# High Velocity Stars as Results of Close Globular Cluster-Massive Black Hole Interaction

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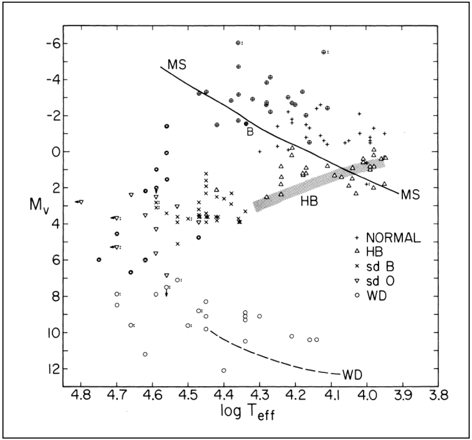
# Outline

# Runaways Observational Evidence




Runaway Stars: OB Galactic halo stars with peculiar motions higher than 40 km $s^{-1}$

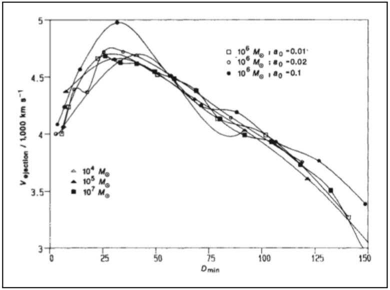
Observational evidence of main sequence B-type stars in Galactic halo (Humason & Zwicky 1947; Greenstein & Sargent 1974)

Young massive stars are not expected to be observed in the halo far from star-forming regions

# HVSs Theoretical Prediction and Observational Evidence

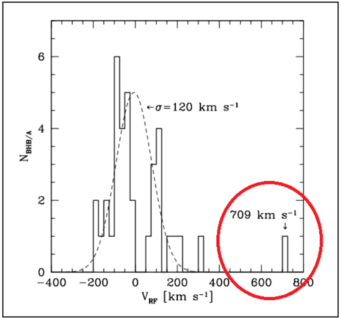
Hyper Velocity Stars (HVSs): Unbound stars escaping the host Galaxy

Theoretical prediction:
Hills 1988




Hills, Nature, 331, 687, 1988

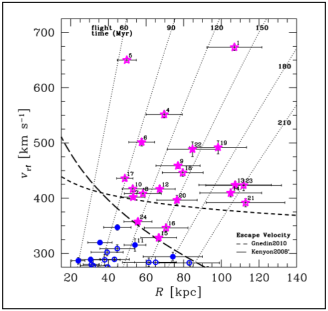
Observational evidence:
Brown+ 2005




Brown, Geller, Kenyon. ApJ, 622, L33, 2005

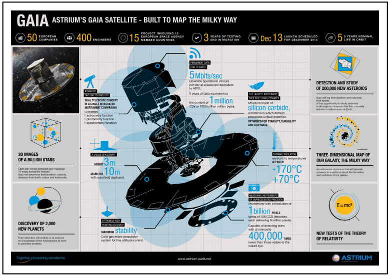
# Present and Future Surveys

MMT Survey: spectroscopic survey of 2.5 ÷ 4 $M_\odot$ late B-type stars




21 HVSs (Brown+ 2014)

GAIA Telescope




Expected to find ∼ 100 HVSs in a catalogue of ∼ $10^9$ stars (Robin+ 2012, de Bruijne+ 2015)

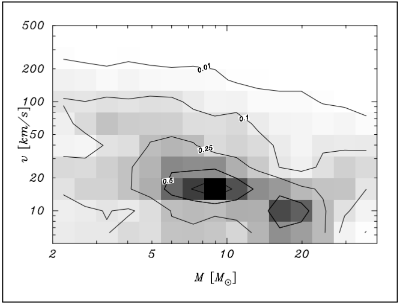
+ US708 Helium-rich subdwarf O star (Hirsch+ 2005)

+ HE0437-5439 MS 9 $M_\odot$ (Edelmann+ 2005)

# Runaways Production Mechanisms

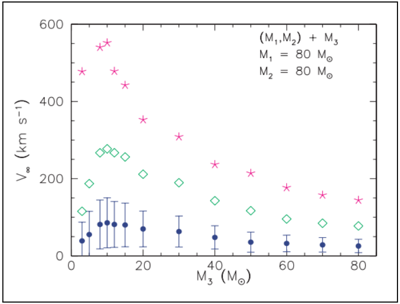
Observations show that both the ejection mechanisms operate in nature (Hoogerwerf+ 01; Pflamm-Altenburg & Kroupa 10)

Supernova Ejection:
Blaauw 61; Przybilla+ 08




Portegies Zwart. ApJ, 544, 437, 2000

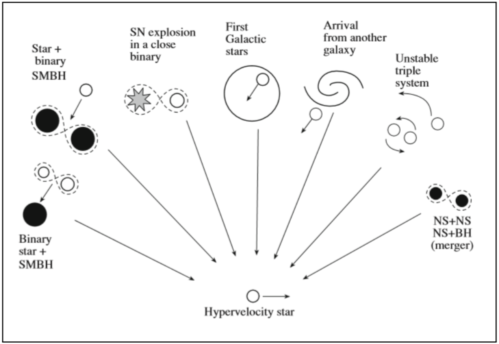
Dynamical Ejection:
Poveda+ 67; Leonard 91




Gvaramadze & Gualandris. MNRAS, 410, 304, 2011

# HVSs Production Mechanisms

HVSs have both slow and rapid rotations suggesting different acceleration mechanisms (Hansen 2007; Lopez-Morales & Bonanos 2008)



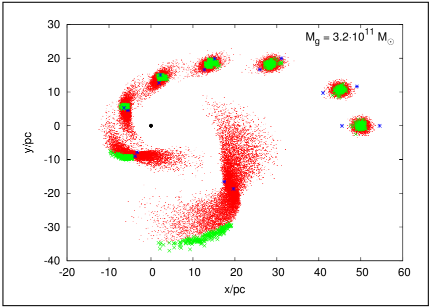

Tutukov & Fedorova. Ast. Rep. 53-9, 839, 2009

Information:

- Three body interaction (Yu & Tremaine 03; Gualandris+ 05; Perets+ 07; Rossi+ 14)
- Composition of the Galactic Centre (Gould & Quillen 03; Sesana+ 07)
- Supernovae (Zubovas+ 13)
- Galactic potential and Dark Matter (Gnedin+ 05; Yu & Madau 07)

# GCs and High Velocity Stars

GCs inspiral and merge in the Galactic Centre (Capuzzo-Dolcetta 93; Capuzzo-Dolcetta & Miocchi 08; Antonini+ 12; Arca-Sedda+ in prep.)



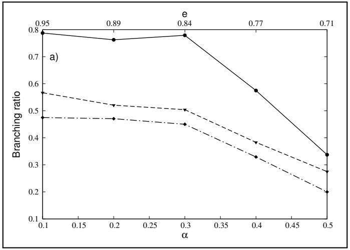

Three-body interaction among BH, GC (approximated as point-mass) and GC-stars

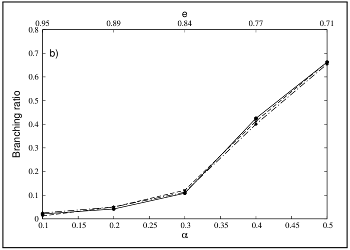
Scheme of simulations:

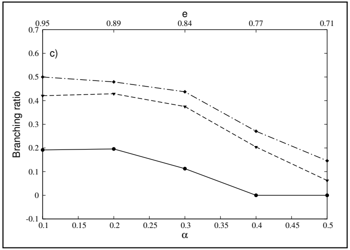
- $M_{BH} = 10^8\ M_\odot$, $M_{GC} = 10^4 \div 10^6\ M_\odot$, $M_* = 1\ M_\odot$
- 5 GC elliptic orbits of same energy ($\alpha = 0.1 \div 0.5$)
- 10 stars orbits around GC ($\beta = 4 \div 13$)

Capuzzo-Dolcetta & Fragione accepted in MNRAS (arXiv:1509.03170)

# Branching Ratios



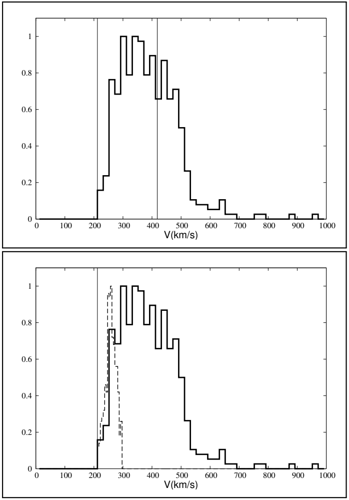




$M_{GC} = 10^4\ M_\odot$ (solid)
$M_{GC} = 10^5\ M_\odot$ (dashed)
$M_{GC} = 10^6\ M_\odot$ (dot-dashed)

- a) Stars bound to BH $E_{BH} < 0$
- b) Stars bound to GC $E_{GC} < 0$
- c) Unbound stars $E_{BH} > 0$, $E_{GC} > 0$

# Velocity Distribution

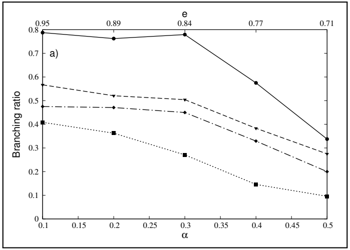


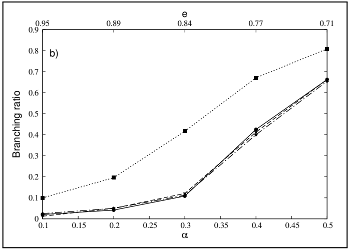

The fraction of HVSs depends on the GC mass and host galaxy model

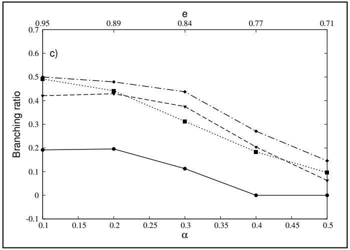
- Example: Elliptical galaxy NGC3377 ($M_{BH} = 10^8$ $M_\odot$, $M_{Bulge} = 7.8 \cdot 10^{10}$ $M_\odot$, $a_b = 5.4$ kpc)
- 18% of unbound stars are HVSs

The introduction of a core radius ($a = 0.5$ pc) makes the distribution shrinks and the peak moves to a lower velocity

# Star Orbital Inclination

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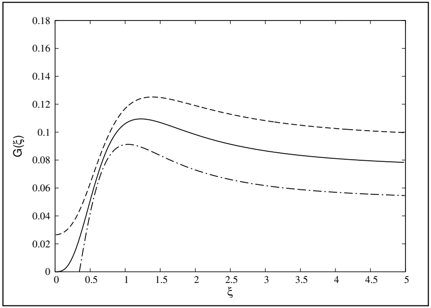
# Distribution Function

$$\Phi(r) = -\frac{GM}{\sqrt{r^2 + a^2}}$$



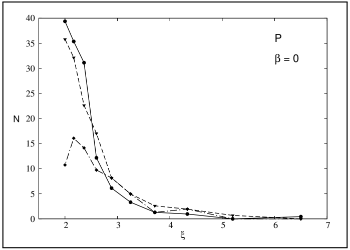

$G(\xi) = \nu_c(\xi)/\nu(\xi)$ local fraction of stars in nearly circular orbit ($\xi = r/a$)

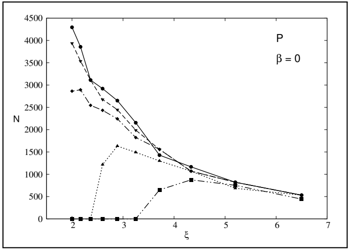
- $\nu(\mathbf{x}) = \int_0^{v_{esc}} d^3v\ f(\mathbf{x}, \mathbf{v})$
  $\nu(\mathbf{x}) = \int_{v_c - \delta v_c}^{v_c + \delta v_c} d^3v\ f(\mathbf{x}, \mathbf{v})$
- $\delta$ tolerance in $v_c$ ($\delta = 0.05$)

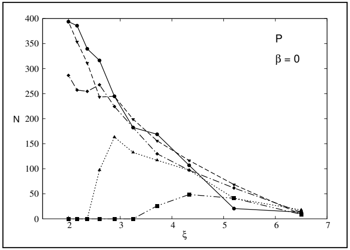
Different anisotropy

- dashed $\beta = -1/2$
- solid $\beta = 0$
- dot-dashed $\beta = +1/2$

# Number of Escapers ($\beta = 0$)




There are $\sim 10 \div 10^2$, $\sim 10^2 \div 10^3$, $\sim 10^3 \div 10^4$ stars ejected at high velocities for
$M_{GC} = 10^4\ M_\odot$ (top-left),
$M_{GC} = 10^5\ M_\odot$ (bottom-left),
$M_{GC} = 10^6\ M_\odot$ (top-right)

# Features of the Model

Different mechanism predict different physical and kinematic features (Brown 15)

- distribution of velocity
- collimation and emission in jets
- similar ages and metallicity of stars
- common flight time

Information about the Globular Cluster progenitor and its last orbits around Black Hole

# Conclusions

- The efficiency of the star acceleration process is almost linear in $M_{GC}$
- A massive GC (composed by $10^6$ identical 1 $M_\odot$ stars) releases $\sim 10^4$ stars in a single close passage around the super massive BH
- In a very close GC-BH encounter ($M_{GC} = 10^6$ $M_\odot$, $\alpha = 0.1$) the probability of stars to remain bound, become bound to BH or escape from the cluster are $\sim 5\%$, $\sim 45\%$, $\sim 50\%$, respectively
- The fractions of stars, respect to the total ejected stars, which escape from the whole galaxy is $\sim 18\%$ for an $M_{tot} = 7.81 \times 10^{10}$ $M_\odot$ elliptical and $\sim 0.5\%$ for an $M_{tot} = 6.60 \times 10^{11}$ $M_\odot$ spiral galaxy
- The results depend on the core radius and on the star orbit inclination