Dynamical friction and the evolution of supermassive black hole binaries: the final hundred-parsec problem

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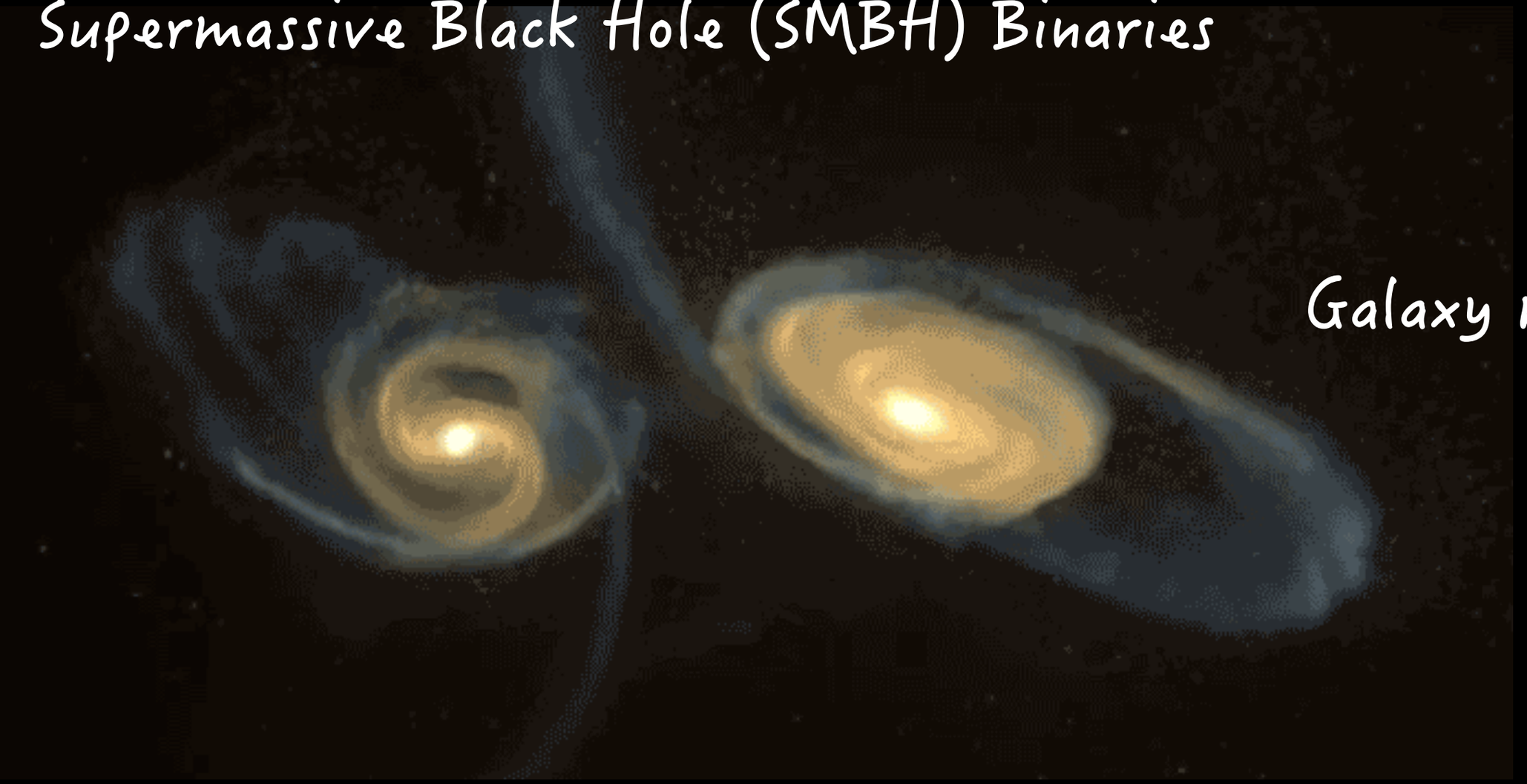
Supermassive Black Hole (SMBH) Binaries



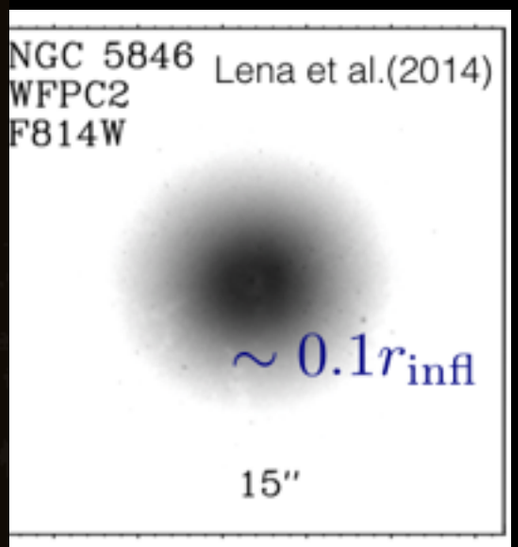
Galaxy mergers

SMBH evolution -> Understanding of fundamental dynamics

Supermassive Black Hole Binaries

Study fundamental dynamical processes

Observational puzzles



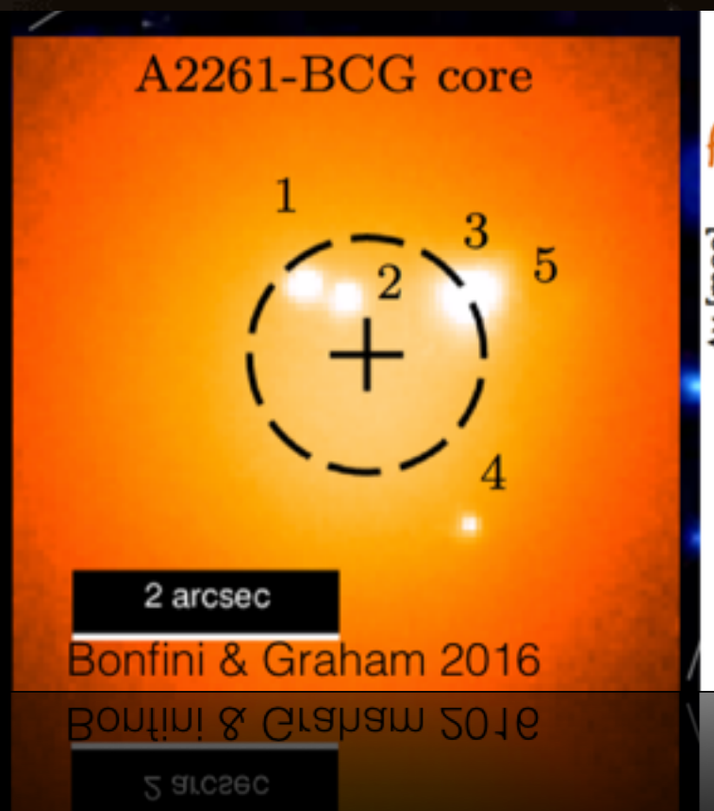
Stalled satellite accreting

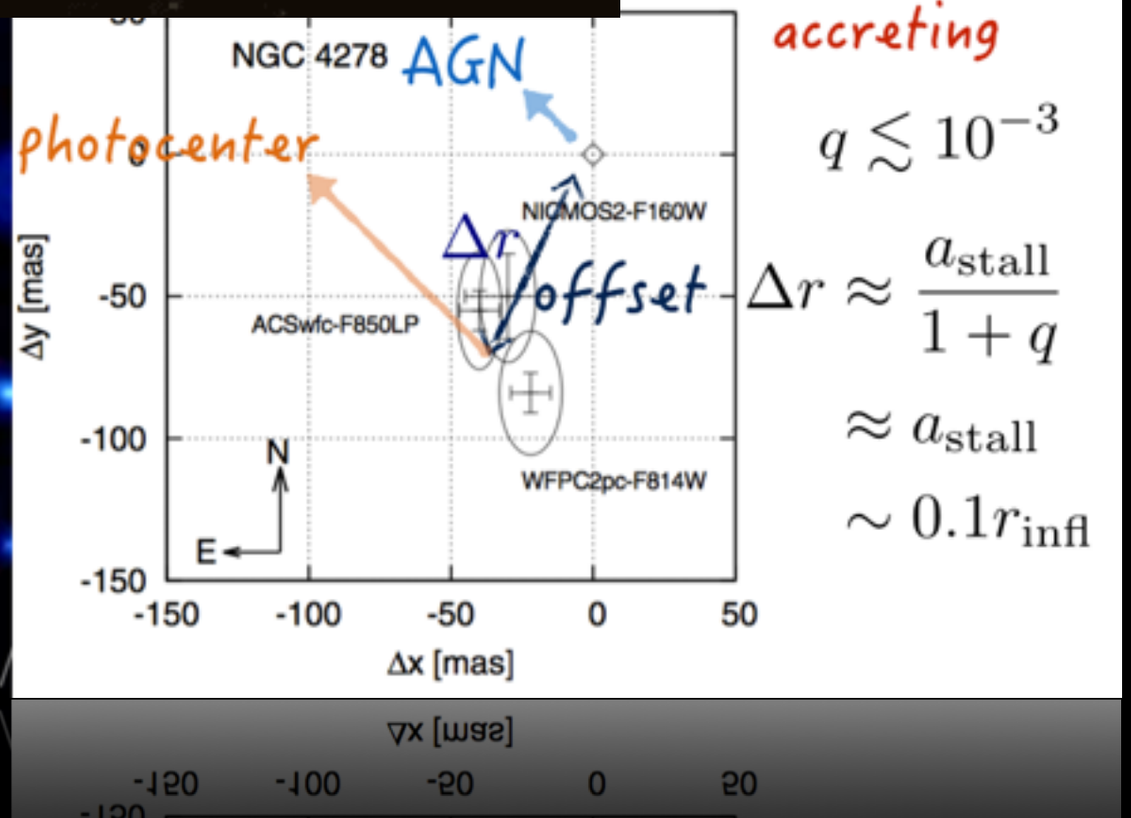
$q \lesssim 10^{-3}$

$\Delta r \approx \frac{a_{\rm stall}}{1+q}$

$\approx a_{\rm stall}$

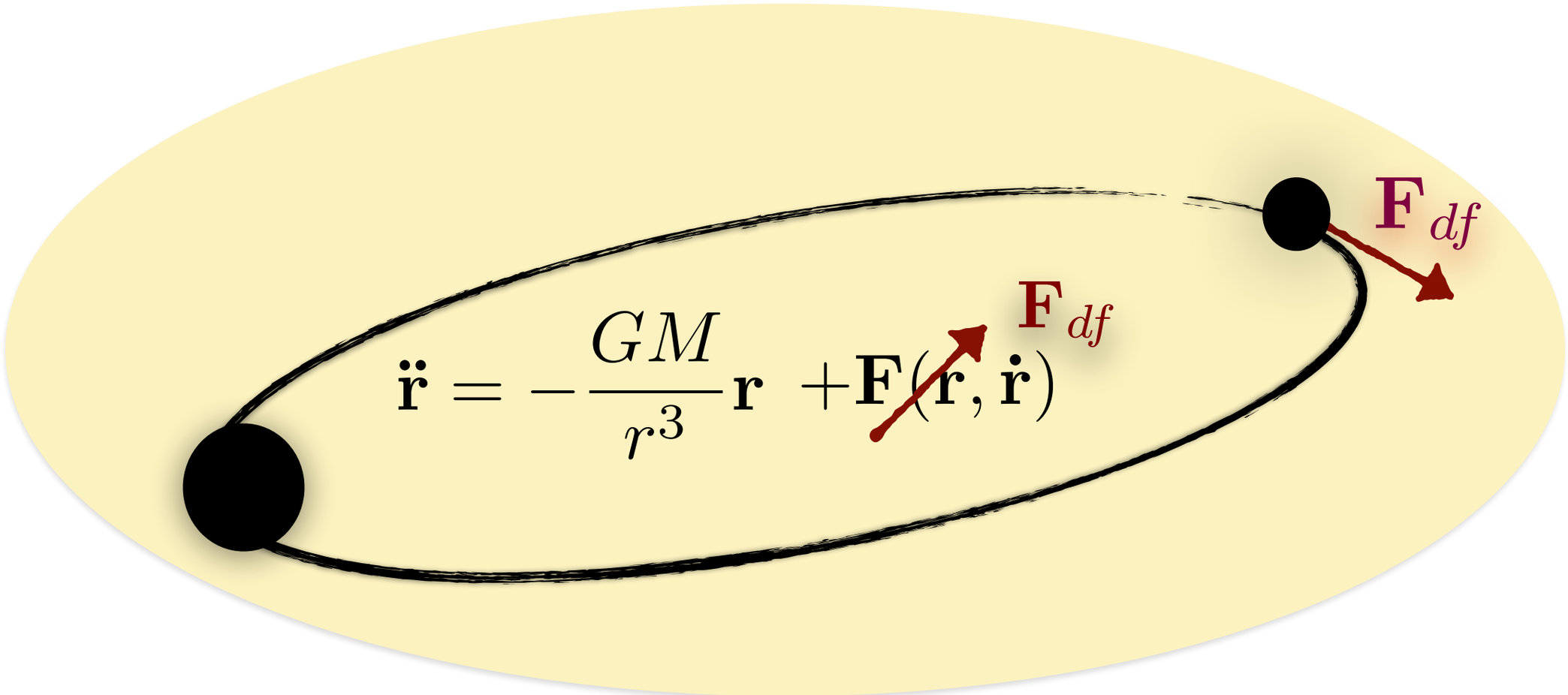
$\sim 0.1 r_{\rm infl}$





Why Supermassive Black Hole Binaries evolve?

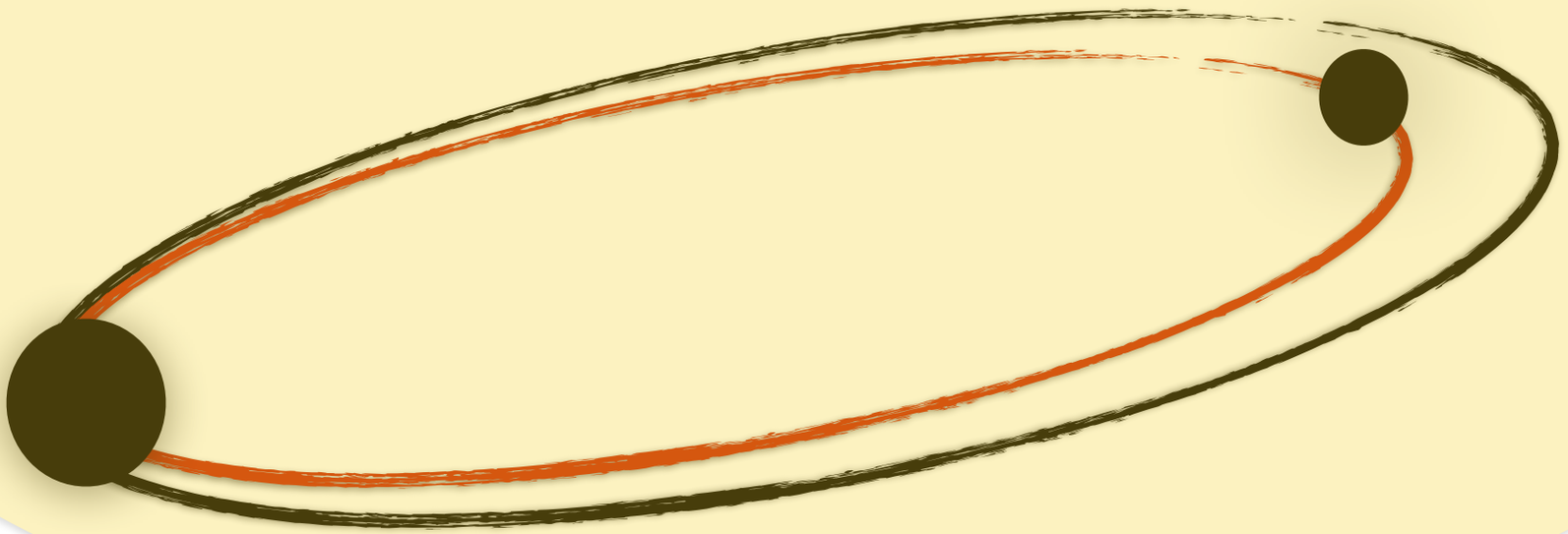
Dynamical friction



Why Supermassive Black Hole Binaries evolve?

Dynamical friction

Segregation

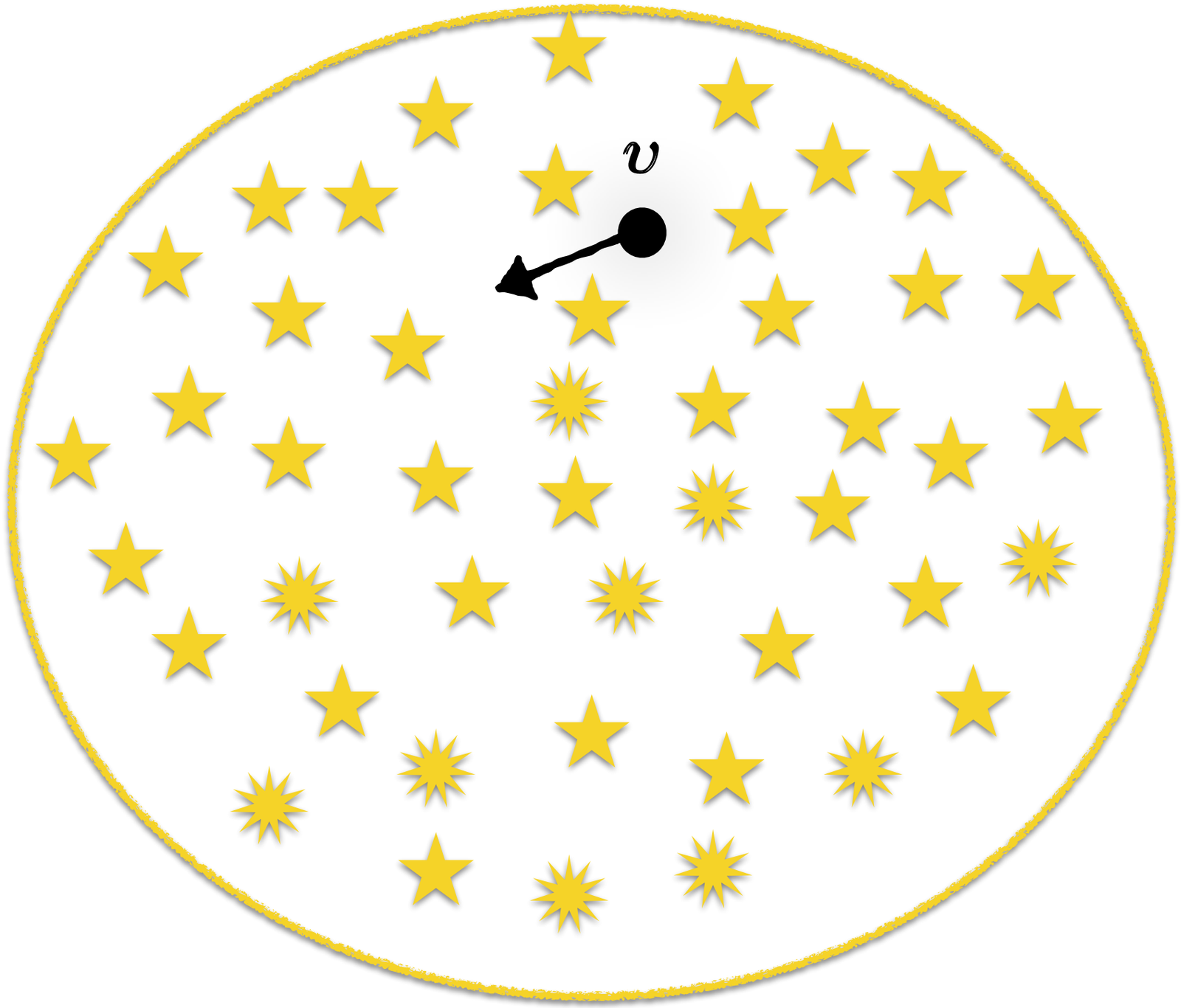


Why Supermassive Black Hole Binaries evolve?

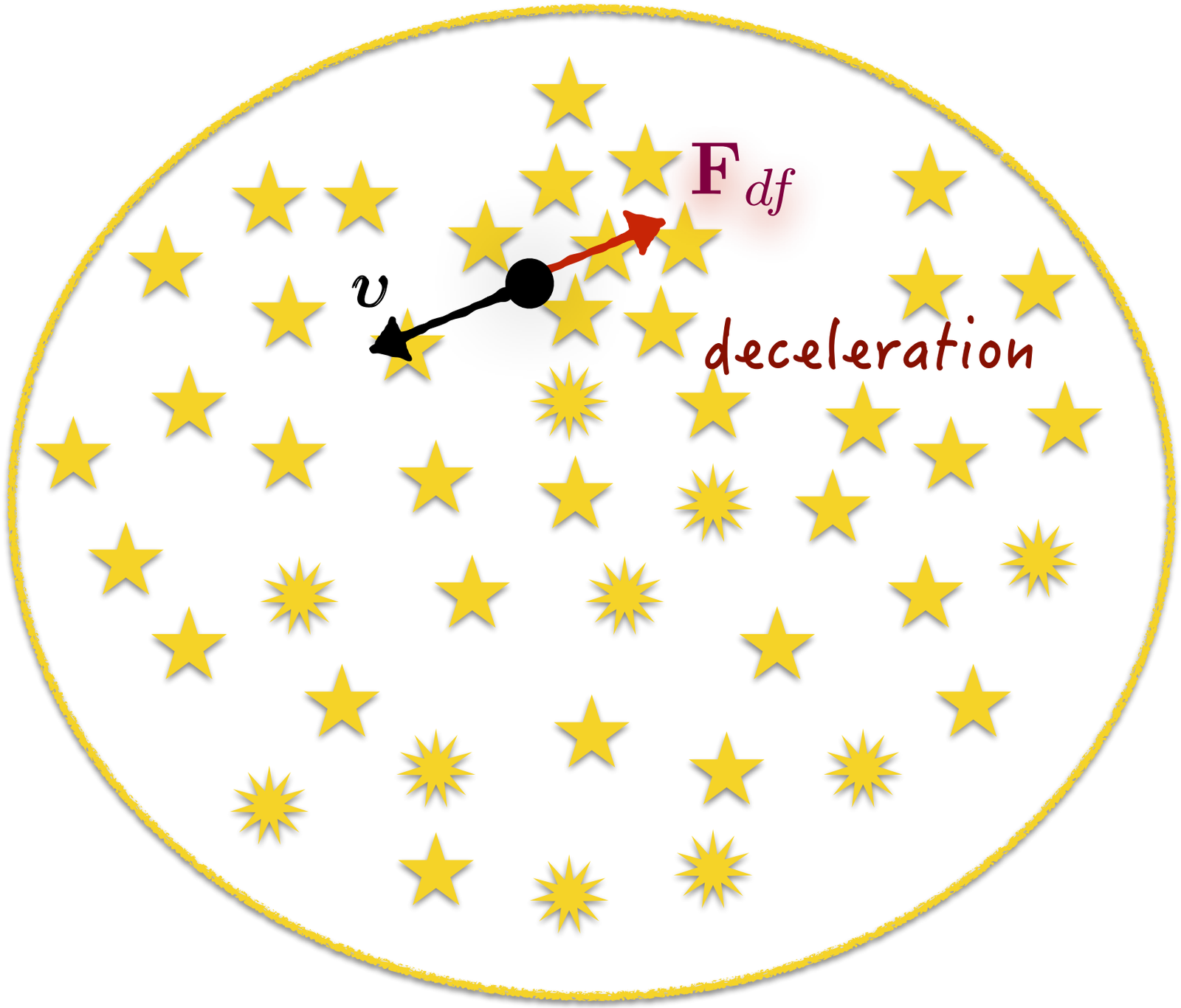
Dynamical friction

Segregation

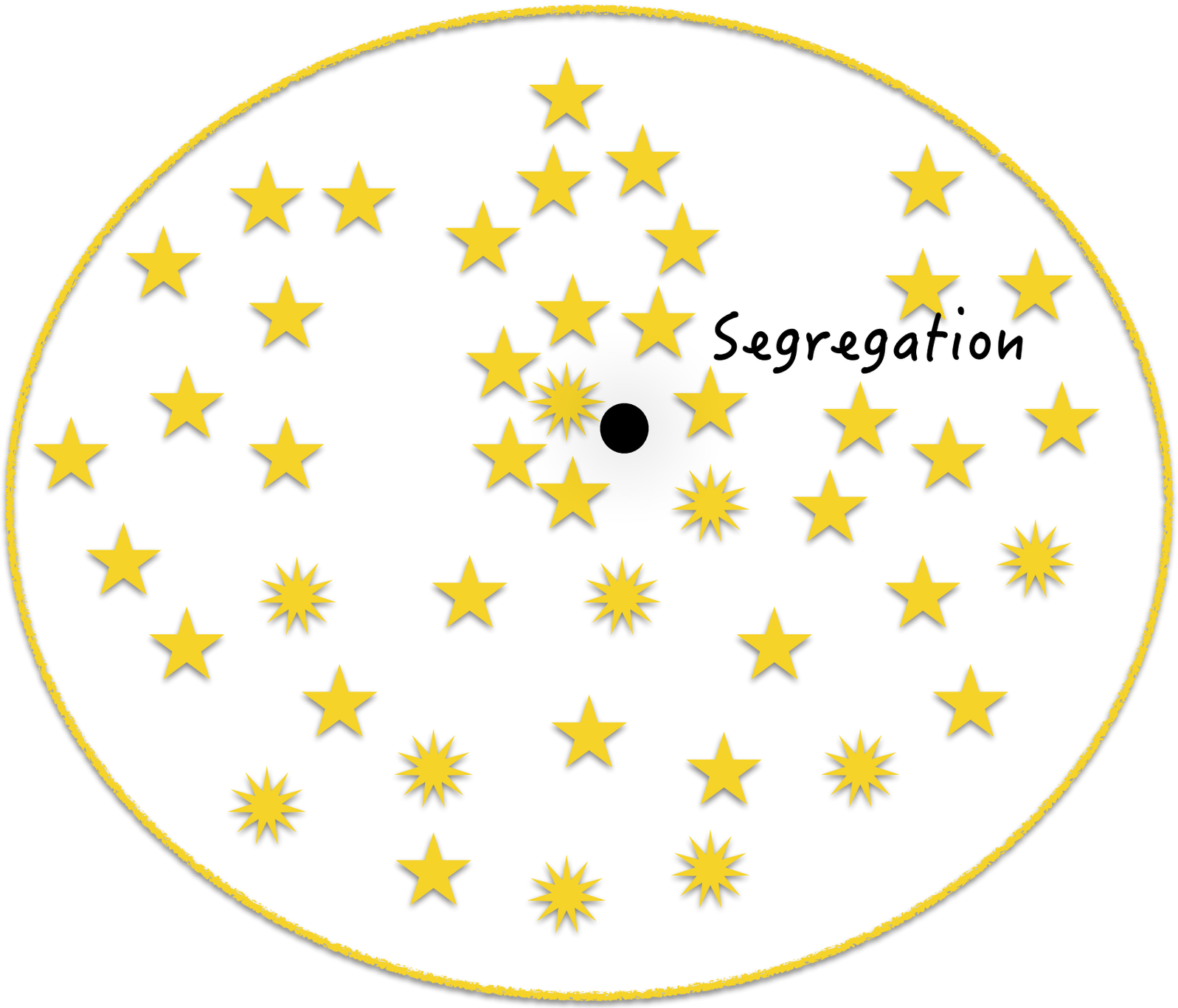
Dynamical friction



Dynamical friction



Dynamical friction



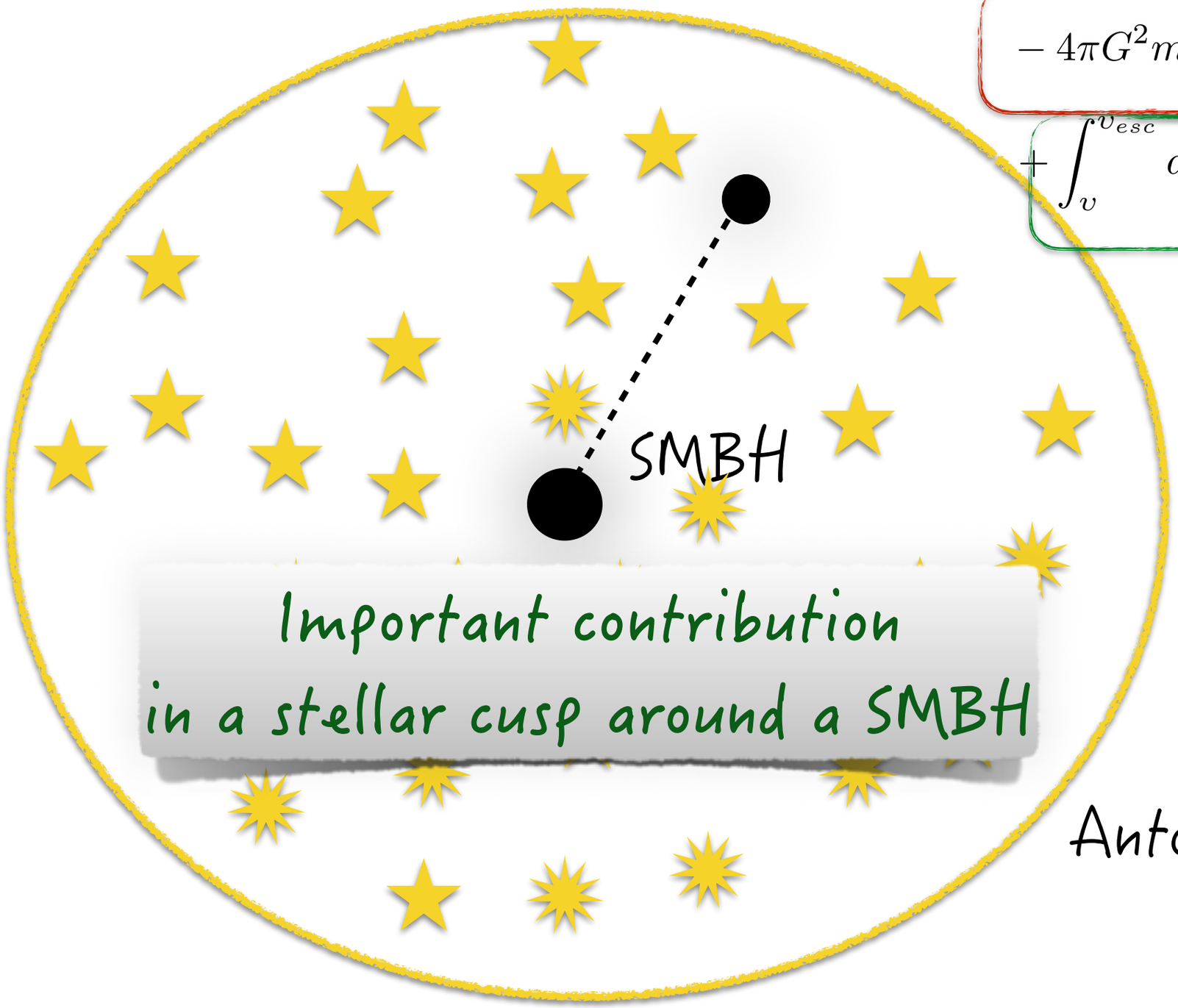
Dynamical friction around a SMBH

$$\boldsymbol{F}_{df} \approx \boldsymbol{F}_{df}^{(v_\star<v)} + \boldsymbol{F}_{df}^{(v_\star>v)} = \text{slow stars}$$

$$-4\pi G^2 m\rho(r)\frac{\boldsymbol{v}}{v^3}\times\left\{\ln\Lambda\int_0^v dv_\star 4\pi f(v_\star)v_\star^2 + \int_v^{v_{esc}} dv_\star 4\pi f(v_\star)v_\star^2\left[\ln\left(\frac{v_\star+v}{v_\star-v}\right)-2\frac{v}{v_\star}\right]\right\}$$

Chandrasekhar (1943)

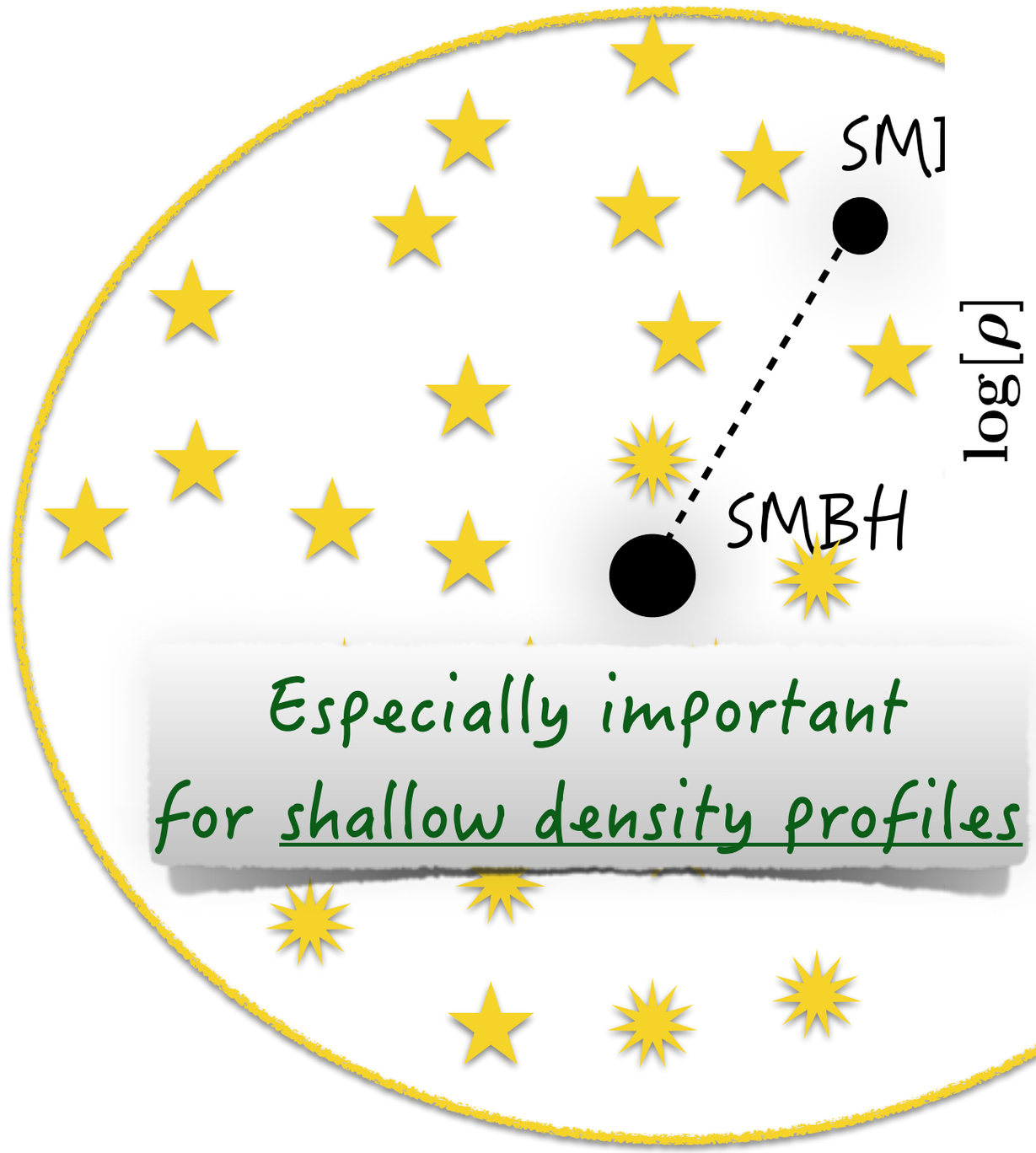
→ slow stars



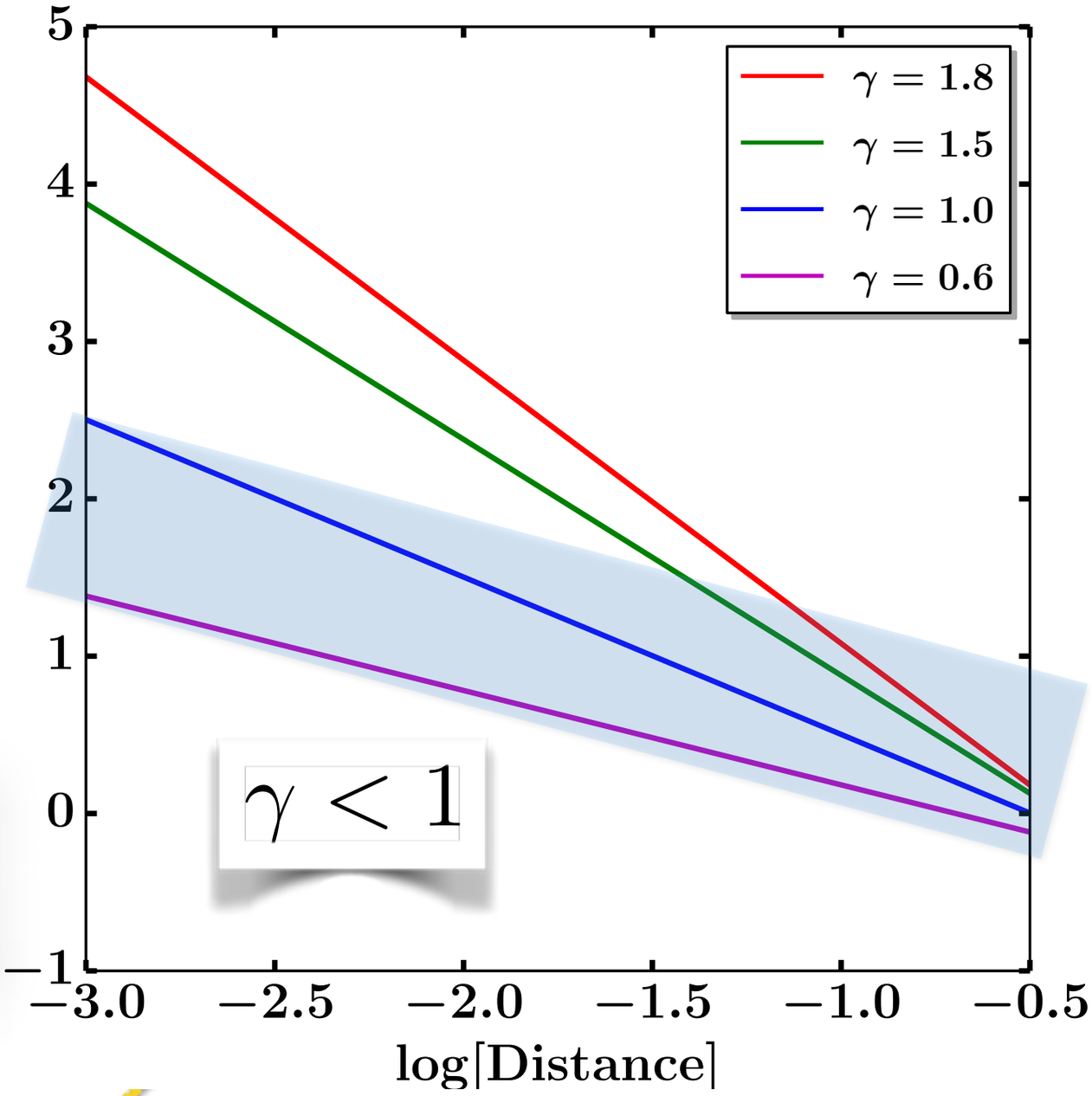
fast stars ?

Antonini & Merritt (2012)

Dynamical friction around a SMBH



Density profiles



fast stars ?

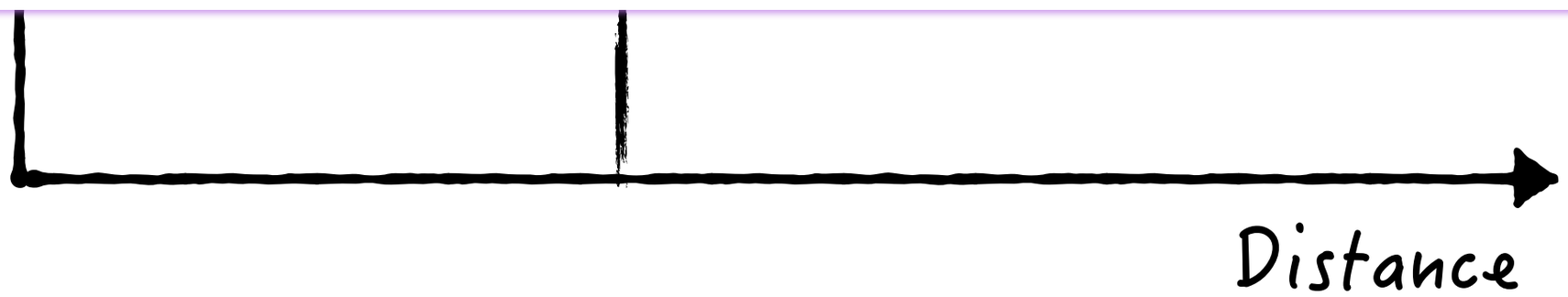
Antonini & Merritt (2012)

Why are we interested in shallow density profiles?

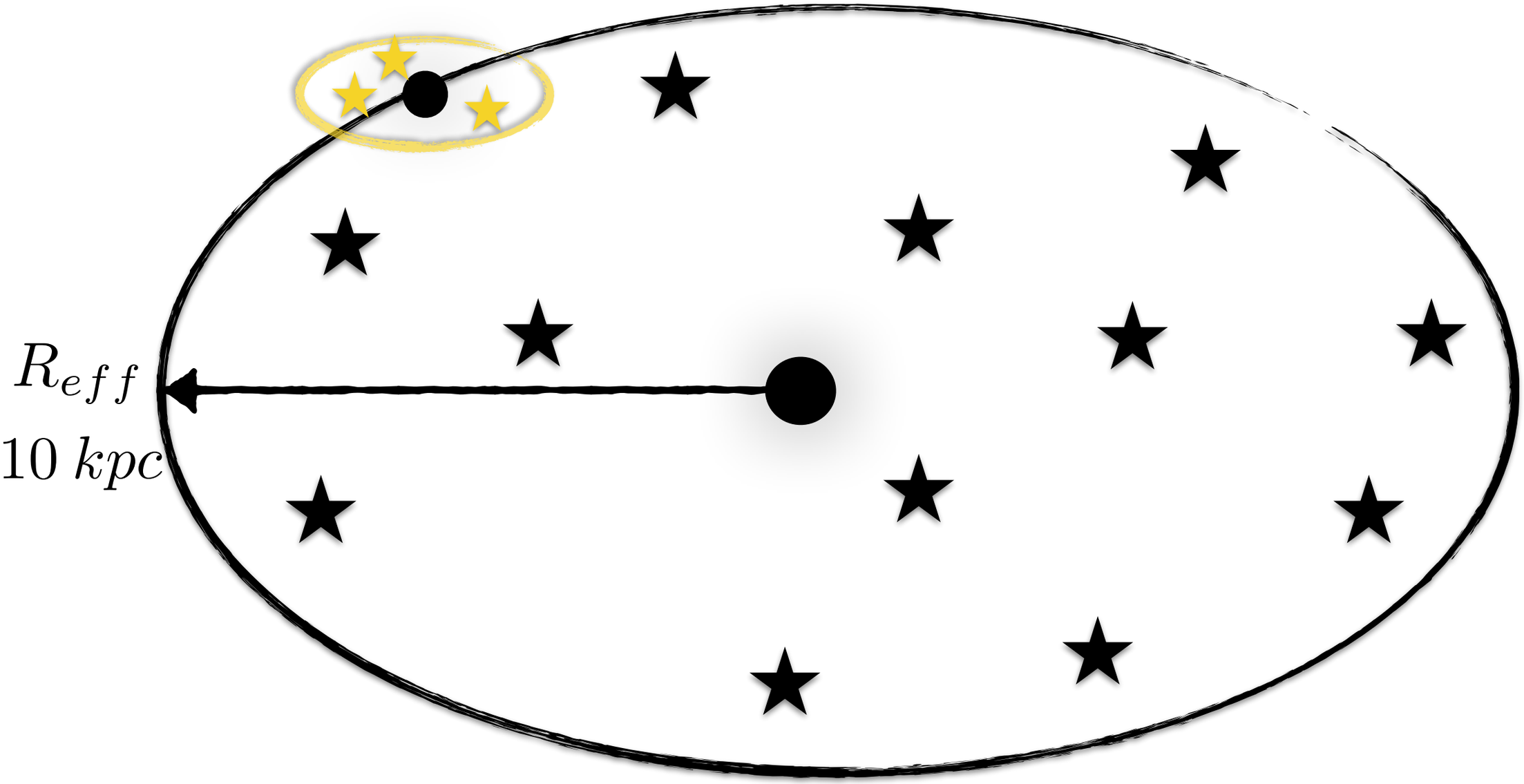
A typical giant elliptical galaxy $> 10^{11} M_\odot$

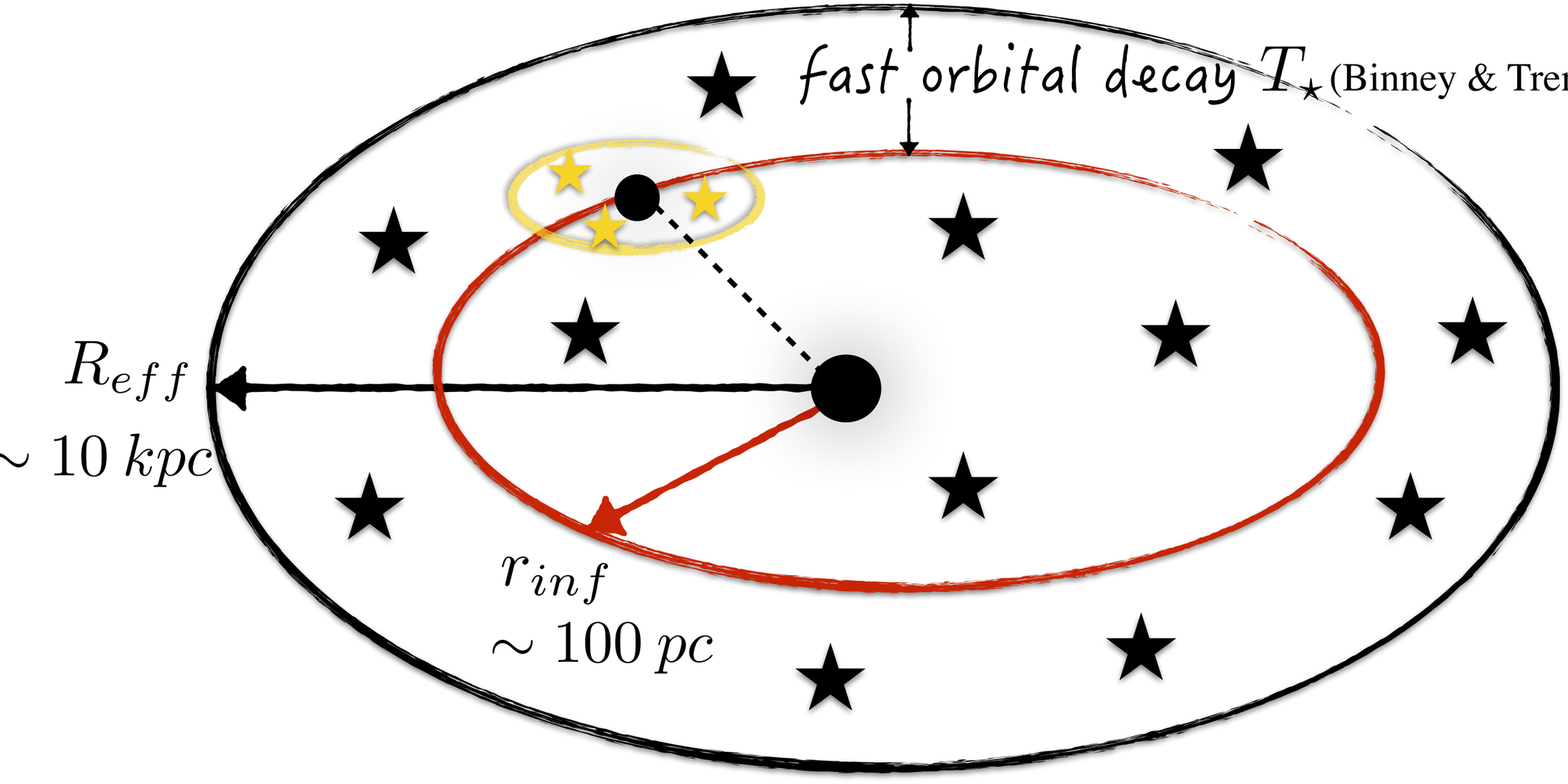
Surface
brig
pr

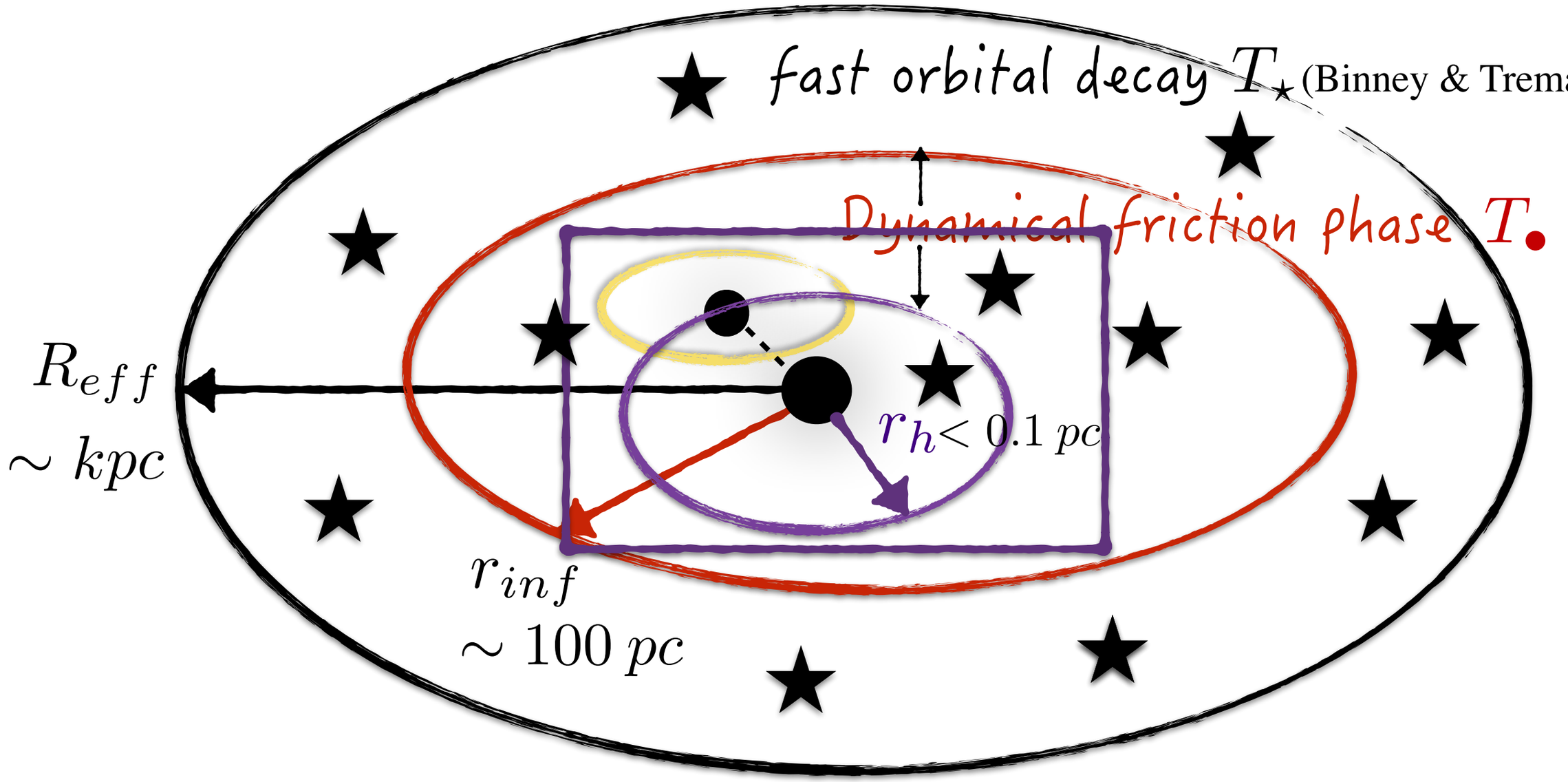
A comprehensive study of dynamical friction in the nuclei of core galaxies containing a SMBH

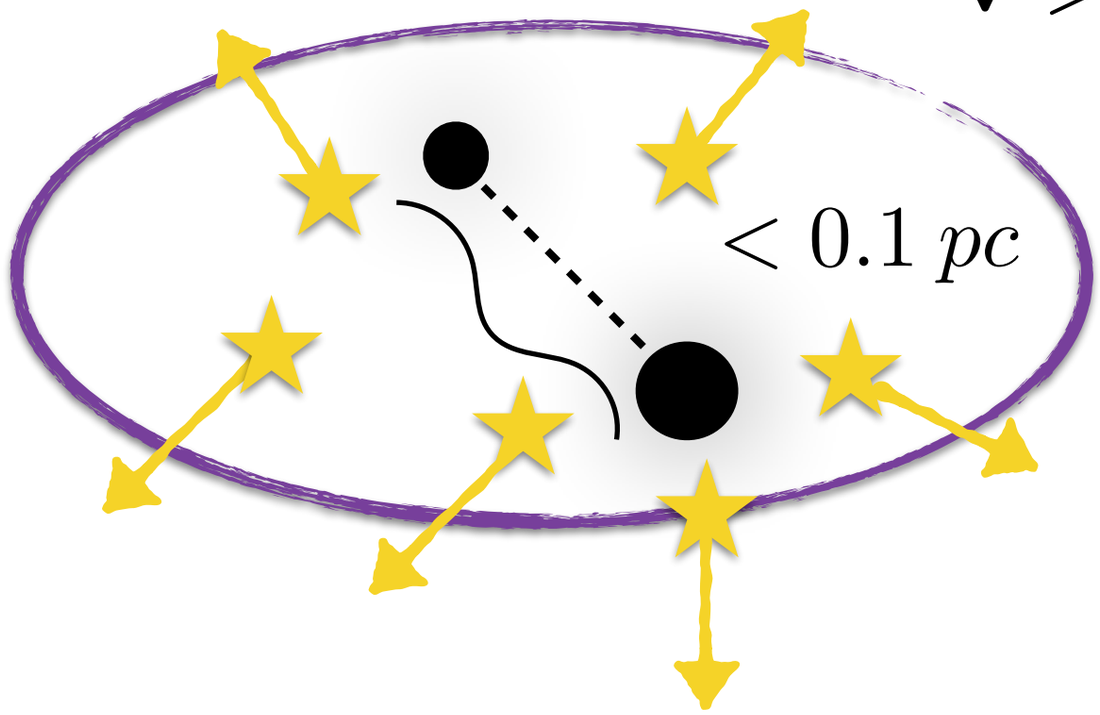


SMBH binary evolution in core galaxies with a central SMBH




fast orbital decay $T_\star$ (Binney & Tremaine 1987)
R_{eff}
$\sim 10\ kpc$
r_{inf}
$\sim 100\ pc$


fast orbital decay $T_\star$ (Binney & Tremaine 1987)
Dynamical friction phase $T_\bullet$
R_{eff}
$\sim kpc$
$r_h < 0.1\,pc$
r_{inf}
$\sim 100\,pc$

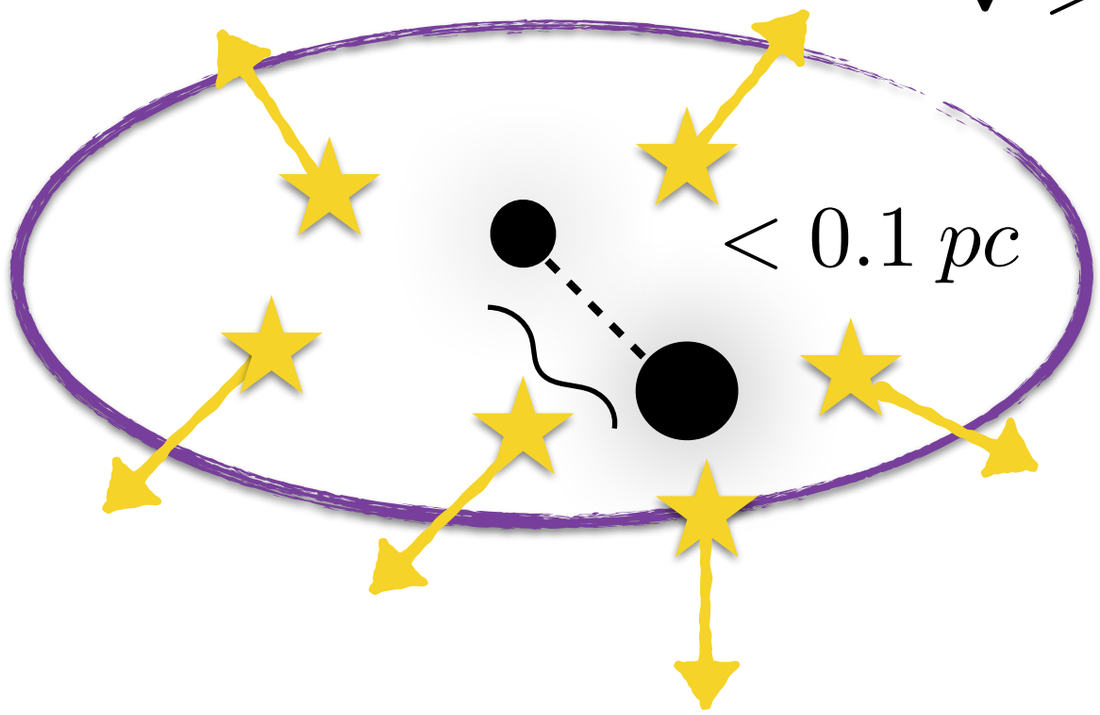


$\mathbf{v} > \mathbf{v}_{esc}$

hardening phase T_h
$\leq 1\, Gyr$

(Vasiliev, E.; Antonini, F.;

Merritt, D. 2014, 2015)



$\mathbf{v} > \mathbf{v}_{esc}$

hardening phase T_h

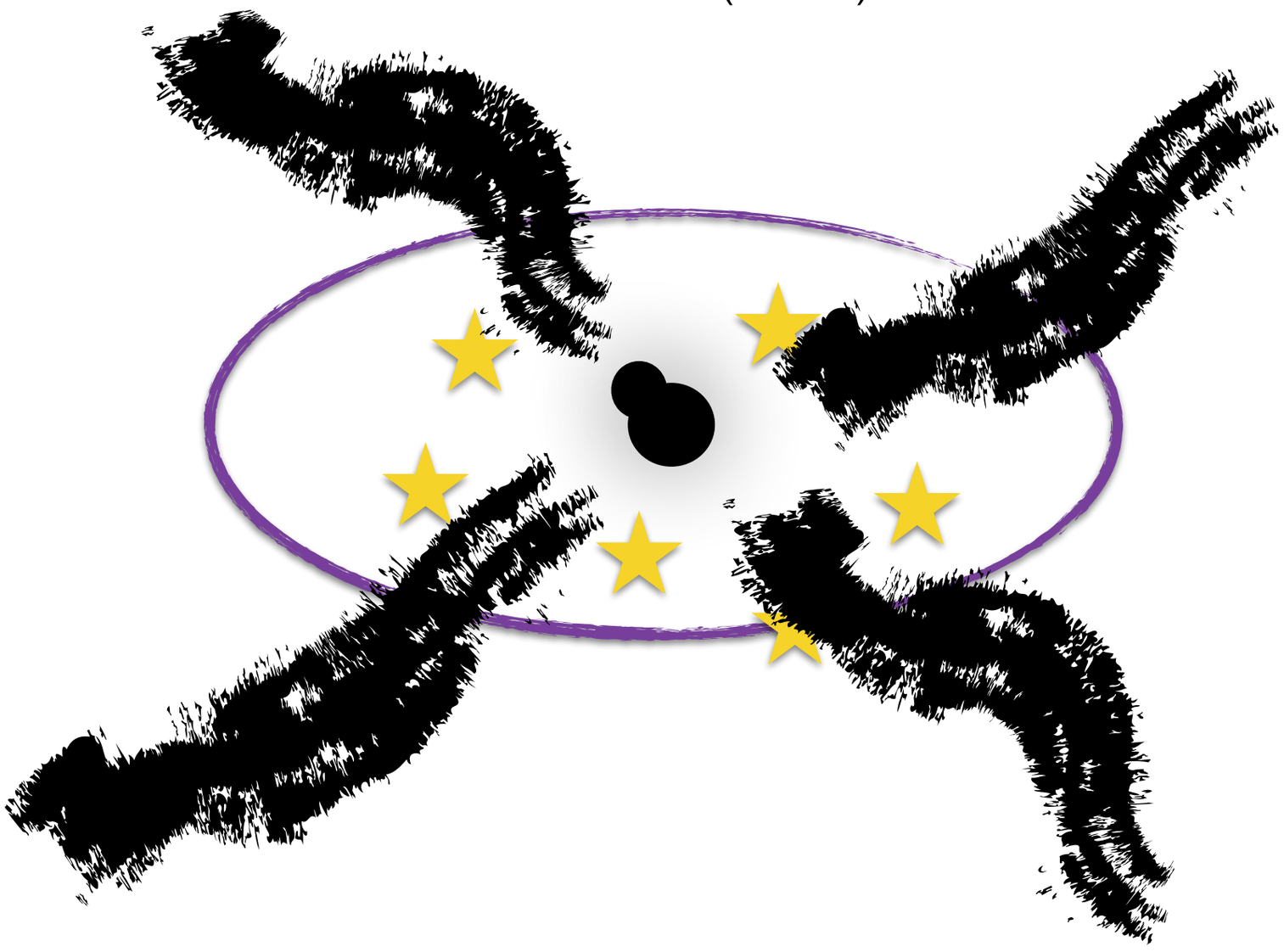
$\leq 1\, Gyr$

(Vasiliev, E.; Antonini, F.;

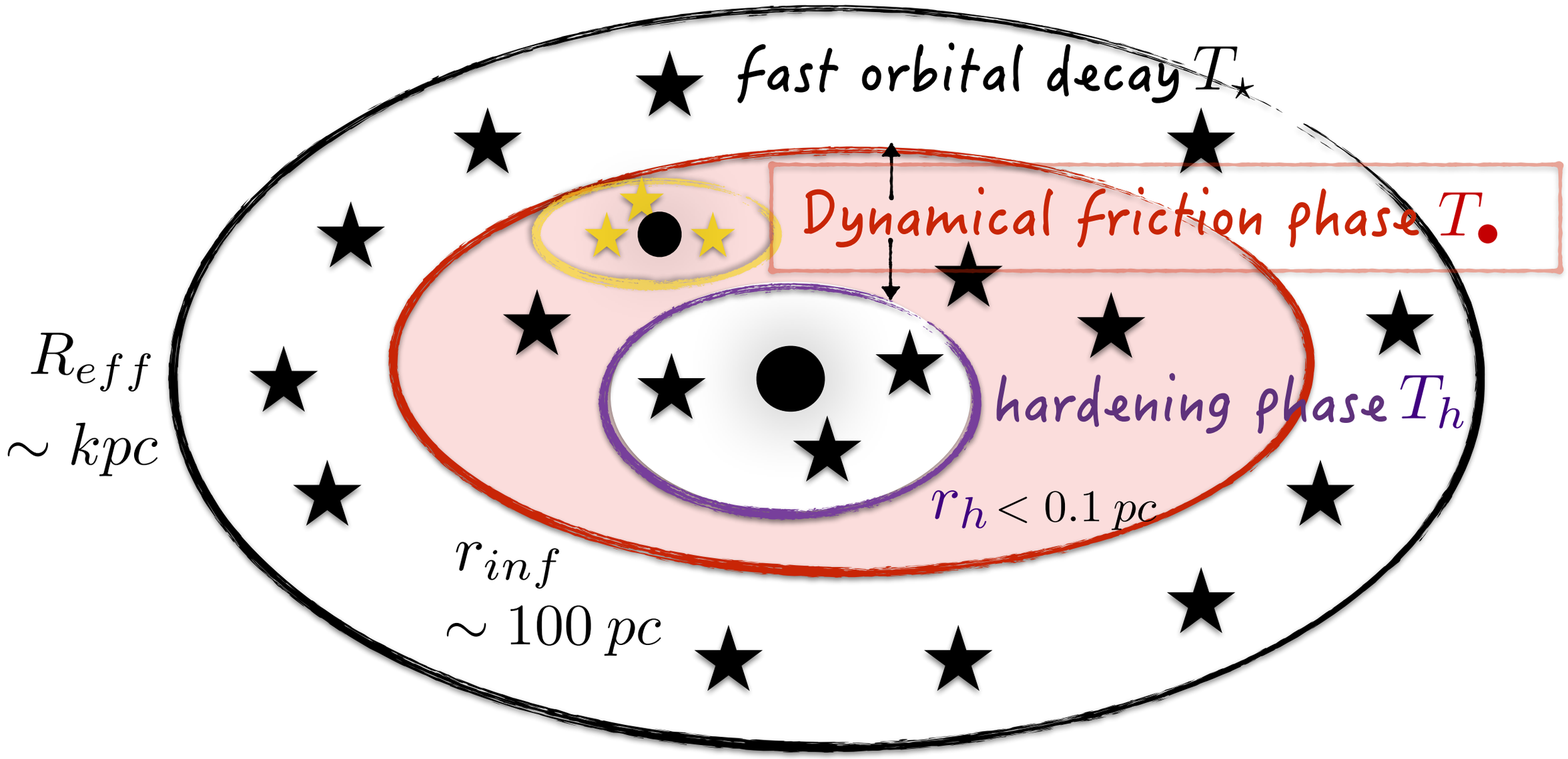
Merritt, D. 2014, 2015)

Gravitational wave emission phase- Coalescence

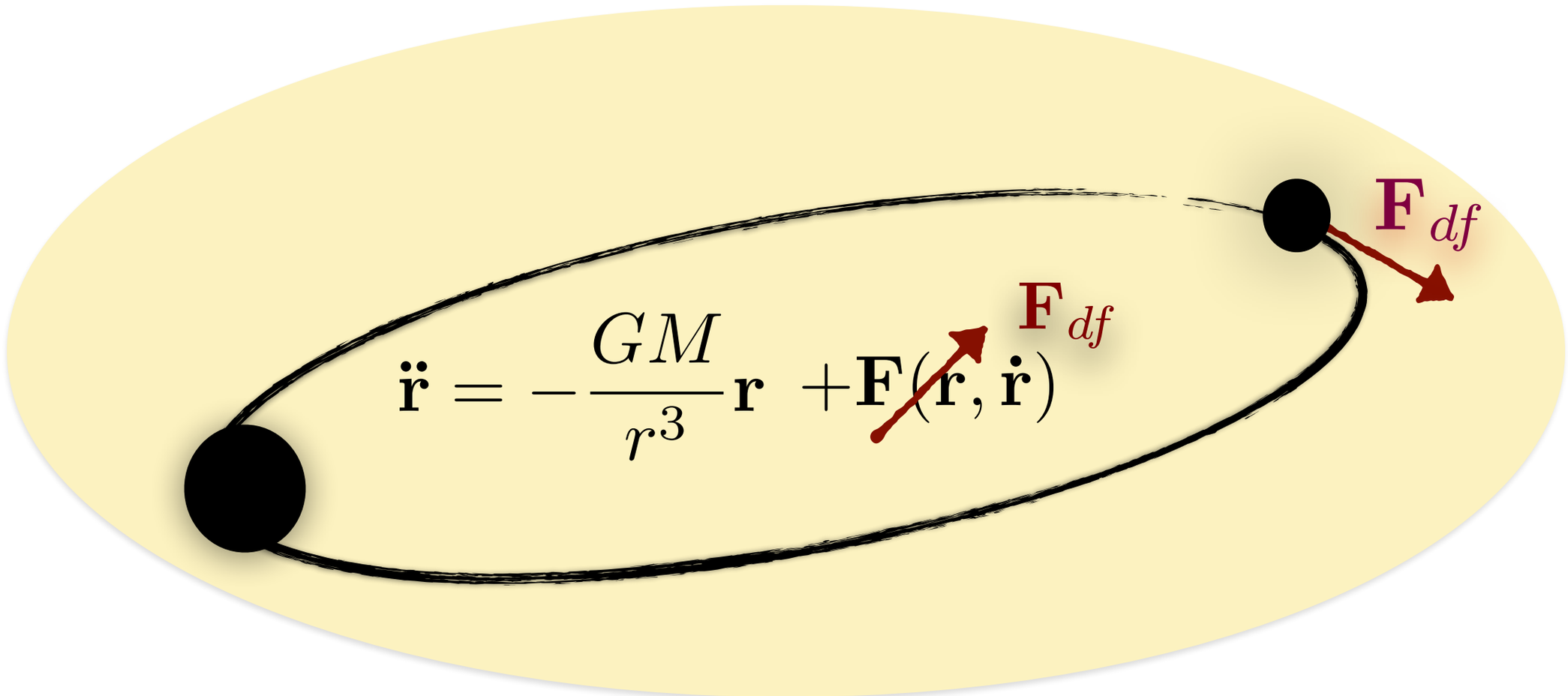
Peters(1964)



How does the SMBH binary evolve in the dynamical friction phase?



How do we study the dynamical friction phase of a SMBH binary?



Analytical treatment- Perturbed two-body problem

$$\ddot{\mathbf{r}} = -\frac{GM}{r^3}\mathbf{r} + \mathbf{F}(\mathbf{r}, \dot{\mathbf{r}})$$

$\mathbf{F}_{df}$

Orbital evolution of the binary

$$\frac{da}{dt} = \frac{2}{na}\mathbf{F}\frac{\partial \mathbf{r}}{\partial \sigma}$$

$$\frac{de}{dt} = \frac{1-e^2}{na^2 e}\mathbf{F}\frac{\partial \mathbf{r}}{\partial \sigma} - \frac{\sqrt{1-e^2}}{na^2 e}\mathbf{F}\frac{\partial \mathbf{r}}{\partial \omega}$$

$$\frac{di}{dt} = \frac{1}{na^2\sqrt{1-e^2}\sin i}\left[\cos i\ \mathbf{F}\frac{\partial \mathbf{r}}{\partial \omega} - \mathbf{F}\frac{\partial \mathbf{r}}{\partial \Omega}\right]$$

$$\frac{d\omega}{dt} = \frac{\sqrt{1-e^2}}{na^2 e}\mathbf{F}\frac{\partial \mathbf{r}}{\partial e} - \frac{\cos i}{na^2\sqrt{1-e^2}\sin i}\mathbf{F}\frac{\partial \mathbf{r}}{\partial i}.$$

$$\frac{d\Omega}{dt} = \frac{1}{na^2\sqrt{1-e^2}\sin i}\mathbf{F}\frac{\partial \mathbf{r}}{\partial i}$$

$$\frac{d\nu}{dt} = \frac{n(1+e\cos\nu)^2}{(1-e^2)^{3/2}} - \frac{d\omega}{dt} - \cos i\frac{d\Omega}{dt}.$$

Analytical treatment- Perturbed two-body problem

$$\ddot{\mathbf{r}} = -\frac{GM}{r^3}\mathbf{r} + \mathbf{F}_{df}(\mathbf{r}, \dot{\mathbf{r}})$$

$$\frac{da}{dt} = \frac{2}{na}\mathbf{F}_{df}\frac{\partial r}{\partial \sigma}$$

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Analytical treatment- Perturbed two-body problem

$$\ddot{\mathbf{r}} = -\frac{GM}{r^3}\mathbf{r} + \boxed{\mathbf{F}_{df}(\mathbf{r}, \dot{\mathbf{r}})}$$

$$\frac{da}{dt} = \frac{2}{na}\mathbf{F}_{df}\frac{\partial r}{\partial \sigma}$$

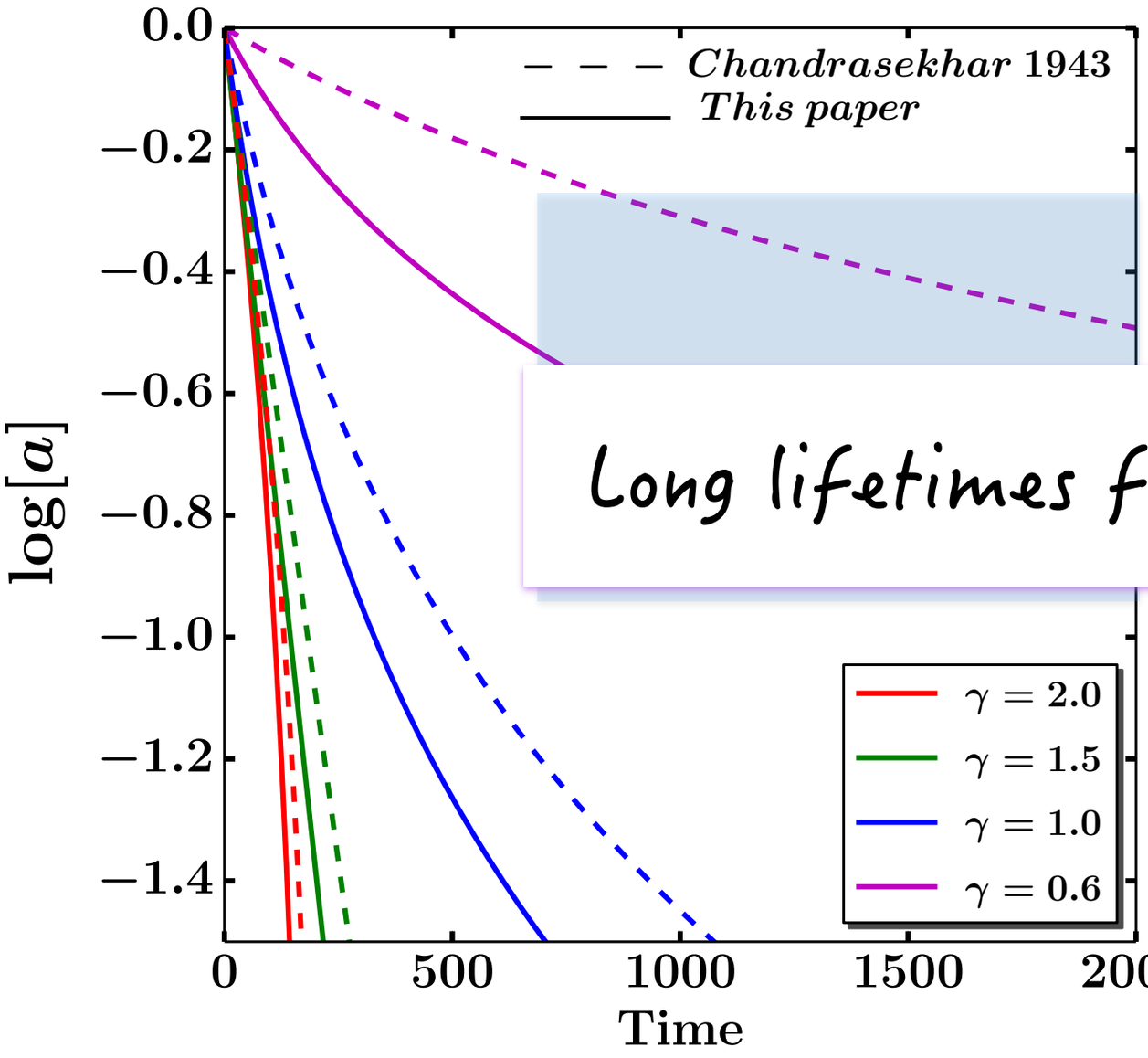
$$\frac{de}{dt} = \frac{1-e^2}{na^2 e}\mathbf{F}_{df}\frac{\partial r}{\partial \sigma} - \frac{\sqrt{1-e^2}}{na^2 e}\mathbf{F}_{df}\frac{\partial r}{\partial \omega}$$

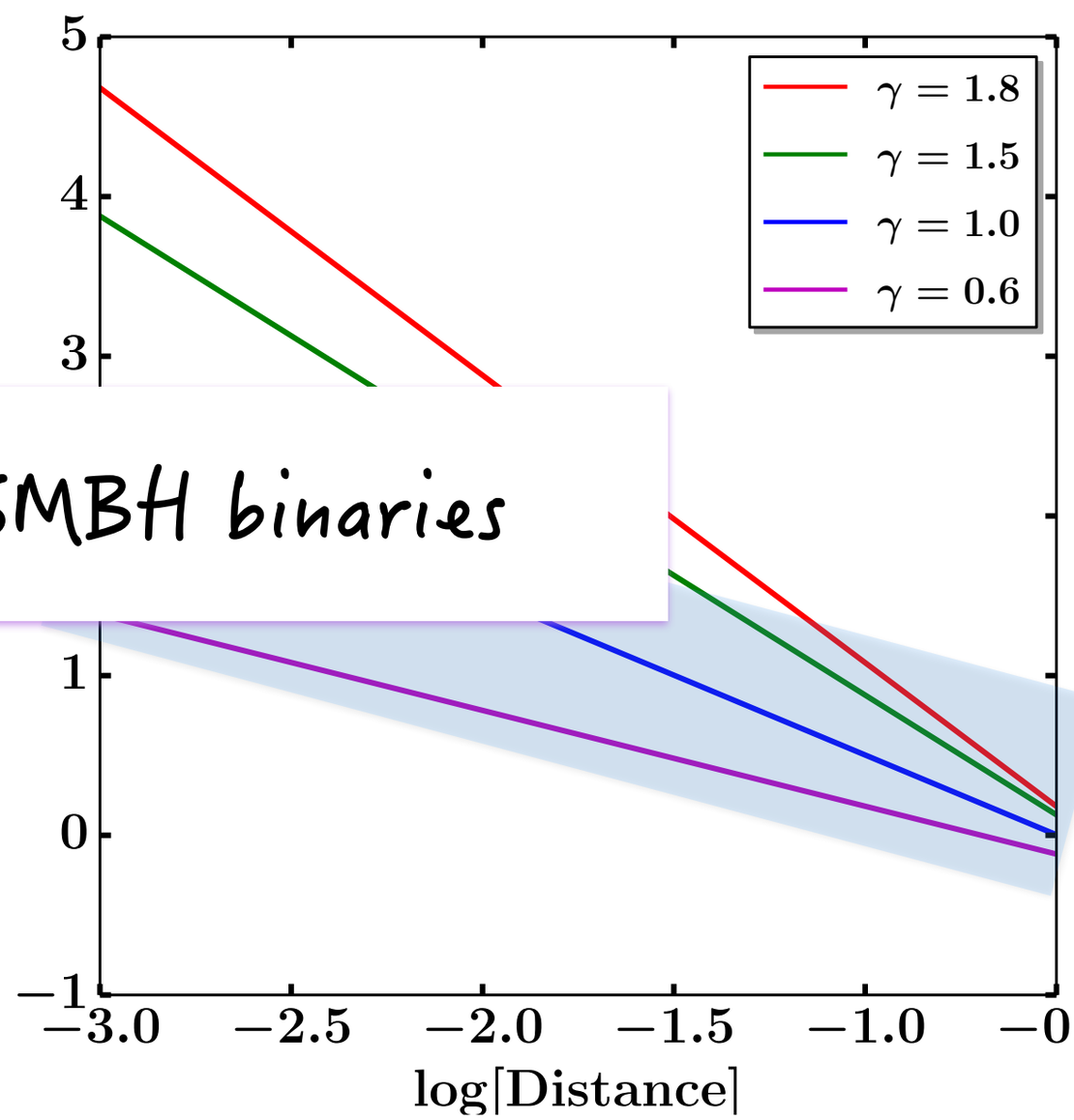
$T_\bullet >> T_{\rm orb} \rightarrow$ Orbit-average $\left\langle \frac{da}{dt} \right\rangle$

$\left\langle \frac{de}{dt} \right\rangle$

Analytical Treatment

Semi-major axis evolution

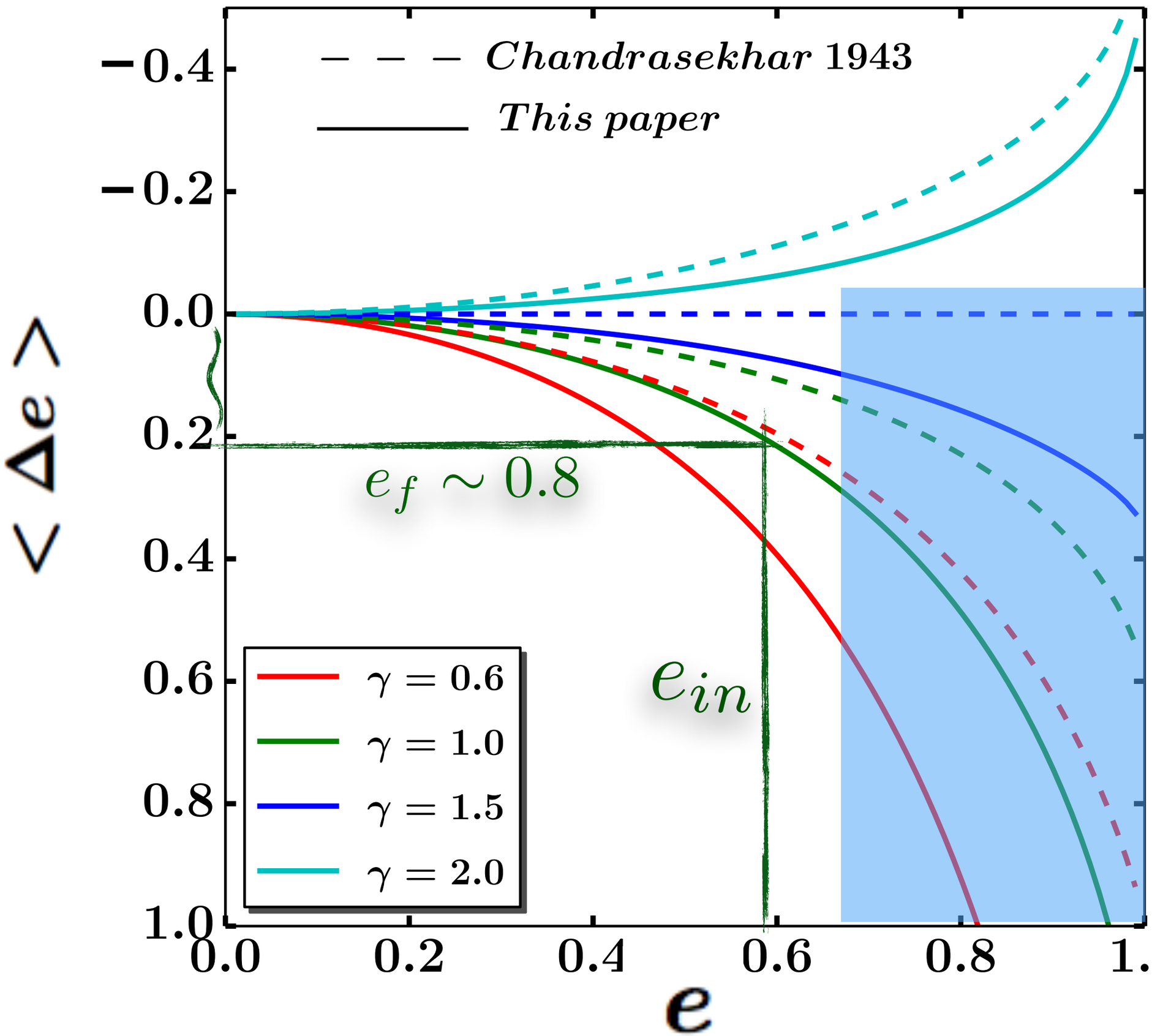




Long lifetimes for SMBH binaries

Orbits stalls for shallow density profiles

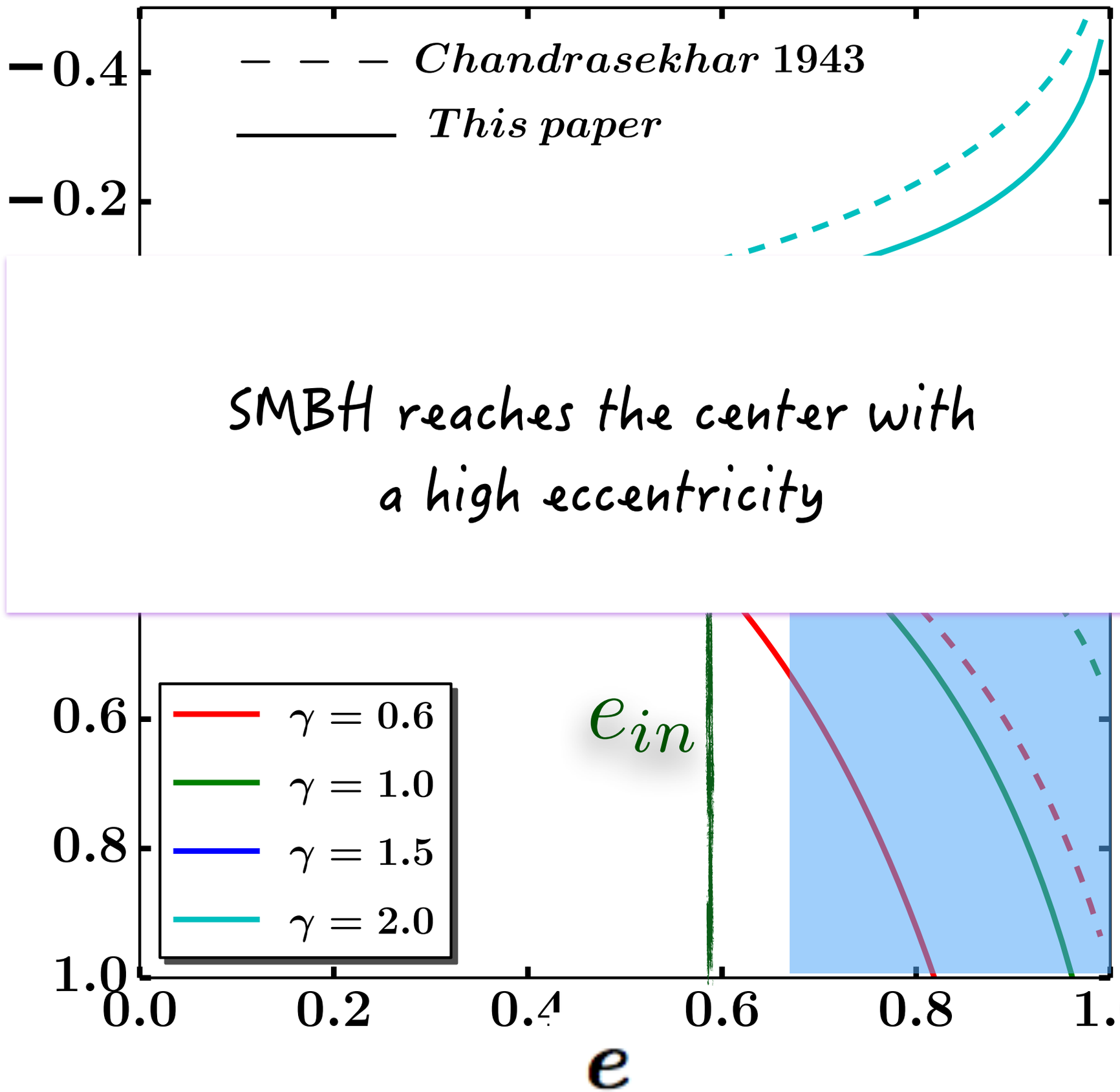
Analytical Treatment - Eccentricity evolution



BH reaches the center on a highly eccentric orbit

$e_f \sim 1$

Analytical Treatment - Eccentricity evolution

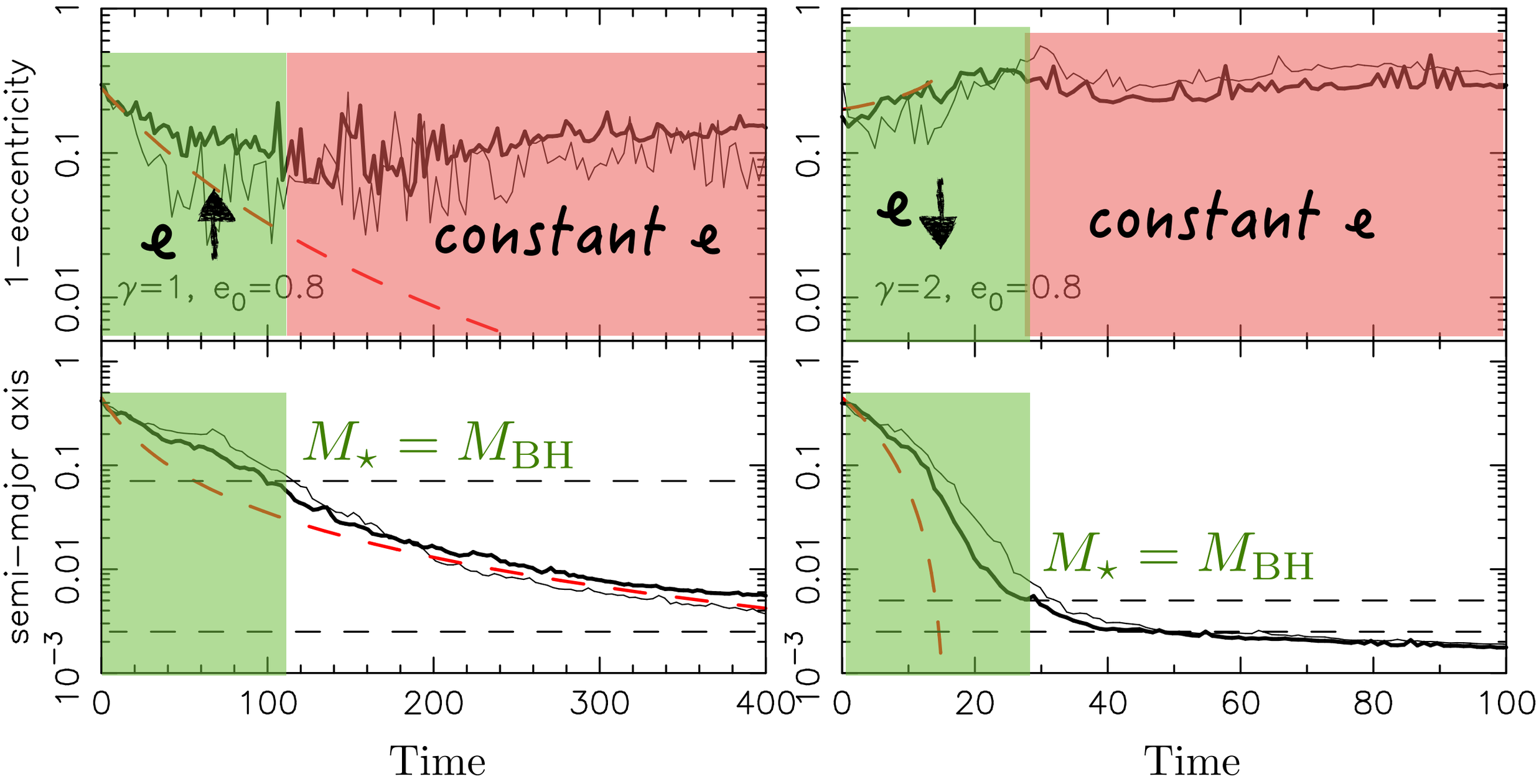


SMBH reaches the center with a high eccentricity

SMBH reaches the center on a highly eccentric orbit

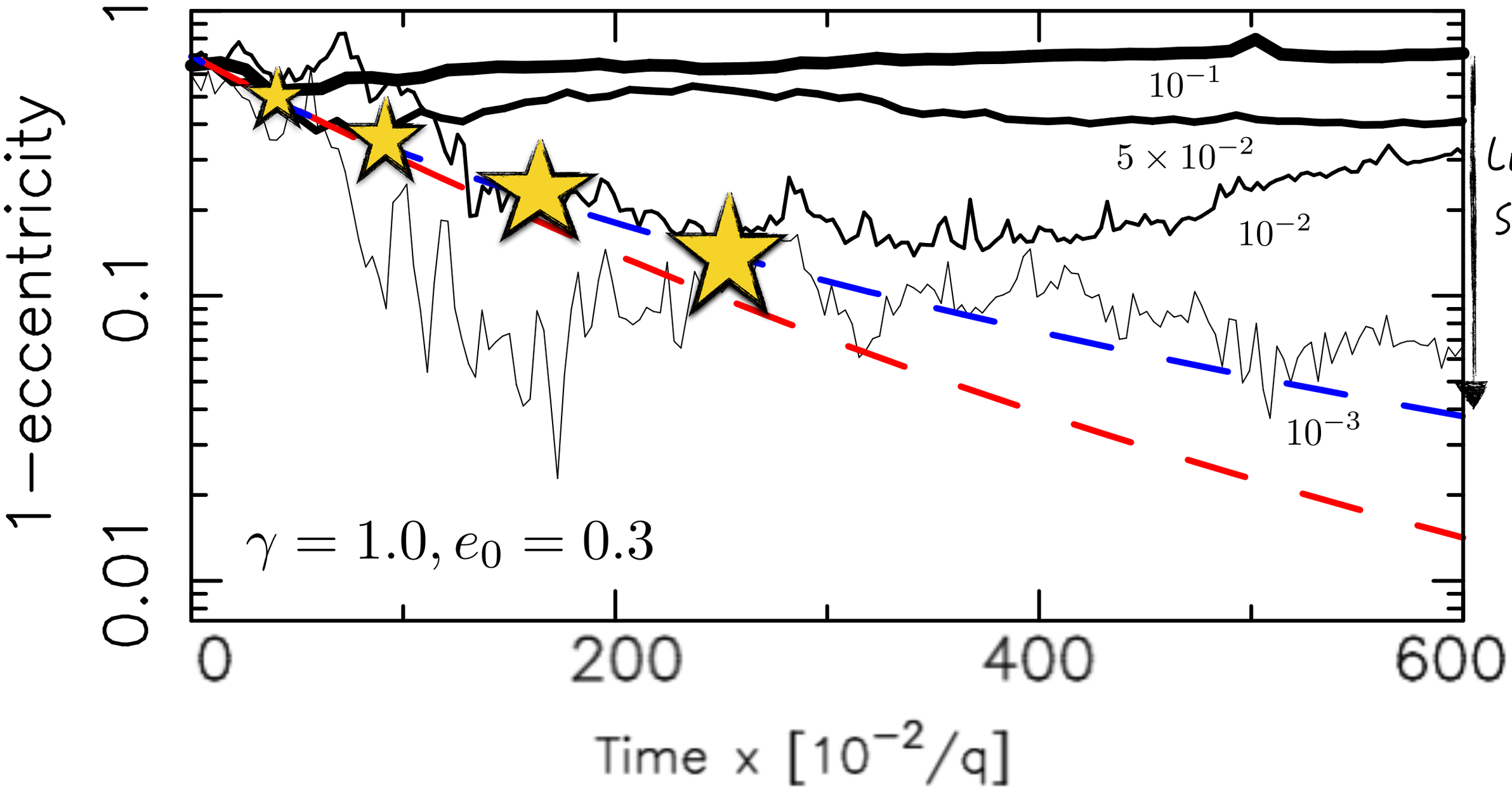
$e_f \sim 1$

N-body simulations: Comparison to analytical predictions

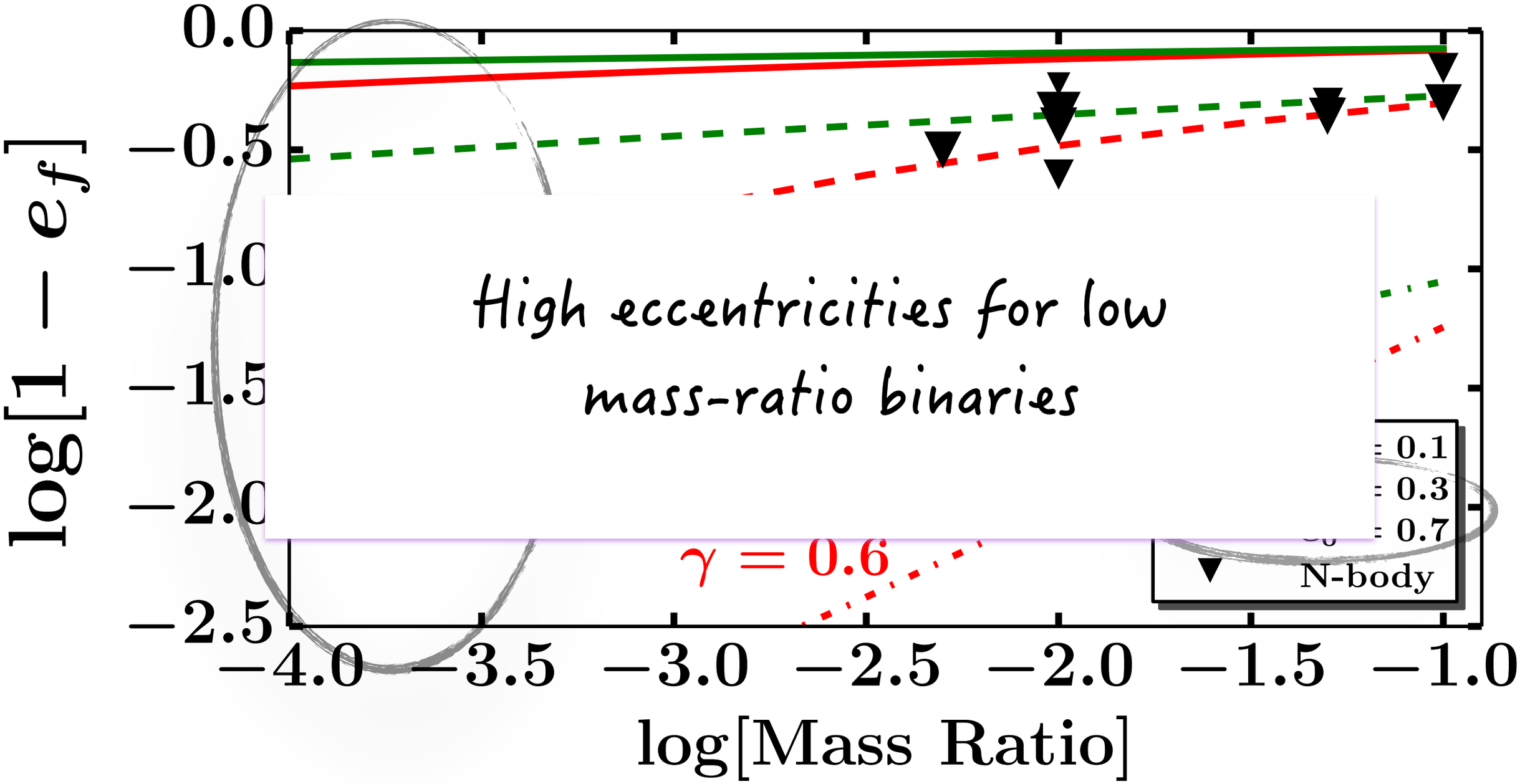


Confirm the expected qualitative result that the eccentricity increases for $\gamma < 2$

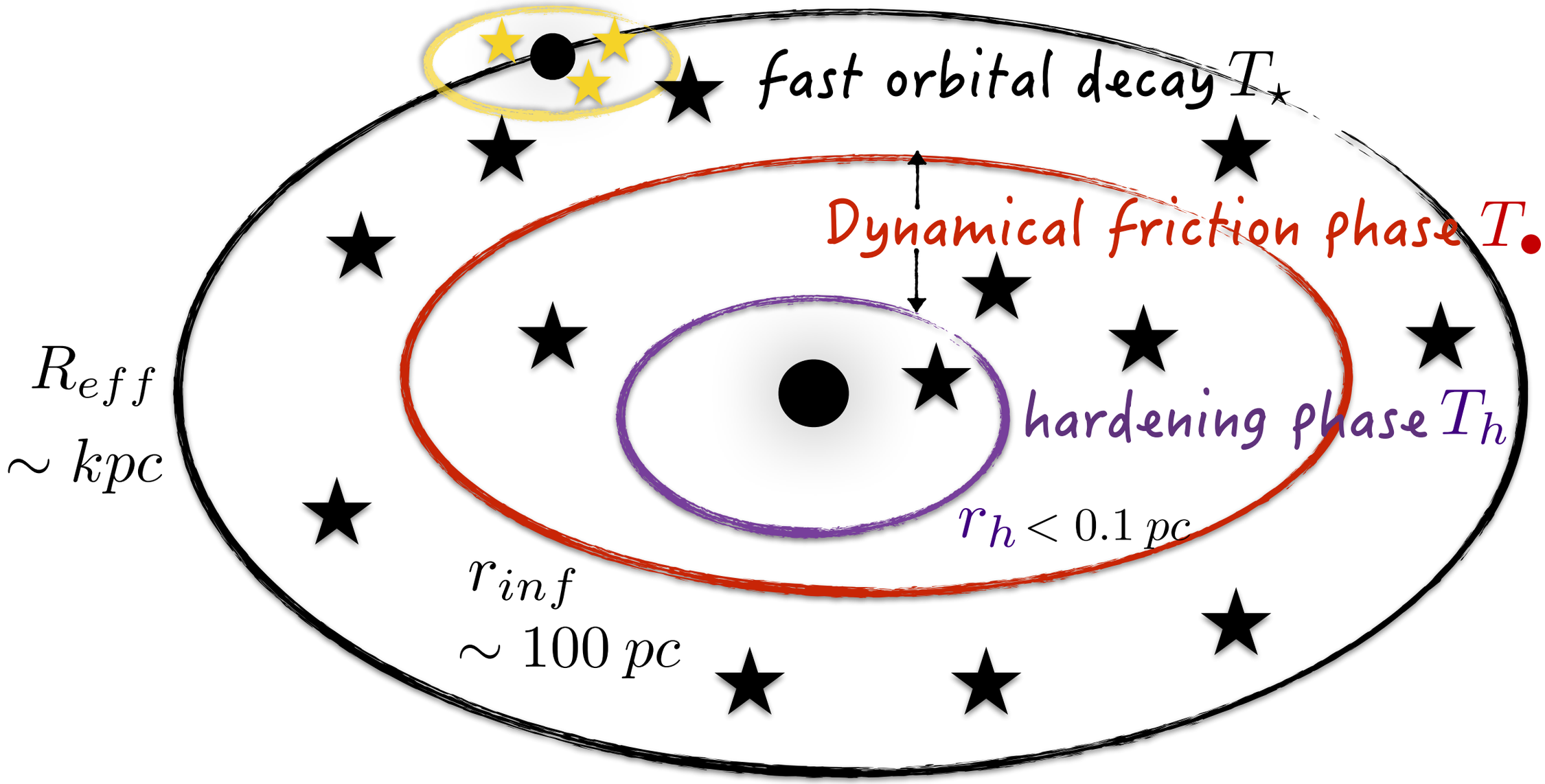
N-body simulations- Different mass ratios



Final eccentricity before hardening ?



Lifetime of a SMBH binary $= T_\star + T_\bullet + T_{\rm h}$



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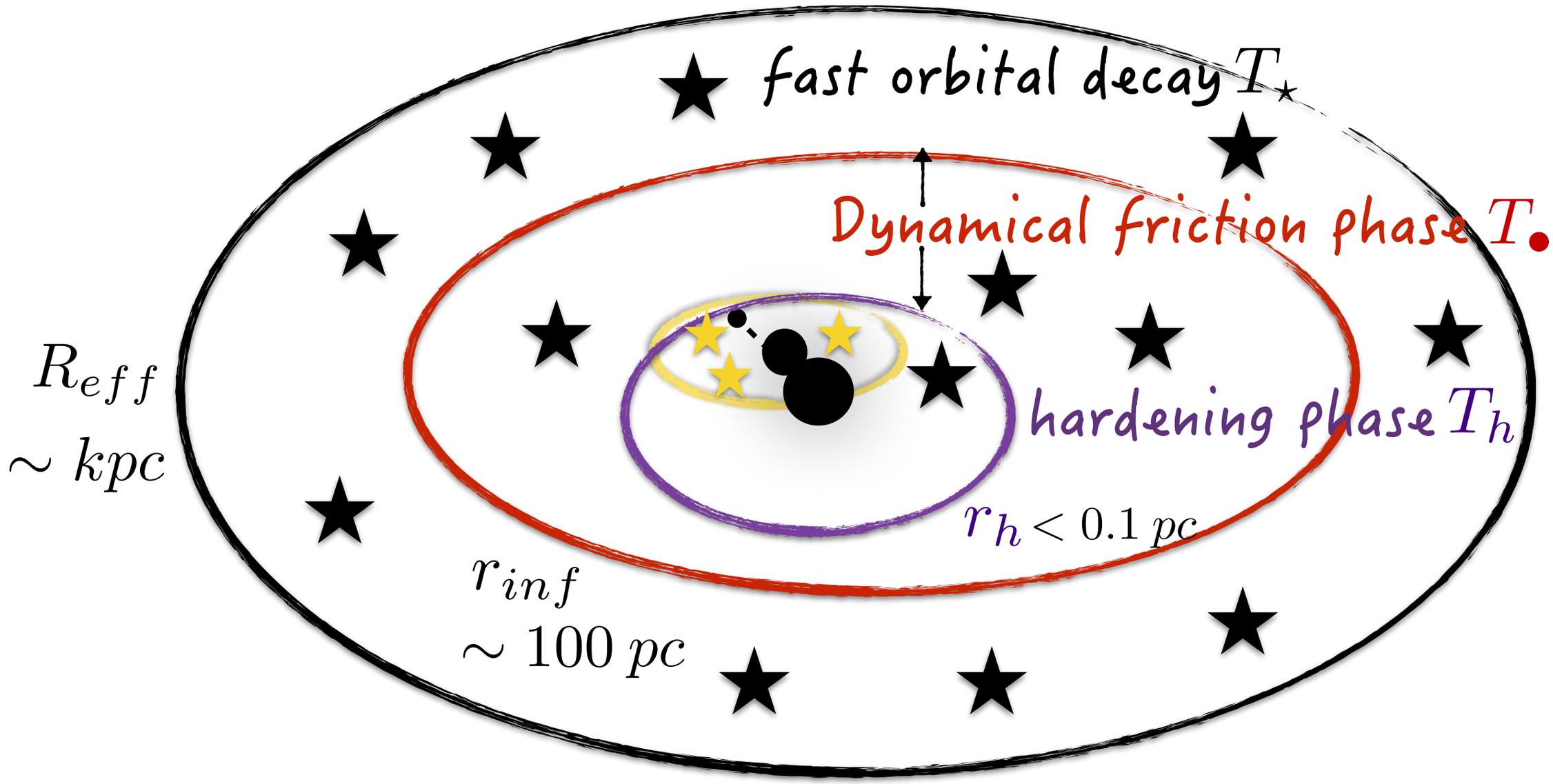
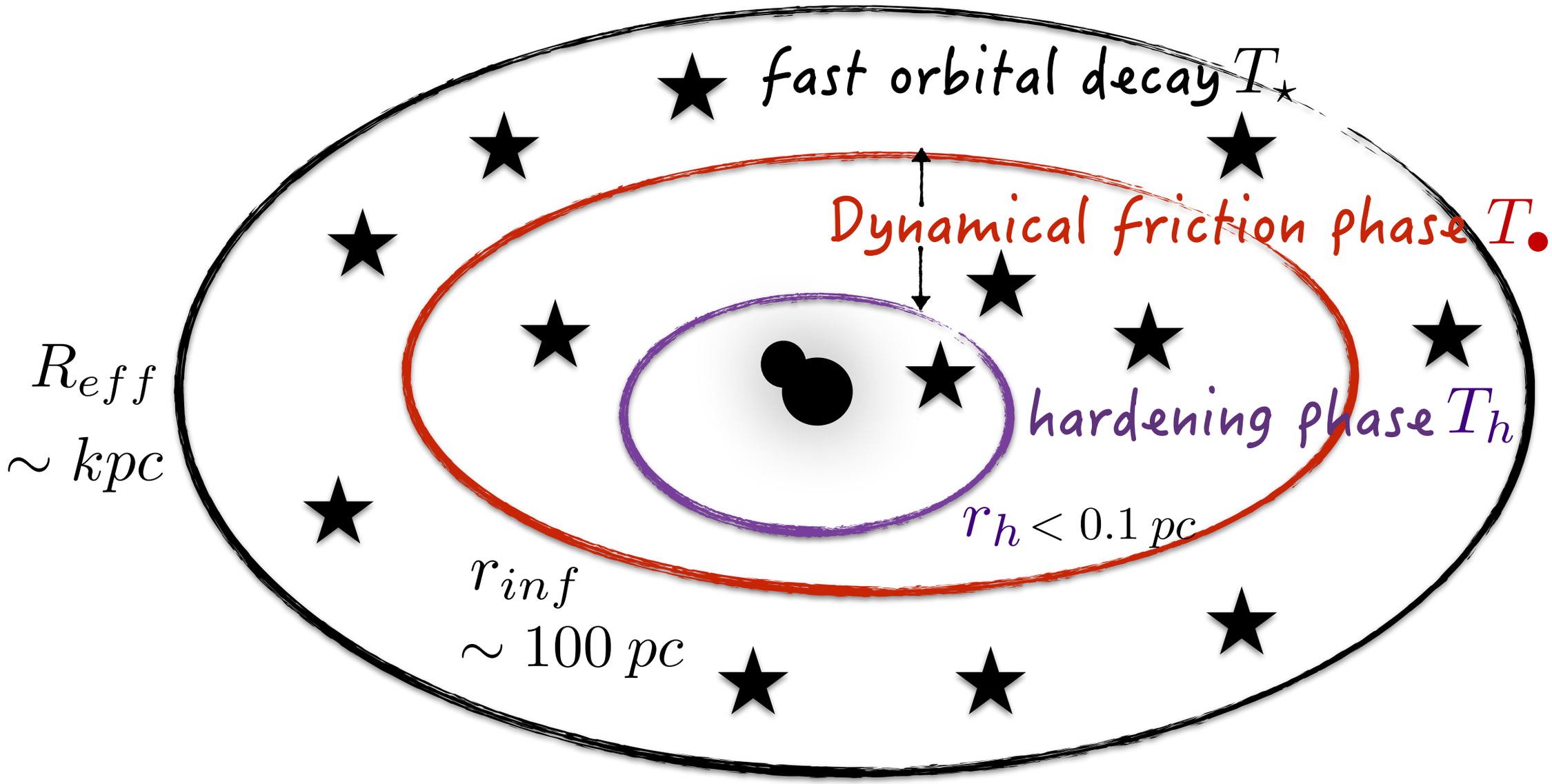


Lifetime of a SMBH binary $= T_\star + T_\bullet + T_{\rm h}$

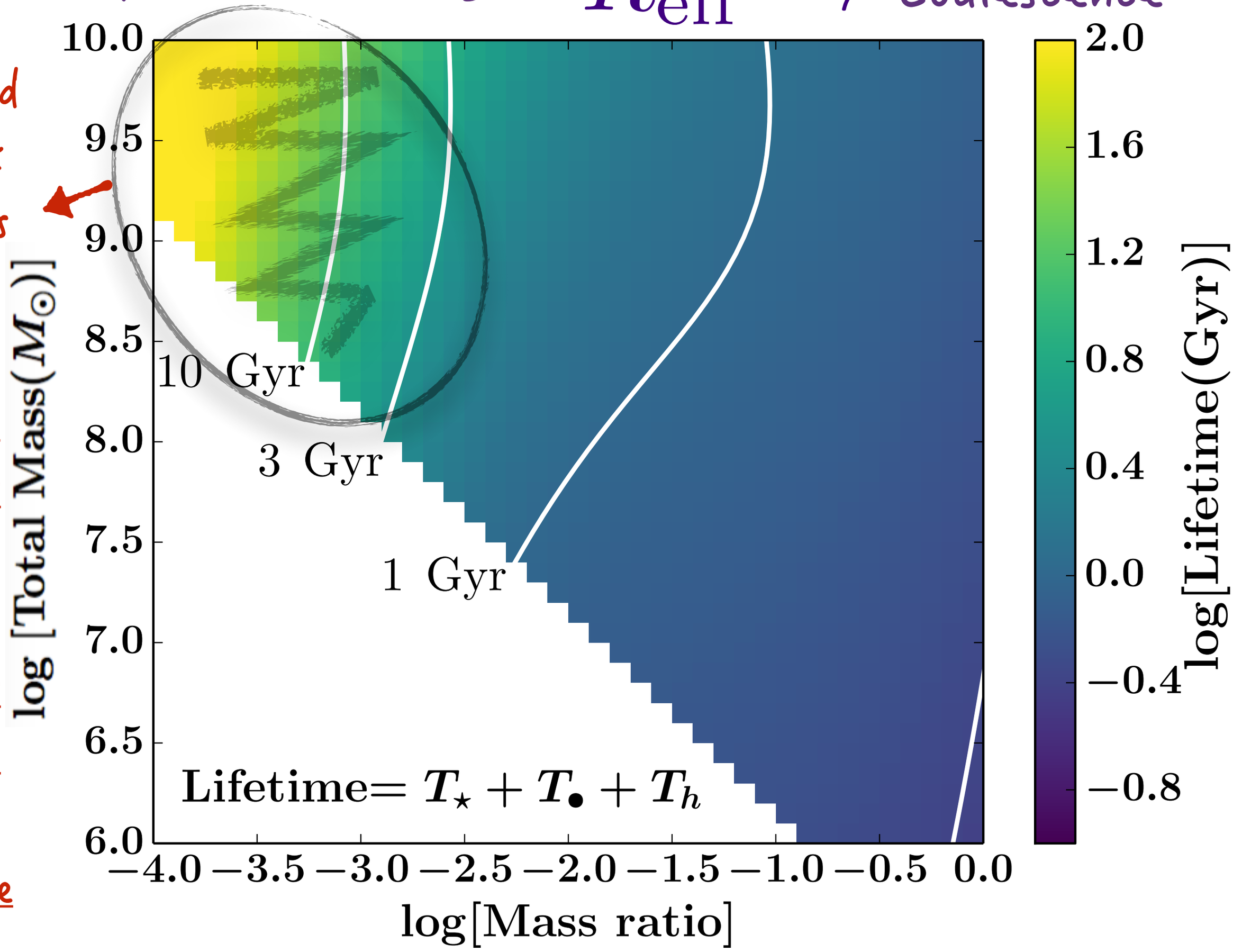


Lifetime of a SMBH binary

$R_{\rm eff} \longrightarrow$ Coalescence

Stalled black holes

high total mass + low mass ratio + high e

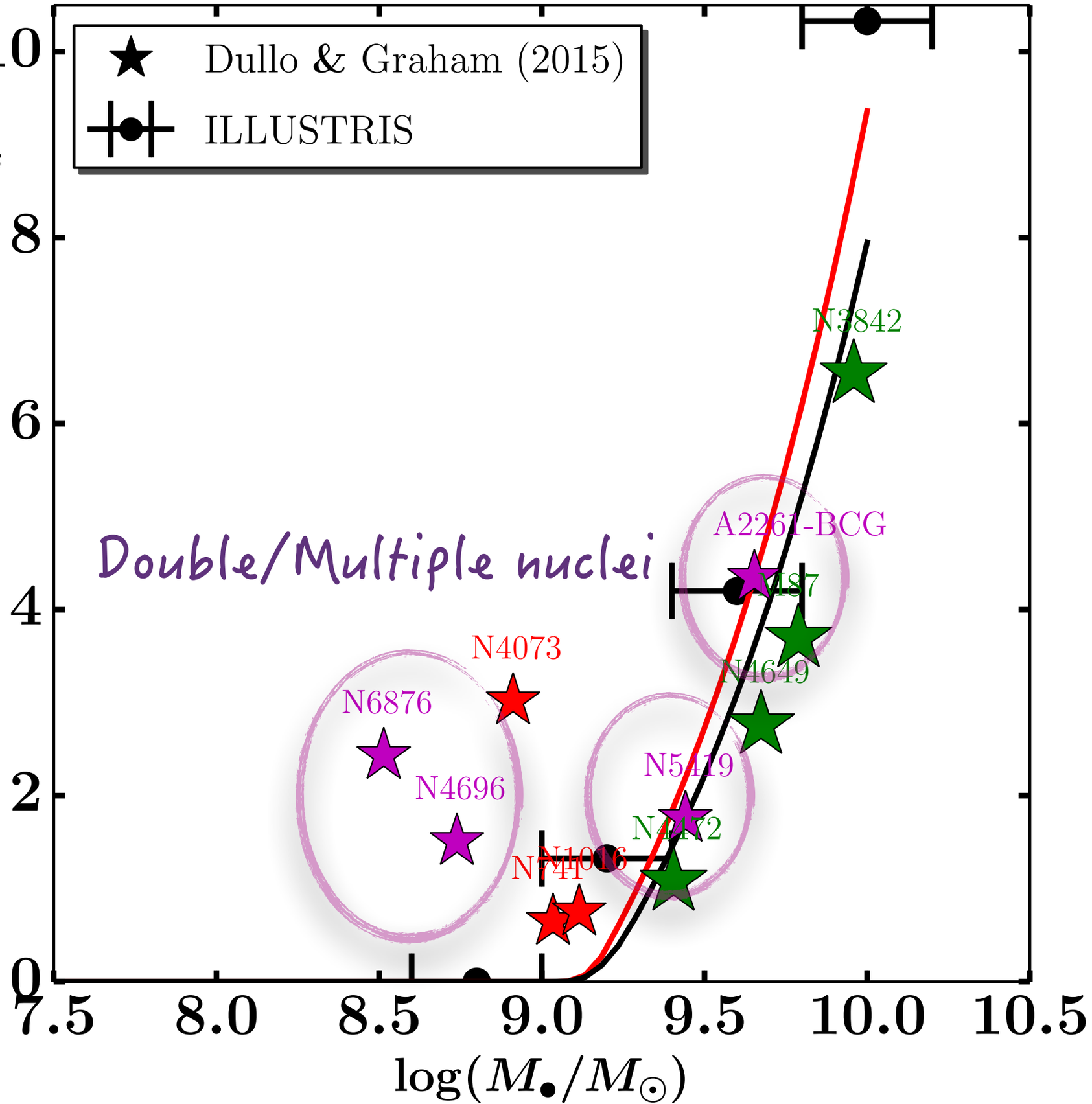


Average expected number of stalled satellites

McWilliams et al.(2014) Lena et al.(2014)

Stalled satellites

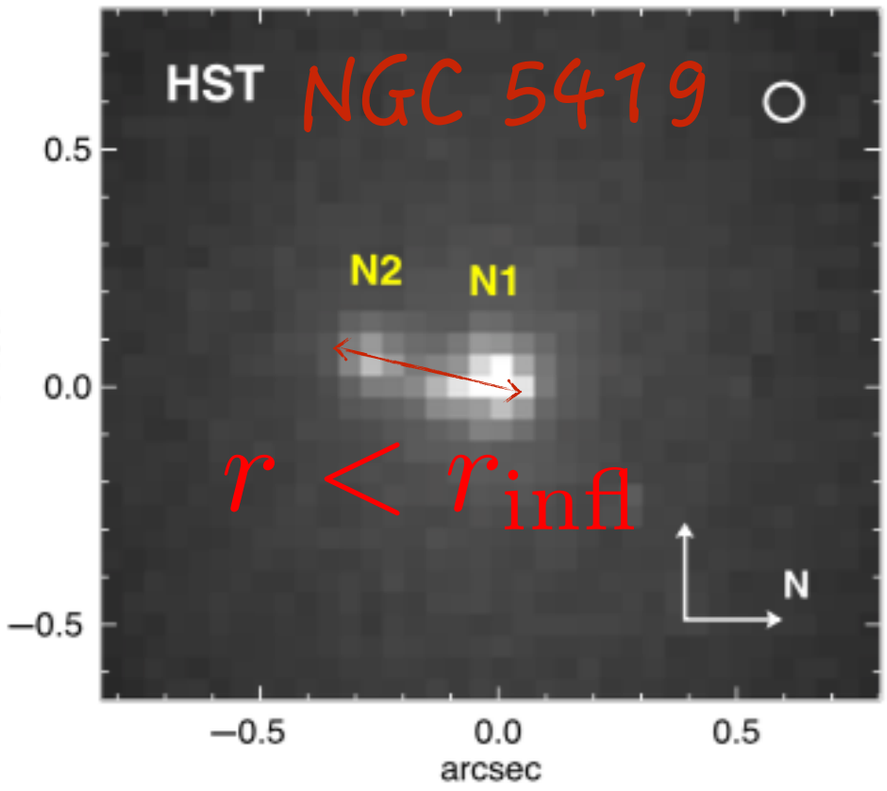
$r < r_{\rm infl}$

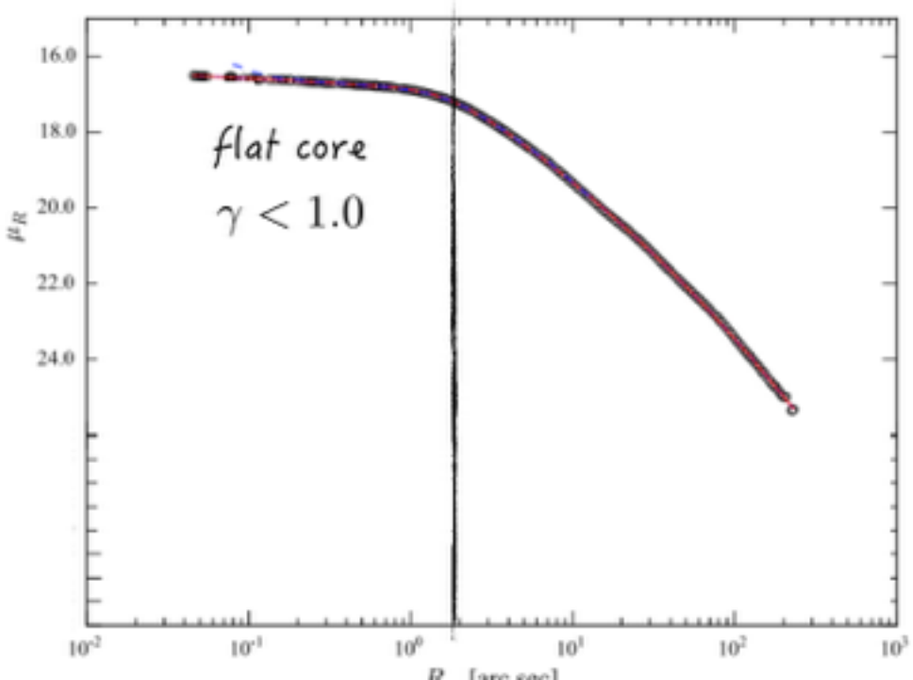


Observational evidence

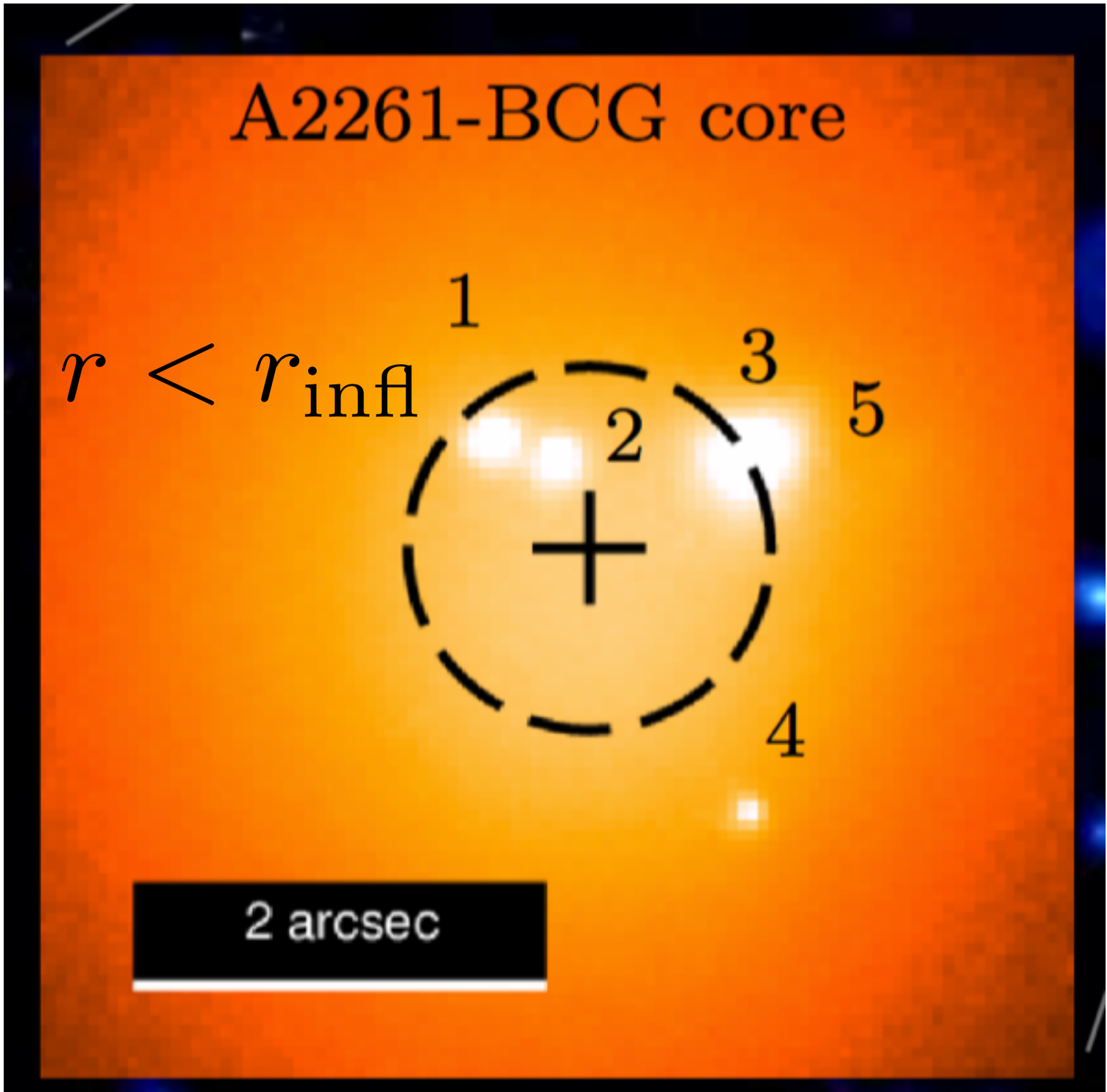
Double/Multiple Nuclei

Mazzalay et al.(2016)





Bonfini & Graham 2016



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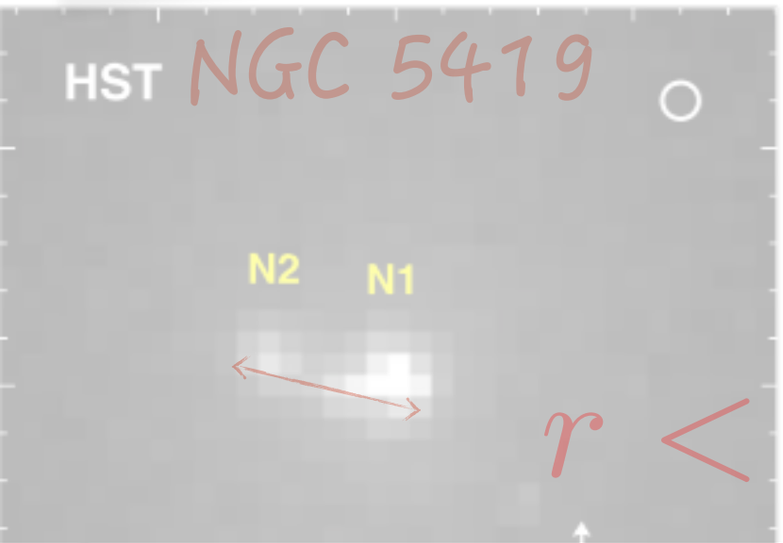
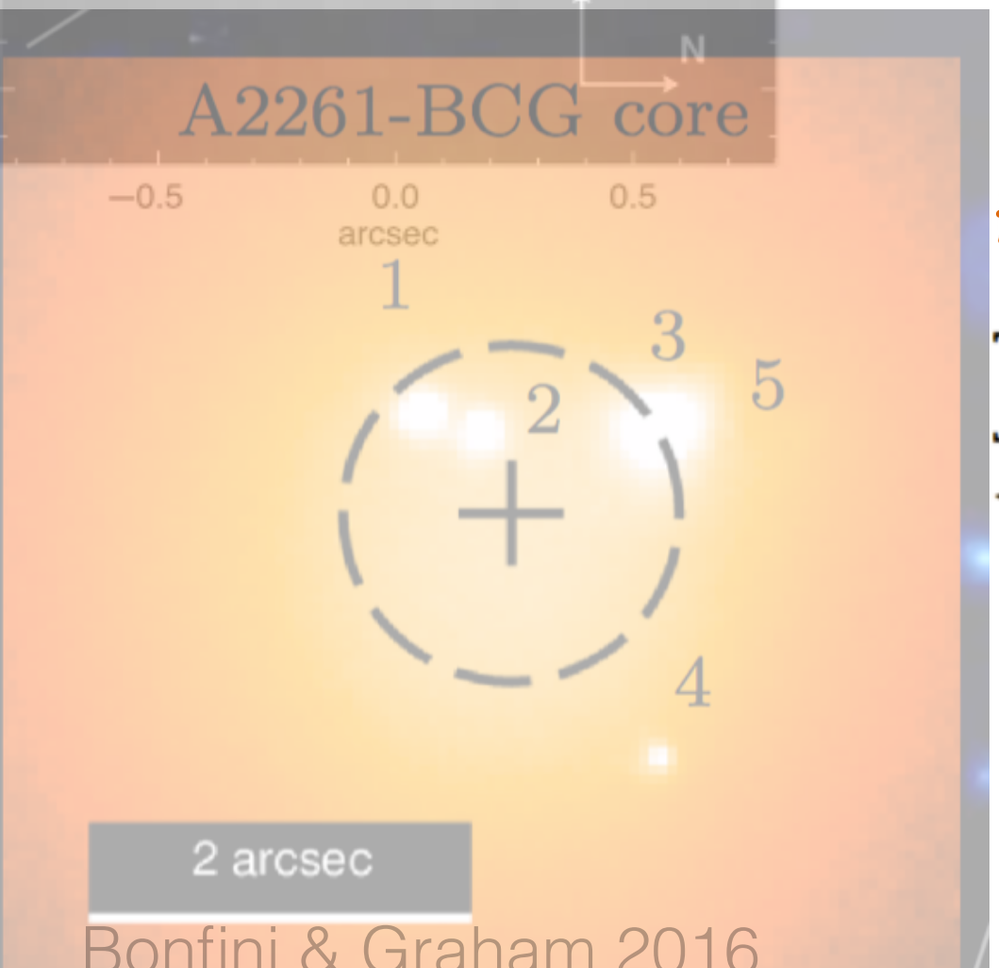


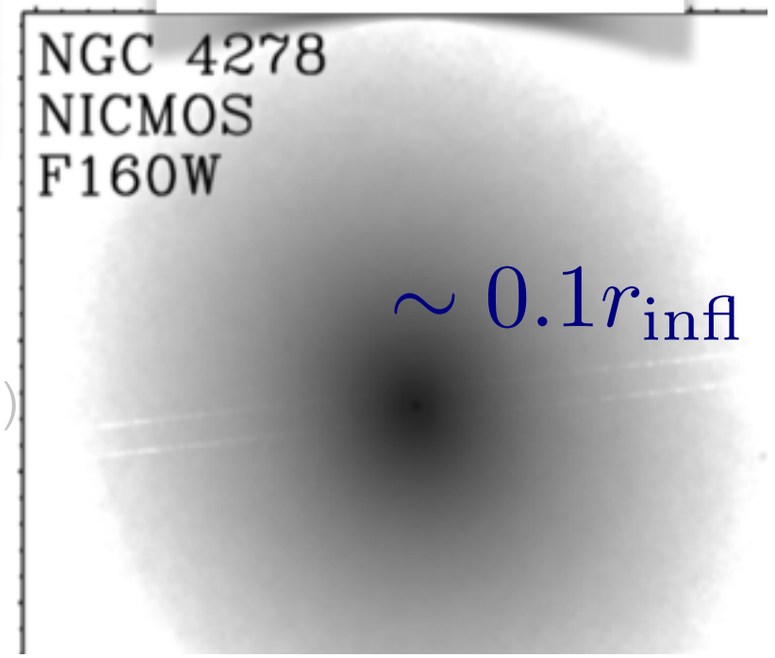
Mazzalay et al.(2016)

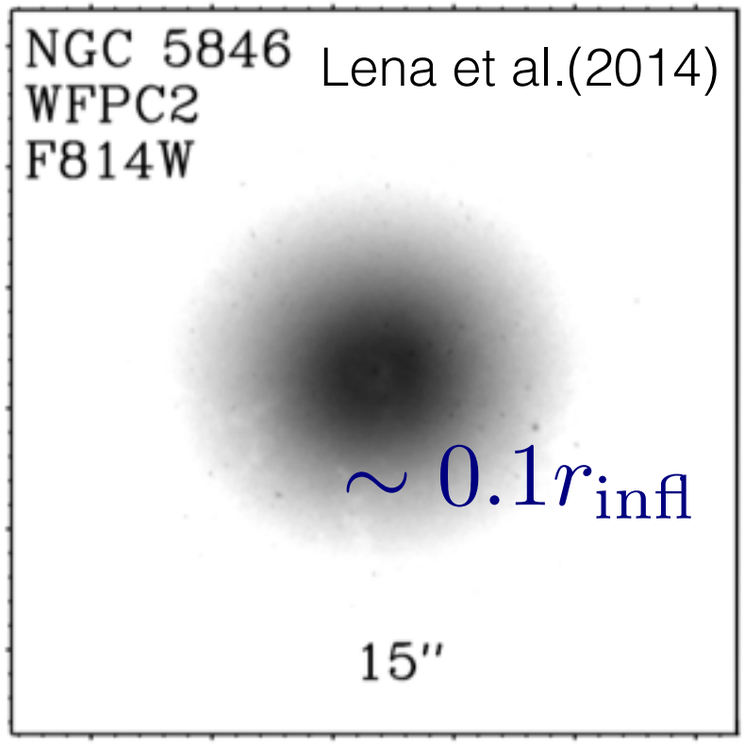
$r < r_{\rm infl}$

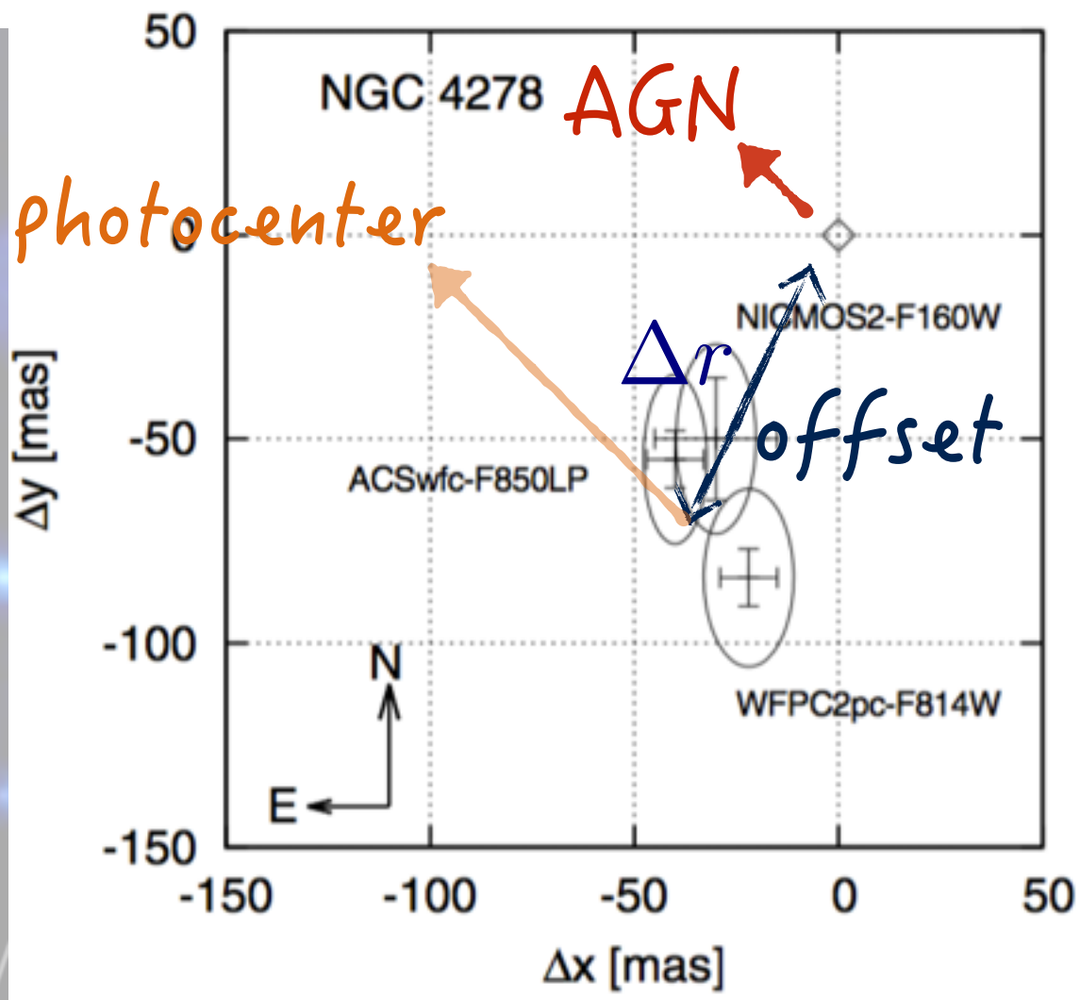


Bonfini & Graham 2016

off-center AGNs

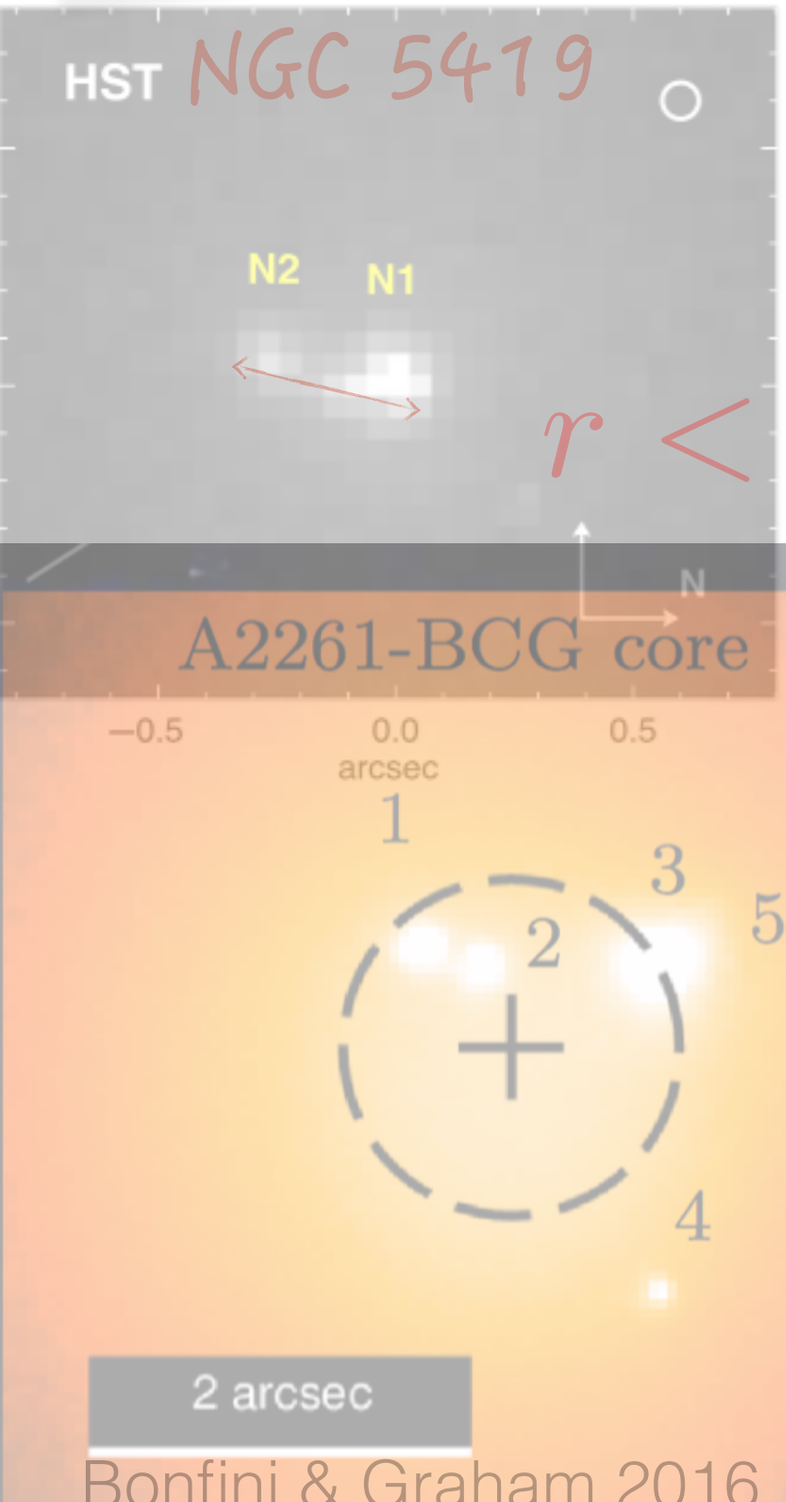






Observational evidence

Double/Multiple Nuclei



Mazzalay et al.(2016)

$r < r_{\rm infl}$

Bonfini & Graham 2016

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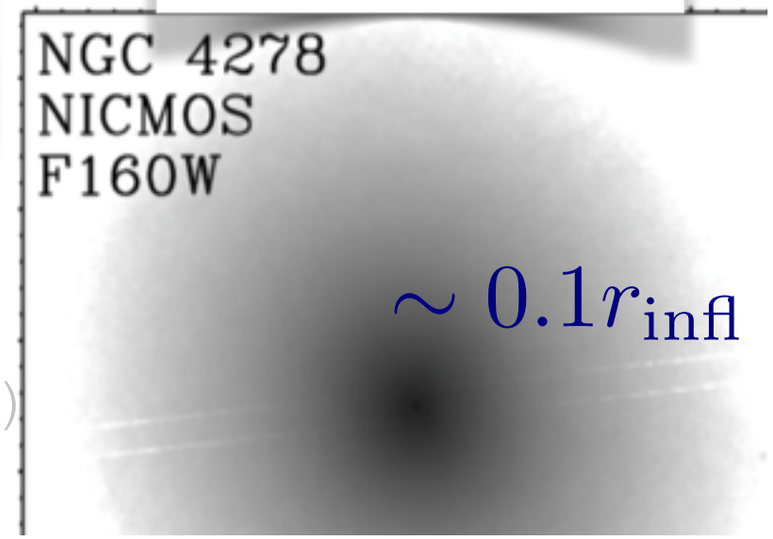

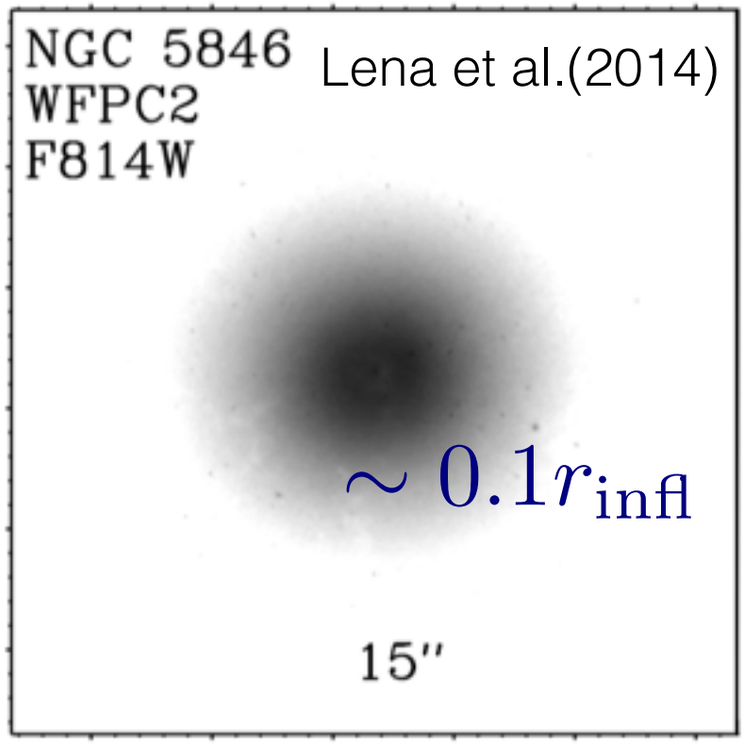

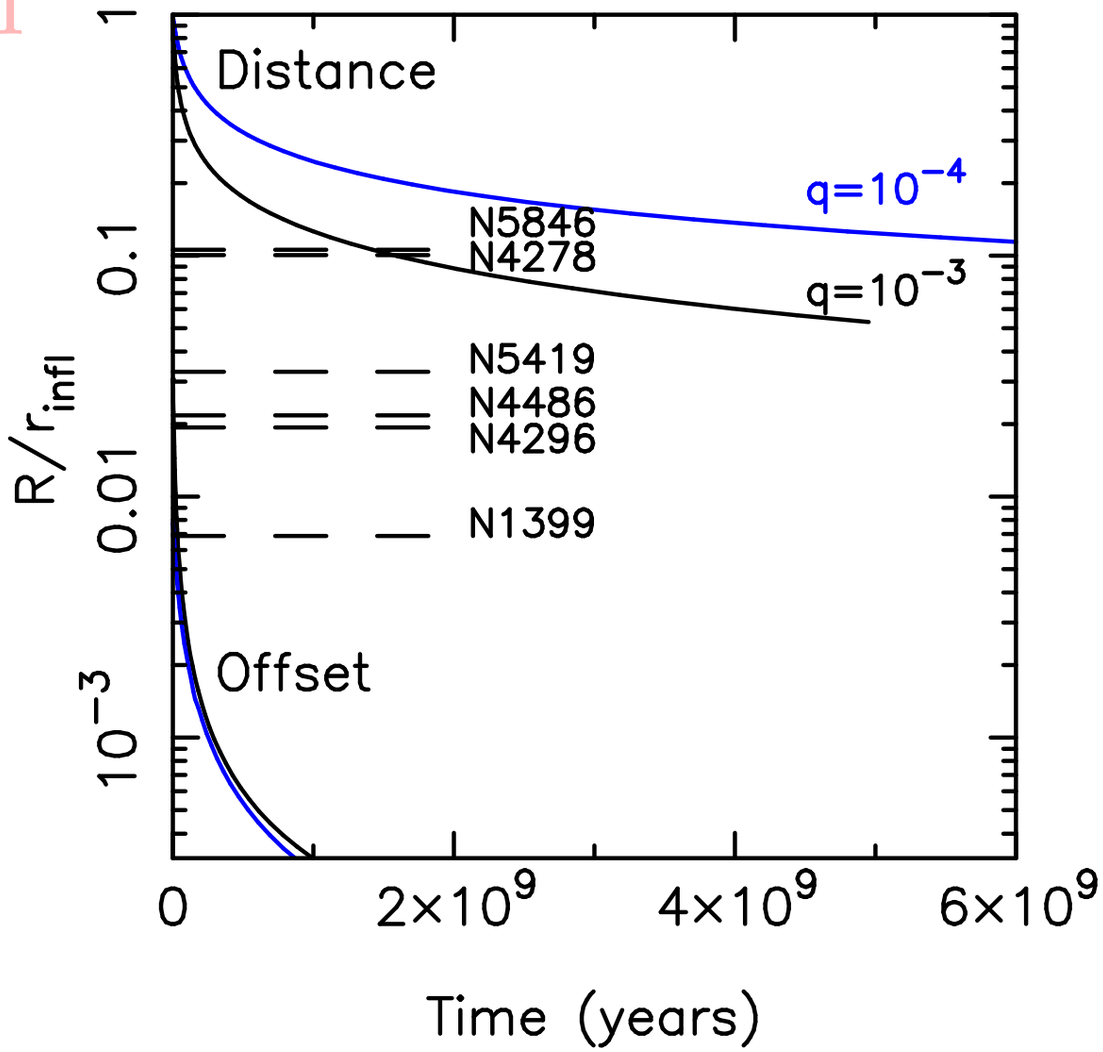

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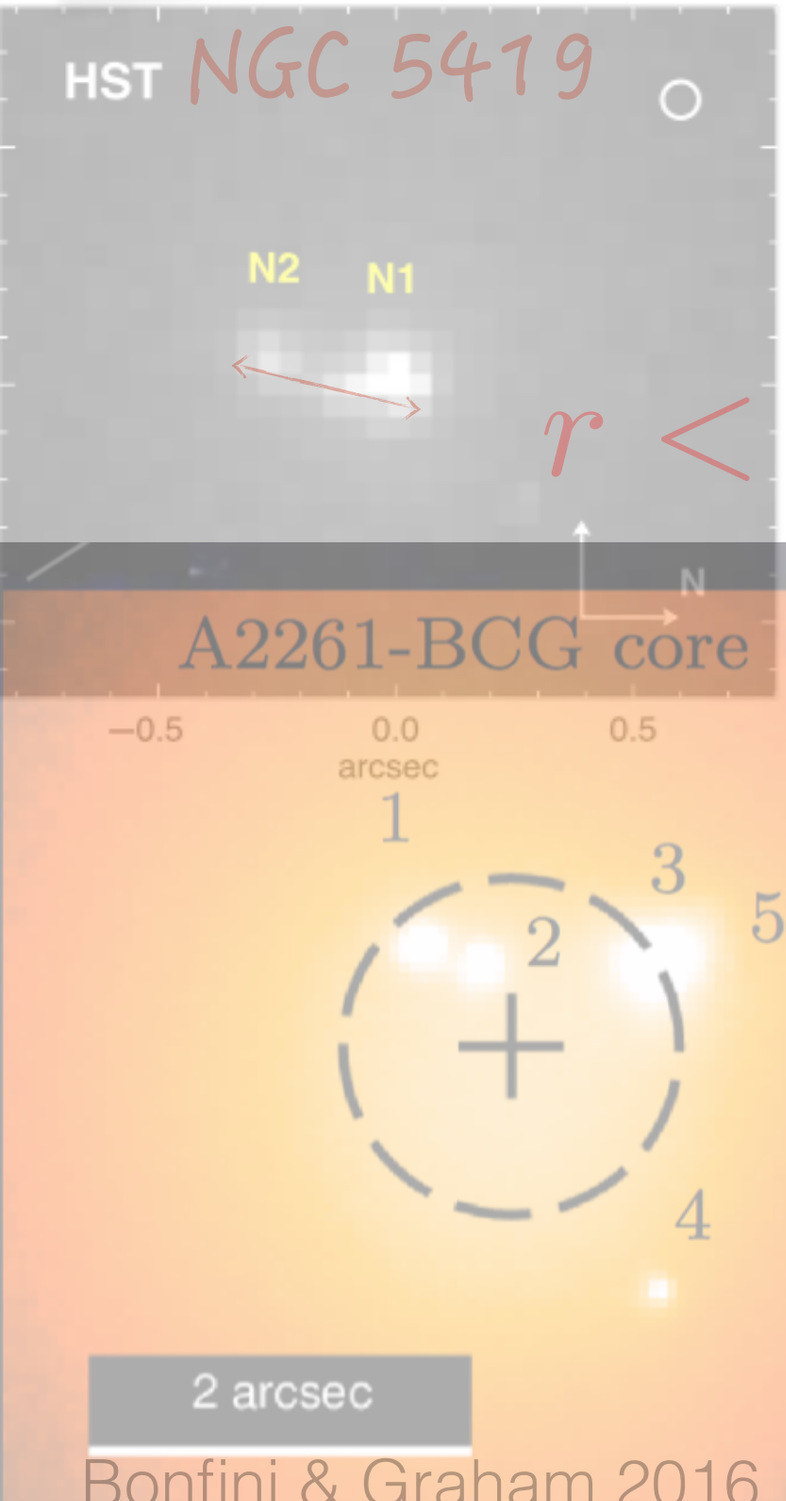

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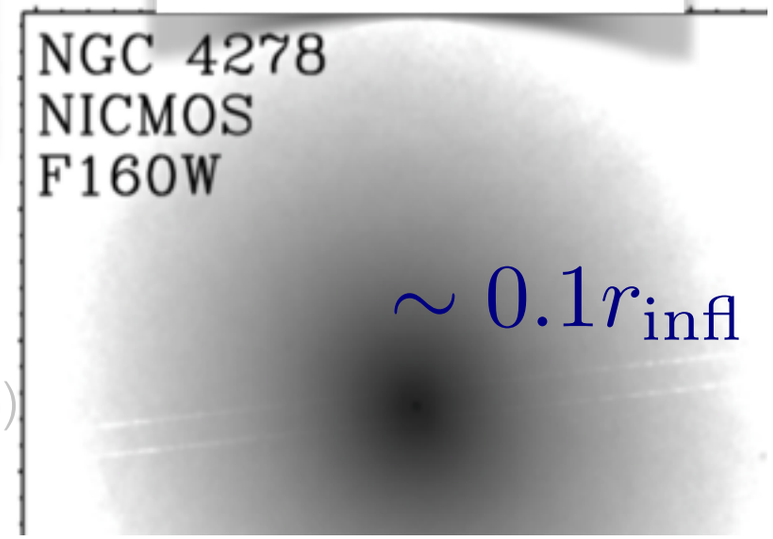
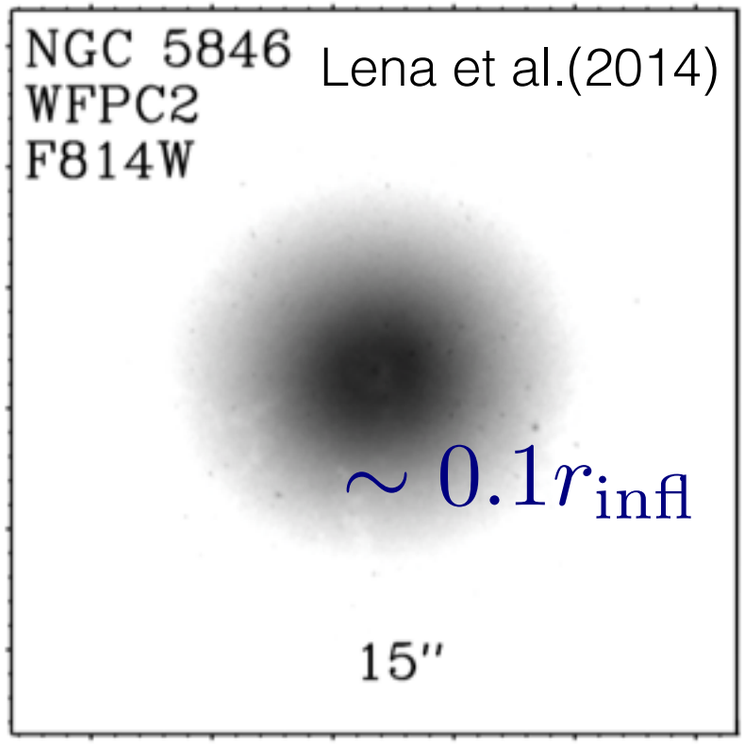
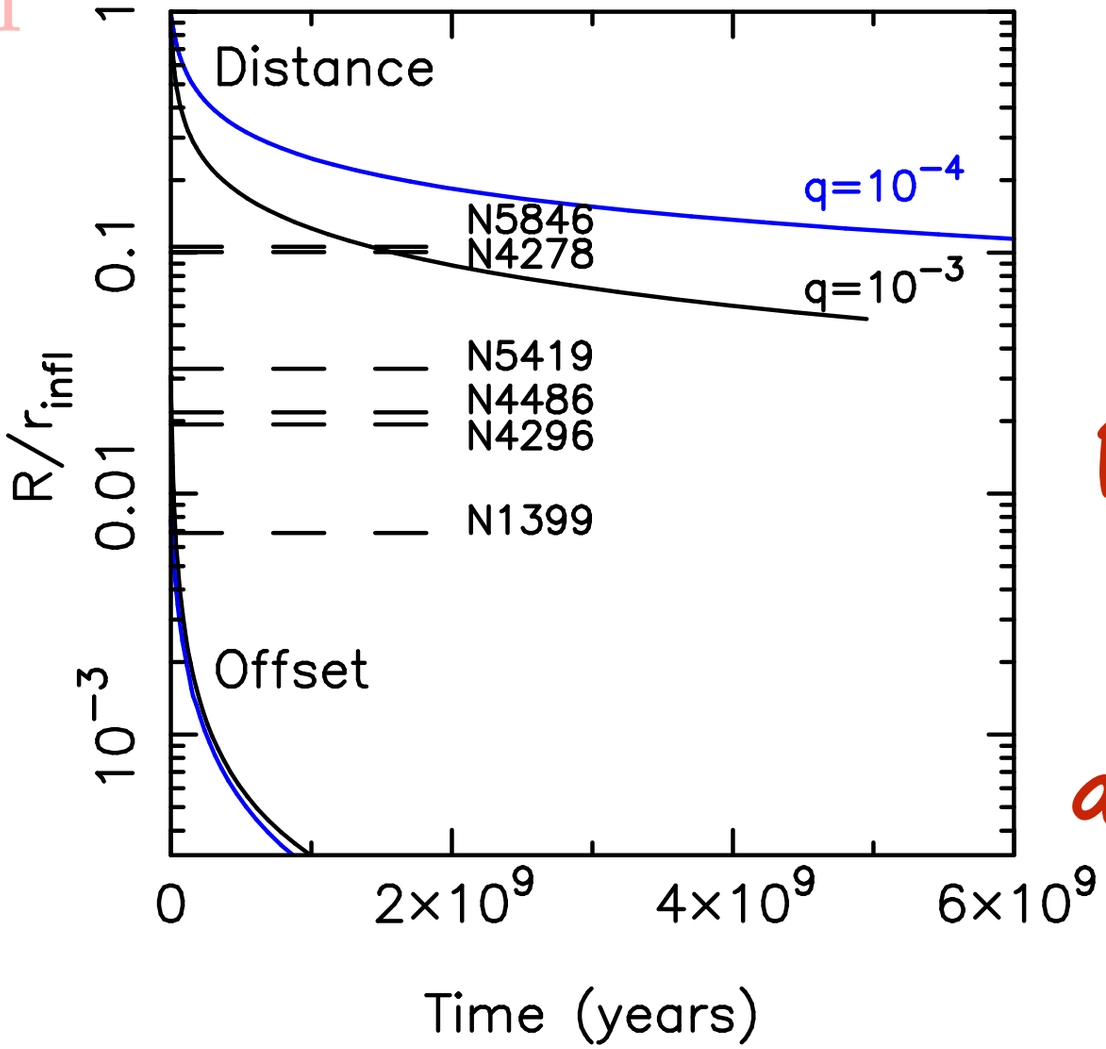
off-center AGNs







AGN

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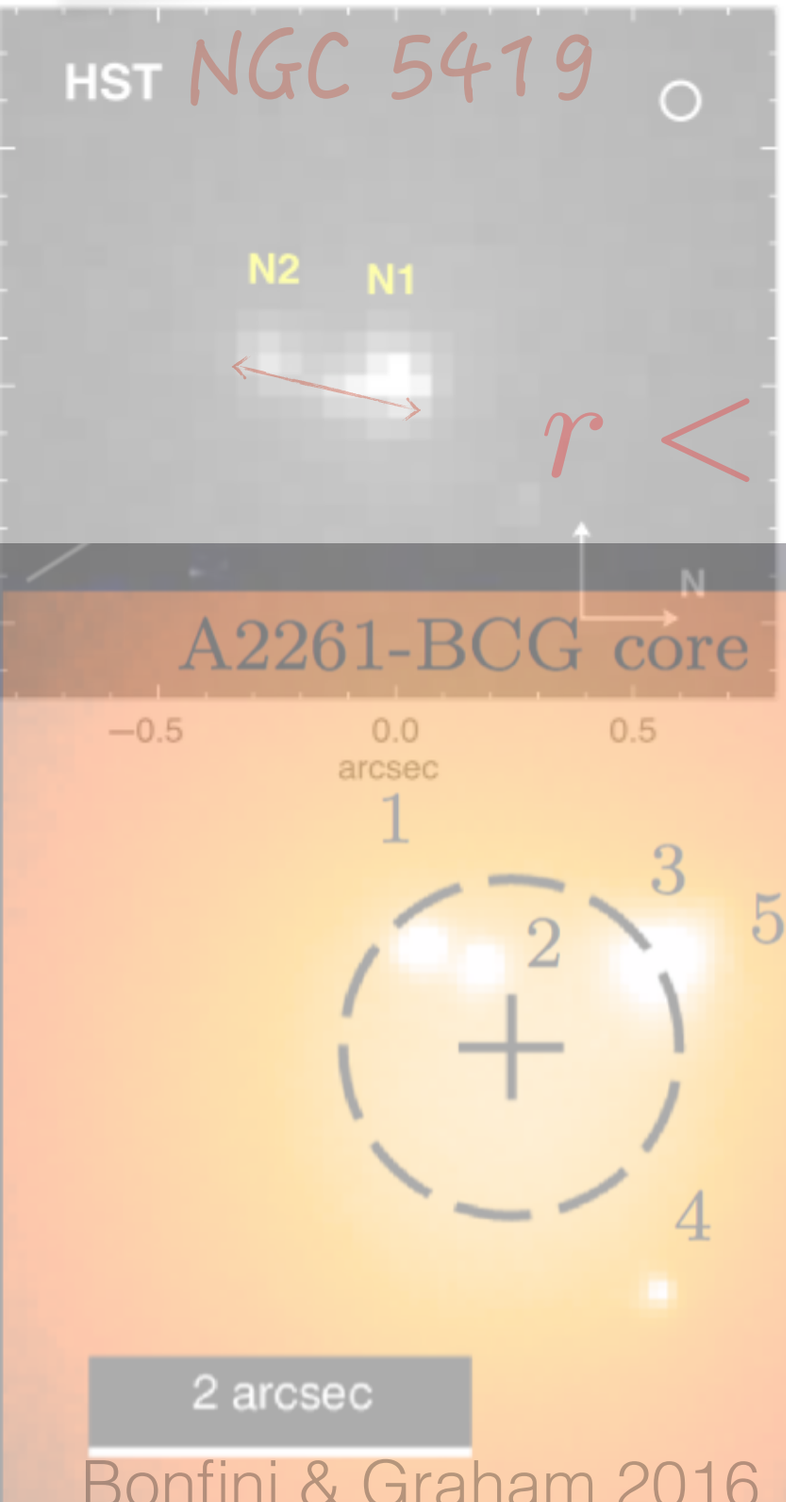
Primary SMBH accreting

Observational evidence

Double/Multiple Nuclei

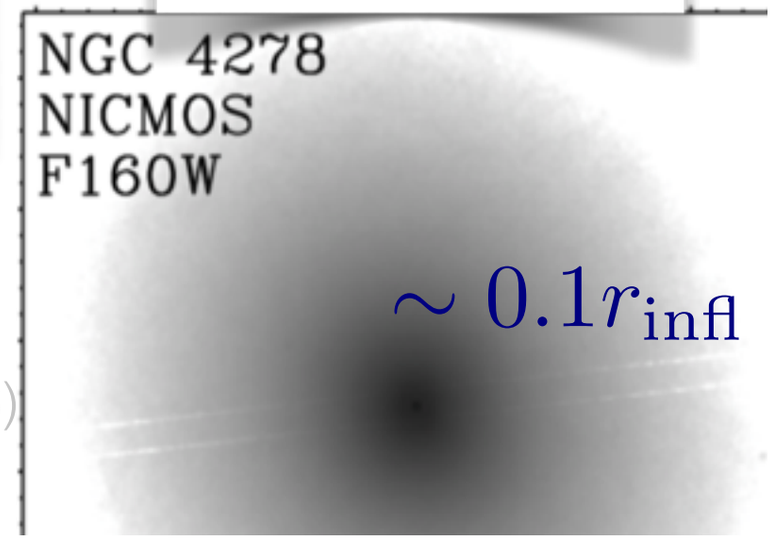


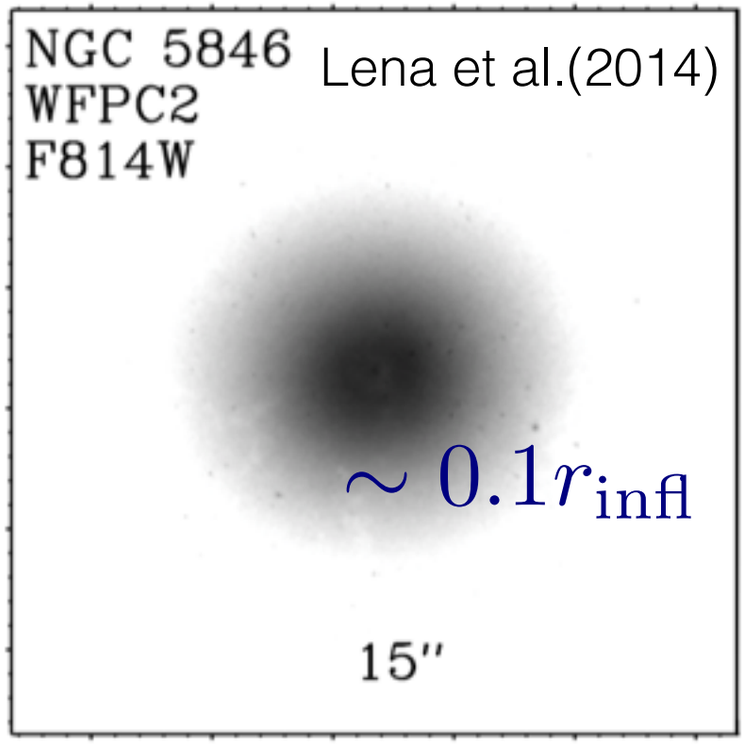
Mazzalay et al.(2016)

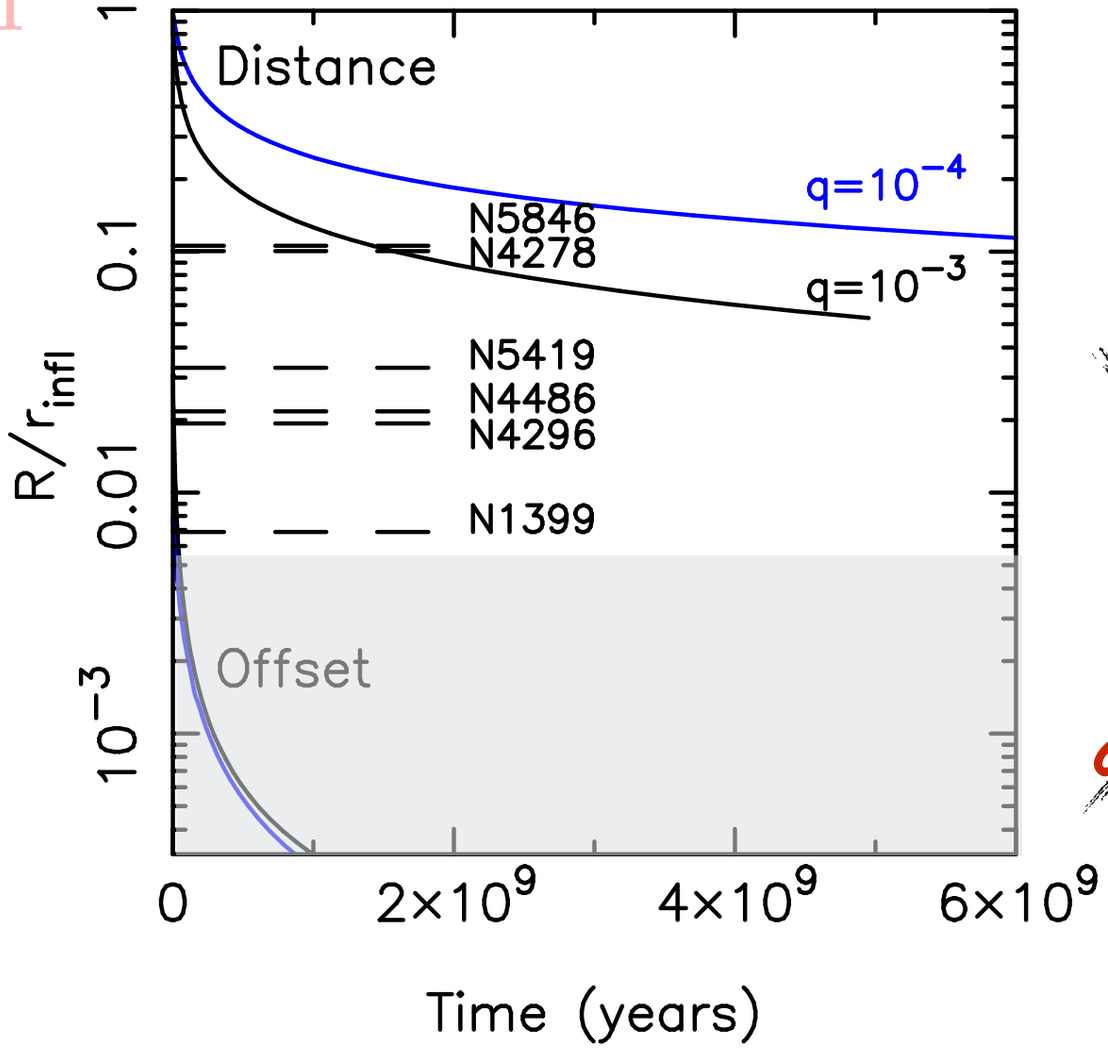
$r < r_{\rm infl}$

Bonfini & Graham 2016

off-center AGNs







AGN

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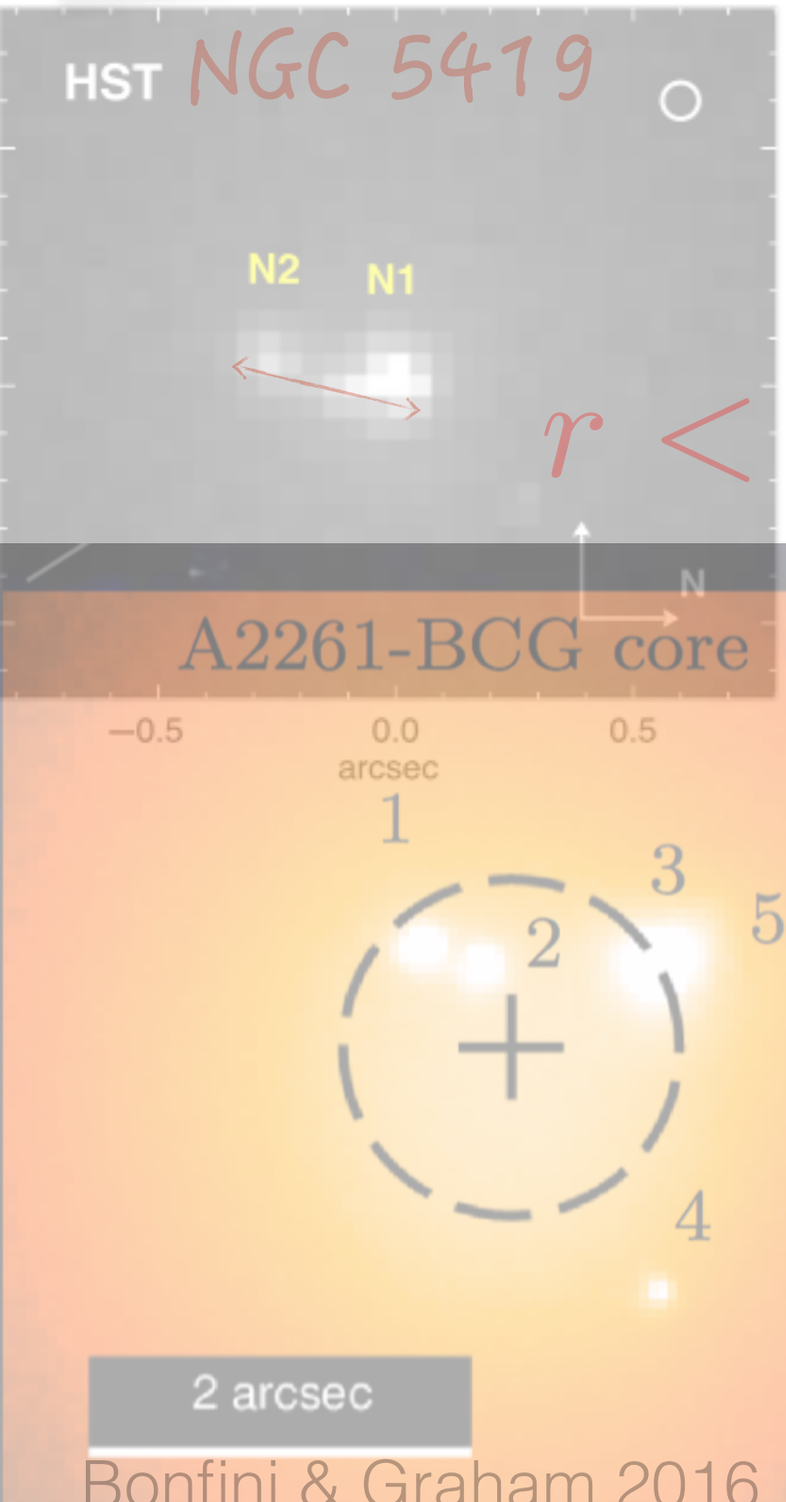
~~Primary SMBH accreting~~

Observational evidence

Double/Multiple Nuclei



Mazzalay et al.(2016)

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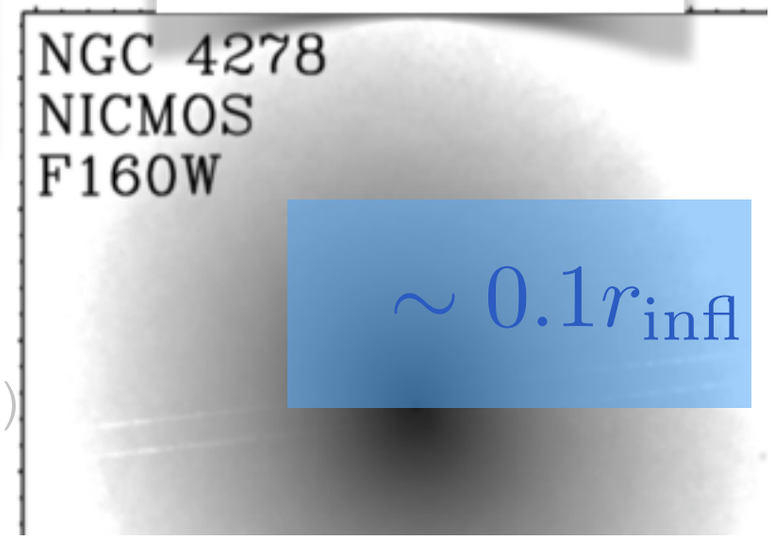
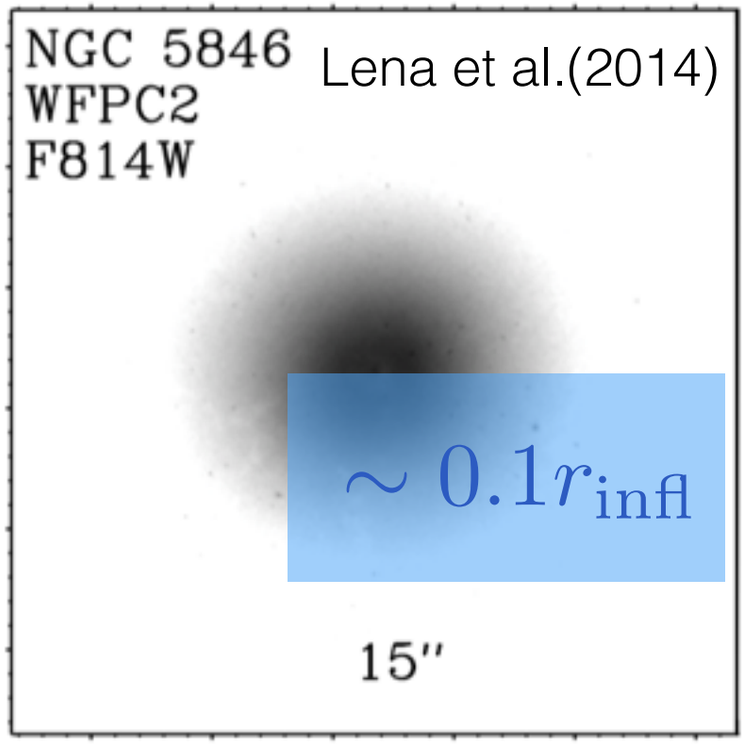
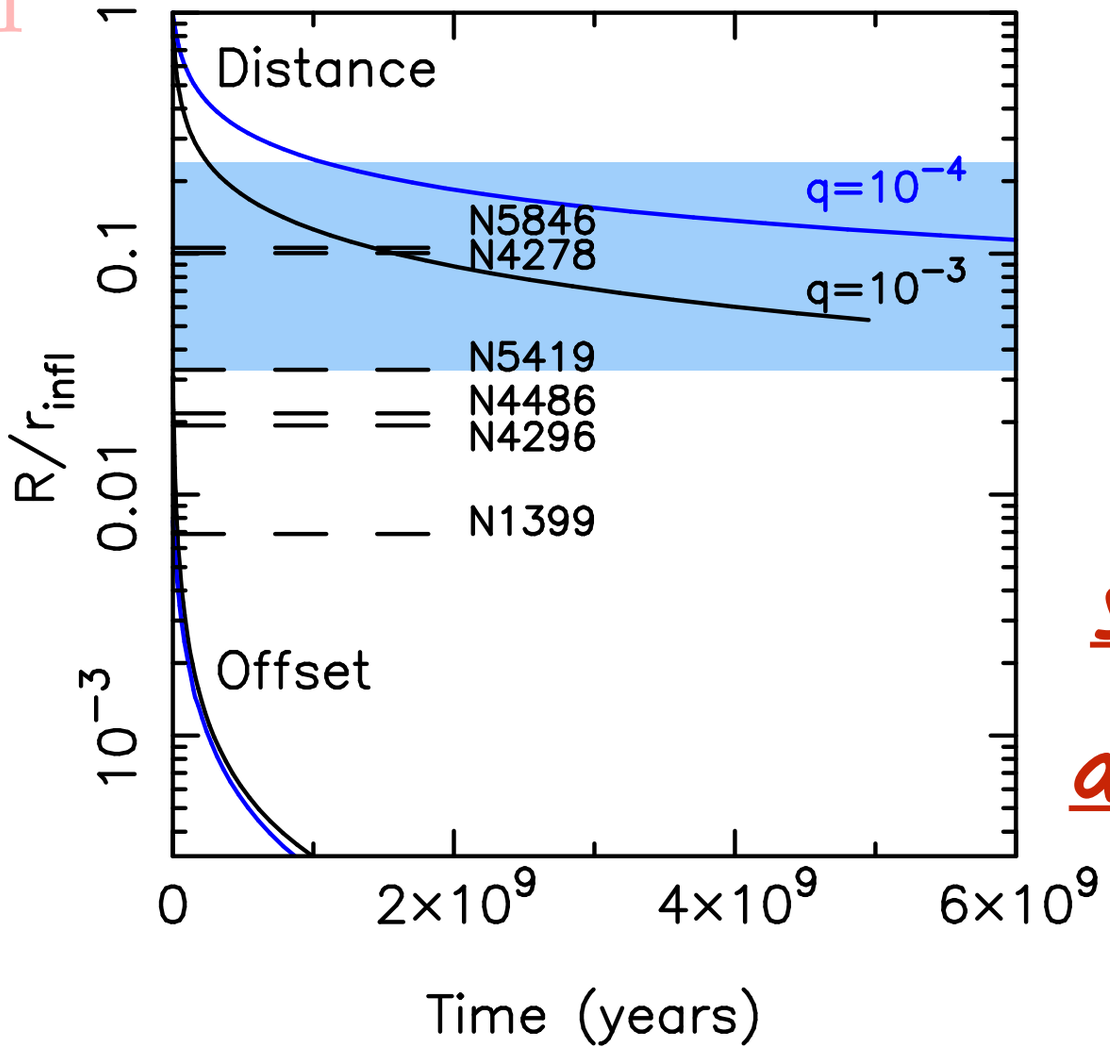
Bonfini & Graham 2016

off-center AGNs







AGN

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Stalled satellite accreting

Thank you!!