Multi-messenger signals from Tidal Disruption Events

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HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

DESY

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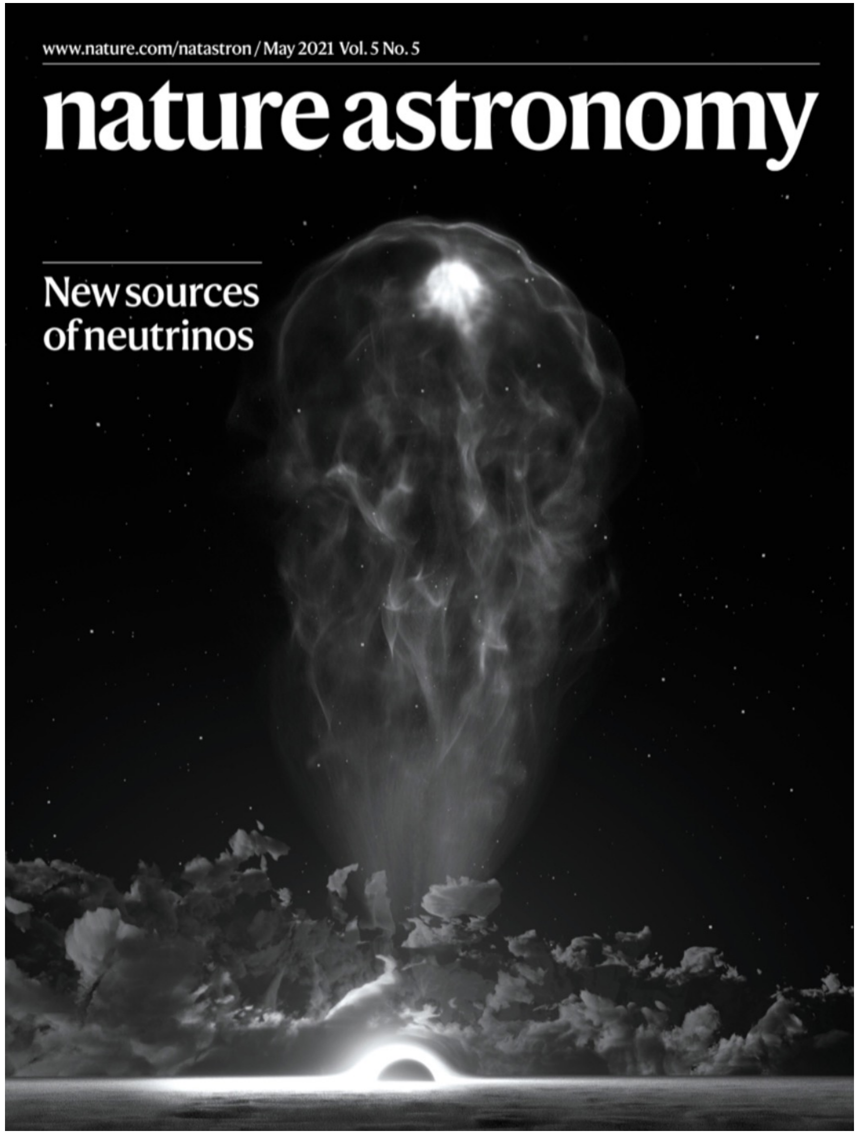


Introduction

Tidal Disuption Events – the electromagnetic picture

How to disrupt a star 101

Gravity

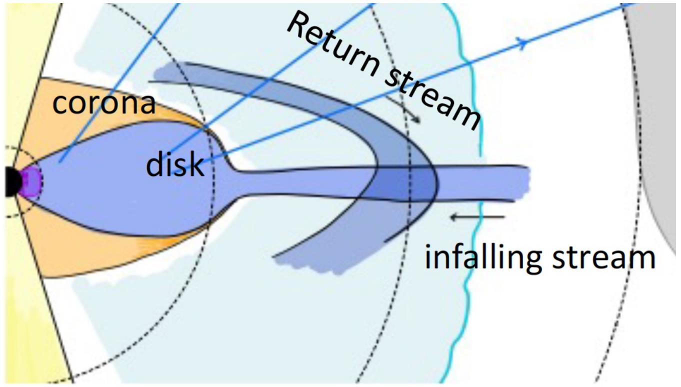
- Force on a mass element in the star (by gravitation) ~ force exerted by the SMBH at distance (tidal radius)

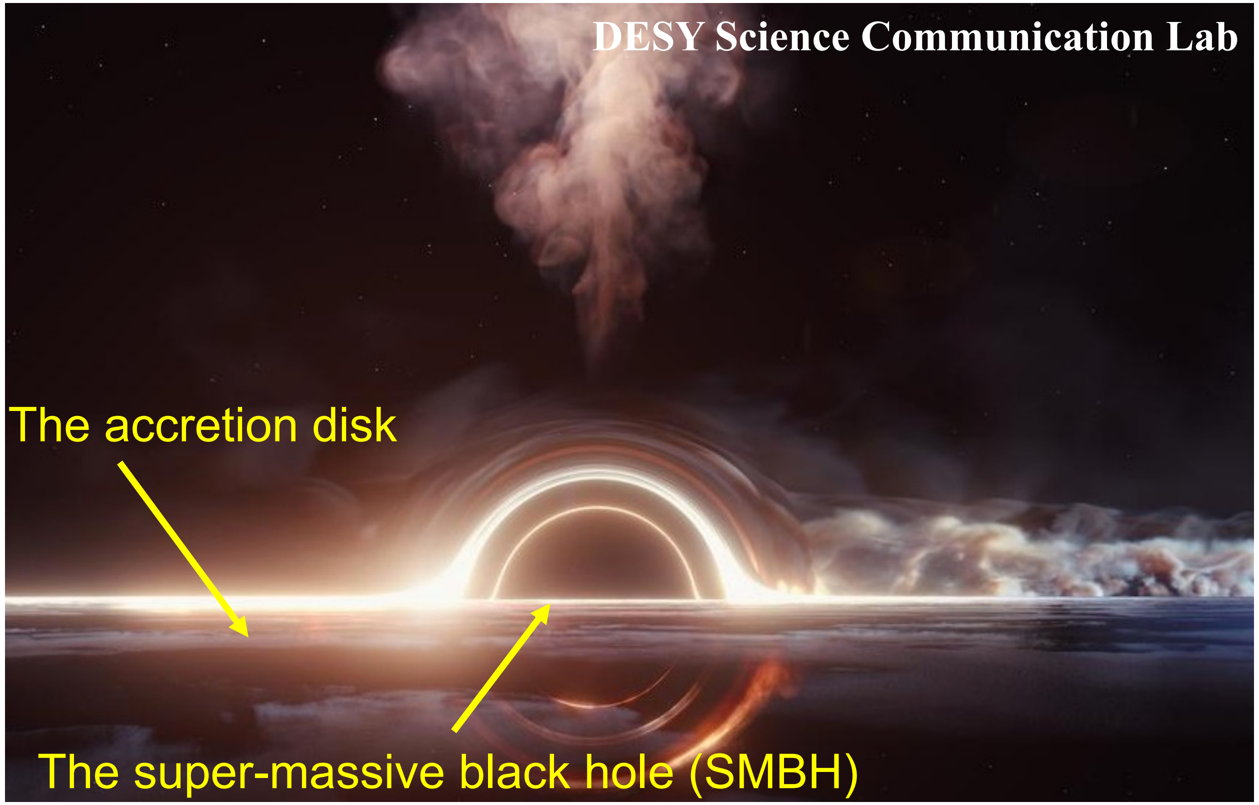
$$r_t = \left(\frac{2M}{m}\right)^{1/3} R \simeq 8.8 \times 10^{12}\,\mathrm{cm} \left(\frac{M}{10^6\,M_\odot}\right)^{1/3} \frac{R}{R_\odot} \left(\frac{m}{M_\odot}\right)^{-1/3}$$

- 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

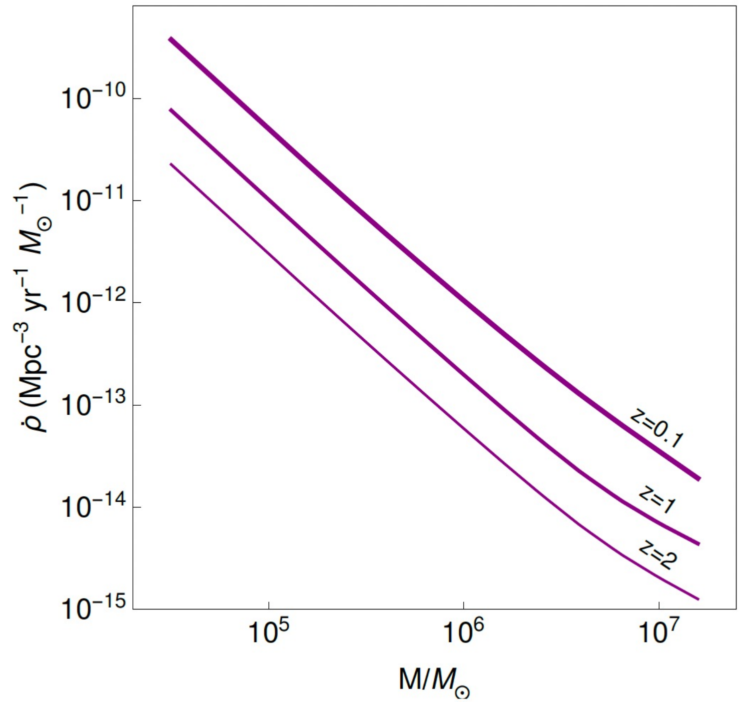
- Measure for the luminosity which can be re-processed from accretion through the SMBH: **Eddington luminosity**

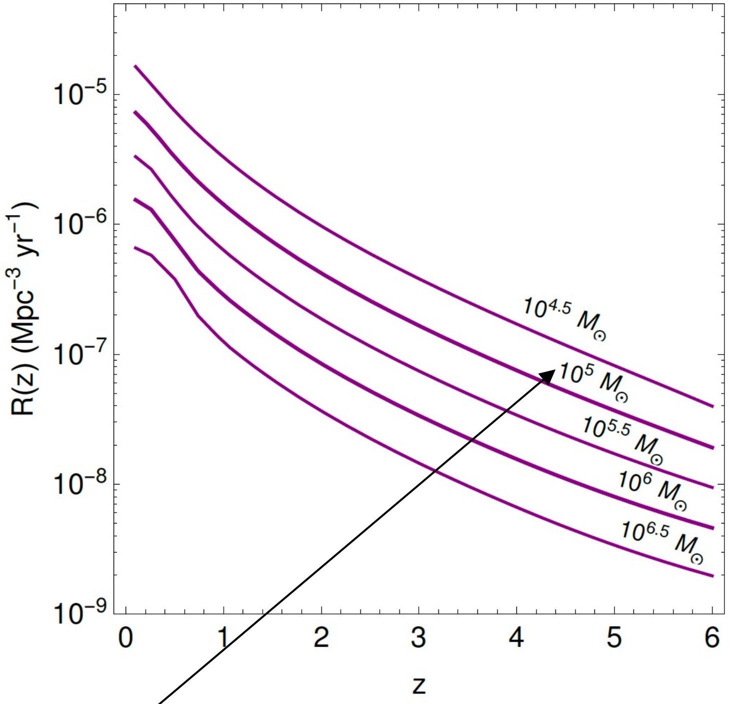
$$L_{\mathrm{Edd}} \simeq 1.3\ 10^{44}\ \mathrm{erg/s}\left(M/(10^6\ M_\odot)\right)$$

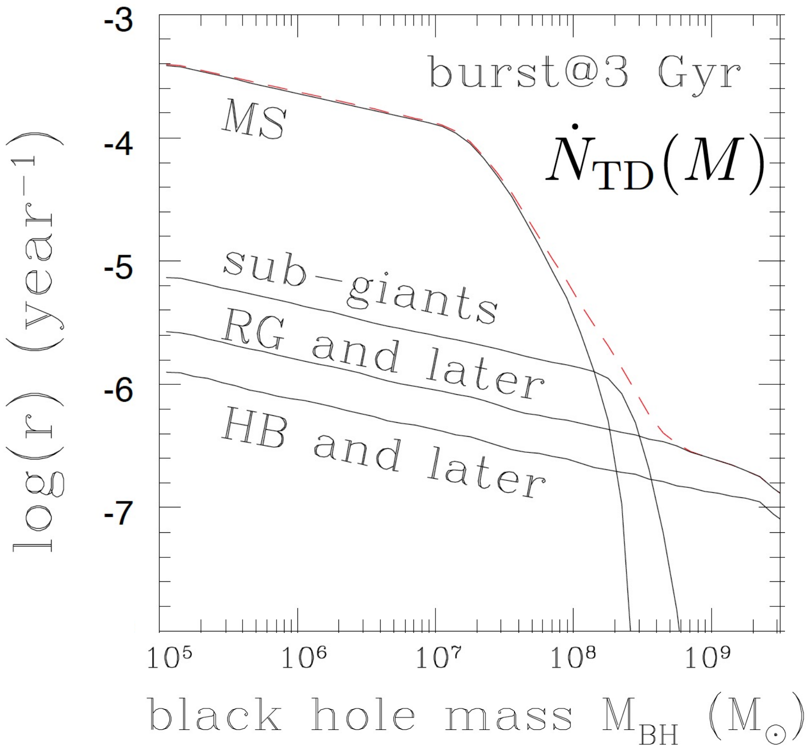
- Energy to be re-processed: about half of a star's mass E ~ 10^{54} erg (half a solar mass)
- Super-Eddington **mass fallback rate** expected at peak to process that amount of energy

Notes on TDE demographics

- **SMBH evolution**
- **Source evolution**
- **Dependence on progenitor**





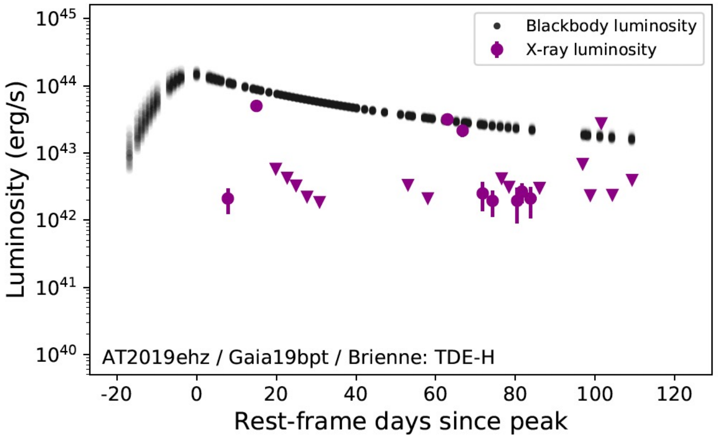


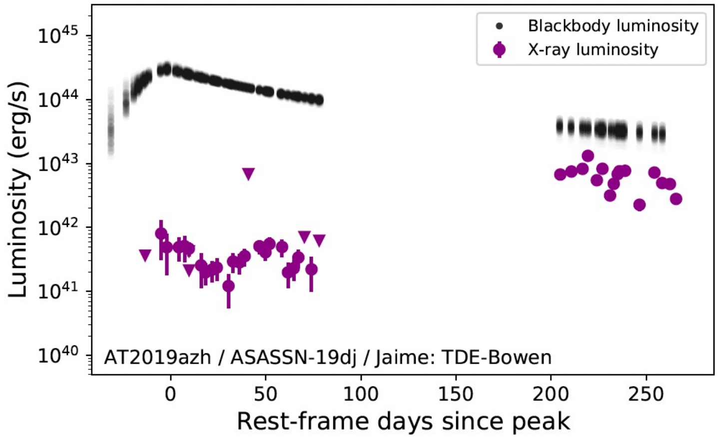
$$\dot{\rho}(z,M) = \dot{N}_{\rm TD}(M)\, f_{\rm occ}(M)\, \phi(z,M)$$

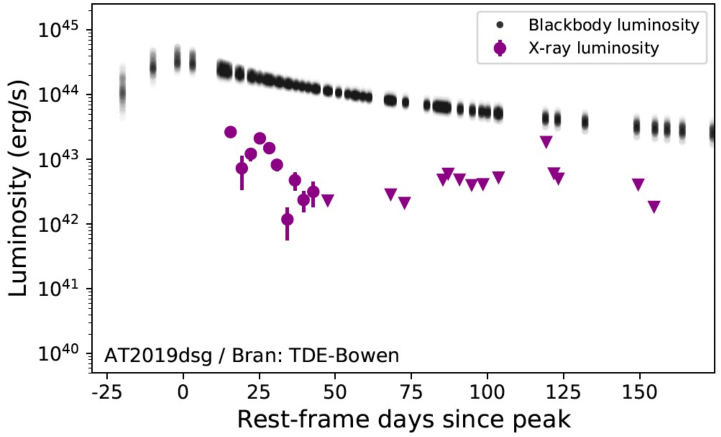
Volumetric TDE rate	TDE rate per SMBH	Occup. factor. Threshold?	SMBH mass function. Strong M, z-dep.

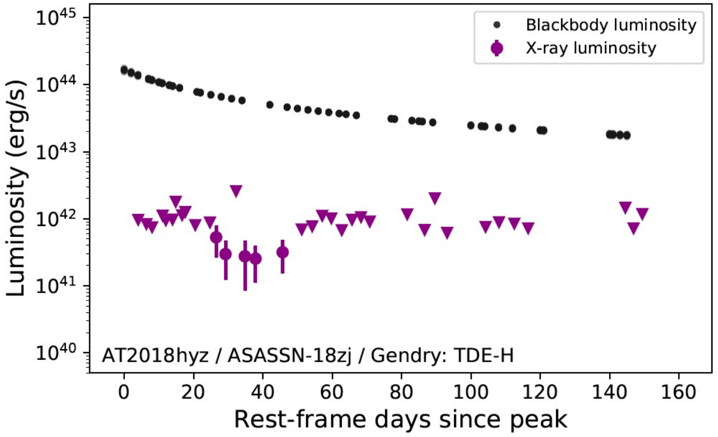
Shankar et al, 2009; Konchanek 2016 (Fig. r.h.s.), Stone, Metzger, 2016; Lunardini, Winter, 2017 (Figs. l.h.s)

TDE observations (general)



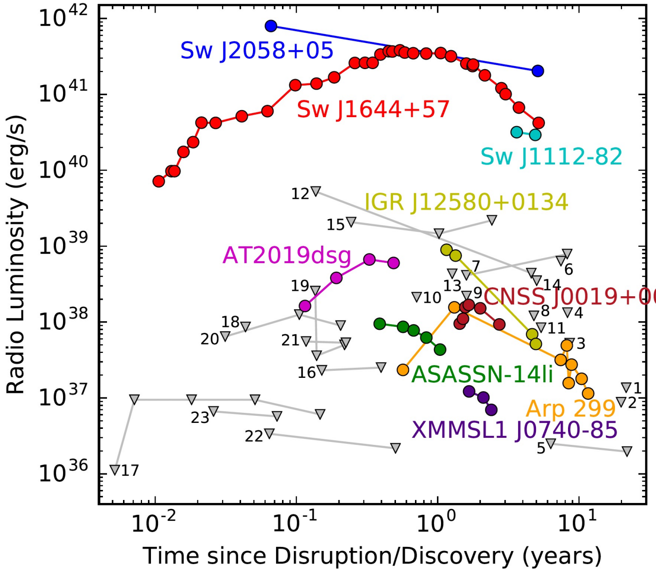






van Velzen et al, Astrophys. J. 908 (2021) 1, 4;
Alexander, van Velzen, Horesh, Zauderer, Space Sci. Rev. 216 (2020) 5, 81

- **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



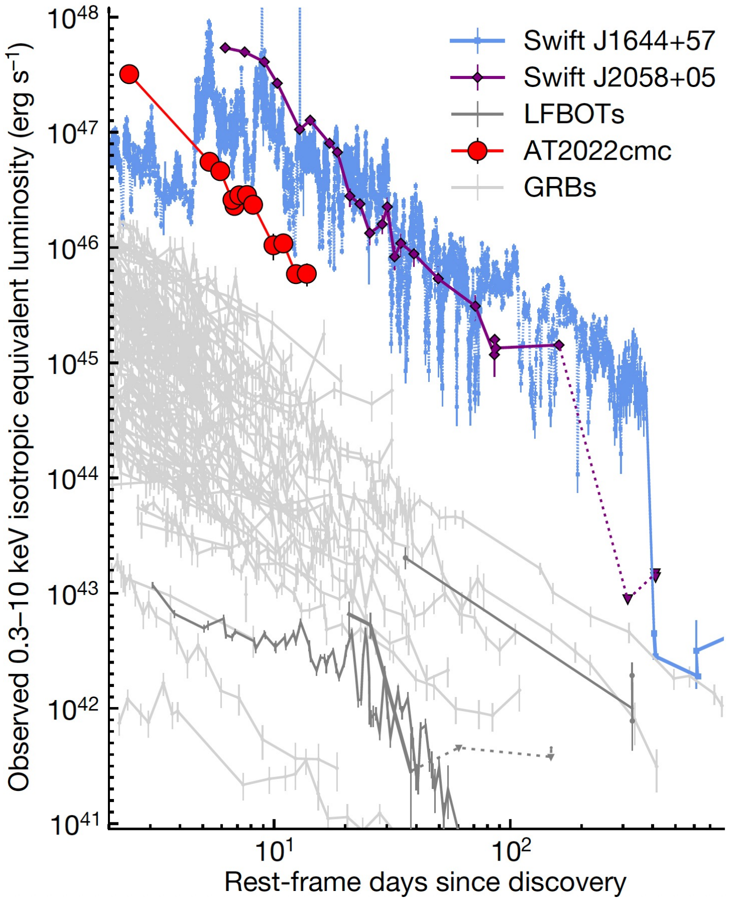
Relat. jets?

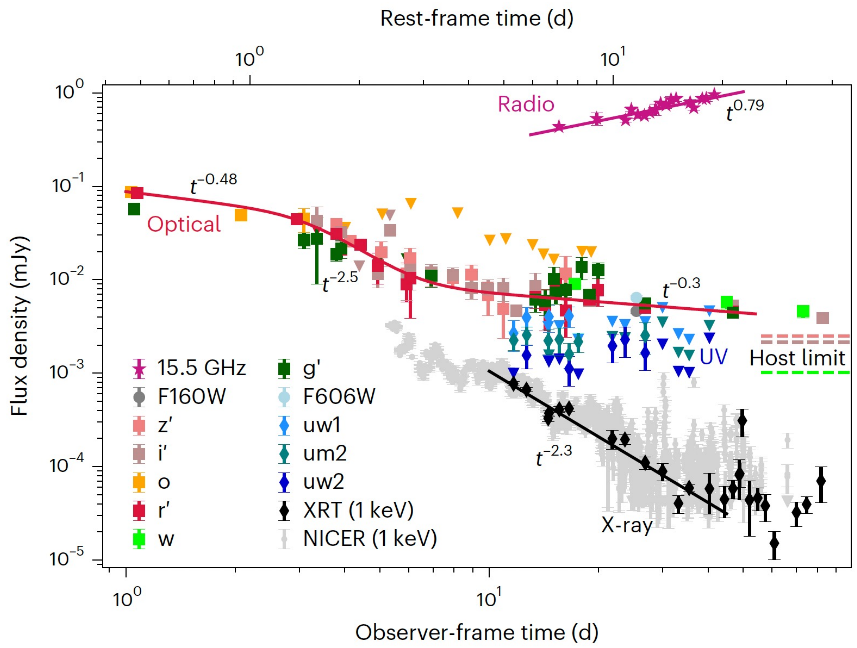
Non-relat. outflows?

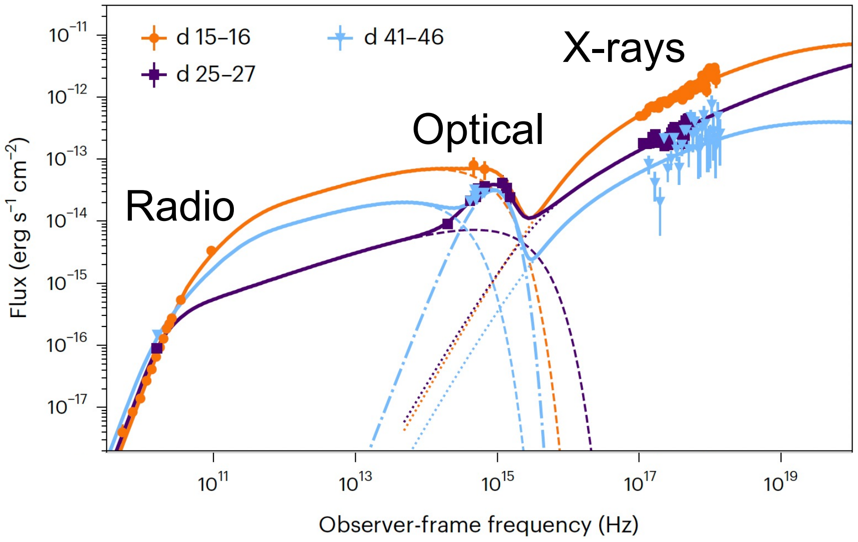
Jetted TDEs

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)





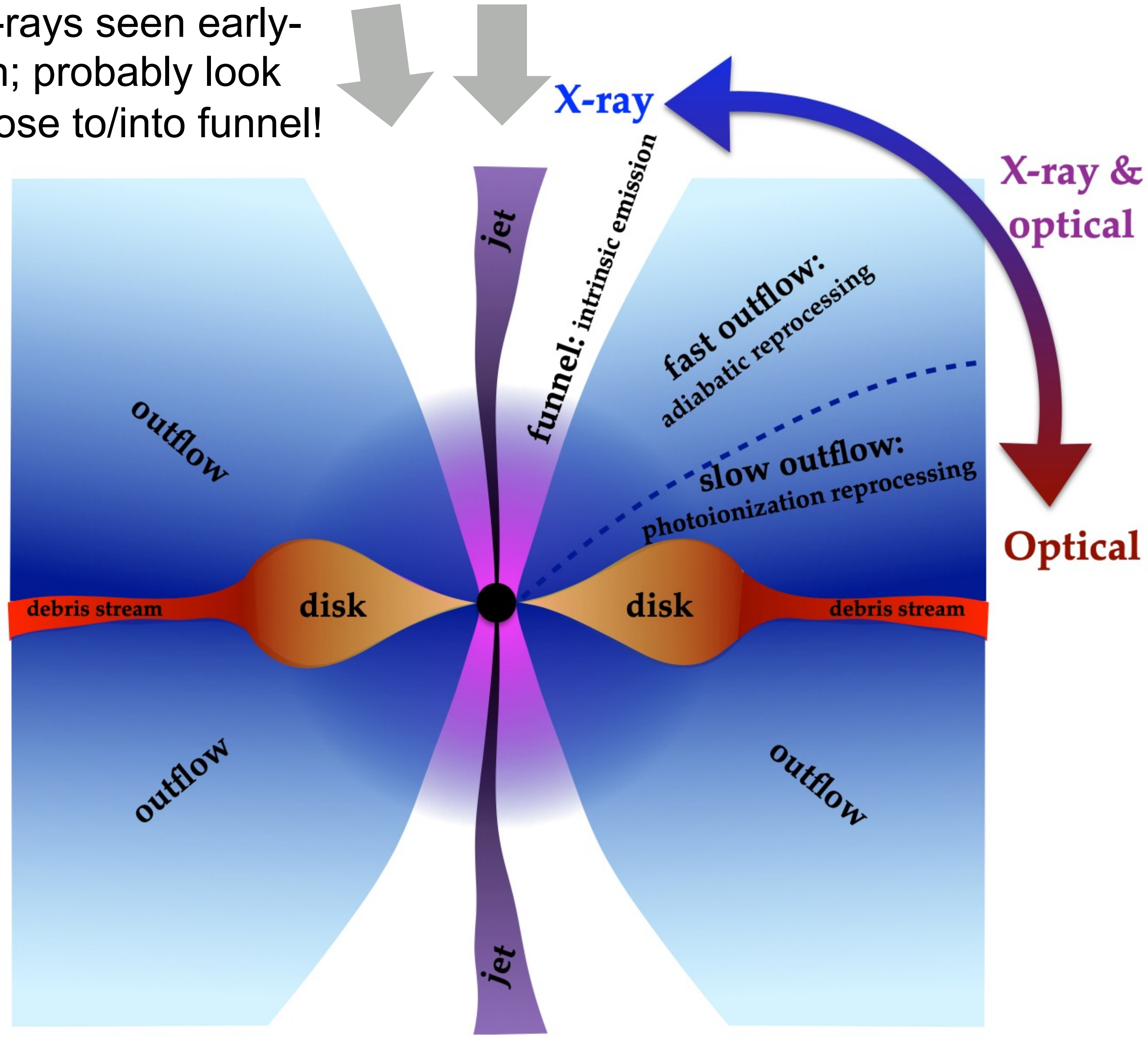


Andreoni et al, Nature 612 (2022) 7940, 430; Pasham et al, Nature Astron. 7 (2023) 1, 88

A TDE unified model

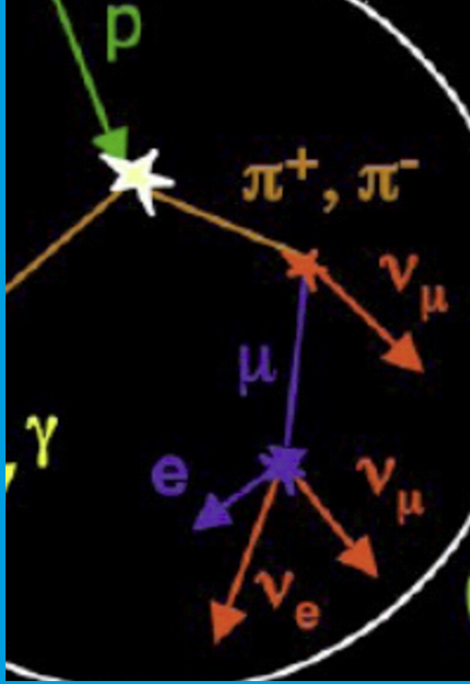
- Supported by MHD simulations; here $M_{SMBH} = 5\ 10^6\ M_\odot$
- A jet is optional in that model, depending on the SMBH spin
- Observations from model:
  - Average mass accretion rate $\dot{M} \sim 10^2 L_{\rm Edd}$
  - ~ 20% of that into jet
  - ~ 3% into bolometric luminosity
  - ~ 20% into outflow
  - 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

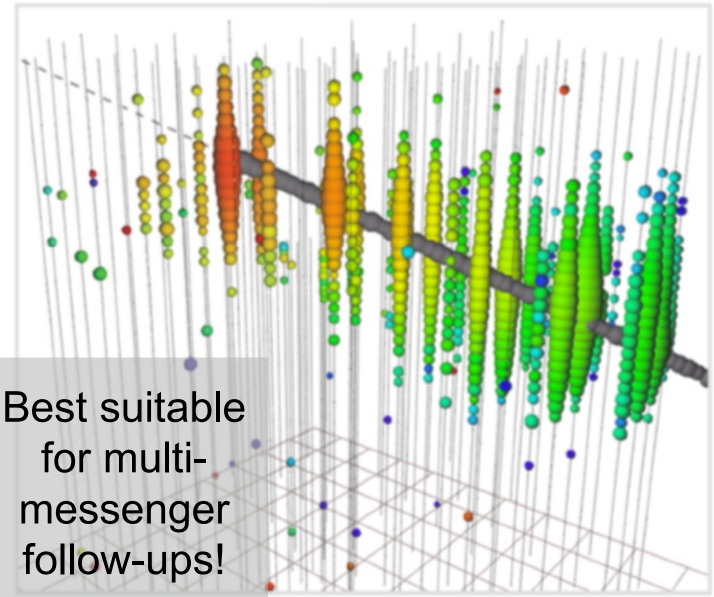
Neutrinos from TDEs



Observations

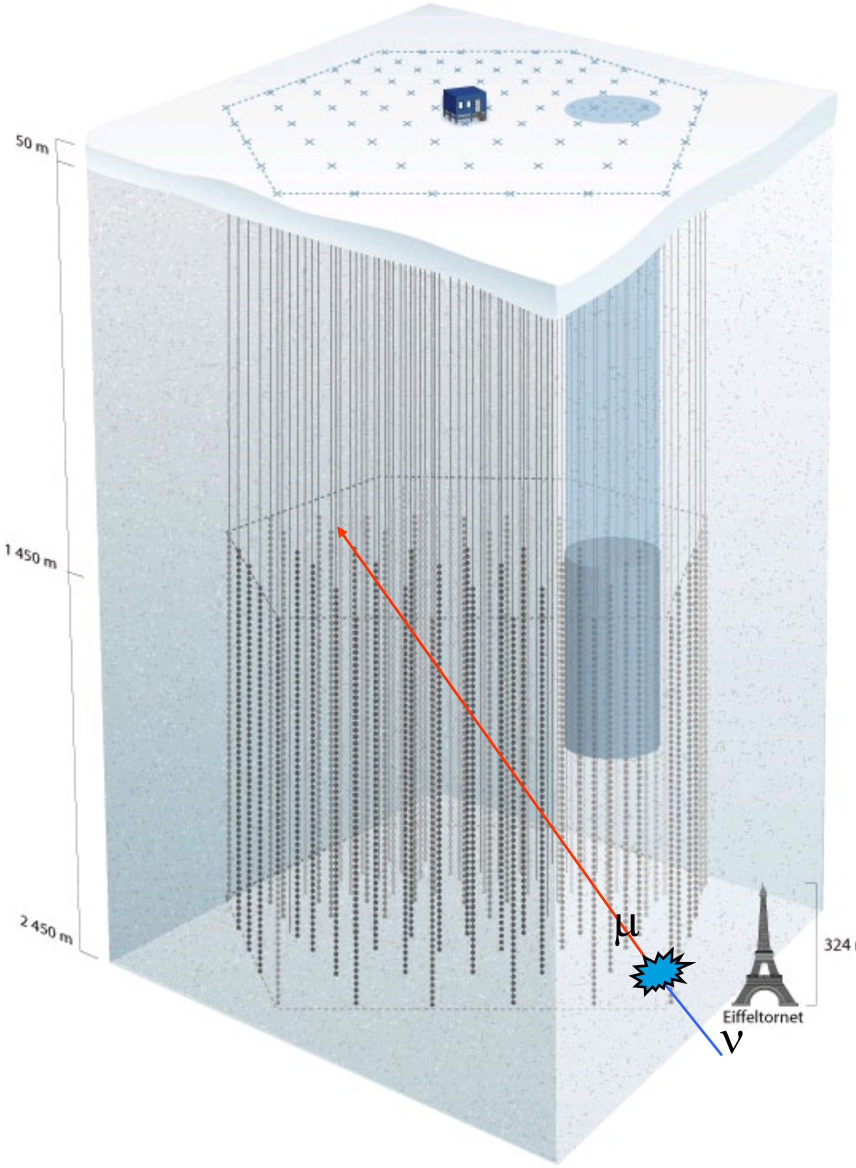
Observing TeV-PeV neutrinos with IceCube

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



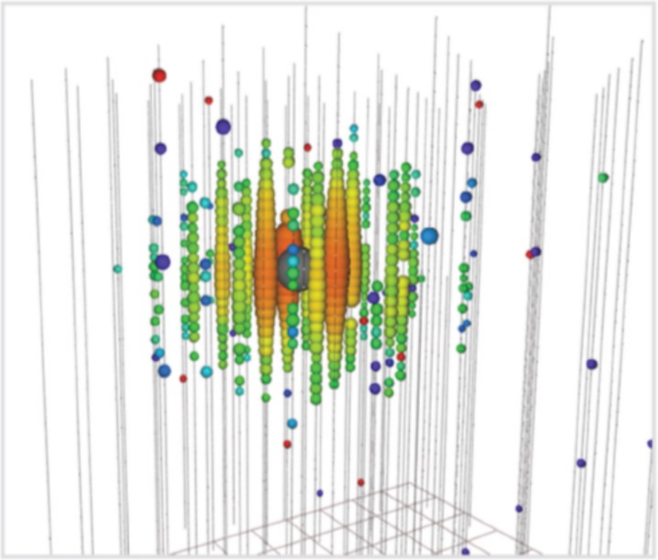
Best suitable for multi-messenger follow-ups!

Better directional info



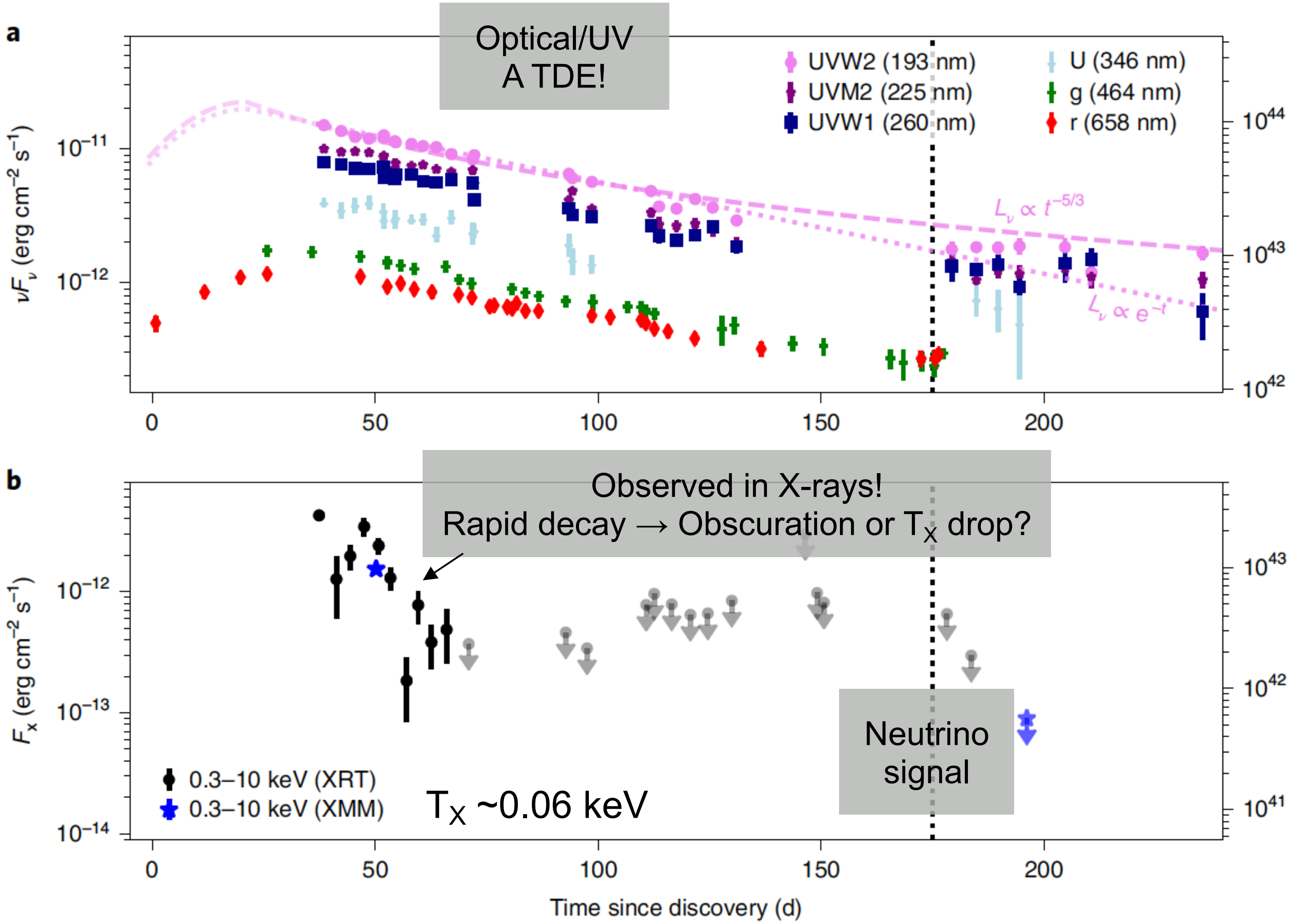
IceCube http://icecube.wisc.edu/

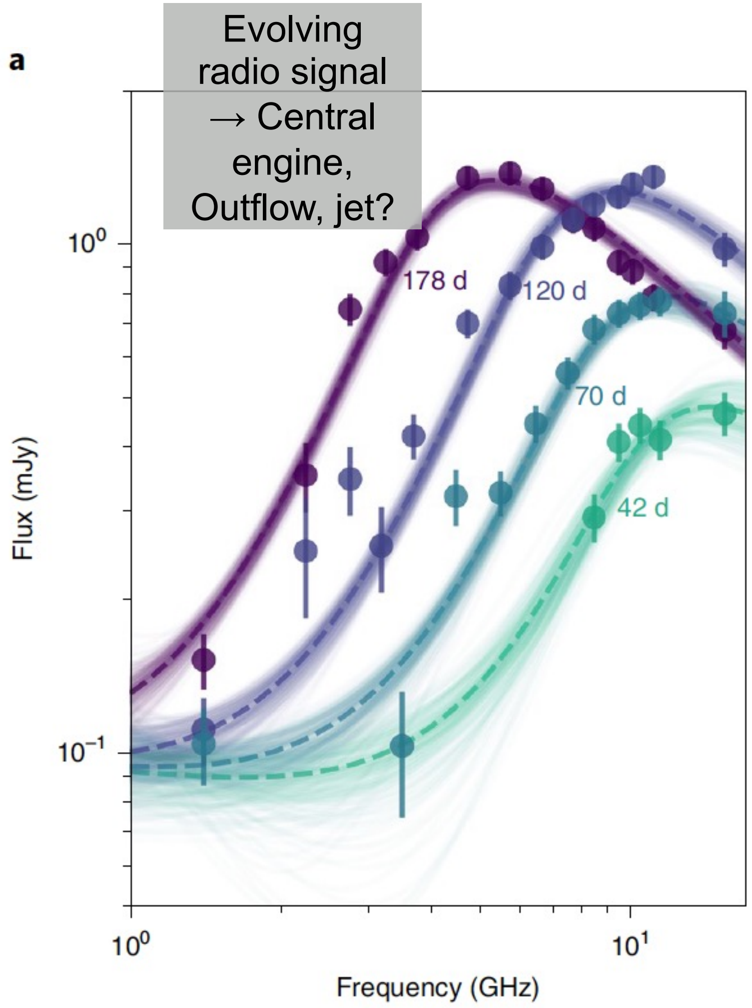
Cascade (shower):
- From ν_e
- From ν_τ
- From ν_e, ν_μ, ν_τ NC interactions



Better energy info

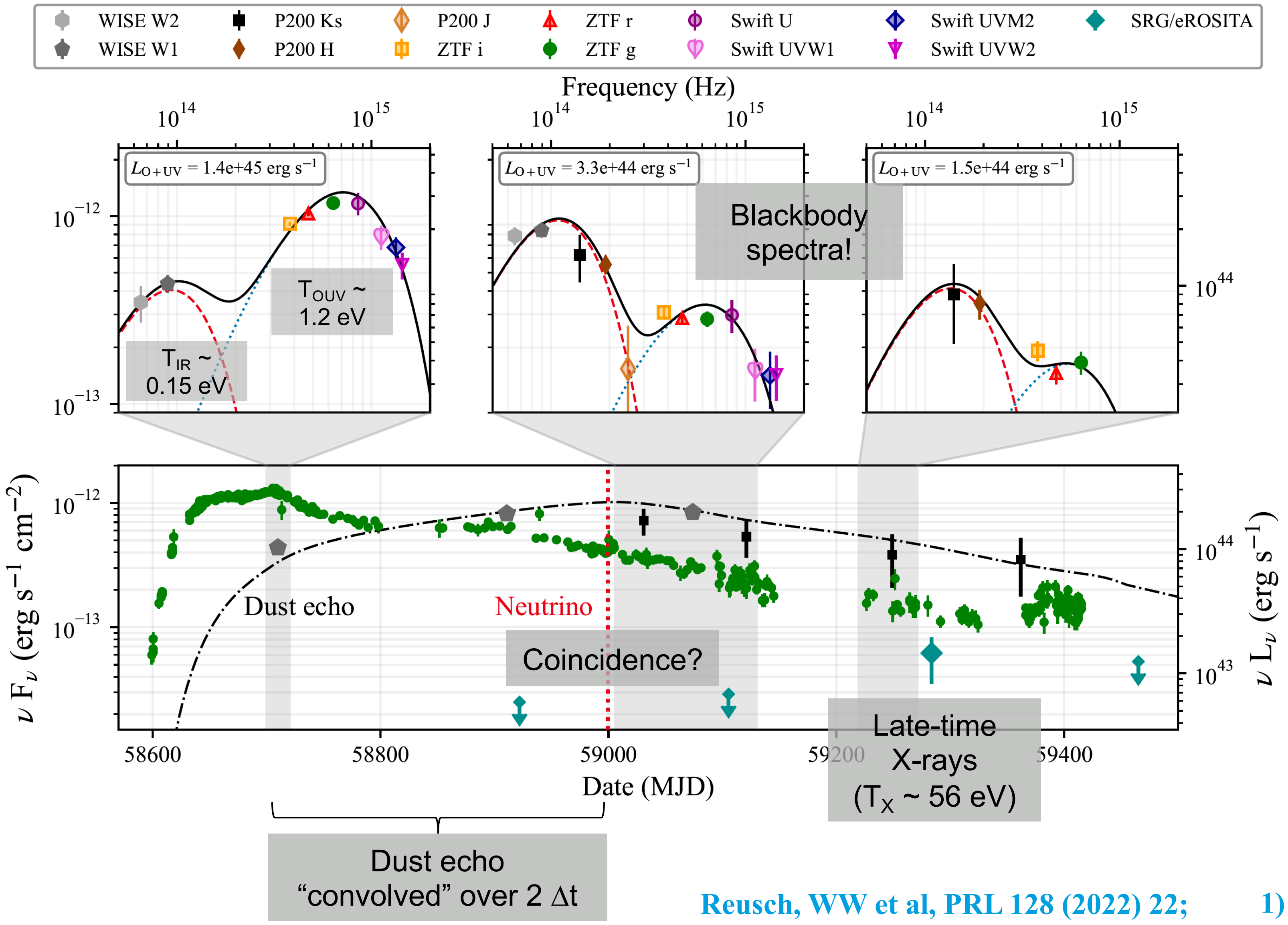
A neutrino from AT2019dsg



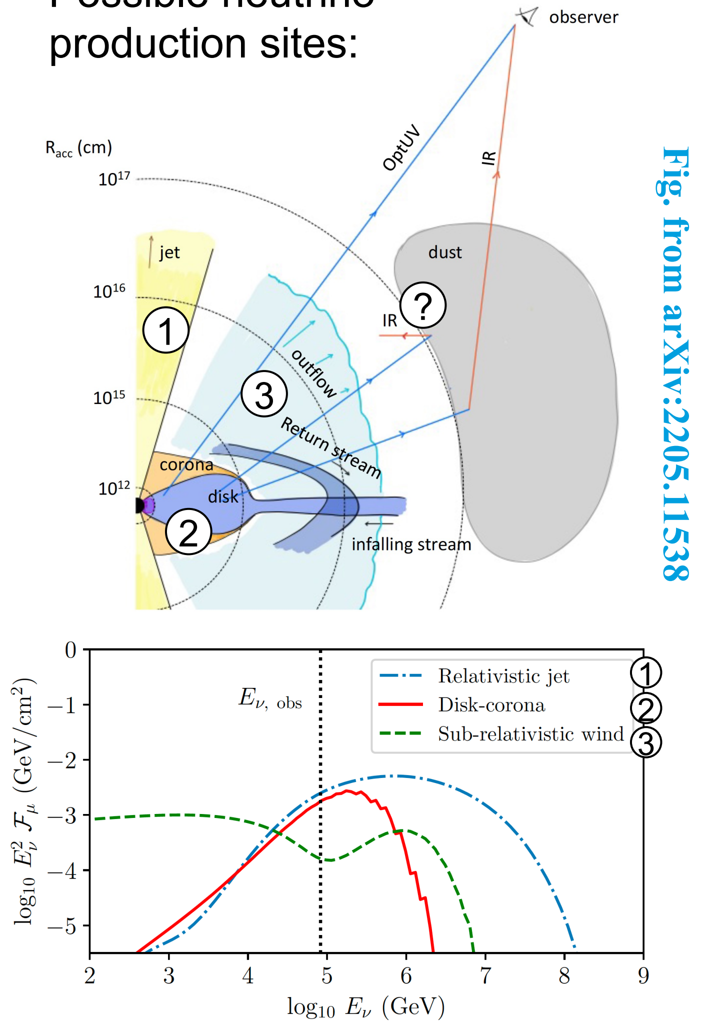


Stein et al, Nature Astronomy 5 (2021) 510

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:



Reusch, WW 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

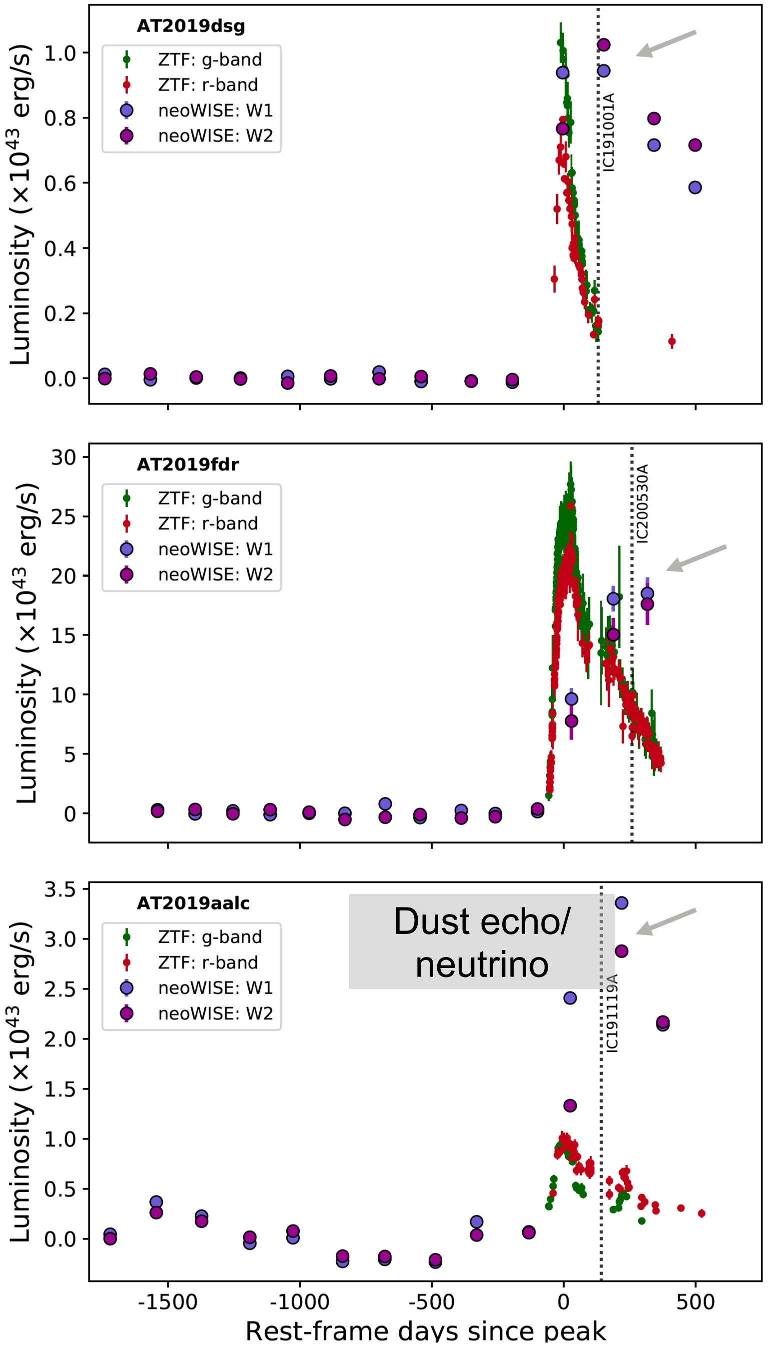
… as third neutrino-TDE association

Analysis

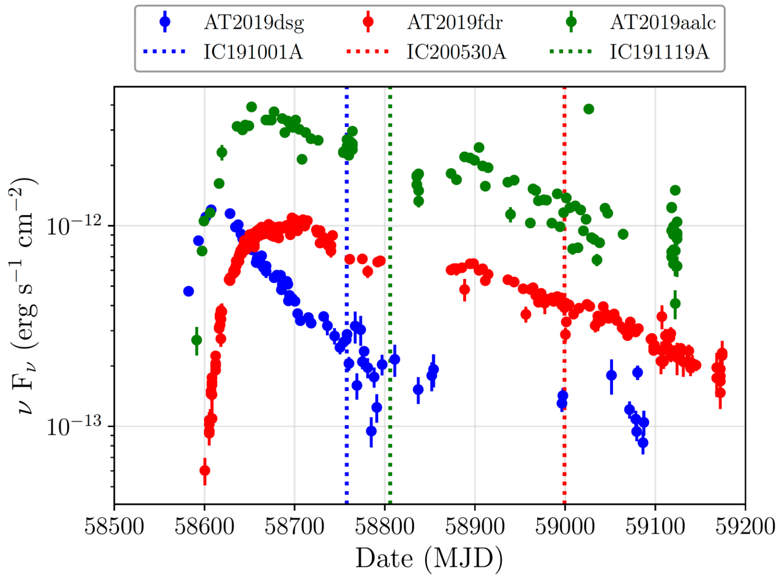
- Selected a sample of 1732 accretion flares with properties similar to AT2019dsg and AT2019fdr (dust echo)
- Found another TDE candidate: AT2019aalc with a similar neutrino time delay
- Overall significance: 3.7σ
  van Velzen et al, arXiv:2111.09391

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



van Velzen et al, arXiv:2111.09391



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)

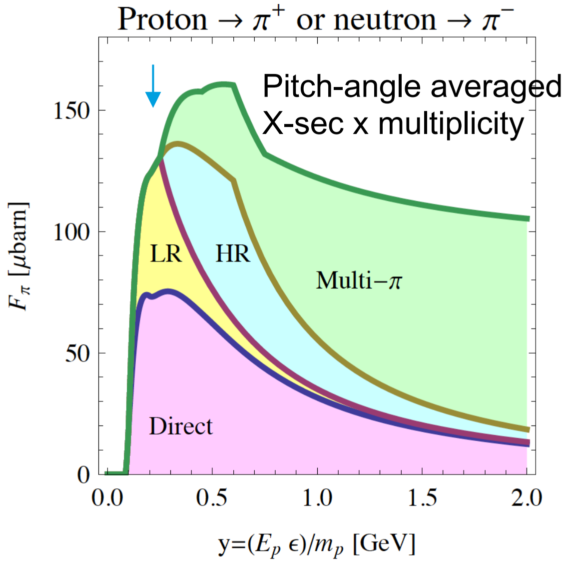
Theoretical modeling

Neutrinos from photo-pion production

- 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 for C.O.M. energy):

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

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

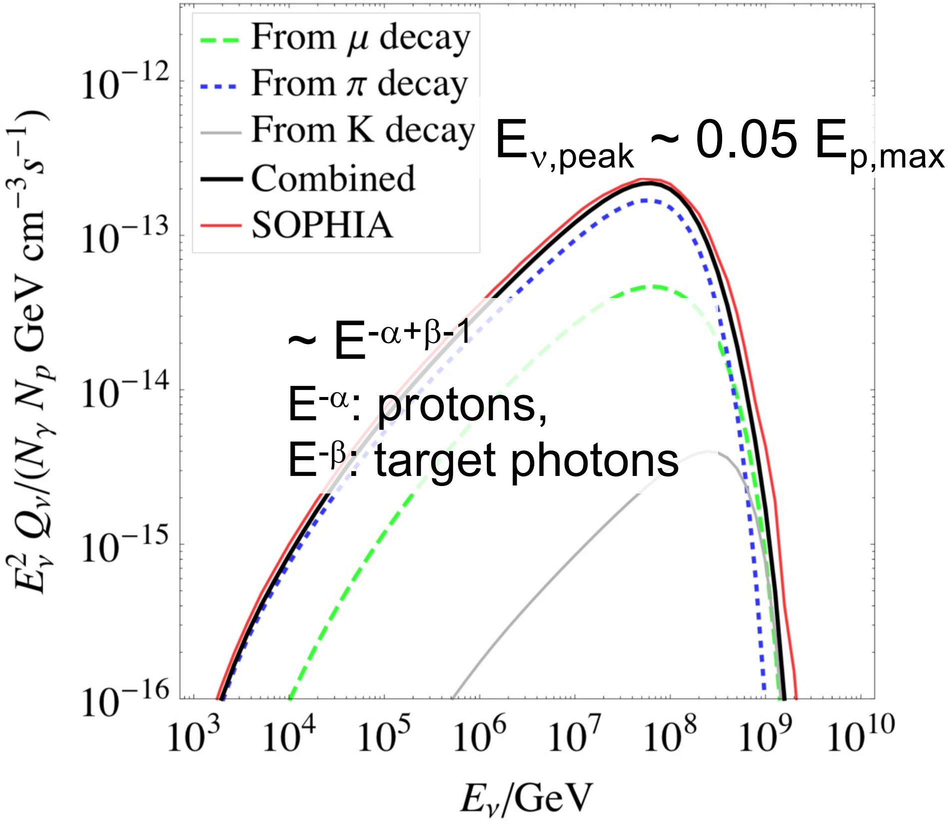


- Photons from pion decay:

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

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

Neutrino spectrum (example)



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

Requirements: Energetics

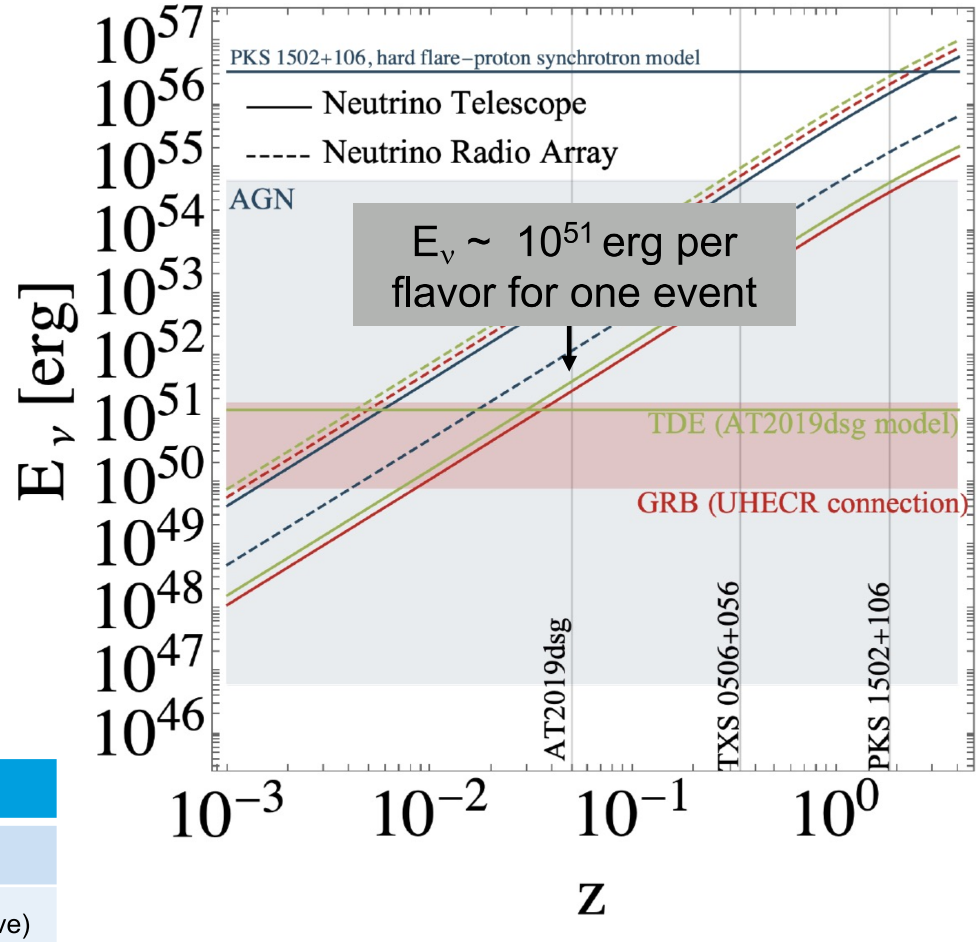
Example: AT2019dsg (similar arguments apply to others)

- Upper limit for average neutrino luminosity (4π solid angle emission, for pp similar):
  $L_\nu \sim 25\ L_{edd}$ x f_{comp} x ε_{acc} x $\tau_{p\gamma}$ x 1/8 **<~ 0.1 L_{edd}**
  - L_{edd}: Average mass accretion rate
  - f_{comp}: Fraction in outflow, BB, jet, ... (0.03-0.2?)
  - ε_{acc}: Accelerated fraction into non-thermal > PeV (!) energy protons (<< 0.2?)
  - $\tau_{p\gamma}$: Optical thickness <= 1, but typically << 1
  - 1/8: Per flavor
- Yields $E_\nu \sim$ 200 days x 0.1 $L_{edd} \sim\ 2\ 10^{50}$ erg ($M_{SMBH}/10^6\ M_\odot$) $\rightarrow$ 0.2 events for $M_{SMBH} \sim 10^6\ M_\odot$ →
- **Conclusion:**
  either $M_{SMBH} >> 10^6\ M_\odot$ and super-efficient energy conversion,
  or the outflow must be collimated with $\theta << 1$ such that $L_\nu \rightarrow L_\nu / \theta^2$

Estimates for SMBH mass

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

(figure for all flavors, typical spectral shapes)

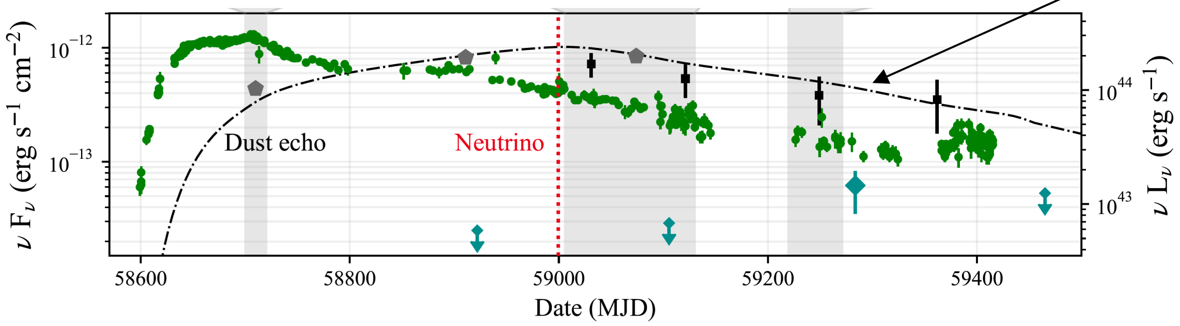


Fiorillo, van Vliet, Morisi, Winter, arXiv:2103.16577

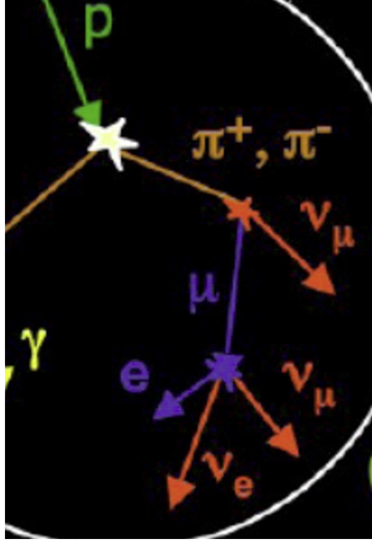
- **However:** small neutrino rate perhaps expected from Eddington bias, non-observation of electromagn. cascade?

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

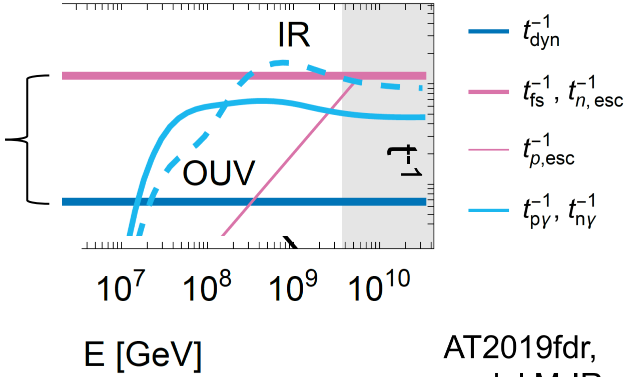


From: Reusch et al, PRL 128 (2022) 22



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

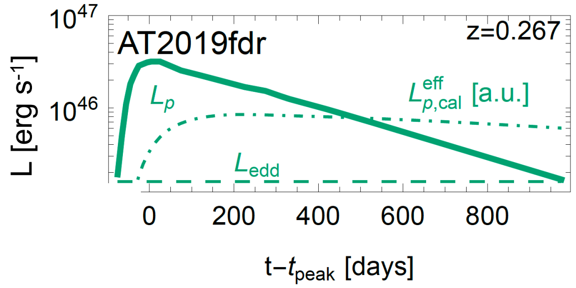
Magnetically confined protons interact over t_{dyn}, but not t_{fs}



AT2019fdr, model M-IR

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

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

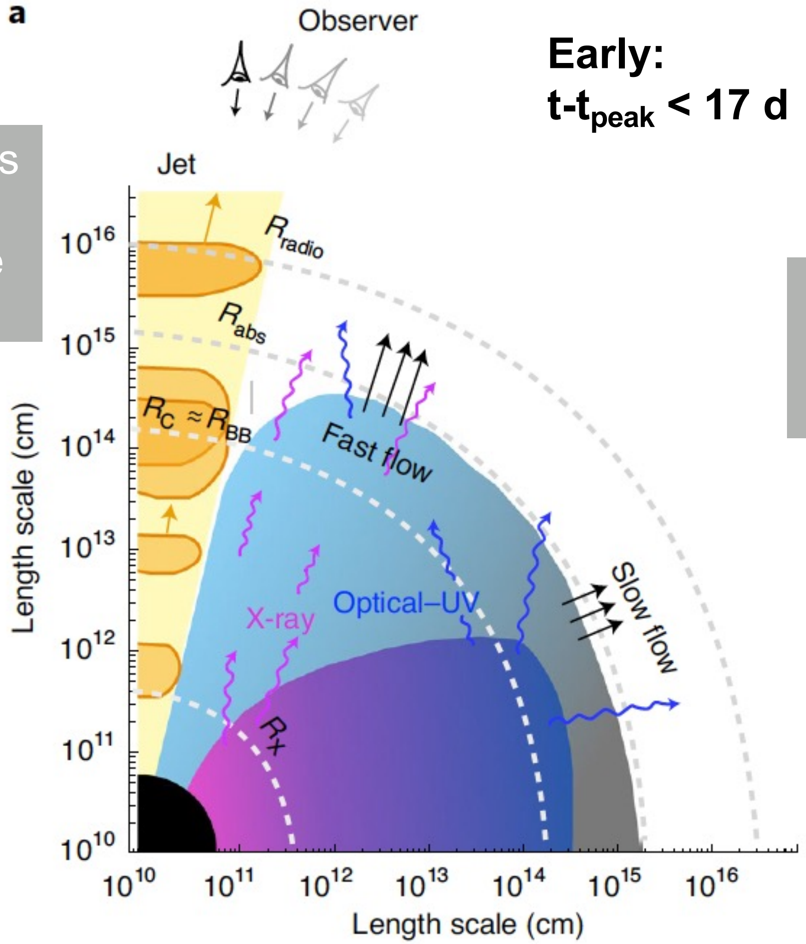


Winter, Lunardini, arXiv:2205.11538

Example: A jetted concordance scenario for AT2019dsg

... based on Dai et al TDE unified model. Addresses energetics issue!

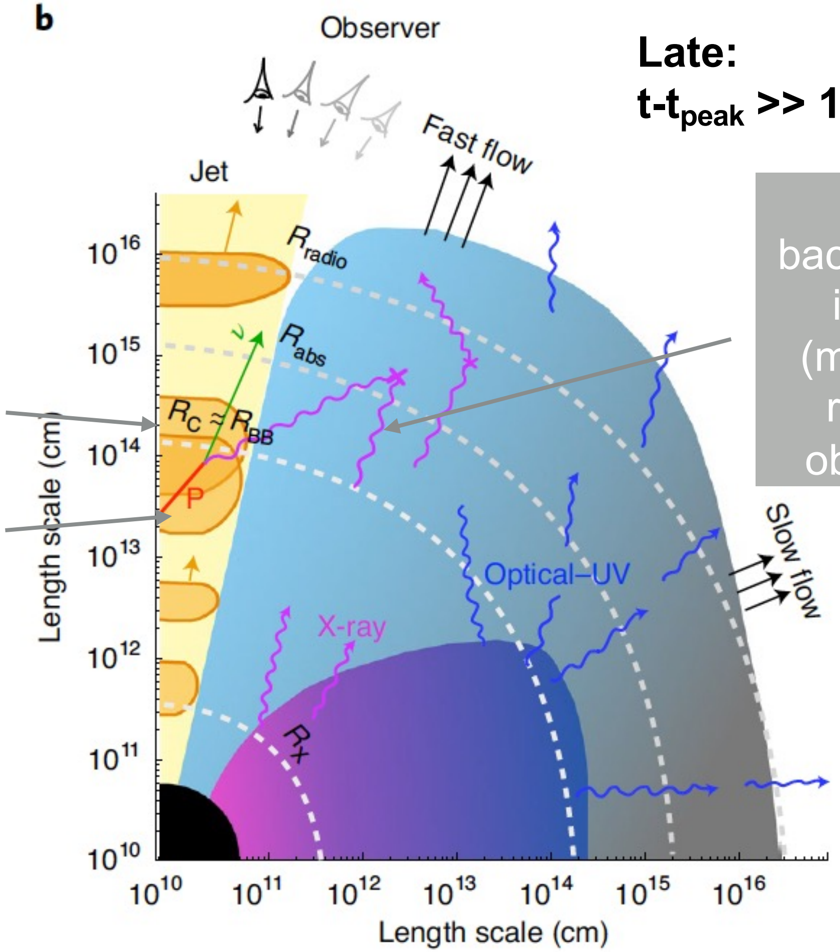
No neutrinos at t_{peak} (no intense target)



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 and Zheng, Liu, Wang, 2022 for choked jets

Results (AT2019dsg)

Pros:

- Best option to satisfy energetics requirement
- Direct connection with X-ray signal
- Neutrino time delay though delayed isotropized X-rays, decreasing production radius
- Neutrino energy well re-produced

Cons:

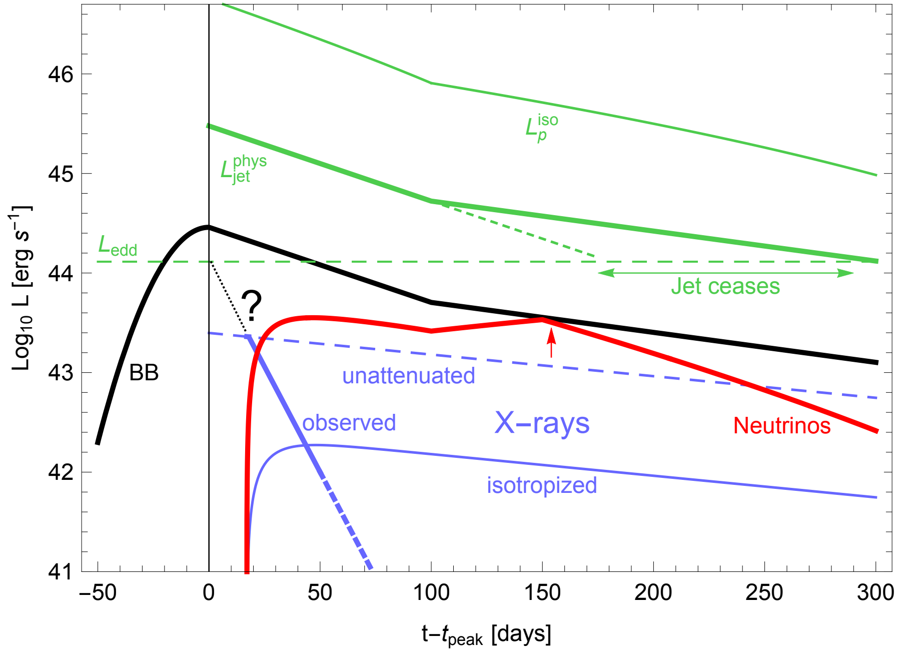
- Evidence for a relativistic jet in AT2019dsg heavily disputed
- No interesting (evolving) radio signals for AT2019fdr, AT2019aalc (no direct evidence for outflow or jet)

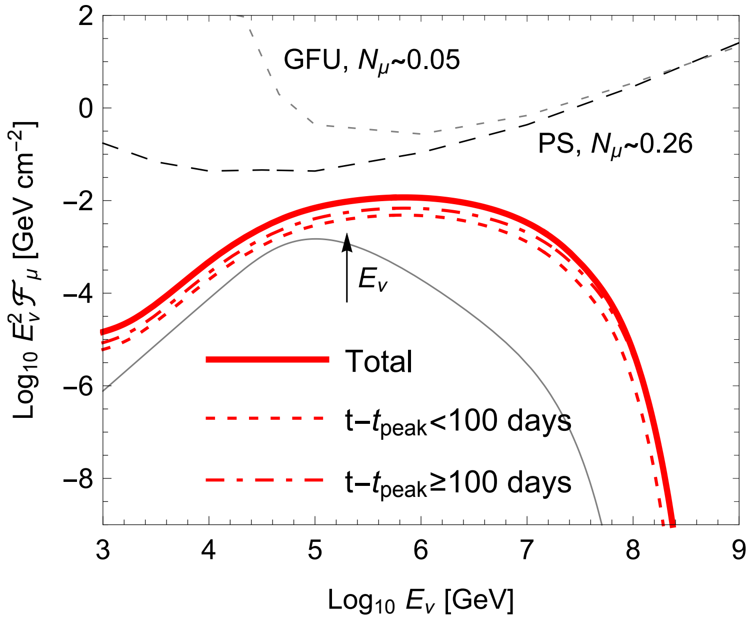
Caveats:

- Jets in TDEs exist in about 1% of all cases Nature 612 (2022) 7940
- Could off-axis jets act as proton accelerators which are then magnetically confined?

Winter, Lunardini, Nature Astronomy 5 (2021) 472

(black/thick purple: follow data; red curve: computational result; others: model ingredients)





Quasi-isotropic emission models

Examples M-X and M-IR

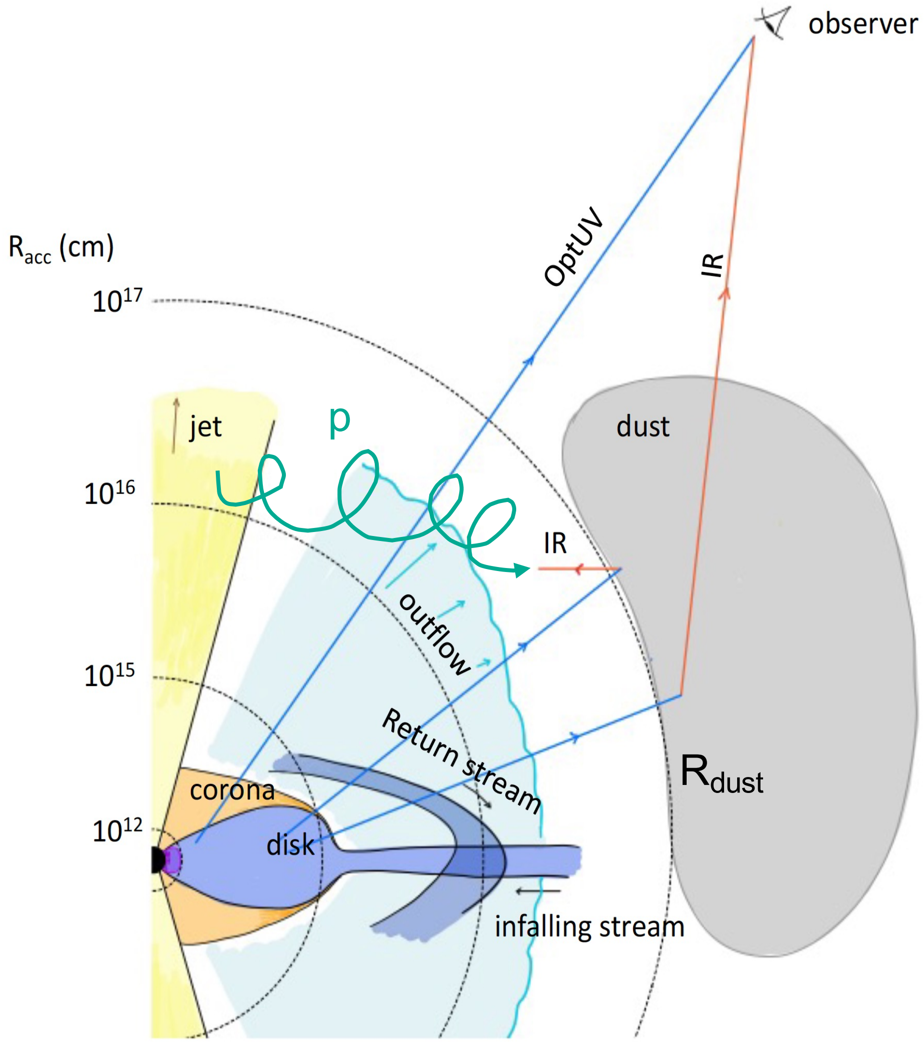
- Assume independent acceleration zone (e.g. off-axis jet, outflow, colliding streams)
- Protons isotropize in magnetic fields in a "spherical cow" production region of radius R (lose memory of initial direction)
- Production region acts as a calorimeter (protons interact efficiently over lifetime of system, but free-streaming optical thickness is low), e.g.

$$\tau_{p\gamma}^{\rm fs} \equiv \frac{t_{\rm fs}}{t_{p\gamma}} \simeq 0.06 \left(\frac{L_X}{10^{44}\,{\rm erg\,s^{-1}}}\right)\left(\frac{T_X}{100\,{\rm eV}}\right)^{-1}\left(\frac{R}{5\,10^{15}\,{\rm cm}}\right)^{-1},$$

$$\tau_{p\gamma}^{\rm cal} \equiv \frac{t_{\rm dyn}}{t_{p\gamma}} \simeq 18 \left(\frac{L_X}{10^{44}\,{\rm erg\,s^{-1}}}\right)\left(\frac{T_X}{100\,{\rm eV}}\right)^{-1}\left(\frac{R}{5\,10^{15}\,{\rm cm}}\right)^{-2}\left(\frac{t_{\rm dyn}}{600\,{\rm days}}\right)$$

- Target photons could be X-rays, OUV or IR photons (next slide); possible interactions with protons from an outflow included

Winter, Lunardini, arXiv:2205.11538



Possible target photons and required proton energies

	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)

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 (Black body)

→ $E_{p,max}$ > 2 PeV (X-rays)

→ $E_{p,max}$ > 1 EeV. UHECRs? (Dust echo)

$E_{p,max}$ controls the available photon targets!

Winter, Lunardini, arXiv:2205.11538

Theoretical interpretation of neutrino-dust echo 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?**
- Re-call that (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} ~ 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

Dust model, geometry

- A fraction of the emitted bolometric luminosity is re-processed into the IR
- IR target averaged over the geometry

Proton acceleration and energetics

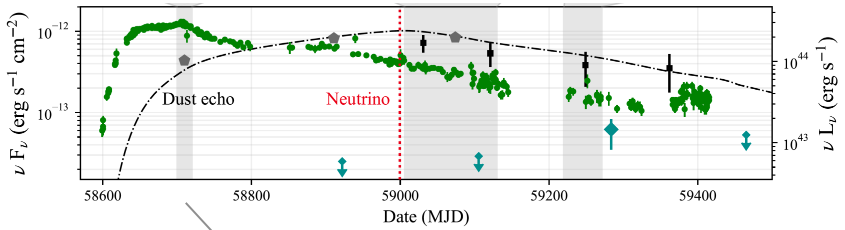
- Protons are injected with an E^{-2} spectrum and $E_{p,max}$=5 EeV
- B ~ 0.1 G, protons are magnetically confined at lower energies over the TDE duration; isotropization!
- Proton injection follows mass accretion

Cons:

- High dissipation efficiency required (> 10% of mass accretion into non-thermal protons)
- Neutrino peak energies too high? But: Some hint for hard spectra from recent TDE stacking analysis? Jannis Neckar @ TeVPA 2022

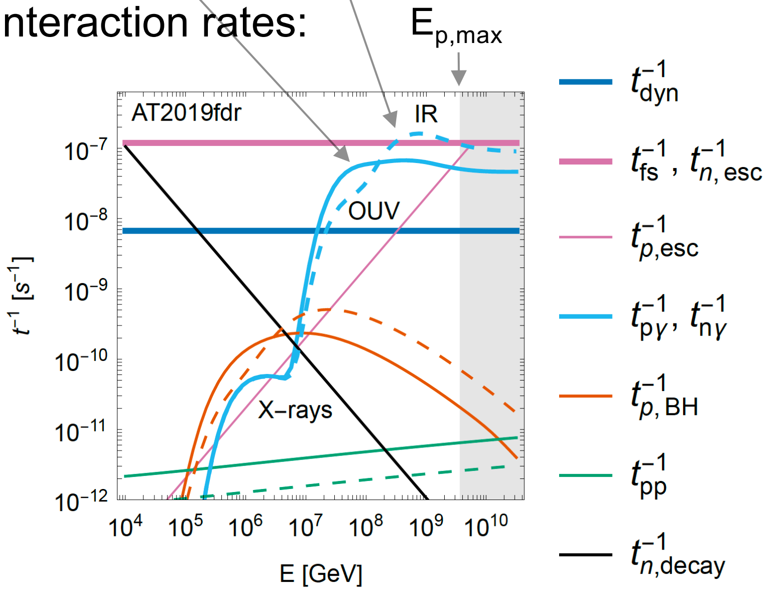
Neutrino production

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



Reusch et al, PRL 128 (2022) 22

- Interaction rates:

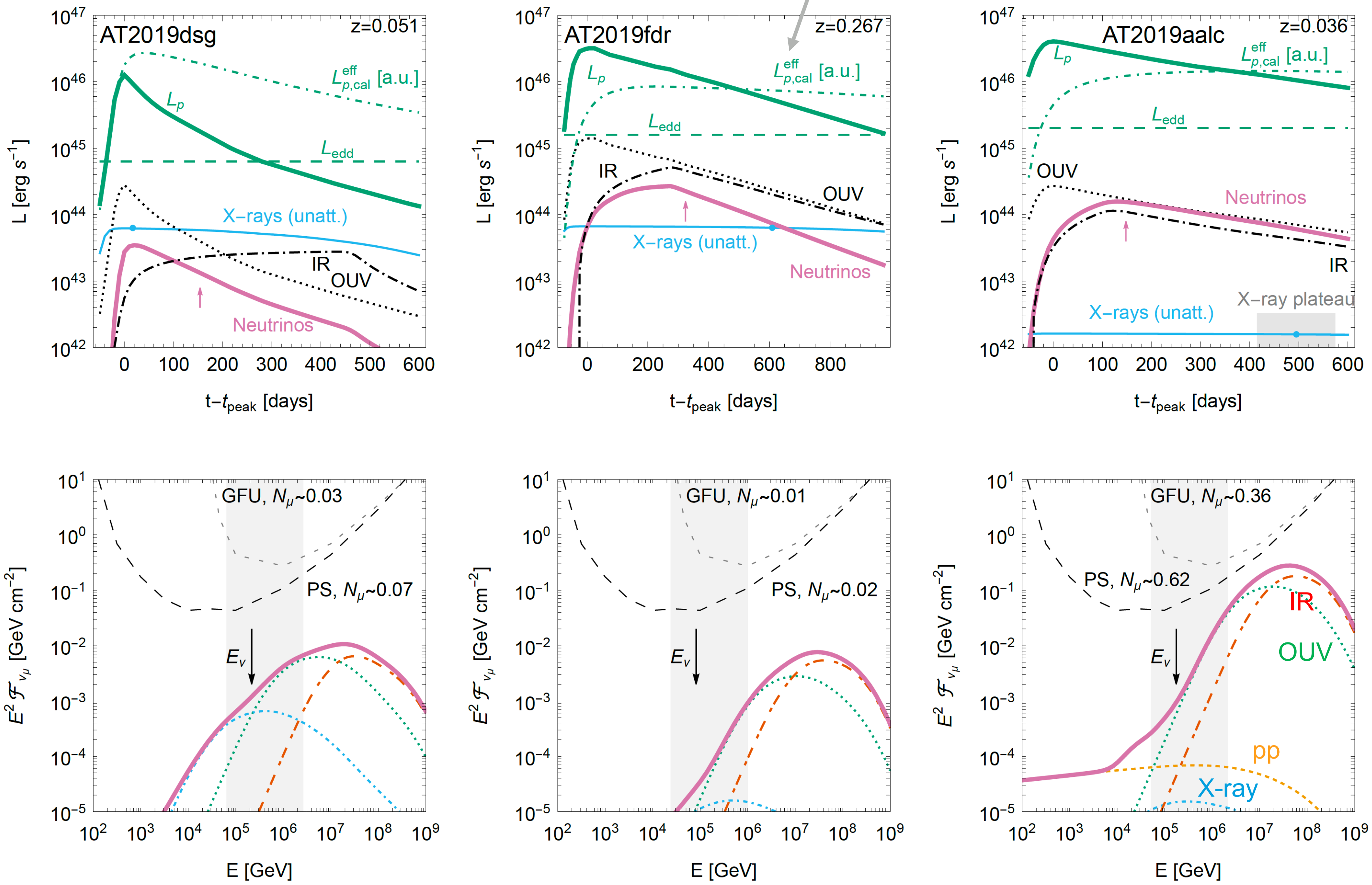


Dashed: neutrino production time
Solid: Peak time of TDE

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

Theoretical results (M-IR)

In-source proton density calorimetric!

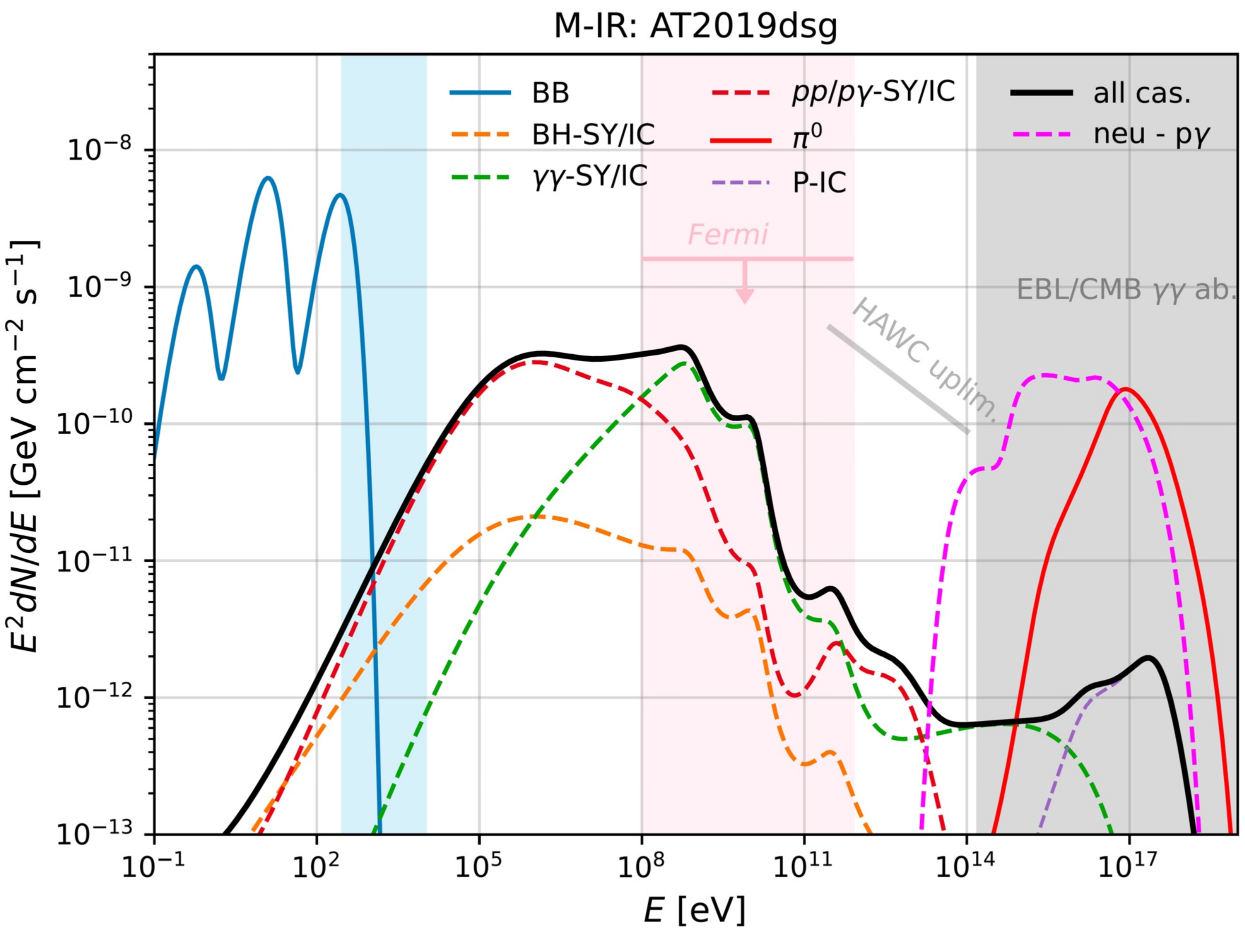


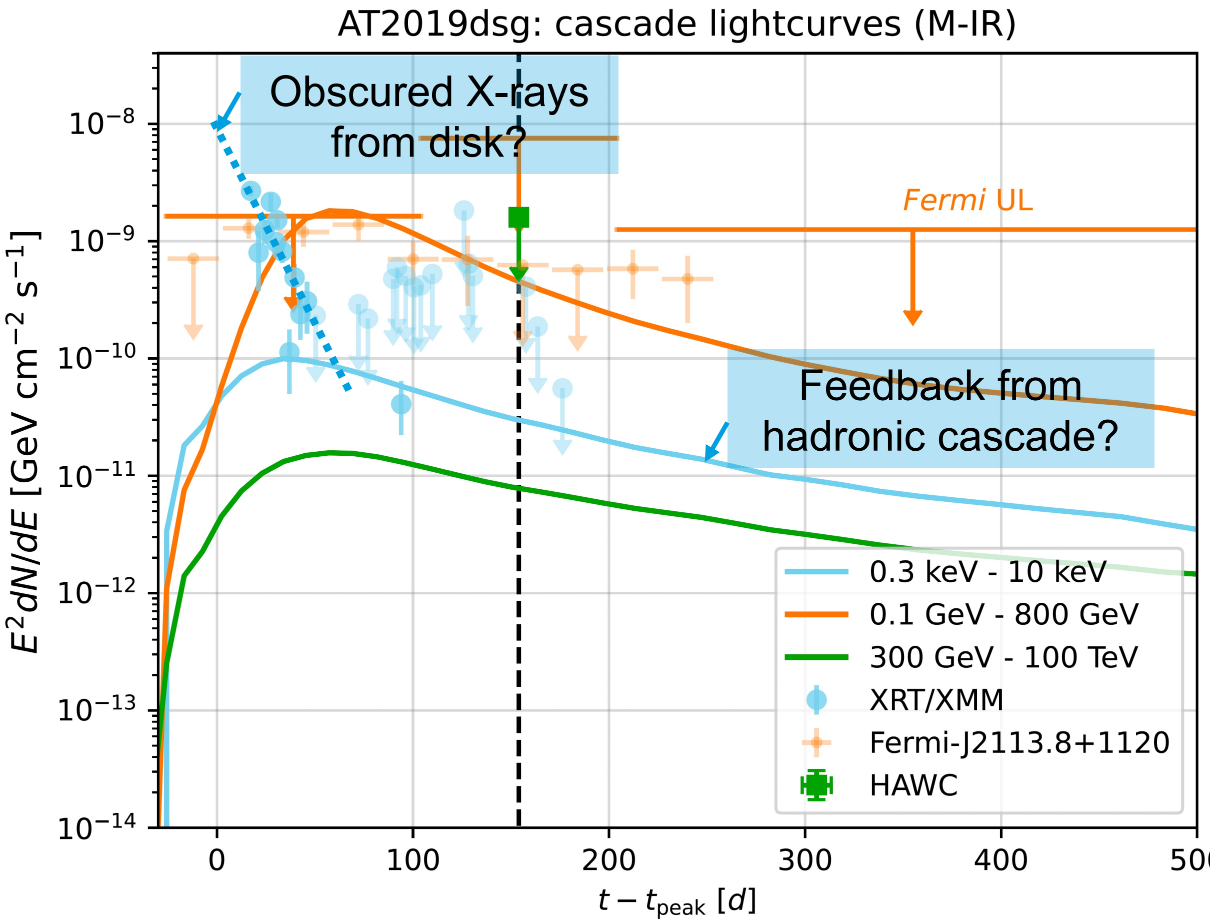
Winter, Lunardini, arXiv:2205.11538v1 (model M-IR)

Chengchao Yuan

Electromagnetic cascade (in source)

Fully time-dependent computation with AM³. Example: AT2019dsg: no strong constraints for model M-IR





PRELIMINARY

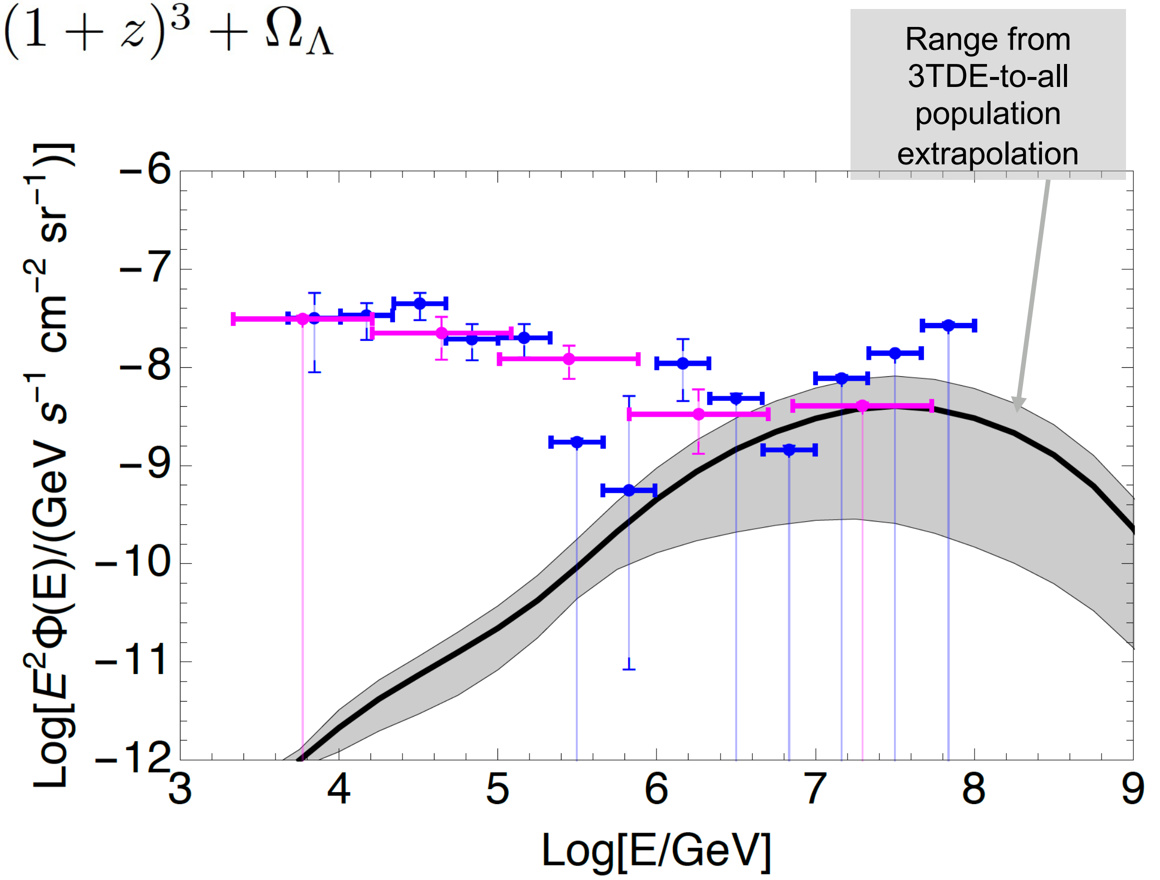
Yuan, Winter, in preparation

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

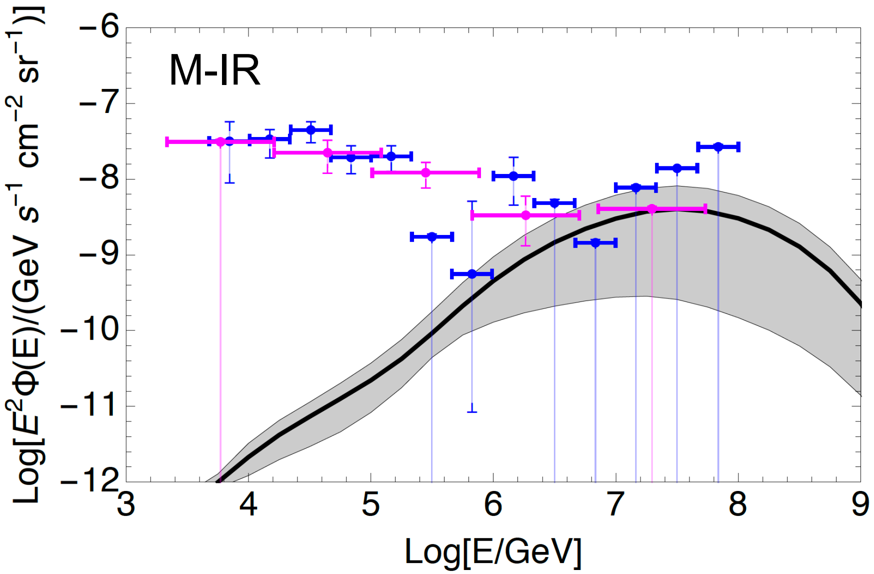


Winter, Lunardini, arXiv:2205.11538, model M-IR

UHECR connection. Example: jetted TDEs

From jets pointing in our direction?

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



Winter, Lunardini, arXiv:2205.11538

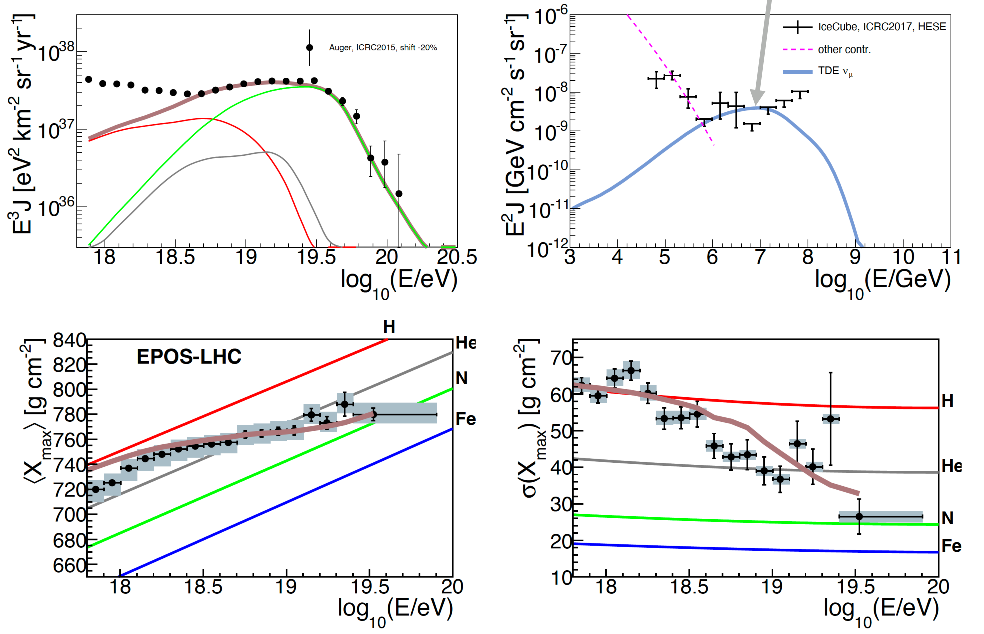
- Estimated UHECR output per TDE ~ 2 10^{52} erg in M-IR model; need local rate of about 5 Gpc^{-3} yr^{-1}
- Assume that off-axis jets accelerator. Rate of jetted TDEs (on-axis) is then R ~ 5 Gpc yr^{-1} / f_B ~ 0.02 Gpc yr^{-1}

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

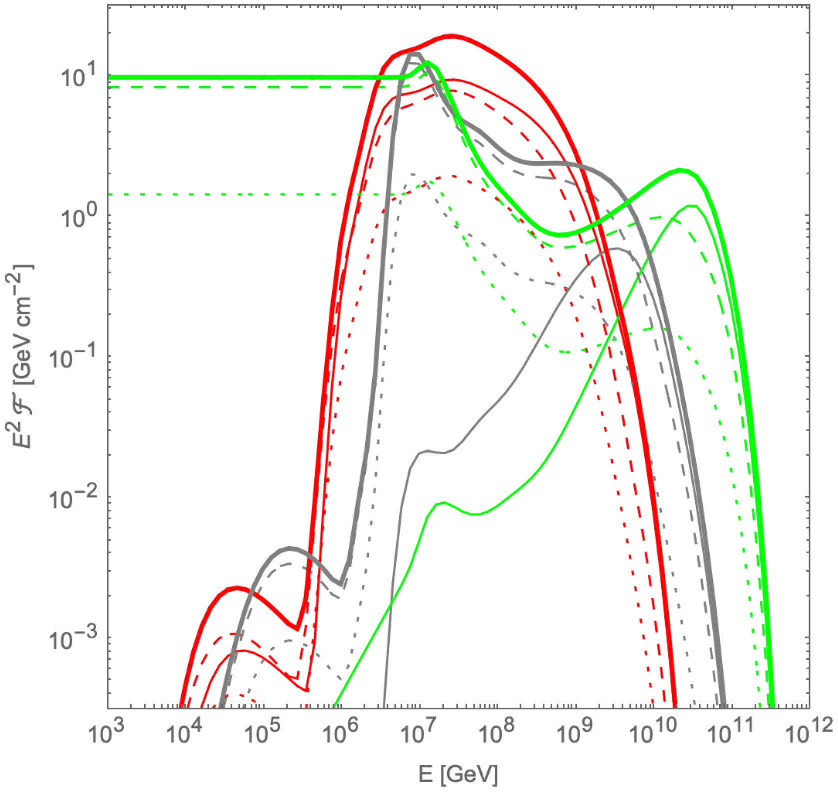


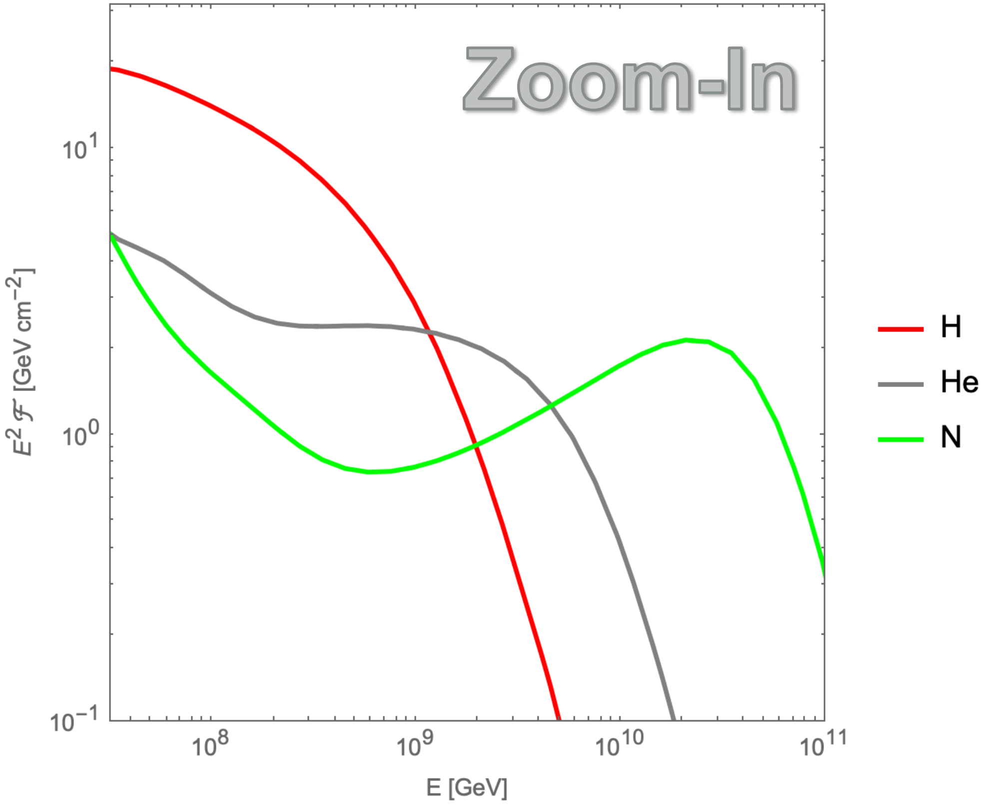
- Limitations:
  1. Jetted TDEs are rare R ~ $0.02_{-0.01}^{+0.04}$ Gpc yr^{-1} Nature 612 (2022) 430
  2. High L_X, L_ν (neutrino multiplet limits!)
  3. Injection composition – white dwarfs?
- But now: high neutrino-TDE rate observed, lower luminosity (L_{OUV}, L_ν)
- Models actually not so different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

Hadronic cascade in source

Example: AT2019aalc source-ejected (no propagation effects except for adiabatic cooling), parameters at face value

- Power law injection (E^{-2}) of pure ^{14}N up to E_{max}=7 x 5 EeV
- UHECR escape mechanisms:
  - Direct/diffusion in Bohm-regime, neutron escape (thin solid)
  - Advective (dashed), v=0.5c (outflow)
  - Instantaneous release after t_{dyn} (dotted)
- Probably requires some re-optimization of parameters (R, E_{max})





PRELIMINARY

Winter et al, in preparation

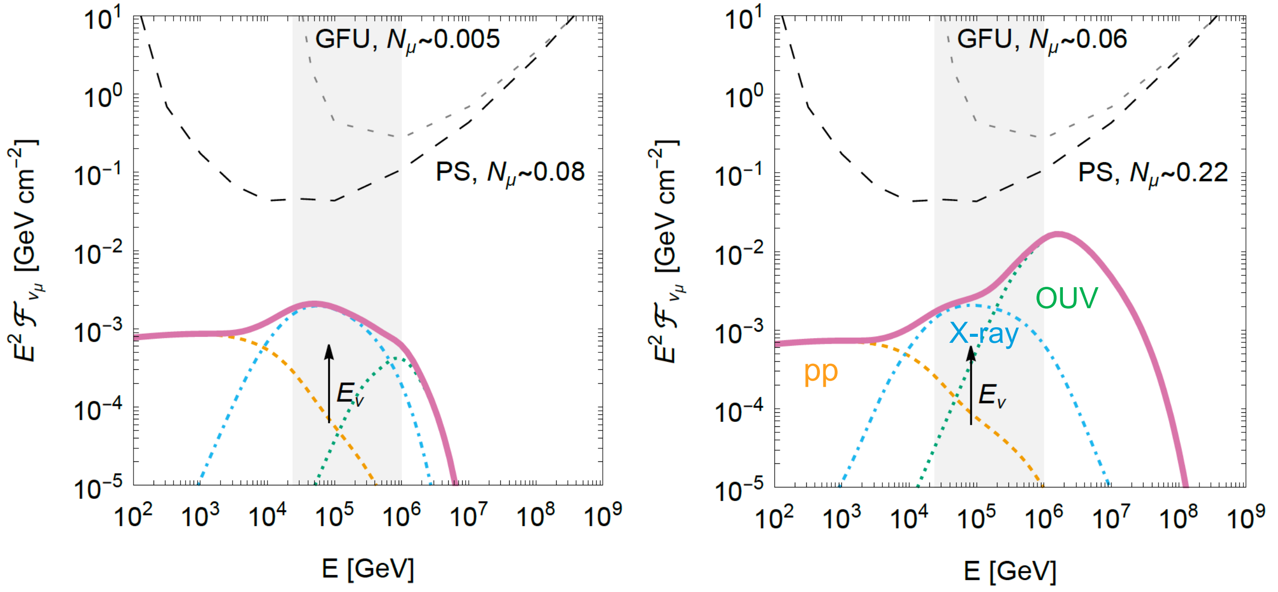
Alternative models

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

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

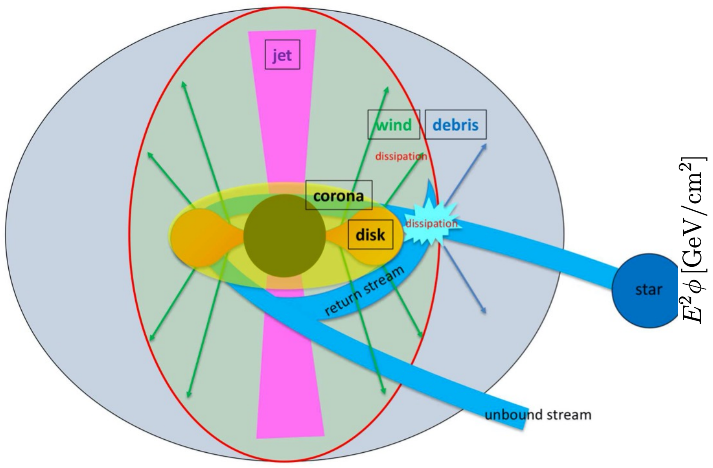
$E_{p,max}$ = 5 PeV
main target: X-rays

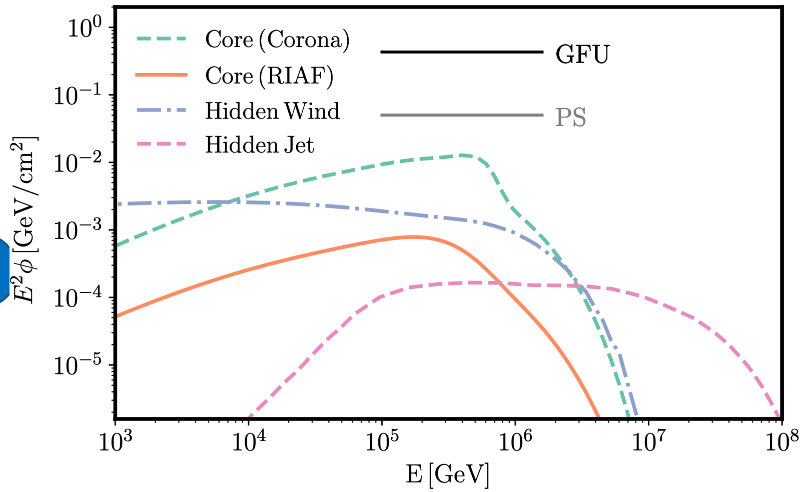
$E_{p,max}$ = 100 PeV
main target: OUV



Specific implementations of accelerator?

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

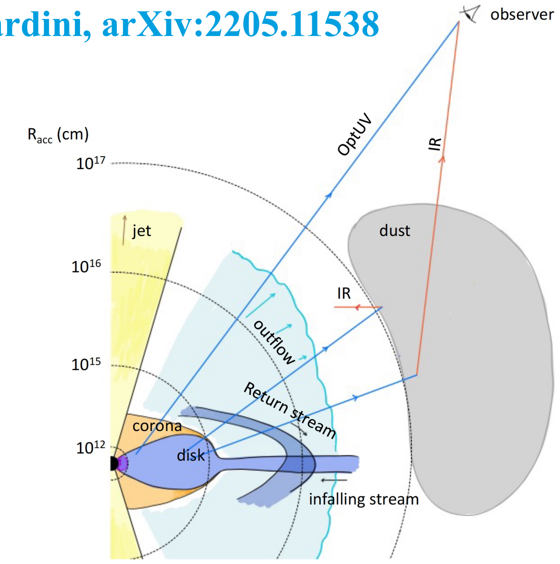




Murase et al, arXiv:2005.08937 (AT2019dsg)

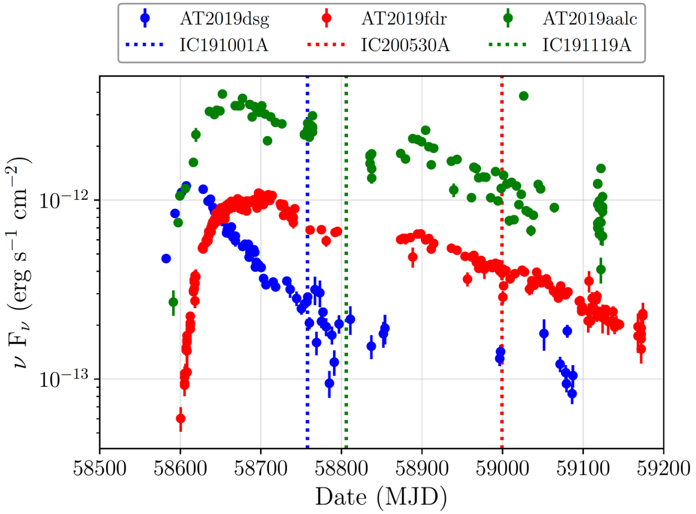
Summary and conclusions

Winter, Lunardini, arXiv:2205.11538



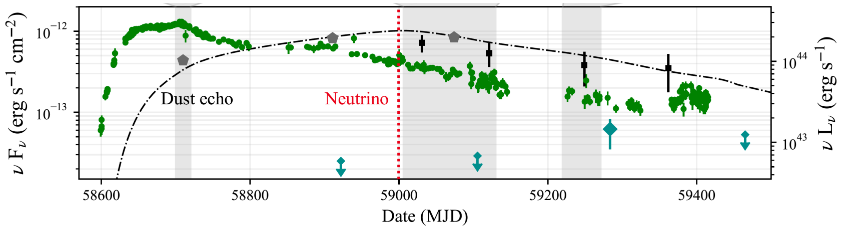
Neutrino-TDE associations

- 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

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
  - Could be related to jets (off-axis)
  - Self-consistent picture requires more work