Neutrino emissions from accretion disks in tidal disruption events

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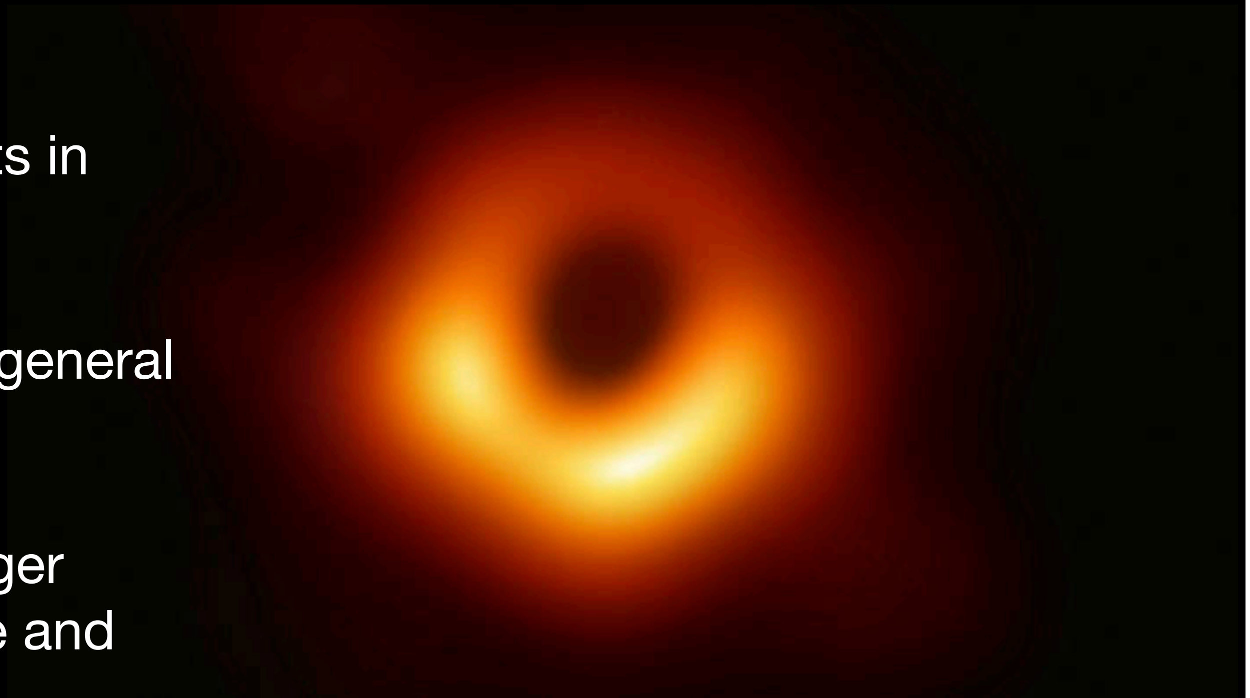
Scientific motivation to study tidal disruption events (TDEs)

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

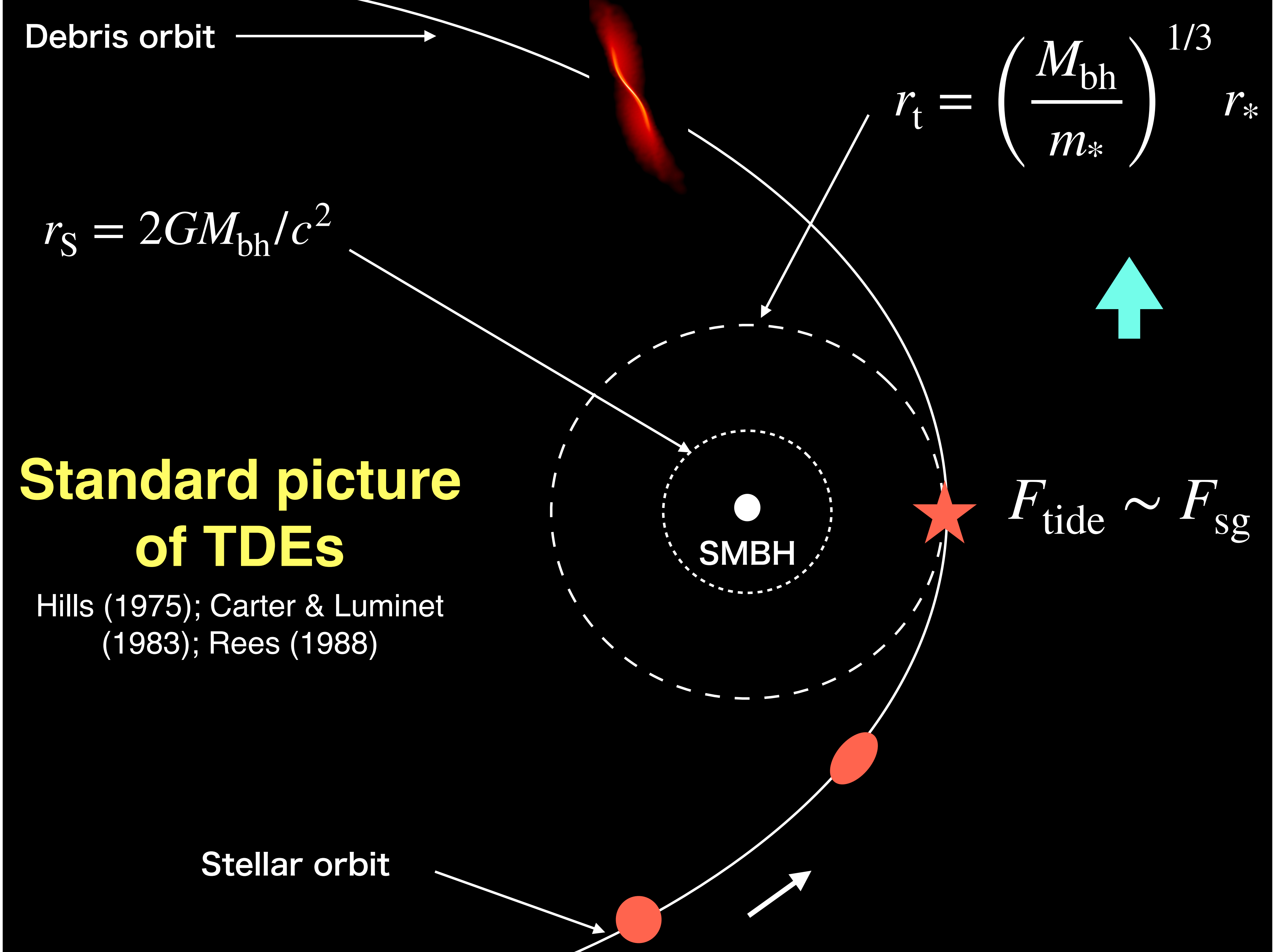
2. Among the brightest transients in optical/UV/soft X-ray

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

4. Candidates for multi-messenger astronomy: gravitational wave and **cosmic-ray/neutrino sources**



EHT collaboration 2019
https://eventhorizontelescope.org/


Debris orbit
$r_t = \left(\frac{M_{bh}}{m_*}\right)^{1/3} r_*$
$r_S = 2GM_{bh}/c^2$
Standard picture of TDEs
Hills (1975); Carter & Luminet (1983); Rees (1988)
SMBH
$F_{tide} \sim F_{sg}$
Stellar orbit

Condition for TDEs (non-spinning case)

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

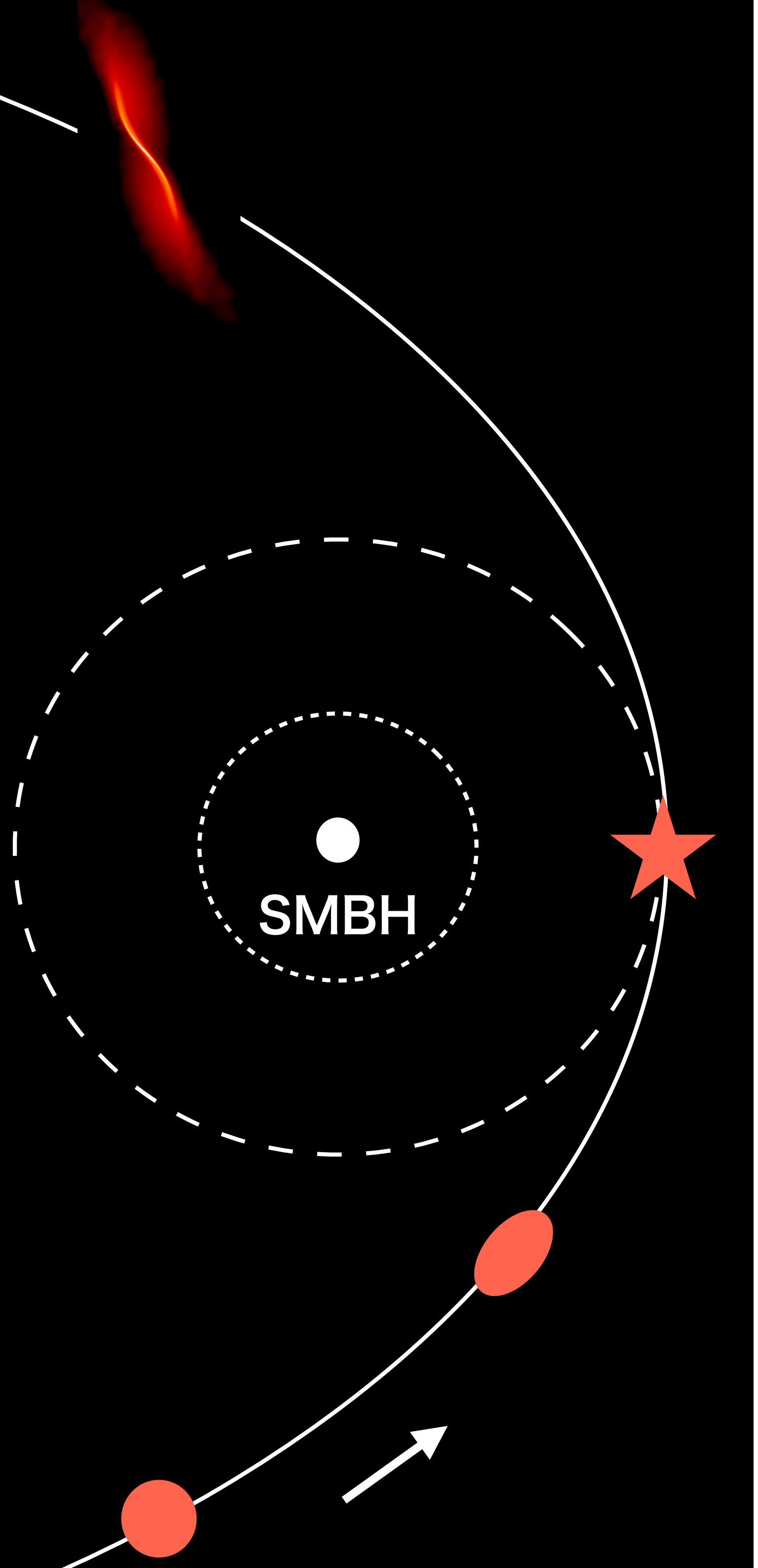
↓

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

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

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

- Duration time of TD flare

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

- Effective temperature (Ulmer 1999)

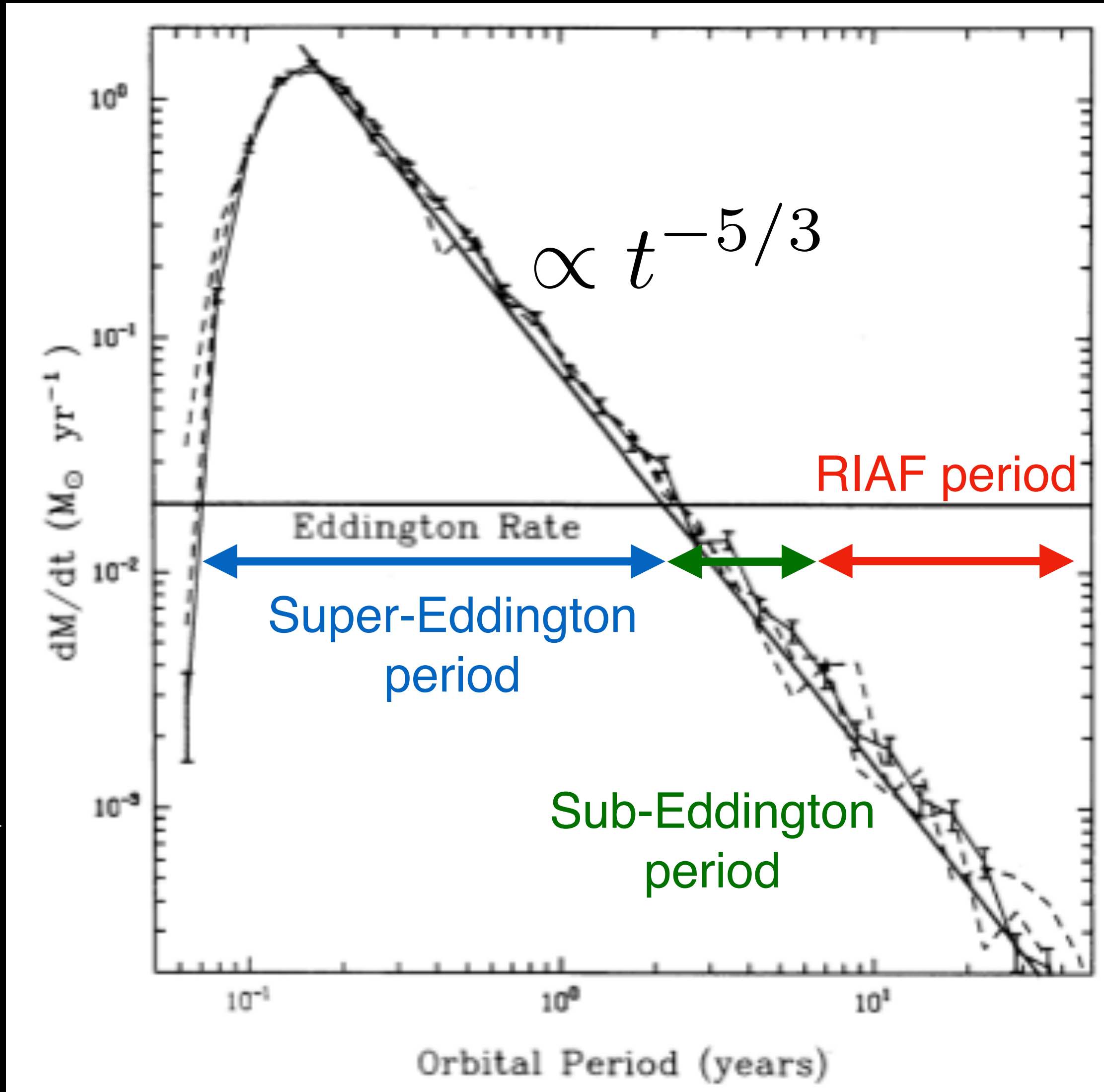
$$T_{\rm eff} = \left(\frac{L_{\rm Edd}}{4\pi\sigma_{\rm SB} r_{\rm t}^2}\right)^{1/4} \sim 3\times10^5\,M_6^{1/12}\,{\rm K}$$

- 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)



Some arguments against $t^{-5/3}$ curve by Lodato et al.(2009) and Park & Hayasaki (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 (or optical only)
     # thermal emissions+ weak radio
  3. **Non-thermal (Jetted) TDEs**
     # hard X-ray and radio (dominant)

- Event rate

  1. Non-jetted TDEs

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

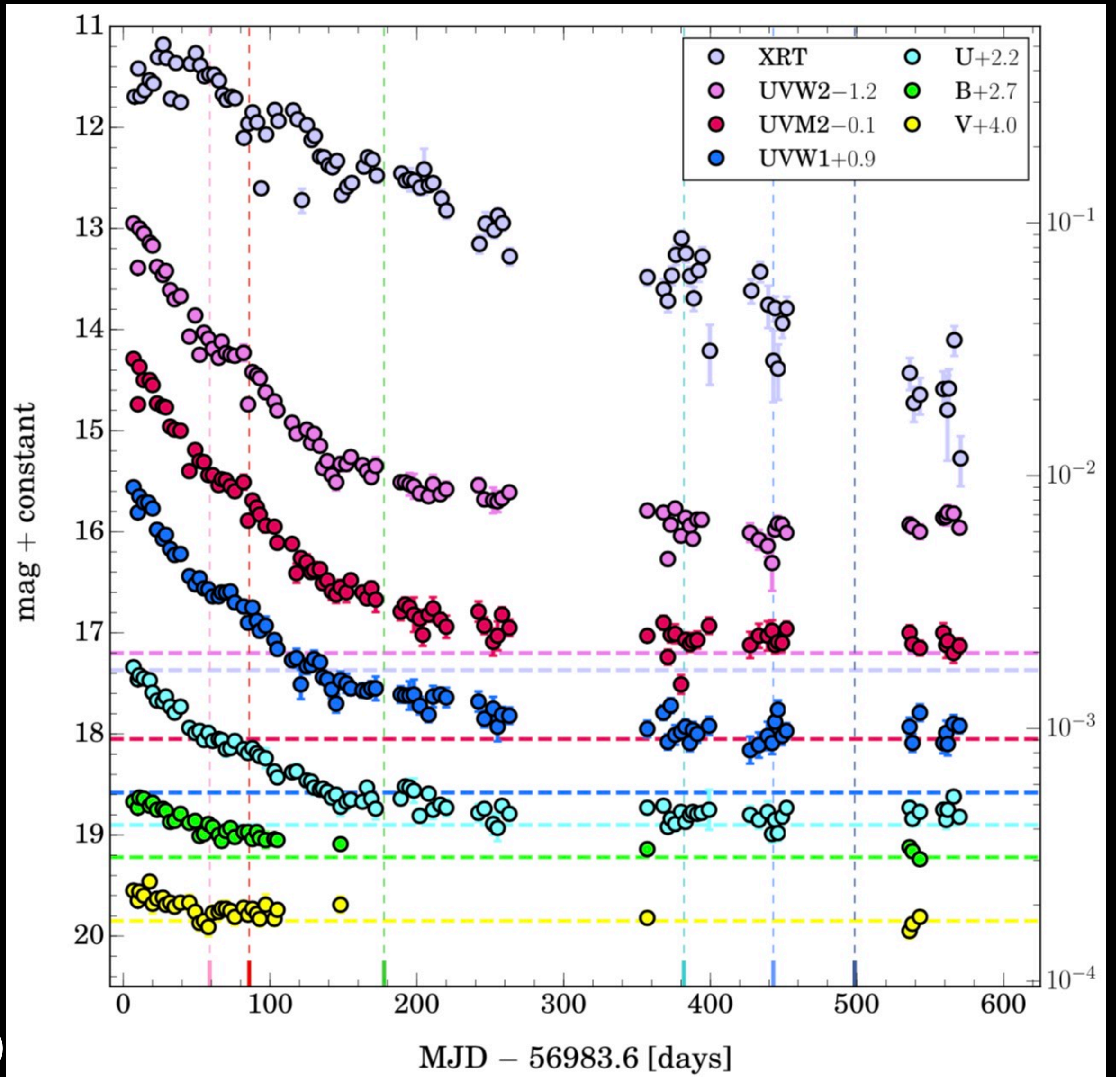
  2. Jetted TDEs

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

Donley et al. (2002); van Velzen et al. (20 14); Leaven et al. (2015); Hung et al. (2018)

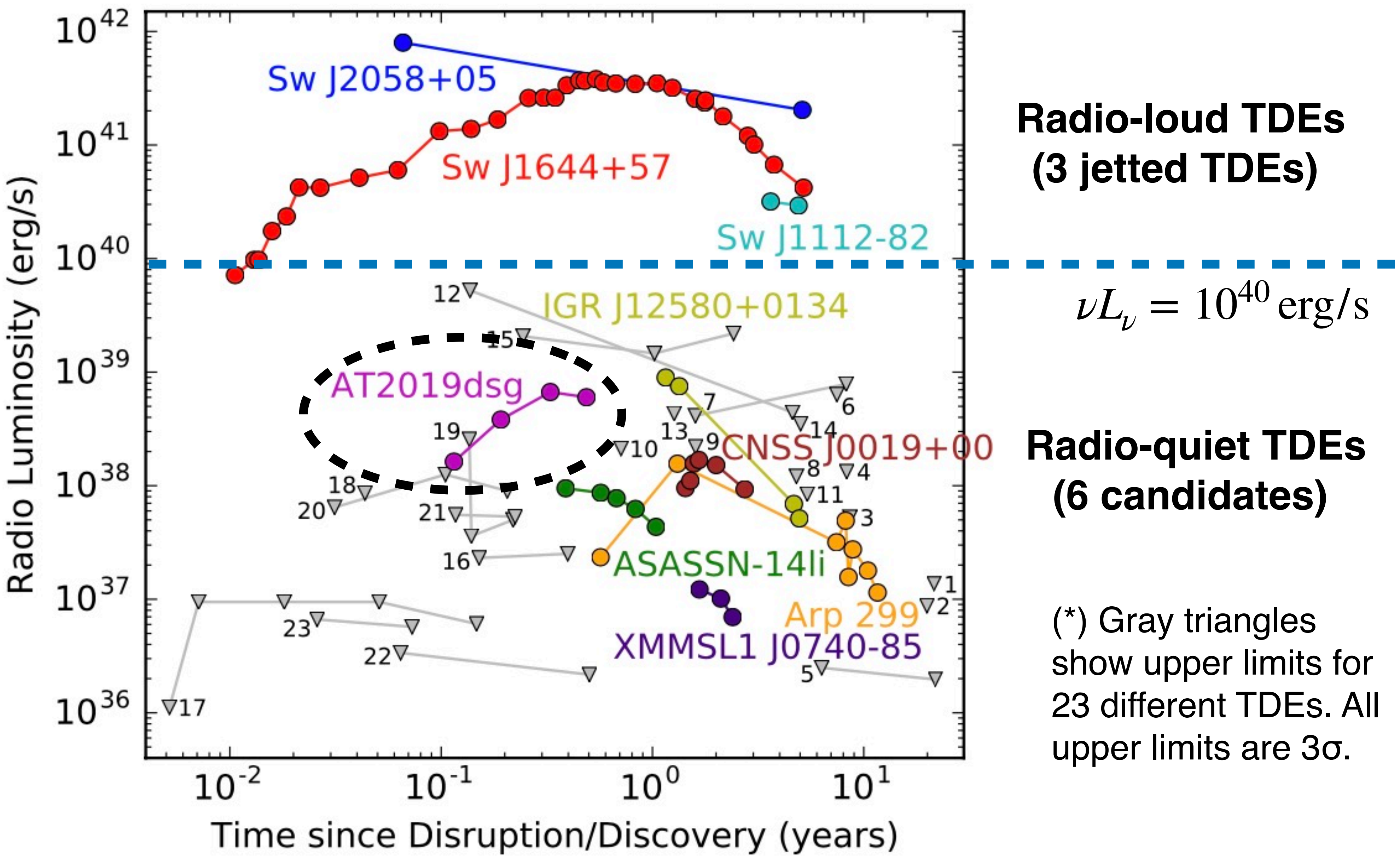
All-Sky Automated Survey for SuperNovae (ASAS-SN; Shappee et al. 2014)

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.

IC191001A - AT2019dsg association

Stein et al. (2020)

AT2019dsg: thermal TDE + weak radio

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

1. Observed by Zwicky Transient Facility (ZTF)

2. z=0.015 (~230 Mpc)

2. Black hole mass ($M_{\rm bh} = 3 \times 10^7 \, M_\odot$)

4. Shinning brightly fro Optical to UV to soft-X-ray

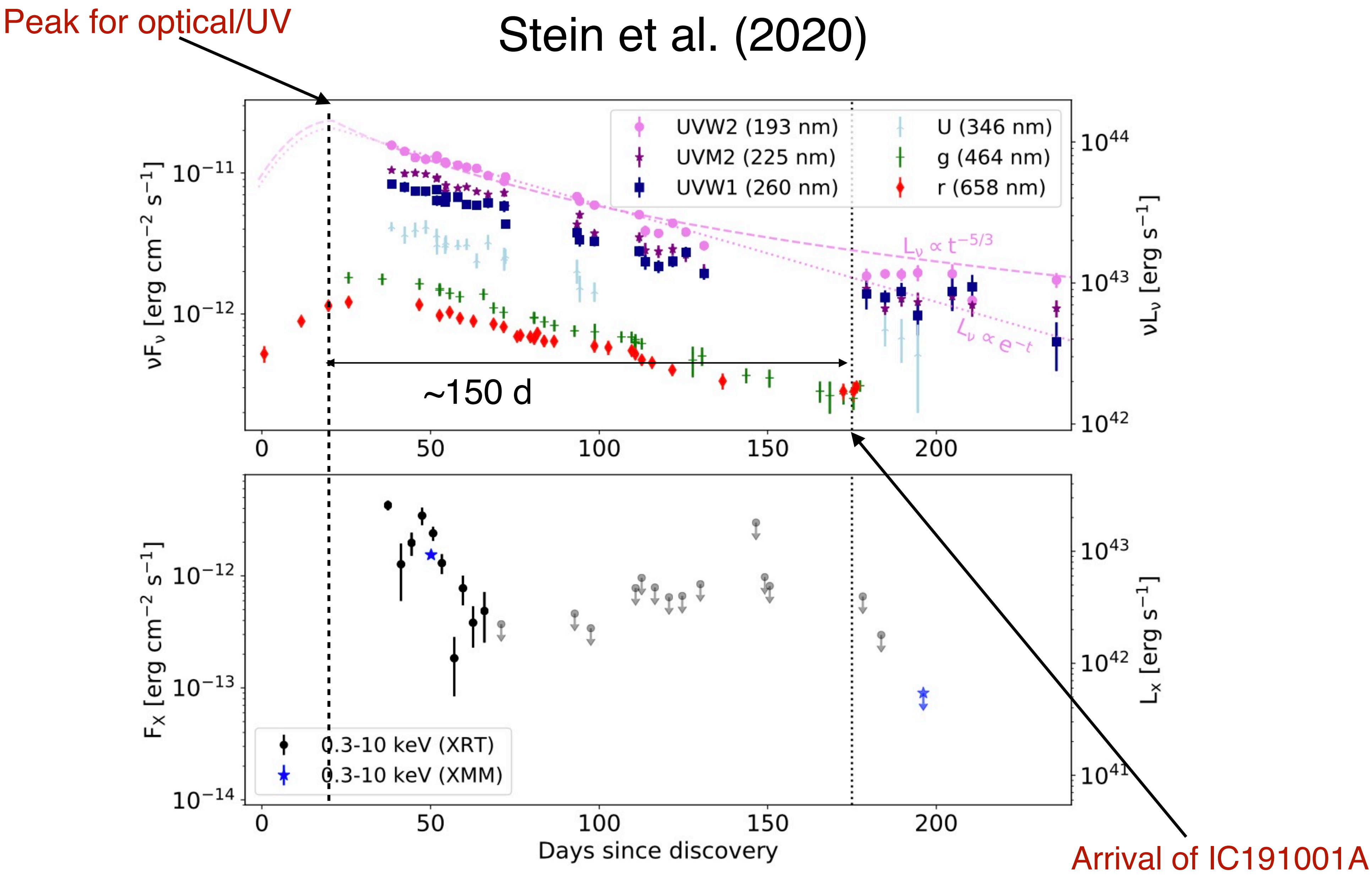
wavebands with relatively weak radio emission (by VLA):

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

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

5. There is no clear signature (e.g., γ-rays) of a relativistic Jet

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



IC191001A - AT2019dsg association

1. sub-PeV neutrino ($\sim 0.2\,\mathrm{PeV}$)

2. ~150 day delay from the optical/UV peak

3. soft-X-ray BB radius ($\sim 2 \times 10^{11}\,\mathrm{cm}$) is much smaller than $R_\mathrm{S} \sim 10^{13}\mathrm{cm}$

4. Probability being an astrophysical origin is 59%. The temporal and spatial association with the TDE increase the probability that the two are associated.

Possible sites to produce neutrinos in TDEs

1. **Relativistic Jet (internal/external shocks)**

   Wang et al. (2010); Dai & Fang (2017);
   Senno et al. (2017); Lunardini & Winter (2017);
   Winter & Lunardini (2020); Liu et al. (2020)

2. **Outflow/Wind**

   Murase et al. (2020)

3. **Corona**

   Murase et al. (2020)

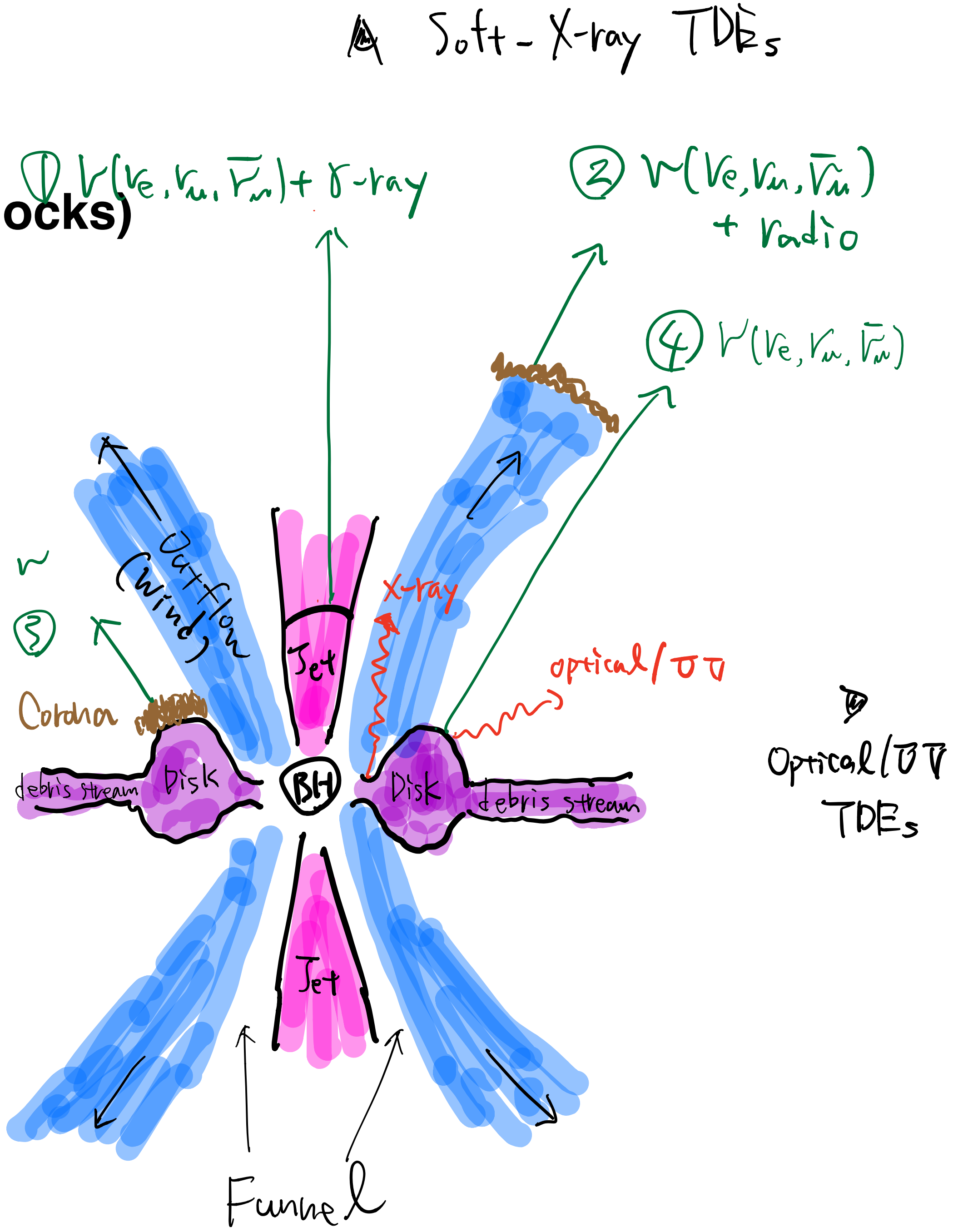
4. **Disk (RIAF/super-Eddington MAD)**

   Hayasaki & Yamazaki (2019)

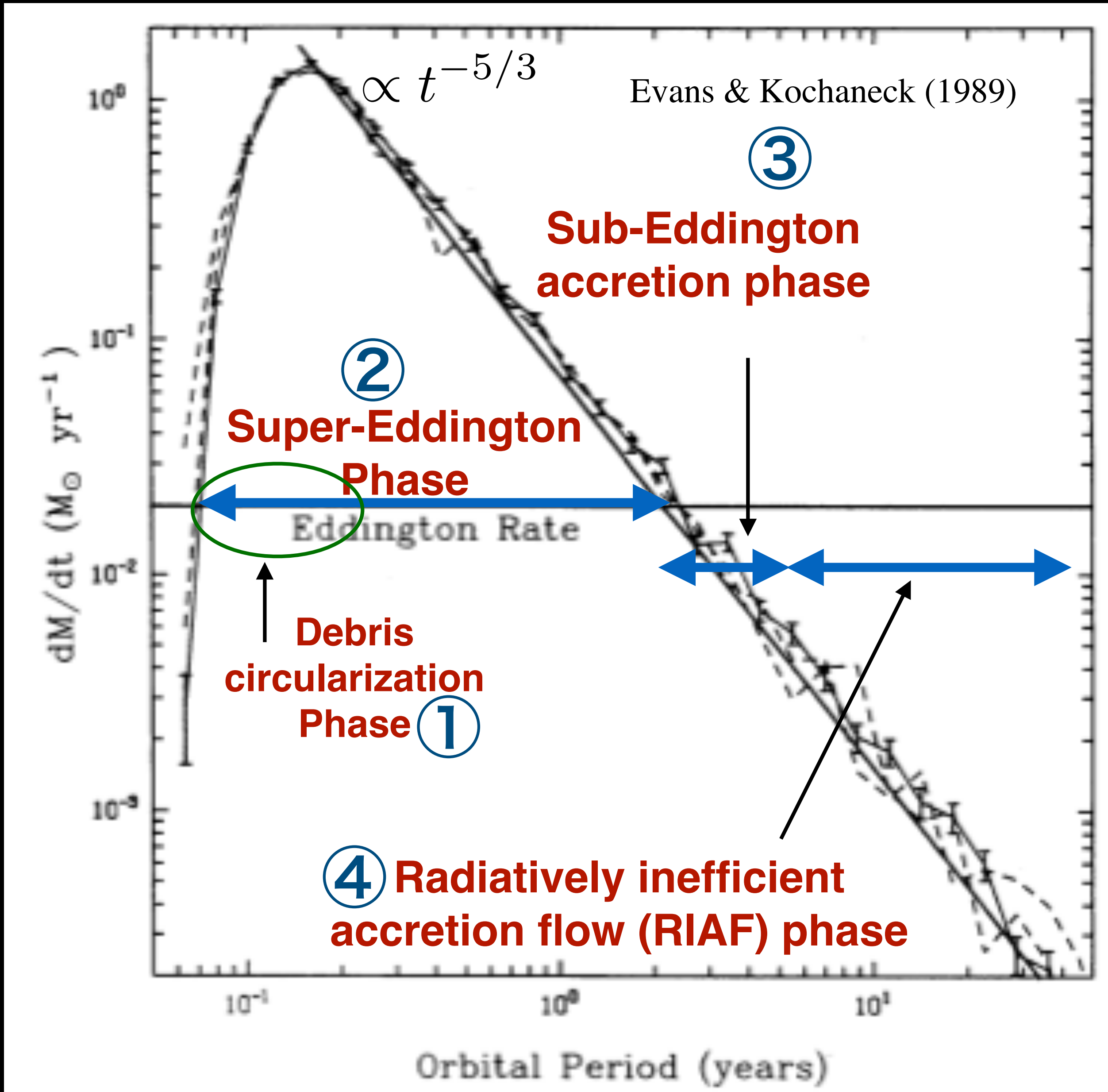
5. **Fifth source**

   Stream-stream collision driven wind?

   Murase et al. (2020)



Four main phases in a tidal disruption remnant (TDR)



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

Four main phases in a TDR

Hayasaki & Yamazaki, ApJ, 886, 114 (2019)

$$\begin{cases} (1)\ t_{\rm mtb} < t \lesssim t_{\rm circ} & \dot{M} \gg \dot{M}_{\rm Edd} & \text{Circularization phase} \\ (2)\ t_{\rm circ} \lesssim t \lesssim t_{\rm Edd} & \dot{M} \gg \dot{M}_{\rm Edd} & \text{Super-Eddington phase} \\ (3)\ t_{\rm Edd} \lesssim t \lesssim t_{\rm RIAF} & \dot{M} < \dot{M}_{\rm Edd} & \text{Sub-Eddington phase} \\ (4)\ t_{\rm RIAF} \lesssim t & \dot{M} \ll \dot{M}_{\rm Edd} & \text{ADAF/RIAF phase} \end{cases}$$

For a solar-type star

$$t_{\rm mtb} \sim 1.0 \times 10^7\,{\rm s} \left(\frac{M_{\rm bh}}{10^7\,M_\odot}\right)^{1/2}$$

$$t_{\rm circ} = \frac{\Delta\epsilon_{\rm circ}}{\eta_{\rm circ}\dot{M}c^2} \sim 1.8 \times 10^7\,{\rm s} \left(\frac{\eta_{\rm circ}}{0.1}\right)^{3/2} \left(\frac{\beta}{1.0}\right)^{-3/2} \left(\frac{M_{\rm bh}}{10^7\,M_\odot}\right)^{-1/2}$$

$$t_{\rm Edd} \sim 1.1 \times 10^8\,{\rm s} \left(\frac{M_{\rm bh}}{10^7\,M_\odot}\right)^{-2/5} \qquad t_{\rm RIAF} \sim 1.7 \times 10^9\,{\rm s} \left(\frac{\dot{m}}{0.01}\right)^{-3/5} \left(\frac{M_{\rm bh}}{10^7\,M_\odot}\right)^{-2/5}$$

Particle acceleration mechanisms

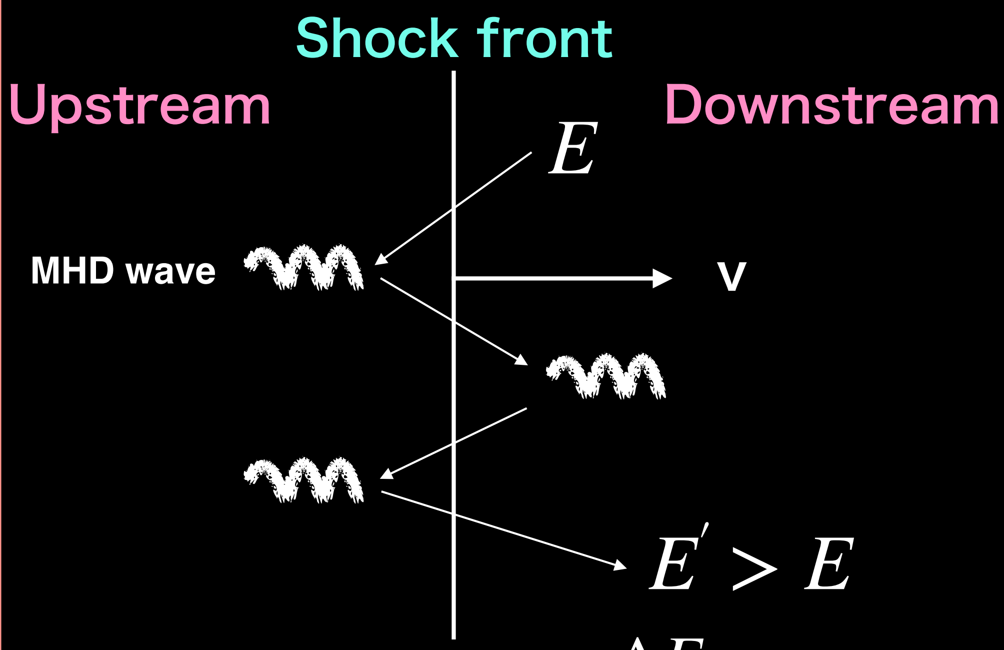
Two types of Fermi acceleration

e.g., Petrosian (2012) arXiv:1205.2136

TDR (disk) case

$$\frac{v}{c} \lesssim 10^{-1}$$

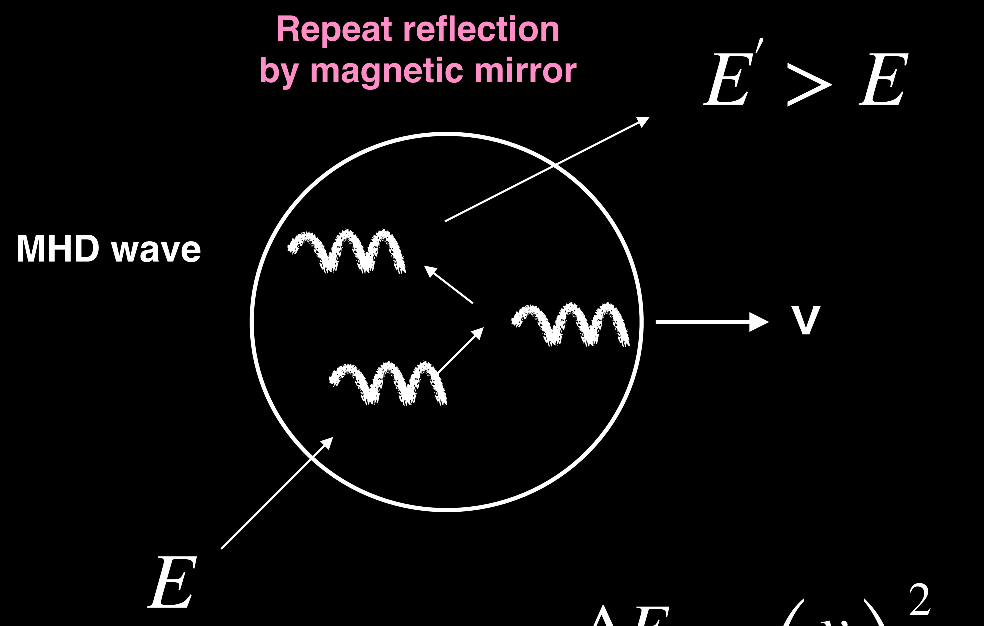
1st order in a shock



Net gained energy: $\frac{\Delta E}{E} \sim \frac{v}{c}$

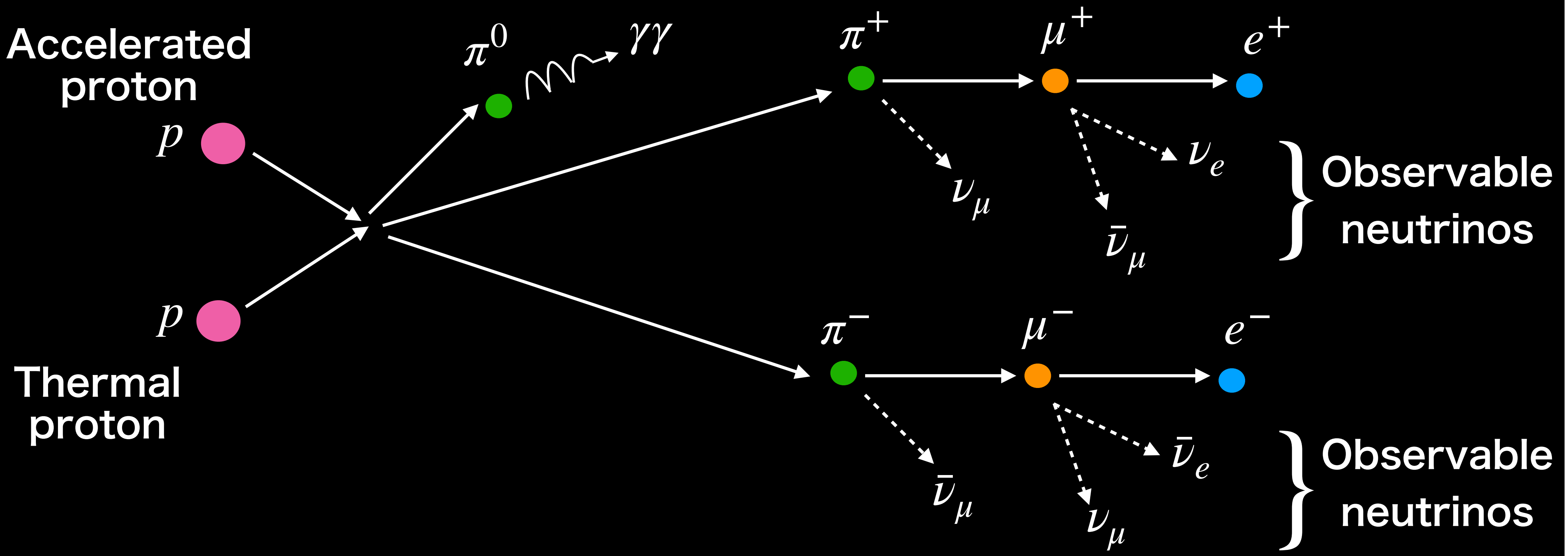
2nd order in a turbulent gas

Head-on collision



Net gained energy: $\frac{\Delta E}{E} \sim \left(\frac{v}{c}\right)^2$

Neutrino production by p-p interaction



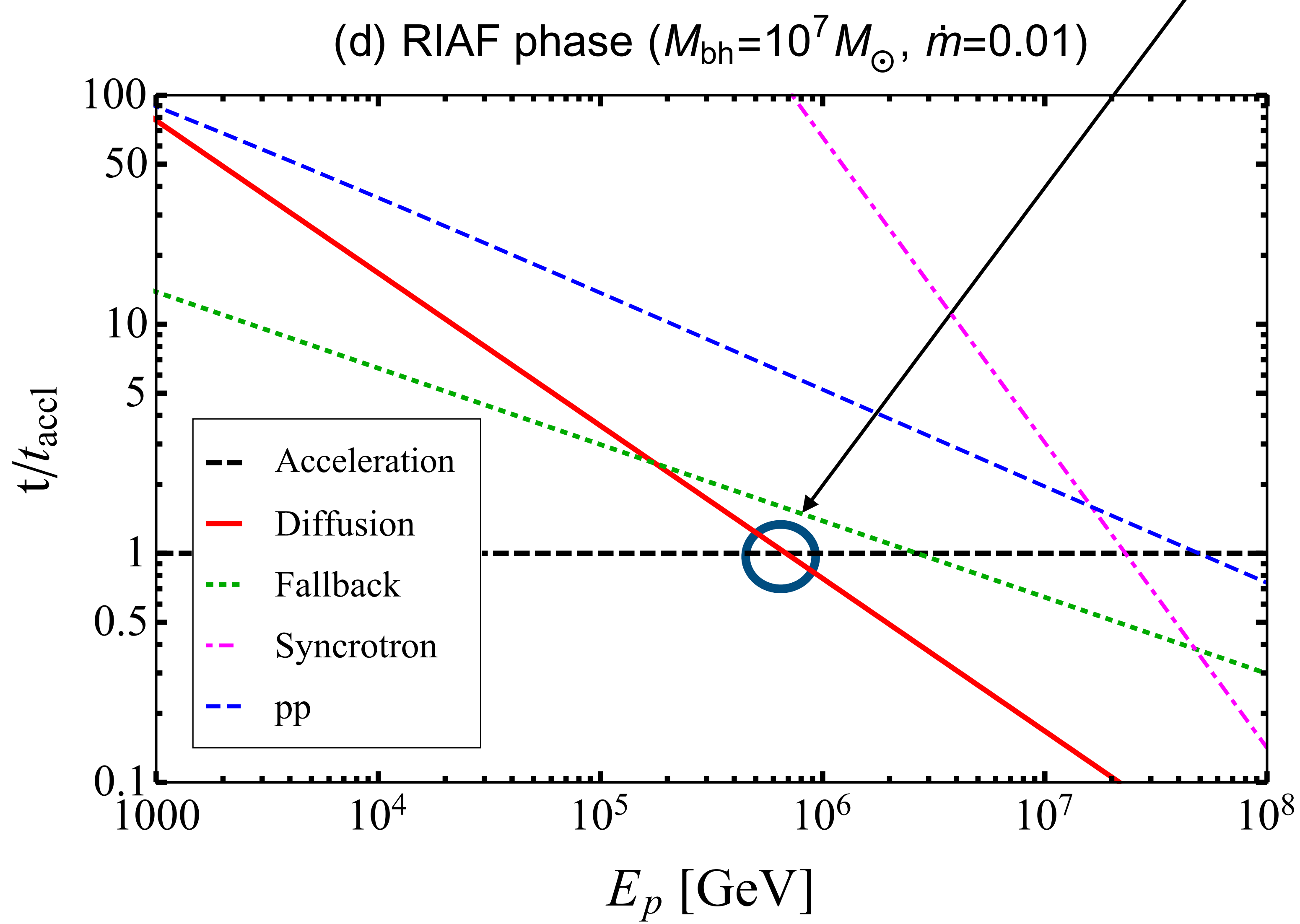
1. p-p collisions produces three types of pions $\epsilon_\pi/\epsilon_p \sim 0.2$
2. pi⁰ decays into two gamma-ray photons $\epsilon_\gamma/\epsilon_p \sim 0.1$
3. pi± decays into e±, and e- and mu-neutrino/antineutrinos through mu± decay. $\epsilon_\nu/\epsilon_p \sim 0.05$

5% of a proton's energy is converted to a neutrino's energy

RIAF phase

Hayasaki & Yamazaki, ApJ, 886, 114 (2019)

Diffusion time is most efficient among other cooling times



The protons are accelerated up to ~0.5 PeV

Lorentz factor at $t_{accl}=t_{diff}$

For a solar type star and $r=r_t$:

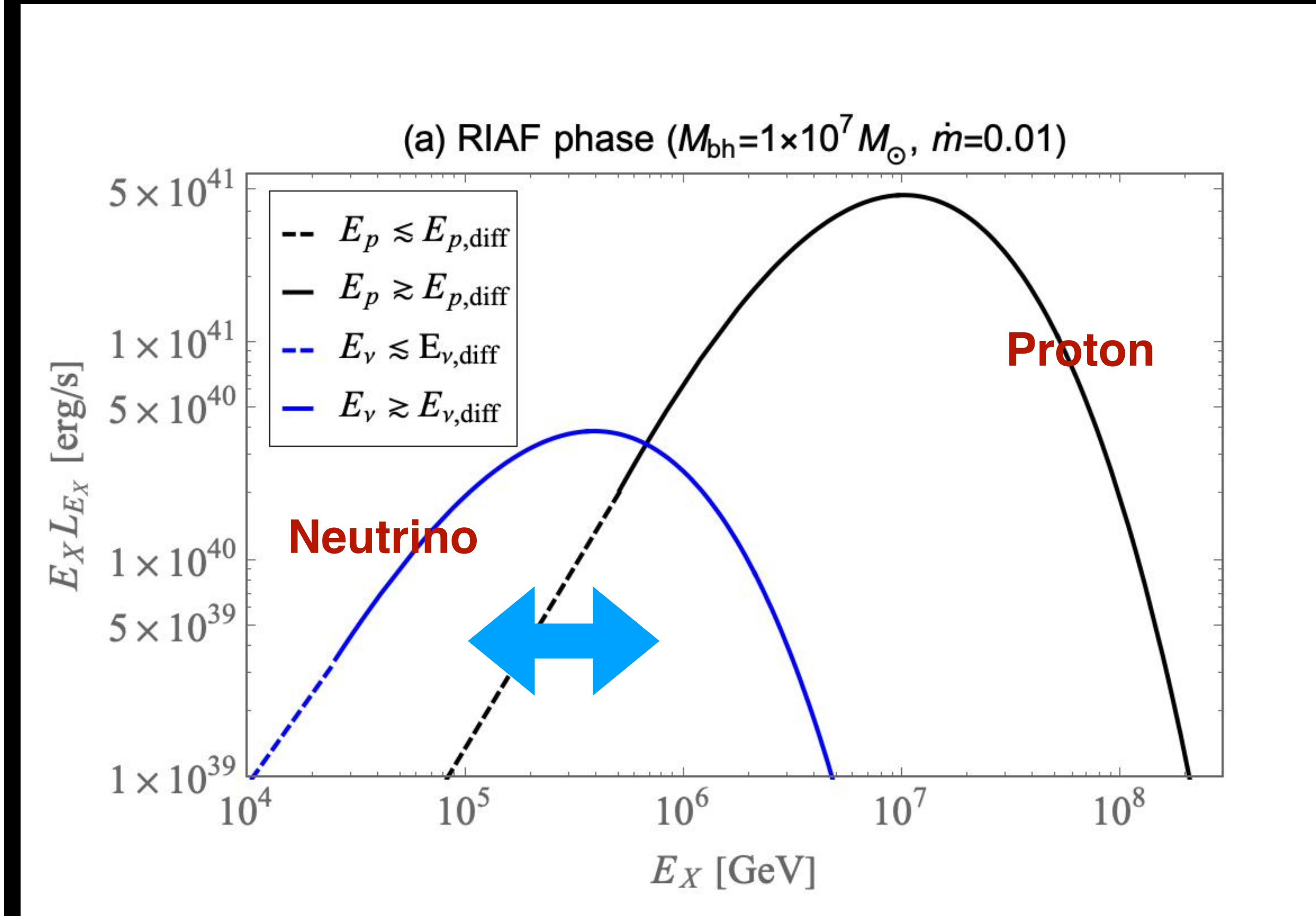
$$\gamma_{\rm diff} \sim 5 \times 10^5 \left(\frac{\dot{m}}{0.01}\right)^{1/2} \left(\frac{M_{\rm bh}}{10^7\,M_\odot}\right)^{5/3}$$

Proton's energy: $E_{\rm p} = \gamma_{\rm diff} m_p c^2 \sim 0.5\,{\rm PeV}$

Neutrino's energy: $E_\nu = 0.05 E_p \sim 25\,{\rm TeV}$

Differential Luminosity spectrum of RIAF phase

Hayasaki & Yamazaki, ApJ, 886, 114 (2019); Hayasaki et al. (in prep)



IceCube et al. (arXiv:1902.05792)

IceCube Flux Limit

$S_{\rm IC} = 5\times10^{-11}\,\rm erg\,s^{-1}cm^{-2}$

IceCube energy range

$0.1\,\rm TeV \lesssim E_\nu \lesssim 100\,\rm TeV$

IceCube beam size

$\sim \mathcal{O}(1)$ degree

Sub-PeV energy neutrinos can be emitted

Summary

There are four plus one possible sites to produce neutrinos in TDEs. For AT2019dsg the RIAF model is promising because of no gamma-ray detection, although it still remains in debate. In the following, our conclusions are summarized below.

1. High-energy particles during the debris circularization (stream-stream collision) and super-Eddington phase are unlikely to be produced.

2. In RIAF phase, sub-PeV neutrino can be emitted for AT2019dsg black hole

3. γ-rays are not emitted from the RIAFs because of the pair creation

4. In RIAF phase, the estimated detection rate ~0.0001 yr^{-1}

5. TDRs can potentially contribute to the diffuse neutrino flux in the range of $10\,\mathrm{TeV} \lesssim E_\nu \lesssim 100\,\mathrm{TeV}$