Radio observations of tidal disruption events

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ANITA 2024 summer school

ICRAR

Radio TDEs part I: Observational properties of TDEs in the radio & synchrotron emission

Tidal Disruption Events

When a supermassive black hole destroys a star

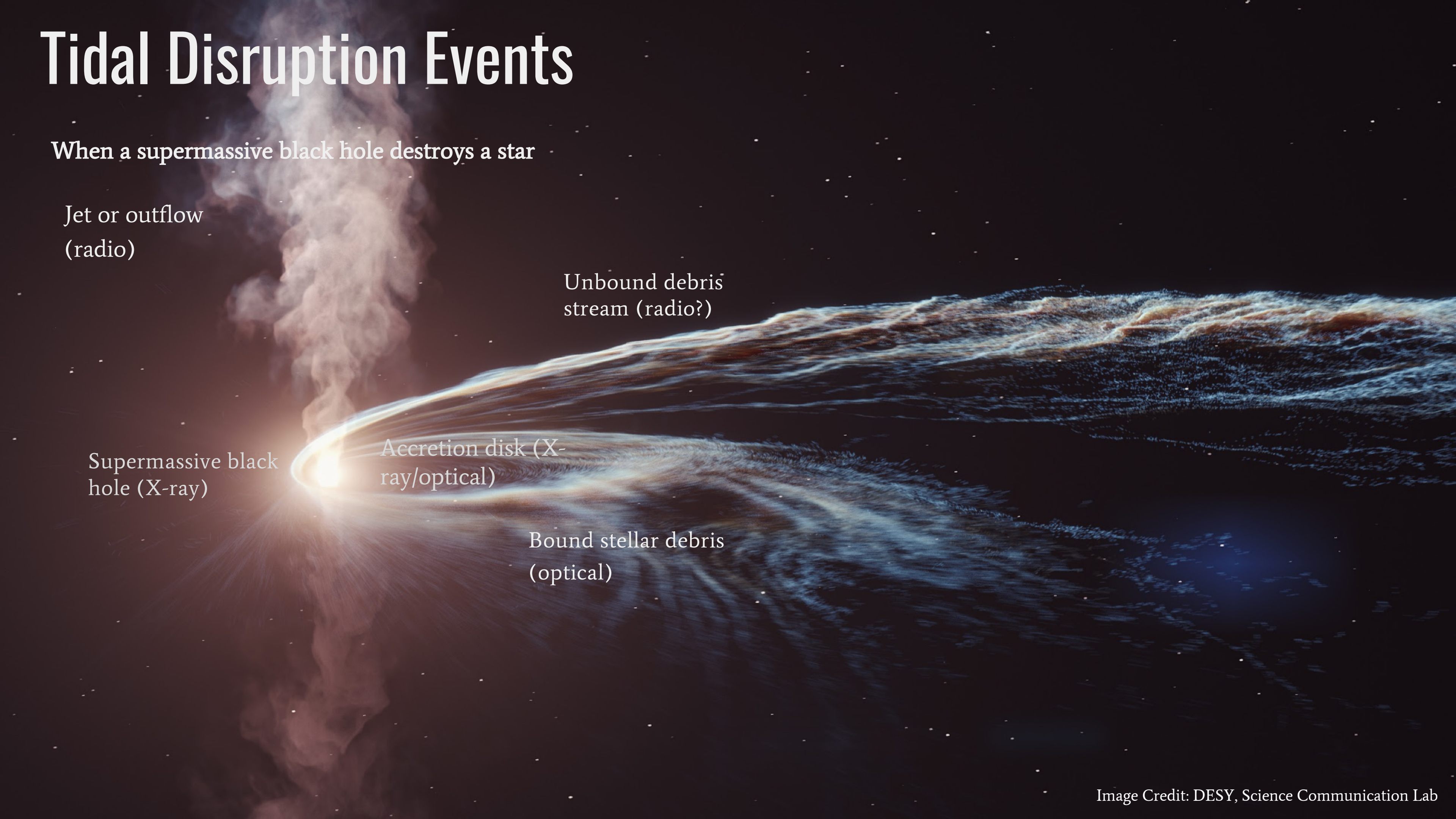

Image Credit: DESY, Science Communication Lab

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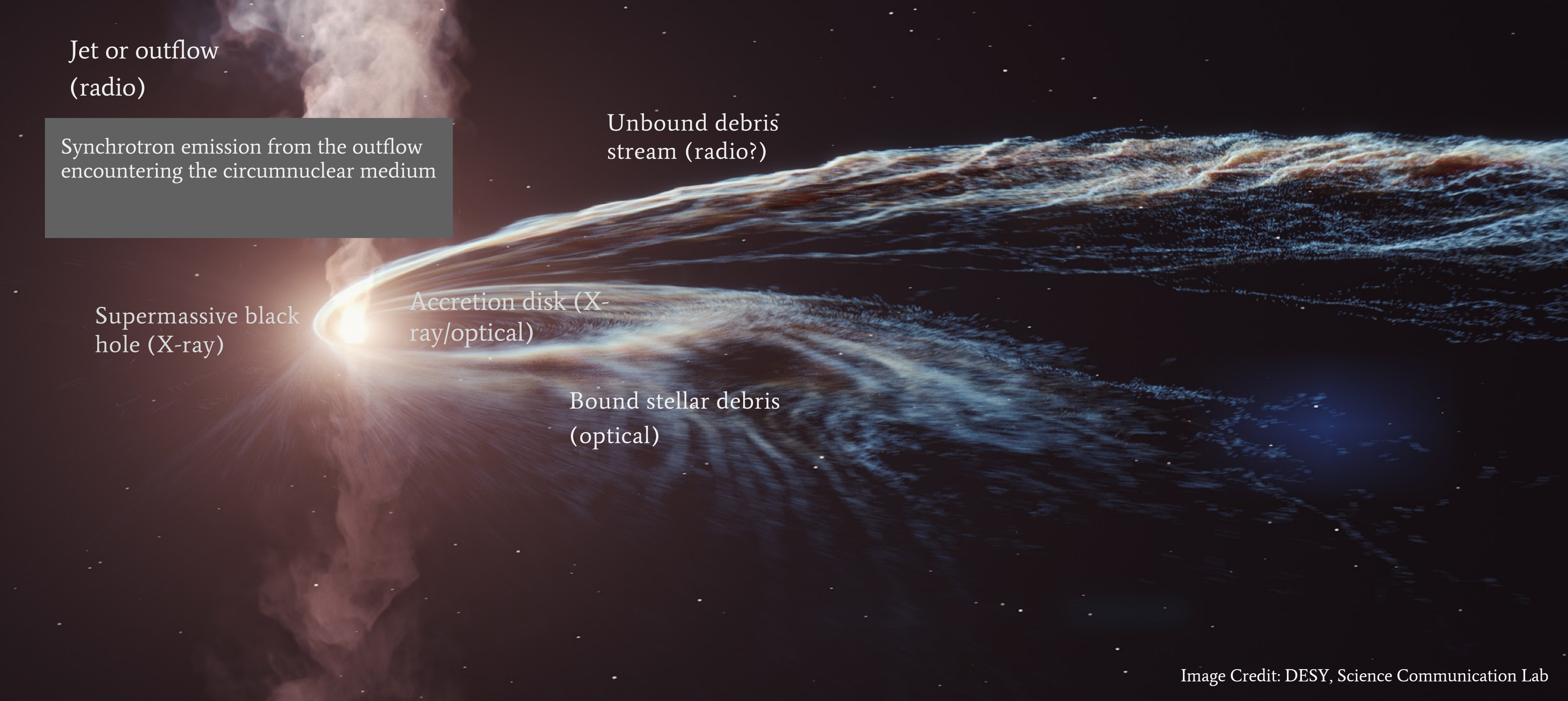
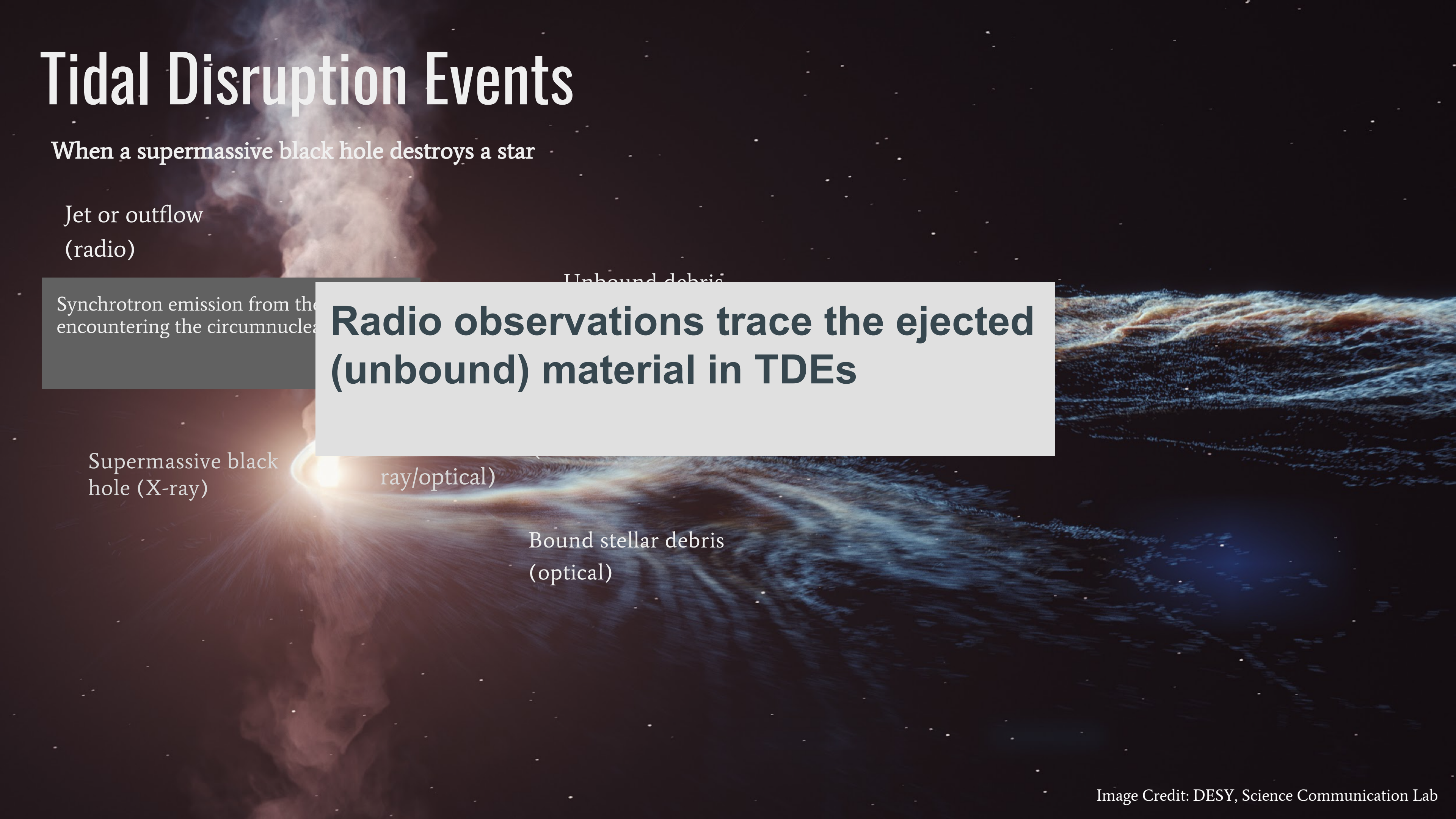


Image Credit: DESY, Science Communication Lab



Tidal Disruption Events
When a supermassive black hole destroys a star
Jet or outflow
(radio)
Synchrotron emission from the
encountering the circumnuclea
Radio observations trace the ejected (unbound) material in TDEs
Supermassive black hole (X-ray)
ray/optical)
Bound stellar debris
(optical)
Image Credit: DESY, Science Communication Lab

Tidal Disruption Events

When a supermassive black hole destroys a star

<u>Radio properties</u>

- ★ Peaked synchrotron spectrum that evolves to lower frequency with time
- ★ Visible for approx 1-2 years (?)
- ★ Two categories:

Tidal Disruption Events

When a supermassive black hole destroys a star

Jet or outflow (radio)

Synchrotron emission from the outflow encountering the circumnuclear medium

Unbound debris stream (radio?)

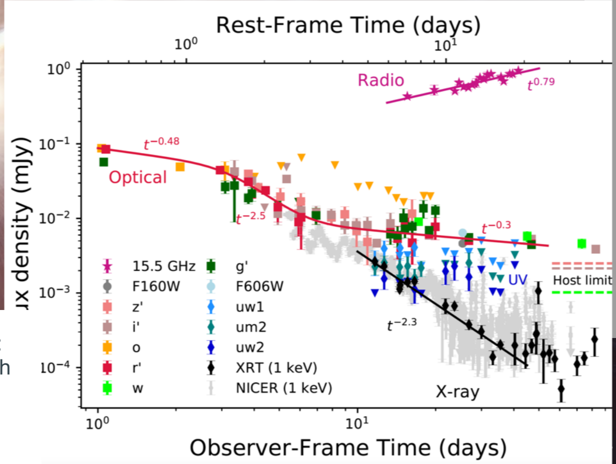
Supermassive black hole (X-ray)

Radio properties

- ★ Peaked synchrotron spectrum that evolves to lower frequency with time
- ★ Visible for approx 1-2 years (?)
- ★ Two categories:

Relativistic

- ★ Jet
- ★ Energetic $E \sim 10^{52}$ erg
- ★ Non-thermal X-ray spectrum
- ★ Very rare



Pasham+2022: Multiwavelength lightcurve of AT2022cmc

Tidal Disruption Events

When a supermassive black hole destroys a star

Jet or outflow
(radio)

Synchrotron emission from the outflow encountering the circumnuclear medium

Unbound debris stream (radio?)

Supermassive black hole (X-ray)

Accretion disk (X-ray/optical)

Bound stellar debr
(optical)

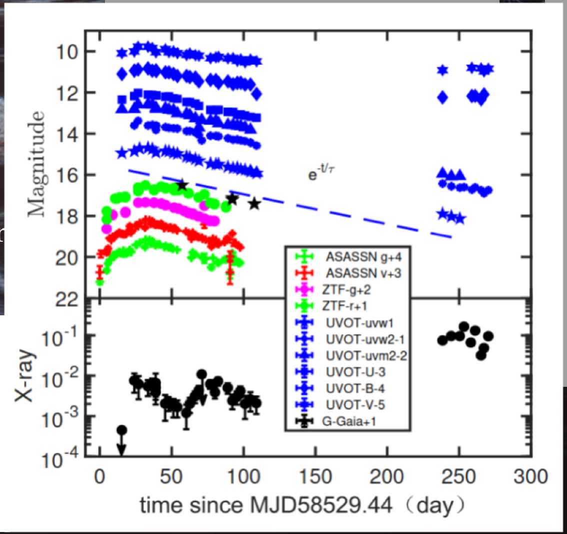
Radio properties

- ★ Peaked synchrotron spectrum that evolves to lower frequency with time
- ★ Visible for approx 1-2 years (?)
- ★ Two categories:

Relativistic

Non-relativistic

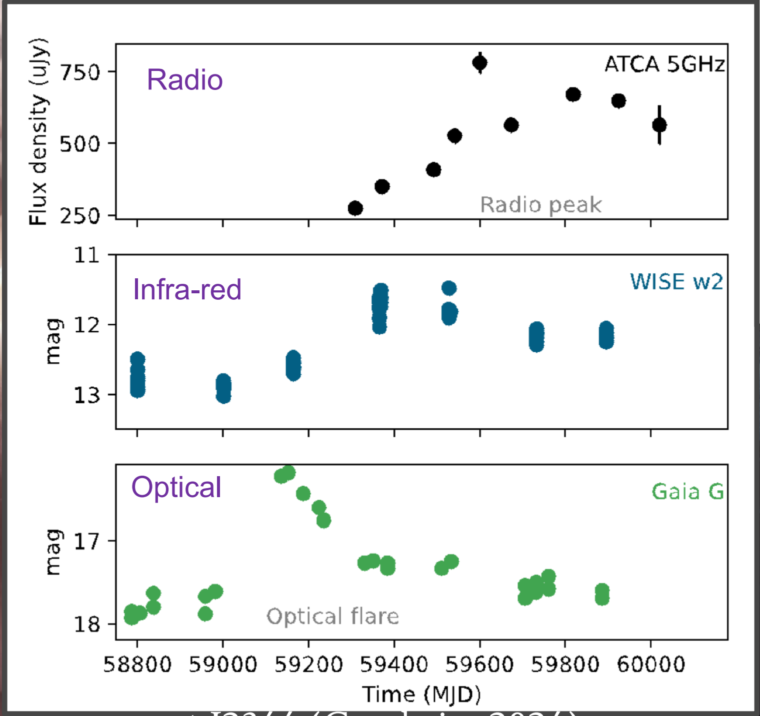
- ★ Jet? Spherical? Conical?
- ★ Less energetic $E \sim 10^{49}$ erg
- ★ Thermal X-ray spectrum
- ★ More common



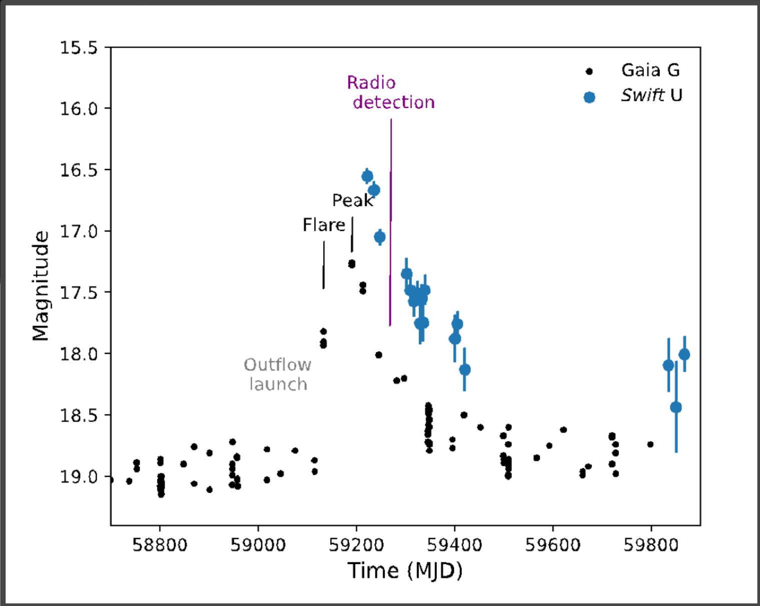
Liu+ 2019: Optical, UV (top) and X-ray (bottom) lightcurve of AT2019azh. X-ray and UV data are from *Swift*.

Multiwavelength properties of TDEs

- ❖ Optical flare lasting 50-100d
- ❖ Bright UV flare
- ❖ Infra-red dust echos
- ❖ X-ray emission
- ❖ Radio flare lasting years



erasst J2344 (Goodwin+2024)



AT2020vwl (Goodwin+2023)

Multiwavelength properties of TDEs

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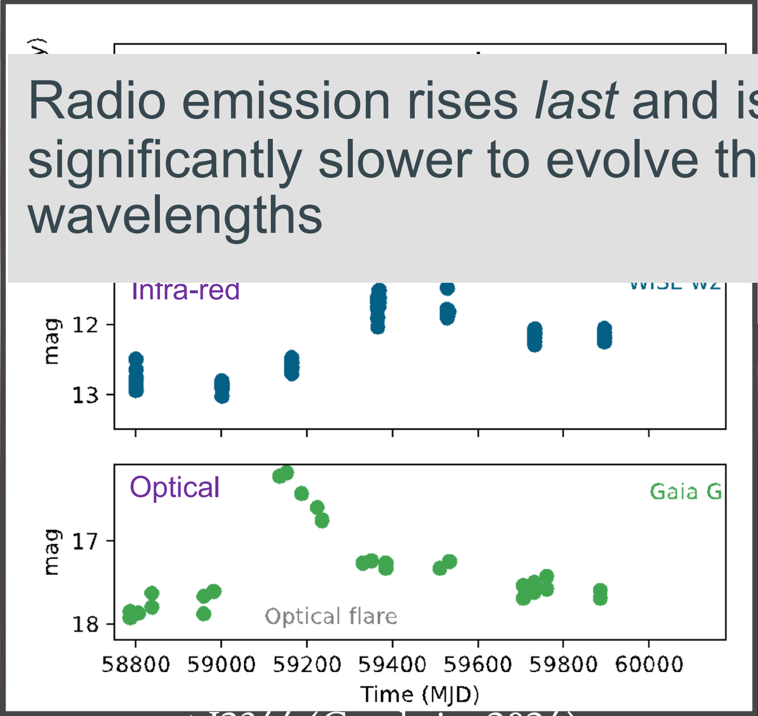
- ❖ Radio flare lasting years

Radio emission rises *last* and is significantly slower to evolve than other wavelengths



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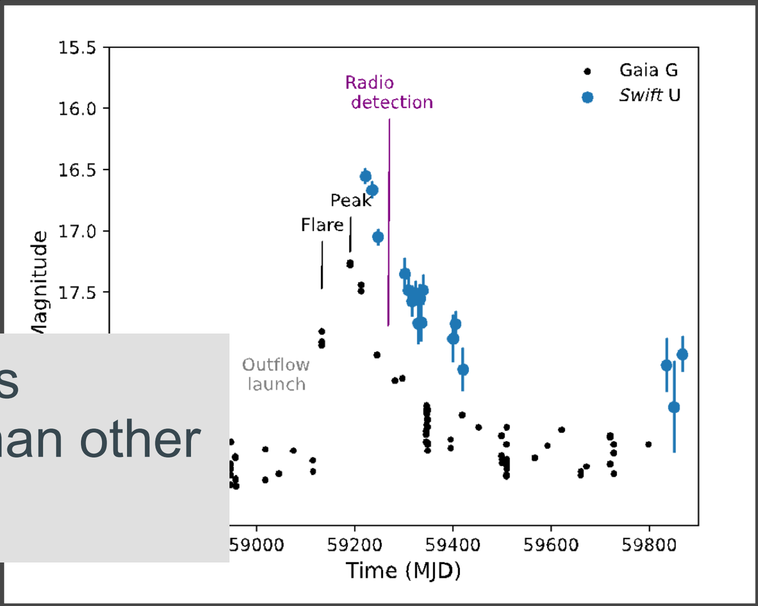
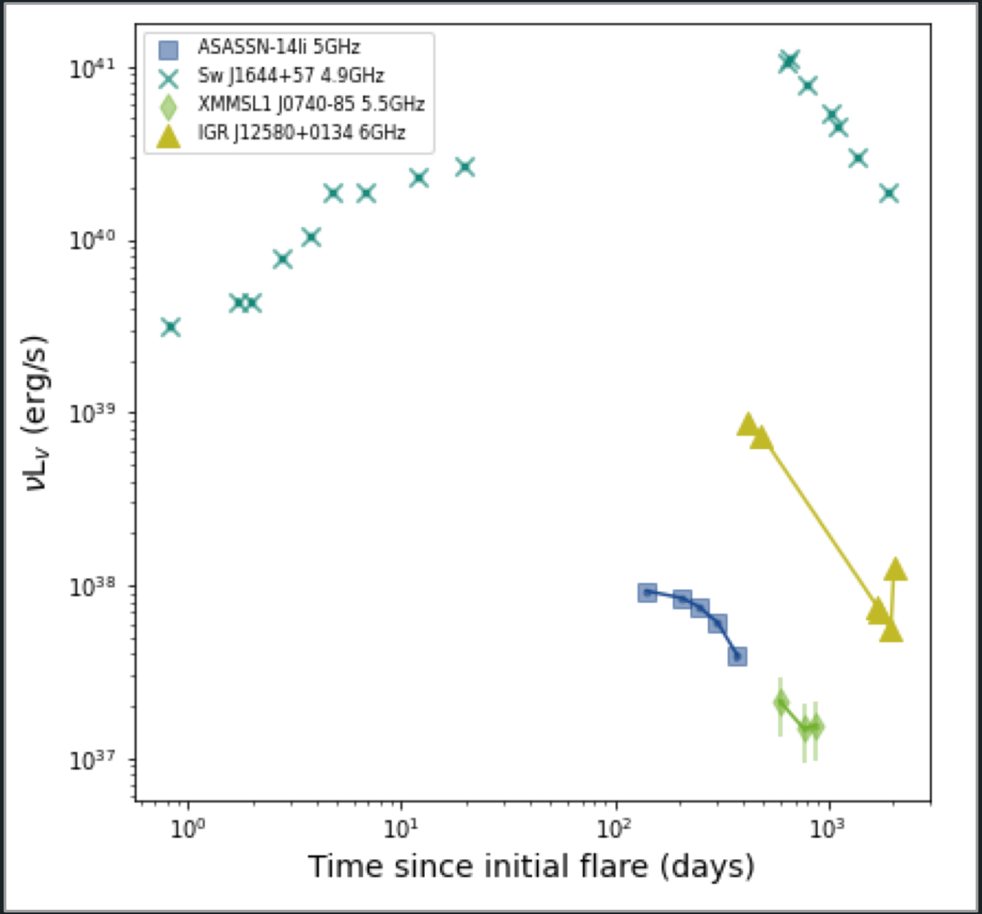


AT2020vwl (Goodwin+2023)

Radio Detections of Tidal Disruption Events

5 years ago..

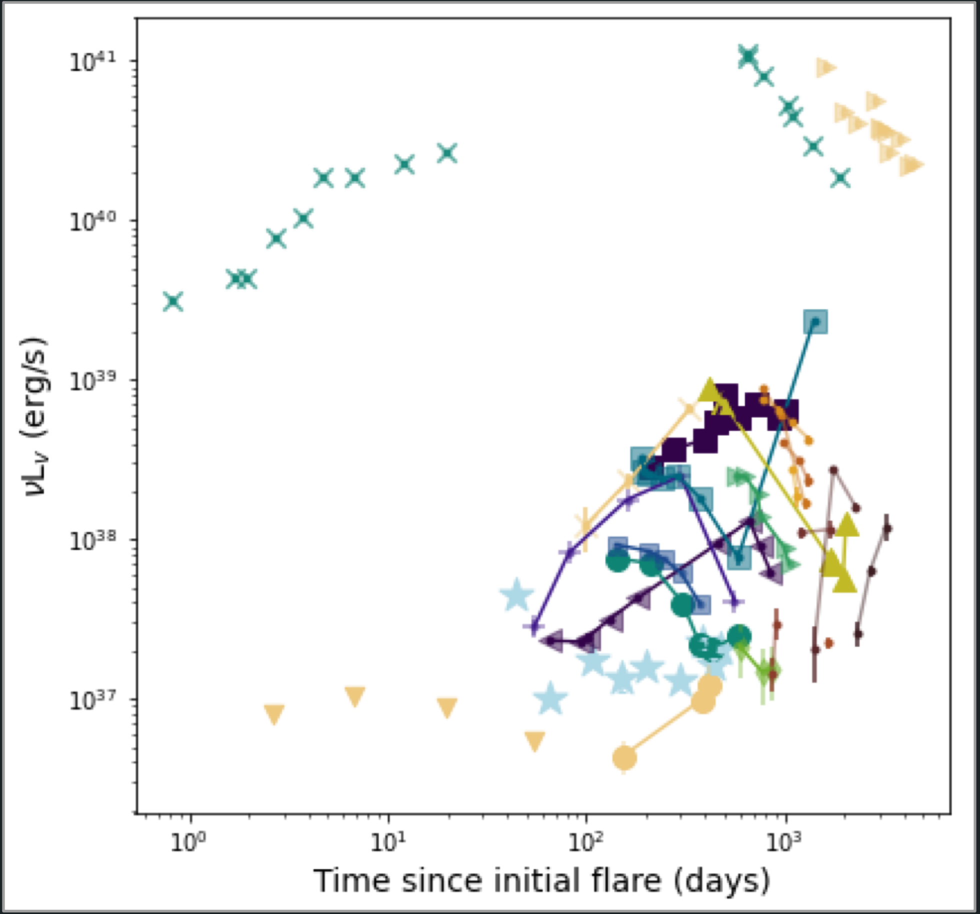
4 radio-detected TDEs



Radio Detections of Tidal Disruption Events

Now

>20 radio-detected TDEs



Radio Detections of Tidal Disruption Events

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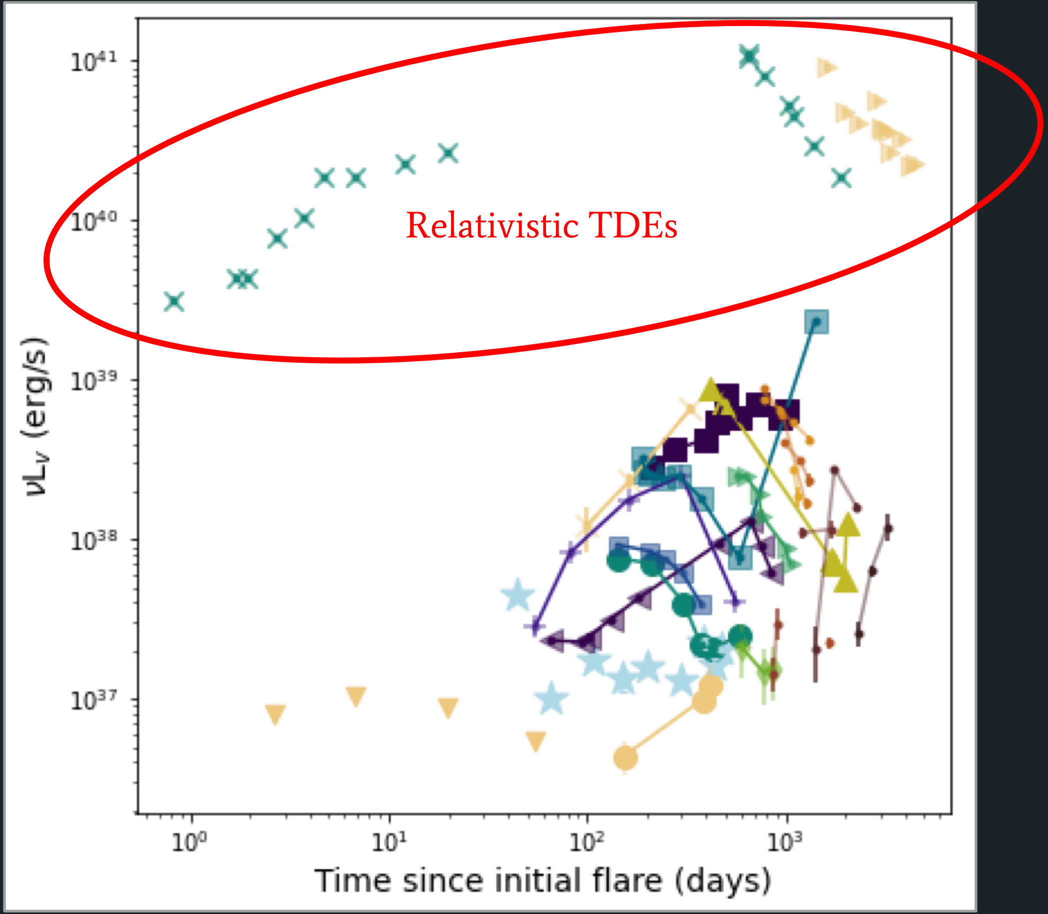

Radio Detections of Tidal Disruption Events

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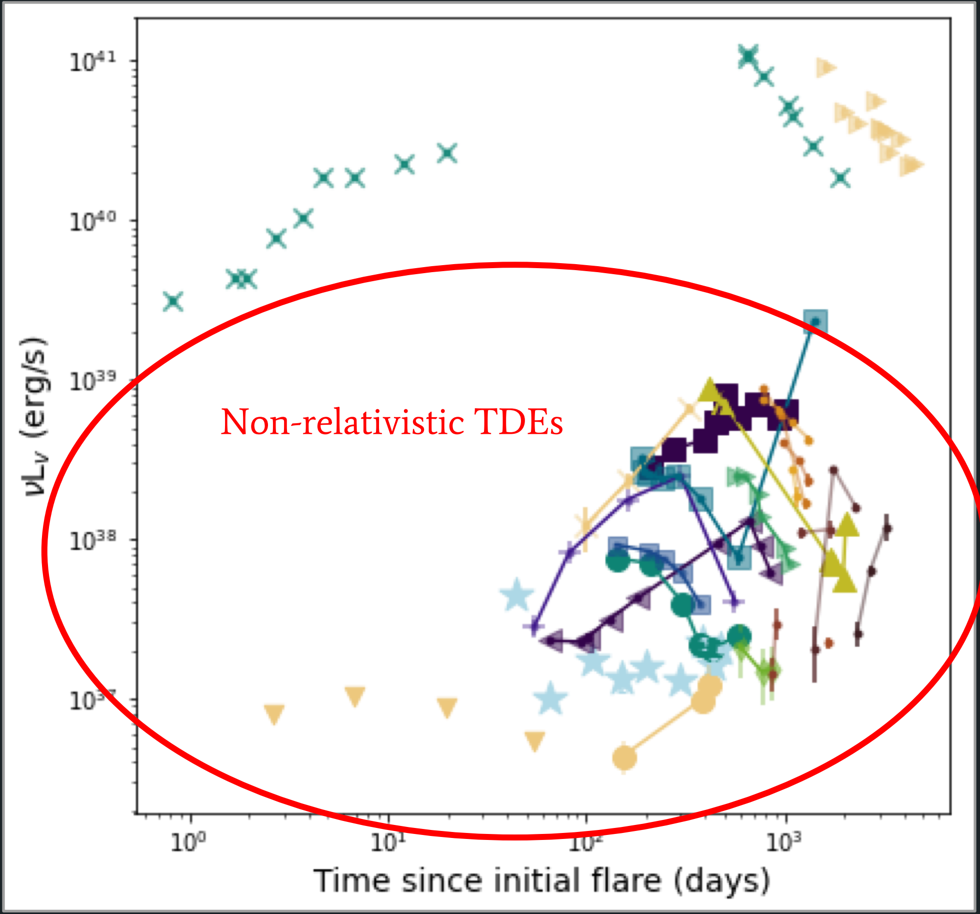
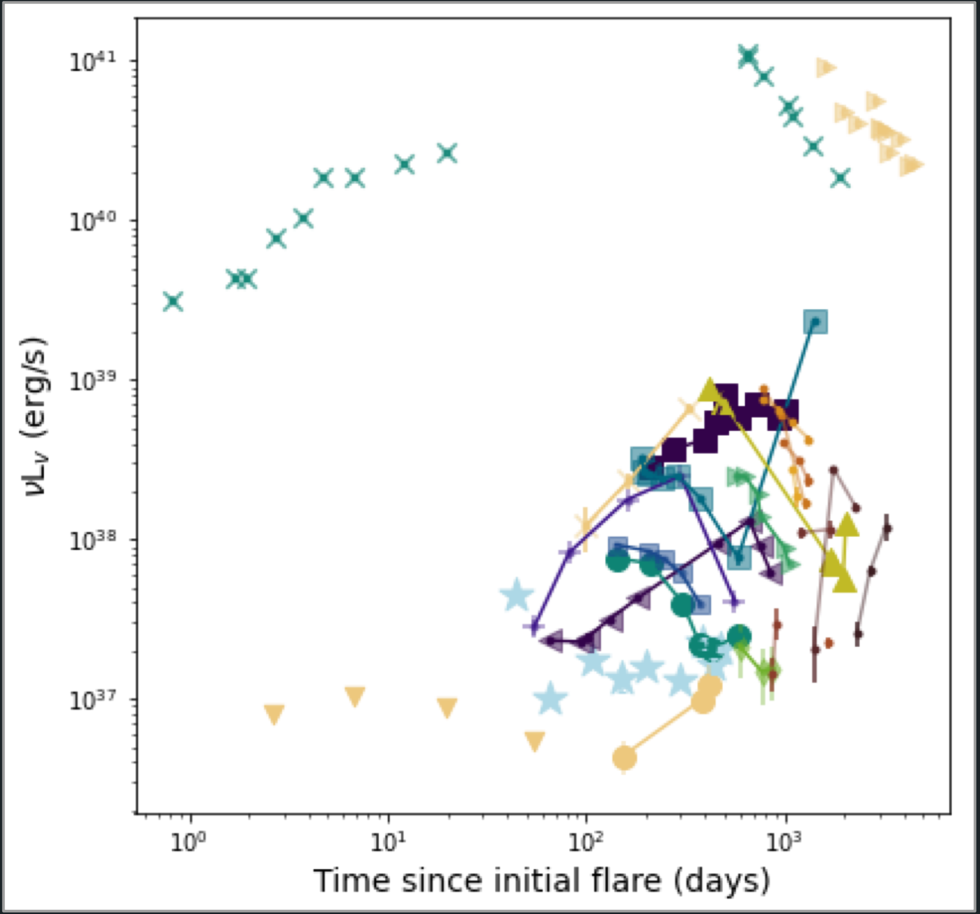


Radio Detections of Tidal Disruption Events

What have we learned?

- ★ Radio emission is common (~50% events)
- ★ A lot of diversity in the population
- ★ Rising radio emission at >1000 d???

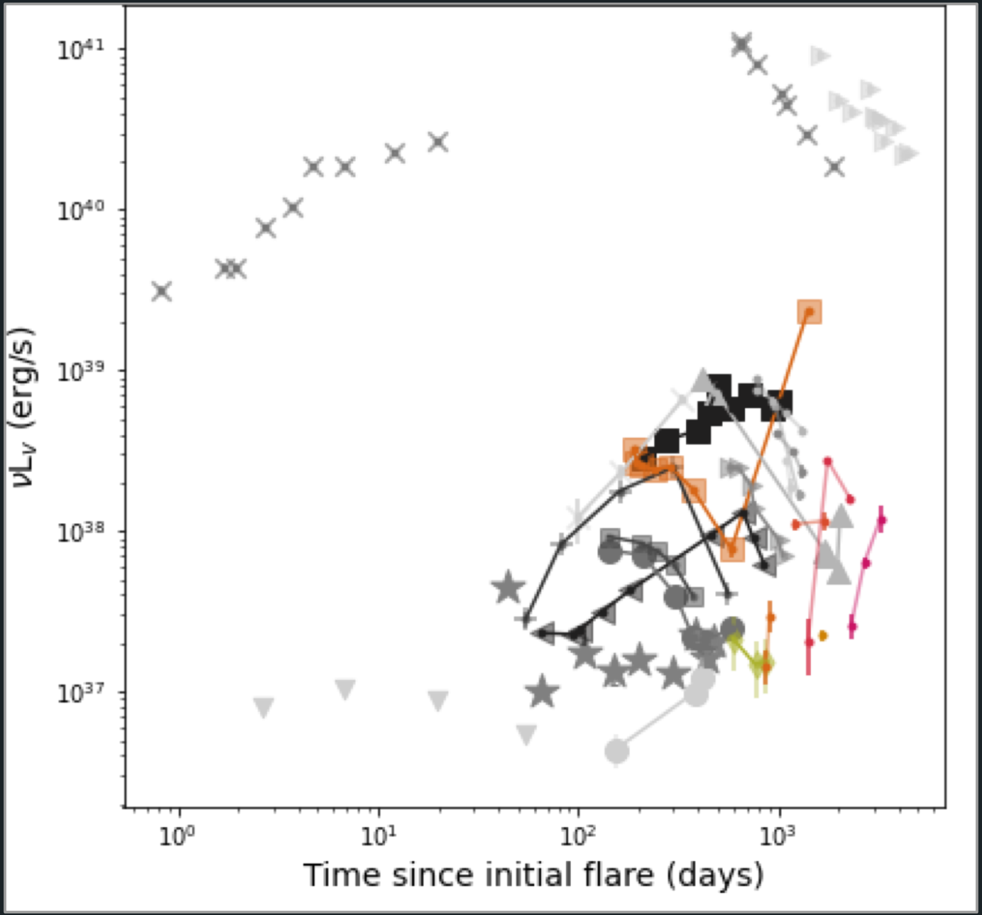


Late time radio flares

- ★ Work led by Yvette Cendes and Assaf Horesh
- ★ Rising radio emission at >1000 d post-disruption

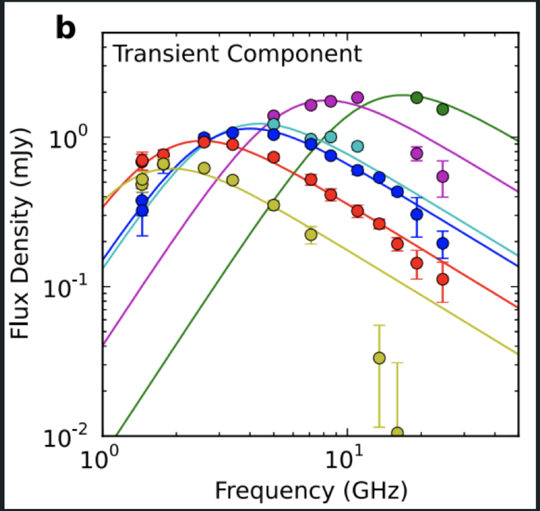
Cause?

- ➔ Late launched jet
- ➔ New interactions with interstellar medium
- ➔ Off axis relativistic jet

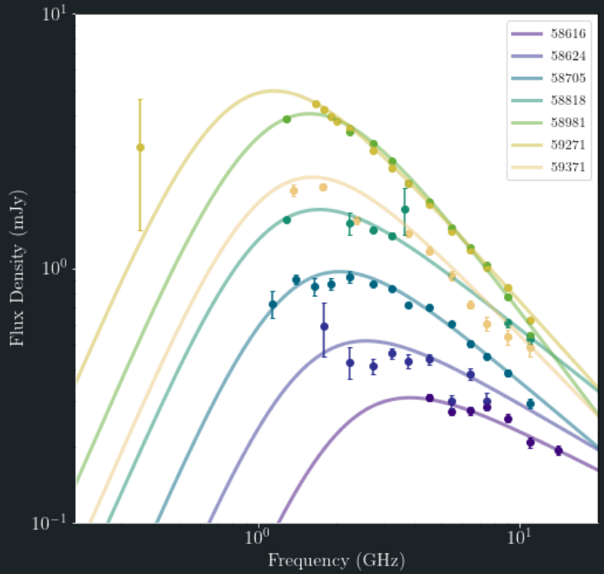


Example radio emission from known non-relativistic TDEs

- ★ Changes on timescales of ~months
- ★ Luminosity ~ 10^{28} erg/s
- ★ Due to synchrotron self-absorption



Radio spectra of ASASSN-14li over 1.5 years (Alexander+ 2016)



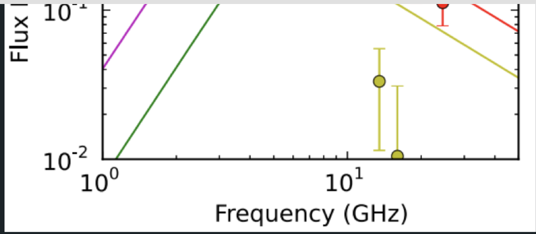
VLA radio spectra of AT2019azh over 2.5 years (Goodwin+ 2022)

Example radio emission from known non-relativistic TDEs

- ★ Changes on timescales of ~months
- ★ Luminosity ~10^{38} ...
- ★ Due to synch...

Open questions:

- ➢ What produces the radio emission in TDEs?
- ➢ What drives the differences in radio emission from TDEs?



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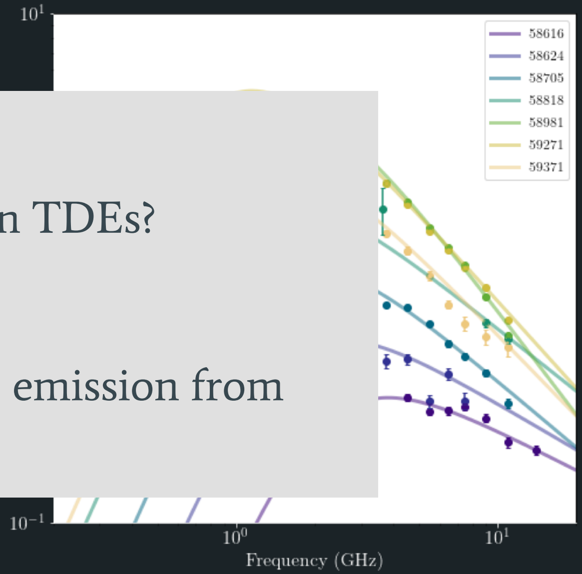
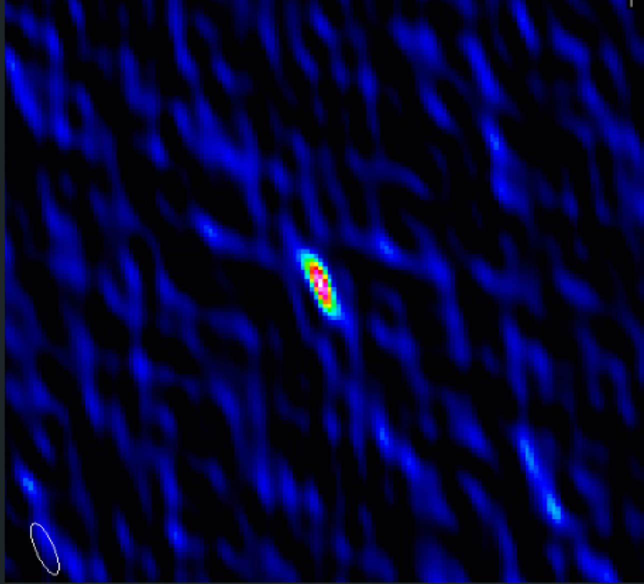


VLA radio spectra of AT2019azh over 2.5 years (Goodwin+ 2022)

Radio observations

- All radio TDEs are point sources (we do not resolve anything)
- So what can we learn? From the radio?



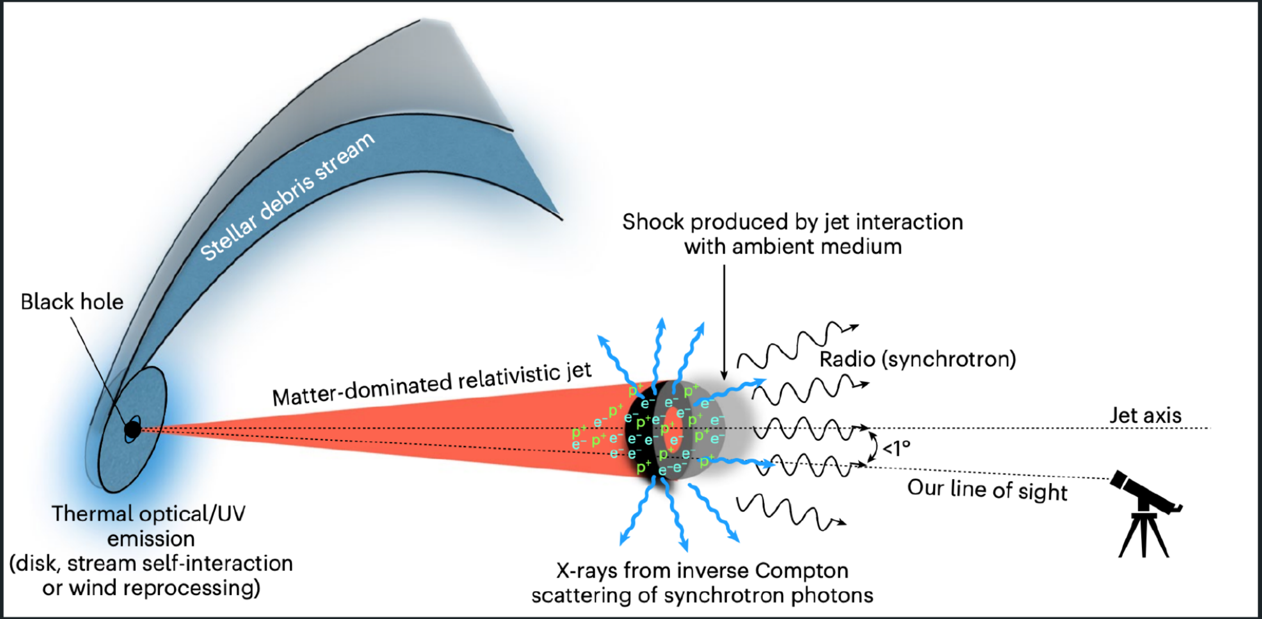
erasstJ2344 (Goodwin+2024)

Radio observations of TDEs

Probe the *ejected* material (up to 50% of the destroyed star!)

Enable constraints on:

- ➢ Radio emitting region size
- ➢ Radio emitting region energy
- ➢ Velocity of outflow
- ➢ Ambient density of the surrounding medium



Pasham+2023

Synchrotron emission basics

Electrons in the shock are accelerated into a power-law distribution

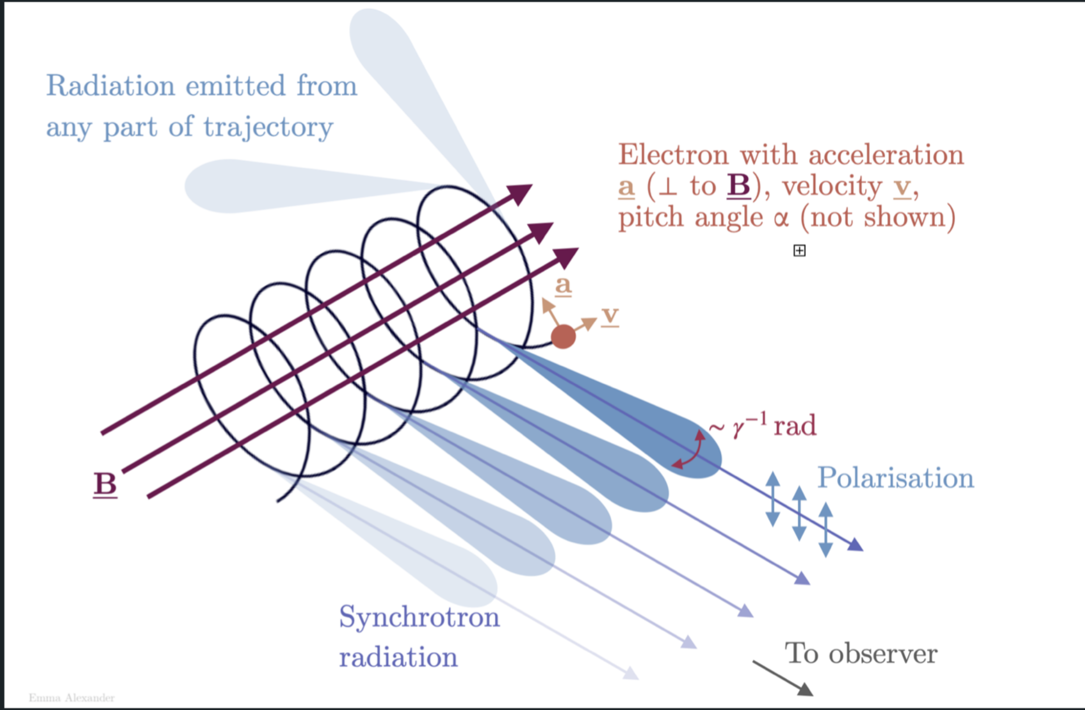


Image credit: E. Alexander

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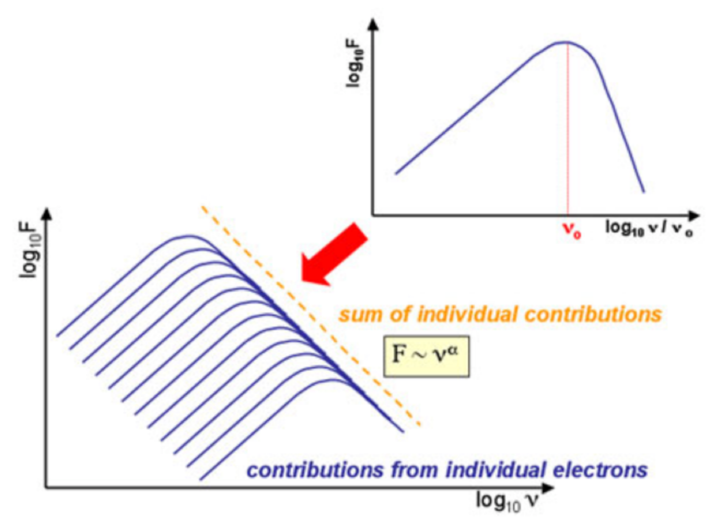
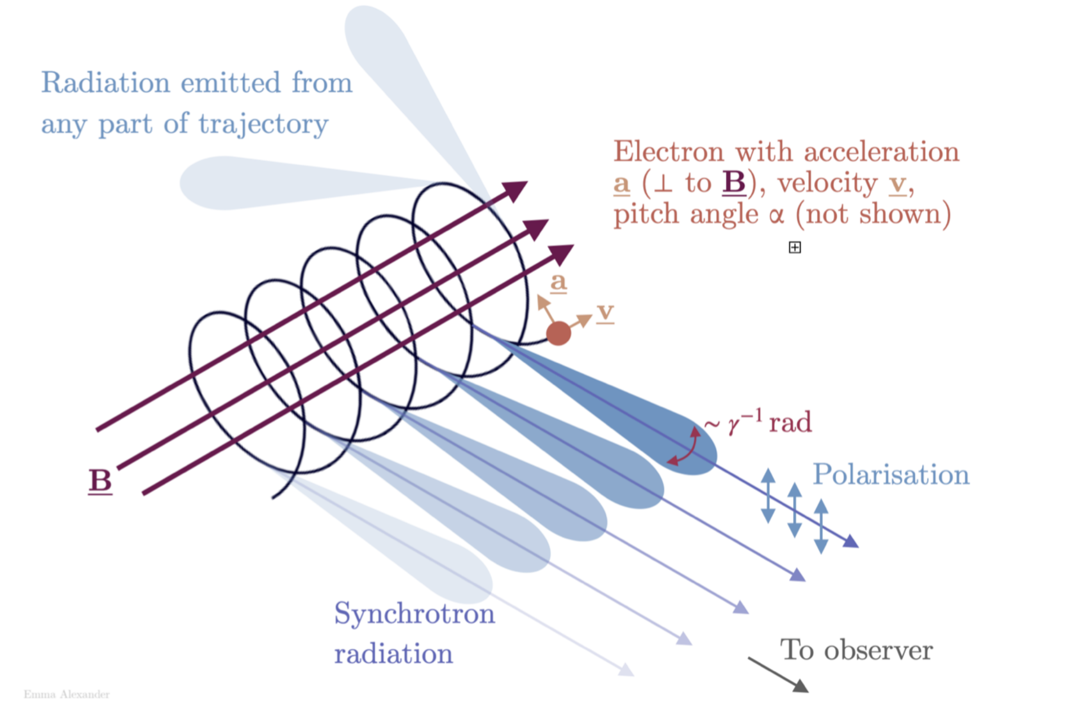


The synchrotron emission spectrum follows a power-law decay, and is constructed by adding the contributions from individual electrons.



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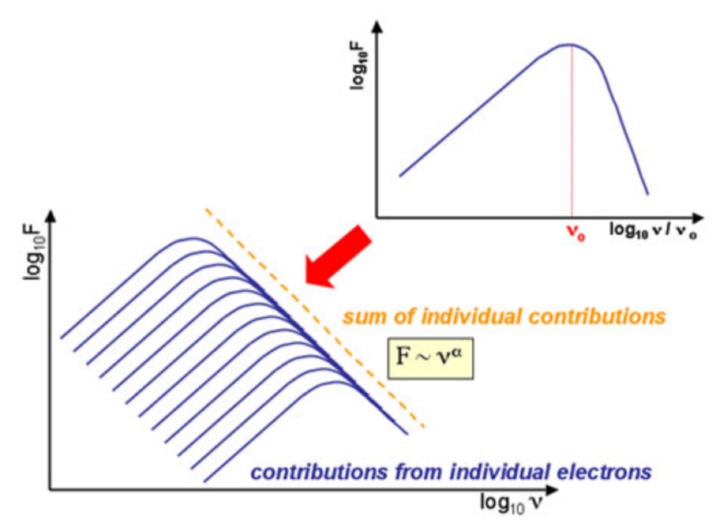

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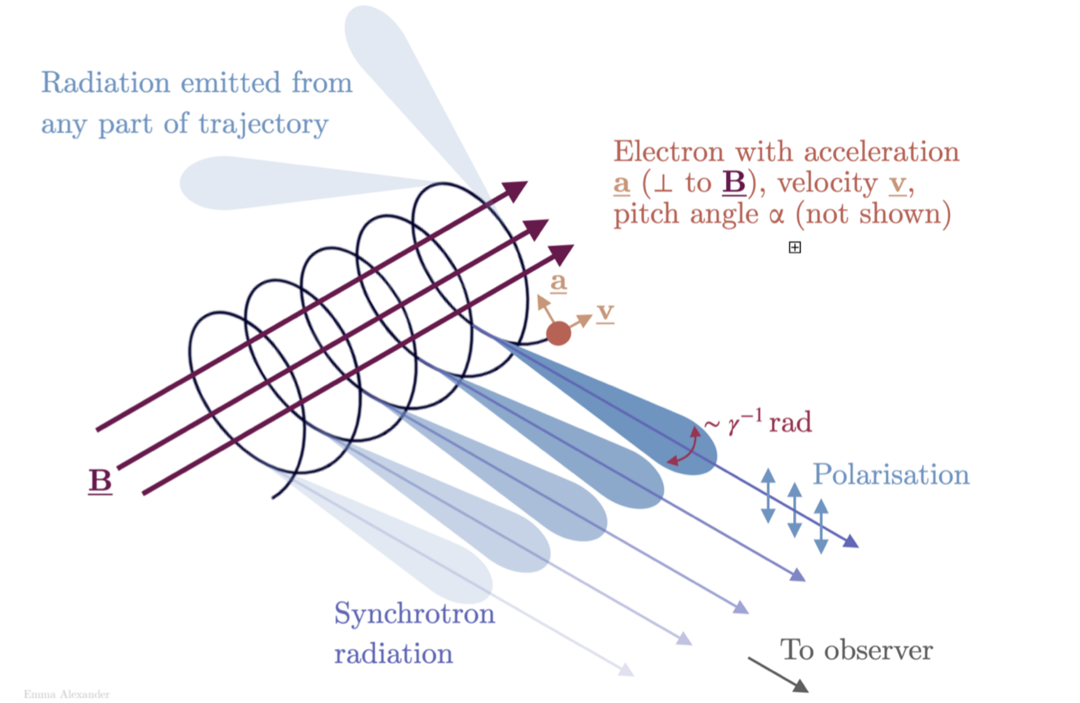


Image credit: E. Alexander

Synchrotron emission is responsible for many radio emitting sources, including GRBs, SNs, AGN, TDEs

Expected spectrum of synchrotron emission

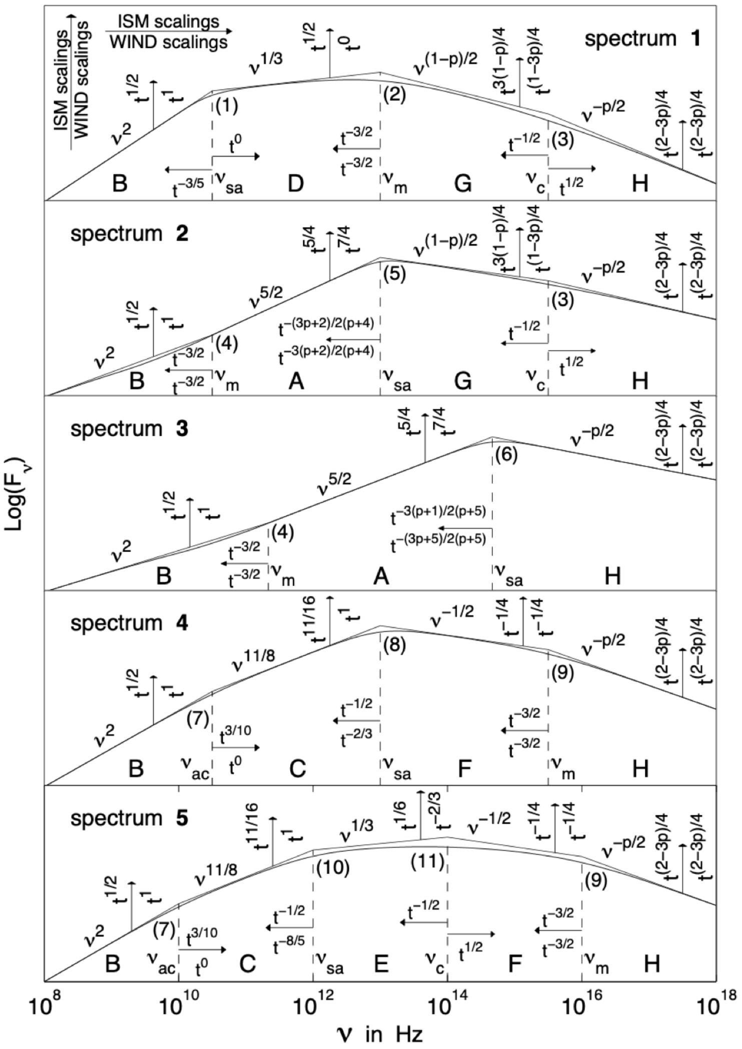
Electrons in the shock are accelerated into a power-law distribution:

$$N(\gamma) \propto \gamma^{-p} \; ; \; \gamma > \gamma_{min}$$

After being accelerated in the shock, the electrons cool because of radiative losses and adiabatic cooling

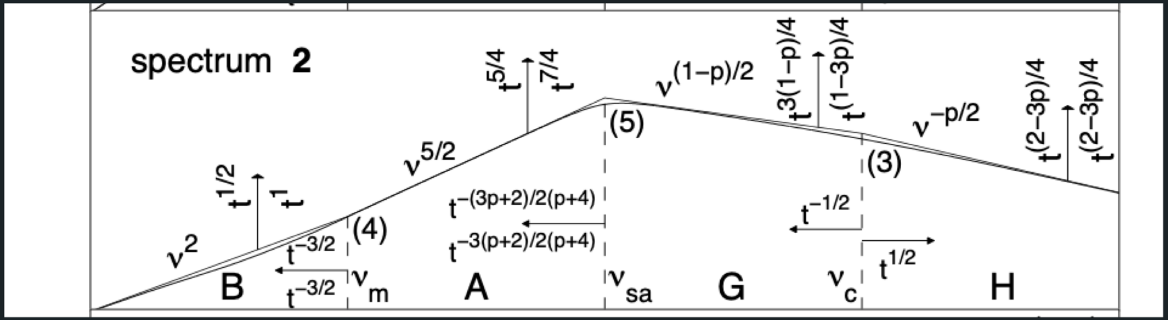
There are several power-law segments that make up a synchrotron spectrum that join at the break frequencies:

- Vsa: self-absorption frequency, below which the optical depth to synchrotron self-absorption is 1
- Vm: minimum frequency, the typical frequency of the minimal electron power-law
- Vc: cooling frequency, the synchrotron frequency of an electron whose cooling time equals the dynamical time of the system



Granot & Sari 2002

Expected spectrum of synchrotron emission – synchrotron self absorption



Granot & Sari 2002

Regime where $\nu_m < \nu_{sa} < \nu_c$

Where do the ν powers come from?

Synchrotron self-absorption

Modified from Essential radio astronomy https://www.cv.nrao.edu/~sransom/web/Ch5.html

The brightness temperatures of synchrotron sources cannot become arbitrarily large at low frequencies because for every emission process there is an associated absorption process.

Electrons in the shock are accelerated into a power-law distribution:

$$N(\gamma) \propto \gamma^{-p} \; ; \; \gamma > \gamma_{min}$$

Electron with energy

$$E = \gamma mc^2$$

Emit most of their synchrotron power near the critical frequency

$$\nu_{crit} = \frac{\gamma^2 eB}{2\pi mc}$$

So the synchrotron emission at frequency ν comes primarily from electrons with Lorentz factors near

$$\gamma \approx \left(\frac{2\pi mc\nu}{eB}\right)^{1/2}$$

In an ultra-relativistic gas, the ratio of specific heats and at constant volume is cp/cv=4/3 (not 5/3 as appropriate for nonrelativistic) so

$$E = 3kT_e$$

Not $E = \frac{3kT_e}{2}$

Therefore the effective temperature of the relativistic electrons is

$$T_e = \frac{E}{3k} = \frac{\gamma mc^2}{3k}$$

We therefore arrive at

$$T_e = \left(\frac{2\pi mc\nu}{eB}\right)^{1/2} \frac{mc^2}{3k}$$

i.e.

$$\frac{T_e}{K} \approx 1.18\times10^6 \left(\frac{\nu}{Hz}\right)^{0.5} \left(\frac{B}{gauss}\right)^{-0.5}$$

At a sufficiently low frequency, the brightness temperature, Tb of any synchrotron source will approach the effective electron temperature and the source will become opaque. In the Rayleigh-Jeans limit, Tb is given by

$$Tb = \frac{I_{\nu c^2}}{2k\nu^2}$$

Setting Tb=Te we find

$$I_\nu \approx \frac{2kT_e\nu^2}{c^2} \propto \nu^{\frac{5}{2}} B^{-0.5}$$

Therefore at low frequencies the spectrum of a synchrotron self-absorbed source has a power law slope of 5/2:

$$S(\nu) \propto \nu^{5/2}$$

Expected spectrum of synchrotron emission

Electrons in the shock are accelerated into a power-law distribution:

$$N(\gamma) \propto \gamma^{-p} \; ; \; \gamma > \gamma_{min}$$

After being accelerated in the shock, the electrons cool because of radiative losses and adiabatic cooling

There are several power-law segments that make up a synchrotron spectrum that join at the break frequencies:

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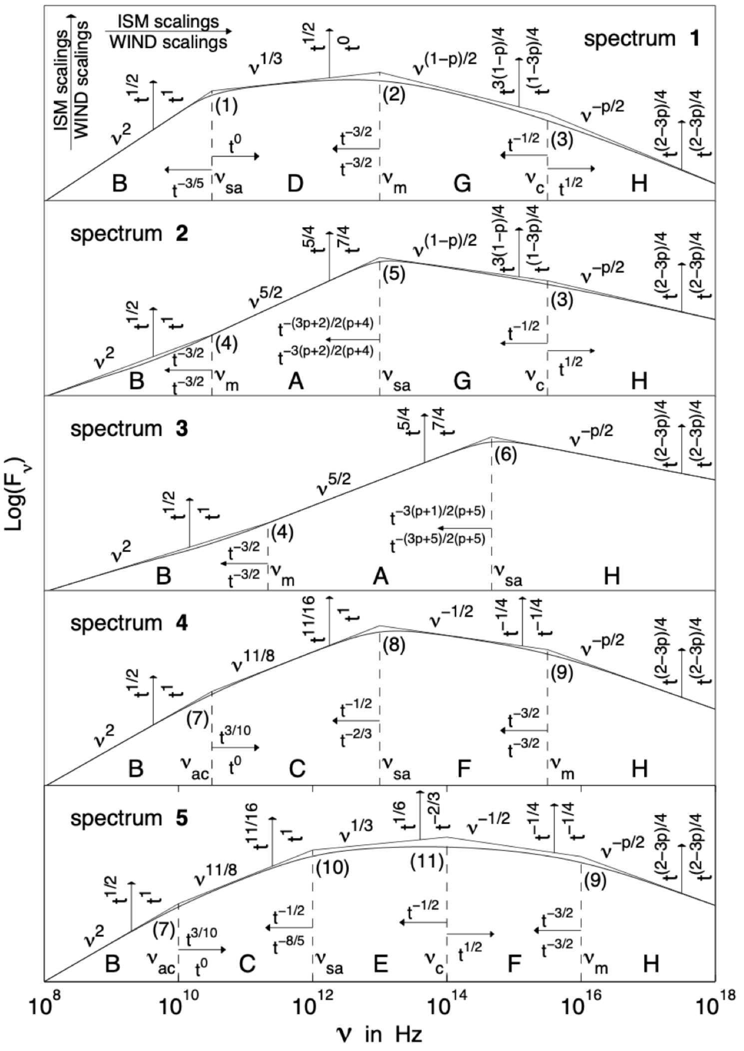
Observed synchrotron emission depend on physical system properties, such as:

- CSM density
- Velocity of outflow
- Total energy carried by outflow
- Fraction of shockwave energy deposited in the electrons and the magnetic field



Granot & Sari 2002

Expected spectrum of synchrotron emission

Electrons in the shock are accelerated into a power-law distribution:

$N(\gamma) \propto \gamma^{-p}$; γ

After being accelerated
the electrons cool becau
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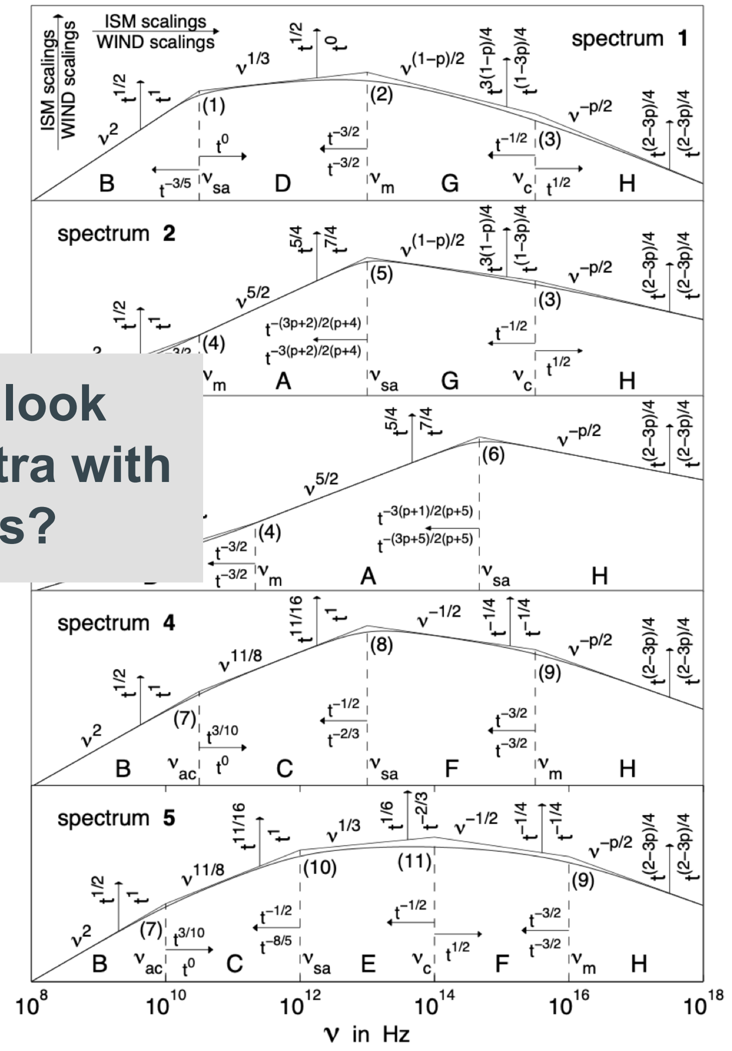
Observed synchrotron emission depend on physical system properties, such as:

Fraction of shockwave energy deposited in the electrons and the magnetic field

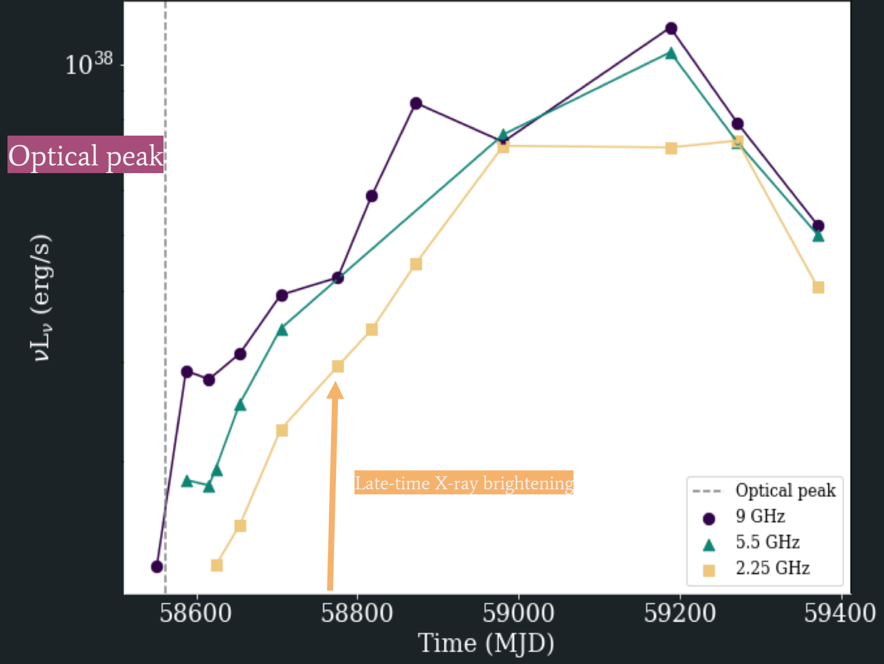
Do radio observations of TDEs look like evolving synchrotron spectra with characteristic break frequencies?

Granot & Sari 2002

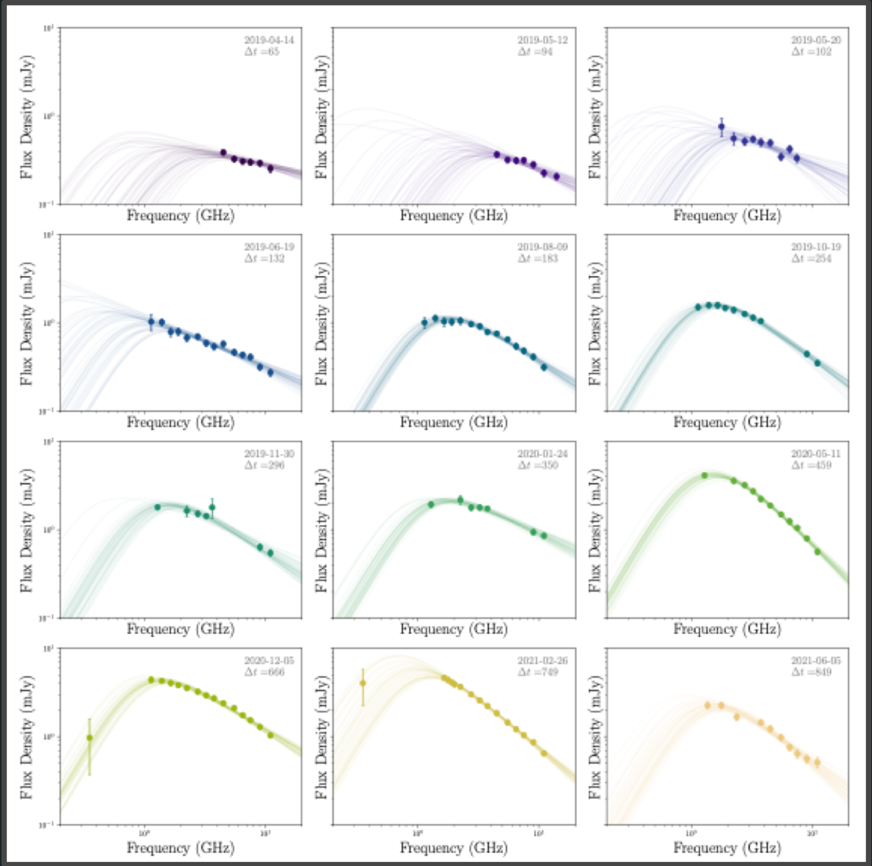


AT2019azh Radio obs

Very large array observations: 14 epochs over 2.5 years with observations spanning 0.3-15 GHz



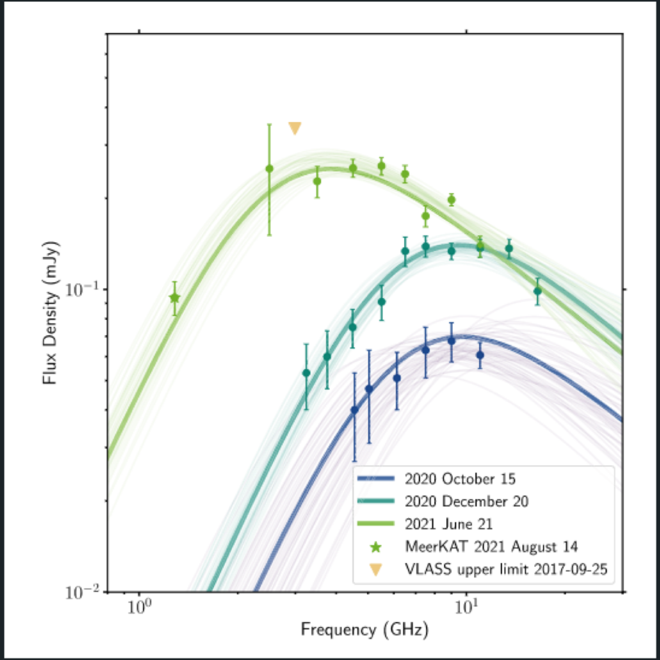
VLA radio lightcurve of AT2019azh (Goodwin+2022)



Synchrotron spectra of AT2019azh (Goodwin+2022)

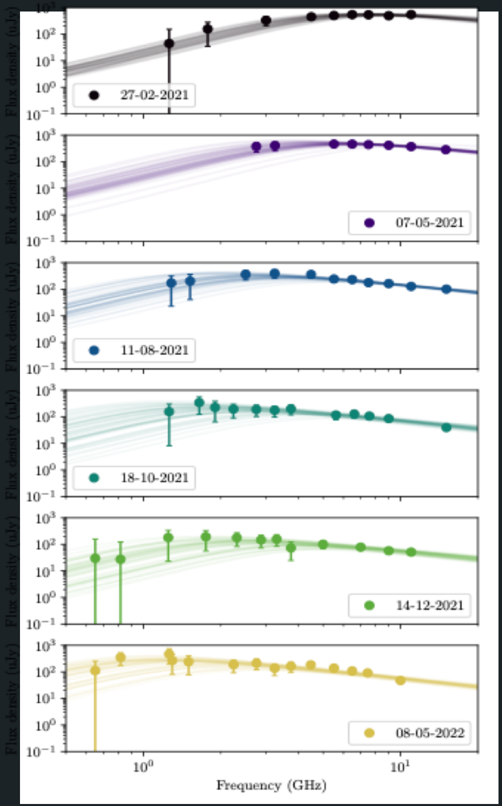
More Broadband radio observations of TDEs!

AT2020opy (Goodwin+2023a)



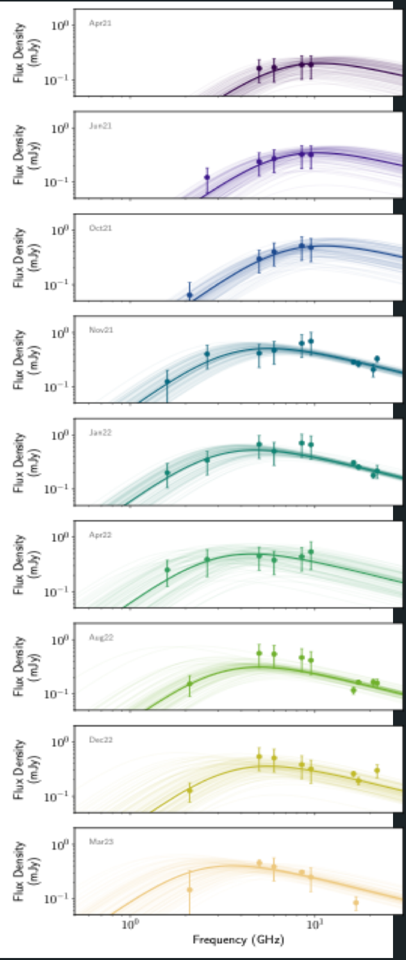
AT2020vwl (Goodwin+2023b)

VLA



erasst J2344 (Goodwin+2024)

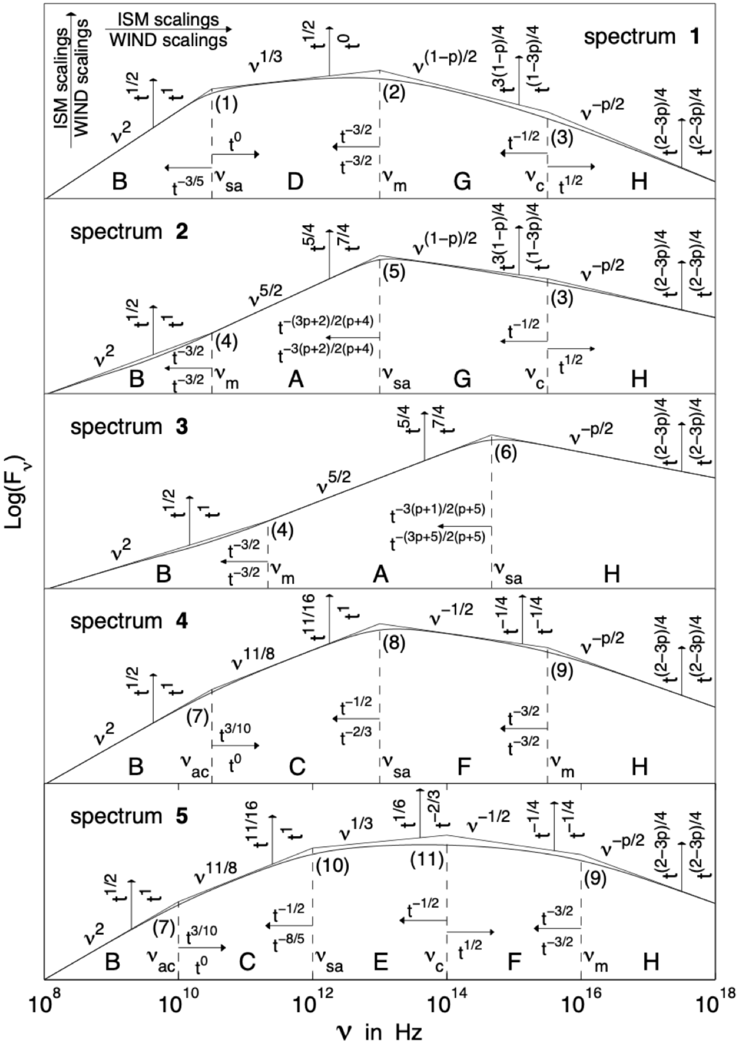
ATCA



Interactive tutorial 1: fitting synchrotron spectra

How do we fit radio spectra?

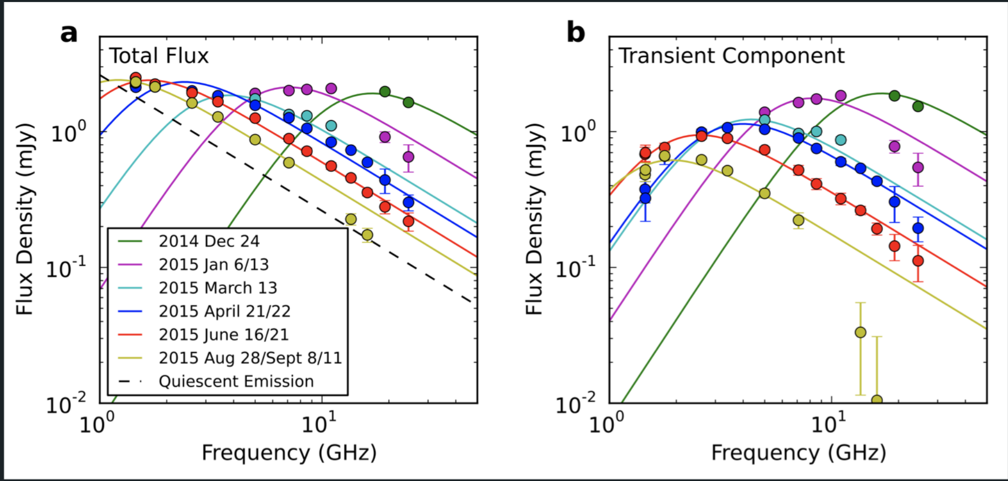
Are the observed radio spectra consistent with synchrotron emission?



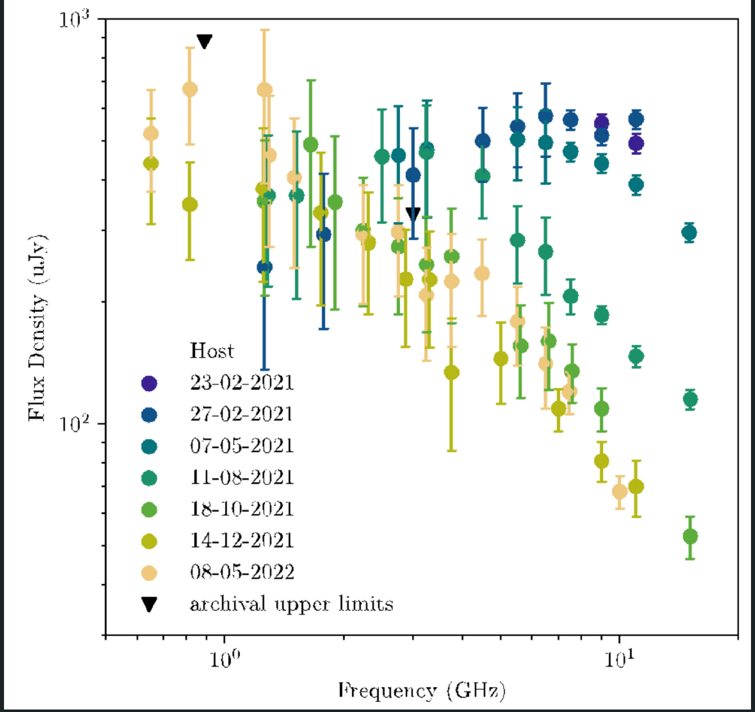
Granot & Sari 2002

TDE radio observations – what about host emission?

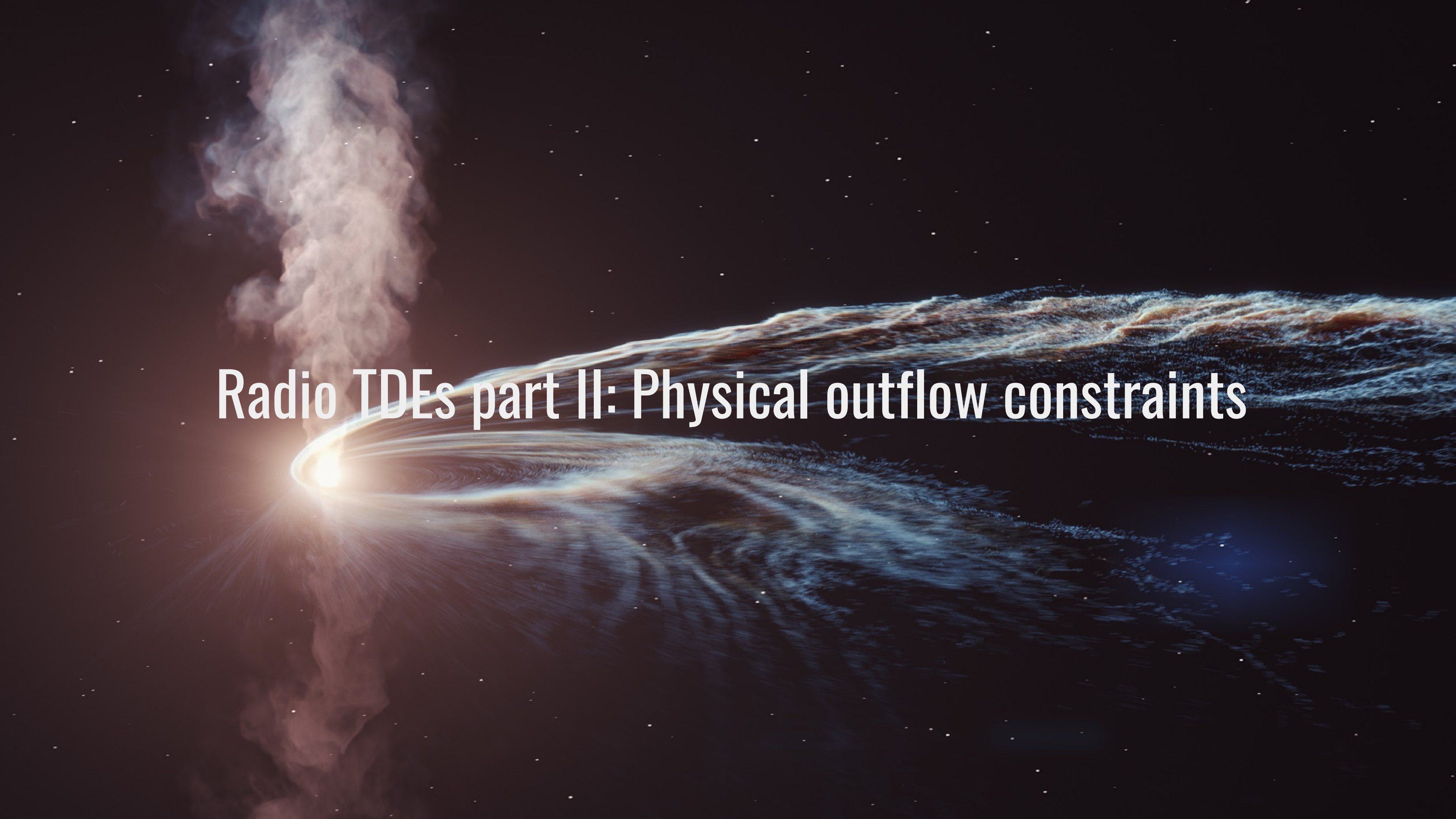
- Most galaxies produce low-level radio emission due to star formation or AGN activity
- How to account for this?



ASASSN-14li (Alexander+ 2016)



AT2020vwl (Goodwin+2023b)



Radio TDEs part II: Physical outflow constraints

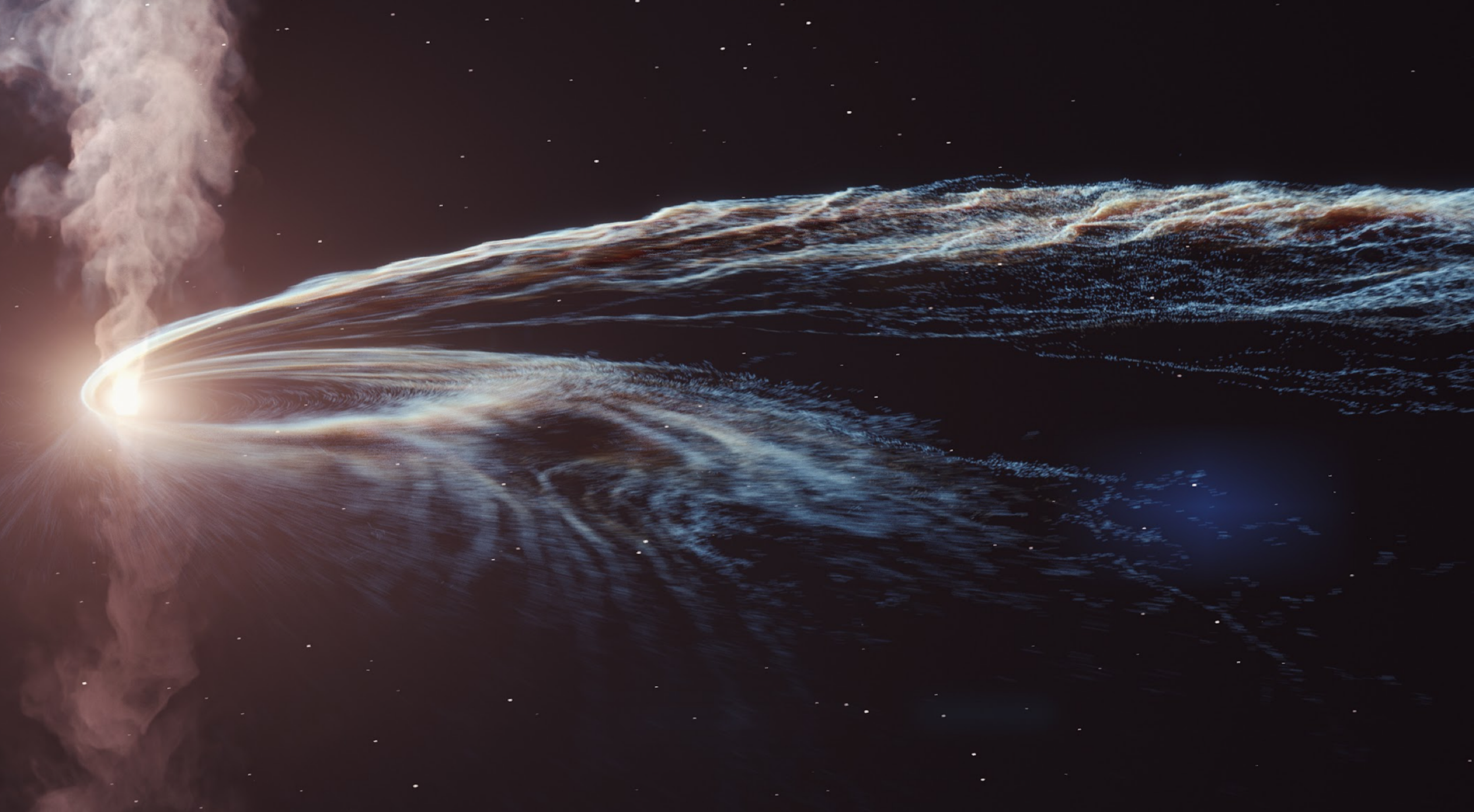
What drives the outflow? Physical outflow mechanism vs environment

Jet?

Not relativistic (not luminous or fast enough)

Maybe sub-relativistic jet from accretion?

Requires coincidence with X-ray accretion



Physical outflow mechanism vs environment

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Accretion induced wind?

- Spherical, low energy outflow
- Requires coincidence with X-ray accretion

Physical outflow mechanism vs environment

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Black hole accretion driven
-> should see link to X-ray (?)
-> perhaps should be delayed wrt initial flare (?)

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Collision induced outflow?

Launched early

No dependence on accretion flow

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Unbound debris stream?

Launched early and would be fastest unbound debris

But very narrow viewing angle

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Accretion induced wind?

Spherical, low energy outflow

Requires coincidence with X-ray accretion

Debris driven outflow -> prompt ejection

Collision induced outflow?

Launched early

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Launched early and would be fastest unbound debris

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Physical outflow mechanism vs environment

Black hole accretion driven -> should see link to X-ray and possible delay from initial flare (?)

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Circumnuclear environment affects propagation of outflow

Physical outflow mechanism vs environment

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Requires coincidence with X-ray accretion

Black hole a
driven -> sh
link to X-ray
possible de
initial flare (

How do we distinguish between these scenarios?

- ➢ We need physical constraints
  - ○ Velocity, mass, energy, geometry
- ➢ Multiwavelength evolution

Accretion induced wind?

Spherical, low energy outflow

Requires coincidence with X-ray accretion

Collision induced outflow?

Launched early

No dependence on accretion flow

Unbound debris stream?

Launched early and would be fastest unbound debris

But very narrow viewing angle

Inferring physical outflow properties

How do we extract physical outflow properties from measured synchrotron spectra?

A measurement of the synchrotron self-absorption flux and frequency provides tight constraints on the physical size of the emitting region and a lower limit on its energy

Observed constraints:

- Peak flux
- Peak frequency
- Synchrotron power-law index, p

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-> Require one more equation to constrain the system

The equipartition method

Pacholczyk 1970; Scott & Readhead 1977; Chevalier 1998

“Condition that the source is reasonable”

i.e. the electron and magnetic energy depend sensitively on R in opposite ways and the total energy is minimised at some radius in which the electrons and magnetic field are roughly in equipartition.

This provides the fourth equation necessary to constrain the system properties!

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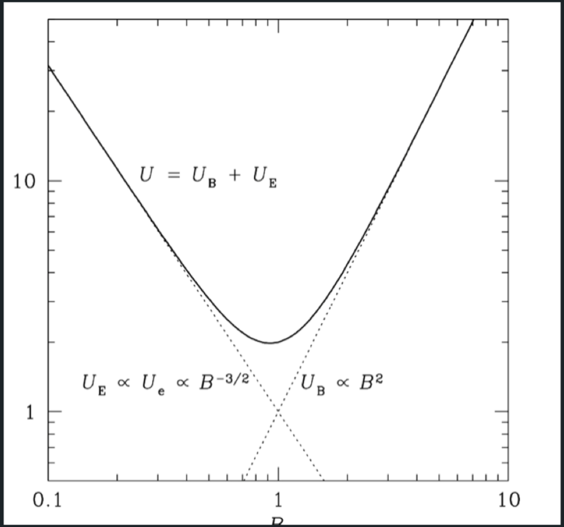
For a source of a given synchrotron luminosity, the particle energy density $U_E=(1+\eta)U_e$ is proportional to $B^{-3/2}$ and the magnetic energy density U_B is proportional to B^2. The total energy density $U=U_E+U_B$ has a fairly sharp minimum near equipartition of the particle and magnetic energy densities:

η = ion/electron energy ratio



Equipartition is therefore defined as the point at which this minimum occurs, i.e.

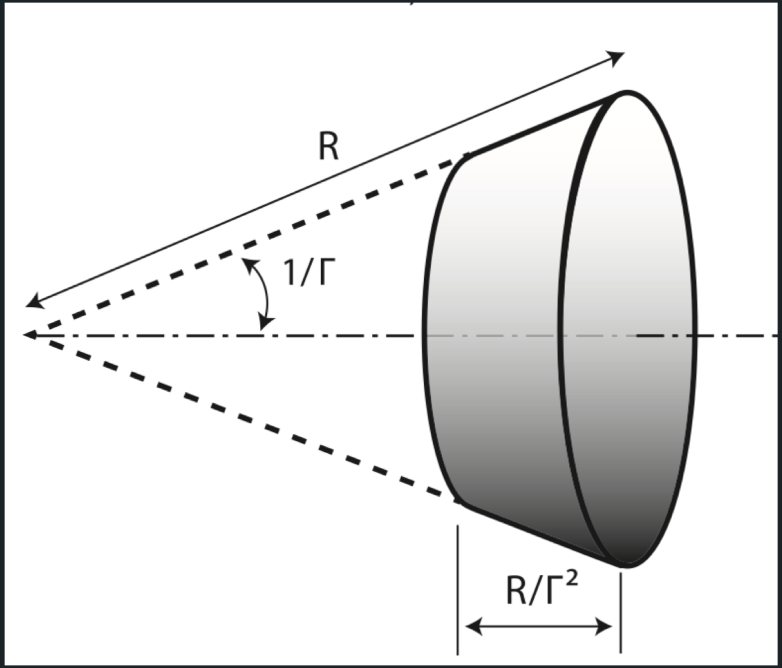
$$\frac{dU}{dB} = 0$$

Which is near $(1+\eta)U_e = U_B$

The equipartition method - assumptions

First, we need to make some assumotions.

The biggest is the geometry of the source (area/volume of emitting region)



Barniol Duran+ 2013

The equipartition method – applied to TDEs

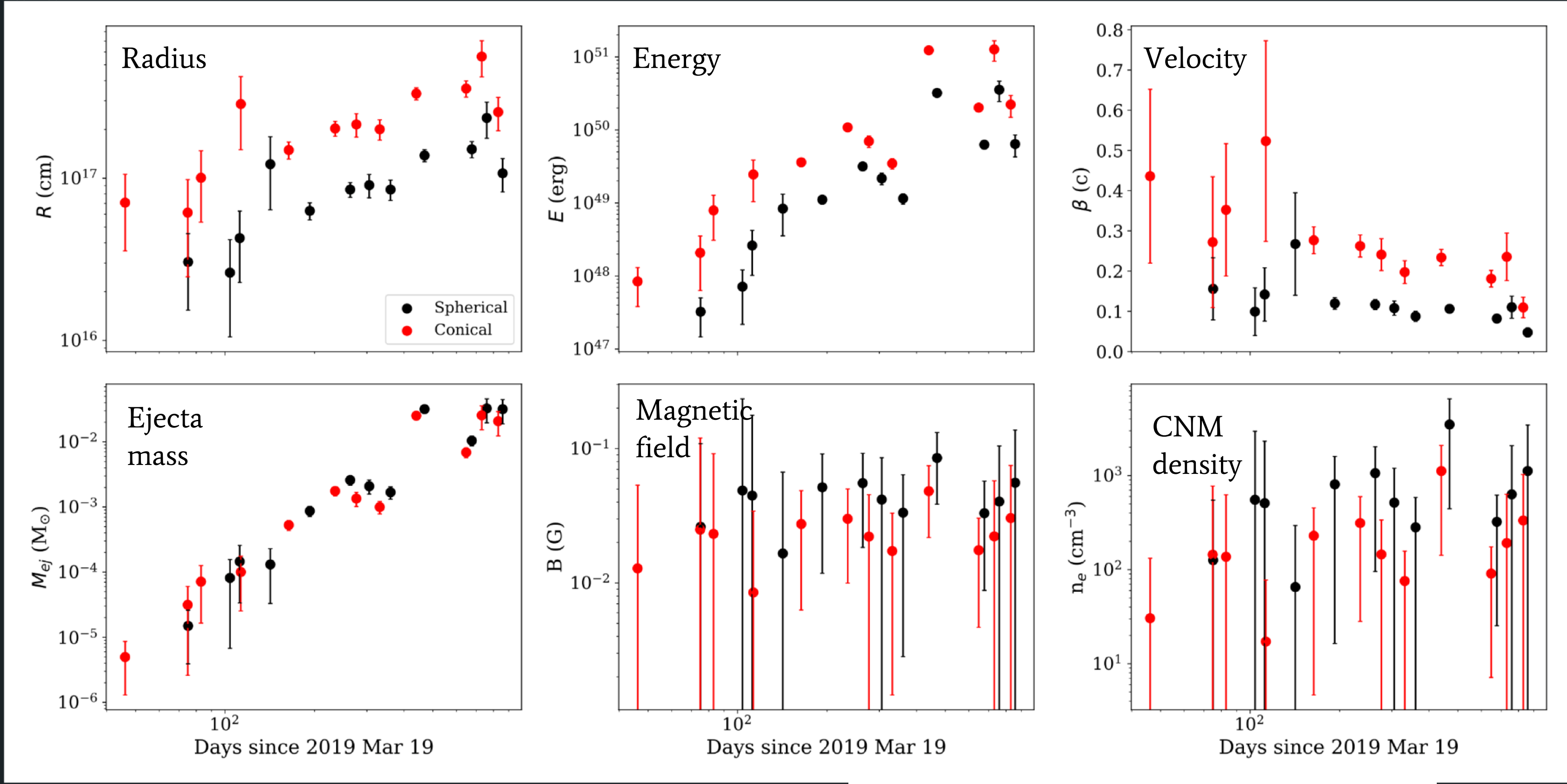
For radio emission from TDEs, we can constrain the radius, energy, velocity, magnetic field strength, ambient density etc. using the assumption of equipartition and the measured synchrotron self-absorption break properties.

If we do this for multiple epochs, we can track the outflow growing and decelerating as the shock front propagates through the central region of the galaxy

Inferring physical outflow properties

Using equipartition analysis from Barniol Duran+ 2013

AT2019azh (Goodwin+2022)



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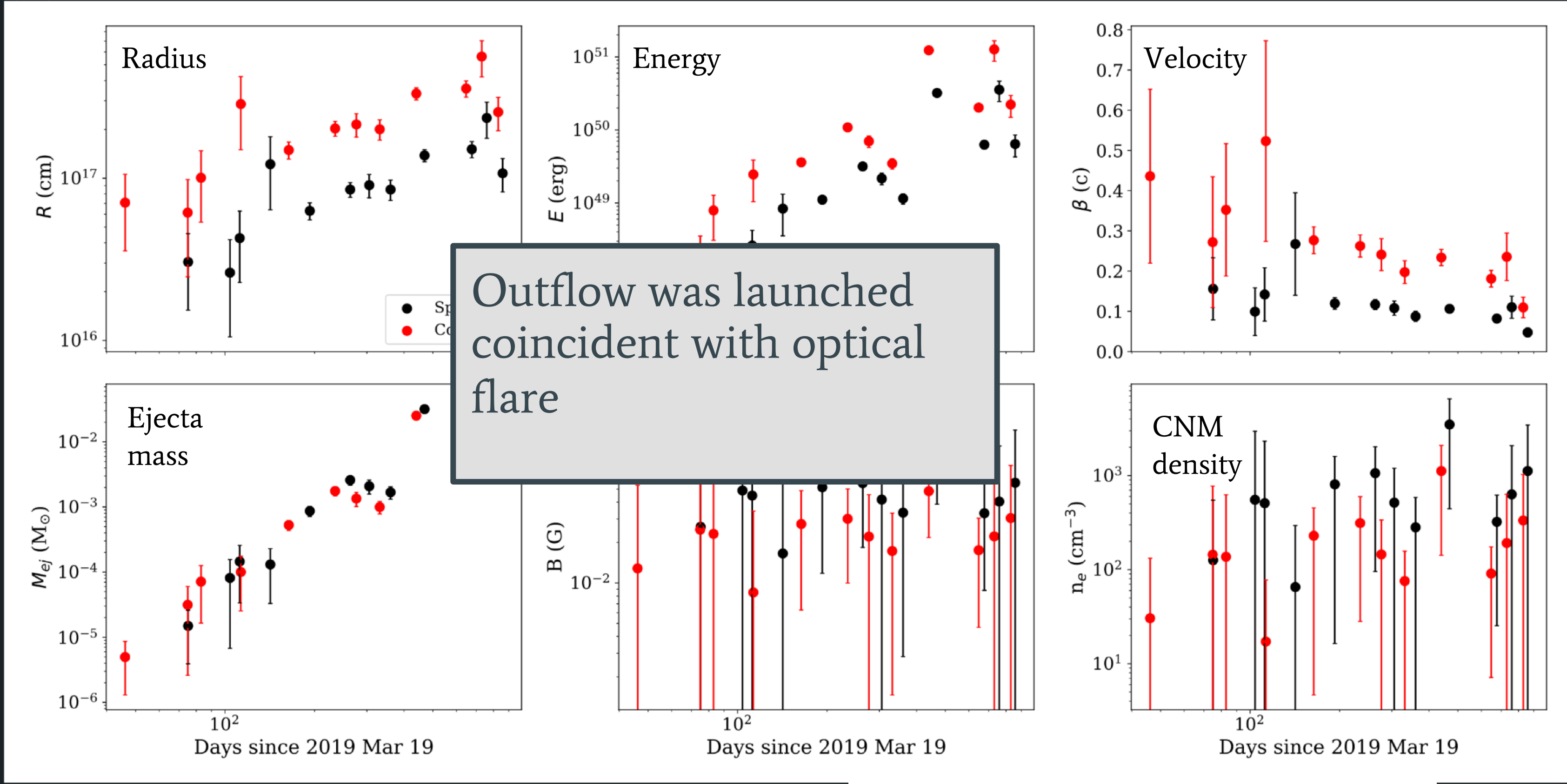
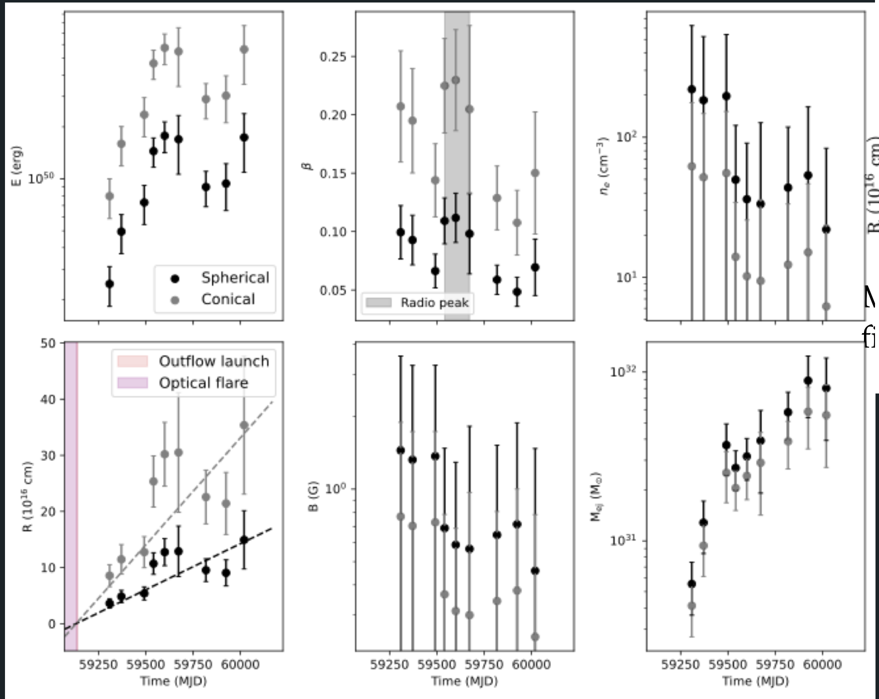
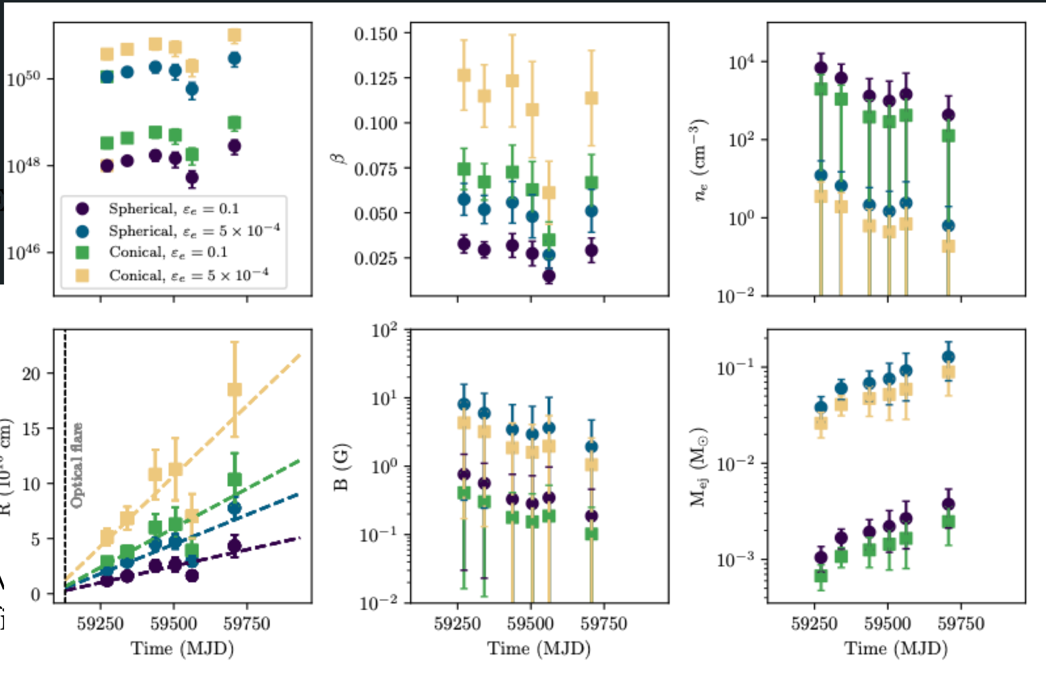


Outflow was launched coincident with optical flare

More Physical outflow properties

Using equipartition analysis from Barniol Duran+ 2013

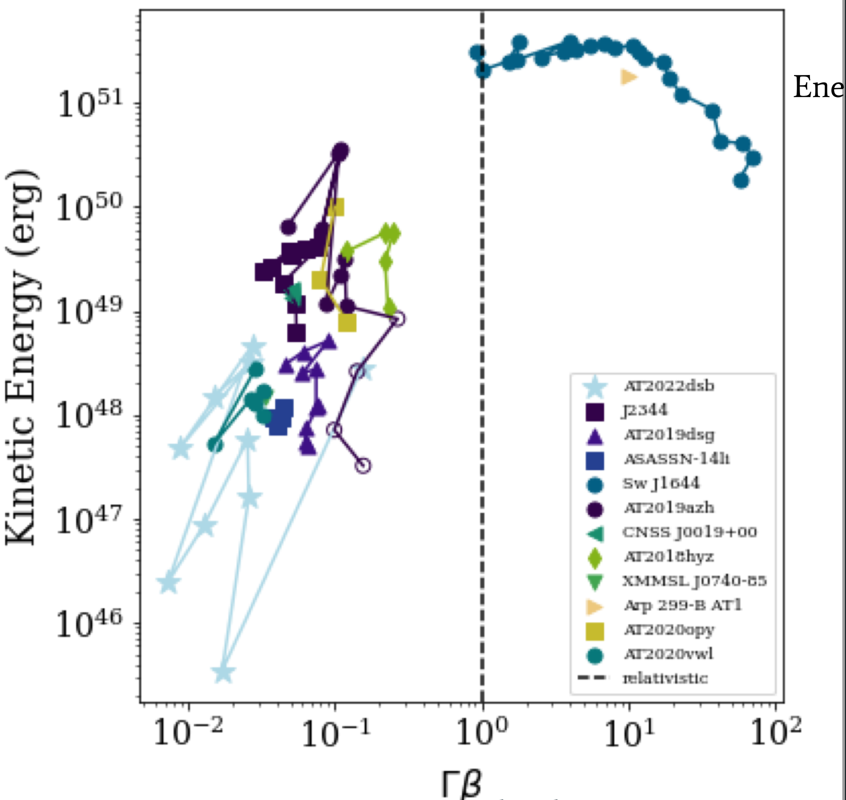




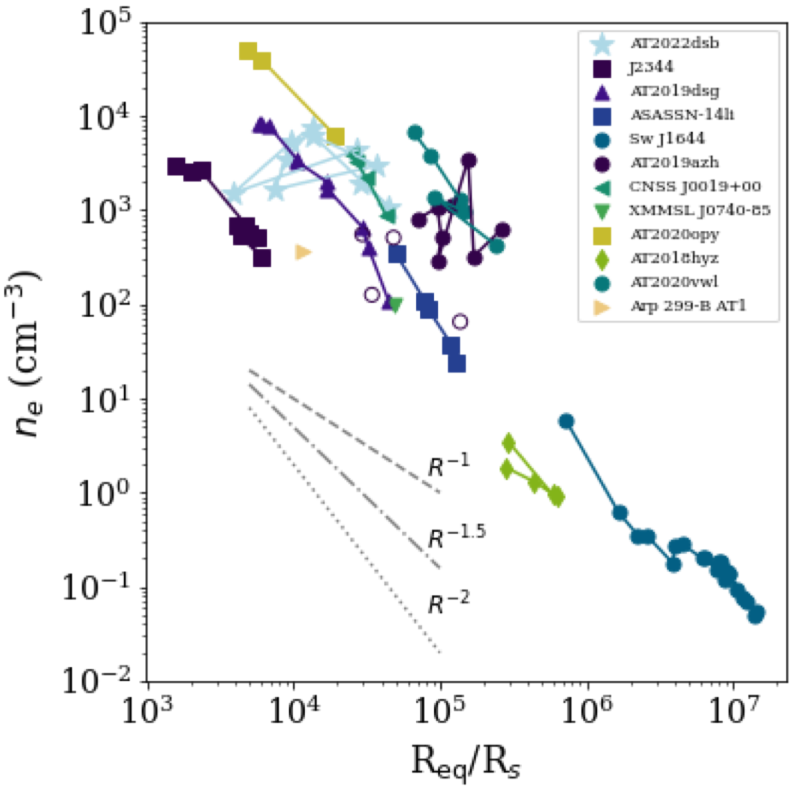
AT2020vwl (Goodwin+2023b)

erasst J2344 (Goodwin+2024)

Putting it all together: what do outflows from TDEs look like?

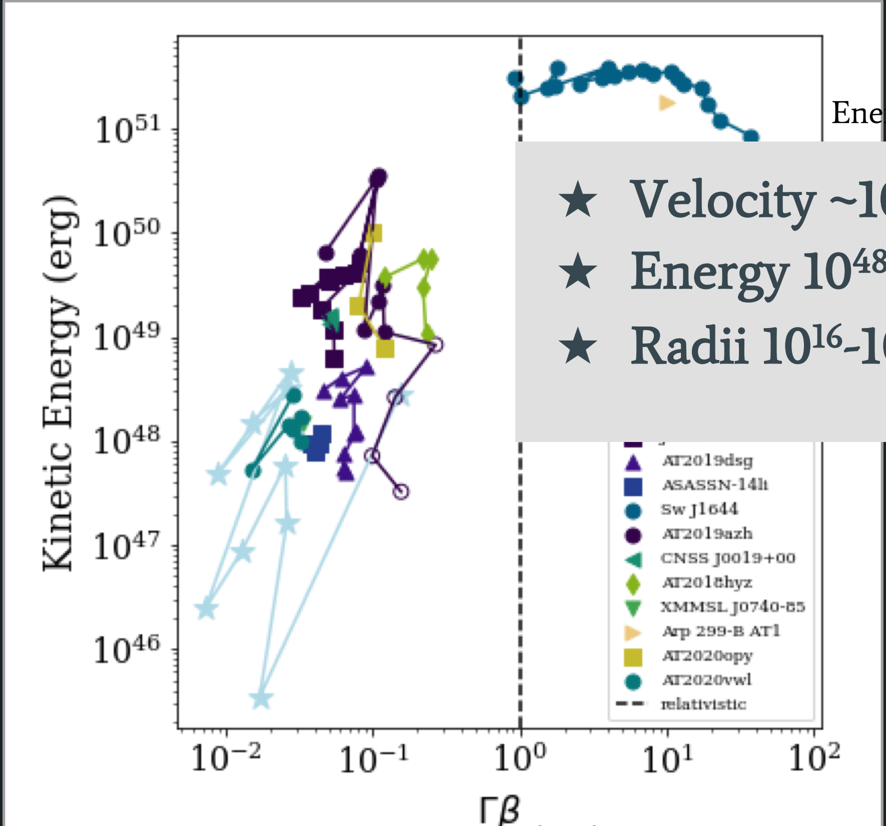


Kinetic energy and velocity



Ambient density and Radius

Putting it all together: what do outflows from TDEs look like?



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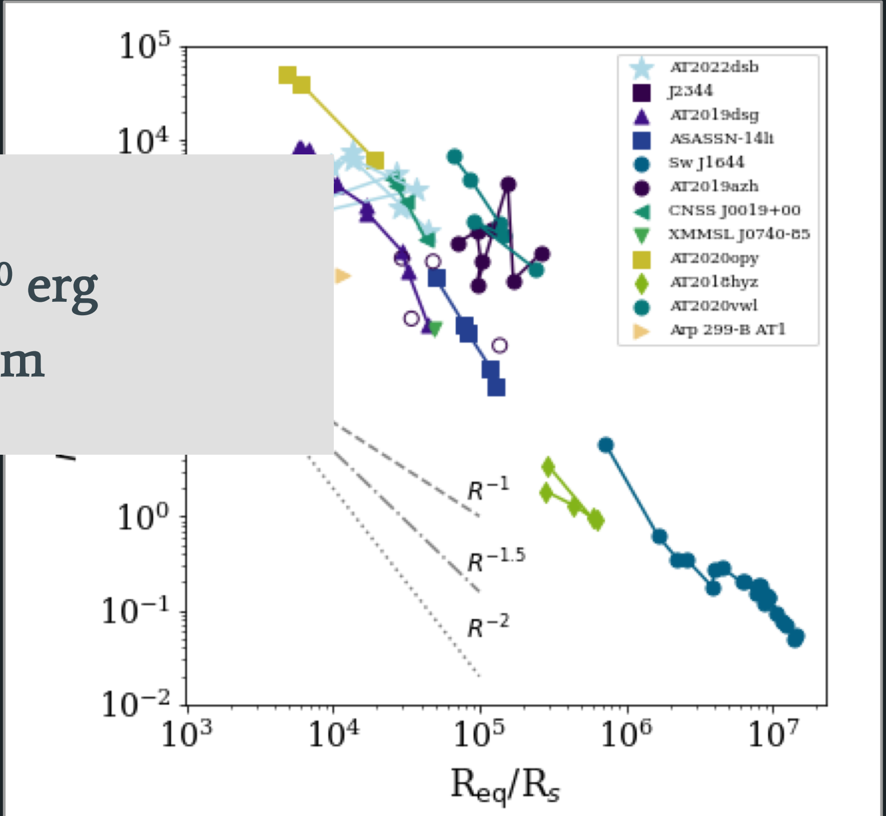


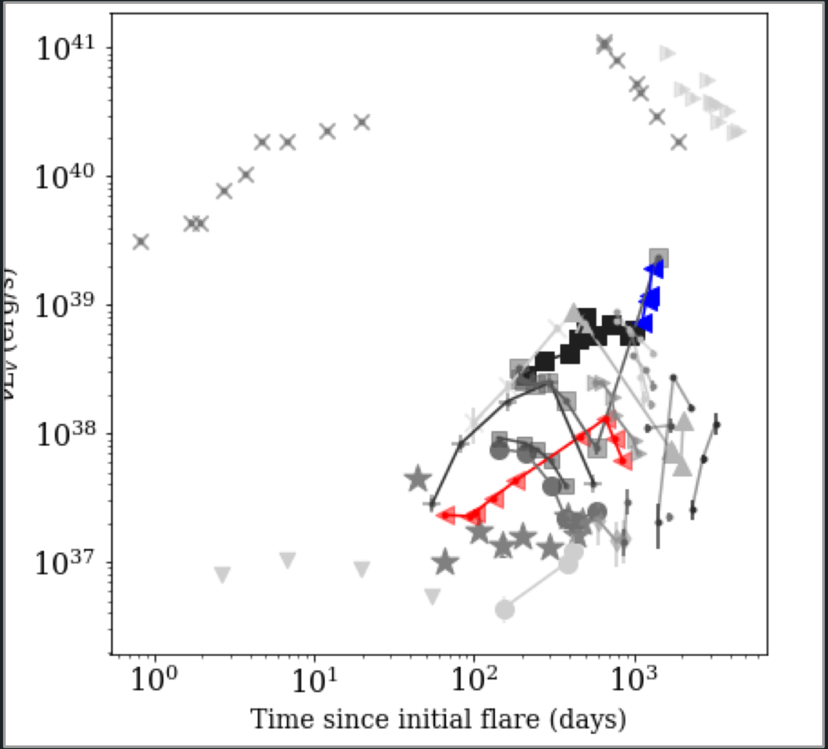
Ambient density and Radius

- ★ Velocity ~10%c
- ★ Energy 10^{48}-10^{50} erg
- ★ Radii 10^{16}-10^{17} cm

Prompt vs delayed outflows

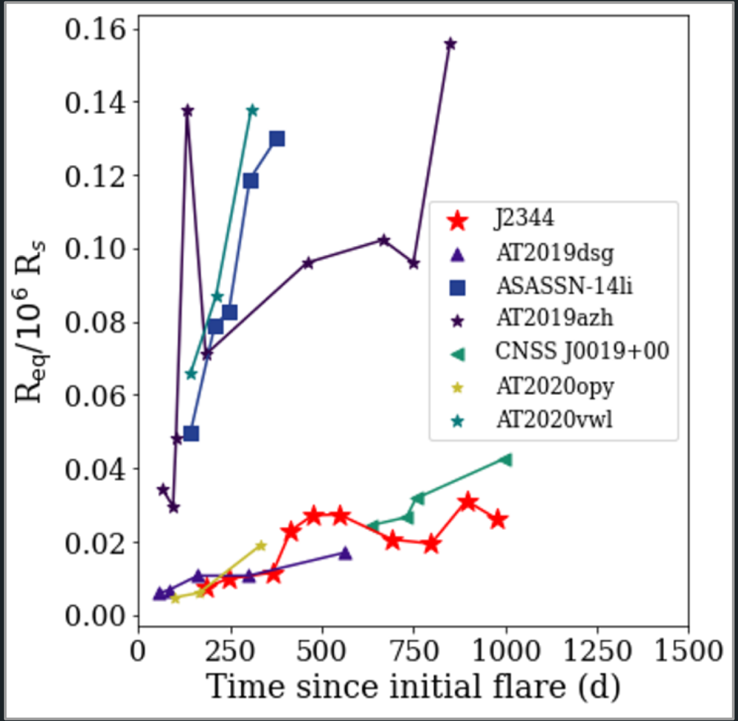
For many outflows the radius can be tracked back to R=0, coincident with the time of the optical flare, e.g. AT2019azh

In some cases, the modelling indicates the outflow was launched well after the optical flare, e.g. AT2018hyz



When are outflows launched?

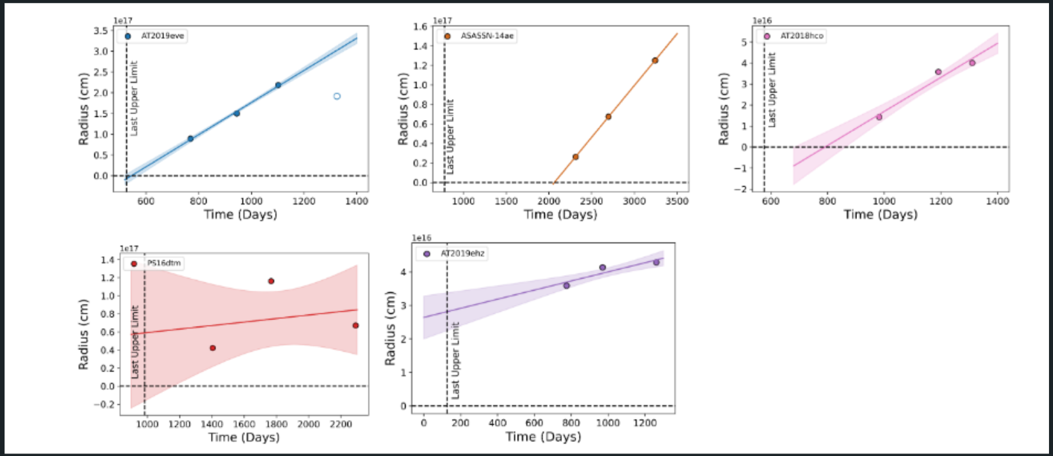
Outflow launch date is coincident with initial flare in some events



Energy

Velocity

Other events seem to launch outflows hundreds of days later (Cendes+2023)



The problem: radio emission is sometimes ambiguous

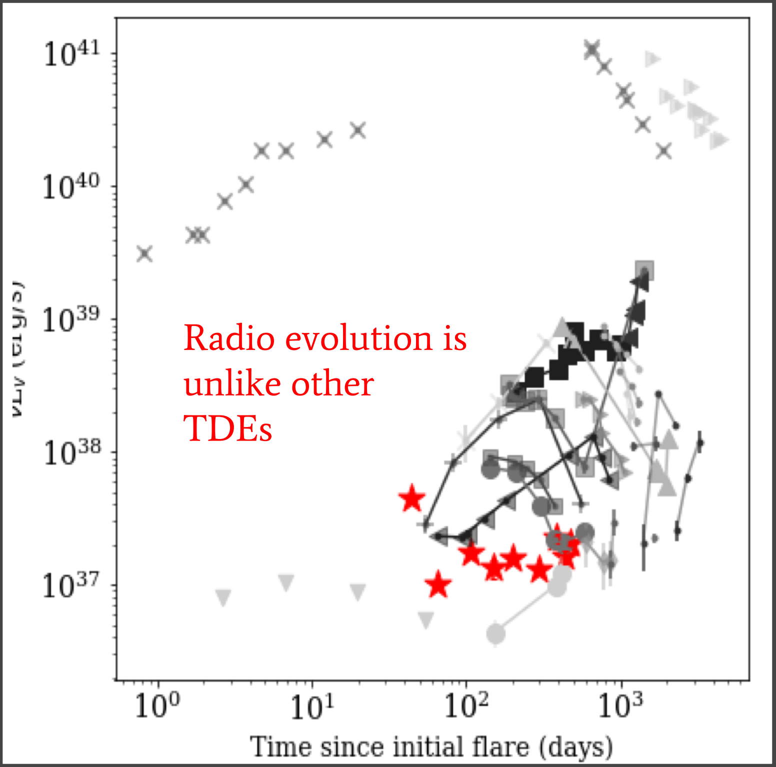
Synchrotron emission is common to a lot of astrophysical phenomena.

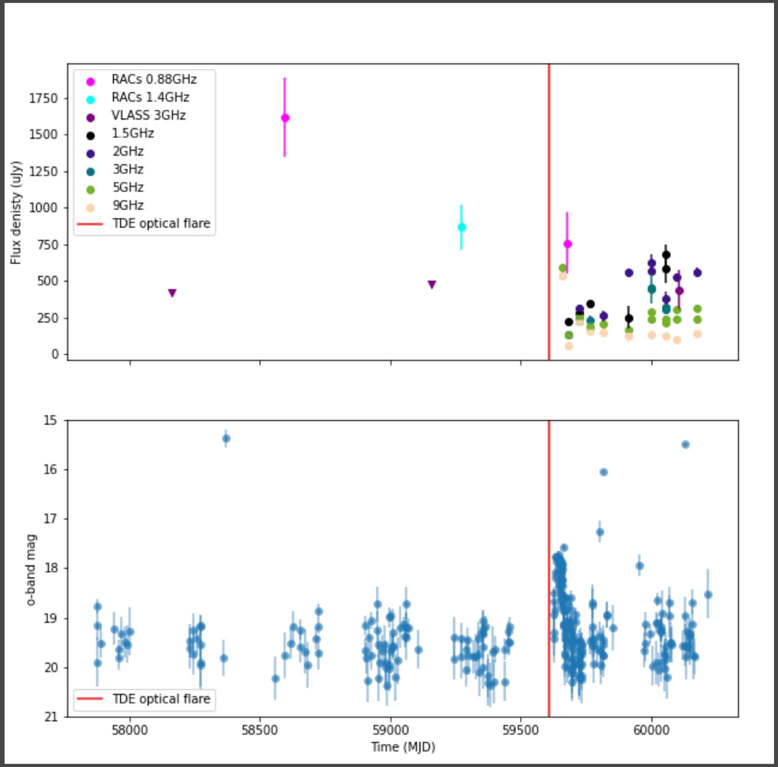
AGN produce a lot of radio emission, that can be variable. So how do we tell the difference?

Galaxies also can produce radio emission from star-forming regions.

Radio contribution to ambiguous nuclear transients

The strange case of AT2022dsb..



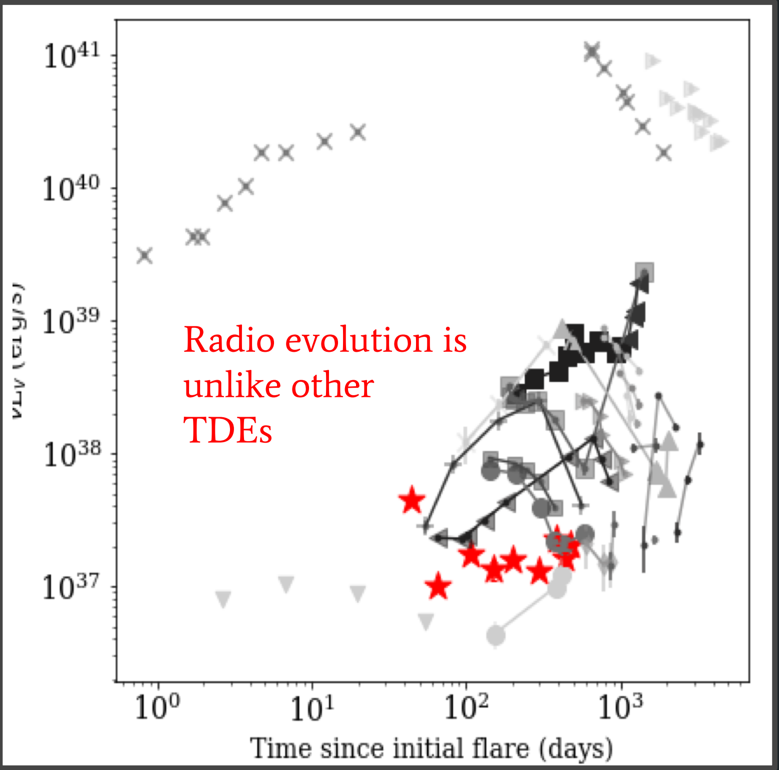


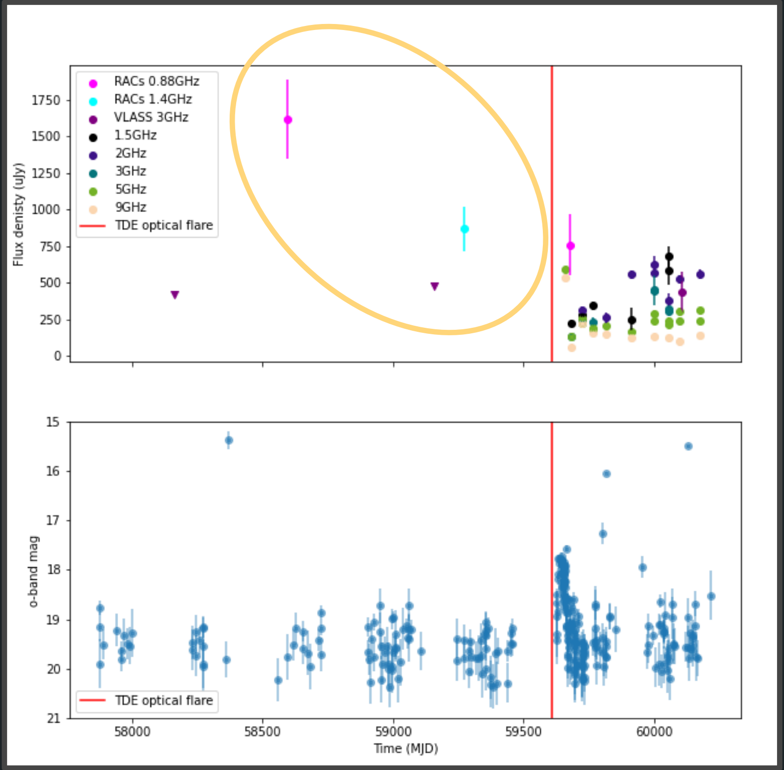
AT2022dsb

The strange case of AT2022dsb..

Radio detections *before* the TDE

- ➢ Brighter radio emission pre-TDE
- ➢ Lots of radio variability post-TDE





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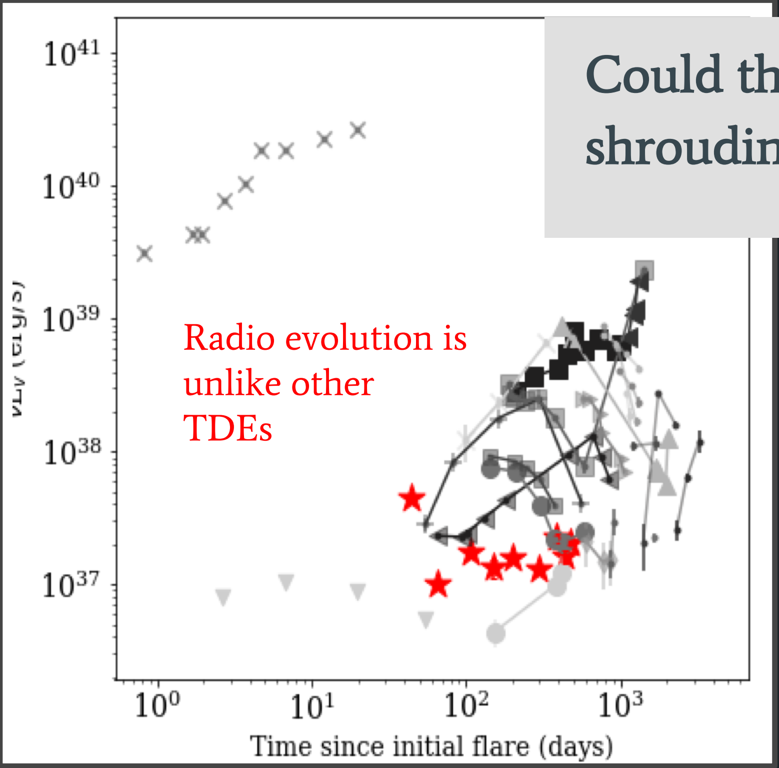
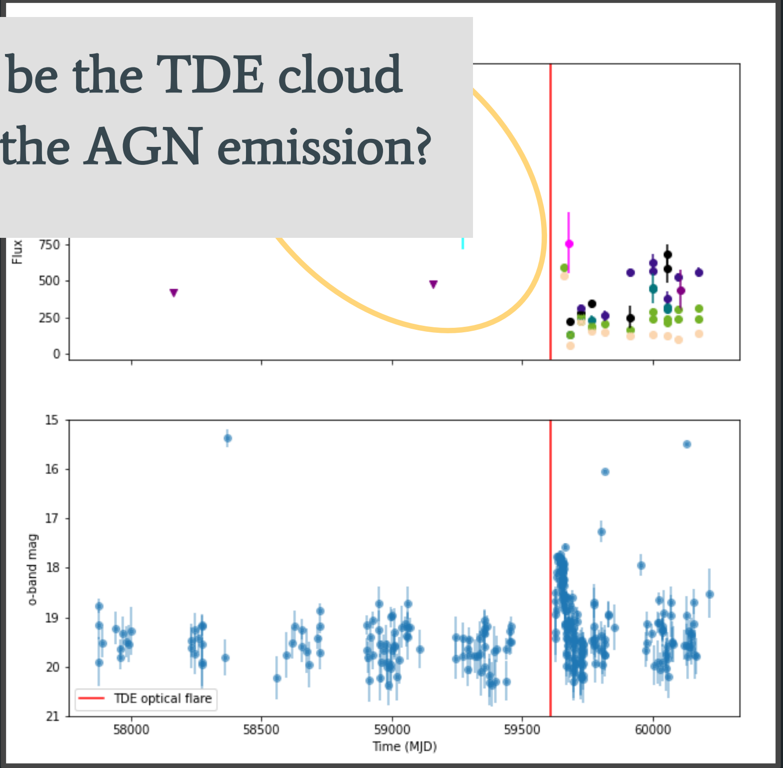


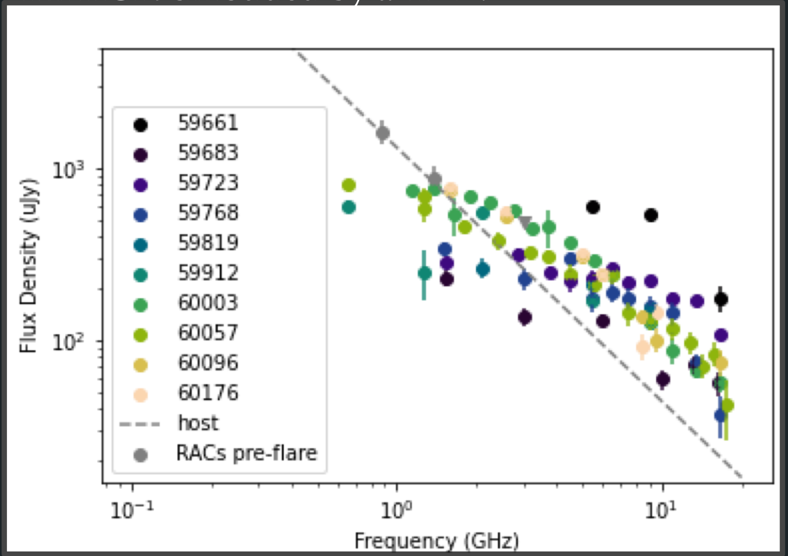
Could this be the TDE cloud shrouding the AGN emission?



AT2022dsb

The strange case of AT2022dsb..

An AGN shrouded by a TDE?



Two things:

1. Significant fading of pre-TDE emission at low freqs
2. Excess emission at high freqs, evolving with time

AT2022dsb

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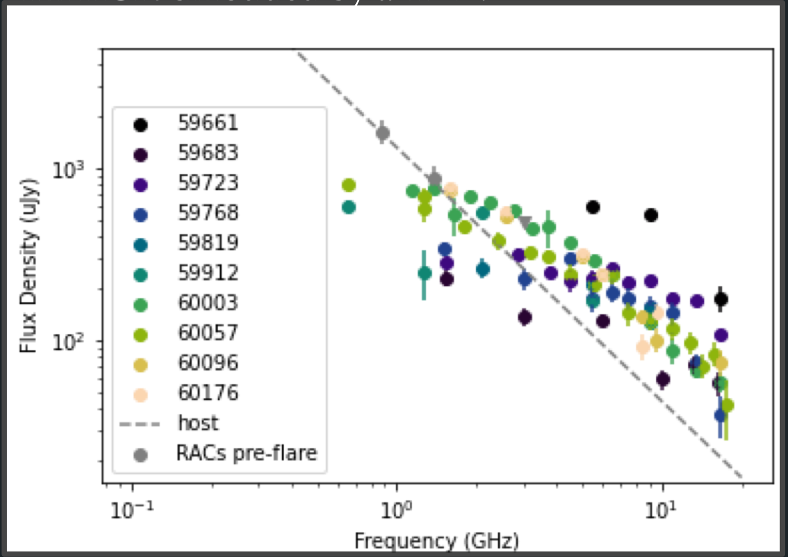

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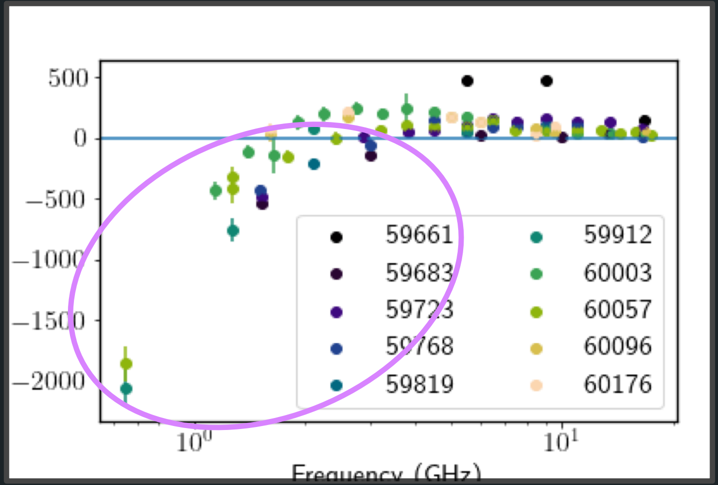

Assume negative flux is due to free free absorption by an inhomogenous cloud

AT2022dsb

The strange case of AT2022dsb..

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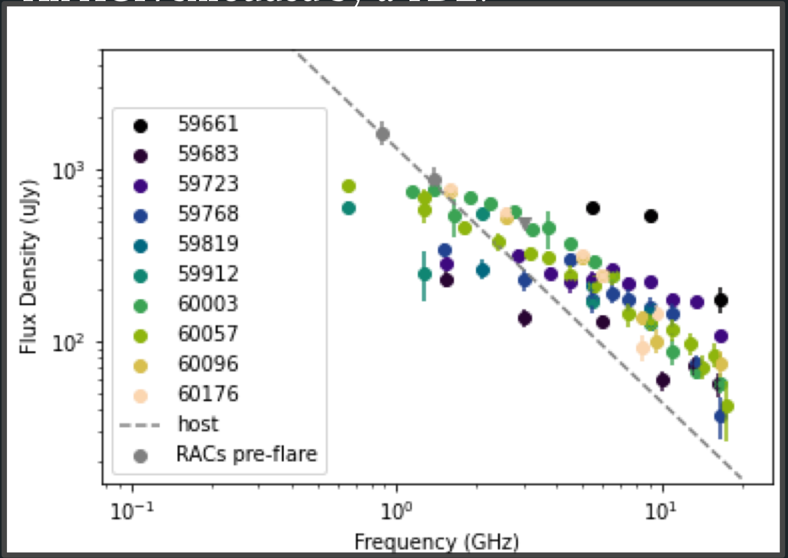

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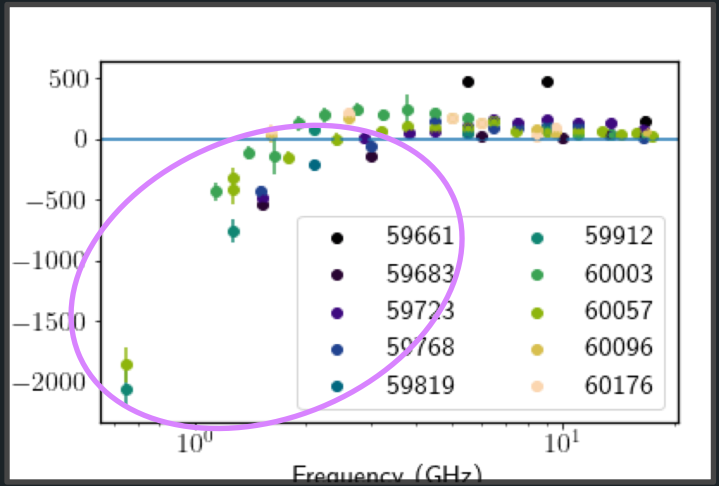

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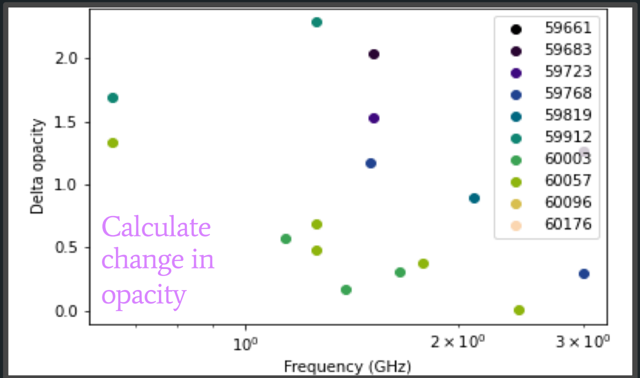
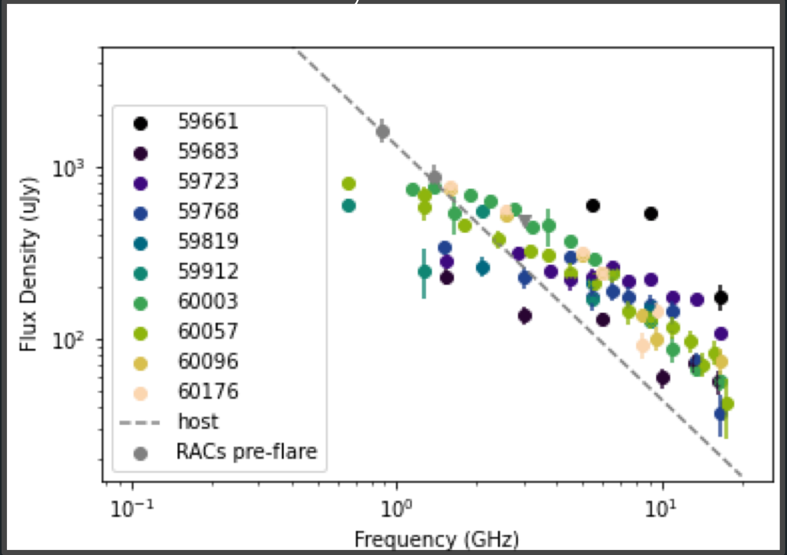


Calculate change in opacity

AT2022dsb

The strange case of AT2022dsb..

An AGN shrouded by a TDE?



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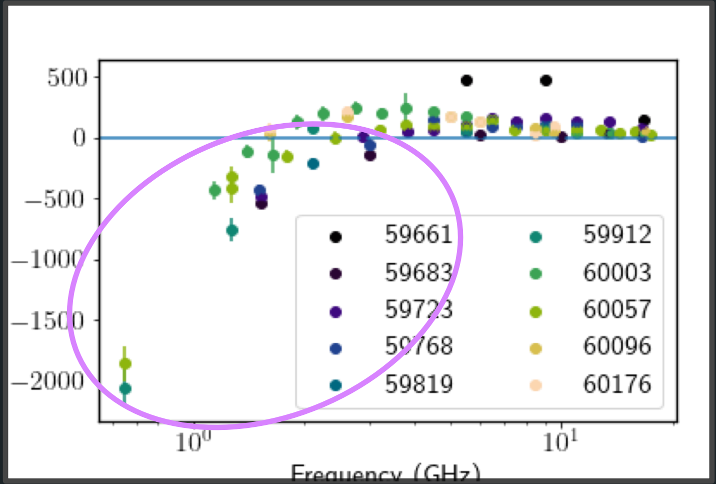

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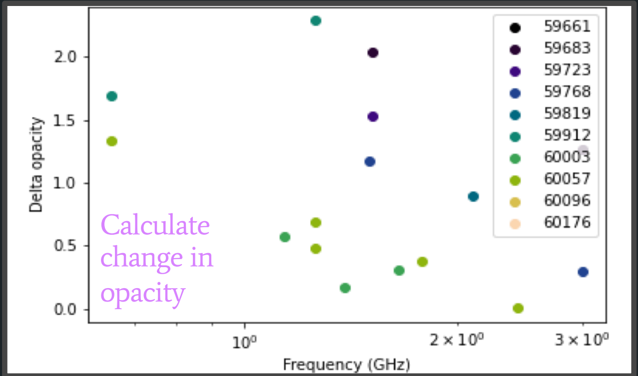
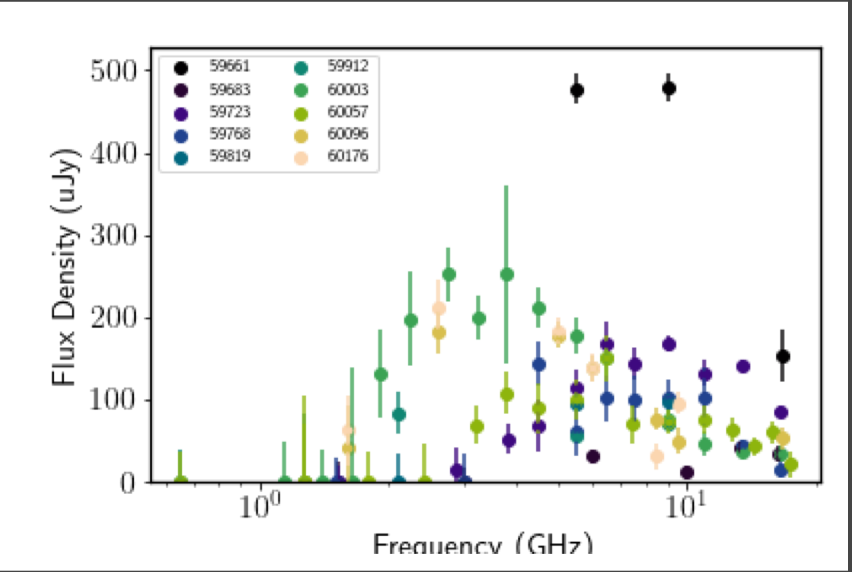


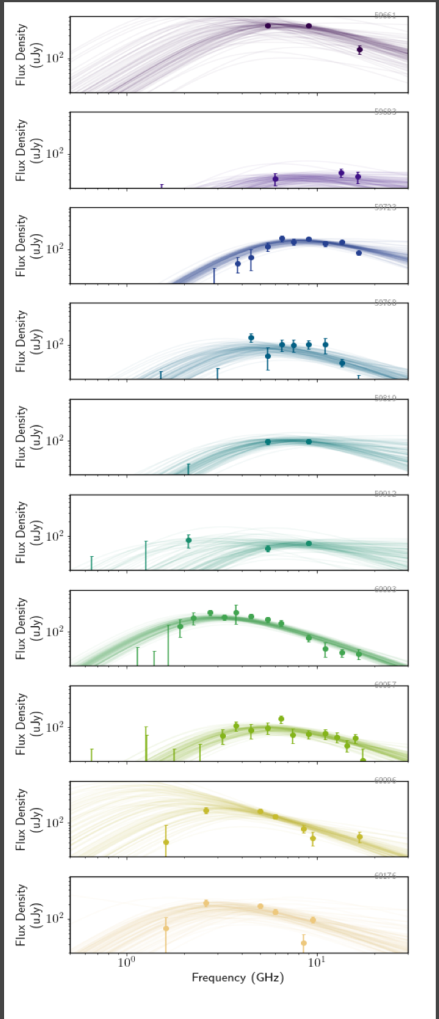
Cloud "blocking" host emission gets less opaque over time

AT2022dsb – what about the excess emission?

The strange case of AT2022dsb..

An AGN shrouded by a TDE?





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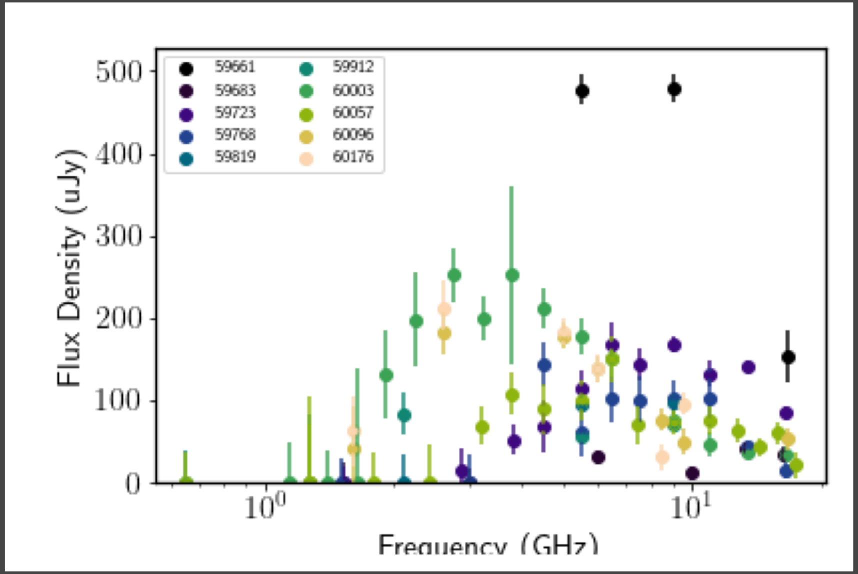
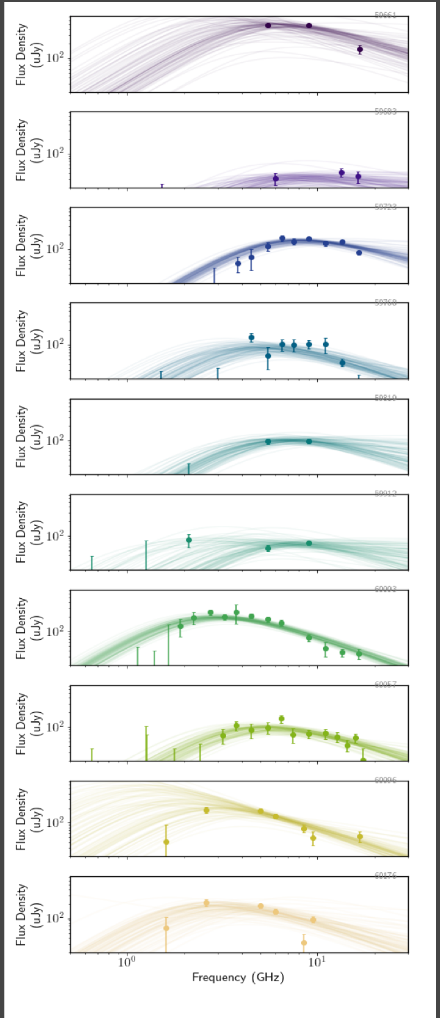


Looks like a faint radio-emitting outflow!



Tutorial Part II: Can you estimate the size of the emitting region for the sources you fit earlier?

Start with va, Fp, p, redshift (z),

Read through derivations in Barniol Duran 2013 (https://ui.adsabs.harvard.edu/abs/2013ApJ...772...78B/abstract)

For each epoch, calculate Req, Eeq, B, ne, and velocity

AT2020vwl
Discovery date: 2020-10-10
Redshift: 0.0325

AT2020opy
Discovery date: 2020-07-08
Redshift: 0.15

Summary

- ★ Radio observations of TDEs track material ejected during the stellar disruption
- ★ Synchrotron emission is produced by interactions with the outflow and the surrounding medium (or from internal shocks in a jet)
- ★ This emission evolves on timescales of months as the outflow expands
- ★ Outflows can be relativistic, narrow jets, or slower spherical shape
- ★ Radio follow-up of TDEs is relatively new but enables detailed insight into the ejected material including
  - ★ Energy, velocity, mass, magnetic field strength
  - ★ Circumnuclear environment of distant galaxies – perhaps key to differences in radio properties
- ★ Lots of open questions such as what produces non-relativistic outflows? Why do a very few number of TDEs appear to produce relativistic jets?