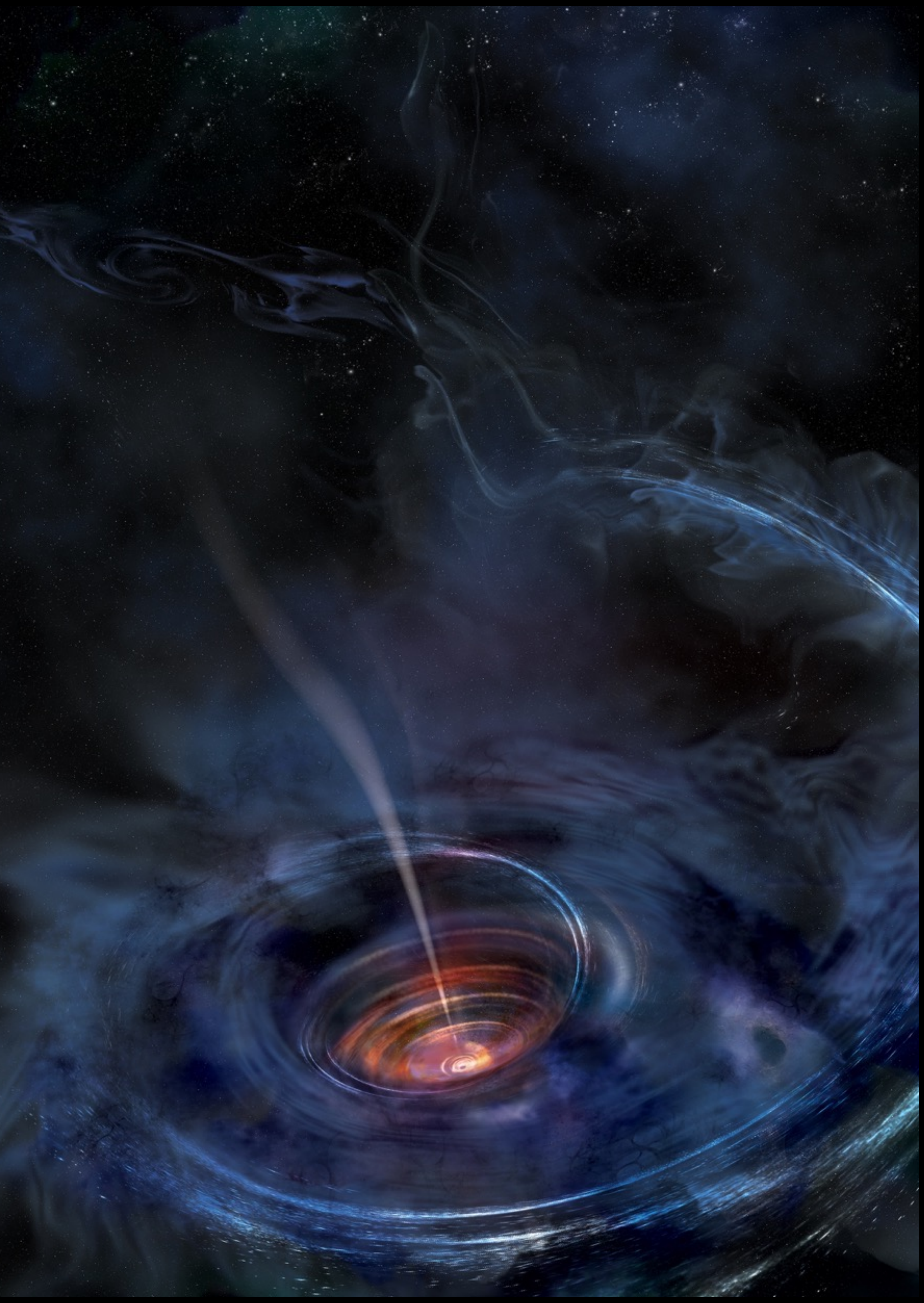


32nd Texas Symposium on Relativistic Astrophysics
December 13, 2023

Tidal Disruption Events: Demographics, Accretion and Outflows

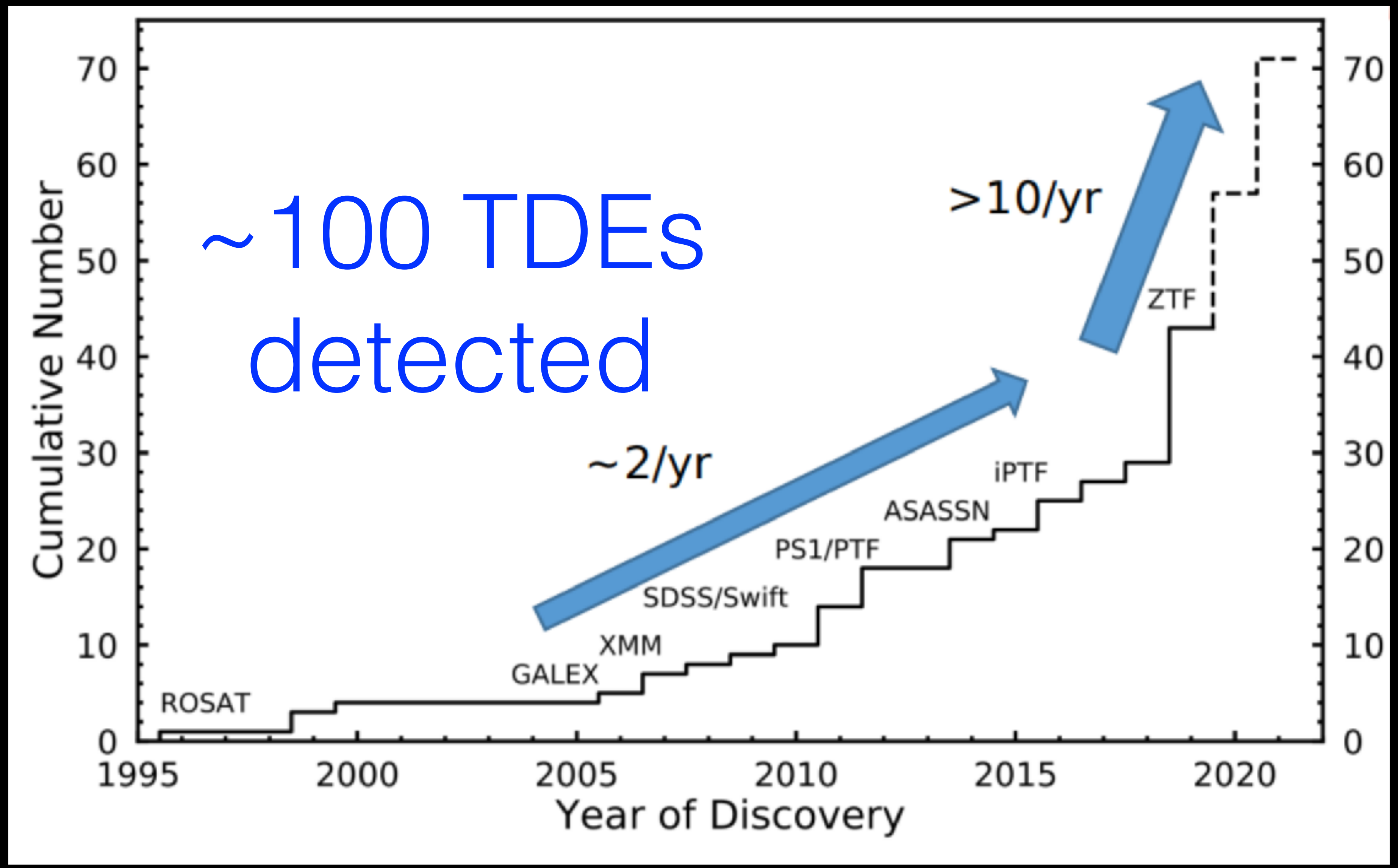
Jane Lixin Dai

The University of Hong Kong

+ Graduate Students: Janet Chang, Tom Kwan, Zijian Zhang, Lars Thomsen, Thomas Wong

M. Bulla, E. Kara, D. Kasen, G. Leloudas, J. McKinney, C. Miller, H. Pfister, E. Ramirez-Ruiz, C. Reynolds, N. Roth, A. Tchekhovskoy, M. Volonteri, F. Yuan

TDE detection with transient surveys



WFST

Einstein Probe

ZTF

eROSITA

Vera Rubin Observatory

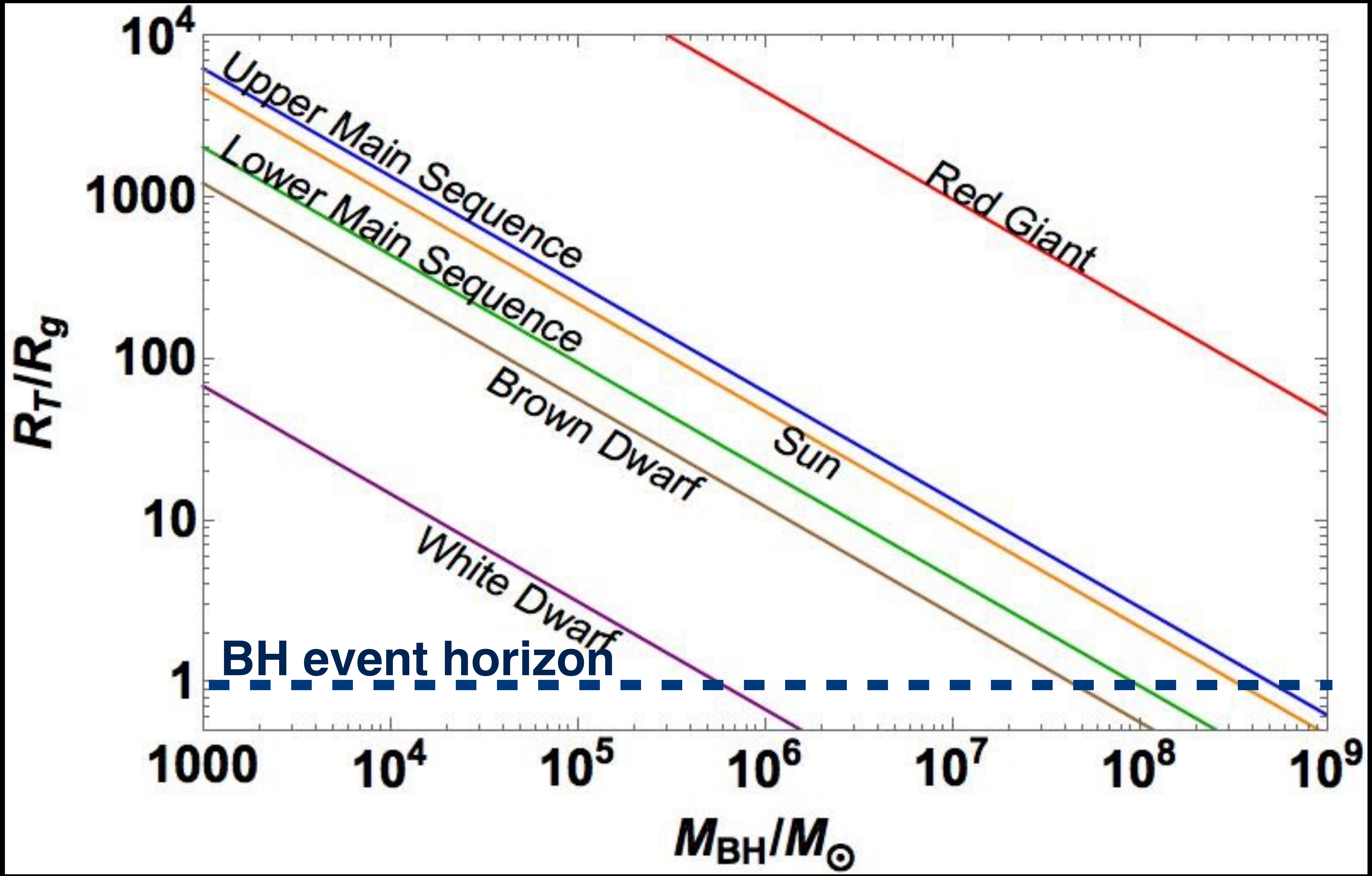
Why do we study TDEs?

- ★ Demographics of dormant massive black holes including IMBHs
- ★ Extreme black hole accretion and outflow physics
- ★ Stellar population & dynamics in galaxy center
- ★ Multimessenger: high-energy astroparticles and gravitational waves

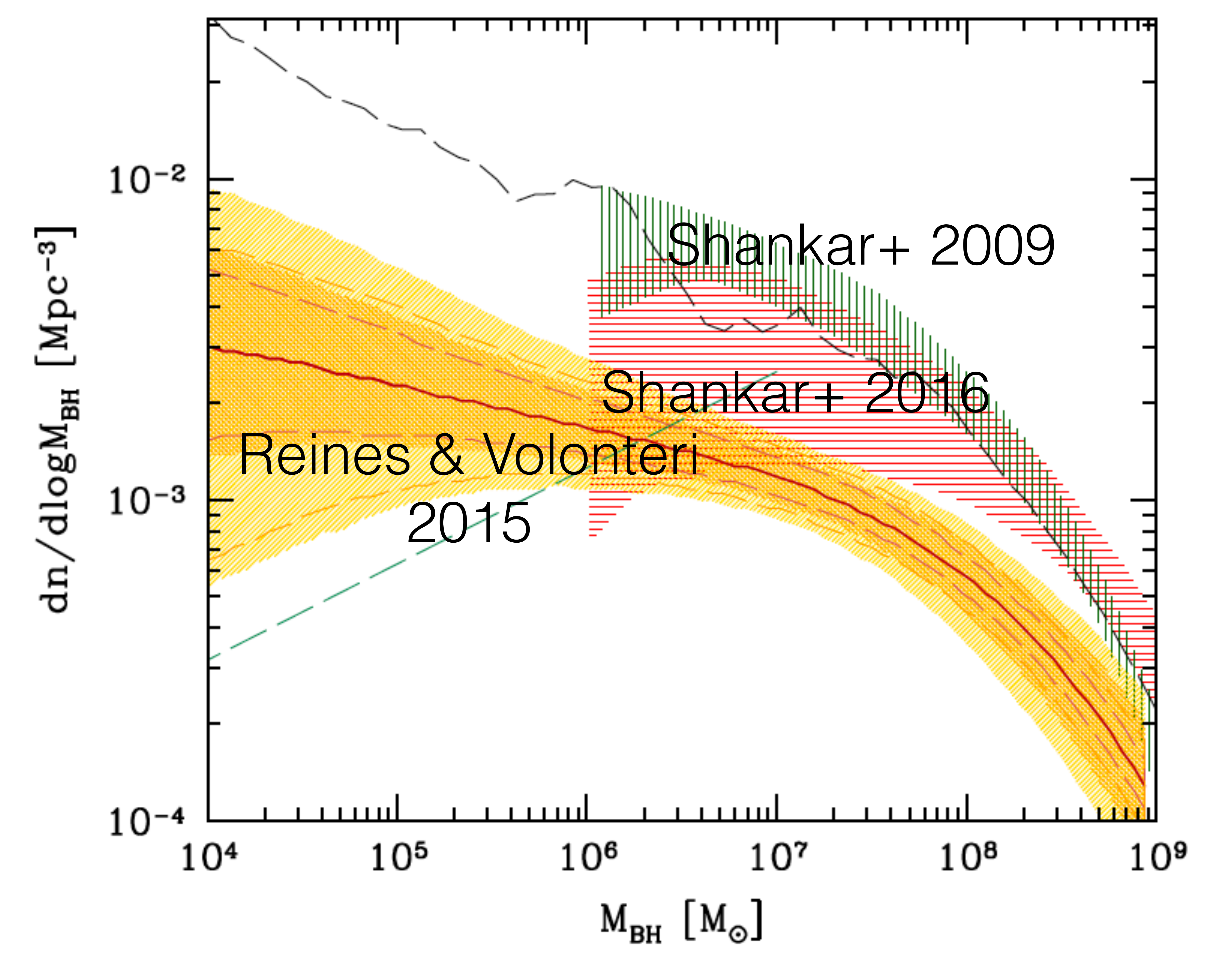
Tidal Disruption Radius: MBH tidal force = stellar self-gravity

$R_T \approx R_\bigstar \, (M_{BH} / M_\bigstar)^{1/3}$

$\Rightarrow R_T / R_g \propto M_{BH}^{-2/3} \; \rho_\bigstar^{-1/3}$



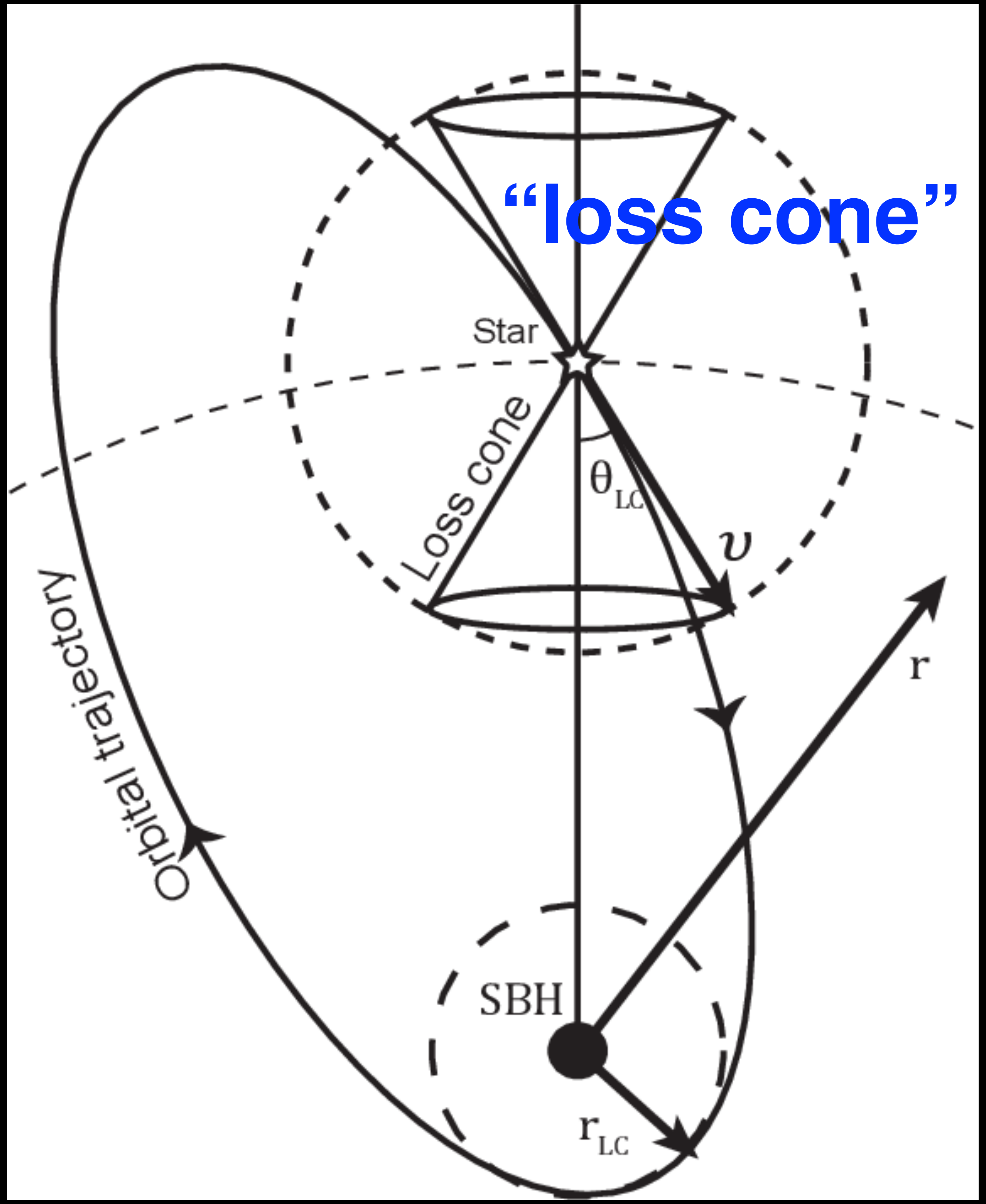
Black Hole Mass Function (from AGNs)



Gallo & Sesana 2019

TDEs are ideal for probing MBHs in the low-mass end.

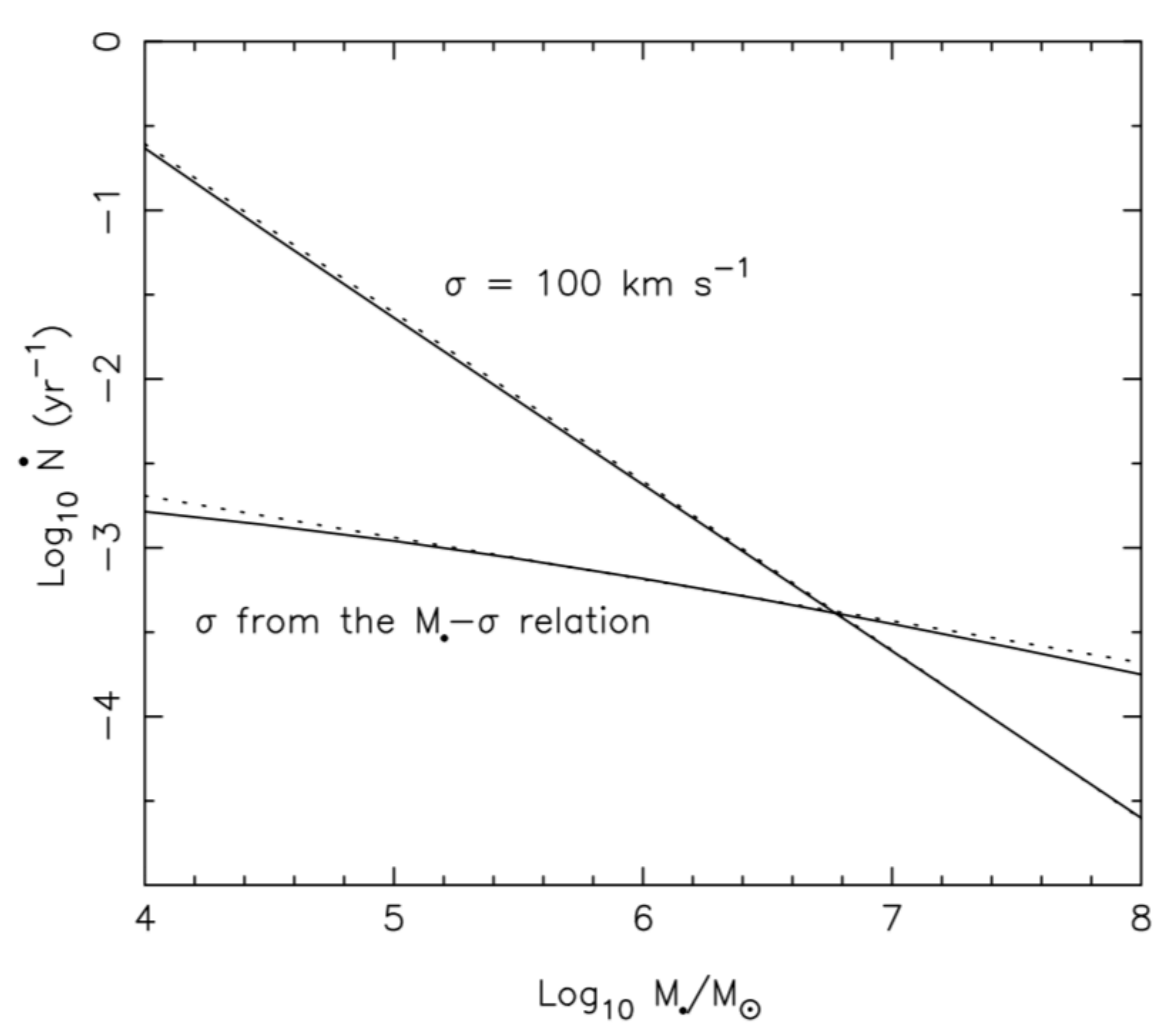
Loss Cone Dynamics



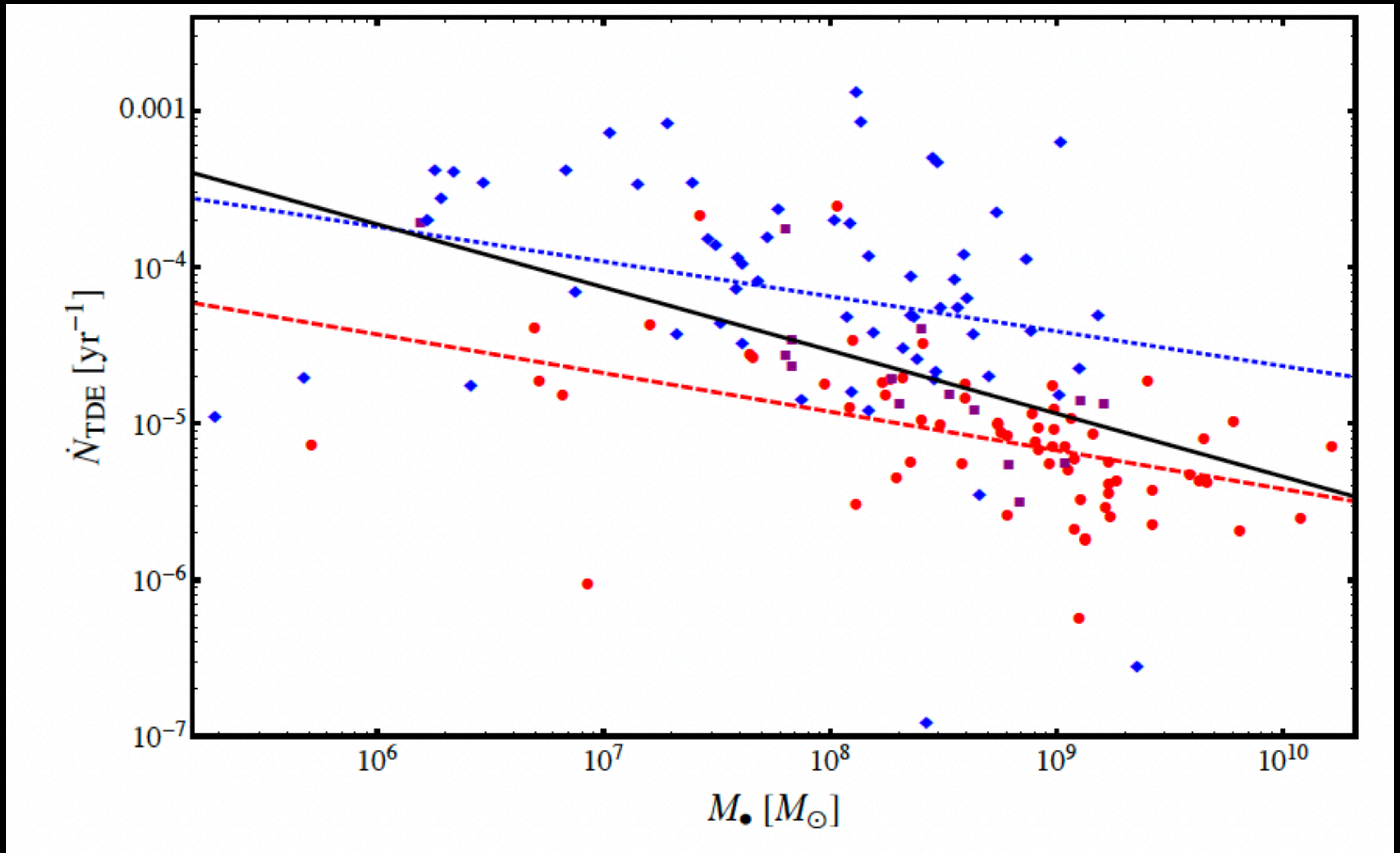
Magorrian & Tremaine 1999
Wang & Merritt 2004

- Stars exchange angular momentum through gravitational scattering.
- Critical angular momentum $L_c = \sqrt{2GM_{\rm BH}R_T}$
- Stars with $L < L_c$ gets tidally disrupted.

TDE rates calculated using theoretical or observed stellar density profiles

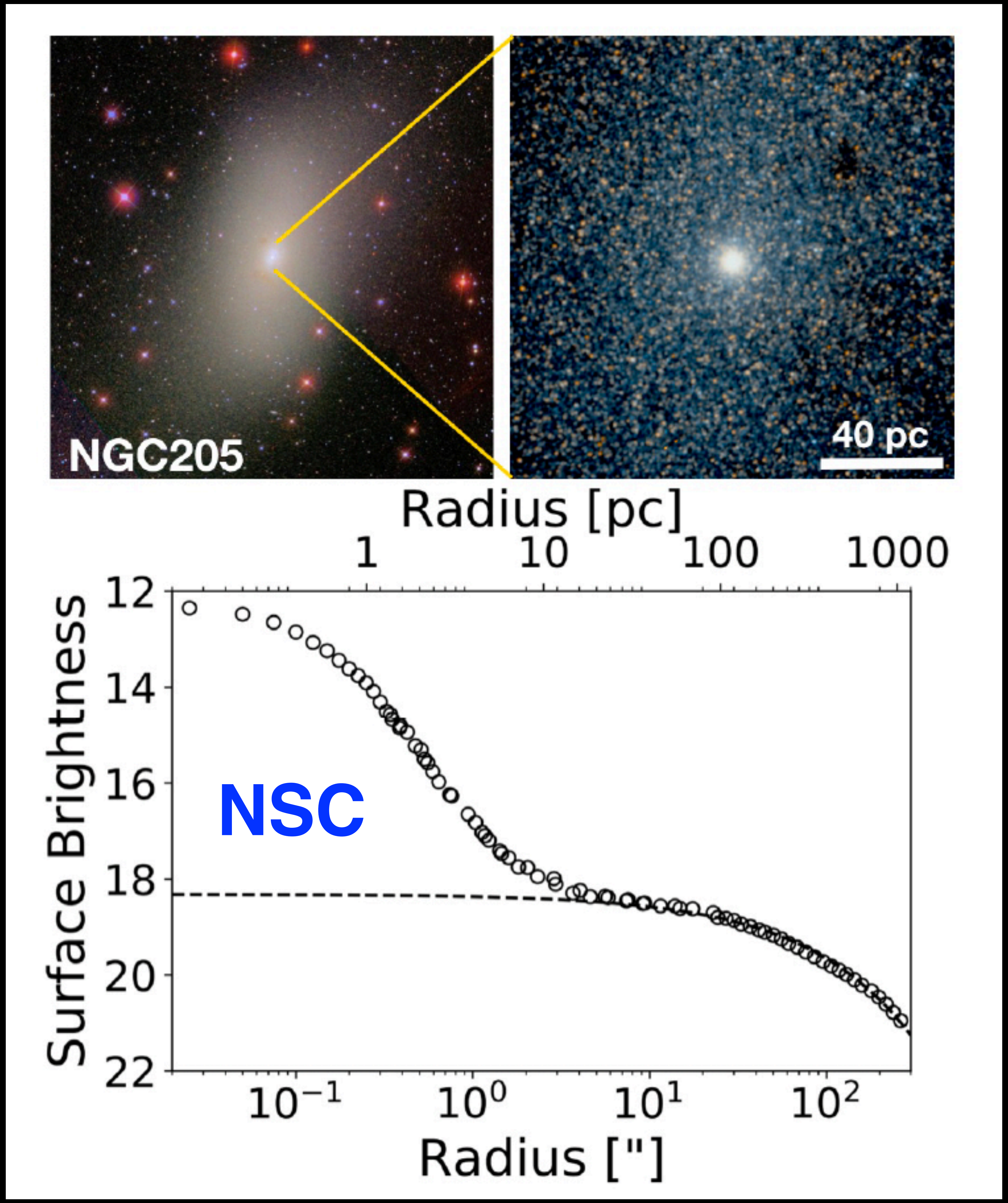


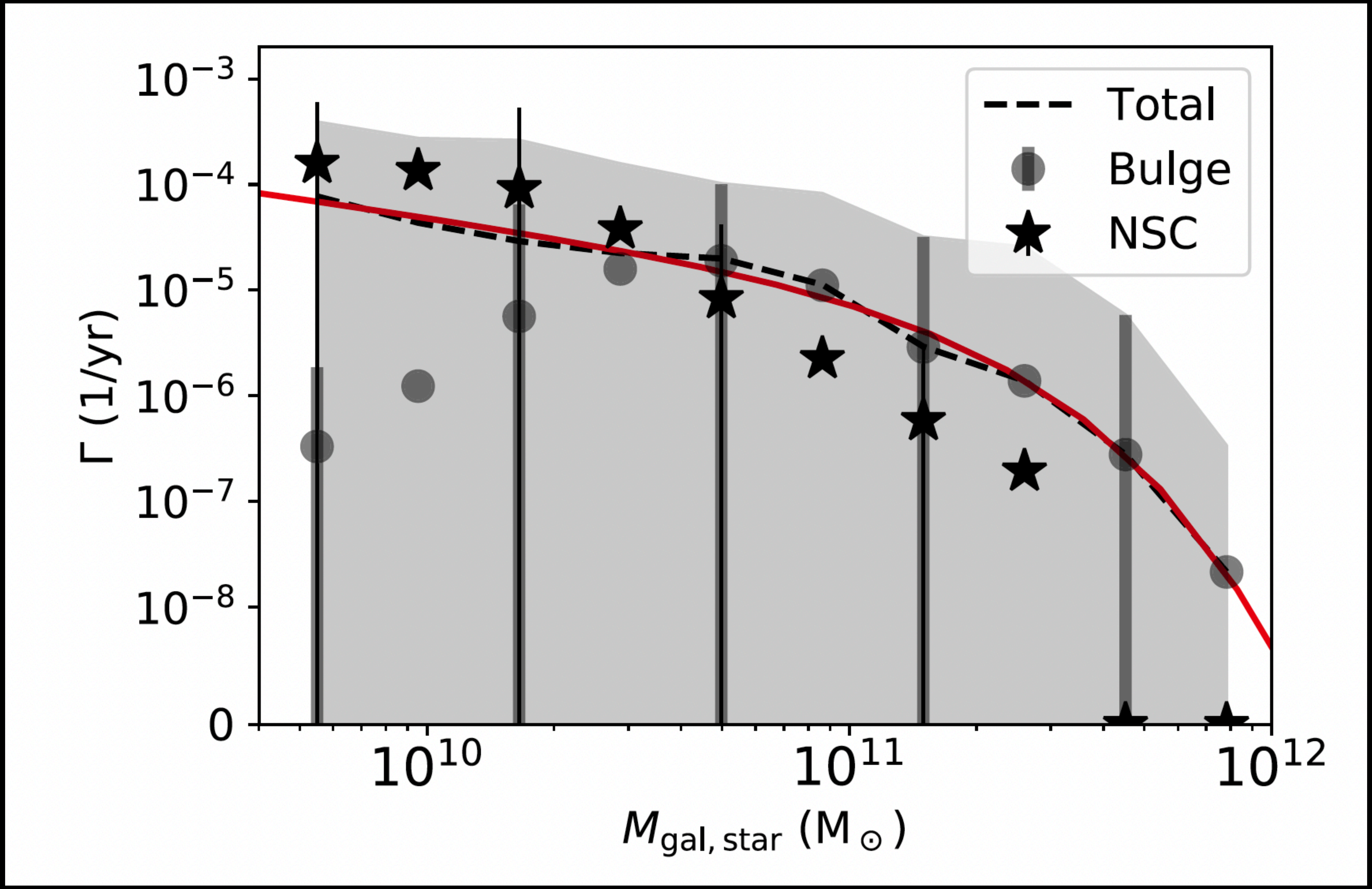
Wang & Merritt 2004



Stone & Metzger 2016

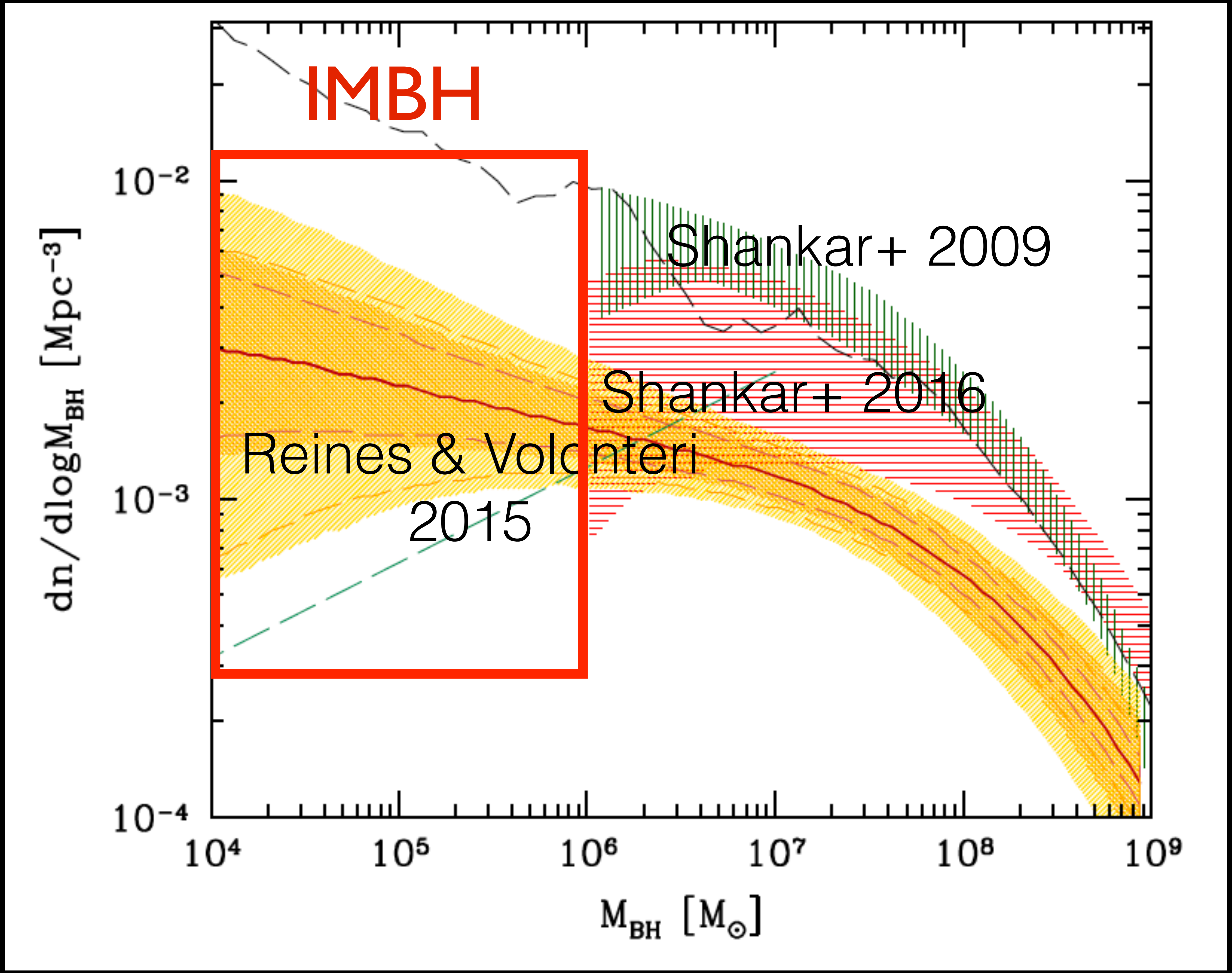
Nuclear star clusters in low-mass galaxies: TDE rate boosted up to 1000 times





Pfister, Volonteri, LD & Colpi 2020

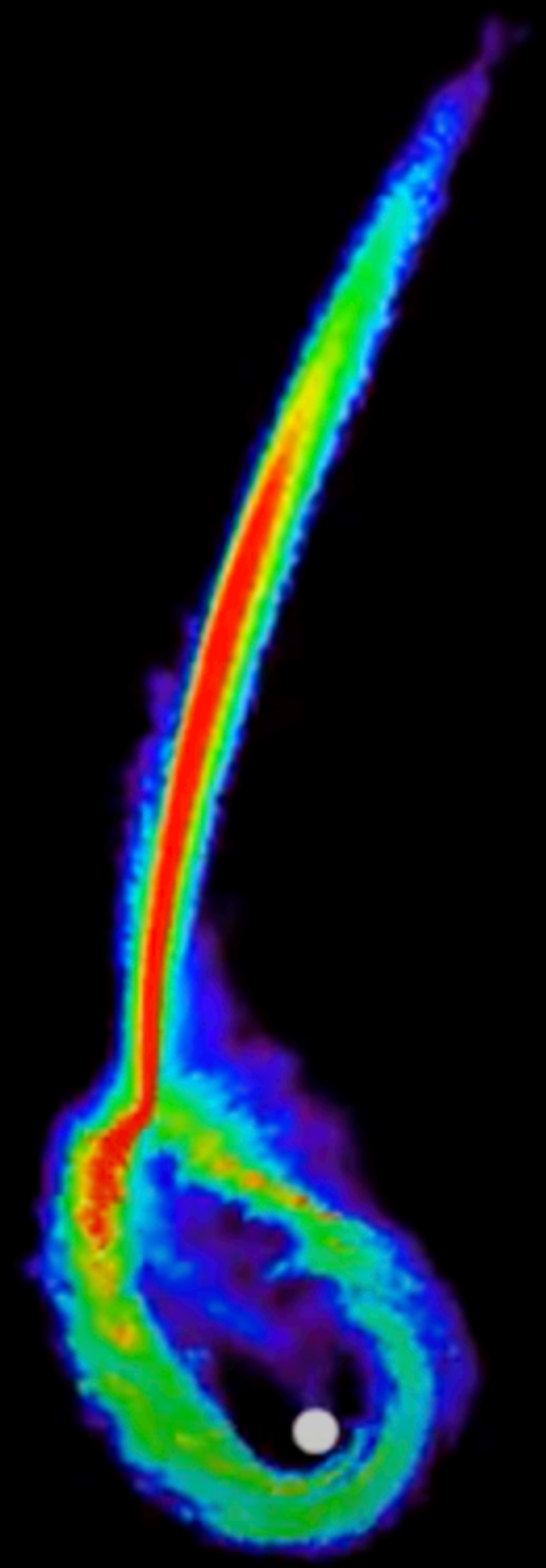
How about TDE rates from IMBHs?



Gallo & Sesana 2019

Next Talk by Janet Chang

Imprint of the TDE disk formation process on observed demographics

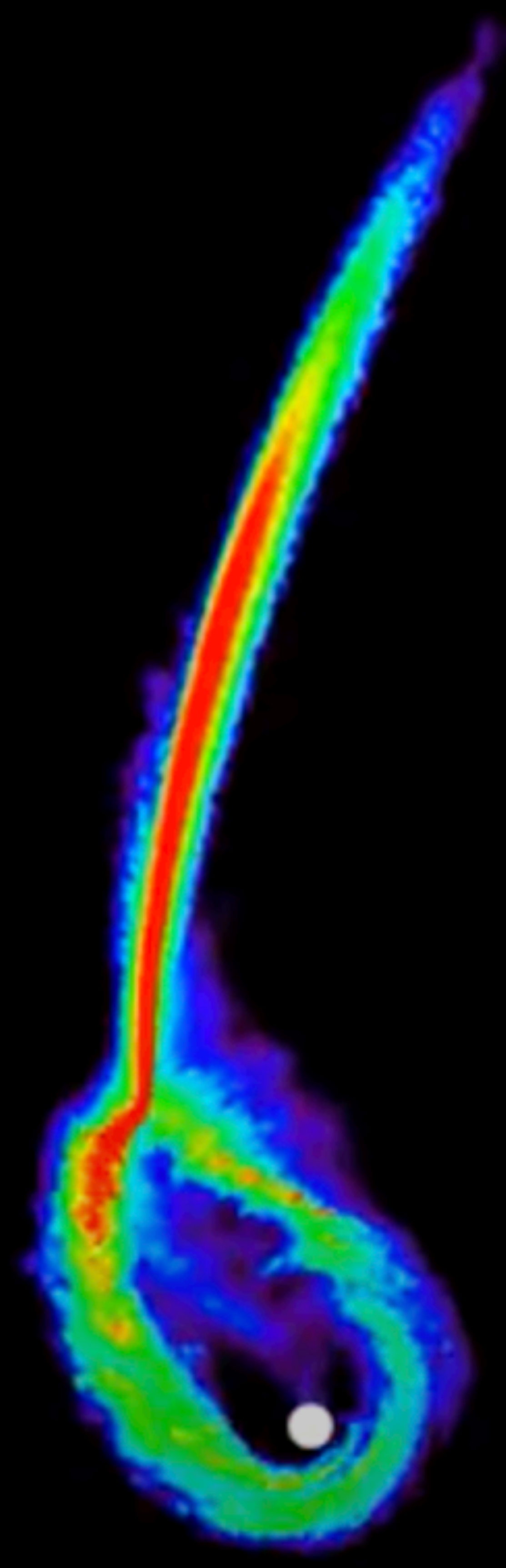


- Do disks form fast in all TDEs?
- How does the disk formation process affect the observed TDE BH demographics?

Bonnerot et al. 2016

Also Shiokawa et al. 2015, LD et al. 2013, 2015, Guillochon & Ramirez-Ruiz 2015, Hayasaki et al. 2016, Sadowski et al. 2016, Jiang et al 2016, Liptai 2019, Lu & Bonnerot 2020, Bonnerot & Lu 2020, Andalman et al. 2020, Steinberg & Stone 2022; Huang et al. 2023

Debris stream self-crossing radius



$R_I = f(M_{BH}, M_{\bigstar}, \boldsymbol{\beta})$

Closer self-crossing, faster disk formation

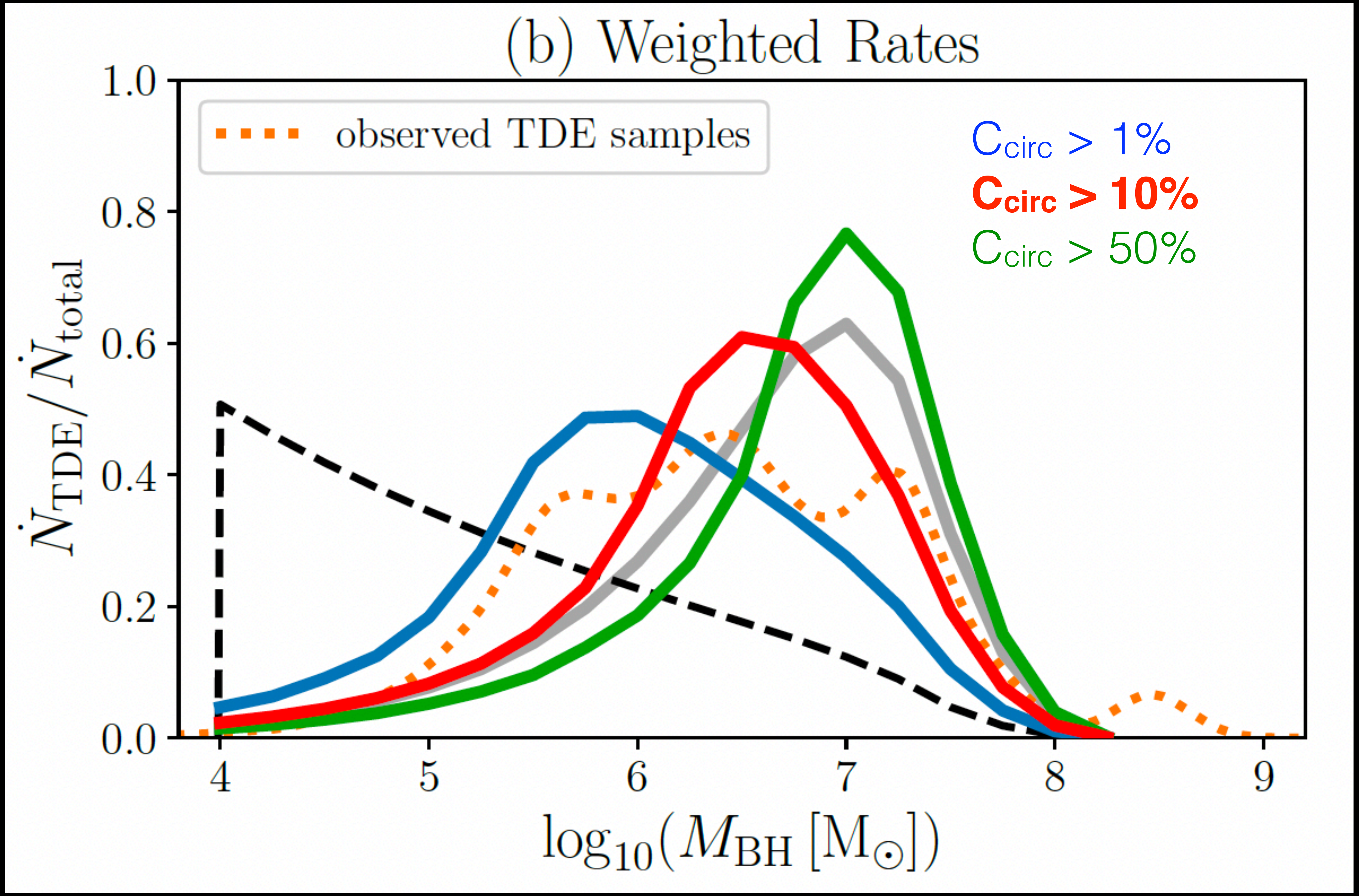
More massive black hole

Denser (smaller) star

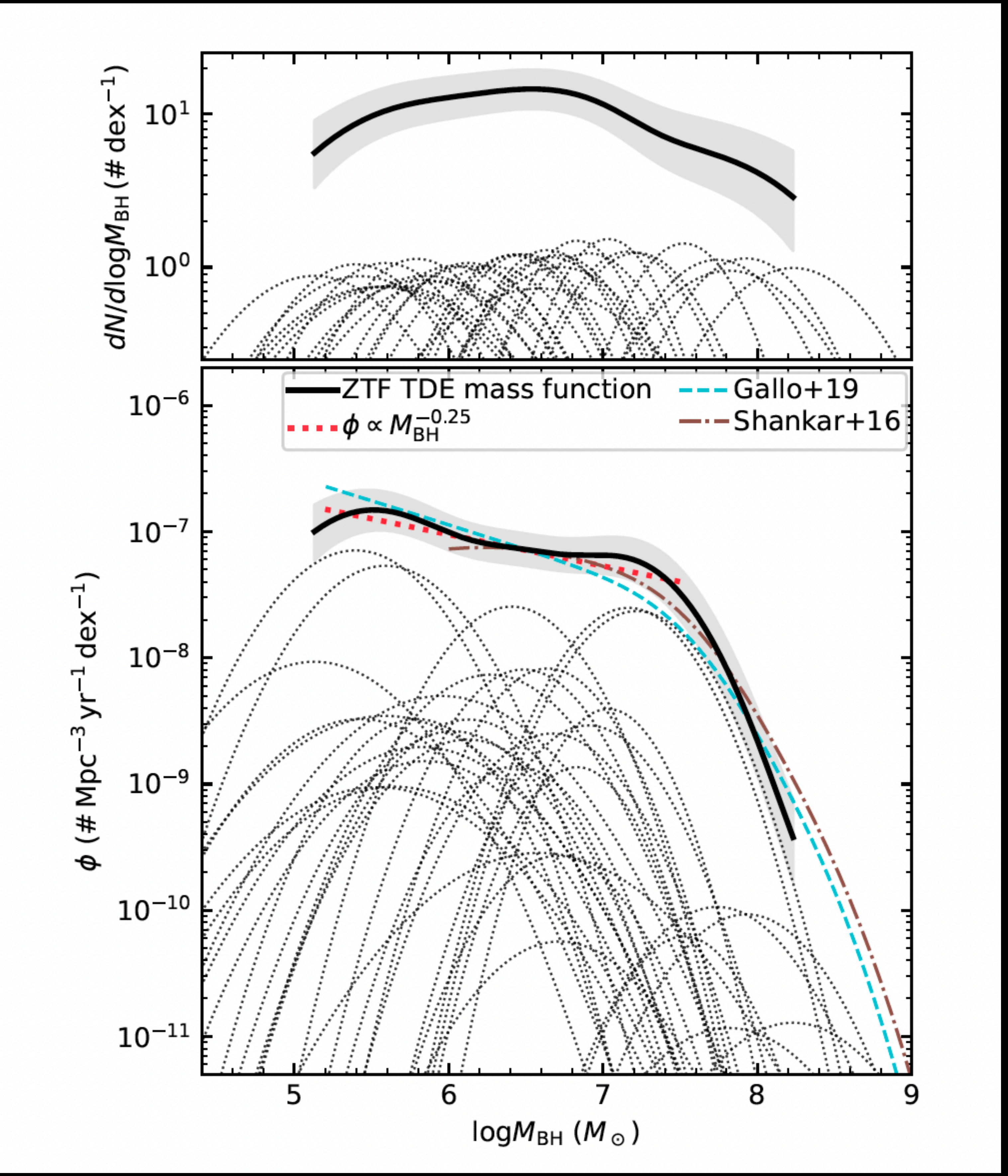
Deeper encounter

LD, McKinney, Miller 2015

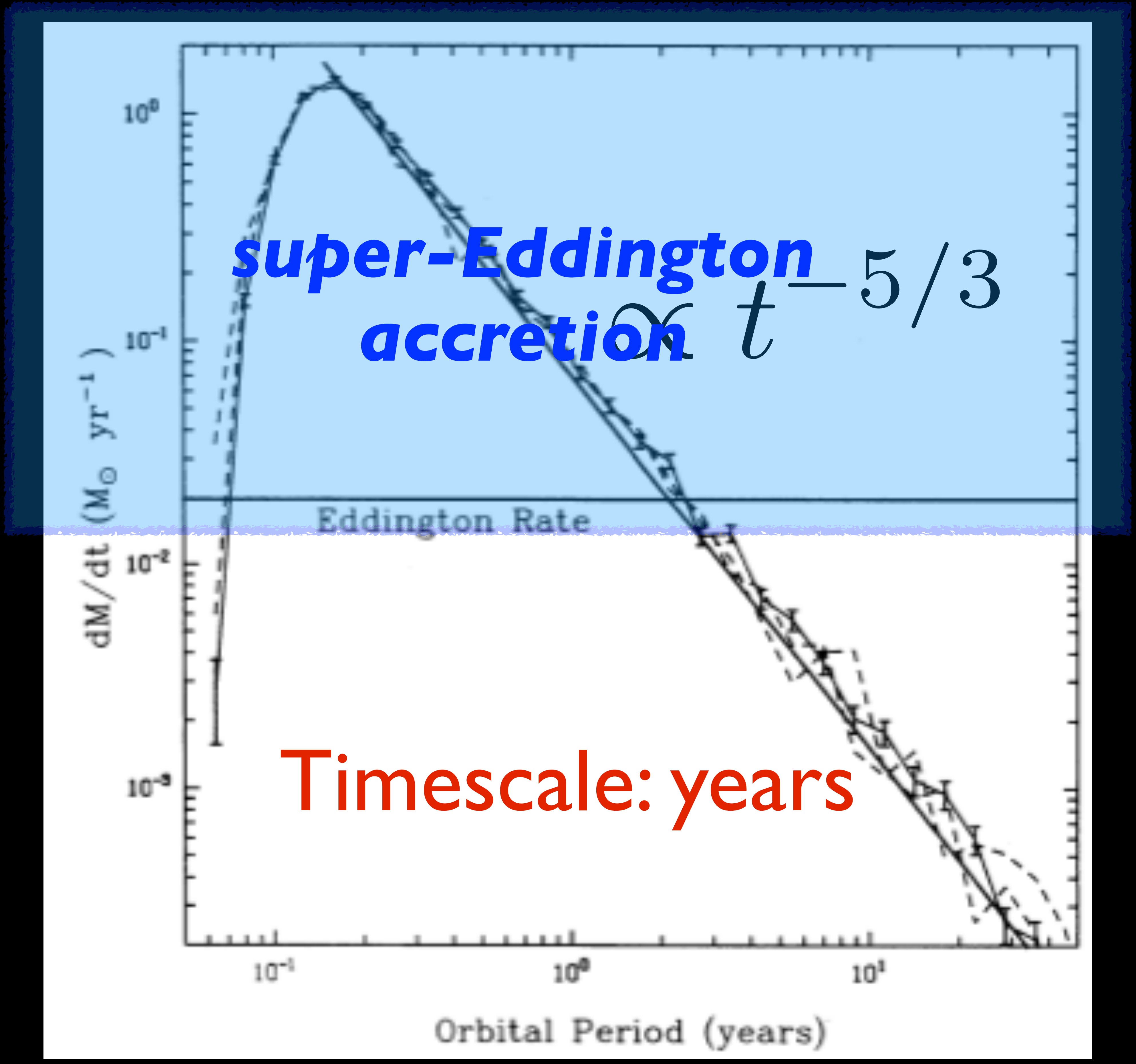
TDE rate from low-mass MBHs is suppressed



Wong, Pfister, LD 2022



Yao et al. 2023

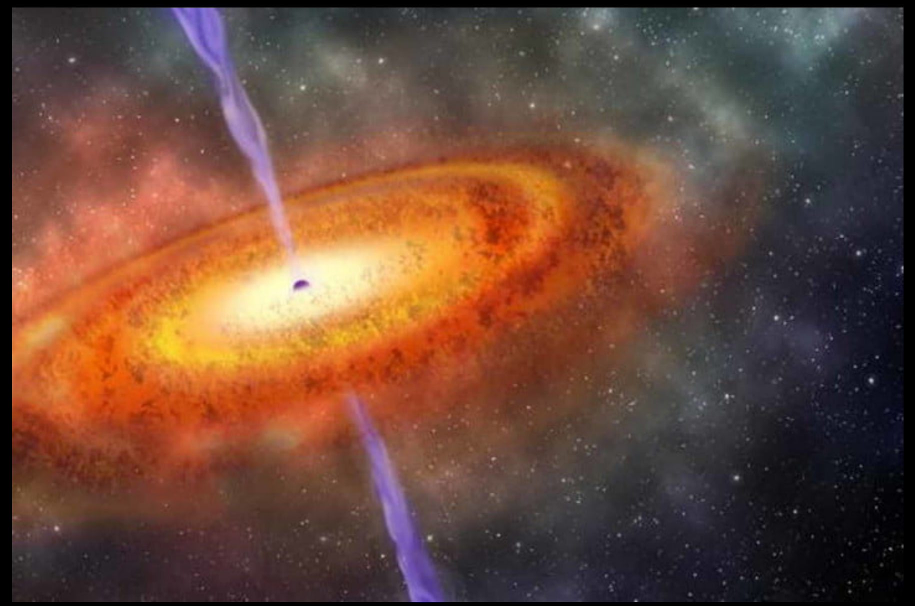


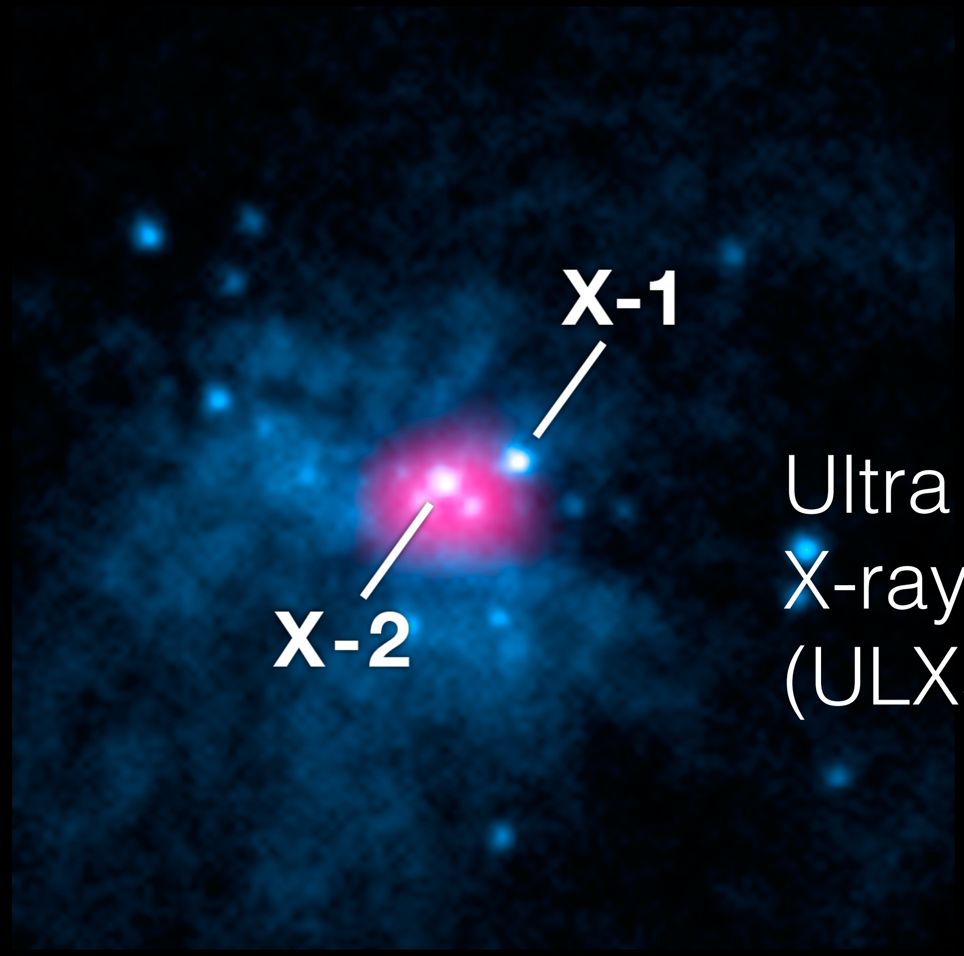
★ Accretion disk, wind & jet physics in the regime of super-Eddington accretion

Review by LD, Lodato & Cheng 2021

Also: Strubbe & Quartaet 2009, Lodato & Rossi 2011, Coughlin & Begelman 2014, Metzger & Stone 2016, Curd & Narayan 2019

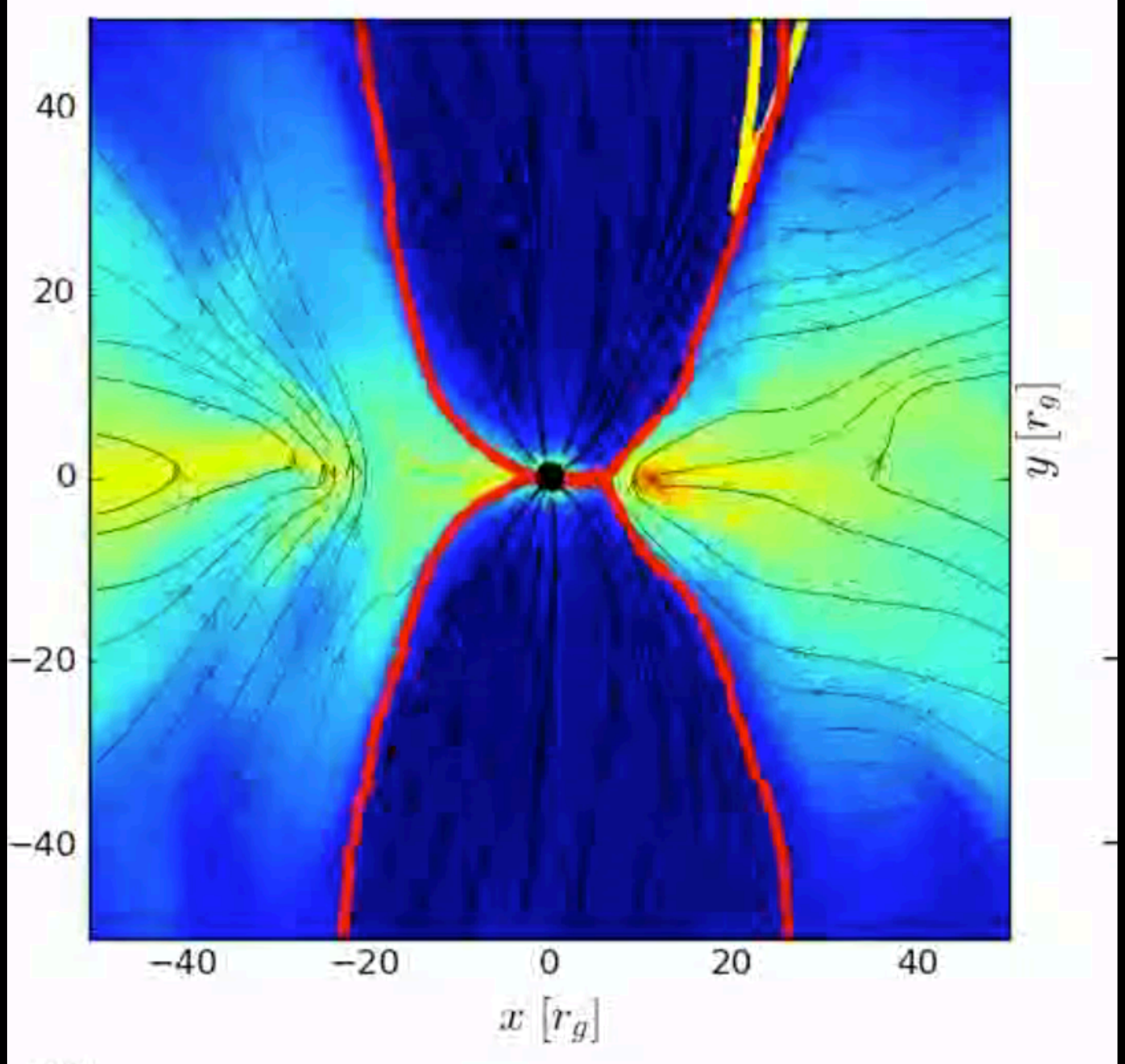
High-redshift quasars



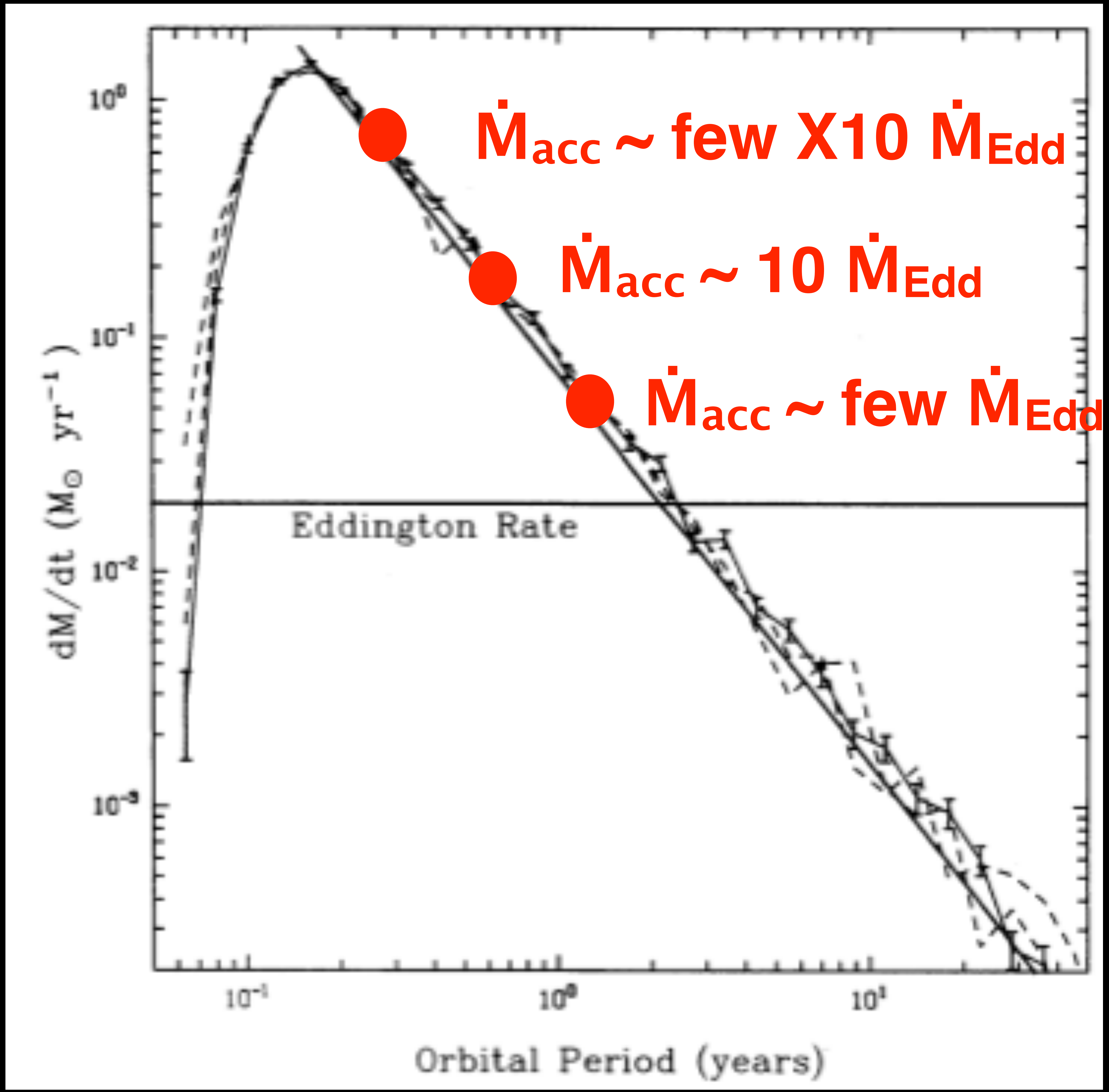


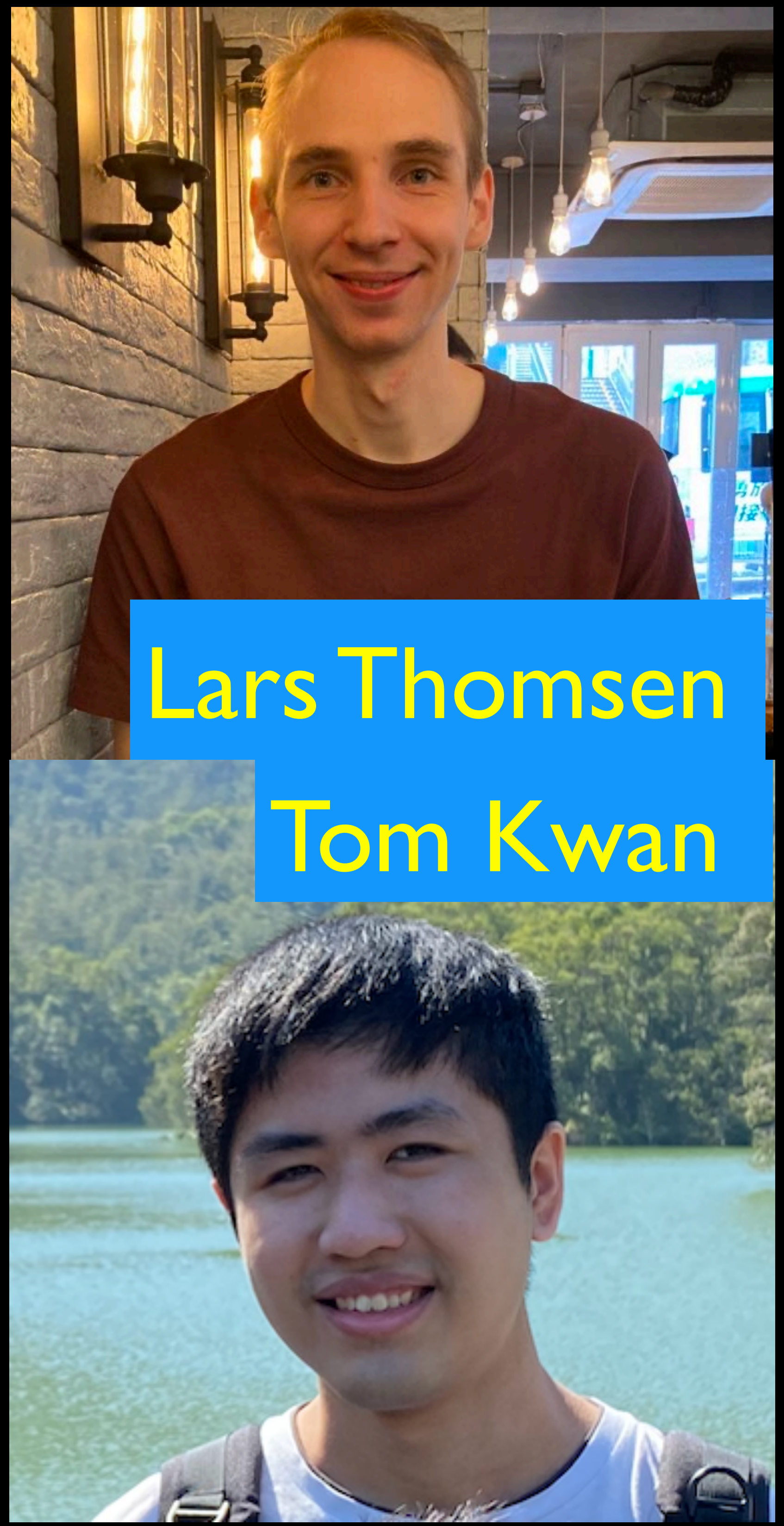
Ultra luminous X-ray sources (ULXs)

Simulation of TDE super-Eddington disks



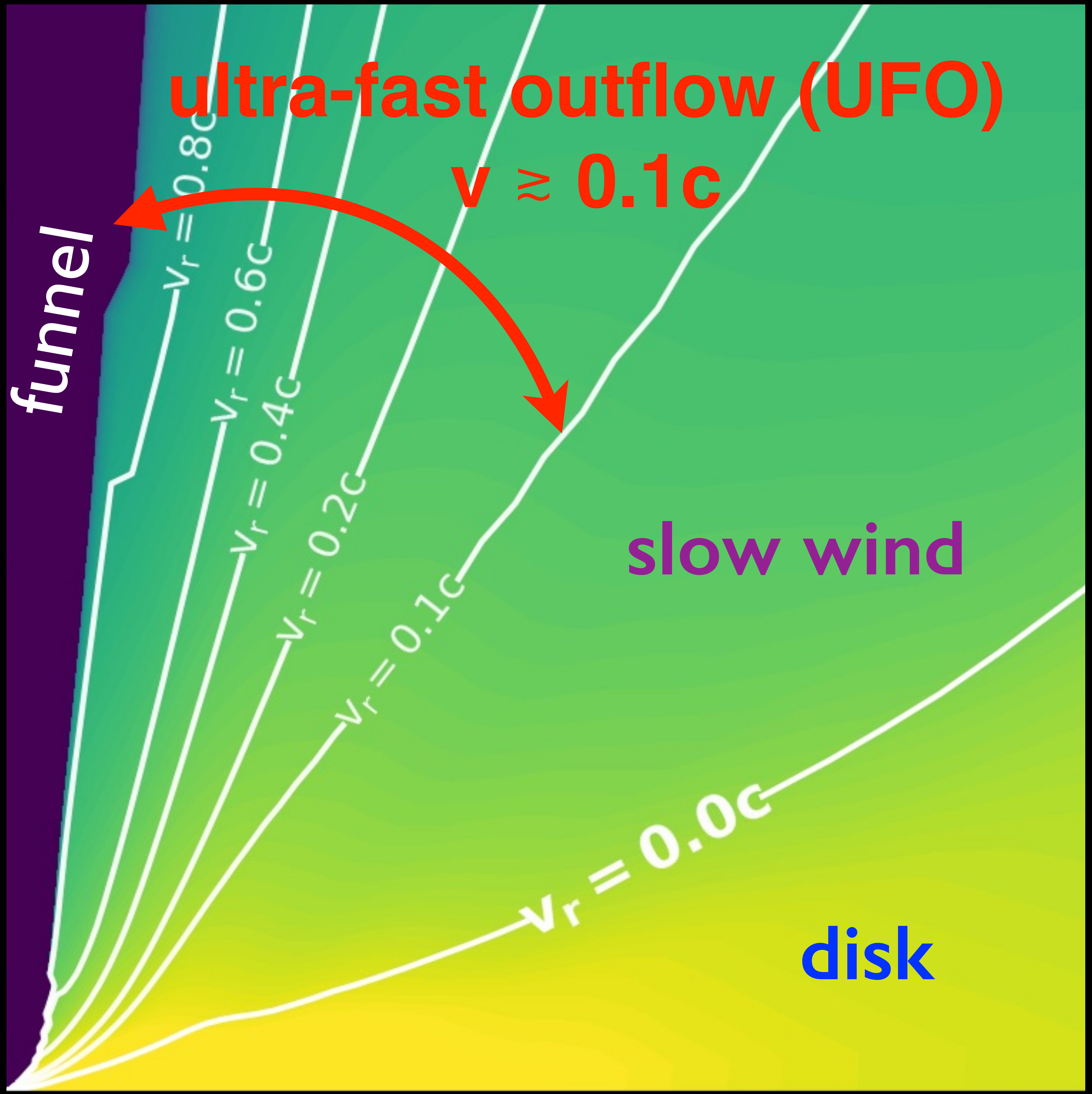
- 3D full GR-Radiation-MHD code HARMRAD (Gammie et al. 03, McKinney et al. 12,14)

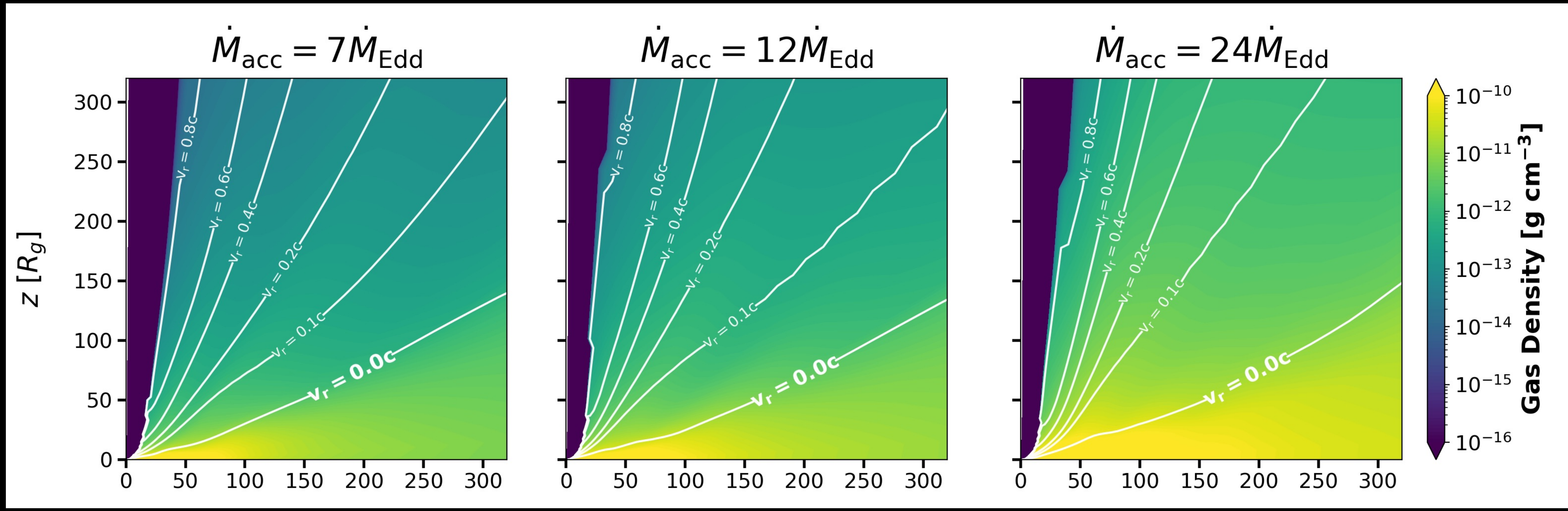




LD, McKinney, Roth et al. 2018
Thomsen, Kwan, LD et al. 2022

Disk-Wind-Funnel Geometry



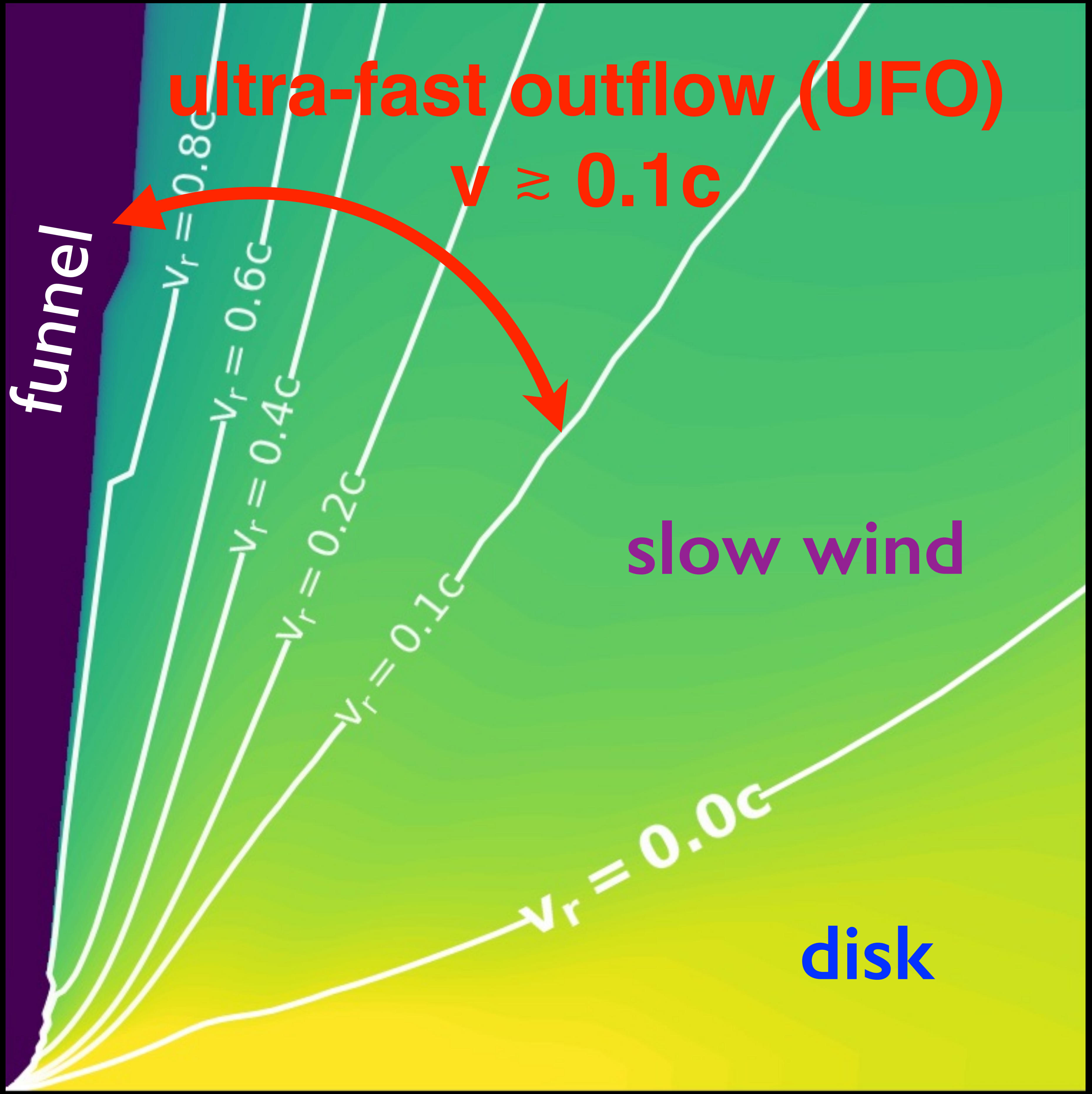


UFO & slow wind observed in TDEs:

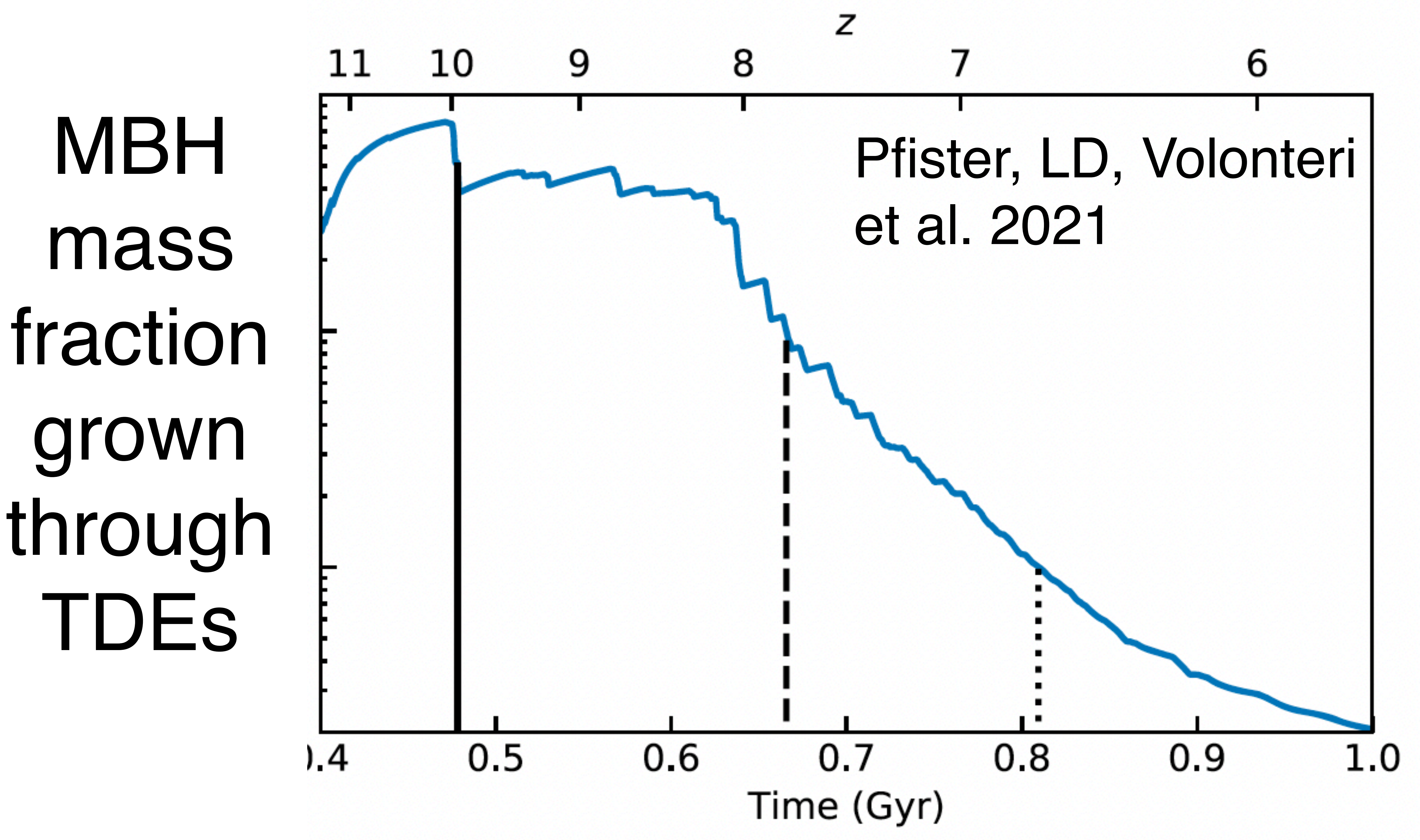
Alexander et al. 2016, 2017; Kara et al. 2016, 2018; Kosec et al. 2023; Lin et al. 2015; Nicholl et al. 2020; Hung et al. 2019, 2021

Disk-Wind-Funnel Geometry

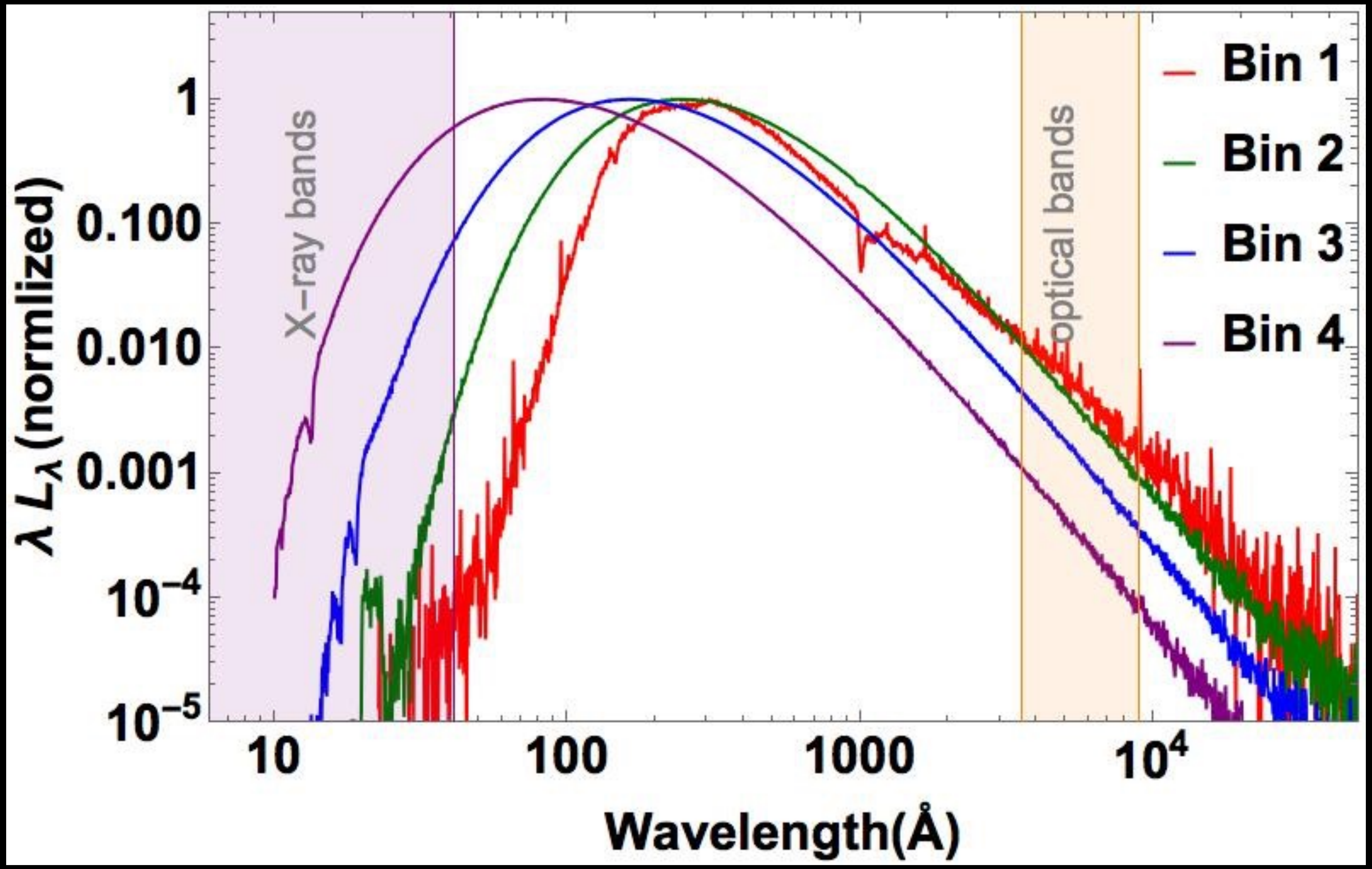
Super-Eddington disk wind:
Talks by Tom Kwan & Zijian Zhang on Thursday!

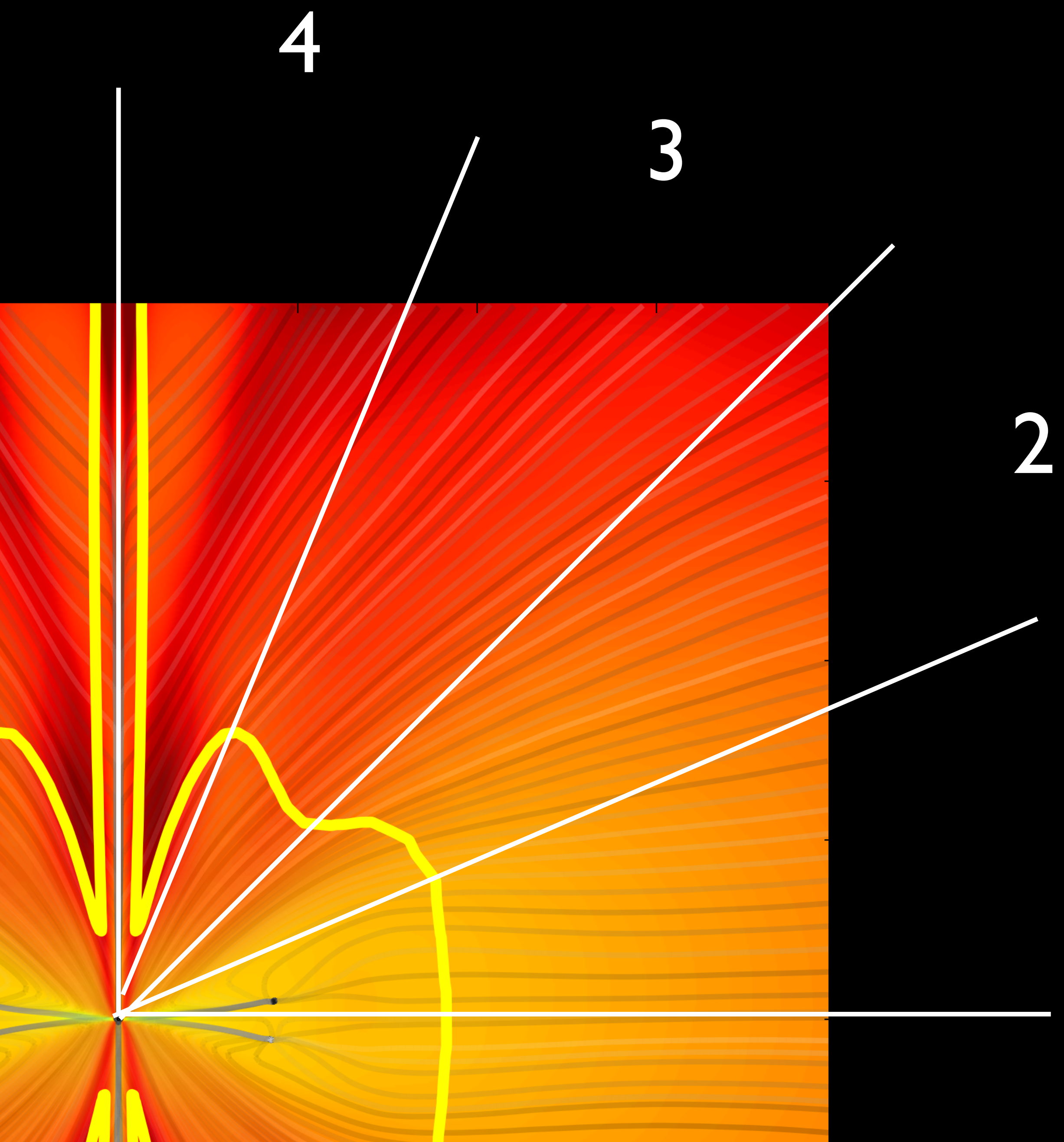


MBHs have grown significantly through TDEs at high-redshifts.



Spectra vs. Viewing Angle

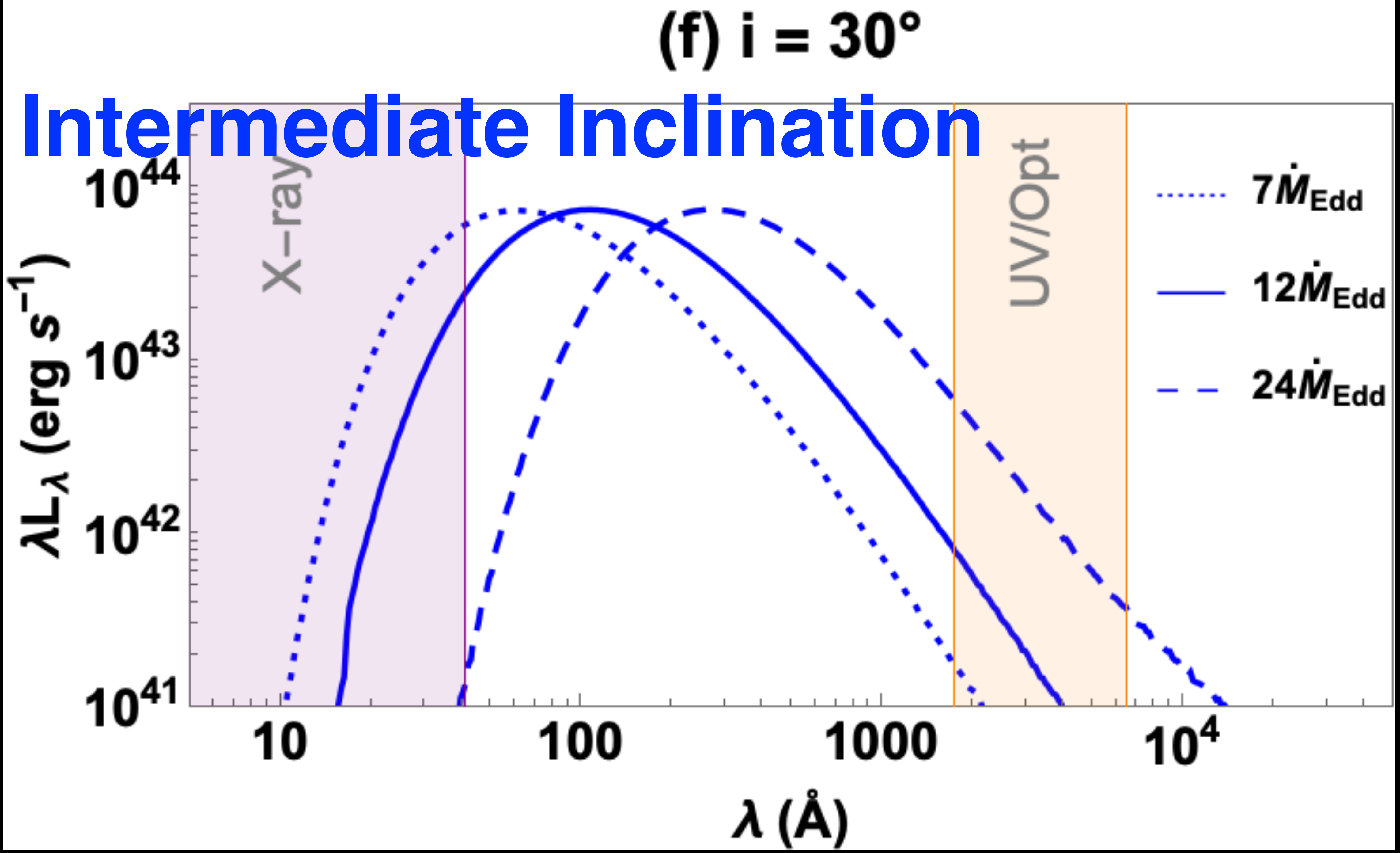




- X-rays heavily reprocessed in wind and disk
- Spectra calculated using radiative transfer code Sedona (Kasen 2006)

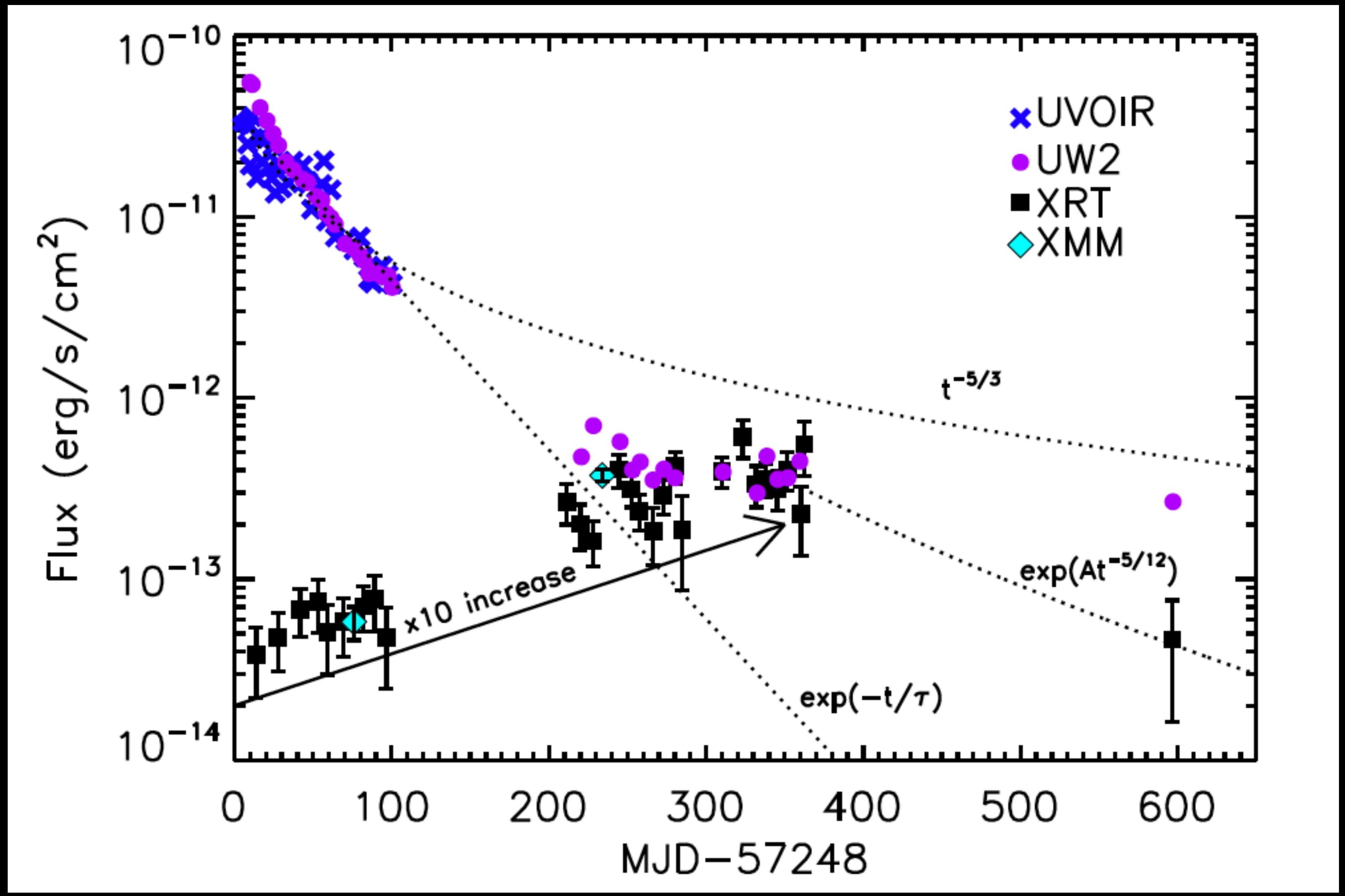
Optical TDEs can brighten in X-rays at late time

- Lower Eddington ratio → smaller outflow ratio
  → less reprocessing of disk emissions



Thomsen, Kwan, LD et al. 2022

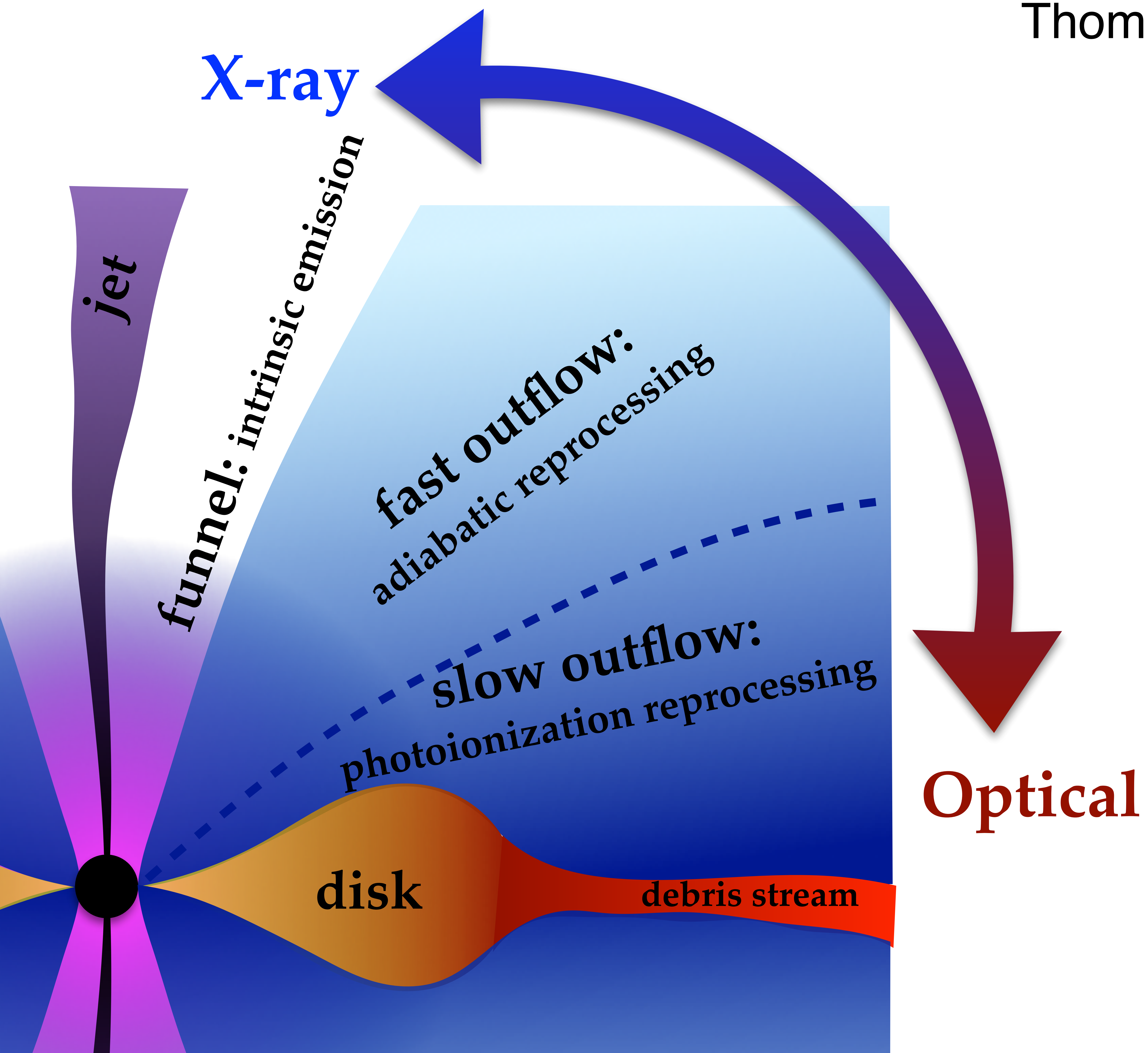
ASASSN 15oi
Gezari et al. 2017, Holoien et al. 2018

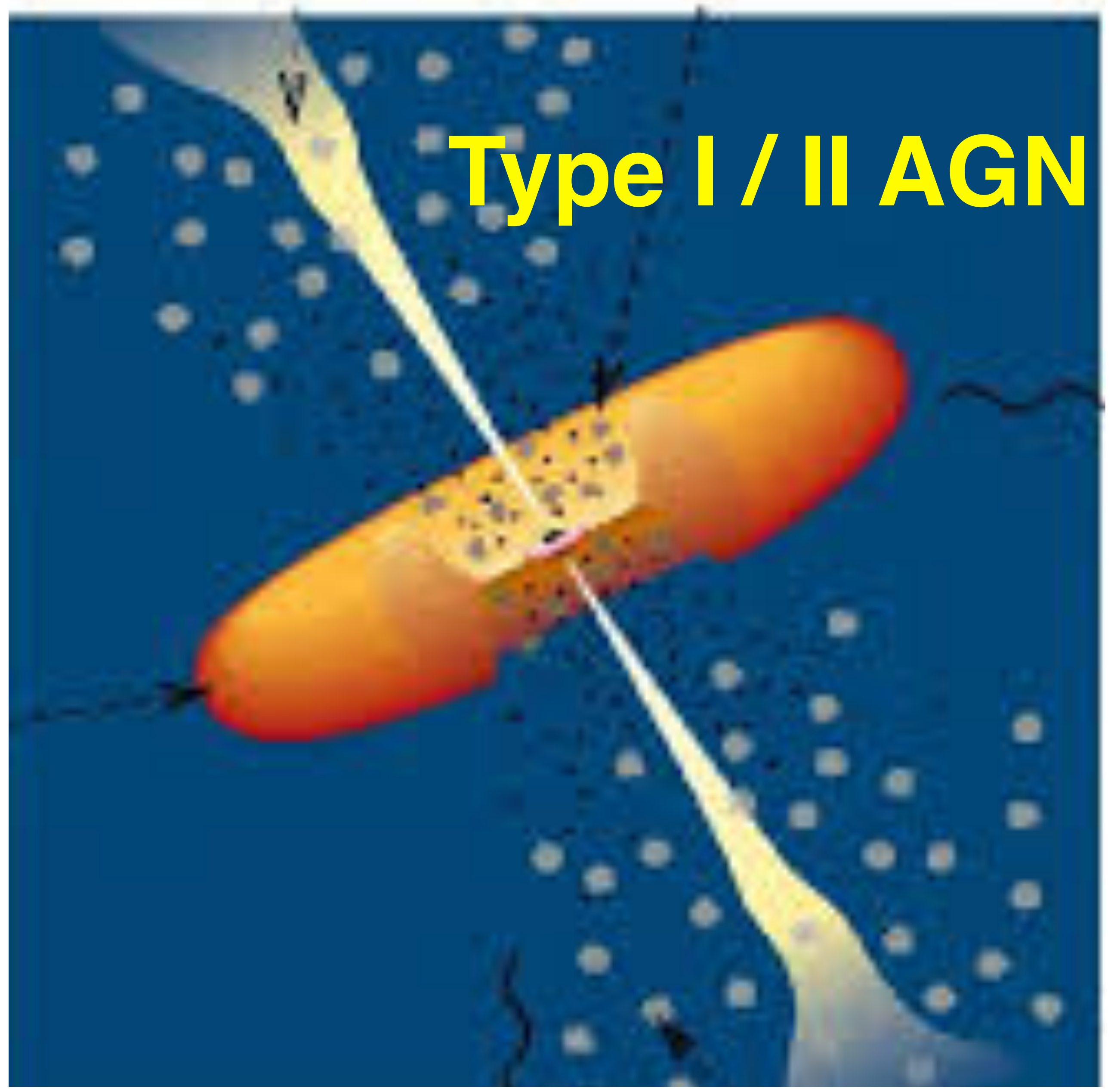


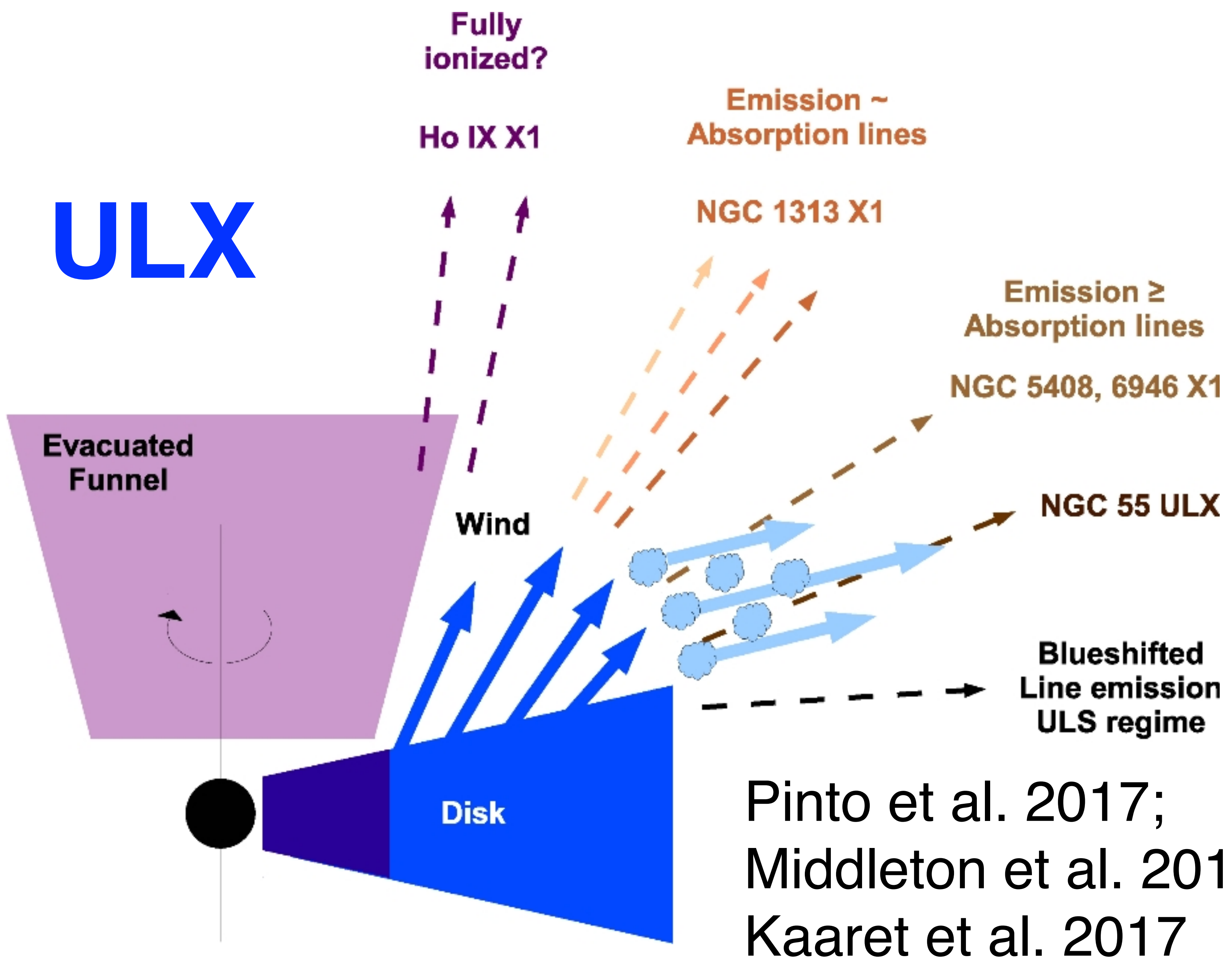
Dynamical Unified TDE Model

LD, McKinney, Roth et al. 2018

Thomsen, Kwan, LD et al. 2022

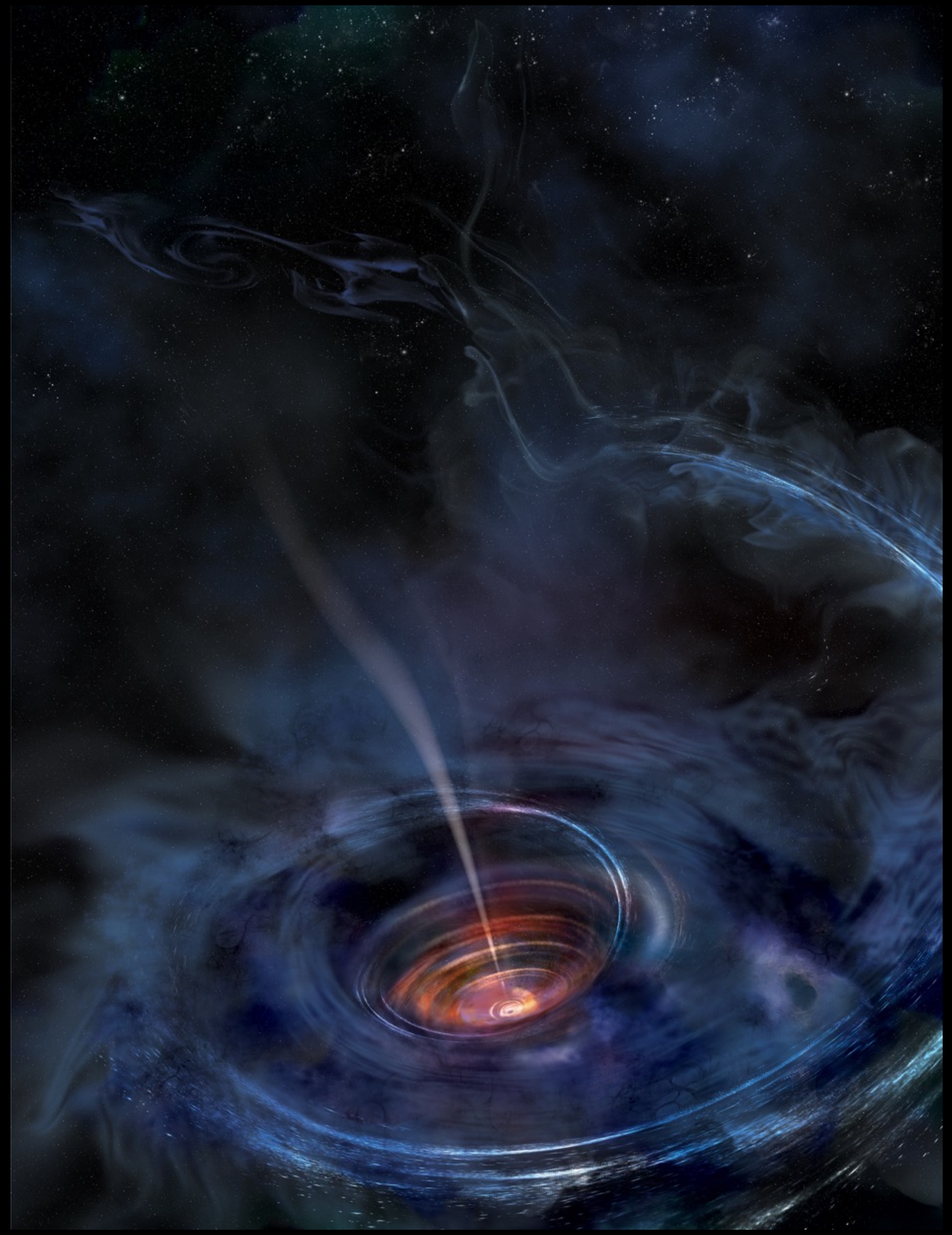






Pinto et al. 2017;
Middleton et al. 2011;
Kaaret et al. 2017

Summary — TDEs are valuable probes



Jane Dai: lixindai@hku.hk

Demographics of MBHs including IMBHs: careful modelling needed to recover the intrinsic demographics

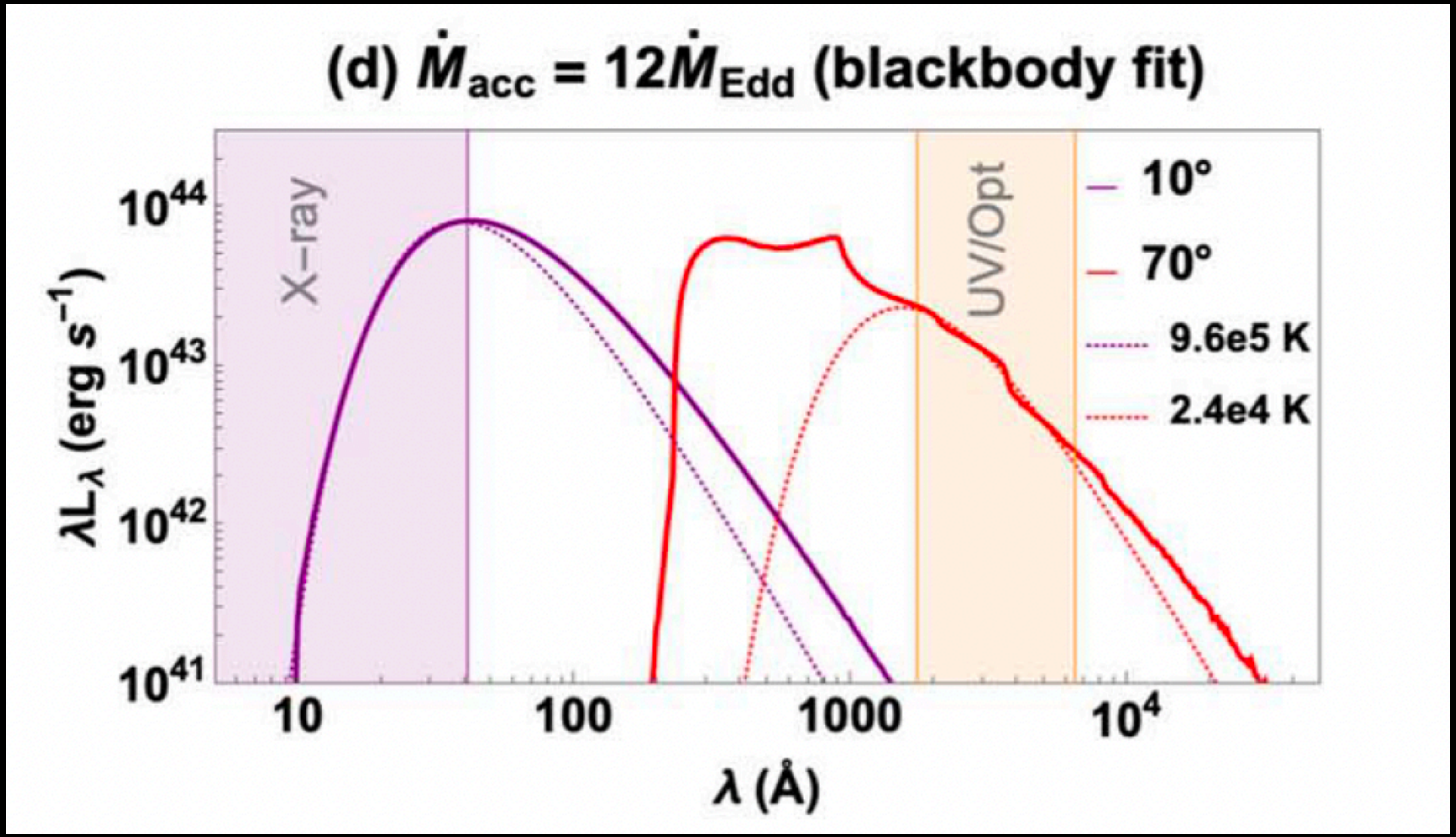
— Inner galaxy structure with implicit dependence on galaxy/BH mass
— TDE physics such as disk formation process with dependence on BH mass and others

Extreme accretion & outflow physics around MBHs:

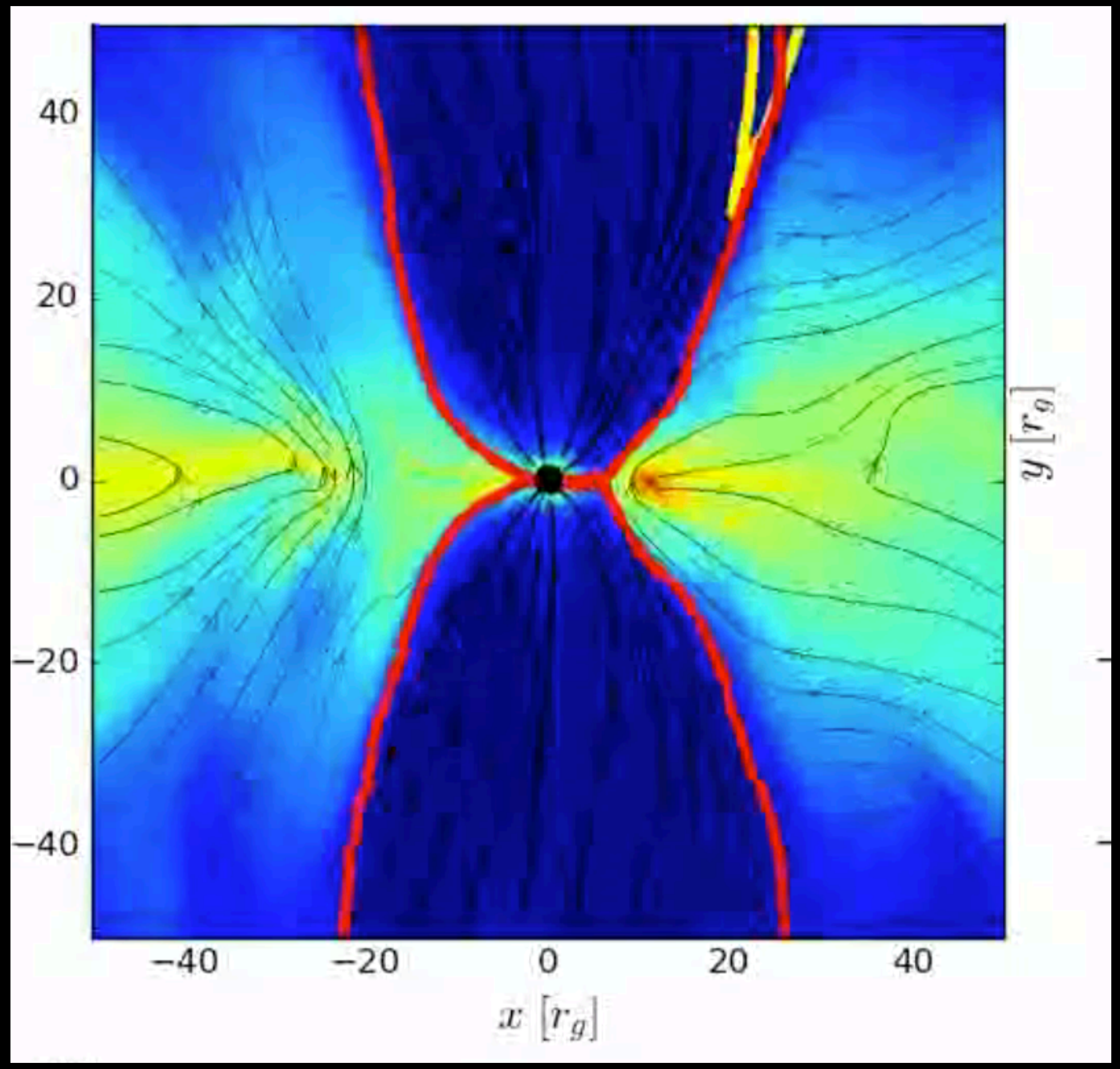
— Launching fast and energetic outflows
— Unique emission physics linking to TDE diversity and evolution.
— Connections to ULXs, NLS1s, high-z quasars…

TDE Missing Energy Problem

- Non-thermal spectra, most energy in EUV
- $L_{BB, fit}$ ~ (1-10)% L_{bol}
- X-ray T_{BB} ~ 10^{5-6} K; Optical T_{BB} ~ 10^4 K



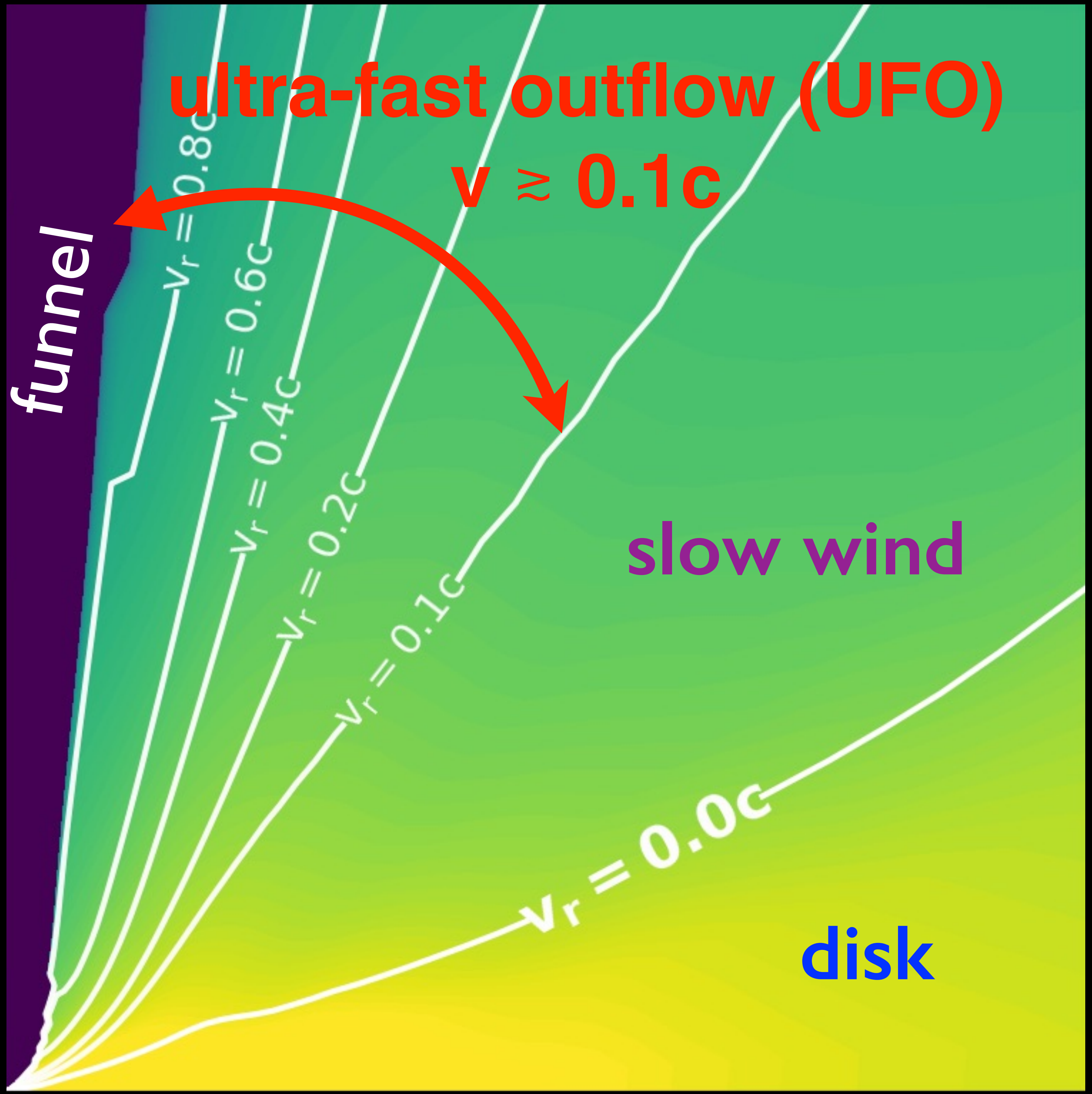
Simulation of TDE super-Eddington disks

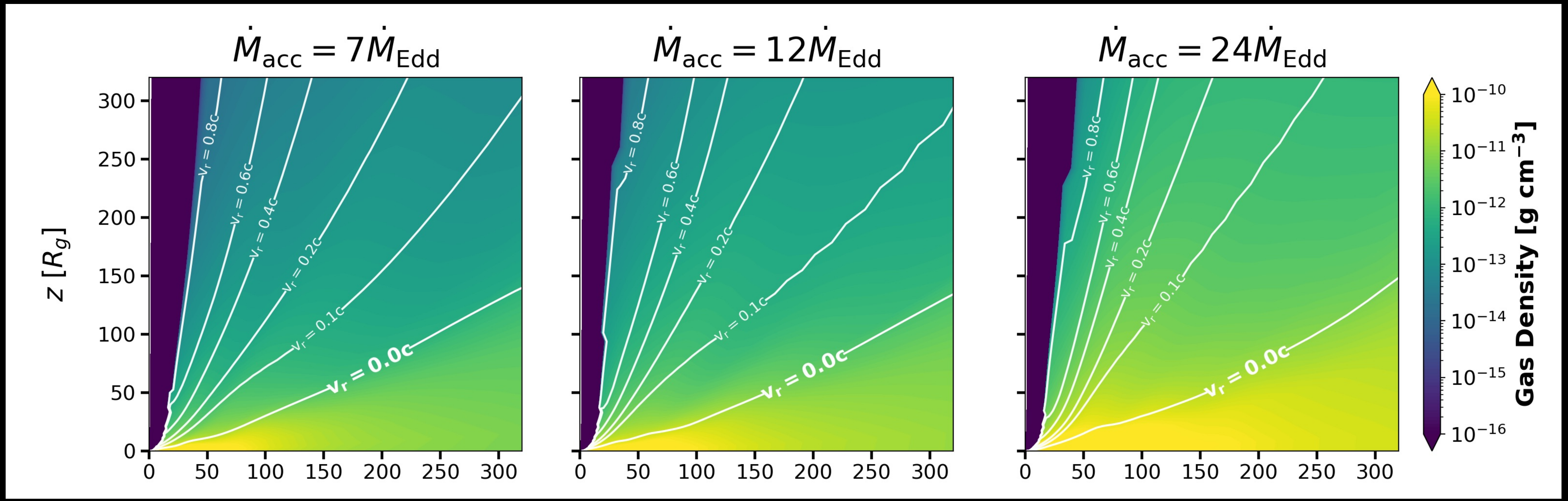


LD, McKinney, Roth et al. 2018
Thomsen, Kwan, LD et al. 2022

- Radiation evolved simultaneously with gas
- M1 approximation for radiation
- Scattering, absorption/emission (grey opacity), thermal Comptonization included
- Supermassive black holes with ~$10^6\ M_\odot$
- Circular disk aligned with black hole spin

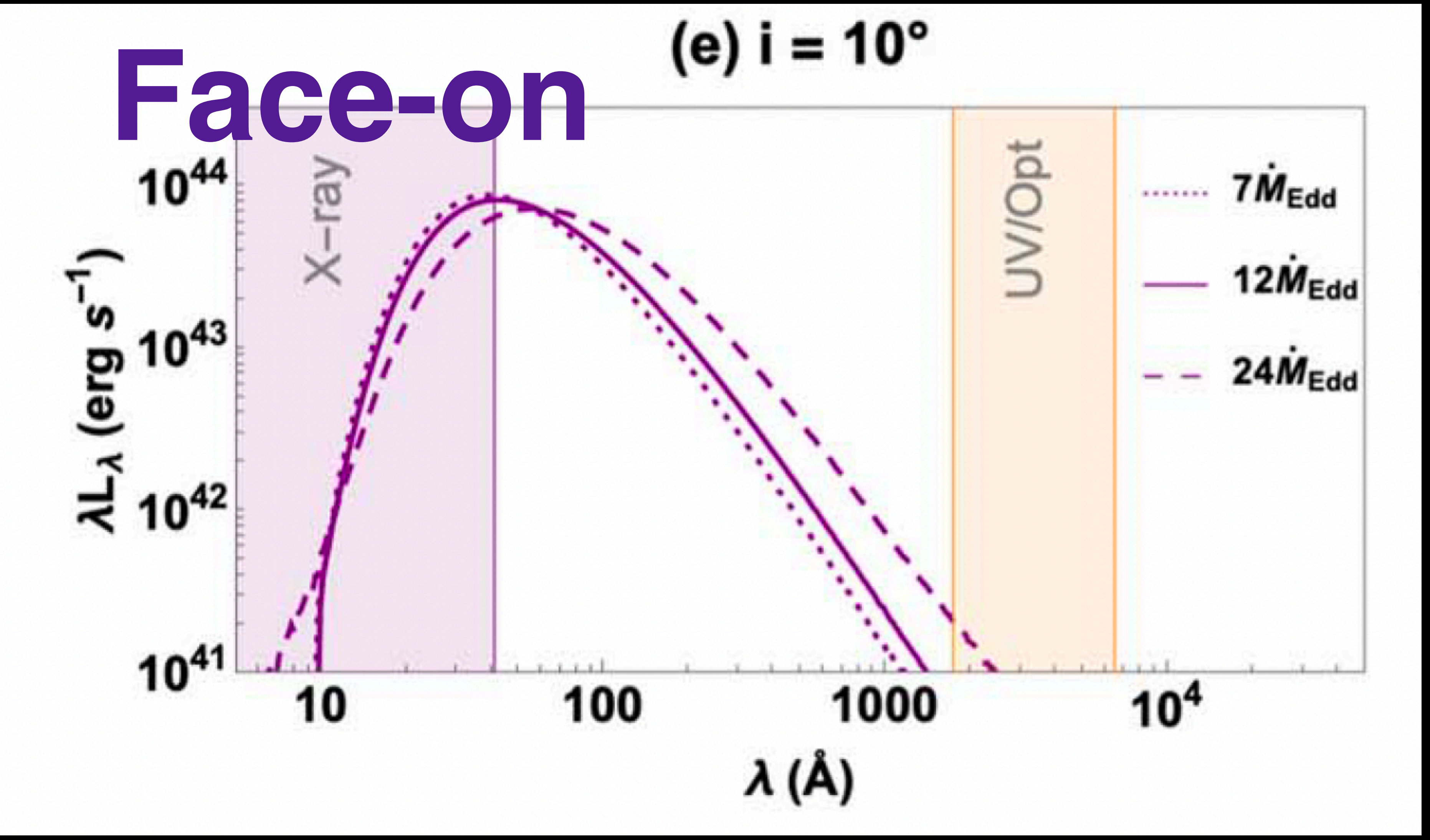
Disk-Wind-Funnel Geometry

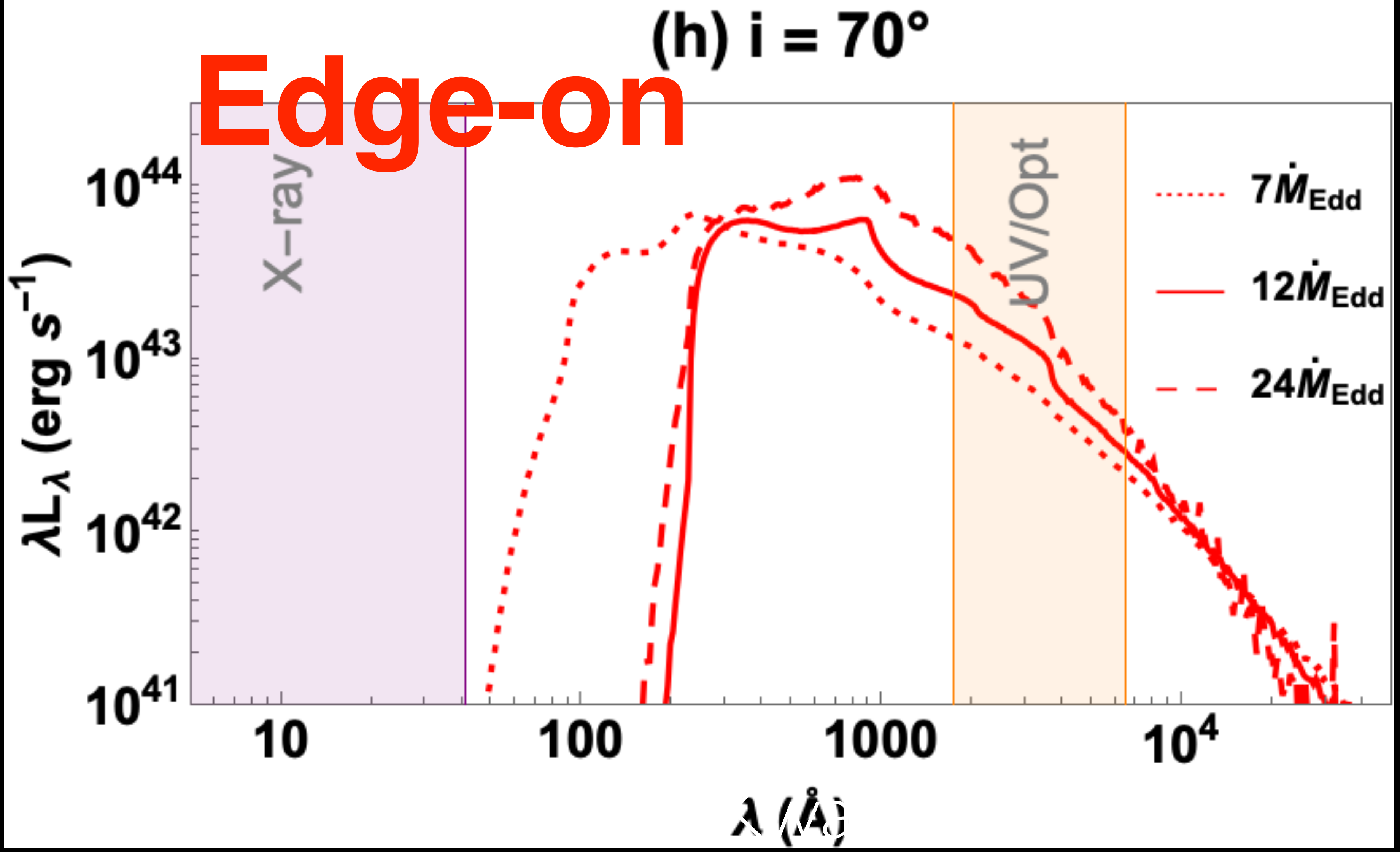


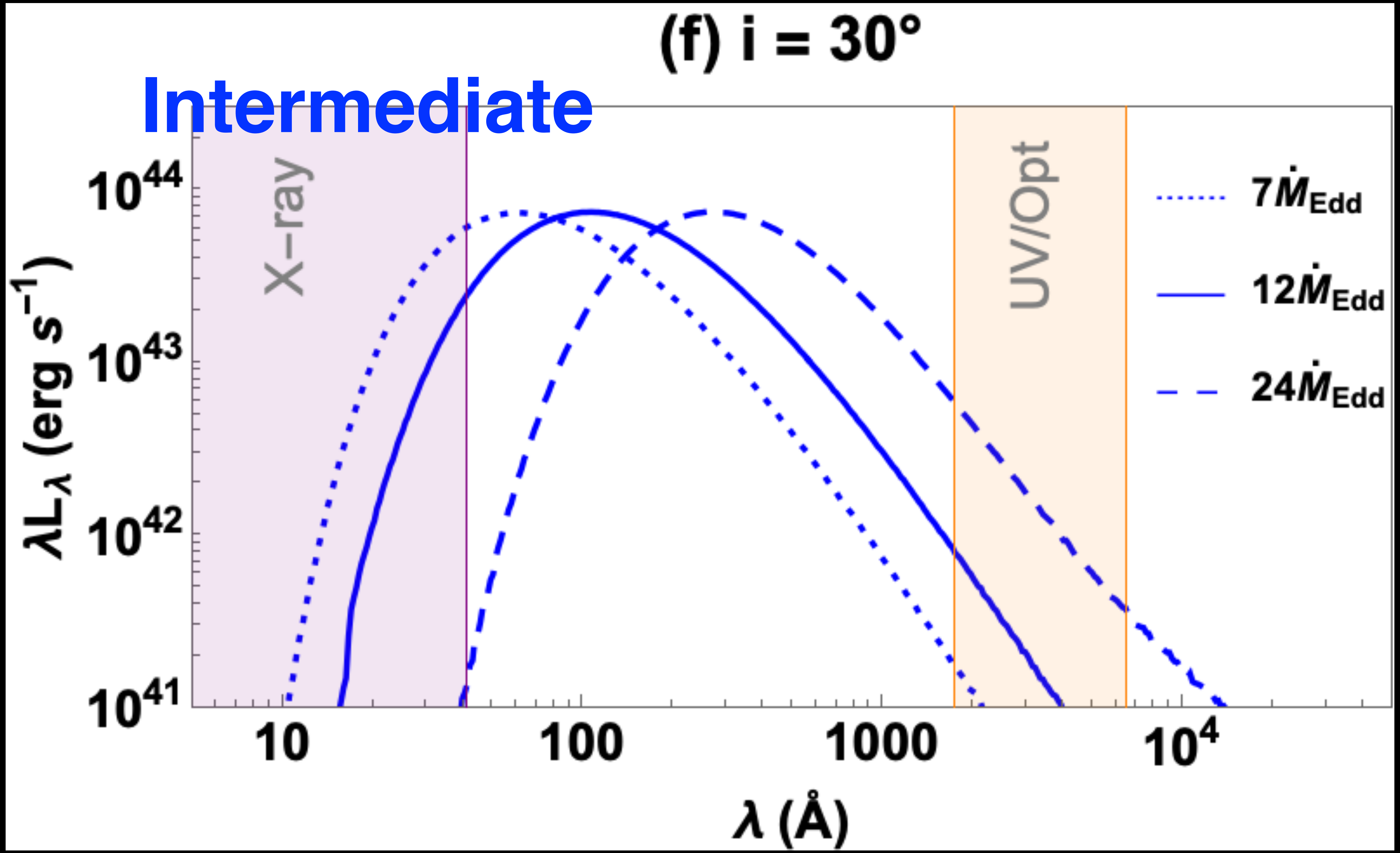


- Stable structure
- Higher Eddington ratio → larger outflow ratio
  → more reprocessing of disk emissions

More X-rays reprocessed at higher accretion rates



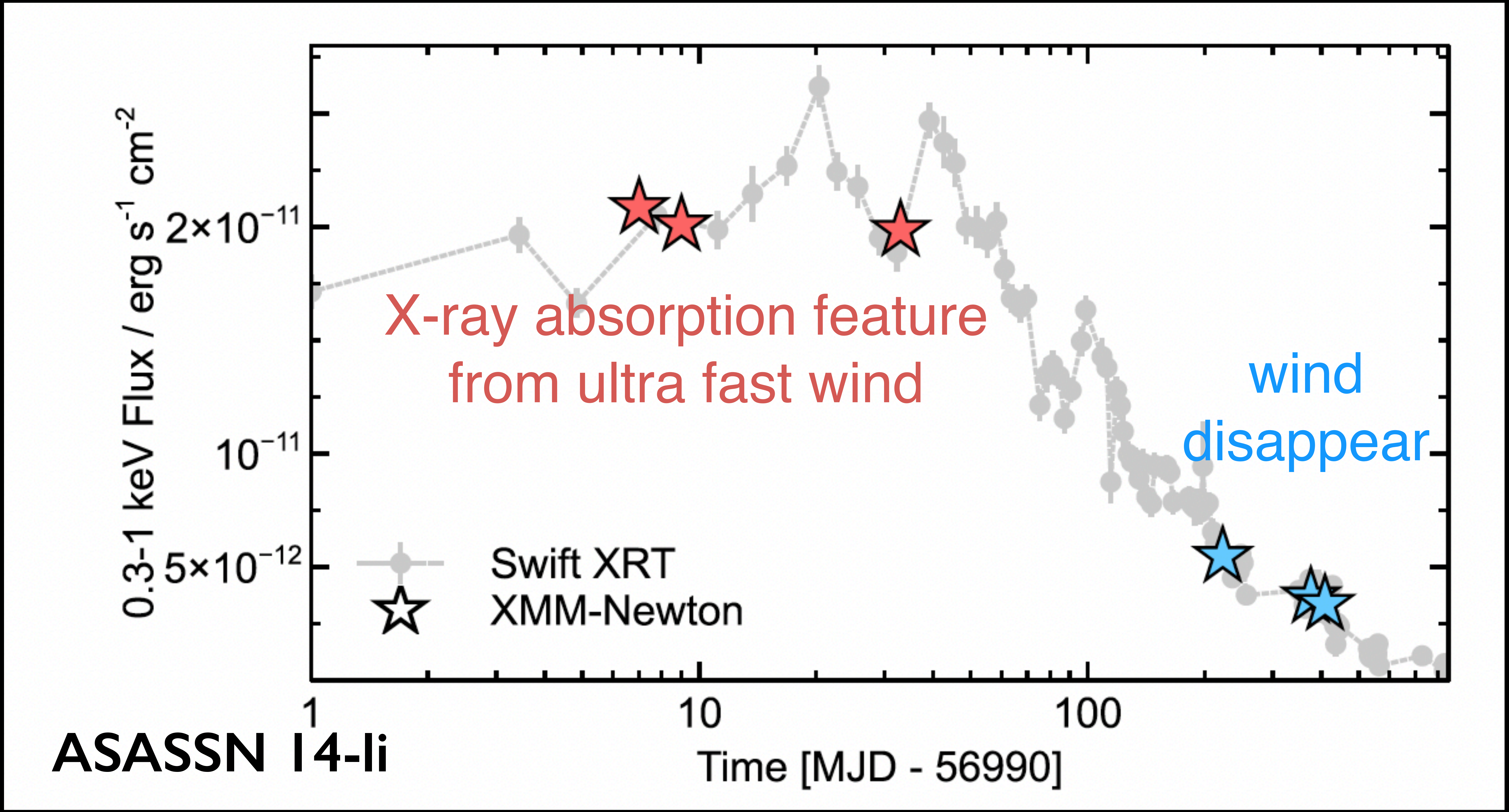




Thomsen, Kwan, LD et al. 2022

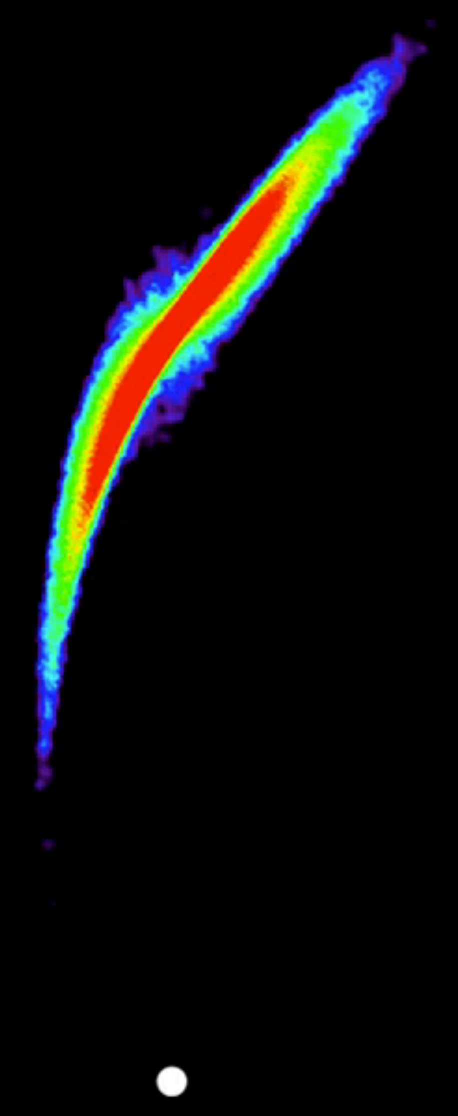
TDEs Launching Ultra-Fast Wind

wind ↔ accretion level



Kara, **LD**, Reynolds et al. 2018 (also Alexander et al. 2016)

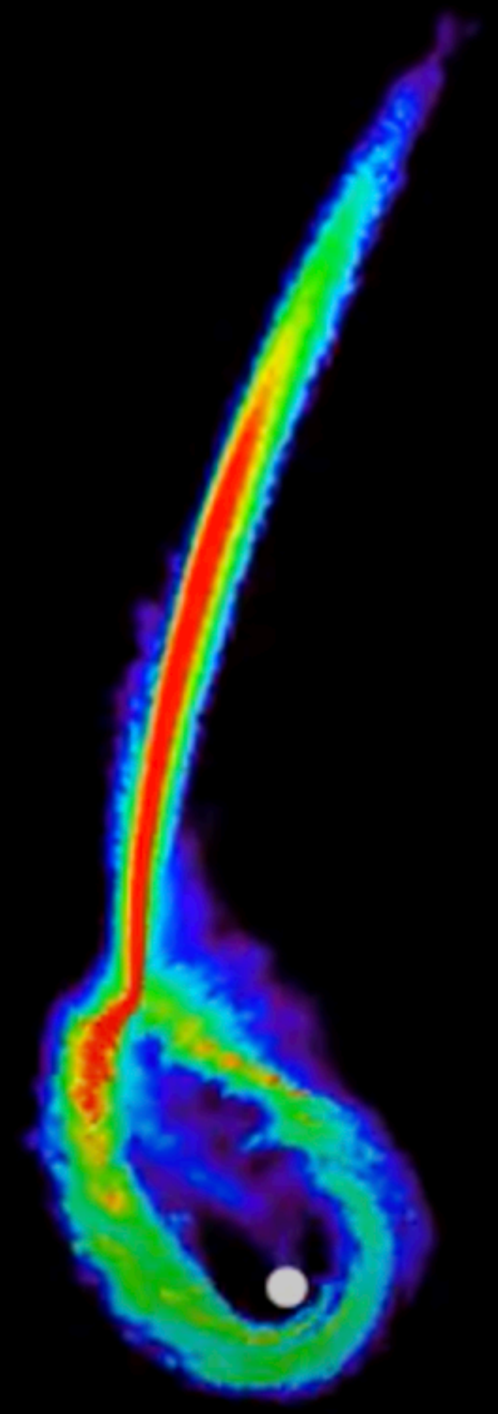
Debris stream collision & Disk formation



- Can stream collision directly power optical TDEs?
- How fast does the TDE disk form through stream collisions?

Piran et al. 2015; Bonnerot et al. 2016; (Also Shiokawa et al. 2015, LD et al. 2013, 2015, Guillochon & Ramirez-Ruiz 2015, Hayasaki et al. 2016, Sadowski et al. 2016, Jiang et al 2016, Liptai 2019, Lu & Bonnerot 2020, Bonnerot & Lu 2020, Andalman et al. 2020, Steinberg & Stone 2022)

Debris stream self-crossing



$R_I = f(M_{BH}, M_\star, \beta)$

Closer self-crossing (stronger shock & faster disk formation)

More massive black hole

Denser (smaller) star

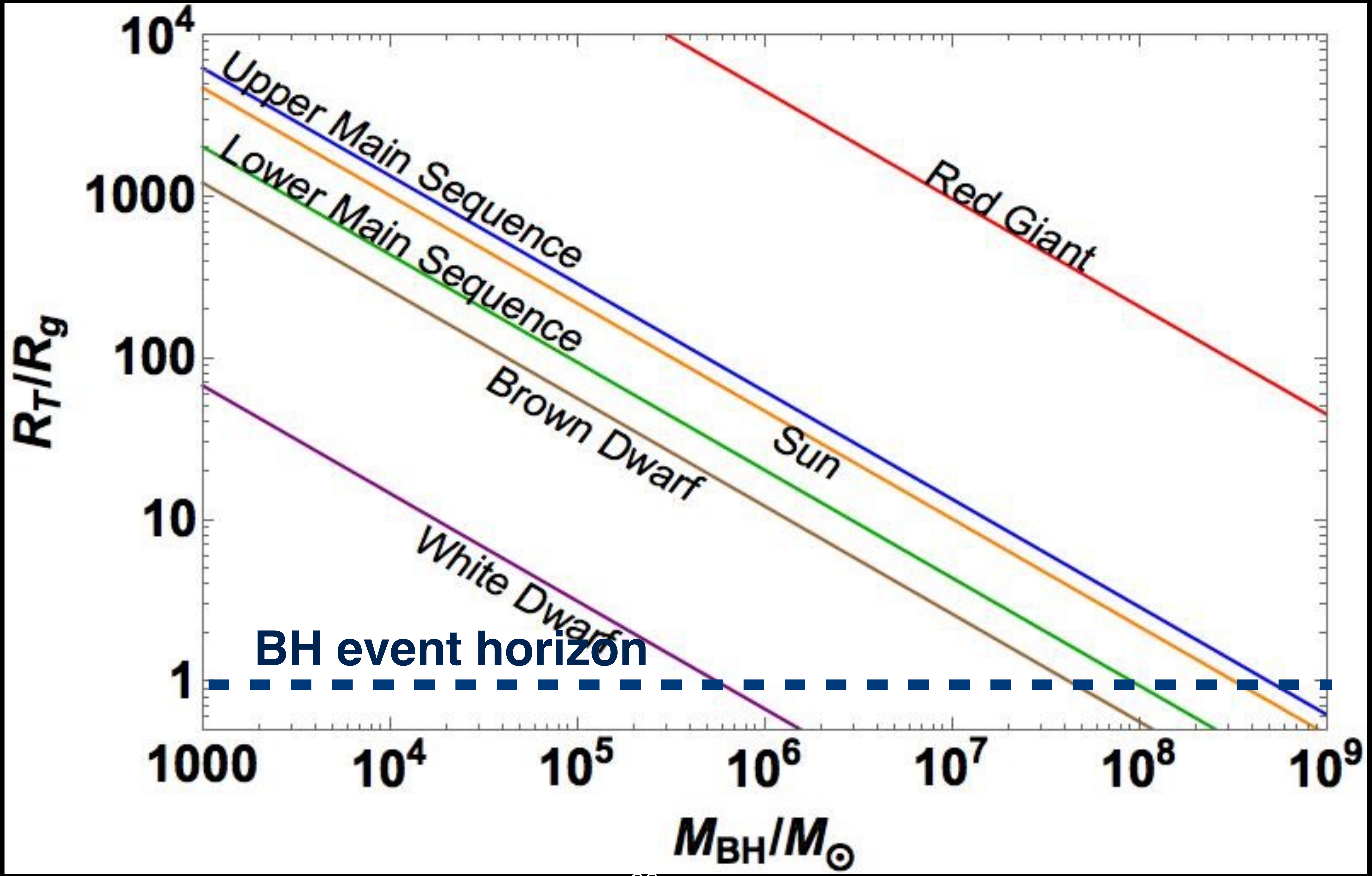
Deeper encounter

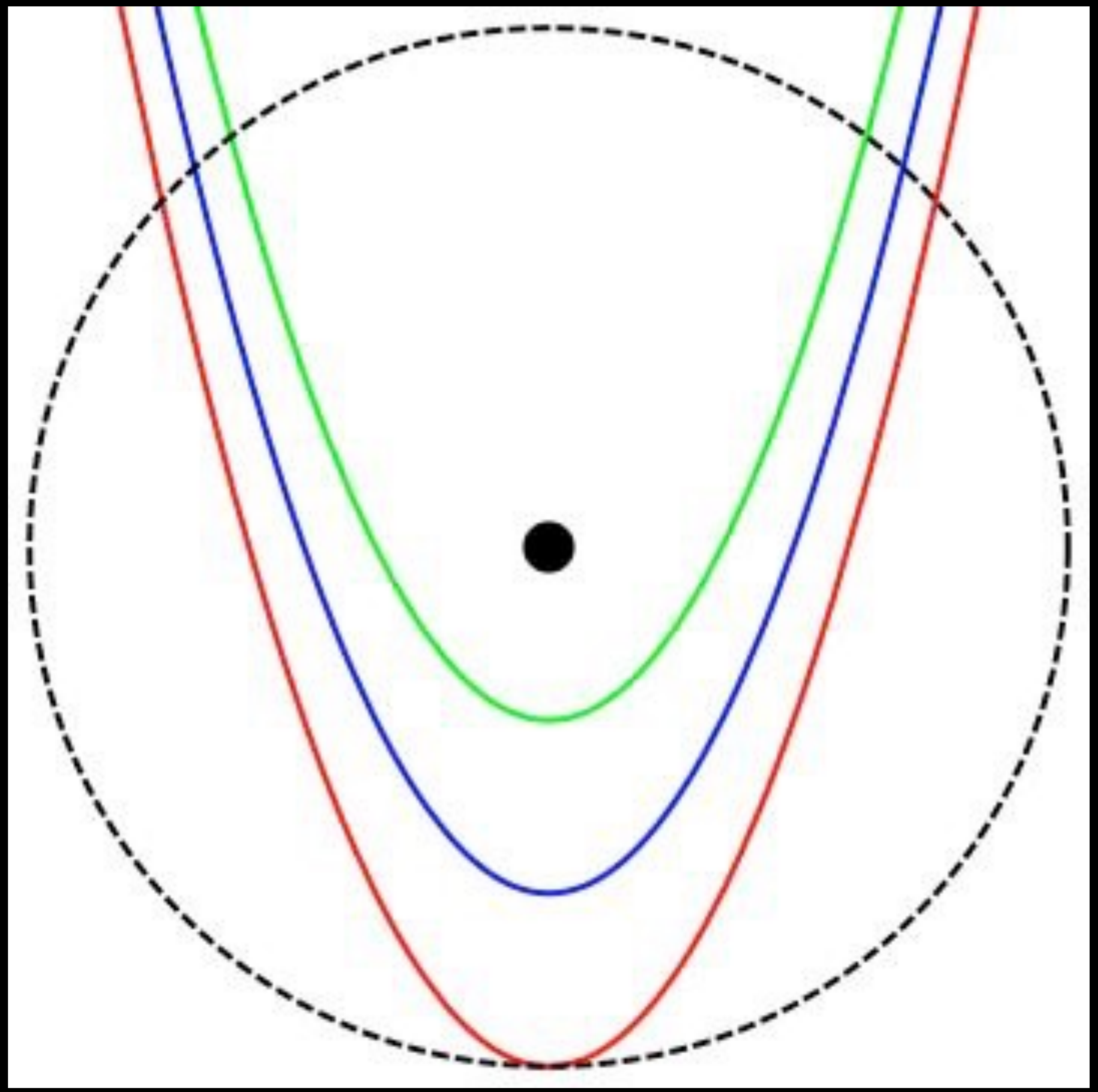
LD, McKinney, Miller 2015

$R_T \approx R_\star \, (M_{BH} / M_\star)^{1/3}$

$R_T / R_g \propto M_{BH}^{-2/3} \;\; \rho_\star^{-1/3}$

Smaller star / Bigger MBH
⇒ closer/stronger collision





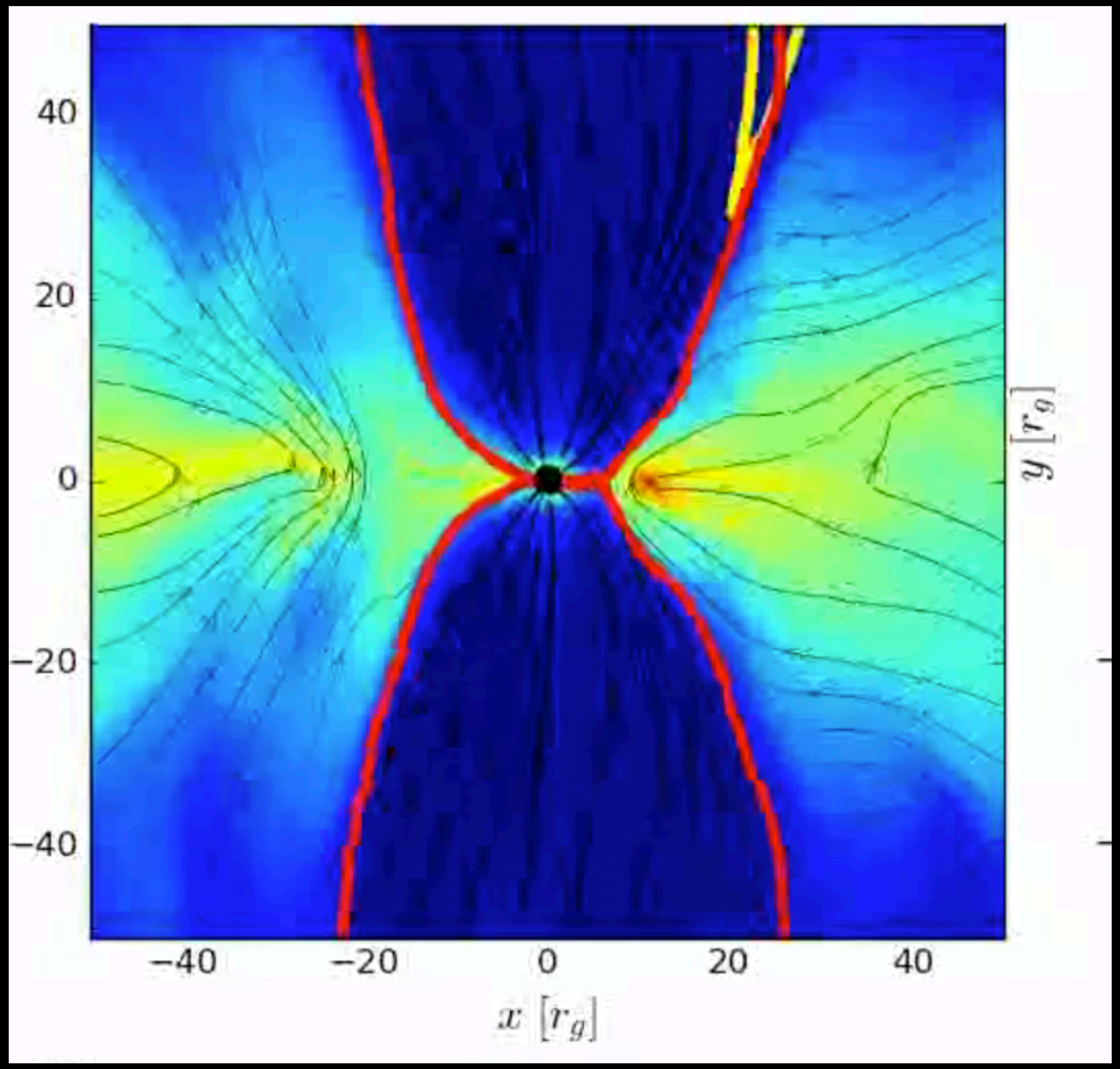
penetration parameter

$\boldsymbol{\beta} \sim R_T/R_p$

Deeper plunge ⇒ more GR apsidal precession

and closer/stronger collision

Simulation of TDE super-Eddington disks



LD, McKinney, Roth et al. 2018
Thomsen, Kwan, LD et al. 2022

- 3D full GR-Radiation-MHD code *HARMRAD* (Gammie et al. 03, McKinney et al. 12,14)

$$\nabla_\mu(\rho_0 \underline{u}^\mu) = 0,$$

$$T^\mu_{\nu\,;\mu} = G_\nu,$$

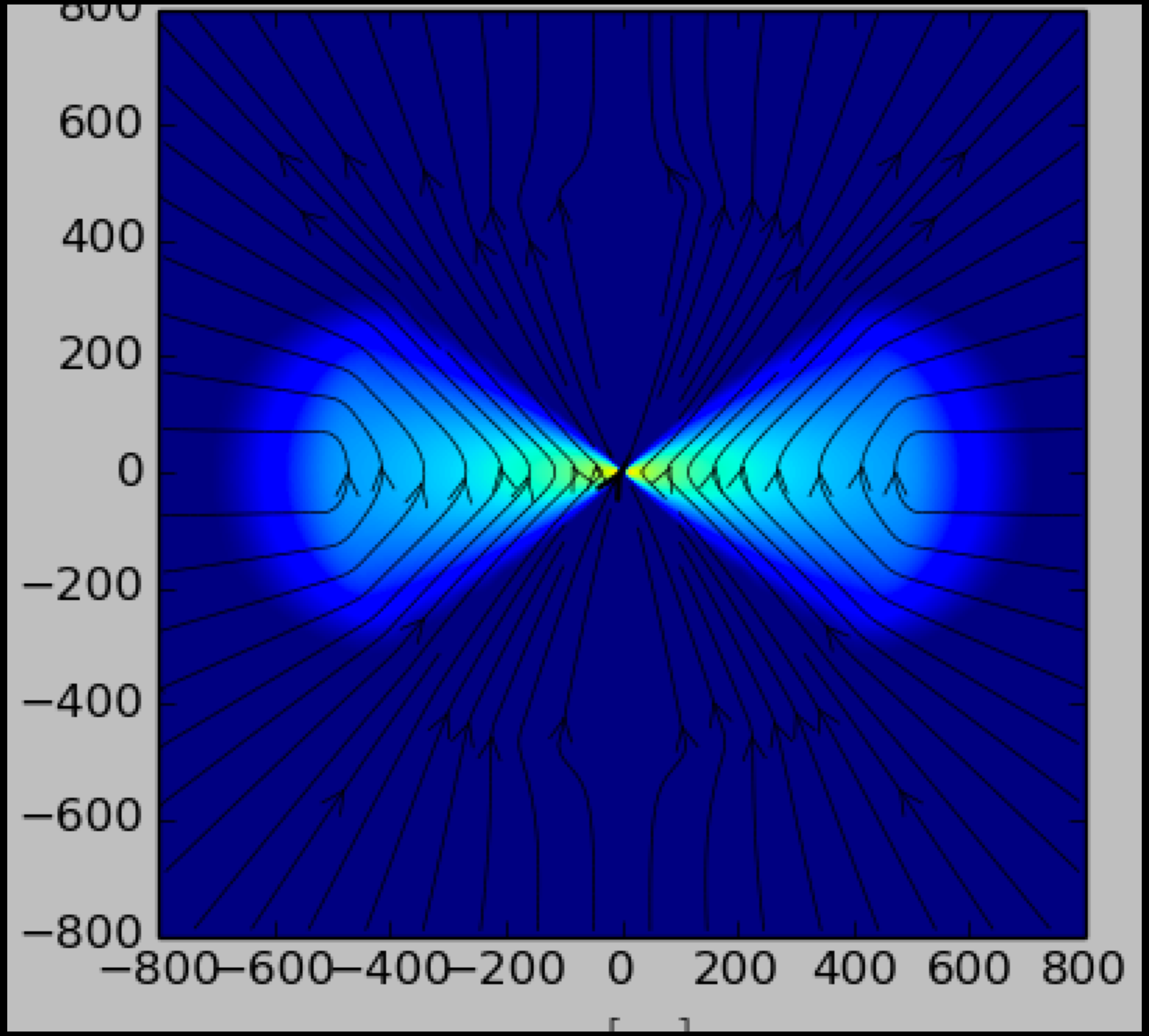
$$R^\mu_{\nu\,;\mu} = -G_\nu,$$

$$\partial_t(\sqrt{-g}\,\underline{B}^i) = -\partial_j[\sqrt{-g}(\underline{B}^i \underline{v}^j - \underline{B}^j \underline{v}^i)],$$

$$R^{\mu\nu} = \frac{4}{3}\bar{E}\,u^\mu_{\rm rad} u^\nu_{\rm rad} + \frac{1}{3}\bar{E}\,g^{\mu\nu}.$$

Conservation of mass, energy-momentum & magnetic flux, ideal MHD

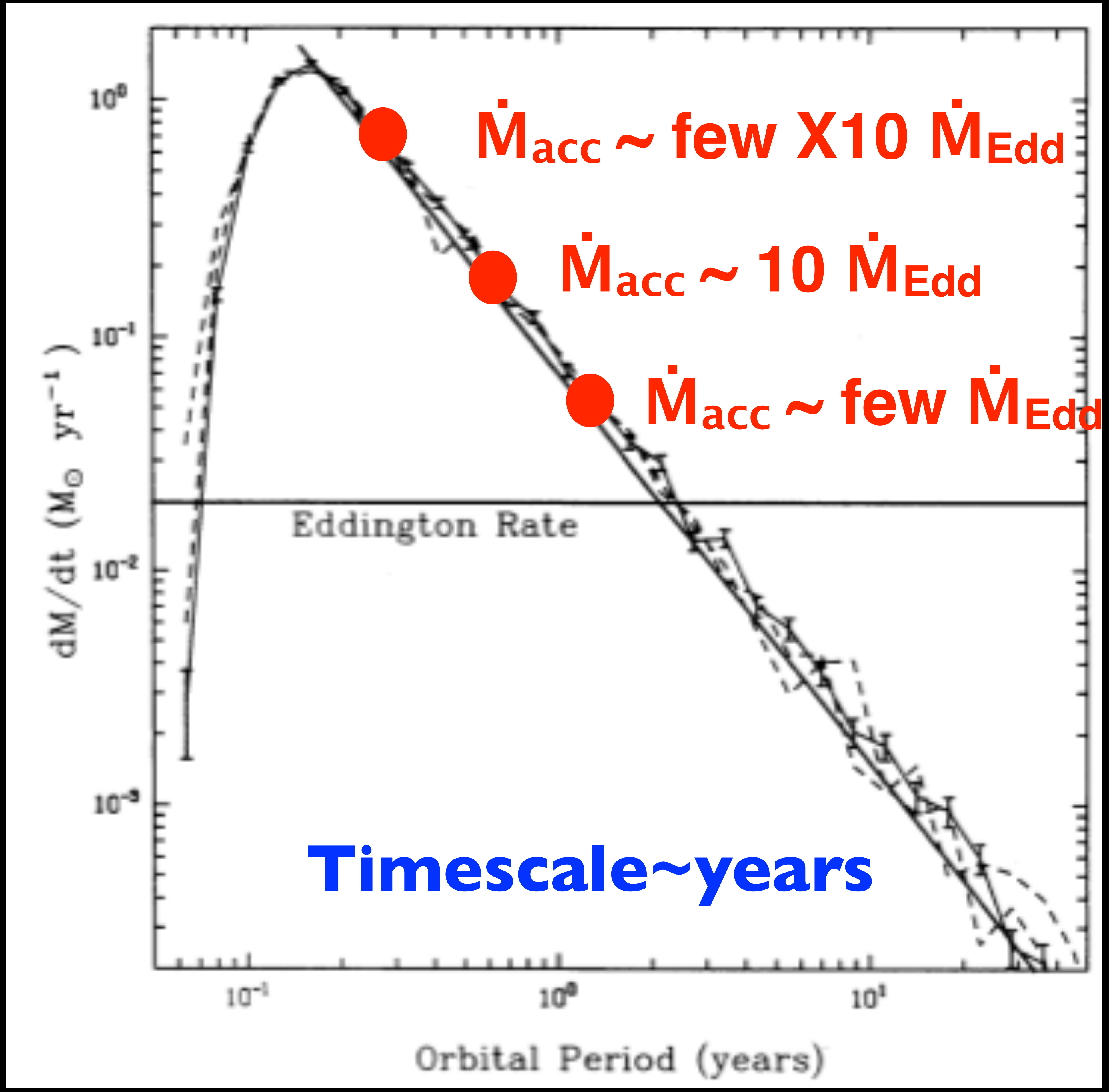
Simulation Set-Up

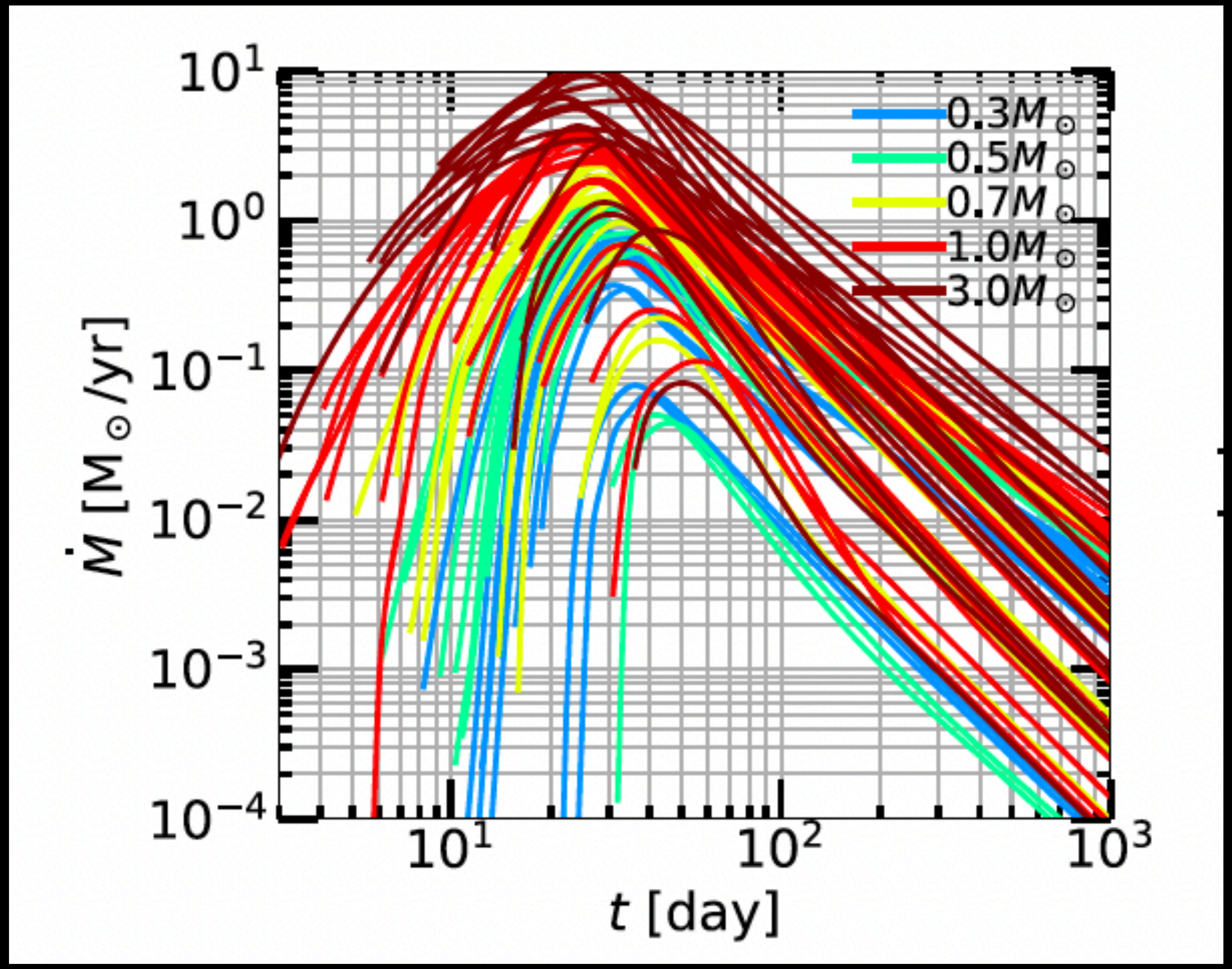


LD, McKinney, Roth et al. 2018
Thomsen, Kwan, LD, et al, 2022

- Supermassive black hole
- Circular disk aligned with black hole spin
- Disk initial profile: Keplerian, H/R ~ 0.3, mid-plane density decaying with radius
- Poloidal B field, initial β~20-30
- Simulation box size ~ 10000 R_g
- Large inflow and outflow equilibrium
- Photosphere resolved at ~1000 R_g

Disk Simulations at Different Accretion Rates





Law-Smith et al. 2020

color: gas density

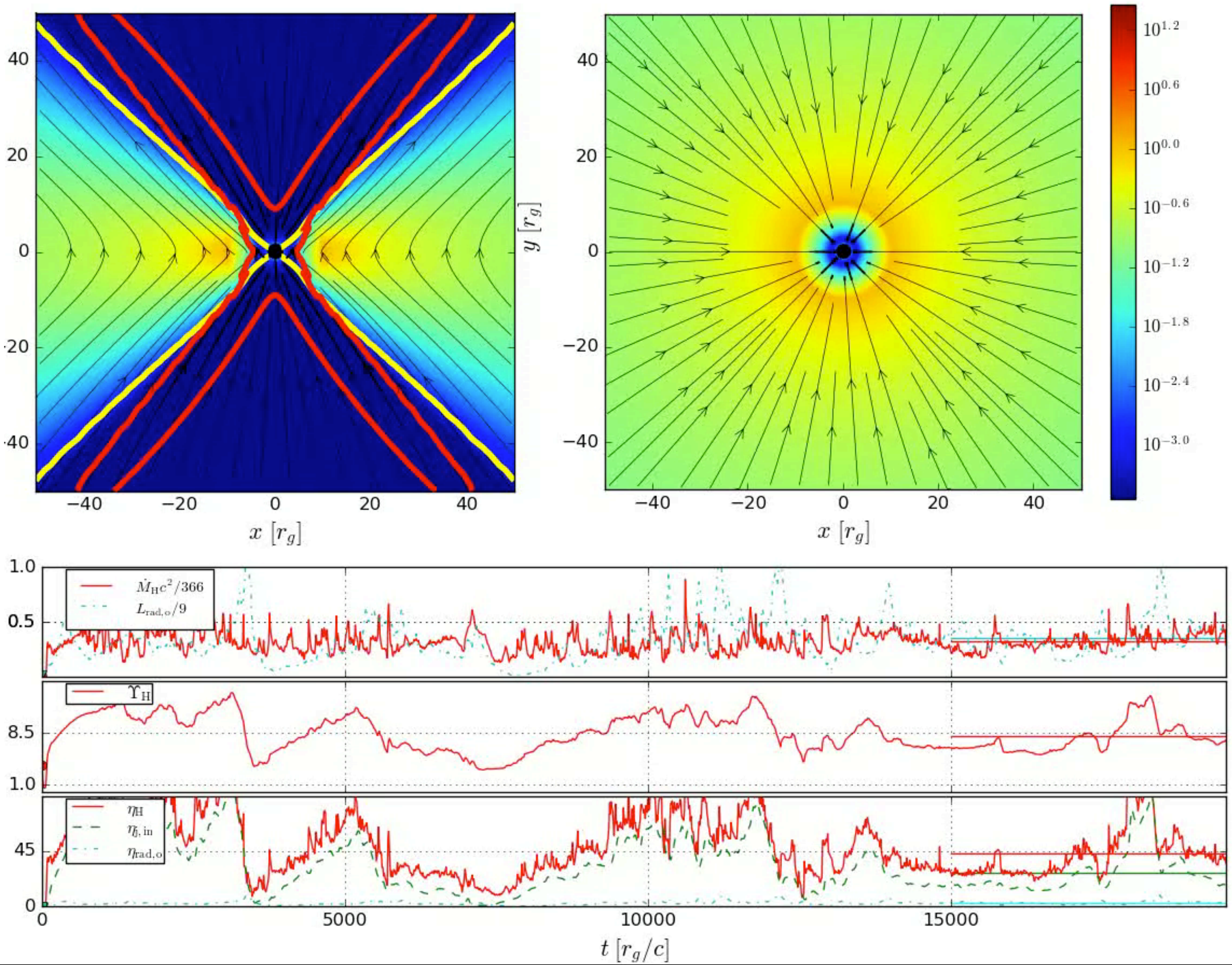
black line: magnetic field

red contour: jet

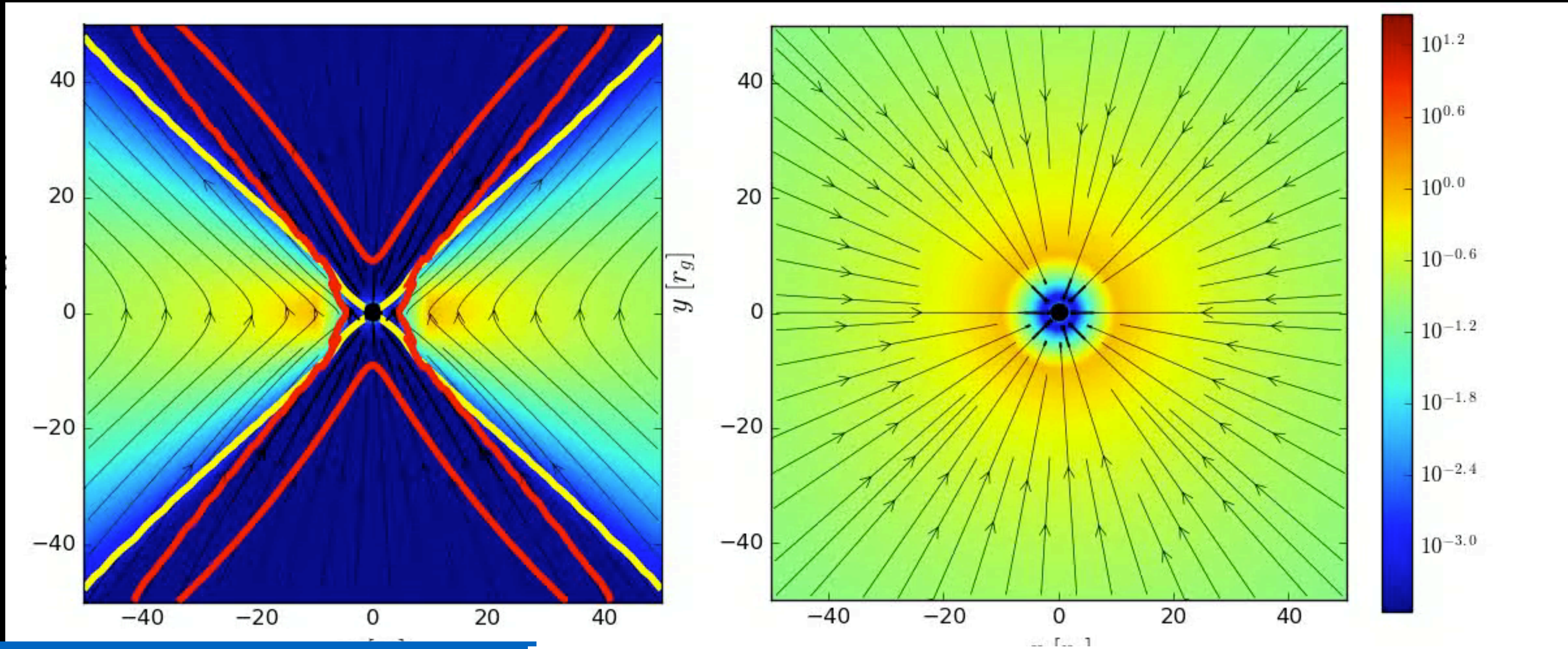
accretion rate

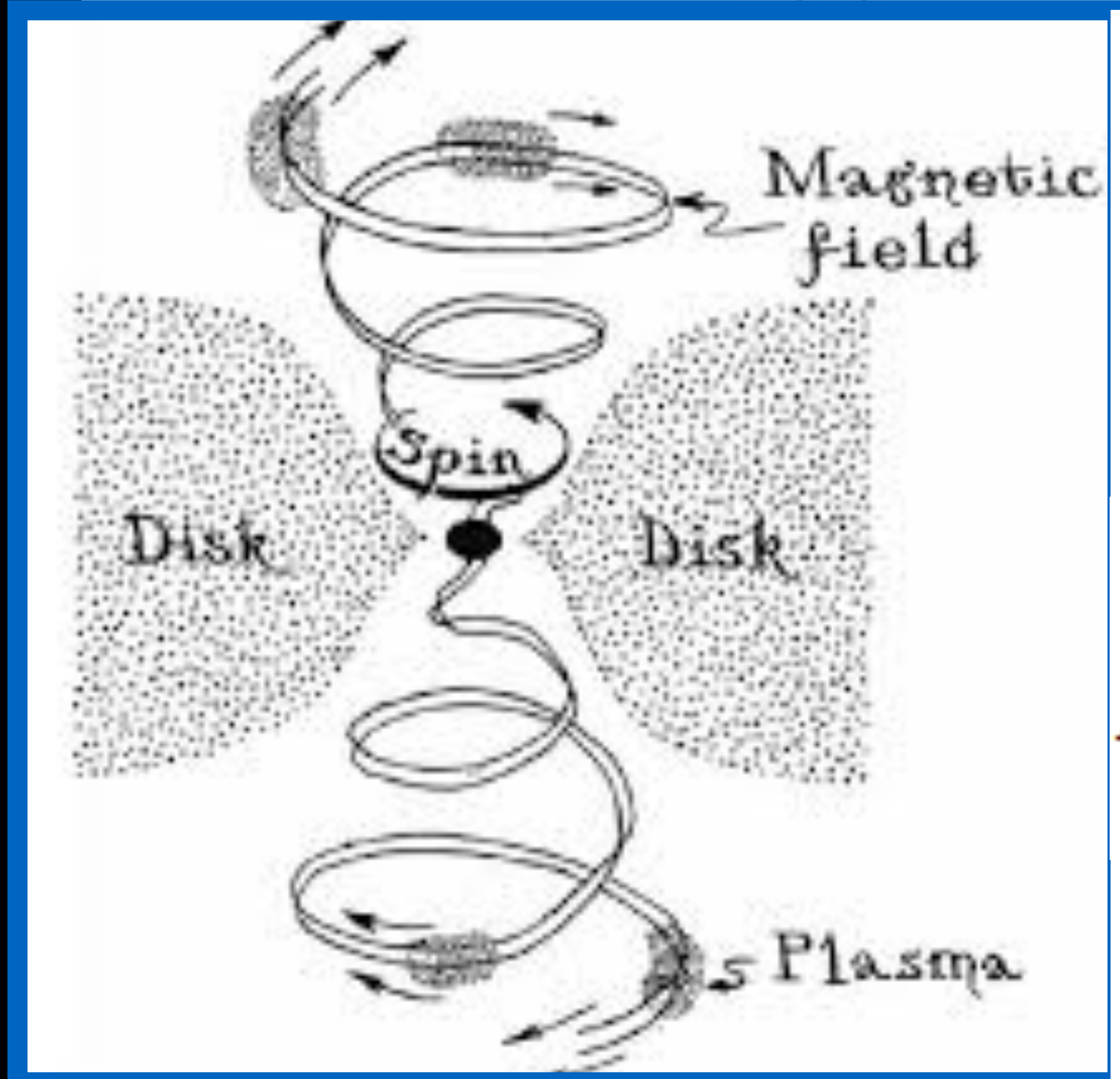
magnetic flux

efficiency



How can relativistic jets form in TDEs?



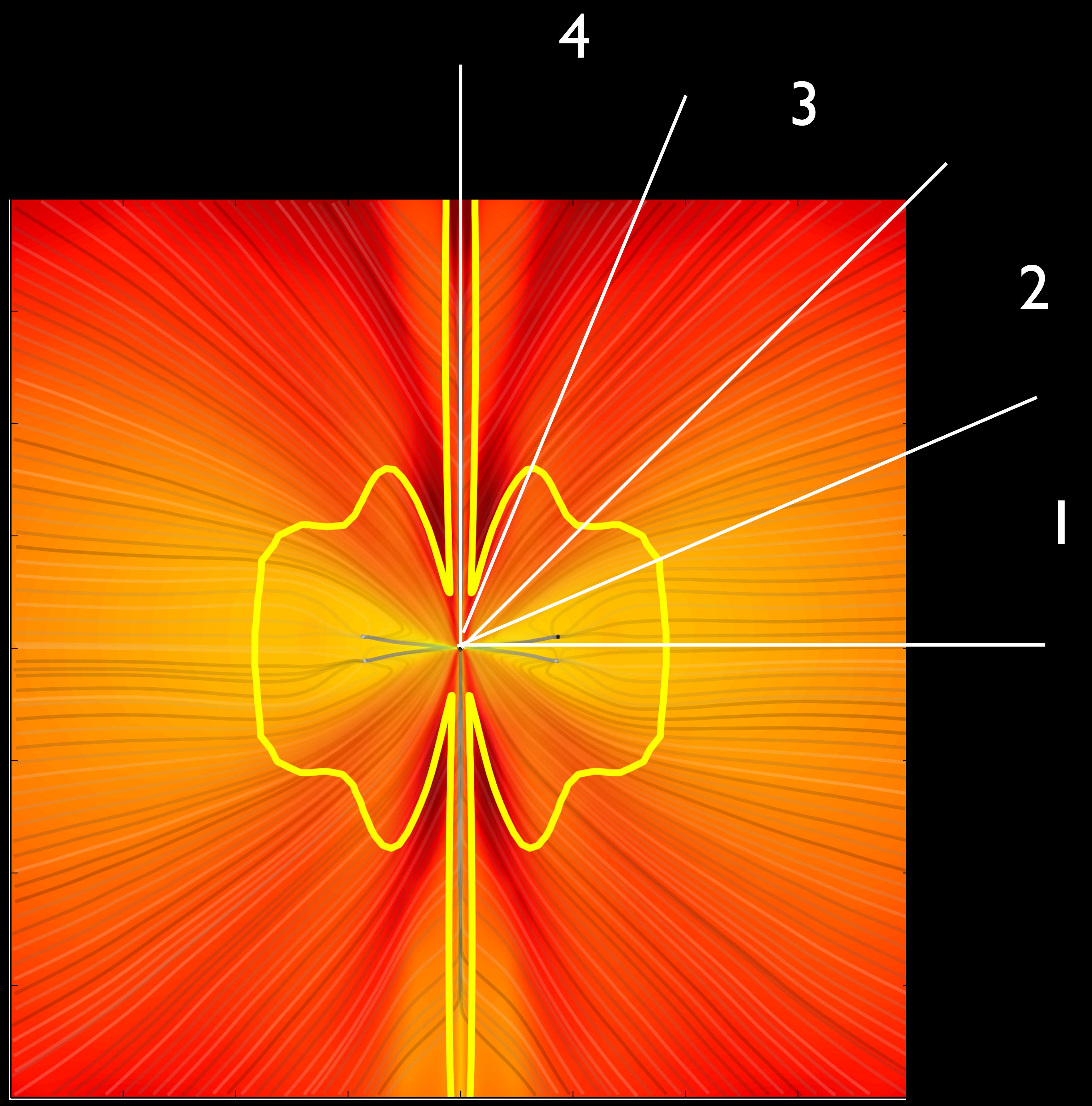


Relativistic Jet:
spinning black hole + magnetic flux

$$P_{BZ,old} \approx P_0 \left(B^r[\mathrm{G}]\right)^2 \left(\Omega_H^2/c\right) r_g^4$$

Blandford & Znajek 1977

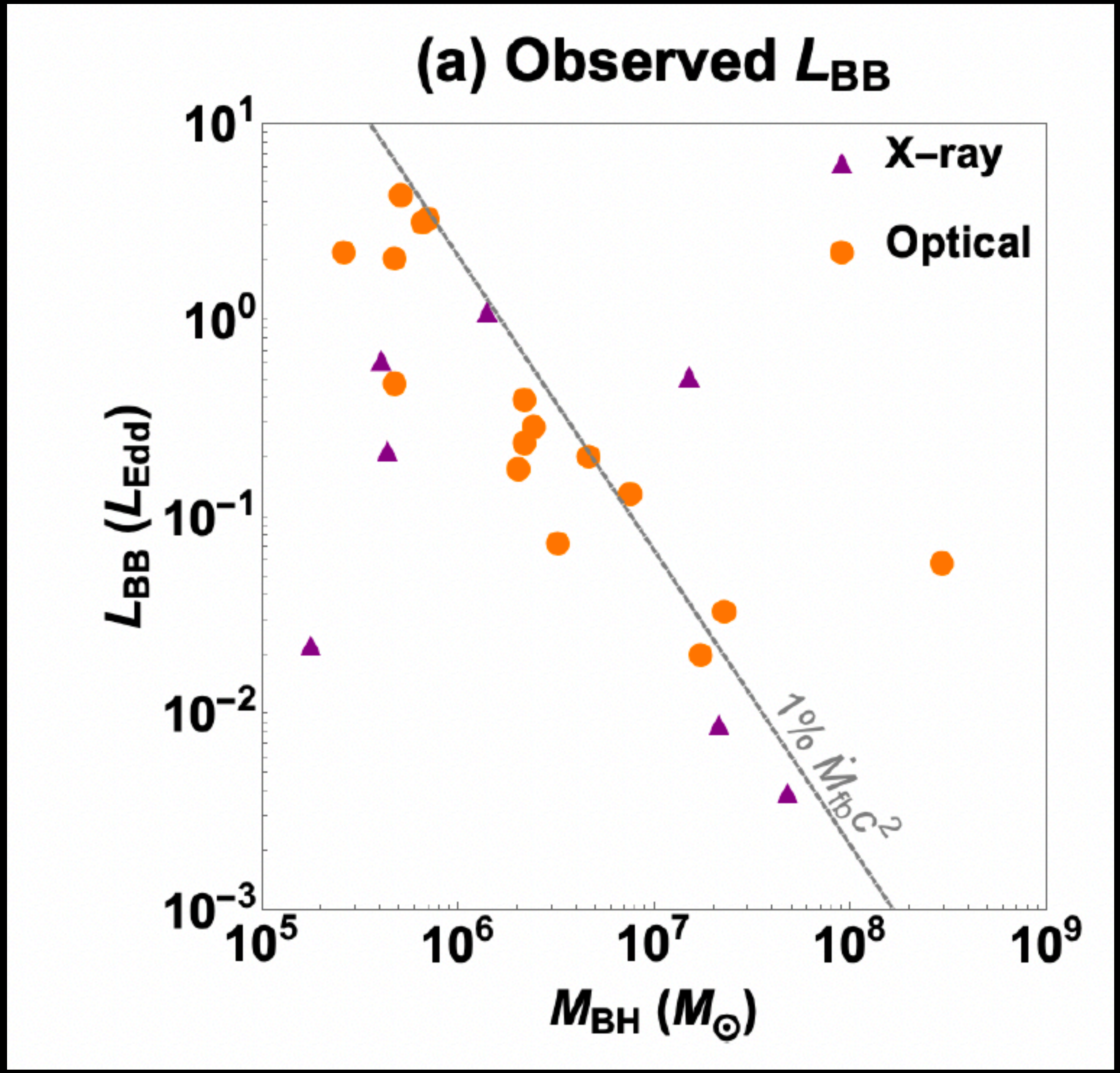
Modelling emissions from super-Eddington disks



- Monte-Carlo radiative transfer code
- Non-LTE equations
- H, He and O elements
- Scattering
- Free-free, bound-free & bound-bound absorption and emission
- Comptonization (thermal & bulk)
- 1D post-processing: spherically symmetric
- Injecting 10^6 K blackbody emission from centre

Kasen 2006, Roth & Kasen 2016

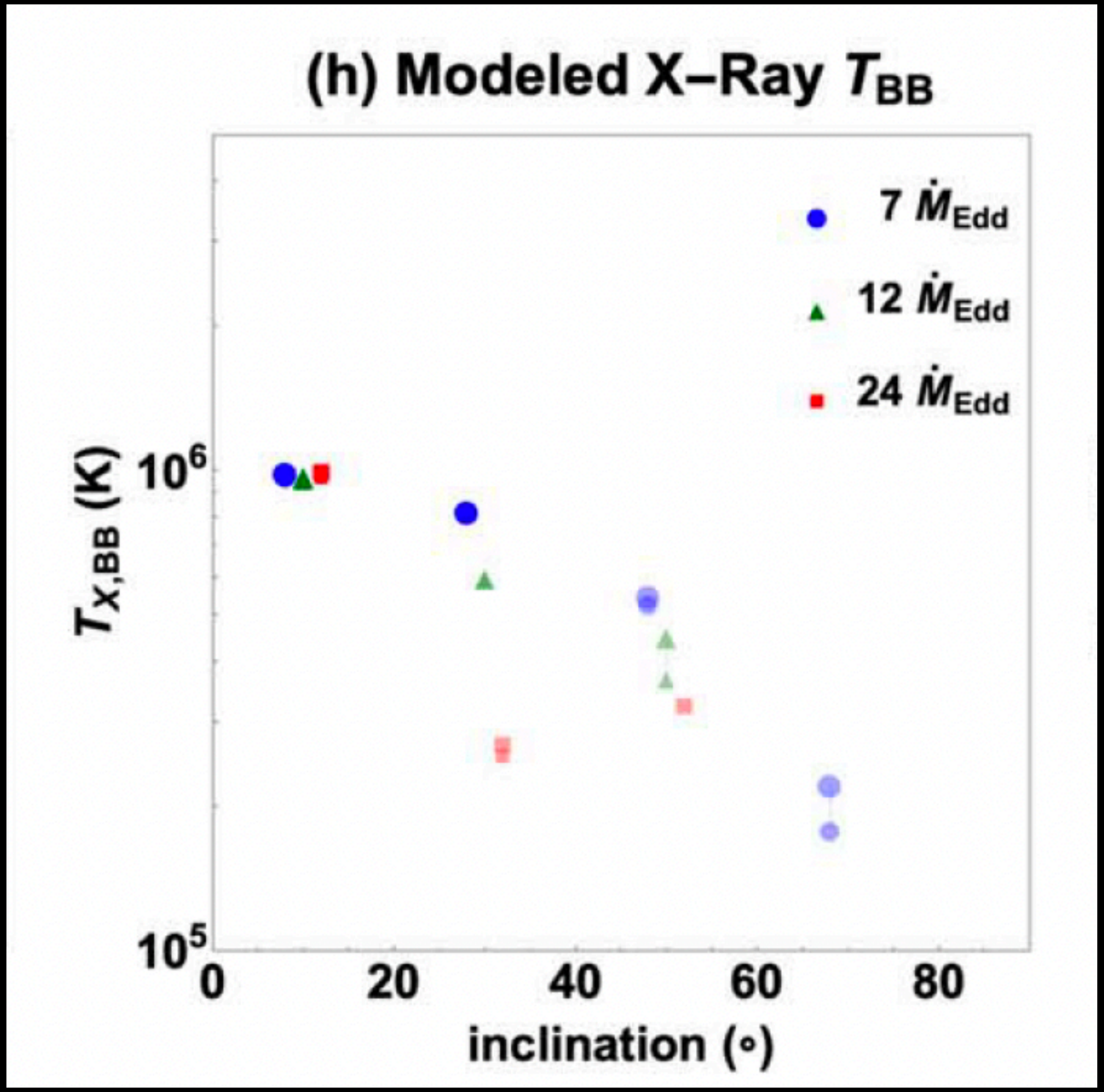
Observed Luminosity & Temperature



- ✦ Super-Eddington luminosity around low-mass MBHs
- ✦ "Missing energy problem"

Thomsen, Kwan, **LD**, et al, 2022

X-ray TDEs

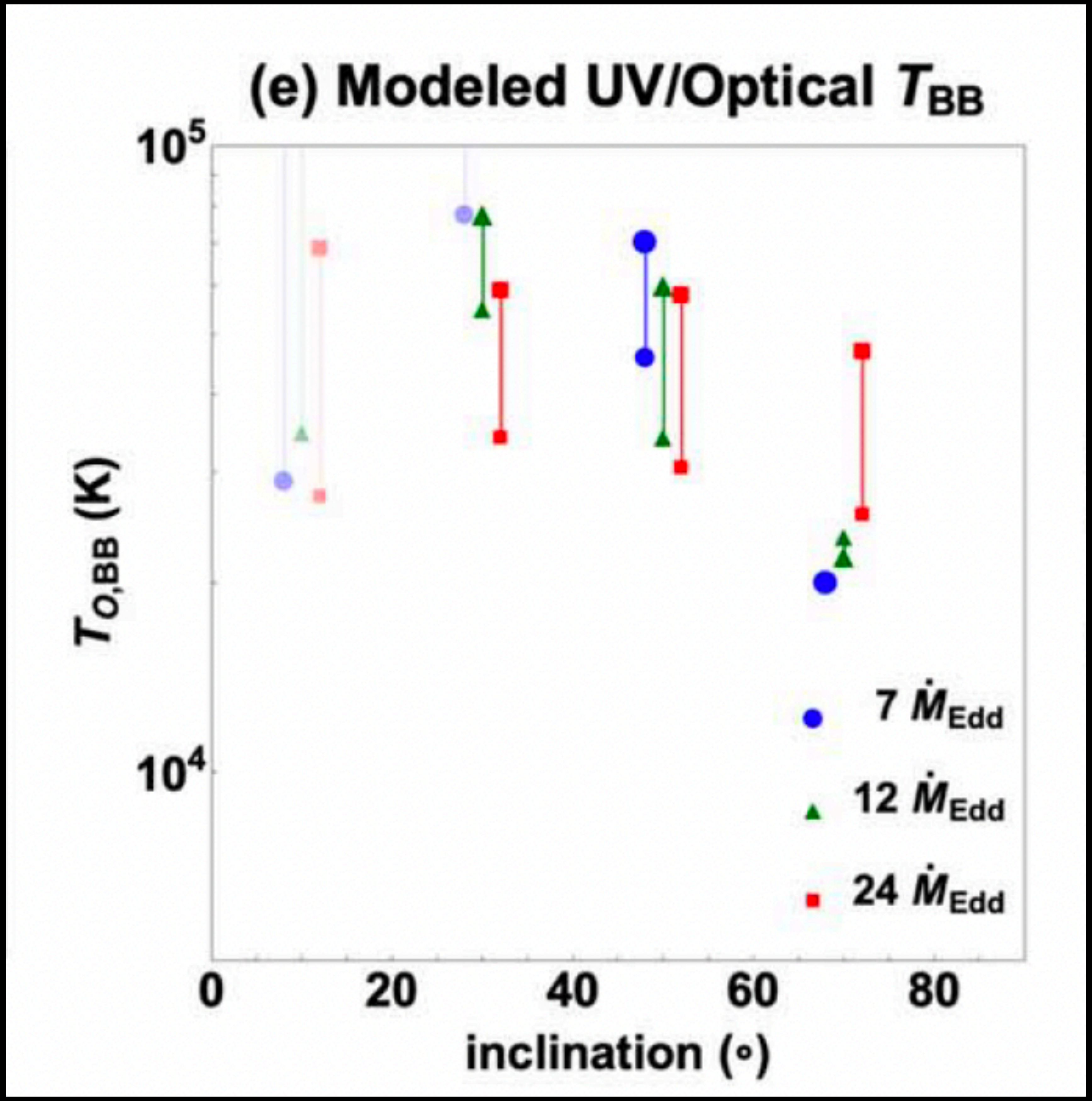


Thomsen, Kwan, **LD**, et al, 2022

$T_{BB} \sim 10^{5\text{-}6}$ K
$L_{BB} \sim 0.1\text{-}10\ L_{Edd}$

Consistent with TDEs detected by ROSAT, eROSITA, etc.

Optical TDEs



$T_{BB} \sim 10^4$ K (very stable)

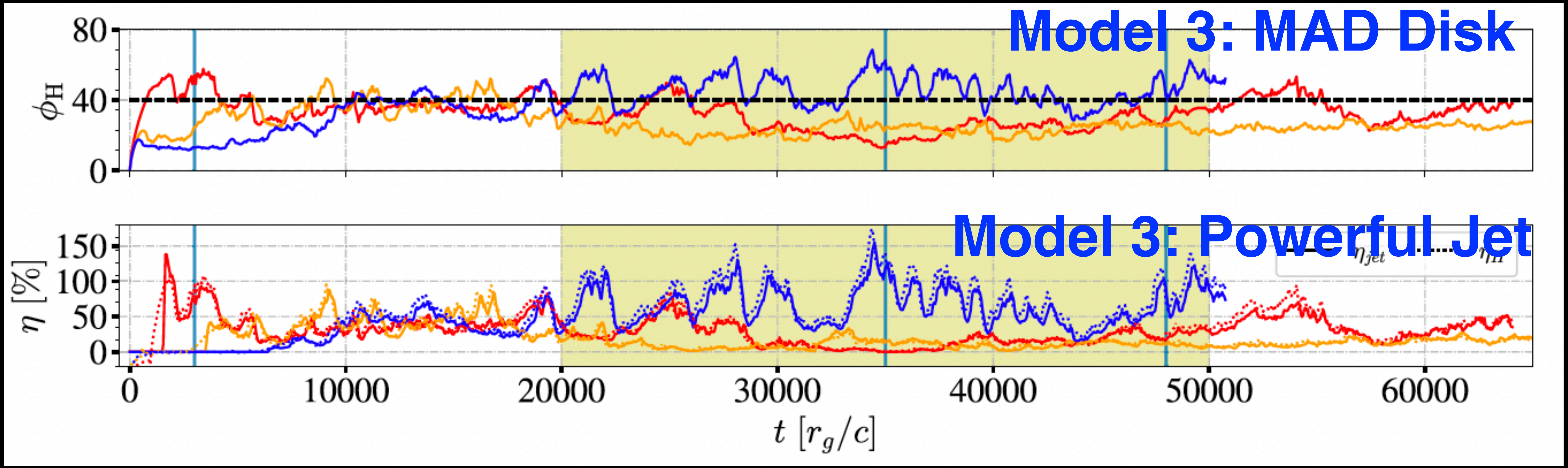
$L_{BB} \sim 0.01\text{-}10\ L_{Edd}$

Consistent with TDEs detected by ZTF, ASASSN, etc.

Thomsen, Kwan, **LD**, et al, 2022

Critical Gas Angular Momentum Needed to Produce Powerful Jets

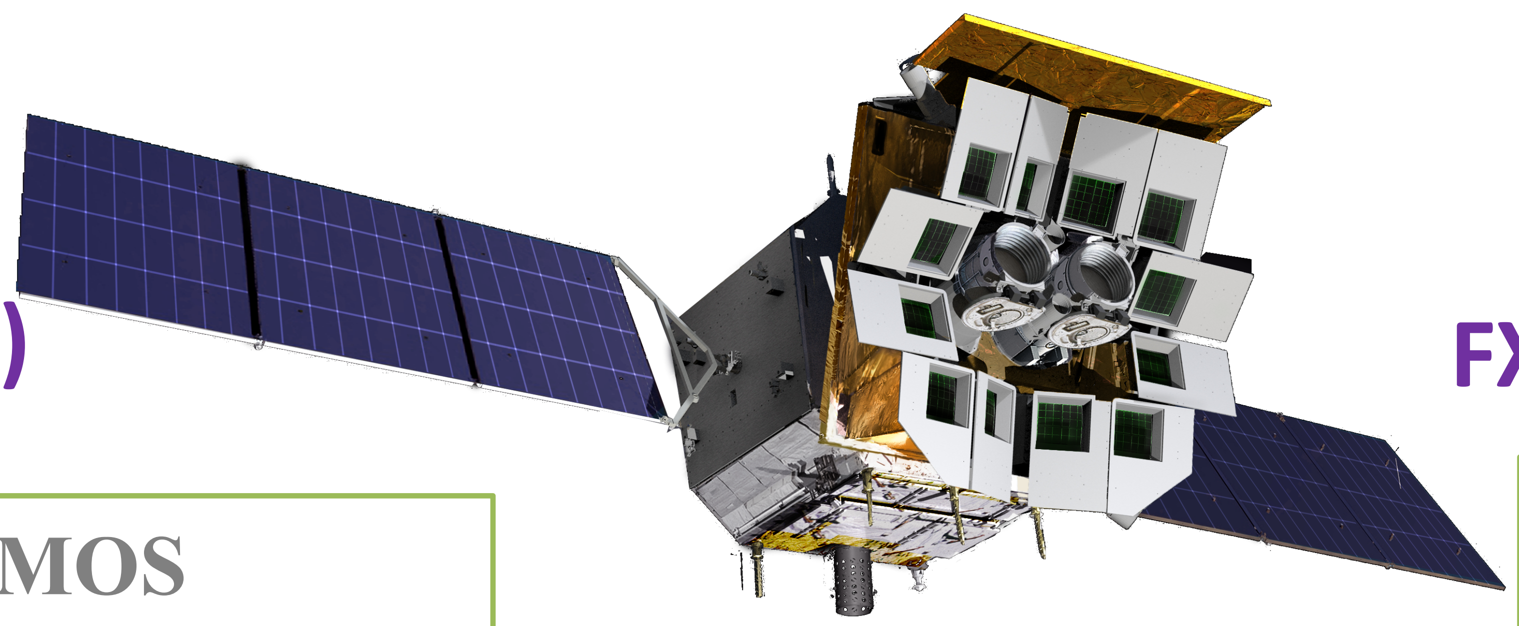
GRMHD Model 1: No angular momentum (Bondi)
GRMHD Model 2: Angular momentum = Keplerian orbit at 10 R_g
GRMHD Model 3: Angular momentum = Keplerian orbit at 50 R_g



Kwan, **LD**, Tchekhovskoy 2023

Einstein Probe (EP) mission

- All-sky monitoring X-ray space mission
- Discover & study high-energy transients and variability
- TDEs, AGN variability, XRBs, GRBs, magnetars, etc.
- Launch: end of 2023



WXT (12 modules)

lobster-eye MPO + CMOS
FoV: 3600 sq deg (1.1 sr)
band: 0.5 - 4 keV soft X-ray
eff. area: ~3 cm² @1keV
FWHM: ~ 5', positioning <1'
Sensitivity: > 10 x increase

FXT (2 modules)

Wolter-1 type + CCD
FoV: 38'
band: 0.3 - 10keV
eff. area: 2x 300cm² @1keV
angular FWHM: 30"
positioning accuracy: <10"

Wide-Field Survey Telescope (WFST)

- Located at Lenghu (northwestern China)
- 2.5m aperture wide-field (~6 deg2) telescope ideal for optical time-domain survey
- Complementary to LSST both in longitude and in latitude; to ZTF in time zone and depth
- Installed in summer 2023

Item	Specification
Optical configuration	Primary focus with corrector lenses
Aperture	2.5 m
FOV	3° diameter
effective area	$\sim 6\ \mathrm{deg}^2$
Etendue	$29.3\ \mathrm{m}^2\mathrm{deg}^2$
Wavelength	320~960 nm
filter	u/g/r/i/z/w
Image Quality	diameter≤0.4″ (80% energy encircled)
Number of pixels	0.73 Gigapixels
pixel size	$0.333\ \mathrm{arcsec\ pixel}^{-1}$

Science white paper submitted to SCPMA (arxiv:2306.07590)