Stellar Dynamics in the Milky Way – issues affecting the GAIA RVS

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Sept 13, 2002

Introduction

- Key science driver of the GAIA mission is to determine the dynamical state and formation history of the Milky Way.
- Radial velocities provide the 6th phase space coordinate, vital for building a complete picture of the stellar dynamics in the Galaxy.
- An unbiased sample of radial velocities is an essential complement to the GAIA proper motion data set (e.g. Binney et al. 1997)
- The spectral resolution and magnitude limit of the RVS determine the fraction of the GAIA data set for which we will have full phase space information.
- Conclusions of preliminary investigation, based on literature results, presented at Ljubljana (June 2002):
  1. Required magnitude limit: $\mathrm{M_V} \sim 17.5$
  2. Required radial velocity accuracy at this limit: $\Delta v \lesssim 10\mathrm{km\,s^{-1}}$
  3. Assuming these accuracies, the RVS radial velocities will be a vital counterpart to the GAIA astrometric data set.

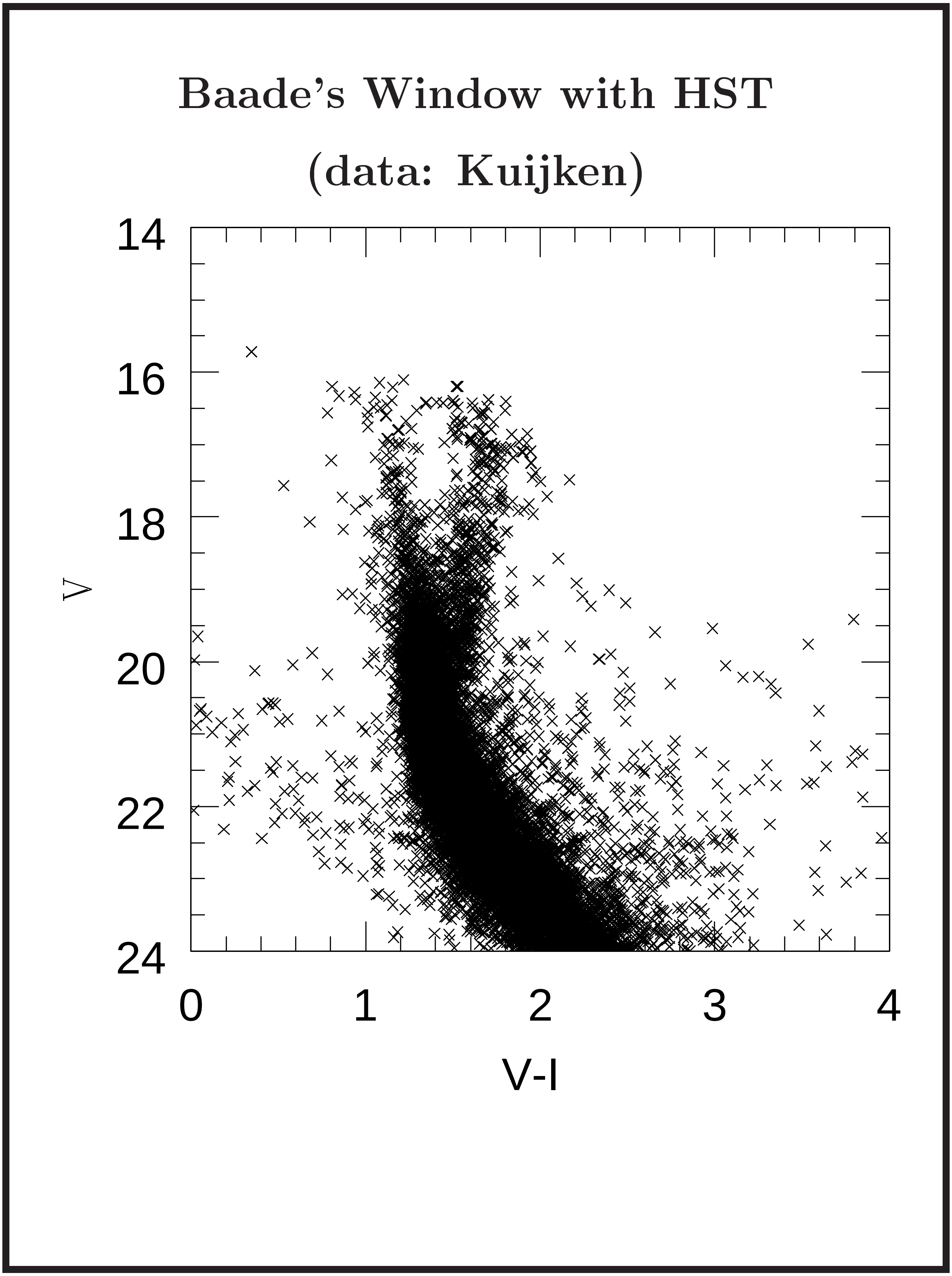
Acknowledgments

- Konrad Kuijken – HST data on Baade's window
- Annie Robin – simulated data from Besancon galaxy models
- Antonella Vallenari – simulated data for some disk fields
- Amina Helmi – halo streams
- Misha Haywood – simulated data and discussions
- HongSheng Zhao, Jan Kleyna, Gijs Nelemans – discussions

The Bulge/Bar

Bar kinematics and the RVS

- Radial velocities are essential to distinguish between kinematics of an axisymmetric bulge and a triaxial bar (Vauterin & Dejonghe 1998) – proper motions alone are not sufficient.
- Current observations are limited to low extinction windows (e.g. Baade's window) – patchiness of extinction will allow GAIA to observe stars in many new regions.
- Typical line of sight velocity dispersions are $\sim 100 \ \mathrm{km\,s^{-1}}$, with variations along l.o.s. of $\sim 30 \ \mathrm{km\,s^{-1}}$ depending on model details.
- Main limitations are due to crowding – strong function of spectral resolution.

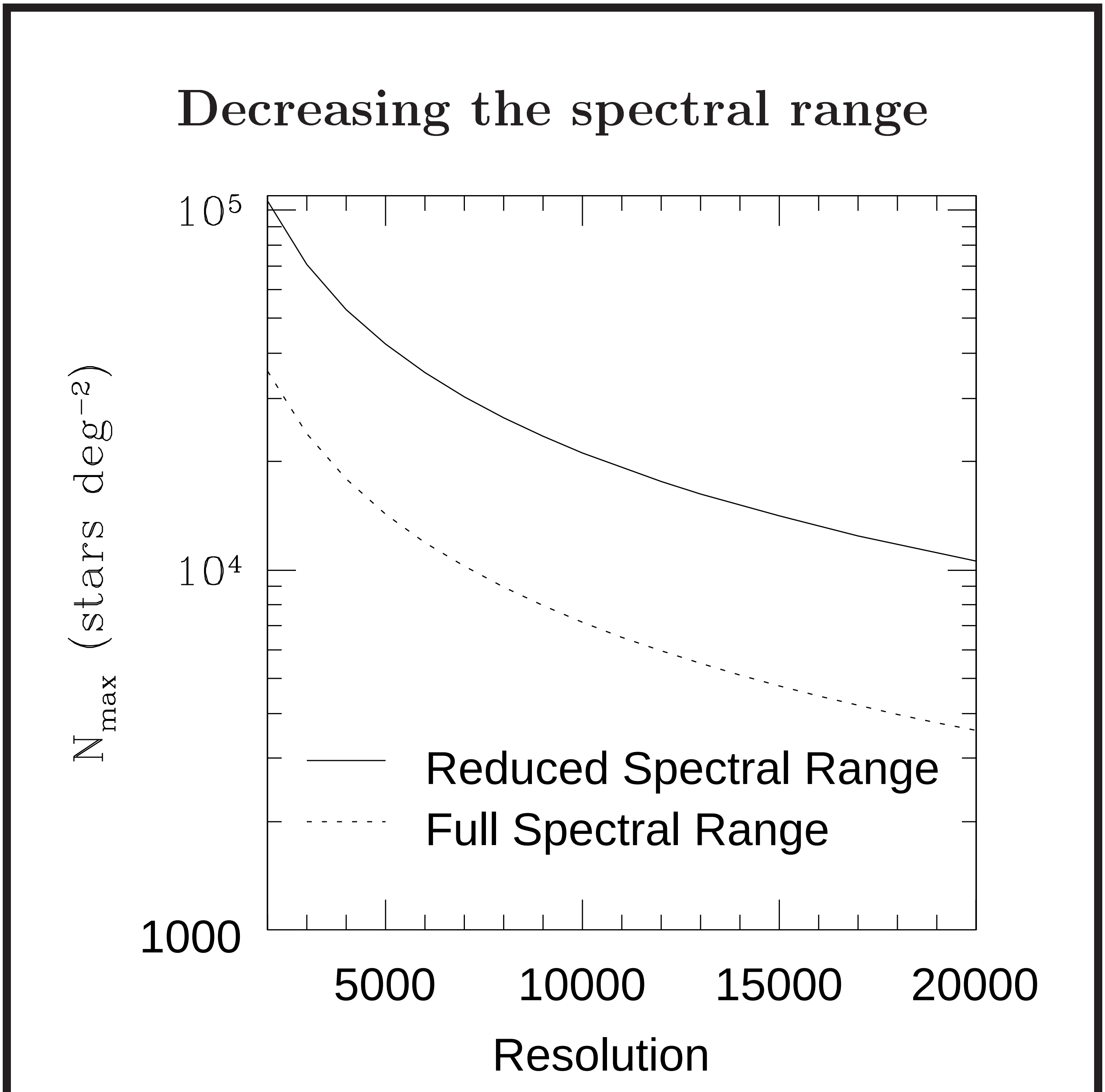

Baade's Window with HST
(data: Kuijken)
14
16
18
20
22
24
V
0
1
2
3
4
V-I

Crowding at low latitudes

- Consider the best case scenario:

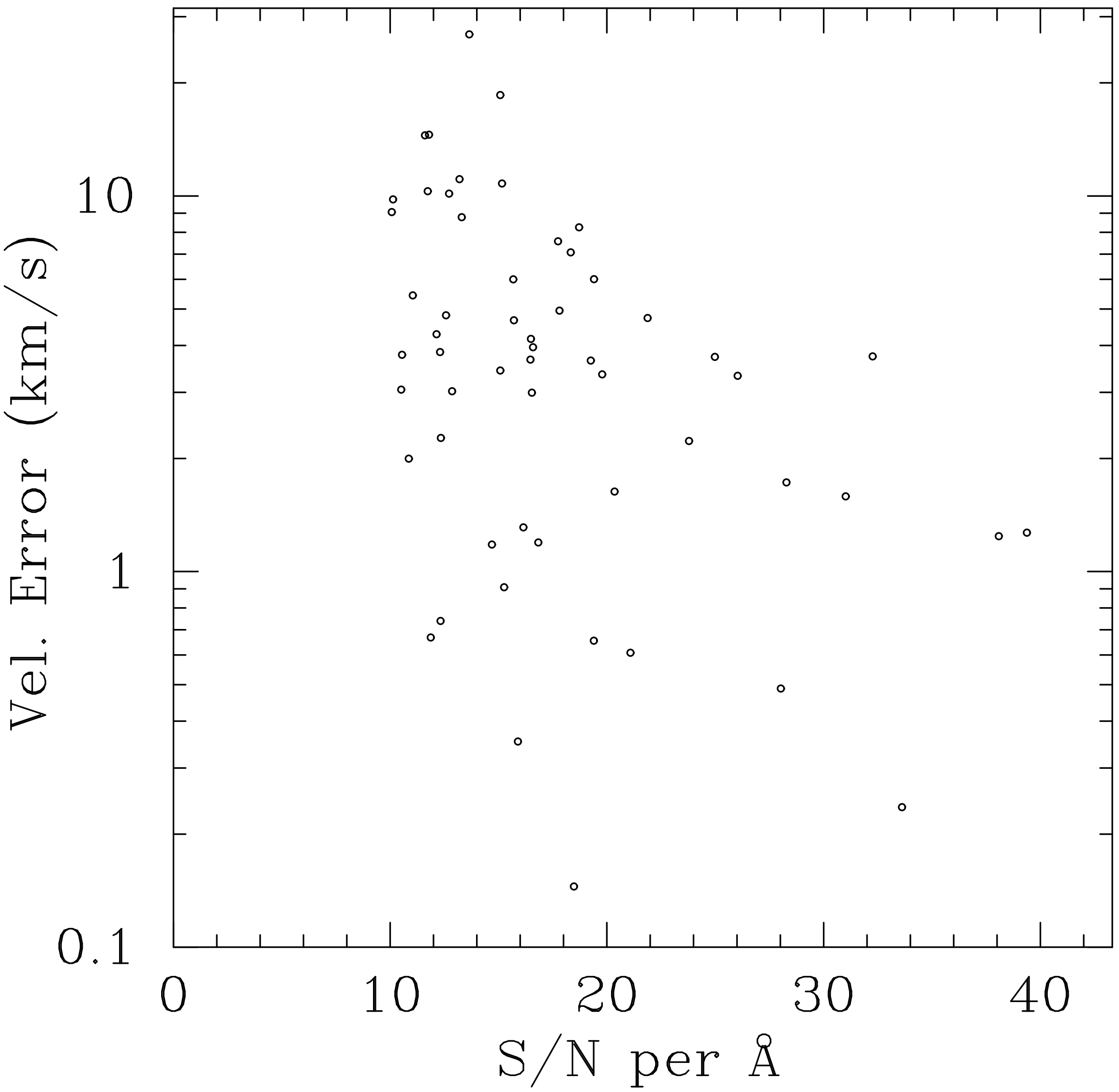
1. Tilt mechanism included $\Longrightarrow$ spectral width $= 2$ pixels
2. Whole CCD can be transmitted $\Longrightarrow$ $n_{\rm max} = 1/(\text{spectral area})$

- Resolution: 5000 - 20000
- Spectral Range:
    1. Full Range: $8490 - 8750\mathring{A}$
    2. Reduced Range: $8490 - 8577\mathring{A}$

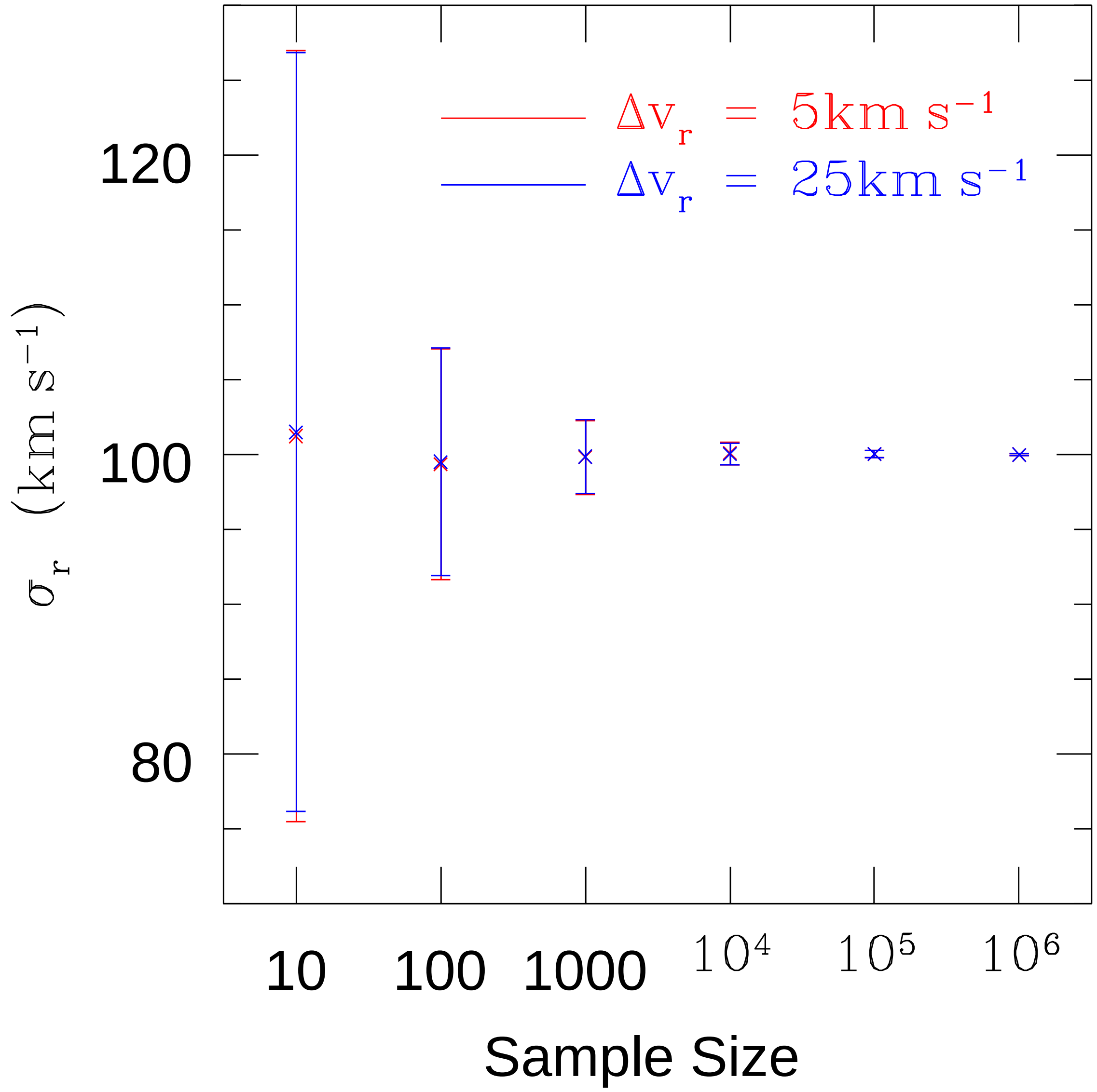


Decreasing the spectral range
10^5
10^4
1000
5000
10000
15000
20000
Resolution
N_{max} (stars deg^{-2})
Reduced Spectral Range
Full Spectral Range

Decreasing the spectral range



Velocity Dispersion Estimation

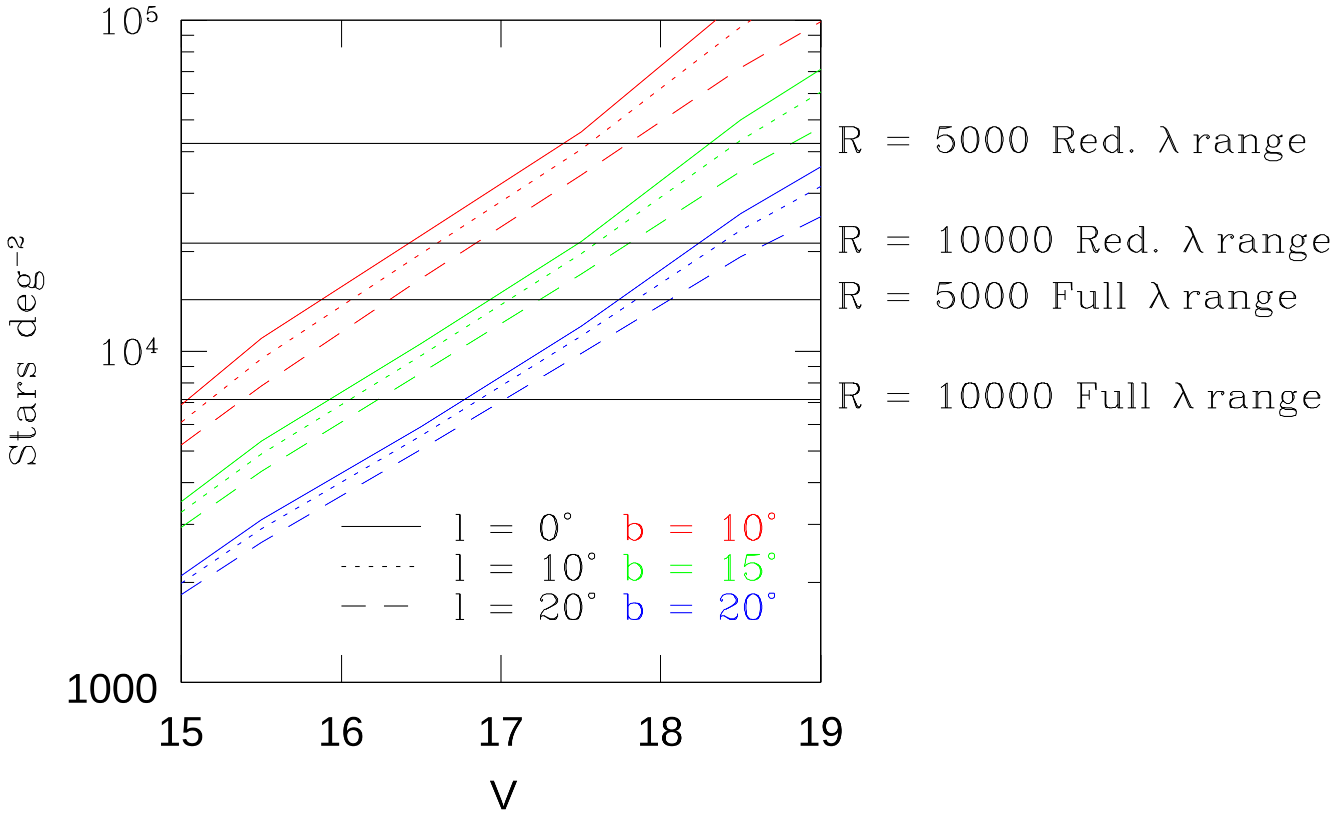


Key Points

- To estimate line of sight velocity dispersion to an accuracy of $\sim 10\mathrm{km\,s^{-1}}$ requires ~ 100 stellar velocities.
- Since dispersion is $\sim 100\mathrm{km\,s^{-1}}$, individual errors of $\lesssim 25\mathrm{km\,s^{-1}}$ are tolerable (if only dispersion is required).
- Require dispersion as a function of distance through the bulge $\Longrightarrow$ we need ~ 1000 stars per low extinction window at all distances through bulge.
- Significantly larger samples required for more detailed modelling (c.f. Vauterin & Dejonghe 1998).
- Typical size of low extinction window: $40' \times 30'$
- Depth of Bulge along line of sight ~ 0.5 mag.
- Bulge (near side) TRGB: $\mathrm{m_V} \sim 14.5 \Longrightarrow$ must go significantly below $V \sim 15$ to see both sides

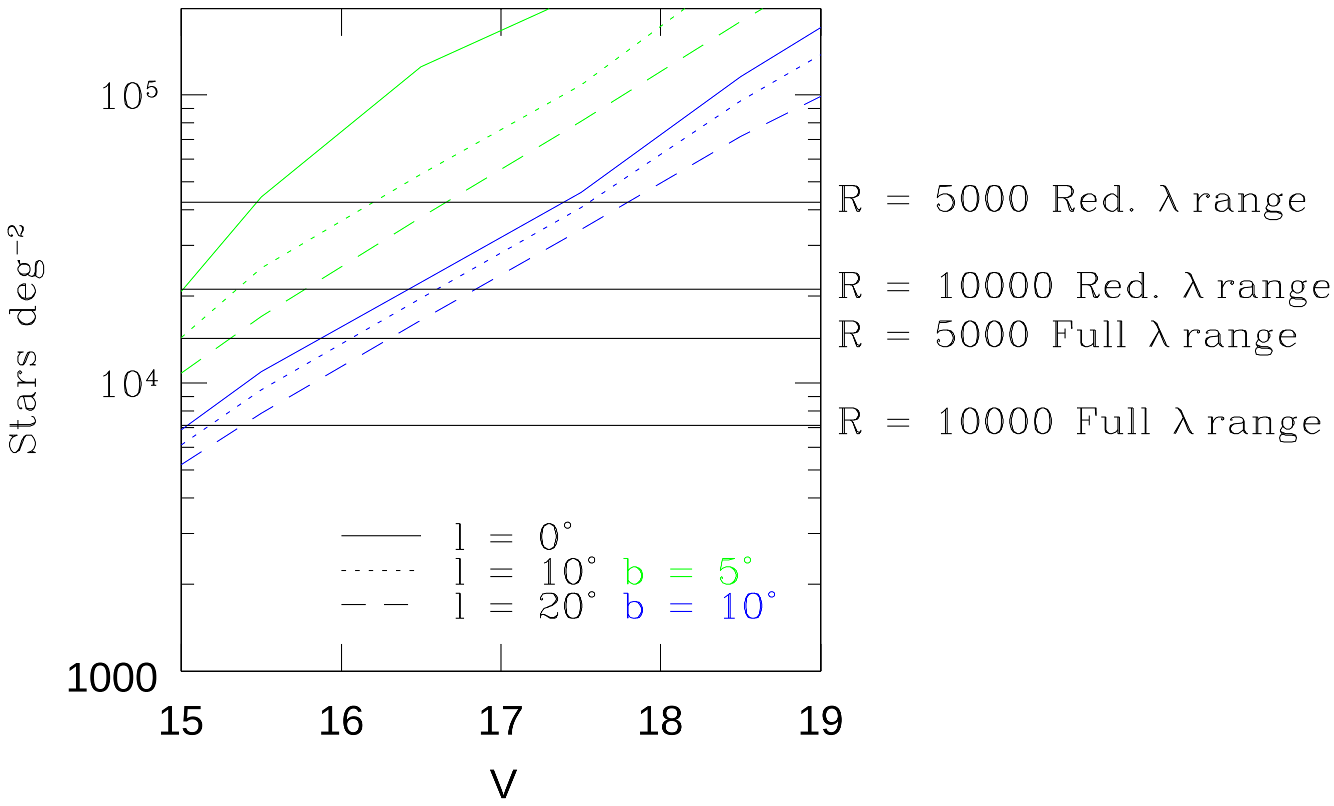
Besancon Model (data: Robin)

All stars $10^\circ < b < 20^\circ$



Besancon Model (data: Robin)

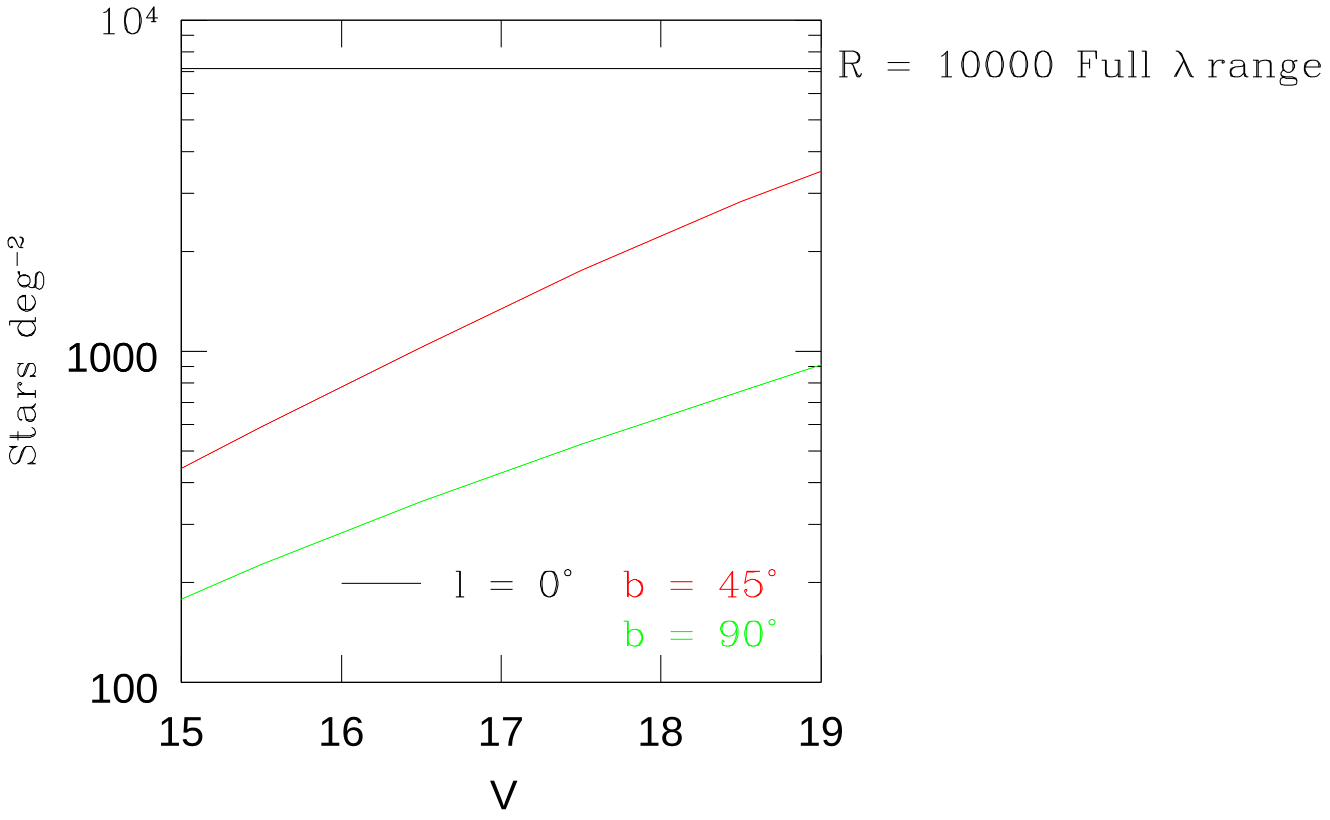
All stars $b < 10°$



- High resolution $\Longrightarrow$ no bulge stars observed within 10° of the Galactic Centre.
- NB: Model does not include accurate extinction map for $b < 5°$
- Partial read-out of CCD will degrade performance.
- Extinction will reduce bulge contribution in these fields.

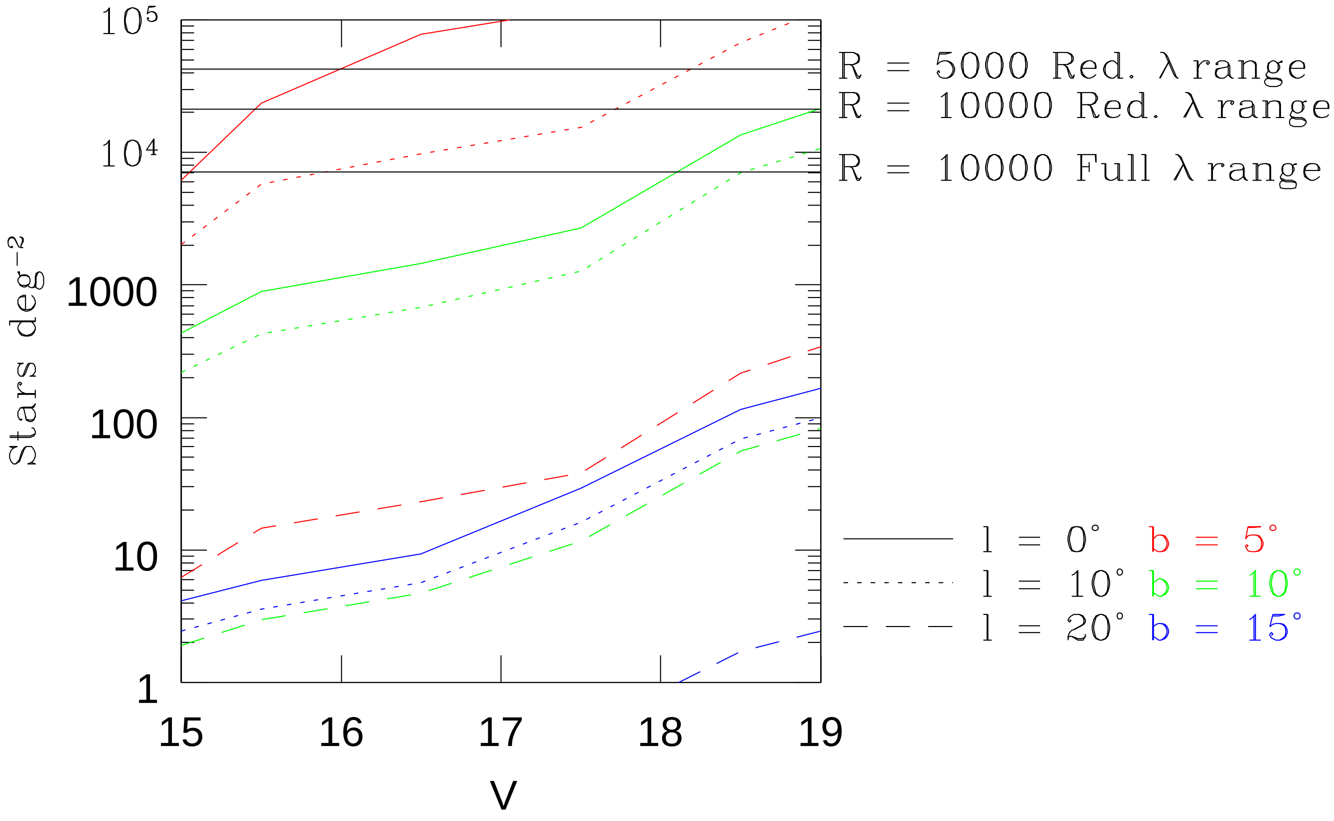
Besancon Model (data: Robin)

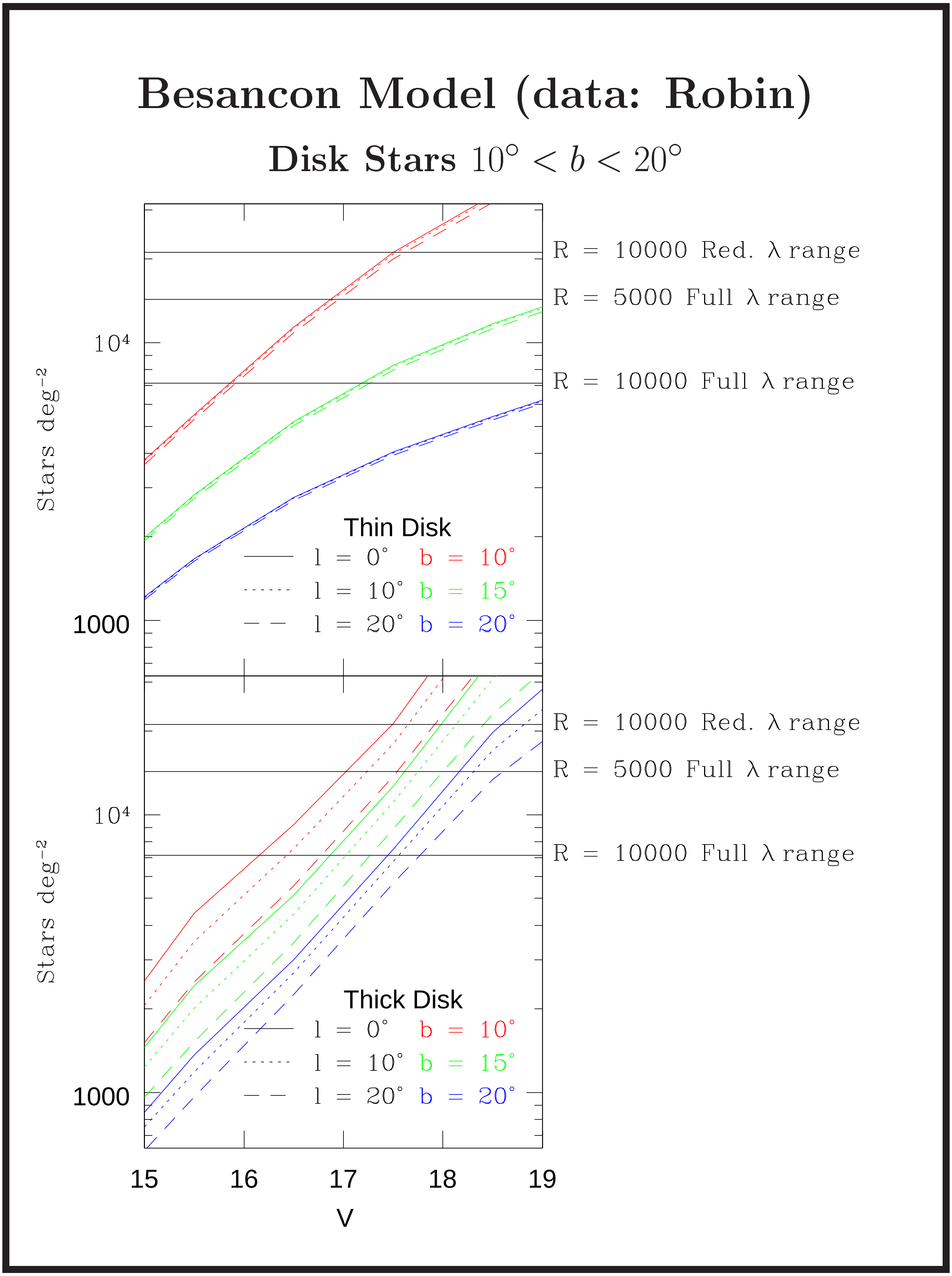
All stars $b > 30°$



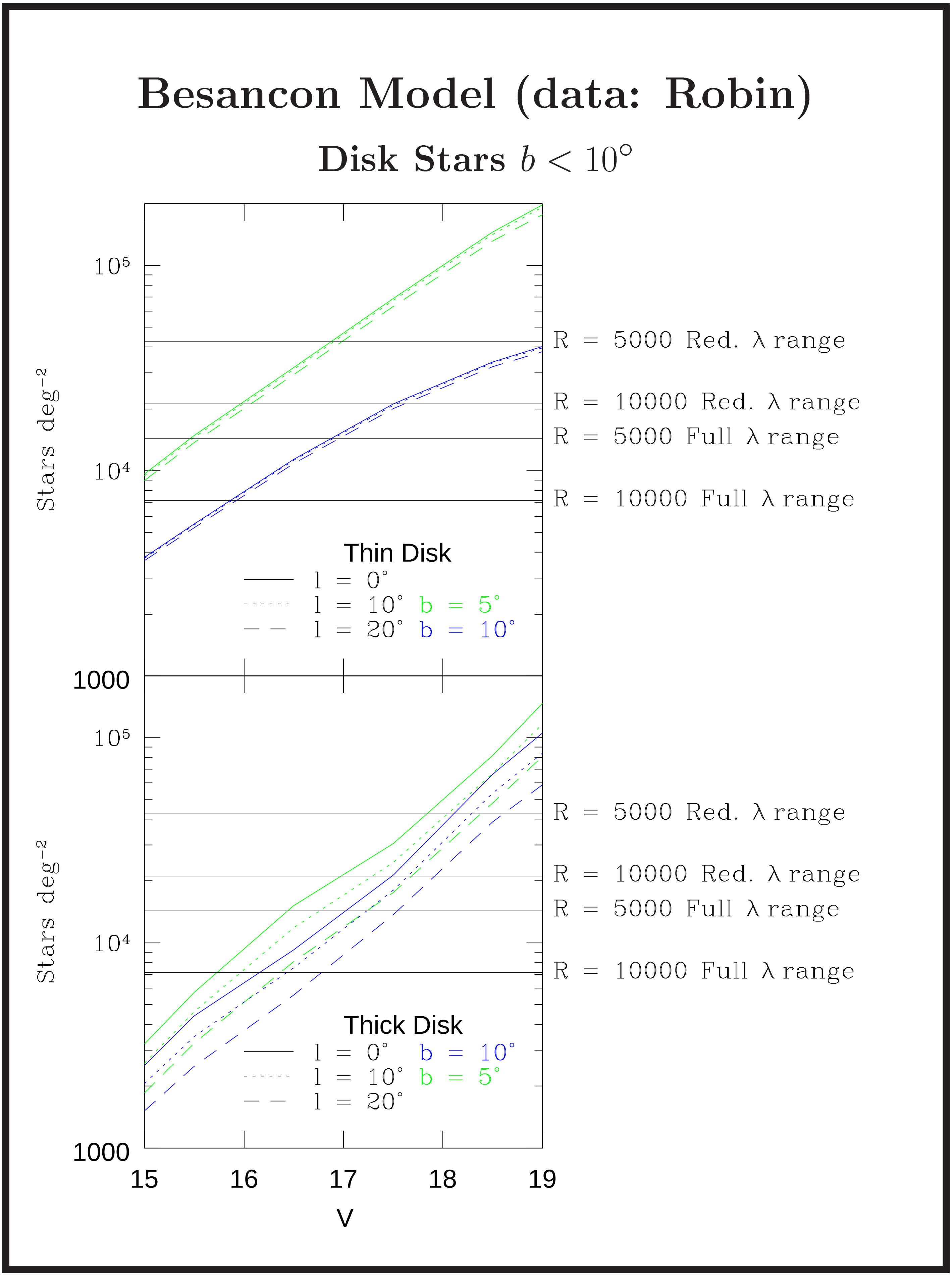
Besancon Model (data: Robin)

Bulge Stars $b < 15°$



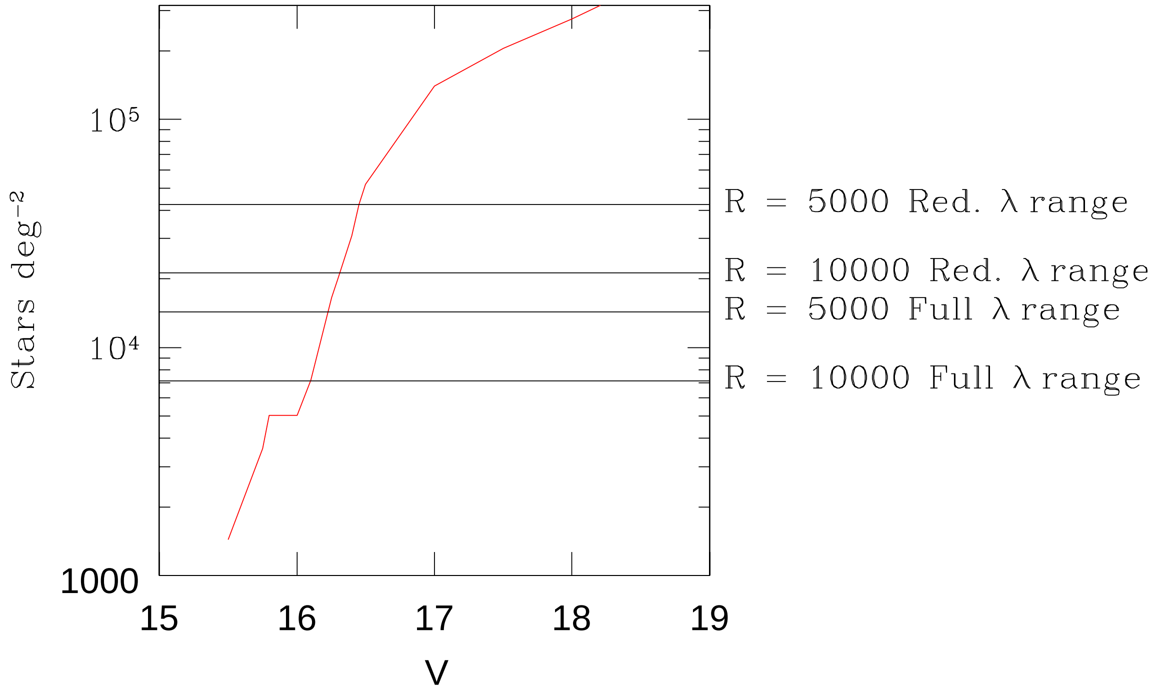


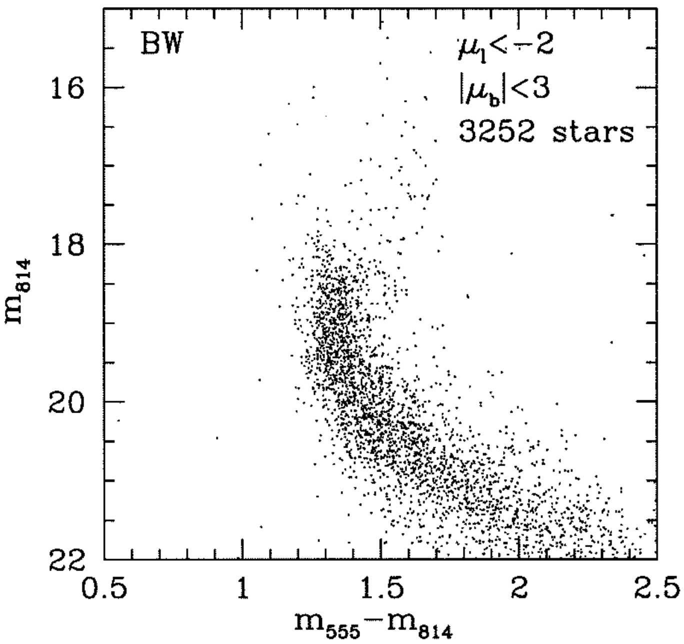
Besancon Model (data: Robin)
Disk Stars 10° < b < 20°
Stars deg⁻²
10⁴
1000
R = 10000 Red. λ range
R = 5000 Full λ range
R = 10000 Full λ range
Thin Disk
l = 0° b = 10°
l = 10° b = 15°
l = 20° b = 20°
Thick Disk
l = 0° b = 10°
l = 10° b = 15°
l = 20° b = 20°
15
16
17
18
19
V


Besancon Model (data: Robin)
Disk Stars $b < 10°$
Stars deg^{-2}
10^5
10^4
1000
R = 5000 Red. λ range
R = 10000 Red. λ range
R = 5000 Full λ range
R = 10000 Full λ range
Thin Disk
l = 0°
l = 10° b = 5°
l = 20° b = 10°
Thick Disk
l = 0° b = 10°
l = 10° b = 5°
l = 20°
15
16
17
18
19
V

HST Star Counts

Baade's Window ($l = 1°, b = -3.9°$)



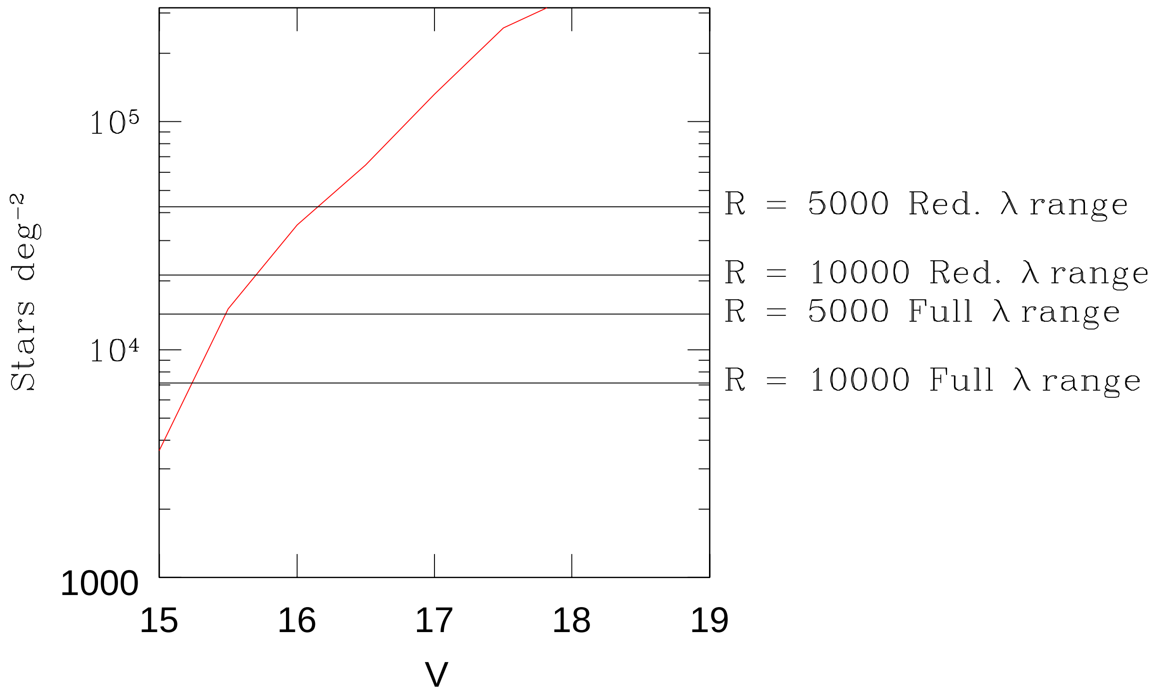


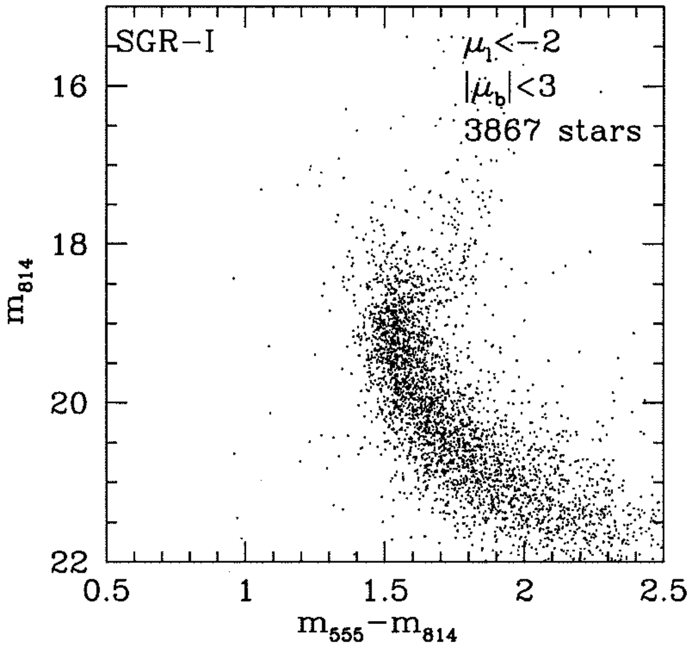
$V < 16 : 8000 \text{ deg}^{-2}$

(Kuijken & Rich 2002)

HST Star Counts

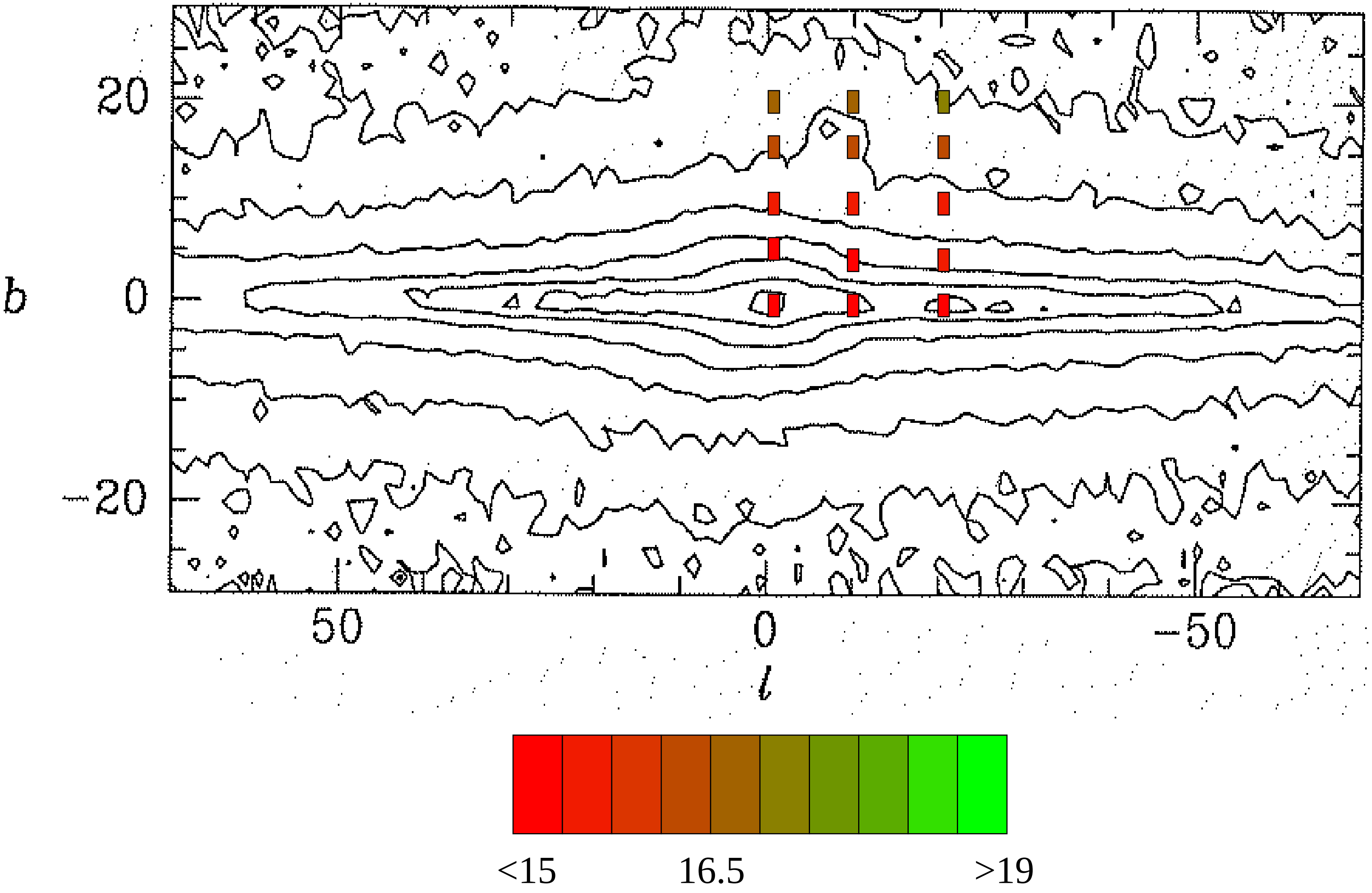
Sgr I Window ($l = 1.25°, b = -2.65°$)





$V < 16 : 10^4 \text{ deg}^{-2}$

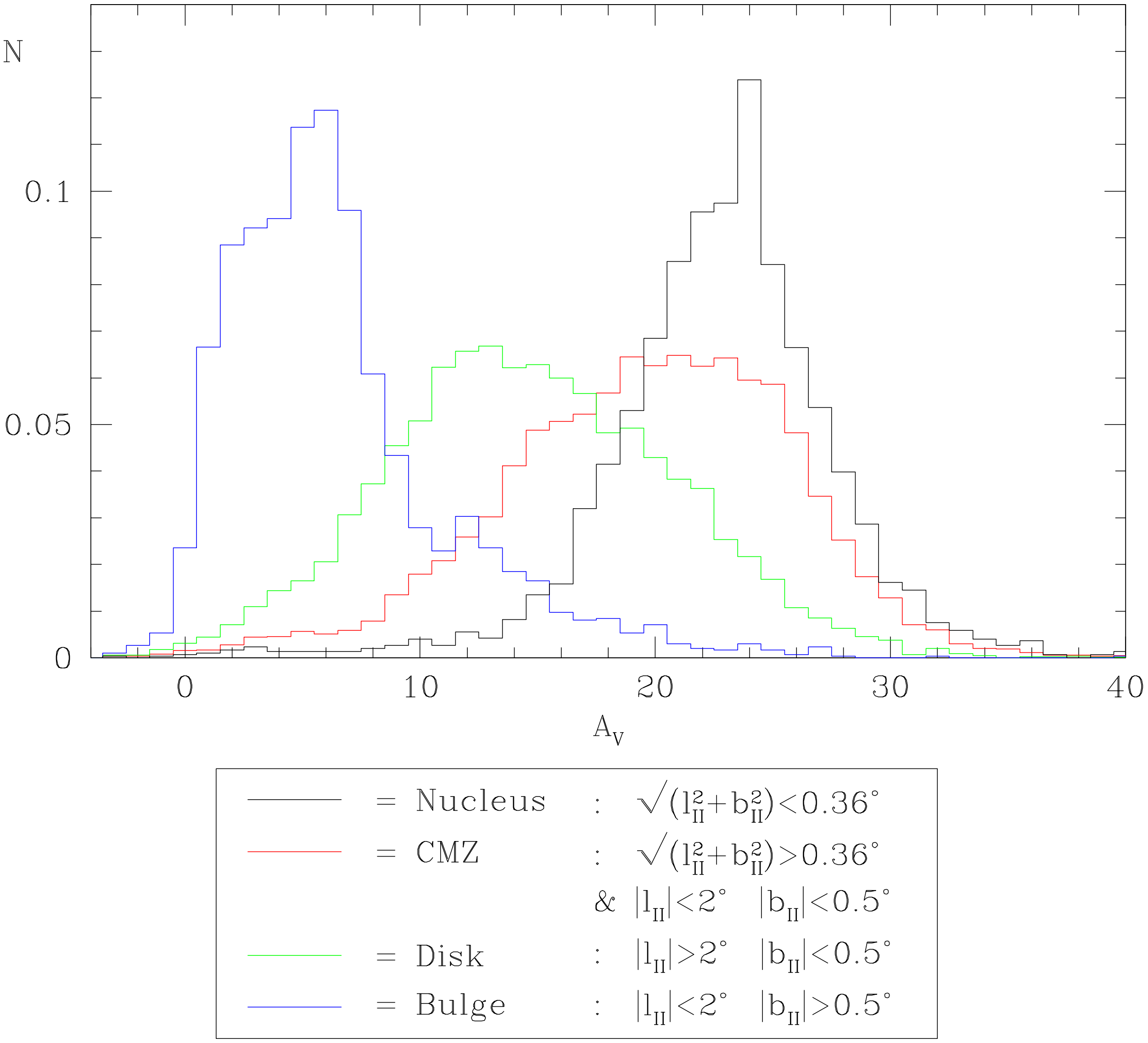
(Kuijken & Rich 2002)



20
b
0
−20
50
0
−50
l
<15
16.5
>19

Extinction Distributions

van Loon et al. (2002)



Thin Disk

- Typical tracer: gK
- Typical metallicity: [Fe/H] ~ 0.0.
- Typical extinction: $A_v = 1 - 5$
- Required magnitude limit: V = 17
  ($14 < m_V < 19$)
- b values: $b < 15^\circ$
- Typical (one dimensional) velocity dispersion:
  $10 - 40\,\mathrm{km\,s^{-1}}$
- Typical tangential velocity errors:
  $\sim 2.5\,\mathrm{km\,s^{-1}}$ at $V \sim 16$ @ 10kpc ($l = 180^\circ$)
- Required v_r accuracy: $\sim 2 - 3\,\mathrm{km\,s^{-1}}$
- Both low and high resolution options give acceptable velocity accuracy at $V = 15 - 16$ (even without tilt mechanism).
- Low resolution allows limiting magnitude $V \sim 16.5$ at sufficiently low Δv_r and $V \sim 17$ with $\Delta v_r \sim 8\,\mathrm{km\,s^{-1}}$

Thick Disk

- Typical tracer: Miras, gK
- Typical metallicity: [Fe/H] $\lesssim -0.5 \implies v_r$ accuracies shift by $\lesssim 0.5$ magnitudes.
- Typical extinction: $\mathrm{A}_v \sim 2$
- Required magnitude limit: $\mathrm{V} = 17$ $(15 < \mathrm{m_V} < 19)$
- b values: $b < 30°$
- Typical (one dimensional) velocity dispersion: $30 - 50\mathrm{km\,s^{-1}}$
- Typical tangential velocity errors:
  $\sim 11.5\mathrm{km\,s^{-1}}$ at $V \sim 17$ @ 8kpc ($l = 0°$)
  $\sim 18\mathrm{km\,s^{-1}}$ at $V \sim 17$ @ 20kpc ($l = 180°$)
- Required v_r accuracy: $10 - 20\mathrm{km\,s^{-1}}$
- Both low and high resolution options give acceptable velocity accuracy (even without tilt mechanism) and limiting magnitude (except for low b)

Tracing Spiral Structure

- Typical tracer: Cepheids
- Typical metallicity: $[Fe/H] \gtrsim -0.5$
- Typical extinction: $A_v = 3 - 7$
- Required magnitude limit: $V = 17$
  $(16 < m_V < 18)$
- b values: $b < 10^\circ$
- Typical (one dimensional) velocity dispersion:
  $\sim 7\mathrm{km\,s^{-1}}$
- Typical tangential velocity errors:
  $\sim 3.5\mathrm{km\,s^{-1}}$ at $V \sim 16$ 10kpc
- Required v_r accuracy: $\sim 3\mathrm{km\,s^{-1}}$
- Both low and high resolution options give acceptable velocity accuracy and limiting magnitude (possibly except for high resolution at low b)

Halo stellar streams (Helmi 2002)

- Number of streams depends on number of accretion events, and stellar masses of accreted objects: probably 300-500 individual streams in the solar neighbourhood (Helmi & White 2000).

- Typical tracer: K giant, $\mathrm{M_V} = 1$

- Typical metallicity: [Fe/H] $\sim -1.6 \implies v_r$ accuracies shift by ~ 1 mag.

- Required magnitude limit: V = 17.5 (though V= 18 strongly preferred)

- Allowed b values: $R = 5000 : b > 15°$
  $R = 10000 : b > 45°$

- Distance uncertainties dominate errors and lead to tangential velocity errors of $\sim 20 \mathrm{km\,s^{-1}}$ at $V \sim 17.5$

- Required velocity accuracy:
  $15 - 20 \mathrm{km\,s^{-1}}$ (< 5 $\mathrm{km\,s^{-1}}$ needed to observe internal structure of individual streams)

- Low resolution option allows deeper limit (V= 17.5 $\Longrightarrow$ factor 2 increase in volume sampled) and greater coverage in b than high resolution.

- V= 18 limit achievable if tilt mechanism included.

The dark halo

- BHB stars ($M_v \sim 0.6$) will be observable out to ~ 25kpc ($m_v \sim 17.5$) with distances beyond 5kpc obtained using GAIA-calibrated absolute magnitude-colour relation

- Tip RGB stars ($M_v \sim -1.0$) will be observable out to ~ 50 kpc – expect sample of 10^2 to 10^3.

Outstanding issues

- Inclusion of detailed extinction map in star count models.
- Investigate whether transition regions from high to low extinction at edges of e.g. Baade's window will be observable by RVS.
- Investigate implications for study of **moving groups**, **star clusters**

Conclusions

- Low resolution ($R \sim 5000$) strongly preferred by dynamics constraints.
- Larger Δv_r tolerable in return for larger data sets and better coverage of bulge fields.
- High resolution rules out any observations within $10°$ of the Galactic Centre (i.e. no observations in the Bulge).
- Low resolution sufficient to measure perspective acceleration effects at $V \sim 15$.
- Further studies of the tilt mechanism and compression algorithms as these impact directly on the amount of dynamical information obtained at low b.
- Higher resolution spectra for a sub-sample of stars could be obtained by ground-based follow-up?