Searching for (and finding) Hyper-velocity stars

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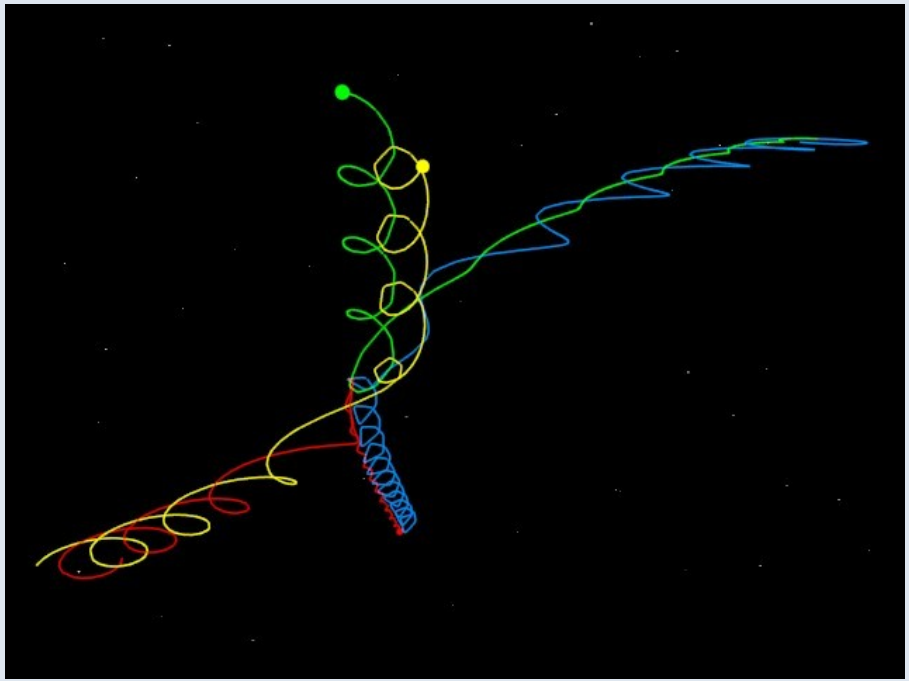
Possible mechanisms of producing fast stars

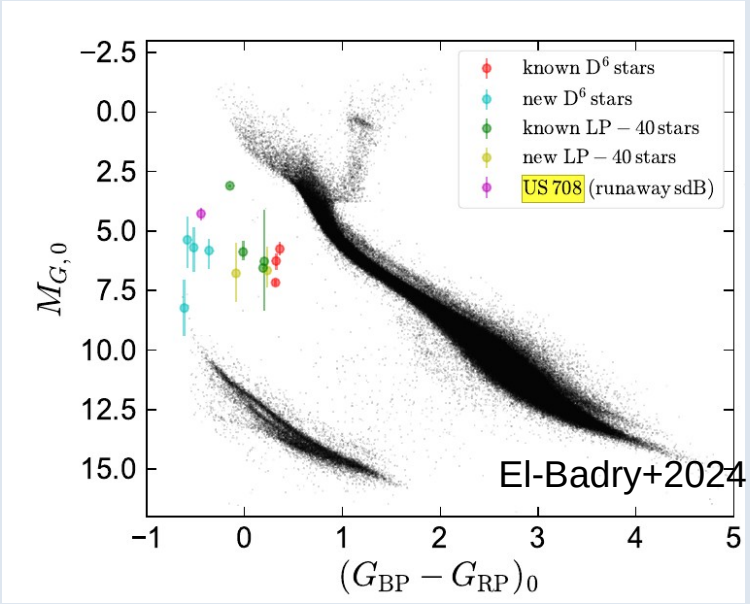
- Disc runaways
- Source – multi-body encounters in young clusters (Poveda+1967)
- V< Vesc(star)~500 km/s



Credit: Errgang

Supernovae

- SN Ia explosions, DD scenarios produce polluted WD with high velocity.
- Several likely candidates identified: D^6 objects Shen+2018, El-Badry+2024
- Identified through Gaia proper-motion + plx selection + spectroscopic followup
- HVS are also possible from SN II in binaries

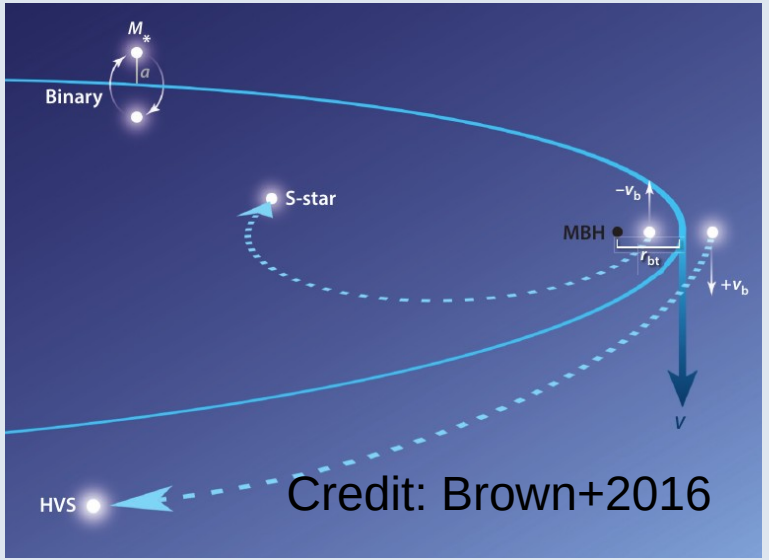


Hills mechanism

- Binary interaction with the SMBH. Binary system is broken and one star is ejected.
- Specific energy gain for the ejected star:

$$\delta E \sim \frac{(V_{orb} + V_{bin})^2}{2} - \frac{V_{orb}^2}{2} \sim V_{orb} V_{bin}$$

- V_{orb} can be ~ Nx1000 km/s
- Alternative scenarios: binary MBH + single star



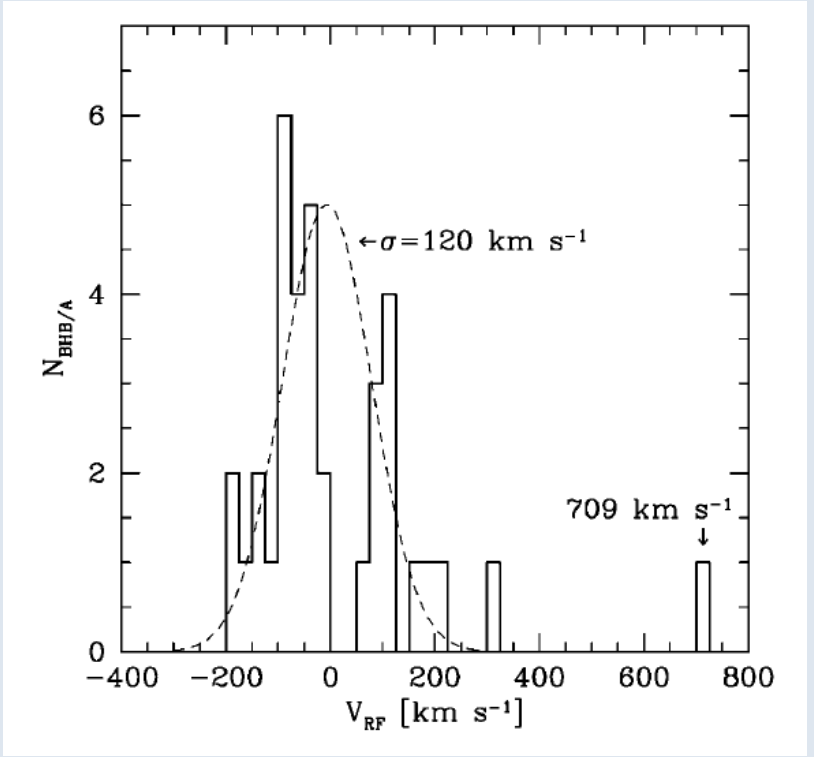
For this talk
Hyper-velocity star = Hills mechanism star

What we look for

- Stars with large |V| or V>Vescape
- Stars with orbit that points to the Galactic center.
- Problem: the HVS stars are not necessarily different (in any other property) to foreground, other than having fast kinematics.

First discovery

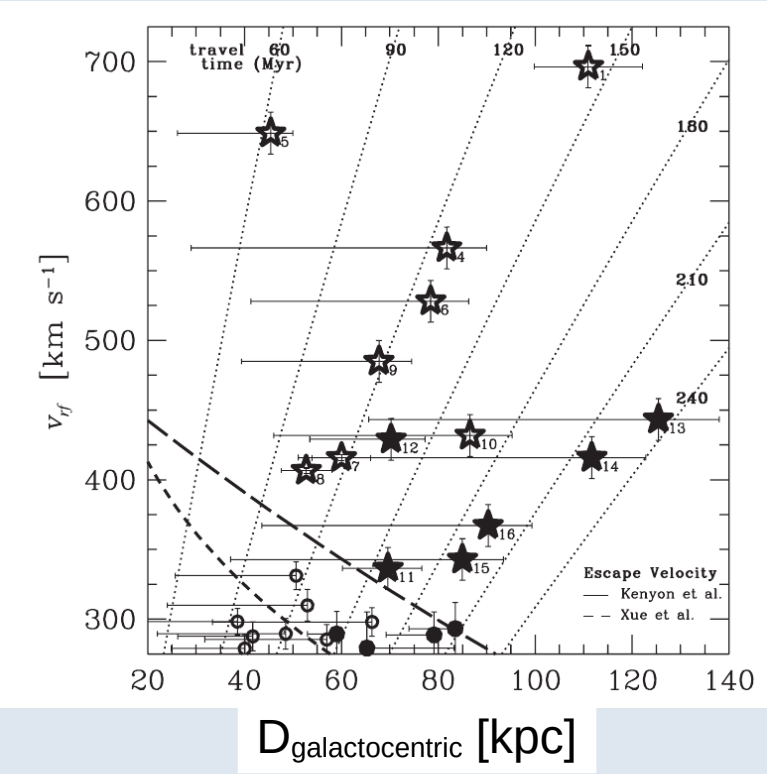
- Brown+2005 survey of faint Blue Horizontal Branch stars in SDSS
- It was simple colour-colour based search
- Discovery of young B-type star HVS1 (V_{gsr}=700 km/s @ 100 kpc)



Brown+2005

Further searches: MMT survey

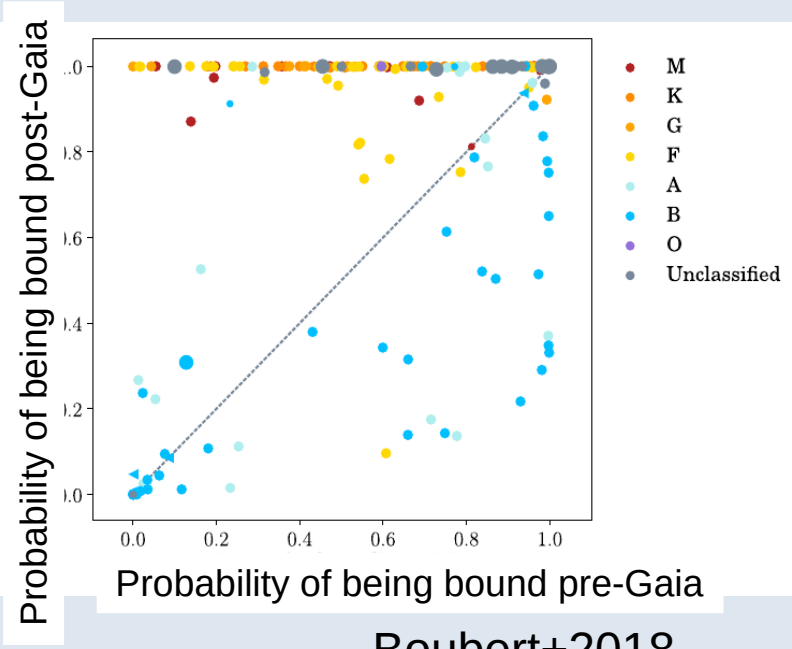
- Brown+2006,2009, Hirsch+2005, Edelmann+2005
- Focus on blue stars hotter than A-stars at high latitude
- The contaminants – WDs , BHBs
- No reason to think we HVS must be hot stars, but that's the only ones that stand out and can be found with smaller observational effort.
- Some more candidates were found based on RV from LAMOST, RAVE, SEGUE (Hawkins+2015, Huang+2017, Palladino+2014)
- Around 10 stars with velocities of 400-700 km/s. Somewhat uncertain distances, uncertain orbits.
- Danger of detections near threshold



Brown+2009

After Gaia

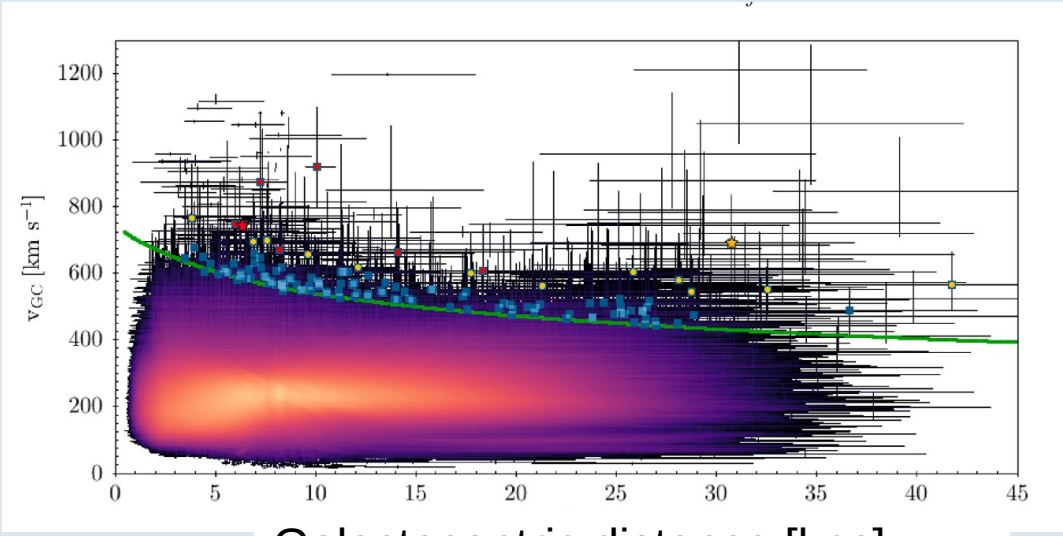
- Parallaxes, and proper motions available for all HVS
- Many/most previously considered HVS were found bound.
- Only a few stars seem consistent with Hills mechanism, but no strong evidence of Hills mechanism vs disk runaway



Boubert+2018

Gaia 6-D searches

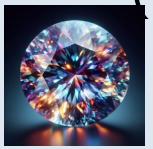
- With Gaia RV, proper motions, parallaxes, you have access to full 6-D
- HVS search done by several groups, including Marchetti+2019,2021, or Li+2021 (with LAMOST)
- Problem – limited to region around the Sun, large distance uncertainties, expected contamination from noise scattered

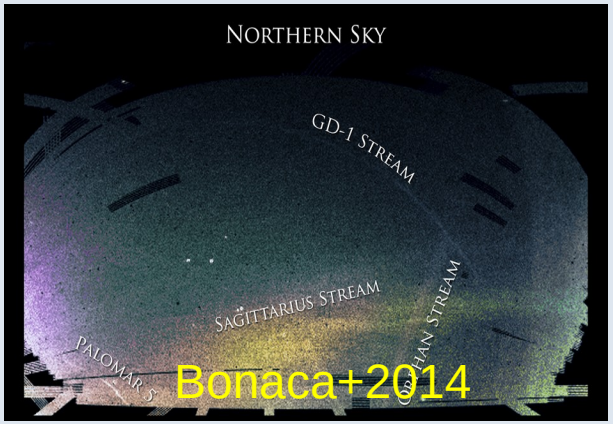


Marchetti+2019

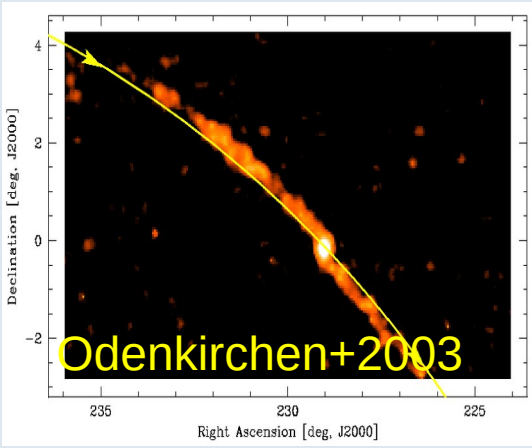
Another rare gem

- Stellar streams from disrupted dwarfs/GCs.
- First streams found in imaging surveys (Ibata+1994,Belokurov+2006,Grillmair+2006)
- The deeper the survey – the more we find (Shipp+2018)
- Also STREAMFINDER (Ibata+2019) in Gaia

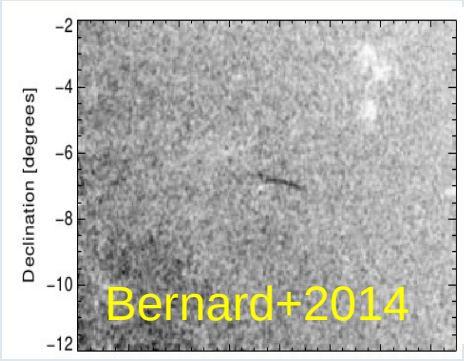




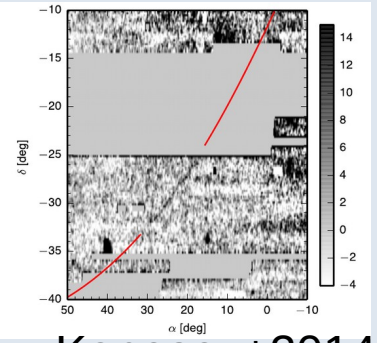
Bonaca+2014



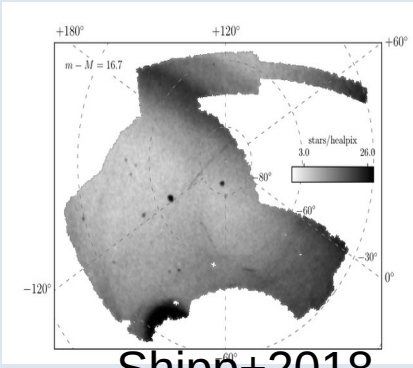
Odenkirchen+2003



Bernard+2014



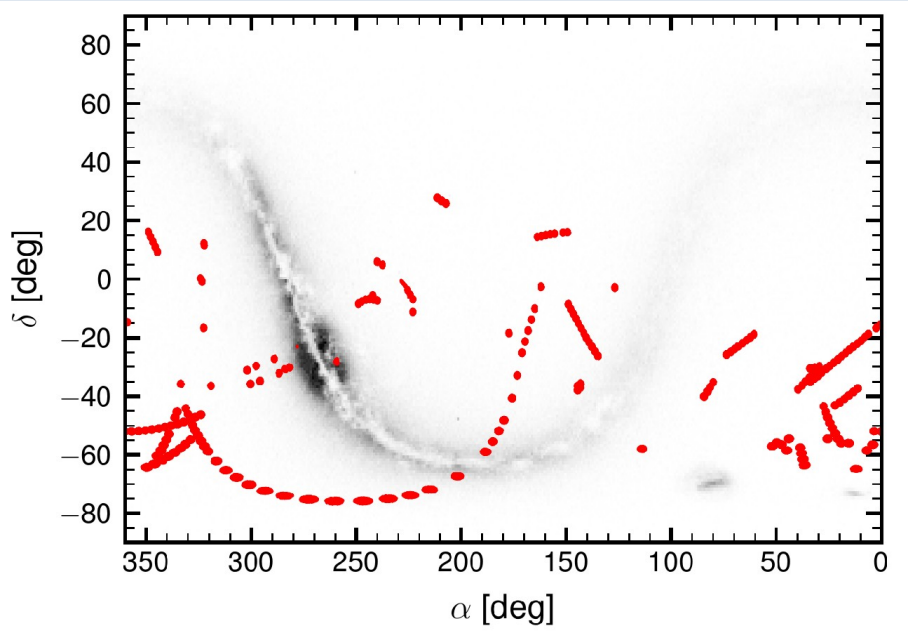
Koposov+2014



Shipp+2018

Stream follow-up

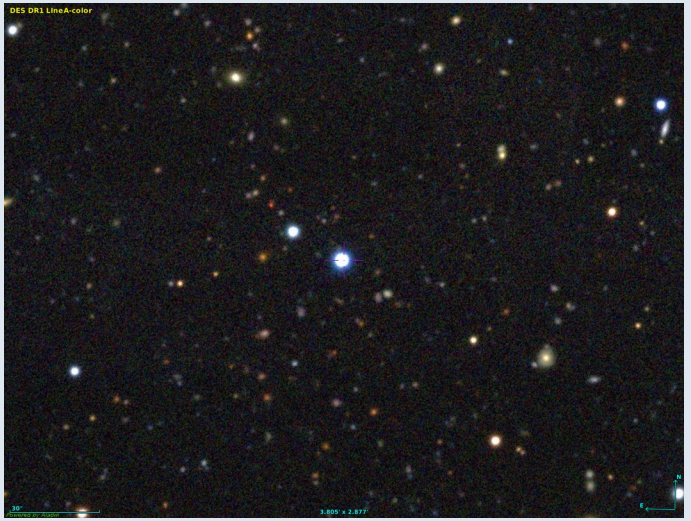
- S^5 - Southern Stellar Streams Spectroscopic Survey (Li,SK+19)
- Spectroscopic follow-up of 20 streams – 100 nights of AAT/2df
- ~ 600 square degrees, mainly Southern sky
- 100k stars with RV, [Fe/H]
- ~ 5000 blue stellar targets (BHB/BS/WD)



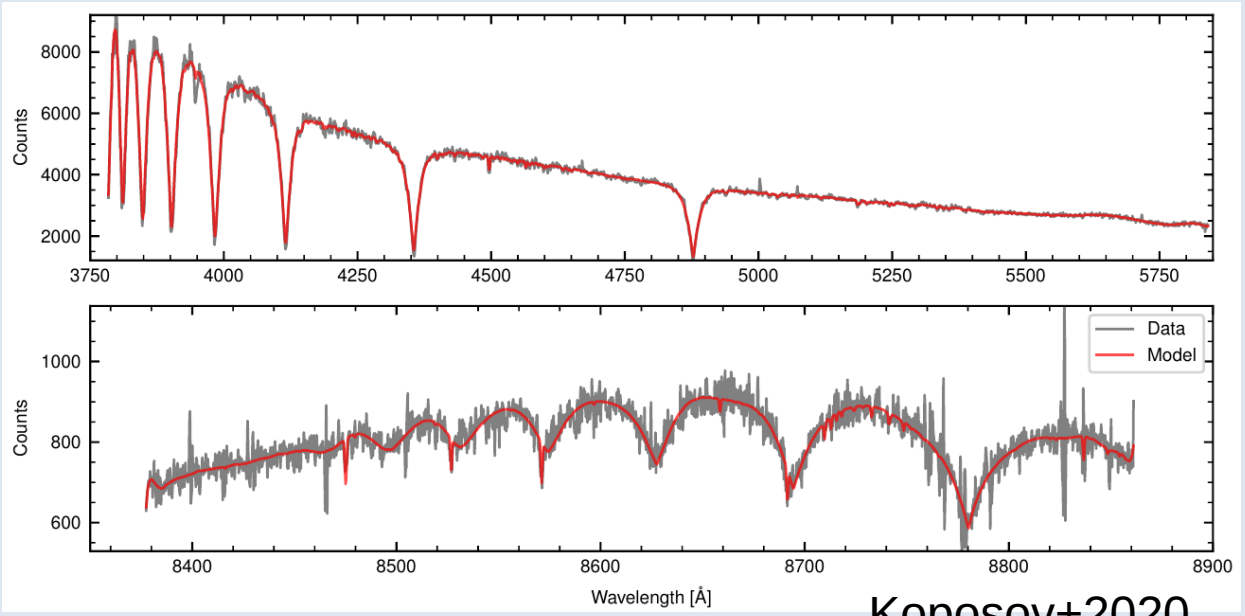
S5 project

- Lead by Ting Li (U of Toronto)
- https://s5collab.github.io

S5-HVS1



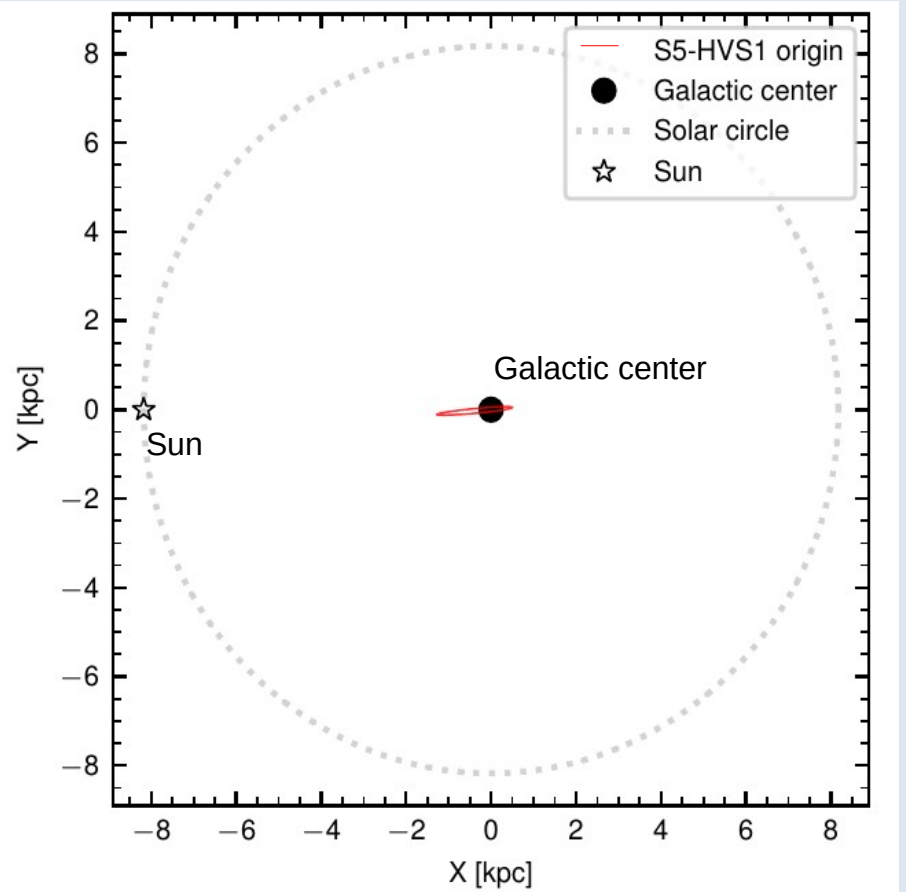
- S5-HVS1 star
- G=15.8
- Radial velocity ~ 1020 km/s
- Hot star Teff = 9600K; metal rich
- D_{helio}=8 kpc
- V_{3d}=1700 km/s



Koposov+2020

Origin of S5-HVS1

- Integrate the orbit back in time till disk crossing point (X,Y)
- The 90% confidence region is an 1500 x 50 pc ellipse centred on the GC
- The association with the GC is highly significant
- Ejection speed 1800 km/s

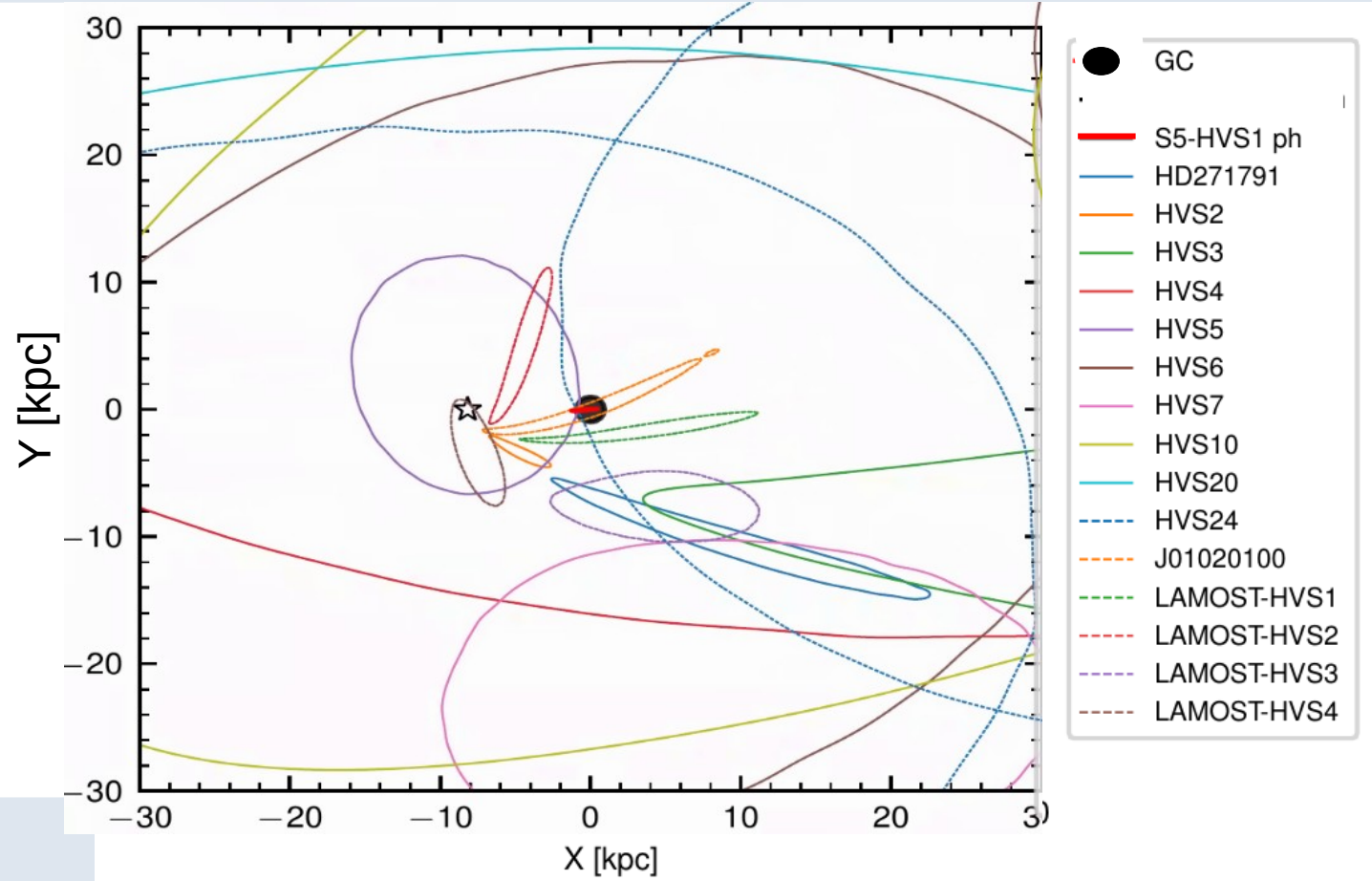


Koposov+2020

S5-HVS1 vs other HVS

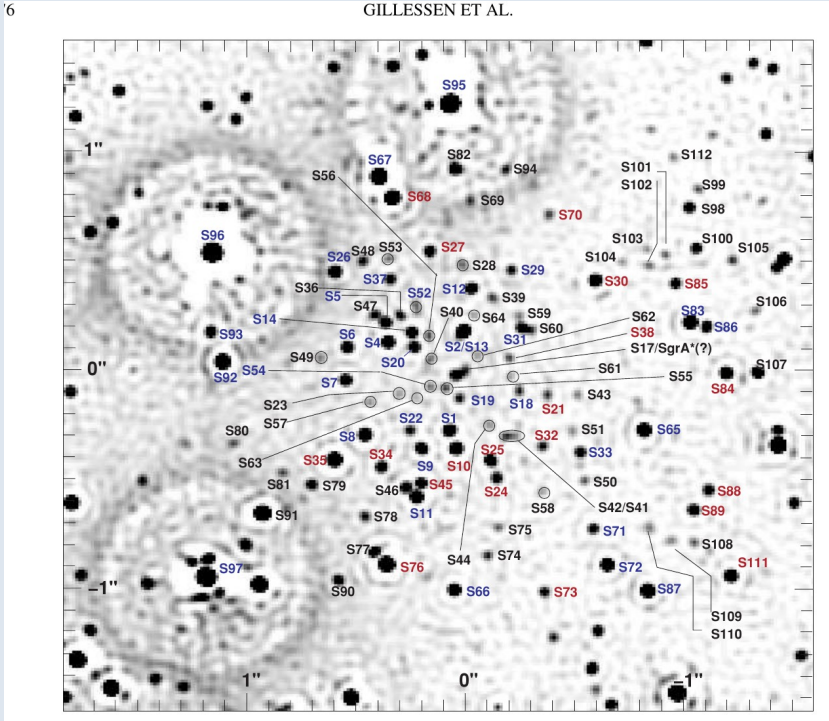
- The most confident association with the Galactic center

Constraints on the origin in the disk for the sample of HVS



Connection to Sgr A*

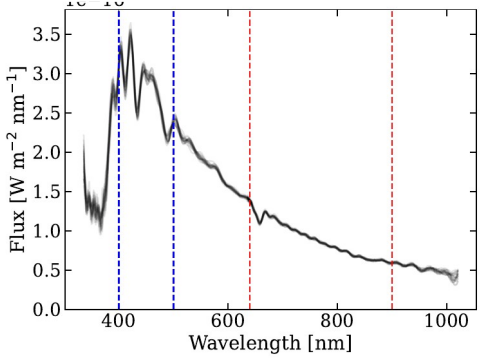
- SMBH is embedded in the star cluster of S-stars – young massive stars.
- S-stars are possibly the direct result of the HVS ejection process (Generozov+2020)
- HVS rate is connected to TDE rate.
- HVS may explain some host-less SN



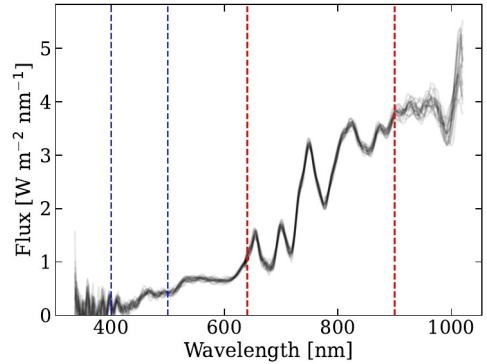
Searching for HVS in Gaia XP data

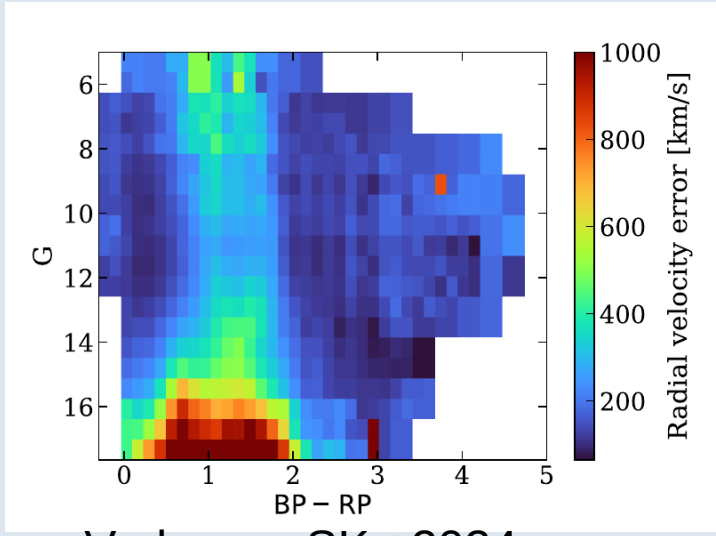
- Gaia BP/RP low resolution spectra -- largest catalog of spectra (250 million sources)
- RV can be extracted from it
- The accuracy ~ 300 km/s can be enough to find some HVS stars, but outliers are too numerous currently.

BP/RP spectrum of hot star



BP/RP spectrum of cool star





Verberne, SK +2024 ;
Arxiv: 2310.18101

Sill Verberne
PhD student @ Uni of Leiden

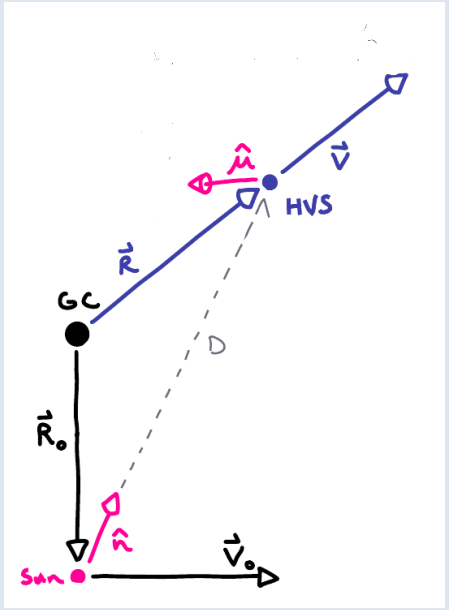
Search for HVS on radial orbits

- If we see the star's proper motion μ and assume it's on a radial trajectory from GC – we know it's distance and it's radial velocity

$$D = \frac{\mathbf{V_0} \cdot (\hat{\mathbf{n}} \times \mathbf{R_0})}{\mu \cdot (\hat{\mathbf{n}} \times \mathbf{R_0})}$$

  R0, V0 are solar position & velocity, n – vector towards the star

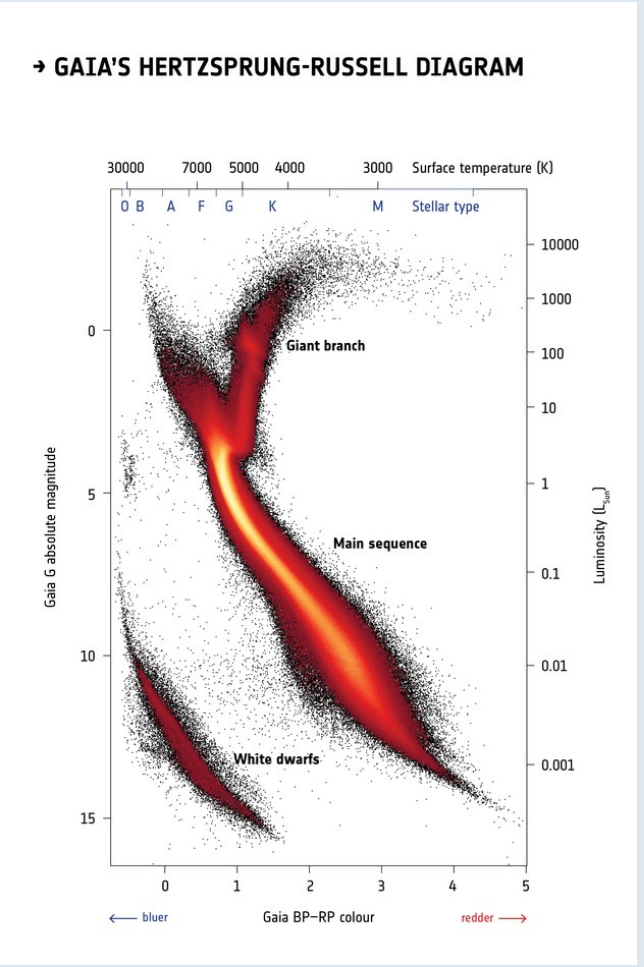
- We can determine 'implied HVS distance' for every star with Gaia proper motion



Verberne, Rossi, SK+2024 (Submitted, on arxiv soon)

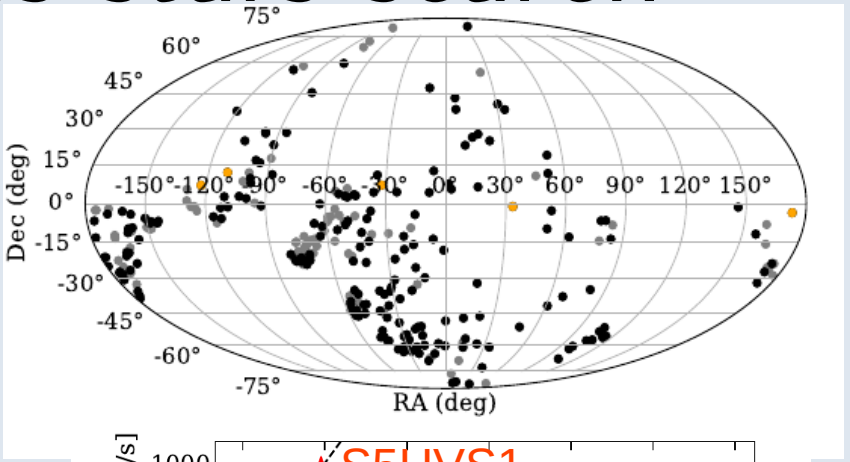
Search for HVS on radial orbits

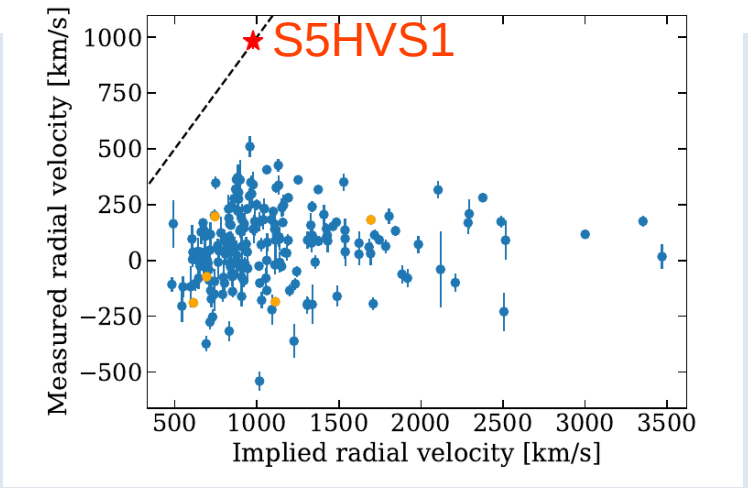
- We only keep stars with ‘implied distance’ consistent with parallax and Gaia HRD and $V_{3d,implied}>600$ km/s

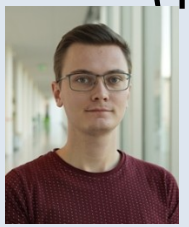


Radial trajectories stars search

- We exclude stars where ‘implied’ distance disagree with parallax, or HRD distribution
- We have ~600 candidates where S5-HVS1 is the top candidate.
- We followed up ~ 200 stars (not finding any new HVS)



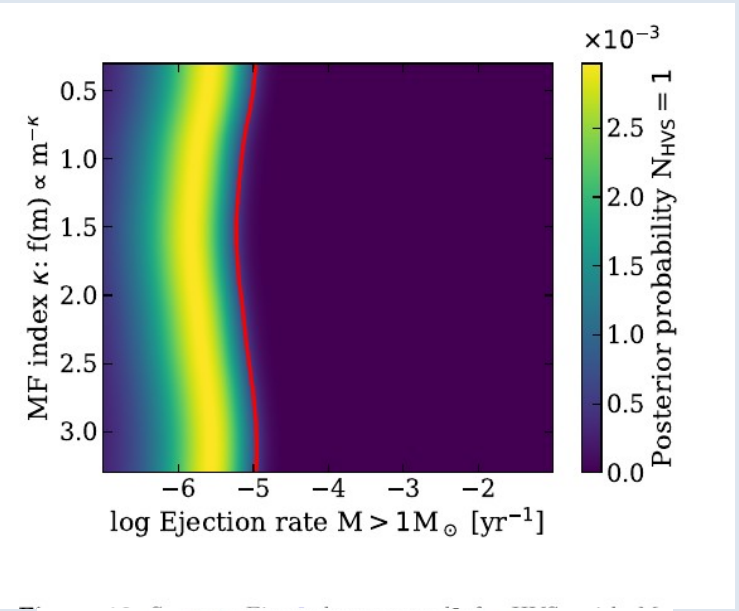


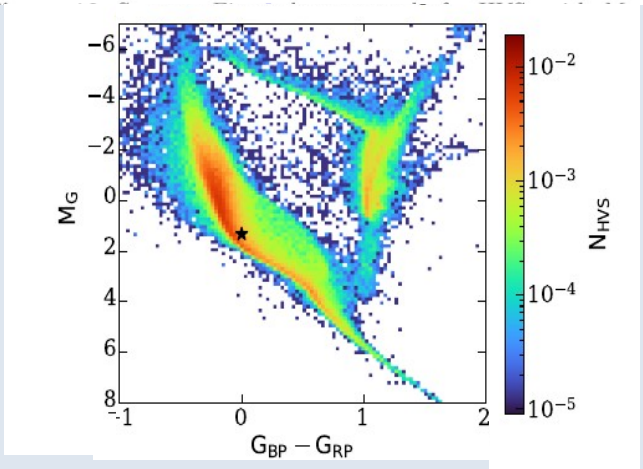


Verberne, Rossi, SK+2024 (submitted)

Predictions

- We constrain the HVS ejection rate $< 10^{-5}$ $M_\odot$/yr (10 times better than the previous constraint)
- We can predict the properties of HVS potentially observable with Gaia ~ 20 HVS





Verberne, Rossi, SK+2024 (submitted)

Future

- Predictions ~20 HVS in Gaia
- The majority likely hot $>1M_{\odot}$ Main Sequence stars
- If we can find HVS giants or lower mass stars, we can probe the source of HVS.

Implications for future surveys

- Spectroscopic surveys: DESI, 4MOST, WEAVE, SDSS-V – need efficient targeting strategies & spare fibre program
- LSST with proper motions – we can detect lower mass HVS
- Proper motions with Roman Observatory
- Gaia NIR for the center of Galaxy

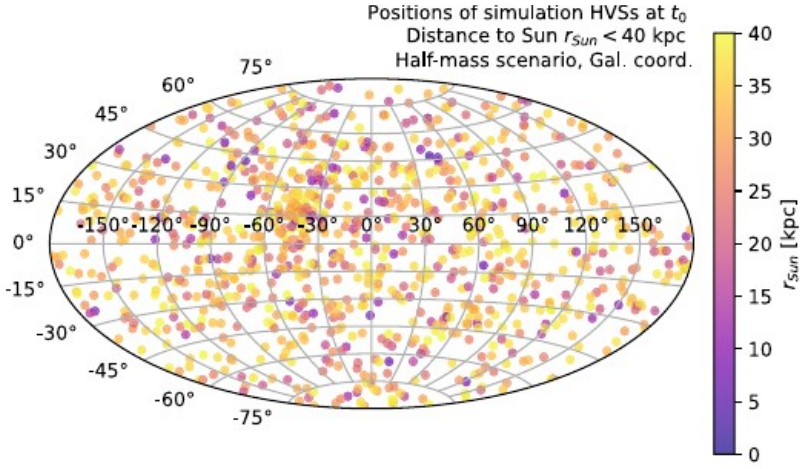
Ejection from other galaxies

- Possible HVS from Sgr (Huang+2021)
- Possible ejection from LMC (Gualandris+2007, Erkal+2019)

M31

- M31 (Sherwin+2006, Gulzow+2024)
- S5-HVS1 @ M31 distance would have apparent magnitude of 25 – should be detectable with Roman out to virial radius – need to be separated from MW WDs (getting RVs will be challenging)
- We can also detect some M31 HVS passing through the MW halo

HVS from M31 passing through MW



Gulzow+2024

Conclusions

- HVS are truly needle in the haystack with 1 star per 10^8-10^9
- We only know one confident Hills mechanism star, and several good candidates – we need more.
- Many of Hills mechanism HVS we found serendipitiously.
- We can potentially extract good RVs from really low-res spectra -- Gaia XP (DR4)
- The search for Hill's stars can be much more efficient with imposing assumptions of GC ejection.
- Spare fibre programs in spectroscopic surveys are very valuable for rare gems discovery.
- Rubin/Roman will help us find many low mass HVS