as a Gaia precursor: what to expect from the RVS?
The **RAVE** Survey

- Spectroscopic high latitude survey of the MW
  - $9 \leq I \leq 13$
- GAIA spectral range and resolution
  - Ca triplet region (8400-8800Å), $R_{\text{eff}}=7500$
- 6dF at the 1.2m UKST in Australia
  - 100-120 fibres
  - 38 sqdeg FoV
  - 7 nights per lunation up to 8/2005
  - 25 nights per lunation since 8/2005
- 574,630 spectra for 483,330 stars
  - catalogue of 40,000 active stars
λ range: 8410-8795Å (Gaia wavelength range)
Resolution R=7500 at 8600Å; Dispersion = 0.4Å/pix

From the RAVE spectra we obtain:
- radial velocities
- stellar parameters (effective temperature, gravity and metallicity)
- chemical abundances
- RAVE + photometry
- distances
RAVE: 4th public data release

- Intermediate resolution (R~7500)
- 425,561 stars,
- 482,430 spectra
  (DR3: 77,461 stars)
- 9 < I < 12 mag

Database:
✓ Radial velocities
✓ Spectral morphological flags
✓ $T_{\text{eff}}$, logg, [M/H]
✓ Mg, Al, Si, Ti, Ni, Fe
✓ Line-of-sight Distances
✓ Photometry:
  DENIS, USNOB, 2MASS, APASS
✓ Proper motions:
  UCAC4, PPMX, PPMXL, Tycho-2, SPM4
The survey footprint we adopted for our study (black line) in Galactic coordinates. The green dots show all RAVE targets. Roughly 10% of these stars have been observed more than once.

In order to provide an unbiased velocity sample the survey footprint is divided into bins in Galactic longitude and Galactic latitude. With the additional constraints from the survey footprint we can assume that the probability, \( S/N > 20 \), is high enough to avoid bad measurements from the catalogue by selecting all stars with typical uncertainties of around 2 km s\(^{-1}\) and \( S/N > 7 \).
completeness

\[ 10.0 < I_{2\text{MASS}} < 10.8 \]
completeness

11.3 < \text{i}_{\text{2MASS}} < 12.0

Galactic

\[ N_{\text{RAVE}} / N_{\text{2MASS}} \]
RAVE DR4
• R~7500
• 425 561 stars,
• 482 430 spectra
  (DR3: 77 461 stars)
• 9 < I< 12 mag

Database:
✓ Radial velocities
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✓ $T_{\text{eff}}, \log g, [\text{M/H}]$
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  - DENIS, USNOB, 2MASS, APASS
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Gaia:
R~11 500 for bright targets
R~7 000 for faintest targets
Same $\lambda$ coverage (CaII triplet)
$\sim 10^7$ - $10^8$ targets with spectra
RAVE’s Galactic 3D velocity errors

Combination of:
- Distance errors (<30%) (<10%)
- Errors in RV (95% of the stars $\Delta V_{\text{rad}} < 4$ km s$^{-1}$)
- Errors in proper motions ($\sim 3$ mas yr$^{-1}$) 50 $\mu$as yr$^{-1}$

<table>
<thead>
<tr>
<th>Error in velocity (km/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DR2</td>
</tr>
<tr>
<td>DR4</td>
</tr>
<tr>
<td>Cumulative</td>
</tr>
</tbody>
</table>

RAVE: 80% of the stars with $\Delta V < 20$ km s$^{-1}$

Gaia: 80% of the stars with $\Delta V < 5$ km s$^{-1}$
RAVE – the Radial Velocity Experiment

Going six-dimensional (and more): Astrometry is giving positions, distances and proper motions. The final dimension to fully define the motion of stars in the Galaxy is provided by RAVE.

- 2003-2013: 574,630 spectra; 483,330 stars
- accuracy of velocity determination ~2 km/s
- stellar parameters
- distance estimates
- elemental abundances

Overview
Some recent Applications
Leonard & Tremaine (1990):
- consider distribution function $f(E)$
  - $f \to 0$ as $E \to \Phi(r_{\text{vir}}) \Rightarrow n(v) \propto (v_{\text{esc}} - v)^k$

Consequently for line of sight:

$$n(v_\parallel) \propto (v_{\text{esc}} - v_\parallel)^{k+1}$$

 Dependence verified via cosmological simulations

Measure distribution $n(v_\parallel)$ for high velocity stars with RAVE on counterrotating orbits

Piffl et al (2014a):
- $493 \text{km/s} < v_{\text{esc}} < 587 \text{km/s}$
- $1.1 \times 10^{12} \text{M}_\odot < M_{200} < 2.1 \times 10^{12} \text{M}_\odot$
Dark mass in the solar neighborhood (Piffl et al 2014)

- Mass Model:
  - three exponential disks
  - flattened bulge
  - NFW dark matter halo
- Binney 2012 model for kinematics (incl. stellar halo)
- Model fit to vertical RAVE data
Results

\[ \rho_{\text{DM}} = 0.0126 \times q^{-0.89} \text{M}_\odot \text{ pc}^{-3} \pm 10\% \]
\[ \Sigma_{\text{DM}}(< 0.9\text{kpc}) = (69 \pm 10) \text{M}_\odot \text{ pc}^{-2} \]
\[ M_{\text{DM}}(< R_0) = (6.0 \pm 0.9) \times 10^{10}\text{ M}_\odot \]
\[ M_{\text{vir}} = (1.3 \pm 0.1) \times 10^{12}\text{ M}_\odot \]

- 46\% of the radial force at \( R_0 \) provided by baryons
- Bienamyé et al (2014): RAVE stars towards Galactic Pole, red clump distances: \( \rho_{\text{DM}}(R=R_0,z=0) = 0.0143\text{M}_\odot\text{pc}^{-3} \)
\[
V_\phi = 225 + \left( -31.2 + 2.6 \frac{R - R_0}{\text{kpc}} \right) \left| \frac{Z}{\text{kpc}} \right|^{1.06} \text{ km s}^{-1}
\]

\[
\sigma_\phi = 27.4 - 5.0 \frac{R - R_0}{\text{kpc}} + 12.4 \left( \frac{Z}{\text{kpc}} \right)^2 \text{ km s}^{-1}
\]

\[
\sigma_R = 38.6 - 3.0 \frac{R - R_0}{\text{kpc}} + 12.5 \left( \frac{Z}{\text{kpc}} \right)^2 \text{ km s}^{-1}
\]

\[
\sigma_Z = 16.2 - 3.1 \frac{R - R_0}{\text{kpc}} + 8.2 \left( \frac{Z}{\text{kpc}} \right)^2 \text{ km s}^{-1}
\]
Figure 11. The trends in average $V_\phi$ (top), $V_R$ (middle) and $V_Z$ (bottom) as functions of position in the $(R, Z)$ plane for RCs stars with RAVE catalog proper motions (left) and SPM4 proper motions (right). The plotted data are box-car averages over $200 \times 200$ pc wide boxes in $(R, Z)$ with $100$ pc increment in the coordinate system of the box’s centre.

The present analysis is consistent with the value of $\delta V_R/\delta R$ reported by S11 in that $-3 \text{ km s}^{-1}/\text{kpc}$ is roughly the average of the gradient $\delta V_R/\delta R \simeq -7 \text{ km s}^{-1}/\text{kpc}$ given by the RAVE proper motions at $Z<0$ and the vanishing gradient at $Z>0$.

If the dominant gradient in $V_R$ is essentially in the vertical direction and an even function of $Z$ as the SPM4 proper motions imply, the suspicion arises that it is an artifact generated by the clear, and expected, gradient of the same type that we see in $V_\phi$. The gradient could be seen to be caused by systematics in the proper motions creating a correlation between the measured value of $V_R$ and $V_\phi$ (see e.g. Schönrich, Binney & Asplund 2012). In Section 8 were explored the line-of-sight detection of the $V_R$, which however corroborates the existence of a gradient and North-South differences.

Schönrich 2012 found a larger value of $U_\odot = 14 \text{ km s}^{-1}$.
High velocity stars in RA VE (Kordopatis et al. 2013b) the probability of drawing a star of that metallicity from the RA VE mother sample, with a mean metallicity of 0.0 dex, 0.0–0.0, but paradoxically is metal-rich ([M/H] = –0.18 ± 0.1 dex).

The mean metallicity of our HiVel sample is slightly higher but consistent within the errors with the inner Galactic halo, –1.2 dex). The mean metallicity of our HiVel sample is slightly higher than the other velocities, –0.9 dex.

To obtain the orbital parameters for our HiVel sample, we integrated the orbit of a test particle through an assumed Galactic potential, similar to the approach used in previous studies. We made use of the same parameter choices as in previous work: $GM = 4 	imes 10^{53}$ erg s$^{-2}$, at the solar radius of 8.28 kpc to 2.0 kpc.

The horizontal lines indicate the adopted kinematic minimum kinematic boundary and require further follow up (more accurate estimates of the high-velocity tail of the thin disk or disk-like component).

The $Z = 3$ kpc (Carollo et al. 2010). The inner Galactic halo is also thought to have a chemical fingerprint that is consistent with the halo.

$Z$ (kpc) and $R$ (kpc) distribution of HiVel stars is –1.18 dex and is consistent with the Galactic halo.

The error bars are computed assuming Poisson noise. The error bar to the left represents the median uncertainty in both parameters. We made use of the same parameter choices as in previous work: $GM = 4 	imes 10^{53}$ erg s$^{-2}$, at the solar radius of 8.28 kpc to 2.0 kpc.

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Follow-up Hires spectroscopy of two HVS candidates and comparison to Venn et al (2004)

- J154401.1-162451 is chemically consistent with the halo field population or a massive dwarf galaxy
- J221759.1-051149 is chemically consistent with the Galactic thick disk ⇒ must be ejected
Towards RAVE DR5

• new new data, but considerable number of „problematic“ fields could be recovered

• Revised temperature priors based on optical photometry (APASS)

• Revised calibration at the metal-rich end using GaiaESO benchmark stars (Joffre et al, 2014), HARPS (Adibekyan et al 2013) and FEROS (Worley et al 2012)

• currently being explored: log g and ages from Kepler Astroseismology (see Chiappini talk)
Recalibration of the metal-rich end

Super-Solar metallicity sample

DR4: [M/H]
DR4: [Fe/H]
DR5: [M/H]
Metallicity distribution function

Stars richer than locally born OC stars
Super-Solar metallicity stars

Stars mainly located close to the plane.

But also:
Fair amount of stars with $0.4 < z < 1$ kpc
• Super Metal-rich giants in RAVE have a “flat” MDF from 0.1 < [M/H]< 0.35 dex
• no dwarfs above 0.25 dex
• Stars formed well inside R_0 (bar/bulge region?)
• Located up to ~1 kpc from the plane
• Same distribution inner and outer Galaxy
• Circular orbits:
  ■ Stars scattered through co-rotational resonances with the spiral arms
  ■ Spirals in the MW are strong, with large spiral structure
• Oscillations in RAVE Red Giants have already been detected in K-2 campaign 0.
• Final light-curves and data for K2-campaign 1 will be available in January 2015.
"Reconstructing the Milky Way's history: Spectroscopic surveys, Asteroseismology and chemo-dynamical models"
1-5 June 2015, Bad Honnef (Germany)
https://escience.aip.de/592-WE-Heraeus-Seminar
Roelof de Jong (AIP)
4MOST PI

www.4most.eu
Gaia needs spectroscopic follow-up!

4MOST extents the Gaia volume by 1000x in the red and 1 million in the blue!

Cover the bulge/halo interaction and the Magellanic Clouds
# Instrument Specification

<table>
<thead>
<tr>
<th>Specification</th>
<th>Concept Design value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Field-of-View (hexagon)</td>
<td>&gt;4.0 degree² (⌀ &gt; 2.5°)</td>
</tr>
<tr>
<td>Multiplex fiber positioner</td>
<td>~2400</td>
</tr>
<tr>
<td>Medium Resolution Spectrographs</td>
<td>R~5000-8000</td>
</tr>
<tr>
<td># Fibres</td>
<td>1600 fibres</td>
</tr>
<tr>
<td>Passband</td>
<td>390-930 nm</td>
</tr>
<tr>
<td>Velocity accuracy</td>
<td>&lt; 2 km/s</td>
</tr>
<tr>
<td>High Resolution Spectrograph</td>
<td>R~20,000</td>
</tr>
<tr>
<td># Fibres</td>
<td>800 fibres</td>
</tr>
<tr>
<td>Passband</td>
<td>395-456.5 &amp; 587-673 nm</td>
</tr>
<tr>
<td>Velocity accuracy</td>
<td>&lt; 1 km/s</td>
</tr>
<tr>
<td># of fibers in ⌀=2’ circle</td>
<td>&gt;3</td>
</tr>
<tr>
<td>Area (5 year survey)</td>
<td>&gt;2h x 16,000 deg²</td>
</tr>
<tr>
<td>Number of 20 min science spectra (5 year)</td>
<td>~100 million</td>
</tr>
</tbody>
</table>
Summary

• RAVE survey: more than 574,000 spectra taken
  - Radial velocities (1km/s)
  - Stellar parameters
  - Distances
  - Abundances
• Local escape speed: low Milky Way DM halo mass confirmed
• Clear correlation between chemical and kinematical signatures in the disk(s)
• Detection of large-scale asymmetries of the velocity field in the solar neighborhood
  - Apparent asymmetry above vs below the plan (wave?)
• Metal-rich end from stars that were radially migrated from the inner disk
• Next major step: Gaia & 4MOST