Connecting AGN Accretion Disks to Black Hole Binaries at Multiple Scales

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at *Building Bridges: Towards a Unified Picture of Stellar & BH Binary Accretion & Evolution*

Roadmap

Things in disks–not just protoplanets!

Migration

Black holes

Gravitational waves

Stars

Consequences/questions for disk modeling

A bridge…

Mass ratio, q	Protoplanetary	AGN
10^{-3}	Jupiter	Big IMBH/Small SMBH
10^{-6}	Earth	stars/stellar mass BH

Star formation in AGN is uncertain…

But nuclear star clusters exist!

This is our nearest galactic nucleus:

(Ghez++)

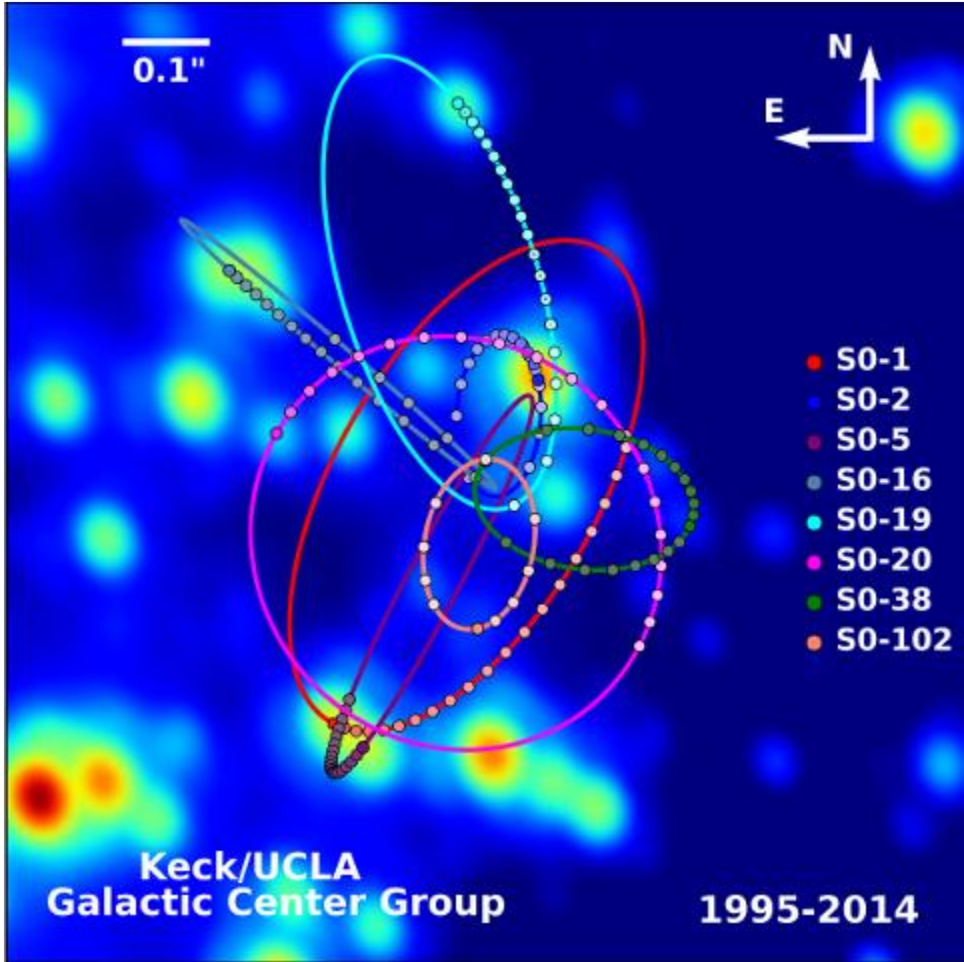
$4\times10^{6}M_{sun}$

$0.1'' \sim 10^{3}AU \sim 10^{4}R_{S}$

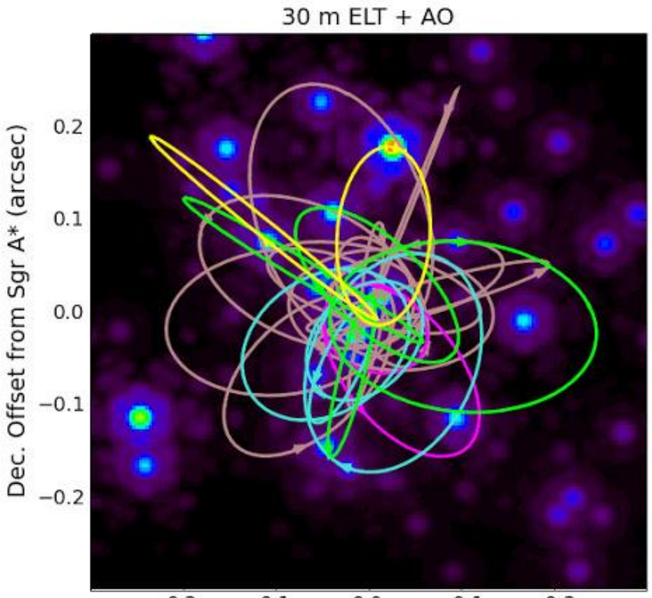
$N_{sBH}\sim2\times10^{4}$ (Hailey++ 2018)

Nuclear Star Clusters (NSCs) common!

N=1 is cautionary tale



Things in Galactic Nuclei=Things in AGN disks!



http://www.astro.ucla.edu/~ghezgroup/gc/pictures/Future_GCorbits.shtml

Expect dense **BH** population in GN (~10^4/pc^3) from decayed GCs, mergers, SF etc.

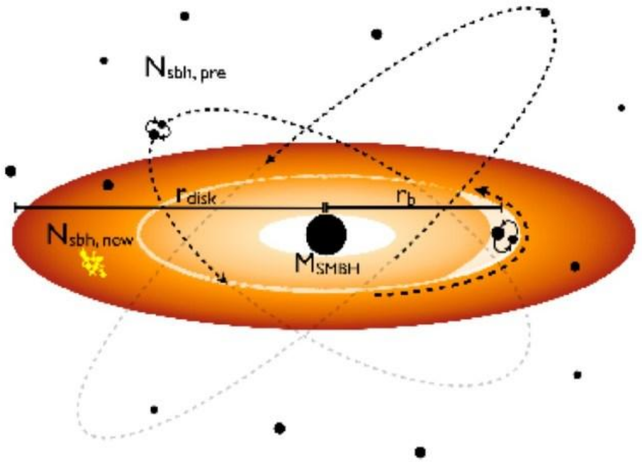


Image credit: Matthew O'Dowd

McKernan, Ford, Lyra, Perets **2012**
McKernan, Ford, Kocsis, Lyra, Winter **2014**

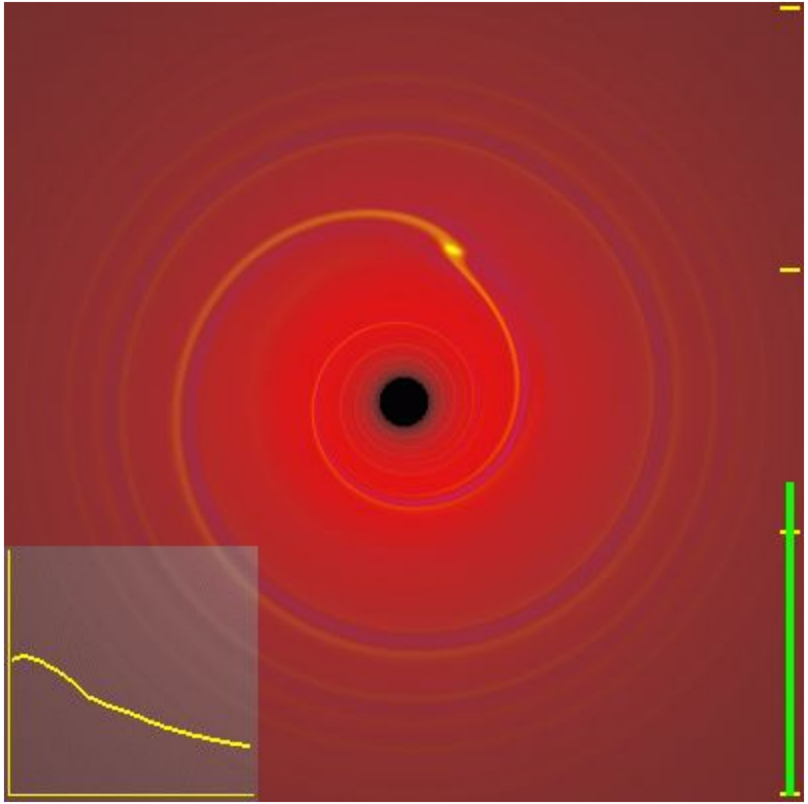
~~Steal~~ Borrow physics

~~Planet~~ BH migration torques

- Type I, non-gap opening
- $q<10^{-4}$
- Inward*
- Gravitational**

PPD get better resolution

PPD leave 'droppings'



Armitage 2005

*Depends on $d\Sigma/dr$, dT/dr

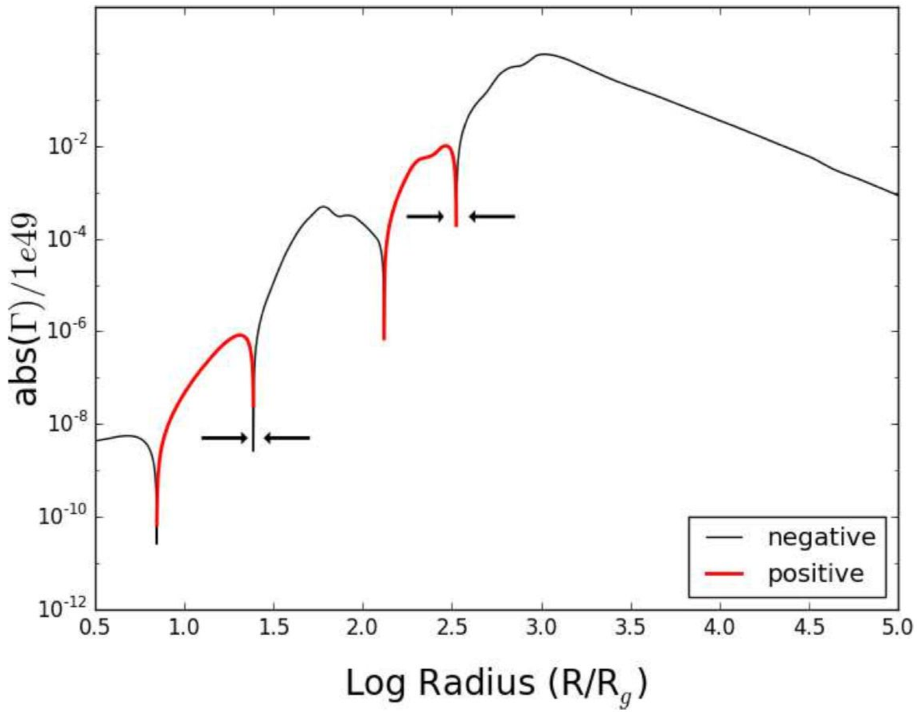
**Feedback can mess up gas

Migration can go both directions

Migration traps: likely but

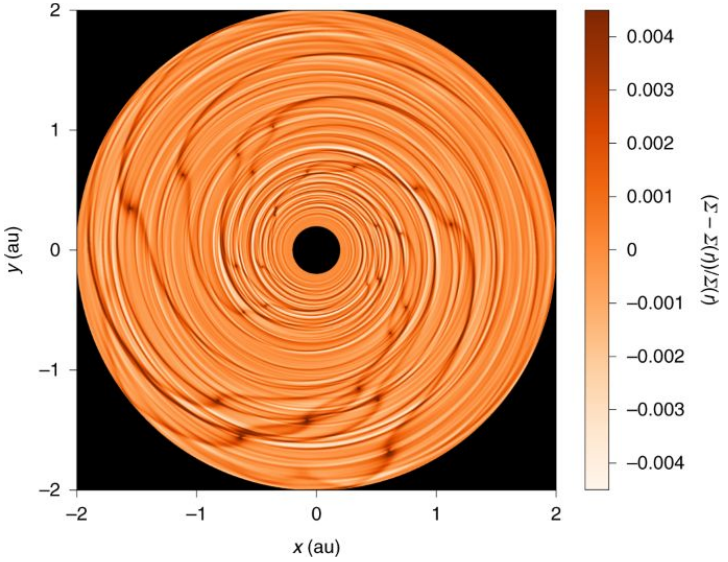
- Requires $d\Sigma/dr$ sufficiently large
- Secondary effect from dT/dr
- See also Dittman & Miller 2020

Important consequences!



Bellovary, MacLow, McKernan, Ford 2016

Gas torques cause migration & binary formation



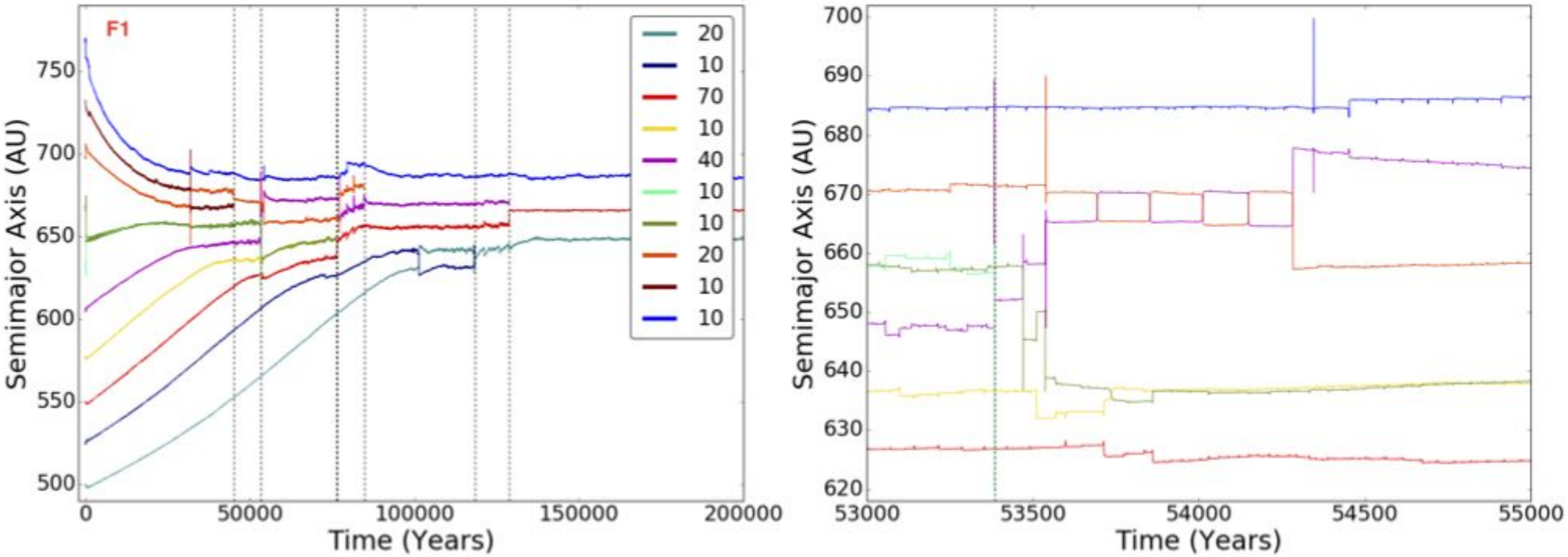
Broz++21

Gas torques causes all things in disk to migrate (spiral in/out)
Forms **new** binaries! (Secunda++19,20, Yang++20, Tagawa++20 but see also Li, Lai & Rodet 22)

$$\tau_{\rm mig} \sim 0.03{\rm Myr}\left(\frac{N}{3}\right)^{-1}\left(\frac{R}{10^3 r_{\rm g}}\right)^{1/2}\left(\frac{M}{5M_\odot}\right)^{-1}\left(\frac{h/R}{0.01}\right)^{2}\left(\frac{\Sigma}{10^7{\rm kg\,m^{-2}}}\right)^{-1}\left(\frac{M}{10^8 M_\odot}\right)^{3/2}$$

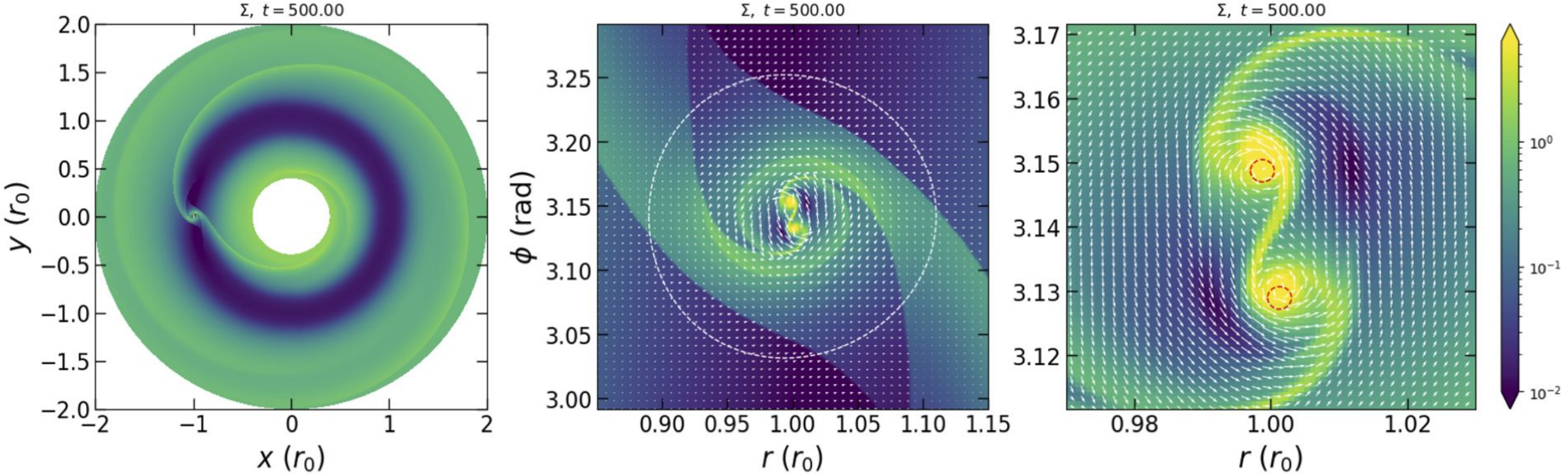
Migration time depends on disk properties!

N-body with migration



Secunda ++2019;
Secunda, Adorno ++ 2020a

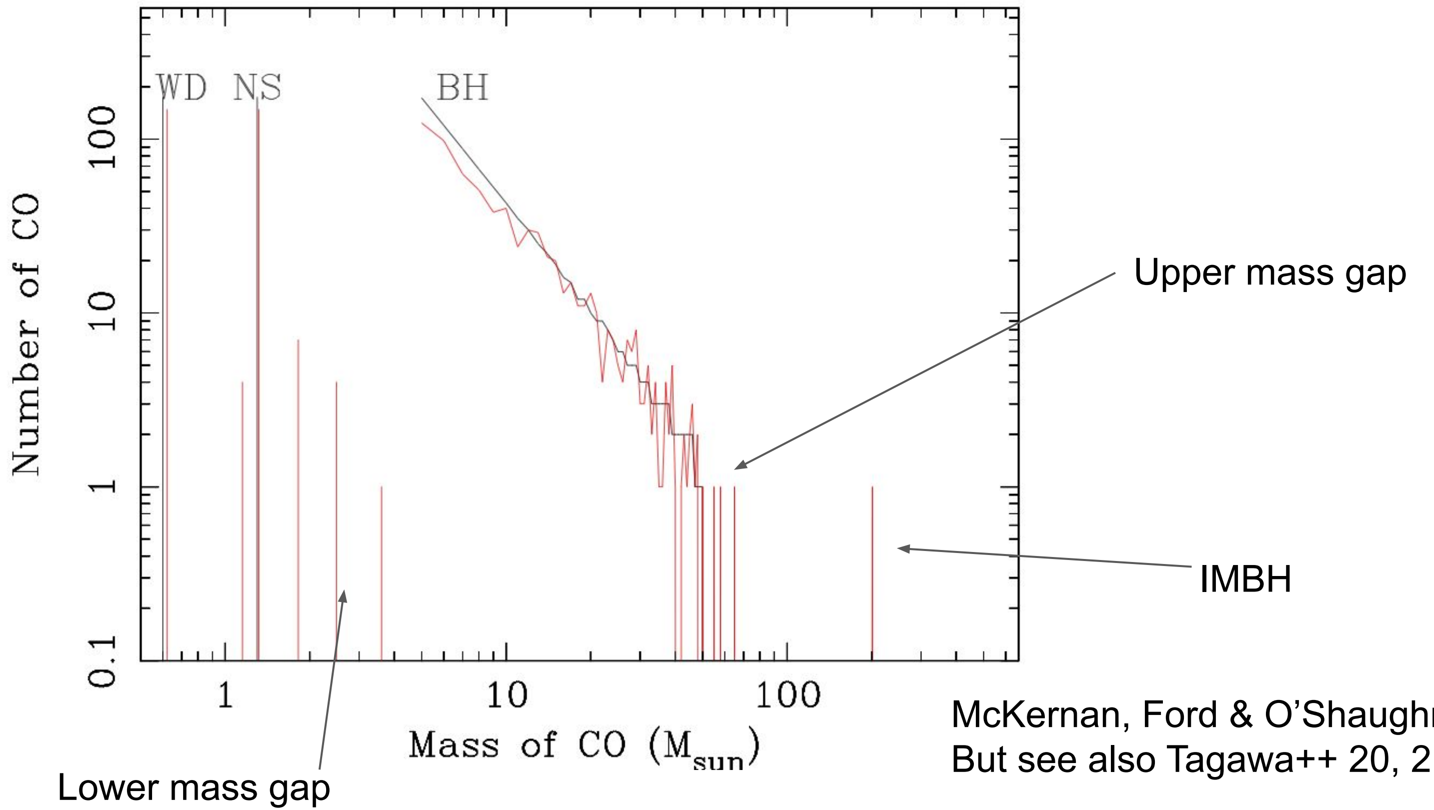
Gas: can harden (& soften) binaries



Ya-Ping Li++ 21 (see also Baruteau+11,Derdzinski+21,Tiede+21,Li & Lai 22, Dempsey++22)

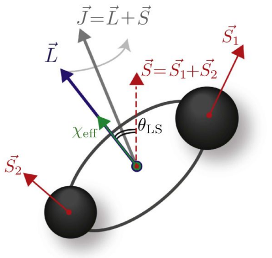
Gravitational Wave BBH mergers probe disk midplane!

Masses: MC results



McKernan, Ford & O'Shaughnessy 20
But see also Tagawa++ 20, 21

Image credit: C.Rodriguez



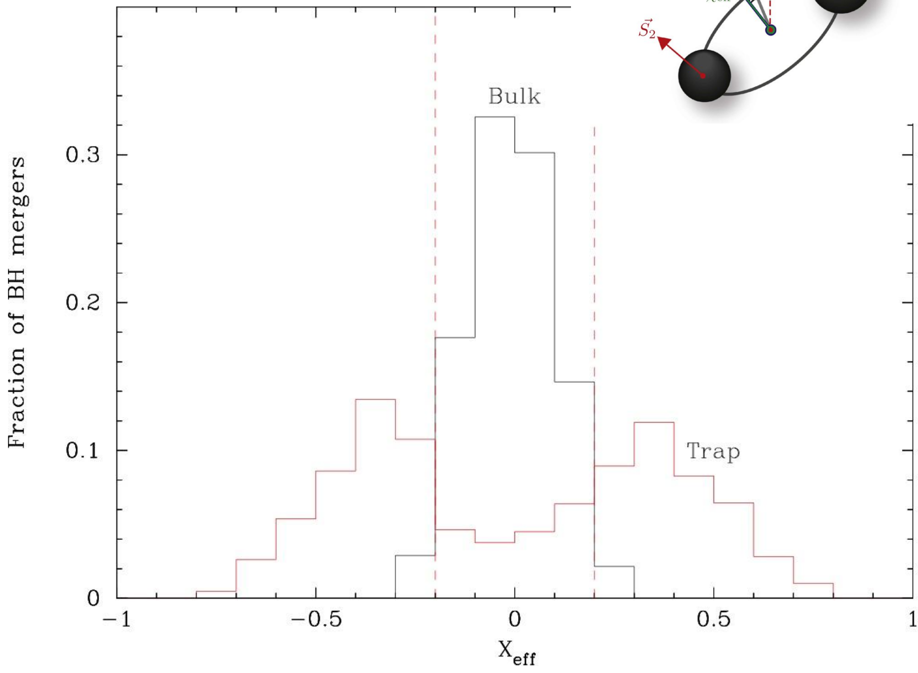
Populations: MC results

Most mergers in **bulk** disk (80-90%)

- q~0.6+/-0.3
- χ_{eff} centered on 0, width depends on natal spin
- 80-90% 1g-1g

Trap mergers 10-20%

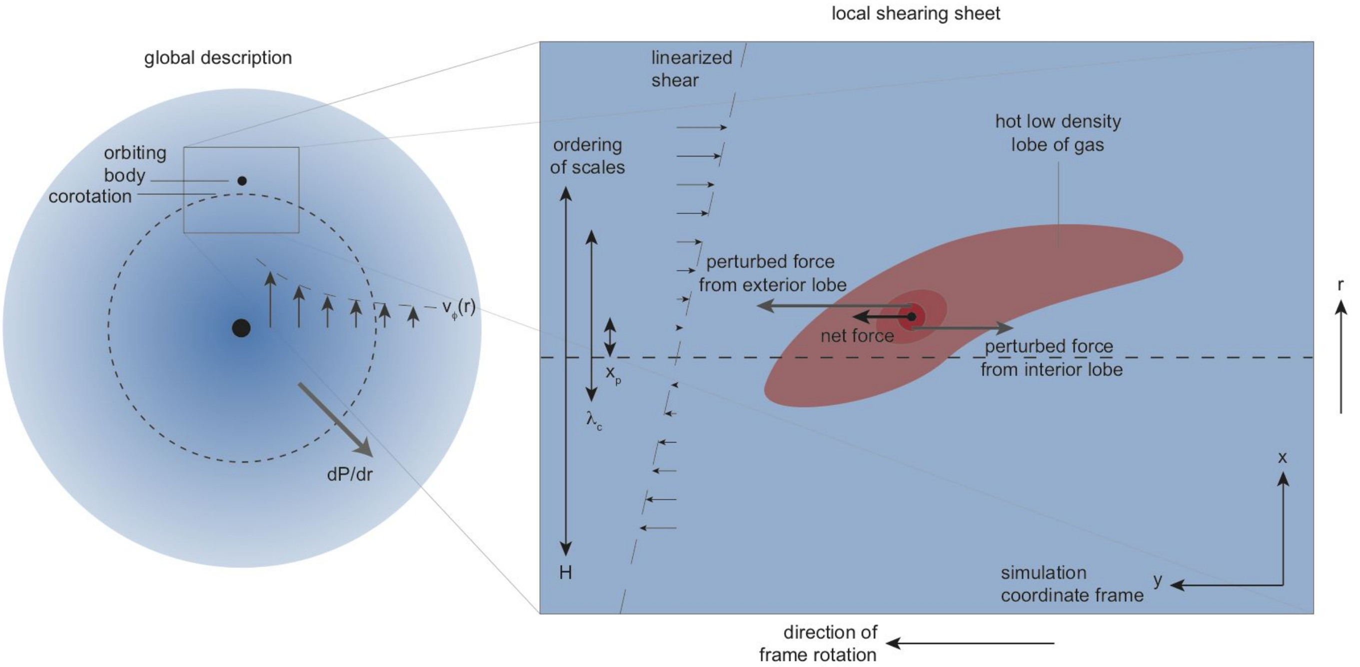
- q~0.1+/-0.1
- χ_{eff} bimodal
- Often ng-2g, ng-3g; n>20 possible



McKernan, Ford, O'Shaughnessy, Wysocki 2020
...but see McK,F,Callister++21

GW190412 (q~0.3) and GW190814 (q~0.1): entirely comfortable

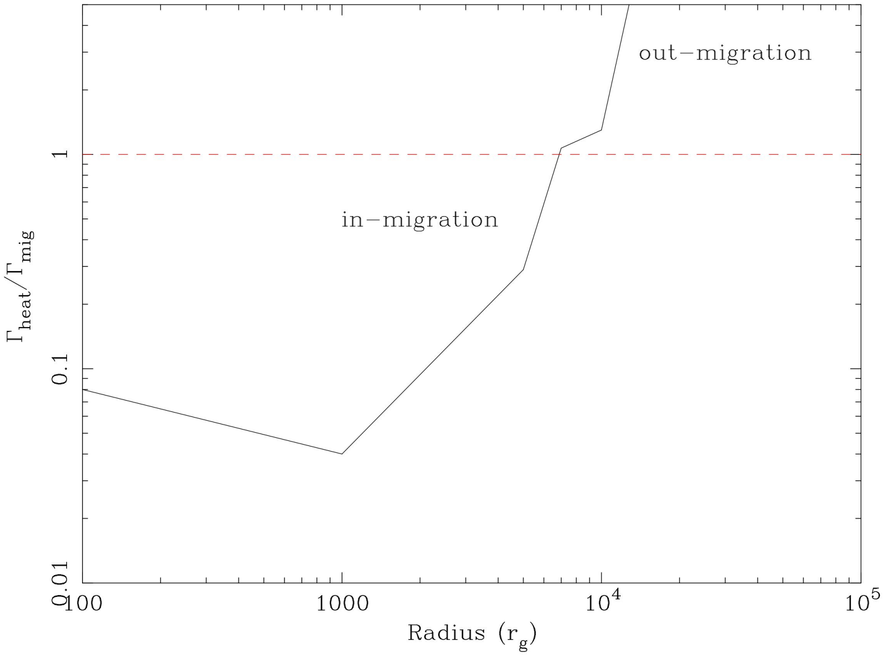
But feedback can change things!

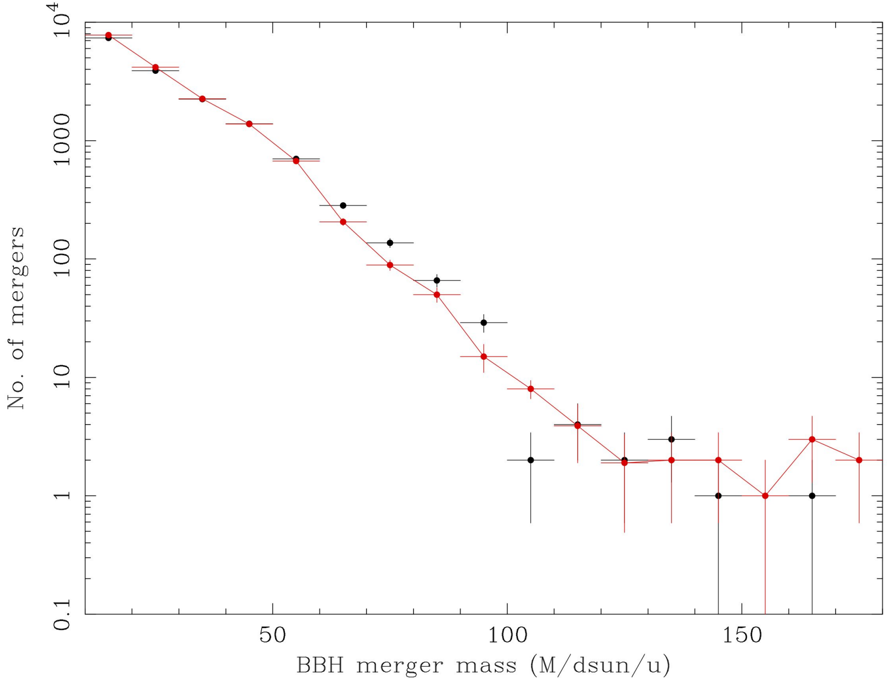


$$\frac{\Gamma_{\rm heat}}{\Gamma_0} \sim 0.07 \left(\frac{c}{v_K}\right) \epsilon \tau^{-1} \alpha^{-3/2}$$

Hankla, Jiang, Armitage 20

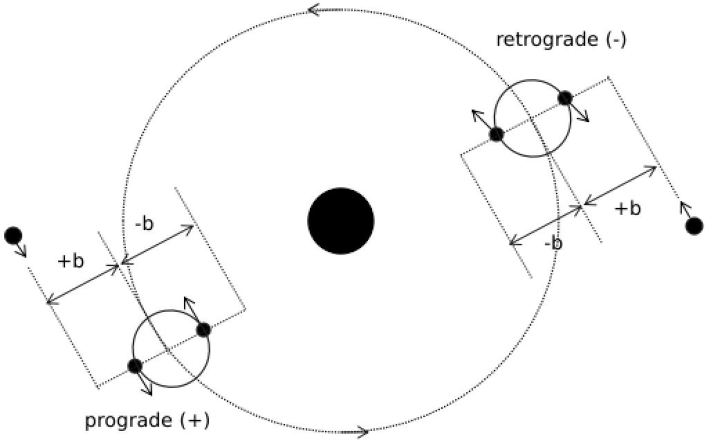
Feedback can change direction of migration

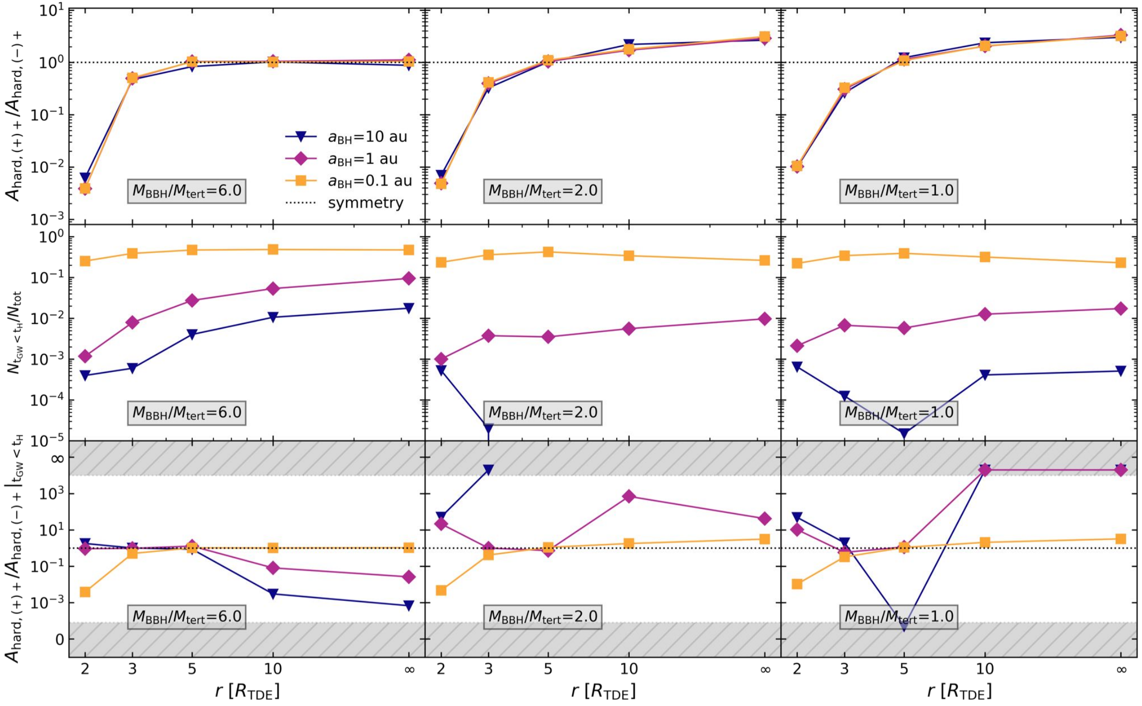




McKernan, Ford, O'Shaughnessy (in prep)

Dynamics probably also involved

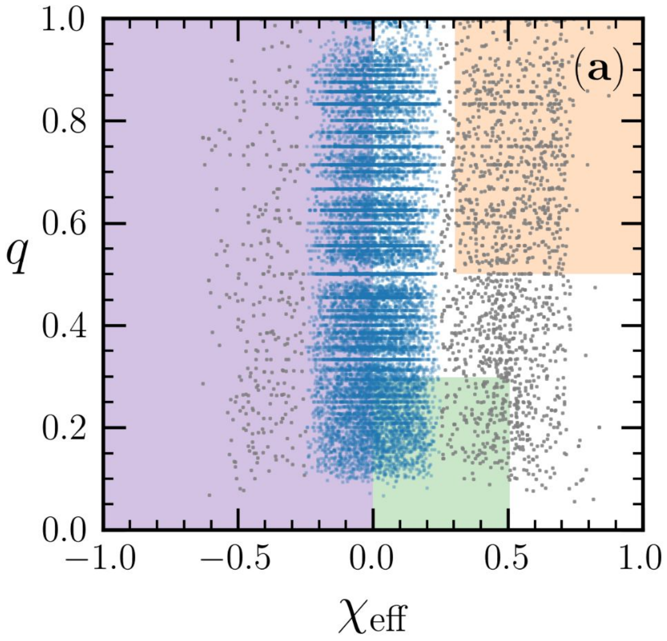


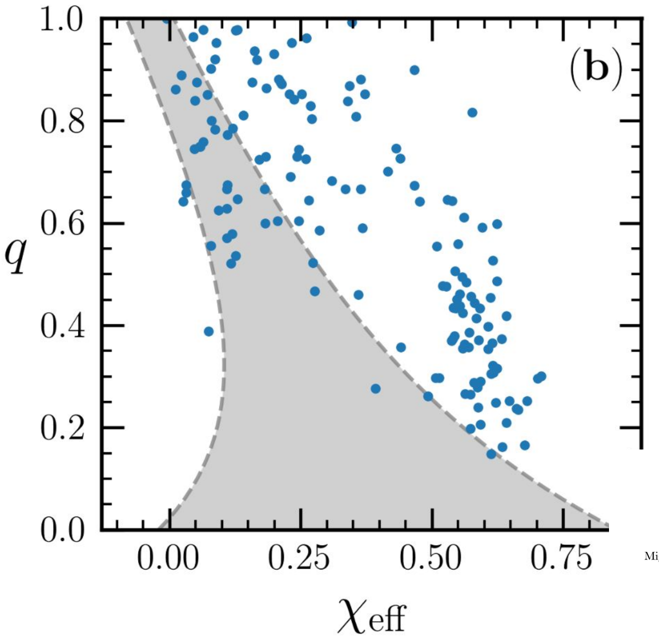


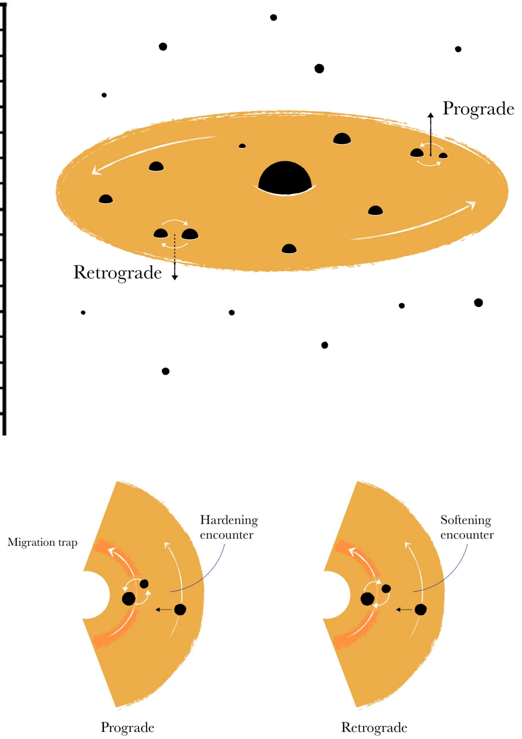
Wang, McK, F, Perna, Leigh & MacLow 21

See also: Samsing++22

Dynamics probably also involved







McK, F, Callister, Farr, O'Shaughnessy, Thrane, Vajpayi++21

AGN likely home of highest mass mergers

-deep potential if >3g

    -if e>0 & natal spin>0, >1g

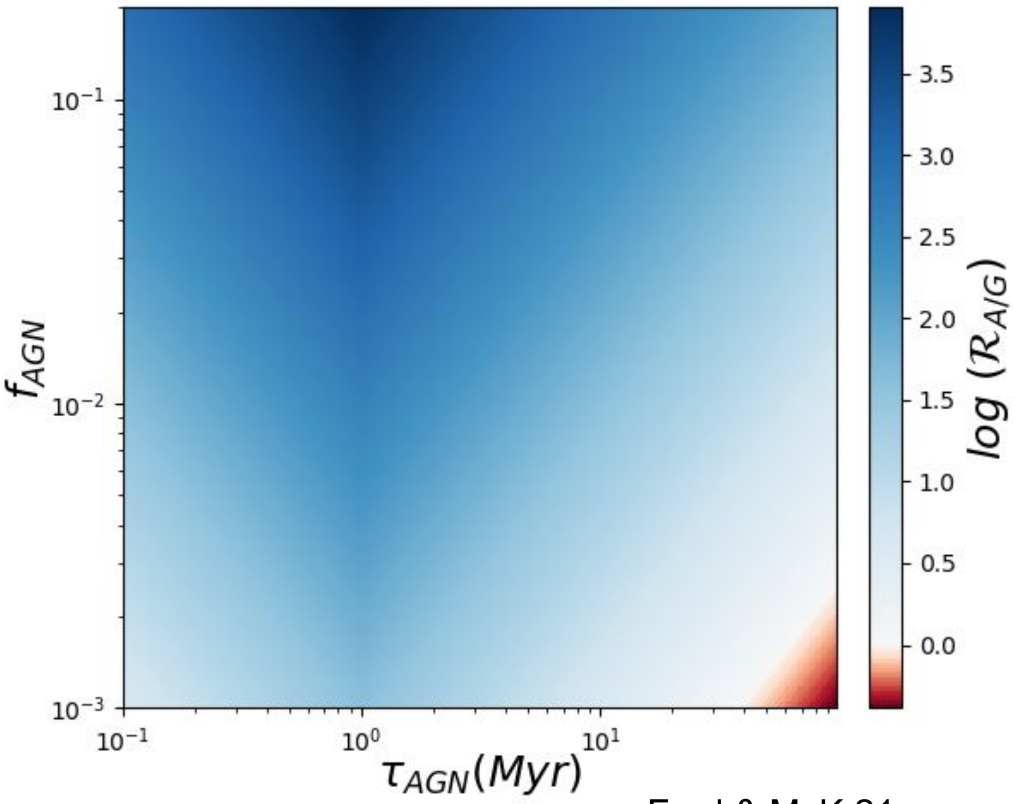
-deep potential = AGN

    -short binary lifetime in AGN

    -versus NSC dynamics

If GW190521 from AGN

    $f_{BBH,AGN}$~0.25-0.8



Ford & McK 21

Reverse-engineering AGN from LIGO-Virgo-KAGRA

These AGN can't live super-long (otherwise spins align), **t<5Myr**, but live long enough **t>0.5Myr** for reasonable BBH rate

Disk dense enough to capture, make binaries & migrate them $\boldsymbol{\varrho > 10^{-11}}$ **g/cc,** not razor-thin ($\mathbf{H/R > 10^{-3}}$)

Disk dynamical hardening prob important, since χ_{eff} asymmetric

These are **brightest AGN** (quasars & Seyferts) -> helps/hurts EM search

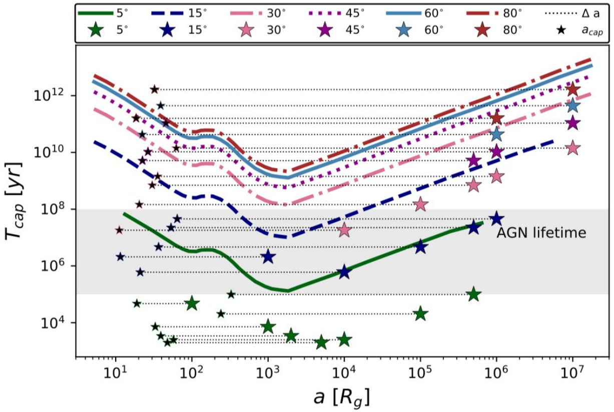
But see also: Bartos++17 (association strategy) and Veronesi++22

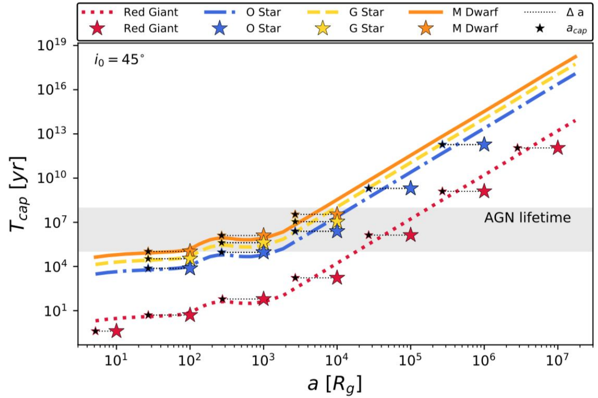
Disk capture

BH

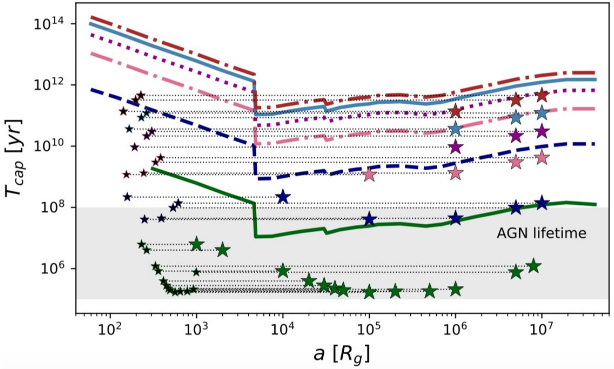
Stars

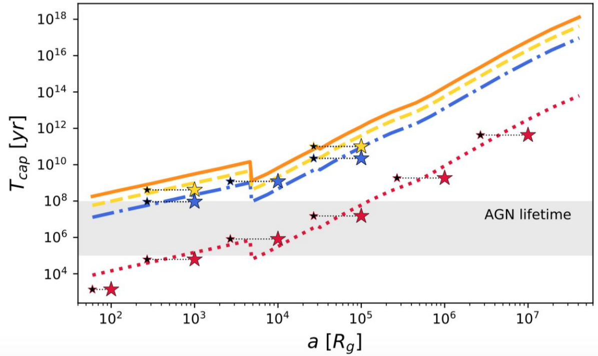
Sirko & Goodman 2003





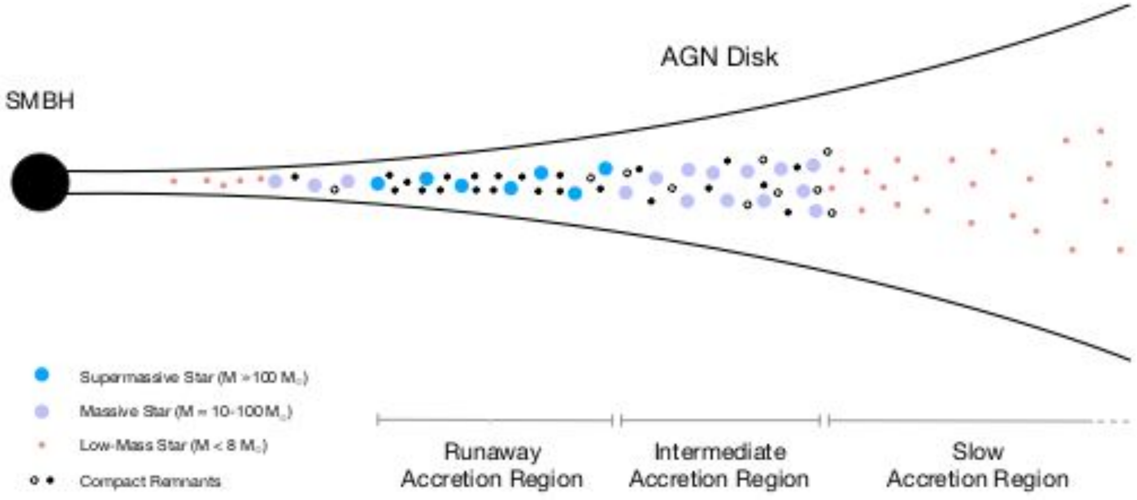
Thompson, Quataert & Murray 2005

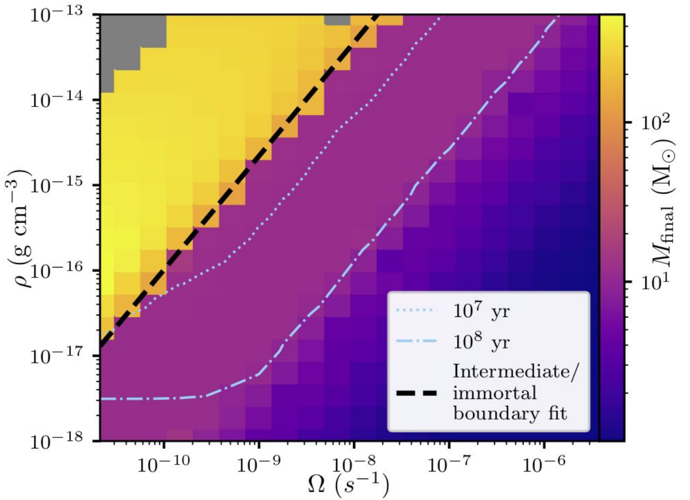




Fabj, Nasim, Caban, McK, Ford+ 20

AGN stars become 'Immortal' Blue stragglers



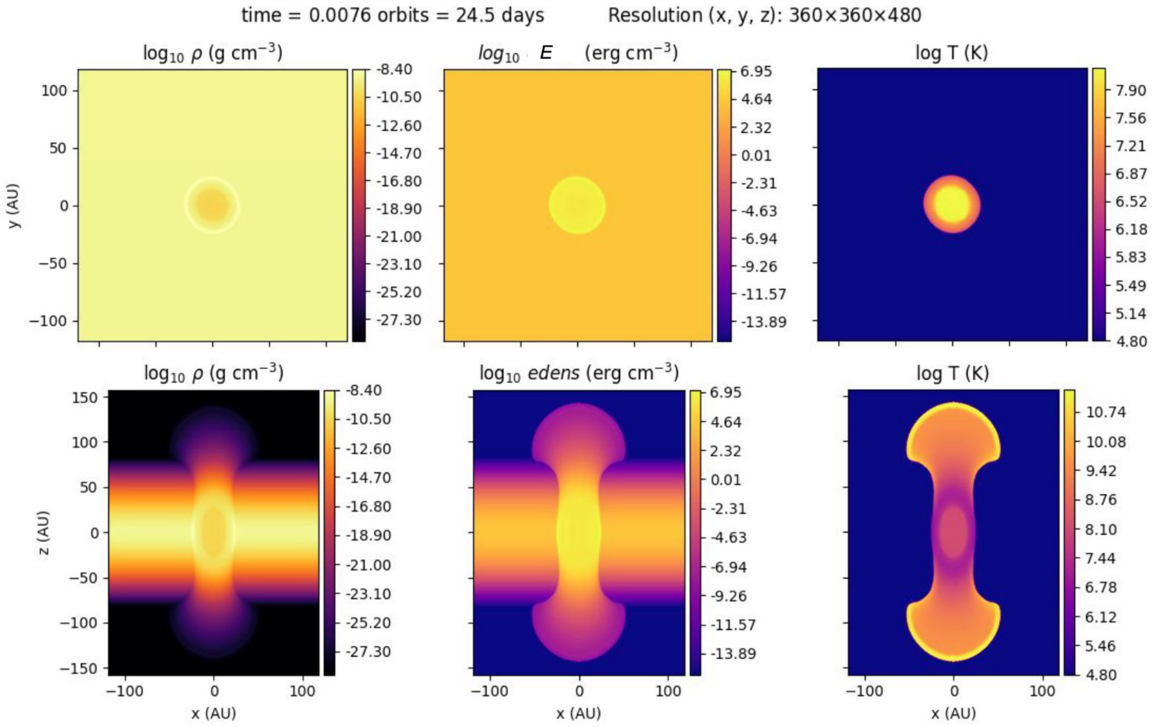


from Dittmann, Cantiello & Jermyn '21, see also Jermyn++22

If don’t reach immortal stage

SNe

Observable flares



Cook, Lyra, MacLow, Ford, McK (in prep) 2022

Disk-star interactions

Drive turbulence

Provide heating mechanism(s)

Change chemistry (and opacity)

Big questions for disk modelers?

-How is migration affected by feedback? Multiple orbiters?

-Binaries hardening/softening by gas torques (prograde/retrograde)?

-What do GW pops look like depending on disk properties?

-What EM signatures might be produced in BBH/BHNS merger?

- **-What other EM signatures of embedded objects?**

-How do embedded objects (esp stars) change disk thermodynamics?

-Can disk capture or embedded objects provide stabilizing heating?