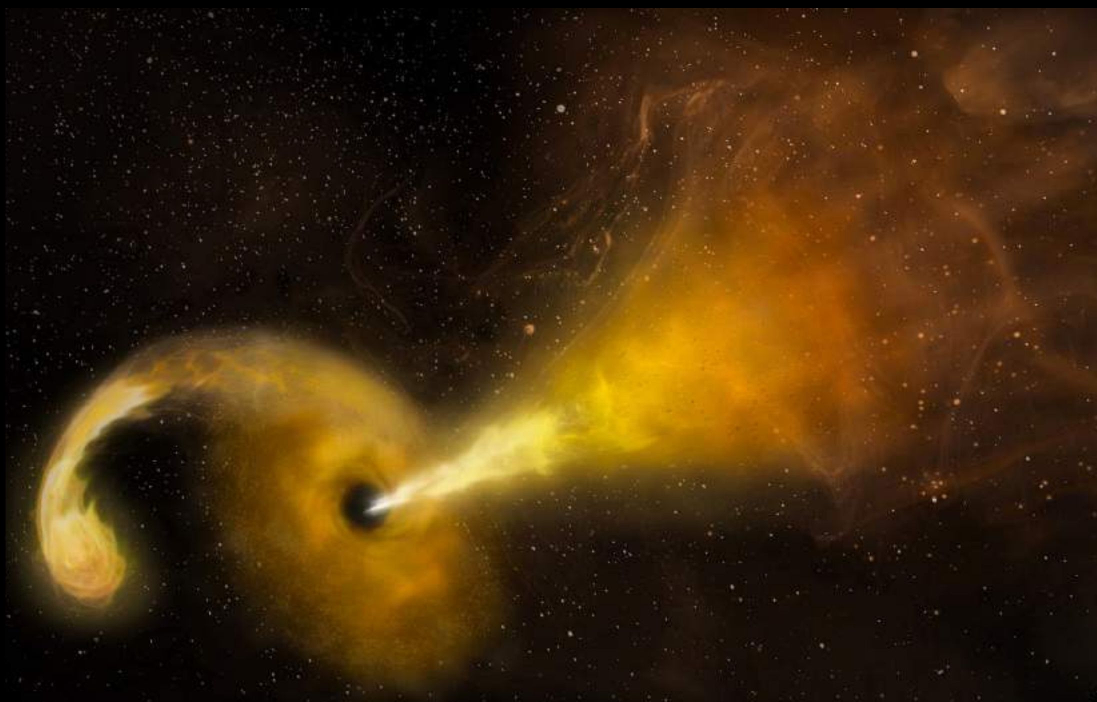
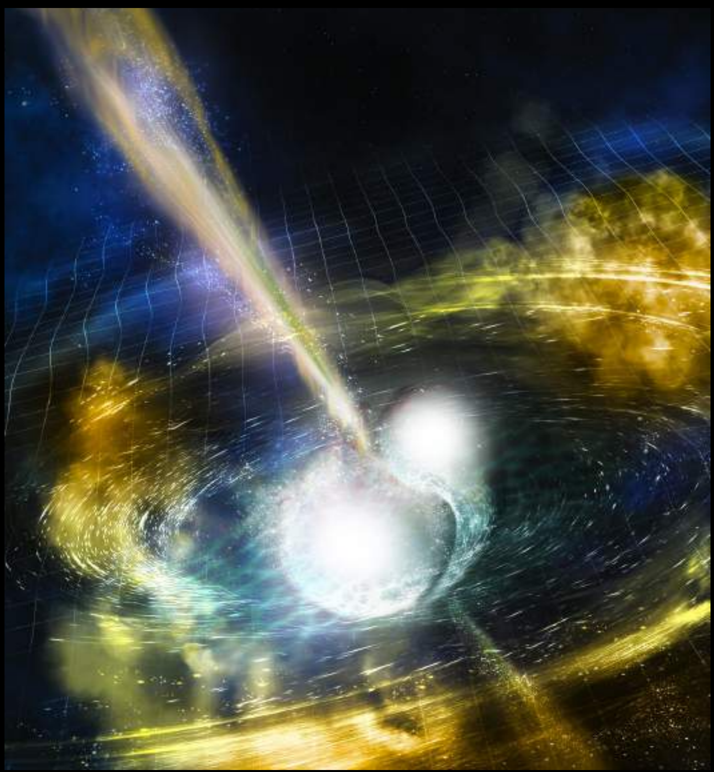
Cosmic Extremes: Time-Domain Astrophysics in a Multi-Messenger World

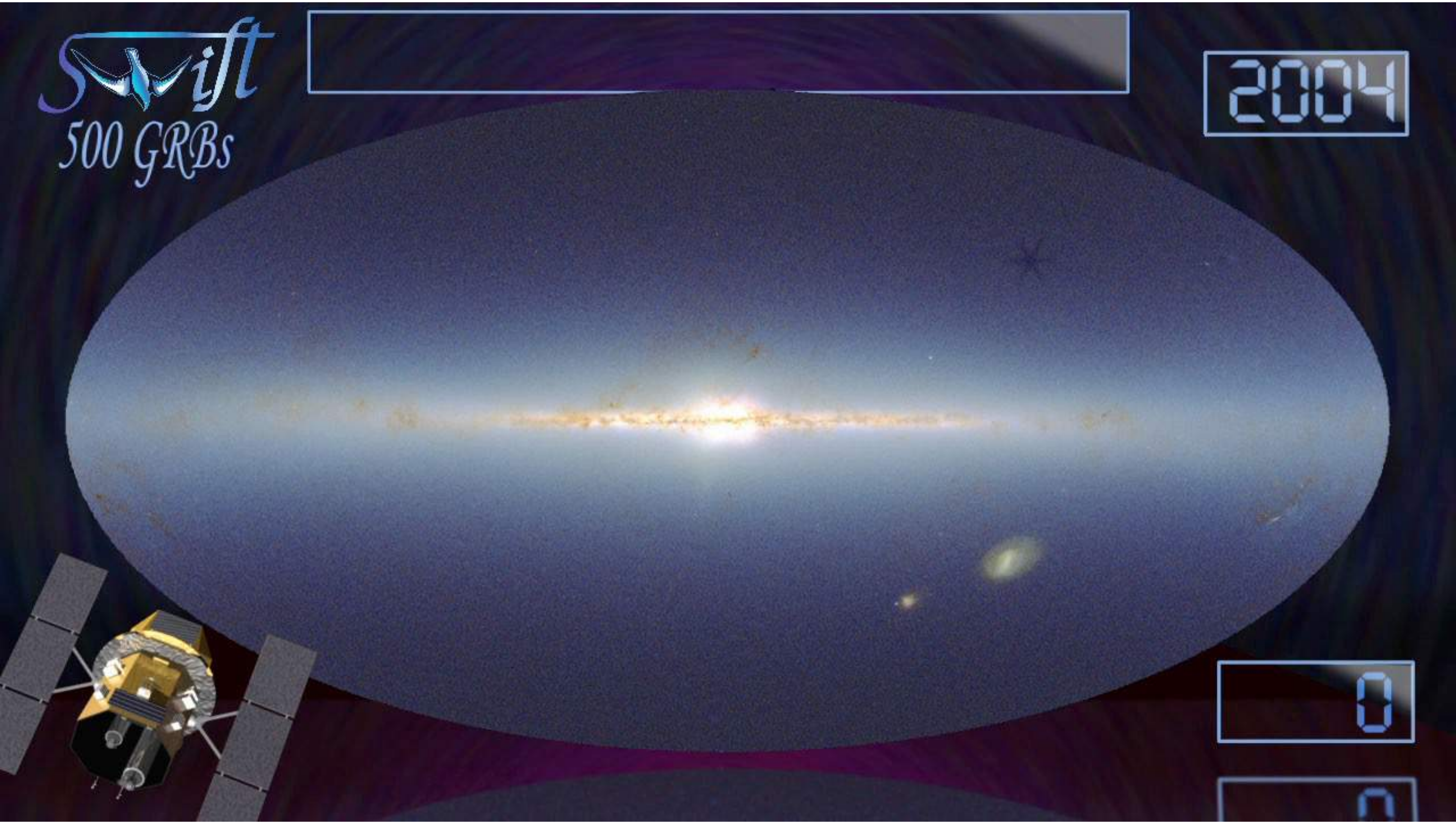




Dr. Kate D. Alexander
CIERA Postdoctoral Fellow, Northwestern University

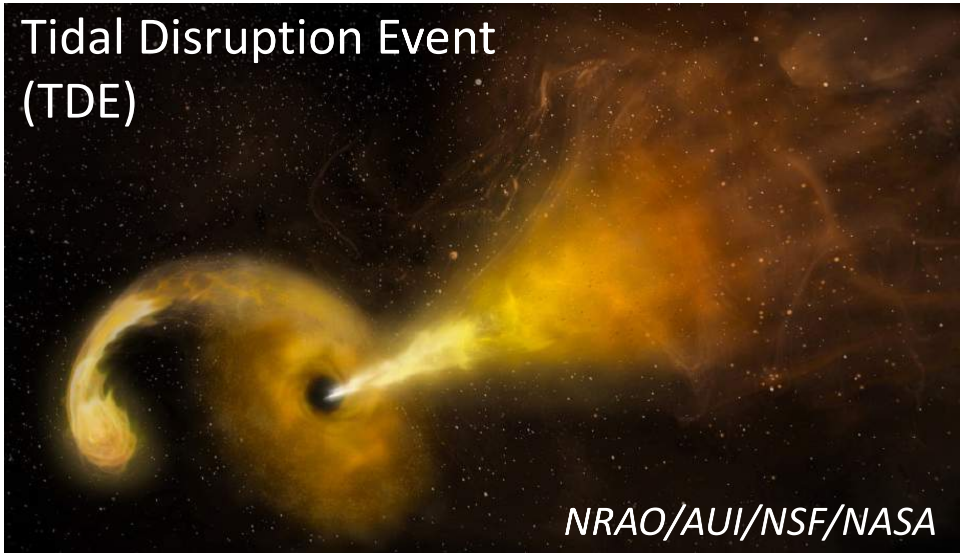
York University Physics Colloquium, November 23, 2021

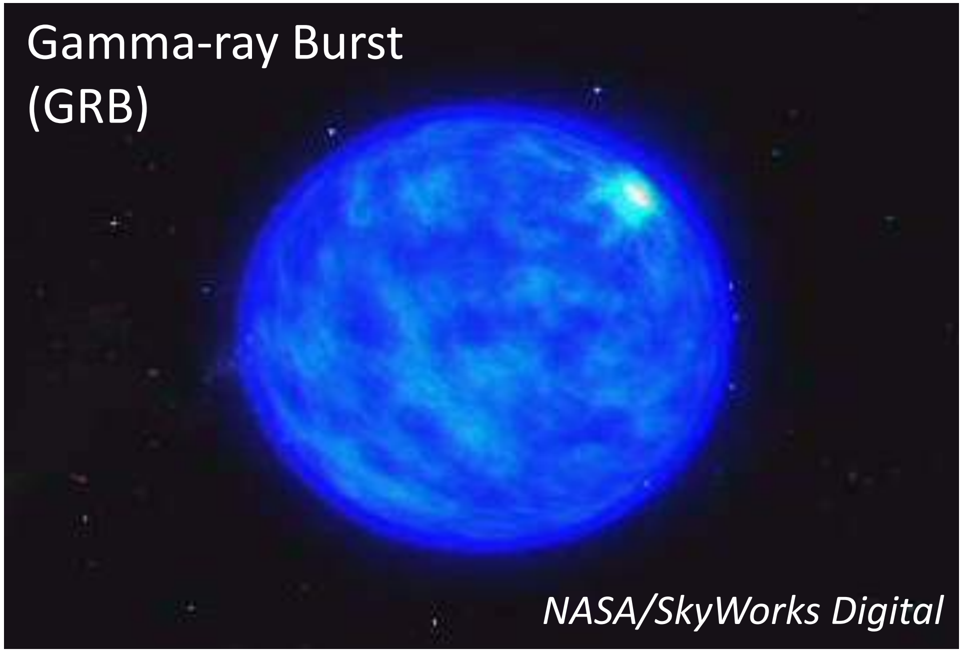
Time Domain Astrophysics



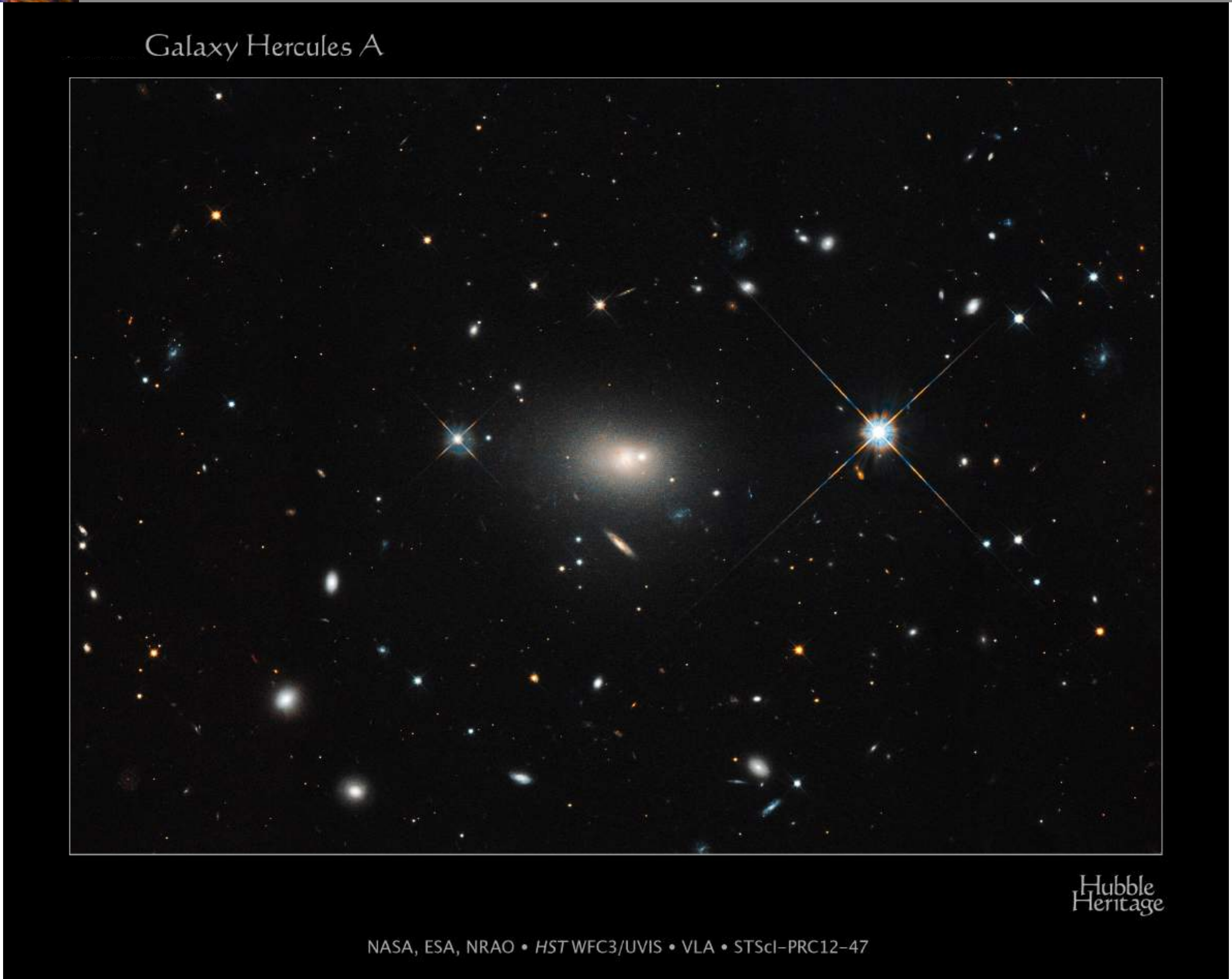
Cosmic Extremes: Collisions, Explosions

- Energetic transients let us probe extreme physical processes:
  - The deaths of massive stars (births of compact objects = extremely dense matter)
  - Black hole accretion
  - Particle acceleration (to extremely high energies)
- Open questions:
  - How do relativistic jets form?
  - How do black holes shape their environments?

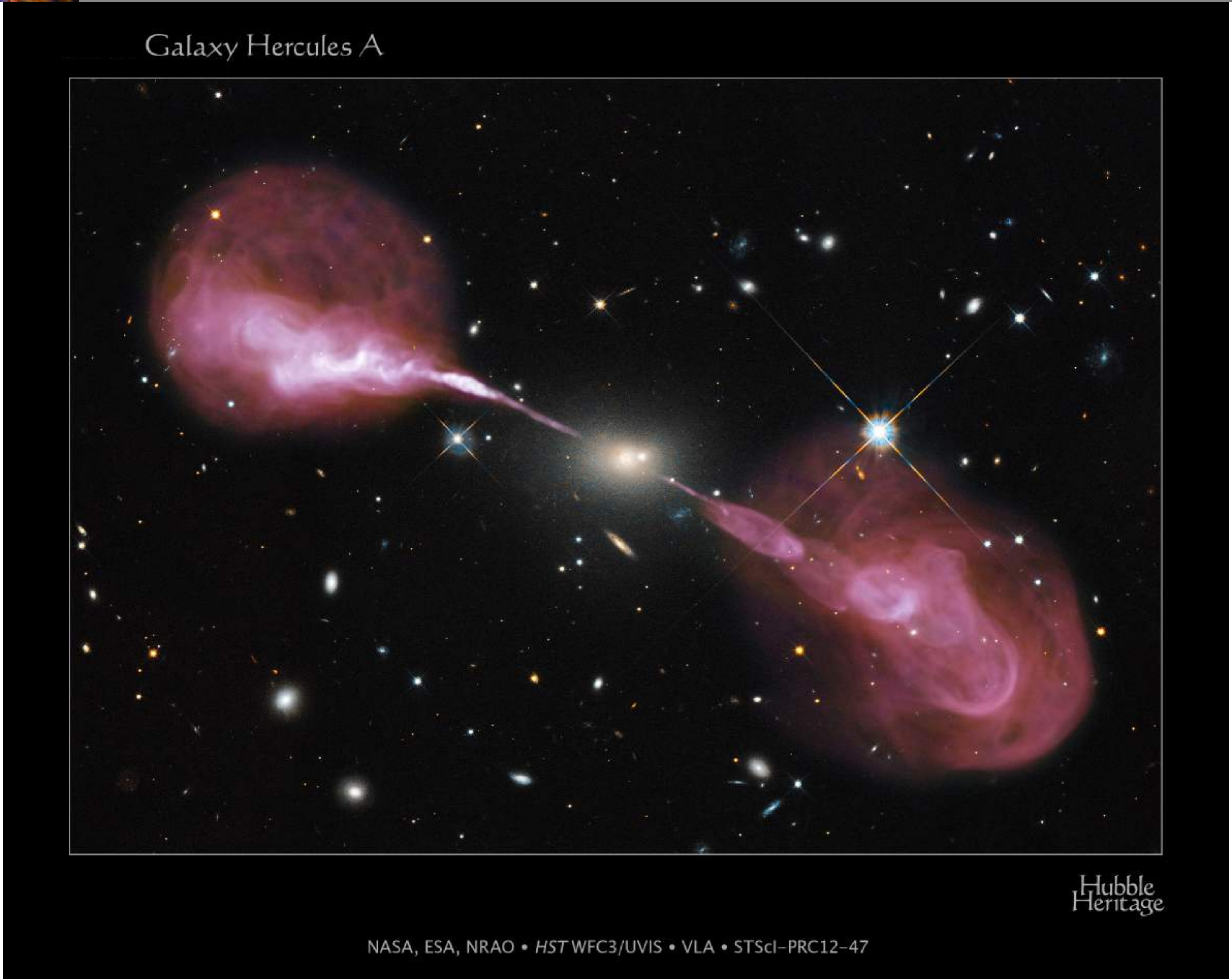




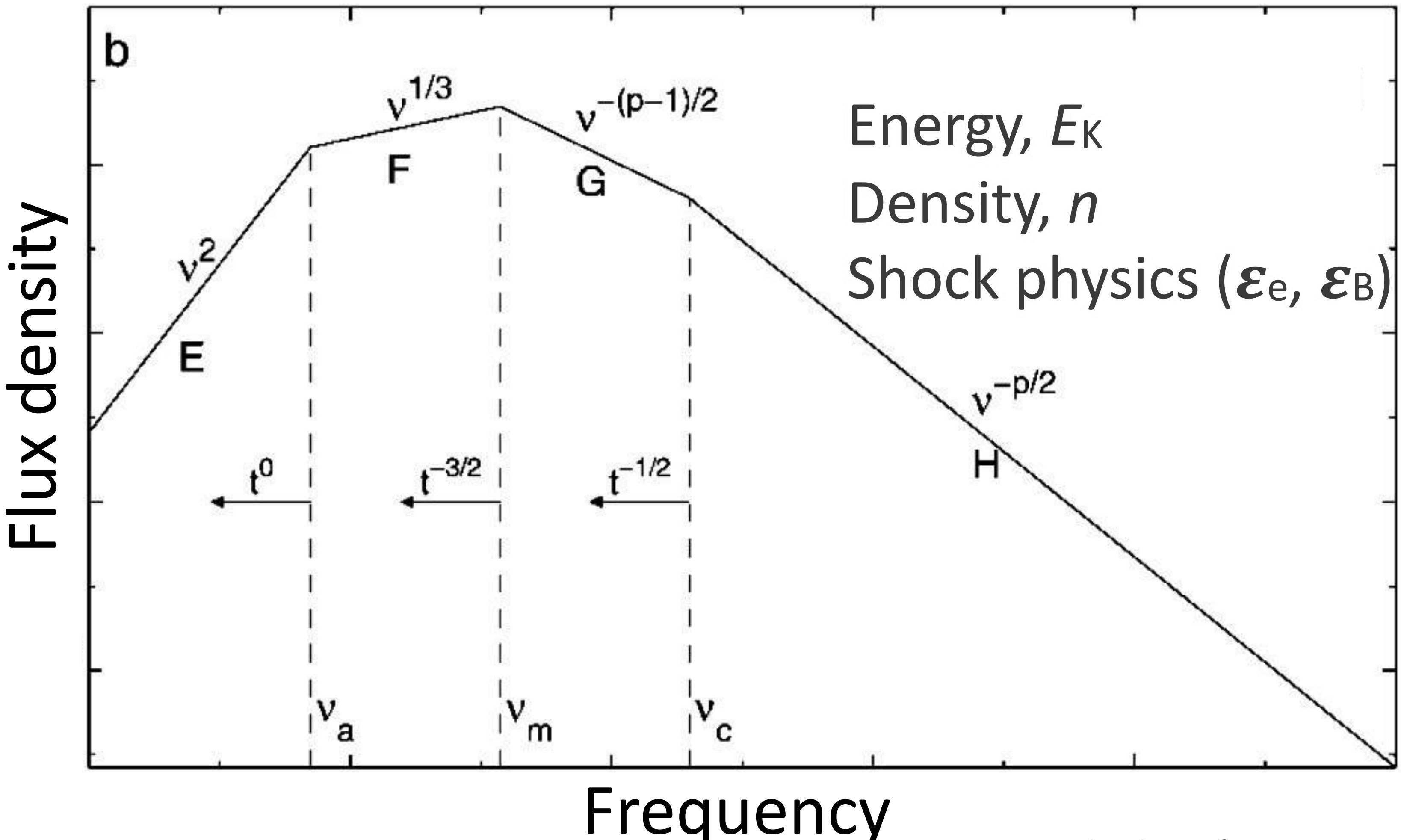
A Multi-Wavelength Perspective



A Multi-Wavelength Perspective

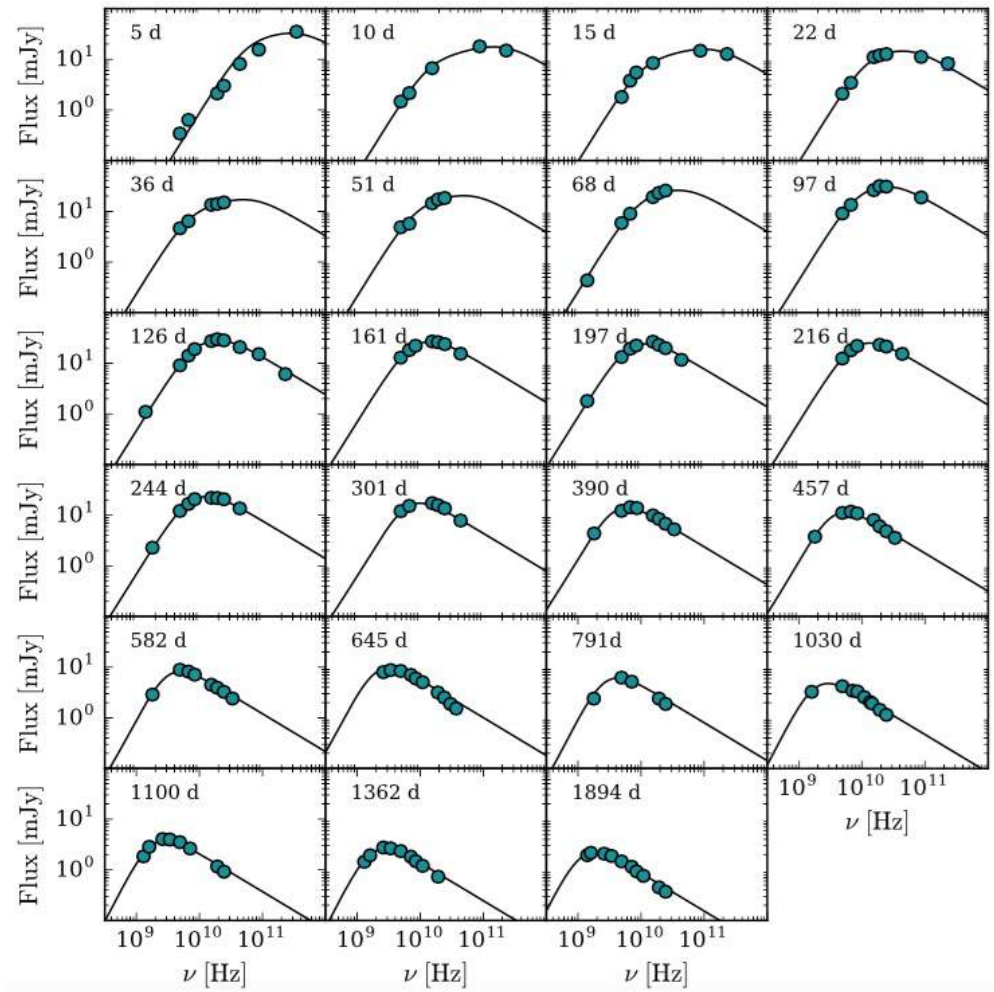


Outflows Generate Synchrotron Emission



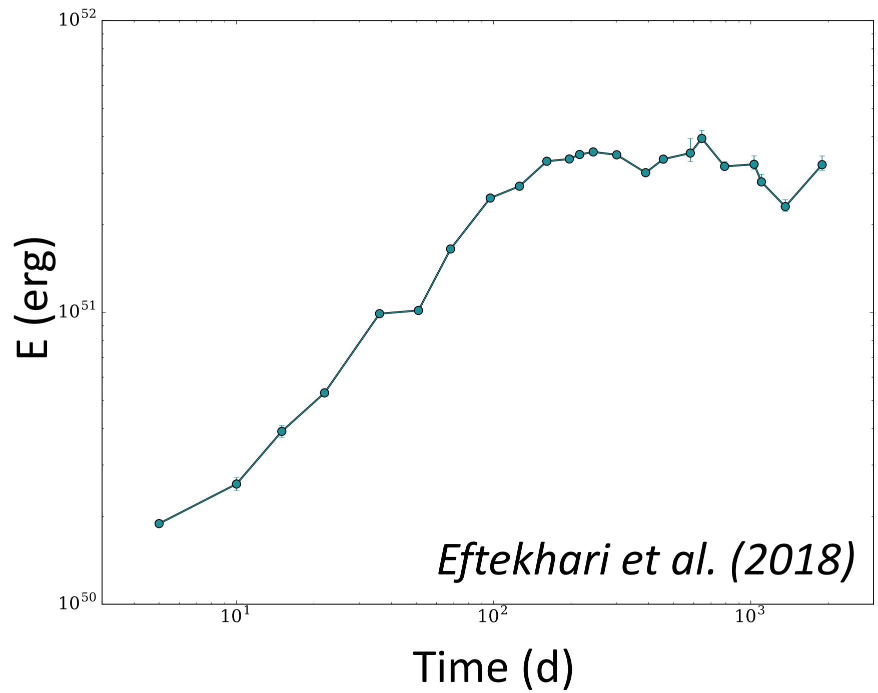
Sari, Piran & Narayan (1998)
Slide courtesy T. Laskar

Outflows Generate Synchrotron Emission

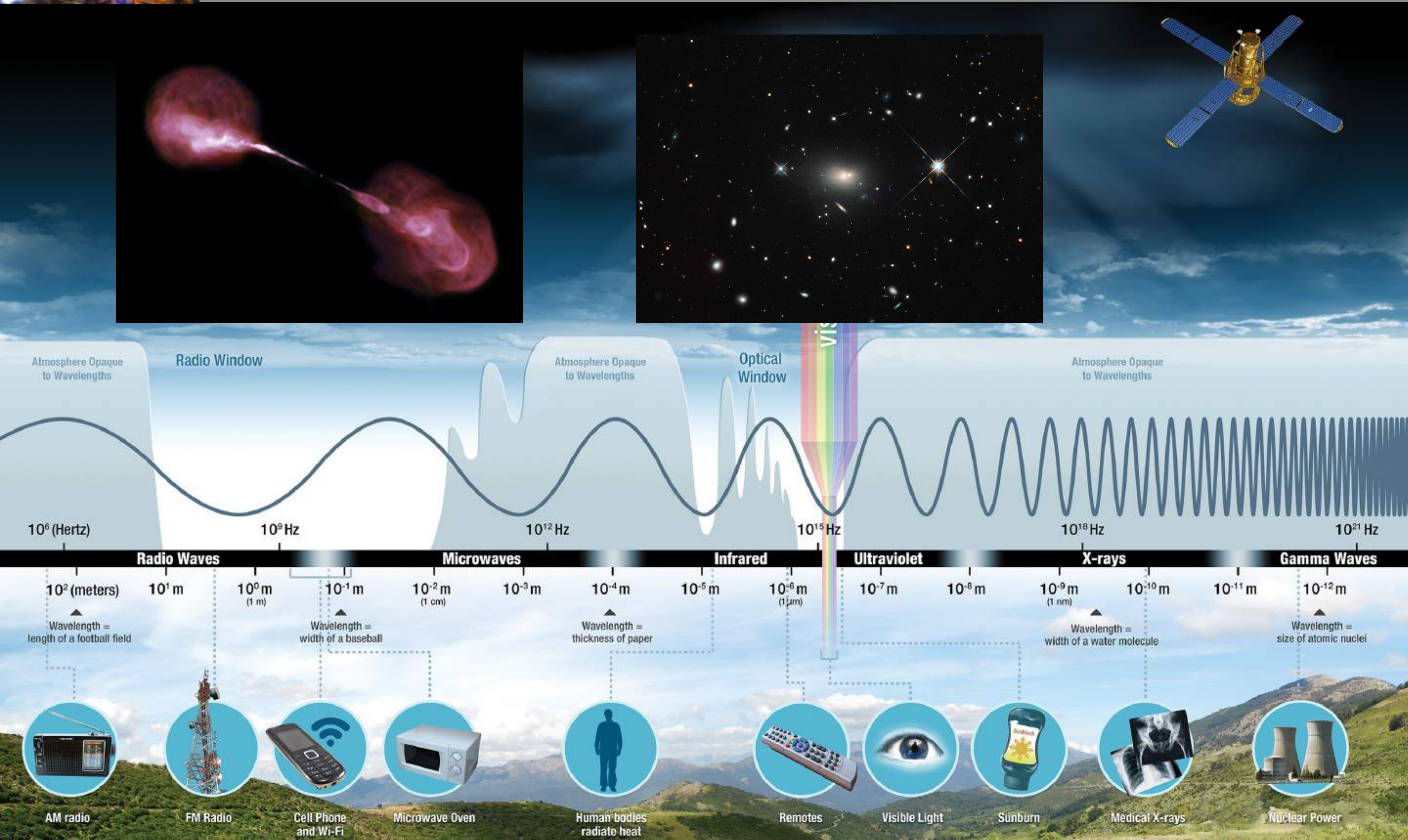


Eftekhari et al. (2018)

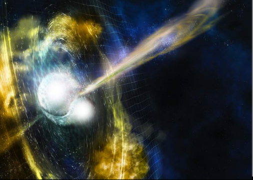
TDE Swift J1644+57



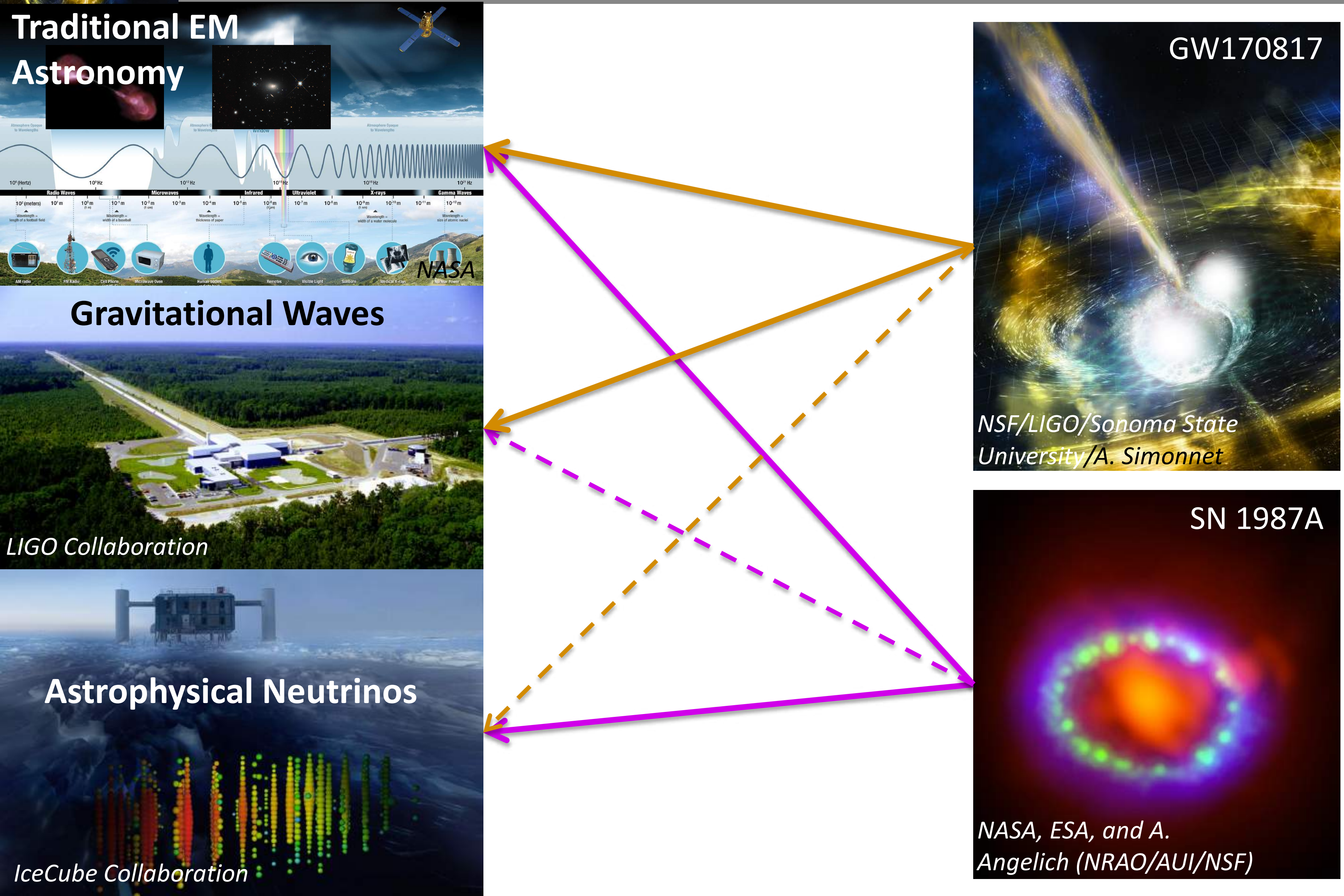
New Wavelengths → New Insights

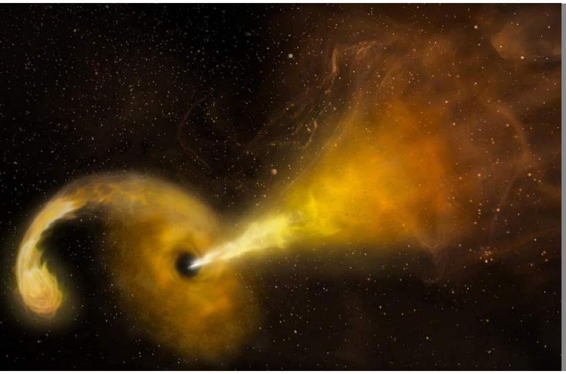


NASA, Science Mission Directorate. (2010). Introduction to the Electromagnetic Spectrum. Retrieved 3 April 2018 from NASA Science website: http://science.nasa.gov/ems/01_intro



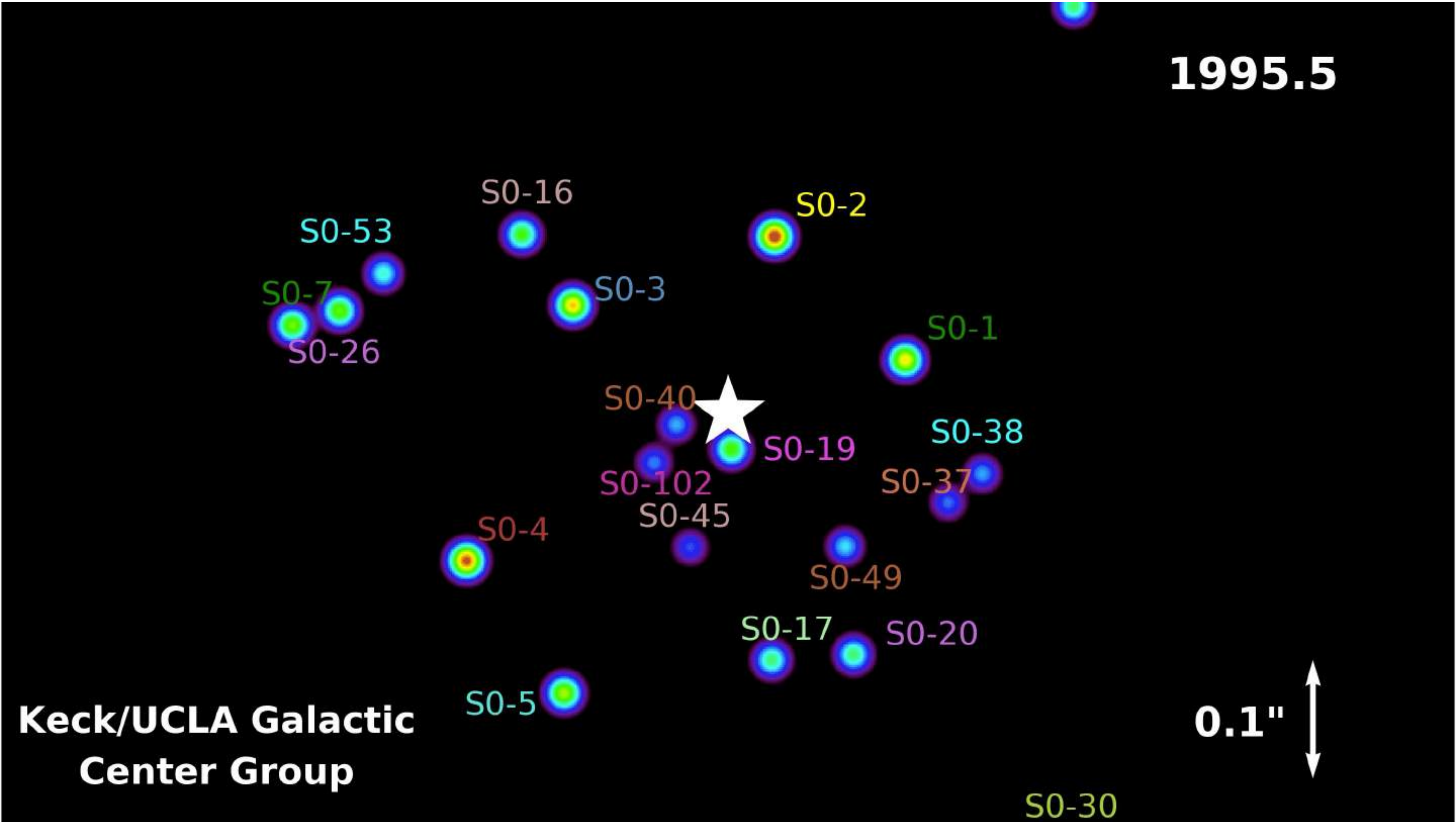
Now: A Multi-Messenger World!





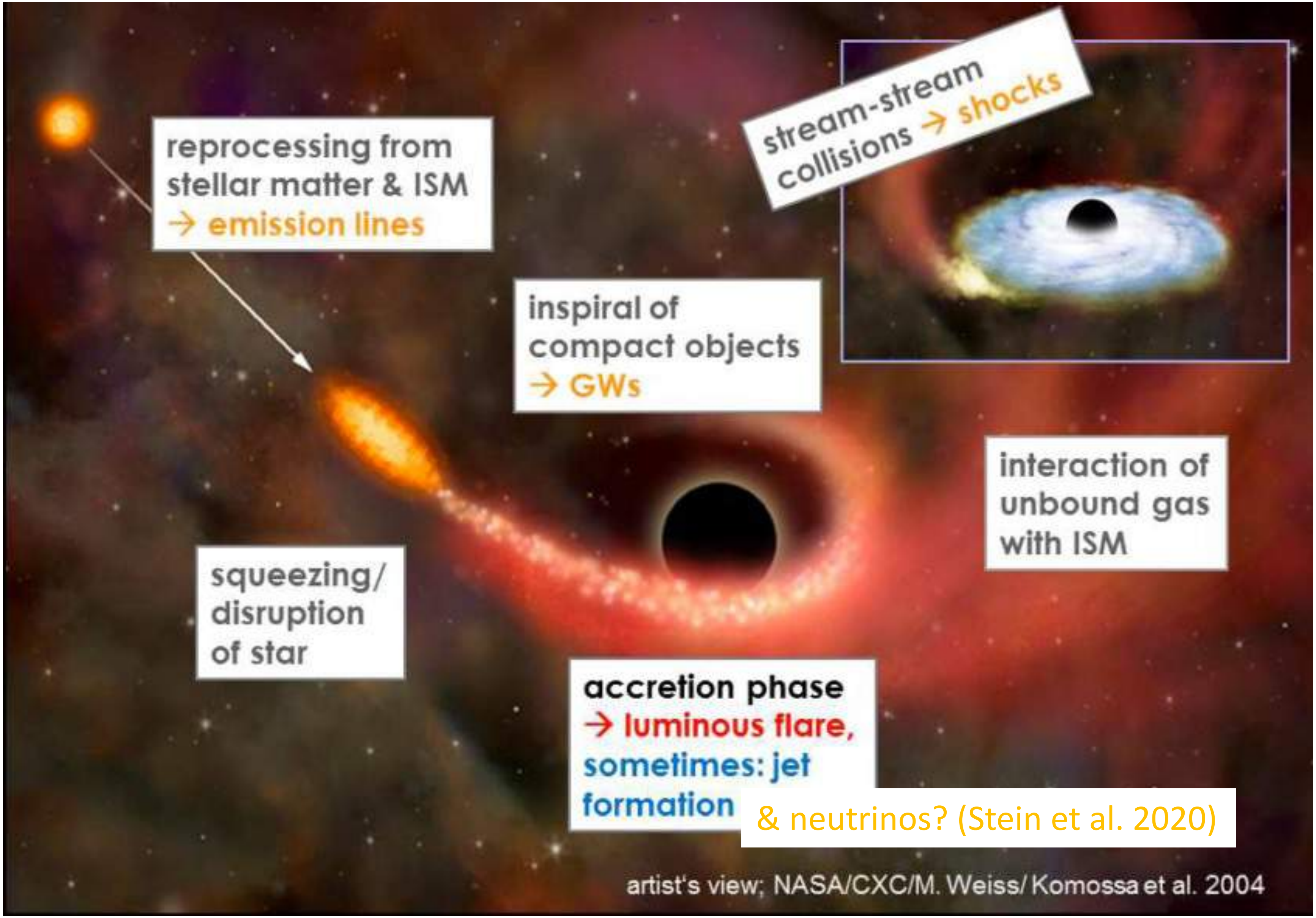
Extreme Transients I: Tidal Disruption Events

Every galaxy hosts a supermassive black hole

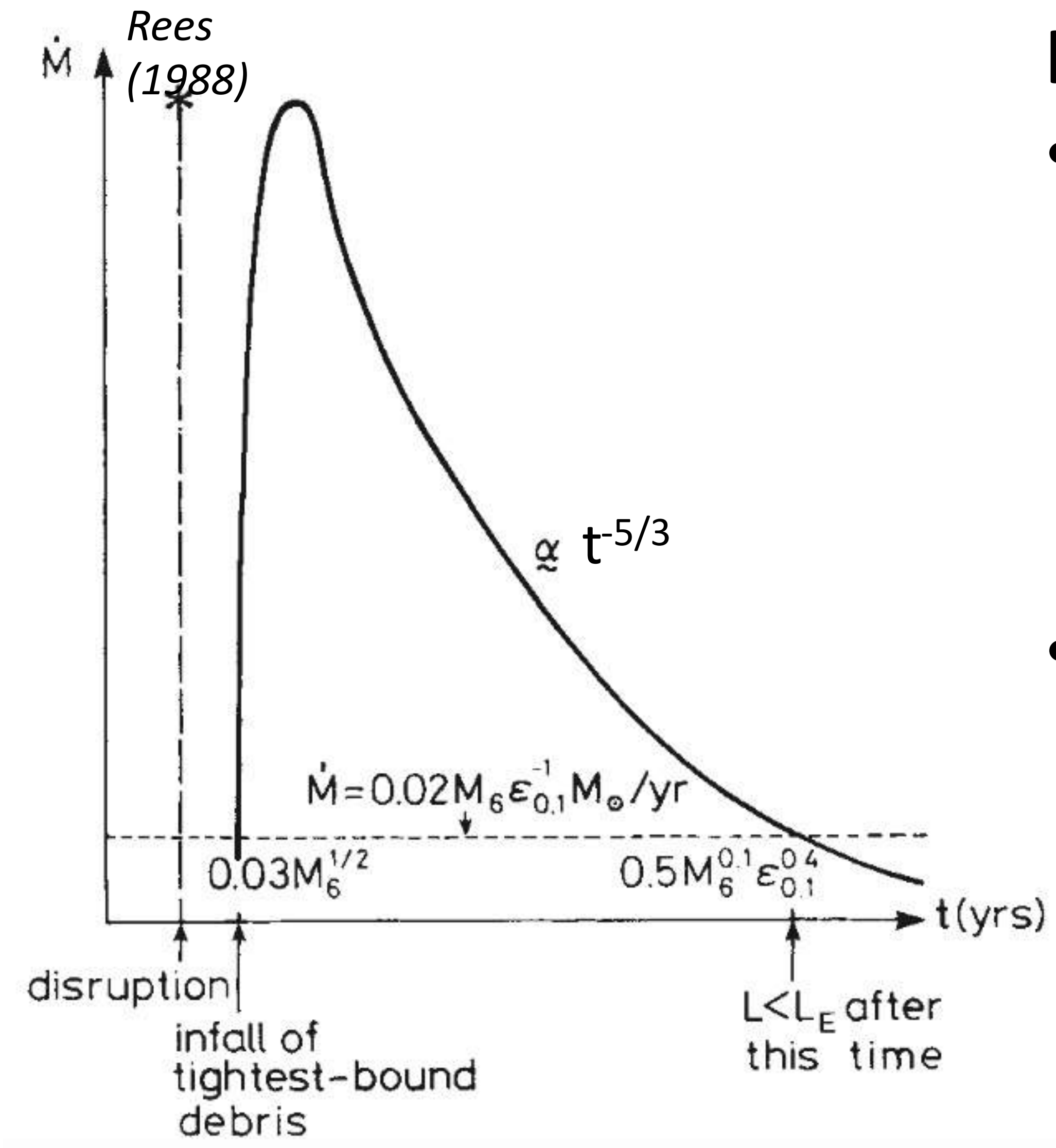


Prof. Andrea Ghez/UCLA Galactic Group
(data from W. M. Keck Telescopes)

Tidal Disruption Events (TDEs)



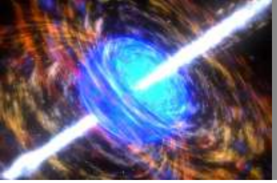
TDEs are unique probes of accretion

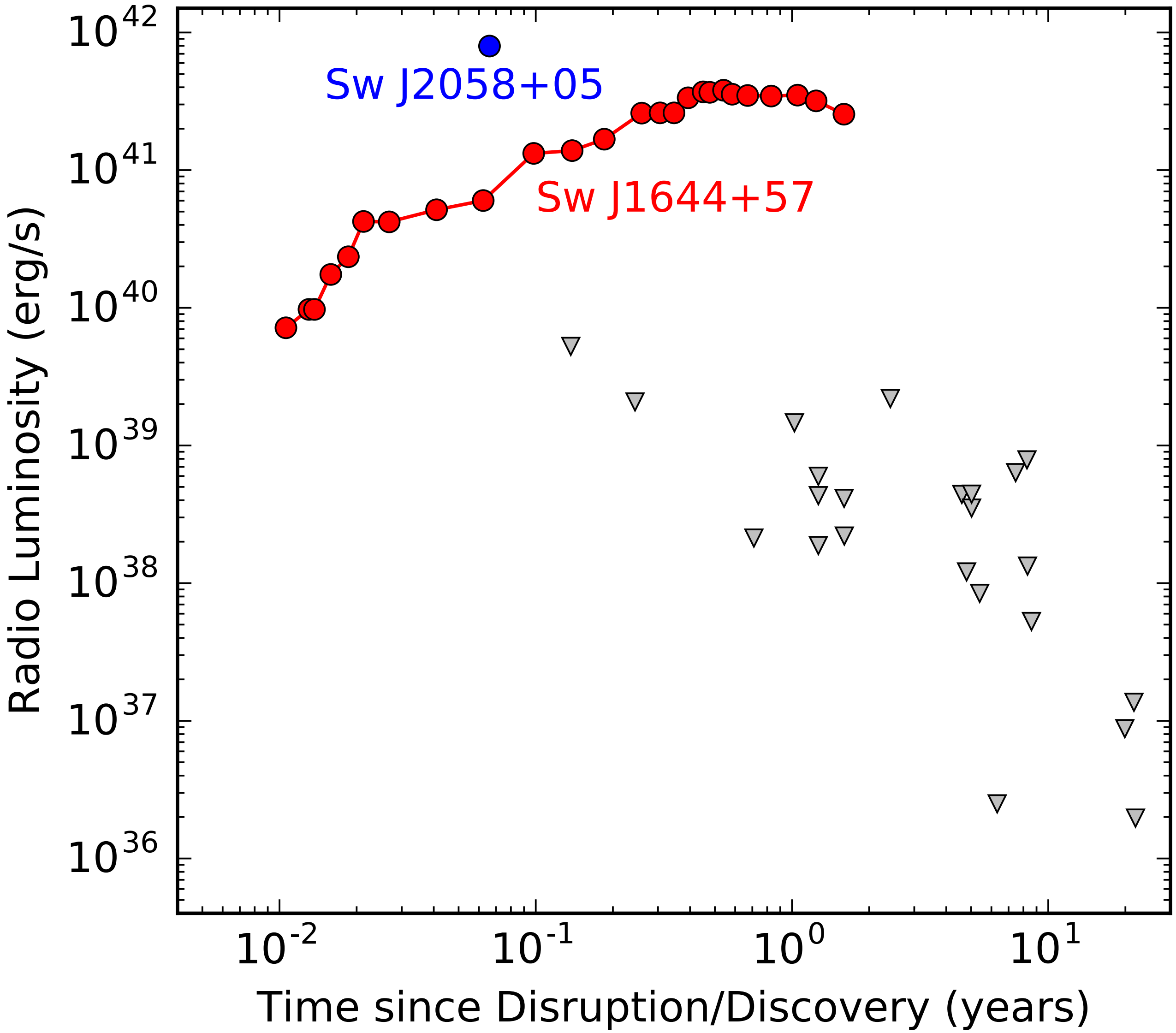


Key Questions:

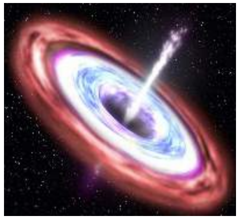
- What can TDEs teach us about the process of accretion onto SMBHs?
- When (how) do TDEs launch relativistic jets and/or non-rel. outflows?

TDE Radio Observations (2014)



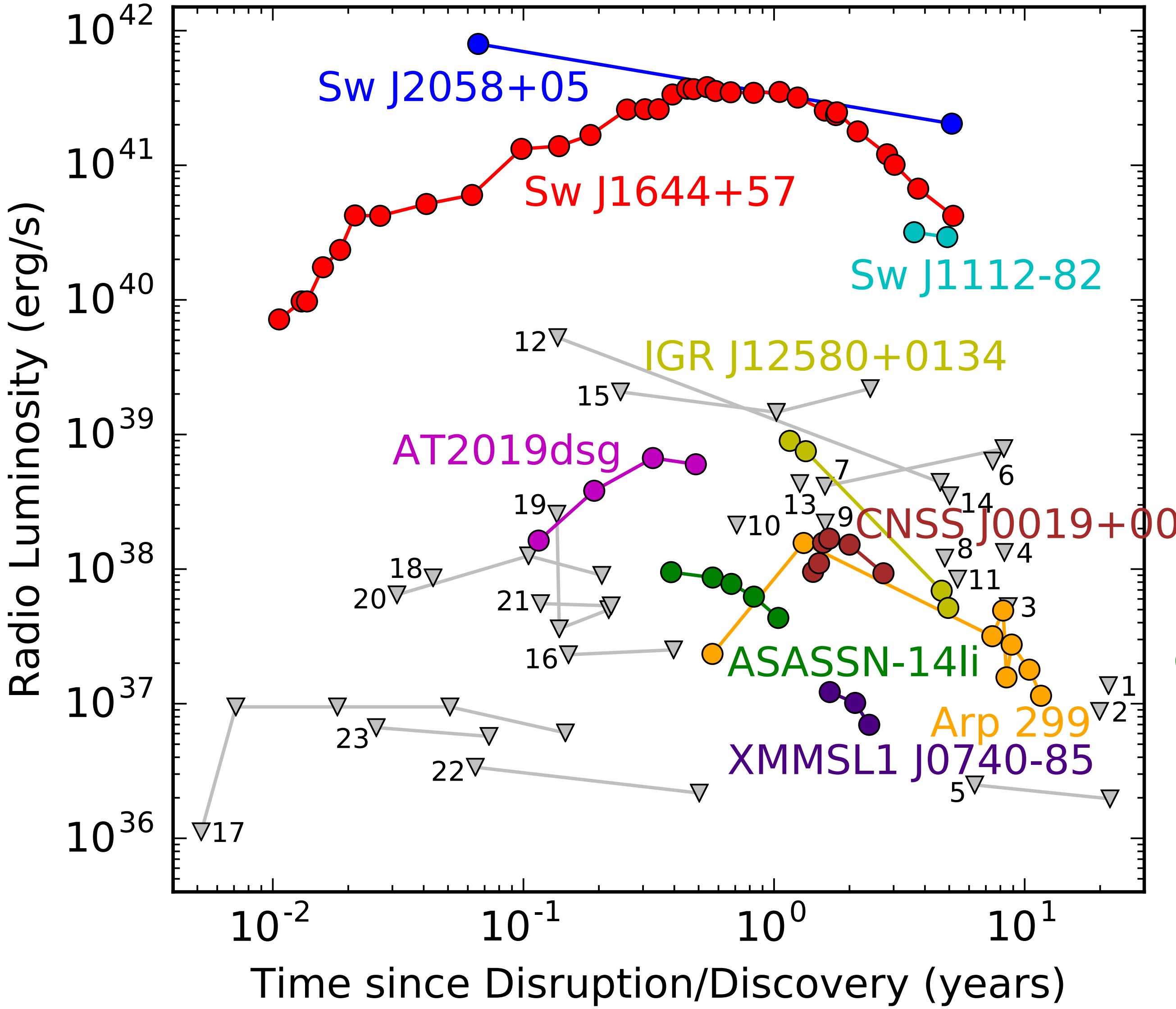


On-axis jet

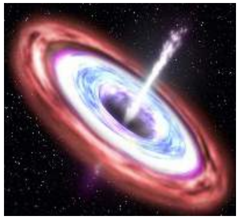


TDE Radio Observations (2020)

Alexander et al. (2020)



On-axis jet



Off-axis jet

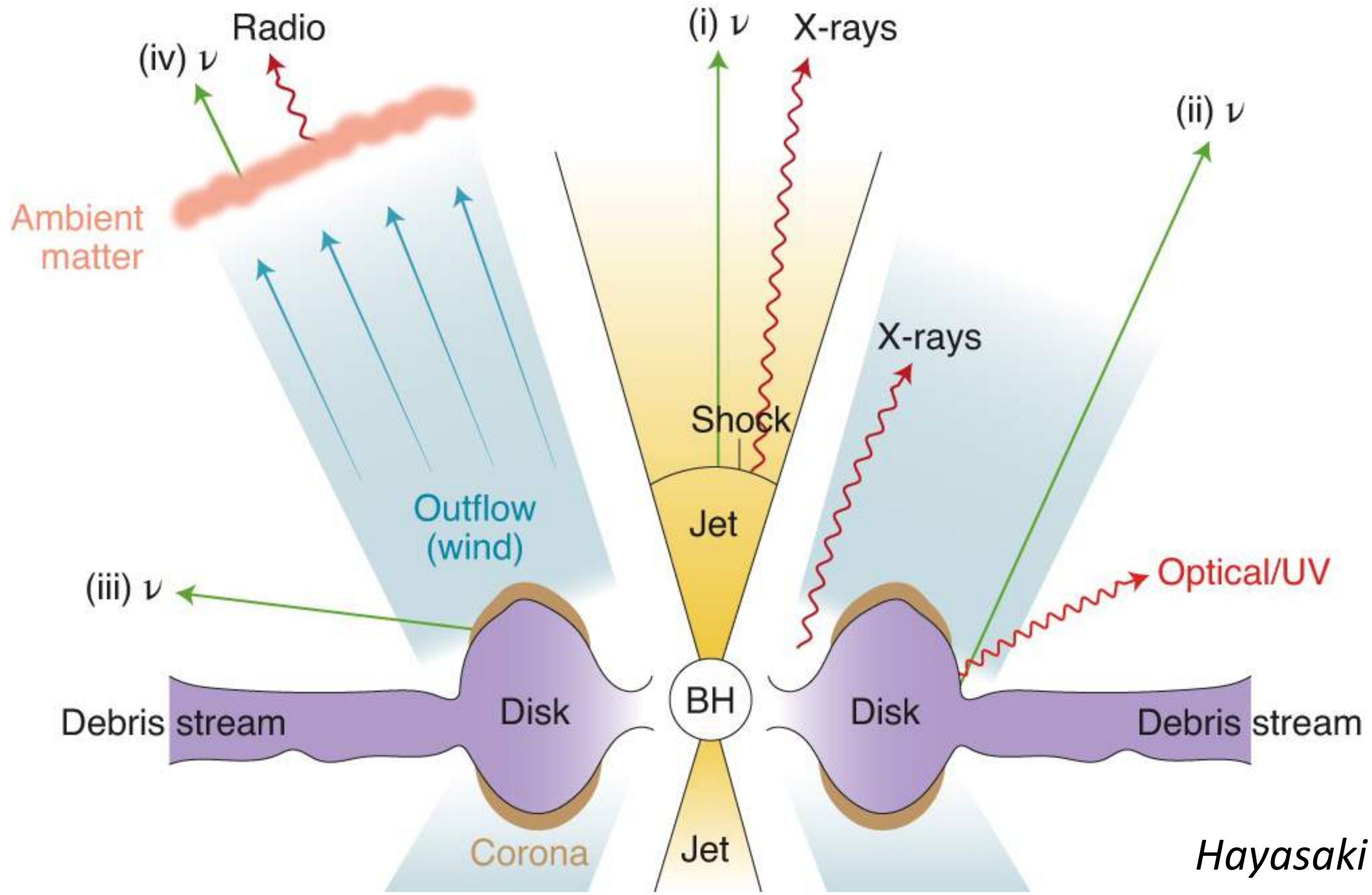
Non-relativistic outflow

AT2019dsg: A TDE with a neutrino?

- Discovered on April 9, 2019 by the ZTF survey
- One of the most luminous optical TDEs (top 10%)
- Detected in soft X-rays, no hard X-ray or gamma-ray emission
- IceCube detected a very high energy neutrino (0.2 PeV) on October 1, 2019, well after peak optical light

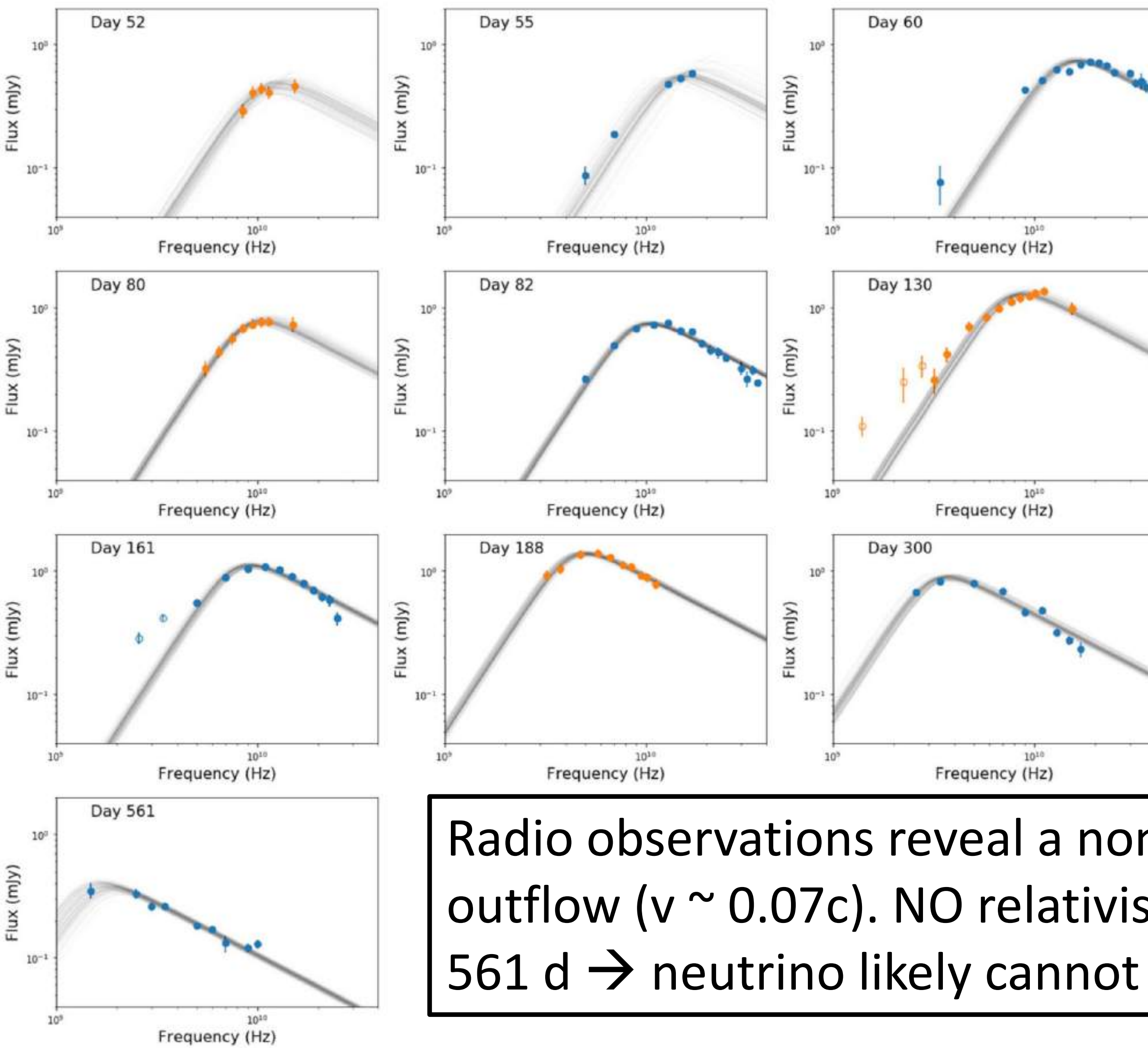
Neutrino production in TDEs

- Possible sites for neutrino production in TDEs include relativistic jets, sub-relativistic wind/outflows, the accretion disk (in a super-Eddington MAD or RIAF state), the disk corona



Hayasaki (2021)

Radio monitoring of AT2019dsg



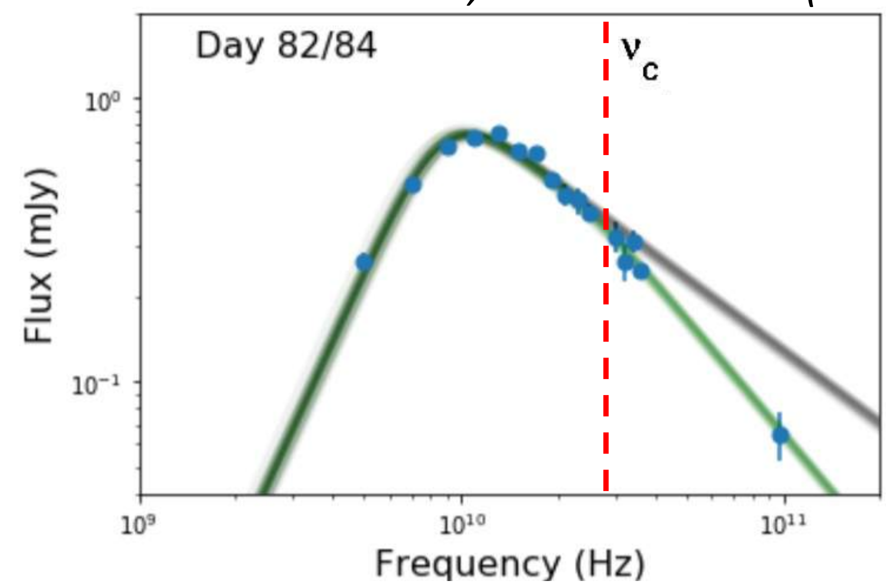
Cendes, Alexander et al. (2021)

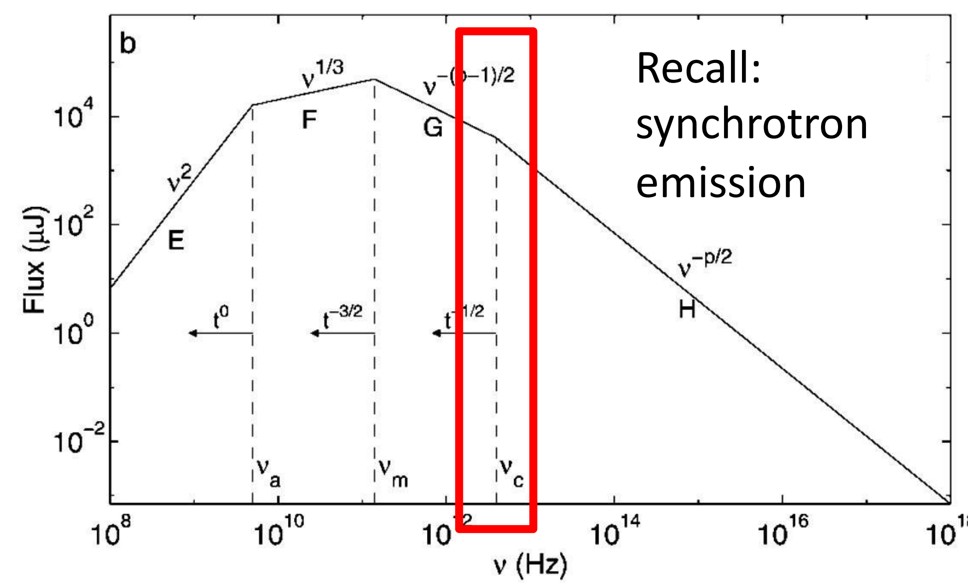
Radio observations reveal a non-relativistic outflow (v ~ 0.07c). NO relativistic jet is seen to 561 d → neutrino likely cannot be from a jet.

Detailed properties of the outflow

- Key measurement of <u>synchrotron cooling break</u> breaks model degeneracies:
  - The outflow energy is **too low** for many neutrino production mechanisms
  - Two possibilities: 1) the neutrino did not actually come from the TDE, 2) new theories needed

Cendes, Alexander et al. (2021)

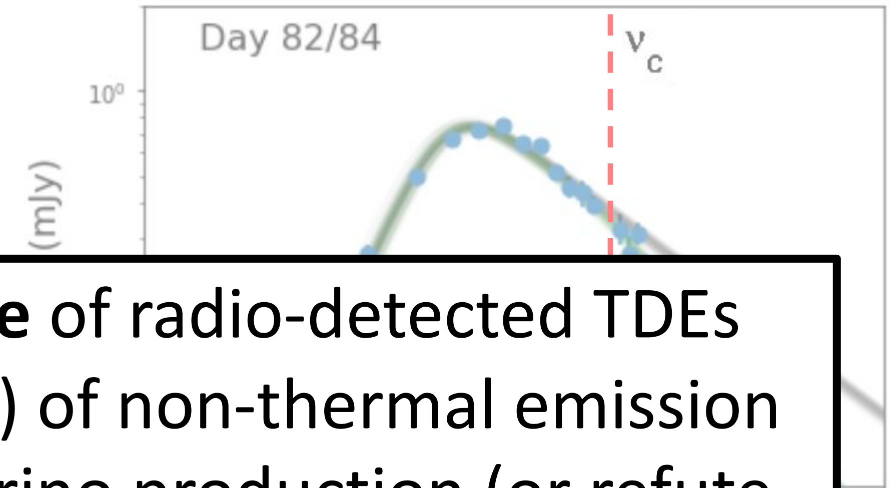




Detailed properties of the outflow

Cendes, Alexander et al. (2021)

- Key measurement of <u>synchrotron cooling break</u> breaks model d

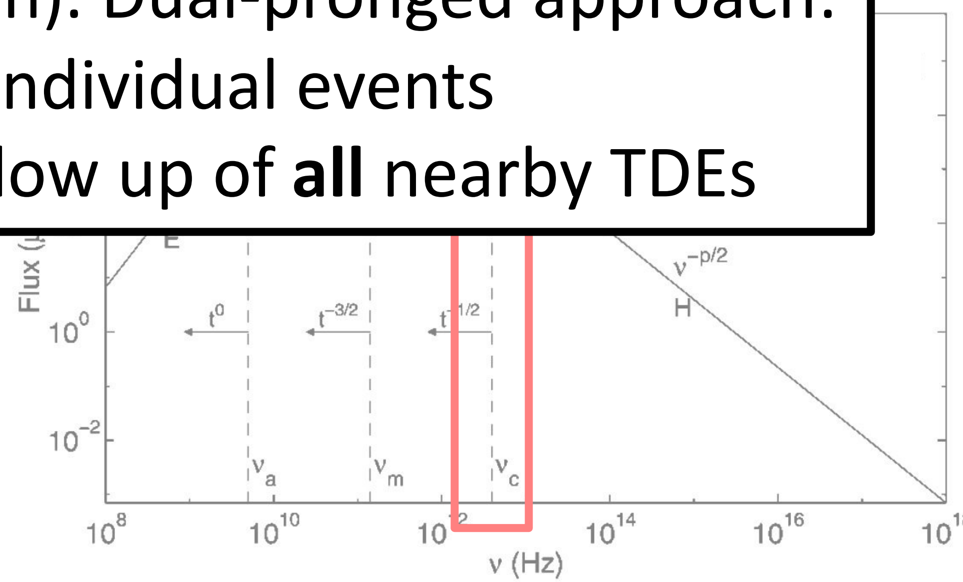


We need a **larger sample** of radio-detected TDEs to pin down the origin(s) of non-thermal emission and test models of neutrino production (or refute the neutrino connection). Dual-pronged approach:

i) Detailed studies of individual events

ii) Systematic radio follow up of **all** nearby TDEs

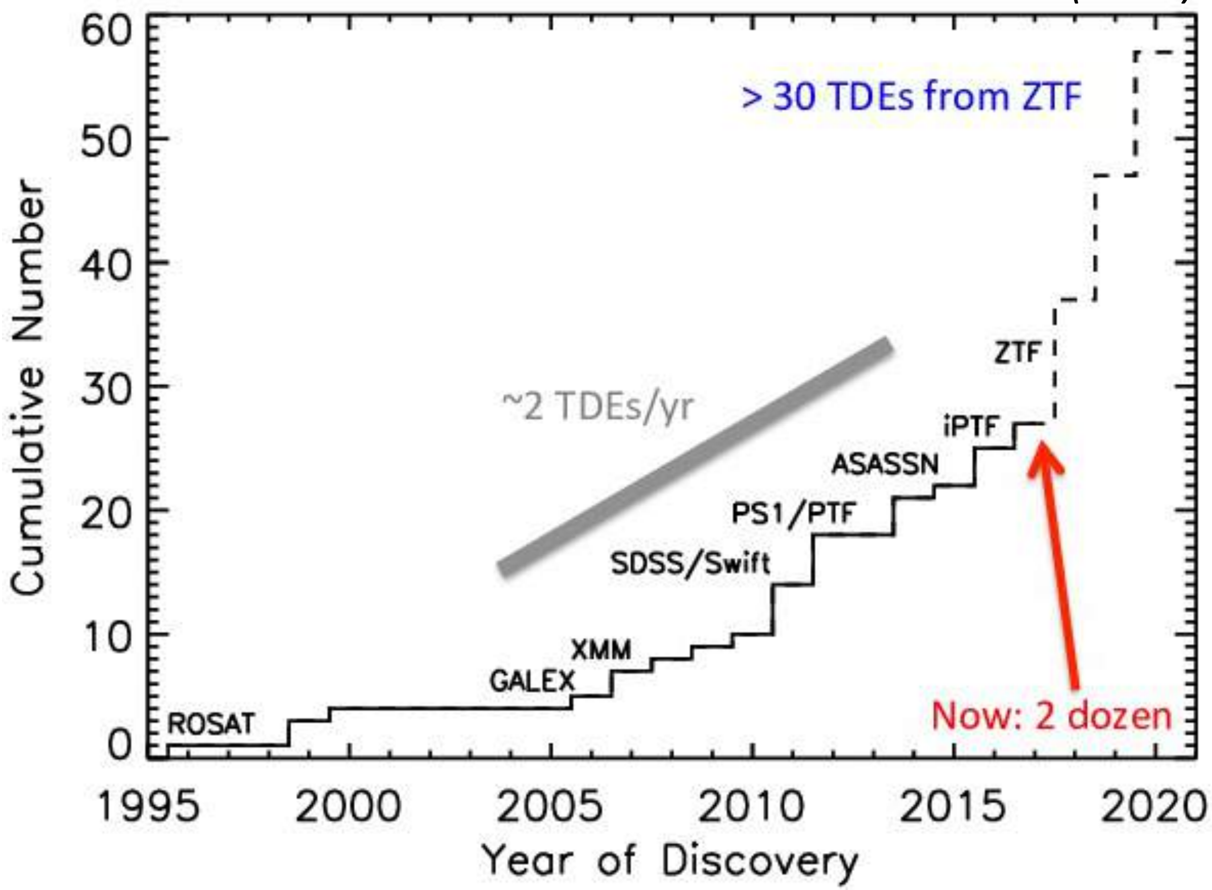
actually come from the TDE, 2) new theories needed



How do we find more TDE outflows?

- At present, most TDEs are discovered by wide-field optical surveys (ASAS-SN, YSE, ZTF, etc.)
  - Or as X-ray transients, IR echoes…
- Discovery rate recently increased to ~10 per year!

Graham et al. (2019)



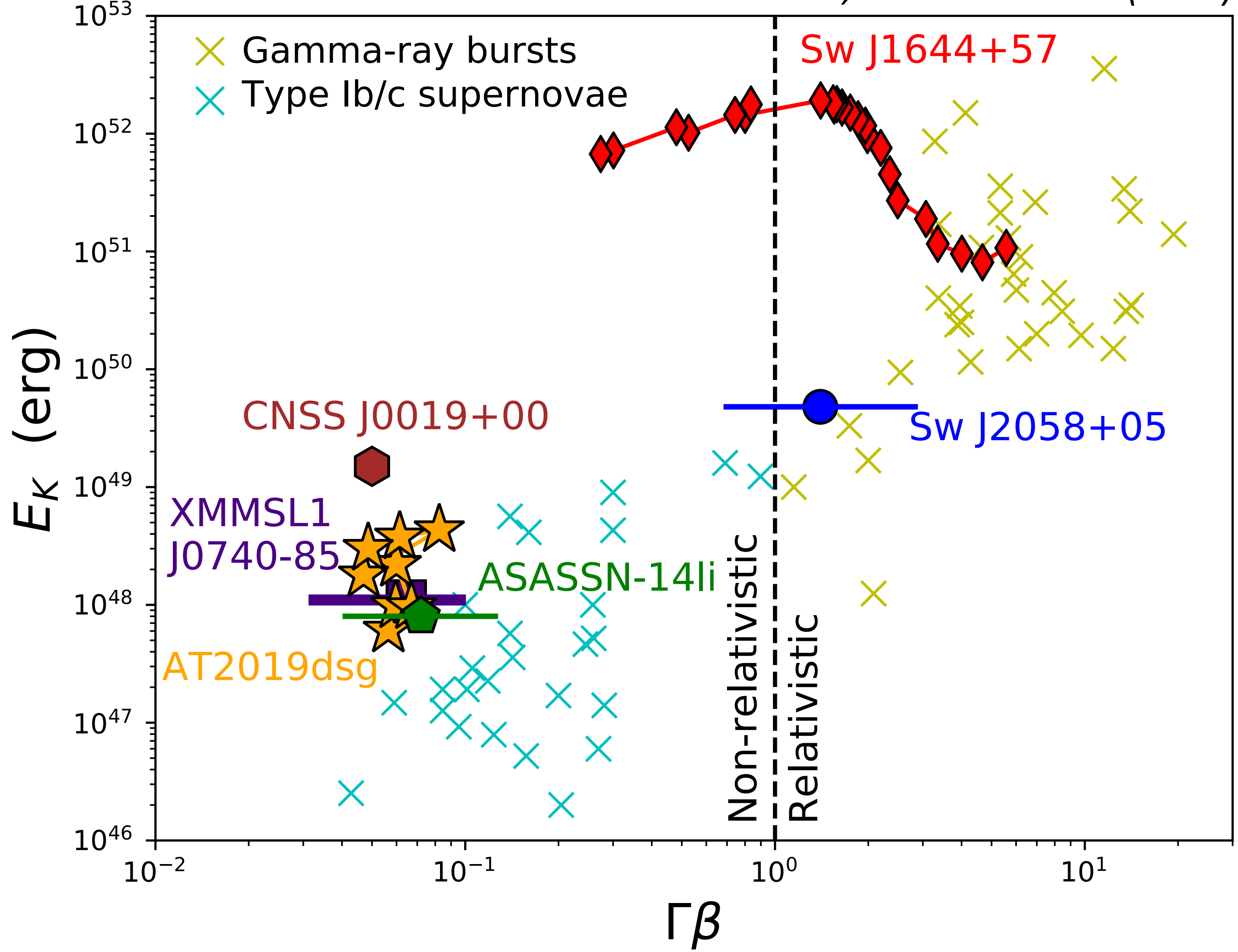
Characterizing local TDEs

- New **VLA Large Program** (PI: Alexander)
  - 300 hours over 3 yr to observe **all** new TDEs at z<0.1, new jetted TDEs at all redshifts
  - The first **systematic** radio program to study TDEs in the local Universe
  - Observations started November 2020, first ATels out! Stay tuned.

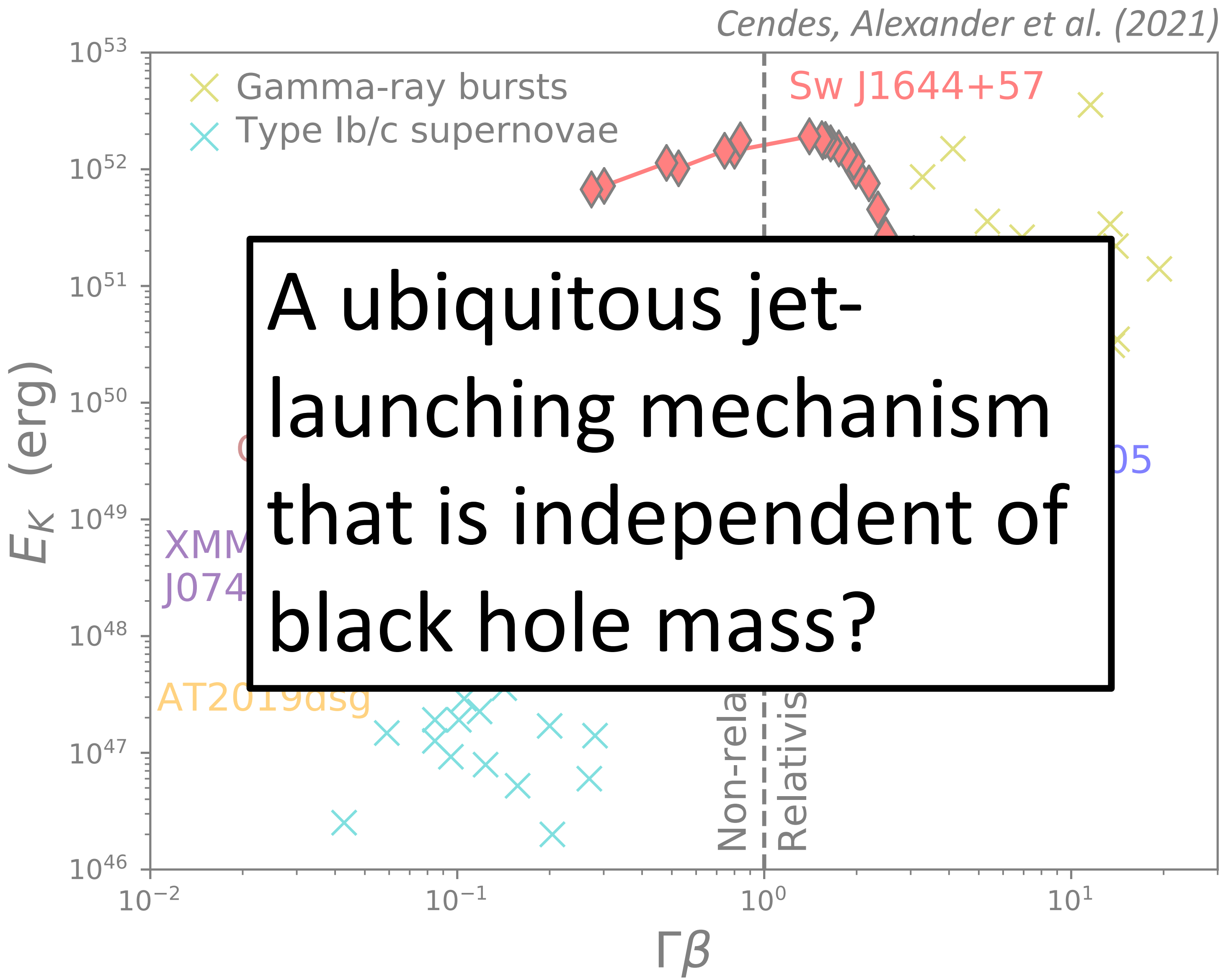
https://sites.northwestern.edu/radiotdes/

Population studies: TDE Energetics

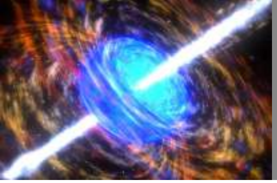
Cendes, Alexander et al. (2021)



Population studies: TDE Energetics

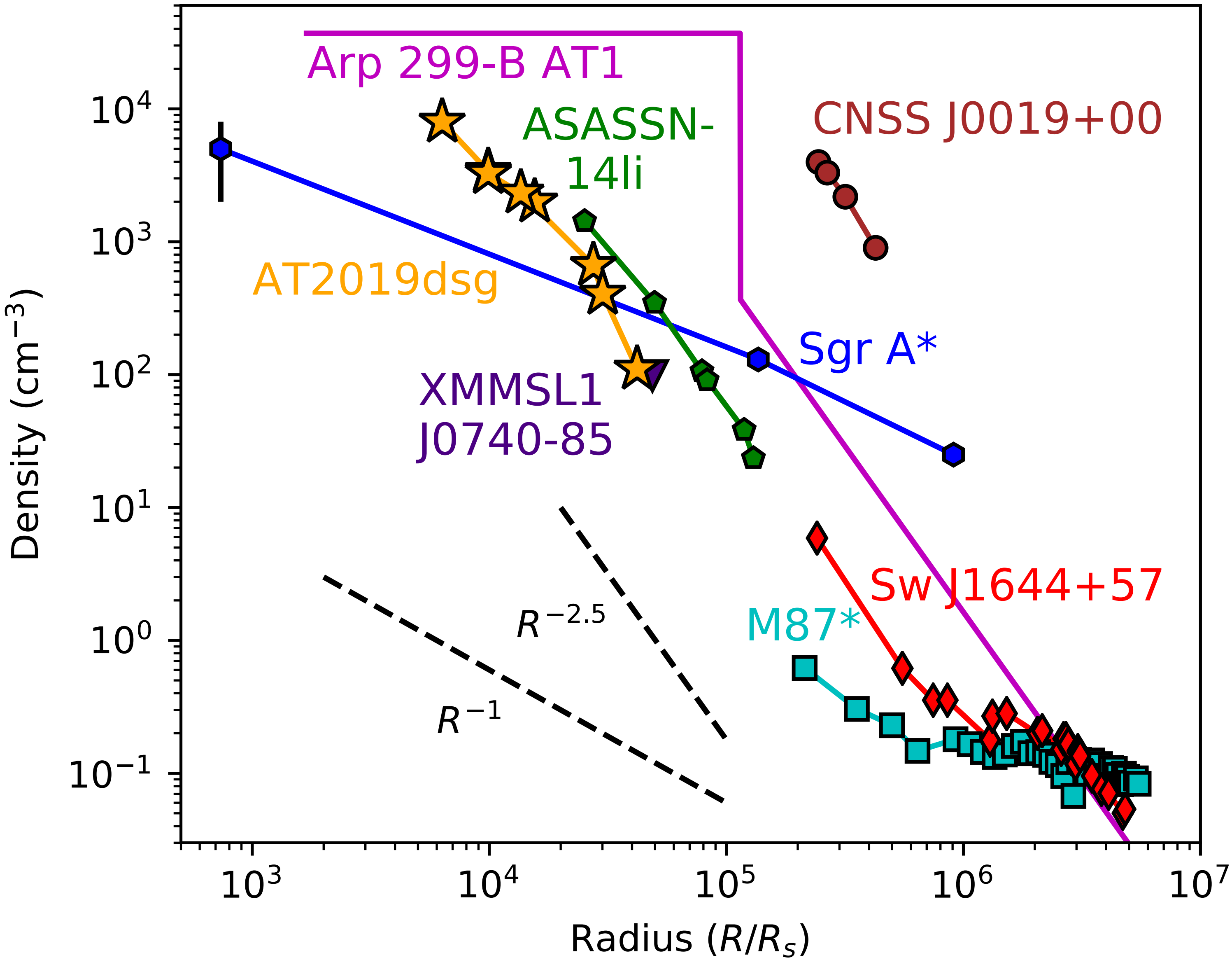


A ubiquitous jet-launching mechanism that is independent of black hole mass?



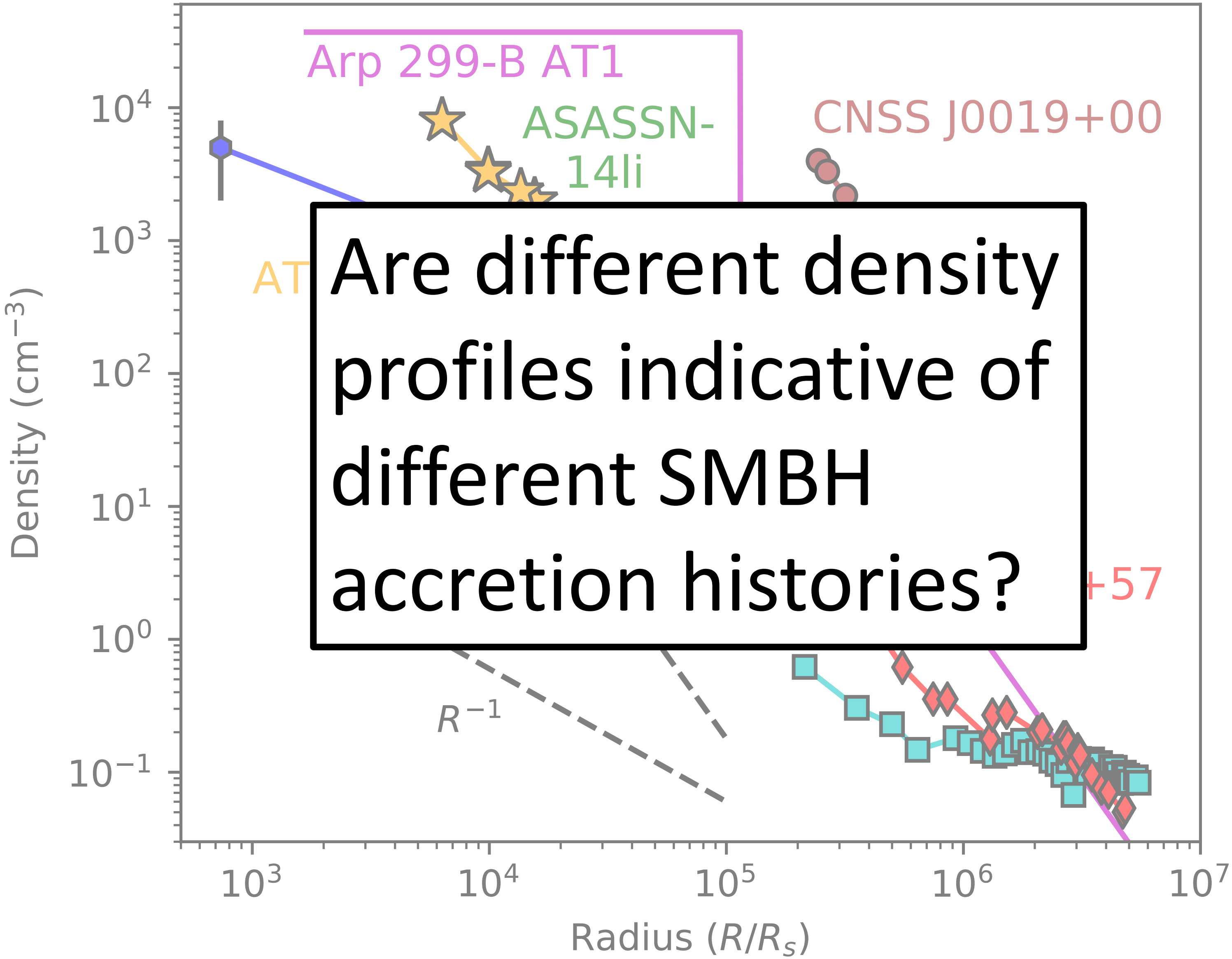
Circumnuclear Density Profiles

Cendes, Alexander et al. (2021)

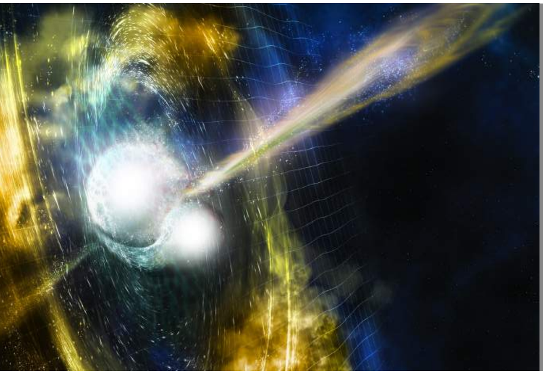


Circumnuclear Density Profiles

Cendes, Alexander et al. (2021)

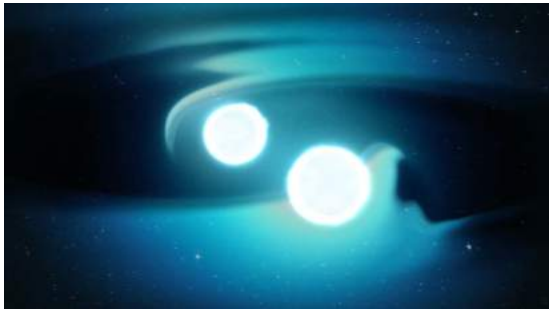


Are different density profiles indicative of different SMBH accretion histories?

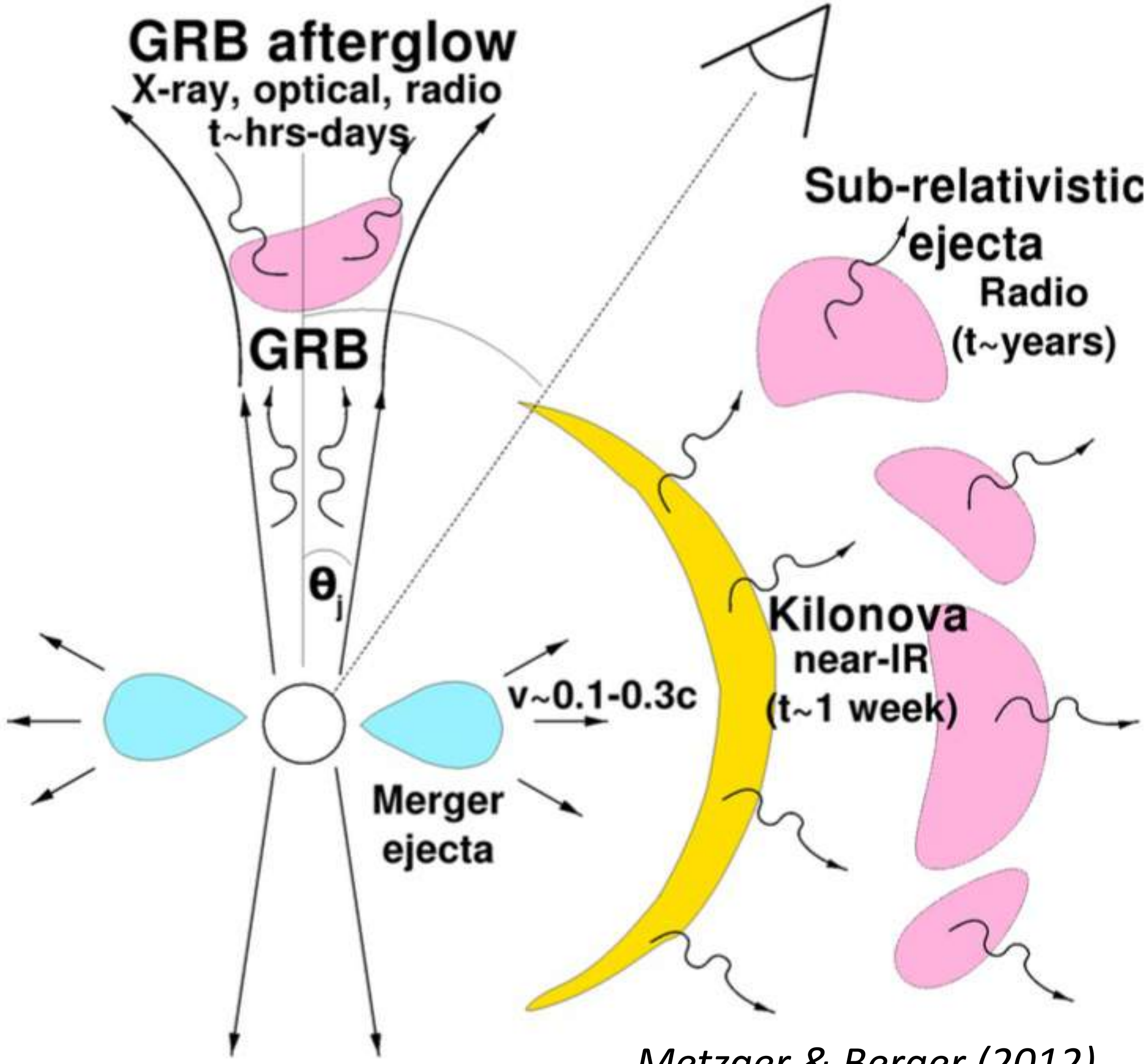


Extreme Transients II: Compact Object Mergers

Portrait of a BNS Merger



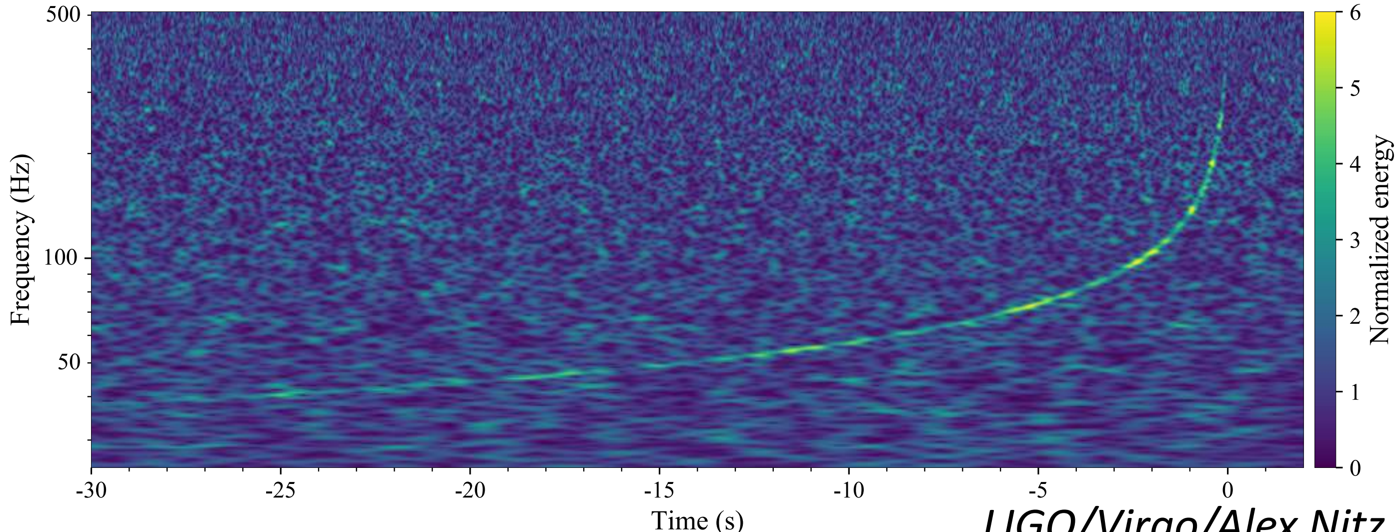
NASA



Metzger & Berger (2012)

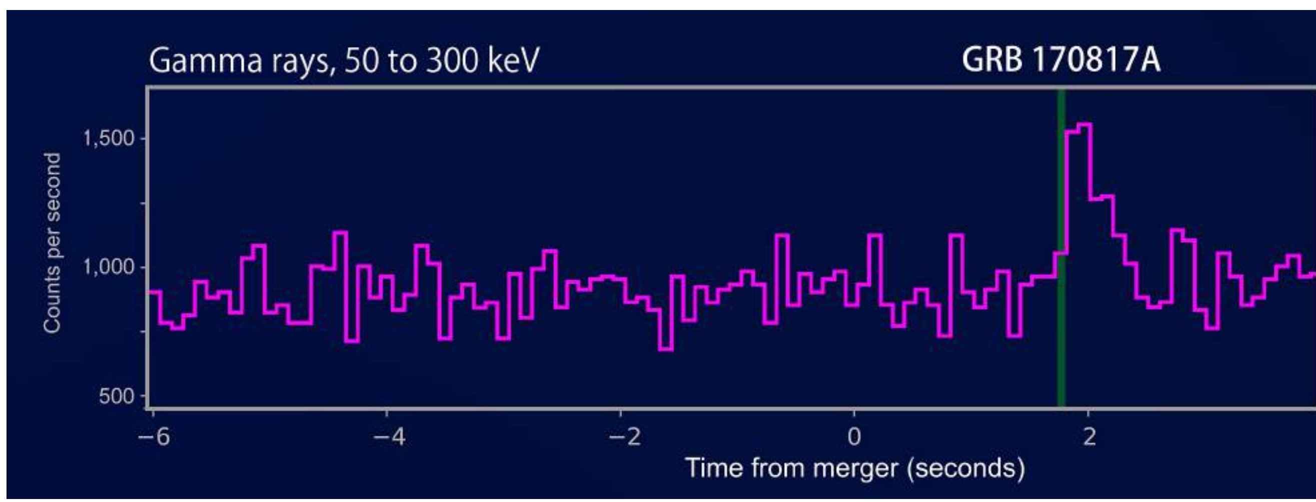
GW170817: The first BNS Merger

Gravitational Waves (LIGO)



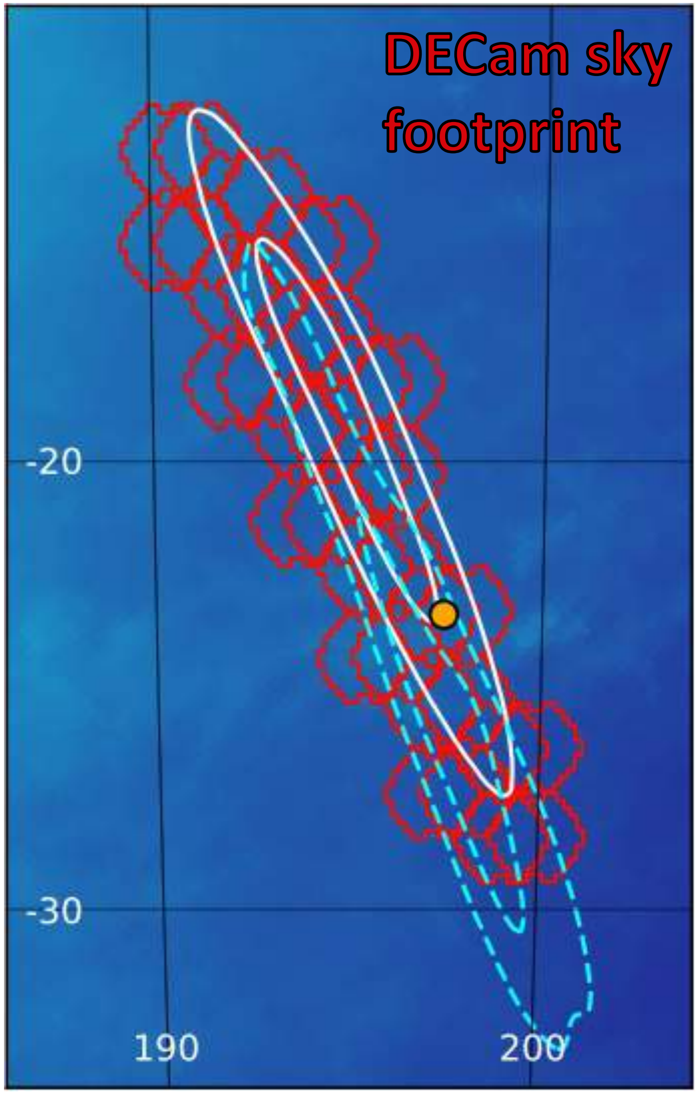
LIGO/Virgo/Alex Nitz

Gamma-rays (Fermi, INTEGRAL)

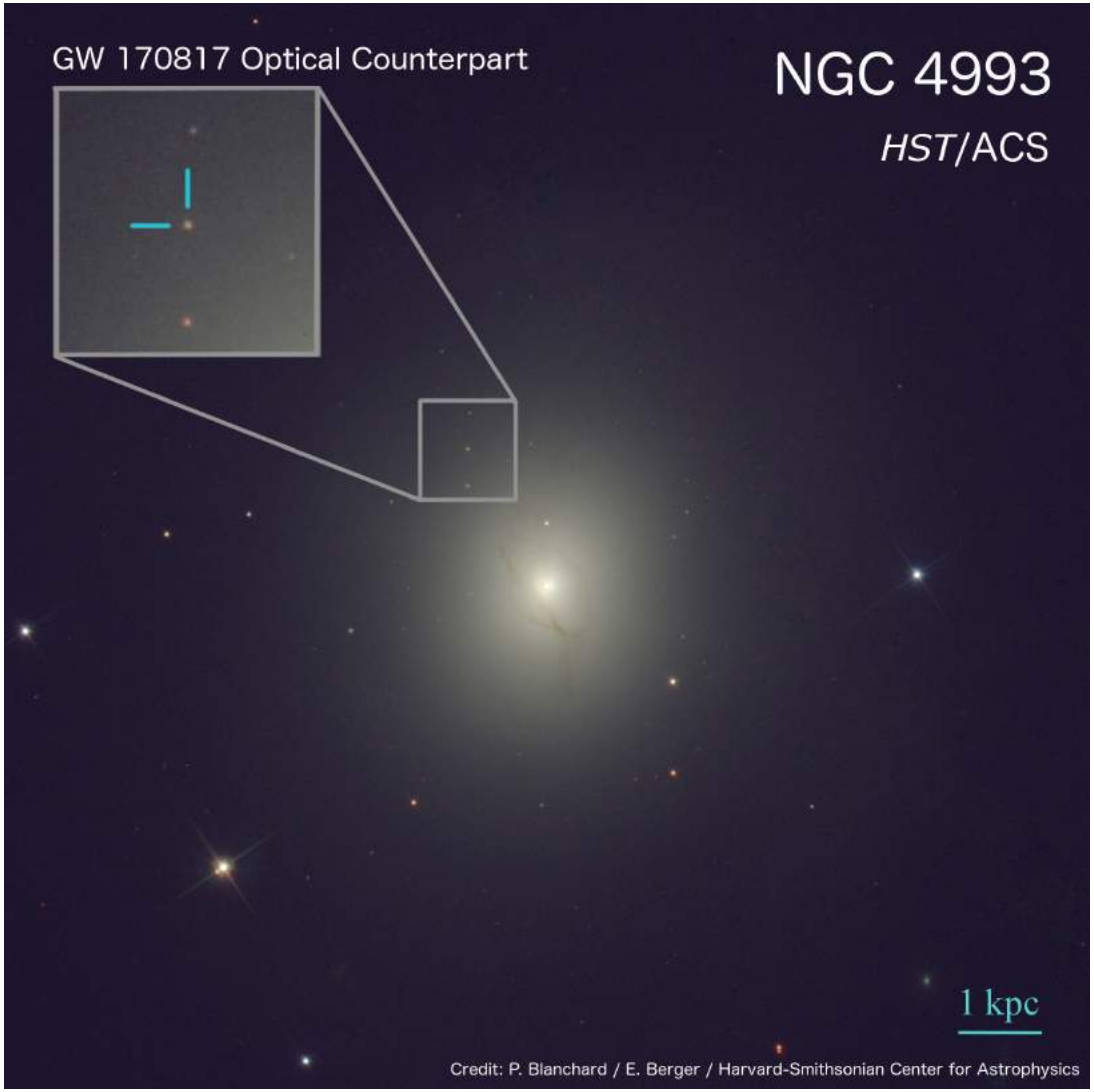


NASA GSFC

First optical detections: t~11 hr

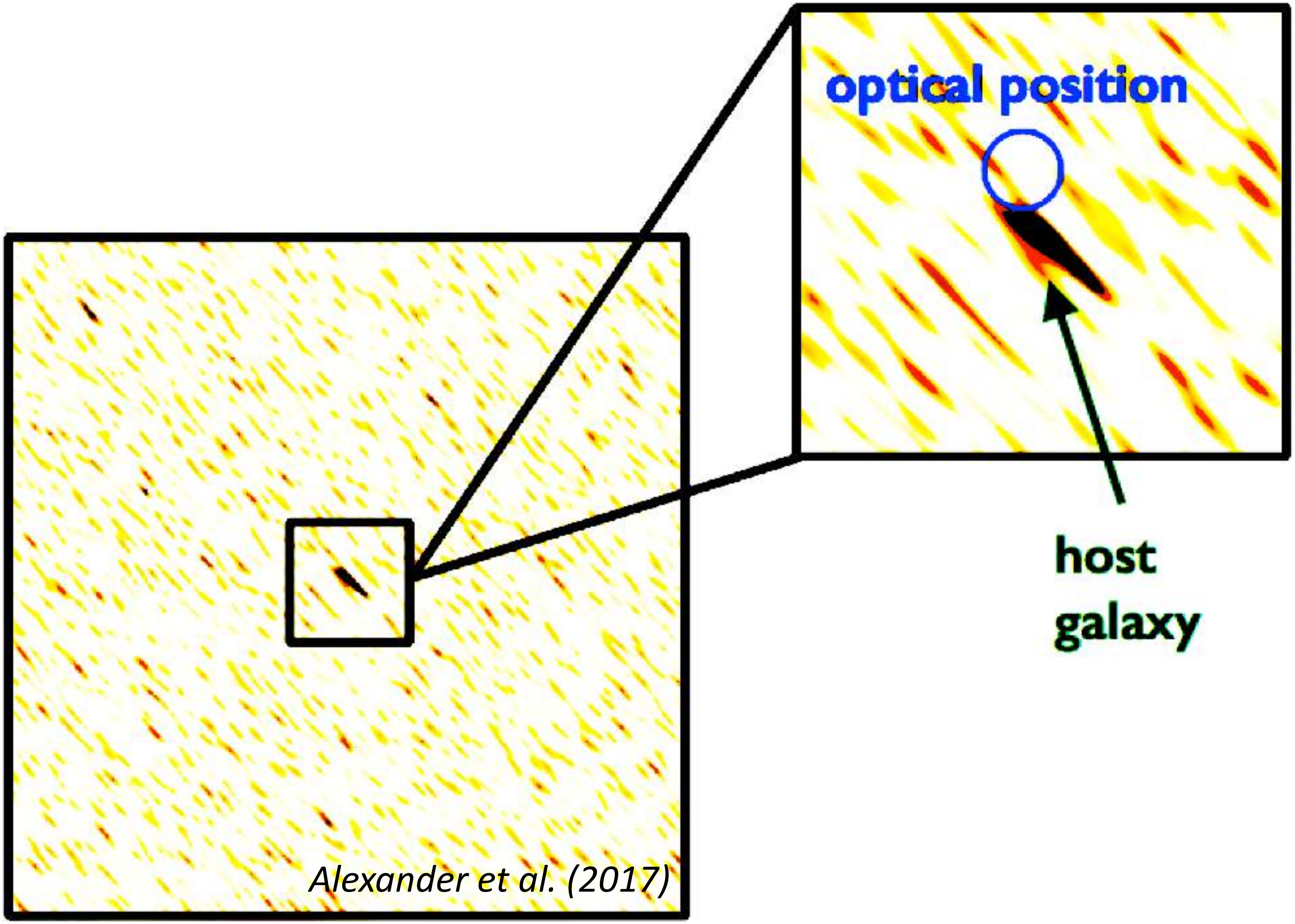


Soares-Santos et al (2017)



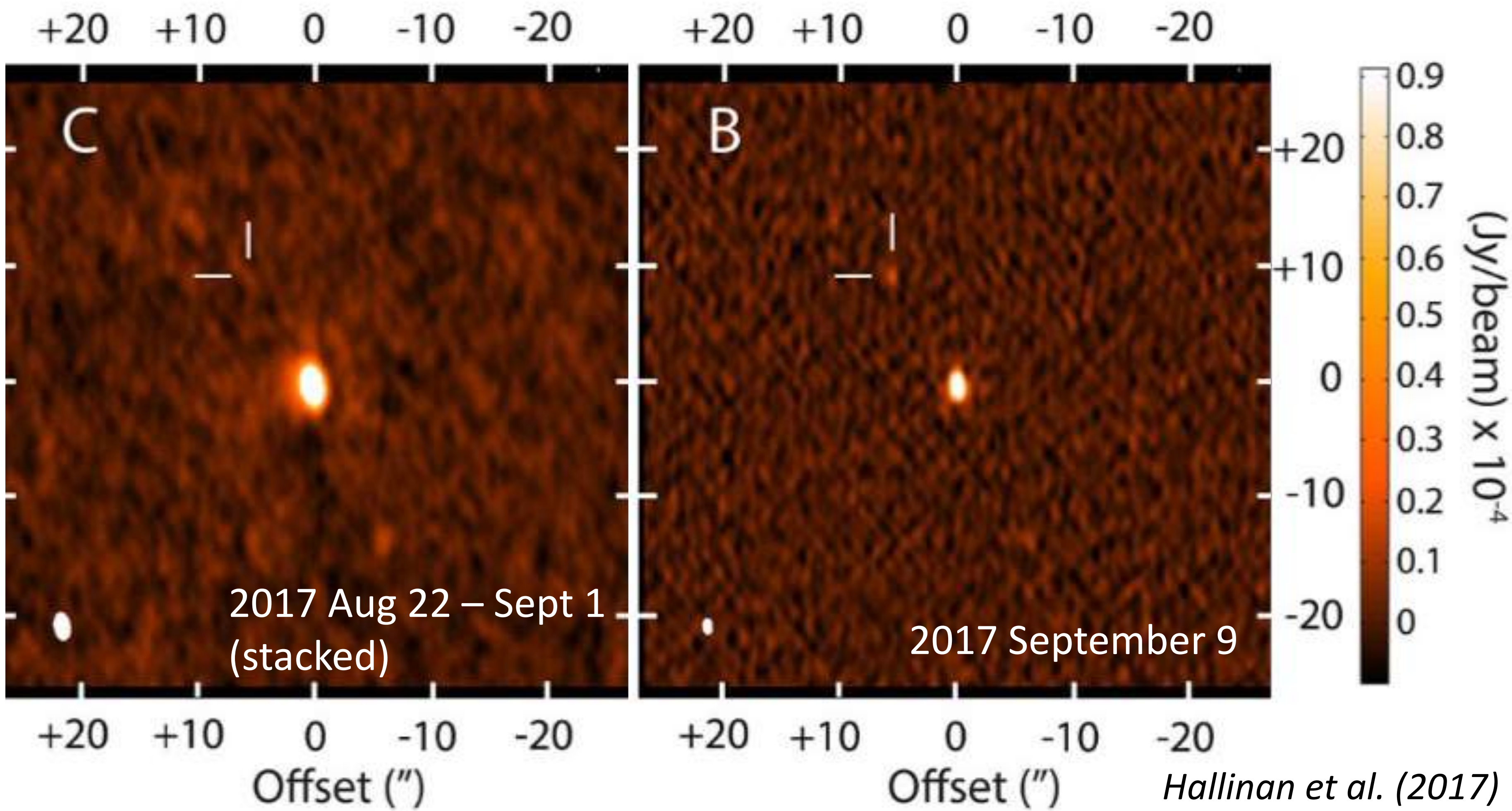
P.K. Blanchard/E. Berger/Harvard-CfA

First radio observations: t~13.7 hr



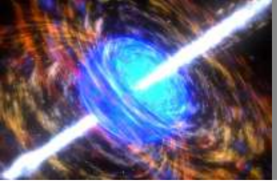
Alexander et al. (2017)

Radio Detection: t~16 d

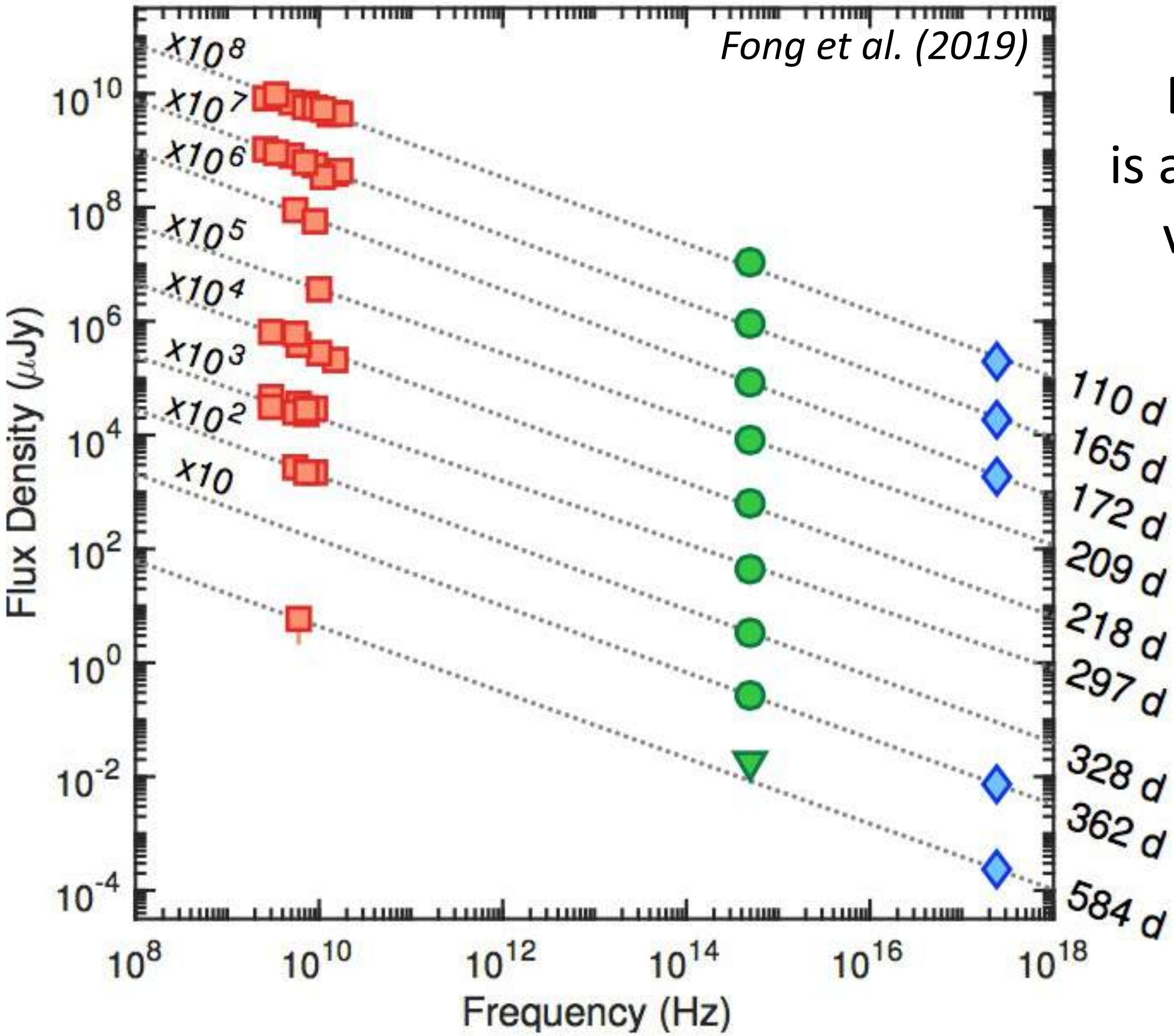


Hallinan et al. (2017)

- 1st detections at 6 GHz and 3 GHz ~16 d after the GW trigger
- Non-detections at 100 GHz with ALMA (Alexander et al. 2017)



SED: A perfect power law

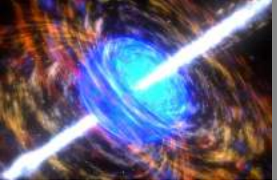


Spectral Energy Distribution (SED) is a pure power law:

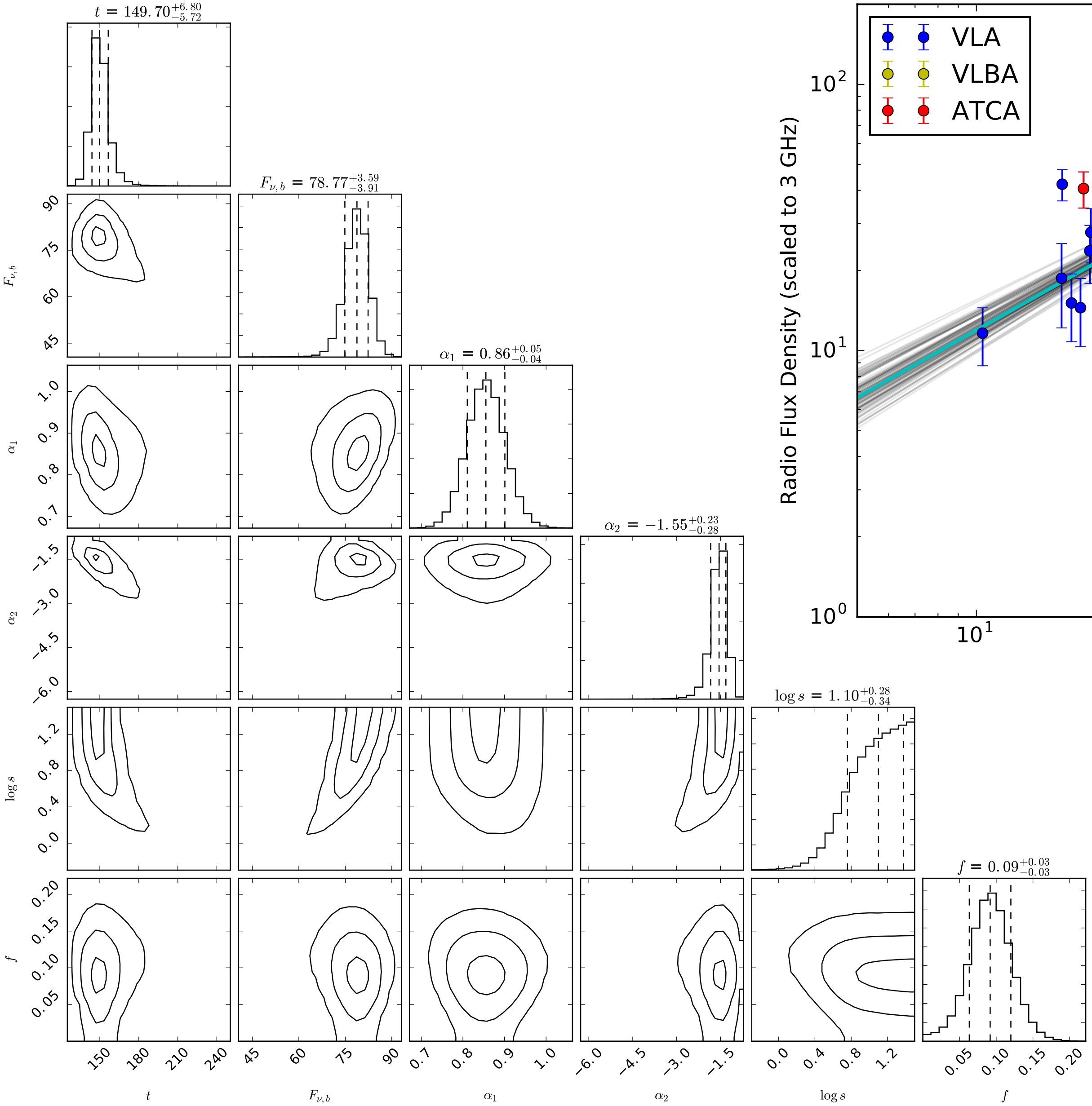
ν_a, ν_m below radio

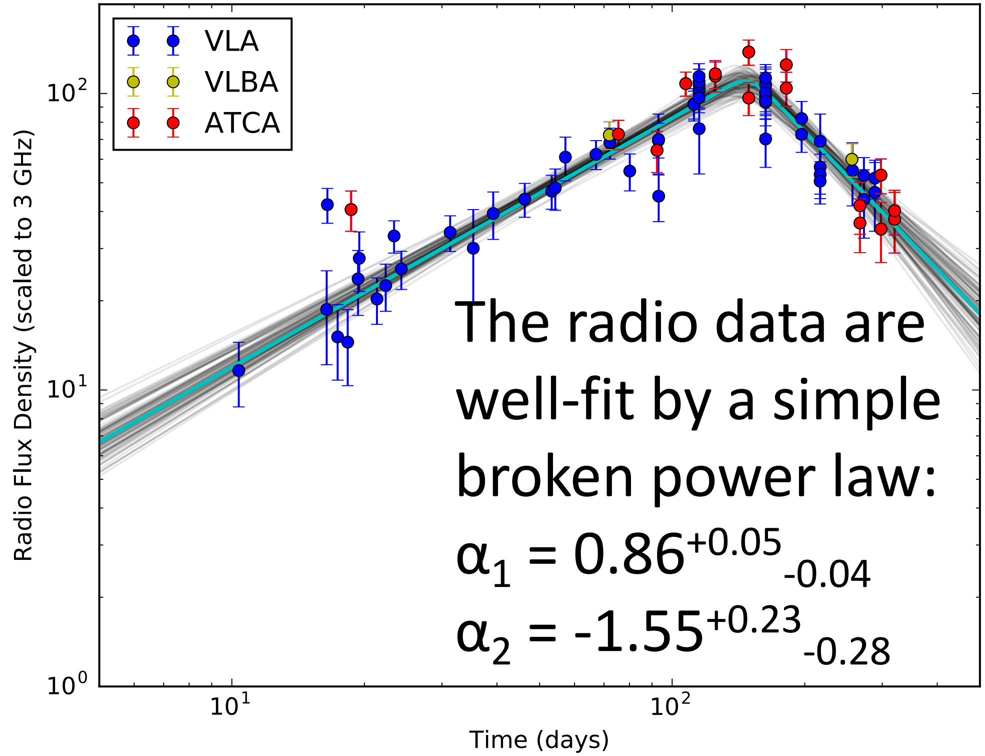
ν_c above X-rays

p = 2.17 ± 0.01



Light curves: Achromatic peak at t~150





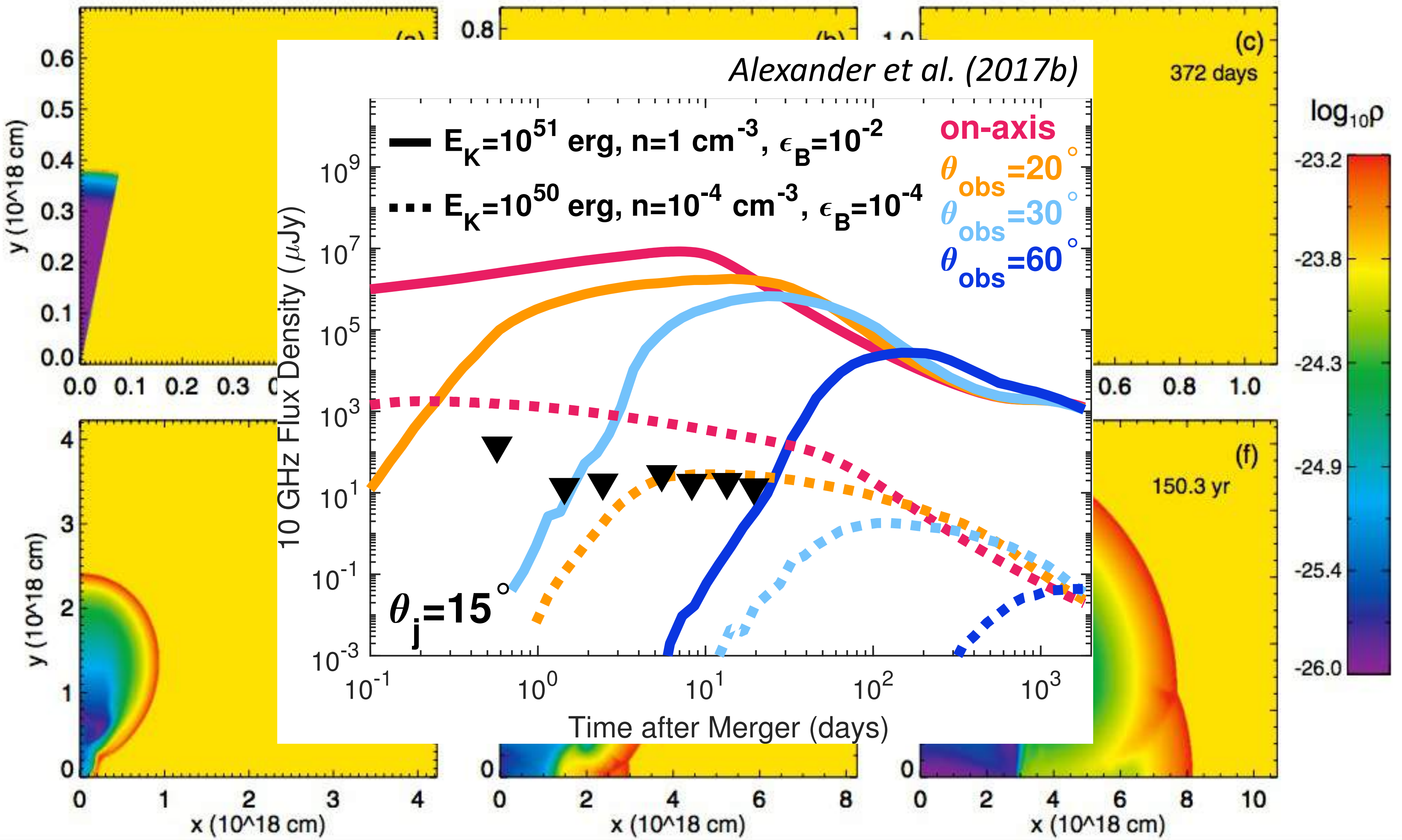
The radio data are well-fit by a simple broken power law:

$\alpha_1 = 0.86^{+0.05}_{-0.04}$

$\alpha_2 = -1.55^{+0.23}_{-0.28}$

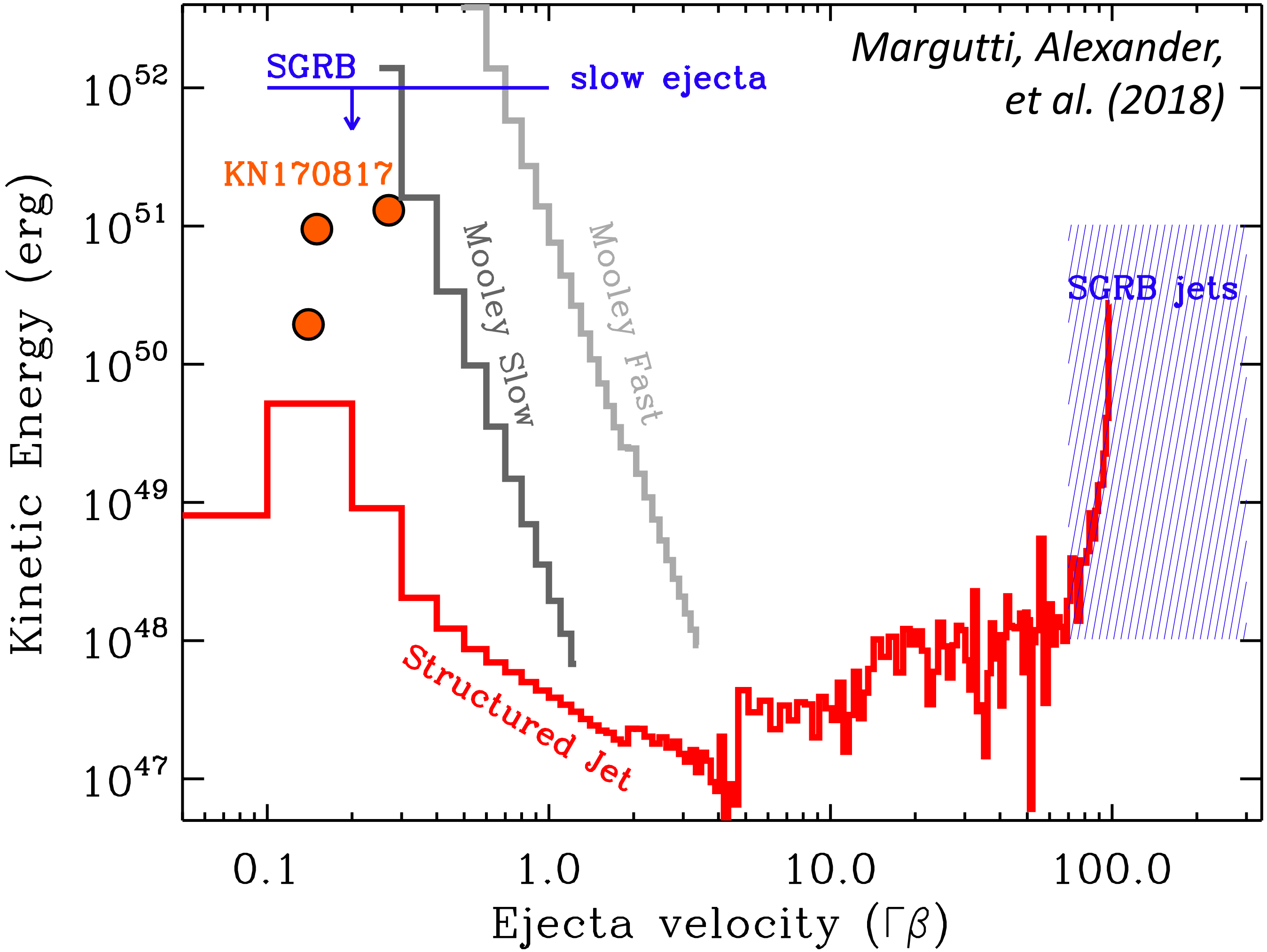
Alexander et al. (2018)

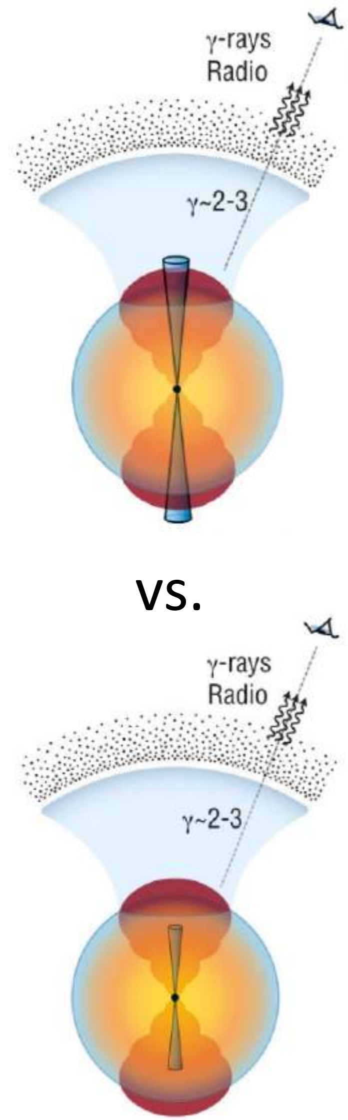
Jet simulations predicted a sharper rise



Zhang & MacFadyen (2009)

Real jets are not uniform

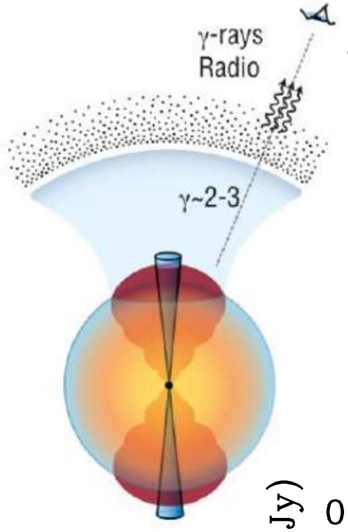




Mooley et al. (2018)

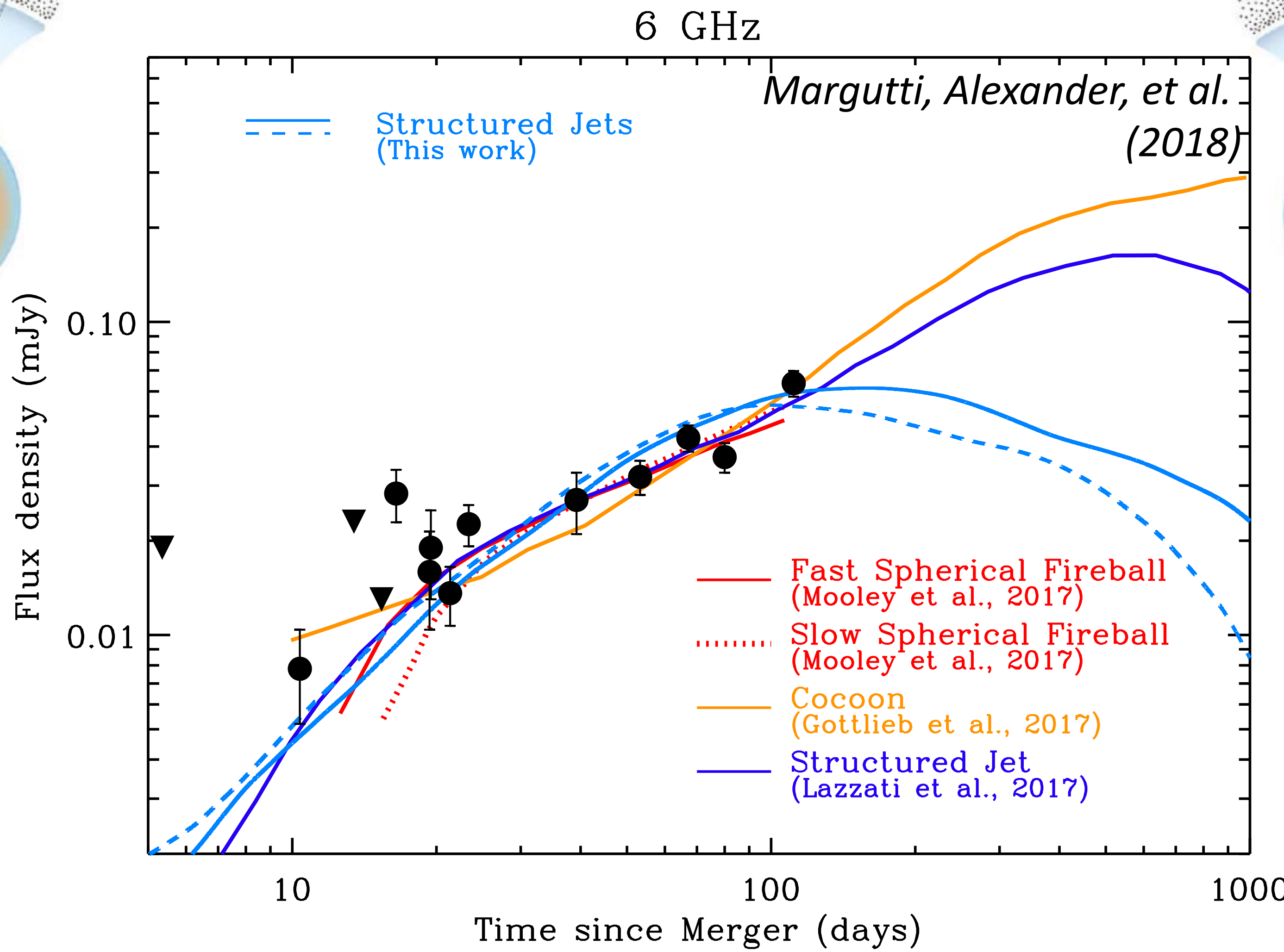
Key question: was a successful jet launched?

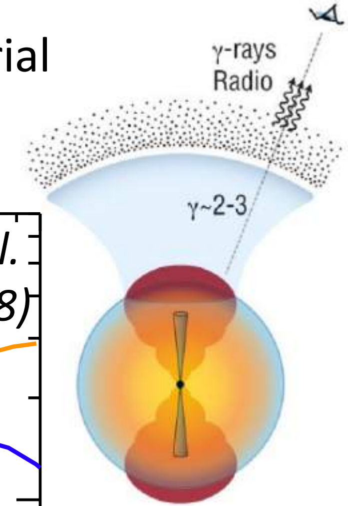
Light curves probe ejecta structure



Successful structured jet model

The early emission is dominated by mildly-relativistic material ($\Gamma \sim$ 3-10): either wings of a structured jet or a cocoon.



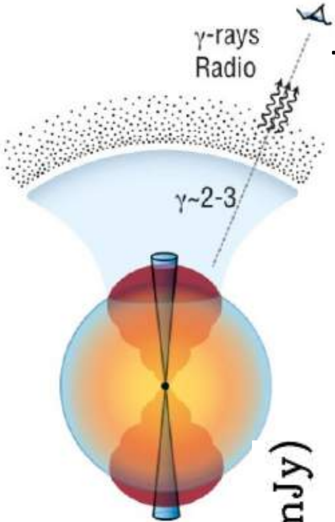


Choked jet/cocoon model

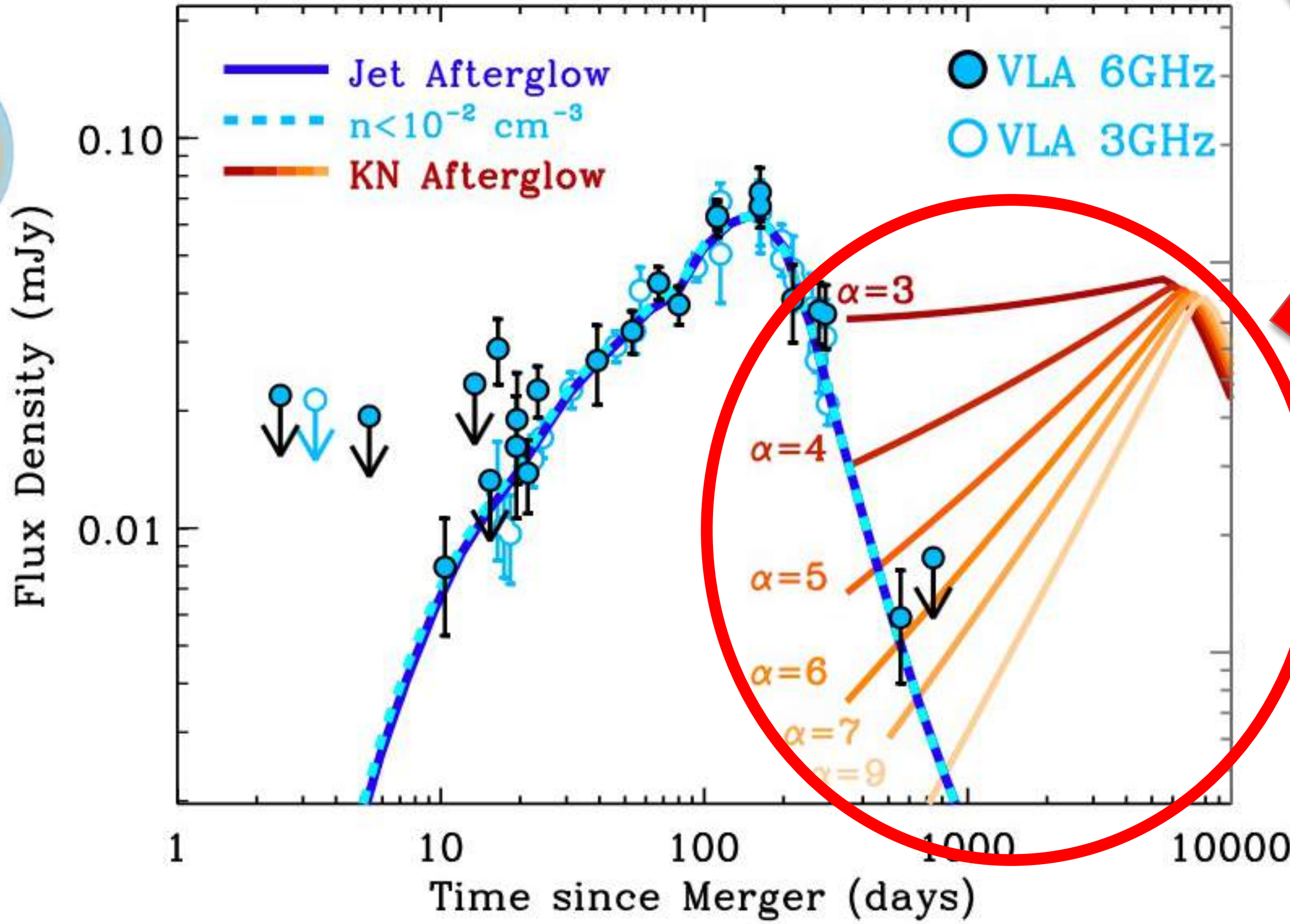
Light curves probe ejecta structure

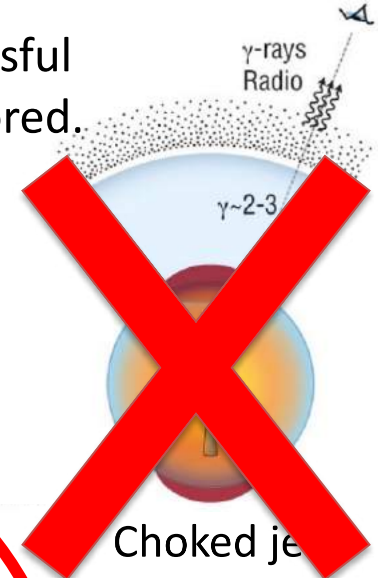
The rapid late-time decline requires a narrow (~5°), successful ultrarelativistic jet (Γ ~ 175): a choked jet/cocoon is disfavored.

Hajela et al. (2019)



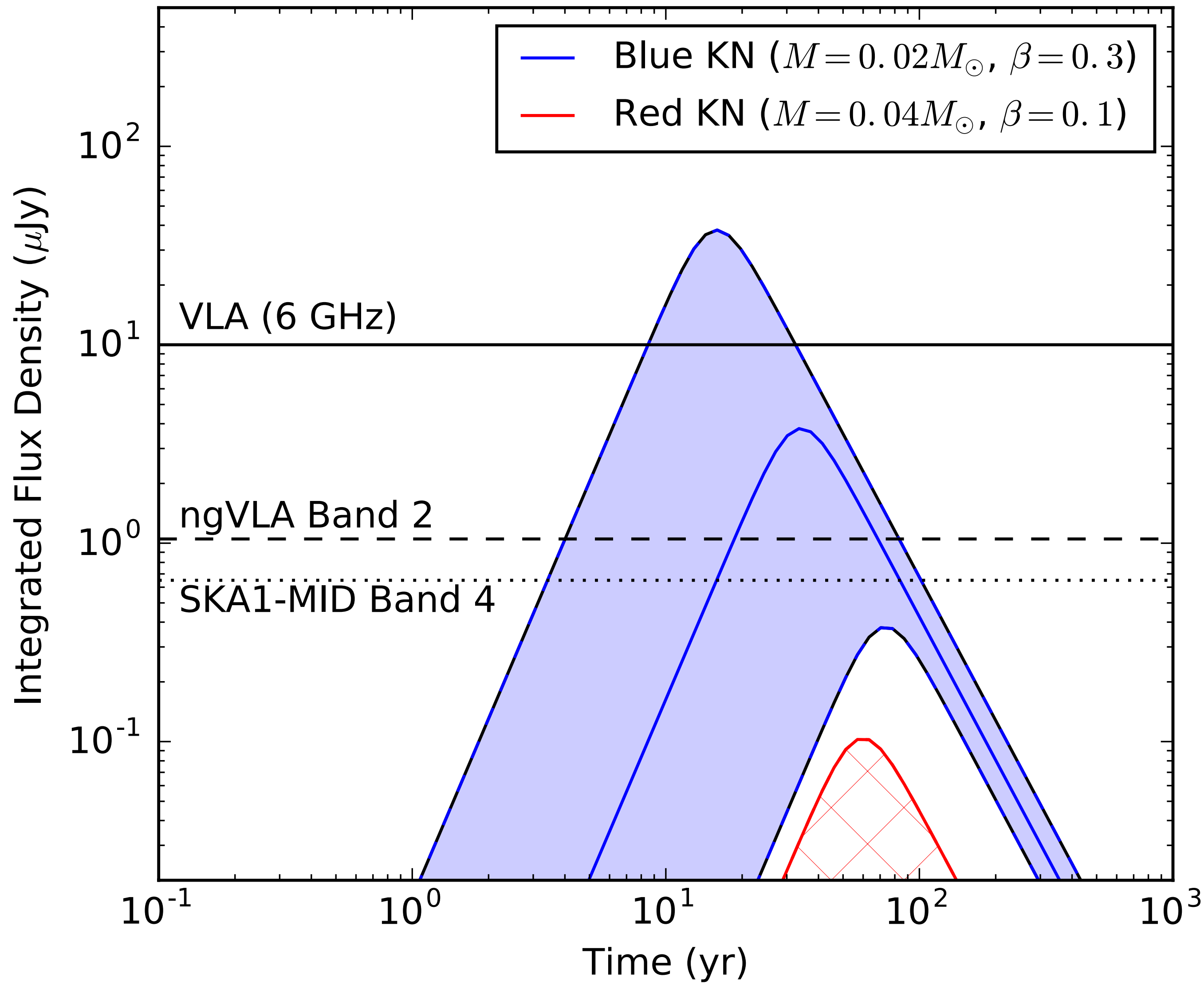
Successful structured jet model





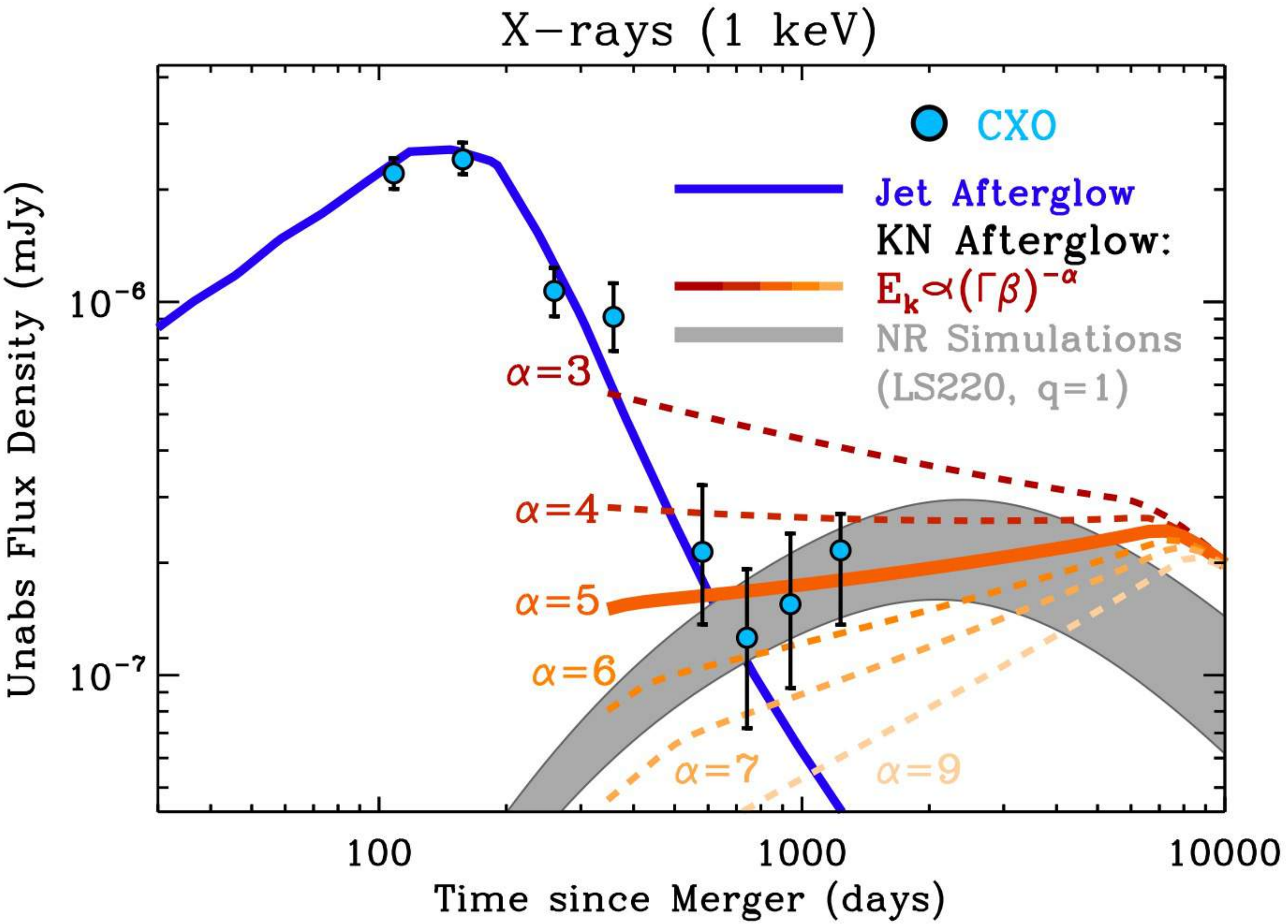
Choked je
cocoon
model

A long-term rebrightening? KN ejecta



Alexander et al. (2017)

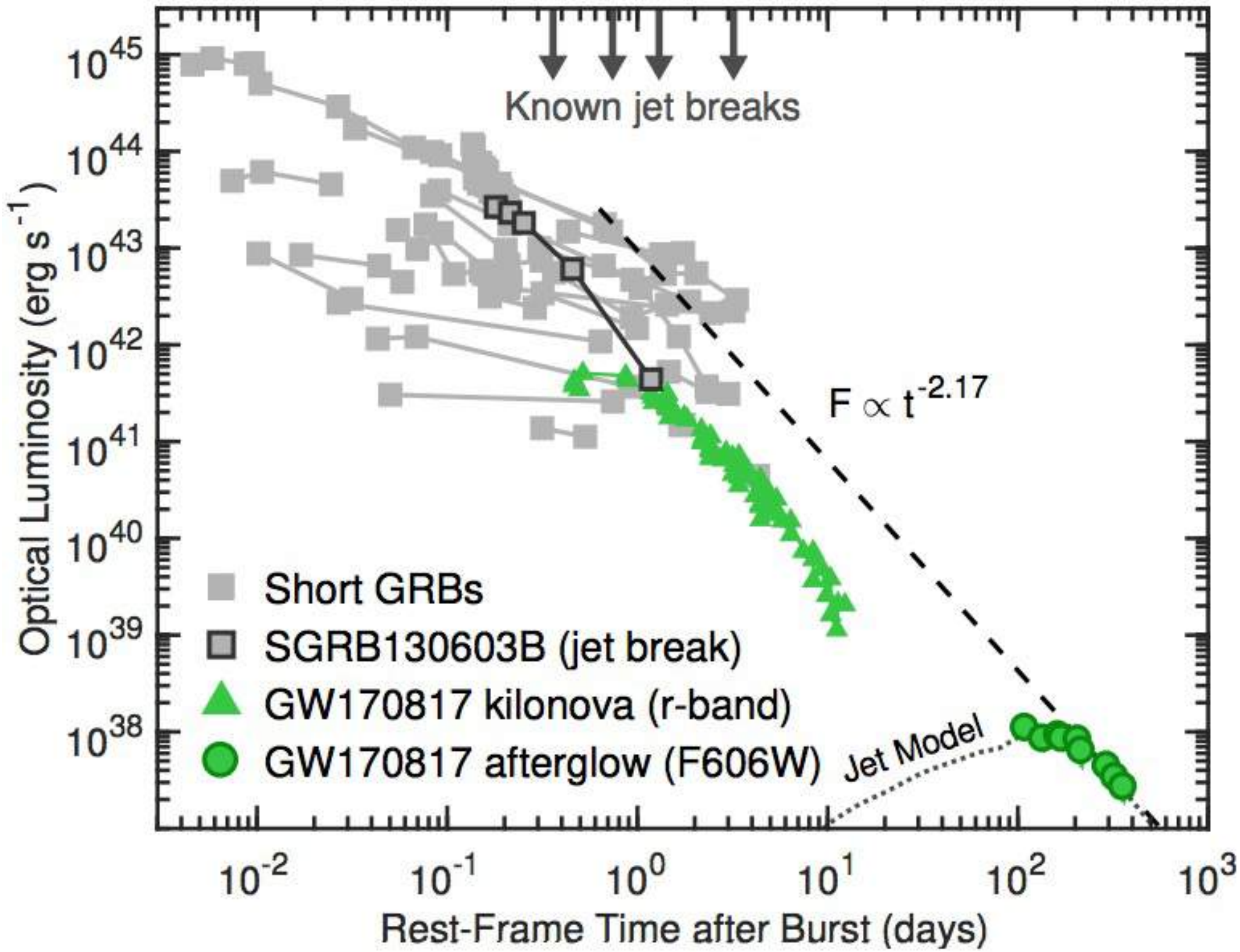
Excess X-ray emission…stay tuned!



Hajela et al. (2021)

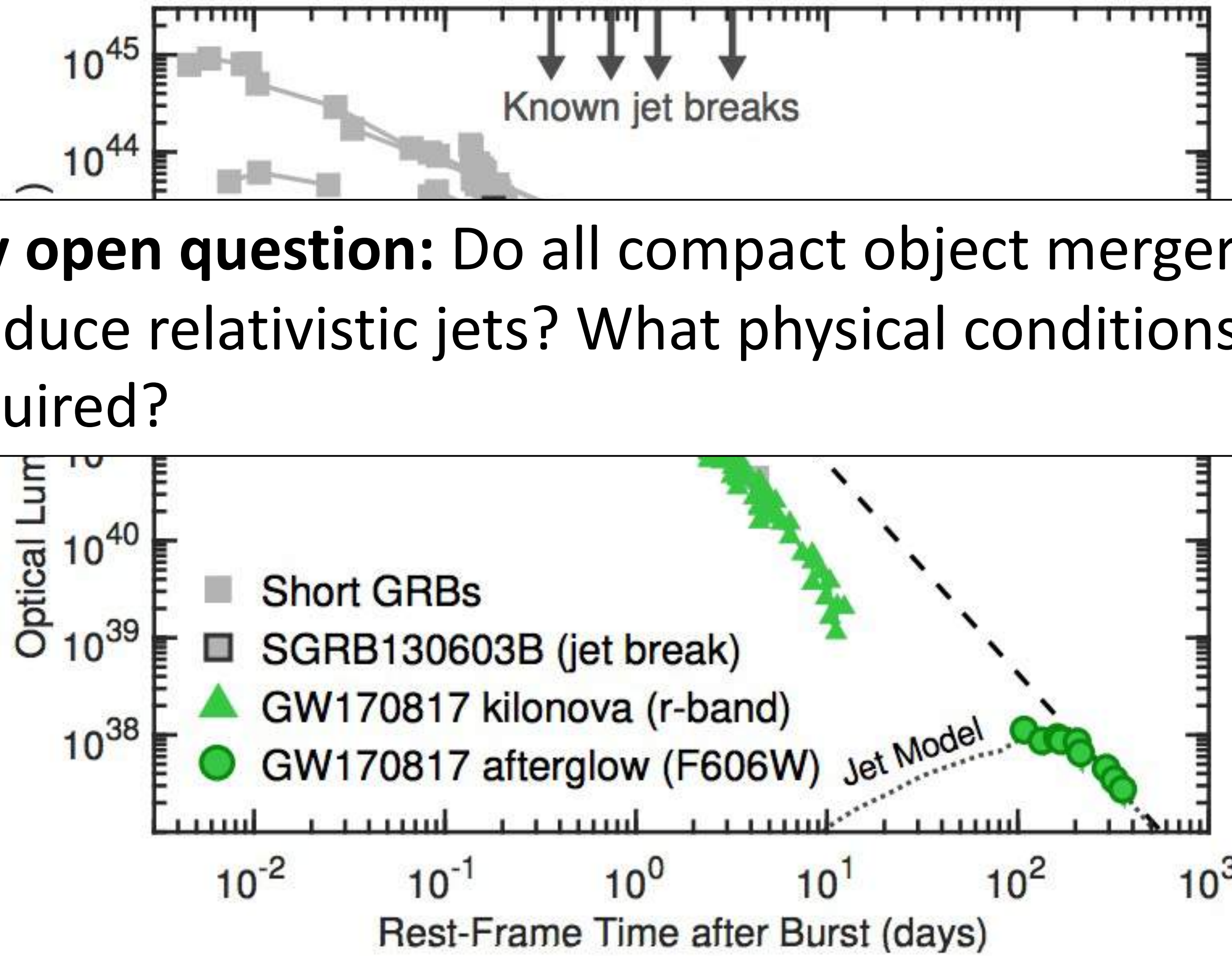
GW170817 was similar to cosmological SGRBs

Fong et al. (2019)

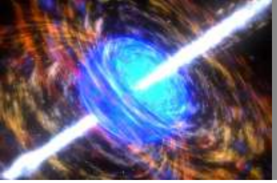


GW170817 was similar to cosmological SGRBs

Fong et al. (2019)



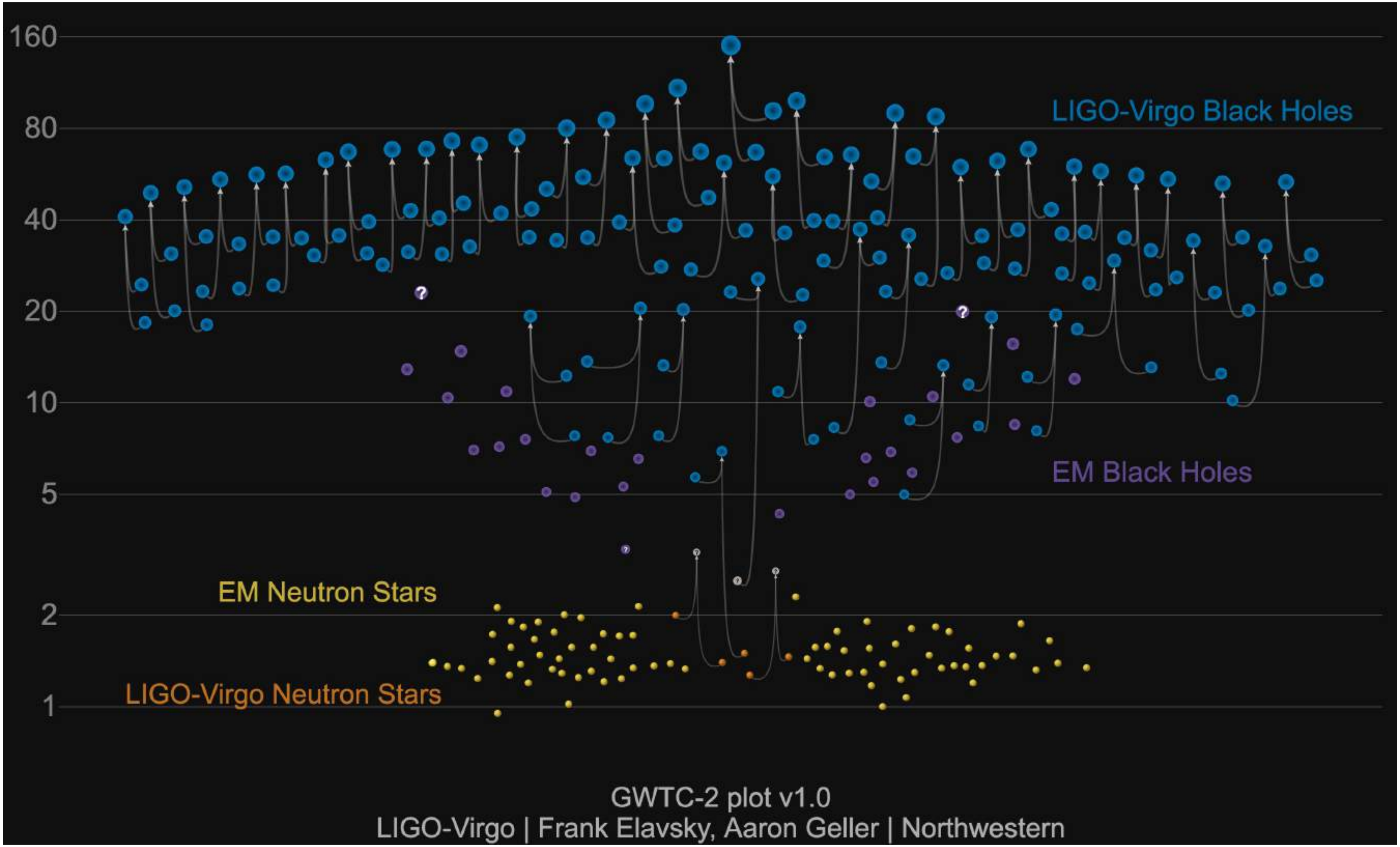
Key open question: Do all compact object mergers produce relativistic jets? What physical conditions are required?



An expanding local population of BH, NS

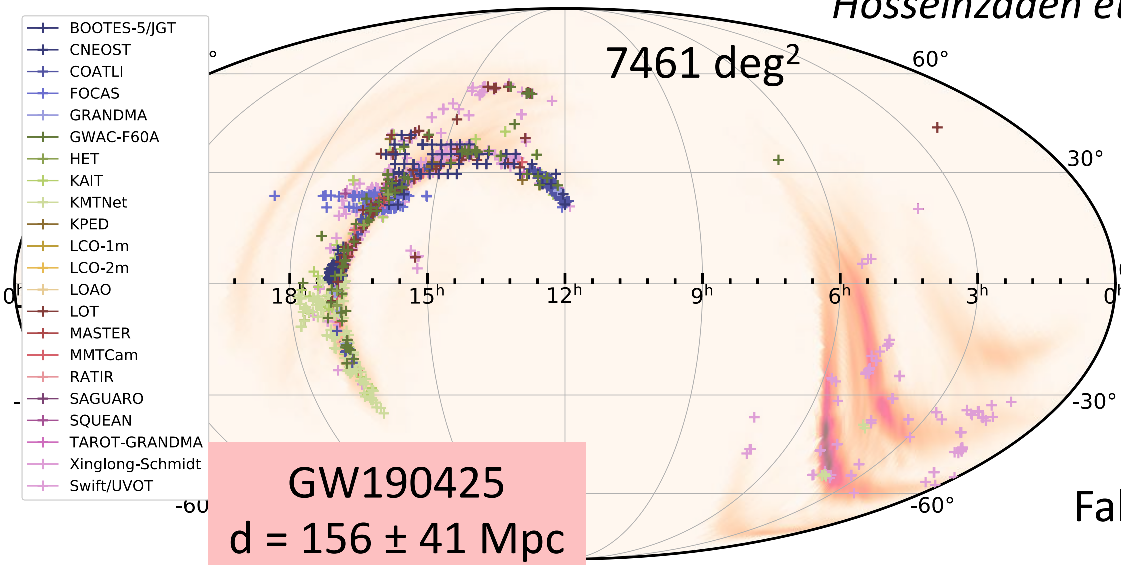
O3 observing run: added dozens of new GW mergers

Mass (solar masses)

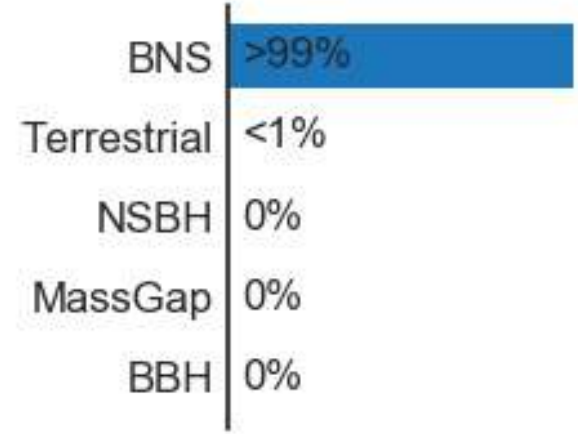


O3: New Challenges for Astronomers

Hosseinzadeh et al. (2019)

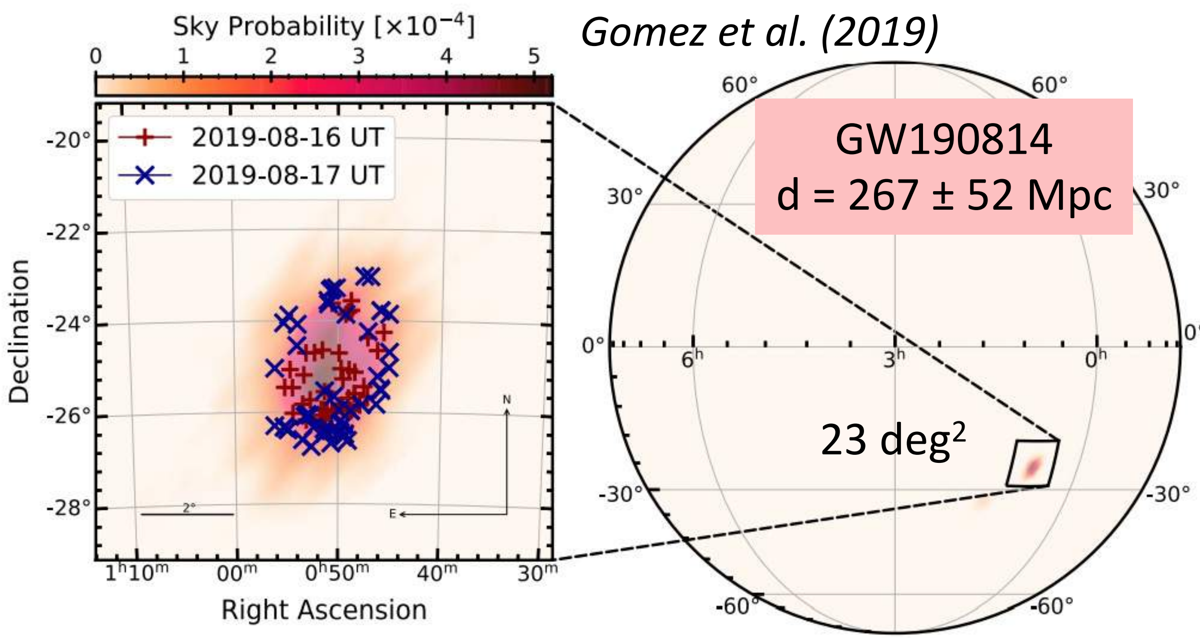


GW190425
d = 156 ± 41 Mpc

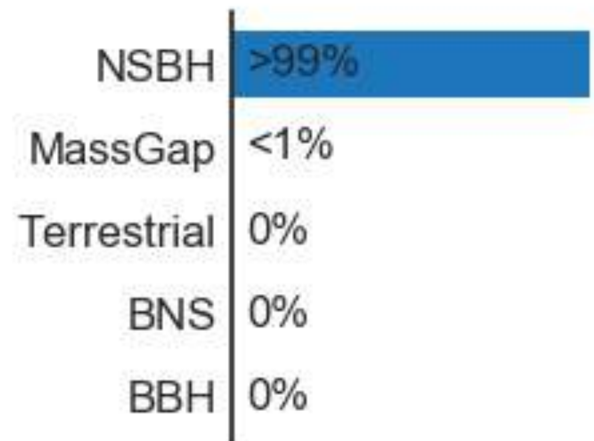


False Alarm Rate (FAR): 1 per 69834 years

Gomez et al. (2019)



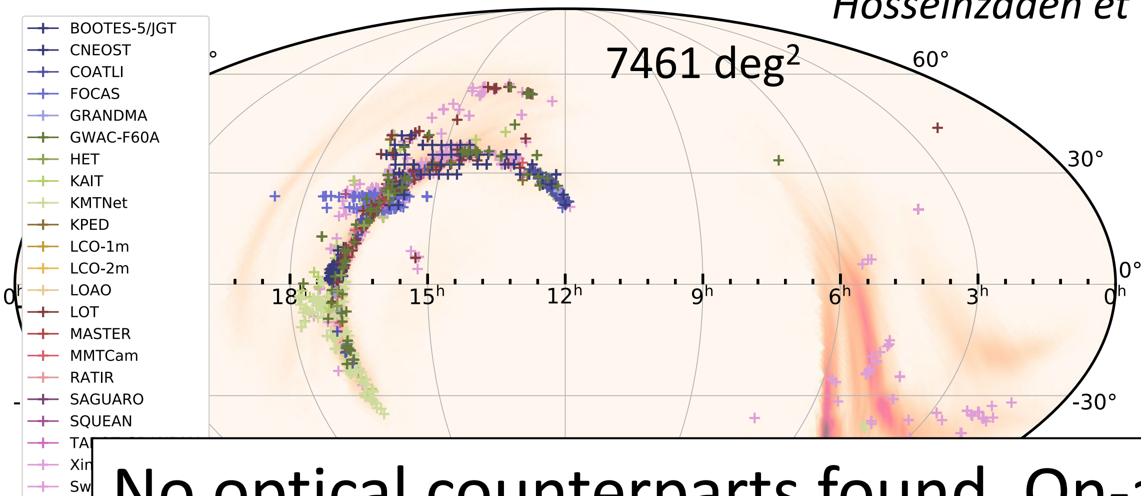
GW190814
d = 267 ± 52 Mpc

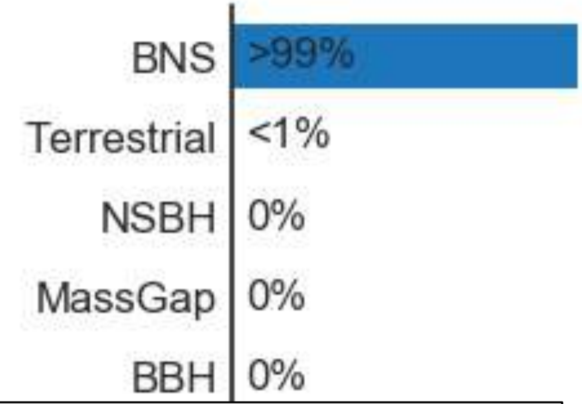


FAR: 1 per 1.559e+25 years

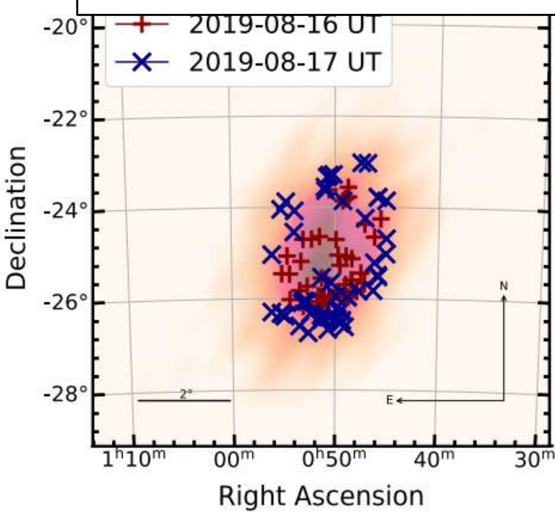
O3: New Challenges for Astronomers

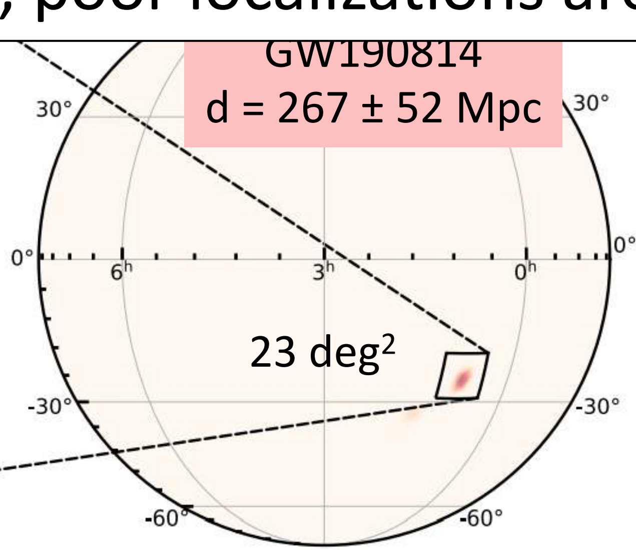
Hosseinzadeh et al. (2019)





No optical counterparts found. On-axis jets ruled out, many kilonovae models would not have been detectable. Larger distances, poor localizations are a major challenge.



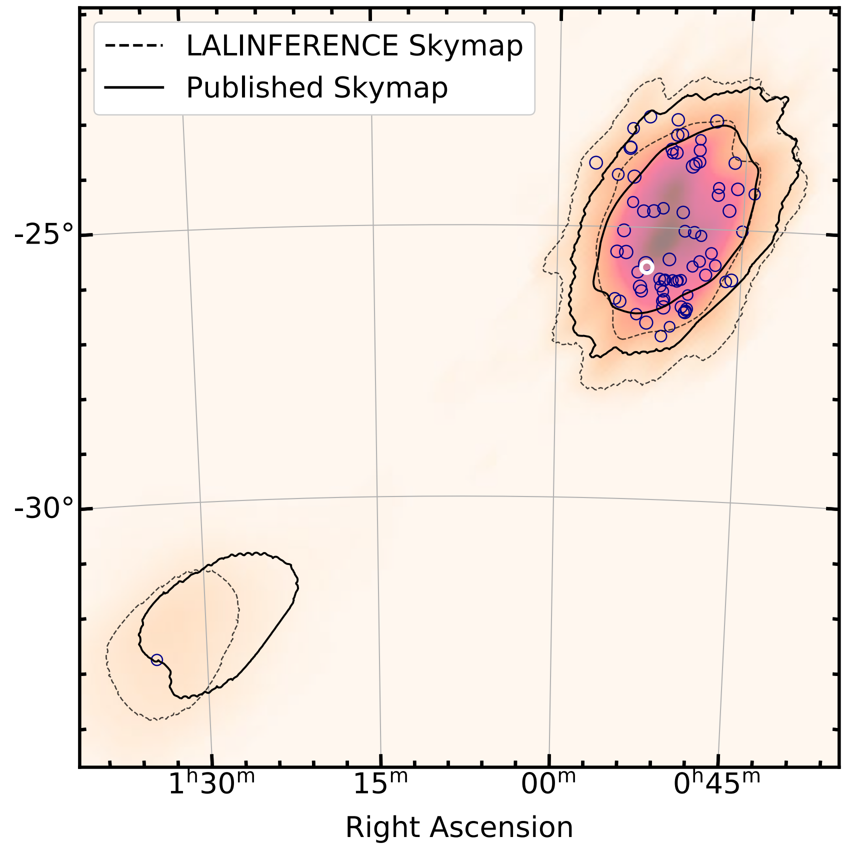


FAR: 1 per 1.559e+25 years

Radio Follow up of O3 GW Events

I led a VLA program to obtain **radio observations of new GW events in O3**, as part of a collaboration of multi-wavelength observers and theorists.

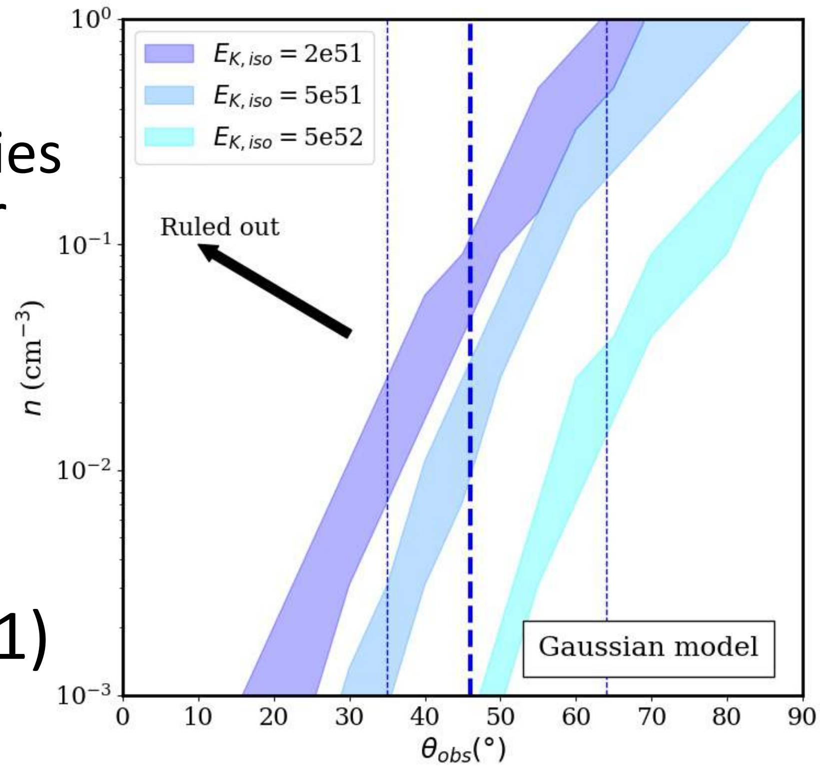
- Search strategies are optimized for technological limits: the VLA's small field of view makes a wide-field search impractical
  - Instead we targeted likely host galaxies within the localization volume, following the stellar light
- Radio follow up of GW190814: a test case for future searches



Alexander et al. (2021, in press)

Radio observations of GW190814

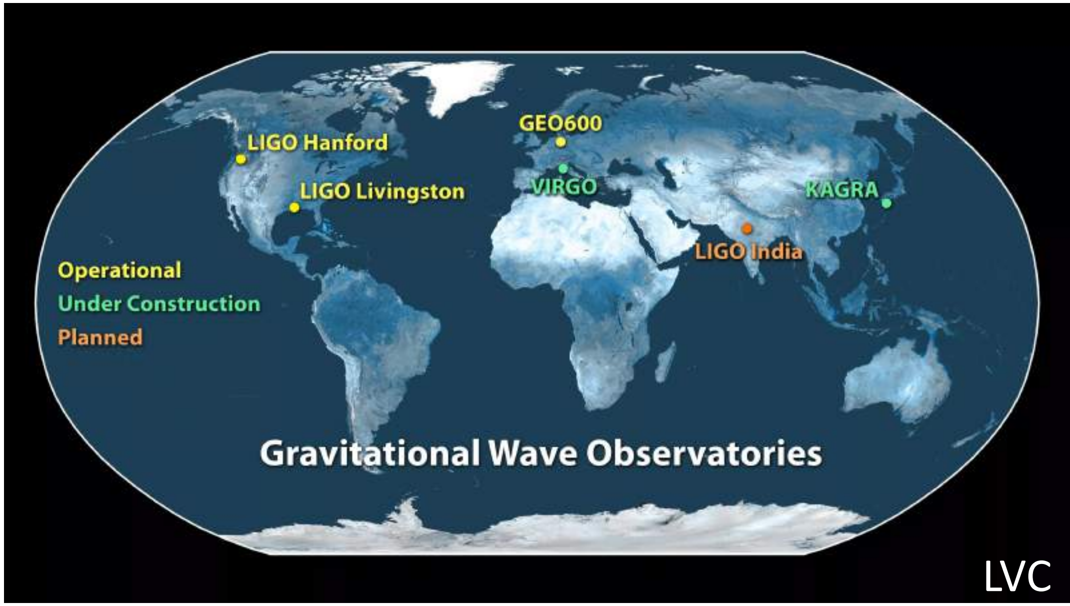
- Galaxy-targeted search with the VLA (Alexander et al. 2021, in press)
  - Observed 75 possible host galaxies of GW190814 (32% of the stellar luminosity)
  - Deep limits rule out energetic SGRB-like jets, even off-axis
  - Variable AGN: largest contaminants
- See also Dobie et al. (2019, 2021)
  - First sensitive wide-field radio follow up of a GW event (w/ASKAP)
  - No radio counterpart found

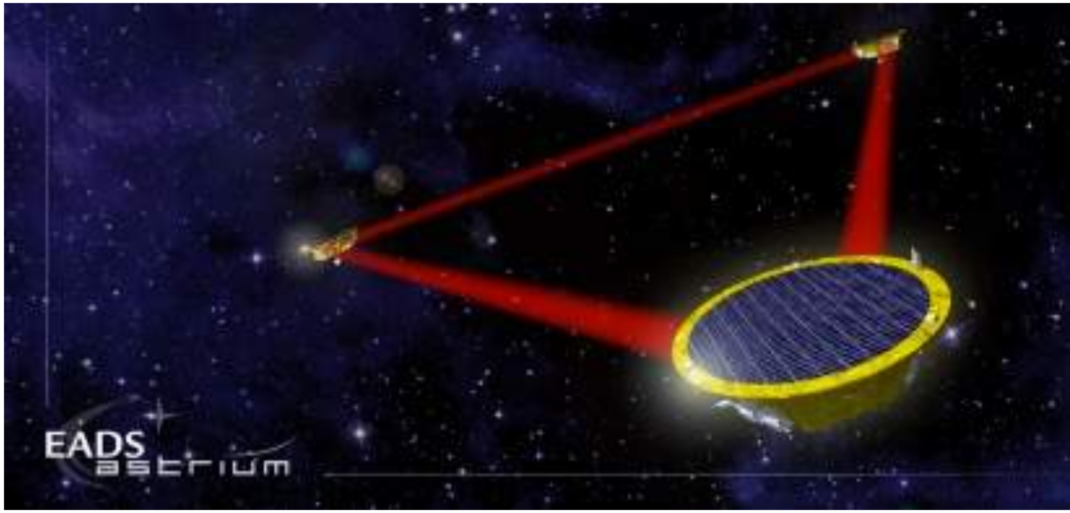


Alexander et al. (2021, in press)

The Future of GW Astrophysics

- **2020s and beyond:** New GW detectors will decrease average localization region size, increase discovery rate
- Space-based detectors (e.g. LISA, pulsar timing arrays) will open up new classes of sources





Summary

- The radio properties of "extreme" transients reveal new physical insights and discoveries:
  - **TDEs** can produce a range of **jets** and **outflows**
    - *Recent review paper: Alexander et al. (2020)*
  - At least some **compact object mergers launch successful GRB-like jets** (GW170817)
    - *True rate will be probed by radio follow up of GW triggers*
- Radio transient science is poised for revolution
  - VLA, ALMA, upcoming facilities (SKA, ngVLA)
  - **Unique** synergies with new GW, neutrino, and multi-wavelength capabilities, **discovery** of transients in the radio band