Stellar rejuvenation and gravitational waves in AGN disks:
Analog of planetary systems around massive black holes.

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in collaboration with

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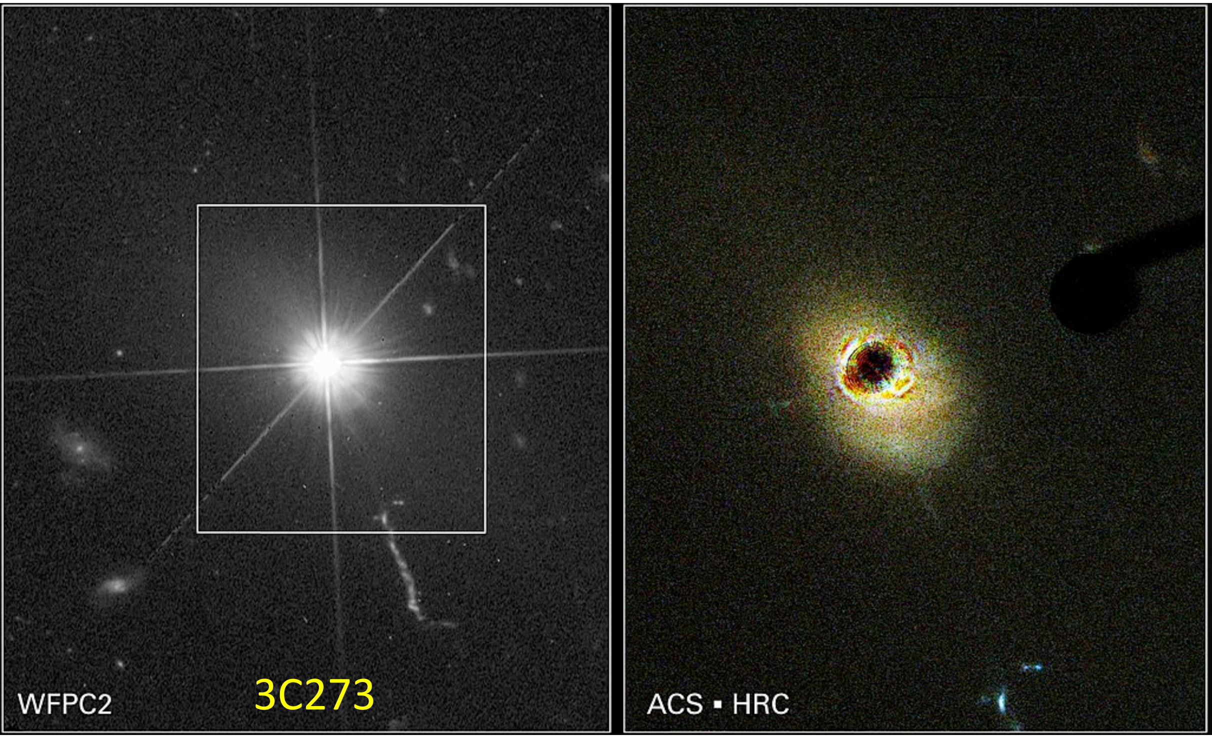
UG,GS,PD,F

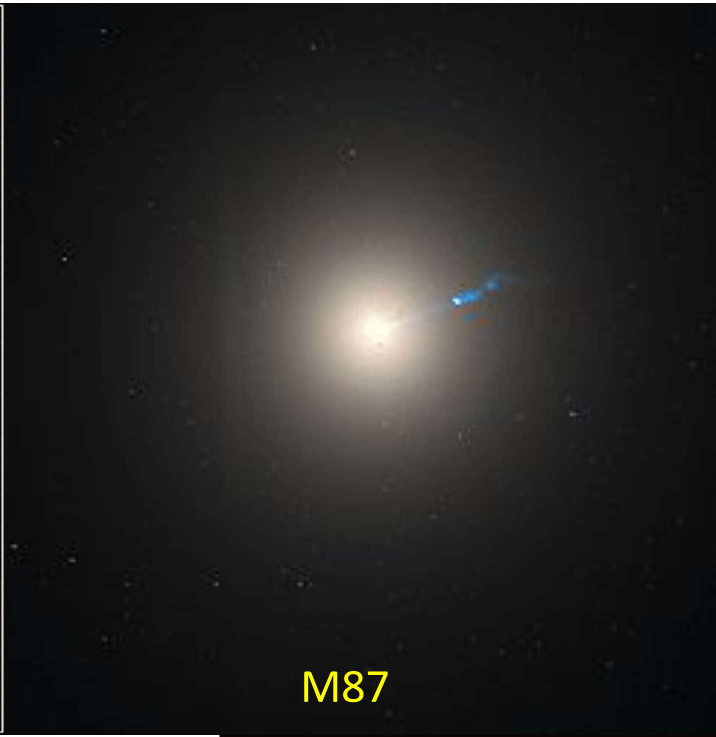
KITP. University of California Santa Barbara, June 20 2

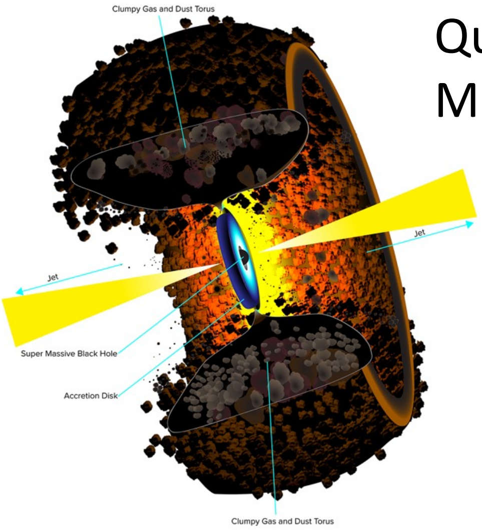
Big picture to tie together fragmentary clues

- Can the dynamical evolution of nuclear clusters be affected by gaseous or stellar disks?
- Why are high-redshift quasars so metal rich?
- What caused the emergence of a disk of young stars around the Galactic Center?
- How do AGN become inactive?
- Can a fraction of gravitational wave events be due to stellar black hole mergers around AGNs ?
- Can we learn something about AGNs & massive black hole formation and evolution from GW events?
- Ask not what AGN can do for gravitation waves & planet formation, ask what they can do for AGN's

Quasars and AGNs

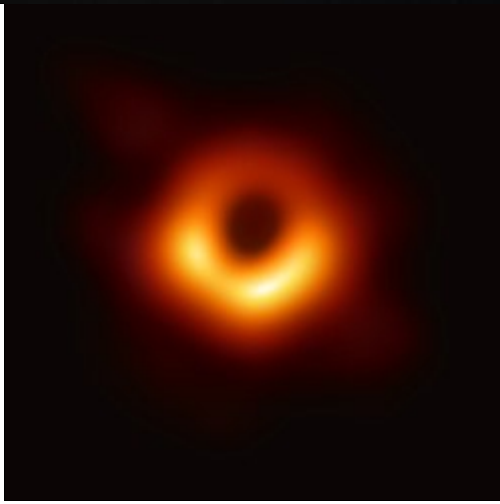






Quasars: Maarten Schmidt 1963

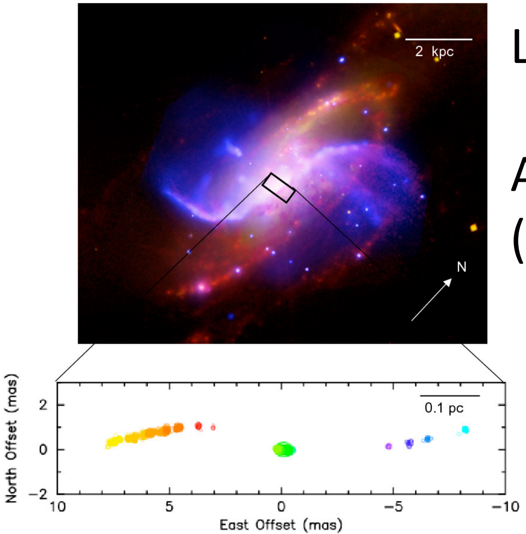
Massive Black Holes: Lynden-Bell 1969

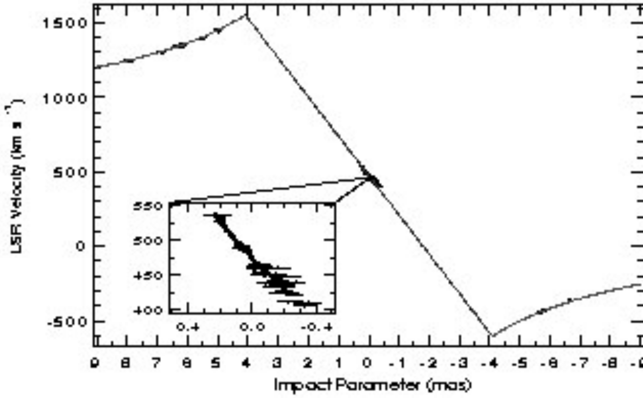


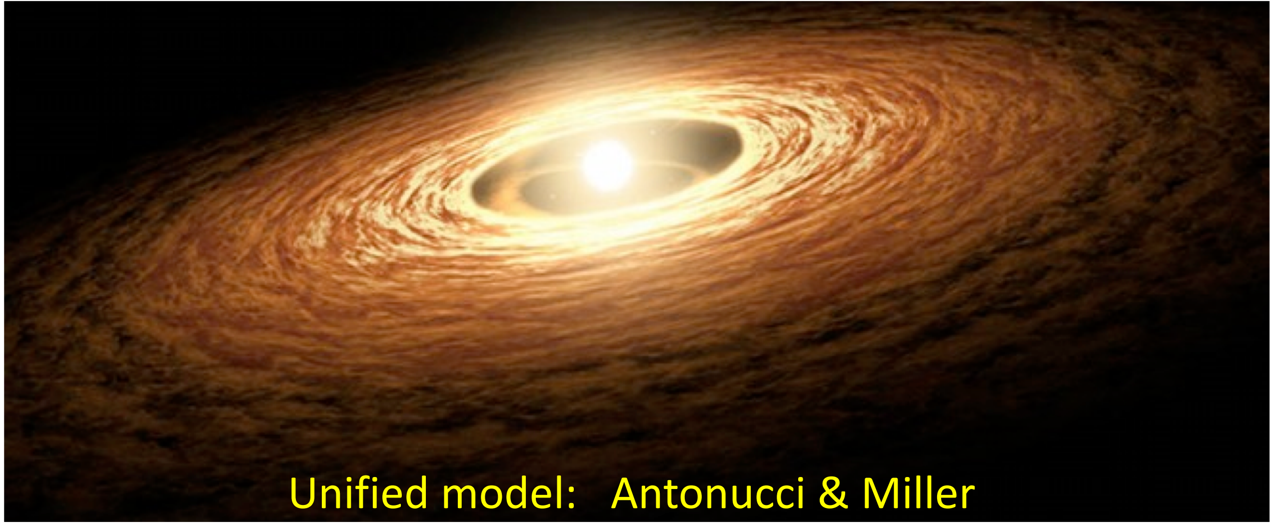
Accretion disk models

Lust 1952 (solar system formation)
Shakura & Sunyaev 1973 (LMXB’s)
Lynden-Bell & Pringle 1974

Active Keplerian disk: NGC4258
(Miyoshi, Moran 1995)

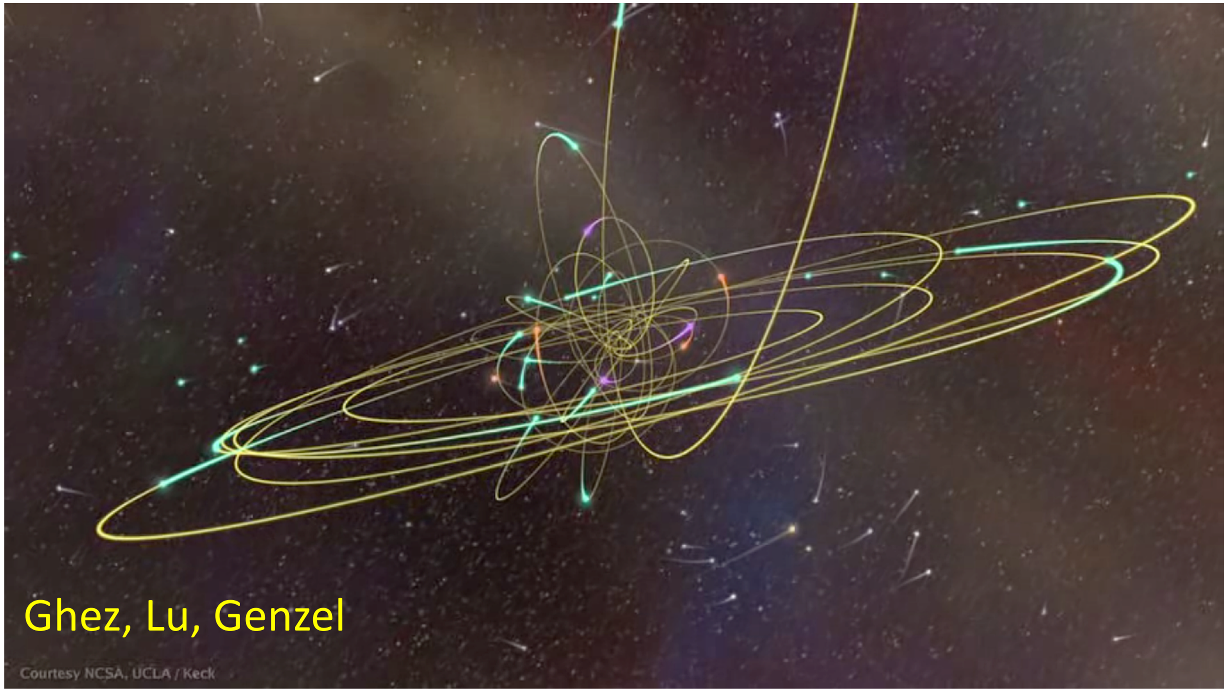


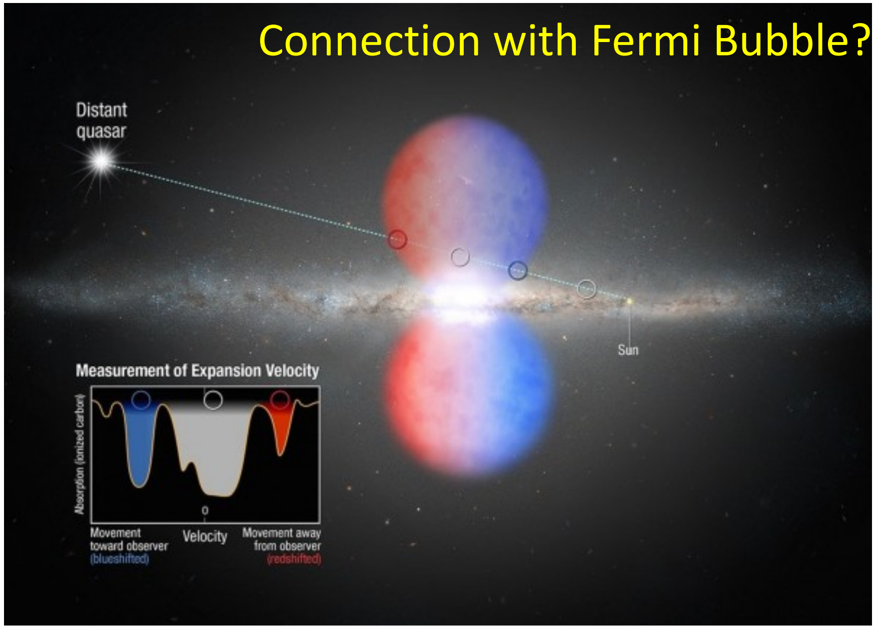




Unified model: Antonucci & Miller

Young stars in the Galactic Center





Coexistence of nuclear clusters & black holes

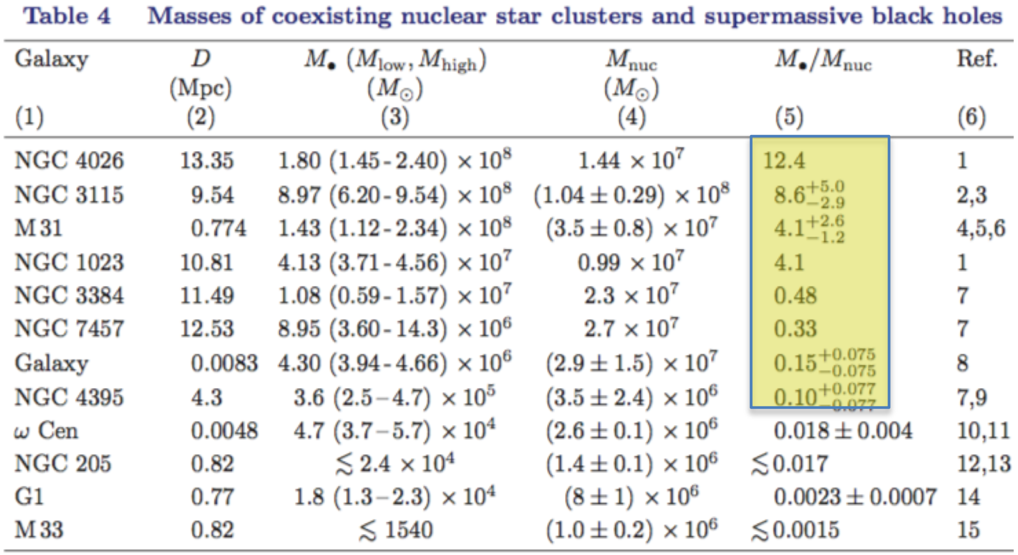
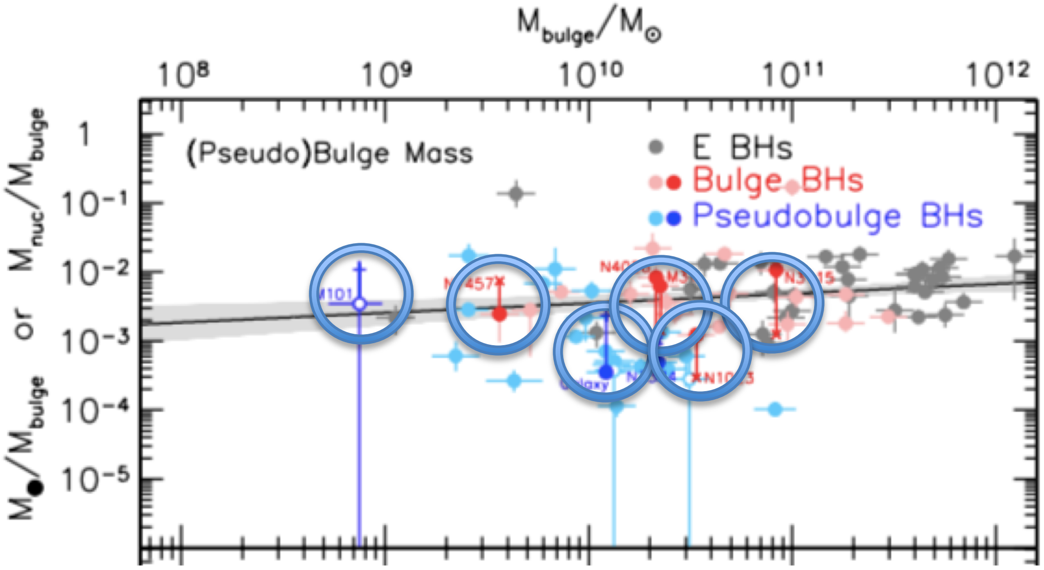
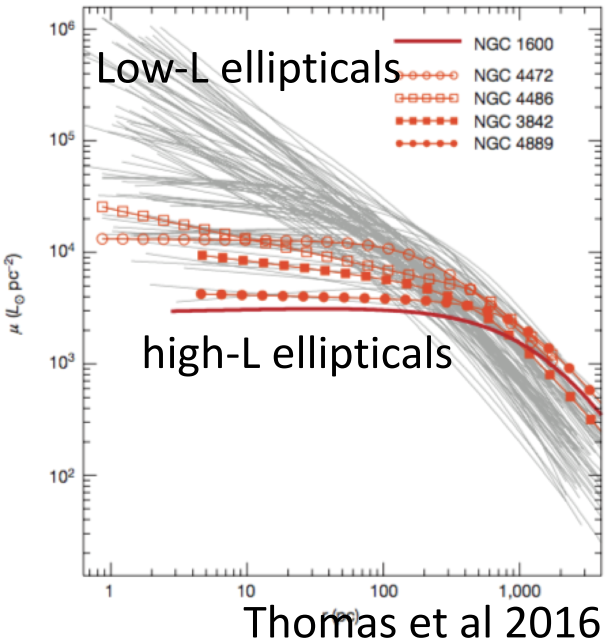


Table 4 Masses of coexisting nuclear star clusters and supermassive black holes

Galaxy (1)	D (Mpc) (2)	$M_\bullet$ ($M_{\rm low}$, $M_{\rm high}$) ($M_\odot$) (3)	$M_{\rm nuc}$ ($M_\odot$) (4)	$M_\bullet/M_{\rm nuc}$ (5)	Ref. (6)
NGC 4026	13.35	$1.80\ (1.45-2.40) \times 10^8$	1.44×10^7	12.4	1
NGC 3115	9.54	$8.97\ (6.20-9.54) \times 10^8$	$(1.04 \pm 0.29) \times 10^8$	$8.6^{+5.0}_{-2.9}$	2,3
M 31	0.774	$1.43\ (1.12-2.34) \times 10^8$	$(3.5 \pm 0.8) \times 10^7$	$4.1^{+2.6}_{-1.2}$	4,5,6
NGC 1023	10.81	$4.13\ (3.71-4.56) \times 10^7$	0.99×10^7	4.1	1
NGC 3384	11.49	$1.08\ (0.59-1.57) \times 10^7$	2.3×10^7	0.48	7
NGC 7457	12.53	$8.95\ (3.60-14.3) \times 10^6$	2.7×10^7	0.33	7
Galaxy	0.0083	$4.30\ (3.94-4.66) \times 10^6$	$(2.9 \pm 1.5) \times 10^7$	$0.15^{+0.075}_{-0.075}$	8
NGC 4395	4.3	$3.6\ (2.5-4.7) \times 10^5$	$(3.5 \pm 2.4) \times 10^6$	$0.10^{+0.077}_{-0.077}$	7,9
ω Cen	0.0048	$4.7\ (3.7-5.7) \times 10^4$	$(2.6 \pm 0.1) \times 10^6$	0.018 ± 0.004	10,11
NGC 205	0.82	$\lesssim 2.4 \times 10^4$	$(1.4 \pm 0.1) \times 10^6$	$\lesssim 0.017$	12,13
G1	0.77	$1.8\ (1.3-2.3) \times 10^4$	$(8 \pm 1) \times 10^6$	0.0023 ± 0.0007	14
M 33	0.82	$\lesssim 1540$	$(1.0 \pm 0.2) \times 10^6$	$\lesssim 0.0015$	15

Kormendy & Ho 2013



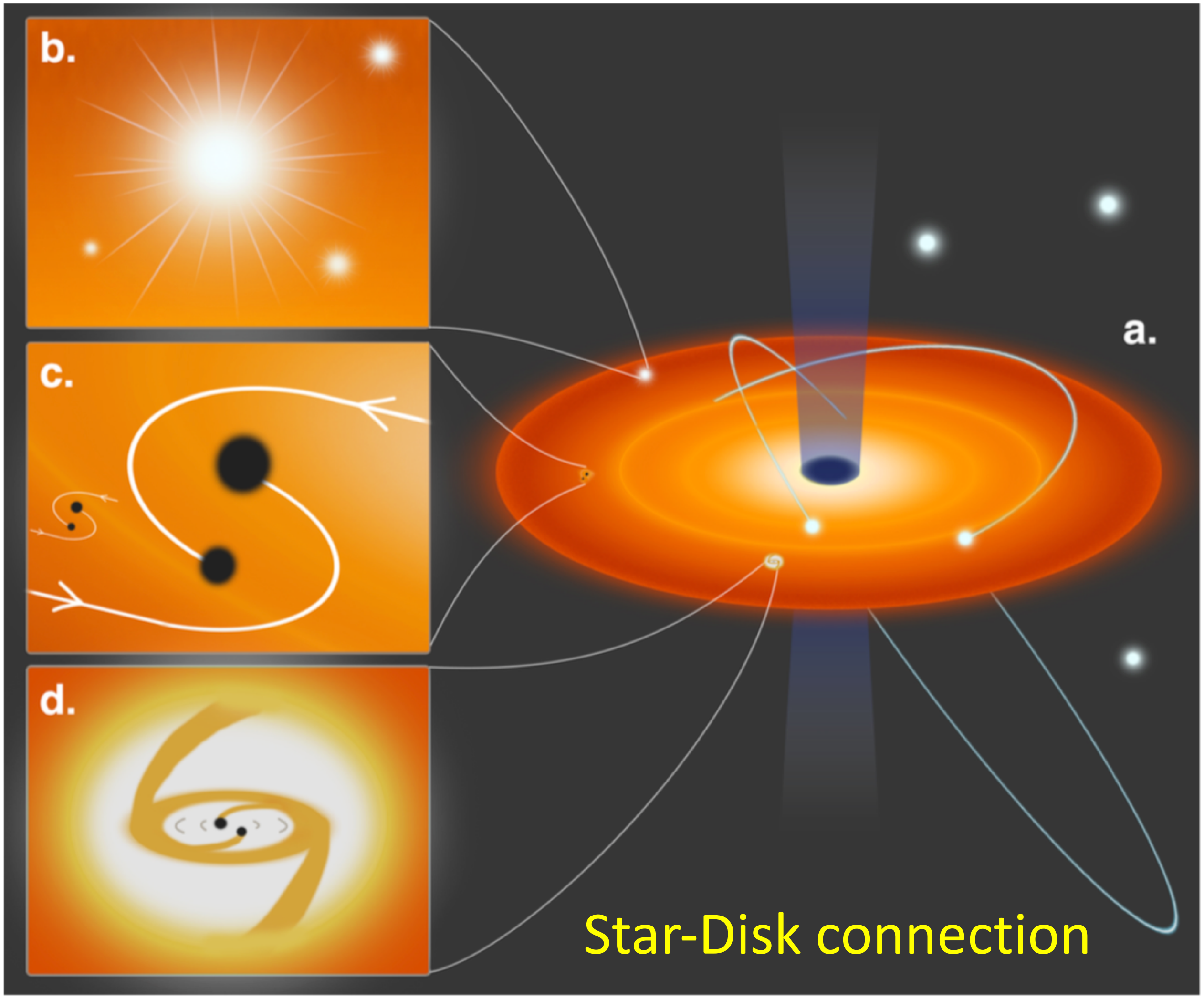


Low-L ellipticals

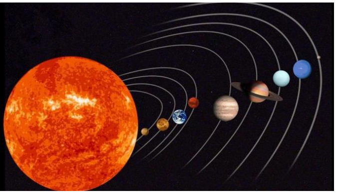
high-L ellipticals

Thomas et al 2016

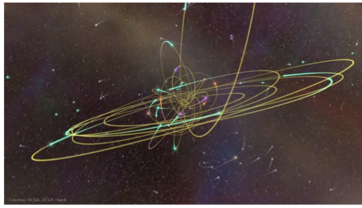
1. There is a MBH in every galaxy
2. Around each MBH there is a nuclear cluster
3. AGN occurs when a MBH is fed by a disk
4. Stars interact with the disk during their passages



Star-Disk connection



AGN-planet connection: Relevant physical parameters



Planetary systems:

1. Mass ratio: 10^{-6} - 10^{-3}
2. Period: days-centuries
3. Radius/semi major axis: 10^{-4}

Galactic Center system:

1. Mass ratio: 10^{-6} - 10^{-3}
2. Period: yrs- millenium
3. Radius/semi major axis: 10^{-5}

Protostellar disks

1. Disk mass/star mass: 0.01-0.1
2. $H/r = 0.05$-0.2
3. $Q > 10$
4. Persistent time scale: 3-10My

AGN and young stellar disk

1. Disk mass/star mass: ~0.01
2. $H/r \sim 0.01$-0.1
3. Q: ~ 1
4. Persistent time scale: 1-100My

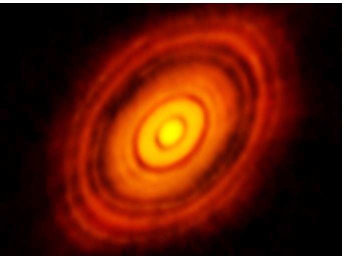
Required model parameters

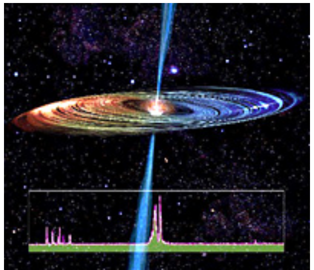
Nuclear star clusters:

1. Stellar density
2. Dynamical property
3. Connection to host galaxy

Accretion disks:

1. Capture rate
2. Accretion & stellar IMF
3. Contamination & BH formation





Dissipation & accretion rate in AGN disks

$\dot{M}$ $=L_{Bol}/\varepsilon c^2$ $\varepsilon\sim0.065$

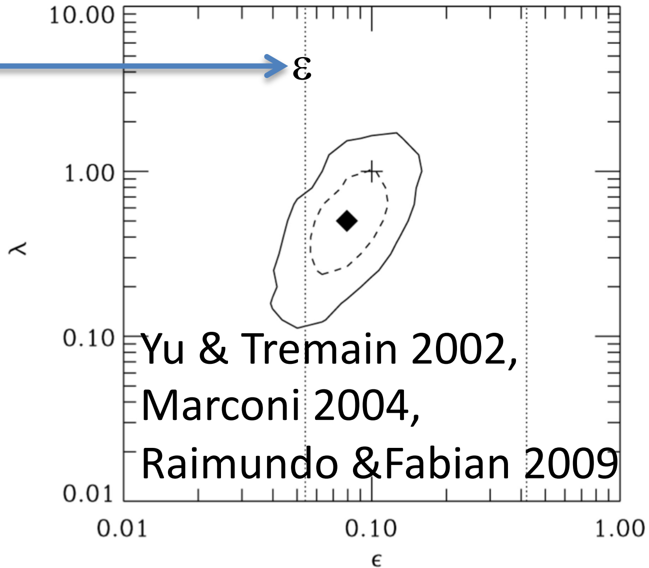
$=\lambda\ \dot{m}_E$ $\lambda\sim0.6$

$\dot{m}_E$ $=4\pi G m_p M_h/\varepsilon\sigma_T c$

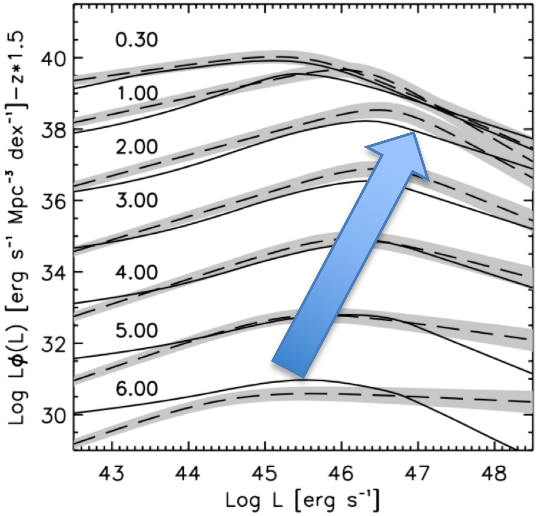
Timescales $\tau_{Sal}=M_h/\dot{m}_E$

$P(R)=(R^3/GM_h)^{1/2}$

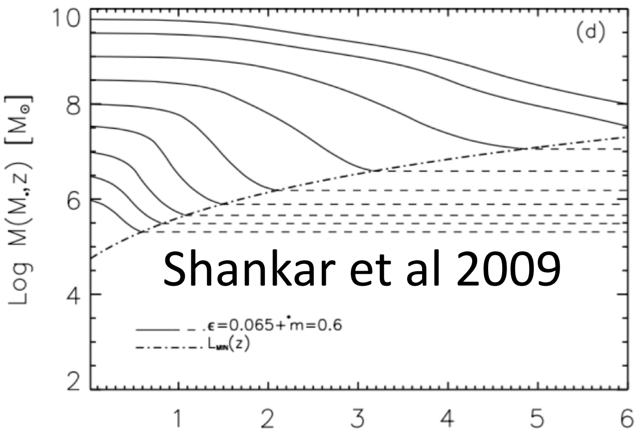
Diffusion: $\tau_{diff}(R_{out})=P(R_{out})/2\pi\alpha h^2$



Yu & Tremain 2002,
Marconi 2004,
Raimundo &Fabian 2009

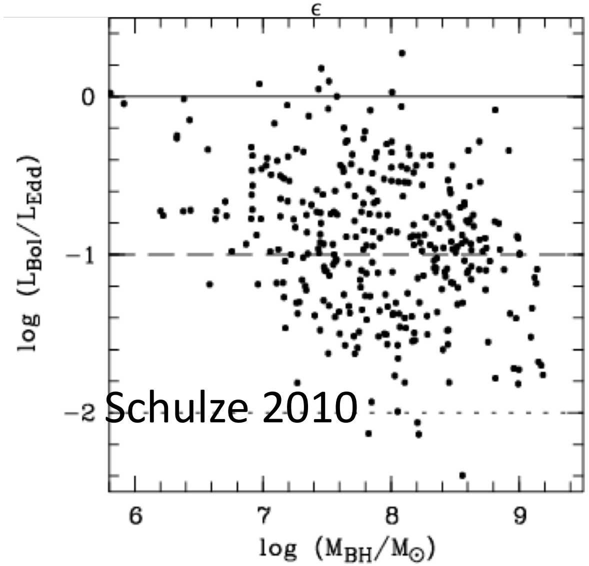


Evolution of AGN luminosity function



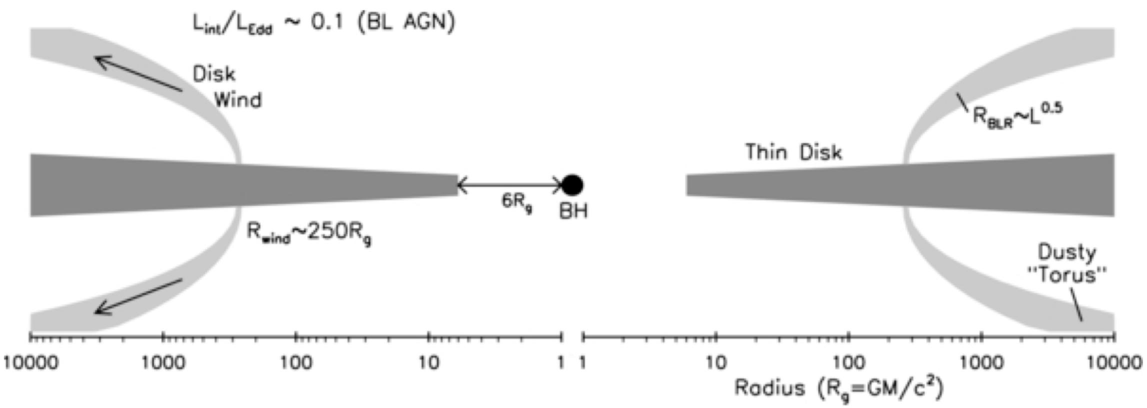
Shankar et al 2009

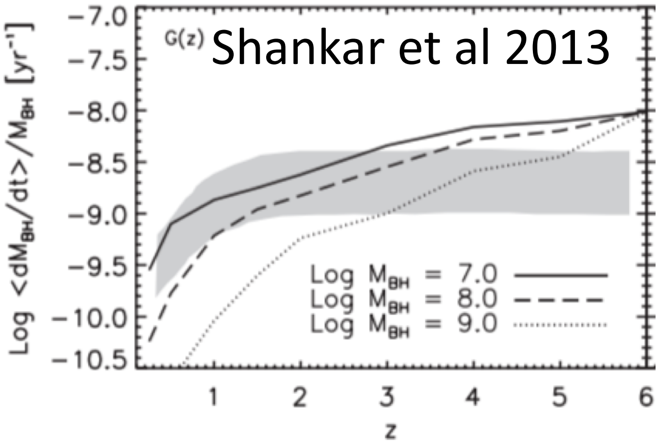
Black hole growth
fed by disk accretion



Schulze 2010

A generic quantitative AGN accretion disk model




Shankar et al 2013

$$R_o = GM_h/\sigma_o^2 = 10 m_8 \sigma_{200}^{-2}\mathrm{pc} \qquad m_8 = M_h/10^8 M_\odot \qquad \sigma_{200} = \sigma_o/200\mathrm{km\ s}^{-1}$$

- Steady state alpha disk ($h=H/R$, $R_{pc}=R/1pc$) Shakura & Sunyaev

$$\dot{M} = 3\pi\Sigma\nu \qquad \nu = \alpha H^2\Omega = \alpha h^2 \Omega R^2$$

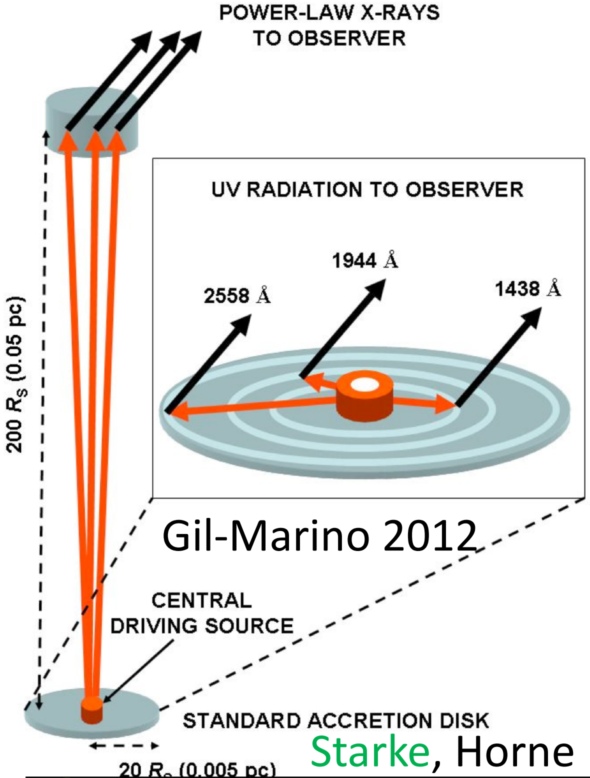
- Marginal gravitational stability (Safronov, Toomre)

$$\Sigma = \Sigma_Q/Q \qquad \Sigma_Q = h(M/\pi R^2),$$

$$\alpha h^3/Q \sim (\lambda/\varepsilon)\,(4\pi/3\sigma_{es})(Gm_p/c\Omega) \sim 10^{-5}\, m_8^{-1/2} R_{pc}^{3/2} \qquad \textbf{(1)}$$

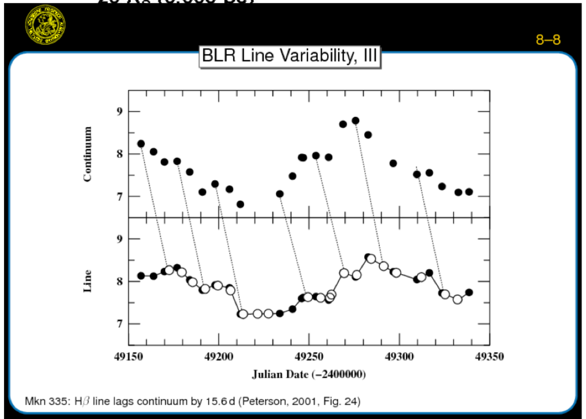
XJZhang

Reverberation from accretion disk to dusty torus



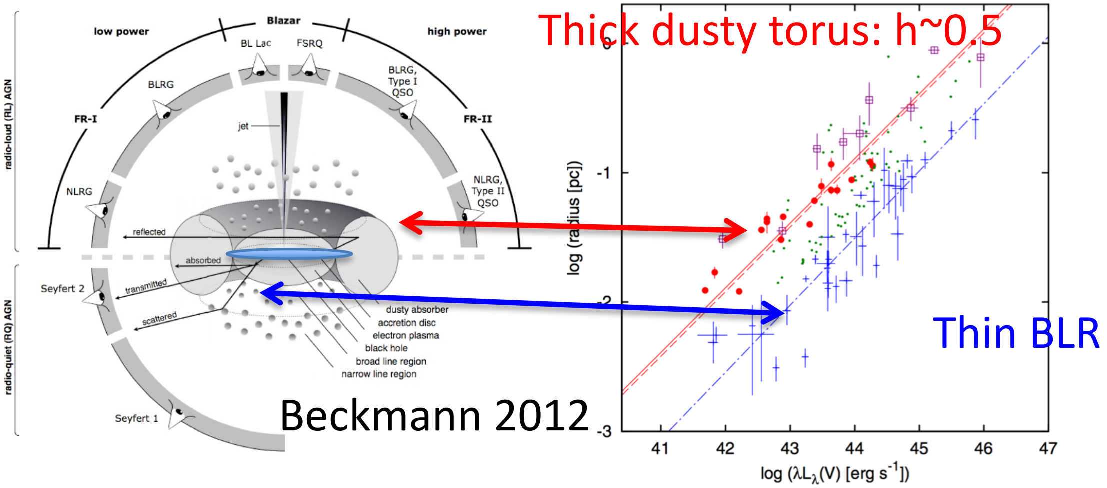
Gil-Marino 2012

Starke, Horne



BLR Line Variability, III

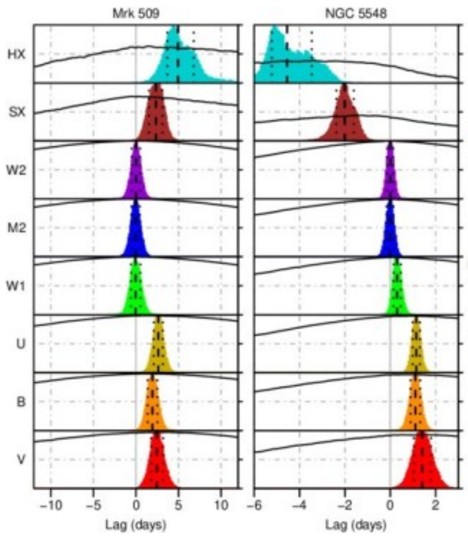
Mkn 335: Hβ line lags continuum by 15.6 d (Peterson, 2001, Fig. 24)



Thick dusty torus: h~0.5

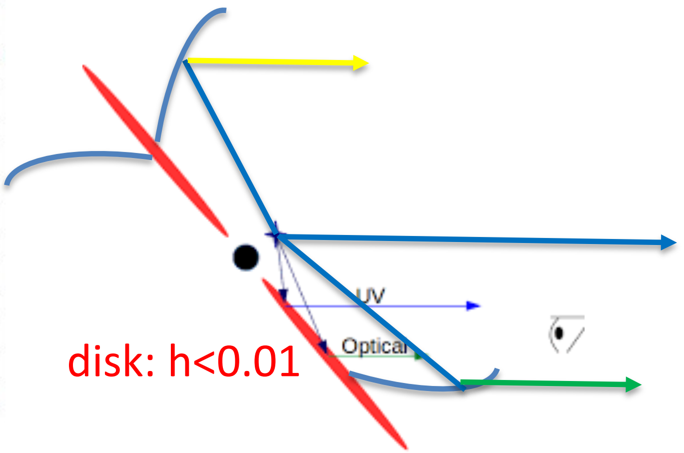
Thin BLR

Beckmann 2012



Edelson et al 2018

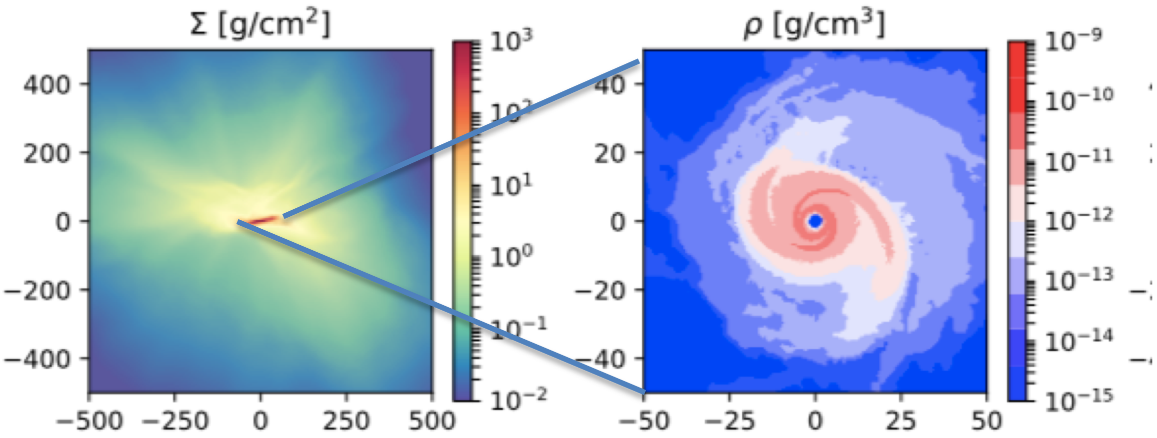
BLR: h<0.1

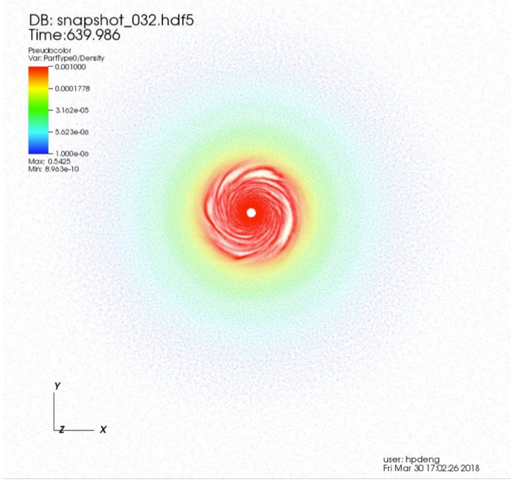


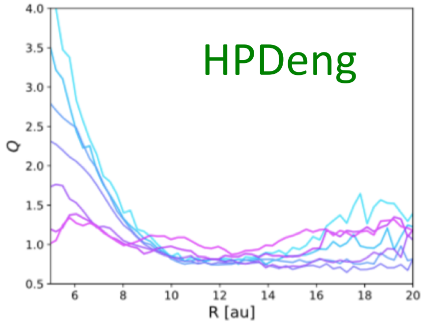
disk: h<0.01

Iso-delay surface:
Blandford, McKee 1982, Gaskell

Gravitational stability & angular momentum transport







L-Pringle, Rees; Rafikov Rice; Riols, Latter

$$\alpha = \psi\alpha^{R}_{gt}(r, \Sigma) + \alpha_m \quad (2)$$

(3)

At $R_{pc}>1$, Q~**1**-10, α~0.1-**1**, h ~ **0.03** $m_8^{-1/6}R_{pc}^{1/2}$,
$\tau_{disk} > 40\, m_8^{5/6}R_{pc}^{-3/2}$(optical depth),
can **NOT** fragment & form stars despite Q~1

XJZhang, ZXWang

Disk parameters are specified for a set of M_8 & R_{pc}

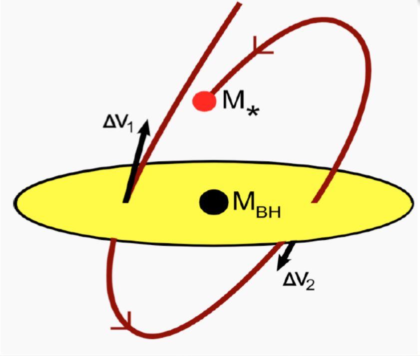
Capture by the disk

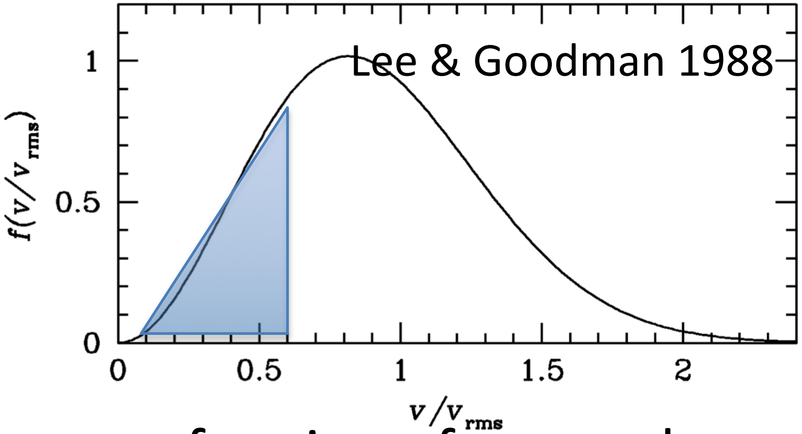
Hydro drag: Artymowicz, L, Wampler1993 $F_d = 4\pi G^2 m_*^2 \rho \frac{C_d}{V_c^2}\left[\left(\frac{V_c}{V}\right)^2 + \left(\frac{V}{V_c}\right)^2\right],$

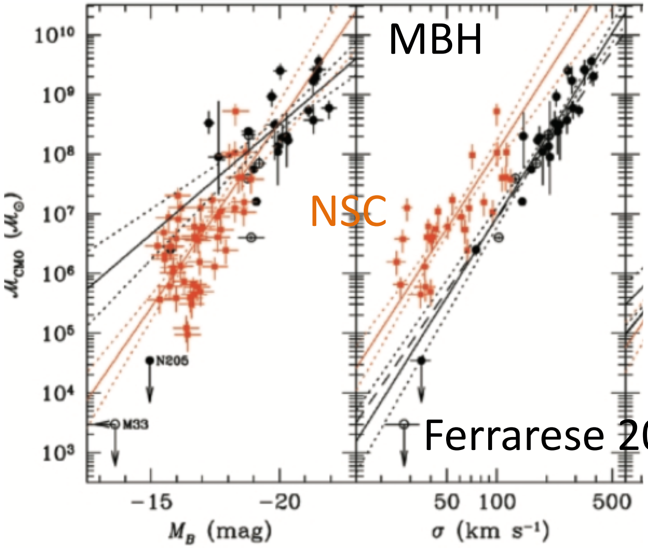
$C_d = C_d^{gas} + C_d^{wave} \sim 6$

Condition for disk trapping within ΔT: $\frac{V_z V^3}{V_K^4} \leq \xi = 32 C_d \frac{m_*}{M_h}\frac{\pi R^2 \Sigma}{M_h}\frac{\Delta T}{P}$

Phase space distribution: $dN_* = \nu_* \exp\left[-\frac{v_r^2 + (v_\phi - V_{\rm rot})^2 + v_z^2}{2\sigma^2}\right]\frac{d^3r\,d^3v}{(2\pi\sigma^2)^{3/2}}$




Lee & Goodman 1988


MBH

NSC

Ferrarese 2006

Phase space fraction of trapped stars:

$$dN = q\,dN_* = 4\pi q R^2 \nu_* \, dR$$

$$q(\zeta) = \left(\frac{\sigma}{v_K}\right)^3 \int_{u_z u^3 \leq \zeta^4} e^{-(E_x + E_z)} \frac{d^2u\, d^2\xi}{(2\pi)^2}$$

Nuclear clusters: stellar reservoir

$\nu_o \sim 2.5\mathrm{x}10^6 M_{c,8}\,\mathrm{pc}^{-3}$

$P_o \sim 5\mathrm{x}10^4 M_{c,8}^{-1/2}\,\mathrm{yr}$

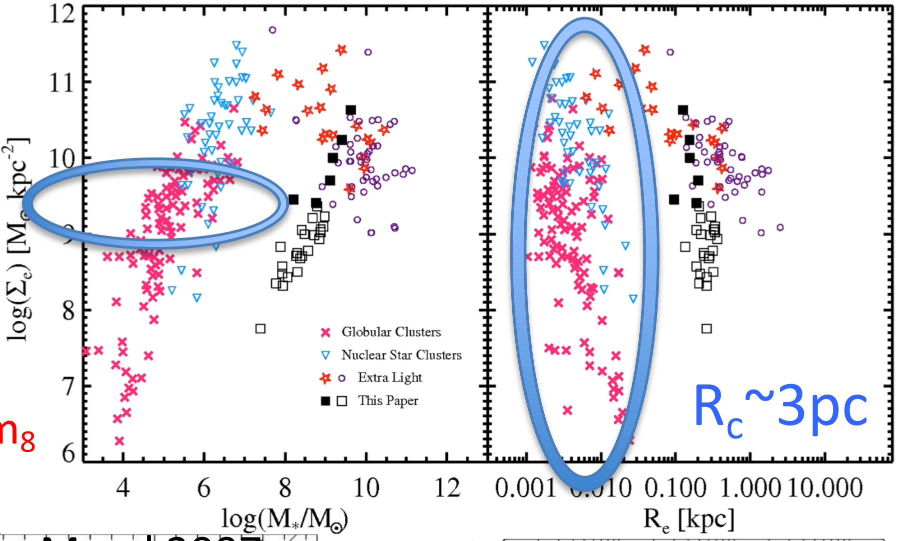
$\sigma_o \sim 350 M_{c,8}^{1/2}\,\mathrm{km\ s}^{-1}$

$M_{c,8} \sim 21\,\sigma_{200}^{4.3}$

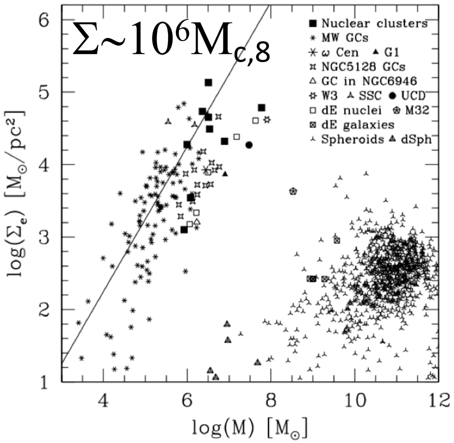
$m_8 \sim 1.8\,\sigma_{200}^{4.4} \sim 0.08 M_{c,8}$

Efficiency of NSC in forming MBH

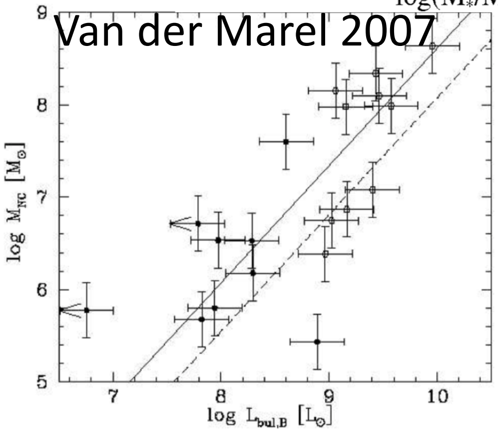
Central stellar density is a function of m_8



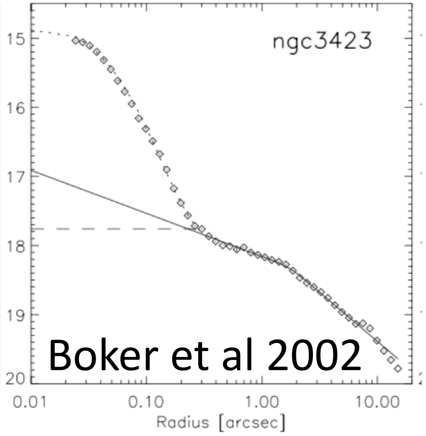
$R_c \sim 3\mathrm{pc}$



$\Sigma \sim 10^6 M_{c,8}$



Van der Marel 2007



Boker et al 2002

Capture rates:
XJZhang

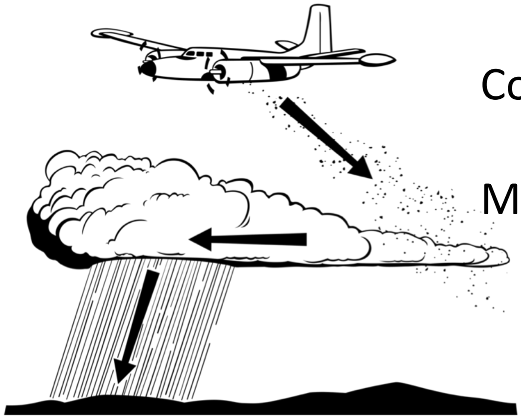
$$d\dot{N} \simeq \frac{\pi\xi^4\nu_* R^2 dR}{2\Delta\tau} \simeq \frac{48C_d}{\sqrt{\pi}P_0}\frac{h}{Q}\frac{dR}{R} \simeq \frac{2.7\times10^{-4}\sigma_{200}^{1.4}}{\mathrm{yr}}\frac{dR_{\mathrm{pc}}}{R_{\mathrm{pc}}^{1/2}}$$

Trapping rate is a function of m_8 and R_{pc}

Accretion onto trapped stars & their rejuvenation

If $R_R<H$, $R_B<R_R$ (**hot**) Bondi accretion (runaway growth)

$$\dot m_* \simeq \frac{4\pi G^2 m_*^2 \rho}{(v^2+c_s^2)^{3/2}} \simeq \frac{2\Omega}{Q}\frac{m_*}{h^3}\frac{m_*}{M_h}$$

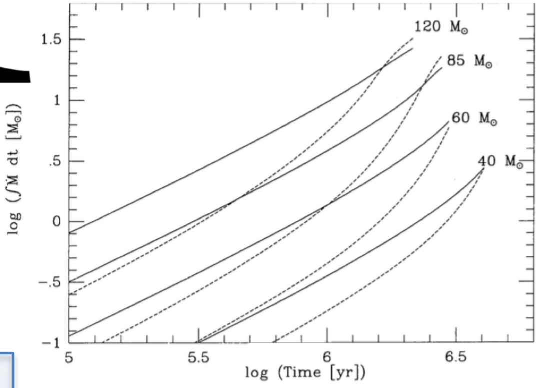


Condensation around seeds

Mass growth onto trapped *

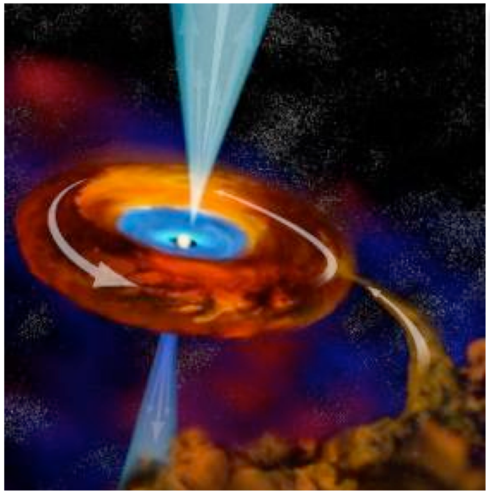
Bondi accretion time scale: (independent of M_h)

$$\boxed{\tau_B = m_*/\dot m_* \simeq 0.6(M_\odot/m_*)R_{pc}^3\,\mathrm{Myr}}$$



Wind loss

$$\log\left(\frac{\dot m}{M_\odot \mathrm{yr}^{-1}}\right) \simeq 1.74\log\left(\frac{L_*}{L_\odot}\right) - 1.35\log T_{\mathrm{eff}} - 9.55$$



J Szulagyi

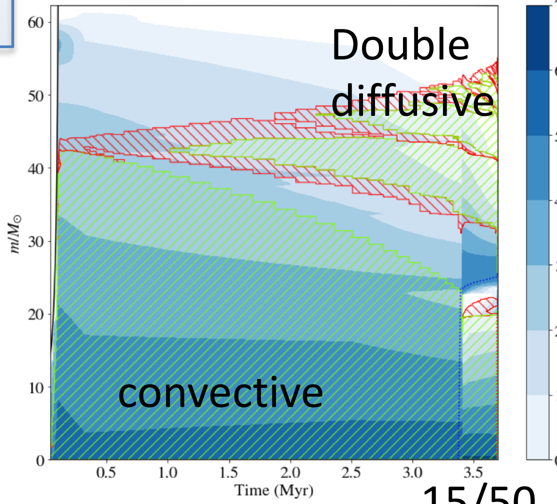
$$\boxed{\tau_w = m_*/\dot m \sim (60M_\odot/m)^3\,\mathrm{Myr}}$$

$$\boxed{m_{*w} \sim 120R_{pc}^{-3/2}M_\odot}$$

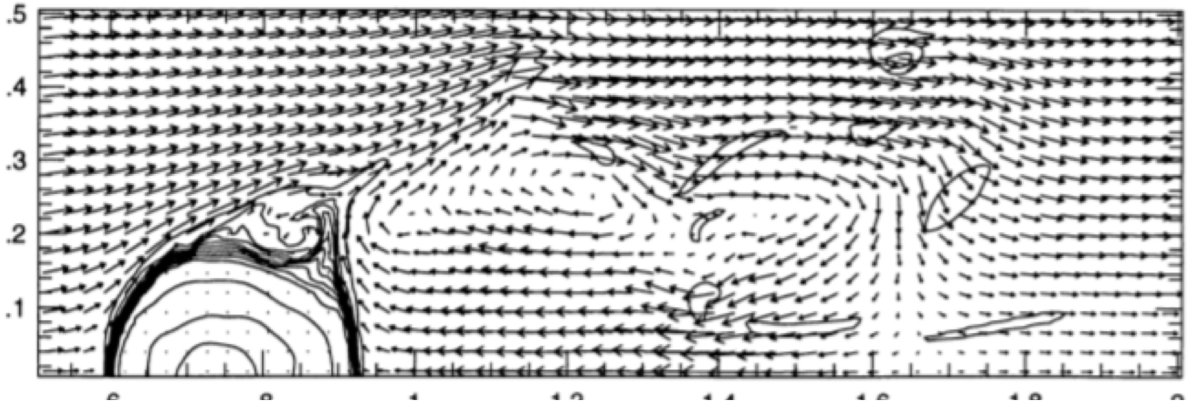
Main sequence evolution time:

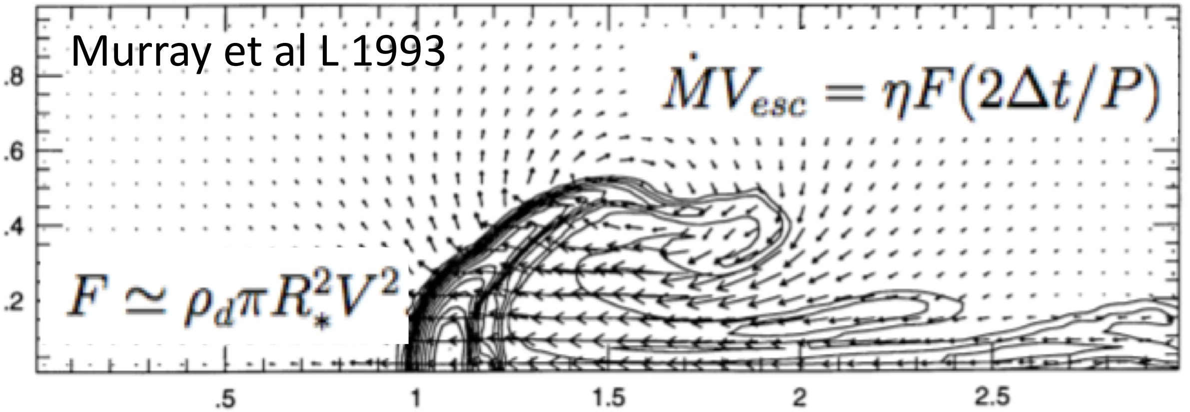
$$\tau_* \sim 10(m/M_\odot)^{-2.5}\mathrm{Gyr}$$

Can be prolonged with mixing, M Cantiello



Ram pressure striping of fast (hard encounters with $V_zV^3>\xi V_k^4$) flyby stars

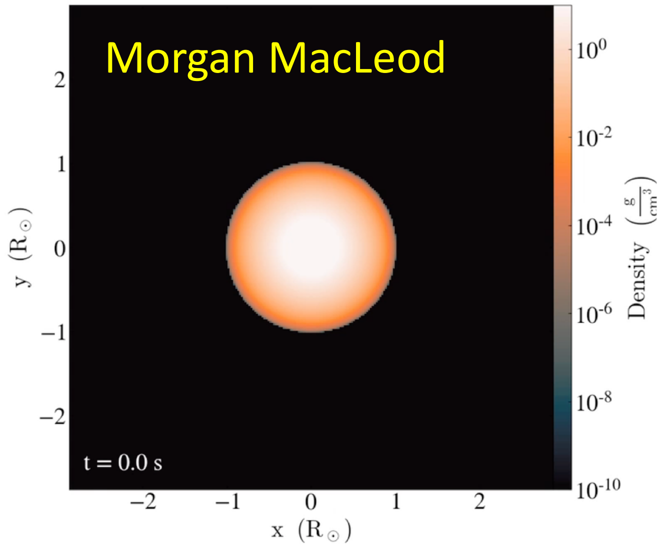




Murray et al L 1993

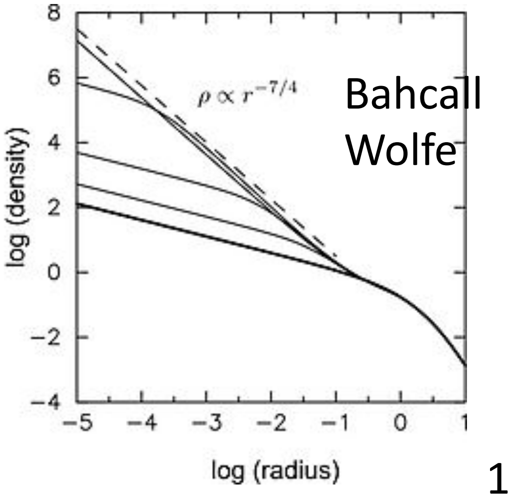
$$\dot{M}V_{esc} = \eta F(2\Delta t/P)$$

$$F \simeq \rho_d \pi R_*^2 V^2$$



Morgan MacLeod

Modify cusp & reduce the TDE rate



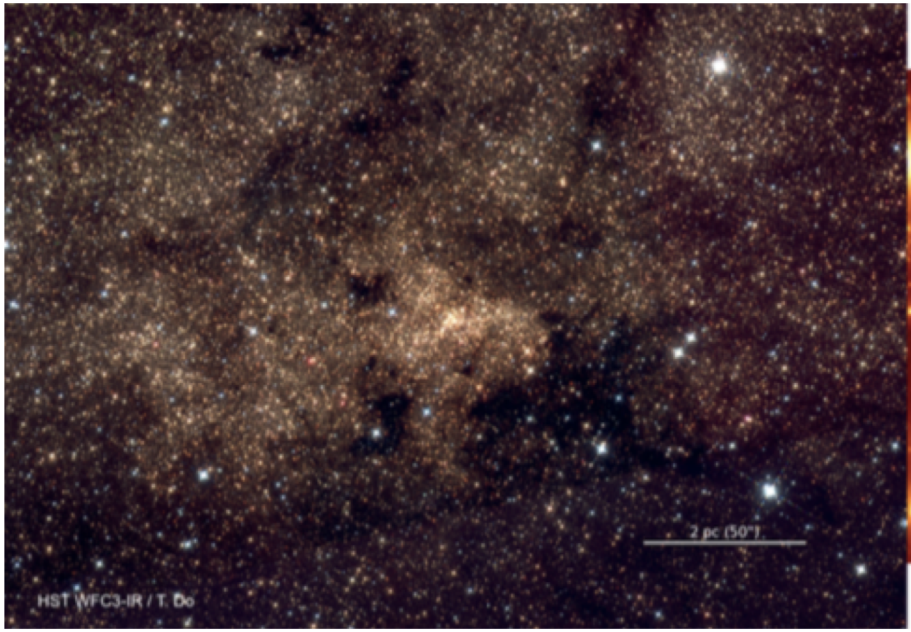
Bahcall Wolfe

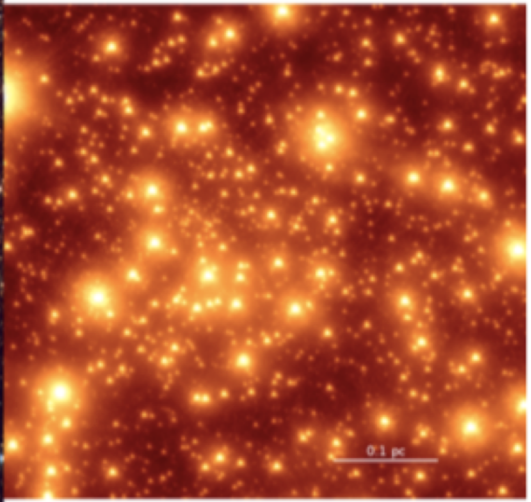
Ram pressure striping: $\rho_* \le 2\pi\rho(V^2/g_*R_*) = 2\pi\rho(V/V_{esc})^2$

$$\frac{r}{a_{tide}} < \frac{r_{remove}}{a_{tide}} \simeq \left[\frac{Nh}{Q}\left(\frac{M_h}{M_*}\right)^{4/3}\right]^{2/13}$$

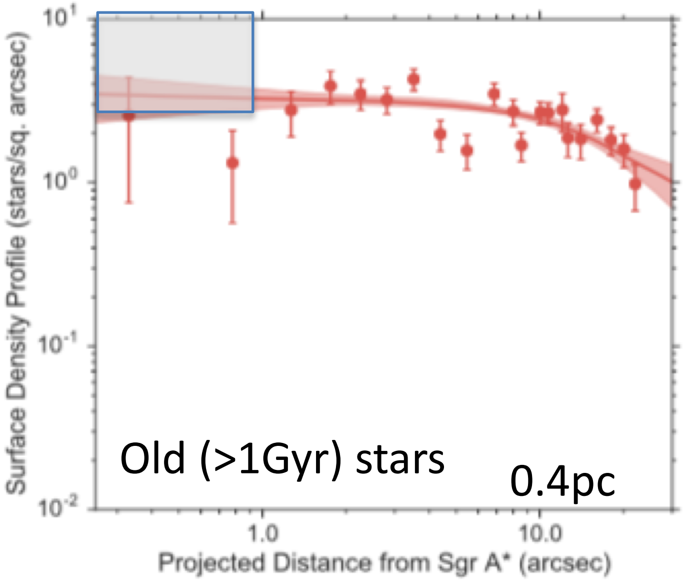
=> Removal by the disk before tidal disruption

``Missing cusp'' in the Galactic Center



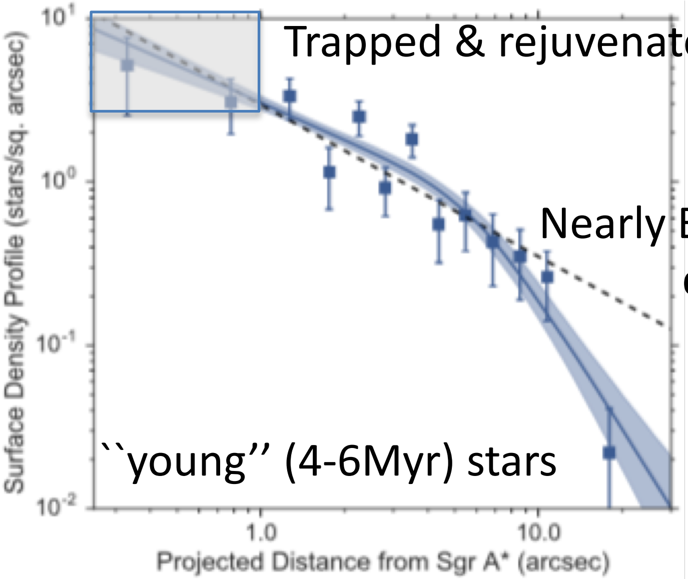


Do et al 2016



Old (>1Gyr) stars

0.4pc



Trapped & rejuvenated stars?

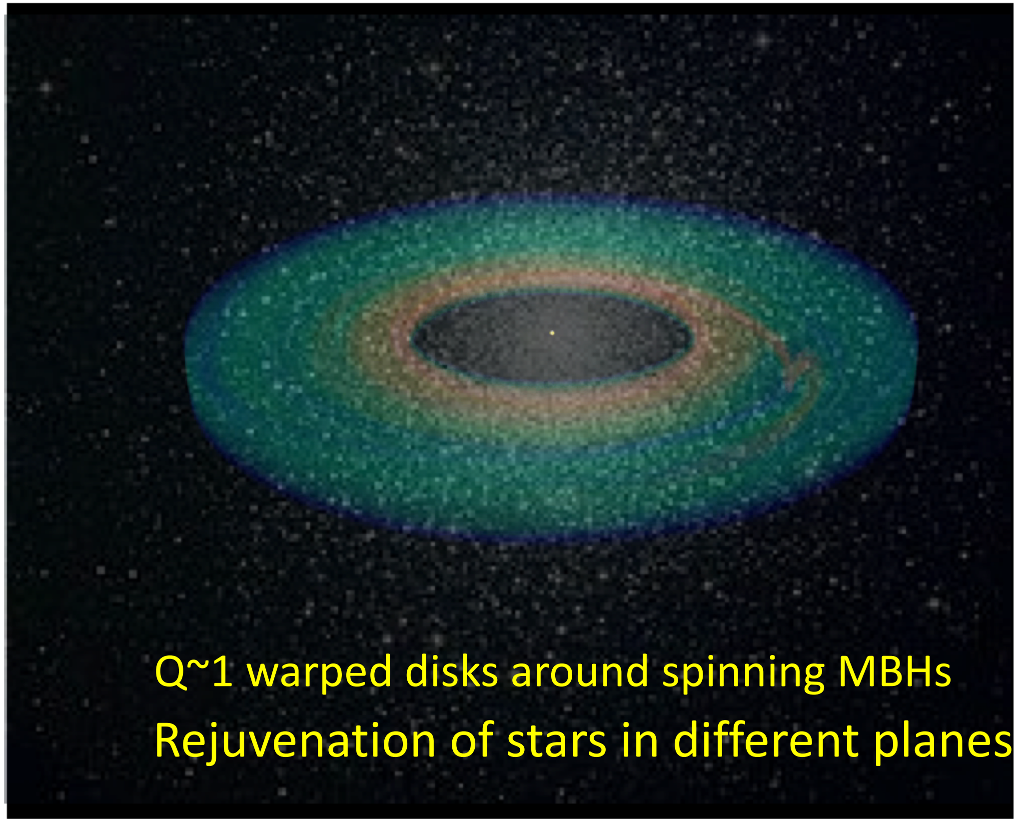
Nearly Bahcall-Wolfe distribution

``young'' (4-6Myr) stars

Disk’s reorientation due to infall of turbulent gas

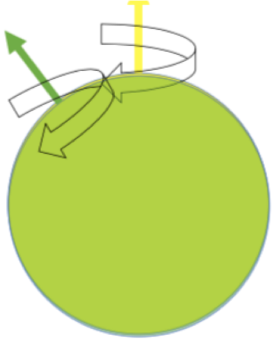
``young’’ S and disk stars

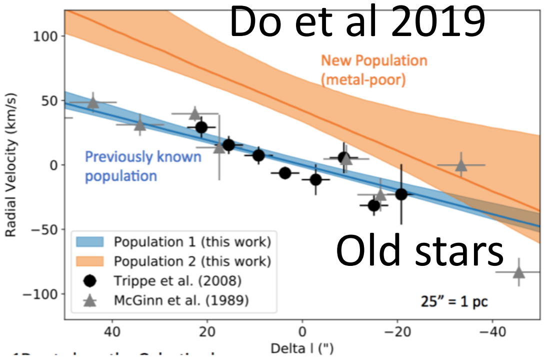
Ghez, Lu, Genzel



Q~1 warped disks around spinning MBHs

Rejuvenation of stars in different planes

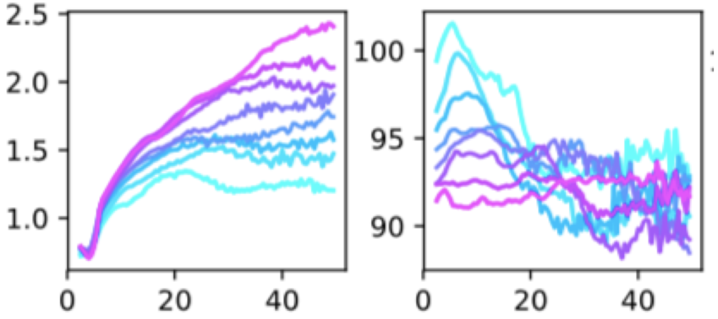


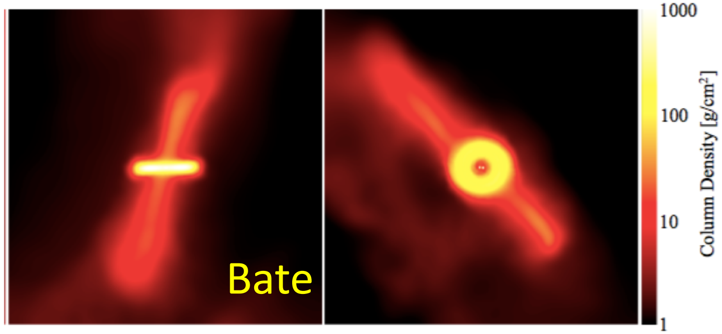


Do et al 2019

Old stars

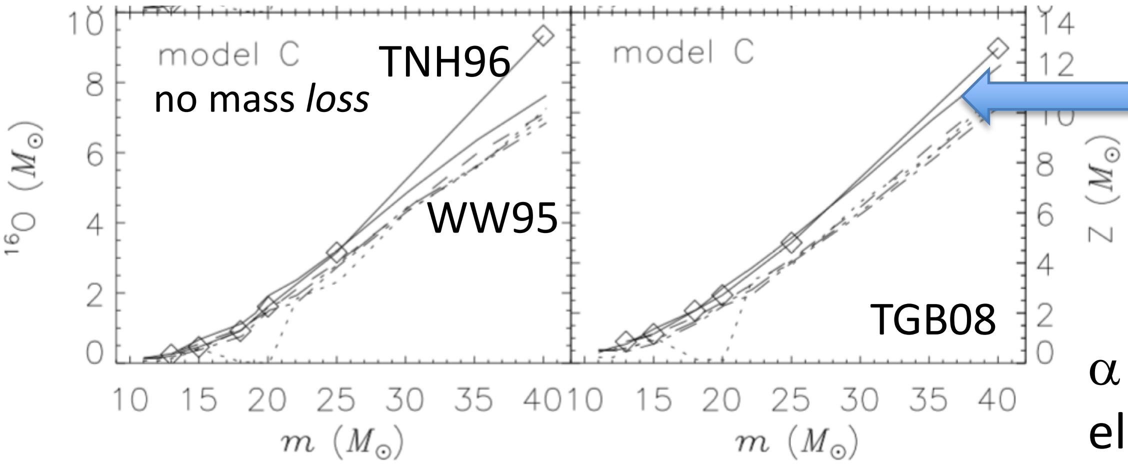
HPDeng, MBate,RNaylor,XJZhang





Bate

Implication: *In situ* metallicity enrichment

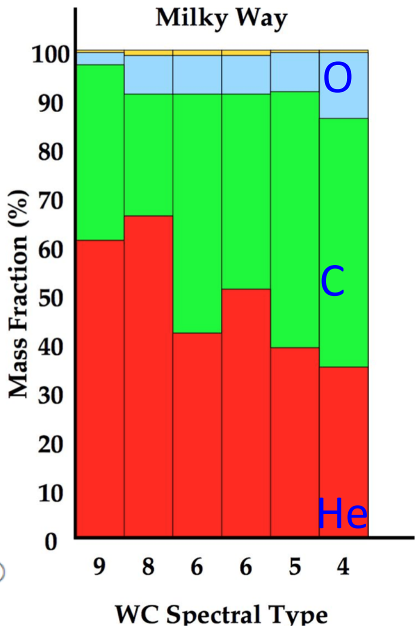


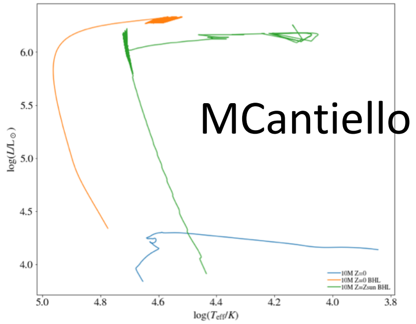
a) Type II supernovae yield:

$$m_{zSN} \simeq 0.3(m_* - 12M_\odot)$$

$$m_O \sim 2m_z/3$$ up to ~10M$_o$

α vs Fe-peak elements



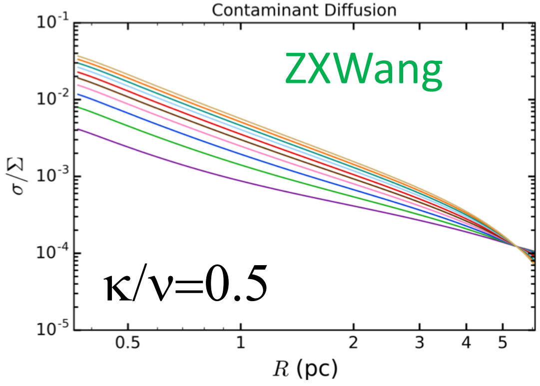


b) **WR** and AGB winds:

$$m_{zw}(m_{*w}) = \dot{m}\tau_*/2 = 35R_{pc}^{-9/4}M_\odot$$

c) Local enrichment: $\dot{\Sigma}_Z = m_z(d\dot{N}_Z/2\pi R dR)$

$$m_z = m_{zw} + m_{zSN} = 35(R_{pc}^{-3/2} + R_{pc}^{-9/4} - 0.1)M_\odot$$



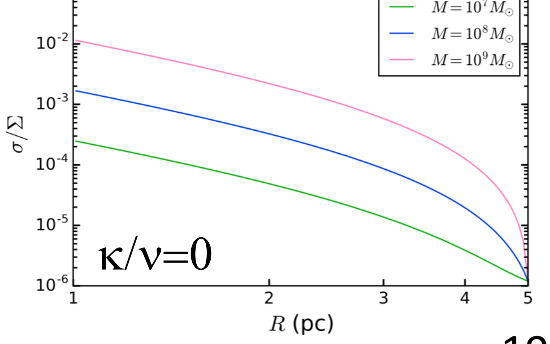
d) Heavy-element diffusion (Clarke 1988)

$$\Sigma\frac{\partial C}{\partial t} + \Sigma U_r\frac{\partial C}{\partial R} = \frac{1}{R}\frac{\partial}{\partial R}\left(R\kappa\Sigma\frac{\partial C}{\partial R}\right) + \dot{\Sigma}_Z$$

$$\kappa = 0 \quad => \quad \Delta Z(R) = \frac{m_z d\dot{N}R}{U_r 2\pi\Sigma R dR} \simeq 3\times 10^{-3}\sigma_{200}^3$$

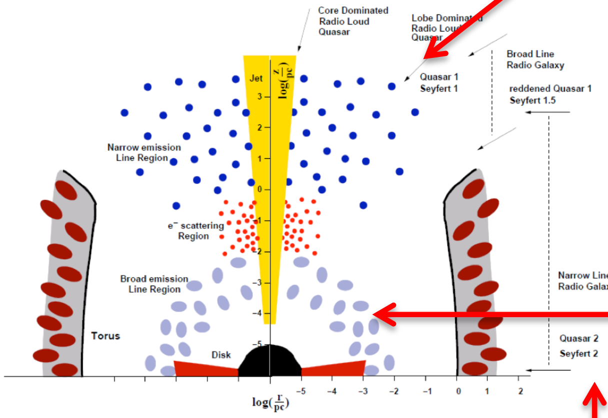
κ/ν=0.5

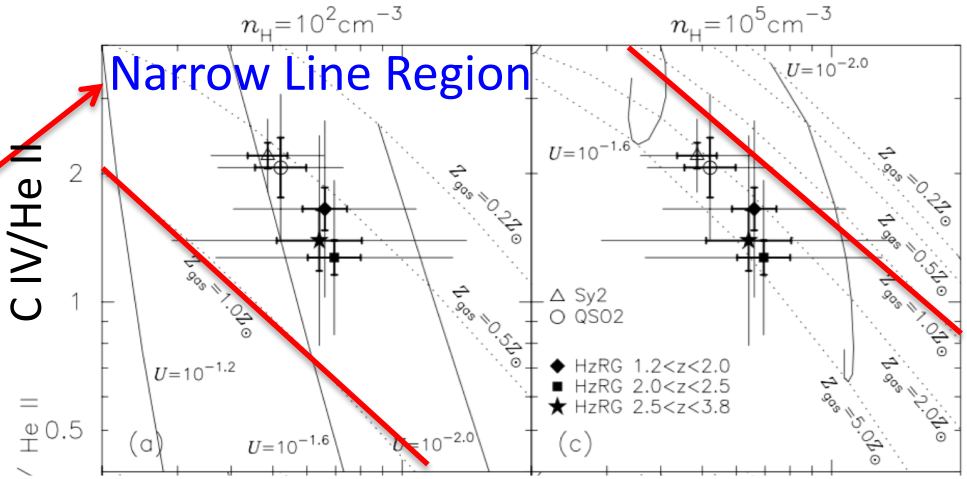
ΔZ~ *Q*(1-10)



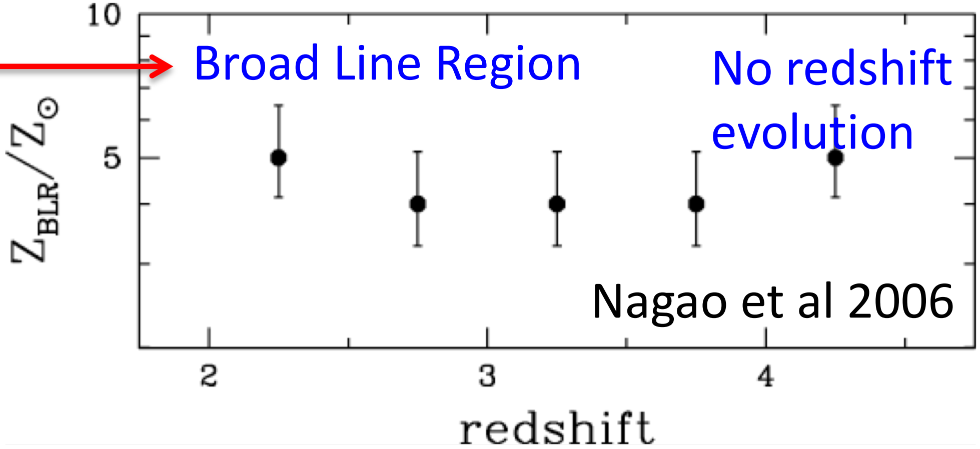
Super-solar metallicity in high-redshift AGNs

$Z_{BLR} > Z_{NLR}$





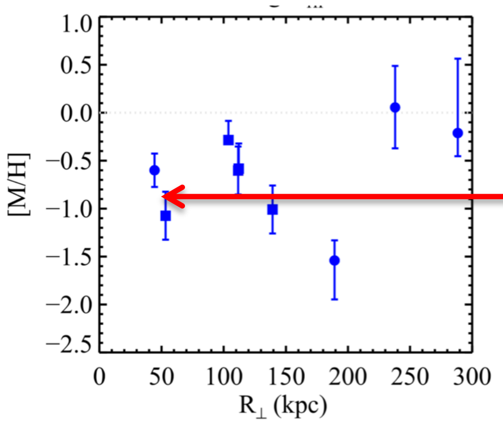
Narrow Line Region



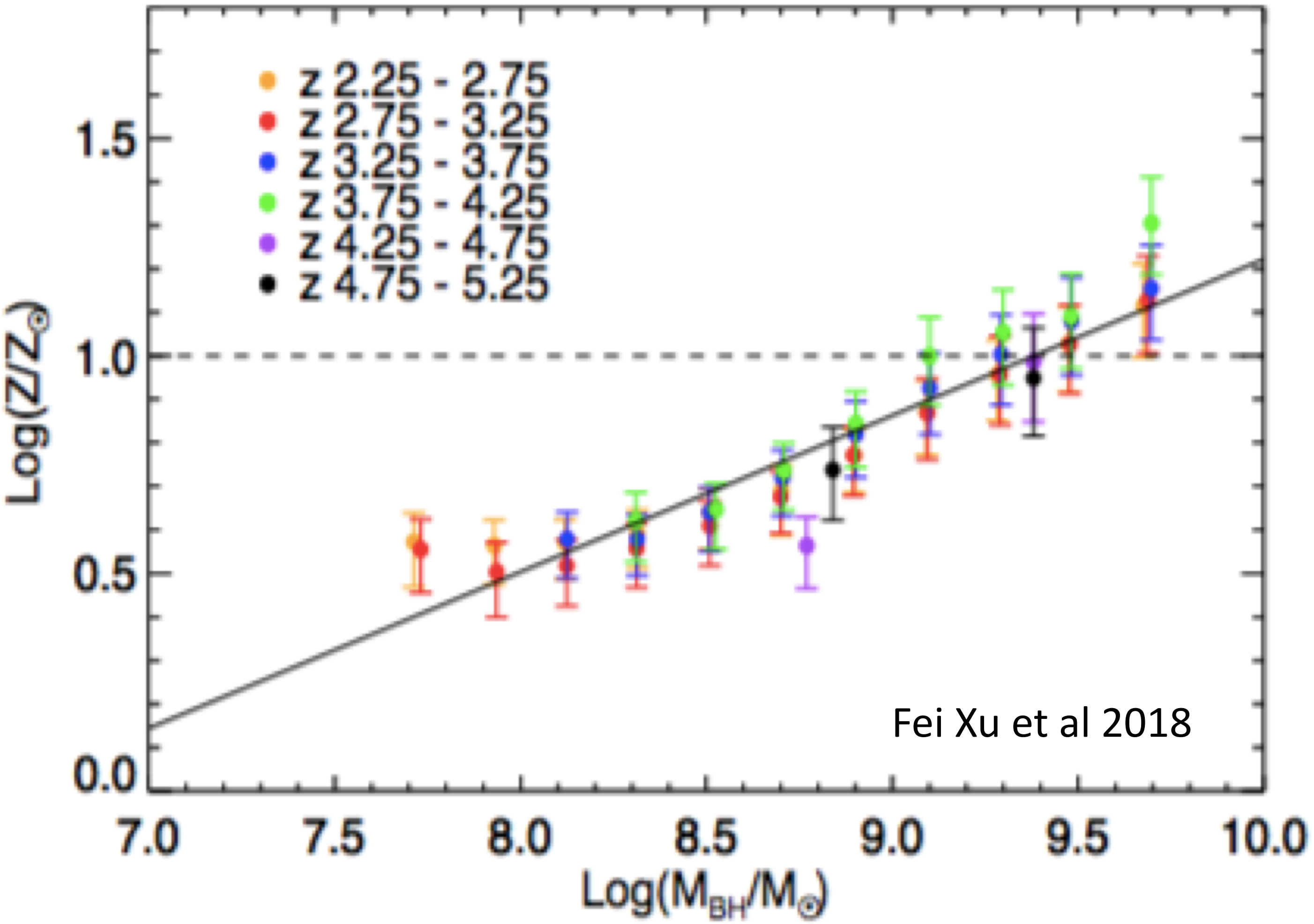
Broad Line Region

No redshift evolution

Nagao et al 2006



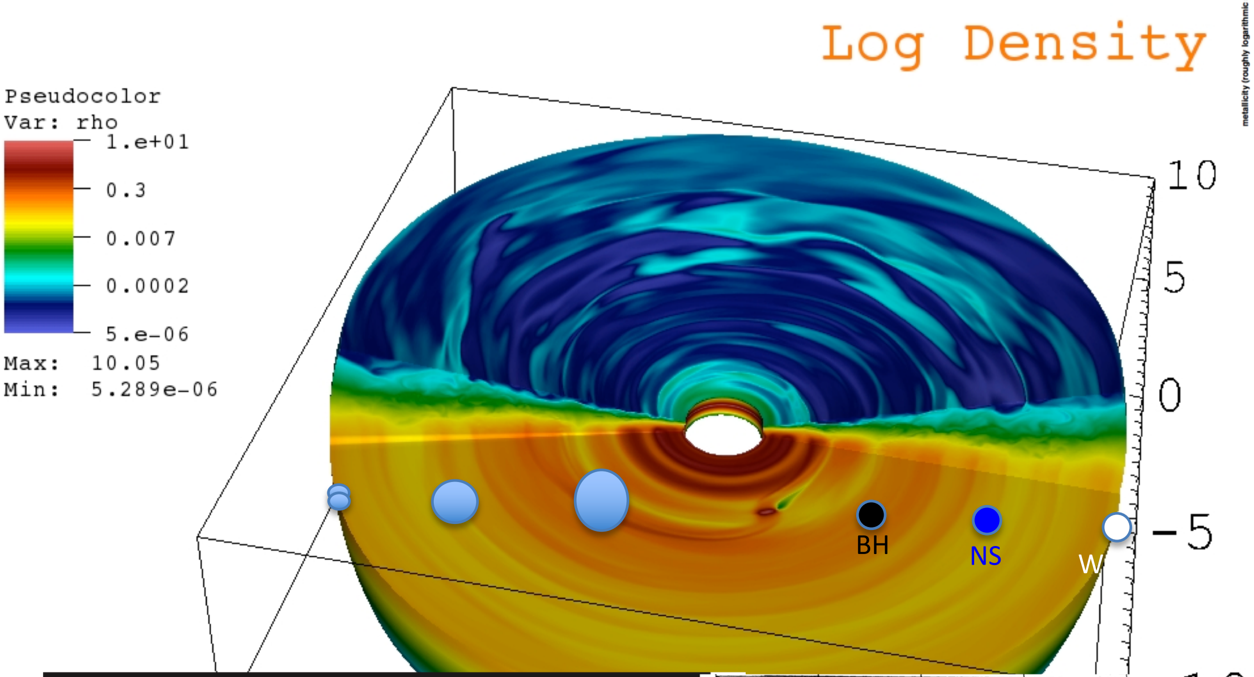
Quasars probing metal-poor outskirts of quasars
Lau, Prochaska, Hennawi 2016

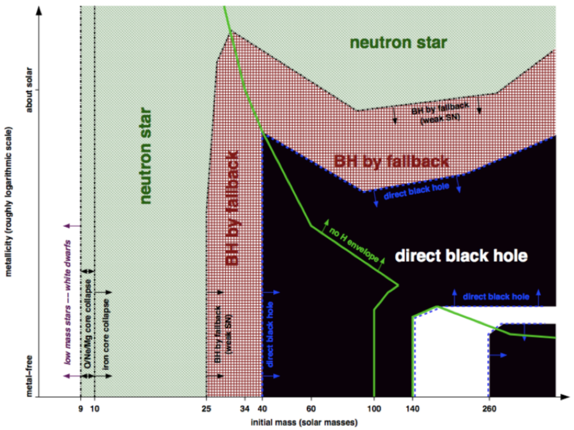


1) Indicators: N V/C IV & (O IV+Si IV)/C IV (α elements)
2) Metallicity increases with ~$M_{BH}^{1/3}$
3) Independent of redshift, no chemical evolution!!!

MBH depository of local heavy-element contaminants

Stellar rejuvenation & evolution





Heger et al 2002

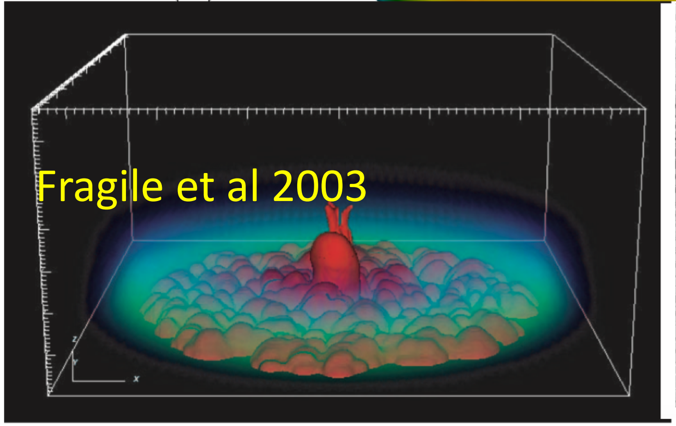
`young’ & massive stars

a) Capture host galaxy stars

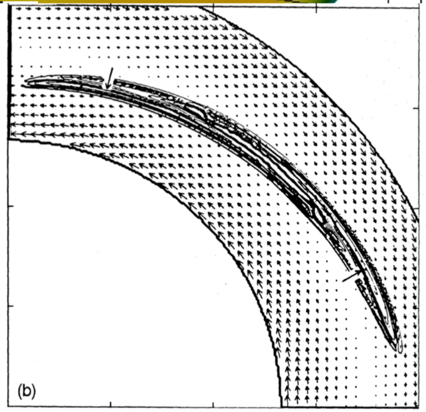
b) Opaque disk ($\tau_{disk}>1$)
$R_{opaque} \sim 12\ m_8^{5/9}$ pc

c) Top heavy IMF:
Min (m_{*B}, m_{*w}) $\sim 10^{1-2} M_o$

d) Binary main sequence stars possible at large a

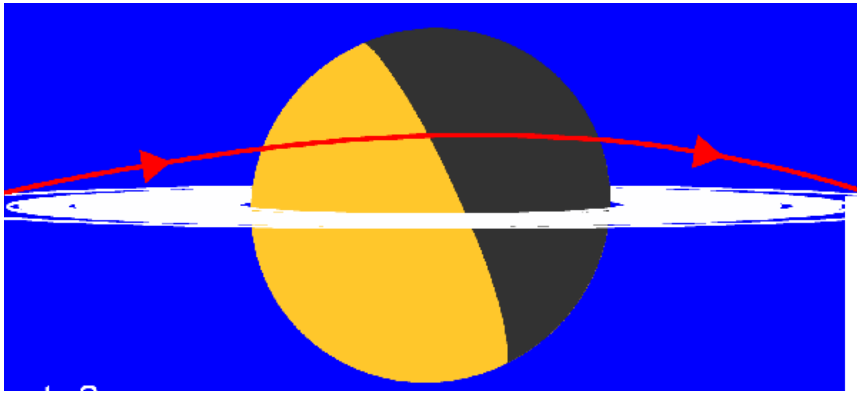


Fragile et al 2003



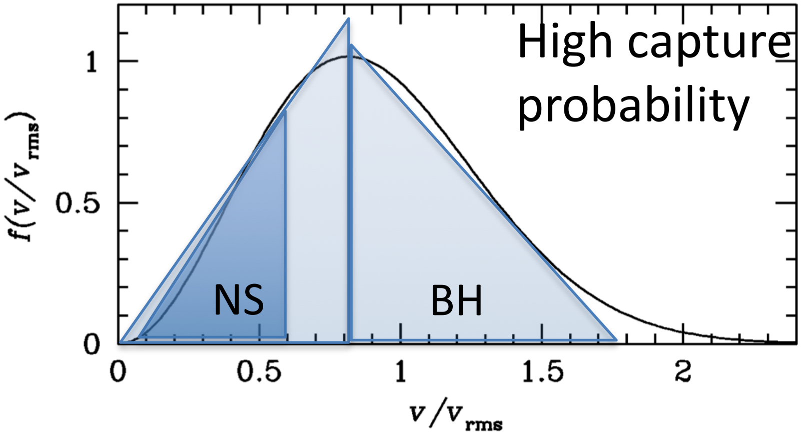
Rozyszka L. Bodenheimer 1995

Recapture of neutron stars and seed black holes



$$\dot{N}_{bh,t} = \int_{R_{in}}^{R_{bh}} d\dot{N} \simeq \frac{8\times10^{-4}}{\text{yr}}\sigma_{200}^{1.4}$$

modest kick speed: $V_{rms}(NS) > V_{rms}(BH)$



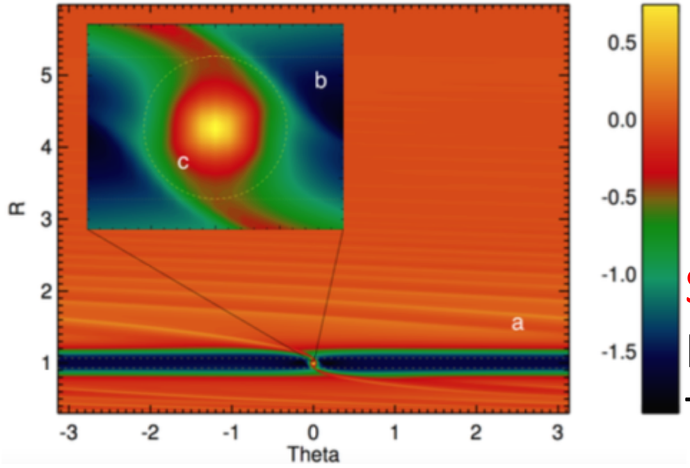
High capture probability

accretion radius = min $[R_B, R_R]$

$\tau_{\text{sal}} = m_*/\dot{m}_E$ =0.45 ε/λ Gyr

Mass growth: Eddington limited if

$\tau_{sal} > \tau_B$ or $m_* > 10^{-3}\varepsilon\lambda^{-1}R_{pc}^{3}M_o$

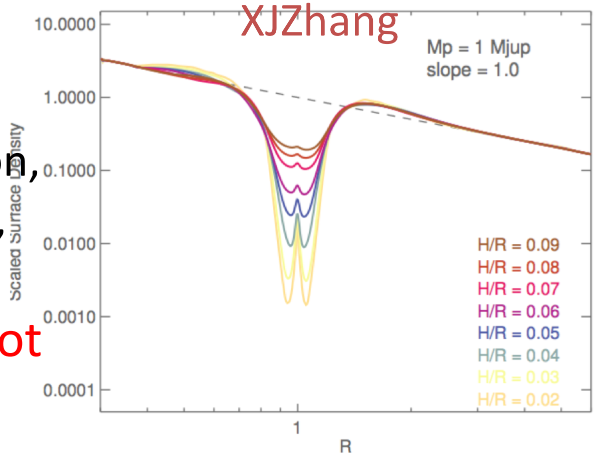


L Papaloizou 1986
Artymowicz, Lubow, Nelson,
Bryden, Masset, Armitage,
Li, Dobbs-Dixon, Kley

Seed BH can grow by a lot

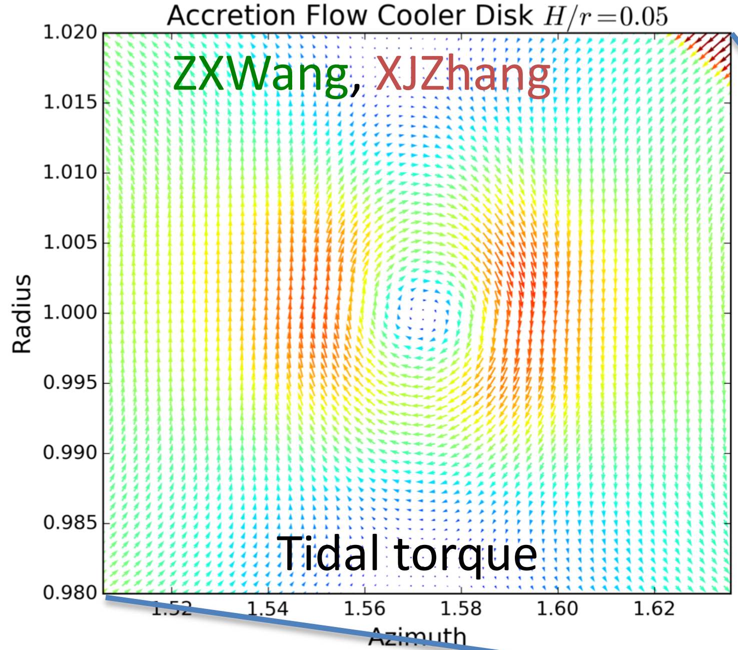
Mass limited by gaps:
Thermal Condition for
gap formation $R_R > H$.

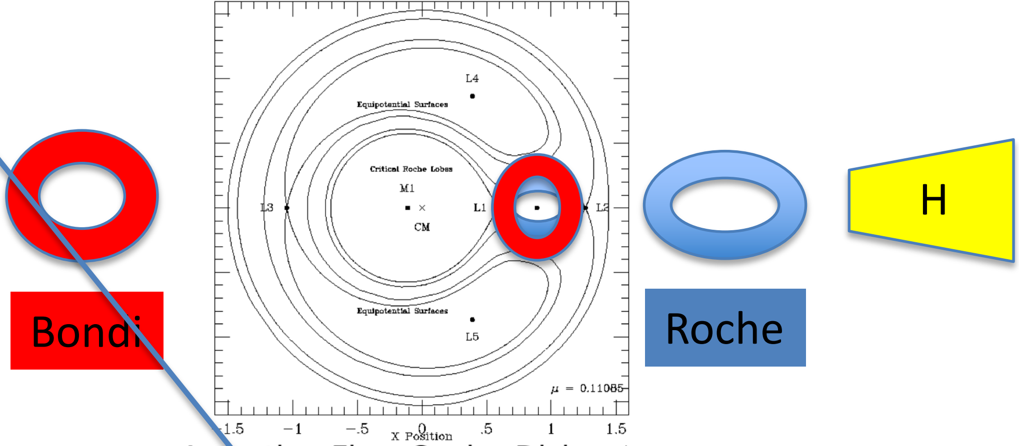
XJZhang

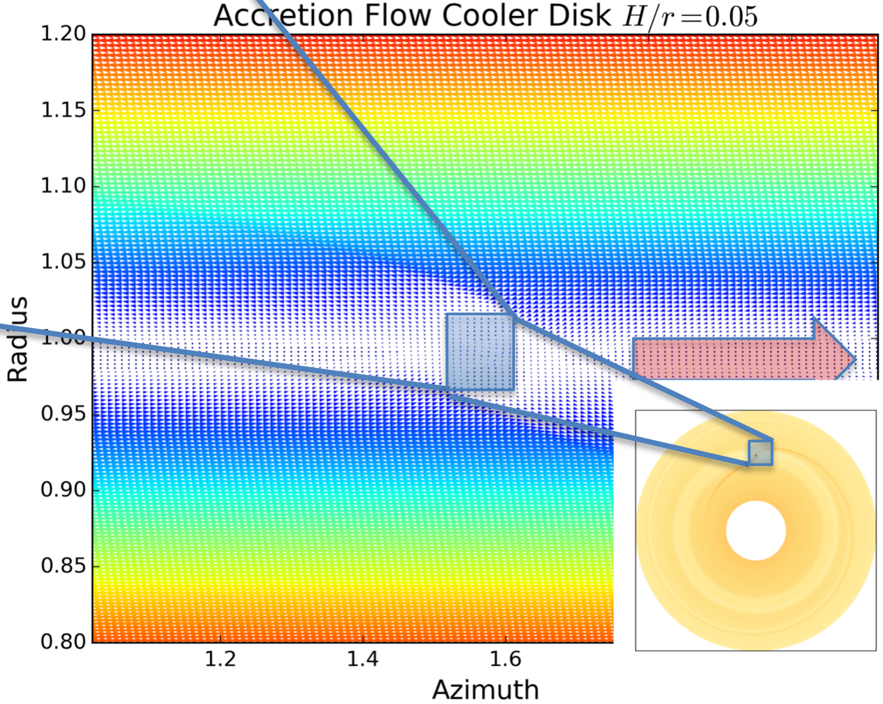


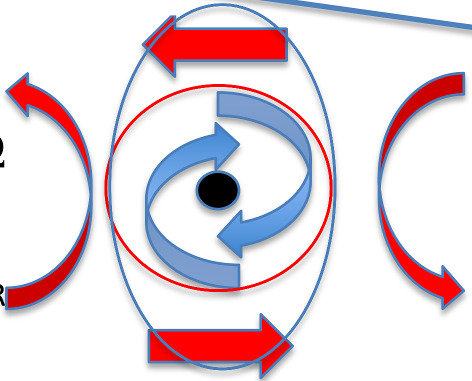
Angular momentum evolution (thin, h=0.05,q=10^{-4})

Modest-m_* seed black holes in **warm** disks with $R_B > R_R \sim H$, i.e. $m_* \sim (H/a)^{1/3} M_h$









Prograde

with $j_a \sim R_R^2 \Omega$

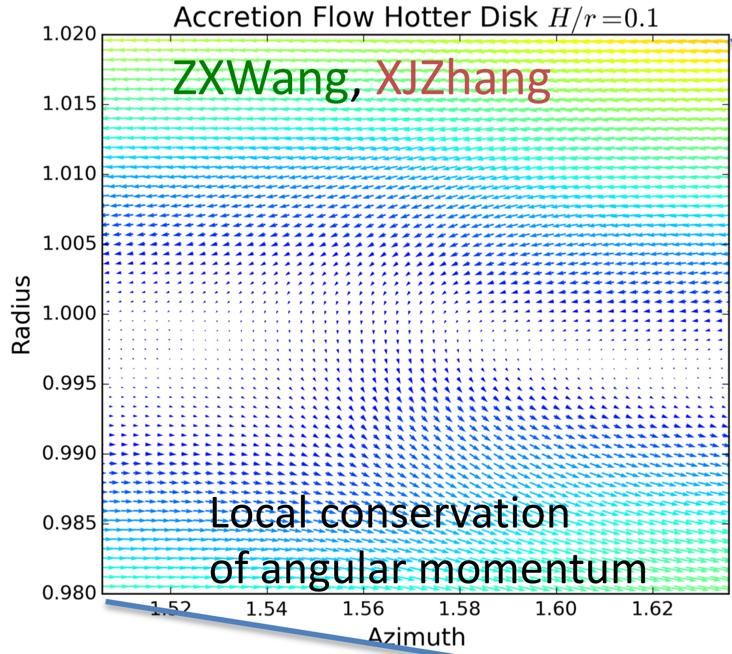
large disk

With $R_{cen} \sim R_R$

But retrograde for smaller q

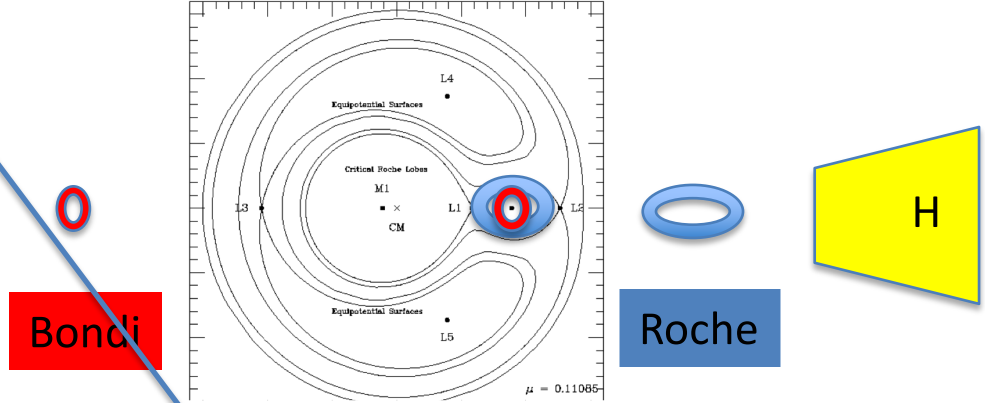
Spin due to local shear (thick, $h=0.1, q=10^{-4}$)

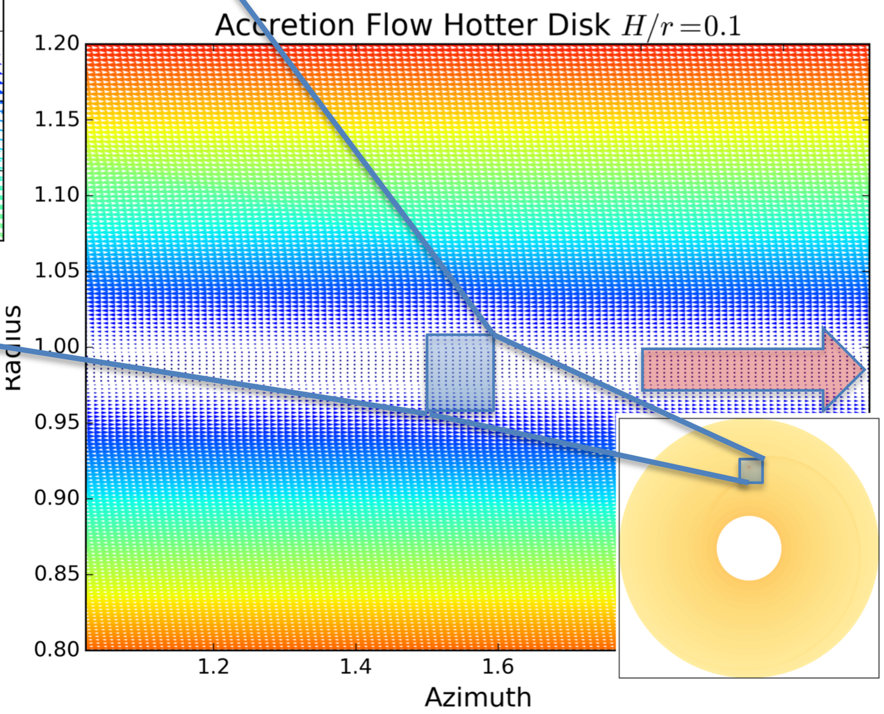
Low-m_* seed black holes in **hot** disks with $R_B < R_R < H$, i.e. $m_* < (H/a)^{1/3} M_h$

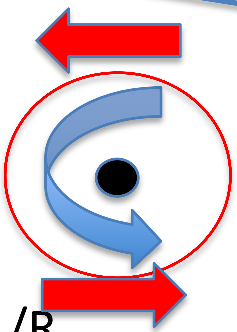


ZXWang, XJZhang

Local conservation of angular momentum



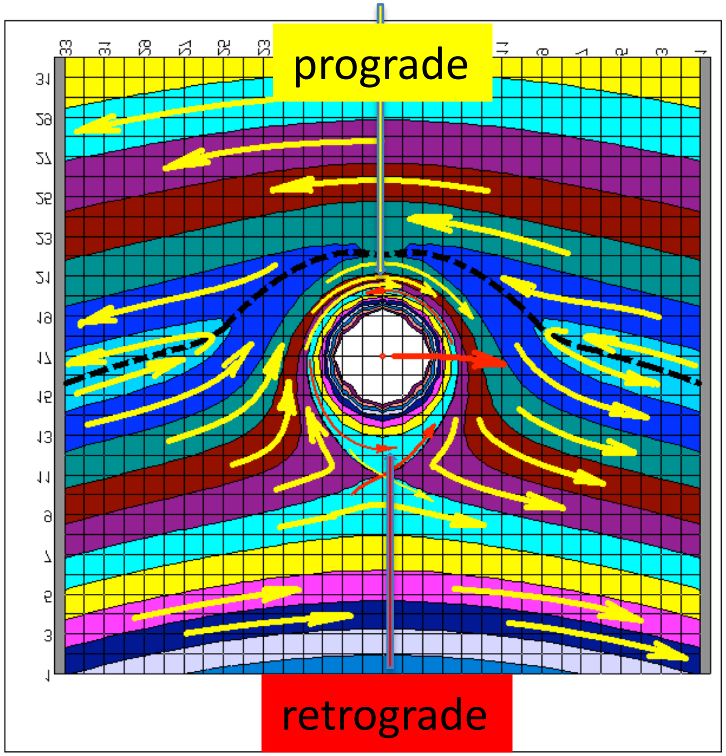


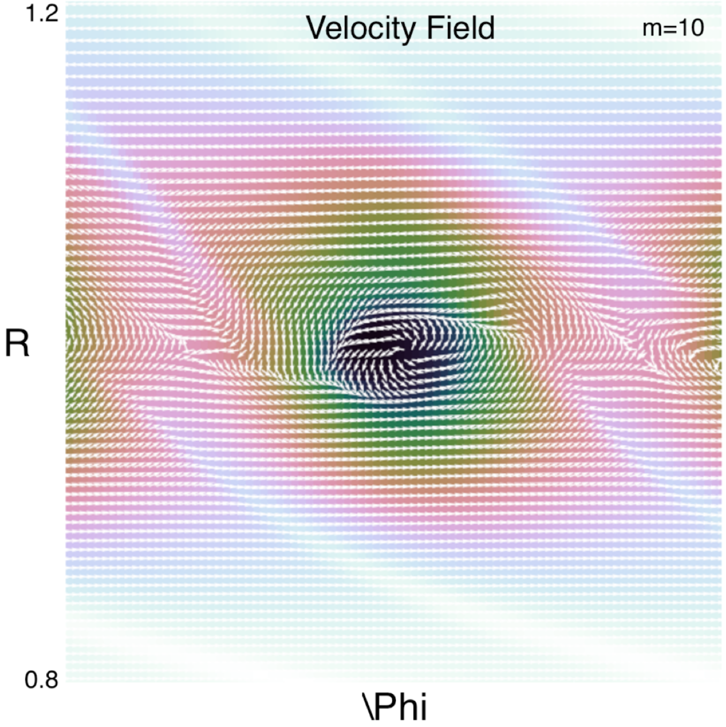


Retrograde
with $j_a = R_B^2 \Omega$,
small disk size
$R_{cen} \sim (R_R/H)^8 R_B$
$\sim (R_R/H)^{14} h^3 a R_{*}/R_{H}$

Seed black holes in hot turbulent disks

Low-m* seed black holes in hot turbulent disks with $R_B < R_R < H$ & $v_{tur} < c_s$





Eddies with $\lambda < H$, can be $> R_B$

$v_{tur}(\lambda) \sim (\lambda / H)^{1/3} v_{tur}(H) < c_s$, can be $> R_B \Omega$

$\tau_{tur} \sim (\lambda / H)^{2/3} [c_s / v_{tur}(H)] \Omega^{-1}$, can be $> \Omega^{-1}$

Spin determined by local vorticity $j_a = \lambda v_{tur}$ $\dot{J}_{\rm turb} = \dot{m}. j_a$

$R_{cen} = A(H/R_R)^4 R_R = A(H/R_R)^6 R_B$ with $A = (\lambda/H)^{8/3} (V_{tur}/c_s)^2$

Seed BH's spin can evolve substantially

Differential migration & binary seed black holes

1)Bound binary: $R_R > a_{12}$

2)Gap formation $R_R > H$ (large m_*)

3)Common envelope $a_{12} > R_b$(wide)

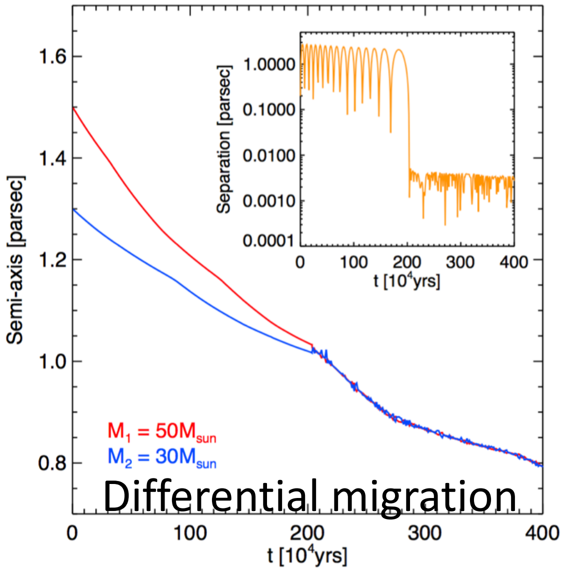
4)Accretion-enhanced drag $R_b > a_{12}$ (compact)

5)Prograde orbit $R_b > R_R$ (medium m_*)

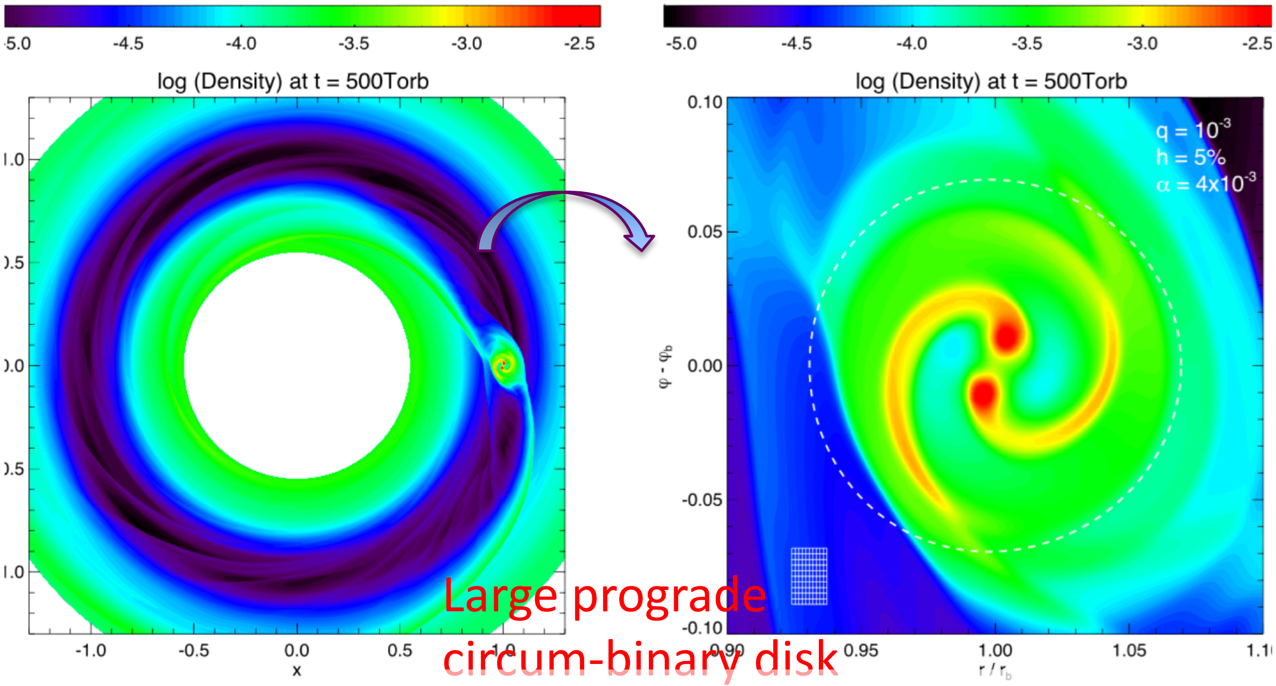
6)Retrograde orbit $R_R > R_b$ (small m_*)

Gap formation by relatively massive binary with $H = C_s/\Omega < R_R = (m_{12}/3M_h)^{1/3}a$ (thermal condition for gap formation) and $R_R > a_{12}$ (bound)

Goldreich & Tremaine, Ward



Differential migration



Large prograde circum-binary disk

Seed BHs capture companions

Nelson, Paardekooper, Baruteau

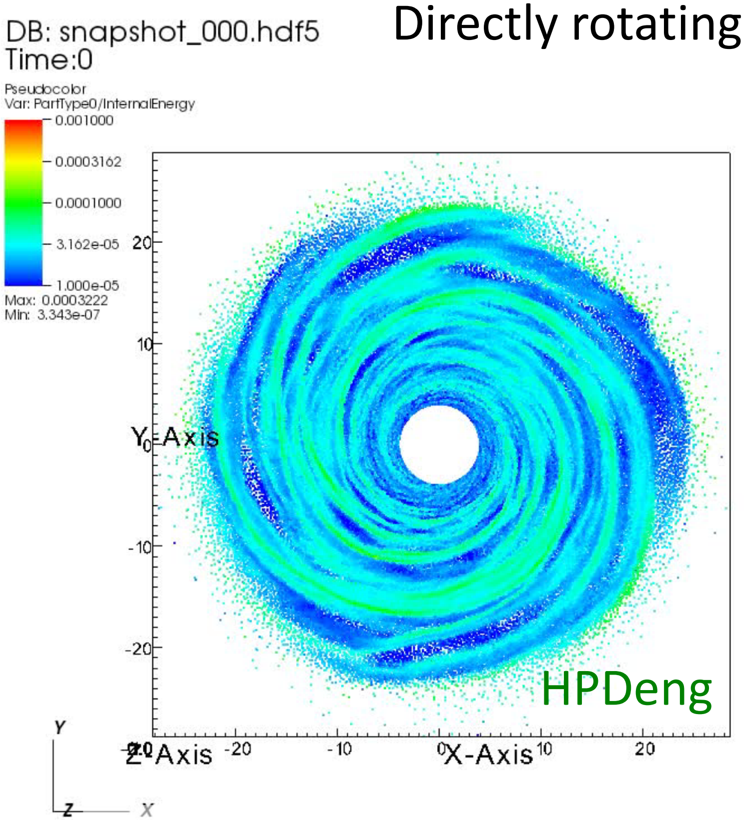
Initial binary tightening

$$\dot{J}_t \simeq 0.23(m_2/m_1)^2\Sigma_b a_{12}^4 \omega_{12}^2 h_b^{-3}$$

Baruteau, Cuadra L 2011 Stone, Haiman 2017

Accretion & tidal torque due to circum-binary disk

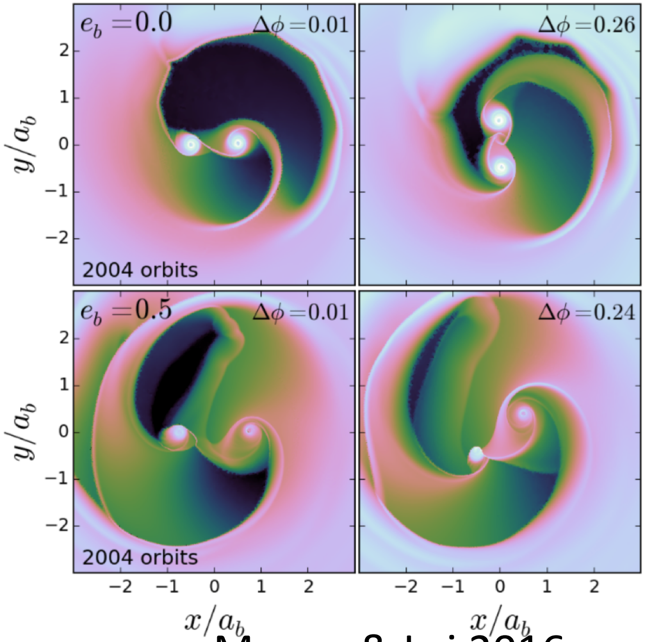
Directly rotating, self-gravitating, circum-binary disk



HPDeng

Accretion onto
seed binary
black holes

Potential sites for
Enhanced
star formation



Munoz & Lai 2016

$$\Gamma_{\rm drag} = 4\pi C_d \rho a_{12} V_{12}^2 \left(\frac{G m_{12}}{V_{12}^2}\right)^2 \left(\frac{m_1}{m_2} + \frac{m_2}{m_1} - 1\right)$$

$\Gamma_{\rm drag} \sim V_{12} a_{12} \dot{m}$.

$$\tau_{at} \simeq \frac{m_1 m_2 \omega_{12} a_{12}^2}{m_{12} \dot{J}_t} \simeq \frac{4 m_1^3}{m_2 m_{12} \Sigma_b a_{12}^2} \frac{h_b^3}{\omega_{12}}.$$

XJZhang

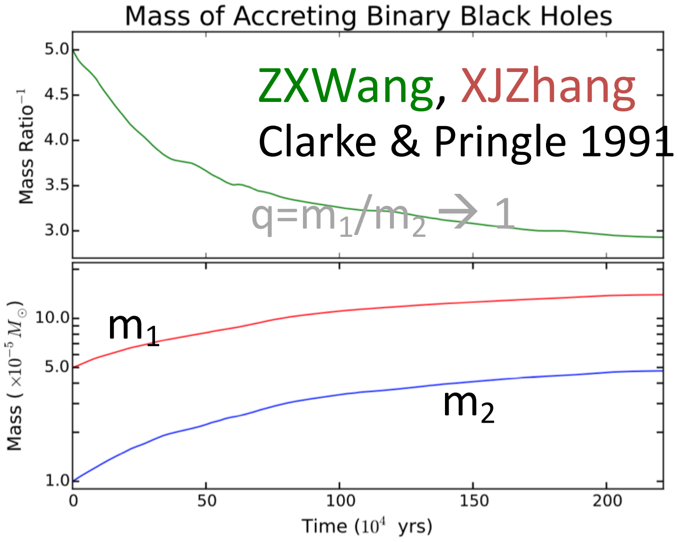
$$\tau_{gr} = \frac{5 a_{12}^4 c^5}{256 G^3 m_1 m_2 m_{12}} \simeq \left(\frac{a_{12}}{1\rm pc}\right)^4 \left(\frac{M_\odot^3 10^{39} {\rm yr}}{m_1 m_2 m_{12}}\right).$$

Peters 1964

Modest-m_* binary with modified disk structure

$H=C_s/\Omega > R_R$ (no gap) ~ R_B (perturbed, prograde) ~a_{12} (bound, no enhancement)

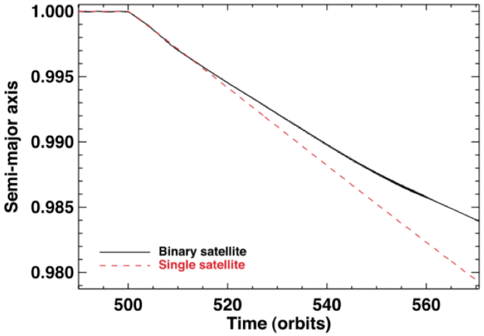
Binary BHs' mass ratio & orbit evolve



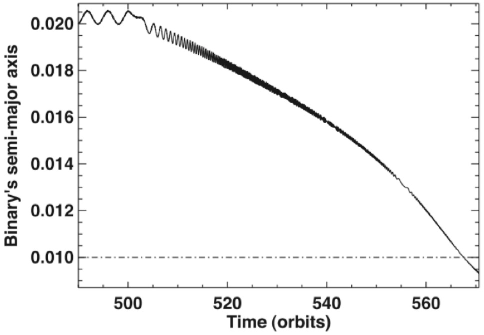
ZXWang, XJZhang

Clarke & Pringle 1991

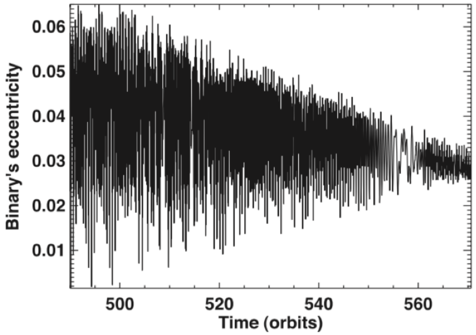
$q=m_1/m_2 \rightarrow 1$



a_{com}

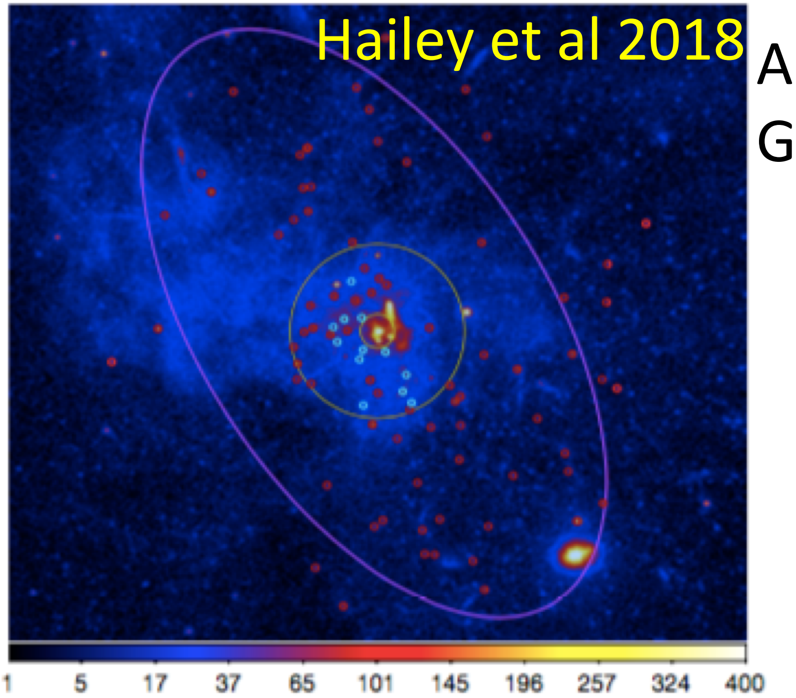


a_{12}

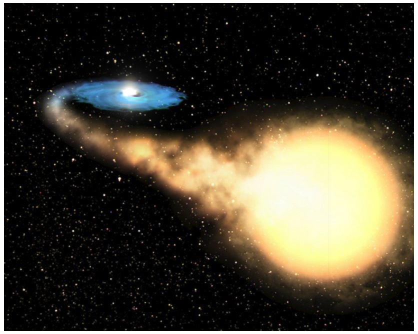


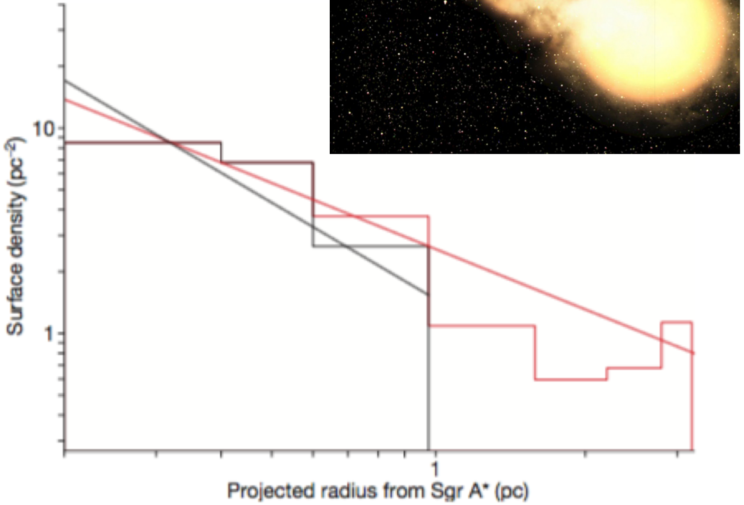
e_{12}

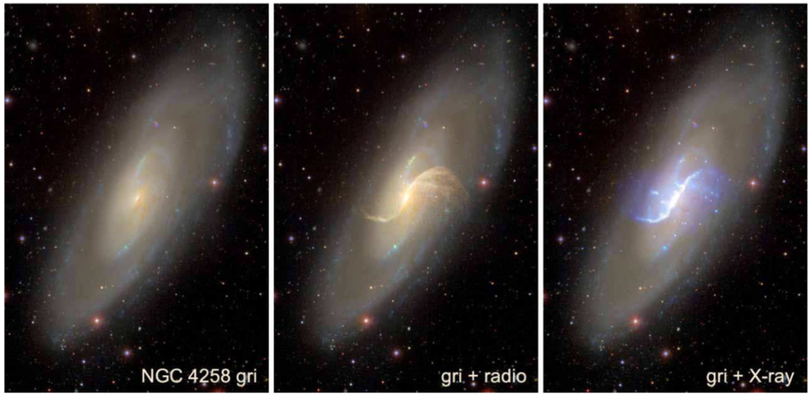
EM signatures: ubiquitous X-ray binaries


Hailey et al 2018

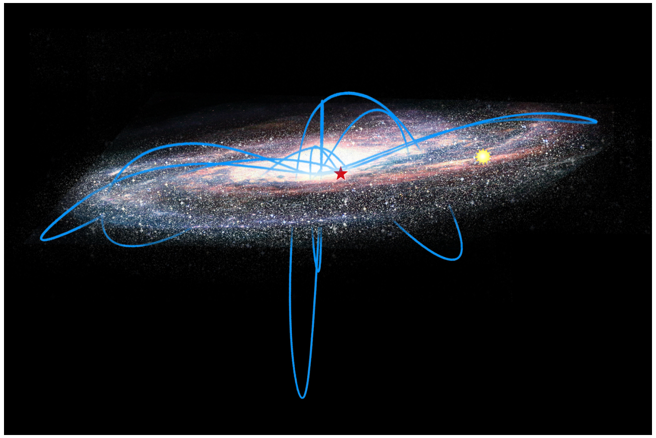
Around the Galactic Center





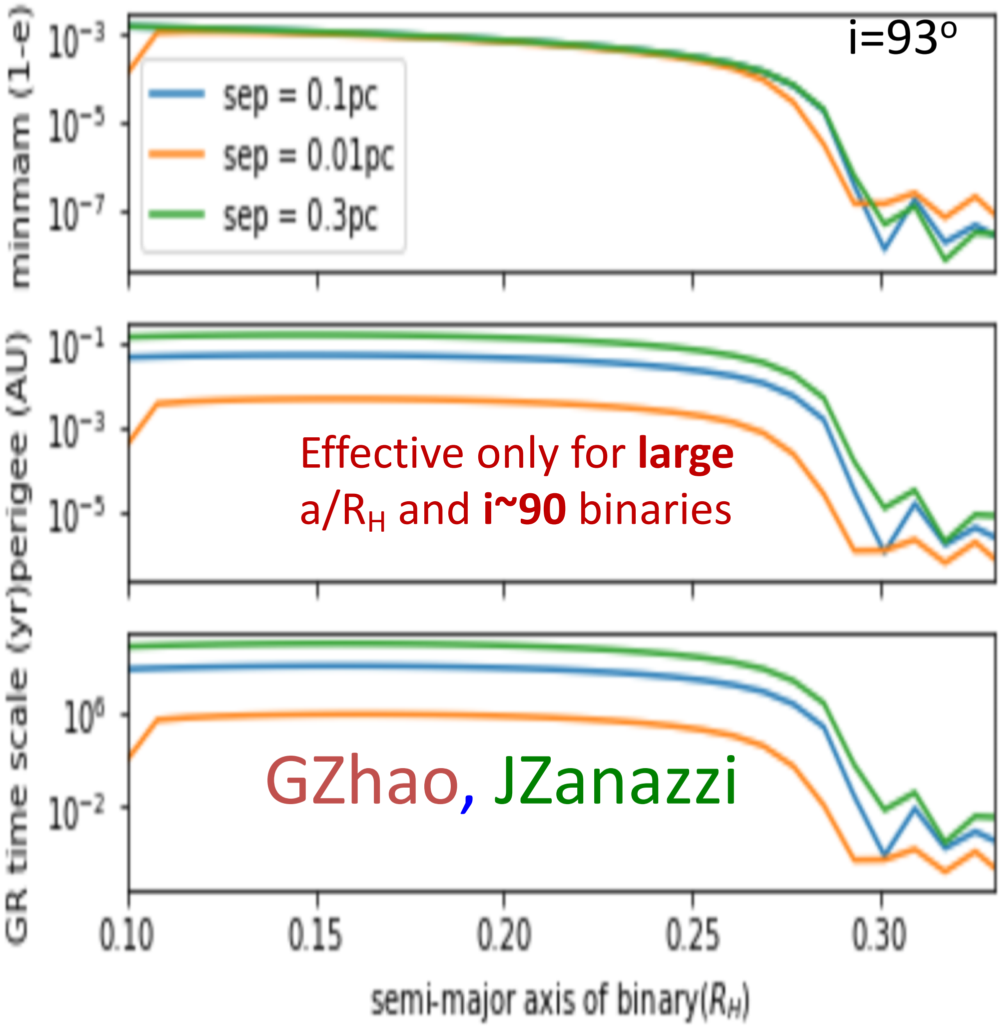


Around AGNs



Binary separation near supermassive black holes

Lidov-Kozai effect + gravitational radiation

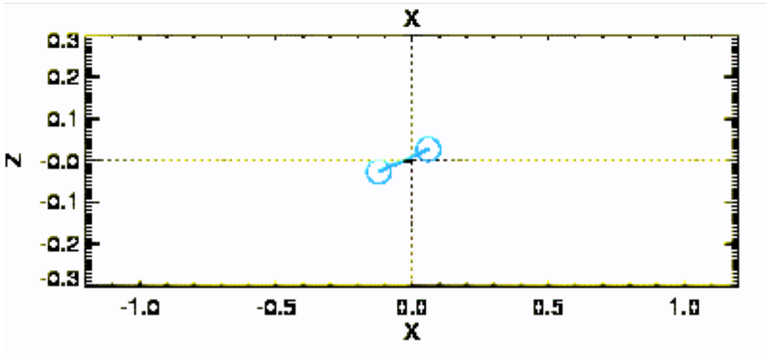


i=93°

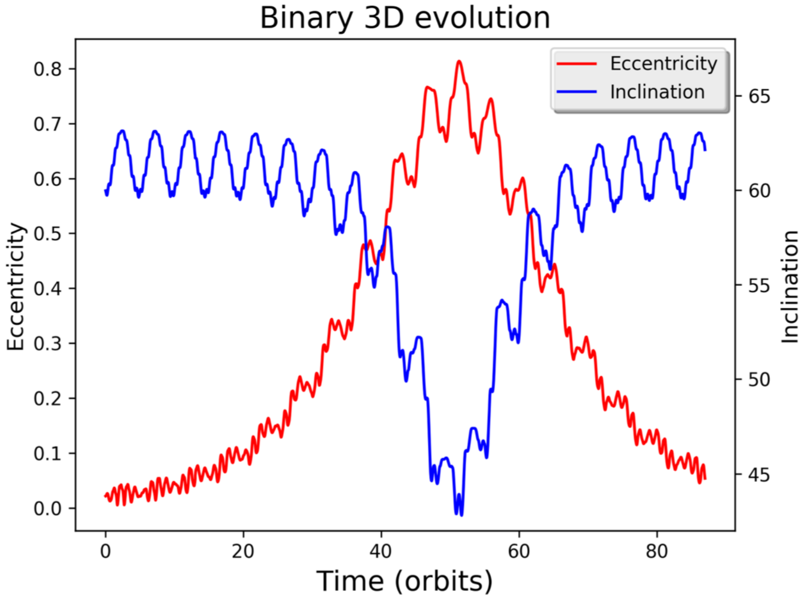
Effective only for **large** a/R_H and **i~90** binaries

GZhao, JZanazzi

Suppressed in the presence of nearby gas

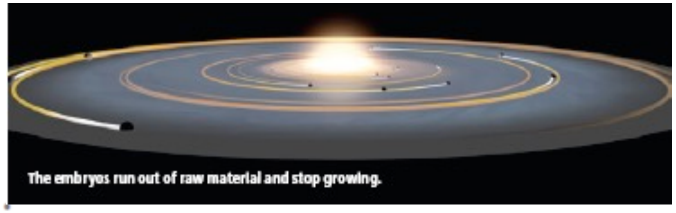


+ disk torque & gas drag



ZXWang, XJZhang

Multiple black holes' eccentricity excitation/damping



Scattering: $d\sigma_h^2/dt \simeq n_0\Omega^3 R_{roc}^6/\Delta^2 R^2$

$$\tau_{e+} = \frac{\sigma_h^2}{2(d\sigma_h^2/dt)} = \left(\frac{R}{R_{roc}}\right)^6 \frac{e^4 P}{4N_{\rm trap}}$$

Type I damping: $\tau_{e-} = h^2\tau_I = \dfrac{h^3QPM}{4f_\Gamma m_*}.$

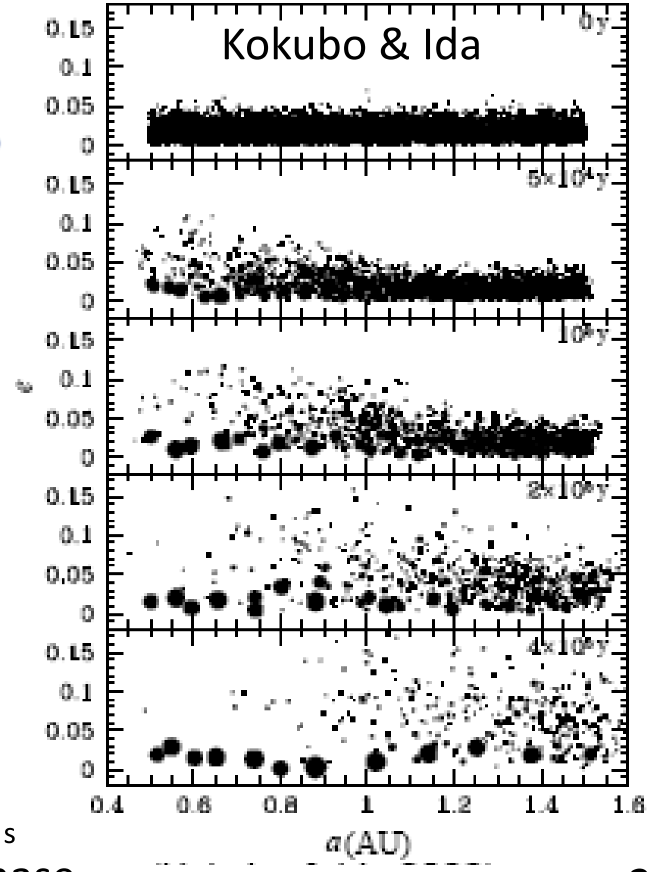
Dynamical equilibrium: low-e orbits

$$\tau_{e+} = \tau_{e-}$$

$$\boxed{\frac{eR}{R_{roc}} = \left(\frac{N_{\rm trap}h^3Q}{3f_\Gamma}\frac{R}{R_{roc}}\right)^{1/4} < 1}$$

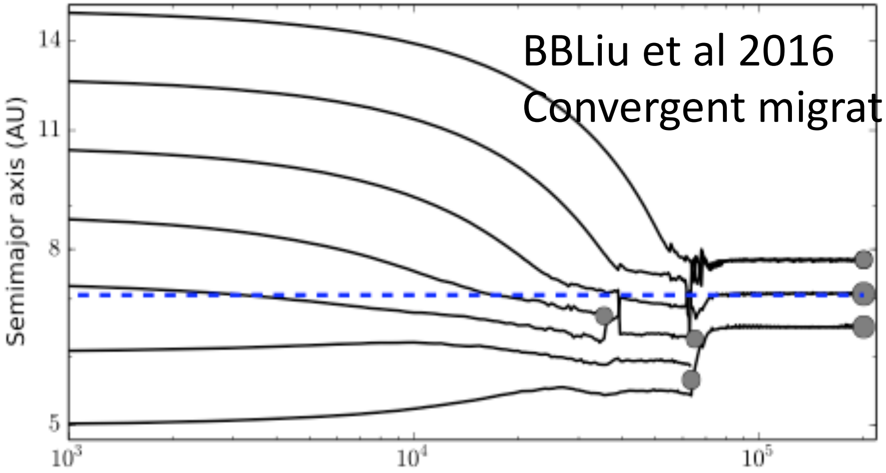
Feeding zones: $\Delta \sim 10\ r_{\rm Hill}$

Isolation mass: $M_{\rm isolation} \sim \Sigma^{1.5} a^3 M_h^{-1/2}$

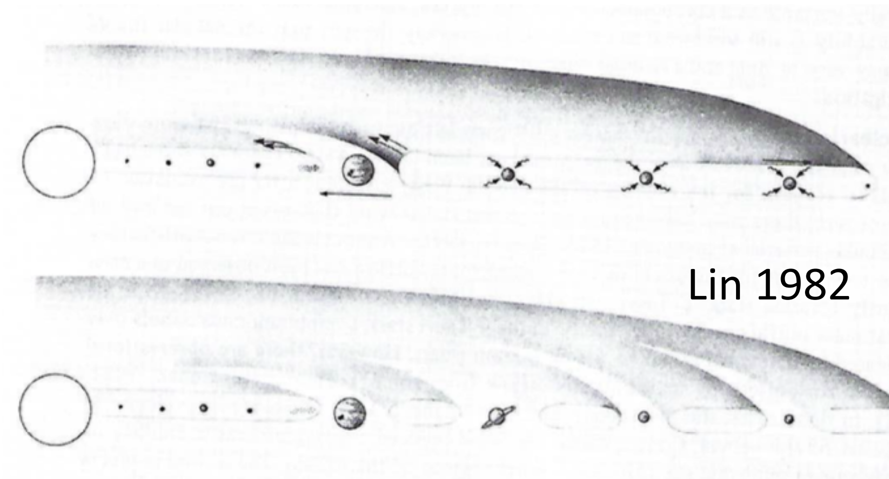


Up to 10^2 clusters with $>10^2$ seed black holes of $\sim 10^{1\text{-}2}\ M_s$ within 10 pc's around $10^8 M_s$ MBH's during $>10^8$ y AGN phase

Clusters of multiple (>) growing seed black holes

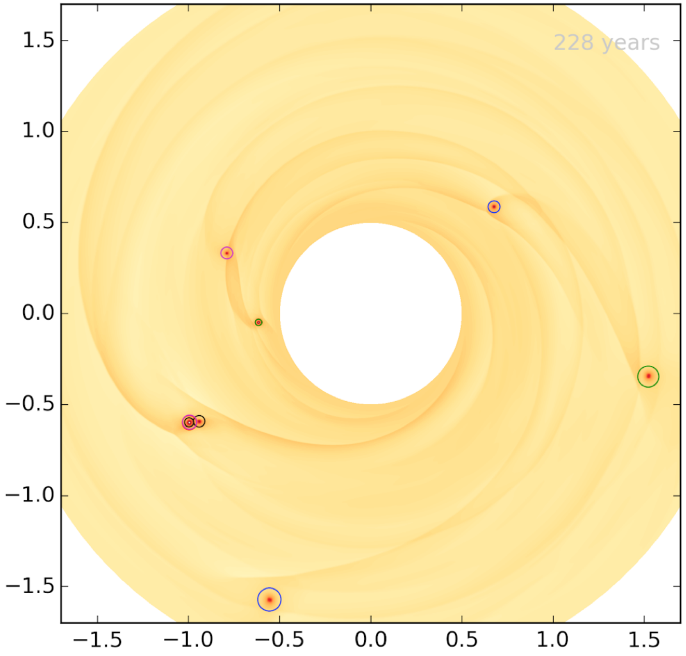


BBLiu et al 2016
Convergent migration



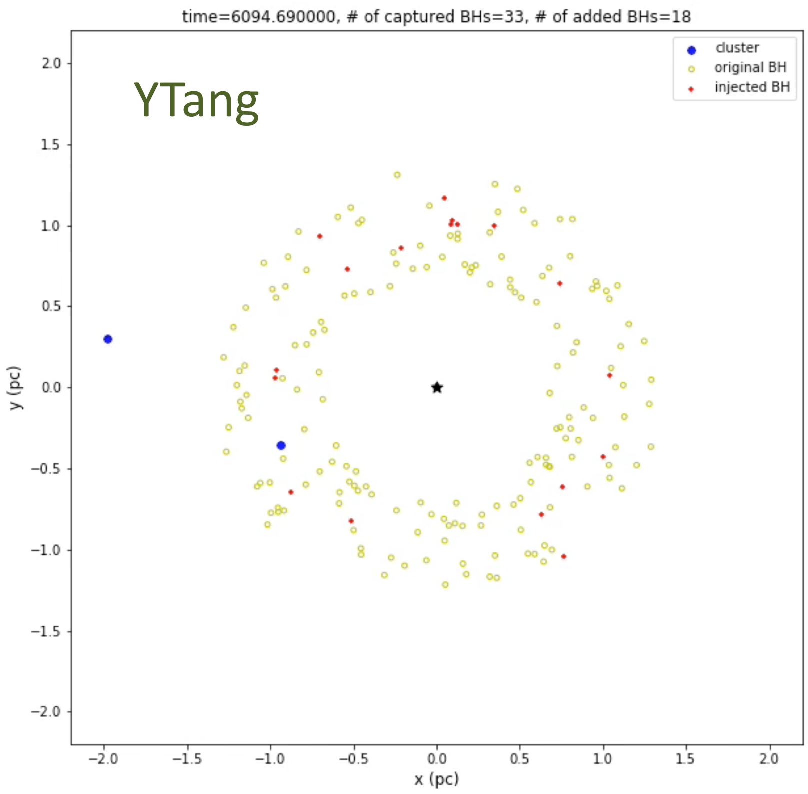
Lin 1982

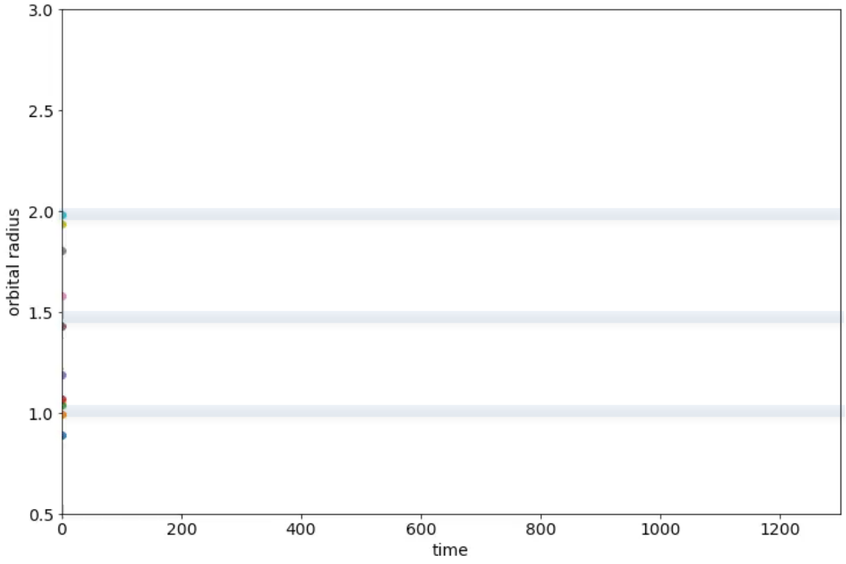
Feeding zone with overlapping Roche radii ZXWang

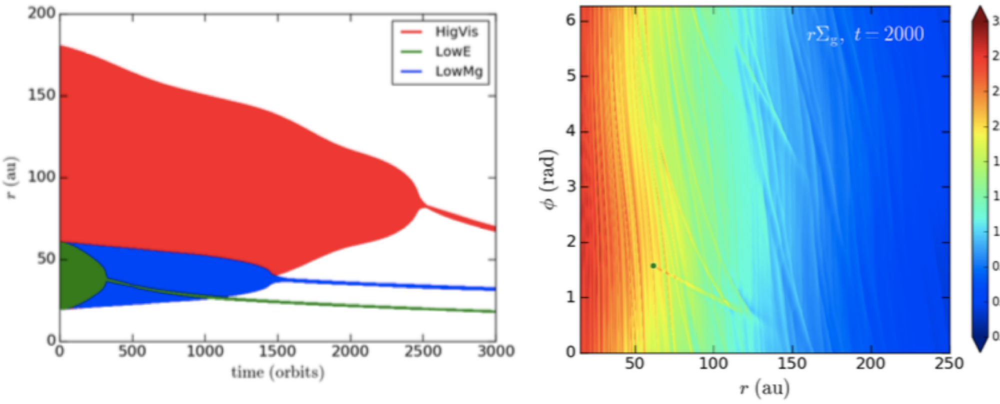


Prolific formation of small clusters of seed black holes

Repeated capture by clusters, triple encounters, companion exchange, ejection from & recapture by clusters in AGN disks







Retention possible if

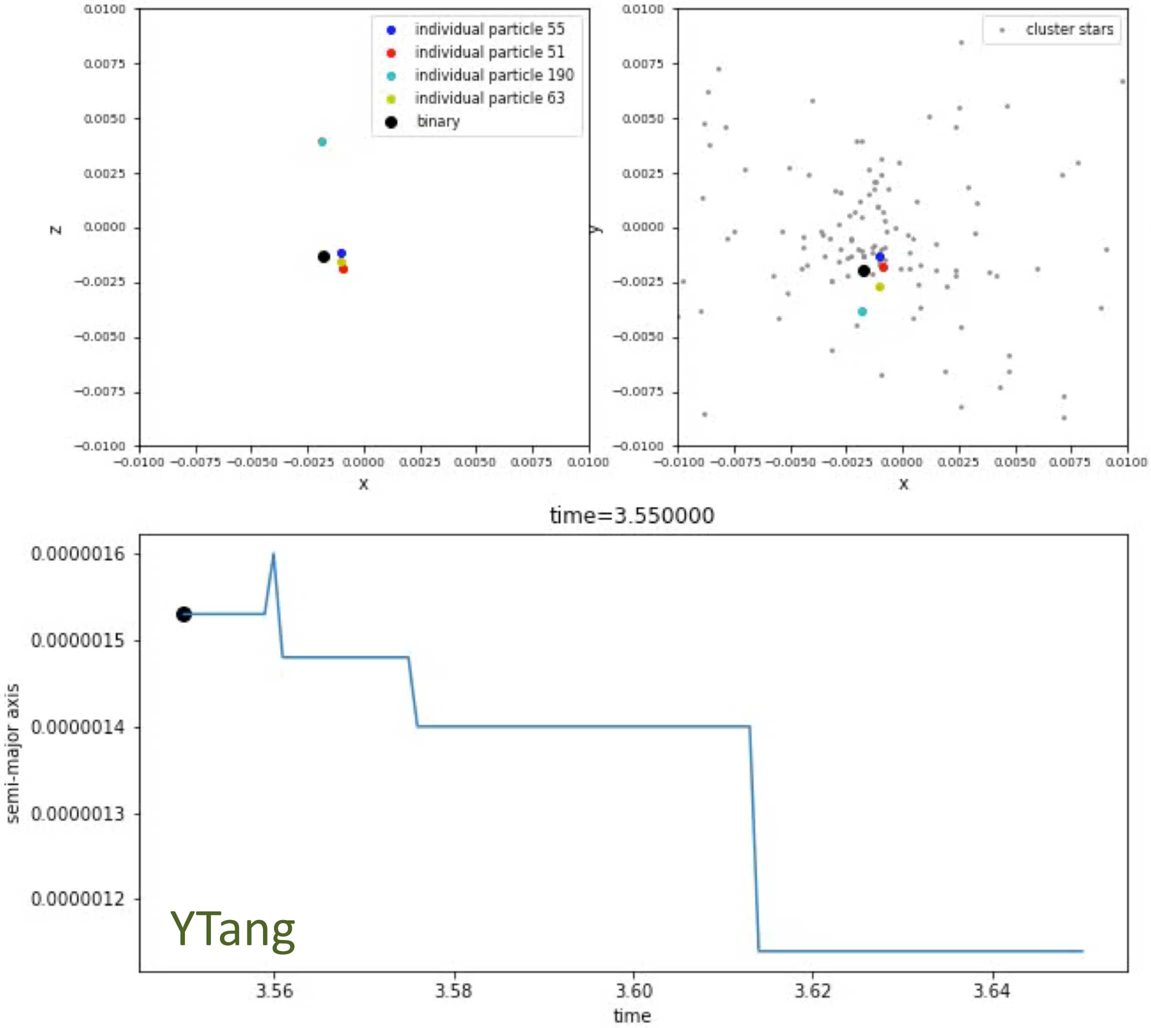
$m_*/a_{12} < \xi^{1/2}\ M_h/a$ or

$a_{12} > \xi^{-1/2}\ a\ m_{12}/M_h$

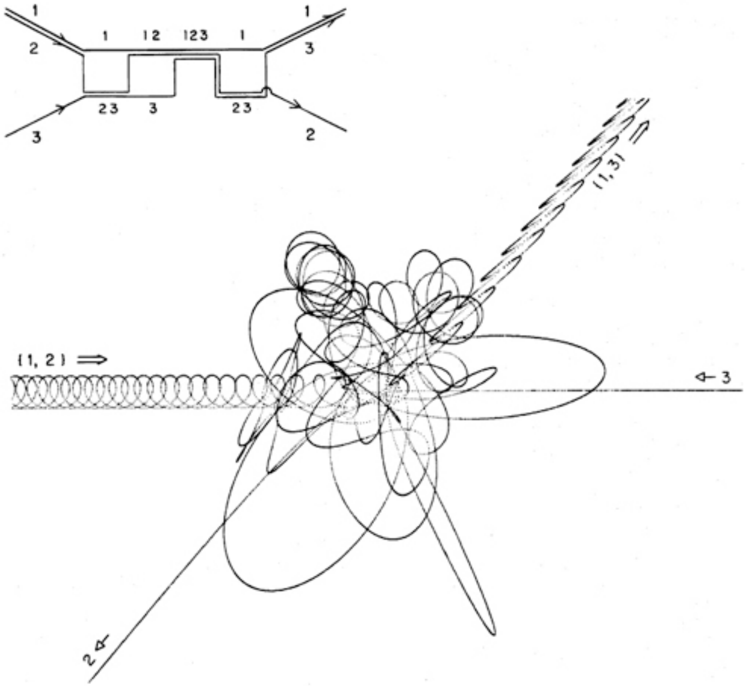
Tidal interaction with disk: eccentricity damping

Ejection from clusters does not lead to escape

Internal relaxation, mass segregation, binary exchanges and tightening in small clusters



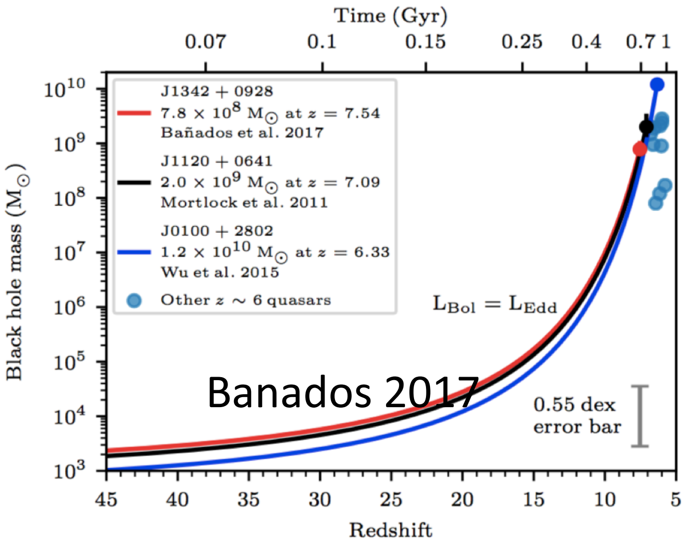
YTang

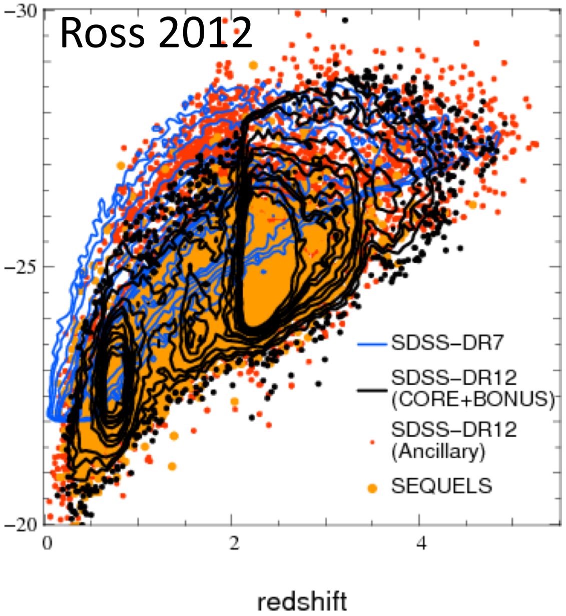


Heggie 1975,
Hut & Bahcall, 1983,
Myllari Valtonen 2018

Binary tightening in very dense environment: limited eccentricity

Speculation on rapid emergence of SMBH





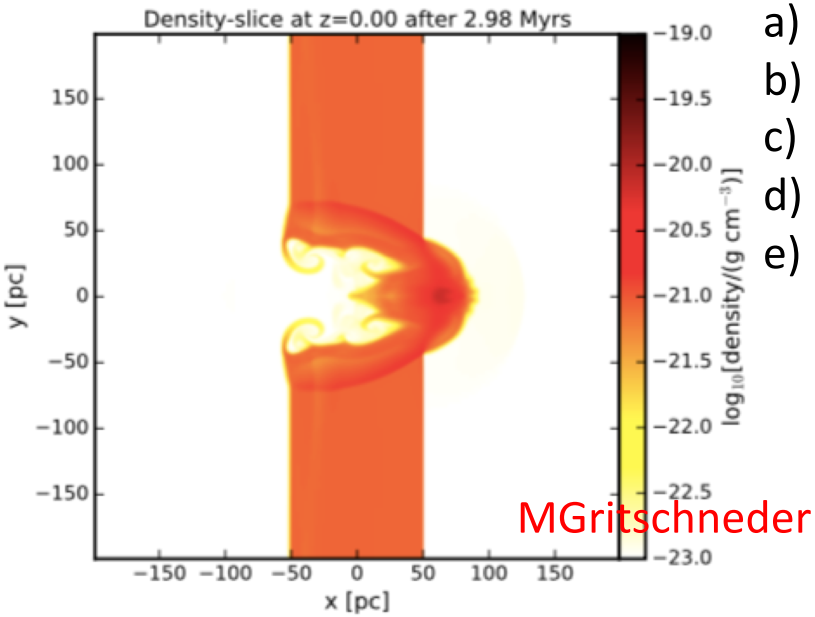
Clusters also accrete gas & migrate

τ_Z < 1Gyr

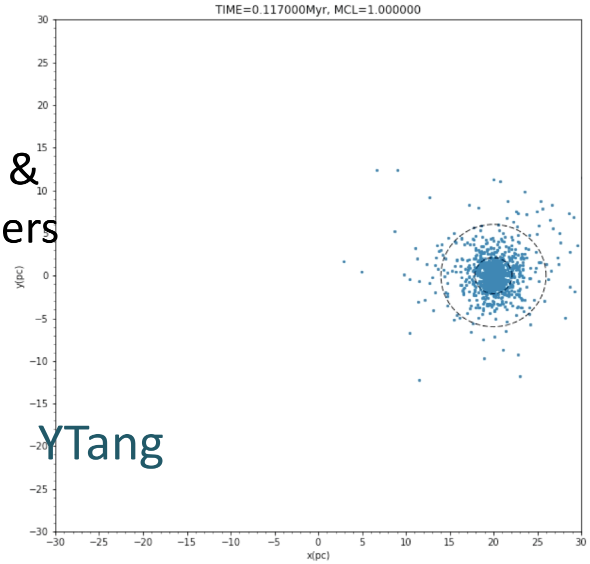
τ_{Sal} = 0.45εGyr

trapped clusters:

a) orbital decay
b) Gas accretion
c) Stars' mass growth
d) Cluster contraction &
e) Star & cluster mergers

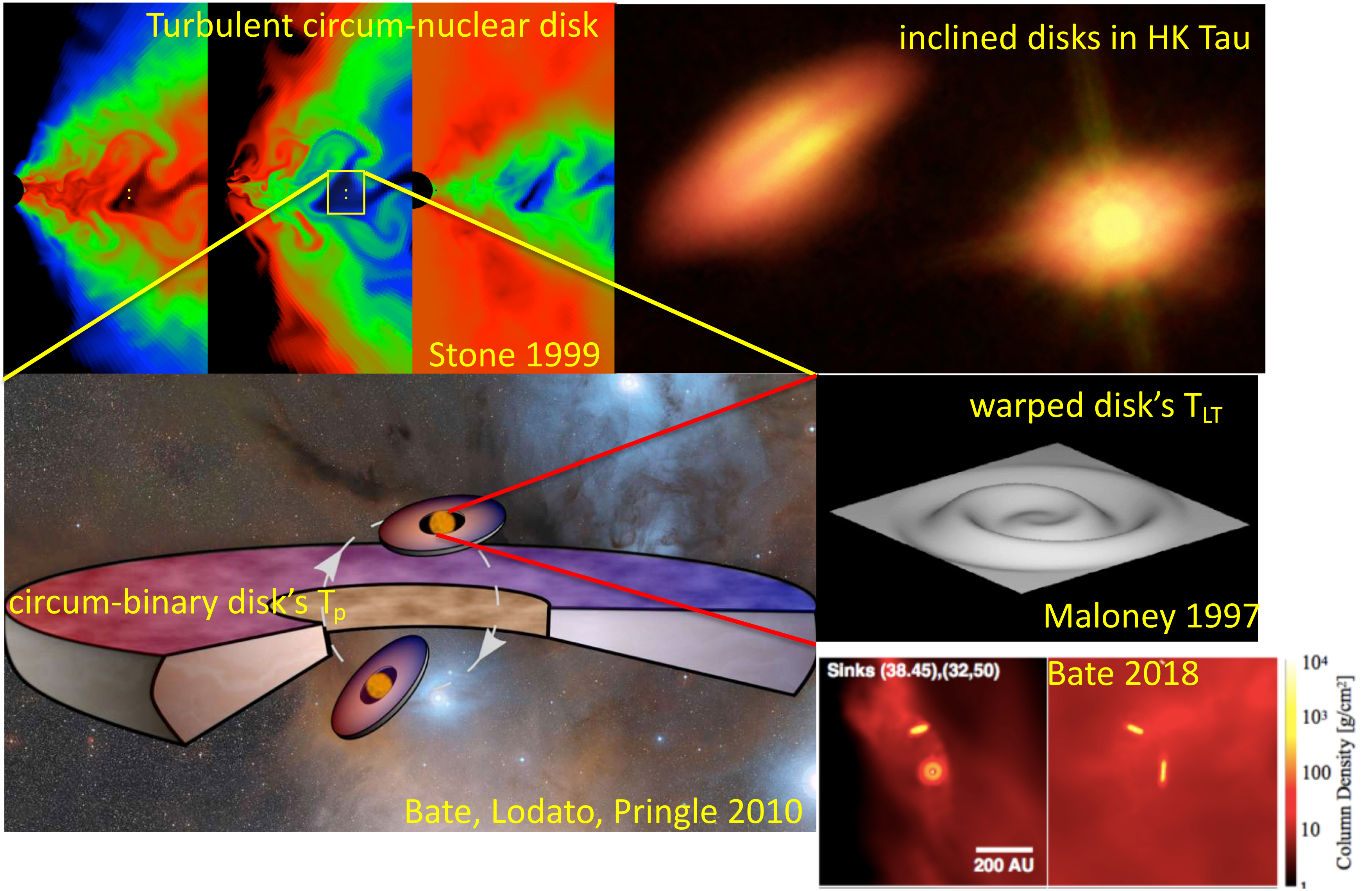


Clusters' gas accretion during disk passage



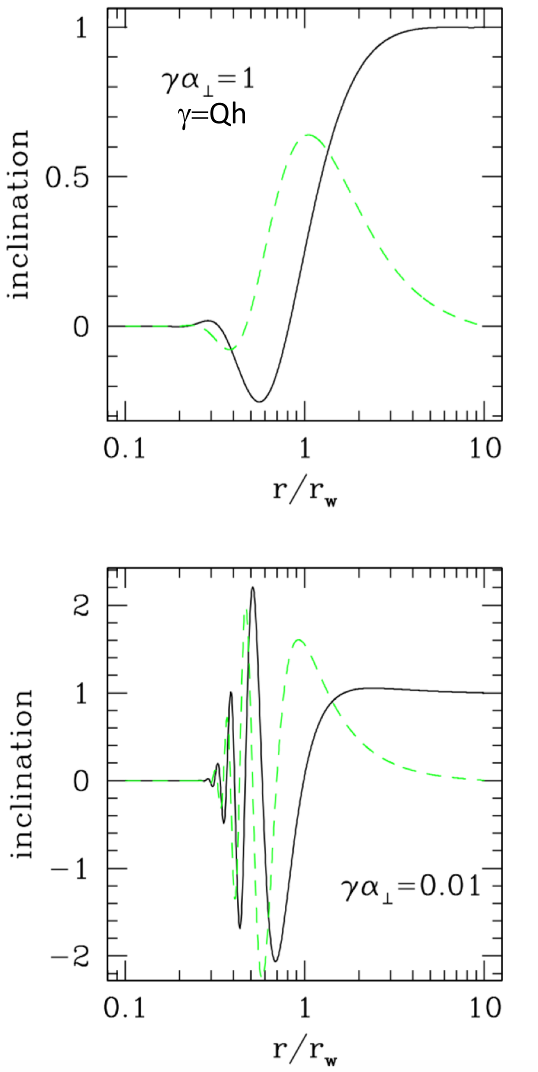
Dynamical friction and internal drag

Accretion of turbulent gas onto seed BH's & **spin angular** momentum of circumbinary disks



Torque through warped accretion disks

S. Tremaine and S. W. Davis



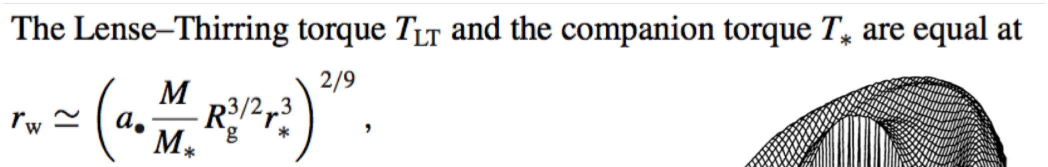
Evolution time scales of binary:

a) turbulent accretion τ_{tur} and drag by common envelope τ_{CE} => $\Delta J_b/J_b \sim \tau_{tur}/\tau_{CE}$ per turn over. For t>τ_{tur}, $\Delta J_b/J_b \sim \tau_{tur}/\tau_{CE}\,(t/\tau_{tur})^{1/2}$

b) circumbinary disks: for $\tau_{tur} < \tau_{Sal}$, $\Delta J_b/J_b \sim \tau_{tur}/\tau_{Sal}$ for $\tau_{tur} > \tau_{Sal}$, $\Delta J_b/J_b \sim 1$.

c) Individual black holes' spin angular momentum For $\tau_{tur} < \tau_{Sal}$, $\Delta J_*/J_* \sim \tau_{tur}/\tau_{Sal}$ & $\tau_{tur} > \tau_{Sal}$, $\Delta J_*/J_* \sim 1$

d) Individual black holes' spin alignment due to LT For $\tau_{tur} < \tau_{Sal}$, $\Delta J_*/J_* \sim \tau_{tur}/\tau_{Sal}\,(r_w/R_{.*})^{1/2}$



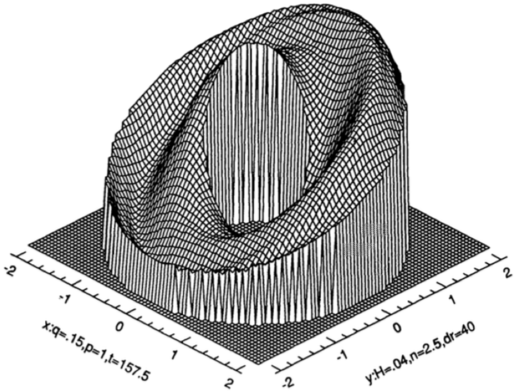
The Lense–Thirring torque T_{LT} and the companion torque T_* are equal at

$$r_w \simeq \left(a_\bullet \frac{M}{M_*} R_g^{3/2} r_*^3\right)^{2/9},$$

Papaloizou & L 1995

Ogilvie & Dubus 2001

Nixon & King 2016



Average infalling envelope: $\tau_a \sim \tau_e \sim \tau_{Sal} \sim (r_w/R_g)^{1/2}\tau_{spin}$

Gravitational radiation from binary black hole

$$\left\langle\frac{da}{dt}\right\rangle = -\frac{64}{5}\frac{G^3 m_1 m_2 (m_1+m_2)}{c^5 a^3 (1-e^2)^{7/2}}\left(1+\frac{73}{24}e^2+\frac{37}{96}e^4\right)$$

$$\left\langle\frac{de}{dt}\right\rangle = -\frac{304}{15}e\frac{G^3 m_1 m_2 (m_1+m_2)}{c^5 a^4 (1-e^2)^{5/2}}\left(1+\frac{121}{304}e^2\right)$$

For nearly circular orbit $$\tau_{\rm gr} = \frac{5 a_{12}^4 c^5}{256 G^3 m_1 m_2 m_{12}} \simeq \left(\frac{a_{12}}{1{\rm pc}}\right)^4 \left(\frac{M_\odot^3 10^{39}{\rm yr}}{m_1 m_2 m_{12}}\right).$$

For nearly parabolic orbit (e~<1) $\tau_{gr}(e)=(768/425)(1-e^2)^{7/2}\tau_{gr}(0)$ Peters 1964

With $m_1 \sim m_2 \sim 30 M_\odot$, binary BHs $\tau_{\rm gr}$ would be less than 1Gyr in the limit $a_{12} \sim 0.1$ AU.

Decoupled from envelope's tides if $a_{12} <= \left((1+q)\alpha h_b^5 \frac{384}{10\pi}\frac{\eta\sigma_T}{R_{s1}}\frac{m_1}{m_p}\right)^{1/4} R_{s1} \sim R_{sun}$

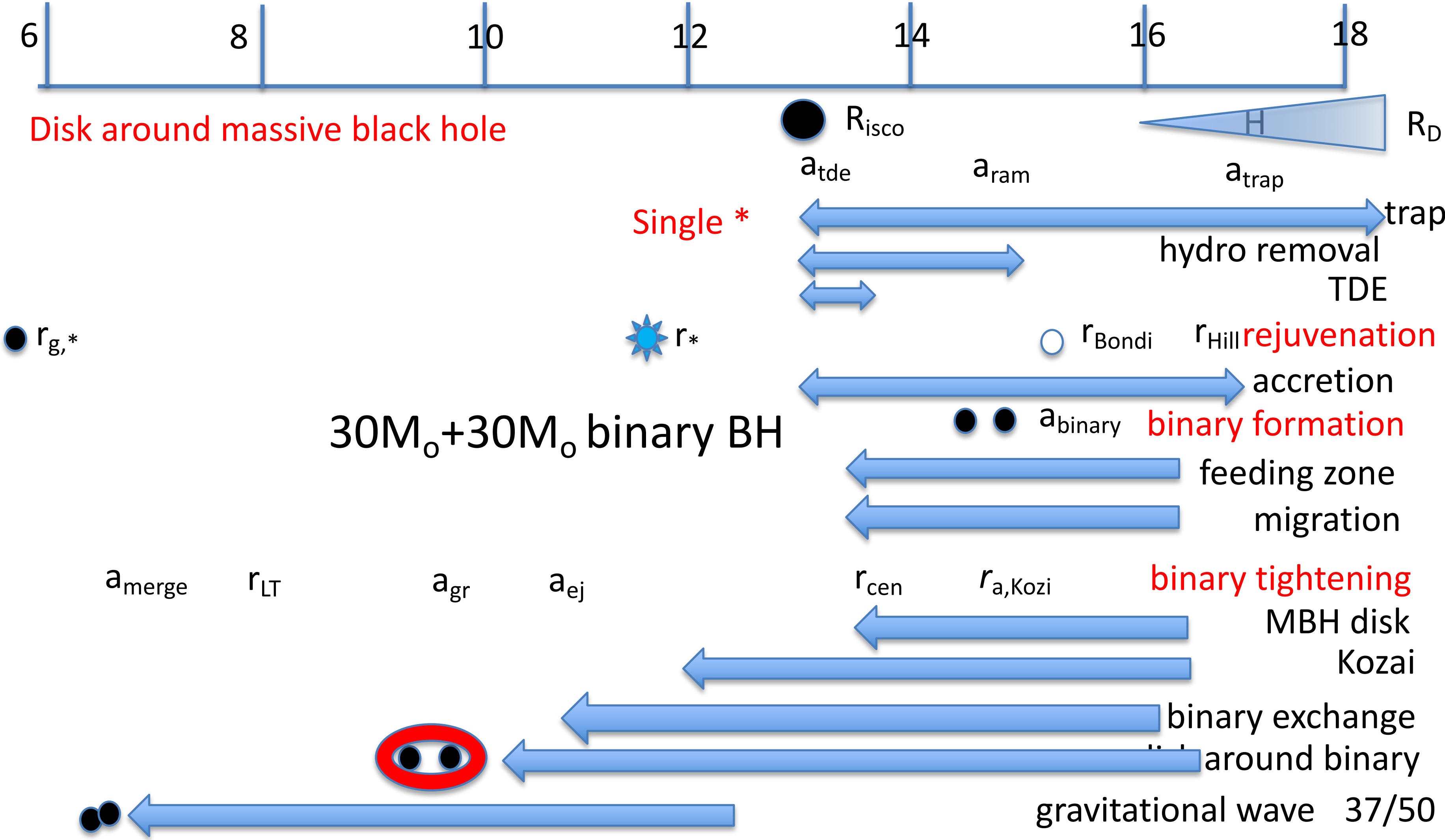
Idealized merger-tree model:

1) total number of collisions= N_{BH} / 2ln2 in active phase τ_{AGN}
2) number of merger per individual black hole 2ln2
3) Average spin parameter ~ a_* $(\tau_{Sal} / \tau_{Agn})(R_g/r_{w.})^{1/2} < 1$

On average, individual black holes spin slowly despite mergers and past encounters

Powers of ten for AGN models

Around a $10^8 M_o$ black hole: log (r/cm)



6 8 10 12 14 16 18

Disk around massive black hole

R_{isco} H R_D

a_{tde} a_{ram} a_{trap}

Single *

trap

hydro removal

TDE

$r_{g,*}$ r_* r_{Bondi} r_{Hill} rejuvenation

accretion

$30M_o$+$30M_o$ binary BH

a_{binary} binary formation

feeding zone

migration

a_{merge} r_{LT} a_{gr} a_{ej} r_{cen} $r_{a,Kozi}$ binary tightening

MBH disk

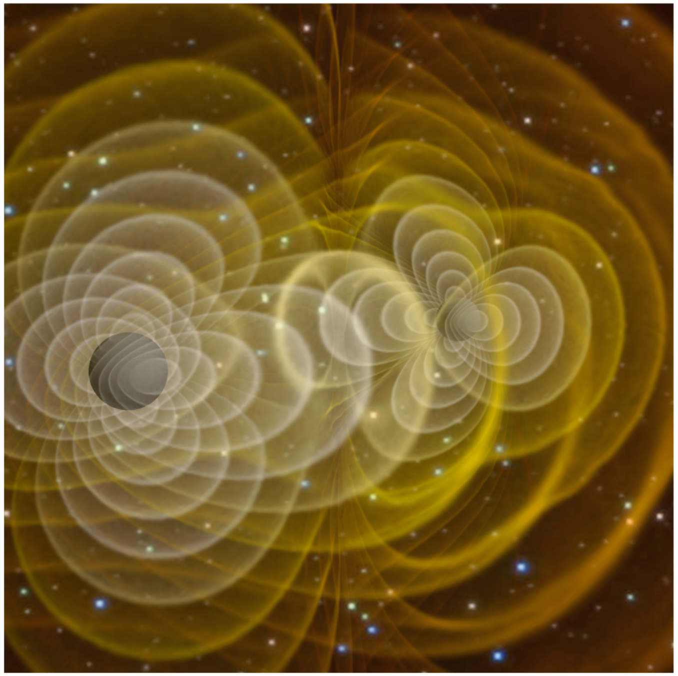
Kozai

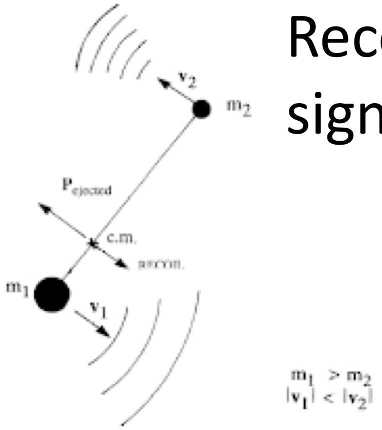
binary exchange

around binary

gravitational wave

Merger & recoil: binaries with spin-orbit obliquity



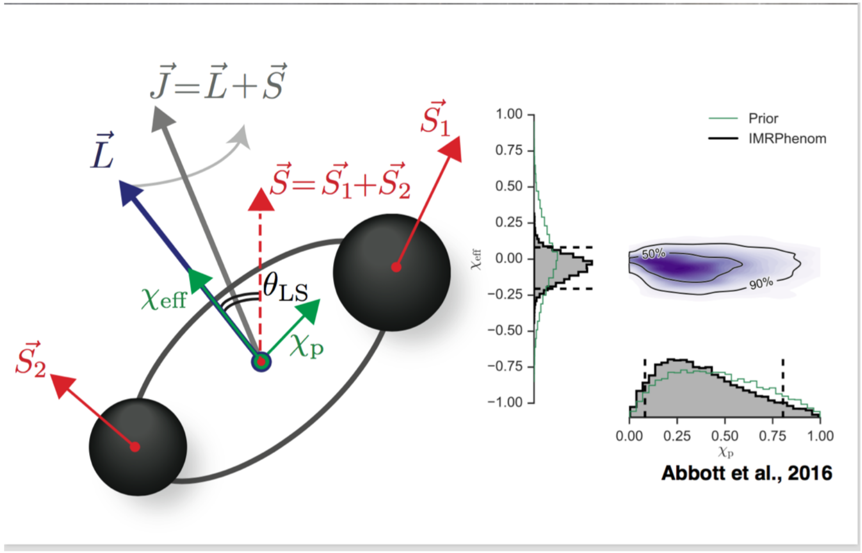


Recoil does not lead to significant disk perturbation

ZXWang, XJZhang

$$V_{\rm rec} \sim \frac{q^2 V_H (a_1 - q a_2)}{(1+q)^5}$$

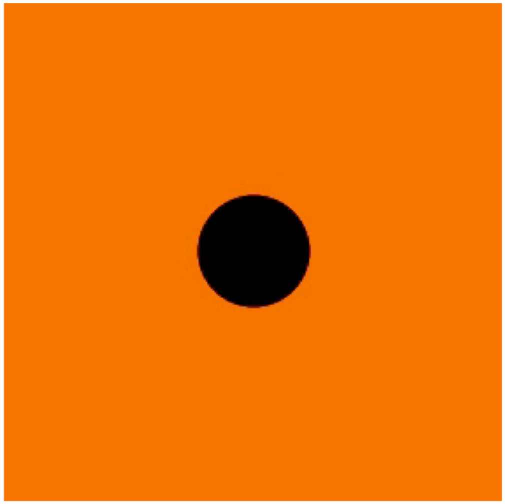
Baker 2008, Volonterri & Madau 2008

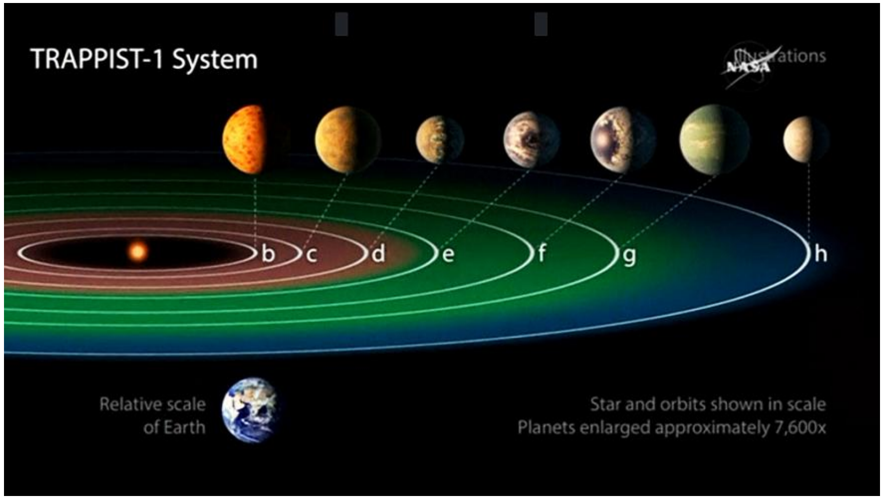


Abbott et al., 2016

Resettle into the disk if $V_{\rm rec}/V_k < \xi$

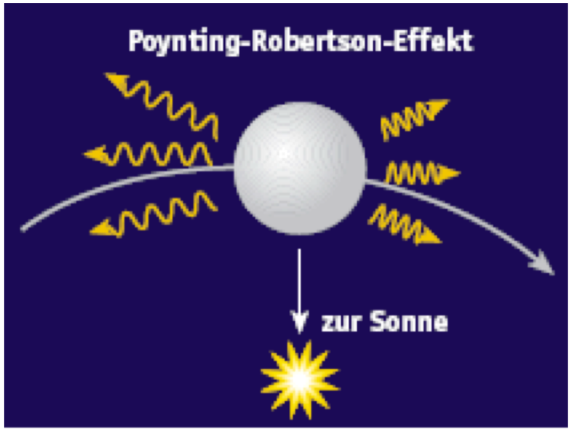
Limits on mergers’ mass: type I migration





$$\frac{dr}{dt} = f(p,q,p_\nu,p_\chi)\frac{M_p}{M_*}\frac{\Sigma r^2}{M_*}\left(\frac{r\Omega_K}{c_s}\right)^2 r\Omega_K$$

$\tau_I \sim (Qh/2f)(M_h/M_*)P$



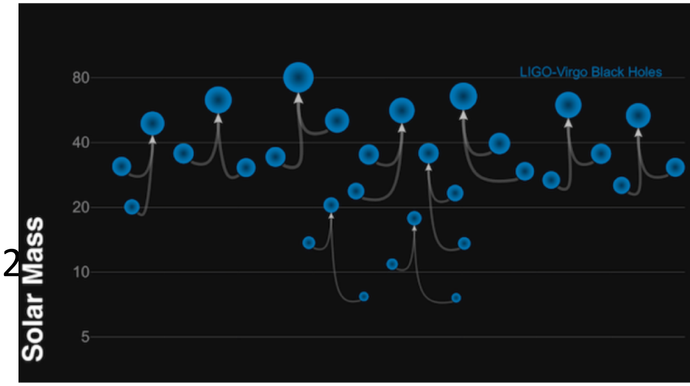
PR drag (zodiacal light)

$F_{PR}=LVR_d^2\,(q/3)^{2/3}/c^2\,R_R^2$

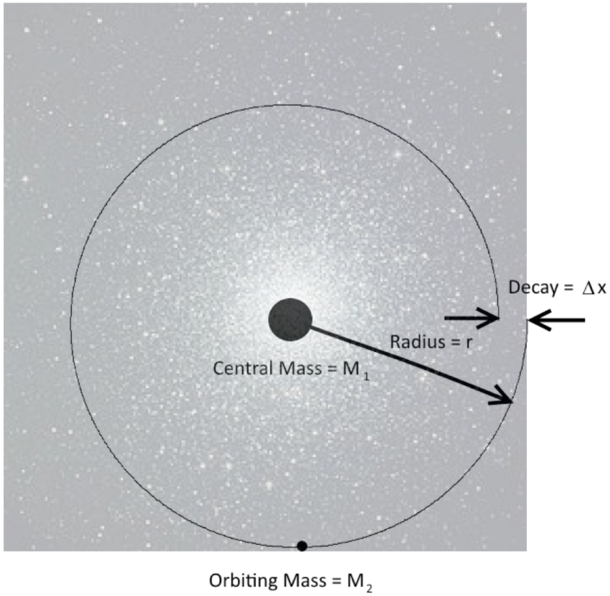
$\quad =M_*\,(dV/dt)$

$\tau_{Sal}/\tau_{PR}=\varepsilon R_d^2(q/3)^{2/3}/3R_R^2$

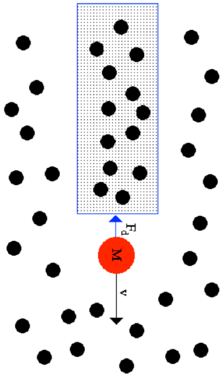
Mass growth limit



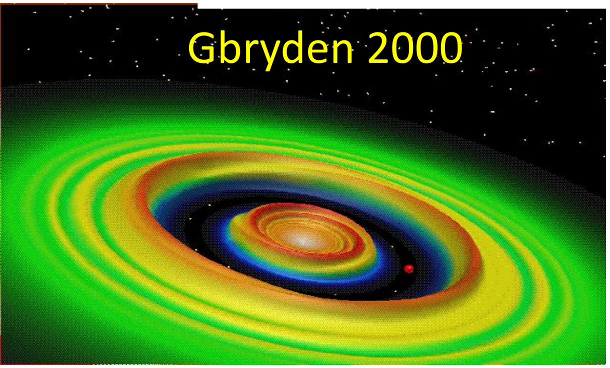
IMBH: gap, dynamical friction, & disk clearing

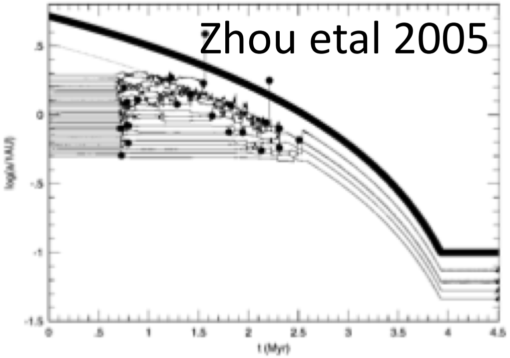


Inefficient type I migration (f <<1)
accretion for τ_{BH}~10 τ_{Sal} (λ~1, ε<<1)
IMBH with M>$10^{2\text{-}3}$ M_{sun}



Dynamical friction, decay
of black hole’s orbit leads
to efficient angular
Momentum transport
Limiting mass ~$10^{2\text{-}3}M_{sun}$





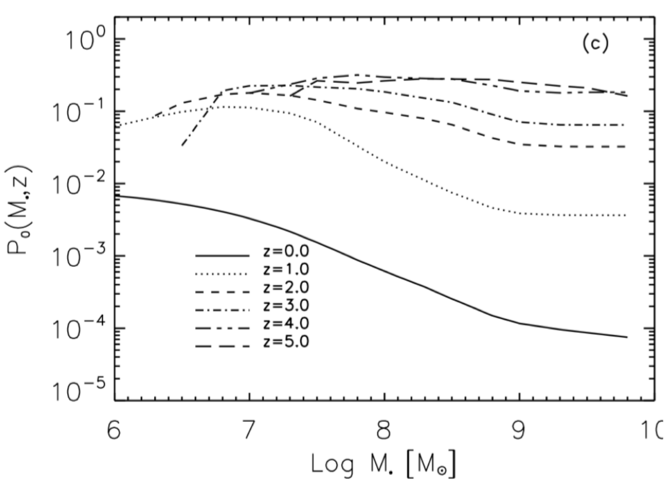
B.Tong

Angular momentum transfer $$\frac{3hR}{4R_{roc}} + \frac{50\alpha h^2}{q} \leq 1.$$

Gap formation with M> 10^3M_o L. Papaloizou 1986,
Bryden 2000, Crida & Morbidelli 2007, many others

AGNs' duty cycle and disk persistent time scale

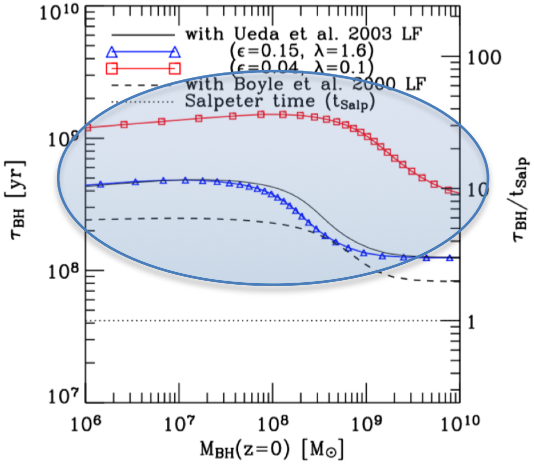
duty cycle



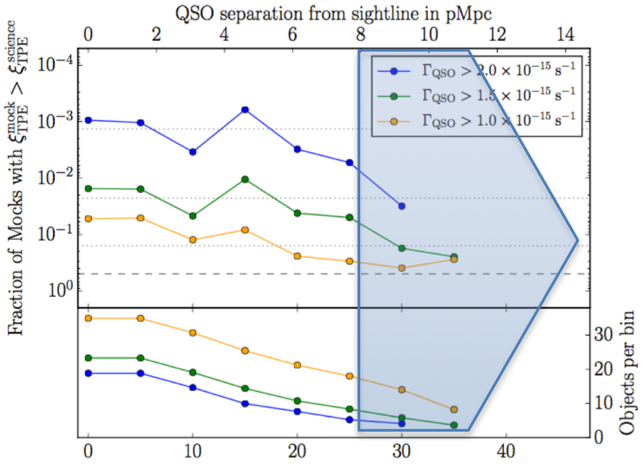
Active phase lasts ~$10^{8\text{-}9}$yr

$$P_0(M_\bullet, z) = \frac{\Phi_L(L, z)\left|\frac{d\log L}{d\log M_\bullet}\right|}{\Phi(M_\bullet, z)} \leq 1$$

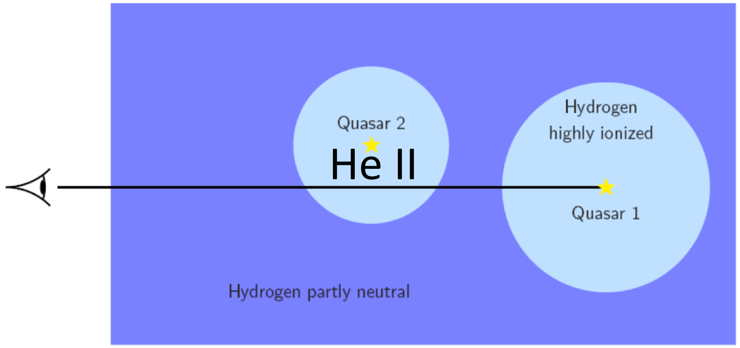
Duration of AGN



Marconi 2004

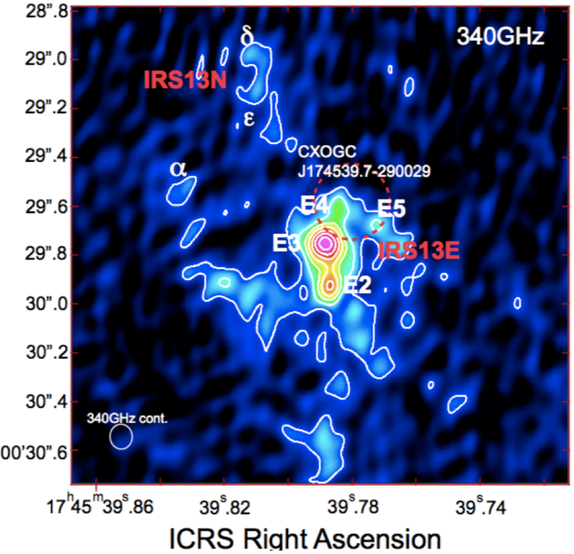


$\tau_{diffusion}(R_{out})>10^8$yr & Rout>10pc

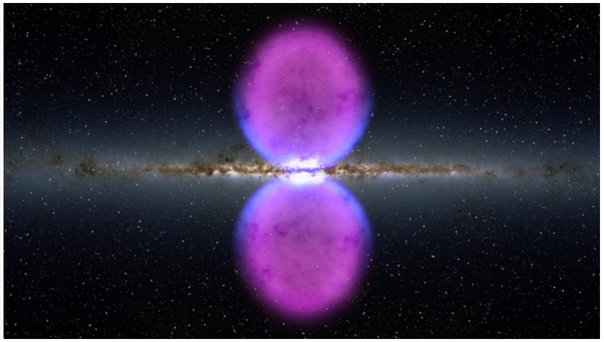


Quasar-on-quasar transverse proximity effect, Schmidt 2017

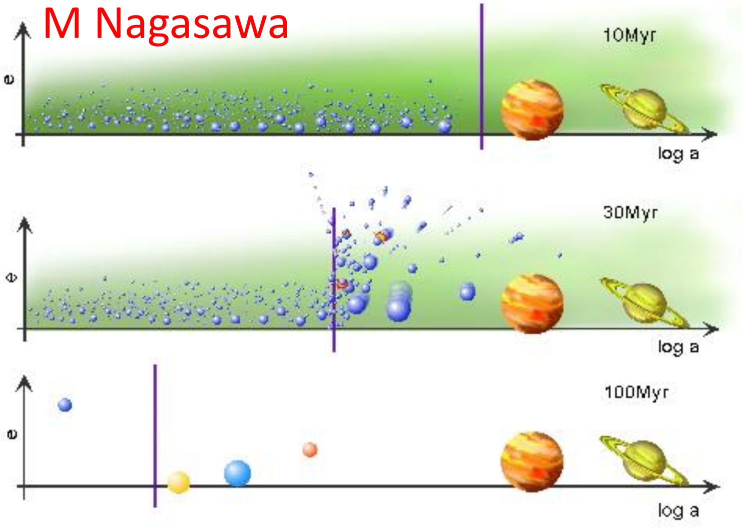
IMBH’s secular perturbation on nearby stars

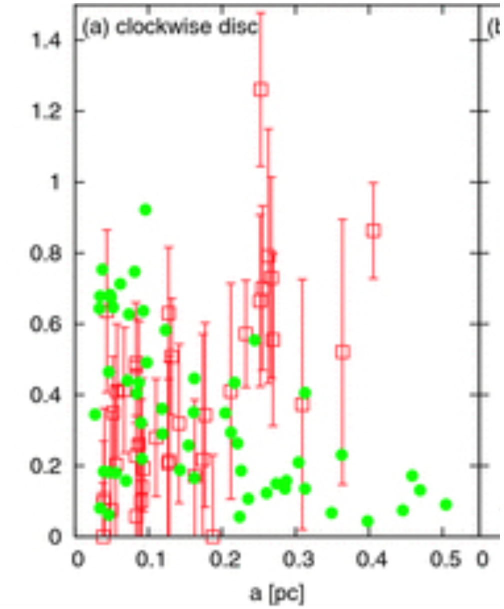


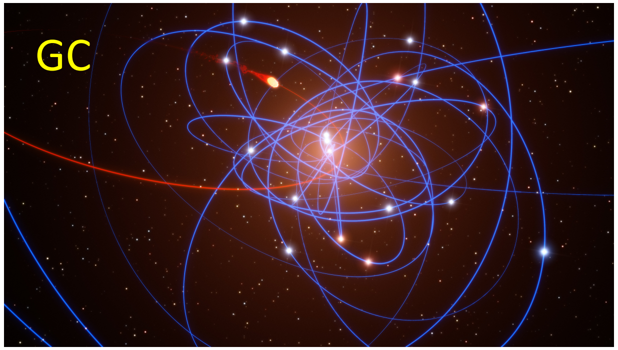
Tsuboi et al 2017, $q<0.002$, $r=0.13$pc



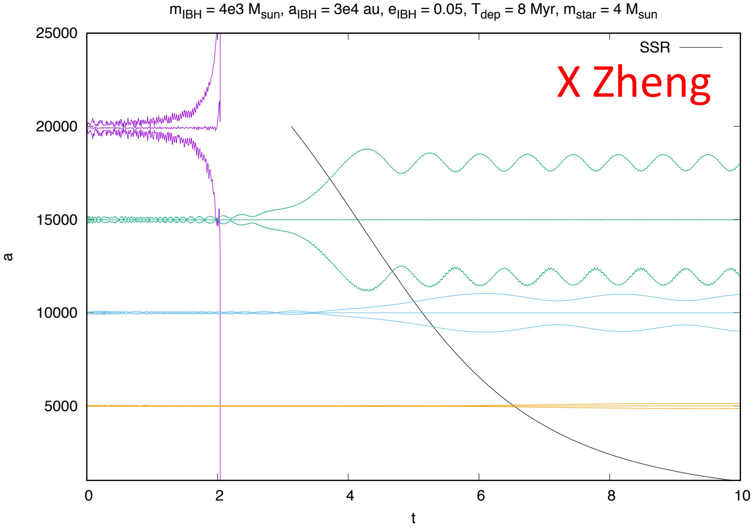
$\lambda \sim 10^{-3}$ and $\tau_{active} \sim 10$ Myr
Can trap stars with a modest
Increase in M_{BH} .



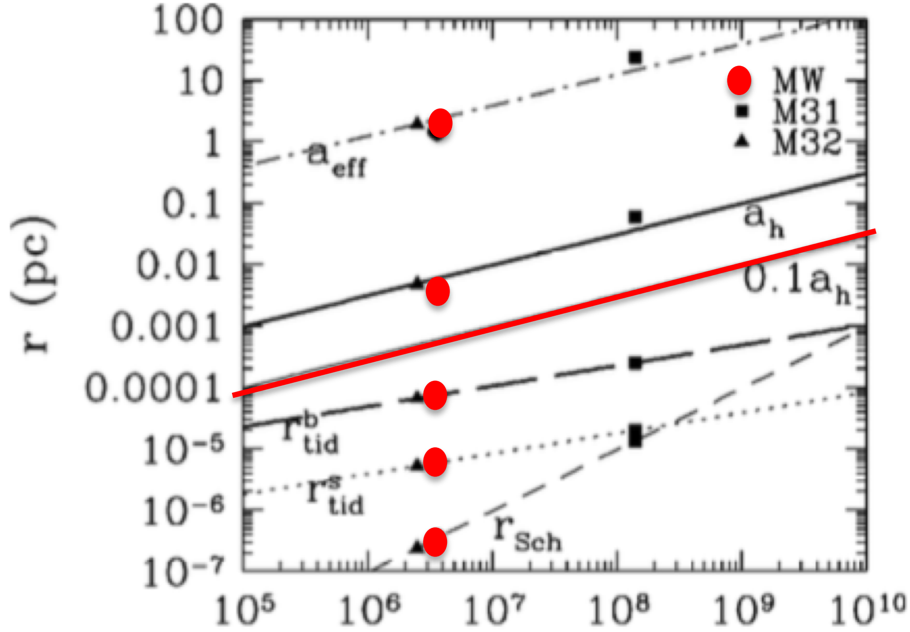


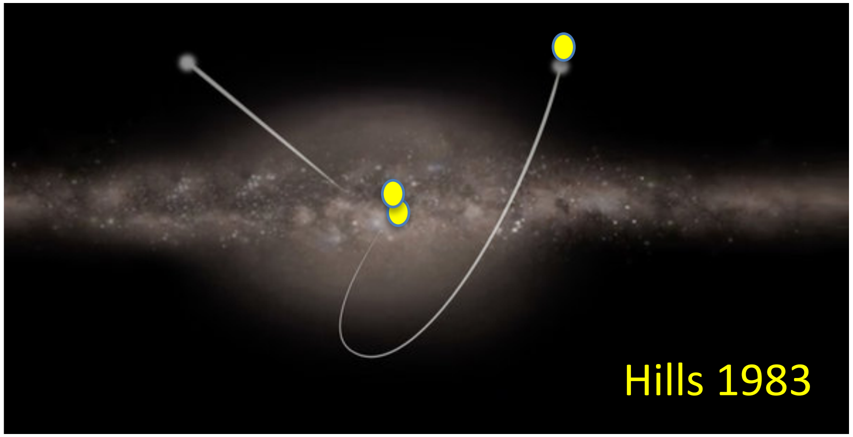


In situ depletion: e-excitation
in disk stars in GC Zheng 2018



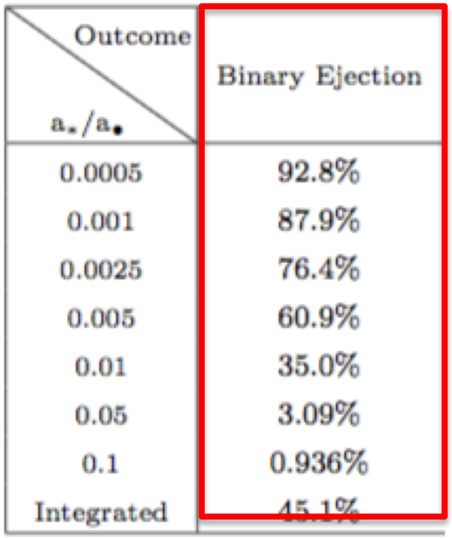
GIAI test: hypervelocity **binary** stars



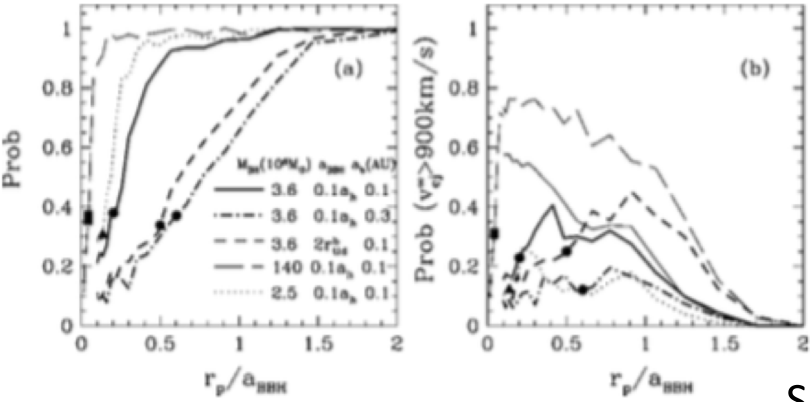


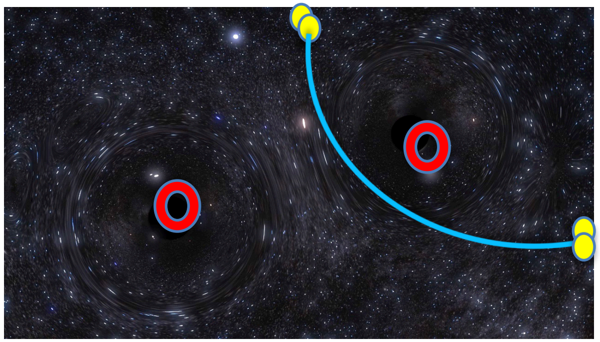
Hills 1983

Lu, Yu, L 2007



Outcome / $a_*/a_\bullet$	Binary Ejection
0.0005	92.8%
0.001	87.9%
0.0025	76.4%
0.005	60.9%
0.01	35.0%
0.05	3.09%
0.1	0.936%
Integrated	45.1%



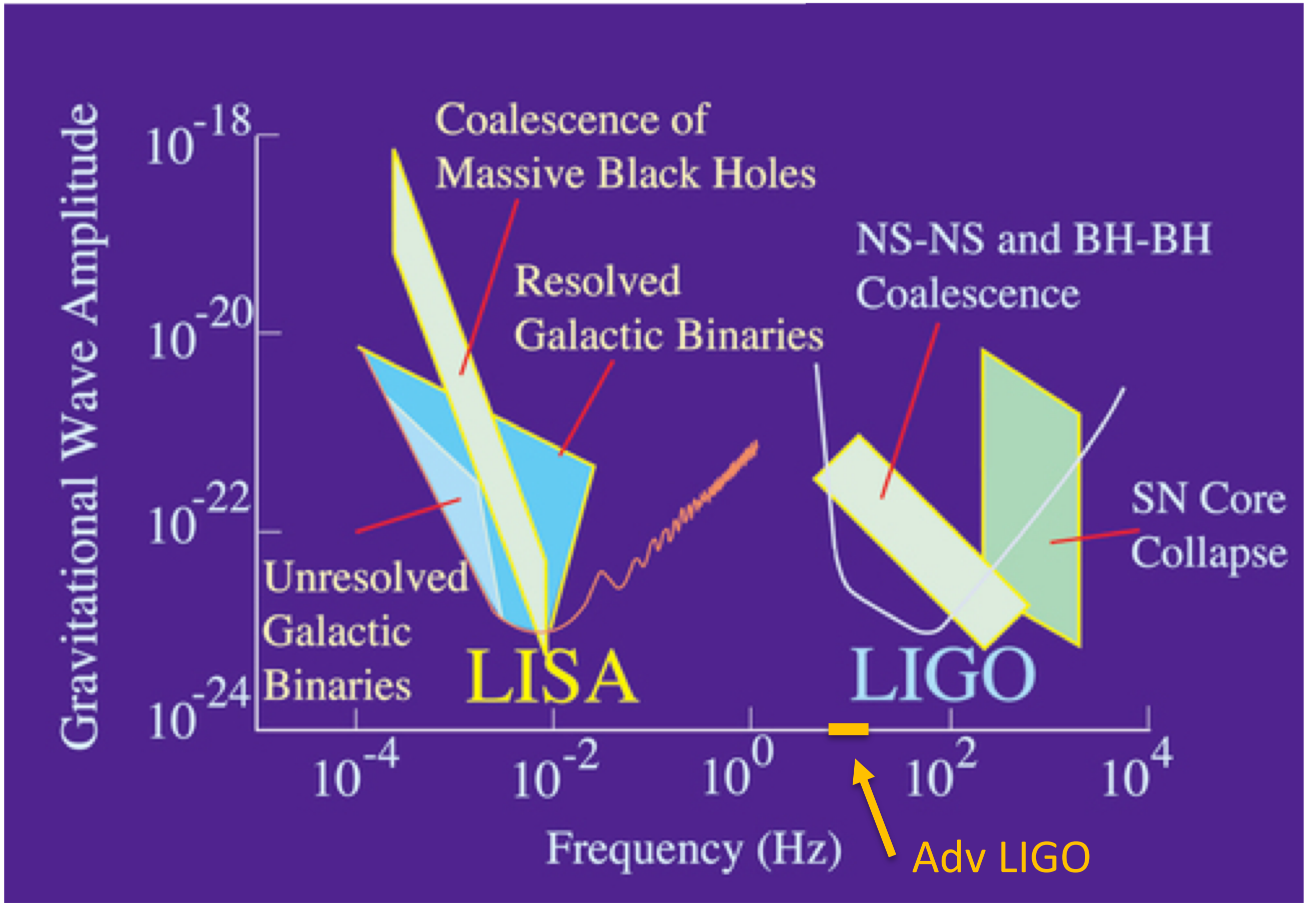


Search for HV binaries with GIAI

Coughlin et al 2018

Intermediate-m_* seed black holes' decay into MBH

$$\tau_{\rm df} = \frac{R_{12}}{\dot{R}_{12}} = \frac{m_{12}R_{12}^2\Omega_{12}}{\dot{J}_{\rm df}} \simeq \frac{P_0}{24\sqrt{\pi}f_{df}\ln\Lambda}\frac{M}{m_{12}}\frac{M}{M_c}$$ $\sim 10^{8\text{-}9}$yr => P_o (M, z<1) $\sim 10^{-2}$



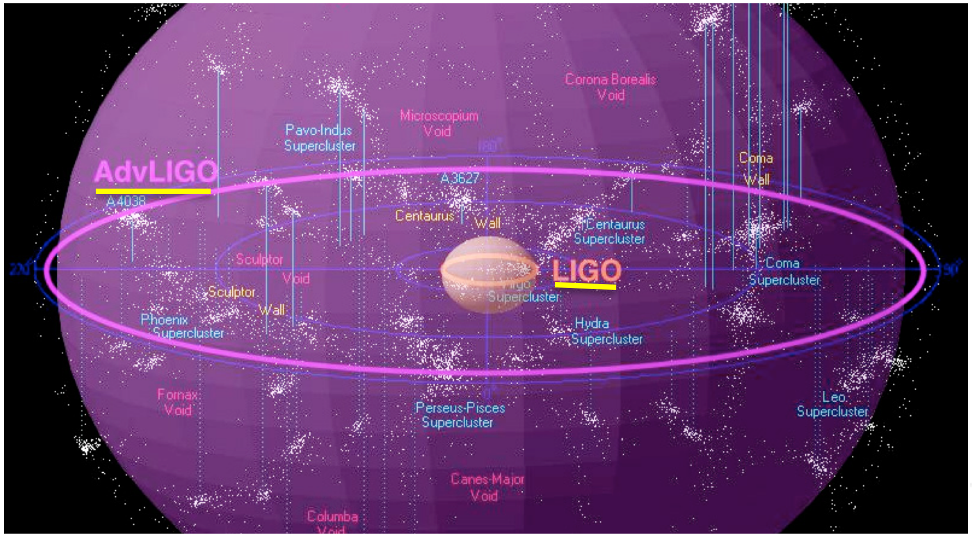
Occurrence rate of BH-MBH may be a fraction that for BH-BH merger events.

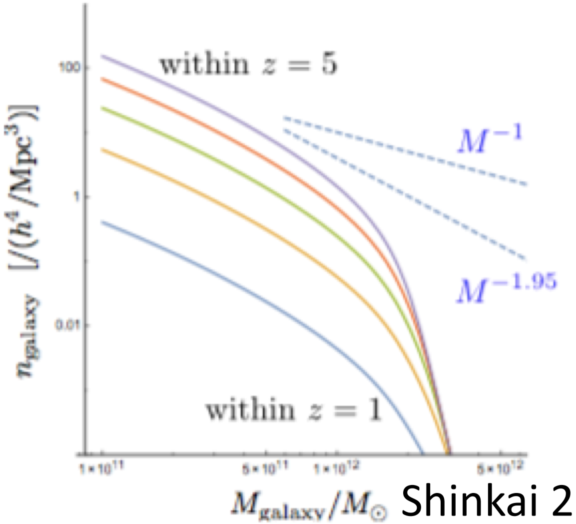
Possible to detect intermediate mass BH with $M_H \sim 10^{2\text{-}3}$ M_o

Occurrence rate of binary black hole merger

$$\dot{N}_{\rm tot} = \int\int \dot{N} \frac{dV_{\rm cm}}{dZ} \frac{dn_A(Z)}{d\sigma_{200}} d\sigma_{200} dZ \qquad D_c(z) = \frac{c}{H_0} \int_0^z \frac{dz'}{E(z')}$$

$$\frac{dV_{\rm cm}}{dz} = \frac{4\pi c}{H_0} \frac{D_c^2(z)}{E(z)} \qquad E(z) = \sqrt{\Omega_m(1+z)^3 + \Omega_\lambda}$$





Shinkai 2018

Order of magnitude estimate in co-moving volume:

$N(L_*) \sim 10^7$ Gpc^{-3} , $N_{\rm AGN} \sim (\tau_{\rm active} / \tau_{\rm Hubble})\ N(L_*) \sim 10^5$ Gpc^{-3}

$\tau_{\rm trap} \sim (M_{\rm disk} / M_*)\ (R_{\rm bondi} / a)^2\ P$ with $R_{\rm bondi} / a \sim (M_*/M_H) h^{-2}$

In $\tau_{\rm active}$, $R_{\rm bondi} / a \sim (P M_* / \tau_{\rm active} M_{\rm disk})^{1/2}$ => $h \sim 0.1$

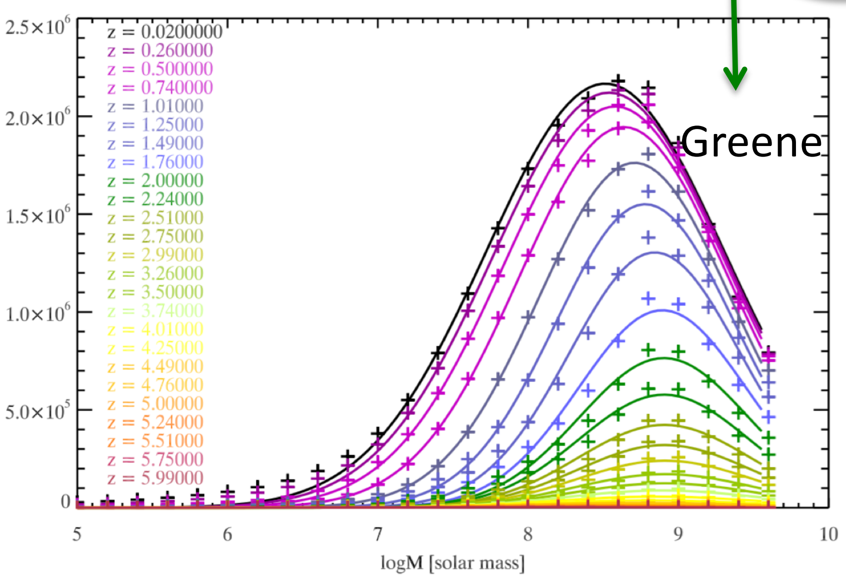
Trapping rate ~ $(h M_H / M_*) / \tau_{\rm active}$ ~10^{-4} yr^{-1} per AGN

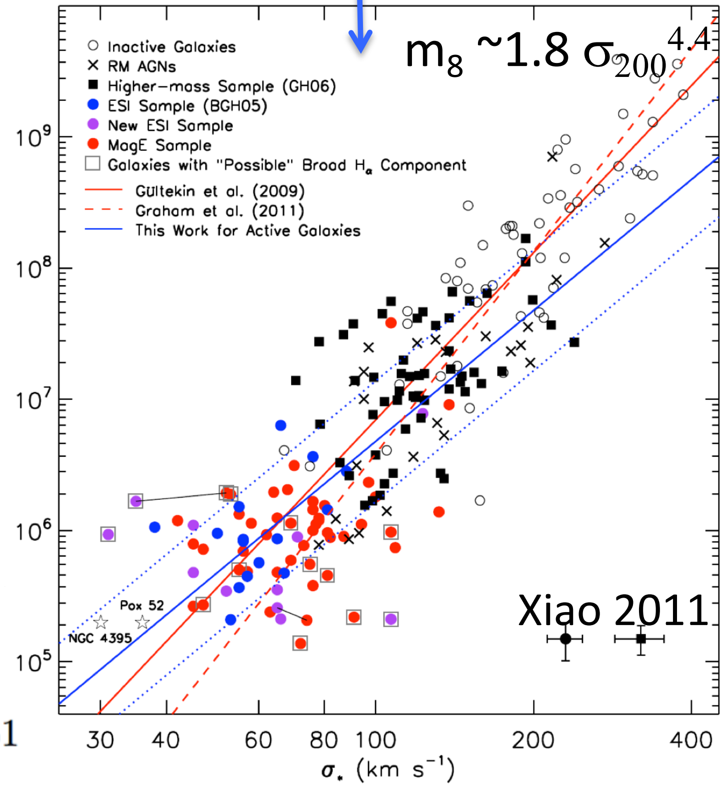
Total rate ~ $\mathcal{O}(1)$ wk^{-1} Gpc^{-3} at z=0. Statistical characterization!

Mass density & M–σ relation

$$\frac{dn_A(Z)}{d\sigma_{200}} = \left(\frac{dn_A(Z)}{dM}\right)\left(\frac{dM}{d\sigma_{200}}\right)$$

Magorrian, Tremaine, Faber
Gebhardt, Ferraresi, Merritt



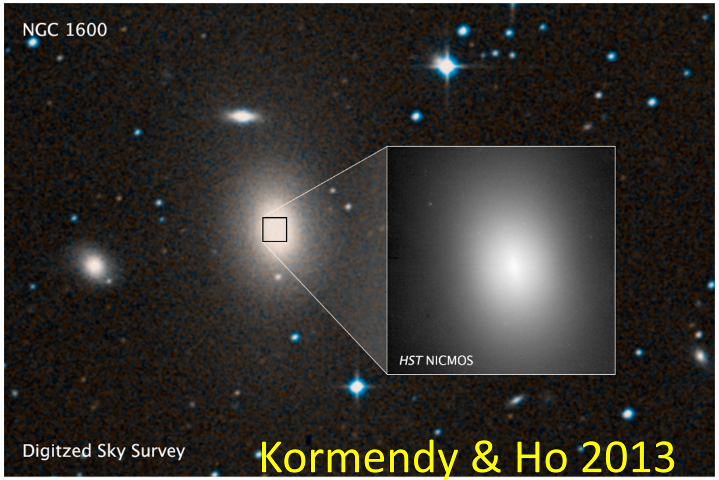


$$\frac{dn_A}{d\sigma_{200}} = \frac{4.4\phi_0}{\sqrt{2\pi}\sigma_{200}\sigma_M}\exp\left(-\frac{(\log m_8-\nu_1)^2}{2\sigma_M^2}\right)$$

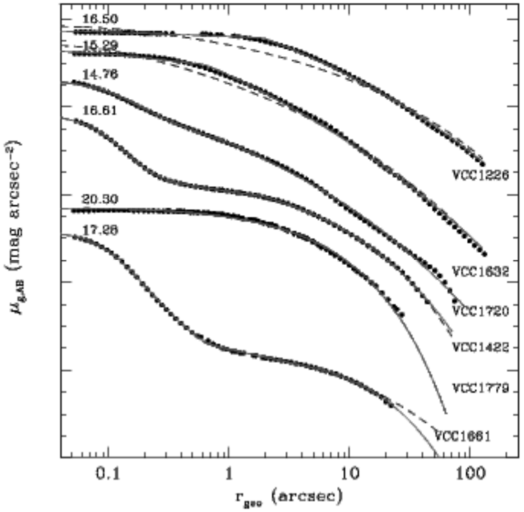
$$\phi_0 = 3.4\times10^{-5}\mathrm{Mpc}^{-3}, \quad \nu_1 = 6.7, \quad \text{and} \quad \sigma_M = 0.61$$

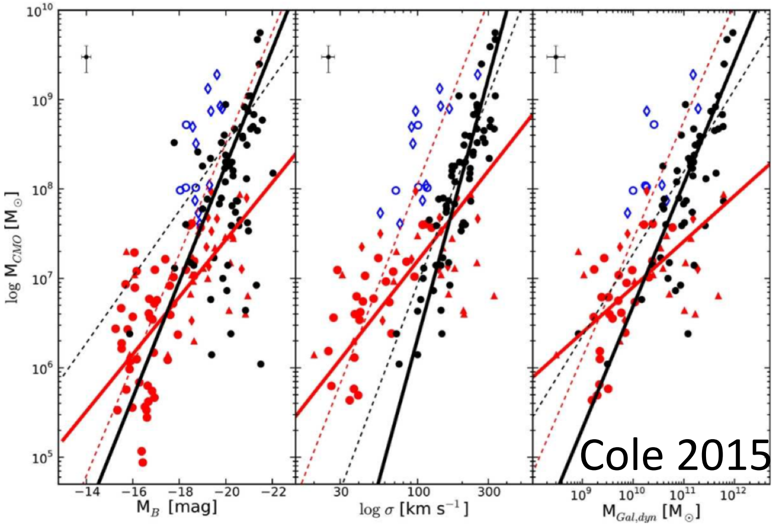
XJZhang, SDMao

$\dot{N}$ (σ) of nuclear stellar clusters (NSC)

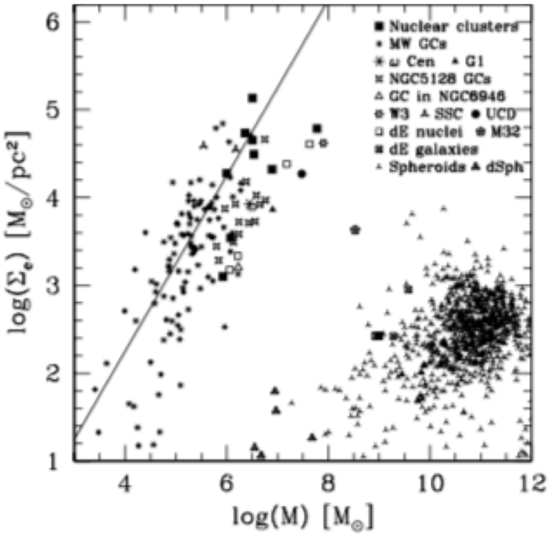


Kormendy & Ho 2013





Cole 2015



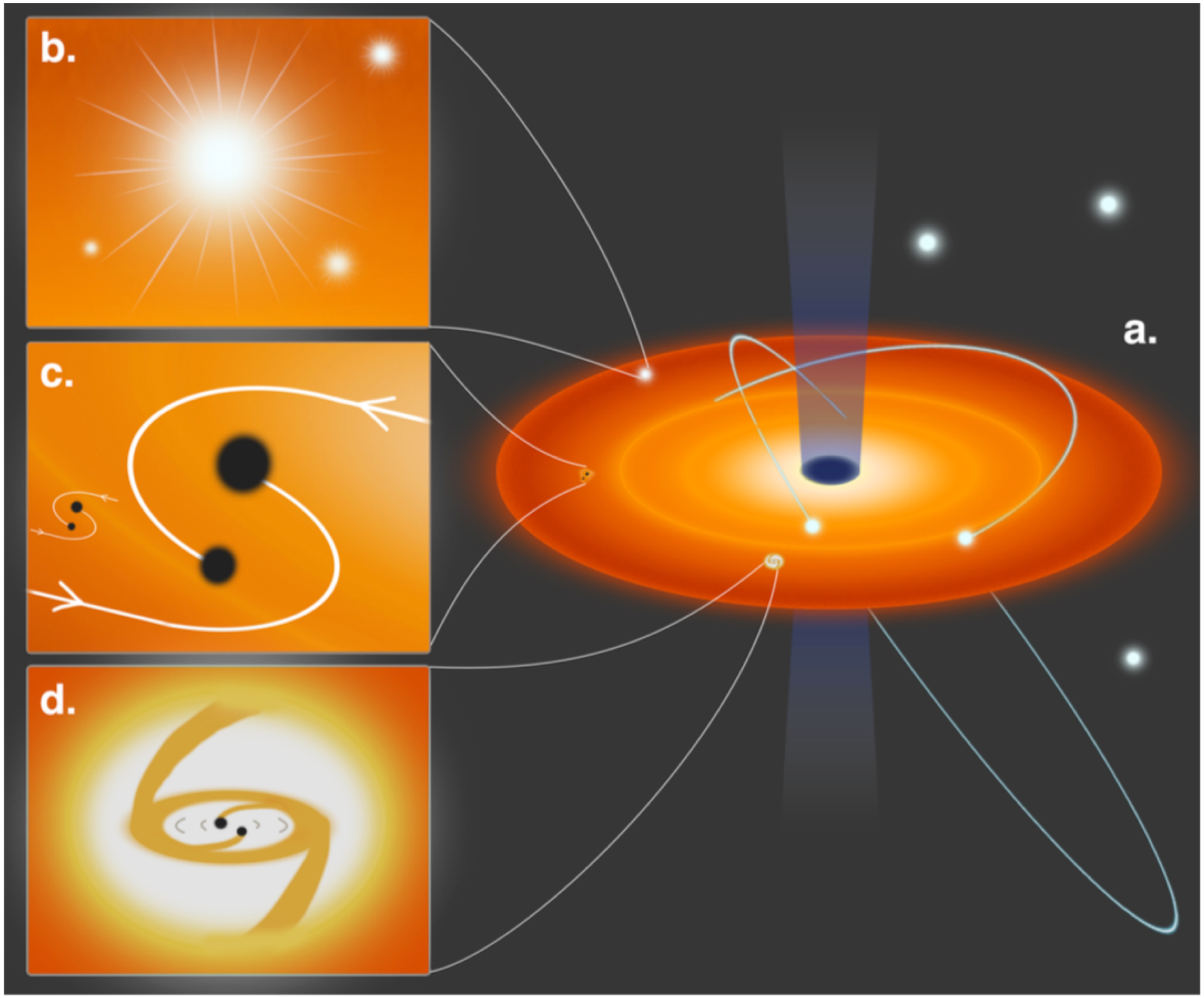
$\dot{N}_{\rm tot}$ ~ 4A original LIGO events per year with

$$A = \int \sigma_{200}^{-3} \exp\left(-\frac{(4.4\log\sigma_{200} - \nu_1)^2}{2\sigma_M^2}\right) d\sigma_{200} \quad \sim \mathcal{O}(1)$$

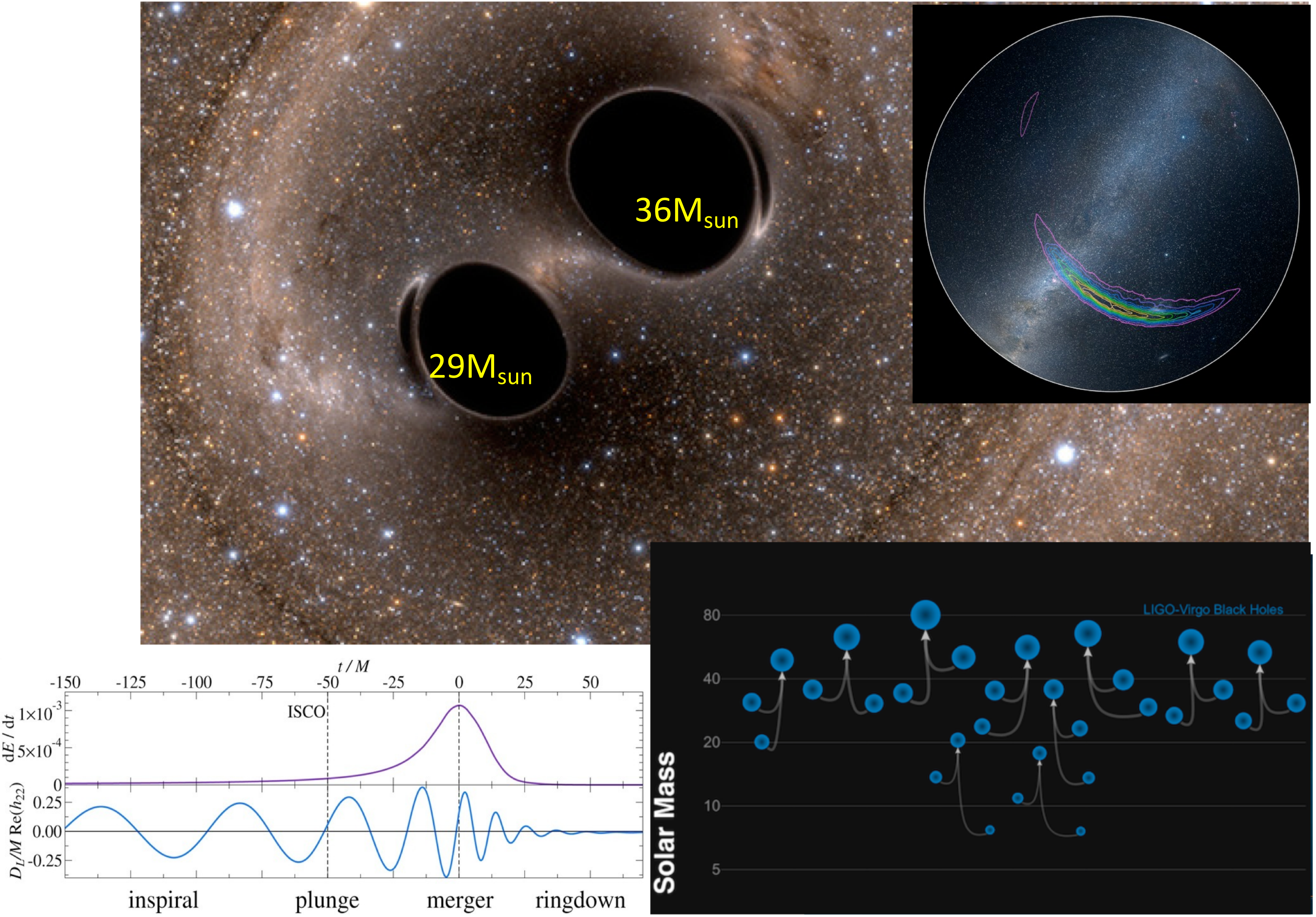
Take-home messages

- AGN disks resemble protostellar disks & may trap nearby stars.
- Trapped stars are rejuvenated, gain mass, and evolve into SNs.
- Supernovae lead to formation of seed black holes with a few M_{sun} and the contamination of AGN disks.
- Seed black holes are retained, grow, migrate, capture partners closely analogous to planetary formation and dynamics.
- Single & multiple seed black holes' mass, spin and orbital angular momenta evolve as they mutually interact & accrete turbulent gas
- Binaries tighten by tides, drag by circum-binary disks, endure companion exchanges, & merge through gravitational radiation.
- Events occur $\sim 10^{1-2}$ yr^{-1} Gpc^{-3} around **metal-rich AGN** with wide masses, small spin angular momenta, and spin-orbit obliquity.
- Occasional intermediate-mass ($\sim 10^{2-3} M_{sun}$) black-hole merger may be detectable by Advanced LIGO. They undergo orbital decay, clear disk gas, & regulate AGN duty cycle and are visible to LISA.

Take-home cartoon

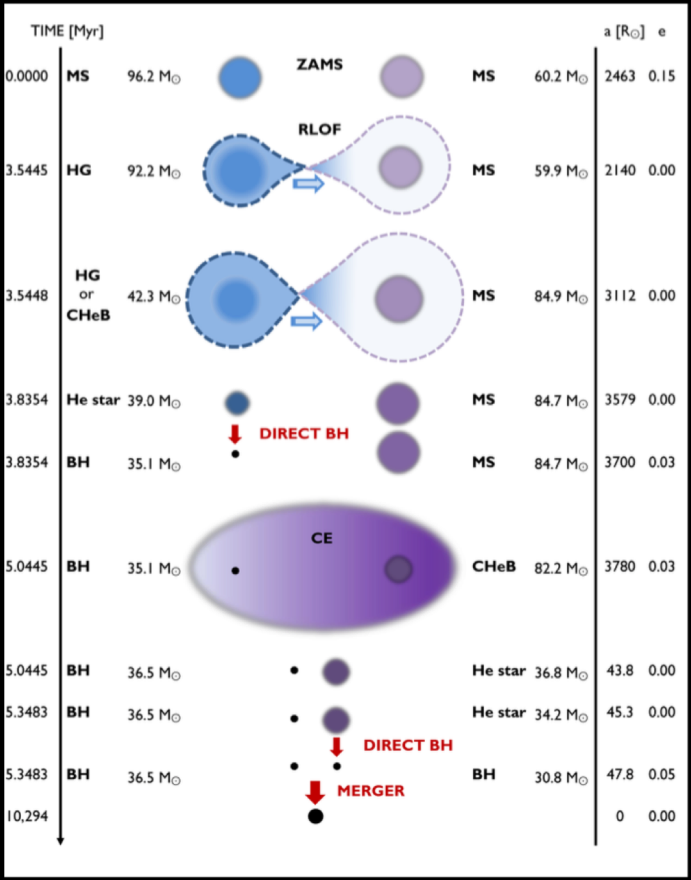


Binary stellar black holes



Common-Envelope vs stellar cluster scenarios

Isolated Binary - Belczynski et al., 2016



Cluster - Rodriguez et al., 2016