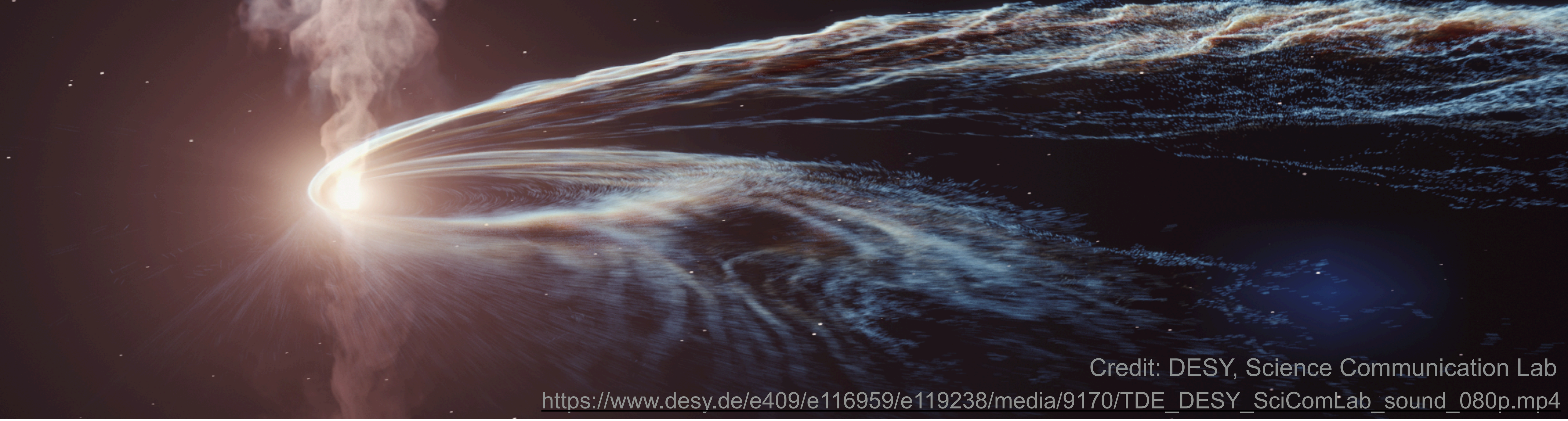

Credit: DESY, Science Communication Lab
https://www.desy.de/e409/e116959/e119238/media/9170/TDE_DESY_SciComLab_sound_080p.mp4

Multi-Messenger Modeling of Neutrino-Coincident Tidal Disruption Events

Chengchao Yuan
yuan-cc.github.io

DESY AP Seminar
November 17, 2023

HELMHOLTZ

Multi-Messenger Modeling of Neutrino-Coincident Tidal Disruption Events

- Theoretical and observational pictures of TDEs
- Particle interactions and isotropic winds models
- Neutrino and EM cascade emissions from neutrino-emitting TDEs, AT2019dsg and AT2019fdr
- A fourth neutrino-coincident with strong dust echo??
- Open questions and outlook

Tidal disruption events

When a massive star passes close enough to a SMBH

- The star can be ripped apart by the tidal force at tidal radius

$$r_T = (M/m_\star)^{1/3} r_\star \simeq 5\times 10^{12}\ \text{cm}\left(\frac{M}{10^6 M_\odot}\right)^{1/3}\frac{r_\star}{r_\odot}\left(\frac{m_\star}{M_\odot}\right)^{-1/3}$$

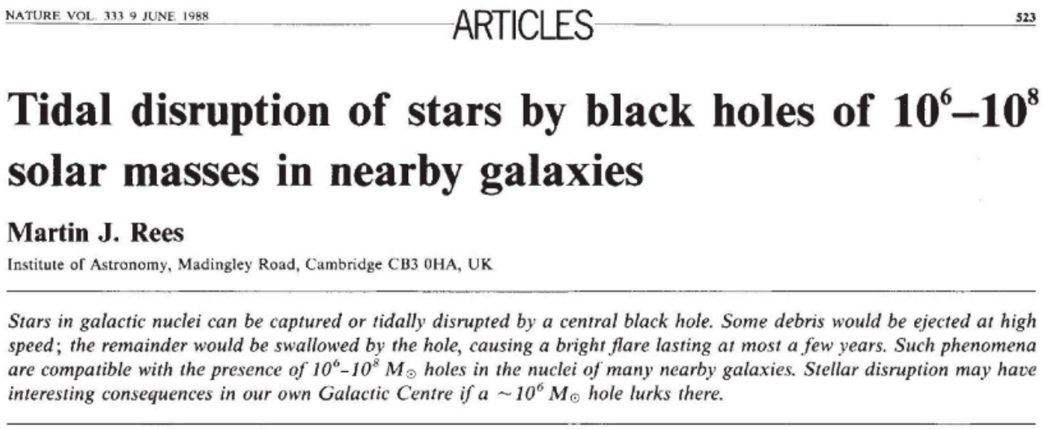
- Should be larger than Schwarzschild radius of SMBH, $r_s = 2GM/c^2 \simeq 3\times 10^{11}\ \text{cm}\ M_6$
- A theoretical up limit of SMBH mass in TDE

$$M < 3.6\times 10^8 M_\odot \left(\frac{m_\star}{M_\odot}\right)^{2-\frac{3}{2}\xi}$$

to disrupt a main sequence star of radius

$$r_\star = R_\odot (M_\star/M_\odot)^{(1-\xi)}$$

$\xi \approx 0.4$ for $M_\star < 10 M_\odot$ (Kippenhahn & Weigert 1990)



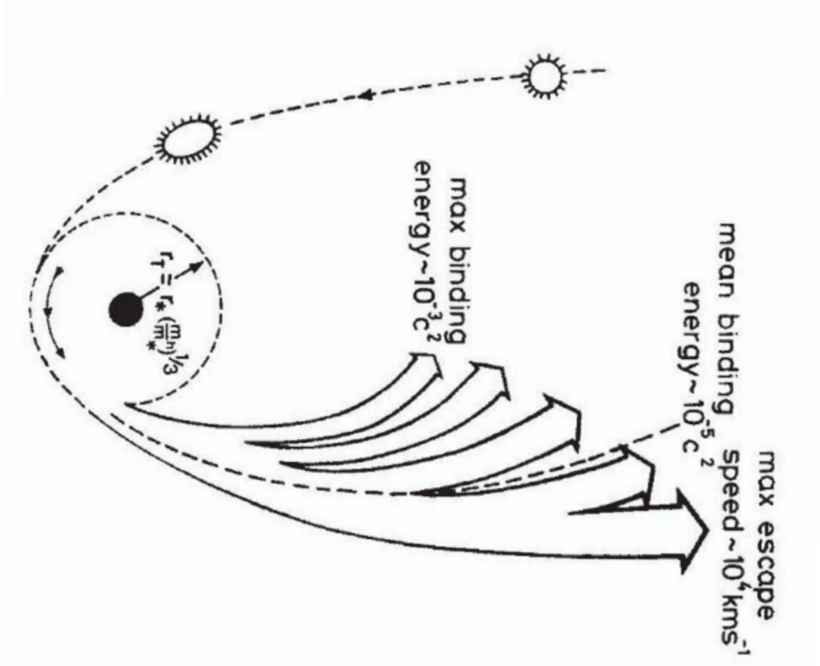
NATURE VOL. 333 9 JUNE 1988 ARTICLES 523

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 $\sim 10^6$ $M_\odot$ hole lurks there.

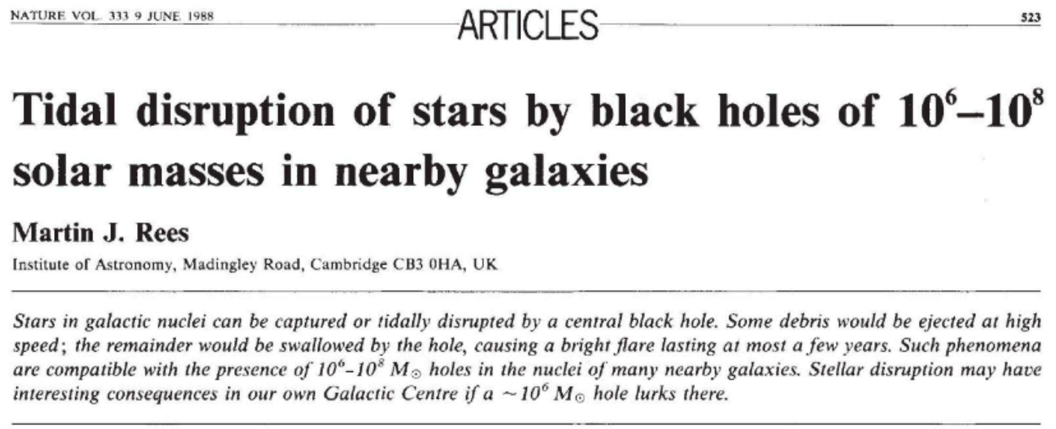
Martin J. Rees, Nature 1988



Tidal disruption events

When a massive star passes close enough to a SMBH

- ~ 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

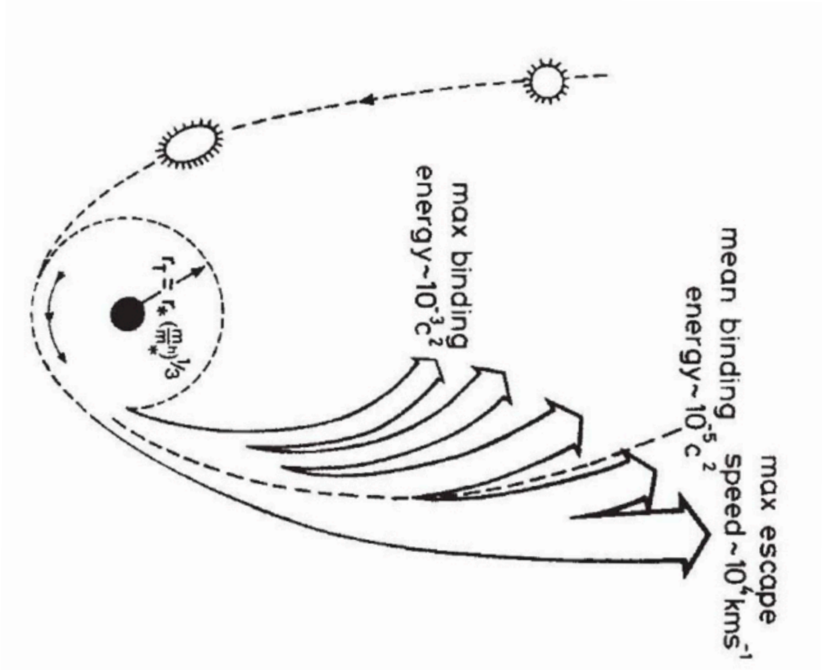
Tidal disruption of stars by black holes of 10^6–10^8 solar masses in nearby galaxies

Martin J. Rees

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

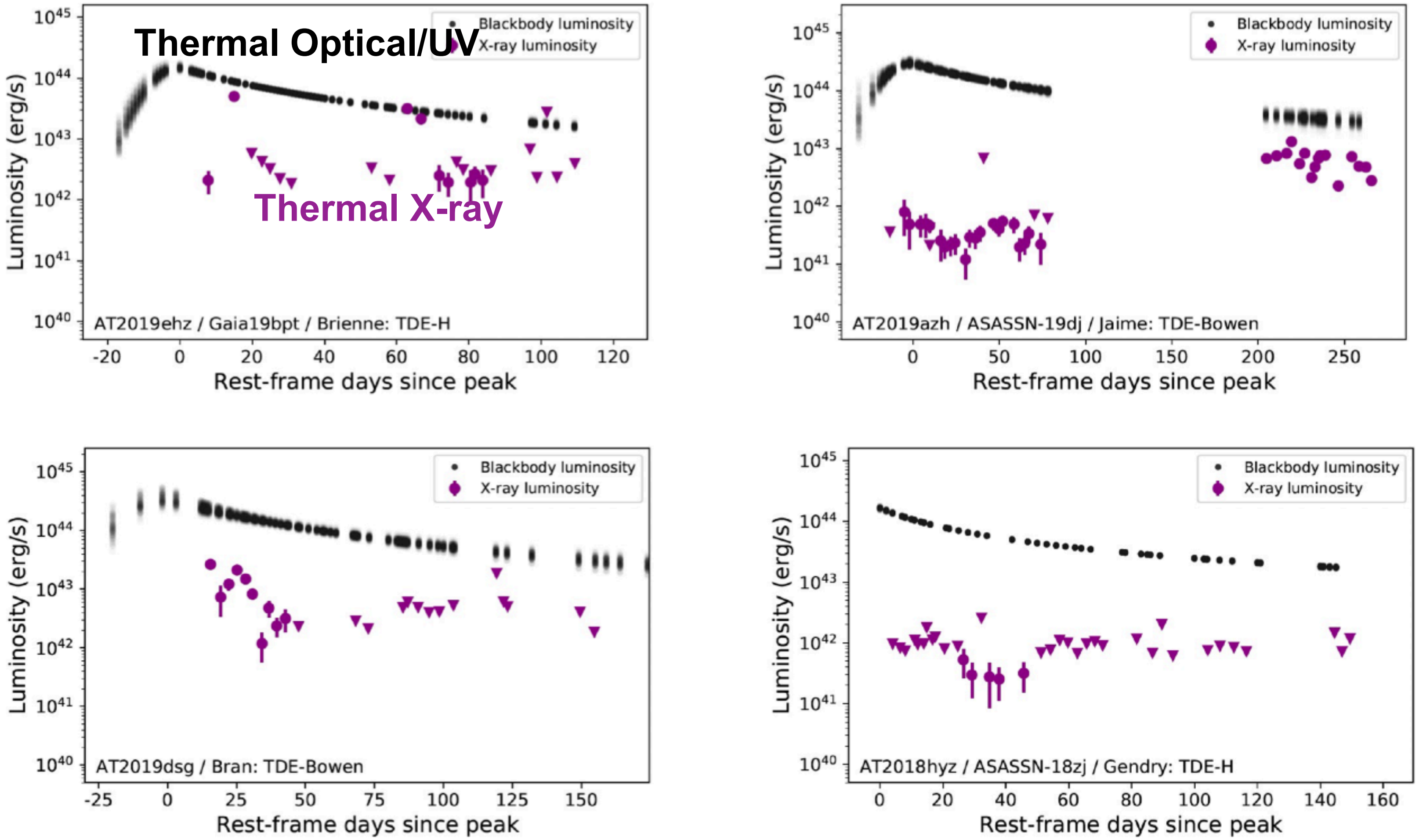
Stars in galactic nuclei can be captured or tidally disrupted by a central black hole. Some debris would be ejected at high speed; the remainder would be swallowed by the hole, causing a bright flare lasting at most a few years. Such phenomena are compatible with the presence of 10^6–10^8 $M_\odot$ holes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

Martin J. Rees, Nature 1988



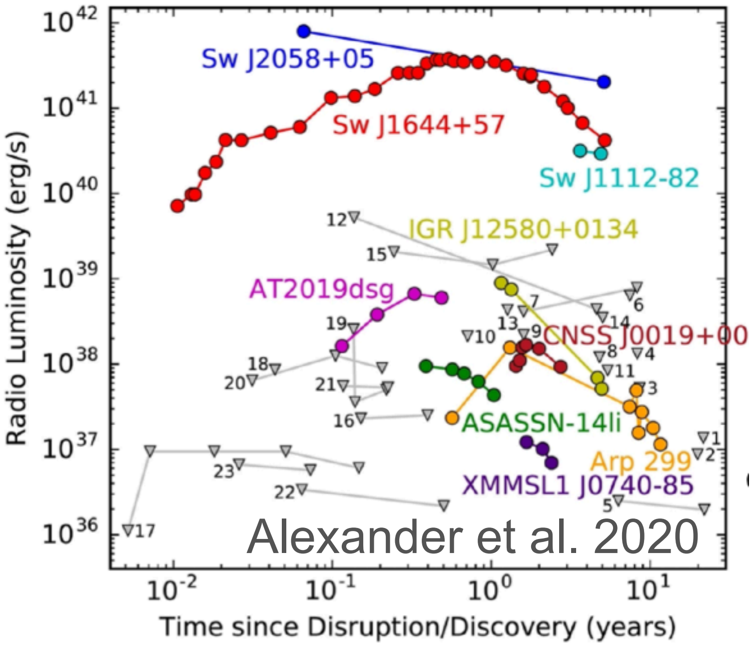
TDE observational signatures: universal

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



Van Velzen et al, 2021

Radio

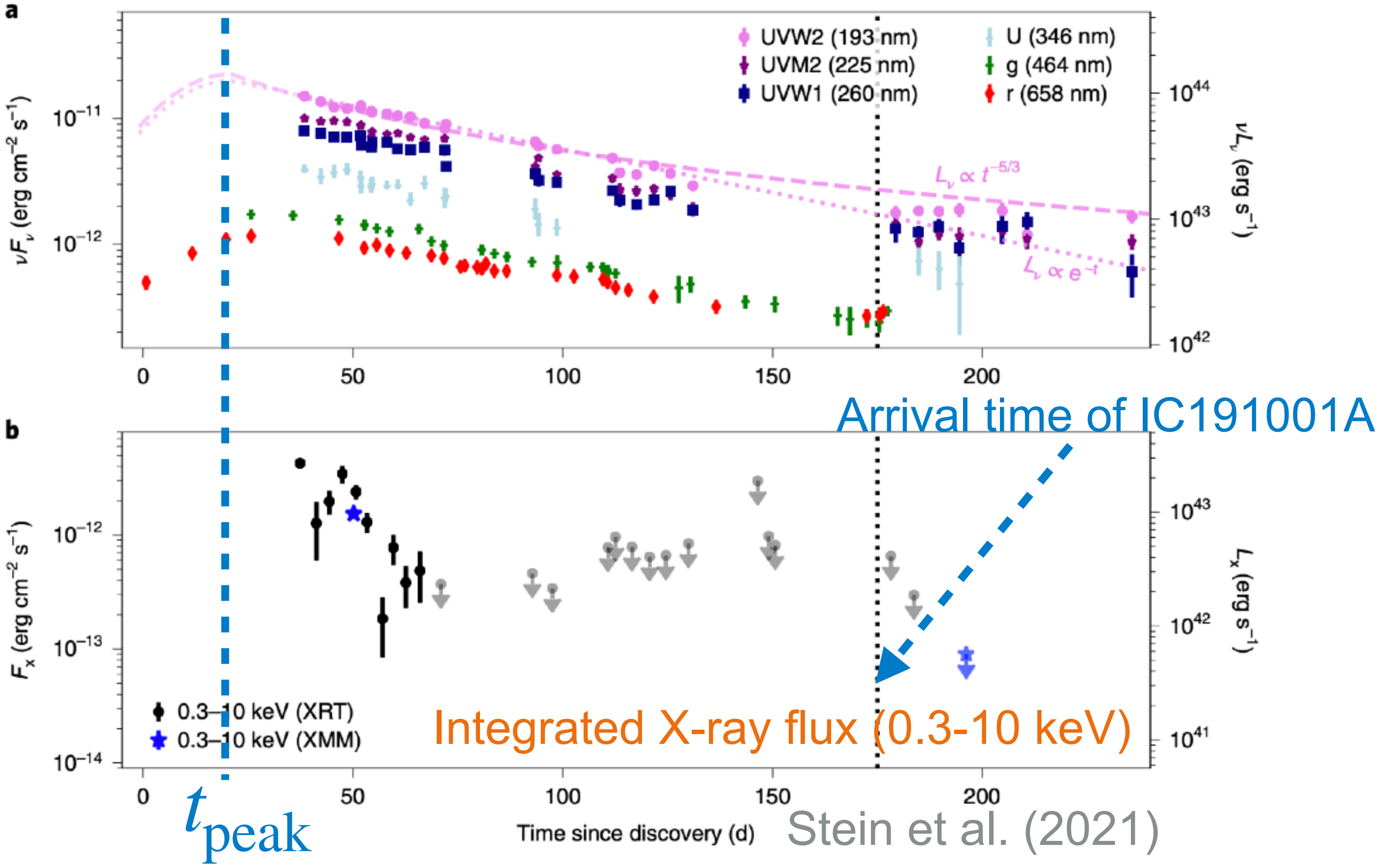


Alexander et al. 2020

- 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

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

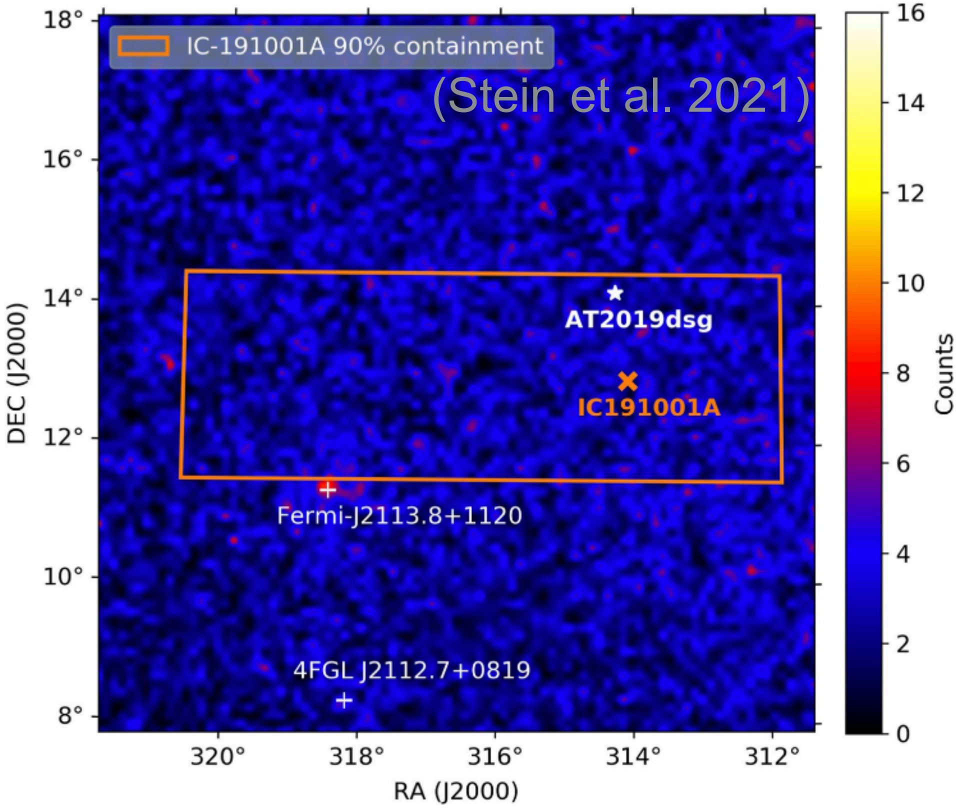


Arrival time of IC191001A

Integrated X-ray flux (0.3-10 keV)

$t_{\rm peak}$

Stein et al. (2021)



(Stein et al. 2021)

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

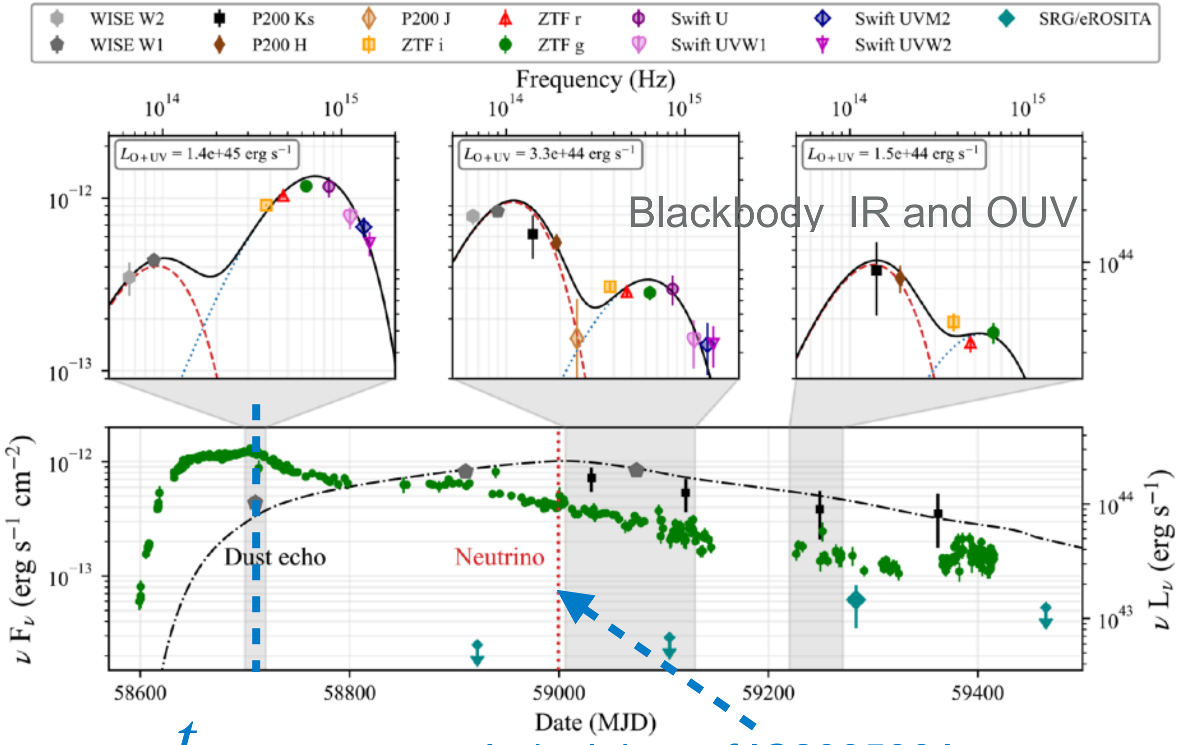
Measured black body spectra:

- **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 (dust echo)

AT2019fdr

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

Reusch et al. (2022)

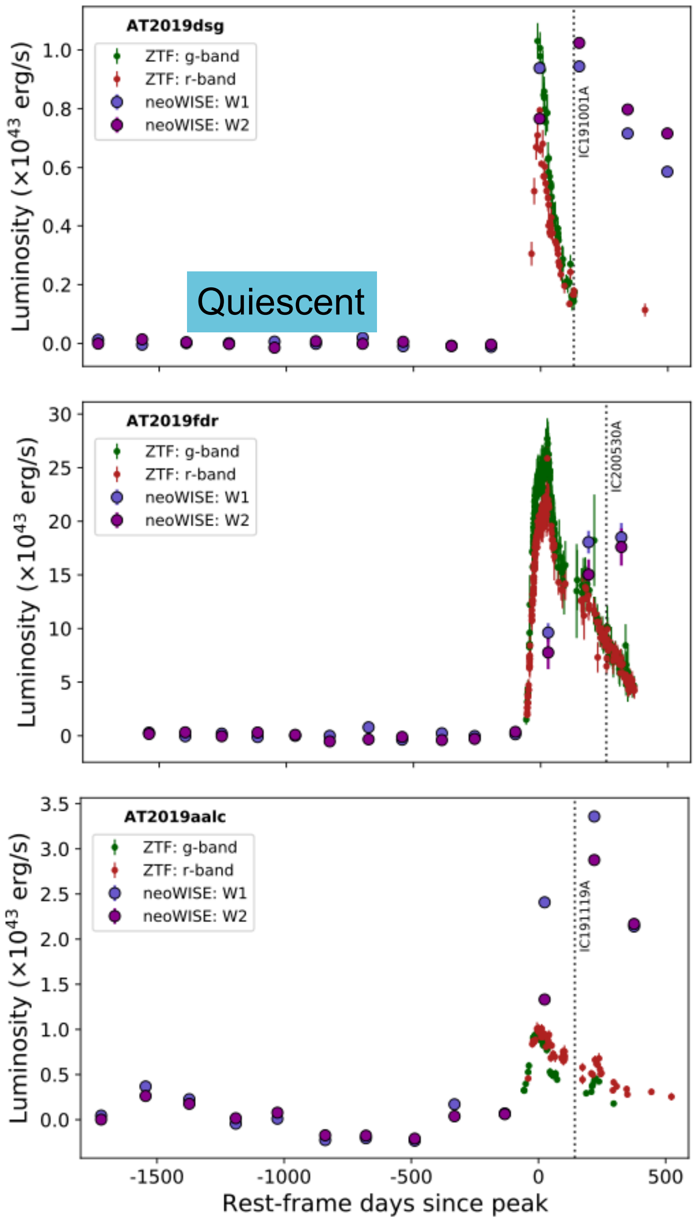


Blackbody IR and OUV

$t_{\rm peak}$

Arrival time of IC200530A

AT2019aalc



Quiescent

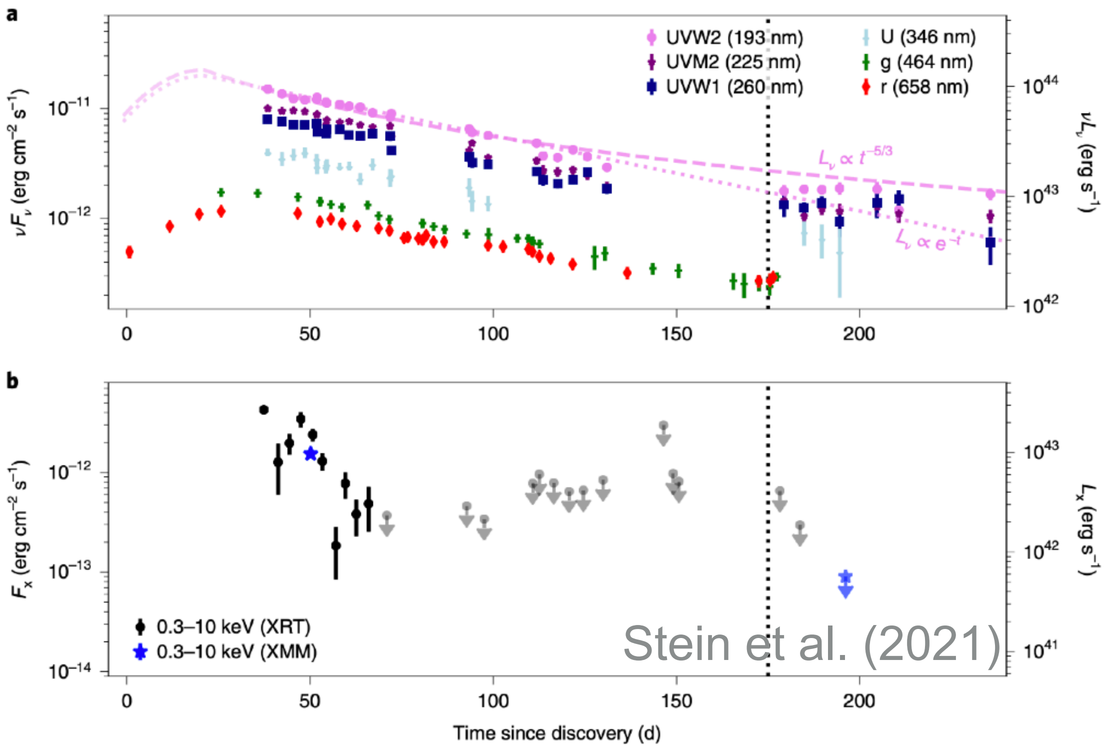
Another TDE candidate with potential neutrino correlation and strong delayed IR emission (dust echo).

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

(van Velzen+ 2021)

Questions for Neutrino-Coincident TDEs

- Where are radio, OUV, IR, X-ray (XRT, eROSITA, NICER), γ-ray and neutrino emissions produced?
- Temporal signatures? delayed infrared and neutrino emissions, EM counterparts in time domain
- Multi-messenger implications, e.g., from X-ray/γ-ray up limits to neutrino constraints



Stein et al. (2021)

What we have

- Thermal optical/ultraviolet, X-ray, and infrared spectra/light curves.
- Up limits from γ-ray flux by Fermi, HAWC etc
- Neutrino correlation: detection time, energy

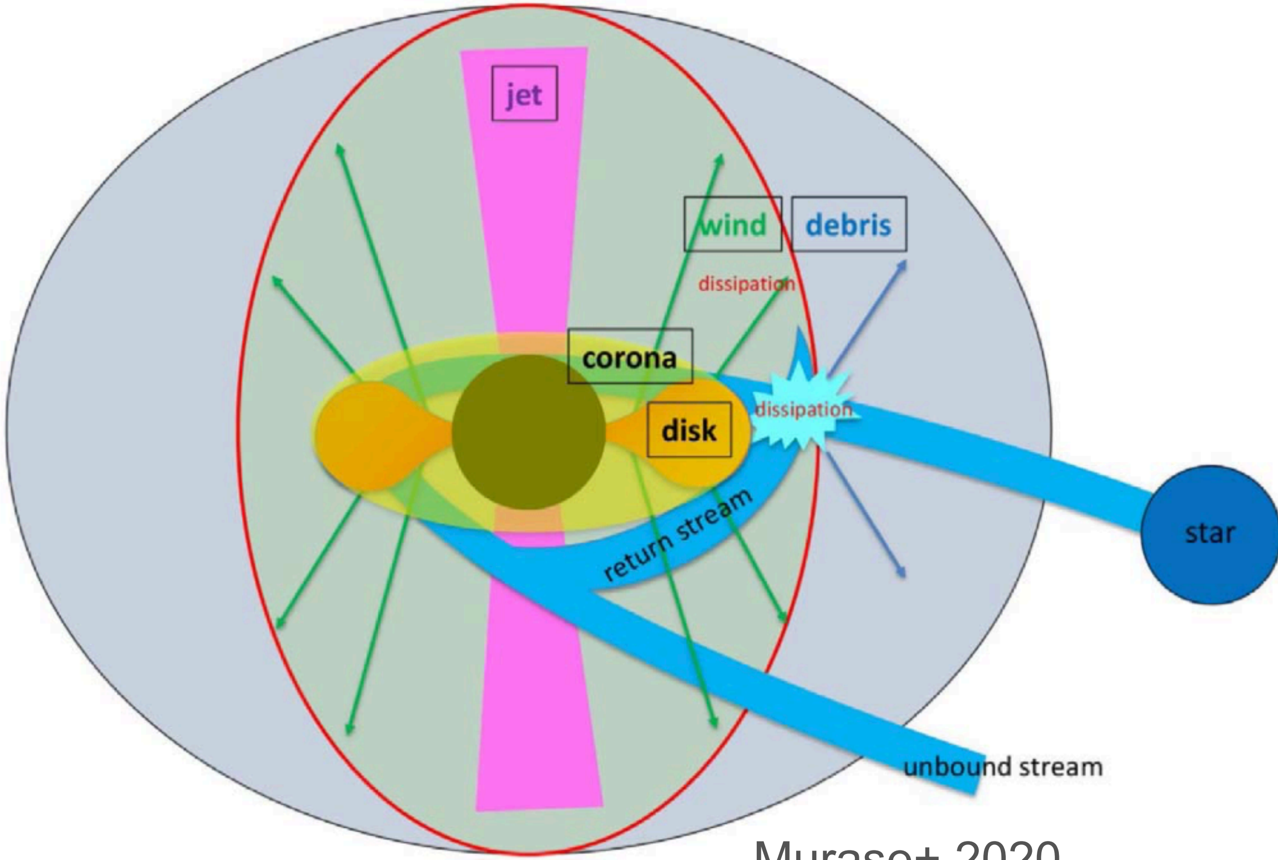
What we need for existing observations

- Radiation sites: jet, wind, disk corona, etc
- CR acceleration/injection
- Theoretical/numerical modeling of interactions

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)



Murase+ 2020

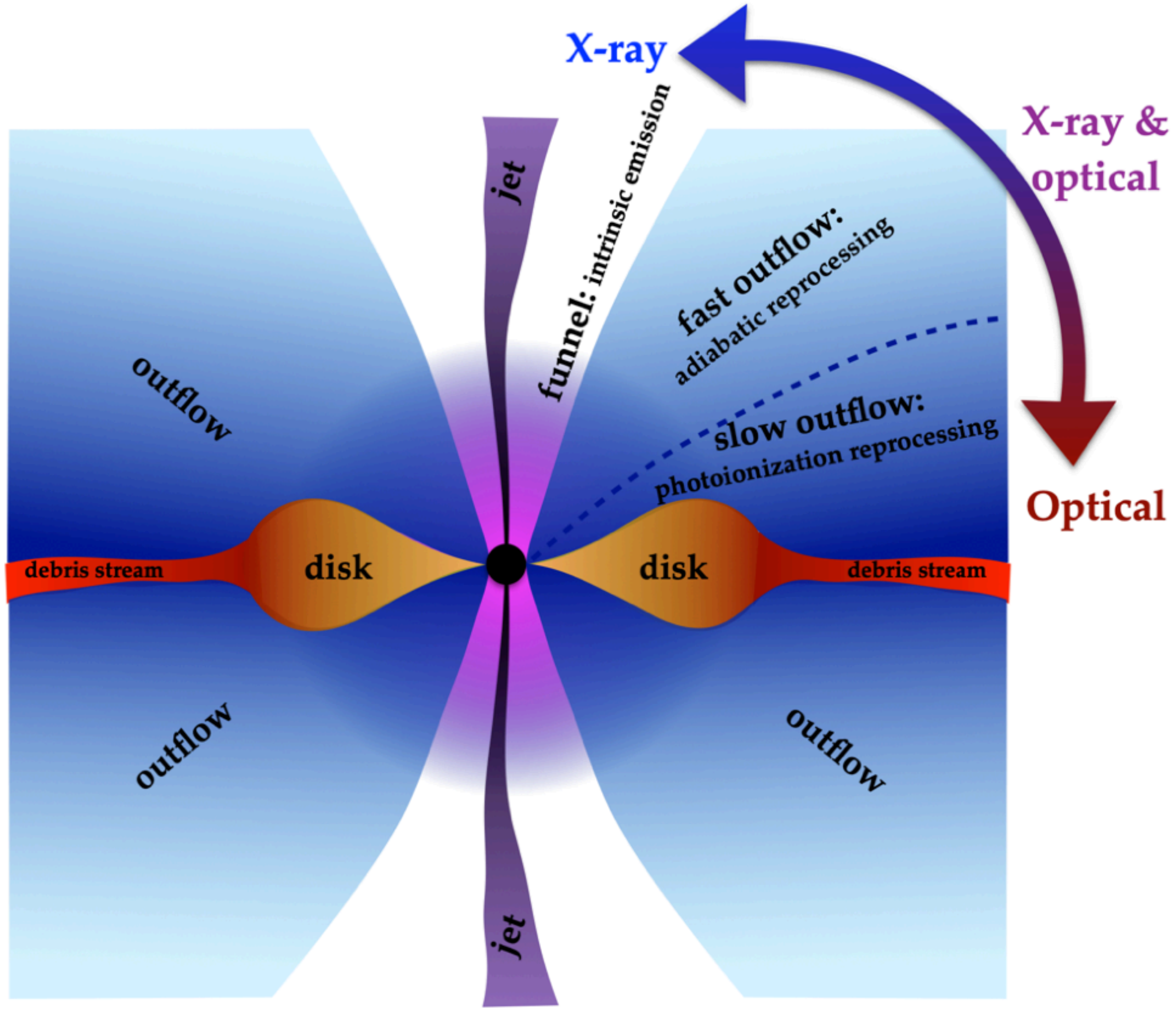
TDE models

- In addition to the EM signatures, neutrinos might be produced in the accretion disks, disk winds (outflows), or jets
- Three TDEs may be associated with IceCube neutrino events
  1. AT2019dsg (IC191001A)
  2. AT2019fdr (IC200530A)
  3. AT2019aalc (IC191119A) - Less complete γ-ray/X-ray constraints

Focus of this work

- Three TDE candidates with luminous jets (no ν association reported):

  Swift J1644+57,Swift J2058+05 & AT2022cmc



Dai+ 2018

Dust Echo: infrared (IR) emission

X-ray/OUV photons heat the dust torus

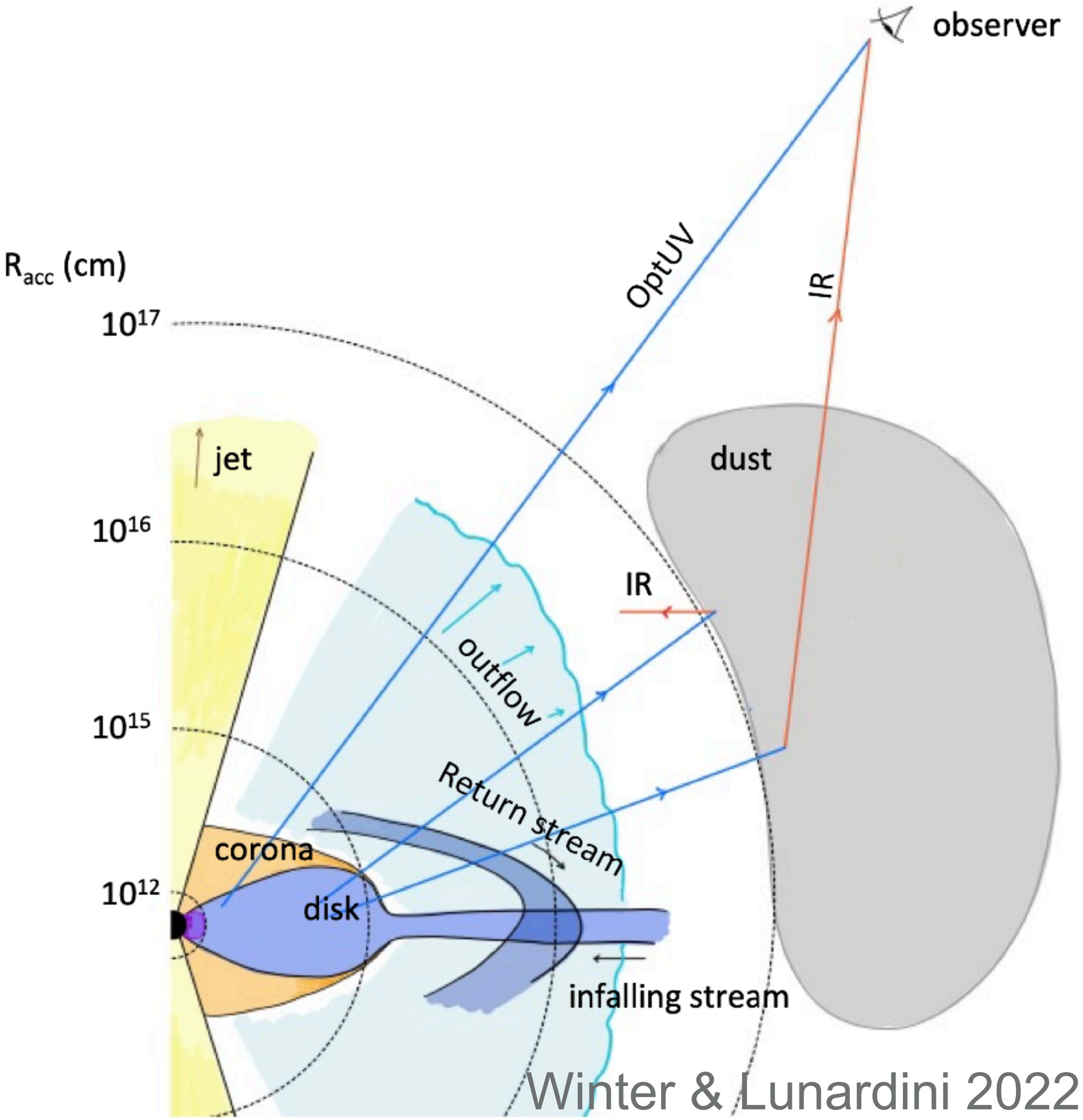
-> thermal IR emission

- could explain delayed IR emission
- feeds IR photons back to the wind/outflow envelope
- temperature $T_{\rm IR} \lesssim 0.16~{\rm eV}$ (Reusch et al. 2022)
- IR luminosity can be obtained by convolving $L_{\rm OUV}$ with a box function $f(T)$, e.g.,

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

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

(Box function reflects the dust distributions)



Winter & Lunardini 2022

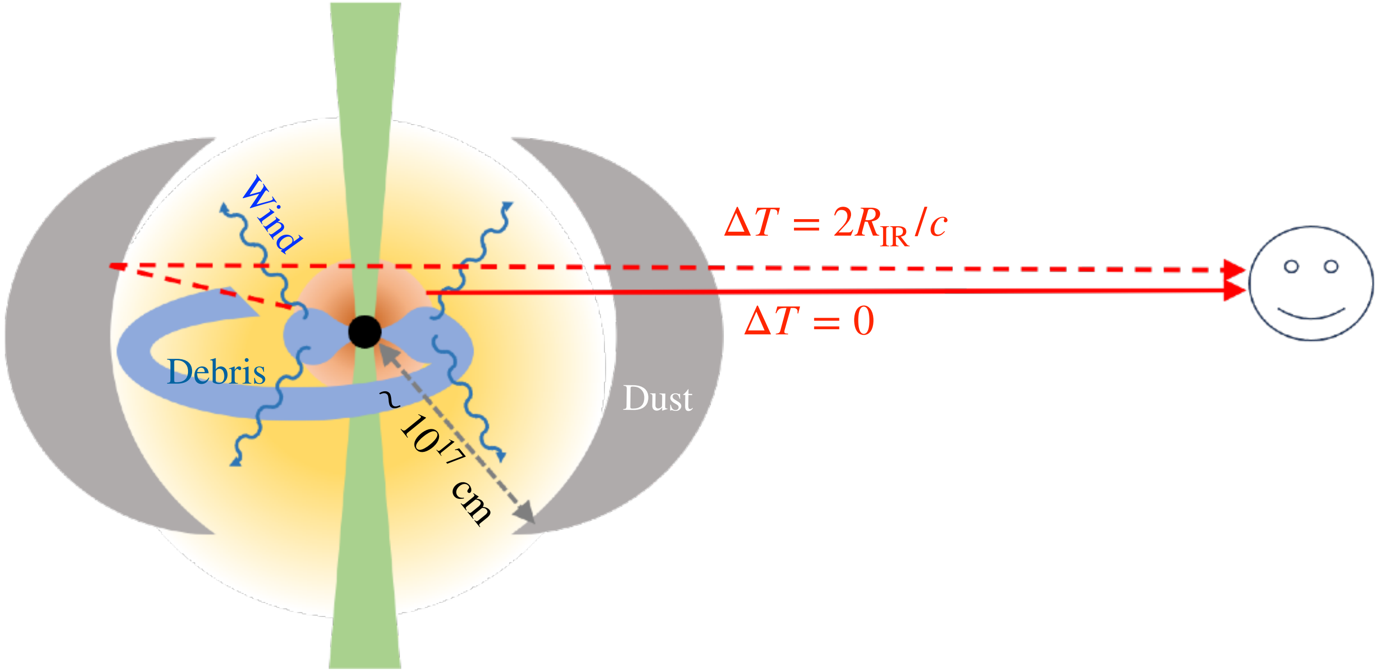
Dust Echo: infrared (IR) emission

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

$R_{\mathrm{IR}} = c\Delta T/2$

One simplest normalized box function is

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



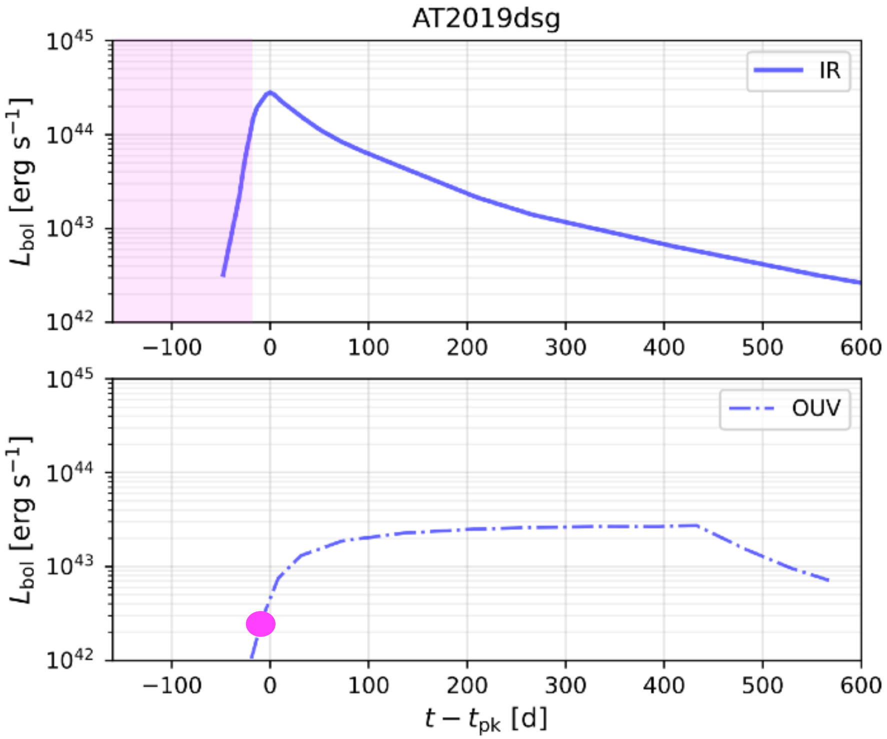
IR light curve fitting

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

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

ϵ_{IR} : re-emitting efficiency

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



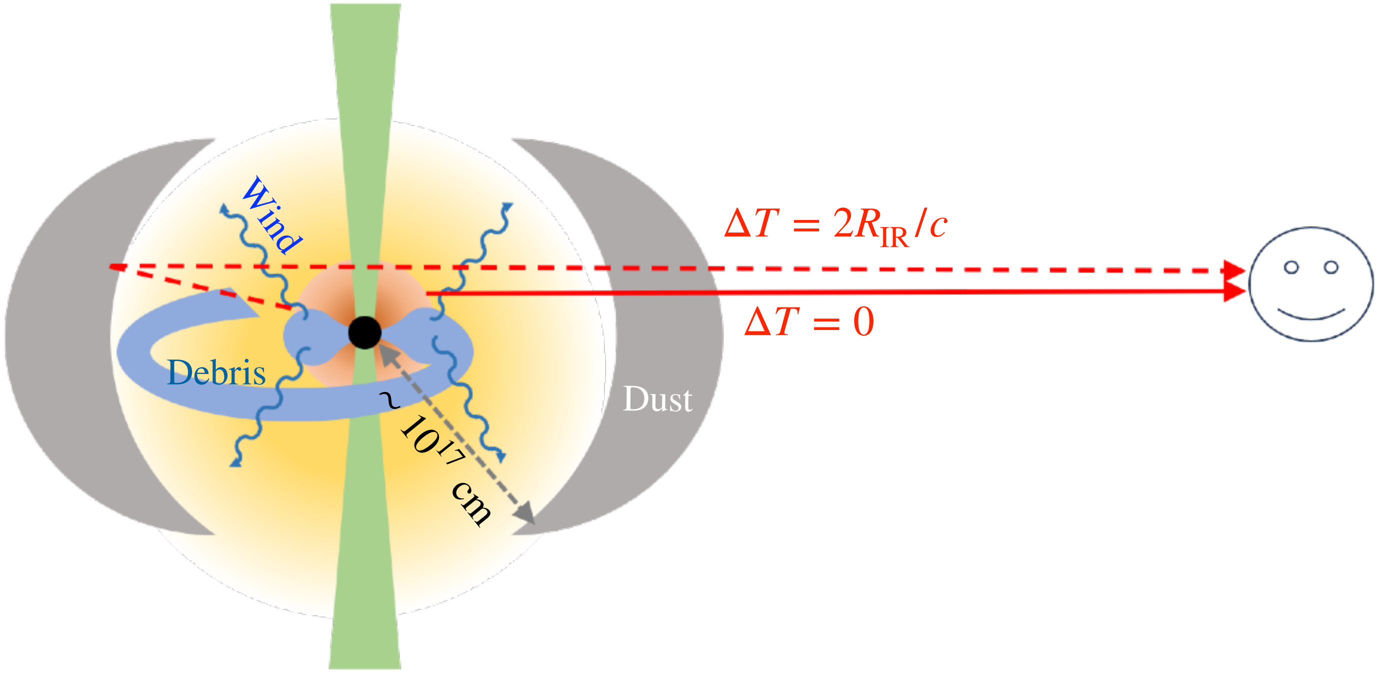
Dust Echo: infrared (IR) emission

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

$R_{\rm IR} = c\Delta T/2$

One simplest normalized box function is

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



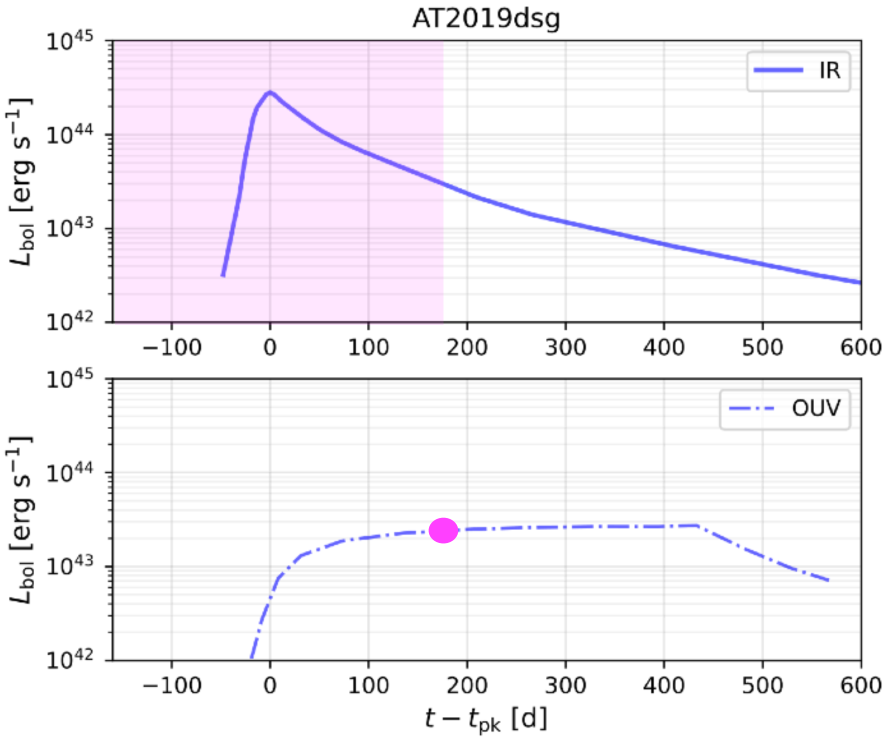
IR light curve fitting

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

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

$\epsilon_{\rm IR}$: re-emitting efficiency

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



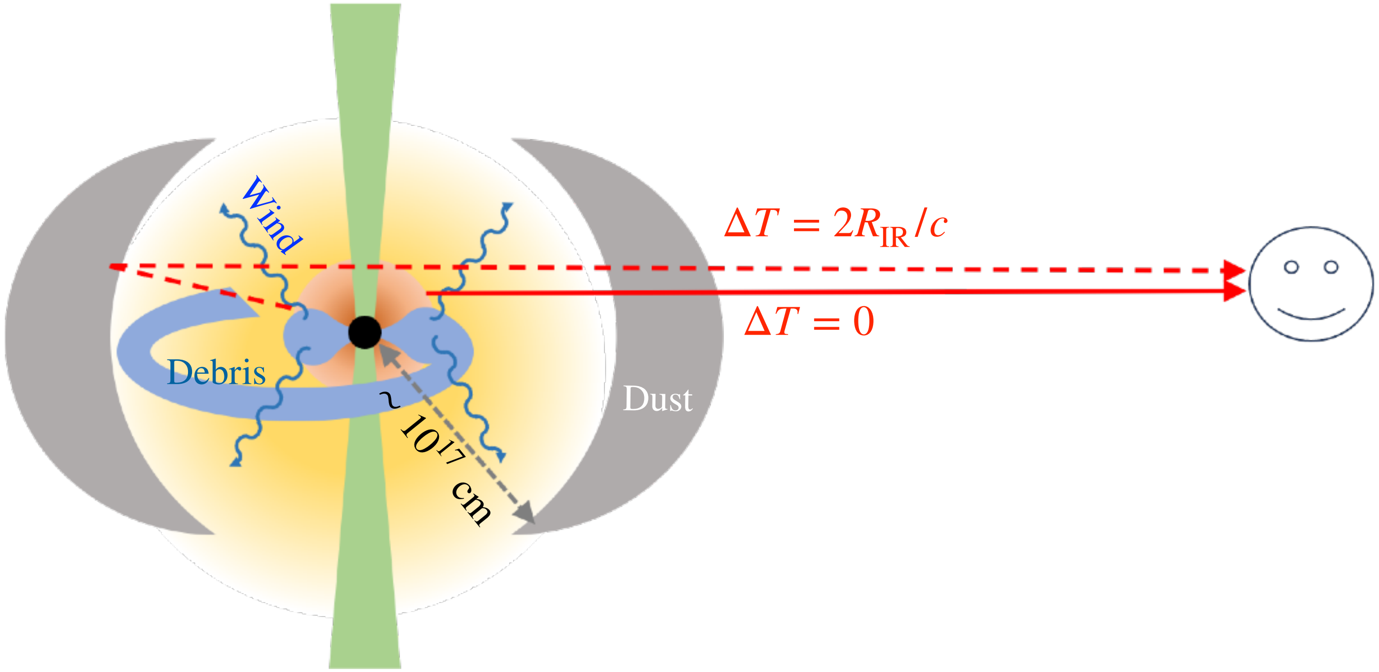
Dust Echo: infrared (IR) emission

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

$R_{\rm IR} = c\Delta T/2$

One simplest normalized box function is

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



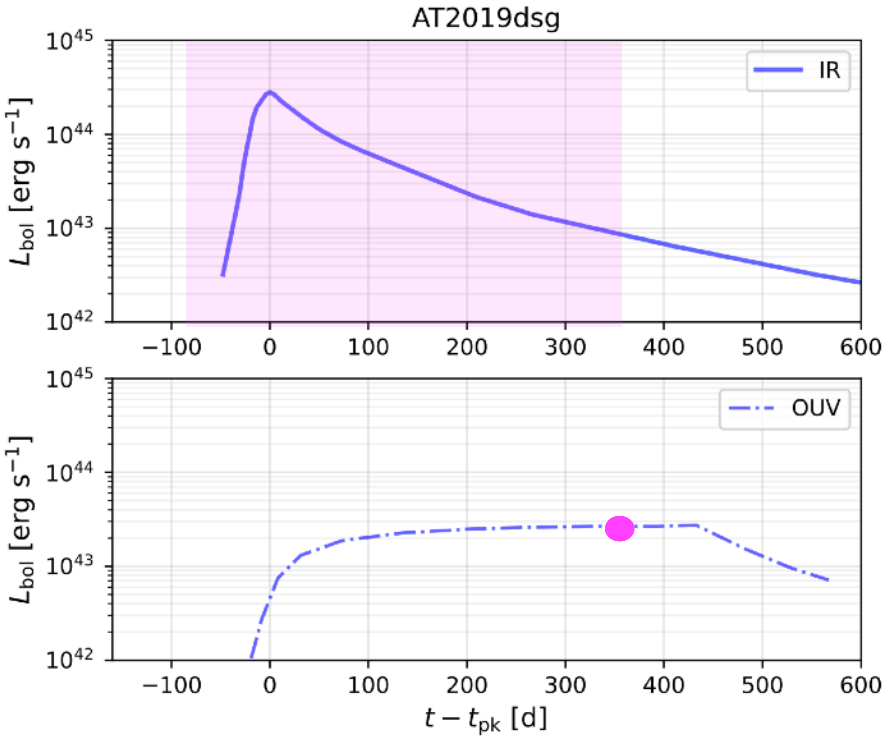
IR light curve fitting

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

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

$\epsilon_{\rm IR}$: re-emitting efficiency

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



Dust Echo: infrared (IR) emission

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

$R_{\rm IR} = c\Delta T/2$

One simplest normalized box function is

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

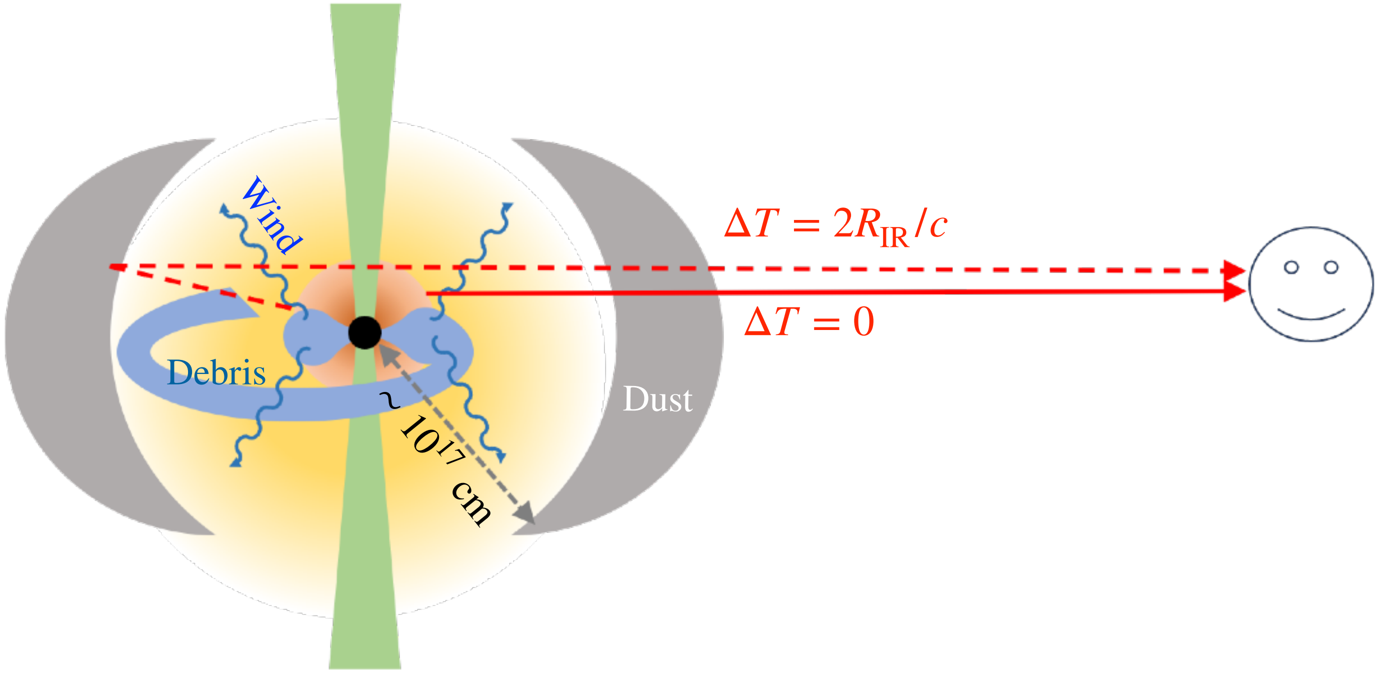
IR light curve fitting

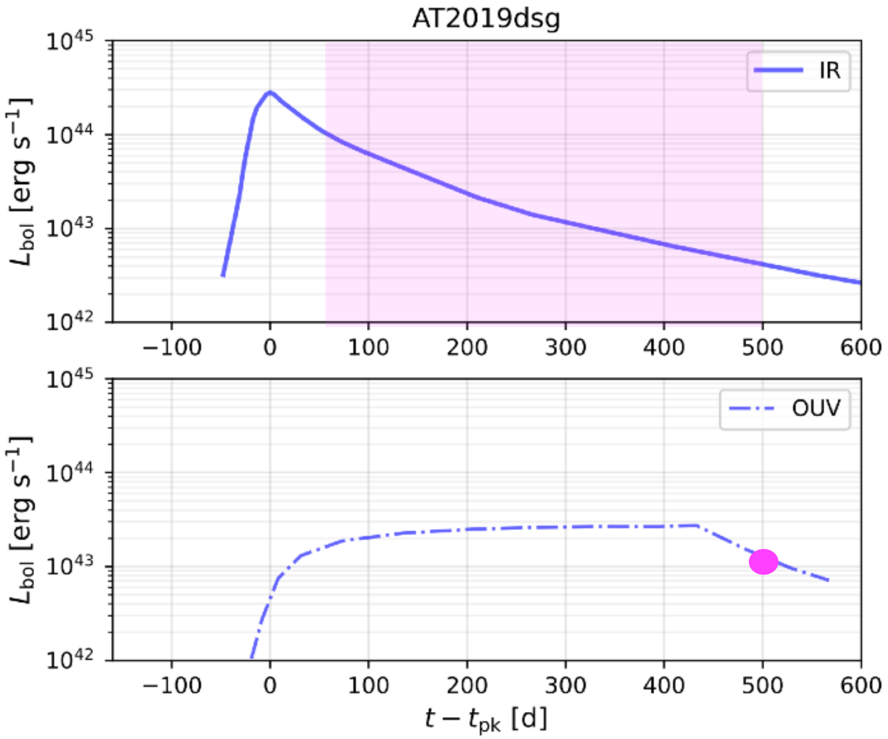
$$L_{\rm IR}(t) = \epsilon_\Omega \epsilon_{\rm IR} \int L_{\rm OUV}(t')f(t-t')dt'$$

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

$\epsilon_{\rm IR}$: re-emitting efficiency

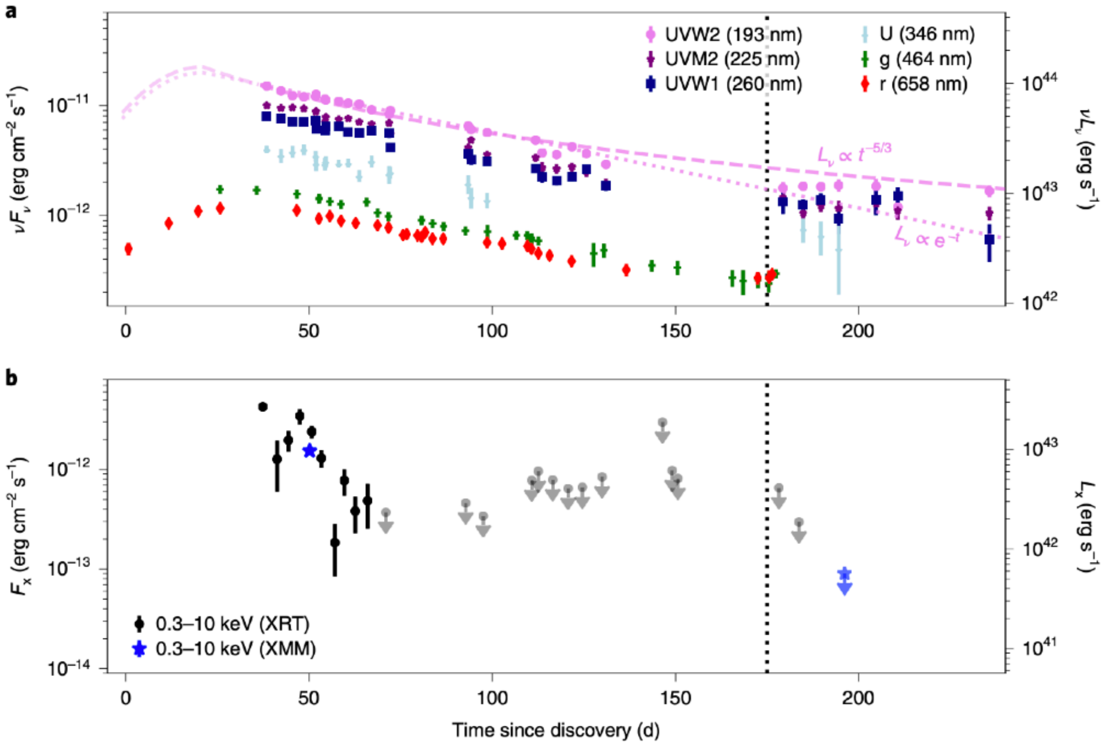
To fit IR light curves for AT2019dsg/fdr/aalc, $\epsilon_\Omega \epsilon_{\rm IR} \sim 0.3 - 0.5$





Questions for Neutrino-Coincident TDEs (revisited)

- Where are radio, OUV, IR, X-ray (XRT, eROSITA, NICER), γ-ray and neutrino emissions produced?
- Temporal signatures? delayed infrared and neutrino emissions, EM counterparts in time domain
- Multi-messenger implications, e.g., from X-ray/γ-ray up limits to neutrino constraints



What we have

- Thermal optical/ultraviolet, X-ray, and infrared spectra/light curves.
- Up limits from γ-ray flux by Fermi, HAWC etc
- Neutrino correlation: detection time, energy

What we need for existing observations

- Radiation sites: jet, wind, disk corona, etc
- CR acceleration/injection
- Theoretical/numerical modeling of interactions

Multi-Messenger Modeling of Neutrino-Coincident Tidal Disruption Events

- Theoretical and observational pictures of TDEs
- Particle interactions and isotropic hidden winds models with dust echoes
- Neutrino and EM cascade emissions from neutrino-emitting TDEs, AT2019dsg and AT2019fdr
- A fourth neutrino-coincident with strong dust echo??
- Open questions and outlook

Proton injection

Four parameters: $E_{p,\mathrm{min}} \sim 1\ \mathrm{GeV},$ spectra index $p = 2$, $E_{p,\mathrm{max}}$ (free-param), normalization factor

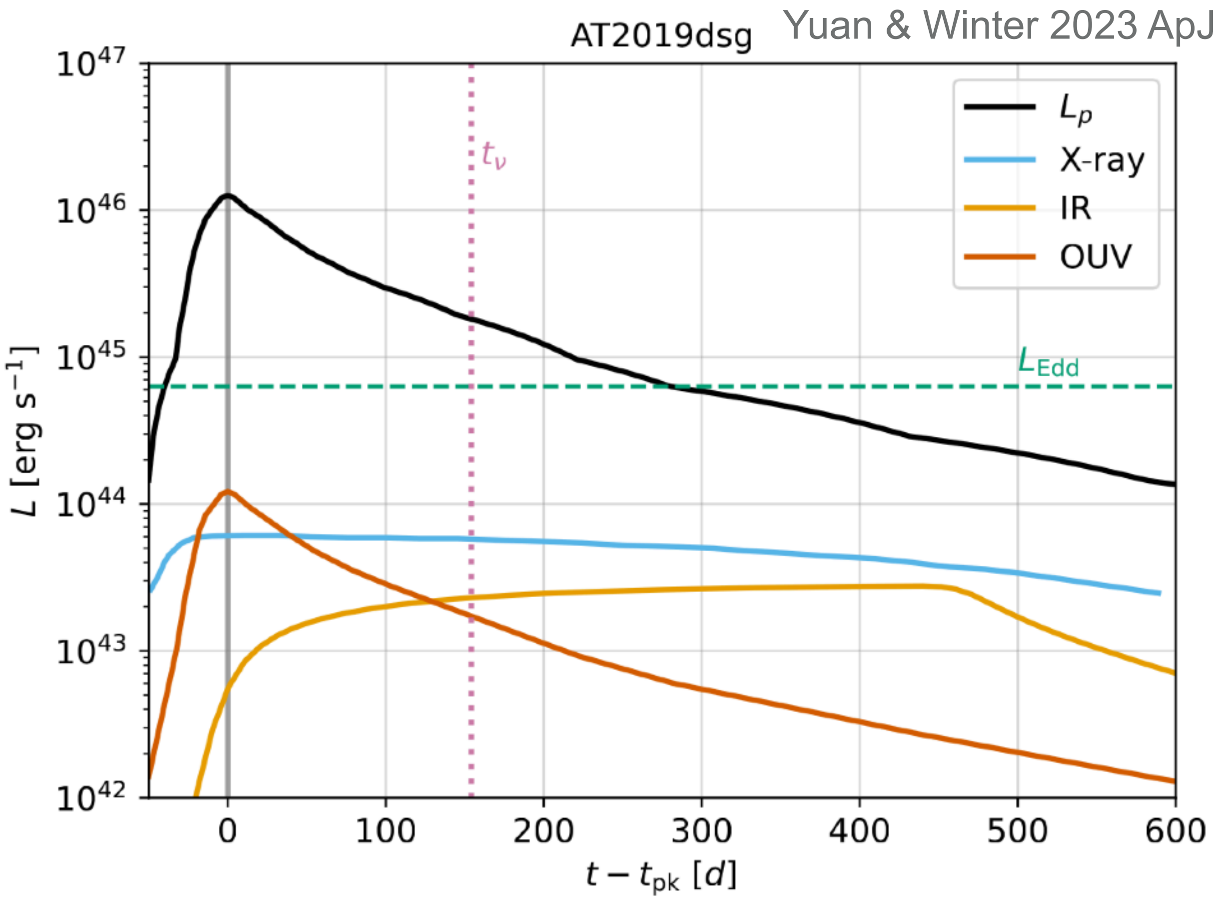
Example - AT2019dsg: $M_{\mathrm{SMBH}} \simeq 5 \times 10^6 M_\odot$ (van Velzen et al. 2021)

We use four parameters to determine the proton injection (do not specify the accelerator)

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

Assumptions

- $\dot{M}_\star(t)/L_{\mathrm{OUV}}(t) = \mathrm{const}$
- $\dot{M}_{\star,\mathrm{peak}}/\dot{M}_{\mathrm{Edd}} \sim 10$ (10-100 from Dai+, 2018)
- Efficient energy dissipation to CRs: $\varepsilon_{\mathrm{diss}} \simeq 0.2$
- Proton diffusion in Bohm regime $D = R_L c$



Yuan & Winter 2023 ApJ

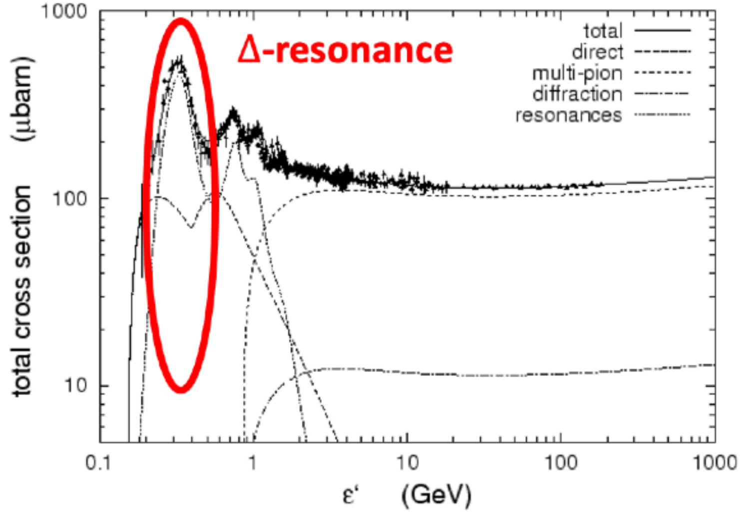
Production of High-Energy Astrophysical Neutrinos

Photo-pion/meson ($p\gamma$) process

$$p + \gamma \rightarrow \Delta^+ \rightarrow \pi^\pm/\pi^0 + X$$

Ingredients: dense (low-energy) target photons [thermal IR/OUV/X-ray photons in TDE winds] + CRs

Delta resonance proton energy: $E_p \gtrsim \dfrac{m_\pi(2m_p + m_\pi)c^2}{4\varepsilon_\gamma}$



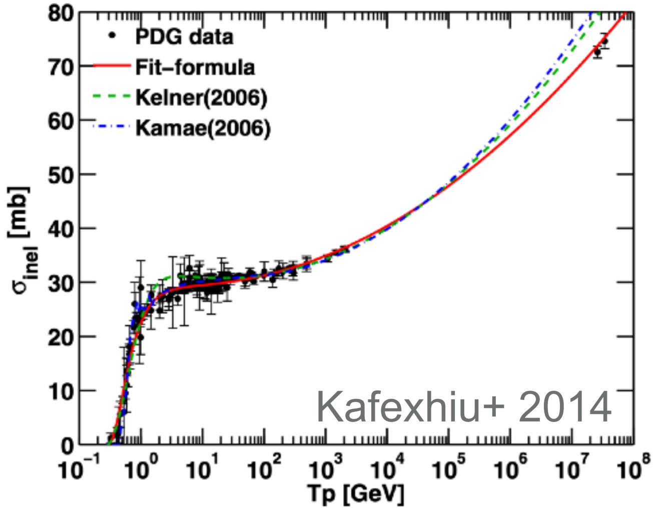
$$\pi^\pm \rightarrow \mu^\pm + \nu_\mu(\bar{\nu}_\mu),\ \ \mu^\pm \rightarrow e^\pm + \bar{\nu}_\mu(\nu_\mu) + \nu_e(\bar{\nu}_e)$$
$$\pi^0 \rightarrow \gamma + \gamma$$

Hadronuclear (pp) process

$$p + p \rightarrow \pi^+/\pi^0 + X$$

Ingredients: dense thermal/rest target protons [outflows/winds in TDEs] + CRs

In TDE wind, depends on the wind params. subdominant even in optimistic cases



Kafexhiu+ 2014

proton kinetic energy in the rest frame of the target proton

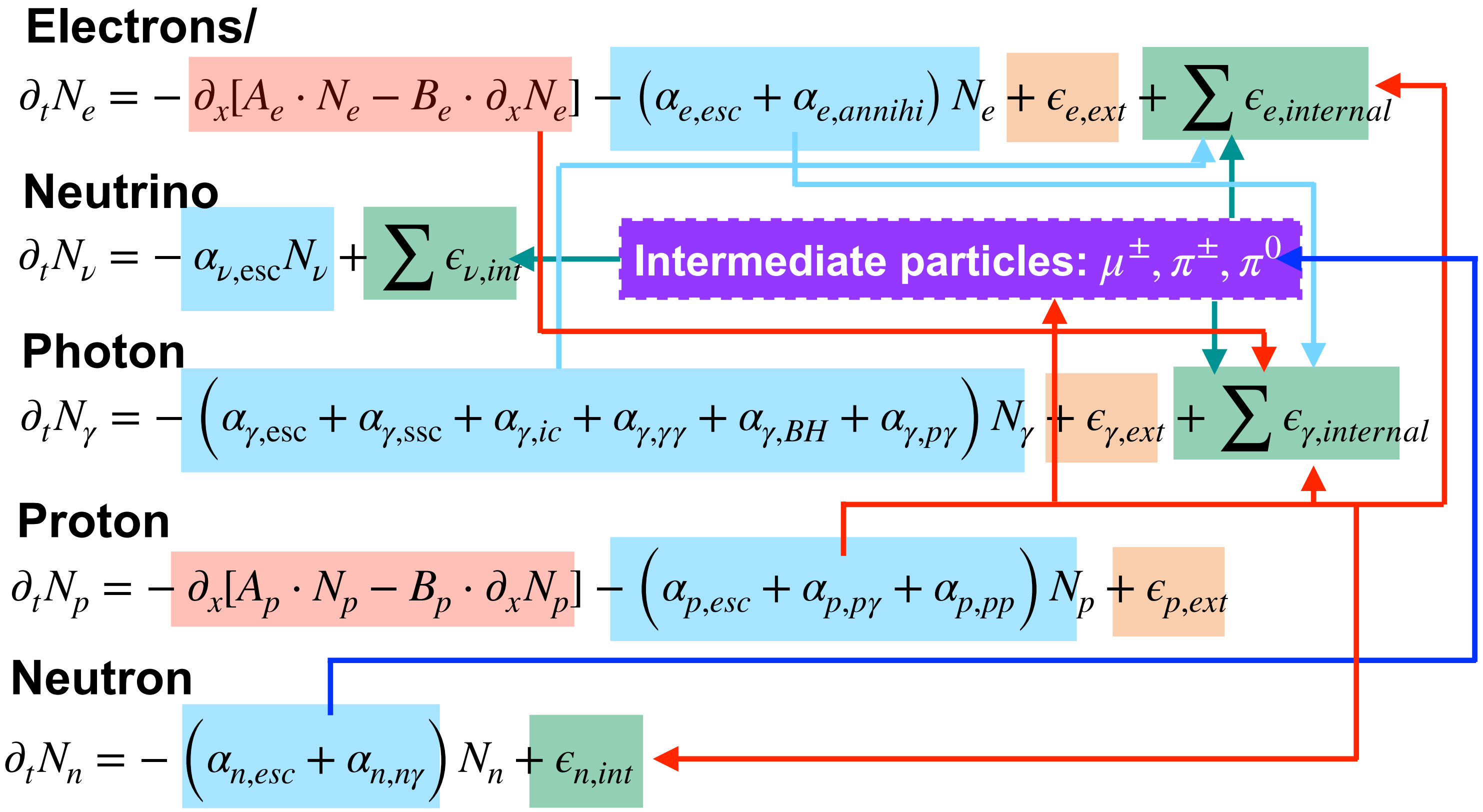
Numerical Method: AM^3 (Astrophysical Multi-Messenger Modeling)

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

$$\partial_t n_i = \underbrace{Q_{i,ext}}_{\text{Injection}} + \sum_k Q_{int,k\to i} - \underbrace{\partial_E(\dot{E}\cdot n_i)}_{\text{Cooling}} - \underbrace{(\alpha_{i,esc}+\alpha_{i,adv})n_i}_{\text{Escape/Advection}}$$

Code will be public soon

Simplified data flow



Electrons/

$$\partial_t N_e = -\partial_x[A_e\cdot N_e - B_e\cdot\partial_x N_e] - \left(\alpha_{e,esc}+\alpha_{e,annihi}\right)N_e + \epsilon_{e,ext} + \sum\epsilon_{e,internal}$$

Neutrino

$$\partial_t N_\nu = -\alpha_{\nu,esc}N_\nu + \sum\epsilon_{\nu,int}$$

Intermediate particles: $\mu^\pm, \pi^\pm, \pi^0$

Photon

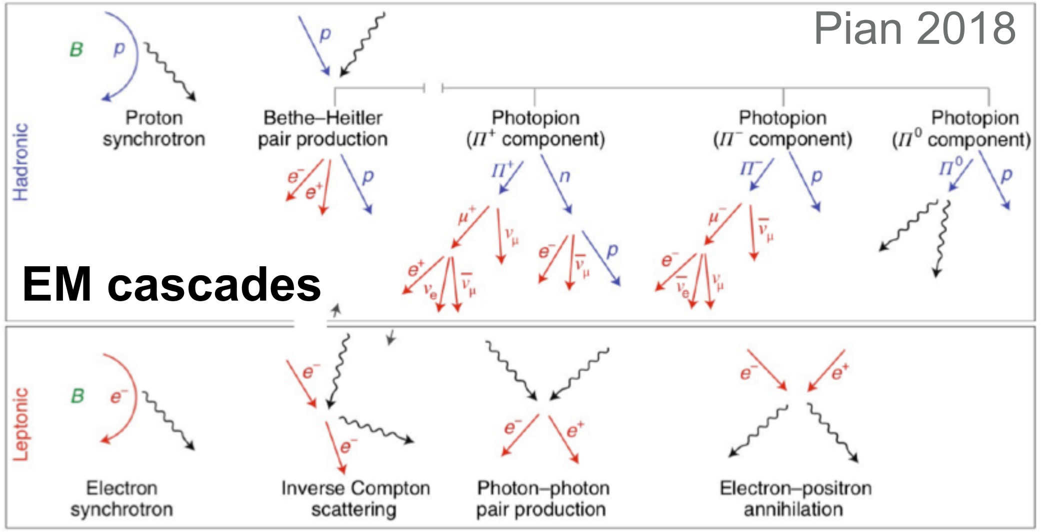
$$\partial_t N_\gamma = -\left(\alpha_{\gamma,esc}+\alpha_{\gamma,ssc}+\alpha_{\gamma,ic}+\alpha_{\gamma,\gamma\gamma}+\alpha_{\gamma,BH}+\alpha_{\gamma,p\gamma}\right)N_\gamma + \epsilon_{\gamma,ext} + \sum\epsilon_{\gamma,internal}$$

Proton

$$\partial_t N_p = -\partial_x[A_p\cdot N_p - B_p\cdot\partial_x N_p] - \left(\alpha_{p,esc}+\alpha_{p,p\gamma}+\alpha_{p,pp}\right)N_p + \epsilon_{p,ext}$$

Neutron

$$\partial_t N_n = -\left(\alpha_{n,esc}+\alpha_{n,n\gamma}\right)N_n + \epsilon_{n,int}$$



EM cascades

Pian 2018

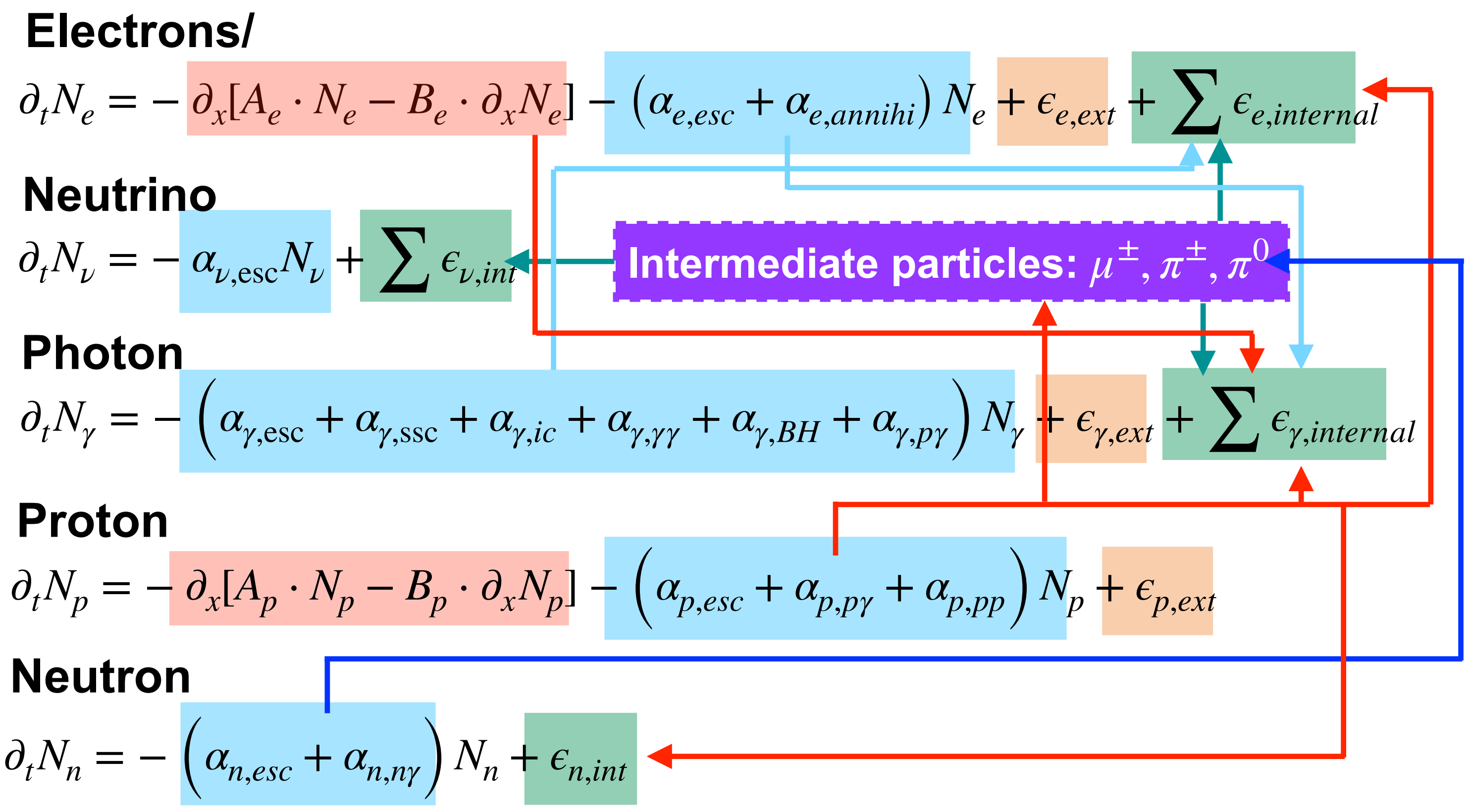
Primary $e^\pm$ injections are not considered in this calculation (will be discussed in later slides)

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

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

$$\partial_t n_i = \underbrace{Q_{i,ext}}_{\text{Injection}} + \sum_k Q_{int,k\to i} - \underbrace{\partial_E(\dot{E}\cdot n_i)}_{\text{Cooling}} - \underbrace{(\alpha_{i,esc} + \alpha_{i,adv})n_i}_{\text{Escape/Advection}}$$

Simplified data flow



Electrons/

$$\partial_t N_e = -\partial_x[A_e\cdot N_e - B_e\cdot\partial_x N_e] - (\alpha_{e,esc} + \alpha_{e,annihi})N_e + \epsilon_{e,ext} + \sum \epsilon_{e,internal}$$

Neutrino

$$\partial_t N_\nu = -\alpha_{\nu,\mathrm{esc}}N_\nu + \sum \epsilon_{\nu,int}$$

Intermediate particles: $\mu^\pm, \pi^\pm, \pi^0$

Photon

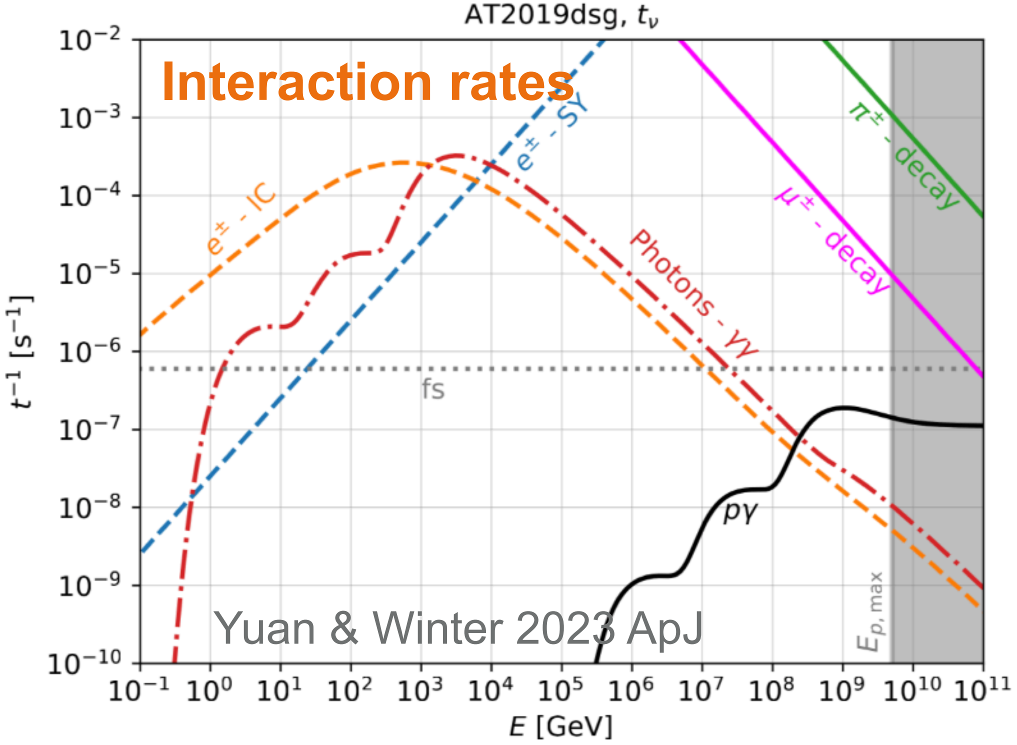
$$\partial_t N_\gamma = -\left(\alpha_{\gamma,\mathrm{esc}} + \alpha_{\gamma,\mathrm{ssc}} + \alpha_{\gamma,ic} + \alpha_{\gamma,\gamma\gamma} + \alpha_{\gamma,BH} + \alpha_{\gamma,p\gamma}\right)N_\gamma + \epsilon_{\gamma,ext} + \sum \epsilon_{\gamma,internal}$$

Proton

$$\partial_t N_p = -\partial_x[A_p\cdot N_p - B_p\cdot\partial_x N_p] - \left(\alpha_{p,esc} + \alpha_{p,p\gamma} + \alpha_{p,pp}\right)N_p + \epsilon_{p,ext}$$

Neutron

$$\partial_t N_n = -\left(\alpha_{n,esc} + \alpha_{n,n\gamma}\right)N_n + \epsilon_{n,int}$$



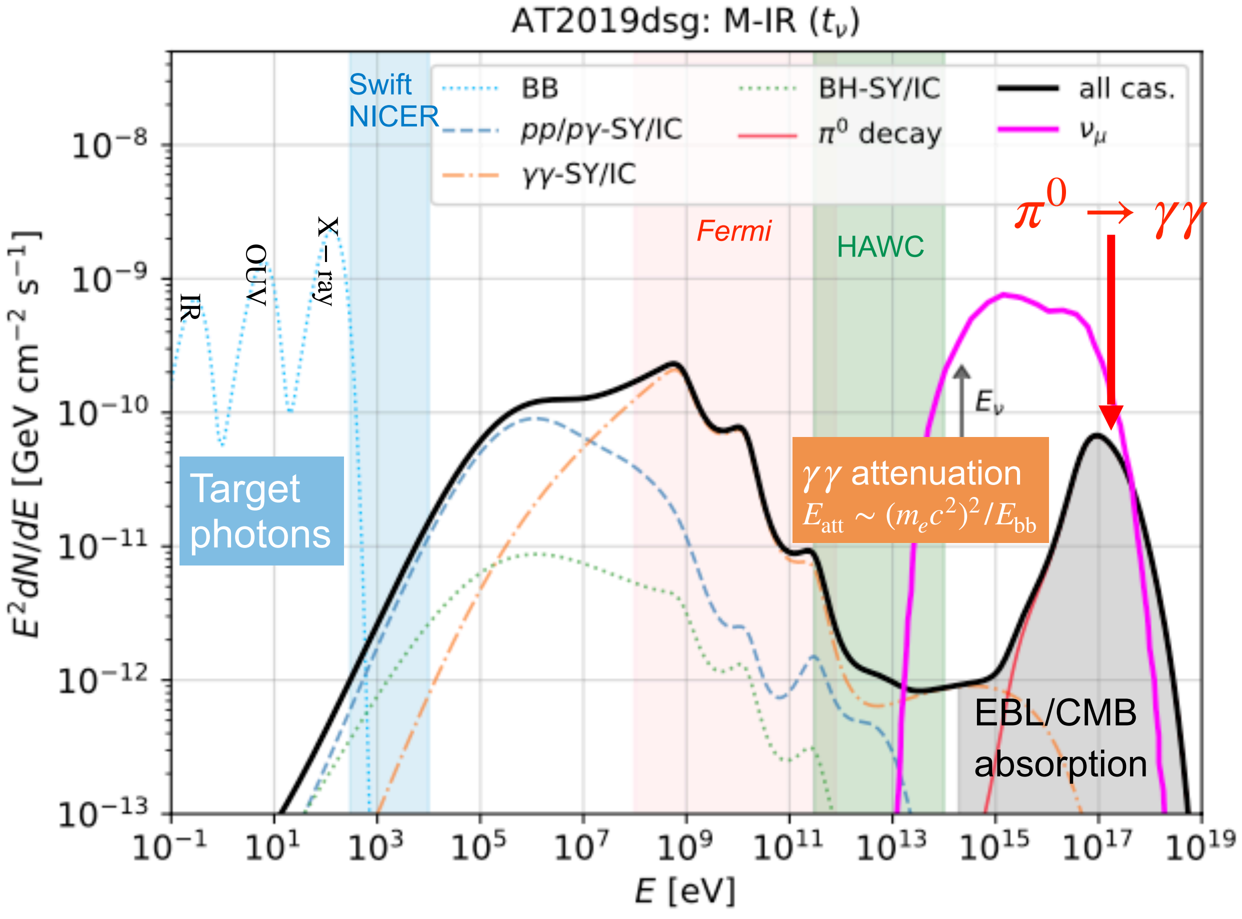
$p\gamma$ time scale ($t_{p\gamma}$) determines the time to develop EM cascade ($\gamma\gamma$ and secondary interactions very efficient)

EM cascade spectra of AT2019dsg: IR target photons

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

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

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



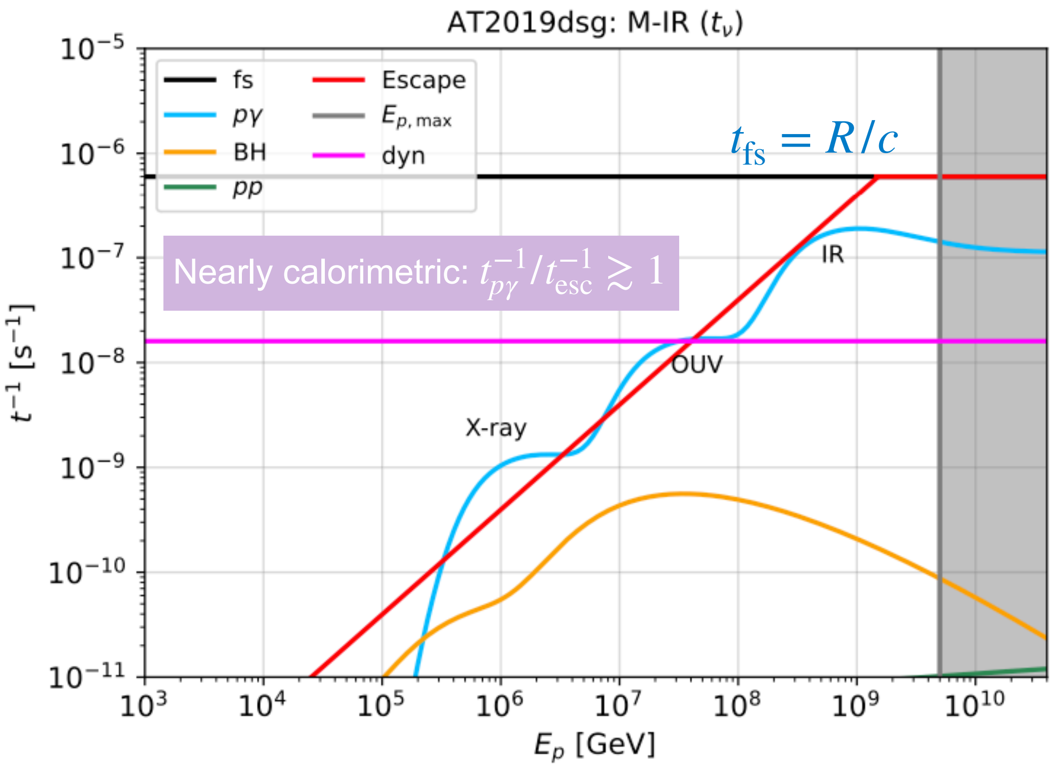
Target photons

$\gamma\gamma$ attenuation
$E_{\mathrm{att}} \sim (m_e c^2)^2/E_{\mathrm{bb}}$

$\pi^0 \to \gamma\gamma$

EBL/CMB absorption

Yuan & Winter 2023 ApJ



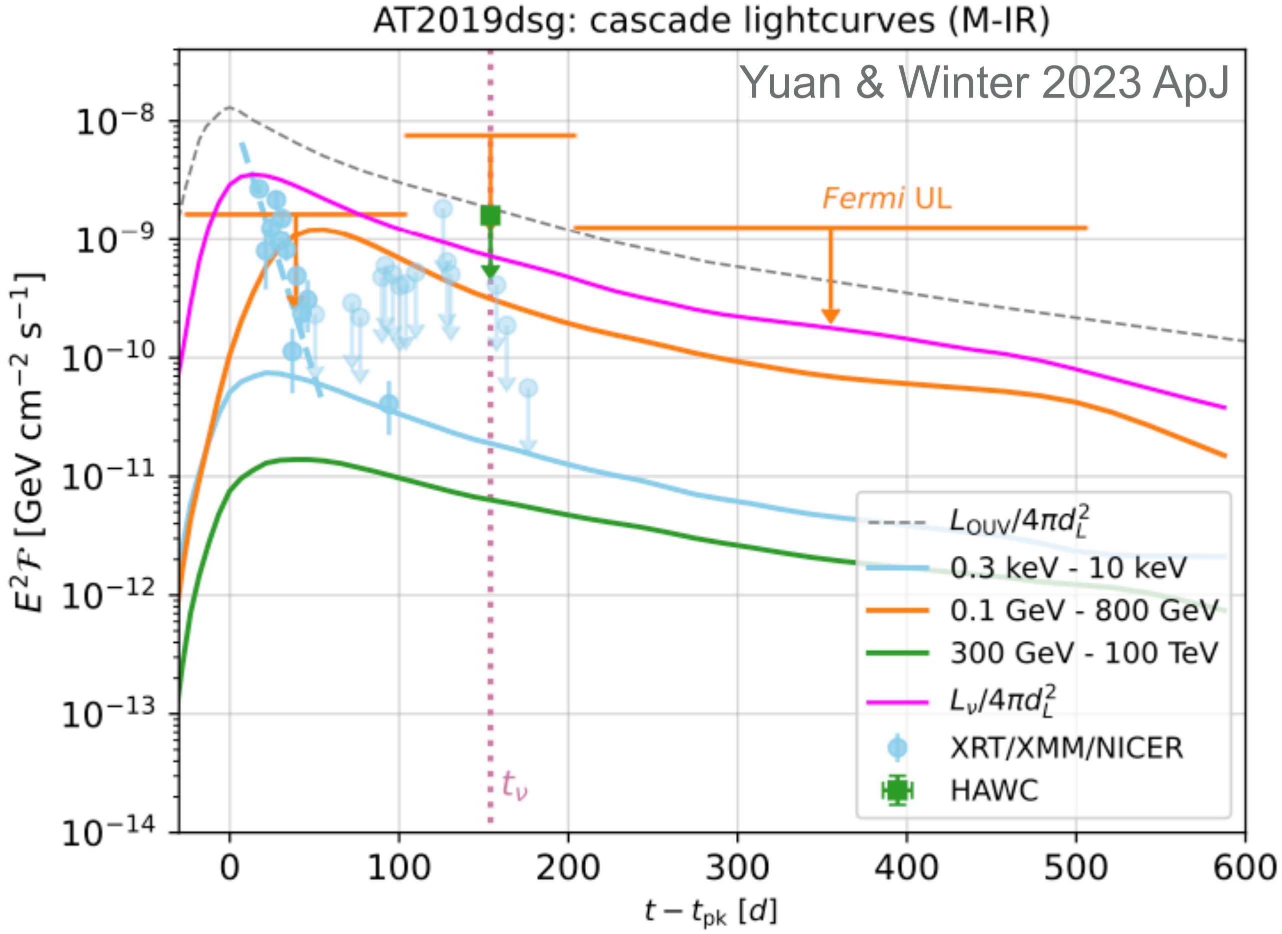
$t_{\mathrm{fs}} = R/c$

Nearly calorimetric: $t_{p\gamma}^{-1}/t_{\mathrm{esc}}^{-1} \gtrsim 1$

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

AT2019dsg Temporal signatures

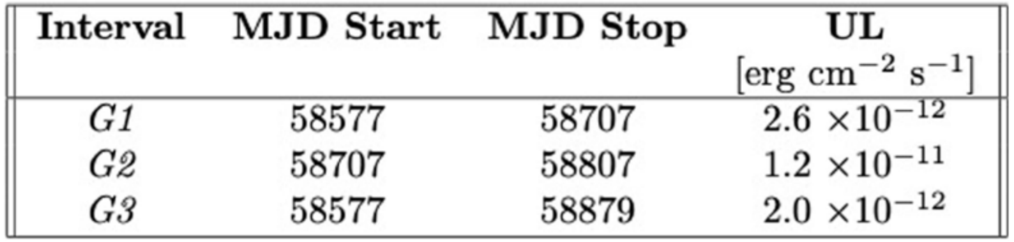
Dust echo IR scenario: $\varepsilon_{\rm diss} = 0.2, B = 0.1\ {\rm G}, R = 5 \times 10^{16}\ {\rm cm}, E_{p,{\rm max}} = 5 \times 10^{9}\ {\rm GeV}$



Rapid (exponential) decay of early X-ray light curve:

- Accretion disk cooling?
- Not the jet/wind signature

Fermi-LAT up limits



Interval	MJD Start	MJD Stop	UL [erg cm^{-2} s^{-1}]
G1	58577	58707	2.6×10^{-12}
G2	58707	58807	1.2×10^{-11}
G3	58577	58879	2.0×10^{-12}

Extended Data Fig. 7 | Gamma-ray energy flux upper-limits for AT2019dsg. The values are derived assuming a point-source with power-law index Γ=2.0 at the position of AT2019dsg, integrated over the analysis energy range 0.1-800 GeV.

Stein et al. 2021

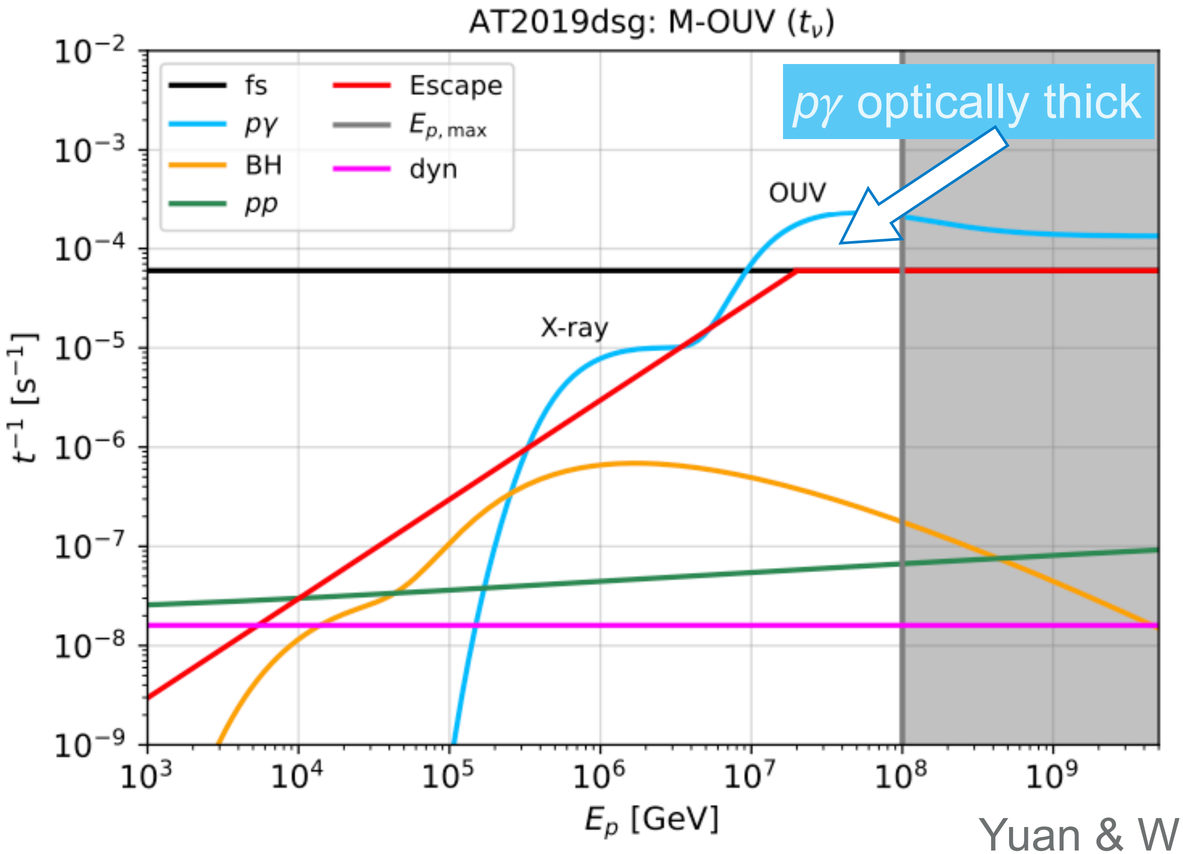
~50 days time delay is compatible with $p\gamma$ interaction time $t_{p\gamma} \sim 10 - 100$ d

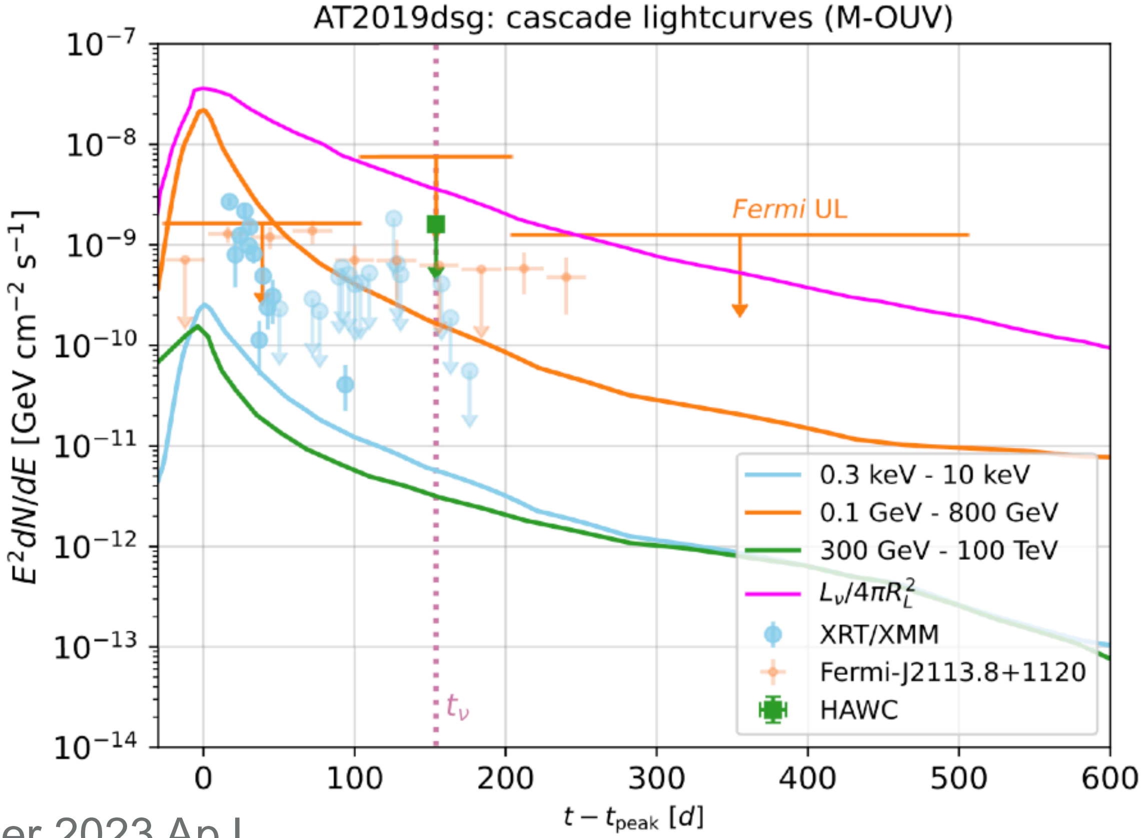
Compact region close to disk corona (OUV photon dominant, M-OUV)

$p\gamma$ optically thick $t_{p\gamma}^{-1}/t_{\rm fs}^{-1} > 1$: EM cascade light curves follows OUV light curve, no significant time delay

$B = 0.1$ G, $R \sim \times 10^{15}$ cm, $E_{p,\rm max} = 1 \times 10^{8}$ GeV

Cascade emission peaks in LAT energy range -> overshoots the γ-ray limits



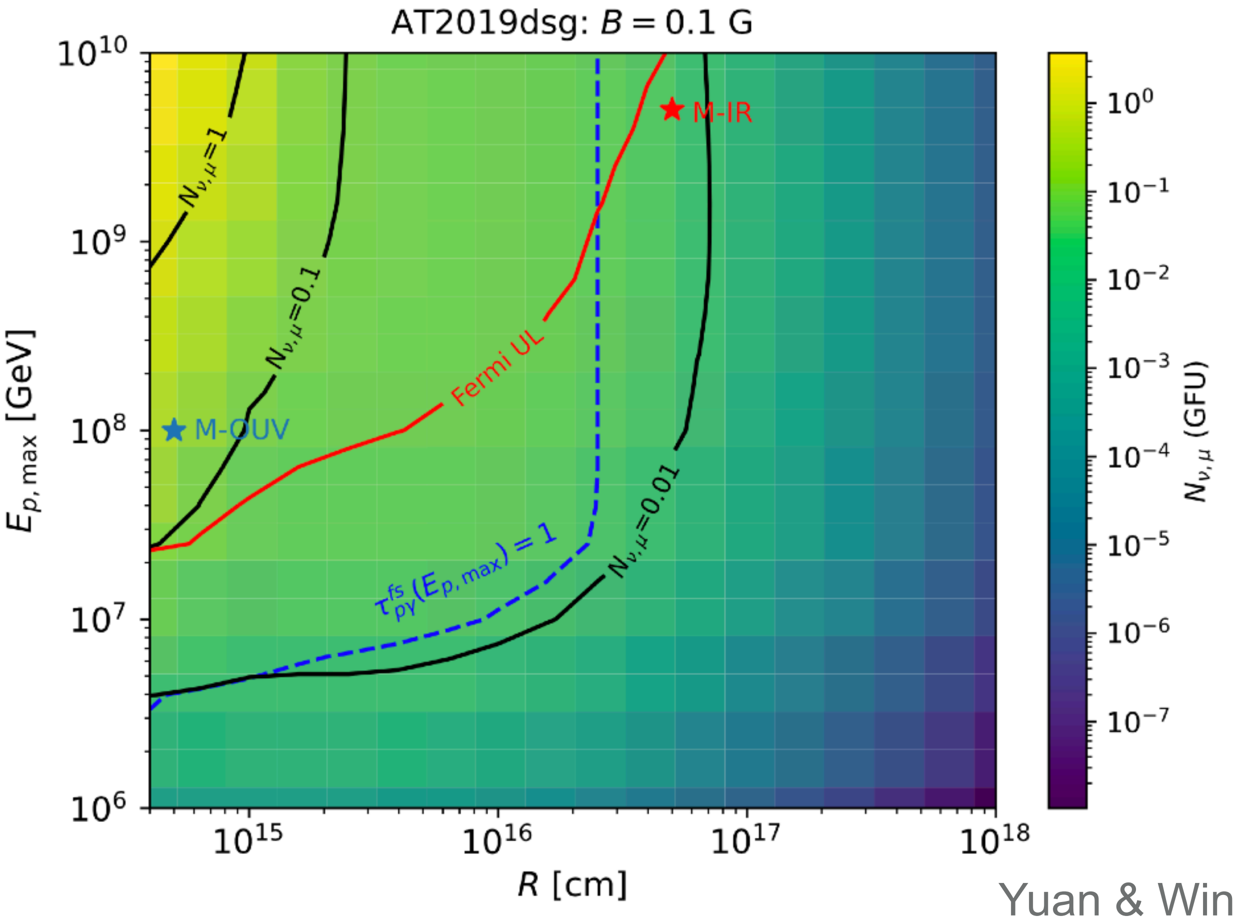


Yuan & Winter 2023 ApJ

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

Expected Gamma-ray Follow Up (GFU) neutrino number

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



Yuan & Winter 2023 ApJ

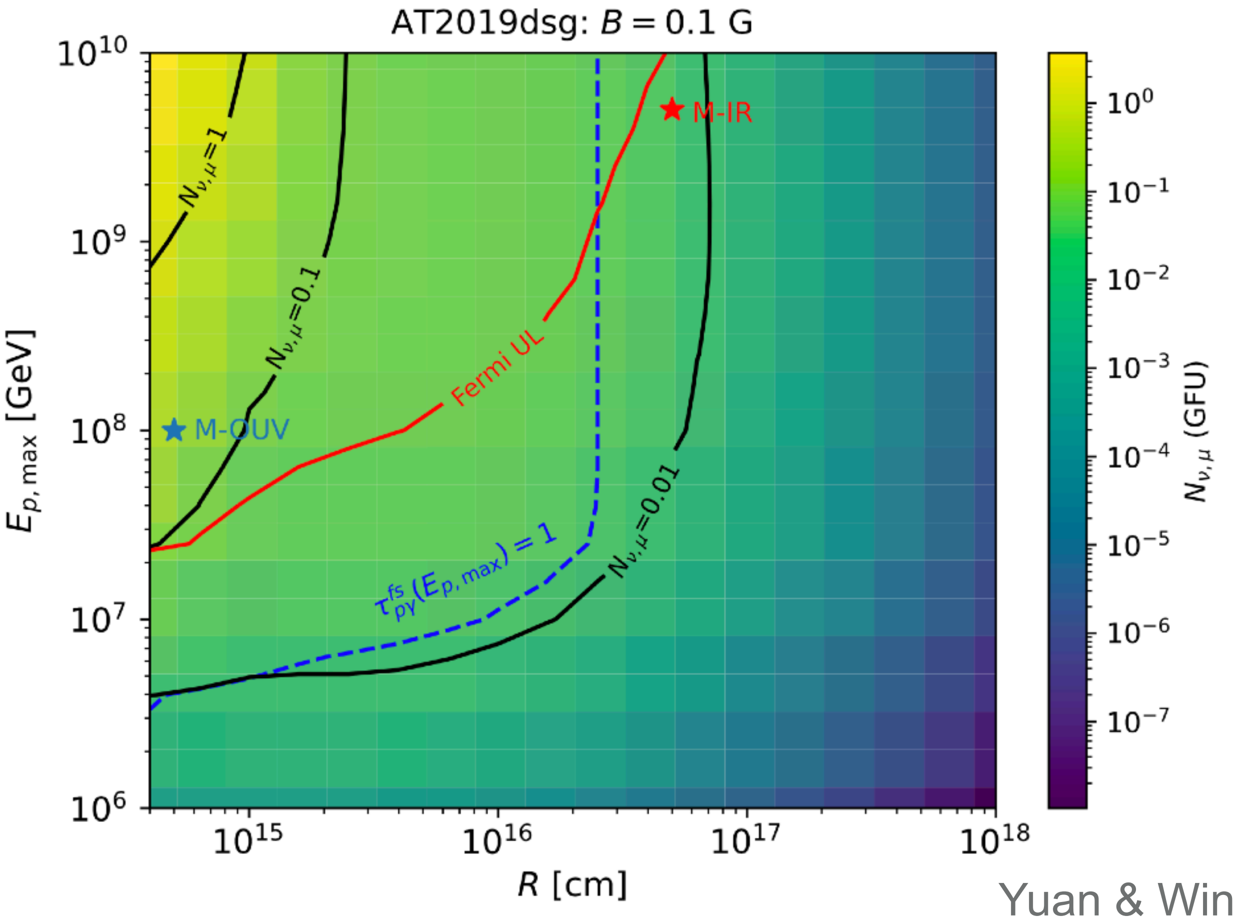
To avoid violating Fermi UL (red curve)

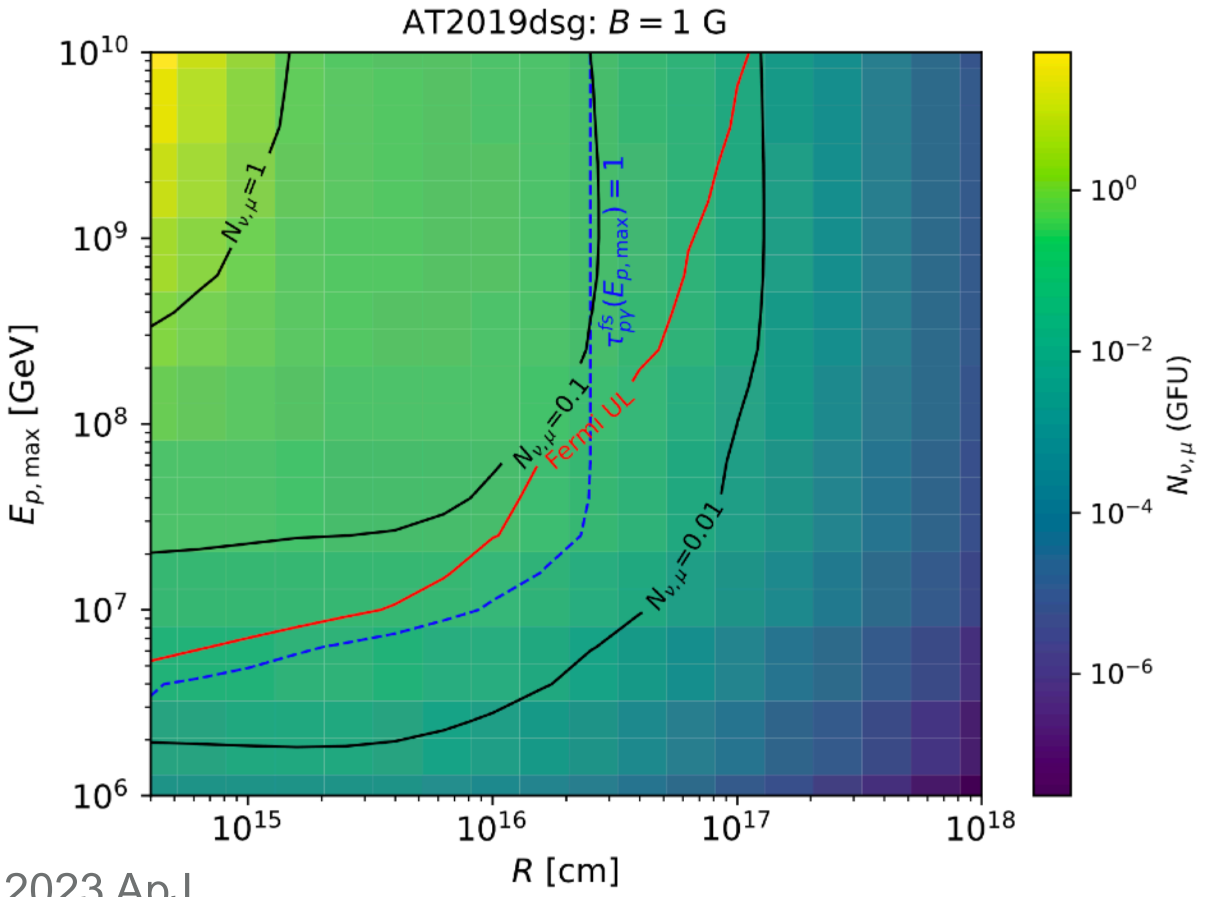
- An extended radiation zone is preferred (exclude M-OUV scenario)
- Neutrino number is constrained to be 0.01-0.1 per TDE
- Expected neutrino number from AT2019dsg, 0.008-0.76 (Stein+ 2021), is consistent with Fermi UL

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

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

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

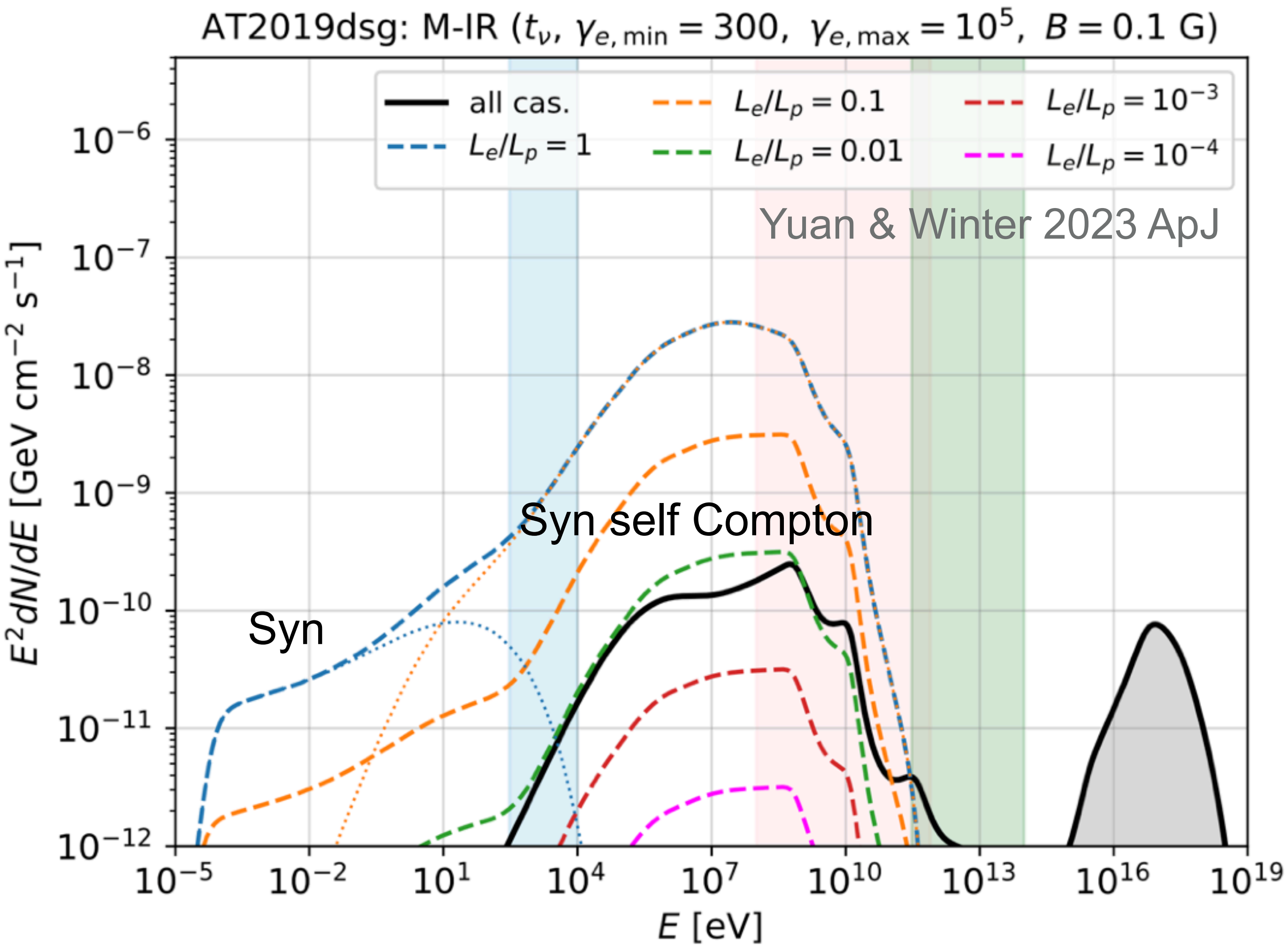
Electron injection spectra

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

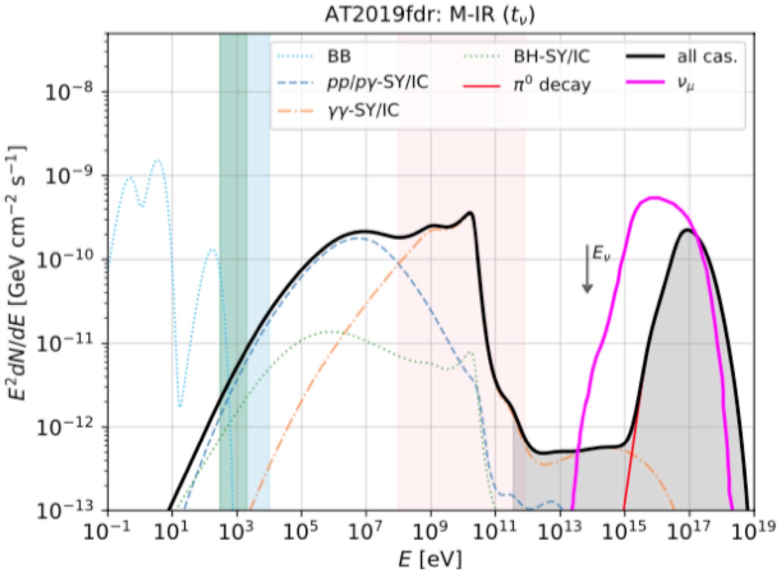
Cascade emission dominates if $L_e/L_p < 10^{-2}$

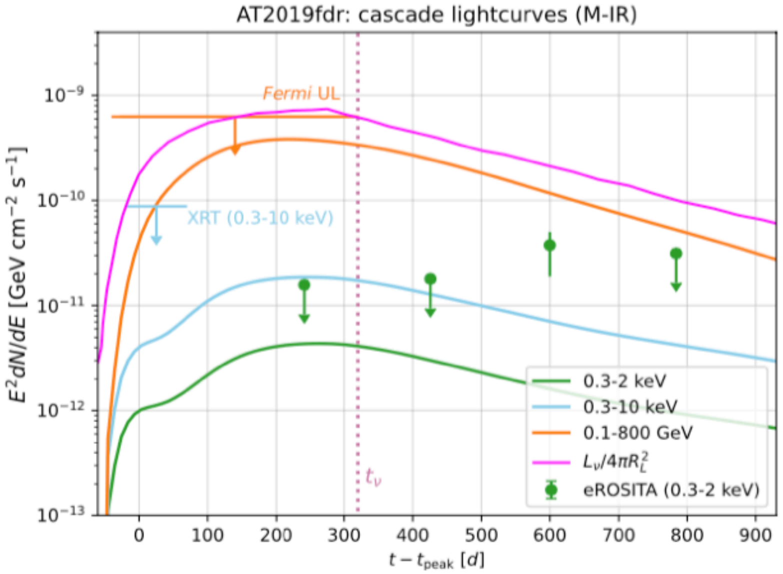
(Supported by the absence of radio signals accompanying OUV/IR)

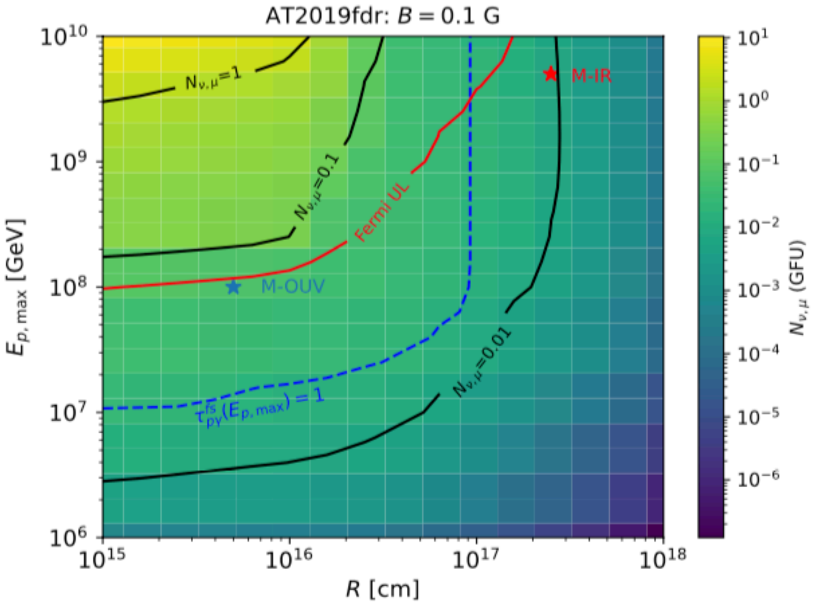
Caveat: leptonic contribution depends on electron minimum energy and magnetic field strengths

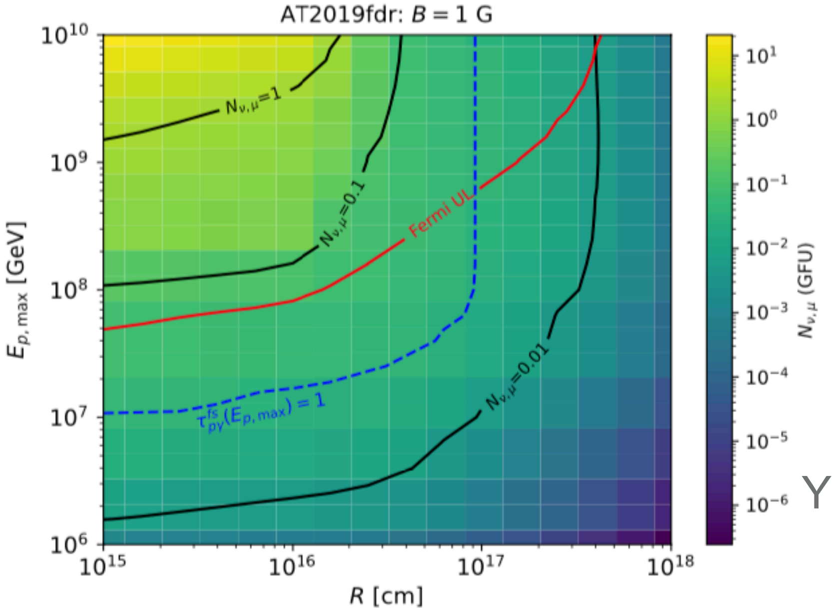


AT2019fdr


AT2019fdr: M-IR (t_ν)


AT2019fdr: cascade lightcurves (M-IR)


AT2019fdr: $B=0.1$ G


AT2019fdr: $B=1$ G

$z = 0.267$

$M_{\rm SMBH} = 1.3\times10^{7}M_\odot$

$E_\nu = 82$ TeV

M-IR:

- $R = 5\times10^{15}$ cm
- $E_{p,\max} = 10^{8}$ GeV

M-OUV:

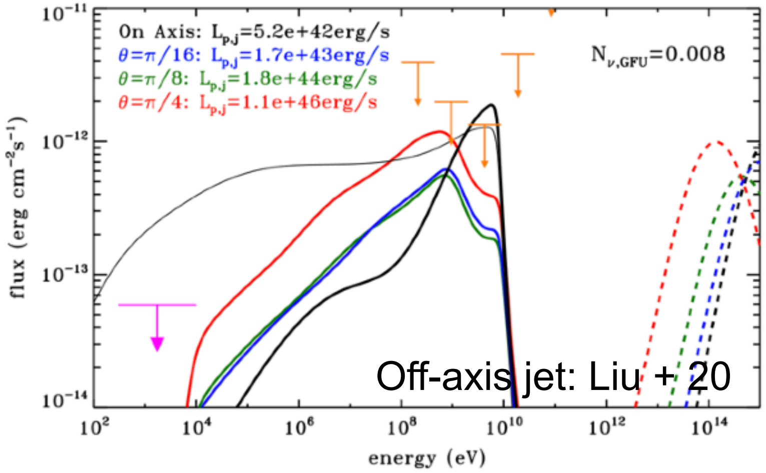
- $R = 2.5\times10^{17}$ cm
- $E_{p,\max} = 5\times10^{9}$ GeV

- For M-IR model, pgamma interaction is less efficient than AT2019dsg
- time delays in X-ray and gamma-ray bands are more prominent, and are determined jointly by target IR peak time and pgamma time scale.

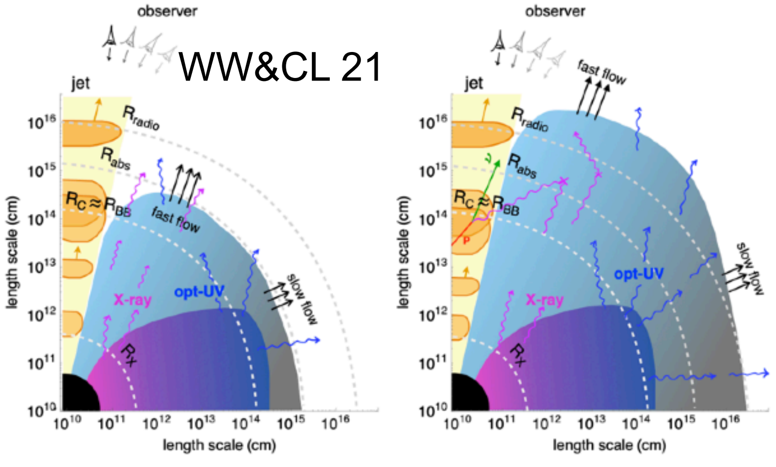
Yuan & Winter 2023 ApJ

Summary

- 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. Time-dependent analyses are needed (steady state may not be achieved with some source parameters).
- To be an efficient neutrino emitter, the accompanying cascade emission would overshoot the X-ray/γ-ray constraints. Fermi upper limits implies $\lesssim$ 0.1 neutrinos per TDE! (jets? γ-ray obscured/hidden models? Off-axis jet?)

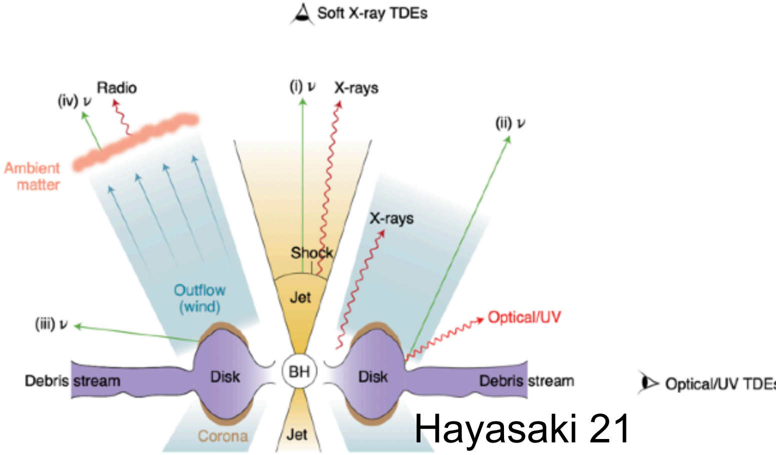


Off-axis jet: Liu + 20



a) Early ($t-t_{peak}$<17 day)

b) Late ($t-t_{peak}$ >> 17 day)



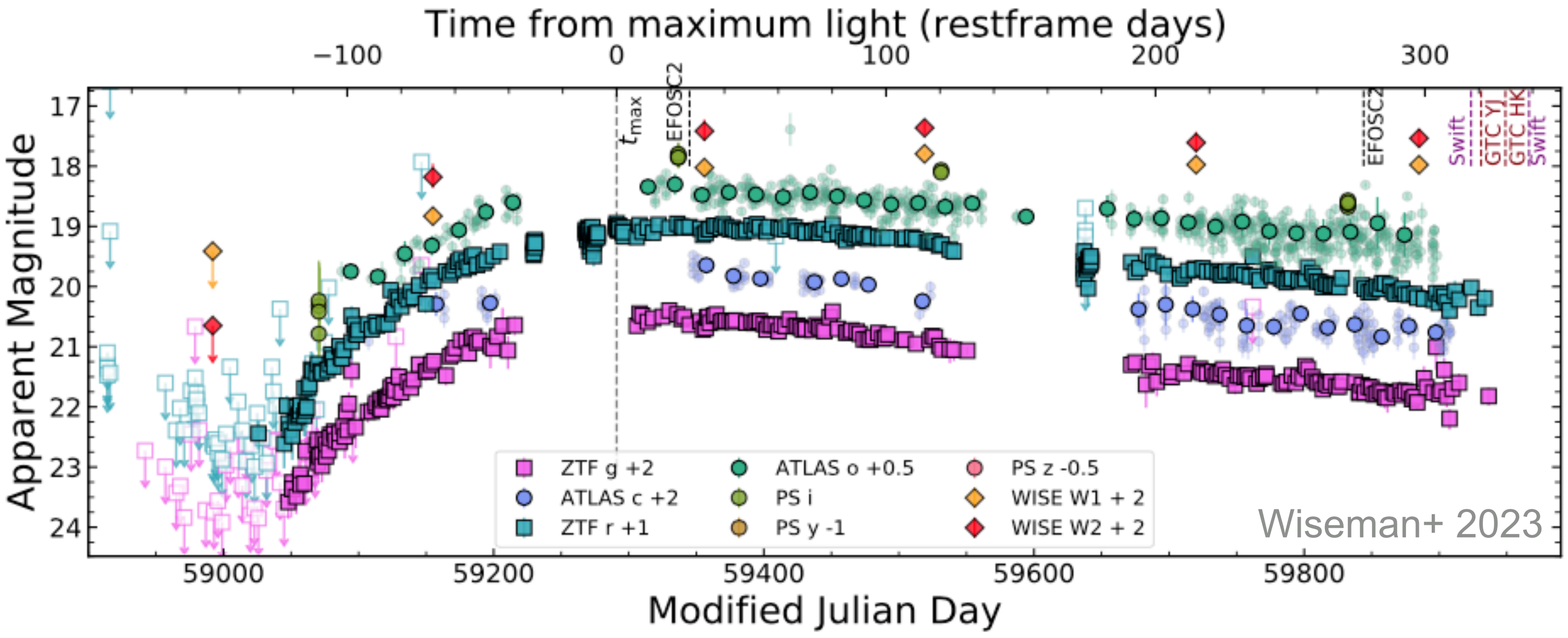
Hayasaki 21

Multi-Messenger Modeling of Neutrino-Coincident Tidal Disruption Events

- Theoretical and observational pictures of TDEs
- Particle interactions and isotropic hidden winds models with dust echoes
- Neutrino and EM cascade emissions from neutrino-emitting TDEs, AT2019dsg and AT2019fdr
- A fourth neutrino-coincident with strong dust echo??
- Open questions and outlook

A Fourth Candidate for a Neutrino-Coincident TDE??

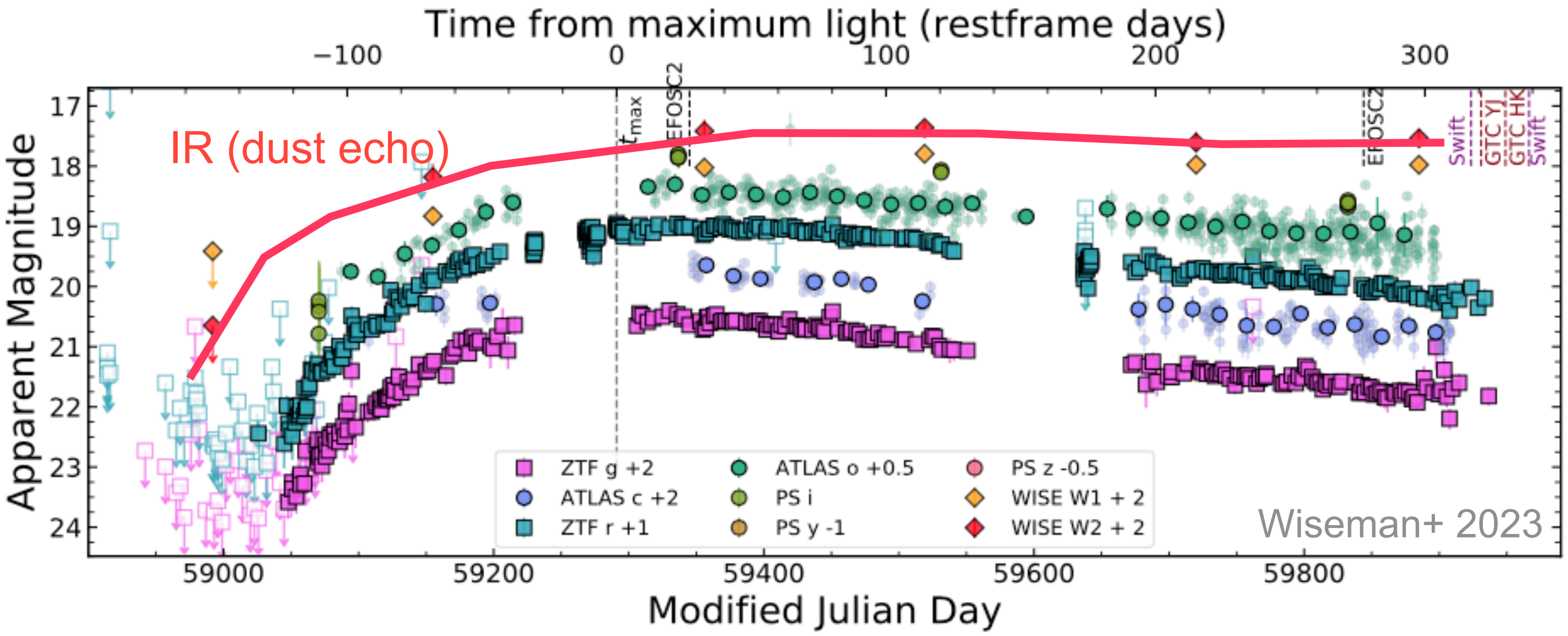
- AT2021lwx (ZTF20abrbeie; aka “Barbie” Subrayan+ 2023)
- Very far away: z = 0.995 (0.05 for AT2019dsg, 0.26 for AT2019fdr, 0.04 for aalc)
- Super bright - peak OUV bolometric luminosity: > 10^{46} erg s^{-1} (super-Eddington)
- SMBH mass ~ $10^8 M_\odot$, $M_\star \sim 14 M_\odot$ (Subrayan+ 2023)
- Potential correlation with neutrino IC220405B: angular offset ~ 2.5 deg; 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)

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 OUV bolometric luminosity: > 10^{46} erg s^{-1} (super-Eddington)
- SMBH mass ~ $10^8 M_\odot$, $M_\star \sim 14 M_\odot$ (Subrayan+ 2023)
- Potential correlation with neutrino IC220405B: angular offset ~ 2.5 deg; 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)

A Fourth Candidate for a Neutrino-Coincident TDE??

Similarities with other 3 TDEs: bright thermal OUV emission; strong dust echo (Wiseman+ 2023); similar neutrino time delay in source rest frame

Dust echo fitting:

- One simple box function cannot fit early IR emission (magenta curve)
- The contribution from dust on the line of slight (LoS) could be enhanced, e.g., by the debris. For example

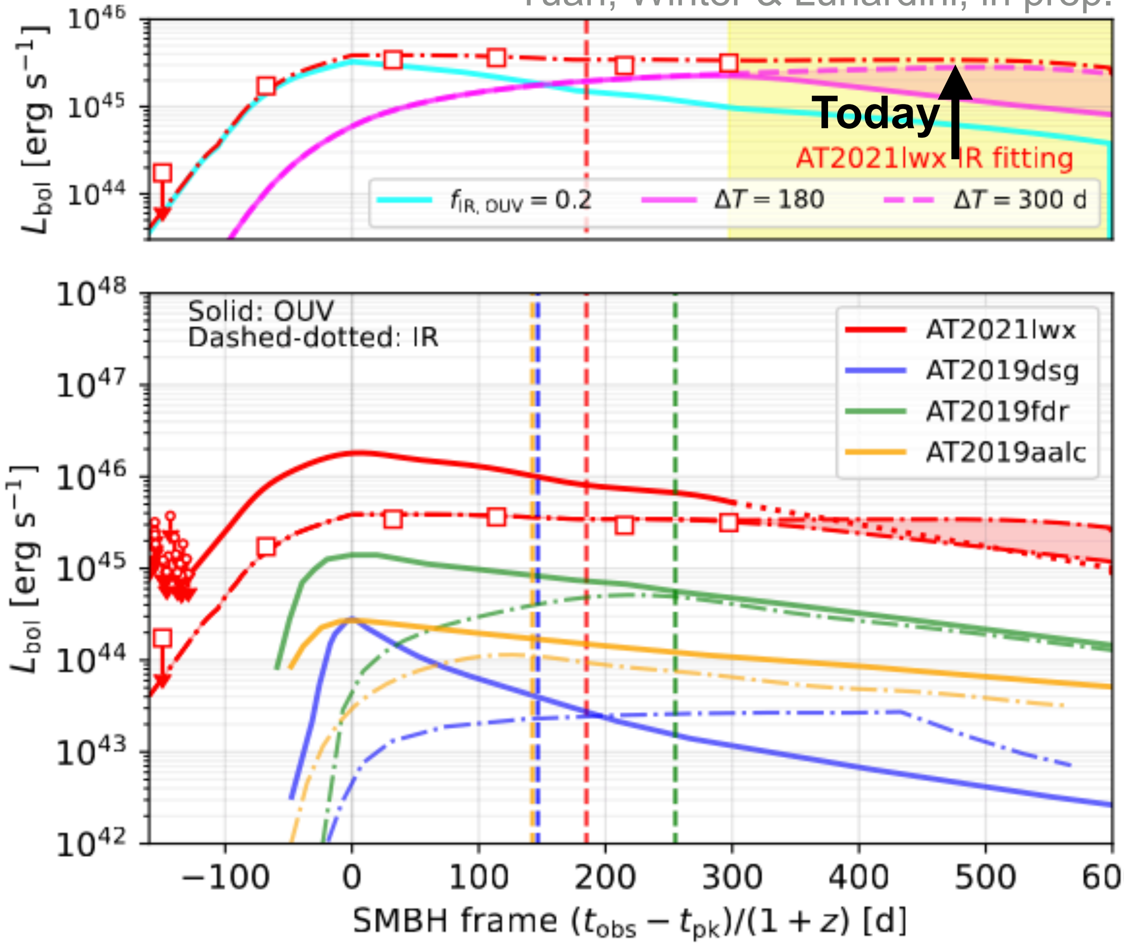
$$\begin{aligned} f(t) &= f_l(t) + f_s(t) \\ &= \lambda\delta(t) + \frac{(1-\lambda)}{2\Delta T}\left[H(t) - H(t-2\Delta T)\right] \end{aligned}$$

- LoS component (no delay): cyan curve
- Spherical component: magenta curve
- No significant decrease observed so far -> IR peak is uncertain -> $\Delta T \sim 180 - 330$ (red areas) $\lambda \sim 0.3 - 0.4$

$$R_{\rm IR} \sim 5\times10^{17} - 10^{18}\ {\rm cm}$$

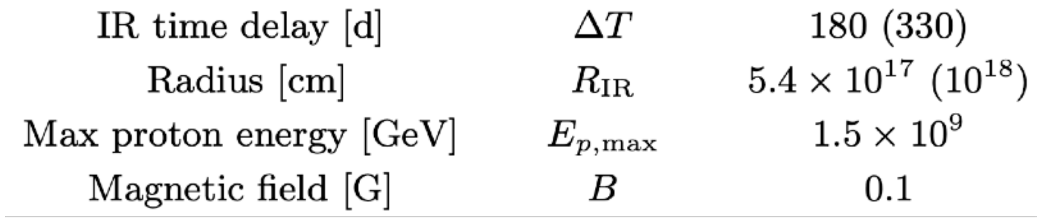
(Follow up IR observations could reduce the uncertainties of IR fitting)

Yuan, Winter & Lunardini, in prep.

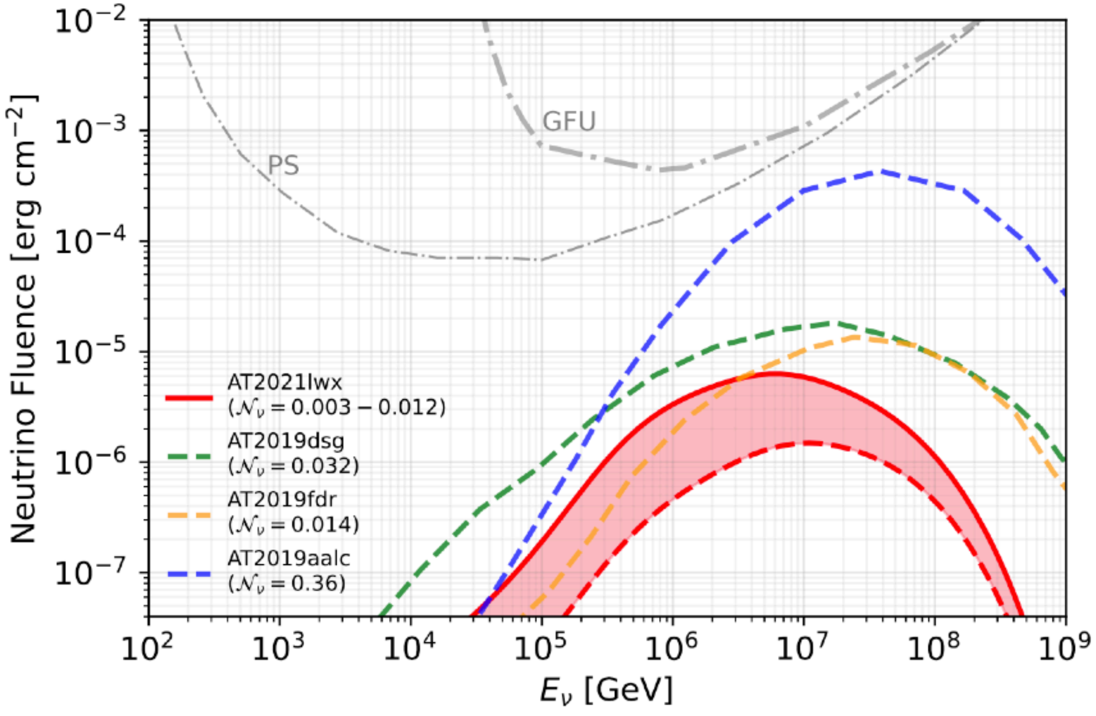


A Fourth Candidate for a Neutrino-Coincident TDE??

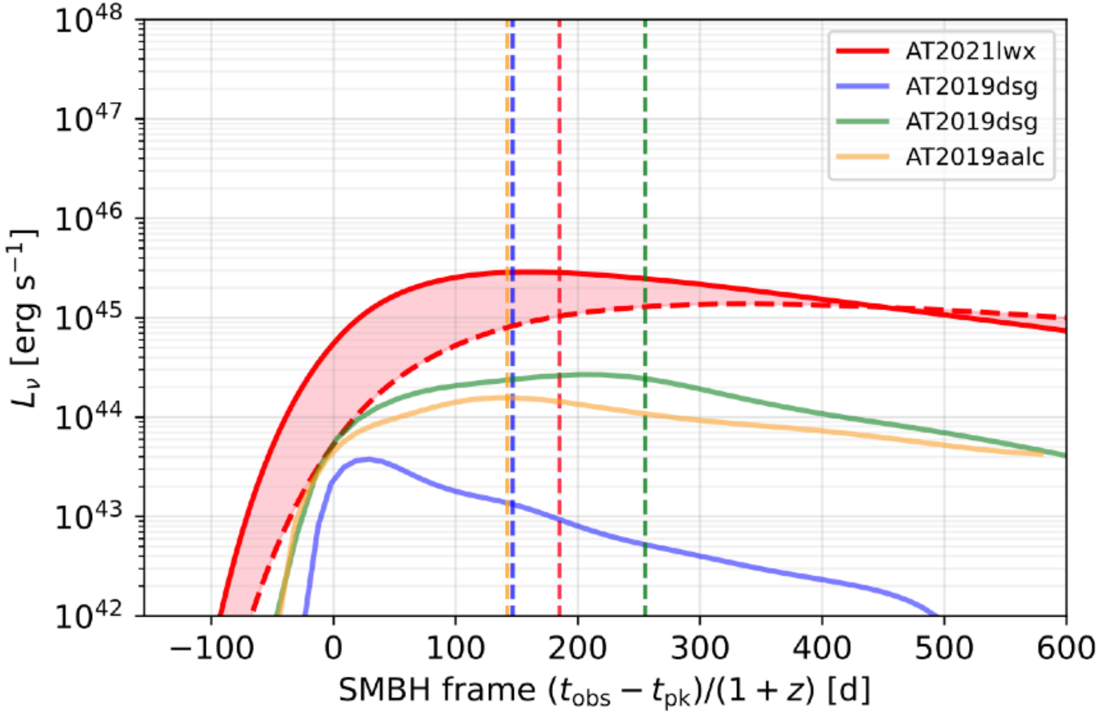
- **Similarities with other 3 TDEs:** bright thermal OUV emission; strong dust echo (Wiseman+ 2023); similar neutrino time delay in source rest frame
- Neutrino fluences and luminosities also share some similarities



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



AT2021lwx: Yuan, Winter & Lunardini, in prep.



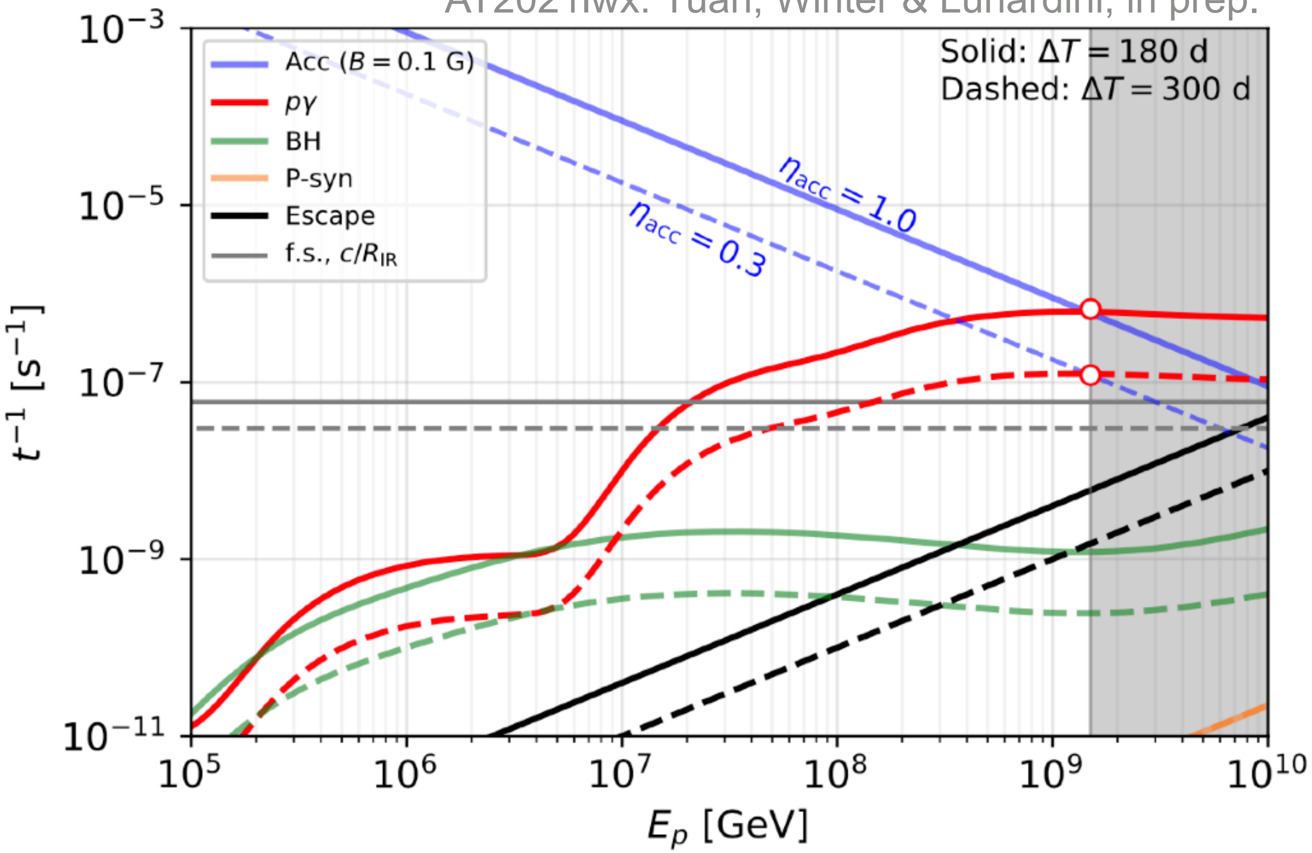
CR acceleration in IR radiation zones with $B = 0.1$ G

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

Larger η_{acc} -> more efficient acceleration

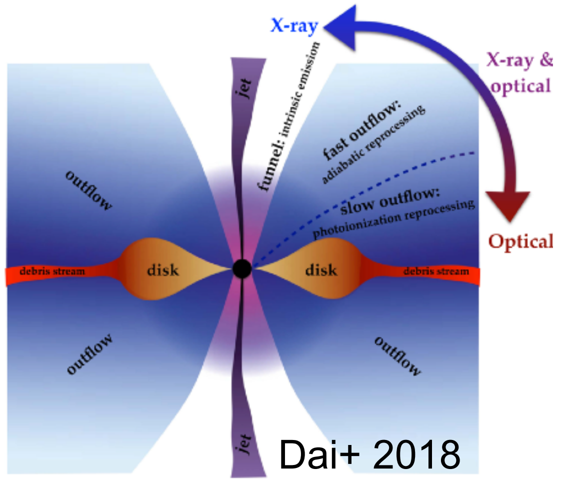
E_max is achievable for a reasonable $\eta_{\mathrm{acc}} \sim 0.3 - 1$ by balancing acc. rate (blue lines) to energy loss rate (red curves), similar to AT2019dsg/fdr/aalc

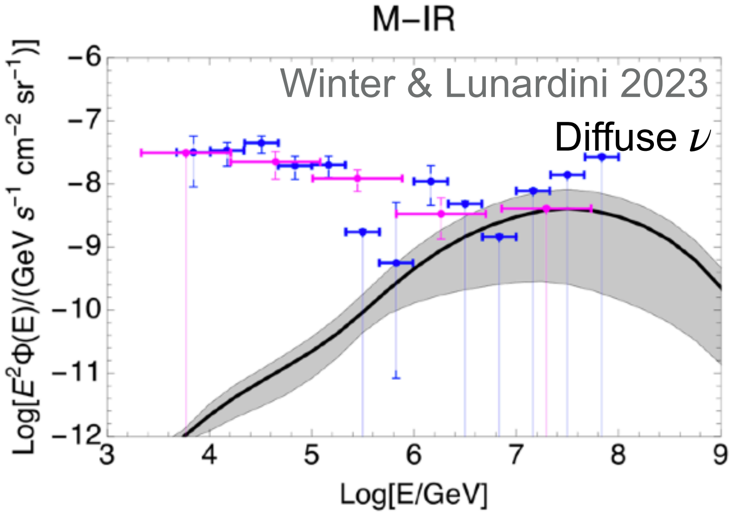
AT2021lwx: Yuan, Winter & Lunardini, in prep.

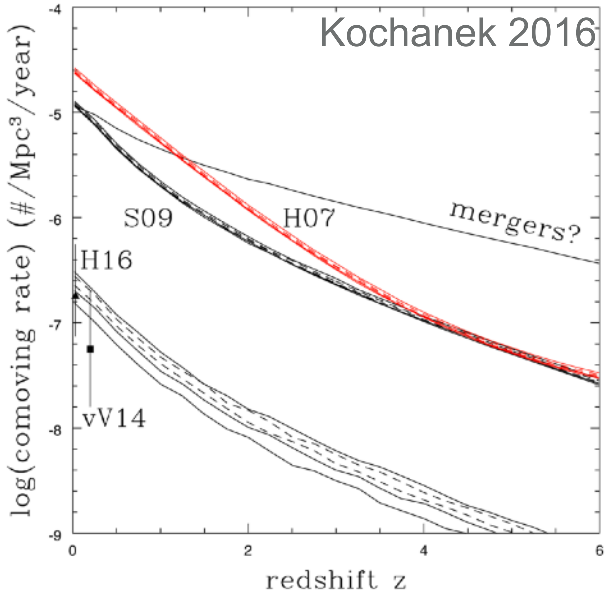


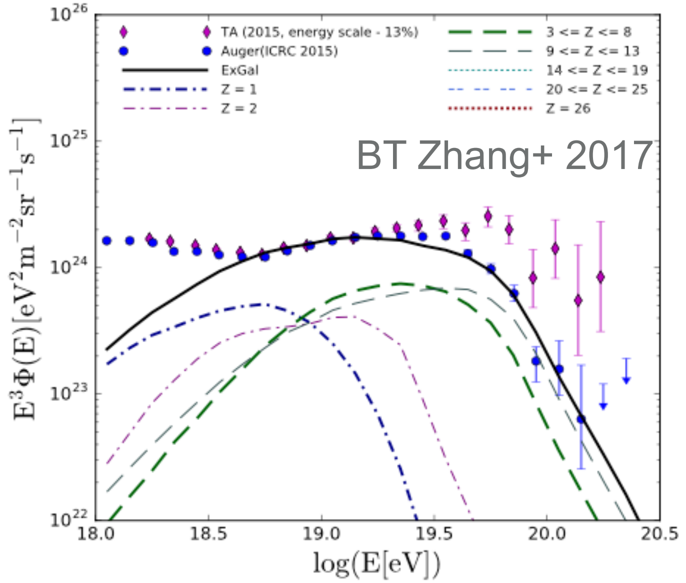
Open Questions and on going works

- Distinguishing TDEs from impostors
- One unified picture for jetted and non-jetted TDEs (like AGNs), e.g., ***Dai + 2018***?
- Months to years time delay of neutrino coincidence (AT2019dsg/fdr/aalc) common for TDEs?
- Self-consistent modeling of the dynamics of TDE jets/winds with persistent energy inputs ***(CY+, work in progress)***
- Can TDEs be promising (VHE) γ-ray emitters? origin of UHECRs ***(P. Plotko +, in prep.)***? Contribute to diffuse neutrino flux?
- Cosmological TDE rate? ν-coincident rate?


Dai+ 2018


Winter & Lunardini 2023

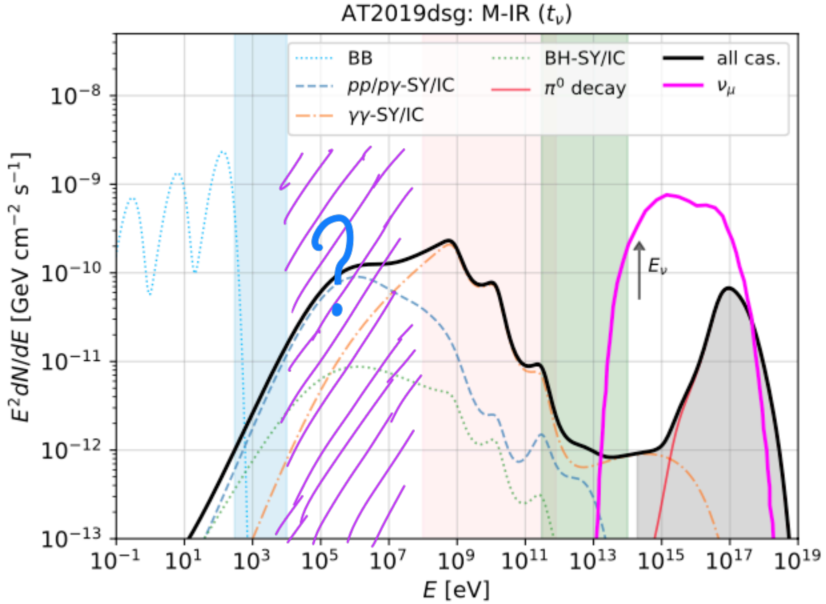

Kochanek 2016


BT Zhang+ 2017

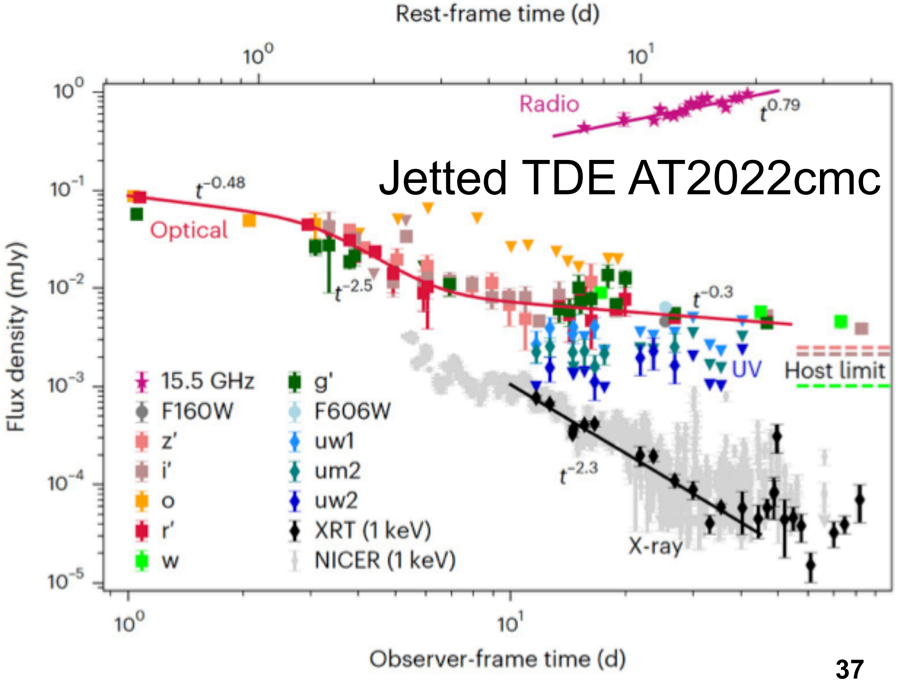
What we may need in the future

- a bold guess -

- ☐ Better angular resolution for neutrino tracks
- ☐ GeV to VHE γ-ray data/constraints from Fermi, HAWC, VERITAS, etc. in time domain (late-time followup)
- ☐ MeV missions between hard X-ray and sub-GeV
- ☐ Time-dependent lepto-hadronic modeling of TDE jets/winds - leptonic process can be important in jets or for a stronger *B* or sufficient leptonic loading $L_e/L_p \gtrsim 10^{-2}$
- ☐ (Surprise us: GWs by LISA? …)



Andreoni+ 2022, Nature



Backup Slides

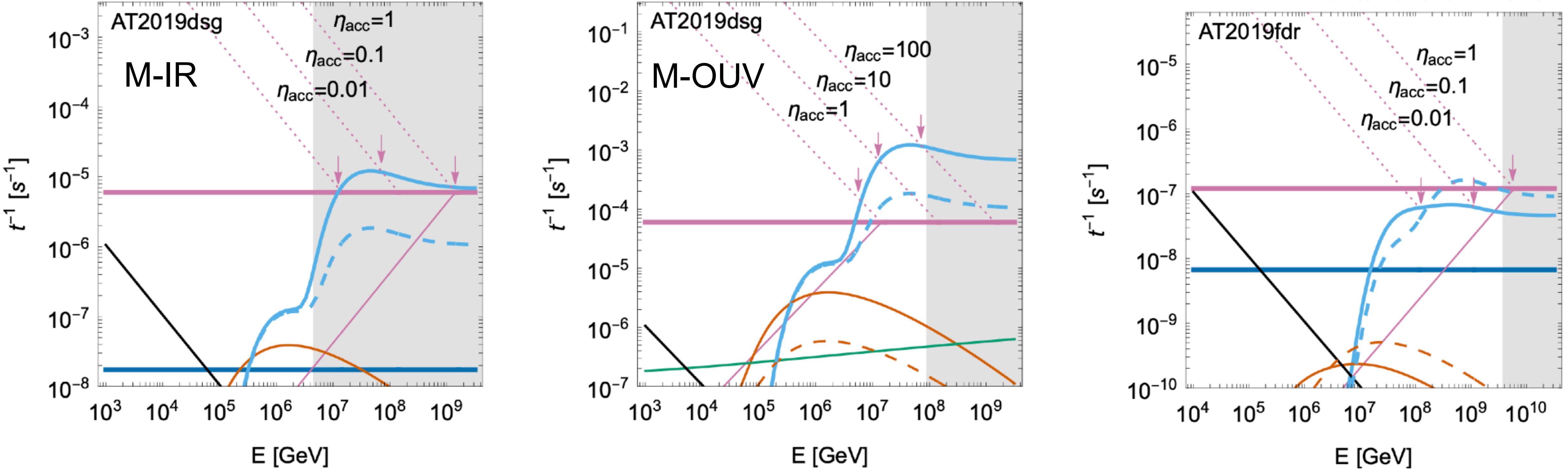
CR acceleration with $B = 0.1\ \mathrm{G}$

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

Larger $\eta_{\rm acc}$ implies efficient CR acceleration; $E_{\rm max}$ depends on B

$B = 0.1 - 1\ \mathrm{G}$ is conservative for M-OUV cases ($R \sim 10^{15}\ \mathrm{cm}$, acceleration sites are close to hot corona, B can be much larger, e.g., $\sim \mathrm{kG}$)

Winter & Lunardini 2023



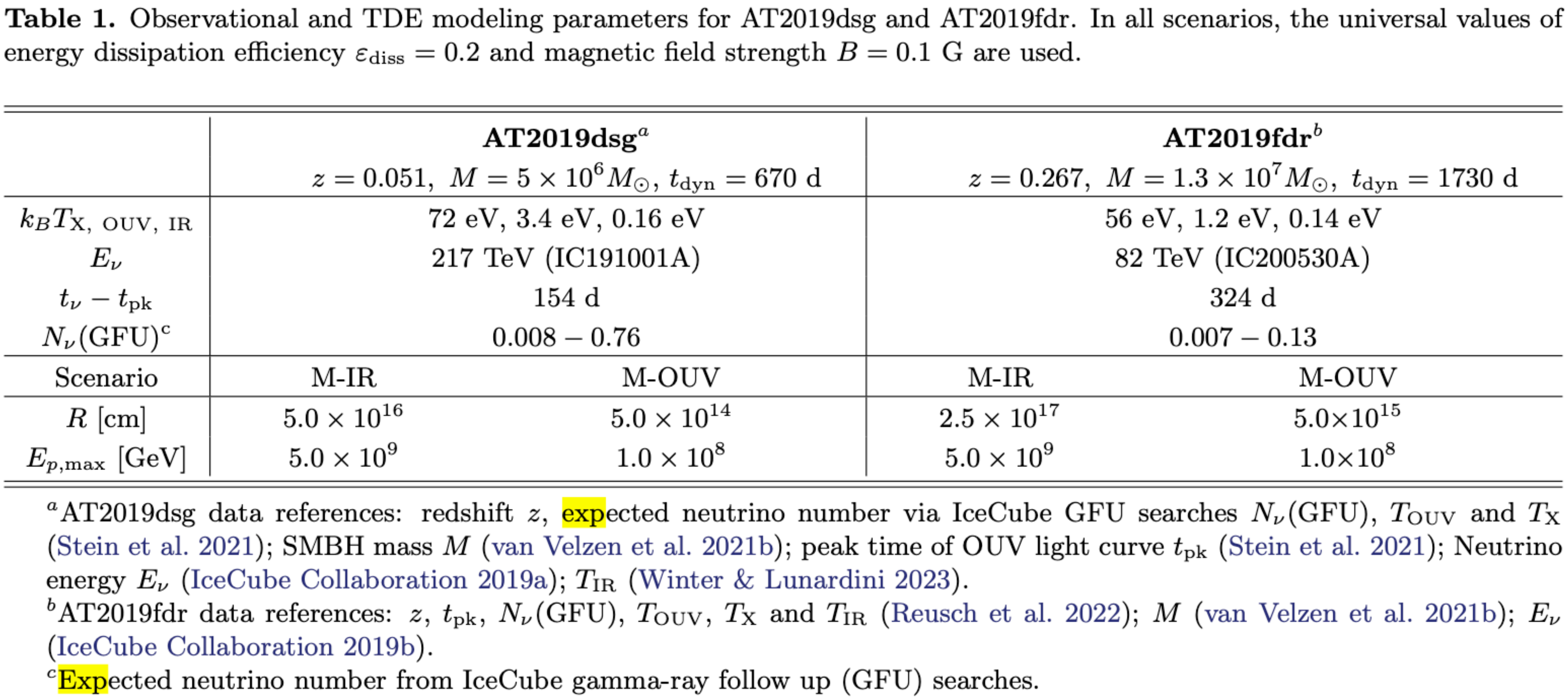


Table 1. Observational and TDE modeling parameters for AT2019dsg and AT2019fdr. In all scenarios, the universal values of energy dissipation efficiency $\varepsilon_{\rm diss} = 0.2$ and magnetic field strength $B = 0.1$ G are used.

	AT2019dsg[a] $z = 0.051,\ M = 5 \times 10^6 M_\odot,\ t_{\rm dyn} = 670$ d		**AT2019fdr**[b] $z = 0.267,\ M = 1.3 \times 10^7 M_\odot,\ t_{\rm dyn} = 1730$ d	
$k_B T_{\rm X,\ OUV,\ IR}$	72 eV, 3.4 eV, 0.16 eV		56 eV, 1.2 eV, 0.14 eV	
E_ν	217 TeV (IC191001A)		82 TeV (IC200530A)	
$t_\nu - t_{\rm pk}$	154 d		324 d	
N_ν(GFU)[c]	0.008 – 0.76		0.007 – 0.13	
Scenario	M-IR	M-OUV	M-IR	M-OUV
R [cm]	5.0×10^{16}	5.0×10^{14}	2.5×10^{17}	$5.0{\times}10^{15}$
$E_{p,\rm max}$ [GeV]	5.0×10^{9}	1.0×10^{8}	5.0×10^{9}	$1.0{\times}10^{8}$

[a] AT2019dsg data references: redshift z, expected neutrino number via IceCube GFU searches N_ν(GFU), $T_{\rm OUV}$ and $T_{\rm X}$ (Stein et al. 2021); SMBH mass M (van Velzen et al. 2021b); peak time of OUV light curve $t_{\rm pk}$ (Stein et al. 2021); Neutrino energy E_ν (IceCube Collaboration 2019a); $T_{\rm IR}$ (Winter & Lunardini 2023).

[b] AT2019fdr data references: z, $t_{\rm pk}$, N_ν(GFU), $T_{\rm OUV}$, $T_{\rm X}$ and $T_{\rm IR}$ (Reusch et al. 2022); M (van Velzen et al. 2021b); E_ν (IceCube Collaboration 2019b).

[c] Expected neutrino number from IceCube gamma-ray follow up (GFU) searches.

AT2021lwx

- Parameters and EM cascade SEDs

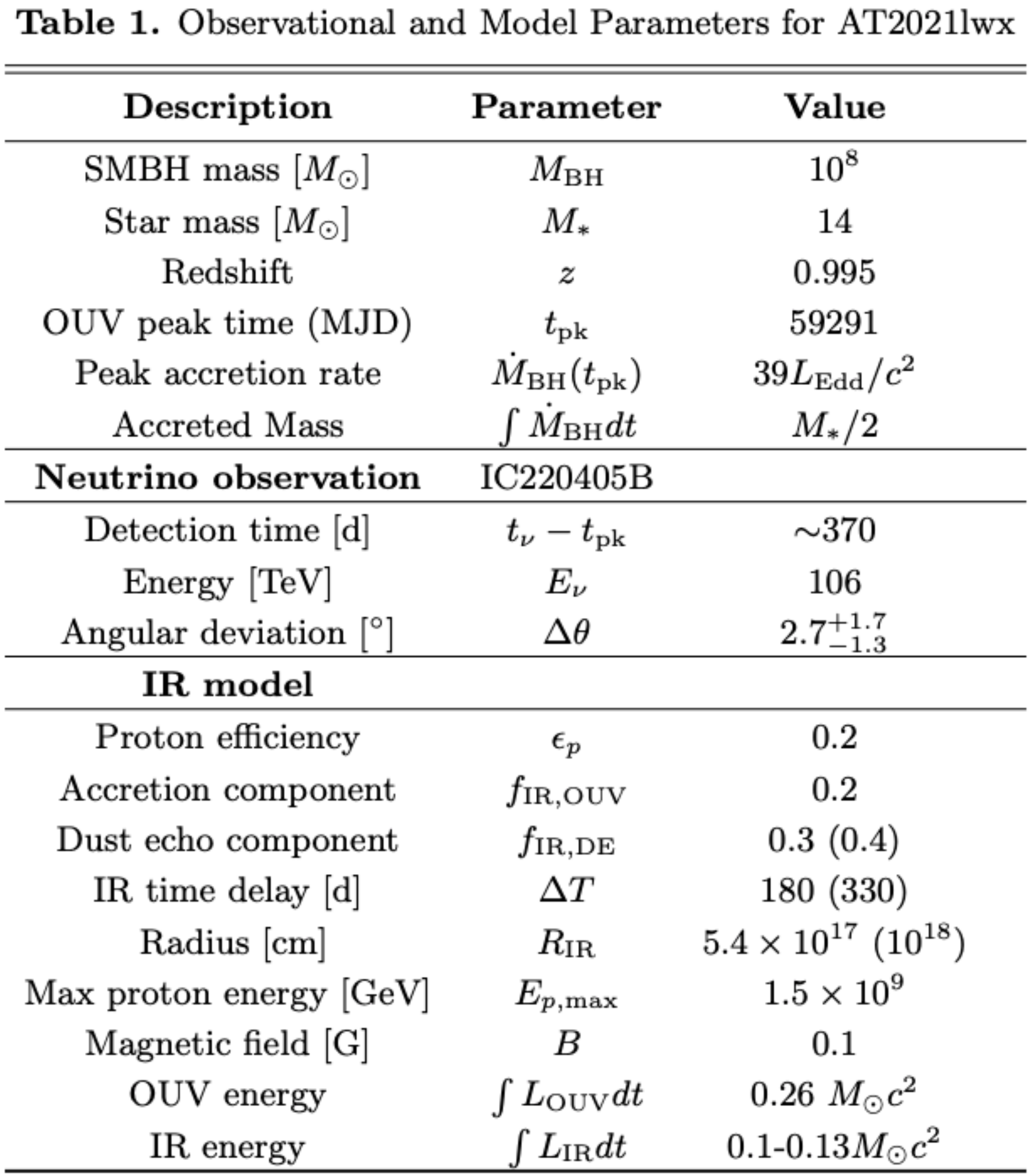
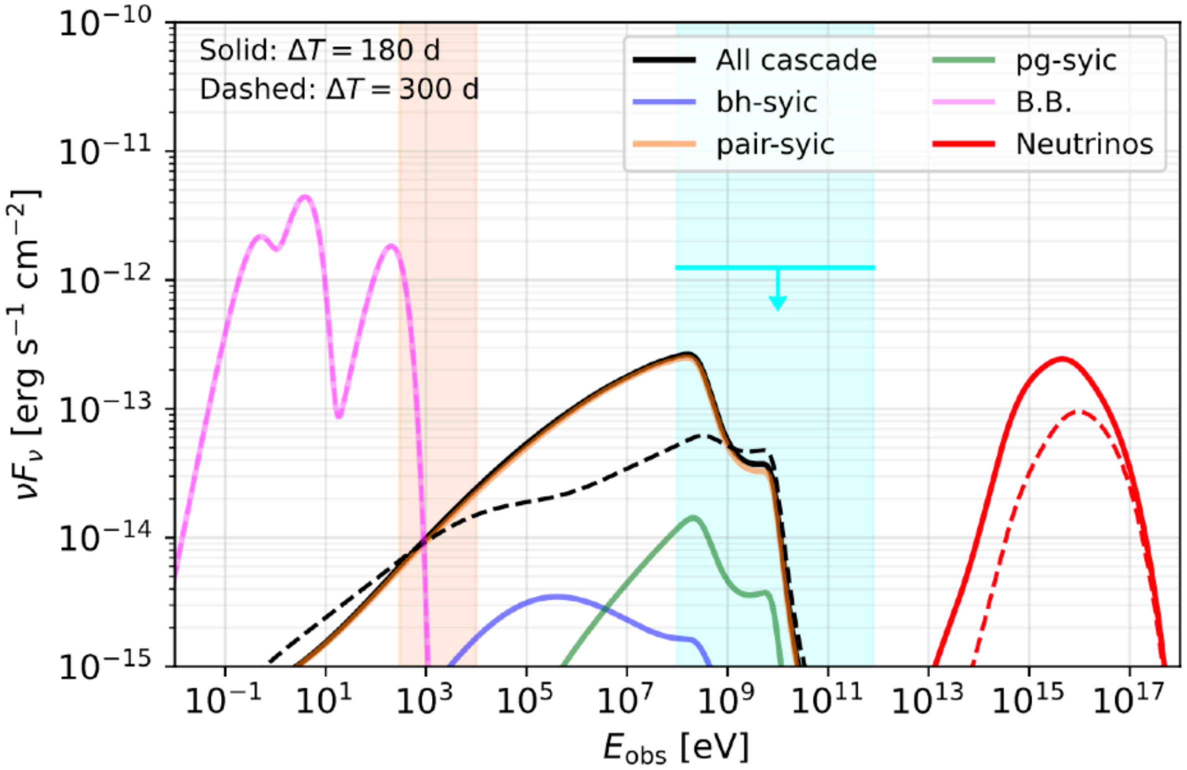


Table 1. Observational and Model Parameters for AT2021lwx

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]	$t_\nu - t_{\rm pk}$	~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	$\int L_{\rm IR}dt$	0.1-0.13$M_\odot c^2$



Radiation processes

Particle cooling:

$p \to p'$

$(e^\pm) \to (e^\pm)' \to (e^\pm)''$

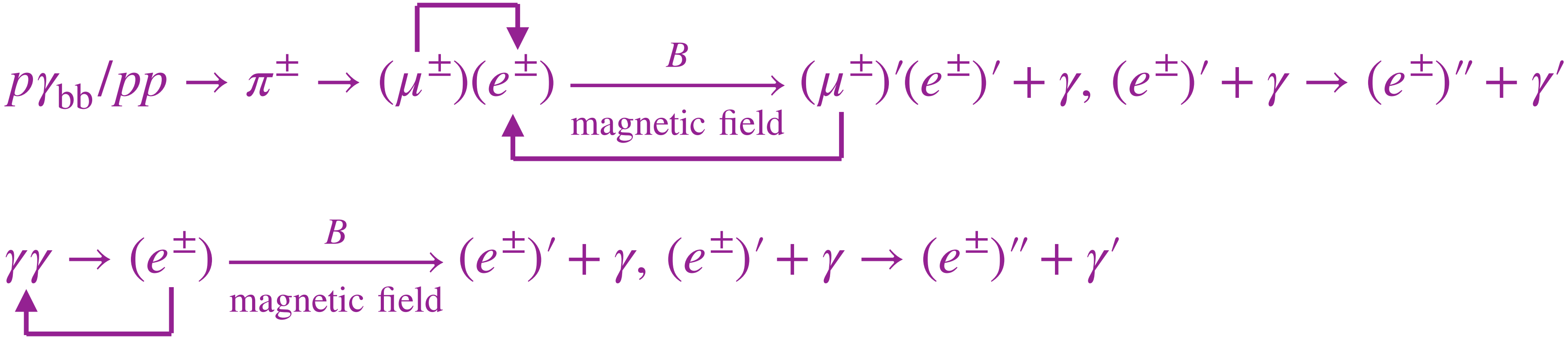
$(\mu^\pm) \to (\mu^\pm)'$

Primary $e^\pm$ injections are not considered in this calculation (will be discussed in later slides)

Neutrino production: $p\gamma/pp \to \pi^\pm \to \nu_e\bar{\nu}_e\nu_\mu\bar{\nu}_\mu$

Proton synchrotron: $p \xrightarrow[\text{magnetic field}]{B} \gamma + p'$

Cascade processes: $\pi^0 \to 2\gamma$



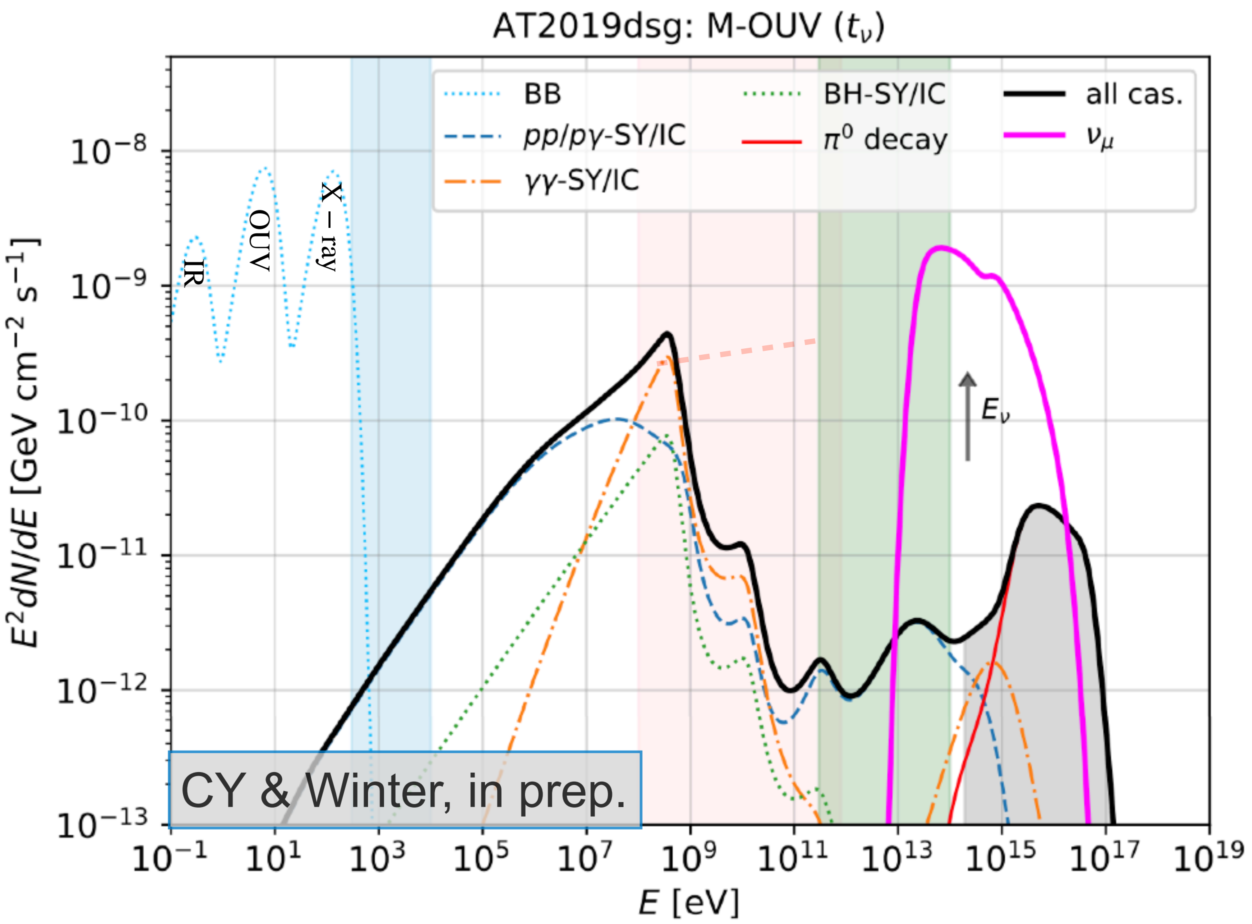
$$p\gamma_{\rm bb}/pp \to \pi^\pm \to (\mu^\pm)(e^\pm) \xrightarrow[\text{magnetic field}]{B} (\mu^\pm)'(e^\pm)' + \gamma,\ (e^\pm)' + \gamma \to (e^\pm)'' + \gamma'$$

$$\gamma\gamma \to (e^\pm) \xrightarrow[\text{magnetic field}]{B} (e^\pm)' + \gamma,\ (e^\pm)' + \gamma \to (e^\pm)'' + \gamma'$$

Bethe-Heitler (BH) pair production $p\gamma_{\rm bb} \to p'(e^\pm) \xrightarrow[\text{magnetic field}]{B} (e^\pm)' + \gamma,\ (e^\pm)' + \gamma \to (e^\pm)'' + \gamma'$

EM cascade spectra of AT2019dsg: M-OUV

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

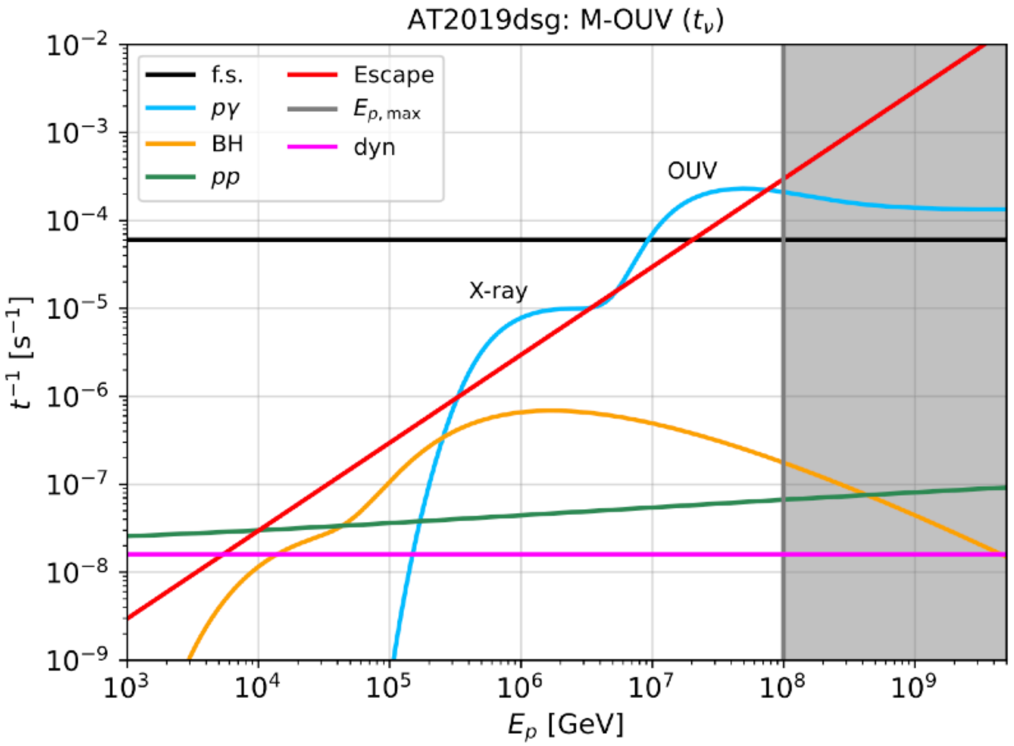


CY & Winter, in prep.

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

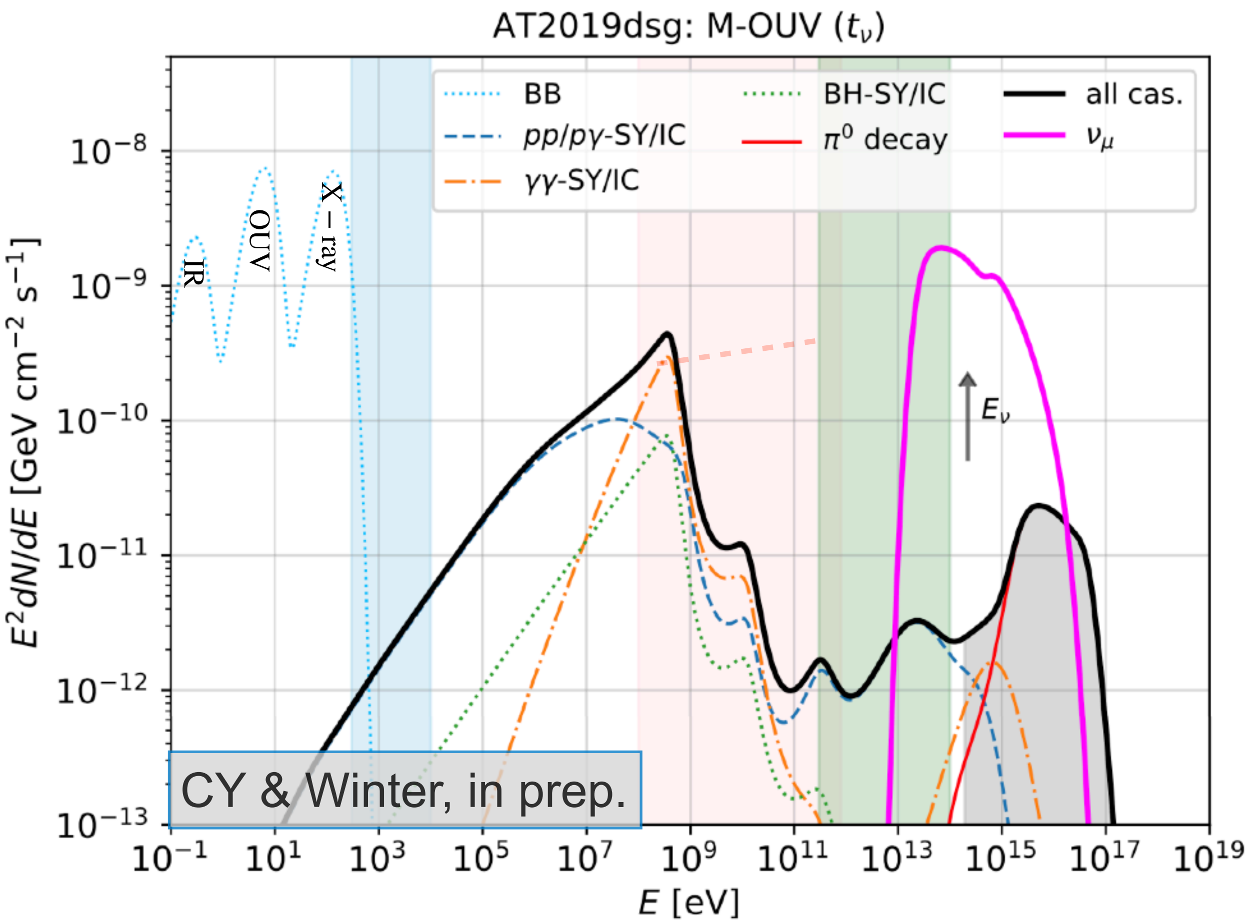
$B = 0.1$ G, $R = 5 \times 10^{14}$ cm, $E_{p,\max} = 1 \times 10^{8}$ GeV

$R_{IR} \gg R$ -> IR subdominant ($n \propto L_{IR} R^{-2} c^{-1}$)



EM cascade spectra of AT2019dsg: M-OUV

$p\gamma$ optically thick $t_{p\gamma}^{-1}/t_{\rm fs}^{-1} > 1$: $(\pi^\pm \to e^\pm \to {\rm SY/IC})$ **+** $(\gamma\gamma \to e^\pm \to {\rm SY/IC})$



CY & Winter, in prep.

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

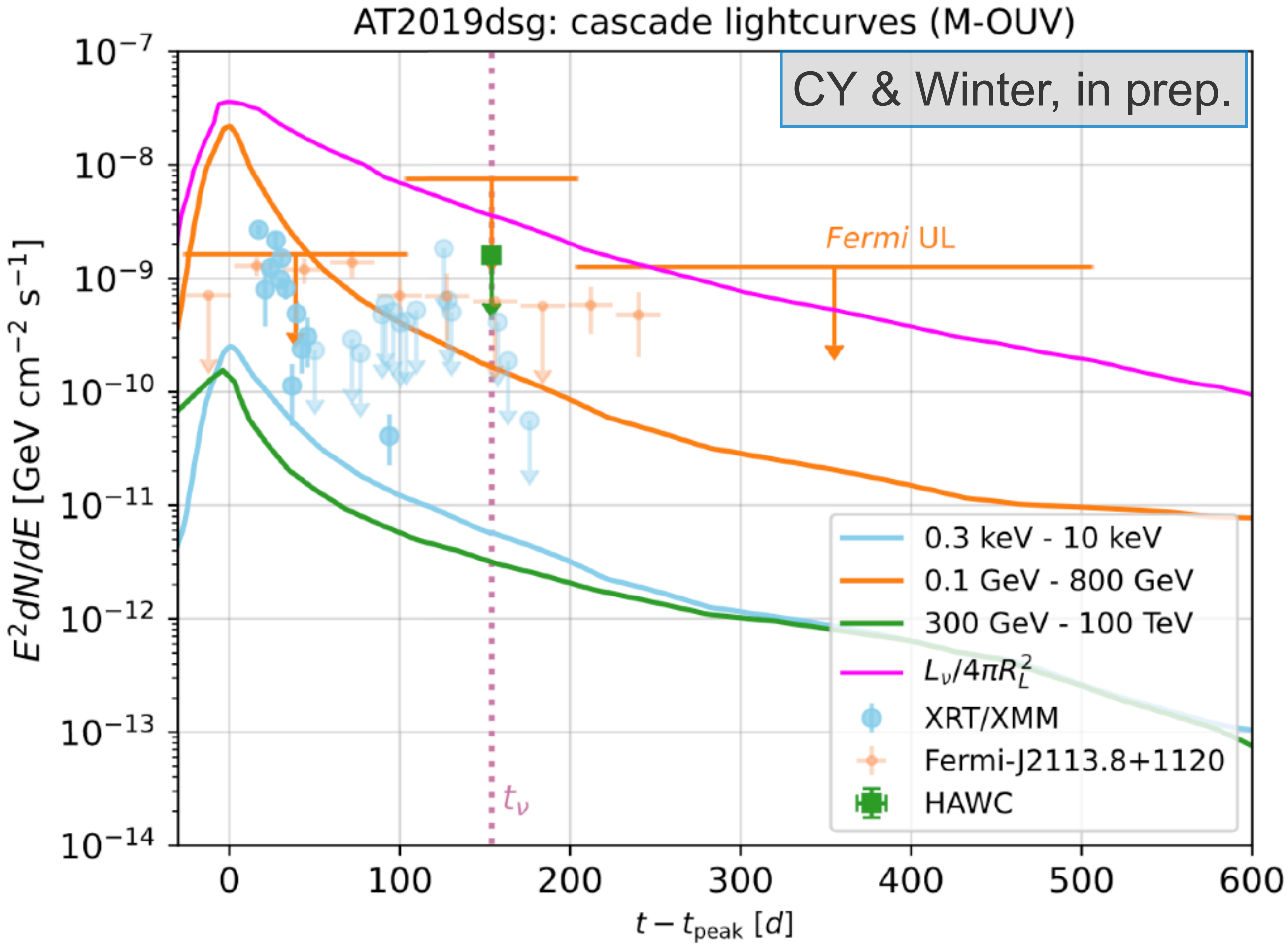
$B = 0.1$ G, $R = 5 \times 10^{14}$ cm, $E_{p,\max} = 1 \times 10^8$ GeV

$R_{IR} \gg R$ -> IR subdominant ($n \propto L_{IR} R^{-2} c^{-1}$)

- Small R leads to fast proton escape
- $E_{p\gamma,\min} \sim 10^{6-7}$ GeV
- Synchrotron peak energy $>$ GeV
- Attenuated before reaching the peak -> spikes
- Promising neutrino emitter in the neutrino energy range

AT2019dsg Temporal signatures: M-OUV

Compact region: $\varepsilon_{\rm diss}=0.2$, $B=0.1$ G, $R=5\times10^{14}$ cm, $E_{p,\max}=1\times10^{8}$ GeV

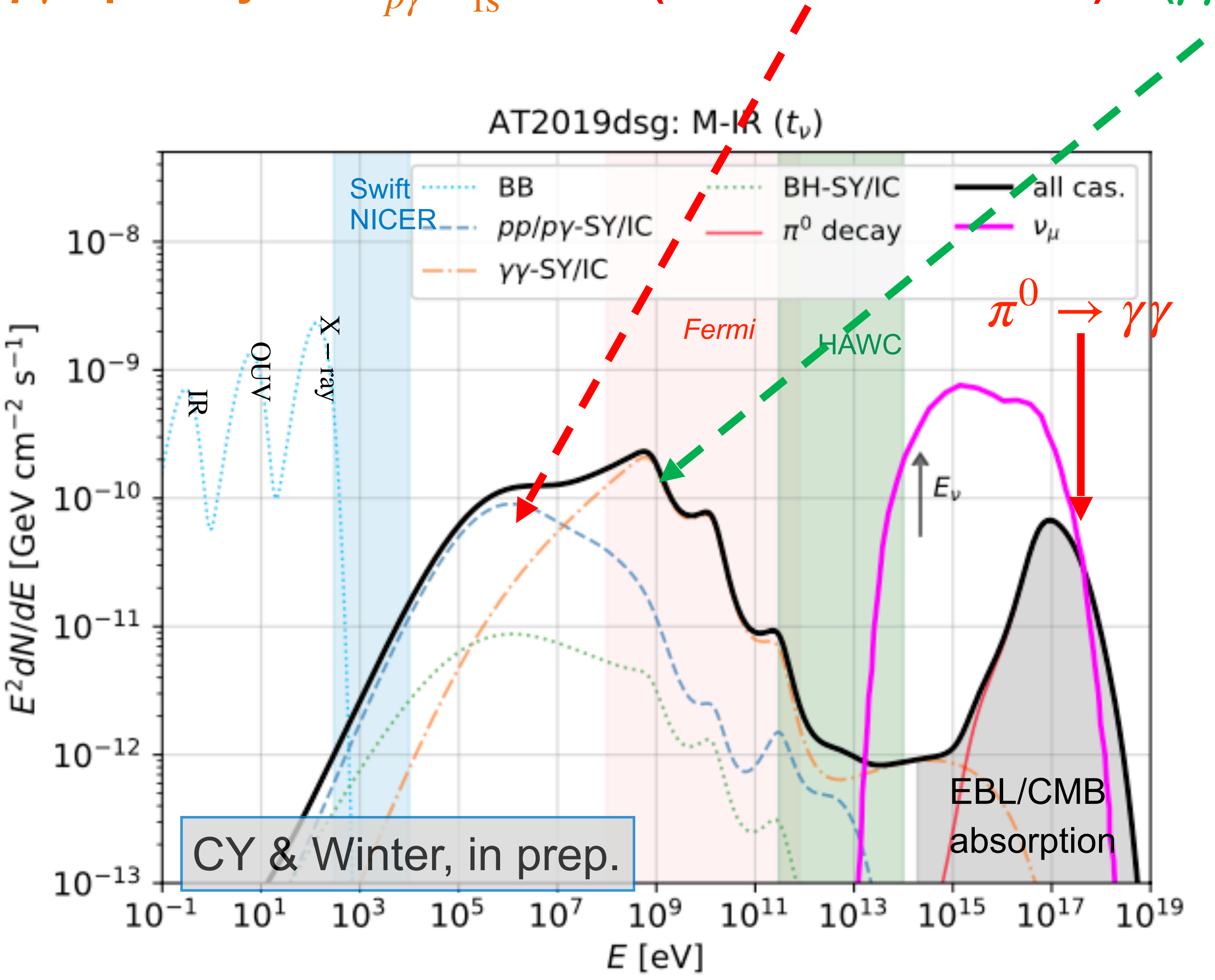


In this compact and dense region, interactions occur very fast

- $p\gamma$ optically thick: $t_{p\gamma}^{-1}/t_{\rm fs}^{-1}>1$
- Cascade emissions follows OUV light curve (no significant time delay)
- Cascade emission peaks in LAT energy range -> overshooting the γ-ray limits

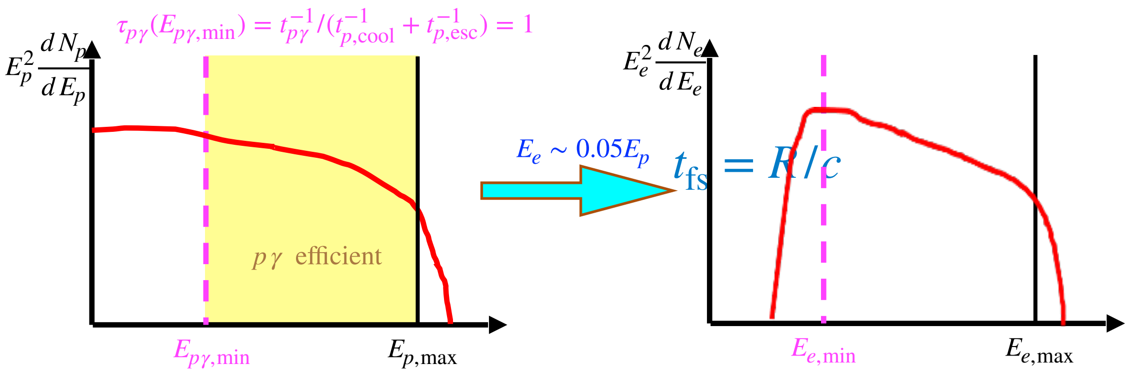
EM cascade spectra of AT2019dsg: M-IR (dust echo)

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



CY & Winter, in prep.

$\pi^{\pm} \to e^{\pm} \to {\rm SY/IC}$



$$E_{pp/p\gamma,\rm SY} \sim \frac{3}{4\pi} h\gamma_{e,min}^2 \frac{eB}{m_e c}$$

$$\sim 420\ B_{-1} \left(\frac{E_{p\gamma,\rm min}}{10^5\ \rm GeV}\right)^2\ \rm keV$$

$\gamma\gamma$ absorption

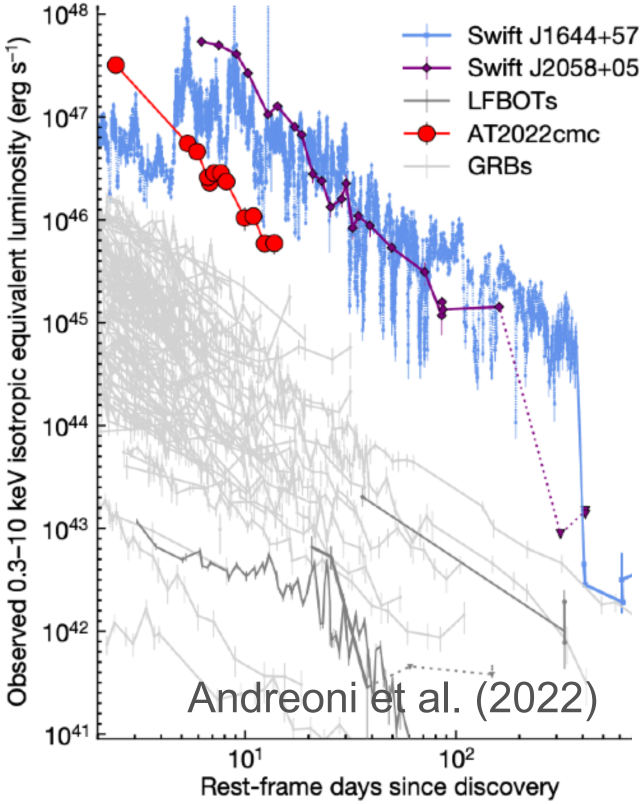
$$E_\gamma \sim m_e^2/E_{\rm bb} \simeq 2\ {\rm GeV}(E_{\rm bb}/100{\rm eV})^{-1}$$

Jetted TDEs

A recent example: AT2022cmc

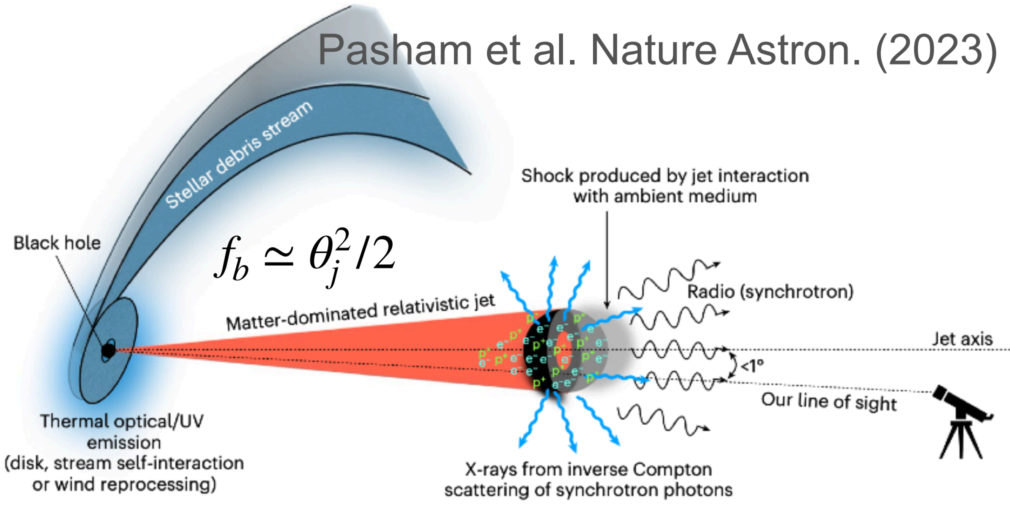
(In addition to Swift J1644+57 and Swift J2058+05)

- z = 1.193
- Very bright
- Non-thermal X-rays may be produced by relativistic jets ($\gtrsim 10^{48}$ erg/s, usually 10^42-44 erg/s)
- A very high Lorentz factor $\Gamma \sim 90$ is assumed (~10 for blazars)



Andreoni et al. (2022)

Pasham et al. Nature Astron. (2023)



$f_b \simeq \theta_j^2/2$