stellar rejuvenation and gravitational waves in AGN disks

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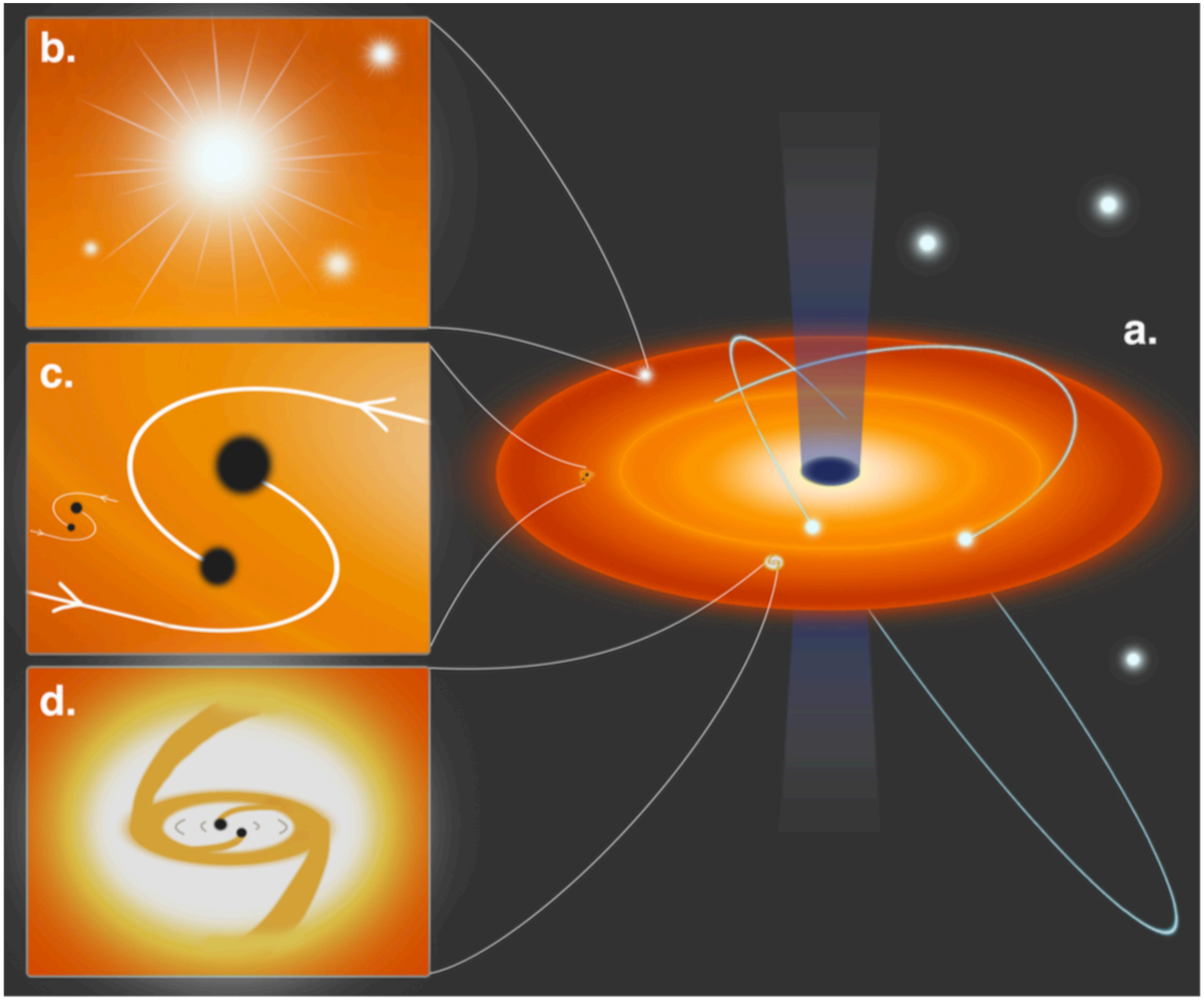
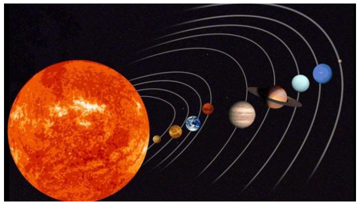
Stars, Planets, and Galaxies

Berlin, April 15, 2018

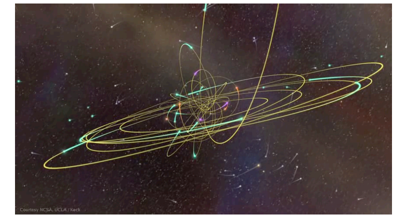
UG,GS,PD,SC



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



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}

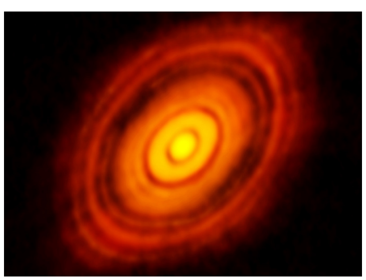
Protostellar disks
1. Disk mass/star mass: 0.01-0.1
2. H/r = 0.05-0.2
3. Q > 10
4. Persistent time scale: 3-10My

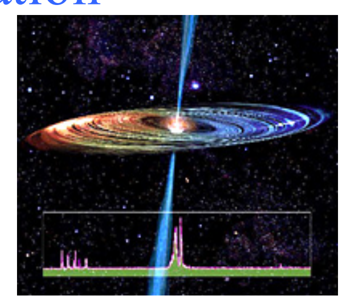
AGN and young stellar disk
1. Disk mass/star mass: ~0.01
2. H/r ~ 0.01-0.1
3. Q: ~ 1
4. Persistent time scale: 1-100My

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

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

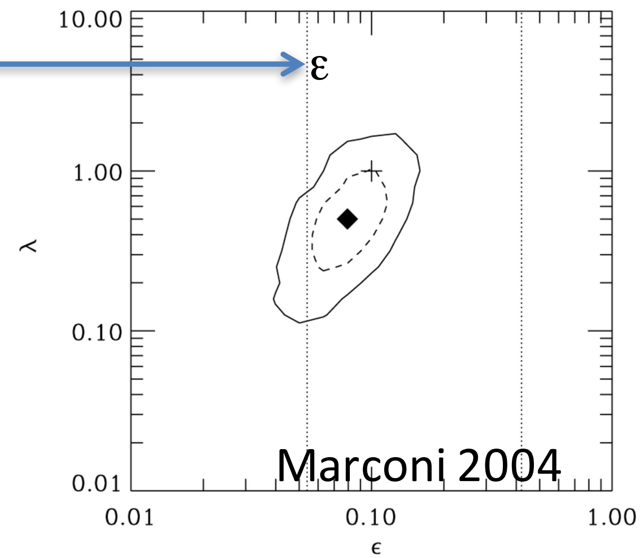
$\quad = \lambda \; \dot{m}_E \qquad \lambda \sim 0.6$

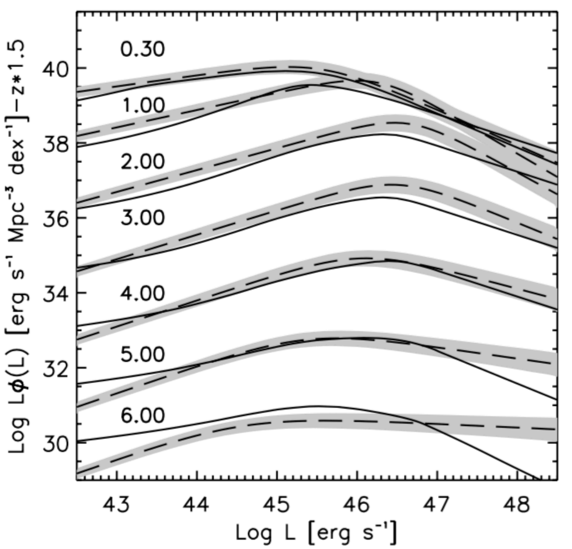
$\dot{m}_E = 4\pi G m_p M_h/\varepsilon \sigma_T c$

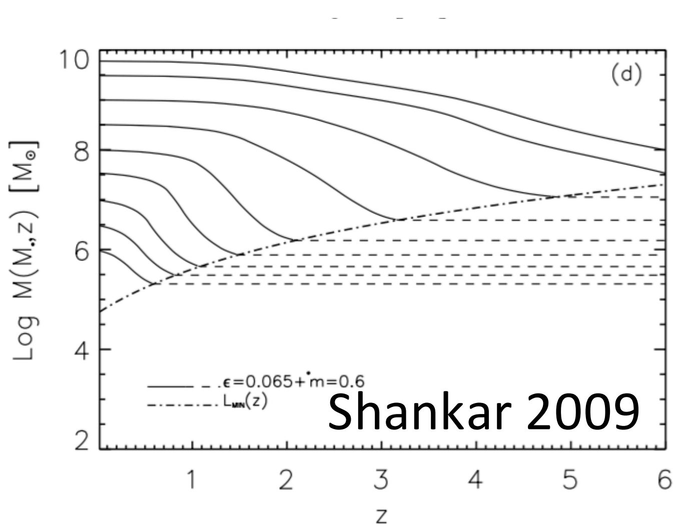
Timescales $\tau_{Sal} = M_h/\dot{m}_E$

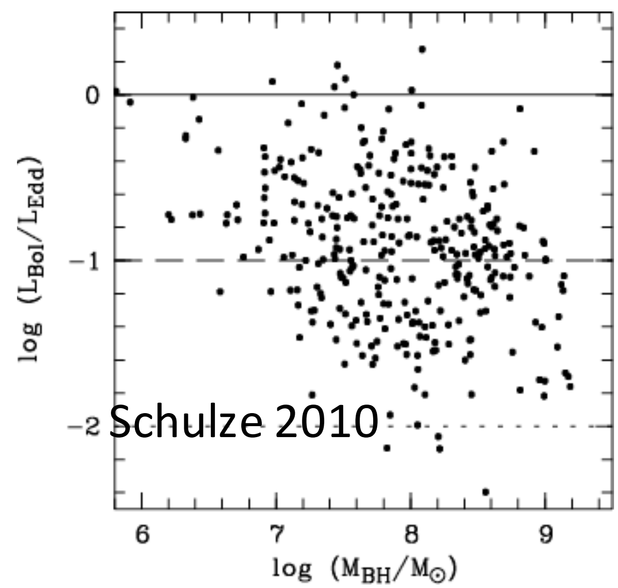
$P(R)=(R^3/GM_h)^{1/2}$

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

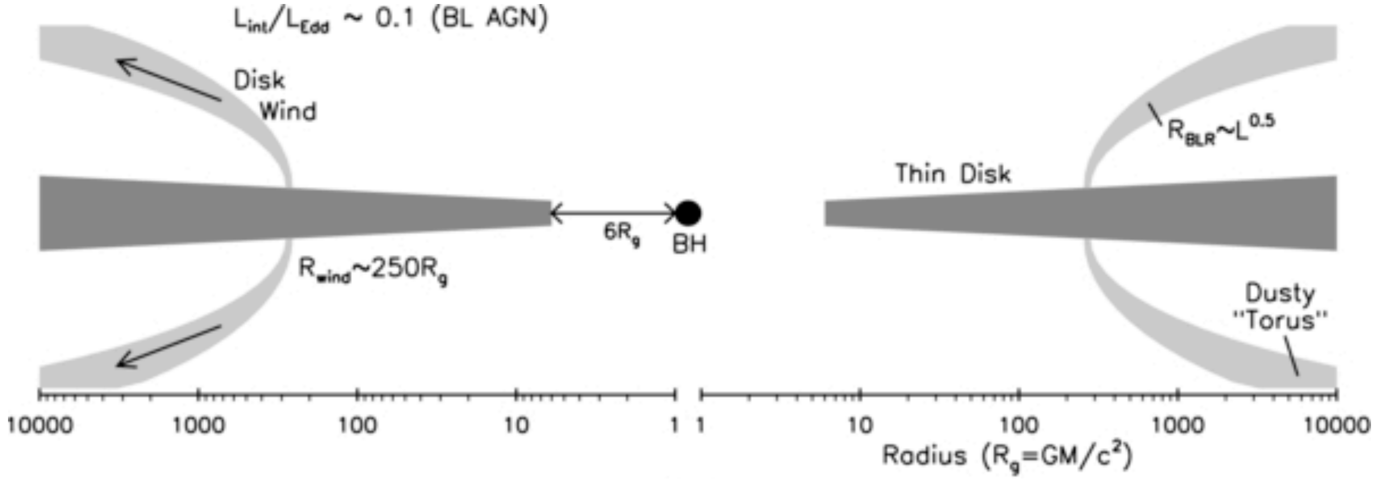








A generic quantitative AGN accretion disk model



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

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

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

- Marginal gravitational stability

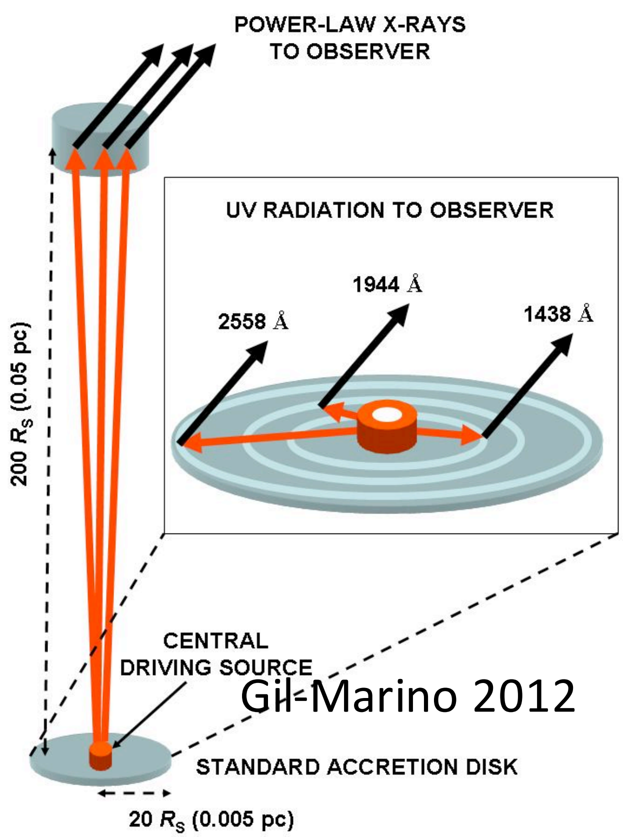
$$\Sigma = \Sigma_Q/Q \qquad \Sigma_Q = h(M/\pi R^2),$$

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

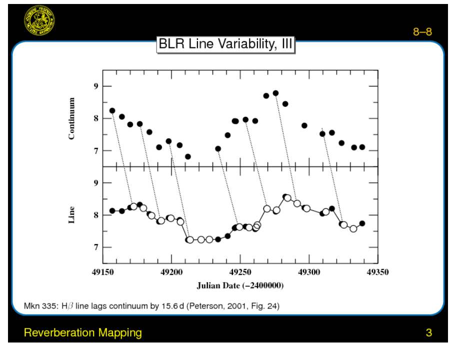
XJZhang

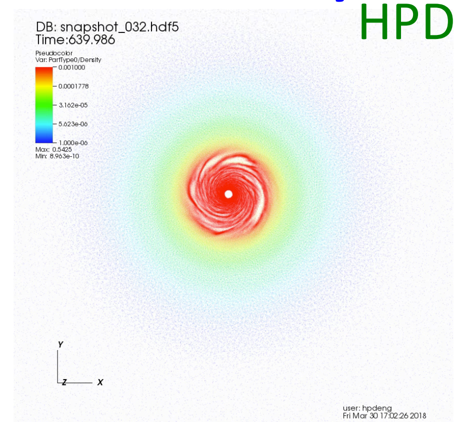
Reverberation from accretion disk to dusty torus

HPDeng

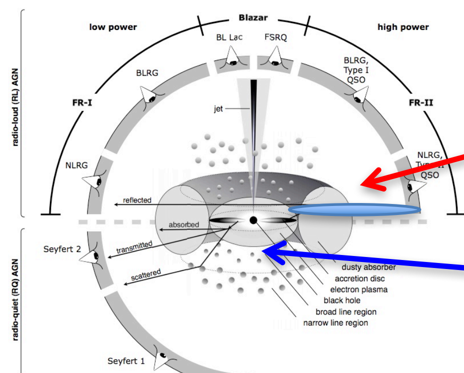


Gil-Marino 2012

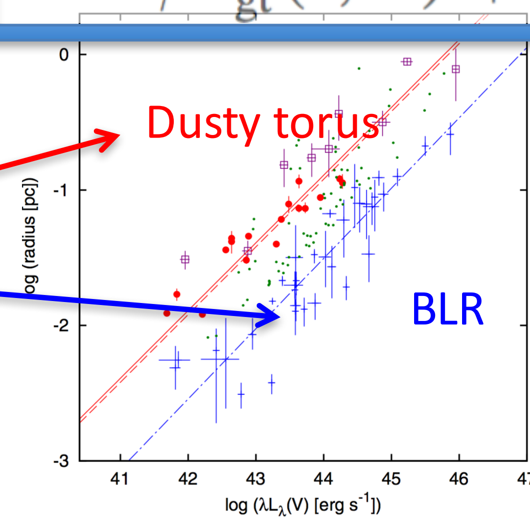




$$\alpha = \psi\alpha_{\rm gt}^{\rm R}(r,\Sigma) + \alpha_m$$



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 1993

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

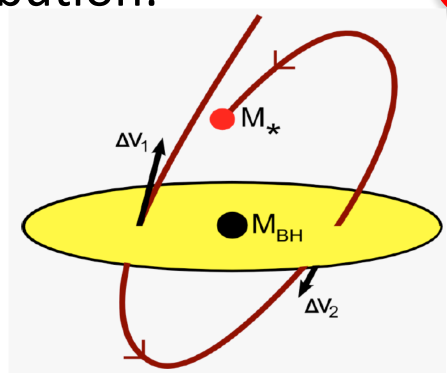
$C_d = C_d^{gas} + C_d^{wave} \sim 6$

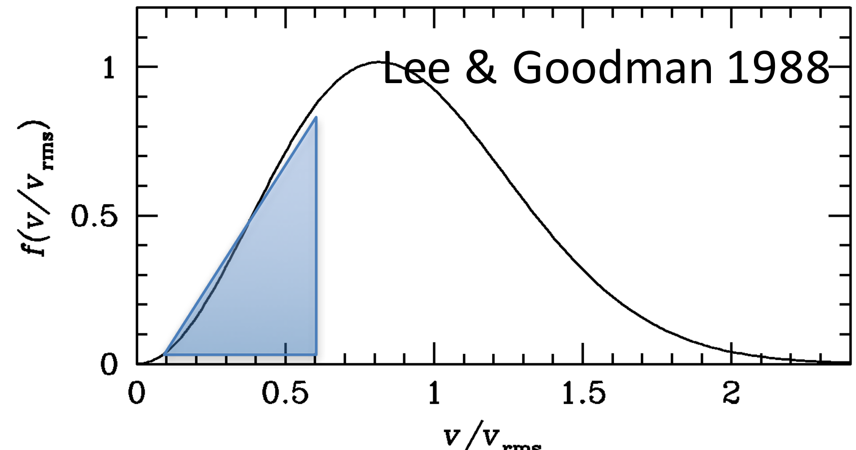
Condition for disk trapping within ΔT:

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

Phase space distribution:

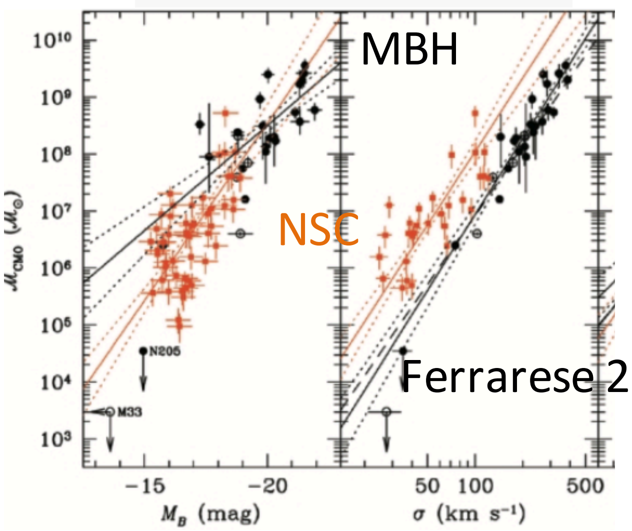
$$dN_* = \nu_* \exp\left[-\frac{v_r^2 + (v_\phi - V_{\rm rot})^2 + v_z^2}{2\sigma^2}\right]\frac{d^3r\, d^3v}{(2\pi\sigma^2)^{3/2}}$$





Phase space fraction of trapped stars:

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



Ferrarese 2006

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

Nuclear clusters

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

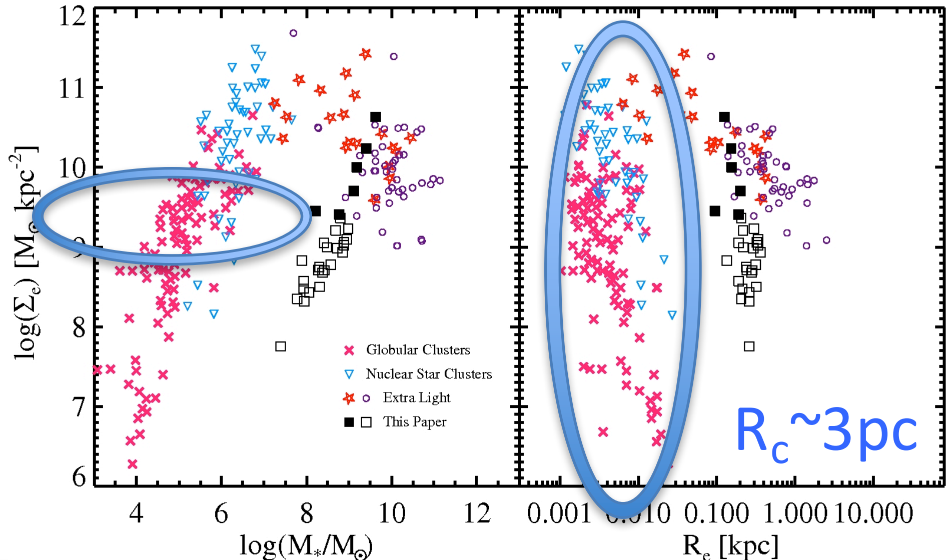
$P_o \sim 5\text{x}10^4 M_{c,8}{}^{1/2}$ yr

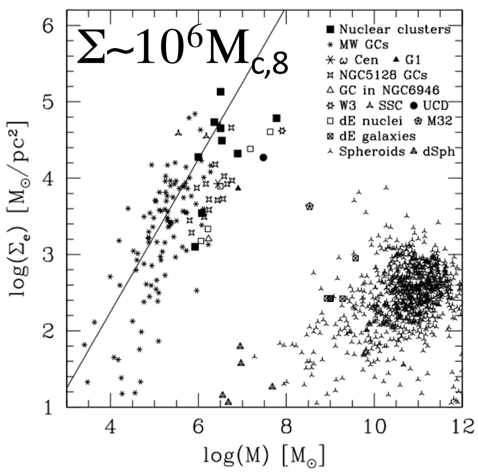
$\sigma_o \sim 350 M_{c,8}{}^{1/2}$ km s^{-1}

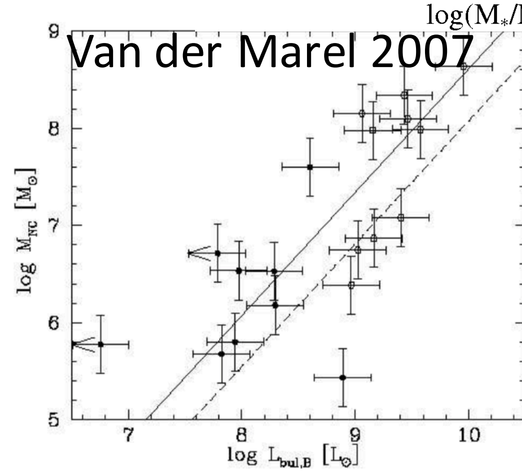
$M_{c,8} \sim 21\ \sigma_{200}{}^{4.3}$

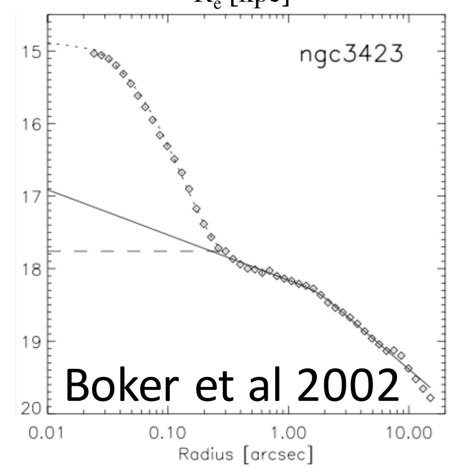
$m_8 \sim 1.8\ \sigma_{200}{}^{4.4} \sim 0.08 M_{c,8}$

Efficiency of NSC< => MBH









Capture rates:
XJZhang

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

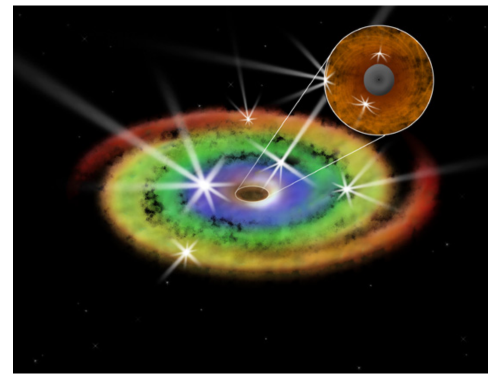
Accretion rate and stellar rejuvenation

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)

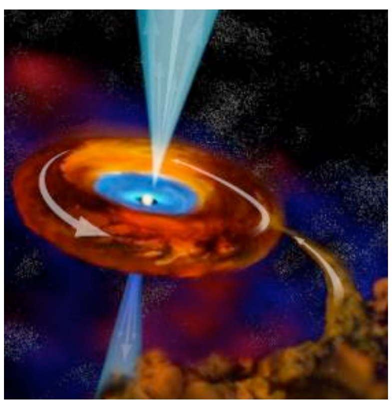
$$\tau_B = m_*/\dot{m}_* \simeq 0.6(M_\odot/m_*)R_{pc}^3\mathrm{Myr}$$



Wind loss

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

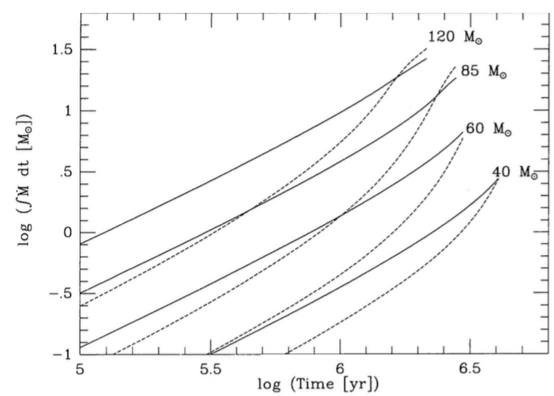
$$\log\left(\frac{\dot{m}}{M_\odot \mathrm{yr}^{-1}}\right) \simeq 1.74\log\left(\frac{L_*}{L_\odot}\right) - 1.35\log T_{\rm eff} - 9.55$$



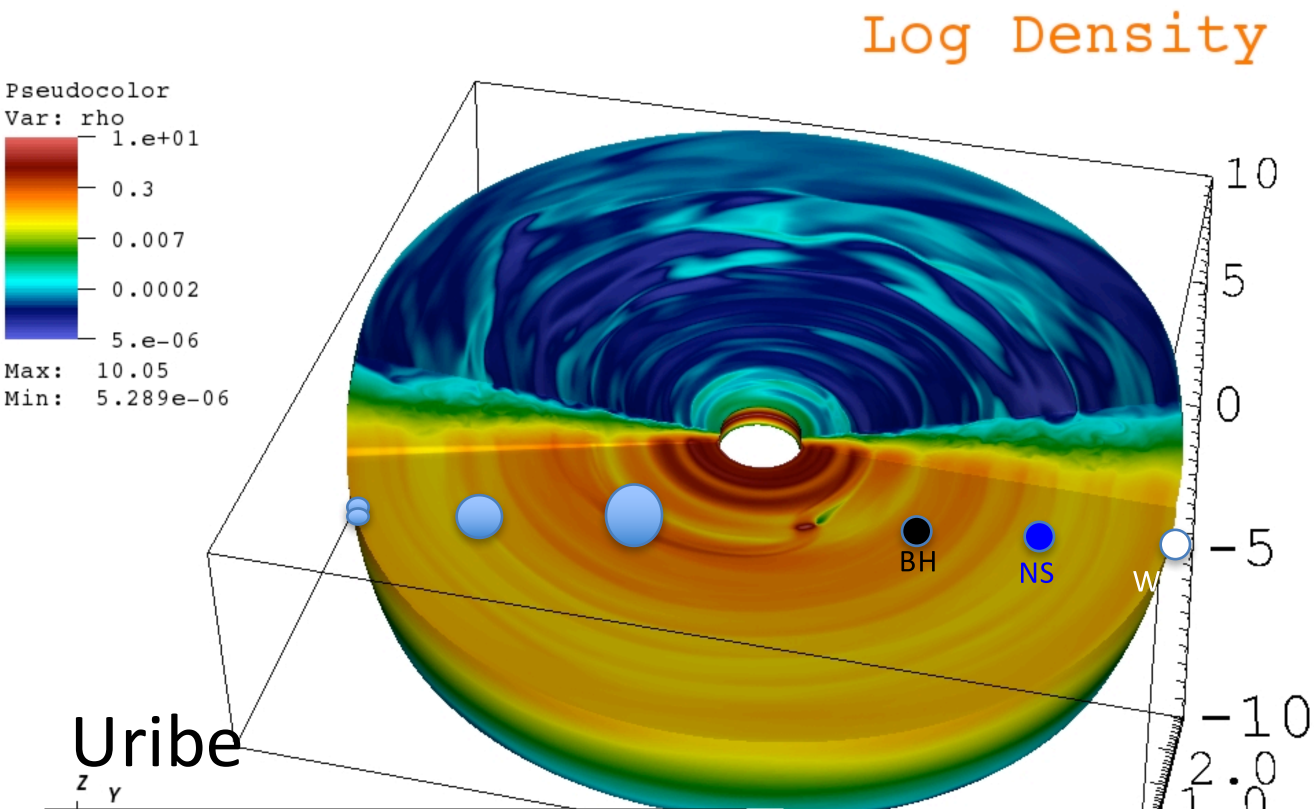
$$m_{*w} \sim 120 R_{pc}^{-3/2} M_\odot$$

Main sequence evolution time:

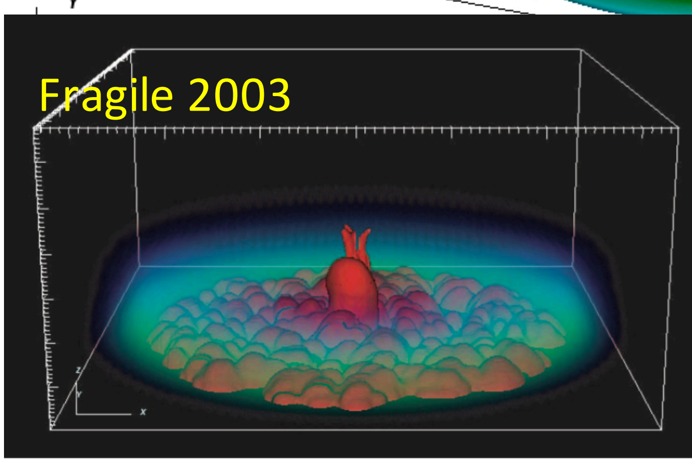
$$\tau_* \sim 10(m/M_\odot)^{-2.5}\mathrm{Gyr}$$



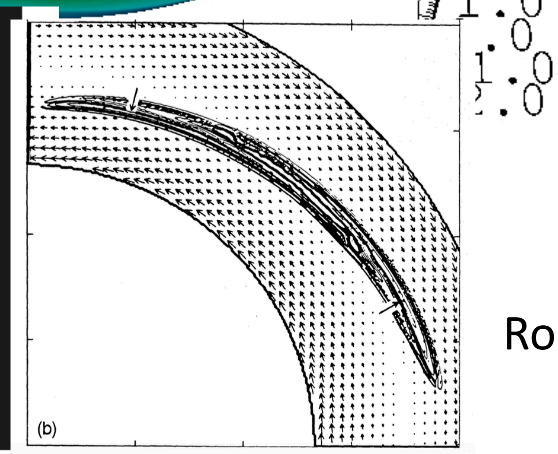
Stellar rejuvenation



Uribe



Fragile 2003



Rozyszka Bodenheimer 1995

Origin of `young' stars

a)Capture host galaxy stars

b) Opaque disk (τ_{disk}>)

R_{opaque}~12 $m_8^{5/9}$ pc

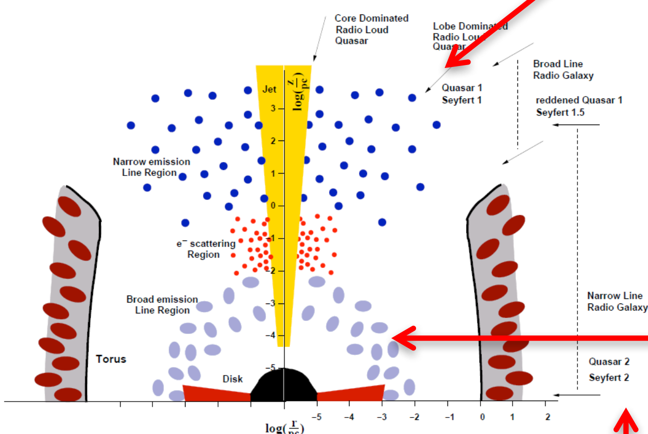
c) Top heavy IMF:

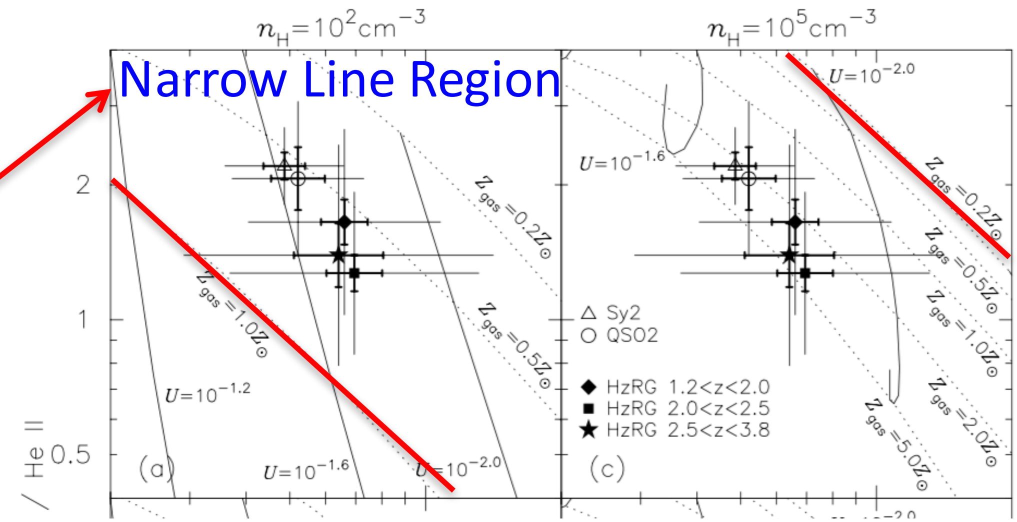
Min (m_{*B}, m_{*w}) ~$10^{1\text{-}2}M_o$

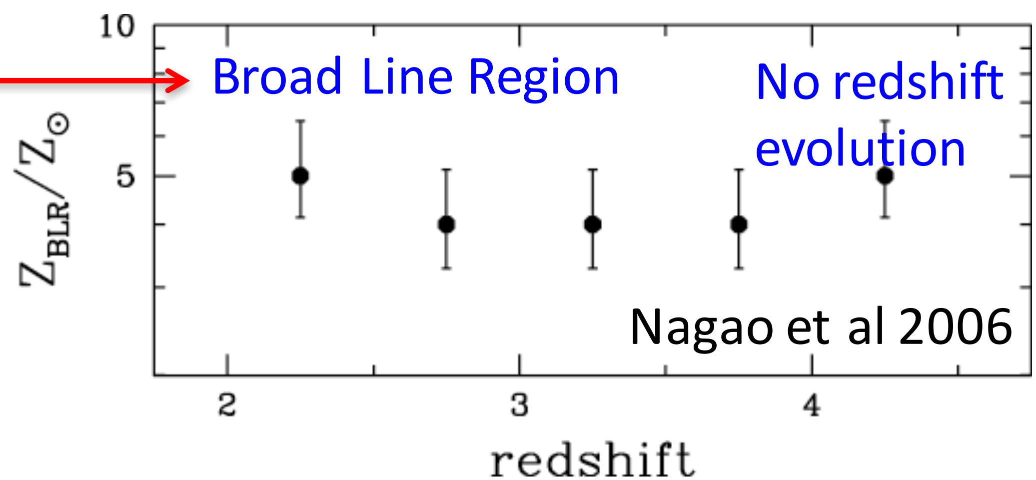
d) Binary main sequence stars possible at large a

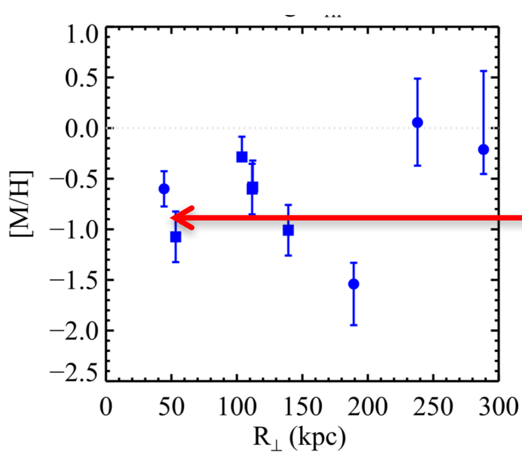
Super-solar metallicity in high-redshift AGNs

$Z_{BLR} > Z_{NLR}$





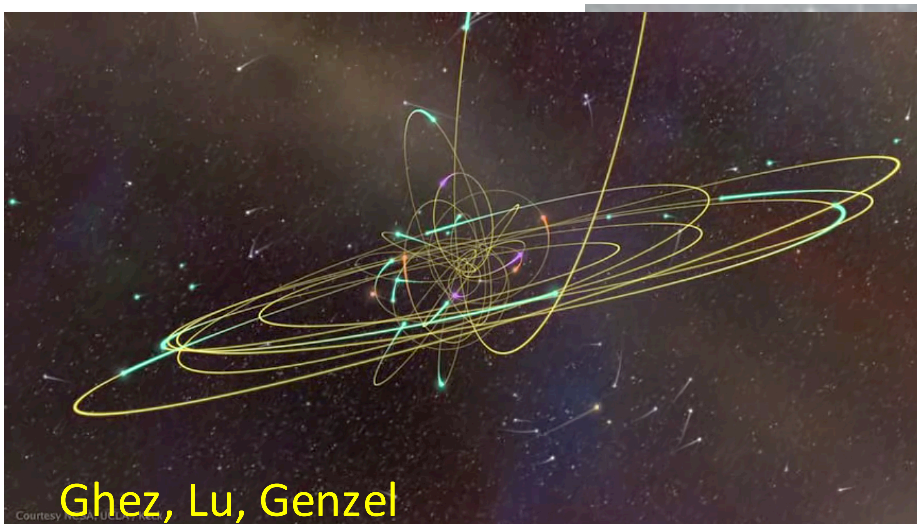


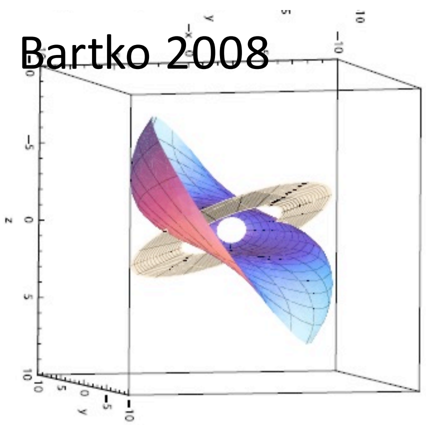


Quasars probing metal-poor outskirts of quasars

Lau, Prochaska, Hennawi 2016

Disk’s reorientation due to infall of turbulent gas

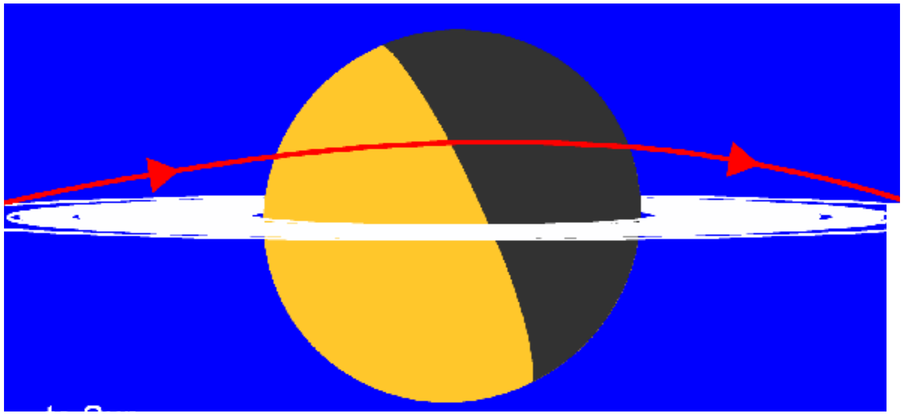




Also in Q~1 warped disks around spinning MBHs

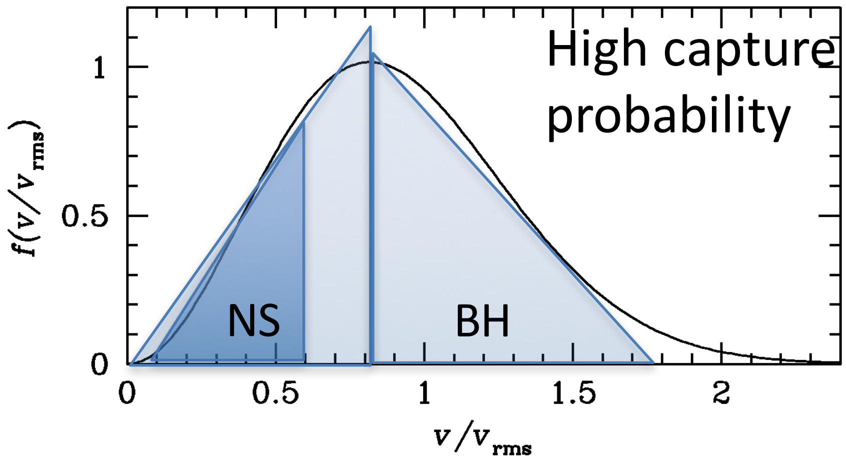
HPDeng, Rnaylor, XJZhang

Recapture of neutron stars and seed black holes



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

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

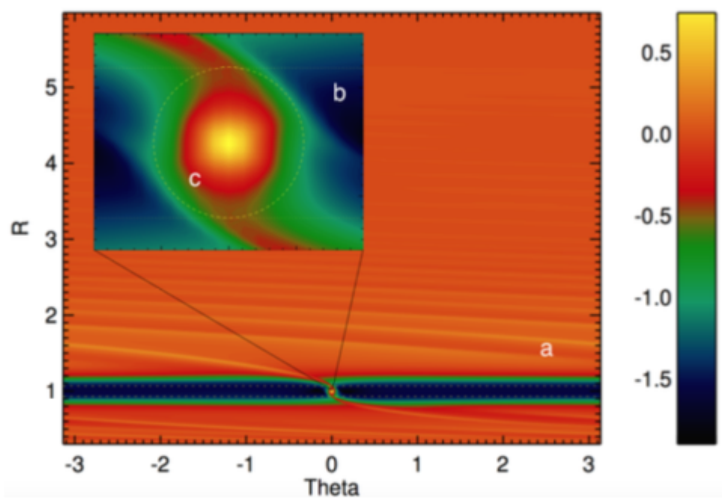


accretion radius = min [R_B, R_R]

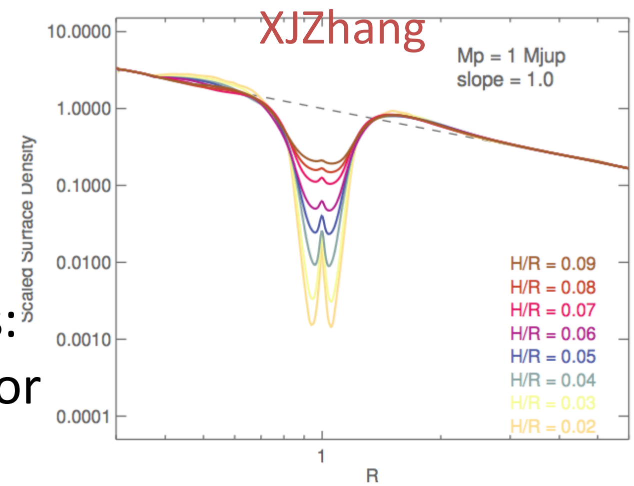
$$\tau_{\rm sal} = m_*/\dot{m}_E = 4.5\times10^8\eta\,{\rm yr}$$

Mass growth: Eddington limited if

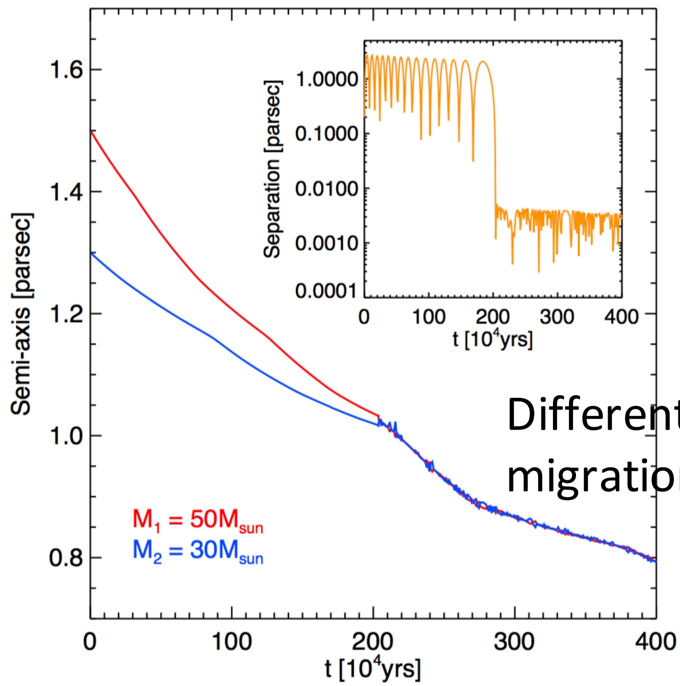
$\tau_{sal} > \tau_B$ or $m_* > 10^{-3}\eta^{-1}R_{pc}^{3}M_o$



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

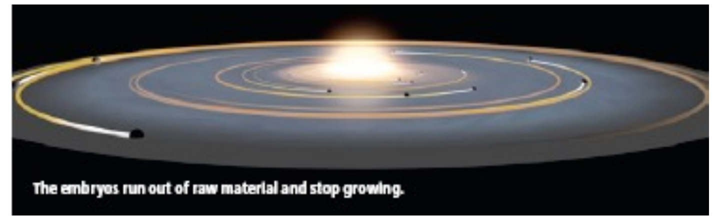


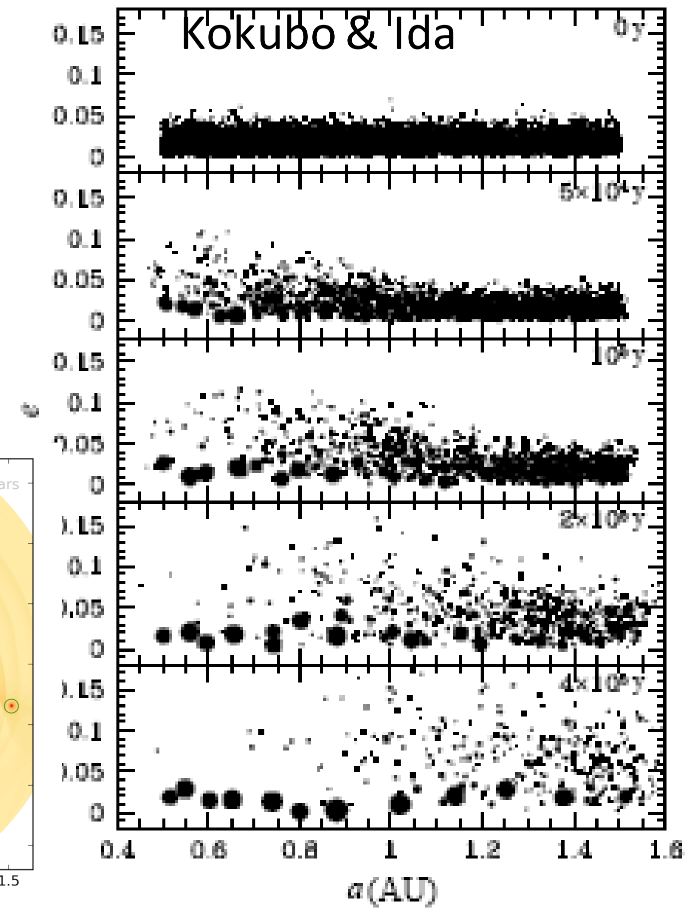
Groups with isolation masses

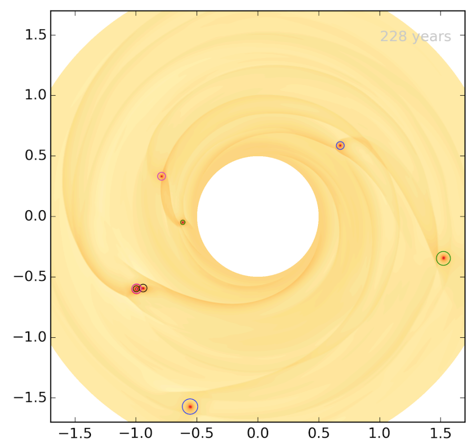


Differential migration

ZXWang



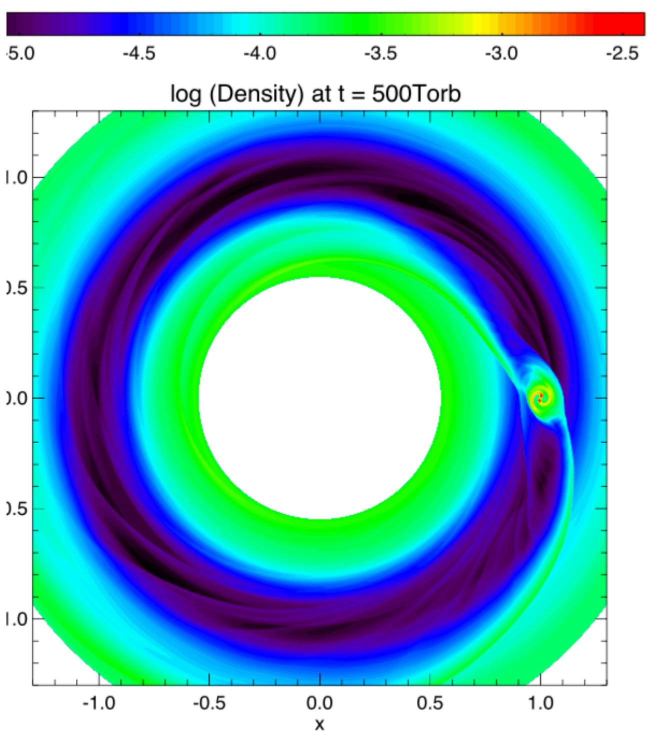


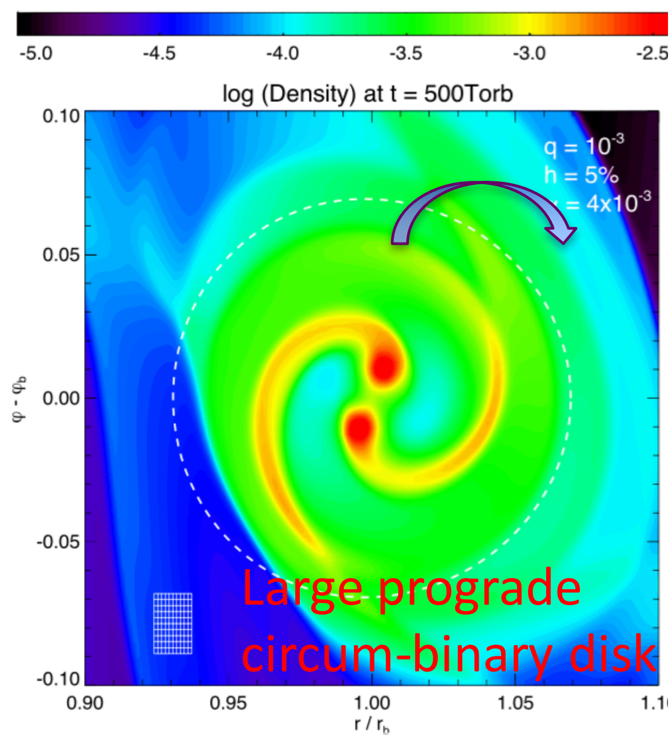


Scales of binary seed black holes in disks

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)



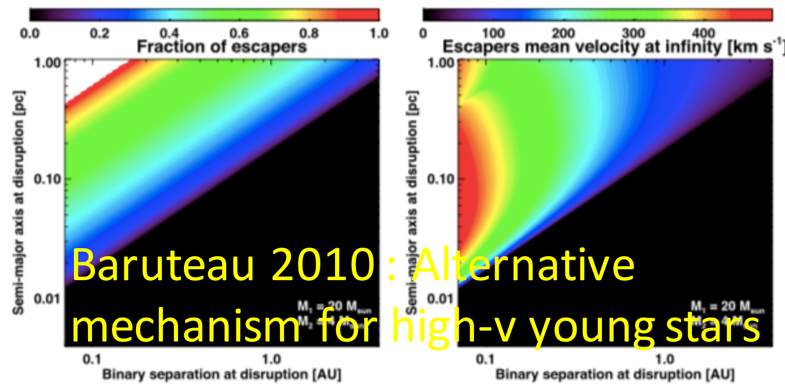


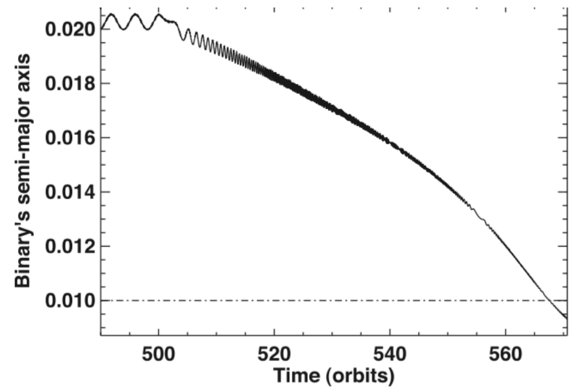
$$\dot{J}_t \simeq 0.23(m_2/m_1)^2 \Sigma_b a_{12}^4 \omega_{12}^2 h_b^{-3}$$

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

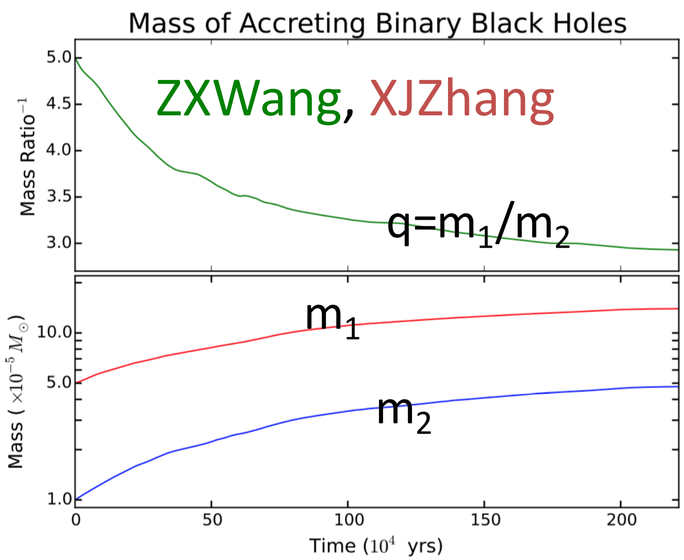
Modest-m$_*$ binary with modified disk structure

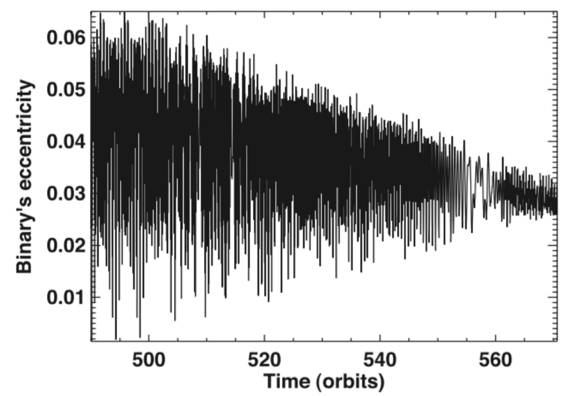
$H=C_s/\Omega > R_R$ (no gap) ~ R_B (perturbed, prograde) ~a_{12} (bound, no enhancement)





a_{12}

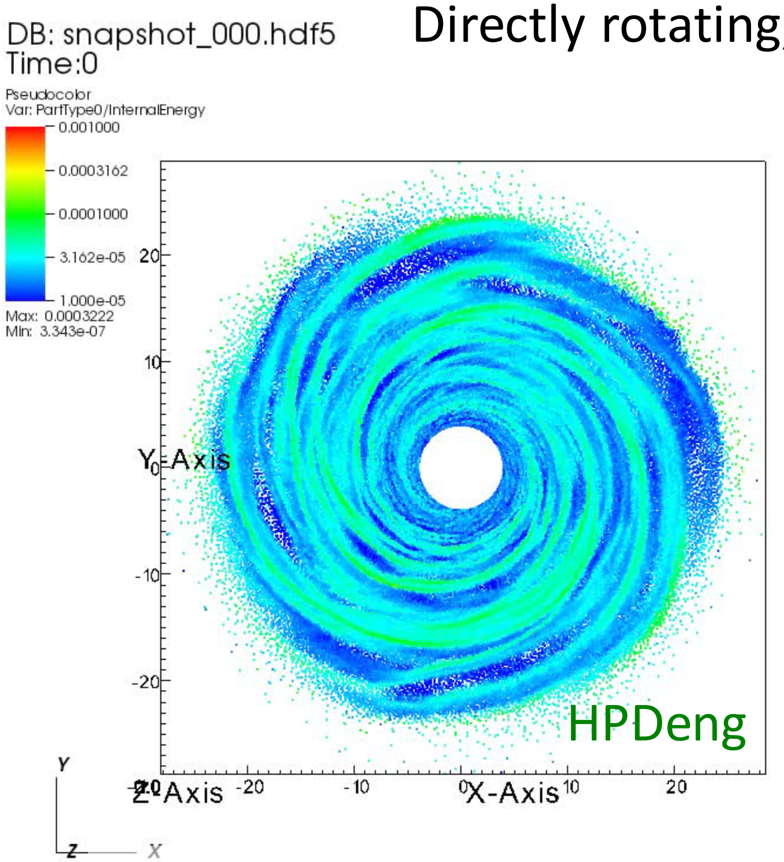




e_{12}

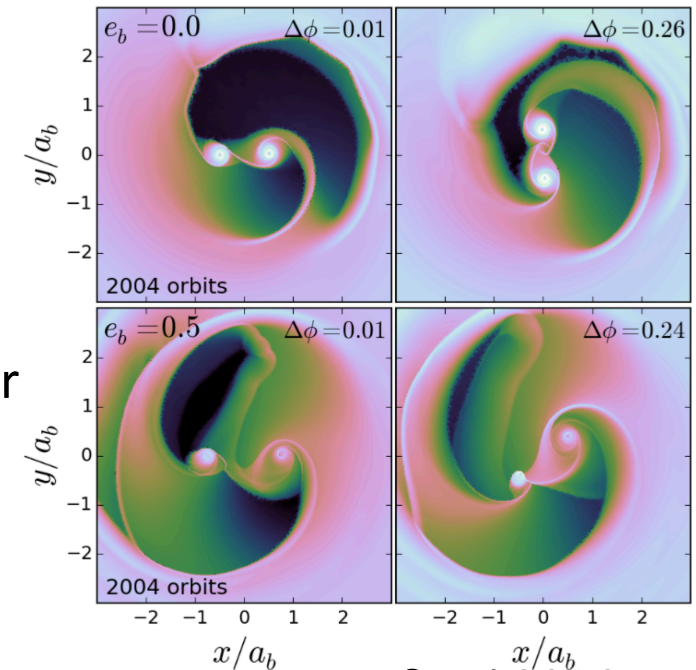
Accretion & tidal torque due to circum-binary disk

Directly rotating, self-gravitating, circum-binary disk



Accretion onto seed binary black holes

Potential sites for Enhanced star formation



Munoz & Lai 2016

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

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

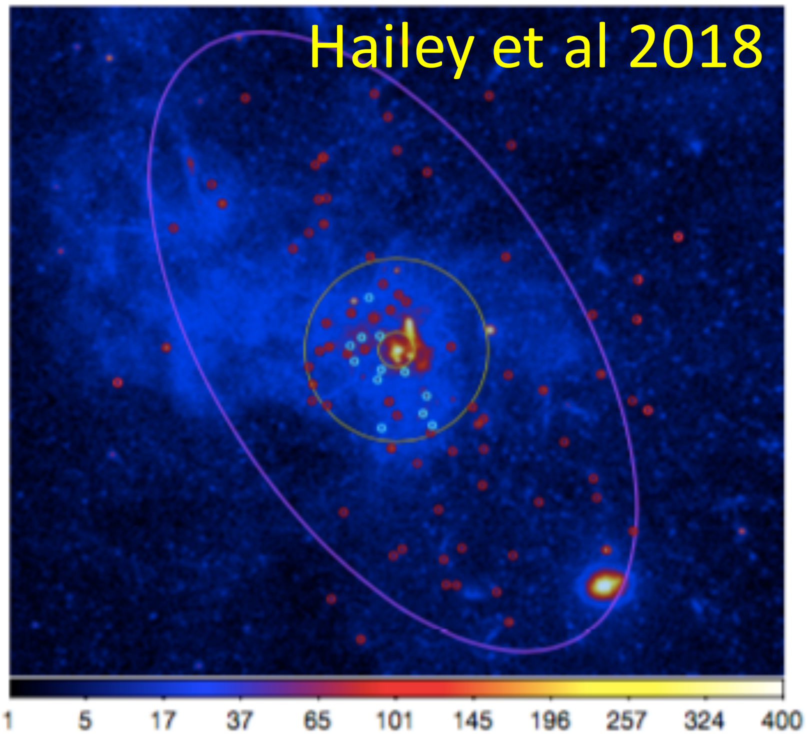
$$\tau_{at} \simeq \frac{m_1 m_2 \omega_{12} a_{12}^2}{m_{12} \dot{J}_t} \simeq \frac{4 m_1^3}{m_2 m_{12} \Sigma_b a_{12}^2} \frac{h_b^3}{\omega_{12}}.$$

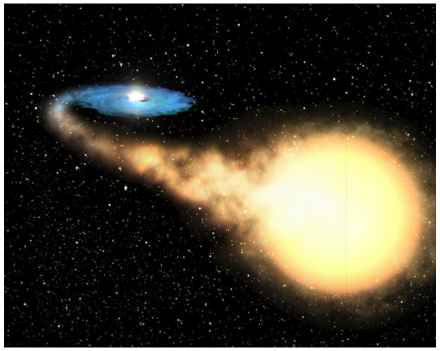
XJZhang

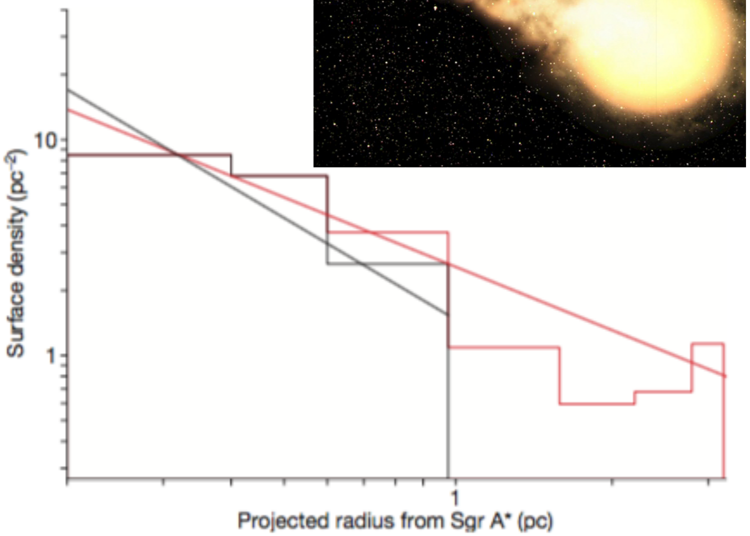
$$\tau_{\rm gr} = \frac{5 a_{12}^4 c^5}{256 G^3 m_1 m_2 m_{12}} \simeq \left(\frac{a_{12}}{1{\rm pc}}\right)^4 \left(\frac{M_\odot^3 10^{39} {\rm yr}}{m_1 m_2 m_{12}}\right).$$

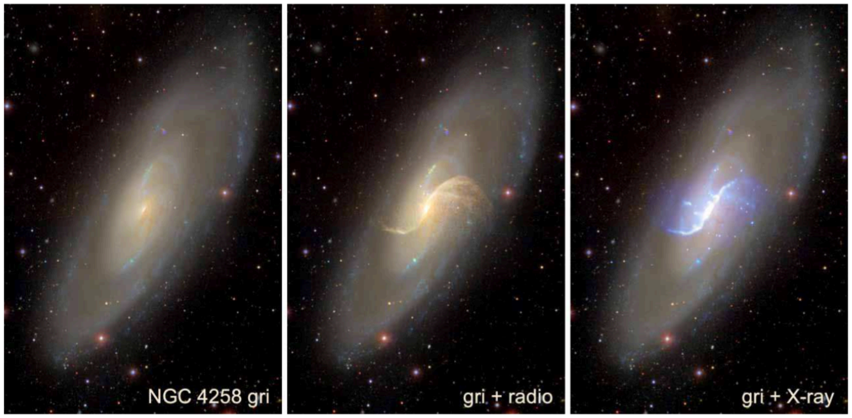
Peters 1964

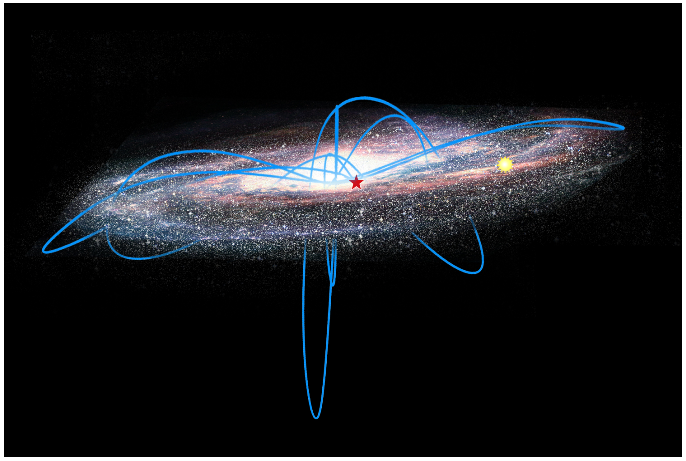
LMXBs, X-ray Luminosity, high-V stars



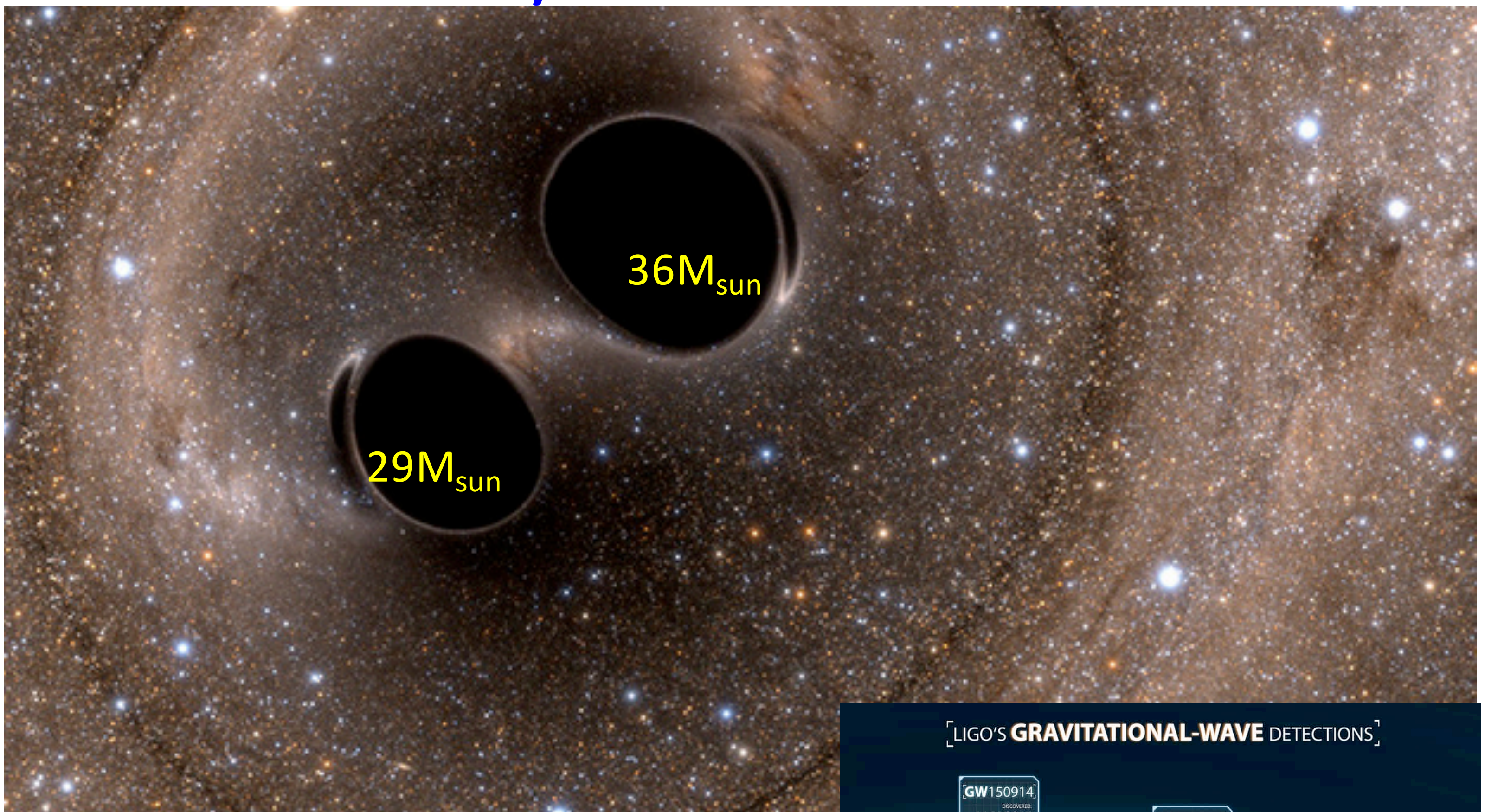


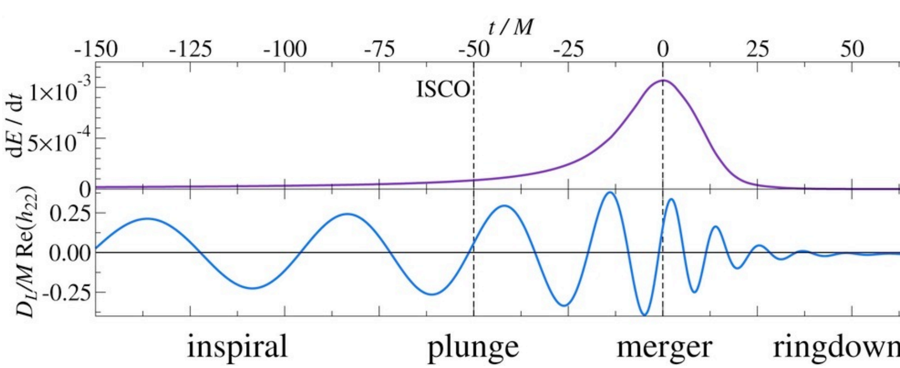


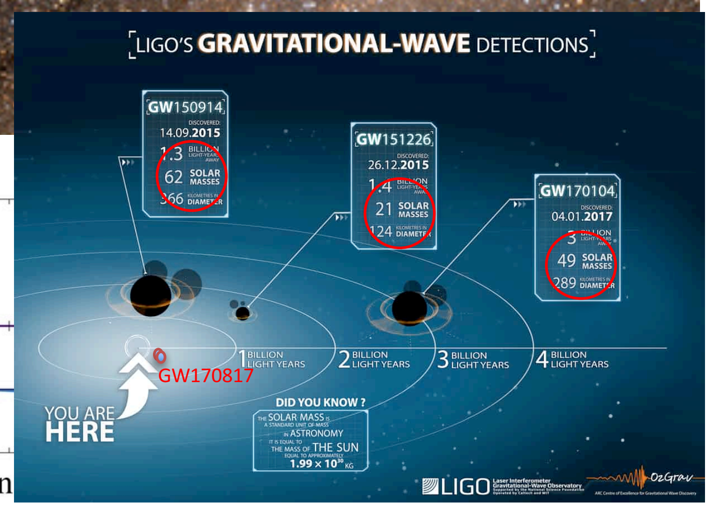




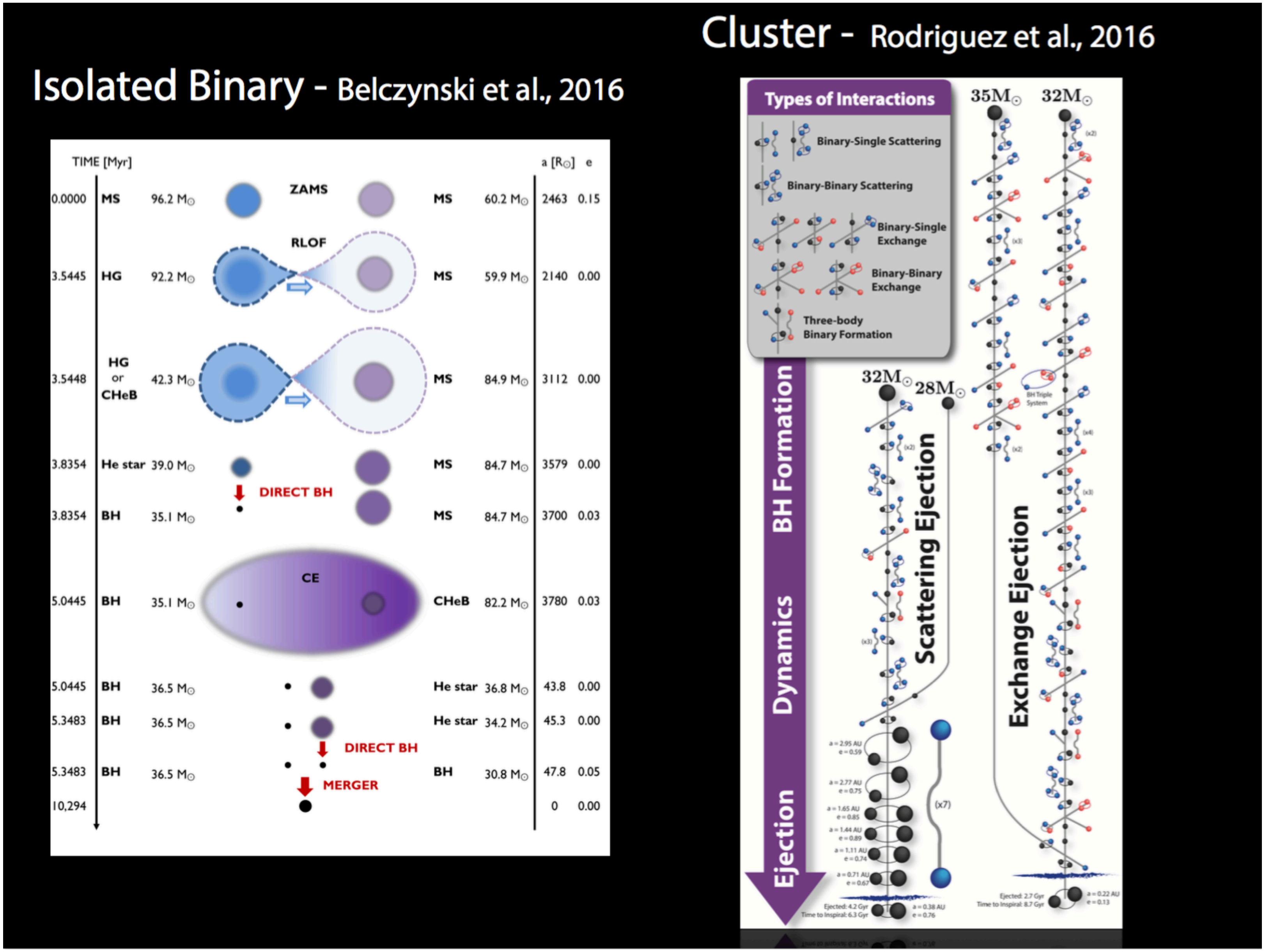
Binary stellar black holes



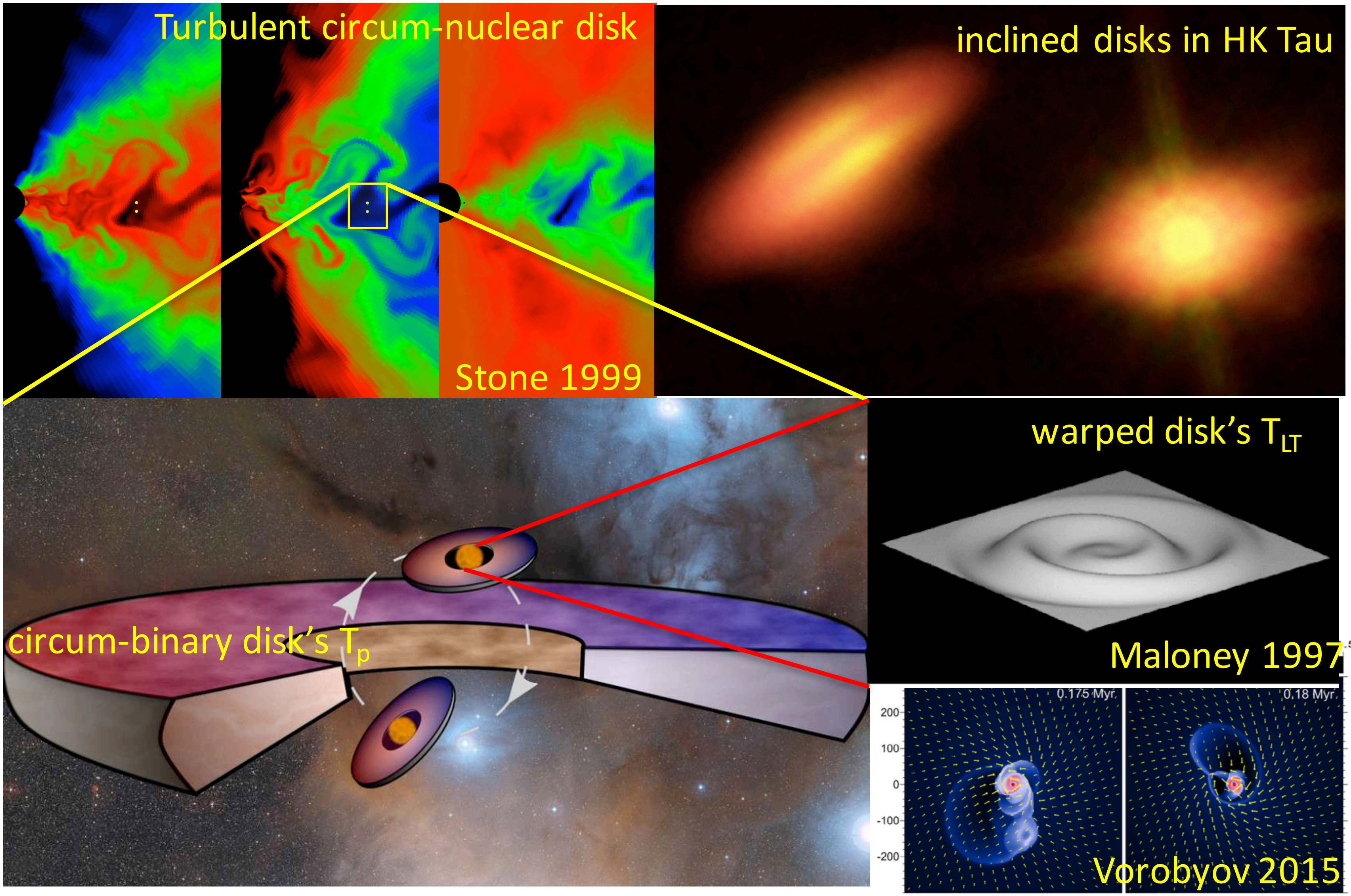




Common-Envelope vs stellar cluster scenarios

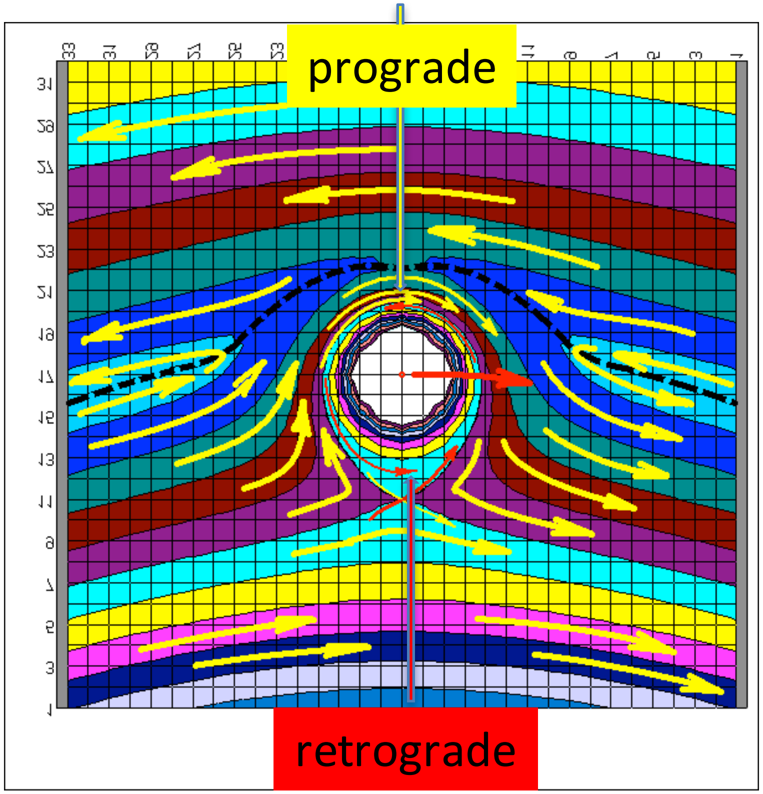


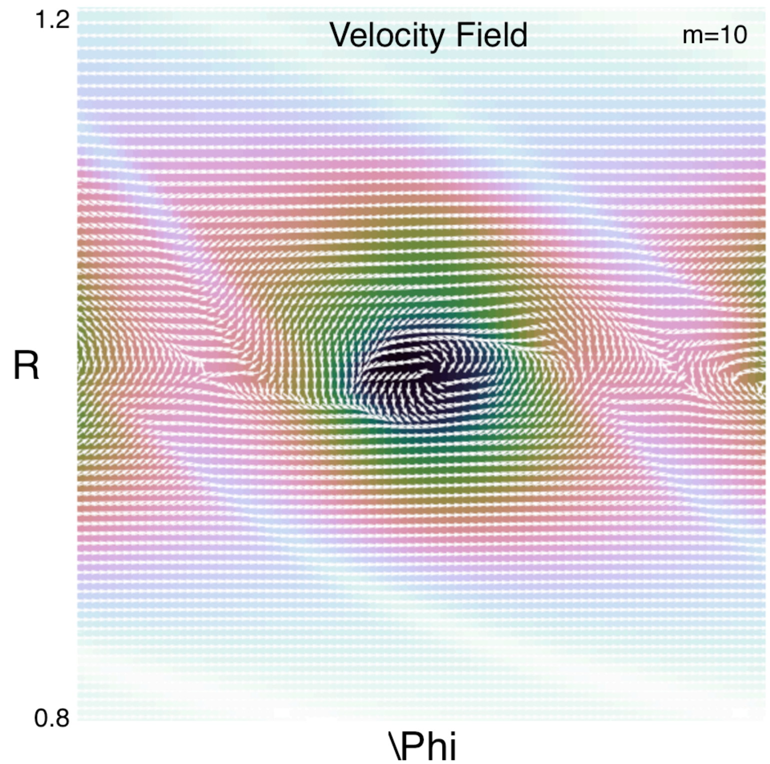
Turbulence in circum-nuclear disks & spin evolution of circumbinary disks



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 $> R_B$

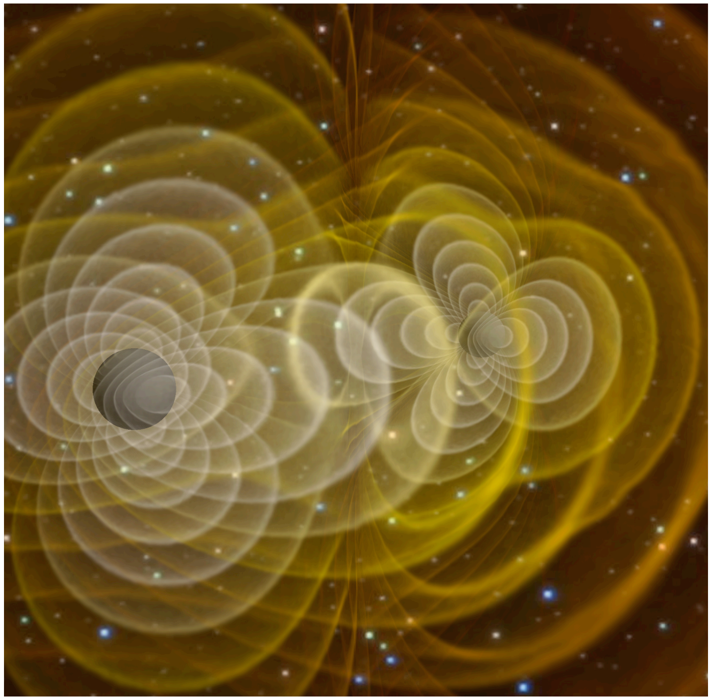
$v_{tur}(\lambda) \sim (\lambda / H)^{1/3} v_{tur}(H) < c_s$, can be $> R_B \Omega$

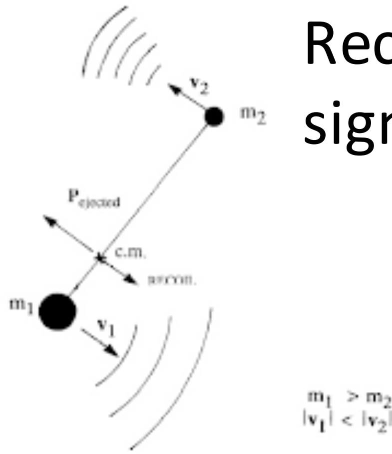
$\tau_{tur} \sim (\lambda / H)^{2/3} [c_s / v_{tur}(H)] \Omega^{-1}$, can be $> \Omega^{-1}$

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 $A = (\lambda / H)^{8/3} (V_{tur}/c_s)^2$

Merger & recoil: binaries with spin-orbit obliquity



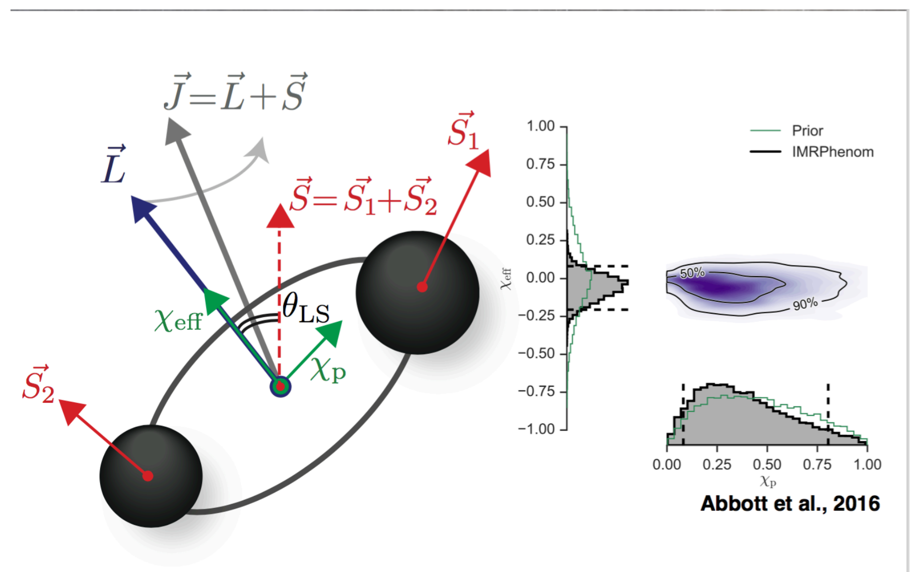


Recoil does not lead to significant disk perturbation

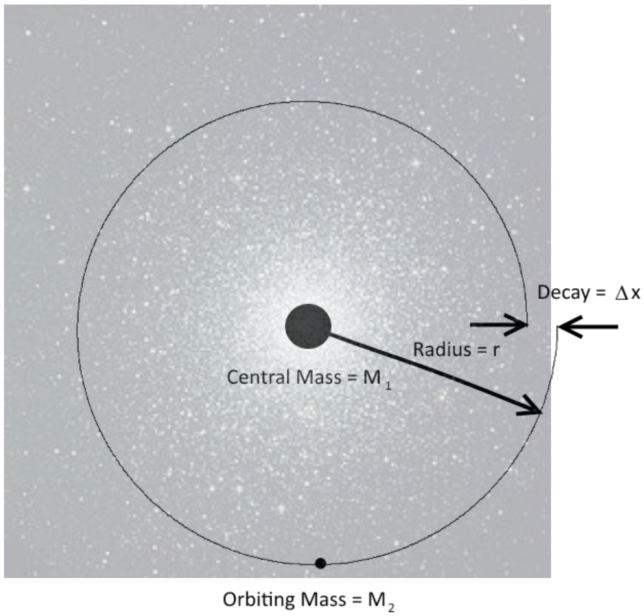
ZXWang, XJZhang

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

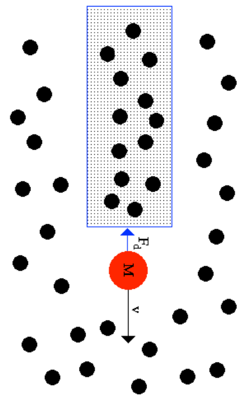
Resettle into the disk if $V_{rec}/V_k < \xi$



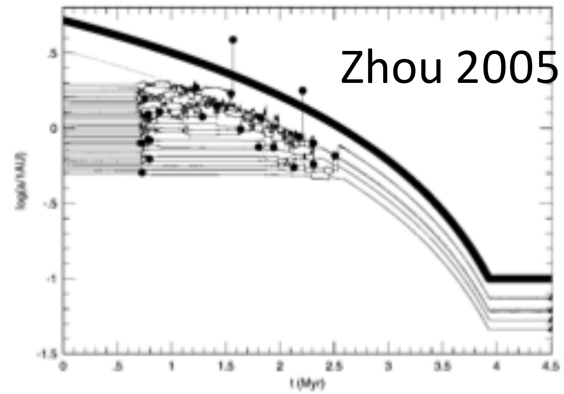
Gap, dynamical friction & disk clearing

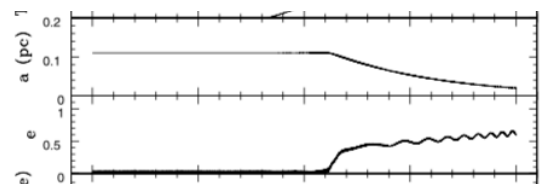


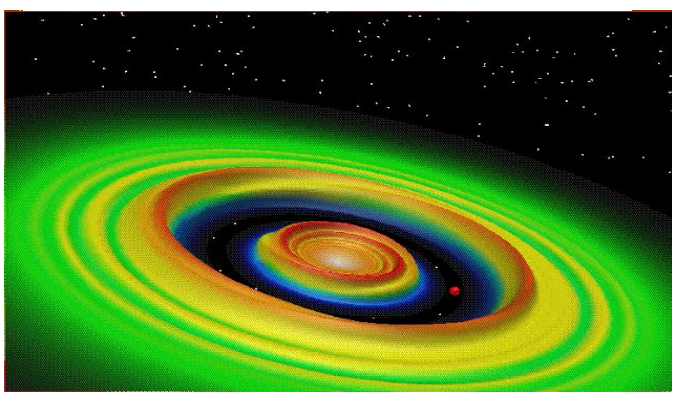
Inefficient type I migration
accretion for τ_{BH}~10 τ_{Sal}
IMBH with M>10^3 M_{sun}



MM Resonant
capture of stars
Yu et al 2007







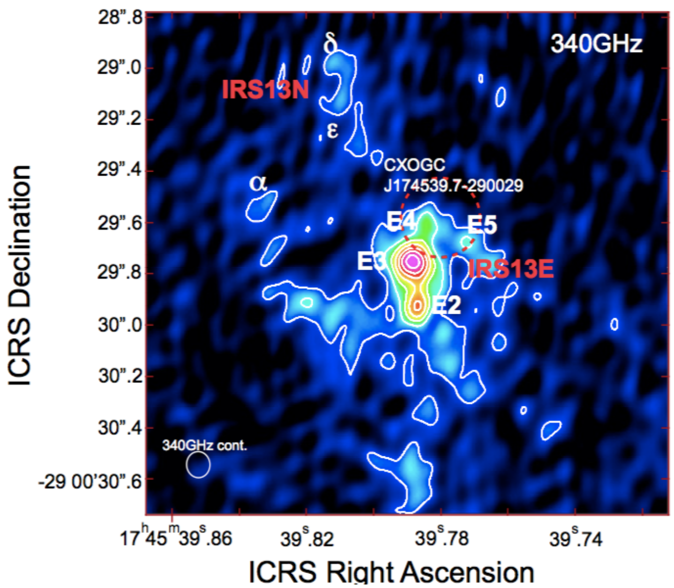
Dynamical friction, decay
of black hole's orbit leads
to efficient angular
Momentum transport

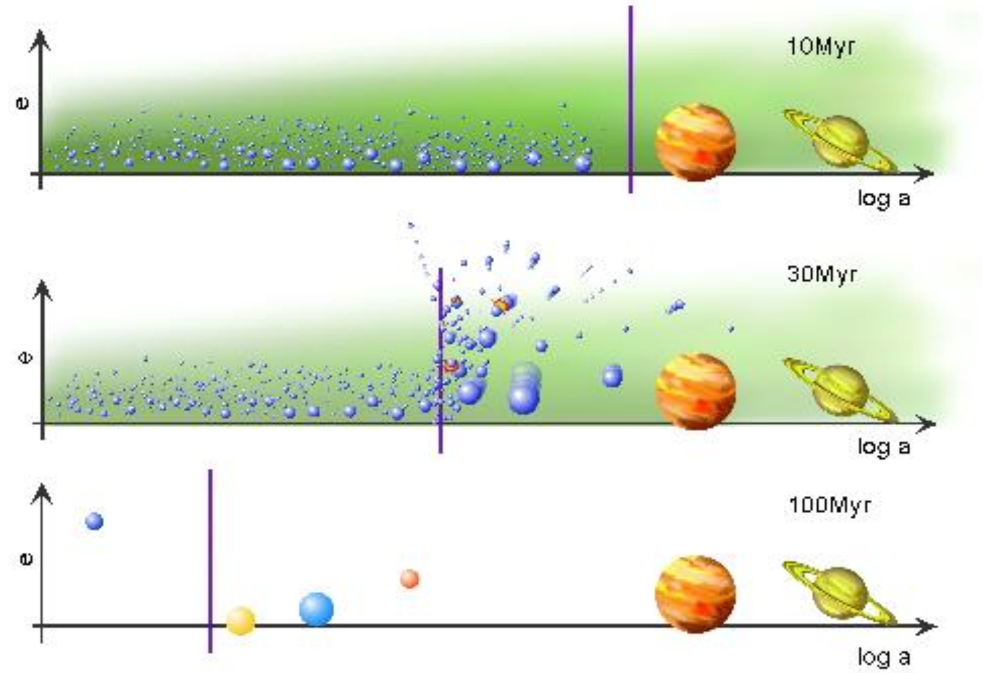
$$\frac{3hR}{4R_{roc}} + \frac{50\alpha h^2}{q} \leq 1.$$

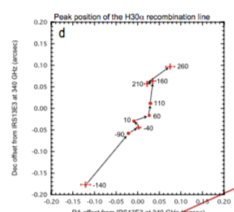
BTong

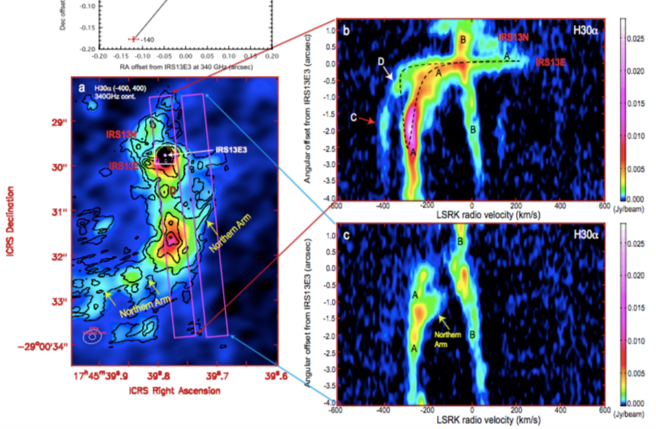
Gap formation with M> $10^3 M_o$

IMBHs: sweeping secular resonance

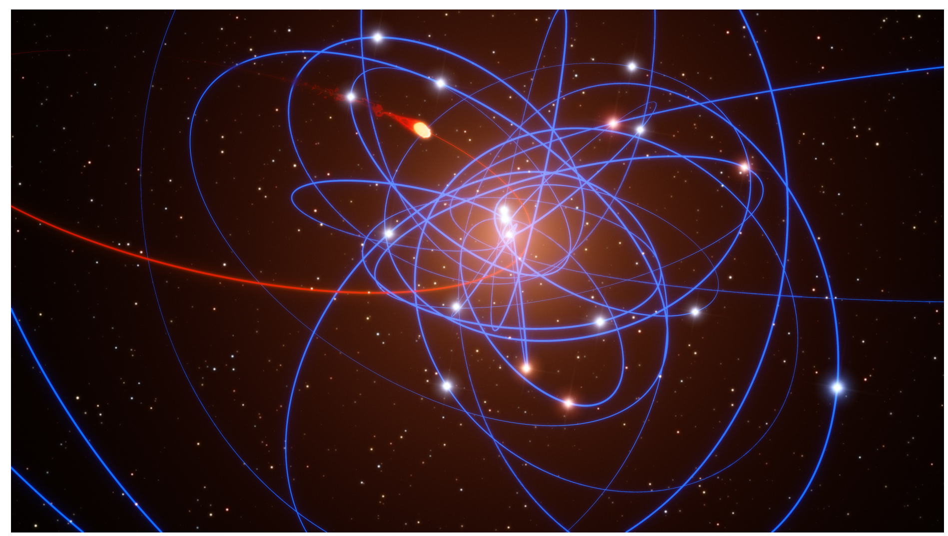






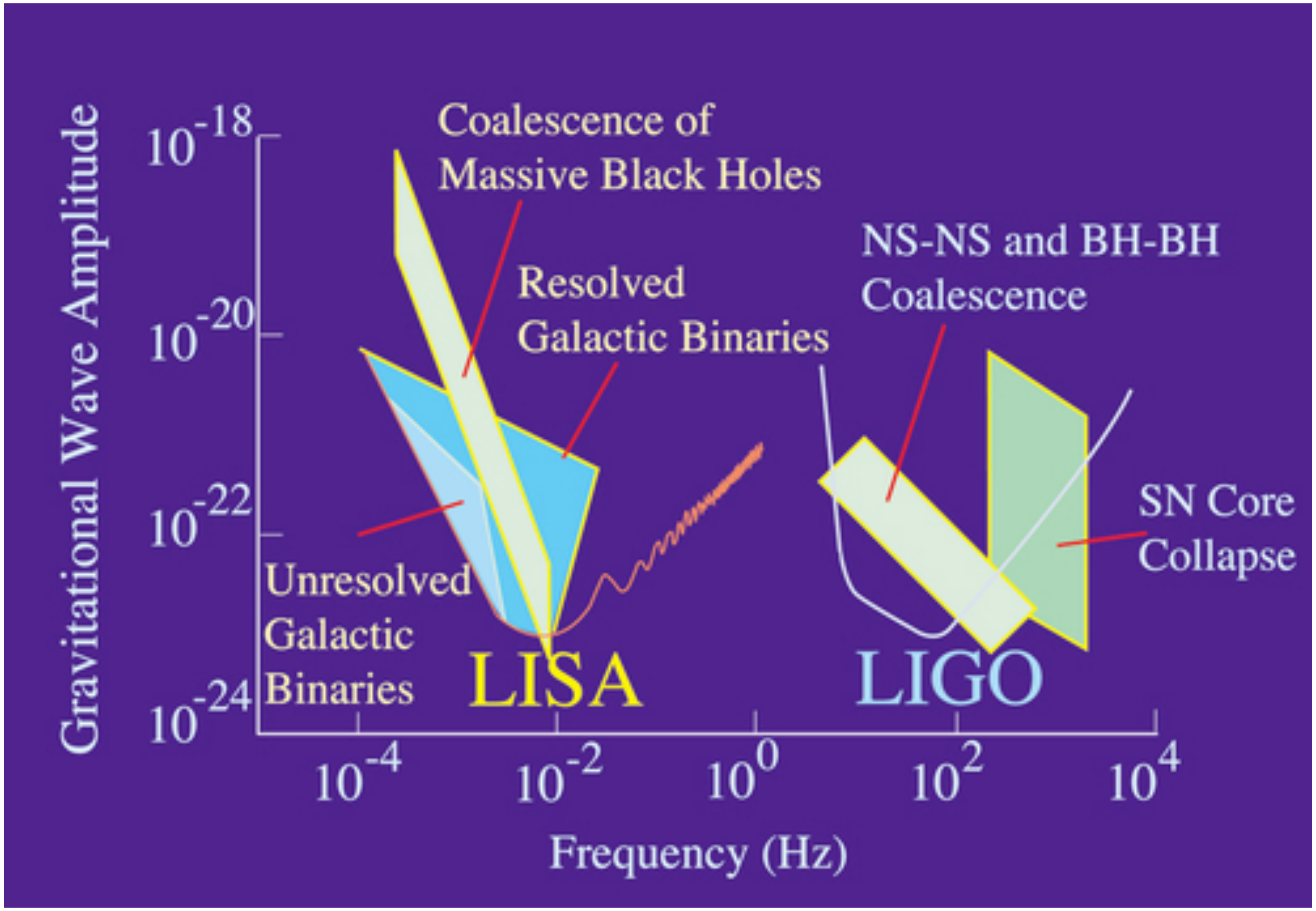


Tsuboi et al 2017
q<0.002, r=0.13pc



Intermediate-m* seed black holes' decay into MBH

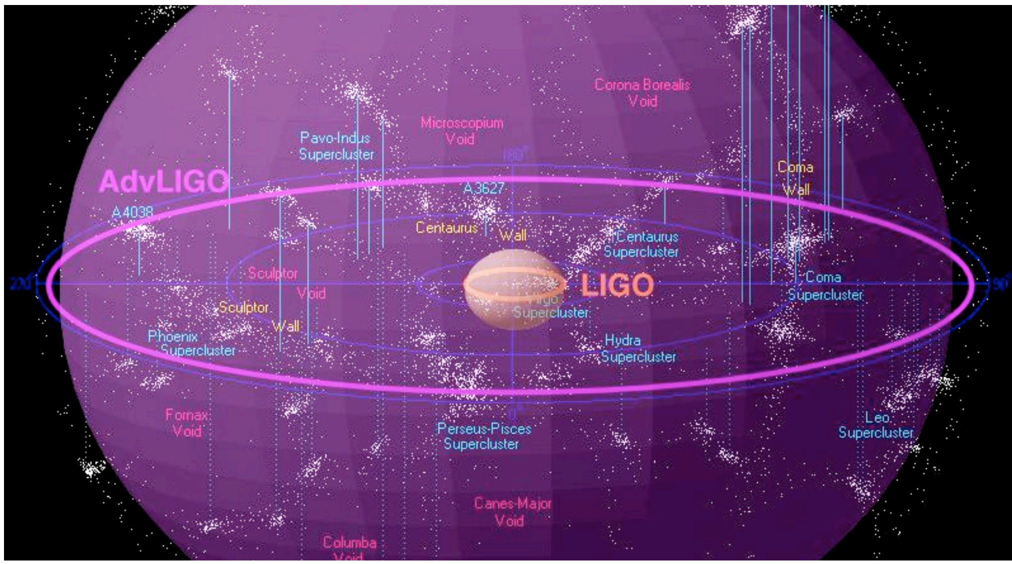
$$\tau_{\rm df} = \frac{R_{12}}{\dot{R}_{12}} = \frac{m_{12}R_{12}^2\Omega_{12}}{\dot{J}_{\rm df}} \simeq \frac{P_0}{24\sqrt{\pi}f_{df}\ln\Lambda}\frac{M}{m_{12}}\frac{M}{M_c}$$ ~$10^{8\text{-}9}$yr => P_o (M, z<1) ~10^{-2}

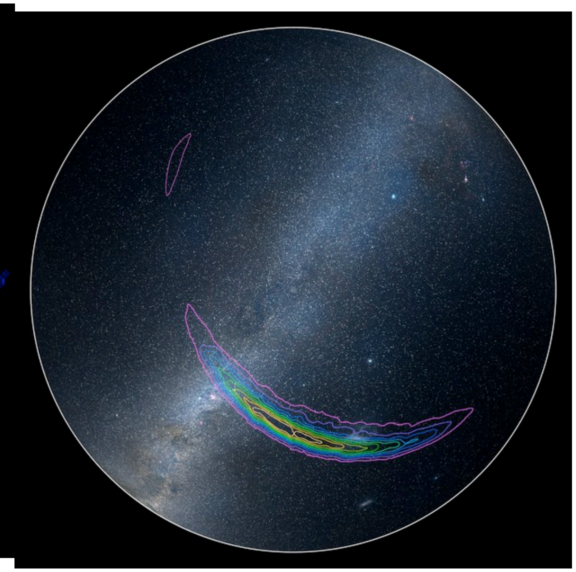


Occurrence rate of BH-MBH may be a fraction that for BH-BH merger events.

Occurrence rate of binary black hole merger

$$\dot{N}_{\rm tot} = \int\int \dot{N} \frac{dV_{\rm cm}}{dZ} \frac{dn_A(Z)}{d\sigma_{200}} d\sigma_{200} dZ$$





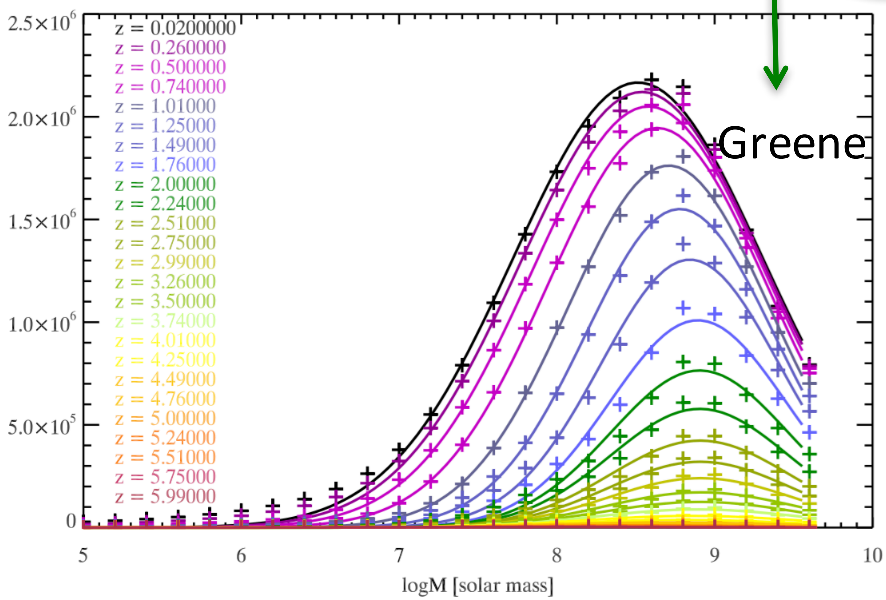
Redshift distribution

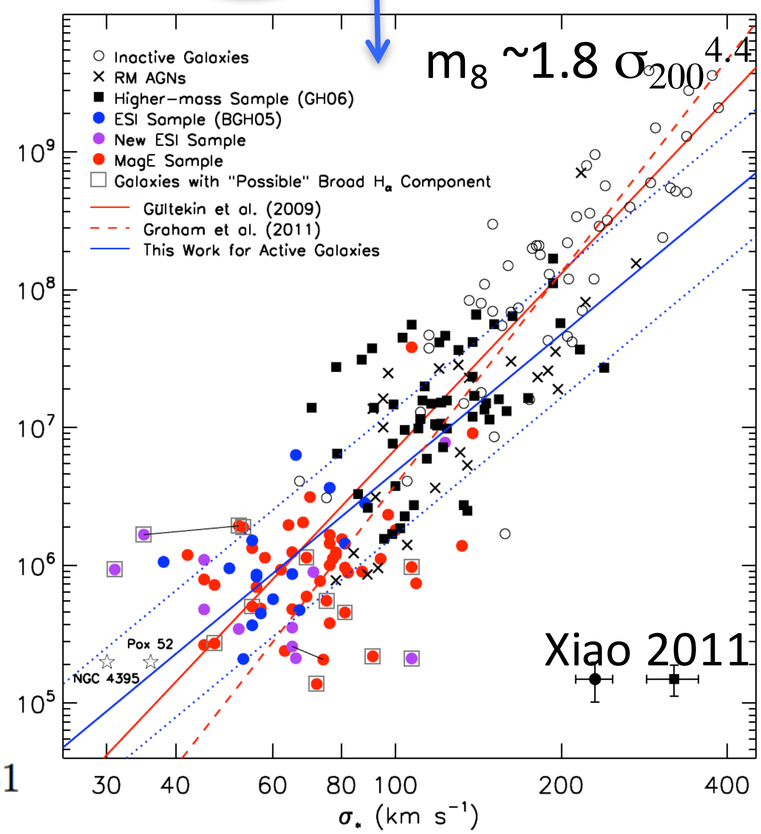
Comoving volume and distance

$$\frac{dV_{\rm cm}}{dz} = \frac{4\pi c}{H_0}\frac{D_c^2(z)}{E(z)} \qquad D_c(z) = \frac{c}{H_0}\int_0^z \frac{dz'}{E(z')} \qquad E(z) = \sqrt{\Omega_m(1+z)^3 + \Omega_\lambda}$$

Mass density & M–σ relation

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





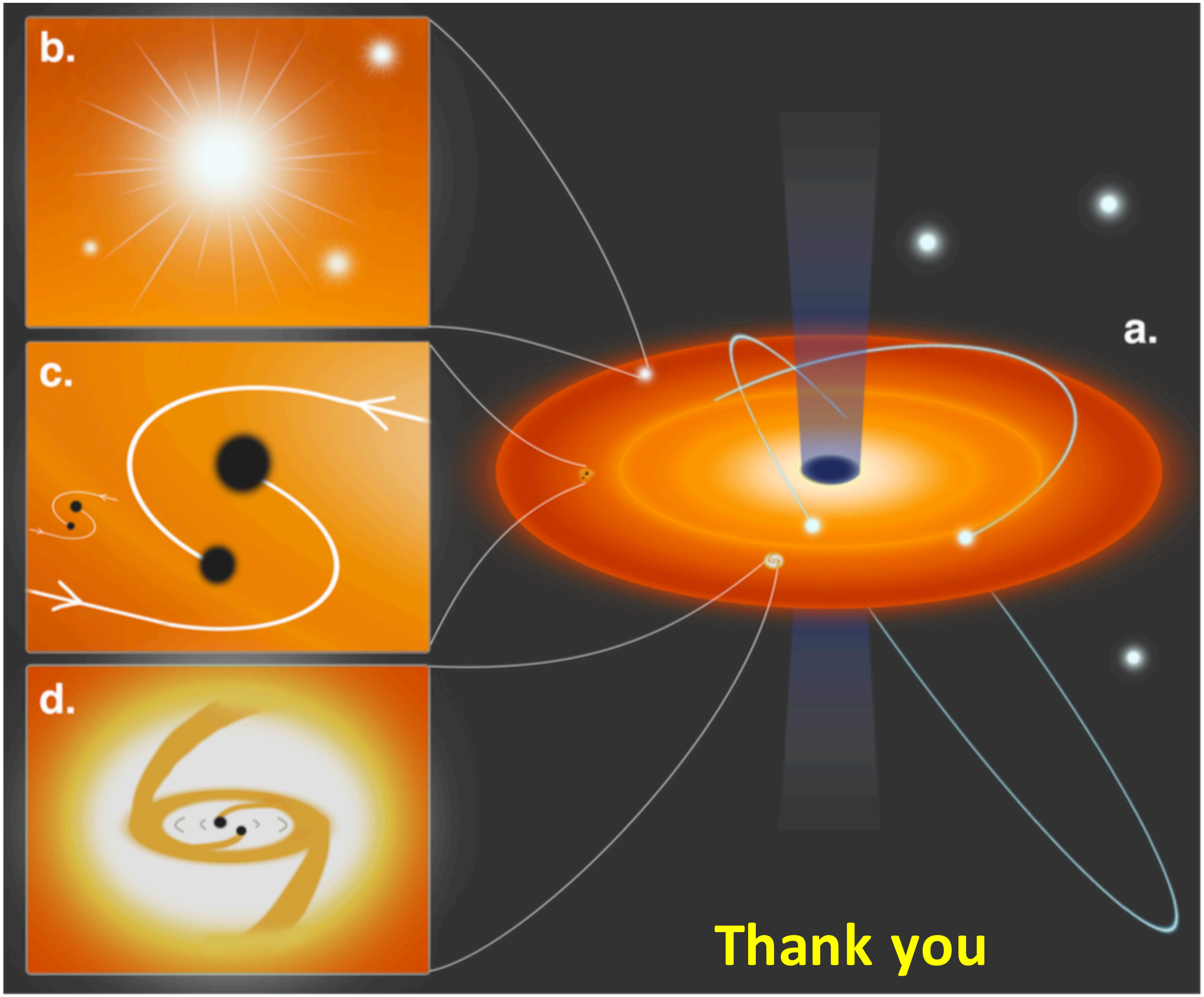
$$\frac{dn_A}{d\sigma_{200}} = \frac{4.4\phi_0}{\sqrt{2\pi}\sigma_{200}\sigma_M}\exp\left(-\frac{(\log m_8 - \nu_1)^2}{2\sigma_M^2}\right)$$

$$\phi_0 = 3.4\times 10^{-5}\mathrm{Mpc}^{-3}, \quad \nu_1 = 6.7, \quad \text{and} \quad \sigma_M = 0.61$$

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

Summary

- AGN disks may trap nearby stars.
- Trapped stars can gain mass and evolve into SNs
- Supernovae lead to formation of single black holes with a few M_{sun} and the contamination of AGN disks
- Seed black holes are retained, grow, migrate, capture partners
- Single & multiple seed black holes' mass, spin and orbital angular momenta evolve as they accrete turbulent gas
- Binaries tighten by tides, drag by circum-binary disks, endure Lidov-Kozai effect, & merge through gravitational radiation
- Events occur a few times a year around metal-rich AGN environments with wide masses and angular momenta
- Intermediate-mass ($>10^3 M_{sun}$) black-hole merger may be detectable. They can undergo orbital decay, clear disk gas, and regulate AGN duty cycle



b.
c.
d.
a.
Thank you