Hypervelocity stars in the *Gaia* era: Runaway B stars beyond the velocity limit of classical ejection mechanisms

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ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS

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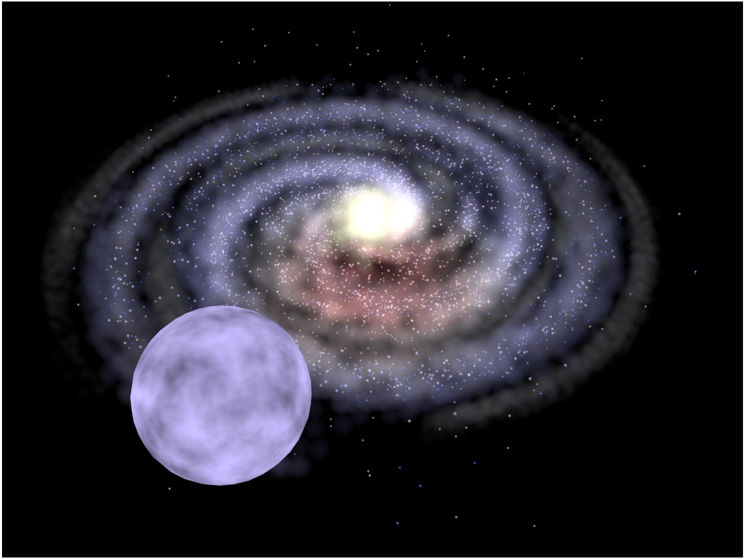
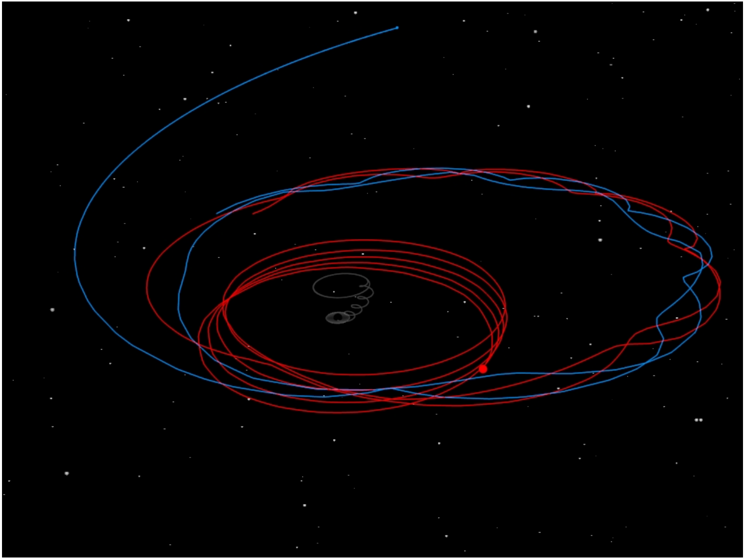
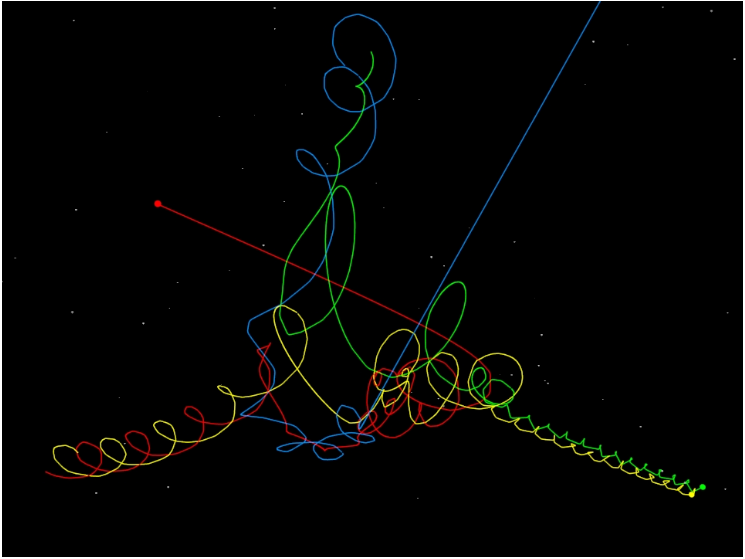
Massive main-sequence B-stars in the Galactic halo



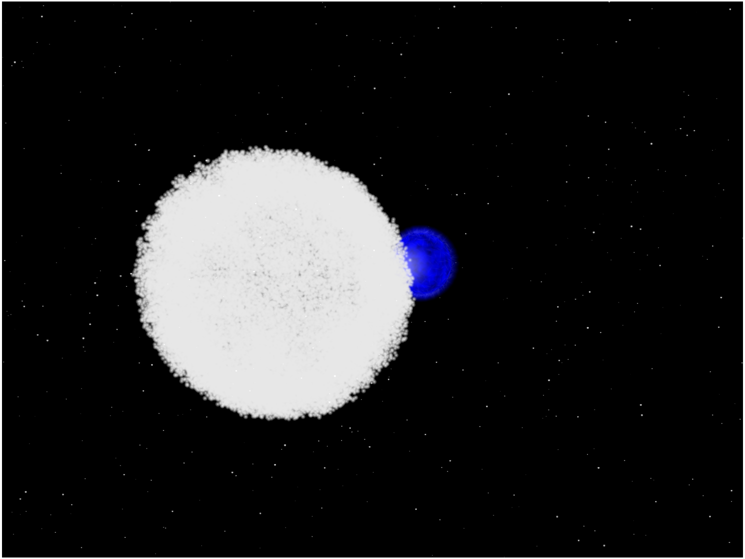
Dynamical ejection I: Hills mechanism



Dynamical ejection II: many-body interaction



Supernova explosion disrupting a binary system

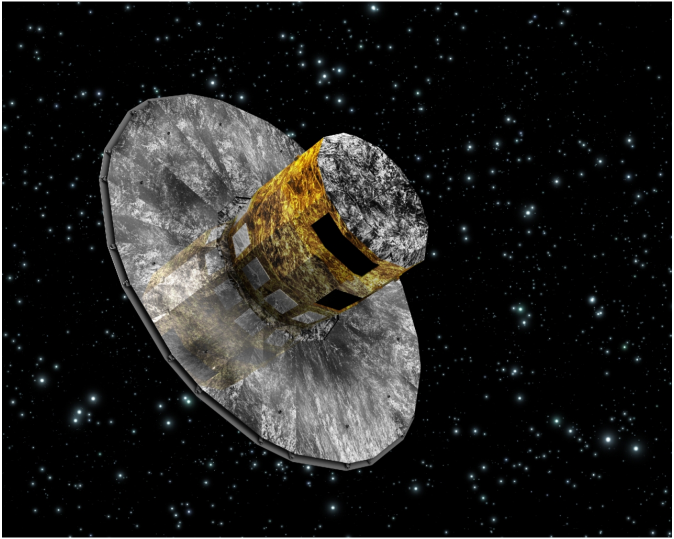


Ejection velocities of those "classical" mechanisms

Mechanism	Ejection velocity ($\mathrm{km\,s^{-1}}$)		Reference
	$\sim 99\%$	$\sim 100\%$	
Hills mechanisms		$\lesssim 4000$	Hills (1988)
Many-body interaction	$\lesssim 200$	$\lesssim 400$	Perets & Šubr (2012)
Many-body interaction	$\lesssim 100$	$\lesssim 400$	Oh & Kroupa (2016)
Supernova channel	$\lesssim 200$	$\lesssim 400$	Portegies Zwart (2000)
Supernova channel	$\lesssim 400$	≤ 540	Tauris (2015)
Supernova channel	$\lesssim 60$	$\lesssim 400$	Renzo et al. (2019)

$\Rightarrow$ Ejection velocities $\gtrsim 500\,\mathrm{km\,s^{-1}}$ seem to be compatible only with the Hills mechanism and, thus, with an origin in the Galactic center

Hypervelocity stars in the *Gaia* era



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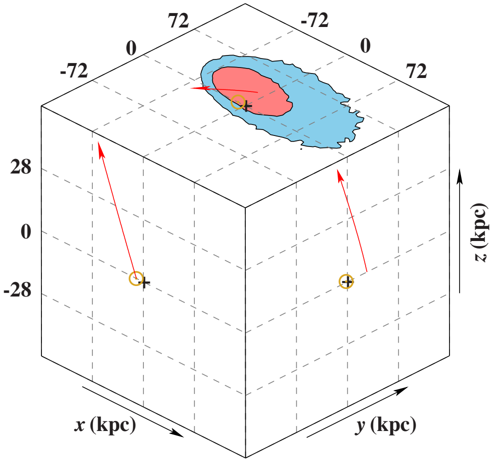
HVS 4: still a candidate for the Hills mechanism



Red and blue shaded areas mark regions where 68% and 95% of the trajectories intersected the Galactic plane.

$T_{\text{eff}} = 13\,280^{+150}_{-140}$ K

$\log(g\,(\text{cm s}^{-2})) = 3.89 \pm 0.07$

$v\sin(i) = 138^{+14}_{-16}$ km s^{-1}

$M = 4.0 \pm 0.2\,M_\odot$

$\tau = 150^{+\ 6}_{-10}$ Myr

$d = 78.3^{+8.6}_{-7.2}$ kpc

$v_{\text{Grf}} = 630^{+120}_{-\ 60}$ km s^{-1}

$P_{\text{bound}} = 0\%$

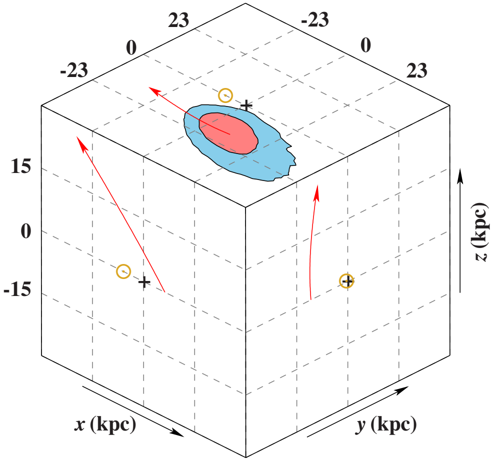
$v_{\text{Grf,p}} = 680^{+90}_{-30}$ km s^{-1}

$v_{\text{ej,p}} = 840^{+\ 70}_{-130}$ km s^{-1}

$\tau_{\text{flight,p}} = 129^{+56}_{-35}$ Myr

(68%-confidence intervals)

HVS 8: an extreme “classical” disk runaway star?



Red and blue shaded areas mark regions where 68% and 95% of the trajectories intersected the Galactic plane.

$T_{\mathrm{eff}} = 10\,960^{+150}_{-130}$ K

$\log(g\,(\mathrm{cm\,s^{-2}})) = 4.04^{+0.08}_{-0.07}$

$v\sin(i) = 282^{+11}_{-27}$ km s^{-1}

$M = 2.9^{+0.2}_{-0.1}\,M_{\odot}$

$\tau = 226^{+24}_{-51}$ Myr

$d = 37.2^{+4.4}_{-3.6}$ kpc

$v_{\mathrm{Grf}} = 500^{+50}_{-40}$ km s^{-1}

$P_{\mathrm{bound}} = 16\%$

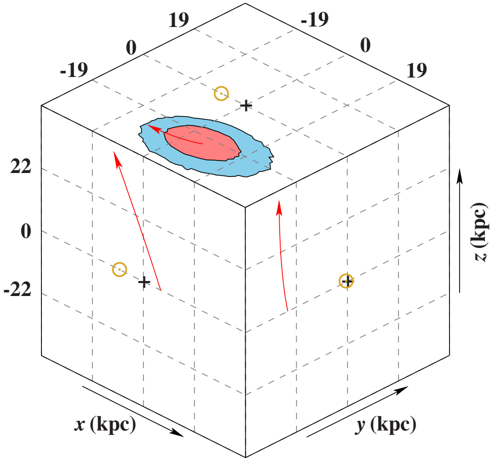
$v_{\mathrm{Grf,p}} = 570^{+20}_{-10}$ km s^{-1}

$v_{\mathrm{ej,p}} = 450^{+40}_{-30}$ km s^{-1}

$\tau_{\mathrm{flight,p}} = 87^{+18}_{-14}$ Myr

(68%-confidence intervals)

HVS 7: a disk runaway star beyond the “classical” limit?



Red and blue shaded areas mark regions where 68% and 95% of the trajectories intersected the Galactic plane.

$T_{\mathrm{eff}} = 12\,500 \pm 110\,\mathrm{K}$

$\log(g\,(\mathrm{cm\,s^{-2}})) = 3.93 \pm 0.05$

$v\sin(i) = 58^{+10}_{-12}\,\mathrm{km\,s^{-1}}$

$M = 3.5^{+0.2}_{-0.1}\,M_\odot$

$\tau = 185^{+\ 7}_{-10}\,\mathrm{Myr}$

$d = 48.2^{+4.3}_{-3.7}\,\mathrm{kpc}$

$v_{\mathrm{Grf}} = 500^{+50}_{-40}\,\mathrm{km\,s^{-1}}$

$P_{\mathrm{bound}} = 5\%$

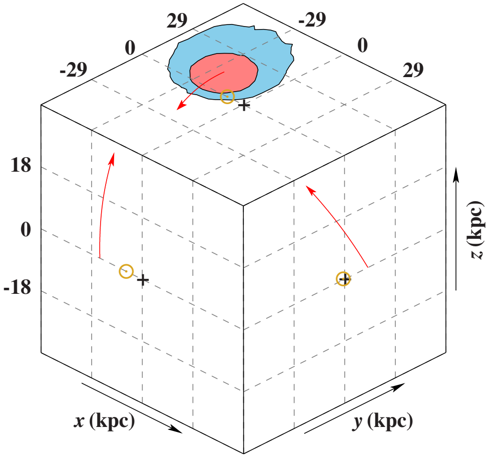
$v_{\mathrm{Grf,p}} = 570^{+20}_{-30}\,\mathrm{km\,s^{-1}}$

$v_{\mathrm{ej,p}} = 530 \pm 30\,\mathrm{km\,s^{-1}}$

$\tau_{\mathrm{flight,p}} = 82^{+10}_{-\ 8}\,\mathrm{Myr}$

(68%-confidence intervals)

B434: a disk runaway star beyond the “classical” limit!



Red and blue shaded areas mark regions where 68% and 95% of the trajectories intersected the Galactic plane.

$T_{\text{eff}} = 10\,190^{+160}_{-110}$ K

$\log(g\,(\text{cm s}^{-2})) = 3.85 \pm 0.07$

$v \sin(i) = 101^{+14}_{-10}$ km s^{-1}

$M = 2.8 \pm 0.1\, M_\odot$

$\tau = 402^{+16}_{-23}$ Myr

$d = 40.5^{+4.7}_{-3.7}$ kpc

$v_{\text{Grf}} = 380^{+50}_{-40}$ km s^{-1}

$P_{\text{bound}} = 92\%$

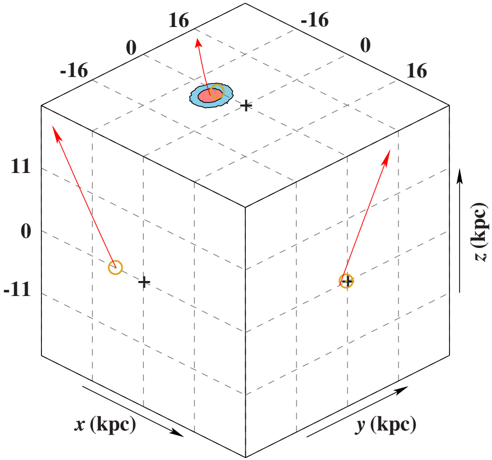
$v_{\text{Grf,p}} = 430^{+20}_{-10}$ km s^{-1}

$v_{\text{ej,p}} = 590 \pm 20$ km s^{-1}

$\tau_{\text{flight,p}} = 118^{+26}_{-19}$ Myr

(68%-confidence intervals)

HVS 5: a disk runaway star beyond the “classical” limit!



Red and blue shaded areas mark regions where 68% and 95% of the trajectories intersected the Galactic plane.

$T_{\text{eff}} = 12\,530^{+130}_{-150}$ K

$\log(g\,(\text{cm s}^{-2})) = 4.20 \pm 0.06$

$v \sin(i) = 131^{+12}_{-13}$ km s^{-1}

$M = 3.3 \pm 0.1\,M_{\odot}$

$\tau = 97^{+31}_{-37}$ Myr

$d = 31.2^{+3.2}_{-2.5}$ kpc

$v_{\text{Grf}} = 650 \pm 10$ km s^{-1}

$P_{\text{bound}} = 0\%$

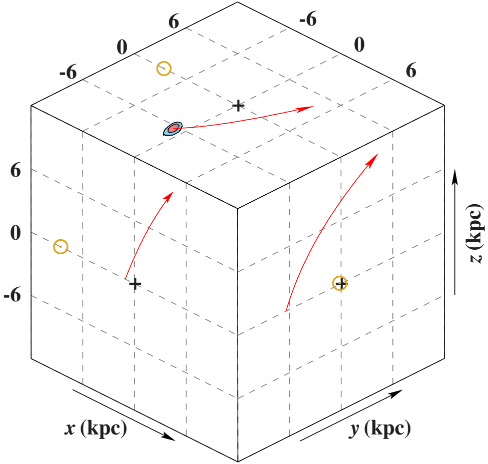
$v_{\text{Grf,p}} = 760 \pm 20$ km s^{-1}

$v_{\text{ej,p}} = 640^{+50}_{-40}$ km s^{-1}

$\tau_{\text{flight,p}} = 46^{+4}_{-5}$ Myr

(68%-confidence intervals)

PG 1610+062: a “nearby” disk runaway star



Red and blue shaded areas mark regions where 68% and 95% of the trajectories intersected the Galactic plane.

$T_{\text{eff}} = 14\,800 \pm 120\,\text{K}$

$\log(g\,(\text{cm s}^{-2})) = 4.05 \pm 0.05$

$v \sin(i) = 16 \pm 1\,\text{km s}^{-1}$

$M = 4.4 \pm 0.1\,M_\odot$

$\tau = 83 \pm 9\,\text{Myr}$

$d = 17.3^{+1.2}_{-1.0}\,\text{kpc}$

$v_{\text{Grf}} = 325 \pm 5\,\text{km s}^{-1}$

$P_{\text{bound}} = 100\%$

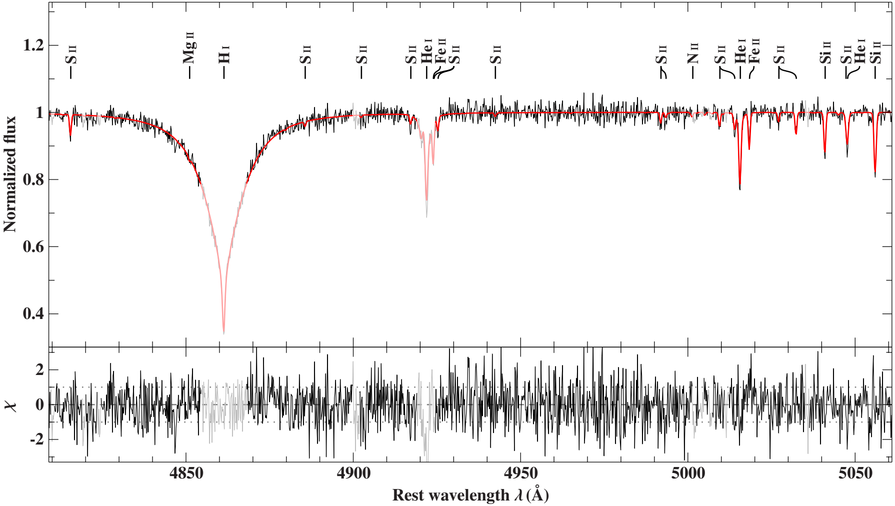
$v_{\text{Grf,p}} = 433^{+6}_{-5}\,\text{km s}^{-1}$

$v_{\text{ej,p}} = 553 \pm 13\,\text{km s}^{-1}$

$\tau_{\text{flight,p}} = 41 \pm 3\,\text{Myr}$

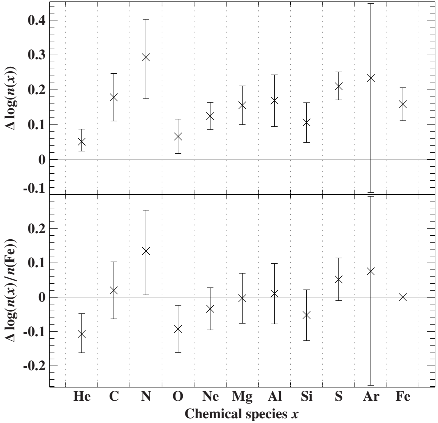
(68%-confidence intervals)

PG 1610+062: Insights from high-quality spectra

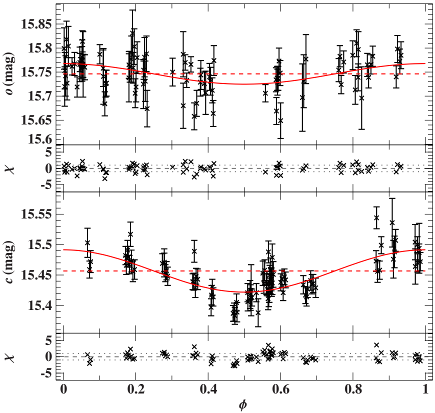


Spectrograph: ESI at the Keck Observatory, $R = \lambda/\Delta\lambda \approx 8000$, S/N ≈ 100

PG 1610+062: a bona fide main-sequence star

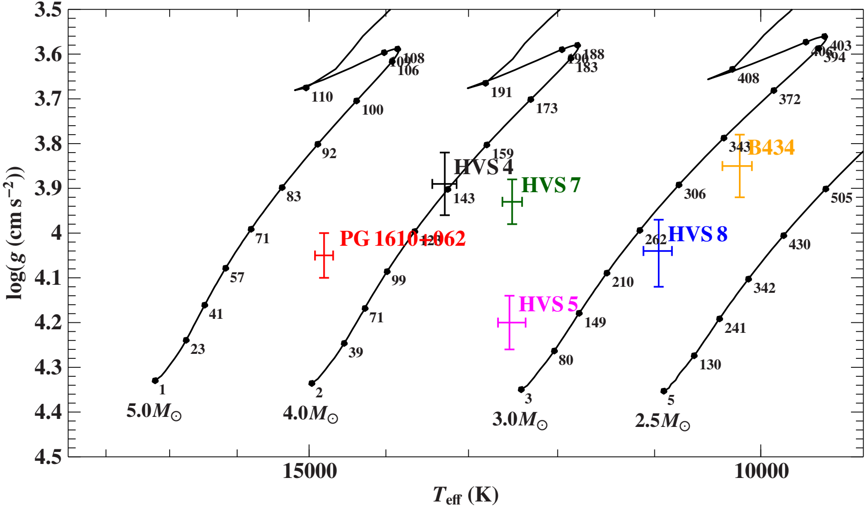


Differential abundance pattern (*top*) and element-to-iron abundance ratios (*bottom*) of PG 1610+062 with respect to the solar neighborhood reference star HD 137366. Error bars are 99% confidence intervals.



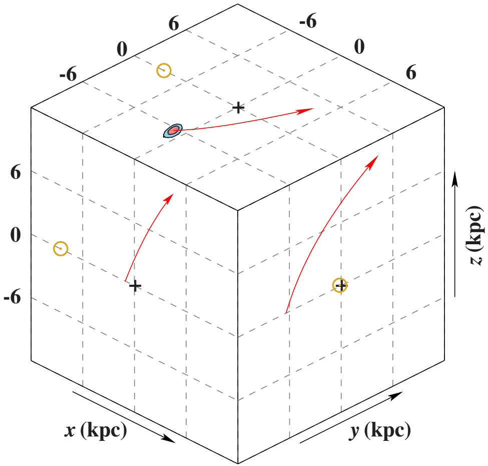
Phased ATLAS light curves for PG 1610+062. The oscillation properties ($P_{\text{osc}} = 4.34 \pm 0.01$ d; semiamplitudes: 21 ± 11 mmag, 35 ± 7 mmag) are typical of slowly pulsating B stars, and, thus indicative of a main sequence nature.

Mass and age determination



Kiel diagram with evolutionary tracks from Ekström et al. (2012). Error bars are 68% confidence intervals.

PG 1610+062: Another star beyond the “classical” limit!



Red and blue shaded areas mark regions where 68% and 95% of the trajectories intersected the Galactic plane.

$T_{\mathrm{eff}} = 14\,800 \pm 120\,\mathrm{K}$

$\log(g\,(\mathrm{cm\,s^{-2}})) = 4.05 \pm 0.05$

$v\sin(i) = 16 \pm 1\,\mathrm{km\,s^{-1}}$

$M = 4.4 \pm 0.1\,M_{\odot}$

$\tau = 83 \pm 9\,\mathrm{Myr}$

$d = 17.3^{+1.2}_{-1.0}\,\mathrm{kpc}$

$v_{\mathrm{Grf}} = 325 \pm 5\,\mathrm{km\,s^{-1}}$

$P_{\mathrm{bound}} = 100\%$

$v_{\mathrm{Grf,p}} = 433^{+6}_{-5}\,\mathrm{km\,s^{-1}}$

$v_{\mathrm{ej,p}} = 553 \pm 13\,\mathrm{km\,s^{-1}}$

$\tau_{\mathrm{flight,p}} = 41 \pm 3\,\mathrm{Myr}$

(68%-confidence intervals)

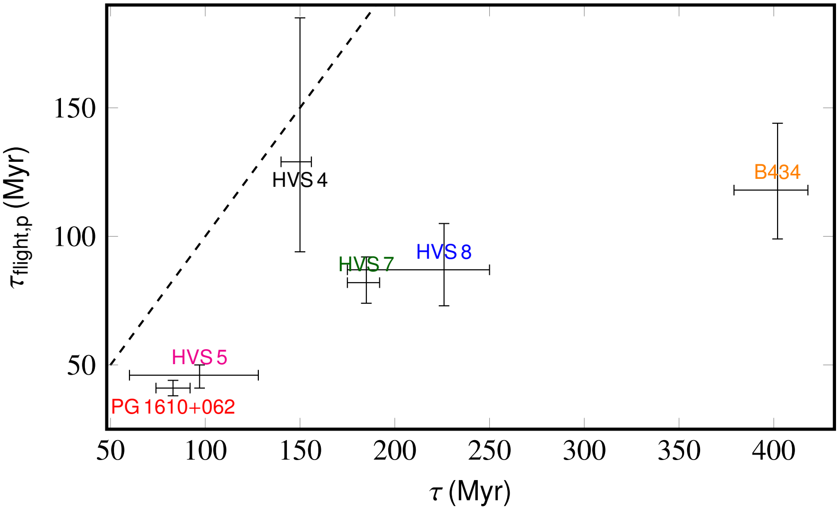
Possible alternative mechanisms

Strong dynamical encounters with very massive stars in young and dense star clusters (Gvaramadze 2009)

- A triple system with an inner binary of two main-sequence stars of $50\,M_\odot$ can eject its outer component of $10\,M_\odot$ with $\lesssim 800\,\mathrm{km\,s^{-1}}$.
- The interaction of massive close binaries could eject stars at velocities as high as the surface escape velocity of the most massive component, which could exceed $1000\,\mathrm{km\,s^{-1}}$ for 20–$40\,M_\odot$ stars.
- Three-body interactions between a massive close binary ($40\,M_\odot$ plus $8\,M_\odot$) and a very massive star ($M \geq 50\,M_\odot$) can eject stars with $\gtrsim 400\,\mathrm{km\,s^{-1}}$.

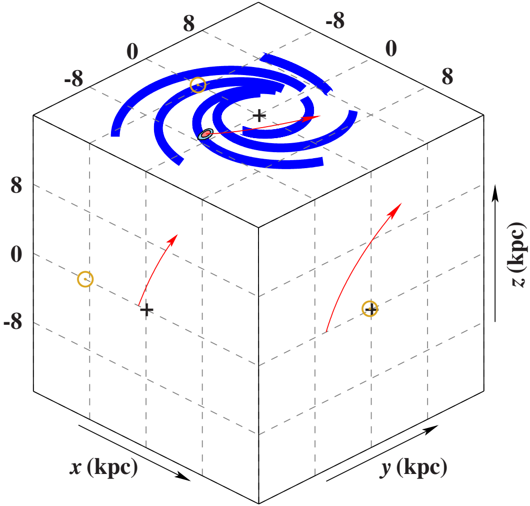
Owing to the very short lifetimes of very massive stars, the ages of the ejected stars would be expected to be almost identical to their flight times.

A possible time problem



The identity line is dashed. Error bars are 68% confidence intervals.

PG 1610+062: Indications for an intermediate-mass black hole in the nearby Carina-Sagittarius spiral arm?



Alternative explanation: interaction with an intermediate-mass black hole (Gualandris & Portegies Zwart 2007).

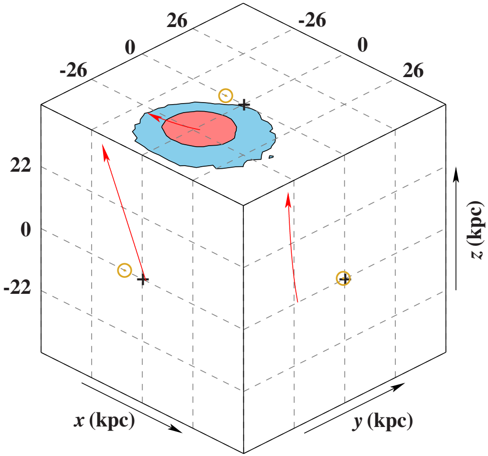
The thick blue solid lines schematically represent the loci of the spiral arms 41 Myr ago based on the polynomial logarithmic arm model of Hou & Han (2014) and the Galactic rotation curve of Model I of Irrgang et al. (2014).

Runaway stars beyond the velocity limit of classical ejection mechanisms

Star	$v_{\text{ej,p}}$ (km s^{-1})	d (kpc)	Reference
HVS 5	640^{+50}_{-40}	$31.2^{+3.2}_{-2.5}$	Irrgang et al. (2018a,b)
B434	590^{+20}_{-20}	$40.5^{+4.7}_{-3.7}$	Irrgang et al. (2018a,b)
LAMOST-HVS1	568^{+19}_{-17}	$19.1^{+5.1}_{-3.8}$	Hattori et al. (2018)
PG 1610+062	553^{+13}_{-13}	$17.3^{+1.2}_{-1.0}$	Irrgang et al. (2019)
HVS 7	530^{+30}_{-30}	$48.2^{+4.3}_{-3.7}$	Irrgang et al. (2018a,b)
HVS 12	510^{+40}_{-30}	$51.7^{+9.0}_{-6.1}$	Irrgang et al. (2018a,b)
LAMOST-HVS4	480^{+13}_{-10}	$27.9^{+1.5}_{-1.5}$	Li et al. (2018)
EC 19596−5356	475^{+74}_{-83}	$13.8^{+4.8}_{-3.7}$	Silva & Napiwotzki (2011)
HIP 56322	471^{+189}_{-99}	$6.1^{+3.2}_{-2.0}$	Silva & Napiwotzki (2011)
HIP 105912	457^{+130}_{-133}	$4.2^{+1.7}_{-1.2}$	Silva & Napiwotzki (2011)
HVS 8	450^{+40}_{-30}	$37.2^{+4.4}_{-3.6}$	Irrgang et al. (2018a,b)

Candidate main-sequence stars that were possibly ejected from the Galactic disk beyond the velocity limit of classical mechanisms.

HVS 12: Based on proper motions from HST



Red and blue shaded areas mark regions where 68% and 95% of the trajectories intersected the Galactic plane.

$T_{\text{eff}} = 11\,170^{+160}_{-180}$ K

$\log(g\,(\text{cm s}^{-2})) = 4.34 \pm 0.08$

$\upsilon \sin(i) \leq 46\,\text{km s}^{-1}$

$M = 2.5 \pm 0.1\,M_{\odot}$

$\tau = 90^{+77}_{-34}$ Myr

$d = 51.7^{+9.0}_{-6.1}$ kpc

$\upsilon_{\text{Grf}} = 500^{+60}_{-50}\,\text{km s}^{-1}$

$P_{\text{bound}} = 8\%$

$\upsilon_{\text{Grf,p}} = 570^{+30}_{-20}\,\text{km s}^{-1}$

$\upsilon_{\text{ej,p}} = 510^{+40}_{-30}\,\text{km s}^{-1}$

$\tau_{\text{flight,p}} = 88^{+19}_{-14}$ Myr

(68%-confidence intervals)