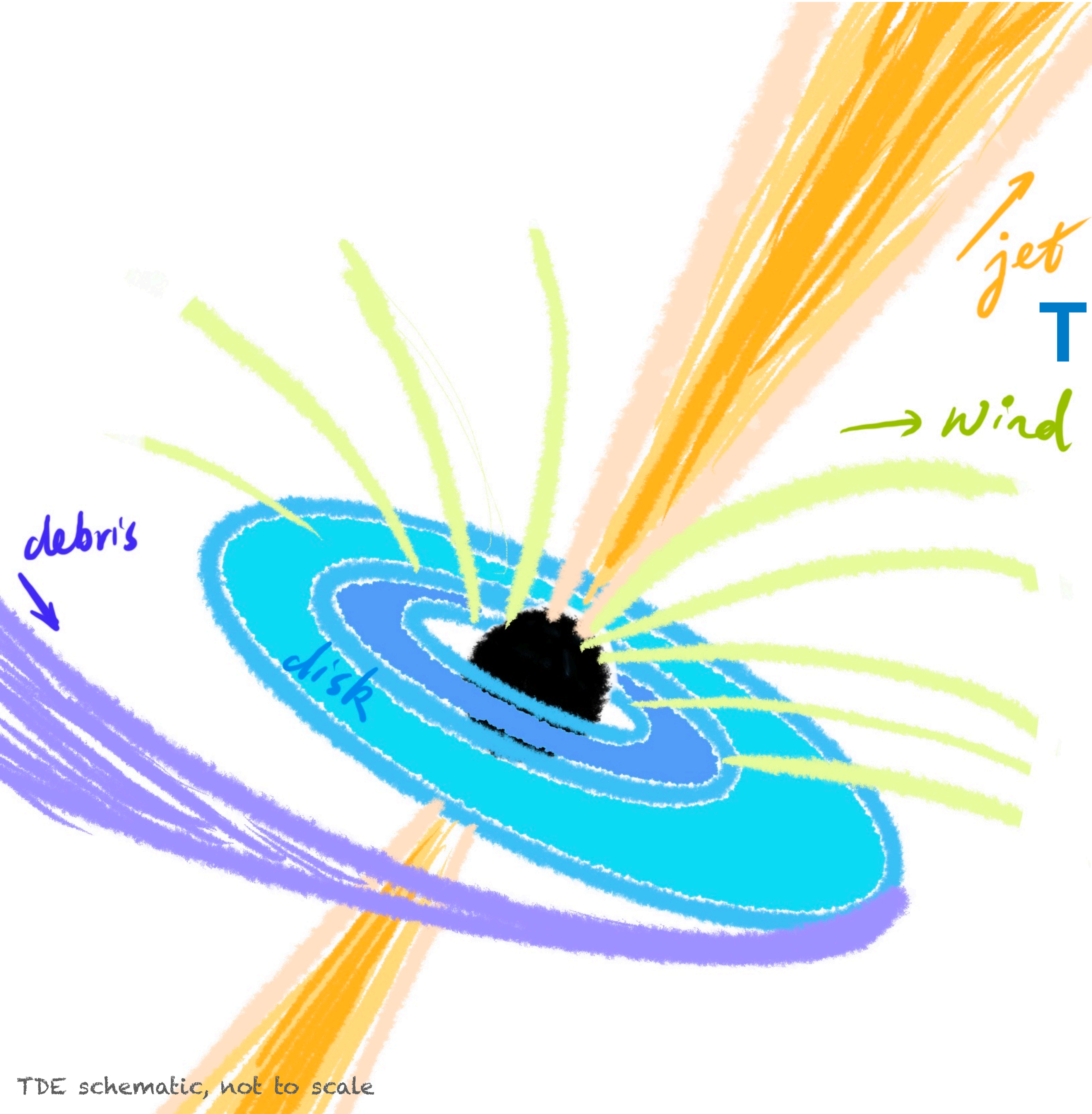



# Neutrinos from Tidal Disruption Events

**Chengchao Yuan**
yuan-cc.github.io
Deutsches Elektronen Synchrotron DESY

RICAP-24
2024/09/26, Frascati (Rome)

# 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

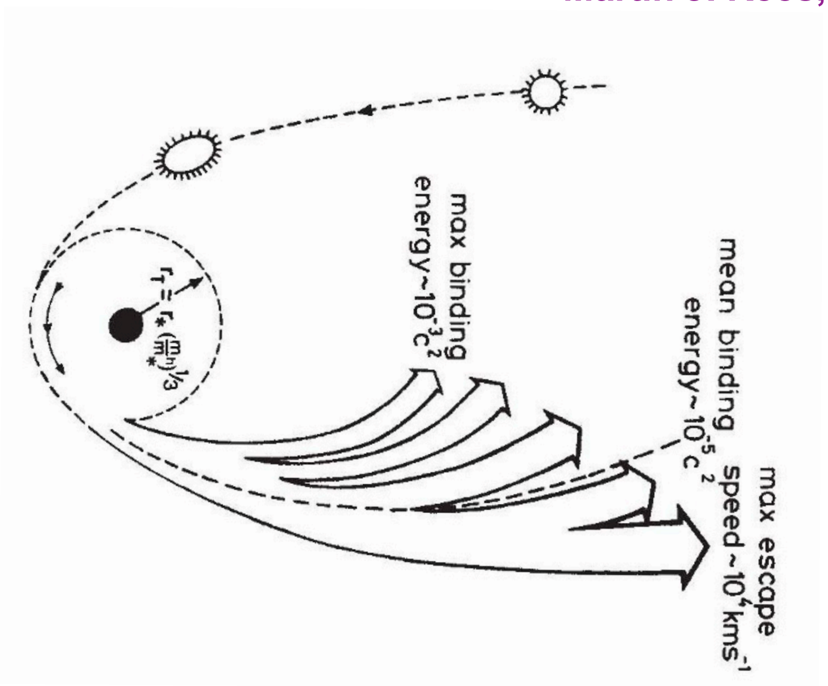
**Tidal disruption of stars by black holes of $10^6$–$10^8$ solar masses in nearby galaxies**

**Martin J. Rees**

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

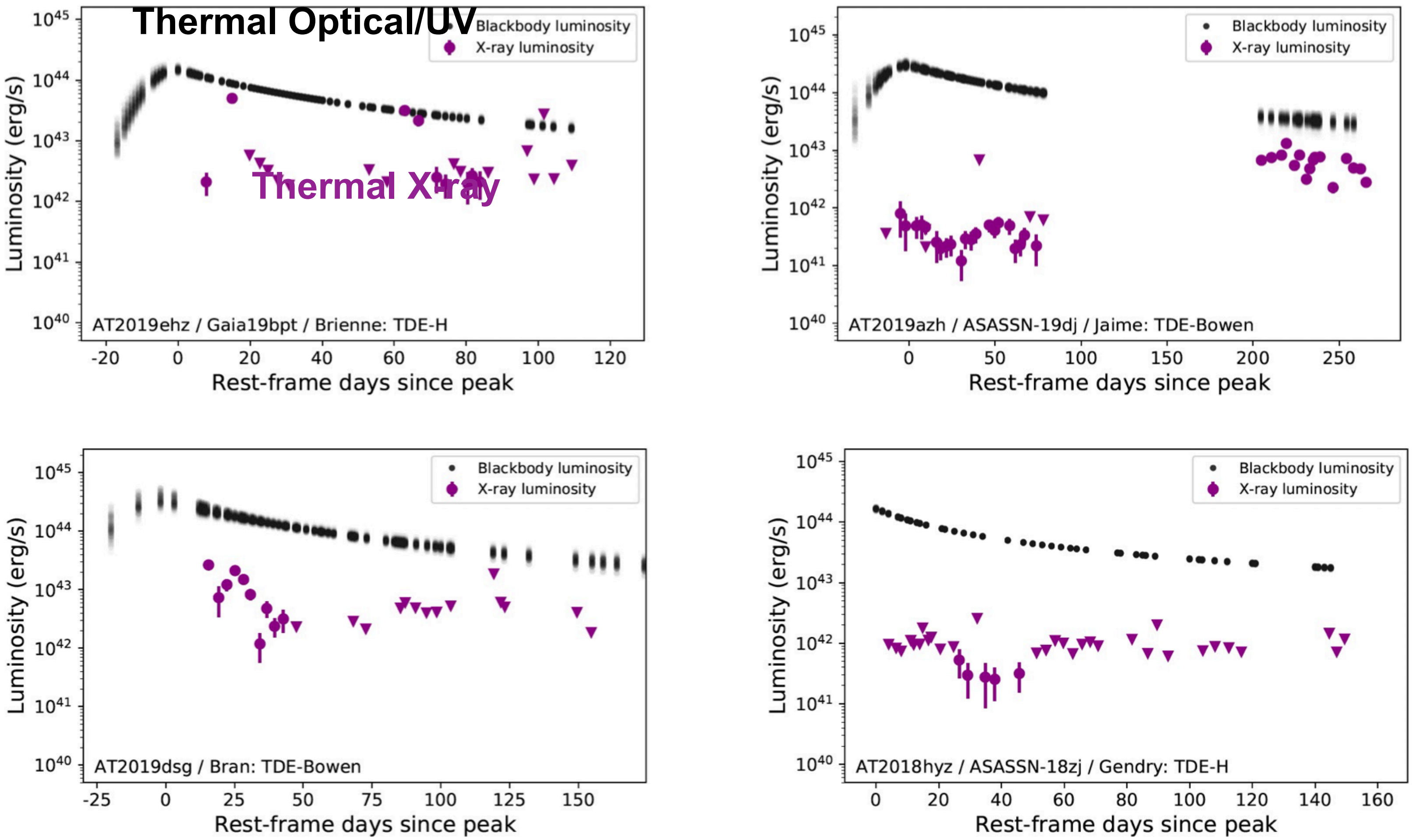
*Stars in galactic nuclei can be captured or tidally disrupted by a central black hole. Some debris would be ejected at high speed; the remainder would be swallowed by the hole, causing a bright flare lasting at most a few years. Such phenomena are compatible with the presence of $10^6$–$10^8$ $M_\odot$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

Martin J. Rees, Nature 1988



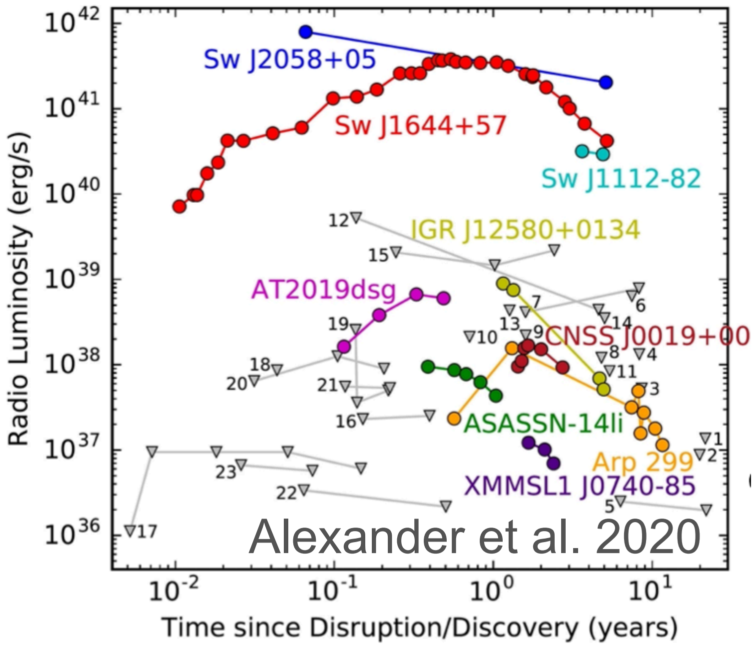
# TDE observational signatures: universal

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




Van Velzen et al, 2021

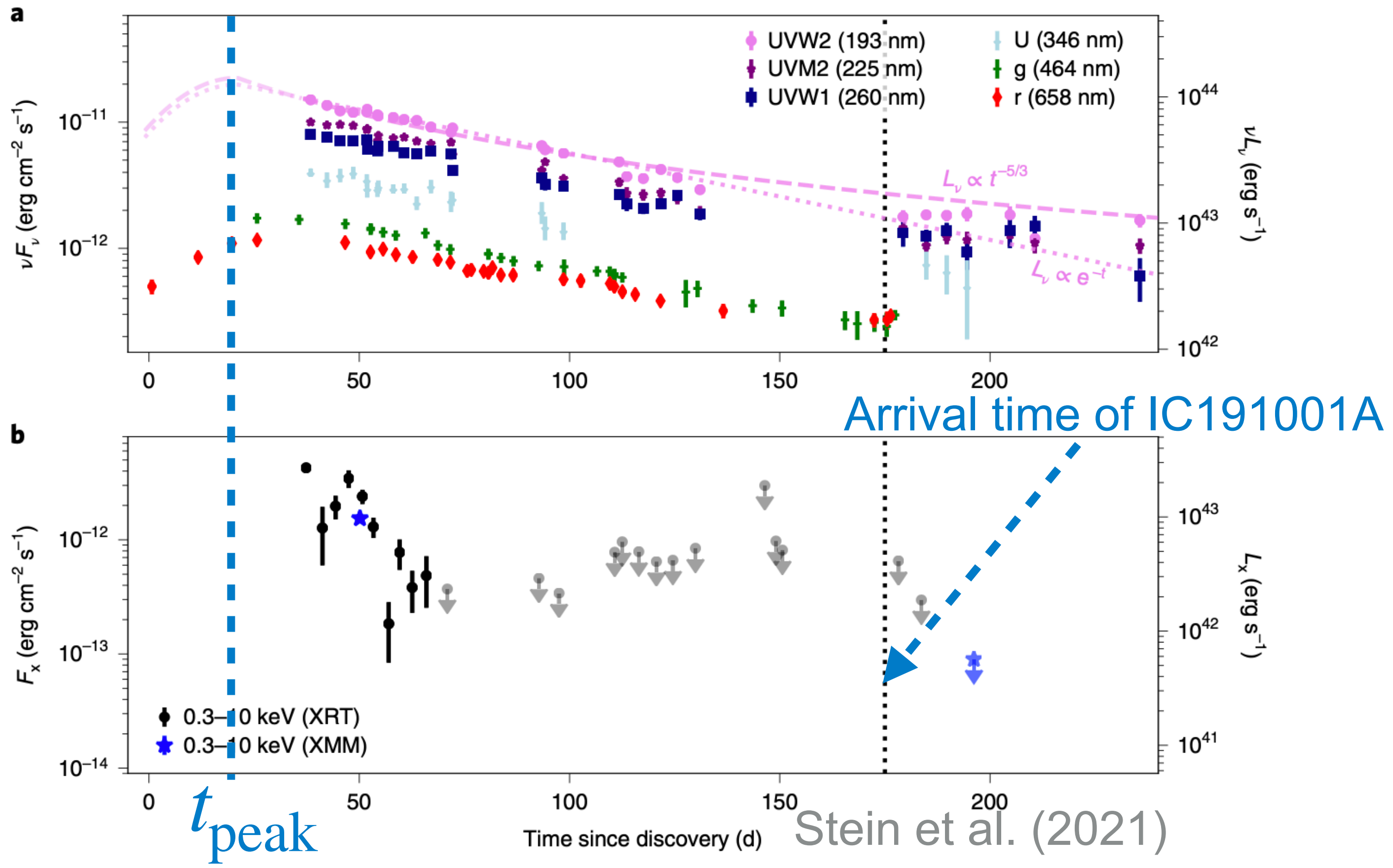
Radio

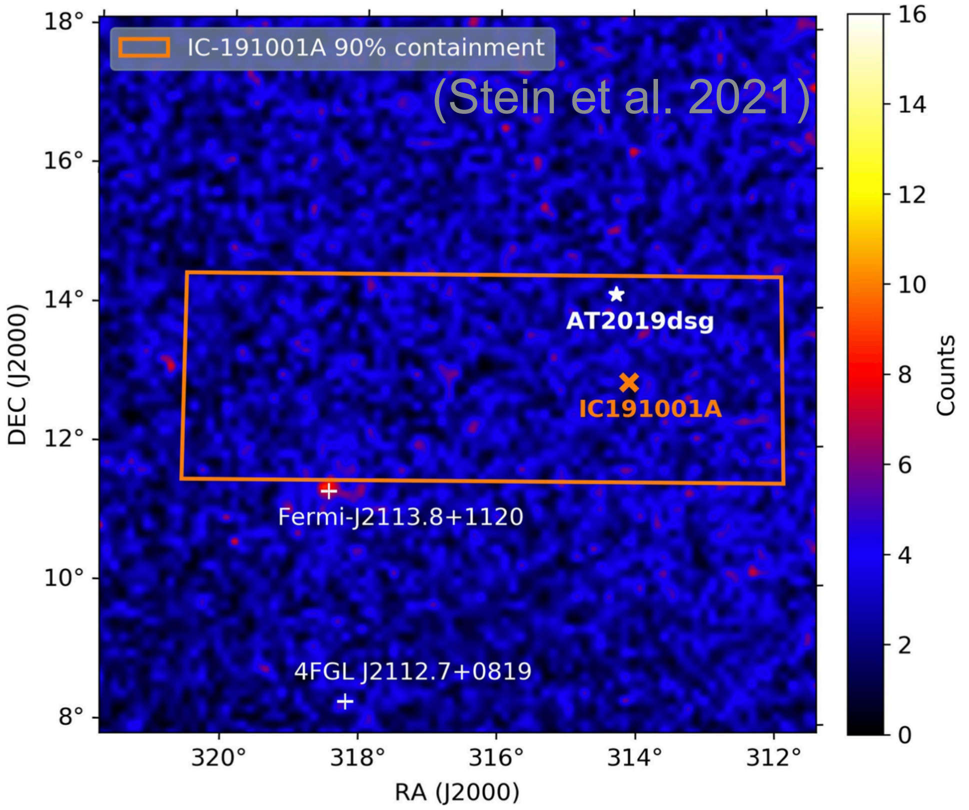



- A small fraction of TDEs exhibit luminous radio relativistic jet. Most are radio quiet.
- Delayed radio may come from jet propagating in wind density profile $\rho(r) \propto r^{-k}$ $(1.5 \lesssim k \lesssim 2)$ (Metzger+ 2016)

# 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
- $t_\nu - t_{\mathrm{pk}} = 150$ d

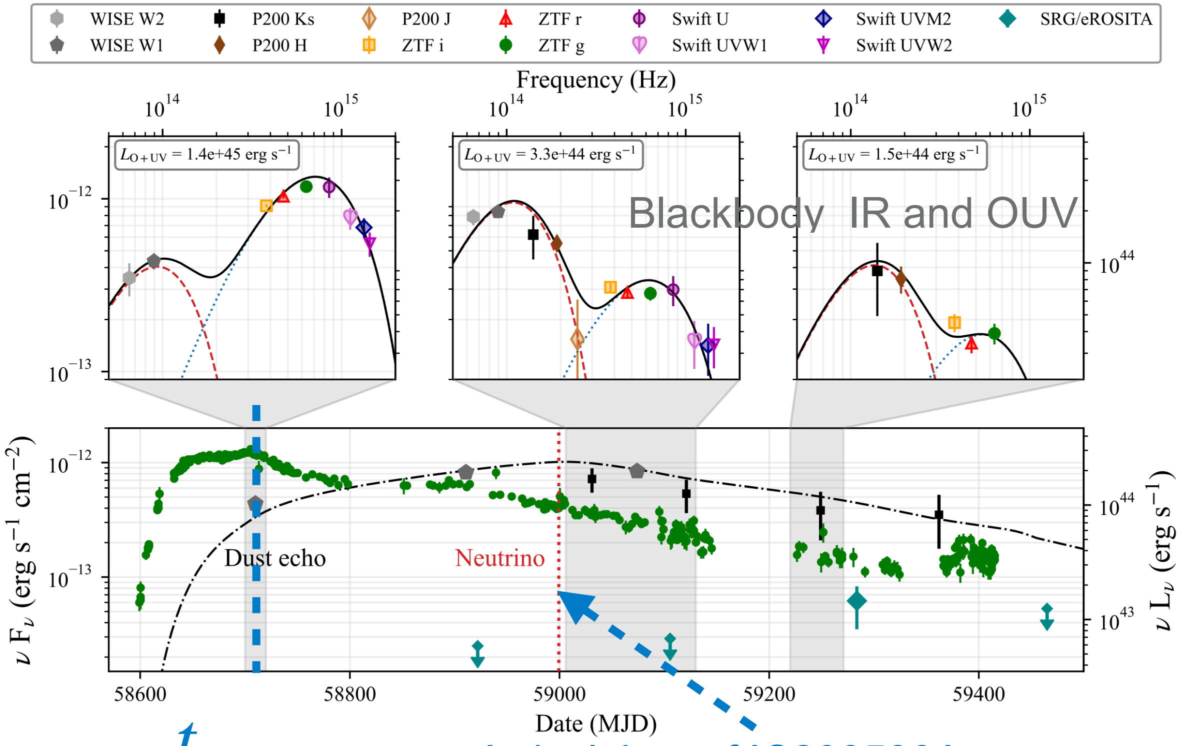
Measured black body spectra:

- **X-ray**: $T_X = 72$ eV, from hot accretion disk
- **OUV**: $T_{\mathrm{OUV}} = 3.4$ eV, from photosphere (nearly constant)
- **IR**: $T_{\mathrm{IR}} = 0.15$ 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; $t_\nu - t_{\rm pk} = 393$ d
- *Fermi* up limit ✓

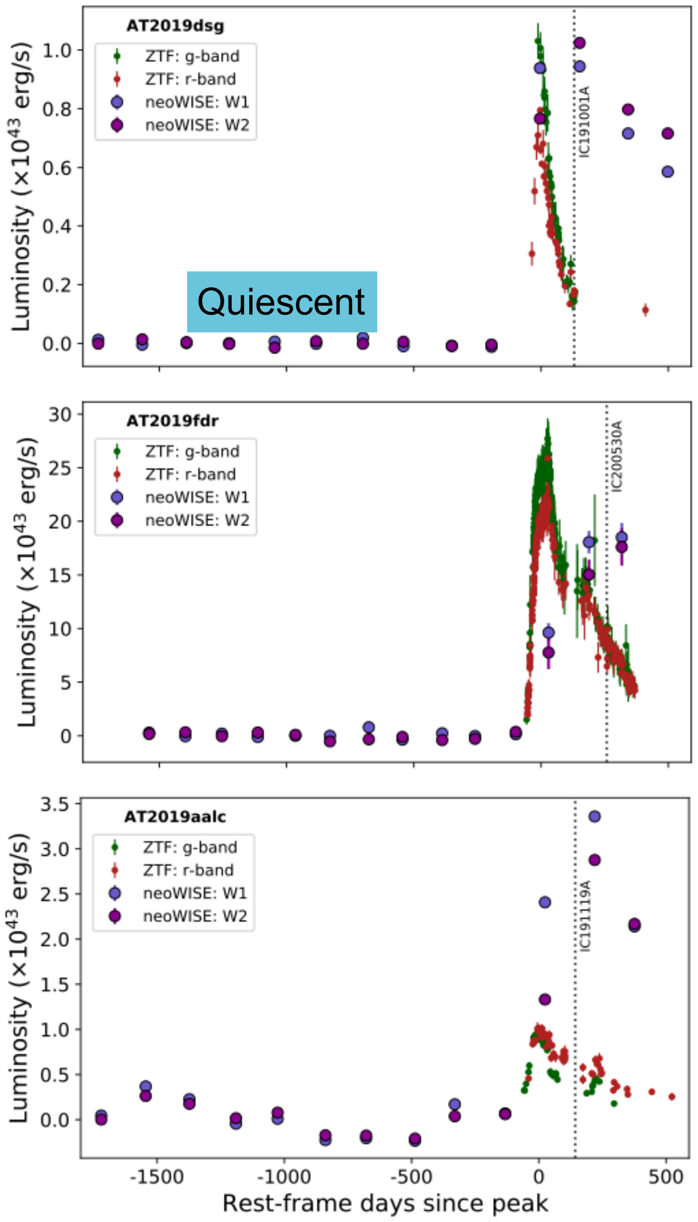
Reusch et al. (2022)




$t_{\rm peak}$

Arrival time of IC200530A

# AT2019aalc




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

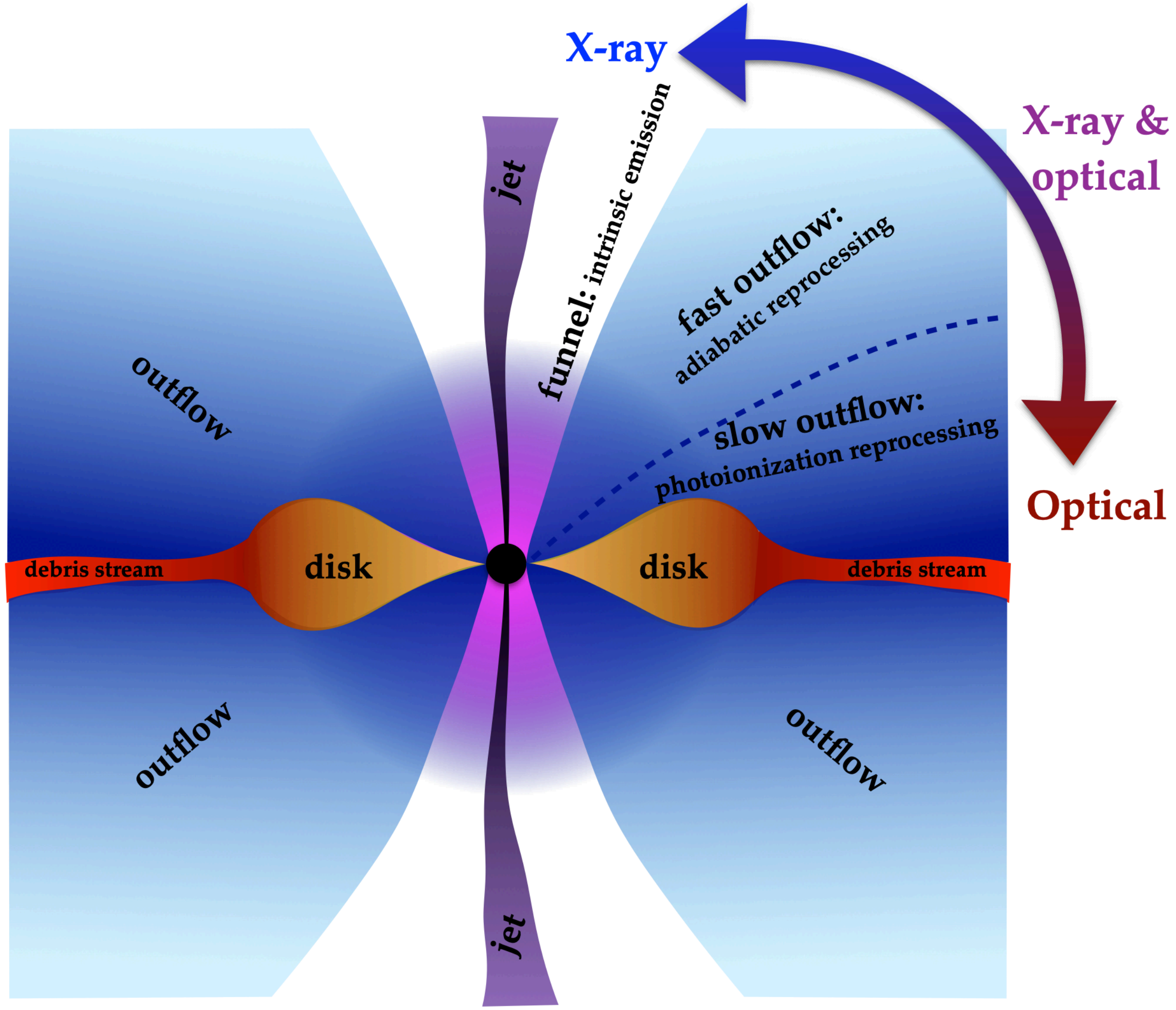
- Angular offset: 1.9 deg
- $t_\nu - t_{\rm pk} = 148$ d
- Significance of neu correlation: 3.6 sigma (van Velzen+ 2021)

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

- **$\gamma$-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, corona…
- **Radio:** non-thermal (particle acceleration in disk, jet, outflow)




Dai+ 2018

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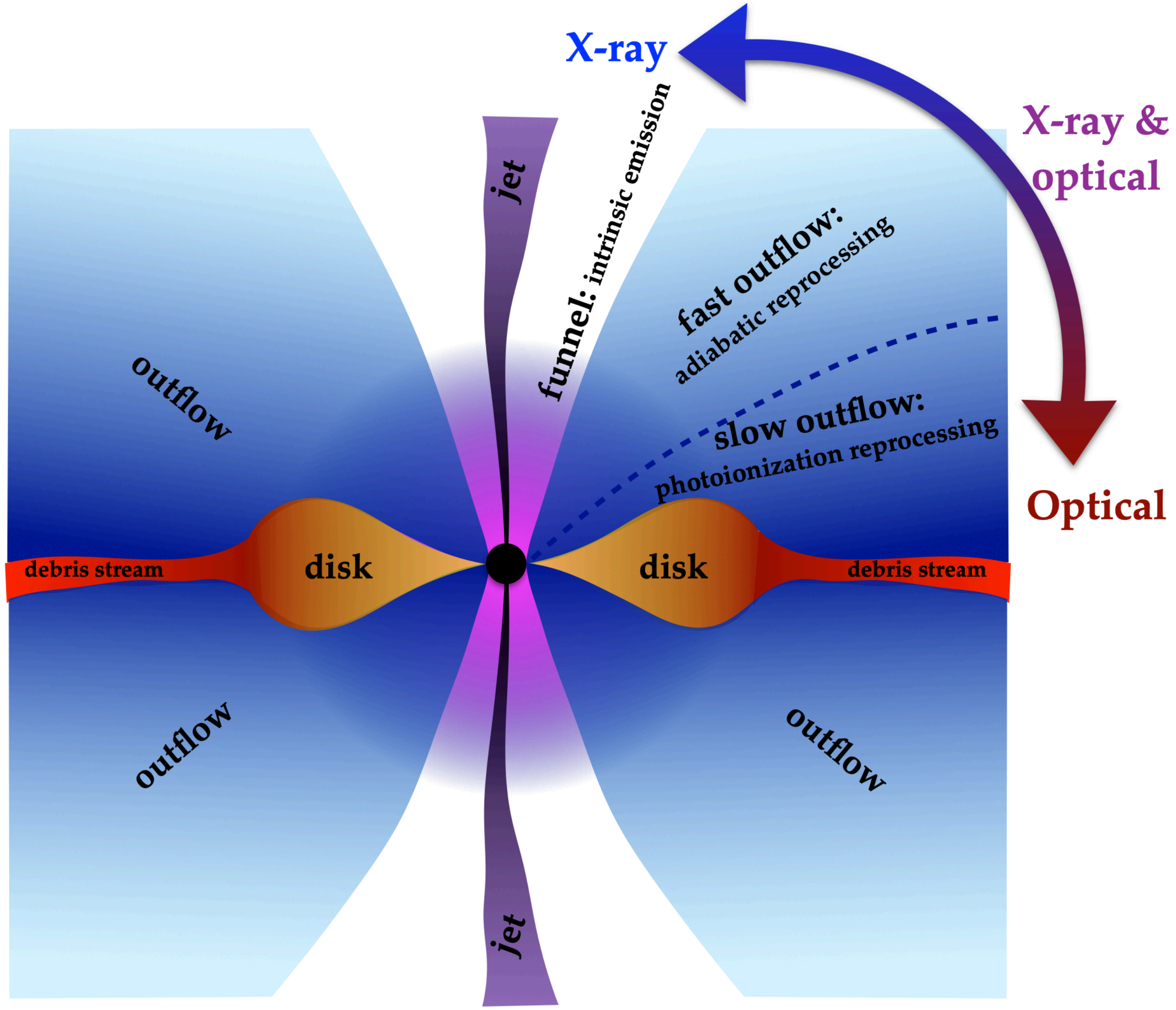
**Wide angle winds** - Fang 20, Murase+ 20
**Stream-stream** - Dai + 15,, HY19,
**Jets** - Wang + 11,Wang & Liu 16, Dai & Fang 17, Lunardini & Winter 17, Senno + 17

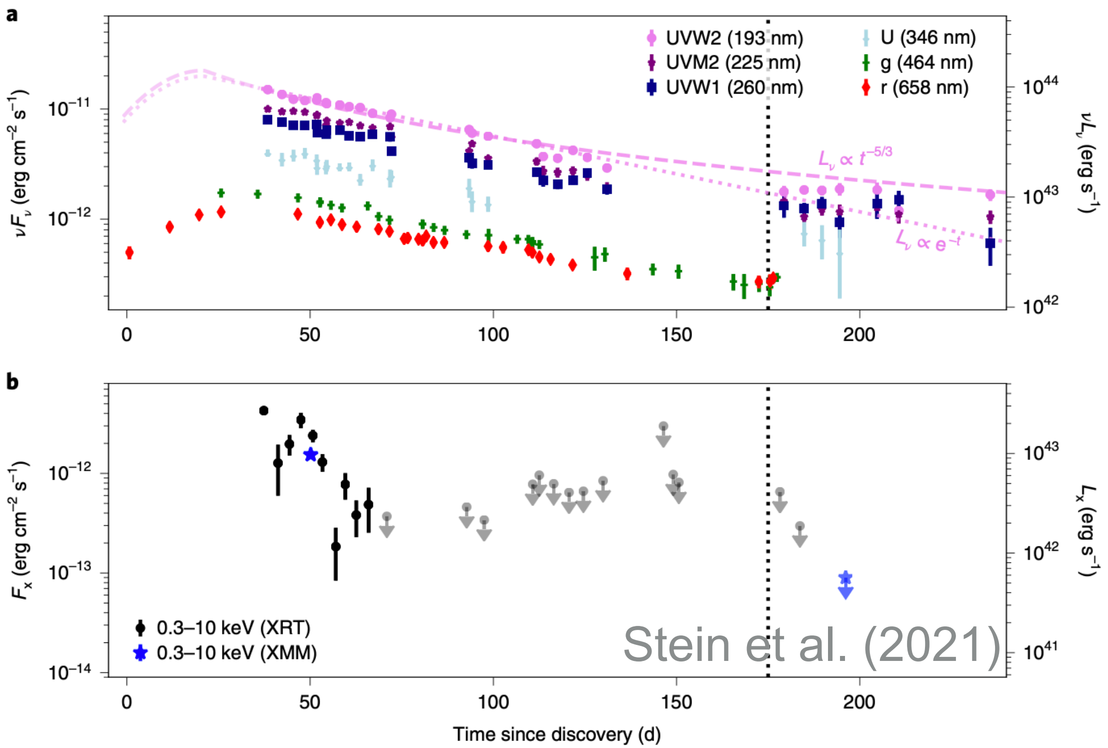
- In addition to the EM signatures, neutrinos might be produced in the accretion disks, isotropic disk winds (outflows), or jets
- Neutrino associated TDEs/candidates
  1. AT2019dsg (IC191001A)
  2. AT2019fdr (IC200530A)
  3. AT2019aalc (IC220405B)
- More neutrino coincident TDEs/candidates are proposed




Dai+ 2018

# Questions for Neutrino-Coincident TDEs

- Where are radio, OUV, IR, X-ray (XRT, eROSITA, NICER), $\gamma$-ray and neutrino emissions produced?
- Temporal signatures? delayed infrared and neutrino emissions
- Multi-messenger implications, e.g., from X-ray/$\gamma$-ray up limits to neutrino constraints




## What we have

- Thermal optical/ultraviolet, X-ray, and infrared spectra/light curves.
- Up limits from $\gamma$-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

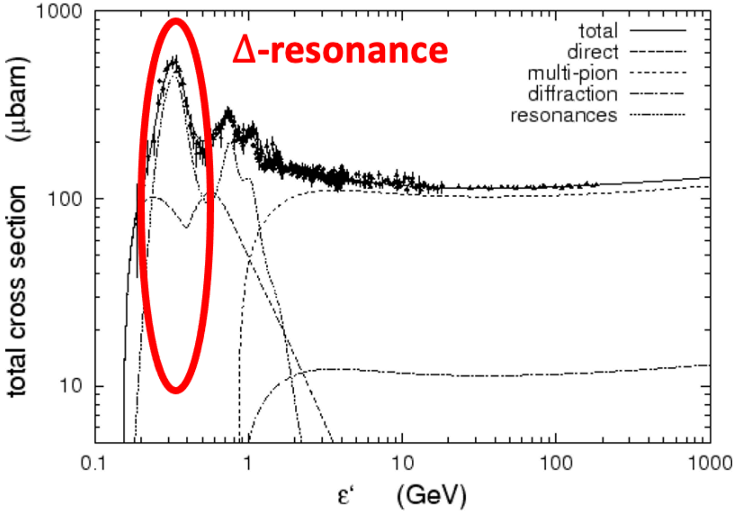
# Production of High-Energy Astrophysical Neutrinos

## 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: $E_p \gtrsim \frac{m_\pi(2m_p + m_\pi)c^2}{4\varepsilon_\gamma}$




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

$$\varepsilon_\nu Q_{\varepsilon_\nu} \approx \frac{3K}{4(K+1)} e^{-f_{pp,p\gamma}} (\varepsilon_p Q_{\varepsilon_p})|_{\varepsilon_p \sim 20\varepsilon_\nu}$$

$$\varepsilon_\gamma Q_{\varepsilon_\gamma} \approx \frac{4}{3K} \varepsilon_\nu Q_{\varepsilon_\nu}|_{\varepsilon_\gamma \sim 2\varepsilon_\nu}$$

$$pp: \ \ K = N_{\pi^\pm}/N_{\pi^0} \sim 2$$

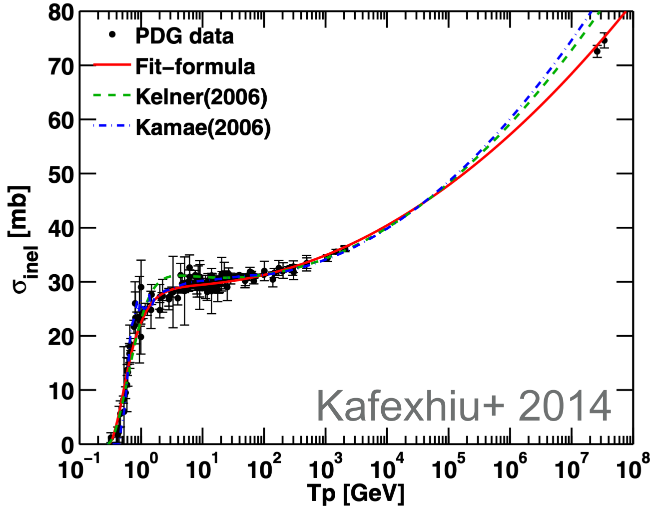
$$p\gamma: \ \ K = N_{\pi^\pm}/N_{\pi^0} \sim 1$$

## Hadronuclear ($pp$) process

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

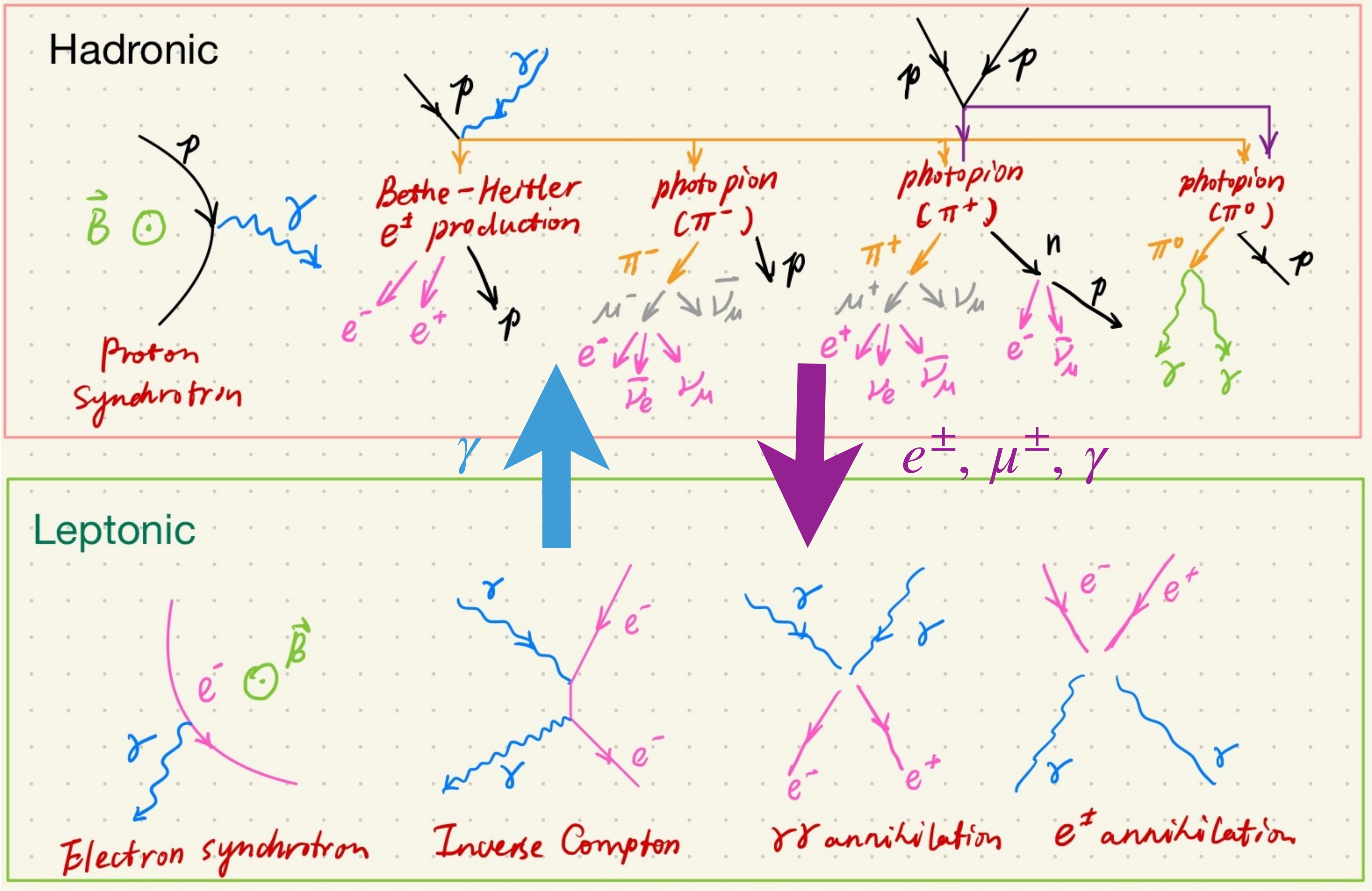
Ingredients: dense thermal/rest target protons [outflows/winds in TDEs] + CRs

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




proton kinetic energy in the rest frame of the target proton

# Electromagnetic cascades

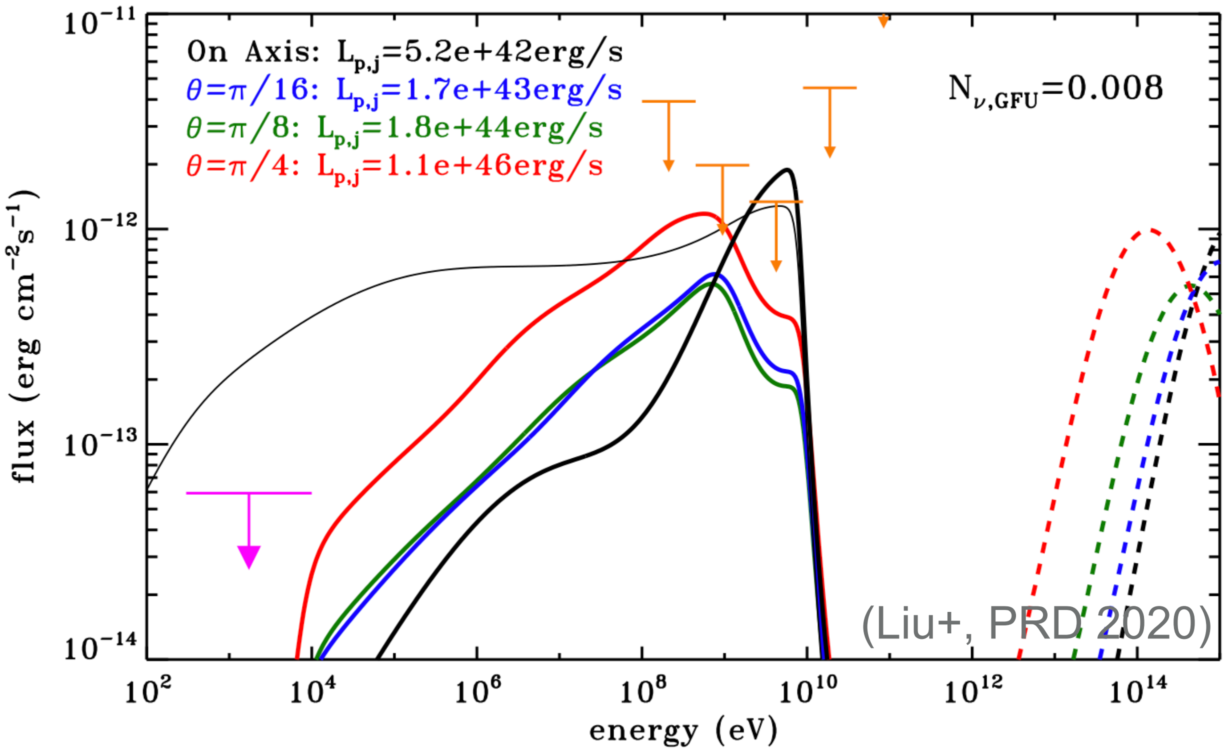


# Neutrino-emitting TDE models

## Off-axis jets

*(e.g., Liu+, PRD 2020)*

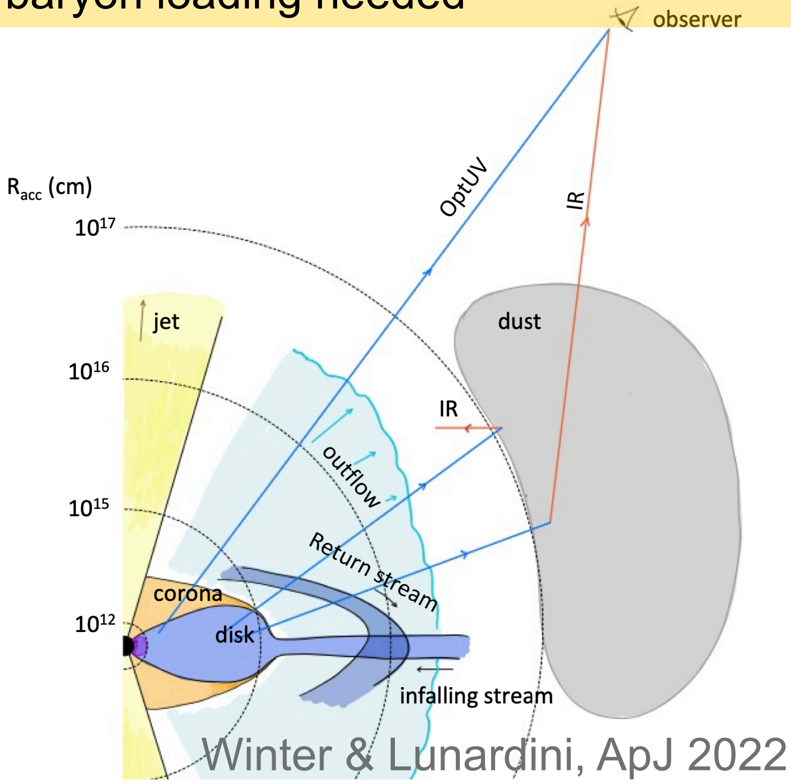
- High gas column density allows internal thermal X-ray
- Off-axis jet TDEs have a higher rate compared to on-axis jetted TDEs
- Gamma-ray limits: 0.008 neutrinos for AT 2019dsg




## Isotropic winds + IR echos

*(e.g., Winter & Lunardini, ApJ 2023; CY & Winter, ApJ 2023)*

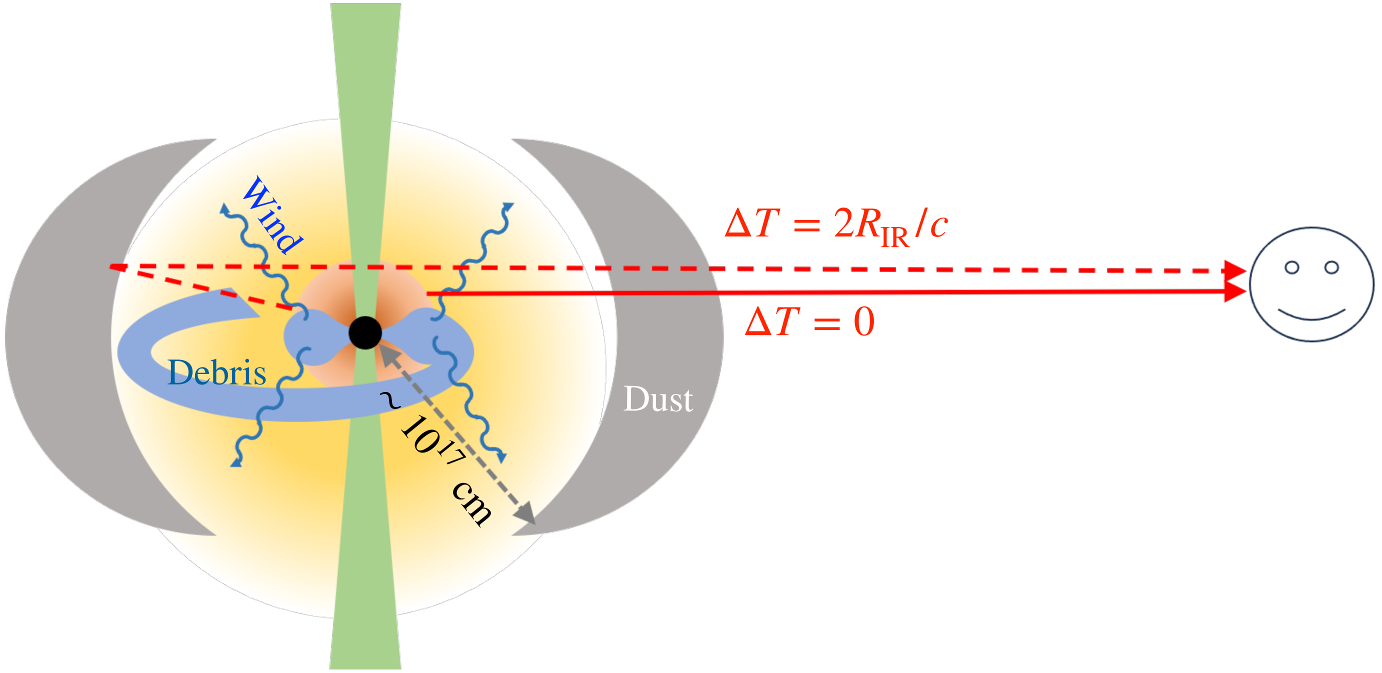
- Dust echo explains delayed IR emission, may associate to delayed neutrinos
- Thermal IR/OUV/X-ray photons $\rightarrow p\gamma$ neutrinos
- Efficient baryon loading needed



# Dust Echo: infrared (IR) emission

**Dust torus reprocess OUV emission to IR bands**

- Thermal IR spectra is consistent with sublimation temperature, $T_{\rm IR} \lesssim T_{\rm sub} \sim 0.16$ eV
- Dust radius ($R_{\rm IR}$) can be inferred from IR time delay w.r.t OUV emissions, $R_{\rm IR} \sim c\Delta T/2$



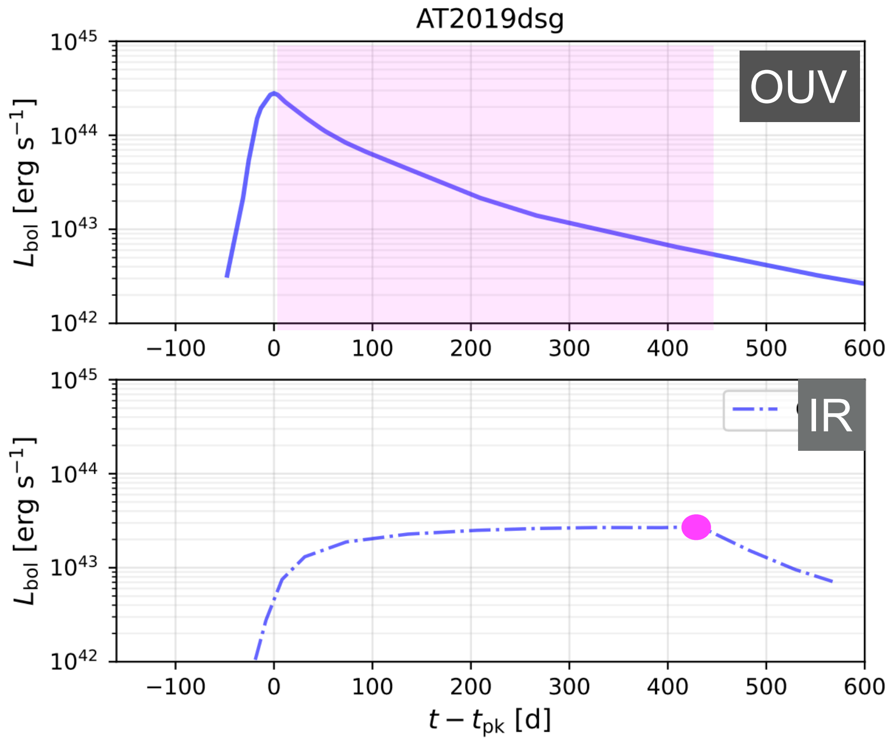

**IR light curve fitting**

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

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

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

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



# Proton injection to TDE winds

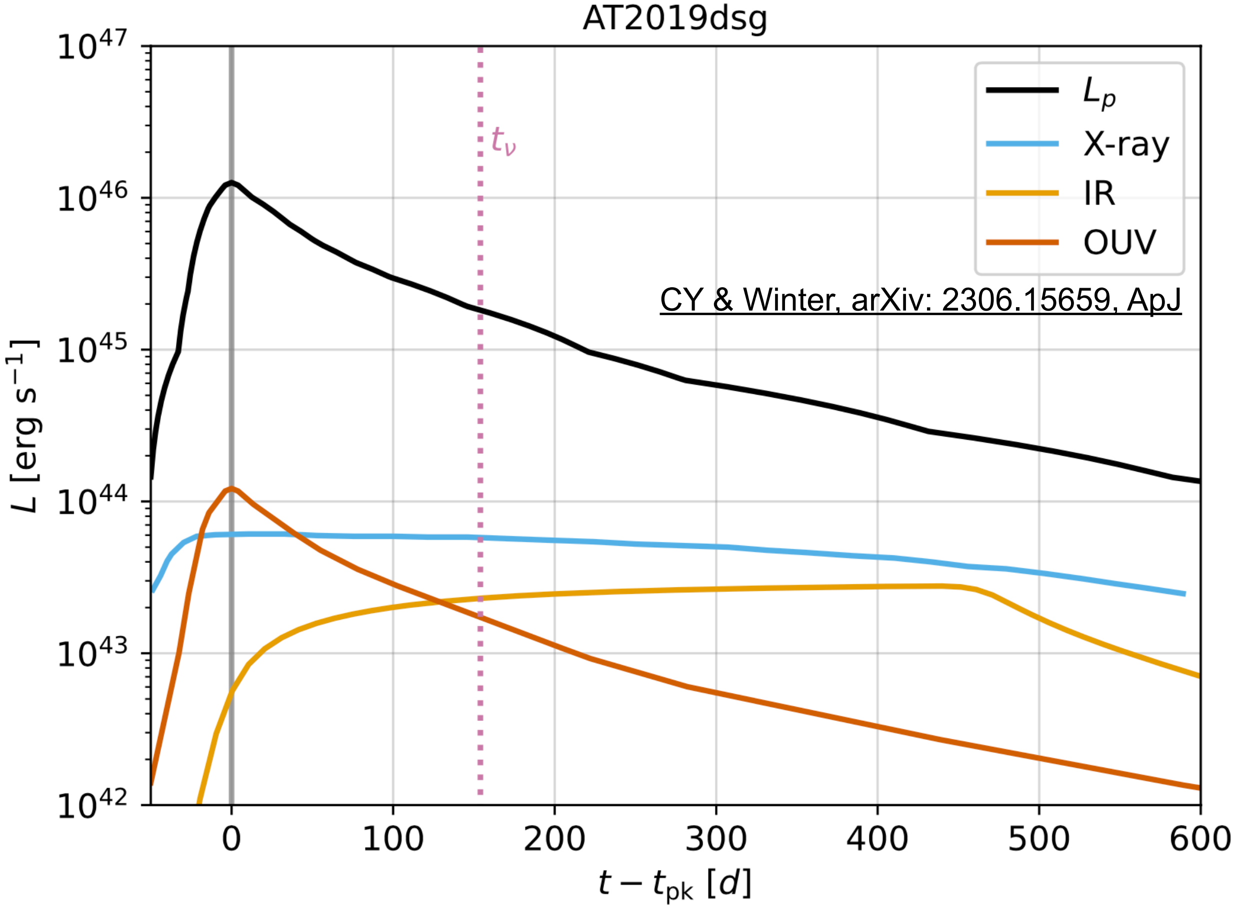
**Four parameters:** $E_{p,\min} \sim 1\ \mathrm{GeV},$ spectra index $p = 2$, $E_{p,\max}$ (free-param), normalization factor

We use four parameters to determine the proton injection

- 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



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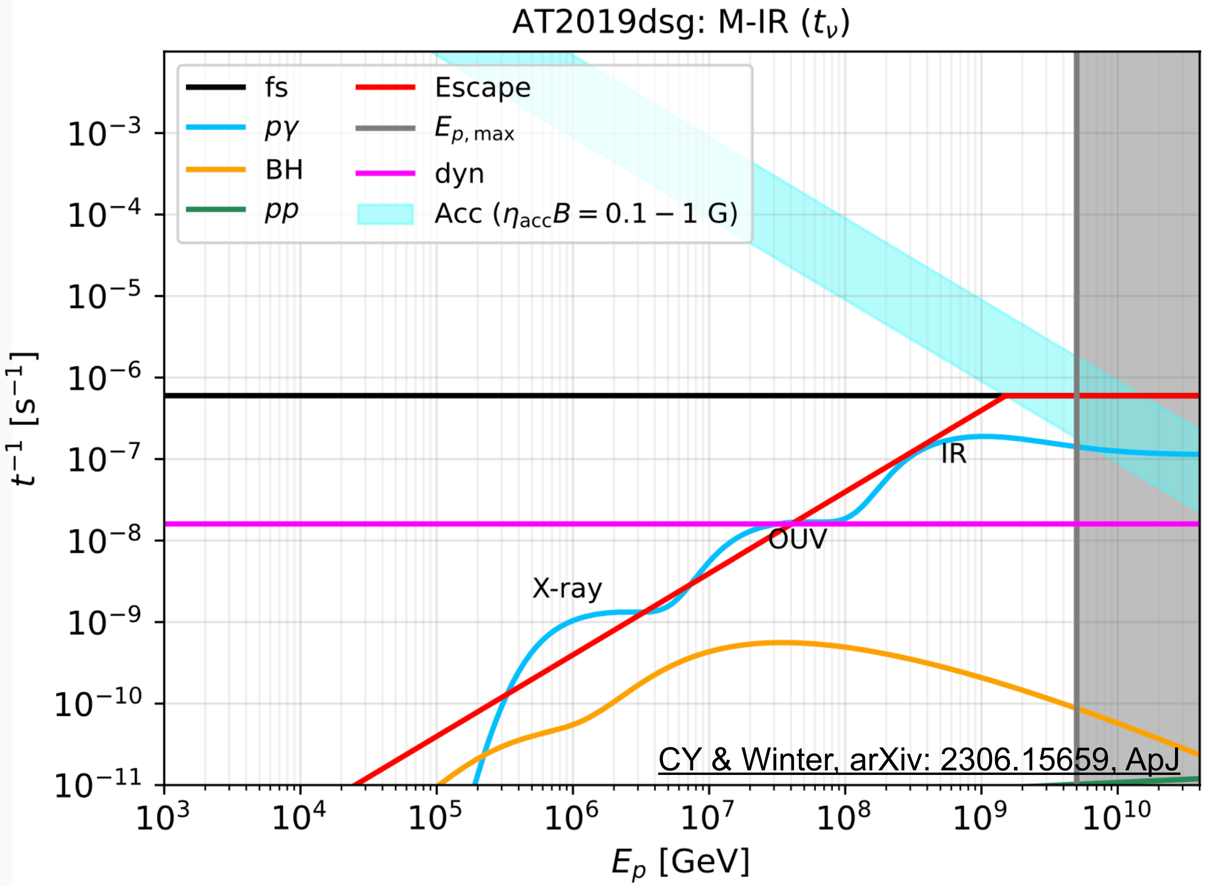
- $L_p(t) = \varepsilon_{\rm diss} \dot{M}_\star(t) c^2$

**Assumptions**

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

***Maximum proton energy***

- Acceleration rate : $t_{\rm acc}^{-1} = \eta_{\rm acc} c/R_L = \eta_{\rm acc} eBc/E_p$
- Cooling/escape rate = acc. rate $\rightarrow E_{p,\max} \sim 10^{9-10}$ GeV

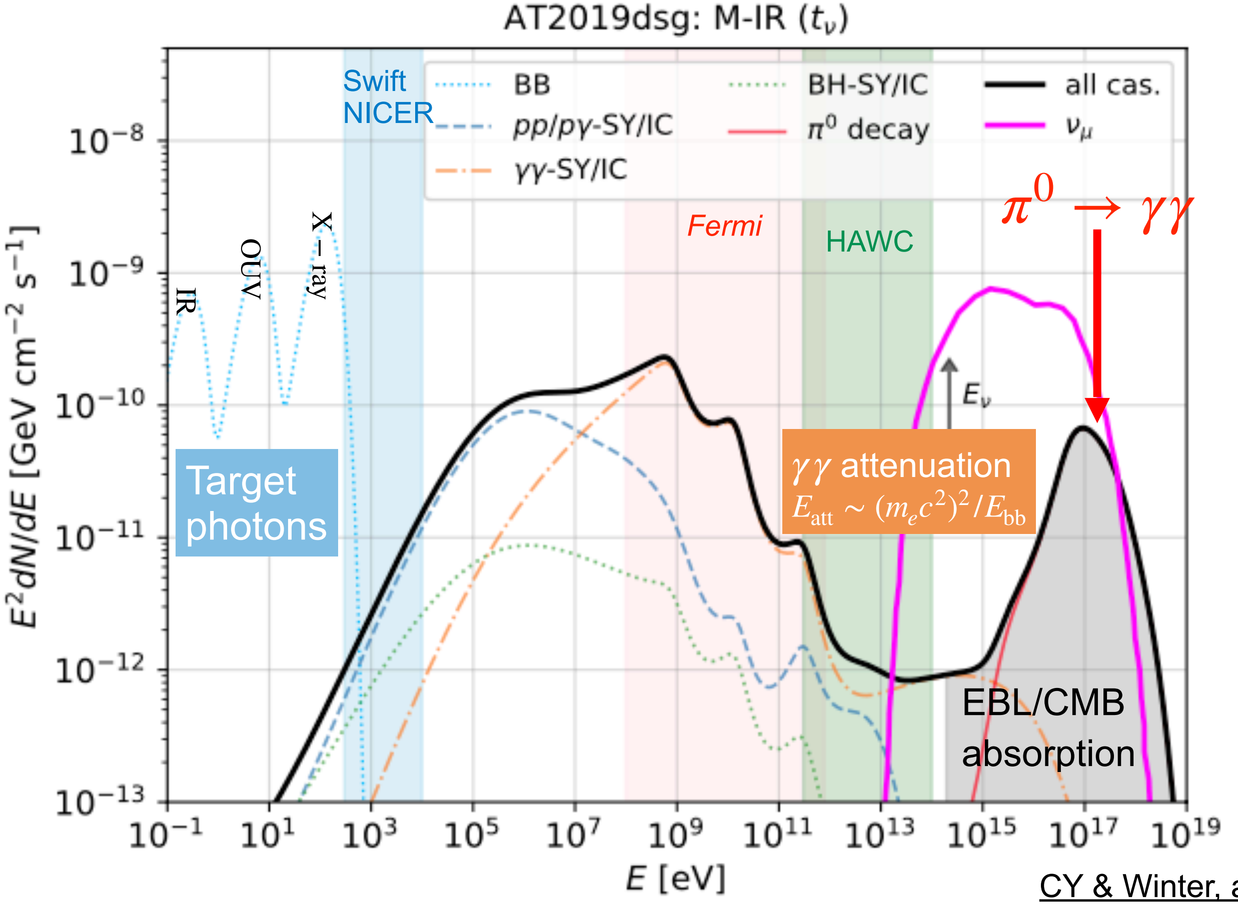


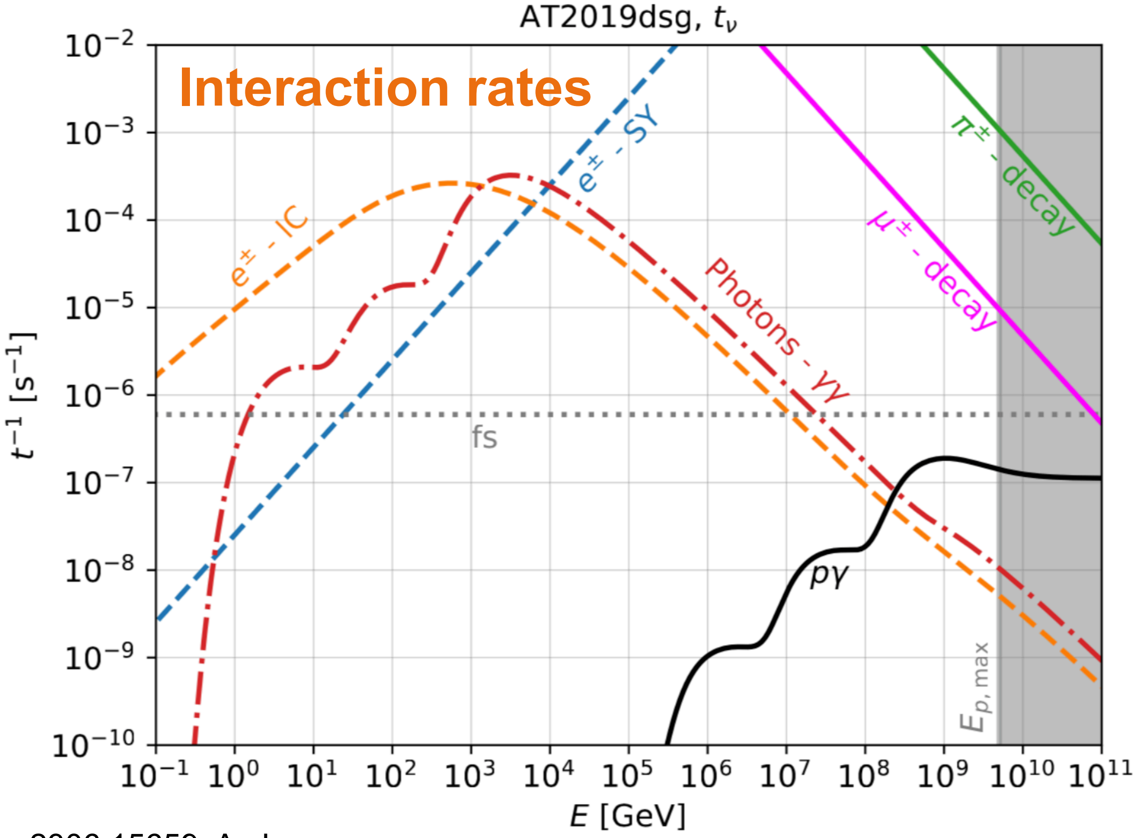
# EM cascade spectra of AT2019dsg: IR target photons

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

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

$p\gamma$ time scale ($t_{p\gamma}$) determines the time to develop EM cascade; AM3 software used for time-dependent cascade emissions



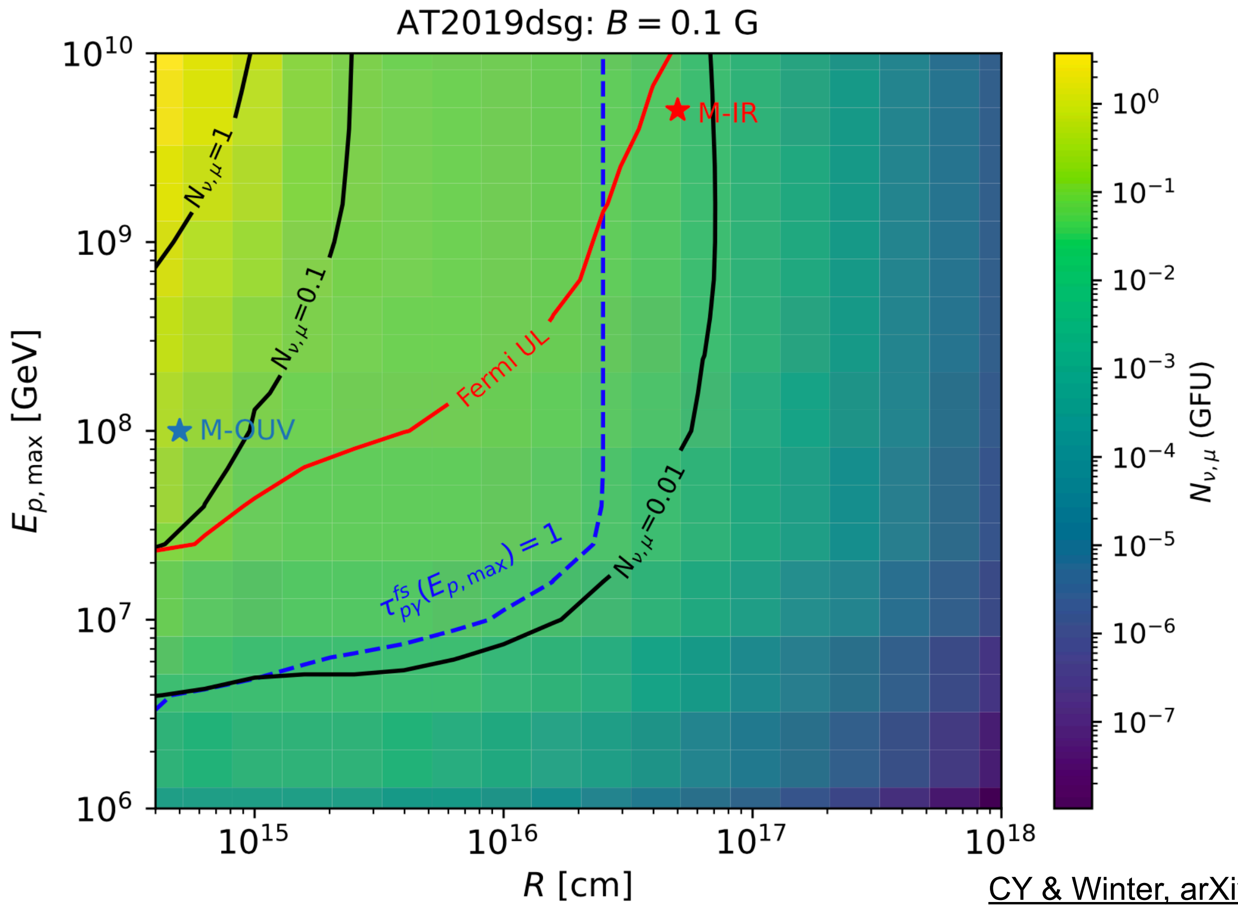




CY & Winter, arXiv: 2306.15659, ApJ

# 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)**

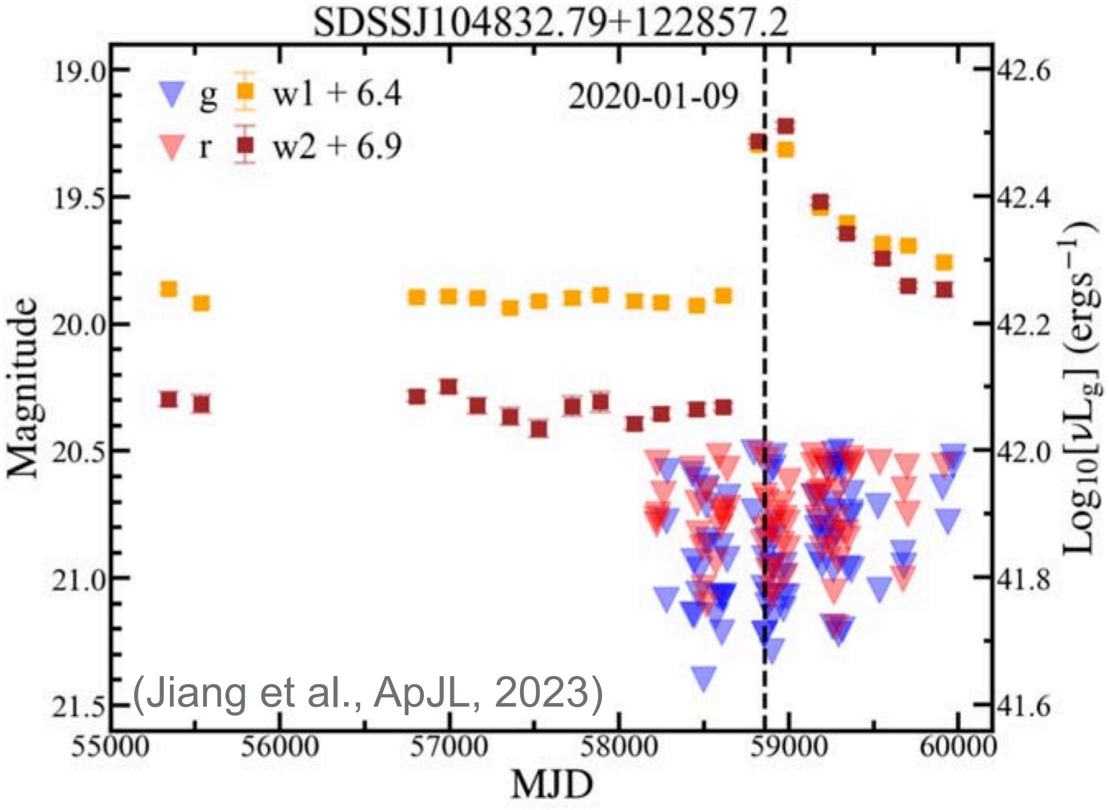
- An extended radiation zone is preferred (exclude M-OUV scenario)
- Neutrino number is constrained to be 0.01-0.1 for AT2019dsg
- Expected neutrino number from AT2019dsg, 0.008-0.76 (Stein+ 2021), is consistent with Fermi UL

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

# More neutrino-emitting TDEs?

**OUV obscured TDE candidates:**

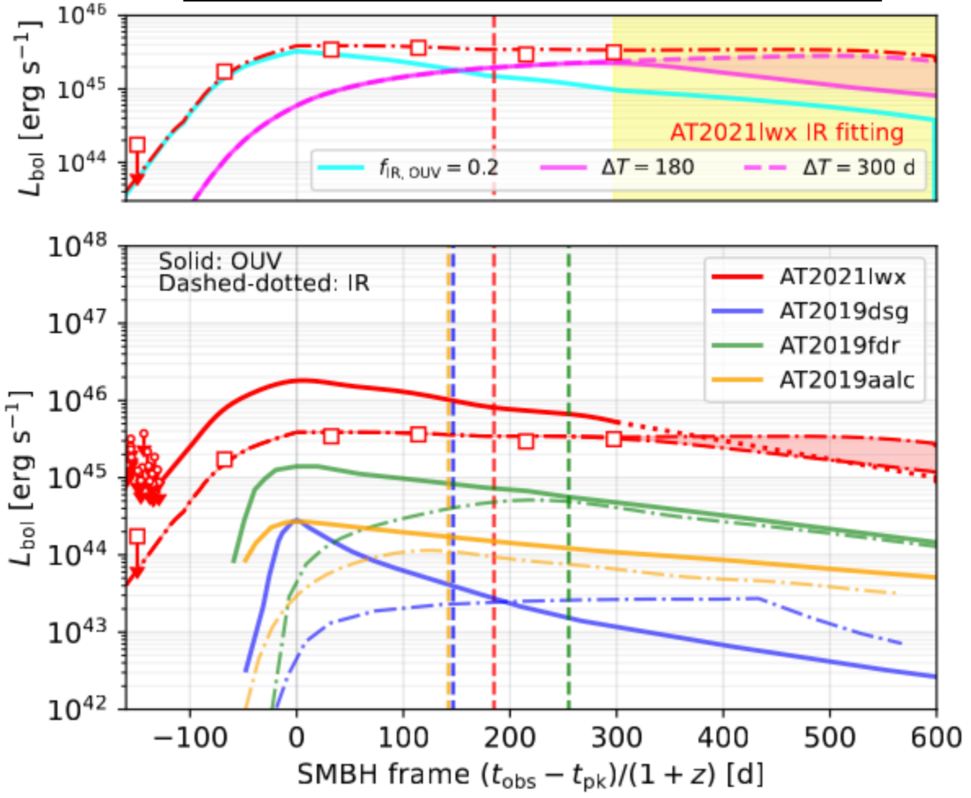
- SDSSJ1048+1228 and SDSSJ1649+2625
- Negligible optical variability, but strong IR echos
- spatially and temporally coincident with neutrino events (Jiang et al., ApJL, 2023)




**AT 2021lwx** (Subrayan+ 2023, z~1.0)

- Likely correlated with neutrino IC220405B: angular deviation ~ 2.6 deg; neutrino time delay in SMBH frame: 185 d

CY, Winter & Lunardini, arXiv: 2401.09320



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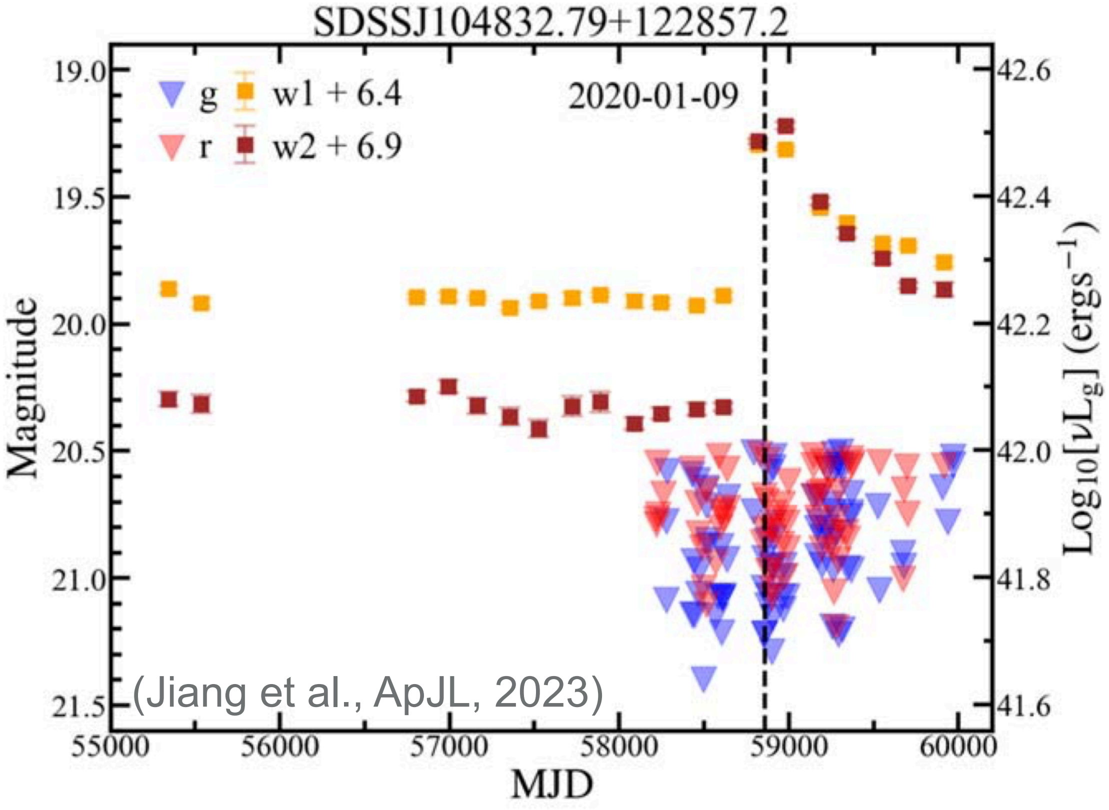


**Refined correlation studies with IceCube systematics are need to confirm or exclude these correlations!**

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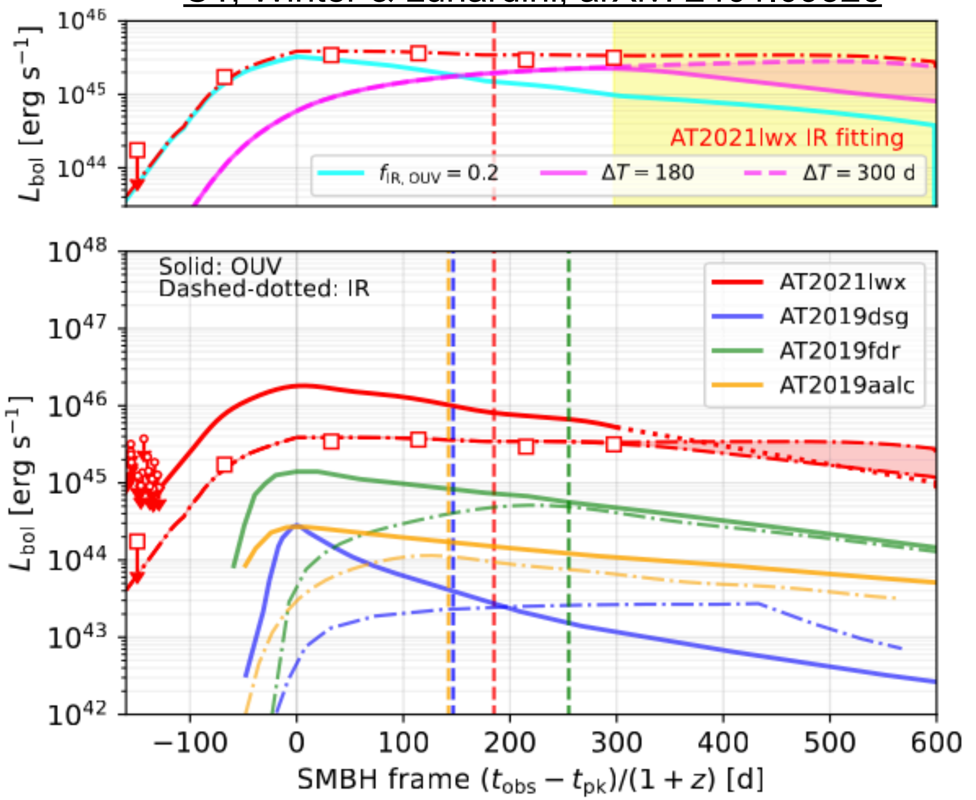
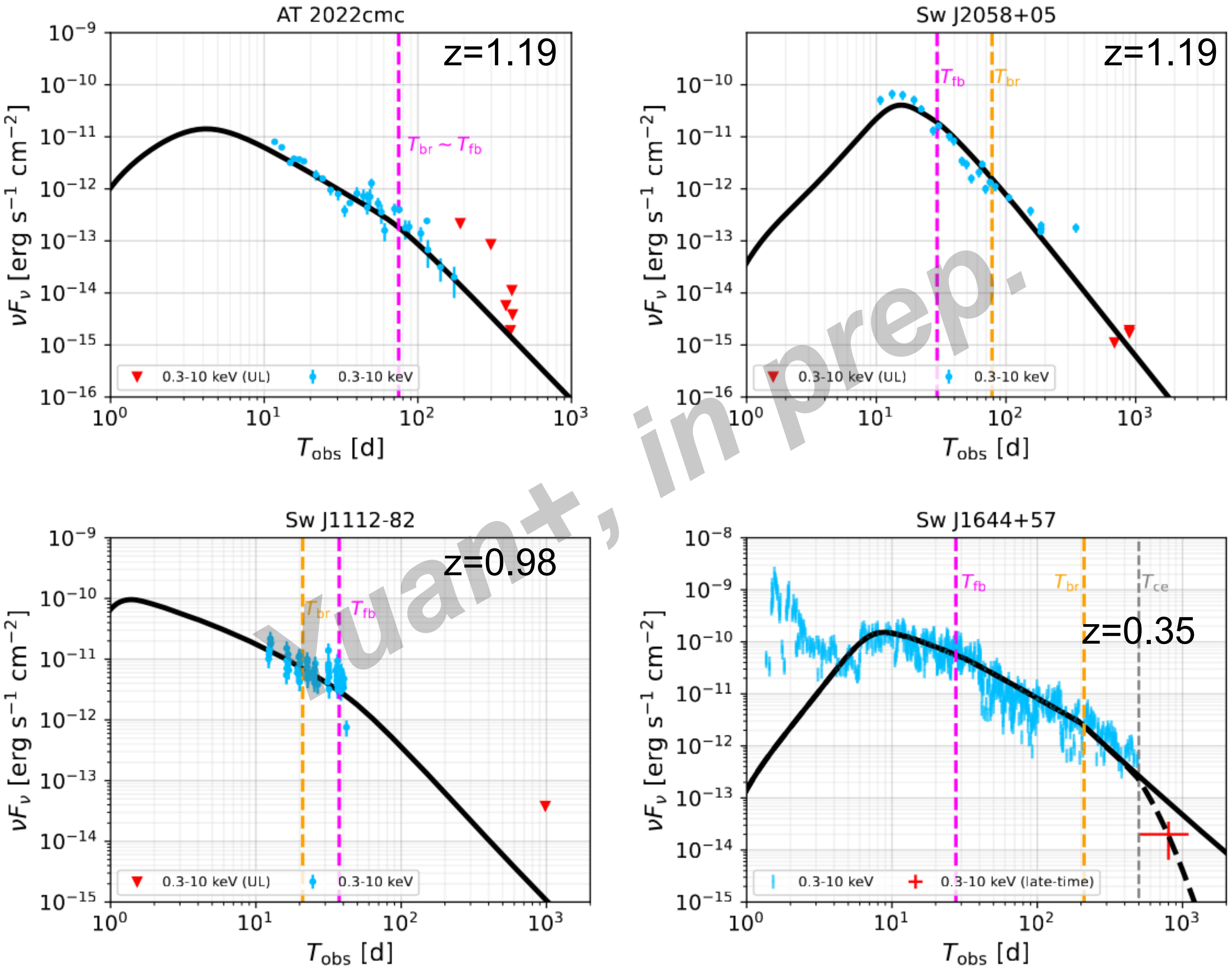


# Neutrinos from jetted TDEs




**4 TDEs/candidates with luminous jets and fast-decaying X-ray afterglows:**

- AT 2022cmc
- Sw 1112-82
- Sw1644+57
- Sw 2058+05

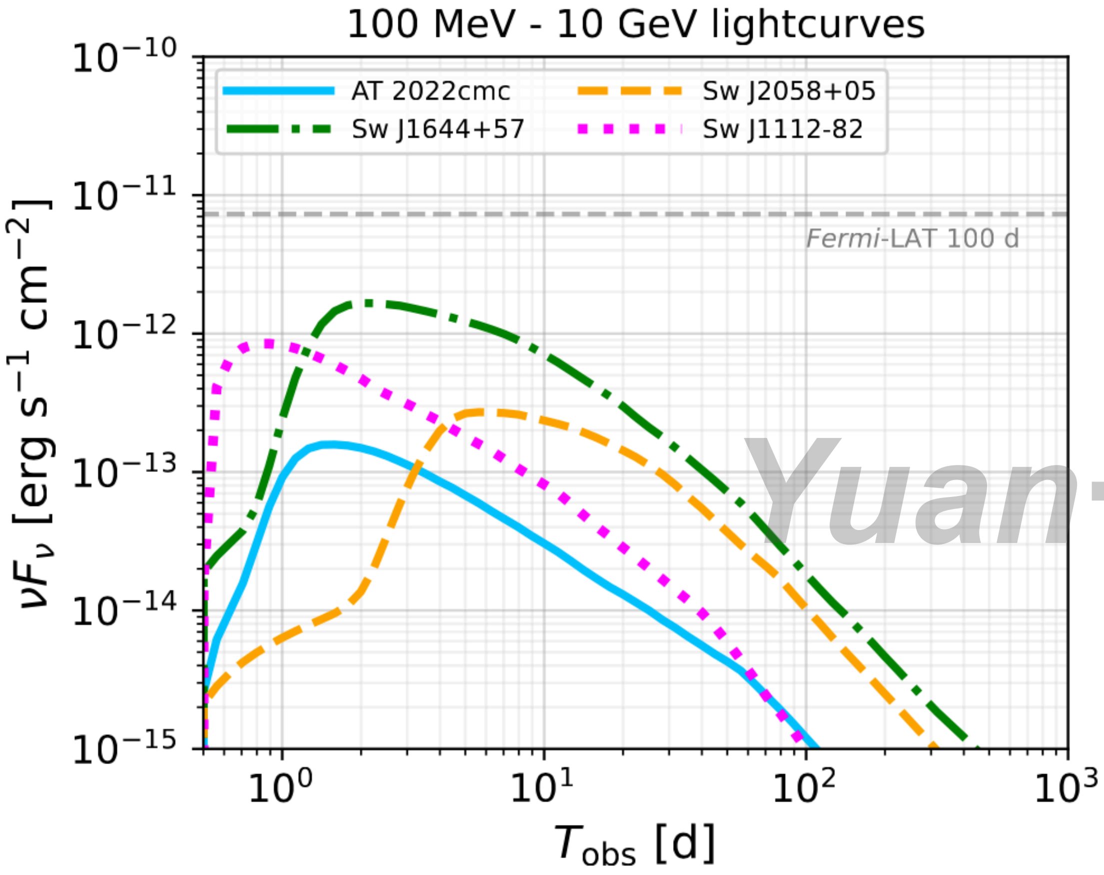
**Early-time X-ray afterglows of 4 jetted TDEs →jet reverse shock model**

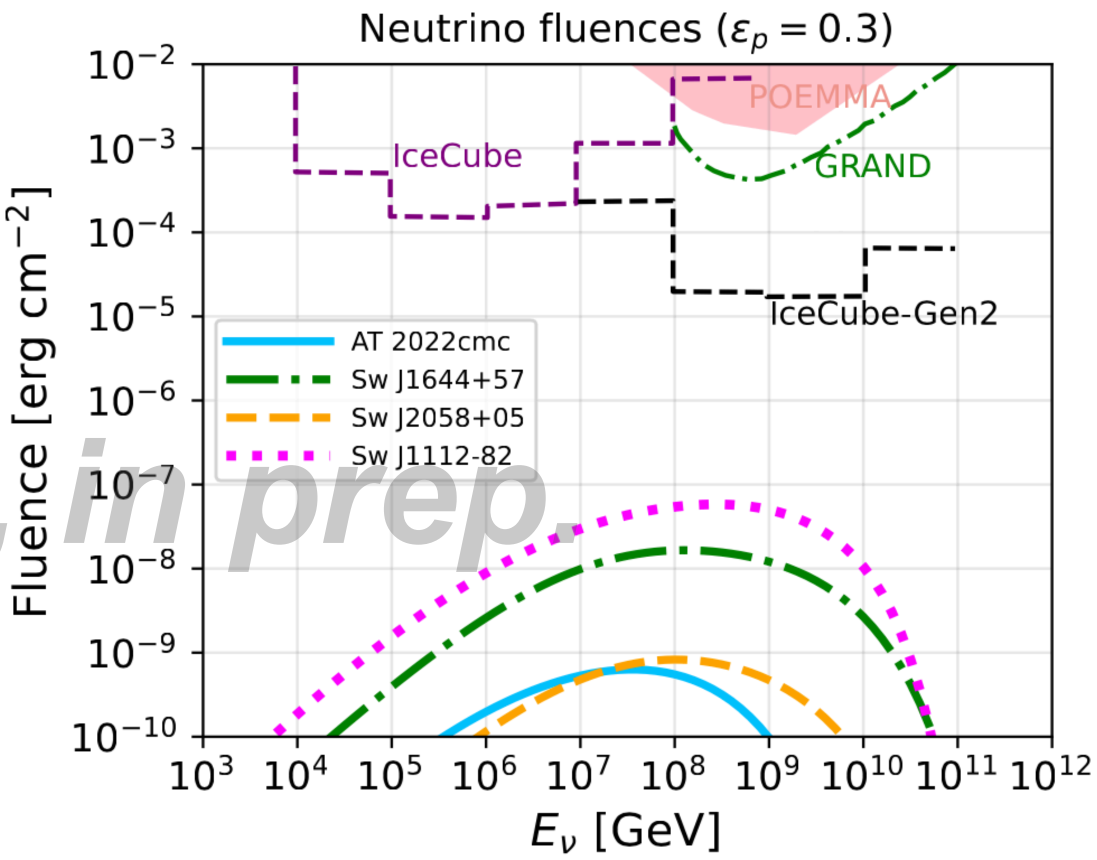
CY, Zhang, Winter & Murase, arXiv: 2406.11513 (ApJ in press)

# Neutrinos from jetted TDEs

**Gamma-ray and neutrino detectability**

- 4 jetted TDEs: lower than Fermi-LAT 100d; Detection horizon for AT2022cmc-like TDEs: $z$ = 0.17, rate ~ 0.02-0.1 per year
- Neutrino fluence from jetted TDEs: two orders lower than IceCube-Gen2 sensitivity←low target photon density for $p\gamma$



# Summary

- 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/$\gamma$-ray emissions. The model can be tested/constrained by future observations or current upper limits.
- ~10-100 days time delay is caused by $p\gamma$ timescale and delayed IR photons.
- To be an efficient neutrino emitter, the accompanying cascade emission would exceed the X-ray/$\gamma$-ray constraints. Fermi upper limits implies $\lesssim$ 0.1 neutrinos per TDE! (Obscured zone? Expanding Wind?)

*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.*

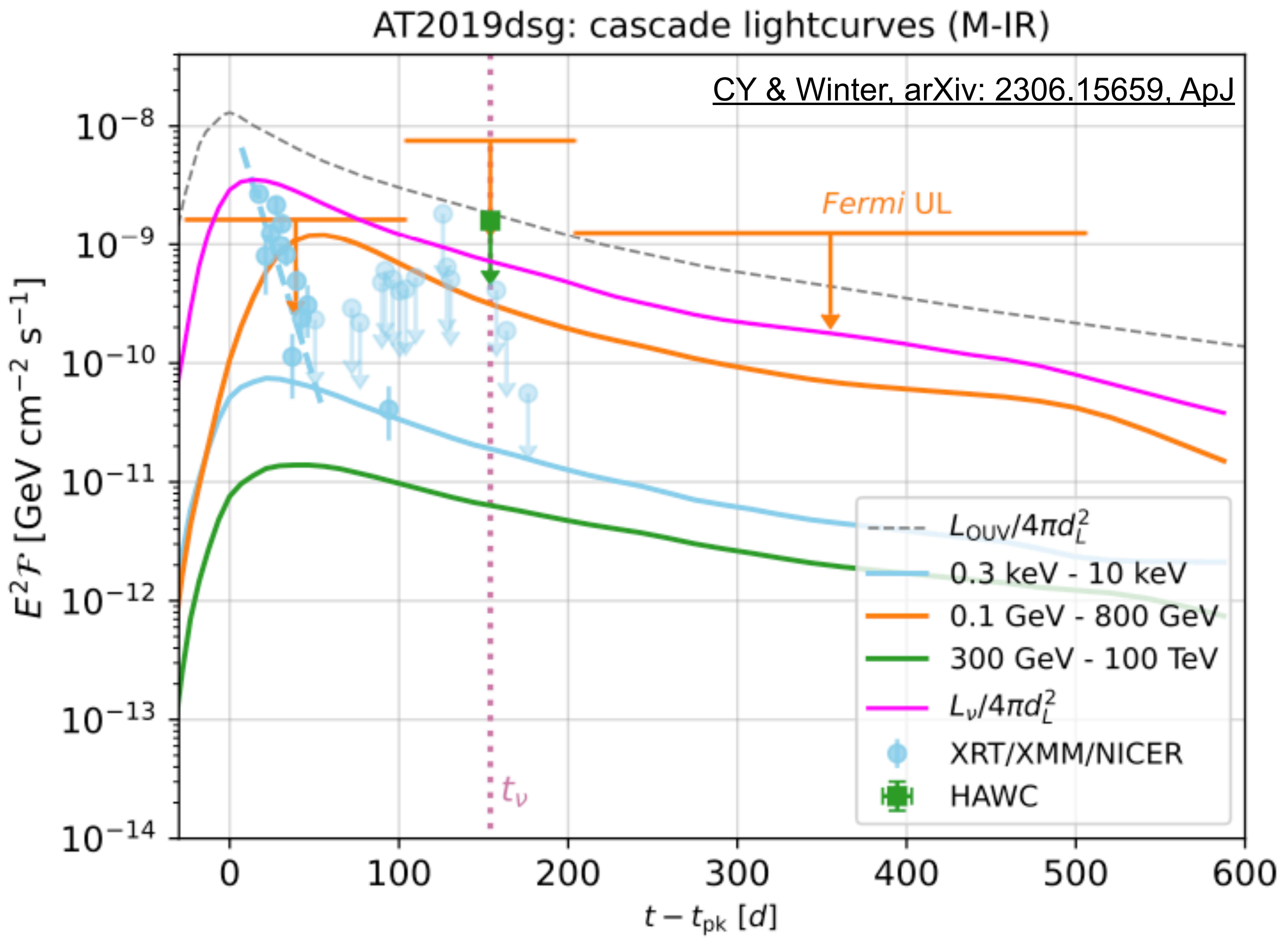
- For extended TDE jets, $p\gamma$ is not efficient unless external photons are introduced.

**Thanks for your attention!**

# Backup Slides

# AT2019dsg Temporal signatures

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




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

- Cannot be explained by our model
- Accretion disk cooling?

**Fermi-LAT up limits**

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

**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

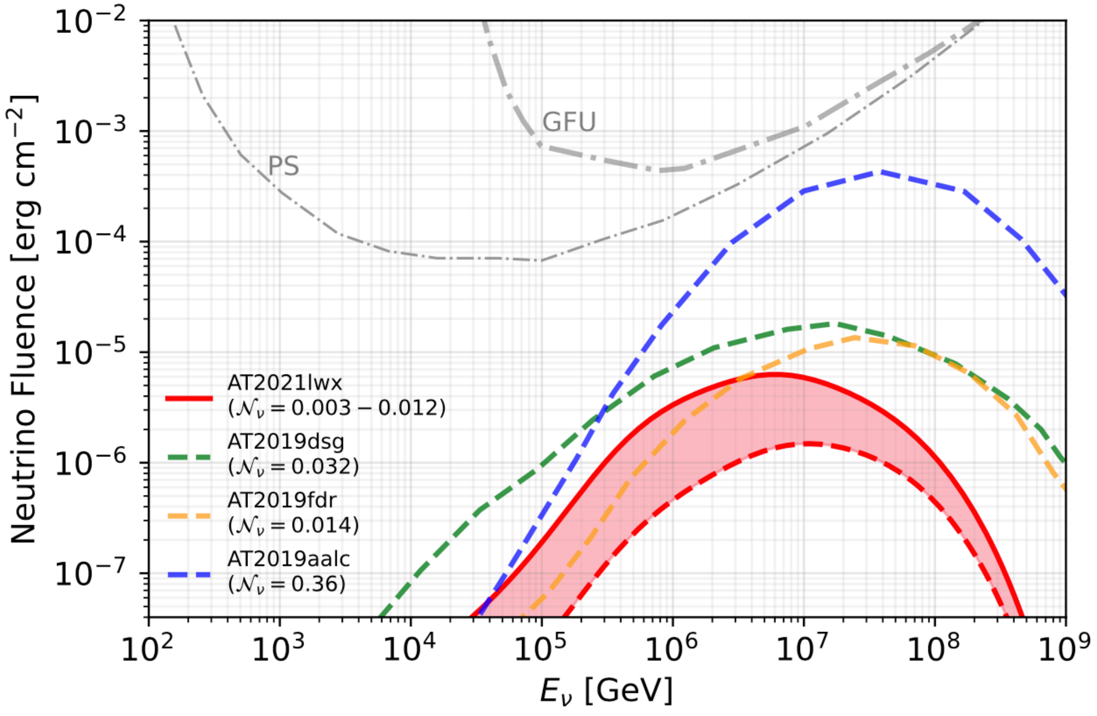
~50 days time delay is compatible with $p\gamma$ interaction time $t_{p\gamma} \sim 10 - 100$ d

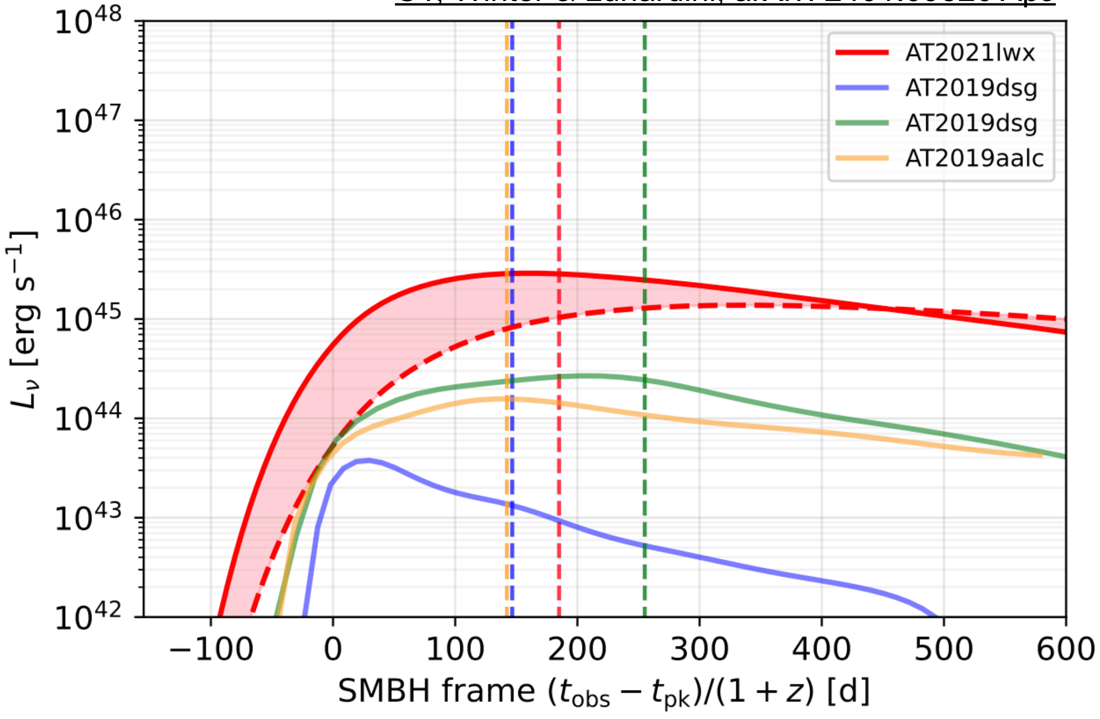
# AT2021lwx: neutrinos (wind-IR model)

- **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] | $\Delta T$ | 180 (330) |
| Radius [cm] | $R_{\rm IR}$ | $5.4 \times 10^{17}$ $(10^{18})$ |
| Max proton energy [GeV] | $E_{p,\rm max}$ | $1.5 \times 10^{9}$ |
| Magnetic field [G] | $B$ | 0.1 |

CY, Winter & Lunardini, arXiv: 2401.09320 ApJ



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

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

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

- An ***Open-Source*** Tool for ***Time-Dependent*** Lepto-Hadronic Modeling of Astrophysical Sources
- Blazars, GRBs, TDEs, etc

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

**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**

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

**Protons**

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

**Core Developers:**

- Marc Klinger (DESY),
- Annika Rudolph (NBI, DESY),
- Xavier Rodrigues (RUB, DESY),
- Chengchao Yuan (DESY),
- Gaetan Clairfontaine (U. Würzburg)
- Shan Gao (DESY),

**Code is now public!**

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Injection — Cooling — Escape/Advection

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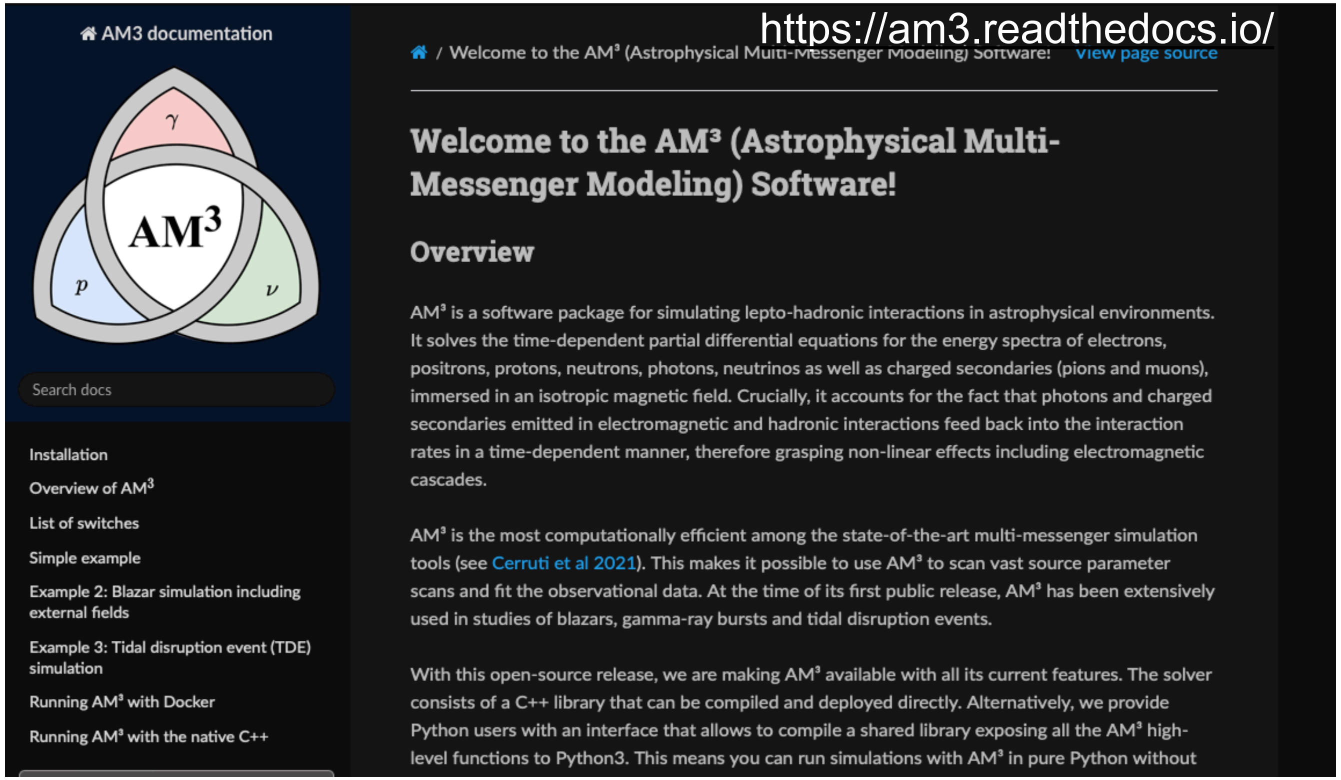
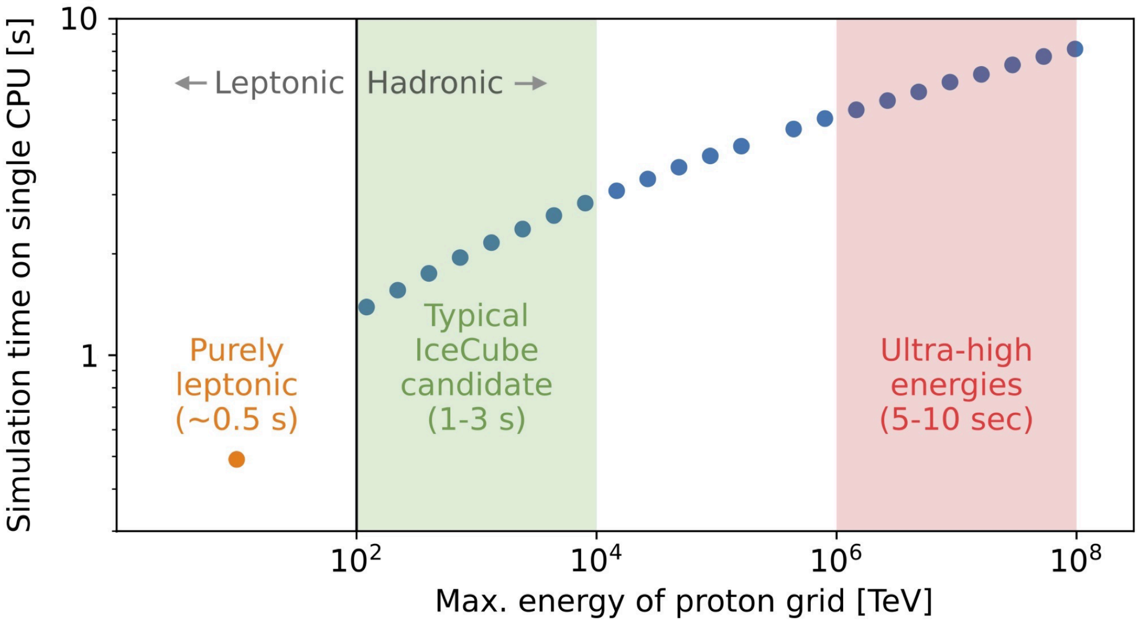
https://am3.readthedocs.io/




***Performance: C++ source code, python interface***

- Simulation: kernel initialization, particle injection, ~30 steps to steady state
- Tested on a single CPU on Apple M2 chip
- Very fast for lepto-hadronic simulations (< 0.5 s/step)



# UHECRs

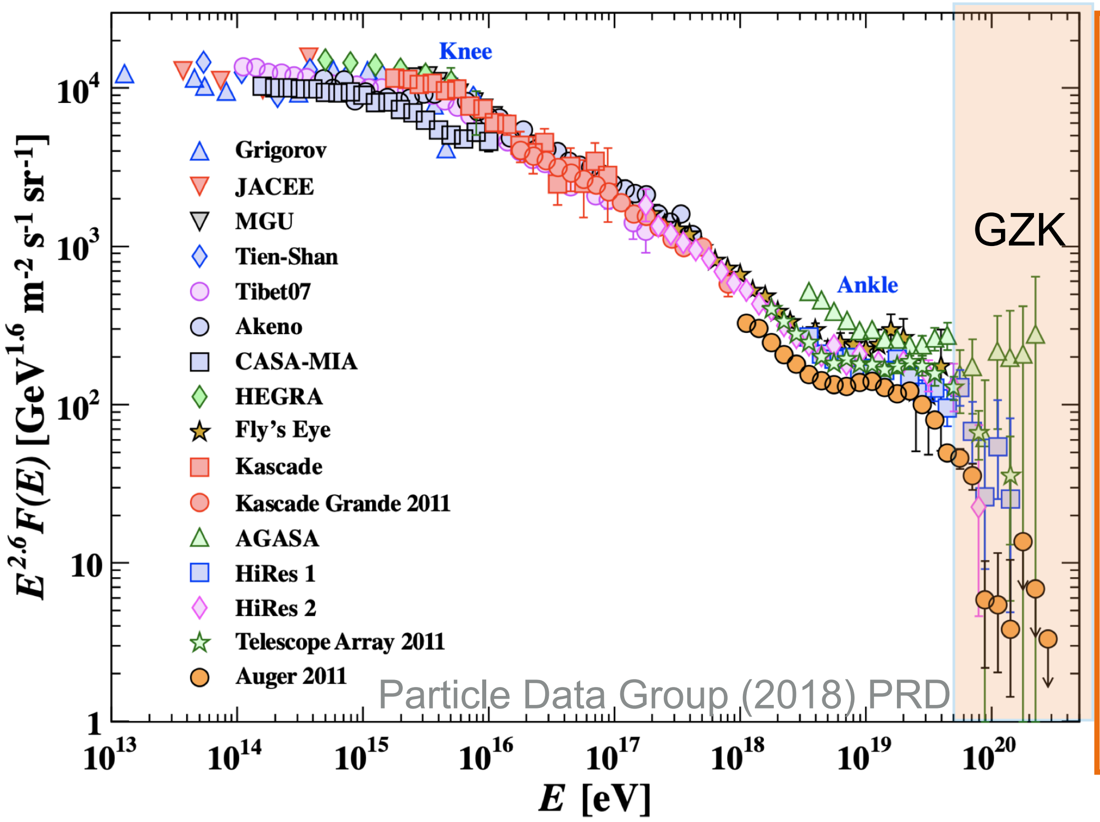
**Energetic particle in the Universe:**

- Firstly discovered by V.F. Hess (1912), Nobel Prize in 1936
- Composition: p (90%), He (8%), heavy nuclei; energy dependent
- Energy measured up to $10^{19-20}$ eV (10-100 EeV)
- Origins unknown

**Hillas condition on UHECR energies:**

$$E_{\rm cr,max} \leq (10^{10}\ \mathrm{GeV})\ Z \left(\frac{B}{0.1\mathrm{G}}\right)\left(\frac{R}{0.1\mathrm{pc}}\right)$$

TDE wind (0.1-1 G, 0.01-0.1 pc) can accelerate CRs to UHECR “ankle”



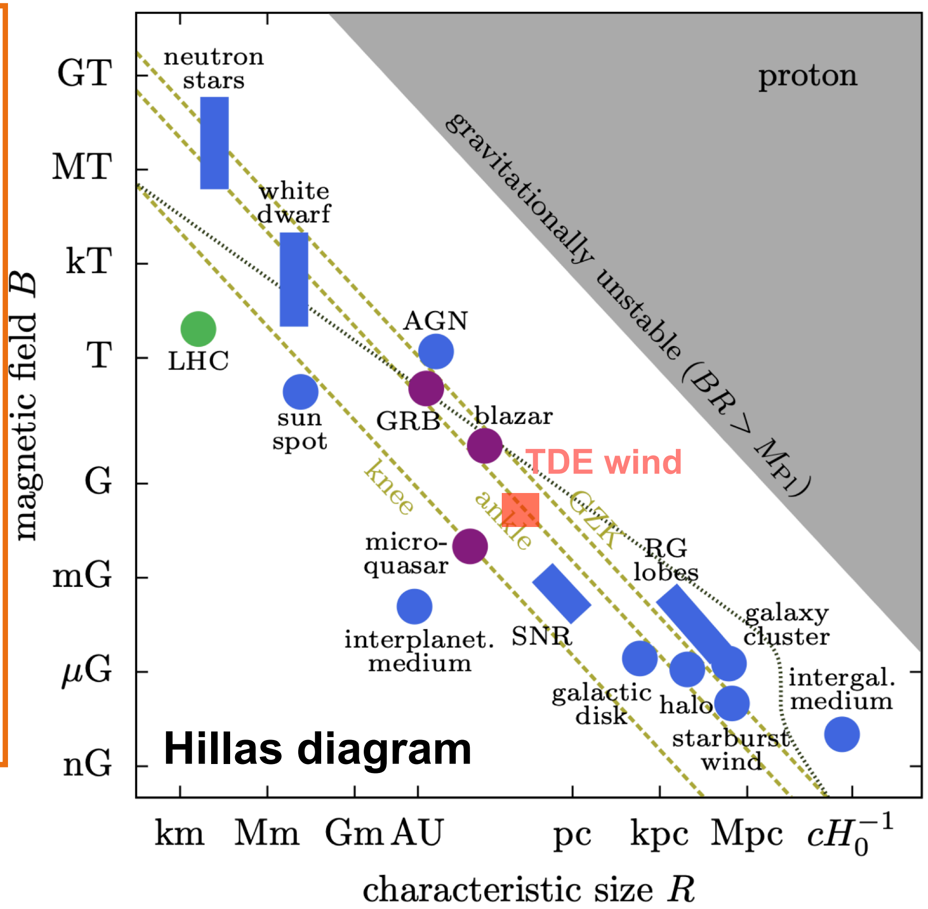

**Greisen-Zatsepin-Kuzmin (GZK) cutoff:**

**CR + CMB (2.7K)**

$$p + \gamma_{\rm CMB} \rightarrow \Delta^+ \rightarrow p + \pi^0$$

$$^A_ZN + \gamma_{\rm CMB} \rightarrow {}^{A-1}_{Z-1}N' + p$$

- MFP for 50 EeV protons/heavier nuclei: 50-100 Mpc
- Cutoff above 50 EeV
- Cosmogenic $\nu$



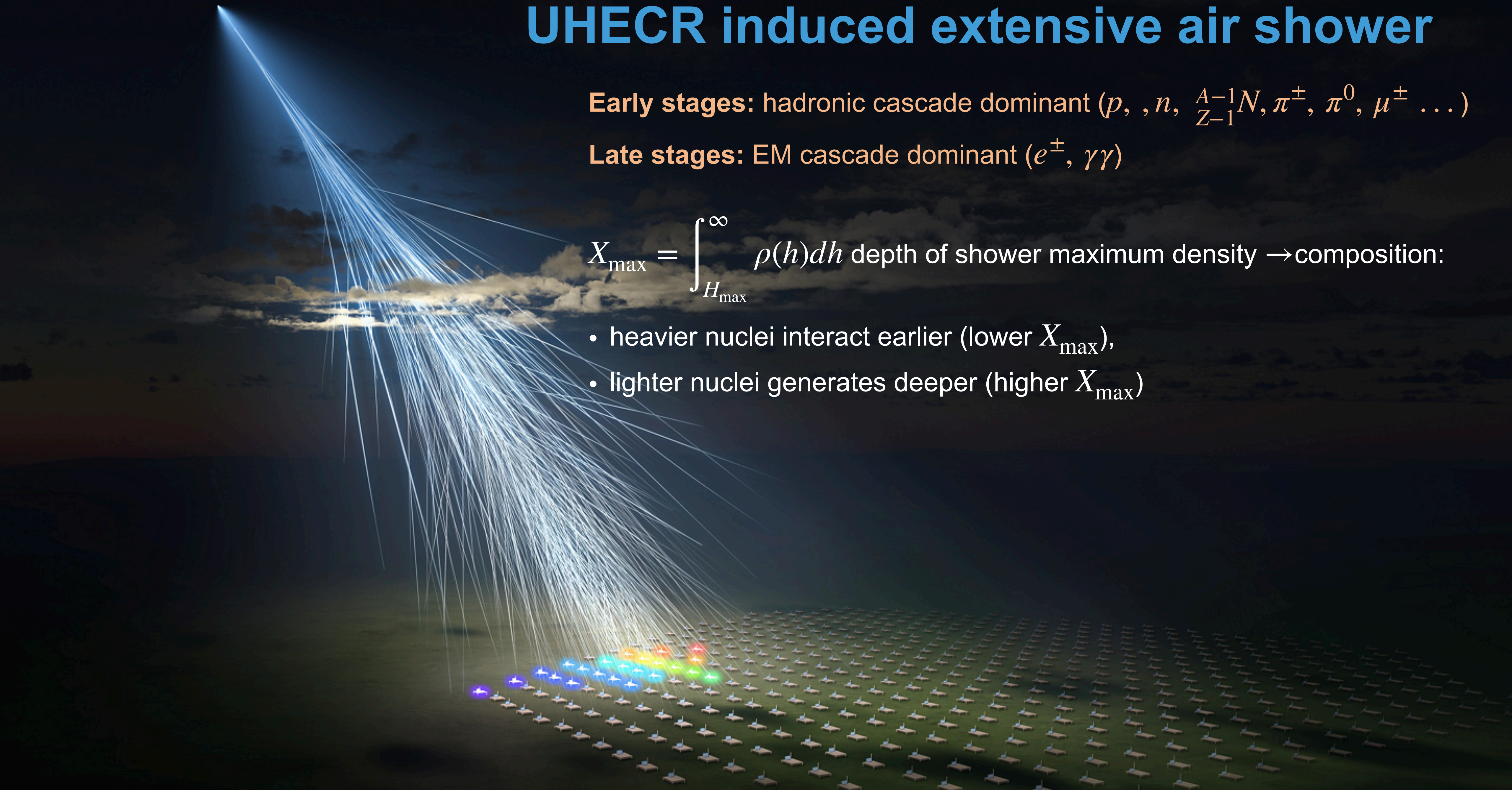
# UHECR induced extensive air shower

**Early stages:** hadronic cascade dominant $(p, \ , n, \ {}^{A-1}_{Z-1}N, \pi^{\pm}, \ \pi^{0}, \ \mu^{\pm} \ \ldots)$

**Late stages:** EM cascade dominant $(e^{\pm}, \ \gamma\gamma)$

$X_{\max} = \int_{H_{\max}}^{\infty} \rho(h) dh$ depth of shower maximum density →composition:

- heavier nuclei interact earlier (lower $X_{\max}$),
- lighter nuclei generates deeper (higher $X_{\max}$)



Credit: Osaka Metropolitan University/L-Insight, Kyoto University

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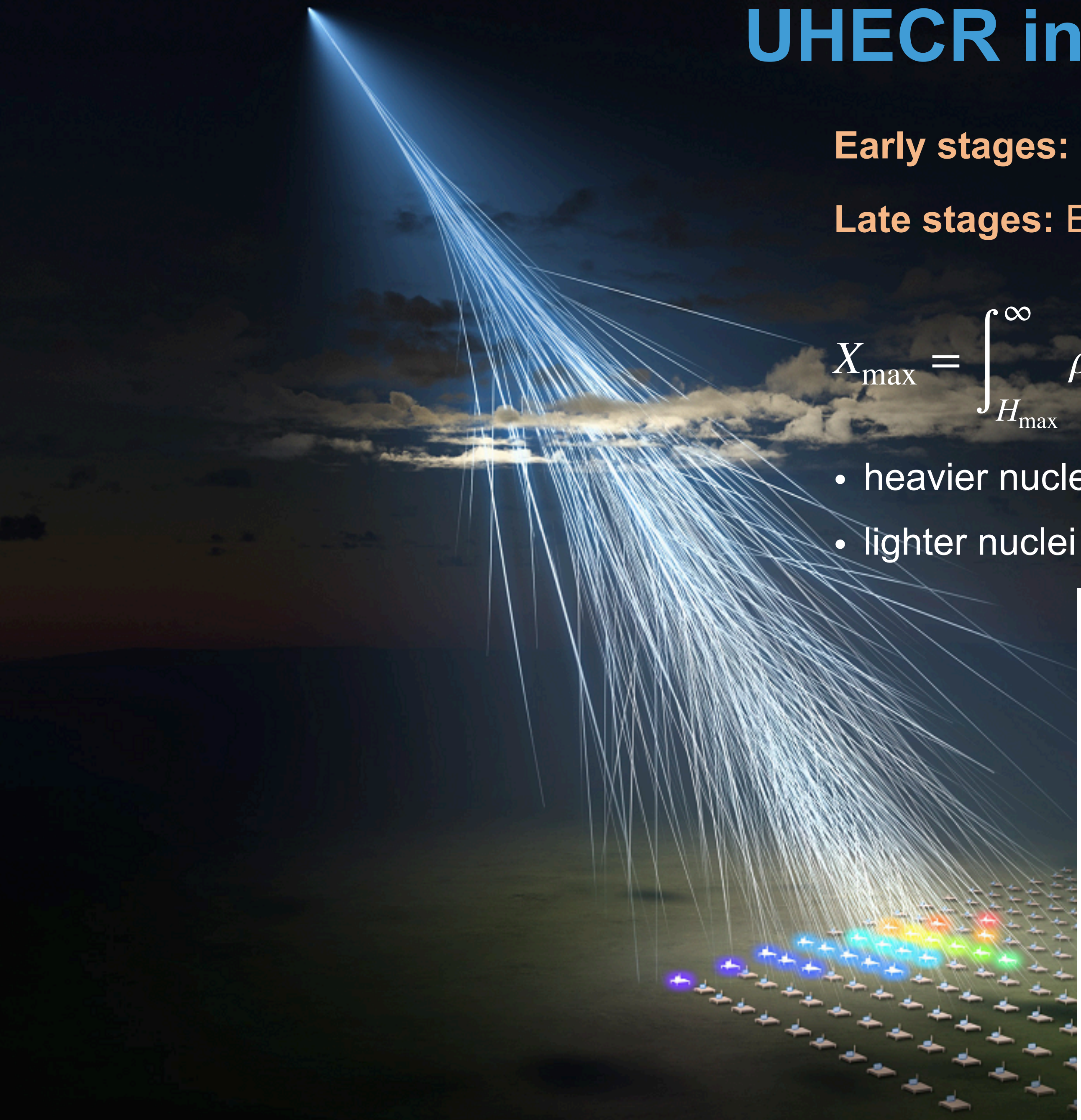

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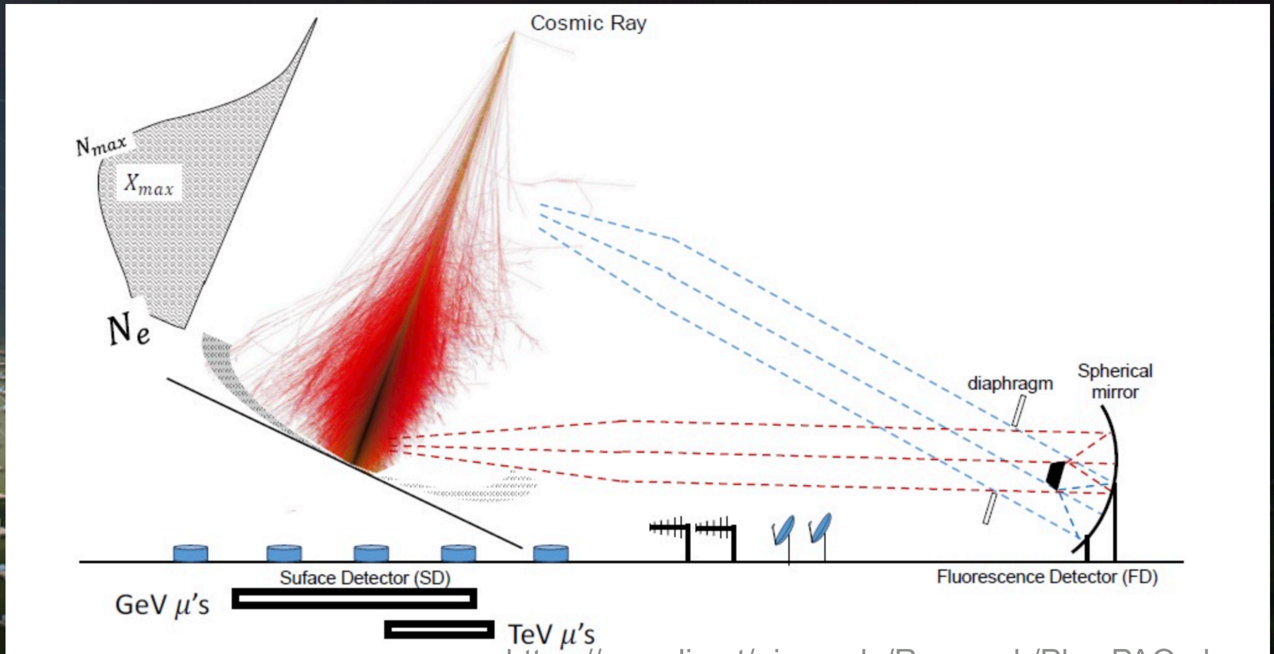



Credit: Osaka Metropolitan University/L-Insight, Kyoto University

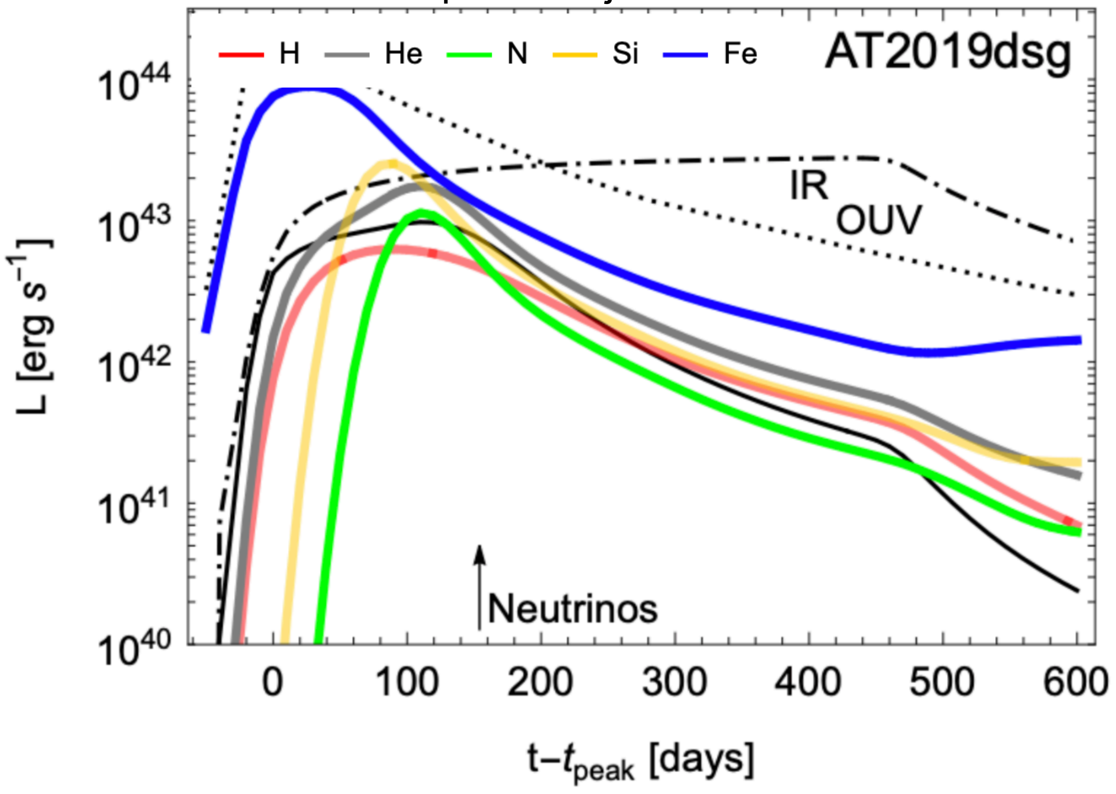
https://www.lip.pt/~jespada/Research/PhysPAO.php

# UHECRs from TDEs

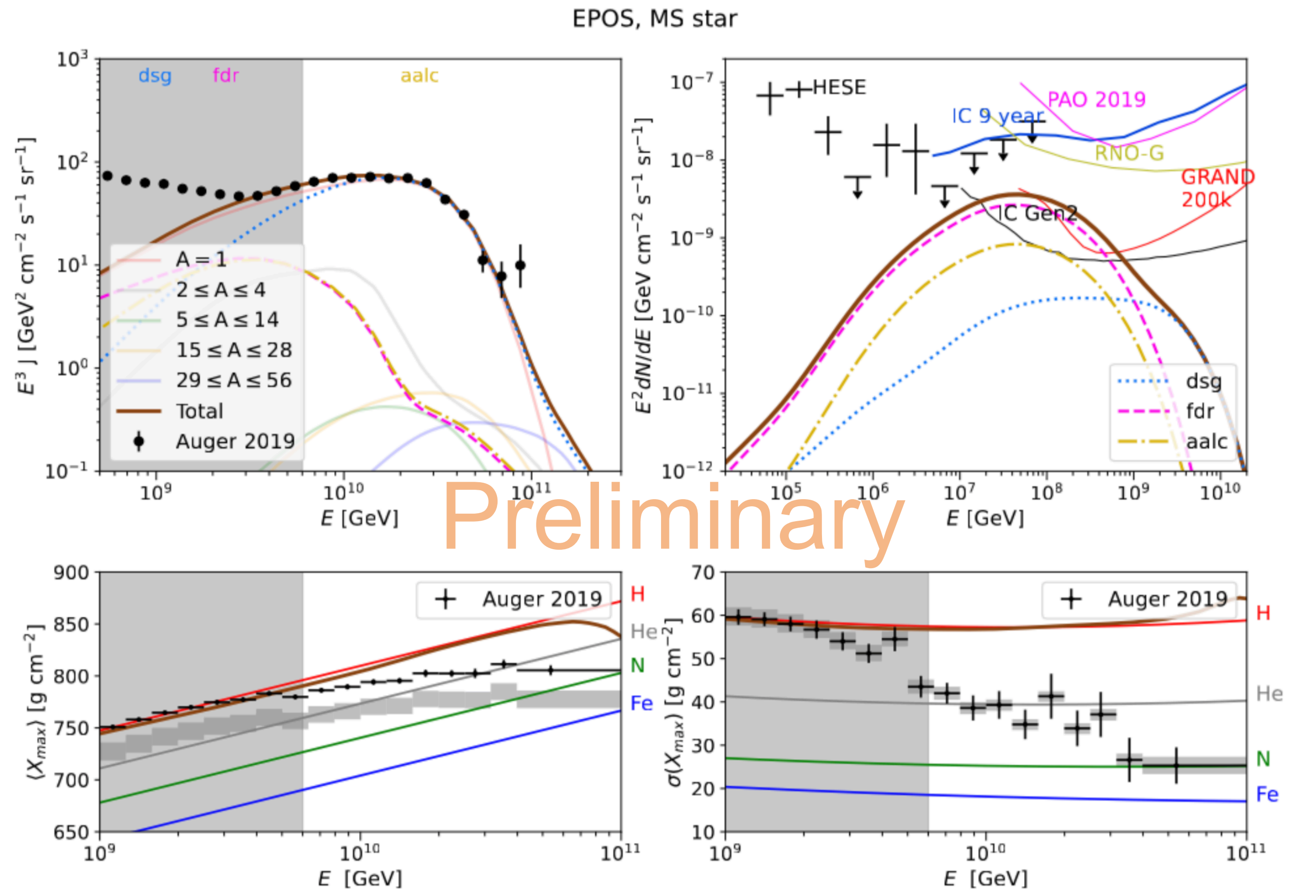
**Disrupted stars: main sequence (MS), red giant (RG), white dwarf (WD)**

- Parameters: local rate, redshift distribution constructed from AT2019dsg/fdr/aalc;
- To be fitted: spectra + composition + IceCube diffuse $\nu$ (TDE + Cosmogenic)
- Fiducial case: composition of accelerated elements = composition of disrupted stars (disfavored!!)

Insource CR spectra: injection + nuclear cascade




EPOS, MS star




*Plotko, Winter, Lunardini, CY, in prep.*

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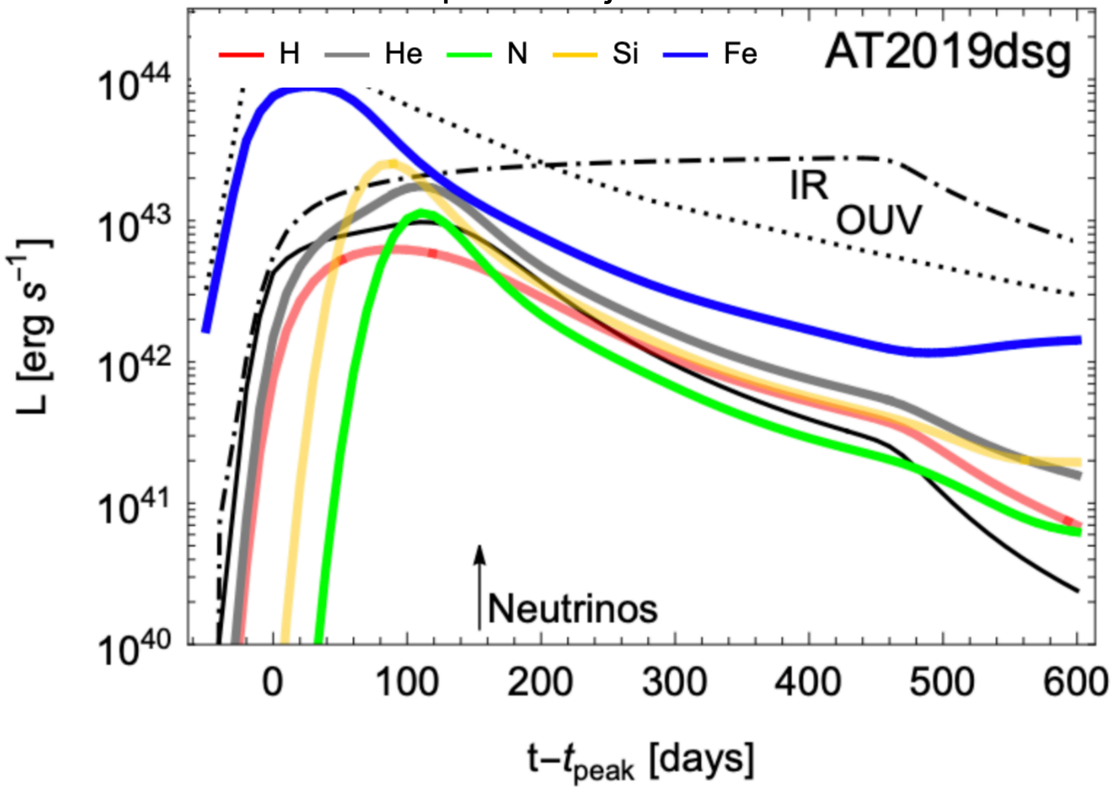


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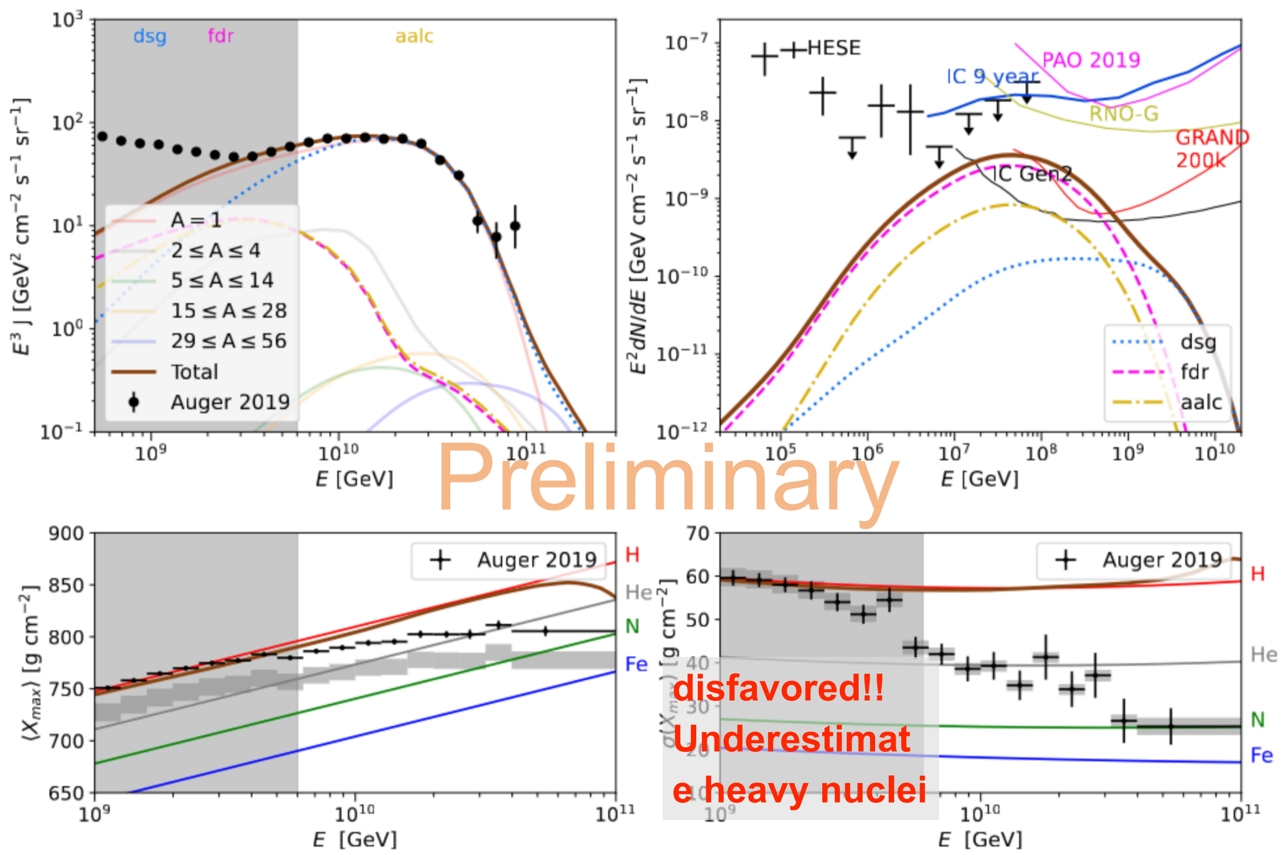


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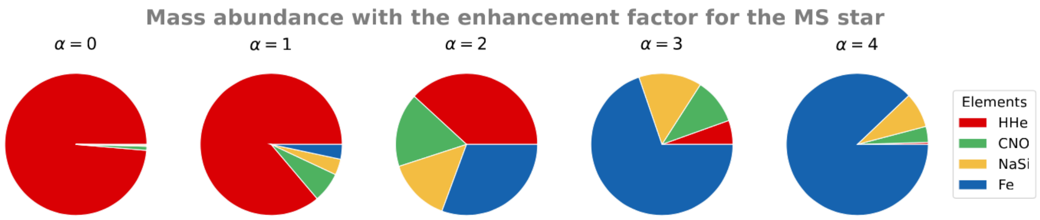
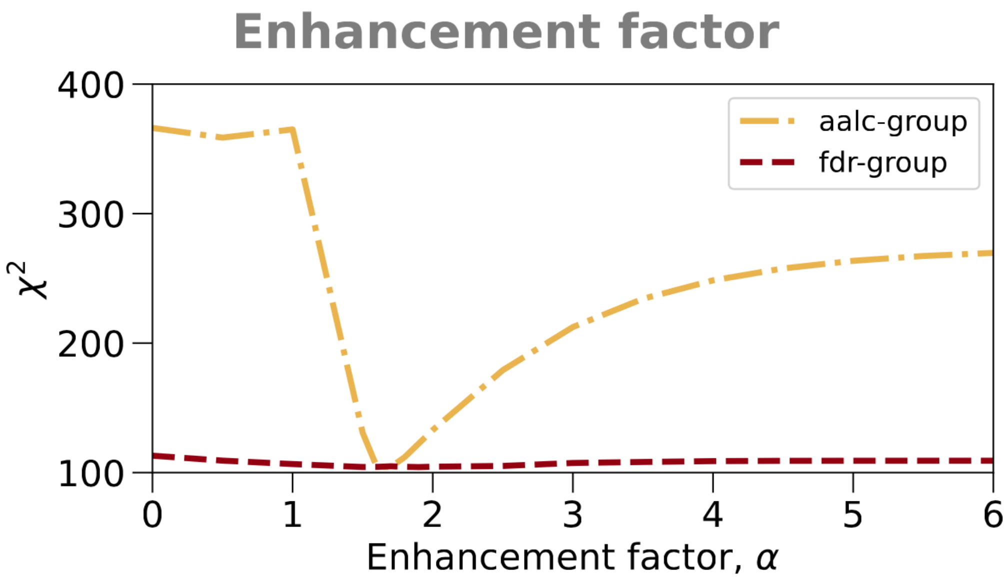
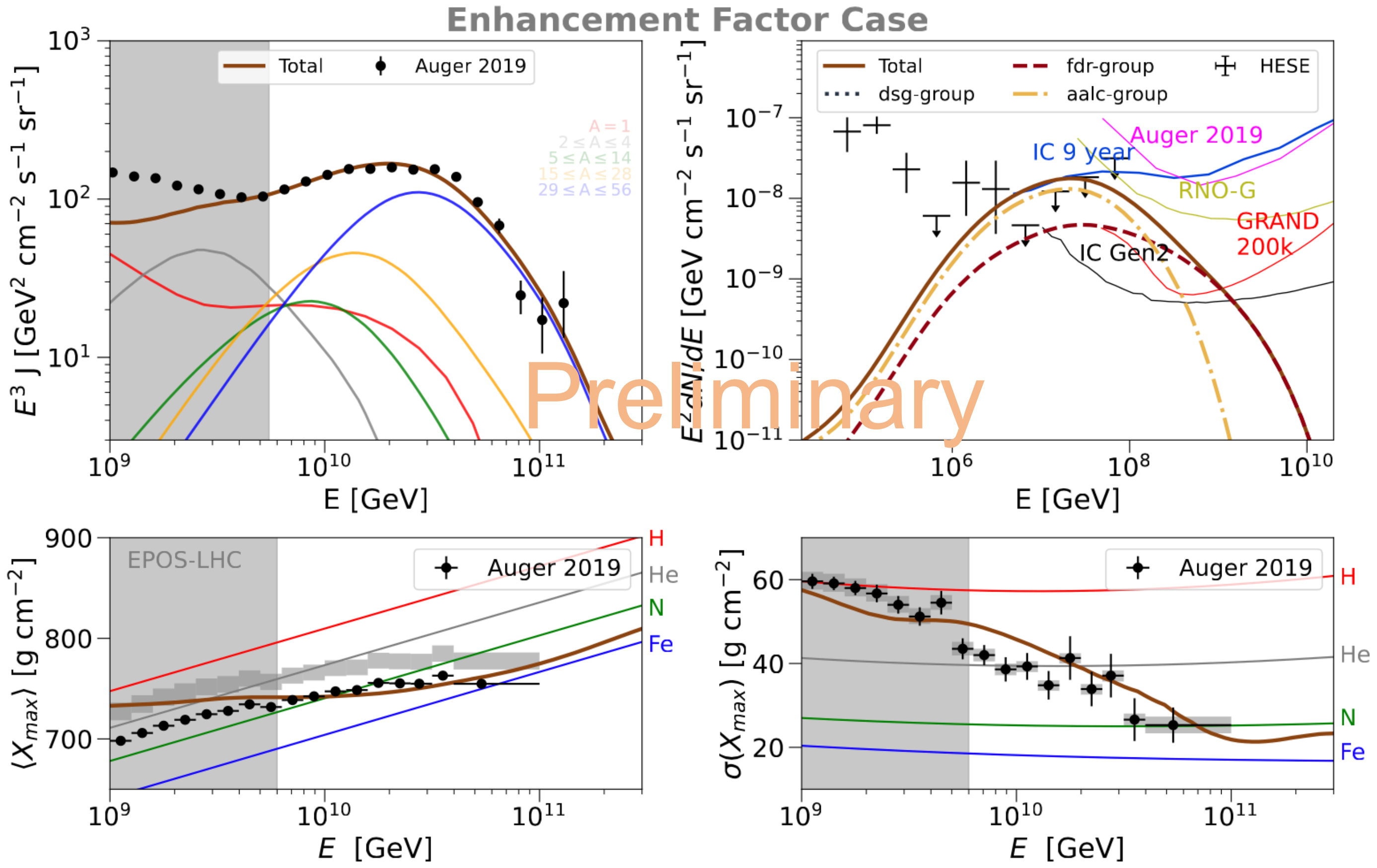
# UHECRs from TDEs

- $Z$-dependent acceleration fraction $f_X \propto (A_X/Z_X^{\mathrm{ion}})^{\alpha}$ : heavier nuclei can be more efficiently accelerated (Caprioli+17, Hanusch+ 19)
- $\alpha = 1.6$ is favored statistically, consistent with simulations ($\alpha \sim 1-2$)
- **Boosted acceleration for heavy nuclei is needed! Local rate $\rho_0 \sim \mathcal{O}(100)\ \mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$ for main sequence stars.**

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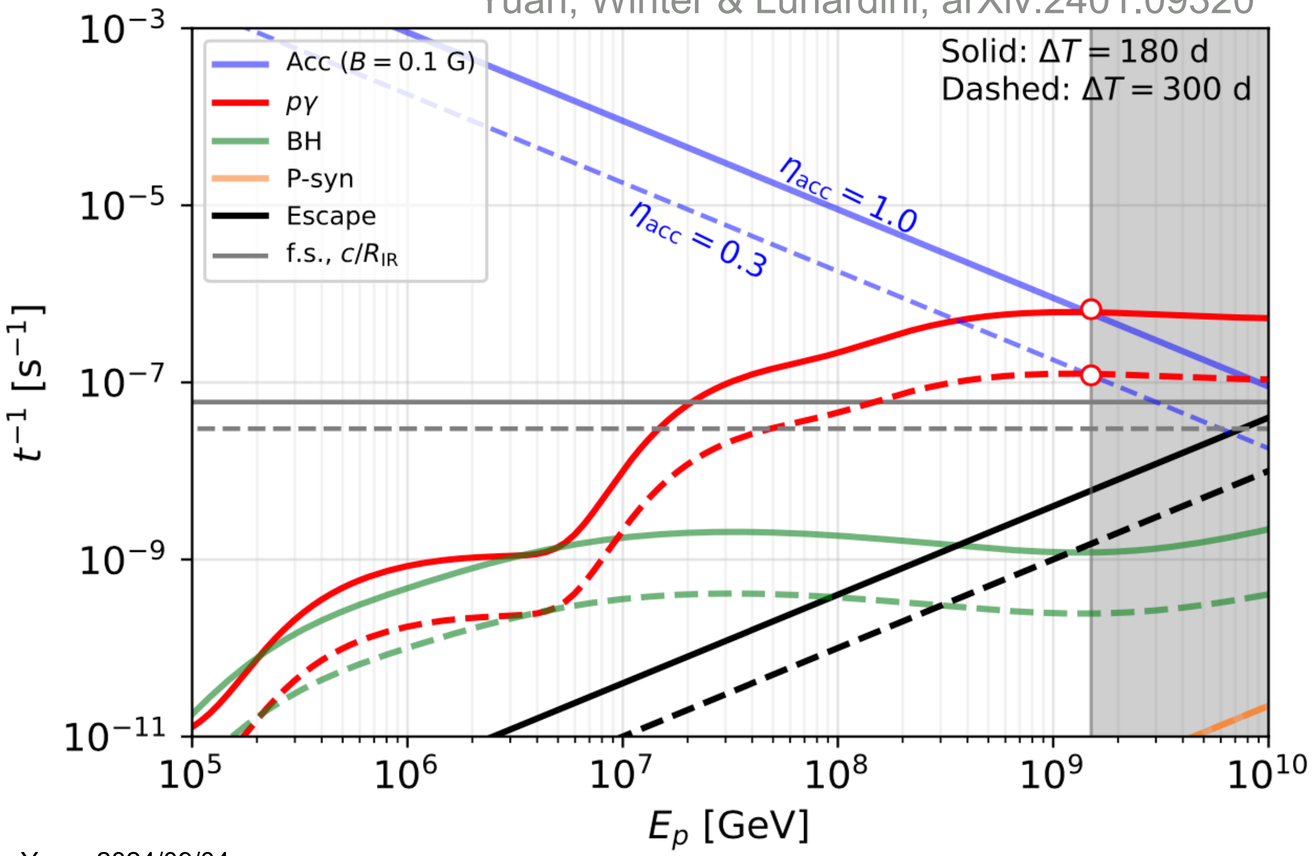
# Proton maximum energy

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

Larger $\eta_{\mathrm{acc}}$ -> 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

Yuan, Winter & Lunardini, arXiv:2401.09320



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

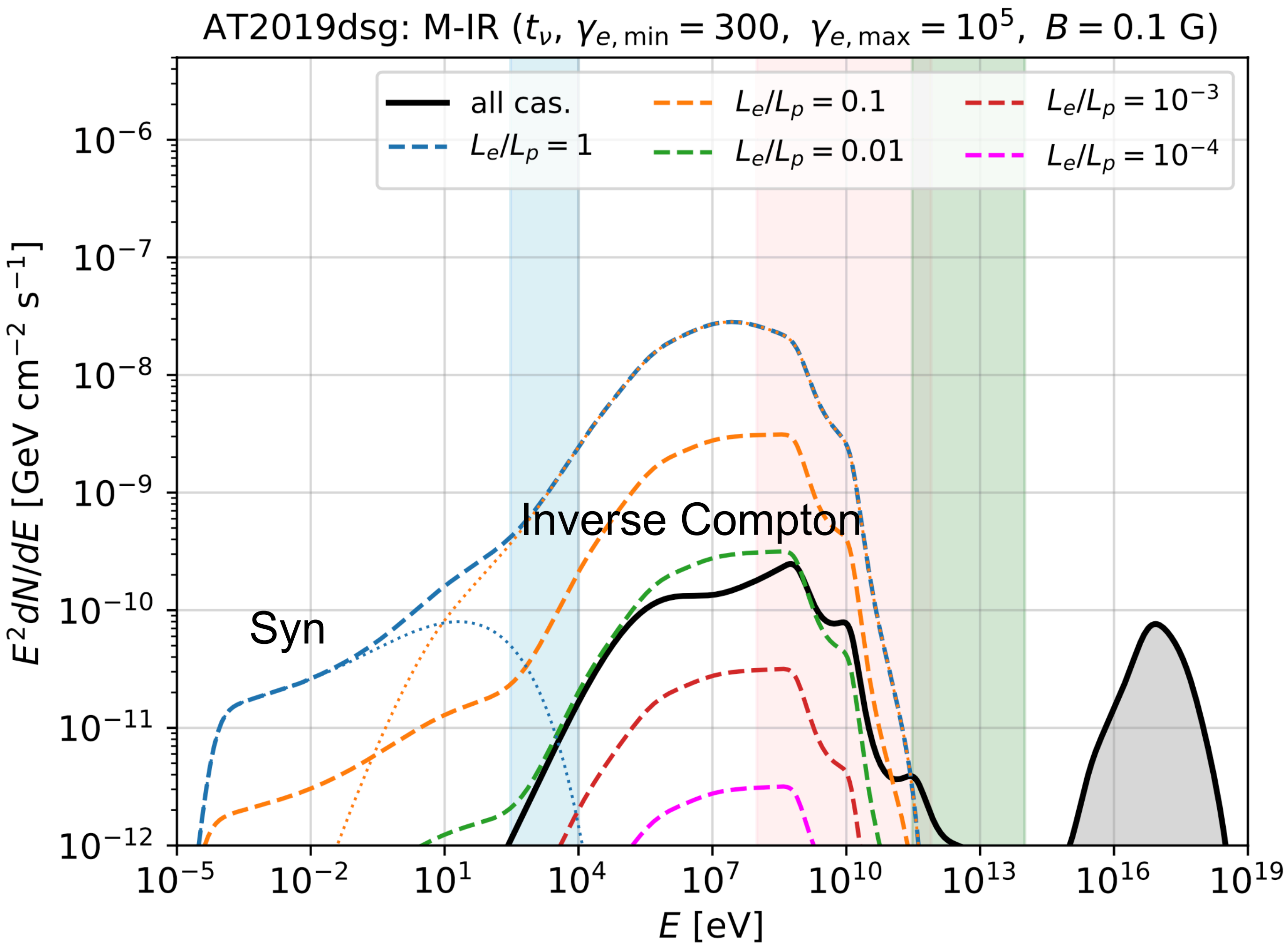
**Electron injection spectra**

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

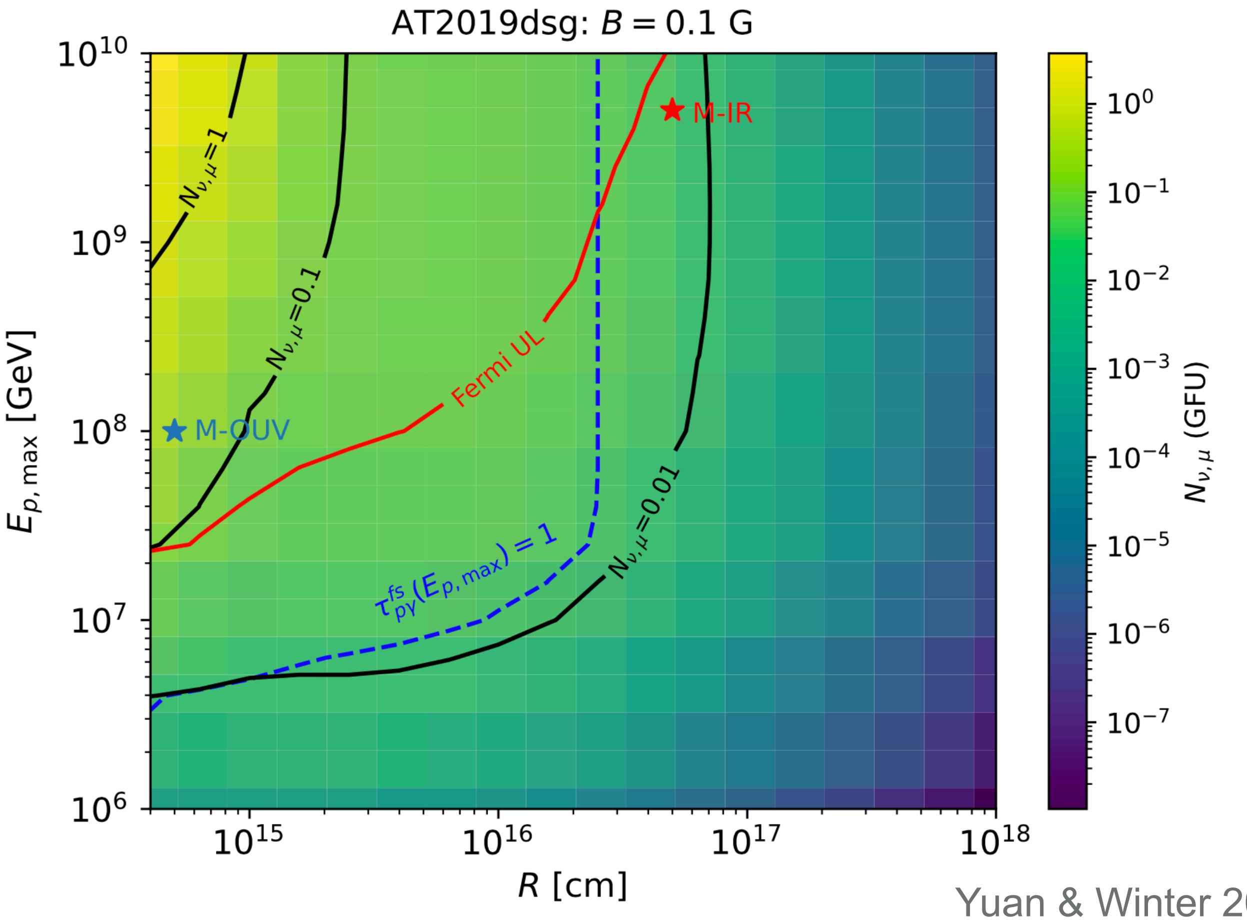
***(Supported by the absence of radio signals accompanying OUV/IR)***

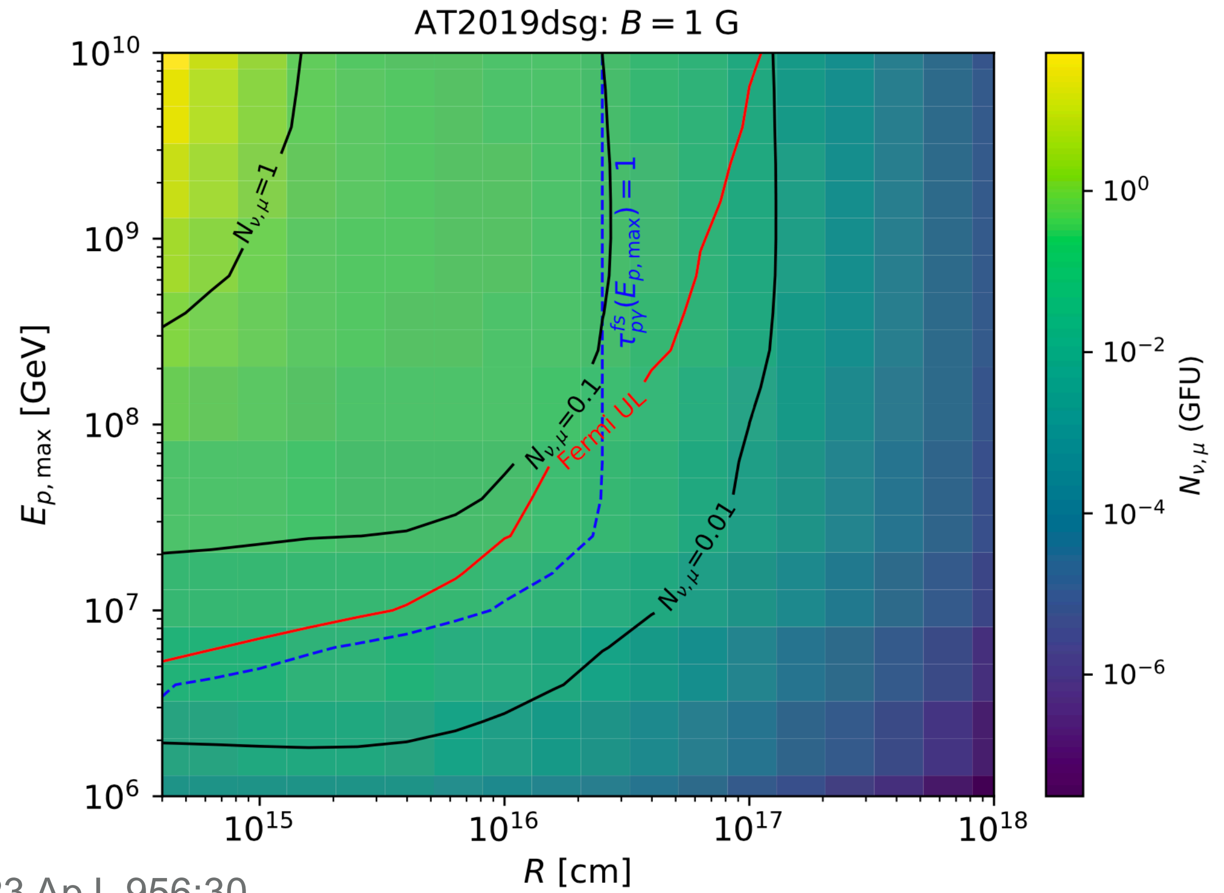
**Caveat**: leptonic contribution depends on electron minimum energy and magnetic field strengths



# 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 $\gamma$-ray up limits)
- Conclusions do not change significantly




Yuan & Winter 2023 ApJ 956:30