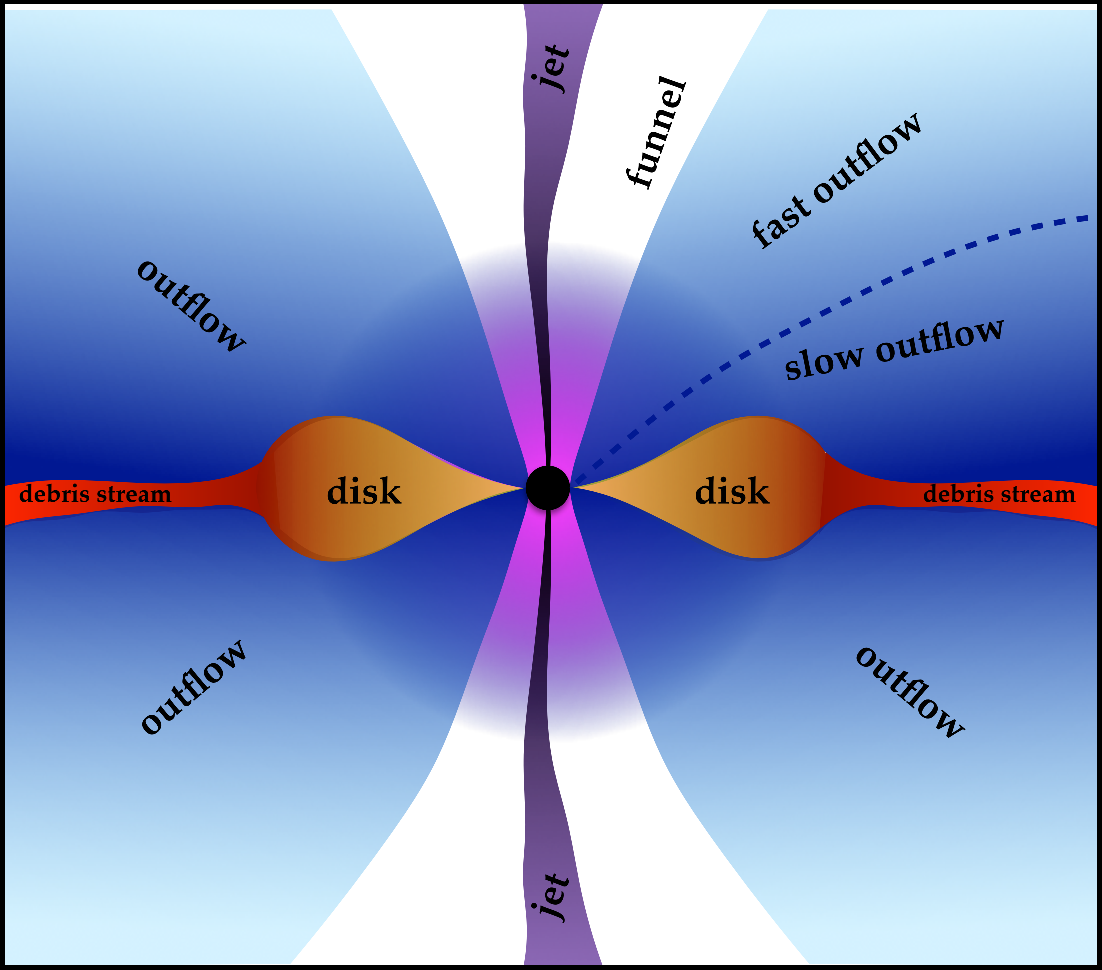
The Restless Nature of AGNs: 10 years later
June 29, 2023

Tidal Disruption Events: Demographics, Accretion and Outflows



Jane Lixin Dai

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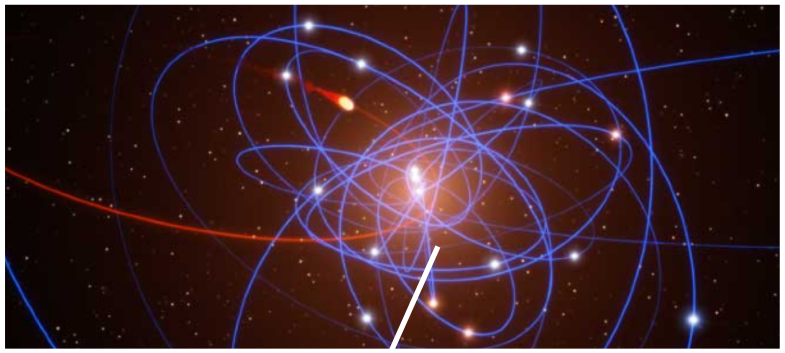
+ **Lars Thomsen, Janet Chang, Tom Kwan, Thomas Wong,** M. Bulla, E. Kara, G. Leloudas, H. Pfister, E. Ramirez-Ruiz, C. Reynolds, N. Roth, A. Tchekhovskoy, S. Wu

Tidal Disruption Event (TDE)

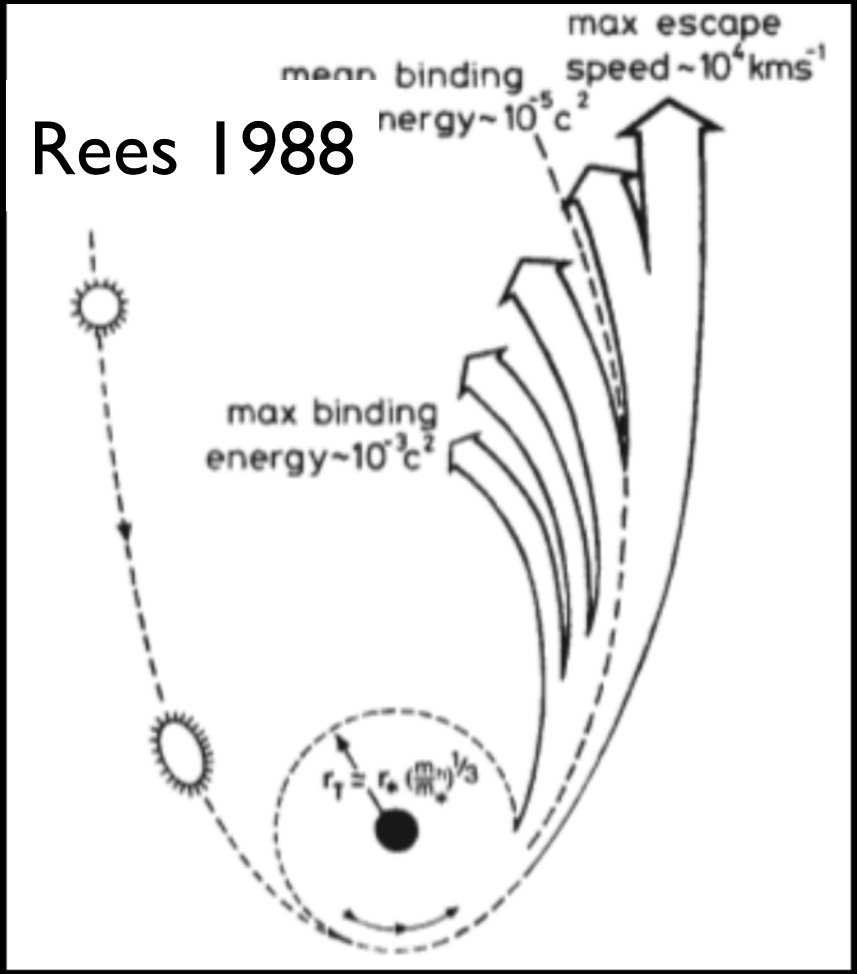
10-100 kpc

1 parsec



MBH tidal force > stellar self-gravity

Rees 1988



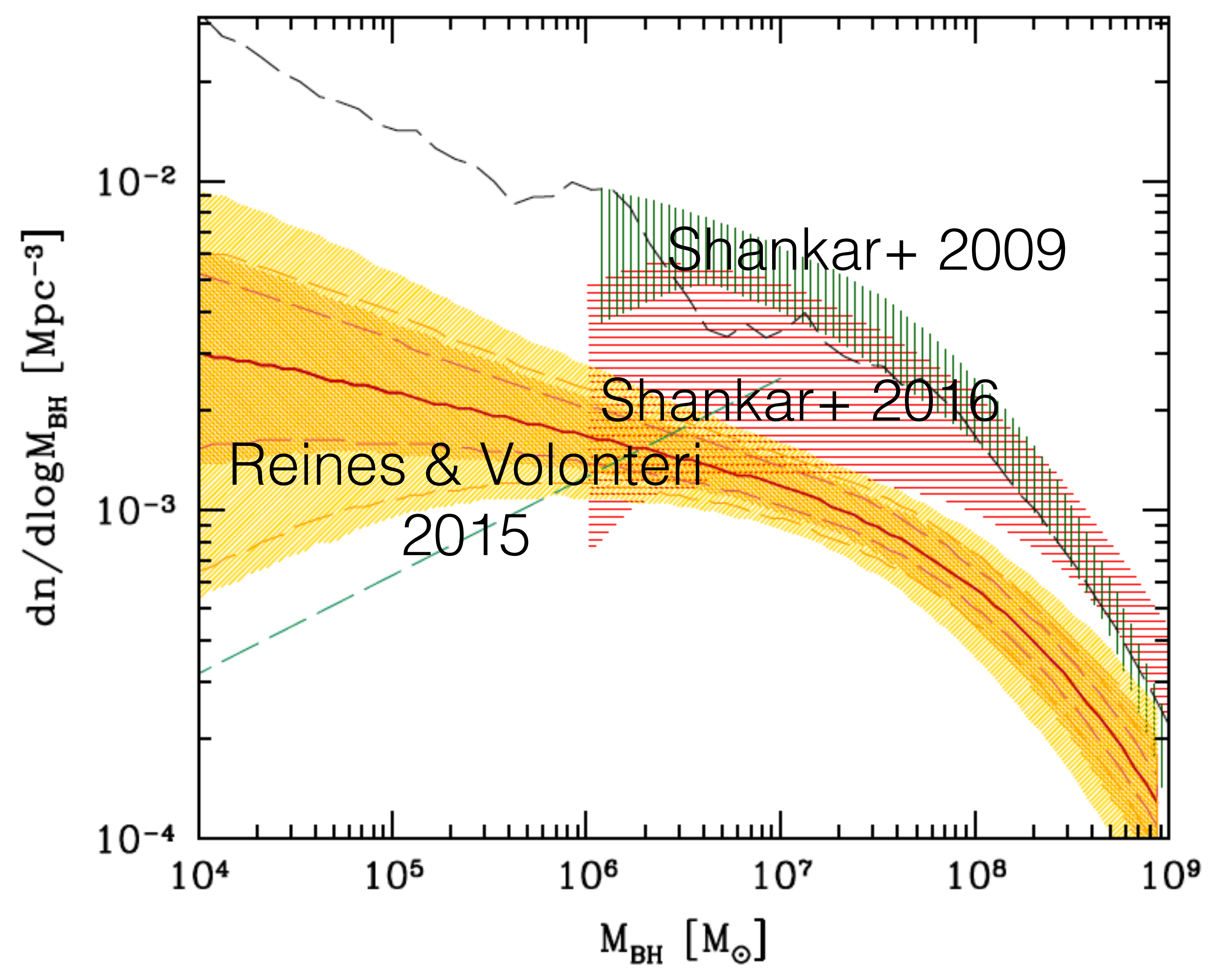
$$GM_\star / R_\star^2 \approx GM_{BH}/R_T^2 \, (R_\star / R_T)$$

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

Why do we care about TDEs?

- Demographics of dormant massive black holes including IMBHs
- Stellar population & dynamics in galaxy center
- Production of high-energy astroparticles and gravitational waves
- Study extreme accretion and outflow physics around black holes (in the super-Eddington regime)

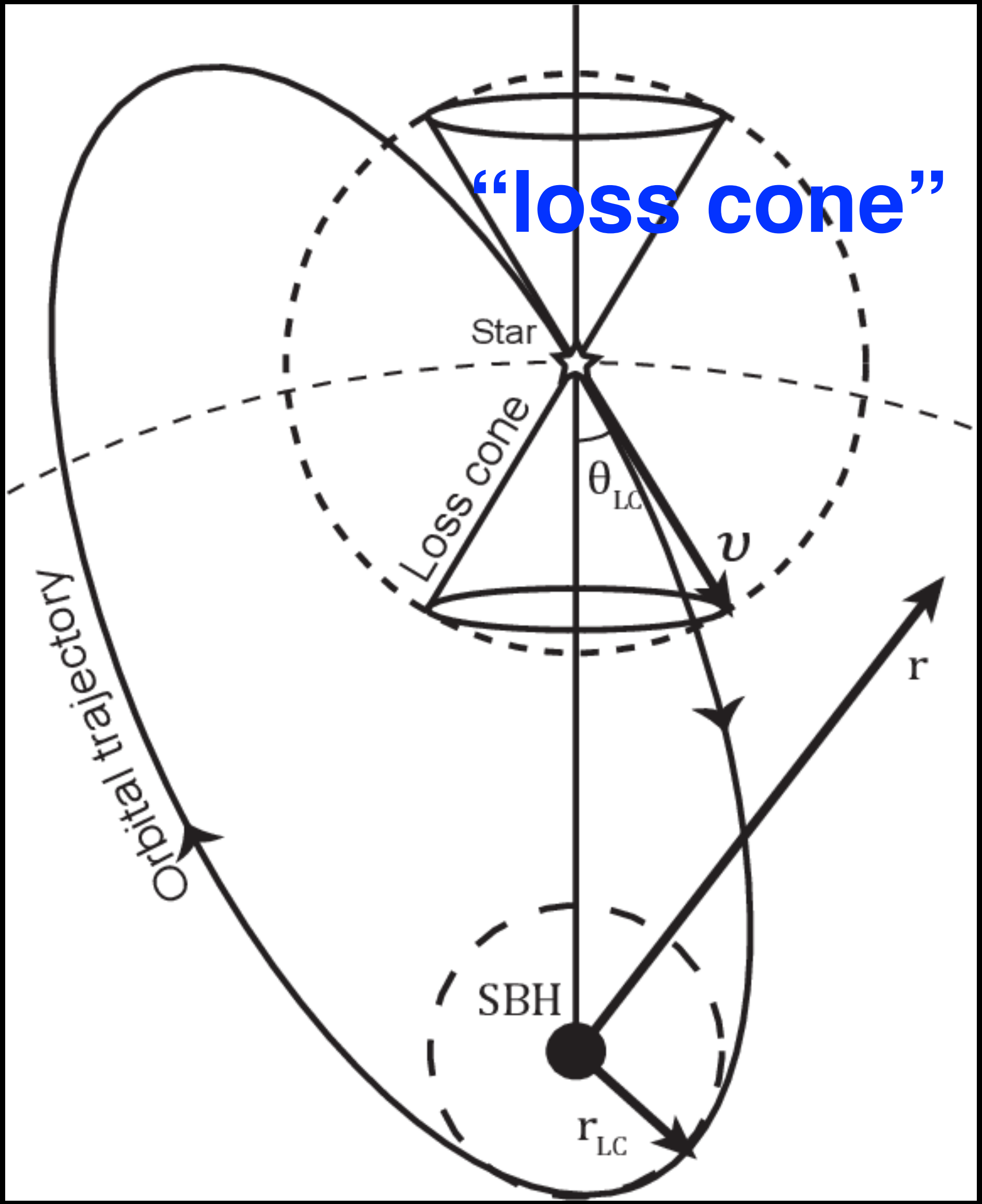
Black Hole Mass Function (from AGNs)



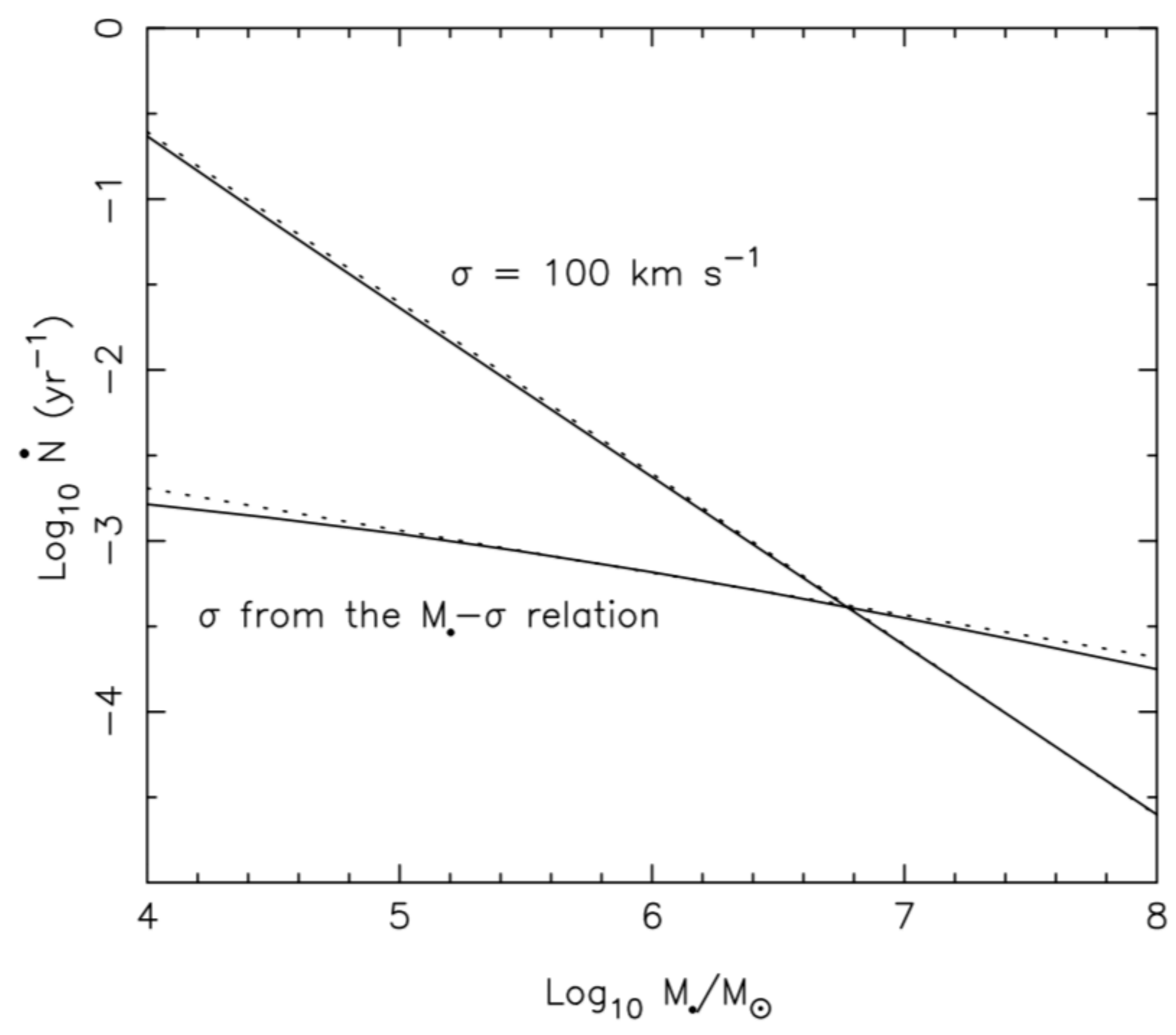
Gallo & Sesana 2019

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

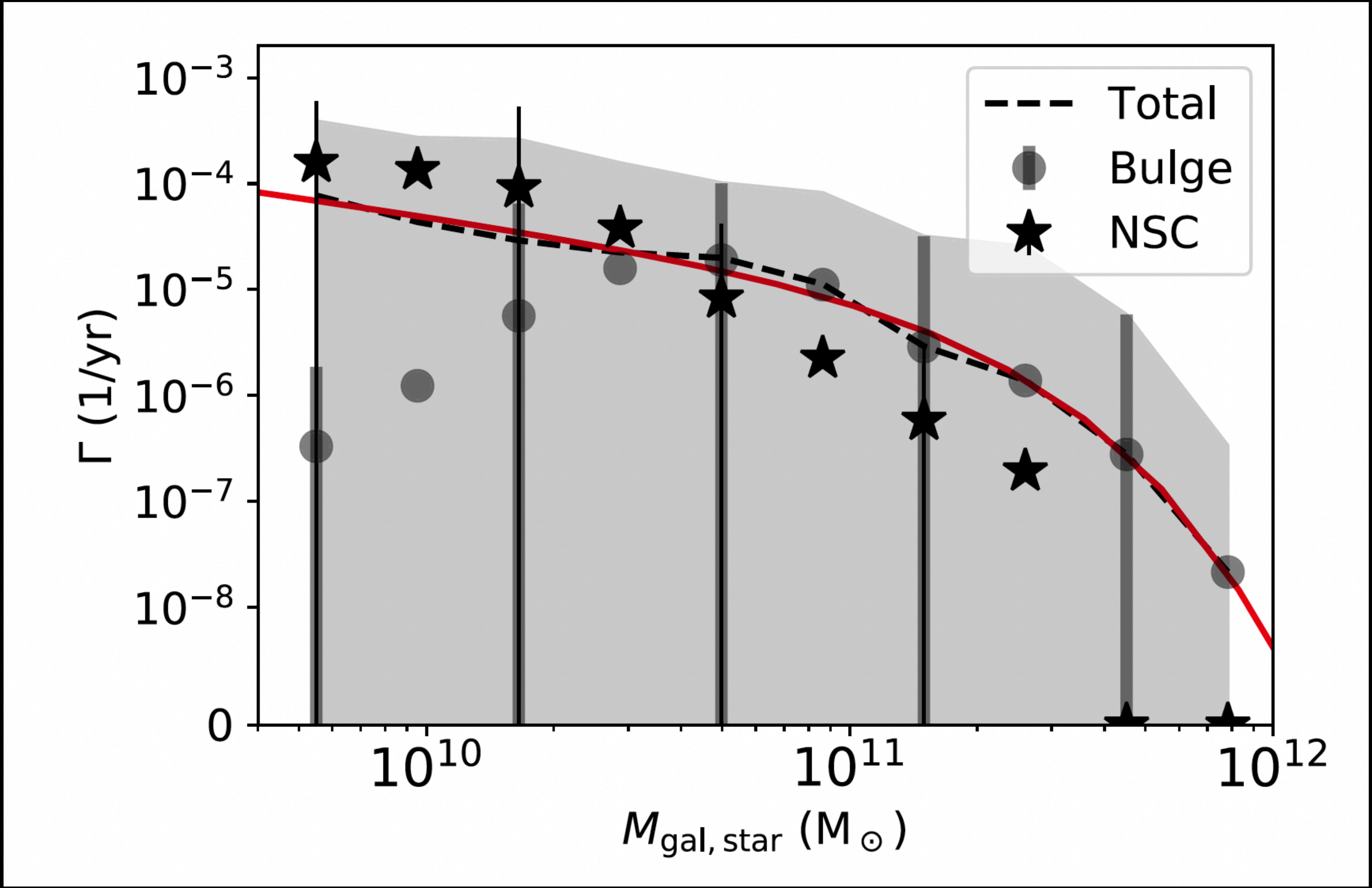
TDE rate ~ 10^{-4} - 10^{-3} galaxy^{-1} yr^{-1} (simple estimation)



Magorrian & Tremaine 1999
Wang & Merritt 2004

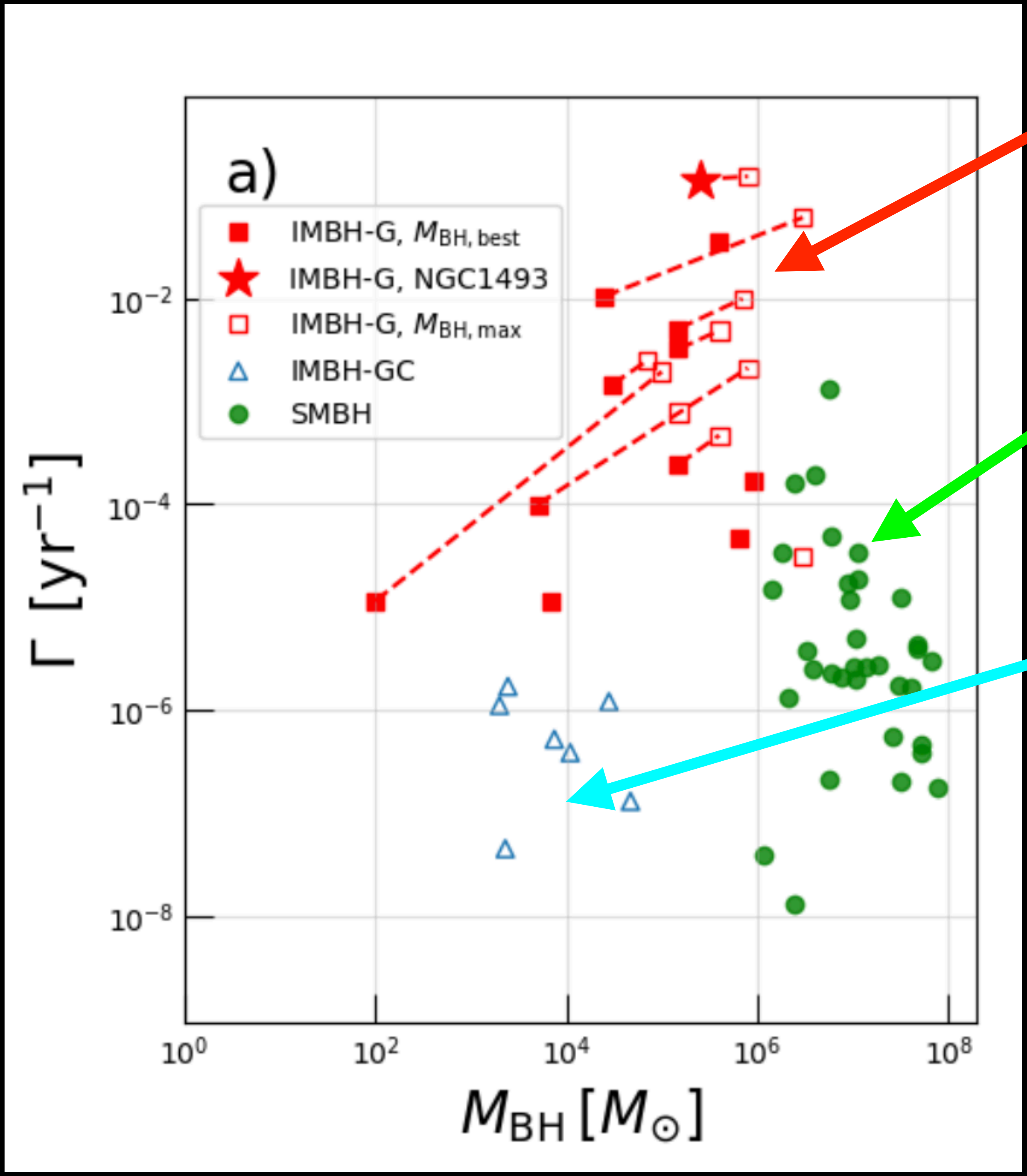


The effect of nuclear stellar cluster



Pfister, Volonteri, **LD** & Colpi 2020

IMBH TDE rates



IMBH: ~ 10^{-5} - 10^{-1} galaxy^{-1} yr^{-1}

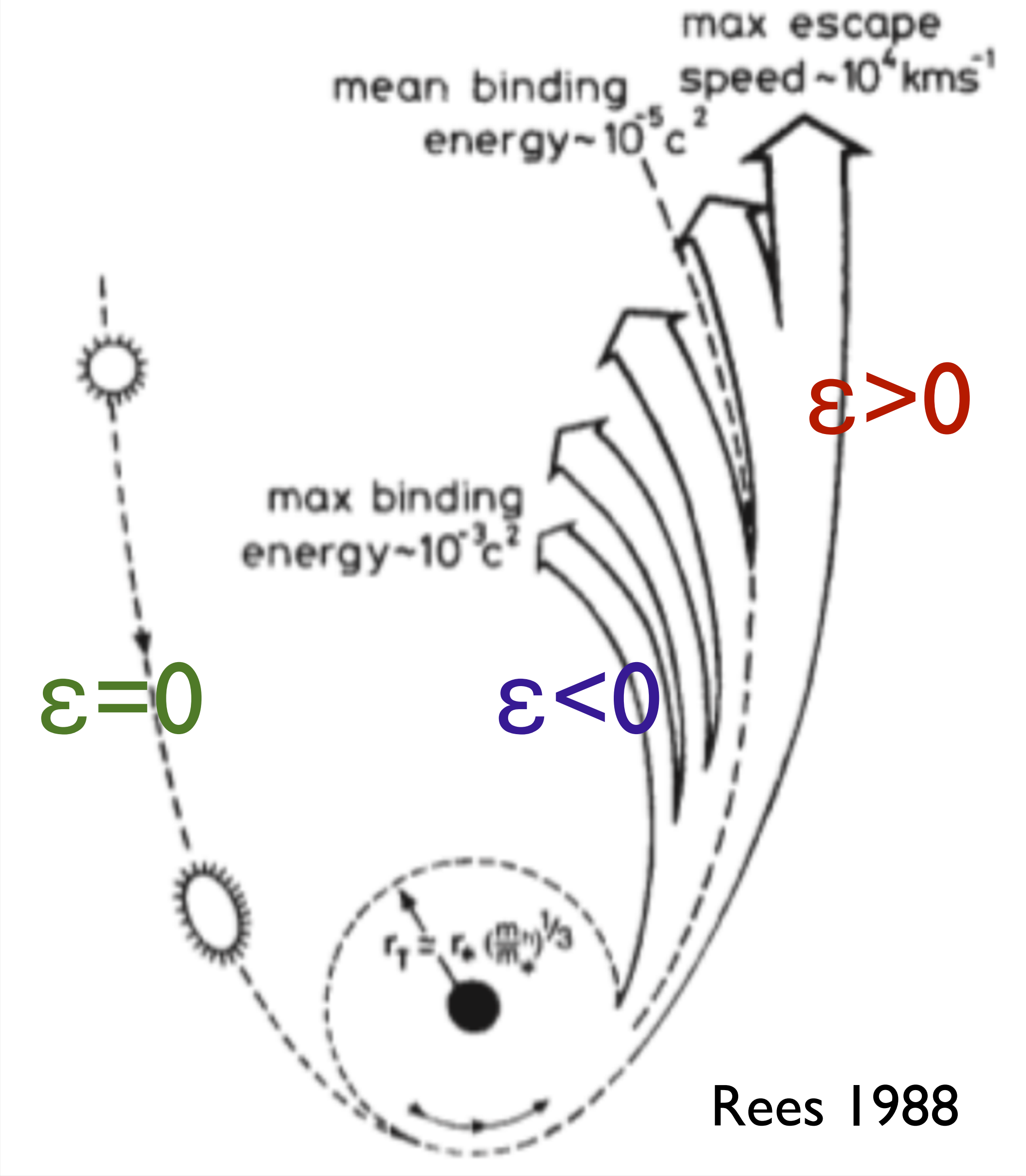
SMBH: ~ 10^{-8} - 10^{-3} galaxy^{-1} yr^{-1}

IMBHs (globular cluster): ~ 10^{-8} - 10^{-6} galaxy^{-1} yr^{-1}


Janet Chang

Chang, **LD**, Pfister, in prep

Disruption Process



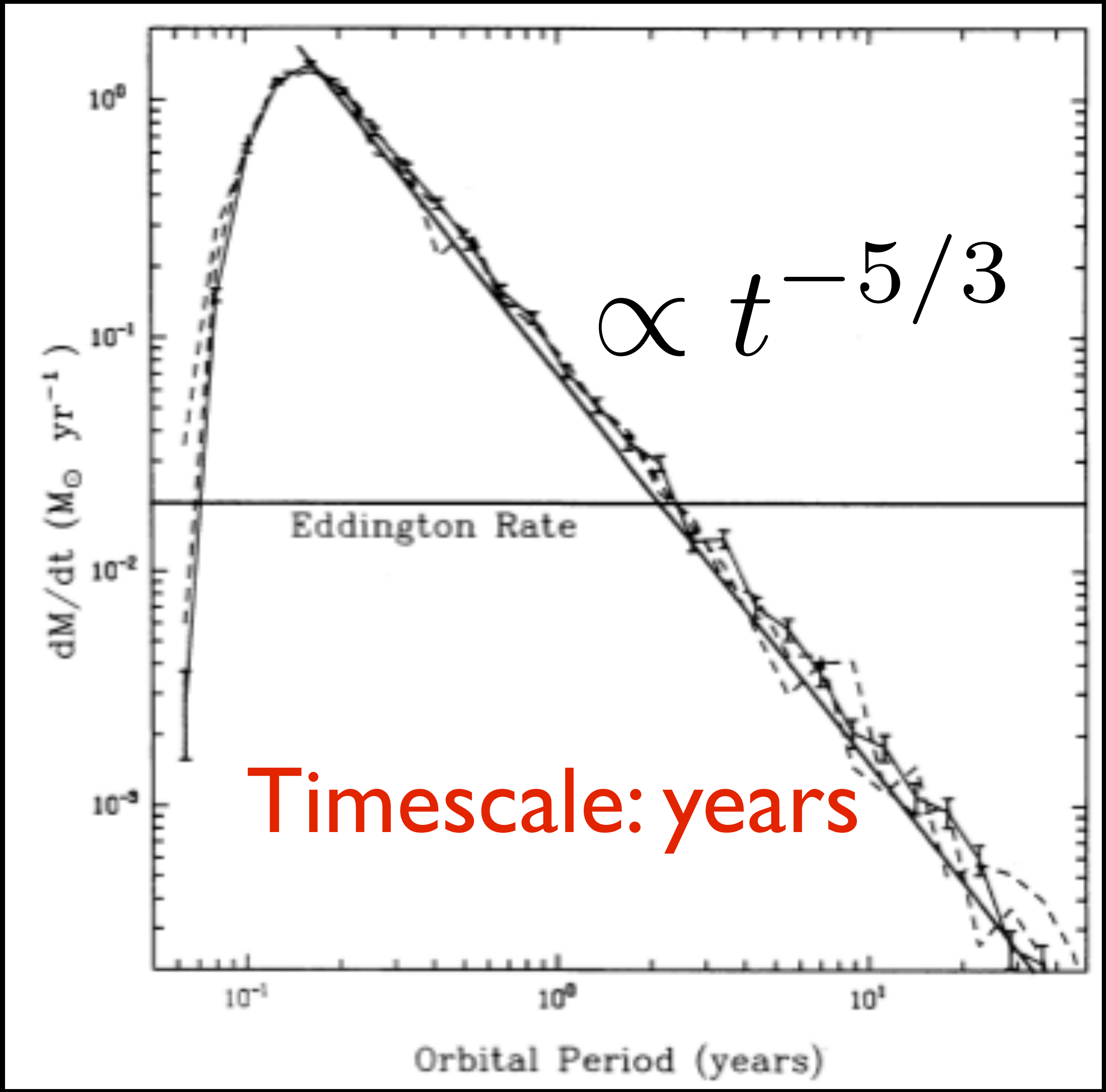
ε=0

ε<0

ε>0

Rees 1988

Debris Fallback Rate

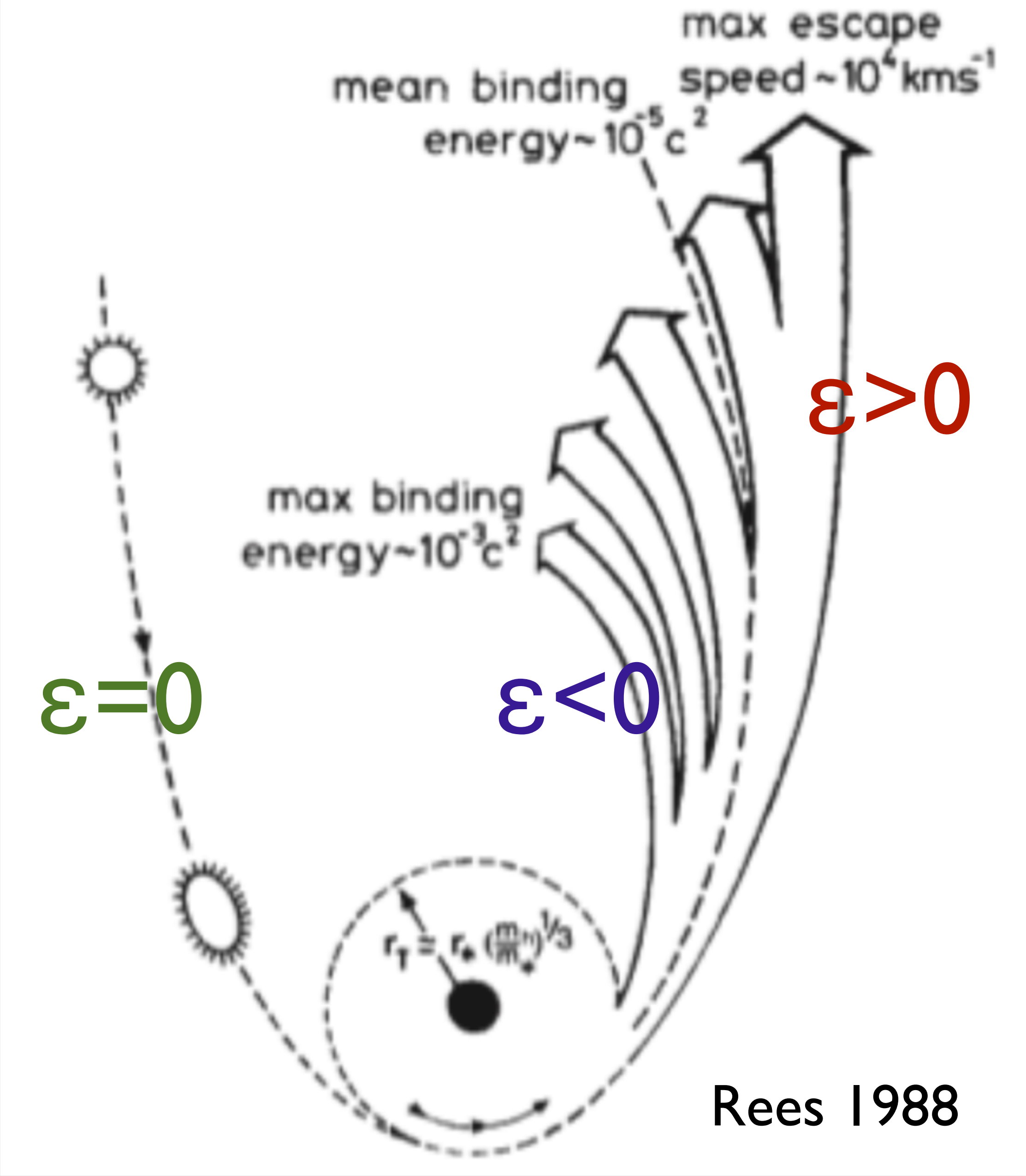


$\propto t^{-5/3}$

Timescale: years

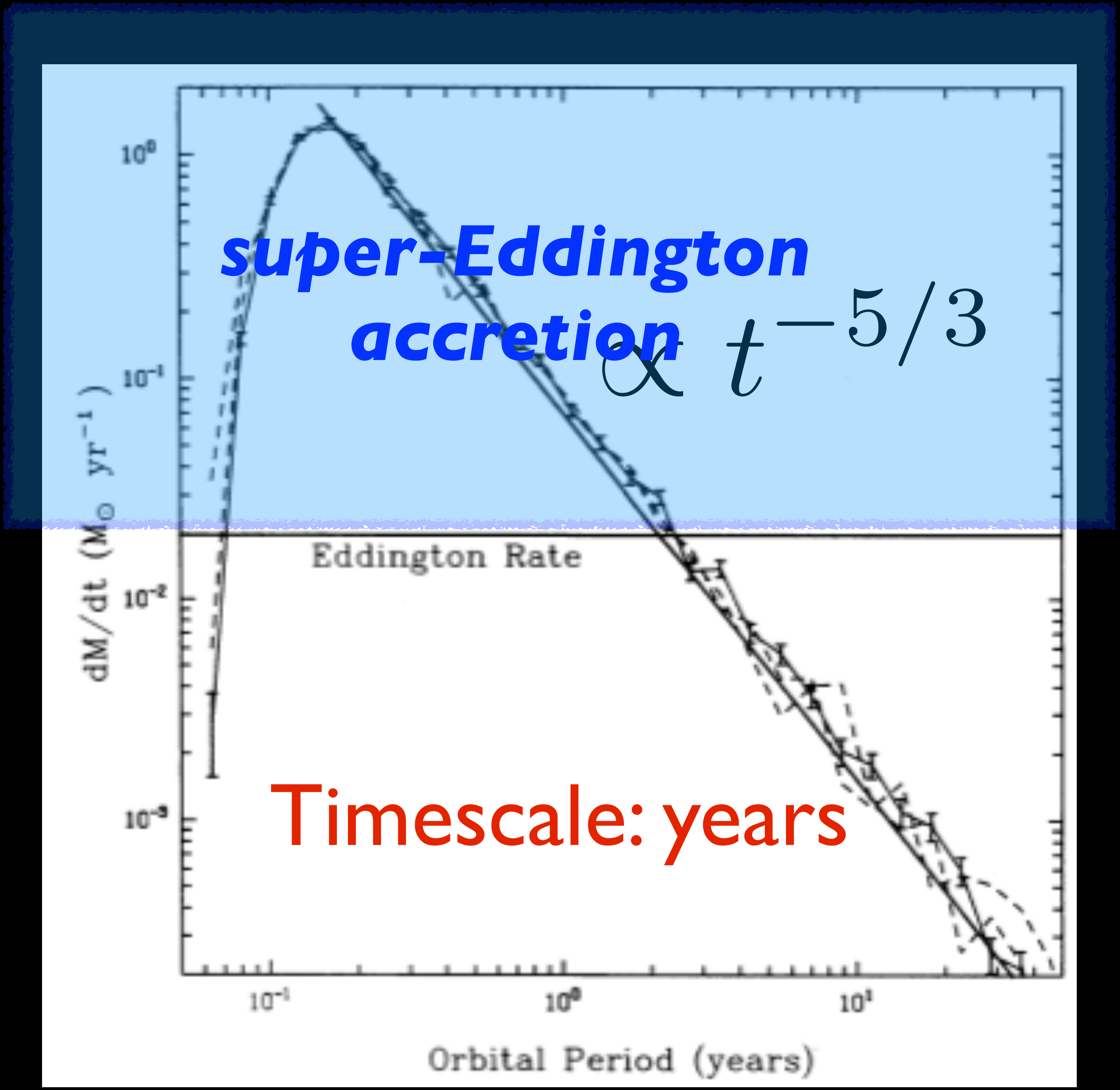
Evans & Kochanek 1989; Phinney 1989; Lodato et al. 2009; Guillochon & Ramirez-Ruiz 2013; Tejeda et al. 2017; Golightly et al. 2019; Gafton & Rosswog 2019; Ryu et al. 2020

Disruption Process



Rees 1988

Debris Fallback Rate



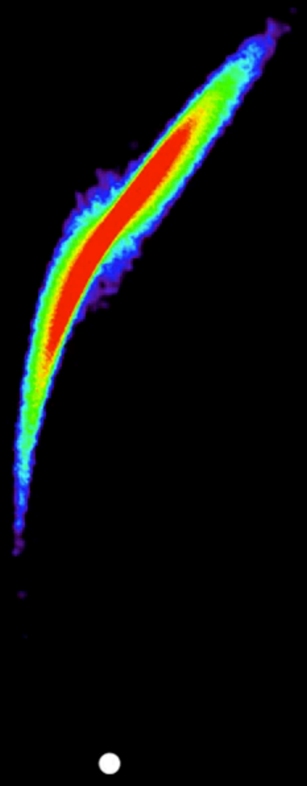
super-Eddington accretion

$\propto t^{-5/3}$

Timescale: years

Evans & Kochanek 1989; Phinney 1989; Lodato et al. 2009; Guillochon & Ramirez-Ruiz 2013; Tejeda et al. 2017; Golightly et al. 2019; Gafton & Rosswog 2019; Ryu et al. 2020

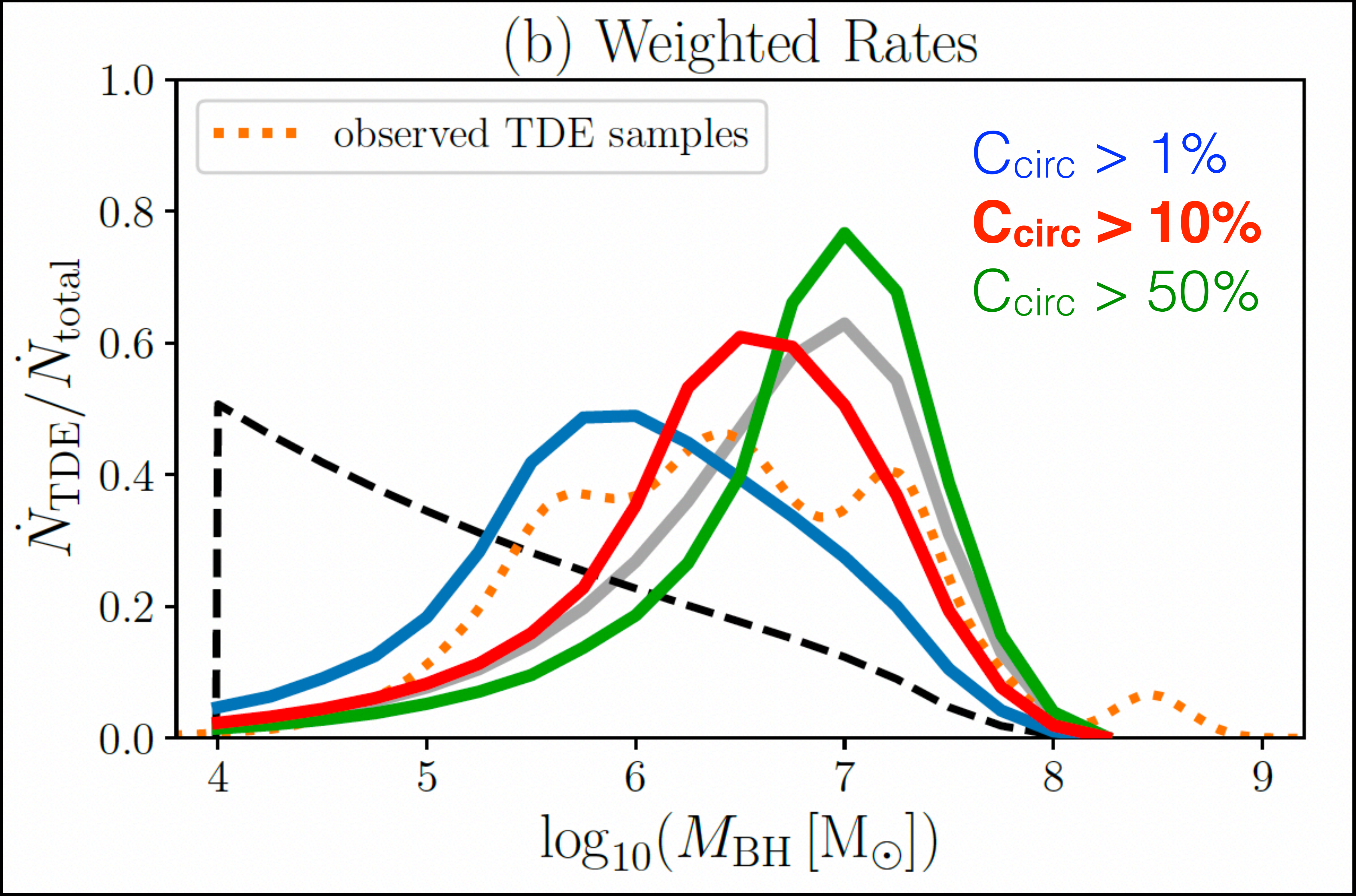
Debris stream collision & Disk formation



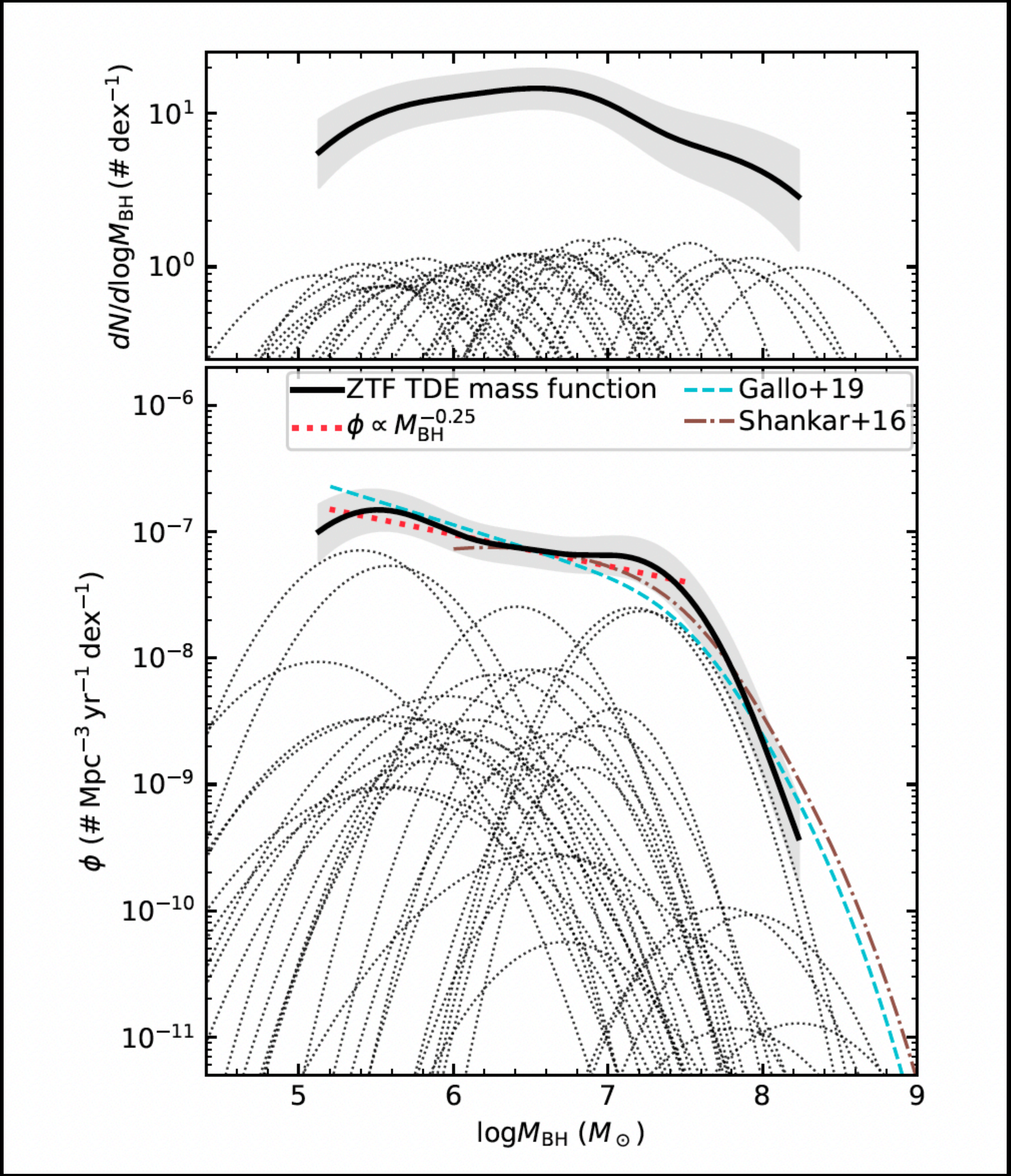
- Directly power optical emission?
- Does TDE disks form fast?

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)

Disk formation suppresses TDE detection from low-mass MBHS



Wong, Pfister, **LD** 2022

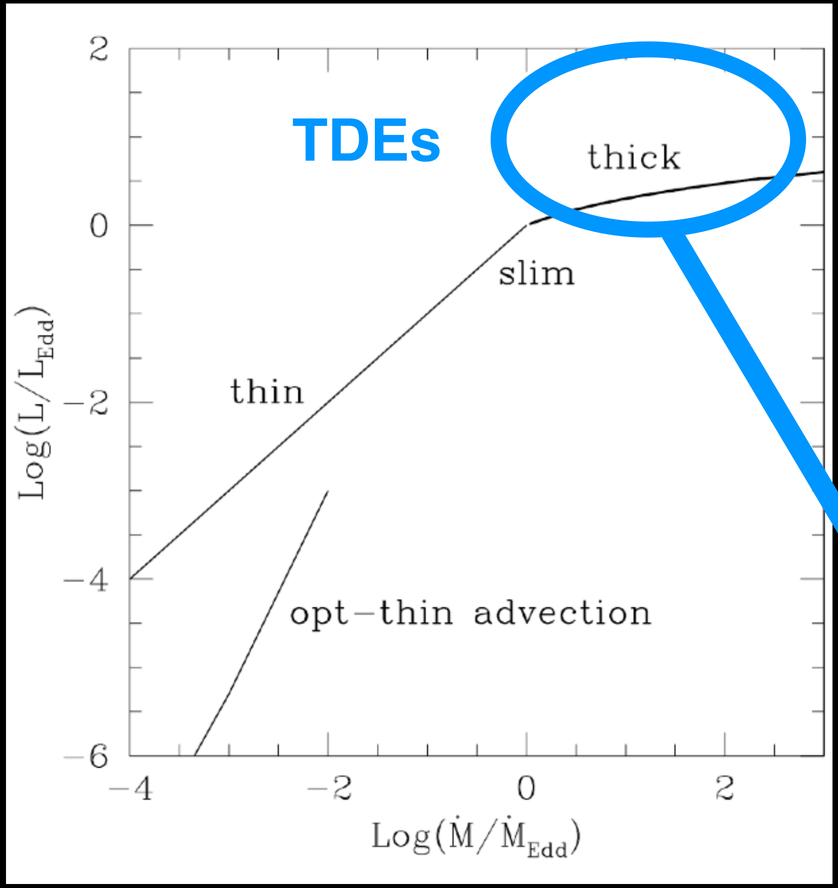


- TDE BHMF not necessarily different from AGN BHMF

Yao et al. 2023 (ZTF)

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

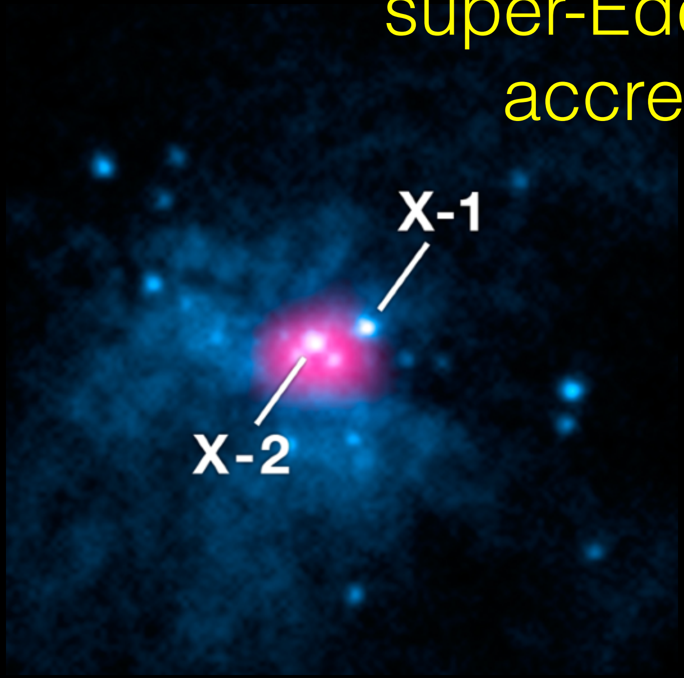
See review by **LD**, Lodato & Cheng 2021

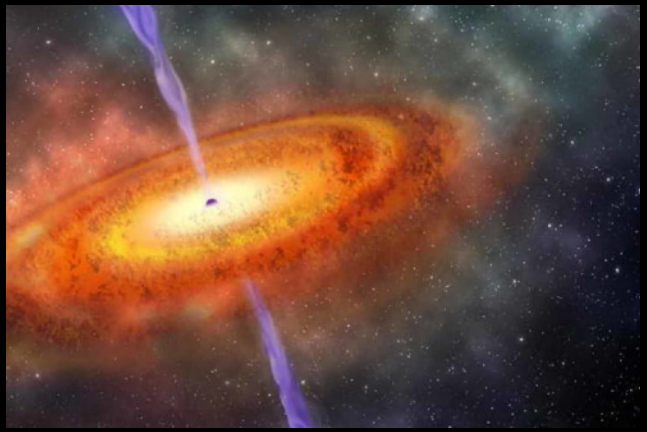


Ulmer 1999

super-Eddington accretion

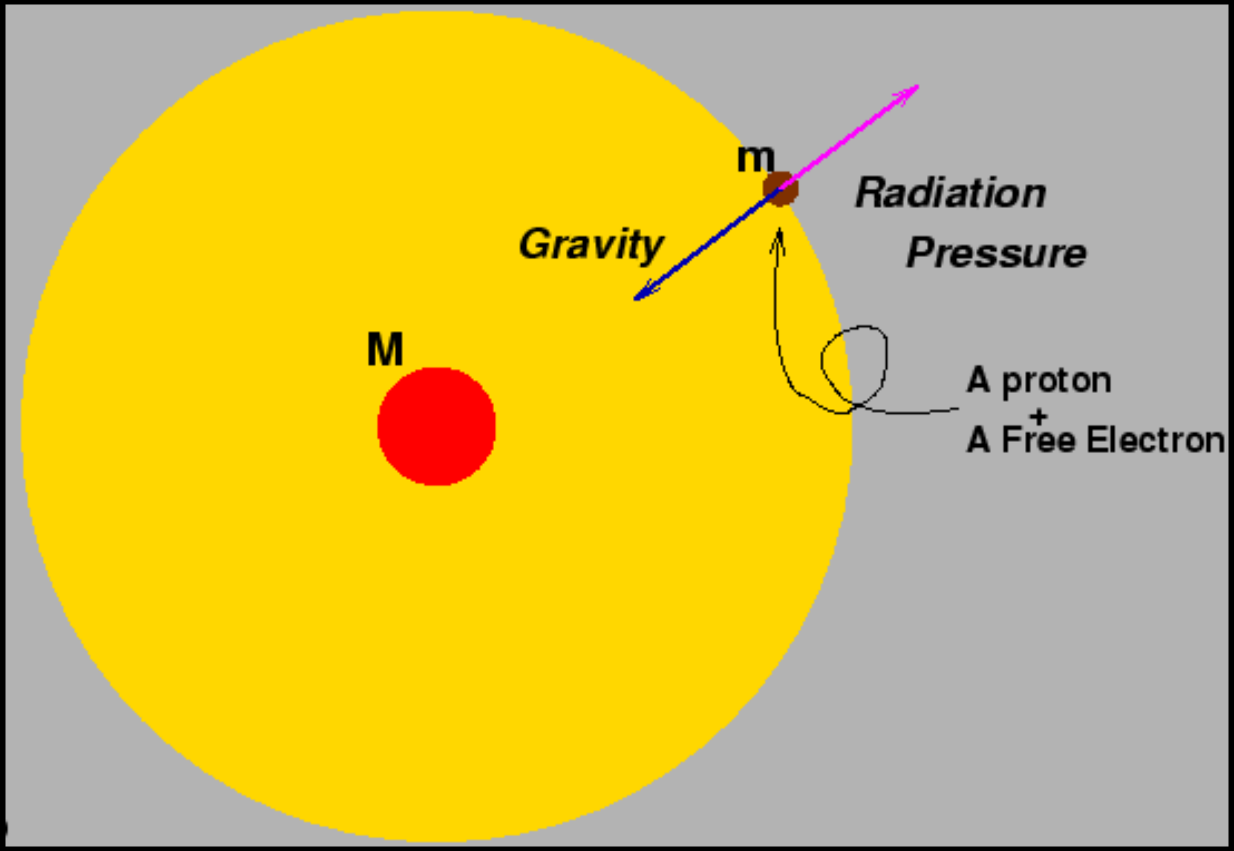
Ultra luminous X-ray sources (ULXs)





High-redshift quasars

The "Eddington Limit"



$F_{\text{radiation}} = F_{\text{gravity}}$

Eddington luminosity:

$L_{Edd} \approx 10^{38} (M_{BH} / M_{\odot})$erg/s

Radiative Efficiency:

$\eta = L / \dot{M}c^2$

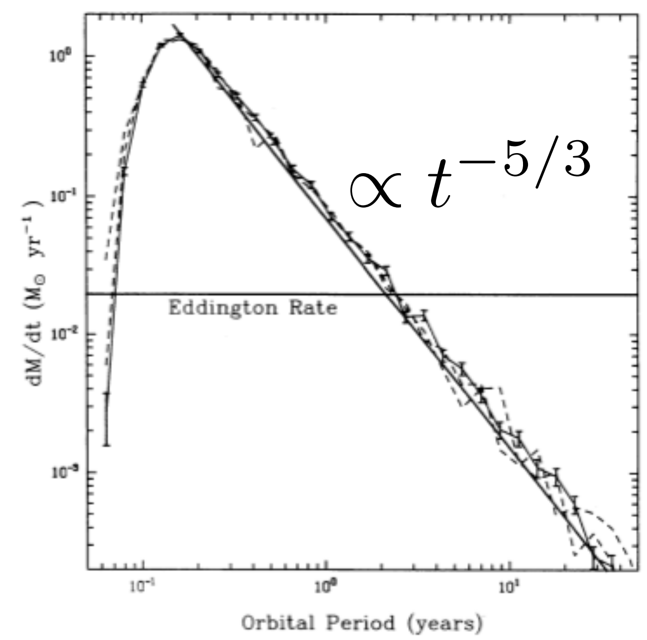
(5-40% depending on BH spin)

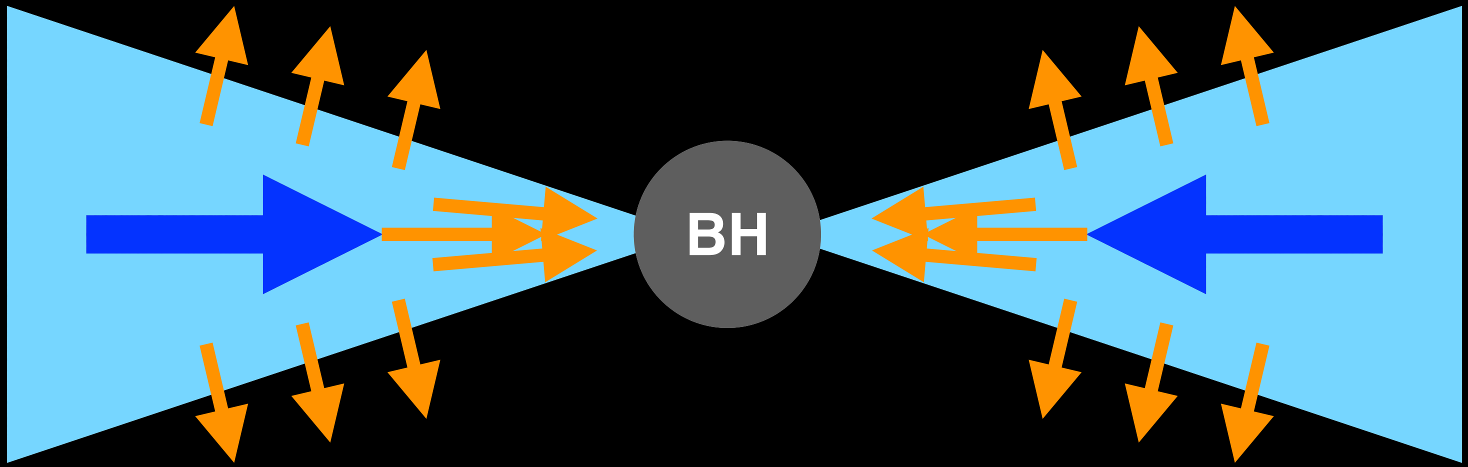
Eddington Accretion rate:

$\dot{M}_{Edd} = L_{Edd} / \eta c^2$

$\approx 10^{-2} (0.1/\eta) (M_{BH} / 10^6 M_{\odot}) M_{\odot} /$ yr

Super-Eddington Accretion in TDEs

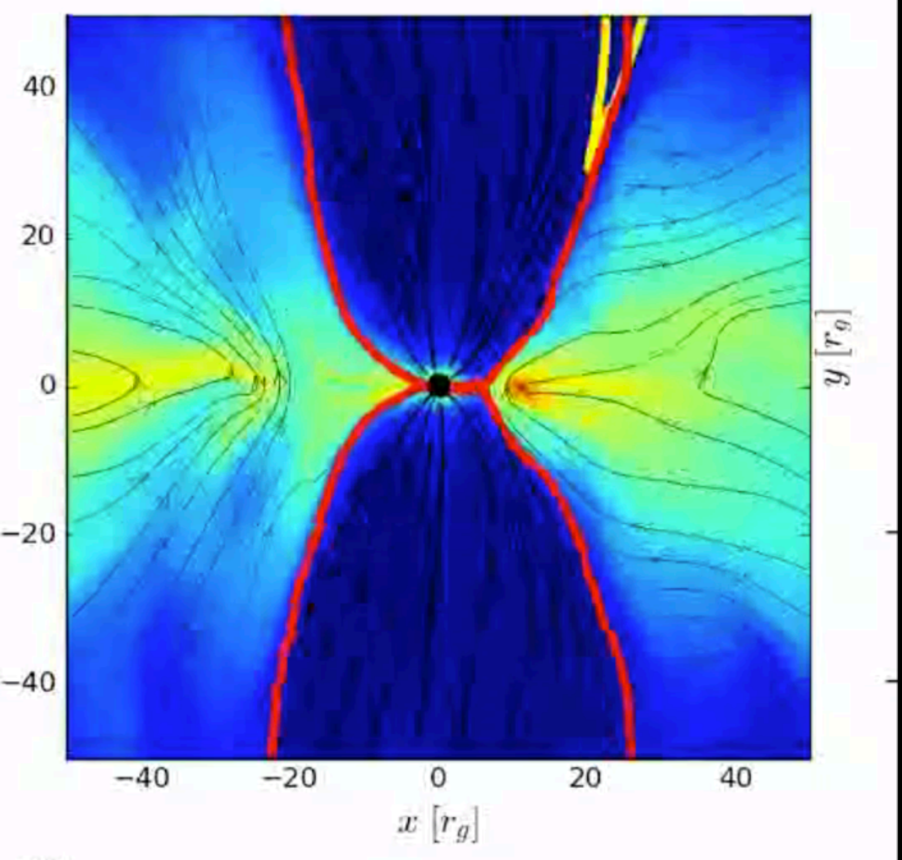




- Large radiation pressure, geometrically thick disk
- Radiation-driven winds
- Photons coupled to gas, photon trapping in the inner disk
- Eddington-regulated luminosity $L \sim L_{Edd} (1 + 0.6 \ln \dot{m})$

Shakura & Sunyaev 1973, Begelman 1978, Abramowicz et al. 1988, Ulmer 1999, Poutanen et al. 2008

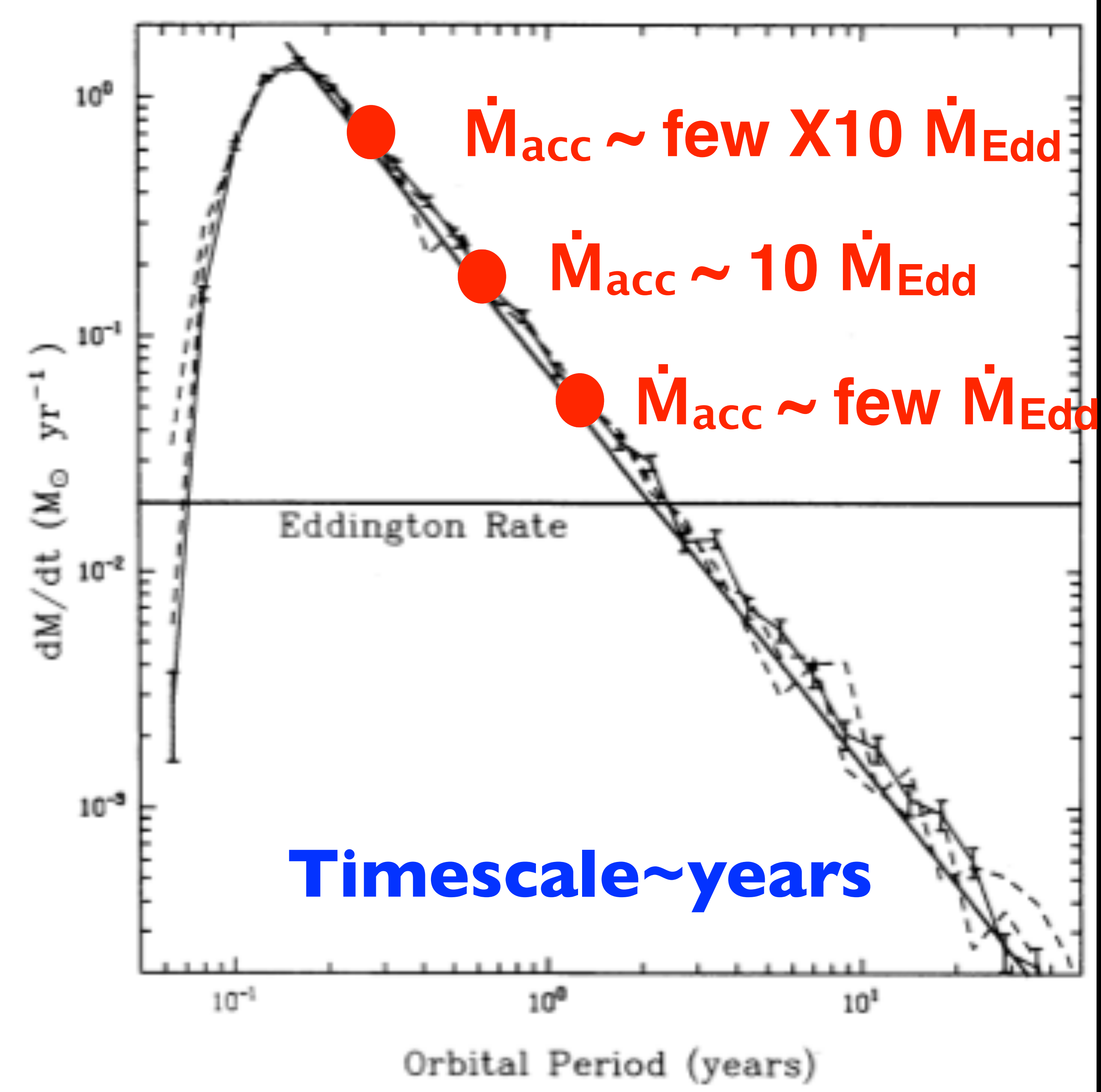
Simulation of super-Eddington disks



- 3D GR-Radiation-MHD code HARMRAD (Gammie et al. 03, McKinney et al. 12,14)
- Radiation evolved simultaneously with gas
- M1 approximation for radiation
- Supermassive black holes with $\sim 10^6\ M_\odot$
- Circular disk aligned with black hole spin

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

Disk Simulations at Different Accretion Rates

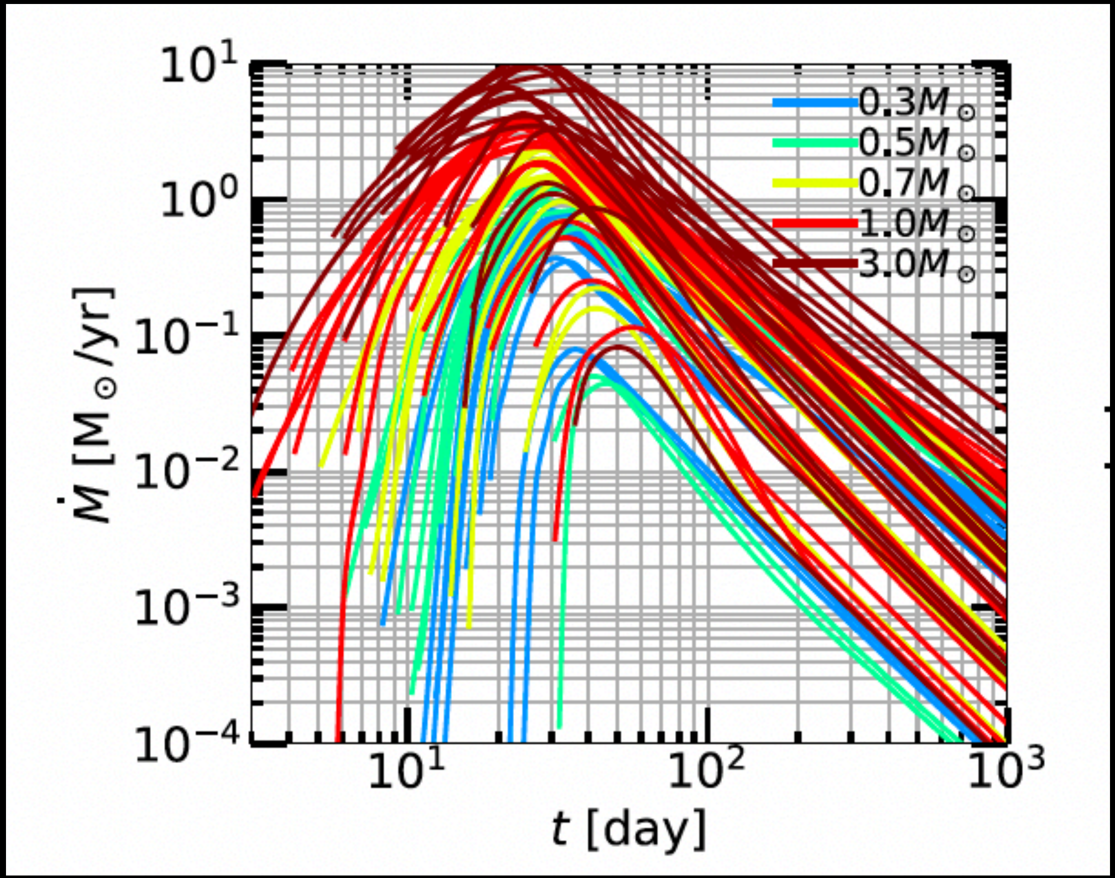


$\dot{M}_{acc}$ ~ few X10 $\dot{M}_{Edd}$

$\dot{M}_{acc}$ ~ 10 $\dot{M}_{Edd}$

$\dot{M}_{acc}$ ~ few $\dot{M}_{Edd}$

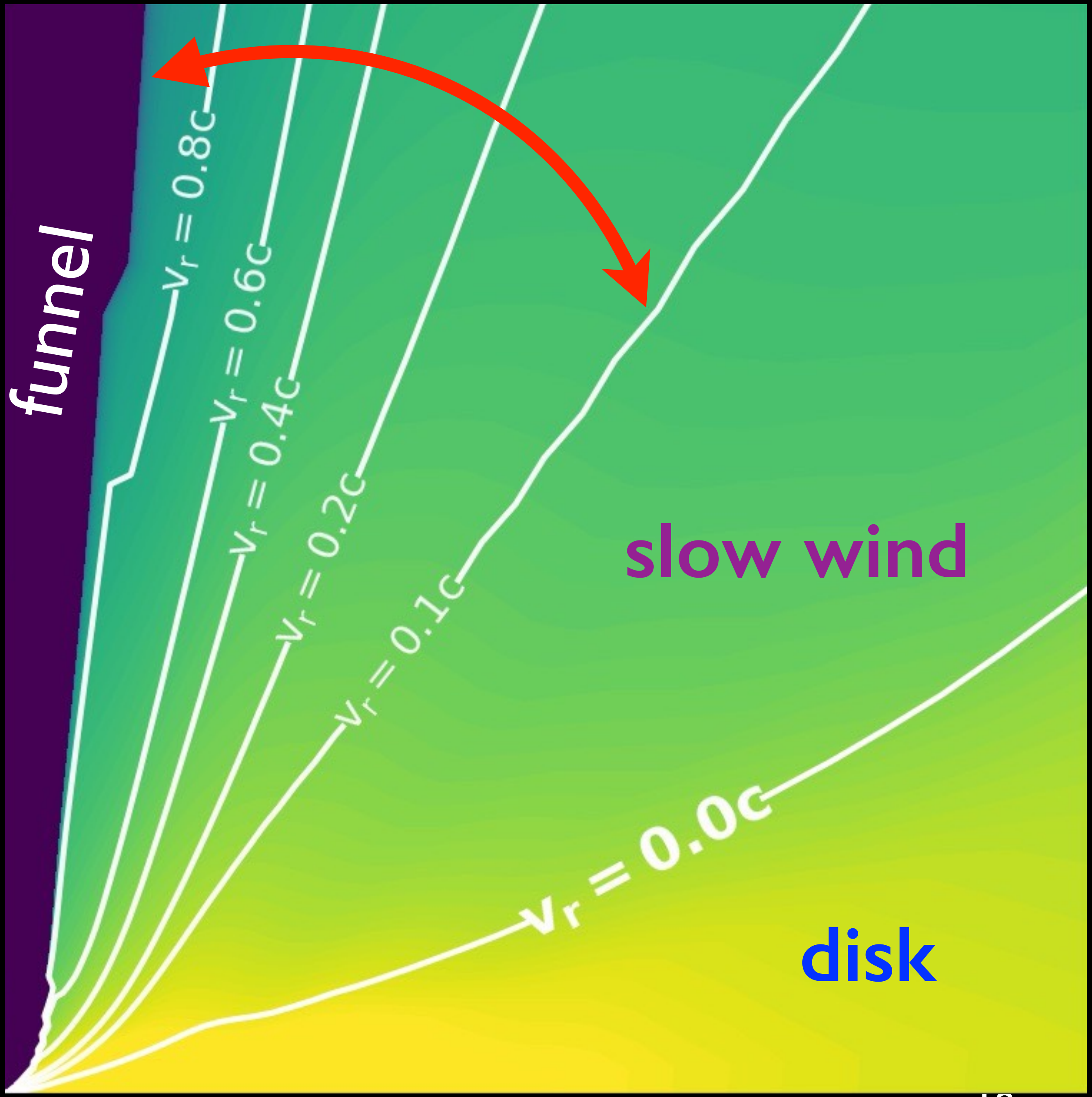
Timescale~years

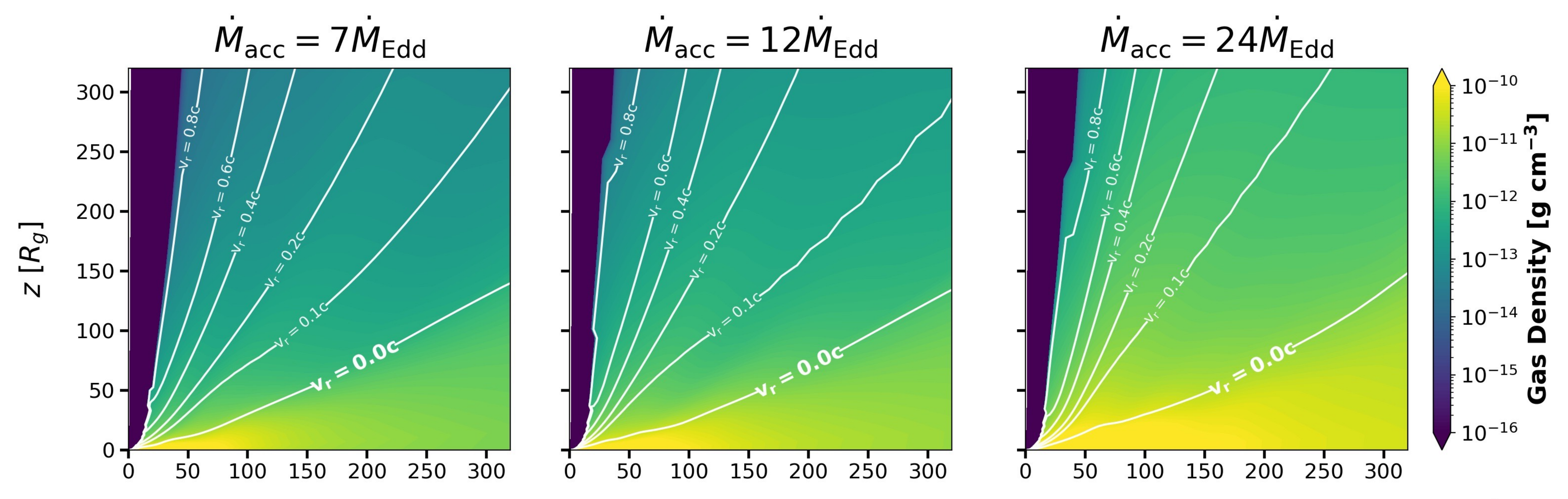


Law-Smith et al. 2020

Disk-Wind-Funnel Geometry

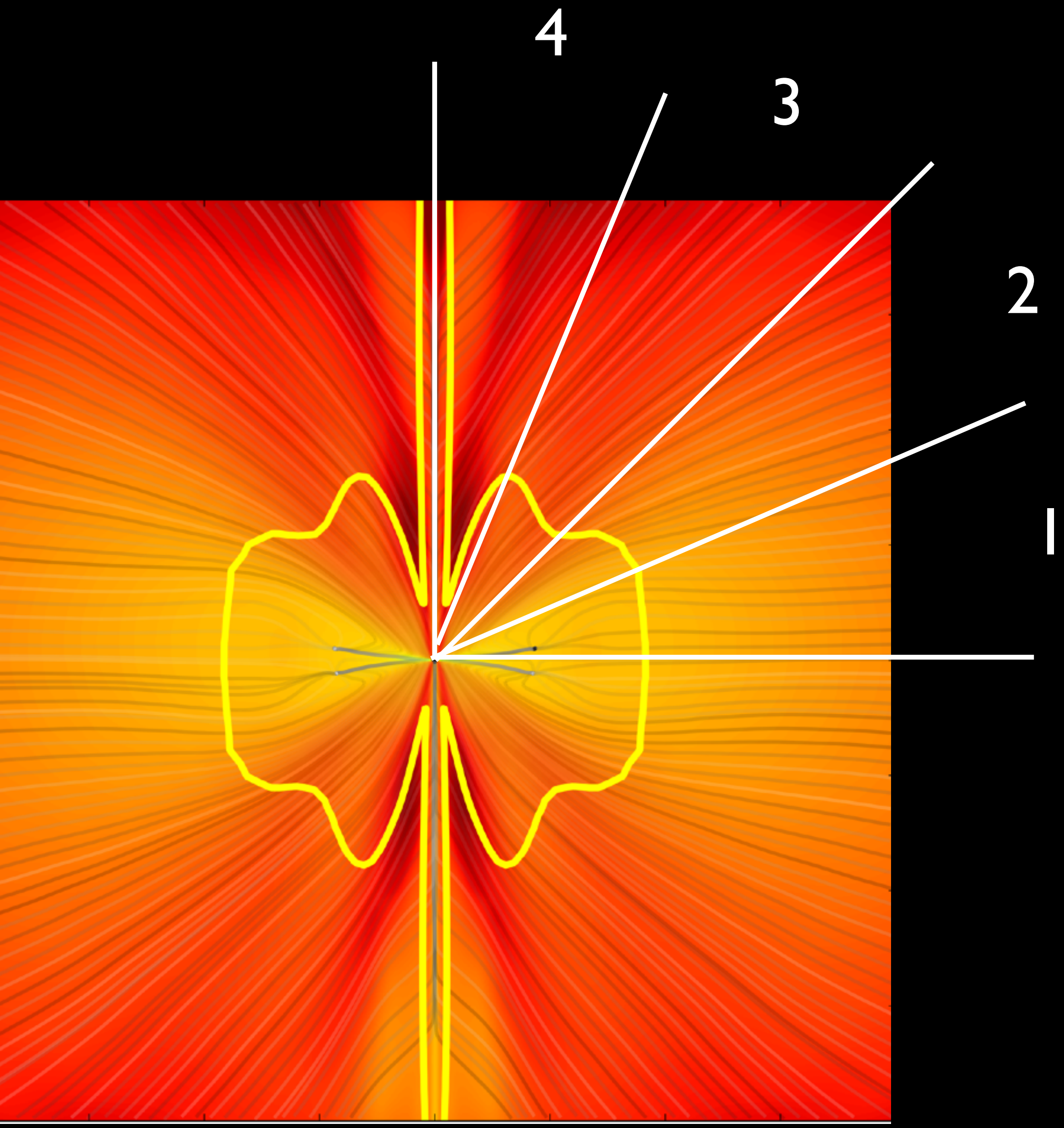
Ultra-fast outflow (UFO)
$v \gtrsim 0.1c$





- Stable structure
- Higher Eddington ratio → Larger outflow/inflow ratio

Modelling emissions from super-Eddington disks

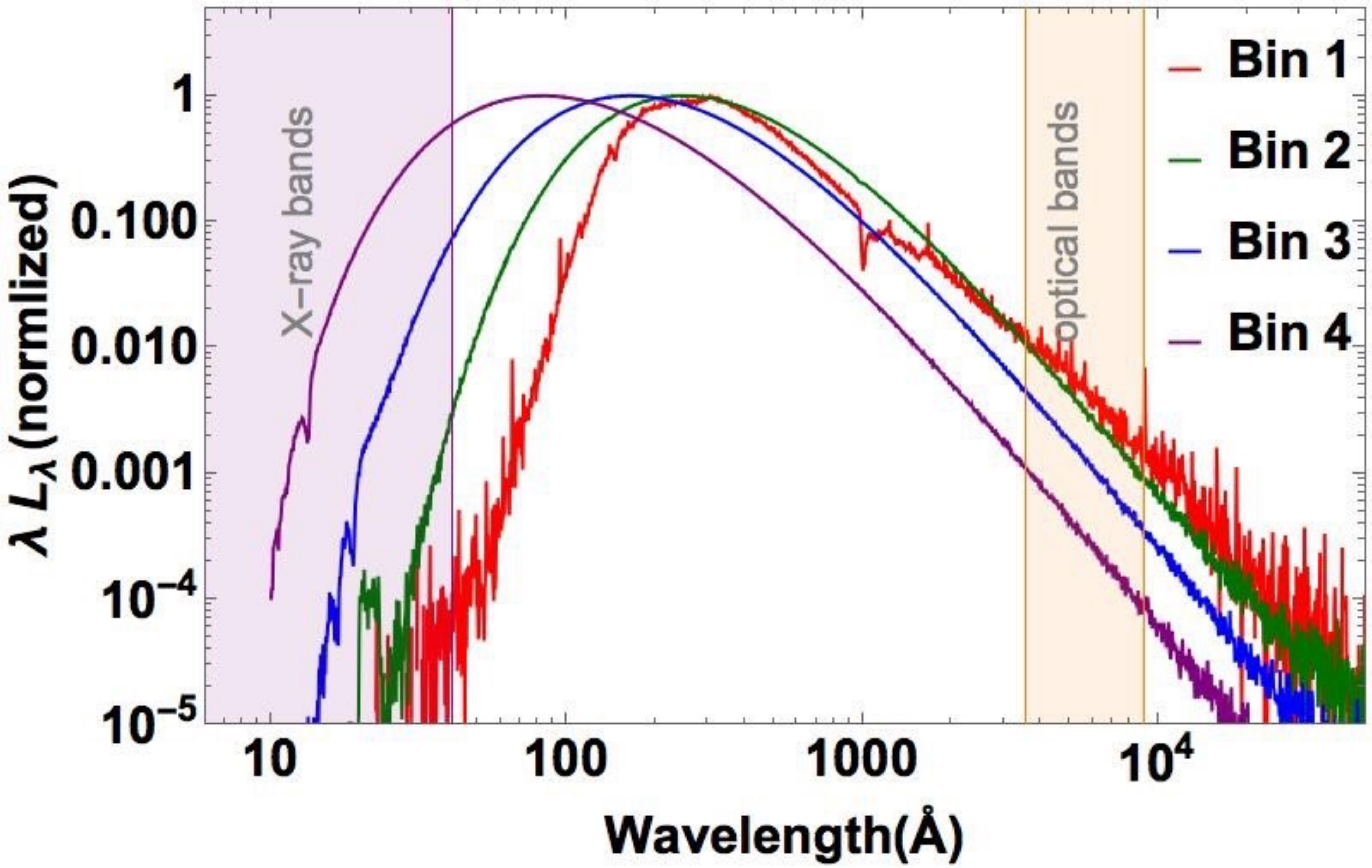


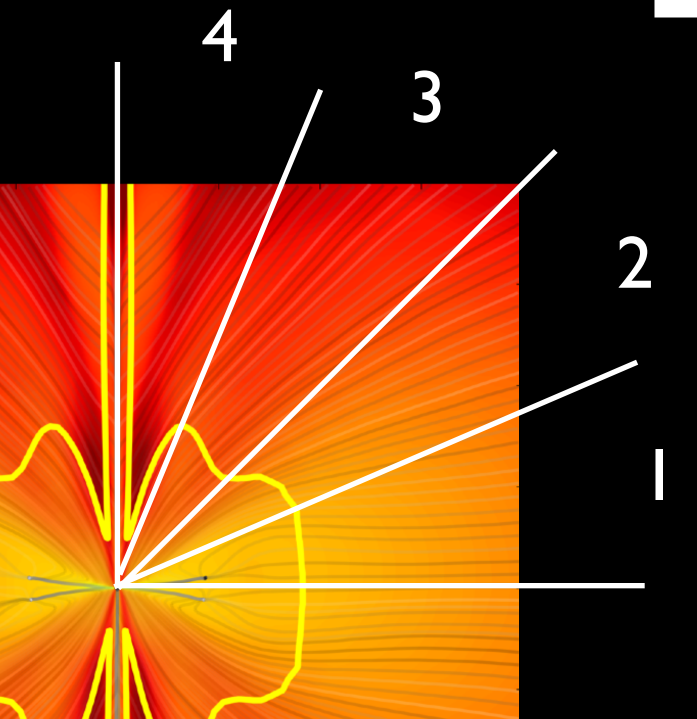
- Monte-Carlo radiative transfer code
- Non-LTE equations
- H, He and O elements
- Scattering
- Free-free, bound-free & bound-bound absorption and emission
- Comptonization (thermal & bulk)
- 1D post-processing: spherically symmetric
- Injecting 10^6 K blackbody emission from centre

Kasen 2006, Roth & Kasen 2016

Spectra vs. Viewing Angle

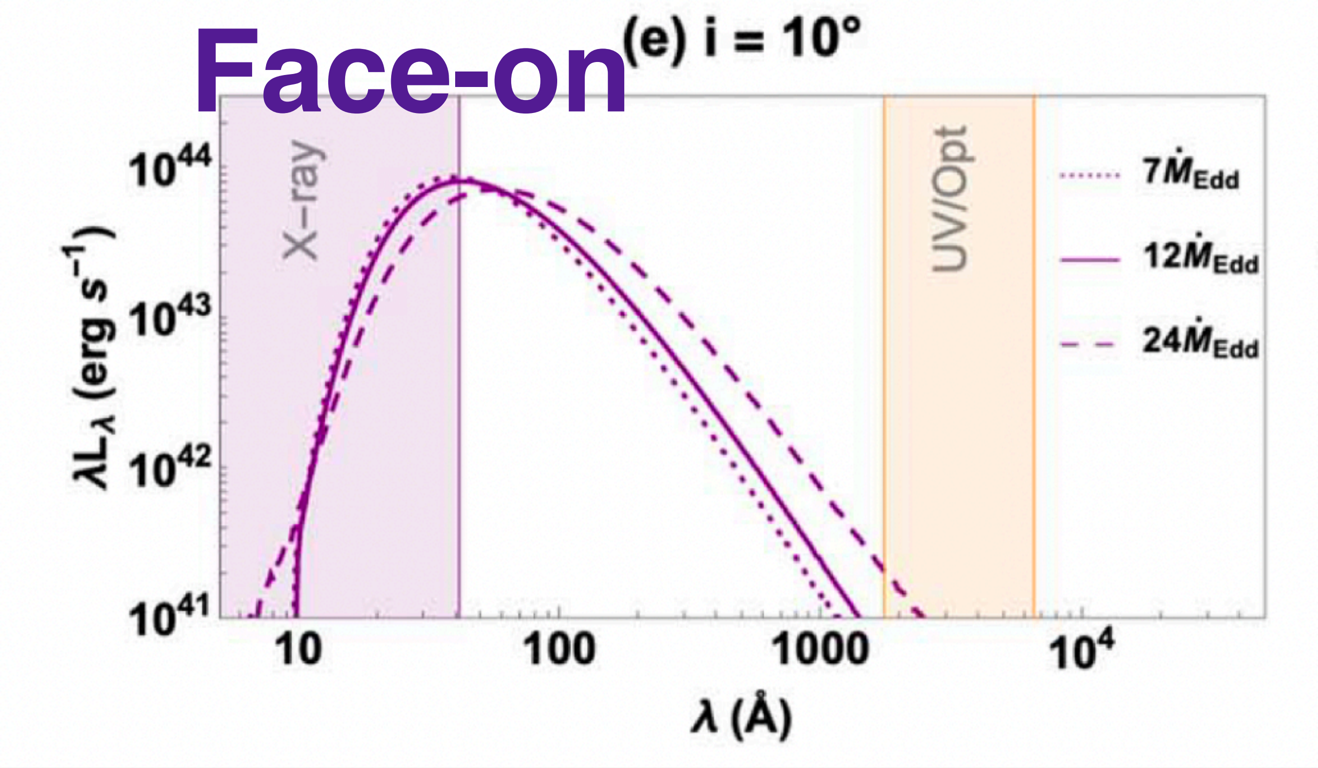
LD et al. 2018

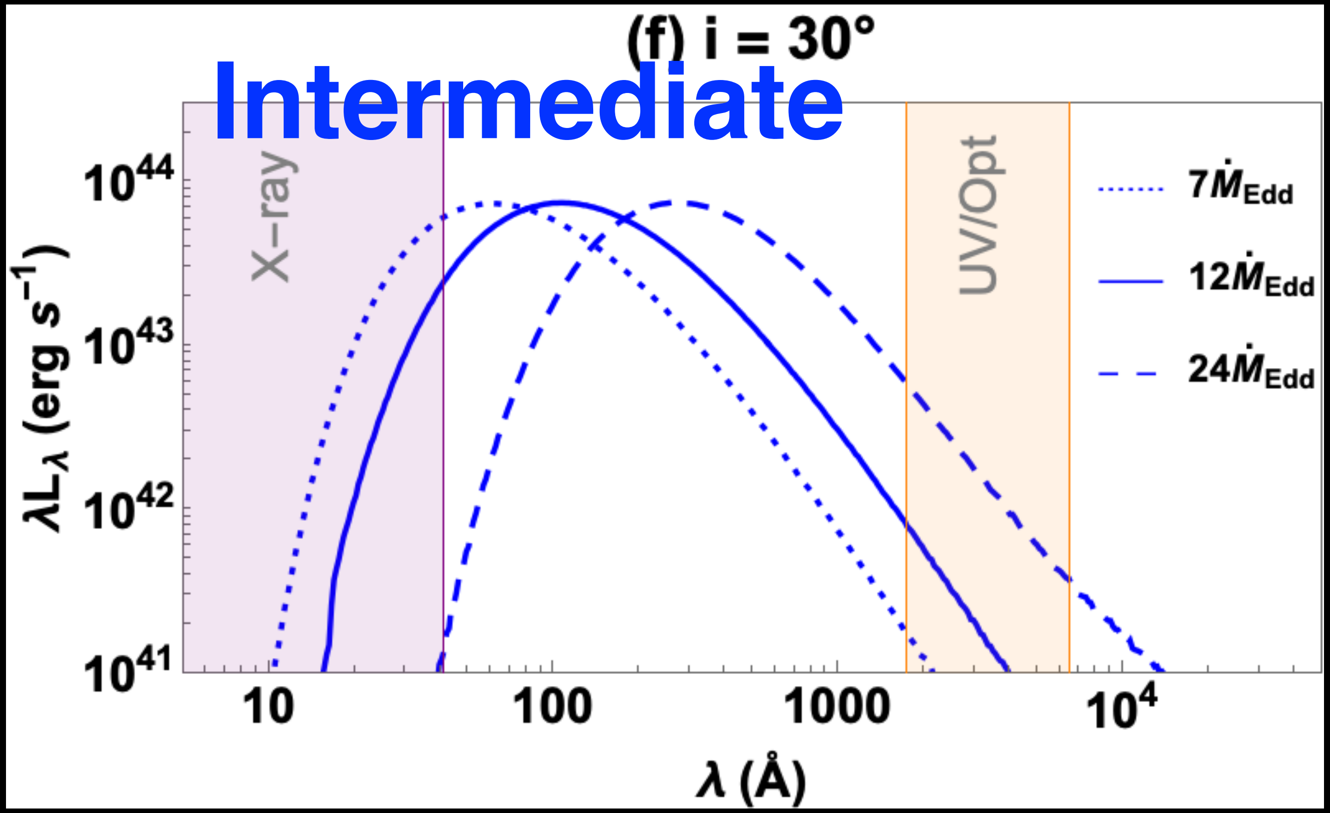


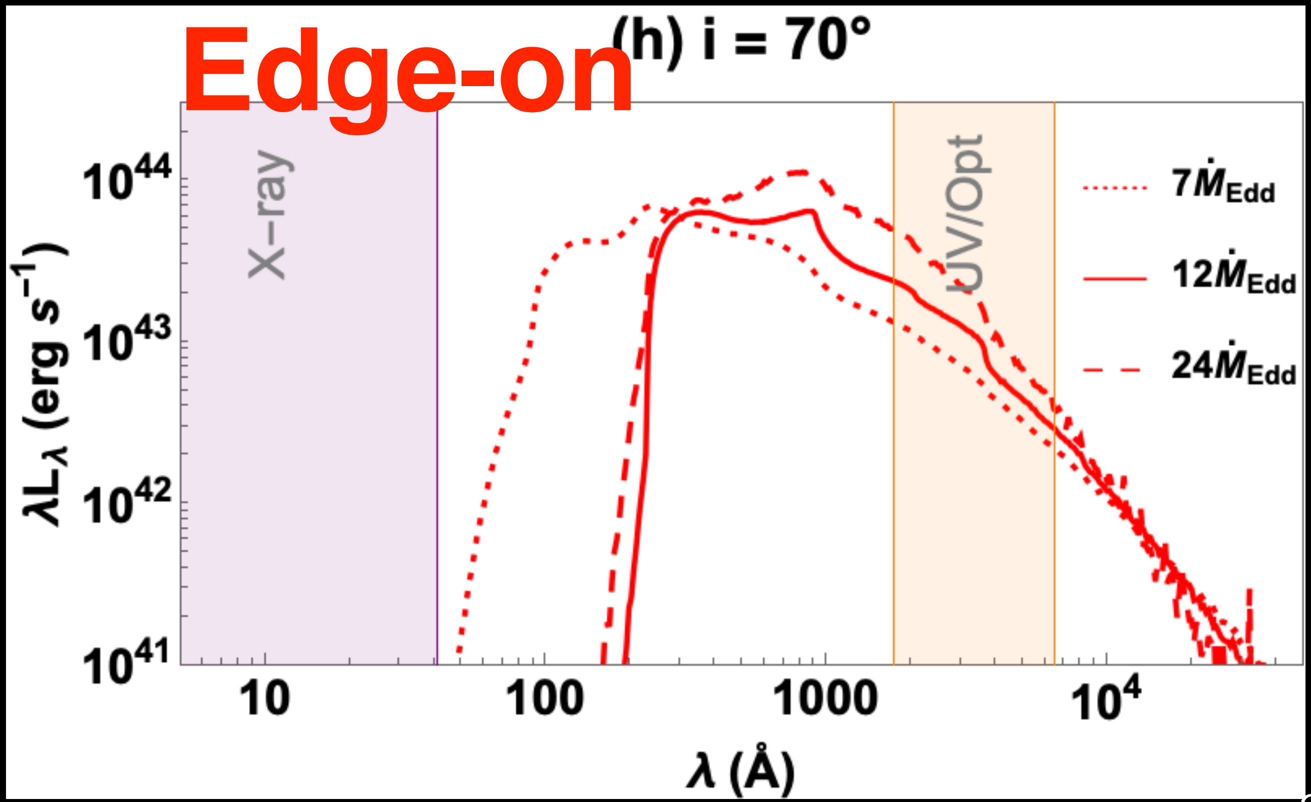


- X-ray heavily reprocessed in wind and disk
- Adiabatic reprocessing (fast wind)
- Photonization/line reprocessing (slow wind+disk)

More reprocessed emissions at higher accretion rates

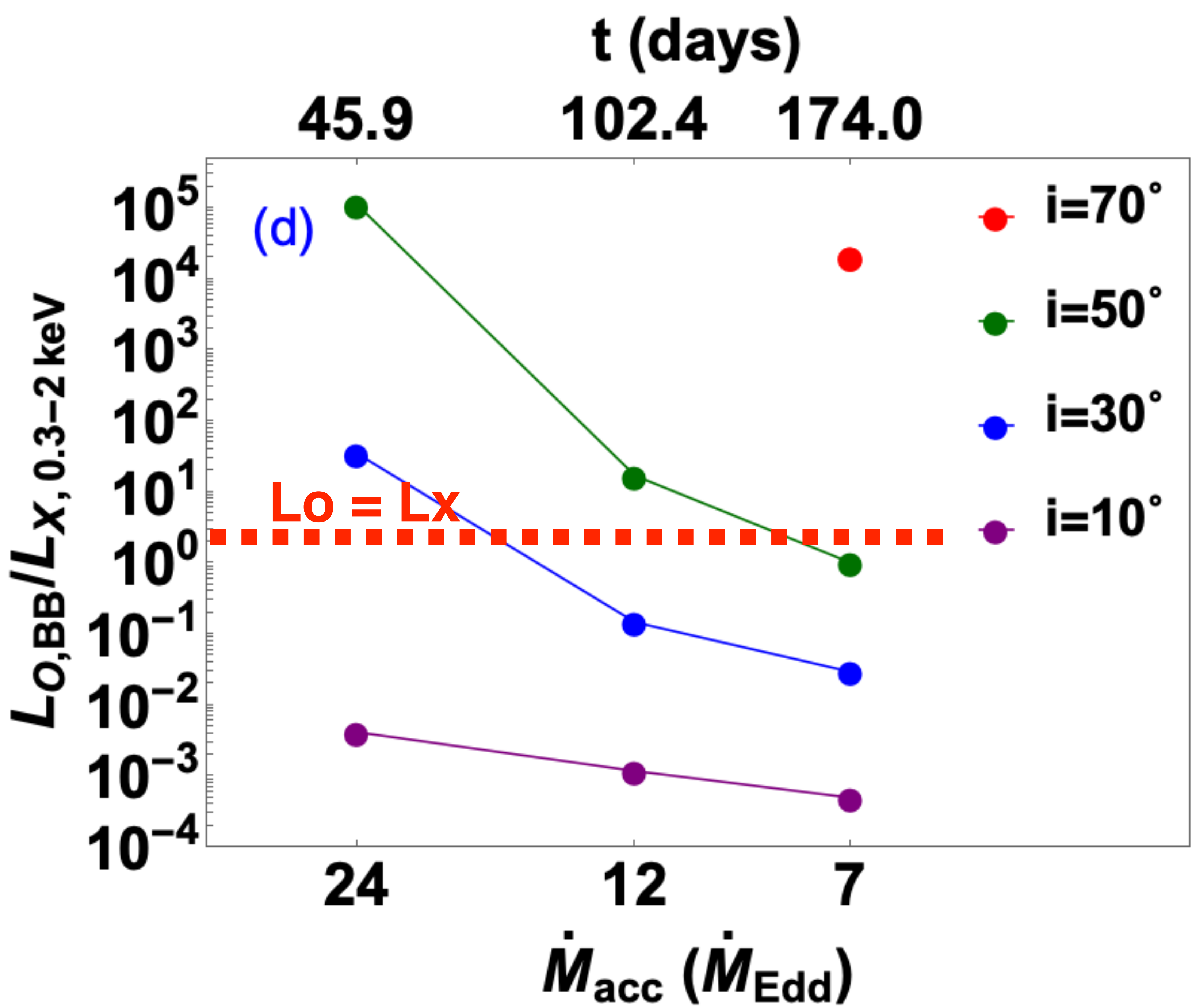






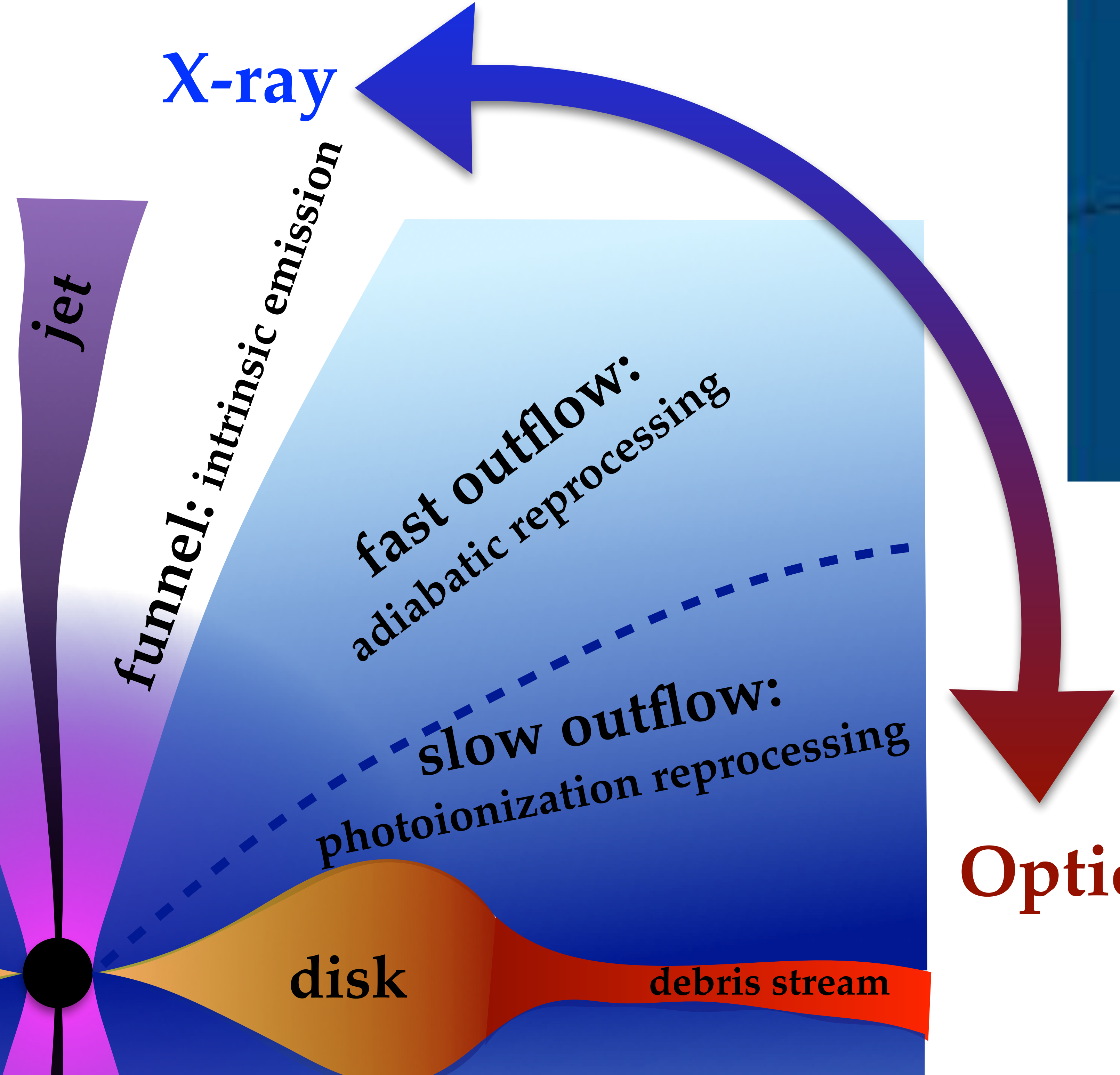
Thomsen, Kwan, **LD**, et al, 2022

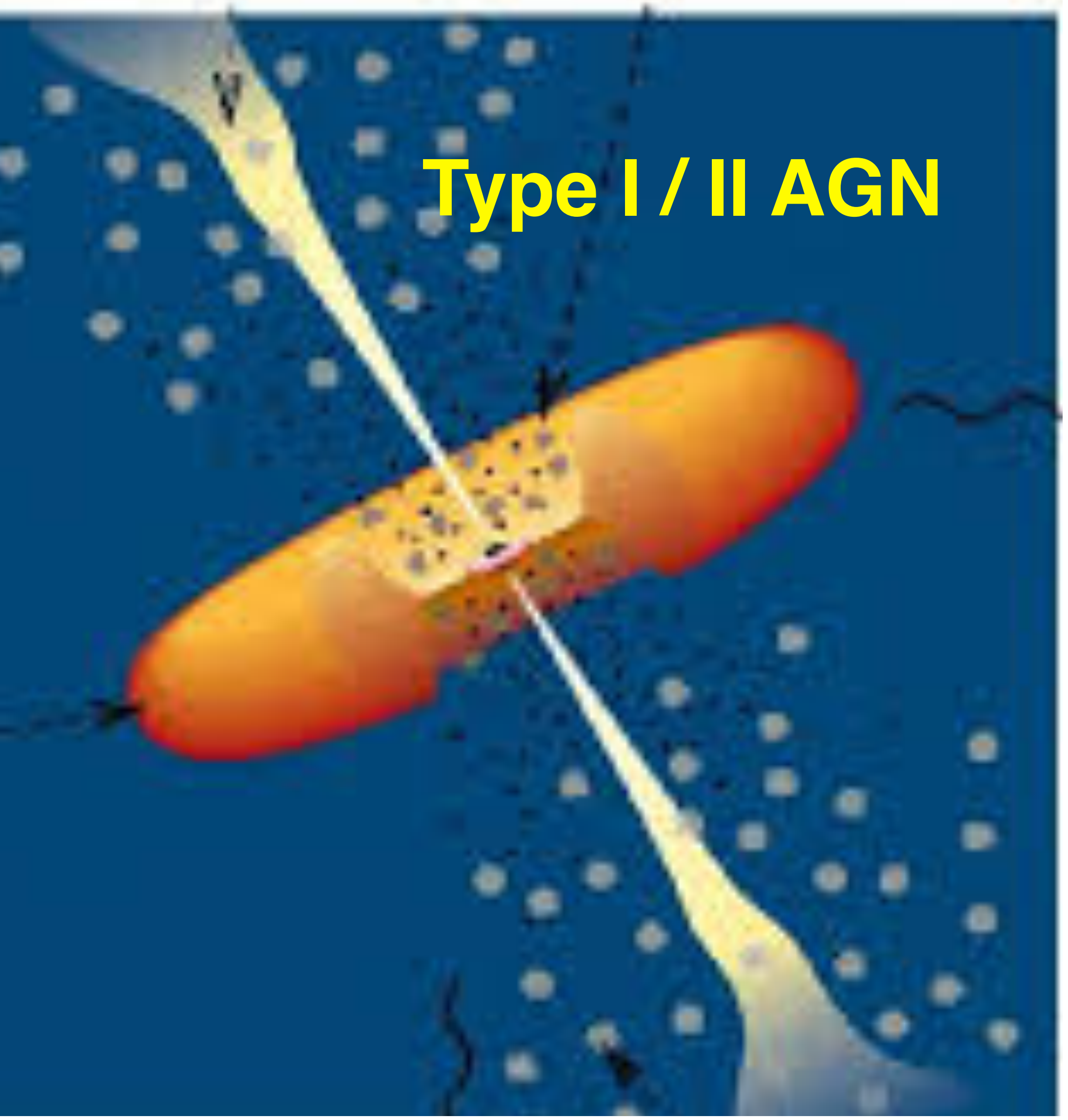
Optical TDEs rebrighten in X-rays



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

Dynamical Unified TDE Model



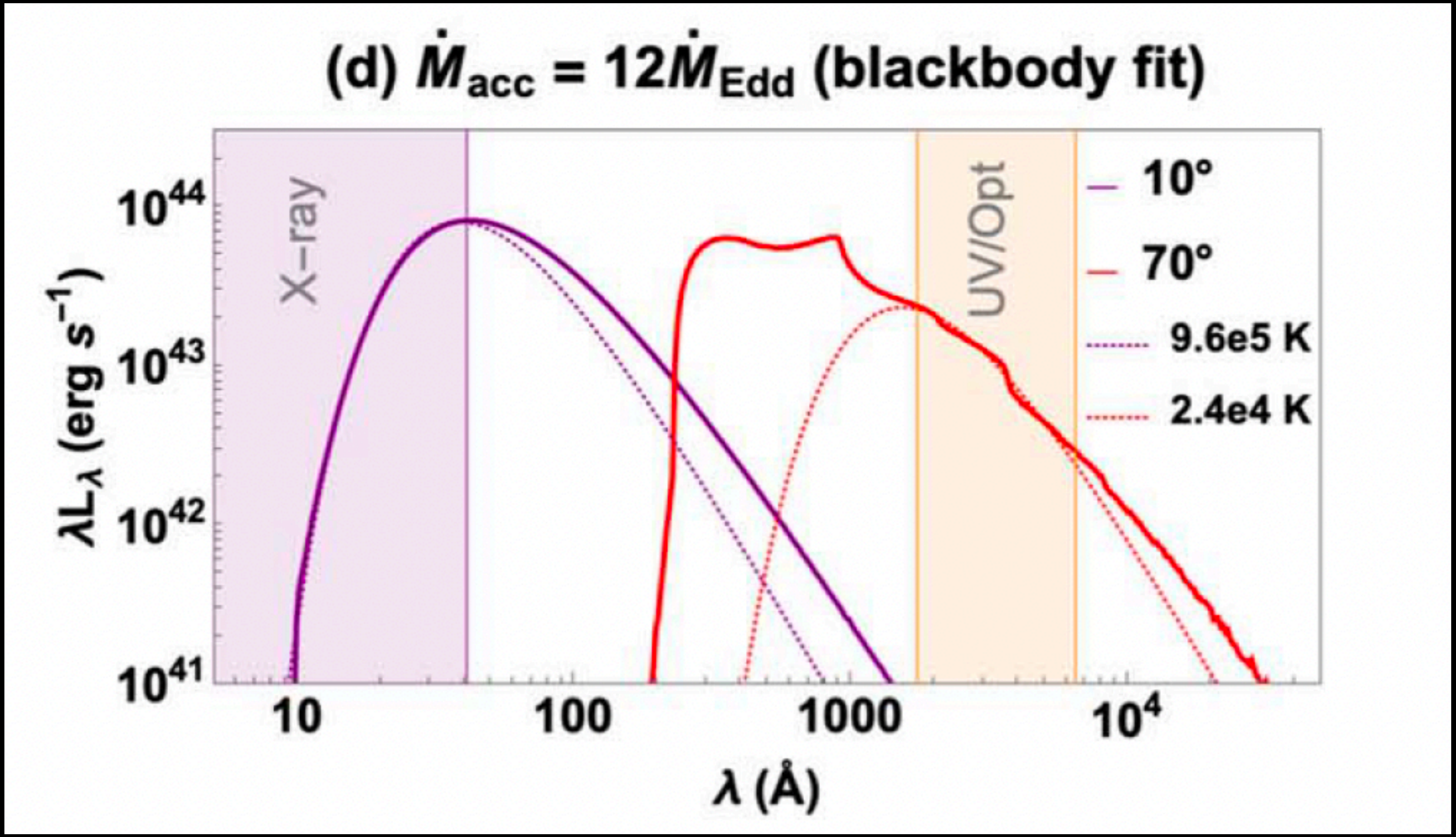


LD, McKinney, Roth et al. 2018

Thomsen, Kwan, LD et al. 2022

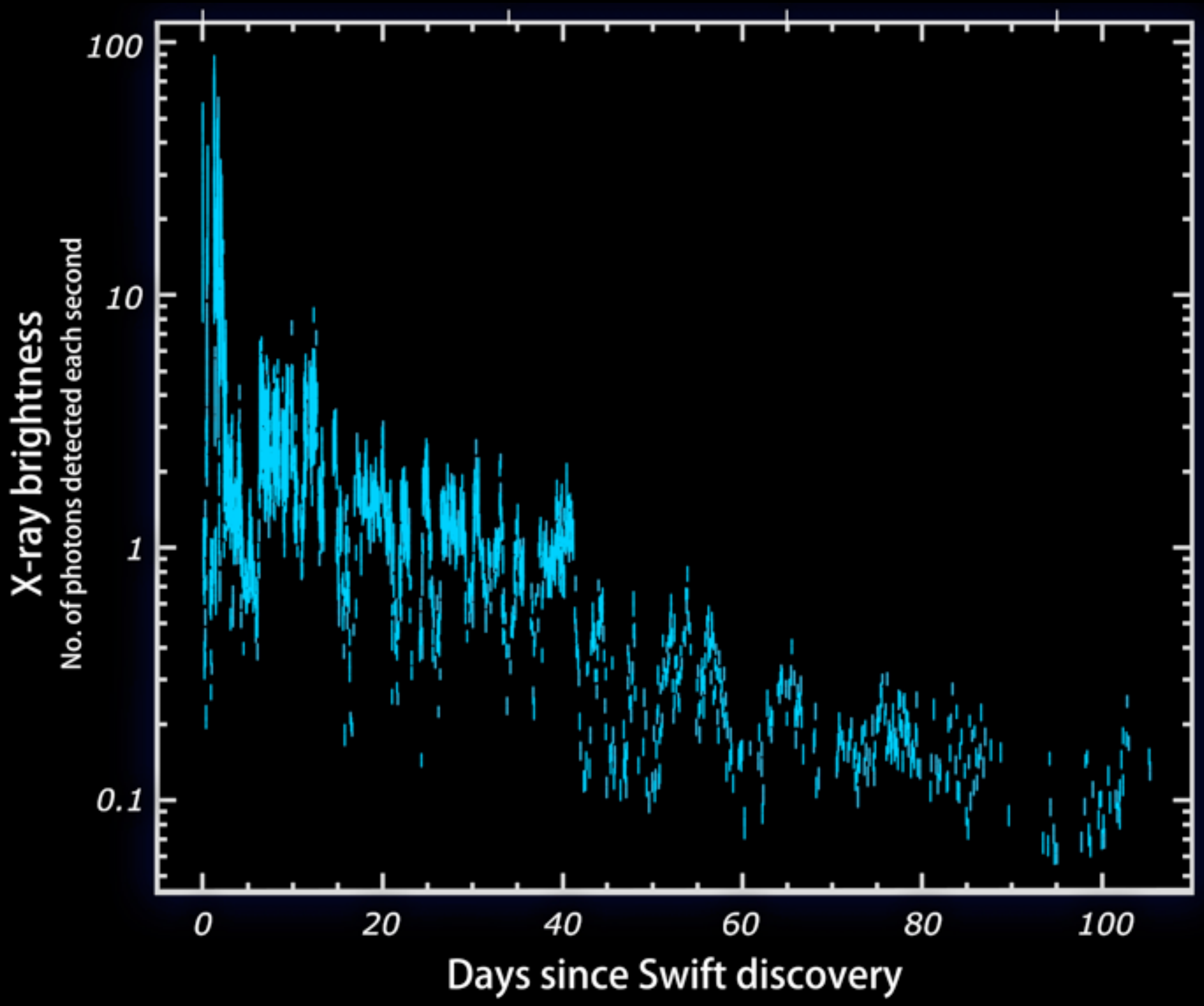
TDE Missing Energy Problem

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



4 Jetted TDEs detected so far

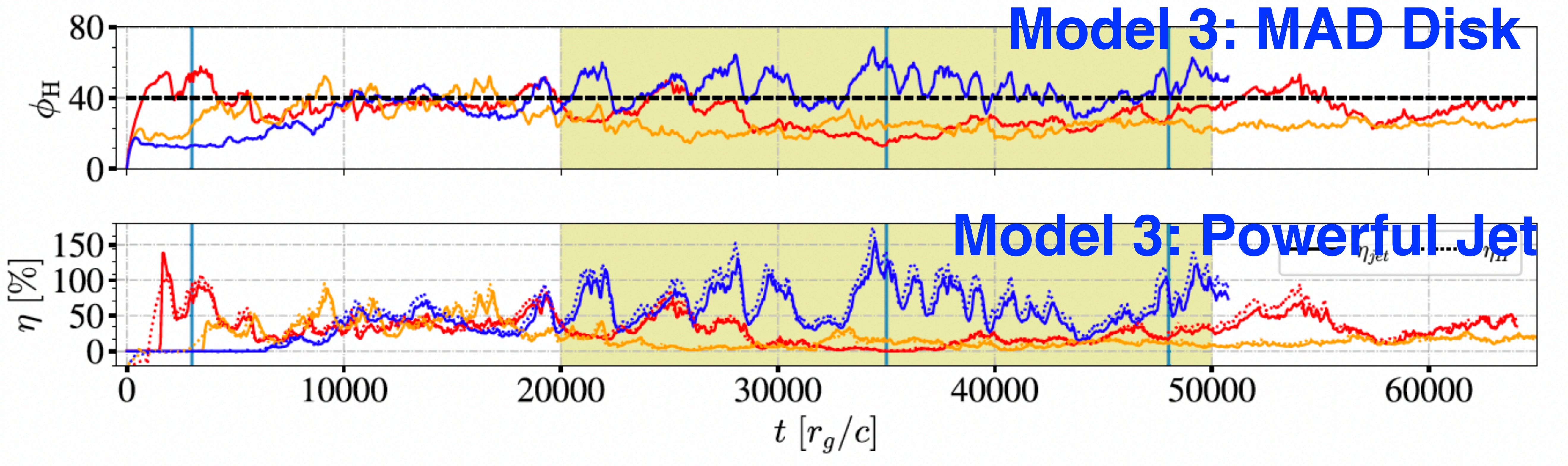
Swift J 1644: Non-thermal $L_{x,\,iso} \sim 10^{47\text{-}48}$ erg/s



Burrows et al 2011, Bloom et al 2011, Levan et al 2011, Zauderer et al 2011

Critical Gas Angular Momentum Needed to Produce Powerful Jets

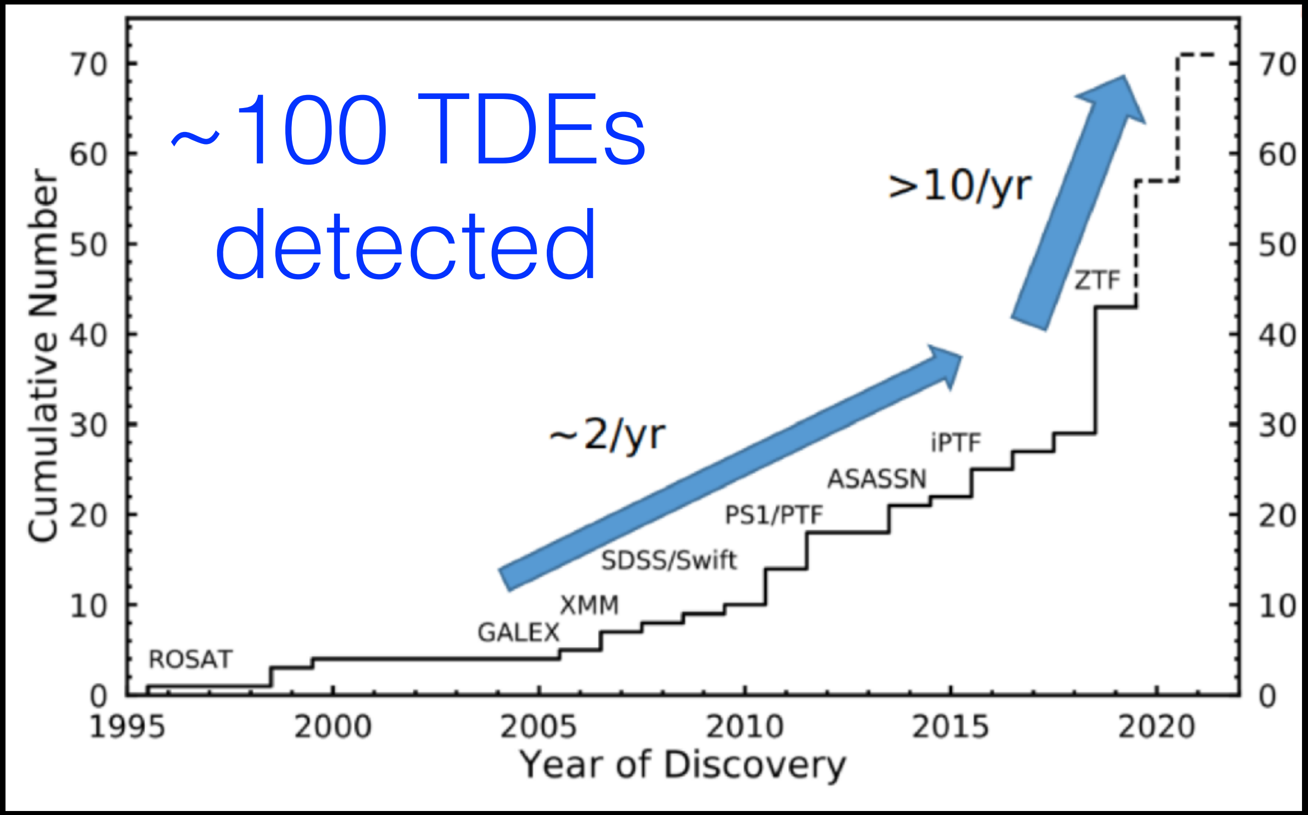
GRMHD Model 1: No angular momentum (Bondi)
GRMHD Model 2: Angular momentum = Keplerian orbit at 10 R_g
GRMHD Model 3: Angular momentum = Keplerian orbit at 50 R_g


Model 3: MAD Disk

Model 3: Powerful Jet

Kwan, **LD**, Tchekhovskoy 2023

Detection of TDEs in Transient surveys



Einstein Probe

WFST

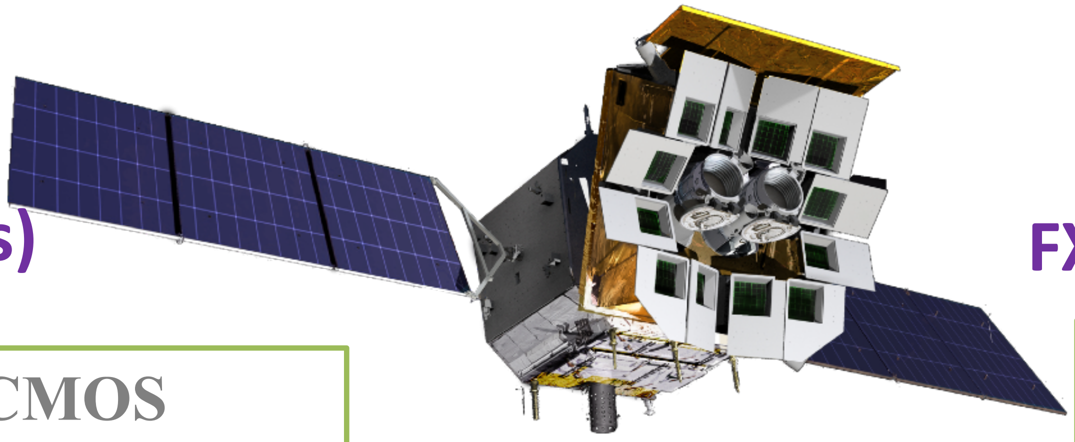
ZTF

eROSITA

Vera Rubin Observatory

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 cm^2 @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 300cm^2 @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)

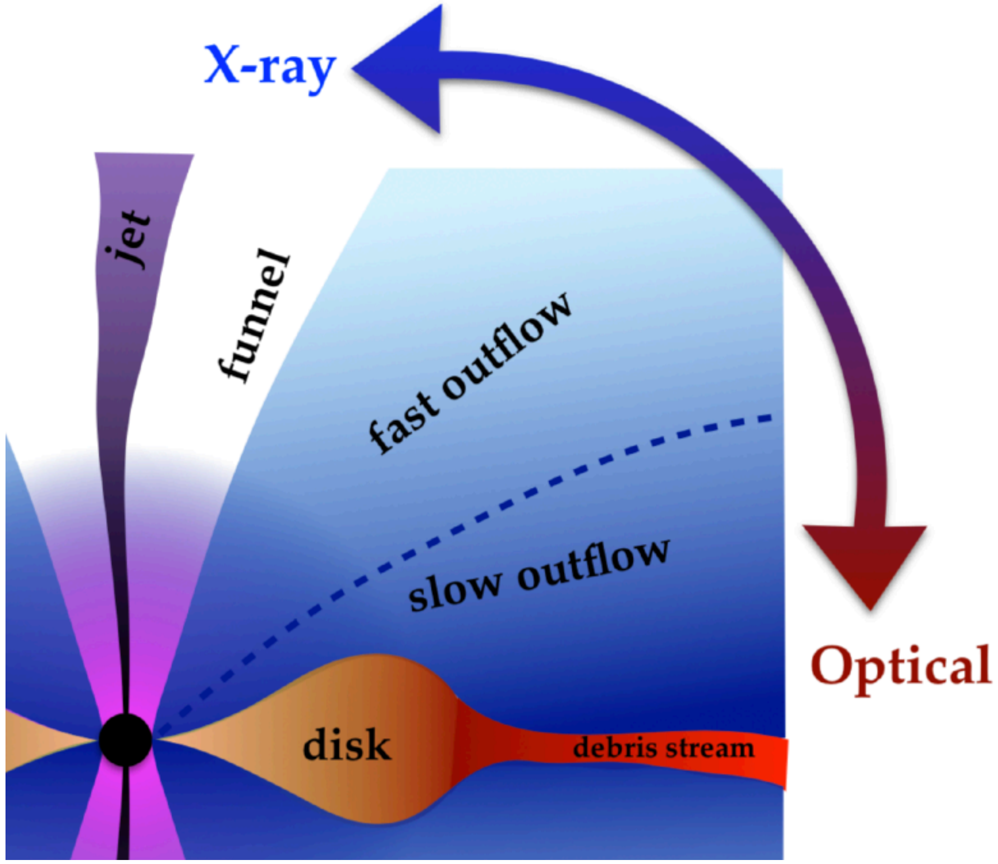
Takeaways

TDEs allow us to constrain MBH demographics and detect IMBHs.

TDEs can be used to study extreme BH accretion and outflow physics.

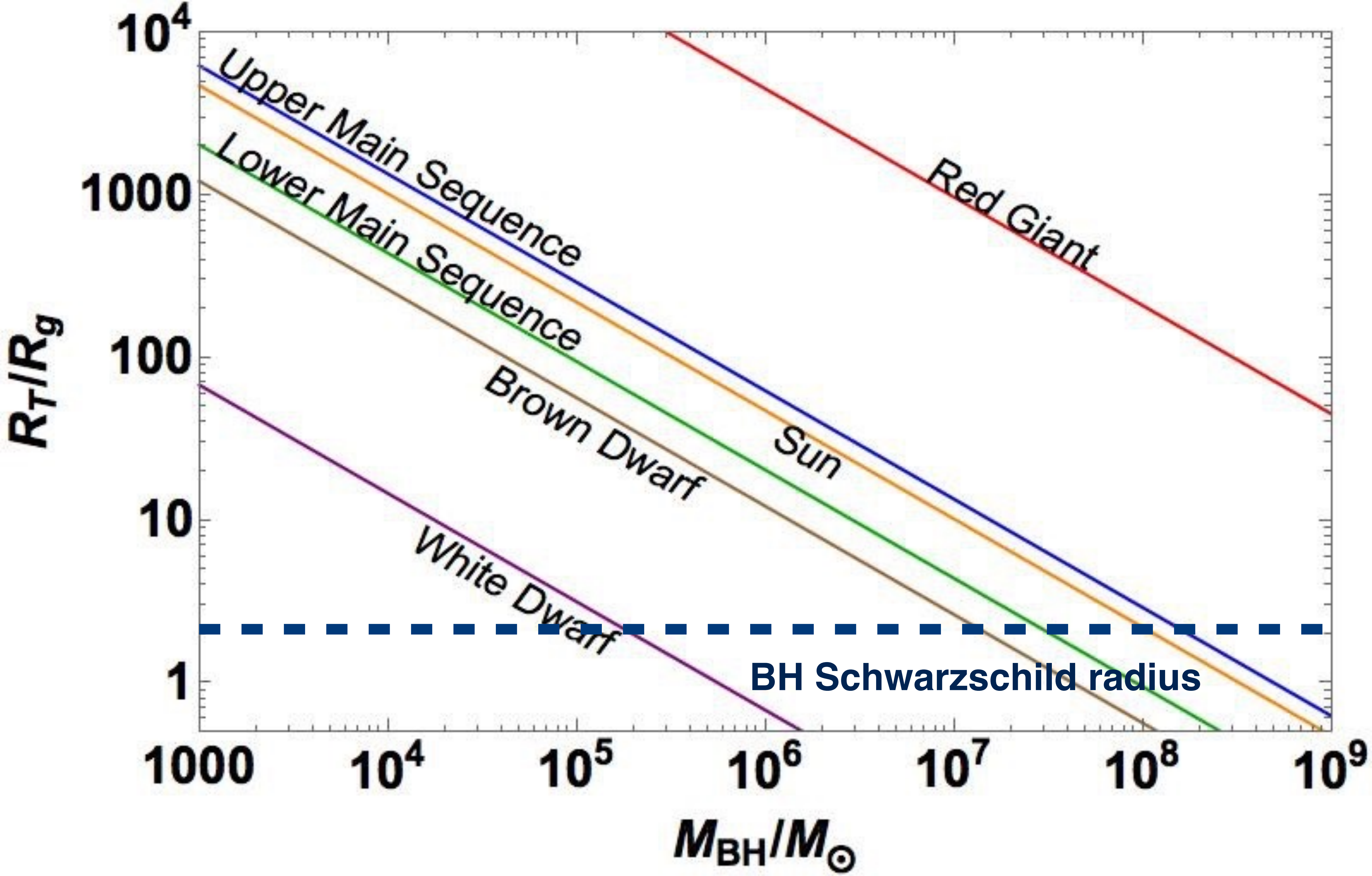
A dynamical unification model involving the reprocessed X-ray emissions using super-Eddington accretion flow can be used to explain the diversity and evolution of TDEs.

Launching powerful jets requires a minimal specific angular momentum of the gas/star.



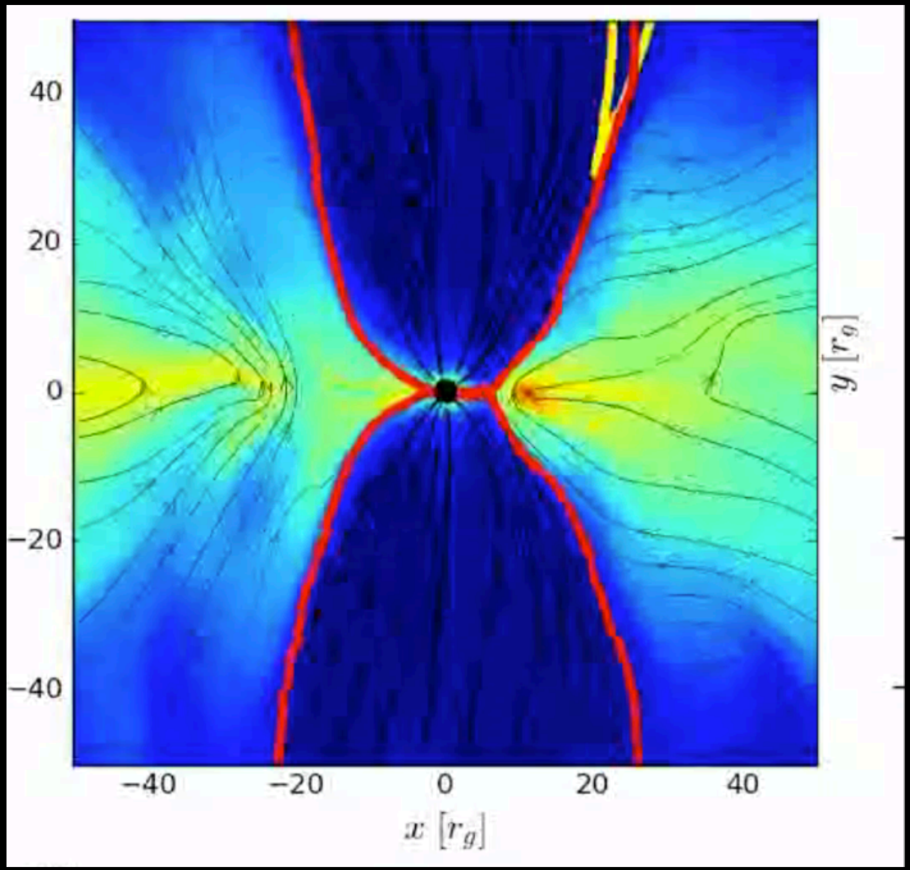
Jane Dai: lixindai@hku.hk

$$R_T \approx R_\star \, (M_{BH} / M_\star)^{1/3} \rightarrow R_T / R_g \propto M_{BH}^{-2/3} \, \rho_\star^{-1/3}$$



TDEs are ideal for probing the low-mass end of MBHs!

Simulation of super-Eddington disks



- Radiation evolved simultaneously with gas
- M1 approximation for radiation
- Radiative transfer physics included:

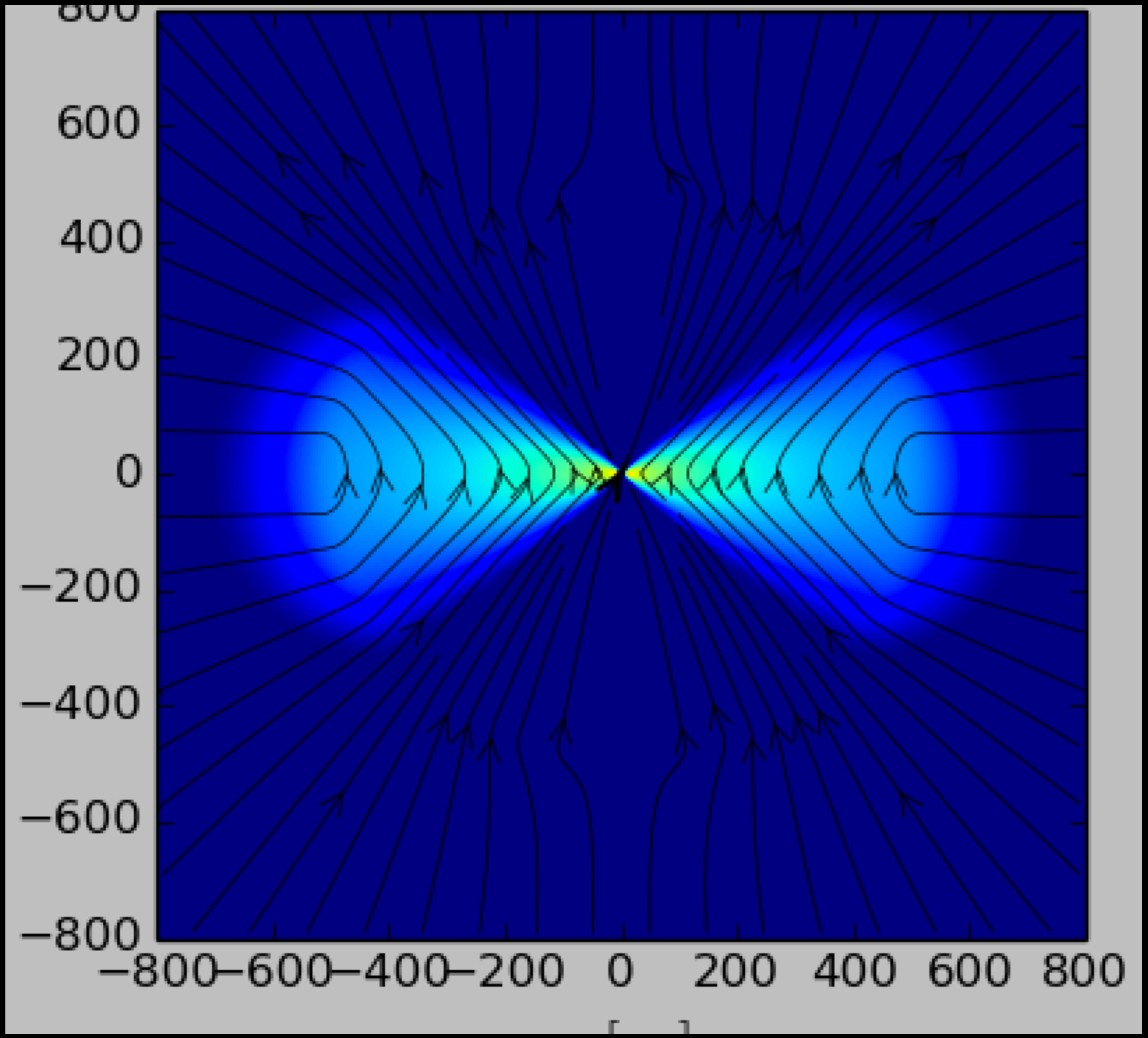
— electron scattering

— absorption and emission

(Rosseland mean opacities)

— thermal Comptonization

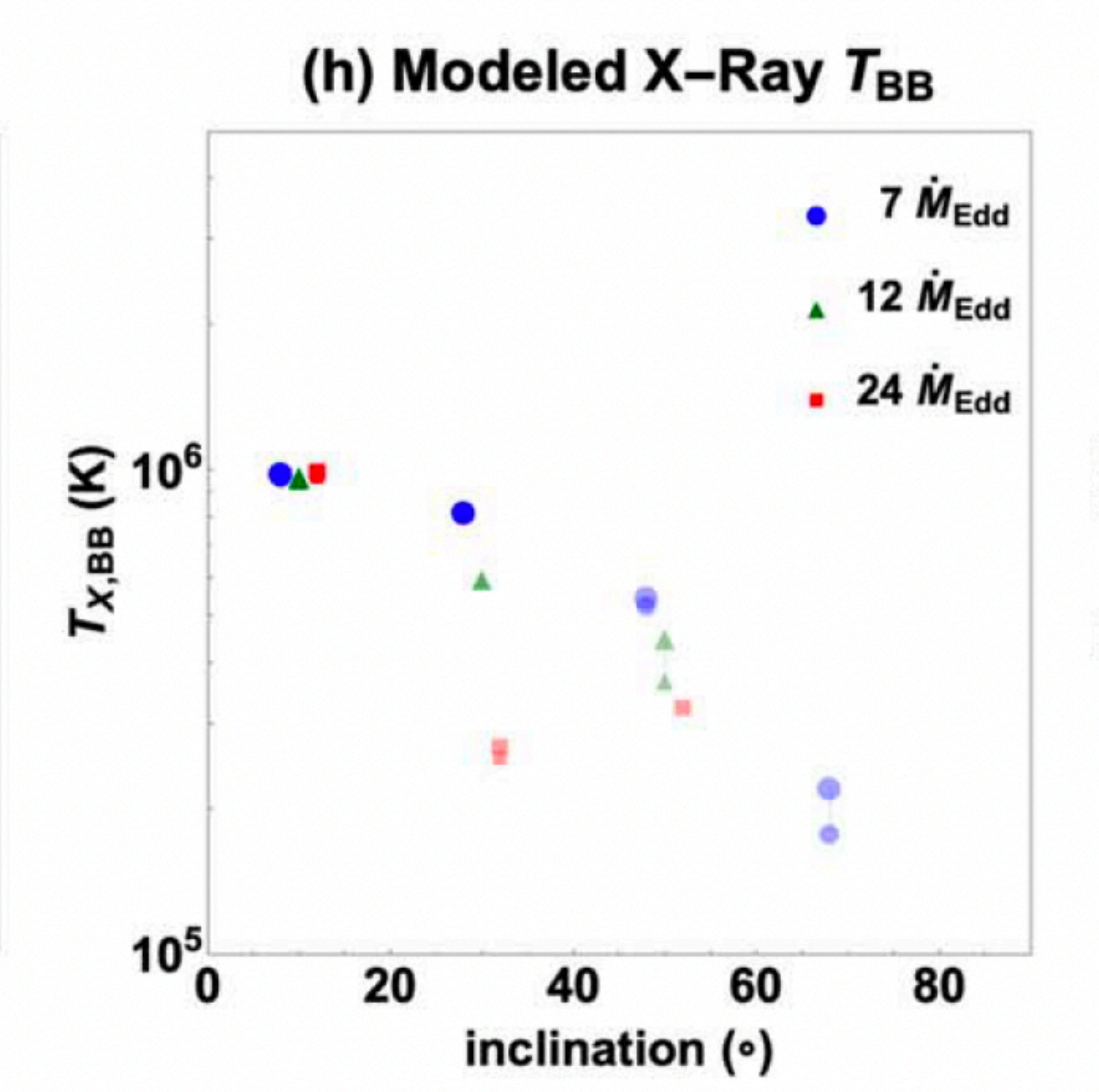
Simulation Set-Up



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

X-ray TDEs

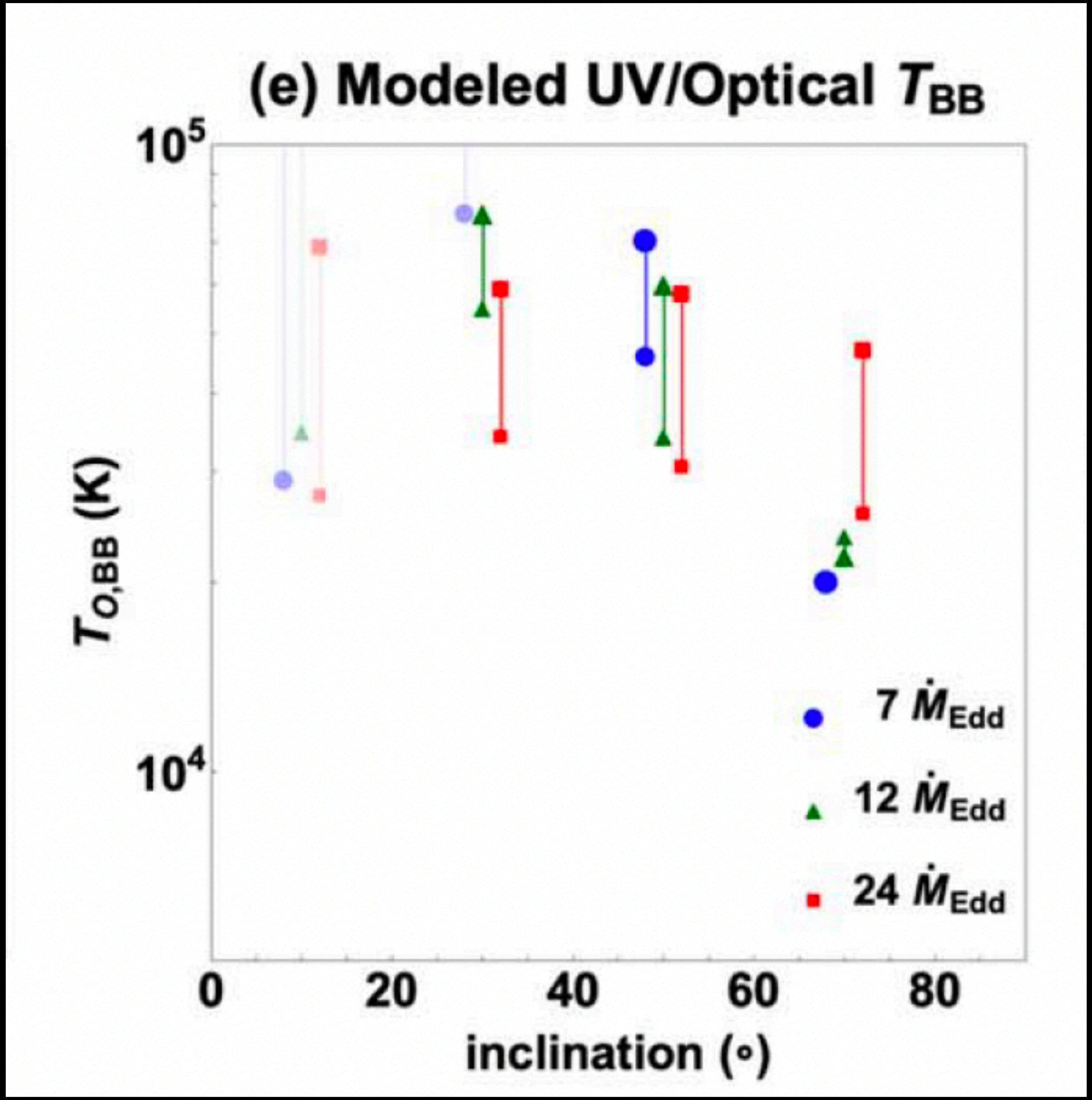


$T_{BB} \sim 10^{5\text{-}6}$ K
$L_{BB} \sim$ 0.1-10 L_{Edd}

Consistent with TDEs detected by ROSAT, eROSITA, etc.

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

Optical TDEs



T_{BB} ~ 10^4 K (very stable)

L_{BB} ~ 0.01-10 L_{Edd}

Consistent with TDEs detected by ZTF, ASASSN, etc.

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