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

Douglas N.C. Lin 林潮
University of California Santa Cruz & 清华大学高研院

in collaboration with
Zhuoxiao Wang 王卓骁, Xiaojia Zhang 张晓佳, Shude Mao毛淑德， Robert Naylor, Hongping Deng 邓洪平， Tang Yao唐尧, Brian Tong， **Sverre Aarseth**, Gang Zhao 赵刚, Xiaochen Zheng郑晓晨, Shangfei Liu刘尚飞, John Zanazzi, Judit Szulagyi

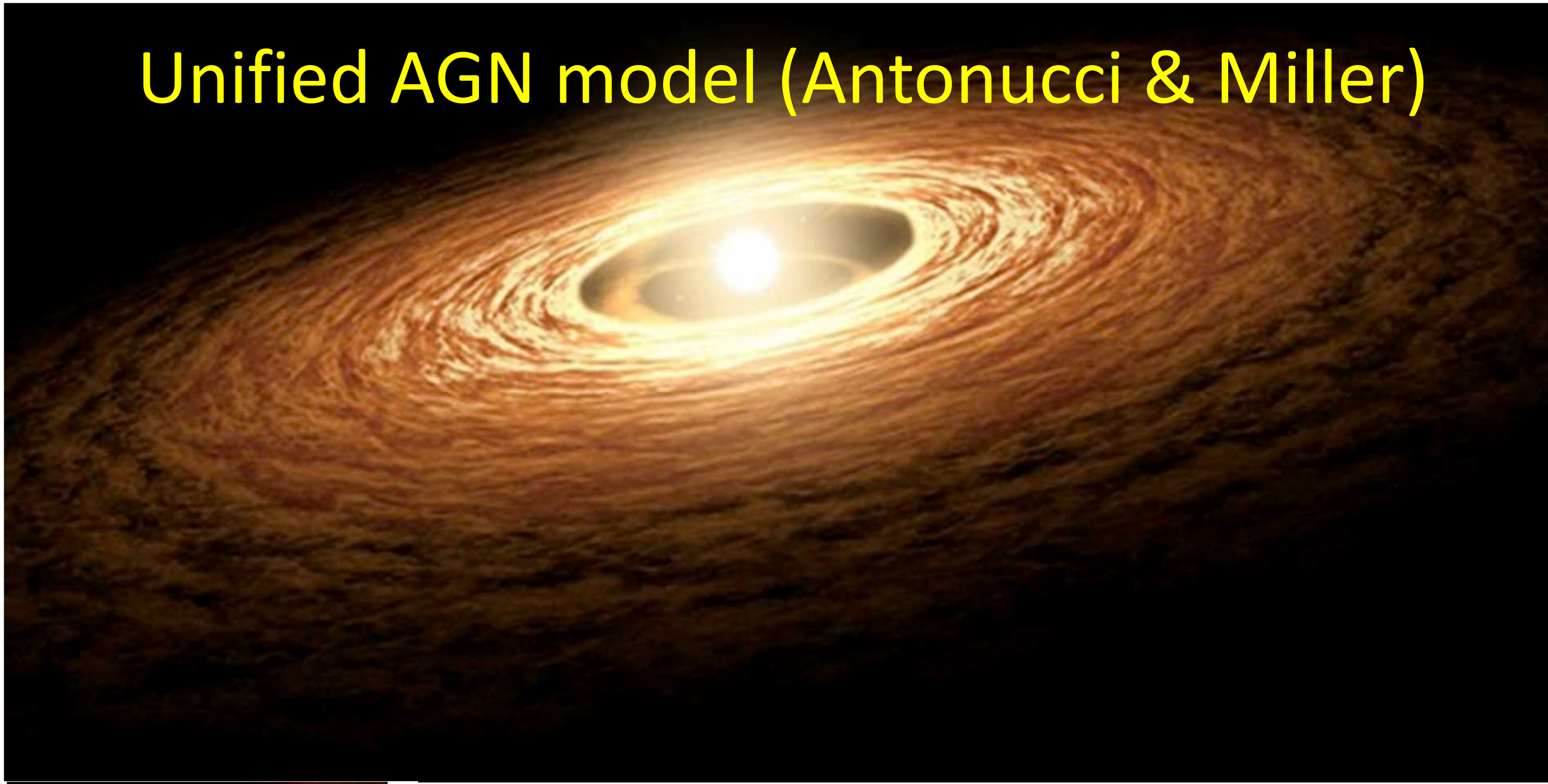
ITC, CfA, Harvard, Sep 2018

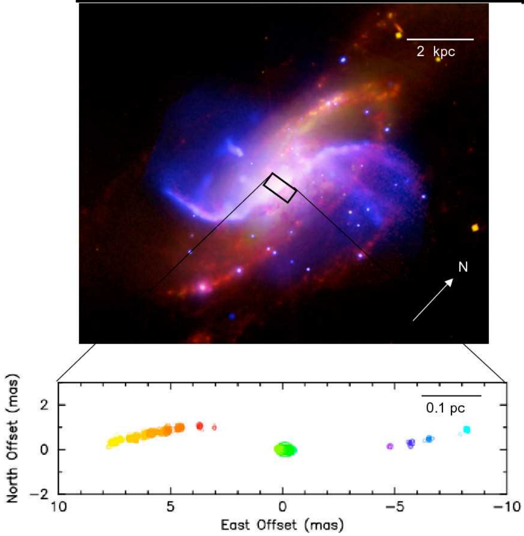

UG,GS,PD,SC

Main motivations

- What caused the emergence of a disk of young stars around the Galactic Center?
- Why are high-redshift quasars so metal rich?
- Can stellar remnants power X-rays in AGNs?
- Can the dynamical evolution of nuclear clusters be affected by gaseous or stellar disks?
- How do AGN become inactive?
- Can a fraction of gravitational wave events be due to stellar black hole mergers around AGNs ?

Unified AGN model (Antonucci & Miller)

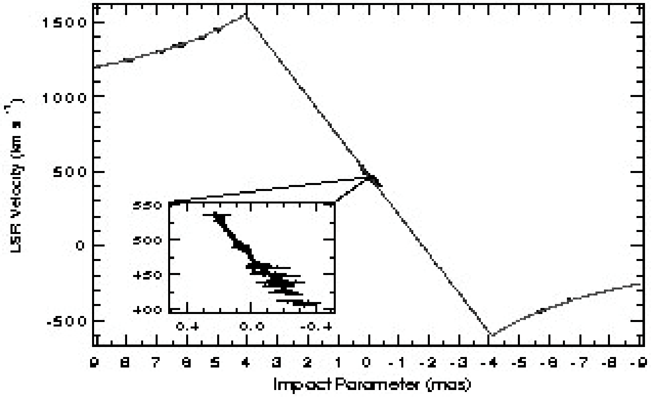




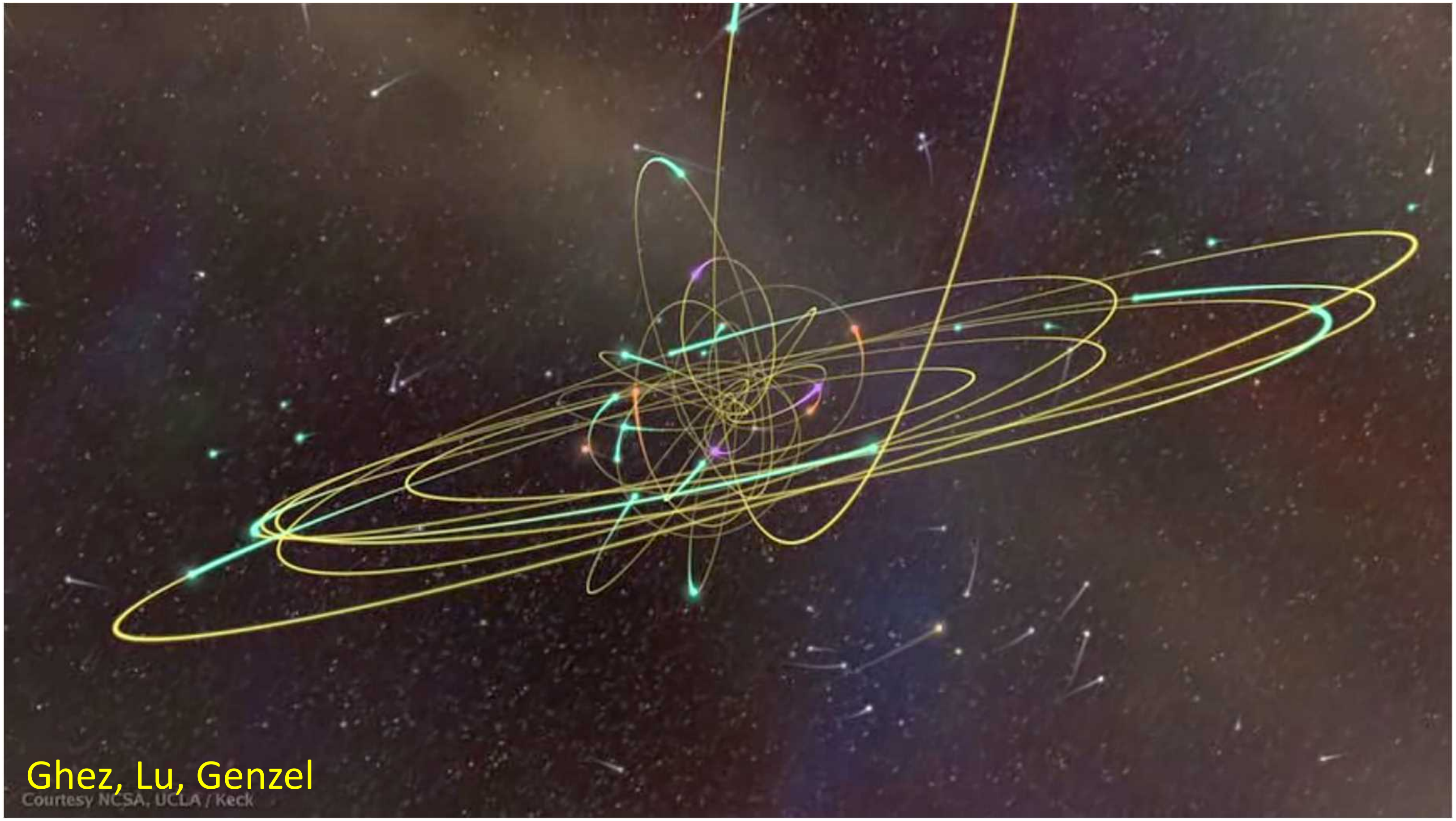
Massive Black Holes:
Lynden-Bell 1969

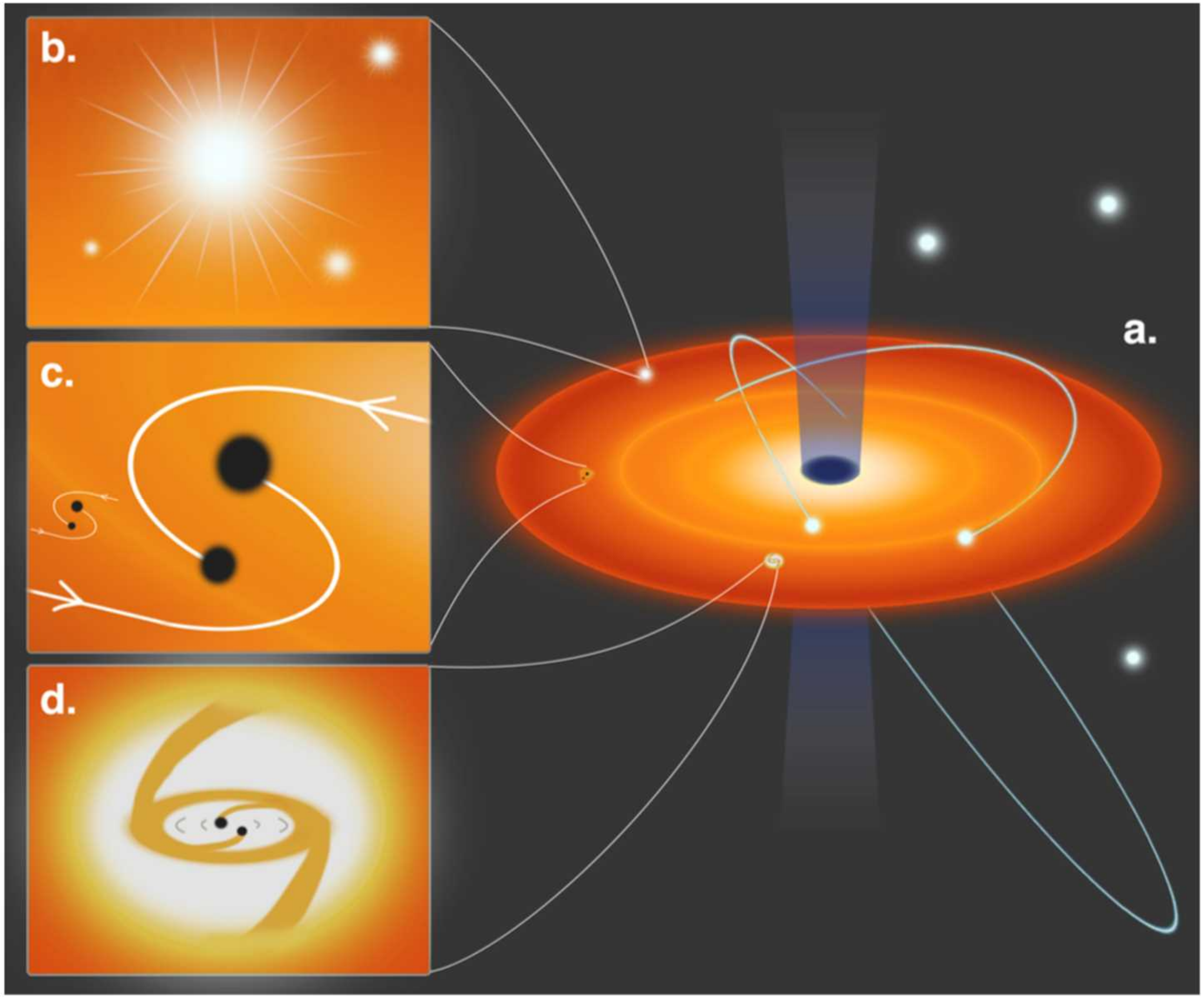
Accretion disk theory:
Lynden-Bell & Pringle

Keplerian disk in NGC4258



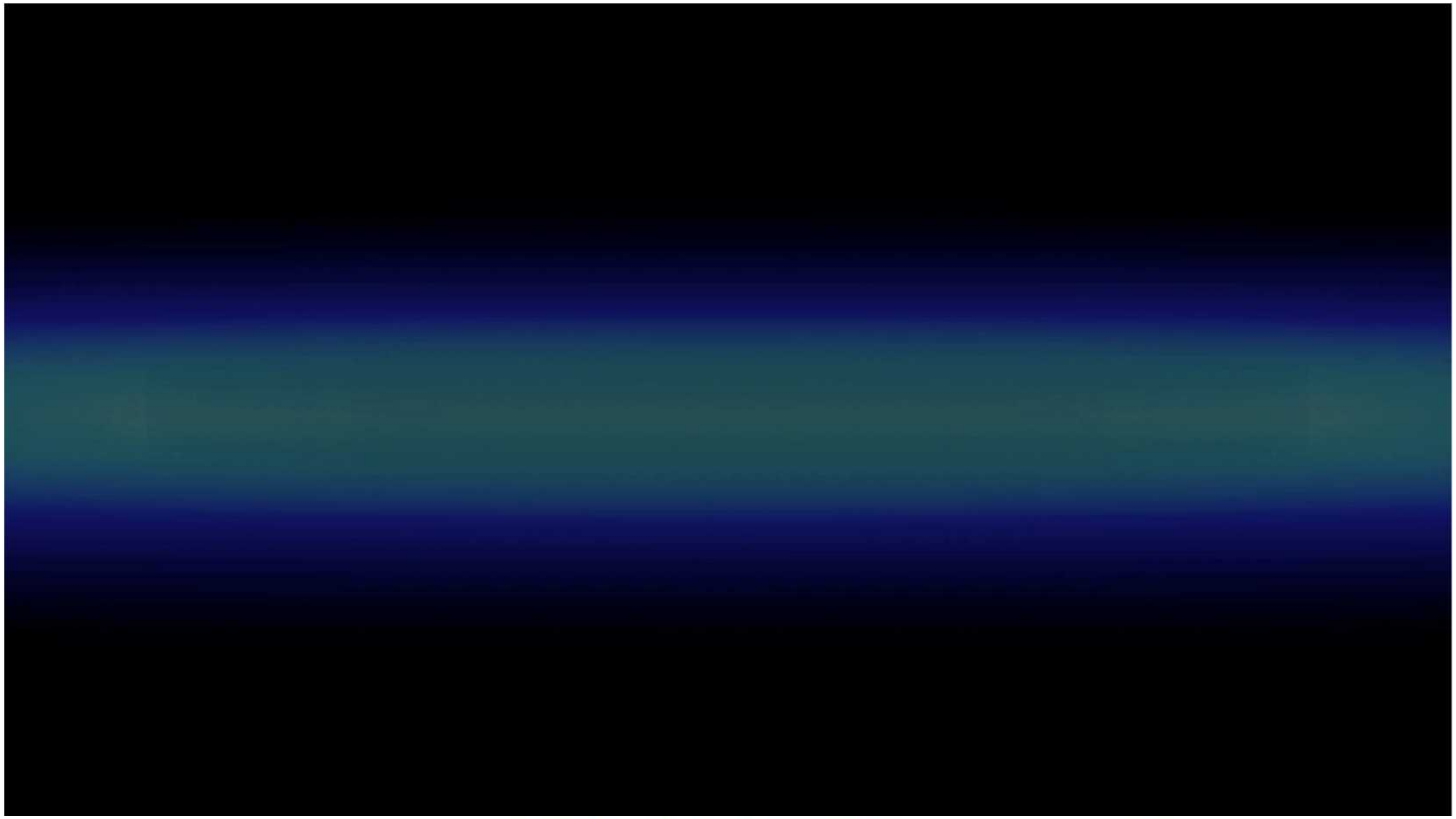
Young stars in the Galactic Center



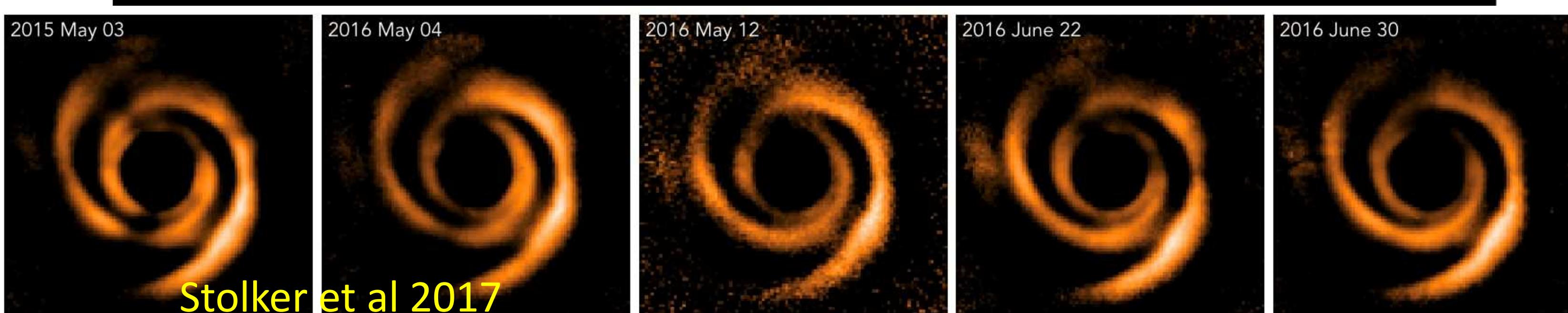


1. There is a MBH in every galaxy
2. Around each MBH there is a nuclear cluster
3. AGN occurs when a MBH is fed by a disk
4. What happens during stars' disk passage ?

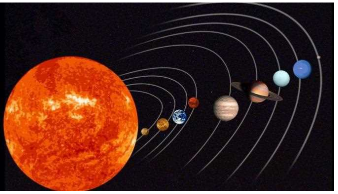
Companions inclined to disks



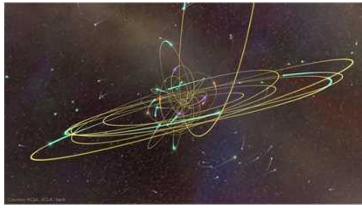
R Naylor



Stolker et al 2017



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

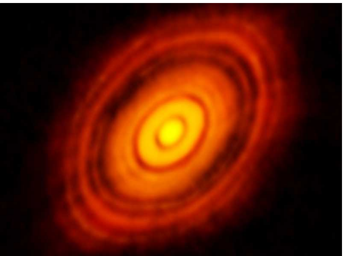
Required model parameters

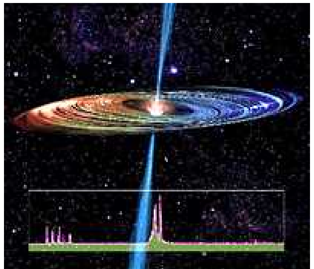
Nuclear star clusters:

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

$\dot{M} = L_{Bol}/\varepsilon c^2 \quad \varepsilon \sim 0.065$

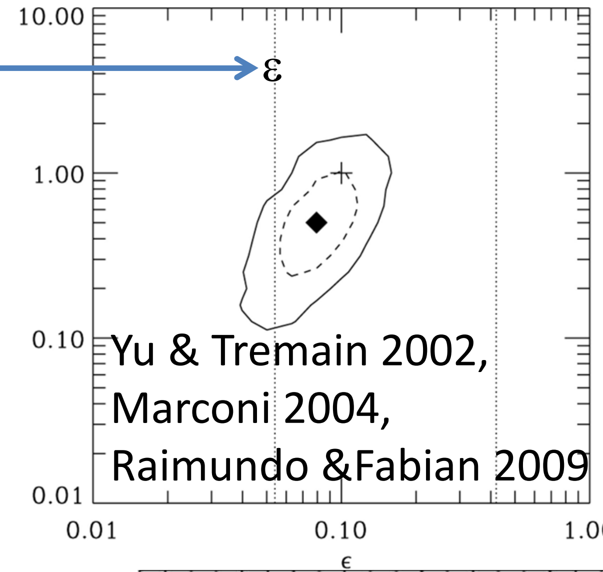
$\quad = \lambda \ \dot{m}_E \quad \lambda \sim 0.6$

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

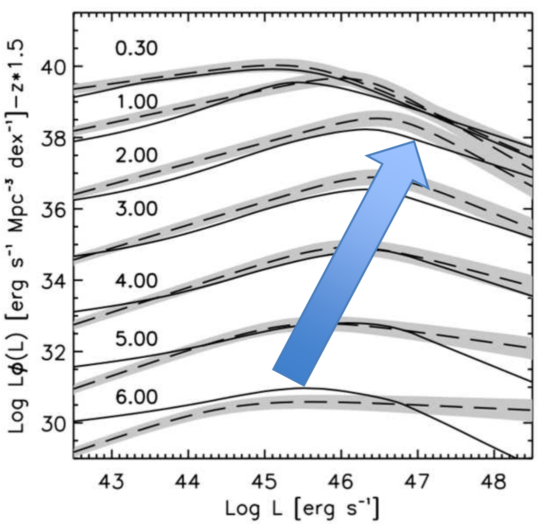
Timescales $\tau_{Sal} = M_h/\dot{m}_E$

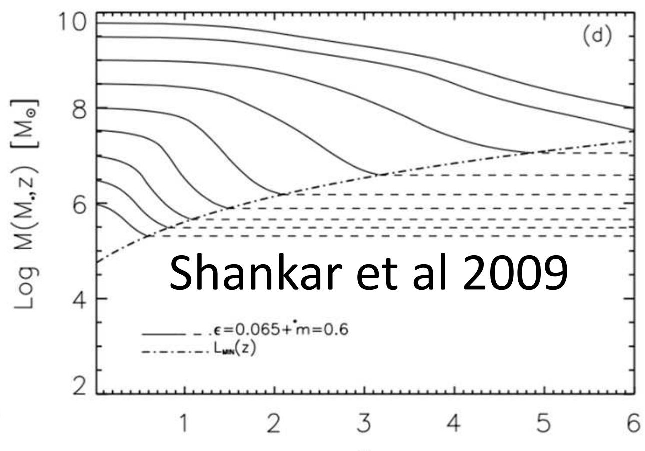
$P(R) = (R^3/GM_h)^{1/2}$

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



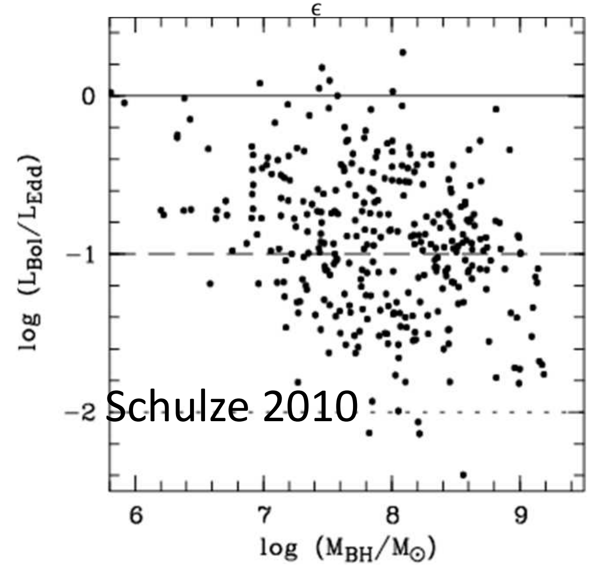
Yu & Tremain 2002,
Marconi 2004,
Raimundo &Fabian 2009





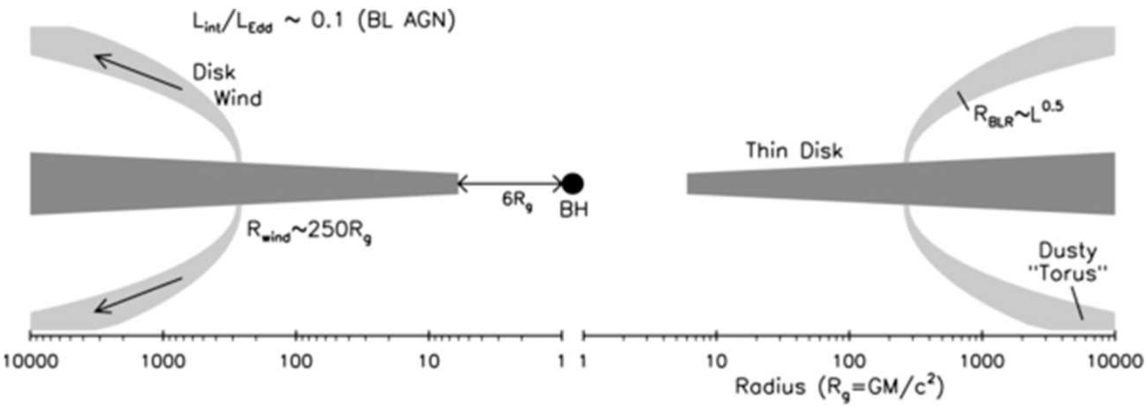
Shankar et al 2009

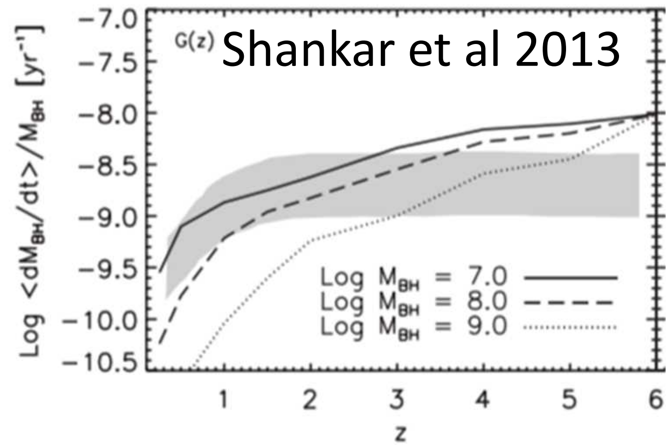
Black hole growth
fed by disk accretion



Schulze 2010

A generic quantitative AGN accretion disk model





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

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

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

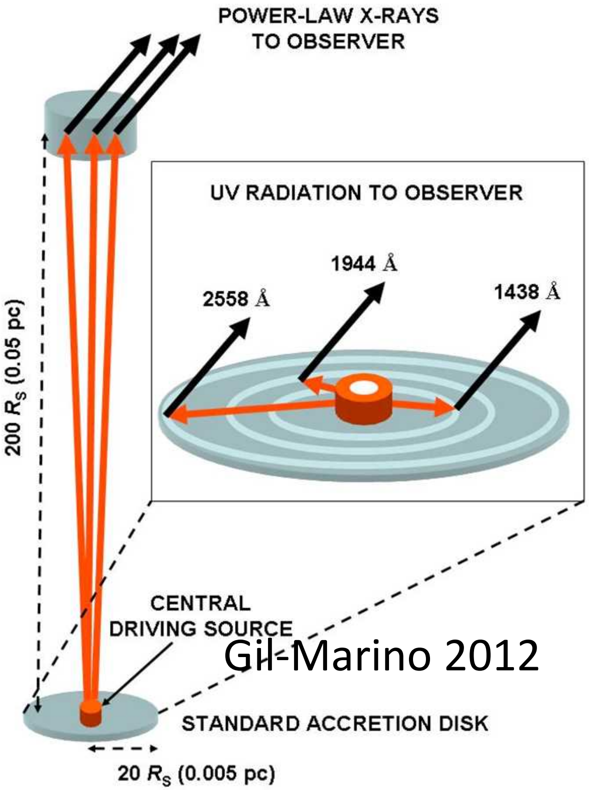
- Marginal gravitational stability (Safronov, Toomre)

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

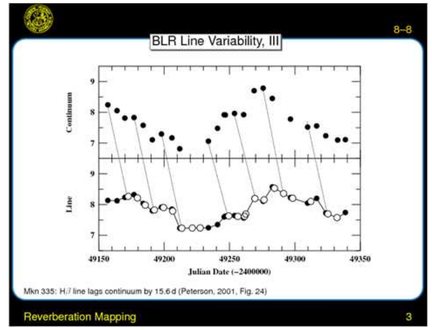
$$\alpha h^3/Q \sim (\lambda/\varepsilon)\ (4\pi/3\sigma_{es})(Gm_p/c\Omega) \sim 10^{-5}\ m_8^{-1/2} R_{pc}^{3/2} \qquad \textbf{(1)}$$

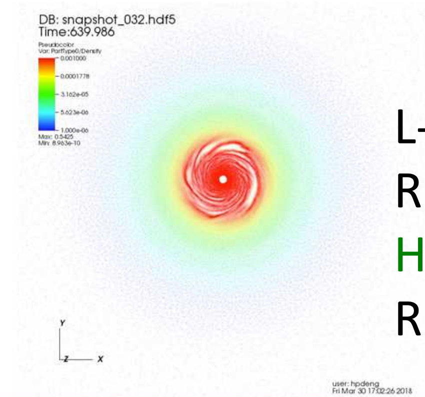
XJZhang

Reverberation from accretion disk to dusty torus



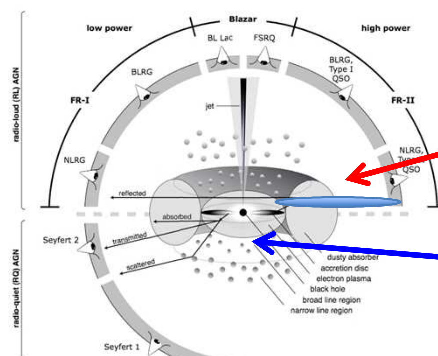
Gil-Marino 2012



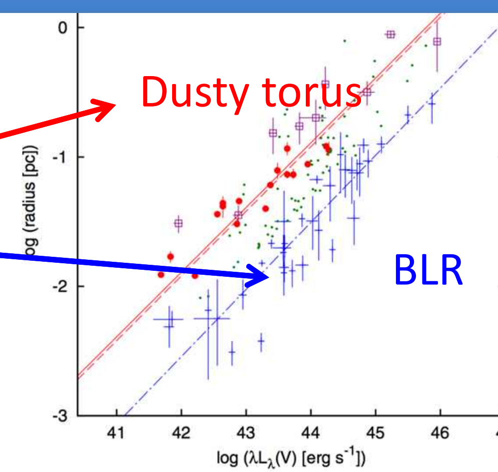


L-Pringle, Rees
Rafikov, Rice,
HPDeng
Riols, Latter

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



Beckmann 2012



3)

At $R_{pc}>1$, Q~**1**-10, α~0.1-**1**, h ~ **0.02**-0.1 $m_8^{-1/6}R_{pc}^{1/2}$,
τ_{disk} >40 $m_8^{5/6}R_{pc}^{-3/2}$(optical depth)

XJZhang, ZXWang

Capture by the disk

Hydro drag: Artymowicz etal 1993

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

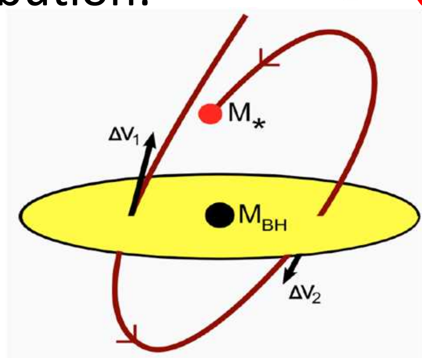
$C_d = C_d^{gas} + C_d^{wave} \sim 6$

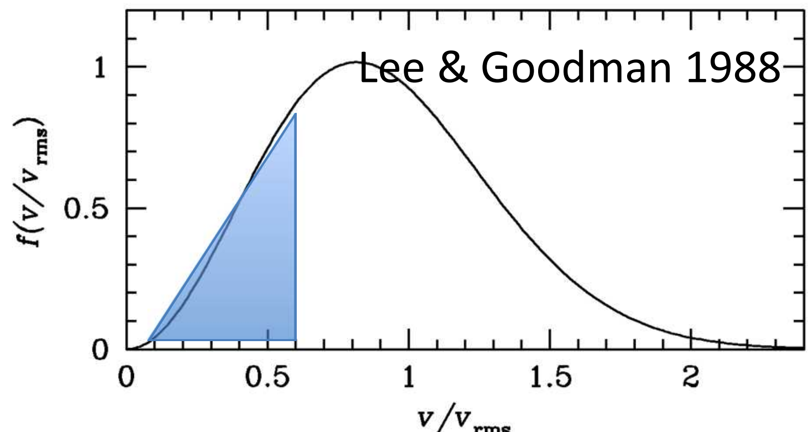
Condition for disk trapping within ΔT:

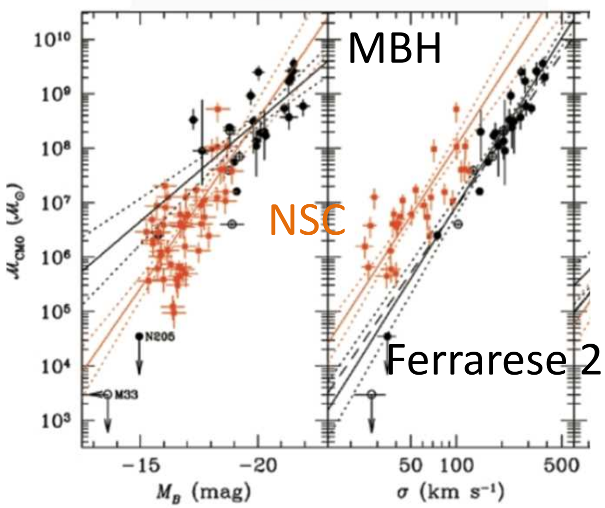
$$\frac{V_z V^3}{V_K^4} \le \xi = 32 C_d \frac{m_*}{M_h} \frac{\pi R^2 \Sigma}{M_h} \frac{\Delta T}{P}$$

Phase space distribution:

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







Phase space fraction of trapped stars:

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

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

Nuclear clusters

$\nu_o \sim 2.5\times10^6 M_{c,8}\,pc^{-3}$

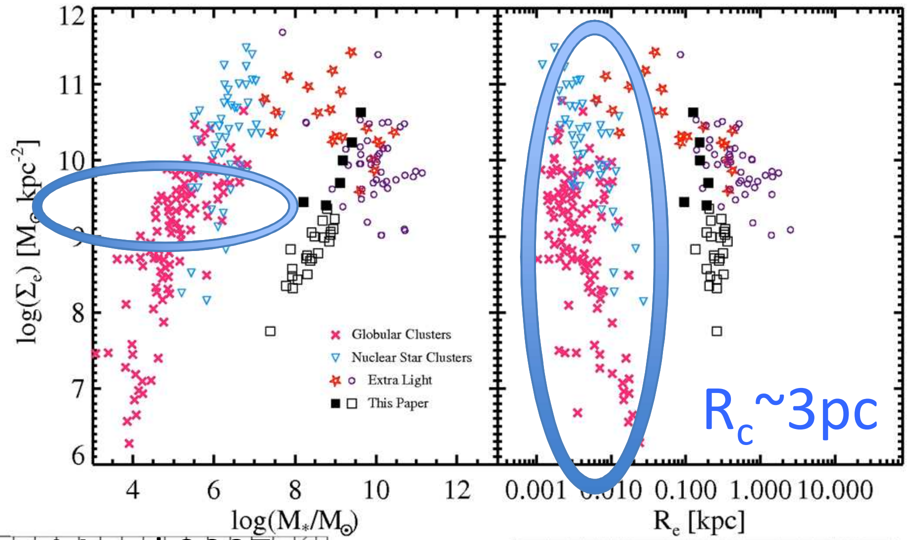
$P_o \sim 5\times10^4 M_{c,8}^{1/2}$ yr

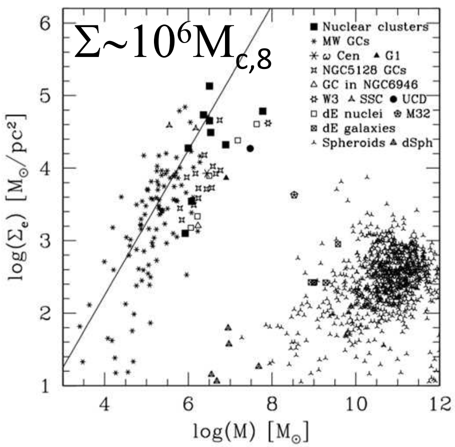
$\sigma_o \sim 350 M_{c,8}^{1/2}$ km s^{-1}

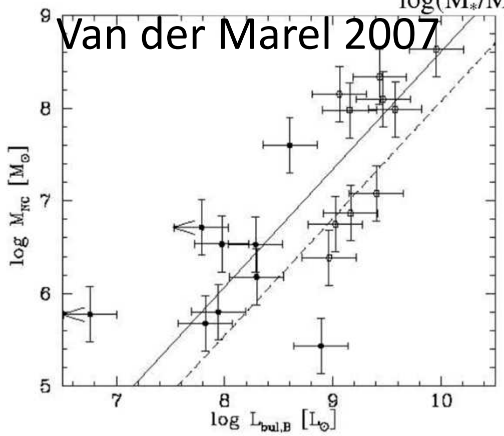
$M_{c,8} \sim 21\,\sigma_{200}^{4.3}$

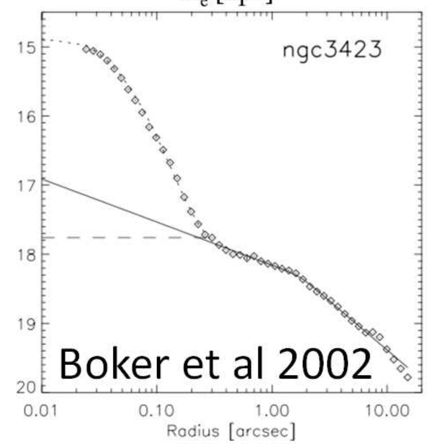
$m_8 \sim 1.8\,\sigma_{200}^{4.4} \sim 0.08 M_{c,8}$

Efficiency of NSC< => MBH









Capture rates:
XJZhang

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

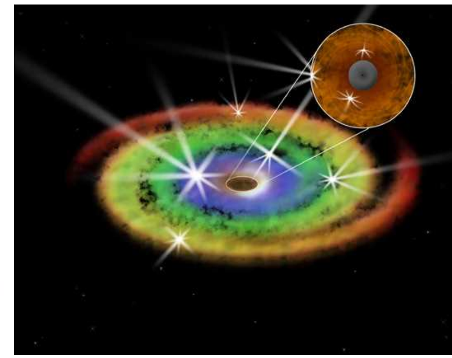
Accretion rate and stellar rejuvenation

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

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

Bondi accretion time scale: (independent of M_h)

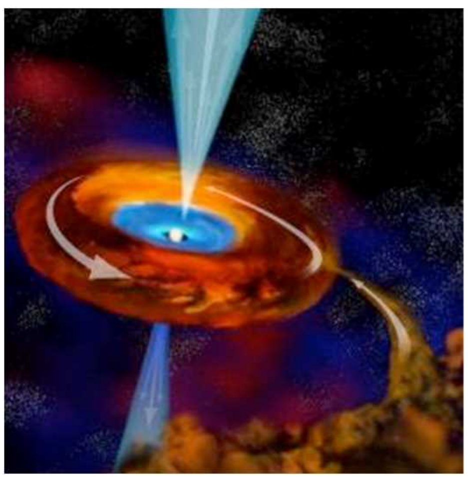
$$\tau_B = m_*/\dot{m}_* \simeq 0.6(M_\odot/m_*)R_{pc}^3\mathrm{Myr}$$



Wind loss

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

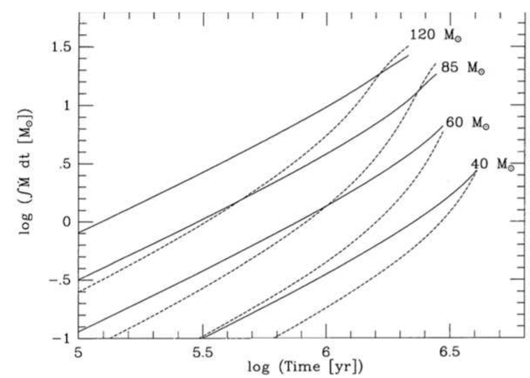
$$\log\left(\frac{\dot{m}}{M_\odot \mathrm{yr}^{-1}}\right) \simeq 1.74\log\left(\frac{L_*}{L_\odot}\right) - 1.35\log T_{\rm eff} - 9.55$$



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

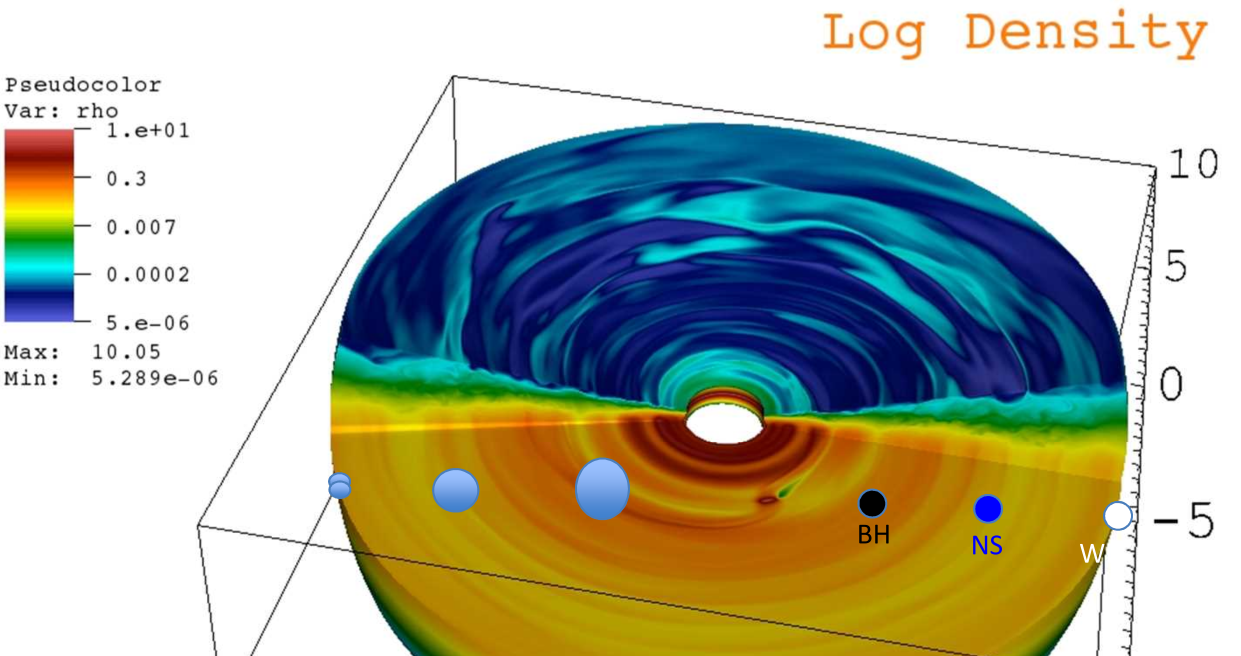
Main sequence evolution time:

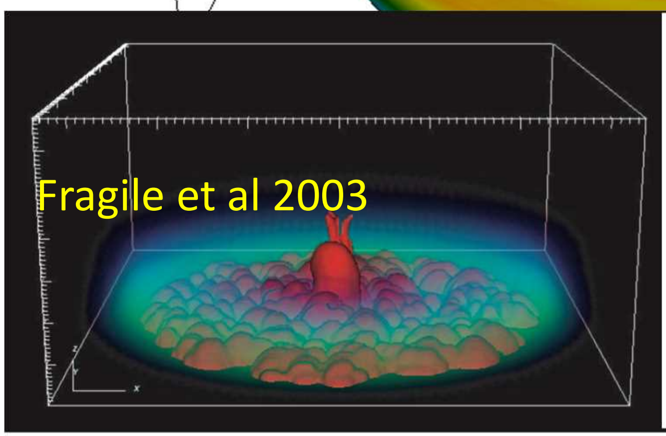
$$\tau_* \sim 10(m/M_\odot)^{-2.5}\mathrm{Gyr}$$

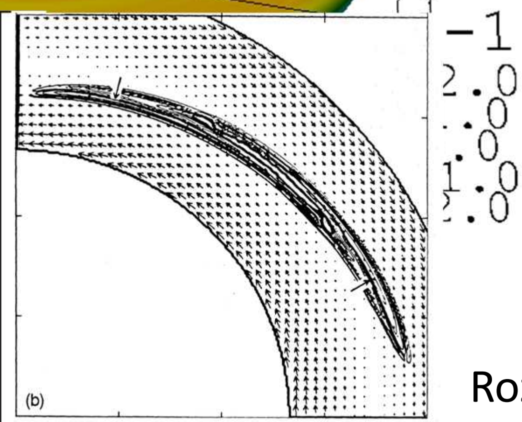


YTang, J Szulagyi

Stellar rejuvenation







Origin of `young' stars

a)Capture host galaxy stars

b) Opaque disk (τ_{disk}>)
R_{opaque}~12 $m_8^{5/9}$ pc

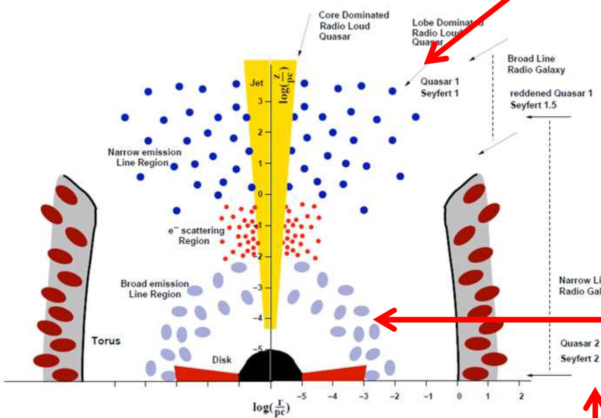
c) Top heavy IMF:
Min (m_{*B}, m_{*w}) ~$10^{1-2}M_o$

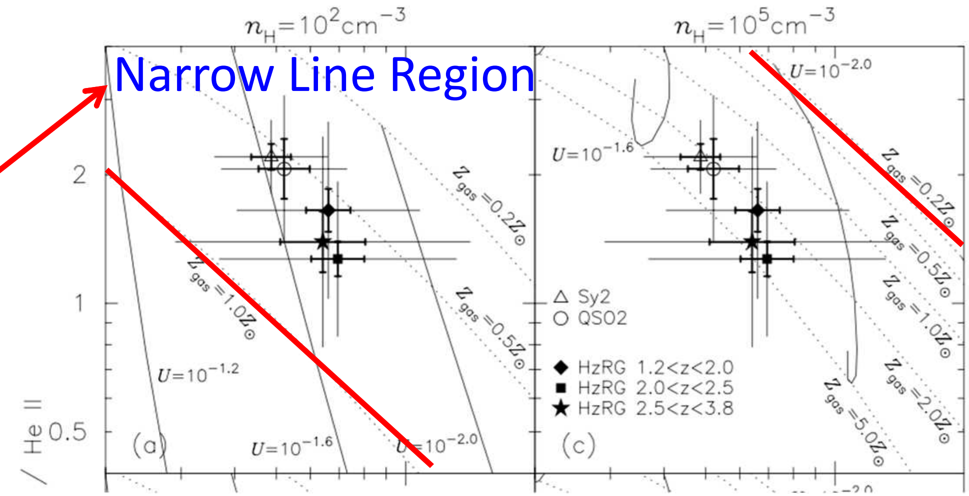
d) Binary main sequence stars possible at large a

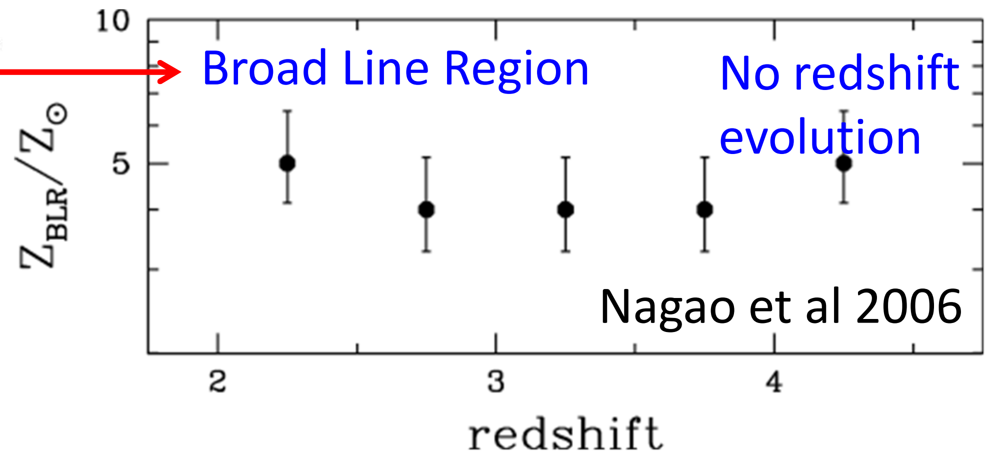
Rozyszka L. Bodenheimer 1995

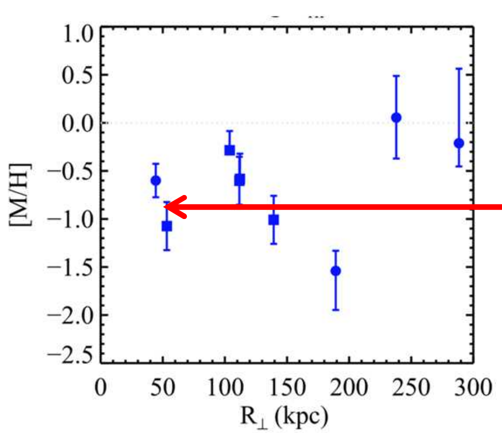
Super-solar metallicity in high-redshift AGNs

$Z_{BLR} > Z_{NLR}$



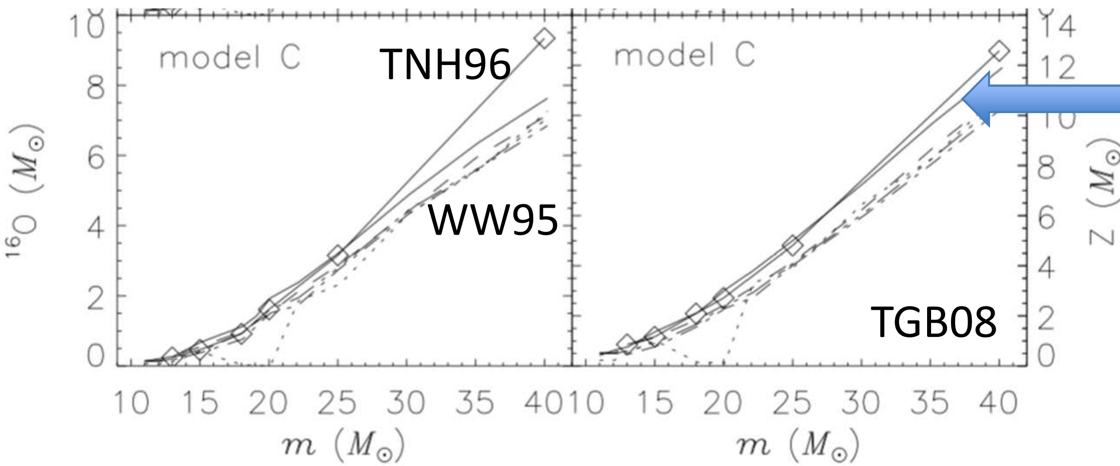






Quasars probing metal-poor outskirts of quasars
Lau, Prochaska, Hennawi 2016

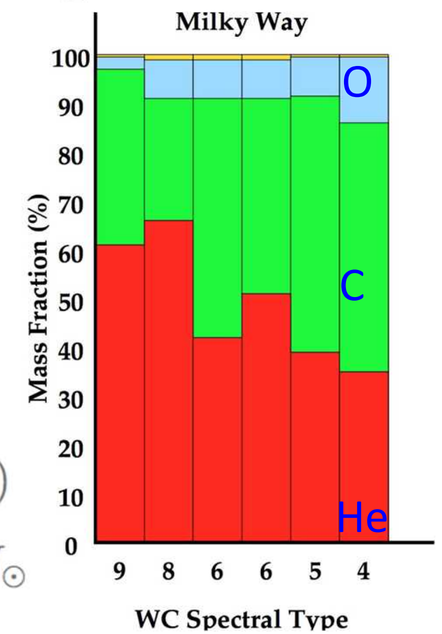
In situ metallicity enrichment

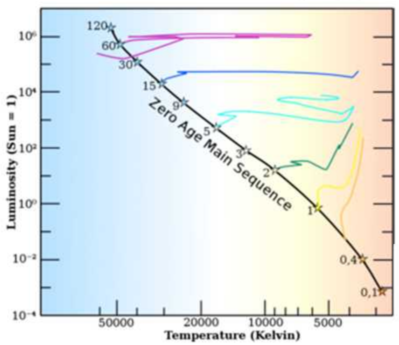


a) Type II supernovae yield:

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

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



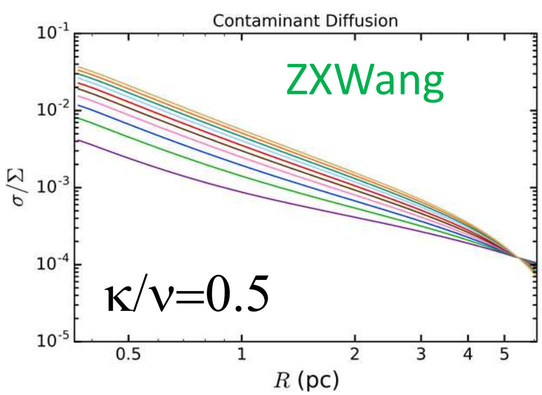


b) WR and AGB winds:

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

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

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

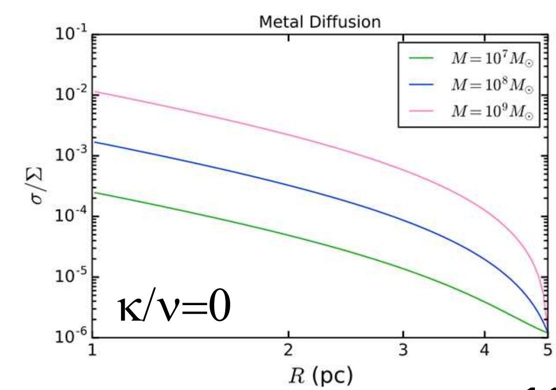


d) [Fe/H] diffusion (Clarke 1988)

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

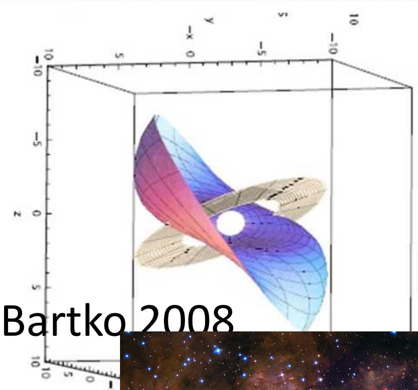
$$\kappa = 0 \quad => \quad \Delta Z(R) = \frac{m_z d\dot{N}R}{U_r 2\pi\Sigma R dR} \simeq 3\times10^{-3}\sigma_{200}^3$$

κ/ν=0.5 $\quad \Delta[Fe/H] \sim O(1-10)$

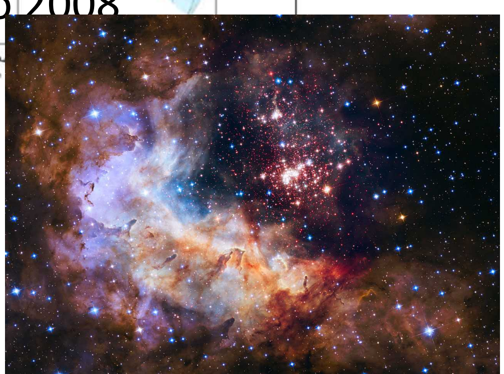


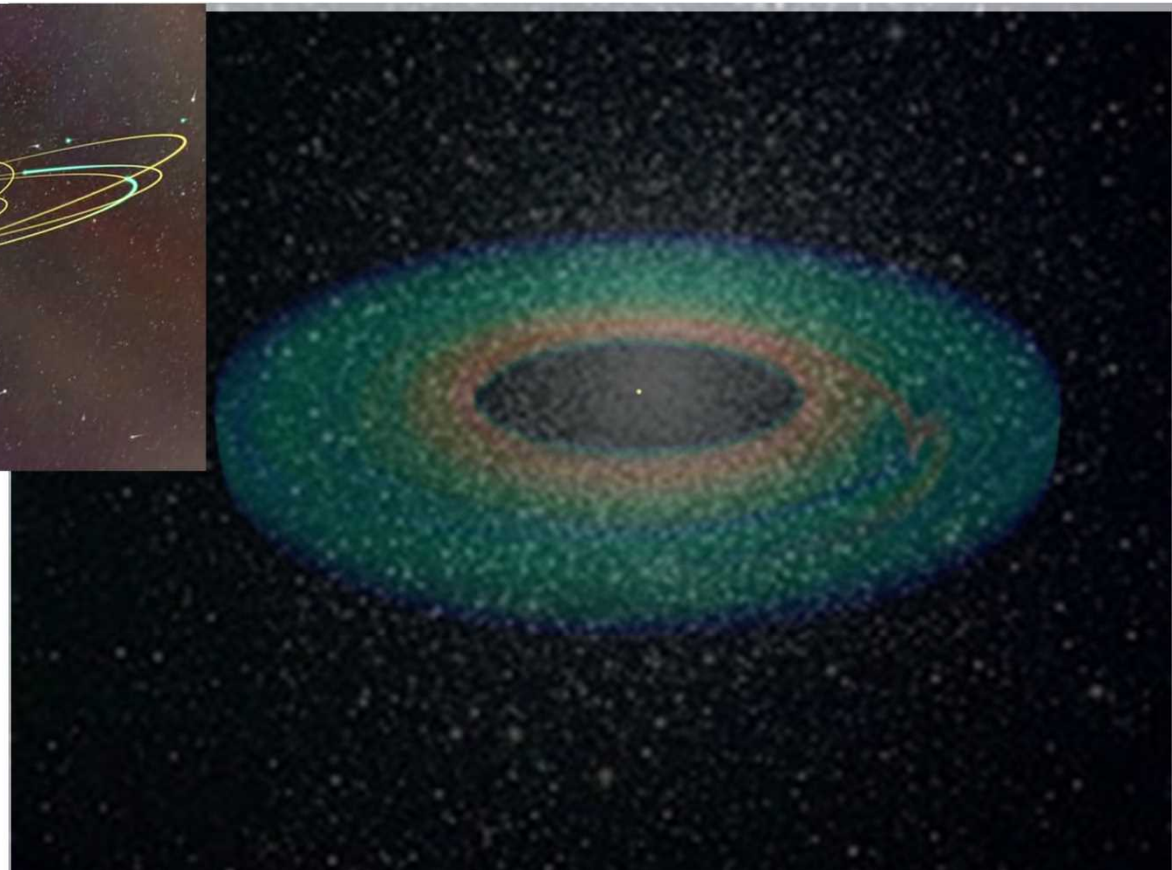
Disk's reorientation due to infall of turbulent gas

Ghez, Lu, Genzel



Bartko 2008



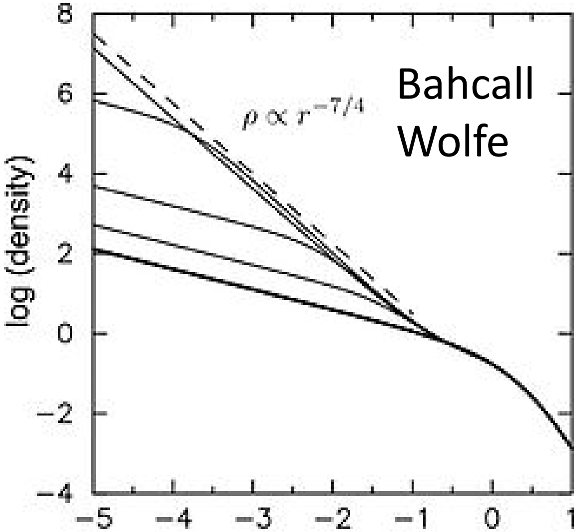


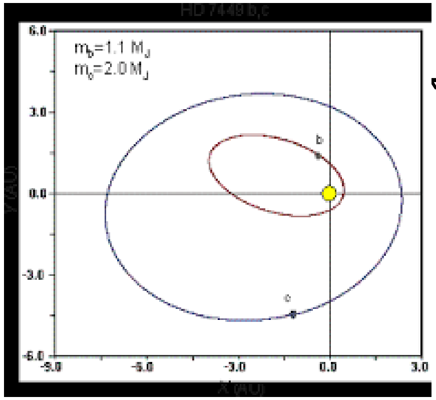
Rejuvenation of stars onto different planes

Also in Q~1 warped disks around spinning MBHs

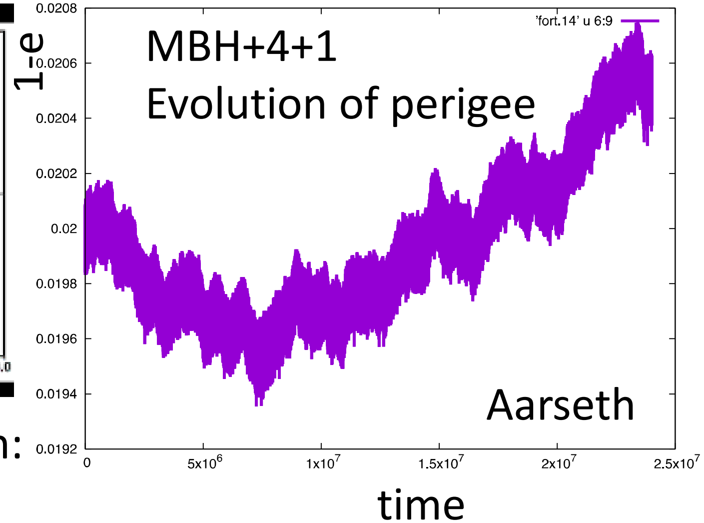
HPDeng, RNaylor, XJZhang

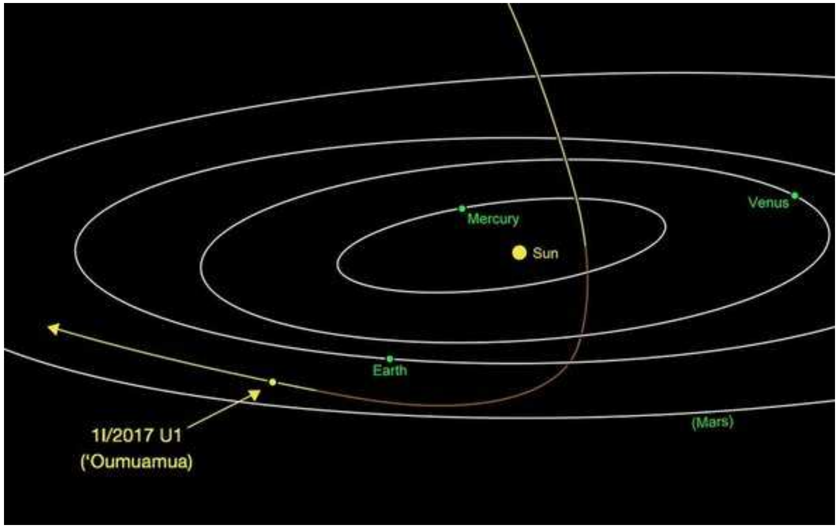
cusp profile, relaxation, & TDEs

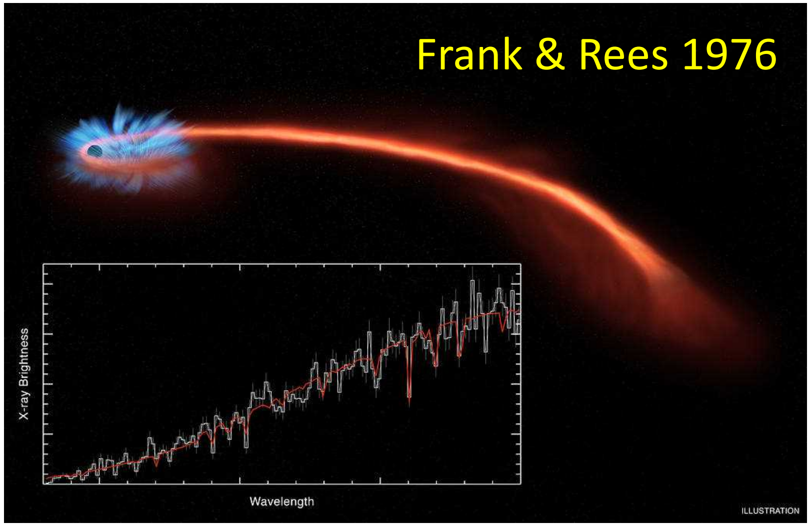




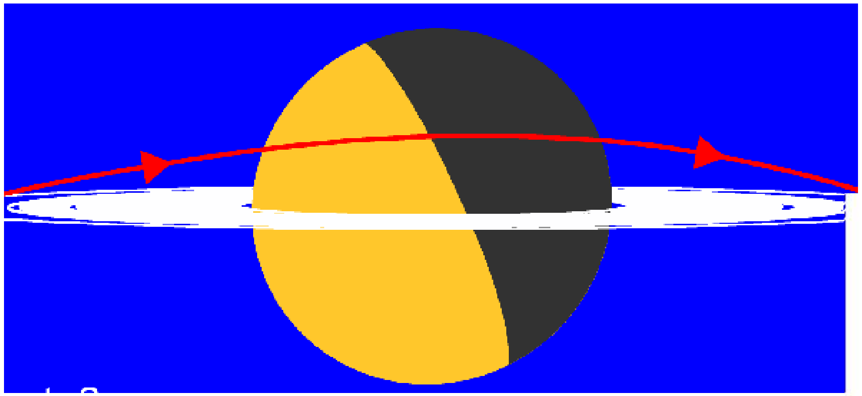
Resonant relaxation:
Rauch & Tremaine





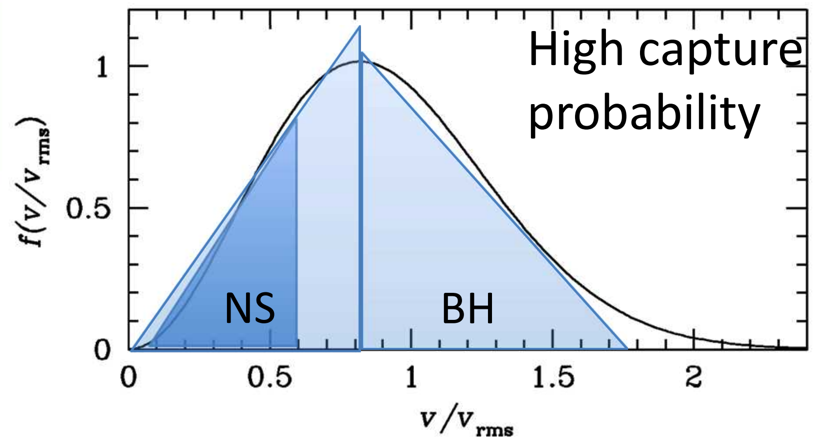


Recapture of neutron stars and seed black holes



$$\dot{N}_{bh,t} = \int_{R_{in}}^{R_{bh}} d\dot{N} \simeq \frac{8\times 10^{-4}}{\mathrm{yr}} \sigma_{200}^{1.4}$$

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

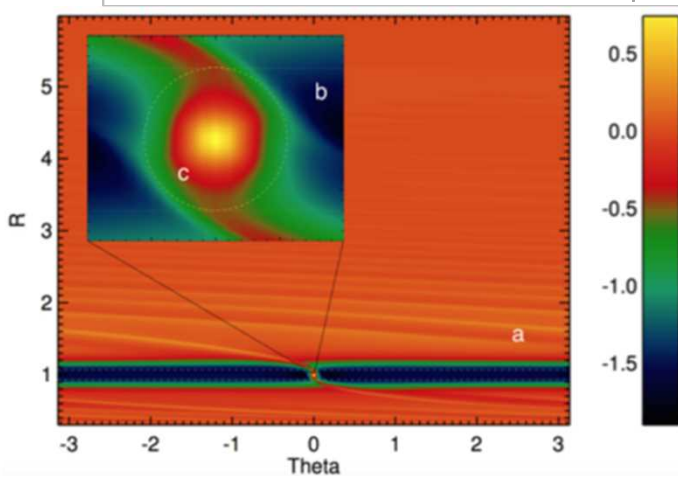


accretion radius = min $[R_B, R_R]$

$$\tau_{sal} = m_*/\dot{m}_E = 4.5\times 10^8 \eta\,\mathrm{yr}$$

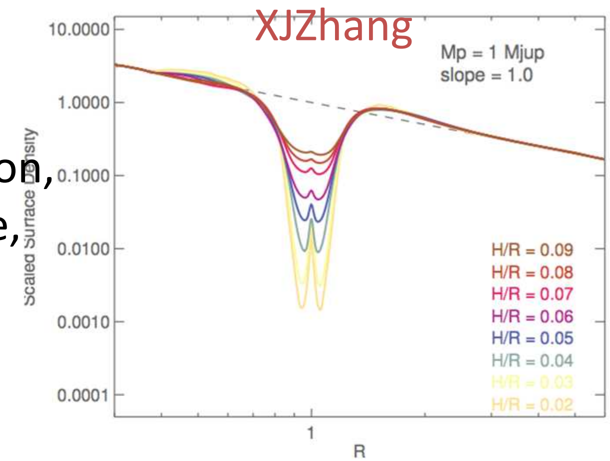
Mass growth: Eddington limited if

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



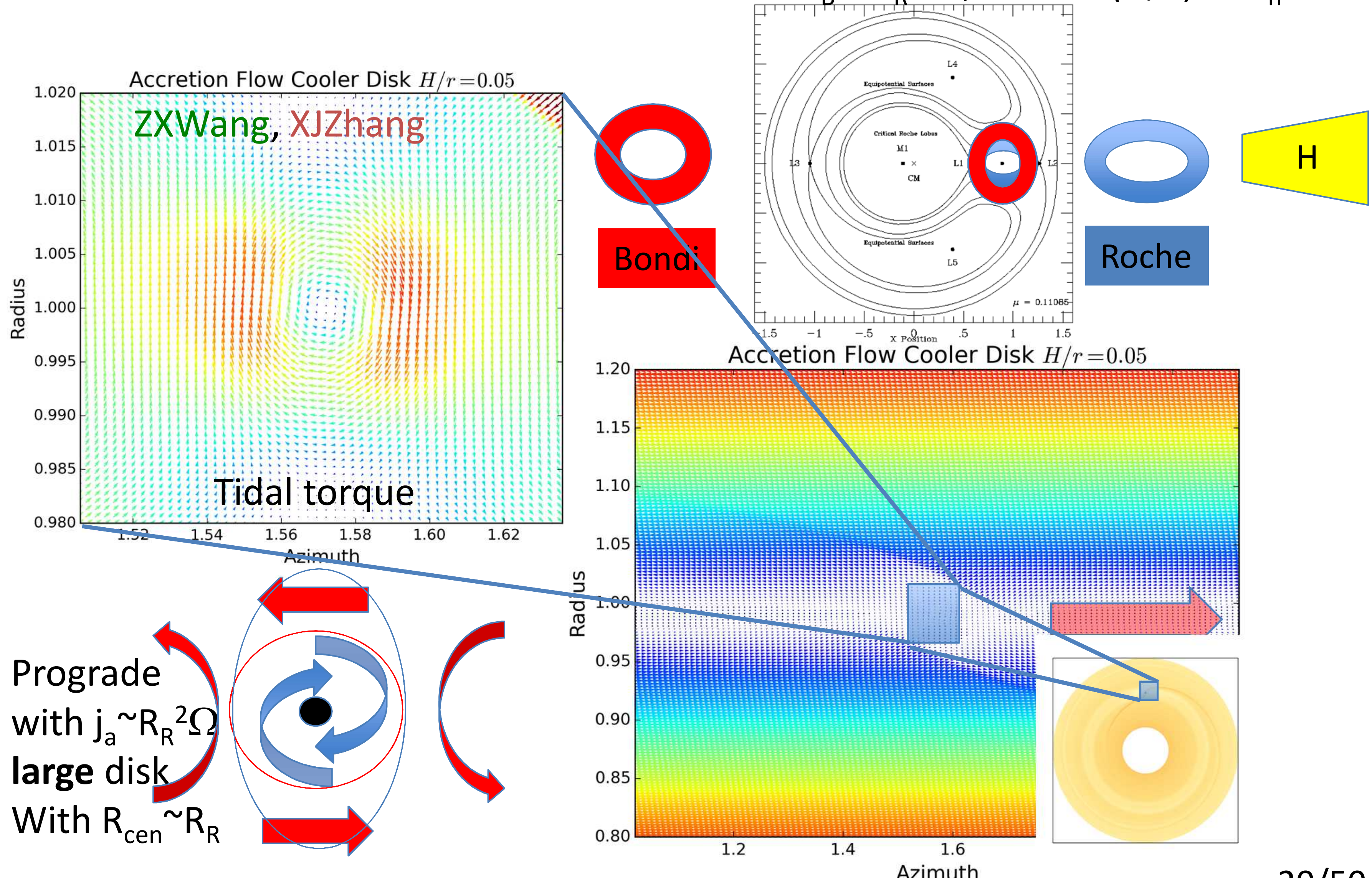
L Papaloizou 1986
Artymowicz, Lubow, Nelson, Bryden, Masset, Armitage, Li, Dobbs-Dixon, Kley

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



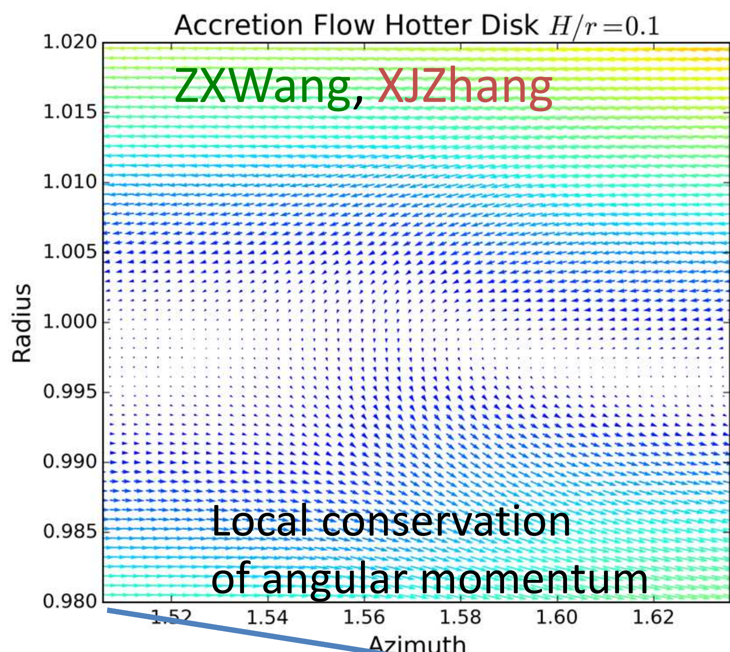
Angular momentum evolution (h=0.05,q=10^{-4})

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

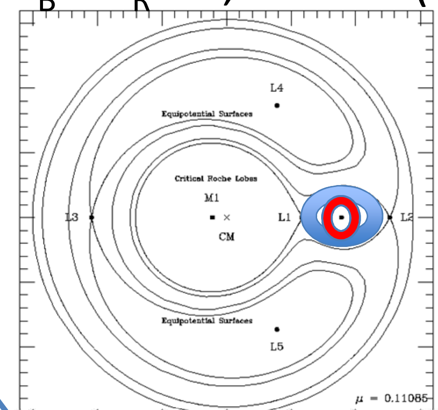


Spin due to local shear ($h=0.1, q=10^{-4}$)

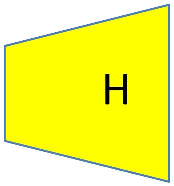
Low-m_* seed black holes in **hot** disks with $R_B < R_R < H$, i.e. $m_* < (H/a)^{1/3} M_h$

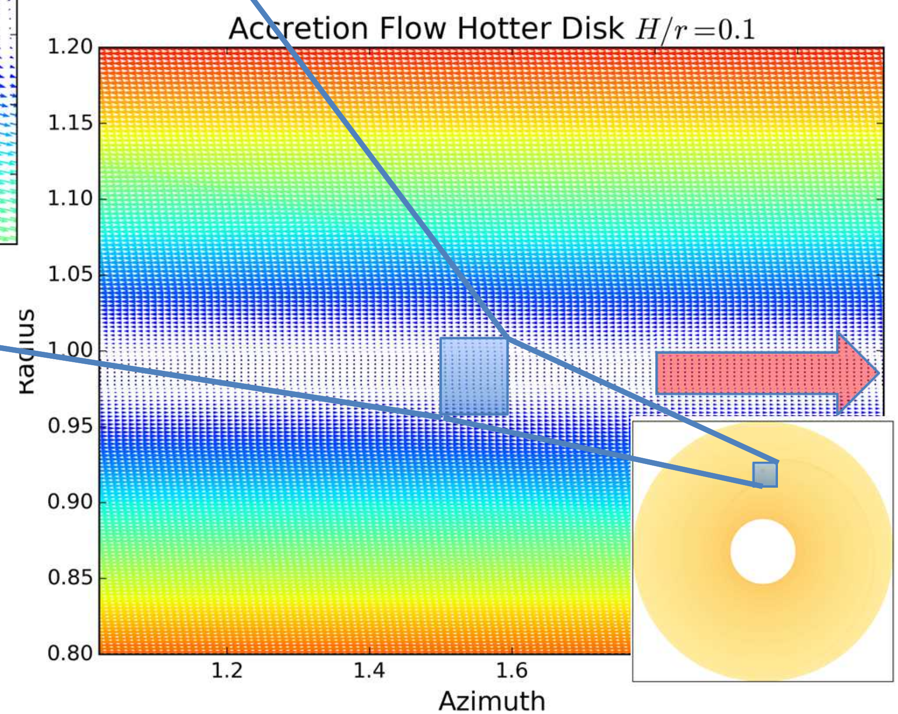


Bondi



Roche





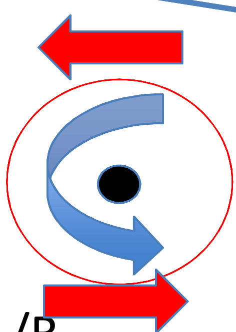
Retrograde

with $j_a = R_B^2\Omega$,

small disk size

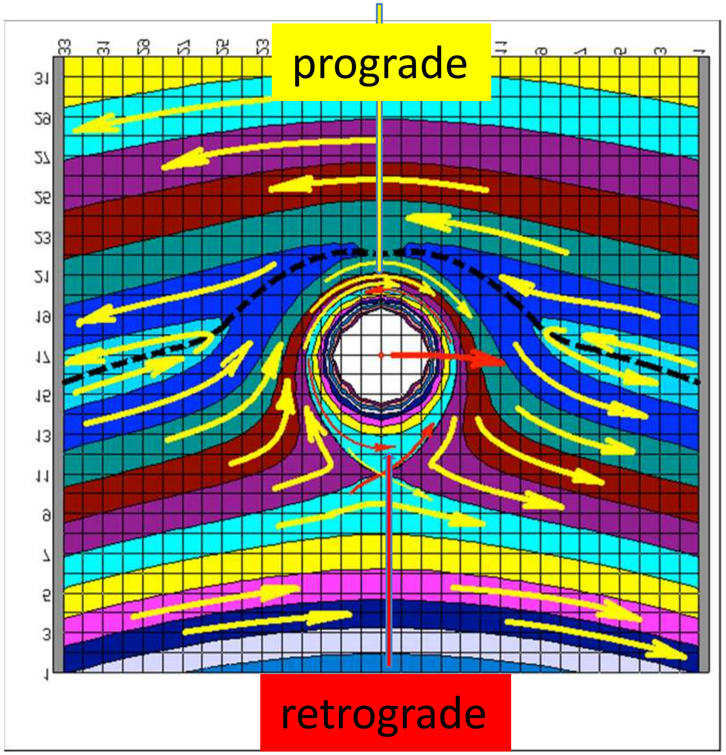
$R_{cen} \sim (R_R/H)^8 R_B$

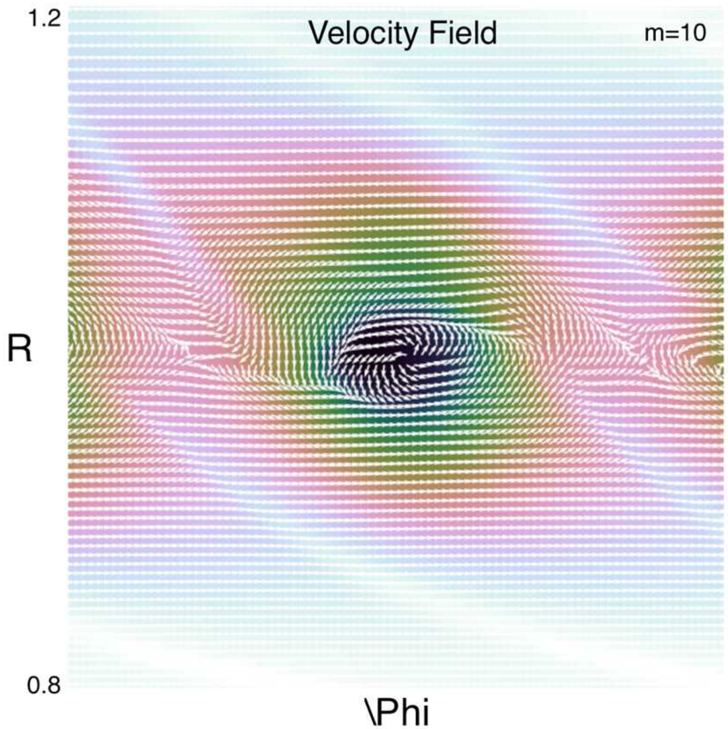
$\sim (R_R/H)^{14} h^3 a R_{\cdot *}/R_{\cdot H}$



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 $j_a = \lambda v_{tur}$ $\quad \dot{J}_{turb} = \dot{m}.j_a$

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

Multiple black holes' eccentricity excitation/damping

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

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

Type I damping: $\tau_{e-} = h^2 \tau_I = \frac{h^3 Q P M}{4 f_\Gamma m_*}.$

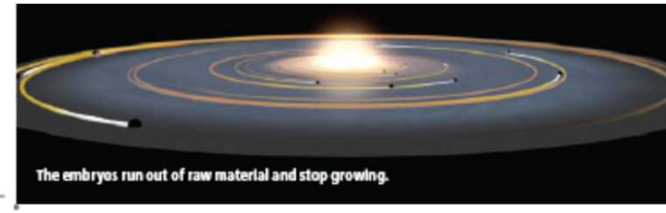
Dynamical equilibrium: low-e orbits

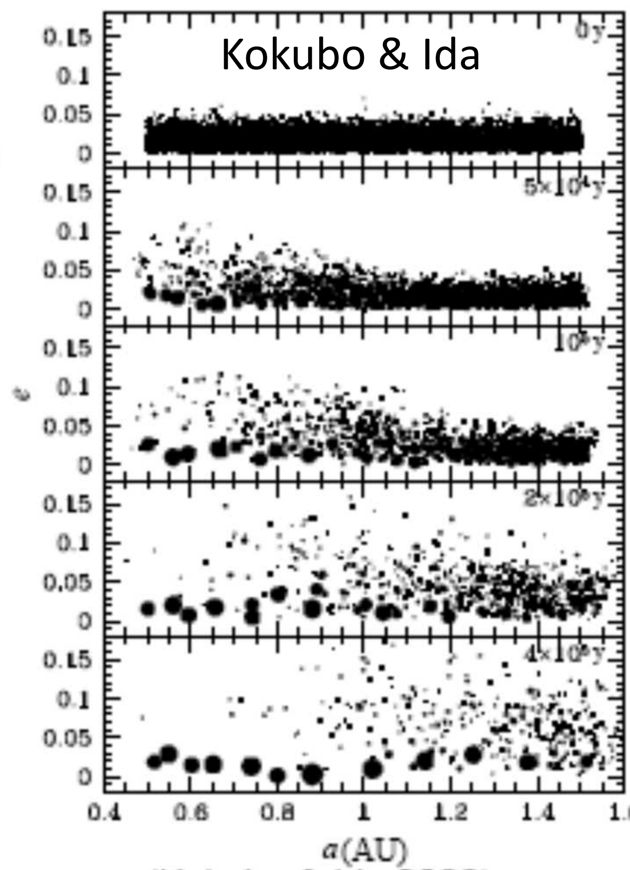
$$\tau_{e+} = \tau_{e-}$$

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

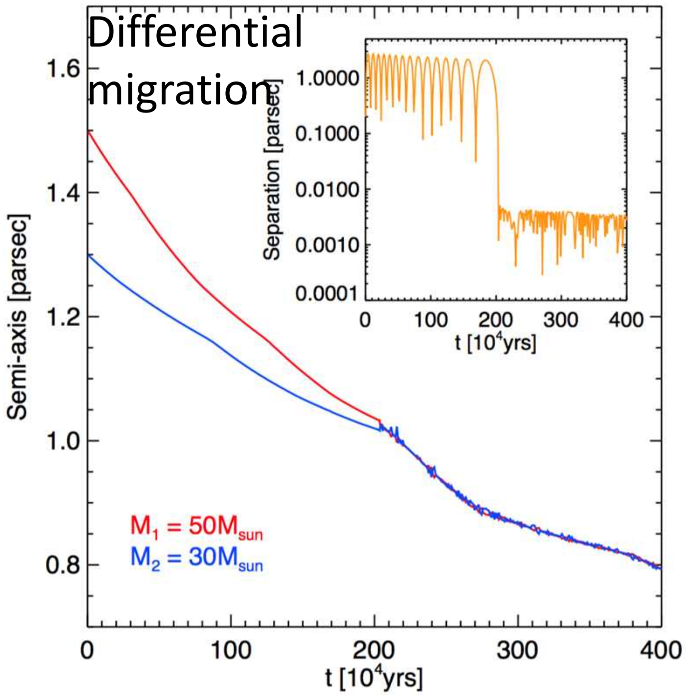
Feeding zones: $\Delta \sim 10\ r_{Hill}$

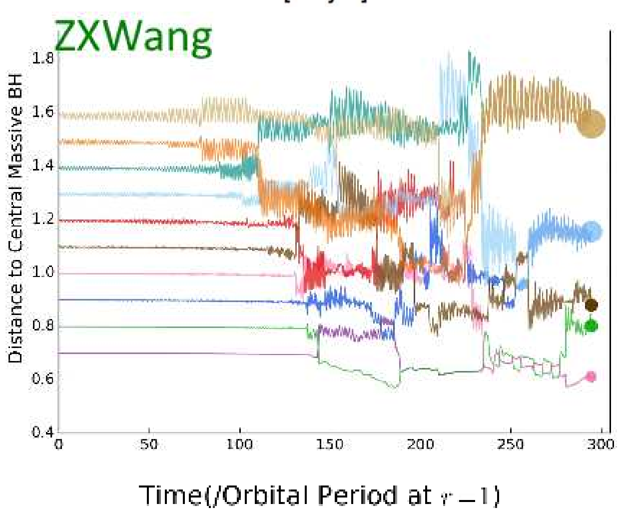
Isolation mass: $M_{isolation} \sim \Sigma^{1.5} a^3 M_h^{-1/2}$

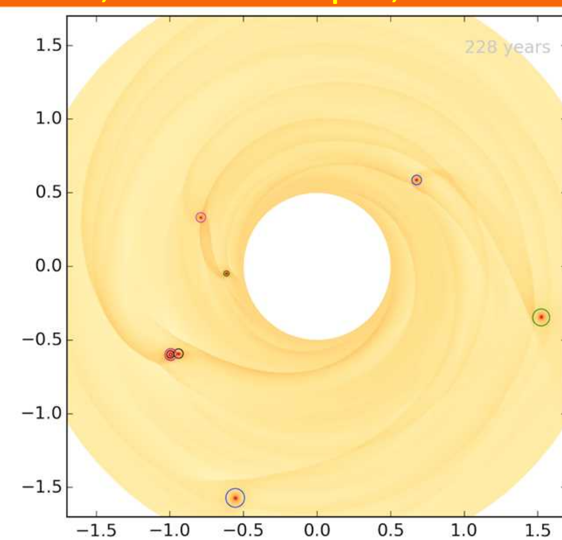




Differential migration & groups with isolation masses



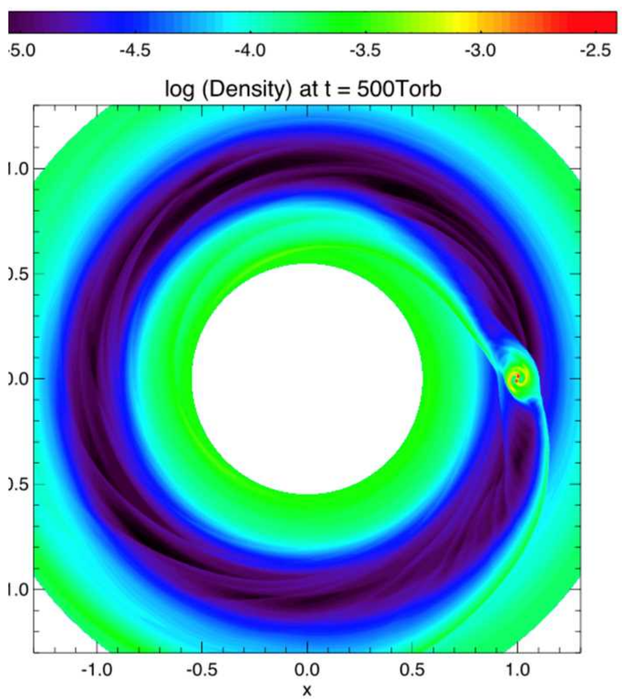


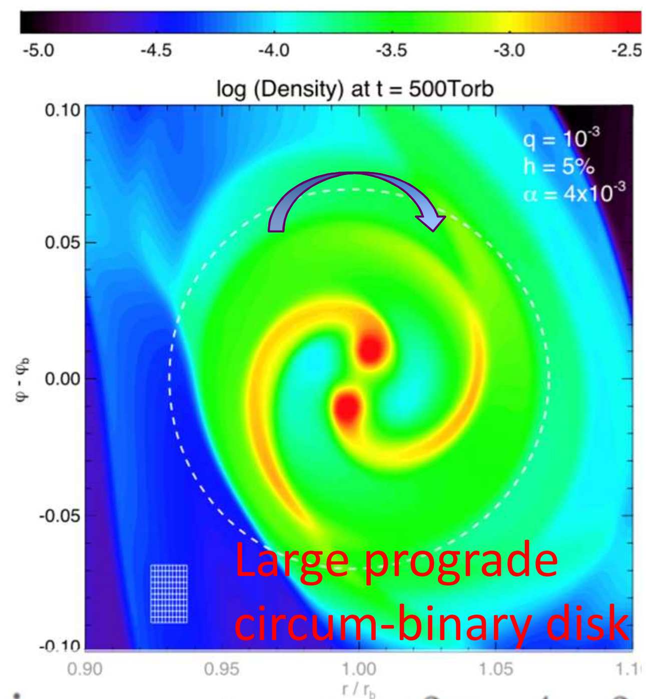


Scales of binary seed black holes in disks

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)





Initial binary tightening

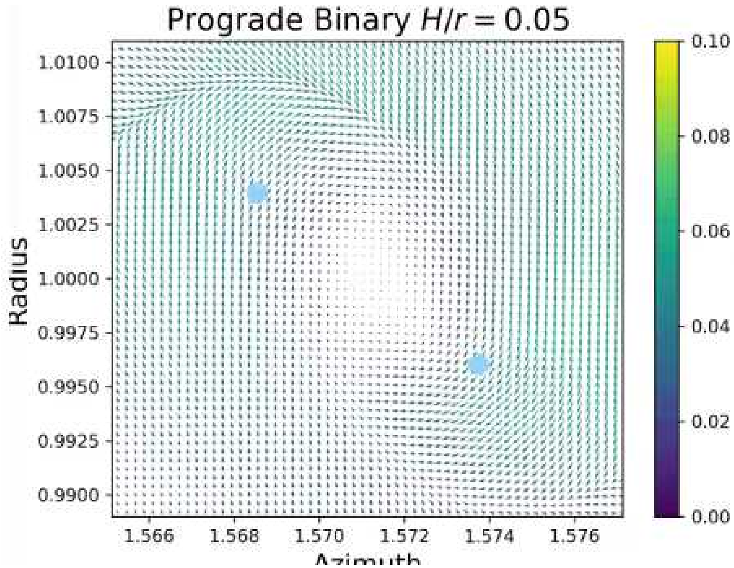
$$\dot{J}_t \simeq 0.23(m_2/m_1)^2 \Sigma_b a_{12}^4 \omega_{12}^2 h_b^{-3}$$

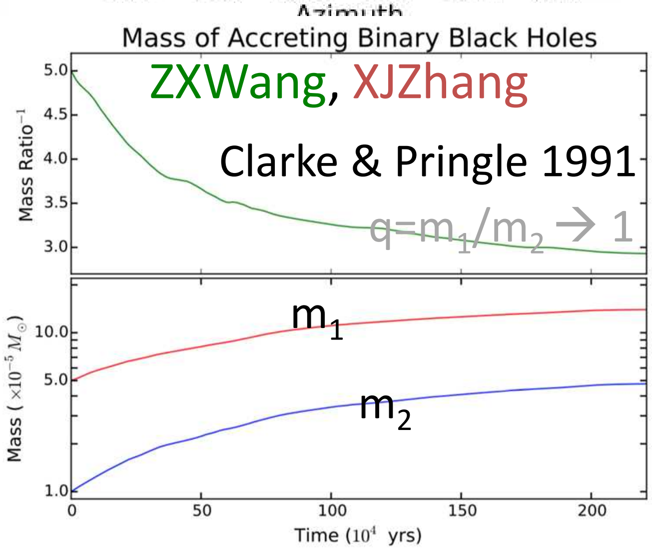
Baruteau, Cuadra L 2011 Stone, Haiman 2017

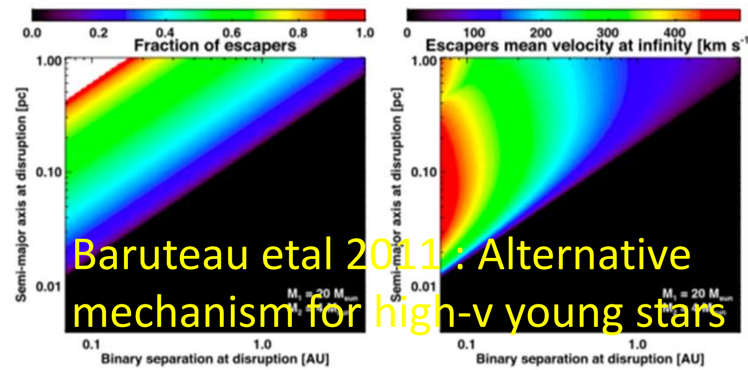
Log r_{cm}	
20	R_o
	R_D
18	H
16	R_R, R_B
14	a_{12}, R_{cen}
12	R_{isco}
10	a_{gr}
08	a_{LT}
06	a_{mer}, R_{gbh}

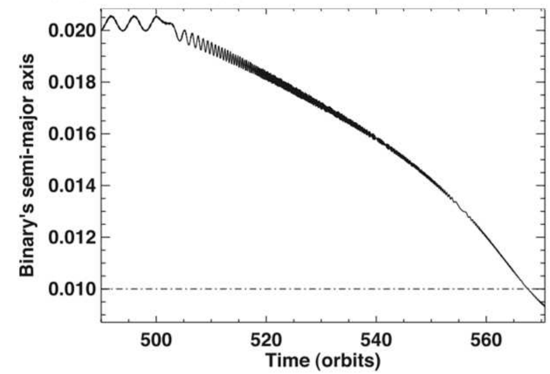
Modest-m_* binary with modified disk structure

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

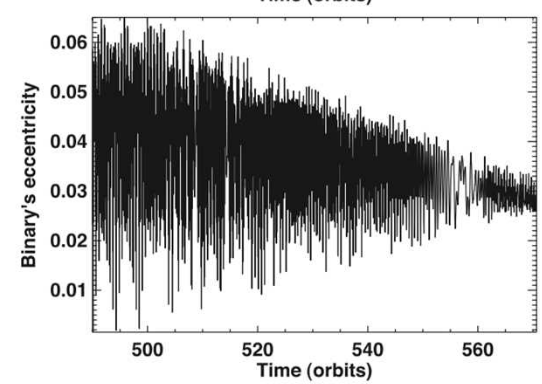








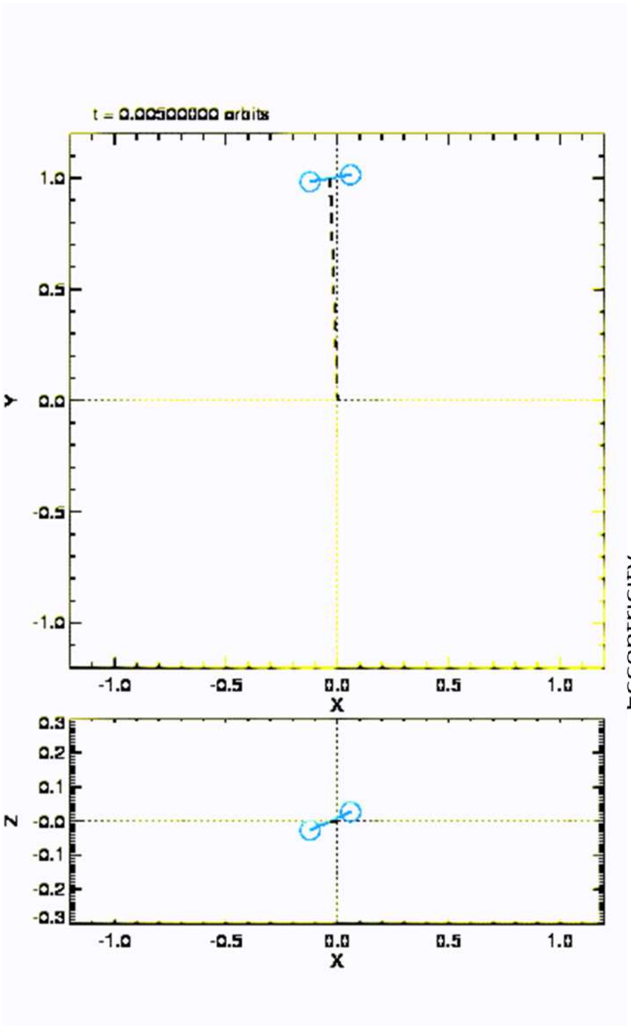
a_{12}

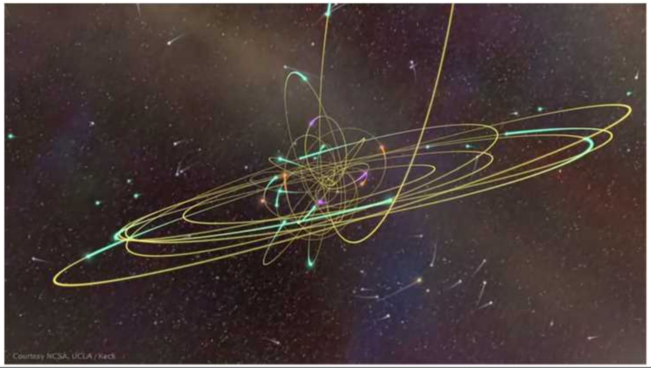


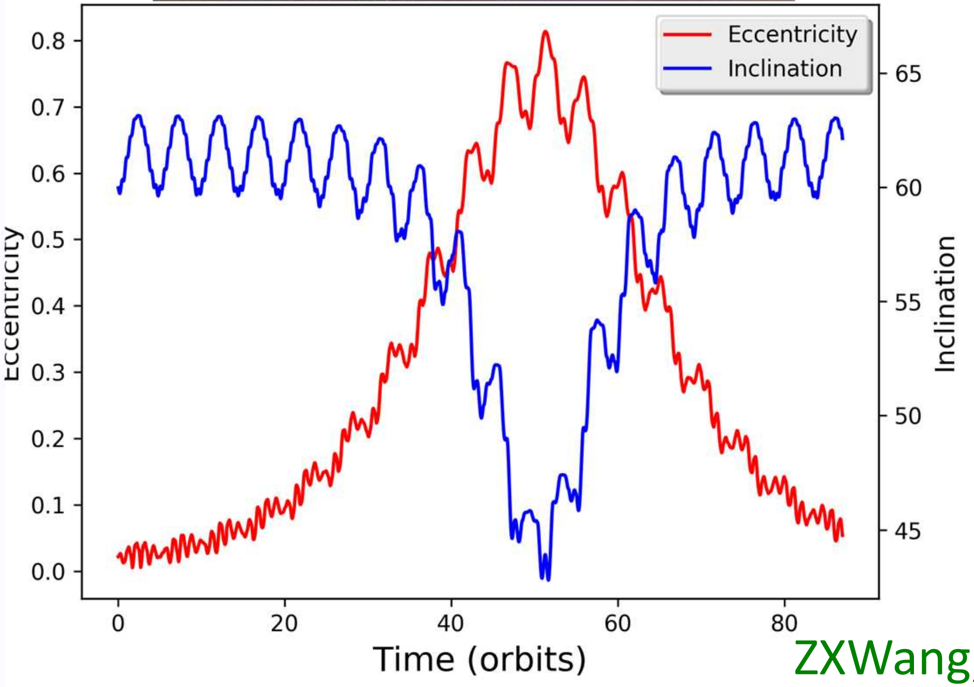
e_{12}

Lidov-Kozai oscillation of binaries in AGN disks

obliquity between the MBH-IMBH-SBH system + disk torque & gas drag



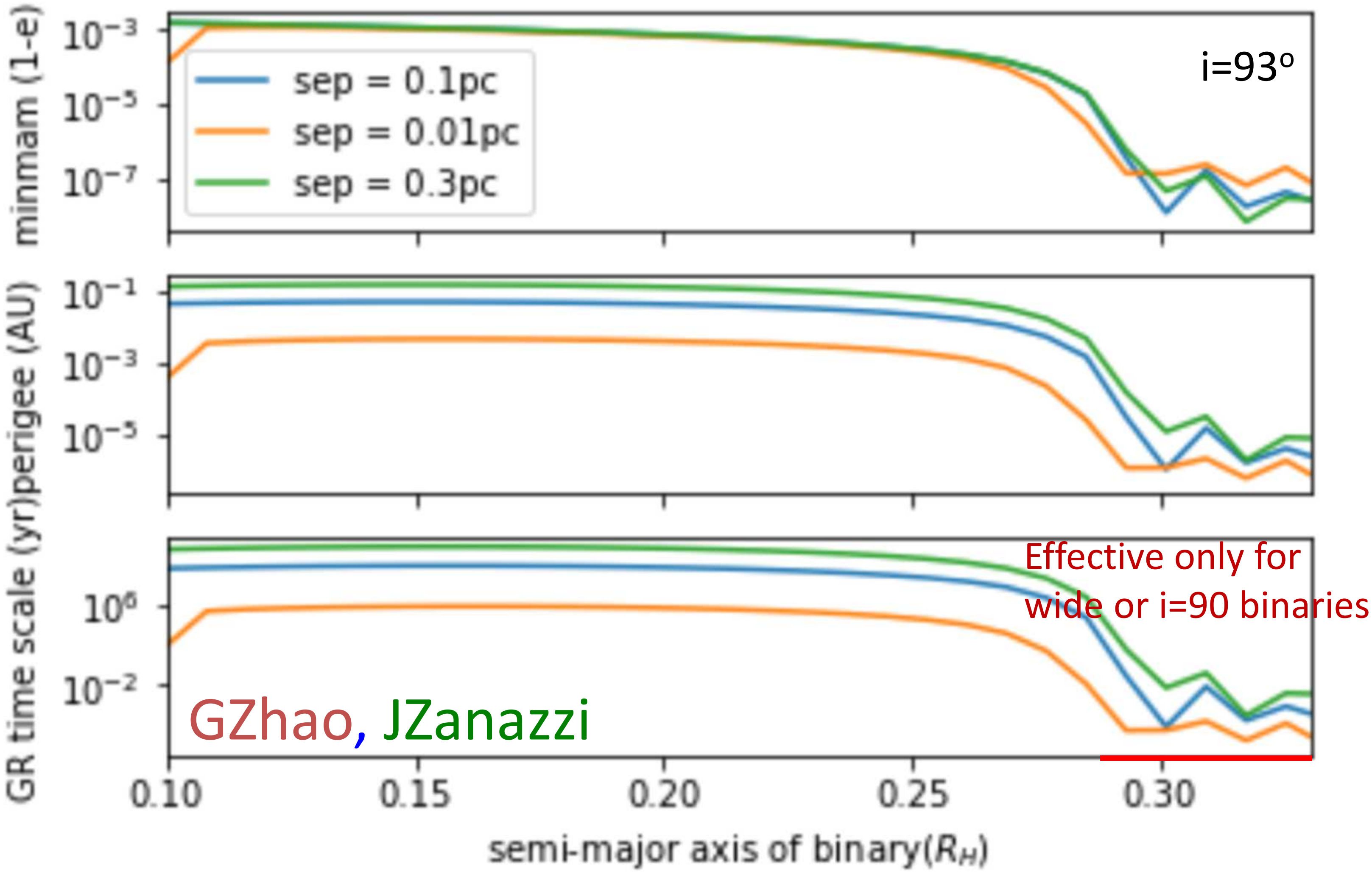




ZXWang, XJZhang

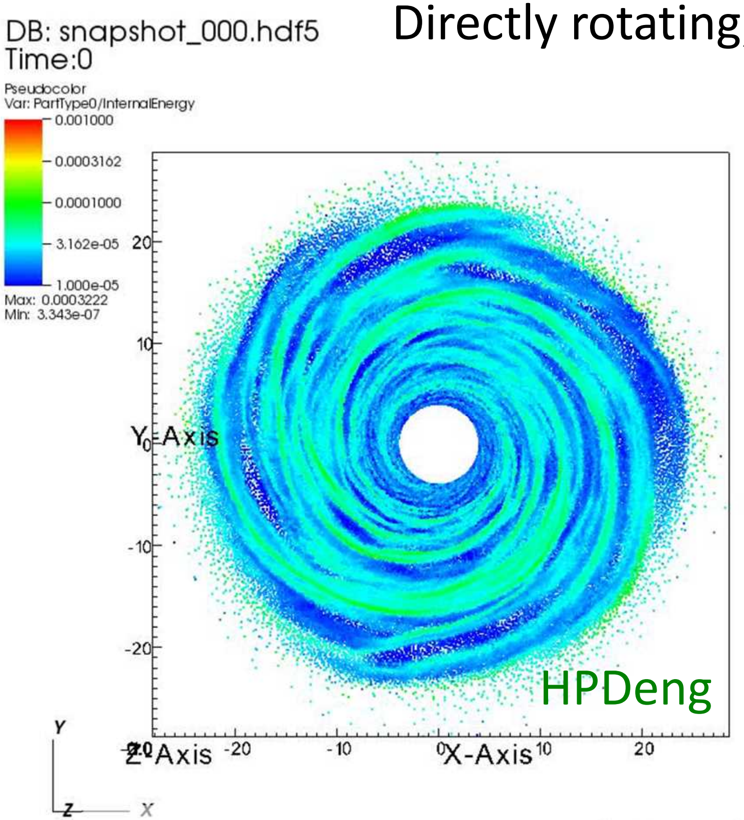
Binary separation near supermassive black holes

Combining Lidov-Kozai effect and gravitational radiation



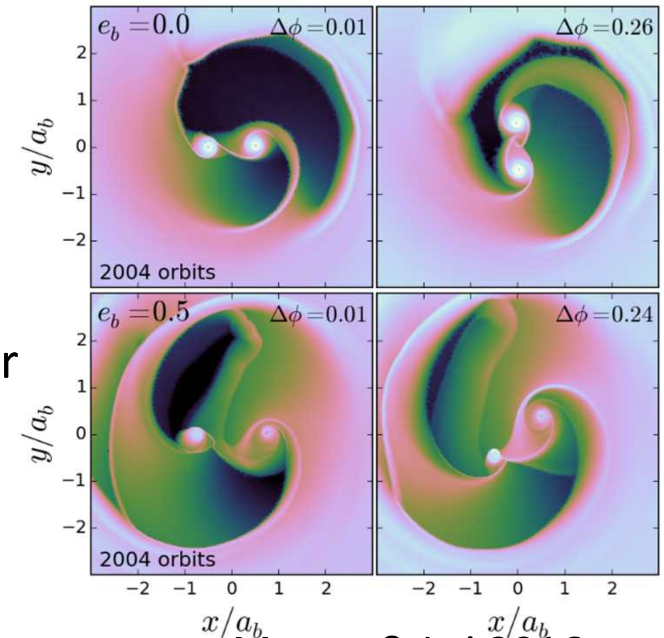
Accretion & tidal torque due to circum-binary disk

Directly rotating, self-gravitating, circum-binary disk



Accretion onto seed binary black holes

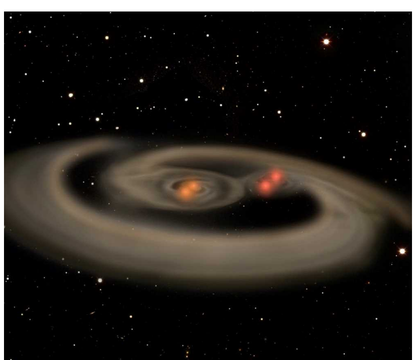
Potential sites for Enhanced star formation



Munoz & Lai 2016

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

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



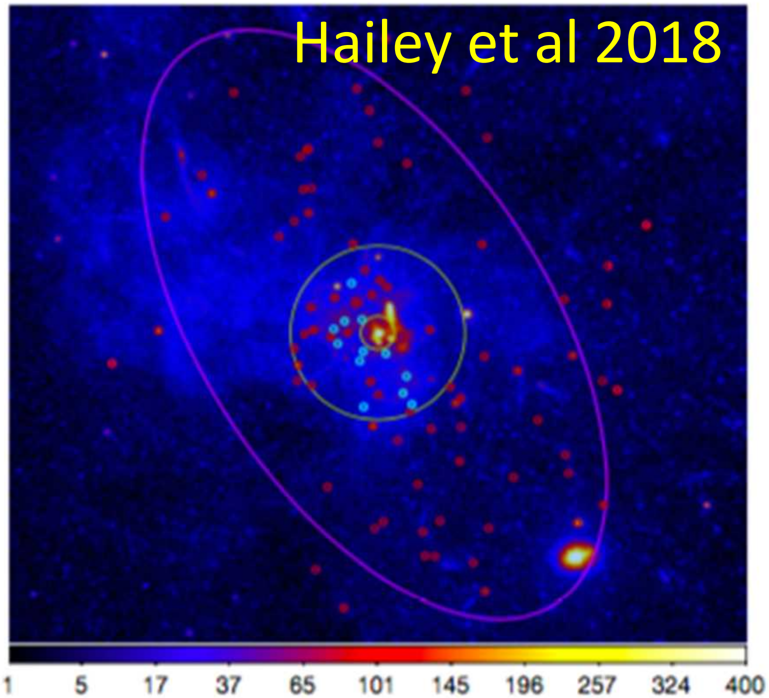
$$\tau_{at} \simeq \frac{m_1 m_2 \omega_{12} a_{12}^2}{m_{12} \dot{J}_t} \simeq \frac{4 m_1^3}{m_2 m_{12} \Sigma_b a_{12}^2} \frac{h_b^3}{\omega_{12}}.$$

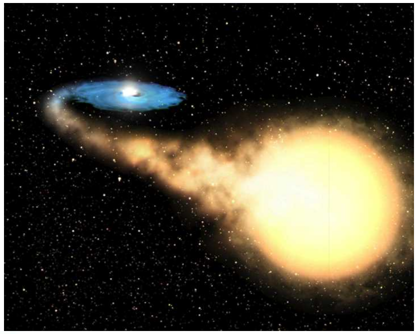
XJZhang

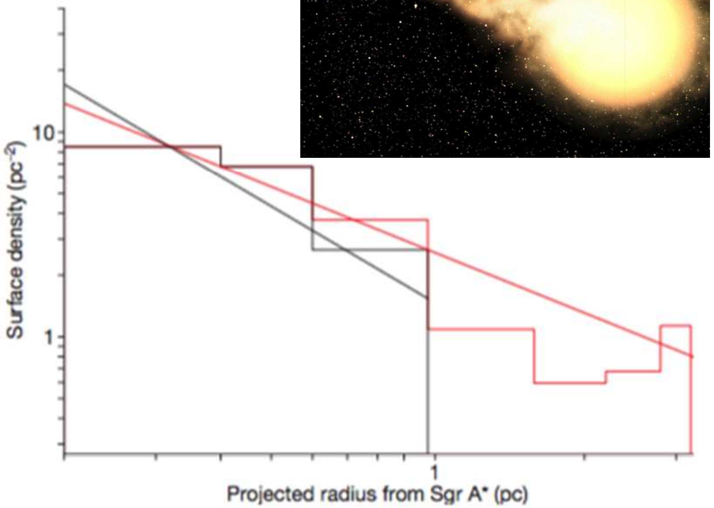
$$\tau_{\rm gr} = \frac{5 a_{12}^4 c^5}{256 G^3 m_1 m_2 m_{12}} \simeq \left(\frac{a_{12}}{1{\rm pc}}\right)^4 \left(\frac{M_\odot^3 10^{39}{\rm yr}}{m_1 m_2 m_{12}}\right).$$

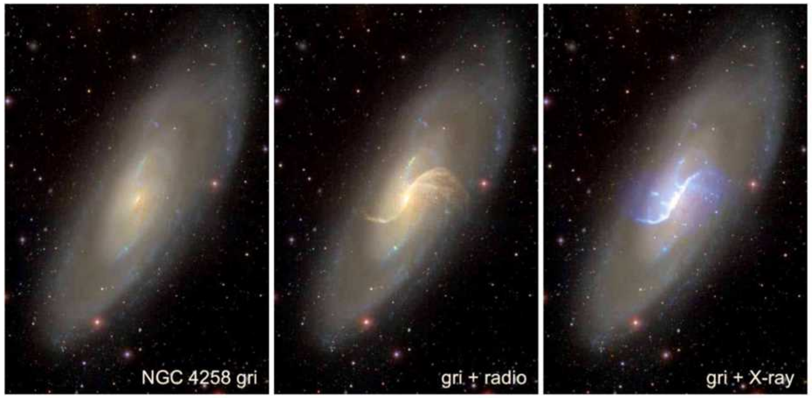
Peters 1964

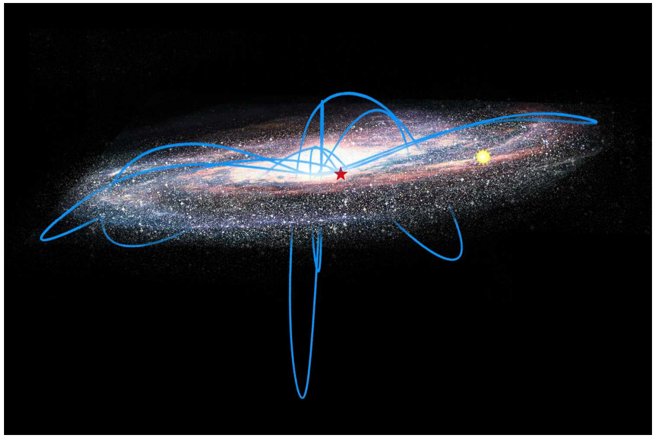
LMXBs, X-ray Luminosity, high-V stars



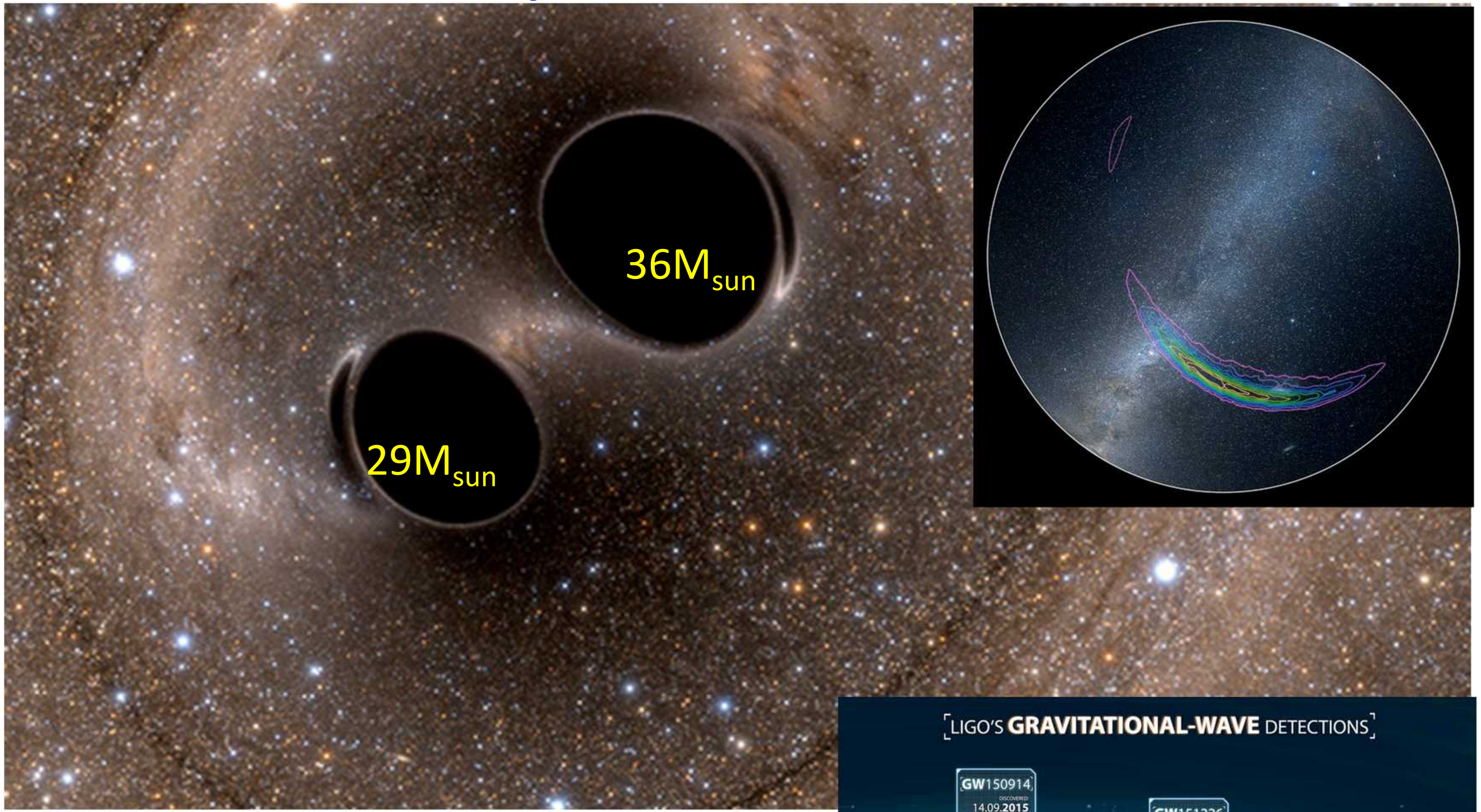


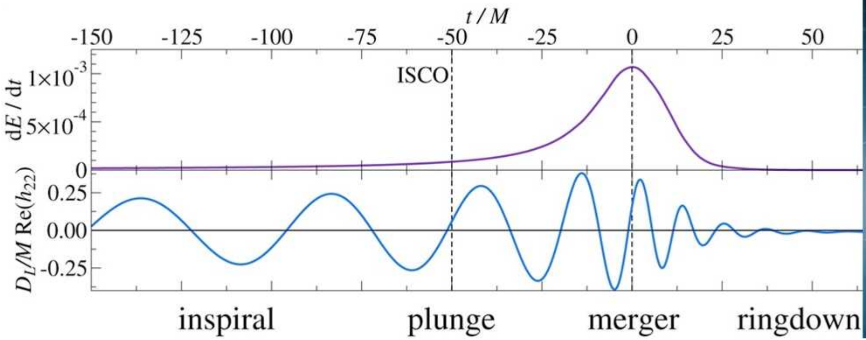


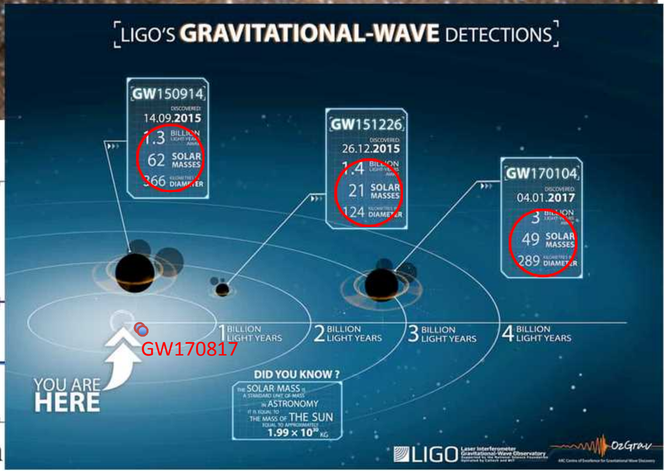




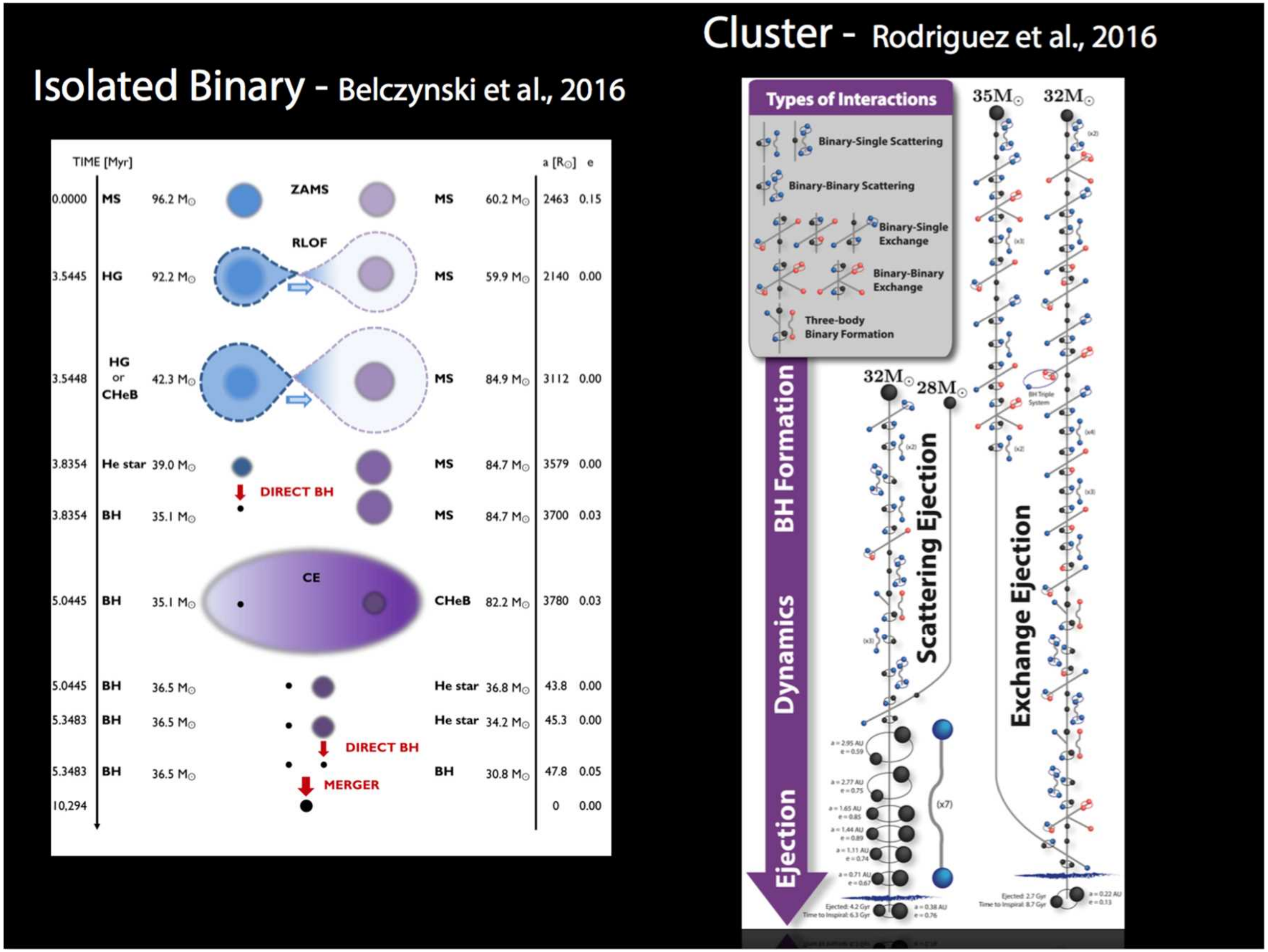
Binary stellar black holes







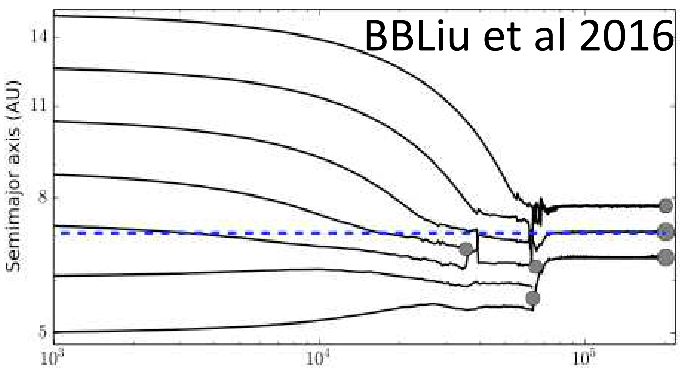
Common-Envelope vs stellar cluster scenarios



AGN model: channels of binaries' dynamical evolution: Multiple capture, tightening of binaries, *slingshot*, recapture

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

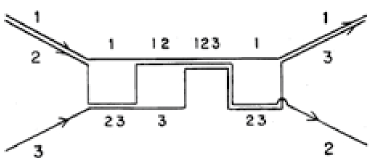
Isolation mass: $\mathbf{M_{isolation} \sim \Sigma^{1.5}\, a^3 M_h^{-1/2}}$

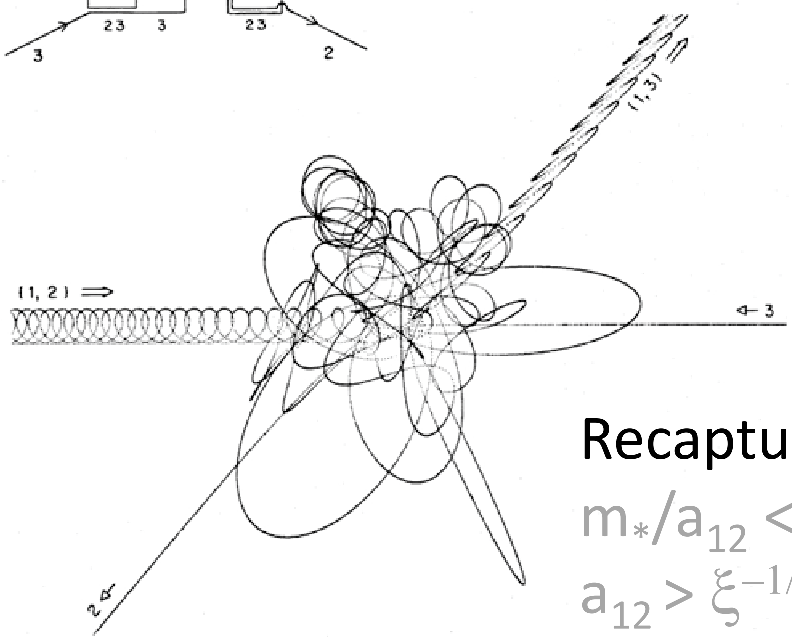


Heggie 1975, Saslaw et al *slingshot* 1975

Hut & Bahcall, 1983, Myllari Valtonen 2018

$(1-e_3)a_3 < (4\text{-}5)a_{12}$ groups of 10+ possible

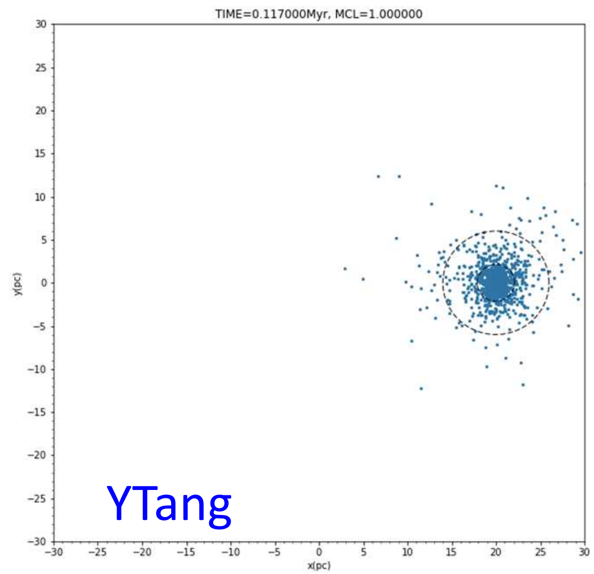




Recapture possible if

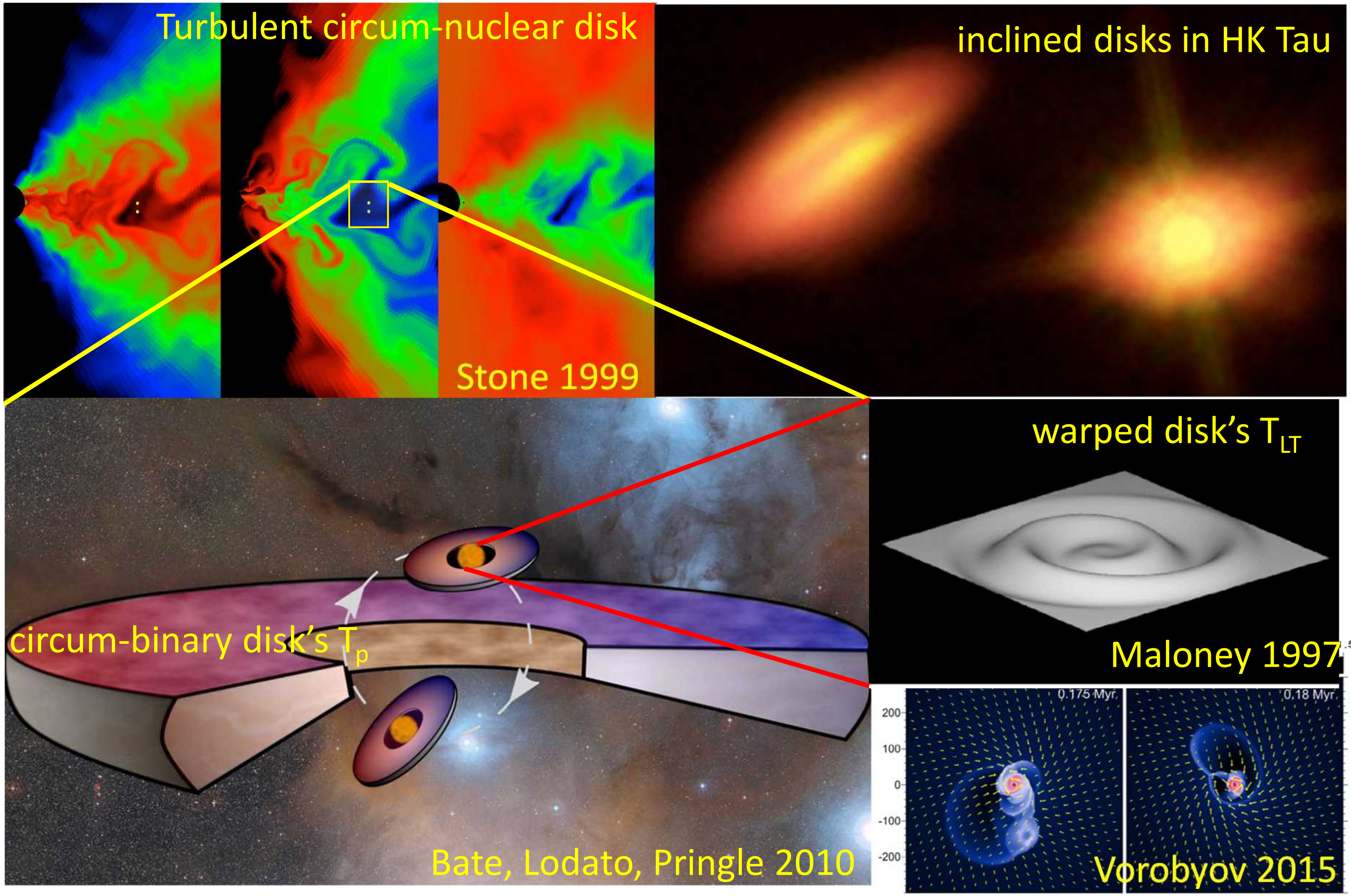
$m_*/a_{12} < \xi^{1/2} M_h/a$ or

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



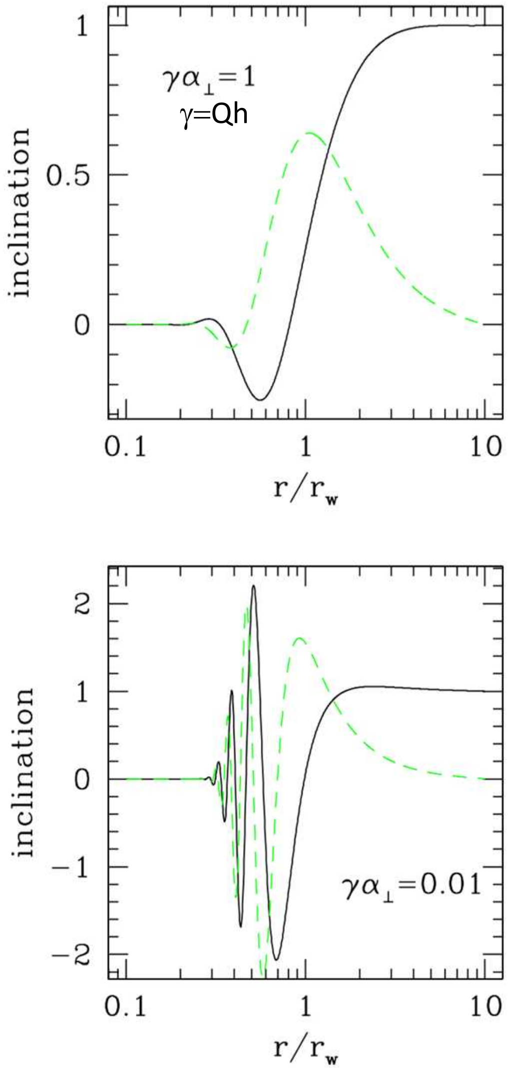
Shangfei Liu

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 $t > \tau_{tur}$, $\Delta J_b/J_b \sim \tau_{tur}/\tau_{CE}\,(t/\tau_{tur})^{1/2}$

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

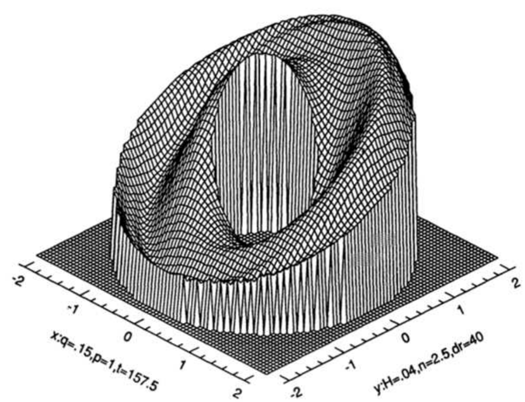
c) Individual black holes' spin angular momentum For $\tau_{tur} < \tau_{Sal}$, $\Delta J_*/J_* \sim \tau_{tur}/\tau_{Sal}$ & $\tau_{tur} > \tau_{Sal}$, $\Delta J_*/J_* \sim 1$

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

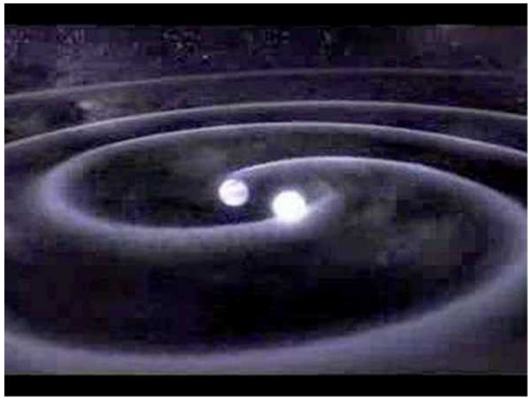
The Lense–Thirring torque T_{LT} and the companion torque T_* are equal at

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

Papaloizou & L 1995
Ogilvie & Dubus 2001
Nixon & King 2016



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

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

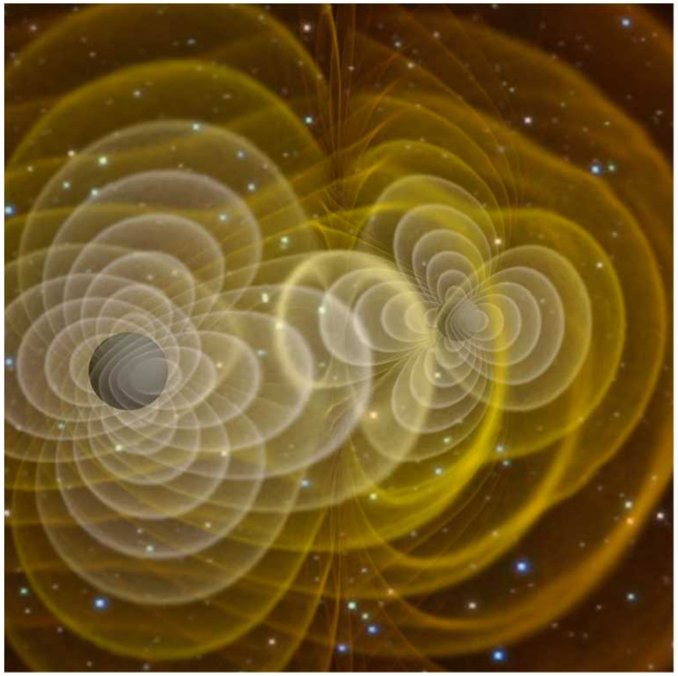
Peters 1964

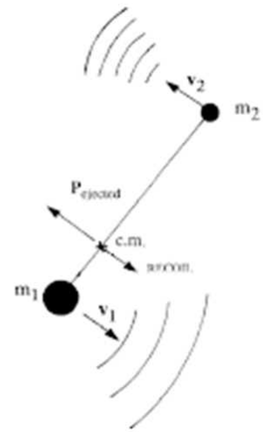
With $m_1 \sim m_2 \sim 30 M_\odot$, binary BHs $\tau_{\rm gr}$ would be less than 1Gyr in the limit $a_{12} \sim 0.1$ AU.

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

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

Merger & recoil: binaries with spin-orbit obliquity

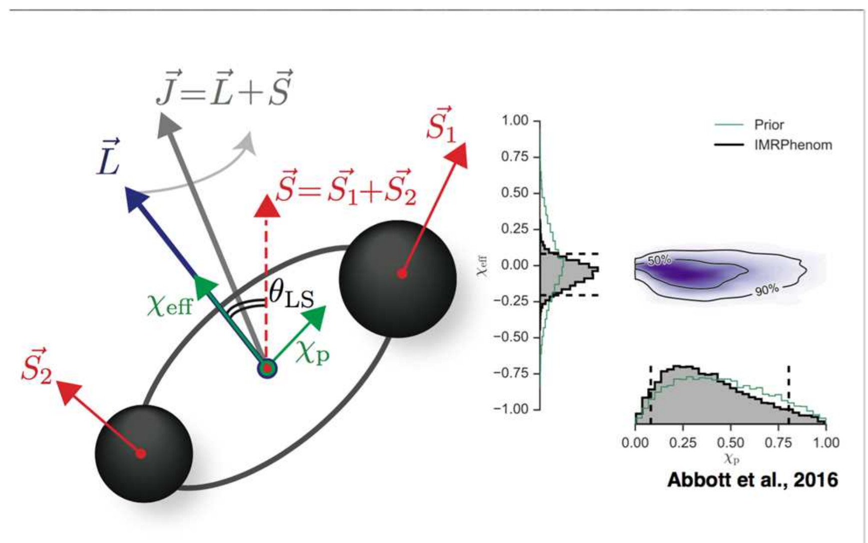




Recoil does not lead to significant disk perturbation

ZXWang, XJZhang

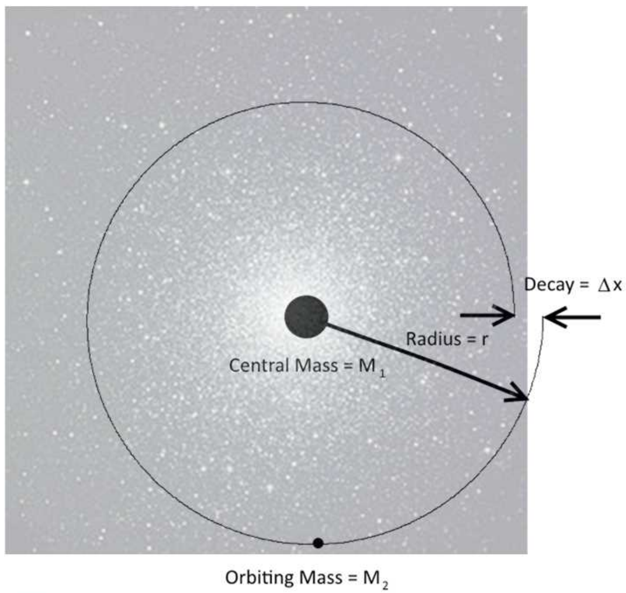
$$V_{\rm rec} \sim \frac{q^2 V_H (a_1 - q a_2)}{(1+q)^5}$$

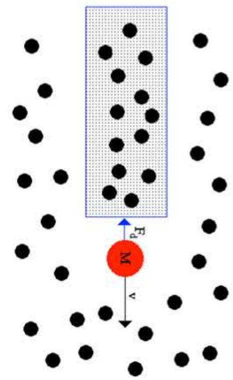


Resettle into the disk if $V_{rec}/V_k < \xi$

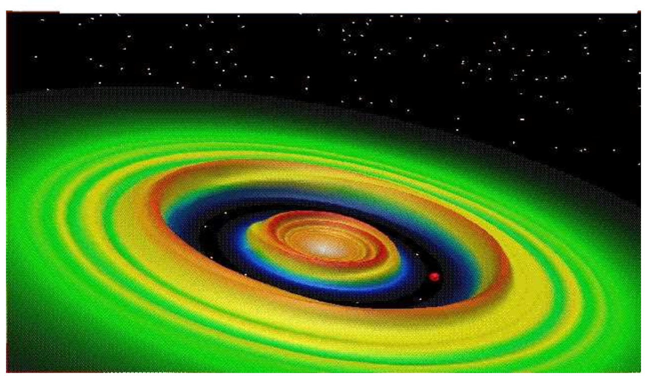
IMBH: gap formation & dynamical friction

Inefficient type I migration
accretion for τ_{BH}~10 τ_{Sal}
IMBH with M>10^3 M_{sun}





Dynamical friction, decay of black hole's orbit leads to efficient angular Momentum transport

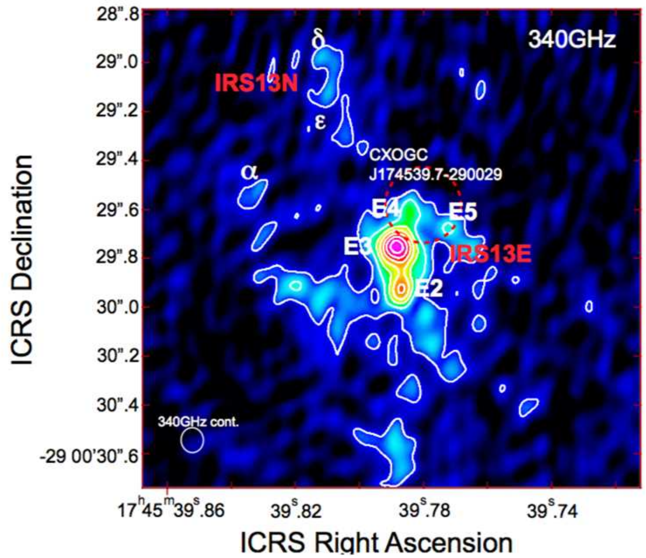


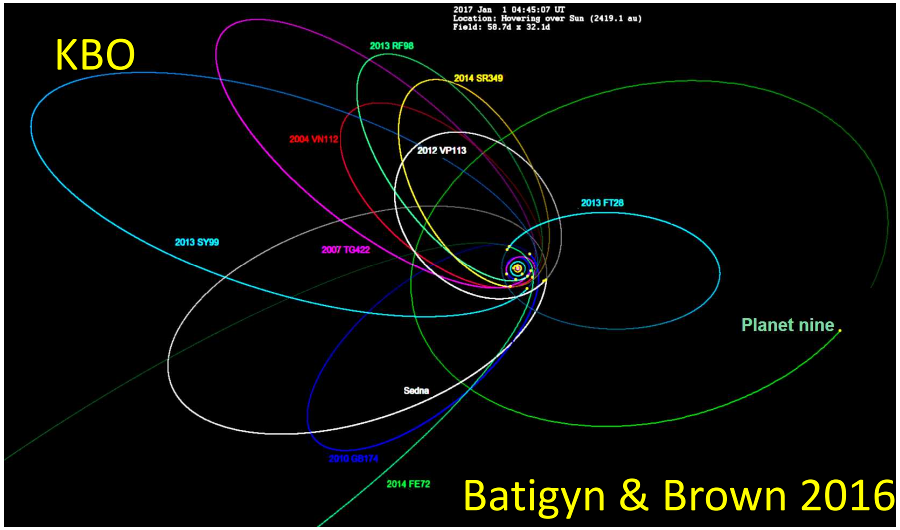
Gap formation:
Angular momentum transfer

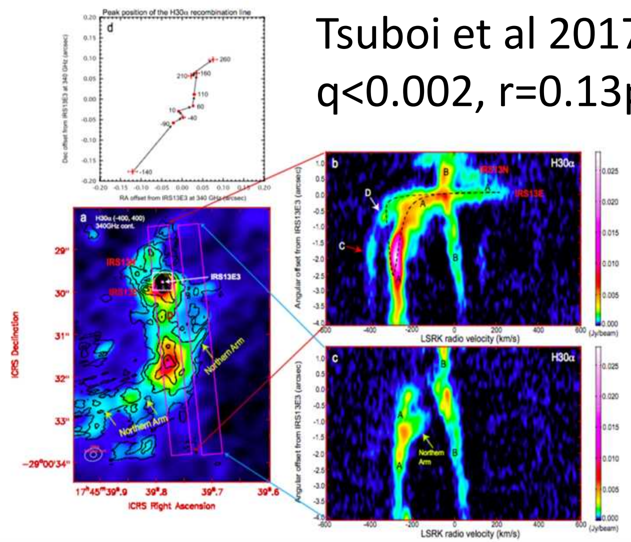
$$\frac{3hR}{4R_{roc}} + \frac{50\alpha h^2}{q} \le 1.$$

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

IMBH's secular perturbation on nearby stars

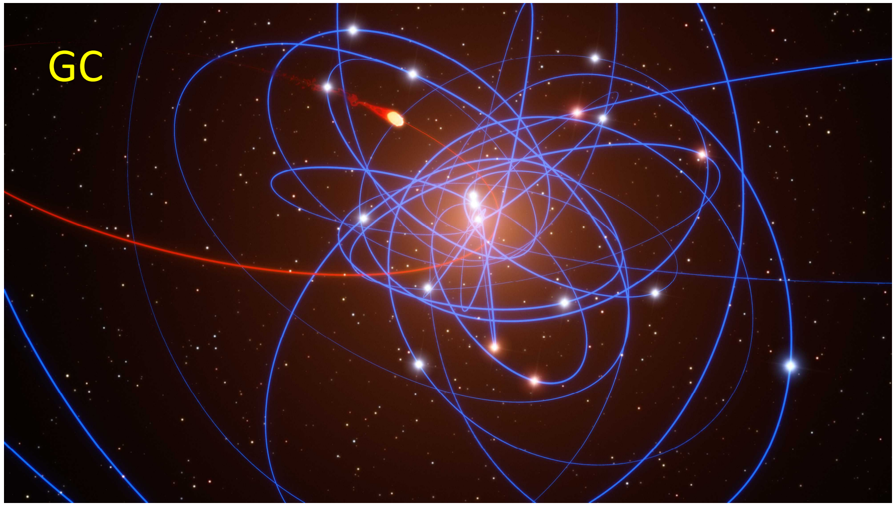




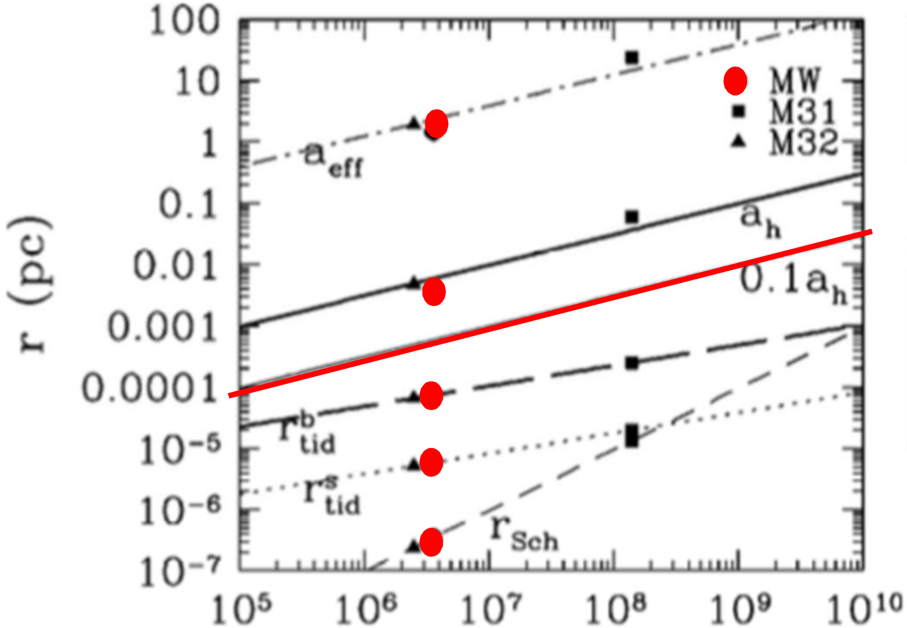


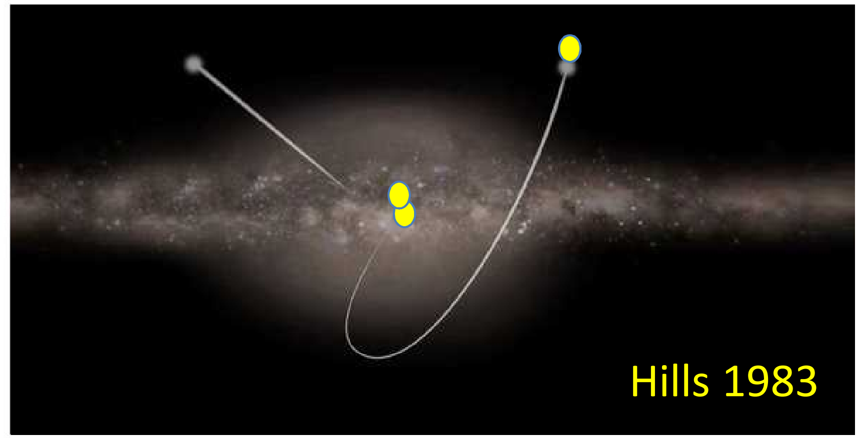
Tsuboi et al 2017

$q<0.002$, $r=0.13pc$

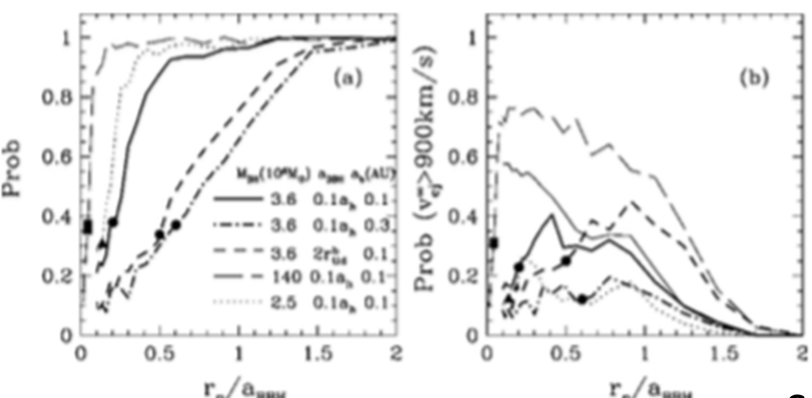


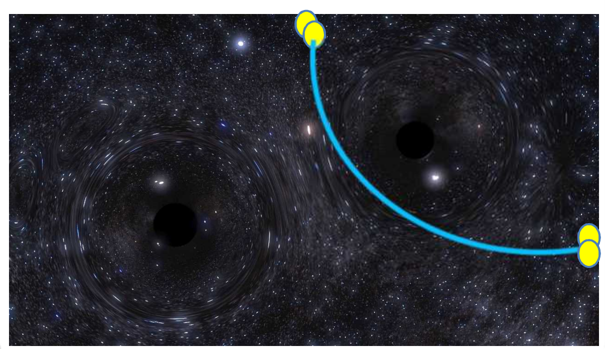
Test: hypervelocity binary stars





Lu, Yu, L 2007

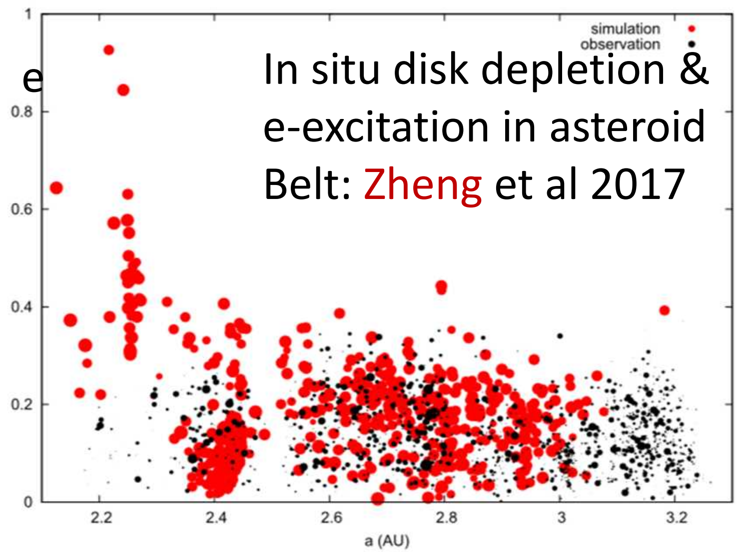


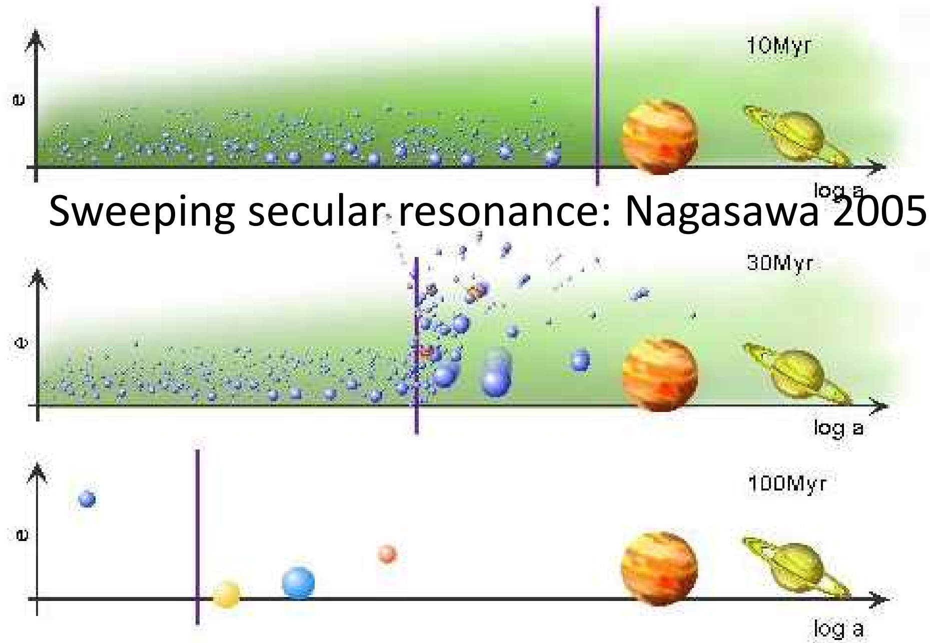


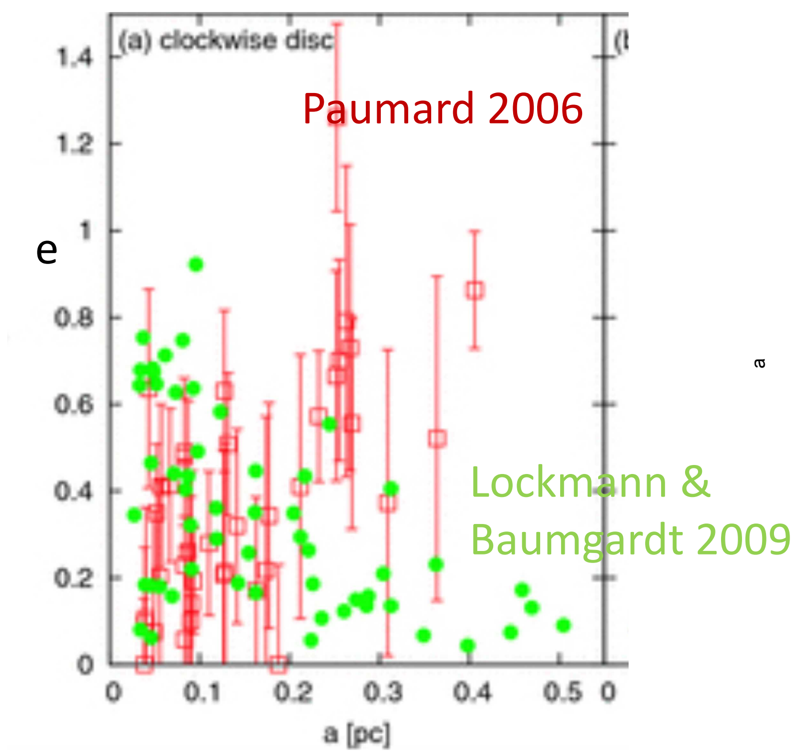
Search for HV binaries with GIAI

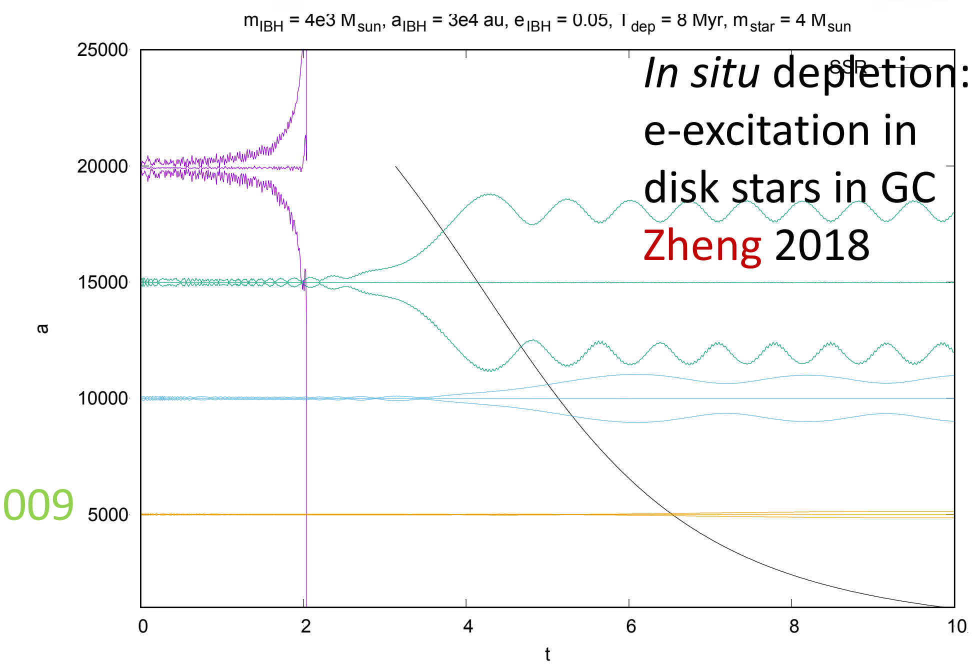
Outcome / $a_*/a_\bullet$	Binary Ejection
0.0005	92.8%
0.001	87.9%
0.0025	76.4%
0.005	60.9%
0.01	35.0%
0.05	3.09%
0.1	0.936%
Integrated	45.1%

Coughlin et al 2018

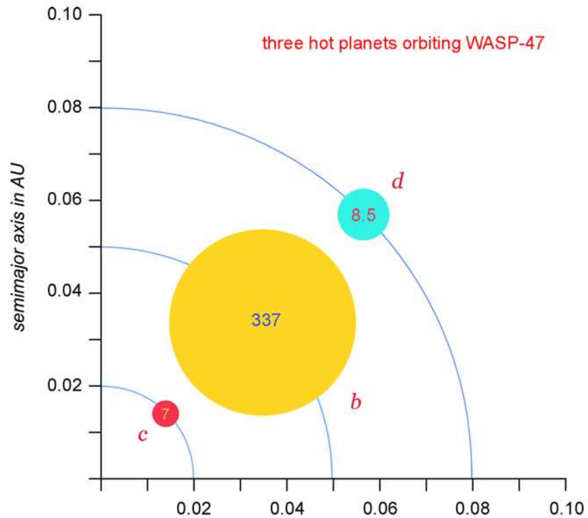

In situ disk depletion &
e-excitation in asteroid
Belt: Zheng et al 2017
simulation
observation
e
a (AU)

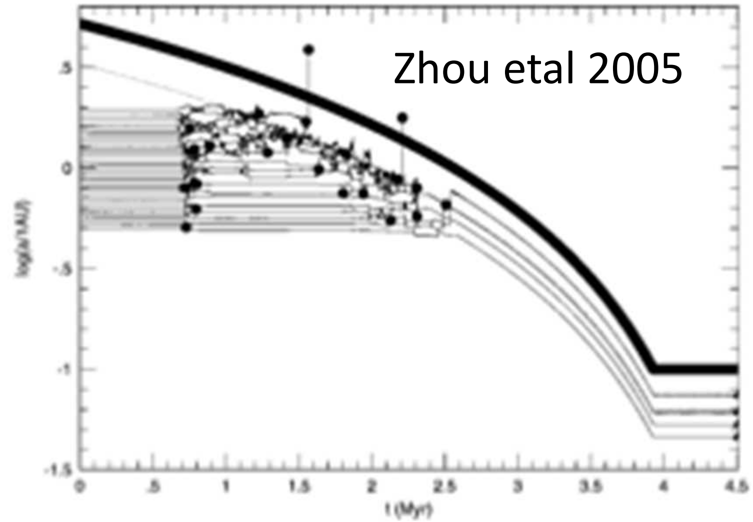

Sweeping secular resonance: Nagasawa 2005
10Myr
30Myr
100Myr
e
log a


(a) clockwise disc
Paumard 2006
Lockmann &
Baumgardt 2009
e
a [pc]

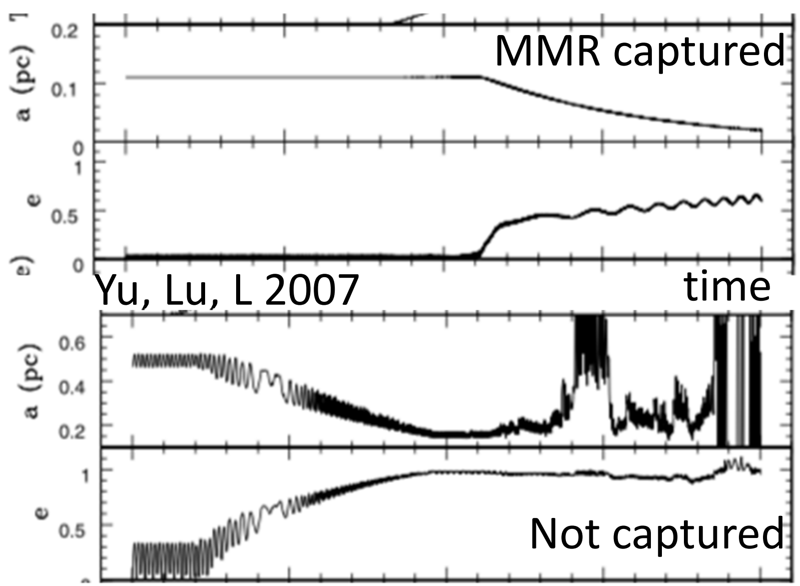

In situ depletion:
e-excitation in
disk stars in GC
Zheng 2018
a
t

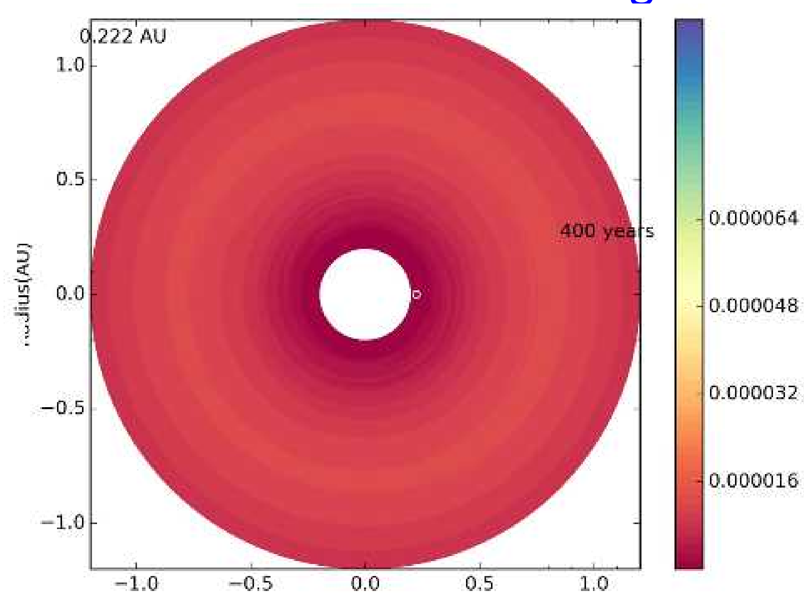
Migrating IMBH's sesonant capture & disk clearing





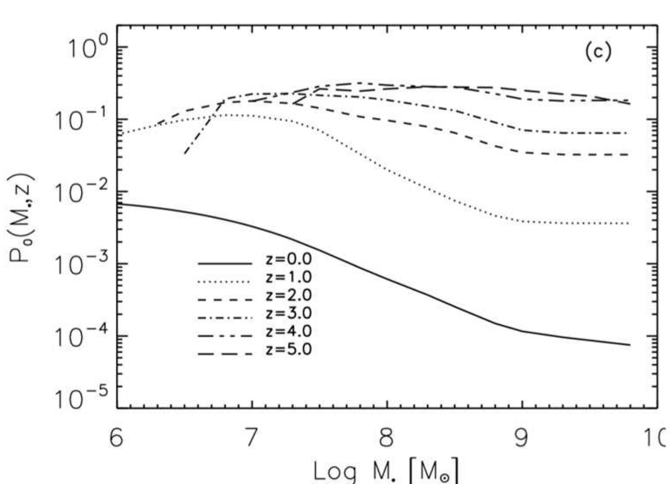
B Tong





AGNs' duty cycle and disk persistent time scale

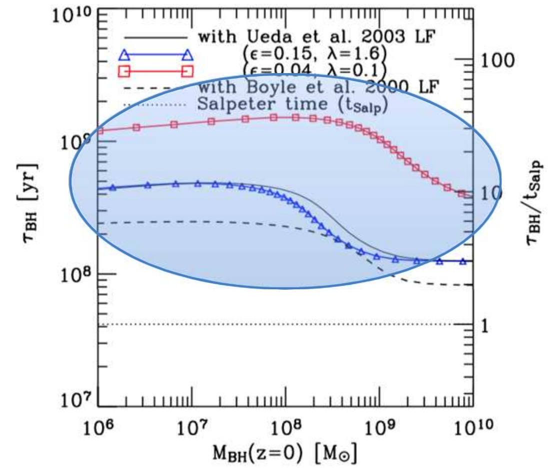
duty cycle



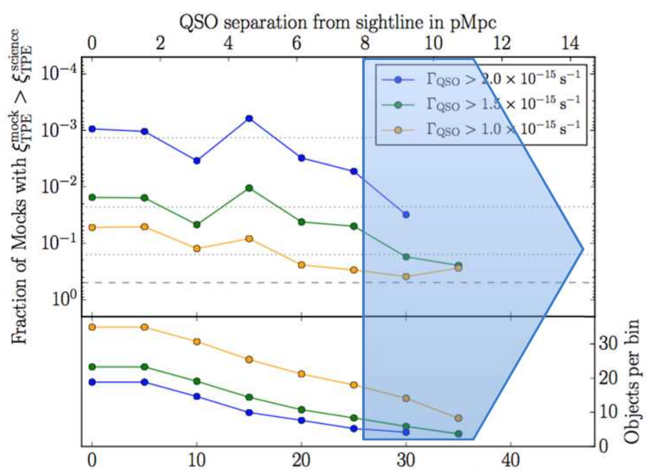
$$P_0(M_\bullet, z) = \frac{\Phi_L(L,z)\left|\frac{d\log L}{d\log M_\bullet}\right|}{\Phi(M_\bullet, z)} \leq 1$$

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

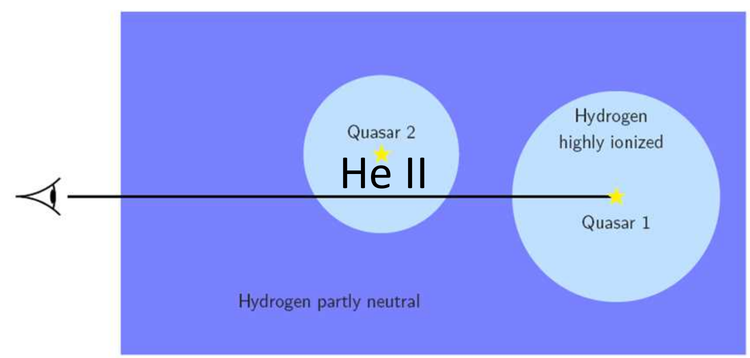
Duration of AGN



Marconi 2004



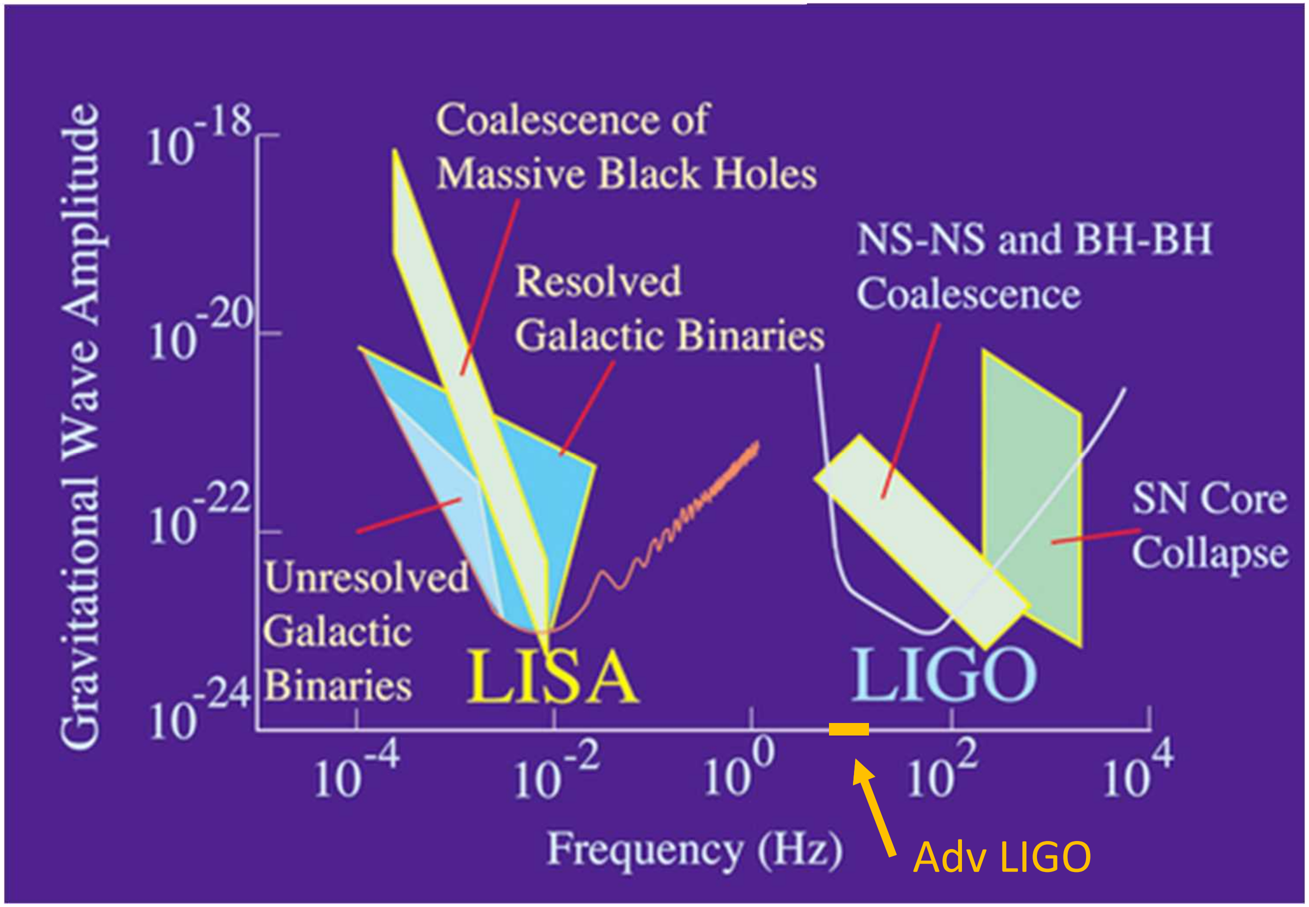
$\tau_{diffusion}(R_{out})>10^8$yr & Rout>10pc



Quasar-on-quasar transverse proximity effect, Schmidt 2017

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) $\sim 10^{-2}$

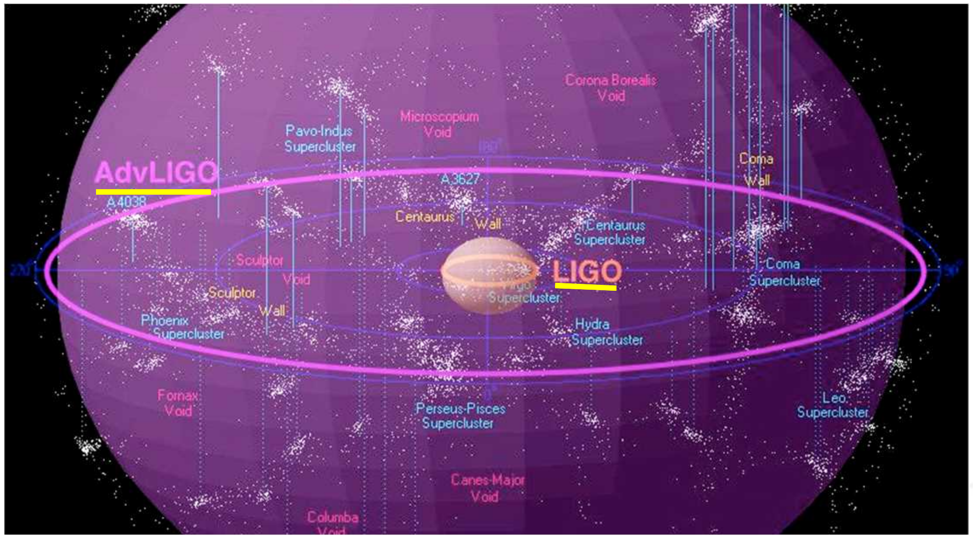


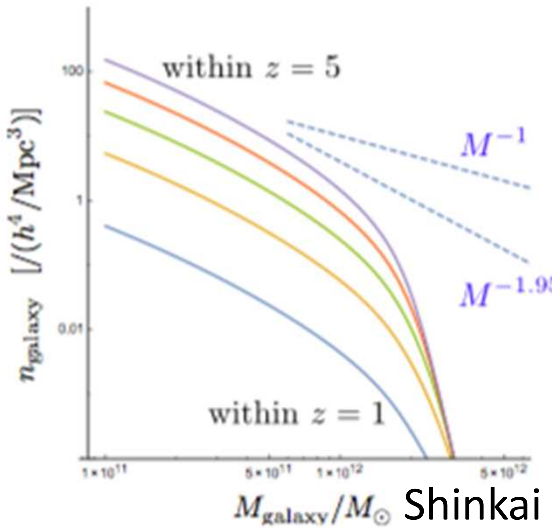
Occurrence rate of BH-MBH may be a fraction that for BH-BH merger events.
Possible to detect intermediate mass BH with $M_H \sim 10^3\ M_o$

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:

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

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

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

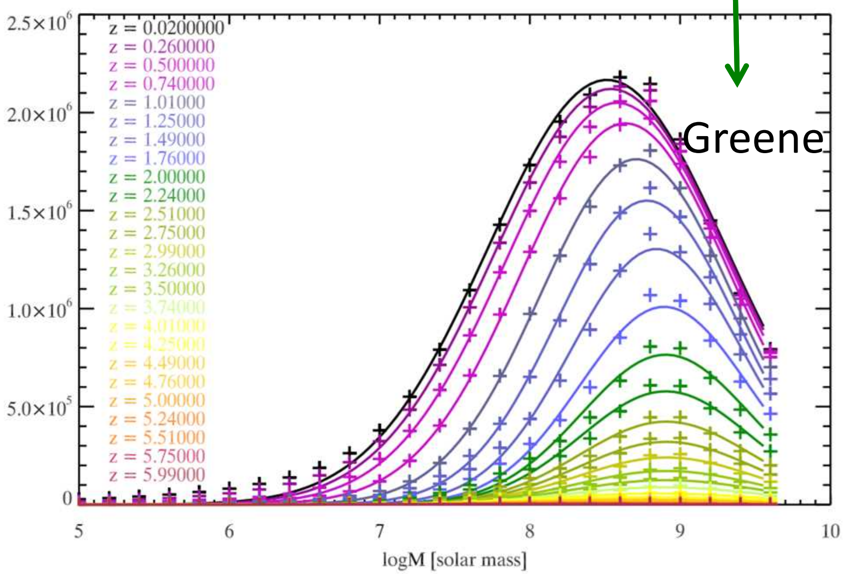
Trapping rate $\sim (h M_H/M_*)/ \tau_{active}$ $\sim 10^{-4}\ {\rm yr}^{-1}$ per AGN

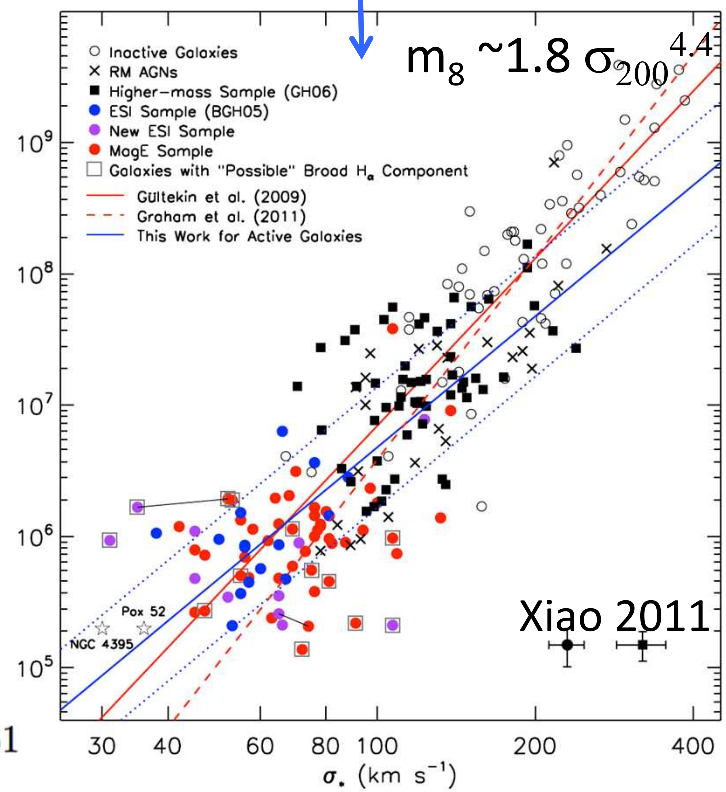
Total rate $\sim O(1)$ ${\rm wk}^{-1}\ {\rm Gpc}^{-3}$ at $z=0$. Statistical characterization!

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



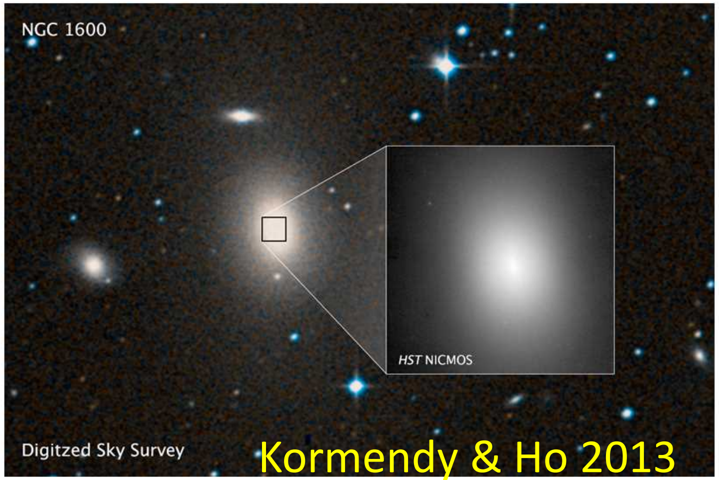


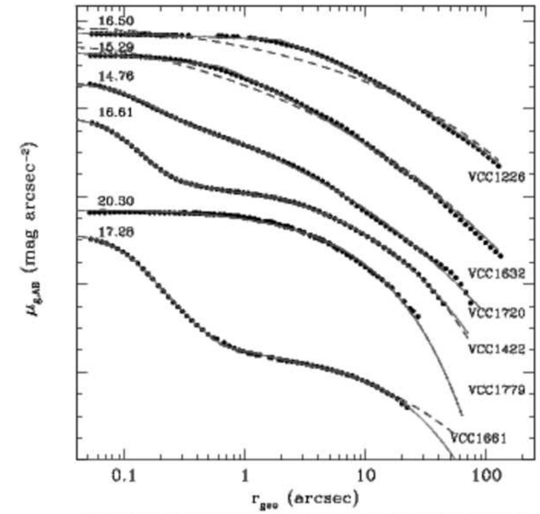
$$\frac{dn_A}{d\sigma_{200}} = \frac{4.4\phi_0}{\sqrt{2\pi}\sigma_{200}\sigma_M}\exp\left(-\frac{(\log m_8 - \nu_1)^2}{2\sigma_M^2}\right)$$

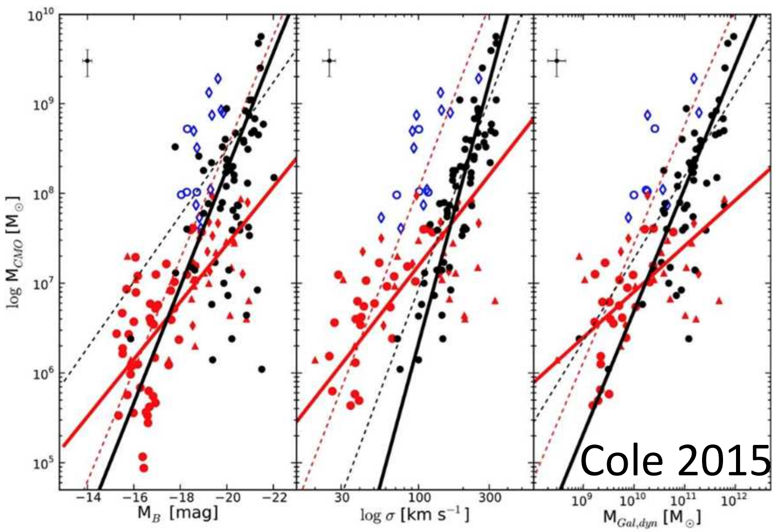
$$\phi_0 = 3.4\times10^{-5}\mathrm{Mpc}^{-3}, \quad \nu_1 = 6.7, \quad \text{and} \quad \sigma_M = 0.61$$

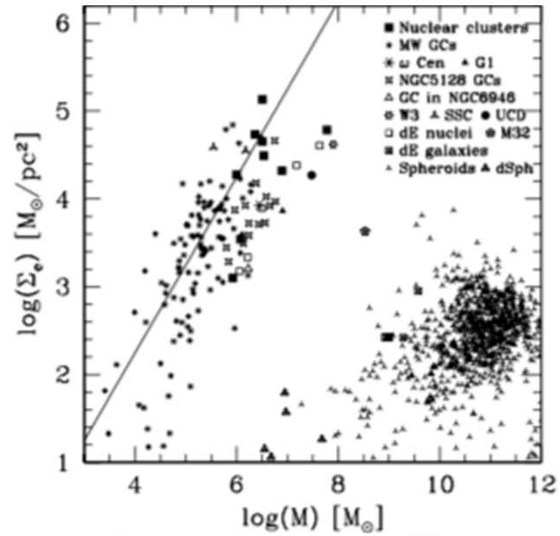
XJZhang, SDMao

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



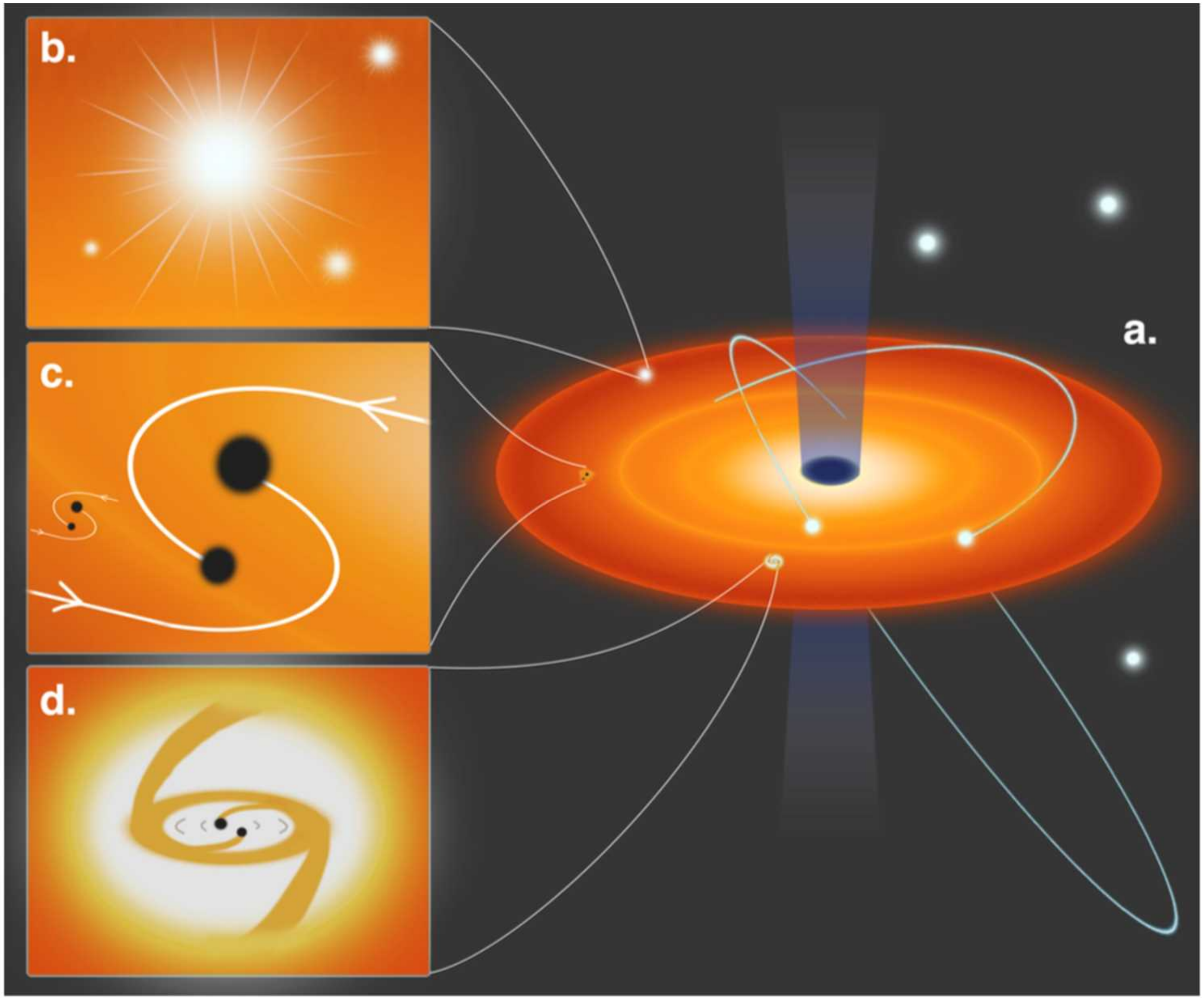






$\dot{N}_{\rm tot}$ ~ 4A LIGO events per year with $A = \int \sigma_{200}^{-3} \exp\left(-\frac{(4.4\log\sigma_{200} - \nu_1)^2}{2\sigma_M^2}\right) d\sigma_{200} \sim$ O(1)

Take-home cartoon



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 Lidov-Kozai effect, & merge through gravitational radiation.
- Events occur $\sim 10^2$ yr^{-1} Gpc^{-3} around metal-rich AGN with wide masses, spin angular momenta, and spin-orbit obliquity.
- Intermediate-mass ($>10^3 M_{sun}$) 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.