The nature of radio emission from the tidal disruption event AT2019dsg

A visualisation of AT2019dsg, found coincident with high-energy neutrino IC191001A. Image credits: DESY, Science Communication Lab.

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"*High-resolution VLBI Observations of and Modeling the Radio Emission from the Tidal Disruption Event AT2019dsg*", Mohan P., An T., Zhang Y.-K., Yang J., Yang X-L., Wang A., 2022, ApJ, 927, 74.

Tidal disruption event (TDE)

Nature	Observational signatures
• Disruption of a star at ≈ tidal radius R_t of a galactic supermassive black hole (SMBH, with a Schwarzschild radius $R_S = 2GM_\bullet/c^2$). $R_t \approx 24\ R_S$ (SMBH mass $M_\bullet = 10^6\ M_\odot$) and $R_t \approx 1.1\ R_S$ (SMBH mass $M_\bullet = 10^8\ M_\odot$). • Association with existing active galactic nuclei or dormant galactic nuclear region.	• Thermal flare (optical/UV) from accretion onto SMBH or from the forming accretion disk (shocked regions at periphery). Bright optically thick photospheric emission for months with peak luminosity of $10^{43} - 10^{44}$ erg s^{-1}. • Declining optical/UV light curve (months) with canonical index of $-5/3$.

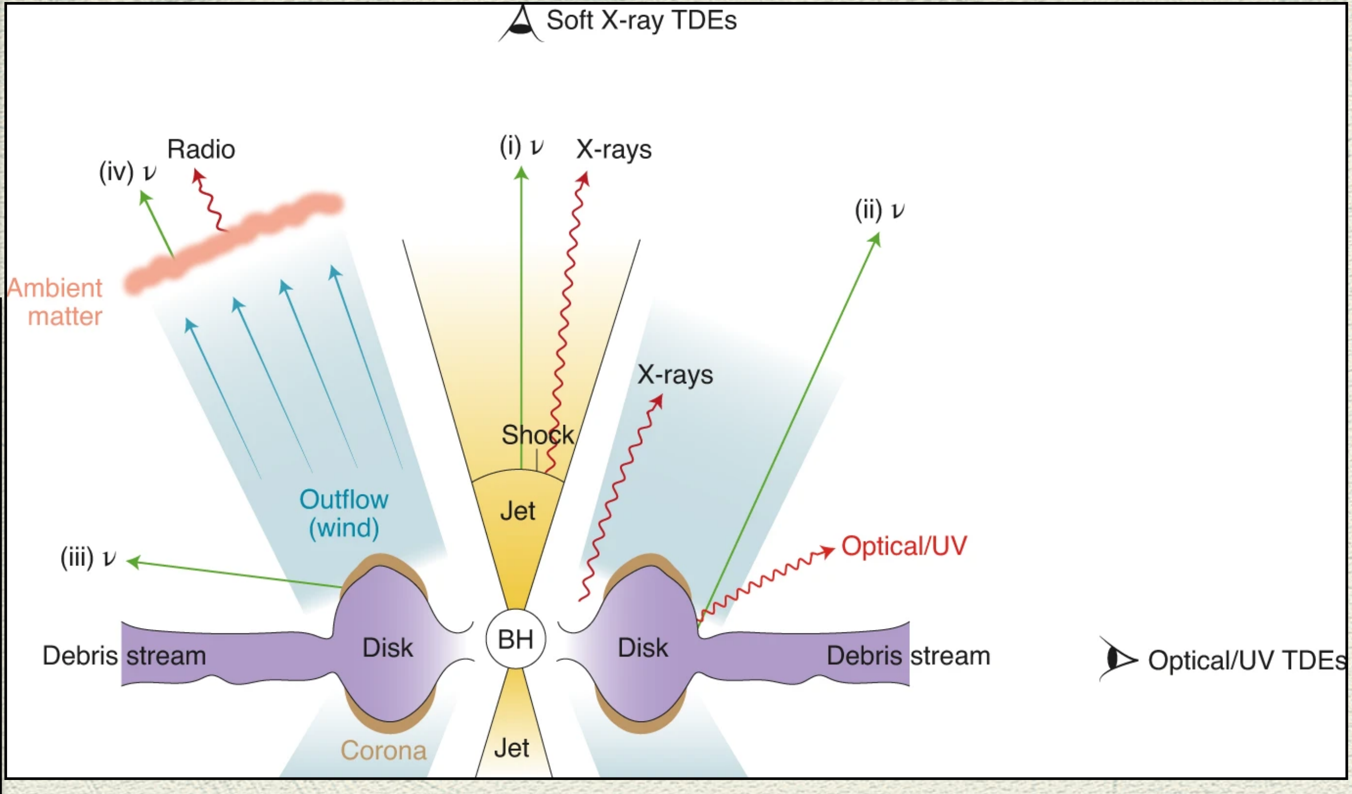
- **Outflow:** during super-Eddington accretion phase, supported by disk based radiation pressure, or launched as unbound debris.
- **Afterglow emission (including radio):** non-thermal nature; internal shocks in outflow or interaction with surrounding circum-nuclear medium (CNM).

Physical properties

- **Total energy released:** 10^{48} - 10^{52} erg over lifetime of months - years.
- **Surrounding medium:** number density (n) and distribution ($n \propto r^{-\alpha}$).
- **Microphysical parameters (shocked CNM):** particle and magnetic field energy density fractions (ϵ_e, ϵ_B), injection index p.
- **Nature of the central engine:** accretion transitioning through phases and potentially supporting a (non-) relativistic outflow.
- **TDE system and geometry:** SMBH and stellar mass, approach distance and orbit, evolution (of disrupted streams and accreting material).

AT2019dsg

- Discovered by ZTF on 2019 April 9 in a host galaxy at $z = 0.051$ (~ 230 Mpc).
- Highly luminous thermal emission (3.5×10^{44} erg s^{-1}), first TDE with putative neutrino (0.2 PeV) association (Stein et al. 2021).



Schematic of expected EM components and potential neutrino emission scenarios. Image credits: Hayasaki, K. 2021, Nature Astronomy.

Non-thermal emission

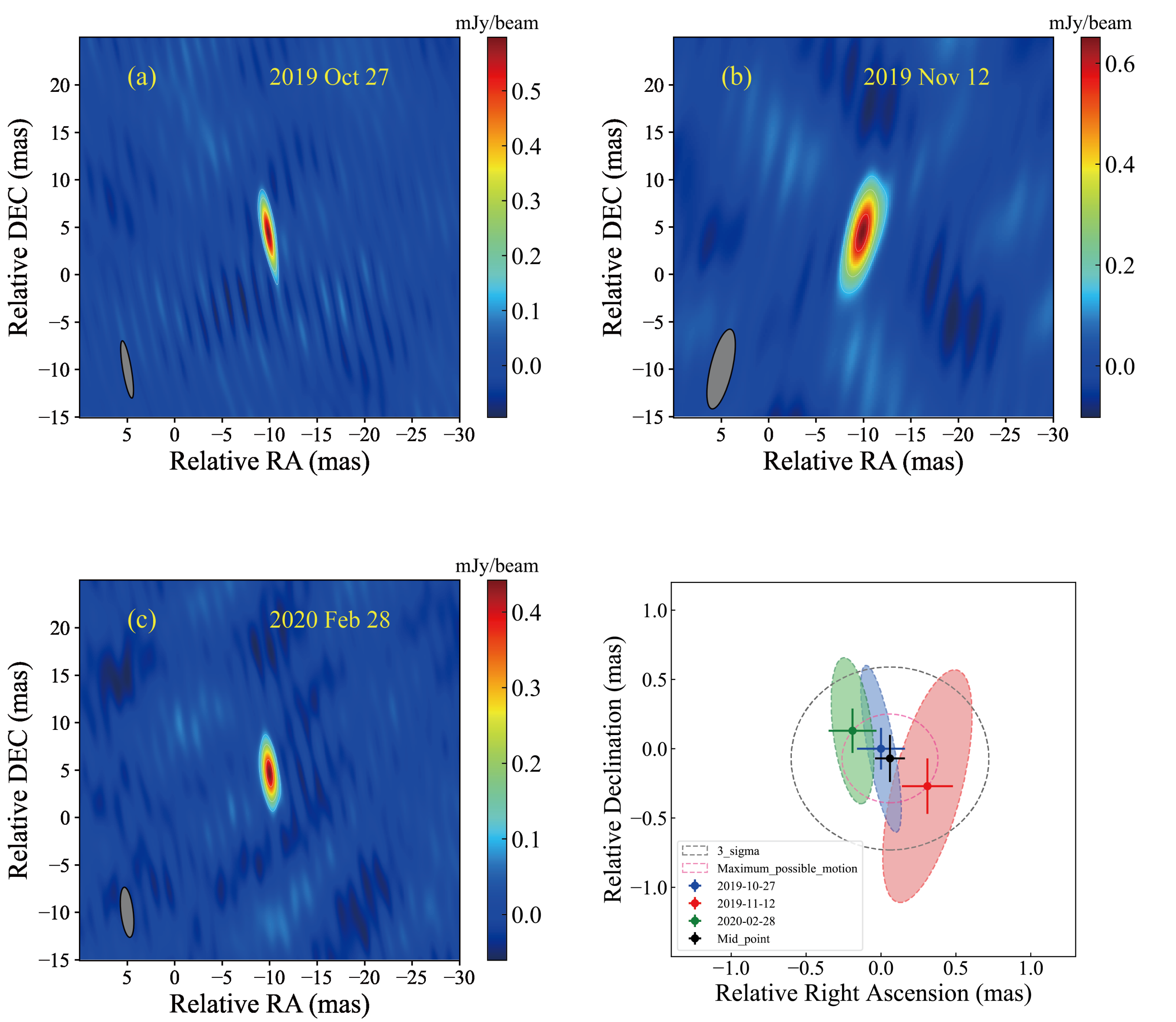
- Central engine powering outflow and enabling neutrino production (Stein et al. 2021). VLA 2 - 12 GHz (42 - 178 d): accelerating **outflow** (0.12 c - 0.21 c), region size $\approx 7 \times 10^{16}$ cm, kinetic energy $\approx 2 \times 10^{50}$ erg.
- eMERLIN 1.4 and 5 GHz (upto 180 days): **compact, stationary source** (1-σ astrometric uncertainty ~ 6 mas) from the phase centre (Cannizarro et al. 2021).
- ALMA mm — radio wavelengths: **outflow** (~ 0.07 c), region size $\leq 6 \times 10^{16}$ cm, kinetic energy of $\geq 5 \times 10^{48}$ erg (Cendes et al. 2021).

Neutrino production

- Acceleration of protons by internal shocks in **relativistic jet**, neutrino production through interaction with photospheric X-rays (Winter & Lunardini 2021).
- Vicinity of optical/UV dense photosphere. High energy photons (X-rays and γ-rays) absorption and sufficient neutrino flux requires a viewing angle of 10 — 30 degrees (**off-axis jet**; Liu et al. 2020).

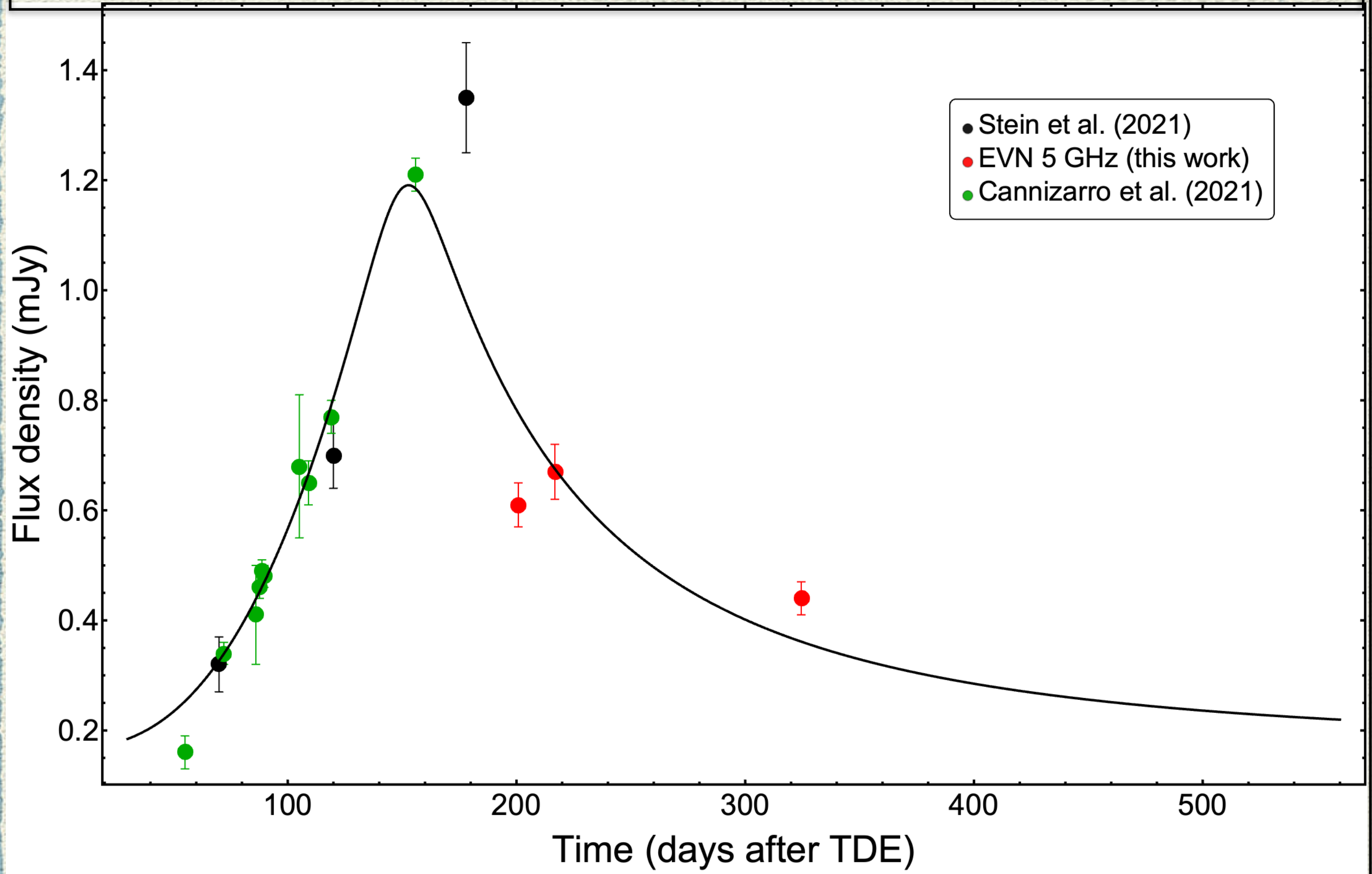
Non-thermal emission and neutrino production: relativistic jet or non-relativistic outflow?

EVN observations: imaging and astrometry



- **5 GHz monitoring** (mas; pc-scale): three epochs between 200 — 324 days post TDE (upto 20 EVN telescopes).
- **Compact unresolved structure**; flux density < 1 mJy, brightness temperatures < 10^8 K.
- **Radio-quiet** (radio luminosity of 3.6×10^{38} erg s^{-1}; similar to ASASSN-14li, CNSS J0019+00); one of three **thermal emission dominated** TDEs with VLBI monitoring.
- **Astrometry:** stationary (< 0.17 mas), proper motion of 0.94 ± 0.65 mas yr^{-1} ($3.2 \pm 2.2\, c$; $1-\sigma$) indicates no relativistic expansion → radio afterglow likely from outflow - CNM interaction.

EVN observations: modeling



- Compact unresolved emission
- Decelerated non-relativistic expansion
- Outflow powered radio emission

- **5 GHz light curve fit:** rising slope $\alpha_R = 2.4 \pm 0.9$, declining slope $\alpha_D = -2.6 \pm 1.3$, peak flux density $S_P = 1.2 \pm 0.2$ mJy(at $t_p = 152.8$ d).
- Assuming region size $R \propto t^{\alpha}$, comparing velocity $v \propto t^{\alpha-1}$ to VLBI constraint, $\alpha \geq 0.59$ (lower limit $\rightarrow$ **decelerated expansion**).
- With $\alpha = 0.59$ and electron injection index $p = 2.7$, expected optically thin flux density decline slope $\alpha_D = -2.8$ (consistent with light curve).
- Any early phase ultra-relativistic expansion restricted to < 18 days (Lorentz factor < 2 on comparing Blandford-McKee solution to VLBI size constraints).

Inferences: Outflow & TDE

Flux density evolution

- Transition of self-absorption frequency ($\nu_a \propto t^{-2.3\alpha}$) through the 5 GHz observation band ($\nu_a \approx 4.6$ GHz at $t_p = 152.8$ d).
- Rapid transition of flux density post peak to optically thin regime.

TDE

- Disrupted stellar mass of $0.1 - 2.1\ M_\odot$.
- Penetration factor (tidal radius of SMBH/pericenter distance) ~ 1 (extremely close approach).

Outflow and emission region

- Outflow velocity of $0.25 - 0.39\ c$ during peak decelerates to $\approx 0.1\ c$.
- Peak outflow rate $\approx (3-5) \times 10^{-2}\ M_\odot \mathrm{yr}^{-1}$, density contrast (CNM/outflow) ≥ 32.3.
- Region size $\geqslant 5 \times 10^{16}$ cm $(3 \times 10^{4}\ R_S)$, magnetic field strength of 0.2 G, energy output $\approx 10^{50}$ erg.

Inferences: neutrino production

Accretion disk

- Production of PeV neutrinos possible during transition from super-Eddington to radiatively inefficient regime.
- Associated timescale is however ~ 565 d, rendering this scenario less likely.

Base of outflow

- Optically thick photosphere (with size $\approx 16\ R_S$ during neutrino detection at ~ 175 d) where protons (constituting cosmic rays) accelerated to PeV energies.
- Detected muon neutrino energy is ~ 1% of this, and sufficient time availability for hadronic interactions.

Summary:
(*Mohan et al. 2022, ApJ, 927, 74*)

- **AT2019dsg:** thermal emission dominated luminous TDE (relatively radio quiet), potential PeV neutrino detection.
- **Origin of non-thermal emission and neutrino production:** relativistic jet or non-relativistic outflow?

- **EVN 5 GHz monitoring (200 - 324 d post TDE):** compact & unresolved (few mas size), stationary (proper motion $\leqslant 1.4 - \sigma$), radio afterglow from outflow - medium interaction.
- **Modeling:** decelerated expansion with velocity $v \propto t^{-0.31}$, flux density decline from synchrotron radiation model consistent with observations (slope of -2.6).

- **Non-relativistic outflow** (rate of $\approx (3-5) \times 10^{-2}\ M_{\odot}\mathrm{yr}^{-1}$) decelerating from $0.25 - 0.39\ c$ to $\approx 0.1\ c$ due to interaction with medium.
- Disrupted **stellar mass** of $0.1 - 2.1\ M_{\odot}$ approaching very close to the SMBH.
- **Neutrino production:** associated with base of outflow.