Medium-resolution spectroscopy along the stellar tidal stream Palomar 5

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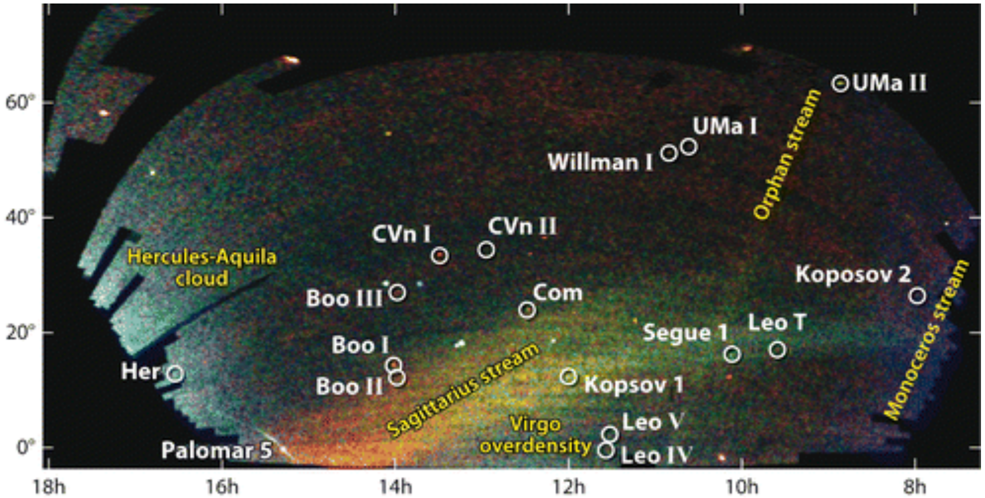
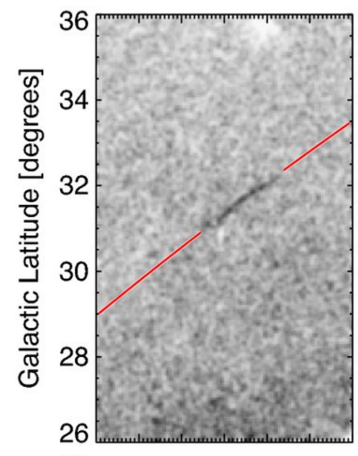
Stellar streams in the Milky Way halo

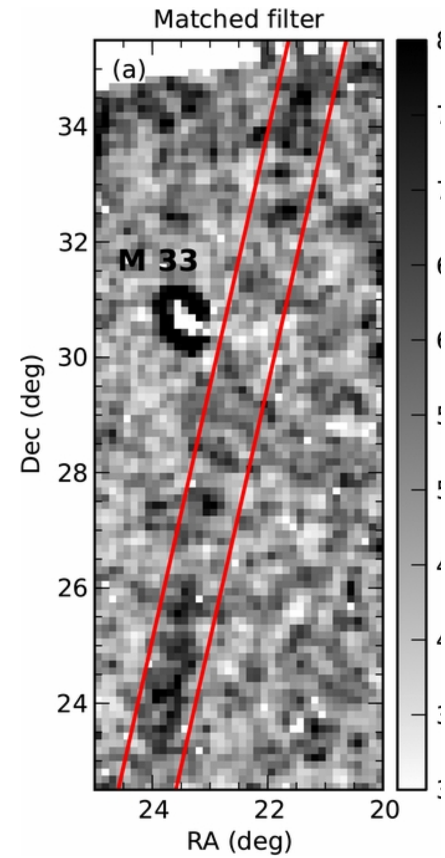
"The Field of streams"
(Belokurov et al. 2006; Ivezic et al. 2012)



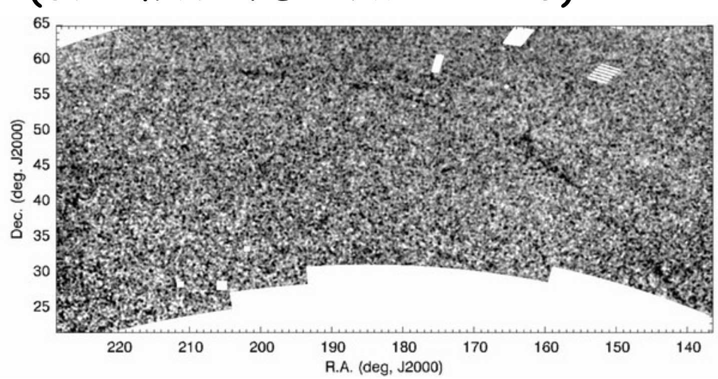
Ophiuchus stream
(Bernard et al. 2014)



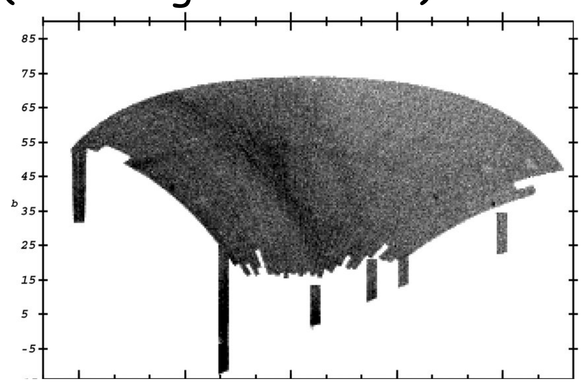
Triangulum stream
(Bonaca et al. 2012)



GD-1 stream
(Grillmair & Dionatos 2006)

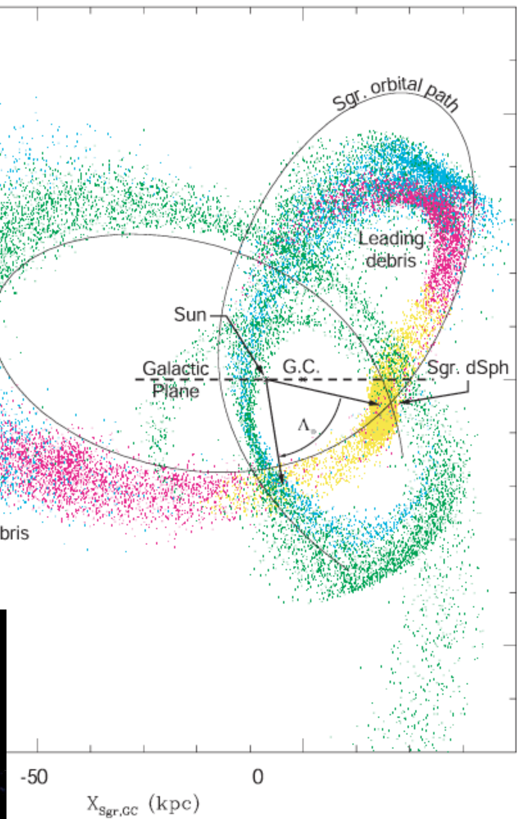


Orphan stream
(Newberg et al. 2010)

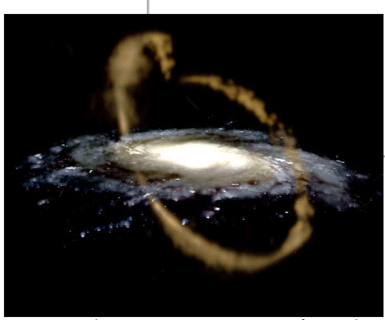


Stellar streams: tracers of the MW potential

Sagittarius streams



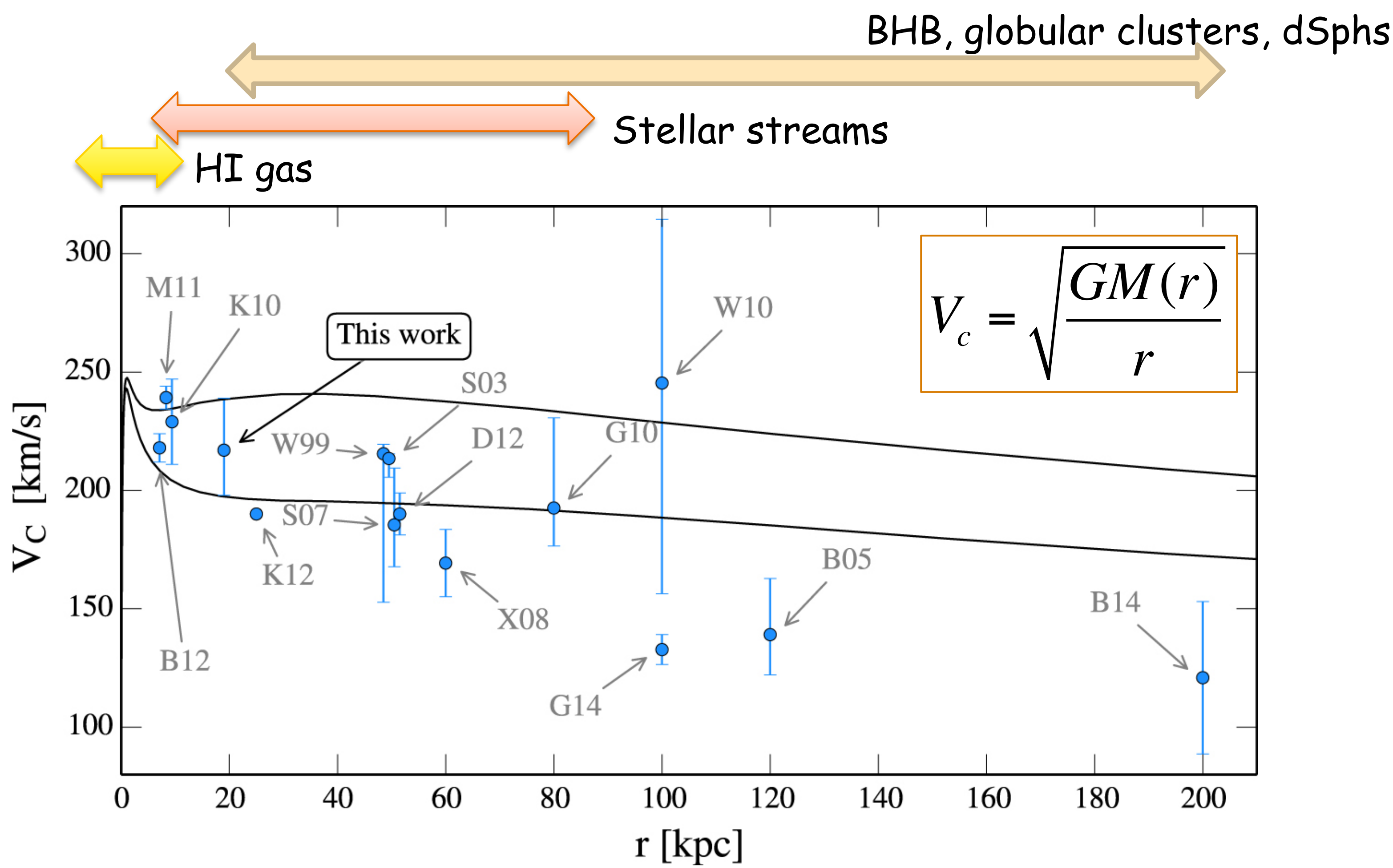
Law et al. 2005



David Martinez-Delgado (MPIA) & Gabriel Perez (IAC)

- Tidal disruption of a dwarf galaxy or a globular cluster
- Once the stars become unbound from the parent galaxy/cluster, they move under the influence of the Galactic potential
- Locations of the streams approximately (but not exactly) follow the orbit of the parent body

Mass of the MW's dark matter halo



Kupper et al. 2015

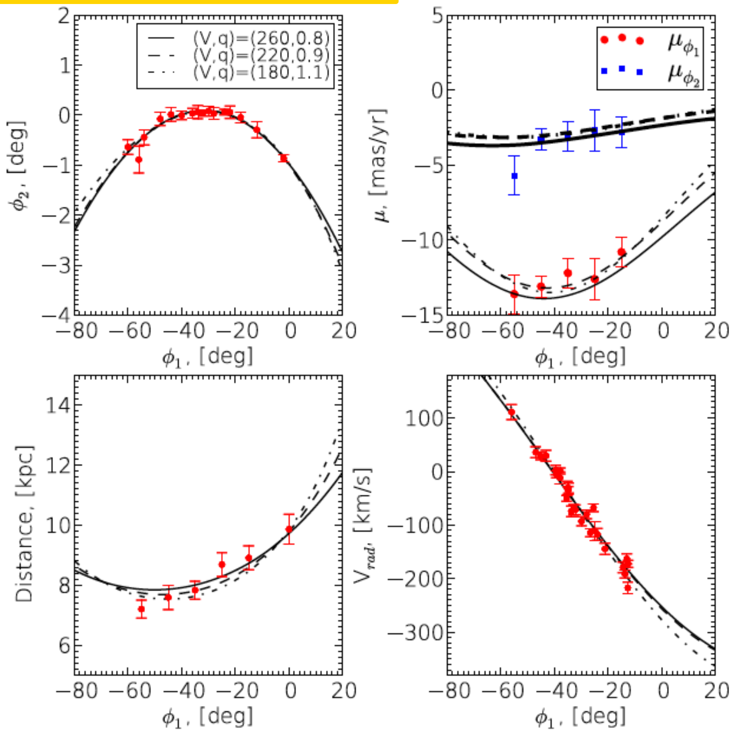
Lack of luminous tracers in the halo leads to large uncertainties
⇒ *Total mass ~0.5 – 2.5 [$10^{12} M_{sun}$] : A factor of ≫ 3 uncertainty*

Constraints on the mass and shape

The GD-1 stream at the Galactocentric radius of ~15kpc
⇒ 6D phase-space information are available!

Spatial location

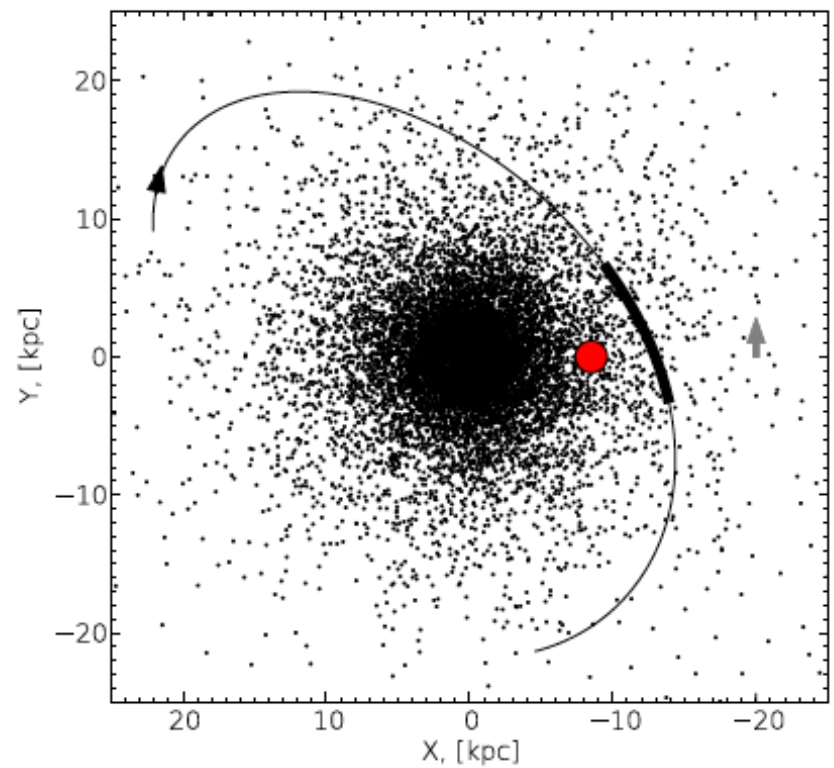
Proper motion



Distance

Line-of-sight velocity

The best-fit orbit for the potential:
V_c=220km/s, q(flattening)=0.9



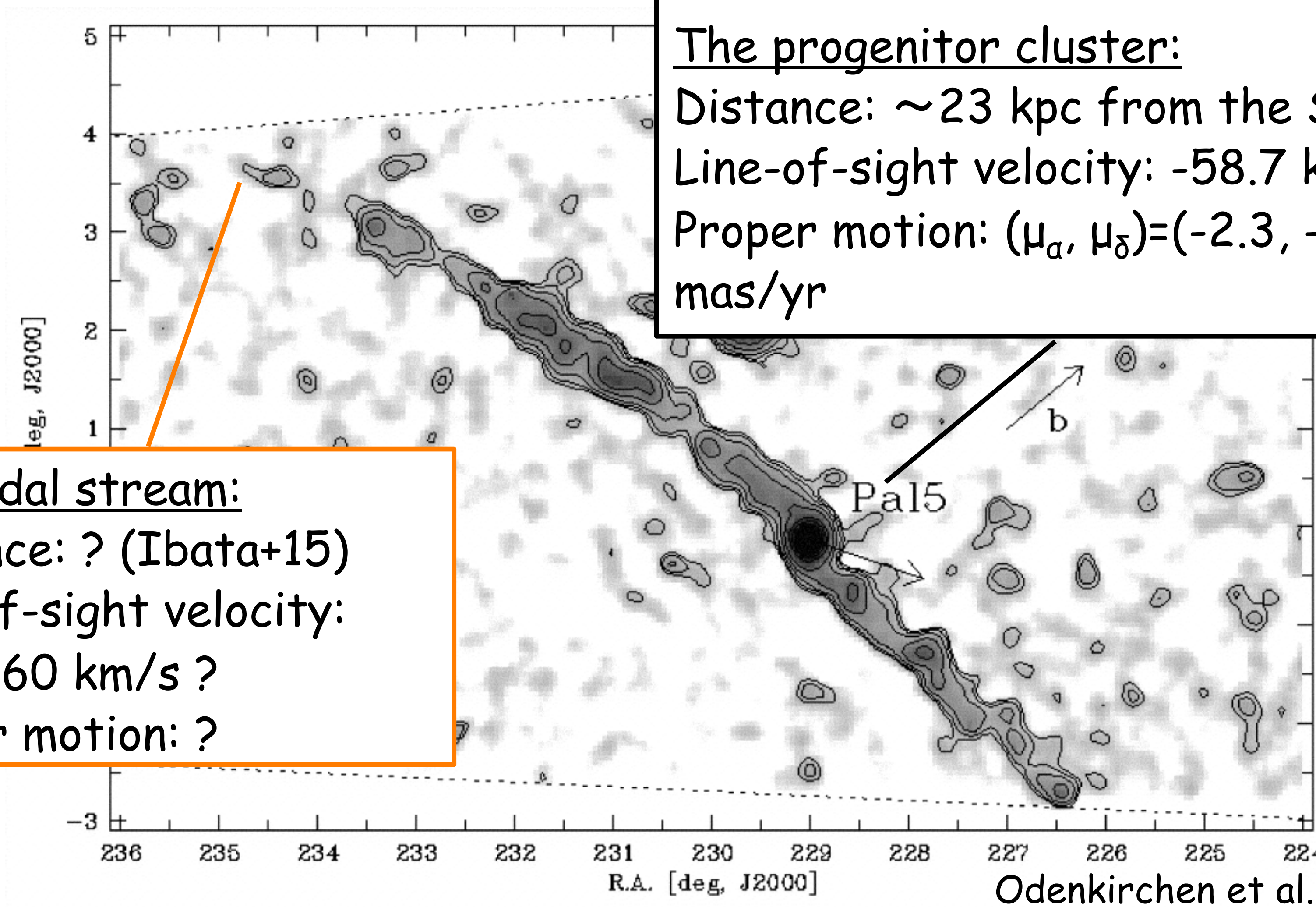
Koposov et al. 2010

This study

- *The Palomar 5 stream: @ d ~ 23 kpc*
- Medium resolution (R~6500-7000) spectra for stars in the central Pal 5 cluster and in the 10 stream regions were obtained with Subaru/FOCAS and Keck/DEIMOS spectrographs
- Stellar atmospheric parameters and *metallicity ([Fe/H])* are derived based on the photometric and spectroscopic data.
- The [Fe/H] information is used to separate the stream stars from contaminating field MW stars
- Currently available data is not deep enough to clearly constrain V_{los} of the streams, but future multi-object spectrographs such as the Subaru/PFS will be very useful

More distant streams: Palomar 5

The only globular cluster in the outer halo associated with a very long (>22°) and thin tidal stream.



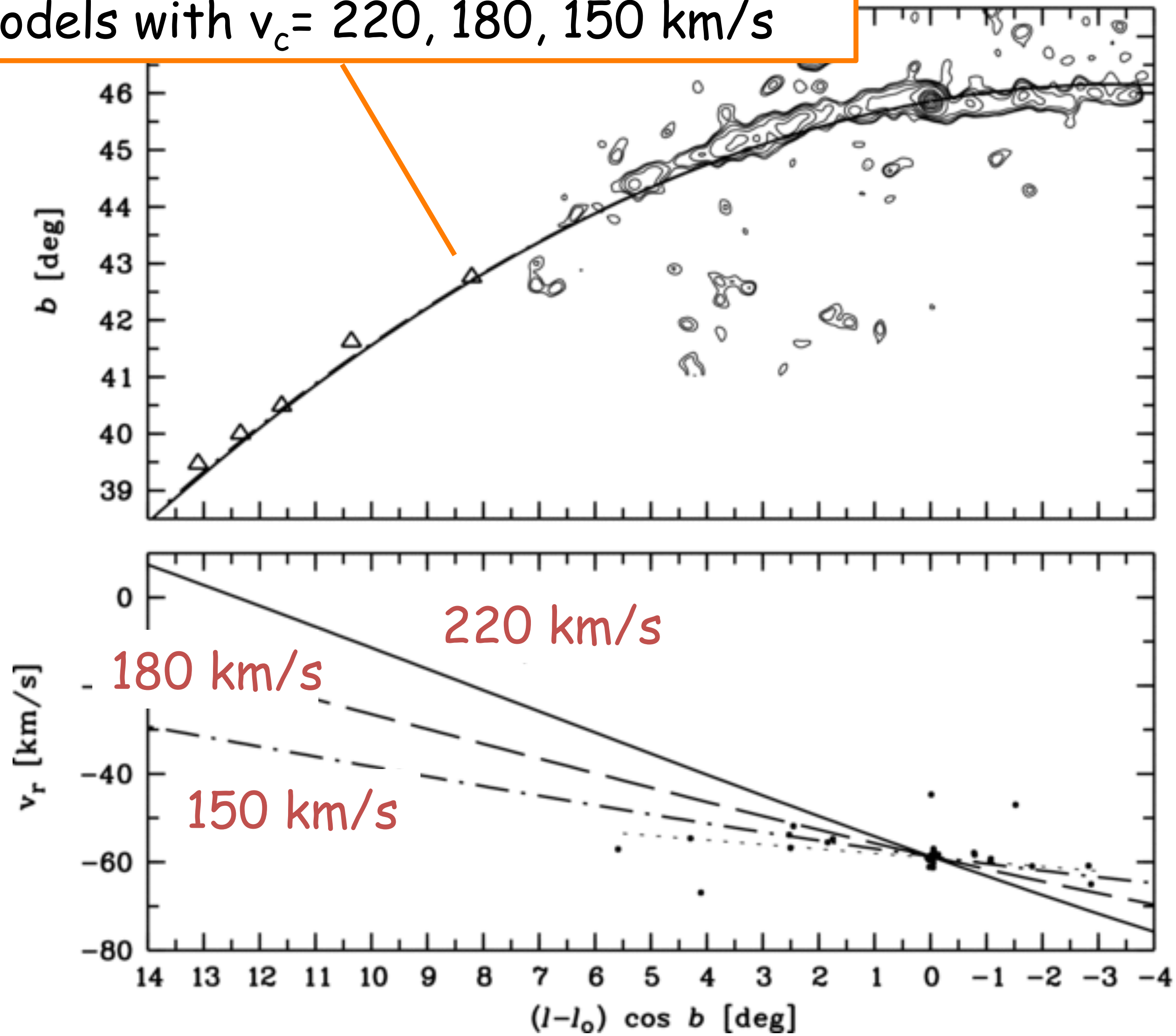
The progenitor cluster:
Distance: ~23 kpc from the Sun
Line-of-sight velocity: -58.7 km/s
Proper motion: (μ_α, μ_δ)=(-2.3, -2.3) mas/yr

The tidal stream:
Distance: ? (Ibata+15)
Line-of-sight velocity: -40~ -60 km/s ?
Proper motion: ?

Odenkirchen et al. 2003

Constraint on dark matter halo potential

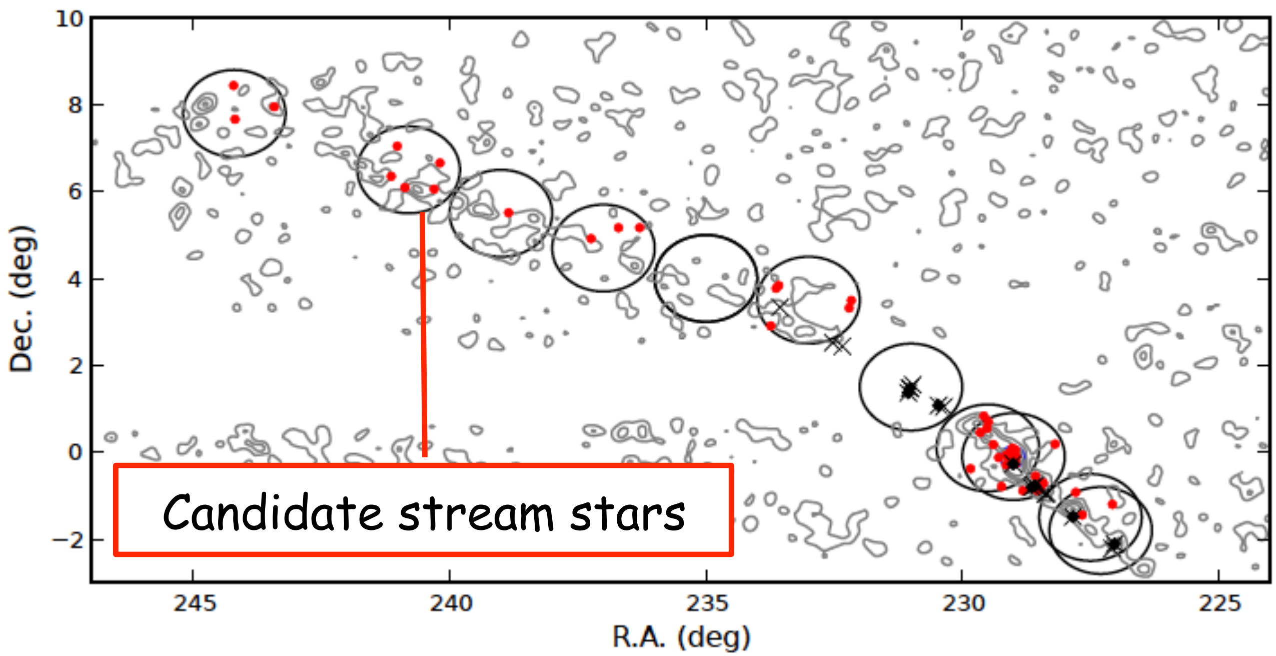
The models with v_c= 220, 180, 150 km/s



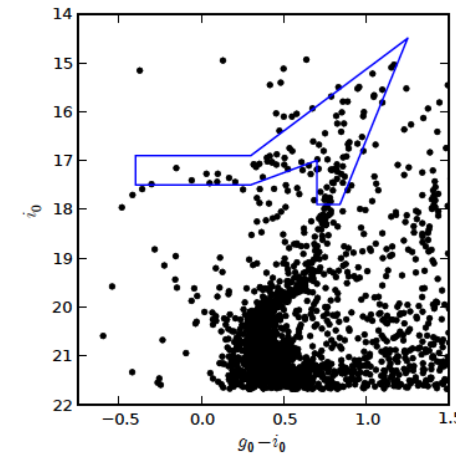
Odenkirchen et al. 2009

Identifying the member stars is difficult!

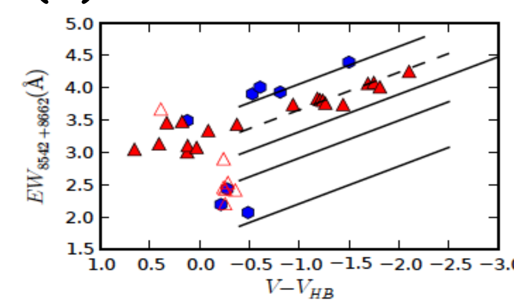
Kuzma et al. 2015



(1) Color-magnitude



(2) CaT EW



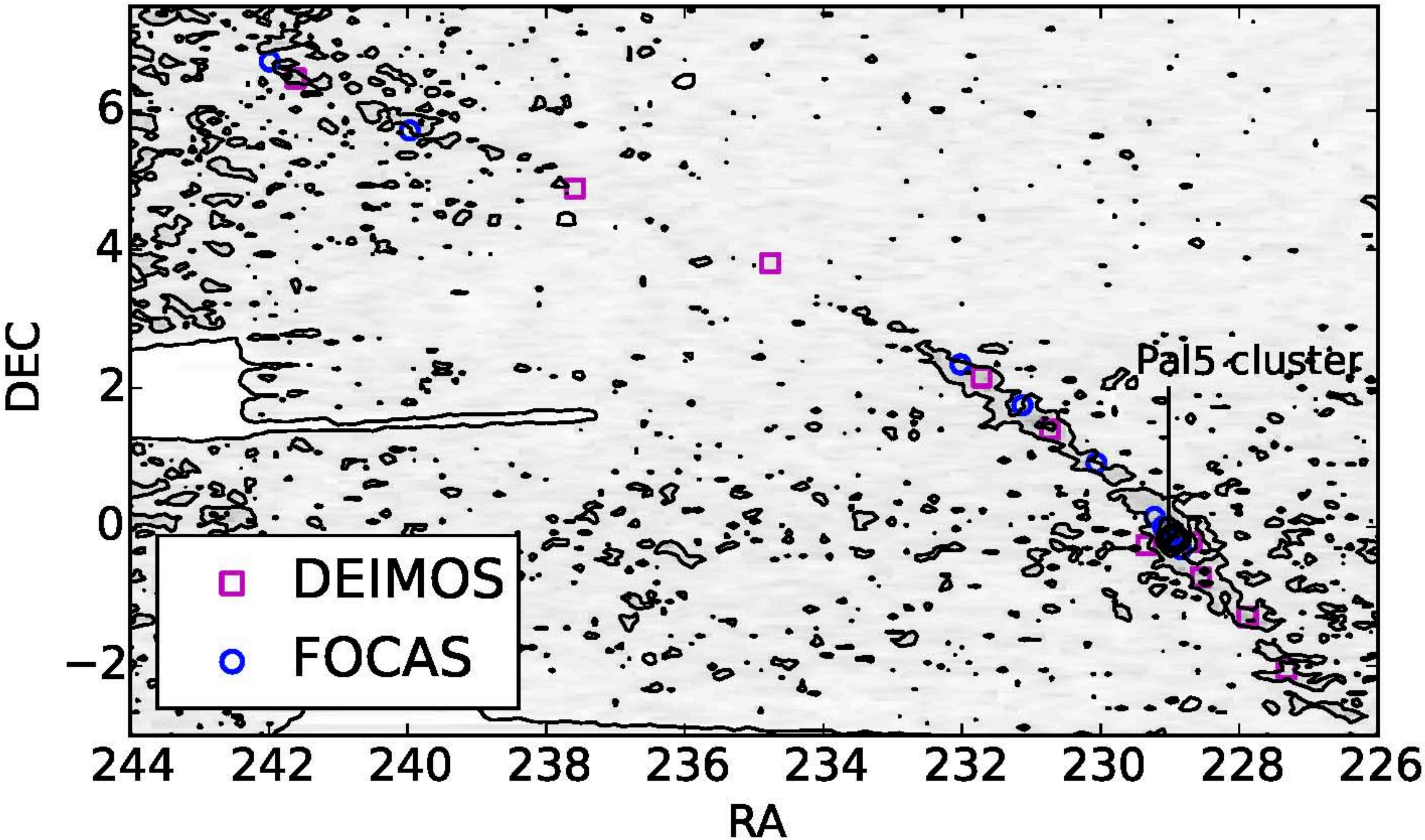
(3) Line-of-sight velocity: -70 < V_{los} < -30 km/s

Heavy contamination from the foreground MW stars!

⇒ Chemical tagging (e.g. [Fe/H]) are important:
The stream stars should have chemical composition similar to that of the progenitor cluster

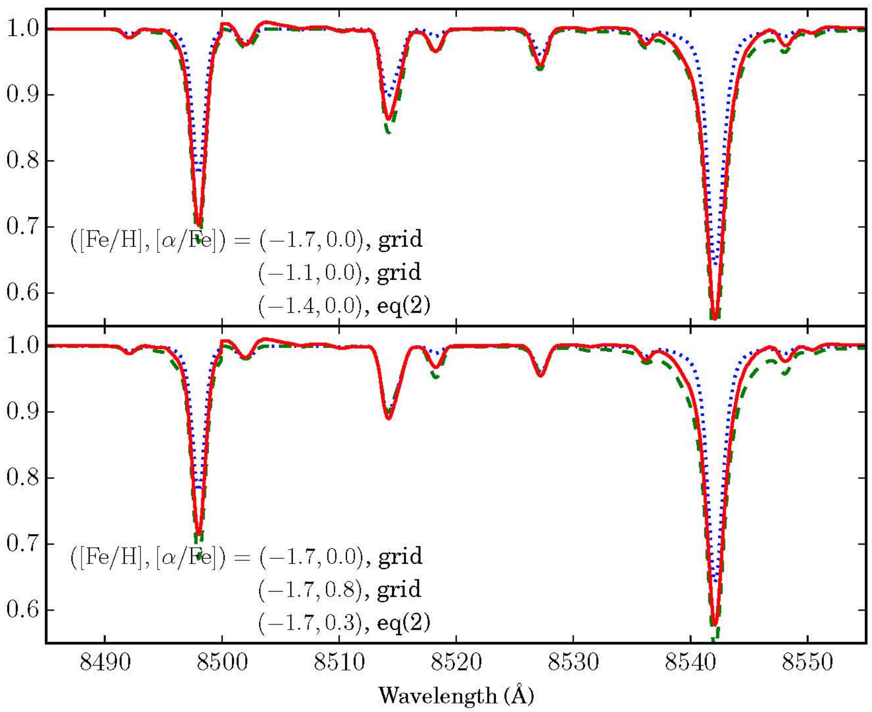
Medium resolution spectroscopy along the Pal 5 streams

Stellar density map for the color-magnitude selected stars based on SDSS DR12



Stellar parameters and [Fe/H] measurements

- V_{los}: Cross-correlating observed and template spectra
- A function of T_{eff}, logg, [Fe/H], [α/Fe] to interpolate a grid of synthetic spectra (W. Aoki-san's code)



$$
\begin{aligned}
f(\log T_{\rm eff}, \log g, [{\rm Fe/H}], \xi, [\alpha/{\rm Fe}]) = \\
a_0 + a_1 \log T_{\rm eff} + a_2 \log g + a_3 [{\rm Fe/H}] + a_4 \xi + \\
a_5 [\alpha/{\rm Fe}] + a_6 \log T_{\rm eff}^2 + a_7 \log g^2 + a_8 [{\rm Fe/H}]^2 + \\
a_9 \xi^2 + a_{10} [\alpha/{\rm Fe}]^2 + a_{11} \log T_{\rm eff} \log g + \\
a_{12} \log T_{\rm eff} [{\rm Fe/H}] + a_{13} \log T_{\rm eff} \xi + \\
a_{14} \log T_{\rm eff} [\alpha/{\rm Fe}] + a_{15} \log g [{\rm Fe/H}] + \\
a_{16} \log g \xi + a_{17} \log g [\alpha/{\rm Fe}] + \\
a_{18} [{\rm Fe/H}] \xi + a_{19} [{\rm Fe/H}][\alpha] + a_{20} \xi [\alpha/{\rm Fe}]
\end{aligned}
$$

⇒ fit to observed spectra with logg, [Fe/H], [α/Fe], etc. as free parameters (T_{eff} is estimated from photometry)

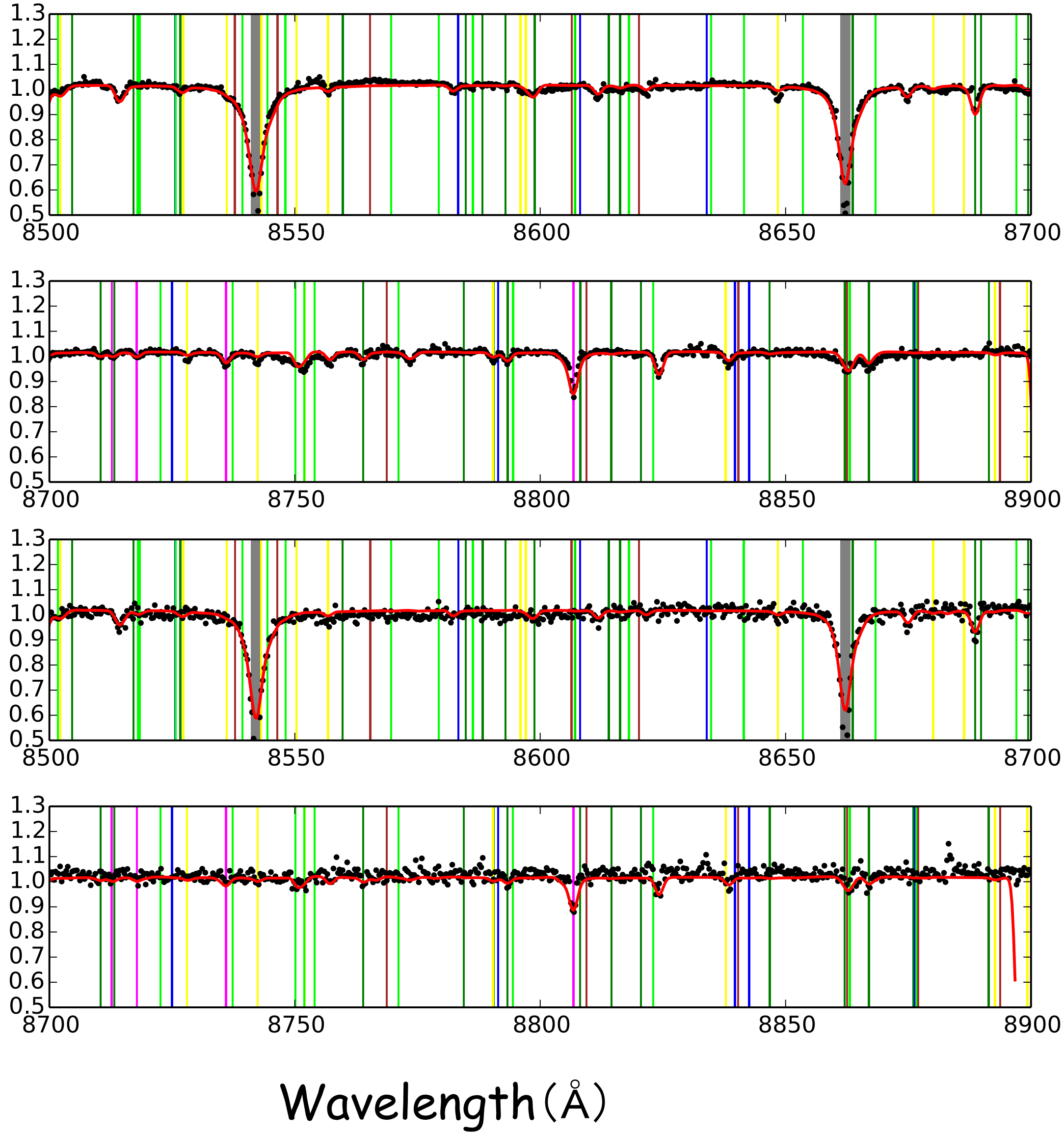
Stellar atmospheric parameters and metallicity estimates

T_{eff}=5508K
logg=4.6
[Fe/H]=-0.94
[α/Fe]=0.09

⇒ a thick disk star

T_{eff}=4898K
Logg=2.7
[Fe/H]=-1.45
[α/Fe]=0.63

⇒ a halo star



Metallicity estimates for the Pal 5 cluster

V_{los} and [Fe/H] for the Pal 5 central cluster by sigma-clipping

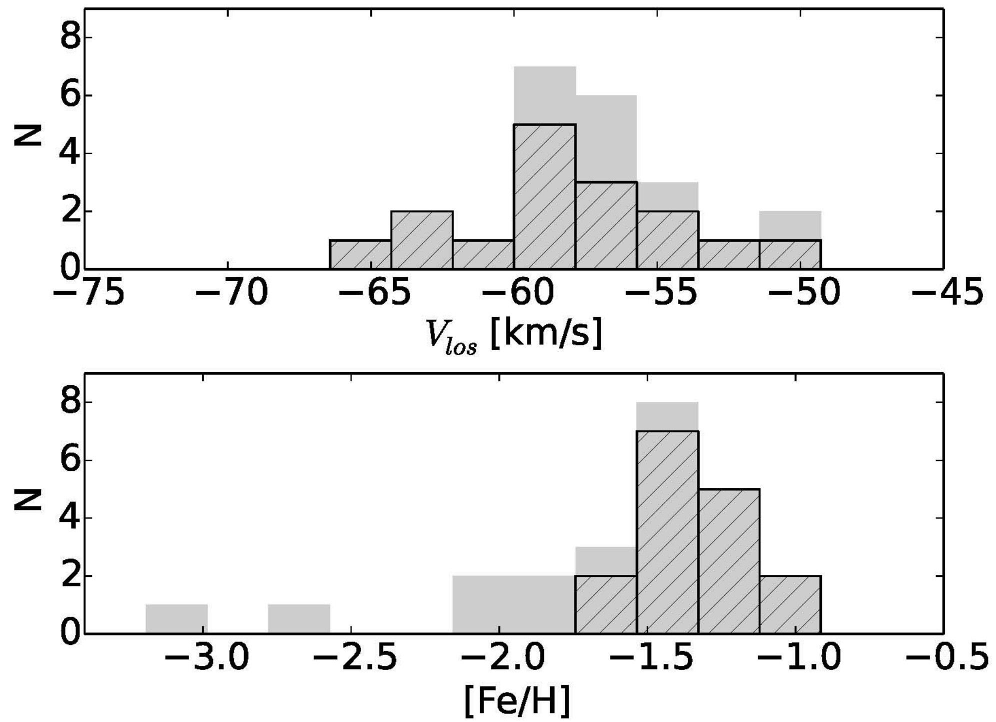
- <[Fe/H]>=-1.34±0.05

  (c.f. [Fe/H]=-1.28±0.03; Smith+02)

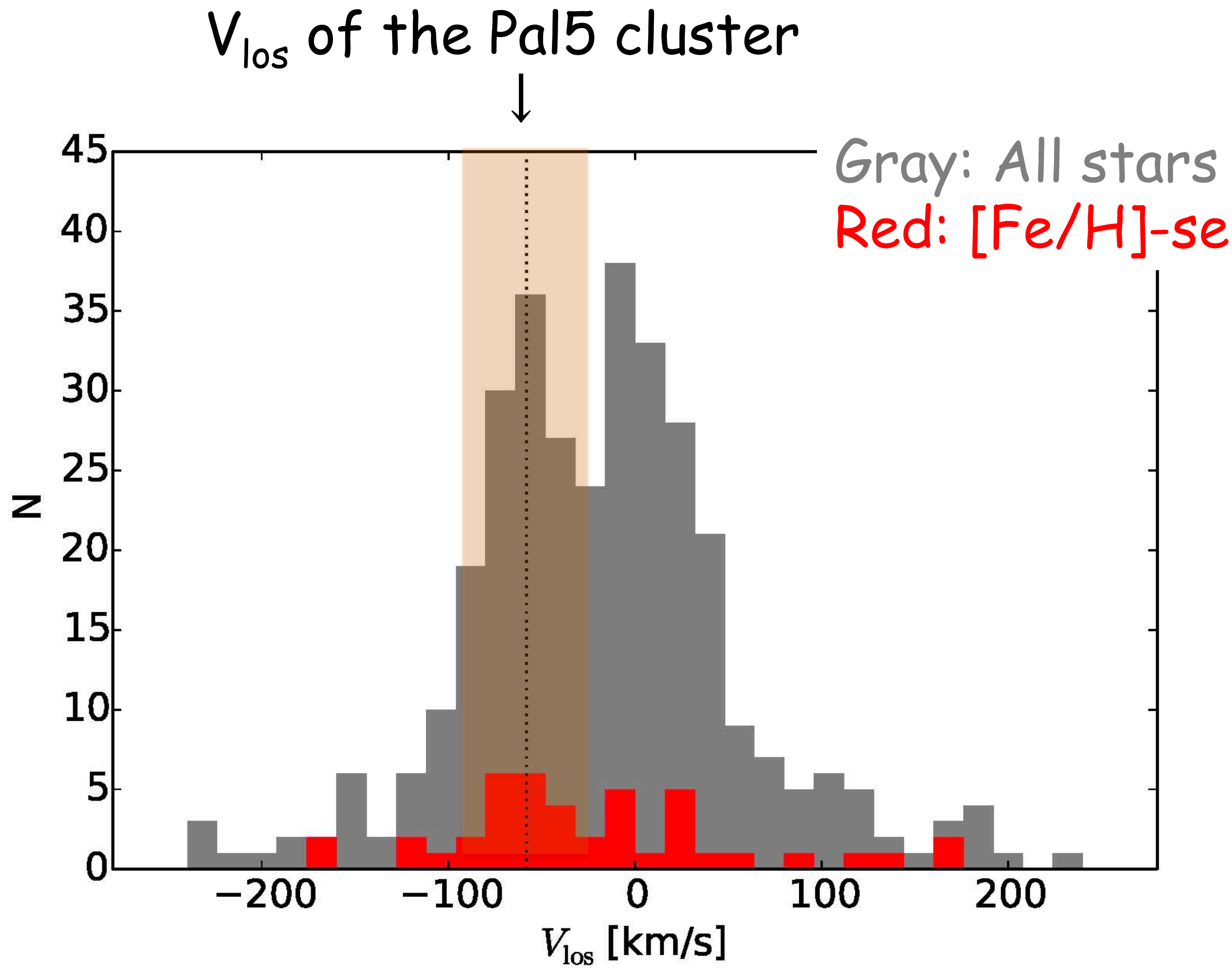
- $\langle V_{los} \rangle = -58.2 \pm 1.0$ km s^{-1}

  (c.f. $V_{los} = -58.7 \pm 0.2$ km s^{-1}; Odenkirchen+09)

- Errors
  - σ[Fe/H]=0.3 dex
  - $\sigma V_{los} = 3.0$ km s^{-1}

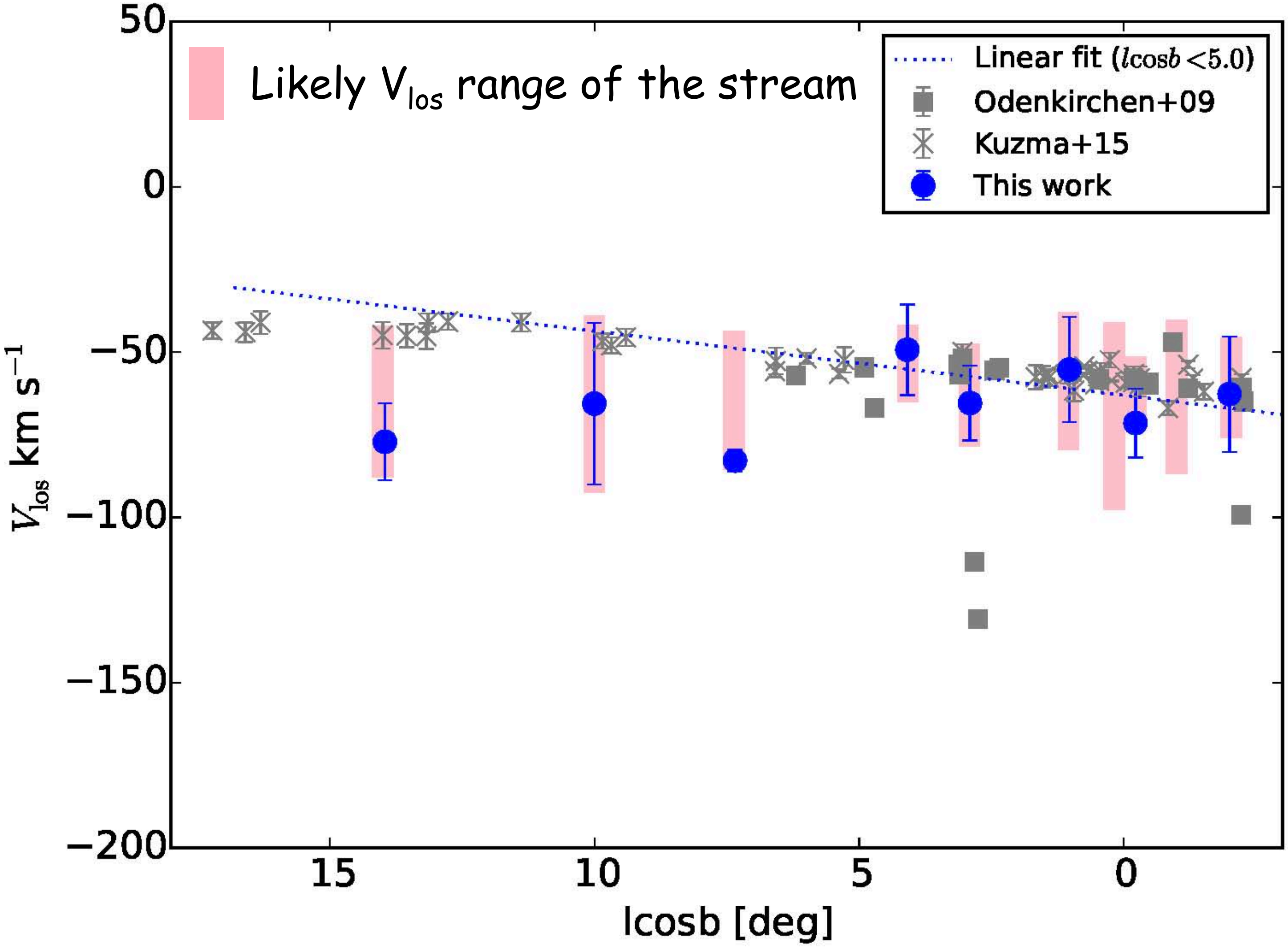


V_{los} distribution in the 10 stream fields



Stream stars likely dominate -90<V_{los}<-30 km/s

The most likely V_{los} ranges for the stream

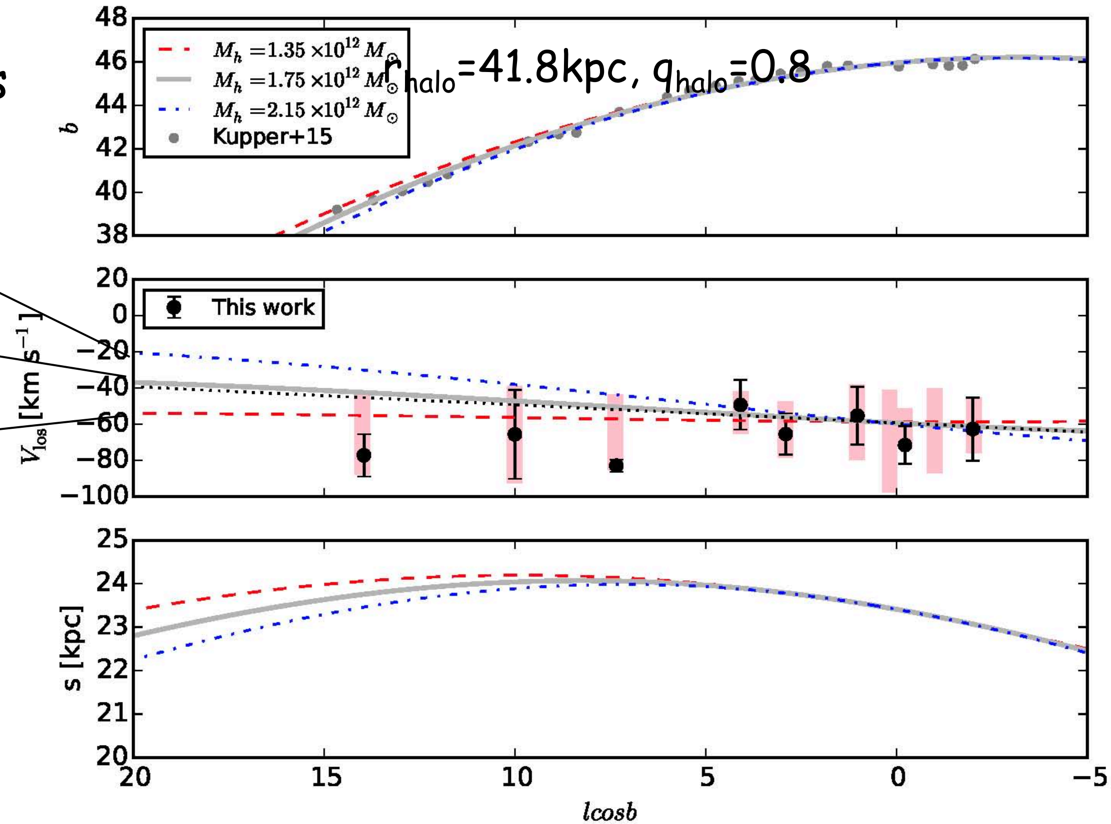


Comparison with models for the dark matter halo

$$\Psi_{\rm halo}(r) = -\frac{GM_{\rm halo}}{r}\ln\left(1+\frac{r}{r_{\rm halo}}\right) \qquad r=\sqrt{R^2+\frac{z^2}{q_{\rm halo}^2}}$$

$V_c(R_\odot)$ of the models

- 237km/s
- 231km/s
- 224km/s



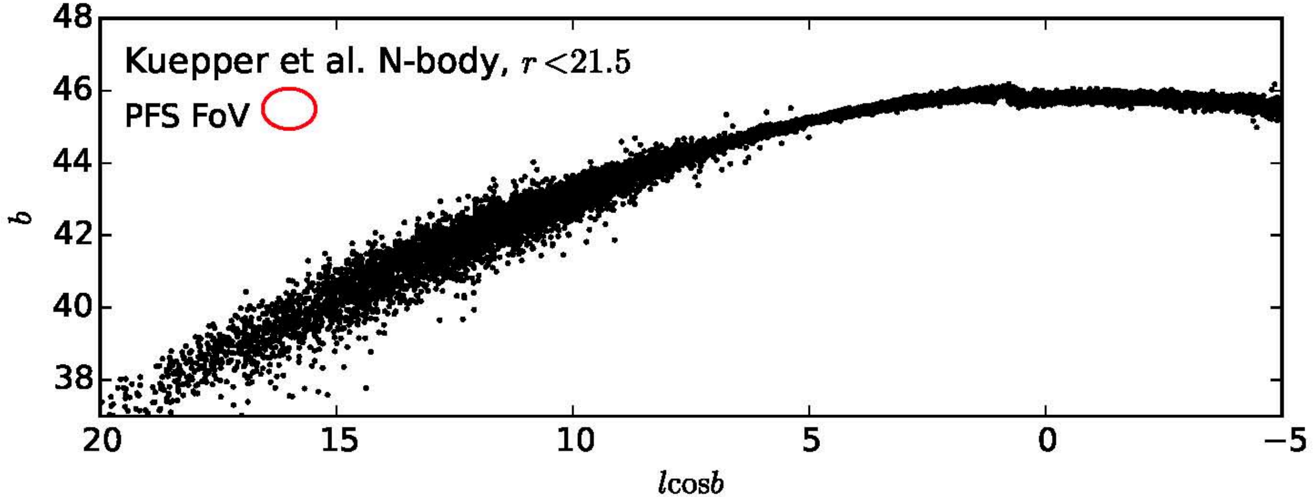
Large uncertainties in the estimated V_{los} ⇒ larger samples are needed to get stringent conclusions on the dark matter halo structure

Prospects with HSC/PFS

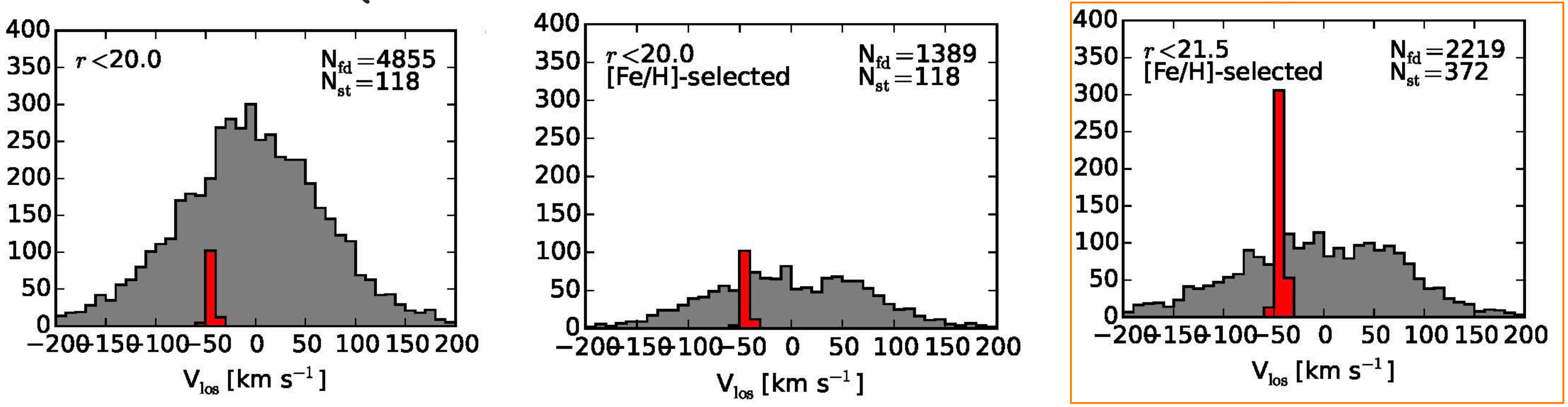
- Line of sight velocity along the Pal 5 stream is important to constrain the mass (Vc) of the MW's dark matter halo.
- Separating the stream stars from contaminating field stars is crucial. ⇒ chemical tagging ([Fe/H]) for a larger sample of stars
- Much deeper and wider FoV spectroscopic data along the stream (e.g. Mid-res mode of Subaru/PFS) are very useful.
- Distances and proper motion measurements from photometry are also essential to better constrain the structure of the dark matter halo (e.g. Subaru/HSC).

Prospects for future stream surveys

Case of Subaru/PFS with FoV=1deg^2 for the Pal 5 streams



Grey：field MW stars (Besancon model; Robin et al. 2003) Red: Pal5 stream stars



Deep spectroscopic surveys (r<21.5) to measure V_{los} +[Fe/H] are important

Distant streams

	d[kpc]	r_TO [mag]	Length [°]	Progenitor
Palomar 5	23	~20.5	>22	GC
Orphan	>20	~20.5	~50	(dwarf?)
GD1	~10	~18.5	~60	(GC?)
NGC5466	16	~19.5	~4	GC
Triangulum	26	~20.5	~12	(GC?)
Ophiucus	9	~18.5	2.5	(GC?)

For distant streams to constrain dark matter halo potential in the outer halo, multi-object spectrograph mounted on 8-10m class telescopes (Keck, Subaru, VLT etc) have great advantages

Summary

- Stellar streams are suggested to be important tracers of the dark matter halo of the Milky Way
- Chemical tagging (e.g. [Fe/H]) based on medium-resolution spectroscopy is useful to separate stars belonging to the streams from contaminating field Milky Way stars
- Future deep spectroscopic surveys such as Subaru/PFS are essential to better constrain the mass of the MW dark matter halo through distant stellar streams