Importance of mass segregation in galactic nuclei

Collaboration with
Pau Amaro-Seoane (Albert Einstein Institut, Golm)
Vicky Kalogera (Northwestern University, Evanston)

astro-ph/0603280 astro-ph/0607001

Marc Freitag
Institute of Astronomy, Cambridge

In a nutshell...

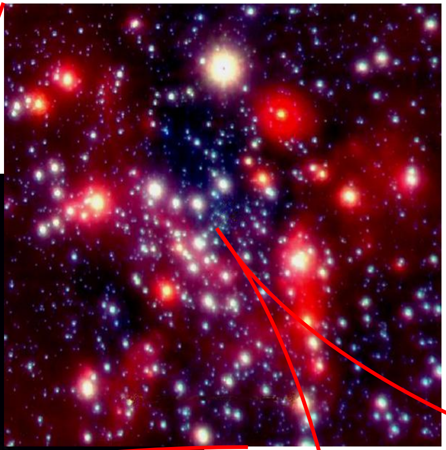
- Nature of mass-segregation
  - Evolution toward kinetic energy equipartition due to 2-body relaxation; timescale $t_{segr} \approx (<m>/m_{heavy}) t_{relax}$
  - More massive objects drift to the centre
- Important for compact stars (stellar BHs)
  - More massive than the average star
  - Long lived (age > t_{segr})!
- Many (possible) observational consequences
  - Distribution of visible stars (pushed out?)
  - Distribution of X-ray sources around Sgr A*
  - Collisions between stars (featuring BHs)
  - Future observations of pulsars around Sgr A*
  - Tidal disruption rates
  - Extreme mass-ratio inspirals for LISA

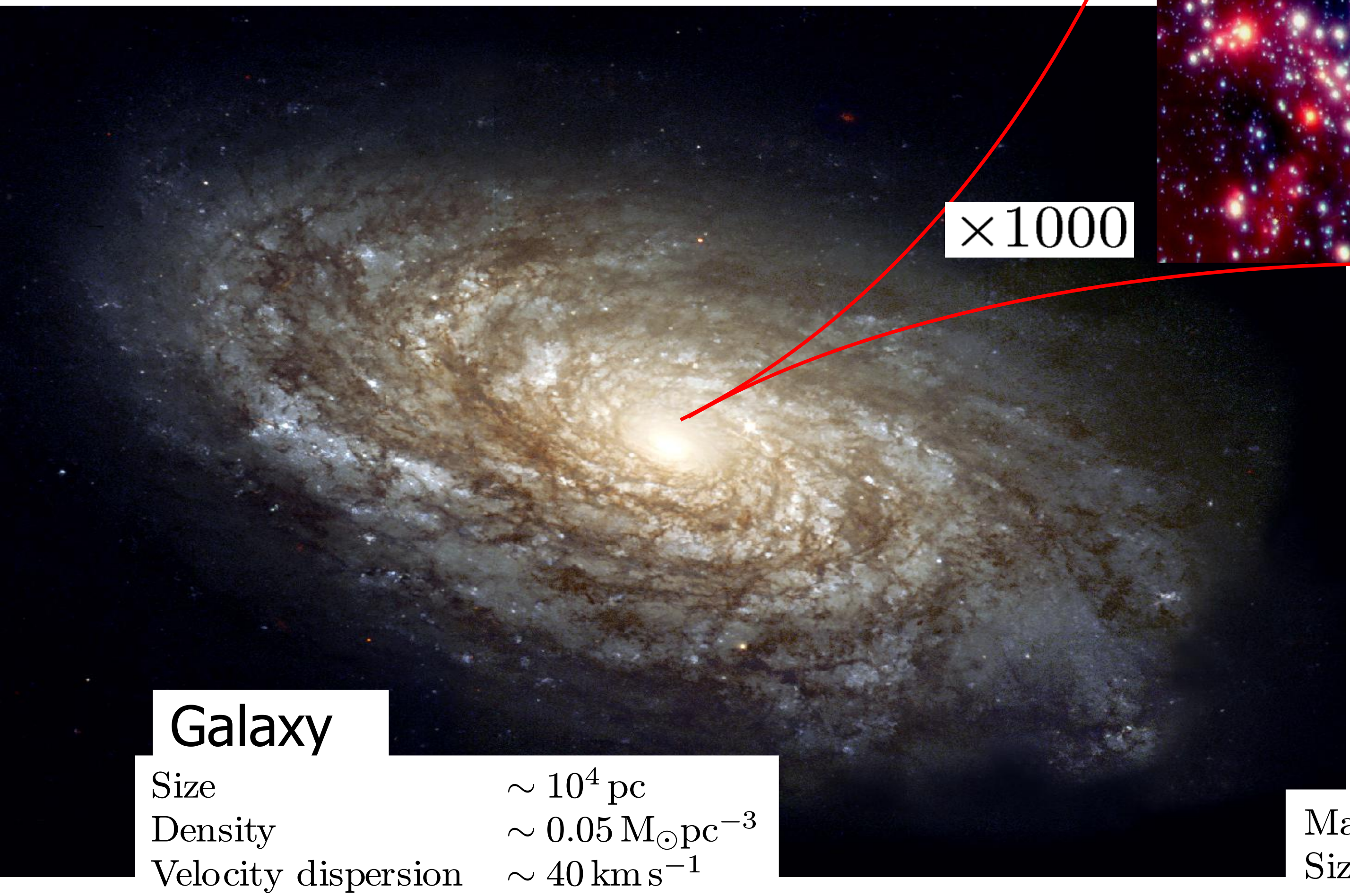
Marc Freitag
freitag@ast.cam.ac.uk

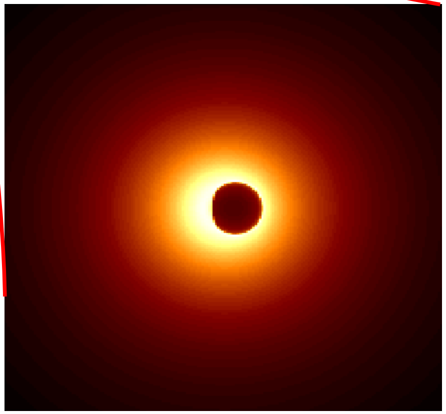
The stage: The galactic nucleus

Galactic nucleus

Size	$\sim 1 - 10\,\mathrm{pc}$
Density	$\sim 10^6 - 10^8\,\mathrm{M_\odot pc^{-3}}$
Velocity dispersion	$\sim 100 - 1000\,\mathrm{km\,s^{-1}}$
Relaxation time	$\sim 10^8 - 10^{10}$ years







Massive Black Hole

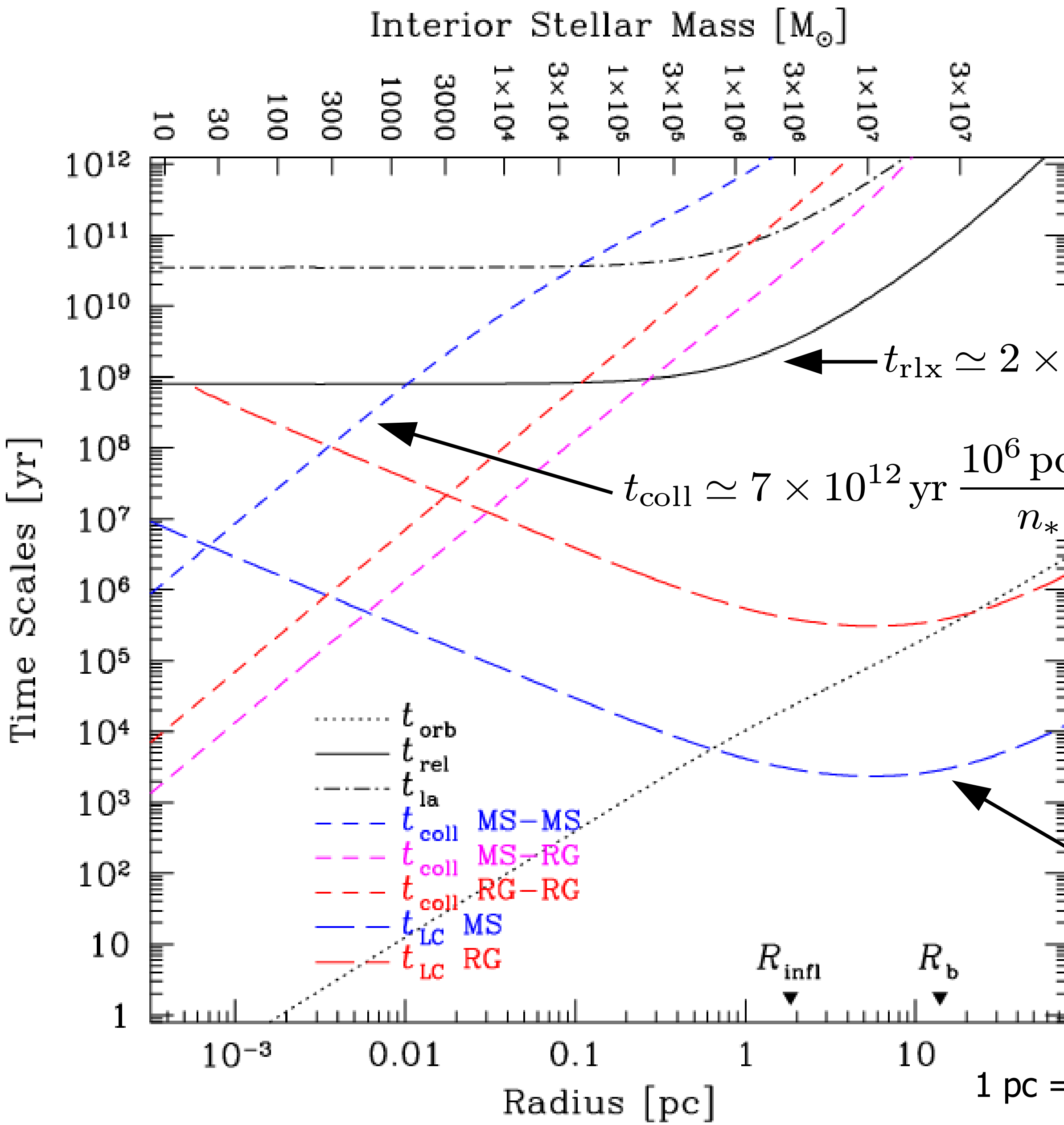
Mass	$10^6 - 10^9\,\mathrm{M_\odot}$
Size	$R_S = 2GM_\bullet/c^2 = 10^{-7} - 10^{-4}\,\mathrm{pc}$
Spin	??

Galaxy

Size	$\sim 10^4\,\mathrm{pc}$
Density	$\sim 0.05\,\mathrm{M_\odot pc^{-3}}$
Velocity dispersion	$\sim 40\,\mathrm{km\,s^{-1}}$
Relaxation time	$\sim 10^{15}$ years

Marc Freitag
freitag@ast.cam.ac.uk

Time scales in Sgr A* nucleus



$$t_{\rm rlx} \simeq 2\times10^9\,{\rm yr}\,\frac{10^6\,{\rm pc}^{-3}}{n_*}\left(\frac{\sigma_v}{100\,{\rm km\,s}^{-1}}\right)^3\left(\frac{{\rm M}_\odot}{M_*}\right)^2$$

$$t_{\rm coll} \simeq 7\times10^{12}\,{\rm yr}\,\frac{10^6\,{\rm pc}^{-3}}{n_*}\,\frac{\sigma_v}{100\,{\rm km\,s}^{-1}}\,\frac{{\rm R}_\odot}{R_*}\,\frac{{\rm M}_\odot}{M_*}$$

Time scale for relax.
to replenish loss cone

$$t_{\rm LC} = \theta_{\rm LC}^2 t_{\rm rlx} \simeq (1-e_{\rm LC})t_{\rm rlx}$$

1 pc = 27 arcsec

Marc Freitag
freitag@ast.cam.ac.uk

The Monte Carlo stellar dynamics method

ME(SSY)**2 "Monte Carlo Experiments with Spherically SYmmetric Stellar SYstems"

Freitag & Benz 2001, 2002

- Uses 3 central assumptions:
  - Spherical symmetry
  - Dynamical equilibrium
  - Diffusive 2-body relaxation (Chandrasekhar; Fokker-Planck)

- Represents the cluster with particles
  - 1 particle = 1 spherical shell (given orbital and stellar prop.)
  - 1 particle = many stars (possibly) ⇒ No limit on N_*
  - Local time steps $\delta t \cdot \ f_{\delta t} \cdot \min(T_{\rm rlx}, T_{\rm coll}, \ldots)$
- Allows rich physics
  - Cluster (+central object) self-gravity; *V*-anisotropy; Any *M*-spectrum
  - 2-body relaxation; Stellar collisions (use SPH data); Stellar evolution
  - "Loss-cone processes": Tidal disruptions; Plunges; GW-captures
- Fast $T_{\rm CPU}/t_{\rm rlx} \propto N \ln N \Rightarrow N \approx 10^4 - 10^7$

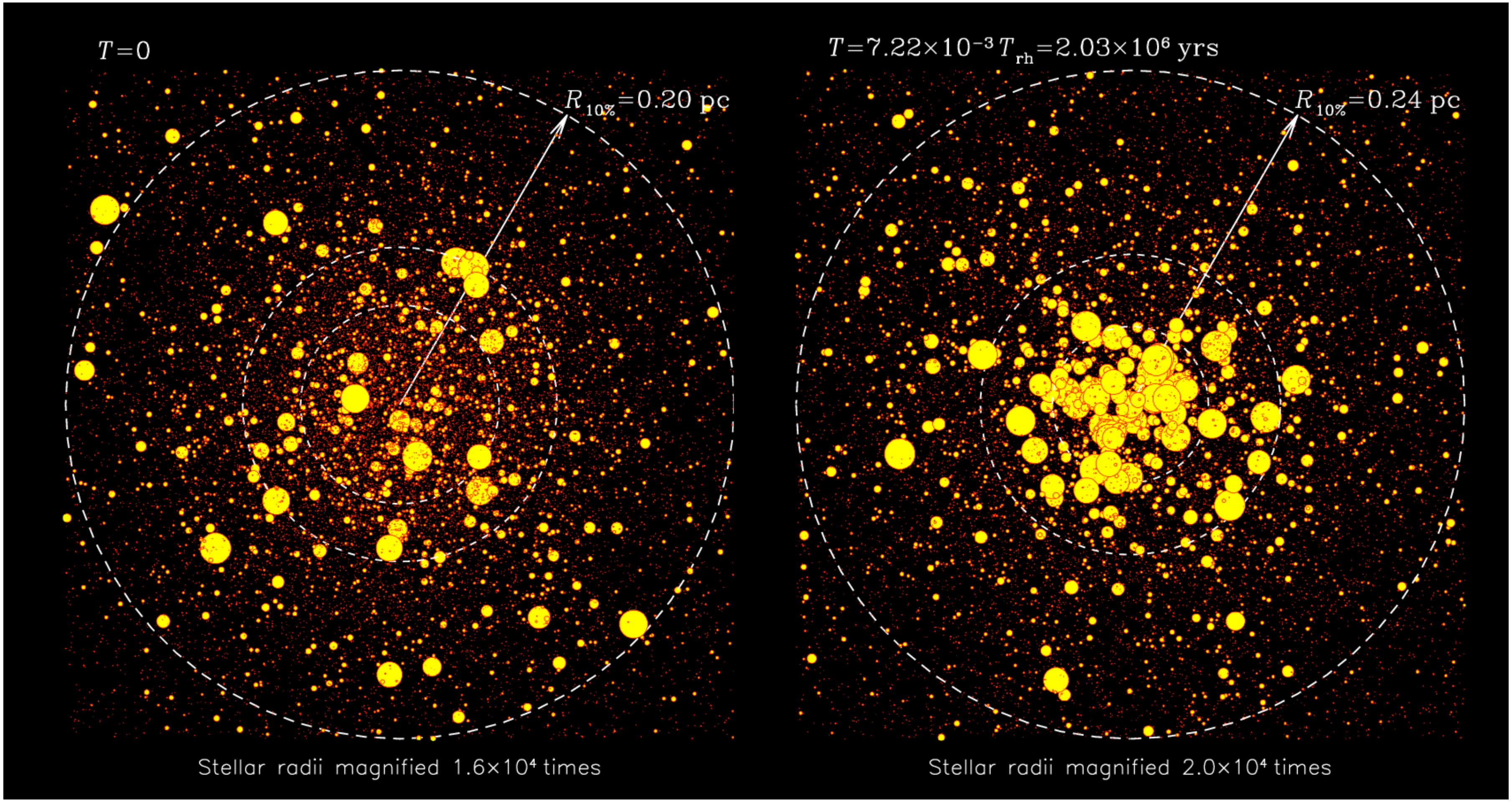
Marc Freitag
freitag@ast.cam.ac.uk

Mass segregation without central object

Young populous cluster

Initial conditions

Core collapse

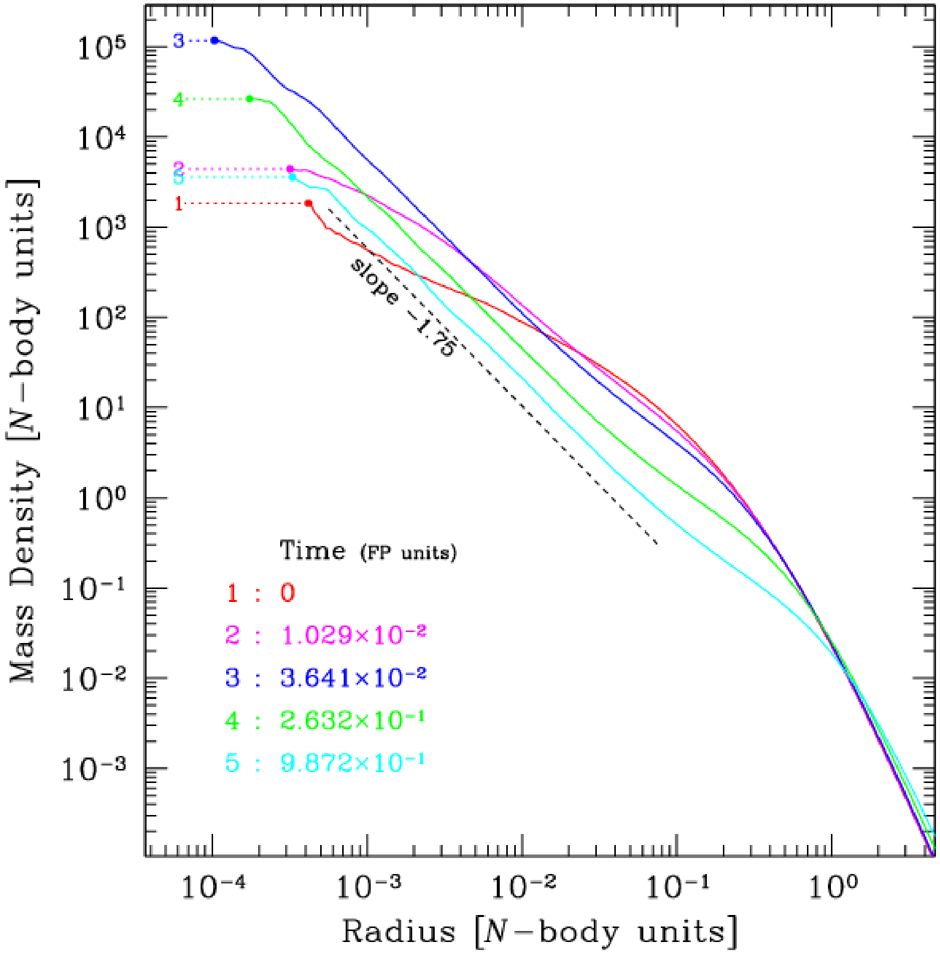


Gürkan, Freitag & Rasio 2004; Freitag, Rasio & Baumgardt 2006

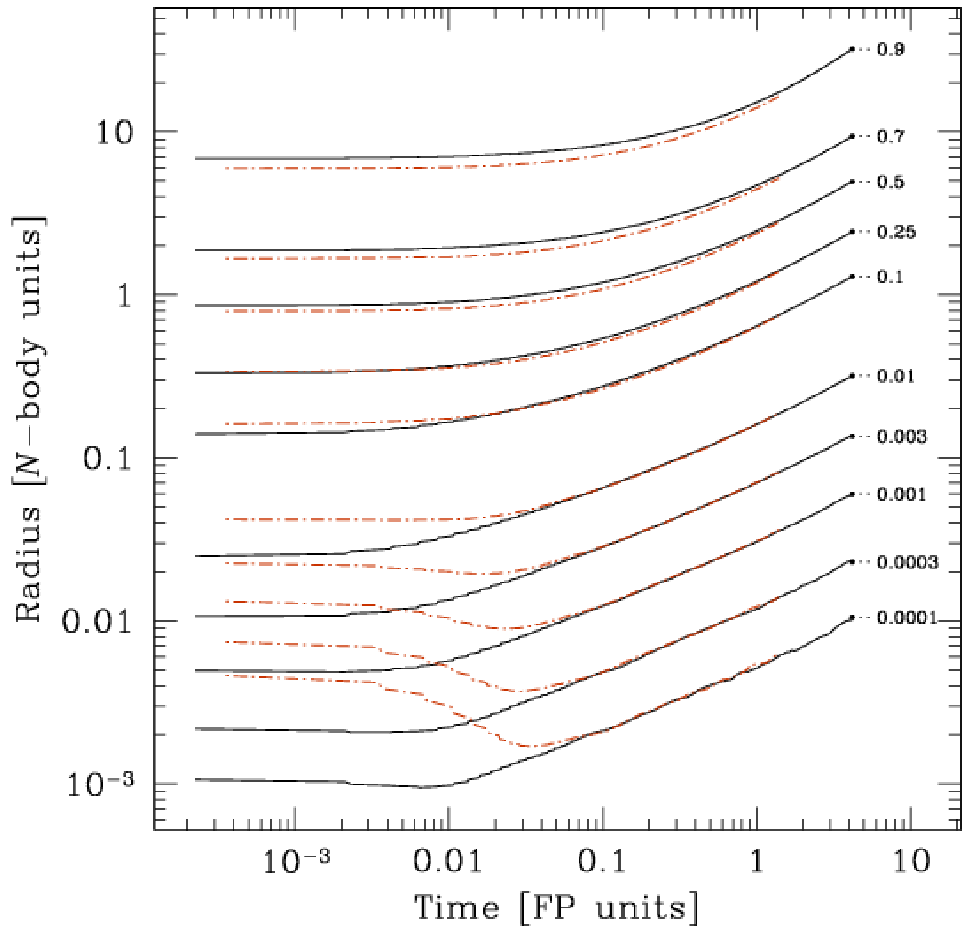
Marc Freitag
freitag@ast.cam.ac.uk

Relaxational evolution of single-mass model

- 2-body relaxation + tidal disruptions
- All stars have same mass; M_{BH}=0.05M_{clust}



Development of Bahcall-Wolf density profile and expansion

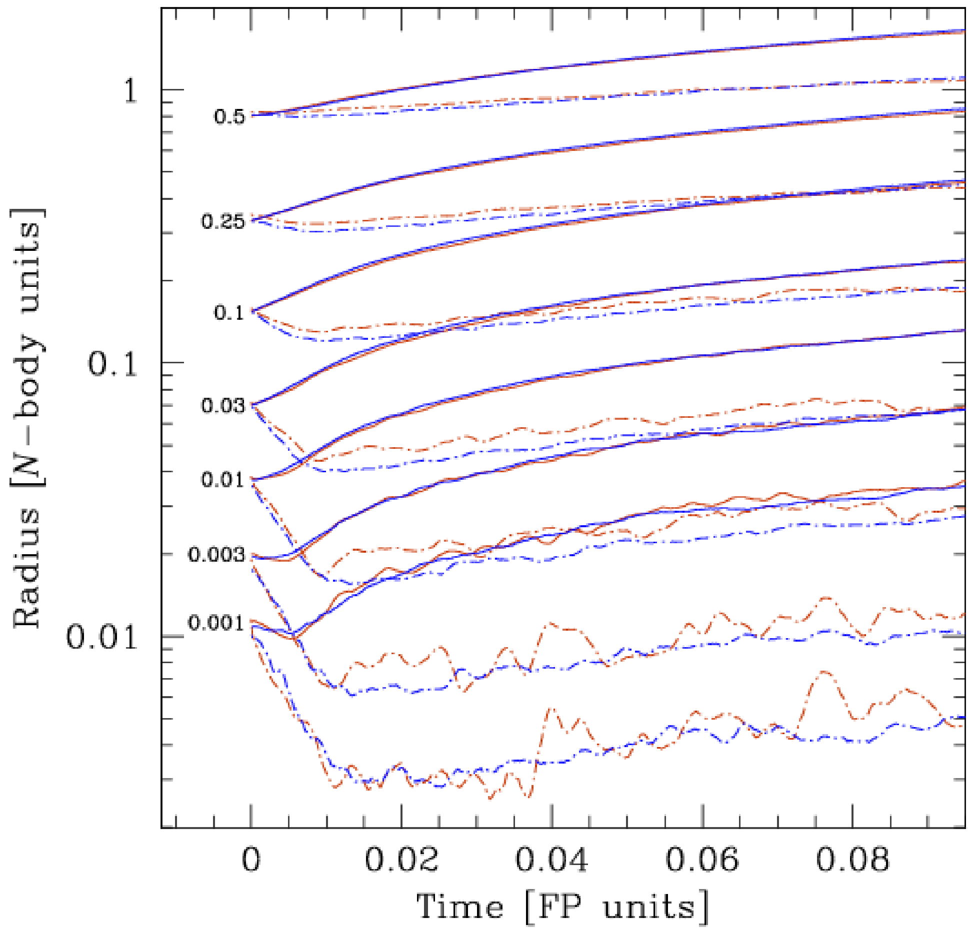


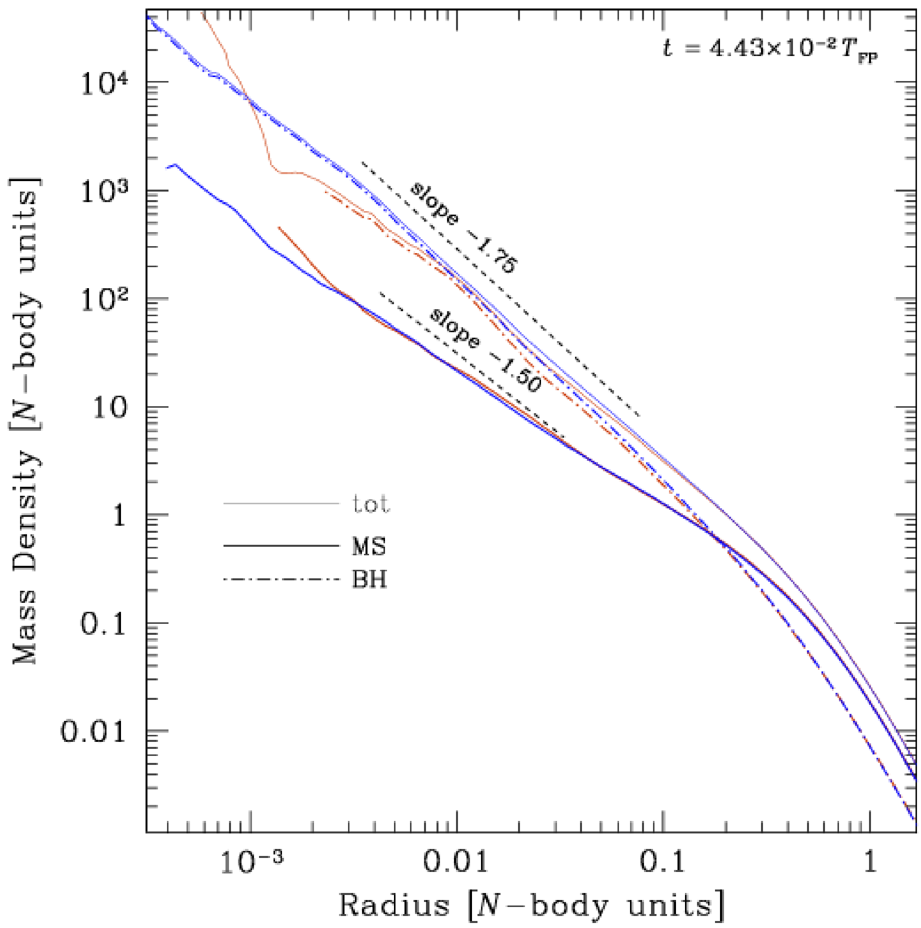
Convergence of evolution for 2 models with different initial central density profiles

Marc Freitag
freitag@ast.cam.ac.uk

Mass segregation around massive object in 2-component model

- 2-body relaxation + tidal disruptions
- 5% of stars are 10x more massive; M_{BH}=0.1M_{clust}
- Comparison with 64k N-body run by Pau Amaro-Seoane

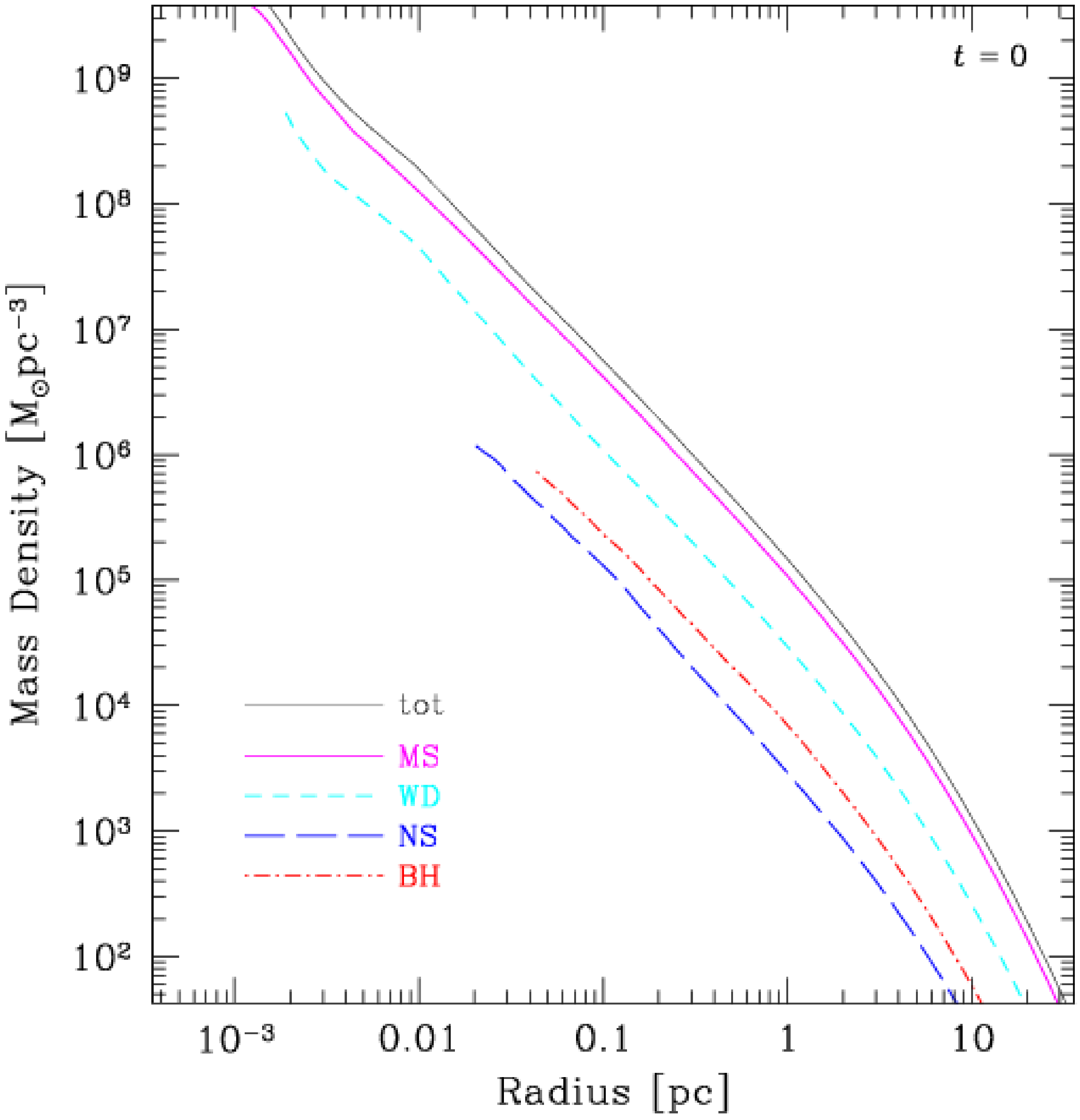




Marc Freitag
freitag@ast.cam.ac.uk

Mass segregation in Sgr A* model

- 2-body relaxation + tidal disruptions
- Full realistic stellar population (10 Gyr old); $M_{BH}=0.05M_{clust}$

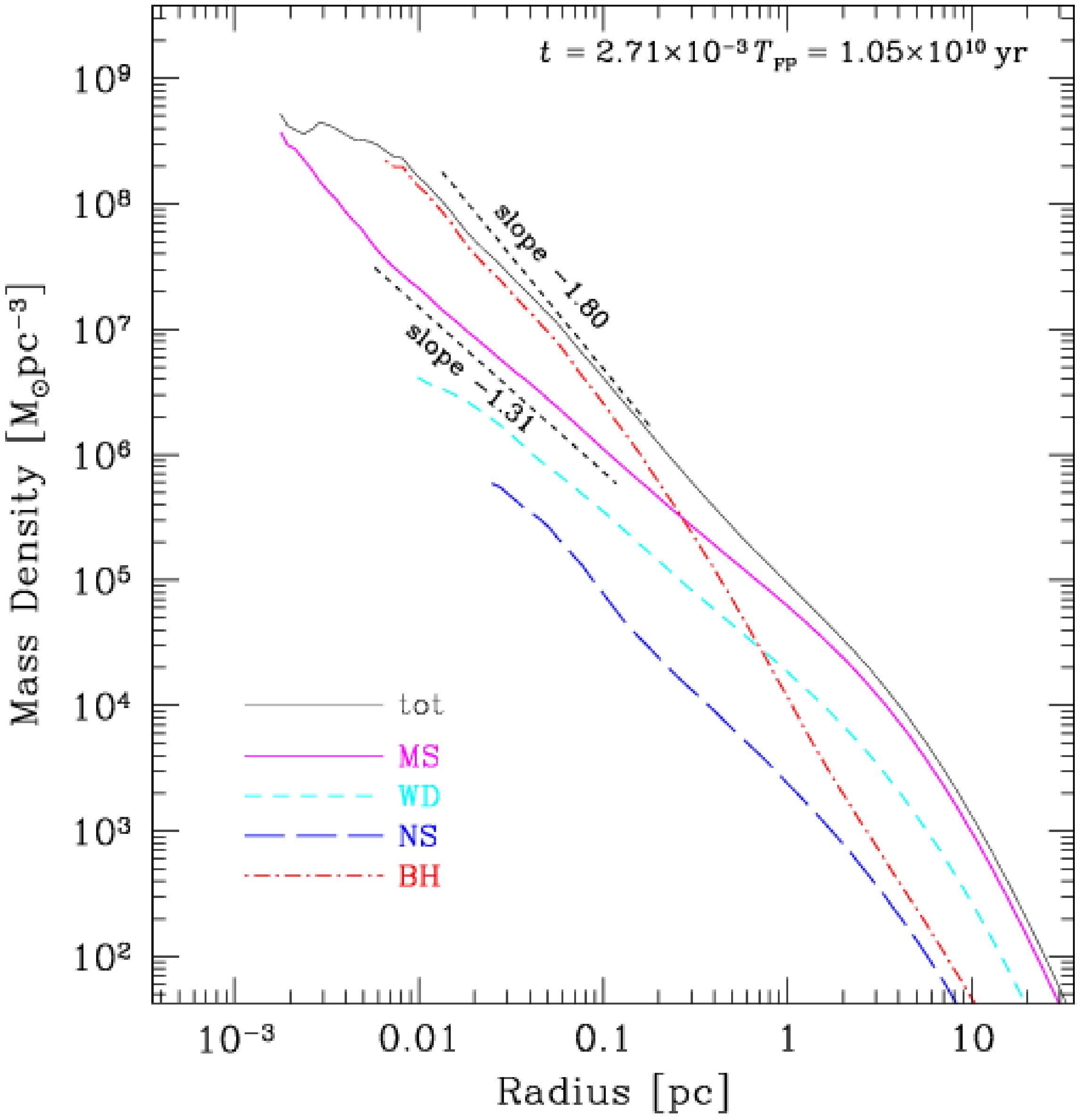


Density profiles for
MS stars, WDs, NSs, stellar BHs

Marc Freitag
freitag@ast.cam.ac.uk

Mass segregation in Sgr A* model

- 2-body relaxation + tidal disruptions
- Full realistic stellar population (10 Gyr old); $M_{BH}=0.05M_{clust}$



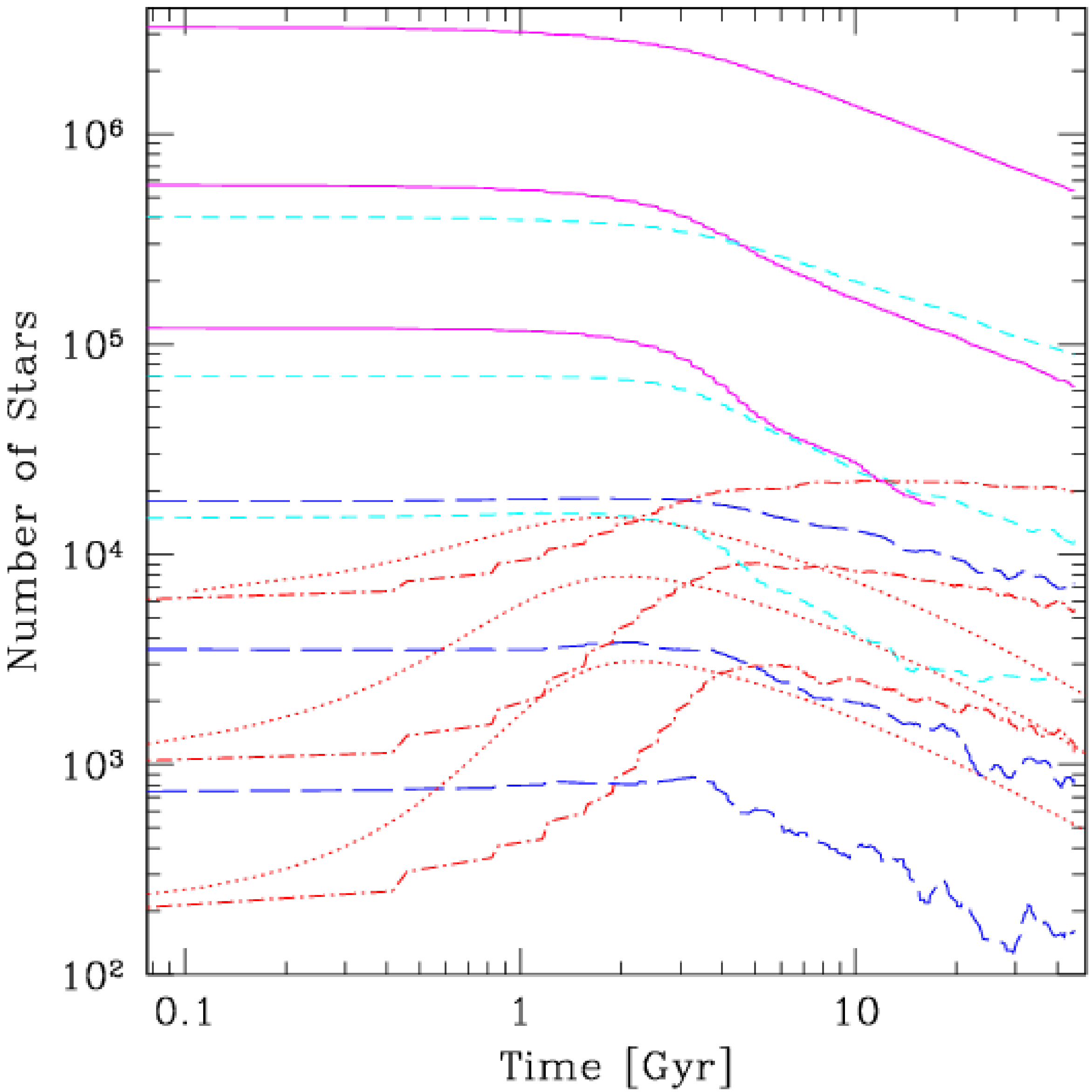
Density profiles for
MS stars, WDs, NSs, stellar BHs

2000 (20000) BHs
within 0.1 (1) pc of Sgr A*

Marc Freitag
freitag@ast.cam.ac.uk

Relaxational evolution of Sgr A* model

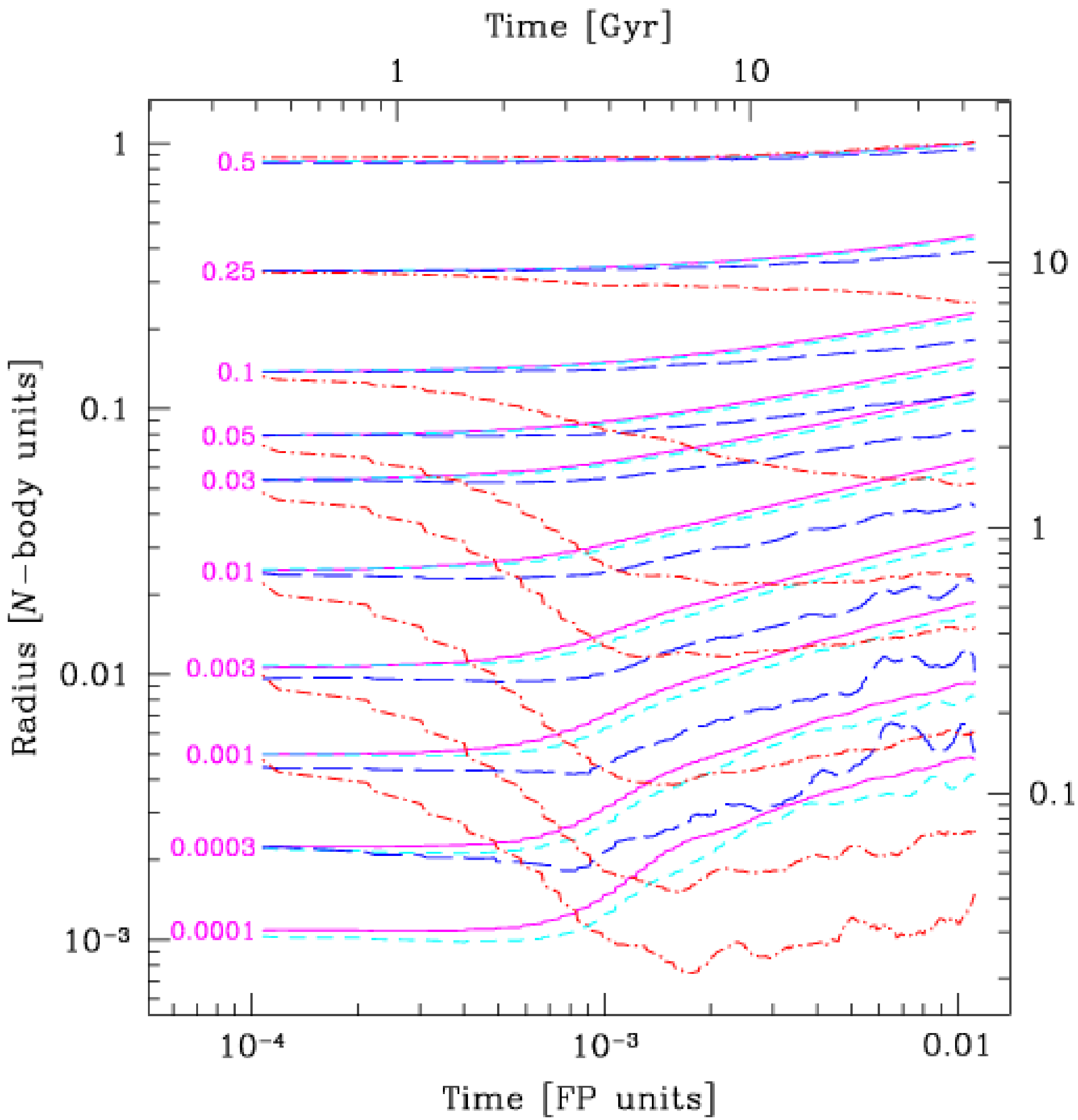
Number of MS stars, WDs, NSs, stellar BHs within 0.1, 0.3, 1 pc of MBH
comparison with dyn. friction for stellar BHs (dotted lines)



Marc Freitag
freitag@ast.cam.ac.uk

Mass segregation in Sgr A* model

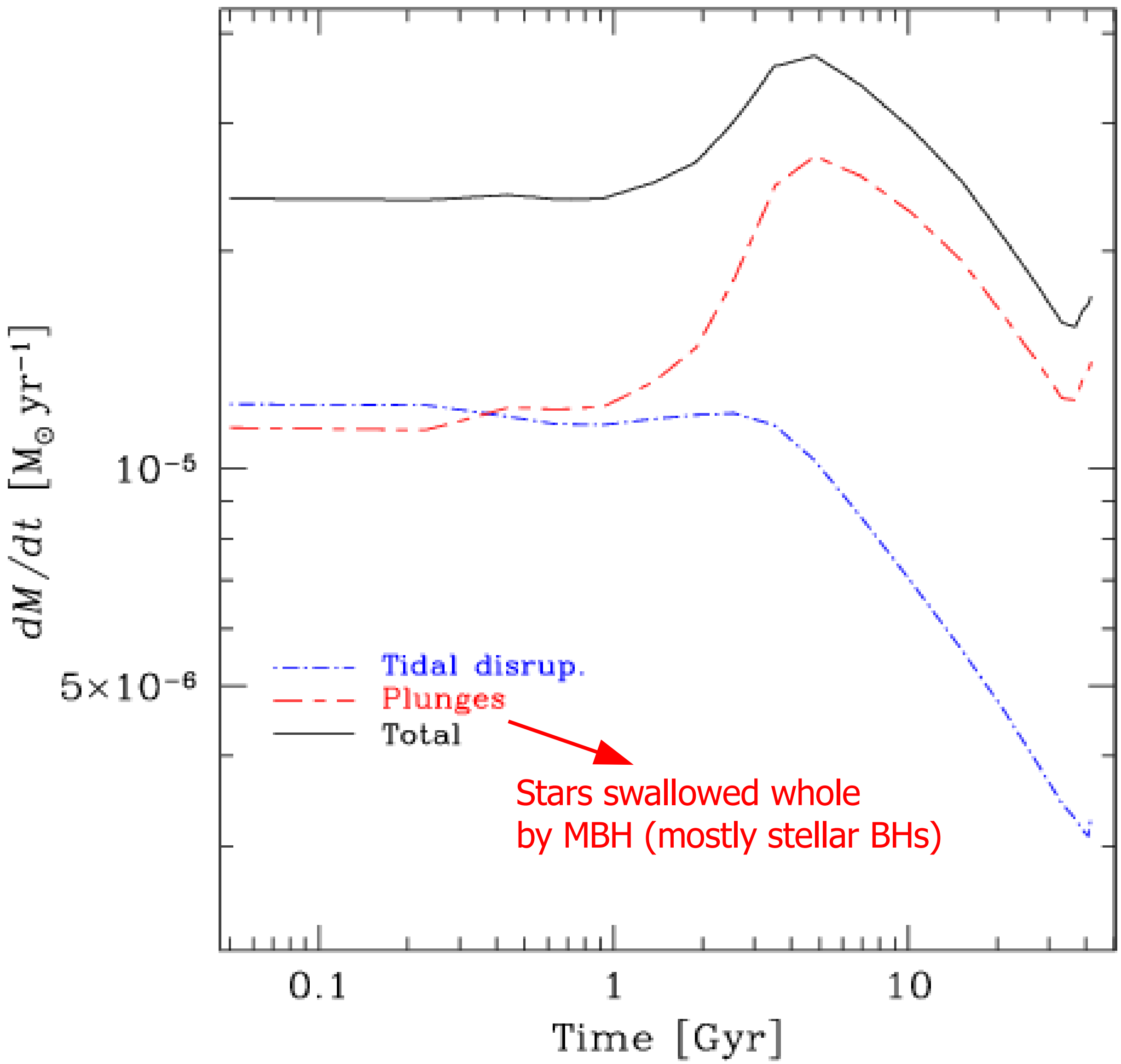
Lagrange radii for MS stars, WDs, NSs, stellar BHs



Marc Freitag
freitag@ast.cam.ac.uk

Sgr A* model

Rate of accretion of stellar mass by the MBH



Marc Freitag
freitag@ast.cam.ac.uk

Extending to other nuclei

- Naïve use of M-Sigma relation to scale with $M_{\rm BH}$

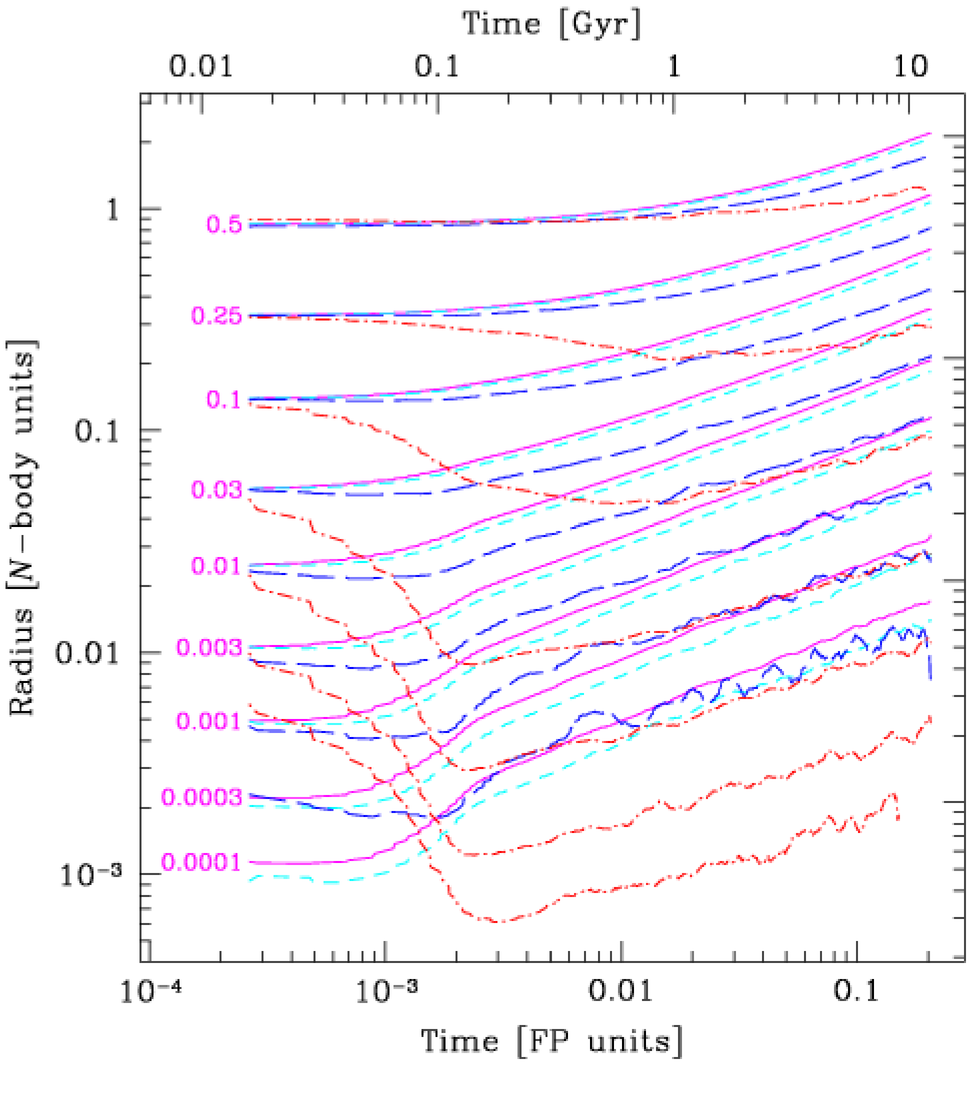
$$M_{\rm BH} \simeq M_{100} \left(\frac{\sigma}{100\,{\rm km\,s^{-1}}} \right)^4 \qquad R = R|_{\rm MW} \left(\frac{M_{\rm BH}}{3.5 \times 10^6\,{\rm M_\odot}} \right)^{1/2}$$

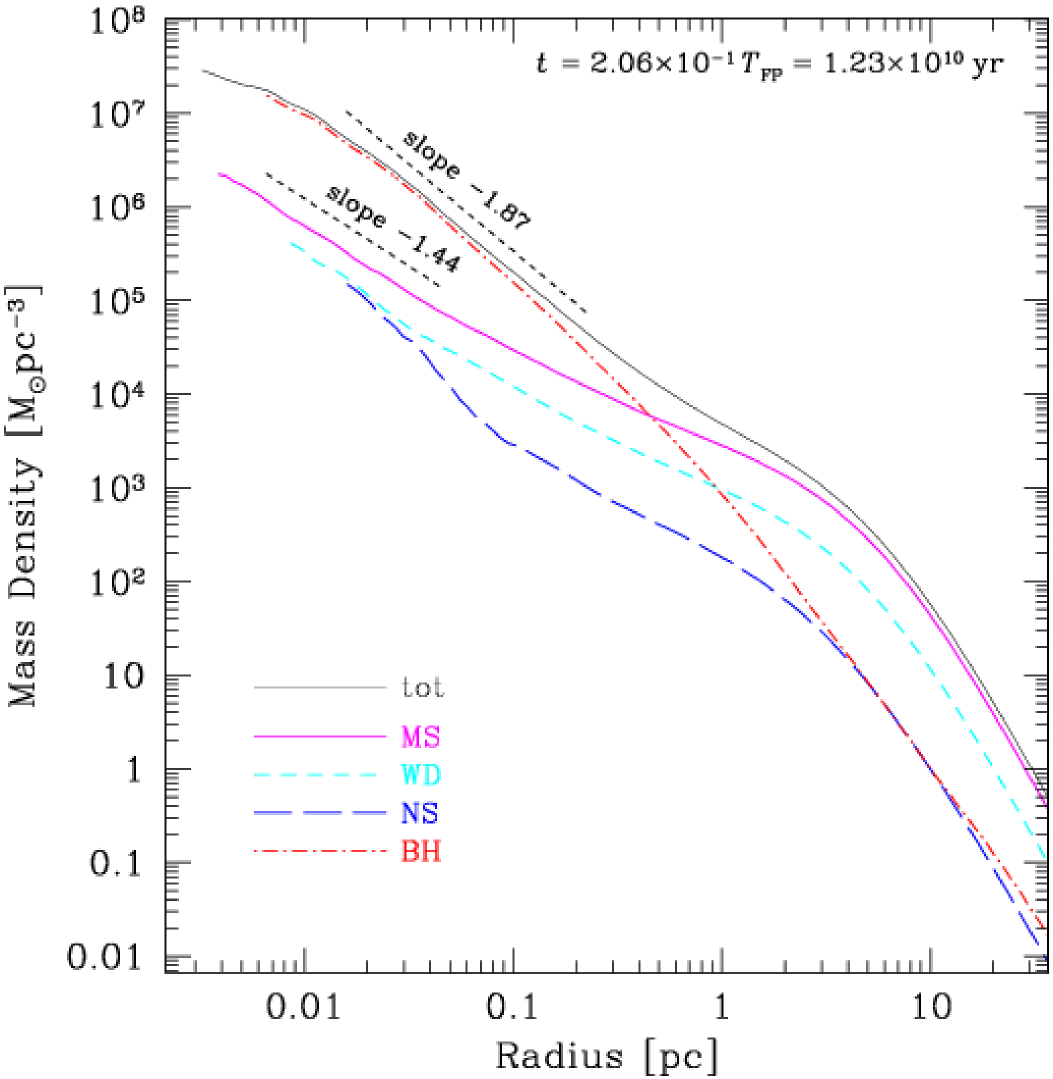
- Range considered: 10^4-10^7 $M_\odot$
  - Lower limit: avoid low-N effects (Monte Carlo not appropriate)
  - Upper limit: relaxed system ($t_{\rm rlx}(R_{\rm infl})$>10 Gyr for $M_{\rm BH}$>10^7 $M_\odot$)
  - Range of interest for LISA

Marc Freitag
freitag@ast.cam.ac.uk

Evolution of a small nucleus

- 2-body relaxation + tidal disruptions
- Full realistic stellar population (10 Gyr old); M_{BH}=0.05M_{clust}
- Scaled-down initial conditions for M_{BH}=10^5 M_{sun}





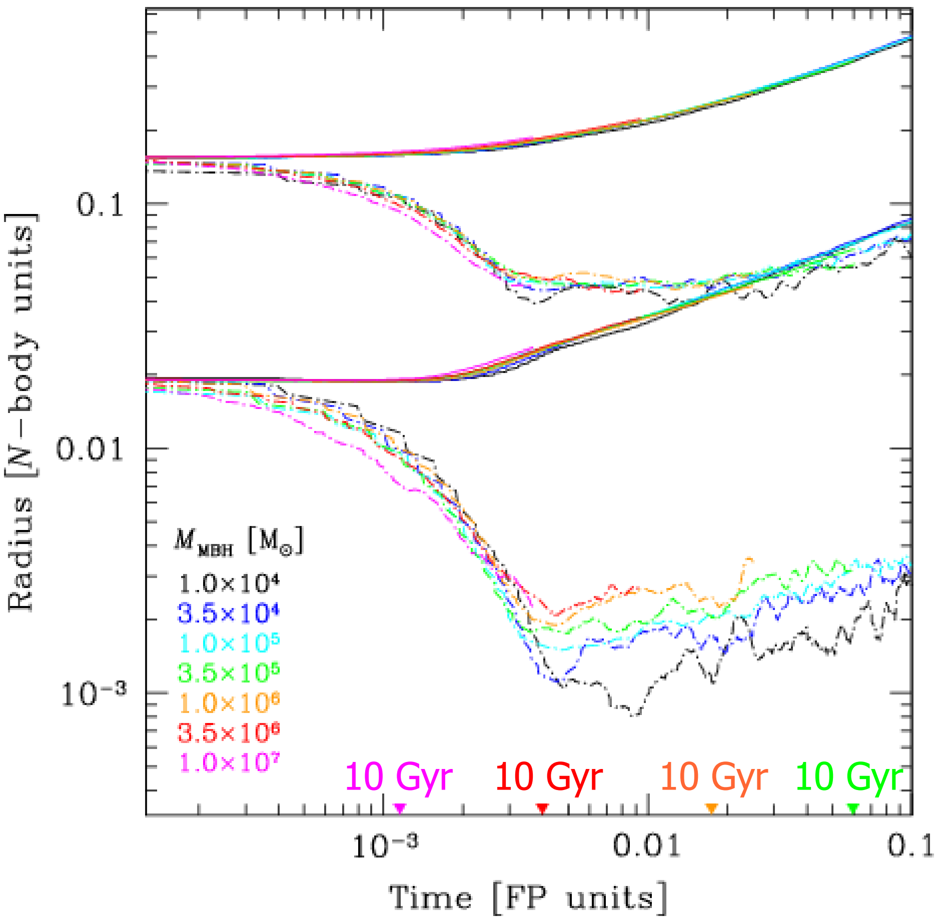
Marc Freitag
freitag@ast.cam.ac.uk

Models for different nucleus masses

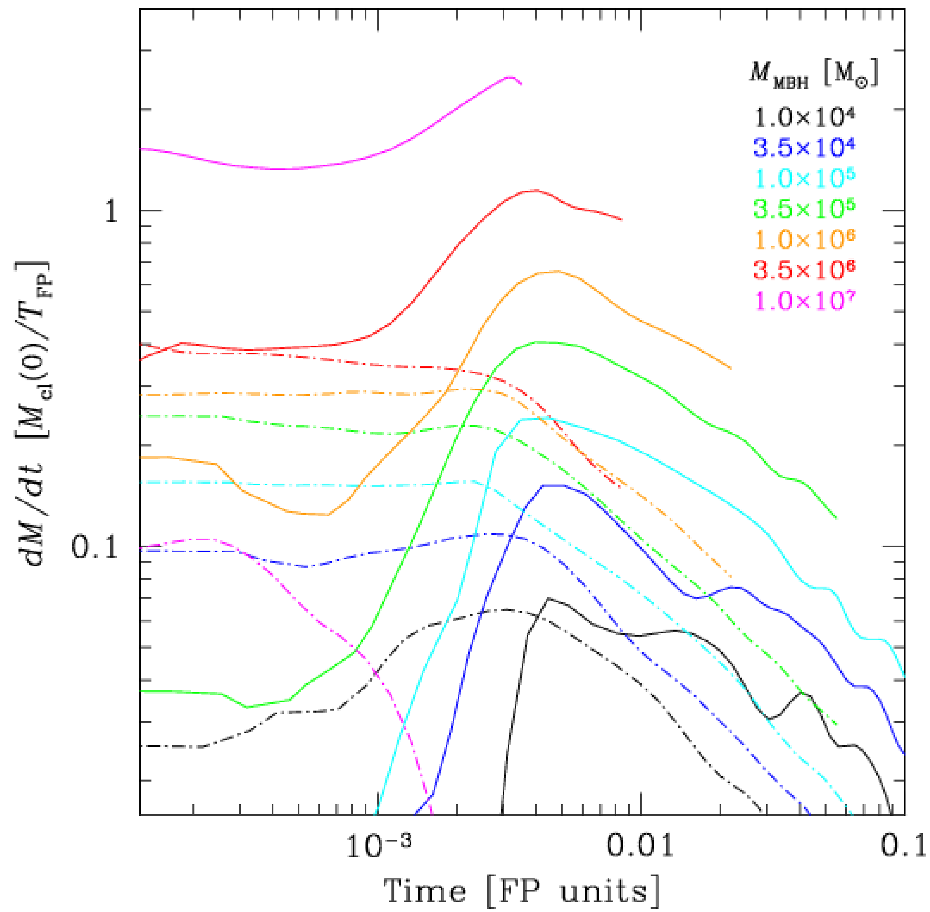
Naïve initial conditions scaling using M-sigma relation $R = R|_{\mathrm{MW}} \left(\frac{M_{\mathrm{BH}}}{3.5 \times 10^6\,\mathrm{M}_\odot} \right)^{1/2}$

$t_{\mathrm{rlx}}(R_{\mathrm{infl}}) > 10$ Gyr for $M_{\mathrm{BH}} > 10^7\,\mathrm{M}_\odot$

0.3% and 10% Lagrange radii of MSs & BHs



Mass accretion rates

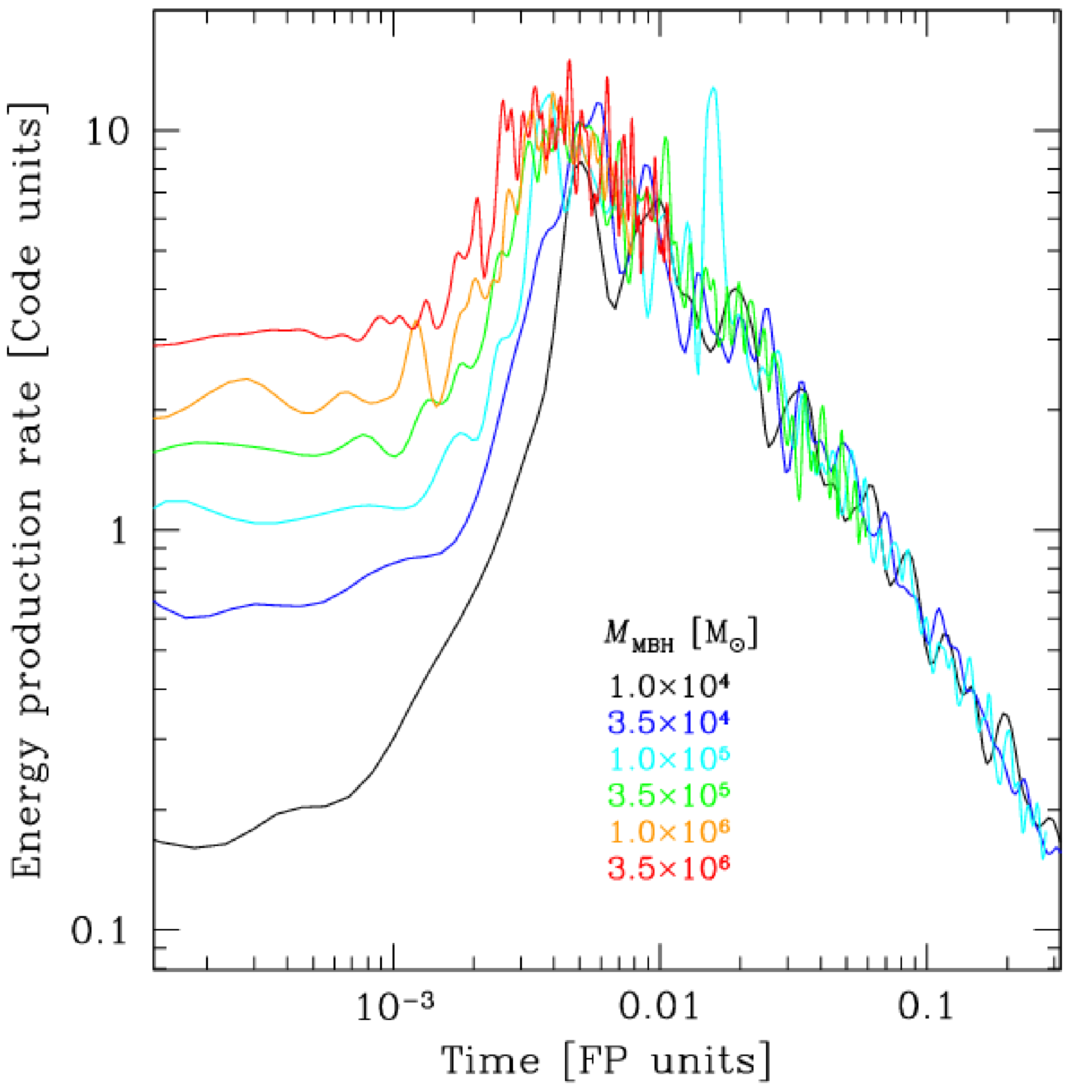


Doesn't scale perfectly...
Larger systems have larger critical radii

Marc Freitag
freitag@ast.cam.ac.uk

Models for different nucleus masses

Rate of energy production by stellar accretion



Central regions adapt to provide same “heating rate” in expansion phase

Marc Freitag
freitag@ast.cam.ac.uk

Summary of results

astro-ph/0603280

- Mass segregation happens in (small) galactic nuclei
  - Takes a few Gyr in Sgr A* - type nucleus
- Affects mostly stellar BHs
  - 2000 (20000) BHs within 0.1 (1) pc of Sgr A*
  - All other species (including NSs) pushed out but probably cannot be used as clear-cut observational evidence for BH cluster
  - Little evolution in 10 Gyr if no stellar BHs
- Test of Bahcall-Wolf predictions $\rho \propto R^{-\gamma}$
  - $\gamma \approx 1.75$ confirmed for massive objects
  - $\gamma = 1.5$ not confirmed for lighter objects (only very close to MBH?)
- Central MBH drives expansion of nucleus
  - Significant for nuclei smaller than Sgr A*
- Model dependence?
  - Weak dependence on initial cusp profile and MBH growth history?
  - Probably strong dependence on SF history

Marc Freitag
freitag@ast.cam.ac.uk

Some (future) astrophysical applications

- Stellar collisions
- Photometric profiles
- Binaries in galactic nuclei
  - X-ray sources at the Galactic centre
  - Tidal separation (capture and hypervelocity ejection)
- Formation of extreme-mass-ratio GW sources

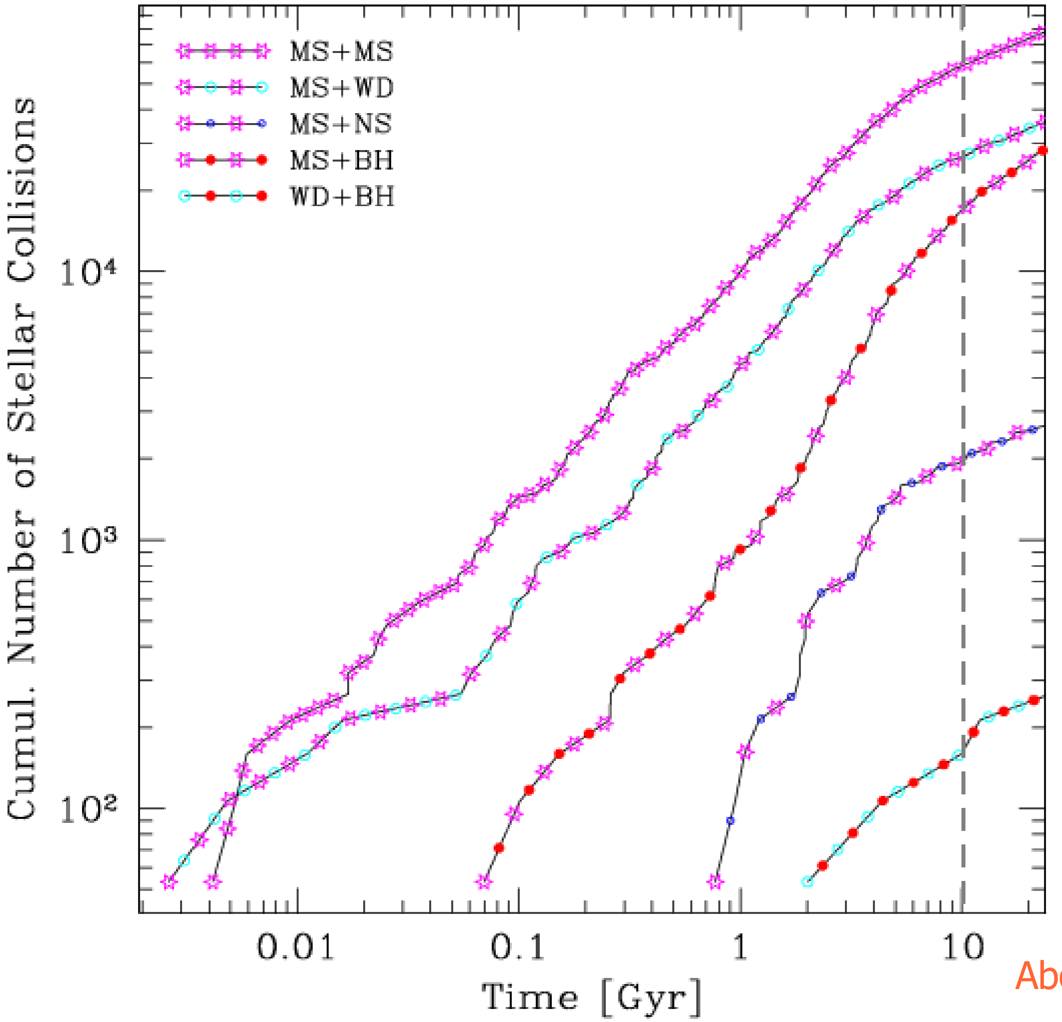
Marc Freitag
freitag@ast.cam.ac.uk

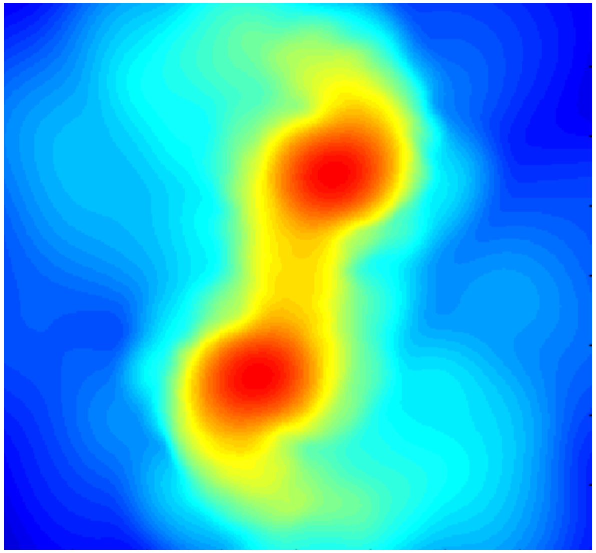
Collisions in galactic nuclei

Sgr A* model

Collisions treated thanks to table of SPH simulations

(Freitag & Benz 2005)



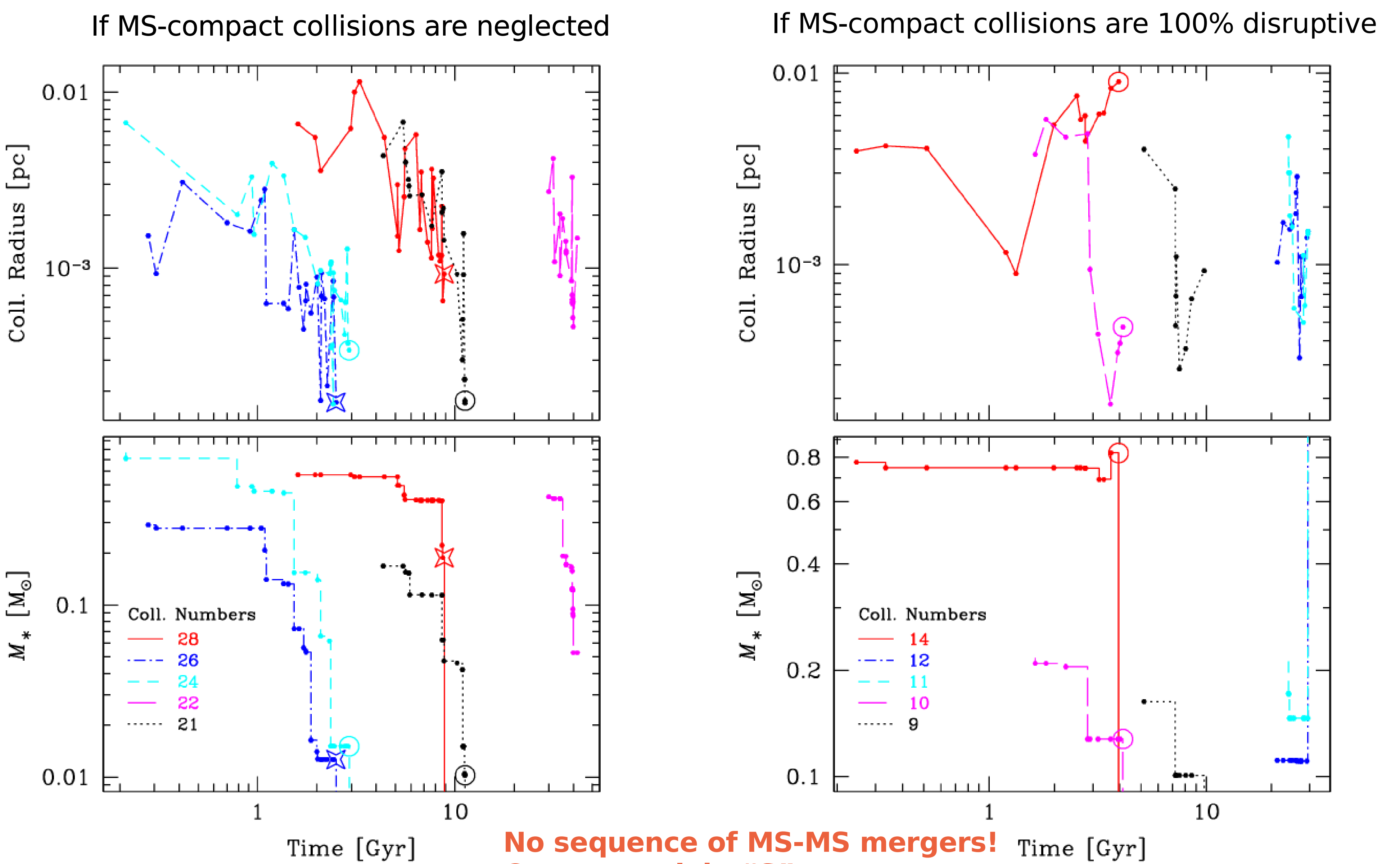


About 6×10^{-5} MS-MS/yr $4\text{-}5\times10^{-5}$ MS-CO/yr

Marc Freitag
freitag@ast.cam.ac.uk

Collisions in galactic nuclei

Sgr A* model



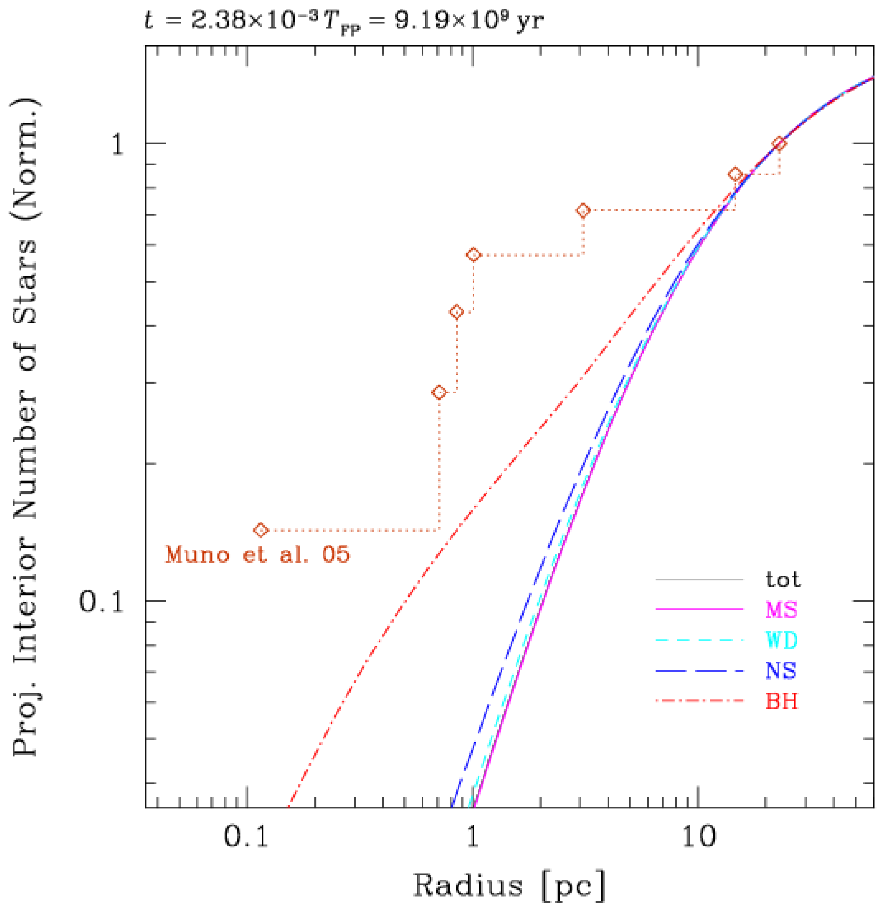
No sequence of MS-MS mergers!
Cannot explain "S" stars

Marc Freitag
freitag@ast.cam.ac.uk

*X-ray binaries around Sgr A**

- 7 transient X-ray sources within 25 pc (Muno et al. 2005)
  - 4/7 within 1 pc of projected distance
  - Probably LMXBs with NS or BH accretor

Comparison of cumulative numbers with MC simulation



Central concentration through passive segregation of BHs not excluded (!) but...

Sources probably formed through 3-body effects.
Need to take binary dynamics into account.

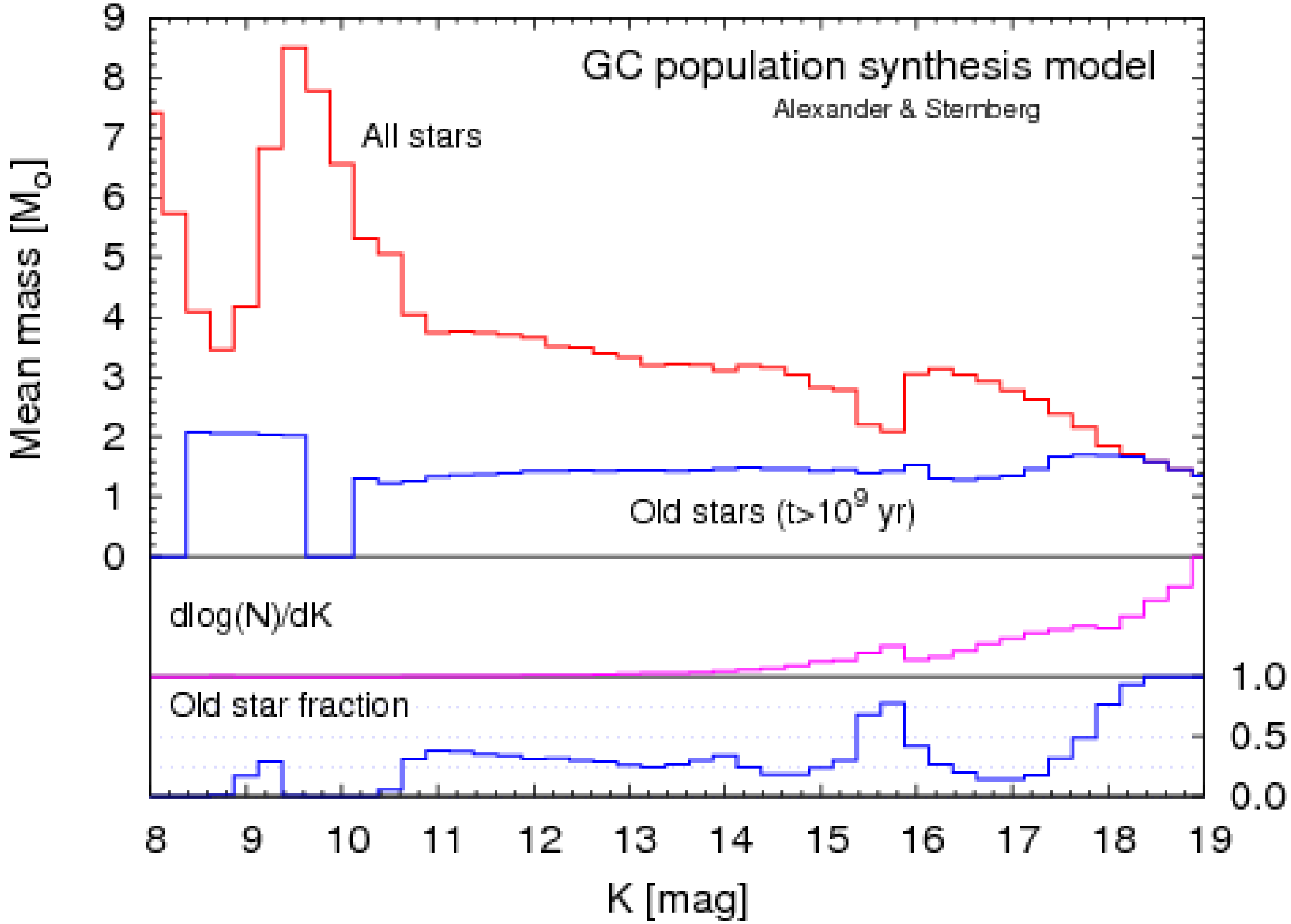
$$\left.\frac{dn}{dt}\right|_{\rm exchange} \propto n_{\rm bin}\, n_{\rm CO}\, \sigma\, \Sigma$$

Marc Freitag
freitag@ast.cam.ac.uk

Photometric profiles in the Galactic centre

The red clump: A visible, relaxed population with a mass lower than the average?

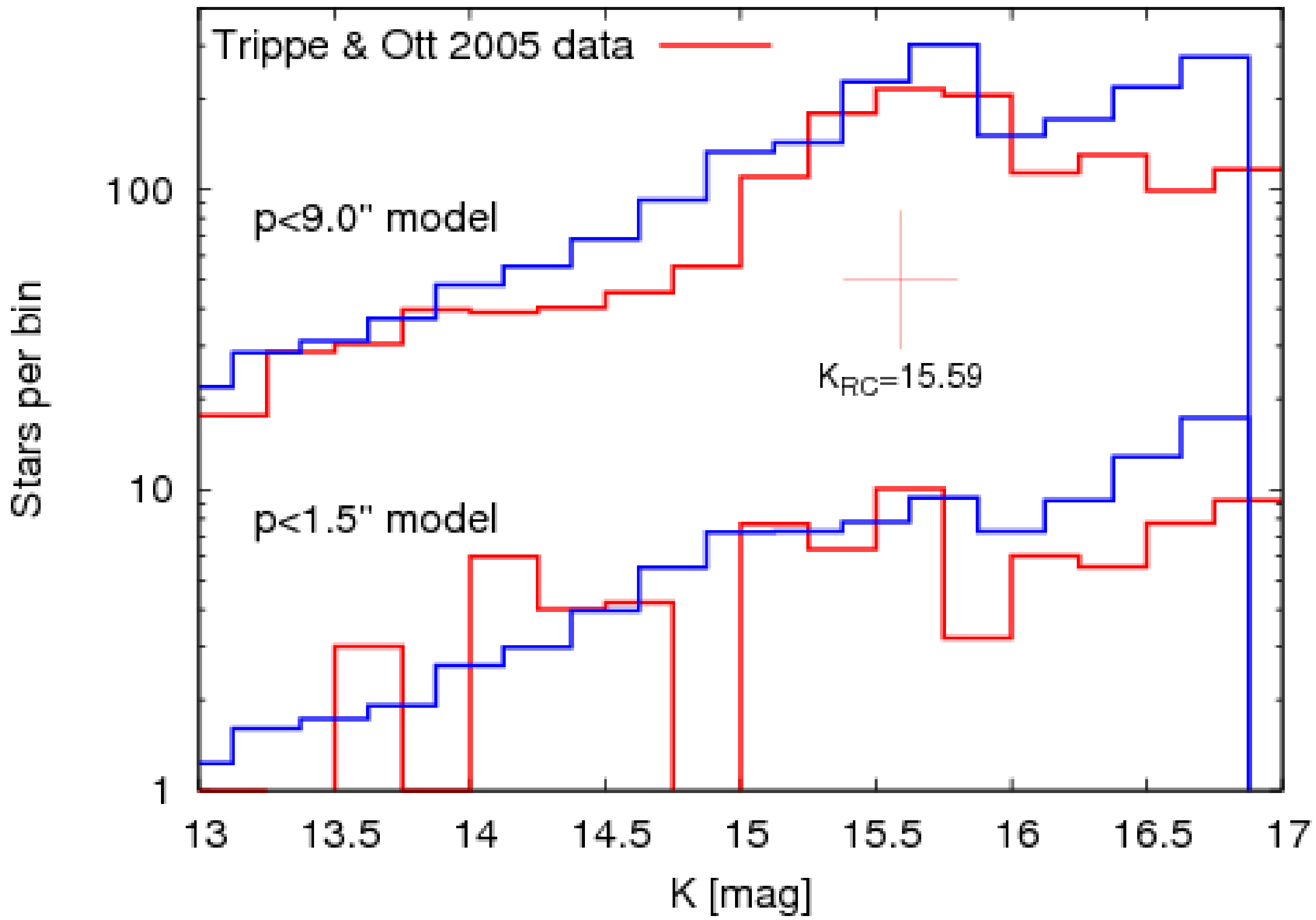
Alexander & Sternberg for Schoedel et al. 2006



Marc Freitag
freitag@ast.cam.ac.uk

Photometric profiles in the Galactic centre

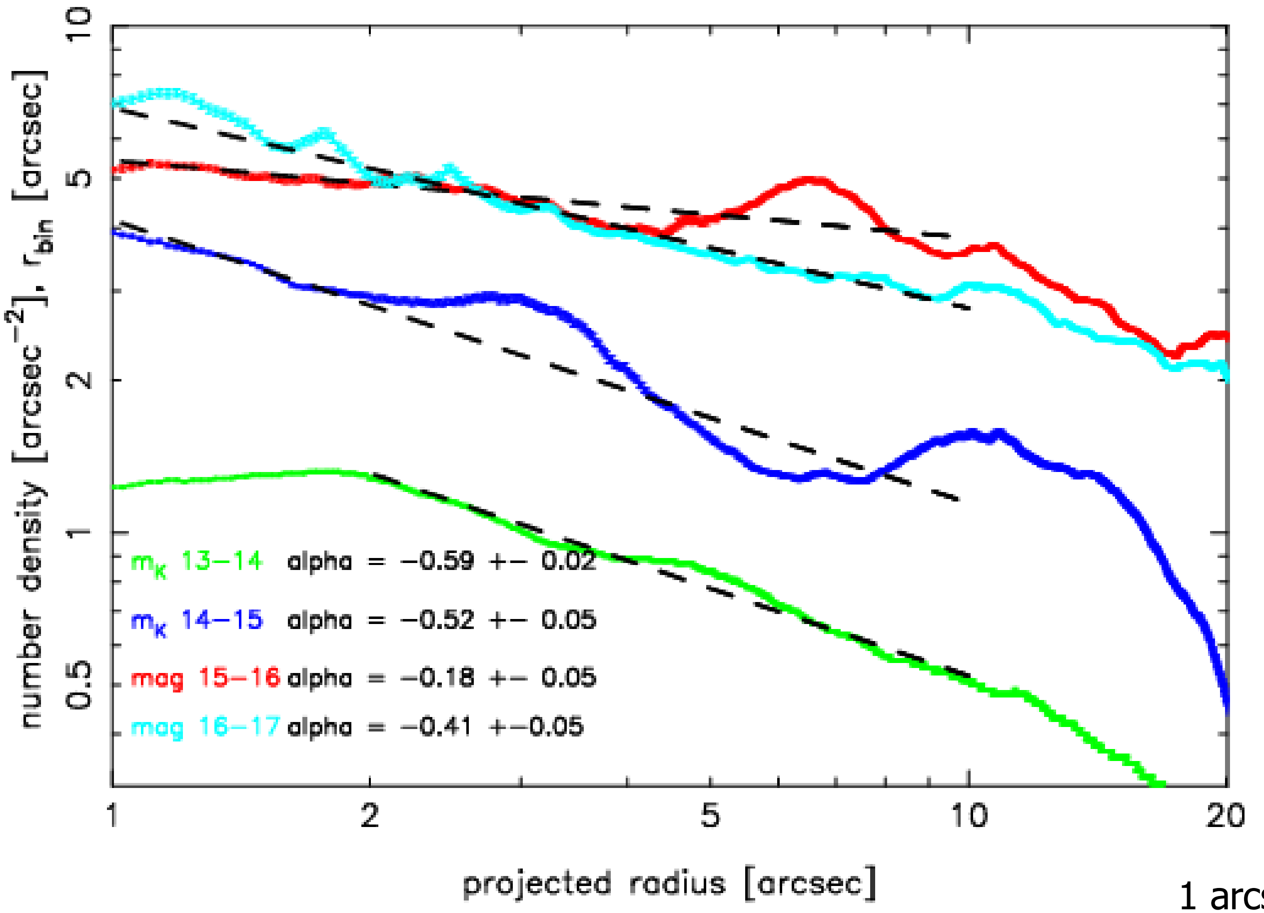
Levi & Alexander: try to explain red clump depletion in the innermost Galactic region (Michele Levi, Master thesis 2006)



Marc Freitag
freitag@ast.cam.ac.uk

Photometric profiles in the Galactic centre

Schoedel et al 2006 (submitted): surface density profiles for different K-magnitude bins



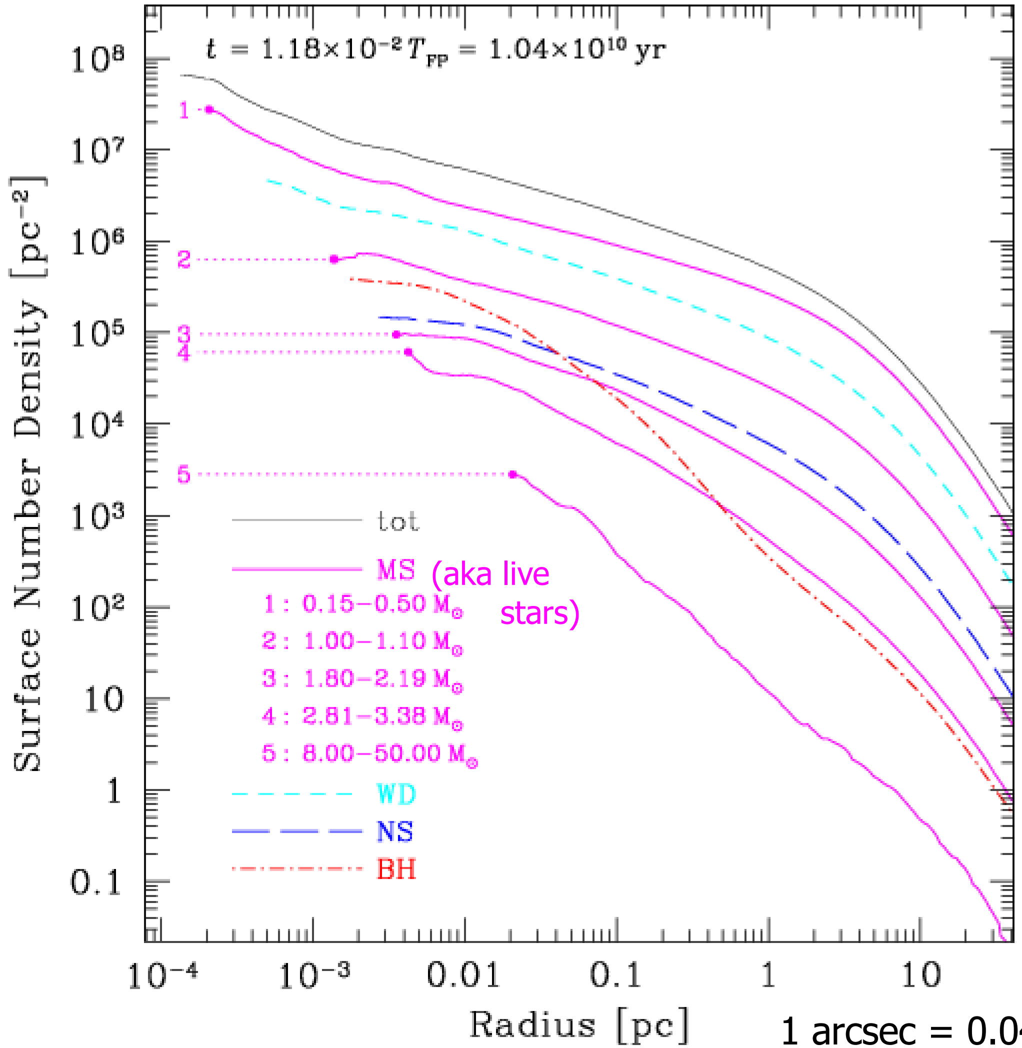
1 arcsec = 0.04 pc

Shallower profile at magnitude of red-clump:
Can this be explained by mass segregation?

Marc Freitag
freitag@ast.cam.ac.uk

Photometric profiles in the Galactic centre: a simulation

- 16 million particle MC model
- Mixed-age stellar population (same as Alexander et al.); no stellar evol but 10 Gyr of relaxation

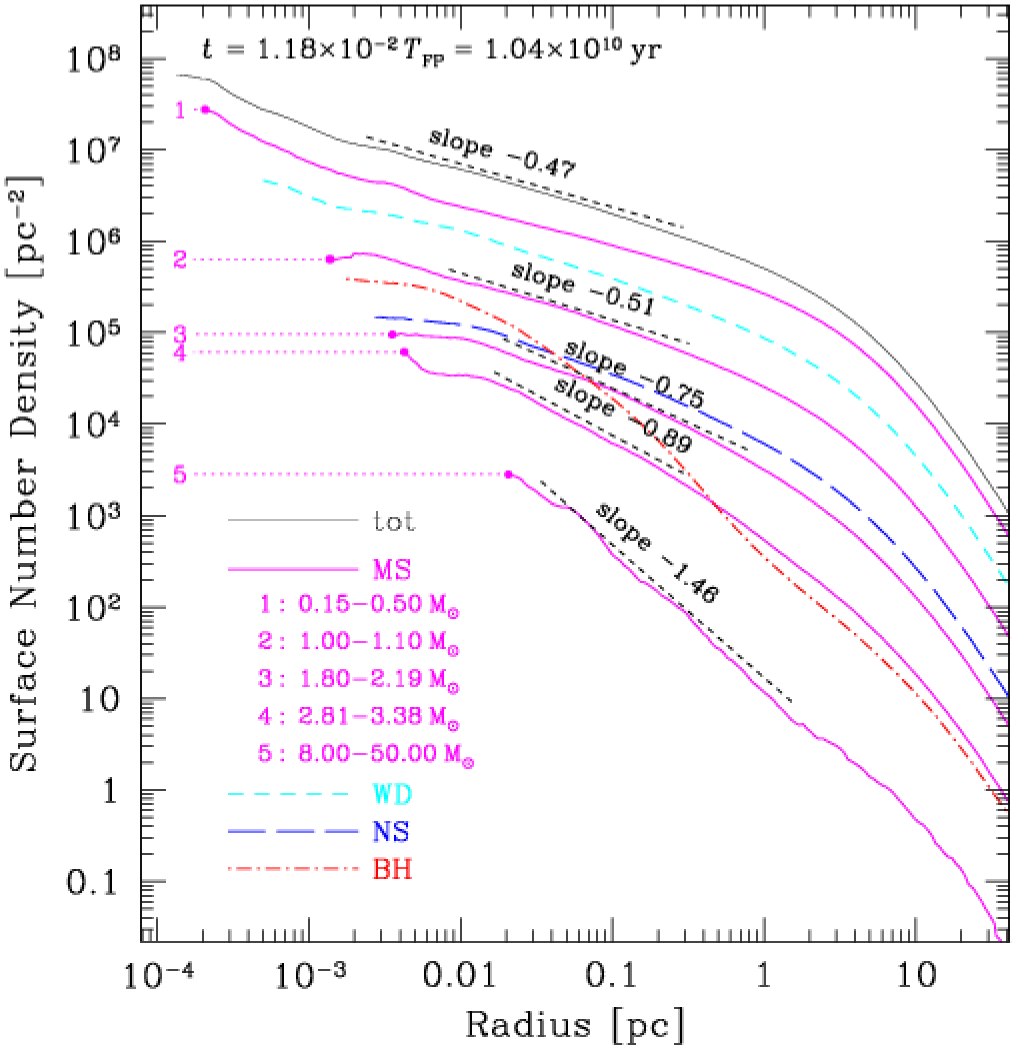


1 arcsec = 0.04 pc

Marc Freitag
freitag@ast.cam.ac.uk

Photometric profiles in the Galactic centre: a simulation

- Profiles steeper than observed
- Small difference between 2 and 3 $M_\odot$



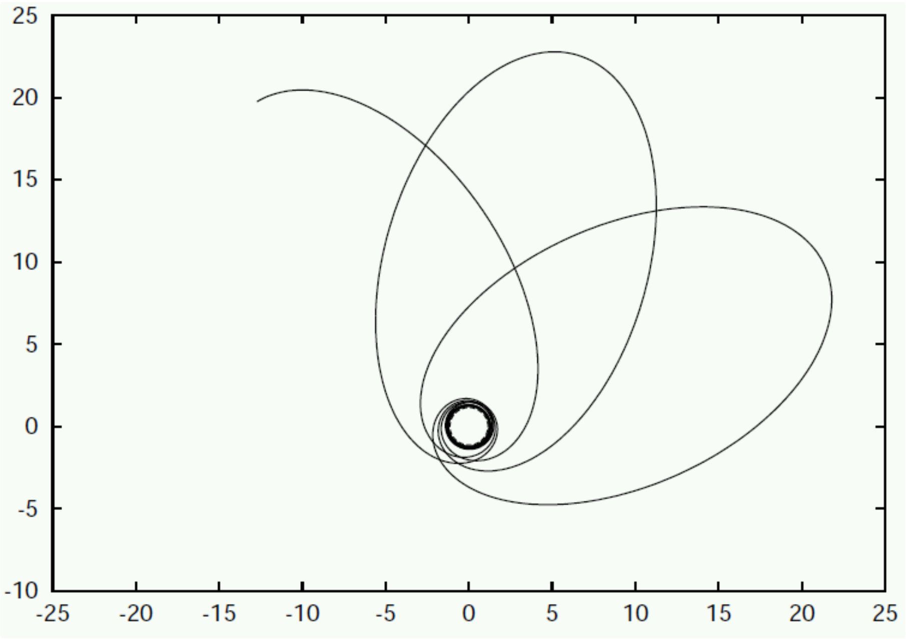
Marc Freitag
freitag@ast.cam.ac.uk

Extreme Mass-Ratio Inspirals for LISA

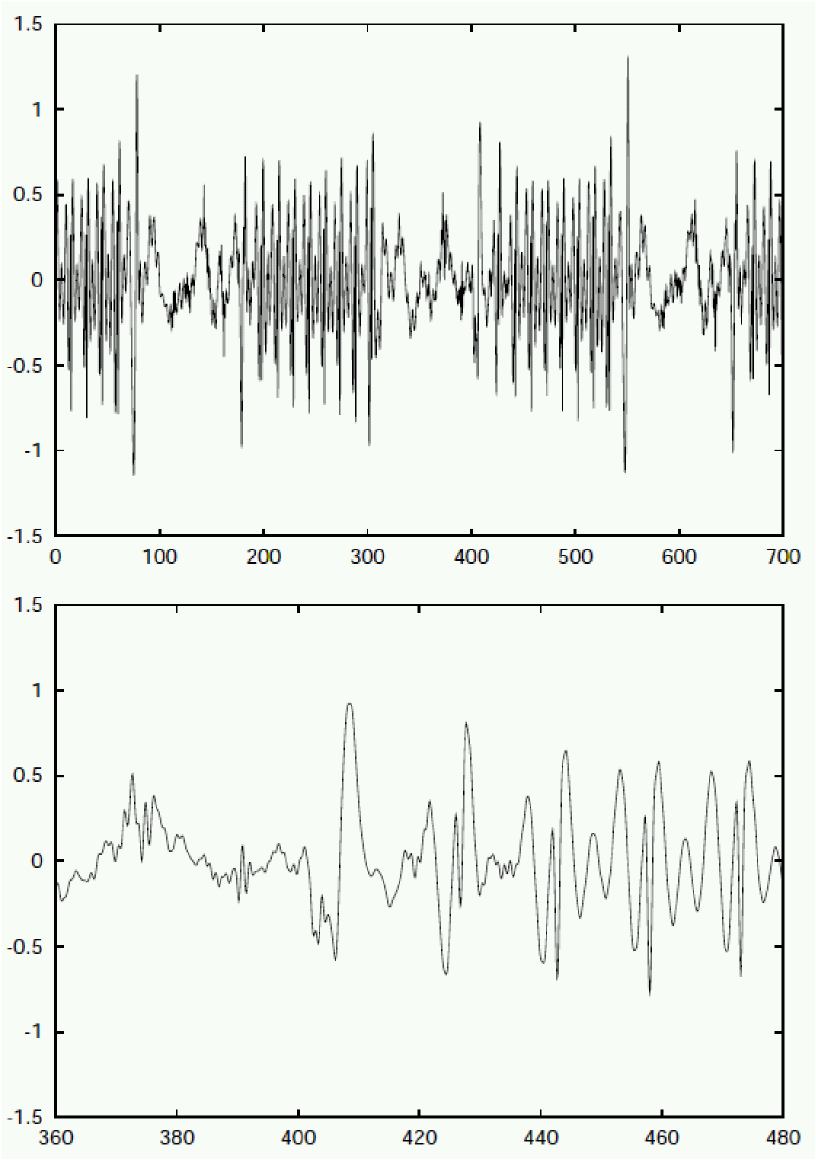
- Stellar mass object spiraling into 10^5-10^7 $M_\odot$ MBH
  - Only compact objects (extended stars disrupted early)
  - Stellar BH detectable to 3 Gpc
- EMRBs will allow "geo"desic mapping of space-time
  - Establishes MBH existence; measures mass and spin
- Theoretical difficulties are plenty! (Gair et al. 2004)
  - "Local" density of MBHs in LISA mass range
  - Rate of captures & "initial" orbital parameters
    - Literature: 10^{-8} – 10^{-4} yr^{-1} per galaxy
      (Hils & Bender 95; Sigurdsson & Rees 97; Freitag 01, 03; Ivanov 02; Sigurdsson 03 [review]; Hopman & Alexander 05, 06)
    - Controlled by 2-body relaxation
  - Orbital evolution & waveform calculation
    (Glampedakis & Kennefick 02; Glampedakis et al. 02; Lousto 05)
    - Full GR required; not done yet but m/M<<1 helps
    - "Zoomwhirl" orbits => complex GW signals
  - LISA signal processing; Detection strategies
    - Low S/N => match-filtering
    - High-D parameter space => exhaustive search impossible
      (Barack & Cutler 04; Gair & Wen 05;Wen & Gair 05)

Orbits around a Kerr MBH

Glampedakis et al. 2002



“Zoomwhirl” orbit



GW signal emitted by particle on“zoomwhirl” orbit

Marc Freitag
freitag@ast.cam.ac.uk

What's next? *(in an ideal world)*

- Consequences of mass segregation
  - Extreme mass ratio inspirals for LISA
    - Fraction of gradual inspirals vs direct plunges (Hopman & Alexander 05)
    - Role of resonant relaxation (Hopman & Alexander 06)
    - Interaction with an accretion disk
  - Survival and dynamical role of compact binaries
    - X-ray sources
    - Tidal splitting of binaries (hyper-velocity stars, EMRIs,...)
  - More work on collisions, tidal destructions/peeling (giants)
- Use *N*-body methods when possible (tests, calibration)
- Develop new tools
  - Fast “external potential” MC code for cusp around (I)MBH
  - Hybrid non-spherical MC/N-body code

Complements

How does the MC work?

- Initialization
  - Realization of cluster with *N* particles according to DF *F(E)* ↪ E_i, J_i, R_i
  - Attribution of masses M_i according to IMF

- Main loop (modifies 2 particles per step)

1) Selection of pair of neighboring particles $P_{\rm selec} \propto \delta t(R)^{-1}$
2) Test for collisions: rand() < $P_{\rm coll}$; modify $M_{1,2}$ & $V_{1,2}$ if needed
3) Relaxation simulated by "Super-encounter" $\theta_{\rm SE} = \frac{\pi}{2}\sqrt{\frac{\delta t}{t_{\rm rlx}}}$
4) New orbital parameters $E_{1,2}$ & $J_{1,2}$ computed
5) For each particle, new position R_i picked at random on (E_i,J_i)-orbit $\frac{dP}{dR}(R) \propto \frac{1}{V_{\rm r}(R)}$

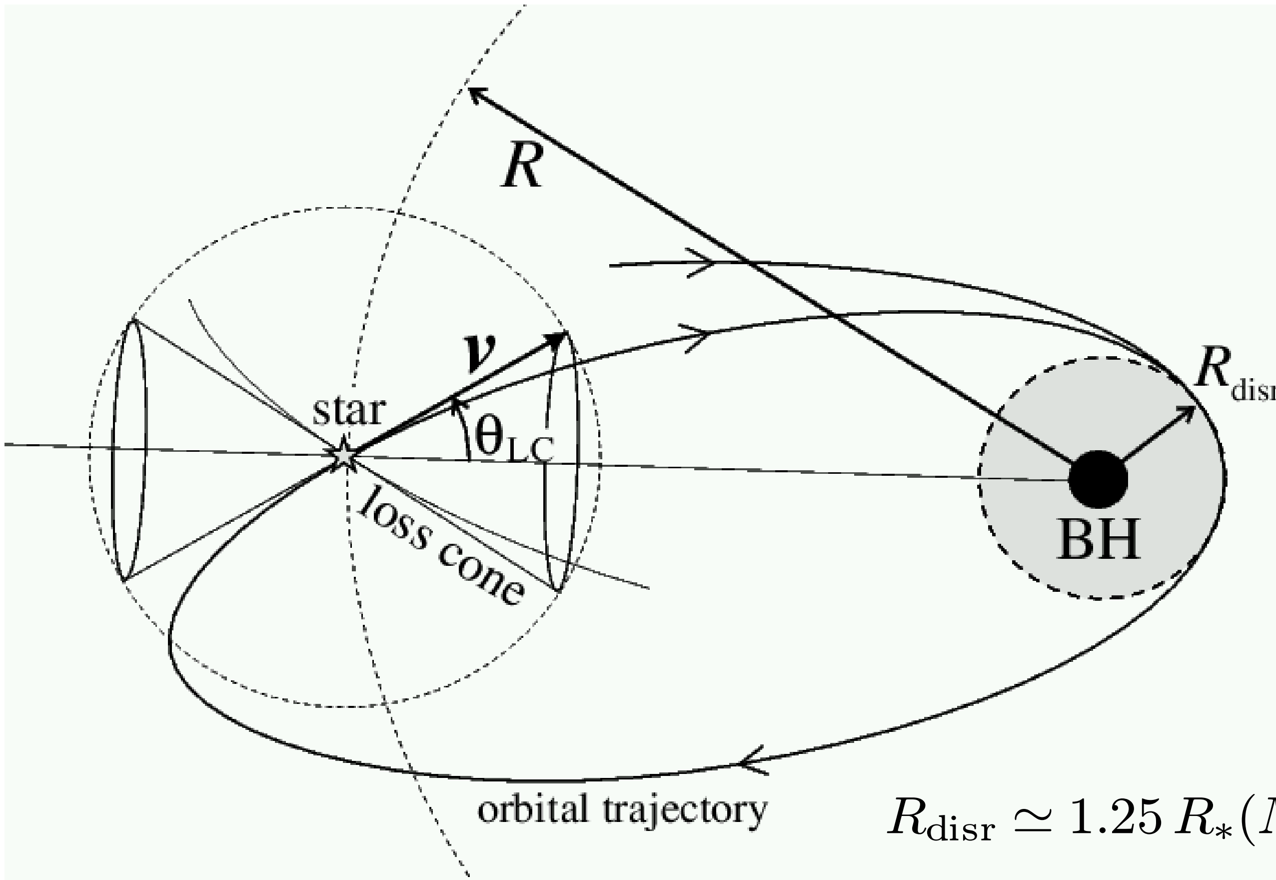
   Cluster's potential updated

Go back to 1

And add many complications!...

Marc Freitag
freitag@ast.cam.ac.uk

Loss Cone



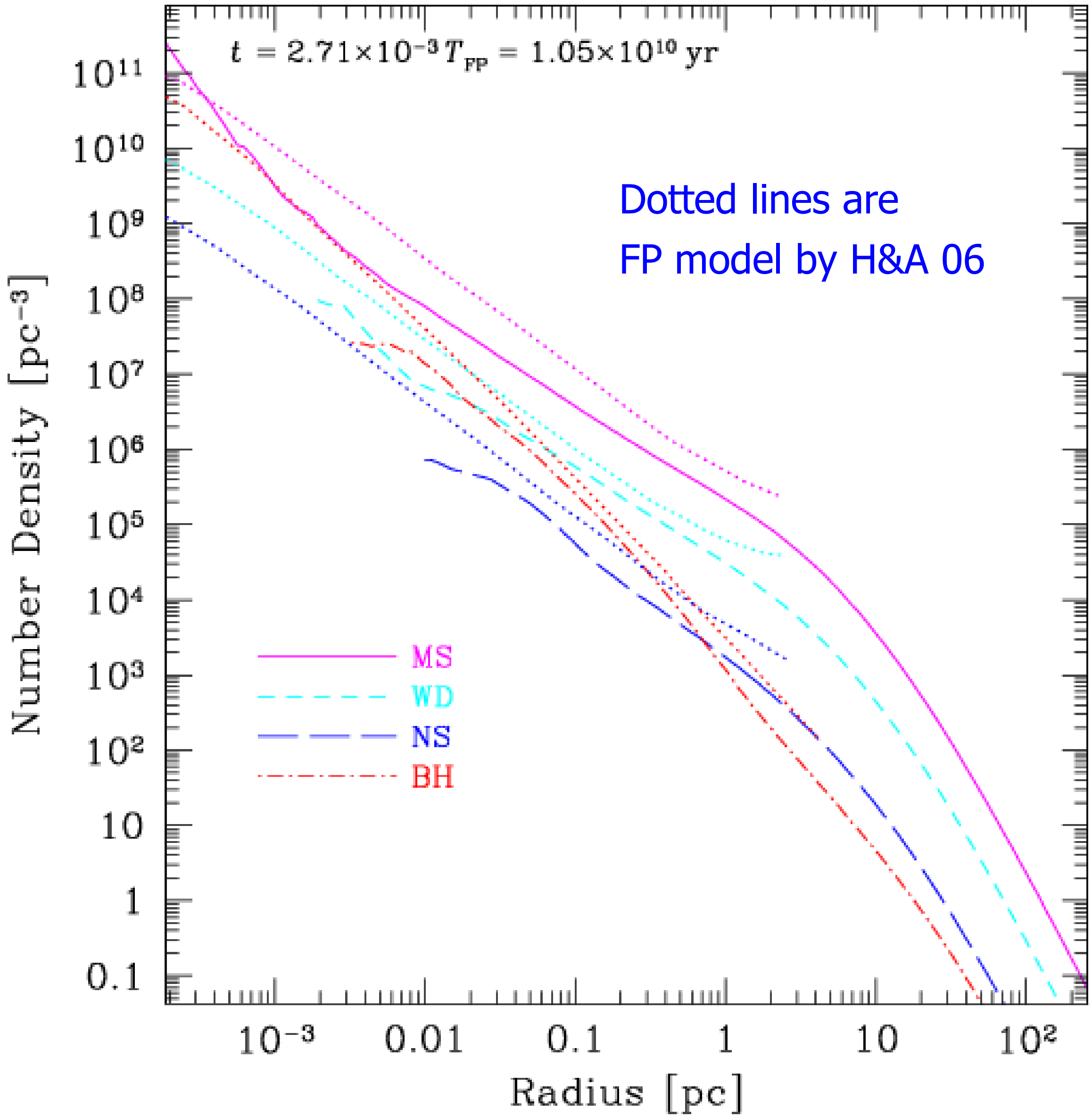
$$R_{\rm disr} \simeq 1.25\, R_*(M_{\rm BH}/M_*)^{1/3}$$

Loss cone aperture: $J < J_{\rm LC} \simeq \sqrt{2GM_{\rm BH}R_{\rm disr}}$

$$\theta_{\rm LC} \simeq \frac{J_{\rm LC}}{Rv} \approx \sqrt{\frac{R_{\rm disr}}{R}}$$

Marc Freitag
freitag@ast.cam.ac.uk

Sgr A* model: Comparison with Hopman & Alexander 06

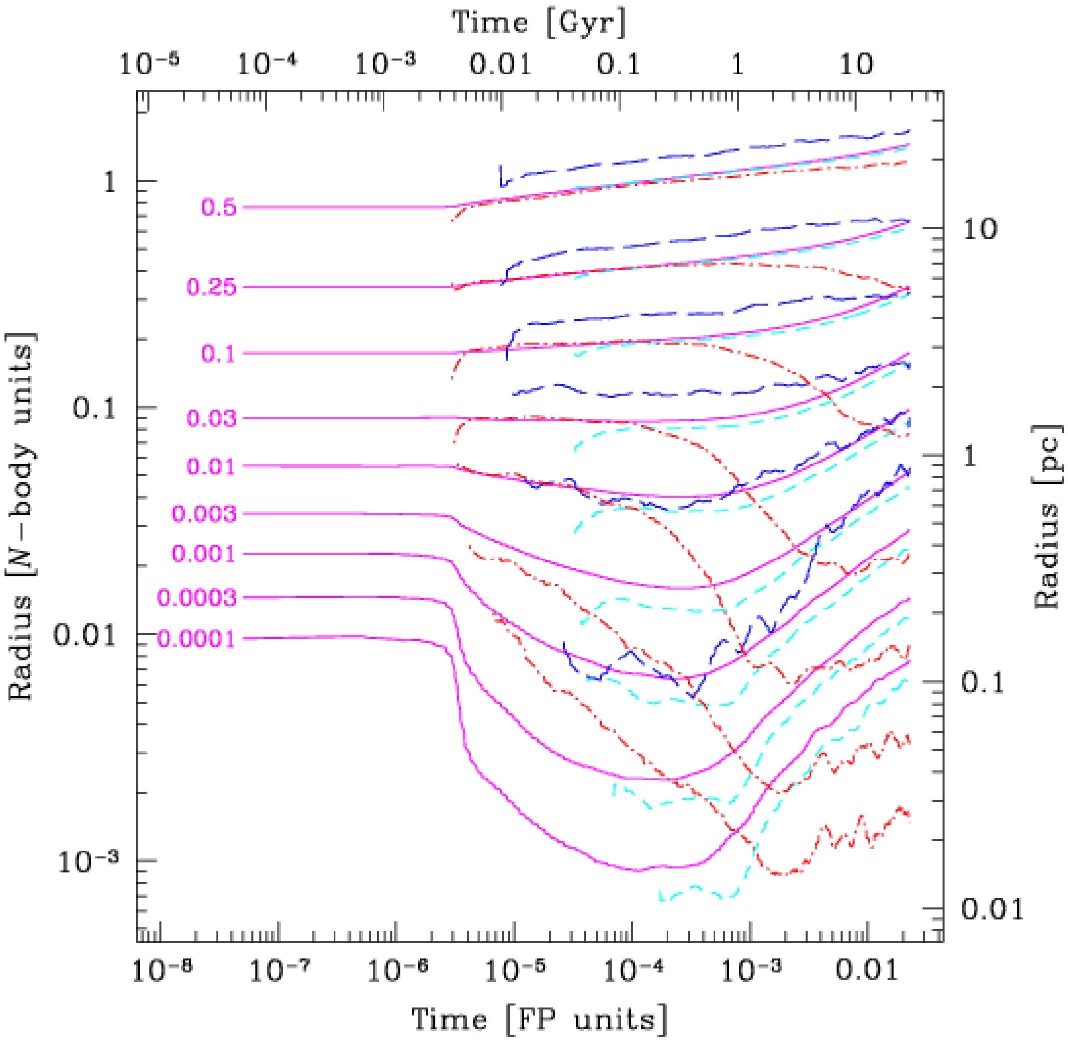


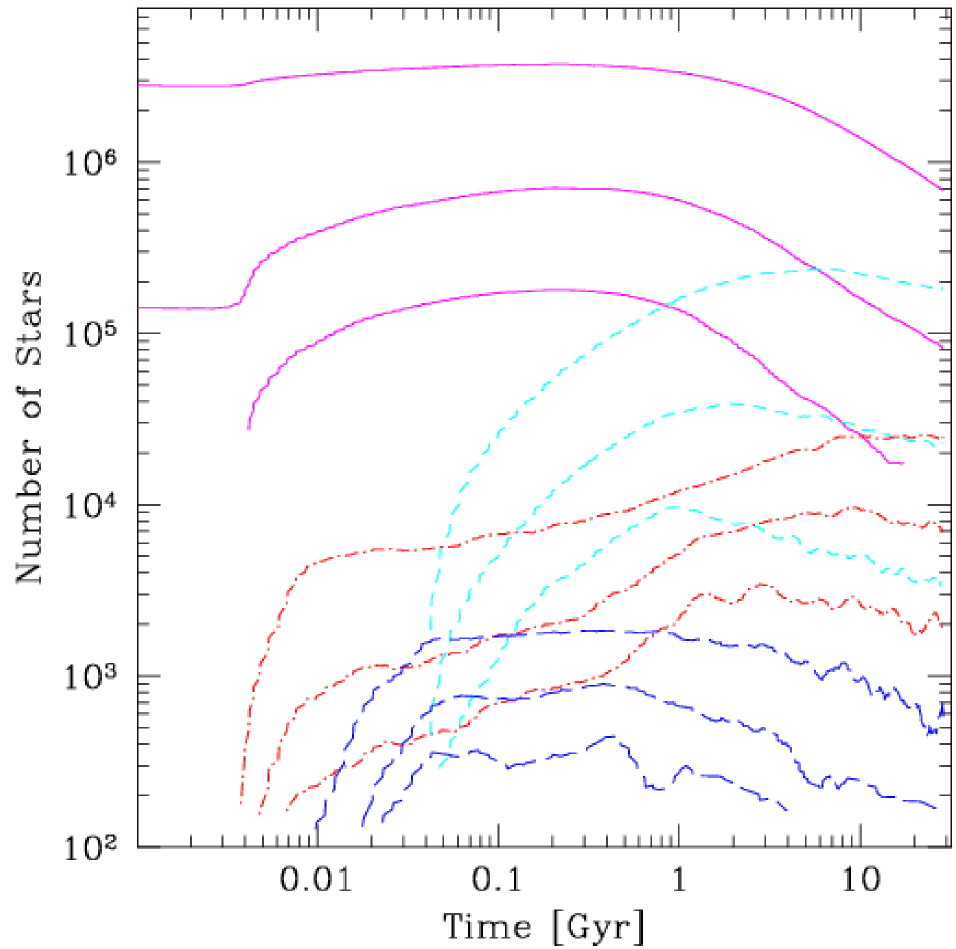
Marc Freitag
freitag@ast.cam.ac.uk

Evolution of Sgr A* model

- 2-body relaxation, tidal disruption
- Stellar evolution; Partial accretion of stellar mass loss
- $M_{BH}(0)\simeq 0$; $M_{BH}(10\text{ Gyr})=0.05M_{clust}$
- Fine tuned to be compatible with MW nucleus around 10 Gyr

Lagrange radii for MS stars, WDs, NSs, stellar BHs



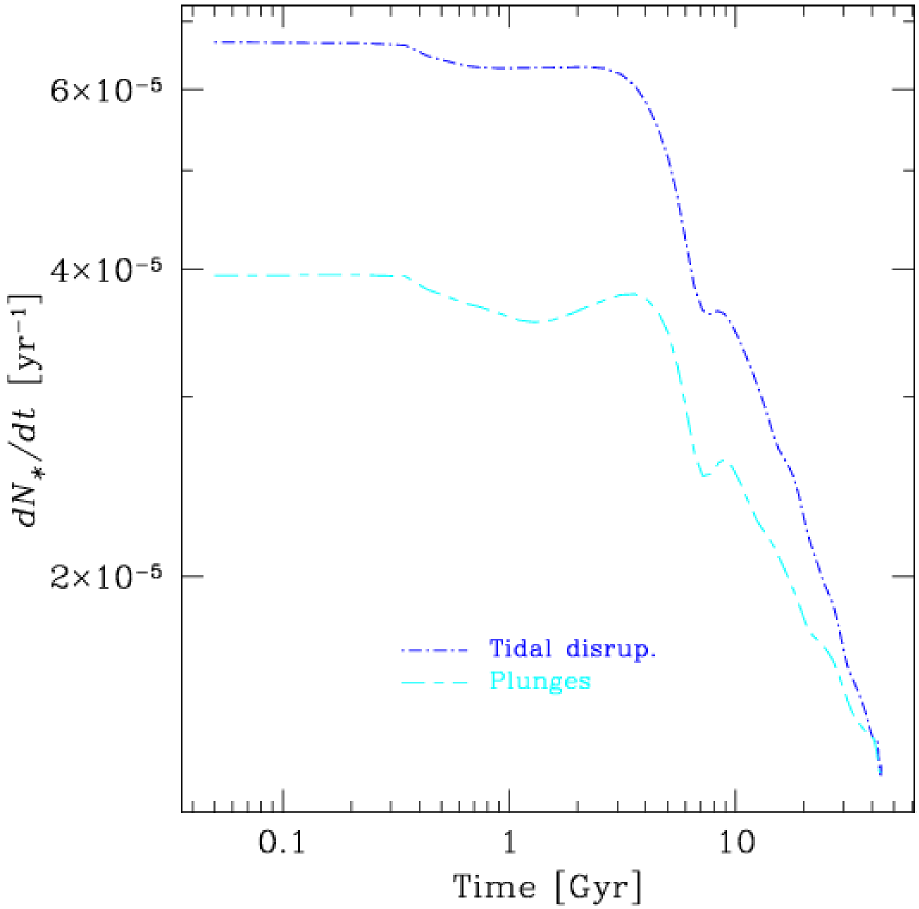


Number of stars within 0.1, 0.3, 1 pc of MBH

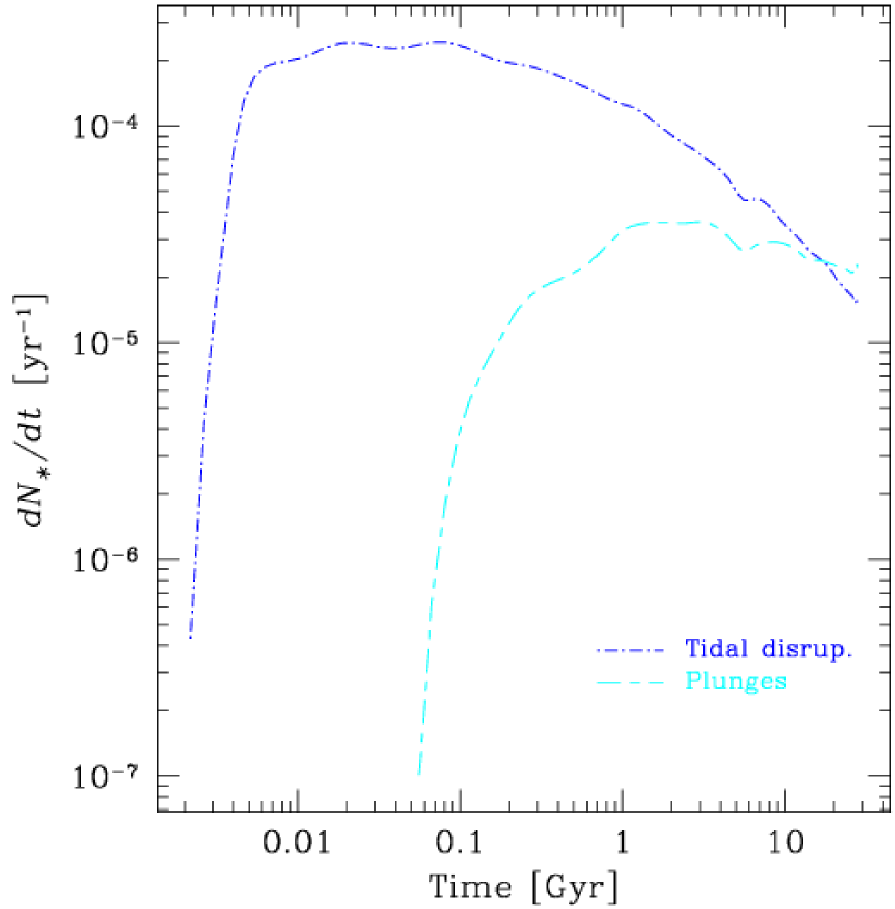
Marc Freitag
freitag@ast.cam.ac.uk

Event rates *(Sgr A* model)*

Large initial MBH, no stellar evolution



Small initial MBH, stellar evolution



Approx. same rates at 10 Gyr

Marc Freitag
freitag@ast.cam.ac.uk