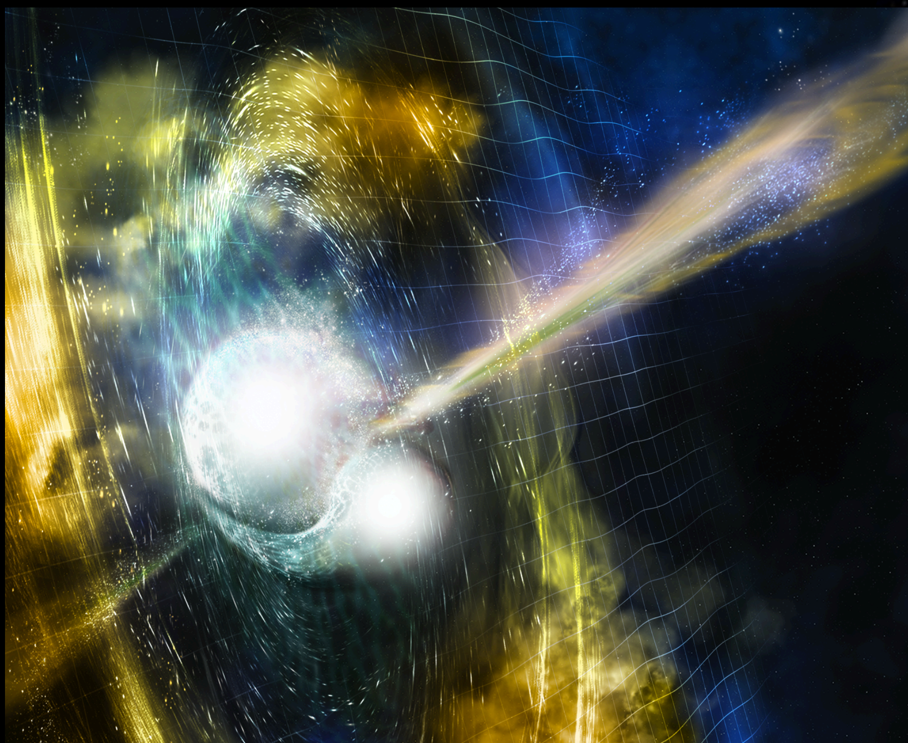
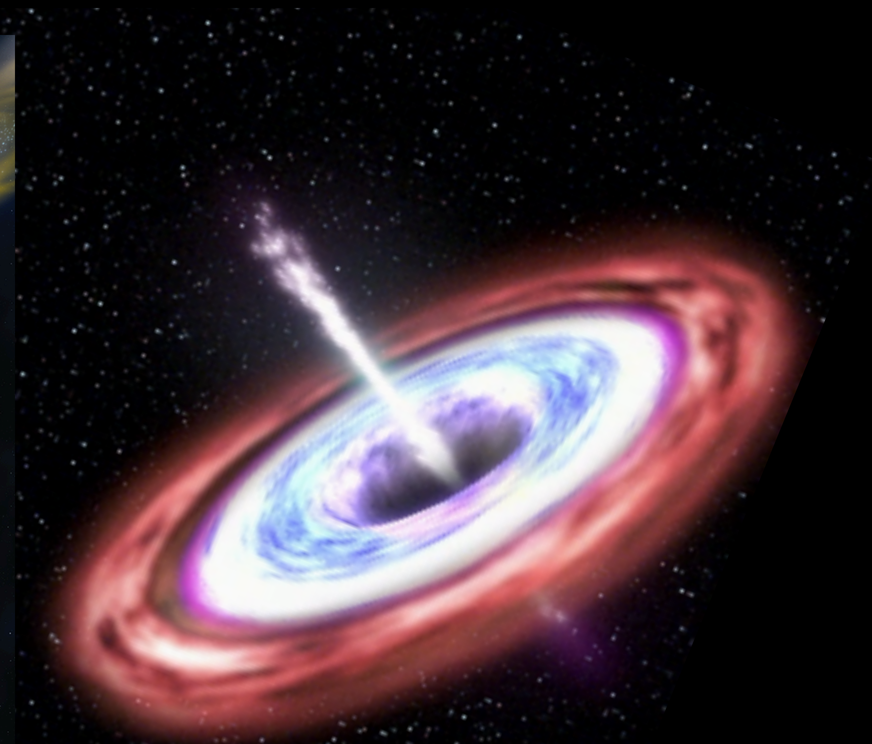
Cosmic Extremes: Probing Energetic Transients with Radio Observations

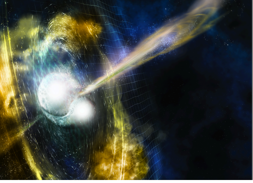




Dr. Kate D. Alexander

NHFP Einstein Postdoctoral Fellow, Northwestern University

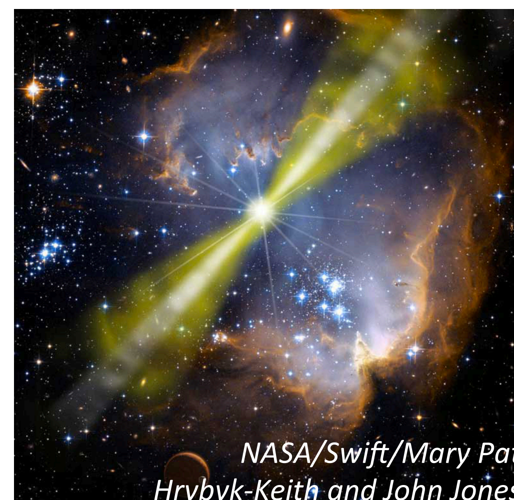
Midwest Workshop on Supernovae and Transients



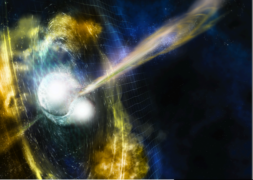
Jets & outflows probe Cosmic Extremes

- **Transient events** reveal **jet evolution** from birth to death
- Jets and outflows let us probe extreme physical processes:
  - The end states of massive stars
  - Black hole formation and growth
- Open questions:
  - How exactly do relativistic jets and outflows form? What physical conditions are required?
  - What is the jet structure?

NASA/JPL-Caltech



NASA/Swift/Mary Pat Hrybyk-Keith and John Jones

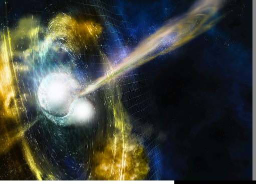


A Multi-Wavelength Perspective

Radio Galaxy Hercules A

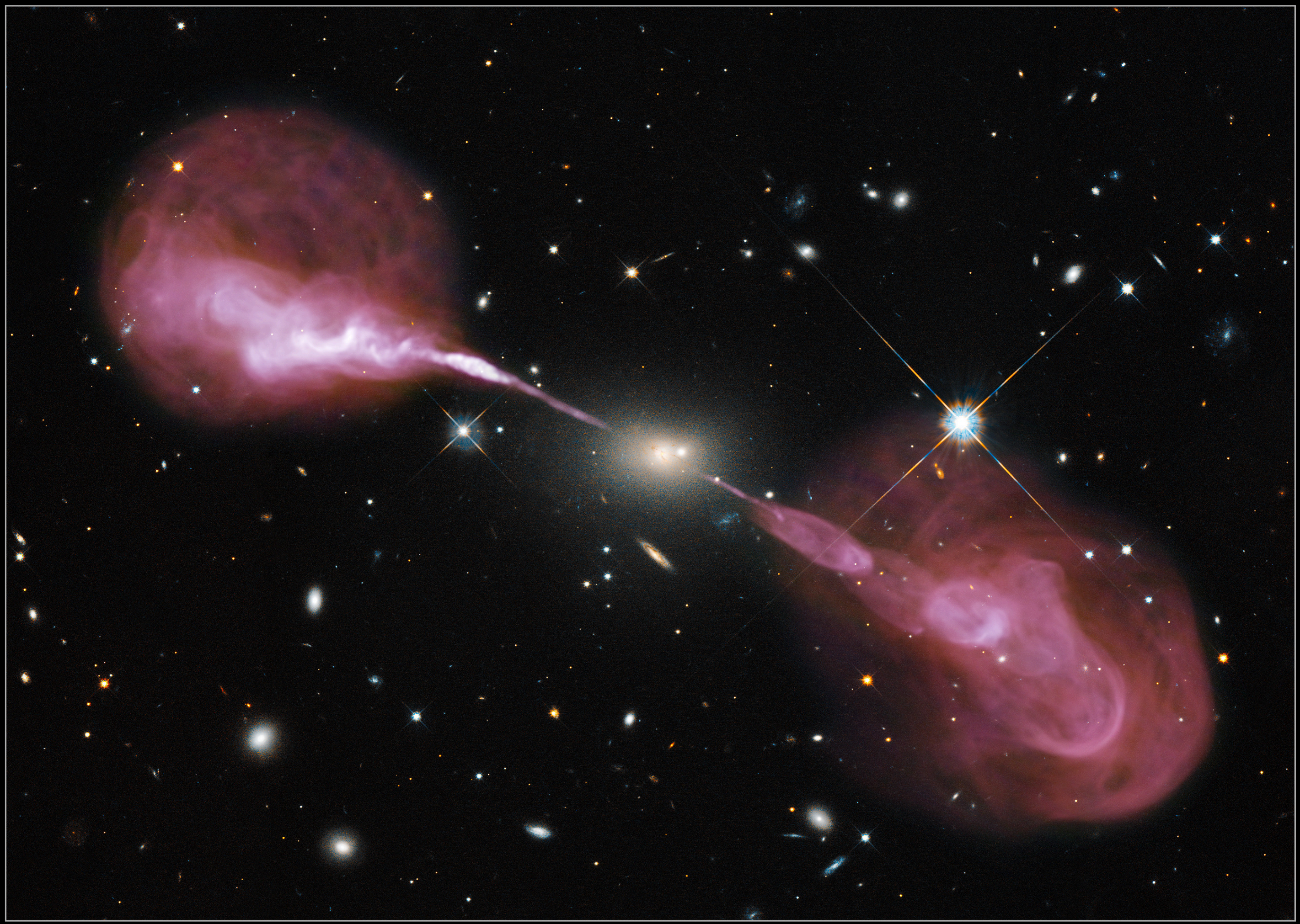
Hubble Heritage

NASA, ESA, NRAO • *HST* WFC3/UVIS • VLA • STScI-PRC12-47



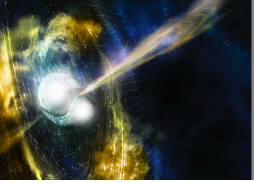
A Multi-Wavelength Perspective

Radio Galaxy Hercules A



Hubble Heritage

NASA, ESA, NRAO • *HST* WFC3/UVIS • VLA • STScI-PRC12-47

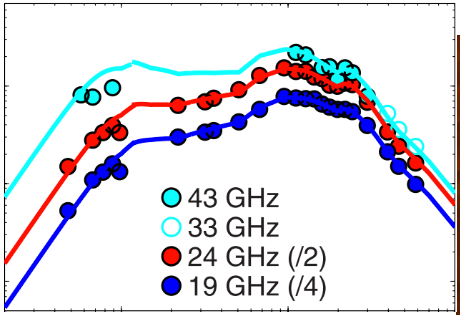


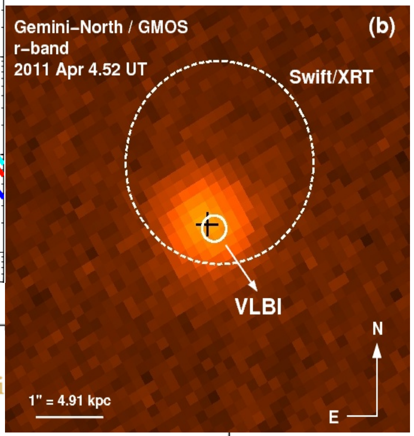
A special role for radio astronomy

Radio observations of transients **uniquely** constrain:

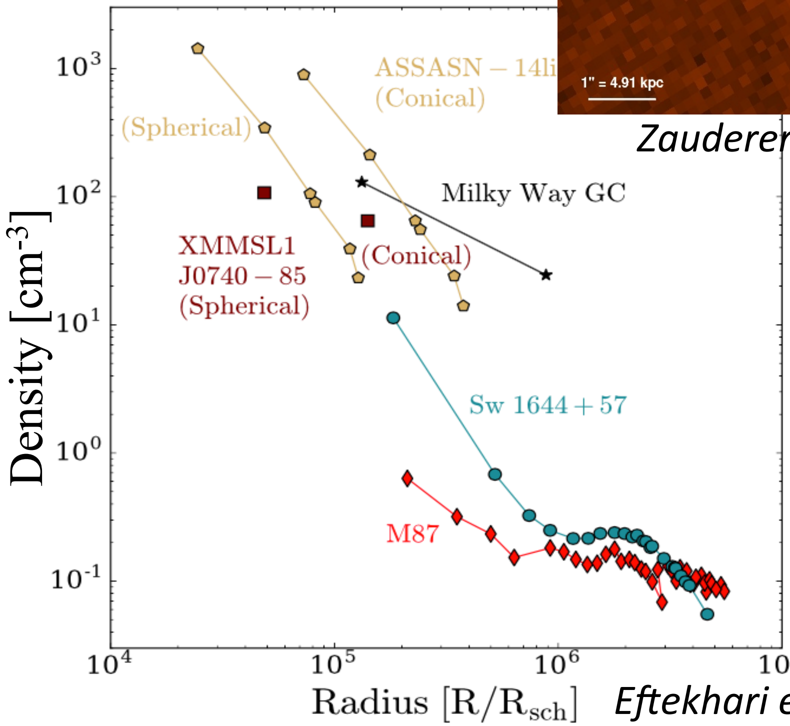
- Localization
- Velocity / energy scale
  - Beaming
  - radius constraints and size evolution
- Ambient density profile
- Magnetic field strength/ outflow line-of-sight orientation (via polarization)

Berger et al. (2012)

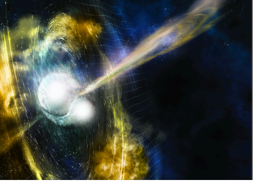




Zauderer et al. (2011)



Eftekhari et al. (2018)



Radio Interferometers Today

- **VLA, ATCA, ALMA,** LOFAR, MWA, ASKAP, MeerKAT, etc.
- To date: surveying large areas of the sky at high sensitivity and resolution is difficult, very time consuming
  - Most radio transients are discovered first at other wavelengths
- Future: era of all-sky radio surveys, real-time transient searches (SKA, others)
  - A better understanding of known radio transient populations will inform survey strategies

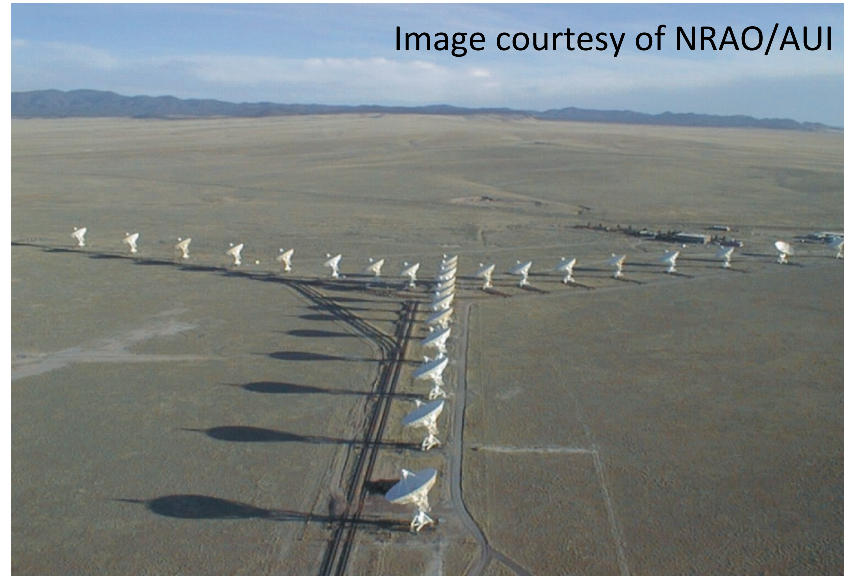
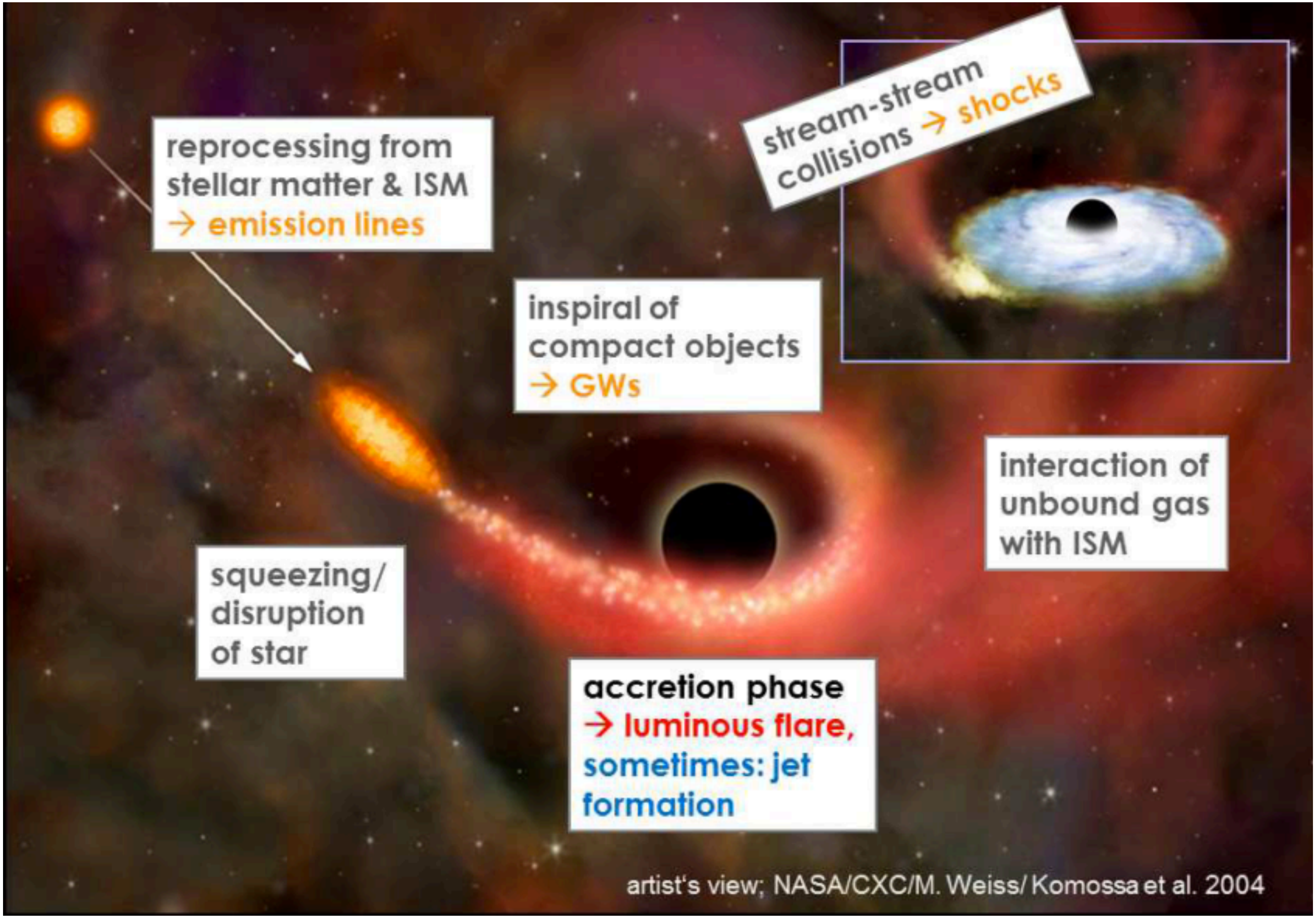
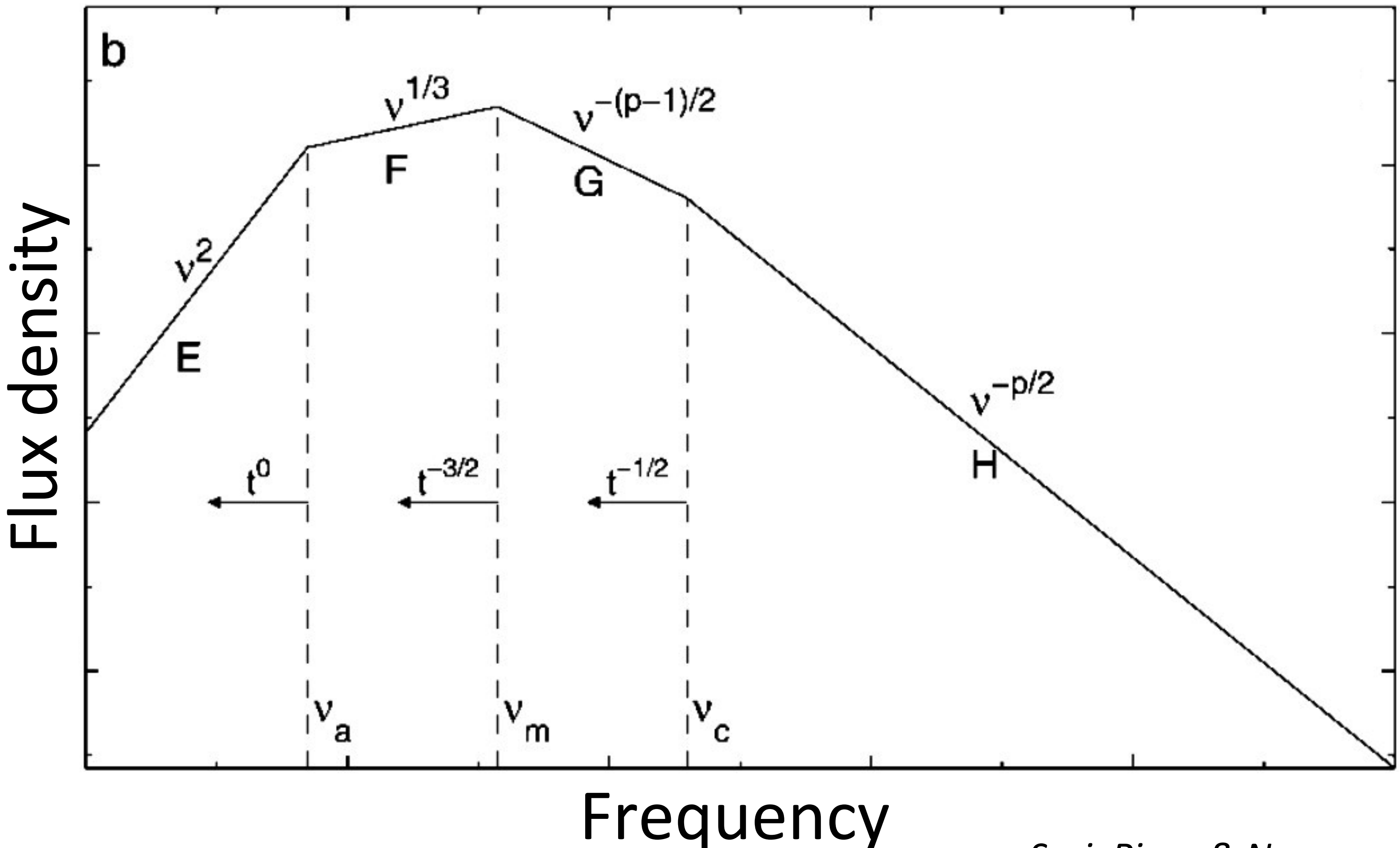


Image courtesy of NRAO/AUI

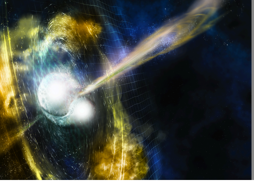
Tidal Disruption Events (TDEs)



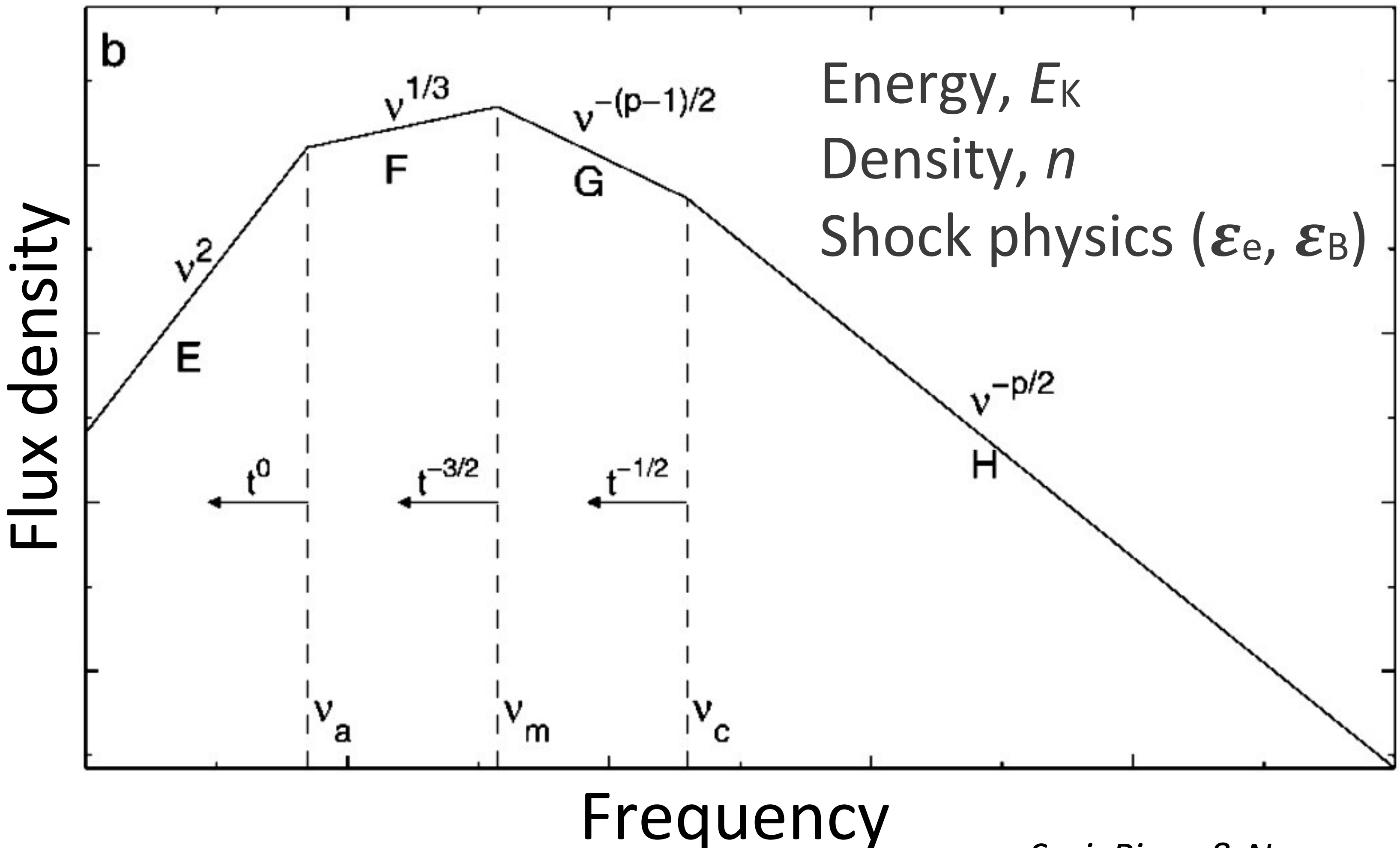
Outflows Generate Synchrotron Emission



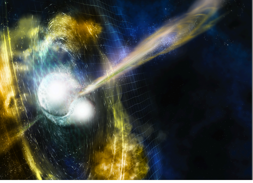
Sari, Piran & Narayan (1998)
Slide courtesy T. Laskar



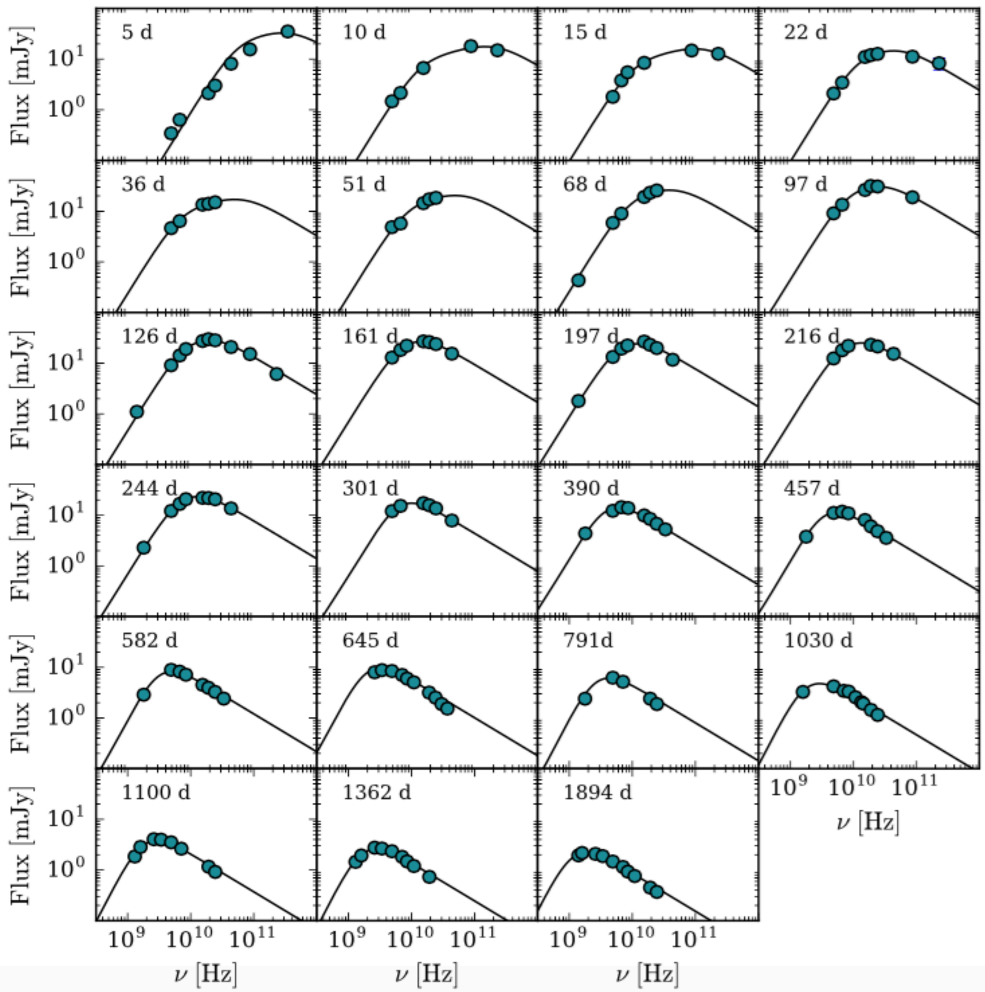
Outflows Generate Synchrotron Emission



Sari, Piran & Narayan (1998)
Slide courtesy T. Laskar

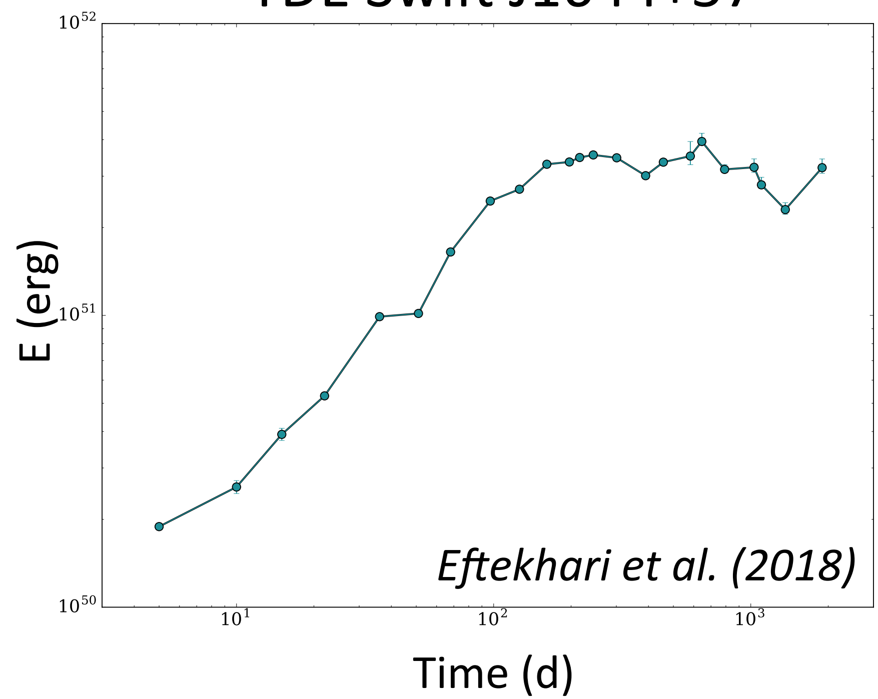


Outflows Generate Synchrotron Emission

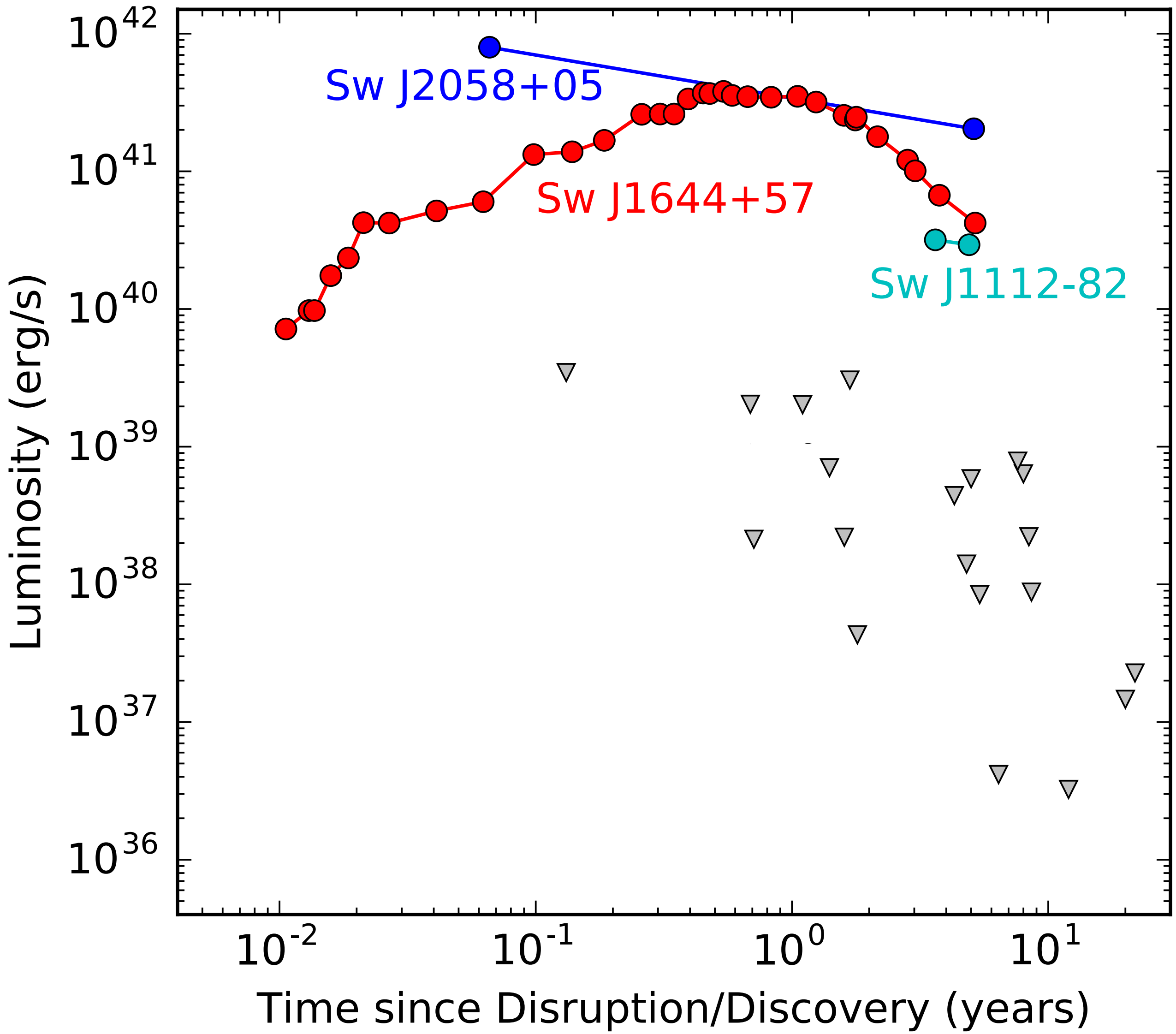


Eftekhari et al. (2018)

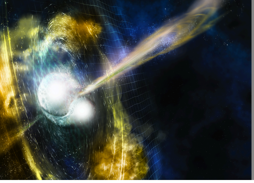
TDE Swift J1644+57



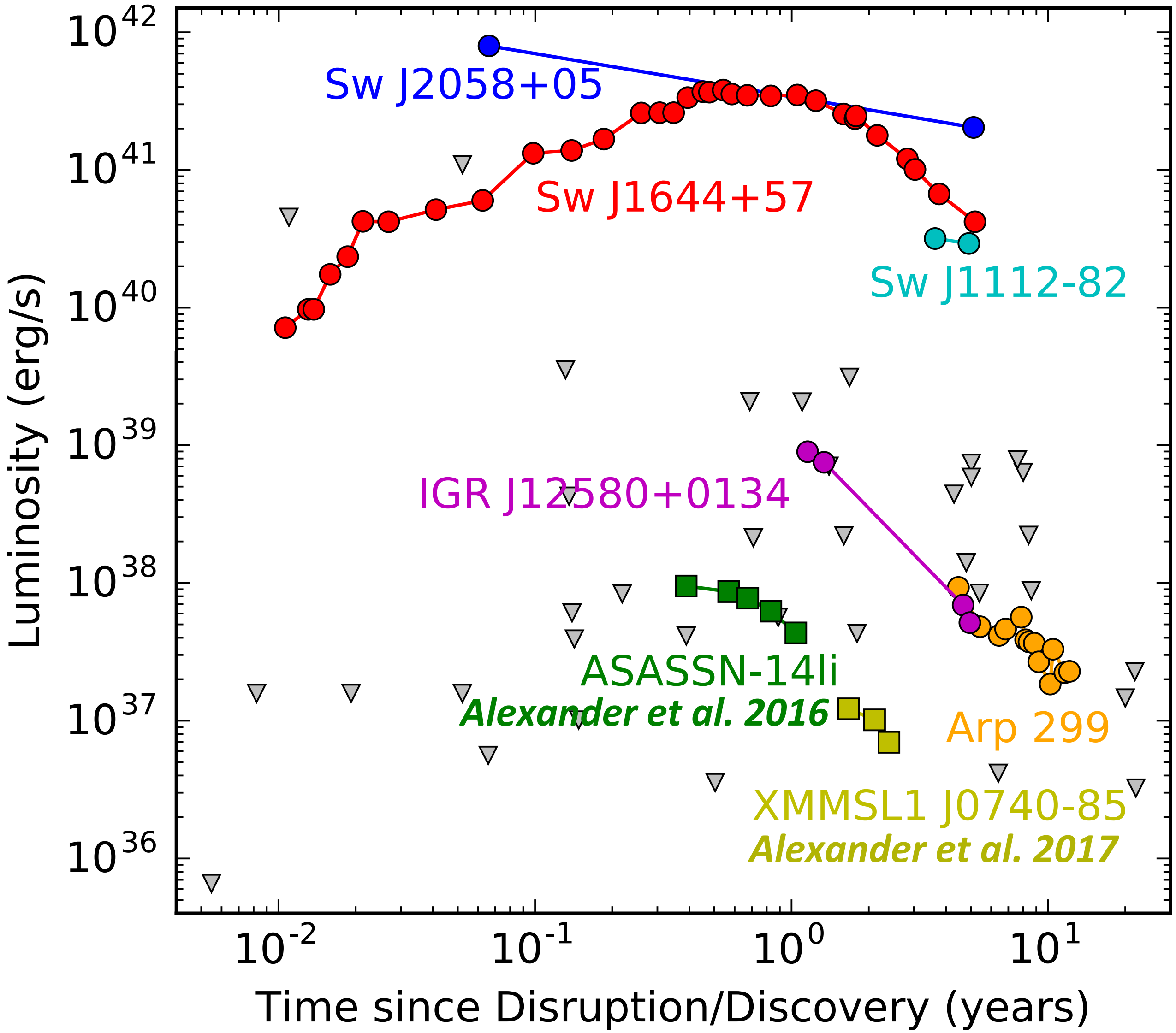
TDE Radio Observations (2014)



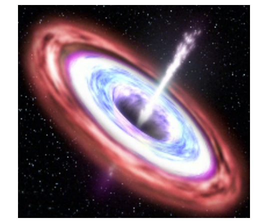
On-axis jet



TDE Radio Observations (2019)

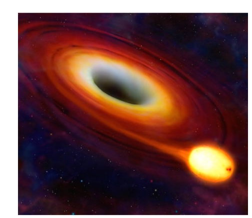


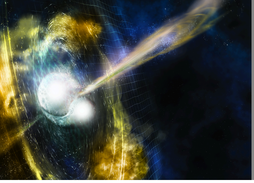
On-axis jet



Off-axis jet

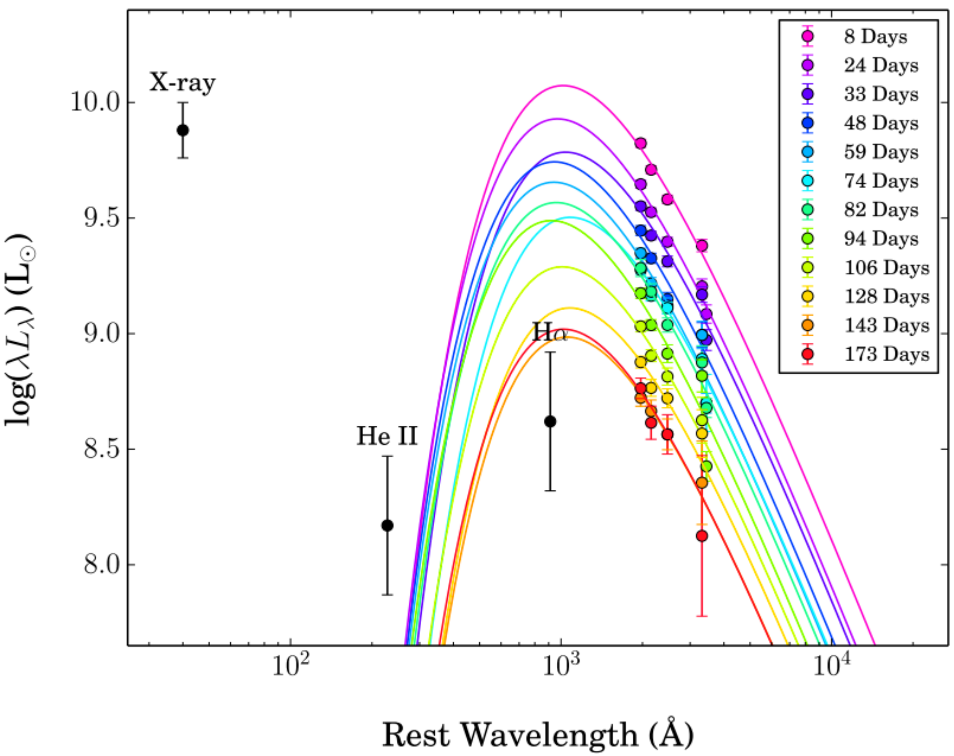
Non-relativistic outflow



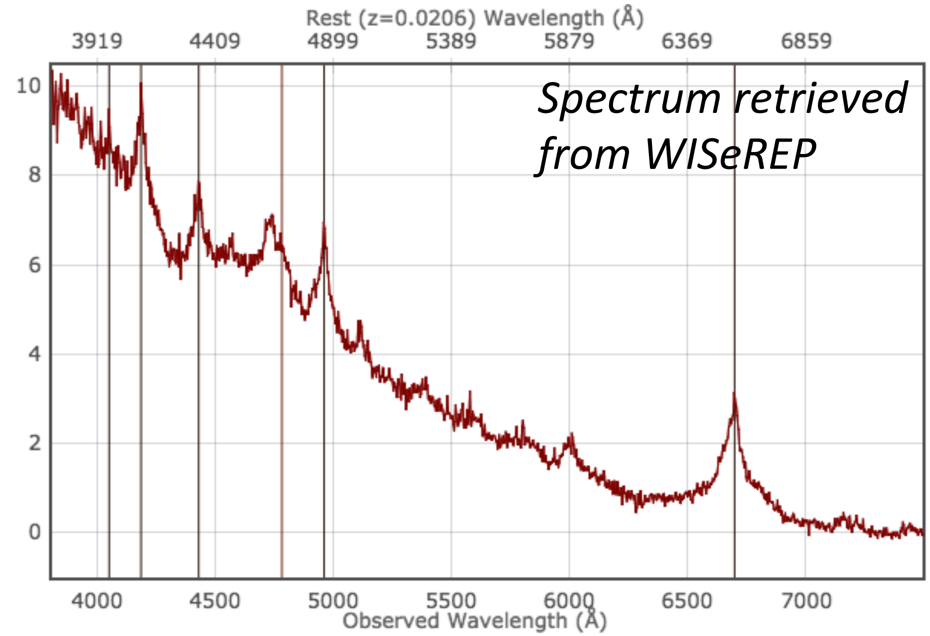


ASASSN-14li: A "typical" TDE?

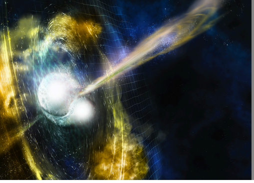
- Discovered November 22, 2014 by the ASAS-SN survey
- Nearby (~90 Mpc)



Holoien et al. (2016)

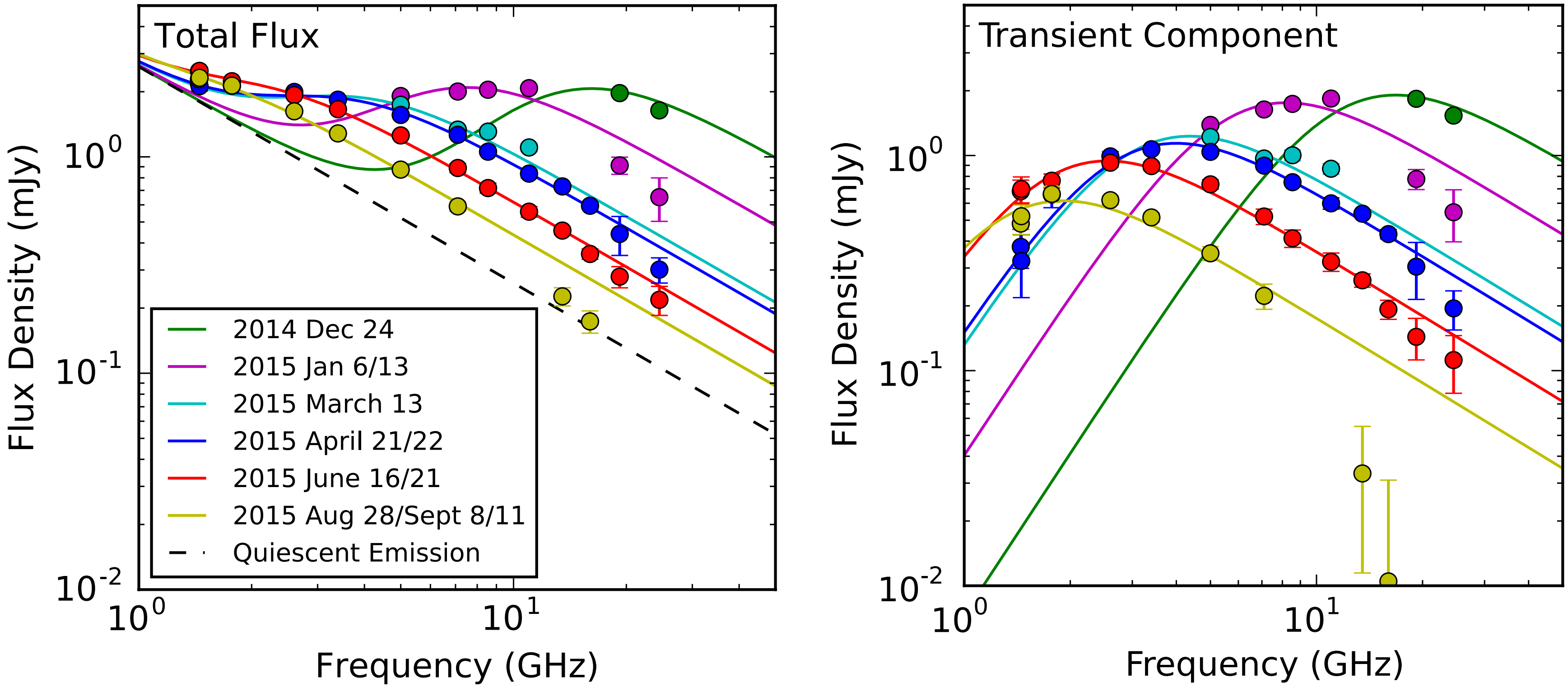


- X-ray, UV, optical observations are consistent with previous TDEs, rule out AGN, supernova (Holoien et al. 2016, Miller et al. 2015)

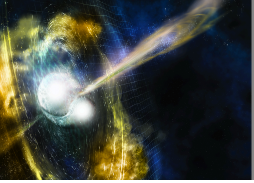


ASASSN-14li: VLA Observations

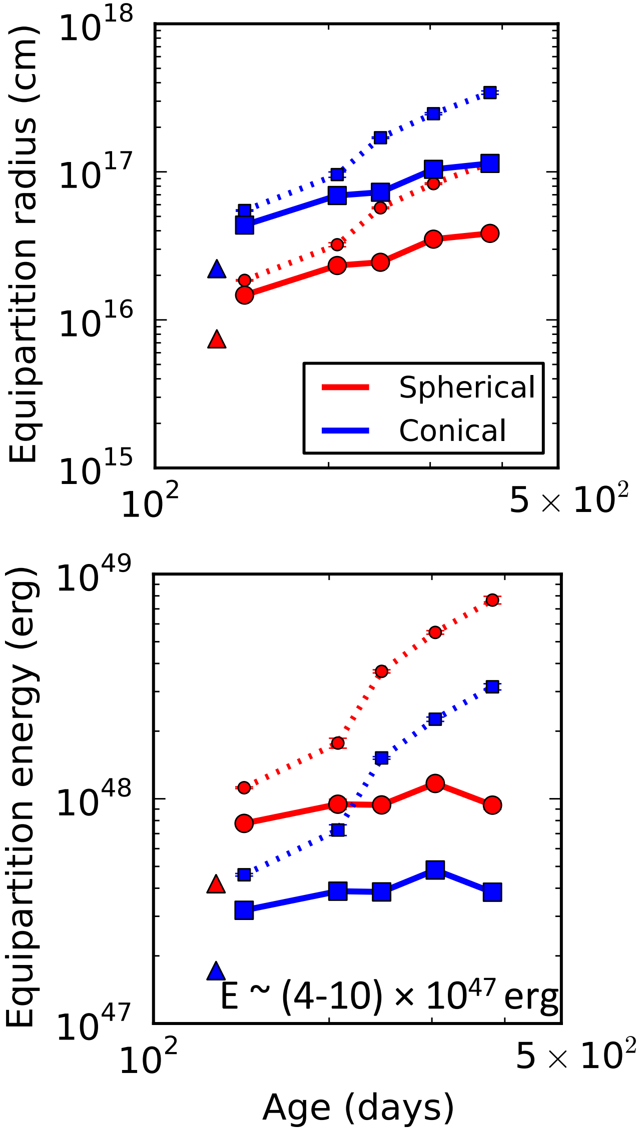
adapted from Alexander et al. (2016)



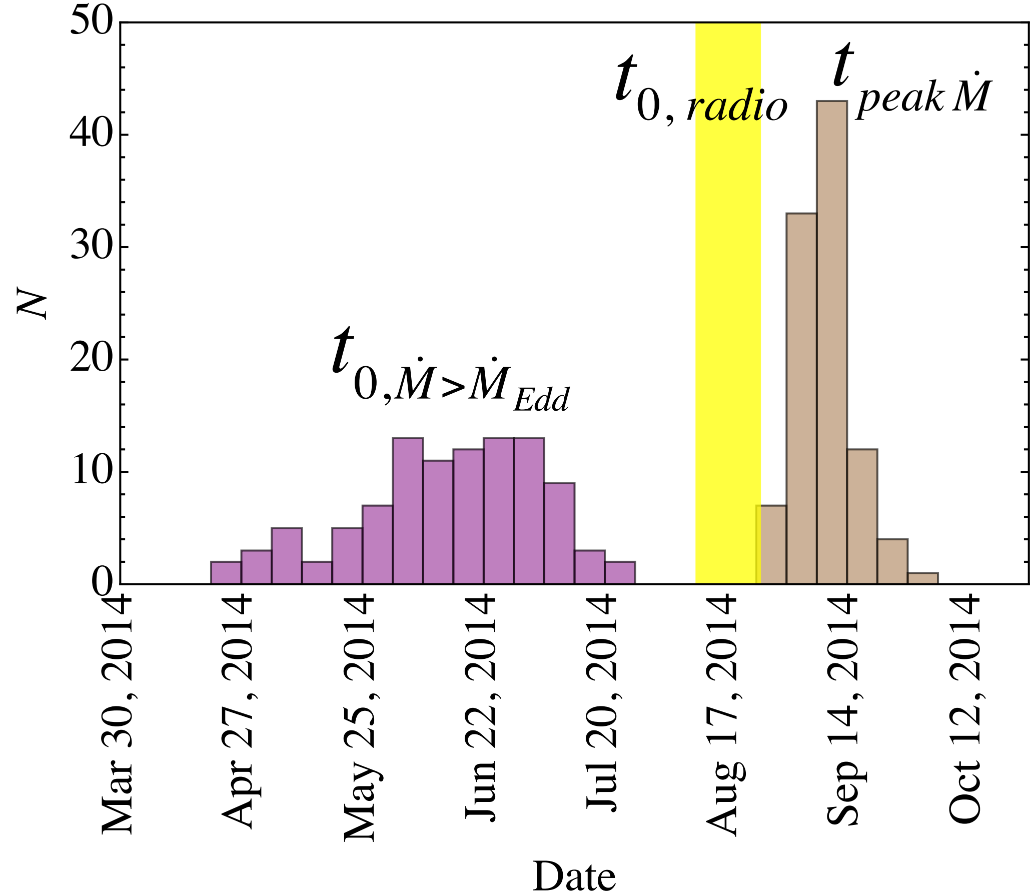
- The emission is best modeled as the sum of a steady source with $F \alpha \nu^{-1}$ (dashed line) and a transient component (right panel)
- The steady component is broadly consistent with archival detections in 1993 and 1999



A Non-Relativistic Outflow

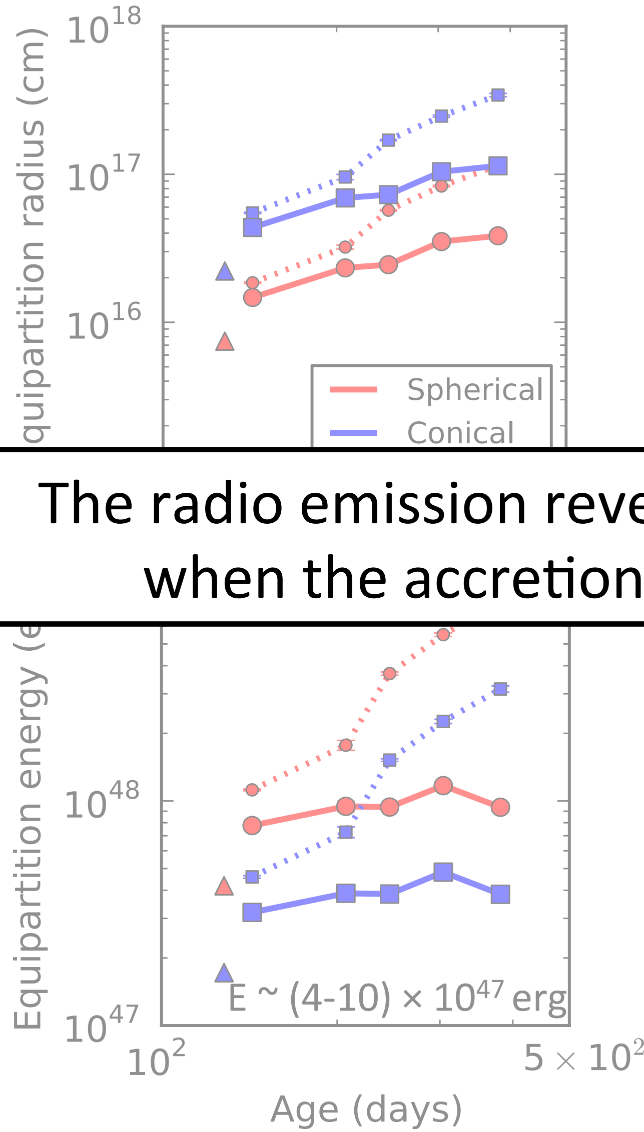


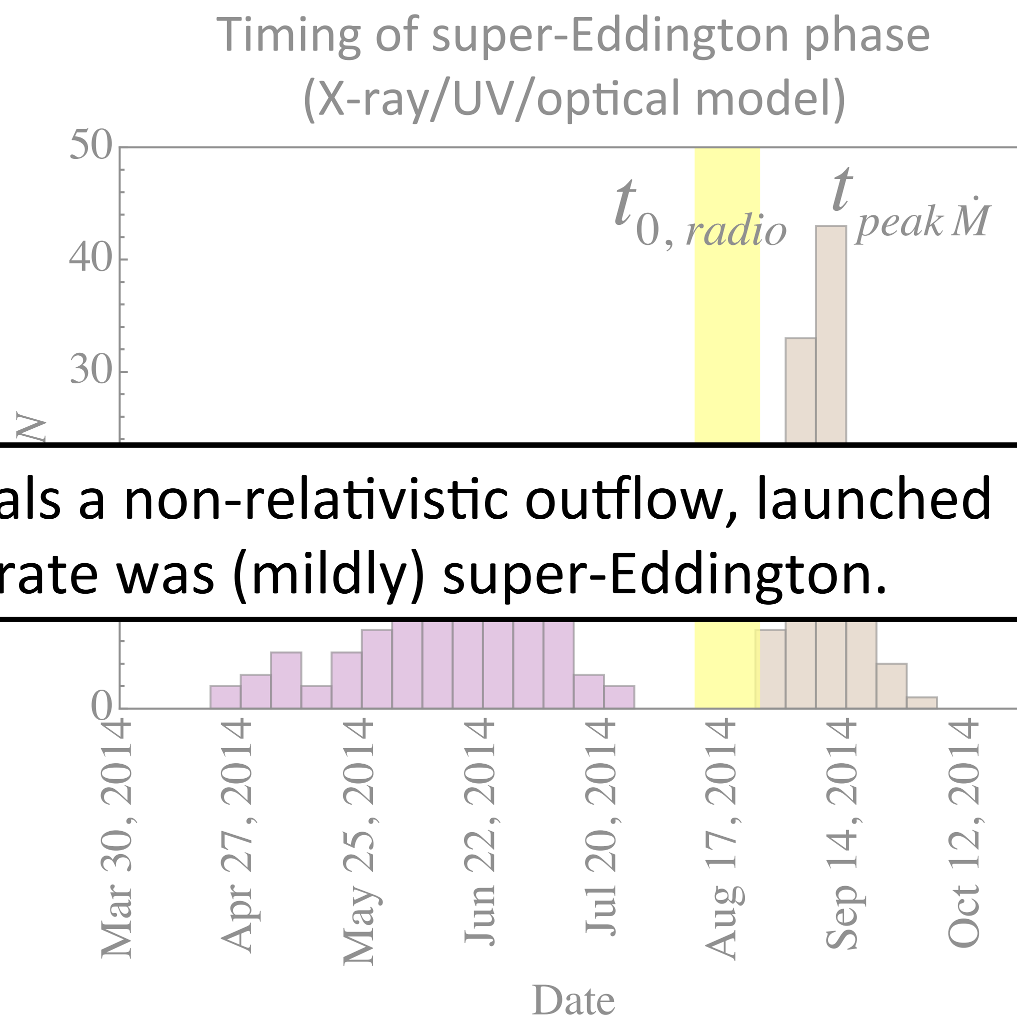
Timing of super-Eddington phase
(X-ray/UV/optical model)



Alexander et al. (2016)

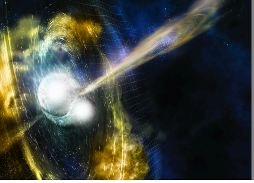
A Non-Relativistic Outflow



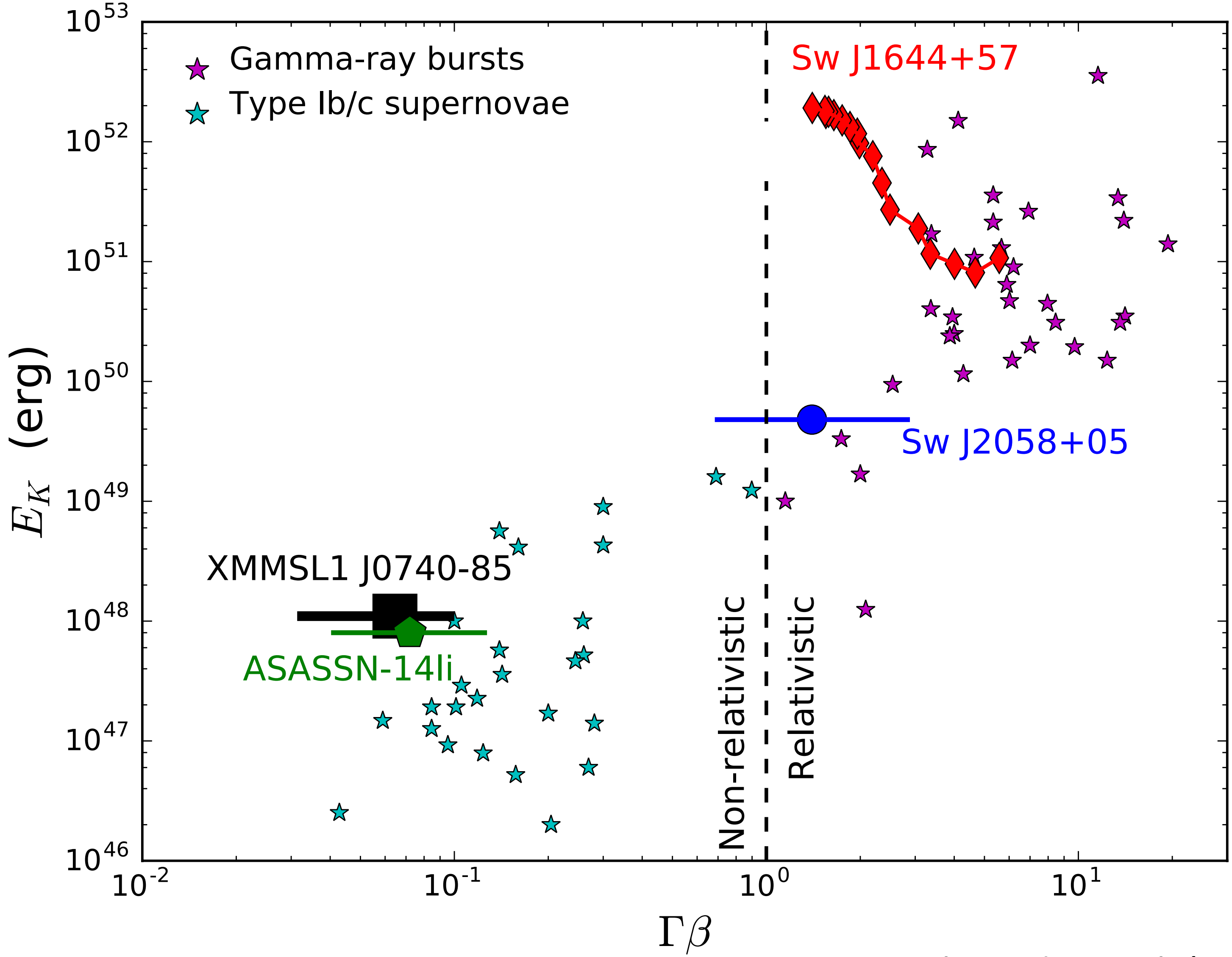


The radio emission reveals a non-relativistic outflow, launched when the accretion rate was (mildly) super-Eddington.

Alexander et al. (2016)

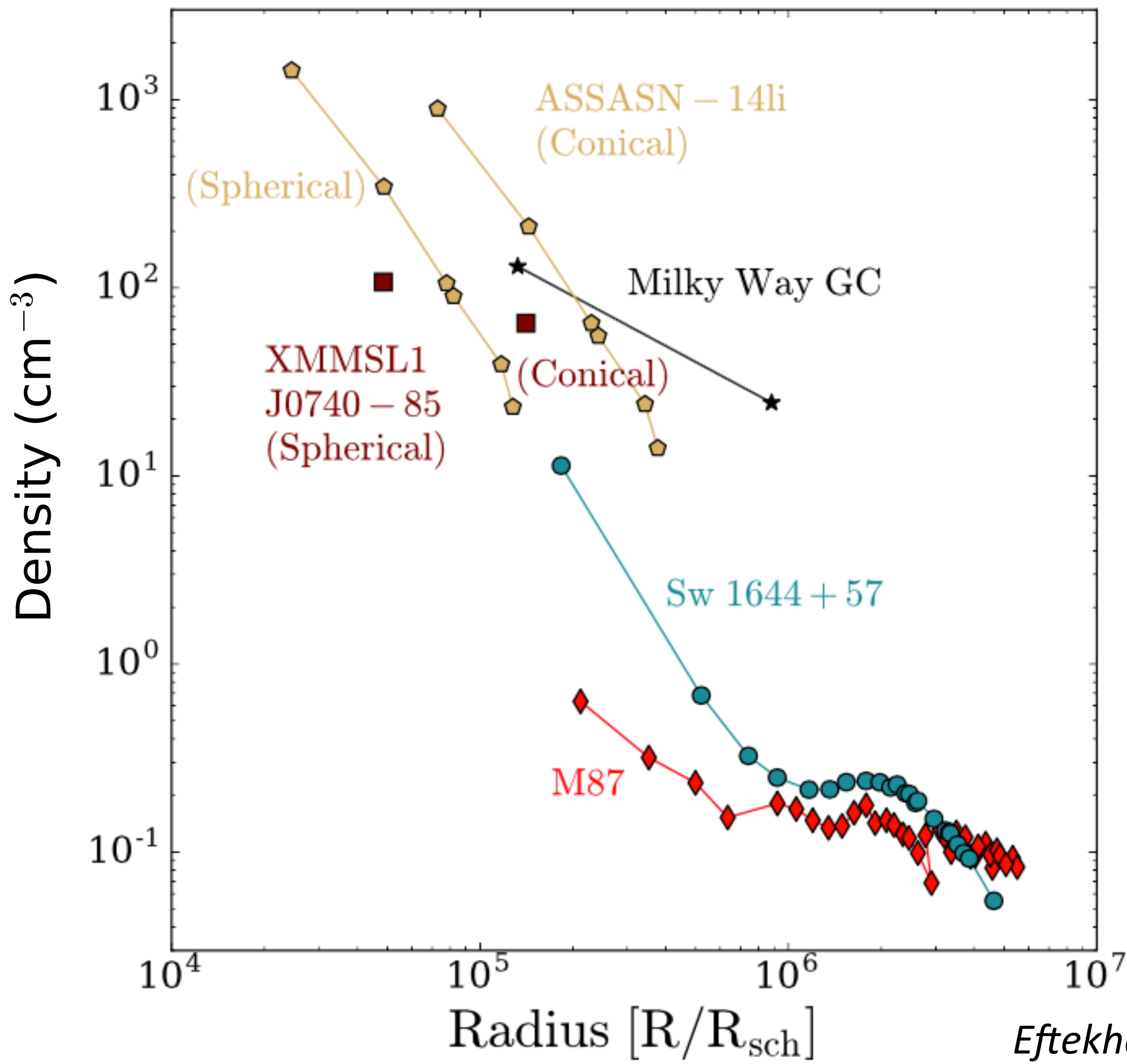


TDE Energetics

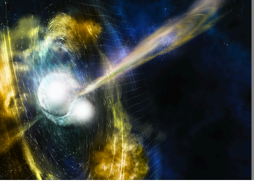


Alexander et al. (2017)

Circumnuclear Density Profiles

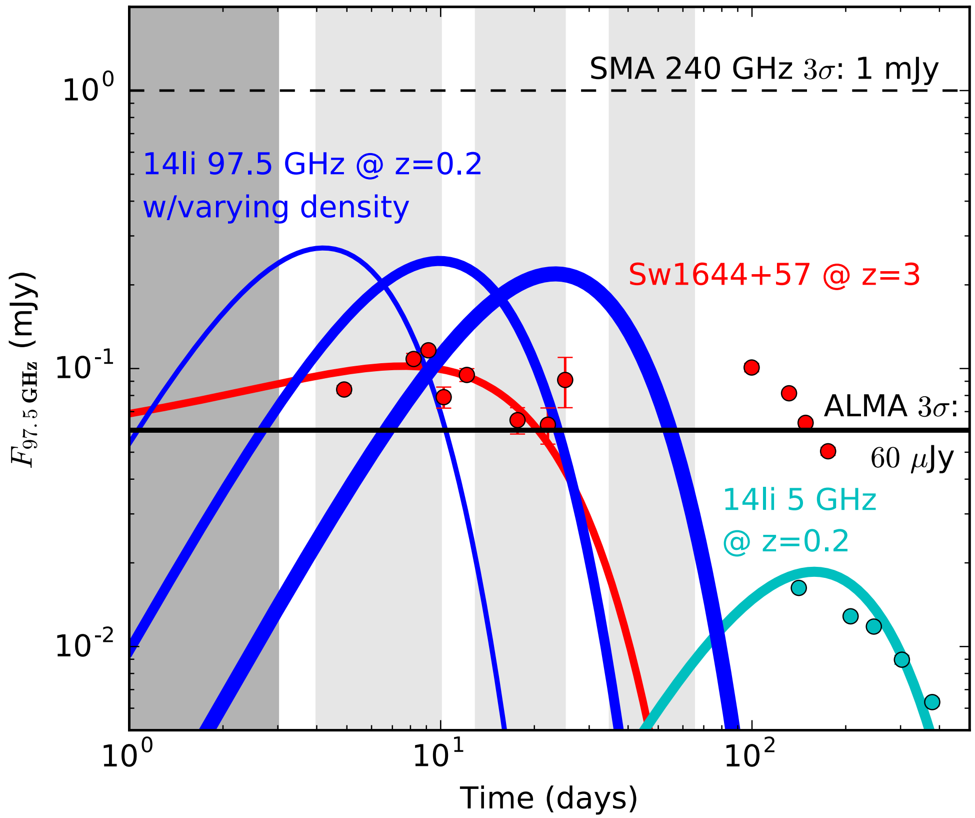


Eftekhari et al. (2018)

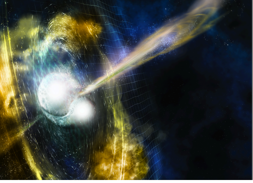


ALMA: A TDE Outflow Machine

- To probe the highest densities, we must go to the mm
- ALMA observations of new TDEs are underway (PI: Alexander)
- Long-term goal: placing TDEs in broader context of AGN variability

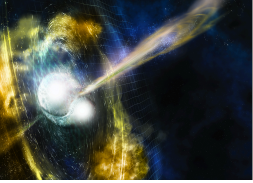


Within the next five years, we will know what fraction of TDEs produce relativistic jets and outflows.



Summary

- The radio properties of “extreme” transients reveal new physical insights and discoveries:
  - The **first** non-relativistic outflows detected in TDEs
    - *Alexander et al., 2016, ApJ, 819, L25; Alexander et al., 2017, ApJ, 837, 153*
  - Steep $r^{-2.5}$ density profile around TDE ASASSN-14li
    - *Alexander et al., 2016. ApJ, 819, L25*
  - mm observations are key: some TDEs may produce no outflows/radio emission
    - *Alexander et al. in prep*
- Radio transient science is poised for revolution
  - VLA, ALMA, upcoming facilities (SKA, ngVLA), synergies with new GW and multi-wavelength capabilities
  - VLA Sky Survey, ThunderKAT, etc: **discovery** of transients in the radio band



The Era of Radio Surveys

- VLA Sky Survey
  - All sky coverage north of declination -40°
  - Survey rms ~69 µJy/beam
  - 9.7 million extragalactic source detections predicted
- Square Kilometer Array
  - ThunderKAT: SKA precursor radio transients survey

Instantaneous 3 GHz Source Counts of Radio Transients