Formation and Evolution of nuclear stellar clusters and their components

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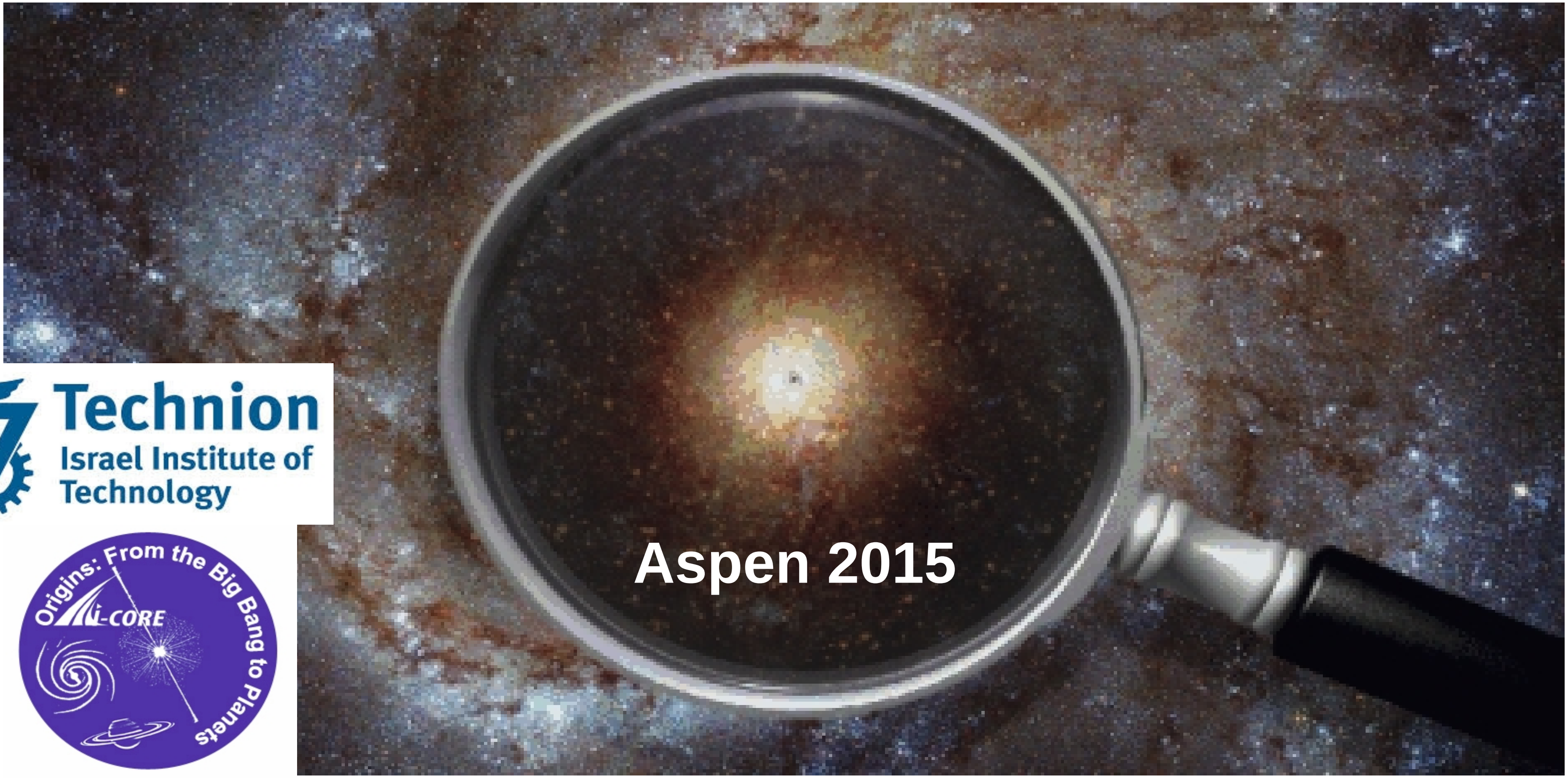
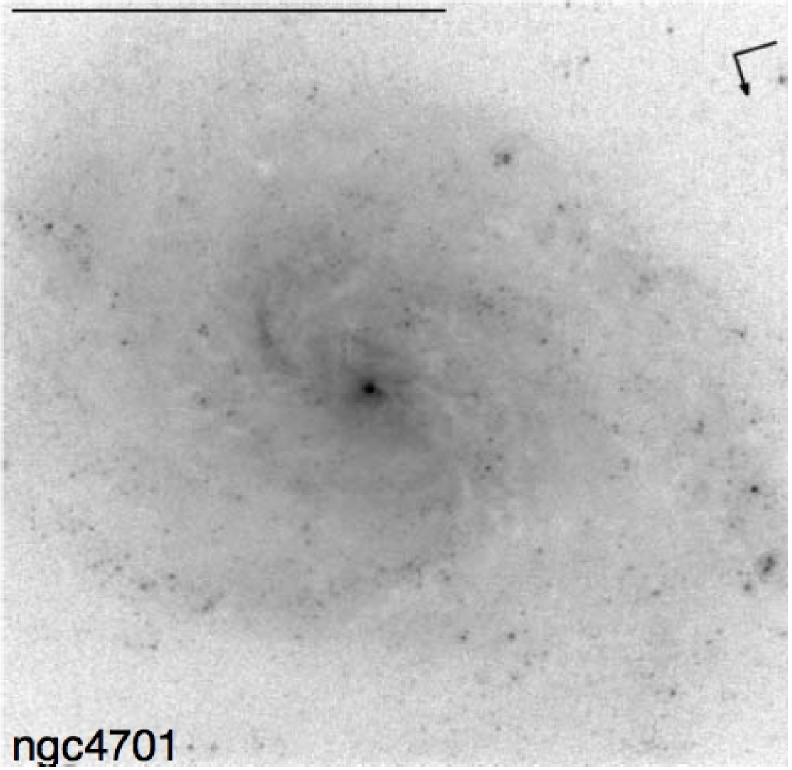
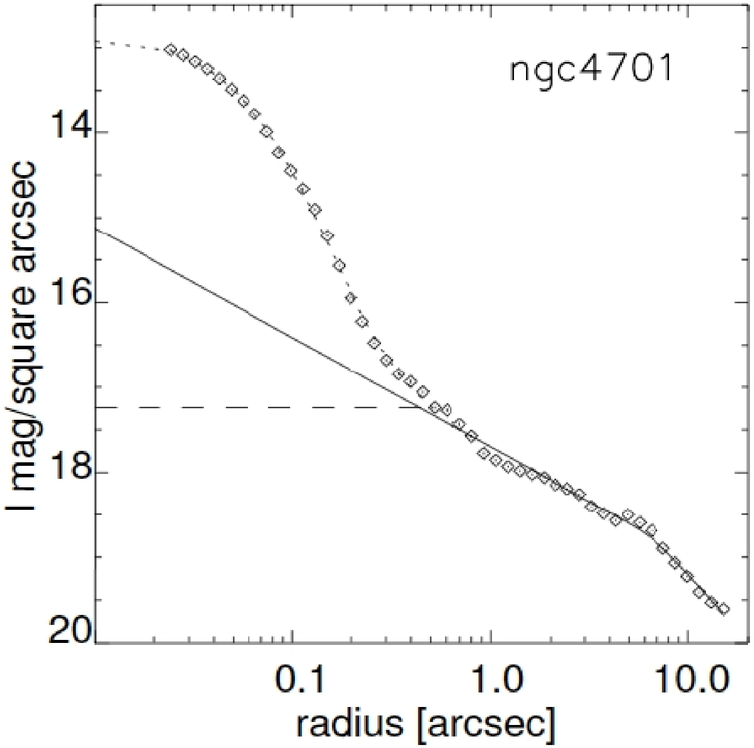


Aspen 2015

Allesandra Mastrobuono-Battisti, Danor Aharon, Diego Michaeloff

Dense Nuclear Stellar Clusters (NSCs) reside in most galactic nuclei





- **NSCs are detected in 50%-80% of spiral, (d)E, and S0 galaxies (e.g., Carollo et al. 1998; Matthews et al. 1999; Boker 2008).**
- **NSCs have typically half-light radii of 2-5 pc and masses of 10^6 - 10^7Msun**

Two NSC-formation scenarios were suggested

- The dry merger/cluster infall scenario in which a NSC is formed from the infall of multiple stellar clusters/galaxy mergers

  (e.g. Tremaine 1975; Ostriker 1988; Capuzzo-Dolcetta 1993, Antonini et al. 2012; Antonini 2014; Gnedin et al. 2014; **HBP** & Mastrobuobo-Battisti 2014; Mastrobuobo-Battisti & HBP 2014)

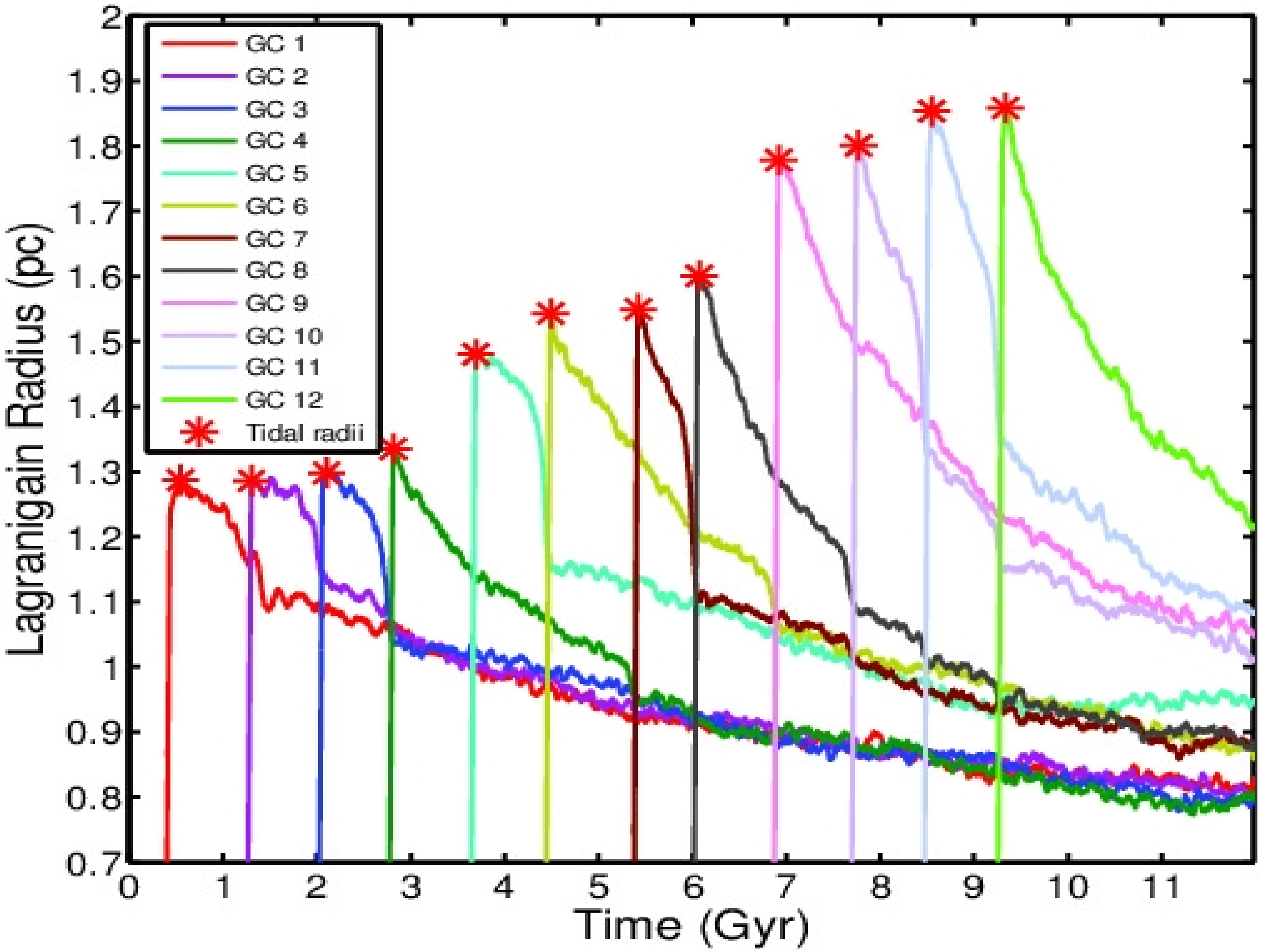
- The in-situ star formation scenario in which multiple star formation epochs in the nucleus build up the the NSC

  (e.g. Loose et al. 1982; Seth et al. 2006, Bekky 2007, Aharon & **HBP** 2015)

The dry scenario: The infall of multiple clusters form an NSC

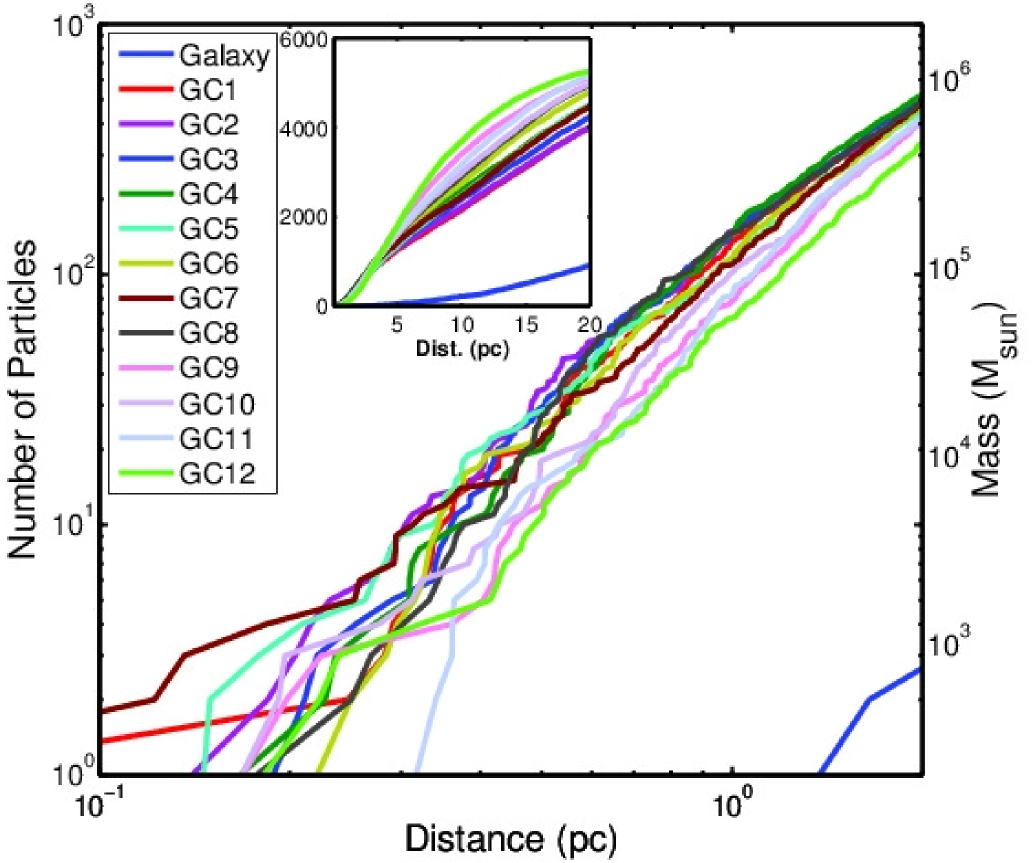
- The NSC is built from the infall of several massive clusters
- Potential problems: Long times for dynamical friction inspiral
  - However violent relaxation, instabilities and massive perturbers may help kick clusters into more radial orbits on shorter time scales
- Clusters infall produce stratification or “age segregation” - stars from later clusters are less concentrated near the center,

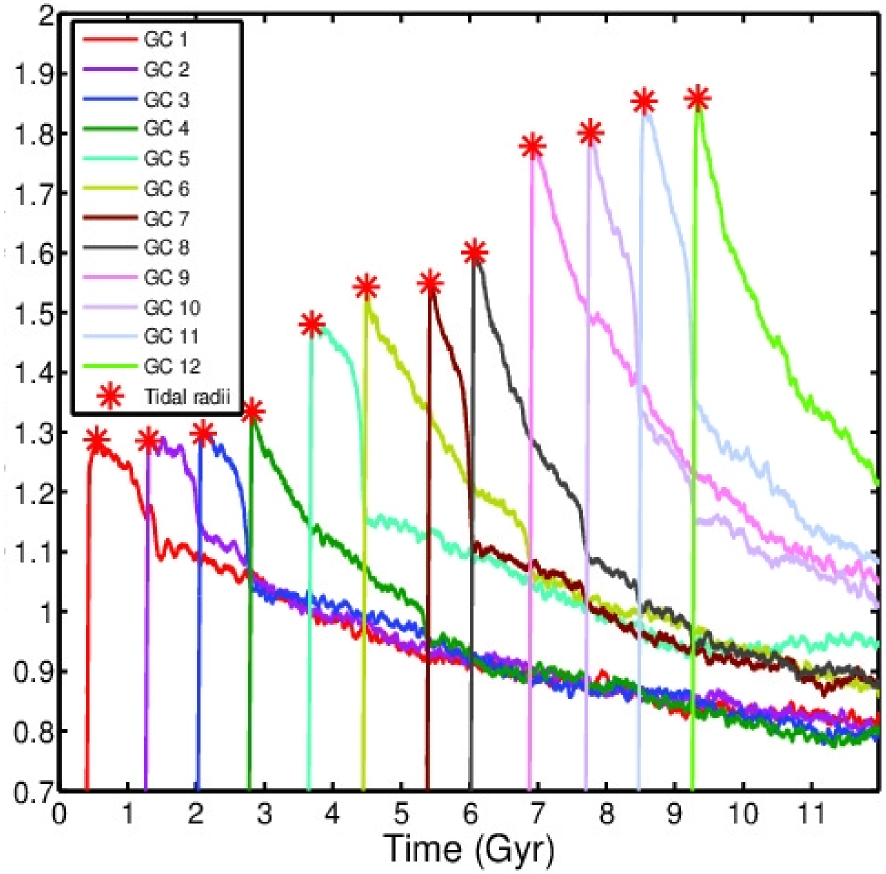
The cluster infall scenario produce a dynamical “age” segregation



HBP & Mastrobuono-Battisti 2014

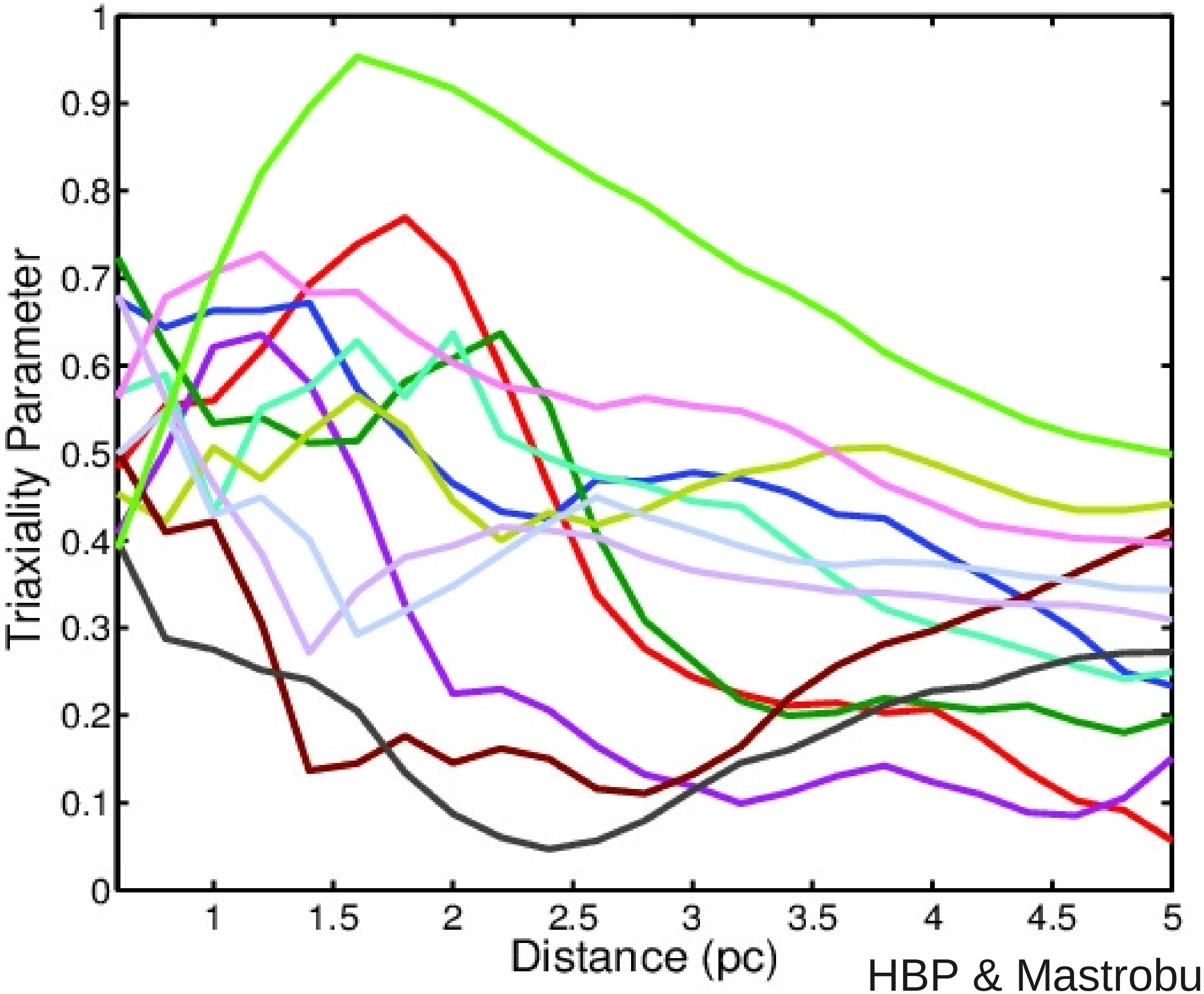
The cluster infall scenario produce a potential age/metallicity segregation





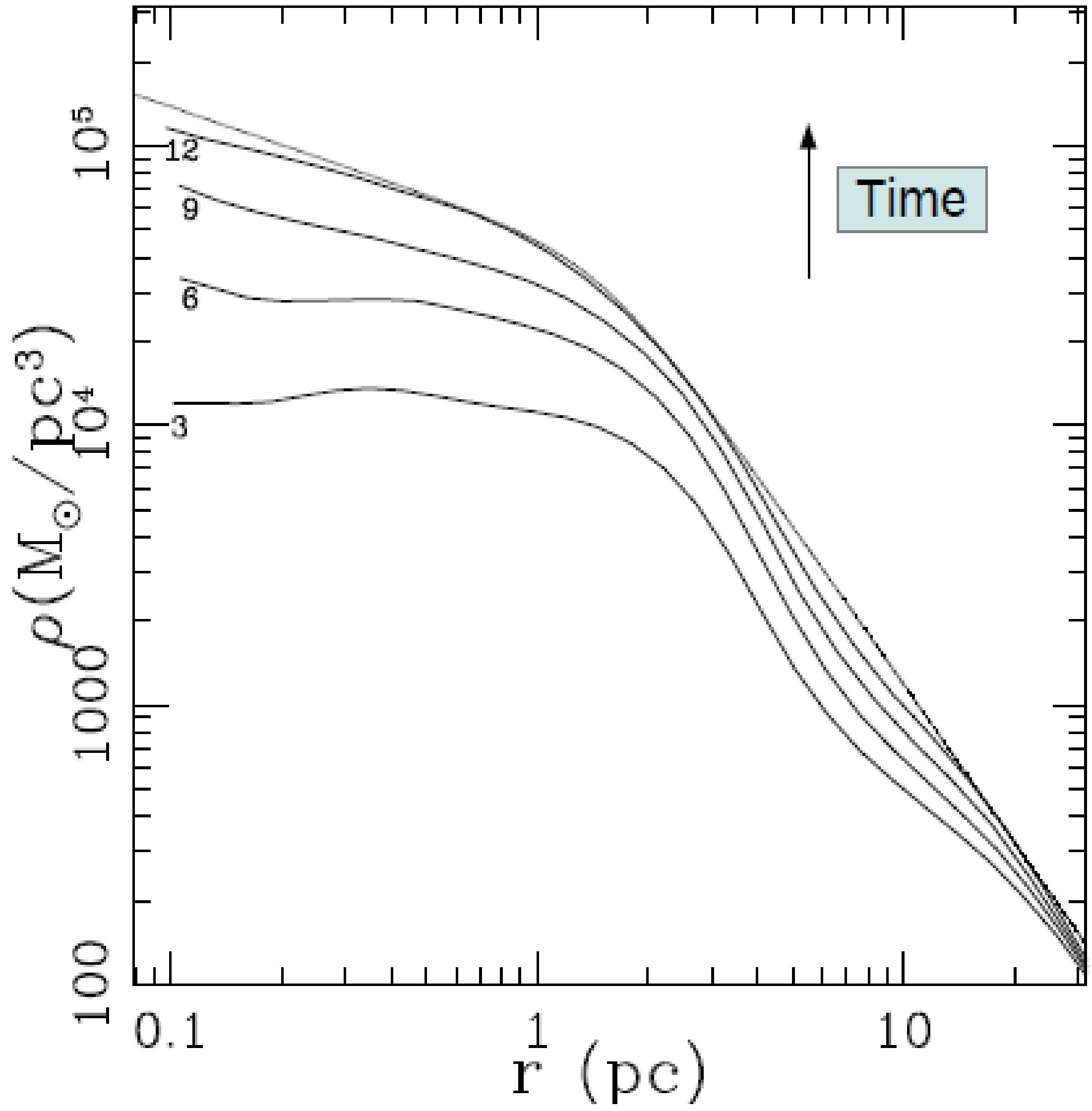
HBP & Mastrobuono-Battisti 2014

The cluster infall scenario also produces triaxiality, anisotropy and streams/disks-like sub-strcutures



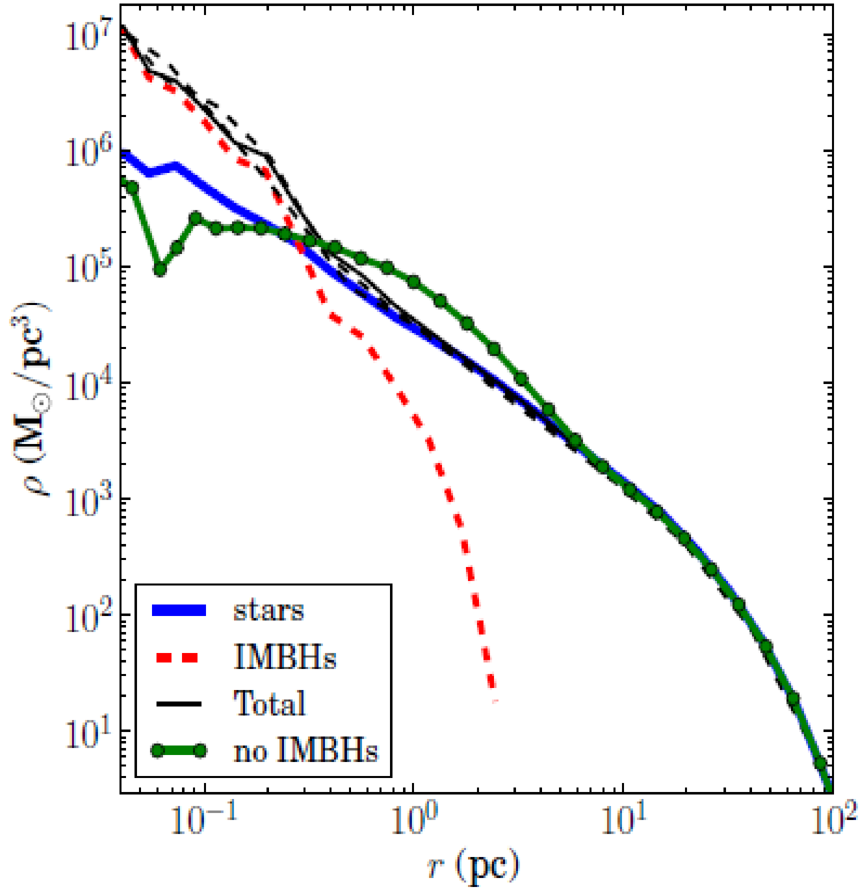
HBP & Mastrobuono-Battisti 2014

The infall scenario forms an NSC with a large core-like structure



NSC structure and global TDE rates can constrain the existence of IMBHs locally and globally

NSC structure W/WO IMBHs



- TDE rates for MW galaxy:
  - With IMBHs:

    ~10^-3 stars/yr
  - W/O IMBH:

    ~10^-5-10^-4 stars/yr

Mastrobuono-Battisti, HBP & Loeb 2014

The wet scenario: In-situ star formation builds-up the NSC

- Infall of a gaseous cloud leads to formation of a gaseous accretion disk
- Star formation may occur in such disks, producing stellar disks (e.g. Artymowicz+1993, Collin & Zahn+1999, Levin & Beloborodov+2003)
- Multiple such star-formation epochs build-up the NSC
- Most recent populations should not be relaxed

Long-term evolution of NSC through multiple SFR epochs: Fokker-Planck

- Stellar cusp around a MBH – Fokker Planck calculations (Bahcall & Wolf, 1976)

$$\underbrace{\frac{\partial g(x,\tau)}{\partial \tau}}_{DF} = \underbrace{-x^{5/2}\frac{\partial Q(x,\tau)}{\partial x}}_{flow\ \ rate} - \underbrace{R_M(x)}_{loss\ \ cone}$$

Aharon & HBP 2015

Long-term evolution of NSC through multiple SFR epochs: Fokker-Planck

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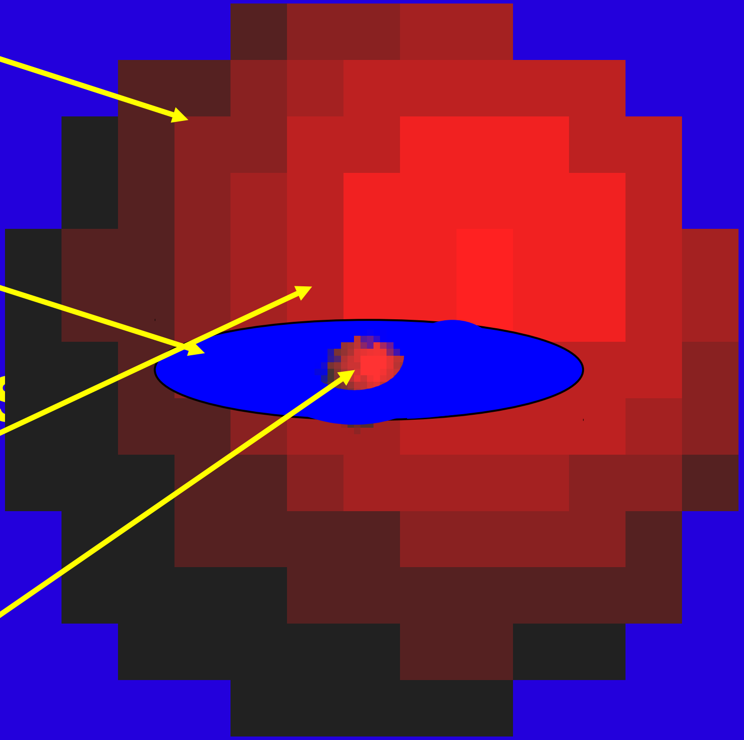
- Adding a source term from star formation

movie

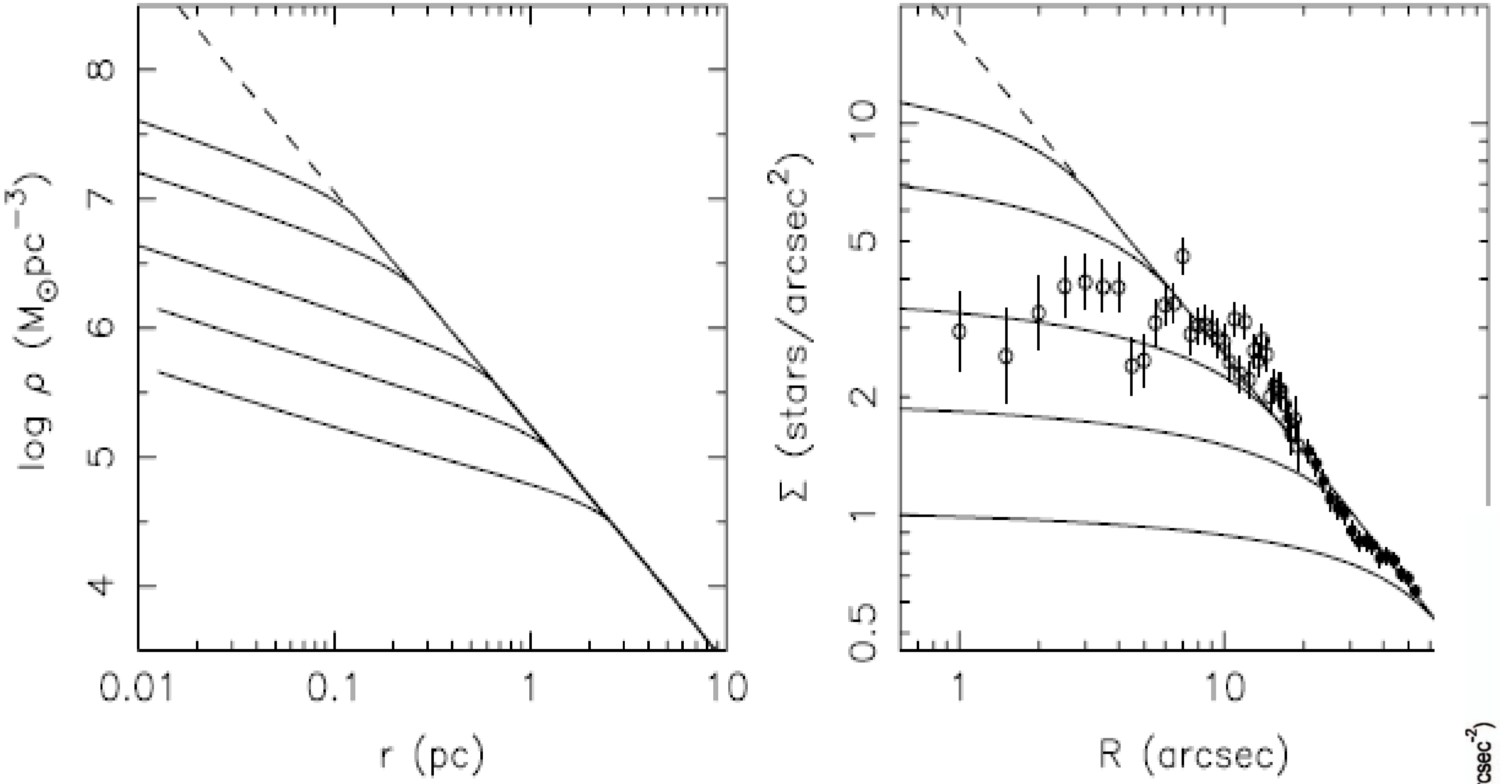
Aharon & HBP 2015

The Galactic Center: an NSC lab

- **Older stellar cusp**
  mass: ~10^6 M_{sun} (2-4 pc scale)
  with an inner-core region
- **Very young stellar disk**
  scale: 0.05-0.5 pc
  mass:10^3-10^4 M_{sun} age: ~5-7 Myrs
  - **Another more massive isotropic component**
- **Young B-stars**
  scale: ~0.5 pc ~200 early type B-stars on slightly super-thermal orbits



The GC NSC shows a core-like distribution for the red giants

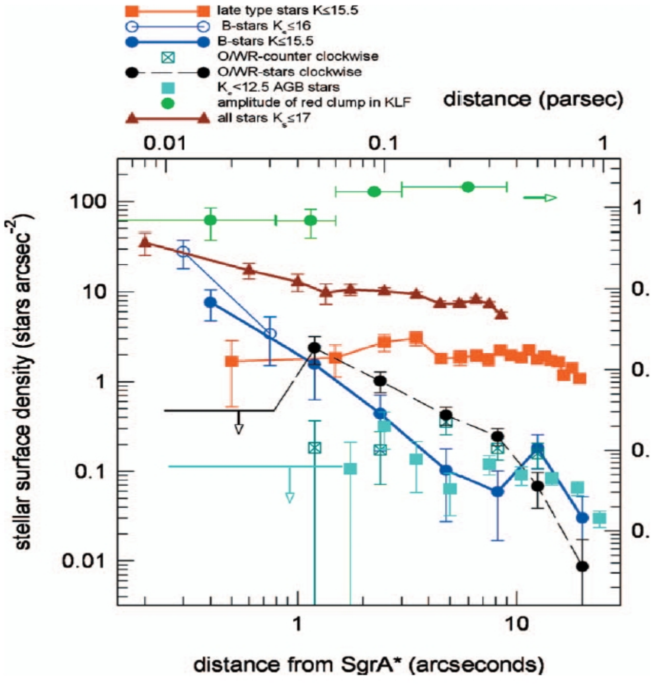


Merritt 2010

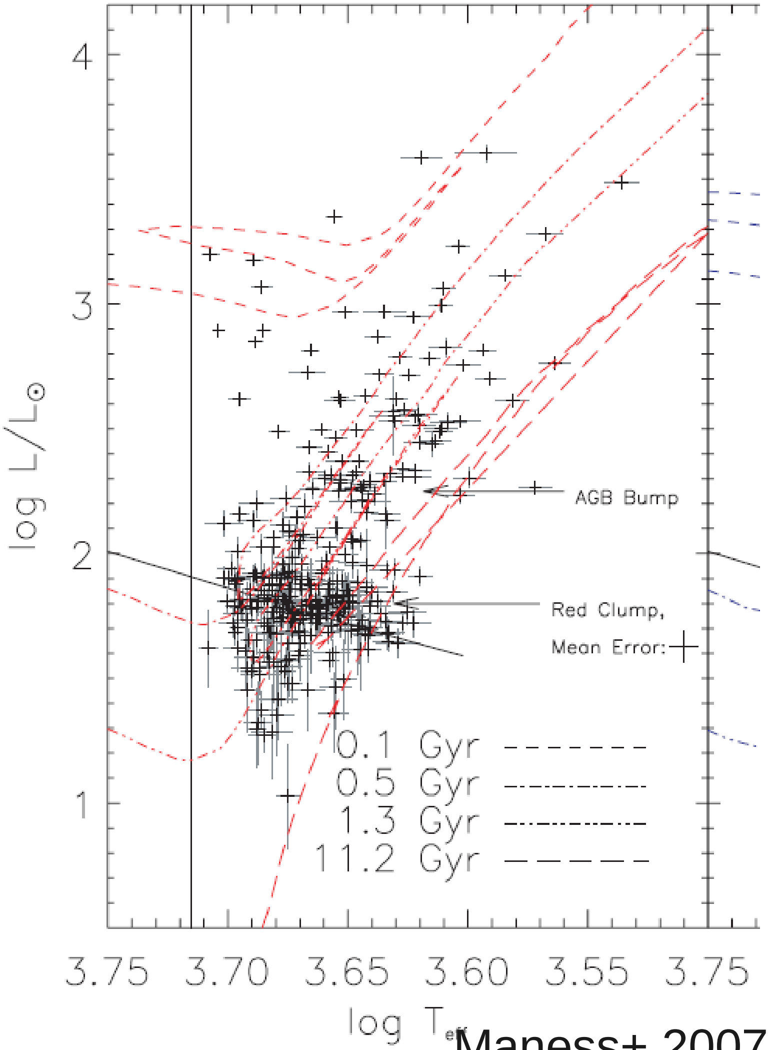
$$\rho(r) = \begin{cases} \text{const}, & \text{if } r \lesssim 0.5\text{pc} \\ \propto r^{-1.8}, & \text{if } 0.5 \lesssim r \lesssim 30pc \end{cases}$$

$$M_{NSC} \sim 10^7 \mathrm{M}_\odot$$

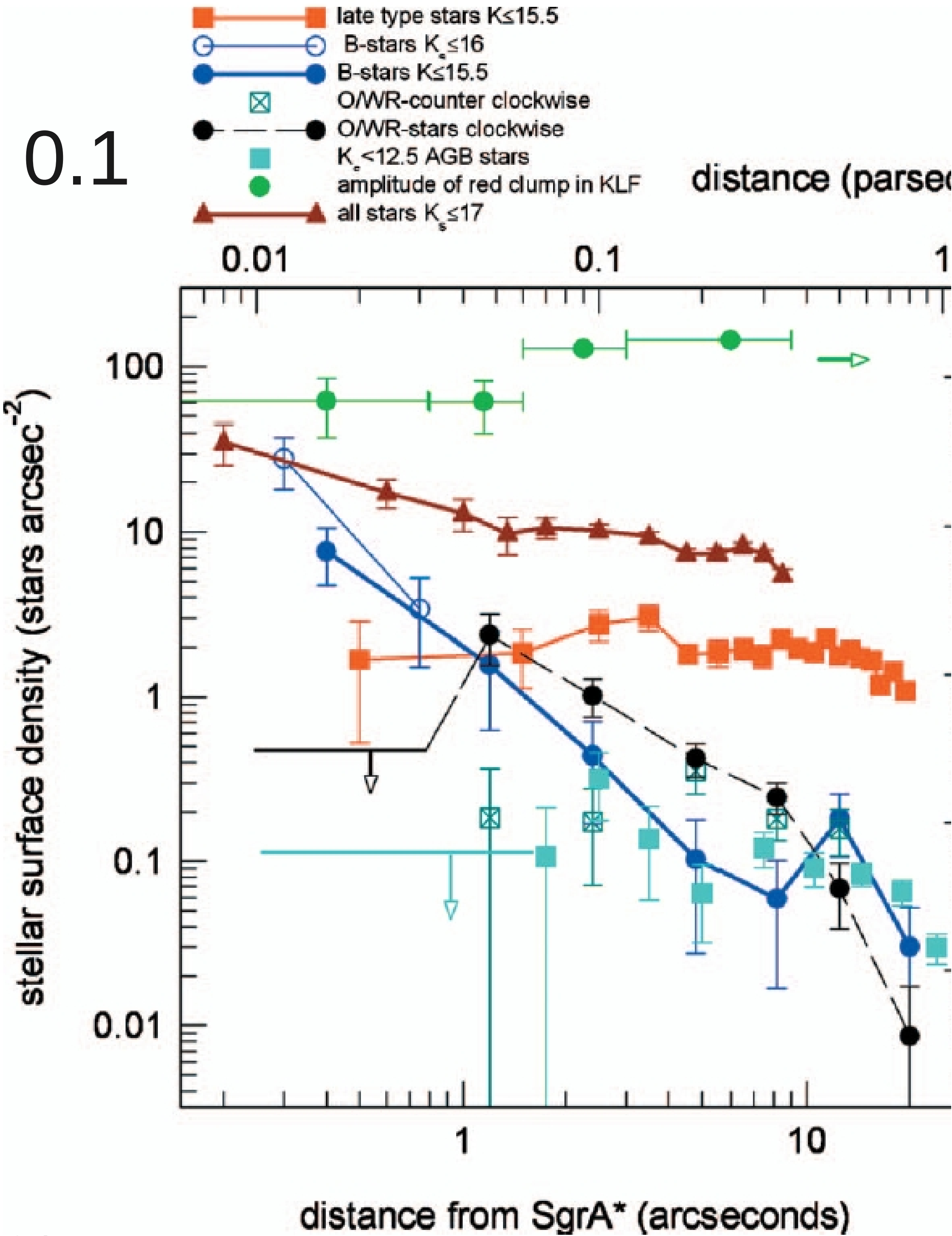
Genzel+2010



The ages of the red-giants range between 0.1 to a few Gyrs



Maness+ 2007, Pfuhl+ 2011

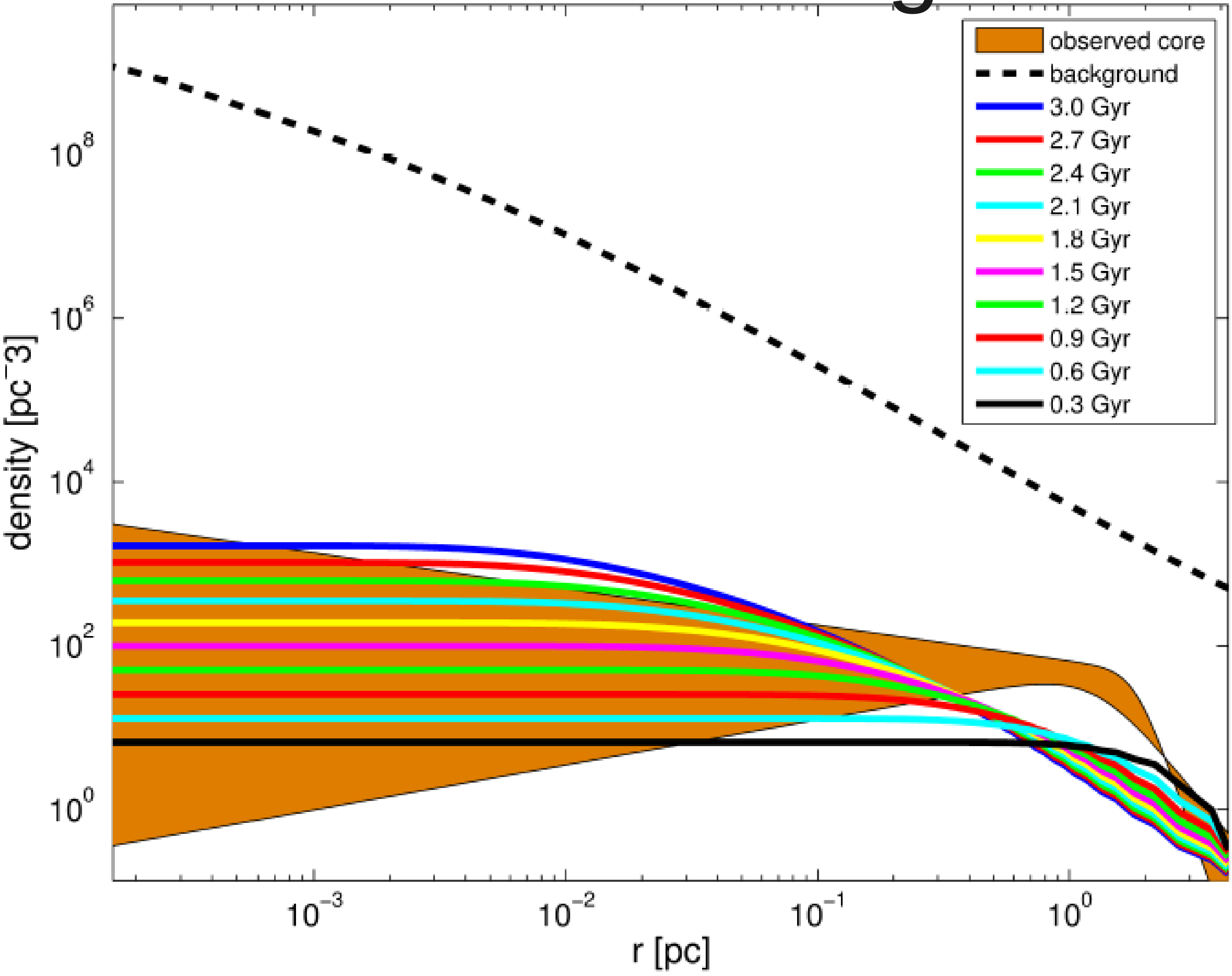


Genzel+ (2010)

Several origins were suggested for the GC core

- **Stellar collisions (e.g. Davies et al. 2010)**
  - > Too inefficient
- **Gaseous disk stripping (Amaro-Seone & Chen 2014)**
  - > Very fine-tuned (extreme radial dependence); marginally works only for very small cores (~0.1 pc at most)
- **Resonant relaxation clearing (Merritt+2015)**
  - Size of core limited. Affects all populations
- **Post IMBH-infall un-relaxed system (merritt 2010)**
  - > No IMBH observed, core for all stellar populations
- **The cluster infall scenario (Antonini et al. 2012, HBP & Mastrobuono-Battisti 2014)**
  - > Very large core of all stellar populations (with some age segregation)
- **In-situ formation scenario (Aharon & Perets 2015)**
  - > Core only for young stellar population, size can vary

SF can form an apparent core of intermediate age stars



Do et al. 2013

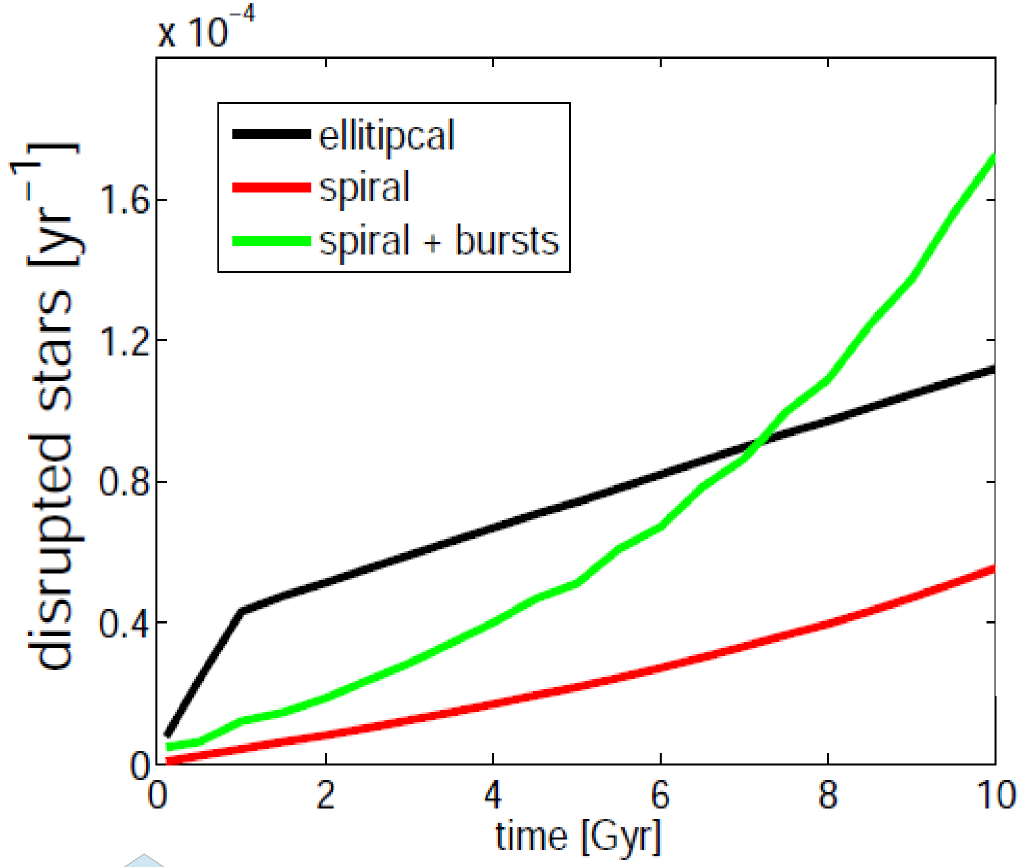
Aharon & HBP 2015.

Origin of the Galactic center NSC components (personal bias in blue...)

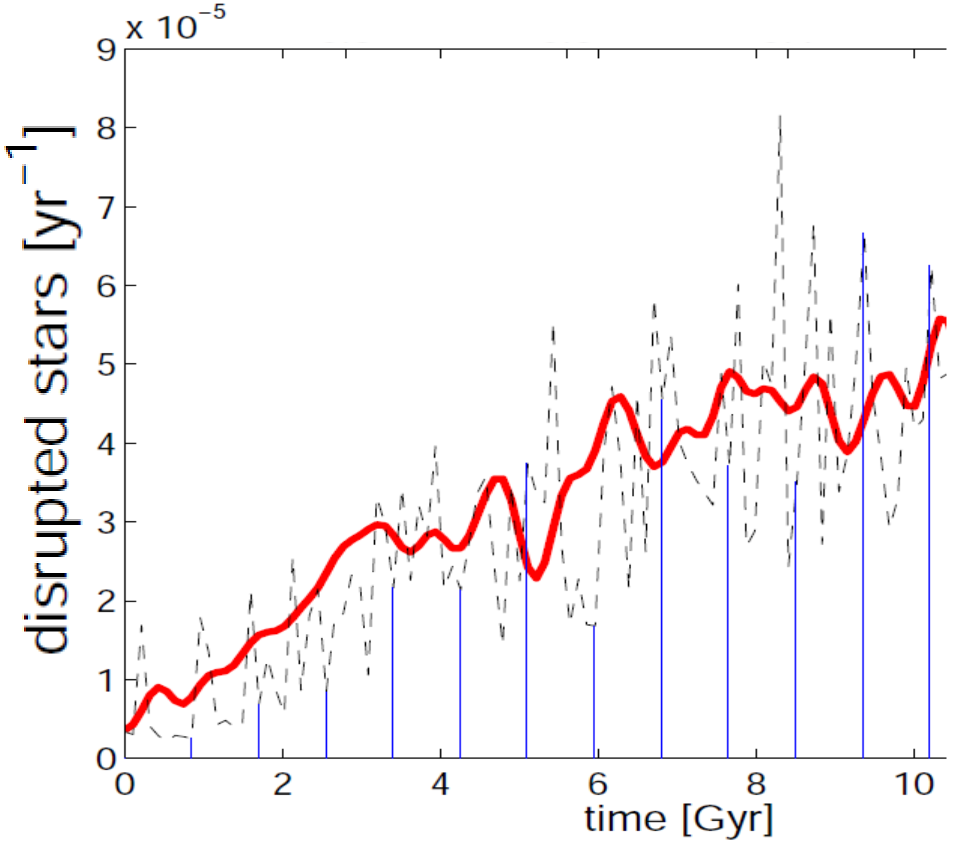
- Cusp -> cluster-infall/in-situ SF
- Disk -> Cloud infall + 2-body relaxation (Mapeli, Gualandris & HBP 2014)
- O-stars cluster -> cloud infall + ??
- Young B-stars -> Tidal binary capture + massive perturbers + resonant relaxation
- G2, G1 -> ?
- Apparent core (only red giants)
  - In-situ SF
- Global core ->
  - Big -> cluster-infall
  - Small -> RR clearing

The tidal disruption rate of stars evolves with time and depends on the NSC build-up history

In-situ SF



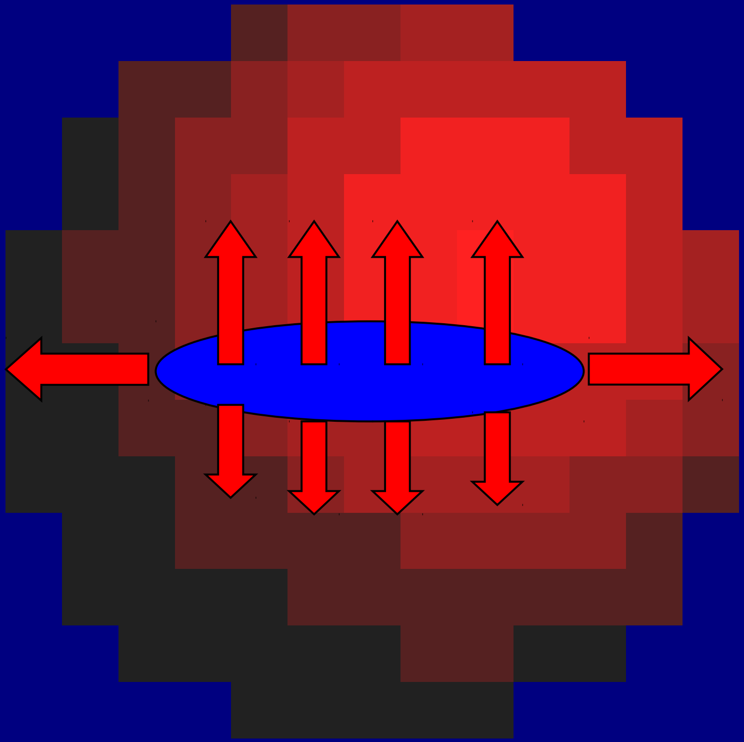
Cluster-infall



Aharon & Mastrobuono-
Battisti & Perets, in prep.

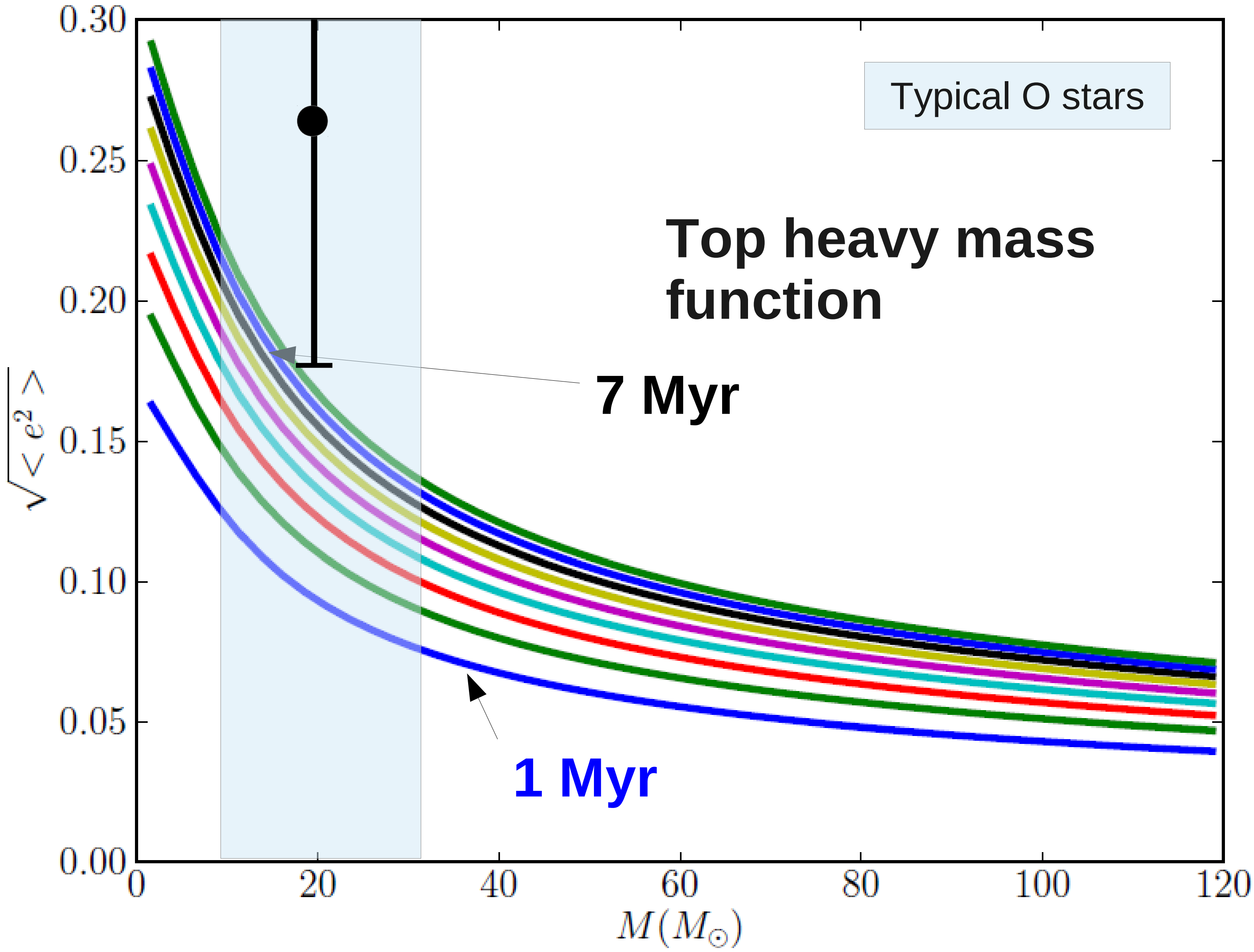
Dynamical evolution of the stellar disk: A hot cluster heats a cold disk

- A cold stellar disk embedded in a hot stellar cusp
- Disk heating:
  - Self interactions
  - Disk-cusp coupling
    - Regular (incoherent) relaxation
    - Collective effects:
      - Resonant (coherent) relaxation
      - Eccentric-disk instability
  - Massive-perturbers

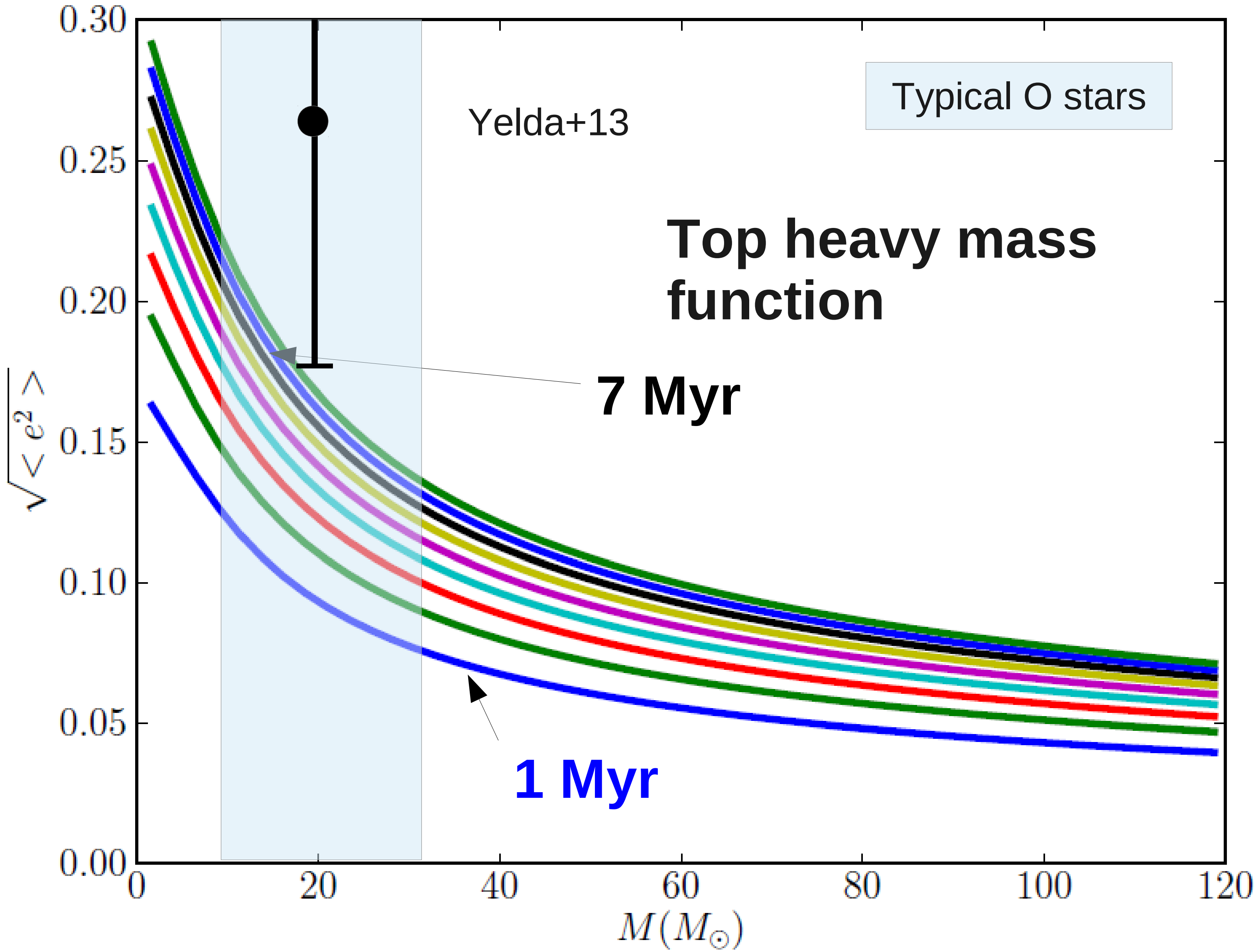


- Important components
  - Massive stars and stellar black holes
  - NSC potential

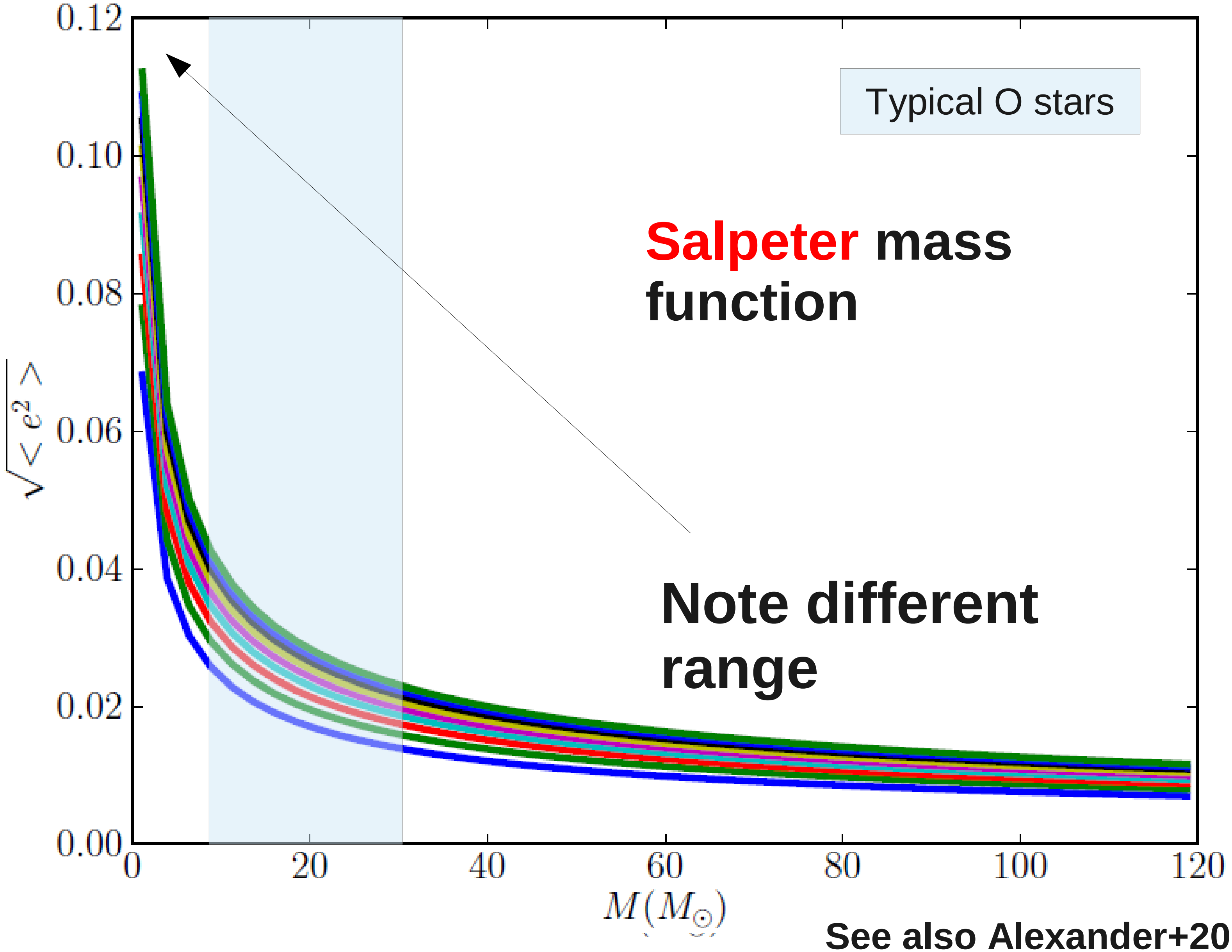
Results of 2-body disk heating are consistent with observations of O-stars



2-body Disk heating produces mass stratification



Top heavy MF required to explain disk properties



Typical O stars

Salpeter mass function

Note different range

See also Alexander+2007

A note on the relation between eccentricity and inclination

- In 2-body relaxation: e~2 x i
- For resonant relaxation inclination evolves much faster than eccentricity
- Eccentric disk instability -> Madigan talk (?)
- The relation can provide a signature for the relaxation process, and can constrain the stellar black holes population

Summary

- Both cluster infall and in-situ star formation can build-up NSCs
- Both processes leave behind “age-segregation” signature from the multiple population
- These can produce radial gradients and distinct strutures in the properties of NSC stellar populations
- In-situ SFR may produce apparent cores structure of younger and even intermediate-age stellar population, possibly explaining the GC core
- The history of TDEs can probe the evolution of NSCs

Summary II

- 2-body relaxation can explain the evolution of the stellar disk, but can not explain the large isotropic component of young stars
- Binary disruptions can also serve a source for stars in NSCs, and in particular the innermost regions of NSCs
- This process could important for understanding the origin of the young B-stars in the GC.

The disk heats due to 2-body releaxtion

$$t_{relax} = \frac{C\sigma^3}{G^2 M_* \rho \ln \Lambda}$$

$$\rho = \frac{NM_*}{2\Pi R_0 \Delta R (2H)}$$

$$t_{orb} = 2\Pi / \Omega$$

$$R = \Delta R = 0.15\, pc$$

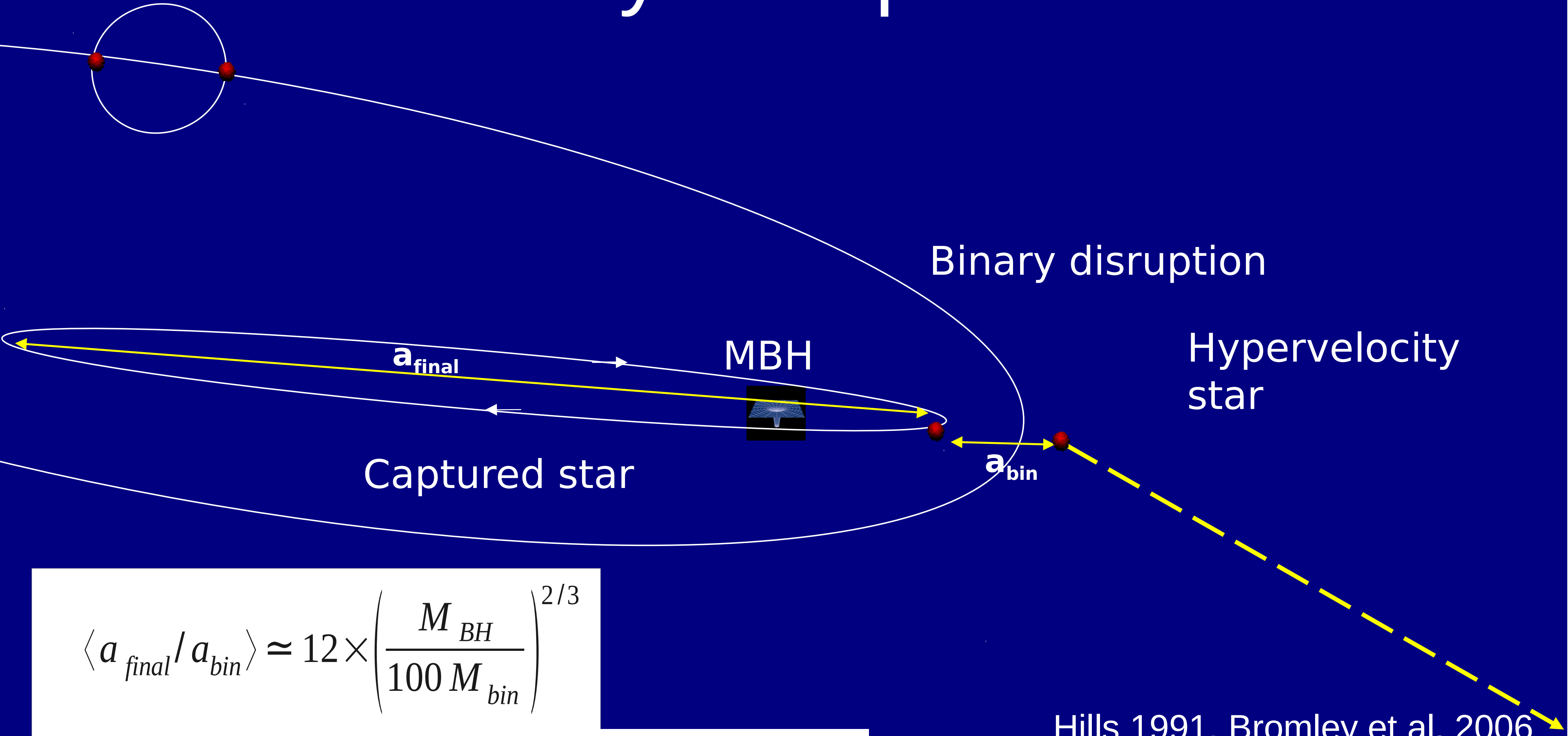
$$H = \sigma / \Omega$$

$$t_{relax} = \frac{C_1 R_0 \Delta R \sigma^4}{G^2 N M_{¿}^2 \ln \Lambda} t_{orb}$$

$$\frac{d\sigma}{dt} = \frac{G^2 N M_{¿}^2 \ln \Lambda}{C_1 R_0 \Delta R t_{orb} \sigma^3}$$

Alexander+2007
Michaeloff & HBP, in prep.

Binary disruption



Binary disruption

MBH

Hypervelocity star

a_{final}

Captured star

a_{bin}

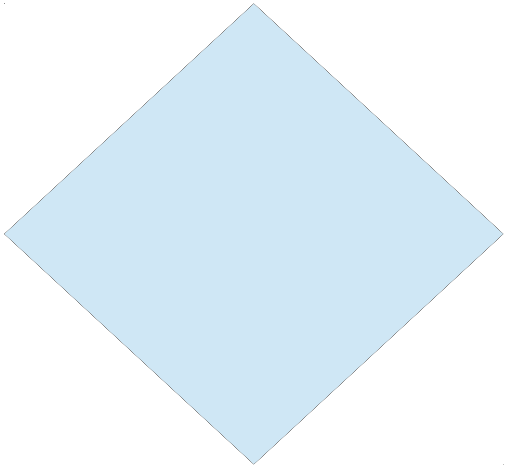
Hills 1991, Bromley et al. 2006

$$\langle a_{final}/a_{bin}\rangle \simeq 12\times\left(\frac{M_{BH}}{100\,M_{bin}}\right)^{2/3}$$

$e_{cap}=1-r_p/a_{cap}\sim 1-(M_{bin}/M_\bullet)^{1/3}>0.95$ in GC

Hills (1991,1992)

$$v_{BH}=892\ \mathrm{km\ s^{-1}}\left(\frac{a_{bin}}{1\ \mathrm{AU}}\right)^{-1/2}\left(\frac{M_{bin}}{8\,M_\odot}\right)^{1/3}\left(\frac{M_{BH}}{3.7\times10^6}\right)^{1/6}$$



Movie

Relaxed NSCs are cuspy

- Relaxed clusters around MBHs are expected to show a power-law radial density profile

  ($\rho \sim r^{-7/4}$; Bahcall-Wolf distribution)
- Binary MBH mergers may destroy nuclear clusters, forming a core
- Many NSCs in spiral galaxies show evidence for young nuclear disks/flattened structures

Relaxed NSCs are cuspy;
but real NSCs have curves...

- Mass segregation: Multiple-mass populations could have power laws ranging between -1.5 - -2
- Binary MBH mergers can scour NSCs and destroy them
-

Relaxed NSCs are cuspy; Real NSCs have curves...

- Relaxed clusters around MBHs are expected to show a power-law radial density profile ($\rho \sim r^{-7/4}$; Bahcall-Wolf distribution)
- Binary MBH mergers may destroy nuclear clusters, forming a core
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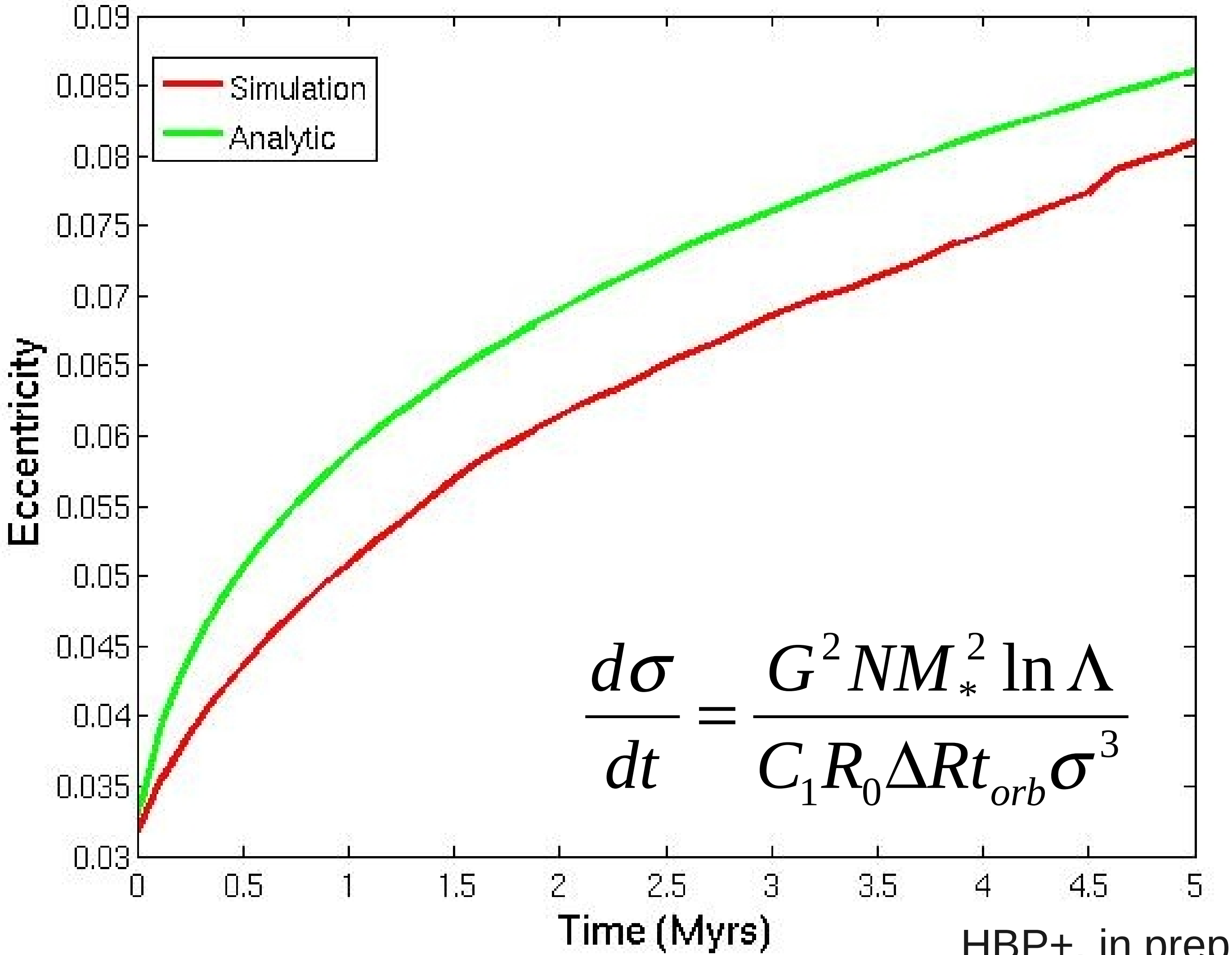
Isolated disk of equal mass stars



$$\frac{d\sigma}{dt} = \frac{G^2 N M_*^2 \ln\Lambda}{C_1 R_0 \Delta R t_{orb} \sigma^3}$$

HBP+, in prep.

Isolated disk of multi-mass stars

$$\frac{d\sigma_1}{dt} = \overbrace{\frac{N_1 M_1^2 \ln \Lambda}{A_1 t_{orb} \sigma_1^3}}^{Self\ Interaction} - \overbrace{\frac{N_2 M_1 M_2 \ln \Lambda}{A_2 t_{orb}} \frac{\sigma_1}{\bar{\sigma}_{12}} \left(1 - \frac{E_2}{E_1}\right)}^{Coupling}$$

$$\frac{d\sigma_2}{dt} = \overbrace{\frac{N_2 M_2^2 \ln \Lambda}{A_1 t_{orb} \sigma_2^3}}^{Self\ Interaction} - \overbrace{\frac{N_1 M_1 M_2 \ln \Lambda}{A_2 t_{orb}} \frac{\sigma_2}{\bar{\sigma}_{12}} \left(\frac{E_1}{E_2} - 1\right)}^{Coupling}$$

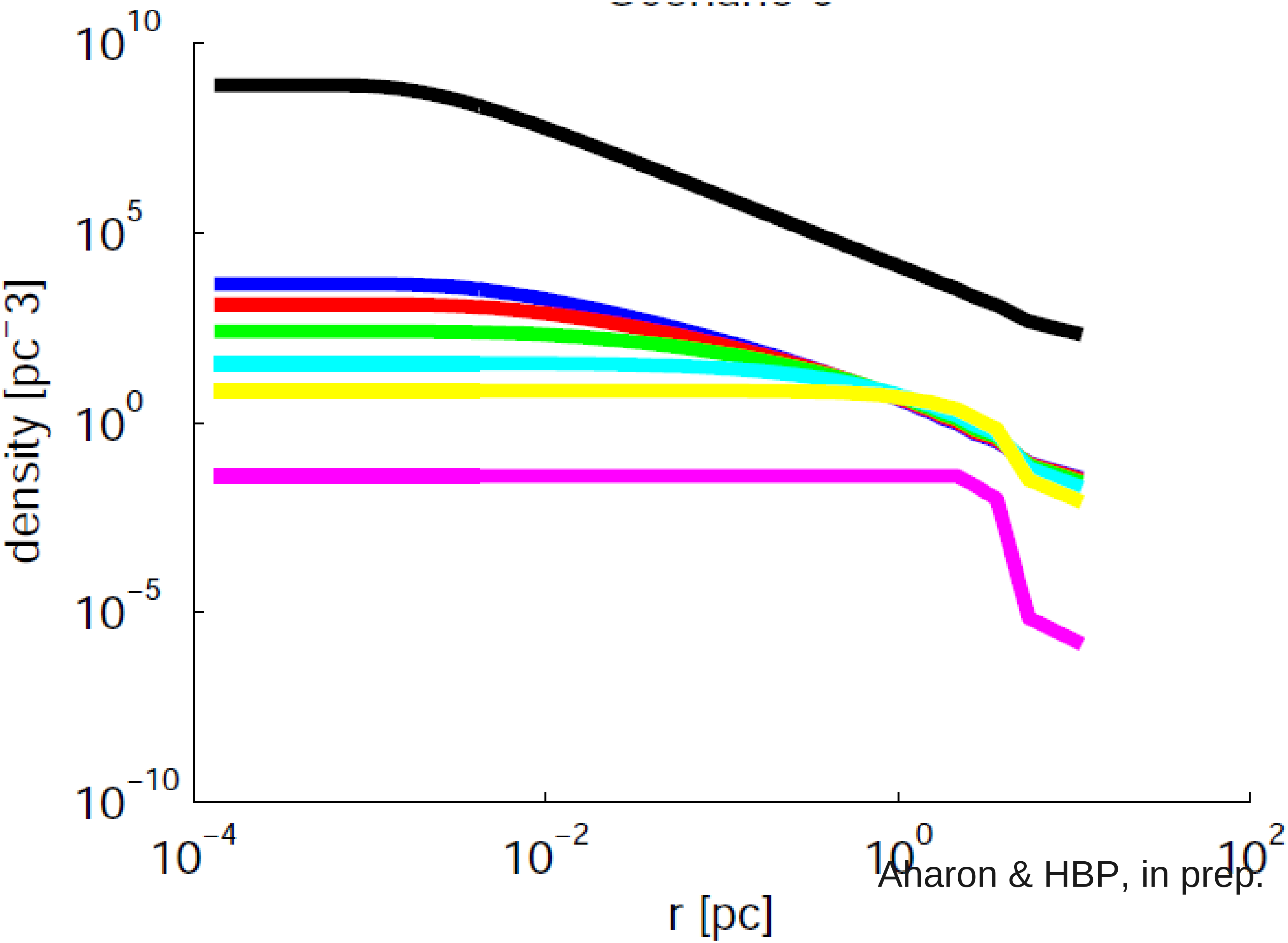
$$E_i = 3 M_i \sigma_i^2 / 2$$

$$A_i = C_i R_0 \Delta R / G^2$$

$$\bar{\sigma}_{12} = (\sigma_1 + \sigma_2) / 2$$

Alexander, R. et al. 2007

NSC-build-up and intermediate age cores



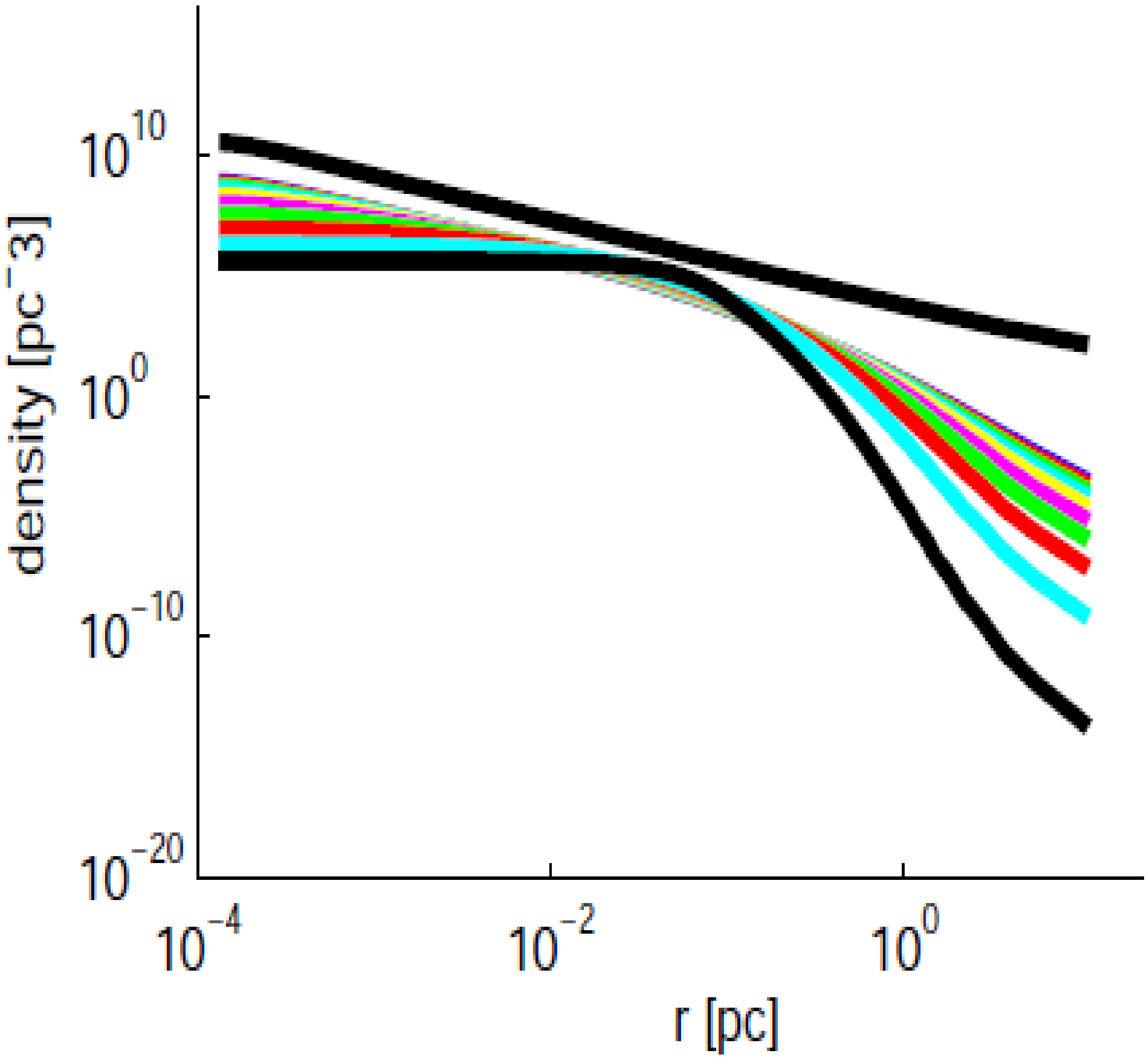
Aharon & HBP, in prep.

Captured Stars and Cusp Structure

- Stellar cusp around a MBH : Fokker Planck calculations (Bahcall & Wolf, 1976)

$$\underbrace{\frac{\partial g(x,\tau)}{\partial \tau}}_{DF} = \underbrace{-x^{5/2}\frac{\partial Q(x,\tau)}{\partial x}}_{flow\ \ rate} - \underbrace{R_M(x)}_{loss\ \ cone} + \boxed{\underbrace{B(x)}_{binary\ \ source}}$$

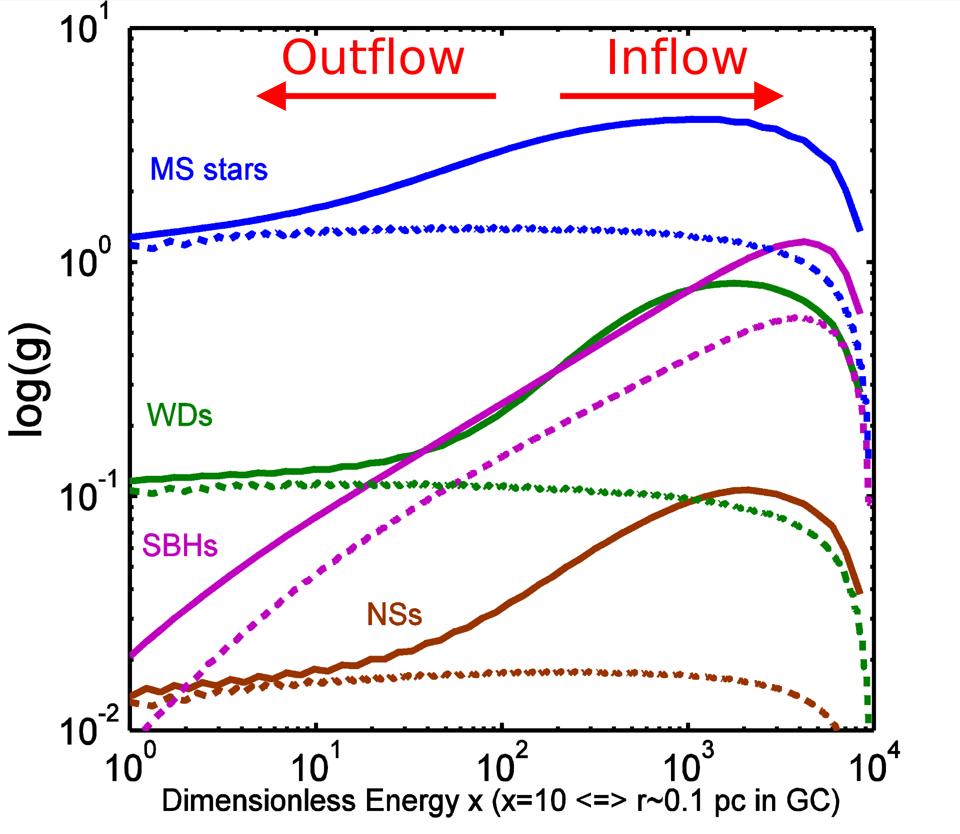
- Adding a source term from binary disruptions

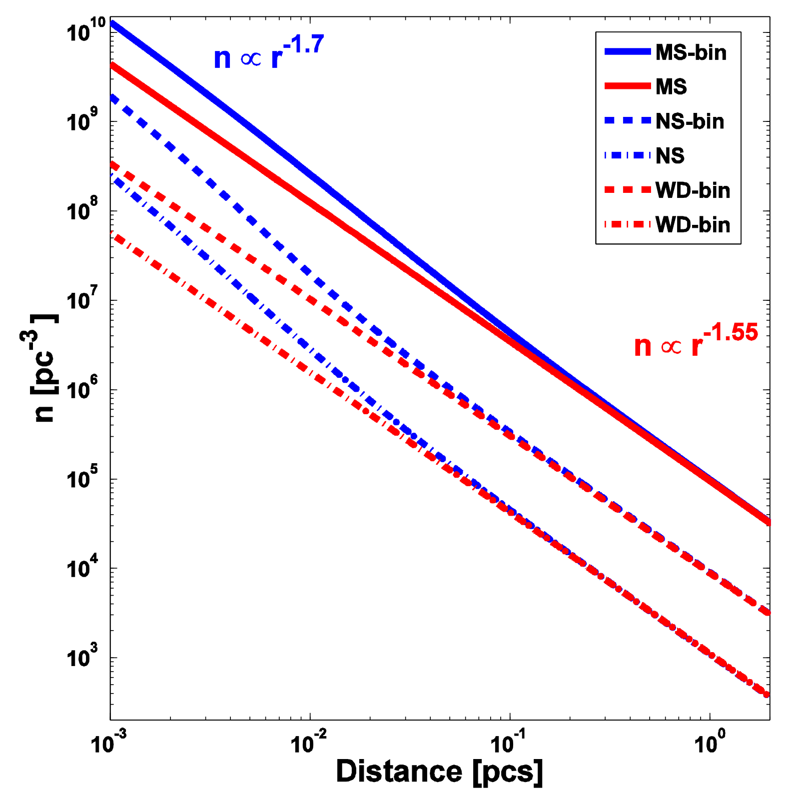

density [pc^-3]
10^{10}
10^{0}
10^{-10}
10^{-20}
10^{-4}
10^{-2}
10^{0}
r [pc]

Population segregation

- Should exist for 2-body relaxing system
- Non-observation will require some type of violent relaxation which produce complete mixing

Compact object and cusp Structure





- Binary source can cause outflow of single stars from the cusp.

Summary

- We discussed the formation and evolution of NSCs through cluster infall and in-situ star formation
- Both processes leave behind “age-segregation” signature from the multiple population
- These can produce radial gradients in the properties of NSC stellar populations
- Hybrid models are likely most realistic
- In-situ SFR may produce apparent cores structure of younger and even intermediate-age stellar population, possibly explaining the GC core

Summary II

- Binary disruptions can also serve a source for stars in NSCs, and in particular the innermost regions of NSCs
- This process could important for understanding the origin of the young B-stars in the GC.

We use N-body simulations to study the cluster-infall scenario

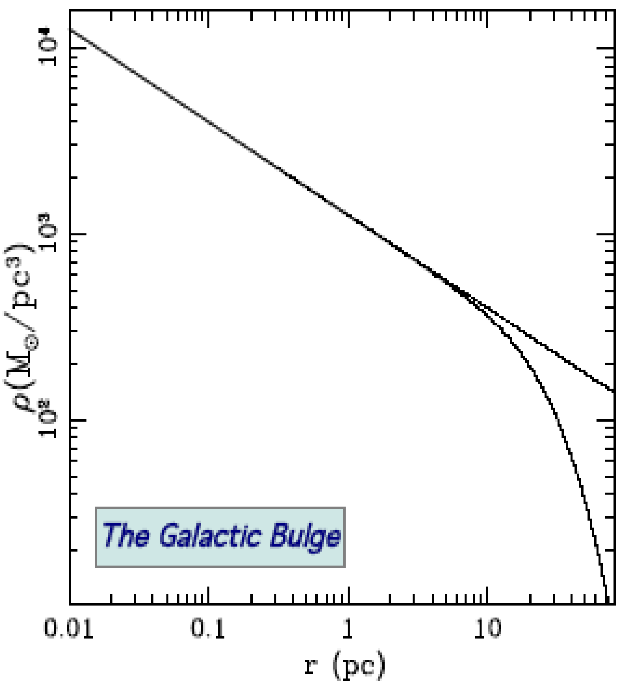
- 12 consecutive infall of 10^6 Msun clusters into galactic nucleus (MBH with 4x10^6 Msun)
- Analysis of the NSC structure, and the distribution of the multiple population of stars
- Later we explored the possibility of infall of IMBH-hosting cluster

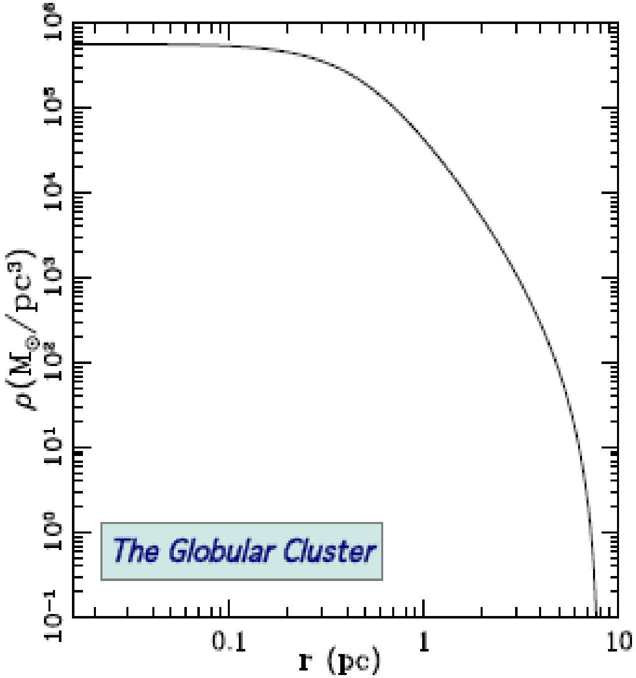
Initial Conditions

We modeled the Galaxy by mean of a truncated power law

$$\rho(r) = 400 \left(\frac{r}{10\mathrm{pc}}\right)^{-0.5} \mathrm{sech}\left(\frac{r}{22\mathrm{pc}}\right) \mathrm{M}_\odot/\mathrm{pc}^3.$$

For The GCs we used a King model with $W_0 = 5.8$, $\sigma_K = 35\mathrm{km/s}$, $r_c = 0.5\mathrm{pc}$, r_t=8pc and $M = 1.1 \times 10^6 \mathrm{M}_\odot$. In one set of simulations, at the center of each GC there is an IMBH with $M = 10^4 \mathrm{M}_\odot$.





The Cluster Infall Scenario: The movie

Movie

The cluster infall scenario: Dynamical age and mass segregation

- Stars at R_c from the infalling cluster center are stripped by MBH and the NSC at Rs, defined as the tidal radius for stars at that position:

$$R_s = \left(\frac{M_{BH} + M_{NSC}(< R_t)}{M(< R_c)} \right)^{1/3} R_c$$

HBP & Mastrobuono-Battisti 2014