Update on neutrino emissions from tidal disruption events

Kimi Hayasaki

(Chungbuk National University)

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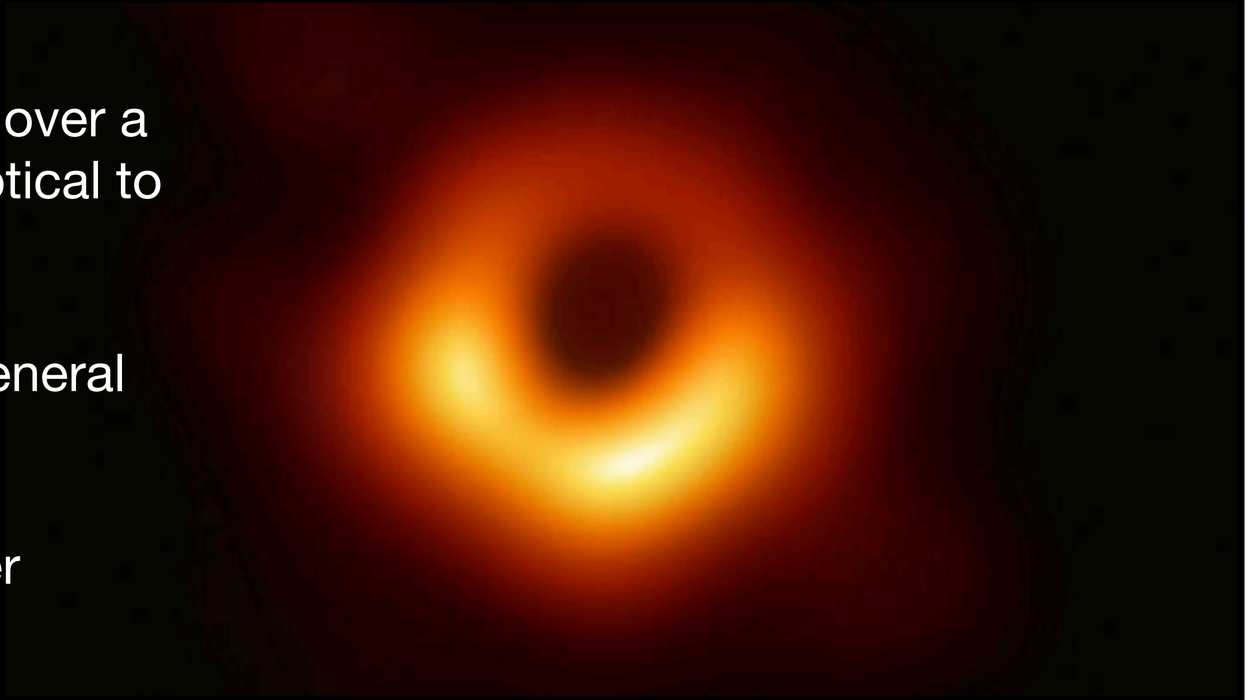
Scientific motivation to study tidal disruption events (TDEs)

1. Probe of quiescent supermassive black holes (SMBHs) and intermediate-mass black holes (IMBHs)

2. Among the brightest transients over a wide range wavebands from optical to UV to soft X-ray

3. Natural laboratory for testing general relativistic (GR) effects

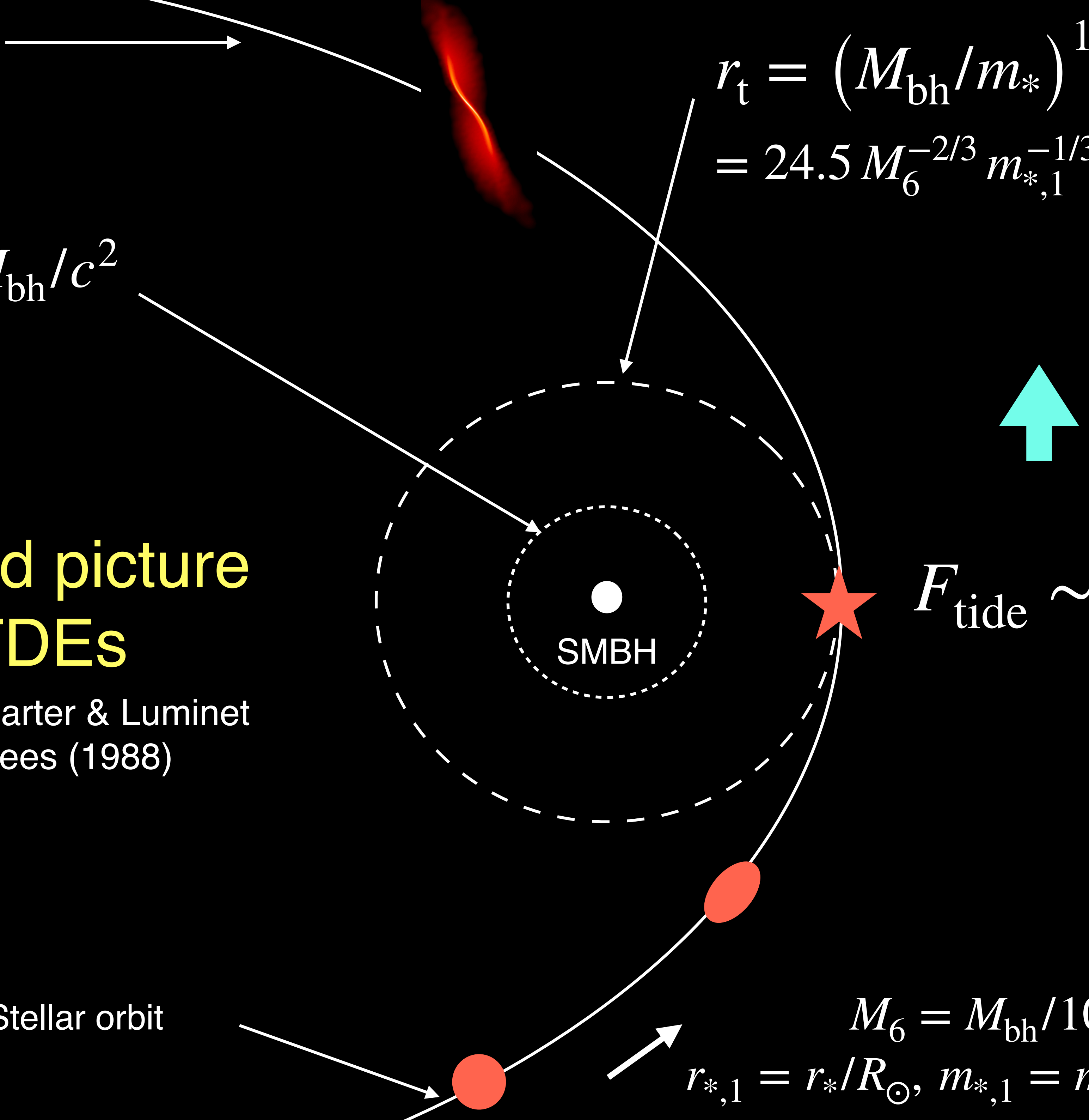
4. Candidates for multi-messenger astronomy: **cosmic-ray/ neutrino sources (gravitational waves)**



EHT collaboration 2019
https://eventhorizontelescope.org/

Standard picture of TDEs

Hills (1975); Carter & Luminet (1983); Rees (1988)



Debris orbit

$$r_\mathrm{t} = \left(M_\mathrm{bh}/m_*\right)^{1/3} r_* = 24.5\, M_6^{-2/3}\, m_{*,1}^{-1/3} r_{*,1}\, r_\mathrm{S}$$

$$r_\mathrm{S} = 2GM_\mathrm{bh}/c^2$$

SMBH

$$F_\mathrm{tide} \sim F_\mathrm{sg}$$

Stellar orbit

$$M_6 = M_\mathrm{bh}/10^6\, M_\odot$$

$$r_{*,1} = r_*/R_\odot,\ m_{*,1} = m_*/M_\odot$$

$$r_{\rm t}/r_{\rm S} = 24.5\, M_{\rm bh,6}^{-2/3}\, m_{*,1}^{-1/3} r_{*,1}$$

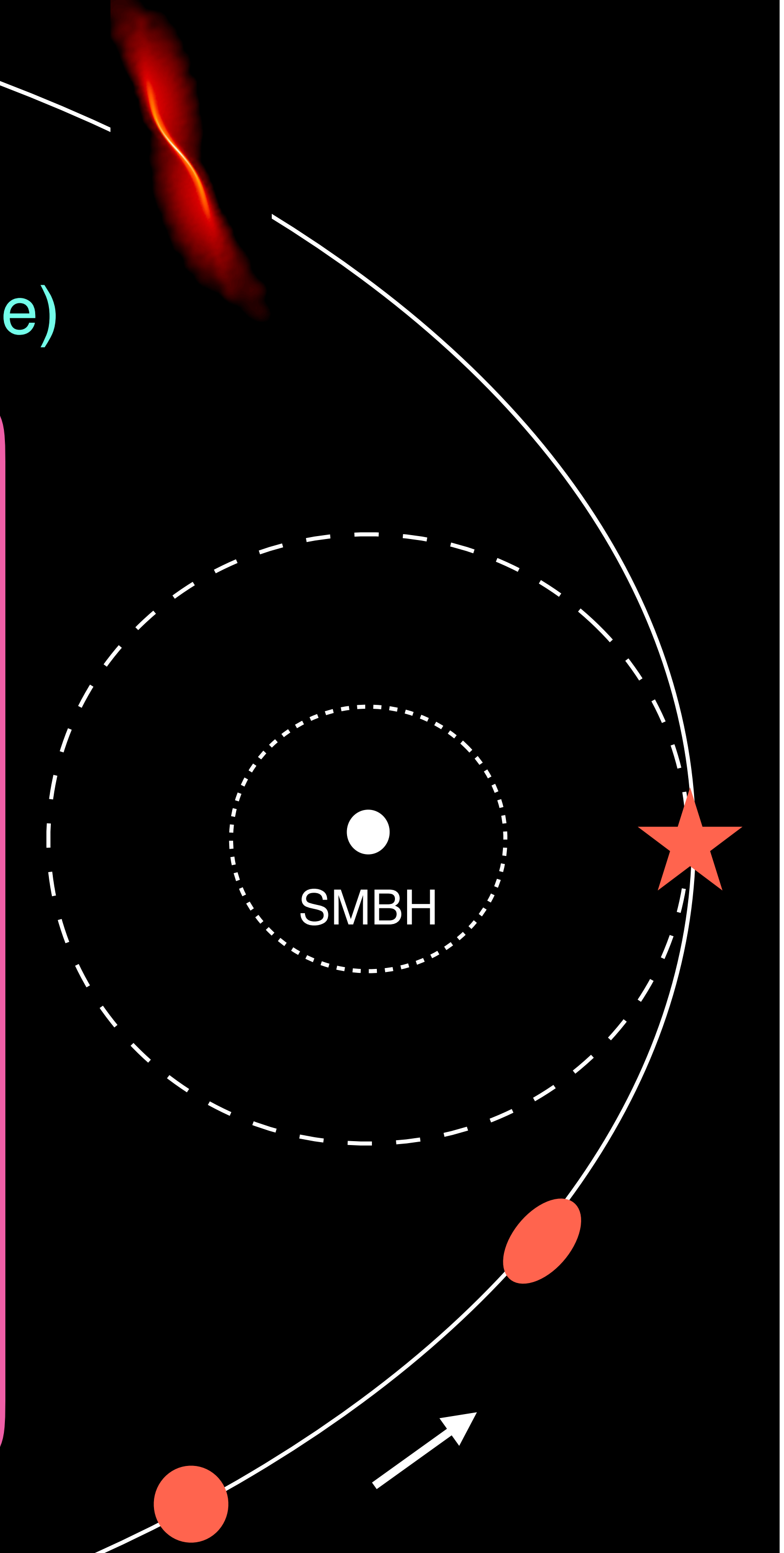
Condition for TDEs (non-spinning BH case)

$$r_{\rm t} \gtrsim r_{\rm S}$$

$$M_{\rm bh} \lesssim 10^8 M_\odot\, (r_*/R_\odot)^{3/2} (m_*/M_\odot)^{-1/2}$$

cf. Hill's mass
(slightly lower mass)

Likely to happen at quiescent SMBHs in inactive galaxies (unlikely for M87* because of $M_{\rm bh} \sim 6.5 \times 10^9\, M_\odot$)



Summary for TDE theory

$$M_6 = M_{\rm bh}/10^6\,M_\odot$$

- Peak (bolometric) luminosity

$$L_{\rm Edd} \lesssim 10^{44}\,M_6\,{\rm erg/s}$$

- Duration time of TD flare

$$t_{\rm flare} \sim 2\,M_6^{-2/5}\,{\rm yr}$$

- Effective temperature (Ulmer 1999)

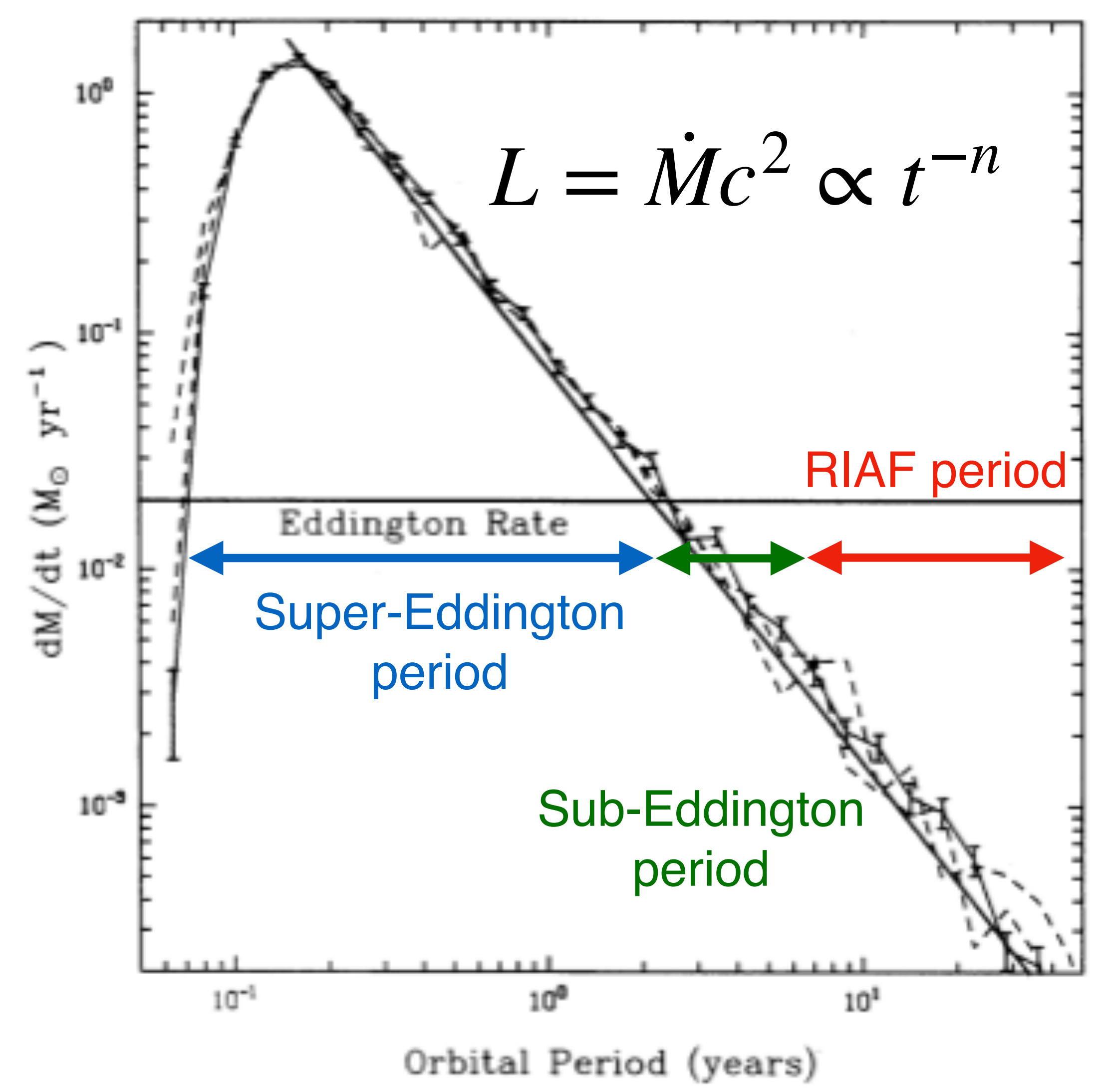
$$T_{\rm eff} = \left(\frac{L_{\rm Edd}}{4\pi\sigma_{\rm SB} r_{\rm t}^2}\right)^{1/4} \sim 3\times10^5\,M_6^{1/12}\,{\rm K}$$

- Event rate

$$10^{-4} \sim 10^{-5}\,{\rm yr}^{-1}\,{\rm galaxy}^{-1}$$

Frank & Rees (1976); Magorrian & Tremaine (1999); Wang & Merritt (2004); Kesen (2012); Stone & Mezer (2016)

SPH simulations (Evans & Kochaneck 1989)



$$L = \dot{M}c^2 \propto t^{-n}$$

Some arguments against $t^{-5/3}$ curve by Lodato et al.(2009) and Park & KH (2020)

Summary for TDE observations

- TDE candidates/suspects/imposters

$$\sim 100$$

- Classification of observed TDEs

1. Thermal, non-jetted TDEs
    # soft-X-rays to optical/UV
    # optical/UV only
    # thermal emissions+ weak radio (2)
    # thermal (?) + non-thermal X-ray (6)
2. Non-thermal, Jetted TDEs
    # hard X-ray and radio (dominant)

- Event rate
    1. Non-jetted TDEs

$$\sim 10^{-7}\,/\mathrm{yr}/\mathrm{Mpc}^3$$

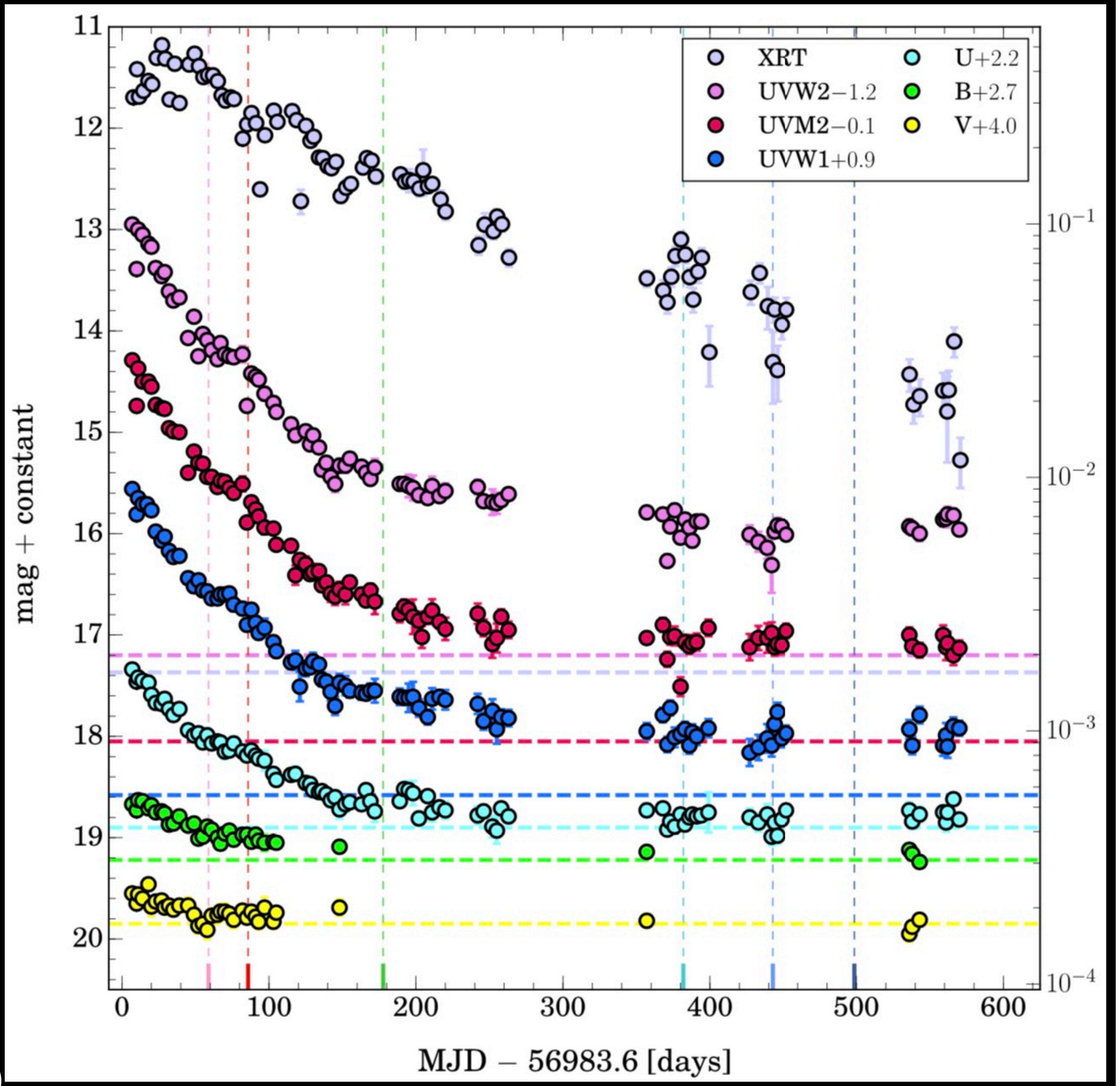
    2. Jetted TDEs

$$\sim 3\times 10^{-11}\,/\mathrm{yr}/\mathrm{Mpc}^3$$

Donley et al. (2002); van Velzen et al. (2014); Leaven et al. (2015); Hung et al. (2018)

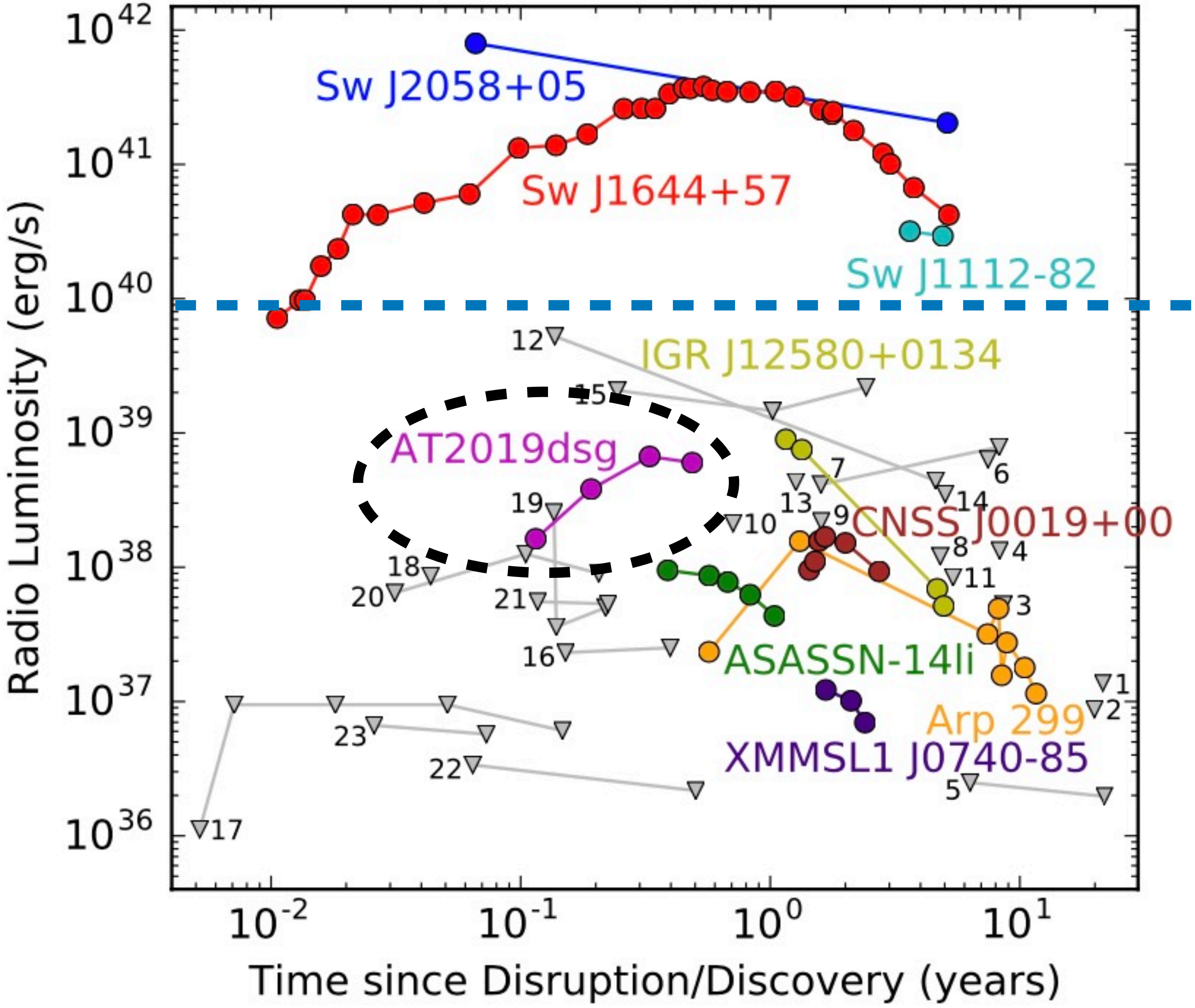
All-Sky Automated Survey for SuperNovae
(ASAS-SN; Shappee et al. 2014)

ASASSN-14li (Brown et al. 2017)



Radio observations of TDEs

Alexander et al. (2020)



Radio-loud TDEs
(3 jetted TDEs)

$$\nu L_\nu = 10^{40}\,\mathrm{erg/s}$$

Radio-quiet TDEs
(6 candidates)

(*) Gray triangles show upper limits for 23 different TDEs. All upper limits are 3σ.

IceCube neutrino - TDE association

ZTF	IceCube
AT2019dsg/ZTF19aapreis	IC191001A
AT2019fdr/ZTF19aatubsj	IC200530A

Stein et al. (2021); Albert et al.(2021)

AT2019dsg: thermal TDE + weak radio

Stein et al. (2021) and van Velzen, S. et al. (2019,2020)

1. Zwicky Transient Facility (ZTF) observation

2. z=0.05

3. Black hole mass: $M_{\rm bh} \sim 5 \times 10^6\, M_\odot$ (Cannizzaro et al. 2020)

4. Shinning brightly from Optical to UV to soft-X-ray wavebands with relatively weak radio emission (VLA):

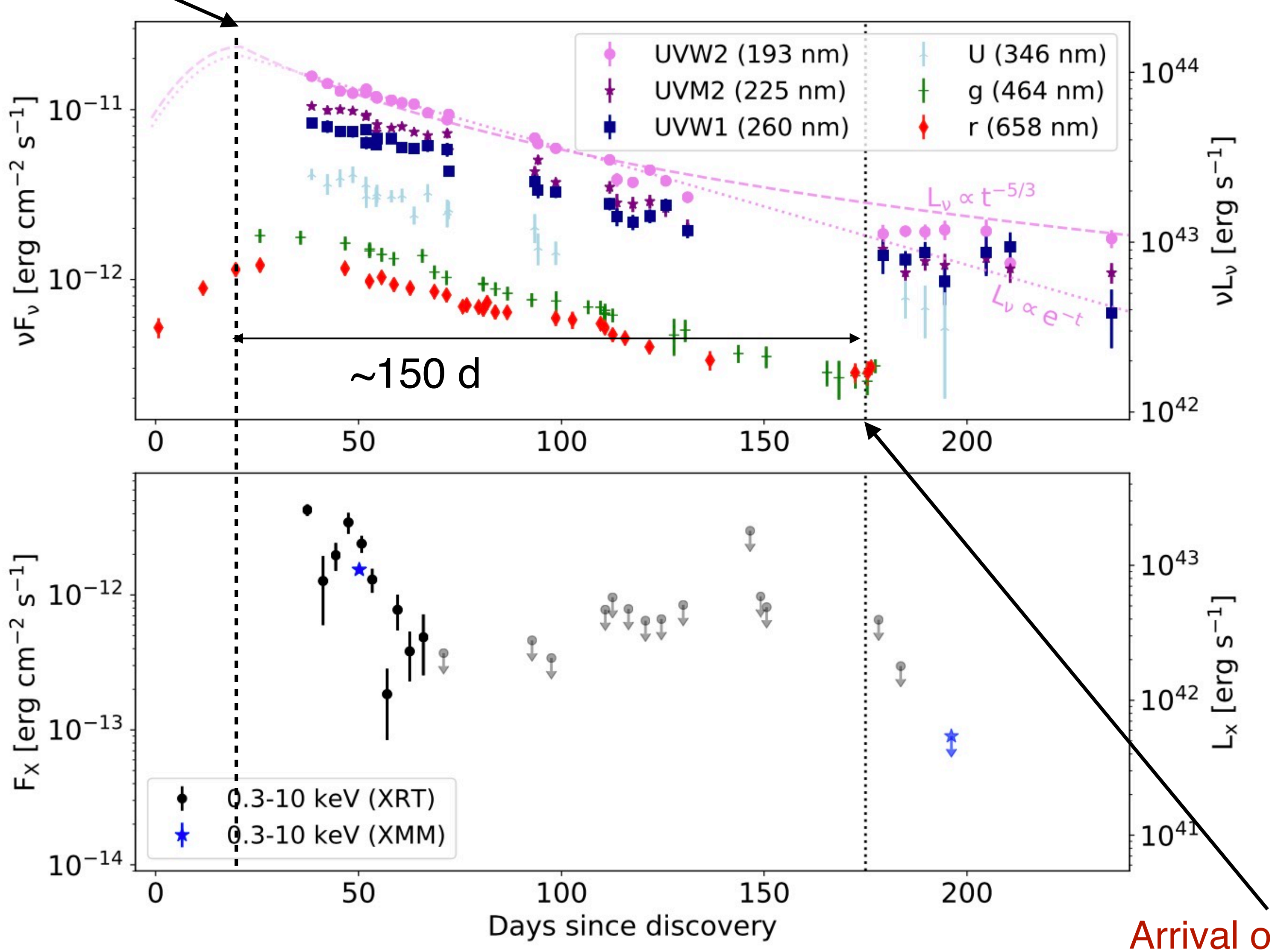
$L_{\rm opt/UV,pk} \sim 10^{44.5}\,{\rm erg/s}$, $L_{\rm X}/L_{\rm opt/UV} \sim 0.1$, and

$L_{\rm radio,pk} \sim 10^{39}\,{\rm erg/s}$

5. There is no clear signature (hard X-ray and γ-rays) of a relativistic Jet

Multi-wavelength observations of AT2019dsg: optical to soft-X-ray wavebands

Stein et al. (2020)



Peak for optical/UV emission

~150 d

Arrival of IC191001A

IceCube neutrino - TDE association

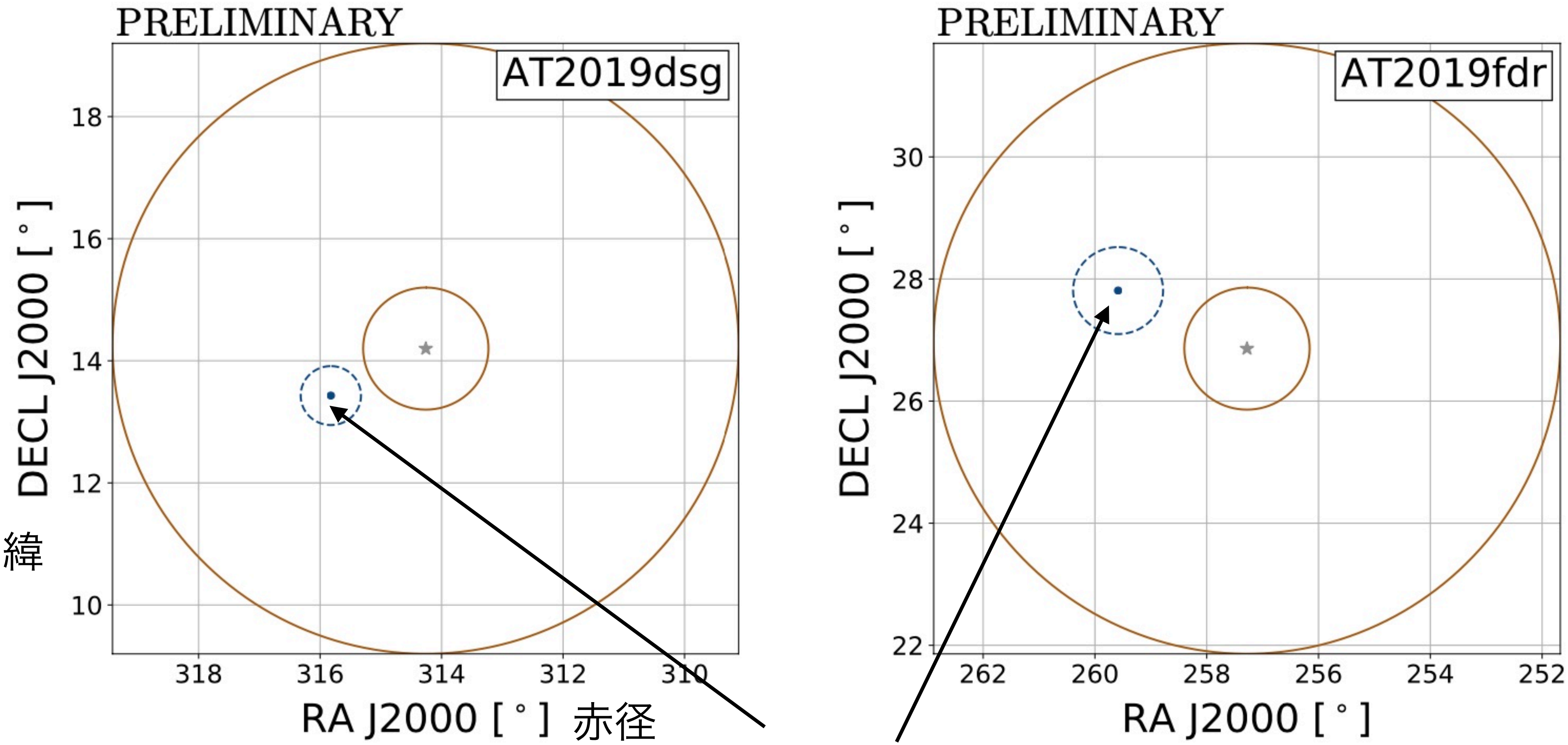
Stein et al. (2020); Albert et al.(2021); Cannizzaro et al.(2020)

	Neutrino energy (PeV)	Delayed time (Days)	Peak optical luminosity (erg/s)	Black hole mass ($M_\odot$)	Redshift	Core
AT2019dsg	~0.2	~150	10^{44-45}	$10^{6.7}$	~0.05	non-AGN
AT2019fdr	~0.08	~300	10^{44-45}	$10^{7.1}$	~0.27	AGN

59% astrophysical origin. The temporal and spatial association
with the TDE increase the probability that the two are associated

Spatial-association

Albert et al.(2021) ANTARES



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Neutrino event

Each neutrino is detected within 5 degree from the corresponding TDE

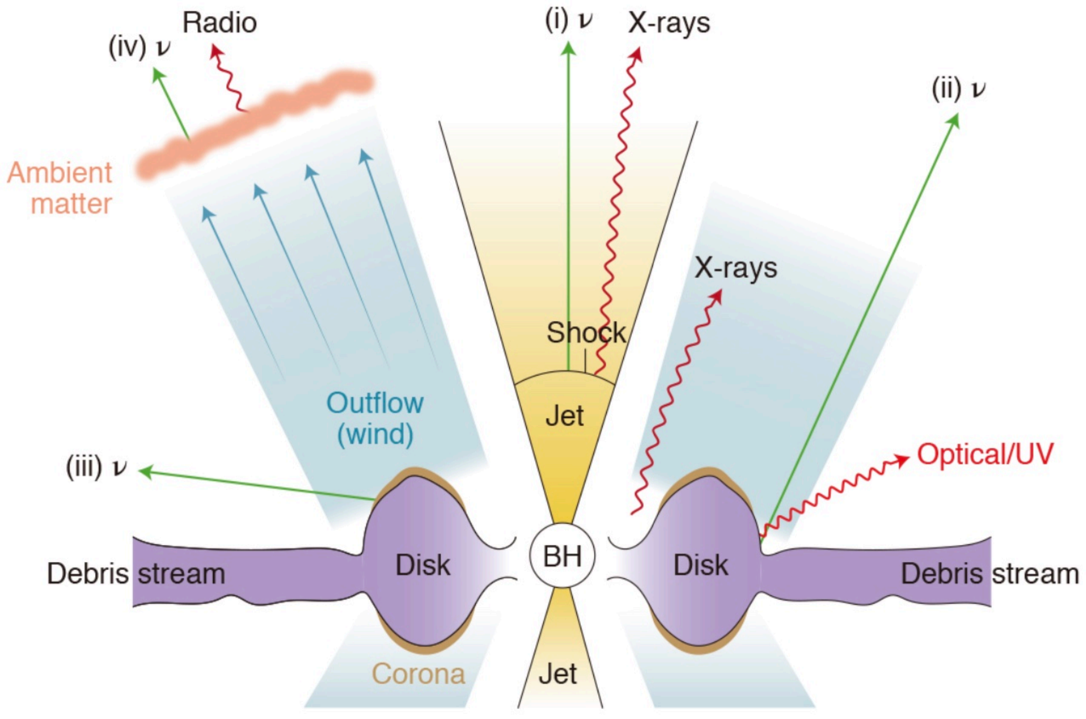
Current Issues

1. No relativistic jet signature
2. Optical/UV + weak radio (+ soft-X-ray) TDEs
3. $L_{\rm peak}^{\rm Opt/UV} \sim L_{\rm Edd}$
4. $M_{\rm bh} \sim 10^7\, M_\odot$
5. Neutrino arrival delay: $\sim 1\ \rm yr$
6. sub-PeV neutrino

PeV energy proton accelerator

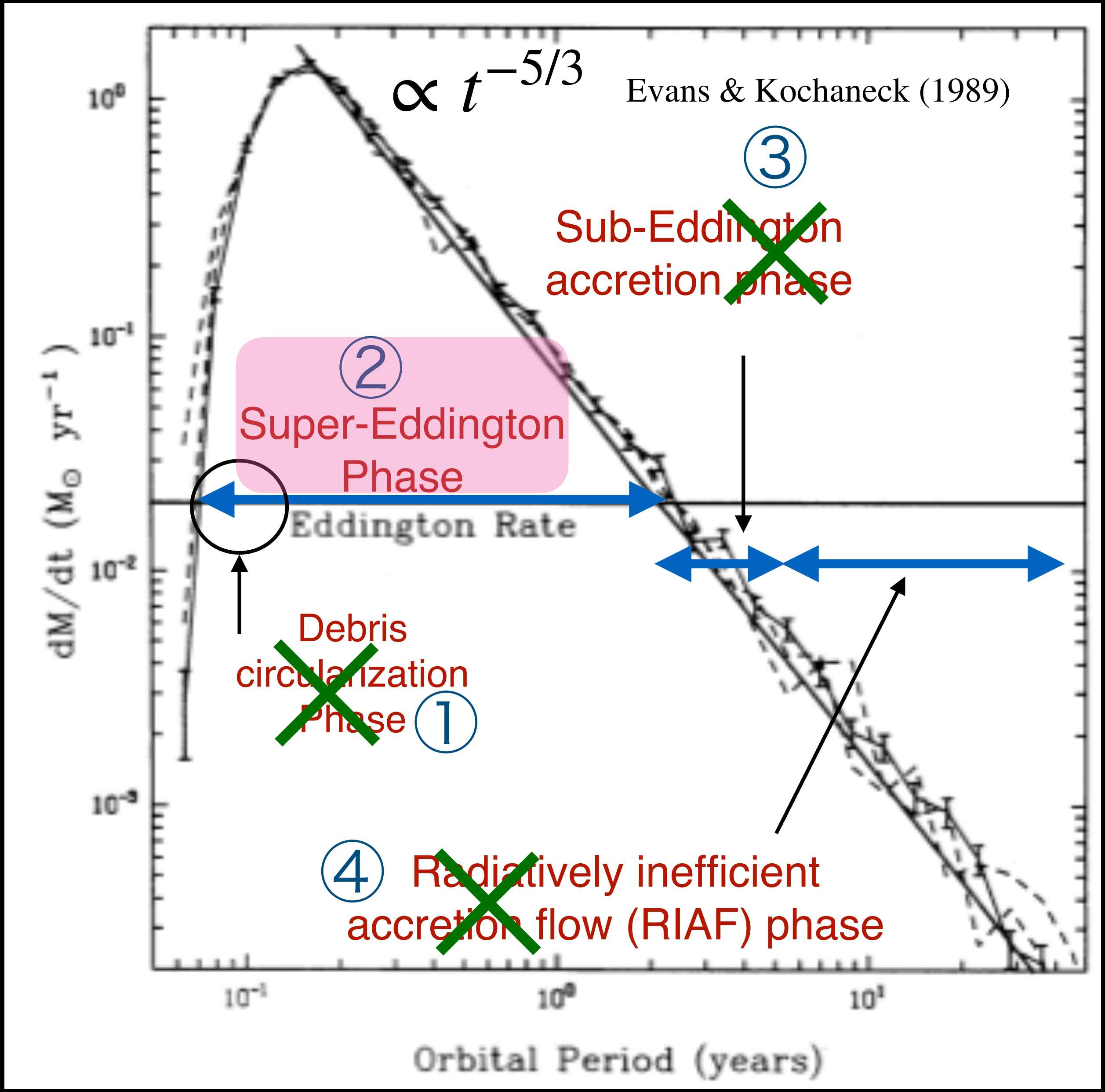
Luminous Disk,
Corona, and etc

Possible sites to produce
High-energy neutrinos in TDEs



KH (2021)

Four main phases in a TDE disk



① Shock by stream-stream collision

Candidate phase for both the 1st order Fermi acceleration and the 2nd one

②〜④ accretion disk

Candidate for the 2nd order Fermi acceleration

MAD B-field

Narayan+2003

Global, poloidal B-field

$$B^2 \sim \frac{GM\Sigma}{r^2} = \overset{v_{\mathrm{ff}}^2}{\boxed{\frac{2GM}{r}}}\,\overset{m_p n}{\boxed{\frac{\dot{M}}{4\pi r^2 v_r}}}$$

M : Black hole mass
B : Magnetic field
v_r : Radial drift velocity
Σ : Surface density
$\dot{M}$: Mass accretion rate

Narayan+2003

$$v_r = \epsilon v_{\mathrm{ff}} \ (\epsilon = 0.001 - 0.1)$$

McKinney+2012

$$B \sim 2.2 \times 10^6 \left(\frac{\epsilon}{0.01}\right)^{-1/2} \left(\frac{M_{\mathrm{bh}}}{10^7 M_\odot}\right)^{-5/12} \mathrm{G}$$

Acceleration time for the 2nd order Fermi

cf. Kimura et al. (2015)
KH & Yamazaki (2019)

$$\text{Accerelation time} : t_{\text{accl}} \equiv p^2/D_p$$

$\text{Proton's momentum} : p$

$\text{Mometum diffusion coefficient} : D_p$

$$t_{\text{accl}} \propto M_{\text{bh}}^{-2/9} B^{-7/3} \gamma^{1/3} \propto 1/B^{7/3}$$

γ : Lorenz factor $\quad$ B : magnetic field strength

As B-field is stronger, the acceleration time is shorter

Maximum proton's energy

$$t = t(\epsilon)$$

Protons can accelerate up to the energy at

$$t_{\mathrm{acc}} = \mathrm{MIN}\underbrace{[t_{\mathrm{inf}}, t_{\mathrm{relax}}, t_{\mathrm{Coul}}, t_{\mathrm{Cd}}, t_{\mathrm{diff}}, t_{\mathrm{pp}}, t_{\mathrm{sync}}, t_{\mathrm{p}\gamma}]}_{\text{Timescales of processes to prevent protons accelerating}}$$

Timescale of each process to prevent protons accelerating 1

$(\text{Common parameters}: r = r_\mathrm{t}, \alpha = 0.1, \zeta = 0.1, H/r \sim 1)$

cf. Kimura et al. (2015)
KH & Yamazaki (2019)

Accretion time of the disk

$$\text{Infall time}: t_\mathrm{inf} = \frac{r}{v_r} \lesssim 1.0 \times 10^5\,\mathrm{s} \left(\frac{M_\mathrm{bh}}{10^7\,M_\odot}\right)^{-1/2}$$

Timescale for the system to thermlize (keeping non-thermal distribution of the protons)

$$\text{pp relaxation time}: t_\mathrm{relax} \sim 1.6 \times 10^5\,\mathrm{s} \left(\frac{\dot{M}/\dot{M}_\mathrm{Edd}}{1.0}\right)^{-1} \left(\frac{M_\mathrm{bh}}{10^7\,M_\odot}\right)$$

Energy loss timescale of accelerated protons by Coulomb collision with lower energy protons

$$\text{Coulomb loss time}: t_\mathrm{Coul} \sim 1.2 \times 10^8\,\mathrm{s} \left(\frac{\gamma}{10^5}\right) \left(\frac{\dot{M}/\dot{M}_\mathrm{Edd}}{1.0}\right)^{-1} \left(\frac{M_\mathrm{bh}}{10^7\,M_\odot}\right)^{-1/2}$$

$$t_\mathrm{inf} \ll t_\mathrm{relax}, t_\mathrm{Coul}$$

Timescale of each process to prevent protons accelerating 2

Protons can spatially diffuse

$$\text{Diffusion time}: t_{\rm diff} \propto M_{\rm bh}^{4/9} B^{1/3} \gamma^{-1/3}$$

cf. Kimura et al. (2015)
KH & Yamazaki (2019)

Cooling by proton synchrotron emissions

$$\text{Sybchrotron cooling time}: t_{\rm sync} \propto B^{-2} \gamma^{-1}$$

Cooling by inelastic p-p collision

$$\text{pp collision time}: t_{\rm pp} \propto M_{\rm bh}^{1/2} \dot{M}^{-1} \beta^{-5/2}$$

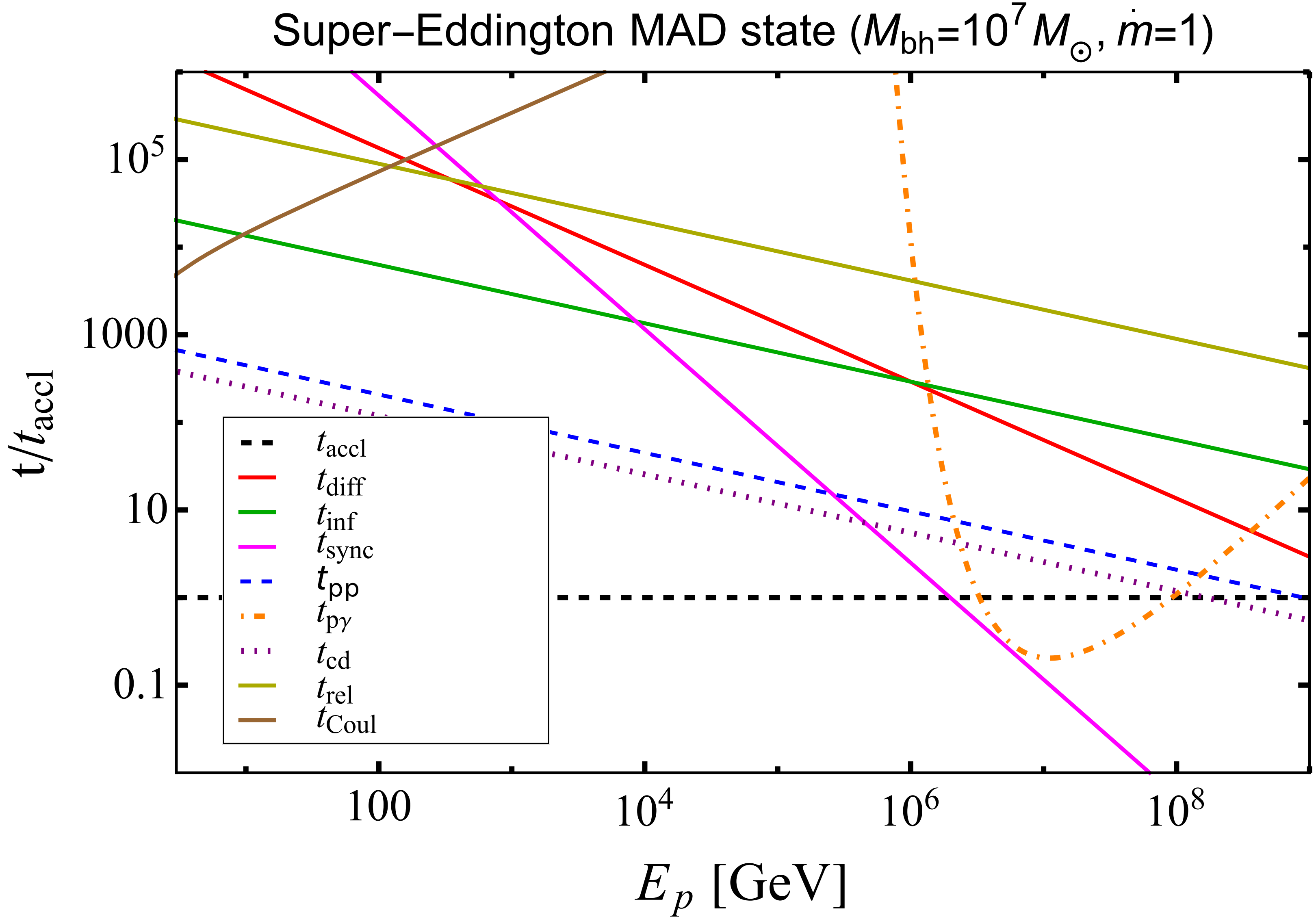
Wave dumping by the Compton drag

$$\text{Compton drag time}: t_{\rm cd} \propto M_{\rm bh}^{4/3} B^{2} \tau^{-1} \eta_p^{-1} \dot{M}^{-1}$$

τ : Thomson's optical depth $\quad$ η_p : conversion efficincy

Super-Eddington MAD case

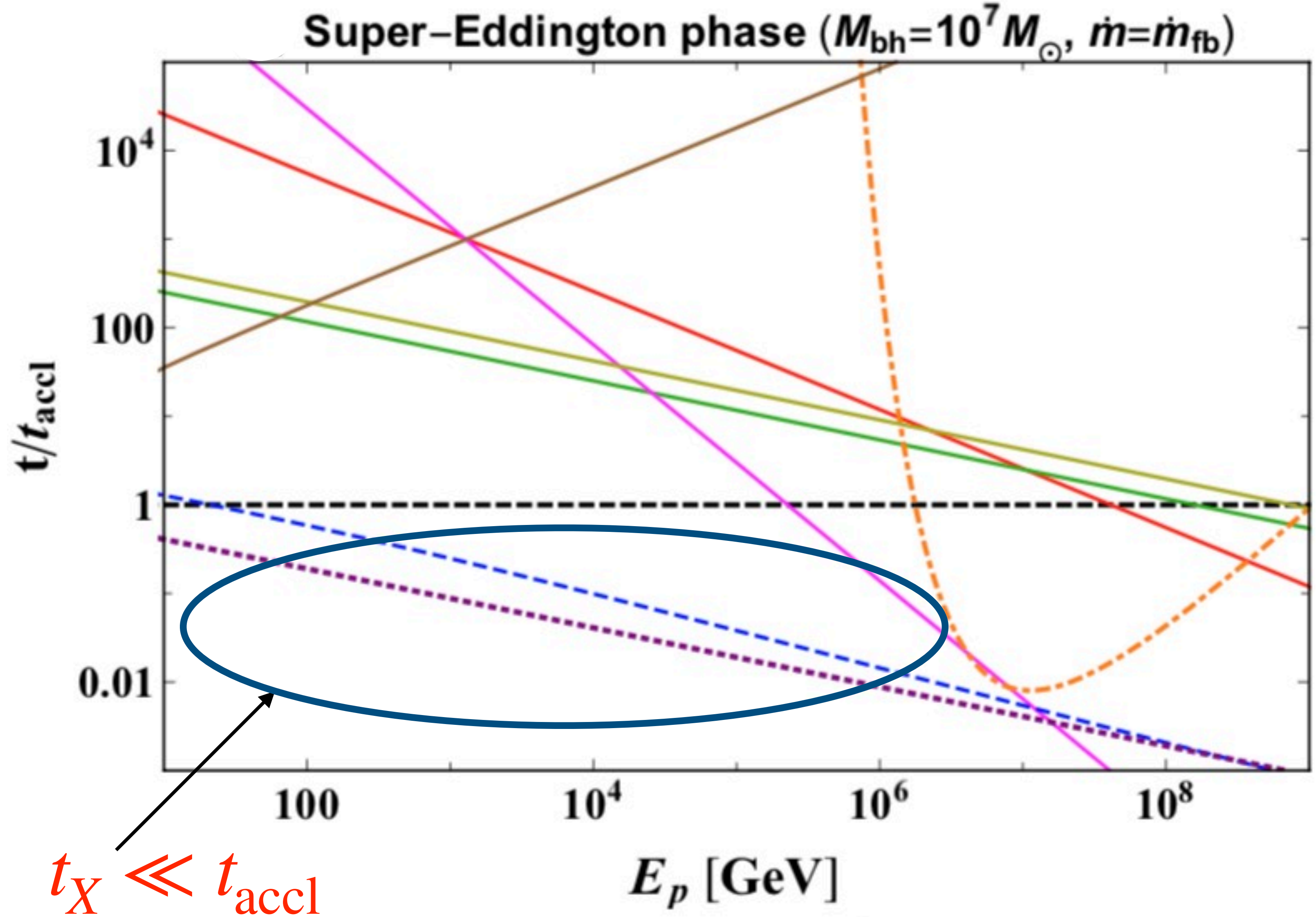
KH & Yamazaki (2019)



$$E_{p,\max} \sim \mathcal{O}(1)\,\mathrm{PeV}$$

Super-Eddington non-MAD case

KH & Yamazaki (2019)



$t_X \ll t_{\rm accl}$

High-energy particles are unlikely to be produced

An explanation for neutrino arrival delay

	Neutrino energy (PeV)	Delayed time from the optical peak (Days)
AT2019dsg	~0.2	~150
AT2019fdr	~0.08	~300

Primitive explanation (Stein et al. 2020)

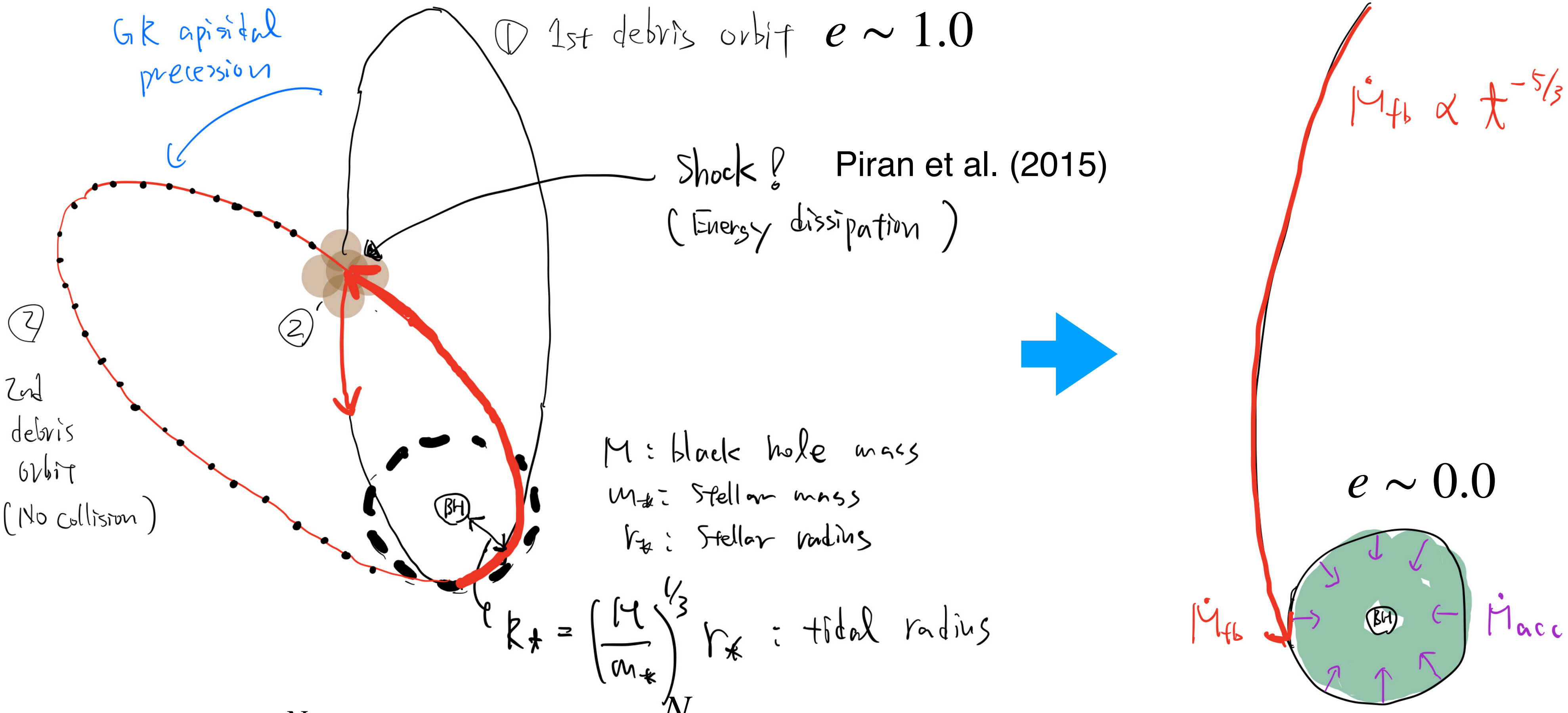
The probability to detect a single neutrino should be constant if the neutrino flux is constant

$(\dot{M}_{\rm acc} = \text{constant})$

Fallback to a SMBH and subsequent circularization

Early times (after tidal disruption)

Late times



$e \sim 1.0$

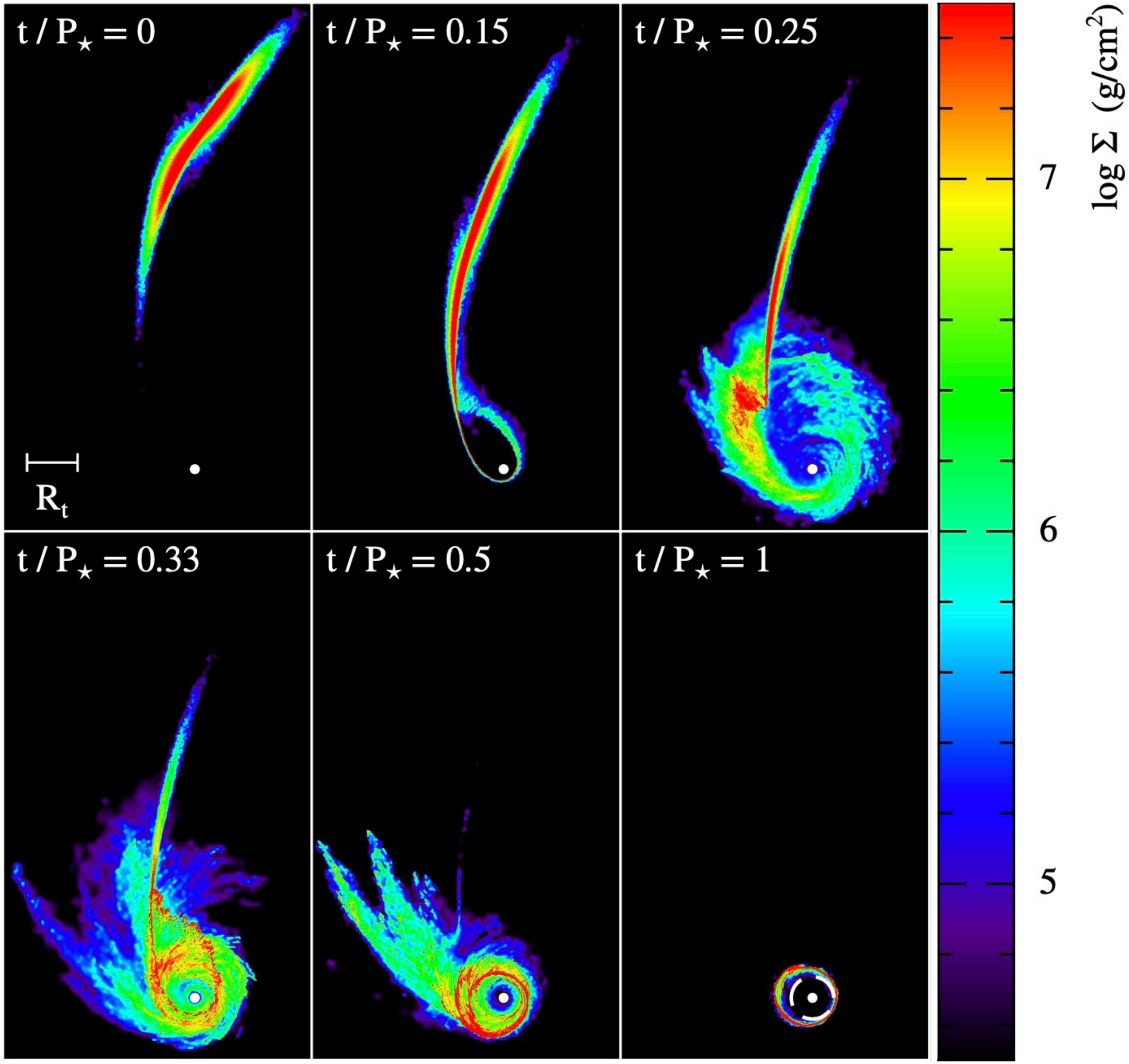
Piran et al. (2015)

$e \sim 0.0$

$$\Delta\epsilon = \frac{GM}{r_{\rm circ}} = \sum_{N=0}^{N_{\rm ev}} \Delta\epsilon_N \qquad t_{\rm circ} = \sum_{N=0}^{N_{\rm ev}} P_N$$

Efficient circularization case

Bonnerot et al. (2016); KH et al. (2013, 2016)



Circularization timescale

Bonnerot et al. (2017)

$$t_{\rm circ} = \sum_{N=0}^{N_{\rm ev}} P_N \approx 8.3\,\beta^{-3} \left(\frac{M_{\rm bh}}{10^6 M_\odot} \right)^{-5/3} t_{\rm mtb}$$

P_N :the debris orbital period of Nth orbit

$t_{\rm mtb}$: period of the most tightly bound orbit

KH & Jonker (2021)

[Introduction of the circularization efficiency and mass-radius relation to above Bonnerot's formula]

$$t_{\rm circ} \approx 0.57\,\beta^{-3} \left(\frac{\eta}{0.1} \right)^{-1} \left(\frac{M_{\rm bh}}{10^7\, M_\odot} \right)^{-7/6} \left(\frac{m_*}{1\, M_\odot} \right)^{8/25} \,{\rm yr}$$

Summary

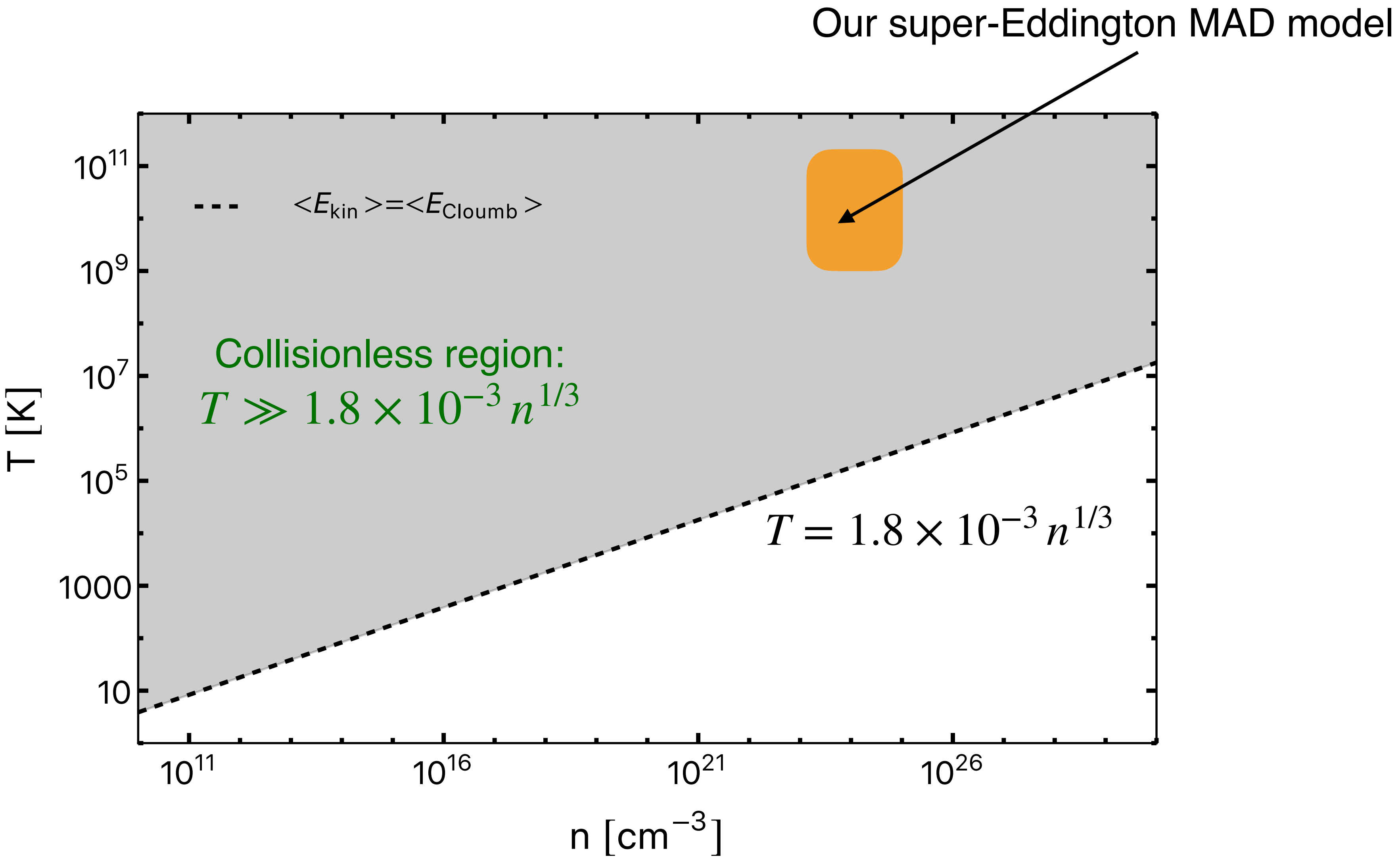
Two neutrino-TDE associations have been found.

1. No relativistic jet signature
2. Optical/UV + weak radio (+ soft-X-ray) TDEs
3. $L_{\rm peak}^{\rm Opt/UV} \sim L_{\rm Edd}$
4. $M_{\rm bh} \sim 10^7\,M_\odot$
5. Neutrino arrival delay: $\sim 1\,{\rm yr}$
6. sub-PeV neutrino

If these associations could be true…(cf. many high-energy physicists have yet a reservation, though)

While a relativistic jet model itself is hard to explain these associations, a super-Eddington MAD model looks plausible for explaining them. The other models are also welcome.

Condition for an ionized gas to be collisionless



Our super-Eddington MAD model

$$\langle E_{\rm kin} \rangle = (3/2)kT$$

$$\langle E_{\rm Coulomb} \rangle = q^2/r \sim q^2\, n^{1/3}$$

r : average distance between particles

q : elementary charge in esu $\quad n$: number density