The Milky Way nuclear star cluster: theoretical perspective

Structure **Formation** **Evolution**

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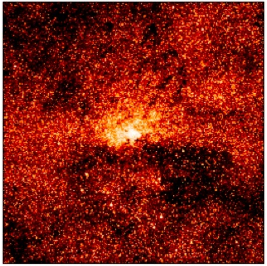
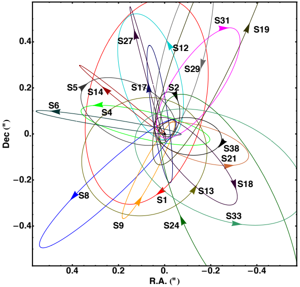
Survival of dense star clusters in the Milky Way system
Heidelberg, November 2018

Structure

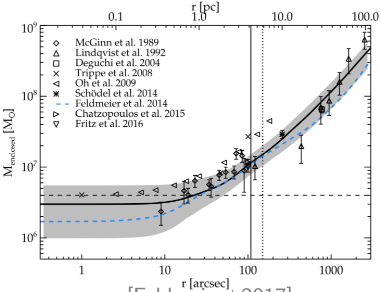


[Schödel+2014]

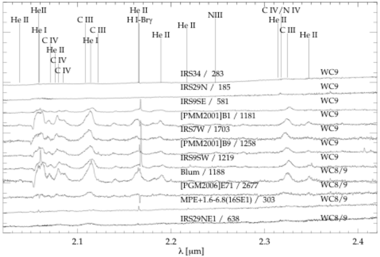


[Gillessen+2009]

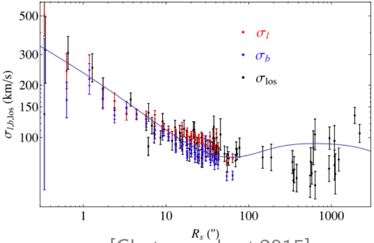
$$\rho(r) = \rho(r_b) 2^{(\beta-\gamma)/\alpha} \left(\frac{r}{r_b}\right)^{-\gamma} \left[1 + \left(\frac{r}{r_b}\right)^{\alpha}\right]^{(\gamma-\beta)/\alpha}$$



[Feldmeier+2017]



[Feldmeier+2015]

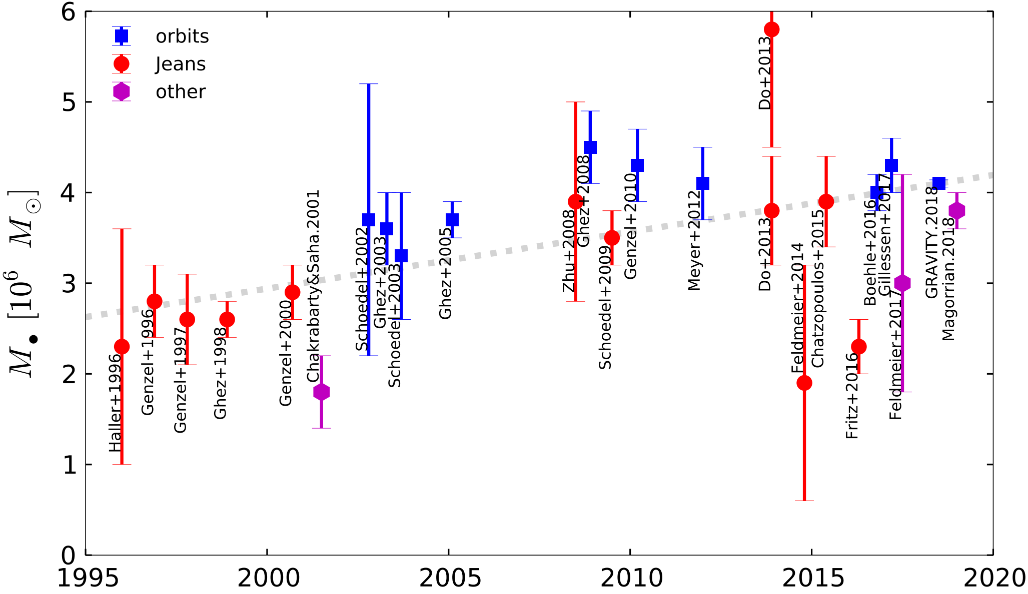


[Chatzopoulos+2015]

Ingredients and challenges

- Newtonian potential $M_\bullet$ + extended mass distribution $M_\star(< r)$
- Density profile of stars (cusp vs. core)
- Distinction between young and old stellar populations
- Geometry of stellar distribution (spherical vs. flattened)
- Stellar profile outside the central few pc
- Non-uniform dust extinction
- Kinematics: 3d velocity field (proper motion, line-of-sight velocity)
- Substructures, young stellar disk(s)
- Degeneracy between $M_\bullet$ and R_0 (distance to MW center)

Black hole mass growth

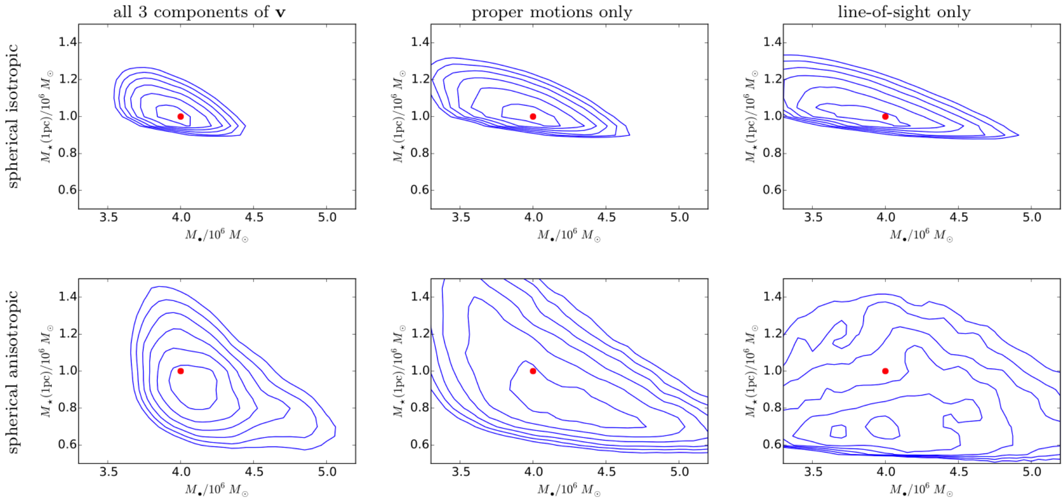


Summary of recent stellar-dynamical models

Reference	data	method	$M_\bullet/10^6\ M_\odot$
Schödel, Merritt & Eckart 2009	6000 PM $R < 0.8$ pc	sph.isotr.Jeans sph.aniso.Jeans	$3.6^{+0.2}_{-0.4}$ $3.5^{+0.15}_{-0.35}$
Do+ 2013	PM (Yelda+2013) 265 $v_{\rm los}$ (Keck/OSIRIS)	sph.iso.Jeans sph.aniso.Jeans	$3.77^{+0.62}_{-0.52}$ $5.76^{+1.76}_{-1.26}$
Feldmeier+ 2014	$\overline{v}_{\rm los}$, $\sigma_{\rm los}$ integrated light (ISAAC) $R < 4$ pc	axi.aniso.Jeans	$1.7^{+1.4}_{-1.1}$
Fritz+ 2016	10000 PM $R < 1.4$ pc 2500 $v_{\rm los}$ (VLT/SINFONI)	sph.isotr.Jeans same+M/L=const	2.26 ± 0.26 4.35 ± 0.12
Chatzopoulos+ 2015	same data	axi.isotr.Jeans	3.9 ± 0.5
Feldmeier+ 2017	LOSVD (v, σ, h_3, h_4) from F+14	triax.Schwarzschild	$3.0^{+1.1}_{-1.3}$
Magorrian 2018	PM+$v_{\rm los}$ from F+16 PM from S+09	sph.Schwarzschild	3.76 ± 0.22

Impact of kinematic diversity

- More measured velocity components $\Longrightarrow$ better constraints
- More flexible modelling assumptions $\Longrightarrow$ loose constraints

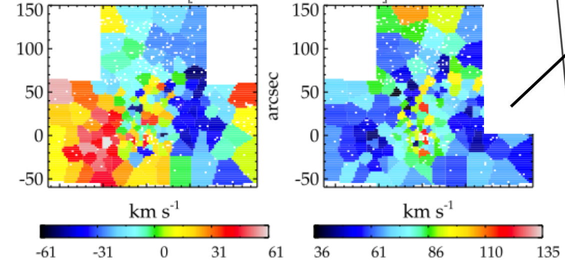


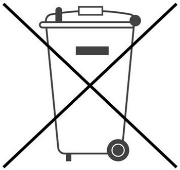
[Magorrian 2018]

Caveats of Jeans models

- May suffer from mass-anisotropy degeneracy
- Do not guarantee a positive distribution function
- Usually require binning of data

[Feldmeier+ 2014]





[Chatzopoulos+ 2015]

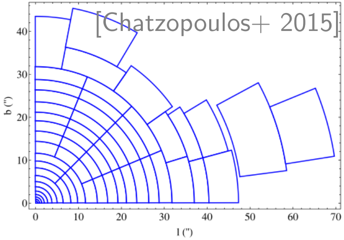


Figure 1. Binning of the PM velocities. The stars are binned into cells according to their distance from Sgr A* and their smallest angle to the Galactic plane (Fritz et al. 2014).

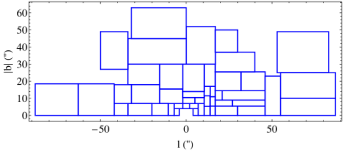
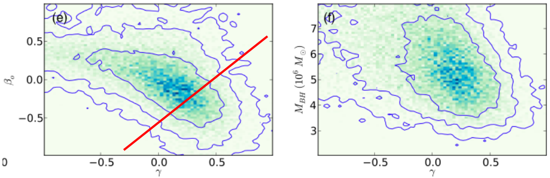


Figure 2. Binning of the los velocities. The stars are binned into 46 rectangular outer cells plus 6 rectangular rings at the centre. The latter are located within the white area around $l = b = 0$ and are not shown in the plot; see appendix E of Fritz et al. (2014).



It has been argued that the non-negativity of the distribution function imposes the constraint $\gamma \geqslant \beta_0 + 1/2$ (An & Evans 2006). This is violated in large parts of the $\beta_0 - \gamma$ preferred region (Figure 1(e)) and this issue deserves a separate investigation. Including this limit will likely result in slightly steeper γ and increased tangential anisotropy. A distribution function analysis similar to that of Wu & Tremaine (2006) will be useful to confirm the present results.

[Do+ 2013]

The role of density profile

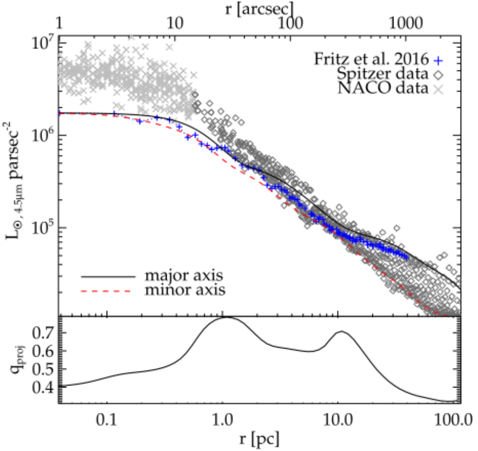
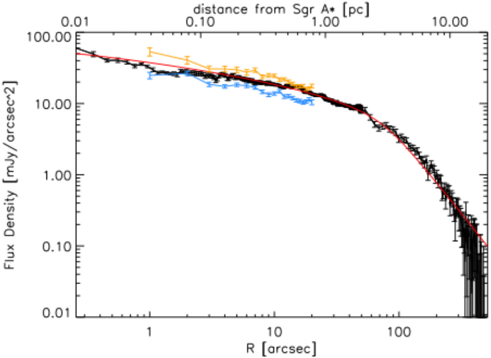


Figure 2. Upper panel: surface brightness profile derived from a dust extinction and PAH emission corrected *Spitzer*/IRAC 4.5 μm image and NACO *H*-band mosaic for the centre, scaled to the measurements of Fritz et al. (2016, blue crosses). The black full line denotes the MGE fit along the major axis, and the red dashed line along the minor axis. Lower panel: projected axial ratio q_{proj} as a function of r. [Feldmeier+ 2017]



[Schödel+ 2018]

Lower $\Sigma_\star \implies$ higher $M_\bullet$

Challenges:

Crowding (esp. faint stars)

Nonuniform extinction

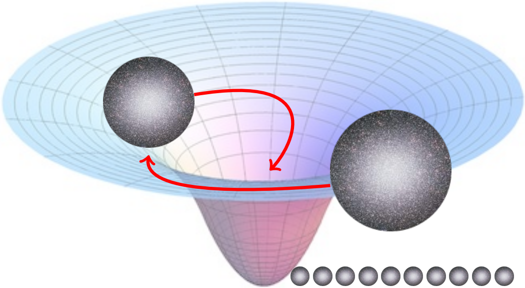
Gas emission (for unresolved stars)

Distinction between young/old stars

Formation scenarios

Migration of globular clusters

from the Galactic bulge
to the Galactic center
due to dynamical friction



In-situ star formation

from the gas flowing
into the Galactic center

Formation scenarios

Migration of globular clusters

Capuzzo-Dolcetta, Miocchi, Di Matteo, Antonini, Mastrobuono-Battisti, Spera, Arca-Sedda, Bortolas, Rastello, . . .

Italian school

In-situ star formation

Loose, Milosavljević, Bekki, Perets, . . .

“American” school

Formation scenarios

Italian school

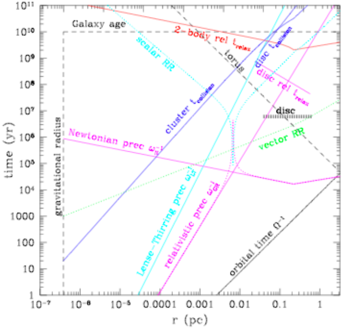
“American” school

Formation scenarios

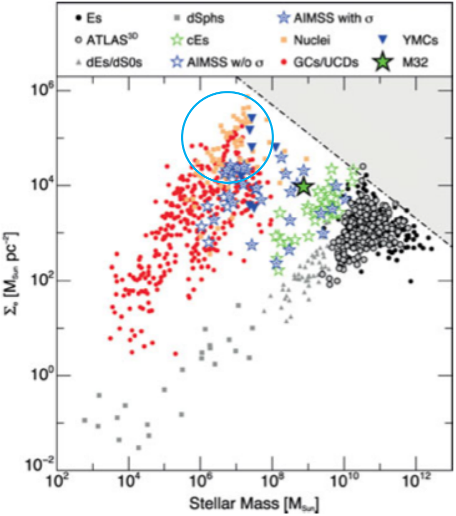
	Migration	In-situ
Kinematics	− (high $\sigma_{R=0}$, low $\overline{v}_{\rm rot}$) [Hartmann+2011] + (at least for MW NSC) [Tsatsi+2016]	+ (rotation)
Stellar ages	+ mixture of ages, most stars $\geq$ 5 Gyr [Blum+2003; Pfuhl+2011; Kacharov+18]	+ young stars $\sim 10^7$ yr [Krabbe+1995]
Chemistry	? large spread – possibly superposition of many populations	+ most stars have [Fe/H]> 0 [Do+15; Feldmeier+16]
Density	+* (seen next slide)	+

Evolution

- Nuclear star clusters are among the densest stellar systems in the Universe!
- Collisionless processes (e.g., mergers of globular clusters) cannot increase the phase-space density $\rho/\sigma^3 \propto T_{\rm rel}^{-1}$.
- However, collisional evolution may be important: relaxation time $T_{\rm rel} \lesssim T_{\rm Hubble}$.



[Kocsis&Tremaine 2011]



[Norris+2014, see also Walcher+2006; Misgeld&Hilker 2011]

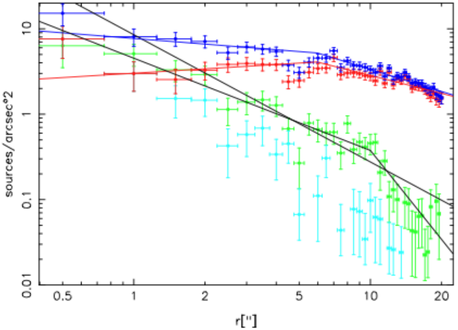
Aspects of dynamical evolution

- Formation (or not?) of a Bahcall–Wolf cusp
- Mass segregation
- Resonant relaxation
- Relativistic effects
- The origin of S-stars
- Hypervelocity stars
- Exotic objects

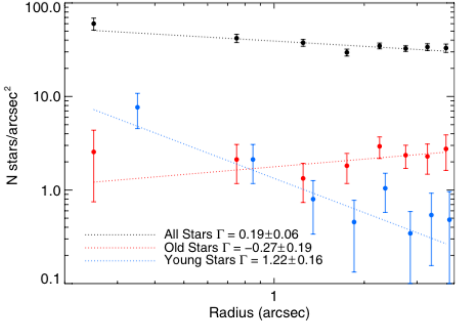
The mythical Bahcall–Wolf cusp

In a relaxed stellar system around a massive black hole, the density should follow a power law: $\rho \propto r^{-7/4}$ (single-mass case), or $\rho \propto r^{-3/2}$ (lighter component in the multimass case) [Bahcall&Wolf 1976,1977].

However, the observed distribution of old stars defies the expectations:



[Buchholz+2009]

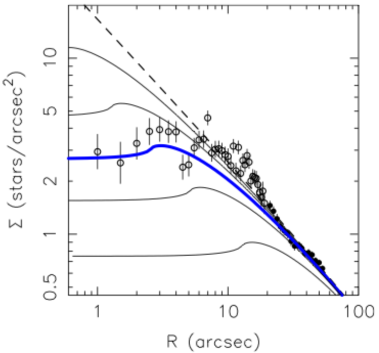


[Do+2009]

The mythical Bahcall–Wolf cusp

Theorists were quick to come up with plausible explanations:

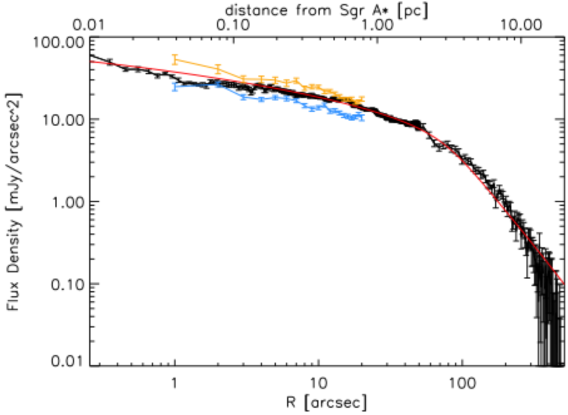
- Incomplete relaxation starting from an initially cored profile or a "hole" left by a binary black hole [Merritt 2009].
- Destruction of red giants by stellar collisions [Dale+2009, Davies+2011].
- Stripping of stellar envelopes by collisions with gaseous disk [Amaro-Seoane&Chen 2014].
- Star formation at $r \gtrsim 1$ pc [Aharon&Perets 2015].



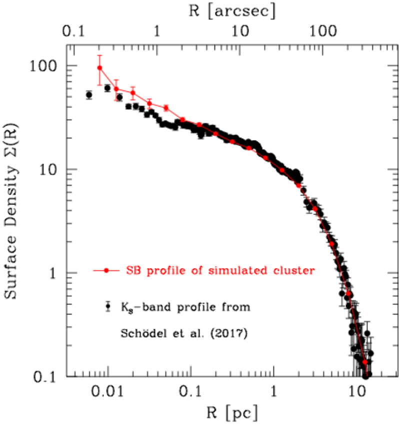
[Merritt 2009]

The mythical Bahcall–Wolf cusp

However, more recent observations do not support the existence of a core, lining up nicely with traditional evolution models:



[Schoedel+2018; Gallego-Cano+2018]

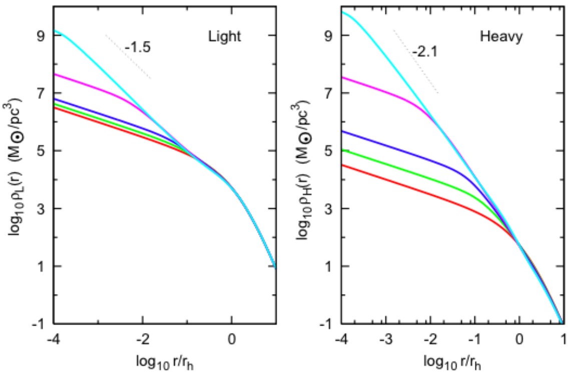


[Baumgardt+2018]

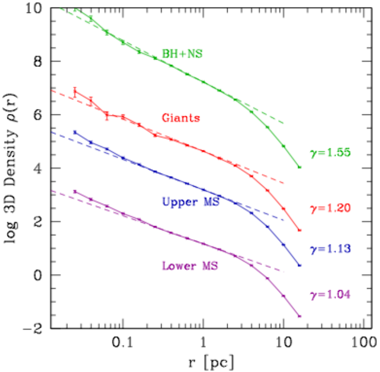
Mass segregation

Heavy objects (BH, NS) sink to the center due to dynamical friction.
In steady state, their density profile is steeper ($r^{-1.75} \dots r^{-2.1}$)
[Bahcall&Wolf 1976; Alexander&Hopman 2009; Preto&Amaro-Seoane 2009].

This is important for GW astronomy (EMRI and all that) [Amaro-Seoane&Preto 2011].



[Preto&Amaro-Seoane 2009]



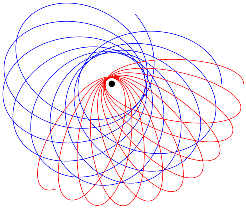
[Baumgardt+2018]

Resonant relaxation

Introduced by Rauch&Tremaine 1996.

Idea: $T_{\text{precession}} \gg T_{\text{radial}} \implies$ coherent interactions between pairs of stars.

Affects only angular momentum, not energy.



- Scalar:
  - Near-Keplerian systems (extended mass around a SMBH $\Rightarrow$ in-plane precession)
  - Changes eccentricity e ($\Leftrightarrow |L|$)
  - Quenched by relativistic precession for $e \to 1$

Hopman&Alexander 2006; Madigan+2011; Merritt+2011; Merritt 2015a,b,c,d;

Bar-Or&Alexander 2014,2016; Sridhar&Touma 2016; Alexander 2017a,b; Fouvry&Bar-Or 2018

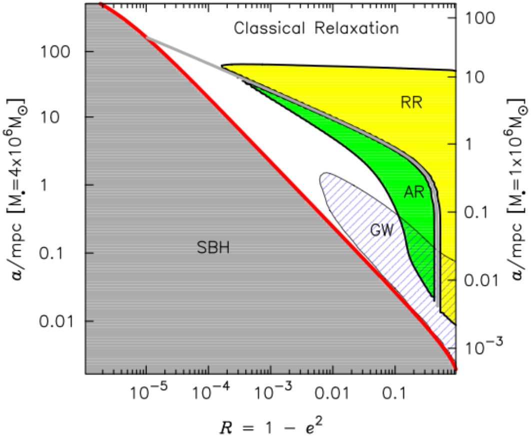
- Vector:
  - Any spherical system (constant orbital planes)
  - Changes orbital inclination ($\vec{L}$ but not $|L|$)

Kocsis&Tremaine 2011,2015; Meiron&Kocsis 2018; Hamers+2018

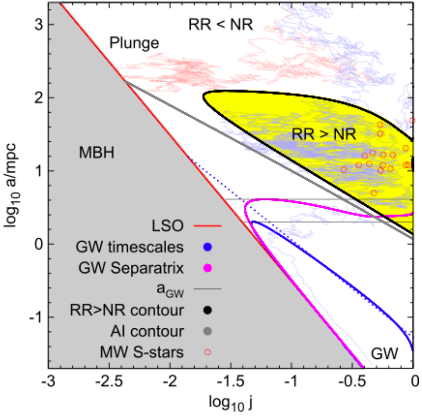
Relativistic effects

The "Schwarzschild barrier" discovered by Merritt,Alexander,Mikkola&Will 2011: quenching of RR by relativistic precession of high-eccentricity orbits $\Longrightarrow$

RR appears to have little net effect on the rate of captures or EMRI.



[Merritt 2015d]



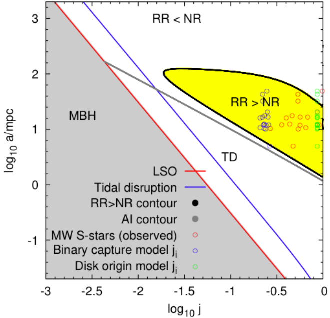
[Bar-Or&Alexander 2016]

Origin and dynamics of S-stars

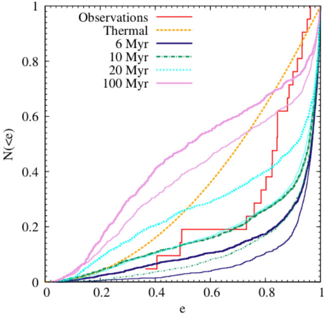
Two main scenarios predicting different eccentricity distributions:

- Formation in a gaseous disk ($e \sim 0$)
- Tidal disruption of binaries [Hills 1988] ($e \sim 1$)

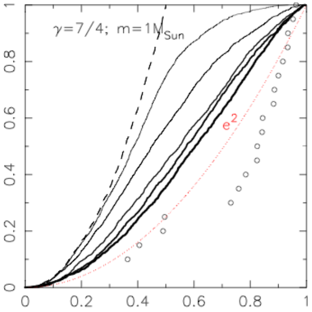
Observed: steeper than thermal $N(< e) \propto e^2$, certainly affected by RR! ($T \lesssim 10^8$ yr)



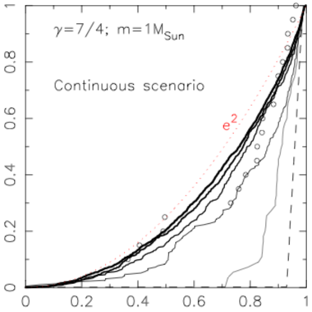
[Alexander 2017]



[Madigan,Hopman&Levin 2011]

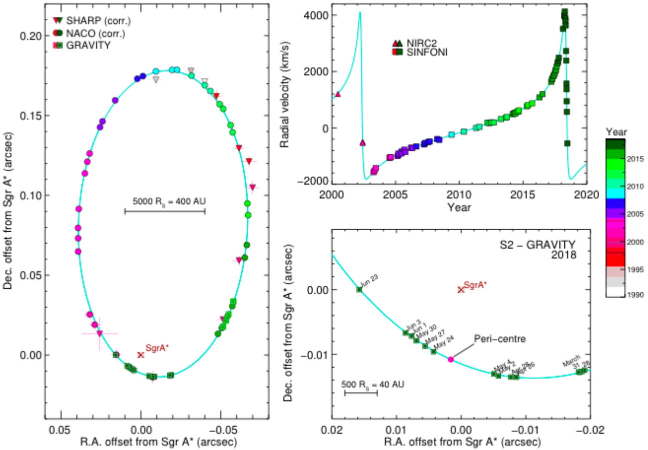


[see also Perets+2009]

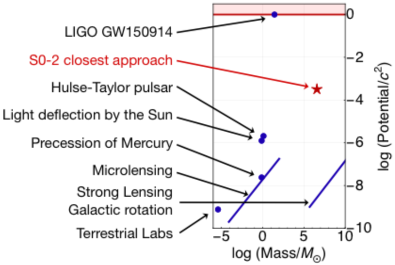


[Antonini&Merritt 2013]

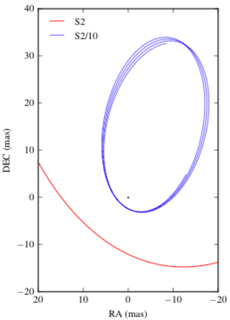
Probing GR effects by S stars



[GRAVITY collaboration 2018]



[from Hees+2017]



[Waisberg+2018]

S2 pericenter at 1400 $R_{\rm Schw}$ – measured $M_\bullet$ to 1%;
measured gravitational redshift (GR not Newton) to 10%;
hope to measure GR precession in a few years;
measurement of BH spin needs a star 10$\times$ closer...
perturbations from other stars or stellar BHs are important! [Merritt+2010]

Hypervelocity stars

Ejection speed $\gtrsim 1000$ km/s ≈ 1 kpc/Myr due to interaction with the SMBH

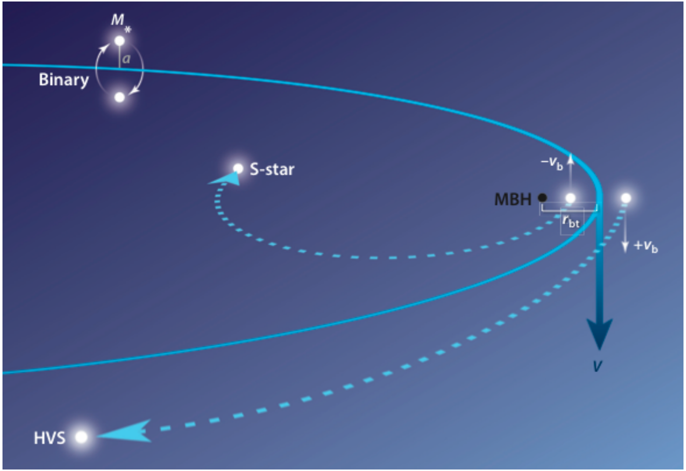
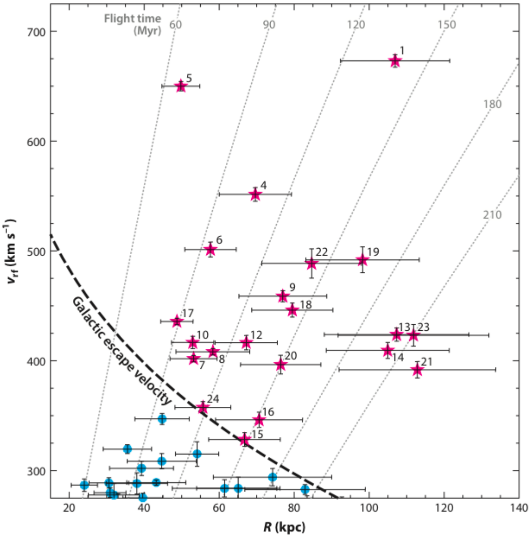


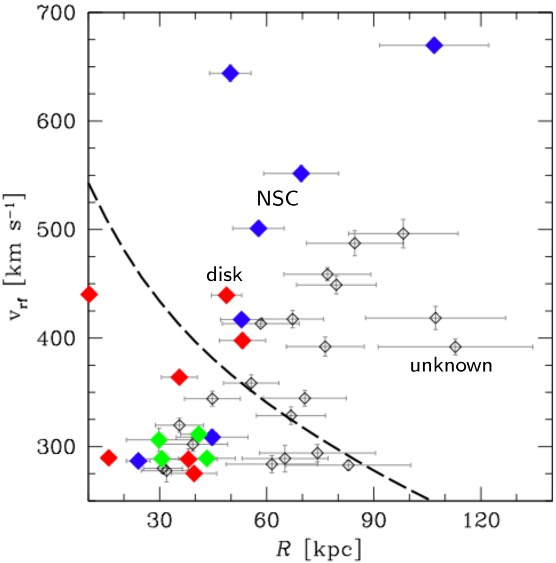
Illustration of the Hills(1988) mechanism [from Brown 2017]

Not to be confused with hyper-runaway stars (ejected from galactic disk with comparable speeds due to binary disruption by supernova or to 3- or 4-body encounters)

Hypervelocity stars



B-type HVS found in a dedicated survey of 12 000 sq.deg. [Brown 2014]



After *Gaia* DR2 [Brown+2018; see also Boubert+2018, Marchetti+2018; Hattori+2018; Kenyon+2018]

Hypervelocity stars

Ejection rate: from $10^{-3} - 10^{-4}$ yr^{-1} (full loss cone, Hills 1988)
to $10^{-5} - 10^{-6}$ yr^{-1} (empty loss cone, Yu&Tremaine 2003);
realistically $10^{-4} - 10^{-5}$ yr^{-1} [Zhang+2013], $\gtrsim$ tidal disruption rate.

Link between S-stars and HVS: Gould&Quillen 2003; Ginsburg&Loeb 2006; Zhang+2013; . . .

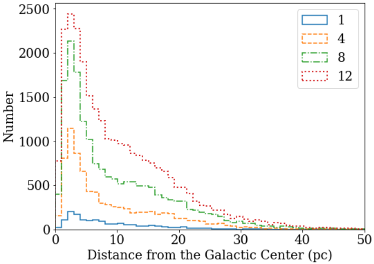
Other scenarios:

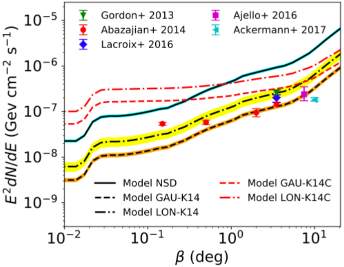
- single star, binary SMBH [Yu&Tremaine 2003; Sesana+2006]
- same but a SMBH+IMBH pair [Portegies Zwart+2006; Levin 2006; Baumgardt+2006; Rasskazov+2018]
- eccentric disk via the Lidov–Kozai mechanism [Löckmann+2008; Šubr&Haas 2016]

Exotic objects

Millisecond pulsars, cataclysmic variables:

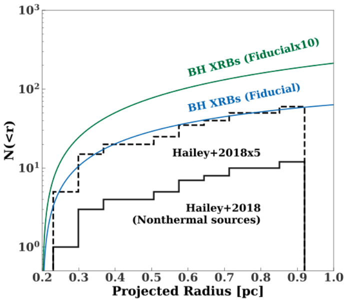
excess of unresolved γ- and X-ray emission
from galactic center [Fermi, NuSTAR]





produced in globular clusters (migration scenario)
[Brandt&Kocsis 2015; Arca-Sedda+2018; Abbate+2018; Fragione+2018a,b]

BH X-ray binaries:



Tidal capture of MS by BH
[Generozov+2018]

Gravitational-wave sources from BH binaries merging via the Lidov–Kozai mechanism
[Antonini&Perets 2012; Hong&Lee 2015; Rodriguez+2016; Antonini&Rasio 2016;. . .]

Conclusion