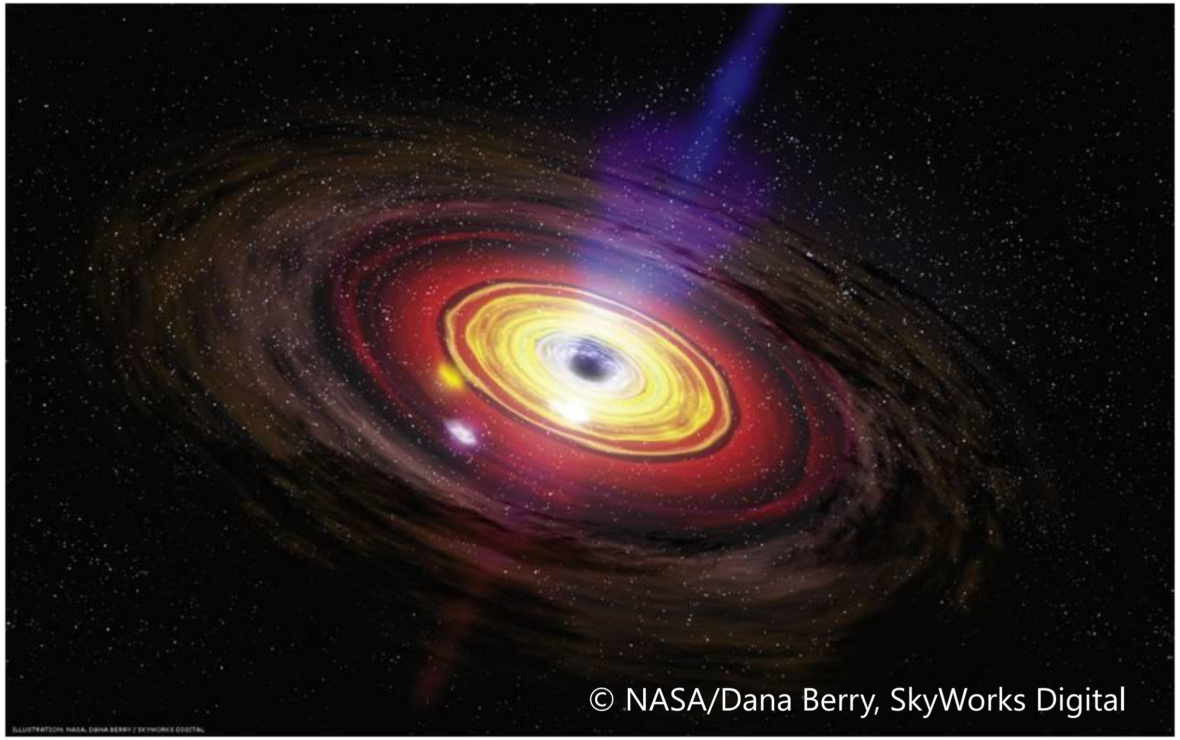
Observational Signatures for Compact Object Mergers in Active Galactic Nuclei

10/17/2024 @ TDLI



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Contents

Evolution and mergers of compact objects in AGN disks

- Observational implications

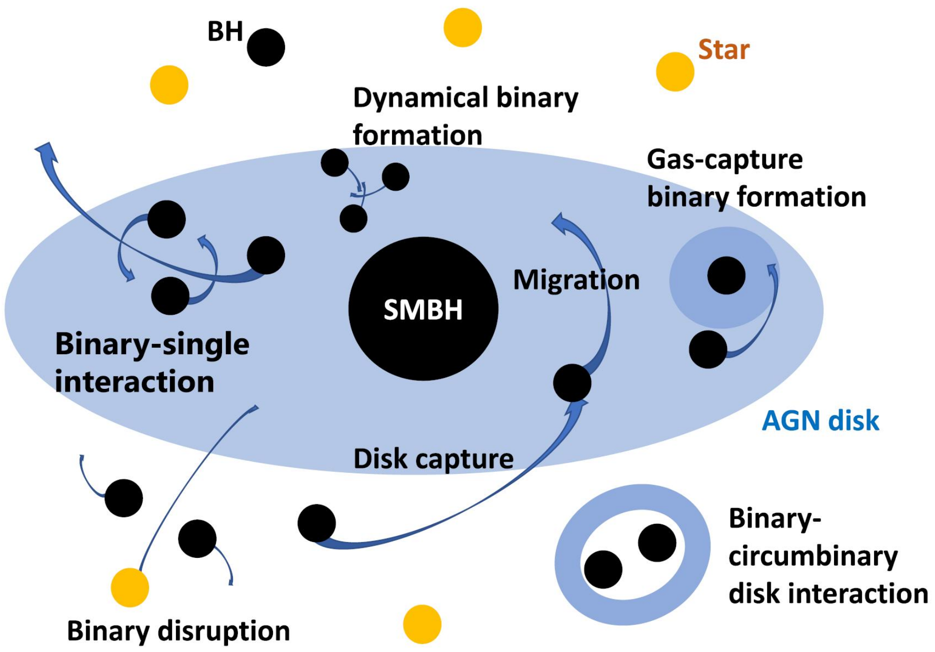
- AGN disk structures

- Properties of mergers

- Electromagnetic counterparts

Compact Objects in an AGN Disk

HT+20



GWs: LIGO/Virgo/KAGRA, LISA/TianQin/Taiji, GR tests, Cosmology

EM observations: GRBs, QPEs, TDEs, SNe, Neutrinos, X-ray binaries, FRBs

AGNs: Accretion processes, AGNs variability, Metallicity evolution

Evolution of COs and GWs

Ostriker 83, Syer+91, Vokrouhlicky+93, 98, Rauch 95, Subr+99, Karas+01, Baruteau+11, Bartos+17ab, Stone+17, McKernan+12, 14, 18, 19, 20, 21, 23, Yang+19ab, 20, HT+20ab, 21ab, Samsing+22, 24, Leigh+18, Secunda+19, 20, 21, Fabj+20, 24, Ford+21, 22, Gayathri+20, 23, Just+12, Kennedy+16, Panamarev+18, Bellovary+16, ArcaSedda+23, Derdzinsky+20,22, Hankla+20, Jermyn+22, Dittman+21, 23, Cantiello+20, Chen K+22, MacLeod+20, Liu+, Li Y-P+21, 22ab, 23, Li J+22, 23, Li G+22, Li G-P+22, Li R+22, 23, 24, Rozner+22,23, Boekholt+23, Generozov+22, Nasim+22, DeLaurentiis+22, Rowan+23ab, Whitehead+23ab, Qian+23, Meiron+17, Inayoshi+17, Bonvin+17, Wong+19, Yu+20, Chen Y-X+22, 23, Vaccaro+23, Calcino+23, Pan+21, Martin+23, Rom+23, Bhaskar+23, Grishin+23, Tamanini+20, Toubiana+21, Sberna+22, Han, Yang, HT+24, Fan+24, Dodici+24, ..

disk structures

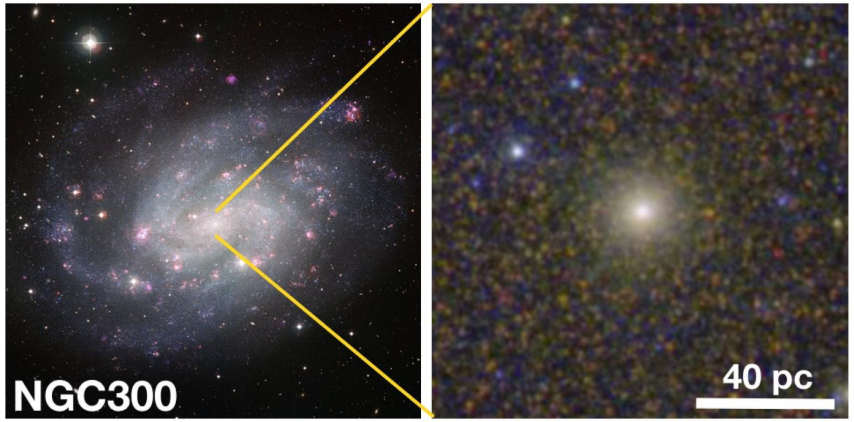
Collin+99,08, Thompson+05, Wang+10,11, Dittmann+20, Gilbaum+21, HT+22, Chen K+23, Chen Y+24, Gangardt+24, Zhou+24, Epstein-Martin+24

electromagnetic/neutrinos

Cheng+99, McKernan+19, Graham+20, 23, Zhu+21abc, 23, Perna+21ab, Yang+21, Moranchel-Basurto+21, Grishin+21, Kimura+21, Wang+21ab, 23, Yuan+21, Ray+22, Ren+22, Zhou+22, Lazzati+23, HT+23abc, 24, Rodriguez-Ramirez+23, 24, Xin+23, Franchini+23, Chan+20ab, 21, Nayakshin+04, Dai+10, Xian+21, Sukova+21, Linial+23, Frenchini+23, Zhou+24ab, Chen K+24, Zhao+24, Ma+24ab, Zhang+24, Liu+24, Huang+24, Venerosi+23, 24, Kathirgamaraju+23, Cabrera+24, ..

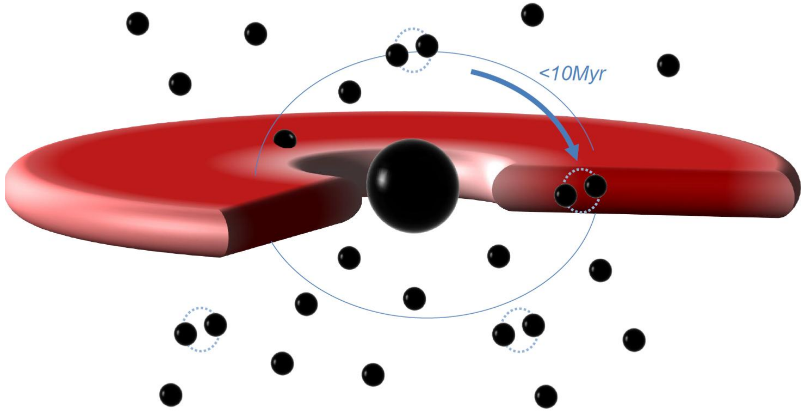
NSCs and AGN Disks

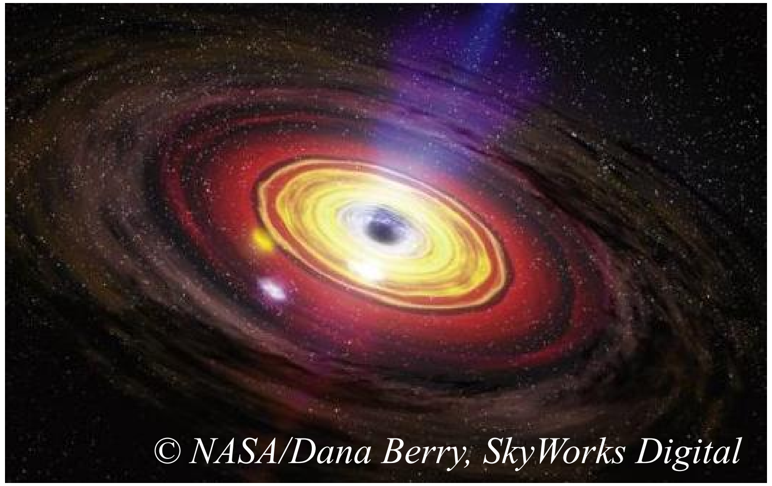
Nuclear Star Cluster



Neumayer et al. 2020

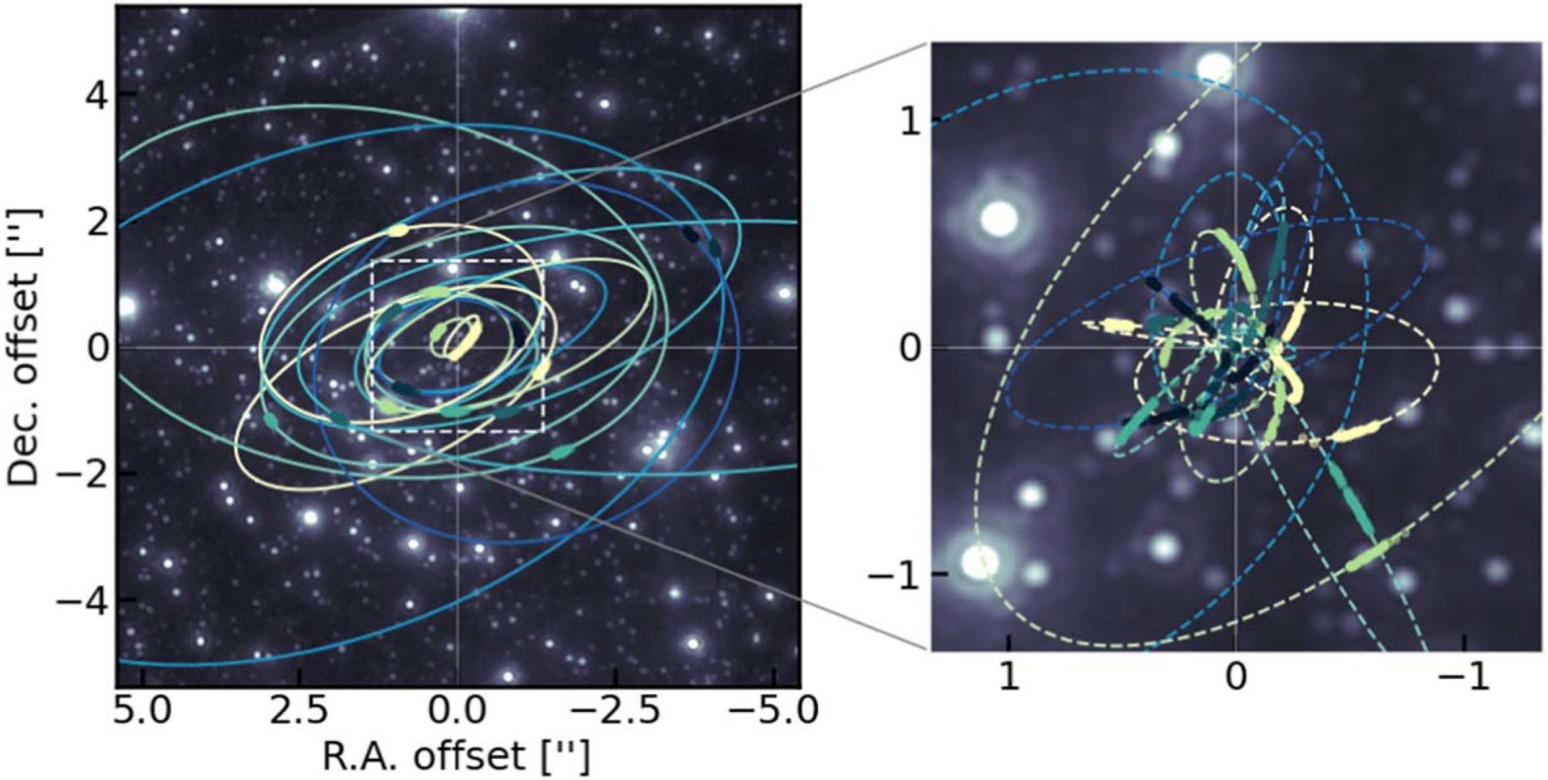
+ =





Active Galactic Nuclei

Observations for stars in the Galactic center



von Fellenberg et al. (2022)

- $\lesssim$ 0.05 pc: **S-stars**

-> capture by an AGN disk

(Fan et al. 2024; see also Generozov & Madigan 2020, Trani et al. 2019, Levin 2007)

- 0.05-0.5 pc: **OB/WR stars in a clockwise disk**

-> in-situ formed stars (e.g. Levin 2022)

Observations for stars/COs in GCs

- $\lesssim$ 0.05 pc: **S-stars**

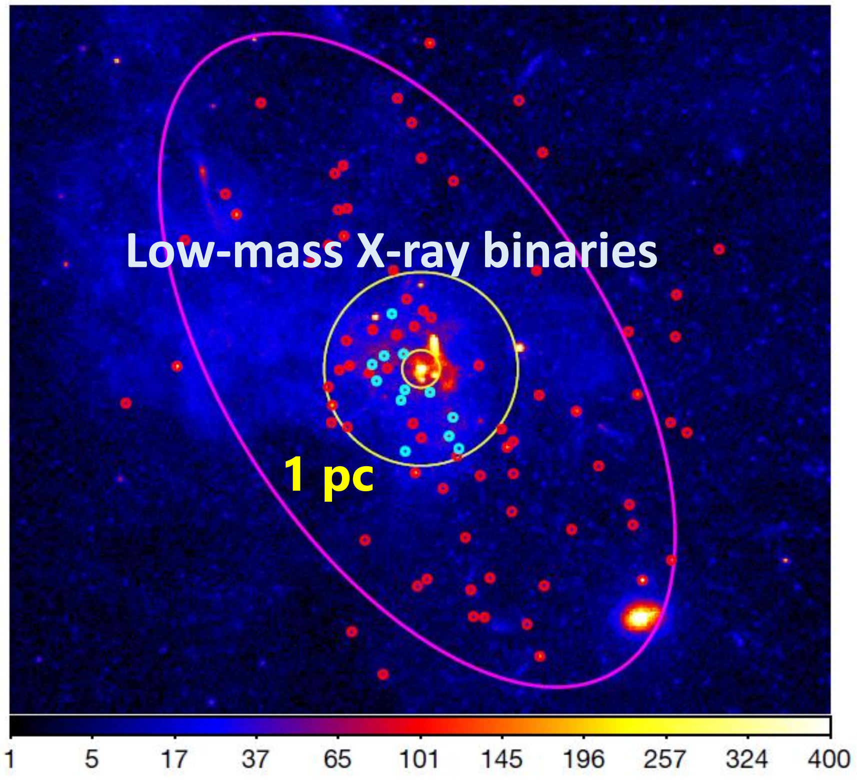
-> capture by an AGN disk
(Fan et al. 2024; see also Generozov & Madigan 2020, Trani et al. 2019, Levin 2007)

- 0.05-0.5 pc: **OB/WR stars in a clockwise disk**

-> in-situ formed stars (e.g. Levin 2022)

- $\lesssim$ 1 pc: **Low-mass X-ray binaries**

-> binary formation in AGN disks
(HT et al. 2020; see also Generozov et al. 2018)



Hailey+18

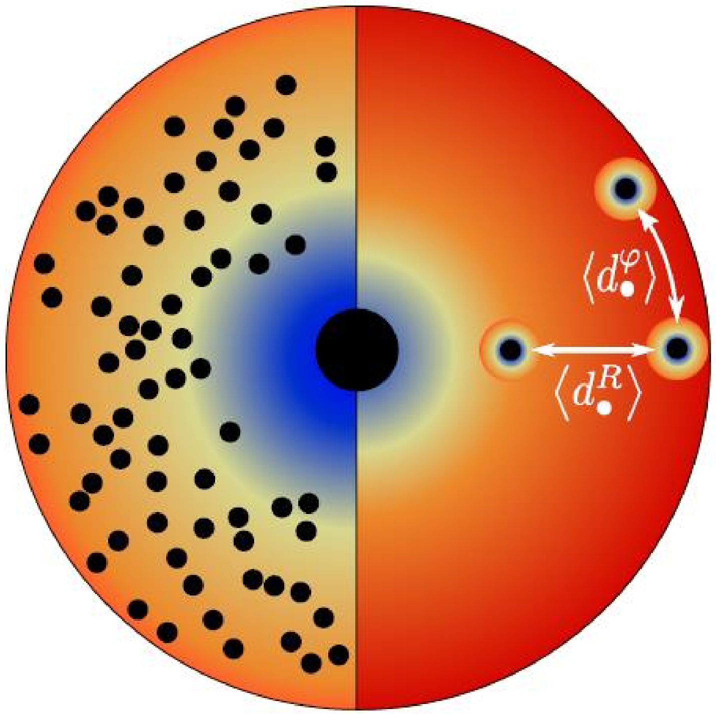
AGN disk models considering outer regions

- **Some heating source**
(Sirko & Goodman 2003)

- **Starburst model**
(Thompson, Quataert & Murray 2005)

- **BH heating model**
(Gilbaum & Stone 2021, see also Dittmann & Miller 2020)

- **Starburst + BH heating model**
(Epstein-Martin, HT, Haiman & Perna, 2024, arXiv: 2405.09380)



Gilbaum & Stone 2021

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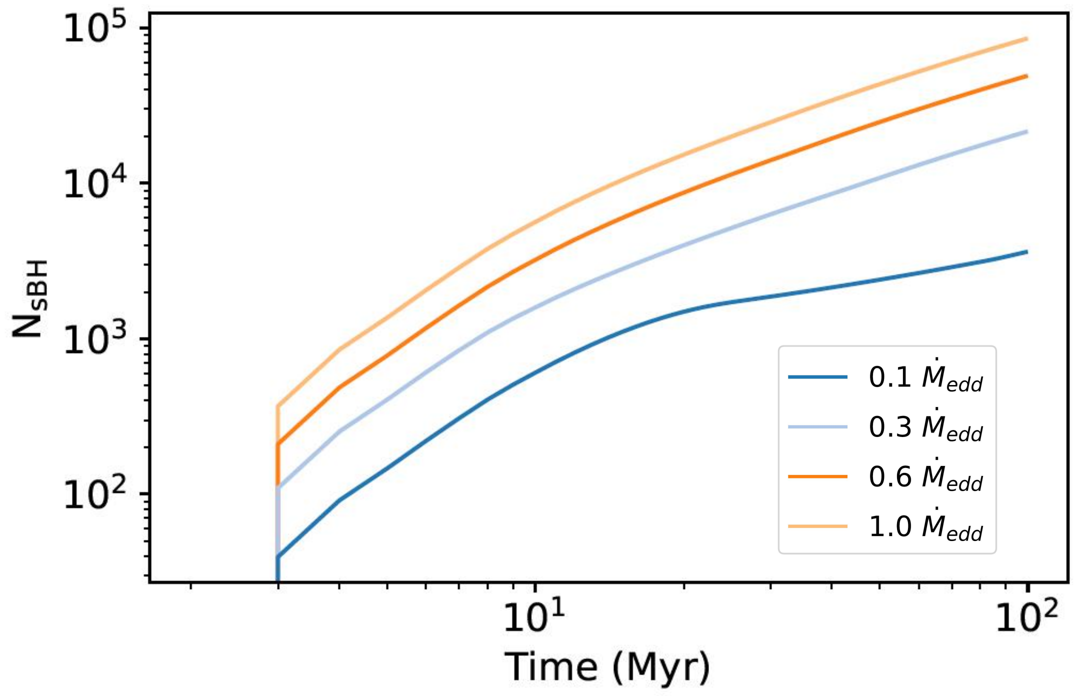
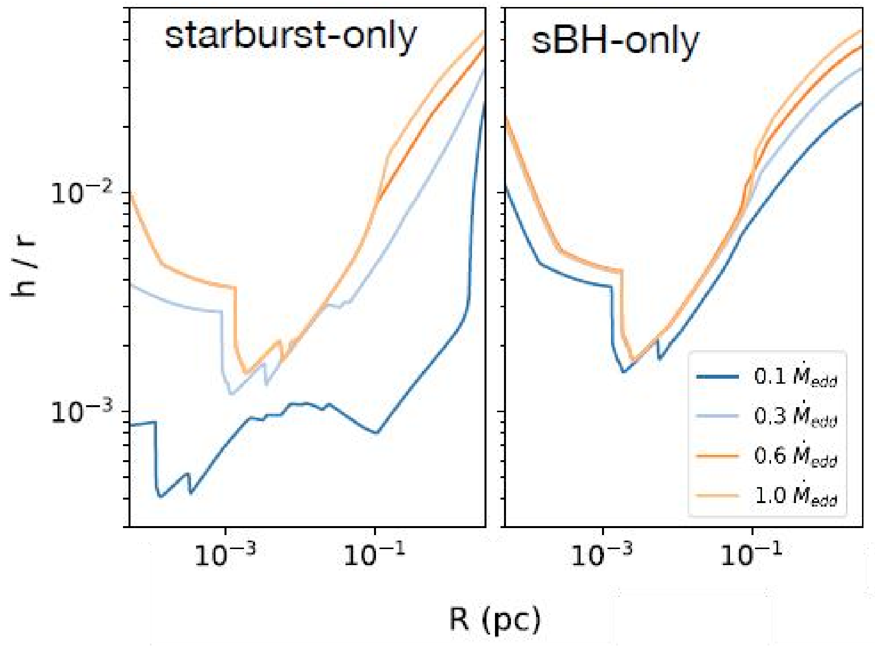
Fiducial: $M_{\rm SMBH} = 4 \times 10^6\,M_{\rm sun}$, $\alpha = 0.1$

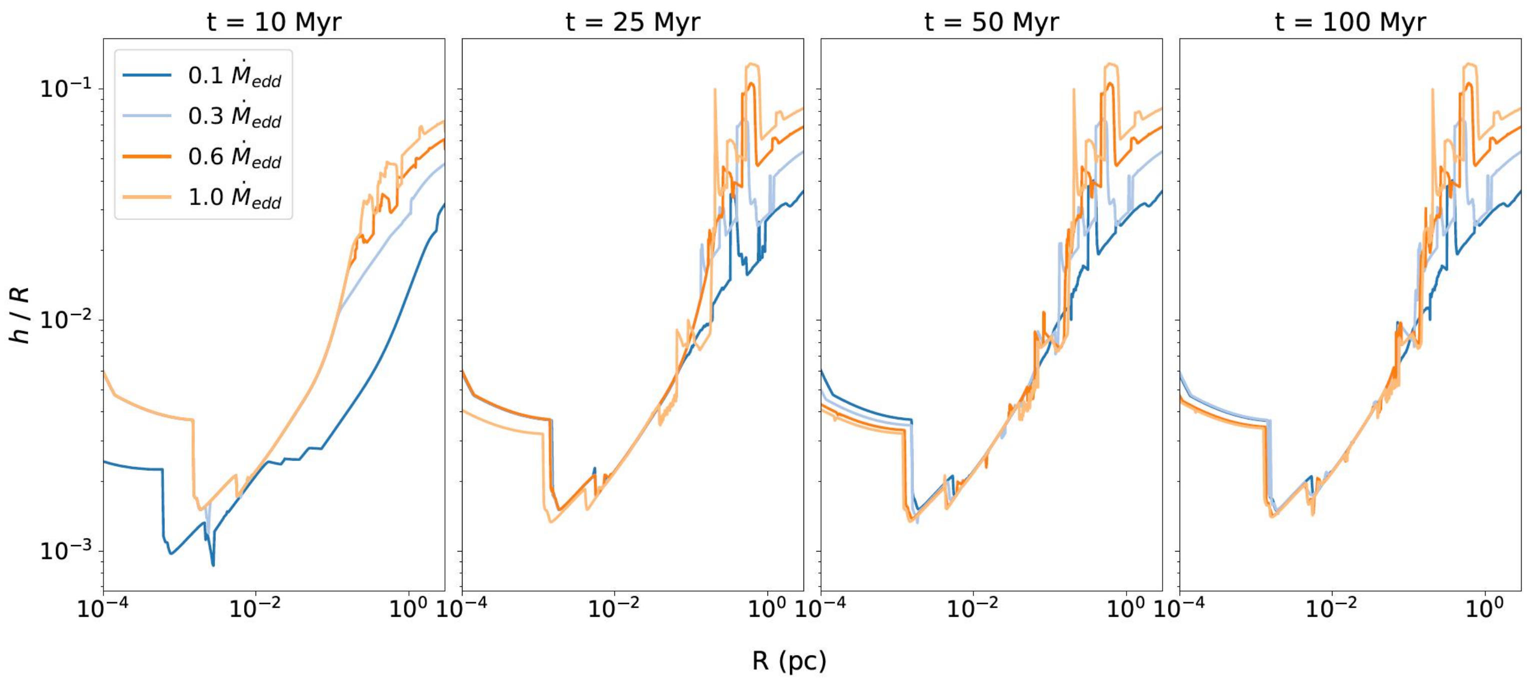


AGN disk structure

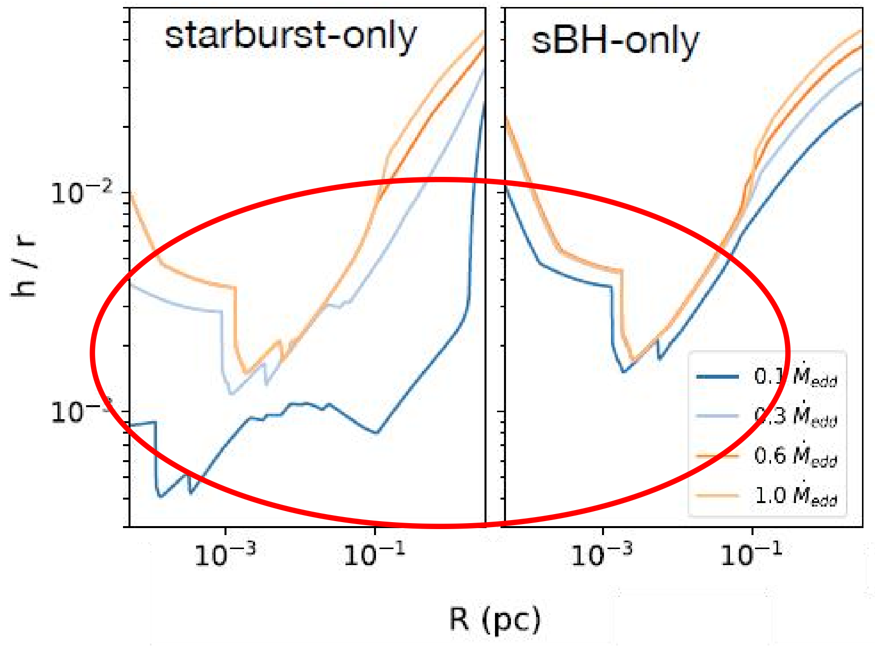


Fiducial: $M_{\rm SMBH}$= $4 \times 10^6\,\mathrm{M_{sun}}$, α =0.1

Starburst + BH model



AGN disk structure

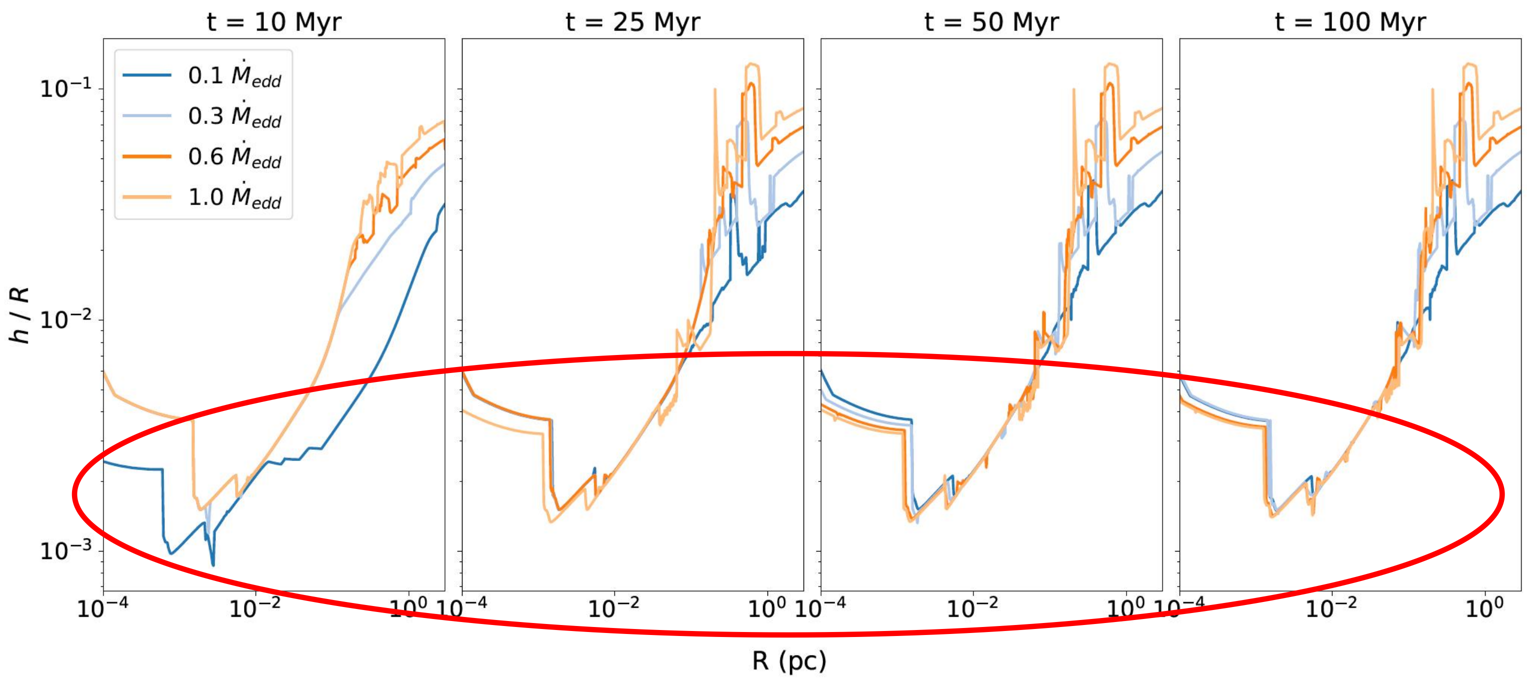


Gap open condition:

$$\frac{h}{r} \lesssim 0.008\left(\frac{m_{\rm BH}/M_{\rm SMBH}}{10^{-5}}\right)^{2/5}\left(\frac{\alpha}{0.1}\right)^{1/5}$$

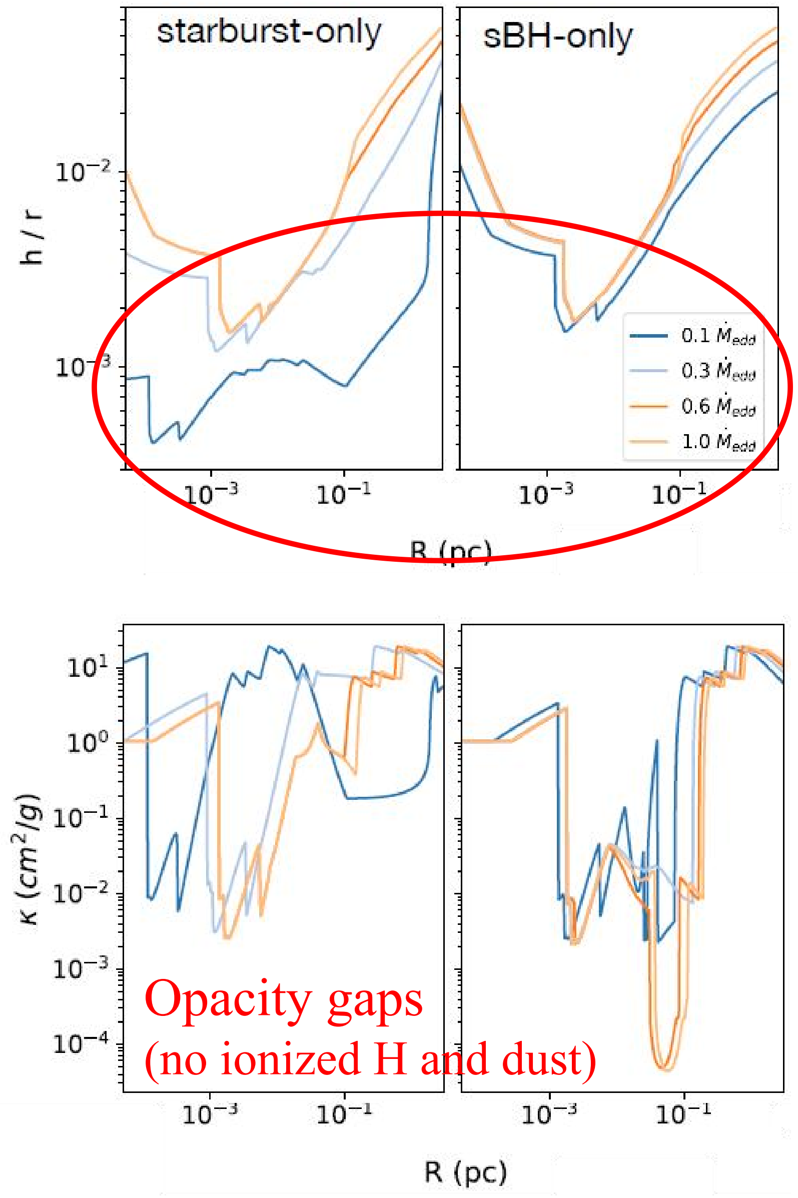
Fung et al. (2014)
Kanagawa et al. (2015)

satisfied independent of $M_{\rm SMBH}$ and α (Gangardt et al. 2024)



Gaps open at ~$10^{3\text{-}5}$ R_g

Gap formation



$\text{low } \kappa \longrightarrow \text{low } \tau$

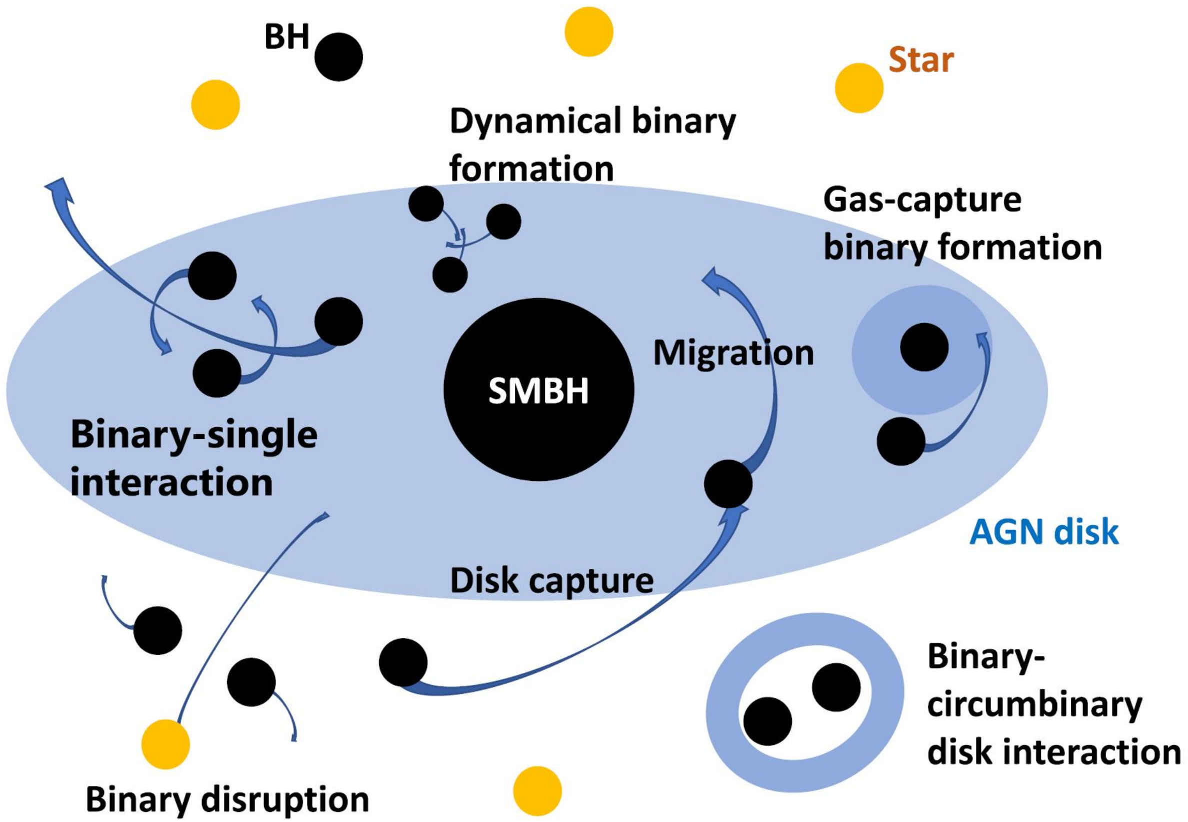
$\longrightarrow \text{low } p_{\text{rad}} \longrightarrow \text{high } p_{\text{gas}}$

$\longrightarrow \text{high } \rho \longrightarrow \text{low } h$

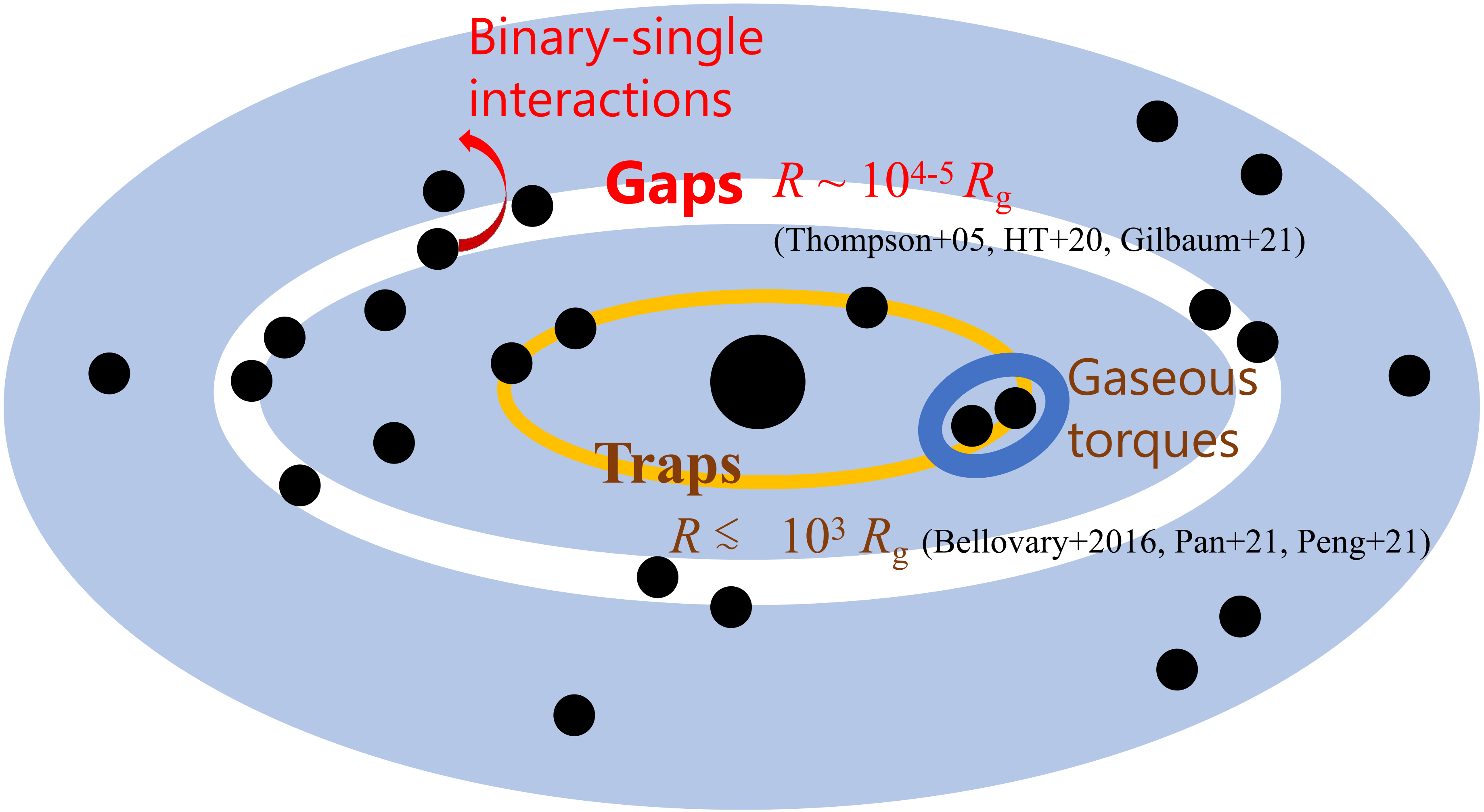
In Sirko & Goodman model,
there is lower limit in $p_{\rm rad}$, $c_{\rm s}$, and h..

Compact object Evolution in an AGN disk

1D N-body simulation + semi-analytical model

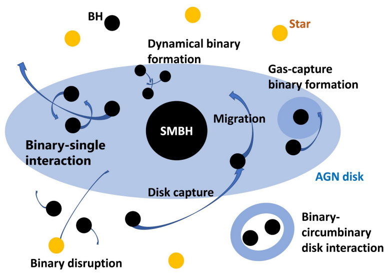


Hardening processes in traps/gaps

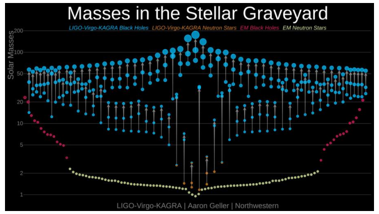


Properties of mergers at gaps

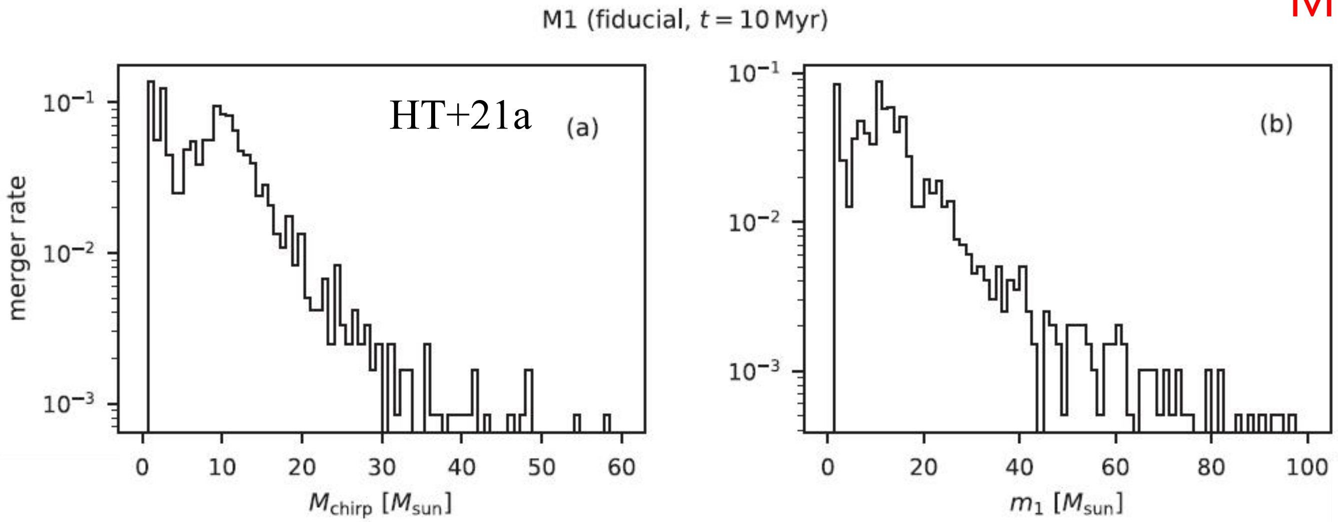
AGN channel

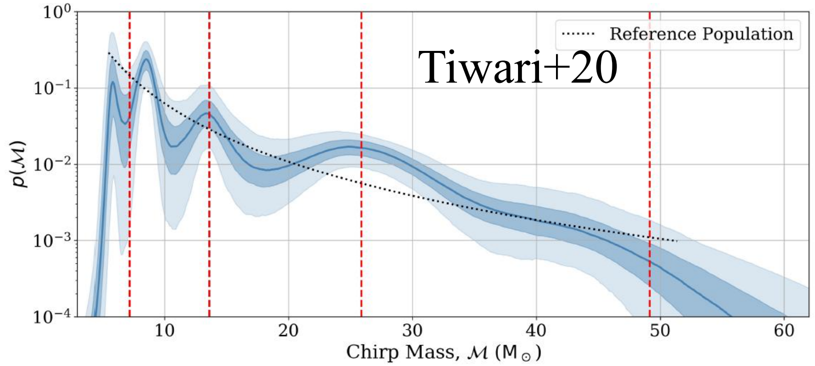


LIGO/Virgo/KAGRA O1-O3b



Merging mass





Spin -> isotropic (HT+20b)

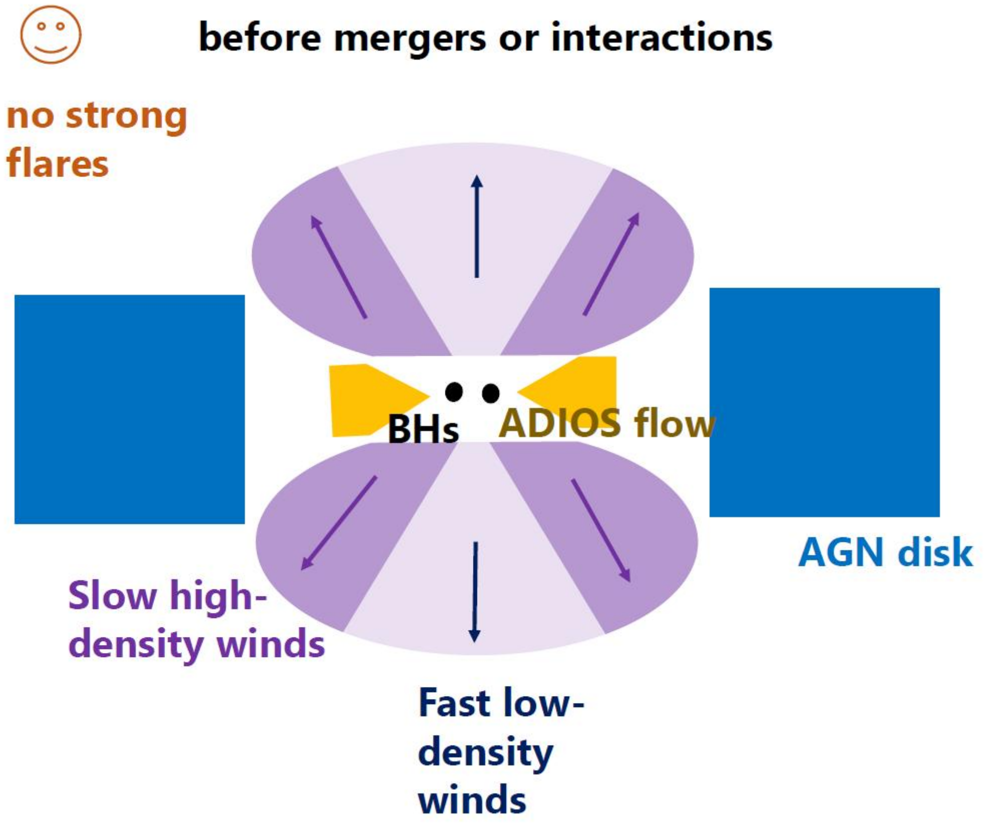
~ nearly isotropic

Rate -> ~0.02-60 $Gpc^{-3}yr^{-1}$ (HT+20a)

17-45 $Gpc^{-3}yr^{-1}$ (LIGO+21)

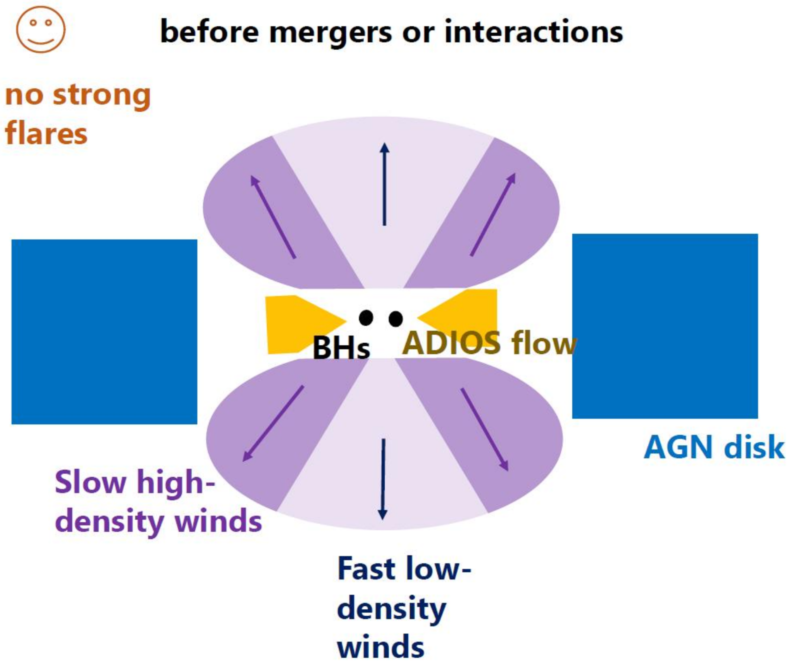
Electromagnetic counterparts

EM from merging BHs in AGNs

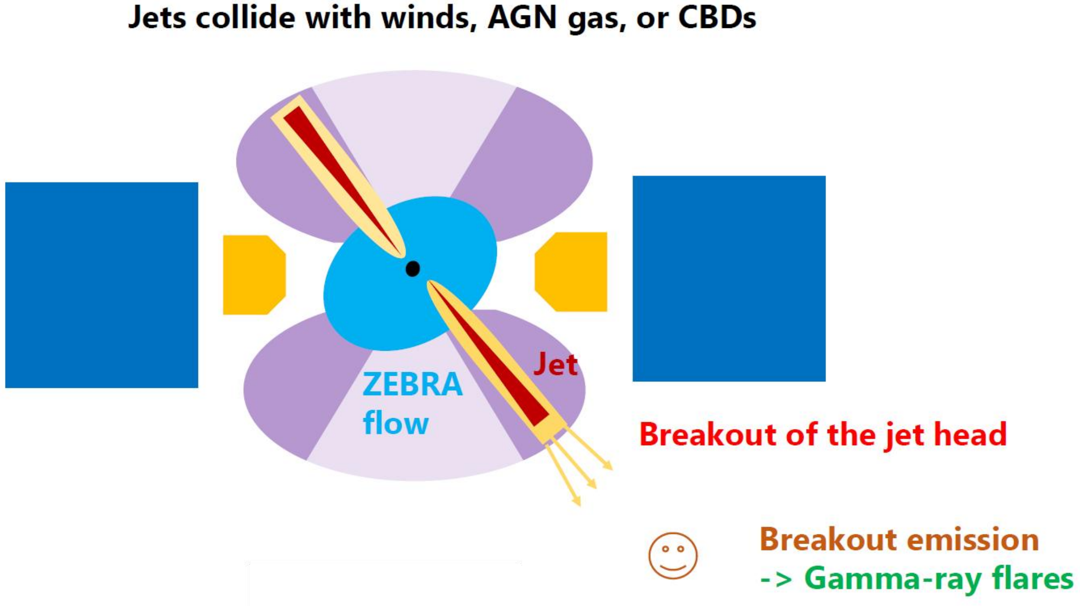


Similar to ultraluminous X-ray sources
(e.g., Poutanen et al. 2007)

EM from merging BHs in AGNs



Due to kicks at mergers or interactions, **shocks form in the CBD and jets are launched**



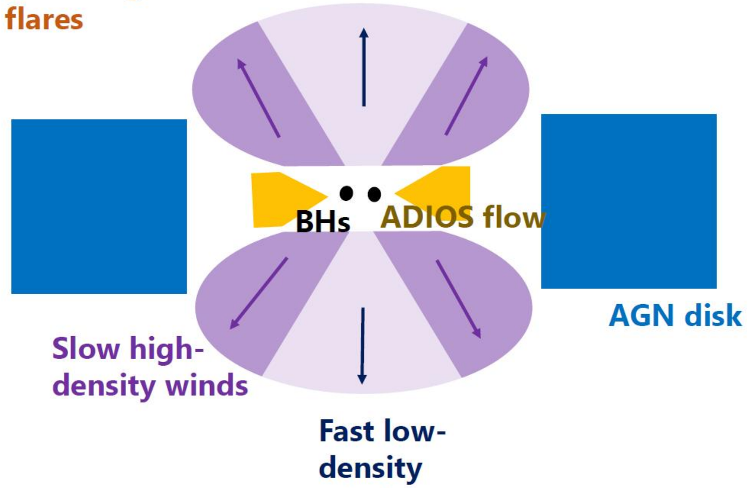
Similar to ultraluminous X-ray sources (e.g., Poutanen et al. 2007)

Similar to tidal disruption events (e.g., Coughlin & Begelman 2014, Begelman & Volonteri 2017)

EM from merging BHs in AGNs

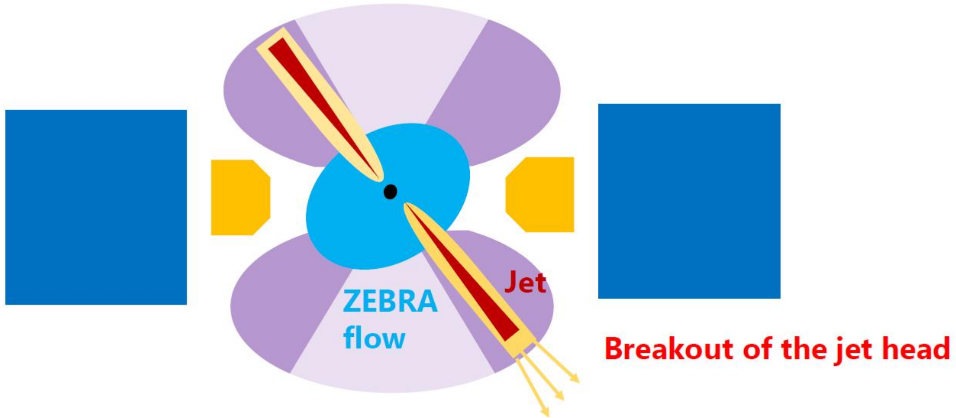
before mergers or interactions

no strong flares



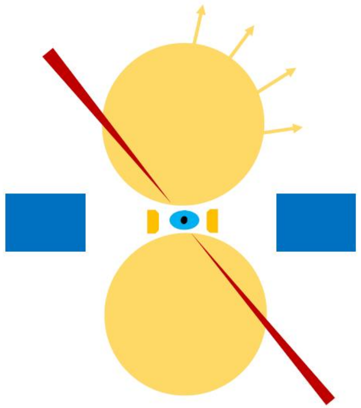
Due to kicks at mergers or interactions,
shocks form in the CBD and jets are launched

Jets collide with winds, AGN gas, or CBDs



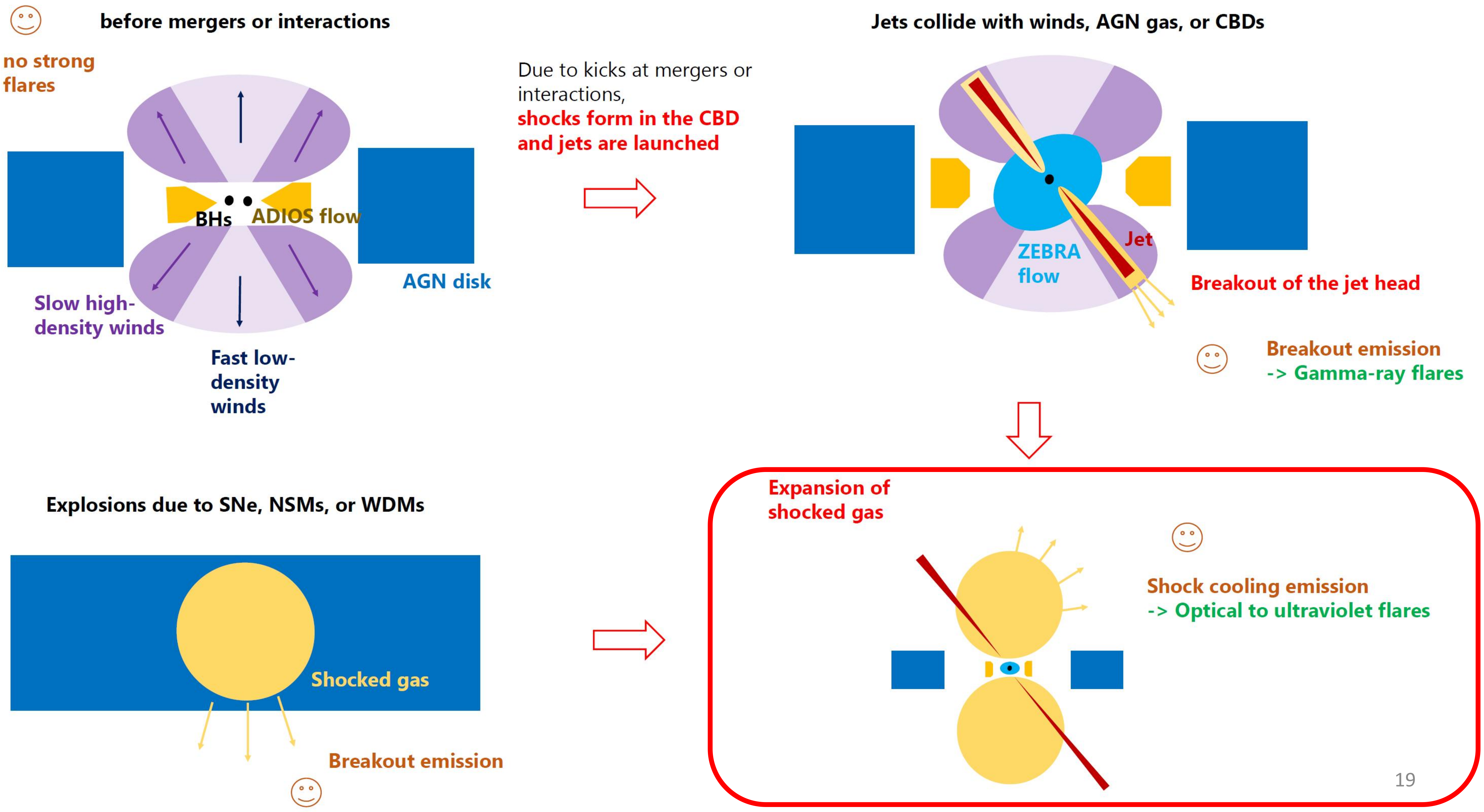
Breakout emission
-> Gamma-ray flares

Expansion of shocked gas



Shock cooling emission
-> Optical to ultraviolet flares

EM from merging BHs in AGNs



Properties of Shock cooling emission

HT+24 in prep

$$L_{\rm SC} = 2\pi c v_{\rm ej}^2 R_{\rm BO}/\kappa$$

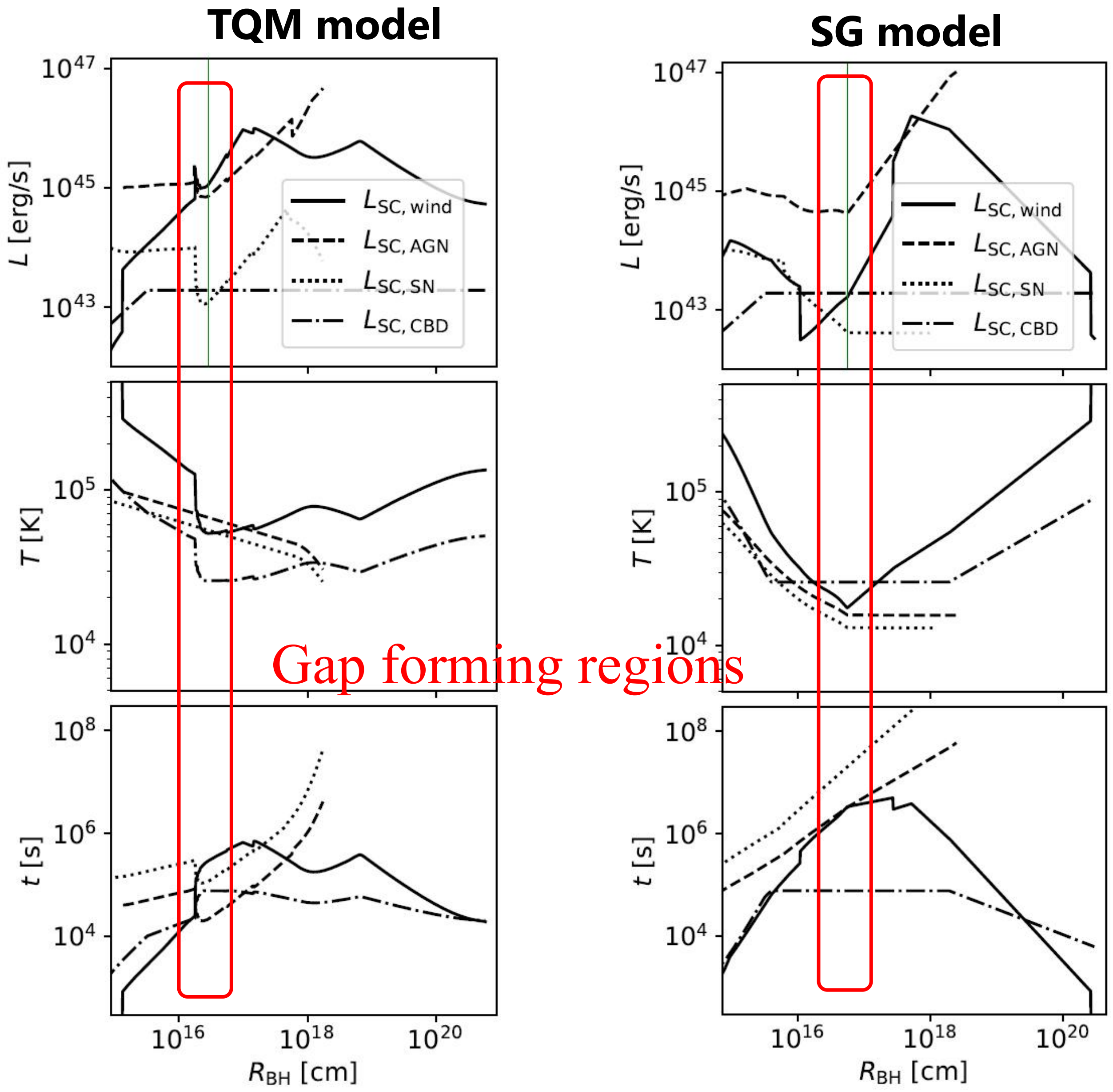
$$T_{\rm SC} = (2\pi c^2 R_{\rm BO}/m_{\rm BO}\kappa^2 a)^{1/4}$$

$$t_{\rm diff} = (\kappa m_{\rm BO}/4\pi c v_{\rm ej})^{1/2}$$

Input parameters:

$M_{\rm SMBH} = 10^8\ {\rm M_{sun}}$, $\dot{M}_{\rm SMBH} = \dot{M}_{\rm Edd}$,

$m_{\rm BH} = 100\ {\rm M_{sun}}$, $\eta_{\rm j} = 0.5$, $\theta_0 = 0.2$



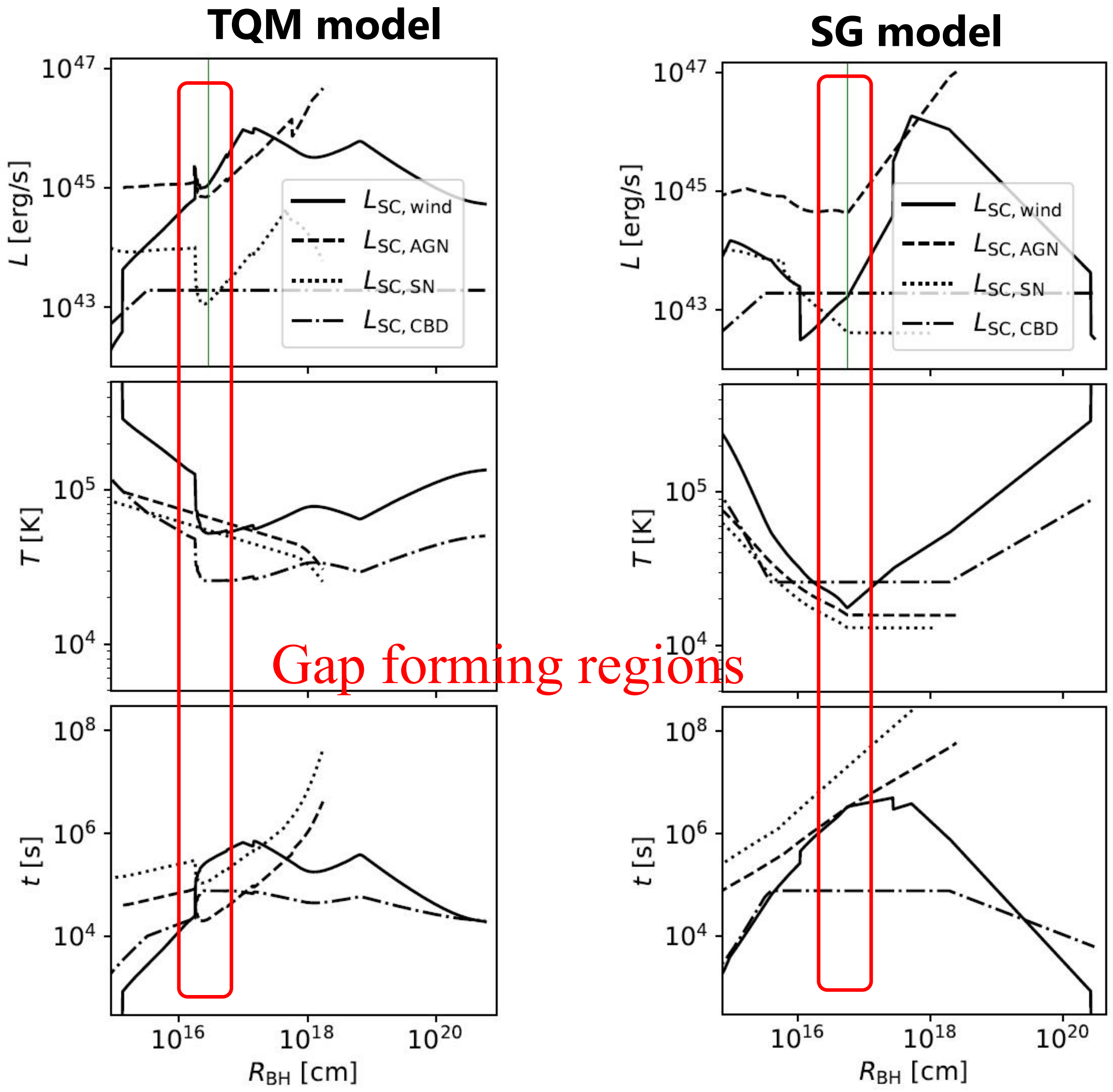
Properties of Shock cooling emission

HT+24 in prep

✓$L_{\rm SC} \sim 10^{43}$ - 10^{45} erg/s

✓Optical-UV

✓$t_{\rm diff} \sim 10^4$ - 10^6 s



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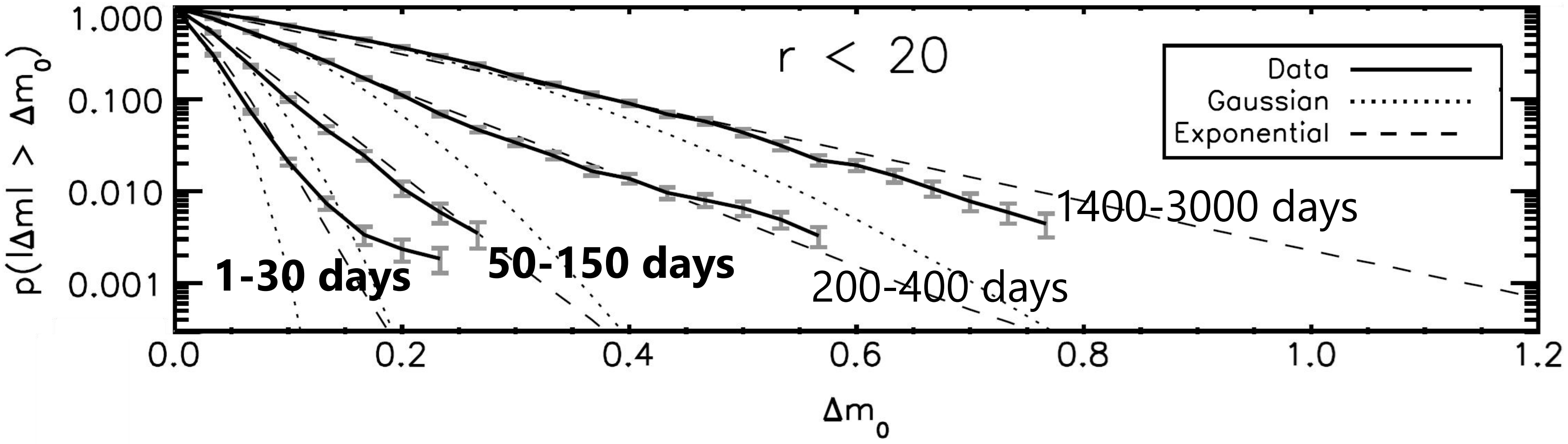
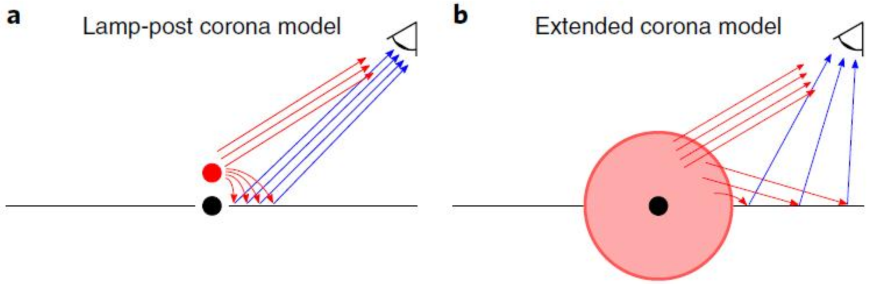
AGN variability

○ Damped Random Walk model

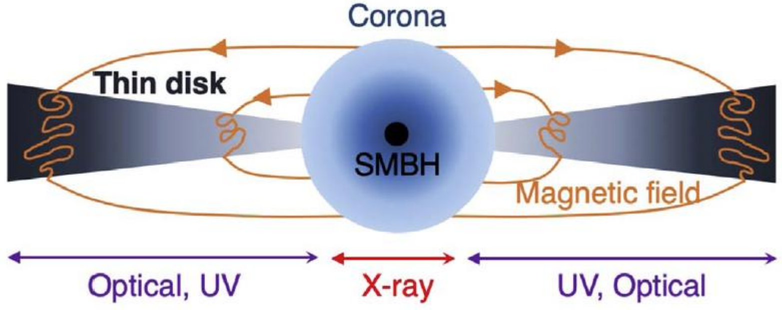
The variance of the variability follows exponential distribution depending on time lag

MacLeod et al. 2012





Chauvin et al. 2018



Sun et al. 2020

$\Delta m \gtrsim$ 1 mag with $\gtrsim$ 10^{-4} /yr/AGN can be candidates

Detection of Shock cooling emission

$L_{\rm SC} \gtrsim L_{\rm AGN}$ or $\Delta m > 1$ mag for

- $L_{\rm AGN} \lesssim 10^{45}$ erg/s for jets
- $L_{\rm AGN} \lesssim 10^{43}$ erg/s for explosions

Detection of Shock cooling emission

$L_{SC} \gtrsim L_{AGN}$ or $\Delta m > 1$ mag for

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Jets:

- Assume $R_{GW} \sim 10\ \mathrm{Gpc^{-3}yr^{-1}}$
- $n_{AGN} \sim 10^4\ \mathrm{Gpc^{-3}}$ for $L_{AGN} \sim 10^{45}$ erg/s at $z \lesssim 0.5$ (Ueda+14, Duras+20)
- Detectable by observing n_{AGN} / R_{GW} ~**10^3 AGNs yr** within $z \sim 0.5$

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SNe:

- Assume $\dot{M}_{\mathrm{SF}} \sim L_{\mathrm{AGN}} / \eta c^2$ and Salpeter IMF
- $R_{\mathrm{SN/gal}} \sim \dot{M}_{\mathrm{SF}} \times R_{\mathrm{SN/SF}} \sim 10^{-6}$ / yr^{-1}/ gal^{-1}
- Less frequent compared to DRW process..

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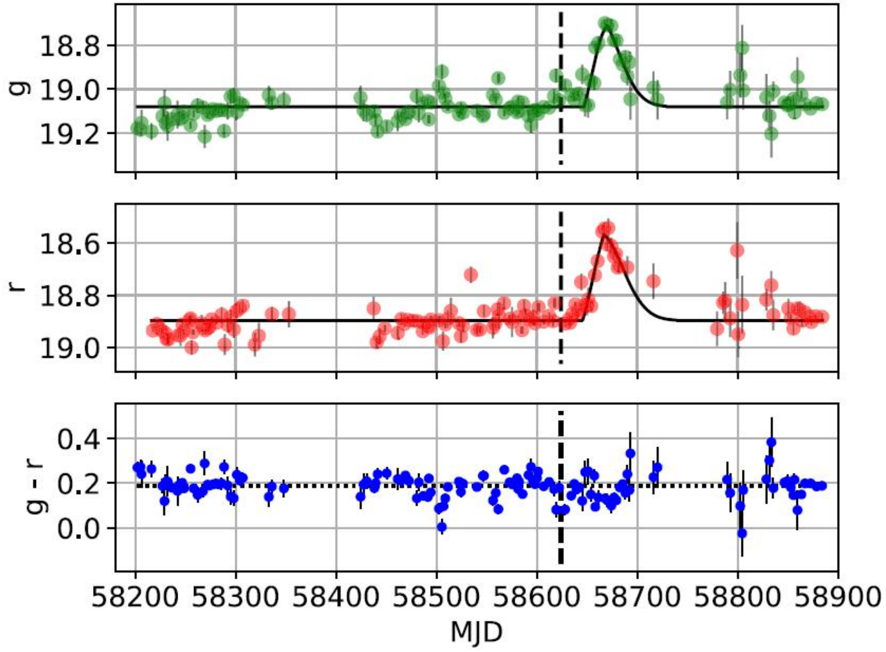
- Less frequent compared to DRW process..

Breakout emission is bright
at the MeV band for jets
at the ultraviolet band for explosions

Properties of EM events associated with GWs

GW190521 (most massive event)

Graham et al. (2020)

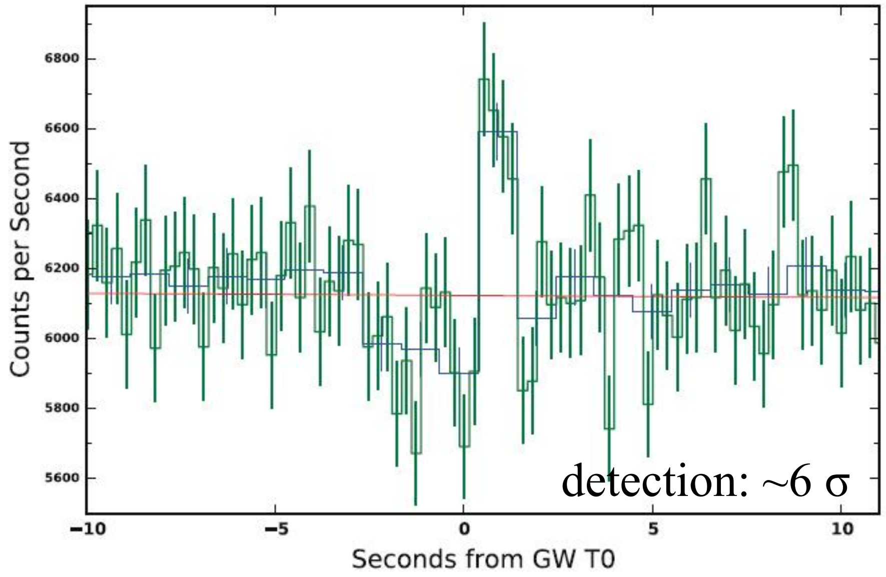


g, *r* bands : ~ 480, 650 nm

\+ 6 optical associations
(Graham et al. 2022)

GW150914 (1st GW event)

Connaughton et al. (2016)



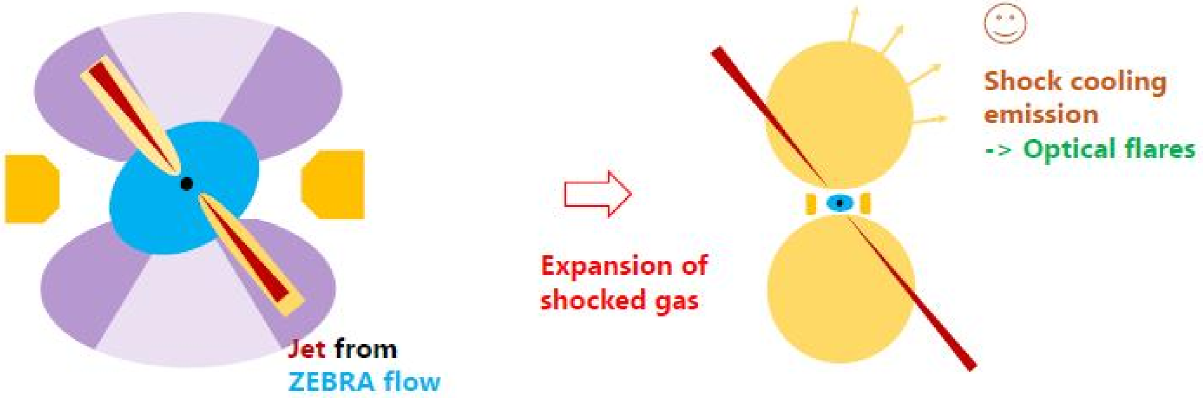
association significance: 2.9 σ

\+ 1 γ-ray association
(Bagoly et al. 2016)

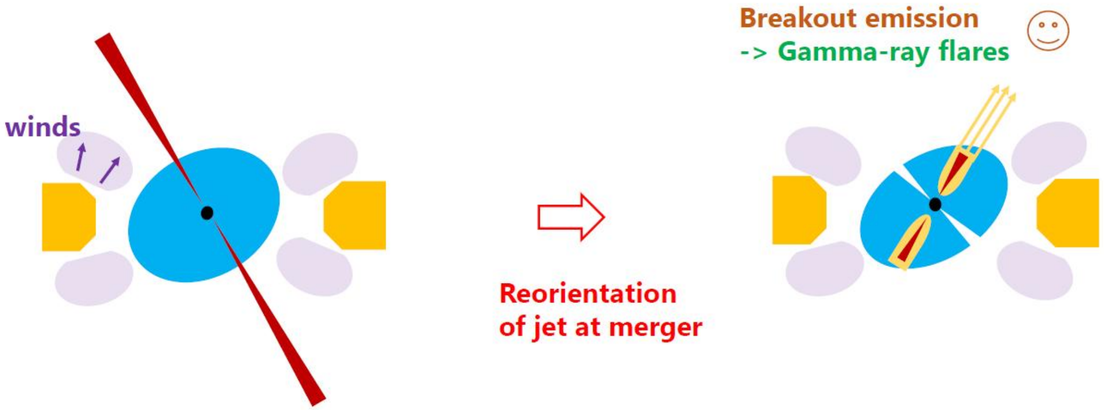
EM from merging BHs in AGNs

After mergers:

- Jet (ZEBRA state, Begelman & Volonteri 2017)
- explosion (SNe/NSMs/WDMs)



Components:
- AGN disk
- Wind
- Circum-binary disk



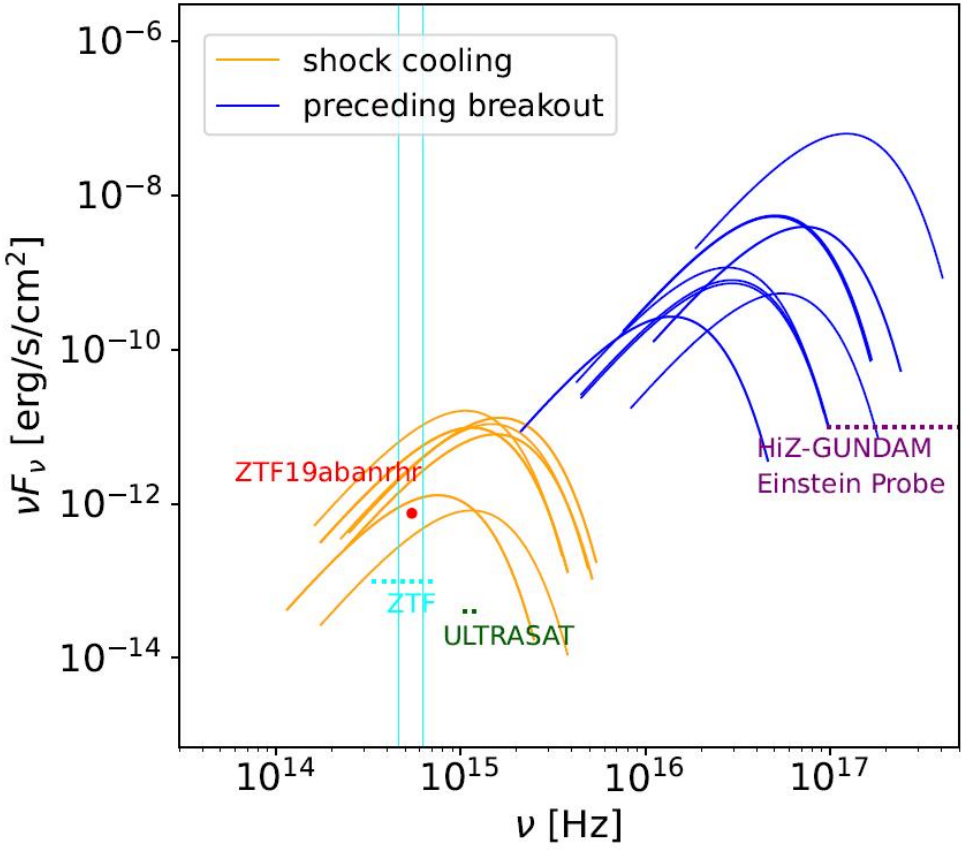
Mechanisms:

- Breakout emission
- Shock cooling emission
- Non-thermal emission

HT+ in prep

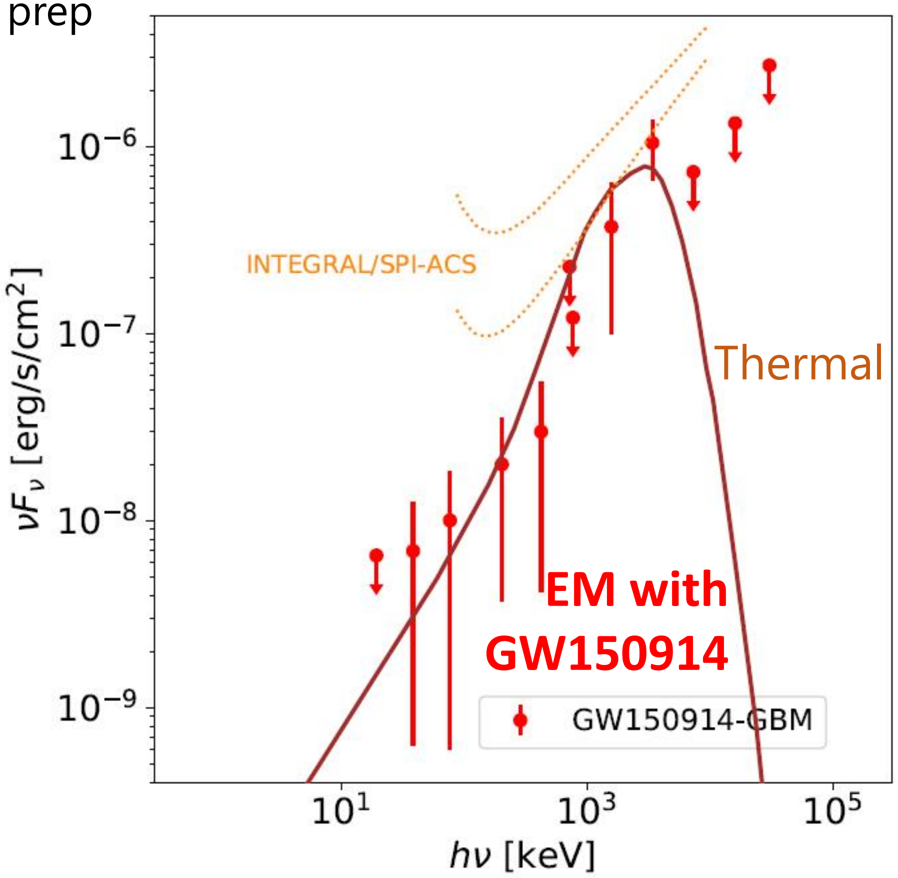
EM emission associations to GWs

from shocked AGN gas/wind



HT+23, 24a, 24b in prep

from shocked circum-BH disks



- SC emission from shocked AGN gas -> various Temperature
- SC emission from shocked wind -> $T_{SC} \sim$ 3-4 $\times 10^4$ K

  -> color evolution, preceding UV, X-rays

- ✓ $v_{kick} \sim 500$ km/s
- ✓ $\theta_0 \sim 0.05$
- ✓ $f_{inc} \sim 60$

Other signatures of the AGN channel

- Doppler acceleration
(e.g. Han, Yang, HT et al. 2024)

- Spatial distribution
(Bartos et al. 2017, Veronesi et al. 2023,24)

- Lensing (e.g. D'Orazio et al. 2019)

- Mass and spin correlation (HT et al. 2021b)

- $q - X_{\rm eff}$ correlation (Callister et al. 2021)

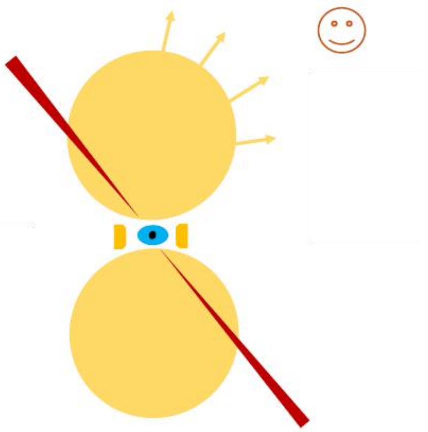
- High eccentricity for massive binaries
(Samsing et al. 2022, HT et al. 2021a)

Summary

AGNs are promising environments for BH-BH mergers discovered by LIGO/Virgo/KAGRA.

Electromagnetic counterparts can be smoking gun signatures for this channel

- ✓ Shock cooling emissions related to jets can be discovered by optical or UV telescopes
- ✓ Breakout emissions related to jets and explosions are bright in gamma-ray and UV bands, respectively



Thank you！