Neutrinos and UHECRs from Tidal Disruption Events (TDEs)

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HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

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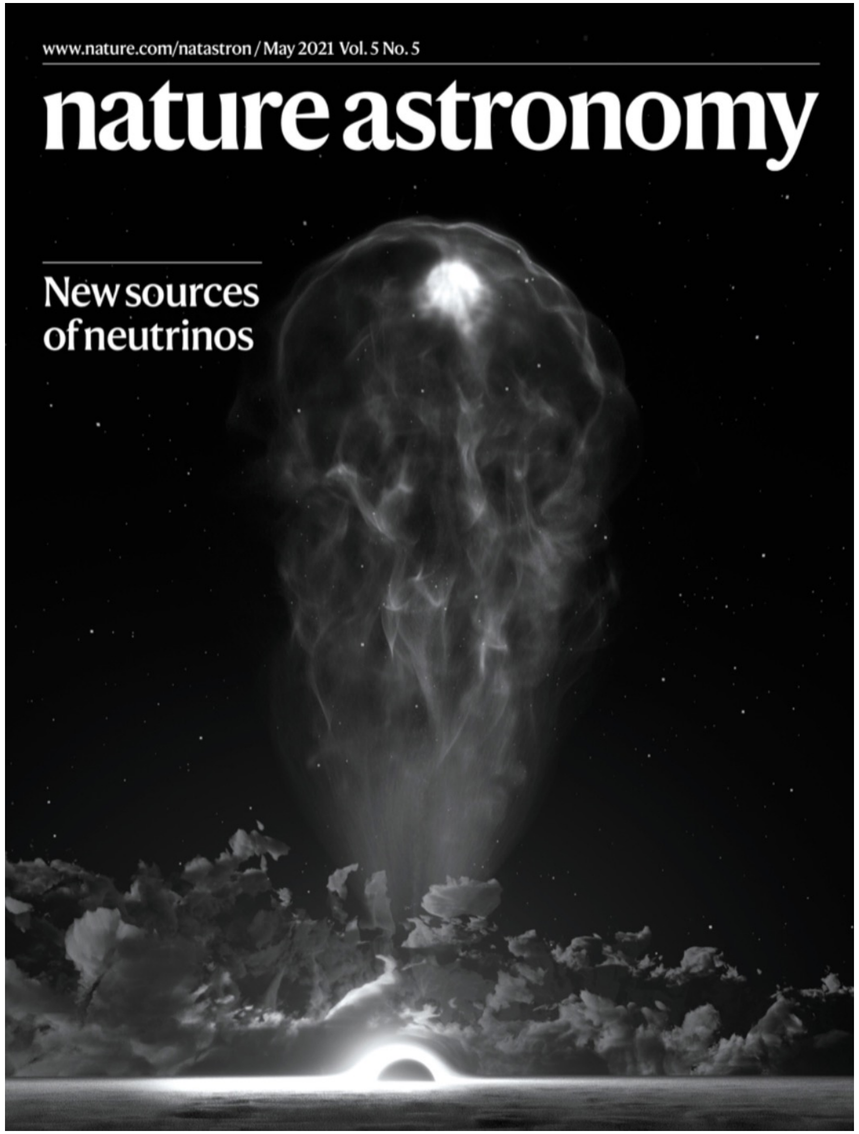
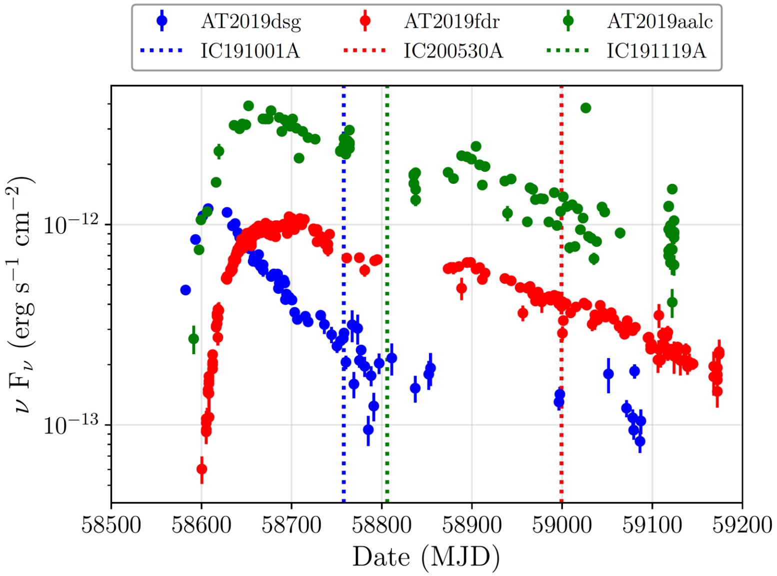


Neutrinos from *three* TDE candidates – in a nutshell



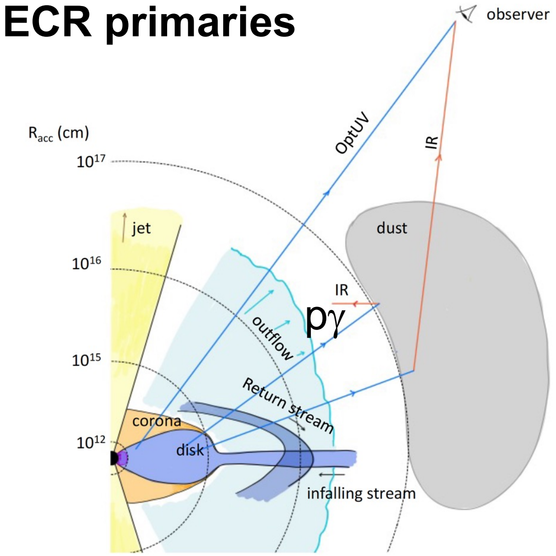
Simeon Reusch @ ECRS 2022

Common features

- Delayed neutrino signal
- Delayed strong dust echoes in the IR range
- High black body luminosities
- X-ray detections

Dust echo – UHECR connection?

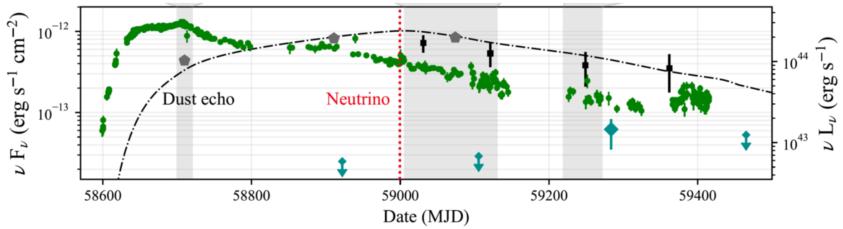
- Third TDE found through strong dust echo commonality; 3.7σ overall
  van Velzen et al, arXiv:2111.09391
- Dust echo correlates with neutrino time delay in all cases. →
  Target for pγ neutrino production?
- Photon energy (infrared) points towards **UHECR primaries**



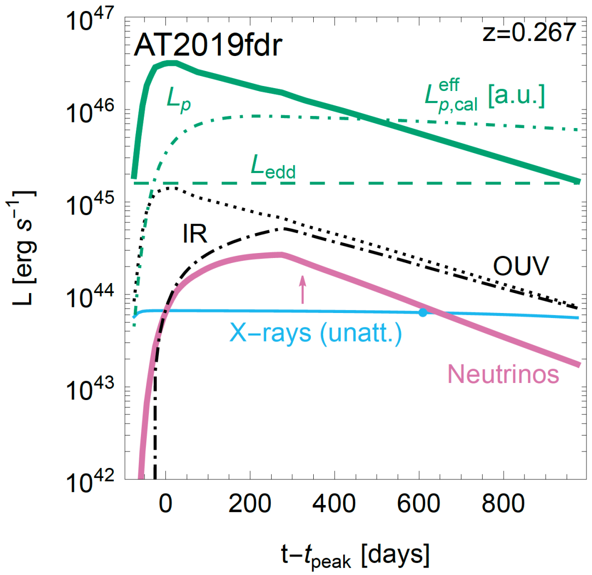
Is the dust echo connection
a **smoking gun signature for the acceleration of UHECRs** in TDEs?

Theoretical interpretation

- Example: AT2019fdr



Reusch et al, PRL 128 (2022) 22



Winter, Lunardini, arXiv:2205.11538, ApJ submitted

How to disrupt a star 101

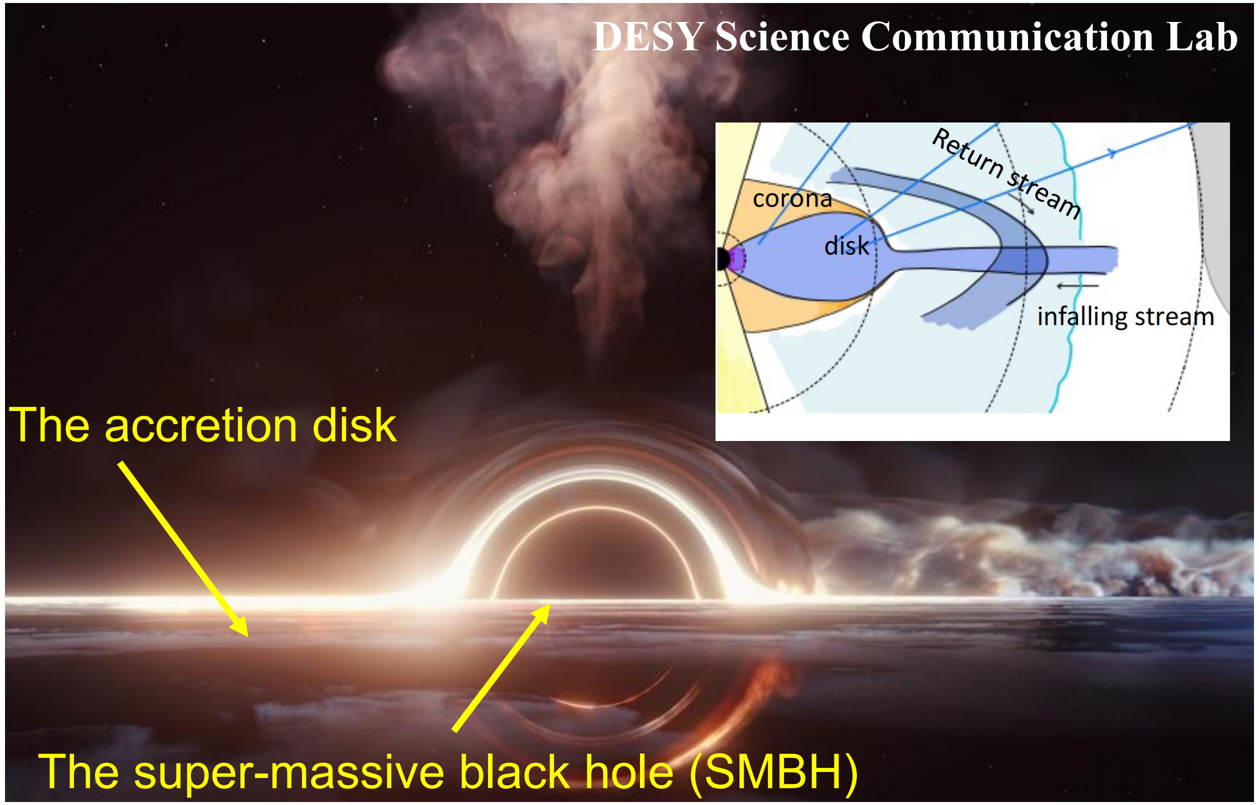
- Force on a mass element in the star (by gravitation) ~ force exerted by the SMBH at distance (tidal radius)

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

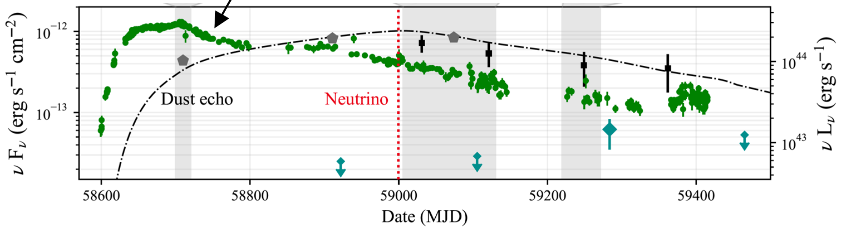
- Has to be beyond Schwarzschild radius for TDE

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

- From the comparison ($r_t > R_s$) and demographics, one obtains (theory) M <~ 2 10^7 $M_\odot$
  Hills, 1975; Kochanek, 2016; van Velzen 2017
- Measure for the luminosity which can be re-processed from accretion through the SMBH: Eddington luminosity
  $L_{\mathrm{Edd}} \simeq 1.3\ 10^{44}\ \mathrm{erg/s}\,(M/(10^6\ M_\odot))$
- Energy to be re-processed: about half of a star's mass E ~ 10^{54} erg (half a solar mass)
- Super-Eddington fallback rate expected at peak to process that amount of energy

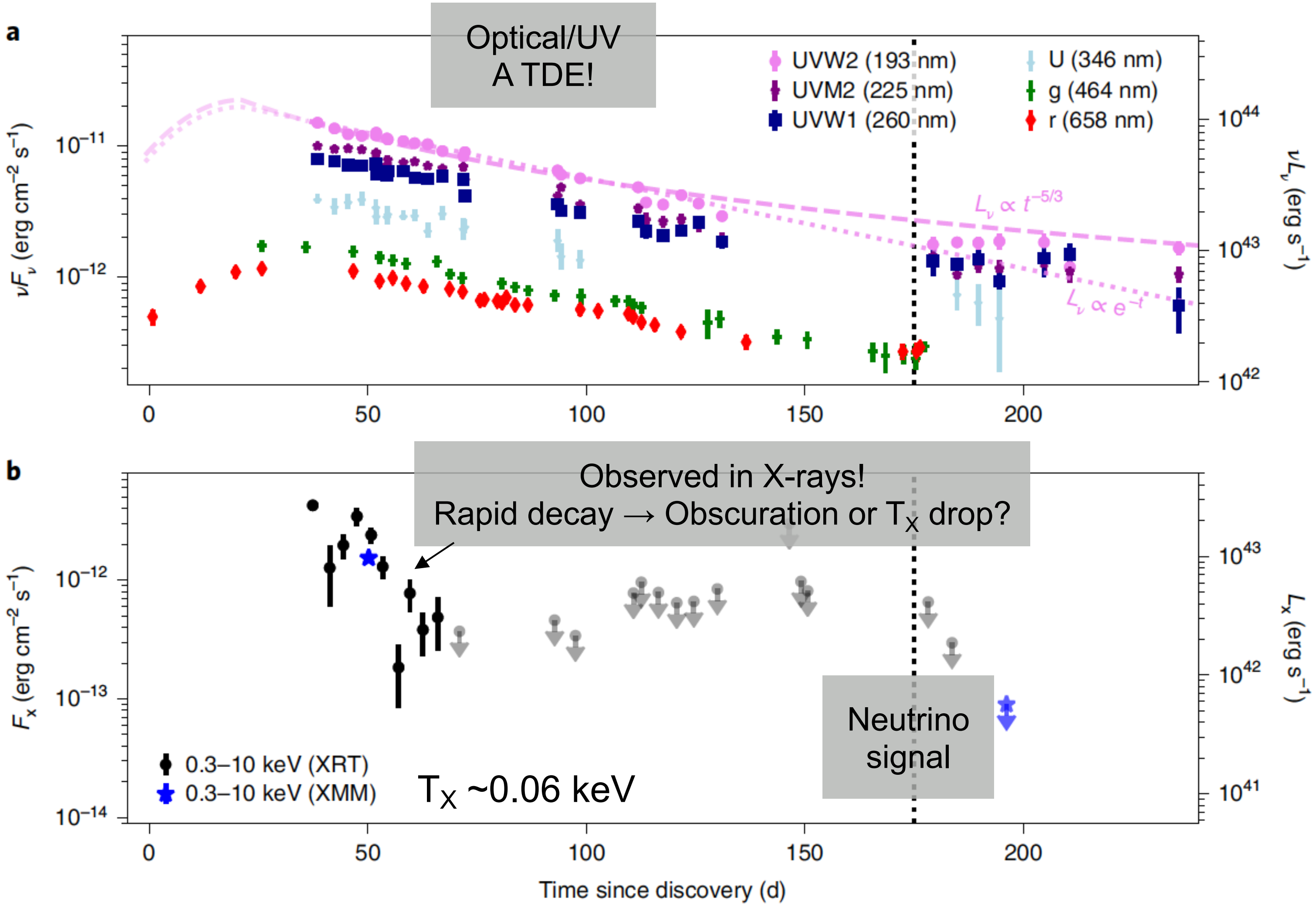


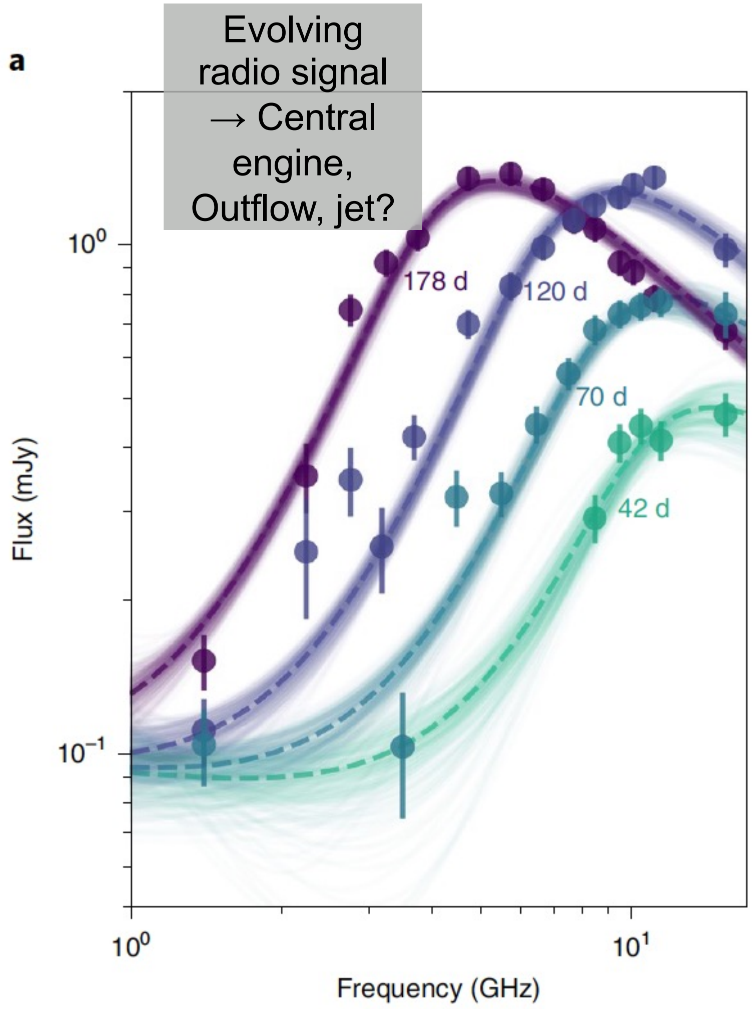
- Mass fallback rate typically exhibits a peak and then a ~ $t^{-5/3}$ dropoff over a few hundred days



From: Reusch et al, PRL 128 (2022) 22

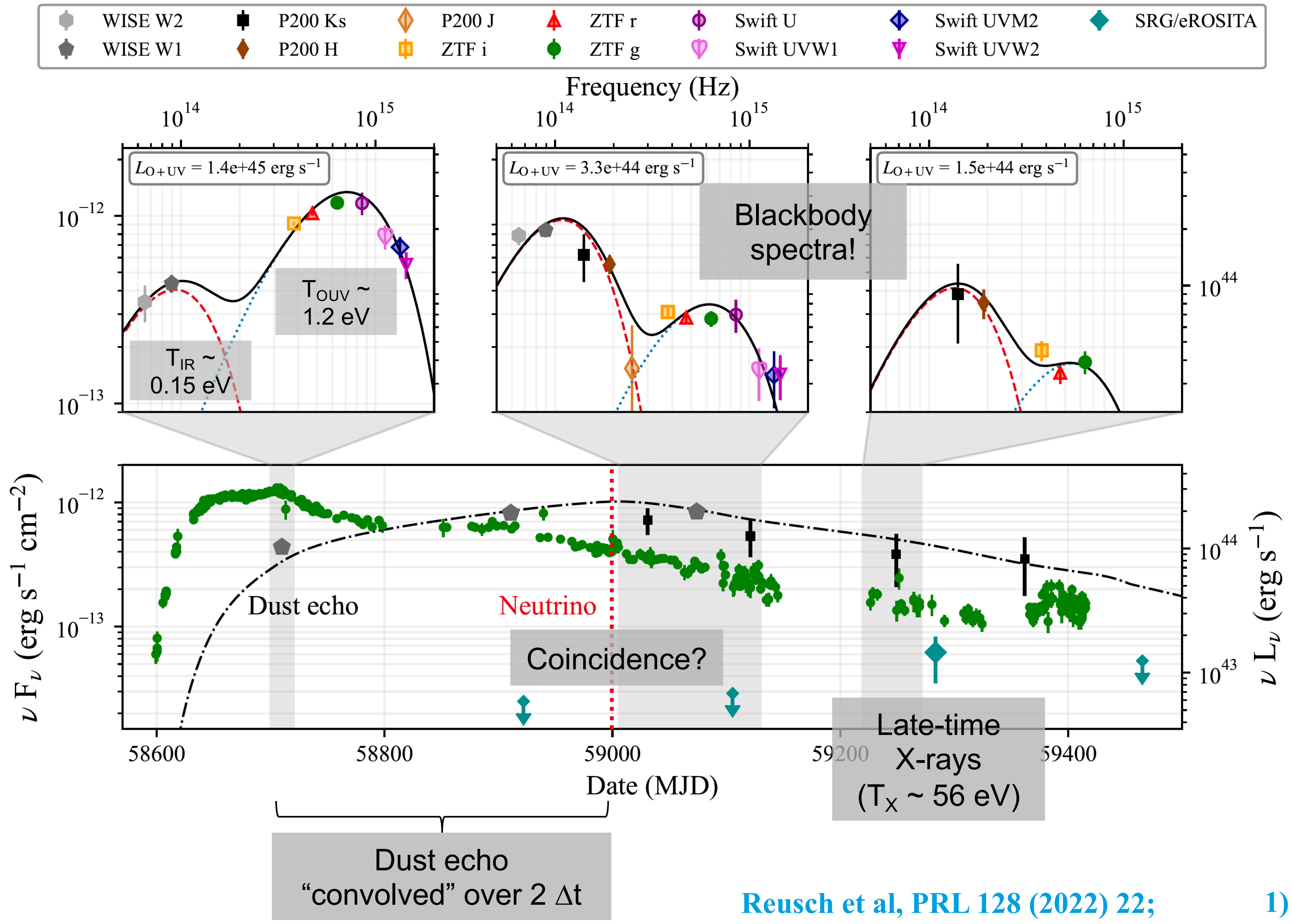
Observation of a neutrino from AT2019dsg





Stein et al, Nature Astronomy 5 (2021) 510

Another neutrino from the TDE candidate AT2019fdr



- Dust echo (IR): Median time delay Δt ~ 150 days ~ 4 10^{17} cm ~ R_{dust}
- Possible neutrino production sites:

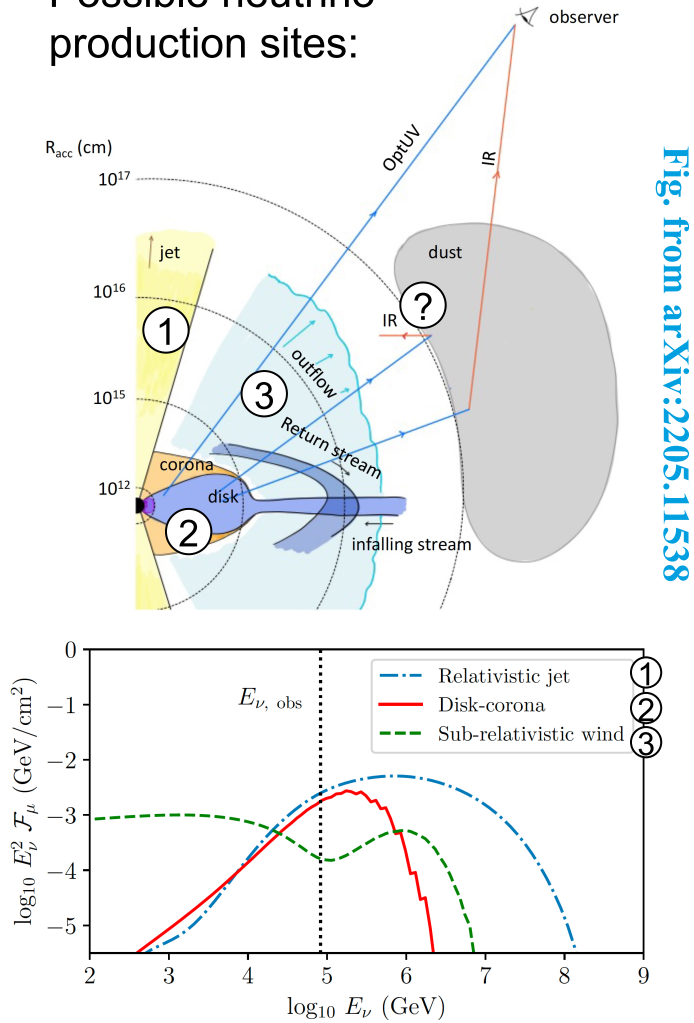


Fig. from arXiv:2205.11538

Reusch et al, PRL 128 (2022) 22;
see Pitik et al, 2022 for SN interpretation

1) Winter, Lunardini, Nature Astron. 5 (2021) 5
2)3) Murase et al, ApJ 902 (2020) 2

AT2019aalc

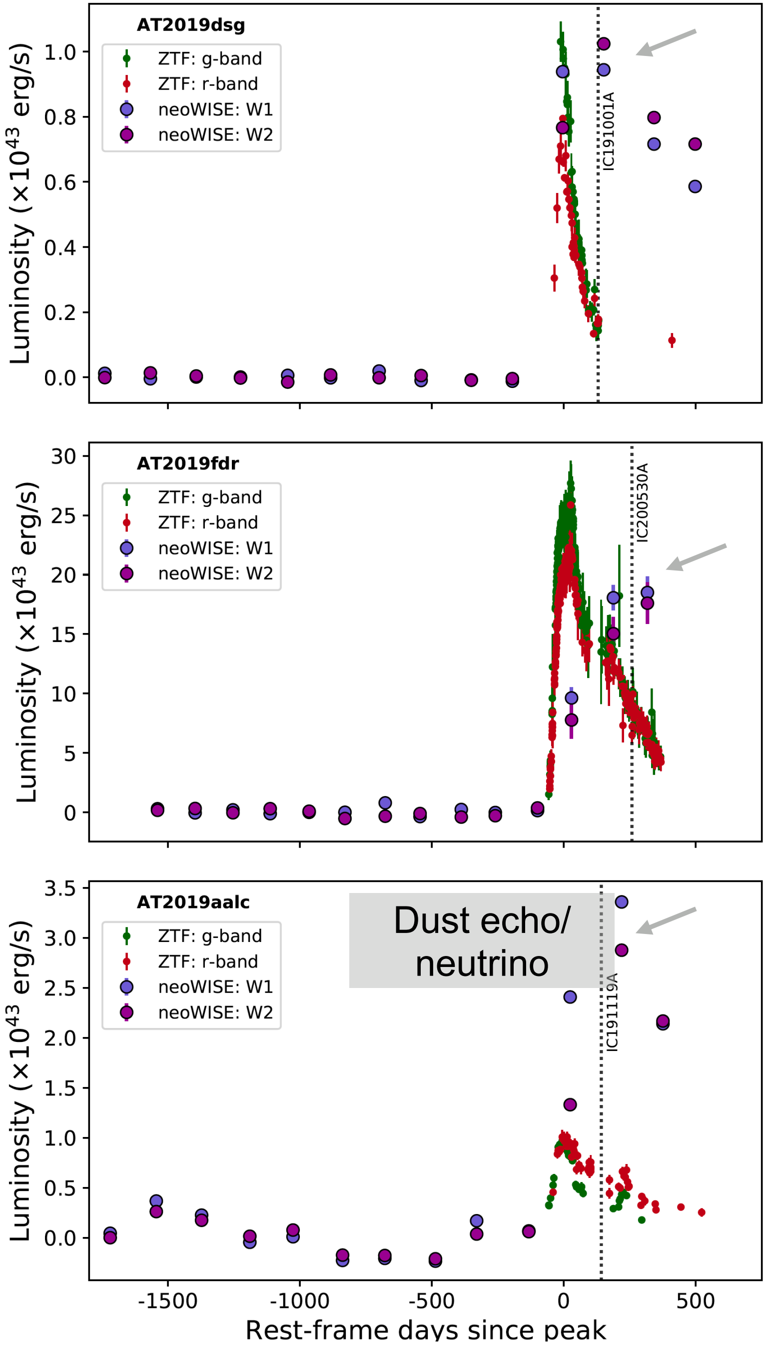
Role of the dust echo …

Analysis

- Selected a sample of 1732 accretion flares with properties similar to AT2019dsg and AT2019fdr (dust echo)
- Found another TDE candidate: AT2019aalc with a similar neutrino time delay
- Overall significance: 3.7σ
  van Velzen et al, arXiv:2111.09391

Caveats

- AT2019aalc also exhibited a late-time X-ray signal
- AT2019fdr and AT2019aalc not uniquely identified as TDEs; happened in pre-existing AGN; no evolving radio signals



van Velzen et al, arXiv:2111.09391

… and UHECR connection?

Interpretation/hypothesis

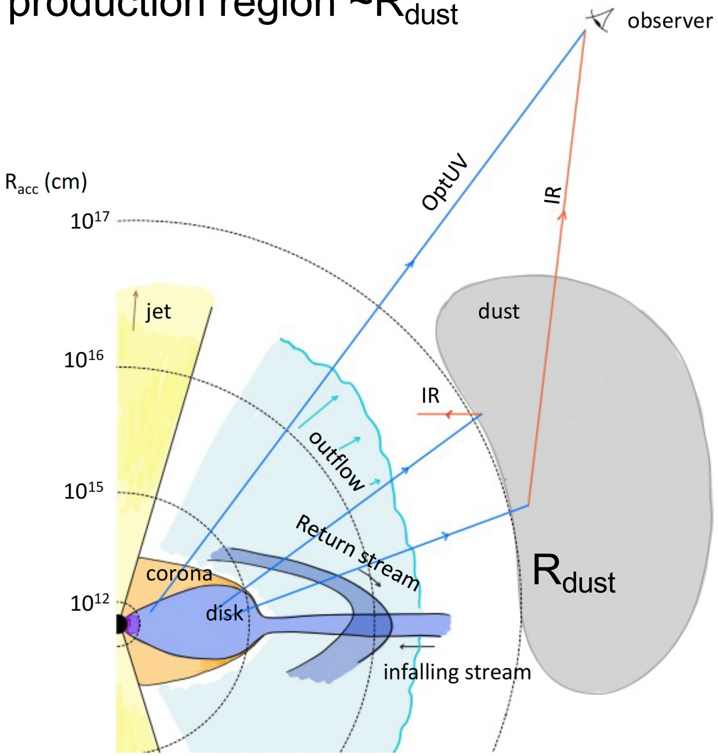
- Neutrino arrival seems to be correlated with dust echo
- **What if … the dust echo itself (IR) is the target for cosmic ray interactions?**
- Consequence (from pγ interactions): $E_p > 1.6$ EeV $(T_{IR}/0.1 \text{ eV})^{-1}$ (for nuclei: rigidity R > 1.6 EV)
- Compatible with UHECR fits, e.g. $R_{max} \sim$ 1.4-3.5 EV. Coincidence?
  Heinze et al, ApJ 873 (2019) 1, 88
- Points towards interactions of **UHECRs**

The direction connection between the neutrino production (incl. time delay) and the dust echo could be a **smoking gun signature for the acceleration of UHECRs** in TDEs

Theoretical interpretation of neutrino-dust echo connection

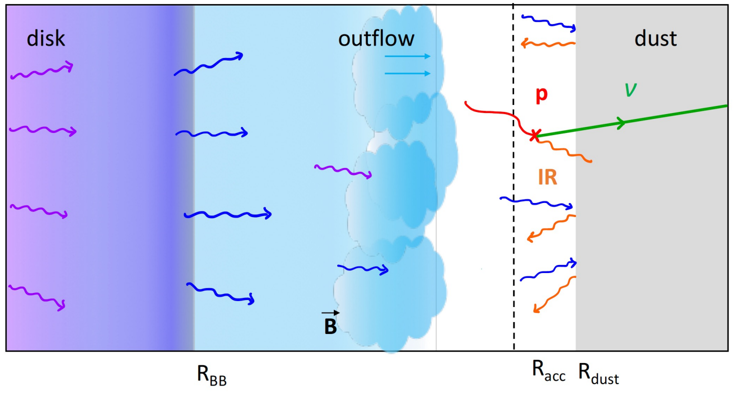
Dust model, geometry

- A fraction of the emitted bolometric luminosity is re-processed into the IR
- IR target averaged over the geometry
- Secondary emission **isotropic** from a production region ~R_{dust}



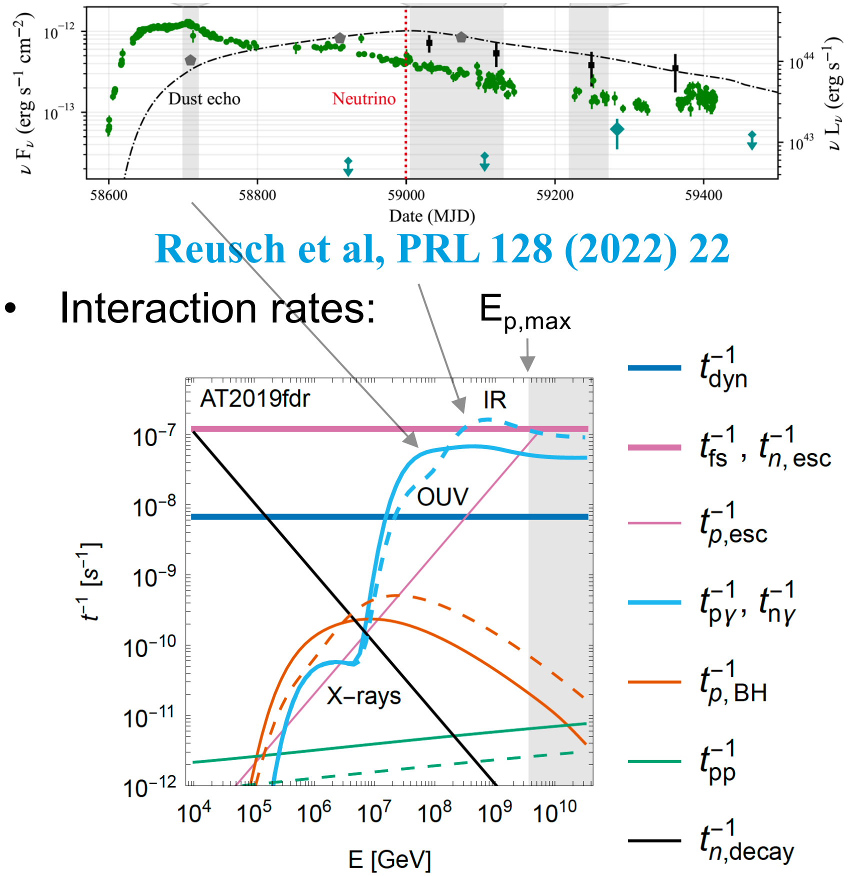
Proton acceleration and energetics

- Protons are injected with an E^{-2} spectrum and $E_{p,max}$=5 EeV
- B ~ 0.1 G, protons are magnetically confined at lower energies over the TDE duration; isotropization!
- Accelerator could be wind, outflow, (truly) off-axis jet, choked jet
- Proton injection follows mass accretion
- However: high dissipation efficiency required (20% of mass accretion into non-thermal protons)



Neutrino production

- From proton interactions with OUV and IR, different time-dependencies:



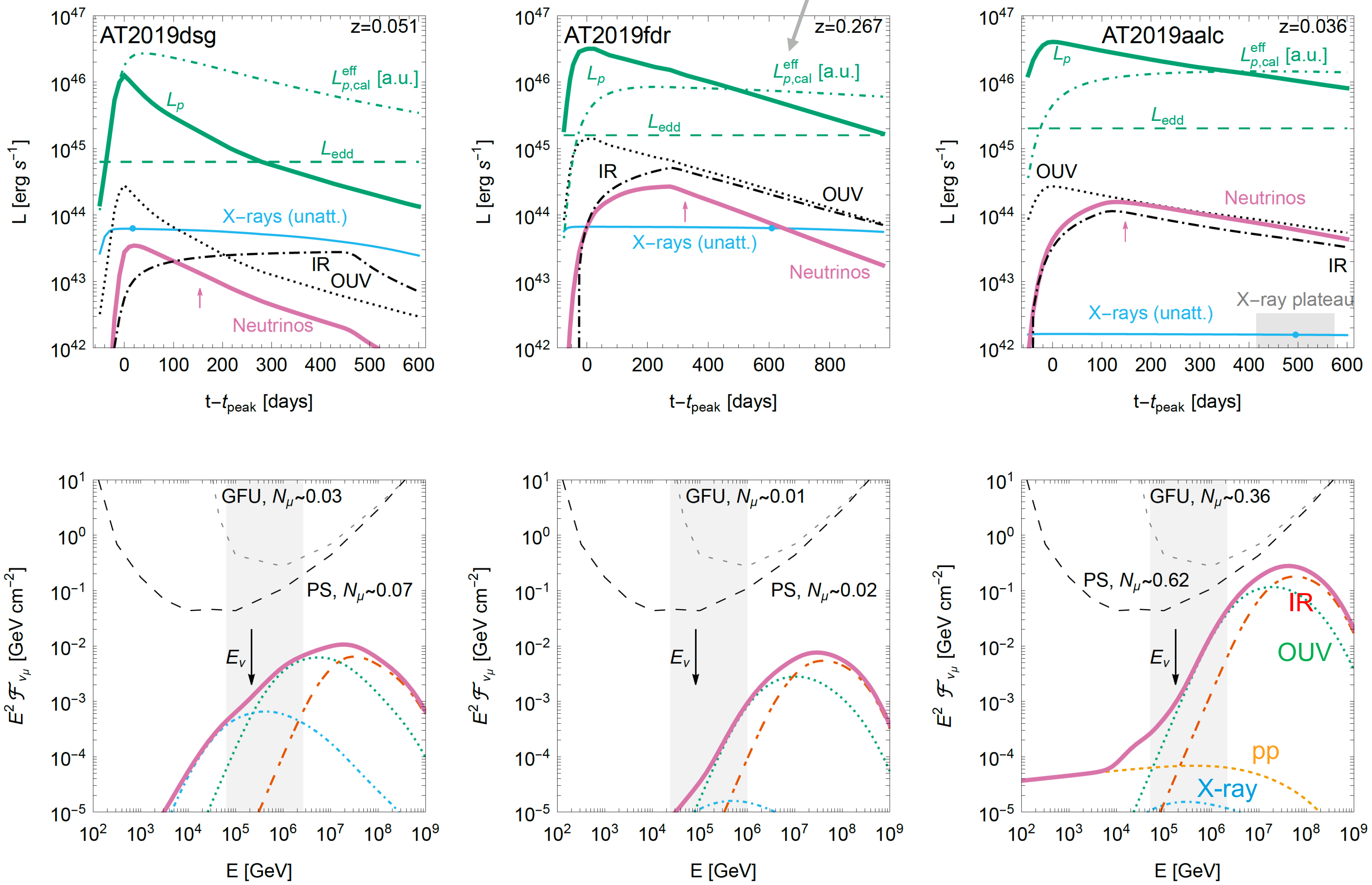
Dashed: neutrino production time
Solid: Peak time of TDE

Winter, Lunardini, arXiv:2205.11538, ApJ submitted (model M-IR)

Theoretical results (M-IR)

In-source proton density calorimetric!

- Neutrino event rates in experimentally expected ranges
- Neutrino signal correlated with dust echo (except AT2019dsg; later proton injection?)
- Interactions with OUV cannot be fully avoided (must be there)
- Source frame neutrino luminosities similar; AT2019aalc produces highest neutrino fluence (low z!)
- Caveat: Neutrino peak energies significantly larger than expected from measurements?
  <u>But:</u> Some hint for hard spectra from recent TDE stacking analysis?
  Jannis Neckar @ TeVPA 2022



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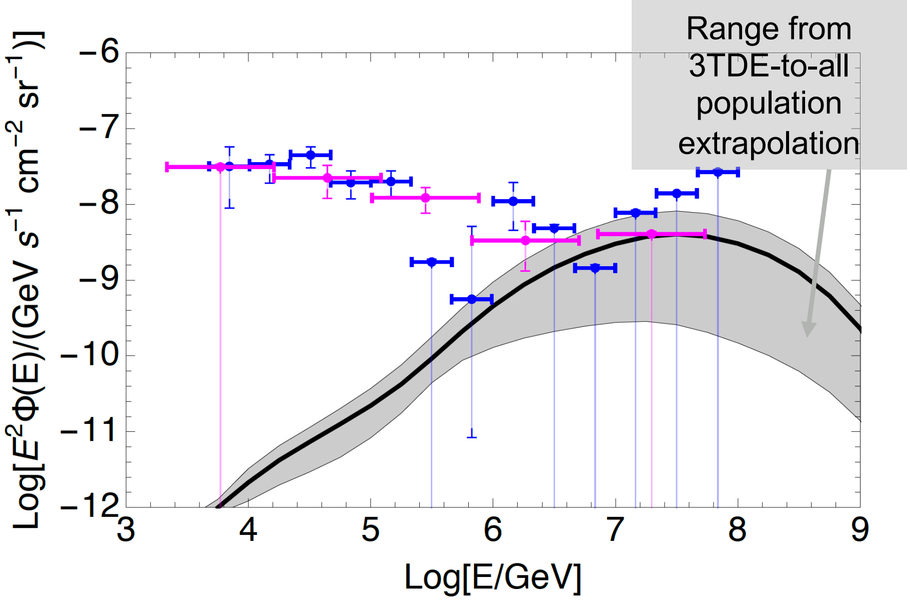
Diffuse fluxes and possible UHECR connection

Expectation for diffuse neutrino flux from TDEs



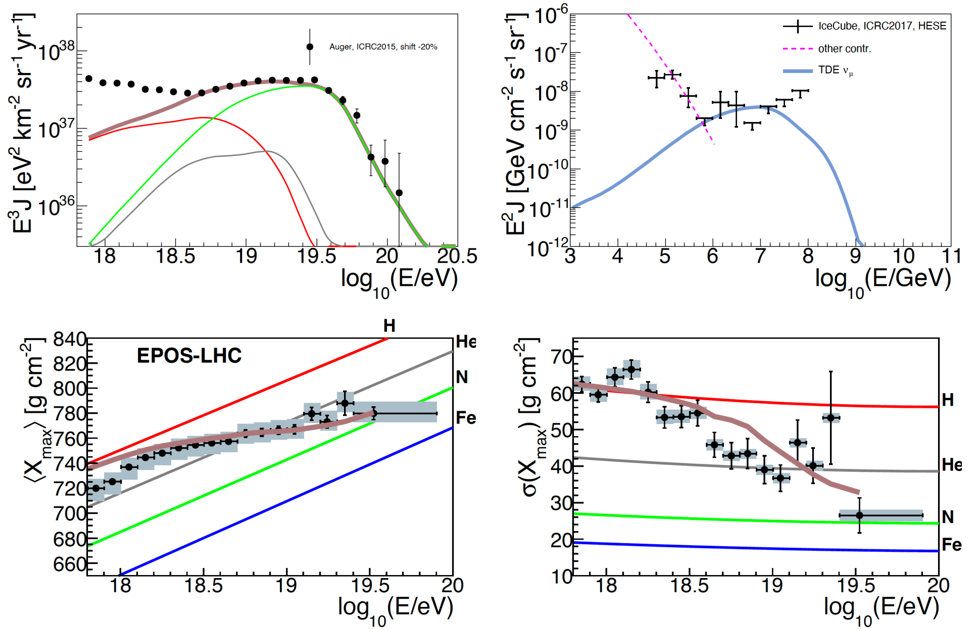
- Might describe diffuse neutrino flux at the highest energies (i.e., only fraction of total neutrino flux)
- Assumption: 1% of all TDEs are efficient neutrino emitters
- Roughly consistent with hypothesis that neutrino-emitting TDEs and TDEs with strong dust echoes are the same populations

Winter, Lunardini, arXiv:2205.11538, ApJ submitted (model M-IR)

Can TDEs be the origin of the UHECRs?

- Tested earlier for Sw J1644+57-like **jetted** TDEs →

Biehl, Boncioli, Lunardini, Winter, Sci. Rep. 8 (2018) 1, 10828; see also Farrar, Piran, 2014; Zhang et al, PRD 96 (2017) 6; Guepin et al, A&A616 (2018) A179

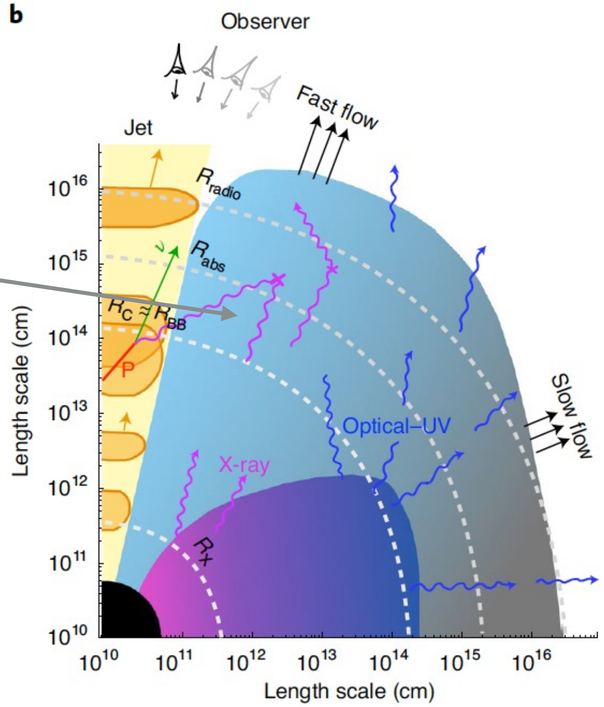


- Main criticisms: Jetted TDEs rare, high L_X, L_ν (multiplet limits!), also: white dwarf disruptions (right composition) rare?
- But now: high neutrino-TDE rate observed, lower luminosity (L_{OUV})
- Estimated UHECR output per TDE ~ 2 10^{52} erg in M-IR model; need a local rate of these TDEs of about 5 Gpc^{-3} yr^{-1}
- High for white dwarf disruptions (but: high rates found for low SMBH masses Tanikawa et al, 2021). Material drawn from pre-existing AGNs?

Alternative models and specific implementations

Jetted models

X-ray
back-scattering
in outflow
(delayed because
of outflow speed)

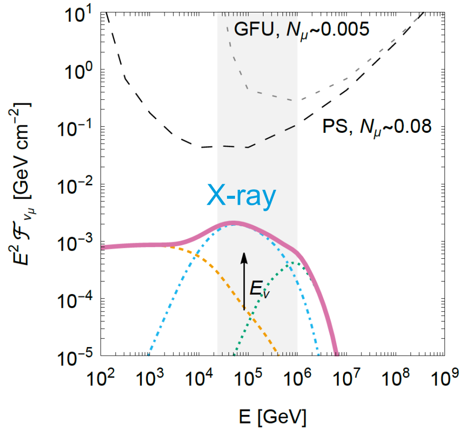


- Attractive for AT2019dsg (radio signal), but no direct evidence for jet
- Advantage: High proton luminosity (collimated outflow)
- Challenges: no evolving radio signals in AT2019fdr, AT2019aalc
- Jets could be off-axis if escaping protons are isotropized (model M-IR discussed earlier). Additional delay?

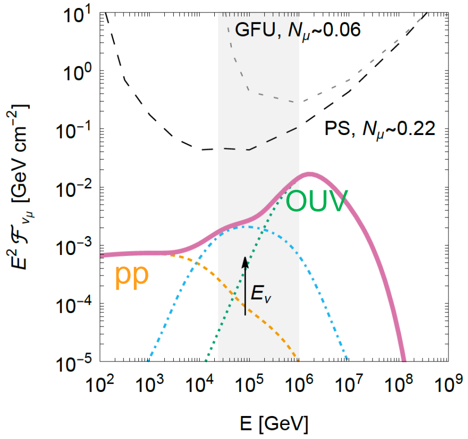
Winter, Lunardini, Nature Astronomy 5 (2021) 472;
see also Liu, Xi, Wang, 2020 for an off-axis jet and
Zheng, Liu, Wang, 2022 for choked jets

Quasi-isotropic model with lower $E_{p,max.}$ Ex.: AT2019fdr

$E_{p,max}$ = 5 PeV
main target: X-rays



$E_{p,max}$ = 100 PeV
main target: OUV

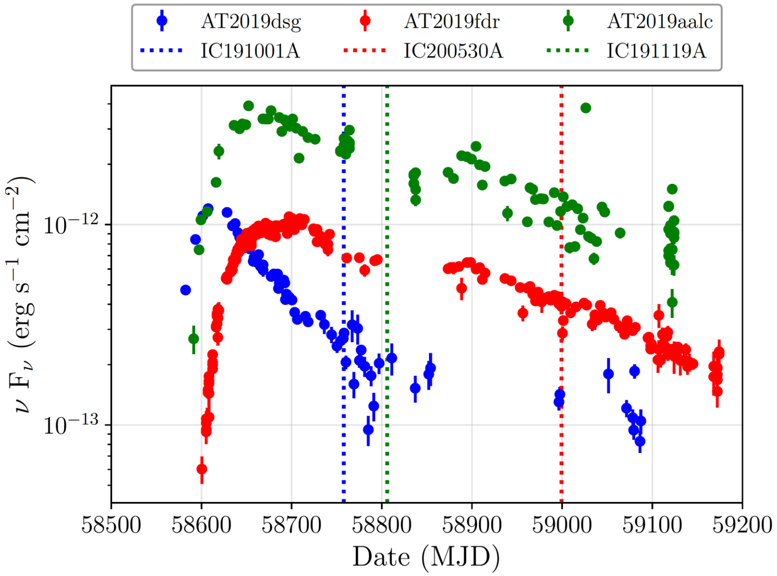


Winter, Lunardini, arXiv:2205.11538 (models M-X, M-OUV)

Specific implementations of accelerator?

- Jets Wang et al, 2011; Wang&Liu 2016; Dai&Fang, 2016; Lunardini&Winter, 2017; Senno et al 2017; refs on l.h.s.
- Disk Hayasaki&Yamazaki, 2019
- Corona Murase et al, 2020
- Winds, outflow
  Murase et al, 2020; Fang et al, 2020; Wu et al, 2021

Neutrinos from *three* TDE candidates – in a nutshell



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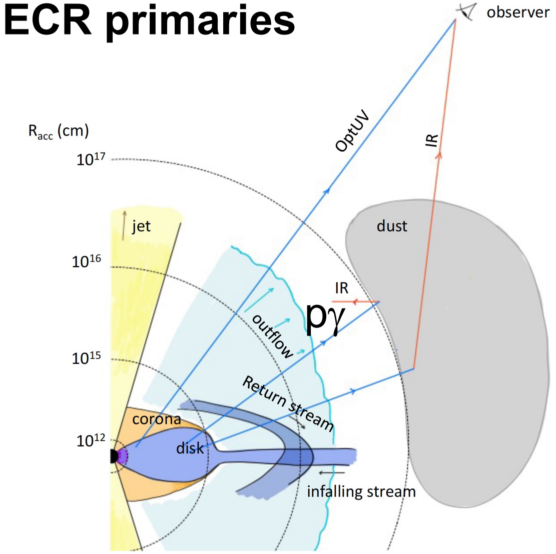

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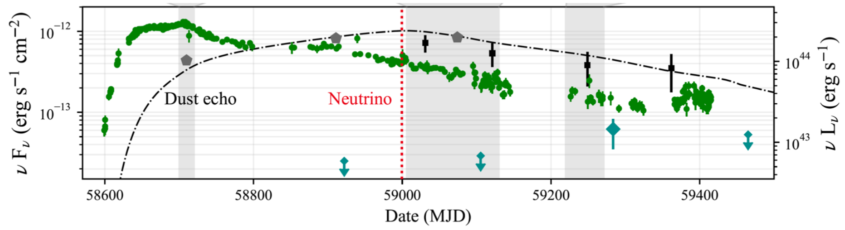
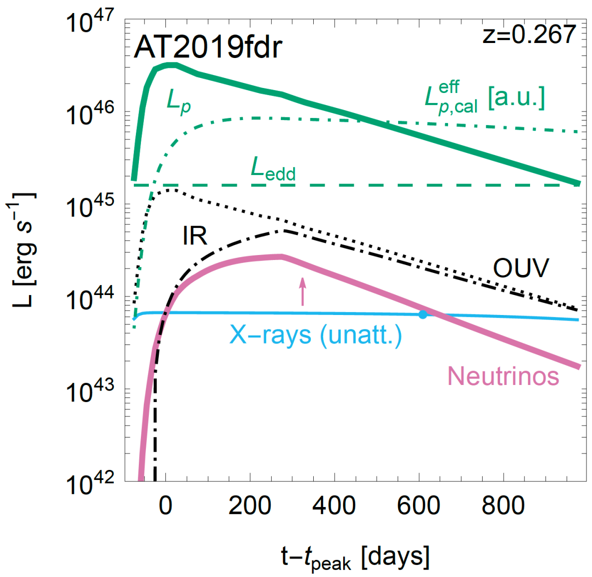


Reusch et al, PRL 128 (2022) 22



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BACKUP

Parameter comparison

	AT2019dsg	AT2019fdr	AT2019aalc
Overall parameters			
Redshift z	0.051 (1)	0.267 (2)	0.036 (3)
$t_{\rm peak}$ (MJD)	58603 (4)	58675 (2)[a]	58658 (3)
SMBH mass M $[M_\odot]$	$5.0\,10^6$ (3)	$1.3\,10^7$ (3)	$1.6\,10^7$ (3)
Neutrino observations			
Name (includes t_ν)	IC191001A (5)	IC200530A (6)	IC191119A (7)
$t_\nu - t_{\rm peak}$ [days]	154	324	148
E_ν [TeV]	217 (5)	82 (6)	176 (7)
N_ν (expected, GFU)	0.008–0.76 (1)	0.007–0.13 (2)	not available
Black body (OUV)			
$T_{\rm BB}$ [eV] at $t_{\rm peak}$	3.4 (1)	1.2 (2)	0.9 [Sec. 2.5]
$L_{\rm BB}^{\rm bol}$ (min.) $[\frac{\rm erg}{\rm s}]$ at $t_{\rm peak}$	$2.8\,10^{44}$ (Sec. 2.5)	$1.4\,10^{45}$ (Sec. 2.5)	$2.7\,10^{44}$ (Sec. 2.5)
BB evolution from	(1)	(2)	(3)
X-rays (X)			
$T_{\rm X}$ [eV]	72 (1)	56 (2,3)	172 (3)
$L_{\rm X}^{\rm bol}$ $[\frac{\rm erg}{\rm s}]$ @ $t - t_{\rm peak}$	$6.2\,10^{43}$ @ 17 d (1)	$6.4\,10^{43}$ @ 609 d (2)	$1.6\,10^{42}$ @ 495 d (3)
Dust echo (IR)			
$T_{\rm IR}$ [eV]	0.16 (Sec. 2.5)	0.15 (2)	0.16 (Sec. 2.5)
Time delay Δt [d]	239 (Sec. 2.5)	155 (Sec. 2.5)	78 (Sec. 2.5)
$L_{\rm IR}^{\rm bol}$ $[\frac{\rm erg}{\rm s}]$ @ $t - t_{\rm peak}$	$2.8\,10^{43}$ @ 431 d (Sec. 2.5)	$5.2\,10^{44}$ @ 277 d (Sec. 2.5)	$1.1\,10^{44}$ @ 123 d (Sec. 2.5)
Universal model assumptions – and their consequences			
$\varepsilon_{\rm diss}$ $(L_p/\dot{M})$	0.2	0.2	0.2
$F_{\rm peak}$ $(\dot{M}/L_{\rm edd}$ at $t_{\rm peak})$	100	100	100
$M_\star/M_\odot$ $(M_\star \simeq 2 \cdot \int \dot{M} dt)$	0.6	5.7	6.3
$t_{\rm dyn}$ [days] (interval with $\dot{M} \gtrsim L_{\rm edd}$)	670	1730	1970

[a] Peak position uncertain; here a value close to epoch 1 of the BB peak in (2) is chosen.

Table 1. Summary of observations and universal model ingredients; references to the original articles or sections in this article are given as well in brackets: (1) Stein et al. (2021), (2) Reusch et al. (2022), (3) van Velzen et al. (2021a), (4) van Velzen et al. (2021b), (5) IceCube Collaboration (2019a), (6) Stein (2020), (7) IceCube Collaboration (2019b). The X-ray and IR luminosities are given at the indicated times, with the evolution determined by our theoretical models (for details, see main text). The neutrino time delay $t_\nu - t_{\rm peak}$ is computed from $t_{\rm peak}$ and t_ν. See caption of Fig. 4 for the definition of the GFU (Gamma-Ray Follow-Up) effective area.

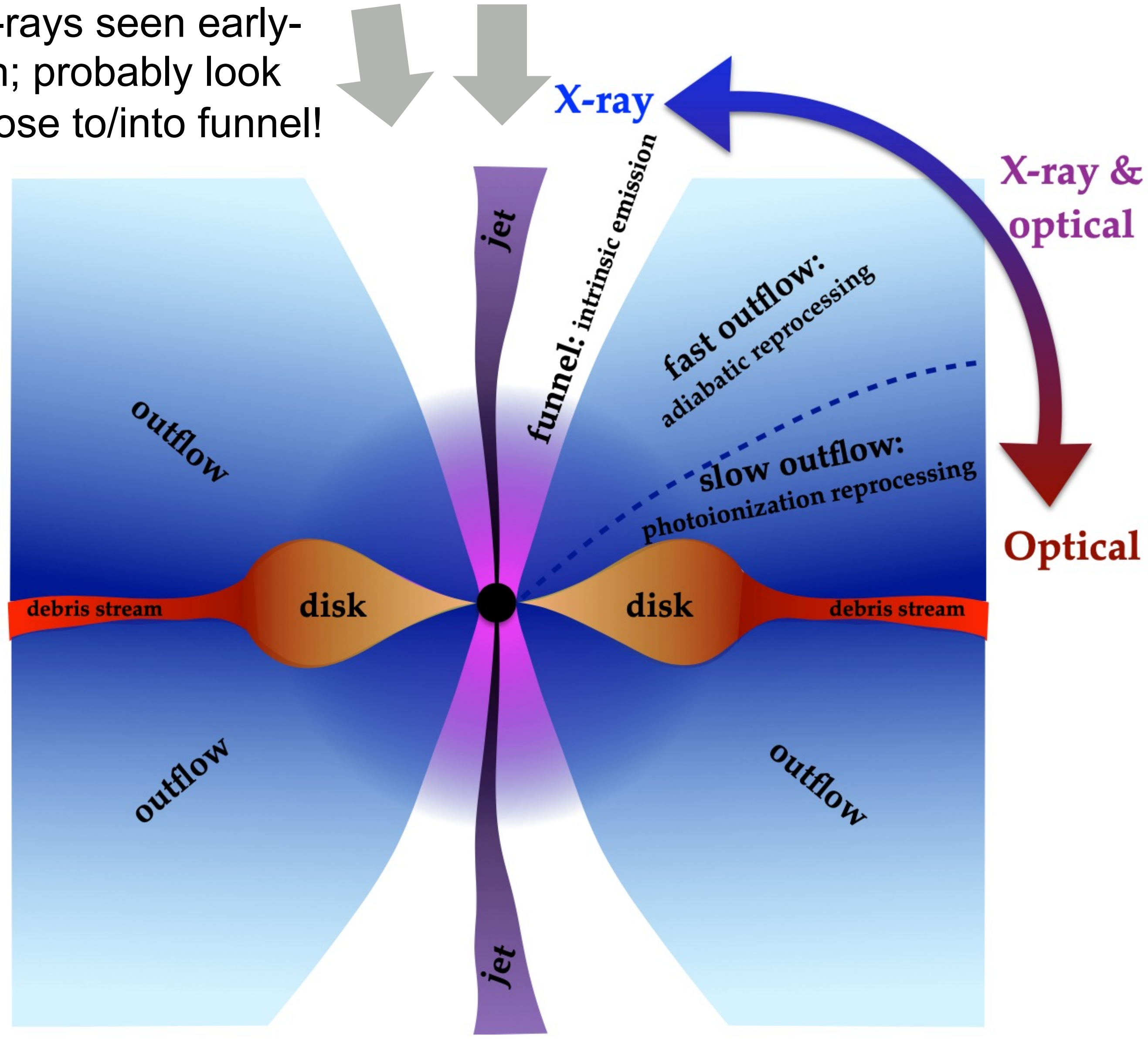
Winter, Lunardini, arXiv:2205.11538, ApJ submitted

A TDE unified model

... used to motivate a concordance model

- Matches several aspects of AT2019dsg very well (L_{bol}, R_{BB}, X-rays/obscuration?)
- Supported by MHD sims; $M_{SMBH} = 5\ 10^6\ M_\odot$ used; we use **conservatively $M_{SMBH} = 10^6\ M_\odot$**
- A jet is optional in that model, depending on the SMBH spin
- Observations from model:
  - Average mass accretion rate $\dot{M} \sim 10^2 L_{\mathrm{Edd}}$
  - ~ 20% of that into jet
  - ~ 3% into bolometric luminosity
  - ~ 20% into outflow
  - Outflow with v ~ 0.1 c (towards disk) to v ~ 0.5 c (towards jet)

X-rays seen early-on; probably look close to/into funnel!



Dai, McKinney, Roth, Ramirez-Ruiz, Coleman Miller, 2018