The observation of a neutrino from the Tidal Disruption Event AT2019dsg: a concordance model

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Walter Winter and C.L., arXiv:2005.06097 **to appear in Nature Astronomy**

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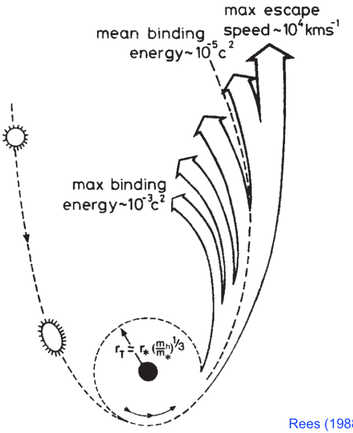
Introduction

jetted Tidal Disruption Events (TDEs) as neutrino sources

A tidal disruption event (TDE)

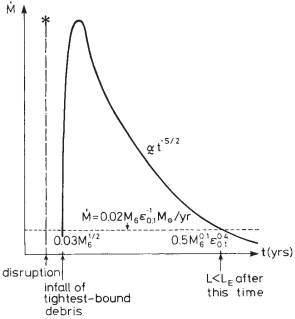
- a star is torn into pieces by the gravitational force of a SuperMassive Black Hole (SMBH)
- part of the debris are accreted, a flare is produced
- extreme flares can host a relativistic hadronic jet
- $\sim$ 100 candidate TDEs observed, 3 with evidence of jets (*hard* X-ray spectrum)

The physics

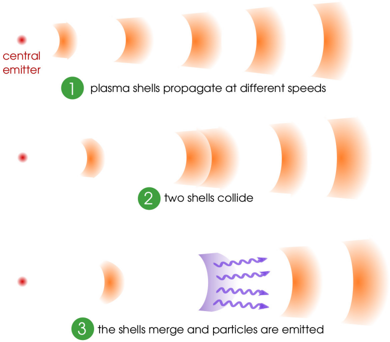


Rees (1988)

- $\sim m/2$ remains bound, falls back onto the SMBH
- flare fades when mass accretion rate drops below Eddington Luminosity, $L_{\rm Edd} \simeq 1.3\ 10^{44}\ \frac{\rm erg}{\rm s} \left(\frac{M}{10^6 M_\odot}\right)$.
    - typical duration $\Delta T \sim \mathcal{O}(0.1-1)$ yr



Jetted TDEs: neutrino production in internal shocks

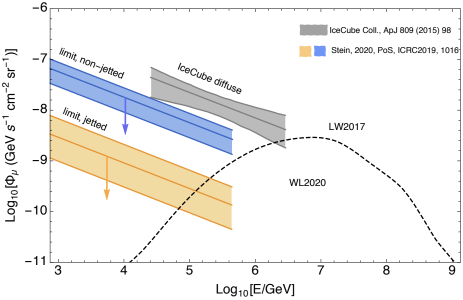


- Neutrinos from $\pi^{\pm}$ decay chain:
  $p + \gamma \to \pi^{+} + anything, \quad \pi^{+} \to \mu^{+} + \nu_{\mu}, \quad \mu^{+} \to e^{+} + \nu_e + \bar{\nu}_{\mu}$
- radial distance of collision region: $R_C \sim 2\Gamma^2 t_v$
- pion production efficiency: $f_{p\gamma} \propto R_C^{-2}$

Fig. from Bustamante, Baerwald, Murase and Winter, Nat. Comm. 6, 6783 (2015)

Theory and upper limits

TDEs contribute to up to $\sim 26\%$ of the diffuse astrophysical flux at IceCube.



Bounds: R. Stein, PoS ICRC2019, 1016 (2020)

Theory curve: Lunardini and Winter, PRD 95 (2017) 12, 123001

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a TDE-neutrino coincidence

IceCube-191001A and AT2019dsg

IceCube-191001A and AT2019dsg: a multimessenger success

- IceCube-191001A discovery announced live online on Oct 1 2019:

```
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NOTICE_DATE:      Tue 01 Oct 19 20:09:48 UT
NOTICE_TYPE:      ICECUBE Astrotrack Gold
STREAM:           24
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EVENT_NUM:        22683750
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                  314.5905d {+20h 58m 22s} (current),
                  313.7588d {+20h 55m 02s} (1950)
SRC_DEC:          +12.5755d {+12d 34' 32"} (J2000),
                  +12.6525d {+12d 39' 09"} (current),
                  +12.3819d {+12d 22' 55"} (1950)
SRC_ERROR:        47.20 [arcmin radius, stat-only, 90% containment]
SRC_ERROR50:      18.38 [arcmin radius, stat-only, 50% containment]
DISCOVERY_DATE:   18757 TJD;   274 DOY;   19/10/01 (yy/mm/dd)
DISCOVERY_TIME:   72558 SOD {20:09:18.17} UT
REVISION:         0
ENERGY:           2.1742e+02 [TeV]
SIGNALNESS:       5.8898e-01 [dn]
```

- observed neutrino energy $E \simeq 0.2$ PeV

- multimessenger campaign ensued, the *Zwicky Transient Facility* (ZTF) announced possible counterparts, Oct 2 2019
- the Tidal Disruption Event **AT2019dsg** ("Bran Stark") was deemed most significant
    - p-value of 0.2% to 0.5% of random association; $\sim 3\sigma$ significance.
- **AT2019dsg** was already $\sim$ 150 days post-peak: large delay of the neutrino arrival

R. Stein et al., arXiv:2005.05340

AT2019dsg basic facts

$z \simeq 0.05$ ($d_L \simeq 230$ Mpc). Optical-UV, X-ray thermal spectra.

Optical-UV

$T_{\rm BB} = 3.35\,{\rm eV}$ $R_{\rm BB} \simeq 5\,10^{14}{\rm cm}$, $L_{\rm BB} = 2.88 \cdot 10^{44}\,{\rm erg\,s^{-1}}$

X-ray

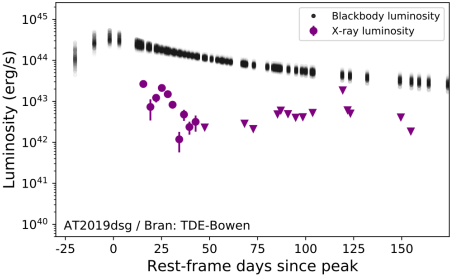
$T_X \sim 0.06$ keV, $R_X \sim 3 - 7\ 10^{11}$ cm,
$L_X \sim 2.5\ 10^{43}\ {\rm erg\,s^{-1}}$ ([0.3 – 8] keV)
$L_X \sim 4\ 10^{44}\ {\rm erg\,s^{-1}}$ ([0.1 – 10] keV).

Radio

radio emission nearly constant with increasing radius of emission $R_{\rm radio} = \mathcal{O}(10^{16})$ cm
indication of mildly relativistic outflow

van Velzen, et al., arXiv:2001.01409, R. Stein et al., arXiv:2005.05340

Time evolution



- L_{BB} exponential (or power-law) decay ($\tau \sim 60$ days), late time flattening
- L_X *faster* exponential decay ($\tau \sim 10$ days), upper limits only at late times

van Velzen, et al., arXiv:2001.01409, R. Stein et al., arXiv:2005.05340

- R_{BB} decreases slightly with time:

$$\frac{R_{BB}}{10^{14}\,\mathrm{cm}} \sim \begin{cases} 5.0 \exp\left(-\frac{t-t_{\mathrm{peak}}}{109\,\mathrm{d}}\right) & , t - t_{\mathrm{peak}} \leq 150\,\mathrm{d} \\ 1.3 & , t - t_{\mathrm{peak}} > 150\,\mathrm{d}\,. \end{cases} \tag{1}$$

van Velzen, et al., arXiv:2001.01409

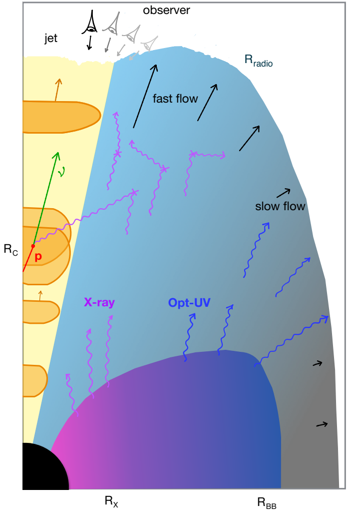
Interpretation

A (*jetted*) concordance model

Walter Winter and Cecilia Lunardini, arXiv:2005.06097

Main ideas

1. AT2019dsg hosted a **jet**
   - provides $\sim 10 L_{BB}$ energy, enough for ν detectability
2. backscattered X-rays are targets for $p\gamma \rightarrow \nu$
   - long absorption time scale helps explain late ν arrival
3. decreasing R_C
   - boosts late time ν production, helps explain late ν arrival



1. Jet energy: from Unified model scalings

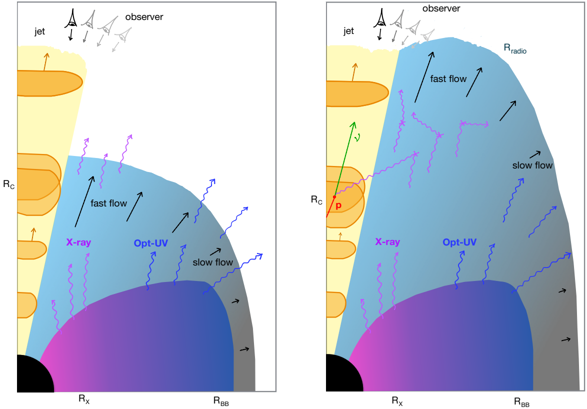
Unified model by Dai et al. good theory match

Dai, McKinney, Roth, Ramirez-Ruiz, & Miller, Astrophys. J. 859, L20 (2018)

scalings favor $M \simeq 10^6\ M_\odot$ for AT2019dsg, and offer a scale for a (hypothetical) jet:

- $R_{\rm BB} \simeq 10^3\, R_S \simeq 3\, 10^{14}\,{\rm cm} \left(\frac{M}{10^6 M_\odot}\right)$ →**Matches observation for $M \simeq 10^6\ M_\odot$**
- $L_{\rm bol} \simeq 3 L_{\rm Edd} \simeq 4\ 10^{44}\ \frac{\rm erg}{\rm s} \left(\frac{M}{10^6 M_\odot}\right)$ →**Matches observation for $M \simeq 10^6\ M_\odot$**
- $L_{\rm jet}^{\rm phys} \simeq 20\, L_{\rm Edd} \simeq 3\ 10^{45}\ \frac{\rm erg}{\rm s} \left(\frac{M}{10^6 M_\odot}\right)$; →**sets scale of (hypothetical) jet**

2. Early and late: backscattered X-rays



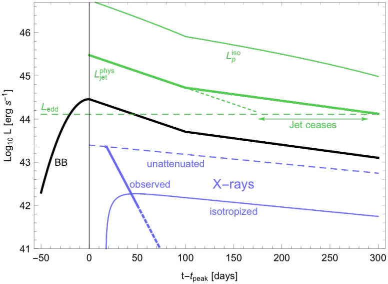
Left: early times ($t \lesssim 17 days$); Right: late times ($t \gtrsim 17 days$)

- X-ray photons (boosted) are needed for ν energy: $E_X/\mathrm{keV} \simeq 0.025\,(E_\nu/\mathrm{PeV})^{-1}$
- fast outflow overtakes R_C for realistic speeds ($v \sim 0.1 - 0.5\ c$)

3. decreasing collision radius

- Lorentz factor: $\Gamma = 7$;
- variability time scale: $t_v \sim 2\pi R_S/c \sim \mathcal{O}(10^2)$ s (for $M = 10^6\ M_\odot$);
- collision radius $R_C \sim 2\Gamma^2 c t_v \sim$ *few* 10^{14} cm *(comparable to R_{BB}!)*
- Ansatz: $R_C \sim R_{BB}$ at all times, i.e., R_C decreases with time. $\rightarrow$ **increased neutrino production efficiency:** $f_{p\gamma} \propto R_C^{-2}$.

Input time profiles



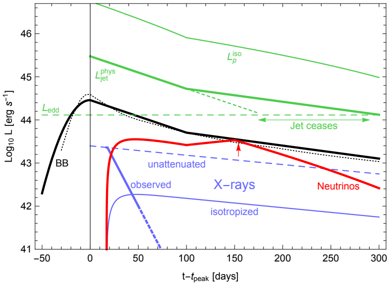
- L_{BB} and jet luminosities: from observation or Unified model scalings
- X-ray unattenuated: from slim disk simulations

  Wen, Jonker, Stone, Zabludoff, Psaltis, arXiv:2003.12583
- X-ray isotropized: assumed 10% photons backscattered at late times

Technical slide: more detailed inputs

- **target photons:**
  - assumed same spectrum as primary for backscattered X-rays
  - checked basic consistency with Unified model using Thomson scattering optical depth
- **Hadronic content of jet:**
  - initial proton spectrum $\propto {E'}_p^{-2}$
  - verified Hillas criterion
  - $L_p^{iso} \simeq 2\Gamma^2 \epsilon L_{jet}^{phys}$ $(\epsilon = 0.2)$
  - require relatively large baryonic loading, from non-observation of (non-thermal) jet X-rays: $\xi_b \gtrsim 10^3 - 10^4$
- **magnetic field, etc.**
  - $\sim 1\%$ of jet kinetic energy in magnetic field, implies $B' \sim 10^2$ G.
  - included neutrino flavor oscillations
  - calculation done in discrete steps of $\Delta t = 1$ day

Results: neutrino luminosity

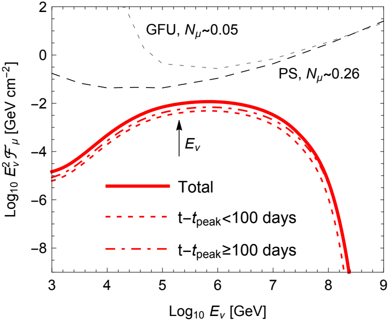


- numerical calculation done with NeuCosmA code

  see Lunardini and Winter, arXiv:1612.03160, and refs. therein.

- double peak in L_ν due to interplay of decline of $L_X^{isotr.}$ and decrease of R_C (i.e., increase in neutrino production efficiency) $\rightarrow$ *reproduces late time neutrino detection!*

Neutrino fluence and expected number of events



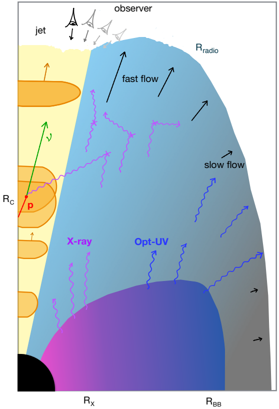
GFU: gamma-ray follow-up effective area ; PS: point source effective area

- good agreement with likely neutrino energy
- number of predicted events: $N_\mu \sim 0.05 - 0.26$ depending on effective detector area used

Discussion and summary

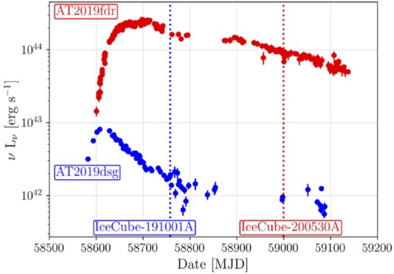
Final words

- **AT2019dsg** is the first TDE to have been identified as a (likely) neutrino source
- X-ray bright TDE might be promising neutrino emitters
- concordance model links X-ray emission and ν emission, explains late ν arrival



New: a second neutrino-TDE association!

The search continues…



ZTF has now completed 18 follow-up campaigns to date, out of 57 neutrino alerts from IceCube.

Have since found second TDE, AT2019fdr, coincident with IC200530A. See Simeon Reusch's poster!

Lightning rarely strikes twice. Strong evidence of an emerging trend. Second paper in prep.

see also dedicated poster by Simeon Reusch at same conference

Thank you!

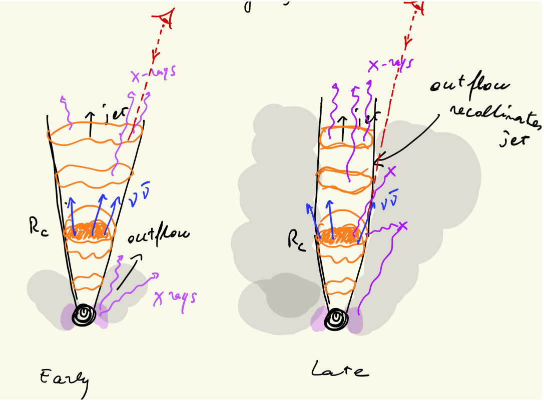
Backup

Hint of jet?

optical polarimetry of AT2019dsg C. H. Lee et al., The Astrophysical Journal 892, L1 (2020).

Explaining non-observation of jet signatures

- suppression of accelerated electron radiation? (high baryonic loading)
- intermittent jet?
- off-axis view?
- jet recollimation, twisting or precession?



Alternate models for AT2019dsg-IceCube-191001A explanation

- isotropic outflow interacting with UV photons

  Stein et al. , arXiv:2005.05340

- non-relativistic shocks forming in the environment

  Fang, Metzger, Vurm, Aydi & Chomiuk, arXiv:2007.15742.

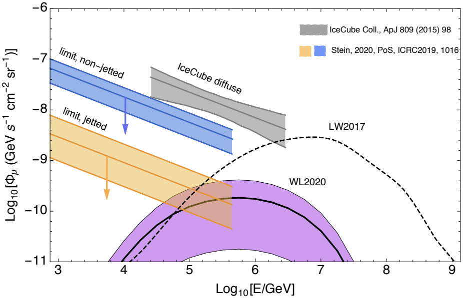
- neutrino production from the accretion disk (radiatively inefficient accretion flows, magnetically arrested disk states, etc.)

  Hayasaki & Yamazaki, ApJ, 886 114 (2019)

- hot corona similar to that of AGN

  Murase, Kimura, Zhang, Oikonomou & Petropoulou, arXiv:2005.08937.

Contribution to diffuse flux at IceCube



Basic physics scales

- masses: $m \sim (0.1 - 2)\ M_\odot$, $M \sim (10^4 - 10^8)\ M_\odot$
- Tidal radius: where SMBH gravity $\simeq$ star's self gravity

$$
\begin{aligned}
r_t &= \left(\frac{2M}{m}\right)^{1/3} R \\
&\simeq 8.8 \times 10^{12}\,\mathrm{cm} \left(\frac{M}{10^6\ M_\odot}\right)^{1/3} \frac{R}{R_\odot} \left(\frac{m}{M_\odot}\right)^{-1/3}
\end{aligned}
$$

- Schwarzschild radius

$$
R_s = \frac{2MG}{c^2} \simeq 3 \times 10^{11}\,\mathrm{cm} \left(\frac{M}{10^6\ M_\odot}\right)
$$

  - Condition for TDE: $r_t \gtrsim R_s \rightarrow M \lesssim M_{\mathrm{max}} \simeq 10^{7.2}\ \ M_\odot$

Analytics: Δ-resonance approximation

X.-Y. Wang, et al., *Phys. Rev.* **D84** (2011) 081301

- $\nu_\mu + \bar{\nu}_\mu$ and $\nu_e + \bar{\nu}_e$ fluence (no oscillations):

$$E^2 F^0_\mu(E) = \frac{1}{32\pi d_L^2} \frac{E_X \xi_p}{\ln\left(E_{p,\rm max}/E_{p,\rm min}\right)} f_{p\gamma} \zeta_\pi (1+\zeta_\mu) \ ,$$

$$E^2 F^0_e(E) = \frac{1}{32\pi d_L^2} \frac{E_X \xi_p}{\ln\left(E_{p,\rm max}/E_{p,\rm min}\right)} f_{p\gamma} \zeta_\pi \zeta_\mu \ .$$

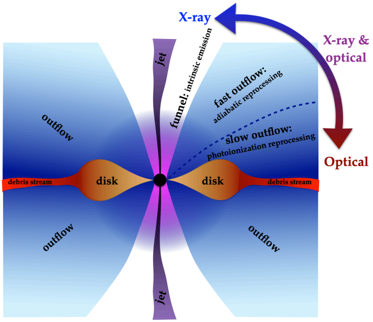
- pion production efficiency: $f_{p\gamma} \propto R_C^{-2}$

$$f_{p\gamma} \simeq 0.35 \left(\frac{L_X}{10^{47.5}\ {\rm erg\,s^{-1}}}\right)\left(\frac{\Gamma}{10}\right)^{-4}\left(\frac{t_v}{10^2\ {\rm s}}\right)^{-1}\left(\frac{\epsilon_b}{\rm KeV}\right)^{-1} \times \begin{cases}(E_p/E_{pb})^{\beta-1} & {\rm for} \quad E_p < E_{p,\rm br} \\ (E_p/E_{pb})^{\alpha-1} & {\rm for} \quad E_p \geq E_{p,\rm br}\end{cases}$$

$$E_{p,\rm br} = 1.5\ 10^7 {\rm GeV}\ \left(\frac{\Gamma}{10}\right)^2 \left(\frac{1\ \rm KeV}{\epsilon_{X,\rm br}}\right)$$

The Unified model

- magnetohydrodynamical simulation (near peak only)
- jet predicted for high BH spin (Blandford-Znajek effect)
- outflow with velocity decreasing from fast to slow away from jet funnel



Dai, McKinney, Roth, Ramirez-Ruiz, & Miller, Astrophys. J. 859, L20 (2018)