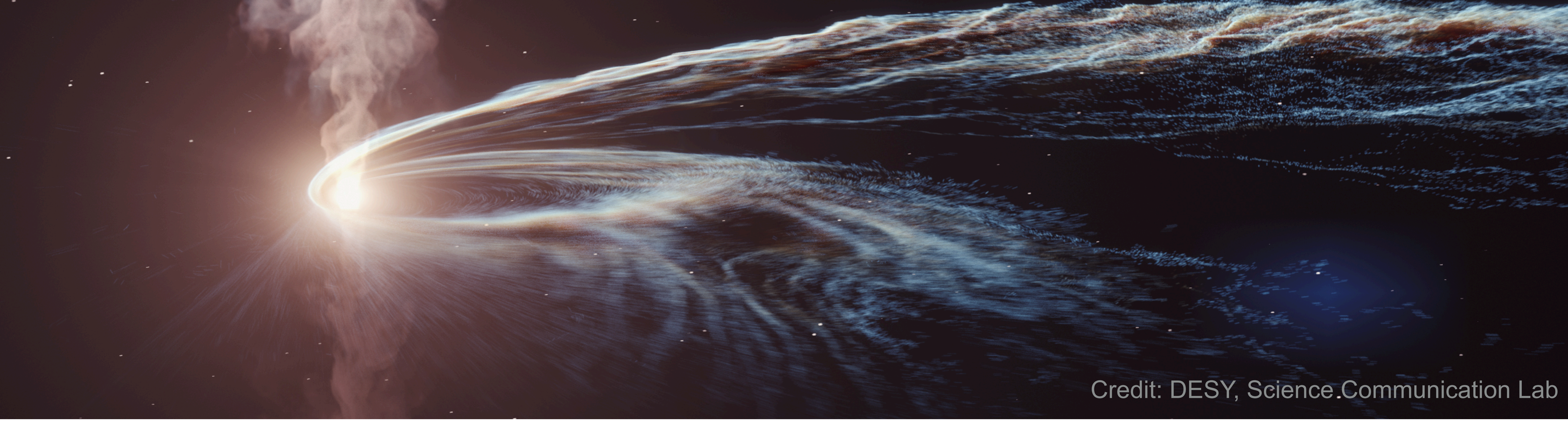

Neutrino and Electromagnetic Signals from TDE Isotropic Winds and Relativistic Jets

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Deutsches Elektronen Synchrotron DESY, Germany

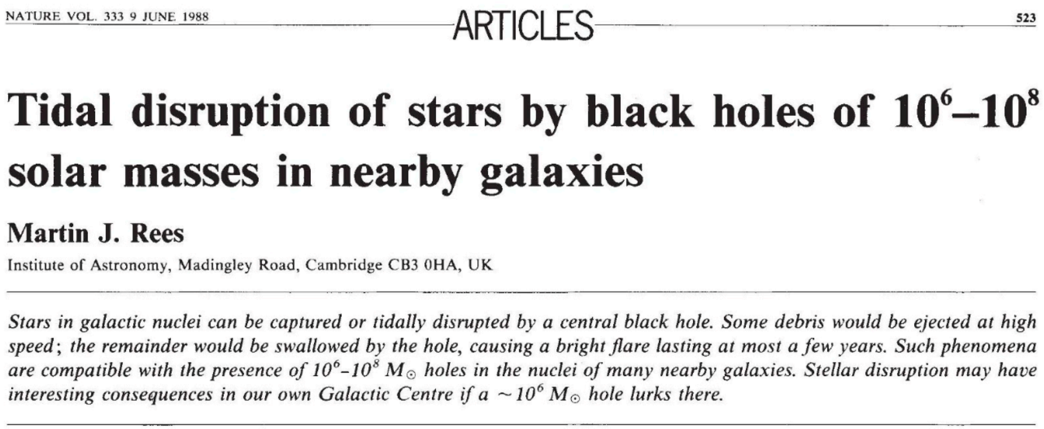
TeVPA 2024, Chicago
2024/08/26

HELMHOLTZ

Tidal disruption events

When a massive star passes close enough to a SMBH

- The star can be ripped apart by the tidal force
- ~ half of the star's mass remains bounded by the SMBH gravitational force
- Mass accretion -> months/year-long flare
- Energy to be reprocessed by accretion ~ 10^{54} erg
- Fallback rate $\propto t^{-5/3}$ (Phinney 1989)
- Thermal black body (bb) emissions in optical/UV (OUV) bands.
- Some (~1/4) TDEs are observed in X-ray and infrared (IR) ranges, e.g., AT2019dsg (Stein et al. 2021)


NATURE VOL. 333 9 JUNE 1988 — ARTICLES — 523

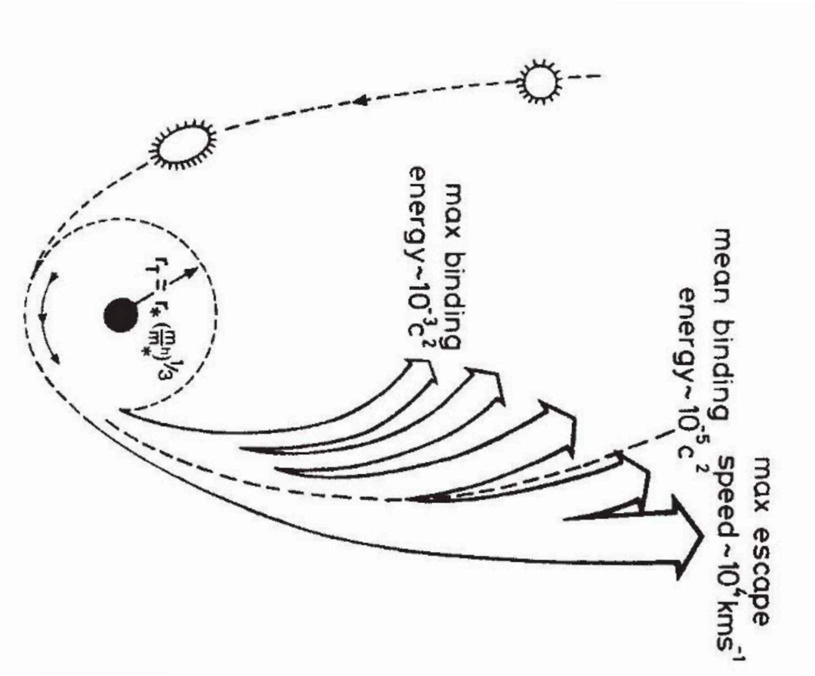
Tidal disruption of stars by black holes of 10^6–10^8 solar masses in nearby galaxies

Martin J. Rees

Institute of Astronomy, Madingley Road, Cambridge CB3 0HA, UK

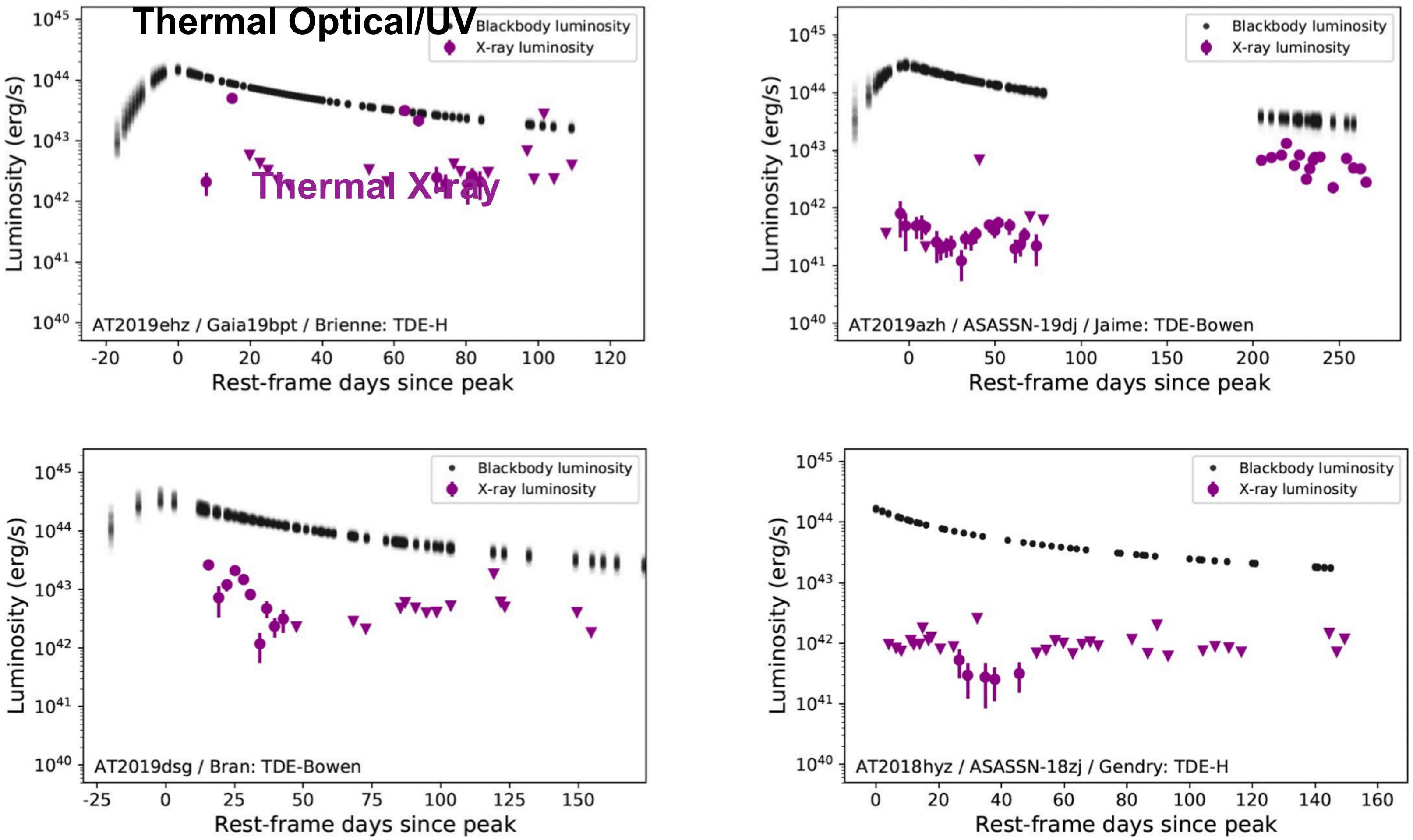
Stars in galactic nuclei can be captured or tidally disrupted by a central black hole. Some debris would be ejected at high speed; the remainder would be swallowed by the hole, causing a bright flare lasting at most a few years. Such phenomena are compatible with the presence of 10^6–10^8 $M_\odot$ holes in the nuclei of many nearby galaxies. Stellar disruption may have interesting consequences in our own Galactic Centre if a ~10^6 $M_\odot$ hole lurks there.

Martin J. Rees, Nature 1988



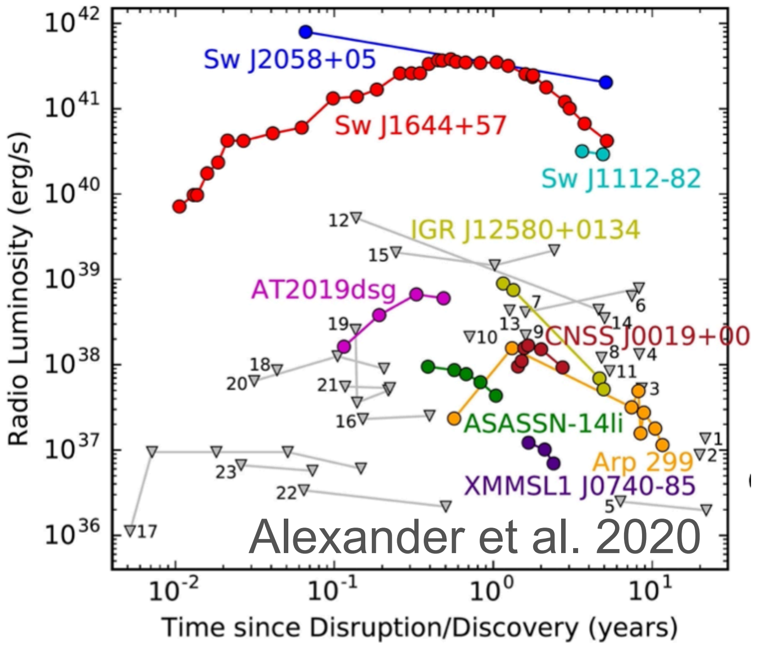
TDE observational signatures: universal

Mass fallback rate $L_{OUV} \propto t^{-5/3}$



Van Velzen et al, 2021

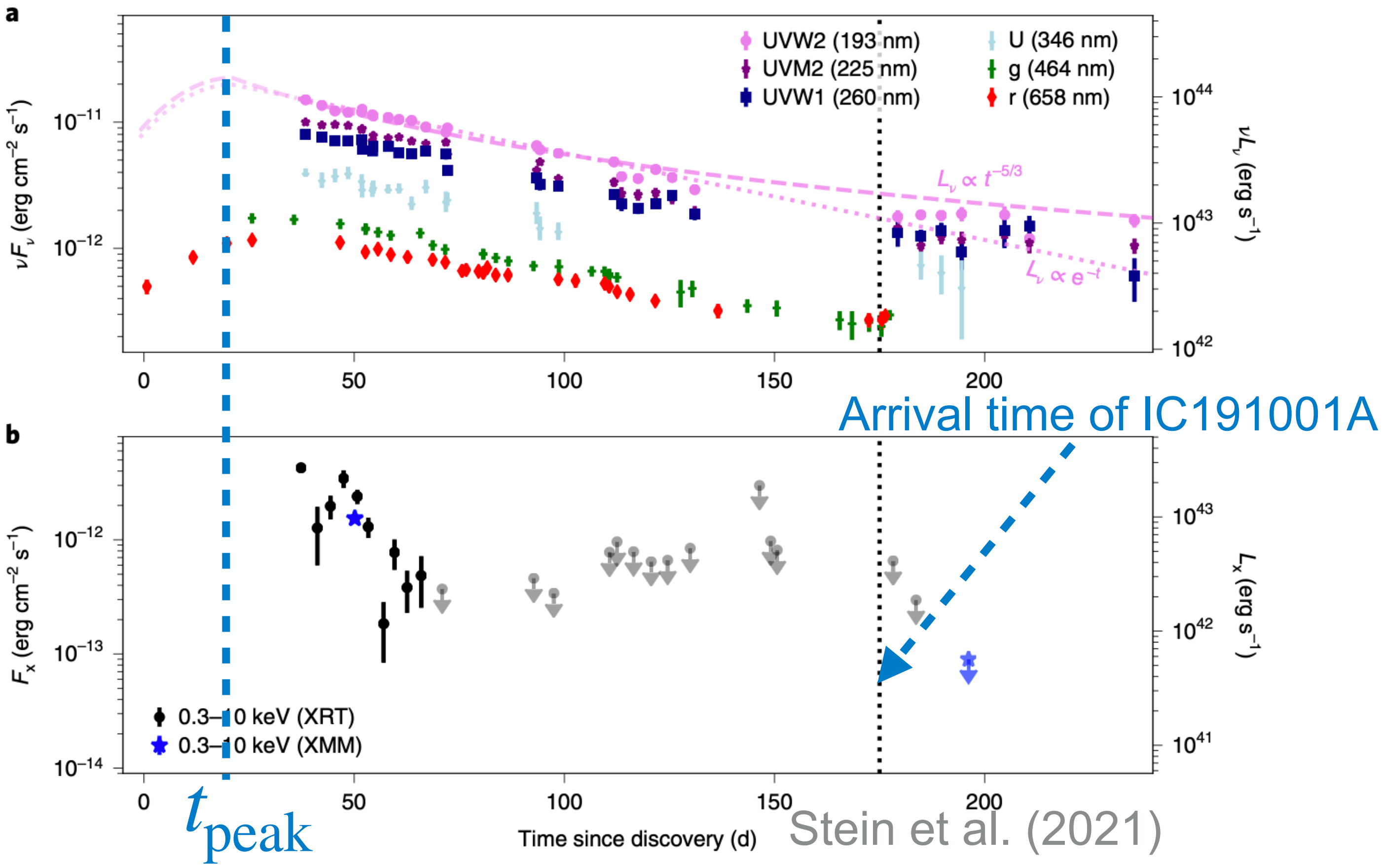
Radio

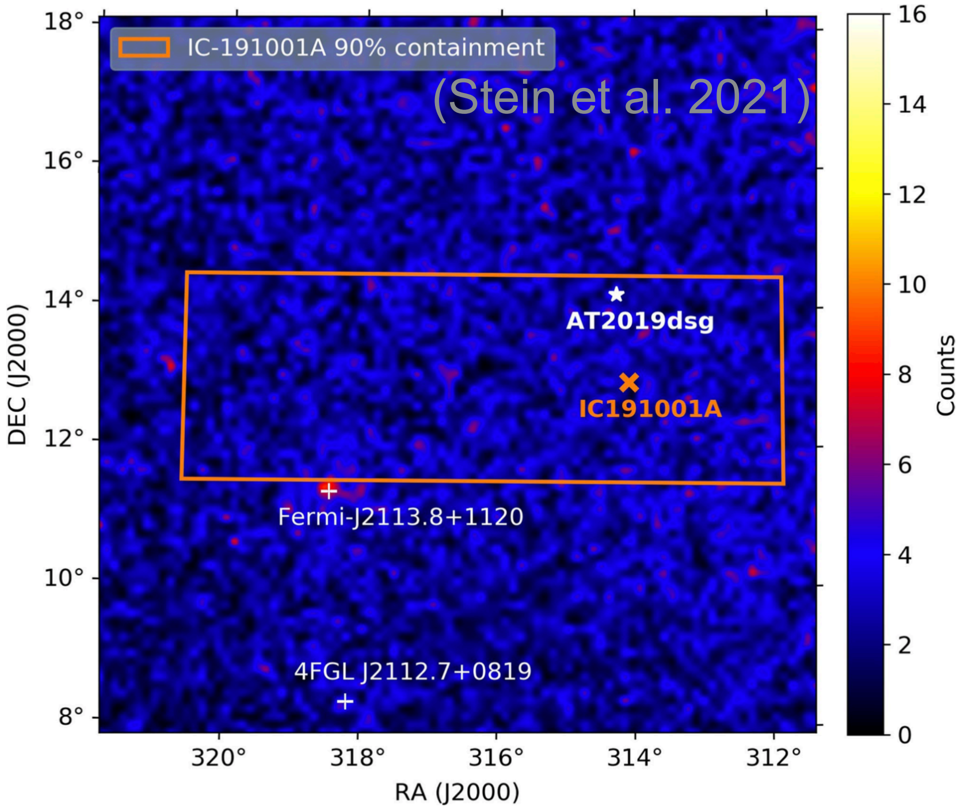


- A small fraction of TDEs exhibit luminous radio relativistic jet. Most are radio quiet.
- Delayed radio may come from jet propagating in wind density profile $\rho(r) \propto r^{-k}$ $(1.5 \lesssim k \lesssim 2)$ (Metzger+ 2016)

AT2019dsg

- $z \sim 0.051$
- ZTF (optical: g, r) + Swift UVOT (UV)
- Swift-XRT/XMM-Newton: X-ray (0.3-10 keV)
- *Fermi* (0.1-800 GeV) and HAWC (0.3-100 TeV) up limits





- Angular offset: 1.3 deg
- $t_\nu - t_{\rm pk} = 150$ d

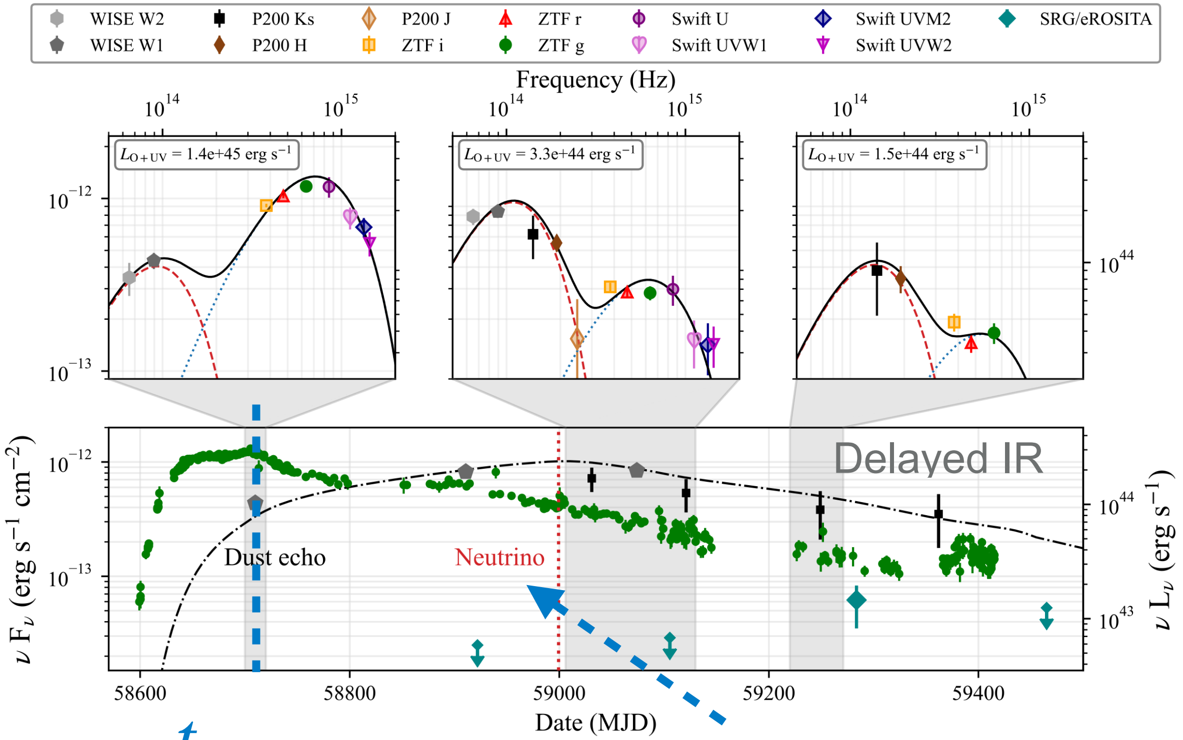
Measured black body spectra:

- **X-ray**: $T_X = 72$ eV, from hot accretion disk
- **OUV**: $T_{\rm OUV} = 3.4$ eV, from photosphere (nearly constant)
- **IR**: $T_{\rm IR} = 0.15$ eV

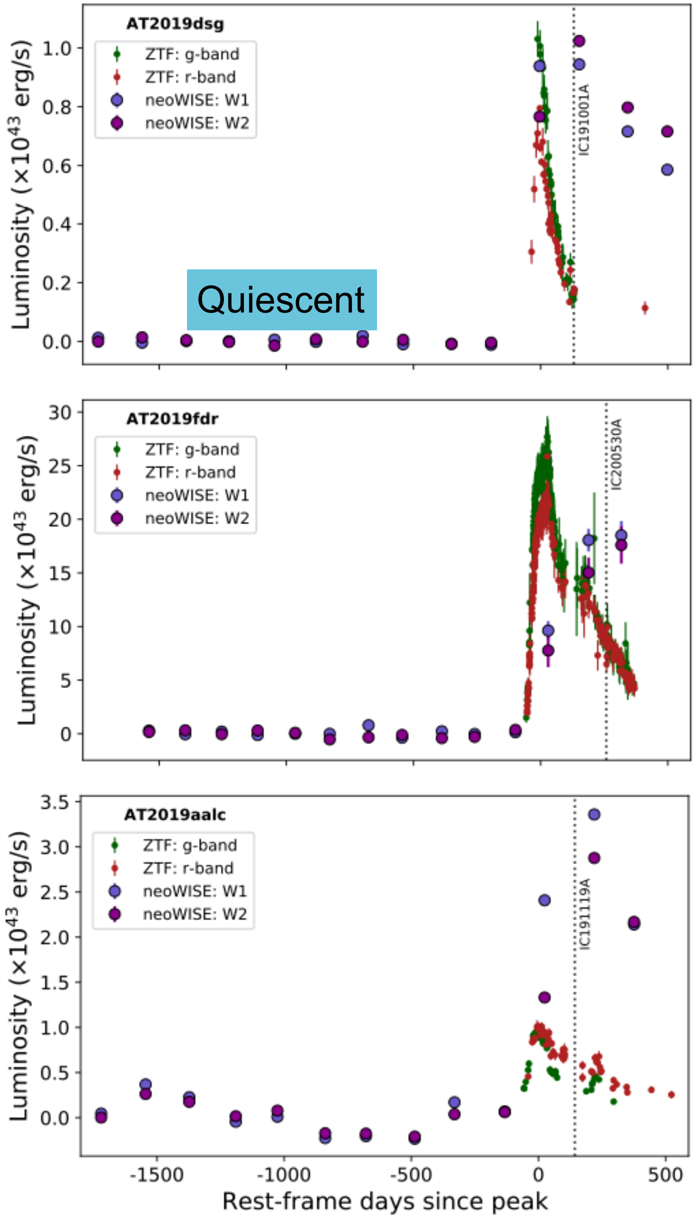
AT2019fdr

- $z \sim 0.267$
- ZTF (optical: g, r) + Swift UVOT (UV) + IR
- Swift-XRT: X-ray (0.3-10 keV)
- Angular offset: 1.7 deg; $t_\nu - t_{\mathrm{pk}} = 393$ d
- *Fermi* up limit ✓

Reusch et al. (2022)



AT2019aalc



Another TDE candidate with potential neutrino correlation and strong delayed IR emission.

- Angular offset: 1.9 deg
- $t_\nu - t_{\mathrm{pk}} = 148$ d
- Significance of neu correlation: 3.6 sigma

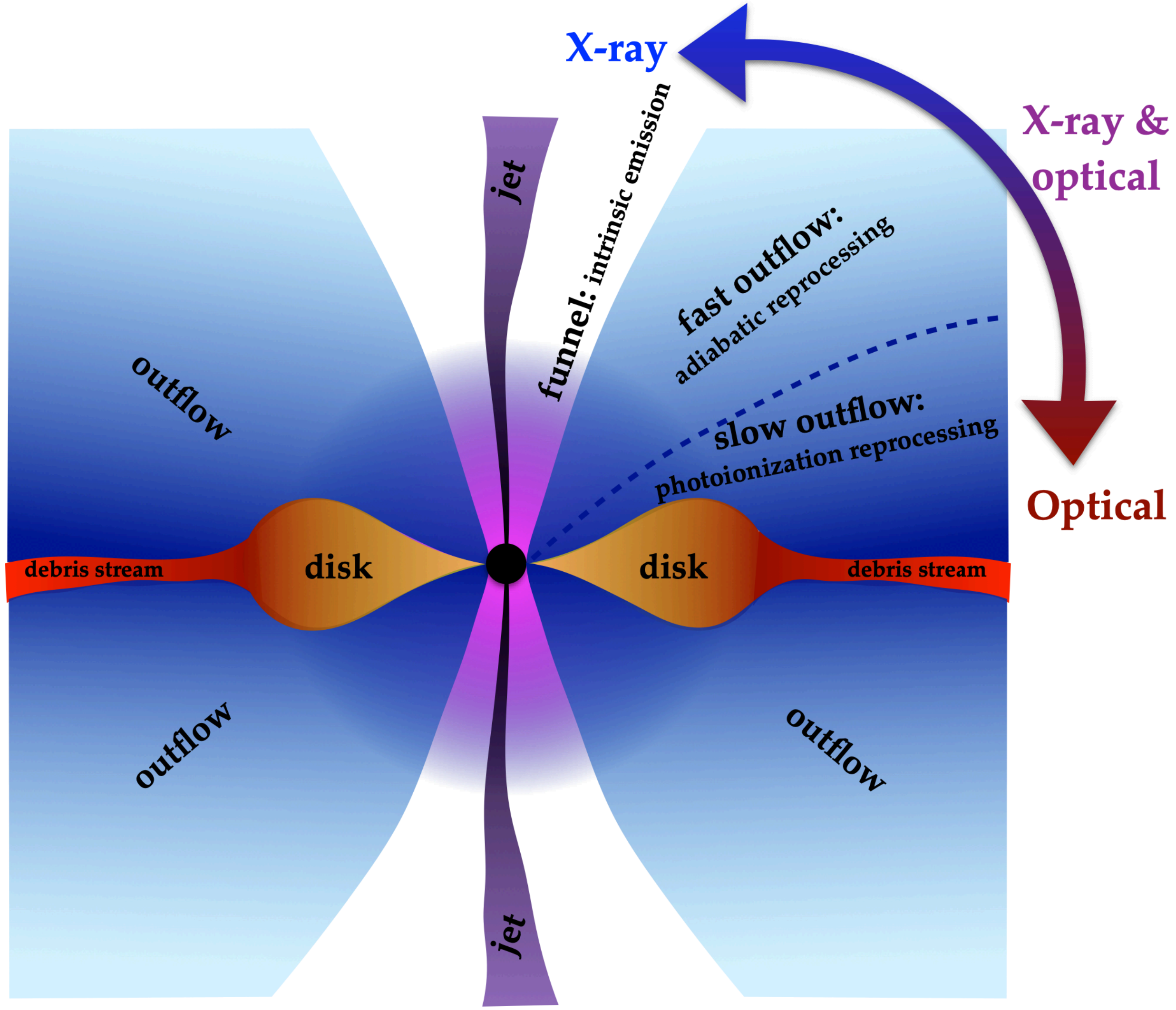
(van Velzen+ 2021)

Caveat: AT2019fdr/aalc are not exclusively identified as TDEs

TDE models

Disks - Hayashaki & Yamazaki 19 (HY19)
Wide angle winds - Fang 20, Murase+ 20
Stream-stream - Dai + 15,, HY19,
Jets - Wang + 11,Wang & Liu 16, Dai & Fang 17, Lunardini & Winter 17, Senno + 17

- ***γ*-rays, non-thermal X-rays**: relativistic jet, sub relativistic wind
- **Thermal X-rays:** close to jet/funnel & hot disk corona
- **Optical/UV:** photosphere of hot disk corona (beyond which integrated optical depth < 1)
- **Infrared (IR):** dust-echo
- **Radio:** non-thermal (particle acceleration in disk, jet, outflow)



Dai+ 2018

TDE models

Disks - Hayashaki & Yamazaki 19 (HY19)
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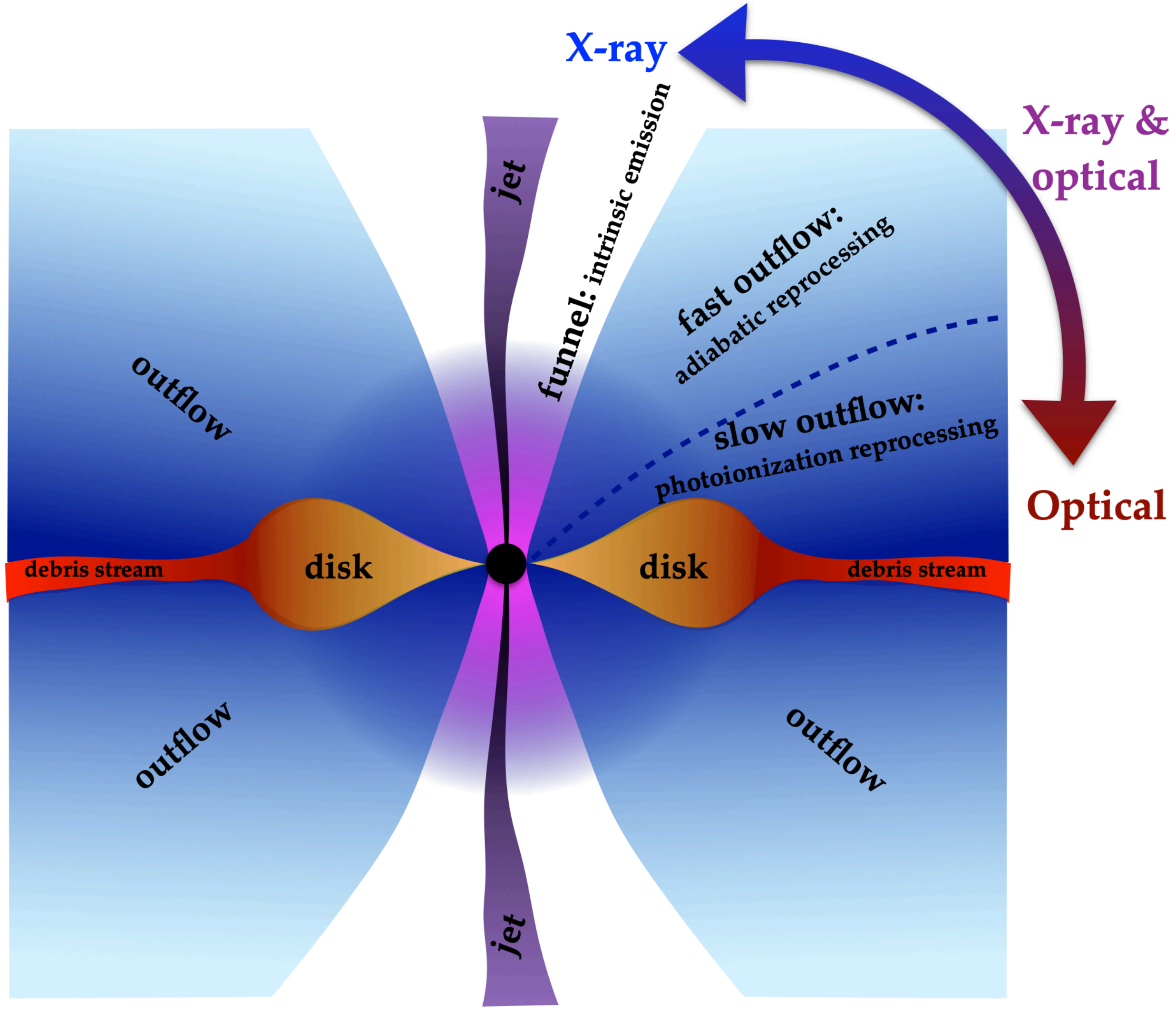
Stream-stream - Dai + 15,, HY19,
Jets - Wang + 11,Wang & Liu 16, Dai & Fang 17, Lunardini & Winter 17, Senno + 17

- In addition to the EM signatures, neutrinos might be produced in the accretion disks, isotropic disk winds (outflows), or jets
- Neutrino associated TDEs/candidates
    1. AT2019dsg (IC191001A)
    2. AT2019fdr (IC200530A)
    3. AT2021lwx? (IC220405B)
    4. AT2019aalc (IC191119A) - Less data

Part I of this talk
Isotropic winds + dust echo

- 4 TDEs/candidates with luminous jets
    1. AT 2022cmc
    2. Sw 1112-82
    3. Sw1644+57
    4. Sw 2058+05

Part II of this talk
Relativistic jets + forward/reverse shocks



Dai+ 2018

Dust Echo: delayed infrared (IR) emission

X-ray/OUV photons heat the dust torus

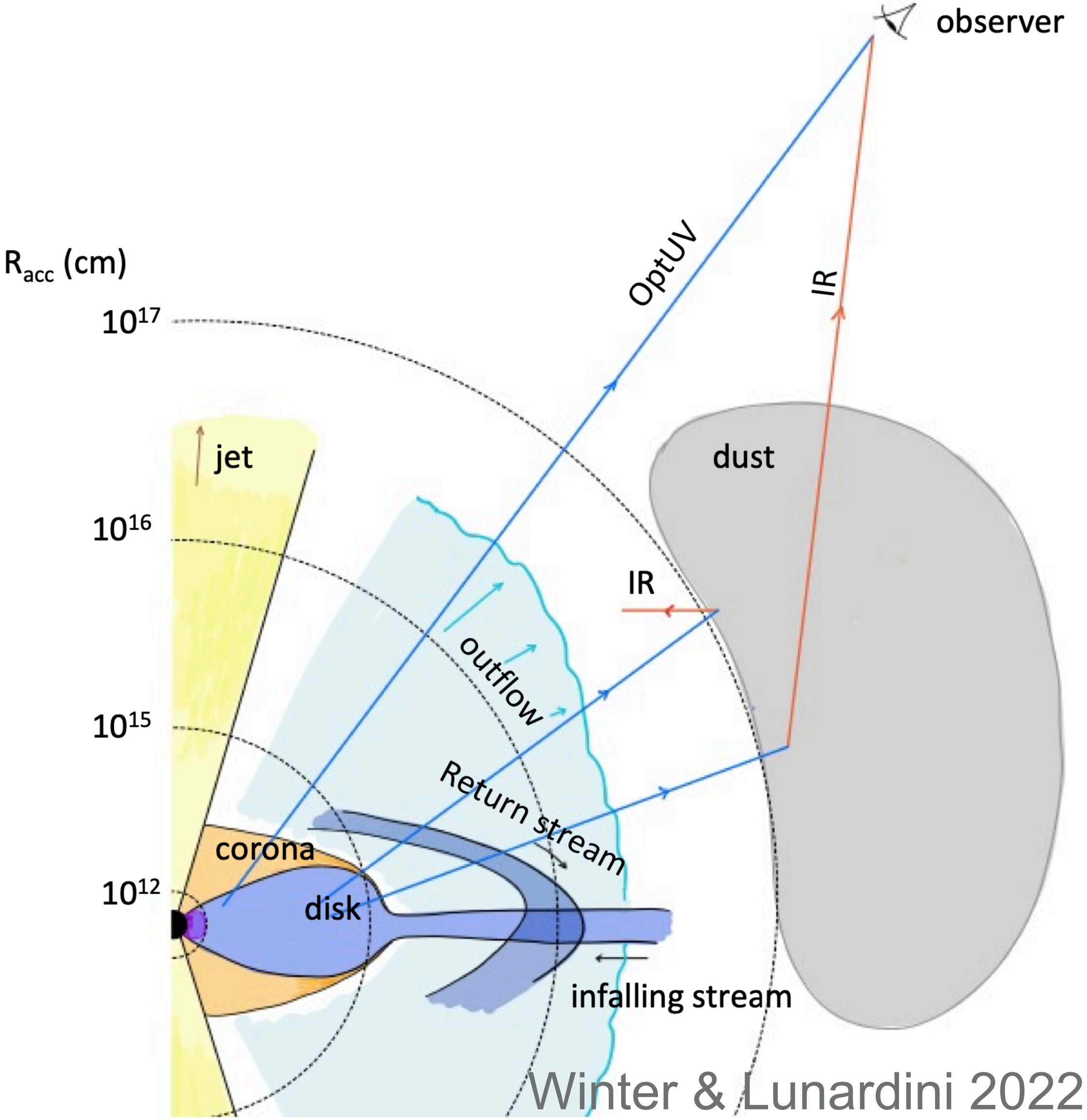
-> thermal IR emission

- delayed IR emission
- feeds IR photons back to the wind/outflow envelope
- temperature $T_{\rm IR} \lesssim T_{\rm sub} \sim 0.16$ eV (sublimation temp.)
- IR luminosity can be obtained by convolving $L_{\rm OUV}$ with a time spreading function $f(T)$, e.g.,

(Reusch et al. 2022, Winter & Lunardini 2022)

$$L_{\rm IR}(t) \propto \int L_{\rm OUV}(t')f(t-t')dt'$$

f(T) reflects the dust distributions



Winter & Lunardini 2022

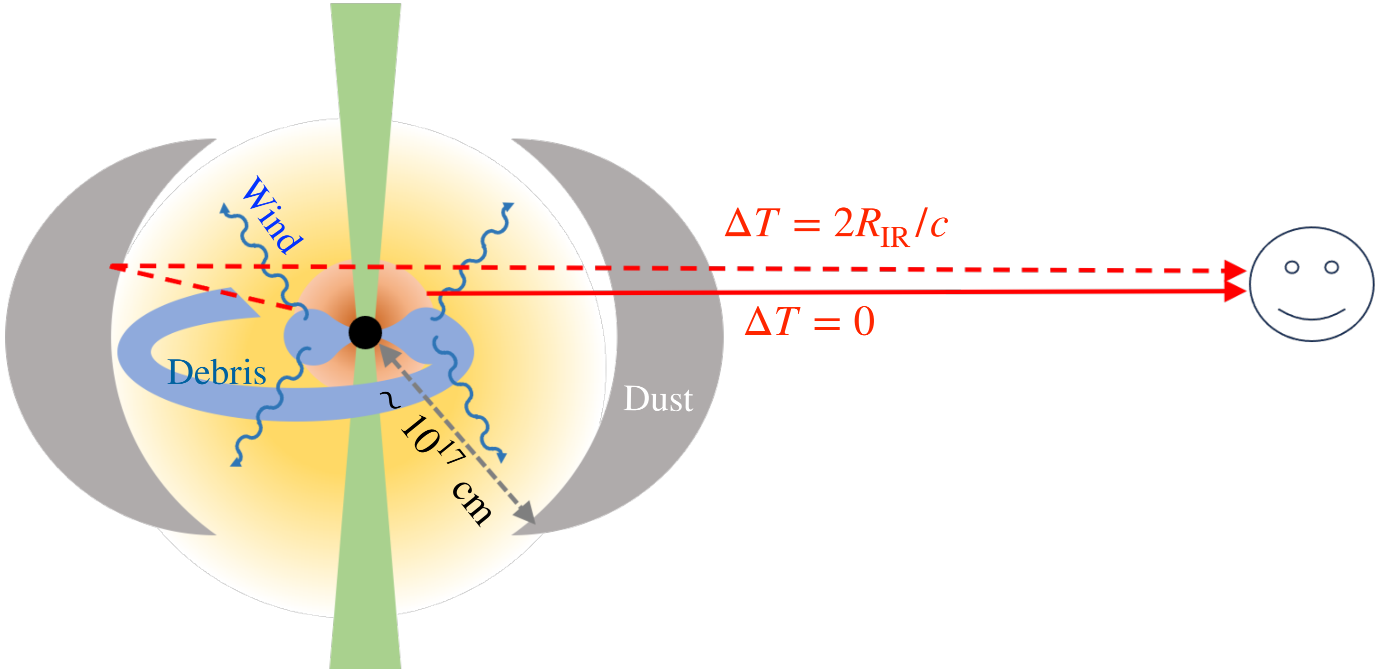
Dust Echo: delayed infrared (IR) emission

Dust radius (R_{IR}) can be inferred from IR time delay w.r.t OUV emissions.

$R_{IR} = c\Delta T/2 \sim 10^{16} - 10^{18}$ cm

One simplest normalized box function is

$f(t) = 1/\Delta T$, if $0 < t < \Delta T$. Otherwise, $f(t) = 0$



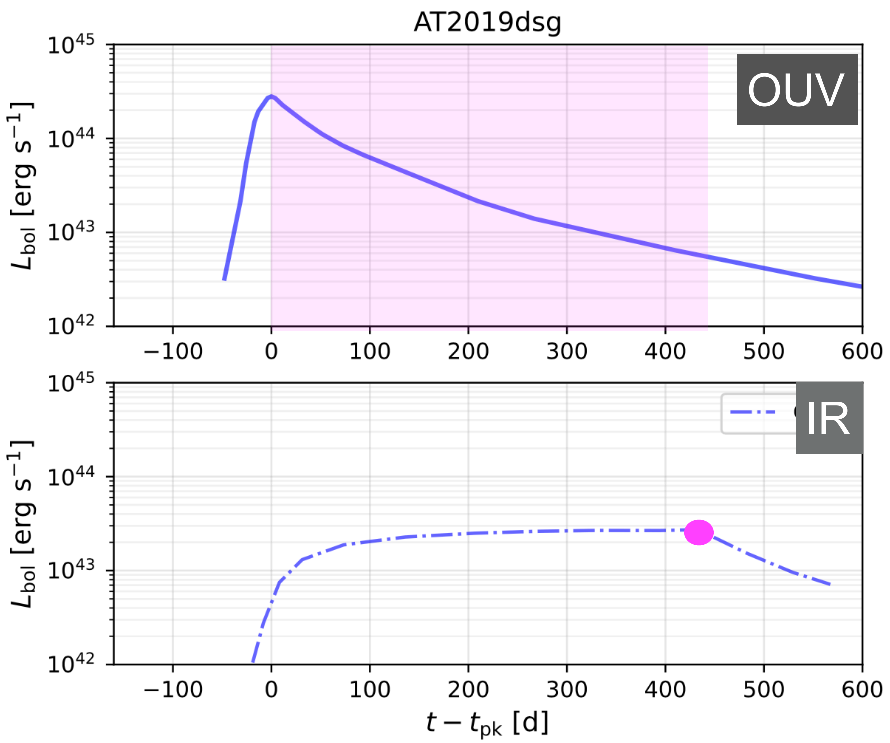
IR light curve fitting

$$L_{IR}(t) = \epsilon_\Omega \epsilon_{IR} \int L_{OUV}(t')f(t-t')dt'$$

$\epsilon_\Omega = \Omega_{dust}/(4\pi)$: solid angle coverage

ϵ_{IR} : re-emitting efficiency

To fit IR light curves for AT2019dsg/fdr/aalc, $\epsilon_\Omega \epsilon_{IR} \sim 0.3 - 0.5$



Isotropic wind model + dust echo

Strong dust echo -> delayed IR emission (yellow curve)
Target photons: thermal IR/OUV/X-ray photons (observation)
$p\gamma$ timescale/delayed IR -> neutrino time delay (few x 100 d)

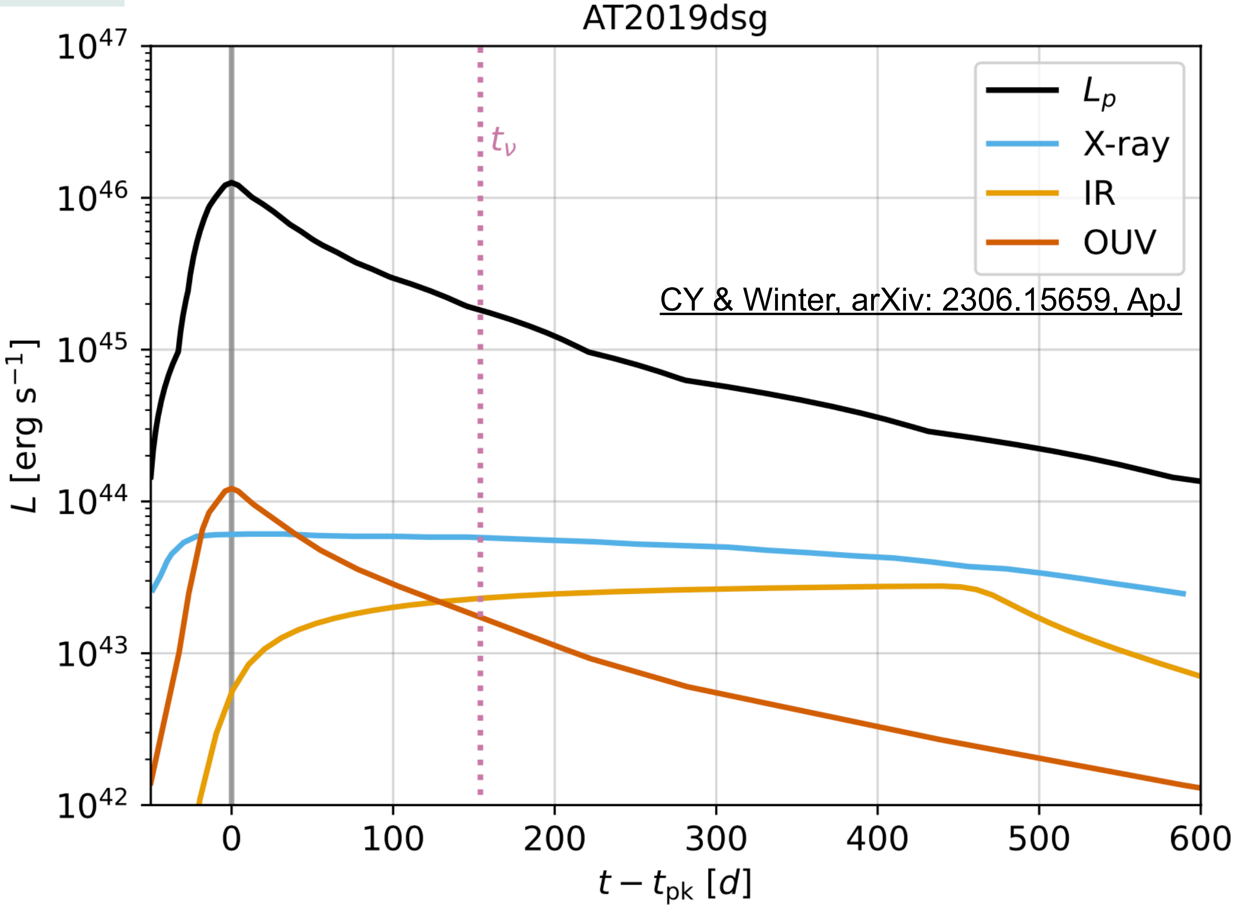
Proton injection: $E_{p,\min} \sim 1\ \mathrm{GeV}$, spectra index $p = 2$, $E_{p,\max}$ (free-param), injection luminosity

- Normalization $\int dE_p E_p \dot{Q}(E_p) = L_p/(4\pi R^3/3)$
- $L_p(t) = \varepsilon_{\rm diss} \dot{M}_\star(t) c^2$

Assumptions

- $\dot{M}_\star(t)/L_{\rm OUV}(t) = \mathrm{const}$
- $\dot{M}_{\star,\rm peak}/\dot{M}_{\rm Edd} \sim \mathrm{a\ few}$ (Dai+, 2018)
- Efficient energy dissipation to CRs: $\varepsilon_{\rm diss} \simeq 0.2$
- Proton diffusion in Bohm regime $D = R_L c$

Proton and target photon luminosities



CY & Winter, arXiv: 2306.15659, ApJ

Numerical Method: AM^3 (Astrophysical Multi-Messenger Modeling)

Numerically solving the coupled PDEs for electron, proton, neutrons, neutrino and photon distributions.

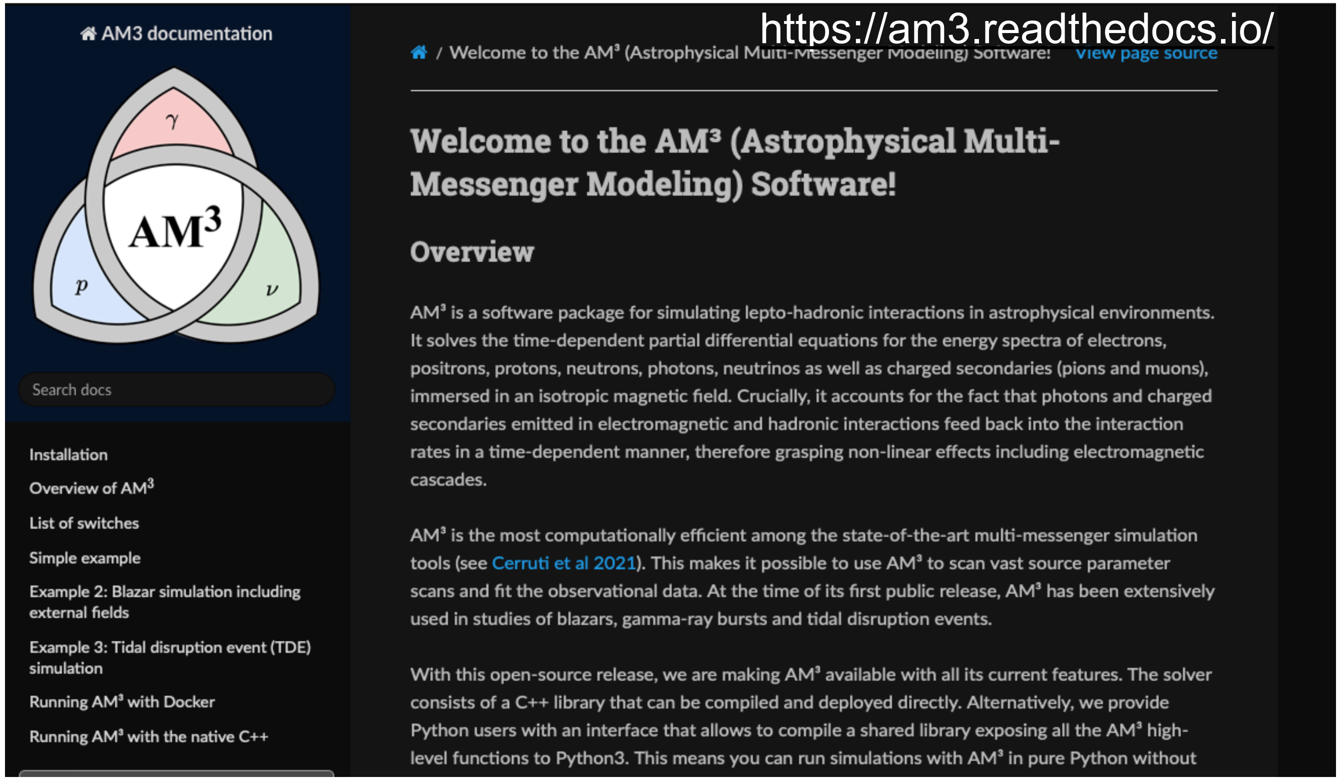
$$\partial_t n_i = Q_{i,ext} + \sum_k Q_{int,k\rightarrow i} - \partial_E(\dot{E}\cdot n_i) - (\alpha_{i,esc} + \alpha_{i,adv})n_i$$

Injection — Cooling — Escape/Advection

- An ***Open-Source*** Tool for ***Time-Dependent*** Lepto-Hadronic Modeling of Astrophysical Sources
- Has been applied to AGN blazars, GRBs, TDEs, etc

(Klinger, Rudolph, Rodrigues, CY +, arXiv: 2312.13371, ApJS in press)

https://am3.readthedocs.io/



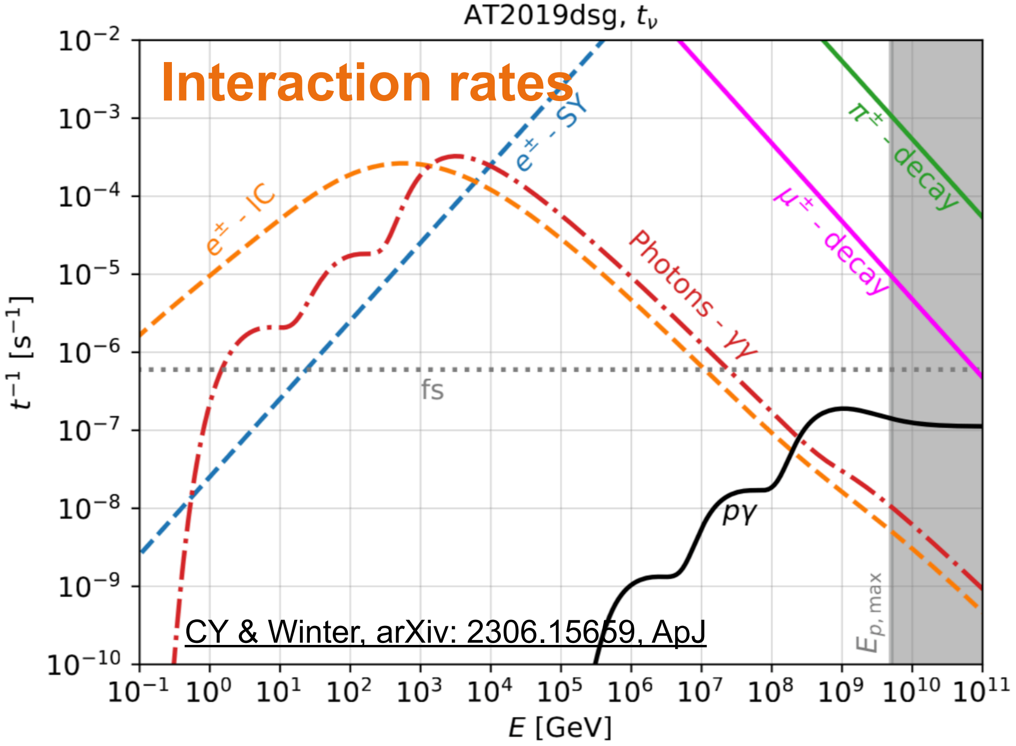
Welcome to the AM³ (Astrophysical Multi-Messenger Modeling) Software!

Overview

AM³ is a software package for simulating lepto-hadronic interactions in astrophysical environments. It solves the time-dependent partial differential equations for the energy spectra of electrons, positrons, protons, neutrons, photons, neutrinos as well as charged secondaries (pions and muons), immersed in an isotropic magnetic field. Crucially, it accounts for the fact that photons and charged secondaries emitted in electromagnetic and hadronic interactions feed back into the interaction rates in a time-dependent manner, therefore grasping non-linear effects including electromagnetic cascades.

AM³ is the most computationally efficient among the state-of-the-art multi-messenger simulation tools (see Cerruti et al 2021). This makes it possible to use AM³ to scan vast source parameter scans and fit the observational data. At the time of its first public release, AM³ has been extensively used in studies of blazars, gamma-ray bursts and tidal disruption events.

With this open-source release, we are making AM³ available with all its current features. The solver consists of a C++ library that can be compiled and deployed directly. Alternatively, we provide Python users with an interface that allows to compile a shared library exposing all the AM³ high-level functions to Python3. This means you can run simulations with AM³ in pure Python without



$p\gamma$ time scale ($t_{p\gamma}$) determines the time to develop EM cascade ($\gamma\gamma$ and secondary interactions very efficient)

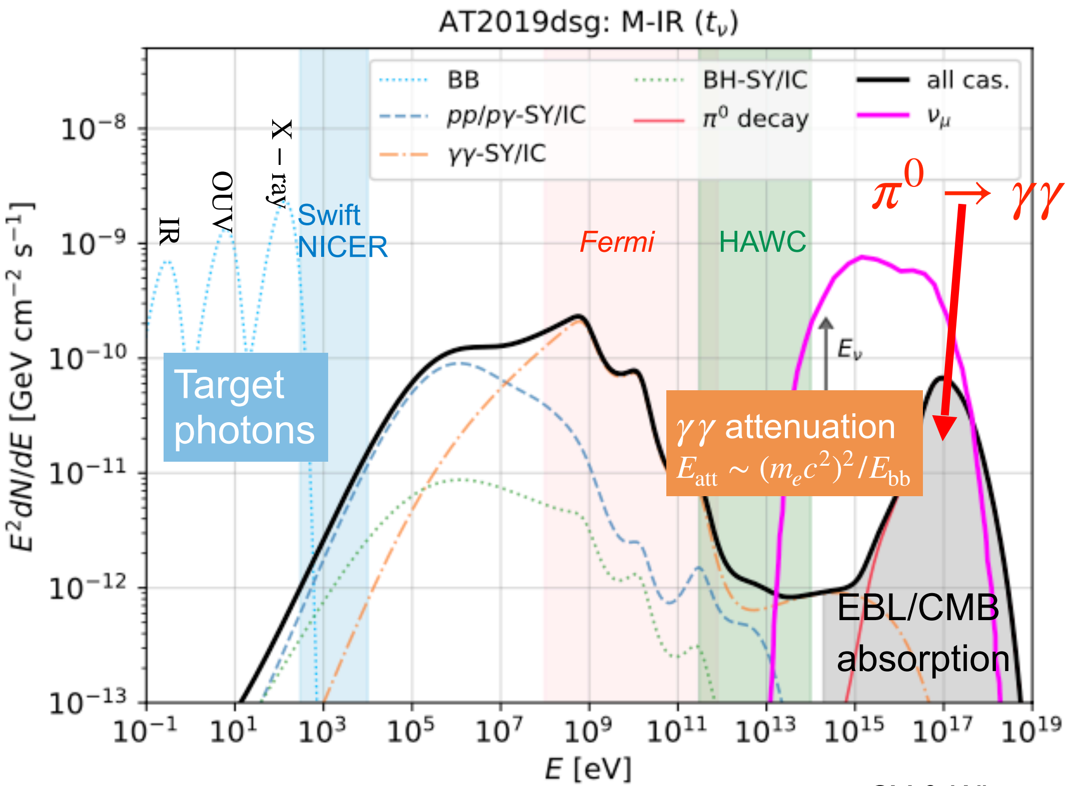
EM cascade spectra of AT2019dsg: IR target photons

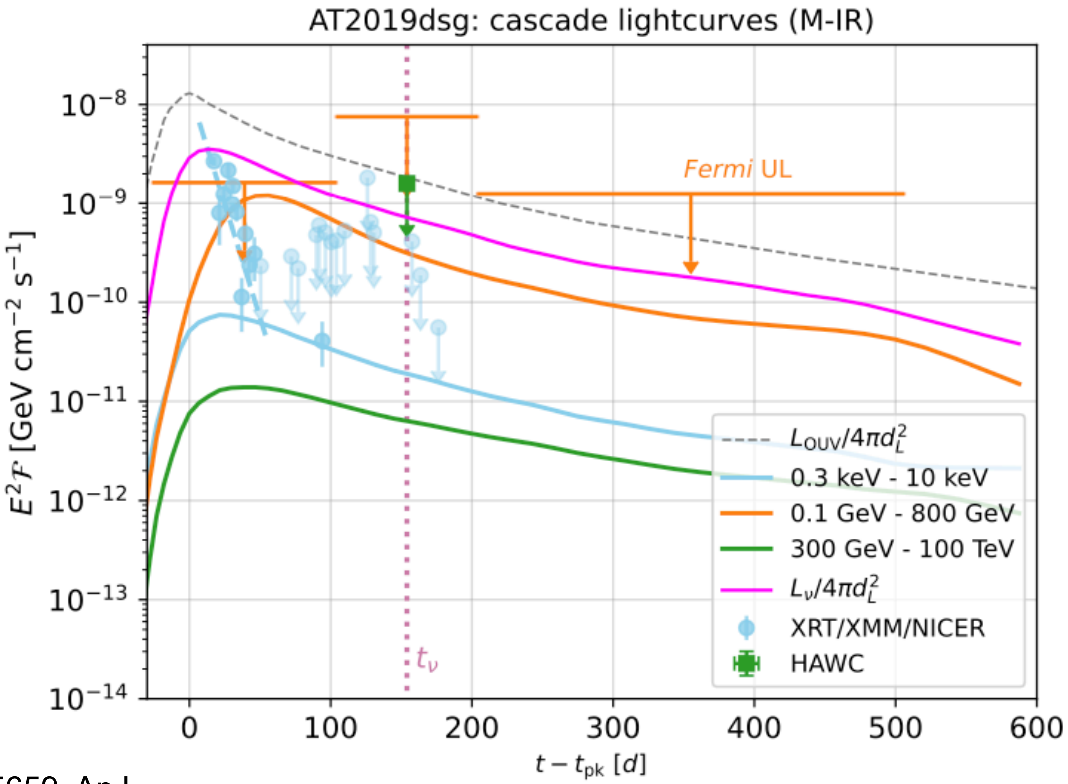
$p\gamma$ optically thin $t_{p\gamma}^{-1}/t_{fs}^{-1} < 1$: $(\pi^{\pm} \rightarrow e^{\pm} \rightarrow \mathrm{SY/IC})$ **+** $(\gamma\gamma \rightarrow e^{\pm} \rightarrow \mathrm{SY/IC})$

Parameters: $\varepsilon_{\mathrm{diss}} = 0.2$

$B = 0.1\ \mathrm{G},\ R = 5 \times 10^{16}\ \mathrm{cm},\ E_{p,\max} = 5 \times 10^{9}\ \mathrm{GeV}$

- Time delay is compatible with $p\gamma$ interaction time $t_{p\gamma} \sim 10 - 100\ \mathrm{d}$
- *Fermi* UL: stringent :-)



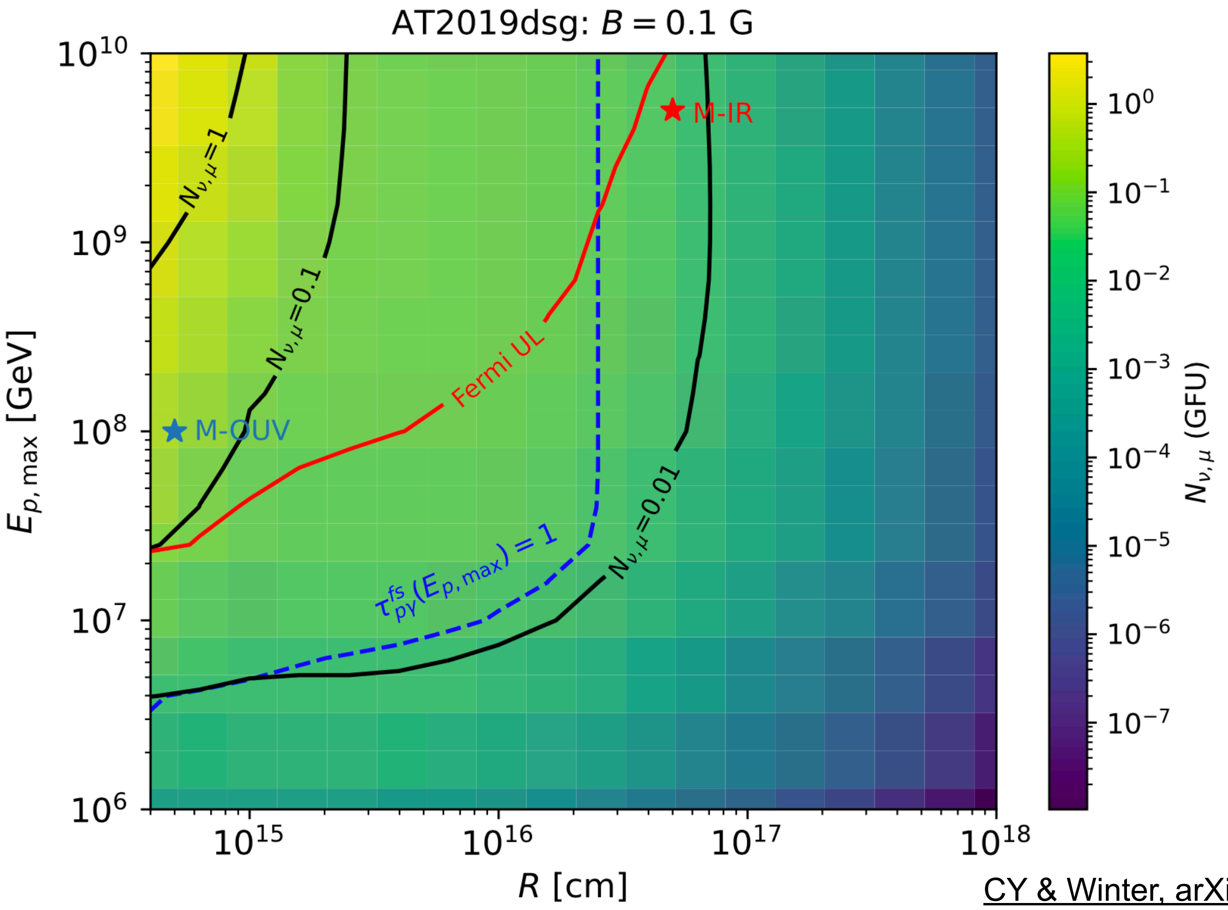


CY & Winter, arXiv: 2306.15659, ApJ

Constraints on $E_{p,\max}$, R and neutrino rates

Expected Gamma-ray Follow Up (GFU) neutrino number

$$\mathcal{N}_\nu(\mathrm{GFU}) = \int dE_\nu \int^{t_\nu} dt F_\nu(E_\nu, t) A_{\mathrm{eff}}(E_\nu)$$



CY & Winter, arXiv: 2306.15659, ApJ

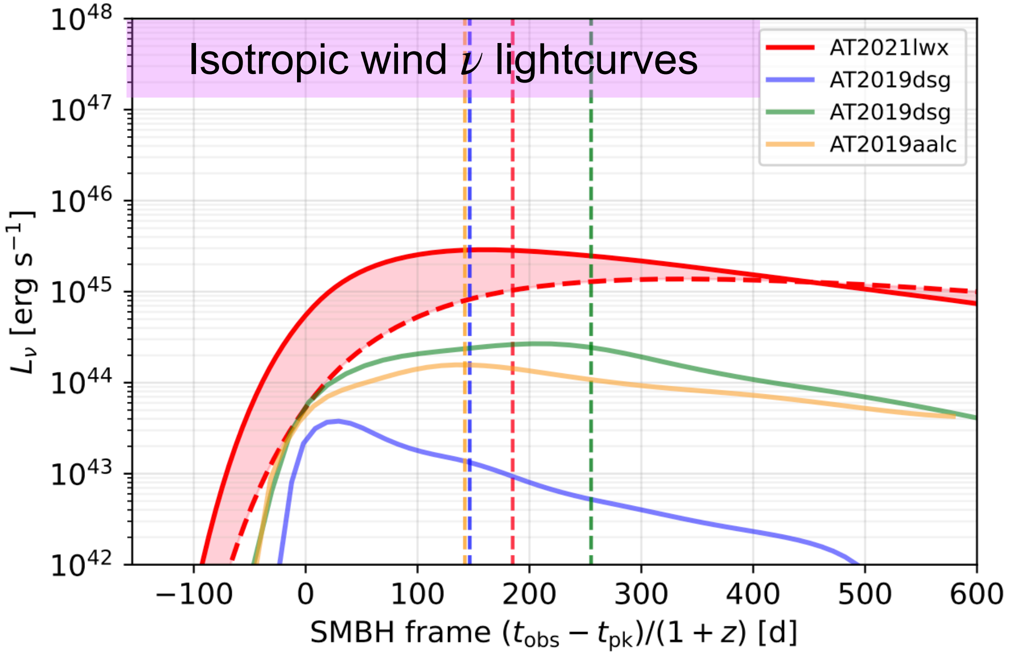
To avoid exceeding Fermi UL (red curve)

- An extended radiation zone is preferred
- Neutrino number is constrained to be 0.01-0.1 for AT2019dsg
- Expected neutrino number from AT2019dsg, 0.008-0.76 (Stein+ 2021), is consistent with Fermi UL
- Similar results for AT2019fdr

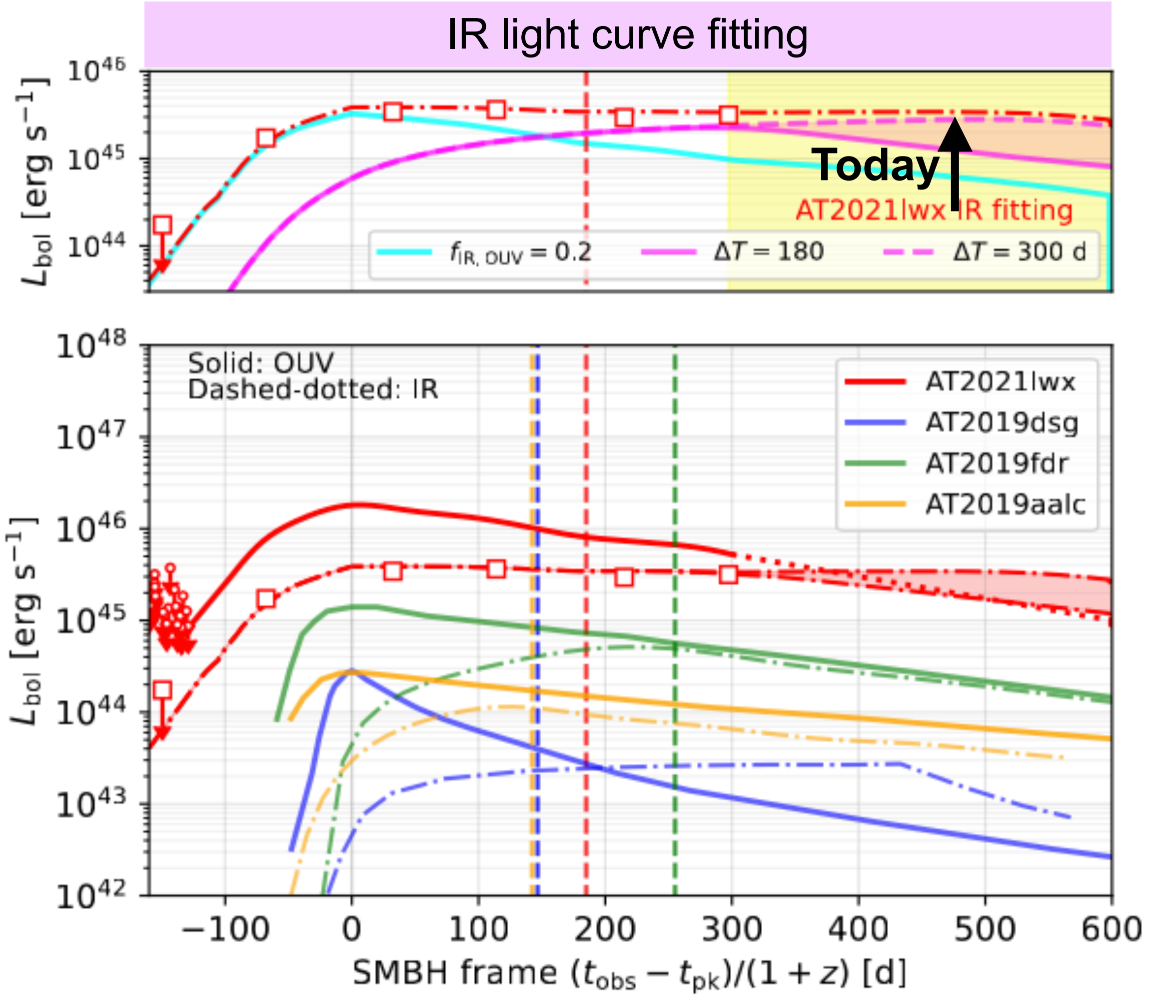
Above blue dashed line -> pg optically thick -> no significant time delay; otherwise a time delay of $t_{p\gamma} \sim 10 - 100$ d is expected

AT2021lwx: another ν-coincident TDE candidate?

- AT2021lwx (ZTF20abrbeie; aka "Barbie" Subrayan+ 2023)
- z = 0.995 (AT2019dsg 0.05, fdr 0.26, aalc 0.04)
- Super bright; SMBH mass ~ $10^8 M_\odot$ (Subrayan+ 2023)
- Likely correlated with neutrino IC220405B: angular deviation ~ 2.6 deg; neutrino time delay in SMBH frame: 185 d
- **Similarities with other 3 TDEs:** bright OUV emission; strong dust echo (Wiseman+ 2023); similar neutrino time delay in source rest frame



CY, Winter & Lunardini, arXiv: 2401.09320 ApJ



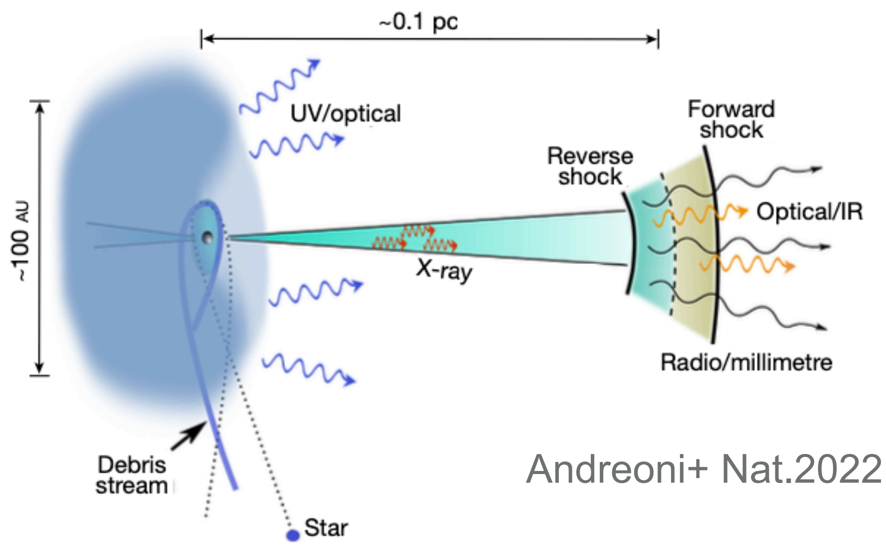
Summary (part I)

- Isotropic wind + dust echo (IR): neutrino time-delay signatures of AT2019dsg/fdr/aalc, *AT2021lwx*
- EM cascade processes in TDE winds can produce detectable (hard) X-ray/γ-ray emissions. The model can be tested/constrained by future observations or current upper limits.
- Significant (~10-100 days) time delay is expected in the $p\gamma$ optically thin regime.
- To be an efficient neutrino emitter, the accompanying cascade emission would exceed the X-ray/γ-ray constraints. Fermi upper limits implies $\lesssim$ 0.1 neutrinos per TDE! (Obscured zone?)

Future Imaging Air Cherenkov Telescopes (IACTs) touch down to $10^{-13}\ \mathrm{erg/s/cm^2}$ *in 50 GeV - 50 TeV range. TDE electromagnetic cascades would be interesting sources.*

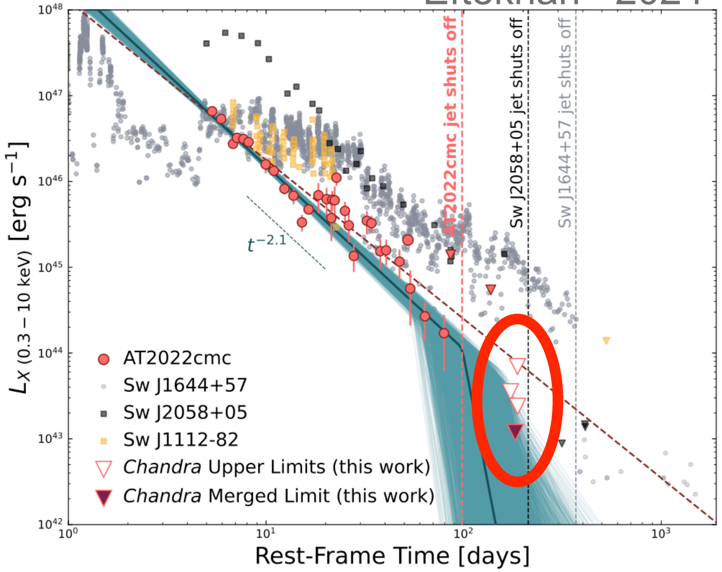
Jetted TDE: AT 2022cmc

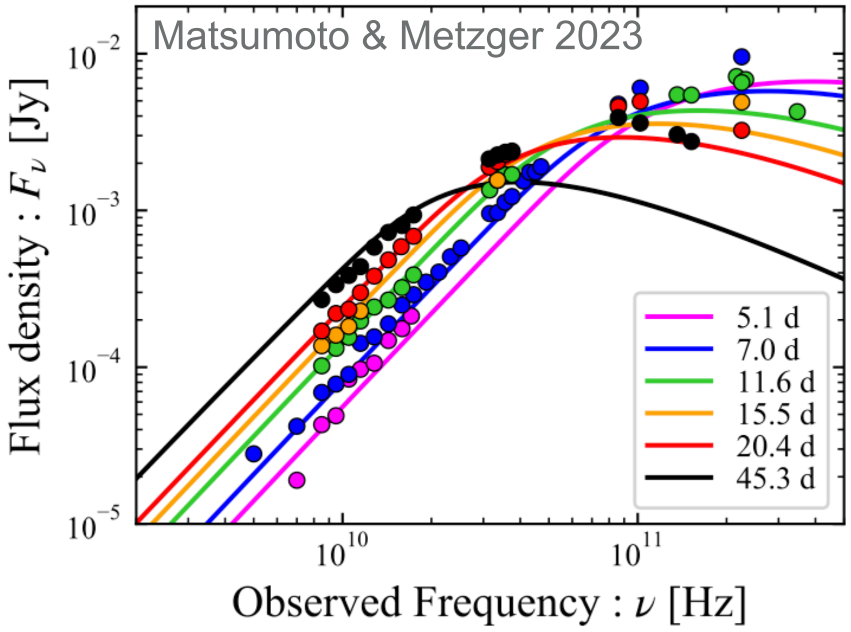
- Recently documented jetted TDE (z = 1.193, Andreoni+ Nat.2022)
- ***Bright non-thermal X-rays:*** $L_{X,\mathrm{iso}} \sim 3 \times 10^{47}$ erg/s $(T/5\ \mathrm{d})^{-2}$ relativistic jets (Pasham+ 2023) + later-time steepening (Eftekhari+ 2024)
- ***Optical***: thermal envelope (Yao+ 2024)
- ***Radio***: GRB-like jet forward shocks $(\Gamma \sim 2-5)$ propagating in the circumnuclear medium (CNM) $n_{\mathrm{cnm}} \propto R^{-k}$, $1{,}5 \lesssim k \lesssim 2.0$ (e.g., Matsumoto & Metzger 2023; Yao+ 2024; Zhou+ 2024)

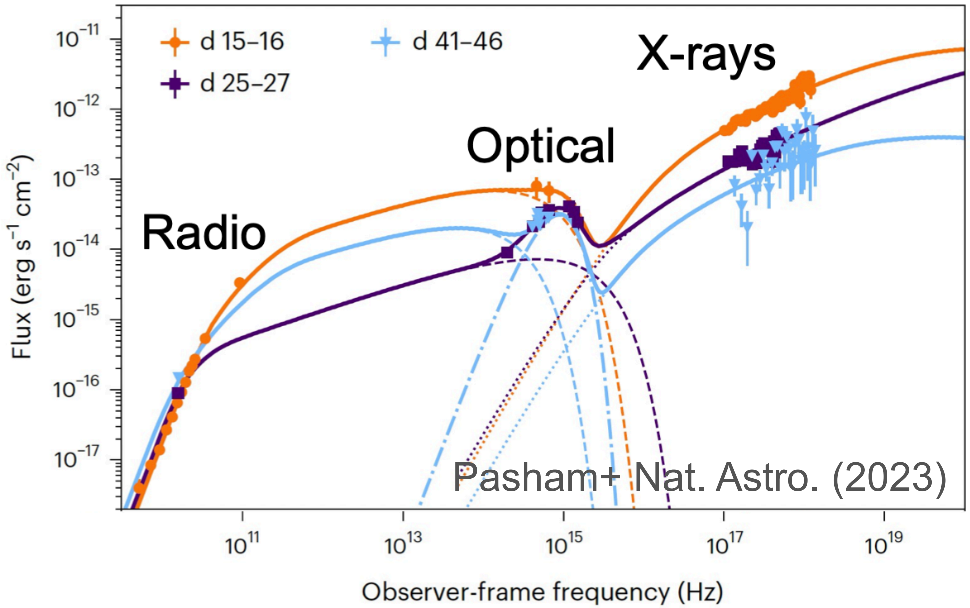


Andreoni+ Nat.2022

Eftekhari+ 2024

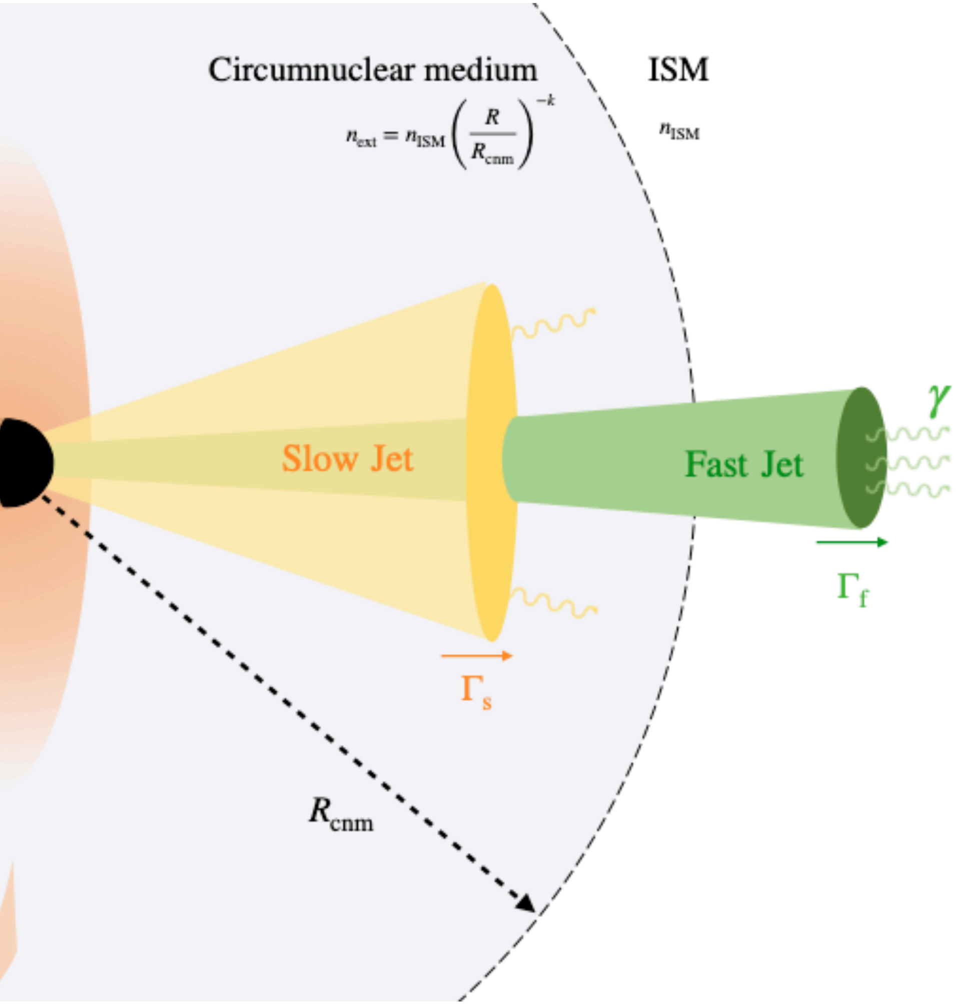






Jetted TDE: AT 2022cmc — structured jet

Narrow fast jet and wide slow jet



CY, Zhang, Winter & Murase, arXiv: 2406.11513 (ApJ in press)

Accretion rate ($\eta_{acc} \sim 0.01 - 0.1$)

t_{fb}: **fallback time**

$$\dot{M}_{BH} = \frac{\eta_{acc} M_\star}{\mathcal{C} t_{fb}} \times \begin{cases} \left(\frac{t}{t_{fb}}\right)^{-\alpha}, & t < t_{fb} \\ \left(\frac{t}{t_{fb}}\right)^{-5/3}, & t > t_{fb}, \end{cases}$$

Jet luminosities

($\eta_{f/s} \sim 0.1$, free parameter)

$$L_{f/s} = \eta_{f/s} \dot{M}_{BH} c^2,$$

CNM density profile

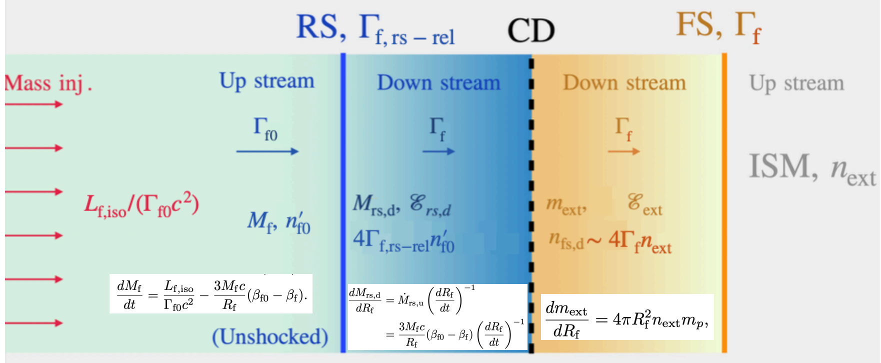
$k = 1.8,\ R_{cnm} = 10^{18}$ cm

$$n_{ext}(R) = \begin{cases} n_{ISM}\left(\frac{R}{R_{cnm}}\right)^{-k}, & R < R_{cnm} \\ n_{ISM}, & R > R_{cnm} \end{cases}$$

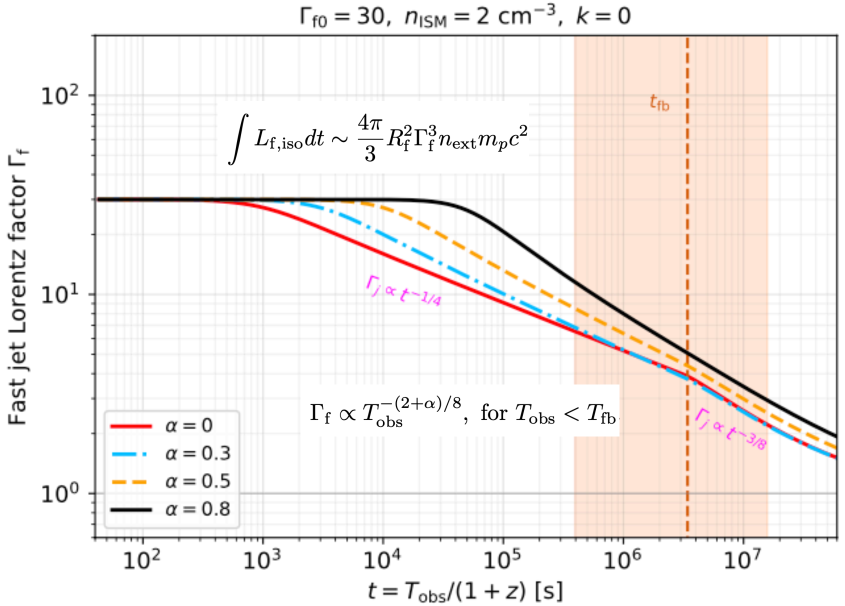
Star mass

$$M_\star \sim \frac{2 f_{bol} f_b E_{X,iso}}{\eta_{acc} \eta_f \epsilon_e^{fs} c^2} \gtrsim 3.3 M_\odot \eta_{acc,-1}^{-1} \eta_{f,-1}^{-1}$$

Fast jet evolution: persistent energy/mass injection



$$\frac{d\Gamma_f}{dR_f} = -\frac{\overbrace{(\Gamma_{fs,eff}+1)(\Gamma_f - 1)c^2 \frac{dm_{ext}}{dR_f}}^{\text{FS term}} + \overbrace{(\Gamma_f - \Gamma_{f0} - \Gamma_{rs,eff} + \Gamma_{rs,eff}\Gamma_{f,rs-rel})c^2 \frac{dM_{rs,d}}{dR_f}}^{\text{RS term}}}{(M_{rs,d} + m_{ext})c^2 + \mathcal{E}_{ext,in}\frac{d\Gamma_{fs,eff}}{d\Gamma_f} + \mathcal{E}_{rs,in}\frac{d\Gamma_{rs,eff}}{d\Gamma_f}},$$



Jetted TDE: AT 2022cmc — structured jet: spectra

Fast jet reverse shock: X-ray (fast cooling)
Slow jet forward shock: radio (SSA)

Radiation modeling

Powerlaw injection $Q_e \propto \gamma_e^{-s}$

Norm. $(4\pi R_f^2 t'_{f,\mathrm{dyn}}) \int Q_e d\gamma_e = f_e N_e$

$$\gamma_{e,\min} = (\Gamma - 1)\frac{s-2}{s-1}\frac{\epsilon_e}{f_e}\frac{m_p}{m_e}$$

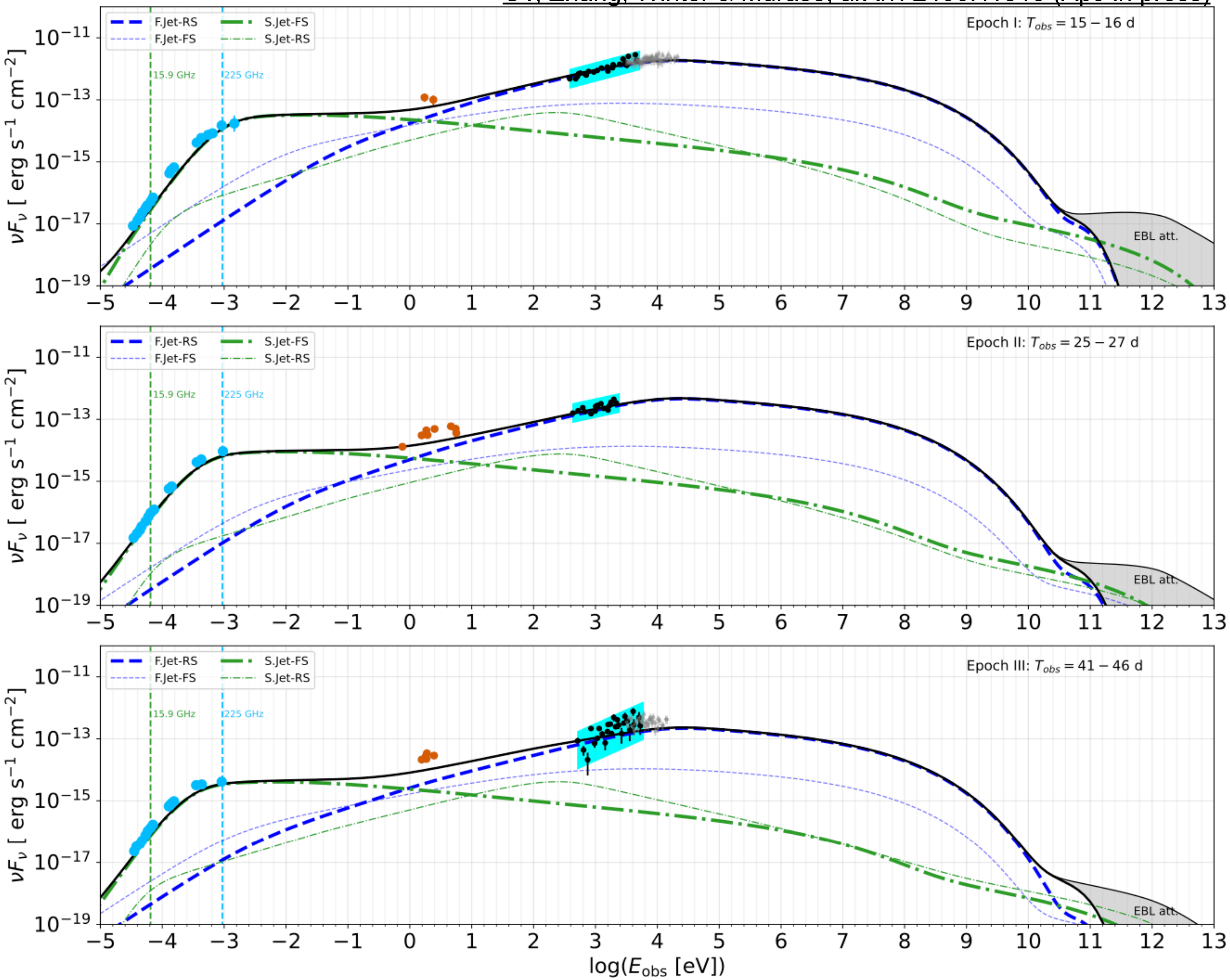
$$B_d = \sqrt{32\pi\epsilon_B \Gamma(\Gamma-1) n_{p,d} m_p c^2}$$

$\Gamma_{\mathrm{f/s}}$ for FS, $\Gamma_{\mathrm{rel}} = (\Gamma_{\mathrm{f/s}}/\Gamma_{\mathrm{f/s,0}} + \Gamma_{\mathrm{f/s,0}}/\Gamma_{\mathrm{f/s}})/2$ for RS

Fitting parameters

Universal	α	0.8
	n_{ISM}	2.0 cm^{-3}
	s	2.3
Fast, slow jets	$\eta_{\mathrm{f,s}}$	0.12, 0.04
	$\theta_{\mathrm{f,s}}$	0.15, 0.3
	$\Gamma_{\mathrm{f0,s0}}$	30, 4.0
FS, RS	$\epsilon_e^{\mathrm{fs,rs}}$	0.1, 0.2
	$\epsilon_B^{\mathrm{fs,rs}}$	3.0×10^{-3}, 0.1
	$f_e^{\mathrm{fs,rs}}$	1.0, 1.5×10^{-3}

CY, Zhang, Winter & Murase, arXiv: 2406.11513 (ApJ in press)



Jetted TDE: AT 2022cmc — structured jet: light curves

Optical:

- Originated from a thermal envelope (Yao+, 2024)
- ULs for structured jets

X-rays:

- Well described by persistently powered reverse shock model
- X-ray lightcurve steepening after ~100 d and the late time ULs after ~200d (red points, Eftekhari+ 2024): *Jet break correction*

$$f_{\rm br} = \frac{1}{1+(\Gamma_{\rm f}\theta_{\rm f})^{-2}} \rightarrow (\Gamma_{\rm f}\theta_{\rm f})^2,\ T_{\rm obs} > T_{\rm br}\ (\Gamma_{\rm f} < \theta_{\rm f}^{-1})$$

- Analytically consistent,

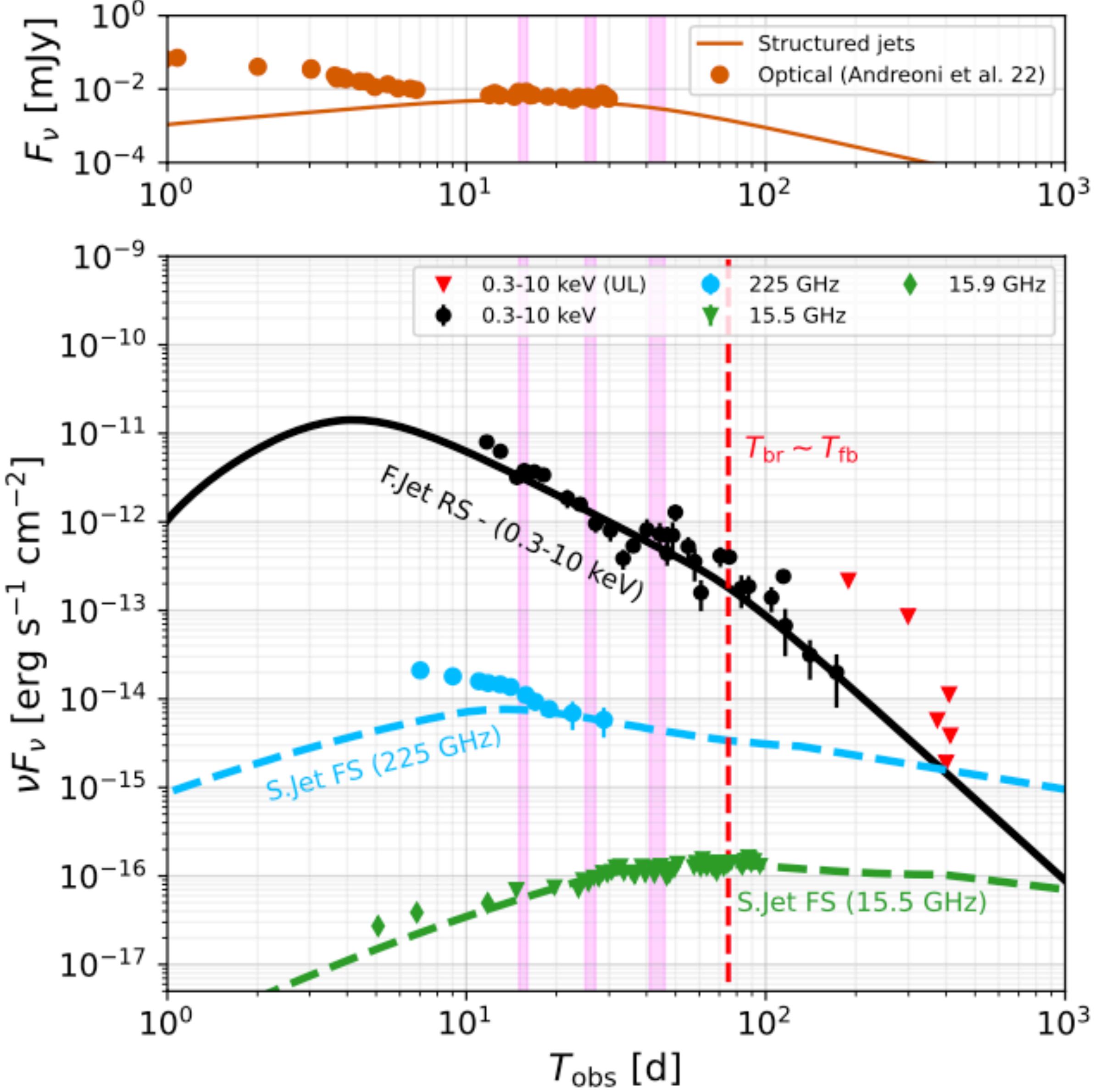
$$\nu F_\nu^{(\rm rs)} \propto \begin{cases} T_{\rm obs}^{-[5\alpha+\alpha(s-1)]/4}, & T_{\rm obs} < T_{\rm br} \simeq T_{\rm fb} \\ T_{\rm obs}^{-(2s+25)/12}, & T_{\rm obs} > T_{\rm br} \simeq T_{\rm fb}. \end{cases}$$

- Variability timescale: *active engine* ($\sim R_{\rm Sch}/c$, short term) and *reverse shock* ($\sim R_{\rm f}/(\Gamma_{\rm f}^2 c)$, long term)

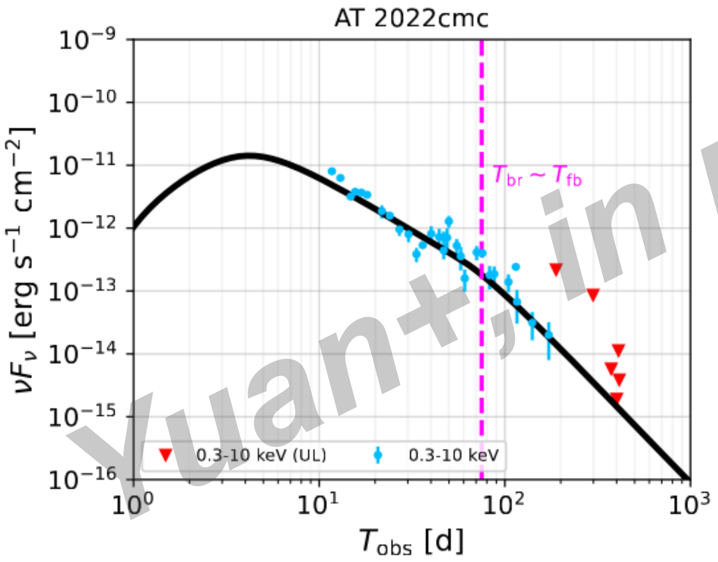
Radio:

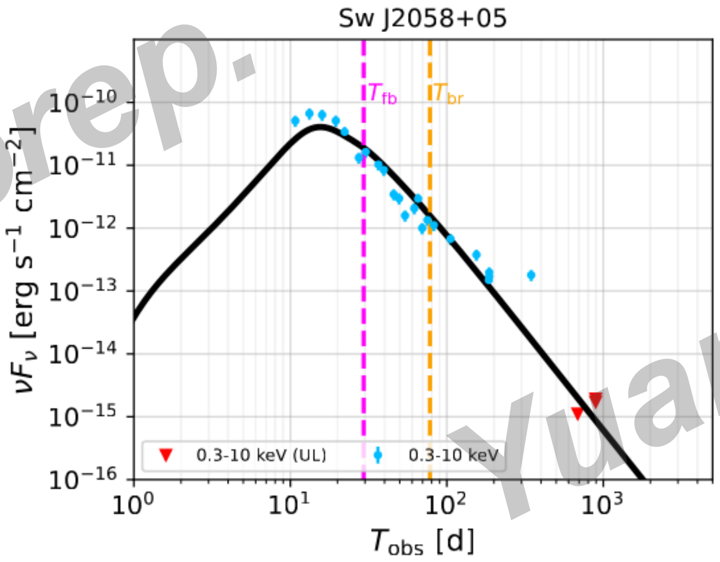
Slow jet forward shock can well describe 16 GHz and later-time 225 GHz light curves

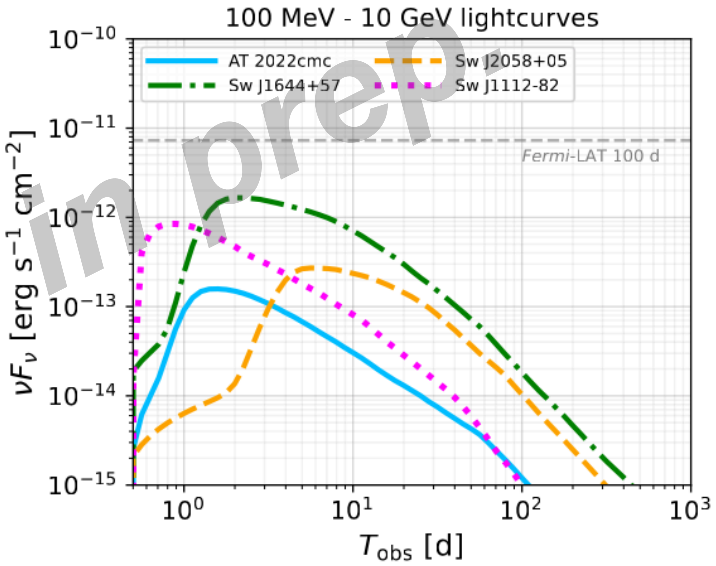
CY, Zhang, Winter & Murase, arXiv: 2406.11513 (ApJ in press)

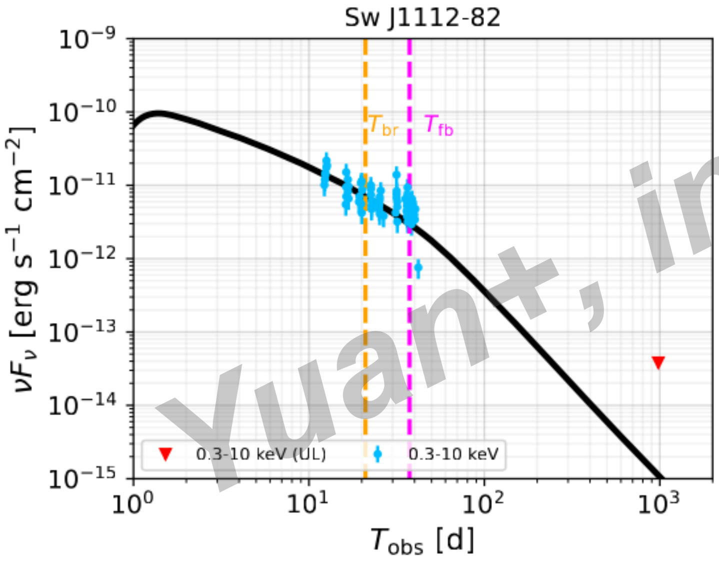


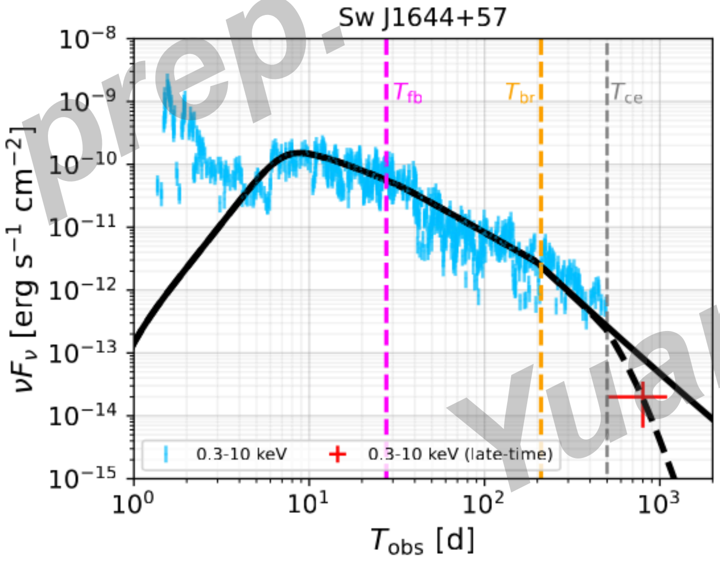
Jetted TDE X-ray afterglows: reverse shock model

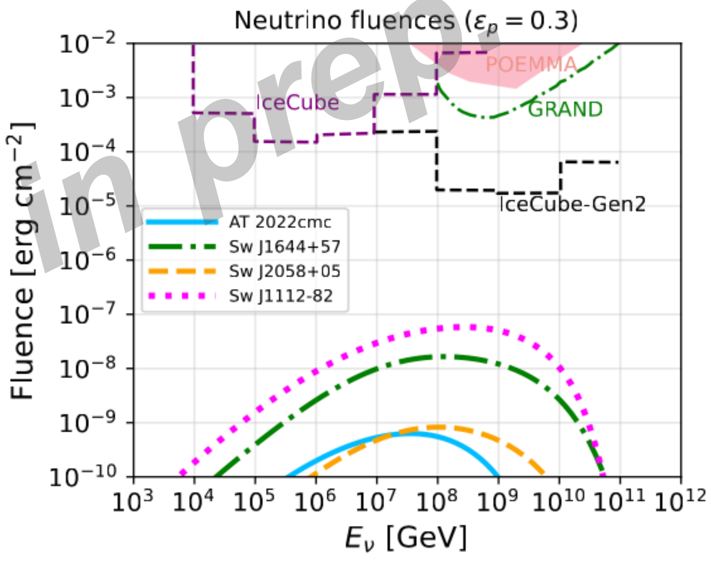












Summary (the final)

- Isotropic wind + dust echo (IR): neutrino time-delay signatures of AT2019dsg/fdr/aalc, *AT2021lwx*
- EM cascade processes in TDE winds can produce detectable (hard) X-ray/γ-ray emissions. The model can be tested/constrained by future observations or current upper limits.
- Significant (~10-100 days) time delay is expected in the $p\gamma$ optically thin regime.
- To be an efficient neutrino emitter, the accompanying cascade emission would exceed the X-ray/γ-ray constraints. Fermi upper limits implies $\lesssim$ 0.1 neutrinos per TDE! (Obscured zone?)

Future Imaging Air Cherenkov Telescopes (IACTs) touch down to 10^{-13} $\mathrm{erg/s/cm^2}$ in 50 GeV - 50 TeV range. TDE electromagnetic cascades would be interesting sources.

- A persistently powered structured (two-component) jet model could explain the radio (e.g., slow jet, forward shock) and X-ray (fast jet, reverse shock) spectra/lightcurves of jetted AT 2022cmc
- The jet break may lead to the late-time steepening in X-ray lightcurves in all 4 jetted TDEs (in prep.)

Backup Slides

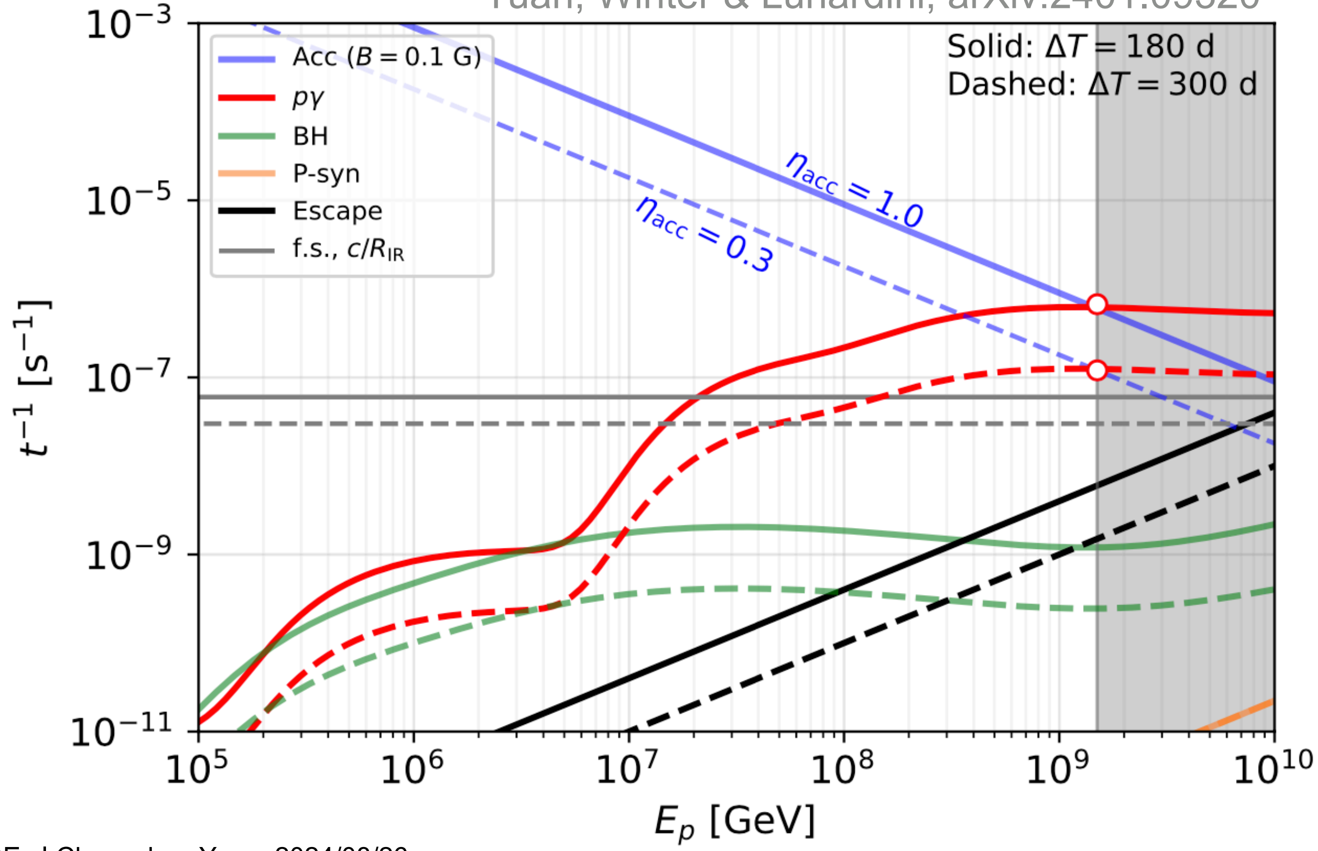
Proton maximum energy

$$\text{Acceleration rate}: t_{\rm acc}^{-1} = \eta_{\rm acc} c/R_L = \eta_{\rm acc} eBc/E_p$$

Larger $\eta_{\rm acc}$ -> more efficient acceleration

E_max is achievable for a reasonable $\eta_{\rm acc} \sim 0.3 - 1$ by balancing acc. rate (blue lines) to energy loss rate (red curves), similar to AT2019dsg/fdr/aalc

Yuan, Winter & Lunardini, arXiv:2401.09320

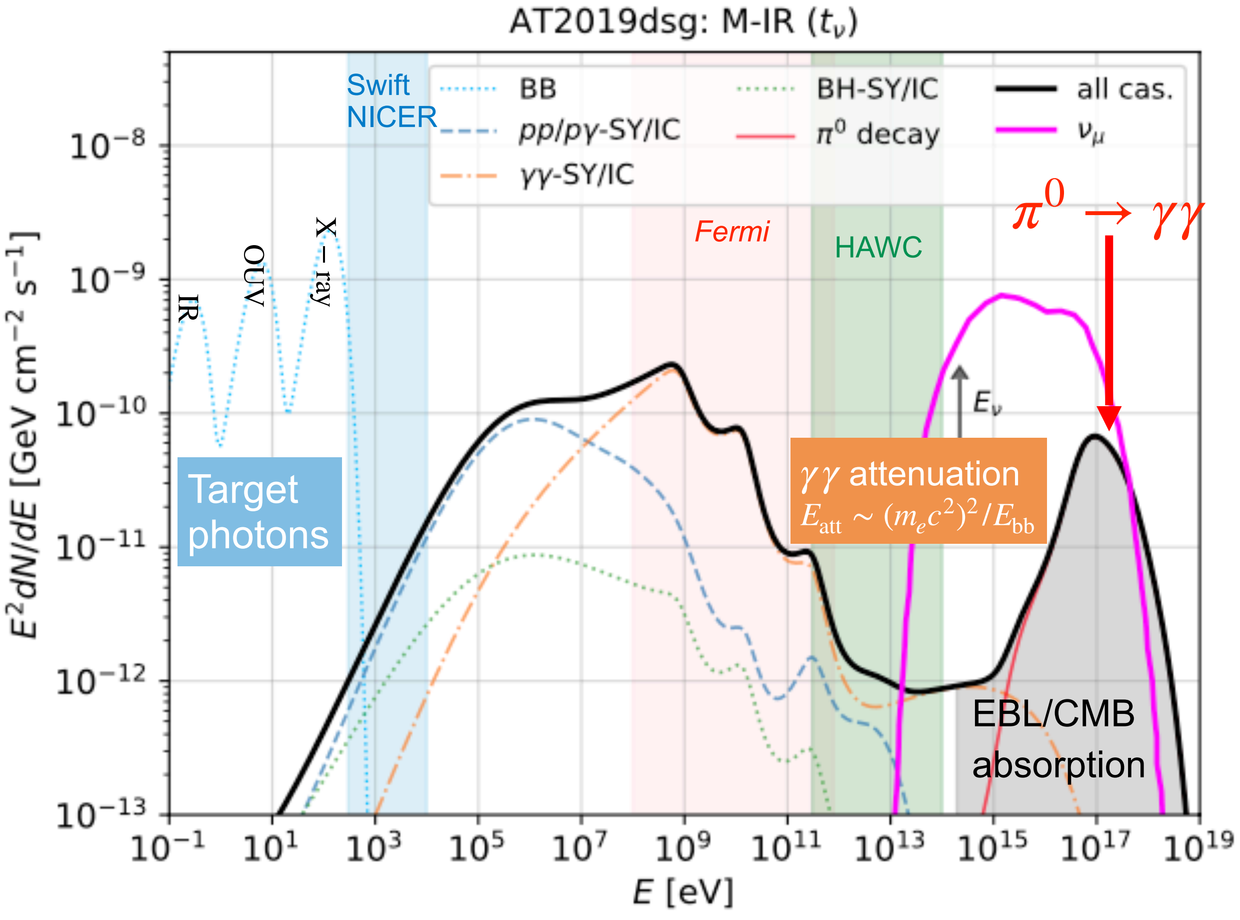


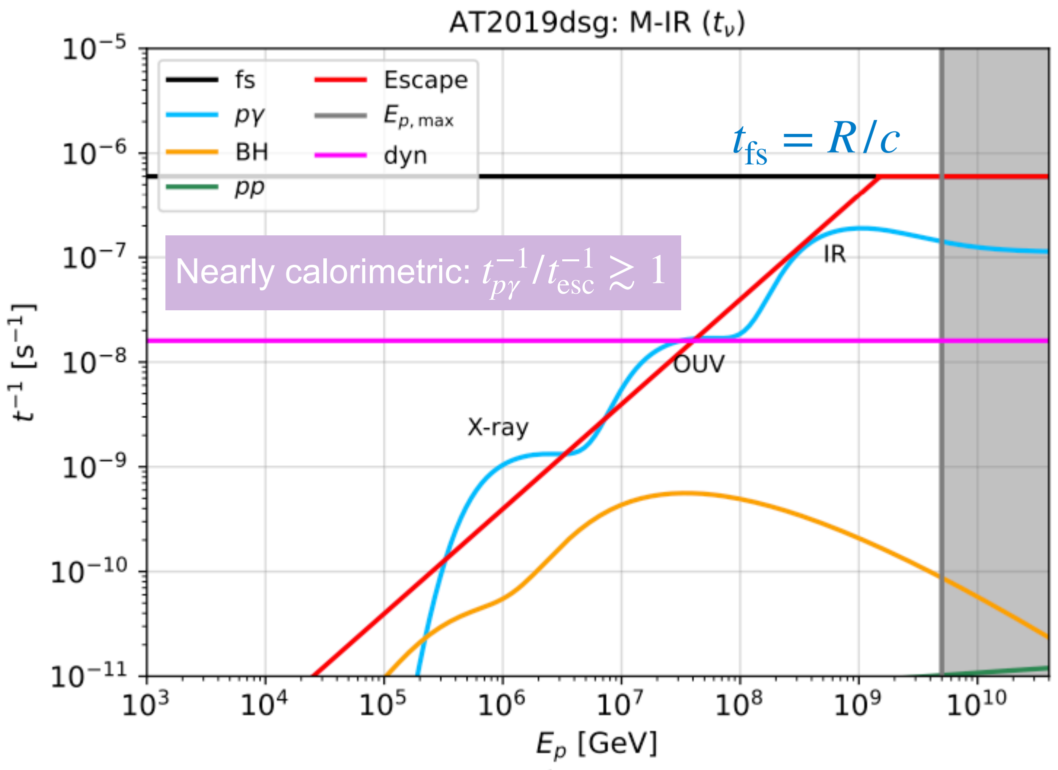
EM cascade spectra of AT2019dsg: IR target photons

$p\gamma$ optically thin $t_{p\gamma}^{-1}/t_{\rm fs}^{-1} < 1$: $(\pi^{\pm} \rightarrow e^{\pm} \rightarrow \mathrm{SY/IC})$ + $(\gamma\gamma \rightarrow e^{\pm} \rightarrow \mathrm{SY/IC})$

Parameters: $\varepsilon_{\rm diss} = 0.2$

$B = 0.1\ \mathrm{G},\ R = R_{IR},\ E_{p,\max} = 5 \times 10^{9}\ \mathrm{GeV}$



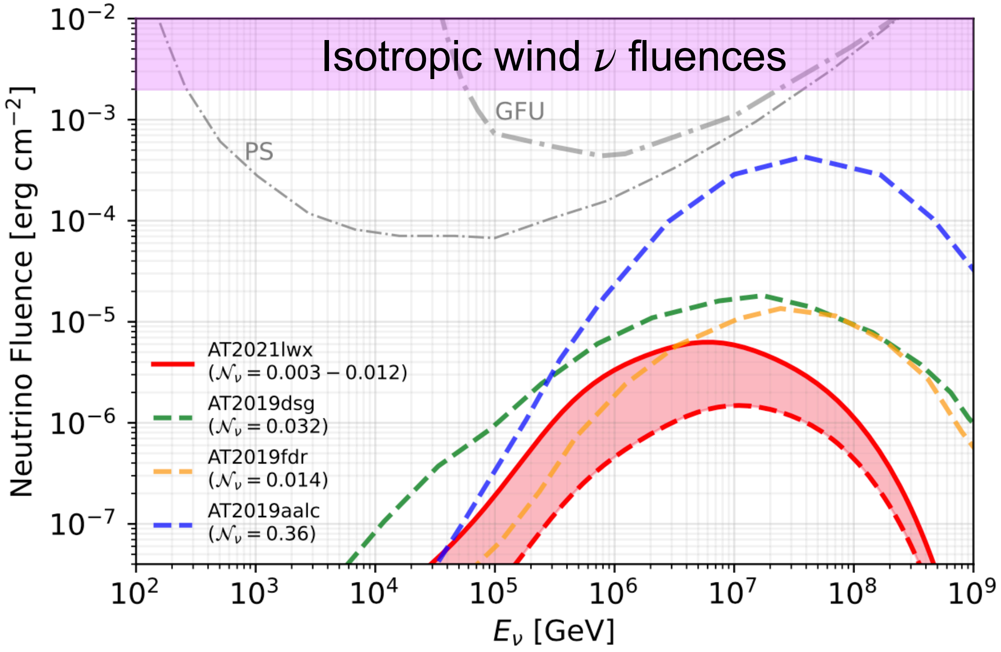


$p\gamma$ efficient (calorimetric) but not very fast (optically thin)

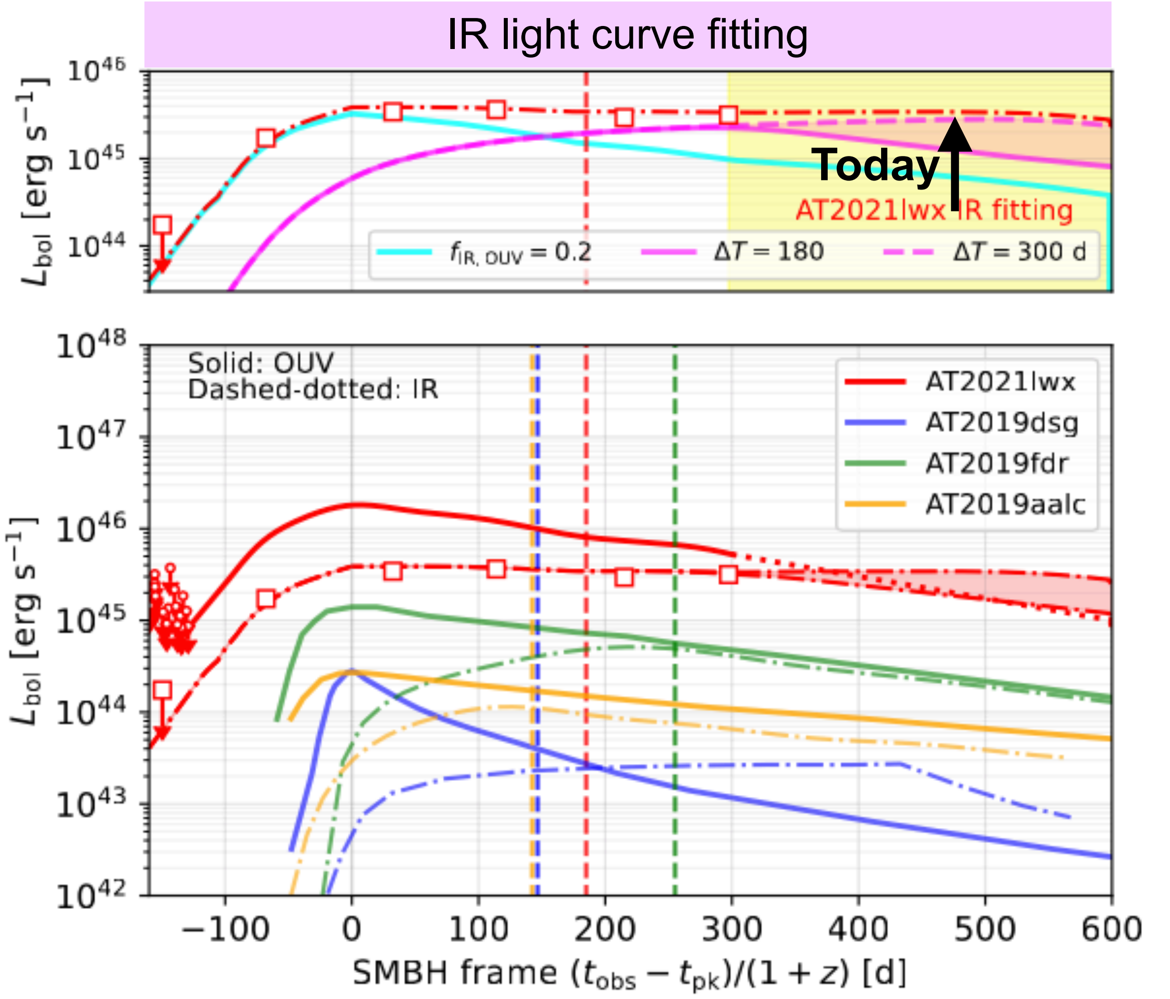
CY & Winter, arXiv: 2306.15659, ApJ

AT2021lwx: another ν-coincident TDE candidate?

- AT2021lwx (ZTF20abrbeie; aka "Barbie" Subrayan+ 2023)
- z = 0.995 (AT2019dsg 0.05, fdr 0.26, aalc 0.04)
- Super bright; SMBH mass ~ $10^8 M_\odot$ (Subrayan+ 2023)
- Likely correlated with neutrino IC220405B: angular deviation ~ 2.6 deg; neutrino time delay in SMBH frame: 185 d
- **Similarities with other 3 TDEs:** bright OUV emission; strong dust echo (Wiseman+ 2023); similar neutrino time delay in source rest frame



CY, Winter & Lunardini, arXiv: 2401.09320 ApJ



Test lepton ($e^{\pm}$) injections

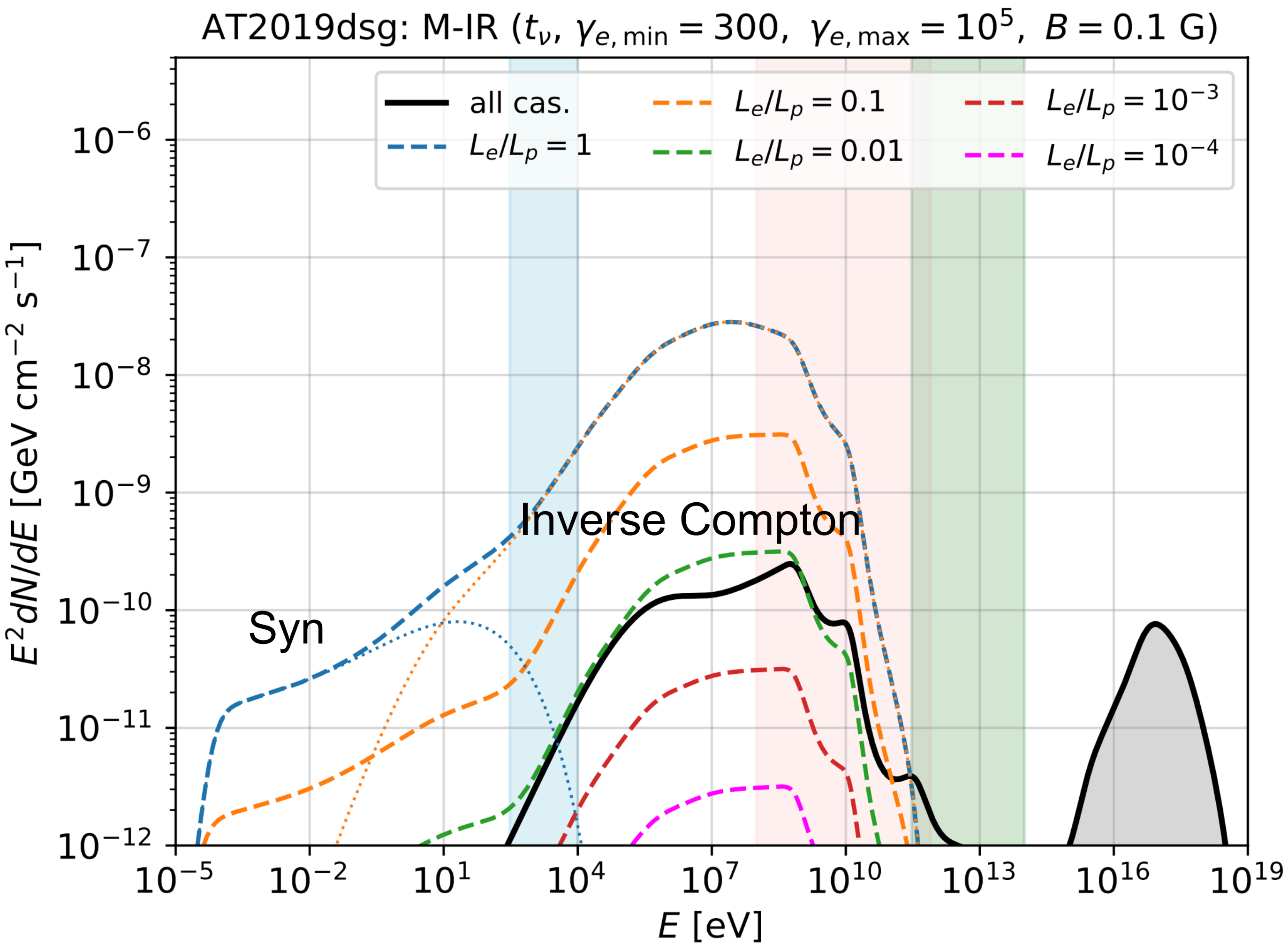
Electron injection spectra

- $dN_e/d\gamma_e \propto \gamma_e^{-2}$
- $\gamma_{e,\min} = 300,\ \gamma_{e,\max} = 10^5$ (AGNs)
- Magnetic field 0.1 G
- Lepton loading factor L_e/L_p varies from 10^{-4} to 1 (magenta to blue dashed lines).

Cascade emission dominates if $L_e/L_p < 10^{-2}$

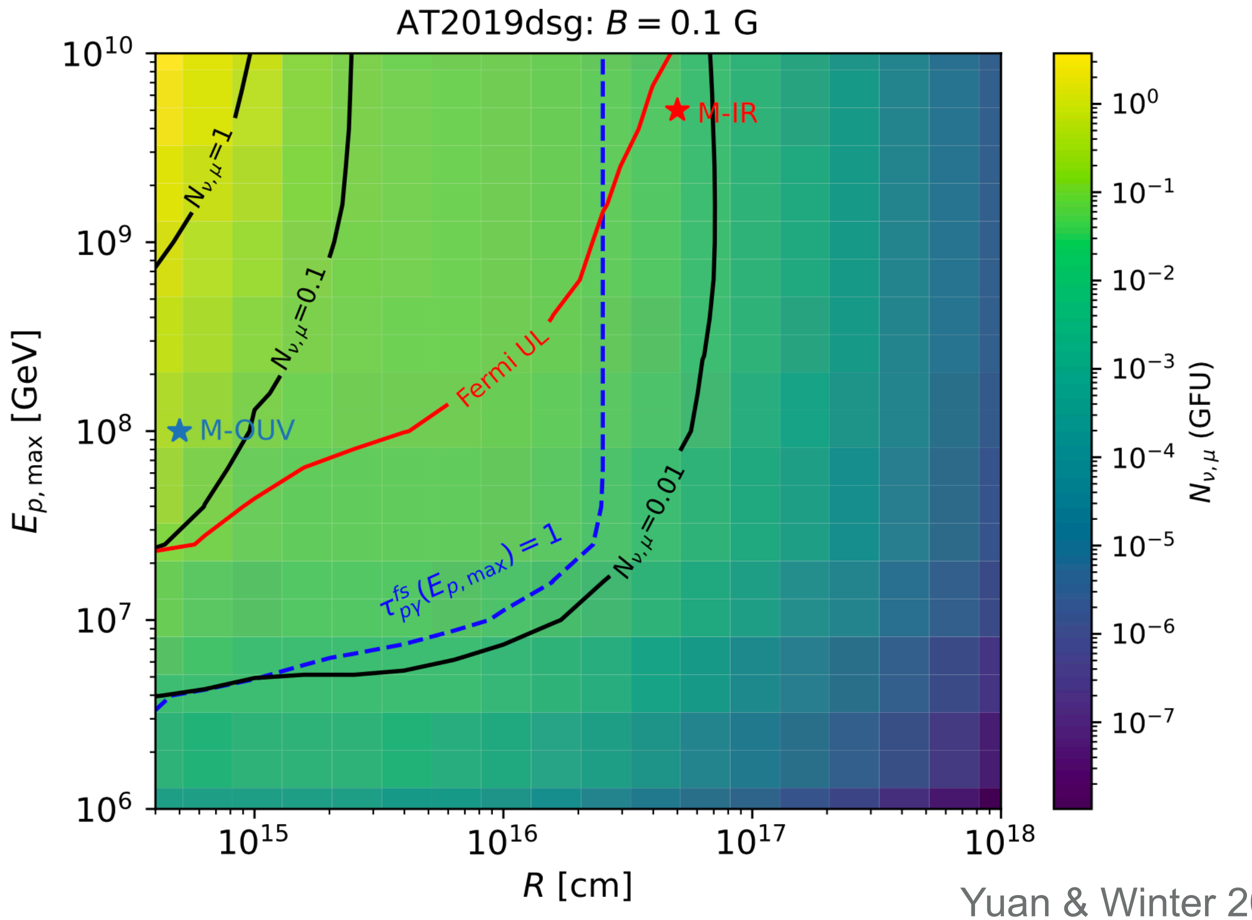
(Supported by the absence of radio signals accompanying OUV/IR)

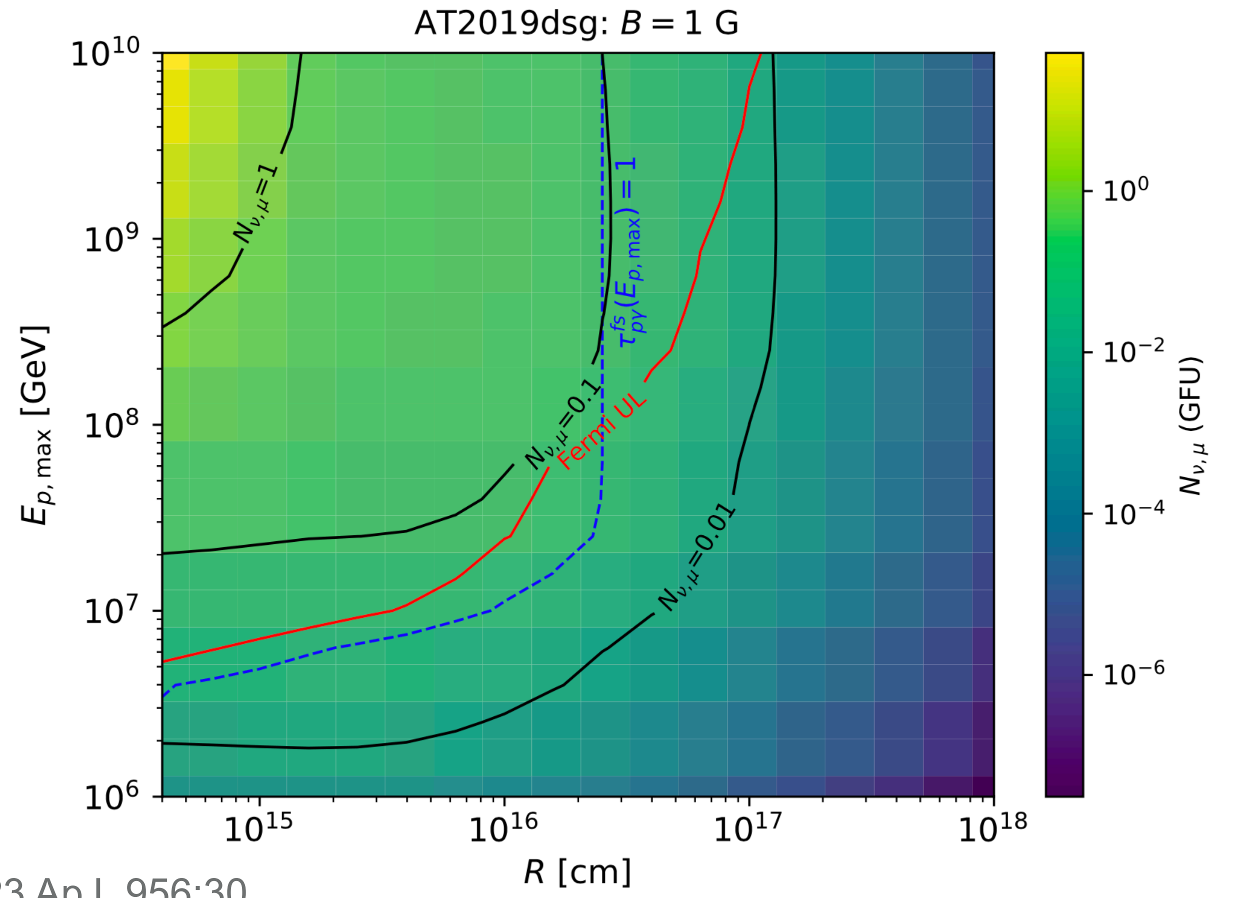
Caveat: leptonic contribution depends on electron minimum energy and magnetic field strengths



Constraints on $E_{p,\max}$, R and neutrino rates: impact of B

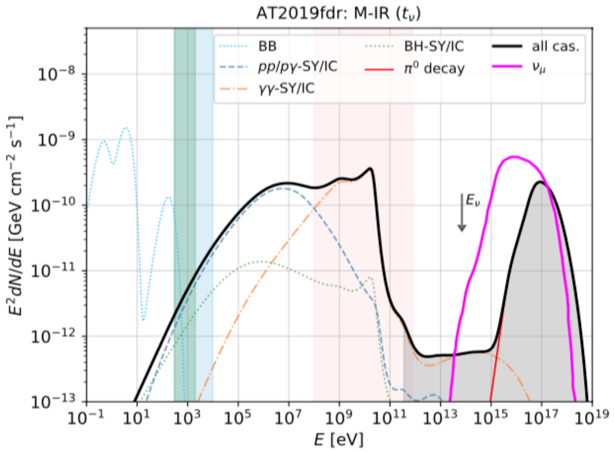
- CRs are more strongly confined with a stronger magnetic field, which enables a less compact region to be a promising neutrino emitter. (Easier to overshoot γ-ray up limits)
- Conclusions do not change significantly

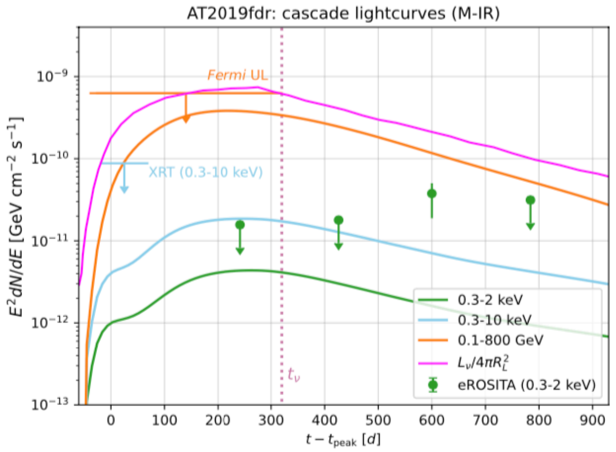


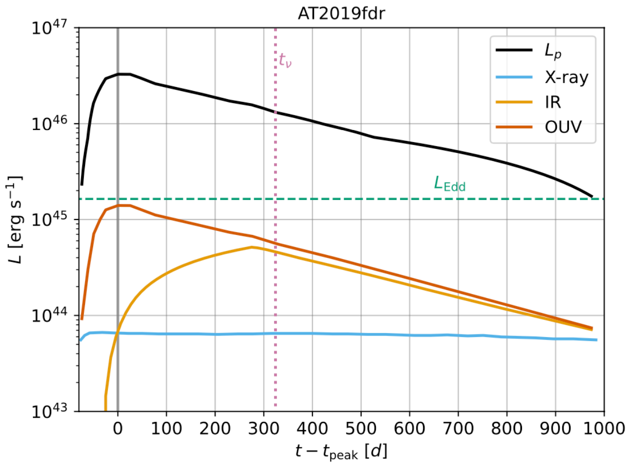


Yuan & Winter 2023 ApJ 956:30

AT2019fdr







$z = 0.267$

$M_{\rm SMBH} = 1.3 \times 10^7 M_\odot$

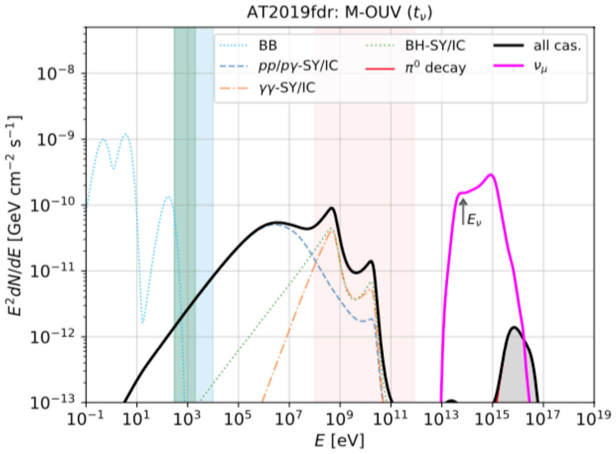
$E_\nu = 82$ TeV

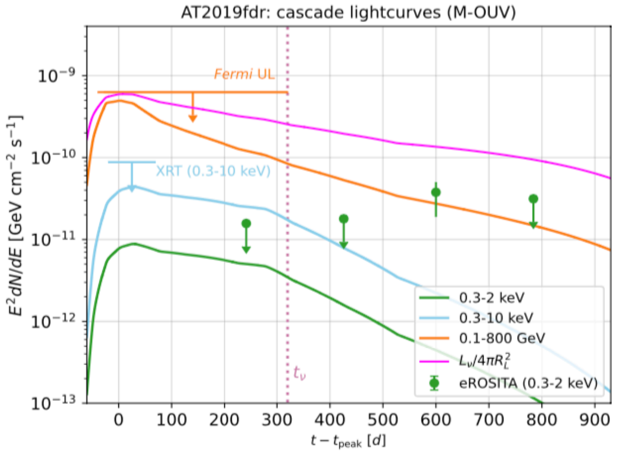
M-IR:

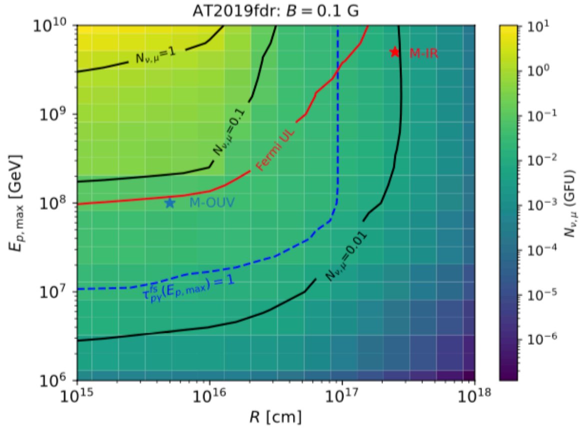
- $R = 5 \times 10^{15}$ cm
- $E_{p,\max} = 10^8$ GeV

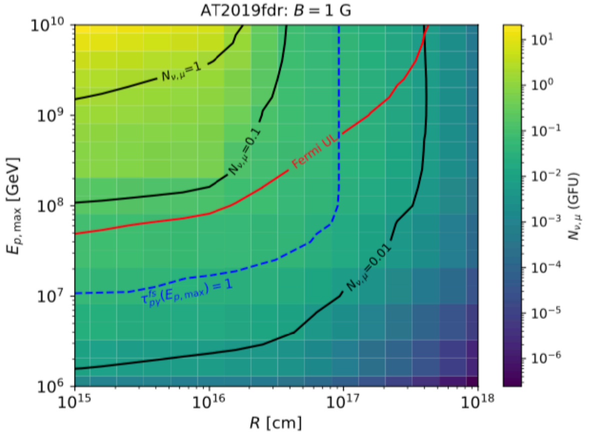
M-OUV:

- $R = 2.5 \times 10^{17}$ cm
- $E_{p,\max} = 5 \times 10^9$ GeV



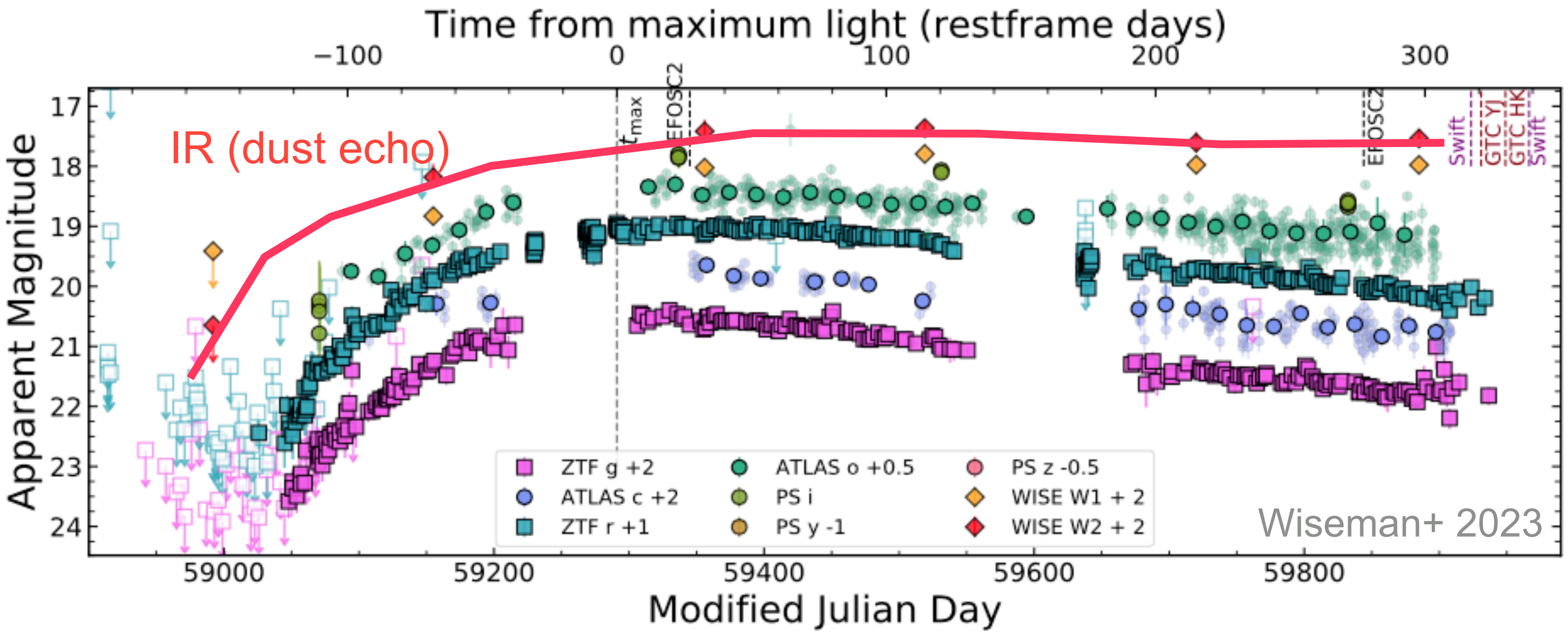






A Fourth Candidate for a Neutrino-Coincident TDE??

- AT2021lwx (ZTF20abrbeie; aka "Barbie" Subrayan+ 2023)
- Very far away: z = 0.995 (0.05 for AT2019dsg, 0.26 for AT2019fdr, 0.04 for aalc)
- Super bright —- peak (IR-corrected) OUV bolometric luminosity: > 10^{46} erg s^{-1} (nearly super-Eddington)
- SMBH mass ~ $10^8 M_\odot$, $M_\star \sim 14 M_\odot$ (Subrayan+ 2023)
- Potential correlation with neutrino IC220405B: angular deviation ~ 2.6 deg; neutrino time delay in SMBH frame: 185 d
- **Similarities with other 3 TDEs:** bright thermal OUV emission; strong dust echo (Wiseman+ 2023); similar neutrino time delay in source rest frame



Caveat:
AT2021lwx is not uniquely identified as TDEs of very large star mass; could be produced by the accretion of a giant molecular cloud onto a SMBH of $10^8 - 10^9 M_\odot$ (Wiseman+ 2023)

AT2021lwx

- Parameters and EM cascade SEDs

Table 1. Observational and Model Parameters for AT2021lwx

Description	Parameter	Value
SMBH mass $[M_\odot]$	$M_{\rm BH}$	10^8
Star mass $[M_\odot]$	M_*	14
Redshift	z	0.995
OUV peak time (MJD)	$t_{\rm pk}$	59291
Peak accretion rate	$\dot{M}_{\rm BH}(t_{\rm pk})$	$39L_{\rm Edd}/c^2$
Accreted Mass	$\int \dot{M}_{\rm BH}dt$	$M_*/2$
Neutrino observation	IC220405B	
Detection time [d]	$t_\nu - t_{\rm pk}$	$\sim$370
Energy [TeV]	E_ν	106
Angular deviation [°]	$\Delta\theta$	$2.7^{+1.7}_{-1.3}$
IR model		
Proton efficiency	ϵ_p	0.2
Accretion component	$f_{\rm IR,OUV}$	0.2
Dust echo component	$f_{\rm IR,DE}$	0.3 (0.4)
IR time delay [d]	ΔT	180 (330)
Radius [cm]	$R_{\rm IR}$	5.4×10^{17} (10^{18})
Max proton energy [GeV]	$E_{p,\rm max}$	1.5×10^9
Magnetic field [G]	B	0.1
OUV energy	$\int L_{\rm OUV}dt$	$0.26\ M_\odot c^2$
IR energy	$\int L_{\rm IR}dt$	$0.1\text{-}0.13 M_\odot c^2$