Time-domain astrophysics of galactic nuclei in radio to submillimeter

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Continuum HAlos in Nearby Galaxies – an EVLA (JVLA) Survey (CHANG-ES)

Selection of 35 edge-on galaxies with

inclination > 75°

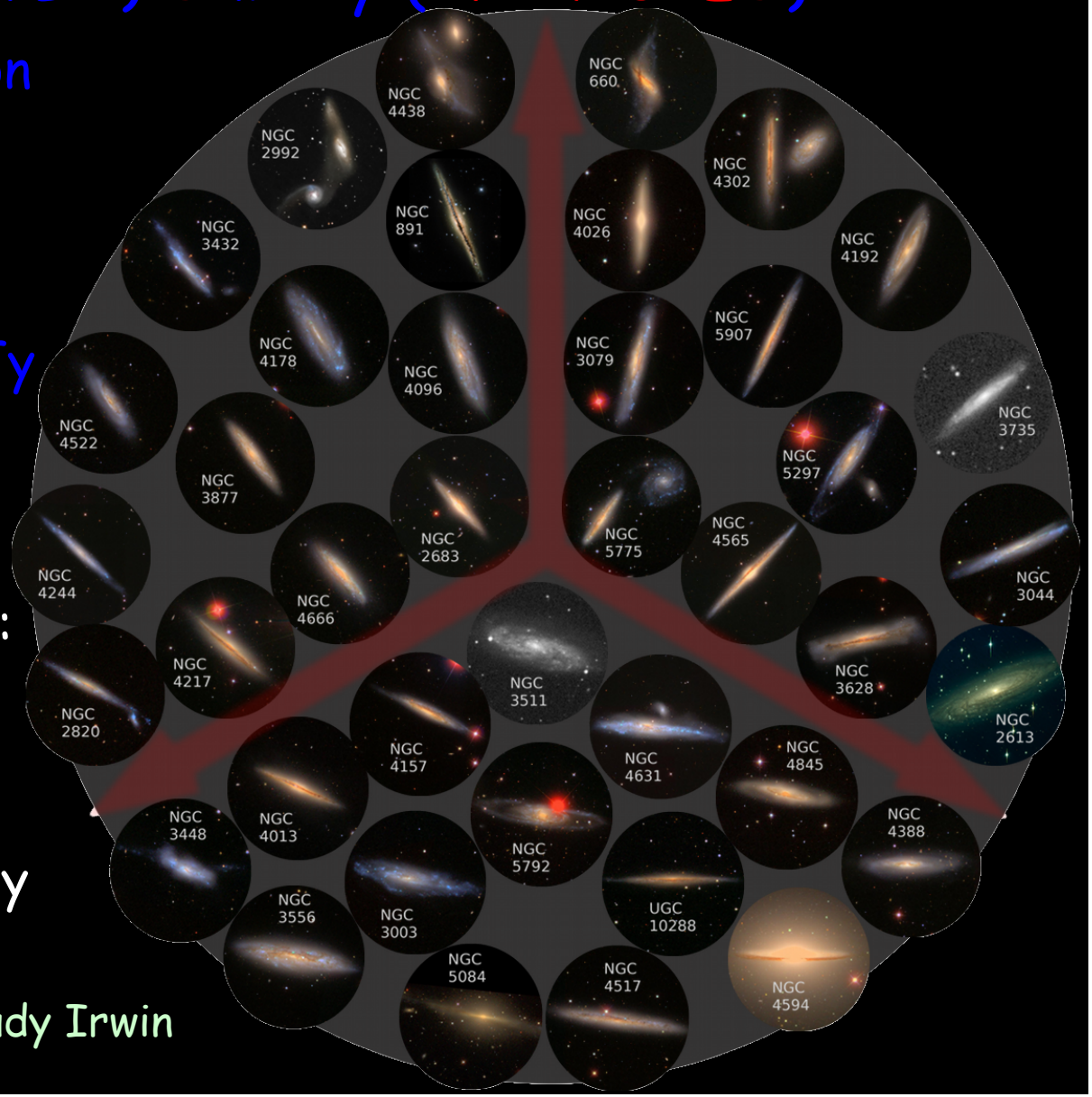
δ > -25°

1.4 GHz fluxes > 20 mJy

$4' \leq D_{25} \leq 15'$,

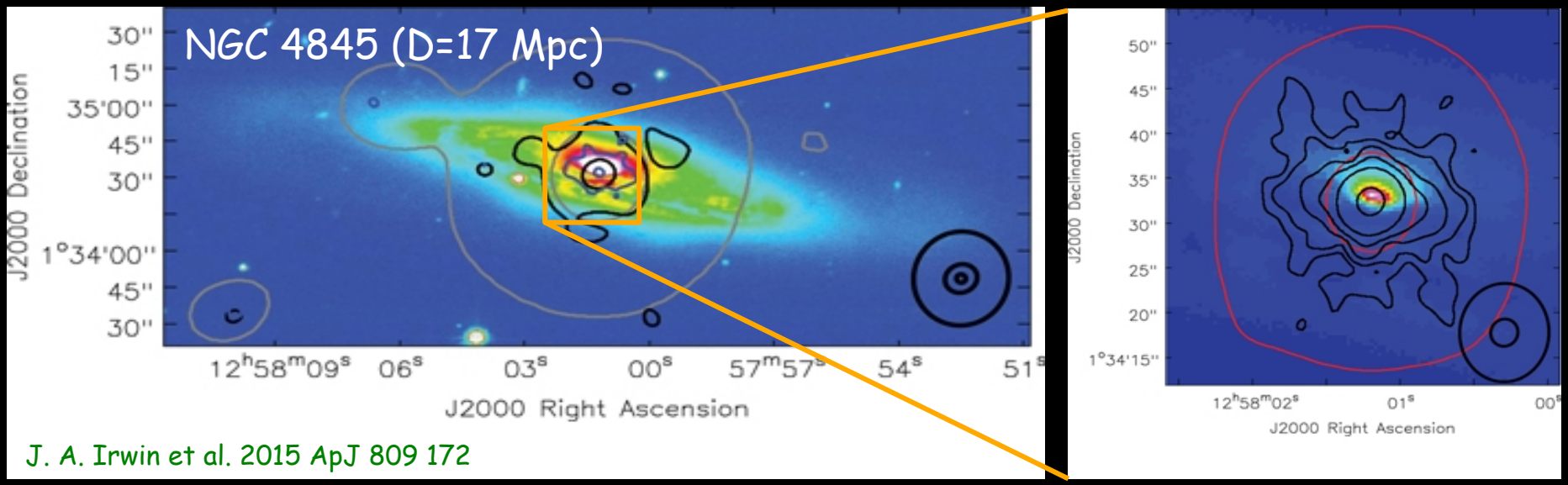
Observations (400+ hrs) were taken in 2011-2013:

- C & D arrays for both L (1.5 GHz) and C (6 GHz) bands
- B array for L band only
- All 4 Stokes.



PI: Judy Irwin

Discovery of a transient radio source at the NGC 4845 nucleus

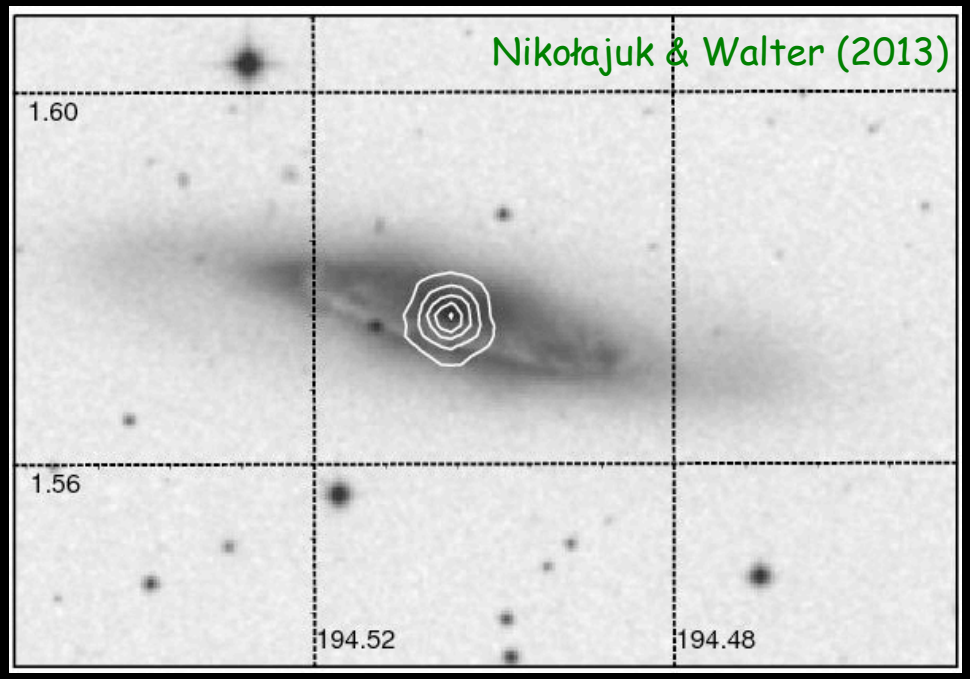


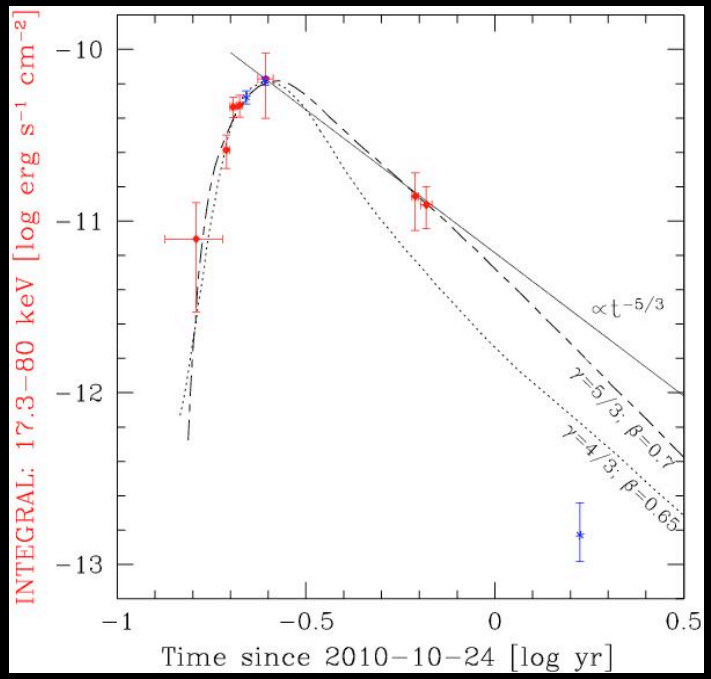
J. A. Irwin et al. 2015 ApJ 809 172

- A factor of ~10 brighter in Dec. 2011 than in ~ 10 years ago
- Inverted radio spectrum at long wavelengths (L and C bands)
- Shifting of the break frequency to longer wavelengths with time.

What could be the nature of this variability?

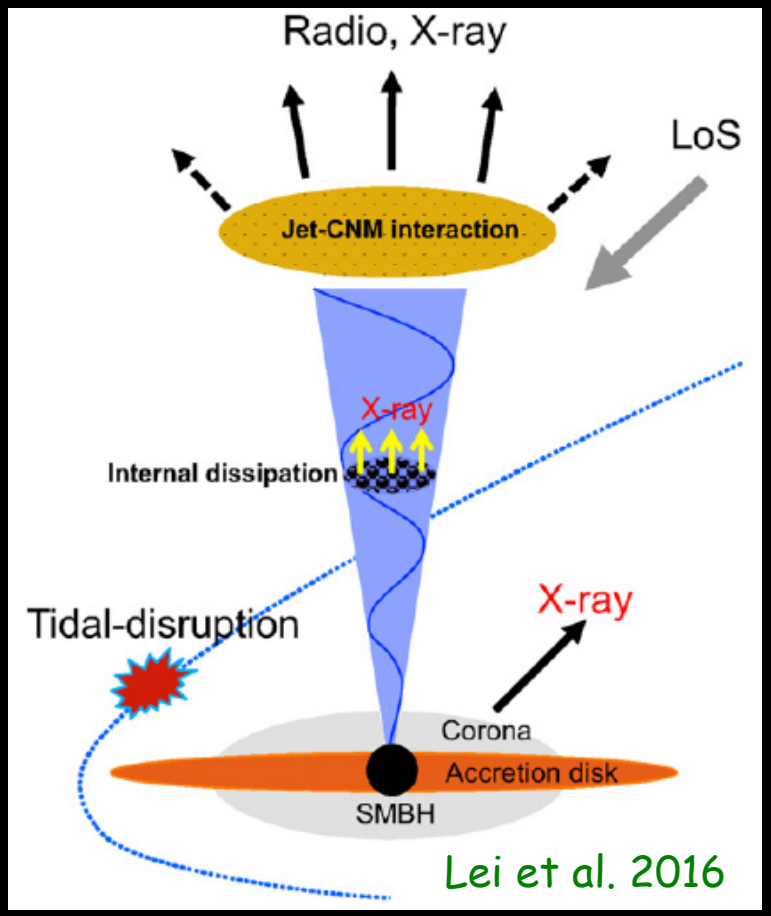
Detections of the X-ray transient IGR J12580+0134 at the NGC 4845 nucleus





- The INTEGRAL detection in 11/2010 (Walter et al. 2011) was followed up by XMM-Newton & Swift (*blue data points*).
- Peak (17.3–80 keV) luminosity: 1.5×10^{42} erg s^{-1}.
- X-ray spectrum: power law with photon index = 2.2.
- Likely resulted from a TDE of a super-Jupiter by the galaxy's central massive black hole (MBH).

Astrophysics of TDEs



- When a star or planet is disrupted, ~ half of its mass is expected to be accreted onto the MBH, producing prompt emission in X-ray, ultraviolet, and optical.
- The luminosity typically follows $t^{-5/3}$ (Phinney 1989).
- Jets, if formed, will interact with the circumnuclear medium (CNM) and will accelerate particles, producing the afterglow in radio-(sub)mm.

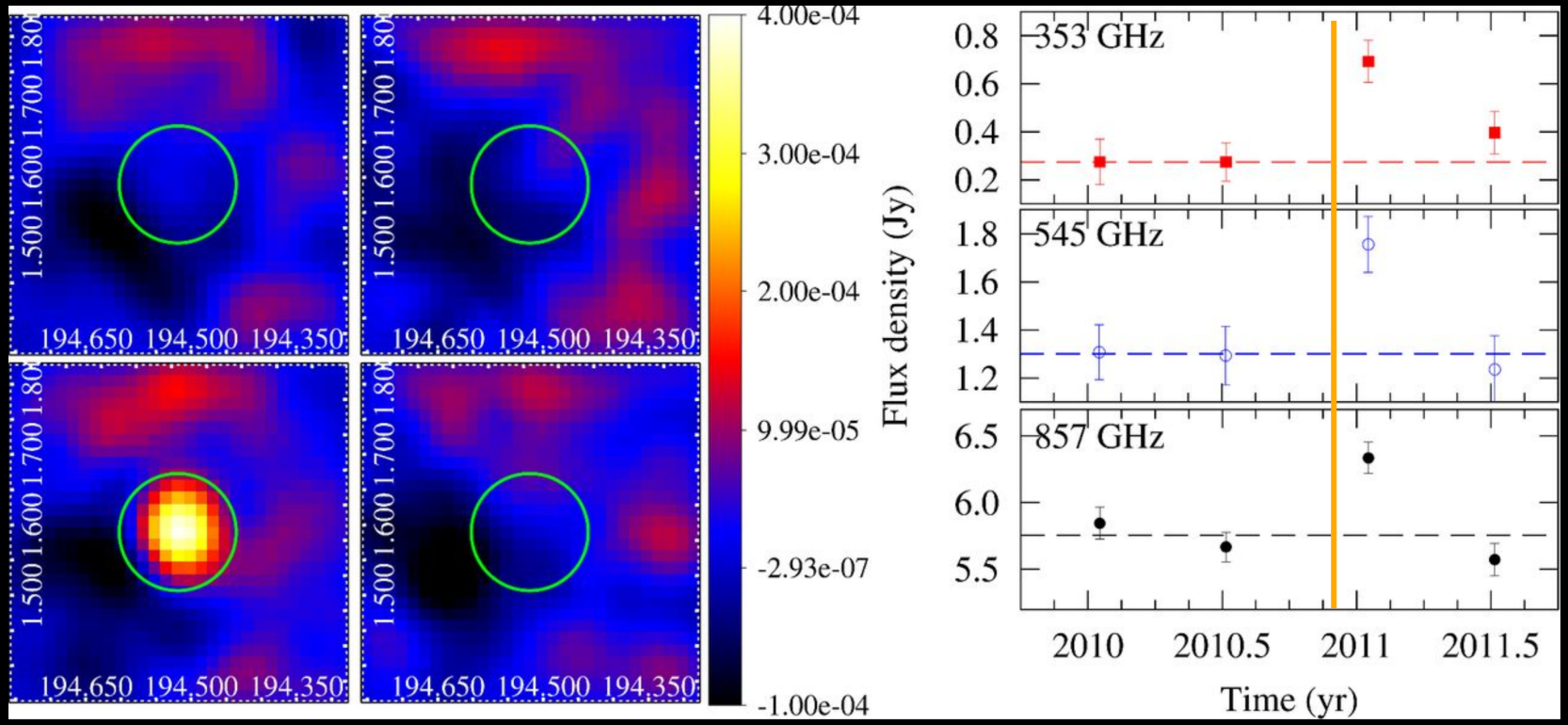
TDEs allow us to probe the stellar population around MBHs, as well as their mass function, while the afterglows are sensitive to the CNM properties and the acceleration process.

IGR J12580 as a TDE with jets observed at an off-axis angle

- The light-curve, low X-ray luminosity, soft spectrum, and the radio emission suggests that IGR J12580 is a TDE with jets.
- But unlike any other previous known TDEs with relativistic jets (e.g., Sw J1644+57, $z = 0.35$; SwJ2058+05, $z = 1.2$), all seen on-axis, IGR J12580 was observed off-axis.
- It was discovered only because it is so nearby, which also makes it particularly interesting.

Planck (sub)mm detection of IGR J12580 in NGC 4845

- Flux jump after the event, followed by substantial decline, in all six high-frequency bands (100 - 857 GHz).
- This is the second TDE with (sub)mm detections; the other is Sw J1644+57, an on-axis jetted TDE at z=0.35.



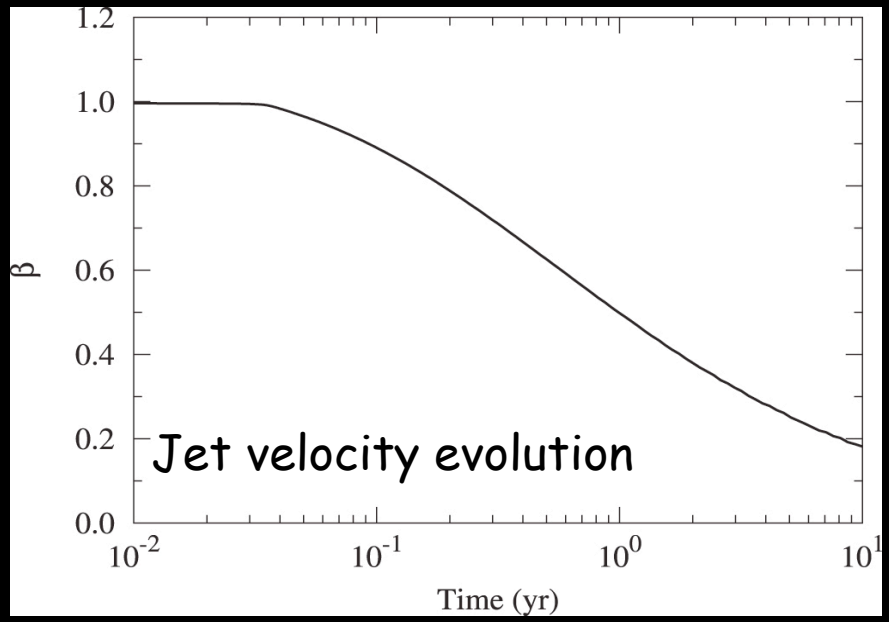
217 GHz band

Yuan, QDW, et al. 2016

Follow-up radio-(sub)mm observations

- One JVLA A-array (6/2015)
- Three JVLA A-array (7/2015),
- Two epoch VLBA (2015, 2016)
- One ALMA (2017).

TDE-jet modeling for IGR J12580



Assuming instantaneous injection of energy into the jets, we solve the dynamics of the forward shock numerically and calculate the synchrotron emission from the accelerated electrons.

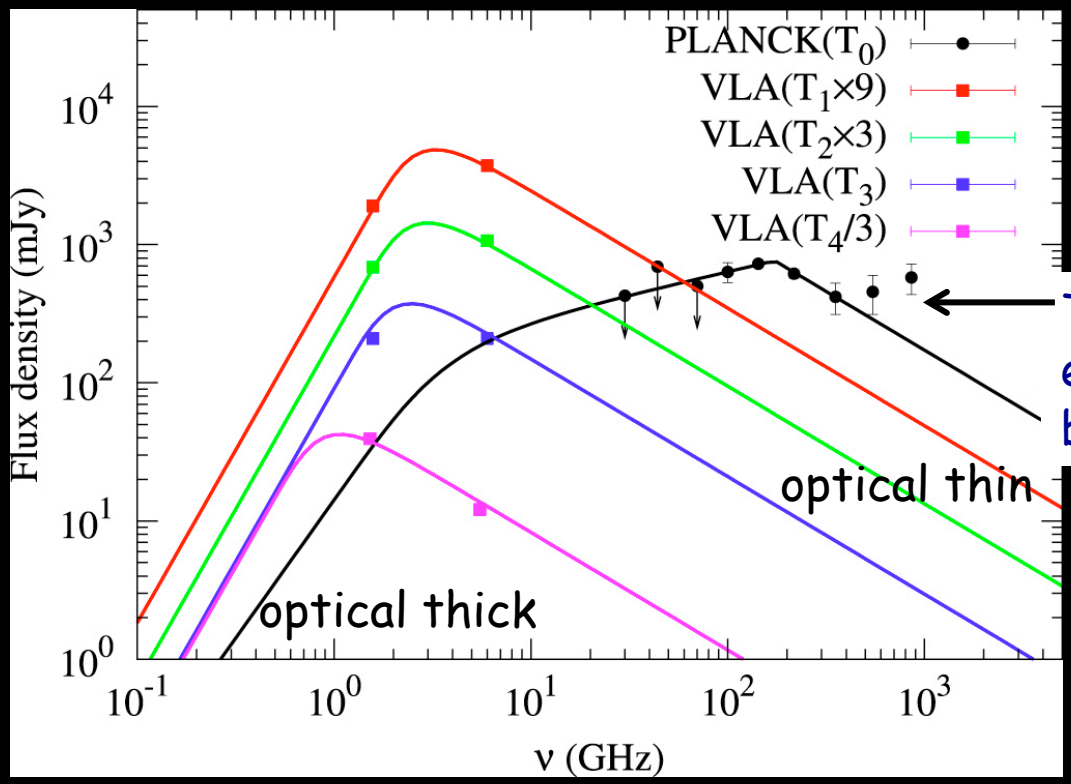
Model Parameters

Jet Launching Time Δt (day)	CNM Density n (cm^{-3})	Viewing Angle θ_{obs} (degree)	Jet KE E_{50}[a]	Initial Γ_j	Initial θ_j (degree)	p[b]	ϵ_e[c]	ϵ_B[c]
18[d]	1.2	35	530	11.2	3.7	2.70	0.21	0.05

Notes.
[a] In 10^{50} erg s^{-1}.
[b] Spectral index of accelerated electrons.
[c] Fraction of the ejecta kinetic energy assigned to accelerated electrons or the magnetic field.
[d] Relative to 2010 December 12.

Lei et al. 2016 Perlman et al. 2017

TDE-jet modeling for IGR J12580



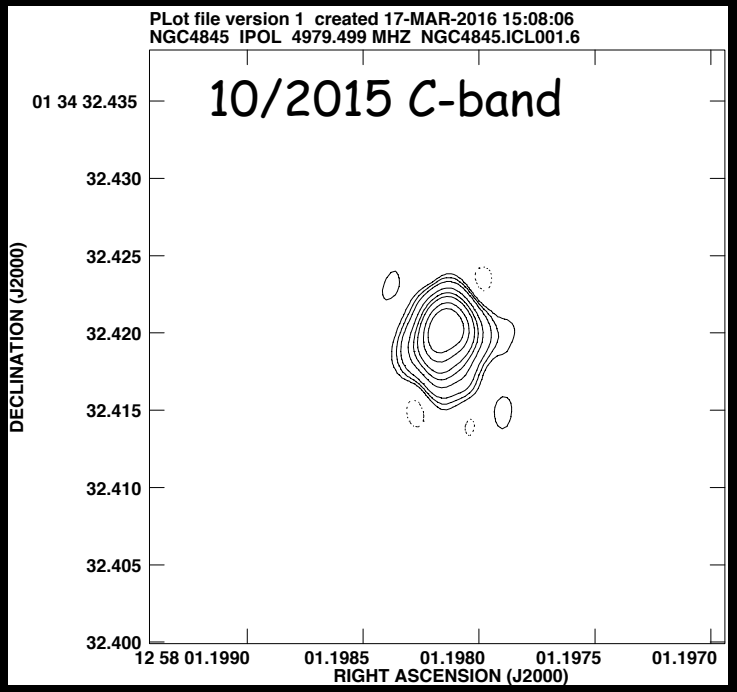
T_0 - 12/2010
T_1 - 12/2011
T_1 - 3/2012
T_3 - 6/2012
T_4 - 6/2015

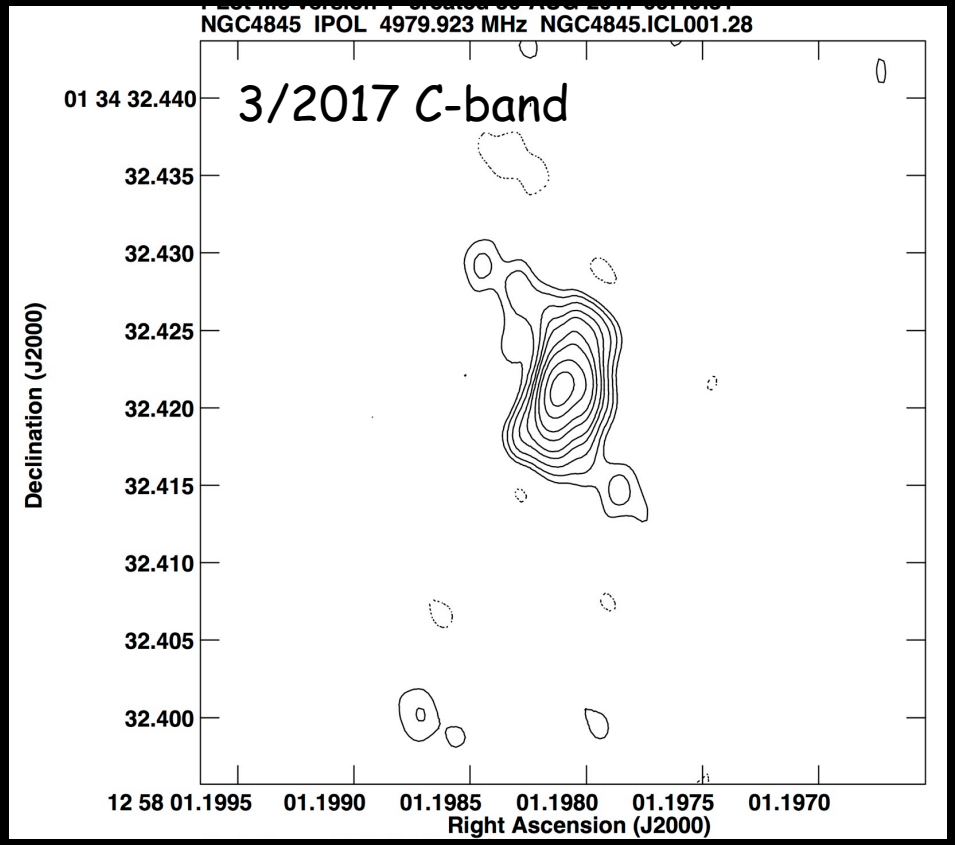
Thermal dust emission heated by the TDE?

Only the radio-(sub)mm data obtained before July, 2015 are used in this model fitting. Later observations, not yet included in the existing modeling, seem to be broadly consistent with the model predictions.

VLBA observations

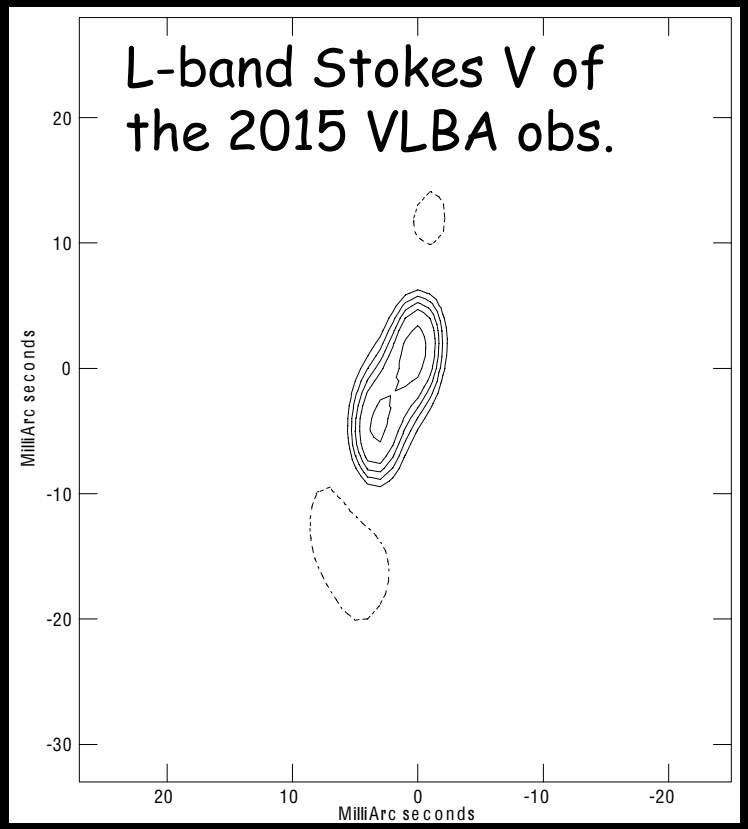
Size change is clearly detected in the C-band, consistent with the model prediction (of avg. v~0.3 c), although the radio beam effect is yet to be accounted for.





Two are shown on the same scale.

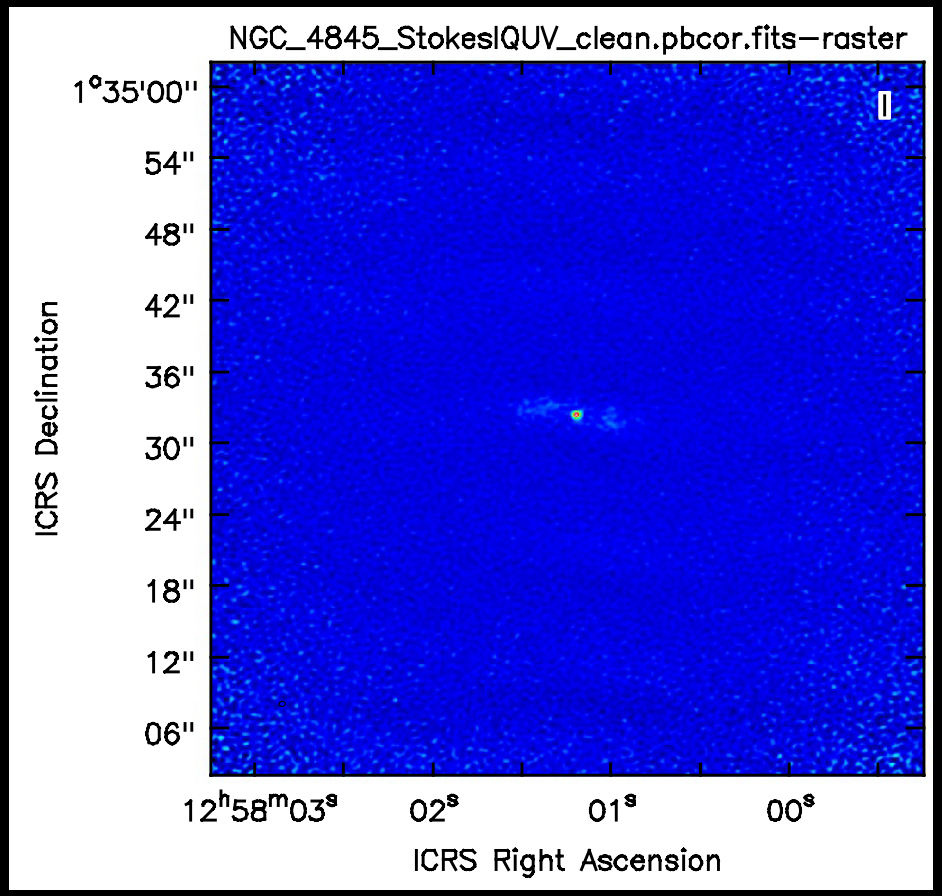
Detection of the circular polarization



Previously, (unresolved) CP was detected only for Sgr A* and M81*.

- No linear polarization (LP) is observed, likely due to strong Faraday depolarization.
- Instead, we detected the circular polarization (CP) in 2011 at ~2% , half of that in 2015, all in the L-band.
- The CP is likely converted from the LP via generalized Faraday rotation (Irwin et al. 2015).
- The decreasing Faraday depth with time may then explain the decreasing degree of the CP.

ALMA observation at 100 GHz



- Show a point-like source, as well as an extended emission (from the galactic disk).
- The source flux is 0.39 mJy in 11/2016, a factor of ~3 below the prediction: synchrotron cooling?
- By 2017, the source became too faint to measure the polarization.

One could do it better!

Need a (sub)mm TOO program for TDEs!

The Large Millimeter Telescope, jointly constructed by Mexico and UMass is now a 50m diameter millimeter-wave telescope at the summit of Volcano Sierra Negra at an elevation of 4600m.

Timely (sub)mm observations will help to determine the early phase of the jet evolution and to initiate observations at longer wavelengths: e.g.,

- Using a single dish (such as the Large Millimeter Telescope with the TolTEC 3-band bolometer array) to determine the flux and spectral shape;
- (sub)mm and/or radio interferometer follow-ups.

(Sub)mm detectability of TDEs

- With a 1 hr exposure, the 50m LMT/TolTEC can detect jetted TDEs up to redshifts $z \sim 1.5$, for a typical disrupted star mass of ~1 M.
- The detection rate can be as high as ~a few yr^{-1} for off-axis (IGR J12580-like) TDEs, or a few x 10s yr^{-1} for on-axis ones (Sw J1644+57-like).
- ALMA would be even more sensitive.
- This rate estimate remains greatly uncertain and will only be improved with an increased sample size of jetted TDEs.
- Ultimately, the detectability depends on the triggering capability, which will be greatly improved in the era of eROSITA and LSST.

(Yuan et al. 2016)

What to learn from monitoring TDE radio-(sub)mm emission?

- Jet properties:
  - Energy, opening angle etc.
- CNM properties:
  - Density structure
  - Magnetic field ← Faraday rotation measure
- Particle acceleration time scale, efficiency, etc.
- Learning about these properties will also help us to better understanding the statistics of TDEs and hence the stellar dynamics around MBHs.

Summary

- We serendipitously discovered the radio-(sub)mm emission from the nearest TDE (IGRJ 1258+0134), which is still detectable, seven years after the event.
- The evolution of this TDE SED is consistent with an off-axis relativistic jet/CNM interaction model and with the changing radio structure, seen in our VLBA observations.
- We have further detected the spatially resolved circular polarization of the emission -- first time for any TDEs.
- A dedicated (sub)mm to radio follow-up observing program of TDEs is highly desirable.

Limitation of existing modeling

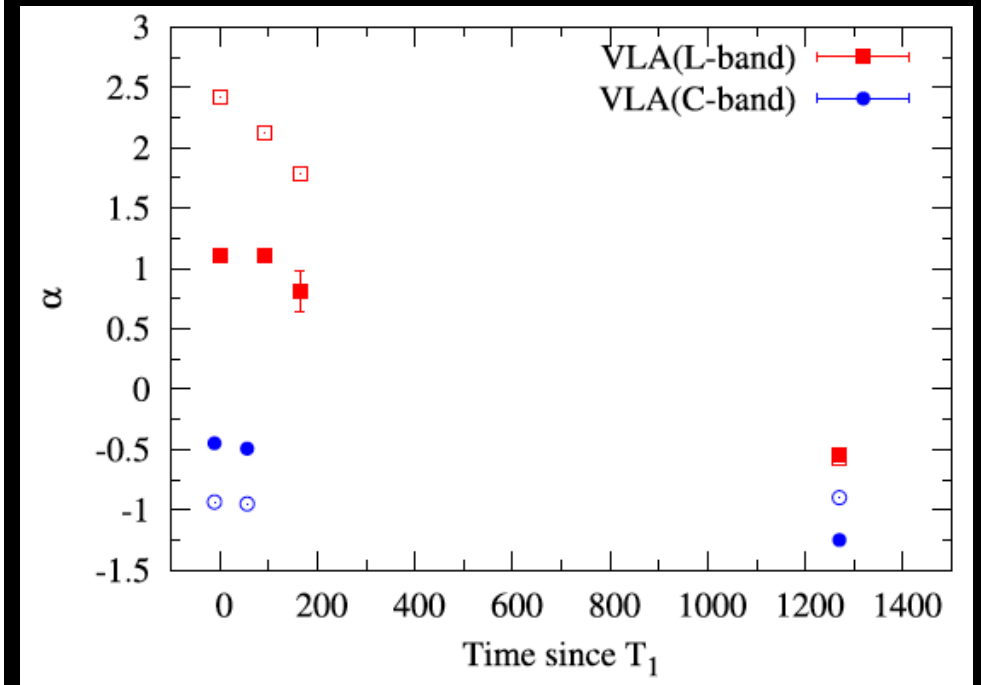


Figure 8. In-band spectral indices of the TDE, from the VLA measurements (filled symbols) at the L-band and C-band, compared with that expected from the jet-CNM model (open symbols).

- Discrepancies between the data and model
- Evidence for ~25% intensity variation at 9 GHz and on ~ one week time scale (VLA/A-array obs.; Yang et al.).
- The toy model does not account for such temporal variation.