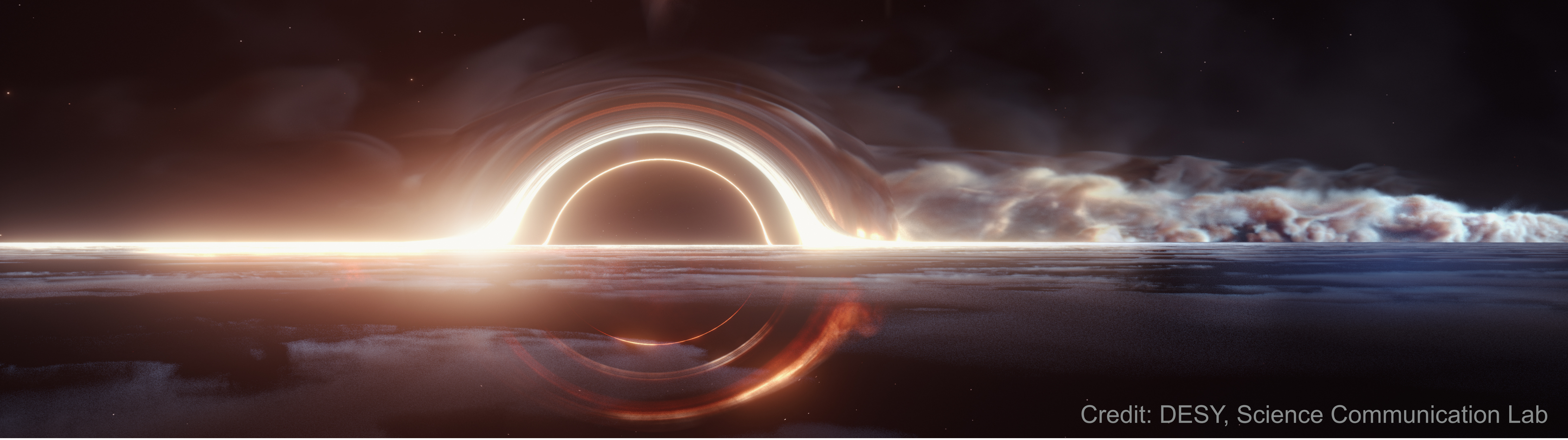

Credit: DESY, Science Communication Lab

Multi-Messenger Modeling of Neutrino-Coincident TDEs

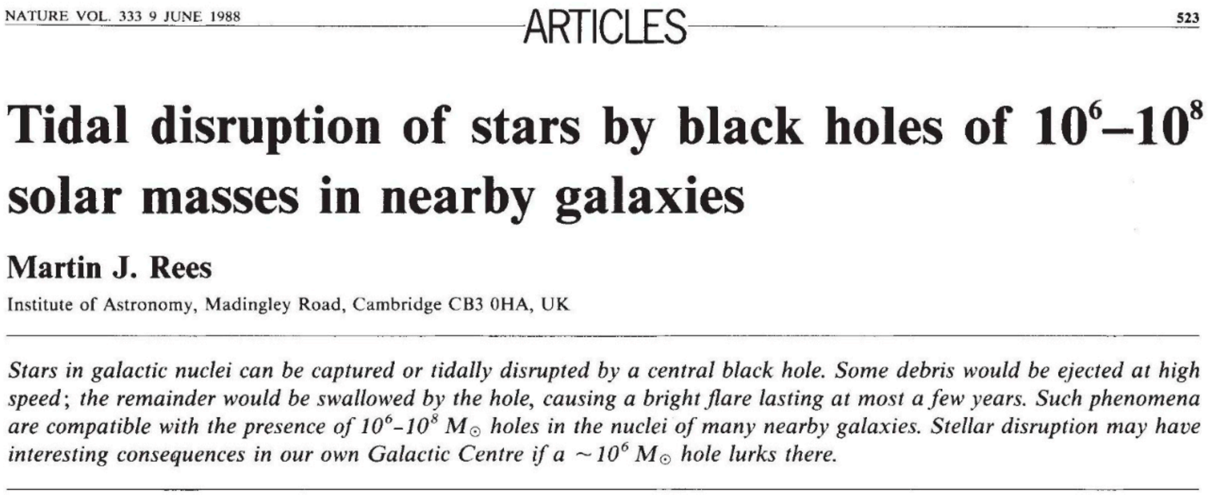
Chengchao Yuan
Deutsches Elektronen-Synchrotron DESY
TeVPA2023, 09/14 - Napoli, Italy

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
- Fallback rate $\propto t^{-5/3}$
- Mass accretion -> <u>months/year-long flare</u>
- Multi-wavelength black body (bb) emissions in optical/UV (OUV) bands.
- Some TDEs are observed in X-ray and infrared (IR) ranges, e.g., AT2019dsg



NATURE VOL. 333 9 JUNE 1988 ARTICLES 523

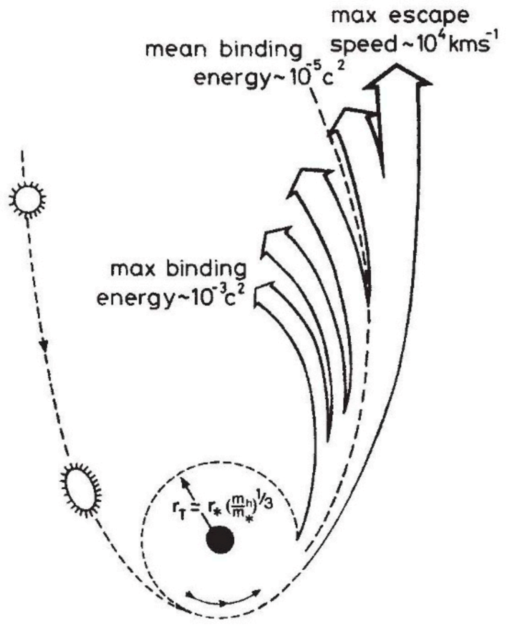
Tidal disruption of stars by black holes of 10^6–10^8 solar masses in nearby galaxies

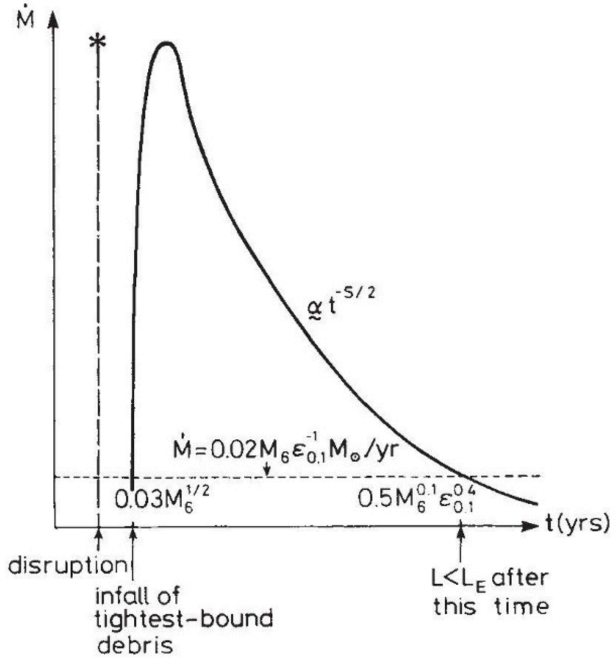
Martin J. Rees

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.

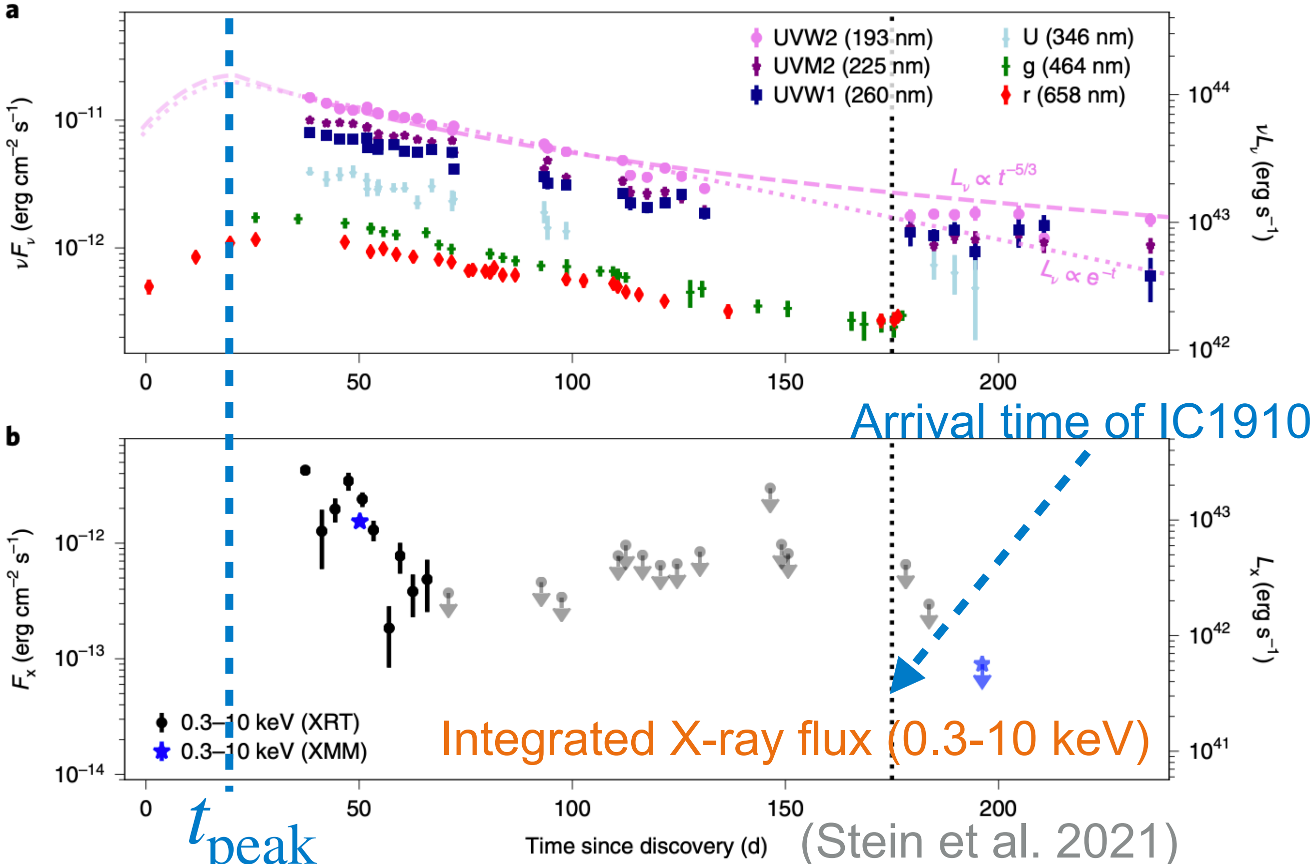
Martin J. Rees, Nature 1988





AT2019dsg

- ZTF (optical: g, r) + Swift UVOT (UV)
- Swift-XRT/XMM-Newton: X-ray (0.3-10 keV)
- $z \sim 0.051$, d_L~230Mpc
- Potential correlation to neutrino event IC191001A

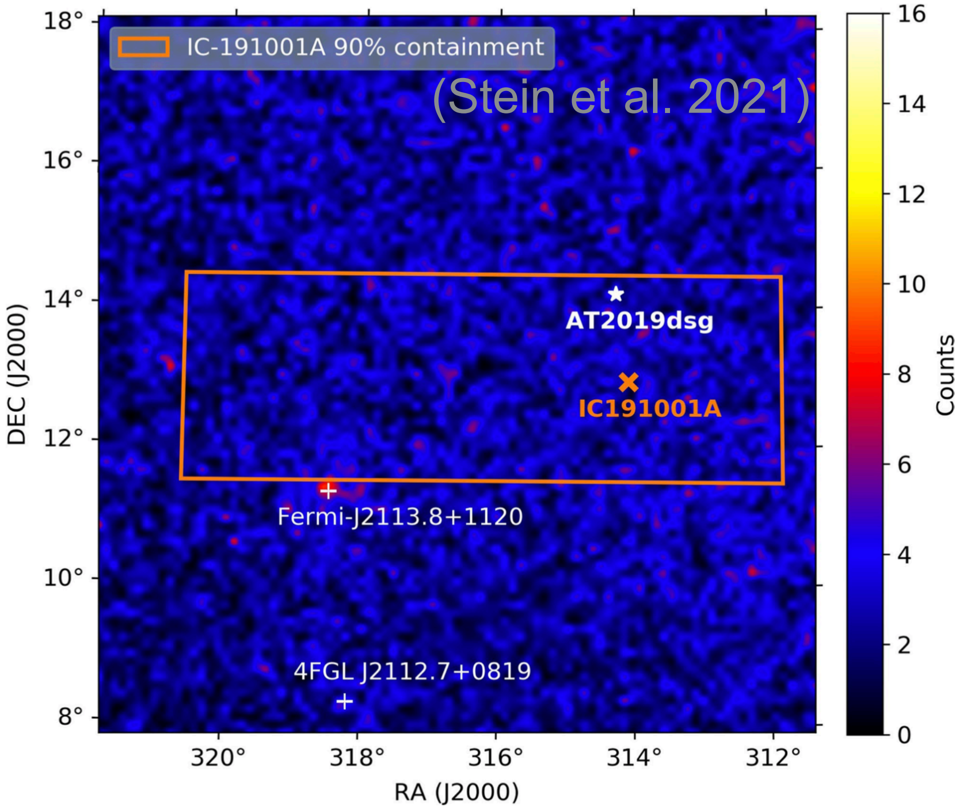


Arrival time of IC191001A

Integrated X-ray flux (0.3-10 keV)

t_{peak}

(Stein et al. 2021)



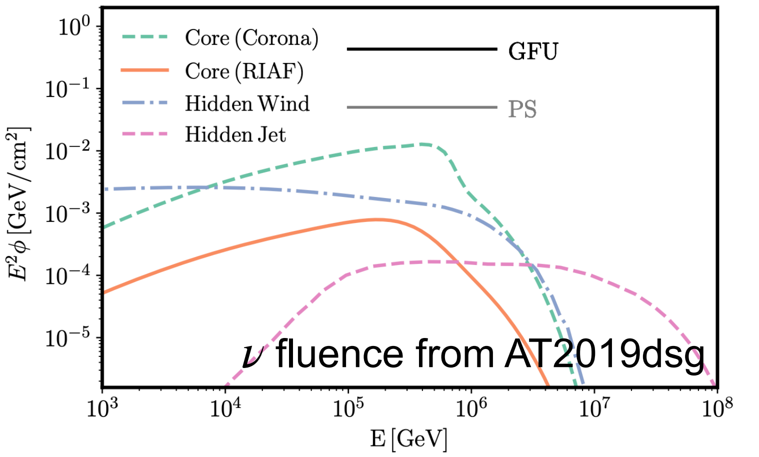
(Stein et al. 2021)

Measured black body spectra:

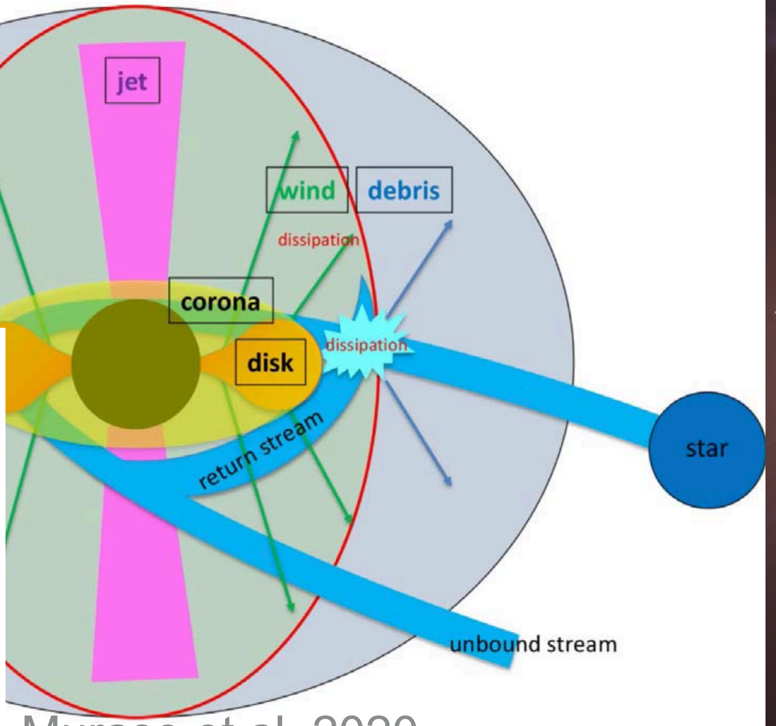
- X-ray: $T_X = 72$ eV, from hot accretion disk
- OUV: $T_{\rm OUV} = 3.4$ eV, from photosphere (nearly constant)

Tidal Disruption Events

- Neutrinos could be produced in the accretion disks, winds, or jets
- Three TDEs may be associated with IceCube neutrino events (so far)
  1. AT2019dsg (IC191001A)
  2. AT2019fdr (IC200530A)
  3. AT2019aalc (IC191119A)

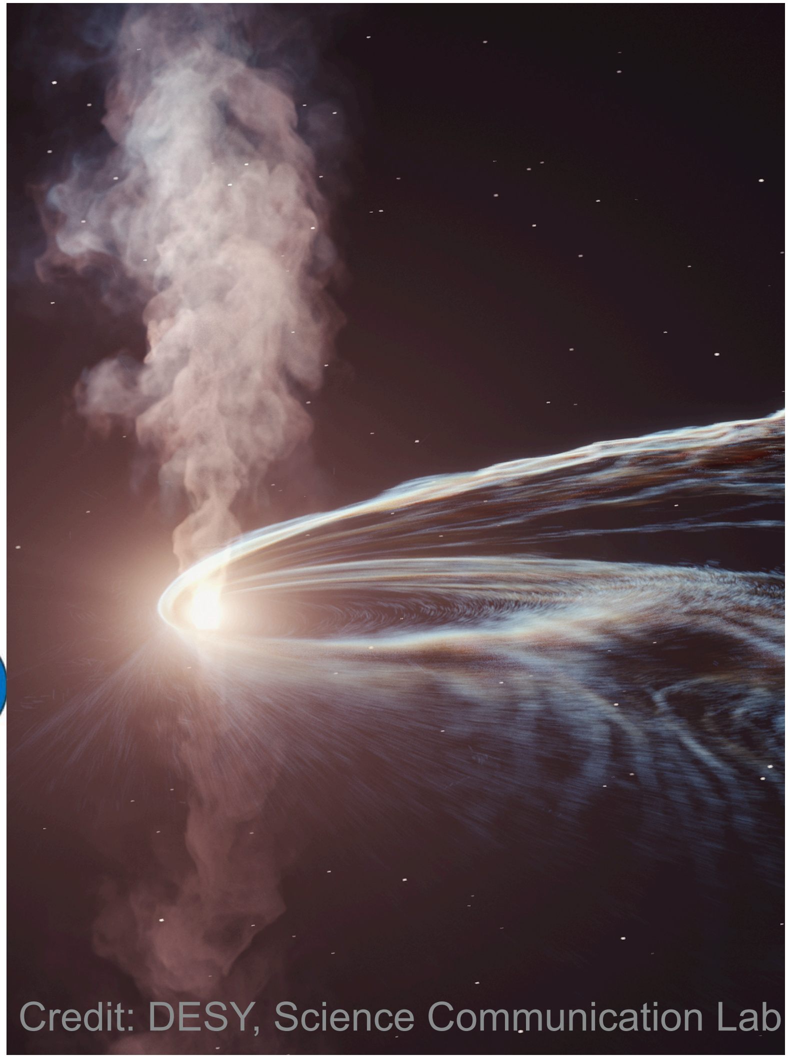


ν fluence from AT2019dsg



Murase et al. 2020

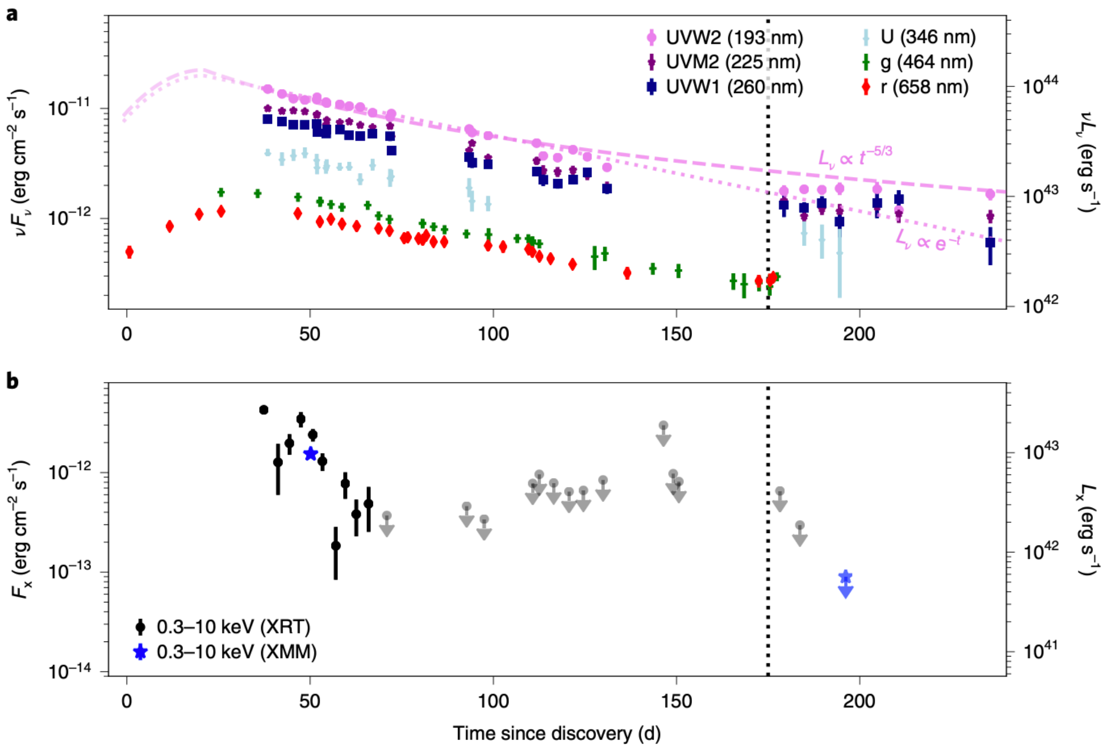
Disks - Hayashaki & Yamazaki 19 (HY19)
Wide angle winds - Fang 20
Stream-stream - Dai + 15,, HY19,
Jets - Wang + 11,Wang & Liu 16, Dai & Fang 17, Lunardini & Winter 17, Senno + 17



Credit: DESY, Science Communication Lab

Questions for Neutrino-Coincident TDEs

- Where are X-ray (XRT, eROSITA, NICER), γ-ray (Fermi, HAWC uplimits) and neutrino emission produced?
- Temporal signatures: delayed infrared and neutrino emissions
- 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

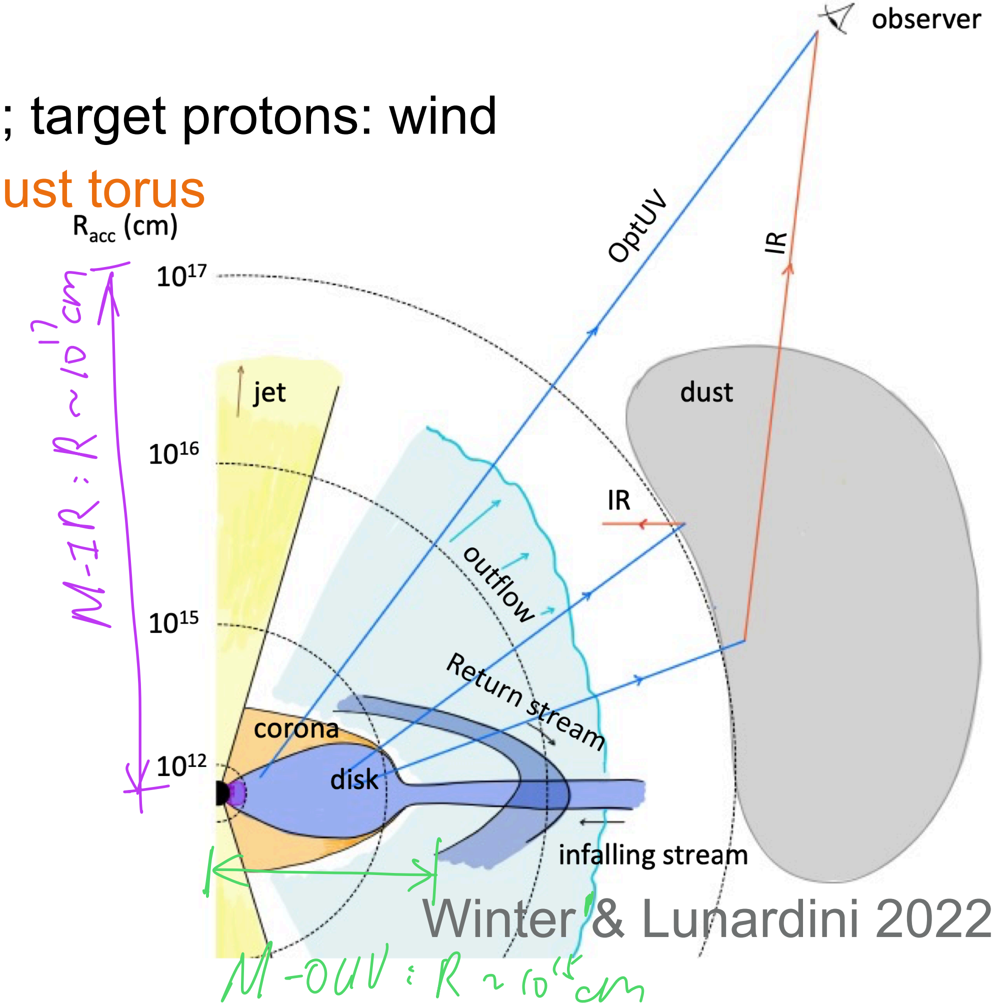
What we need for existing observations

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

Electromagnetic (EM) cascade emission from AT2019dsg

- **Proton injection**: spectral index = 2, $E_{\max}$ (free parameter), injection power $(L_p = \epsilon_p \dot{M} c^2 \propto L_{\rm OUV})$
- **Radiation site:** **sub-relativistic wind energy dissipation radius** $10^{15}\ {\rm cm} \lesssim R \lesssim 10^{17}\ {\rm cm}$ (free parameter), $B = 0.1\ {\rm G}$ (similar to AGNs)
- **Target photons:** IR, OUV and X-ray blackbody photons; target protons: wind
- IR photons from dust echos: re-emitting IR photons by dust torus

	AT2019dsg[a] $z = 0.051,\ M = 5 \times 10^6 M_\odot,\ t_{\rm dyn} = 670$ d	
$k_B T_{\rm X,\ OUV,\ IR}$	72 eV, 3.4 eV, 0.16 eV	
E_ν	217 TeV (IC191001A)	
$t_\nu - t_{\rm pk}$	154 d	
N_ν(GFU)[c]	0.008 – 0.76	
Scenario	M-IR	M-OUV
R [cm]	5.0×10^{16}	5.0×10^{14}
$E_{p,\max}$ [GeV]	5.0×10^{9}	1.0×10^{8}

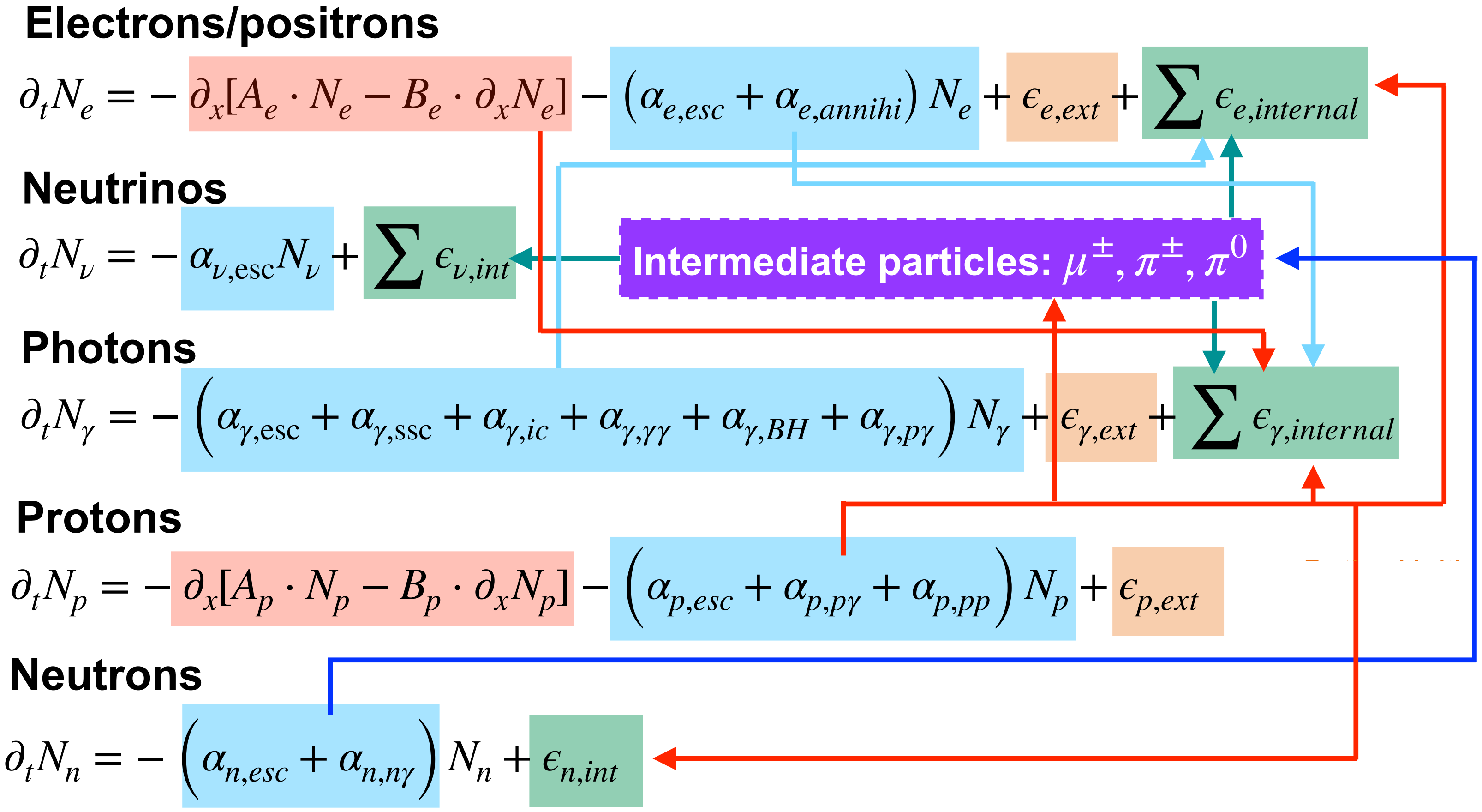


Winter & Lunardini 2022

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

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

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



Electrons/positrons

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

Neutrinos

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

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

Photons

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

Protons

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

Neutrons

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

EM cascades

$$\pi^0 \to 2\gamma$$

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

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

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

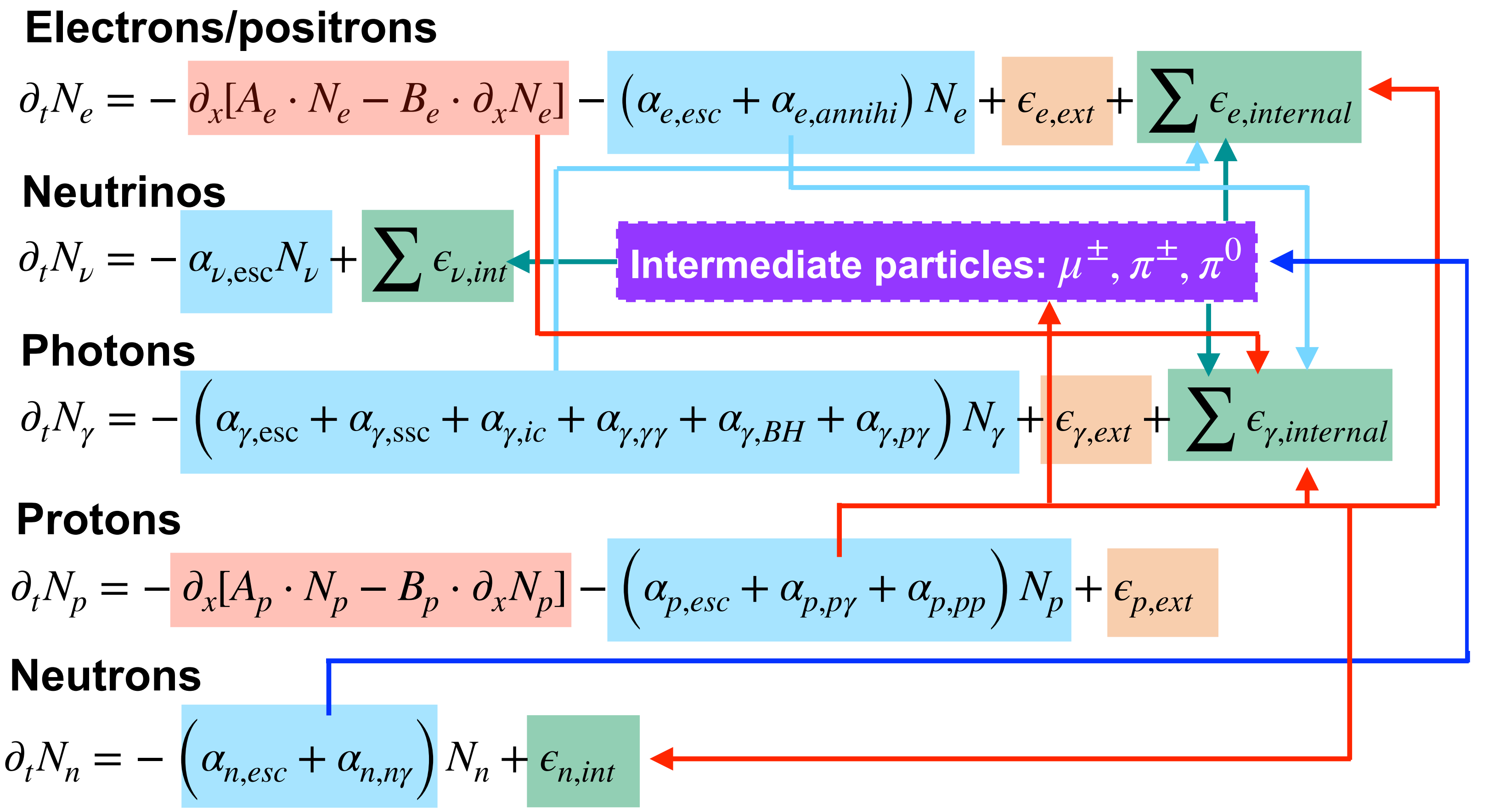
Code publication in preparation!

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

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

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

Injection Cooling Escape/Advection



Electrons/positrons

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

Neutrinos

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

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

Photons

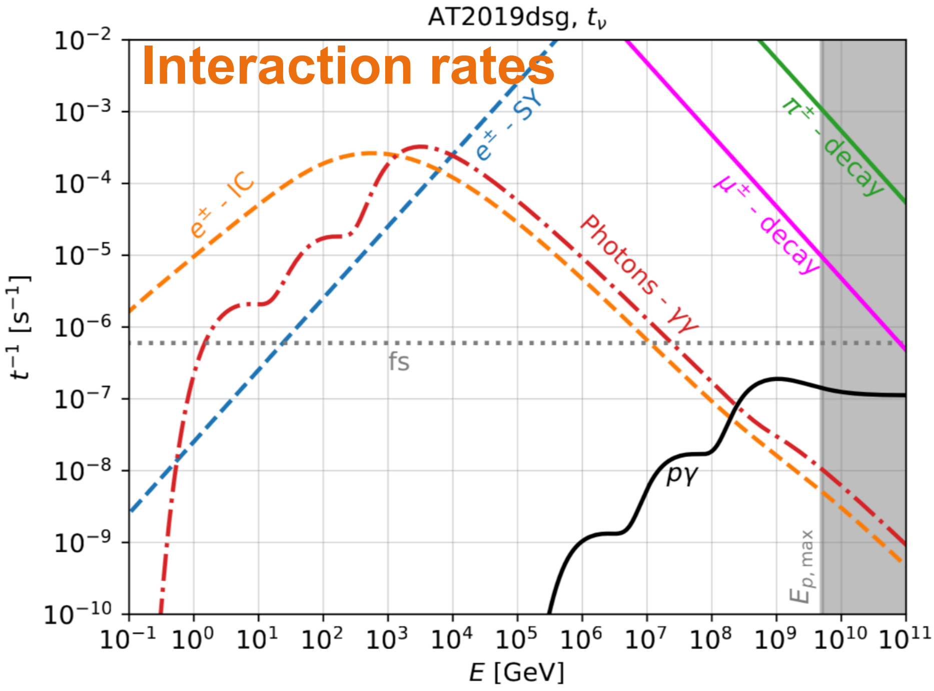
$$\partial_t N_\gamma = -(\alpha_{\gamma,esc} + \alpha_{\gamma,ssc} + \alpha_{\gamma,ic} + \alpha_{\gamma,\gamma\gamma} + \alpha_{\gamma,BH} + \alpha_{\gamma,p\gamma})N_\gamma + \epsilon_{\gamma,ext} + \sum \epsilon_{\gamma,internal}$$

Protons

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

Neutrons

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

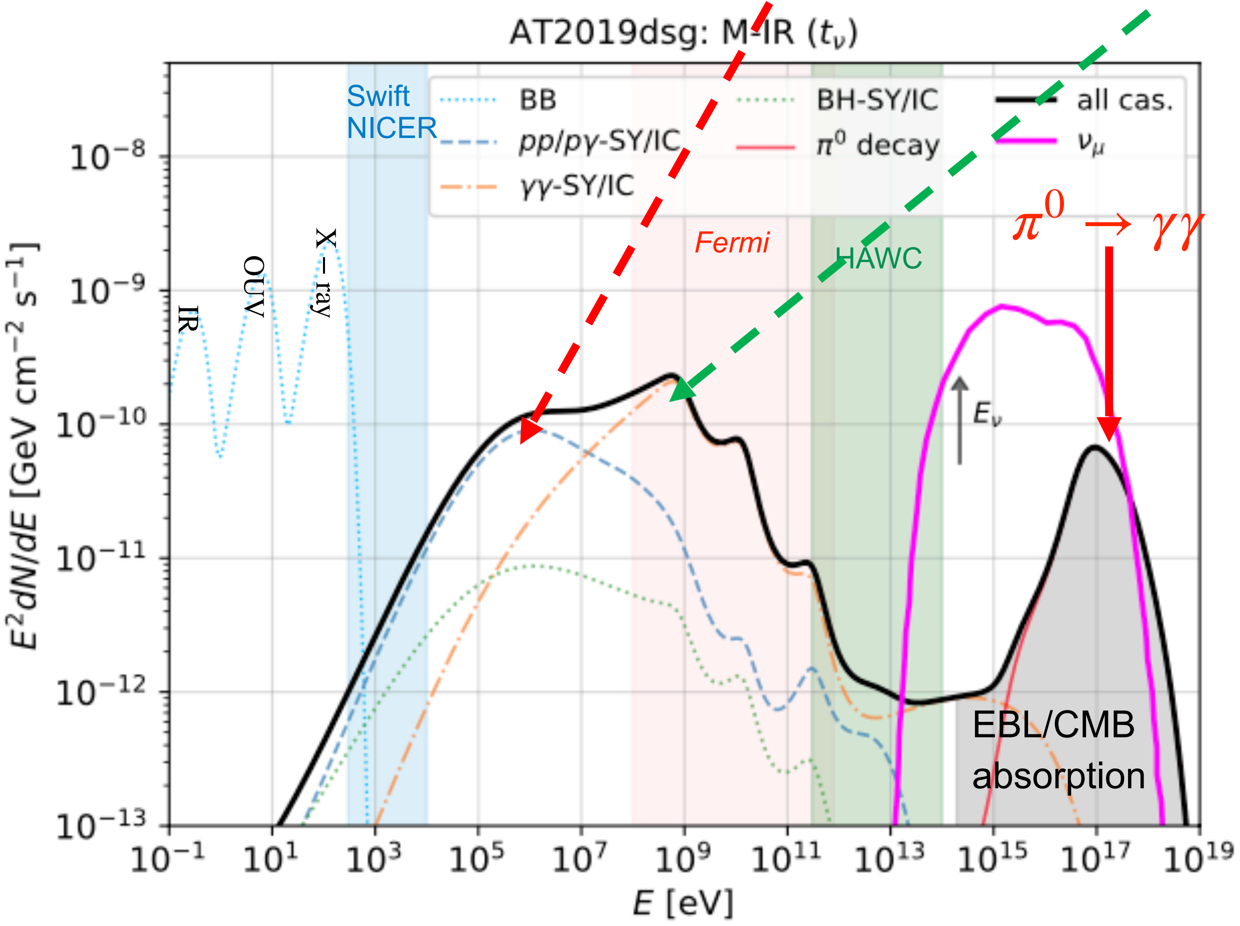


$p\gamma$ time scale ($t_{p\gamma}$) determines the time to develop EM cascade

M-IR: extended radiation zone close to dust torus

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

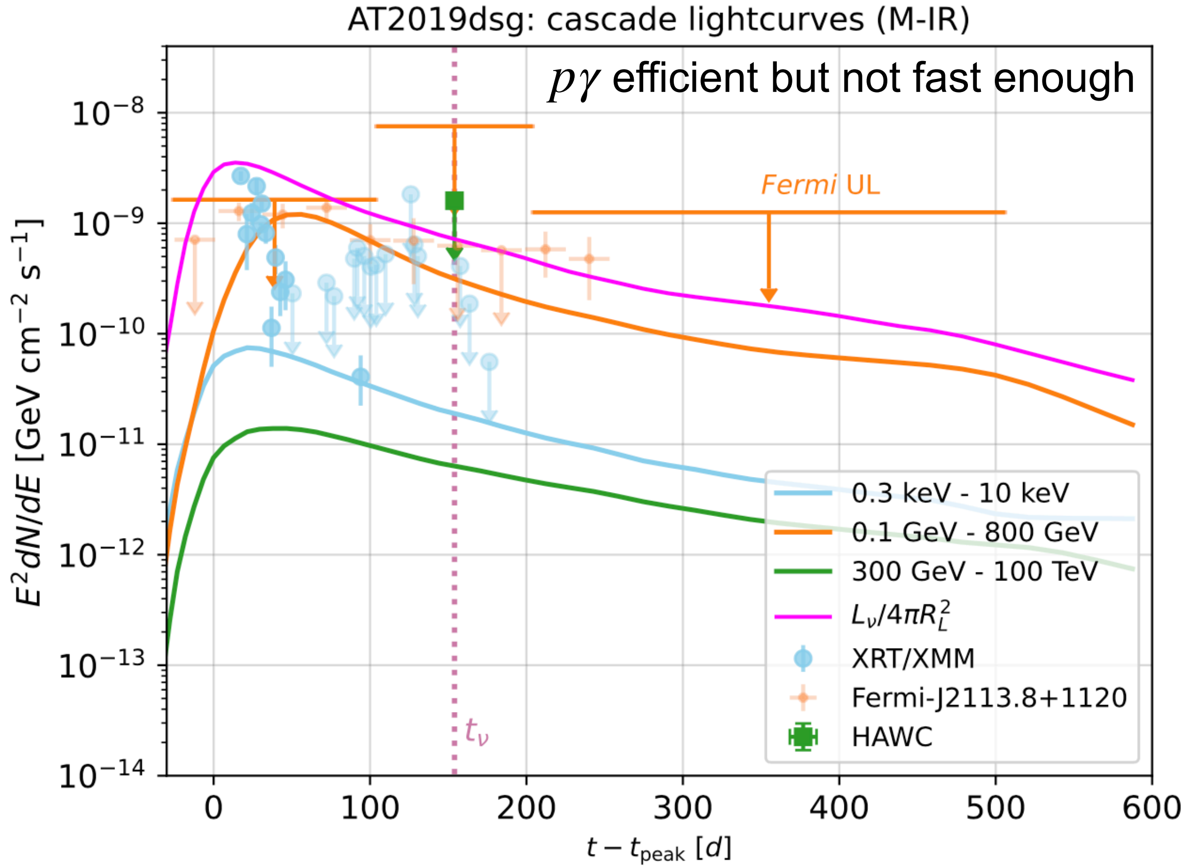
$B = 0.1$ G, $R = 5 \times 10^{16}$ cm $= R_{IR}$, $E_{p,\max} = 5 \times 10^9$ GeV, $\epsilon_p = 0.2$



$\pi^0 \rightarrow \gamma\gamma$

EBL/CMB absorption

CY & Winter, arXiv: 2306.15659 (ApJ in press)



$p\gamma$ efficient but not fast enough

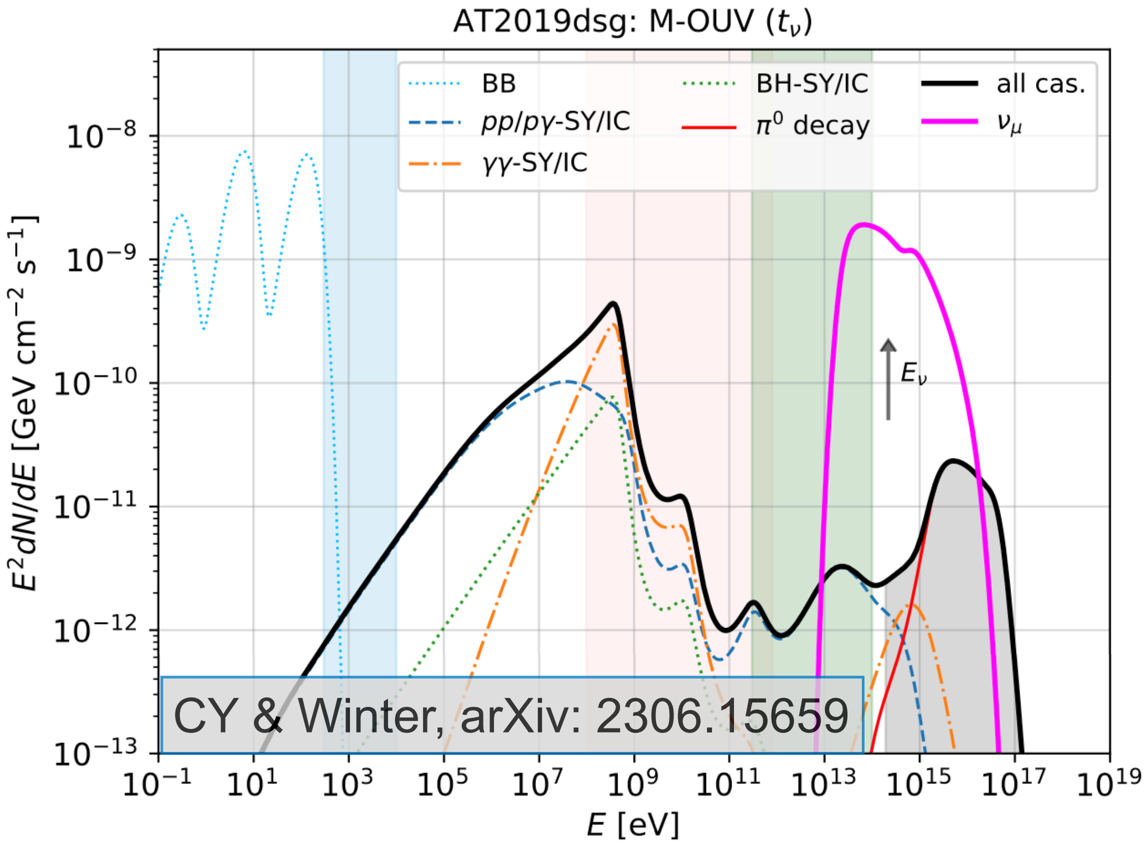
~30 - 50 days time delay is compatible with $p\gamma$ interaction time $t_{p\gamma} \sim 10 - 100$ d

M-OUV: compact region close to OUV photons

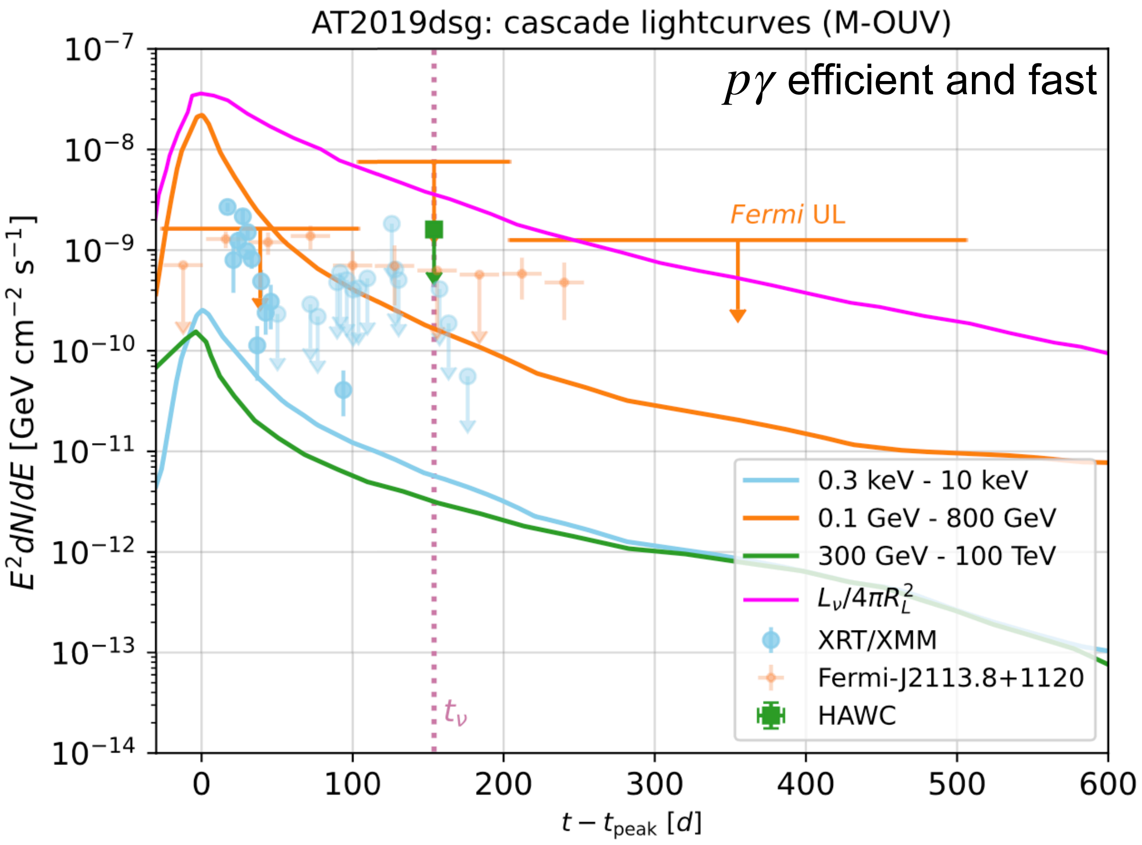
$p\gamma$ optically thick $t_{p\gamma}^{-1}/t_{\rm fs}^{-1} > 1$: EM cascade light curves follows OUV light curve, no significant time delay

$B = 0.1$ G, $R = 5\times10^{14}$ cm, $E_{p,\rm max} = 1\times10^{8}$ GeV, $\epsilon_p = 0.2$

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



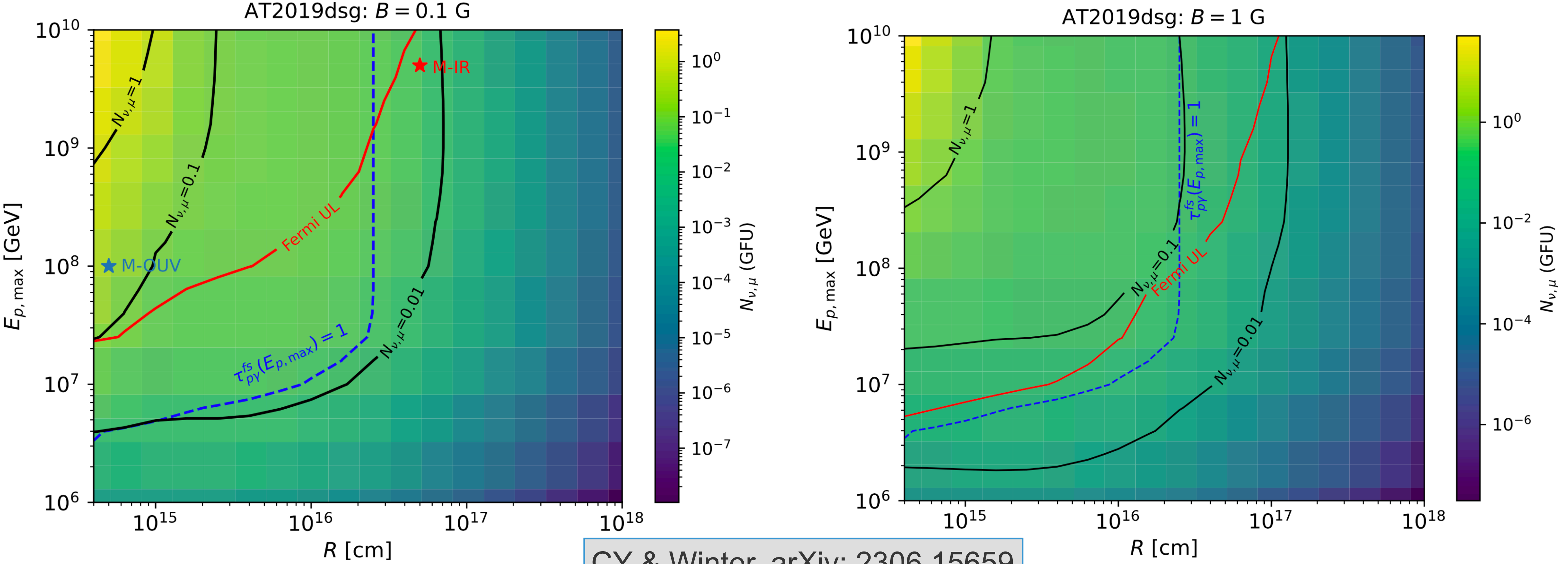
CY & Winter, arXiv: 2306.15659



Fermi γ-ray Constraints on $E_{p,\max}$ and B, and Neutrino Rates

GFU neutrino rate is limited to be 0.01 - 0.1 per TDE (below red curves)

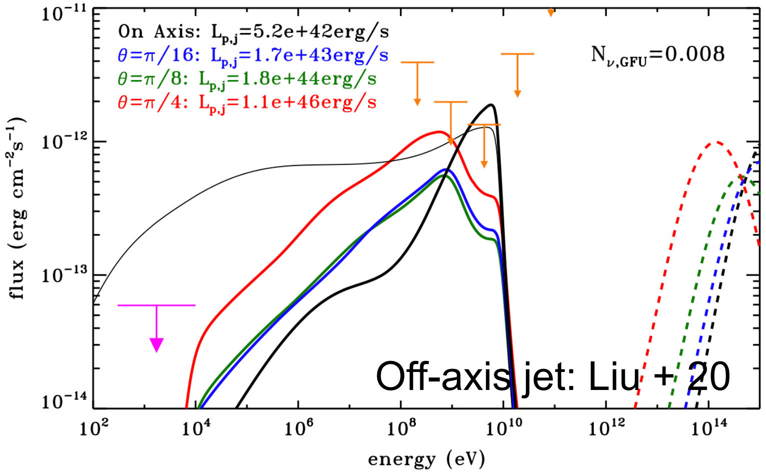
CRs are more confined with a stronger magnetic field, which enables a less compact region to be a promising neutrino emitter. (Easier to overshoot γ-ray up limits)



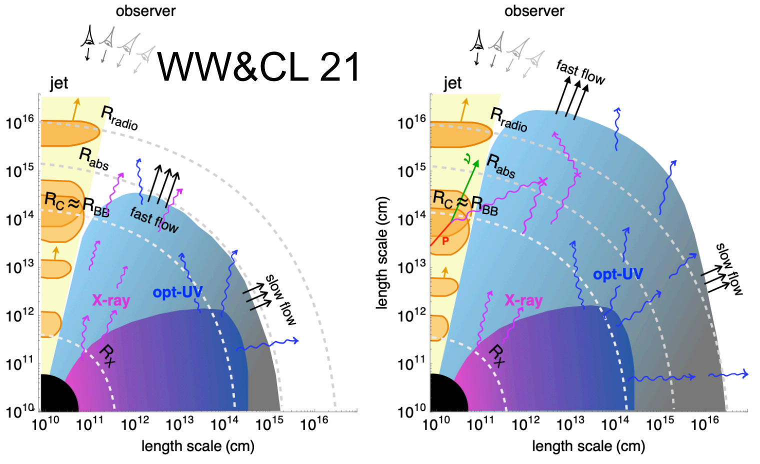
CY & Winter, arXiv: 2306.15659

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?) Ongoing work: (VHE) γ-ray observations, Lepto-Hadronic modeling of TDE jets, radio emission, and contribution to UHECRs/diffuse ν flux.



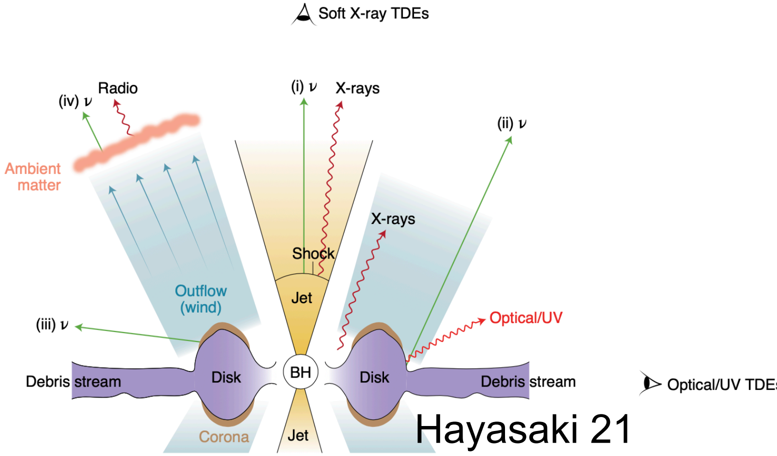
Off-axis jet: Liu + 20



WW&CL 21

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

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



Hayasaki 21

Public release of AM^3

- C++ code with efficient hybrid solver combining analytical and numerical approaches.
- Source code with tutorials on various astrophysical objects,
  - AGN.
  - Gamma-ray bursts.
  - Tidal disruption events.
- Join with turn-key installations (Docker) on Linux and Mac OS systems.
- **Soon to be published - stay tuned!**

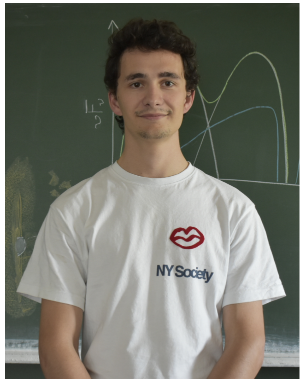
AM^3 : An open-source tool for time-dependent lepto-hadronic modelling of astrophysical sources


Xavier Rodrigues - ESO


Annika Rudolph - Niels Bohr Institute


Marc Klinger - DESY


Chengchao Yuan - DESY


Credit:

Gaëtan Fichet de Clairfontaine

Backup slides

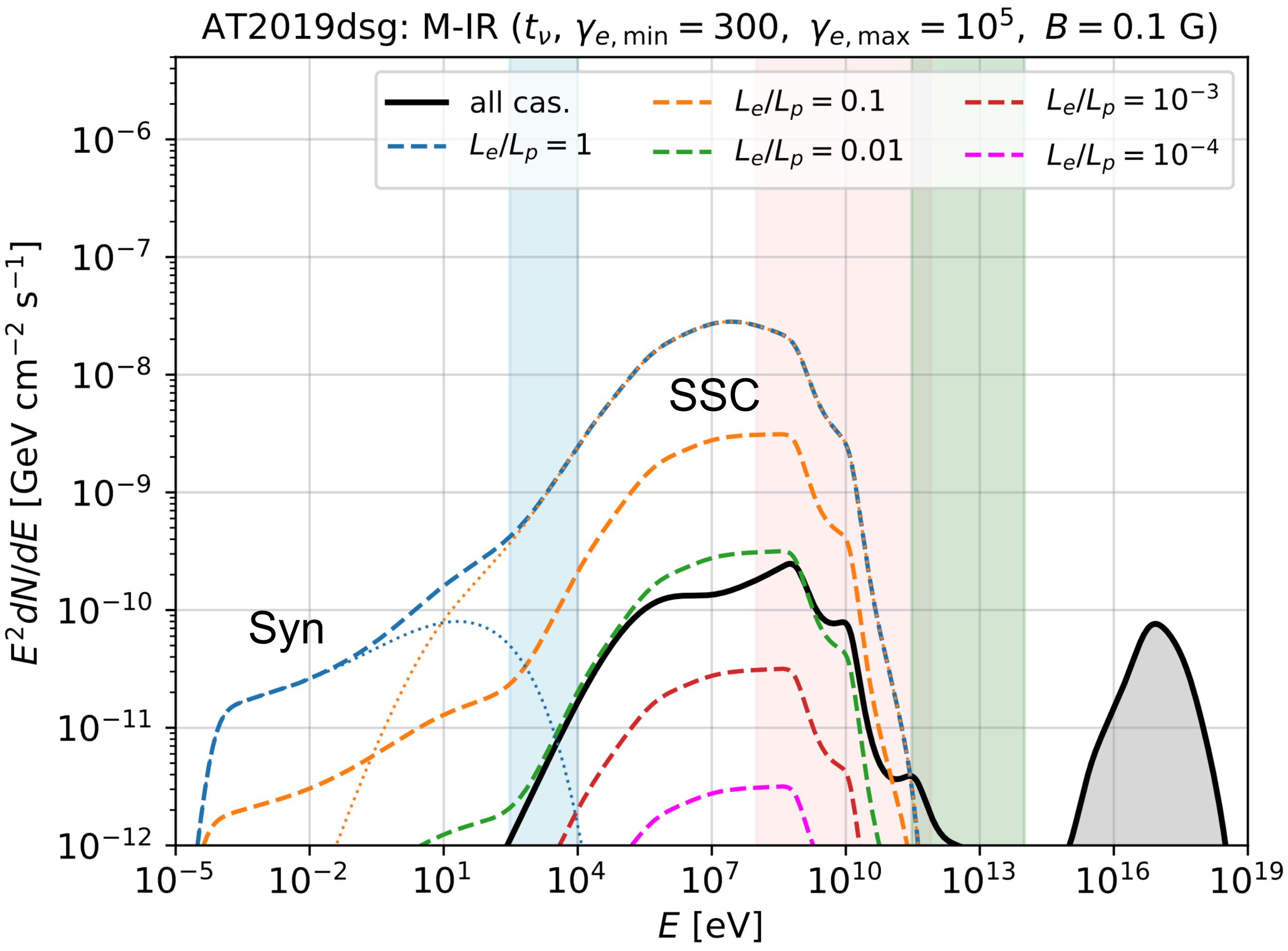
Test lepton ($e^{\pm}$) injections: a simple case

Electron injection spectra

- $dN_e/d\gamma_e \propto \gamma_e^{-2}$
- $\gamma_{e,\min} = 300$, $\gamma_{e,\max} = 10^5$ (typically used for 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 $L_e/L_p < 10^{-2}$

(Caveat: depends on B and γ_m)

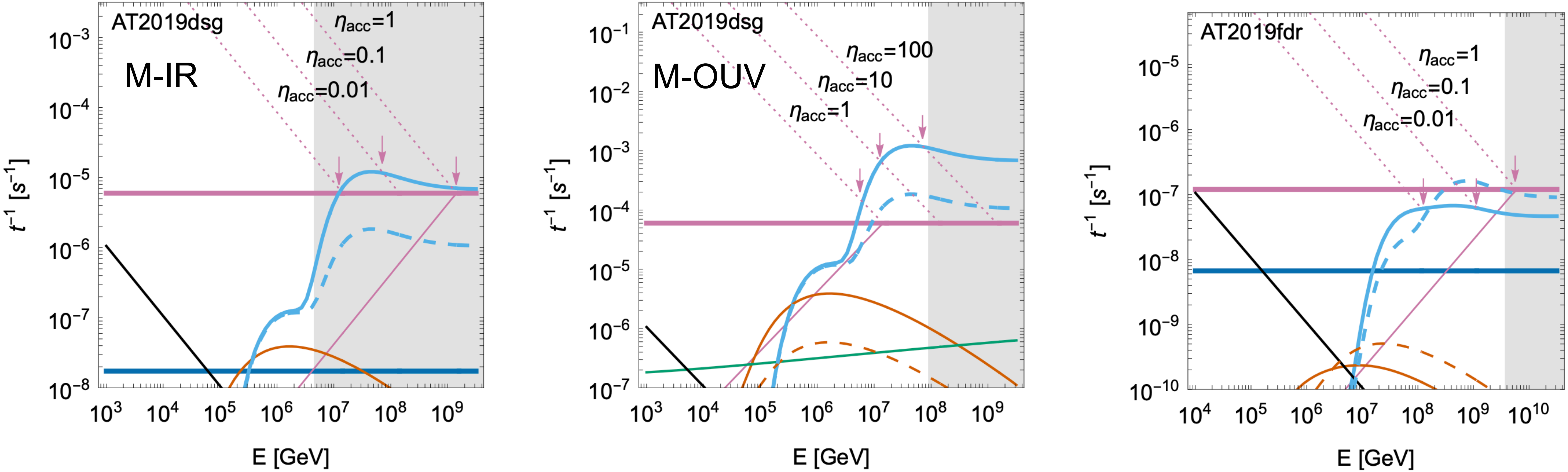


CR acceleration with $B = 0.1$ G

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

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

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



Proton injection

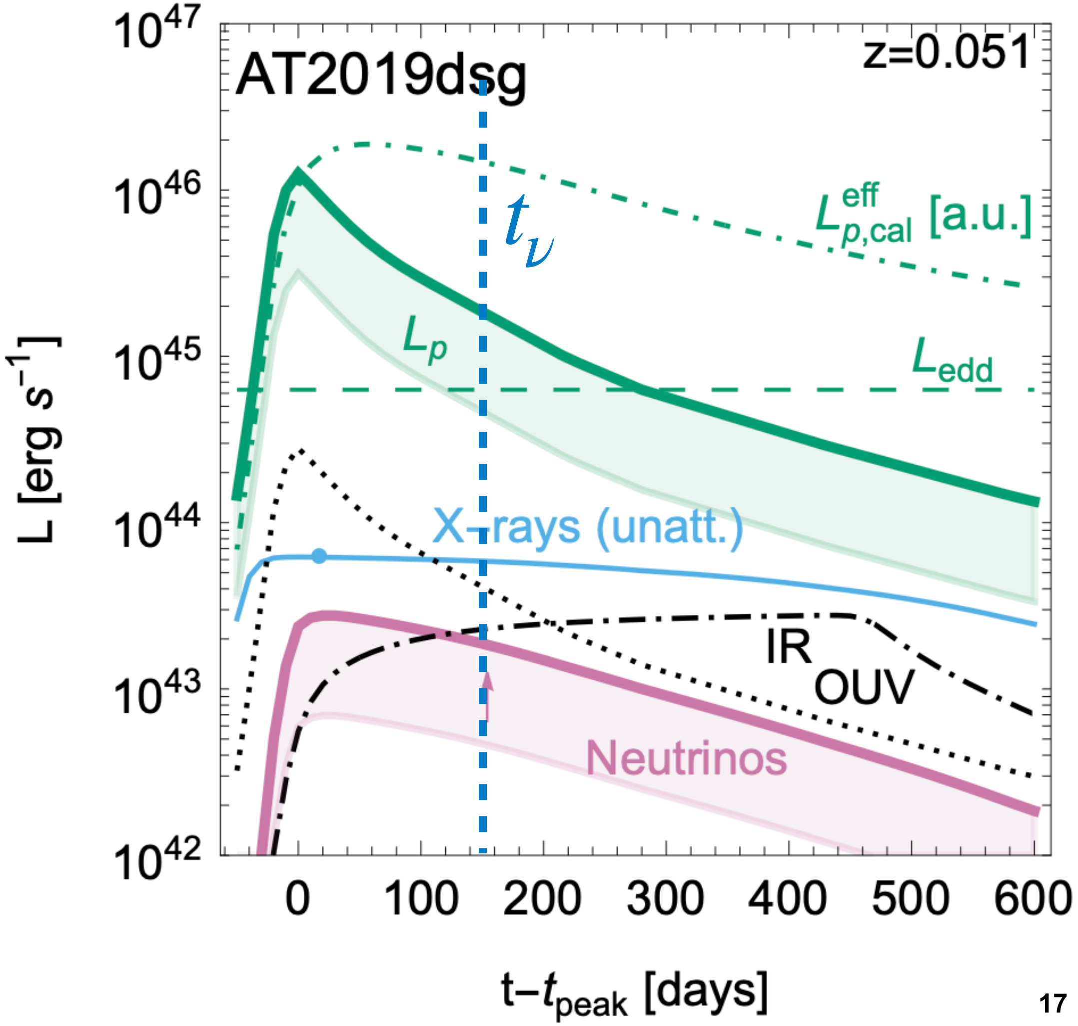
Four parameters: $E_{p,\min} \sim 1\ \mathrm{GeV},$ spectra index $p = 2,\ E_{p,\max}$ (free-param), normalization factor

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

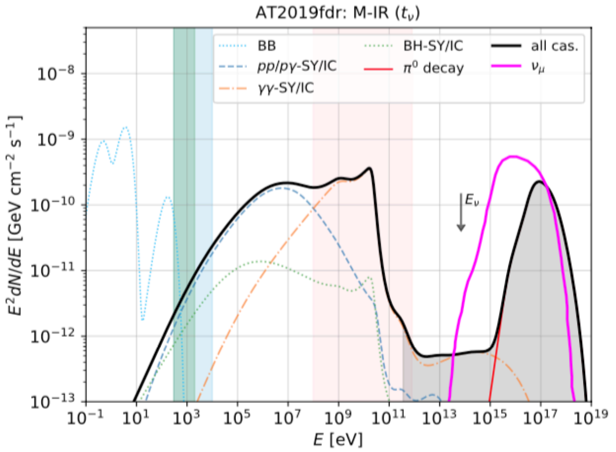
Winter & Lunardini 2022

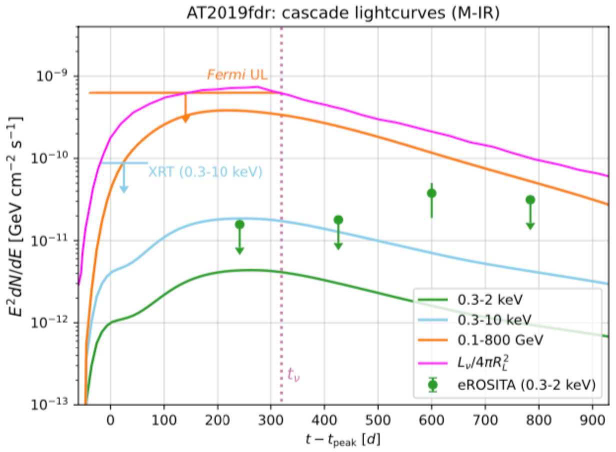


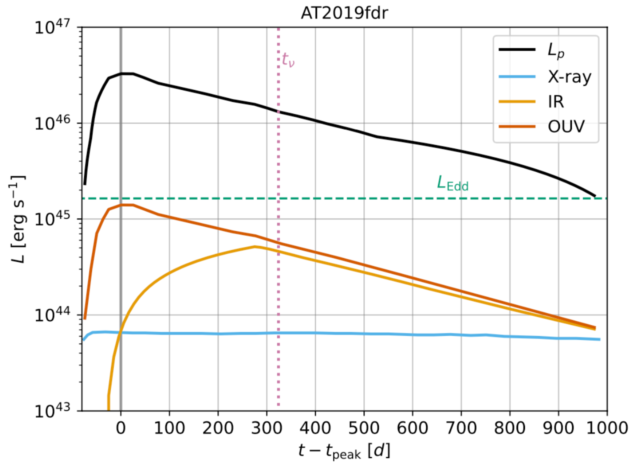
Assumptions

- $\dot{M}_\star(t)/L_{\mathrm{OUV}}(t) = \mathrm{const}$
- Super-Eddington: $\dot{M}_{\star,\mathrm{peak}}/\dot{M}_{\mathrm{Edd}} = 10$ (Dai+ 2018)
- Proton diffusion in Bohm regime $D = R_L c$

AT2019fdr


AT2019fdr: M-IR (t_ν)


AT2019fdr: cascade lightcurves (M-IR)


AT2019fdr

$z = 0.267$

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

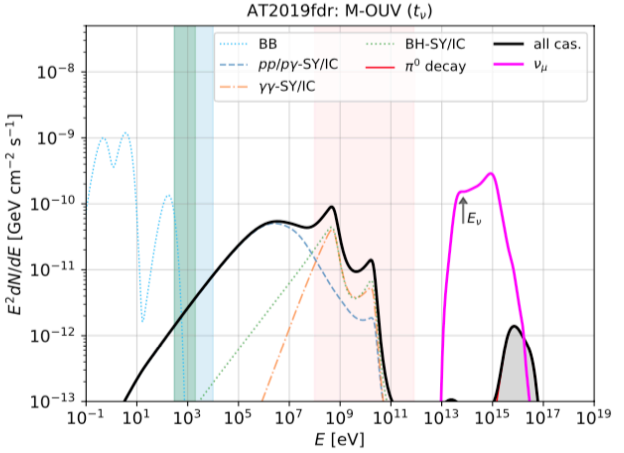
$E_\nu = 82$ TeV

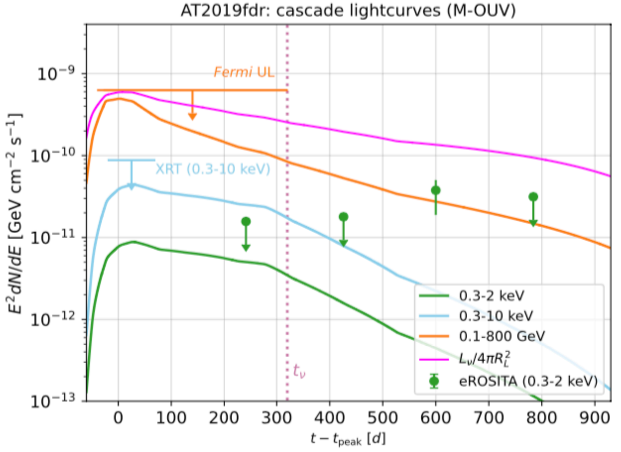
M-IR:

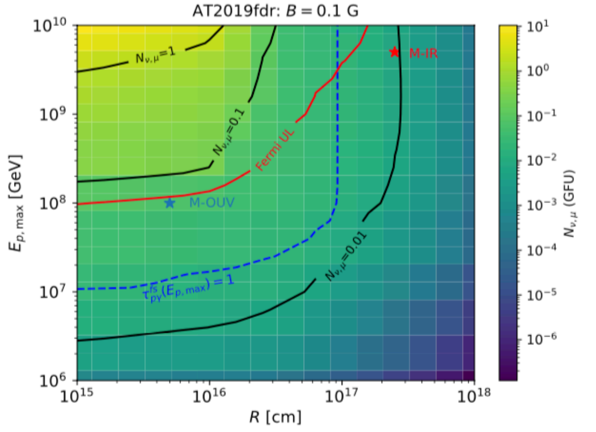
- $R = 5\times10^{15}$ cm
- $E_{p,\max} = 10^8$ GeV

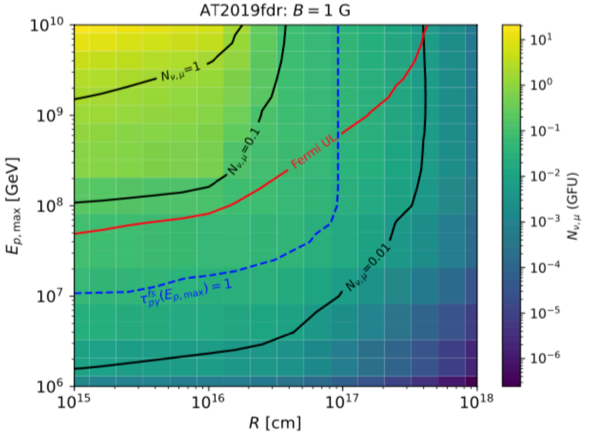
M-OUV:

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


AT2019fdr: M-OUV (t_ν)


AT2019fdr: cascade lightcurves (M-OUV)


AT2019fdr: $B = 0.1$ G

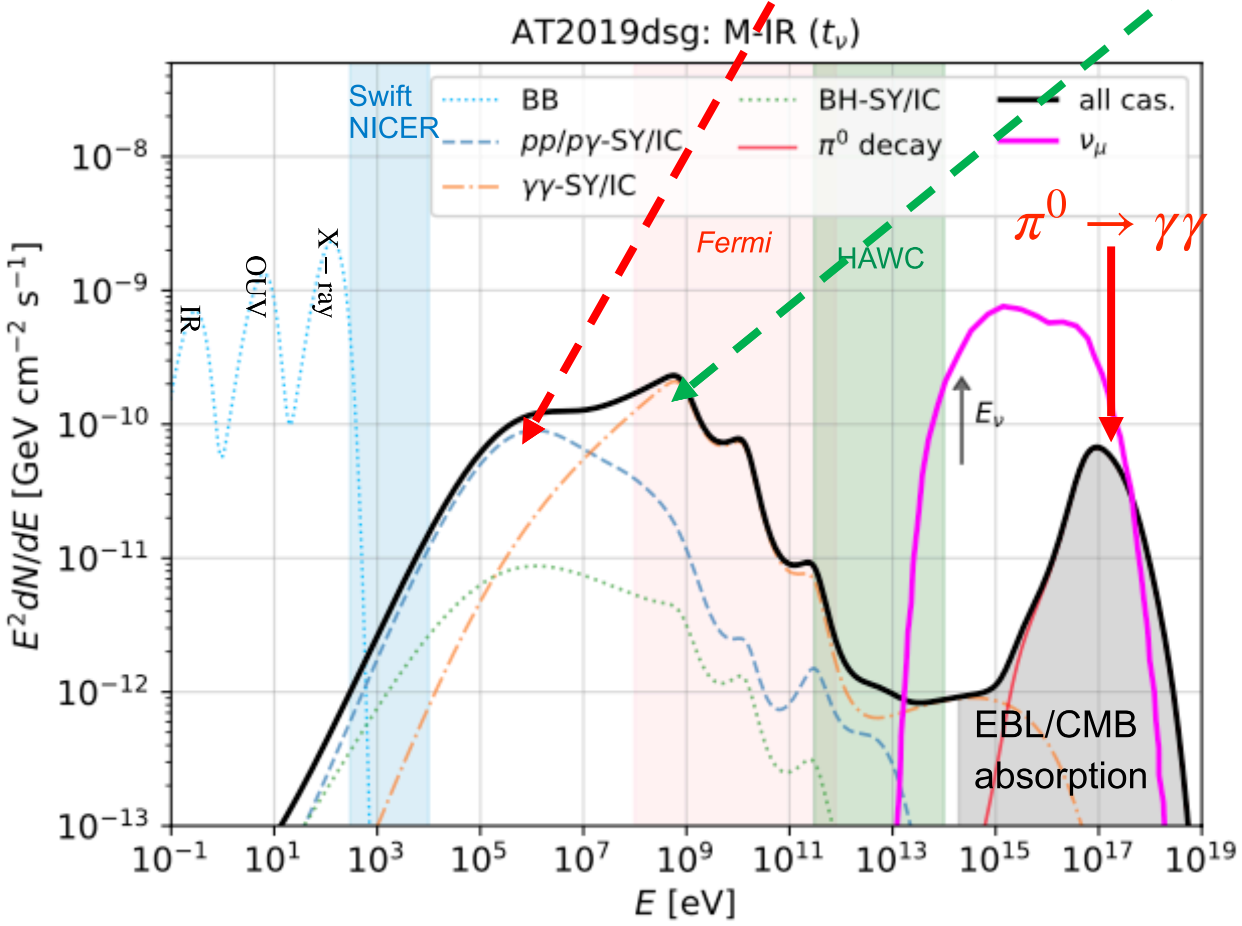

AT2019fdr: $B = 1$ G

CY & Winter, arXiv: 2306.15659

M-IR: extended radiation zone close to dust torus

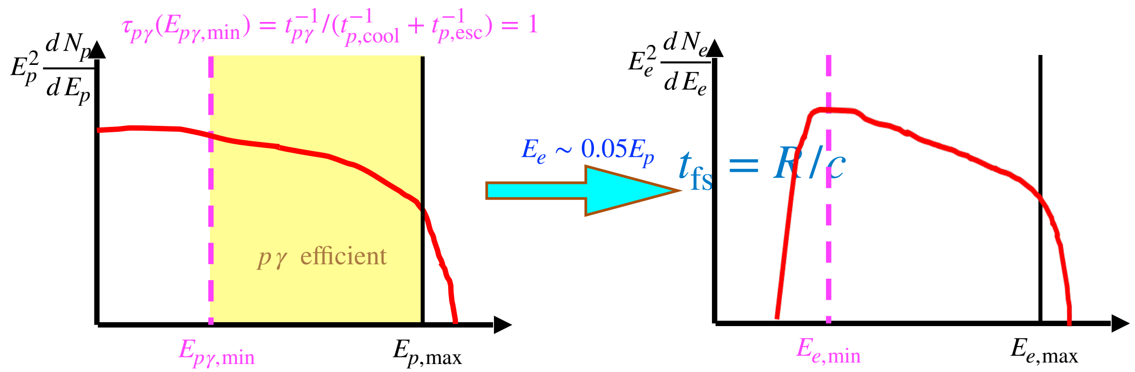
$p\gamma$ optically thin $t_{p\gamma}^{-1}/t_{\rm fs}^{-1} < 1$: $(\pi^{\pm} \to e^{\pm} \to \mathrm{SY/IC})$ + $(\gamma\gamma \to e^{\pm} \to \mathrm{SY/IC})$

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



CY & Winter, arXiv: 2306.15659 (ApJ in press)

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



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

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

$\gamma\gamma$ absorption

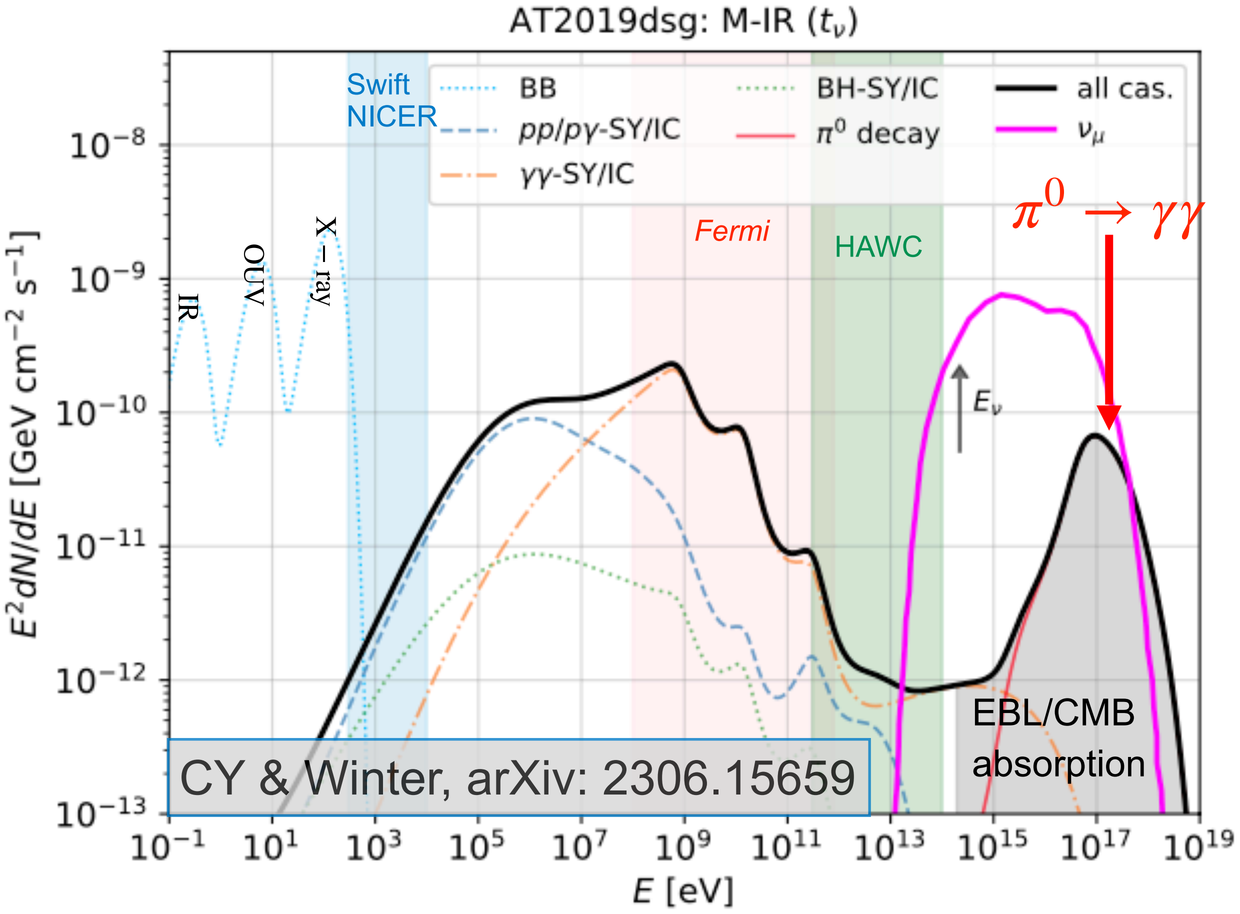
$$E_\gamma \sim m_e^2/E_{\rm bb} \simeq 2\ \mathrm{GeV}(E_{\rm bb}/100\mathrm{eV})^{-1}$$

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

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

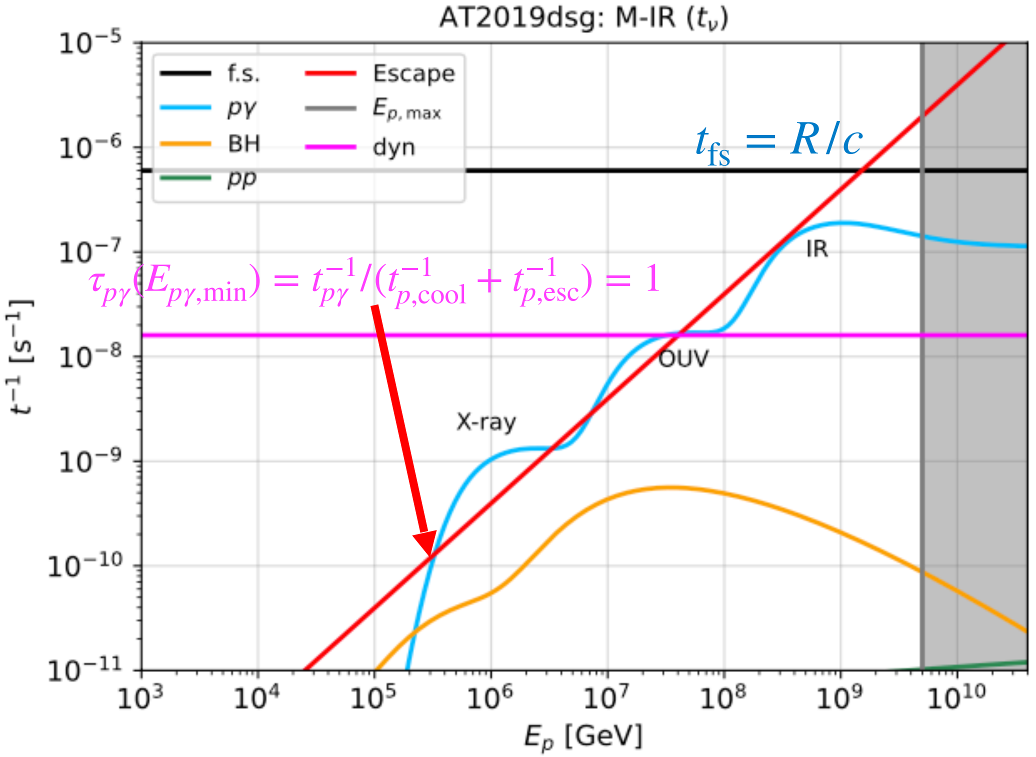
Parameters: $\varepsilon_{\rm diss} = 0.2$

$B = 0.1$ G, $R = 5\times10^{16}$ cm $= R_{IR}$, $E_{p,\rm max} = 5\times10^{9}$ GeV



$\pi^0 \rightarrow \gamma\gamma$

CY & Winter, arXiv: 2306.15659



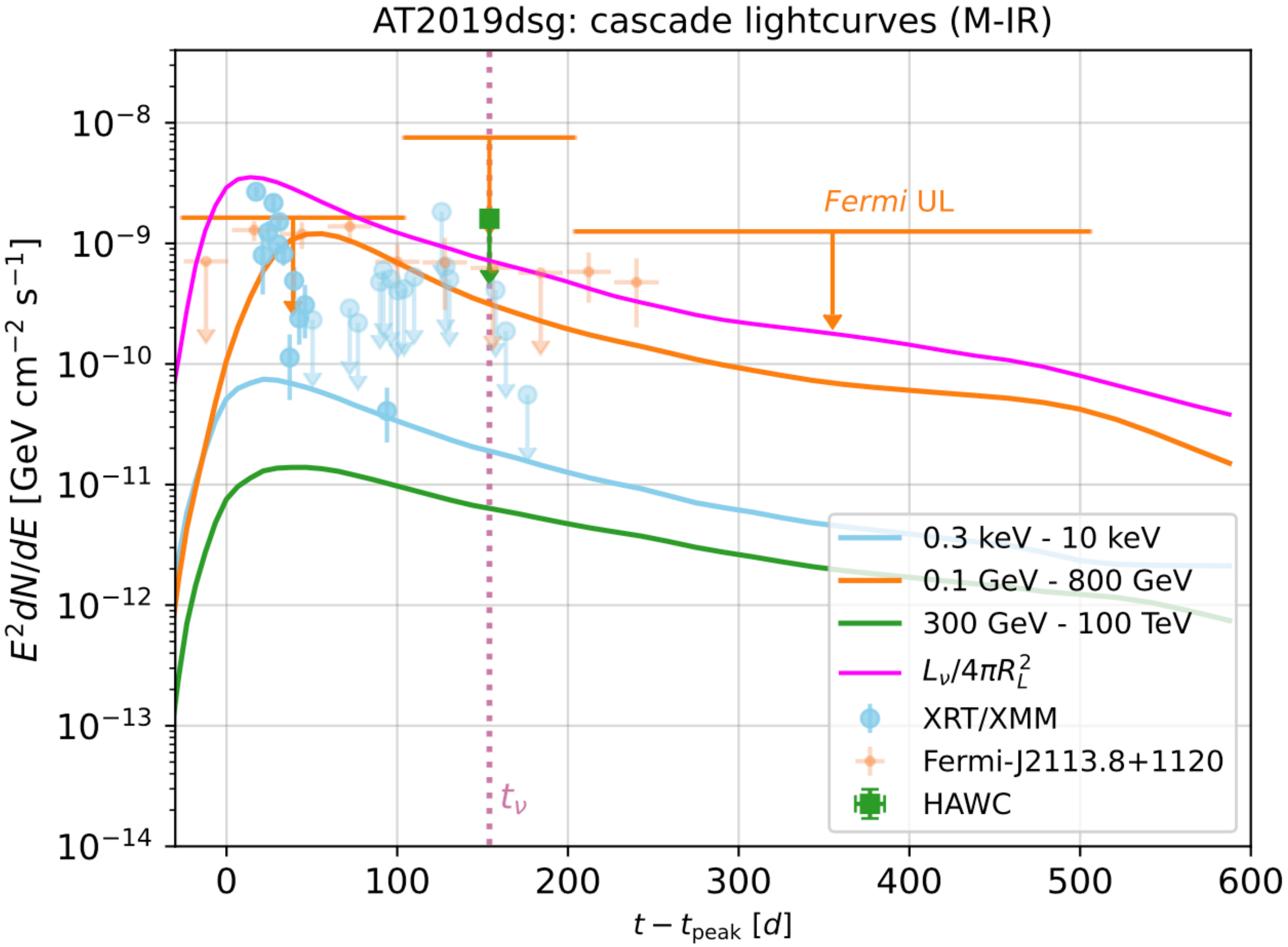
$t_{\rm fs} = R/c$

$\tau_{p\gamma}(E_{p\gamma,\rm min}) = t_{p\gamma}^{-1}/(t_{p,\rm cool}^{-1} + t_{p,\rm esc}^{-1}) = 1$

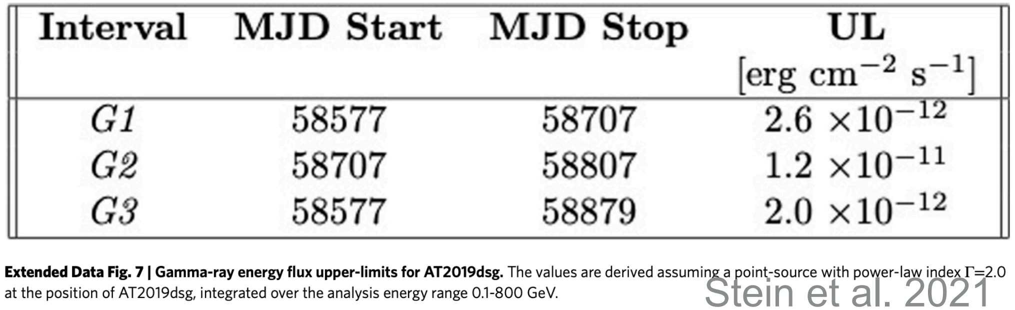
Neutrino peak energy is significantly higher than the detected energy (green area) ->low N_ν

AT2019dsg Temporal signatures: M-IR

Dust echo scenario: $\varepsilon_{\rm diss} = 0.2, B = 0.1\ {\rm G}, R = 5\times10^{16}\ {\rm cm}, E_{p,\rm max} = 5\times10^{9}\ {\rm GeV}$



Fermi-LAT uplimit $(0.1 - 800\ {\rm GeV})$



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

Consistent with Fermi UL., but predicts a low neutrino number

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

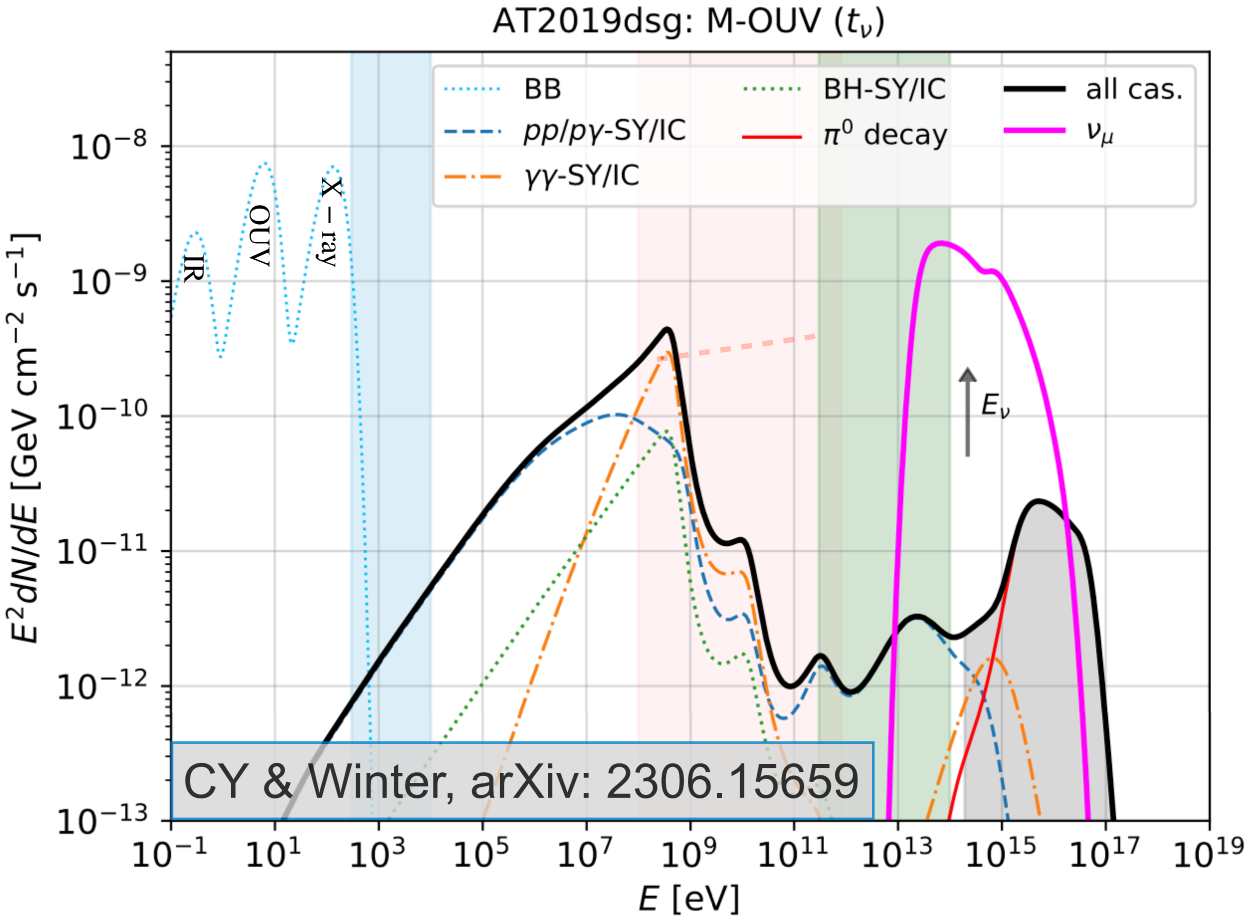
EM cascade spectra of AT2019dsg: M-OUV

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

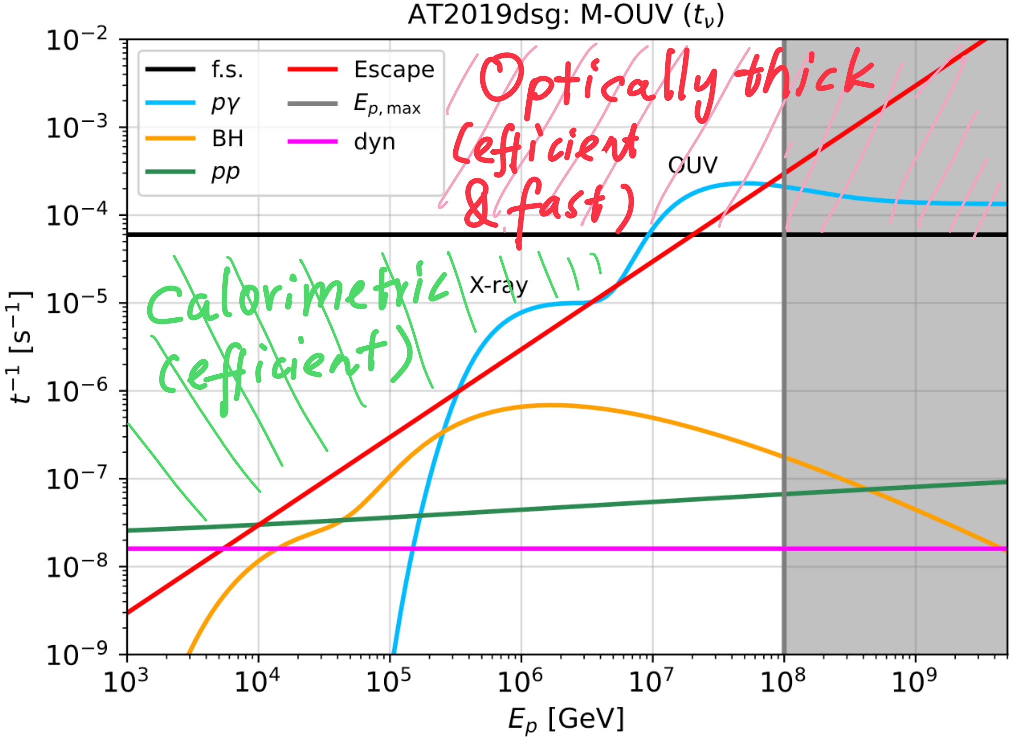
Parameters: $\varepsilon_{\rm diss} = 0.2$

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

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

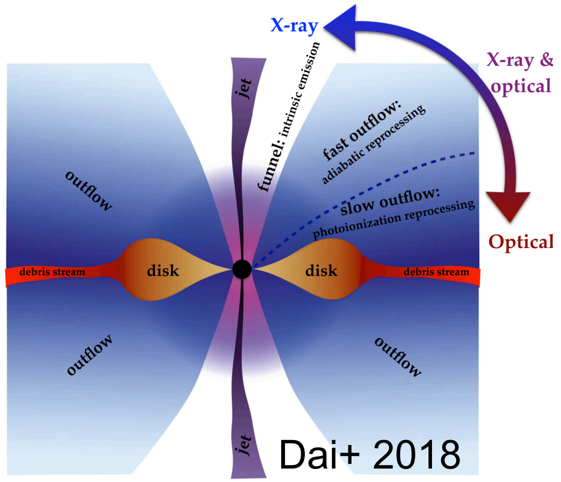


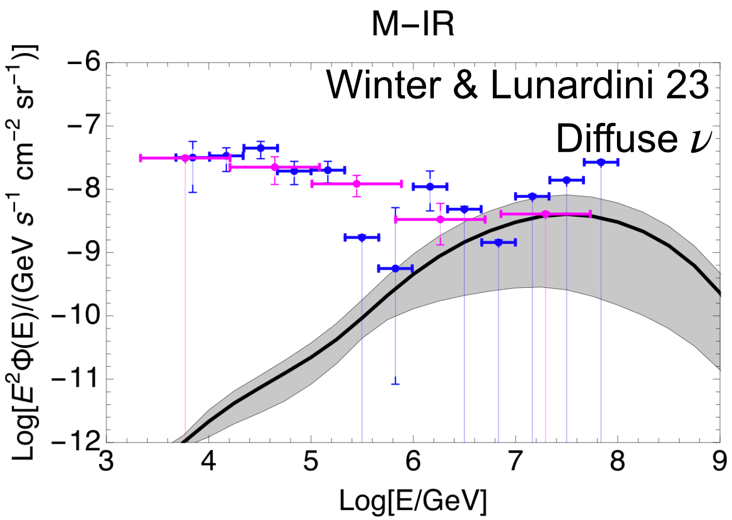
CY & Winter, arXiv: 2306.15659

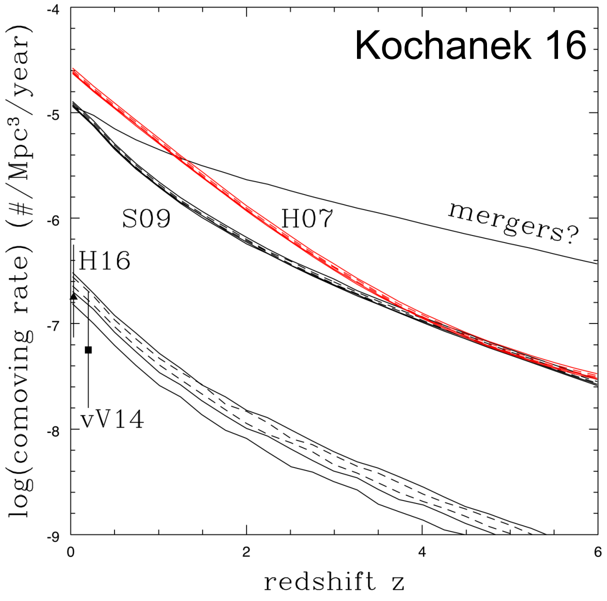


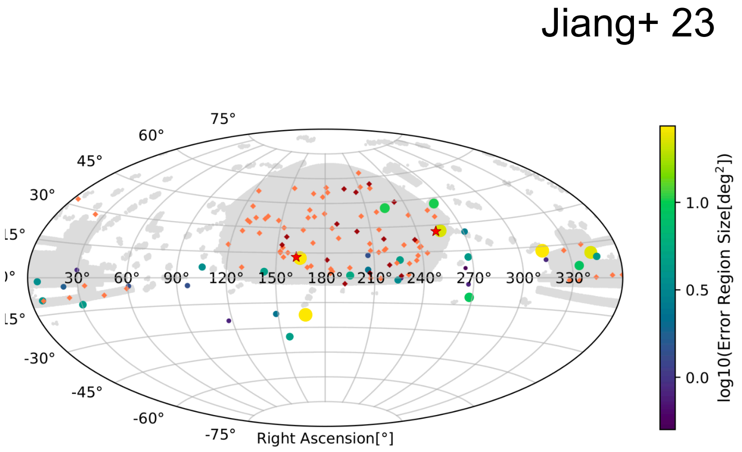
Open Questions

- 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?
- Two more dust-obscured TDEs coincident (Jiang+ 23) with neutrinos identified by similar spatial/temporal correlation?
- Cosmological TDE rate? ν-coincident rate?
- Can TDEs be promising (VHE) γ-ray emitters? origin of UHECRs? Contribute to diffuse neutrino flux?





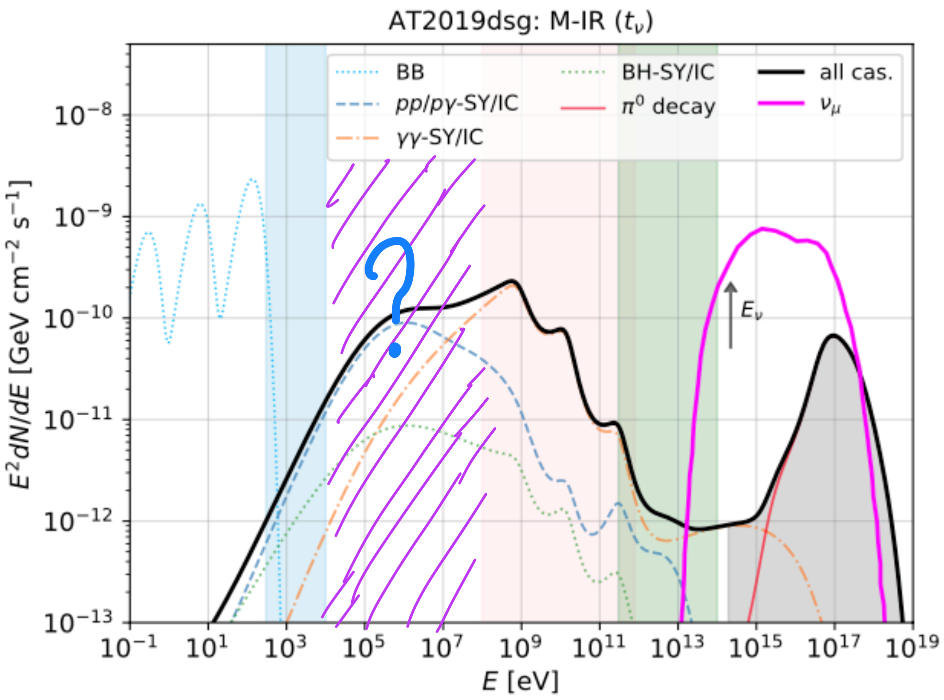


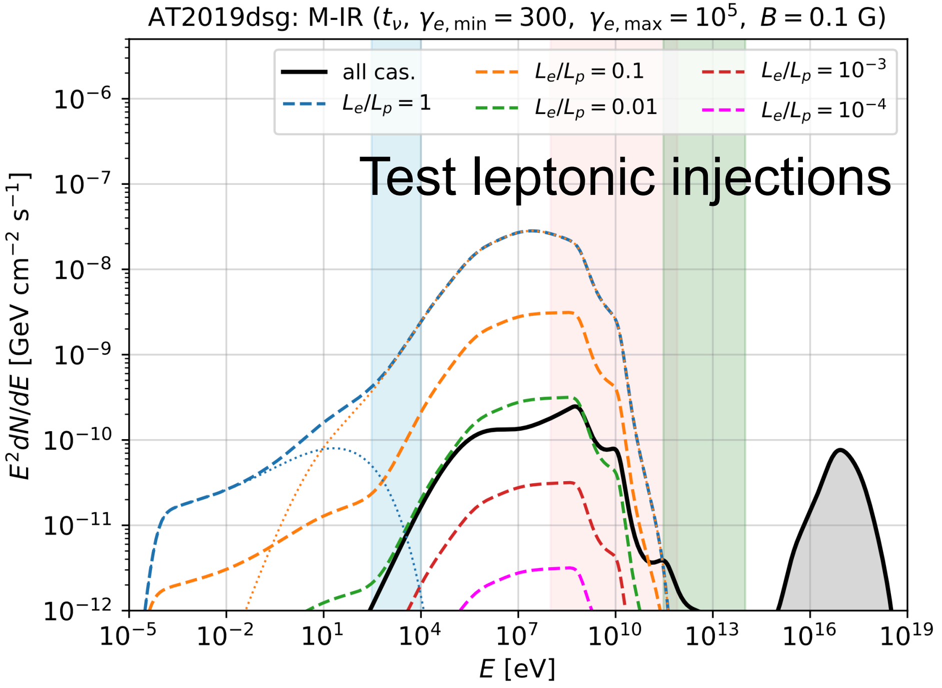


What we may need in the future

- a bold guess -

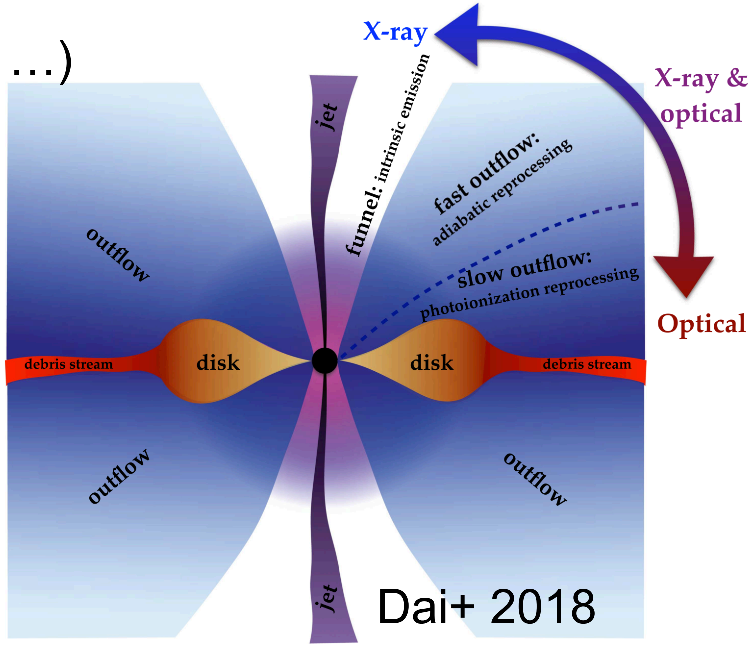
- ☐ Better angular resolution for neutrino tracks
- ☐ GeV to VHE γ-ray data/constraints from Fermi, HAWC, VERITAS, etc. in time domain (late-time followup)
- ☐ MeV missions between hard X-ray and sub-GeV
- ☐ Time-dependent lepto-hadronic modeling - leptonic process can be important for a stronger *B*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





Test leptonic injections

Mango v.s. Parrot



Dai+ 2018