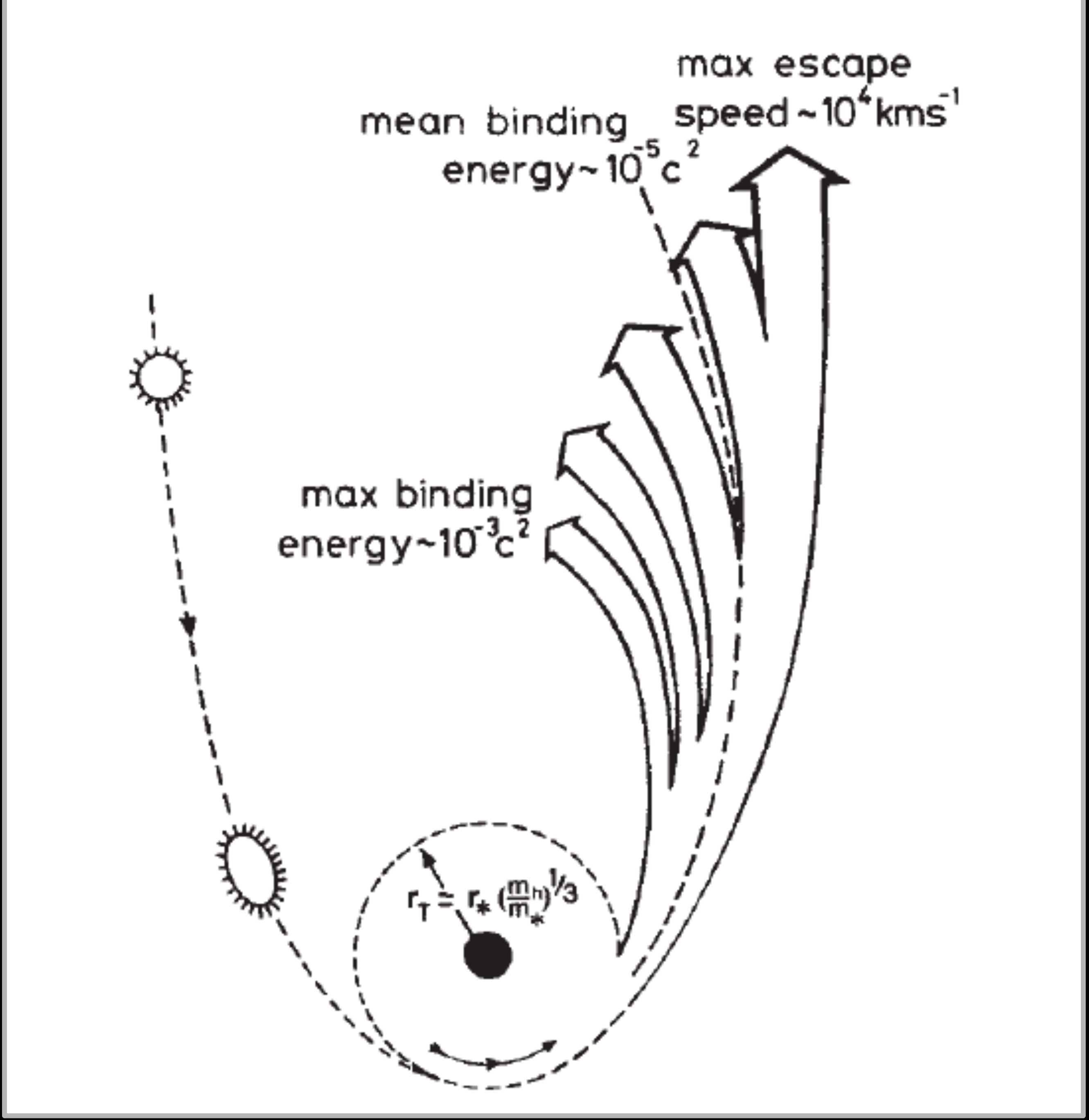
NATURE VOL. 333 9 JUNE 1988 ARTICLES 523

Tidal disruption of stars by black holes of 10^6–10^8 solar masses in nearby galaxies

Martin J. Rees



$$r_T \simeq 5 \times 10^{12}\, M_6^{1/3}\, (r_*/r_\odot)\, (m_*/m_\odot)^{-1/3}\ \mathrm{cm}$$

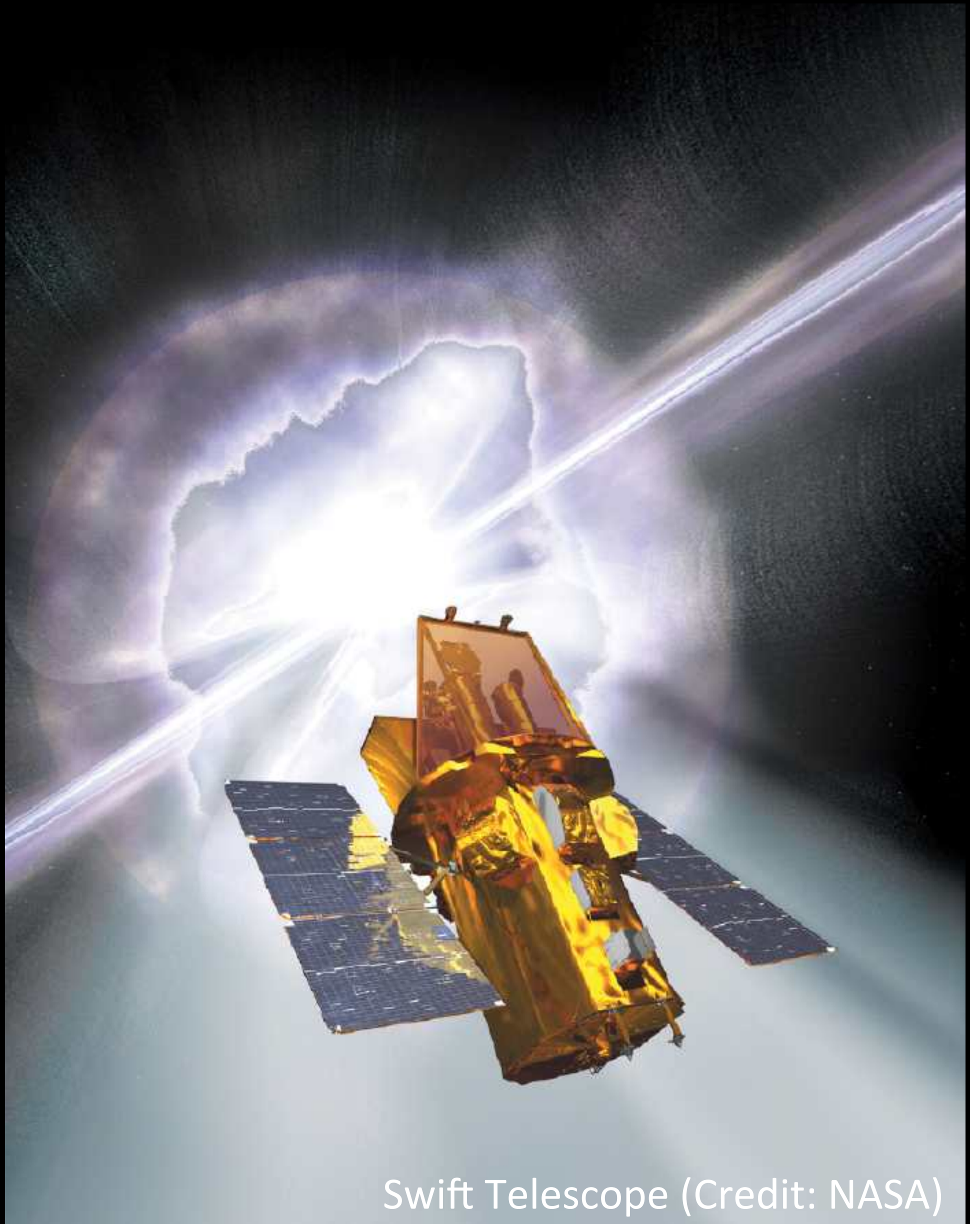


Rees 1988 (Nature)

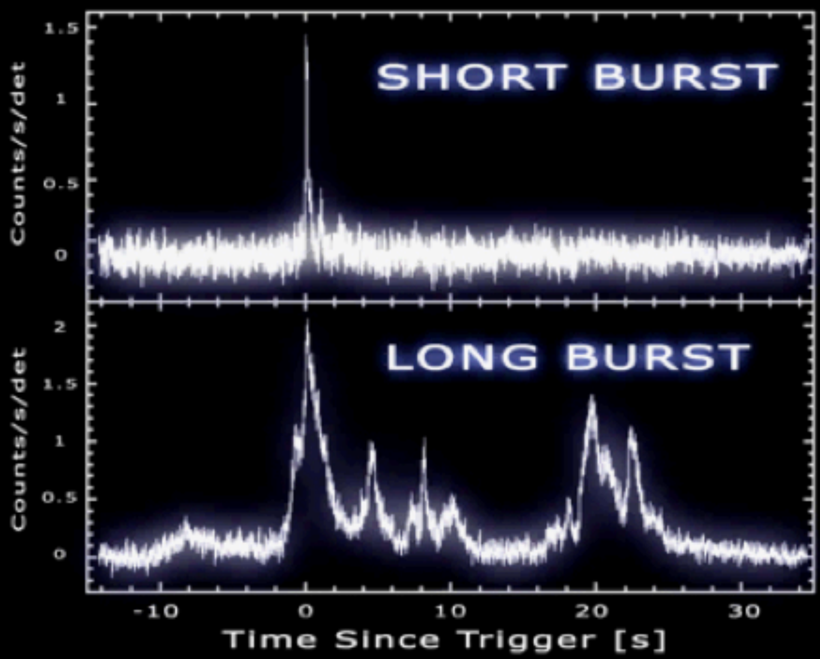
GRB 110328 / Swift J164449.3+573451

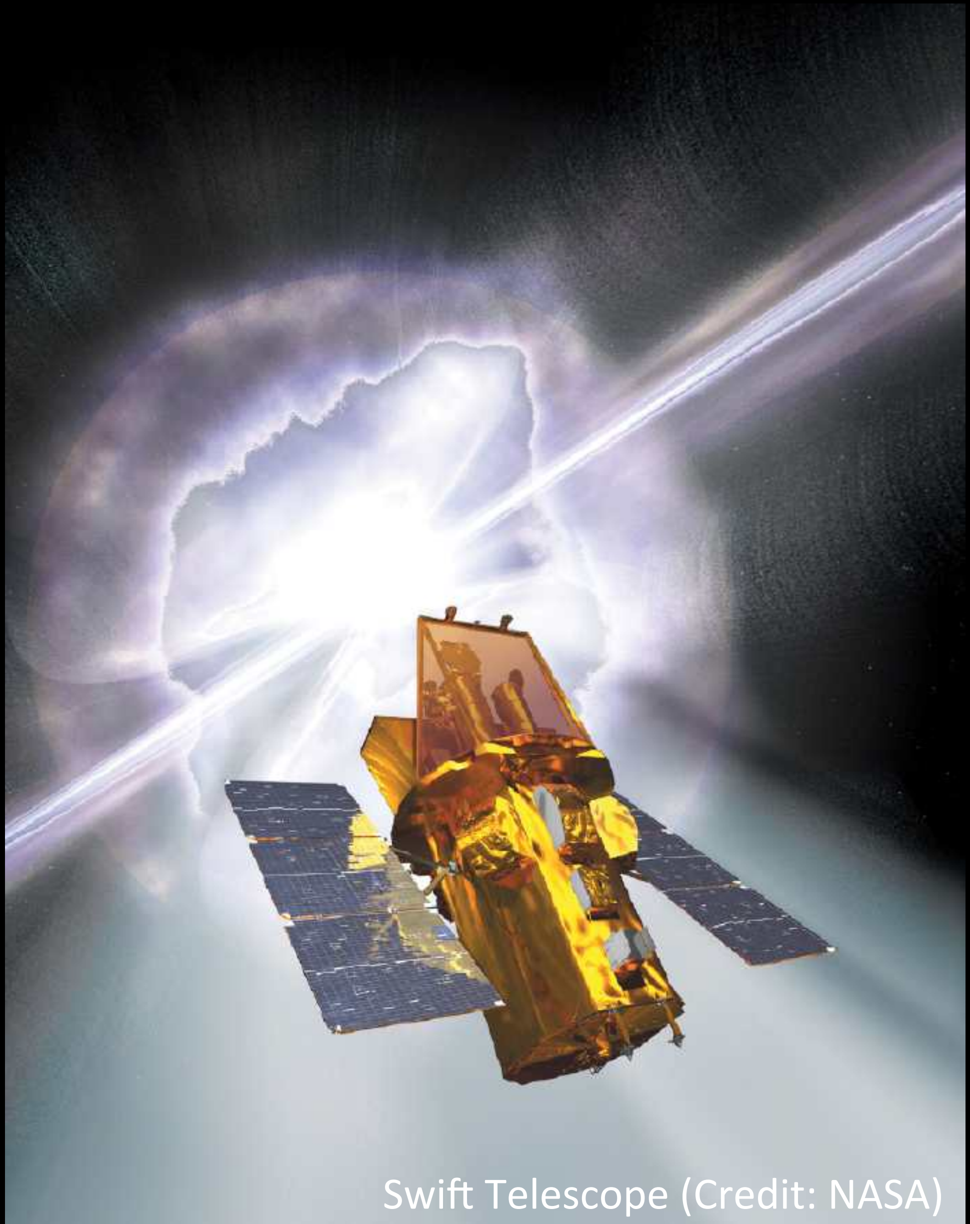
Postcard from collection by
Don Hillger and Garry Toth
Colorado State University

- *Intense short bursts of energy*
- *Approx. 3 per day, 2 per week detected*
- *Energy release: Isotropic:* 10^{52} - 10^{54} *ergs / Actual:* 10^{51} - 10^{52} *ergs (typical beaming 10°)*
- *outflow highly relativistic:* $\Gamma = 100 - 1000$
- *Prompt emission: .01 - 100 s / Afterglow - longer timescales*

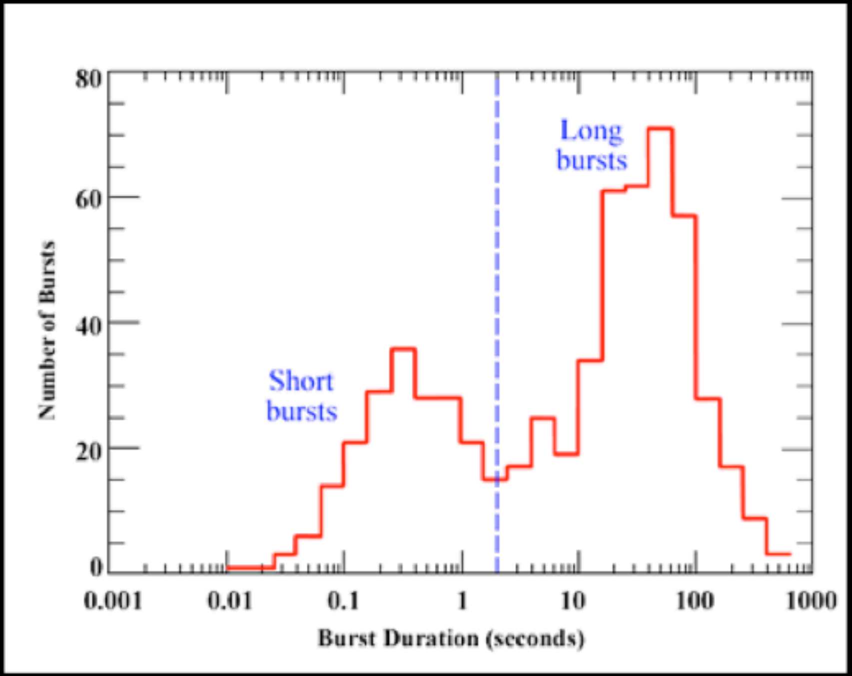


Swift Telescope (Credit: NASA)

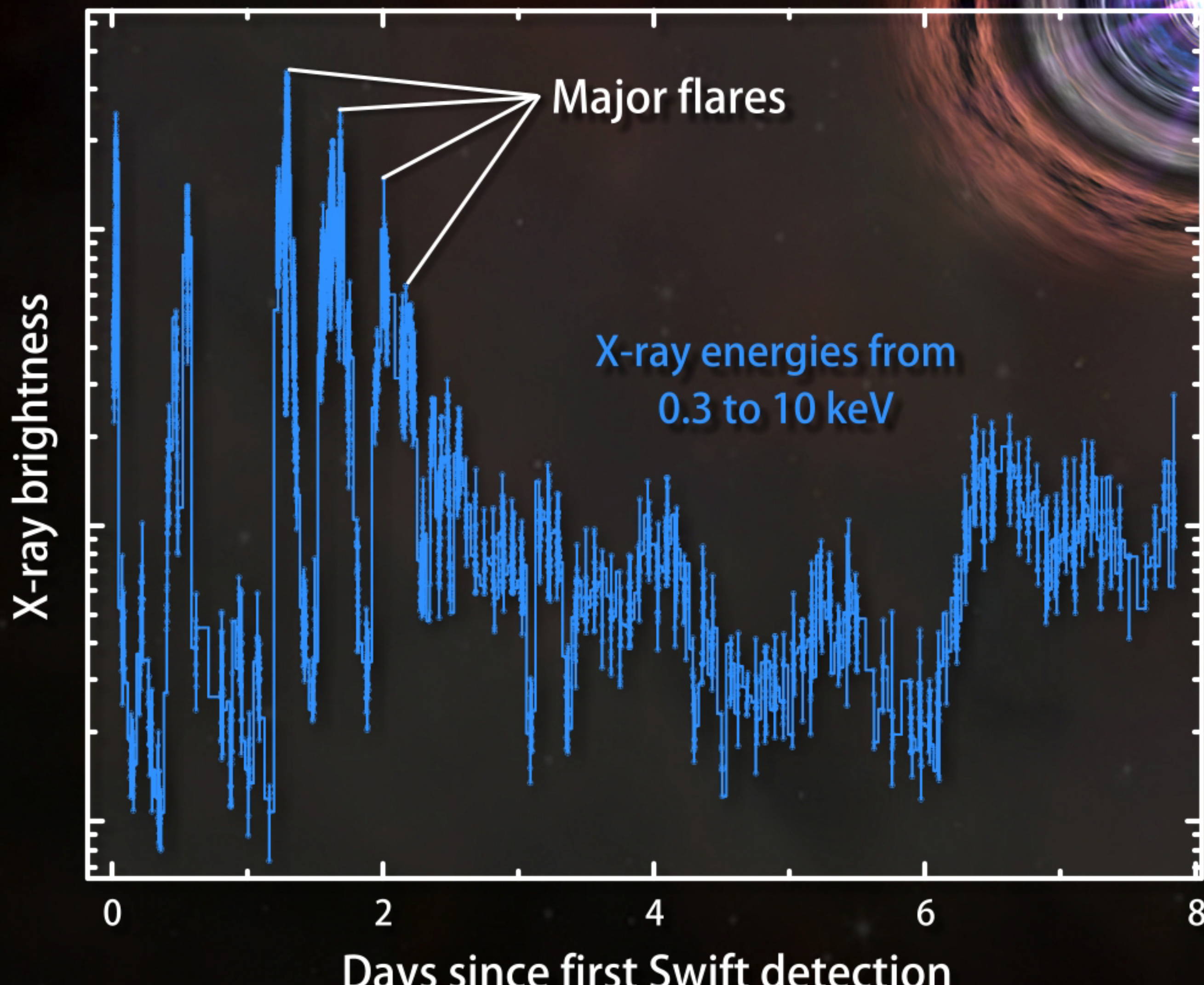




Swift Telescope (Credit: NASA)



Kouveliotou et al. **1993**



Initial trigger:

2011 March 28.54 UT

followed by five additional triggers

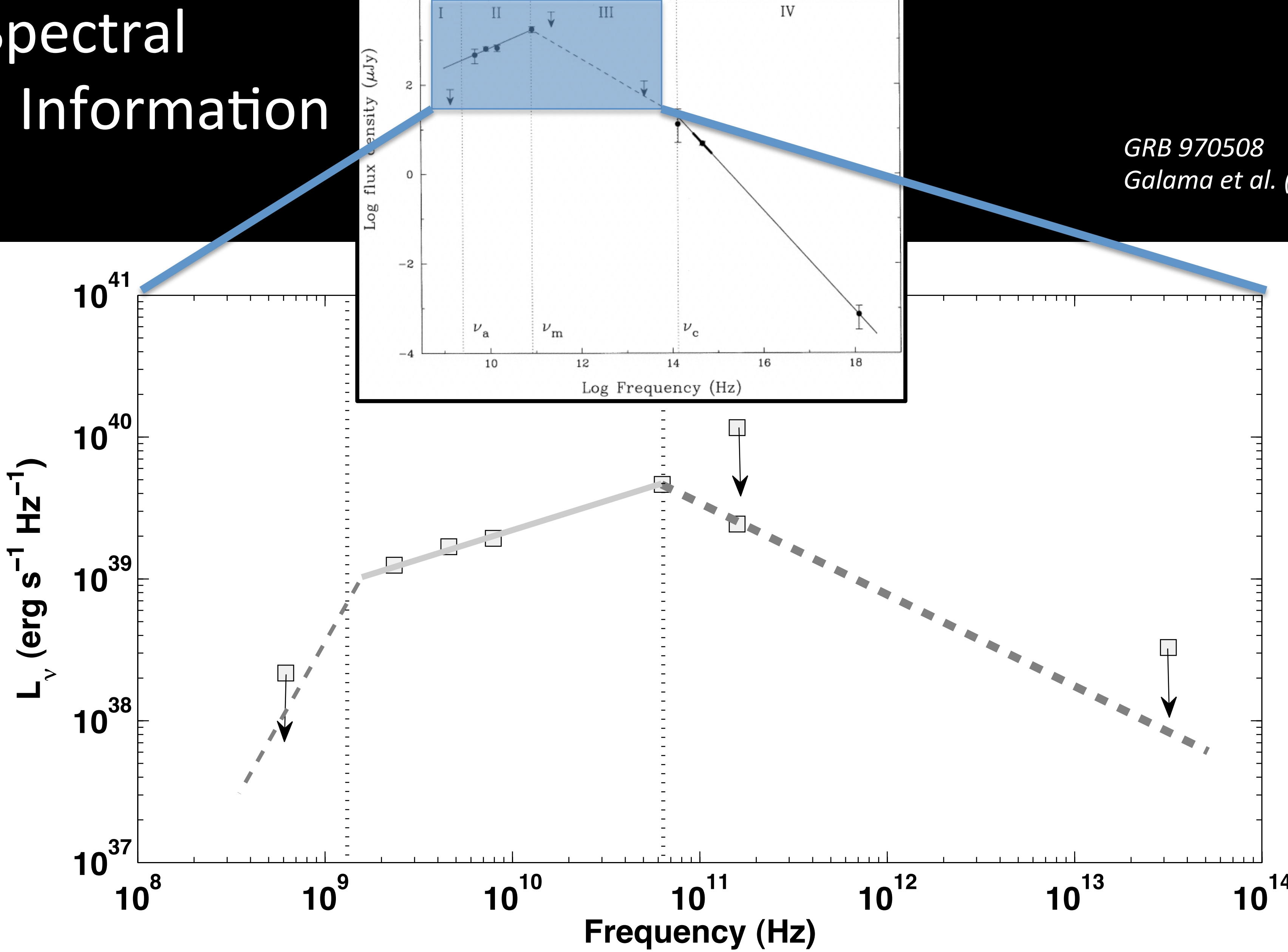
γ-ray emission detected starting 2011 March 25 UT

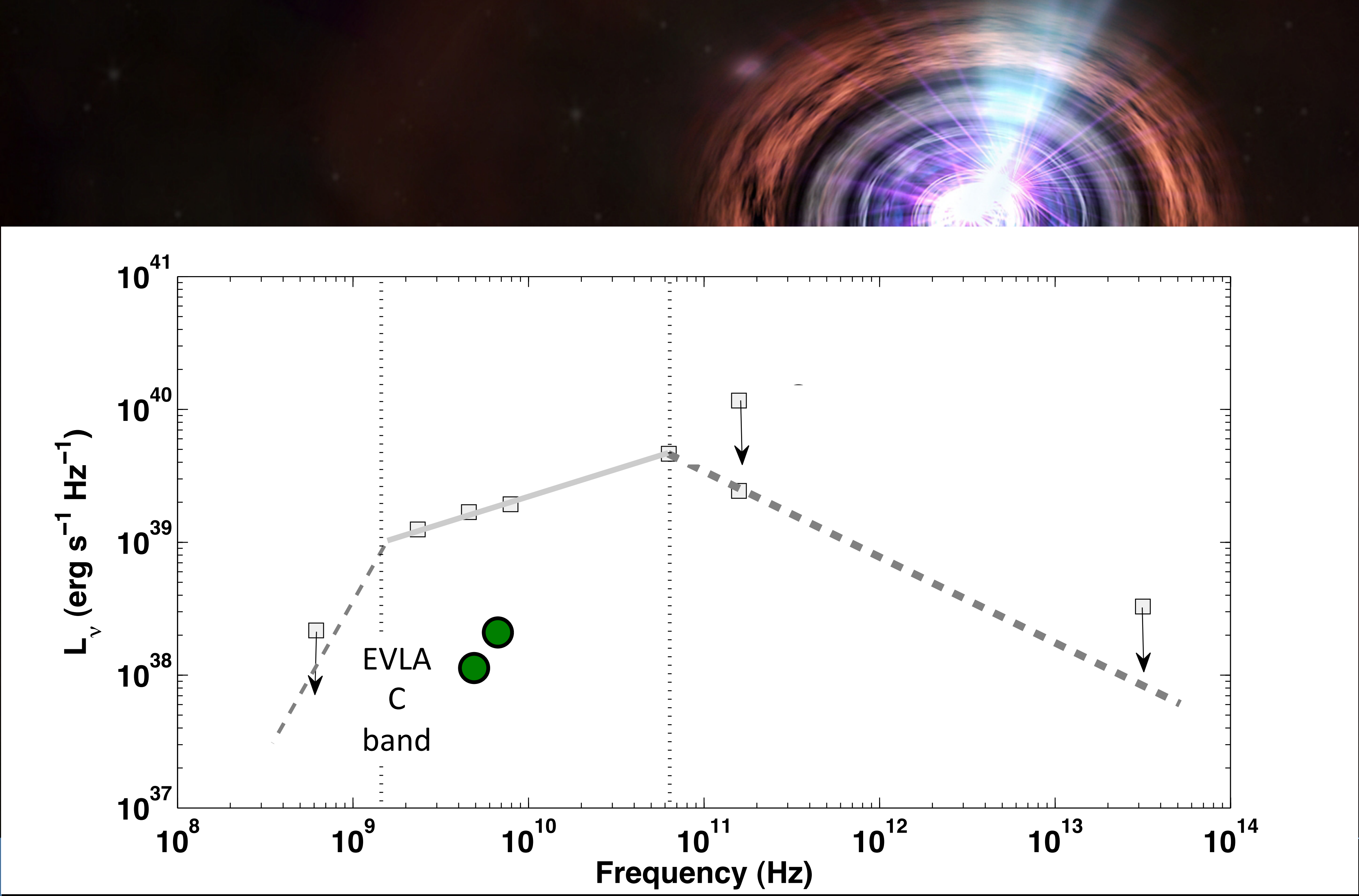
Burrows et al. Nature (2011)

NASA/CXC/Warwick/A.Levan et al.

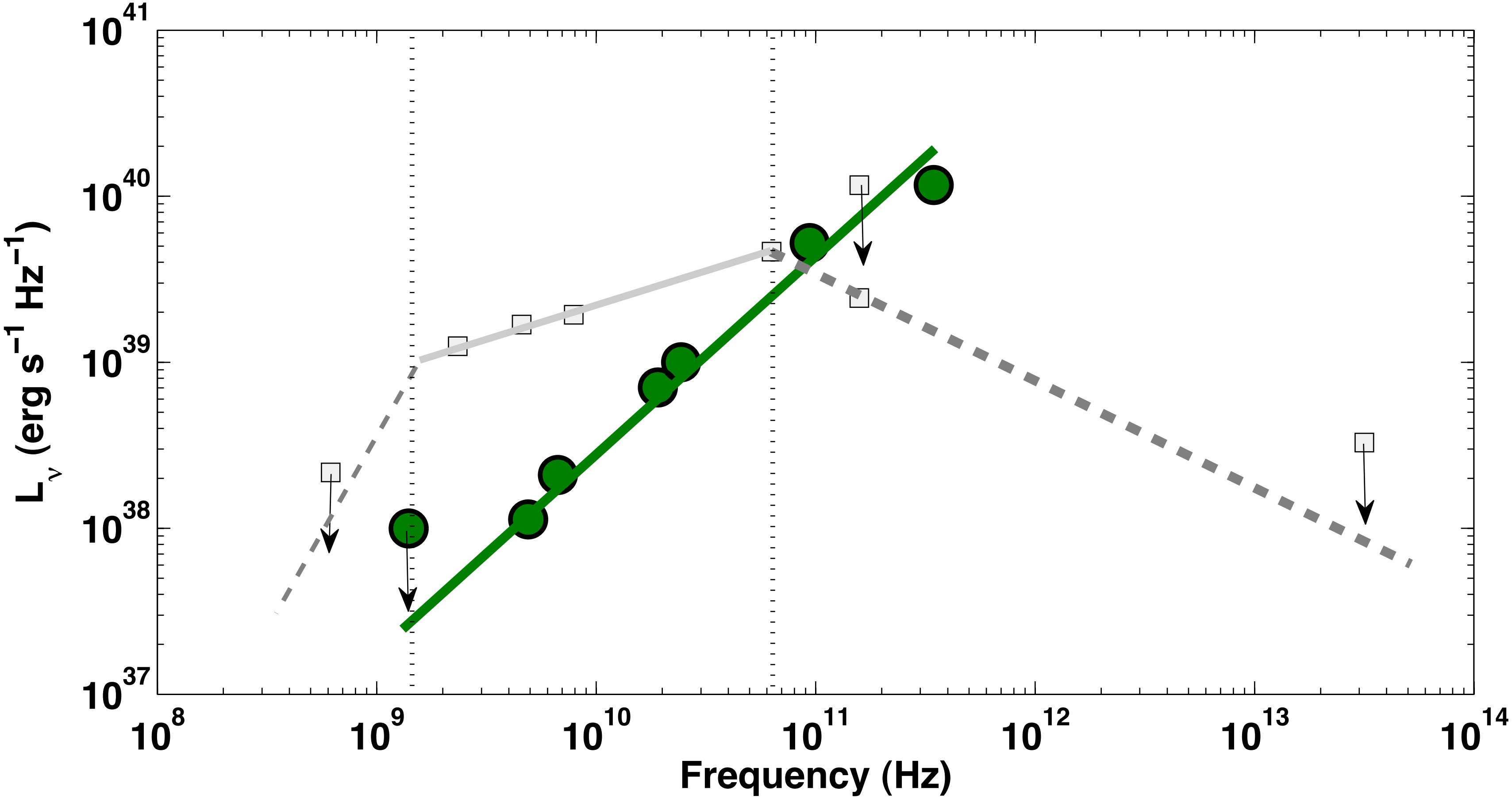
Spectral Information

GRB 970508
Galama et al. (1998)

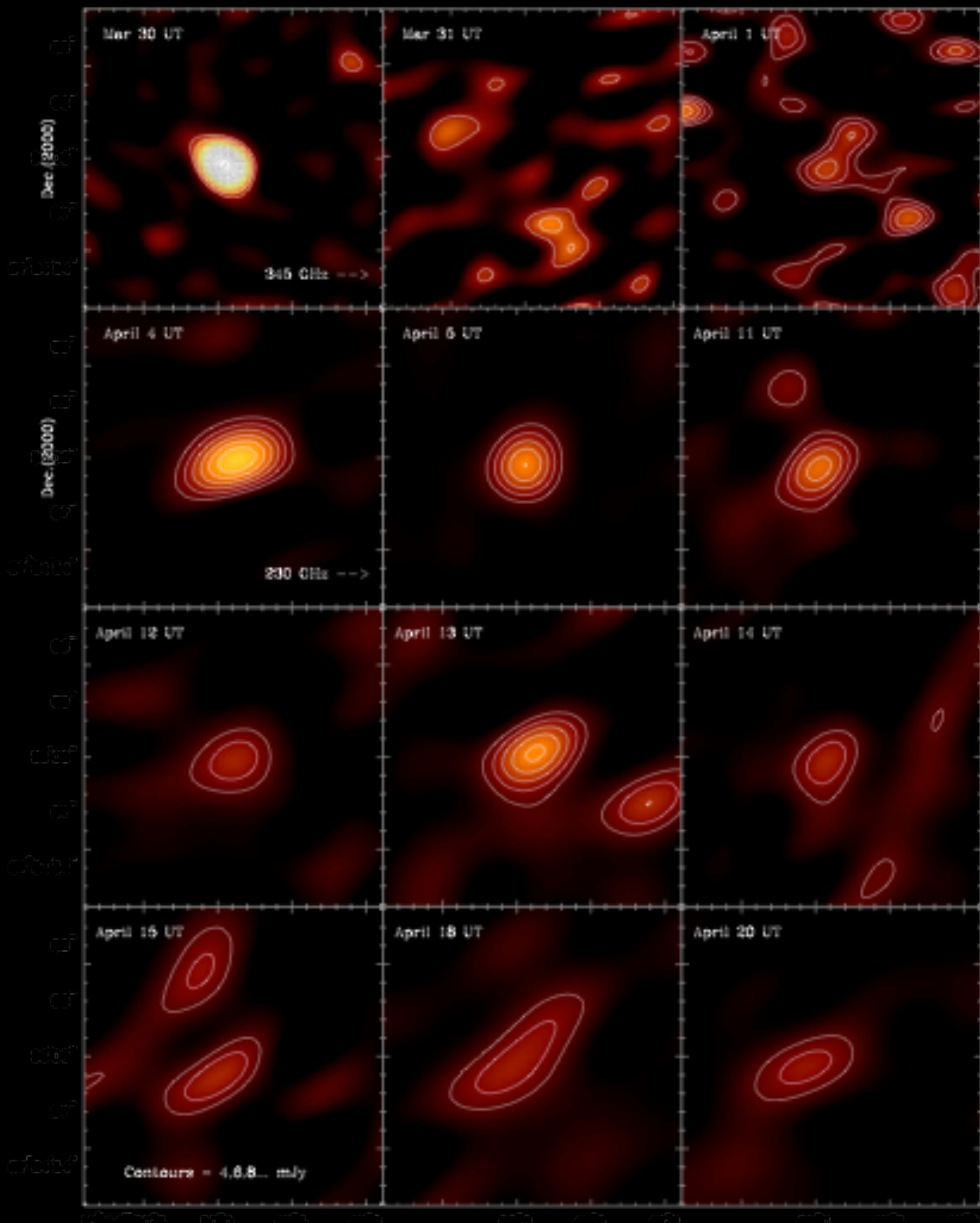




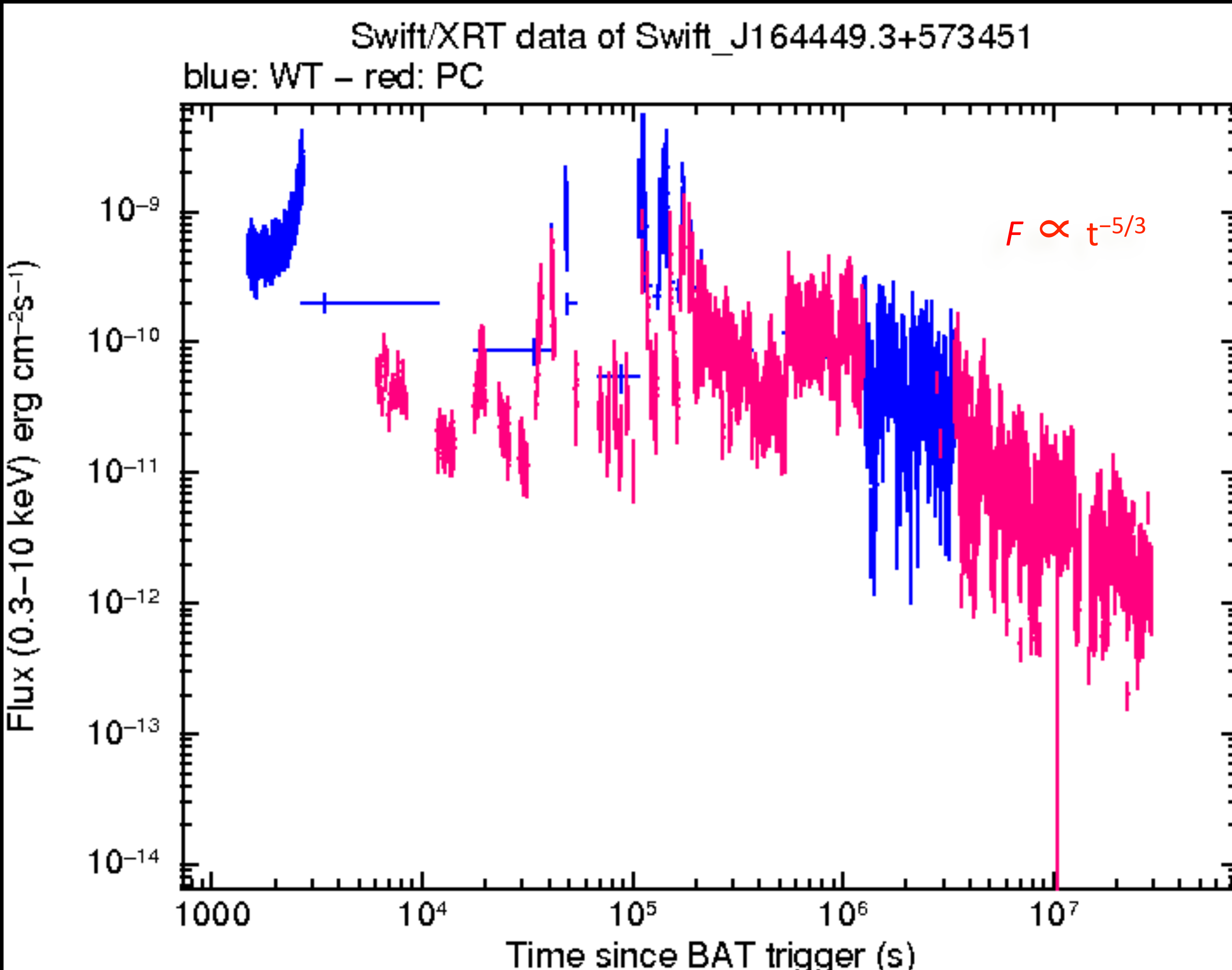
L_ν (erg s^{-1} Hz^{-1})
10^{41}
10^{40}
10^{39}
10^{38}
10^{37}
EVLA
C
band
10^{8}
10^{9}
10^{10}
10^{11}
10^{12}
10^{13}
10^{14}
Frequency (Hz)



10^{41}
10^{40}
10^{39}
10^{38}
10^{37}
L_ν (erg s^{-1} Hz^{-1})
10^{8}
10^{9}
10^{10}
10^{11}
10^{12}
10^{13}
10^{14}
Frequency (Hz)

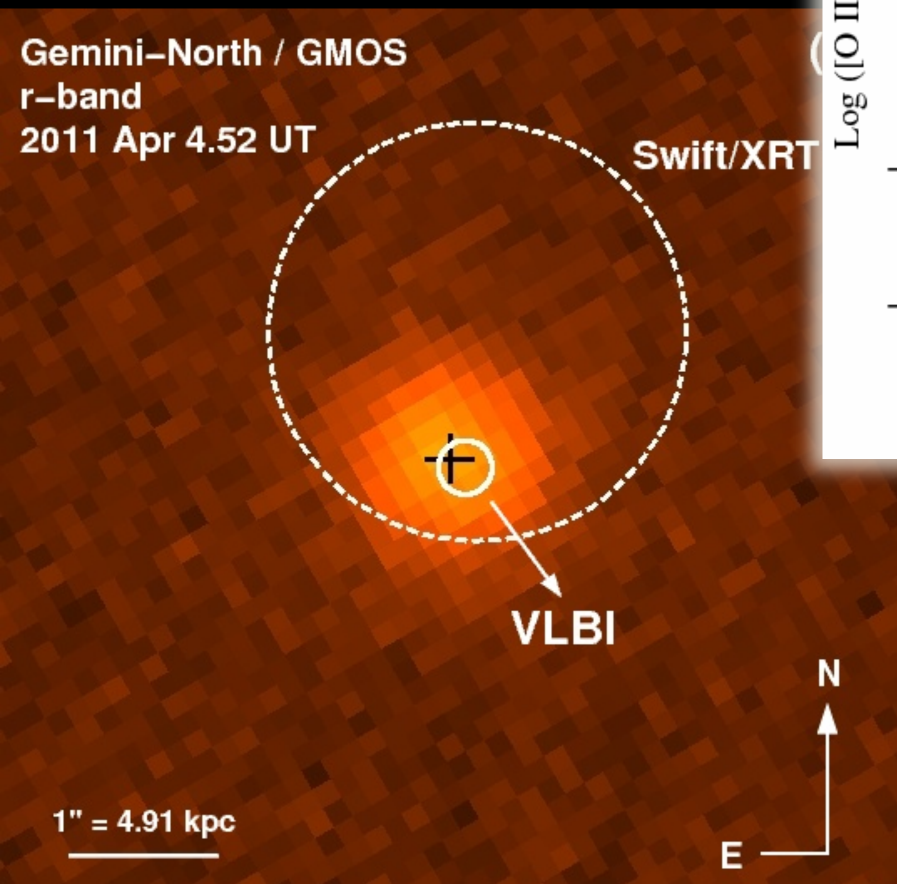


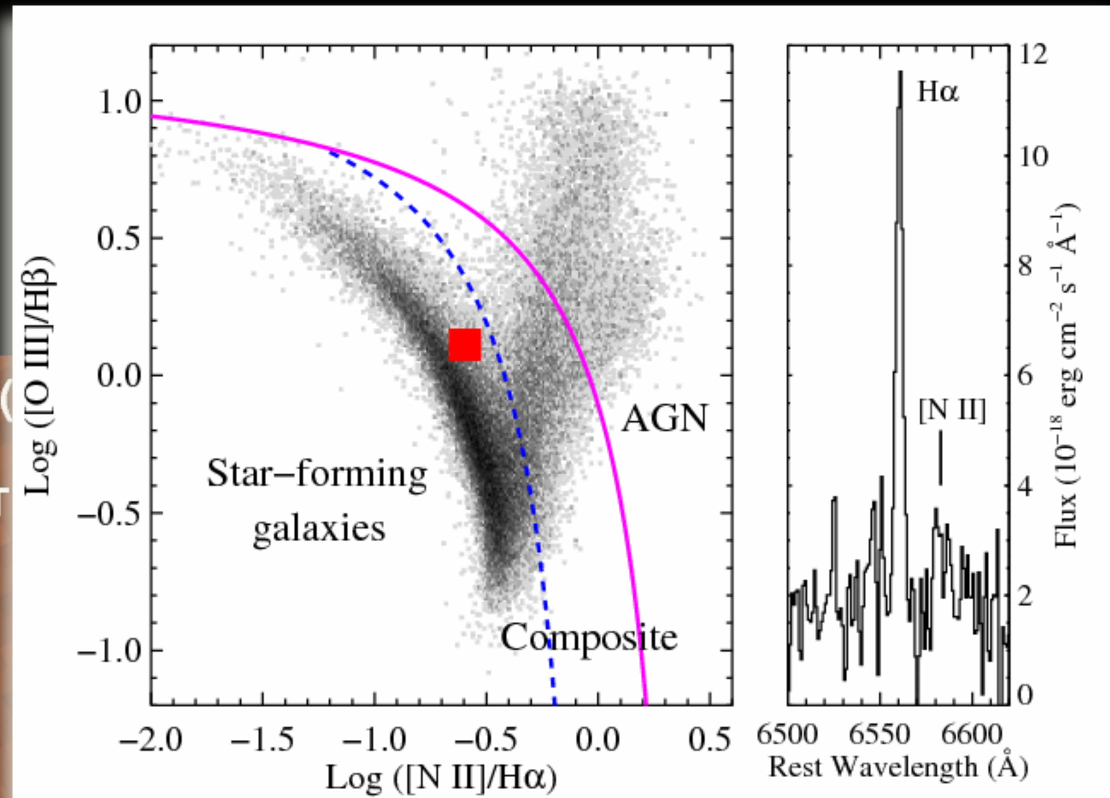
Glen Petitpas
SMA


Swift/XRT data of Swift_J164449.3+573451
blue: WT – red: PC
Flux (0.3–10 keV) erg cm⁻²s⁻¹)
Time since BAT trigger (s)
1000
10^4
10^5
10^6
10^7
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
$F \propto t^{-5/3}$

Galaxy at z = 0.354 located inside *Swift*/XRT error circle

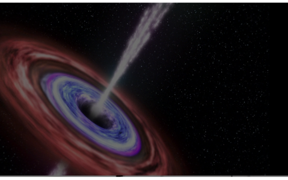
Radio emission localizes the transient to the nucleus



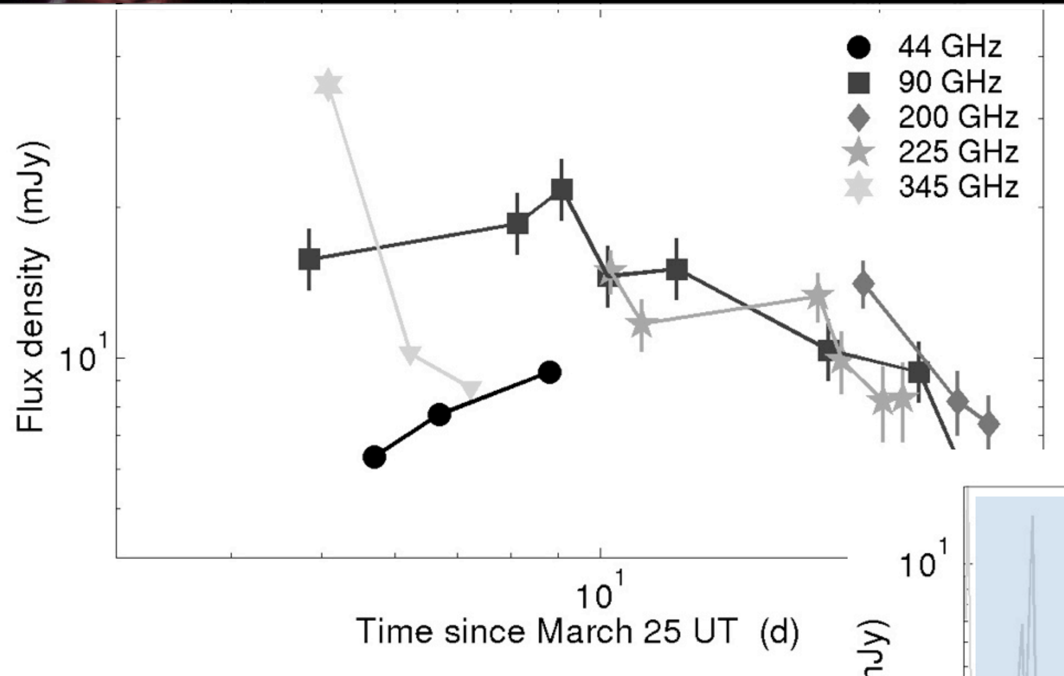


Zauderer et al. 2011

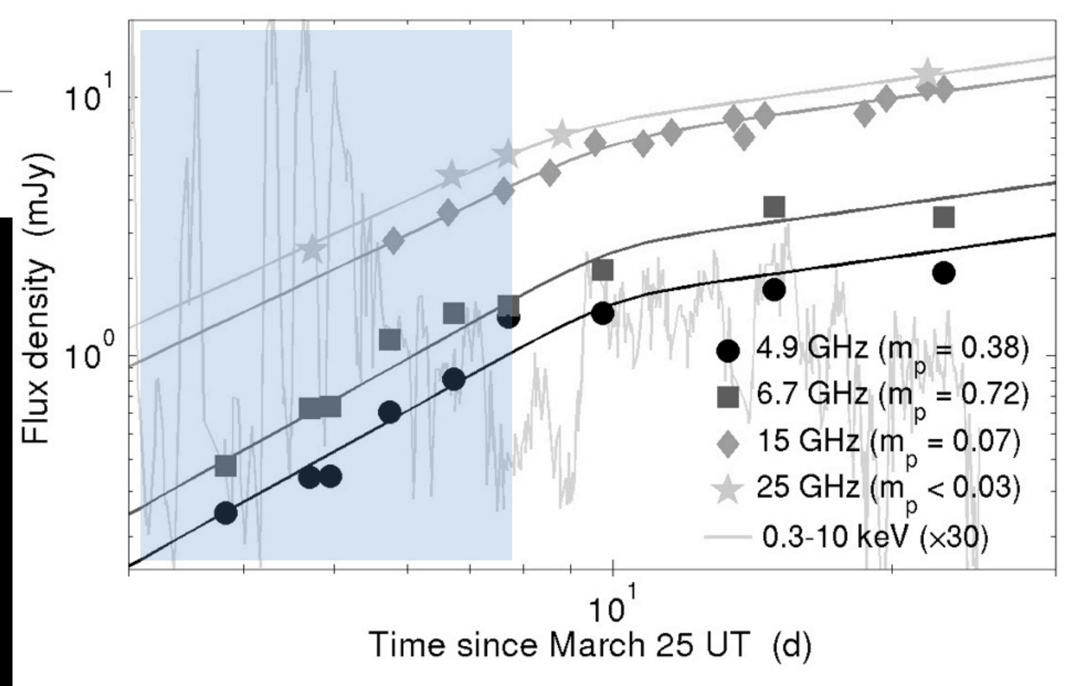
No evidence for AGN activity (line ratios, widths, lack of previous radio/X-ray emission)



Sw1644+57: Early Light Curve

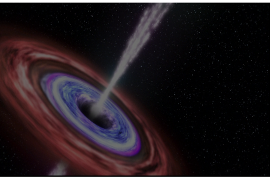


Large variations in X-rays are not accompanied by variations in radio



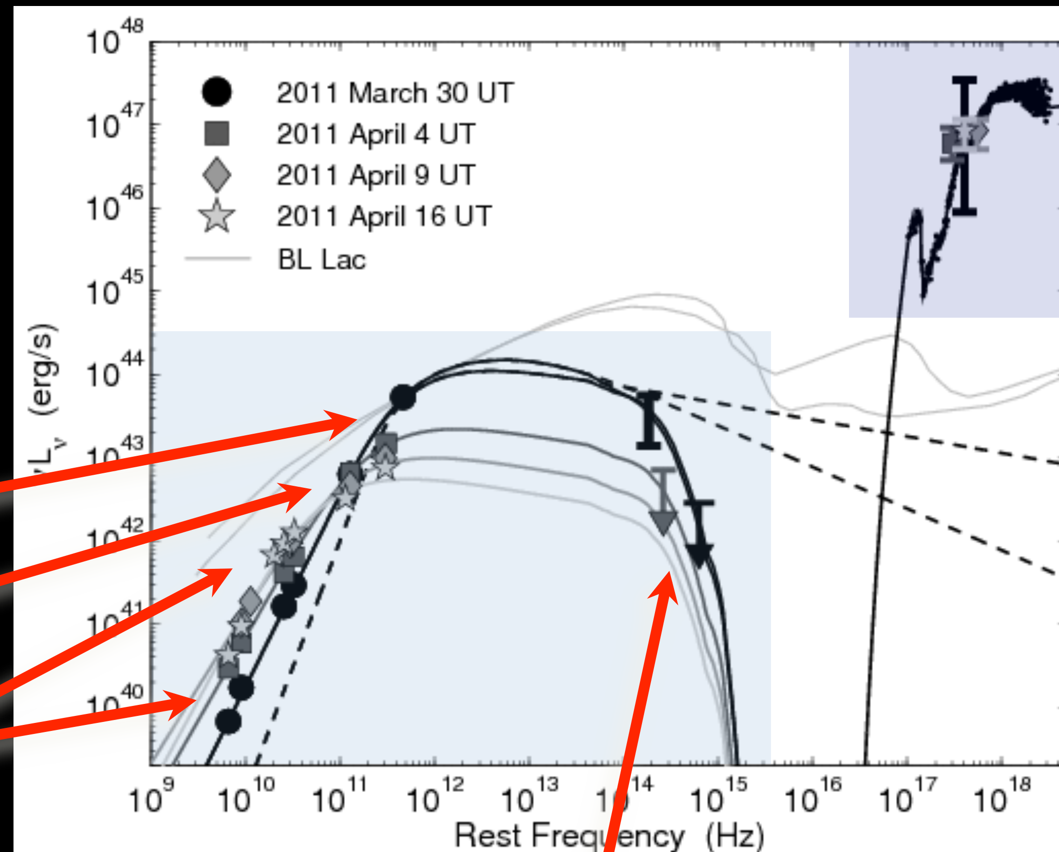
⇒ X-ray emission region distinct from radio emission region

Zauderer et al. 2011

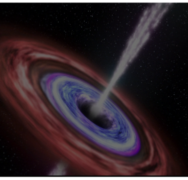


Sw1644+57: SED

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



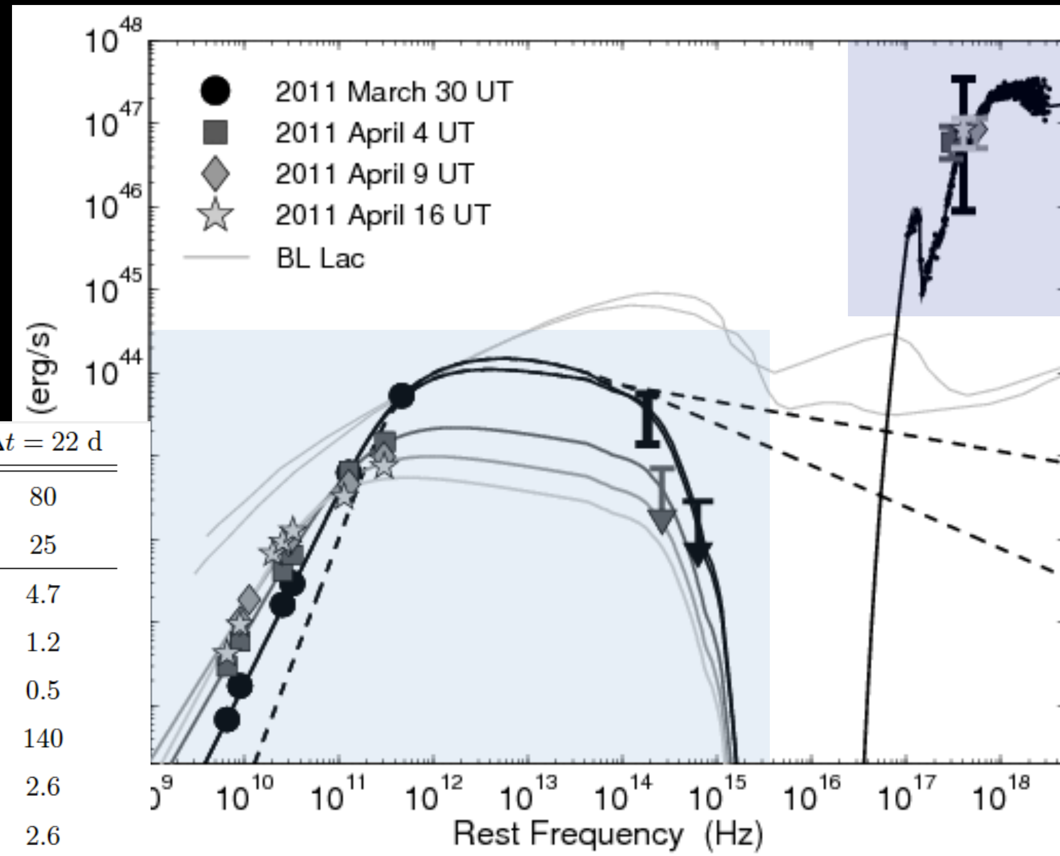
Zauderer et al. 2011



Sw1644+57: Synchrotron Modeling

Assumptions: peak freq = abs. freq
equipartition, spherical

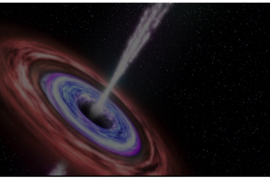
Calculate: radius, Lorentz factor, magnetic field strength, electron number density, angular size



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.

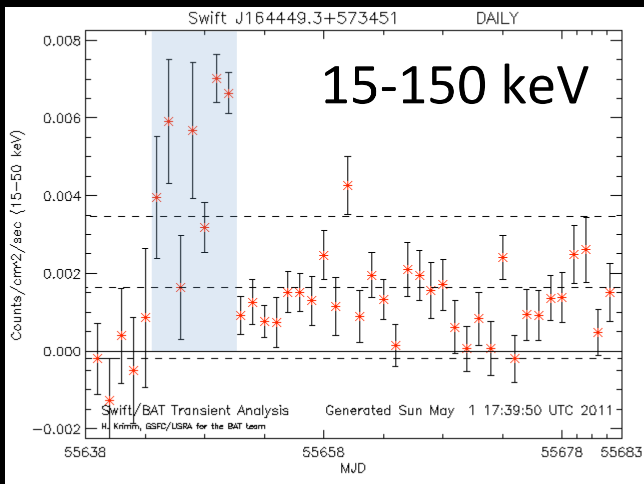


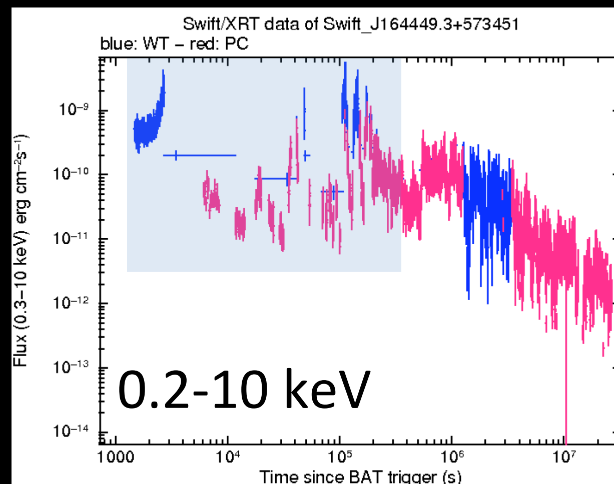
Sw1644+57: Overview

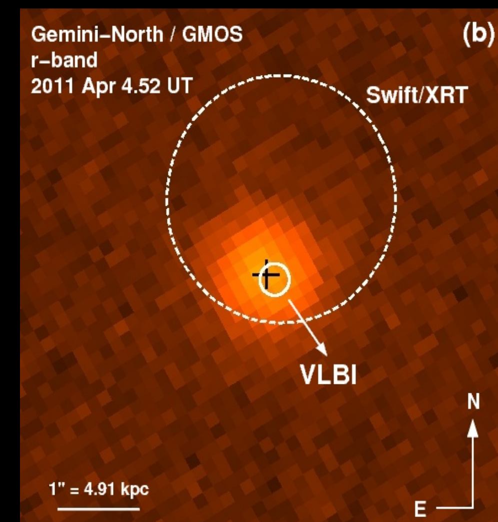
- *Swift* discovery on 2011 March 28.5 UT; multiple triggers; emission on 3/25

Burrows et al. Nature (2011), Levan et al. Science (2011)

- 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

See also Bloom et al. Science (2011), Castro-Tirado et al. 2012

Summary of Radio Monitoring Program

- Frequencies from < 1 GHz – 345 GHz
    - GMRT (< 1 GHz)
    - EVLA (L, C, X, K, Ka and Q bands)
    - VLBI (K band)
    - AMI-LA (15 GHz)
    - CARMA (95 GHz)
    - SMA (230, 345 GHz)

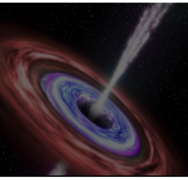
- Light curve sampled from 0.28 – 1000+ days since Swift trigger / Fluxes published

  Zauderer et al. 2011, Nature

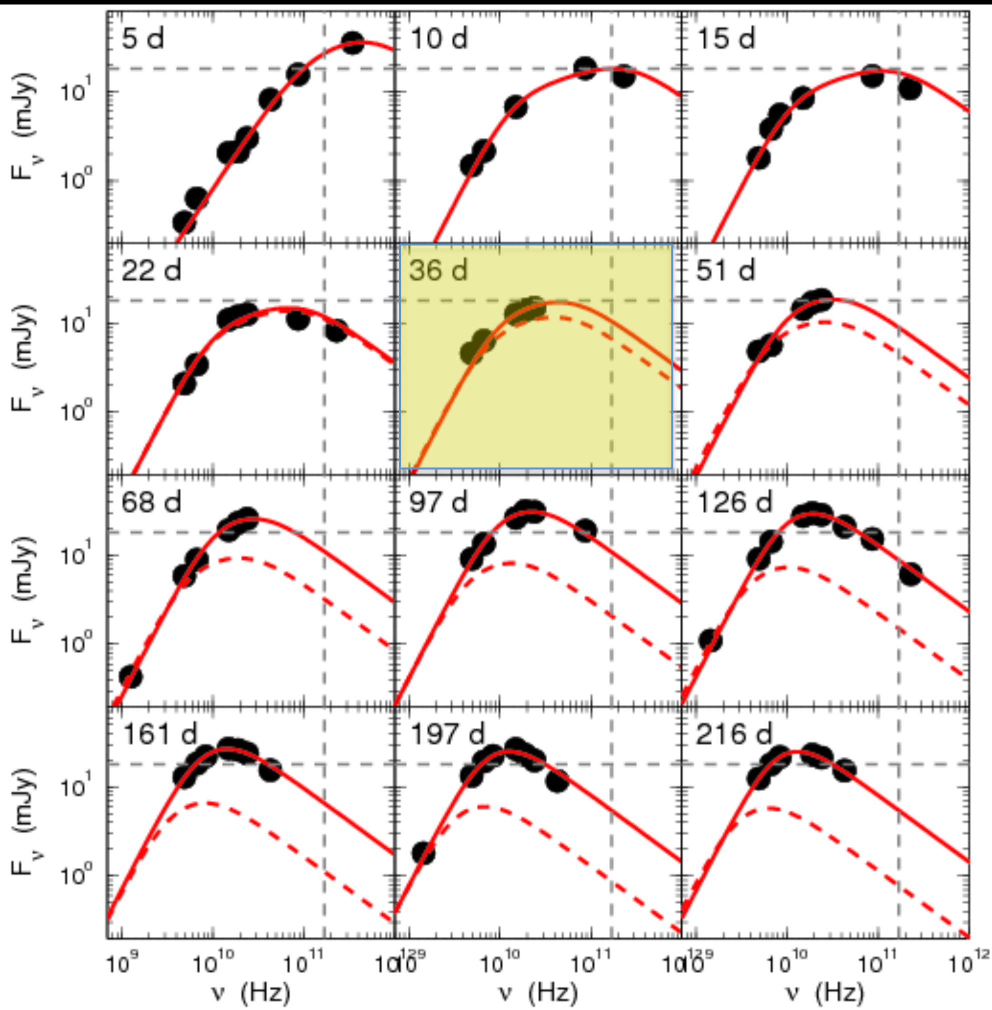
  Berger et al. 2012, ApJ, Paper I

  Zauderer et al. 2013, ApJ, Paper II

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



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)

Sw1644+57: Radio Monitoring

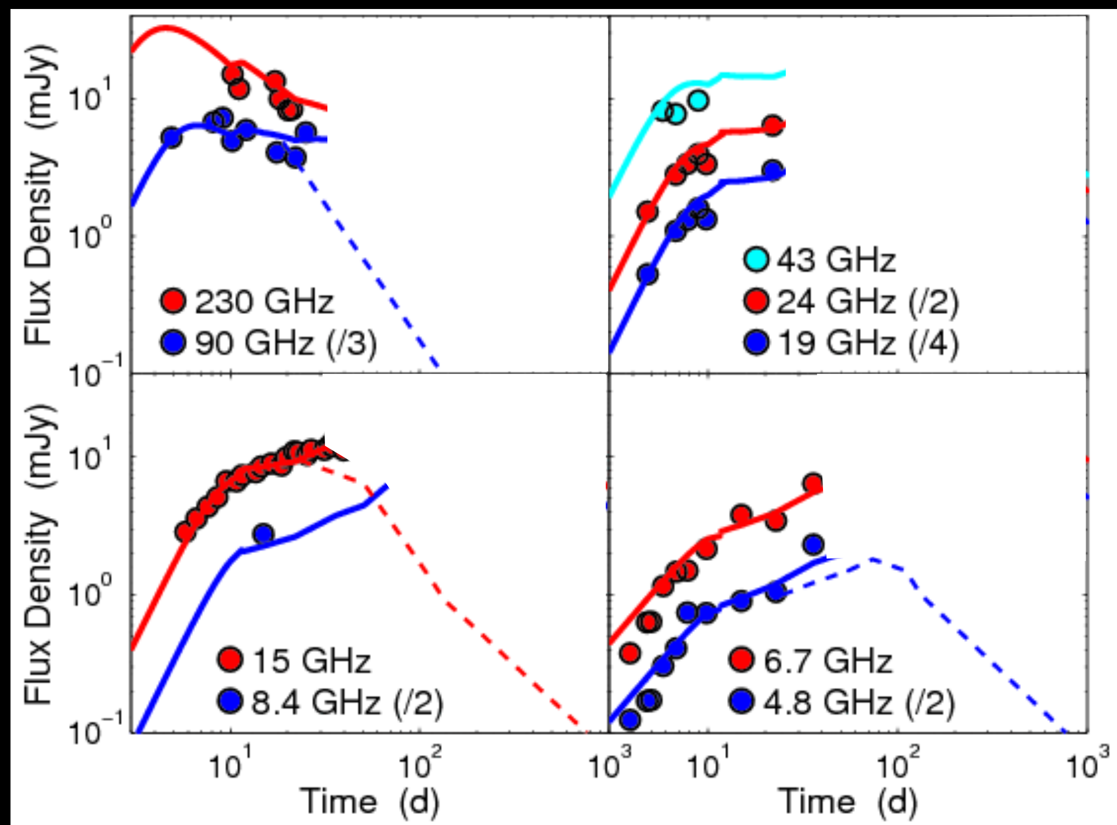
Long-term radio study provides several unique opportunities:

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

SMA
CARMA
EVLA
AMI-LA

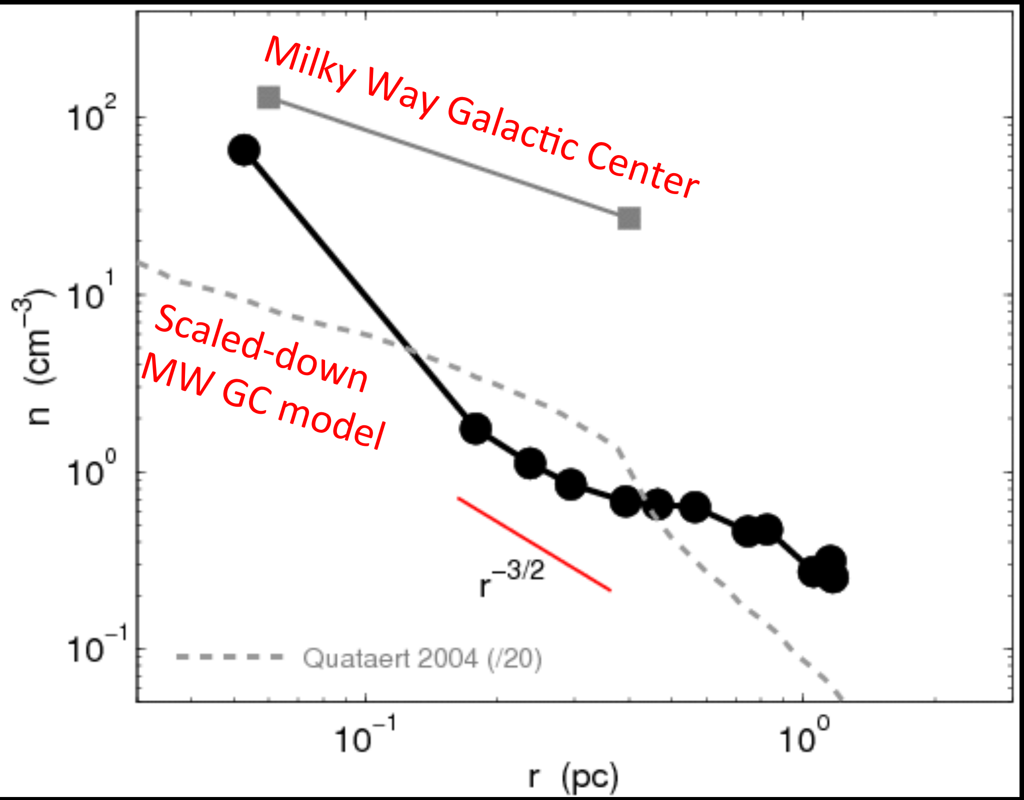
Observed radio evolution reveals much longer rise time and brighter emission than initially expected

⇒ <u>increase in *E*, *ρ*, both?</u>



Berger et al. ApJ (2012)

Parsec-Scale Environment



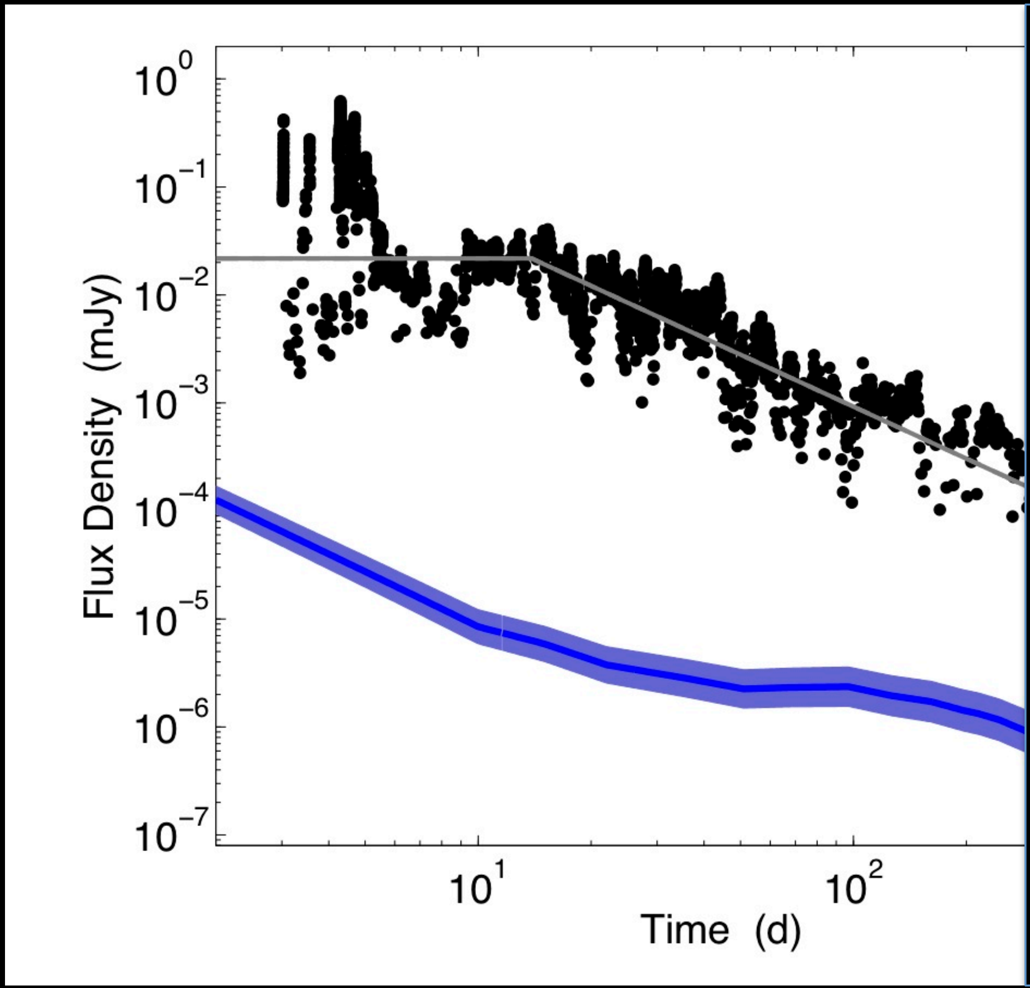
Berger et al. ApJ (2012)

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

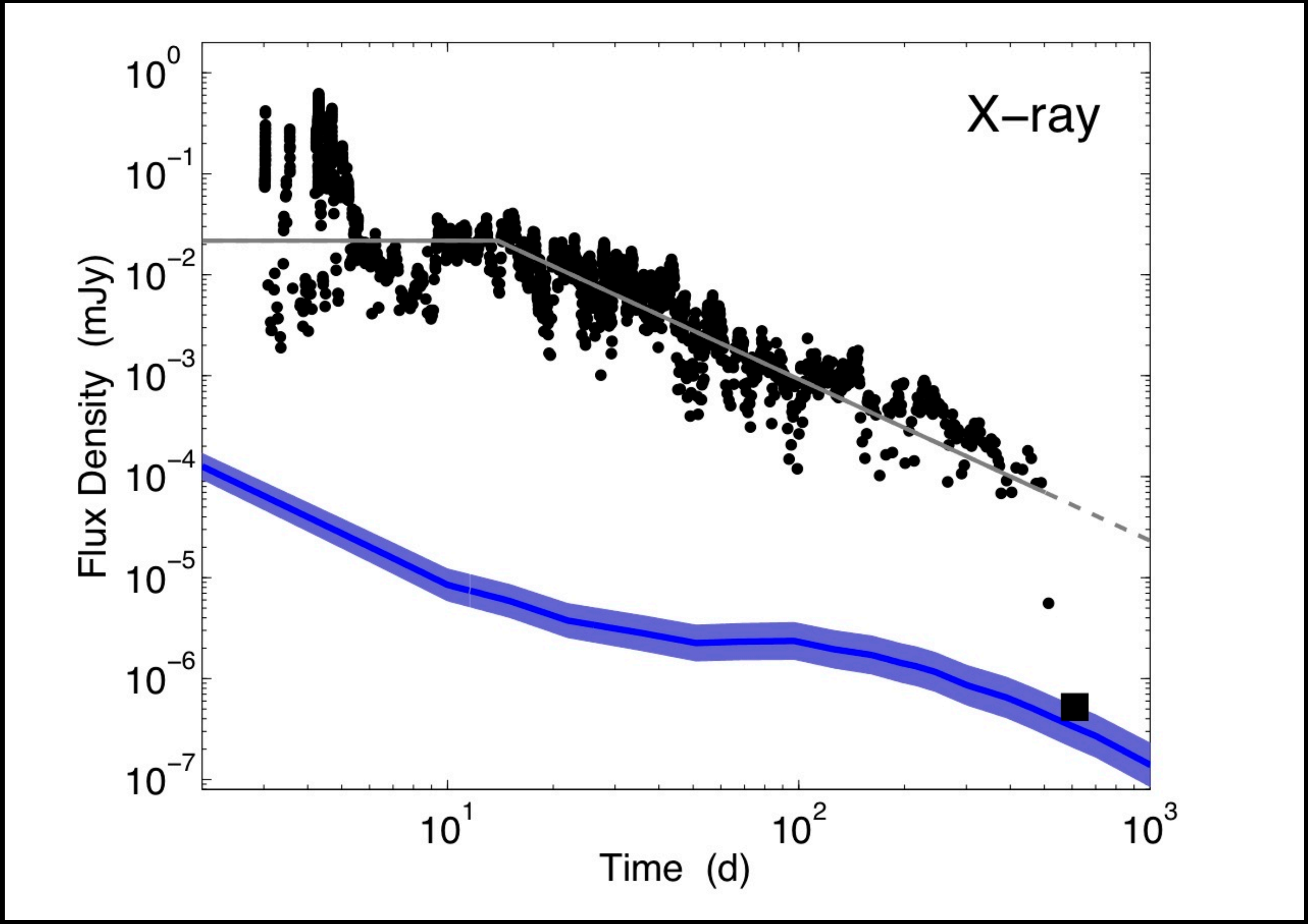
Lower density relative to Galactic Center indicative of lower SFR?

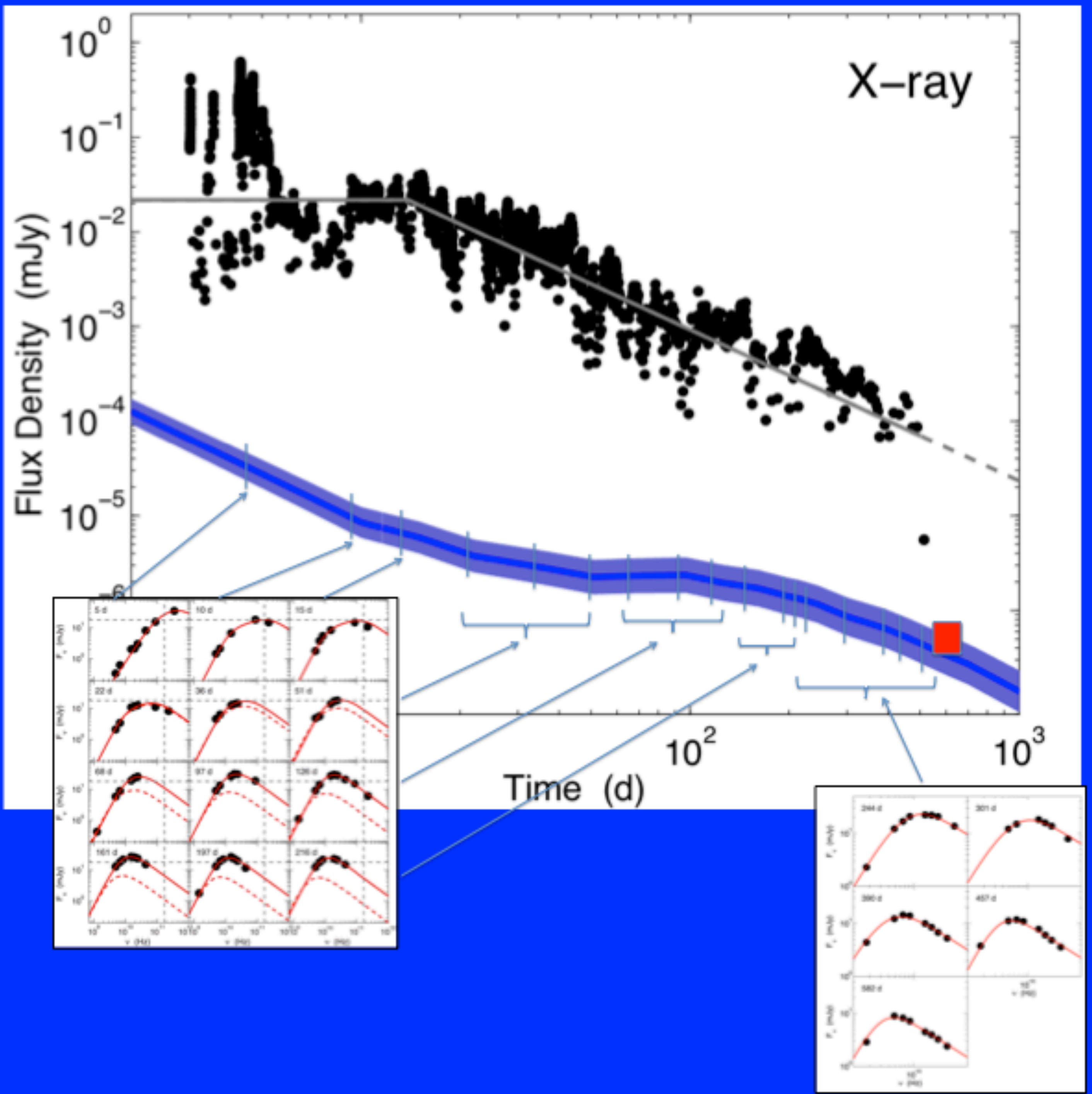
The density profile around a dormant SMBH at z = 0.354 measured with better spatial resolution than for the Milky Way Galactic Center

Jet Shuts off?



Jet Shuts off?



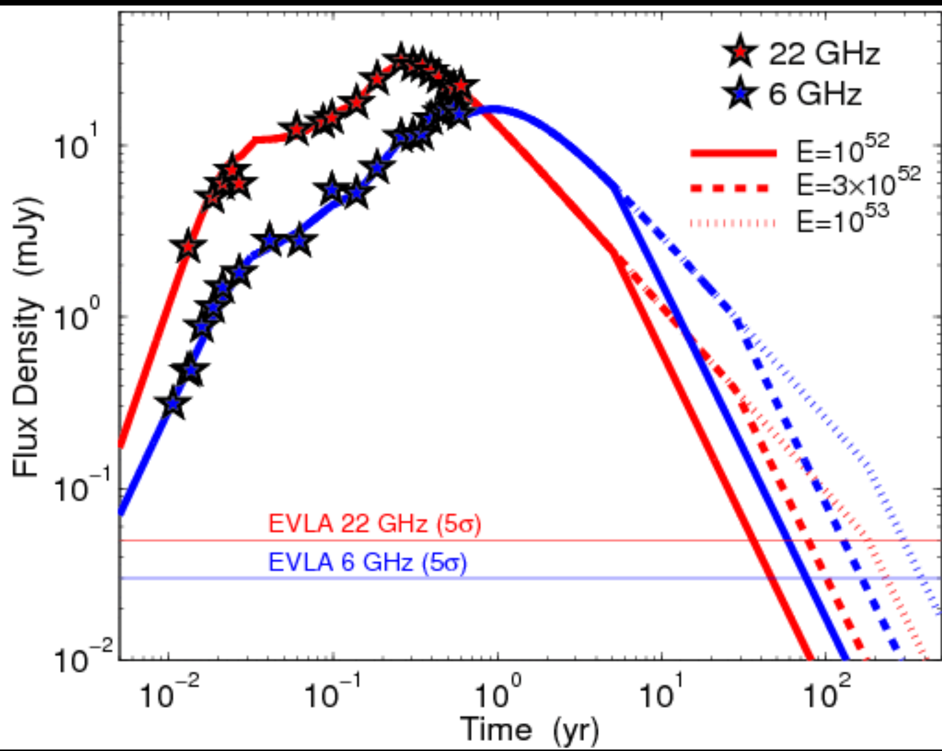


Chandra X-ray detection at dt ~610 days by A. Levan and N. Tanvir (November 2012) Atel 4610

Conclusions
Ongoing & Future Work

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

VLBI

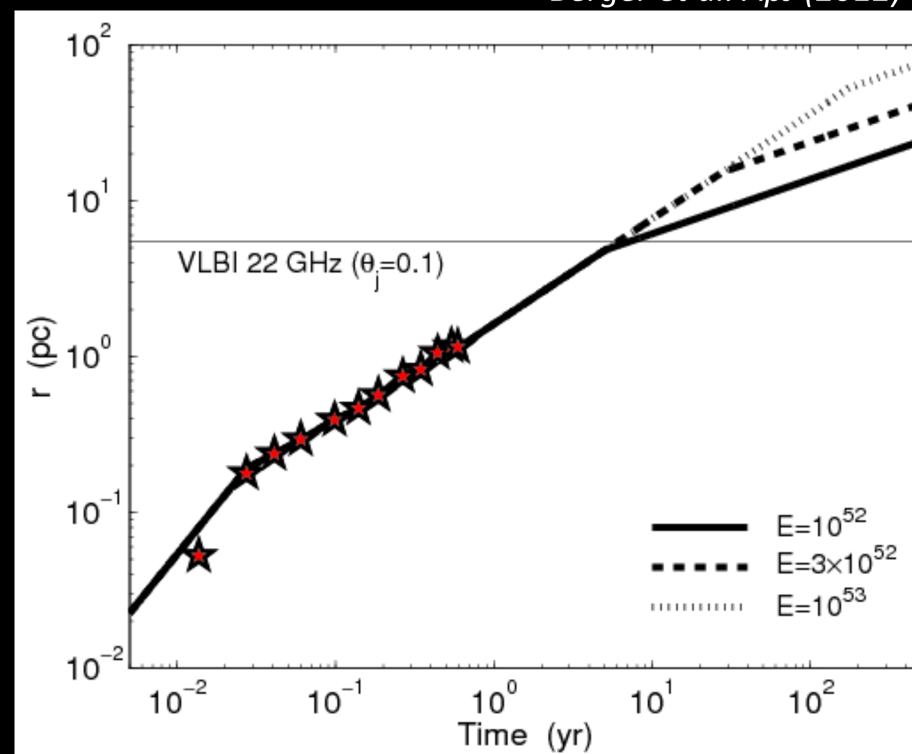


Berger et al. ApJ (2012)

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

Initial prediction:
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)



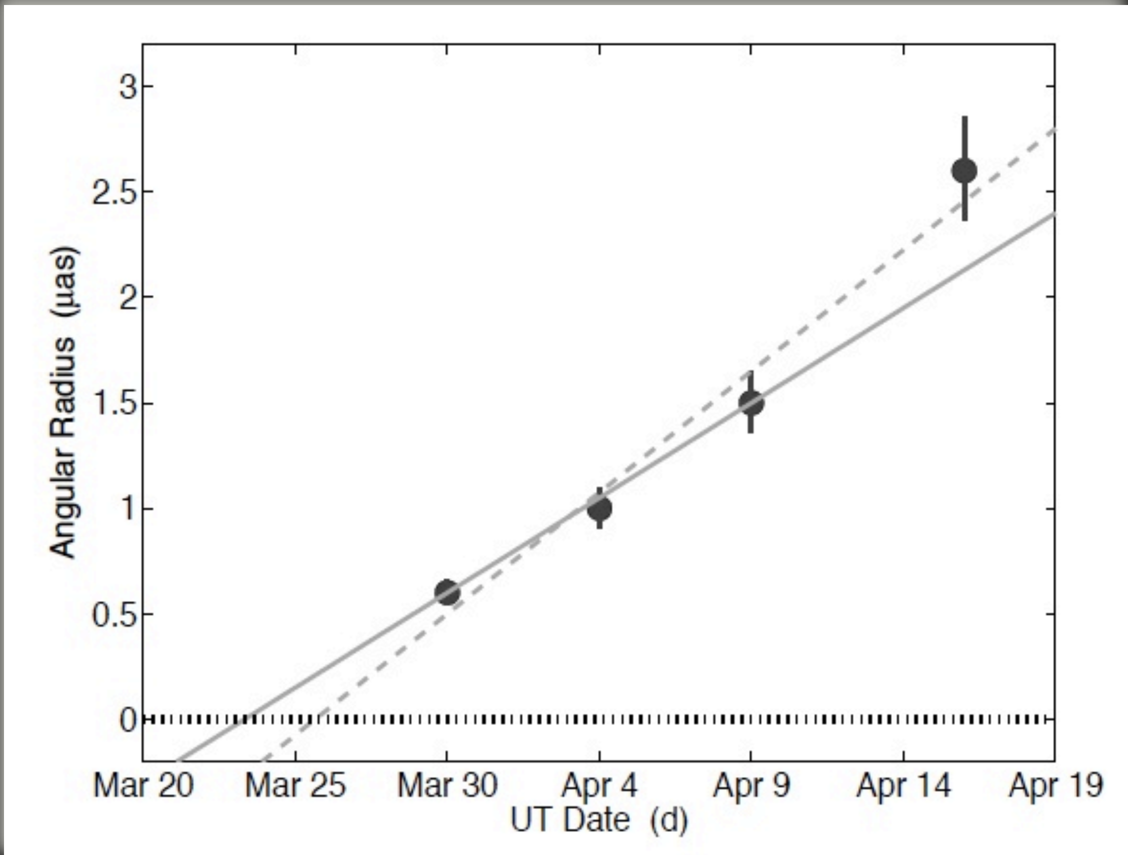
Sw1644+57
J2058.4+0516 (Cenko et al. 2012)
X-ray selected (Bower et al. 2013)

Thank you

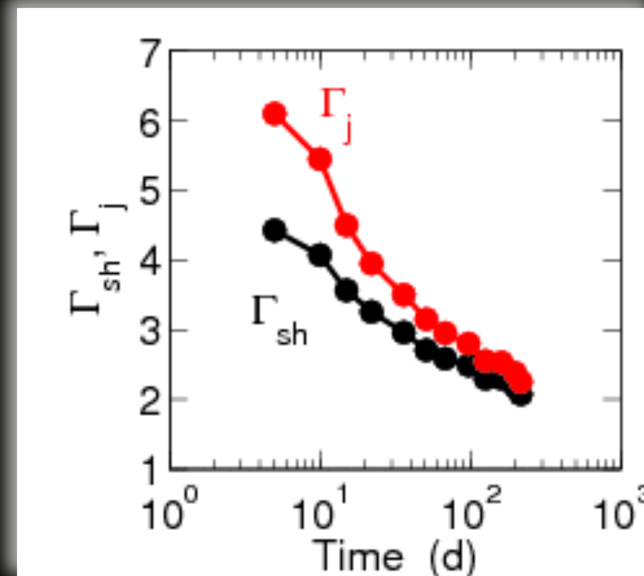
Video credit: NASA/Goddard Space Flight Center/CI Lab

Relativistic Expansion?

1. Modeling



Zauderer et al.



Berger et al. ApJ (2012)

Formation epoch: March 23-26

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

Relativistic Expansion

2. Interstellar scintillation:

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

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

for $\nu > \nu_0$

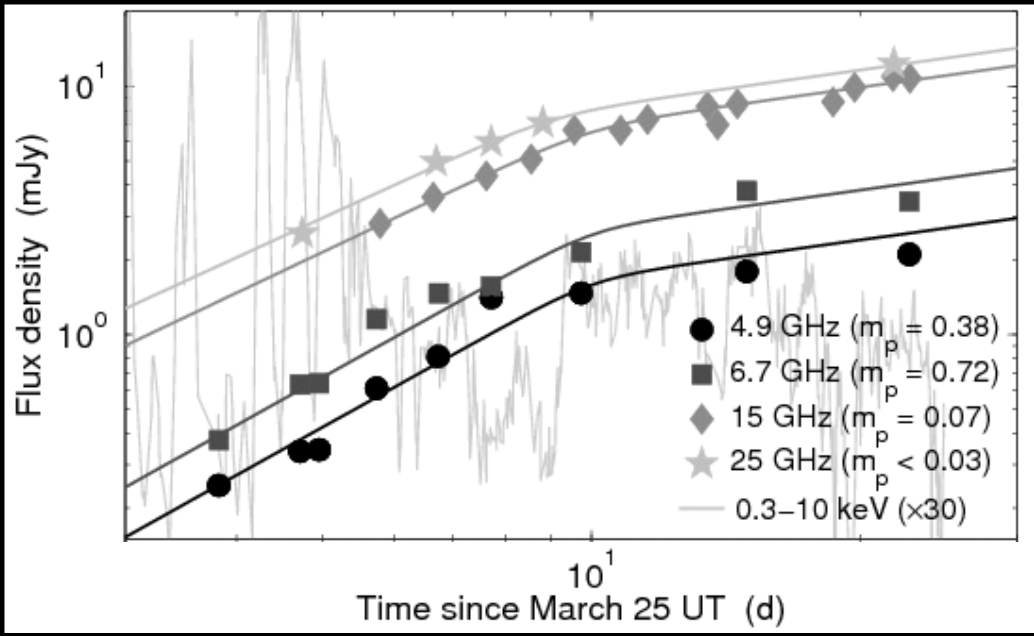
$$m_p \propto (\nu/\nu_0)^{-17/12} (\theta_s/\theta_{F,0})^{-7/6}$$

for $\nu < \nu_0$

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

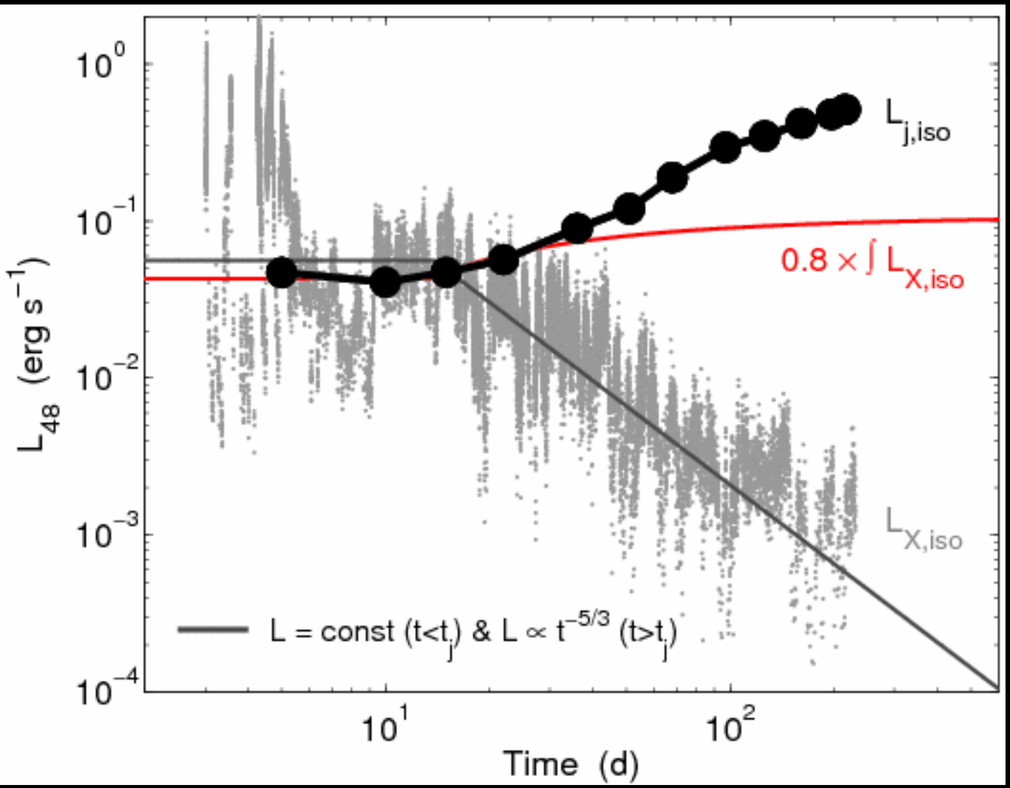
$$\theta_s \approx 5 \ \mu\text{as}$$

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



Zauderer et al.

Jet Energetics



Berger et al. ApJ (2012)

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

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

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

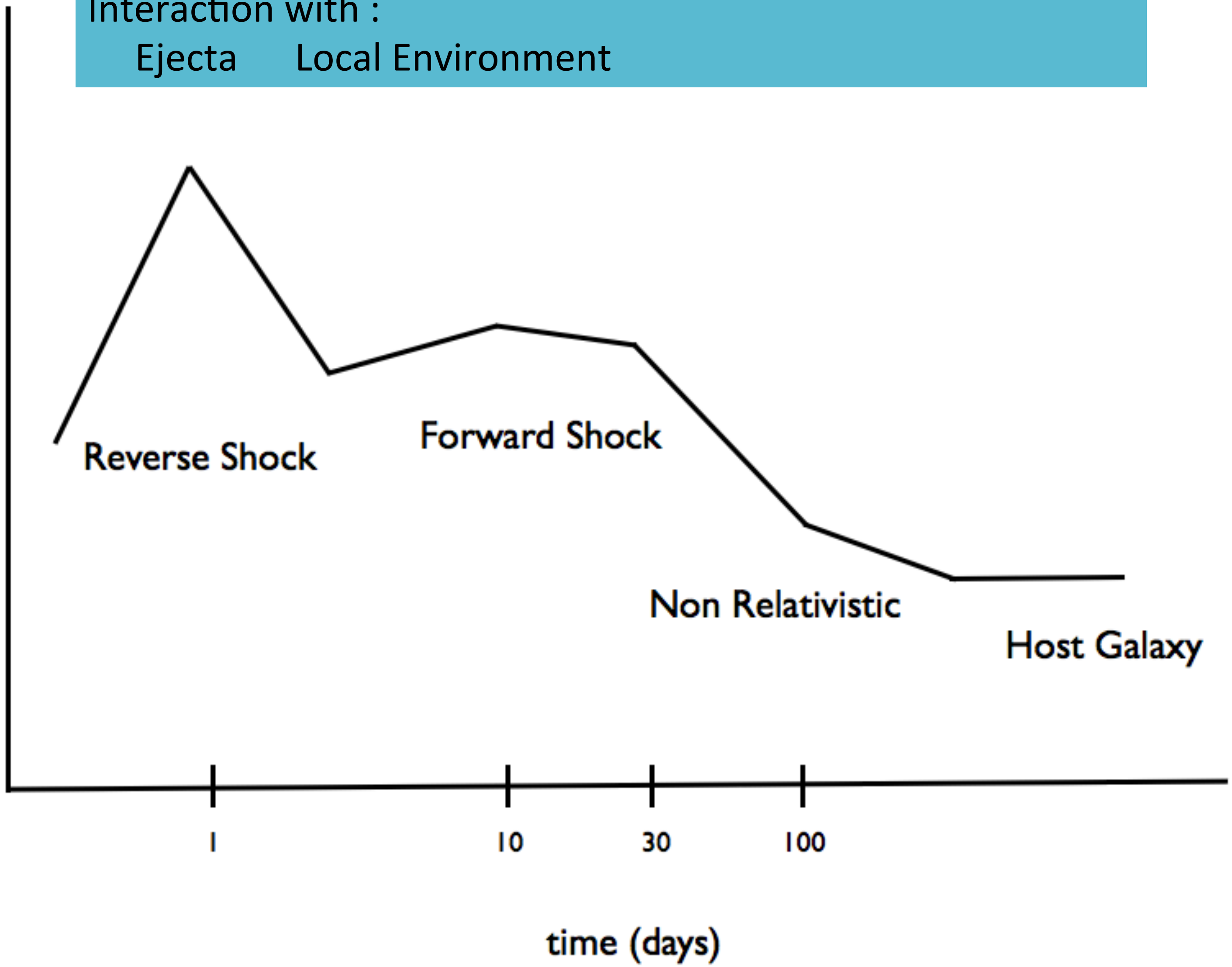
(as seen in X-rays w/ $L \propto t^{-5/3}$).

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

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

Interaction with :

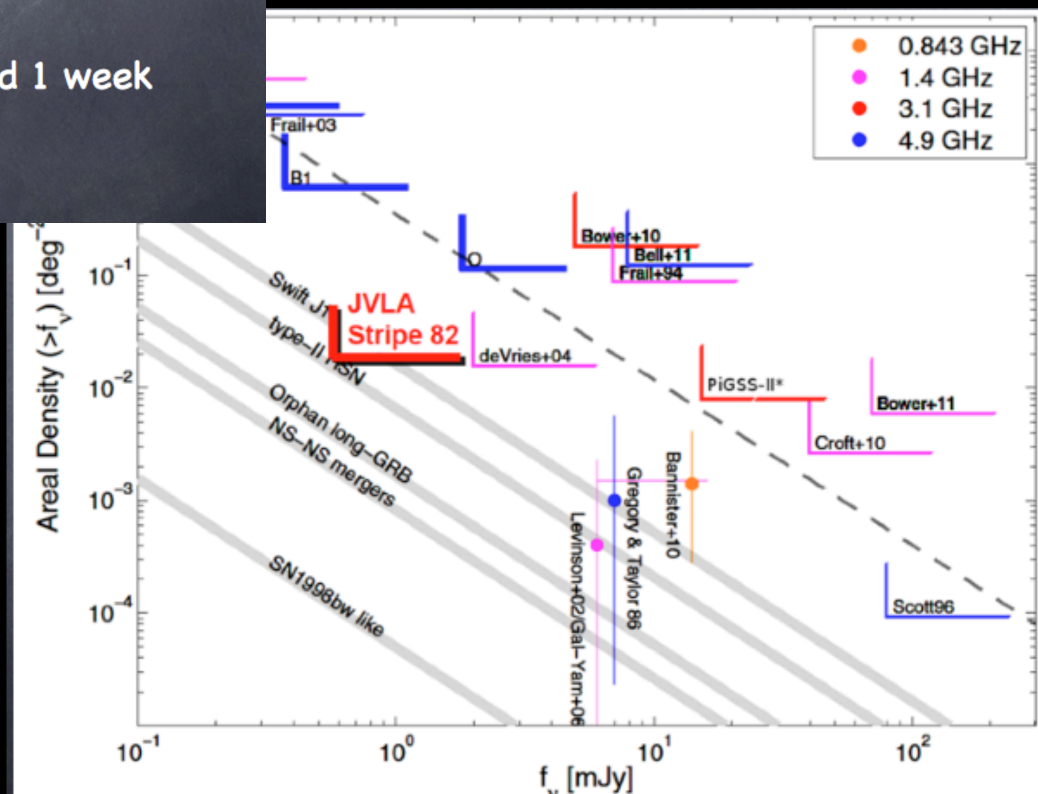
Ejecta Local Environment



The VLA Stripe 82 Survey

EVLA time-domain survey (PI Shri Kulkarni)

- Area - 50 square degrees
- Frequency - 3GHz
- Sensitivity - 75 micro Jy
- Cadence - 3 epochs separated 1 month and 1 week
- PTF optical monitoring



Frail et al. 2012

Slides from Assaf Horesh presentation
“Radio Astronomy in the LSST era”

TDE Background

Year	Work	Summary	Prediction
1976 1988	Frank & Rees Rees	Tidal disruption of stars by black holes of 10^6–10^8 solar masses in nearby galaxies	-stars in galactic nuclei can be captured or tidally disrupted -some debris ejected at high speeds, some captured -UV or soft X-ray radiation from the innermost region of the accretion disk
2000	Ayal, Livio and Piran	Tidal disruption of a main sequence star by a SMBH	2 consecutive Sne-like events
2004	Bogdanovic et al.	-Simulations of 2 TDEs using relativistic smoothed particle hydrodynamic code -calculated the physical conditions and radiative processes in the debris	Time variable H-alpha emission -don’t see double-peak expected from rotating disk as debris doe not settle into a stable disk at early times -line profiles depend sensitively on the orientation of the tail relative to the line of sight, vary on short time scales
2009	Strubbe & Quataert		A radiatively driven wind, existing as a consequence of the super-Eddington fallback, may dominate emission of TDE at early time
2010	Giannios & Metzger	Radio emission *posited*; peak at ~1 year	Radio emission peaks at t~1 year

Year	Work	Summary	Observations
2006, 2008, 2009	Gezari et al.	**UV/Optical Detections of Candidate Tidal Disruption Events by *GALEX and CFHTLS***	2 luminous UV/optical flares from nuclei of apparently inactive early-type galaxies at z=.37 and 0.33 that have radiative properties of a flare from the tidal disruption of a star
1996 1999, 2003	Komossa & Bade Komossa et al.	Chandra and XMM Newton observations of X-ray flares	
2011	Sjoert van Velzen et al.	Optical Discovery of Probable Stellar Tidal Disruption Flares	Analysis of archive SDSS data

Fallback to the Black Hole: Simple picture

- Energy distribution + Kepler's Laws give mass fallback rate

$$\dot{M}_{\rm fallback} = \frac{dm}{dt} \sim \boxed{\frac{dm}{d\epsilon}} \frac{d\epsilon}{dt} \propto \frac{d\epsilon}{dt}$$

assume const
(square const-density star)

Keplerian potential: $\epsilon \sim \frac{GM_{\rm BH}}{a}$ $\quad P \propto a^{3/2}$ $\quad a \propto P^{2/3}$

$$\epsilon \propto P^{-2/3}$$

$$\frac{d\epsilon}{dt} \propto P^{-5/3}$$

$$\Rightarrow \dot{M}_{\rm fallback} \propto t^{-5/3}$$

Slide Courtesy L. Strubbe