Multi-messenger signals from Tidal Disruption Events

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HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

DESY

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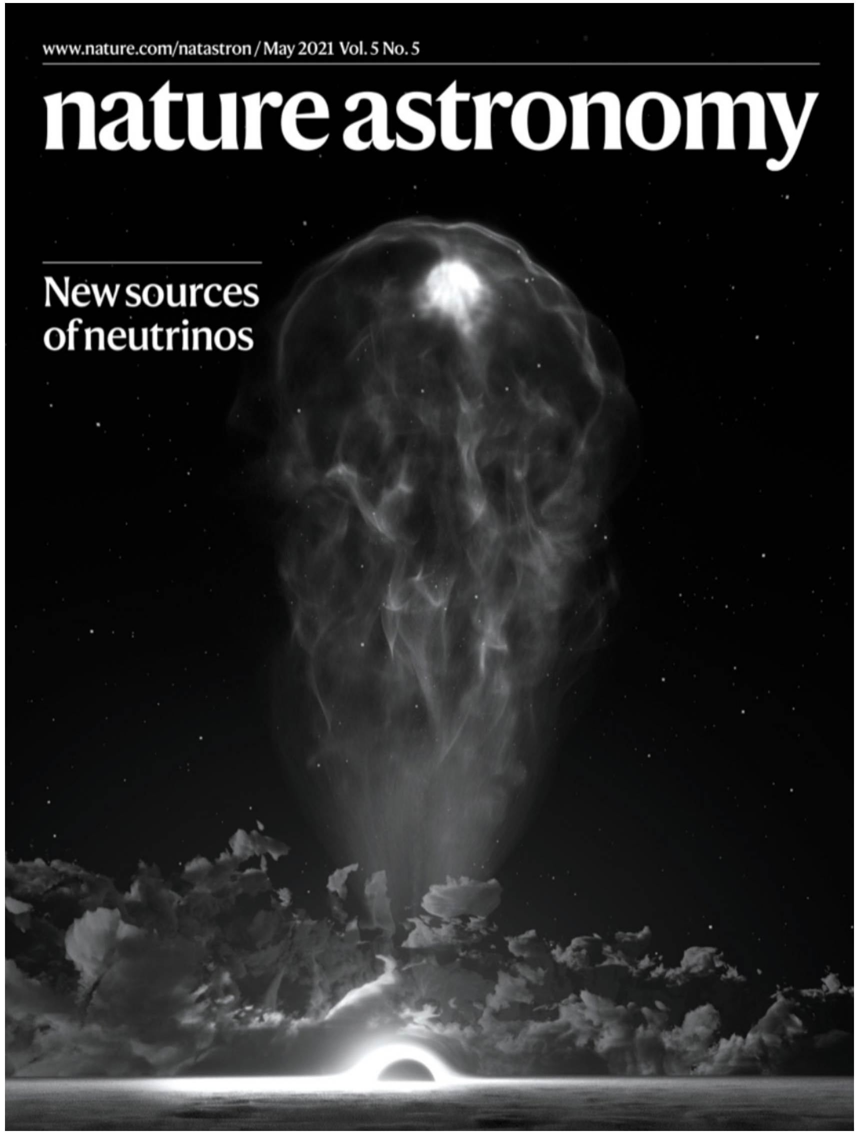


Introduction

Tidal Disuption Events – the electromagnetic picture

How to disrupt a star 101

Gravity

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

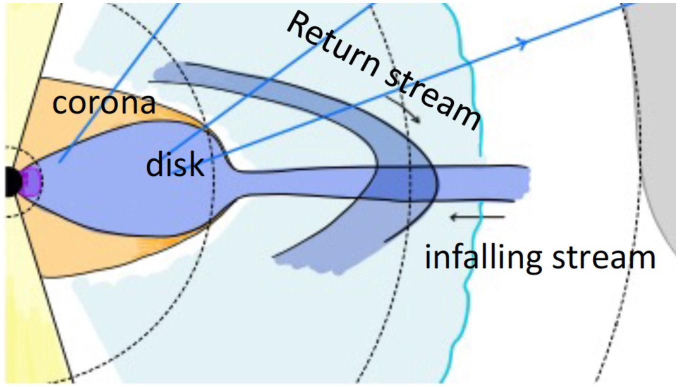
$$r_t = \left(\frac{2M}{m}\right)^{1/3} R \simeq 8.8 \times 10^{12}\,\mathrm{cm} \left(\frac{M}{10^6\, M_\odot}\right)^{1/3} \frac{R}{R_\odot} \left(\frac{m}{M_\odot}\right)^{-1/3}$$

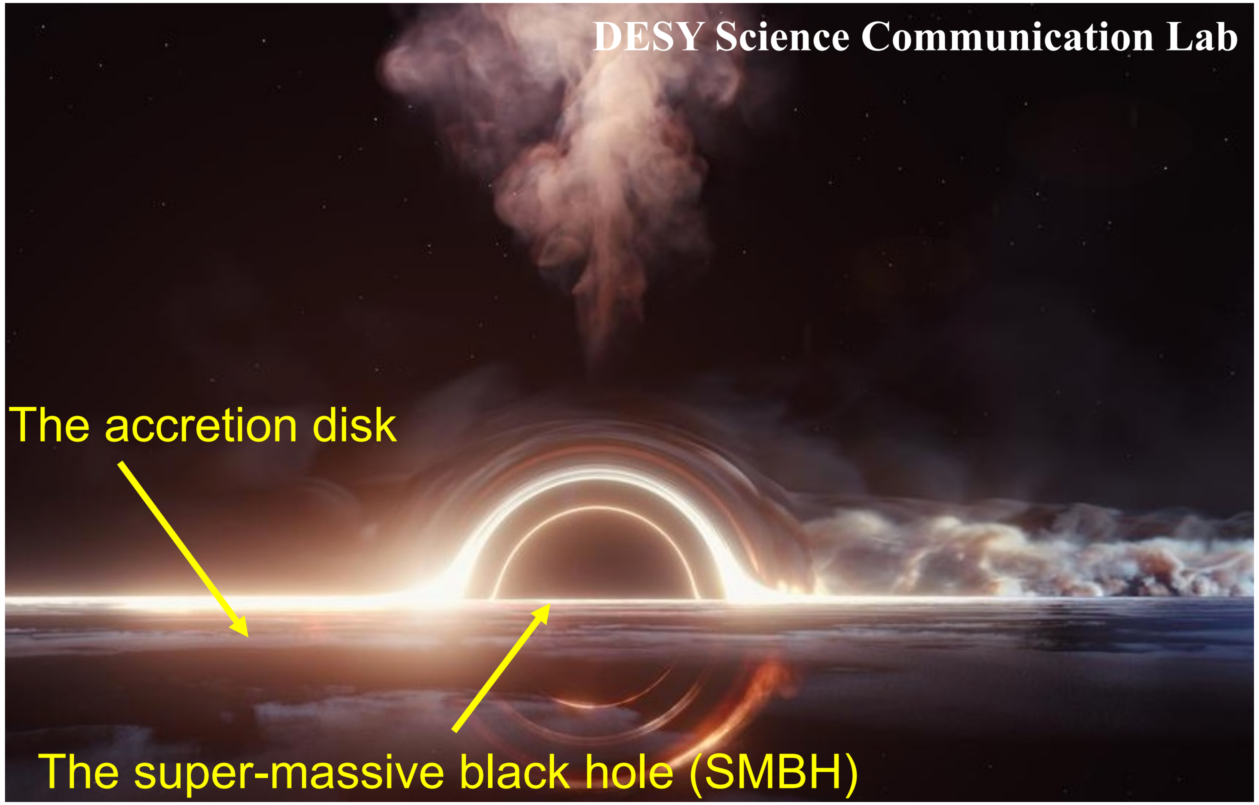
- Has to be beyond Schwarzschild radius for TDE

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

- From the comparison ($r_t > R_s$) and demographics, one obtains (theory) M <~ 2 10^7 $M_\odot$ (lower limit less certain …)

  Hills, 1975; Kochanek, 2016; van Velzen 2017





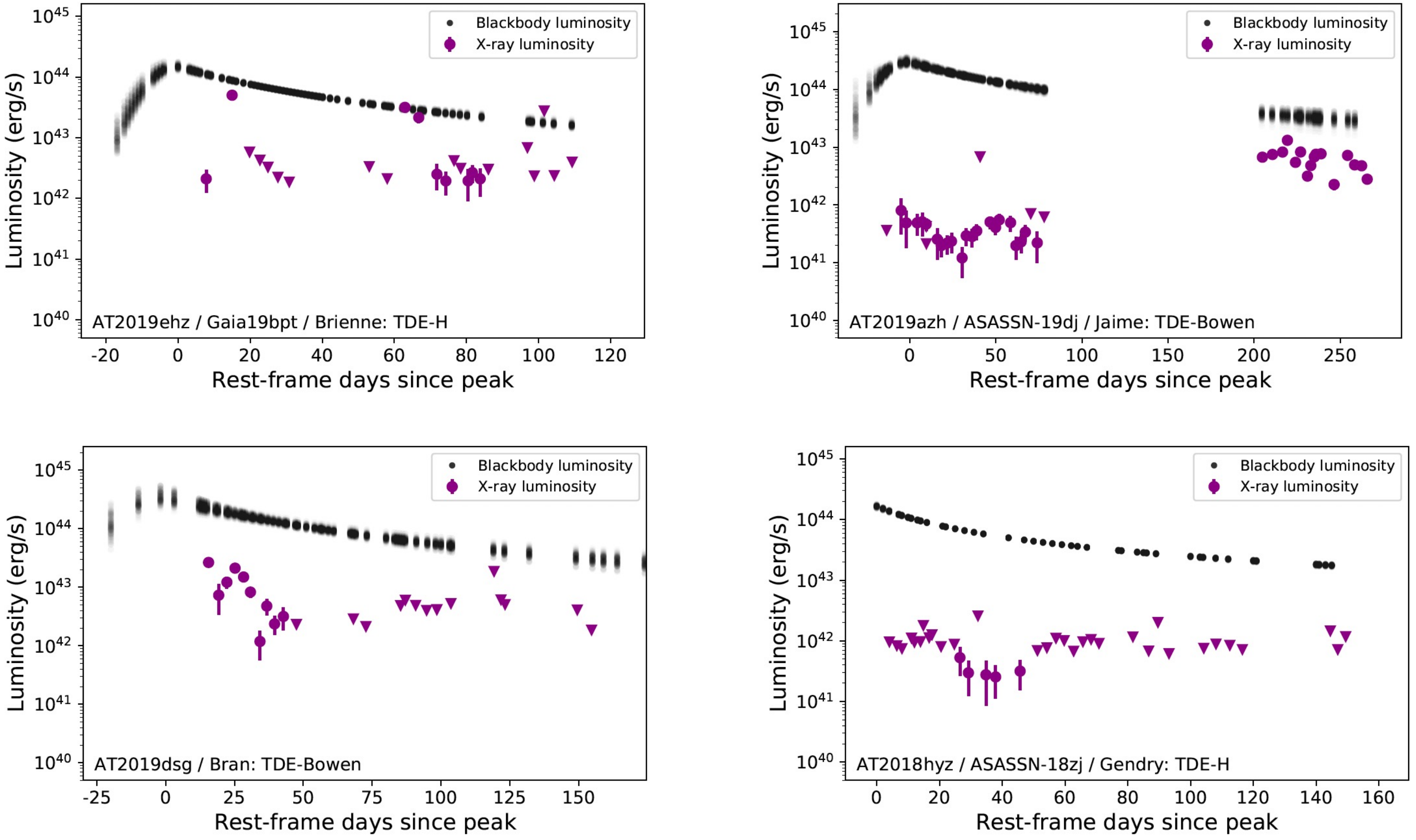
Energetics

- Measure for the luminosity which can be re-processed from accretion through the SMBH: **Eddington luminosity**

$$L_{\mathrm{Edd}} \simeq 1.3\ 10^{44}\ \mathrm{erg/s}\,\left(M/(10^6\ M_\odot)\right)$$

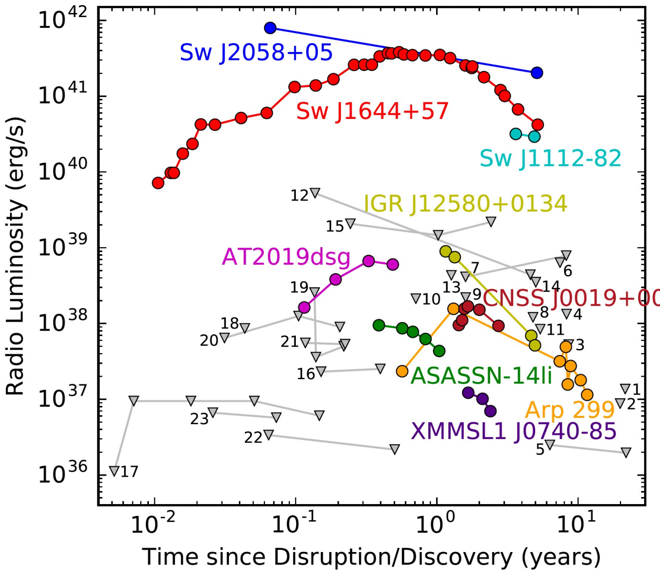
- Energy to be re-processed: about half of a star's mass E ~ 10^{54} erg (half a solar mass)
- Super-Eddington **mass fallback rate** expected at peak to process that amount of energy

TDE observations (general)



van Velzen et al, Astrophys. J. 908 (2021) 1, 4;
Alexander, van Velzen, Horesh, Zauderer, Space Sci. Rev. 216 (2020) 5, 81

- **Optical-UV (blackbody):** Mass fallback rate typically exhibits a peak and then a ~ $t^{-5/3}$ dropoff over a few hundred days
- **X-rays:** Only observed in rare cases (here about 4 out of 17). X-ray properties very different
- **Radio:** Interesting signals in about 1/3 of all cases. Evolving radio signals interpreted as outflow or jet



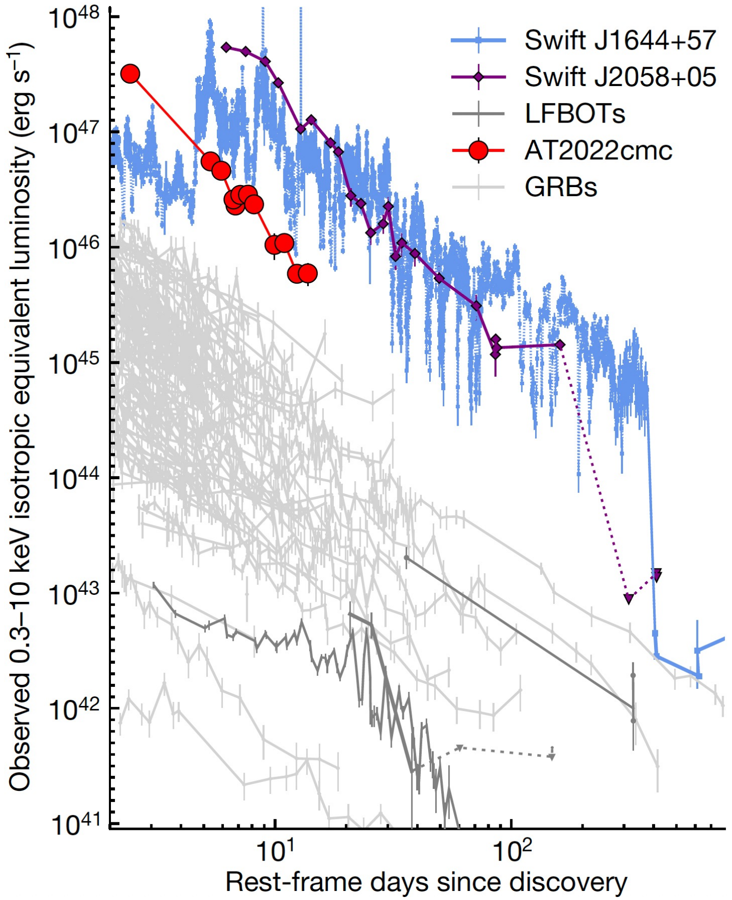
Relat. jets?

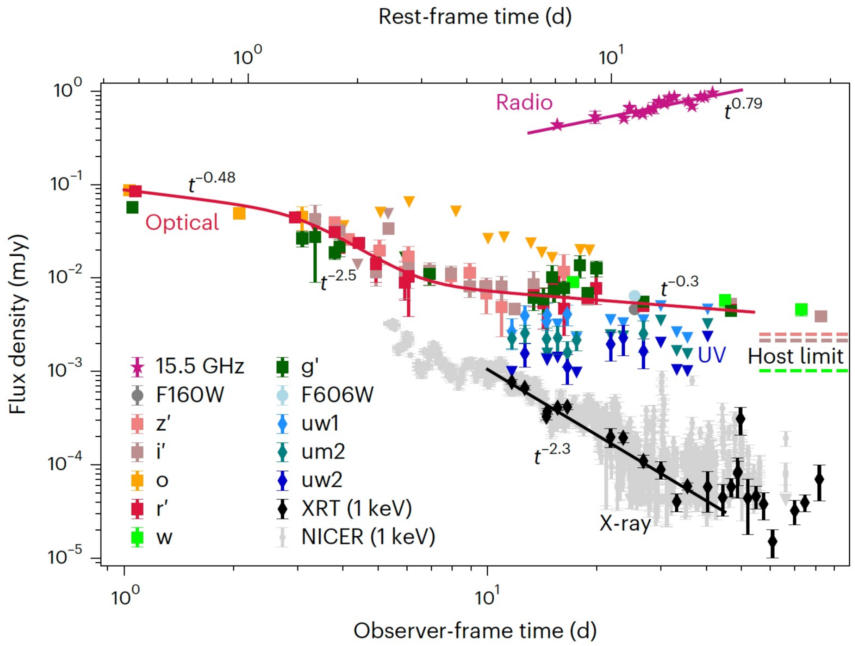
Non-relat. outflows?

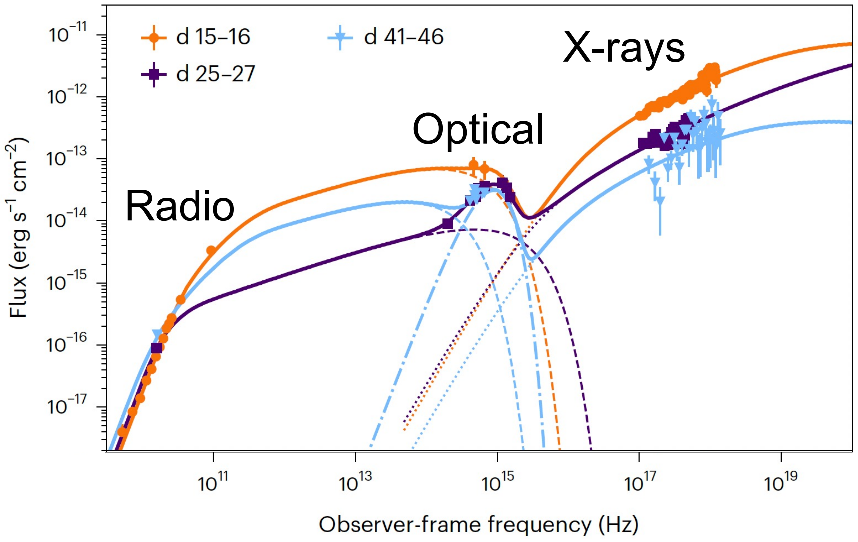
Jetted TDEs

A brand-new example: AT2022cmc

- Extremely luminous
- Non-thermal spectra in X-rays
- Associated with on-axis (or slightly off-axis) relativistic jets
- Γ ~ few to 90 (one model AT2022cmc)
- Typical assumption Γ ~ 10
- Conclusion: About 1% of all TDEs have relativistic jets (not necessarily pointed in our directions)



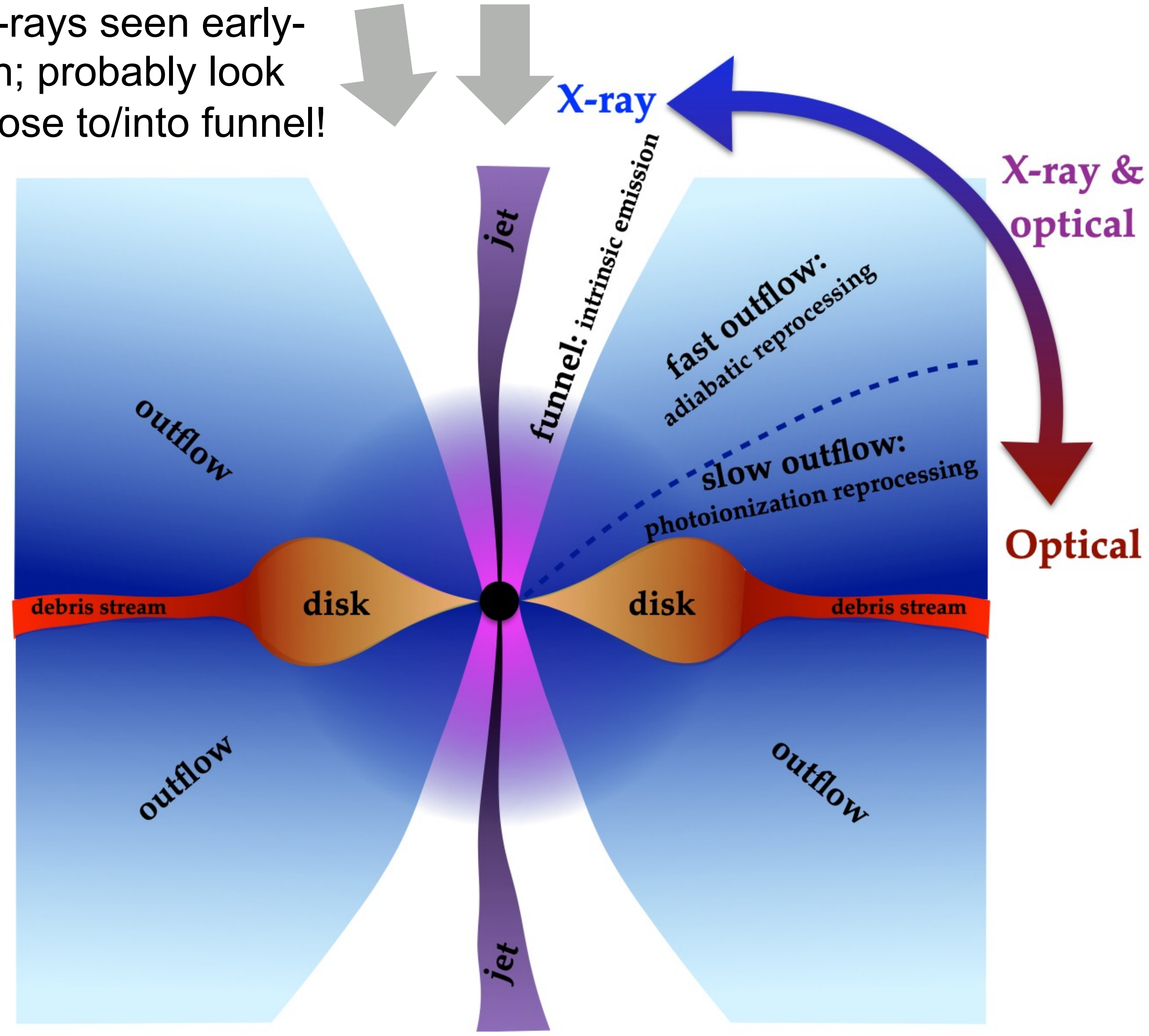




Andreoni et al, Nature 612 (2022) 7940, 430; Pasham et al, Nature Astron. 7 (2023) 1, 88

A TDE unified model

- Supported by MHD simulations; here $M_{\mathrm{SMBH}} = 5\ 10^6\ M_\odot$
- 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)

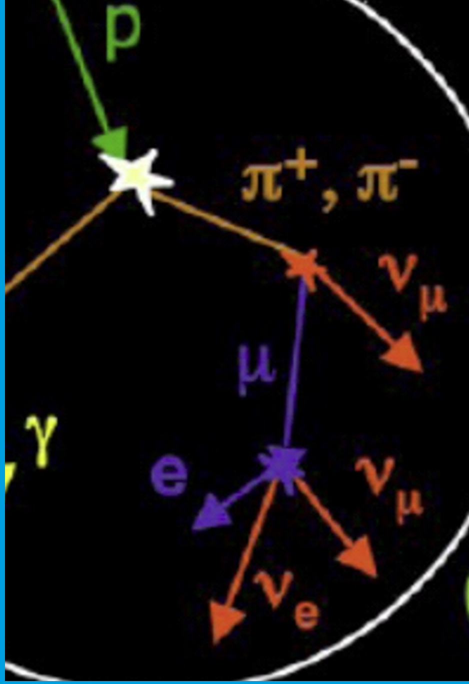


X-rays seen early-on; probably look close to/into funnel!

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

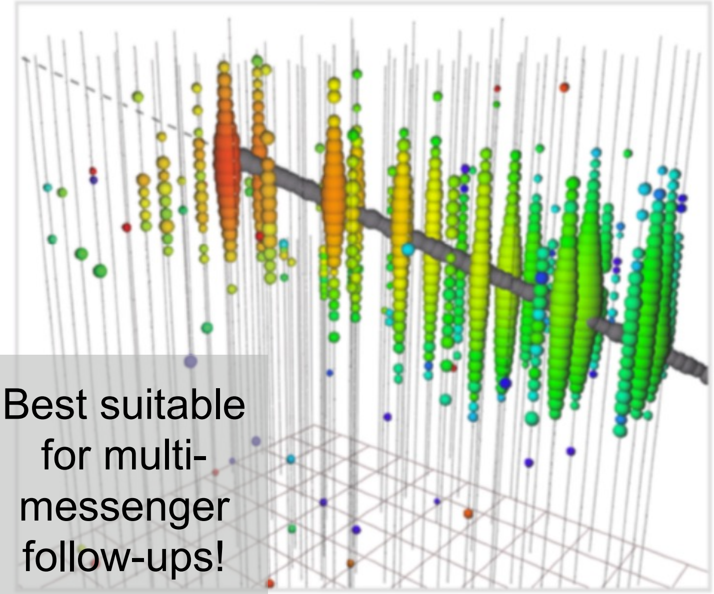
Neutrinos from TDEs

Observations



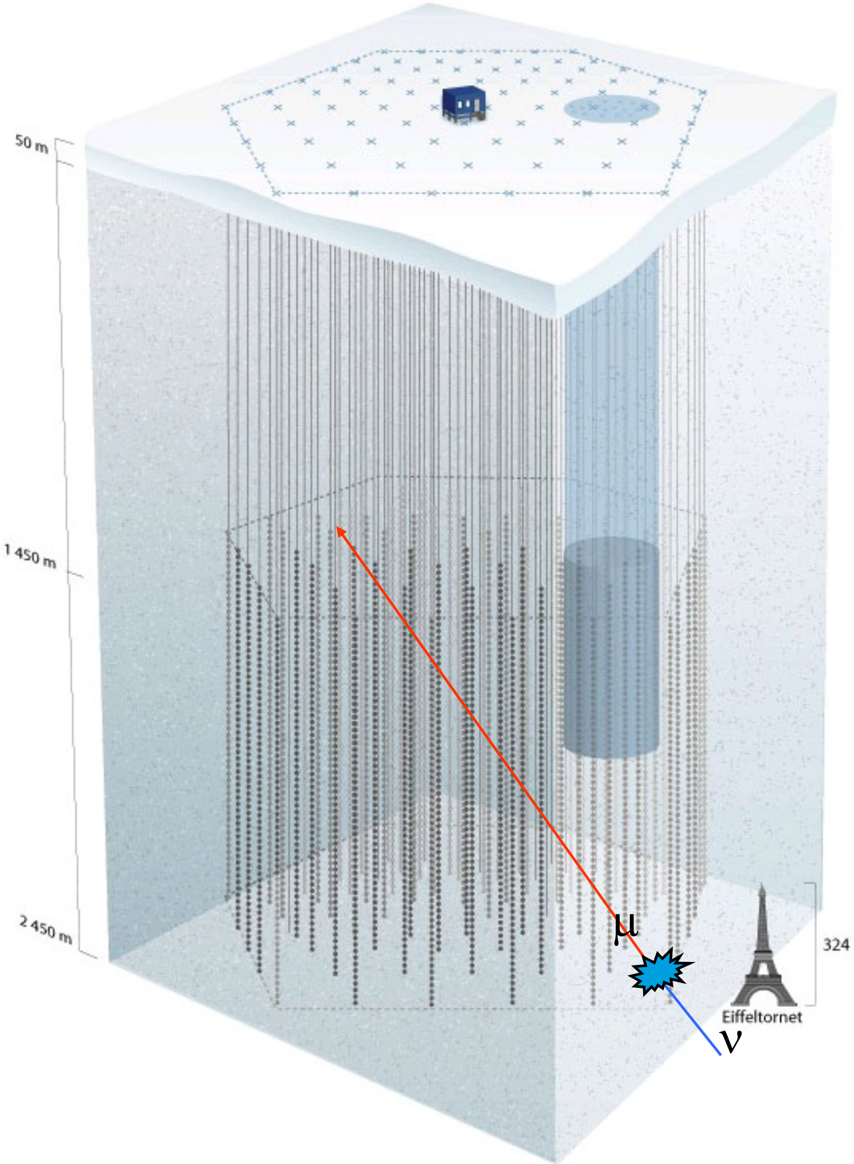
Observing TeV-PeV neutrinos with IceCube

Muon track:
- From ν_μ
- From ν_τ (17 %)



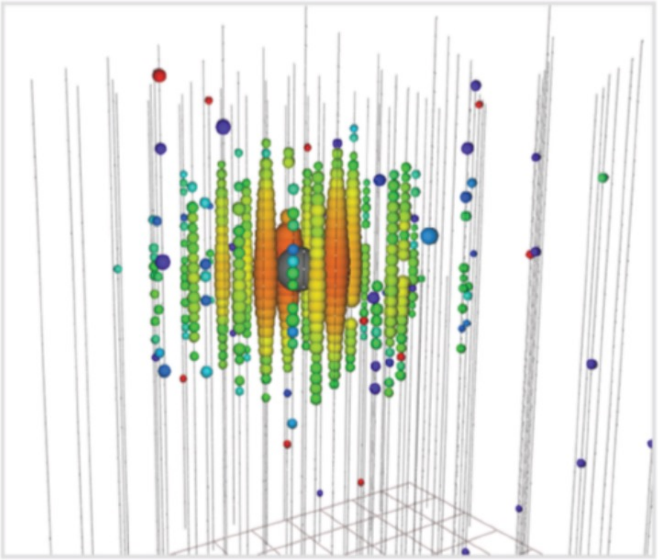
Best suitable for multi-messenger follow-ups!

Better directional info



IceCube http://icecube.wisc.edu/

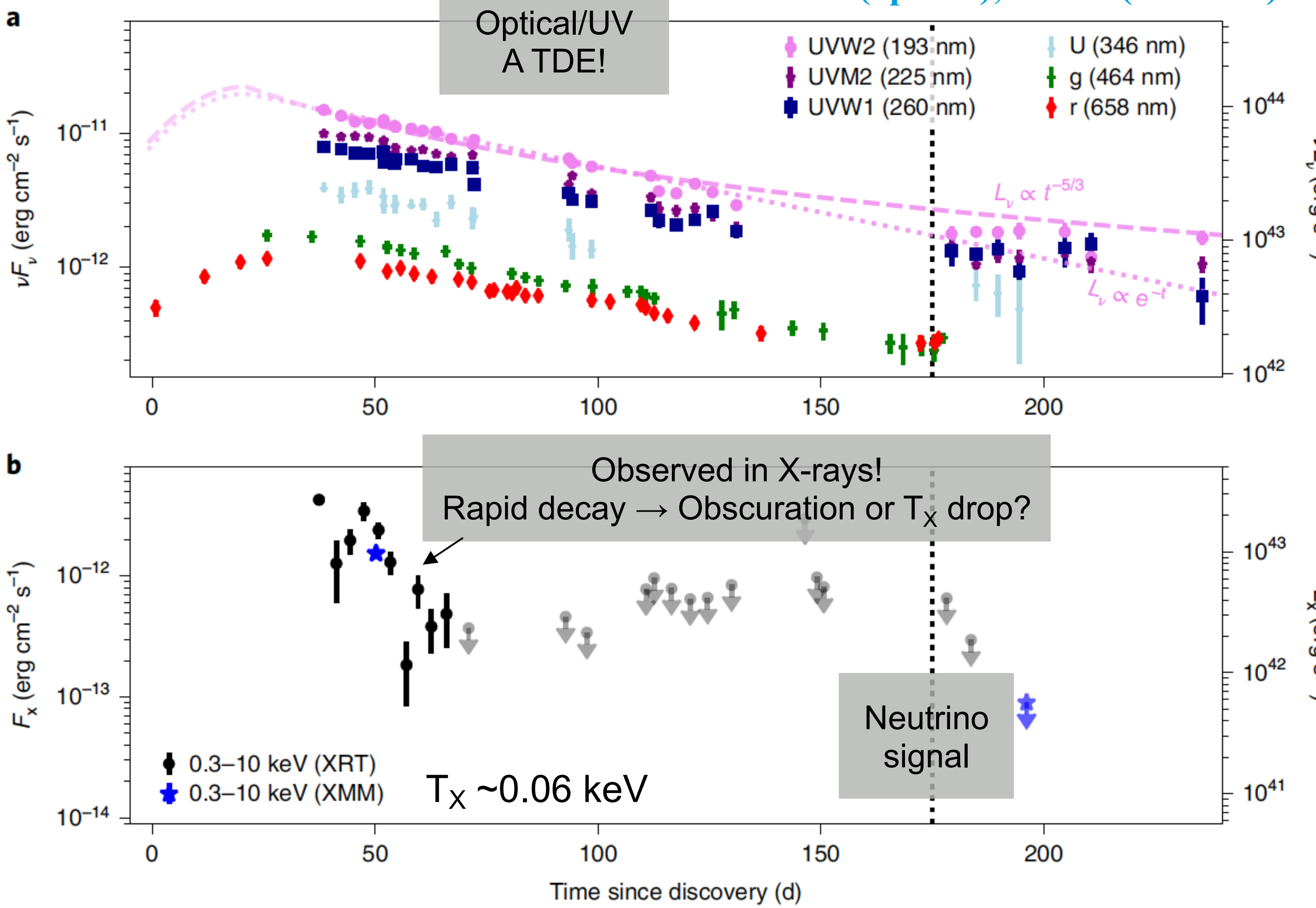
Cascade (shower):
- From ν_e
- From ν_τ
- From ν_e, ν_μ, ν_τ NC interactions



Better energy info

A neutrino from AT2019dsg

ZTF (optical), WISE (infrared) data

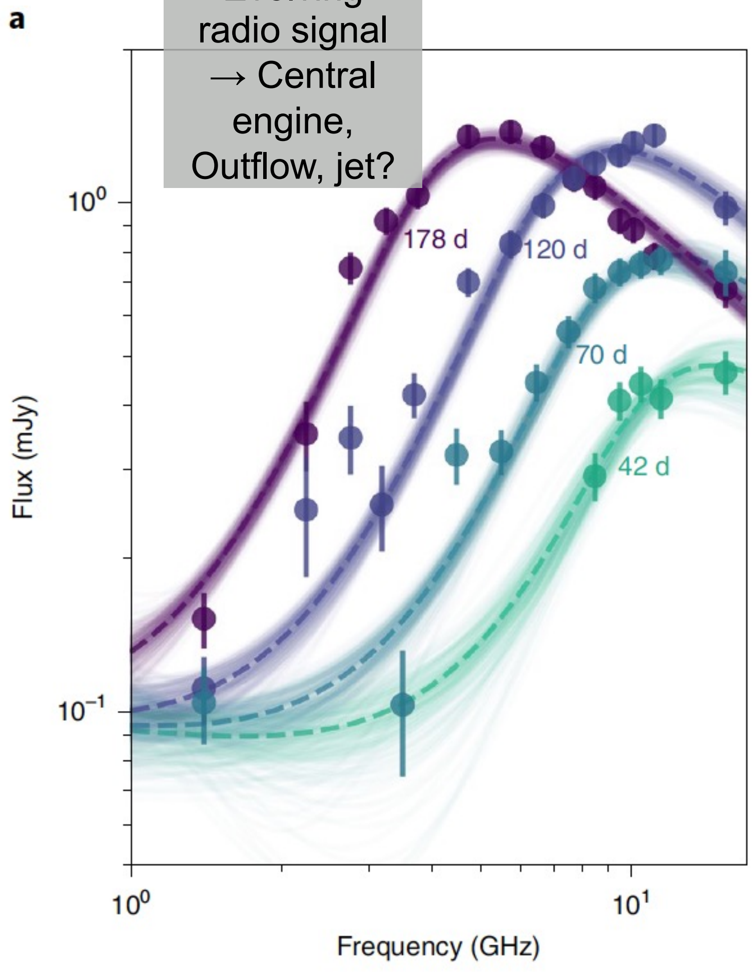


Optical/UV
A TDE!

Observed in X-rays!
Rapid decay → Obscuration or T_X drop?

T_X ~0.06 keV

Neutrino
signal

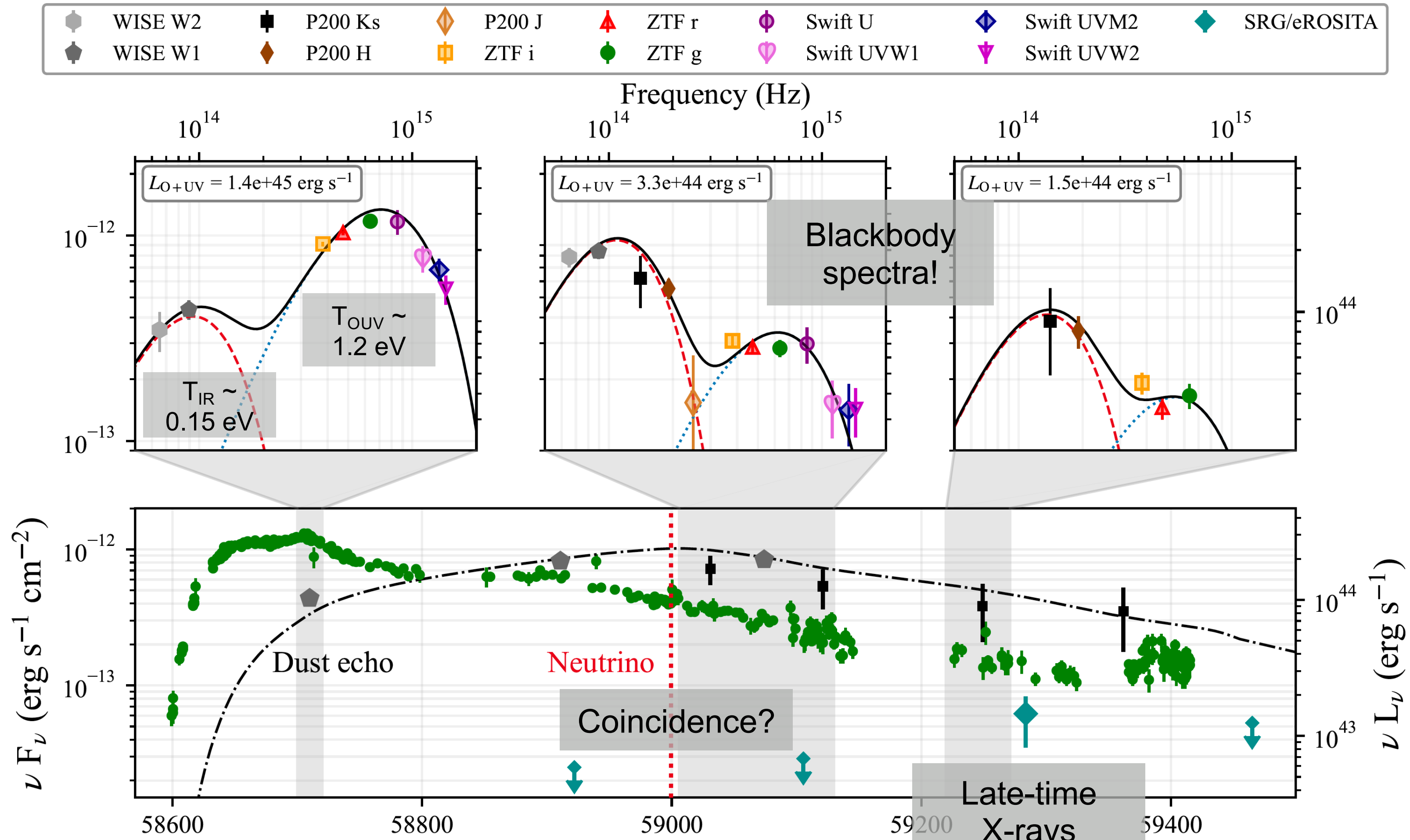


Evolving
radio signal
→ Central
engine,
Outflow, jet?

Stein et al, Nature Astronomy 5 (2021) 510;

also interesting: AT2019dsg exhibits late radio re-brighteting two years after discovery; Cendes et al, arXiv:2308.13595

Another neutrino from the TDE candidate AT2019fdr



T_{OUV} ~ 1.2 eV

T_{IR} ~ 0.15 eV

Blackbody spectra!

Coincidence?

Late-time X-rays (T_X ~ 56 eV)

Dust echo "convolved" over 2 Δt

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

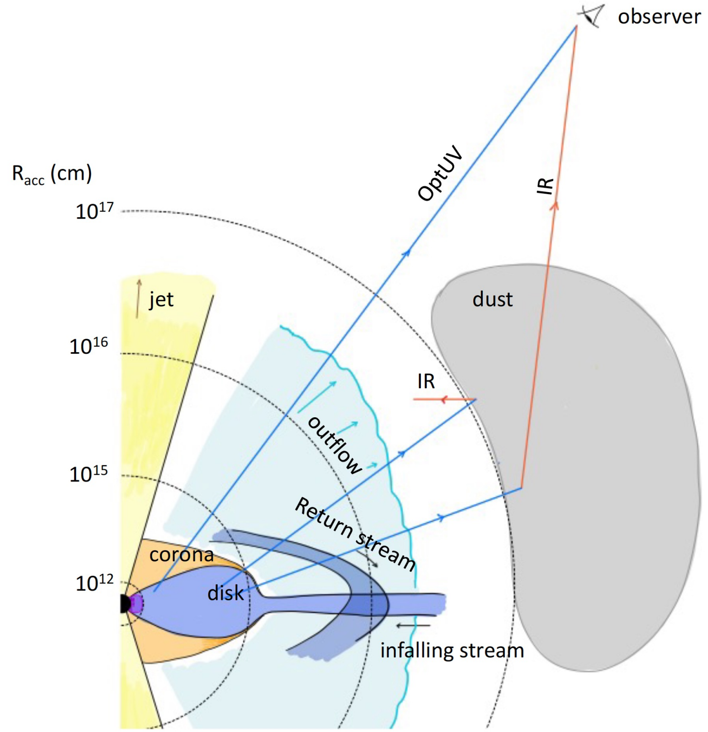


Fig. from Winter, Lunardini, ApJ 948 (2023) 1, 42

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

AT2019aalc

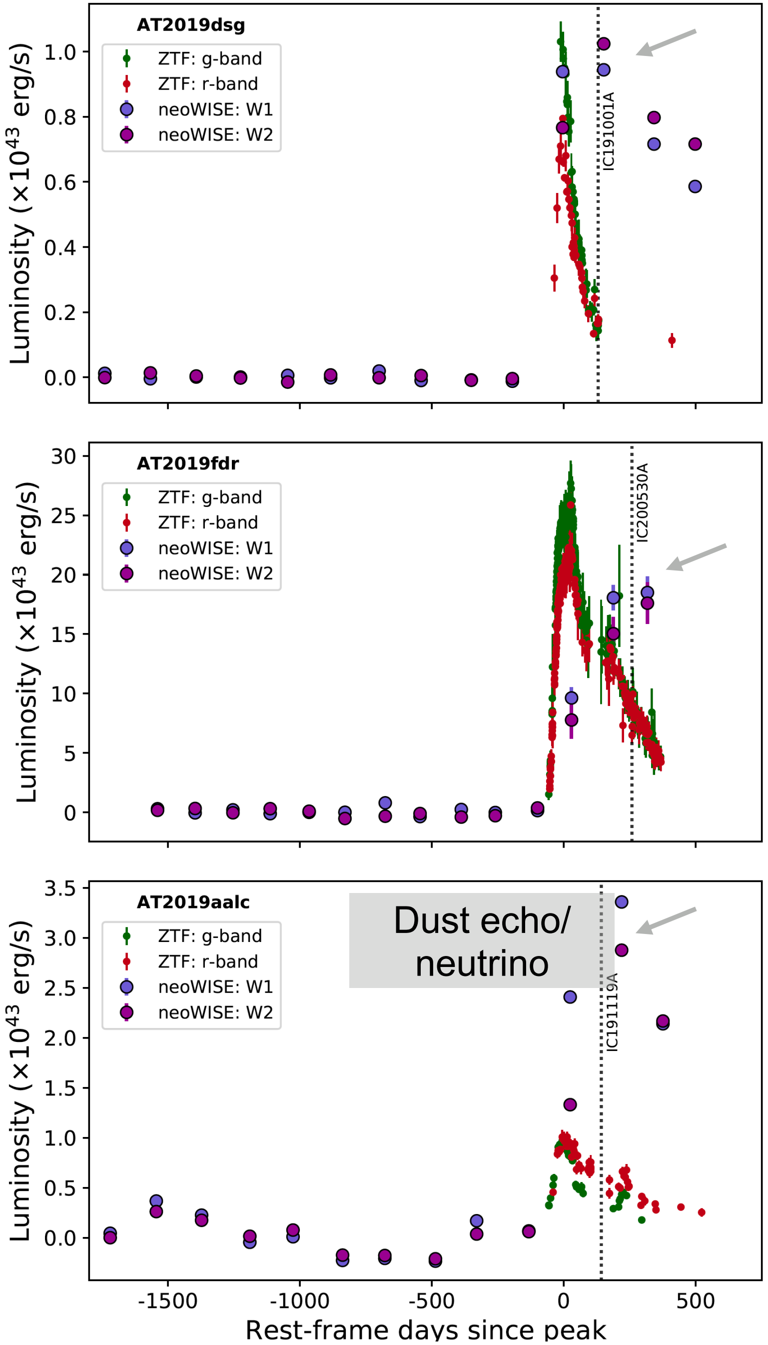
… as third neutrino-TDE association

Analysis

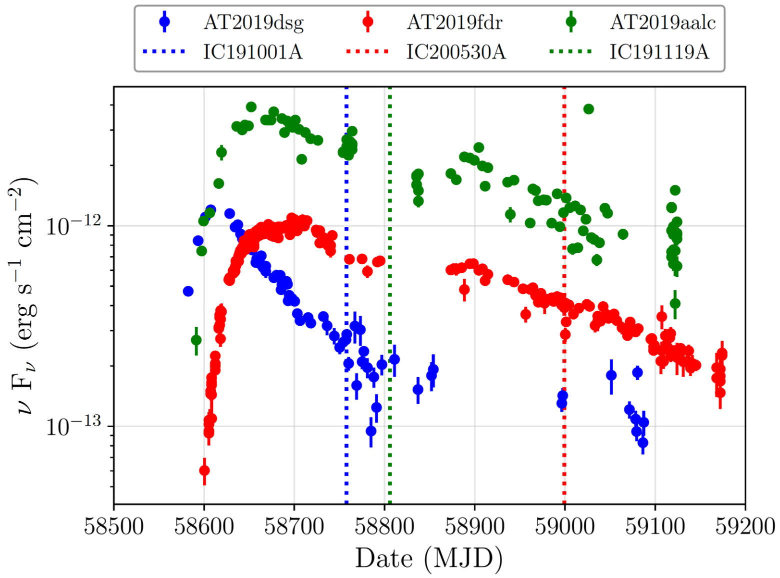
- Selected a sample of 1732 accretion flares with properties similar to AT2019dsg and AT2019fdr (dust echo)
- Found another TDE candidate: AT2019aalc with a similar neutrino time delay
- Overall significance: 3.7σ
  van Velzen et al, arXiv:2111.09391

Caveats

- AT2019aalc also exhibited a late-time X-ray signal
- AT2019fdr and AT2019aalc not uniquely identified as TDEs;
  e.g. Pitik et al, Astrophys. J. 929 (2022) 2, 163
  happened in pre-existing AGN;
  no evolving radio signals



Dust echo/
neutrino



Simeon Reusch @ ECRS 2022

Common features of these three "TDEs":

- Detected in X-rays (but X-ray signals qualitatively different)
- Large BB luminosities
- Strong dust echoes in IR
- Neutrinos all delayed wrt peak by order 100 days (close to dust echo peak)

van Velzen et al, arXiv:2111.09391; two more candidates in Jiang et al, ApJL 953 (2023) 1, L12

Interpretation

Possible particle acceleration sites

① Jets (on-axis, off-axis, choked)
Wang et al, 2011; Wang&Liu 2016; Dai&Fang, 2016; Lunardini&Winter, 2017; Senno et al 2017; Winter, Lunardini, 2020; Liu, Xi, Wang, 2020; Zheng, Liu, Wang, 2022; Mukhopadhyay et al, 2023

② Disk
Hayasaki&Yamazaki, 2019

③ Corona
Murase et al, 2020

④ Winds, outflow, stream-stream collisions
Murase et al, 2020; Fang et al, 2020; Wu et al, 2021

Based on the experimental evidence, it is difficult to establish a particular particle accelerator!

However: probably the accelerator is "TDE-particular" (otherwise other sources would outshine the TDE neutrino flux)

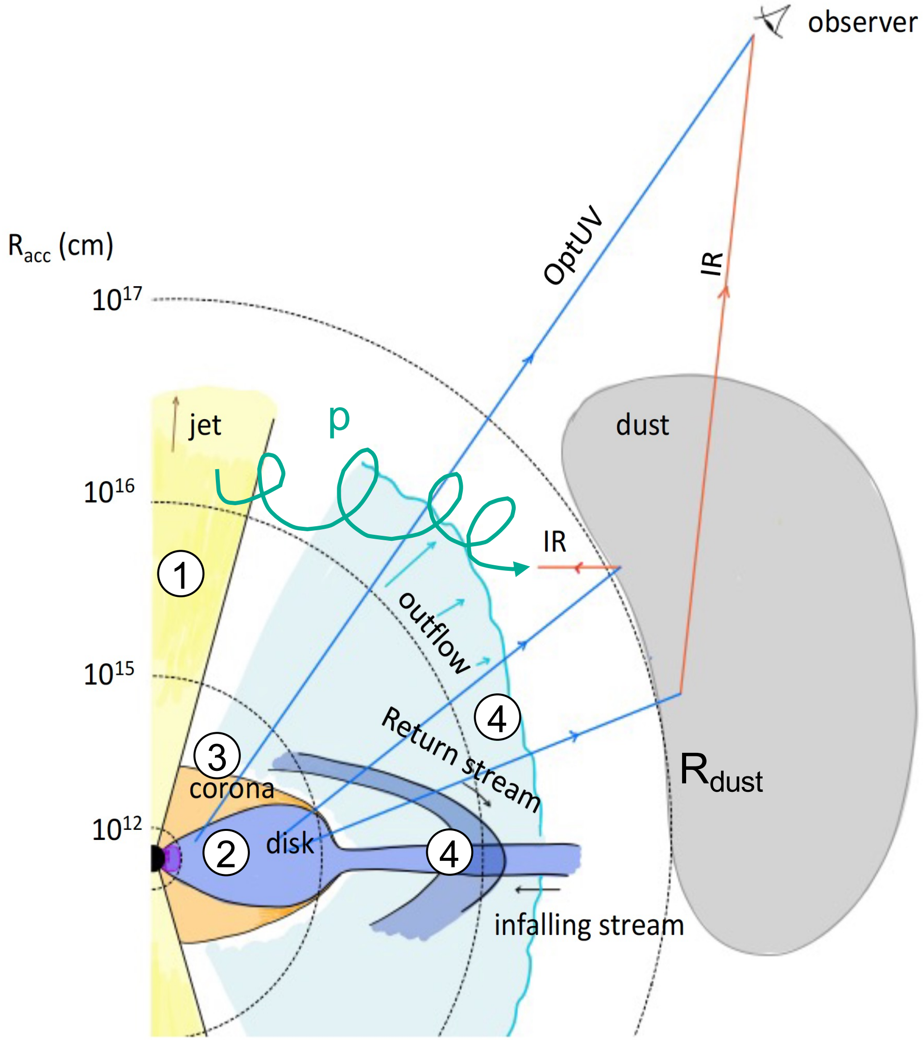
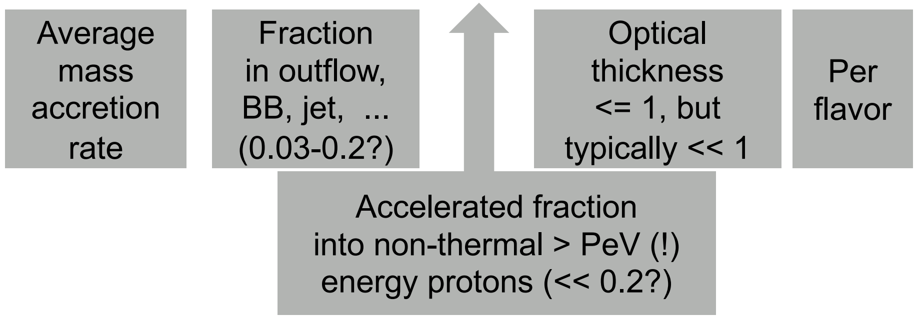


Fig: Winter, Lunardini, ApJ 948 (2023) 1, 42

The energetics challenge

Example: AT2019dsg (similar arguments apply to others)

- Upper limit for average neutrino luminosity (4π solid angle emission, for pp similar):
  $L_\nu \sim 25\ L_{edd} \quad \mathrm{x} \quad f_{comp} \quad \mathrm{x} \quad \varepsilon_{acc} \quad \mathrm{x} \quad \tau_{p\gamma} \quad \mathrm{x} \quad 1/8 \quad \boldsymbol{<\sim 0.1\ L_{edd}}$



Average mass accretion rate

Fraction in outflow, BB, jet, ... (0.03-0.2?)

Accelerated fraction into non-thermal > PeV (!) energy protons (<< 0.2?)

Optical thickness <= 1, but typically << 1

Per flavor

Estimates for SMBH mass

$M_{SMBH}/M_\odot$	Reference
$\sim 2\ 10^7$	McConnel, Ma, 2012
$3\ 10^5 \ldots 10^7$	Wevers et al, 2019 (conservative)
$1.2\text{-}1.4\ 10^6$	Ryu, Krolik, Piran, 2020
$2.2\text{-}8.6\ 10^6$	Cannizzaro et al, 2021

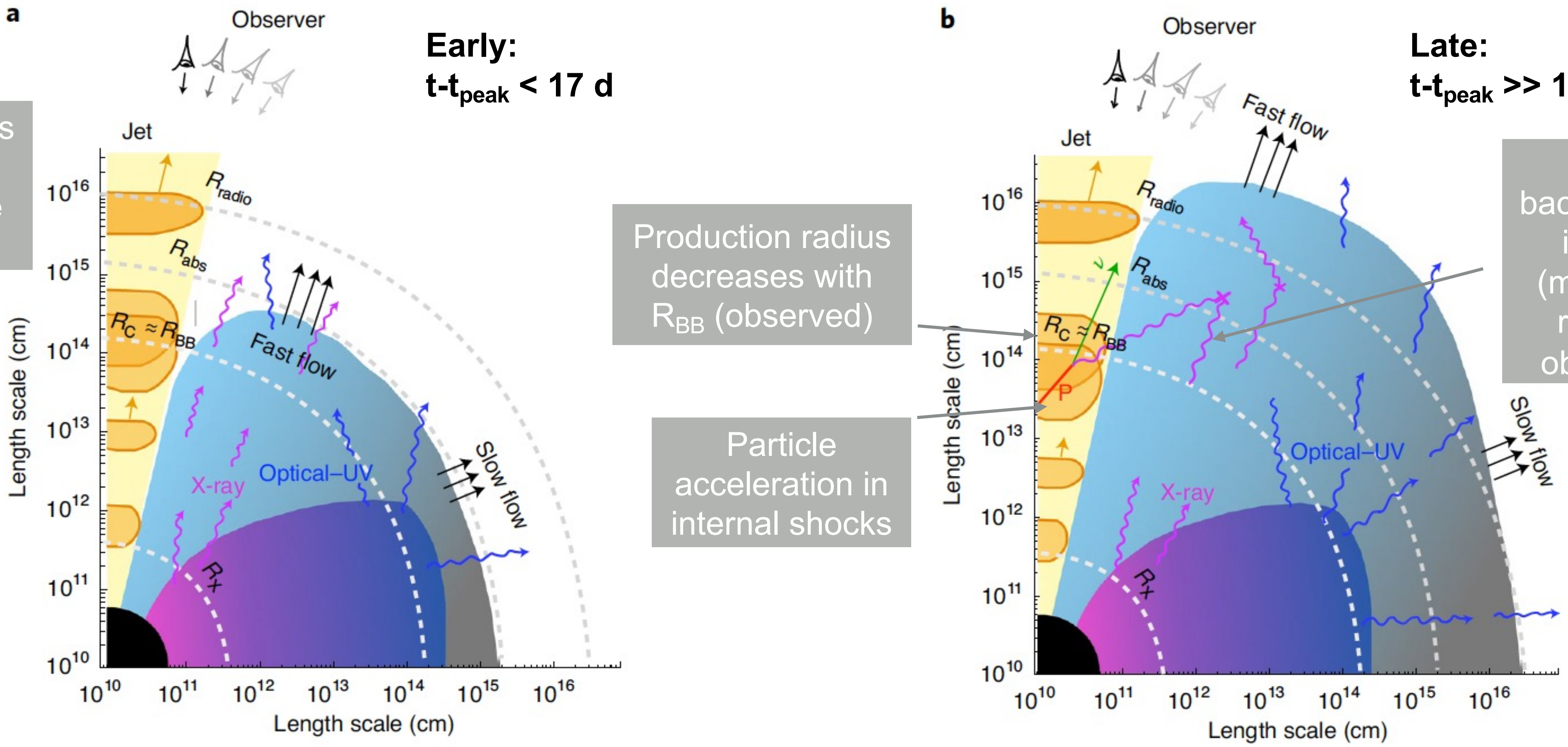
- Yields $E_\nu \sim 200$ days x $0.1\ L_{edd} \sim\ 2\ 10^{50}$ erg $(M_{SMBH}/10^6\ M_\odot)$
  Corresponds to 0.2 neutrino events for $M_{SMBH} \sim 10^6\ M_\odot$ e.g. Fiorillo, van Vliet, Morisi, Winter, JCAP 07 (2021) 028

- **Conclusion:**
  either $M_{SMBH} >> 10^6\ M_\odot$ and super-efficient energy conversion (mass accretion into non-thermal protons),
  or the outflow must be collimated with $\theta << 1$ such that $L_\nu \rightarrow L_\nu / \theta^2$. Relativistic jet?

- **However:** small neutrino rate perhaps expected from
  Eddington bias (many such faint events?), non-observation of electromagnetic cascade?

Example: A jetted concordance scenario for AT2019dsg

... based on Dai et al TDE unified model. Addresses energetics issue, but radio observations disfavor a jet



No neutrinos at t_{peak} (no intense target)

Early:
$t-t_{peak} < 17$ d

Production radius decreases with R_{BB} (observed)

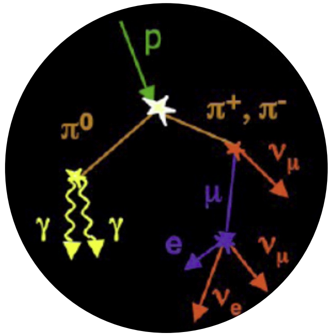
Particle acceleration in internal shocks

Late:
$t-t_{peak} >> 17$ d

X-ray back-scattering in outflow (may also be reason for obscuration)

Winter, Lunardini, Nature Astronomy 5 (2021) 472;
see also Liu, Xi, Wang, 2020 for an off-axis jet; Zheng, Liu, Wang, 2022, Mukhopadhyay et al, 2023 for choked jets

Neutrinos from pγ interactions … and the multi-messenger connection



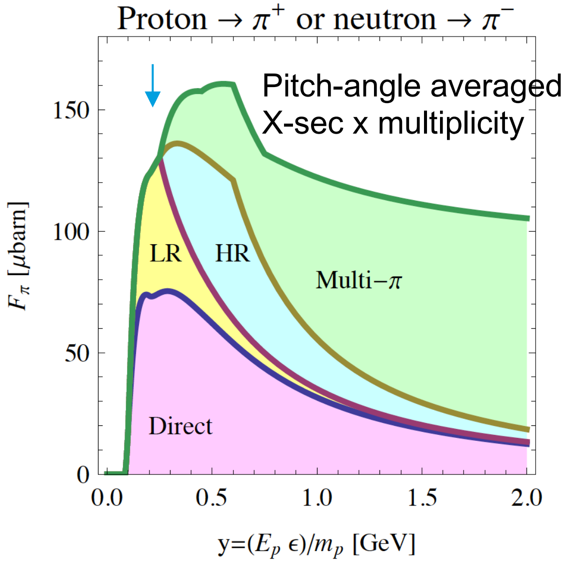
- Neutrino peak determined by maximal cosmic ray energy →
  [conditions apply: for target photons steeper (softer) than ε^{-1} (and low enough ε_{min})]
- Interaction with target photons
  (Δ-resonance approximation):

$$p+\gamma \longrightarrow \Delta^+ \longrightarrow \begin{cases} n+\pi^+ & \rightarrow \nu \\ p+\pi^0 & \rightarrow \gamma \end{cases}$$

E_γ [keV] ~ 0.01 Γ^2/E_ν [PeV]
X-rays interesting!
(computed for Δ-res, yellow) →

Thermal target, all processes:

$$E_{p,\max} \gtrsim 20\, E_\nu \simeq 160\,\mathrm{PeV} \left(\frac{T}{\mathrm{eV}}\right)^{-1}$$



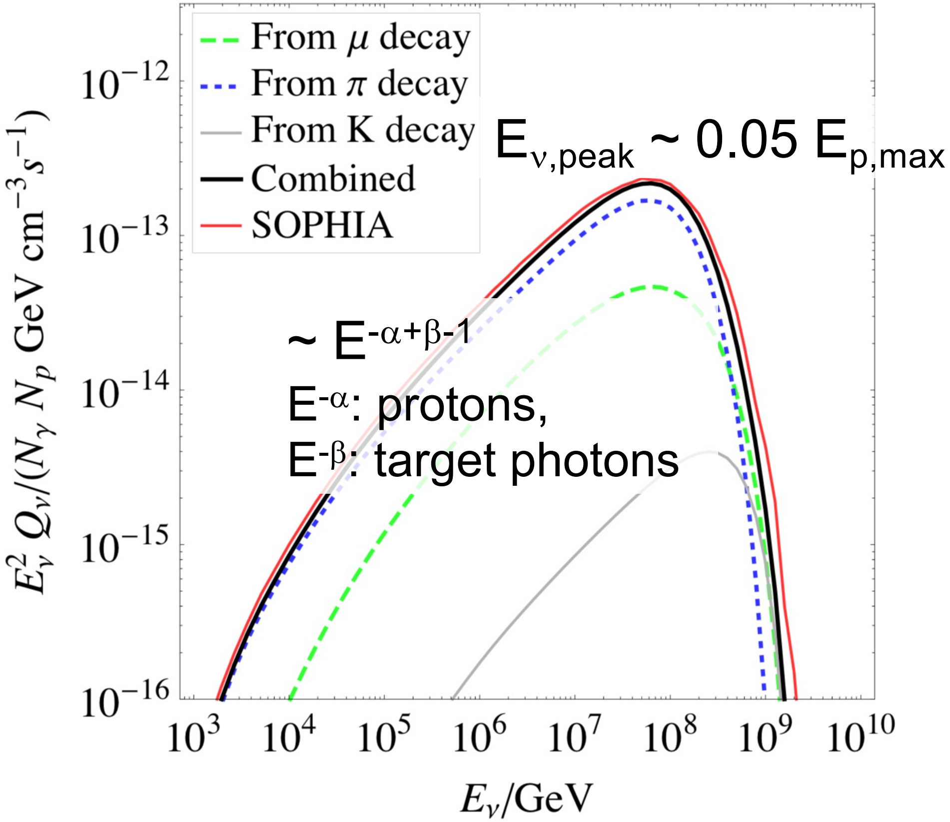
Pitch-angle averaged
X-sec x multiplicity

- Photons from pion decay:

$$\pi^0 \longrightarrow \gamma+\gamma$$

Injected at $E_{\gamma,peak}$ ~ 0.1 $E_{p,max}$
TeV–PeV energies interesting! (but: EM cascade in source!)

Neutrino spectrum (example)



$E_{\nu,peak}$ ~ 0.05 $E_{p,max}$

~ $E^{-\alpha+\beta-1}$
$E^{-\alpha}$: protons,
$E^{-\beta}$: target photons

From: Hümmer et al, Astrophys. J. 721 (2010) 630; for a more complete view of possible cases, see Fiorillo et al, JCAP 07 (2021) 028

Possible target photons and required proton energies

	AT2019dsg	**AT2019fdr**	**AT2019aalc**
Overall parameters			
Redshift z	0.051 (1)	0.267 (2)	0.036 (3)
t_{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)
$t_\nu - t_{\mathrm{peak}}$ [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_{BB} [eV] at t_{peak}	3.4 (1)	1.2 (2)	0.9 [Sec. 2.5]
$L_{\mathrm{BB}}^{\mathrm{bol}}$ (min.) $[\frac{\mathrm{erg}}{\mathrm{s}}]$ at t_{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_{X} [eV]	72 (1)	56 (2,3)	172 (3)
$L_{\mathrm{X}}^{\mathrm{bol}}$ $[\frac{\mathrm{erg}}{\mathrm{s}}]$ @ $t - t_{\mathrm{peak}}$	$6.2\,10^{43}$ @ 17 d (1)	$6.4\,10^{43}$ @ 609 d (2)	$1.6\,10^{42}$ @ 495 d (3)
Dust echo (IR)			
T_{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)
$L_{\mathrm{IR}}^{\mathrm{bol}}$ $[\frac{\mathrm{erg}}{\mathrm{s}}]$ @ $t - t_{\mathrm{peak}}$	$2.8\,10^{43}$ @ 431 d (Sec. 2.5)	$5.2\,10^{44}$ @ 277 d (Sec. 2.5)	$1.1\,10^{44}$ @ 123 d (Sec. 2.5)

Winter, Lunardini, ApJ 948 (2023) 1, 42

Required target photon temperature (pγ):

$$T \simeq 80\,\mathrm{eV} \left(\frac{E_\nu}{100\,\mathrm{TeV}} \right)^{-1}$$

Translates into:

$$E_{p,\max} \gtrsim 20\,E_\nu \simeq 160\,\mathrm{PeV} \left(\frac{T}{\mathrm{eV}} \right)^{-1}$$

→ $E_{p,\max}$ > 100 PeV

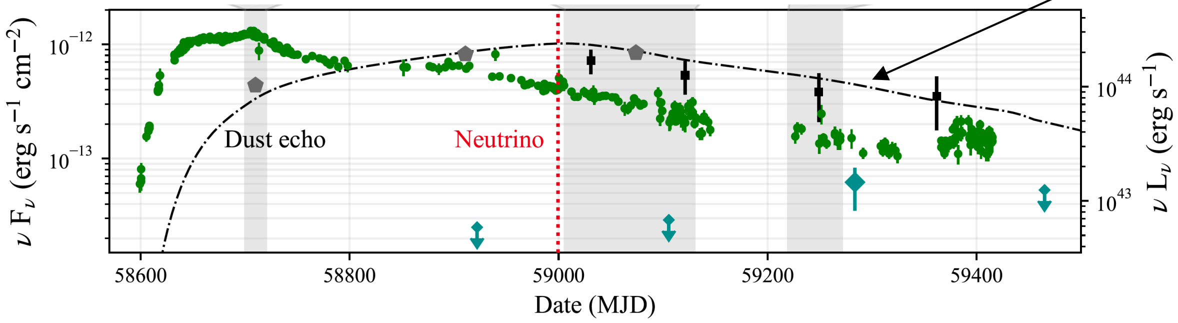
→ $E_{p,\max}$ > 2 PeV

→ $E_{p,\max}$ > 1 EeV. **UHECRs?**

$E_{p,\max}$ (related to efficiency of accelerator) controls the available photon targets!

Origin of neutrino time delay?

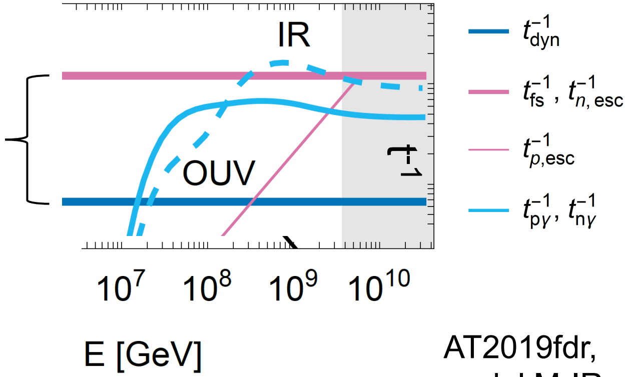
1. Target builds up over time (e.g. through evolution of outflow, dust echo). Apparently related to size of (newly formed) system



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

2. Accelerator appears delayed (transition in accretion disk state, circularization time, delayed launch of outflow/jet …)
3. Protons are magnetically confined (calorimeter), i.e., do not interact immediately.

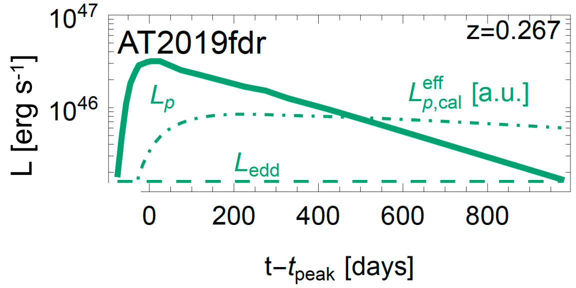
Magnetically confined protons interact over t_{dyn}, but not t_{fs}



AT2019fdr, model M-IR

Displacement over dynamical timescale (Bohm-like diffusion assumed):

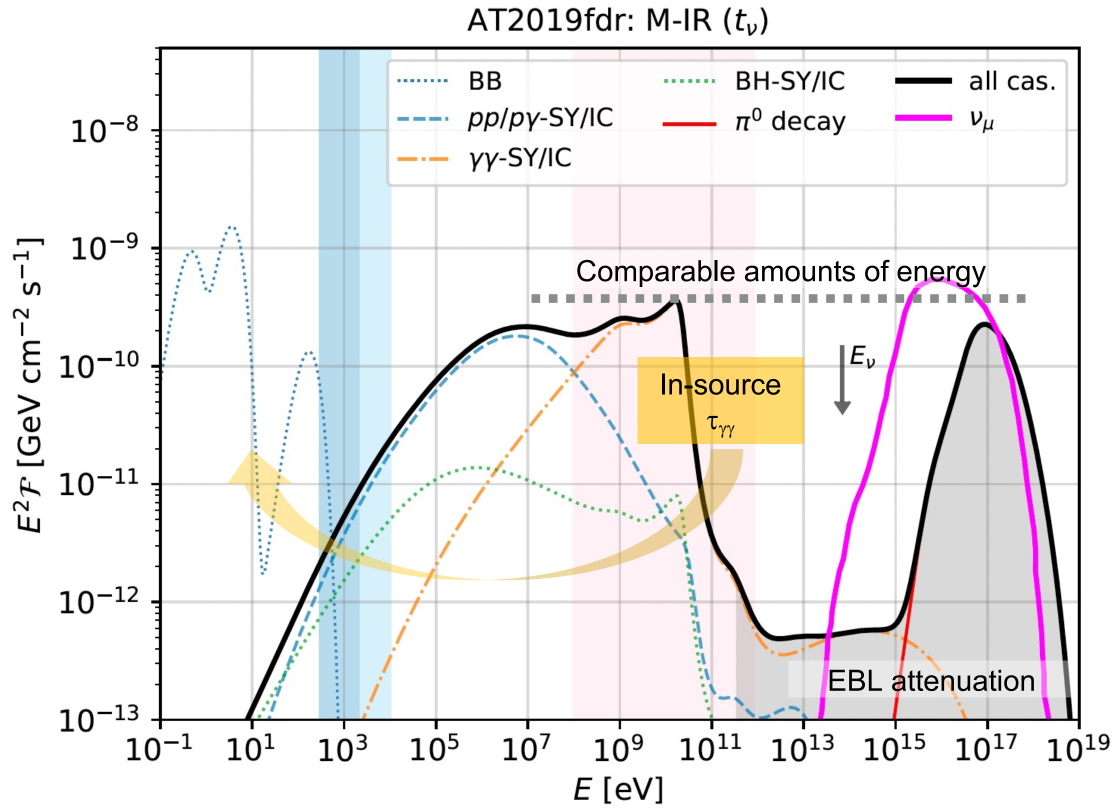
$$R \simeq \sqrt{D\, t_{p,\mathrm{diff}}} = 3\, 10^{15}\,\mathrm{cm} \left(\frac{E_p}{\mathrm{PeV}}\right)^{1/2} \left(\frac{B}{\mathrm{G}}\right)^{-1/2} \left(\frac{t_{\mathrm{dyn}}}{1000\,\mathrm{days}}\right)^{1/2}$$

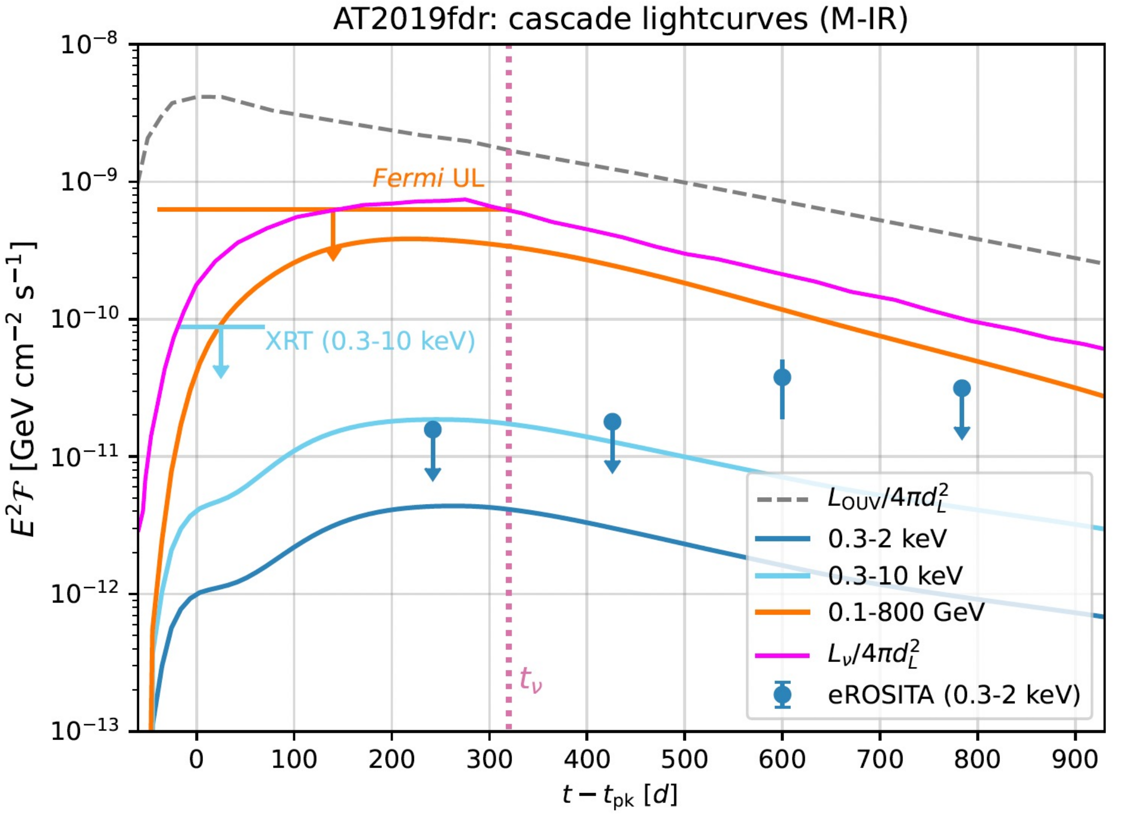


Winter, Lunardini, ApJ 948 (2023) 1, 42

An example with high proton energies – dust echo as target

- Gamma-ray and predicted neutrino signals tend to be correlated; here calorimetric system
- Too compact production regions excluded; limits predicted neutrino event rate to 0.01-0.1 events per TDE


AT2019fdr: M-IR (t_ν)


AT2019fdr: cascade lightcurves (M-IR)

Yuan, Winter, 2023 (ApJ accepted); based upon model in Winter, Lunardini, ApJ 948 (2023) 1, 42

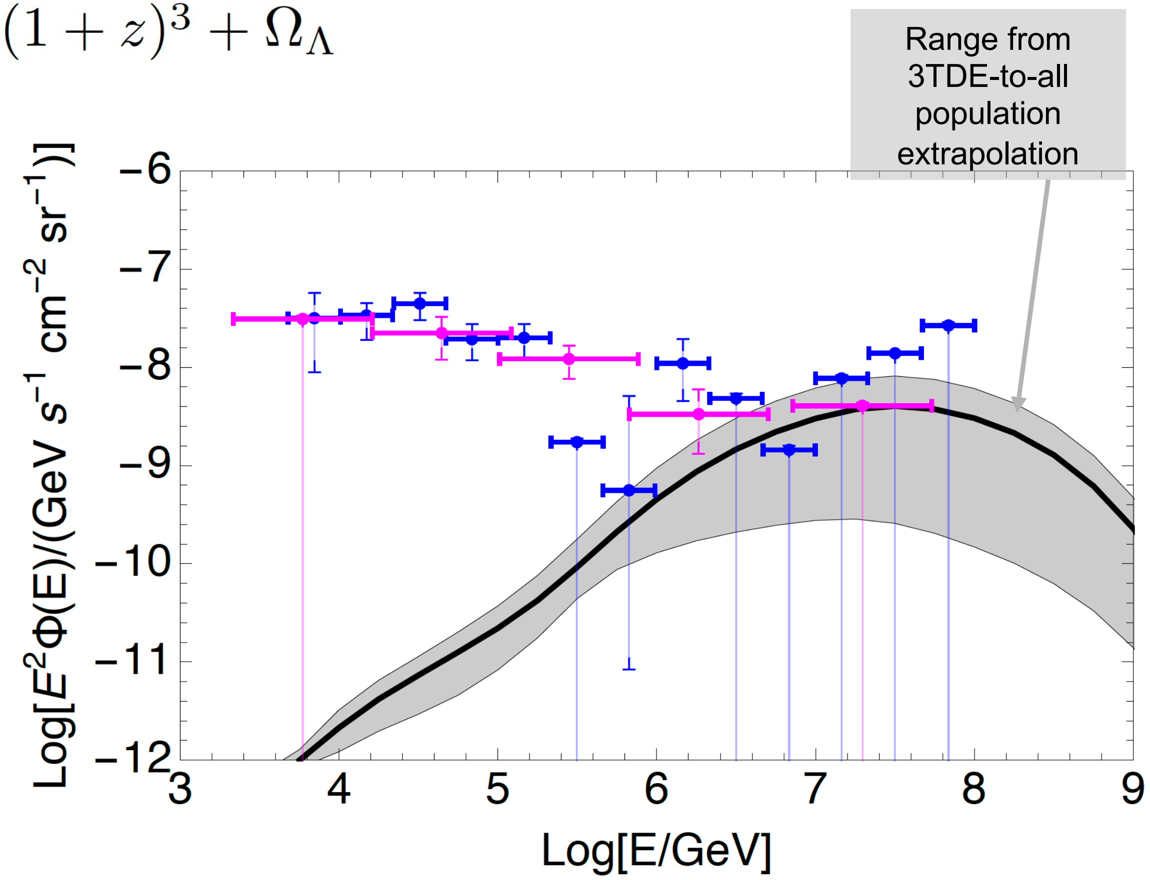
Expected diffuse neutrino flux

- Computation of diffuse neutrino flux:

$$\Phi_\alpha(E) = \frac{\eta\, c}{4\pi H_0} \int_{M_{\min}}^{M_{\max}} dM \int_0^{z_{\max}} dz\, \frac{\dot{\rho}(z, M) Q_\alpha(E(1+z), M)}{\sqrt{\Omega_M (1+z)^3 + \Omega_\Lambda}}$$

  η: Fraction of neutrino-emitting TDEs

- Might describe diffuse neutrino flux at the highest energies (i.e., only fraction of total neutrino flux)
- Assumption here: η=1% of all TDEs are efficient neutrino emitters
- Roughly consistent with the following hypotheses:
  - There is about one neutrino-TDE association observed per year
  - Neutrino-emitting TDEs and TDEs with strong dust echoes are the same populations
  - The fraction of neutrino-emitting and jetted (1% from **Nature 612 (2022) 430**) TDEs are the same

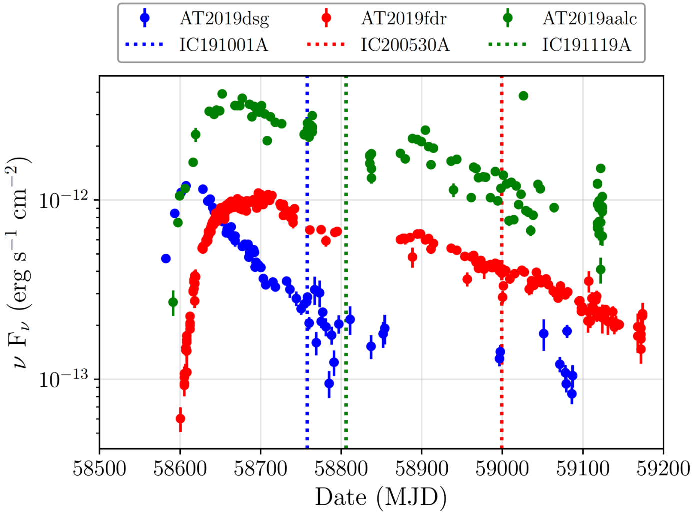

Range from 3TDE-to-all population extrapolation

Winter, Lunardini, ApJ 948 (2023) 1, 42; model M-IR

Summary and conclusions

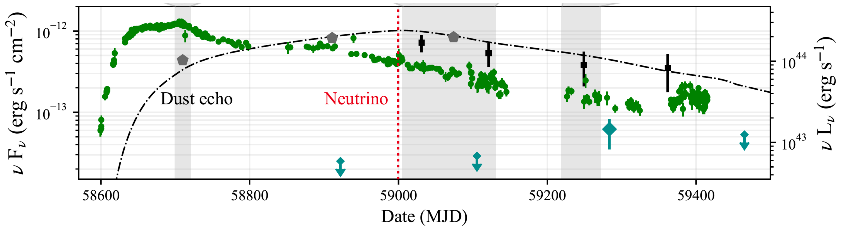
Neutrino-TDE associations

- Three candidates, moderate significance (3.7σ)
- Common features:
  - Detected in X-rays
  - Large BB luminosities
  - Strong dust echoes in IR
  - Neutrinos all delayed wrt peak by order 100 days



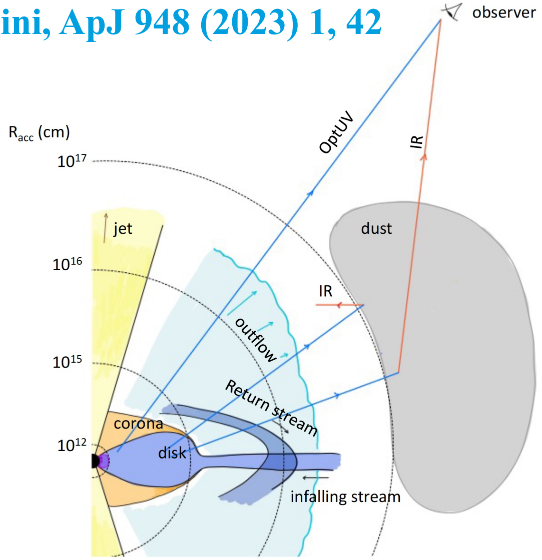
Simeon Reusch @ ECRS 2022

- Possible UHECR connection if dust echo is target for neutrino production



AT2019fdr, Reusch et al, PRL 128 (2022) 22

Winter, Lunardini, ApJ 948 (2023) 1, 42



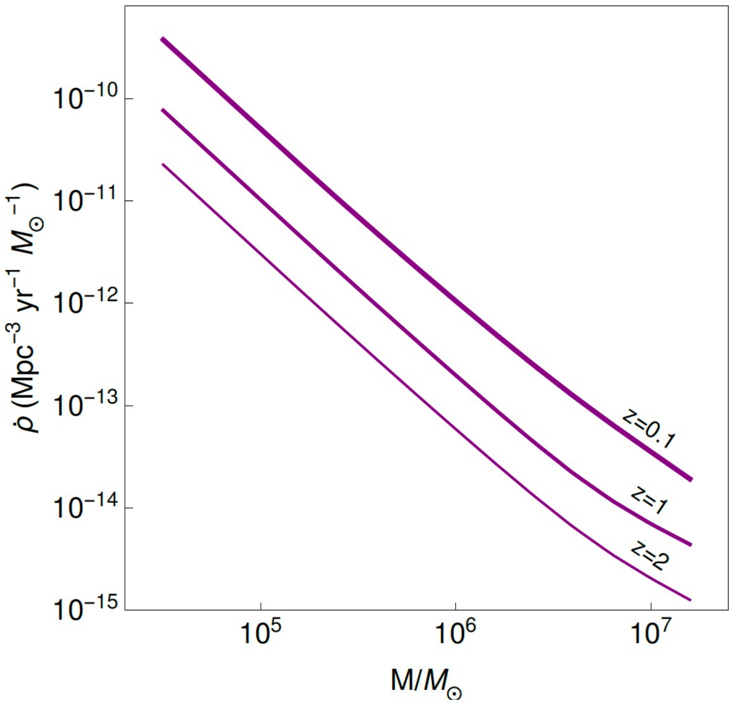
Models for the ν production

- Several possibilities for proton acceleration (disk, corona, jet, outflow, stream-stream collisions etc)
- **Energetics** is a challenge: either collimated outflow, or very efficient dissipation into non-thermal protons
- Origin of neutrino **time delay** may be
  - Related to size of system (e.g. outflow, dust echo)
  - Intrinsic from accelerator
  - From calorimetric effects
- **UHECR connection?**
  - Plausible if dust echo target. Have the sources of the UHECRs been seen here?
  - Could be related to jets (off-axis)
  - Self-consistent picture requires more work (ongoing)

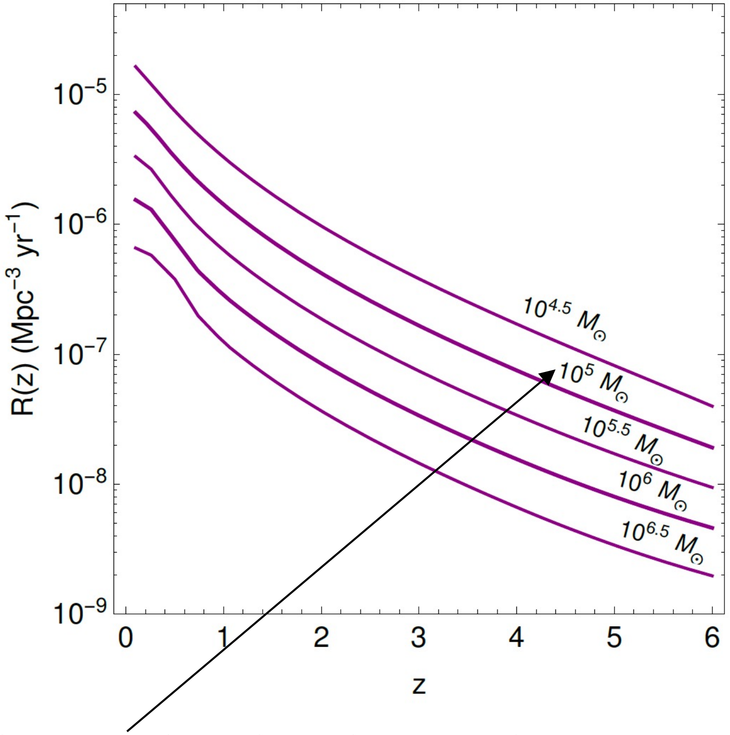
BACKUP

Notes on TDE demographics

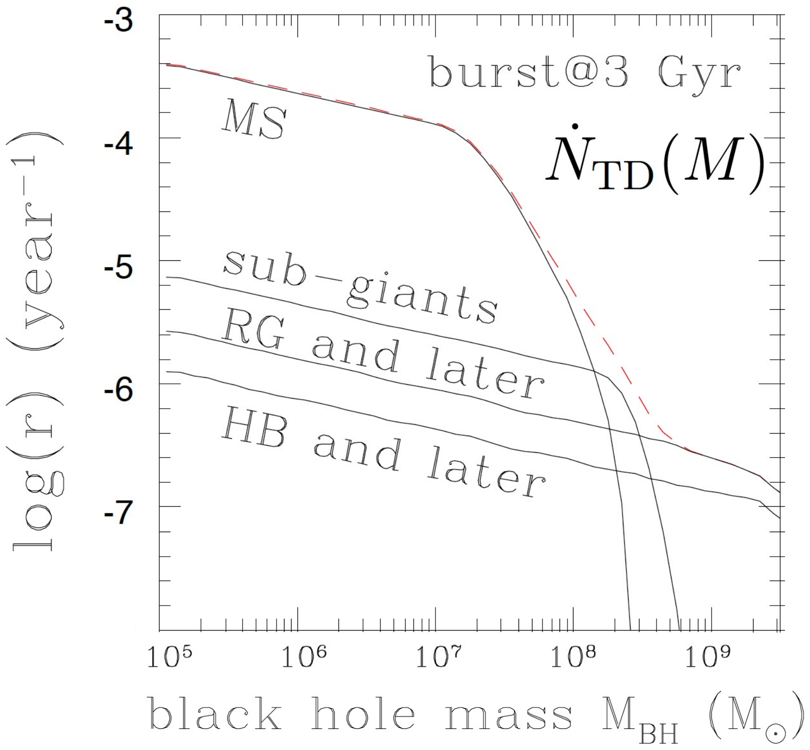
- **SMBH evolution**



- **Source evolution**



- **Dependence on progenitor**



$$\dot\rho(z,M) = \dot N_{\rm TD}(M)\, f_{\rm occ}(M)\, \phi(z,M)$$

Volumetric TDE rate

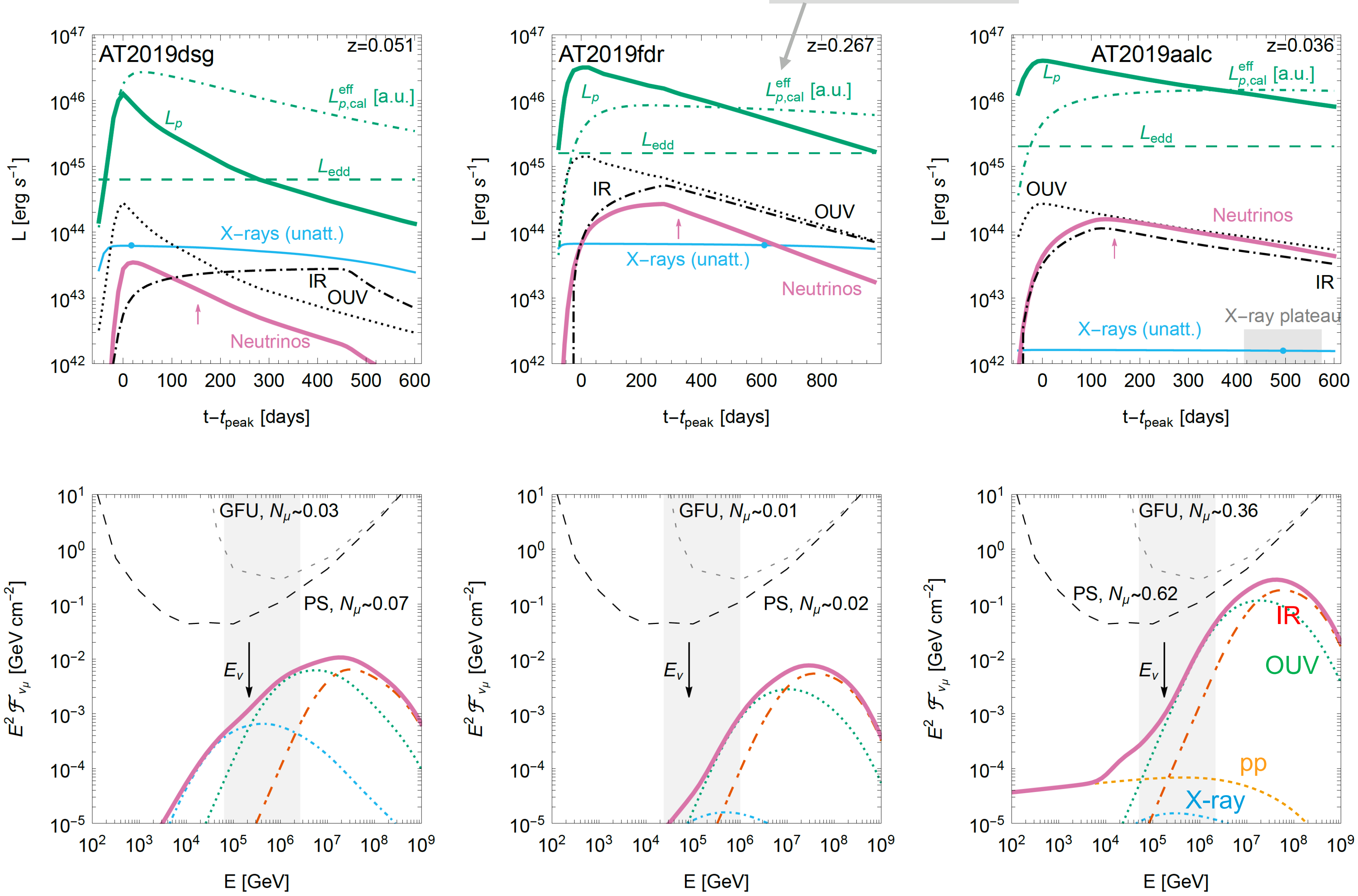
TDE rate per SMBH

Occup. factor. Threshold?

SMBH mass function. Strong M, z-dep.

Shankar et al, 2009; Konchanek 2016 (Fig. r.h.s.), Stone, Metzger, 2016; Lunardini, Winter, 2017 (Figs. l.h.s)

Theoretical results (M-IR)



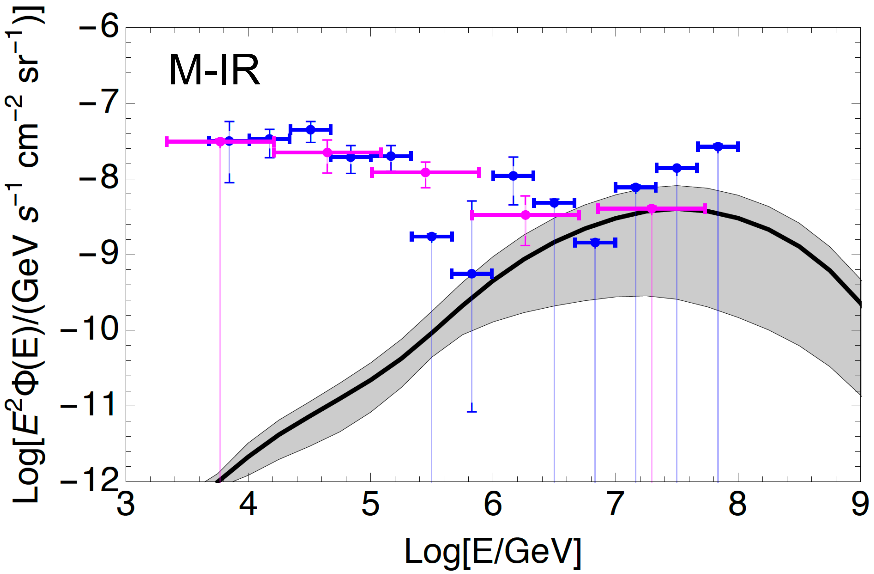
In-source proton density calorimetric!

Winter, Lunardini, ApJ 948 (2023) 1, 42

UHECR connection. Example: jetted TDEs

From jets pointing in our direction?

Diffuse neutrino flux M-IR (off-axis jets?)



Winter, Lunardini, arXiv:2205.11538

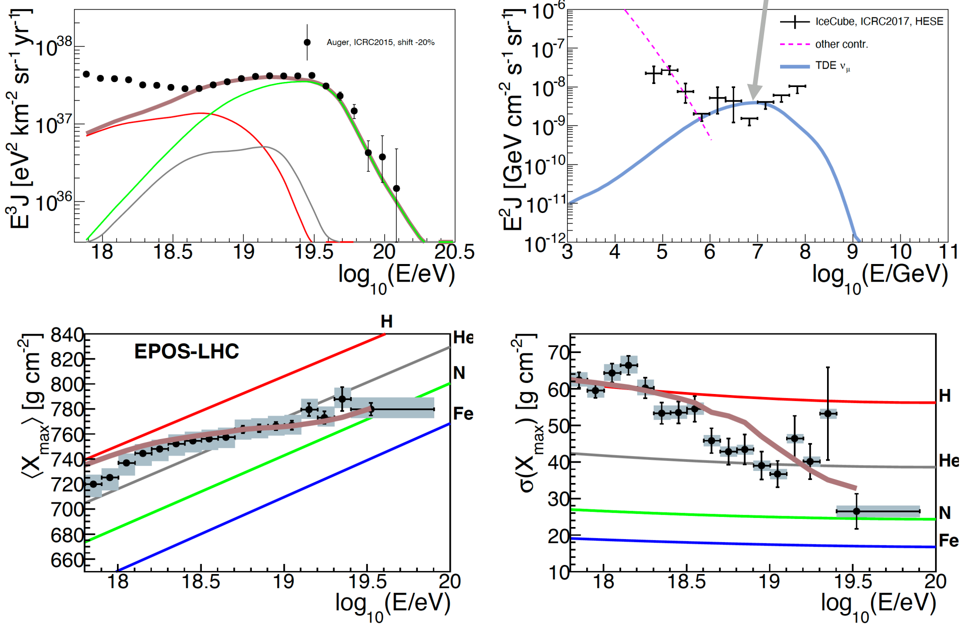
- Estimated UHECR output per TDE ~ 2 10^{52} erg in M-IR model; need local rate of about 5 $\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$

- Assume that off-axis jets accelerator. Rate of jetted TDEs (on-axis) is then R ~ 5 $\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$ / f_B ~ 0.02 Gpc yr^{-1}

Beaming ~ Γ^2

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

- Limitations:
  1. Jetted TDEs are rare R ~ $0.02_{-0.01}^{+0.04}$ $\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$ Nature 612 (2022) 430
  2. High L_X, L_ν (neutrino multiplet limits!)
  3. Injection composition – white dwarfs?
- But now: high neutrino-TDE rate observed, lower luminosity (L_{OUV}, L_ν)
- Models actually not so different from the UHECR perspective. Neutrino production in jet perhaps different.