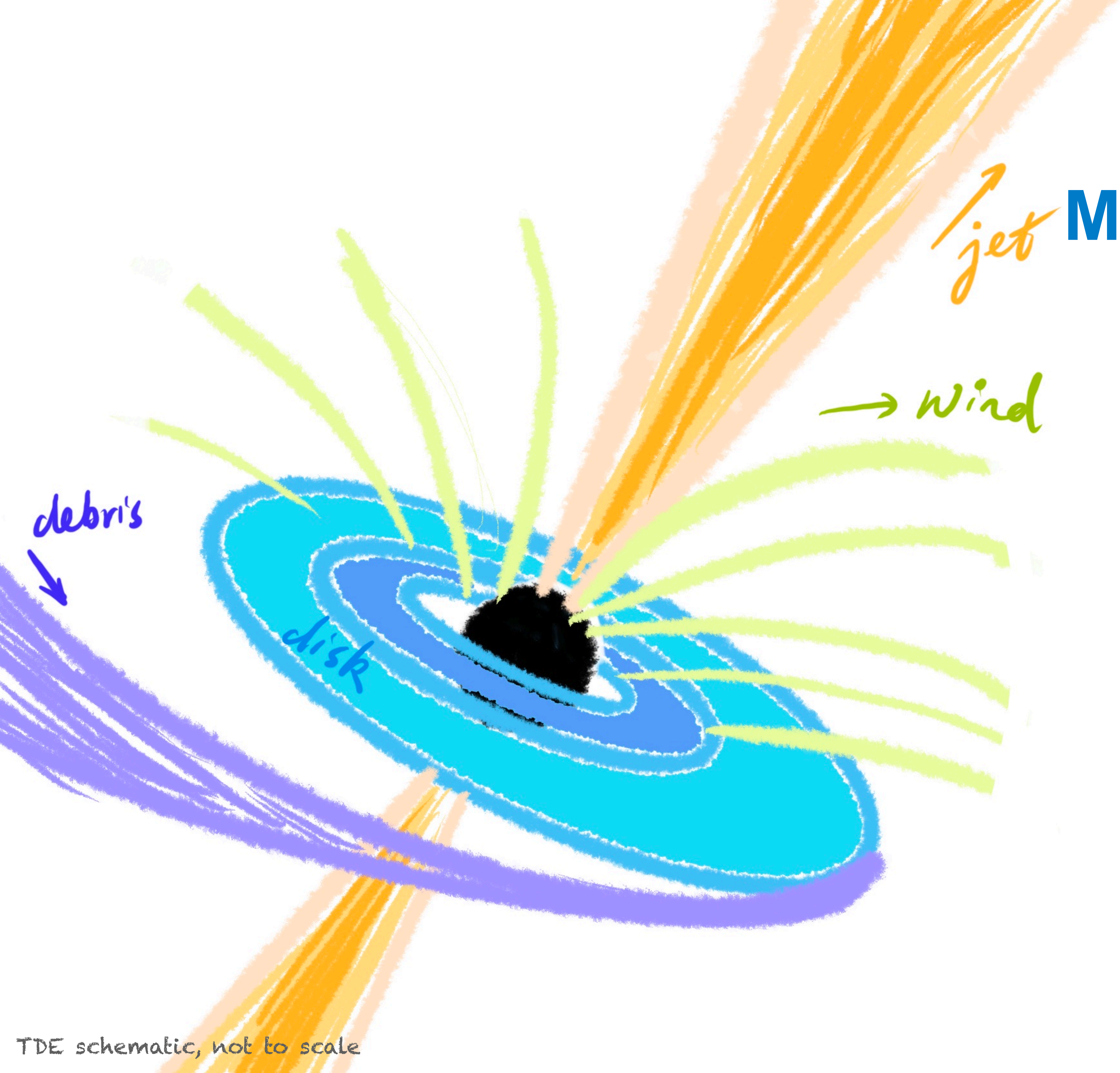


TDE schematic, not to scale

Modeling radio and X-ray afterglows of jetted tidal disruption events

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

Hamburg “Matter and the Universe” Days
2024/12/12, Hamburg

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 -> relativistic jet -> months/year-long flare (optical transient)

- Energy to be reprocessed by accretion ~ 10^{54} erg

  TDE

  Fallback rate $\propto t^{-5/3}$ (Phinney 1989)

  Thermal black body (bb) emissions in optical/UV (OUV) bands

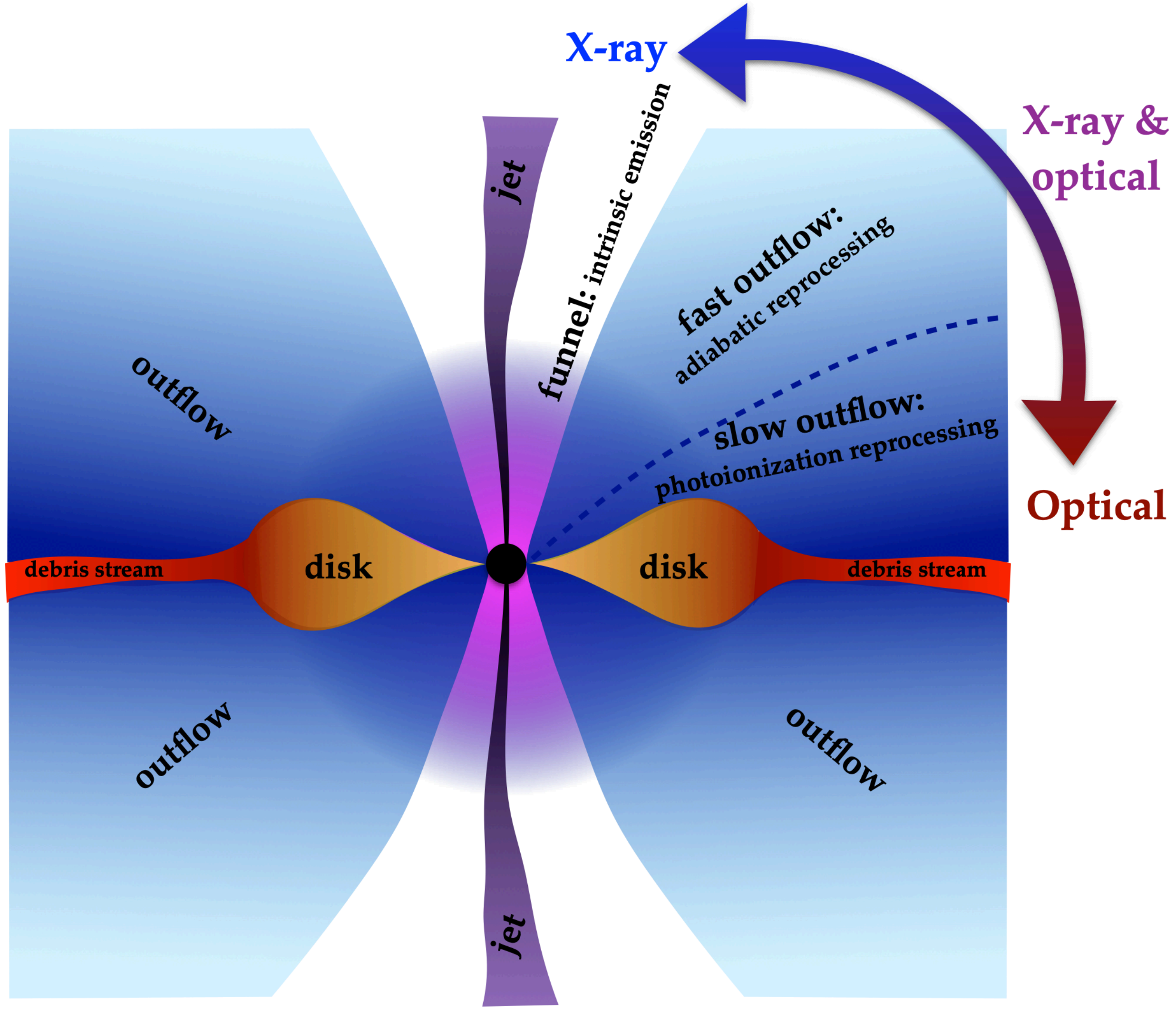
  Some (~1/4) TDEs are observed in (thermal) X-ray and infrared (IR)

https://www.desy.de/e409/e116959/e119238/media/9170/TDE_DESY_SciComLab_sound_080p.mp4

TDE models

- **Radio, 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, corona…
- **4 TDEs/candidates with luminous X-ray jets among hundreds of TDEs**
    1. AT 2022cmc
    2. Sw 1112-82
    3. Sw1644+57
    4. Sw 2058+05

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

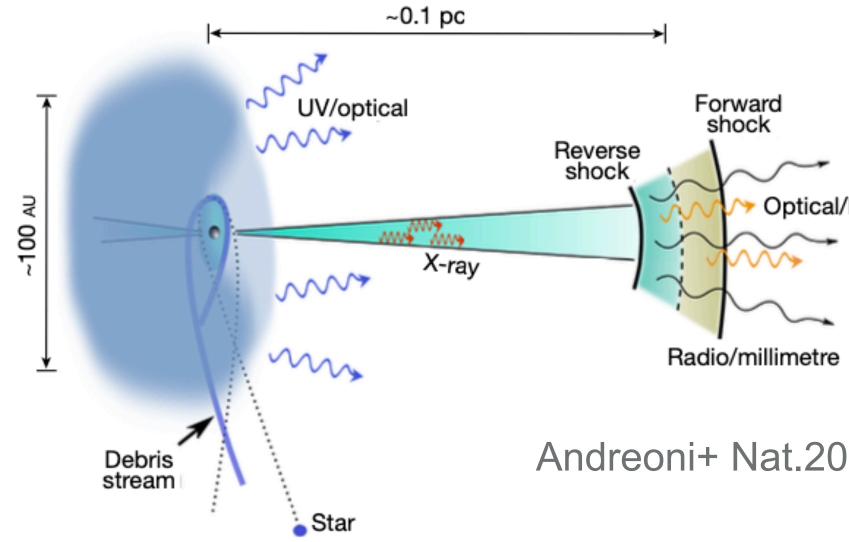


Dai+ 2018

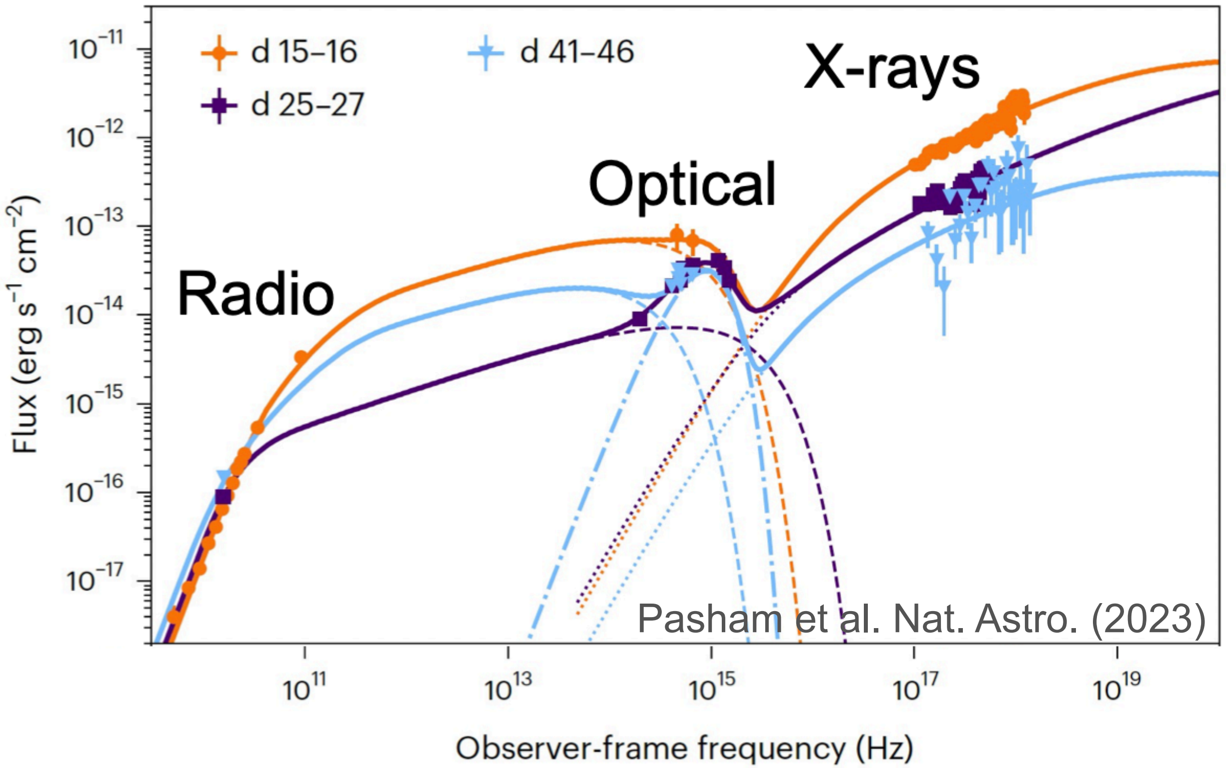
Jetted TDE: AT 2022cmc

- Recently documented jetted TDE (z = 1.193, Andreoni+ Nat.2022)
- ***Bright non-thermal X-rays:*** $L_{X,\mathrm{iso}} \sim 3 \times 10^{47}$ erg/s $(T/5\ \mathrm{d})^{-2}$ relativistic jets (Pasham+ 2023) + later-time steepening (Eftekhari+ 2024)
- ***Optical***: black body emission from thermal envelope (Yao+ 2024)
- ***Radio***: GRB-like jet forward shocks ($\Gamma \sim 2-5$) propagating in the circumnuclear medium (CNM) $n_{\mathrm{cnm}} \propto R^{-k},\ 1.5 \lesssim k \lesssim 2.0$

  (e.g., Matsumoto & Metzger 2023; Yao+ 2024; Zhou+ 2024)

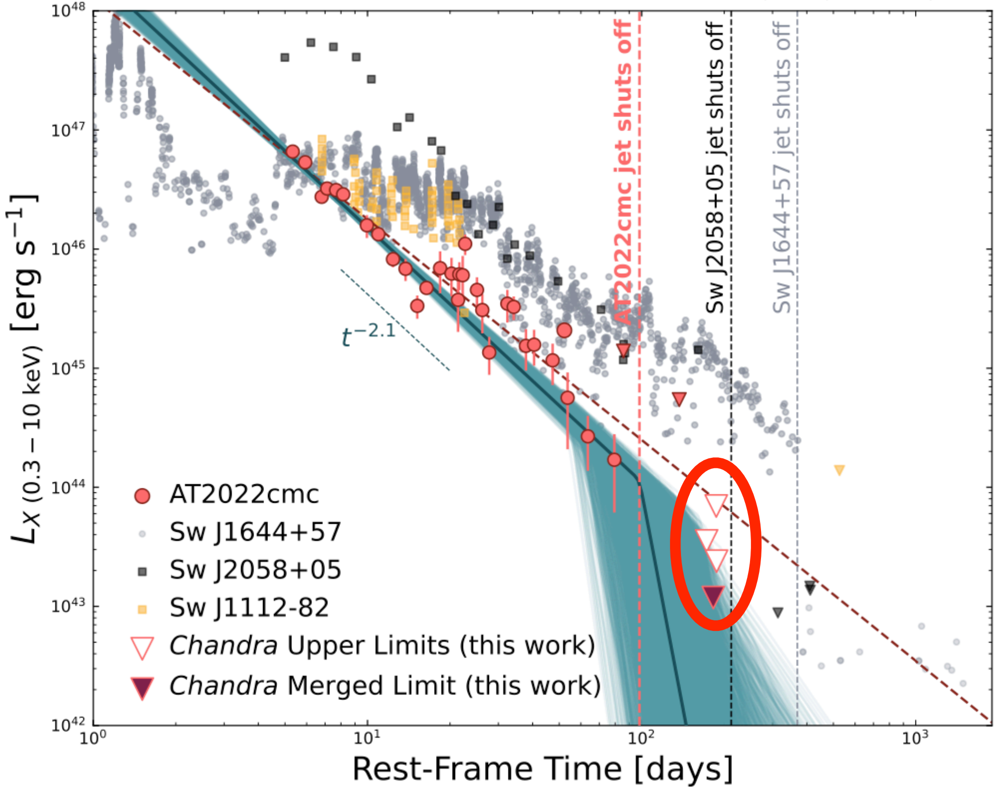


Andreoni+ Nat.2022



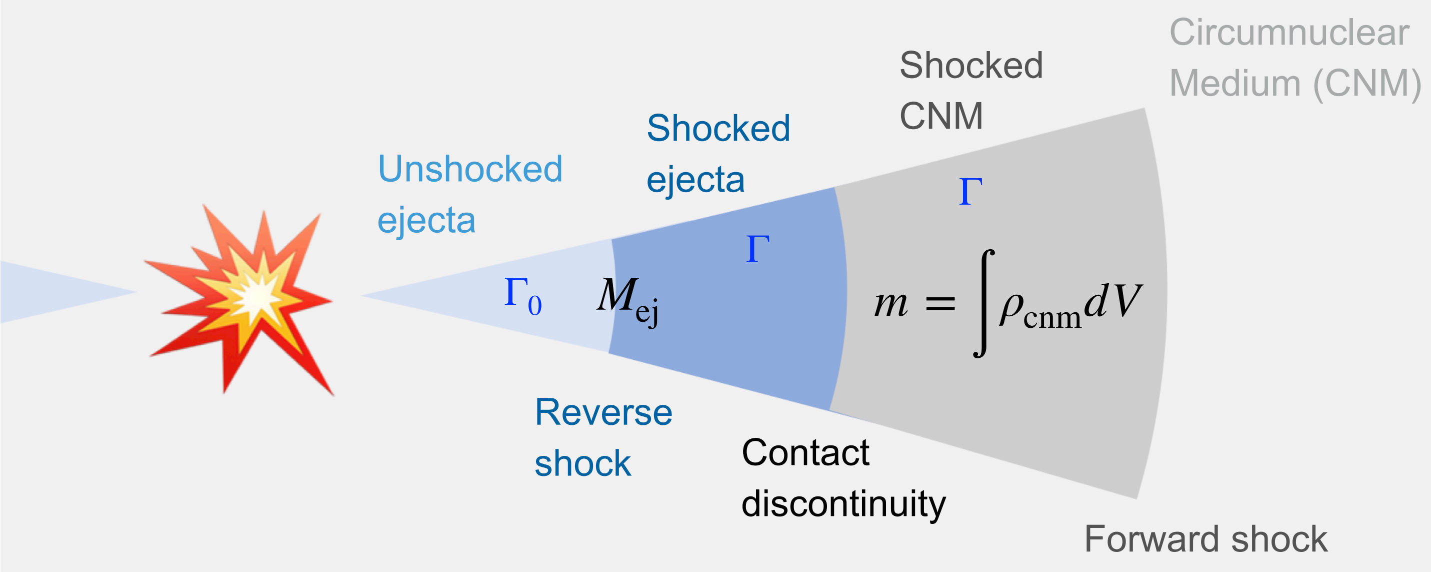
Pasham et al. Nat. Astro. (2023)

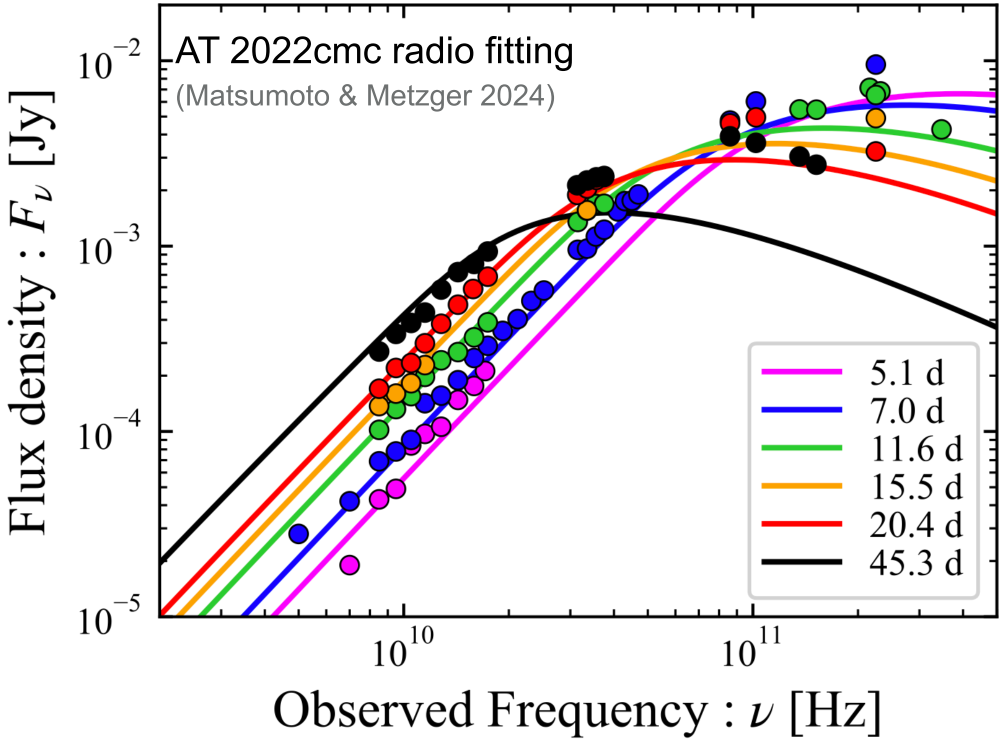
Eftekhari+ 2024



Jetted TDE: forward shock model

Jet schematic (not to scale)





FS dominated jet evolution with explosion energy $E_0 = \Gamma_0^2 M_{\rm ej} c^2$:

Isotropic equivalent energy of the jet

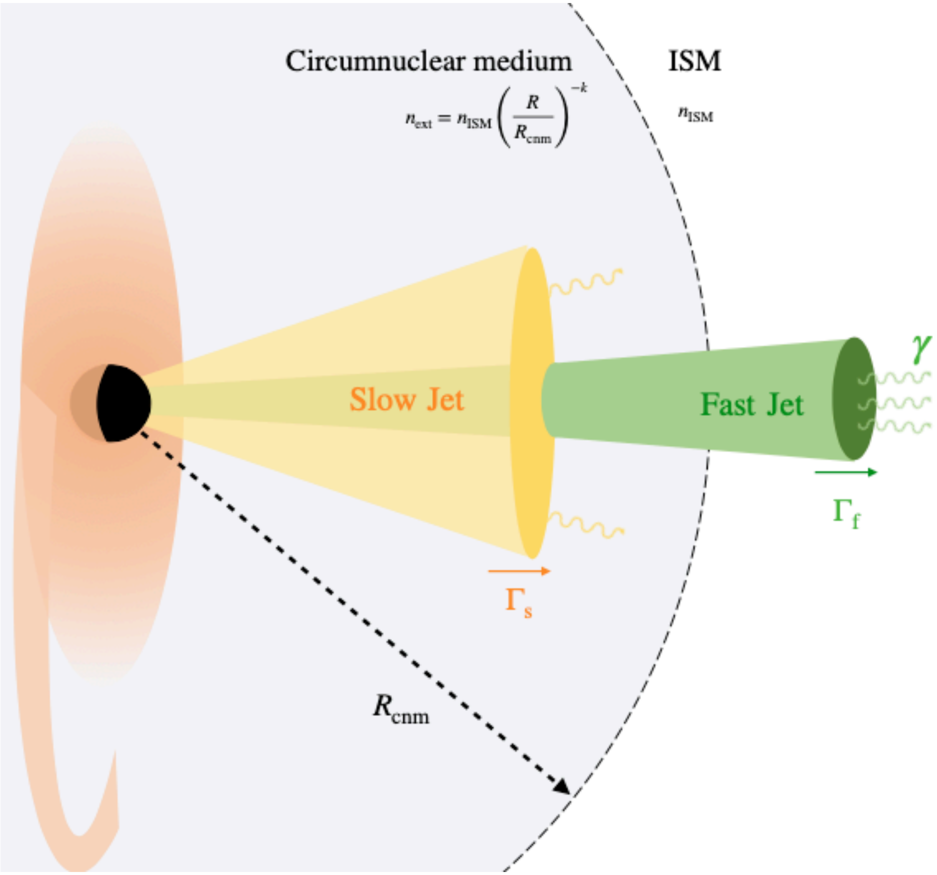
$$\left.\begin{array}{l} E_{\rm iso} = \Gamma M_{\rm ej}^2 + \Gamma m c^2 + \dfrac{(\Gamma-1)(\hat{\gamma}\Gamma^2-\Gamma+1)}{\Gamma} m c^2 \\ dE_{\rm iso} = c^2 dm \text{ (No internal energy injection)} \end{array}\right\} \quad \frac{d\Gamma}{dm} = -\frac{\Gamma - 5\Gamma^3 + 4\Gamma^5}{3M_{\rm ej}\Gamma^3 - 2m + 8\Gamma^4 m}.$$

TDE FS model → radio spectra/lightcurves:

- Explosion, no continuous power injection
- $\Gamma_0 \sim 1 - 10$
- Synchrotron emission from accelerated e^-
- Wind-like CNM profile $\rho_{\rm cnm} \propto R^{-k}$ $(1.5 < k < 2)$
- ***Cannot explain X-ray observations→two component jet***

Jetted TDE: AT 2022cmc — structured jet

Narrow fast jet and wide slow jet



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

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

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

Fallback time

$$t_{\rm fb} \simeq 3.3 \times 10^6 \ {\rm s} \ f_{T,-1.2}^{1/2} M_{{\rm BH},7}^{1/2} M_{\star,0.7}^{-1/10}$$

Jet luminosities ($\eta_{\rm f/s} \sim 0.1$)

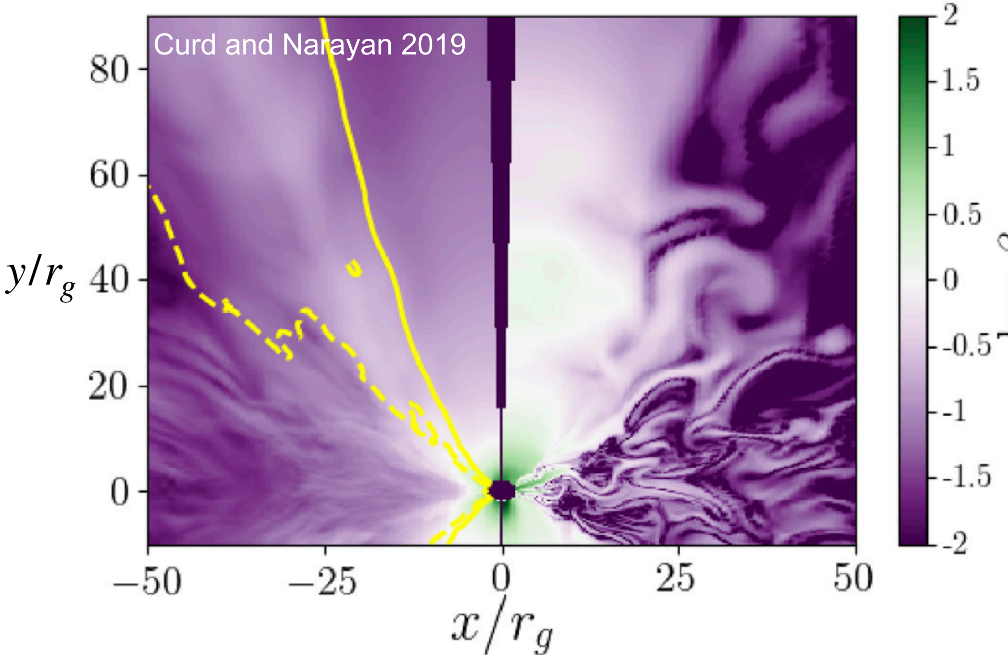
$$L_{\rm f/s} = \eta_{\rm f/s} \dot{M}_{\rm BH} c^2,$$

CNM density profile
$k = 1.8, \ R_{\rm cnm} = 10^{18}$ cm

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

Two components

- Slow outflow (quasi-isotropic)
- Fast relativistic jet (beamed)

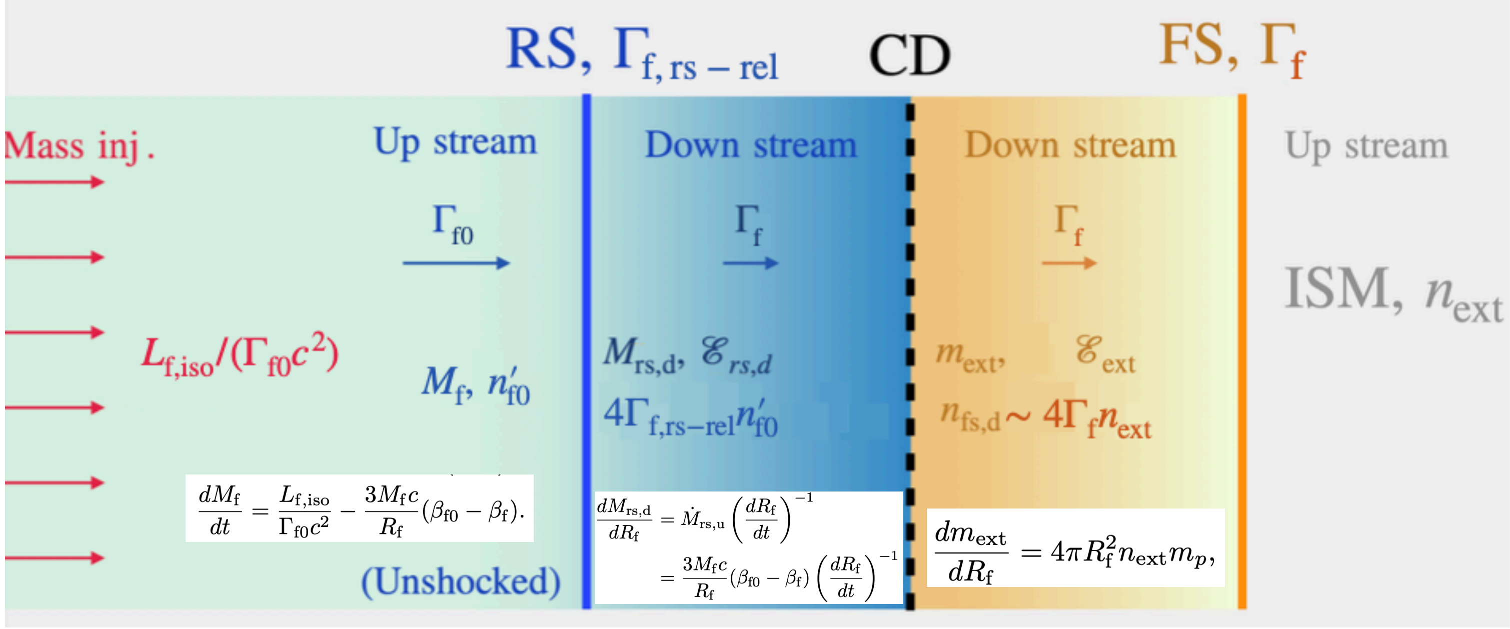


Curd and Narayan 2019

Radiation pressure

Jetted TDE: AT 2022cmc — jet dynamics

Jet evolution: continuous energy/mass injections; GRB-like treatment; forward/reverse



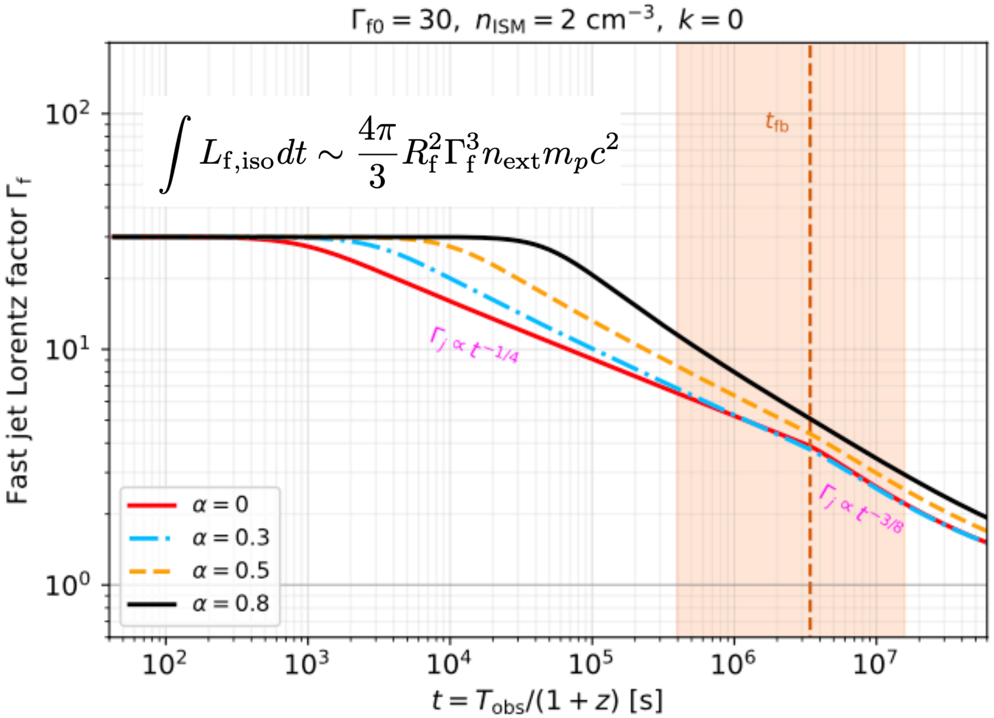
$$\frac{dM_{\rm f}}{dt} = \frac{L_{\rm f,iso}}{\Gamma_{\rm f0}c^2} - \frac{3M_{\rm f}c}{R_{\rm f}}(\beta_{\rm f0} - \beta_{\rm f}).$$

$$\frac{dM_{\rm rs,d}}{dR_{\rm f}} = \dot{M}_{\rm rs,u}\left(\frac{dR_{\rm f}}{dt}\right)^{-1} = \frac{3M_{\rm f}c}{R_{\rm f}}(\beta_{\rm f0} - \beta_{\rm f})\left(\frac{dR_{\rm f}}{dt}\right)^{-1}$$

$$\frac{dm_{\rm ext}}{dR_{\rm f}} = 4\pi R_{\rm f}^2 n_{\rm ext} m_p,$$

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

A more comprehensive treatment including:
- Continuous power injection from central engine
- Reverse shock deceleration of unshocked ejecta



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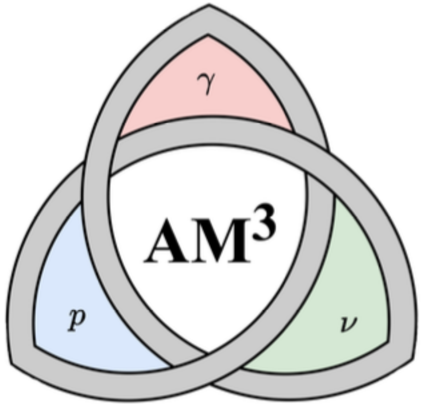
Numerical method: AM^3 (Astrophysical Multi-Messenger Modeling)

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

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



- An ***Open-Source*** Tool for ***Time-Dependent*** Leptoic-Hadronic Radiation Modeling
- Applied to active galactic nuclei, gamma-ray bursts, TDEs

  Klinger, Rudolph, Rodrigues, CY, Clairfontaine, Fedynitch, Winter, Pohl, Gao, arXiv: 2312.13371 (ApJS)

- Developed at DESY; Public to the community (*https://gitlab.desy.de/am3/am3*)
- Dedicated for single-zone isotropic multi-messenger (EM and neutrinos) emissions
- Compiled in C++ with a Python interface: fast and easy to use
- Reliable and trackable
- Well-documented with detailed instructions and examples
- More than 14 papers on GRBs, AGNs, and TDEs are published based on AM3. The number keeps expanding!
- Check the doc website to learn more: *https://am3.readthedocs.io*

Jetted TDE: AT 2022cmc — spectra

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

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

Radiation modeling

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

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

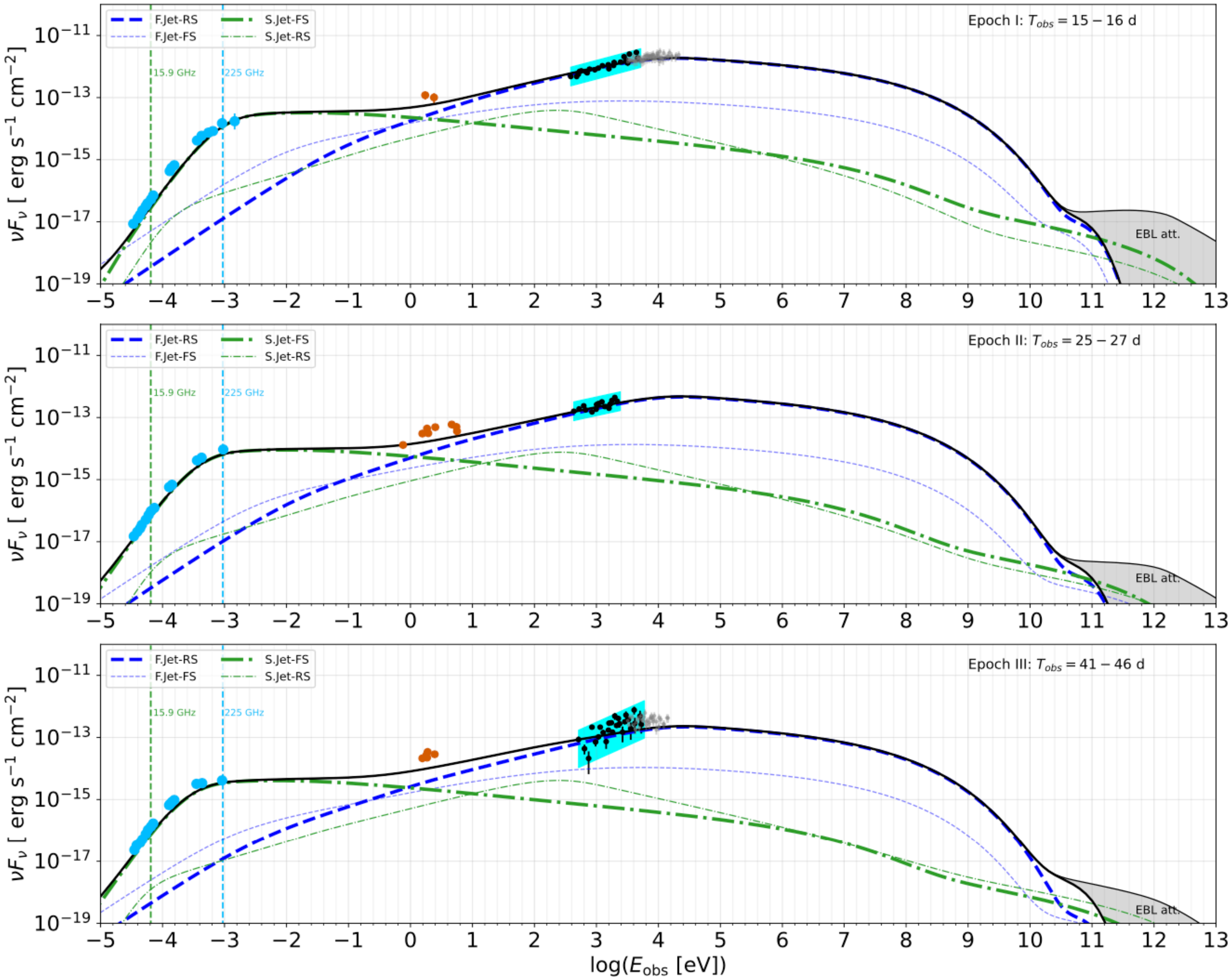
$$\gamma_{e,\min} = (\Gamma - 1)\frac{s-2}{s-1}\frac{\epsilon_e}{f_e}\frac{m_p}{m_e}$$

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

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

Fitting parameters

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



AT 2022cmc: structured jet light curves

Optical:

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

X-rays:

- Continuously powered reverse shock model: works good!
- Lightcurve steepening after ~100 d and the late time ULs after ~200d (red points, Eftekhari+ 2024): *Jet break correction*

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

- Analytically consistent,

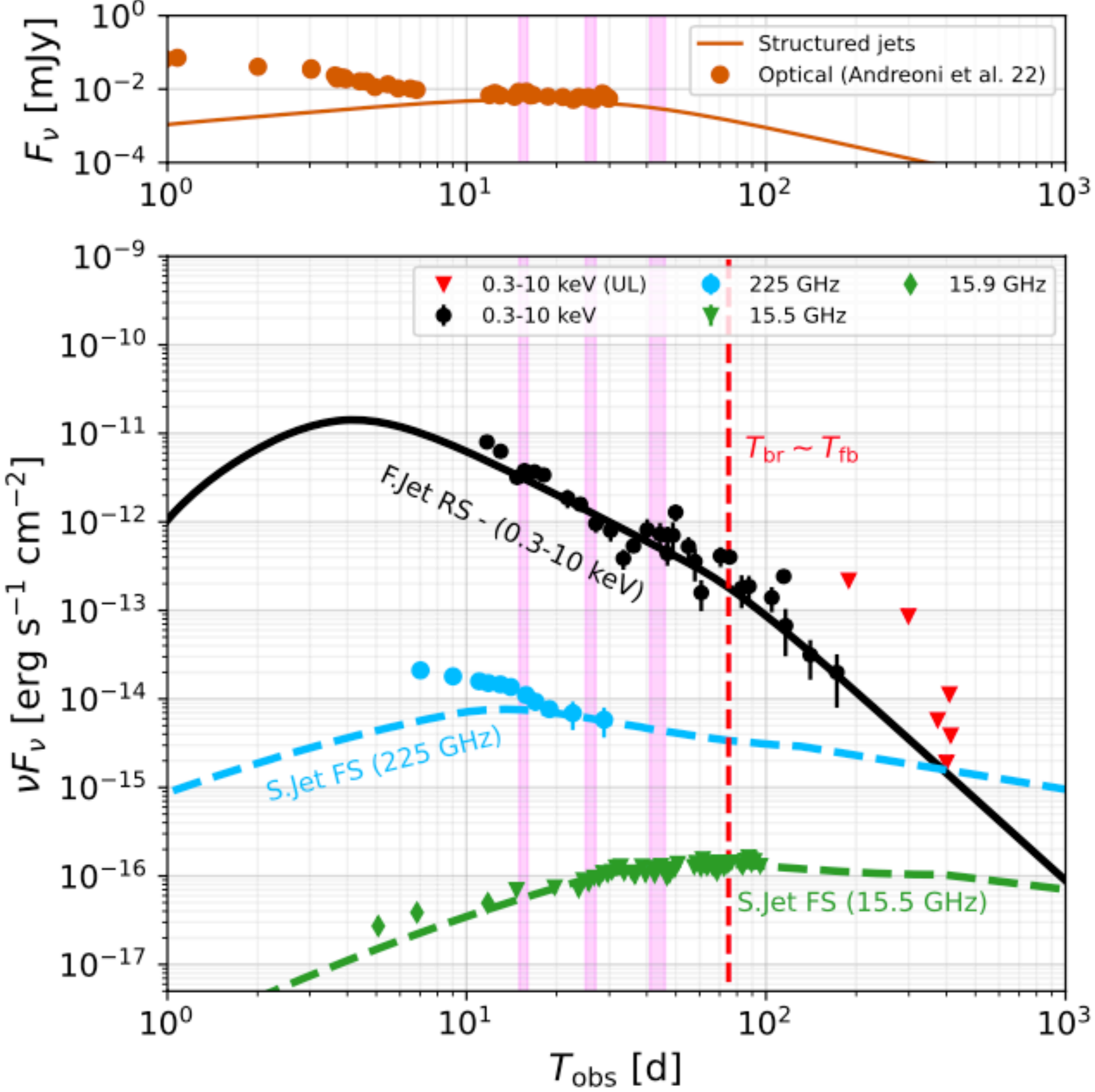
$$\nu F_\nu^{(\rm rs)} \propto \begin{cases} T_{\rm obs}^{-[5\alpha+\alpha(s-1)]/4}, & T_{\rm obs} < T_{\rm br} \simeq T_{\rm fb} \\ T_{\rm obs}^{-(2s+25)/12}, & T_{\rm obs} > T_{\rm br} \simeq T_{\rm fb}. \end{cases}$$

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

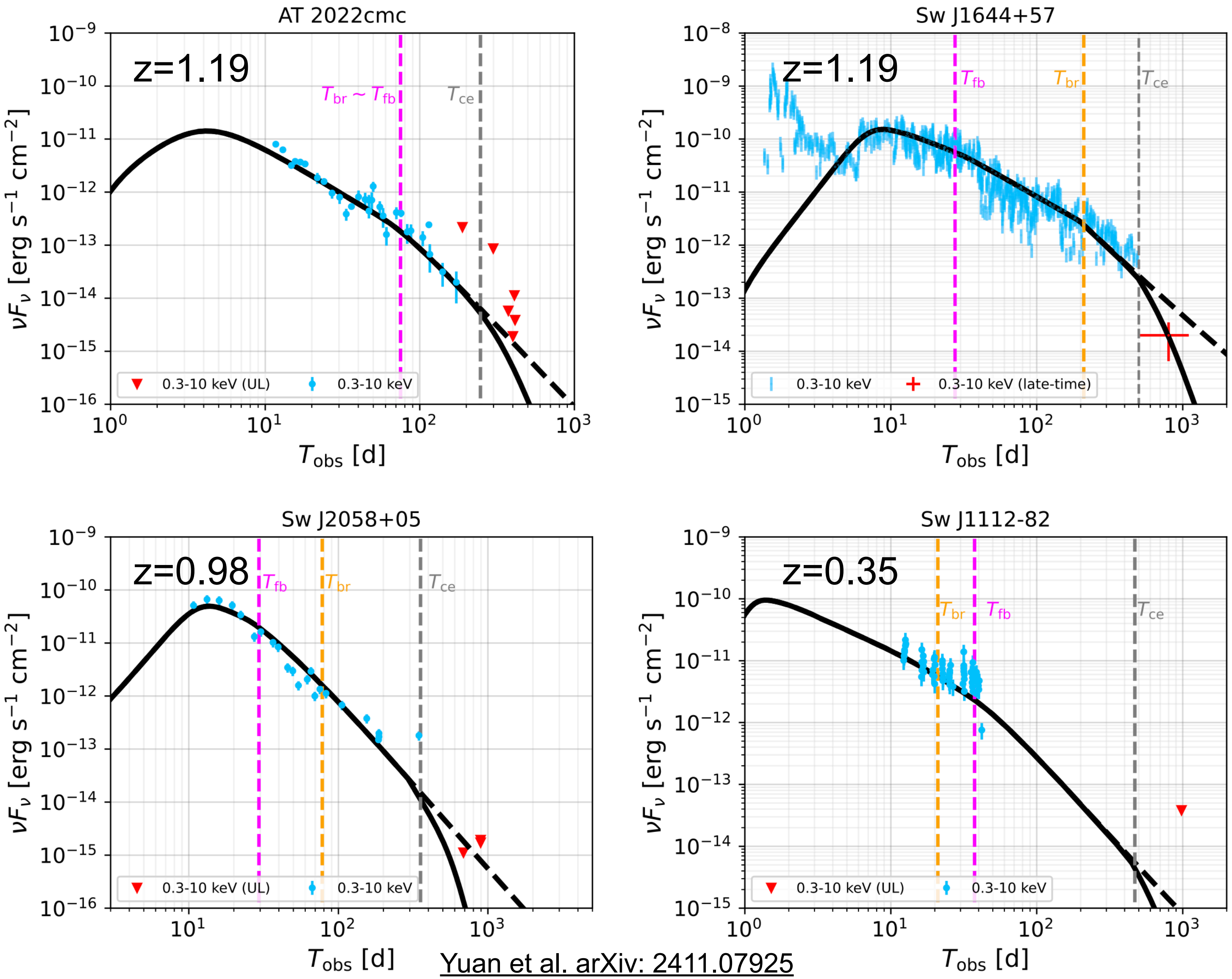
Radio:

Slow jet forward shock: 16 GHz and later-time 225 GHz light curves

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



Revisiting X-ray afterglows of 4 jetted TDEs



Yuan et al. arXiv: 2411.07925

Fast jet reverse shock model

Late-time X-ray limits:

- **Ceased central engine + jet break:** SW J1644 (sharp X-ray break)
- Transition to sub-Eddington rate→jet power injection stops

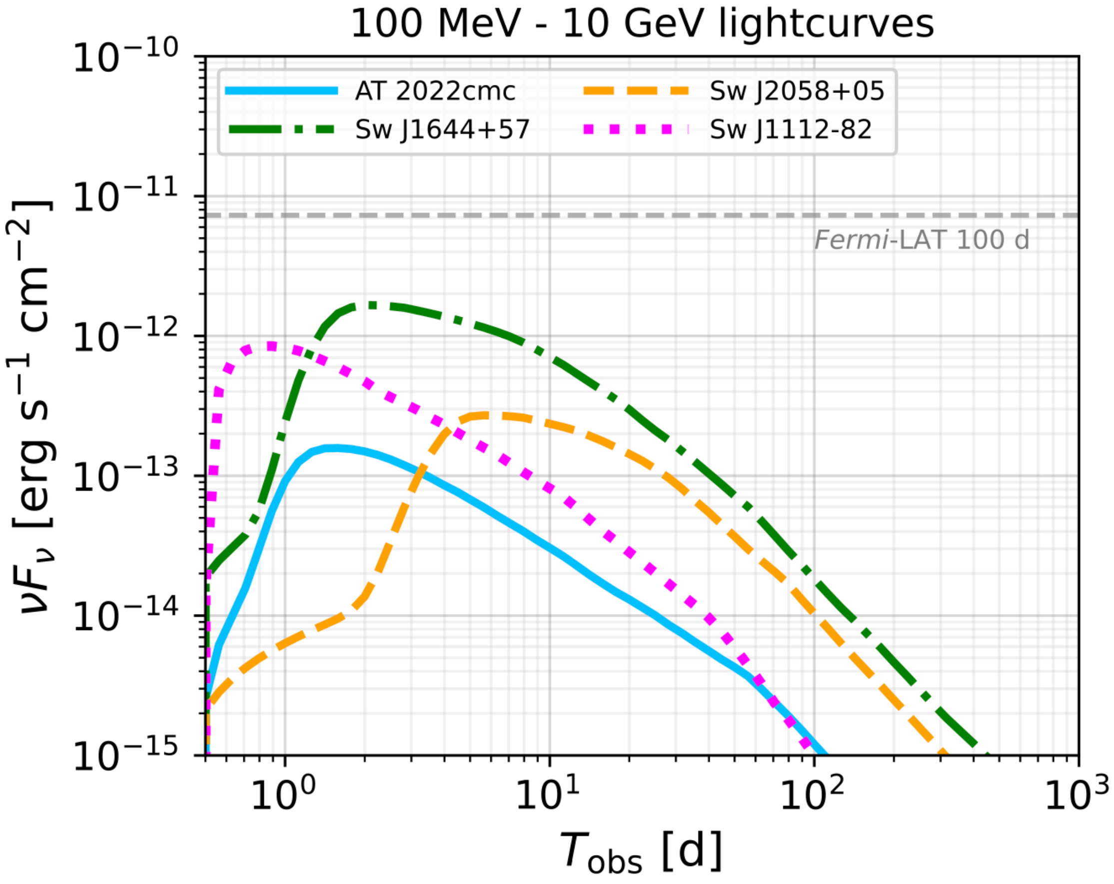
$$\dot{M}_{\rm BH}(t_{\rm ce}) = \frac{L_{\rm Edd}}{\eta_{\rm rad} c^2}$$

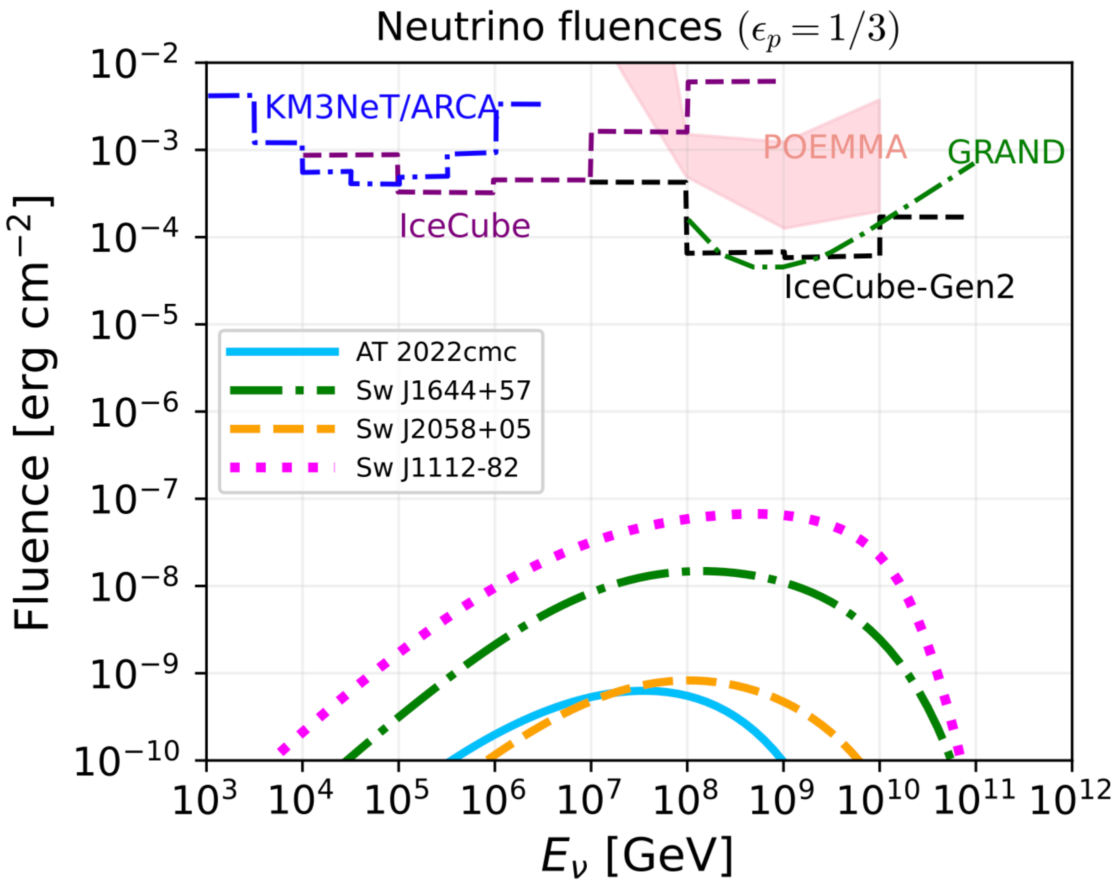
TDEs $^{(a)}$	AT 2022cmc	J1644	J2058	J1112
z	1.19	0.35	1.19	0.89
$M_{\rm BH}$ $[M_\odot]$	10^7	10^6	10^6	2×10^6
Model parameters				
α	0.80	0.65	0.85	0.70
$\mathcal{E}_j$ $[10^{52}$ erg$]$	5.4	3.5	2.9	6.3
$n_{\rm ISM}$ $[{\rm cm}^{-3}]$	10	6.0	1.0	10
θ_j	0.15	0.1	0.1	0.1
Γ_0	30	25	42	35
ϵ_B	0.10	0.15	0.20	0.15
Results				
$M_\star^{(b)}$ $[M_\odot]$	3.0	1.9	1.6	3.5
$T_{\rm fb}$ [d]	77	28	27	21
$T_{\rm br}$ [d]	79	212	76	37
$T_{\rm ce}^{(c)}$ [d]	227	352	331	470

Jetted TDE X-ray afterglows

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 $p\gamma$





Yuan et al. arXiv: 2411.07925

Summary and conclusions

- The continuous power injection effects the early time light curves
- A persistently powered structured (two-component) jet model could explain the radio (e.g., slow jet, forward shock) and X-ray (fast jet, reverse shock) spectra/lightcurves of jetted AT 2022cmc
- Joint spectral and lightcurve fitting could reduce the parameter degeneracy
- The jet break and central engine cessation may lead to the late-time steepening in X-ray lightcurves in all 4 jetted TDEs
- TDE relativistic jets are challenging to be detected by current gamma-ray and neutrino detectors.
- Additional contributions, such as hidden winds and external photon fields, are needed to be efficient gamma-ray/neutrino emitters. *The neutrino and electromagnetic cascade signals from neutrino-emitting TDEs will be presented in the poster session.*

Thanks for your attention!

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 -> relativistic jet -> months/year-long flare (optical transient)
- Energy to be reprocessed by accretion ~ 10^{54} erg
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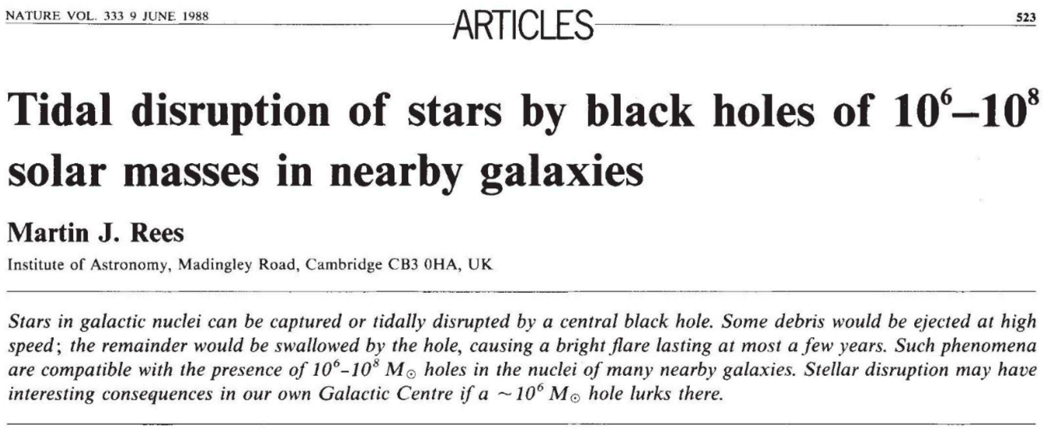


NATURE VOL. 333 9 JUNE 1988 ARTICLES 523

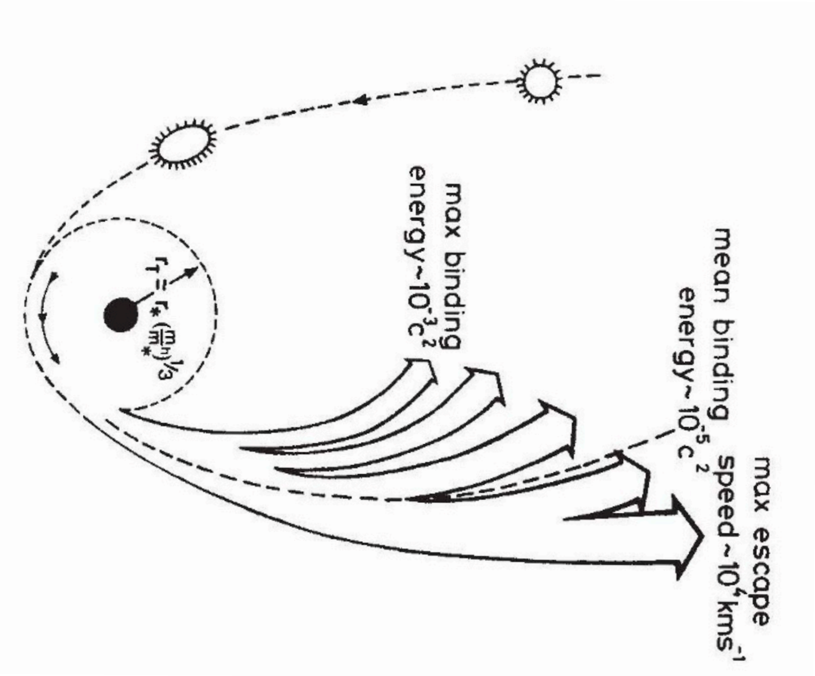
Tidal disruption of stars by black holes of 10^6–10^8 solar masses in nearby galaxies

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



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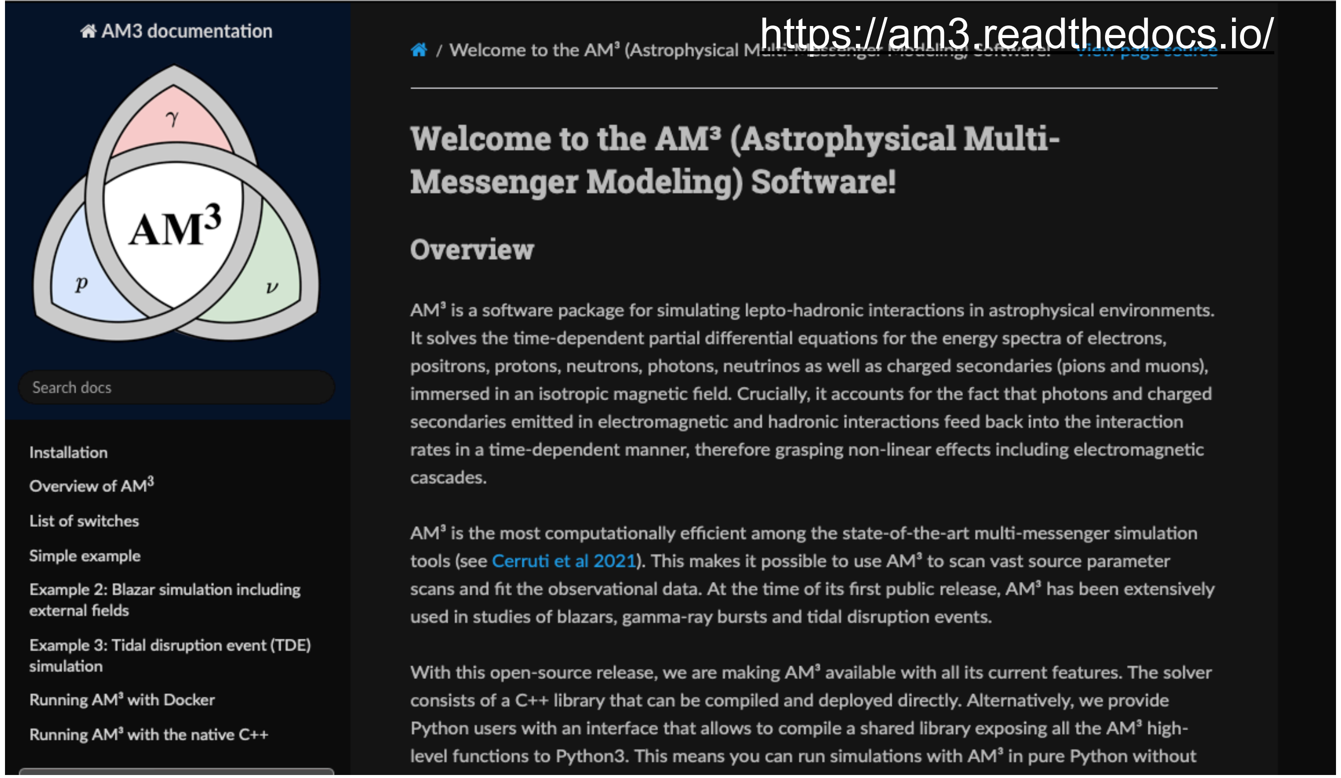
- An ***Open-Source*** Tool for ***Time-Dependent*** Lepto-Hadronic Modeling of Astrophysical Sources
- Blazars, GRBs, TDEs, etc

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

https://am3.readthedocs.io/



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

Overview

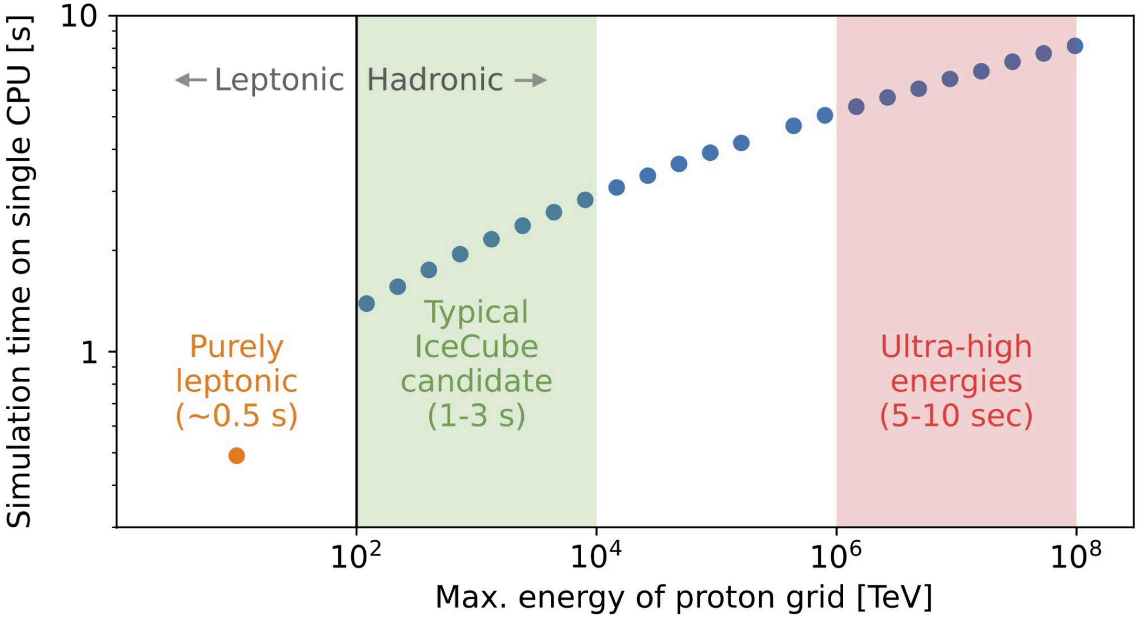
AM³ is a software package for simulating lepto-hadronic interactions in astrophysical environments. It solves the time-dependent partial differential equations for the energy spectra of electrons, positrons, protons, neutrons, photons, neutrinos as well as charged secondaries (pions and muons), immersed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

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

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

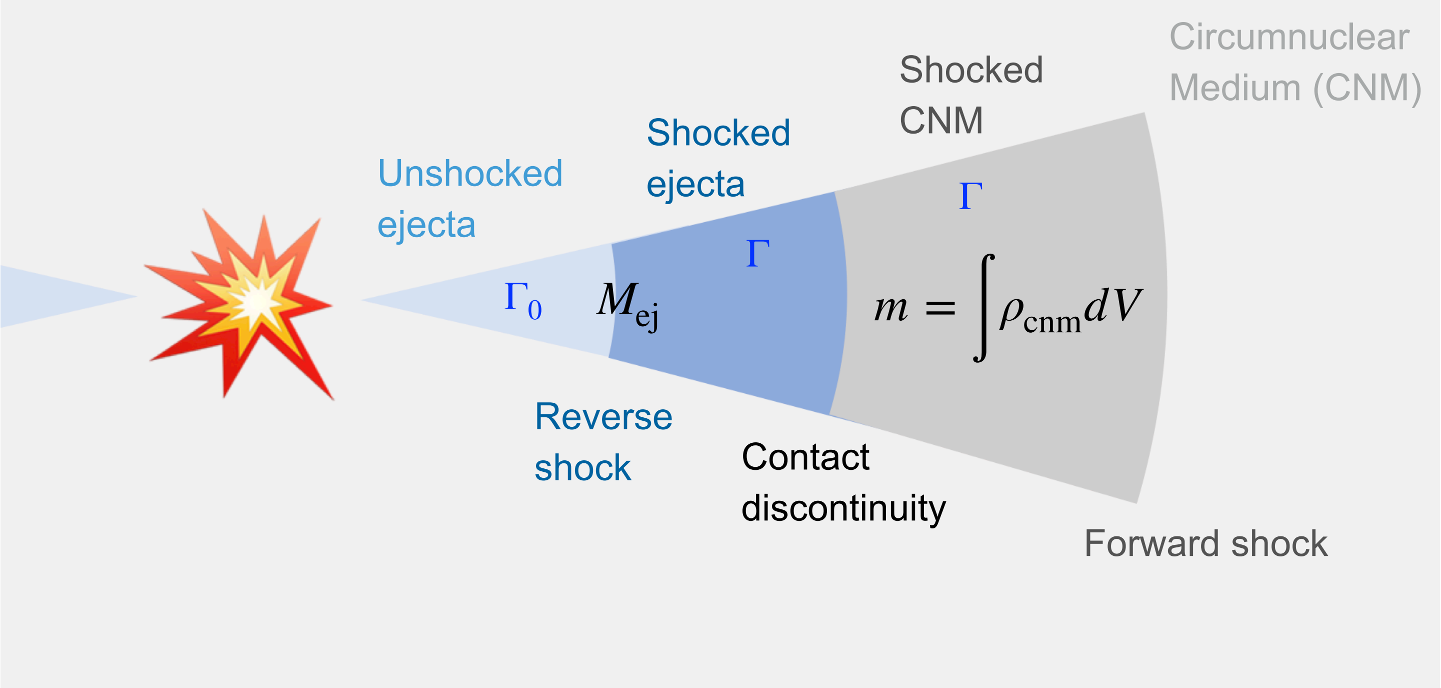
Performance: C++ source code, python interface

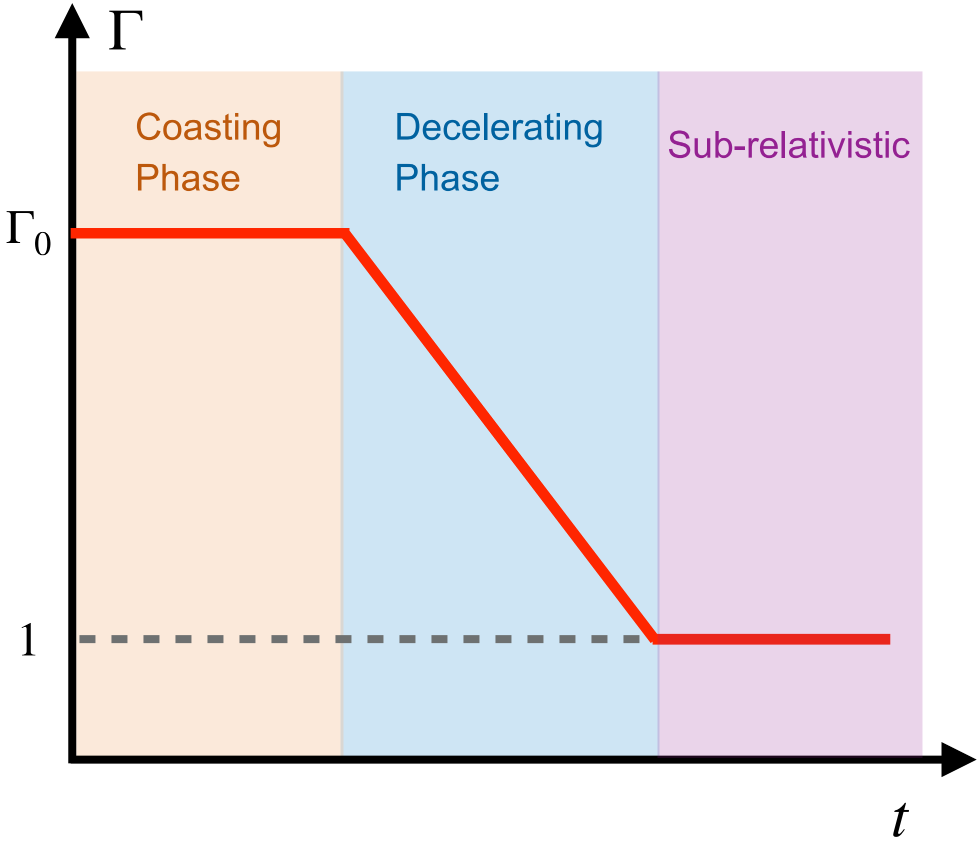
- Simulation: kernel initialization, particle injection, ~30 steps to steady state
- Tested on a single CPU on Apple M2 chip
- Very fast for lepto-hadronic simulations (< 0.5 s/step)



Jetted TDE: forward shock model

Jet schematic (not to scale)





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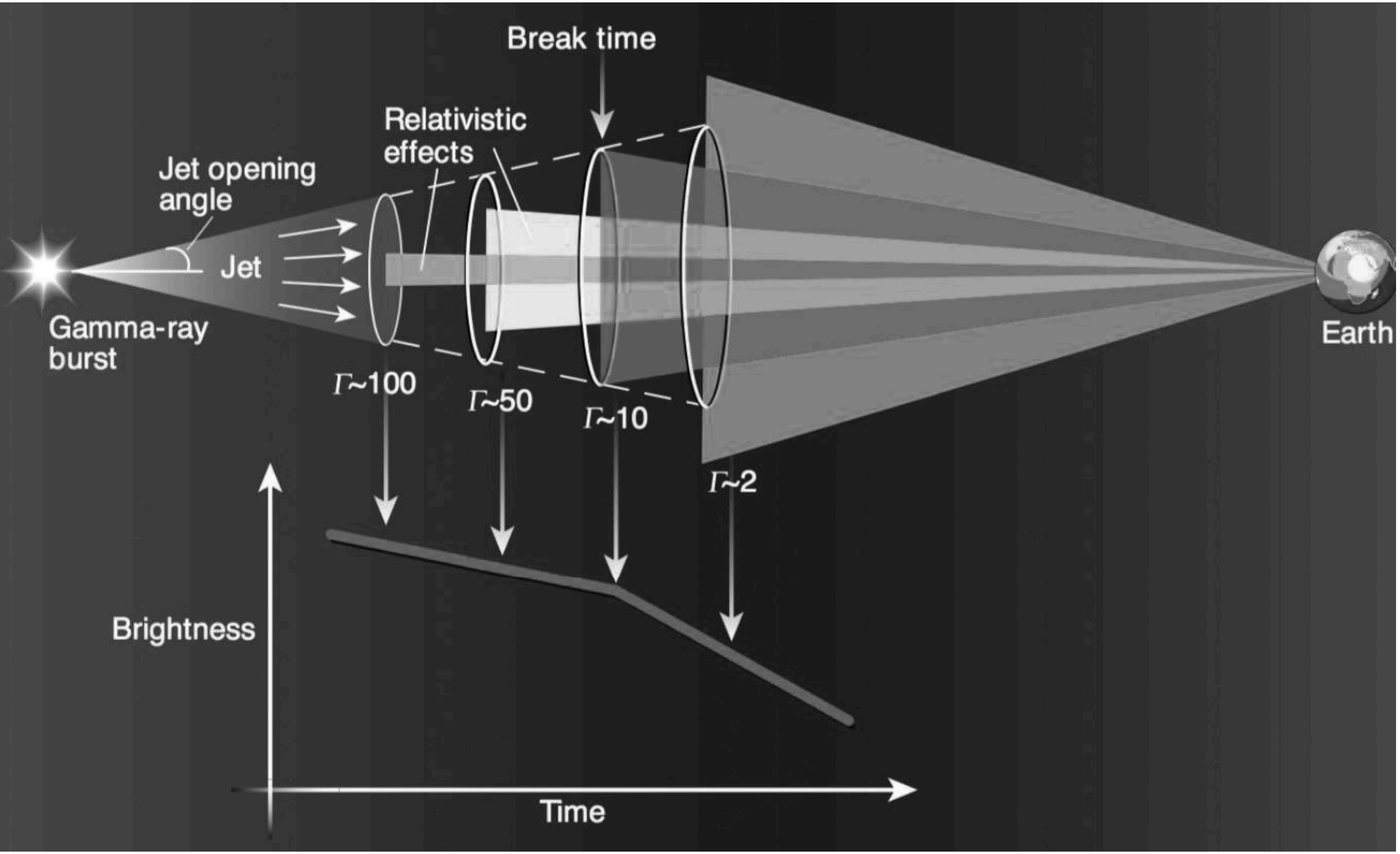
Jet break

Geometric effect of decelerating jet

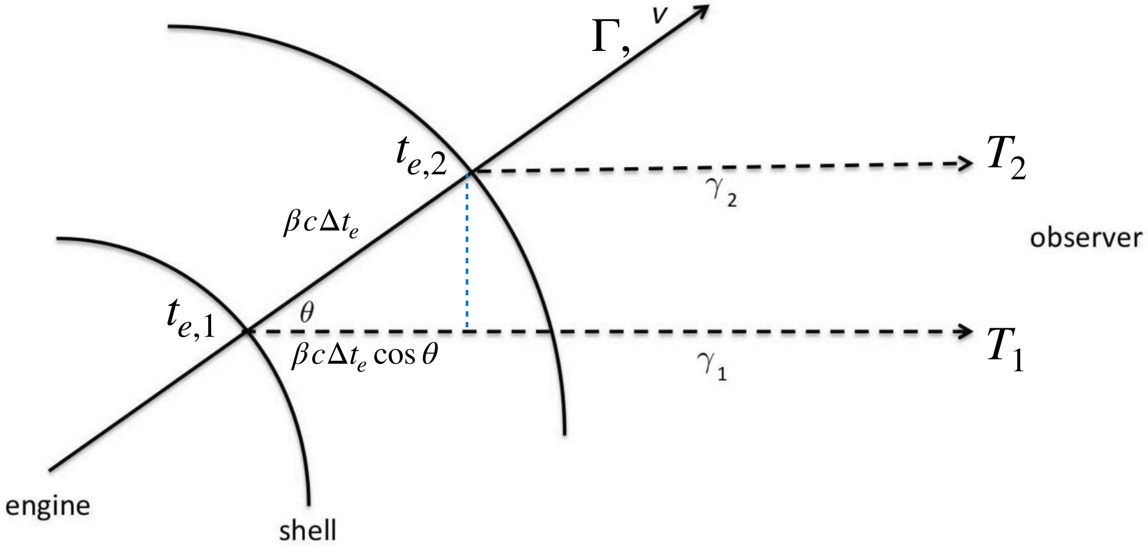


For jets with opening angle θ_j

- $\theta_j > 1/\Gamma$**:** observer has no knowledge outside Γ^{-1} cone
- $\theta_j < 1/\Gamma$: observer feels the progressive deficit of energy with in Γ^{-1} since no emission outside the jet cone is available
- $\theta_j = 1/\Gamma$ defines break time $t_{\rm br}$, correction factor $(\theta_j\Gamma)^2$ applies after $t_{\rm br}$

Equal-arrival-time surface (EATS)

Relate the time interval ΔT in the observer's frame to the emission time interval in the jet Δt_e (engine frame)



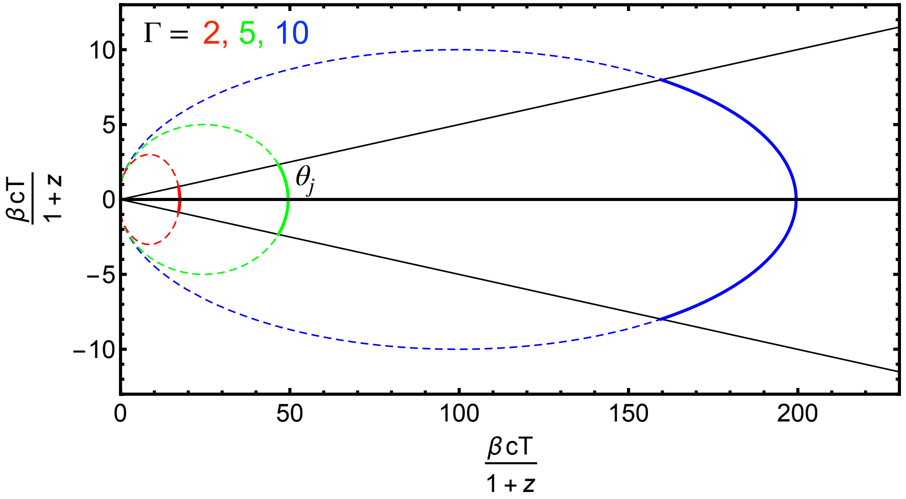
$$T_1 = t_{e,1} + d/c$$

$$T_2 = t_{e,2} + d/c - \beta \Delta t_e \cos\theta$$

$$\Delta T = T_2 - T_1 = \Delta t_e (1 - \beta \cos\theta)$$

Set $t_{e,1} = 0$, **radius** $R = \int \beta c dt_e \sim \dfrac{\beta c T}{1 - \beta \cos\theta}$

For $\theta = 0$, $T = (1+z) t_e (1-\beta) \simeq (1+z) t_e / (2\Gamma^2)$



Photons from the EATS arrives simultaneously

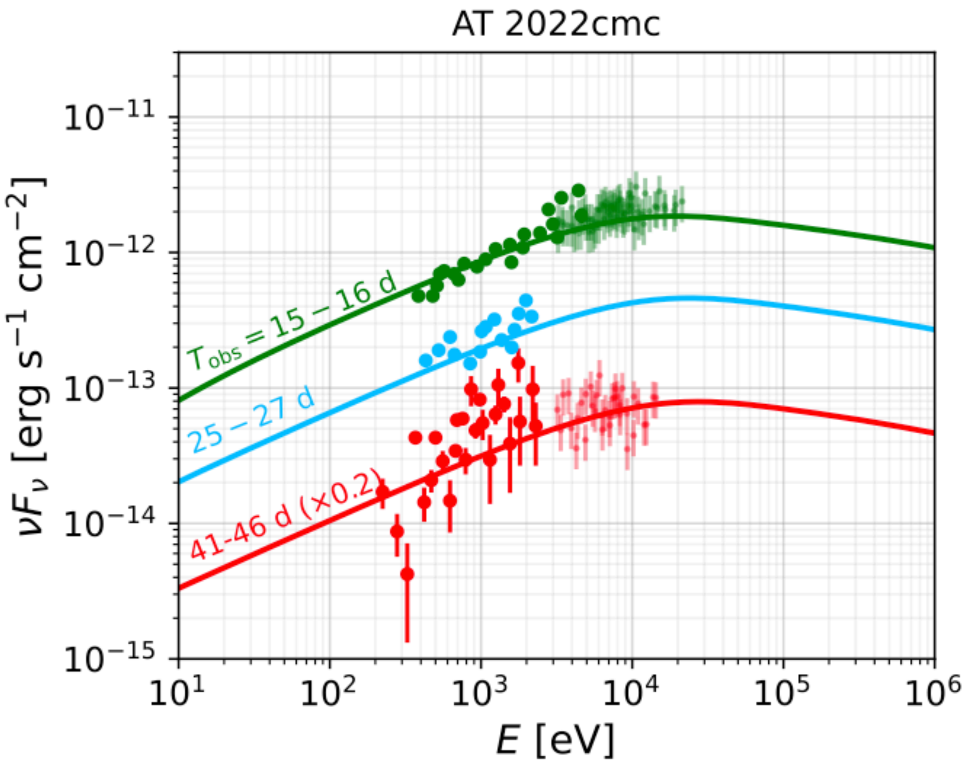
$$\boxed{R = \frac{\beta c T}{(1 - \beta \cos\theta)(1+z)}}$$

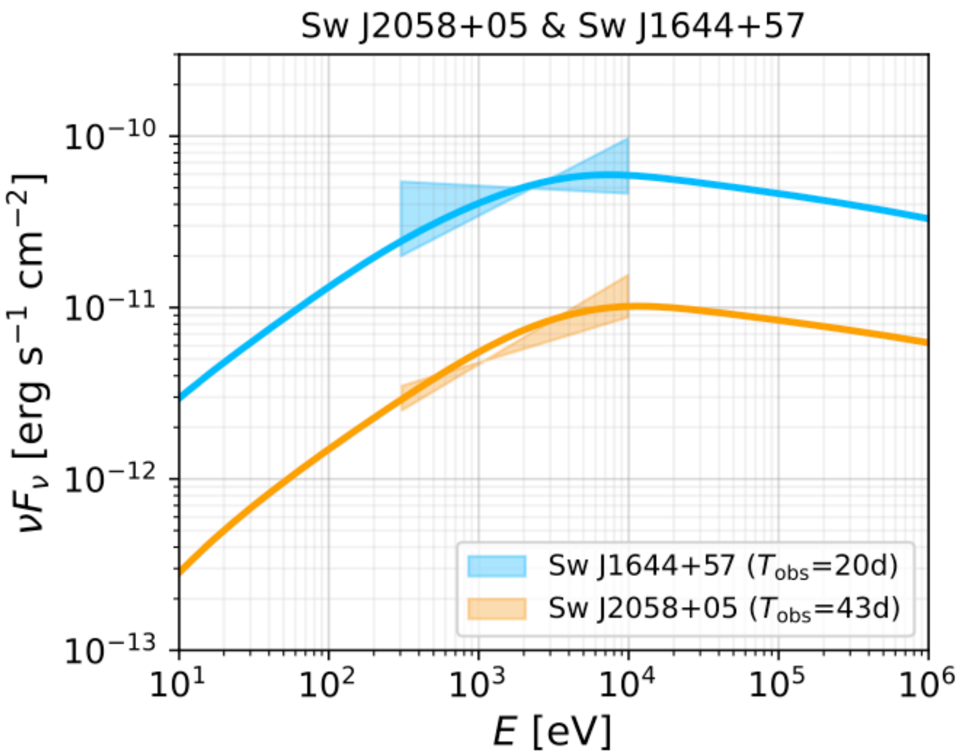
Integrate the emissivity over the EATS:

$$F(E, T_{\rm obs}) = \frac{2\pi(1+z)}{d_L^2} \int_0^{\theta_j} d\theta \sin(\theta) R_j^2 \times \Delta R_j f_{\rm br} \frac{j'(\hat{t}, R_j, \varepsilon')}{\Gamma^2 (1 - \beta\mu)^2}\Big|_{\hat{t} = \frac{T_{\rm obs}}{1+z} + \frac{\mu R_j}{c}},$$

Revisiting X-ray afterglows of 4 jetted TDEs

Spectral fitting





Yuan et al. arXiv: 2411.07925