Neutrino emissions from tidal disruption remnants

Hayasaki & Yamazaki, 2019, ApJ, 886, 114

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MMAA in Muju on 5-7/Feb/2020

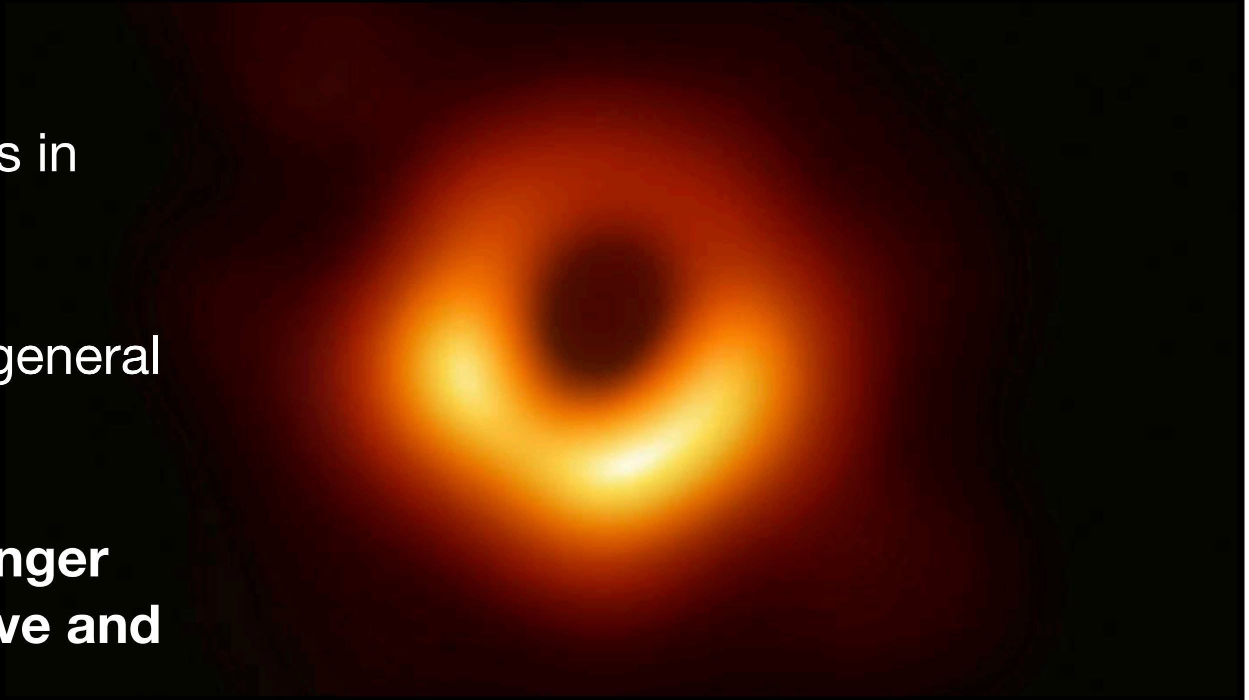
Scientific motivation to study tidal disruption events (TDEs)

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

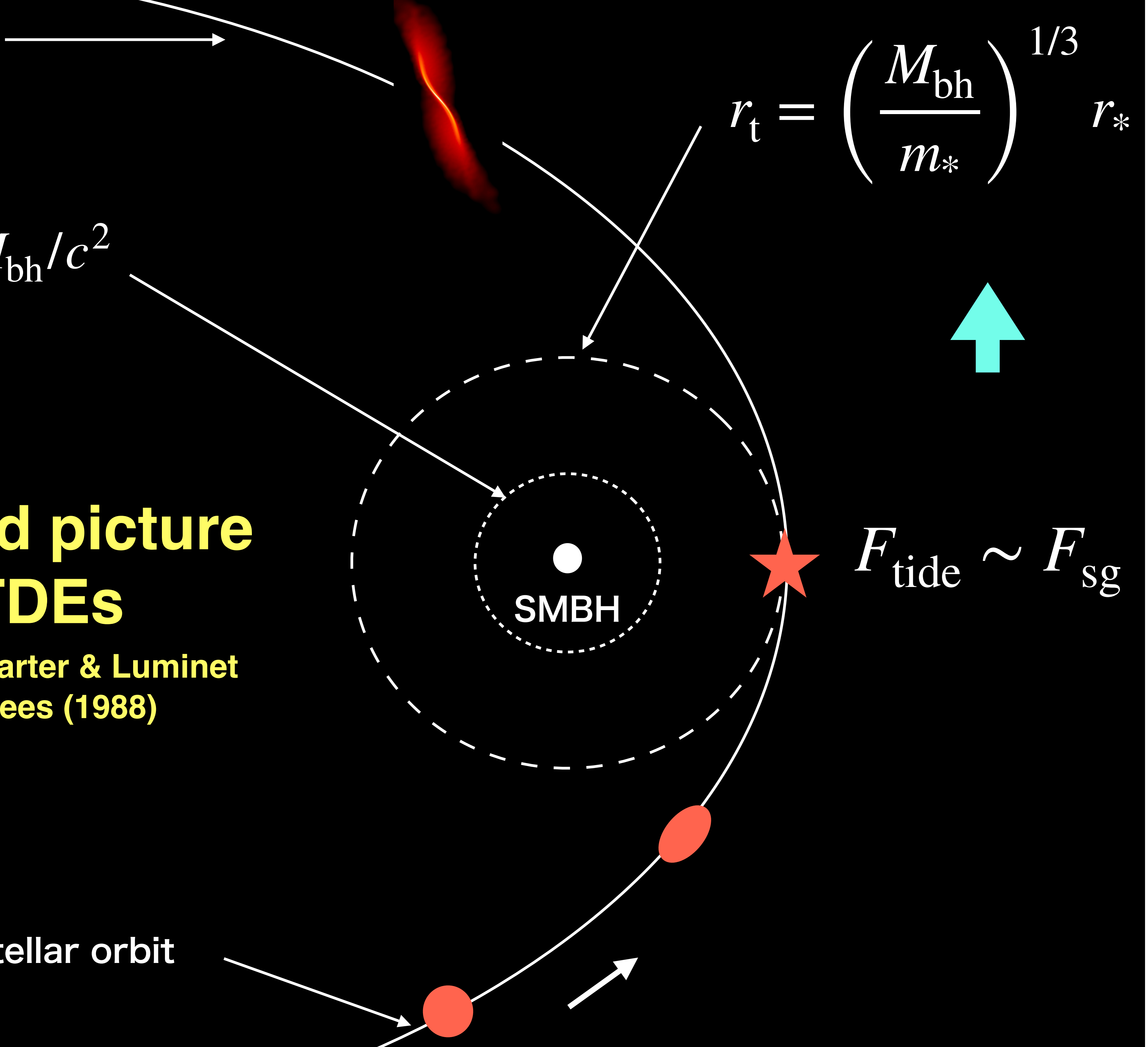
4. **Candidates for multi-messenger astronomy: gravitational wave and cosmic-ray/neutrino sources**



https://eventhorizontelescope.org/

Standard picture of TDEs

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



Debris orbit

$$r_t = \left(\frac{M_{\rm bh}}{m_*}\right)^{1/3} r_*$$

$$r_S = 2GM_{\rm bh}/c^2$$

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

SMBH

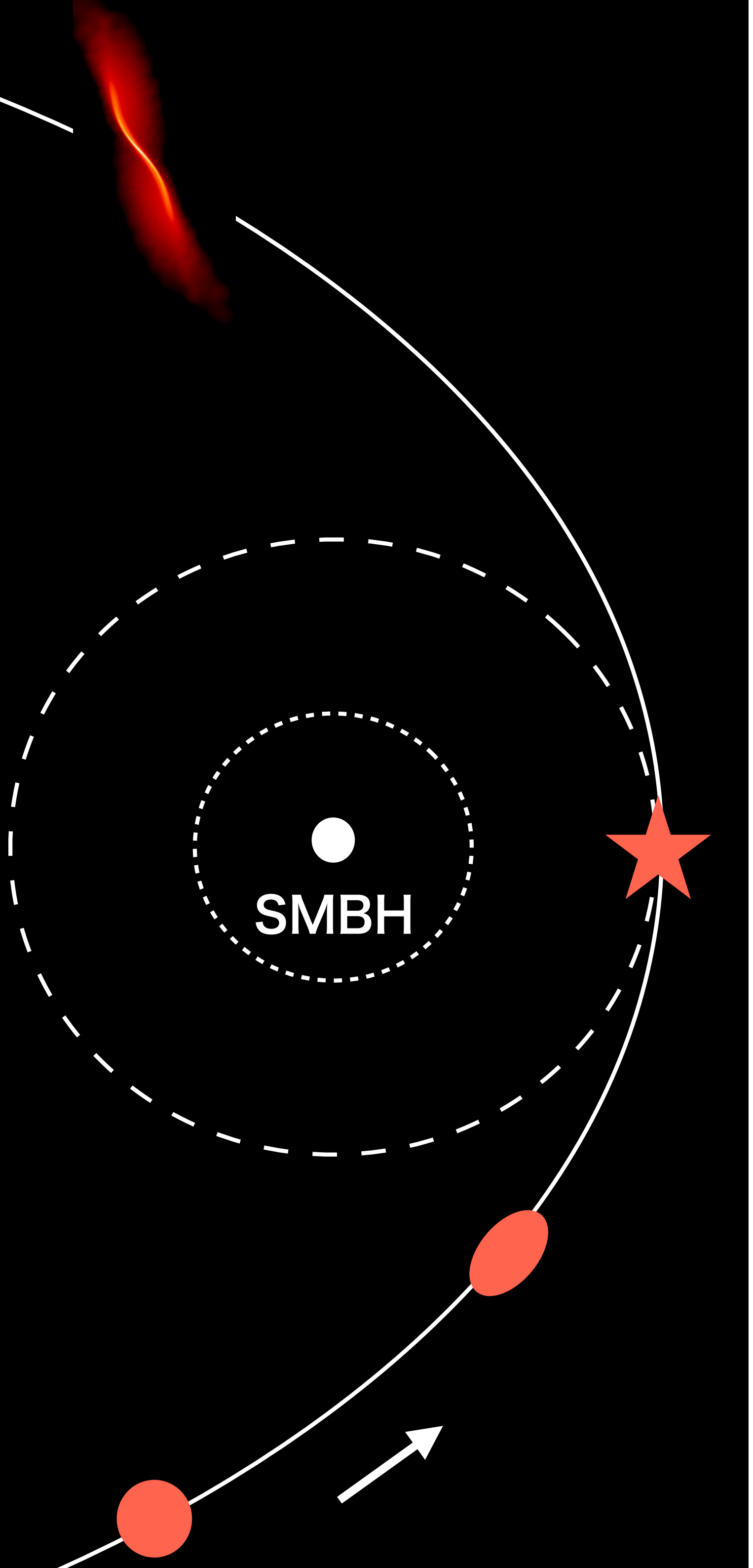
Stellar orbit

Condition for TDEs (non-spinning case)

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

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

Likely to happen at quiescent SMBHs
in inactive galaxies



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)

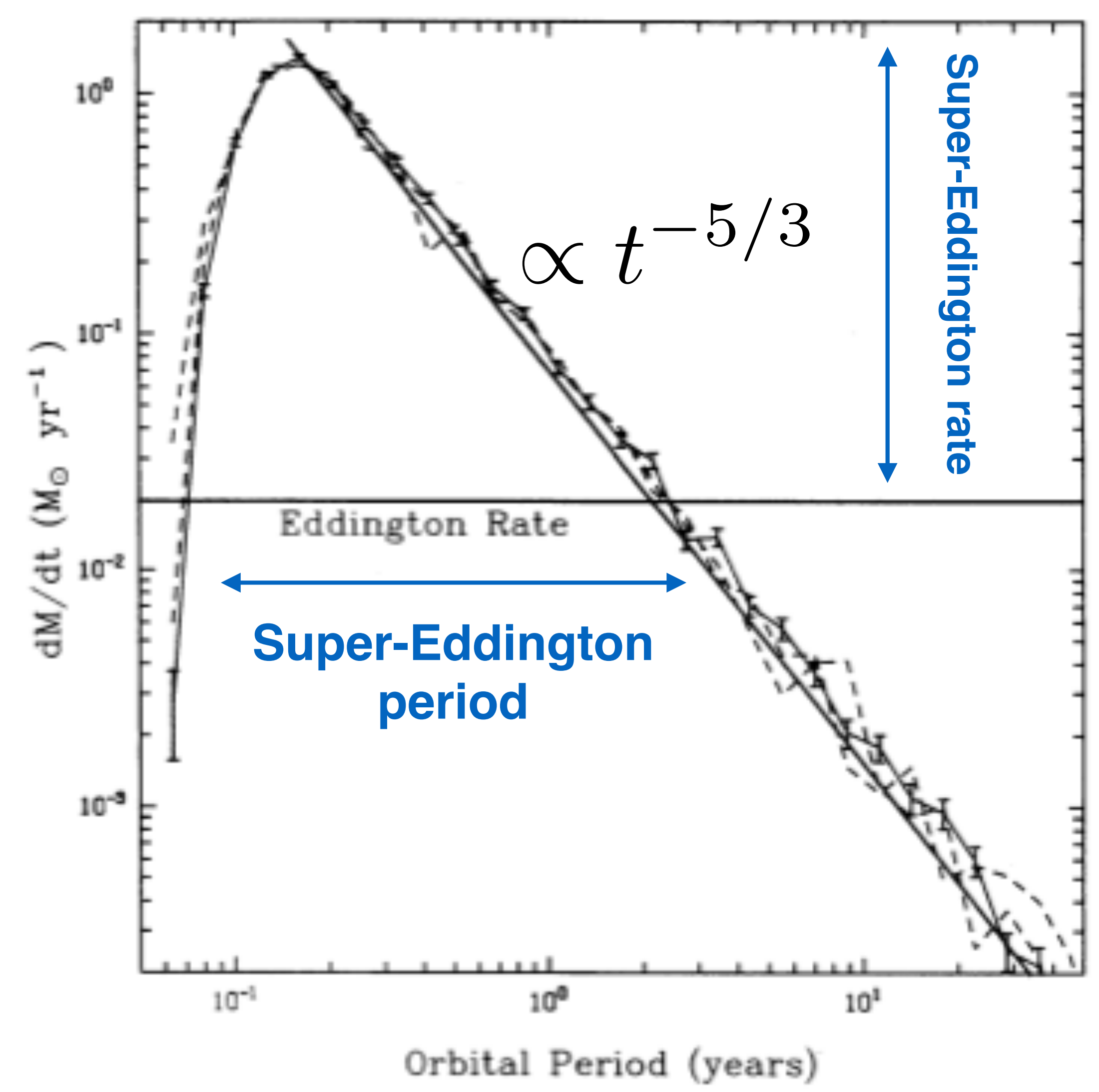
$$T_{\rm eff} = \left(\frac{L_{\rm Edd}}{4\pi\sigma_{\rm SB} r_{\rm t}^2}\right) \sim 3\times10^5\,M_6^{1/12}\,{\rm K}$$

- 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 observation

- TDE candidates/suspects/imposters

$$\sim 100$$

- Classification of observed TDEs

  1. **Non-jetted TDEs**
     # X-ray to optical/UV to radio
     # Optical/UV or optical only
  2. **Jetted TDEs**
     # X-ray and radio only

- Event rate

  1. Non-jetted TDEs

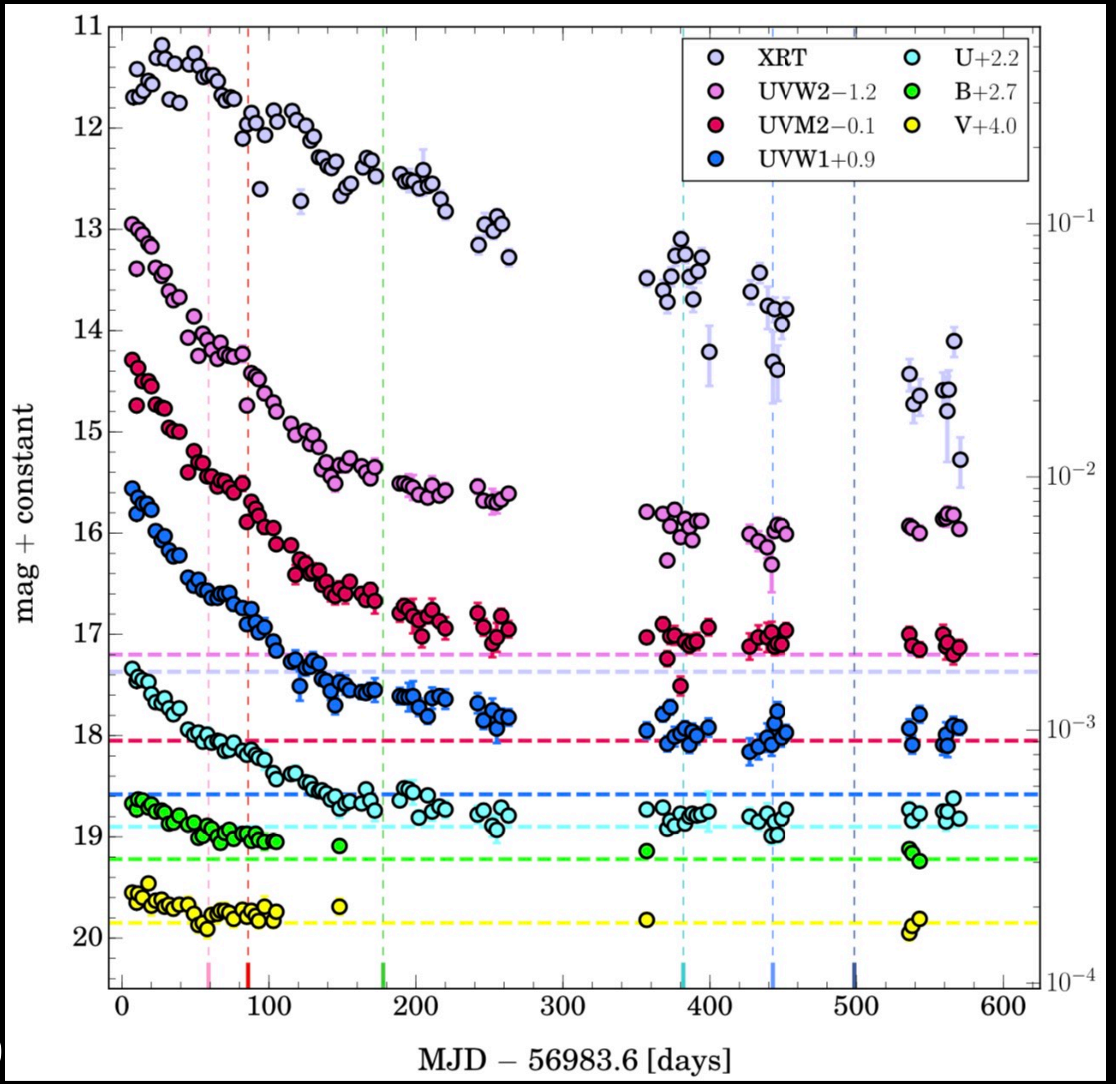
$$\sim 10^{-7}\,/\mathrm{yr}/\mathrm{Mpc}^3$$

  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)

ASASSN-14li (Brown et al. 2017)



Expected GW emissions from TDEs

1. Characteristic amplitude and frequency

$$h \sim 2\times 10^{-22}\beta\left(\frac{D}{10\,\mathrm{Mpc}}\right)^{-1}\left(\frac{M_{\rm bh}}{10^{6}\,M_\odot}\right)^{2/3}\left(\frac{r_*}{R_\odot}\right)^{-1}\left(\frac{m_*}{M_\odot}\right)^{4/3}$$

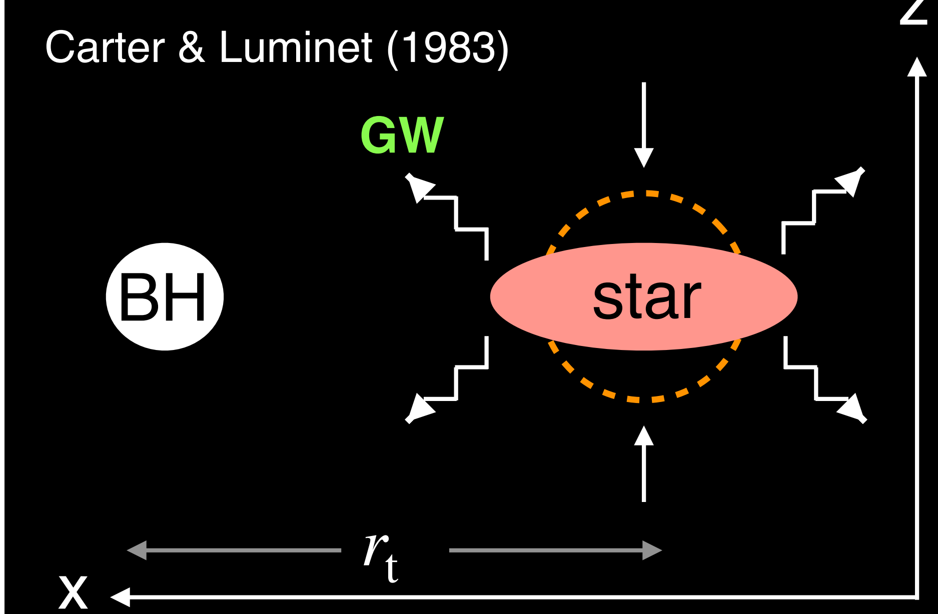
Sigurdsson & Rees (1997)
Kobayashi et al. (2004)
(cf. Stone et al. 2013;
Toscani et al. 2020)

$$f \sim 6\times 10^{-4}\,\beta^{3/2}\left(\frac{r_*}{R_\odot}\right)^{-3/2}\left(\frac{m_*}{M_\odot}\right)^{1/2}\ \mathrm{Hz}$$

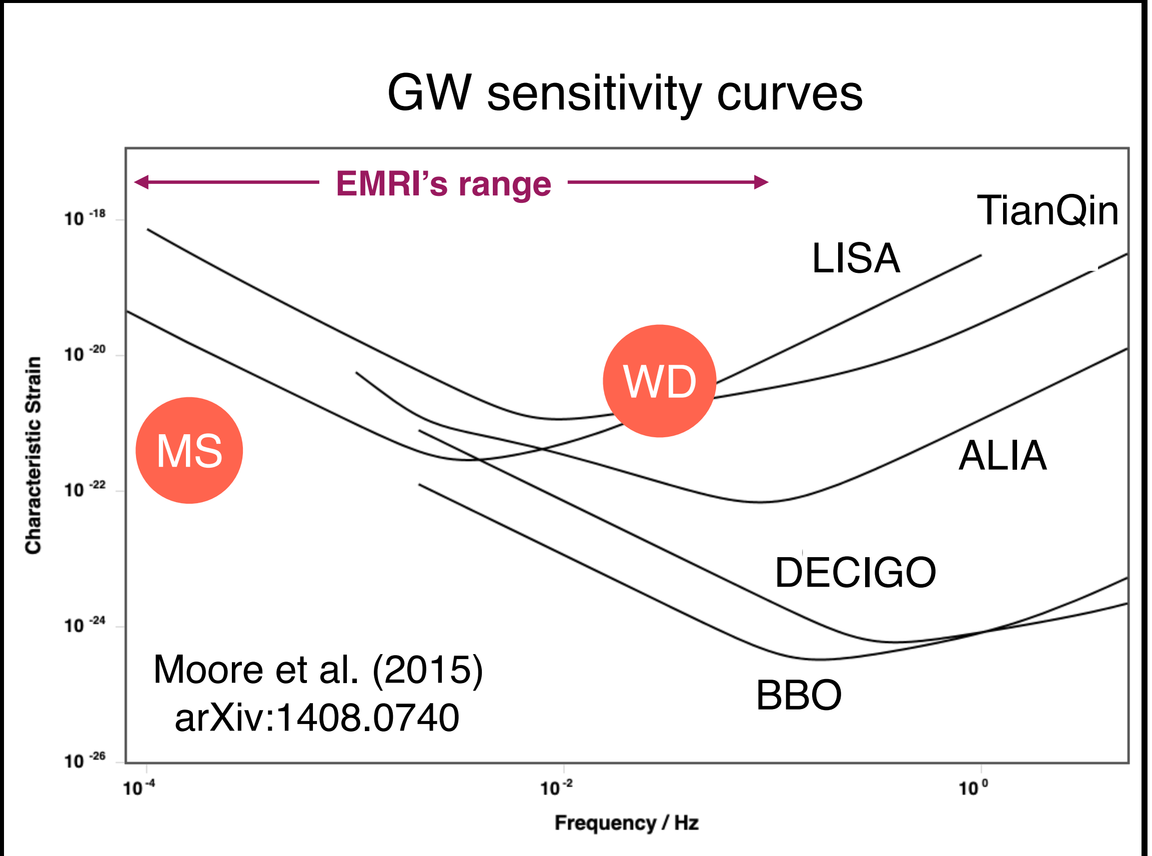
$$\beta = r_{\rm t}/r_{\rm p}$$

Vertical collapse
(Pancaking)

Carter & Luminet (1983)



2. Detectability



GW sensitivity curves

Moore et al. (2015)
arXiv:1408.0740

Can neutrinos be emitted from TDEs?

If

Go studying GW emissions
from TDEs for your future

1. How and where?
2. Energy ?
3. Event rate?

Contribution to the neutrino background? (e.g., see Murase & Fukugita 2018)

High energy emissions from TDEs

1. Jetted TDEs

Farrar & Piran (2014);

Senno et al. (2017); Lunardini & Winter (2017); Dai & Fang 2017; and so on

Natural cosmic-ray accelerators but only three candidates

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

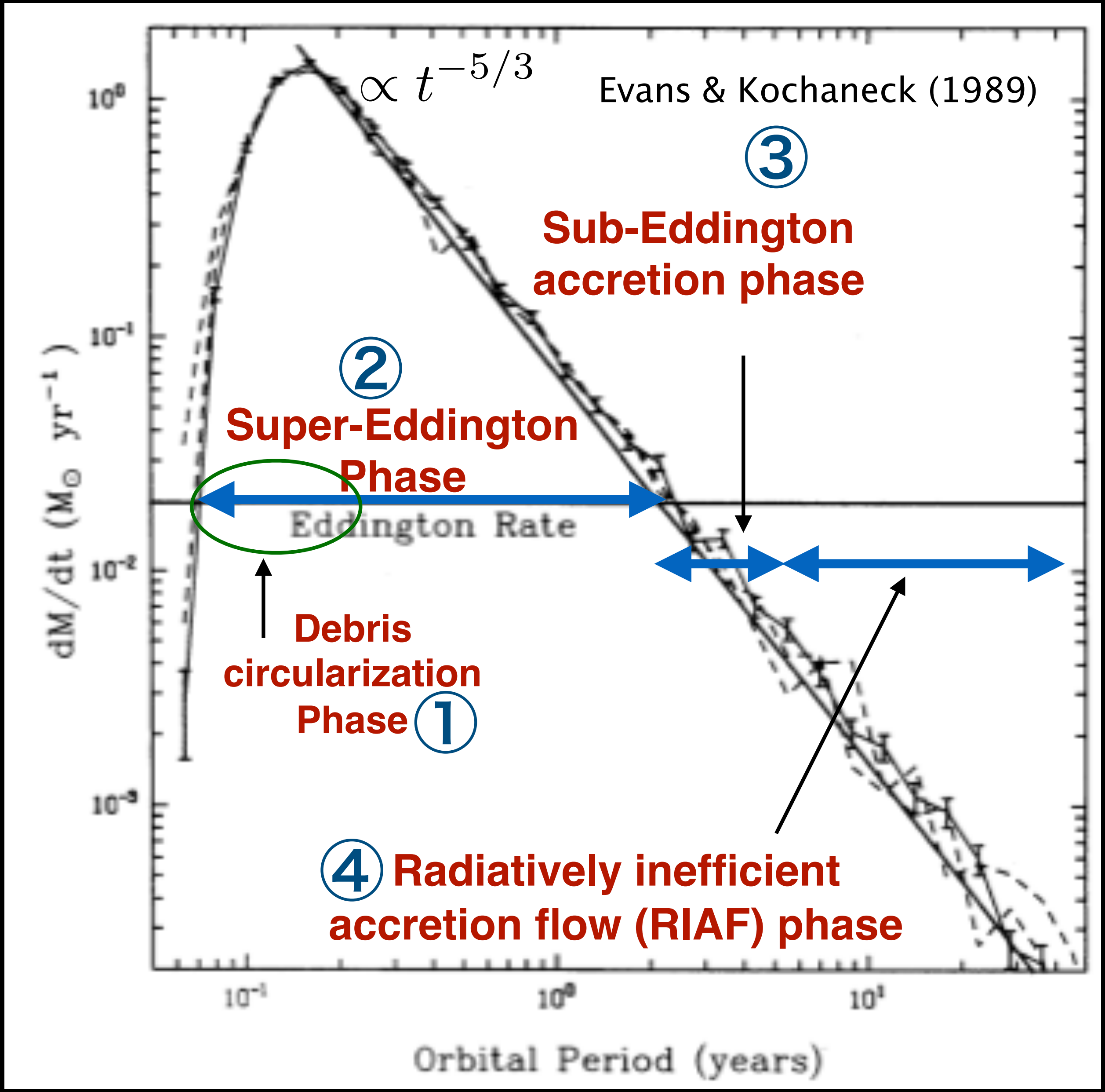
2. Non-Jetted TDEs

Unclear cosmic-ray accelerators but many candidates

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

We examine the possible sites in non-Jetted TDEs

Four main phases in a tidal disruption remnant (TDR)



③ **Sub-Eddington accretion phase**

② **Super-Eddington Phase**

Debris circularization Phase ①

④ **Radiatively inefficient accretion flow (RIAF) phase**

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 (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

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

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

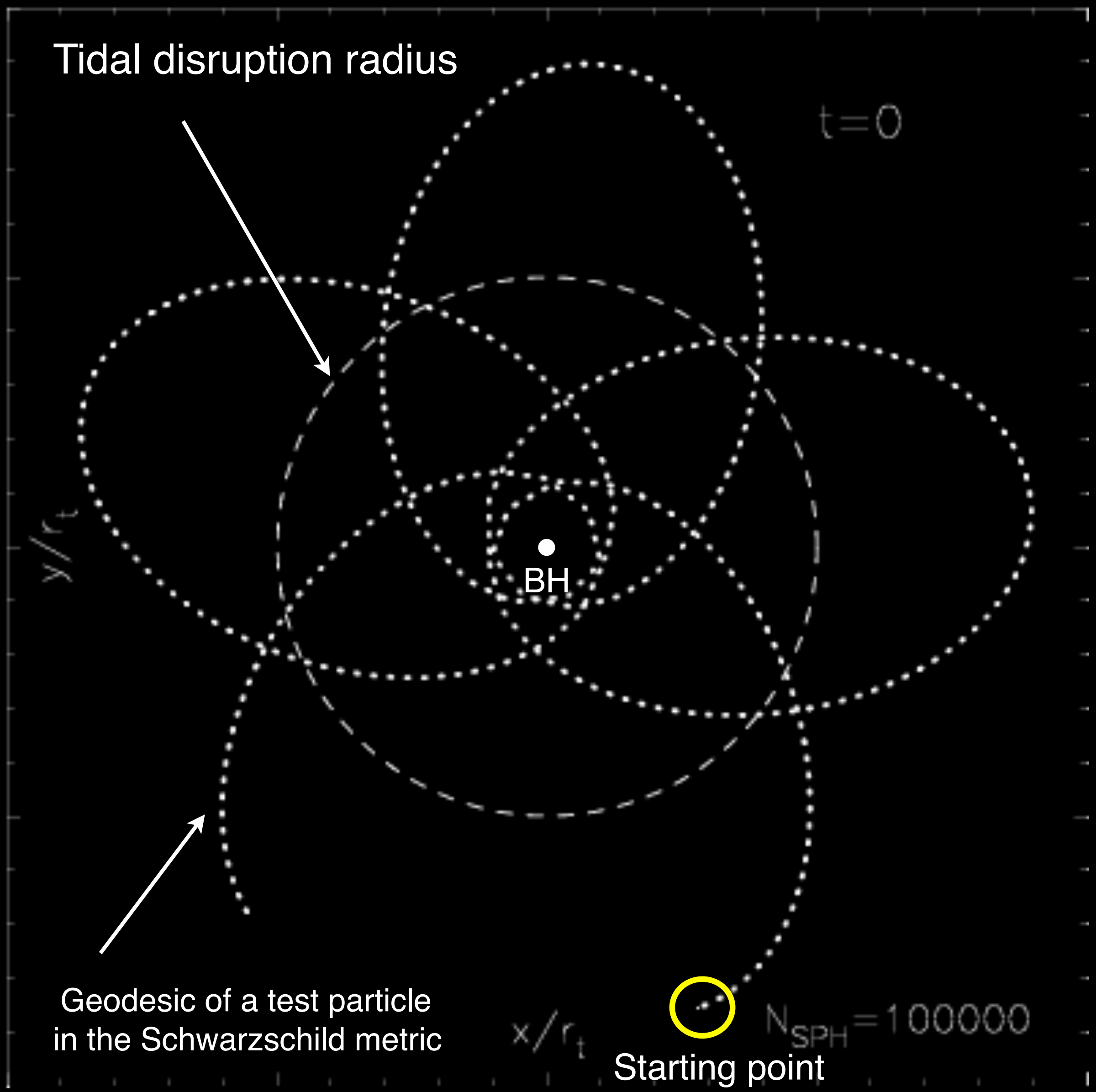
$$t_{\rm Edd} \sim 1.1 \times 10^8\,{\rm s} \left(\frac{M_{\rm bh}}{10^7\,M_\odot}\right)^{-2/5}$$

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

The shock during the debris circularization

Hayasaki et al. (2013)
(See also Bonnerot et al . (2016) for higher resolutions)

- Dotted line shows the geodesic of a test particle
- Dashed circle shows the tidal disruption radius
- Central point represents the black hole



Tidal disruption radius

BH

Geodesic of a test particle in the Schwarzschild metric

Starting point

Accretion disk is formed around the black hole due to **shock** energy dissipation of orbital crossings induced by perihelion shift

Particle acceleration mechanisms

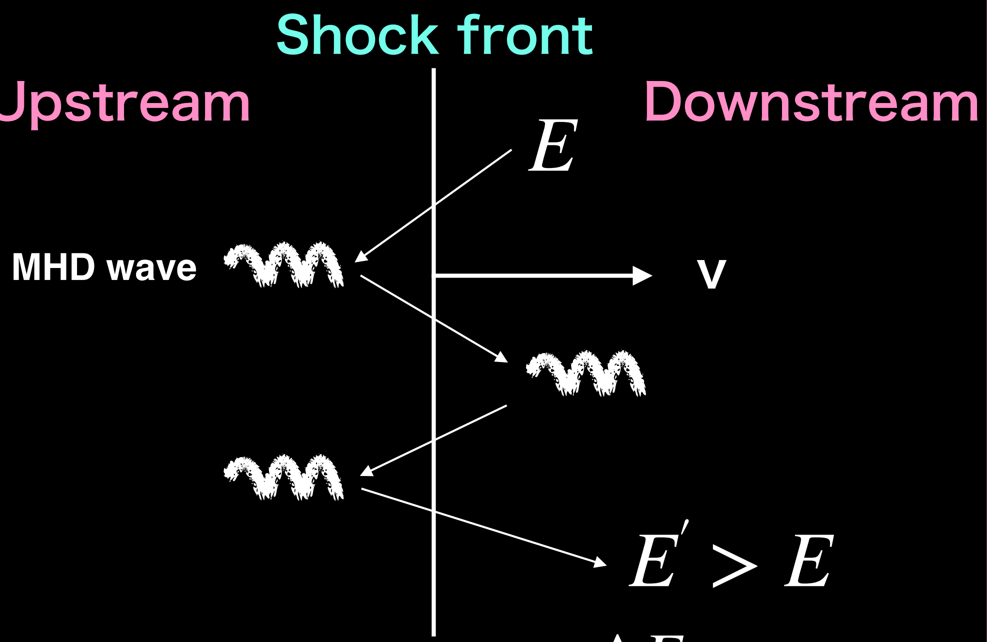
Two types of Fermi acceleration

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

TDR (disk) case

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

1st order in a shock


Shock front

Upstream

Downstream

E

MHD wave

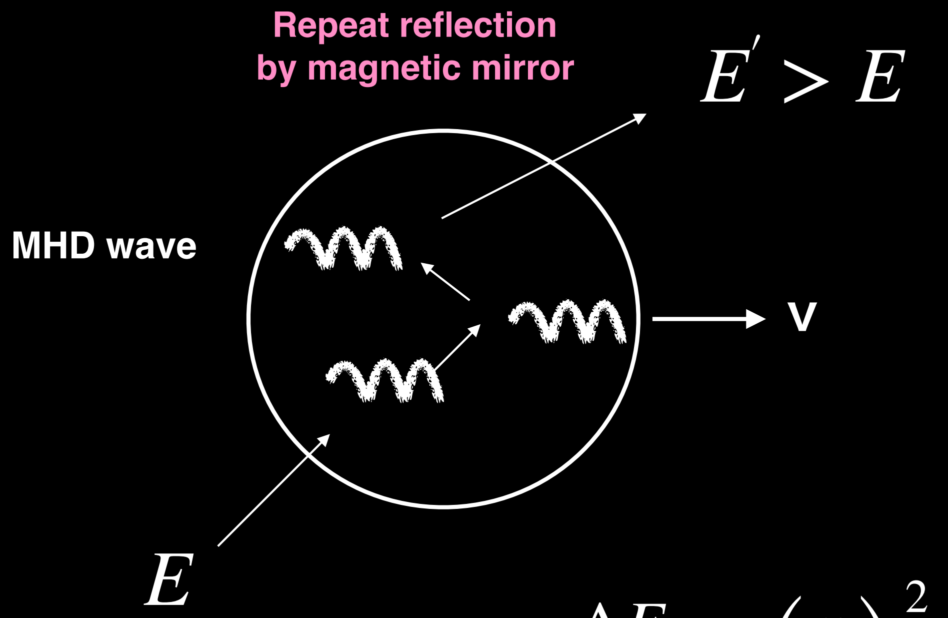
v

$E' > E$

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

2nd order in a turbulent gas

Head-on collision


Repeat reflection by magnetic mirror

$E' > E$

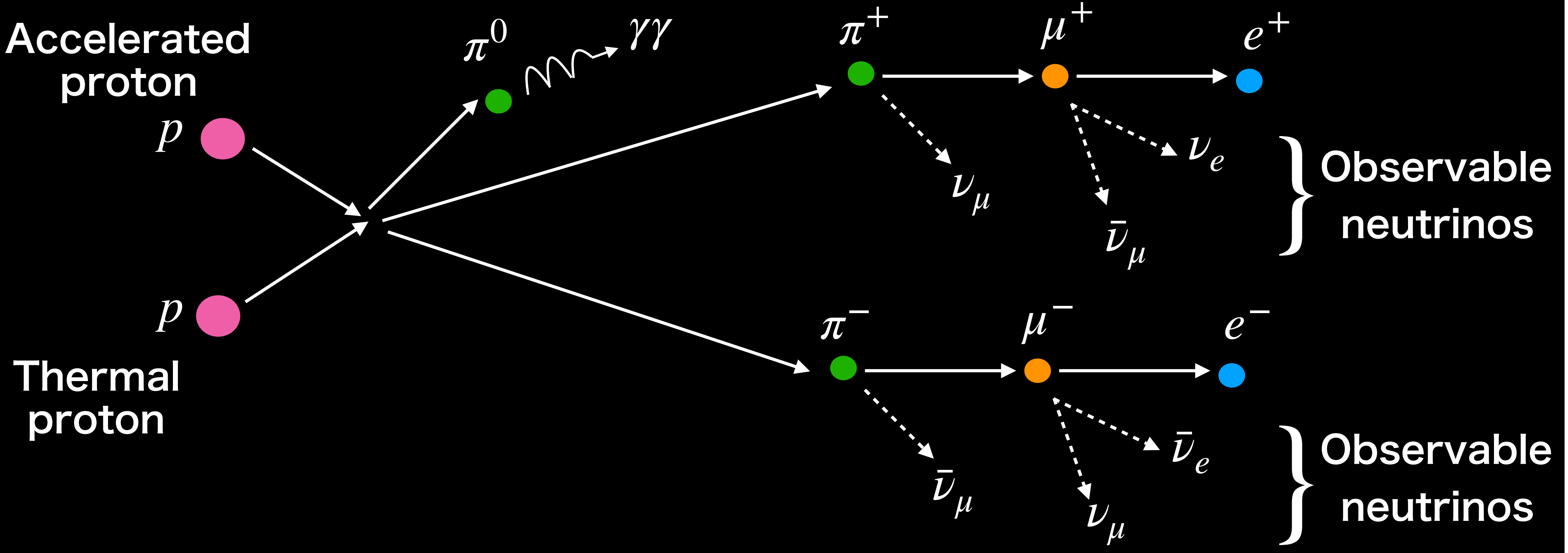
MHD wave

v

E

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. pi^0 decays into two gamma-ray photons $\epsilon_\gamma/\epsilon_p \sim 0.1$
3. pi$^\pm$ decays into e$^\pm$, and e- and mu-neutrino/antineutrinos through mu$^\pm$ decay. $\epsilon_\nu/\epsilon_p \sim 0.05$

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

Acceleration time for the 1st order Fermi

$$\mathrm{Accerelation\ time}\ :\ t_{\mathrm{accl}} = \frac{l_{\mathrm{diff}}^2}{D} \sim \frac{r_{\mathrm{L}}}{V}$$

$\mathrm{Diffusion\ length}\ :\ l_{\mathrm{diff}}$ $\mathrm{Spatial\ diffusion\ coefficient}\ :\ D$

$\mathrm{Larmor\ radius}\ :\ r_{\mathrm{L}}$ $\mathrm{Shock\ velocity}\ :\ V$

$$t_{\mathrm{accl}} \propto M_{\mathrm{bh}}^{-1} B^{-1}$$

$B\ :\ \mathrm{B-field\ strength}$

As BH mass and B-field are stronger, the acceleration time is shorter

Acceleration time for the 2nd order Fermi

$$\text{Acceleration time}: t_{\text{accl}} \equiv \frac{p^2}{D_p}$$

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

$\text{Mometum diffusion coefficient}: D_p$

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

γ : Lorenz factor B : B – field strength

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

Timescale of each process to prevent protons accelerating 1

$$(\mathrm{Common\ parameters} : r = r_{\mathrm{t}}, \alpha = 0.1, \zeta = 0.1, H/r = 0.01)$$

Accretion time of the disk

$$\mathrm{Infall\ time} : t_{\mathrm{inf}} = \frac{r}{v_r} \sim 2 \times 10^8\ \mathrm{s} \left(\frac{M_{\mathrm{bh}}}{10^7\, M_\odot} \right)^{-1/2}$$

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

$$\mathrm{pp\ relaxation\ time} : t_{\mathrm{relax}} \sim 6 \times 10^6\ \mathrm{s} \left(\frac{\dot{M}/\dot{M}_{\mathrm{Edd}}}{0.1} \right)^{-1} \left(\frac{M_{\mathrm{bh}}}{10^7\, M_\odot} \right)$$

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

$$\mathrm{Coulomb\ loss\ time} : t_{\mathrm{Coul}} \sim 4 \times 10^5\ \mathrm{s} \left(\frac{\dot{M}/\dot{M}_{\mathrm{Edd}}}{0.1} \right)^{-1} \left(\frac{M_{\mathrm{bh}}}{10^7\, M_\odot} \right)^{-1/2}$$

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

Timescale of each process to prevent protons accelerating 2

Protons can spatially diffuse

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

Cooling by proton synchrotron emissions

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

Cooling by inelastic p-p collision

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

Wave dumping by the Compton drag

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

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

Maximum proton's energy

Protons can accelerate up to the energy at

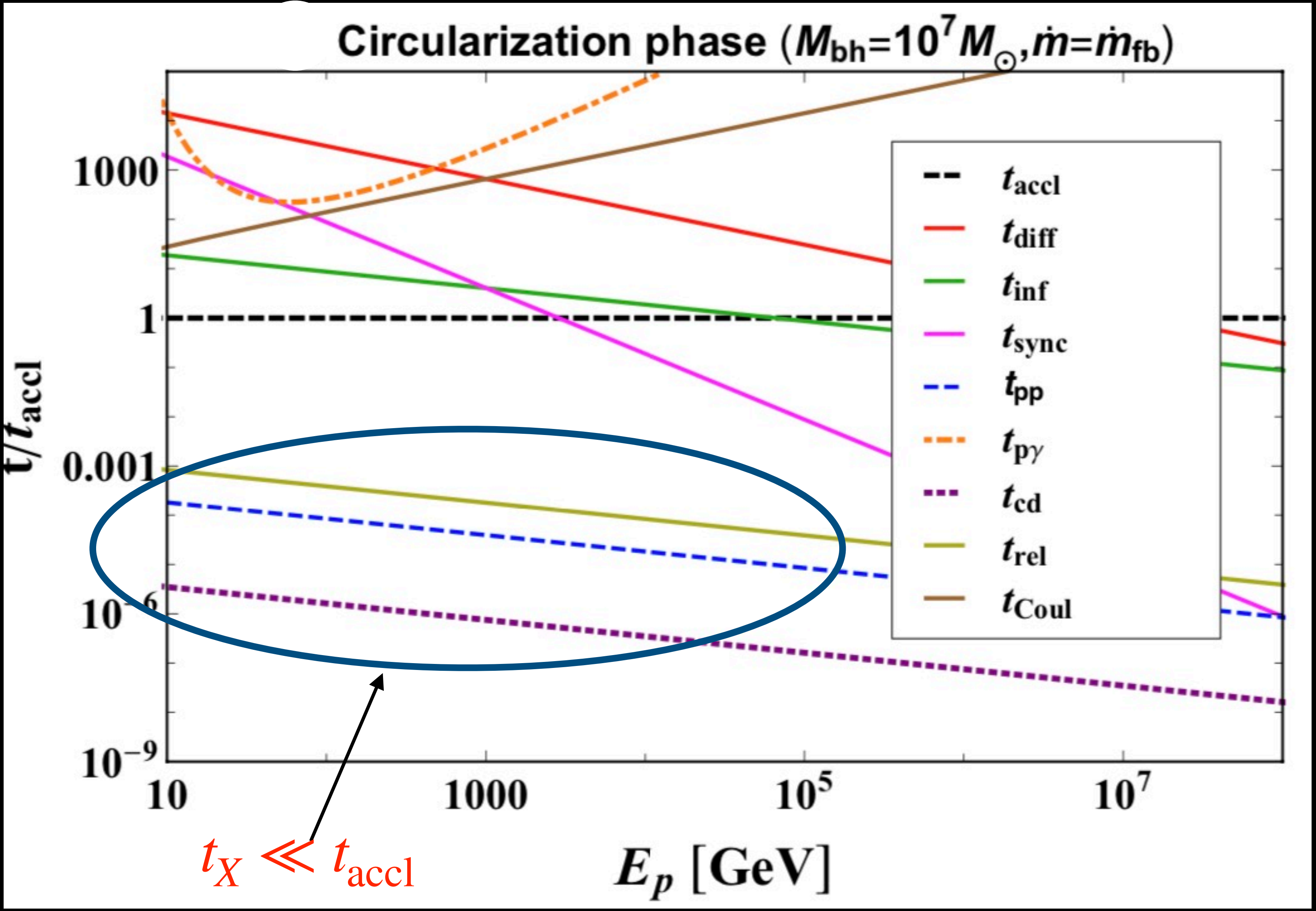
$$t_{\rm acc} = {\rm MIN}[t_{\rm inf}, t_{\rm relax}, t_{\rm Coul}, t_{\rm Cd}, t_{\rm diff}, t_{\rm pp}, t_{\rm sync}, t_{\rm p\gamma}]$$

for respective TDR sites

⬇

① Strong shock in debris circularization

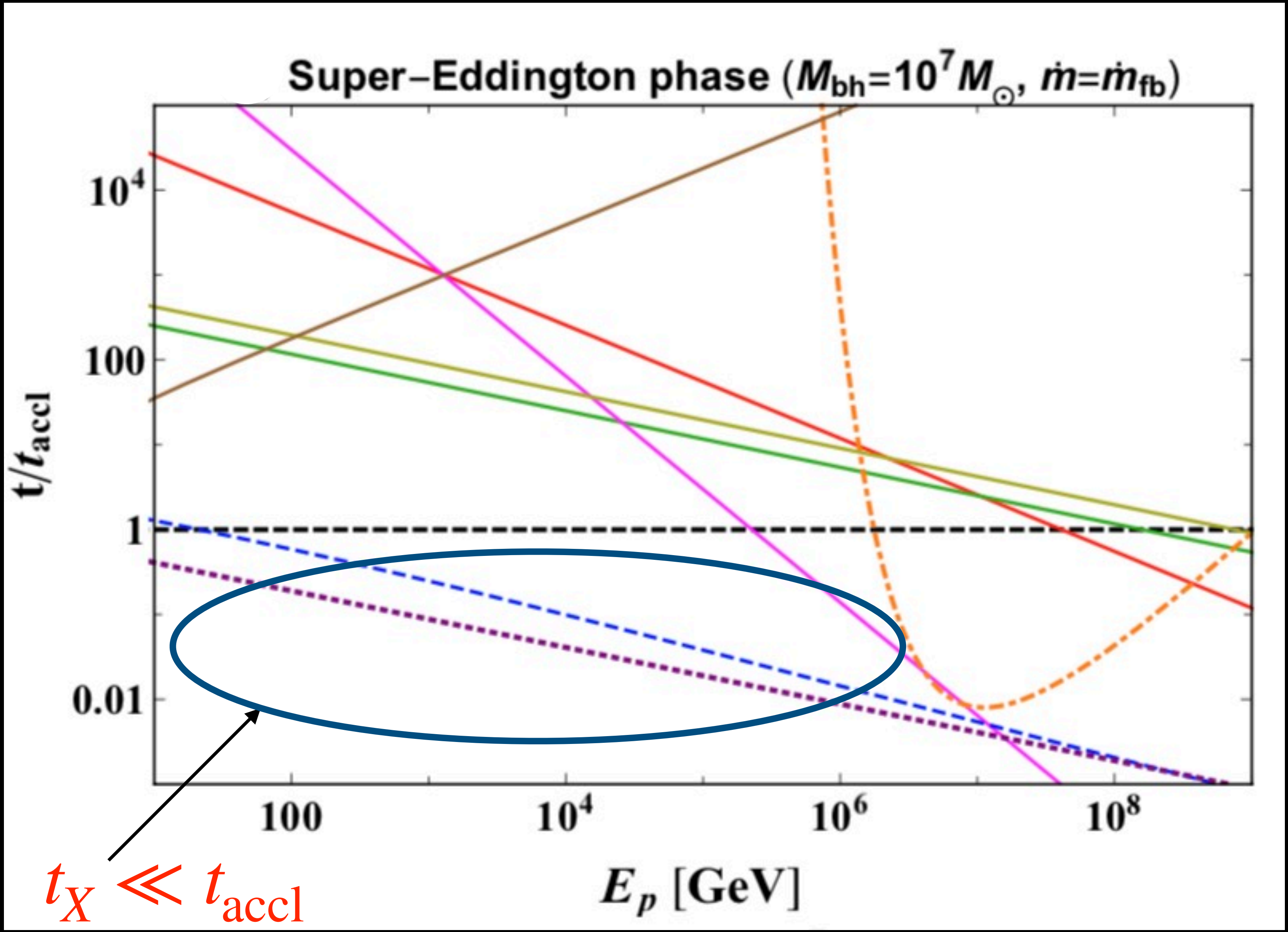
KH & Yamazaki (2019)



High-energy particles are unlikely to be produced

② Super-Eddington accretion phase

KH & Yamazaki (2019)



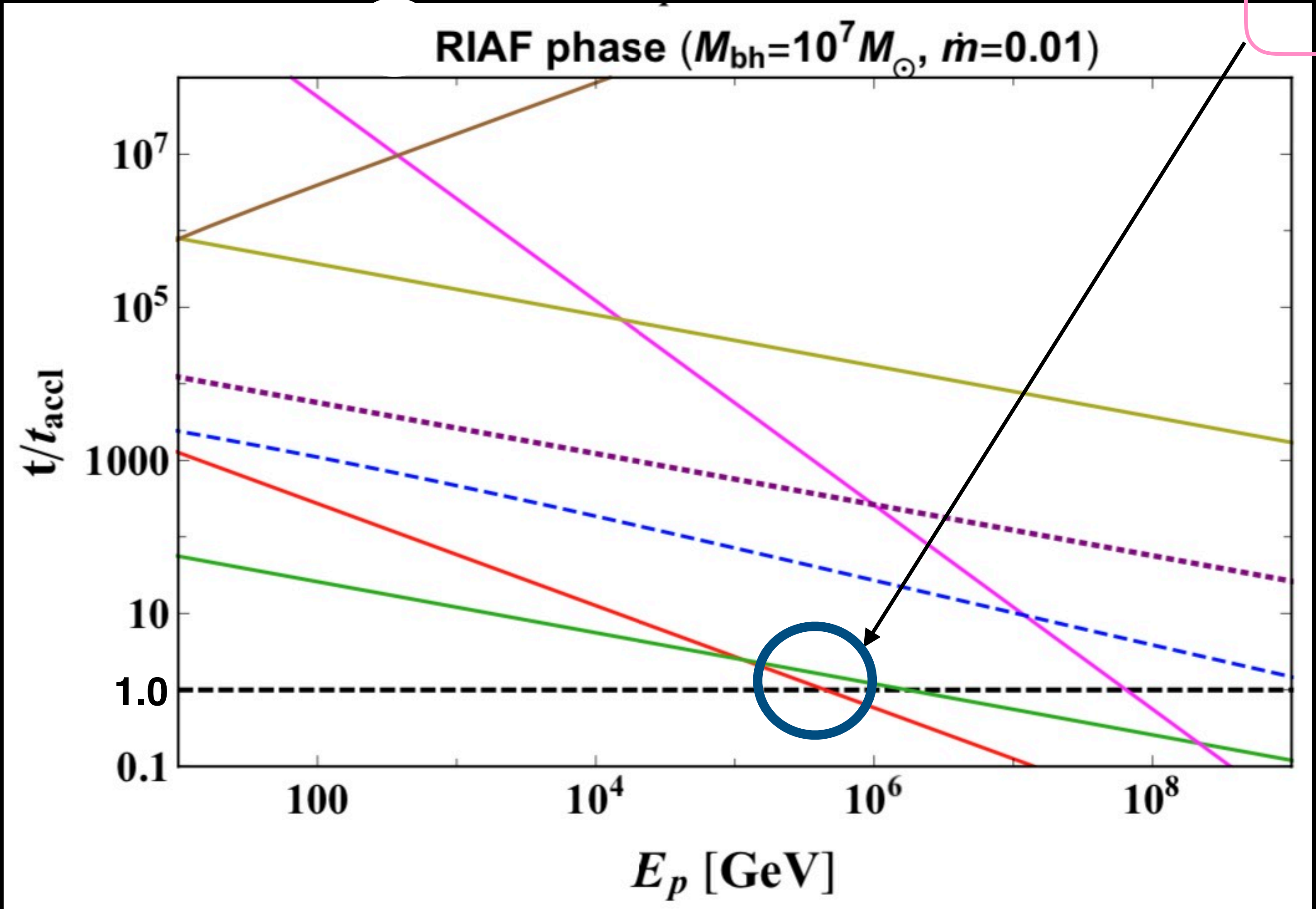
$t_X \ll t_{accl}$

High-energy particles are unlikely to be produced

④ RIAF phase

Diffusion time is most efficient among other cooling times

KH & Yamazaki (2019)



The protons are accelerated up to ~0.5 PeV (The resultant neutrino energy is 25 TeV)

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

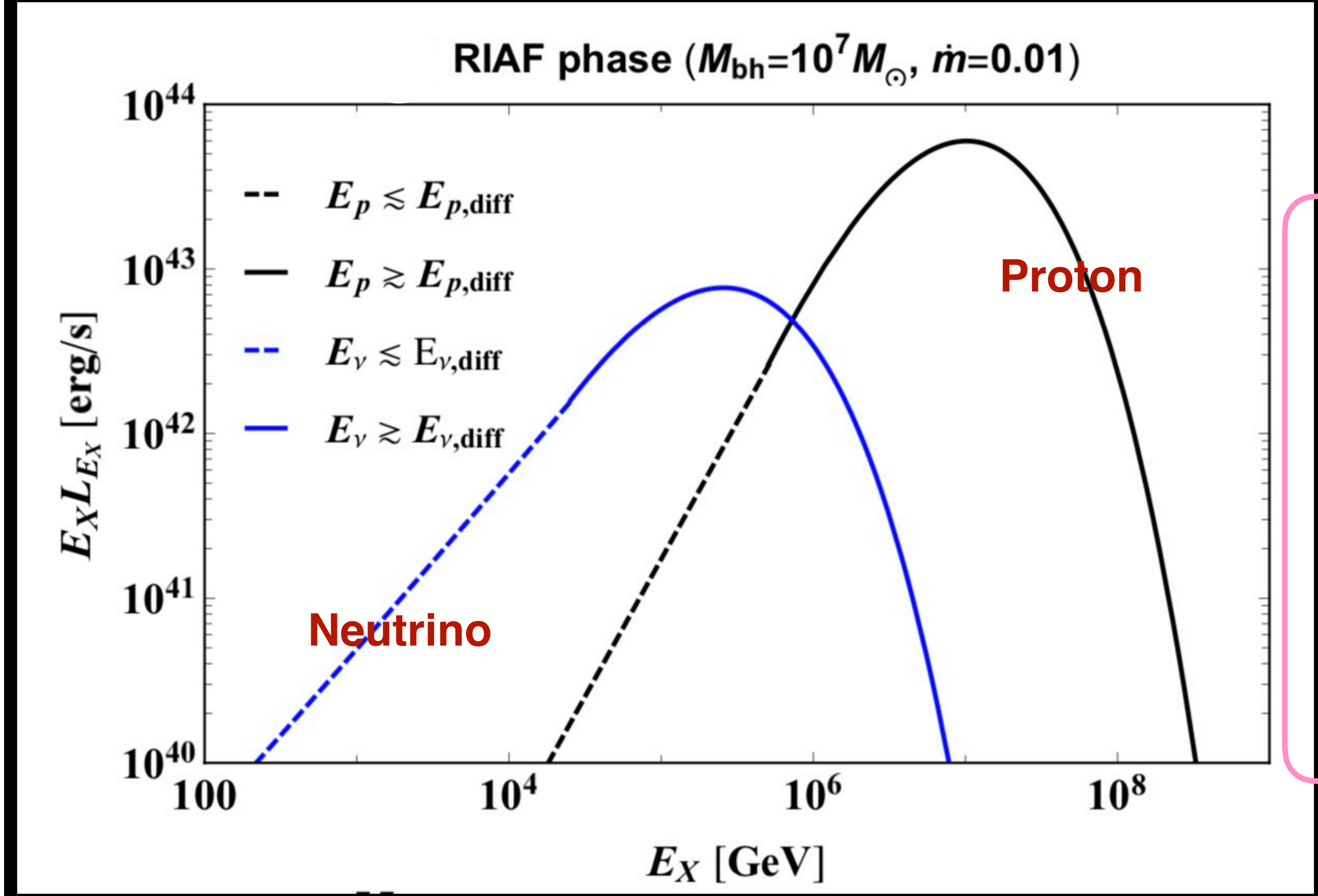
For a solar type star and $r=r_t$:

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

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

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

Differential Luminosity spectrum of RIAF phase



Hayasaki & Yamazaki (2019)

IceCube et al. (arXiv:1902.05792)

IceCube Flux Limit

$$S_{\rm IC} = 5 \times 10^{-11}\,{\rm erg\,s^{-1}cm^{-2}}$$

IceCube energy range

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

IceCube beam size

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

Neutrino Horizon: $$D_\nu = \sqrt{\frac{L_\nu}{4\pi S}} \sim 0.5\,{\rm Gpc}\left(\frac{L_\nu}{L_{\rm Edd}}\right)^{1/2}\left(\frac{S}{S_{\rm IceCube}}\right)^{-1/2}$$

Neutrino Flux: $$F_{\nu,pk} = \frac{|E_X L_X|_{\rm pk}}{4\pi D_\nu^2} \sim 1.0 \times 10^{-9}\,{\rm erg\,s^{-1}cm^{-2}}\left(\frac{S_{\rm IceCube}}{S}\right)$$

Detection rate: $$n_{\rm gal} D_\nu \mathscr{R} \sim 10^{-2}\,{\rm yr^{-1}}({\rm n_{gal}}/0.003\,{\rm Mpc^{-3}})({\rm D}_\nu/34\,{\rm Mpc})^3(\mathscr{R}/10^{-4}\,{\rm yr^{-1}})$$

Energy generation rate argument

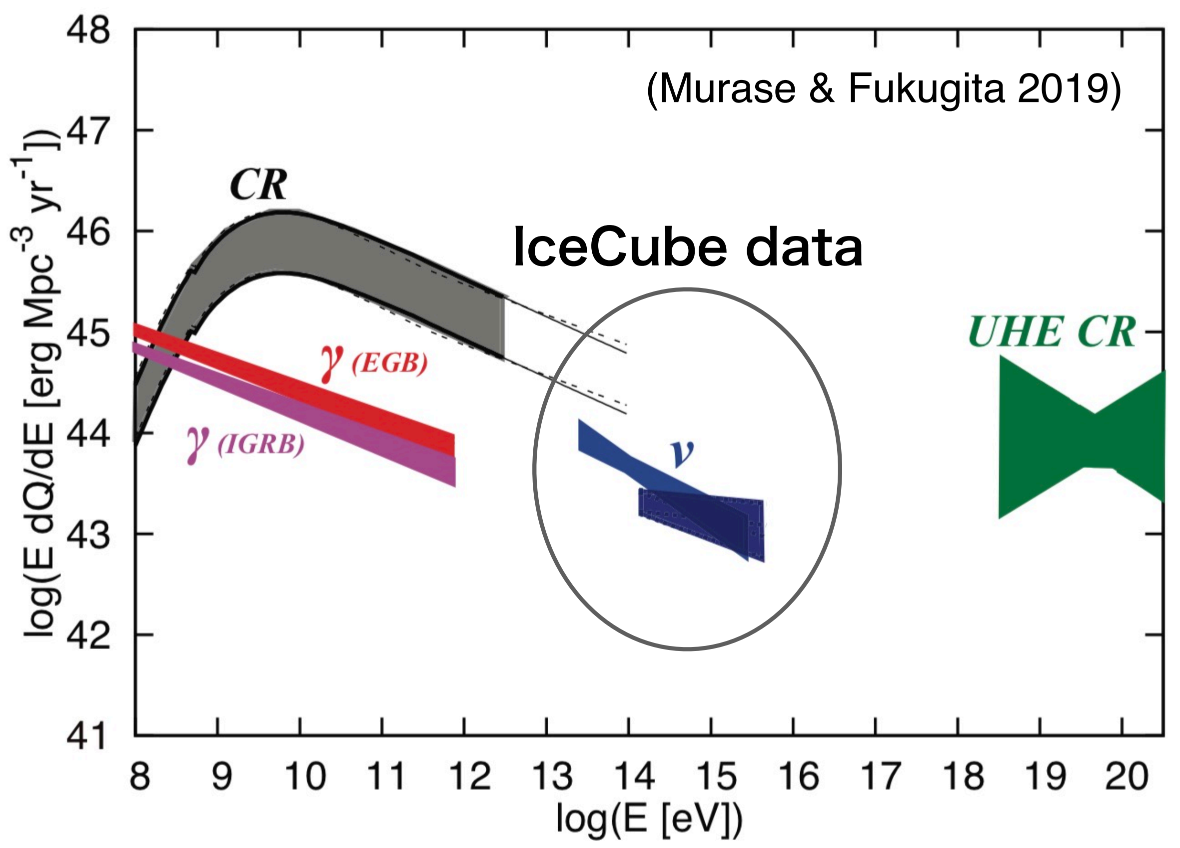
The observed energy generation rate

$$\rho_{E_\nu} \sim 10^{43-44}\,\mathrm{erg/Mpc^3/yr}$$

Energy range

$$10\,\mathrm{TeV} \lesssim E_\nu \lesssim 100\,\mathrm{TeV}$$

The neutrino energy generation rate inferred from the observed isotropic neutrino flux



The expected energy generation rate from TDRs

$$\rho_{E_\nu} = L_\nu t_{\mathrm{RIAF}} \mathscr{R}_V \sim 2 \times 10^{43}\,\mathrm{erg/Mpc^3/yr}$$

TDRs can potentially contribute to the diffuse neutrino flux

Summary

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

2. In RIAF phase, the protons are accelerated up to ~0.5 PeV. The corresponding neutrino energy is 25 TeV

3. In RIAF phase, the estimated detection rate 0.1~0.01 yr^{-1}

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

Thank you for your attention