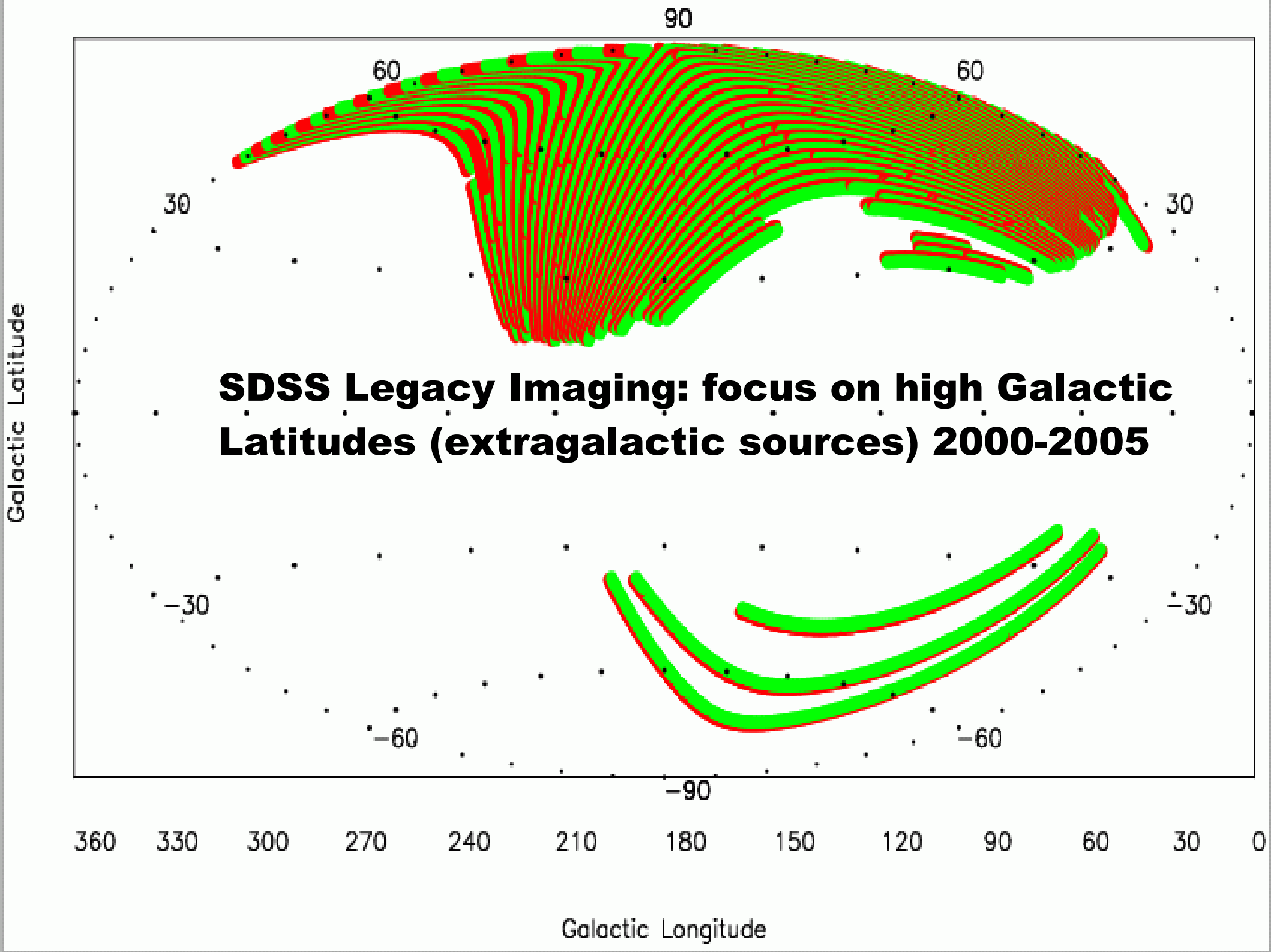
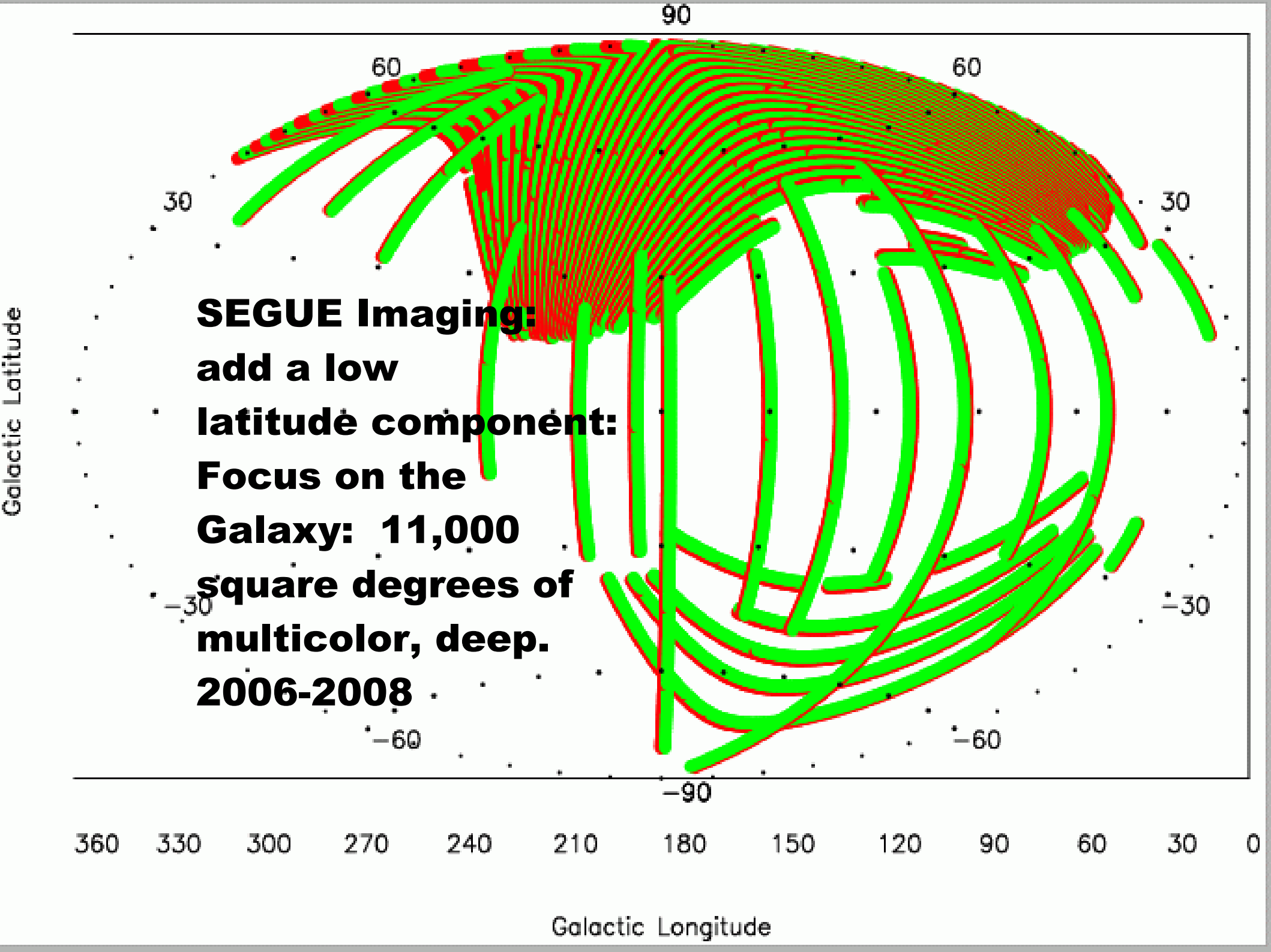
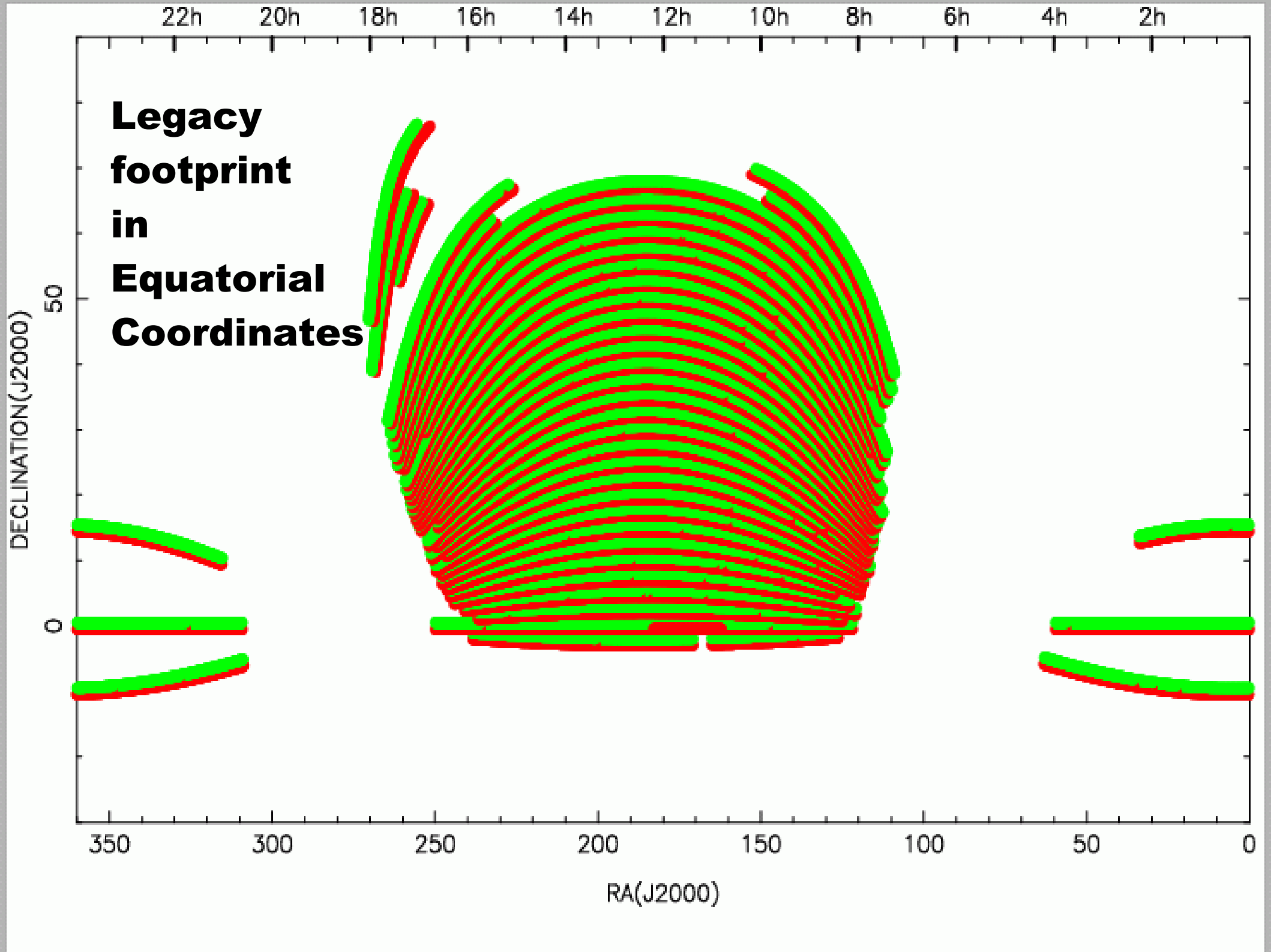
Sloan Extension for Galactic Understanding and Exploration

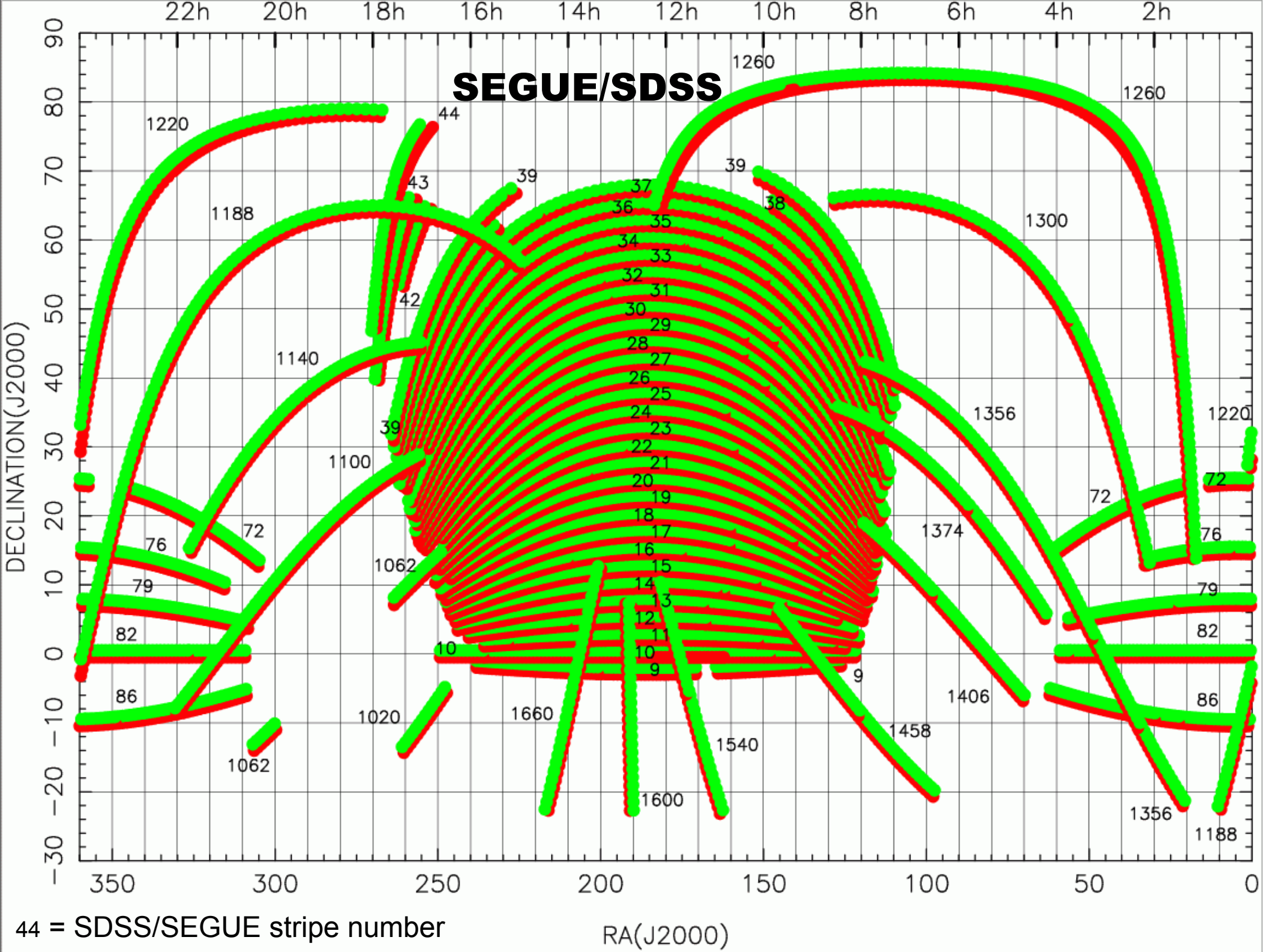
Brian Yanny
Fermilab
Oct 12, 2009

"(another of) America's Best Idea(s)"

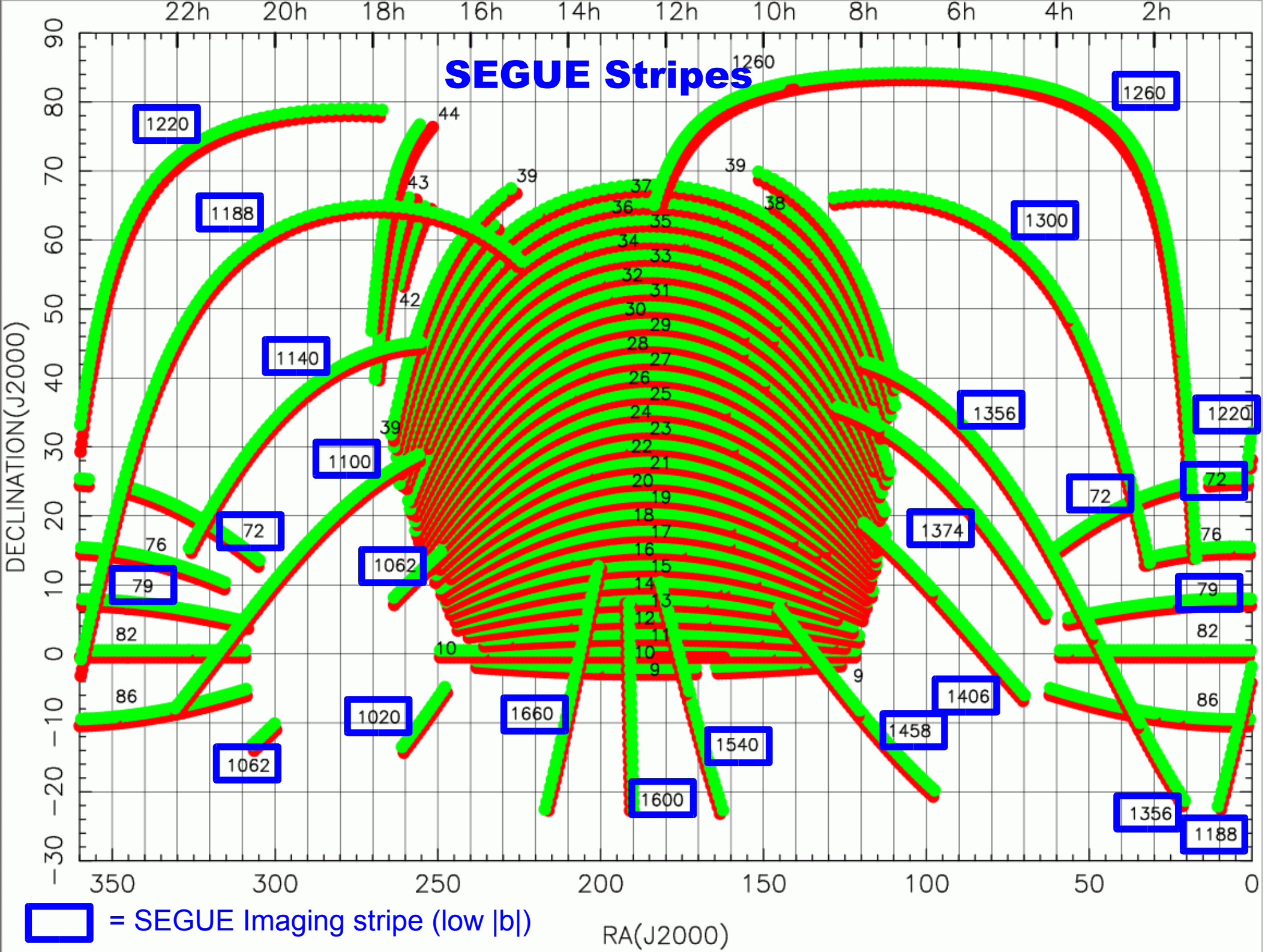

SDSS Legacy Imaging: focus on high Galactic Latitudes (extragalactic sources) 2000-2005
90
60
60
30
30
−30
−30
−60
−60
−90
360
330
300
270
240
210
180
150
120
90
60
30
0
Galactic Latitude
Galactic Longitude

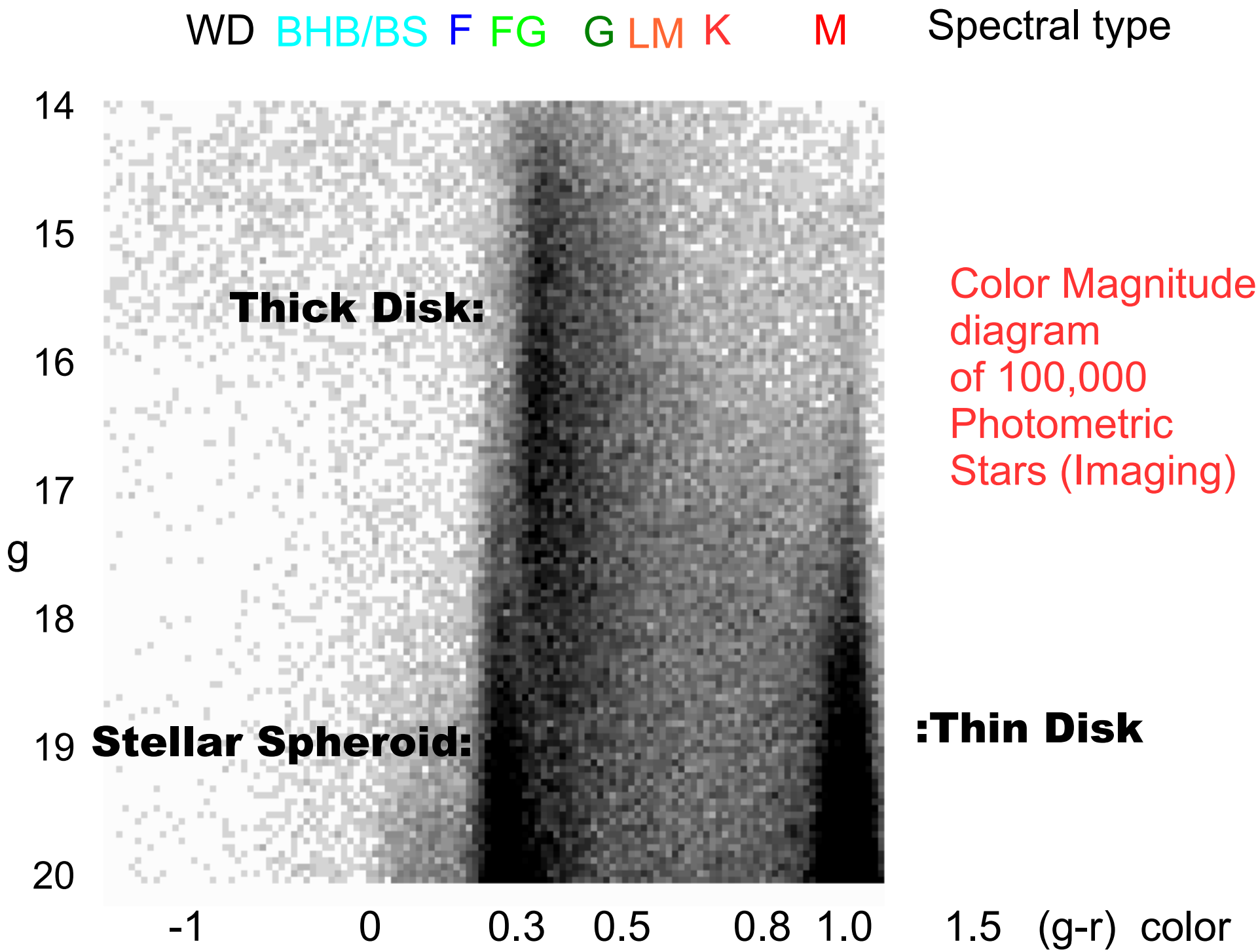

SEGUE Imaging: add a low latitude component: Focus on the Galaxy: 11,000 square degrees of multicolor, deep. 2006-2008
90
60
60
30
30
−30
−30
−60
−60
−90
360
330
300
270
240
210
180
150
120
90
60
30
0
Galactic Latitude
Galactic Longitude

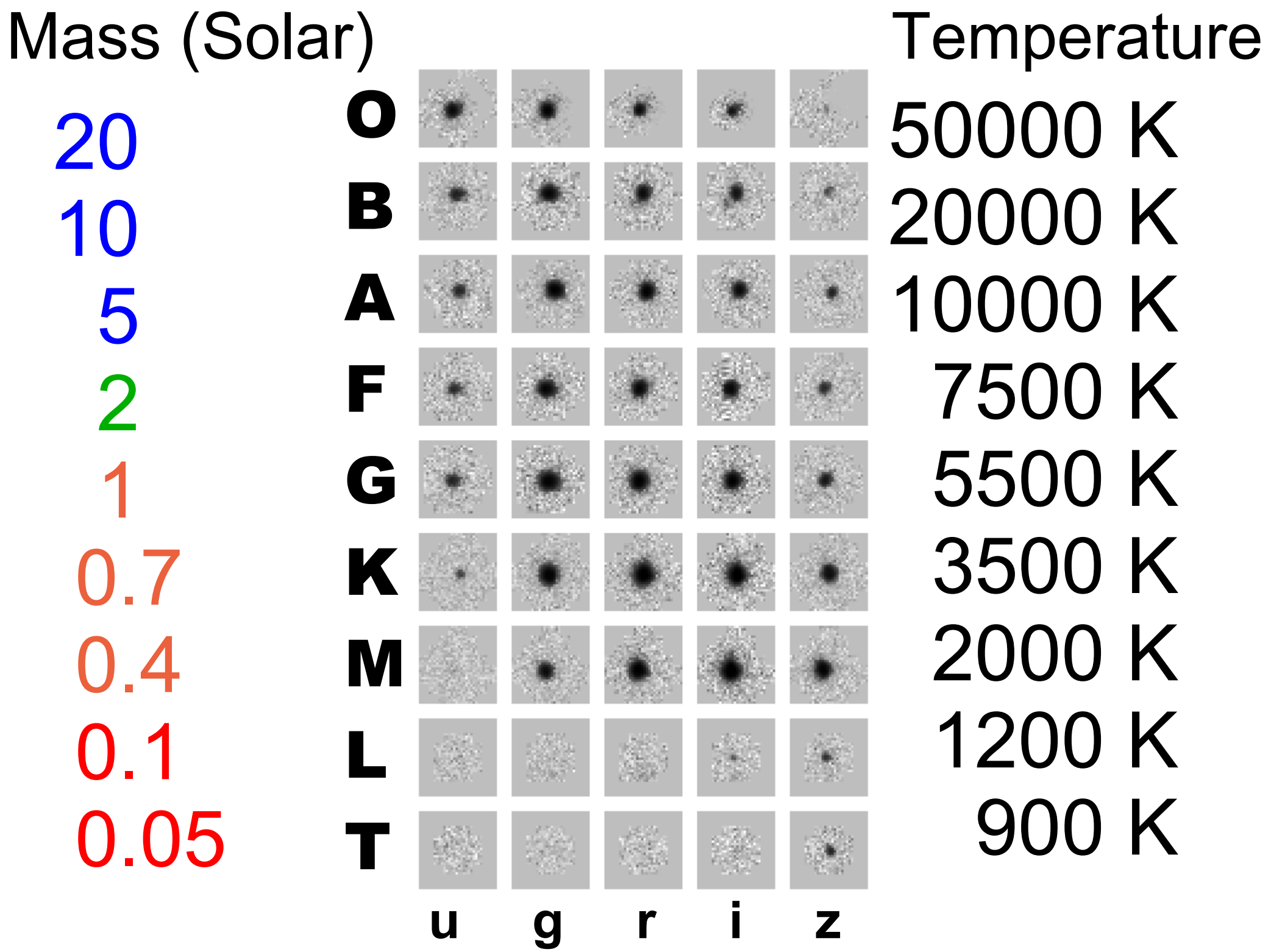

Legacy footprint in Equatorial Coordinates
22h
20h
18h
16h
14h
12h
10h
8h
6h
4h
2h
50
0
DECLINATION(J2000)
350
300
250
200
150
100
50
0
RA(J2000)

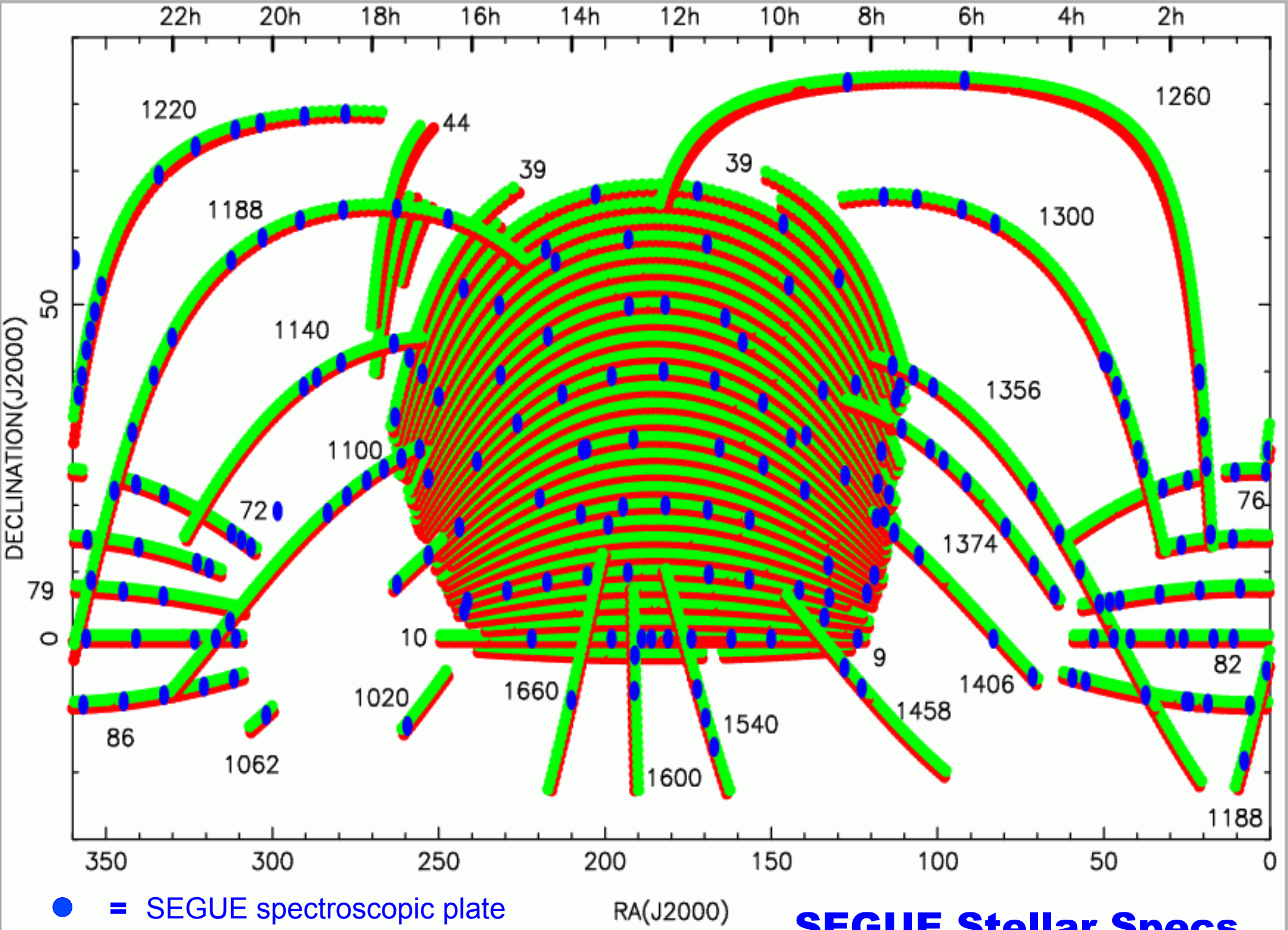


44 = SDSS/SEGUE stripe number


SEGUE Stripes
22h
20h
18h
16h
14h
12h
10h
8h
6h
4h
2h
DECLINATION(J2000)
RA(J2000)
= SEGUE Imaging stripe (low |b|)
1220
1188
1140
1100
1062
1020
1660
1600
1540
1458
1406
1374
1356
1300
1260
72
76
79
82
86
44
43
42
39
38
37
36
35
34
33
32
31
30
29
28
27
26
25
24
23
22
21
20
19
18
17
16
15
14
13
12
11
10
9

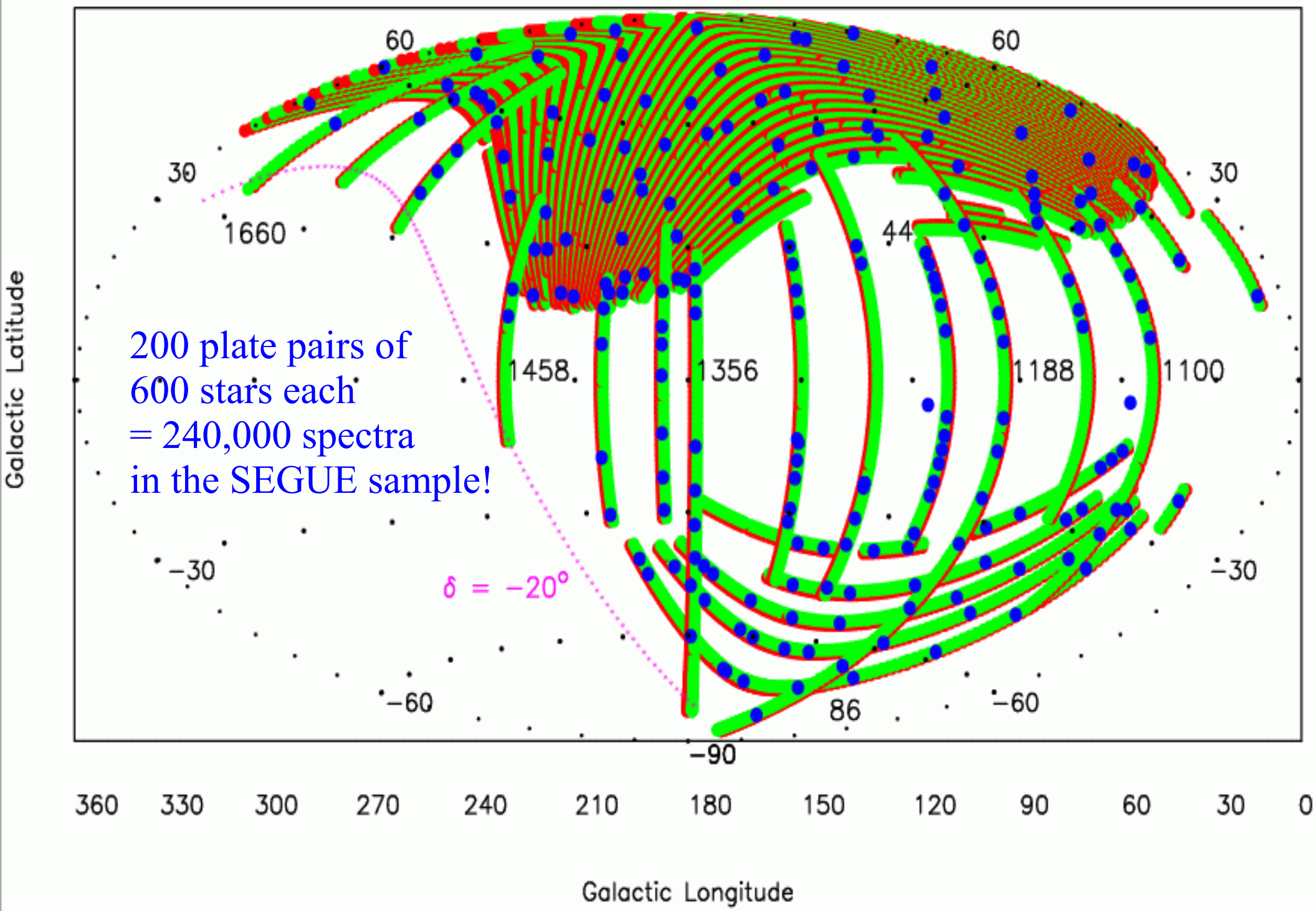

WD BHB/BS F FG G LM K M
Spectral type
14
15
16
17
g
18
19
20
Thick Disk:
Stellar Spheroid:
:Thin Disk
-1
0
0.3
0.5
0.8
1.0
1.5
(g-r) color
Color Magnitude diagram of 100,000 Photometric Stars (Imaging)

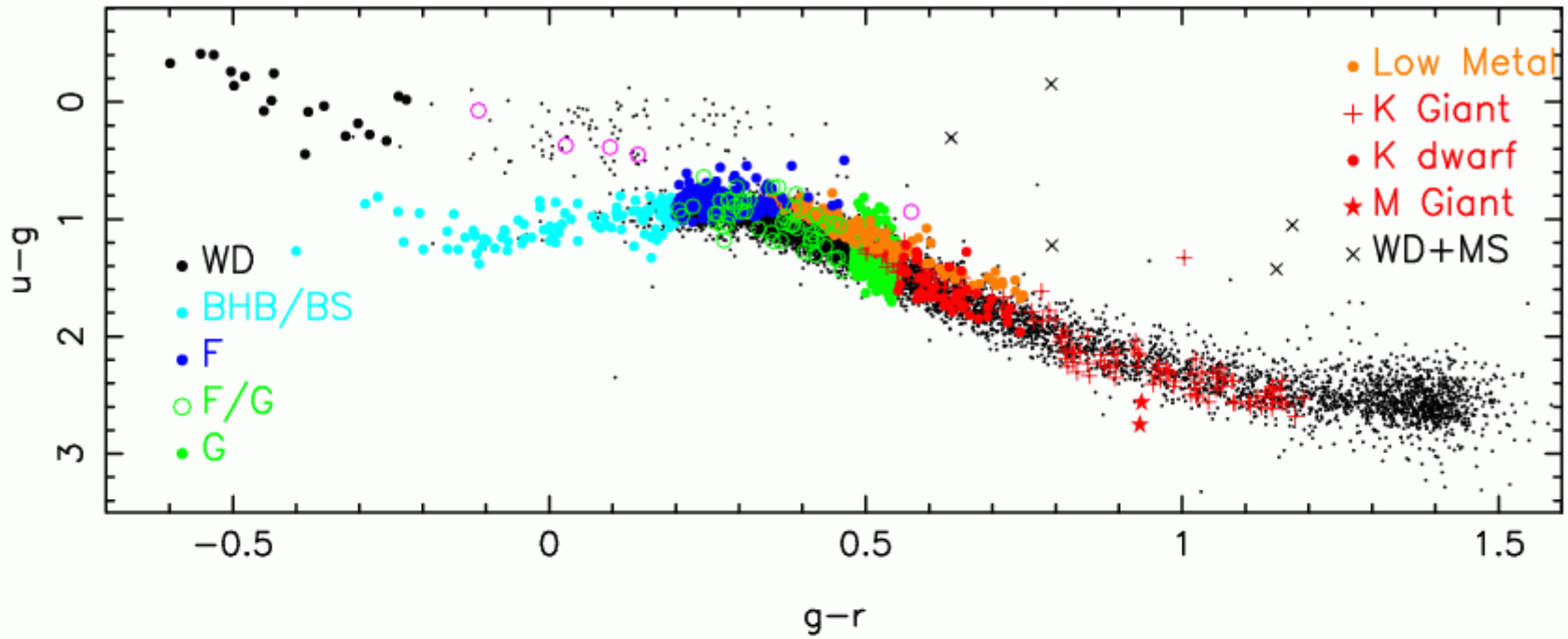

Mass (Solar)
Temperature
20
10
5
2
1
0.7
0.4
0.1
0.05
O
B
A
F
G
K
M
L
T
50000 K
20000 K
10000 K
7500 K
5500 K
3500 K
2000 K
1200 K
900 K
u
g
r
i
z



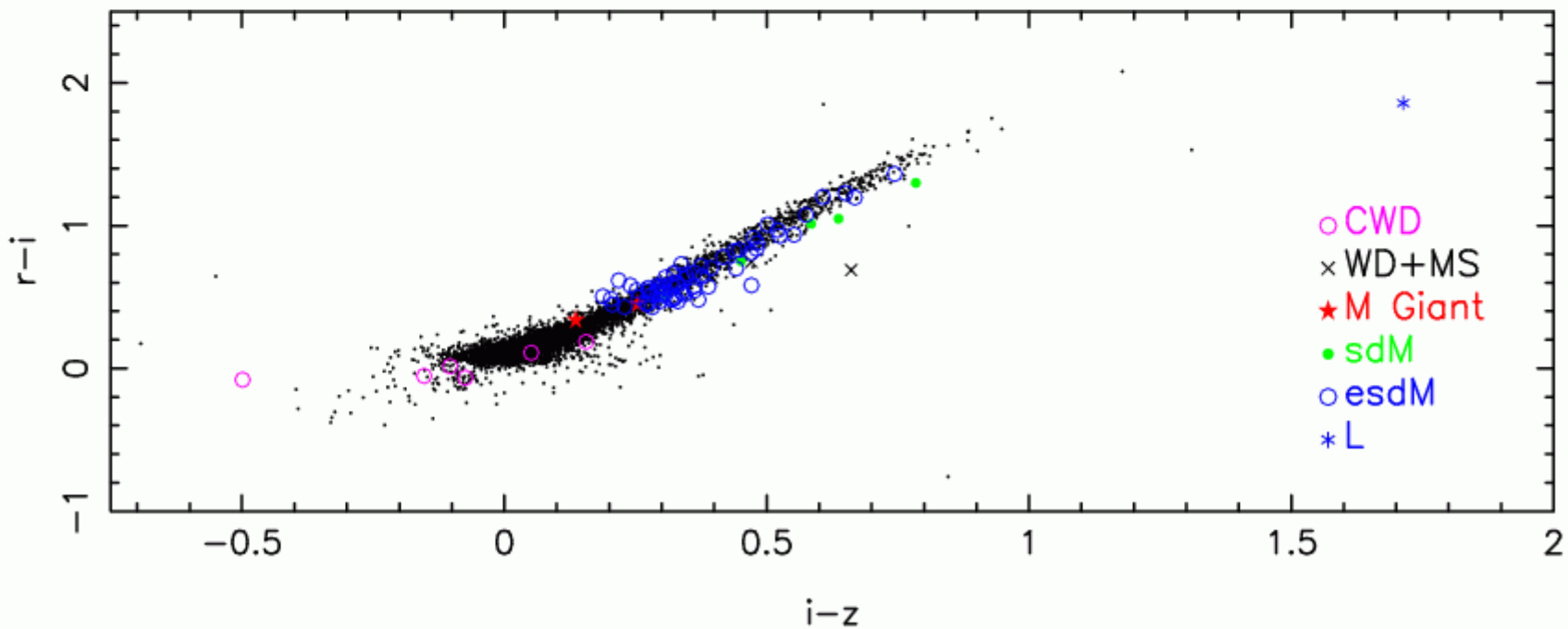
SEGUE Stellar Specs

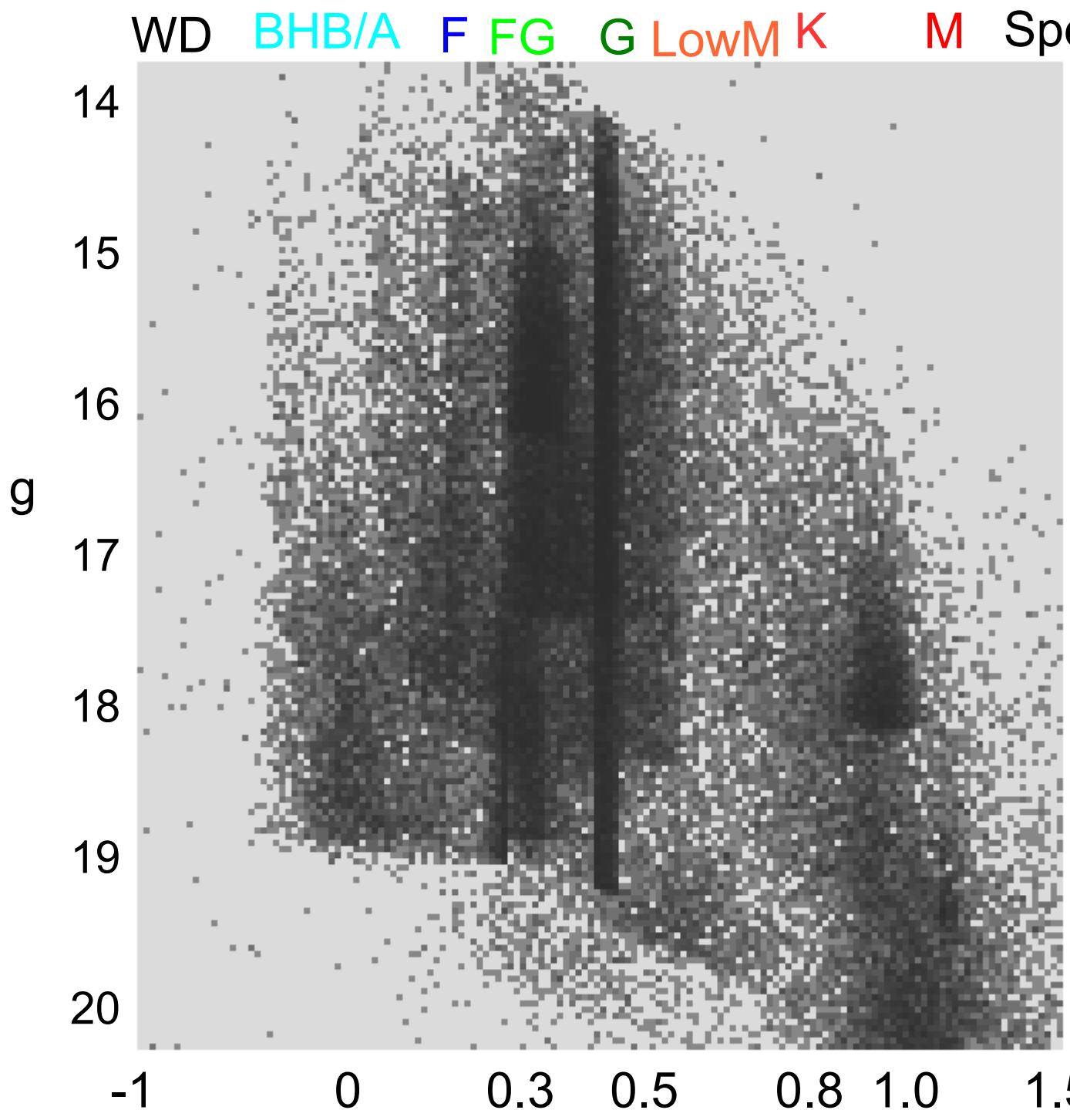
SEGUE Spectroscopic Coverage





SEGUE Target Selection (color,color)



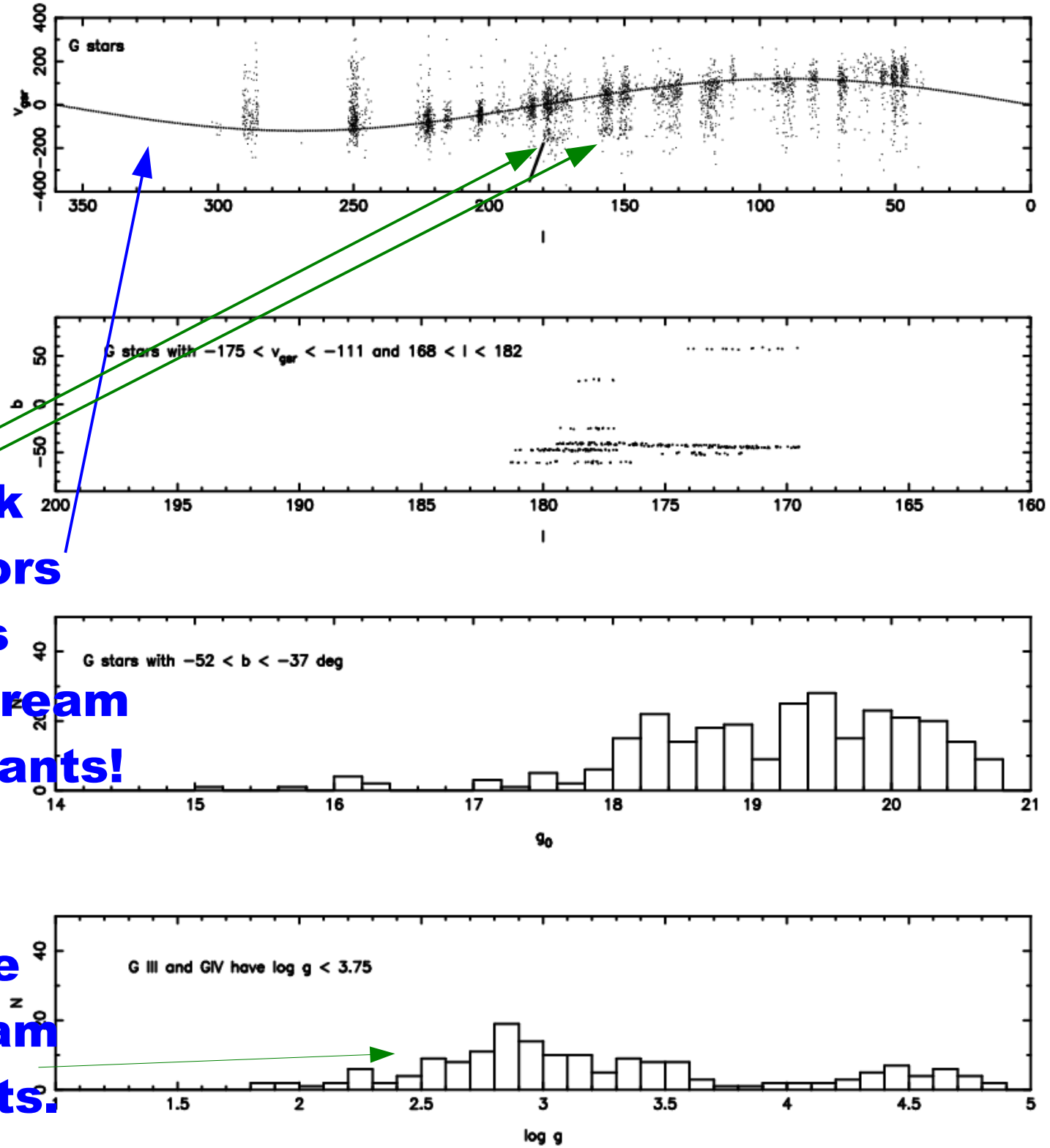


Color-Mag. of 100,000 Spectra

SEGUE: Spectroscopic Target Selection is NOT uniform. Specific Spectral Types (BHB, F,G) are heavily favored.

SEGUE 'G' star sample: Outliers from Disk co-rotators suggests a halo stream of sub-giants!

In fact these are Sgr stream sub-giants.

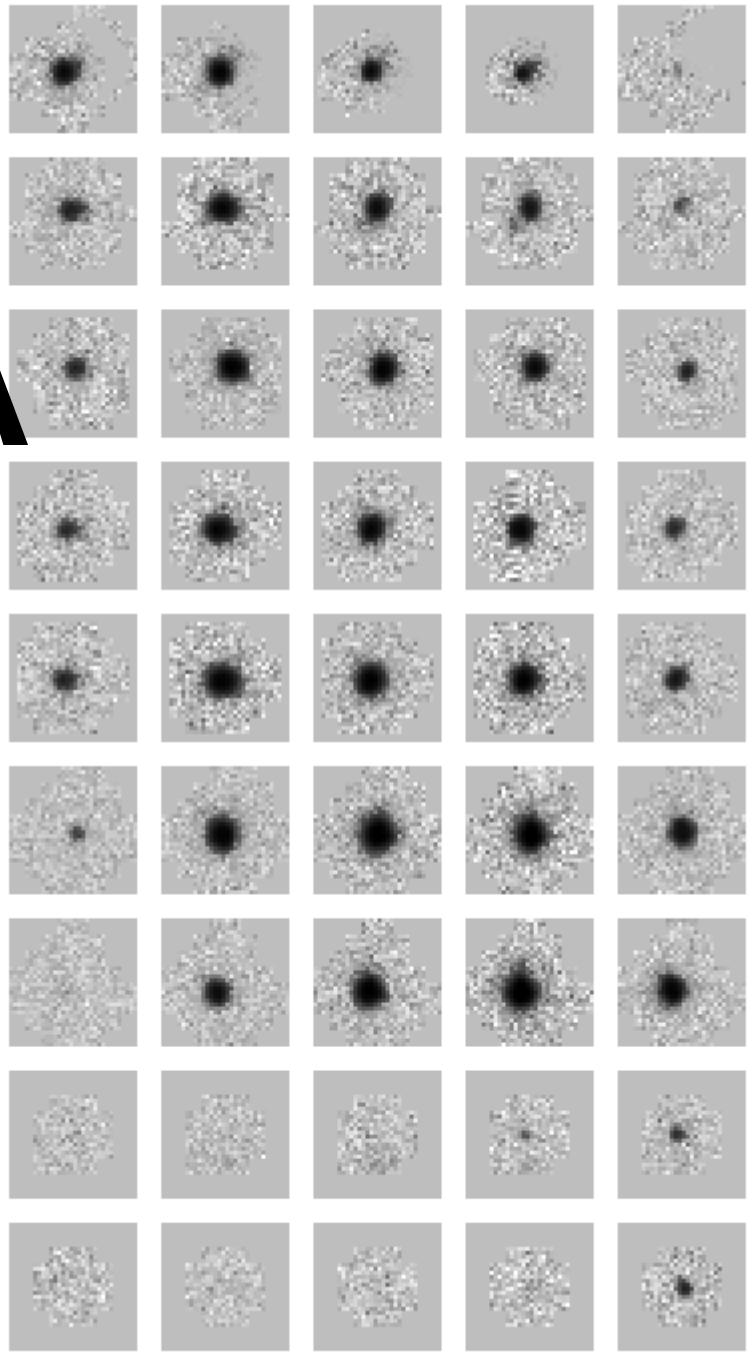


Sample use of the SEGUE spectra:

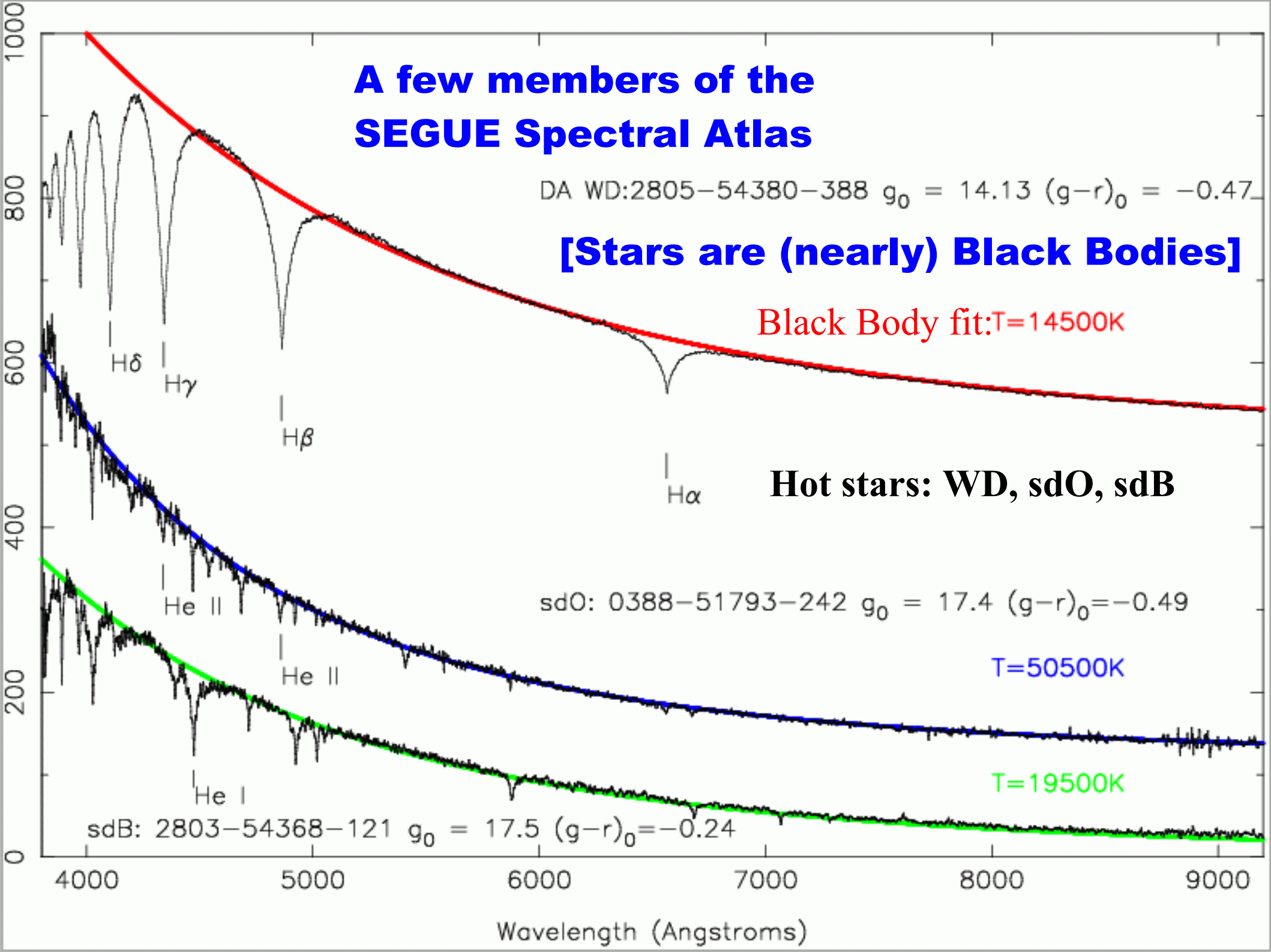
Look for structure in the halo moving at speeds different than the disk.

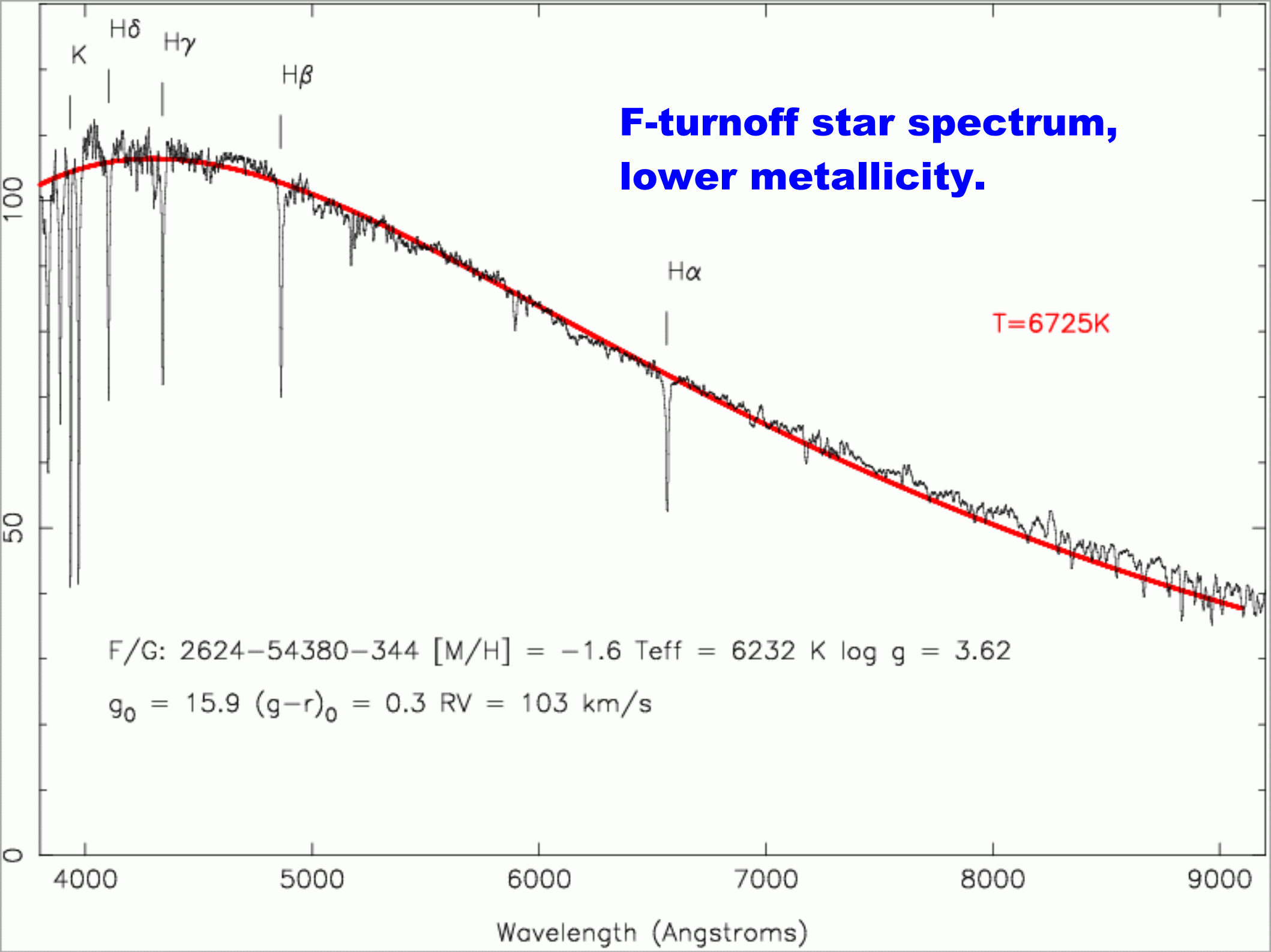
What spectra go with these?

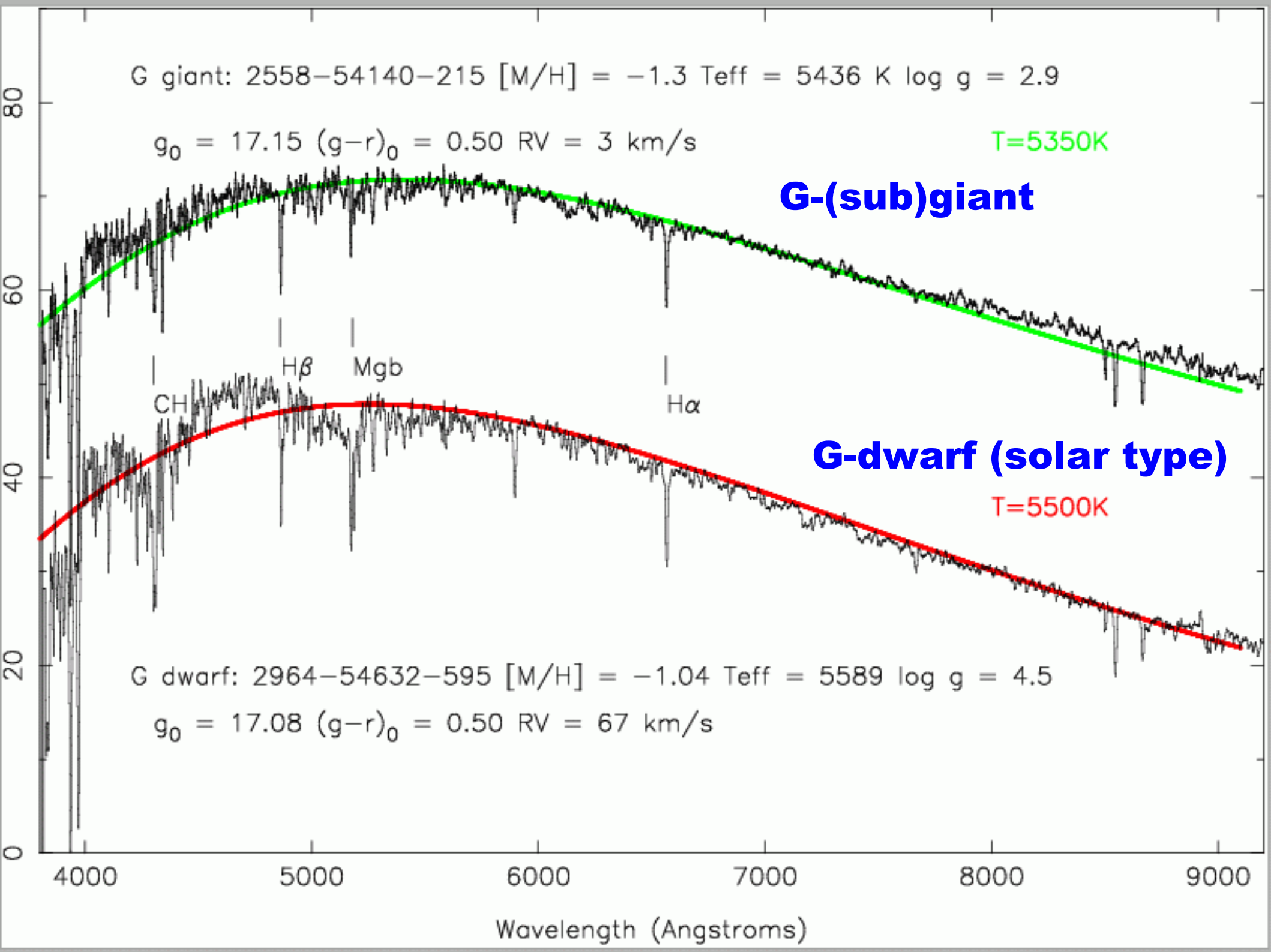
Mass (Solar)	Type	Temperature
	sdO	50000 K
	sdB	20000 K
	BHB/A	10000 K
2	F	7500 K
1	G	5500 K
0.7	K	3500 K
0.4	M	2000 K
0.1	L	1200 K
0.05	T	900 K

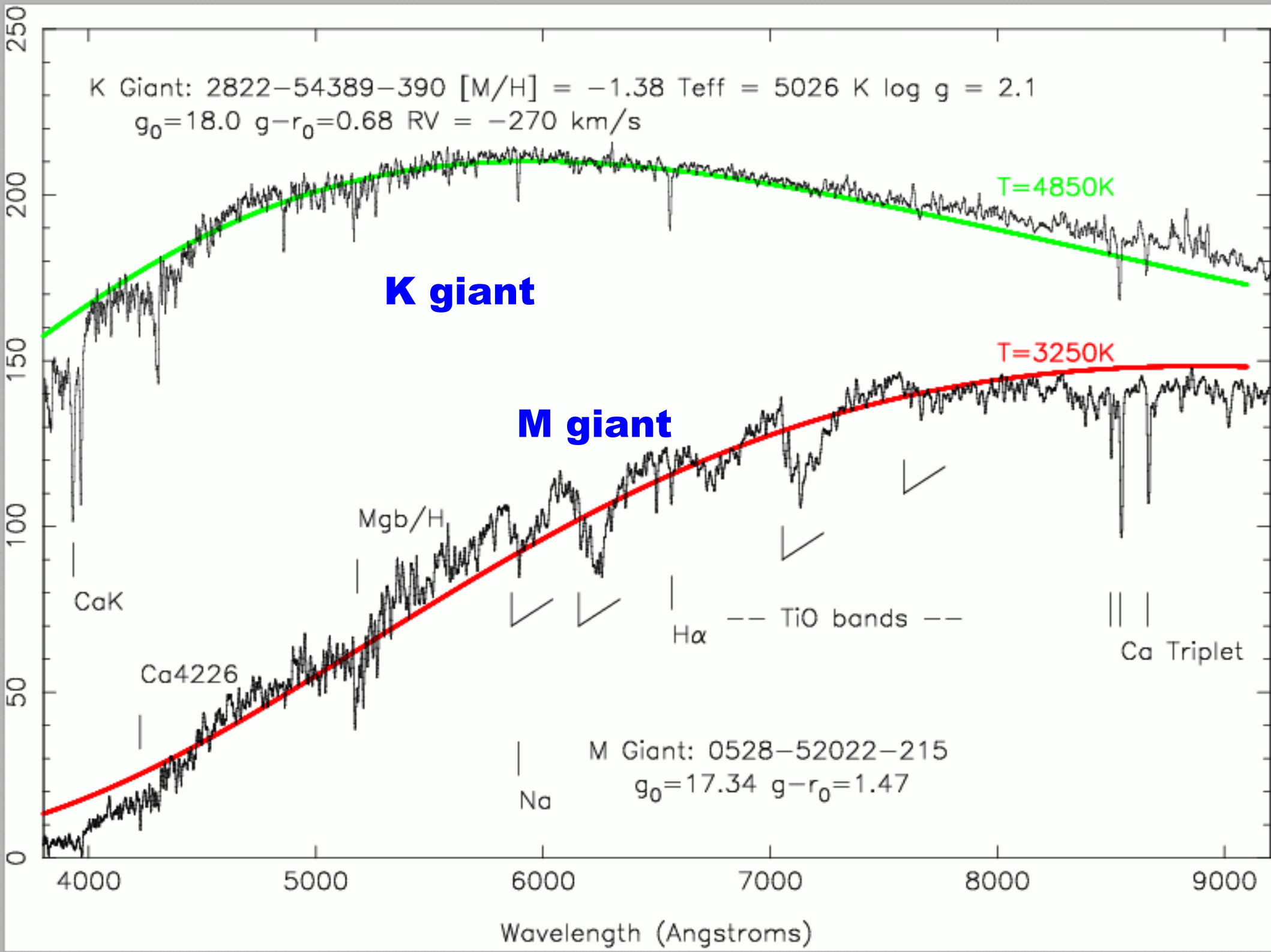


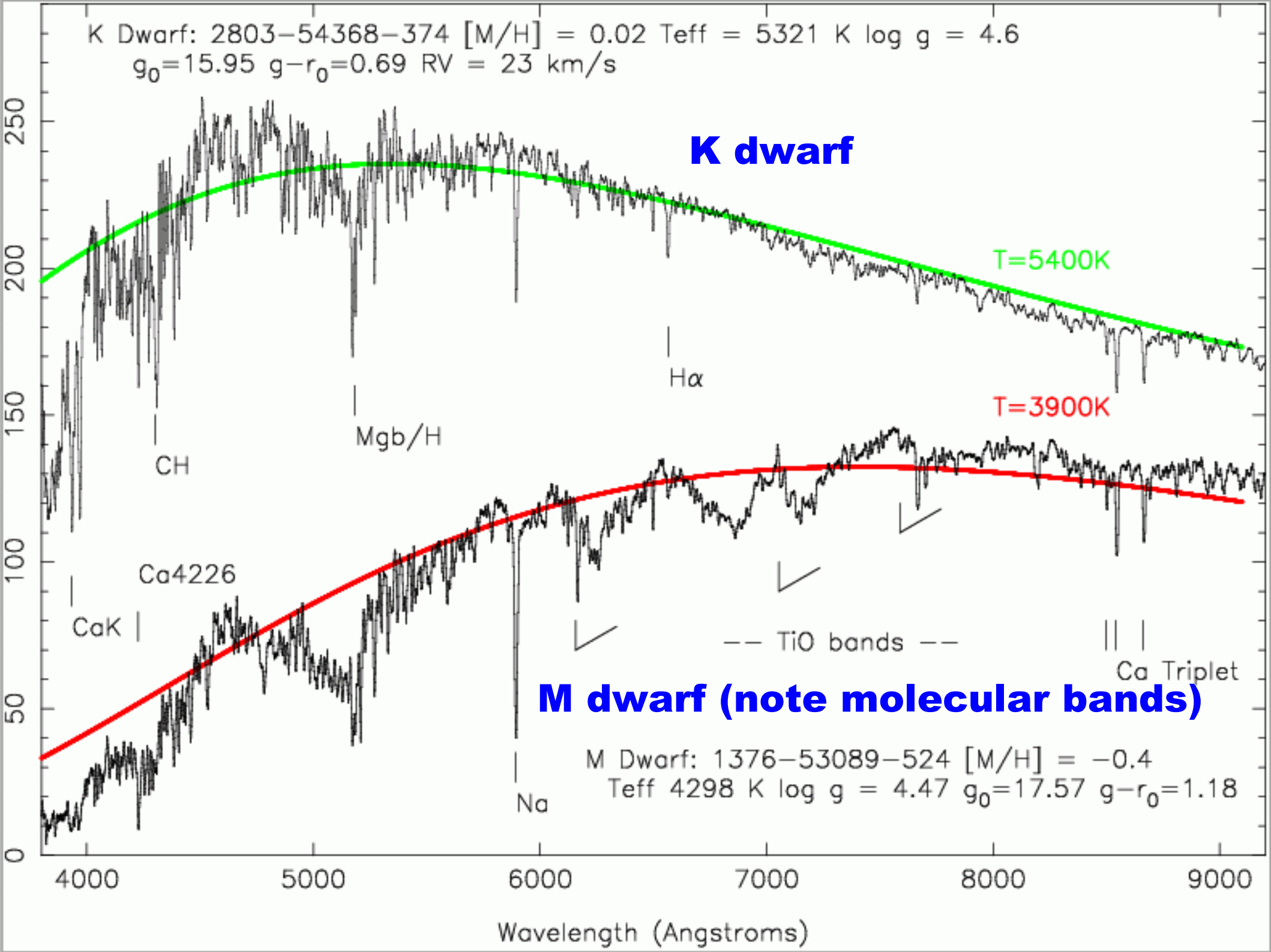
u g r i z

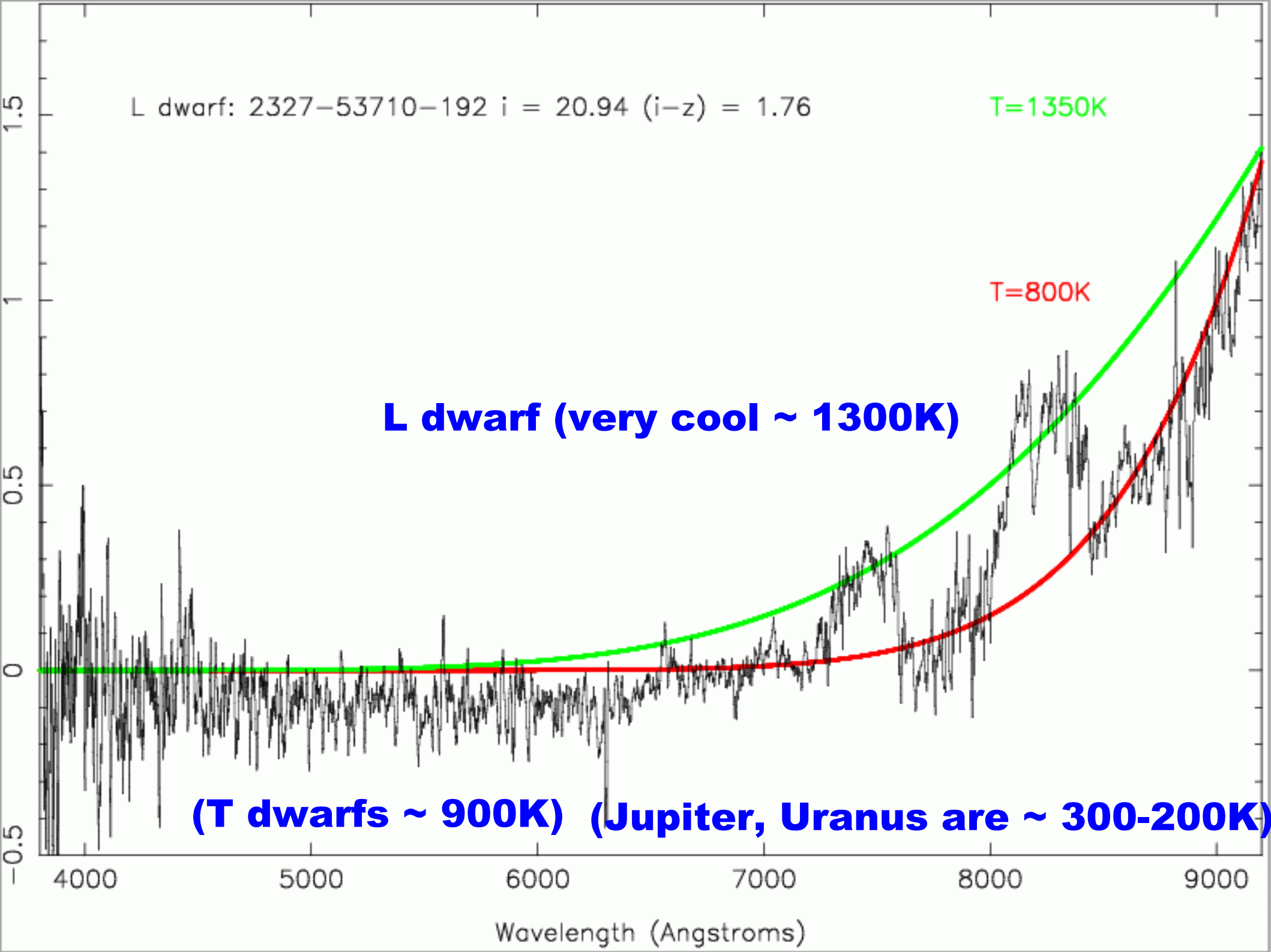

A few members of the
SEGUE Spectral Atlas
[Stars are (nearly) Black Bodies]
DA WD:2805−54380−388 g_0 = 14.13 $(g-r)_0$ = −0.47
Black Body fit:T=14500K
Hδ
Hγ
Hβ
Hα
Hot stars: WD, sdO, sdB
He II
He II
sdO: 0388−51793−242 g_0 = 17.4 $(g-r)_0$=−0.49
T=50500K
He I
T=19500K
sdB: 2803−54368−121 g_0 = 17.5 $(g-r)_0$=−0.24
0
200
400
600
800
1000
4000
5000
6000
7000
8000
9000
Wavelength (Angstroms)

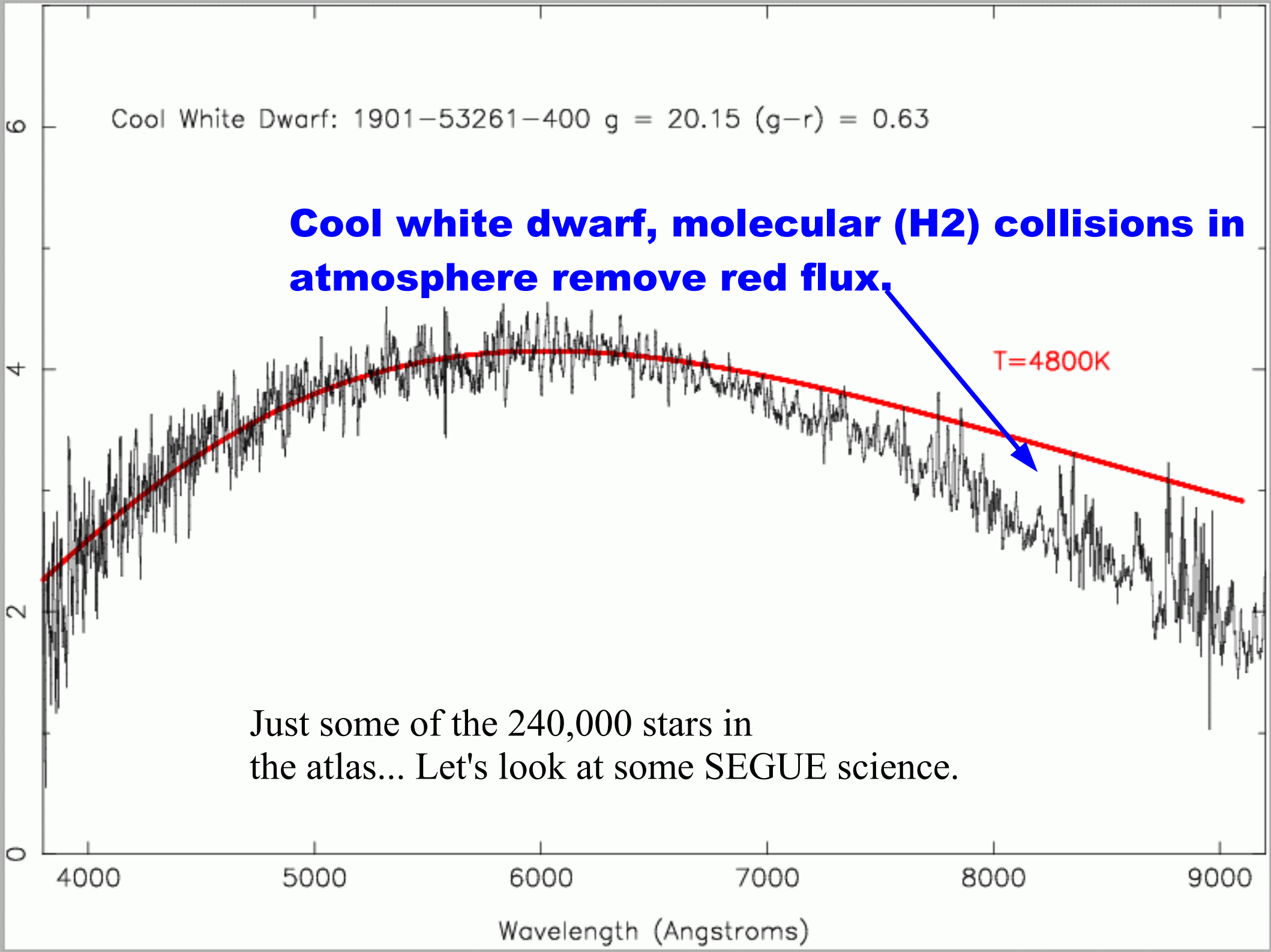

F-turnoff star spectrum,
lower metallicity.
K
Hδ
Hγ
Hβ
Hα
T=6725K
F/G: 2624−54380−344 [M/H] = −1.6 Teff = 6232 K log g = 3.62
g_0 = 15.9 $(g-r)_0$ = 0.3 RV = 103 km/s
0
50
100
4000
5000
6000
7000
8000
9000
Wavelength (Angstroms)


G giant: 2558−54140−215 [M/H] = −1.3 Teff = 5436 K log g = 2.9
g_0 = 17.15 $(g-r)_0$ = 0.50 RV = 3 km/s
T=5350K
G-(sub)giant
CH
Hβ
Mgb
Hα
G-dwarf (solar type)
T=5500K
G dwarf: 2964−54632−595 [M/H] = −1.04 Teff = 5589 log g = 4.5
g_0 = 17.08 $(g-r)_0$ = 0.50 RV = 67 km/s
0
20
40
60
80
4000
5000
6000
7000
8000
9000
Wavelength (Angstroms)

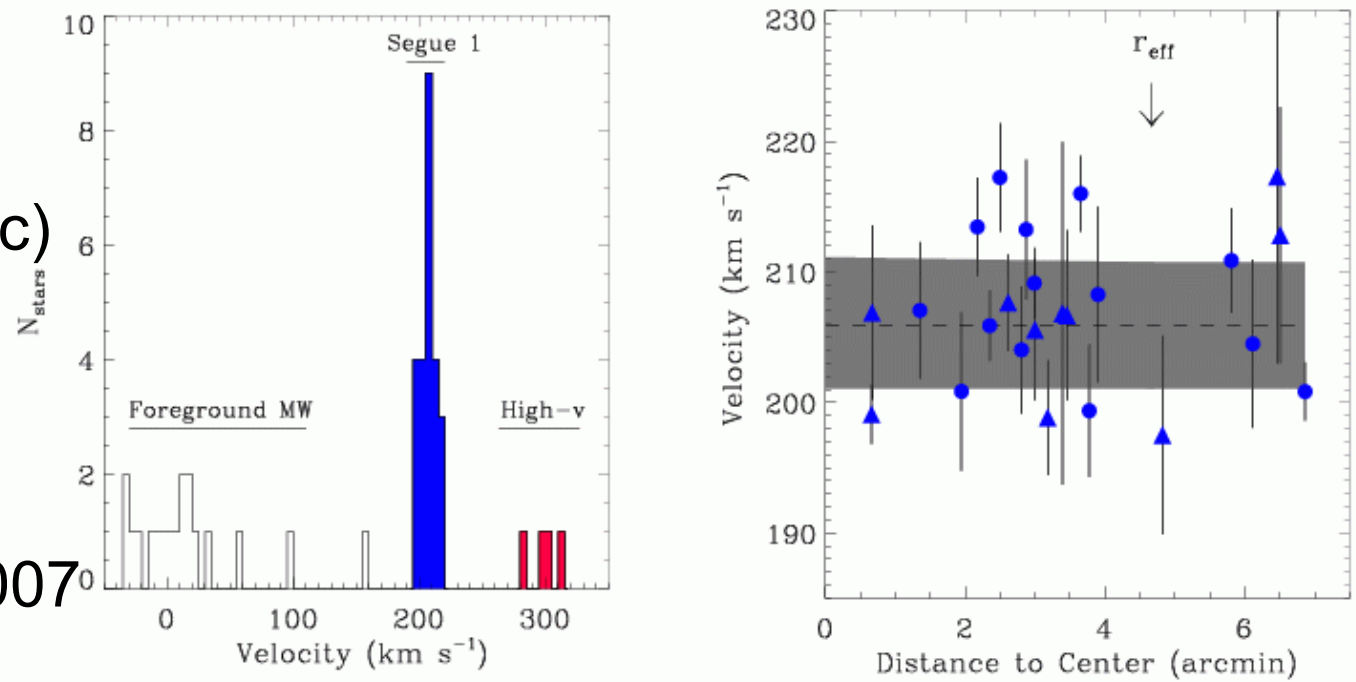

K Giant: 2822−54389−390 [M/H] = −1.38 Teff = 5026 K log g = 2.1
g_0=18.0 $g-r_0$=0.68 RV = −270 km/s
T=4850K
K giant
T=3250K
M giant
Mgb/H
CaK
Ca4226
Hα
-- TiO bands --
Ca Triplet
Na
M Giant: 0528−52022−215
g_0=17.34 $g-r_0$=1.47
0
50
100
150
200
250
4000
5000
6000
7000
8000
9000
Wavelength (Angstroms)


K Dwarf: 2803−54368−374 [M/H] = 0.02 Teff = 5321 K log g = 4.6
g0=15.95 g−r0=0.69 RV = 23 km/s
K dwarf
T=5400K
Hα
T=3900K
Mgb/H
CH
Ca4226
CaK
-- TiO bands --
Ca Triplet
M dwarf (note molecular bands)
M Dwarf: 1376−53089−524 [M/H] = −0.4
Teff 4298 K log g = 4.47 g0=17.57 g−r0=1.18
Na
0
50
100
150
200
250
4000
5000
6000
7000
8000
9000
Wavelength (Angstroms)


L dwarf: 2327−53710−192 i = 20.94 (i−z) = 1.76
T=1350K
T=800K
L dwarf (very cool ~ 1300K)
(T dwarfs ~ 900K) (Jupiter, Uranus are ~ 300-200K)
1.5
1
0.5
0
−0.5
4000
5000
6000
7000
8000
9000
Wavelength (Angstroms)


Cool White Dwarf: 1901−53261−400 g = 20.15 (g−r) = 0.63
Cool white dwarf, molecular (H2) collisions in atmosphere remove red flux.
T=4800K
Just some of the 240,000 stars in the atlas... Let's look at some SEGUE science.
0
2
4
6
4000
5000
6000
7000
8000
9000
Wavelength (Angstroms)

SEGUE-1,
a nearby (d=25 kpc)
Dwarf Galaxy,
discovered
in SDSS/SEGUE
data by
Belokurov et al. 2007

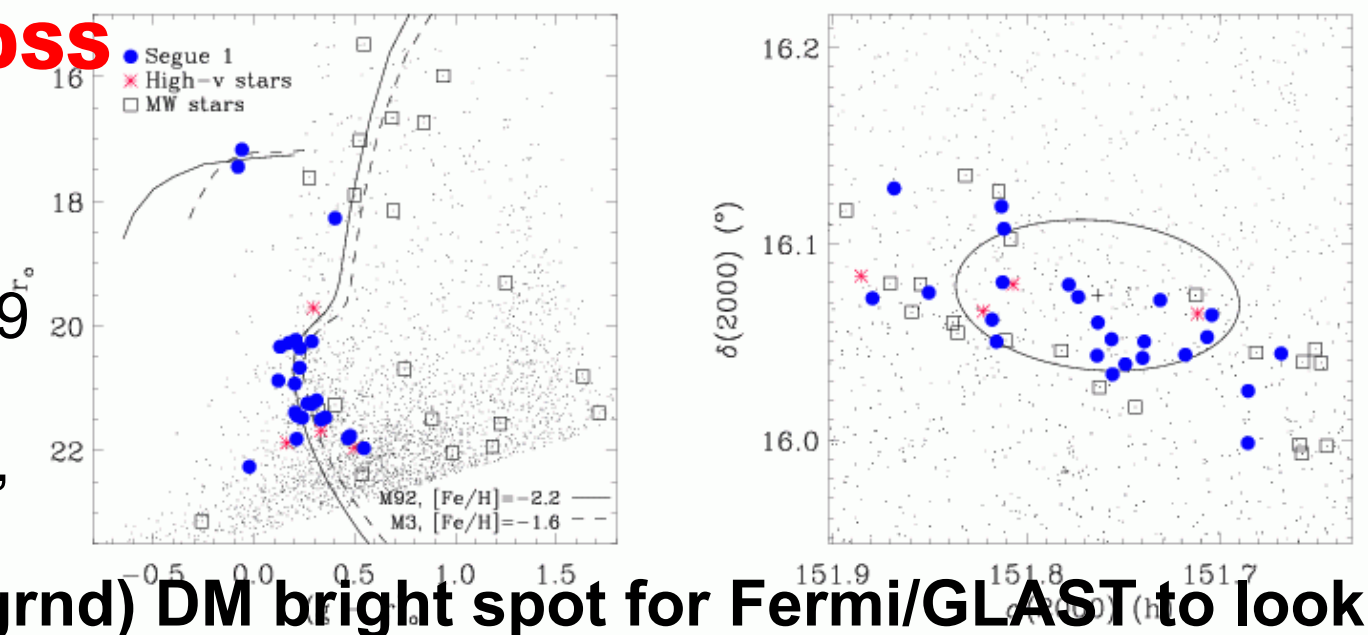


1.

FIG. 1.— *Left:* Color-magnitude diagram of all stars (small black points) within 30′ of the center of Segue 1 from SDSS DR 6 g- and r-band photometry. The larger symbols indicate stars with measured Keck/DEIMOS velocities: solid blue circles fulfill our requirements for membership in Segue 1, red asterisks are higher velocity stars and open squares are foreground Milky Way stars. Two fiducial isochrone are shown shifted to the distance of Segue 1: M92 ([Fe/H] =−2.3, solid line) and M3 ([Fe/H]=−1.6, dashed line). *Right:* Spatial distribution of stars near Segue 1. The solid ellipse is the half-light radius of Segue 1 as measured by Martin et al. (2008).

Sample Science from SEGUE/SDSS

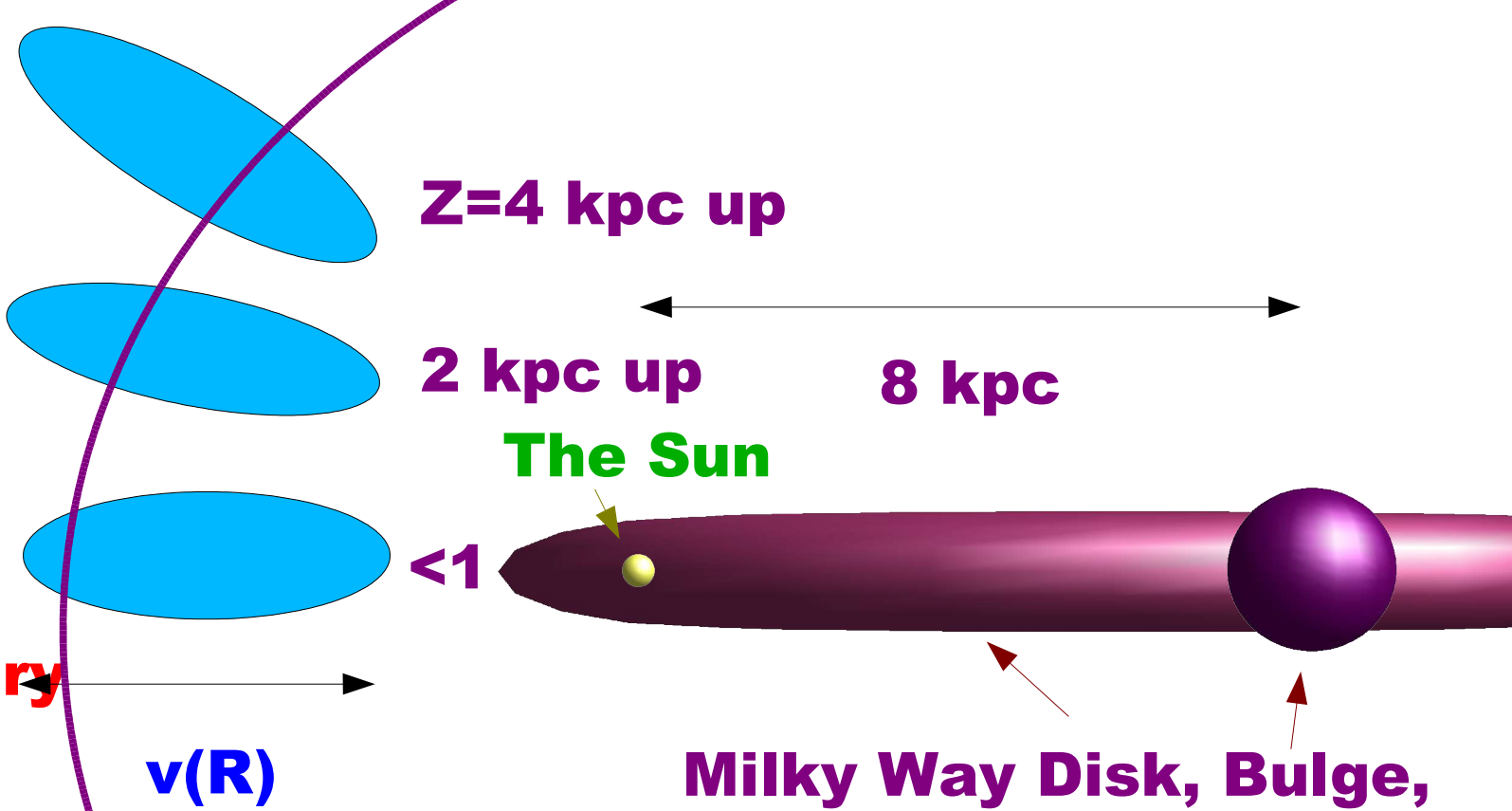
This followup
spectroscopy
by Geha et al. 2009
shows 4.3 km/s
velocity dispersion,



Possible (low bkgrnd) DM bright spot for Fermi/GLAST to look at.

2.

SEGUE Data enables testing of theory from the dark ages (1991)!



Kent and DeZeeuw 1991

These methods have been used to compute the tilt of the velocity ellipsoid for disk stars in the solar neighborhood based on a specific model for the Galactic potential. For small distances above the Galactic plane, we find that the tilt term can be written in the form

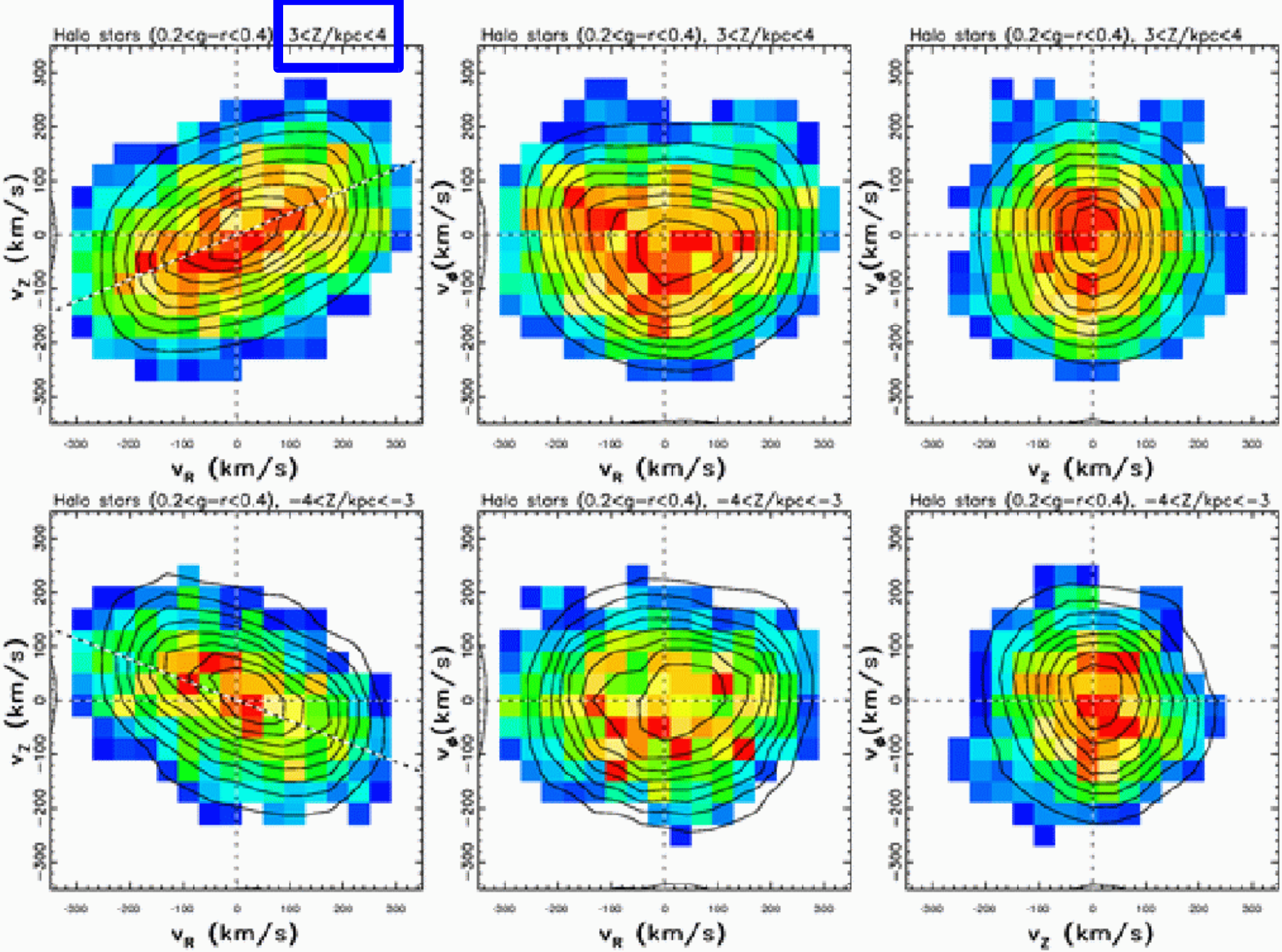
$$\sigma_{Rz}^2 = \langle C \rangle (\sigma_{RR}^2 - \sigma_{zz}^2) z/R,$$

where $\langle C \rangle$ is a correction factor to the value that this term would have if the velocity ellipsoid pointed towards the Galactic center. For old disk stars, we find that

$$\langle C \rangle \simeq \boxed{0.51} + 0.15 z_{\mathrm{kpc}} + 0.05 R_{\mathrm{kpc}}$$

over the range $6.8 < R < 8.8$ kpc and $0 < z < 600$ pc. Al-

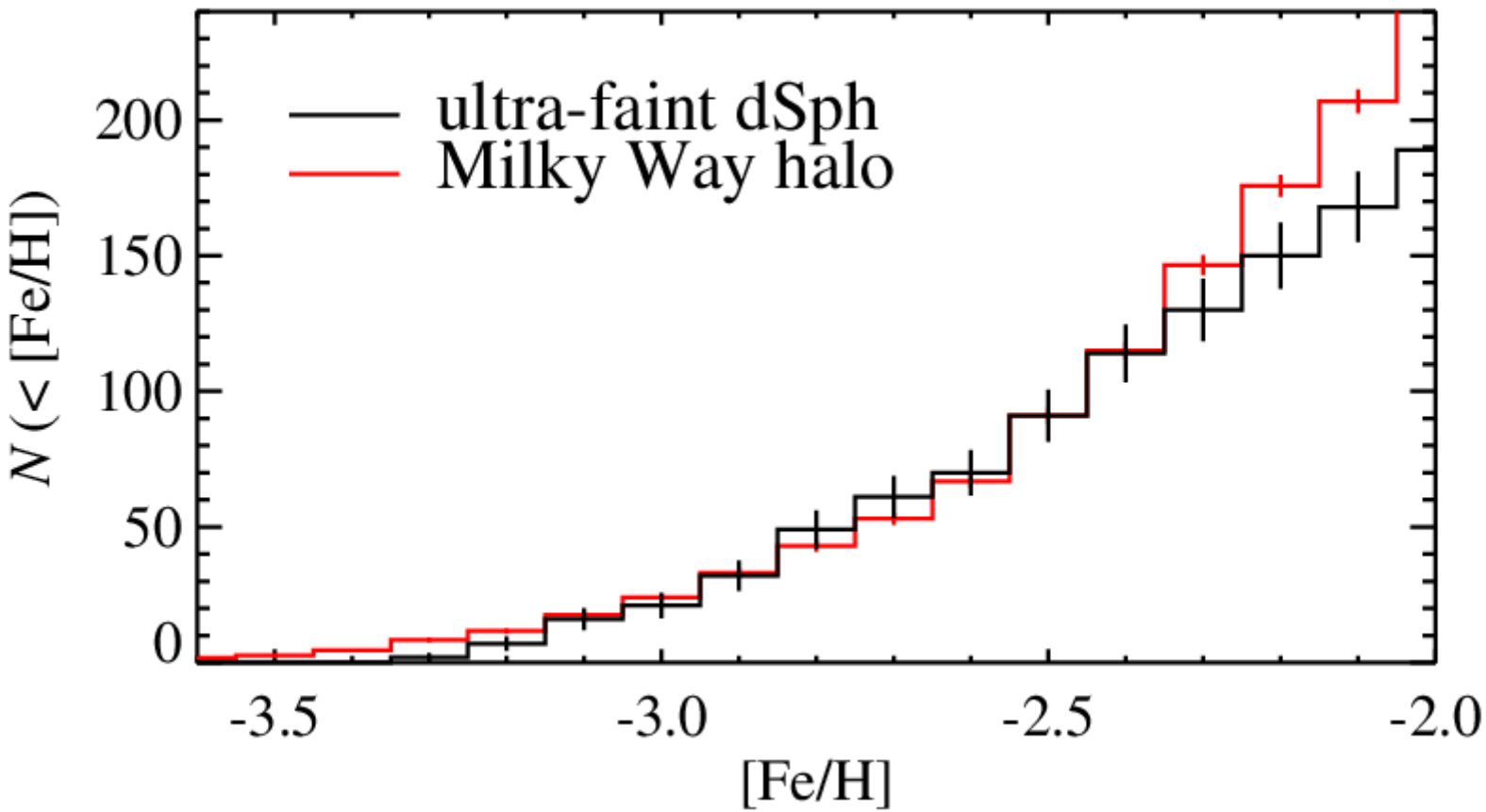
Tilt of Ellipsoid is indication of relative strength of Disk vs. Halo (Z)



Tilt of the v_r/v_z velocity ellipsoid (Bond, Ivezic et al. 2009)

From Kirby et al. 2008

A `paradigm shift' is underway in understanding how our halo formed. Used to be that Halo metallicities went below [Fe/H] < -3.0, but dwarf galaxy star metallicities didn't. Now, with help from SDSS/SEGUE,
there are many faint dwarfs with [Fe/H] < -3.0.



3.

4.

Not ALL Theories confirmed with SDSS/SEGUE:

The Thin and Thick Disks appear to be mysteriously linked, in that the lag of the thick disk doesn't change as the metallicity becomes higher.

Ivezic et al. 2008

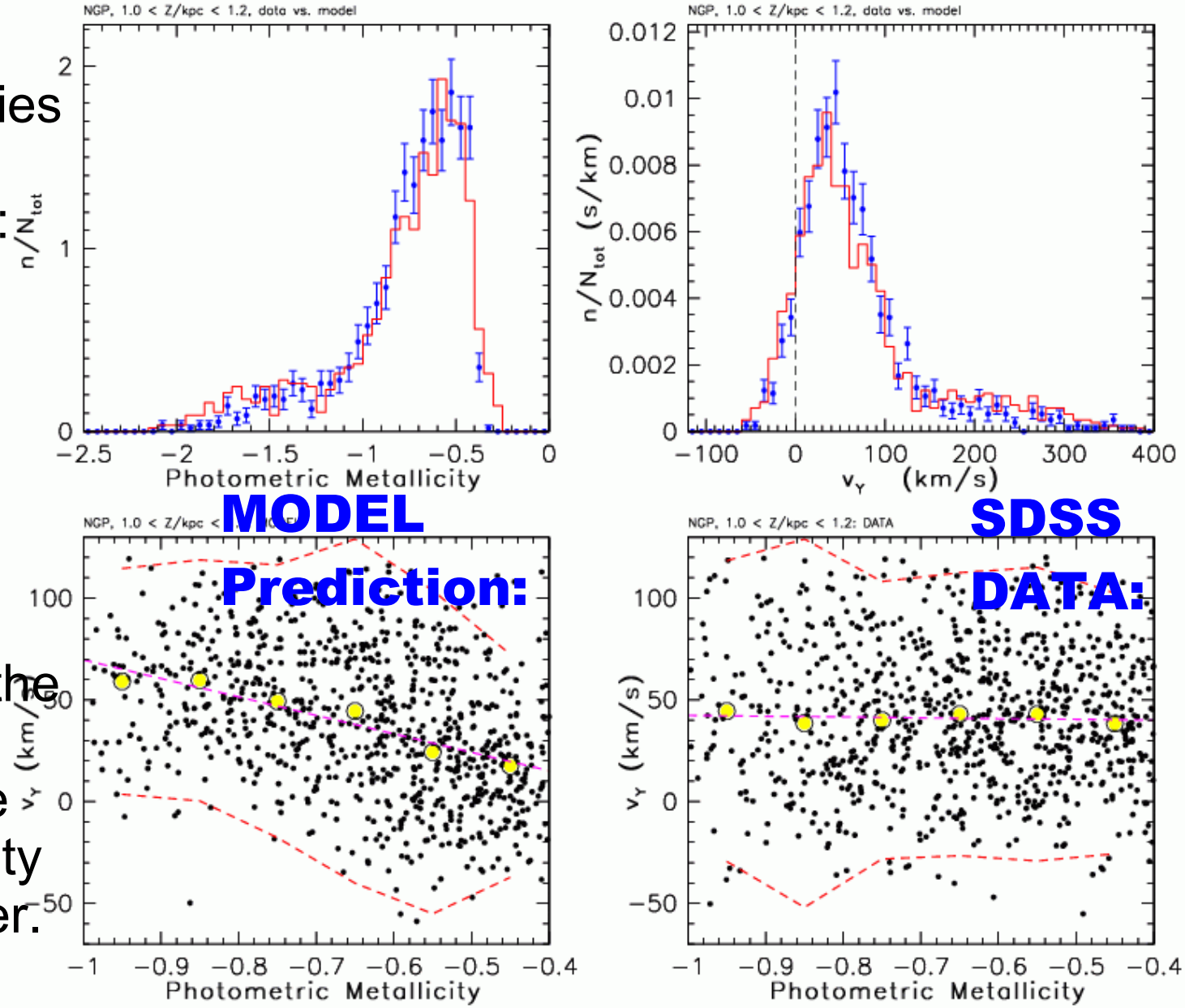
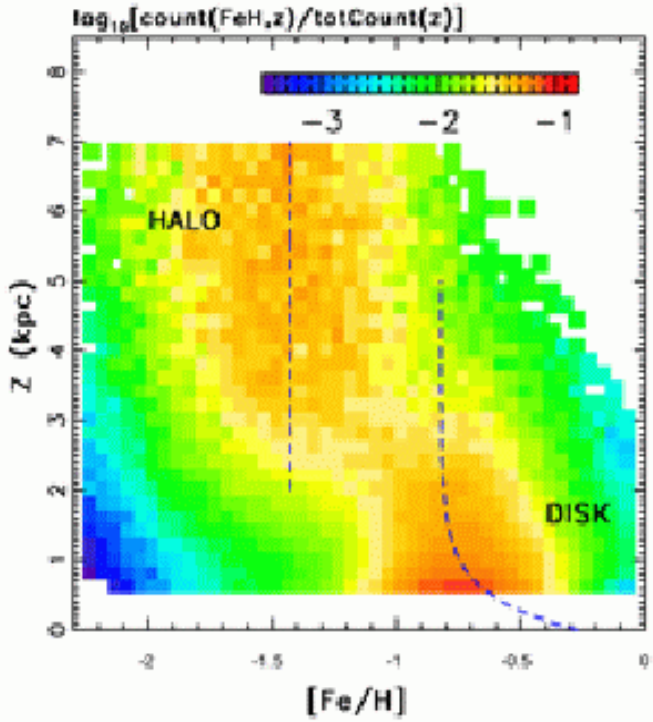
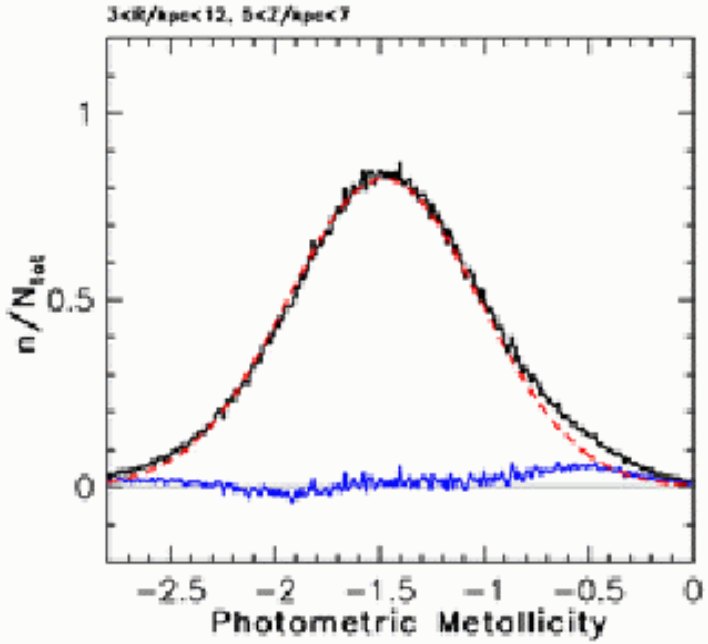


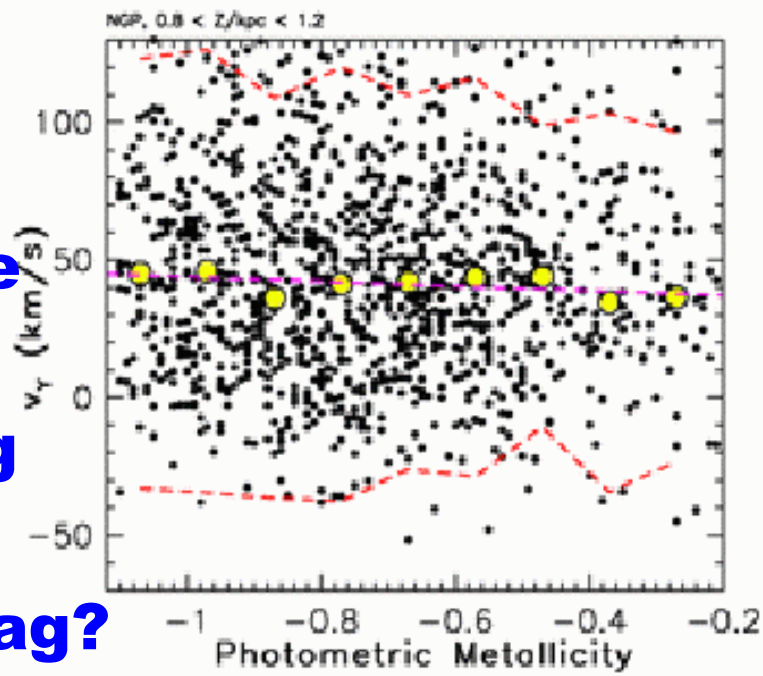
FIG. 16: A comparison of data for 1,142 stars with $b > 80$ and $1.0 < |Z|/\mathrm{kpc} < 1.2$ kpc, and a model based on a traditional disk decomposition into thin and thick components. The model assumes three Gaussians with contributions of thin disk, thick disk and halo stars equal to 28%, 52%, and 20%, respectively. The Gaussians describing the metallicity distribution (top left panel, symbols represent data and histogram represents model) are centered on $[Fe/H] = -0.50, -0.72$ and -1.37, and have widths of 0.04, 0.15, and 0.32, dex, respectively. The Gaussians describing the velocity distribution (top right panel) are centered on 9, 57 and 205 km/s, and have widths of 25, 33, and 80 km/s, respectively. The two bottom panels show the two-dimensional distributions in the velocity/metallicity diagram for the model (left) and the data (right), with individual stars shown as small dots. The large dots show the median velocity in 0.1 dex wide metallicity bins, for stars with velocity in the -60 km/s to 120 km/s range. The 2-σ envelope around these medians is shown by the two outer dashed lines. The dashed lines in the middle show the best linear fit to the median velocity, with slopes of -91 km/s/dex (model) and -4.1 km/s/dex (data).

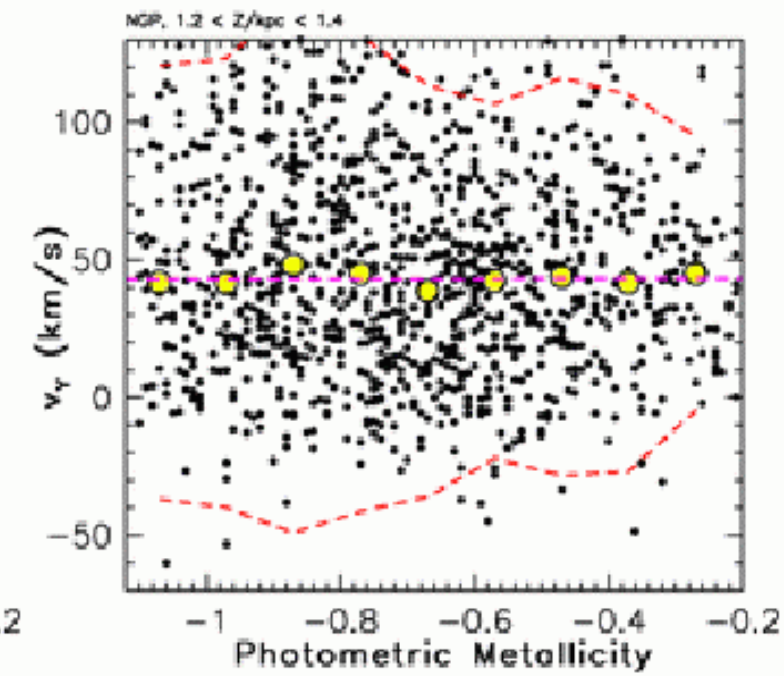
SEGUE confirms puzzle to higher metallicity:

Why don't high metal stars at Z = 1 kpc above plane show thin disk vel. lag rather than thick disk lag?



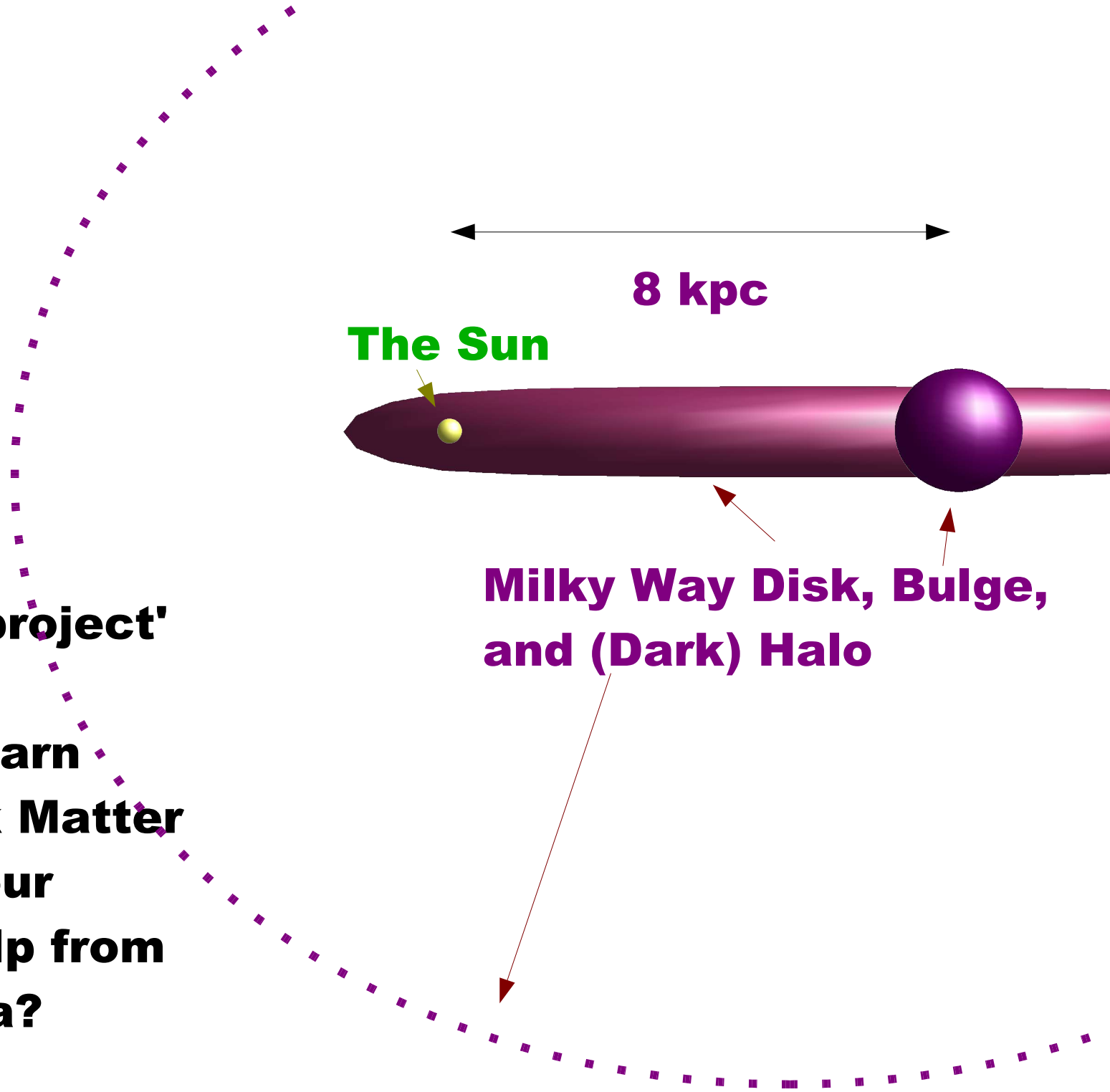






Mixing? Thin disk extends very high above plane?

SEGUE Science 5, this one in depth...



A SEGUE `key project'

What can we learn about the Dark Matter in and around our Galaxy with help from the SEGUE data?

Quick Review of Newtonian Dynamics

(Where do those 'flat rotation curve' models come from?)

Start with:

$$F = ma$$

Centripetal acceleration

Gravitational Force

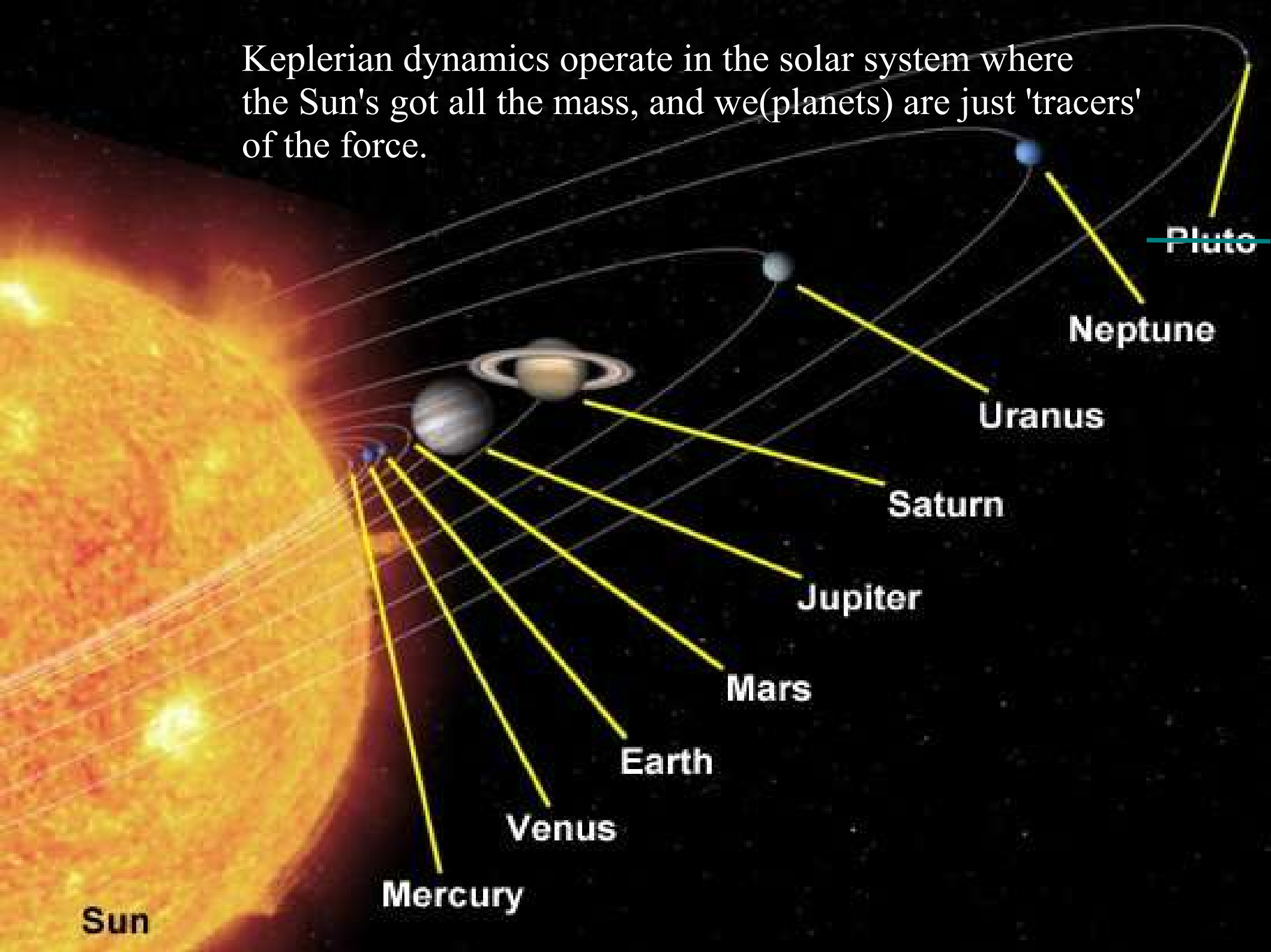
$$\mathrm{F(r)} = -\nabla\Phi(\mathrm{r}) = \frac{\mathrm{GM}}{\mathrm{r}^2}$$

$$F(r) = \frac{v_c^2}{r}$$

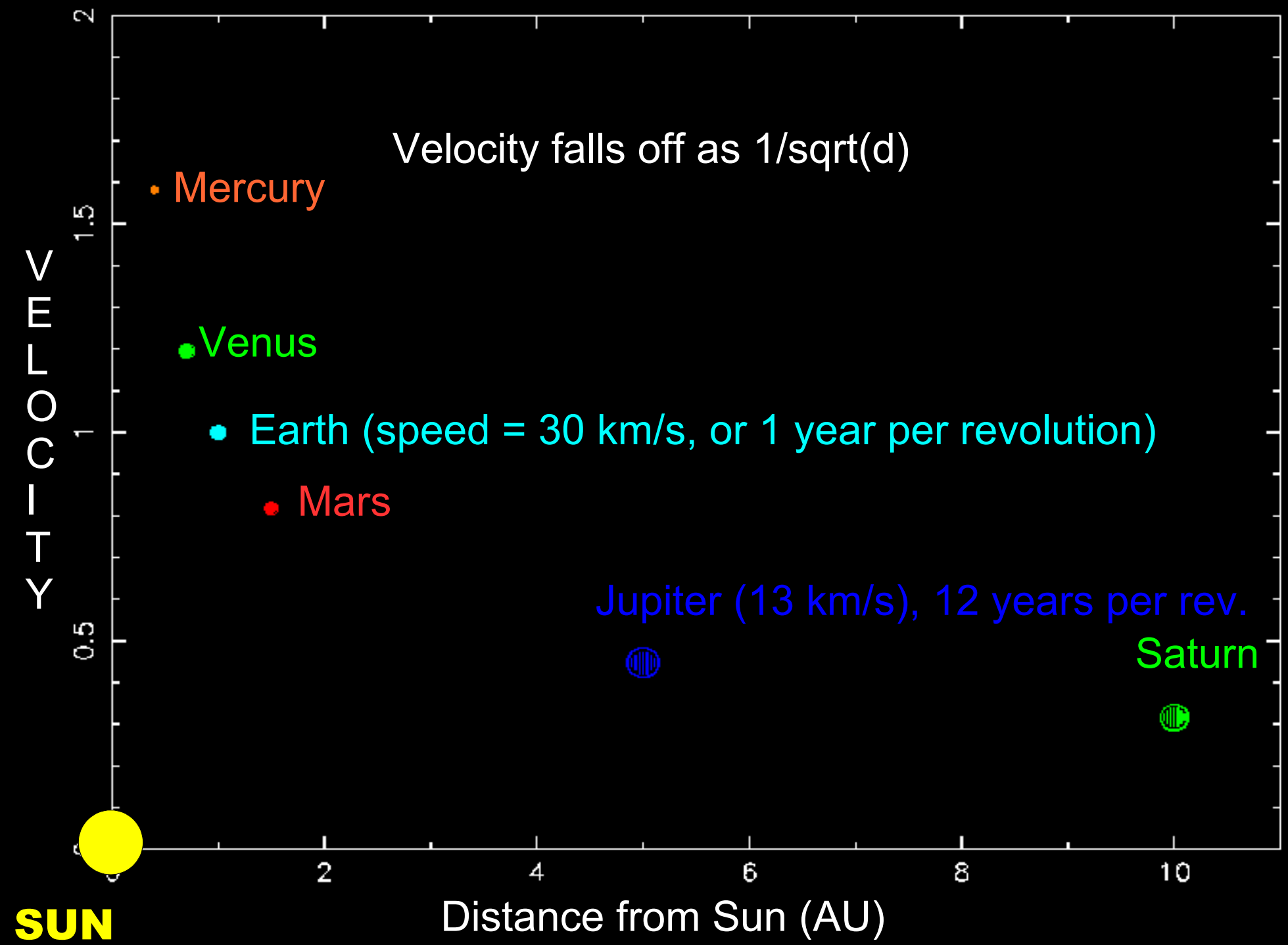
Kepler's Third Law: $v_c(r) \sim \frac{1}{\sqrt{r}}$

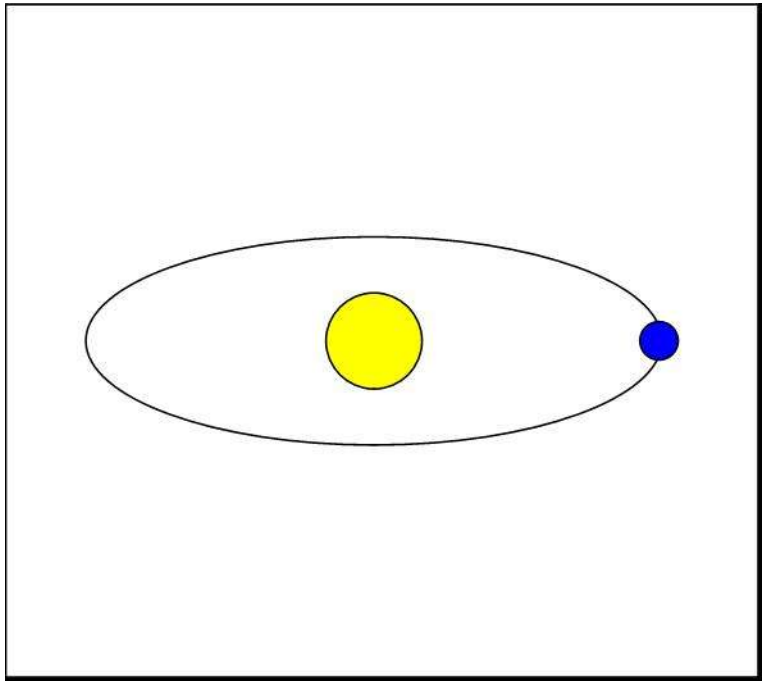
Homework excercise:
Show that this
is the same as
Semi-axis^3 ~ Period^2

Keplerian dynamics operate in the solar system where the Sun's got all the mass, and we(planets) are just 'tracers' of the force.



Keplerian Dynamics – All mass concentrated in the center at d=0

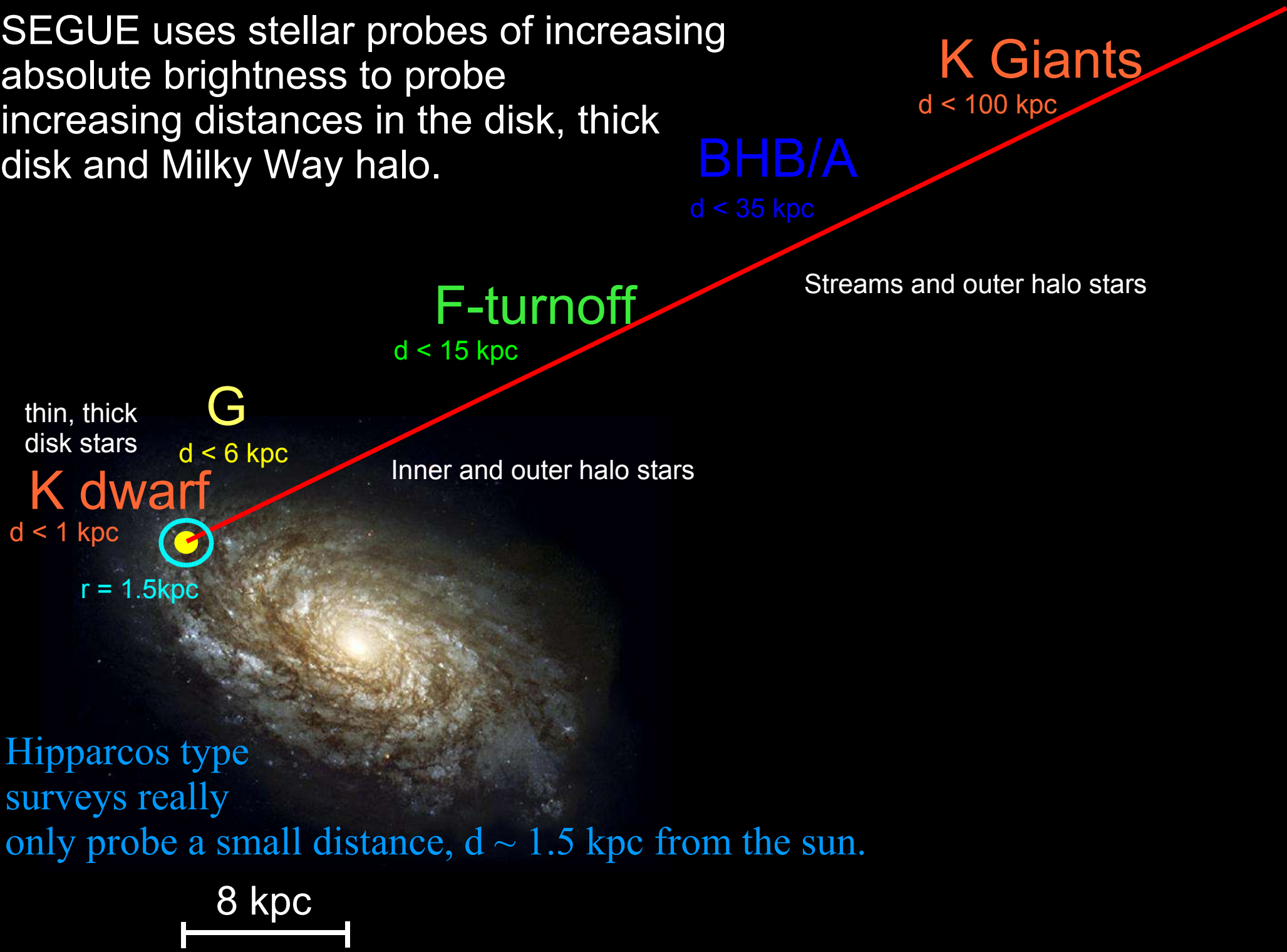




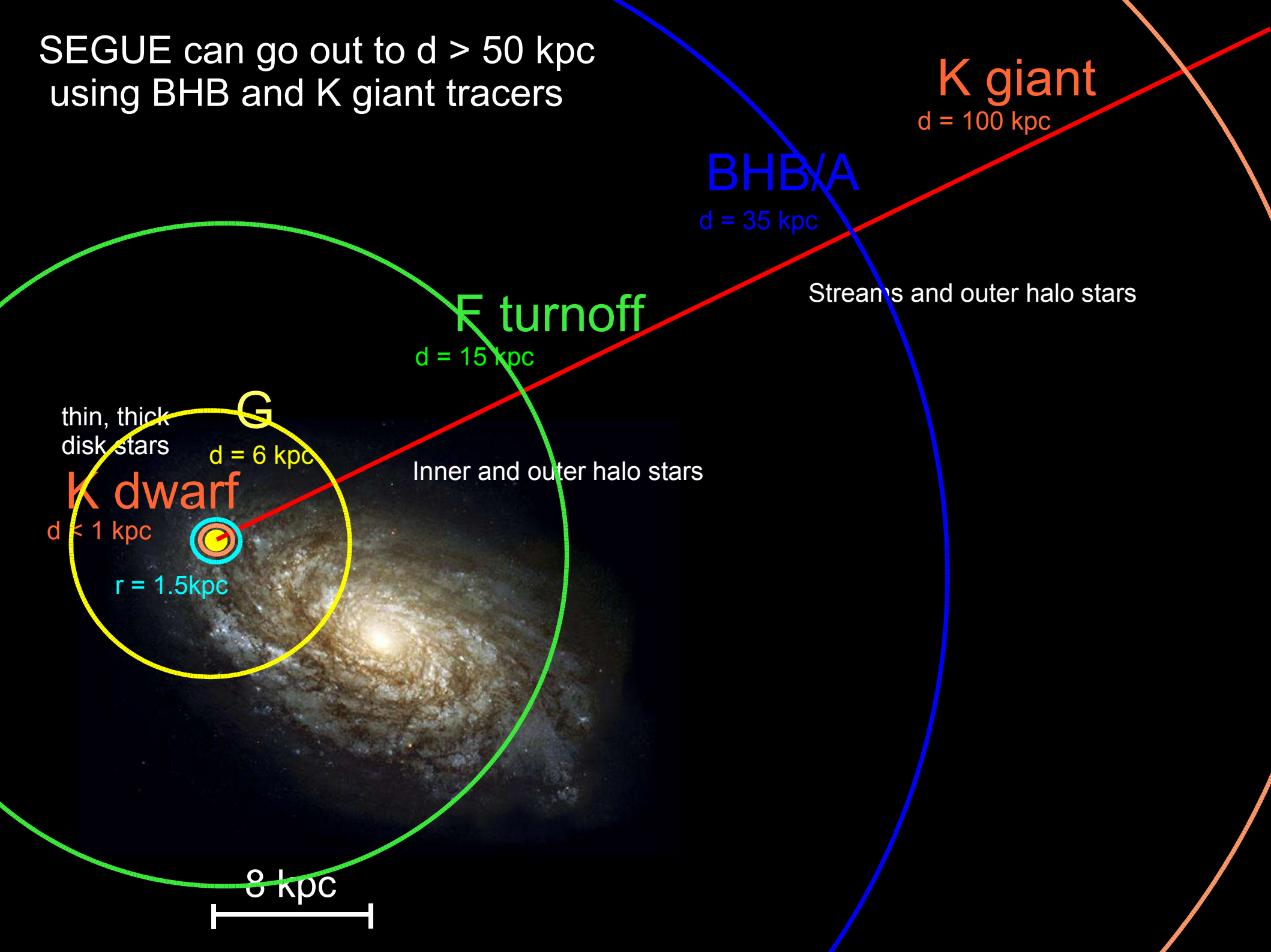
Orbits in this simple Keplerian system are ellipses,
with the 'planets' as tracers of the Potential.

When we do Galactic dynamics, we need to generalize
to Galactic scales, using stars as tracers of the Milky Way's
potential. (note that we are still in the Newtonian ($v \ll c$) realm).

SEGUE uses stellar probes of increasing absolute brightness to probe increasing distances in the disk, thick disk and Milky Way halo.



Hipparcos type surveys really only probe a small distance, d ~ 1.5 kpc from the sun.


SEGUE can go out to d > 50 kpc
using BHB and K giant tracers
K giant
d = 100 kpc
BHB/A
d = 35 kpc
Streams and outer halo stars
F turnoff
d = 15 kpc
thin, thick
disk stars
G
d = 6 kpc
Inner and outer halo stars
K dwarf
d < 1 kpc
r = 1.5kpc
8 kpc

Generalize Kepler's Third law for mass distributions where all the mass is not a point source at the center:

Handy Mathematical Tools:

Use 'Potentials' rather than 'Forces' (scalars vs. vectors)

$$\vec{F} = -\vec{\nabla}\phi$$

Poisson's eqn. connects density (mass) distributions to the Potential (Gravity Law)

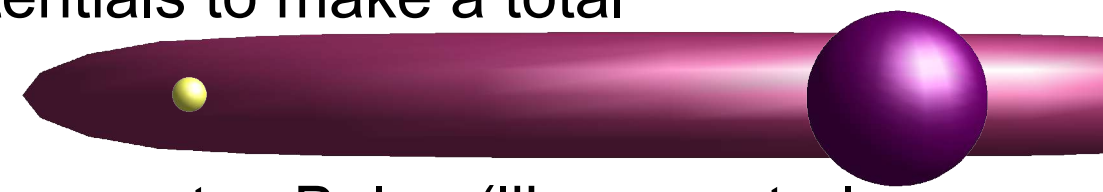
$$\nabla^2\Phi(r) = 4\pi G\rho(r)$$

$$F(r) = \frac{v_c^2}{r}$$

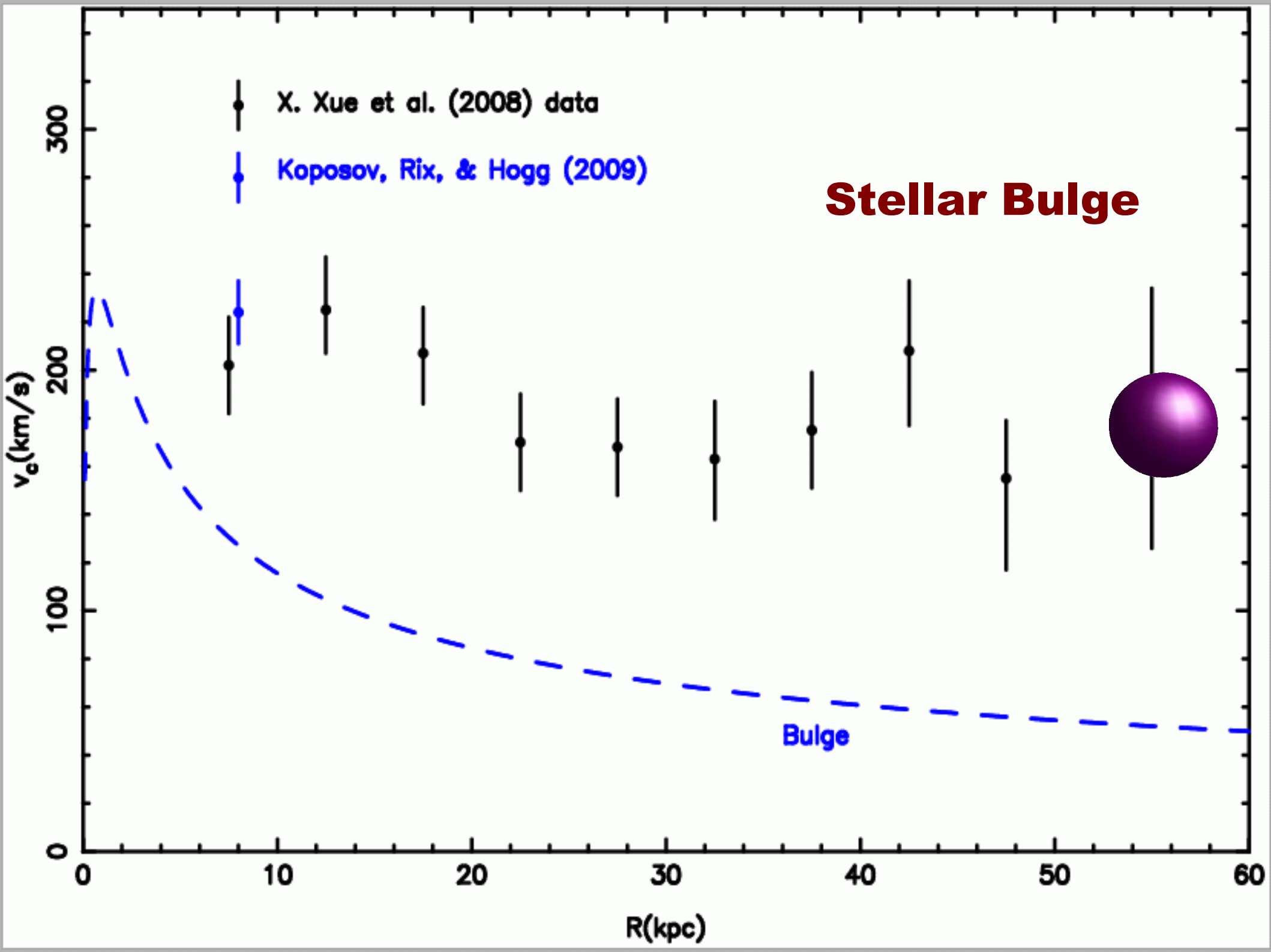
Centripetal Acceleration force law becomes the relation for circular velocity vs. r.

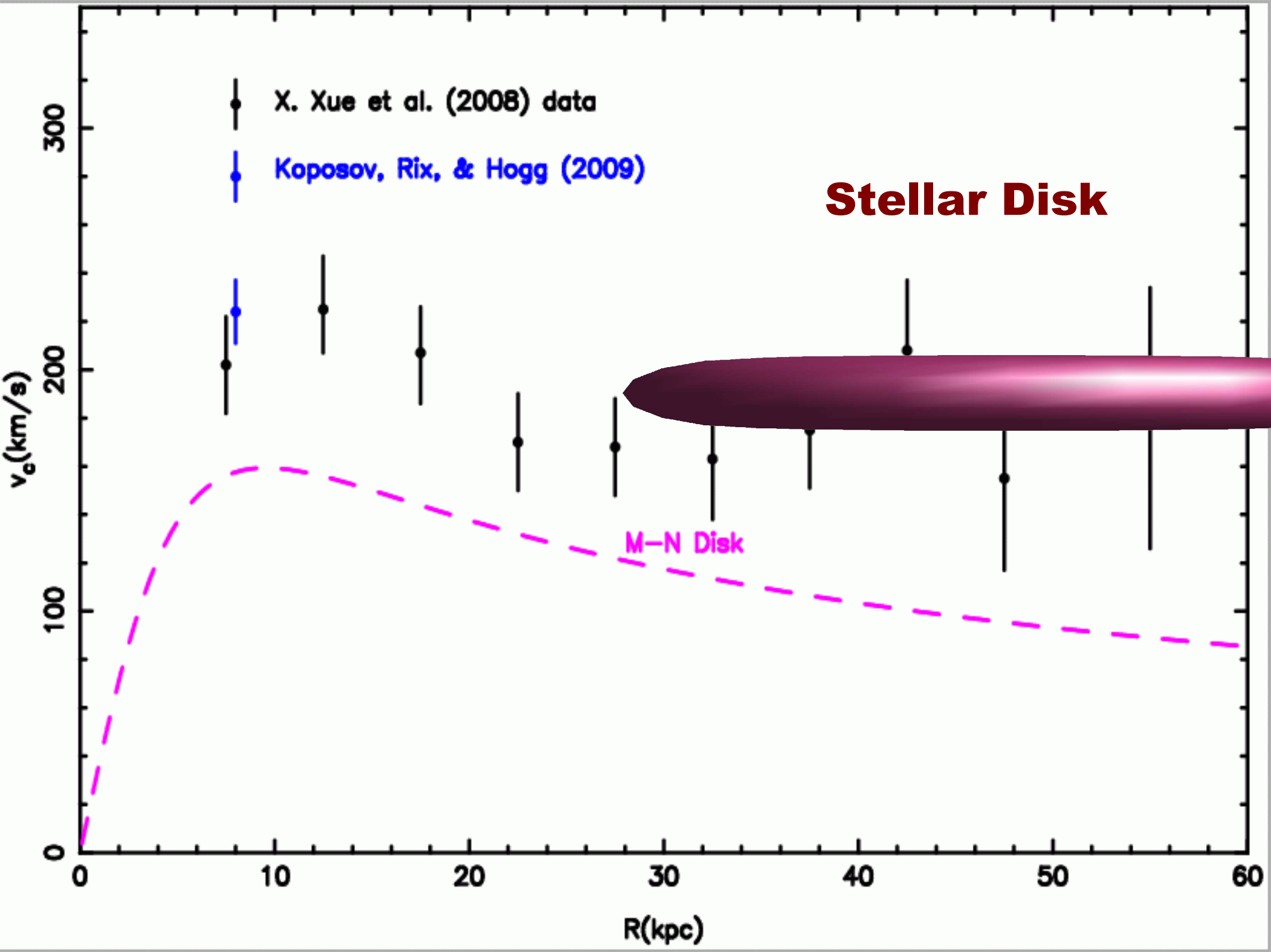
$$v_c^2(r) = r\frac{d\Phi}{dr}$$

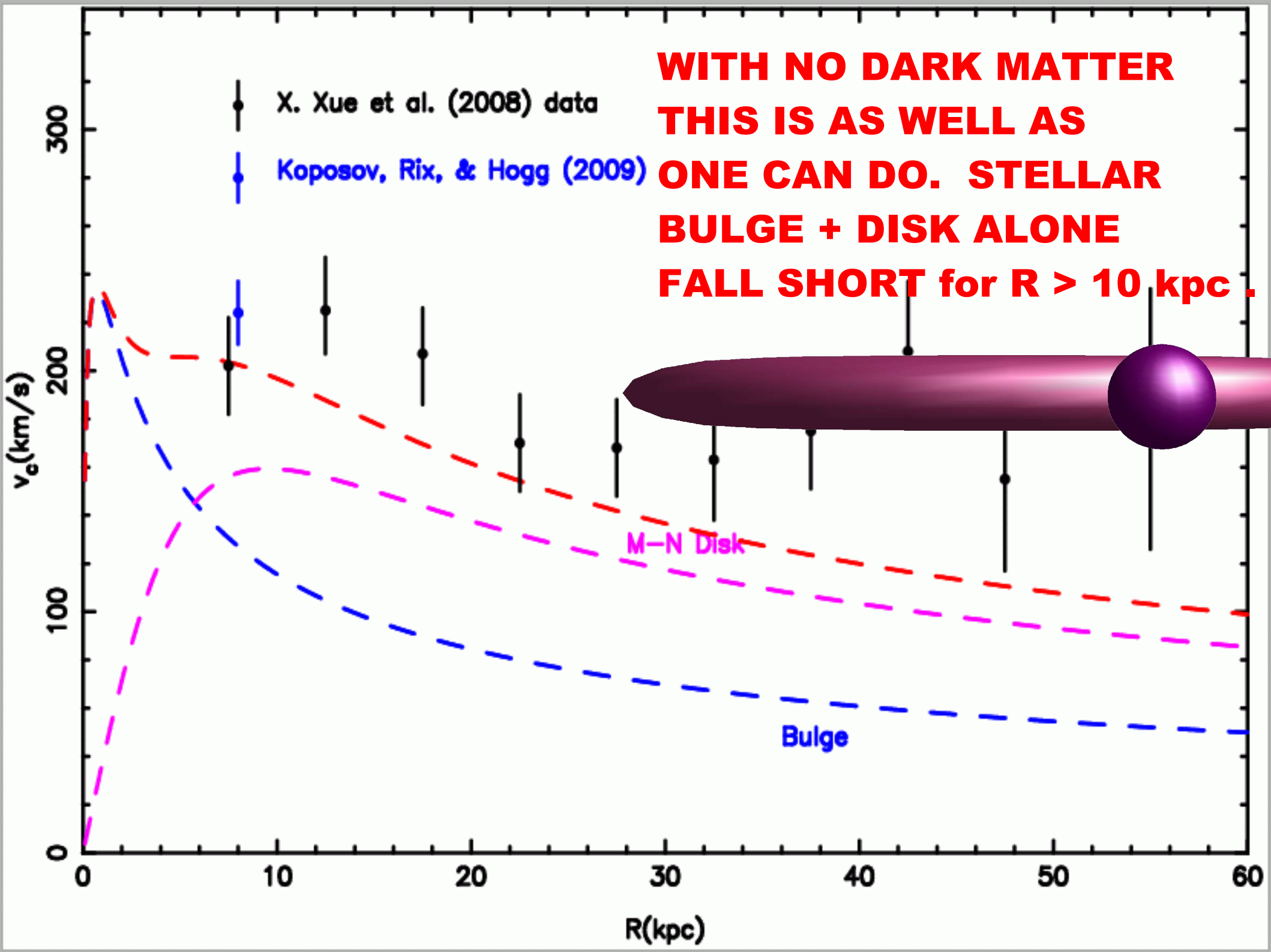
The nice thing about working with potentials (rather than forces), is that they are scalars (not vectors) and the Poisson eqn. is linear in potential and density (also a scalar), so you can 'synthesize' a multi-component model of the Galaxy by simply taking the density profiles of each component, solving Poisson's eqn for each component and summing the potentials to make a total potential for the Galaxy.



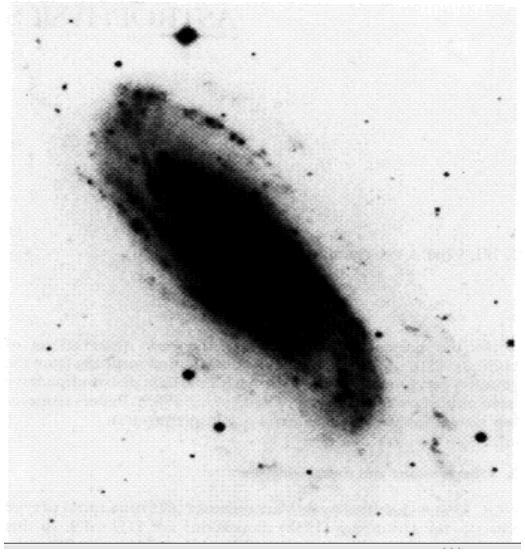
Common models have three components: Bulge (like a central point source), Stellar Disk (Either an exponential disk or a slightly more complicated Miyamoto-Nagai disk model), and a Dark Halo component (either a log(r+c) potential, r^-2, with a central core) or an NFW (density falls as r^-3 in the outer parts). These three potentials have several parameters to be fit, including scale lengths, height of the disk, flattening (shape) of the Dark component, and relative amplitudes between disk and halo.

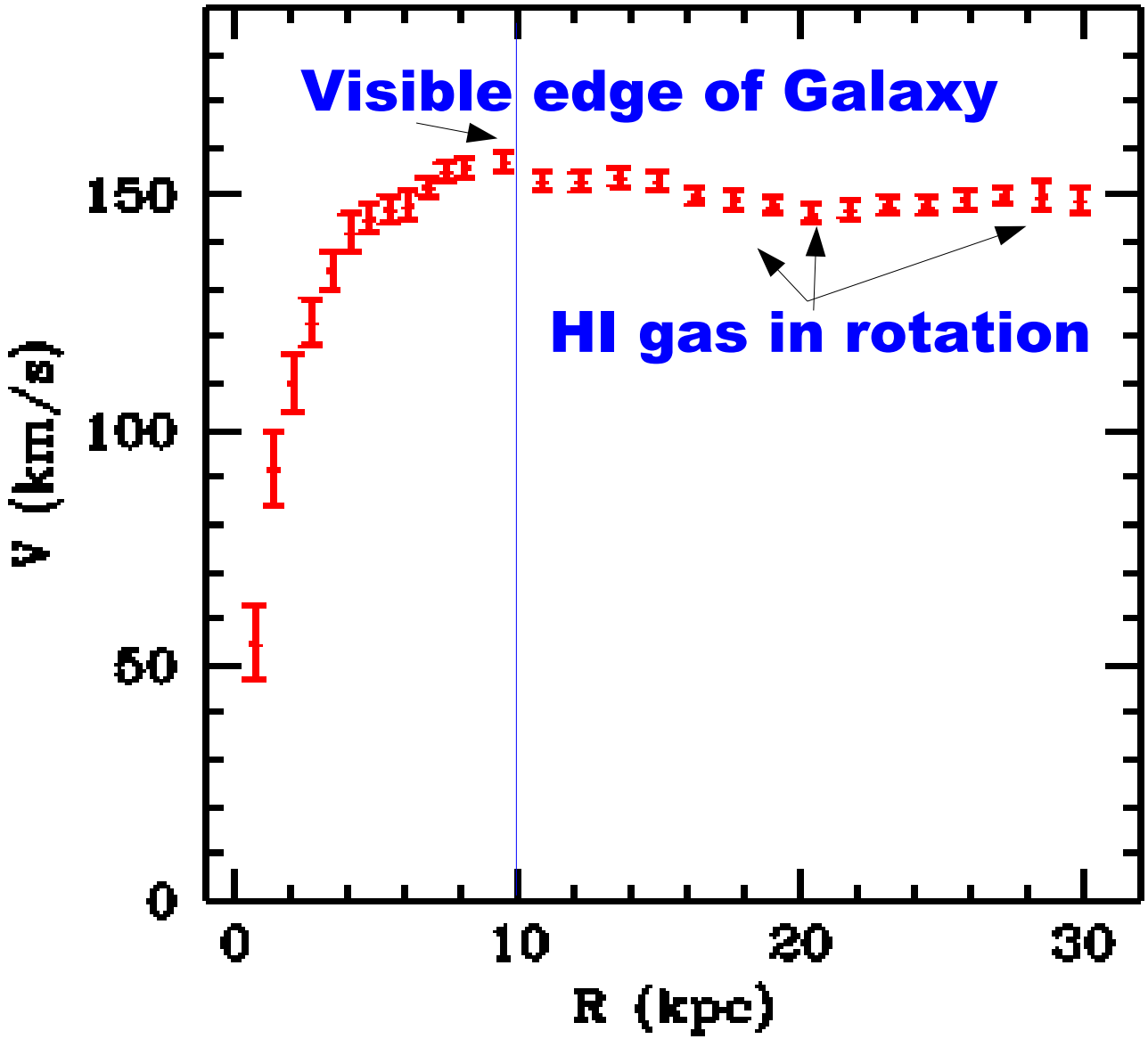

X. Xue et al. (2008) data
Koposov, Rix, & Hogg (2009)
Stellar Bulge
Bulge
v_c(km/s)
R(kpc)
0
100
200
300
0
10
20
30
40
50
60


X. Xue et al. (2008) data
Koposov, Rix, & Hogg (2009)
Stellar Disk
M−N Disk
v_c(km/s)
R(kpc)
0
100
200
300
0
10
20
30
40
50
60

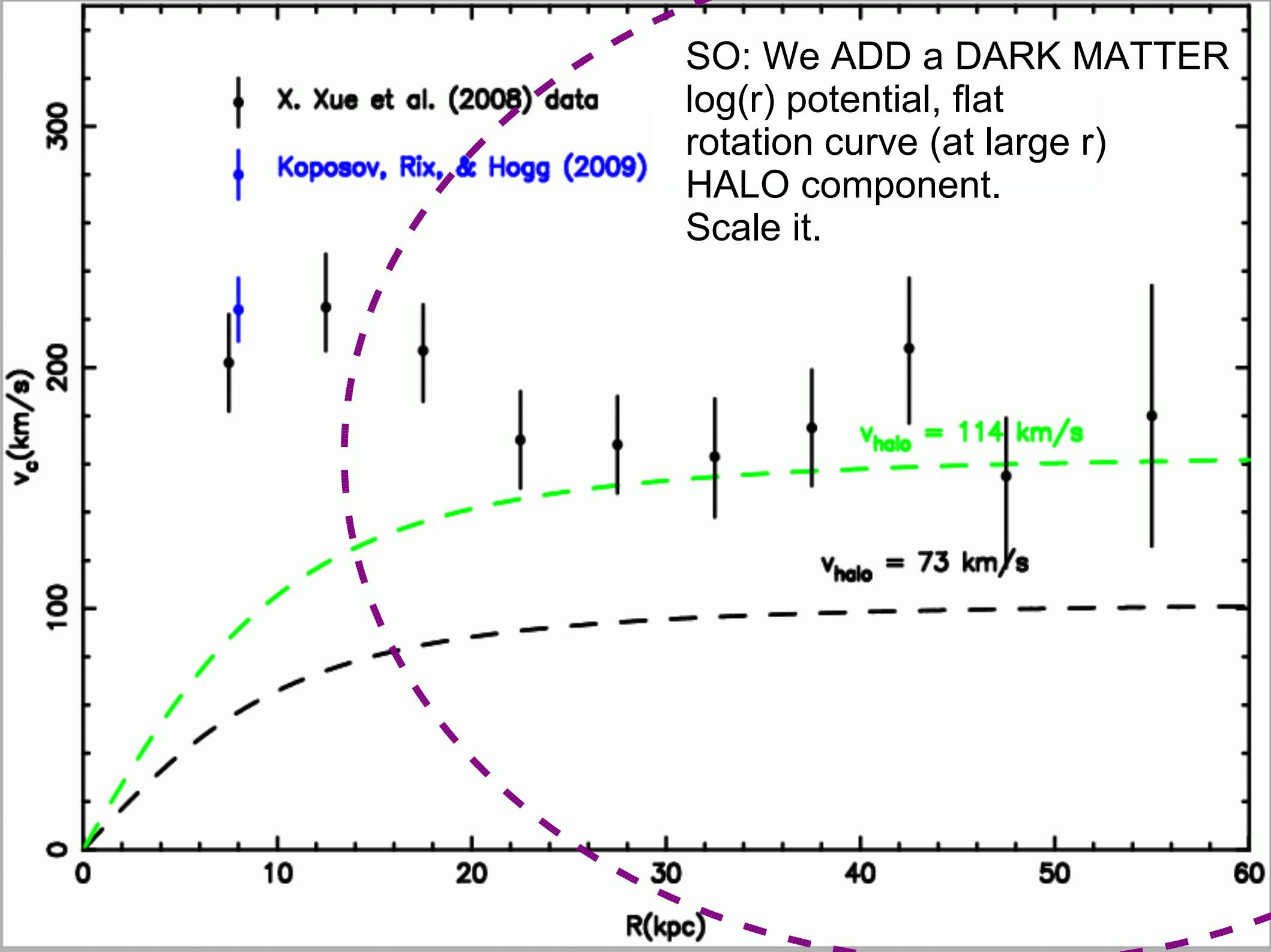

WITH NO DARK MATTER
THIS IS AS WELL AS
ONE CAN DO. STELLAR
BULGE + DISK ALONE
FALL SHORT for R > 10 kpc .
X. Xue et al. (2008) data
Koposov, Rix, & Hogg (2009)
M–N Disk
Bulge
v_c(km/s)
R(kpc)
0
100
200
300
0
10
20
30
40
50
60

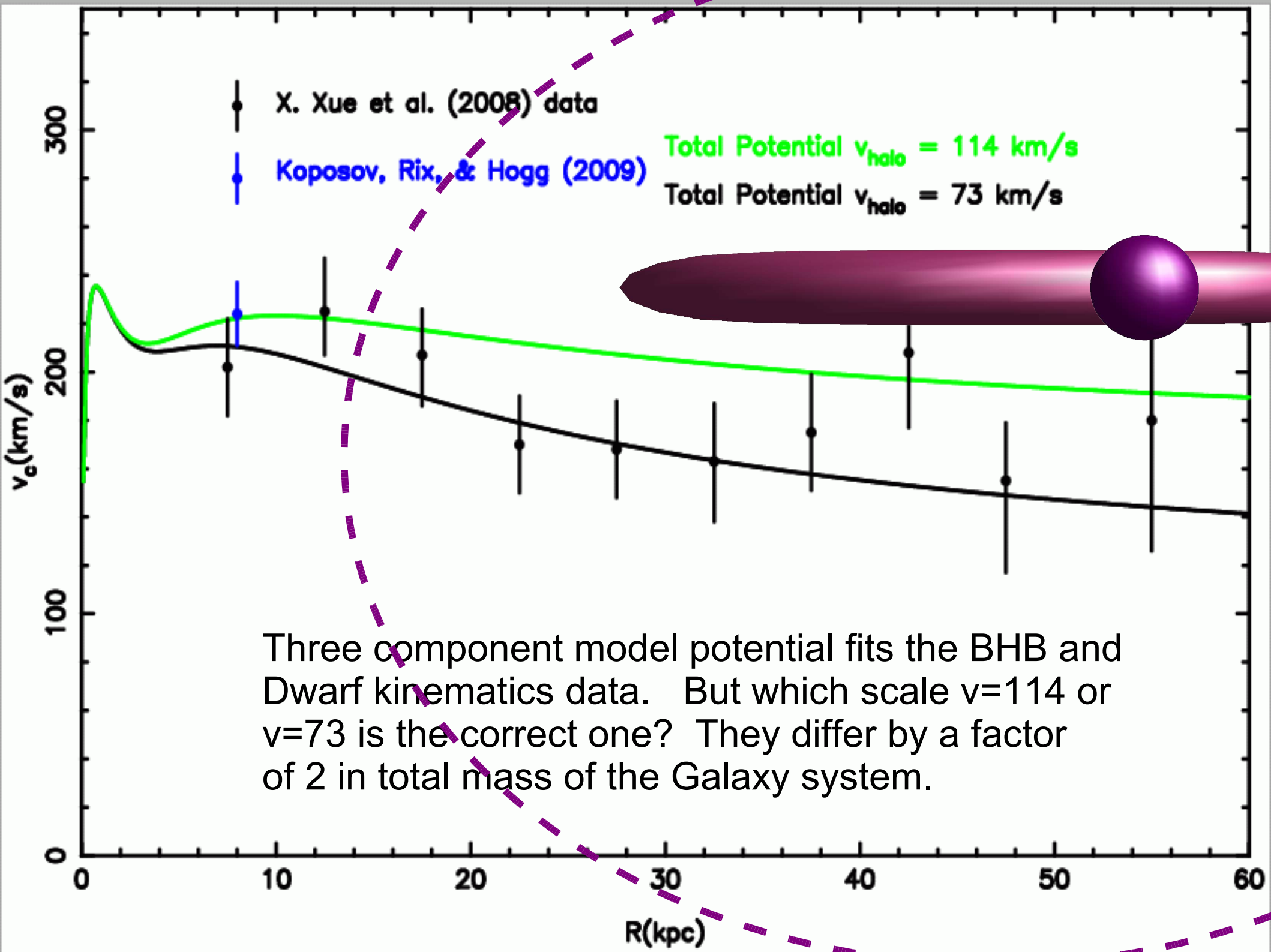
Data for a Galaxy like the Milky Way, in HI Gas.





Data from Begeman 1989 for the spiral galaxy NGC 3198

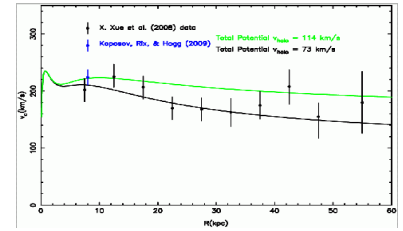

X. Xue et al. (2008) data
Koposov, Rix, & Hogg (2009)
SO: We ADD a DARK MATTER
log(r) potential, flat
rotation curve (at large r)
HALO component.
Scale it.
v_{halo} = 114 km/s
v_{halo} = 73 km/s
v_c(km/s)
R(kpc)
0
100
200
300
0
10
20
30
40
50
60



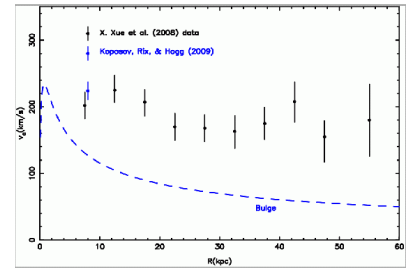
Three component model potential fits the BHB and Dwarf kinematics data. But which scale v=114 or v=73 is the correct one? They differ by a factor of 2 in total mass of the Galaxy system.

So, in summary, what we have for models:

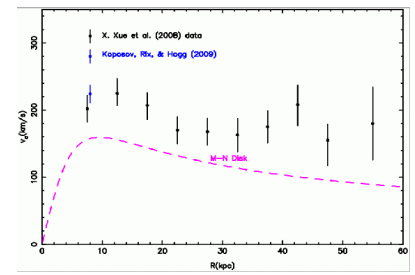
$$\Phi_{\text{total}} = \Phi_{\text{Bulge}} + \Phi_{\text{Disk}} + \Phi_{\text{Halo}}$$



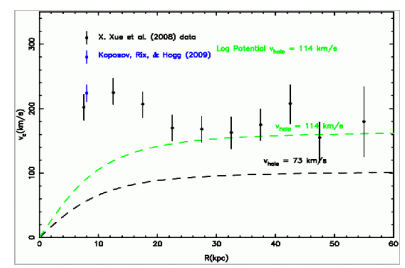
$$\Phi_{\text{Bulge}}(r) = -\frac{M_{\text{Bulge}}}{(r+c)}$$



$$\Phi_{\text{Disk}}(r) = -\frac{M_{\text{Disk}}}{\sqrt{R^2 + (a + \sqrt{z^2 + b^2})^2}}$$



$$\Phi_{\text{Halo}}(r) = v_{\text{Halo}} log(R^2 + \frac{z^2}{q^2} + d^2)$$



$$R^2 = x^2 + y^2,\ a = 6.5 \text{ kpc},\ b = 0.26 \text{ kpc},\ c = 0.7 \text{ kpc},\ d = 12 \text{ kpc}$$

$$M_{\text{Bulge}} = 3.4 \times 10^{10} M_{\odot},\ M_{\text{Disk}} = 10^{11} M_{\odot}.$$

Key parameters fit: v_{Halo}, q

Keplerian Potential
(Solar System)
Central Point Mass

$$\Phi(r) = -GM/r$$

$$v_c(r) \sim \frac{1}{\sqrt{r}}$$

M(r<R) = M (constant)

Isothermal Potential
(Dark Matter Halo)

$$\rho(r) \sim r^{-2}$$

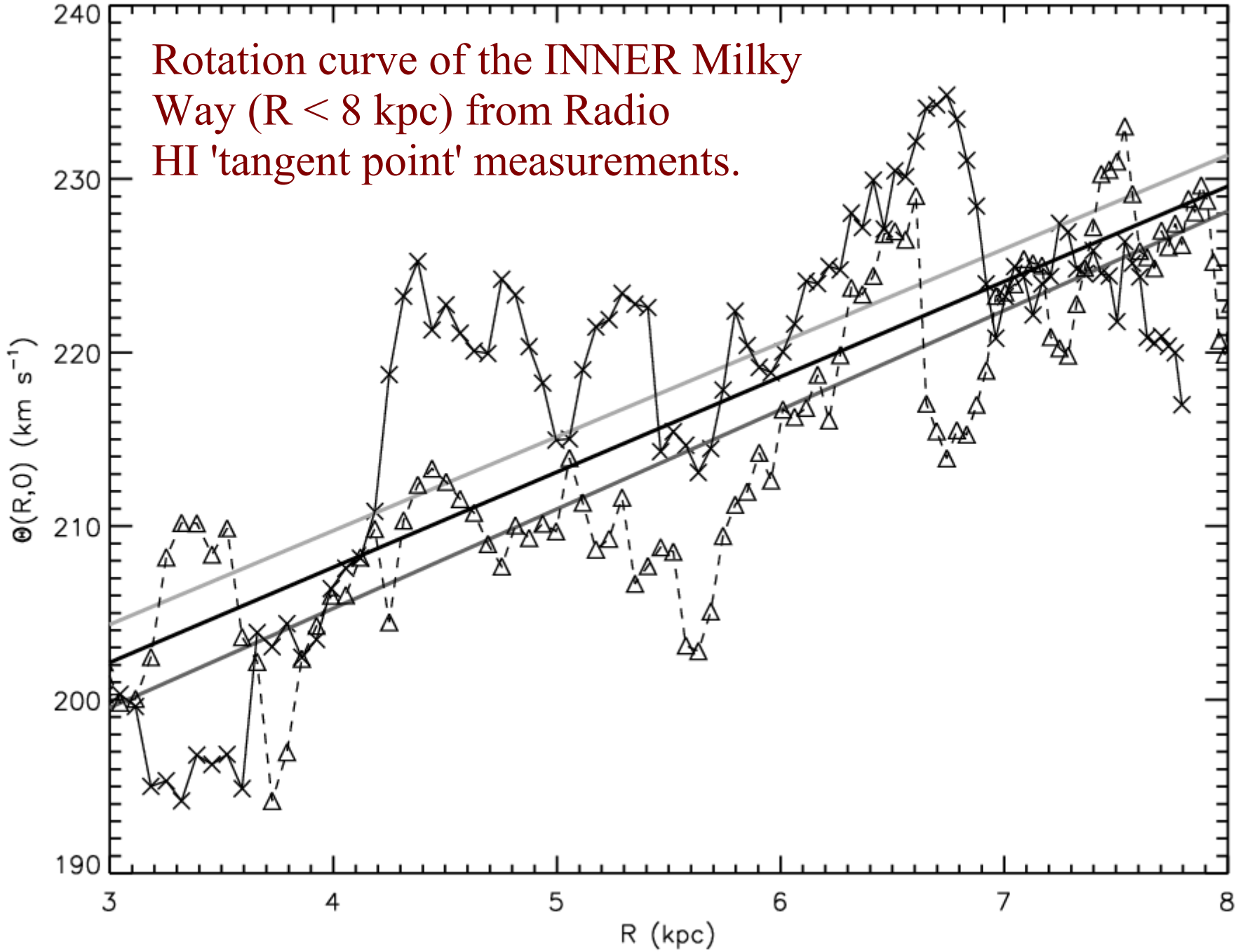
$$\Phi(r) \sim log(r)$$

$$v_c^2(r) \sim r\frac{d\Phi}{dr} \sim \frac{r}{r} \sim constant$$

FLAT ROTATION CURVE!

$$M(r < R) \sim R$$

Levine, Heiles, and Blitz 2009 ApJ



Maciel and Lago 2005

For points beyond the solar radius (R ~ 8 kpc), the tangent point method doesn't work any more, and other methods must be used.
H II regions in the outer Galaxy and Planetary Nebula in the Outer Galaxy are some methods.
The errors bars here are significantly larger than for the inner Galaxy.

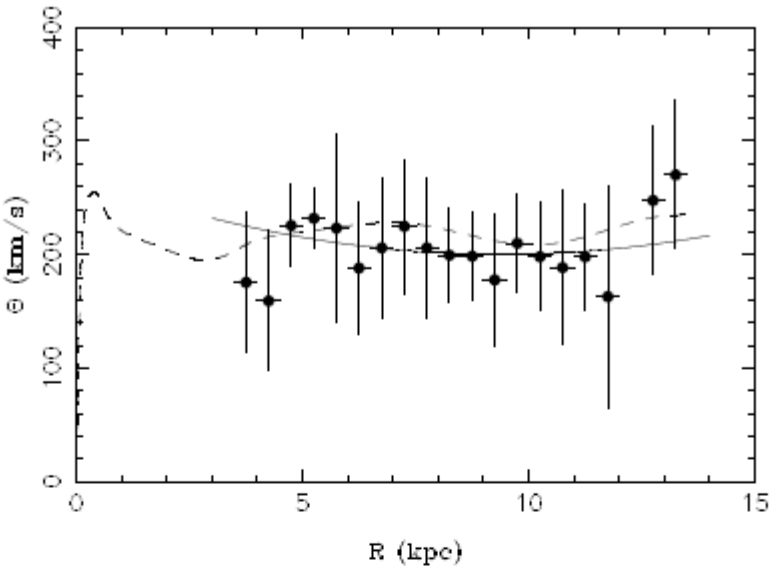


Fig. 2. Rotation curve from PN (solid line) and average velocities in 0.5 kpc bins (dots with error bars), adopting distances by Maciel (1984). Also shown is the rotation curve from H II regions by Clemens (1985, dashed line).

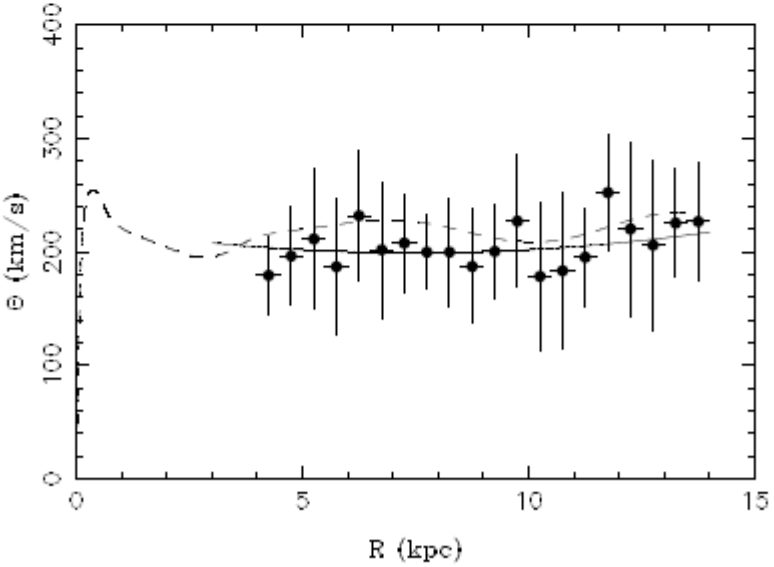
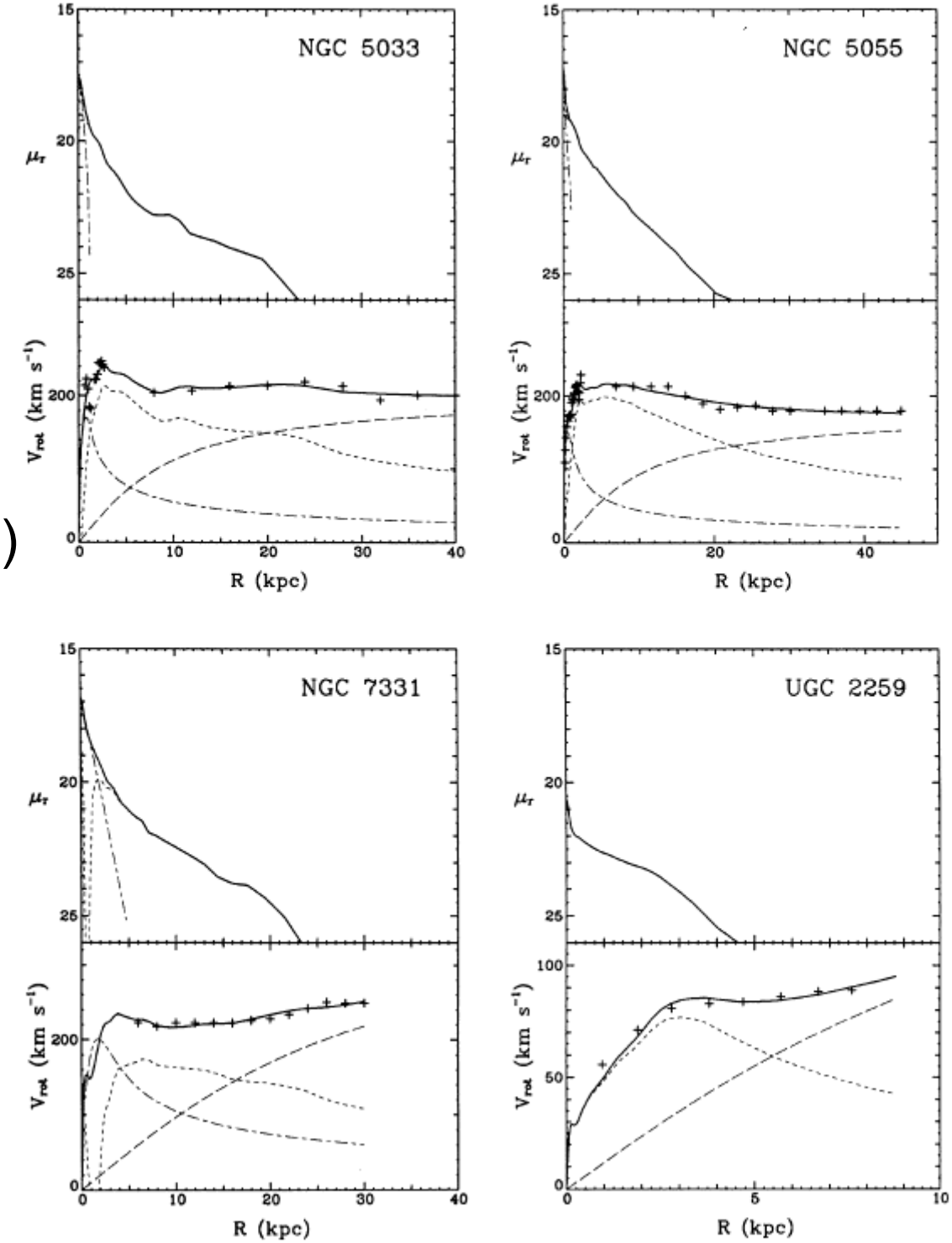


Fig. 3. The same as Fig. 2 with distances by Cahn et al. (1992).

Four (other) Galaxies
Optical+HI rotation curves
from Kent, S. M. 1987 ApJ

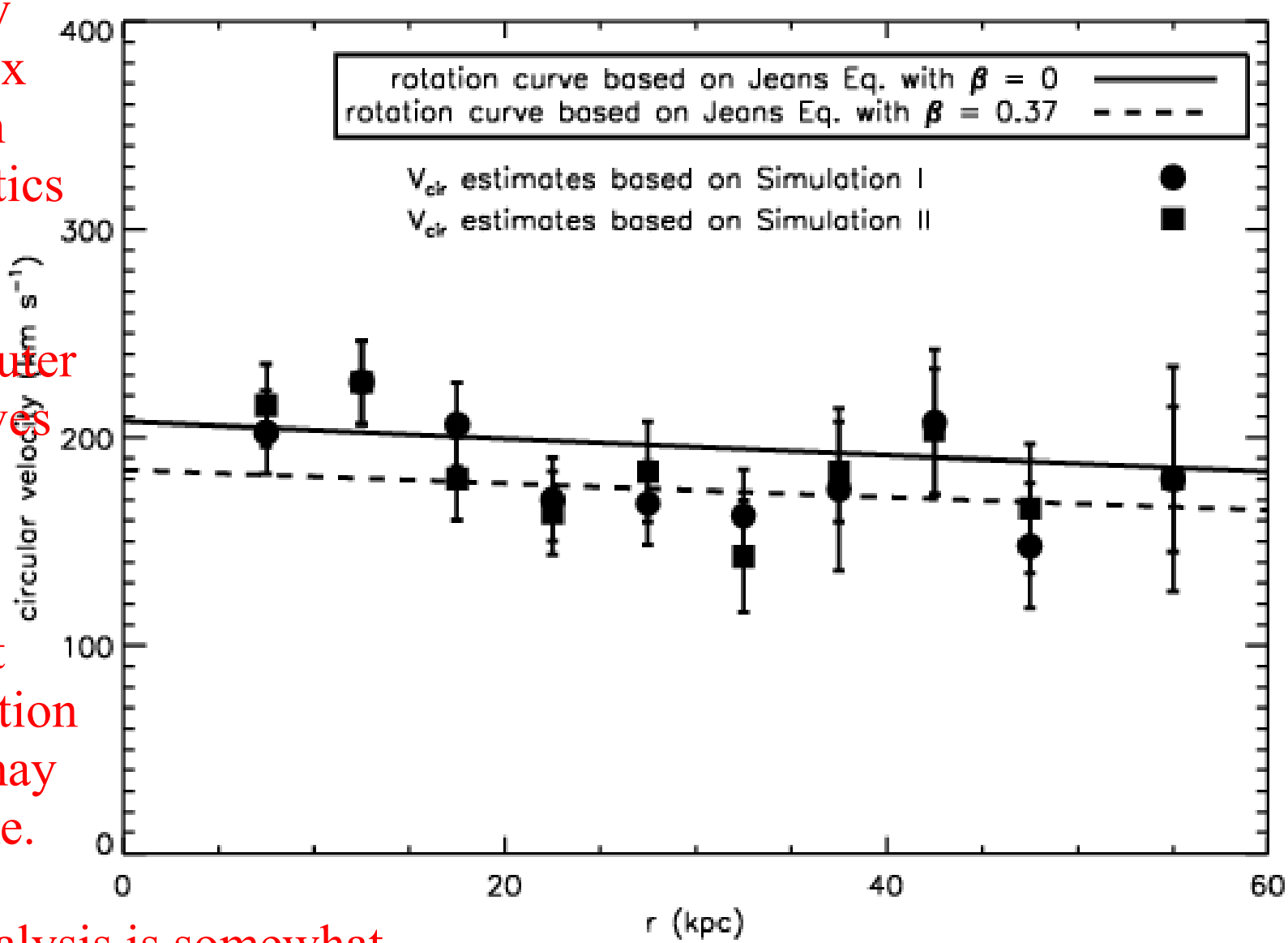
In other Galaxies,
rotation curves have been
observed from HI gas
profiles and from (sometimes)
optical profiles.

In general, rotation curves
are more or less flat,
requiring an ~ log(r) potential
halo component out to a
few times the radius of the
visible (optical) disk light.



Recent SDSS work by Xue, Rix et al. on kinematics of BHB stars in the outer halo gives us a new handle on what the rotation curve may look like.

Xue, X. et al. 2008: SDSS BHB stars and model

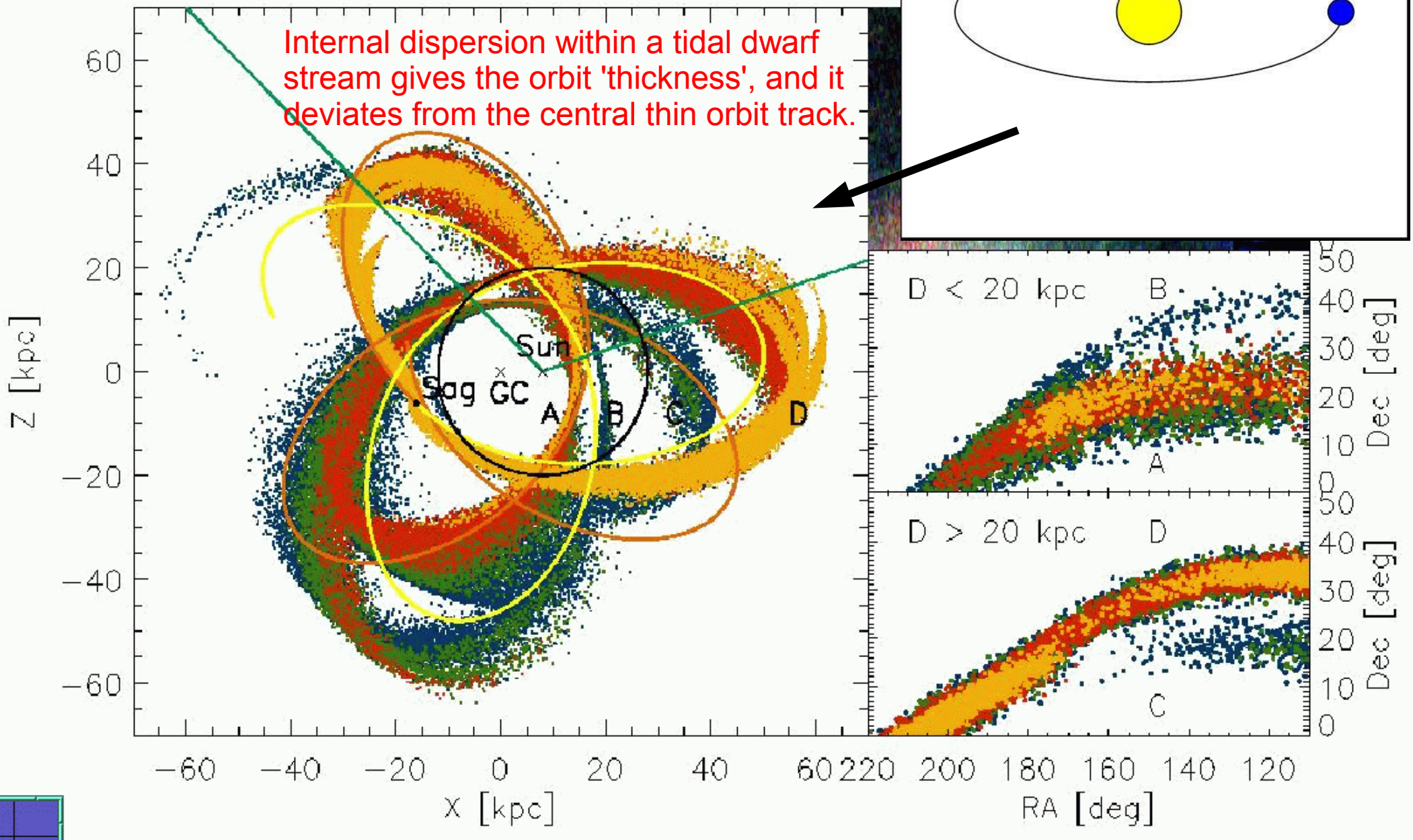


This analysis is somewhat model dependent, and assumes that the BHB stars in the halo have 'relaxed'.

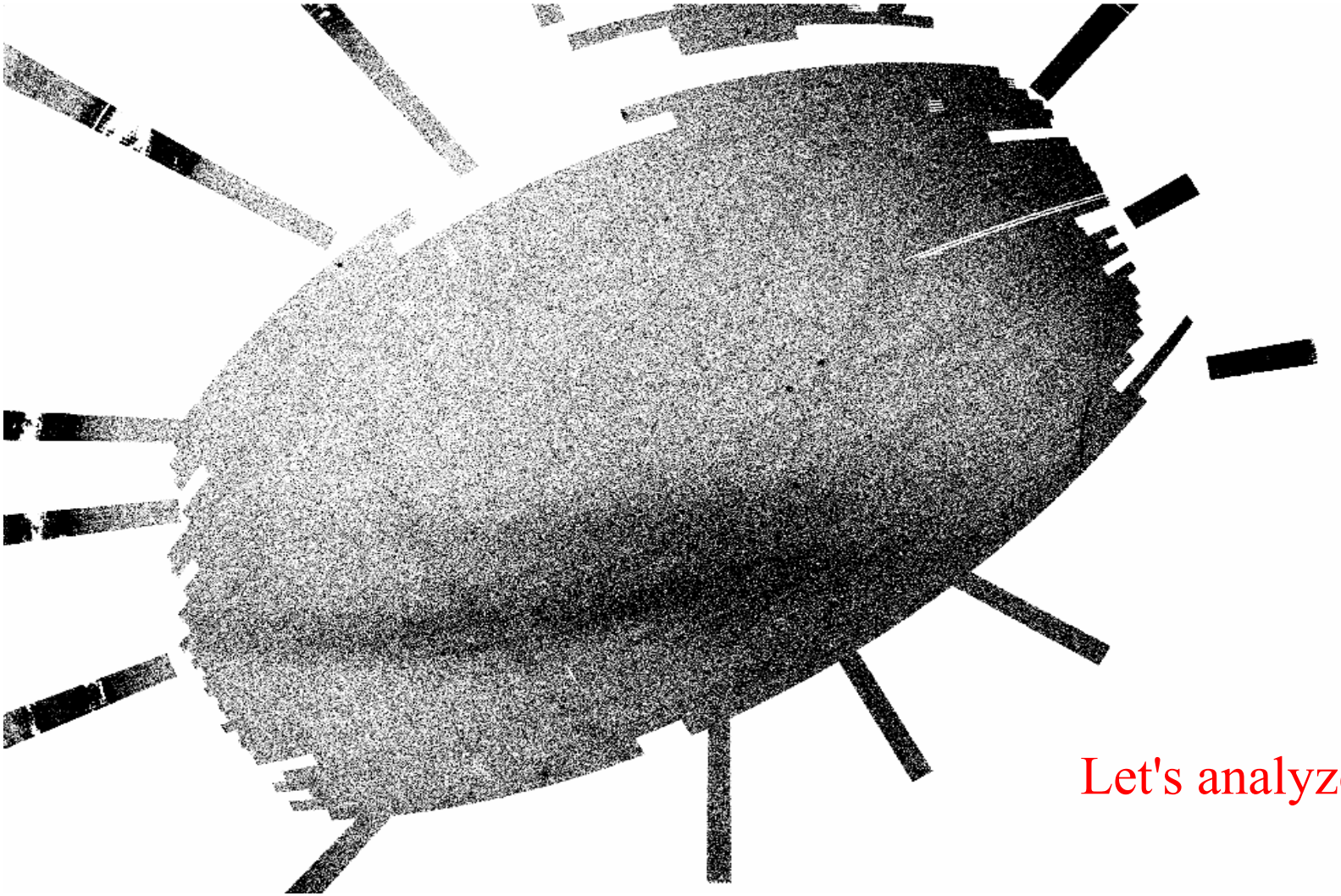
Using this data on the Milky Way rotation curve, we are ready to fit orbits...

Tracer star orbits within a 'log r' potential have a characteristic 'trefoil' shape:

(Toto, we're not in Kepler's Solar system any more)



Halo stars in tidal streams are excellent tracer objects, because, in addition to position (and a single velocity), one has a whole set of velocities along the stream which help to uniquely map out the orbit of the stream embedded within the Milky Way's Potential.



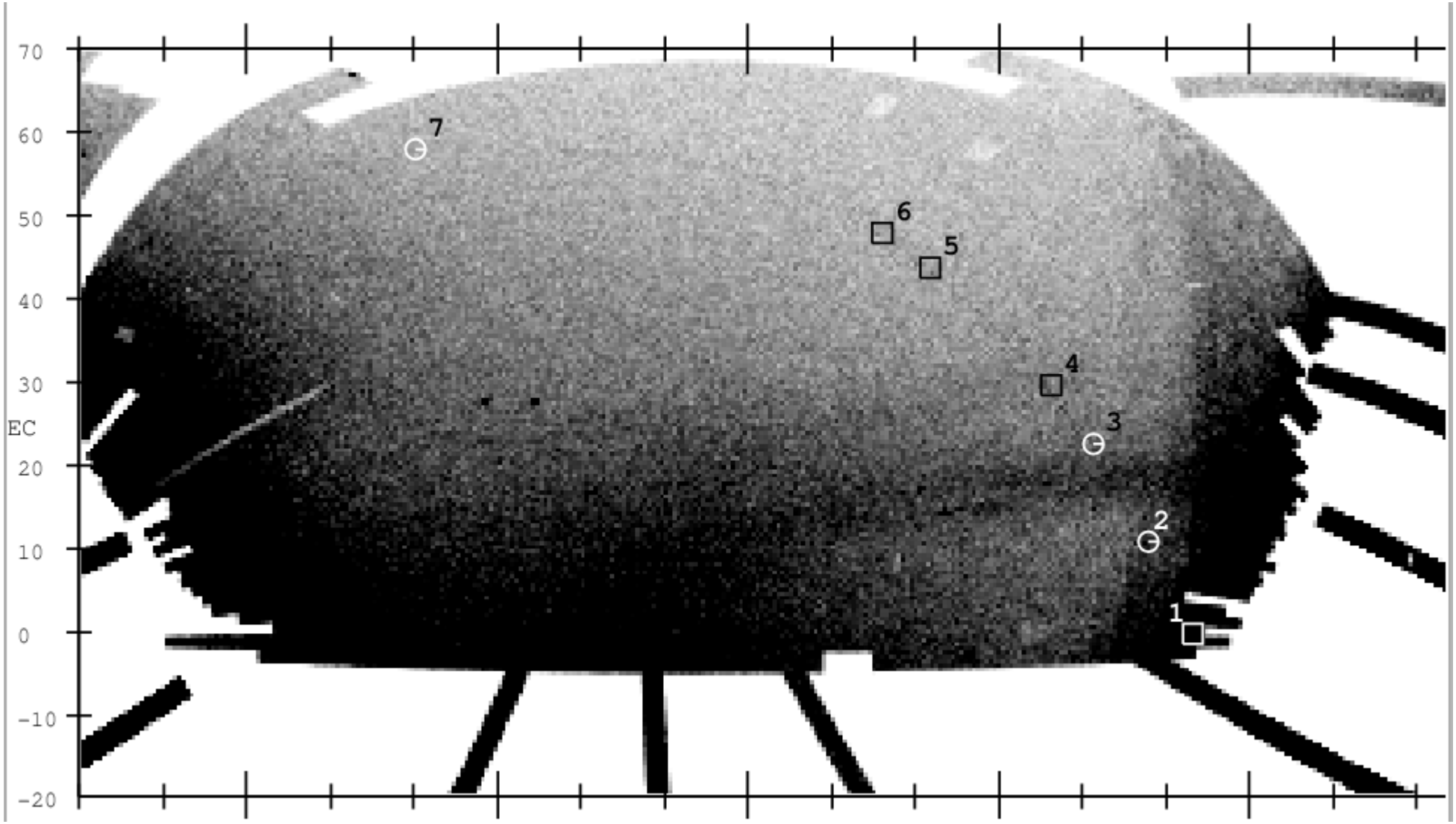
F stars at 10-20 kpc from Sun.

Center of plot is North Galactic Pole.

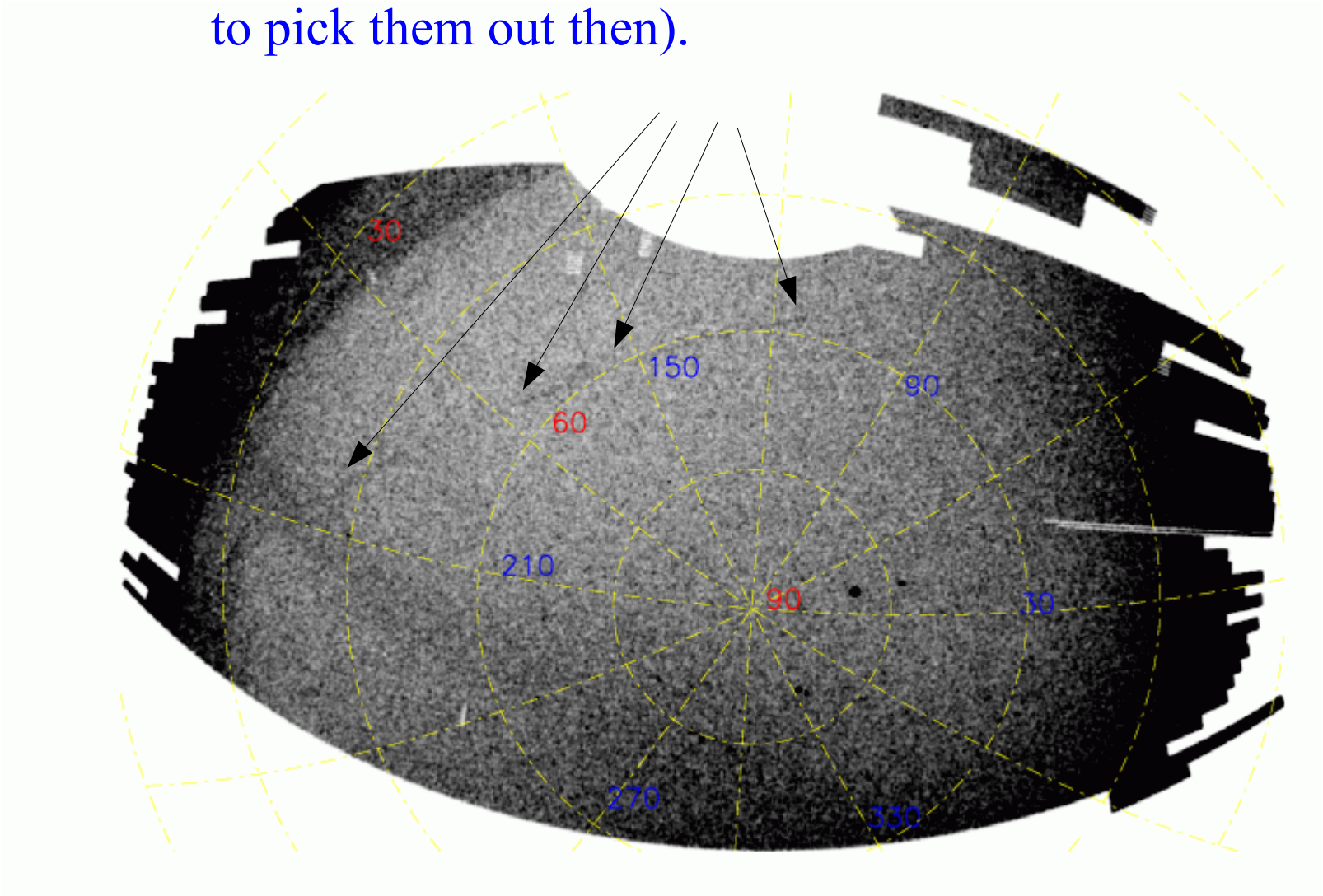
Let's analyze a halo stream....

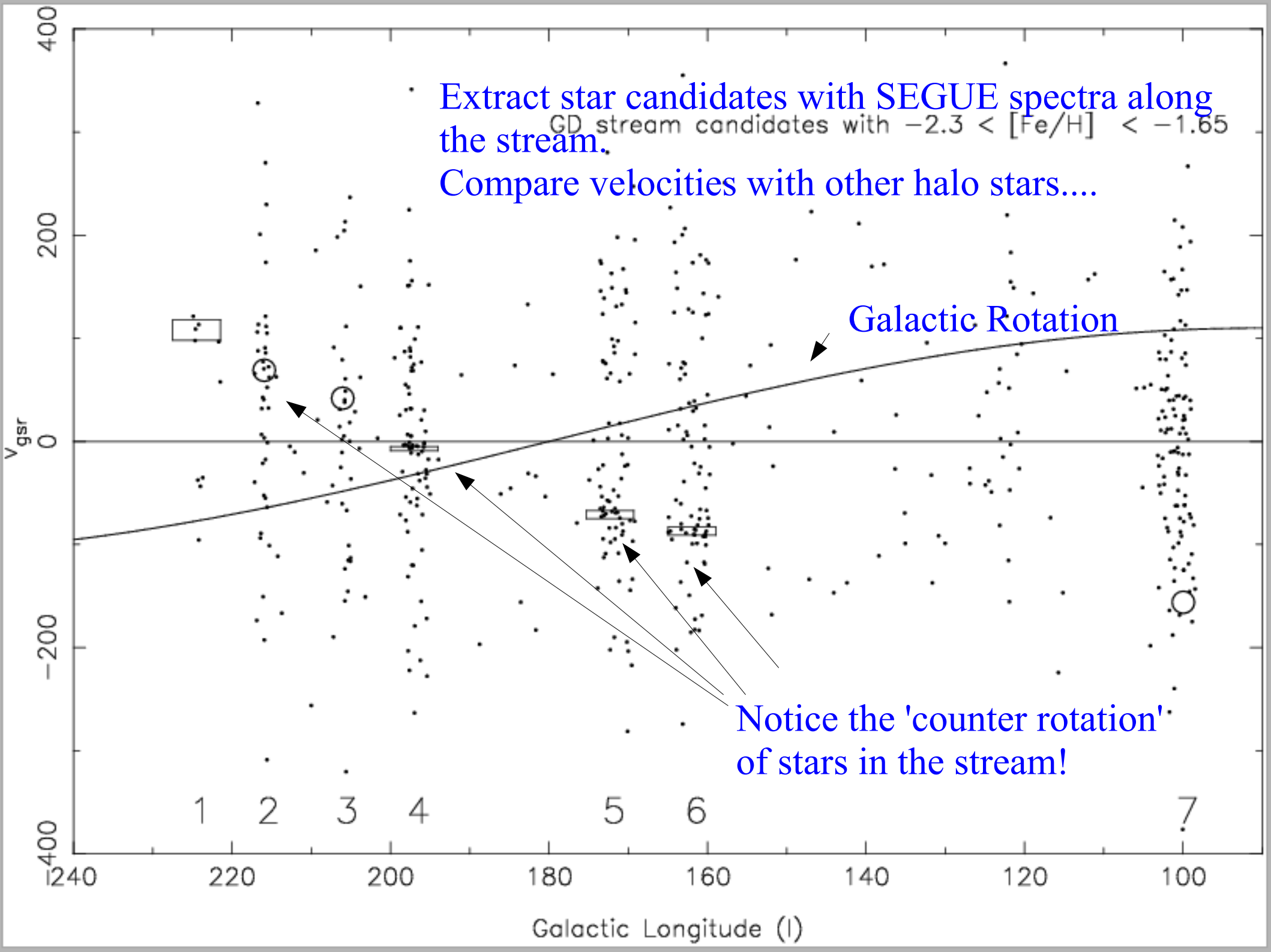
Another view of the “Field of Streams”

First stream to try: Grillmair-Dionatos (2006) stream.
It's nearby (~8 kpc from Sun), very thin and moving fast...



We geometrically distort the sky so that the stars in the stream lie along a straight line (easier to pick them out then).




GD stream candidates with −2.3 < [Fe/H] < −1.65
Extract star candidates with SEGUE spectra along the stream.
Compare velocities with other halo stars....
Galactic Rotation
Notice the 'counter rotation' of stars in the stream!
1
2
3
4
5
6
7
400
200
0
−200
−400
v_{gsr}
240
220
200
180
160
140
120
100
Galactic Longitude (l)

The Method to constraining the Dark Matter Potential of the Milky Way with SEGUE/SDSS data:

1. Identify a star stream photometrically, use photometric parallax for distances (x,y,z).

2. Isolate the stream, get as many spectra along the stream as possible, use metallicity and spectral type to help.

3. Get the velocities of the stream stars (v_parallel),
   and maybe proper motions (v_perp x2).

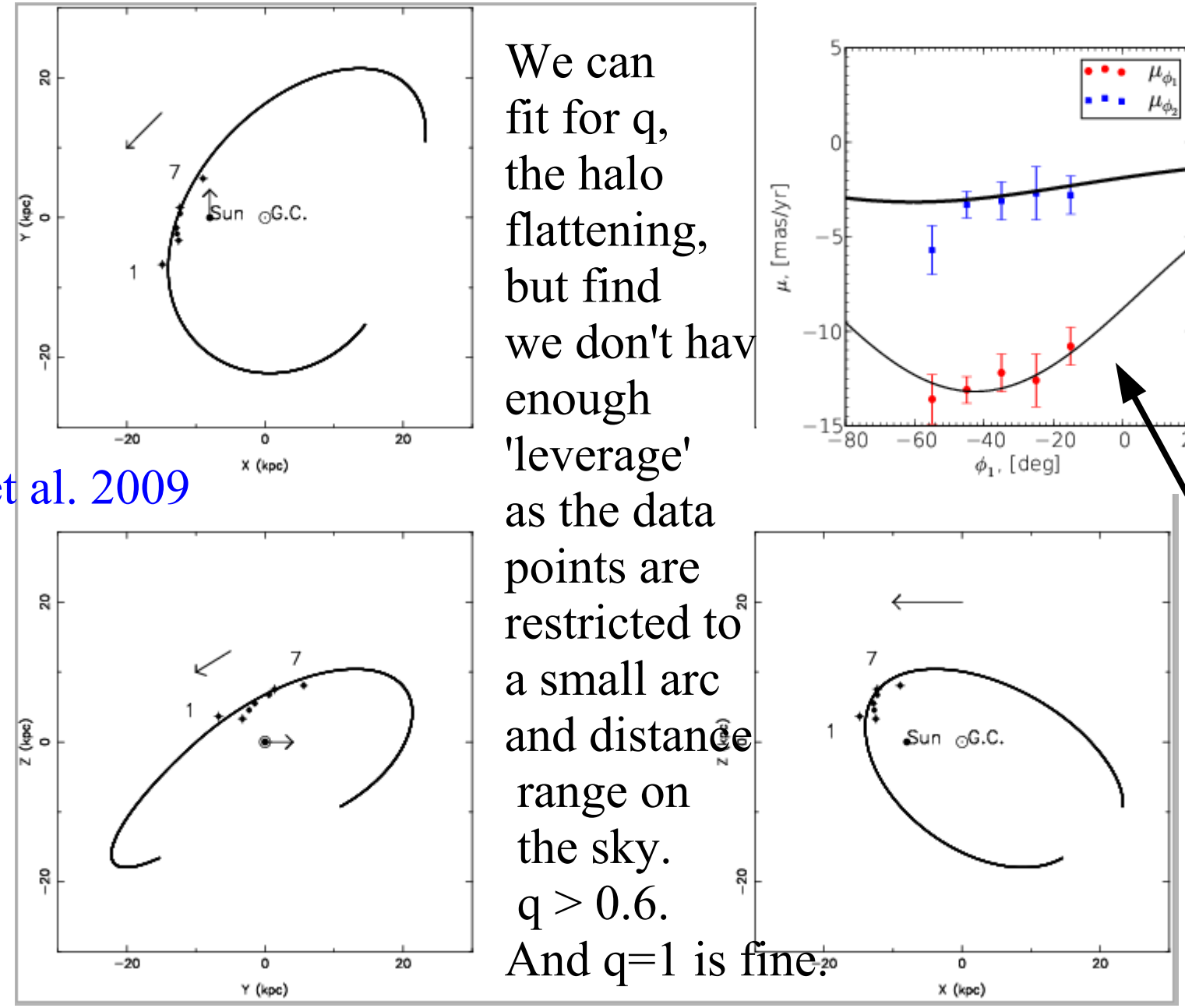
3. Model the stream, assuming 'Generic halo parameters' initially:
   Spherical Halo, Flat Rotation curve with v_c,max = 220 km/s to 50 kpc.

4. Get a Chi-sq for the model, tweak the halo parameters (and disk/bulge), and iterate back to step 3.

5. With best fit parameters, generate a N-body model to correct for the fact that the central orbit doesn't follow the actual orbit exactly.

6. Iterate if necessary. {NEW, more direct method: see Eyre and Binney 2009}

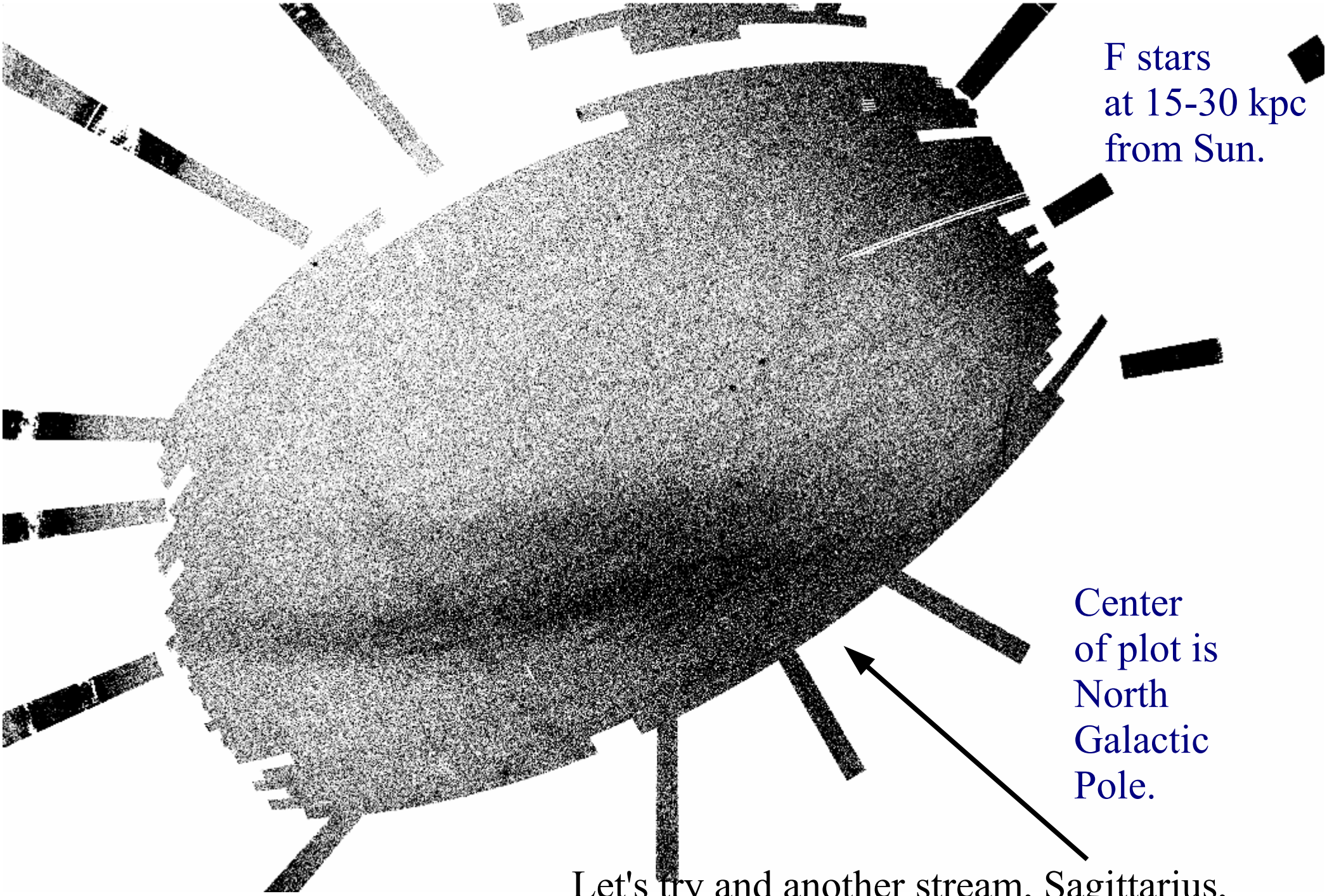
Here's the orbit for the Grillmair-Dionatos stream (note retrograde):



Willett et al. 2009

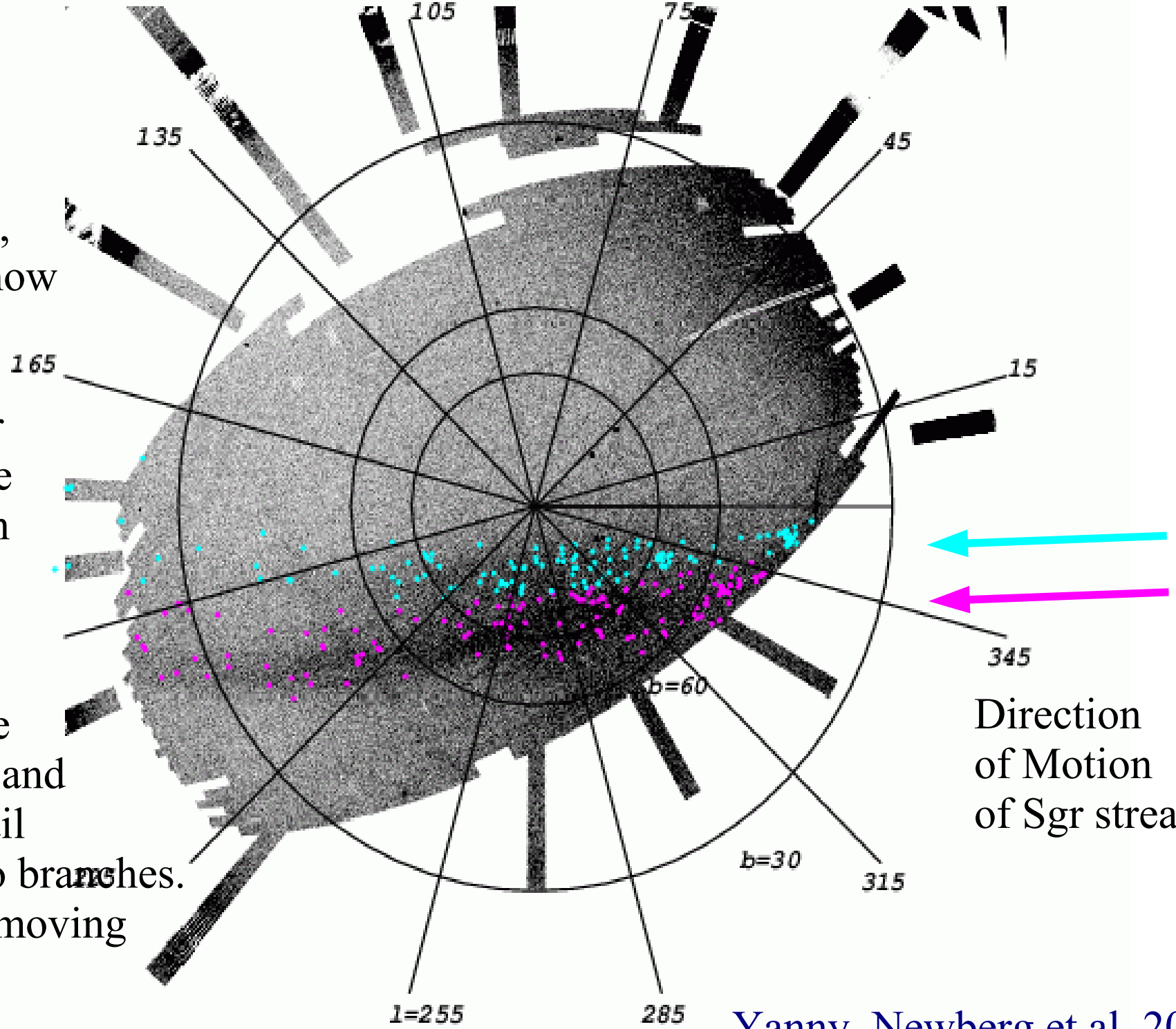
We can fit for q, the halo flattening, but find we don't hav enough 'leverage' as the data points are restricted to a small arc and distance range on the sky. q > 0.6. And q=1 is fine.

For retrograde stream, at d=7 kpc proper motions are available! Koposov, Rix and Hogg 2009 have fit stream too, find q_phi > 0.9



Let's try and another stream, Sagittarius, the `elephant in the sky.'

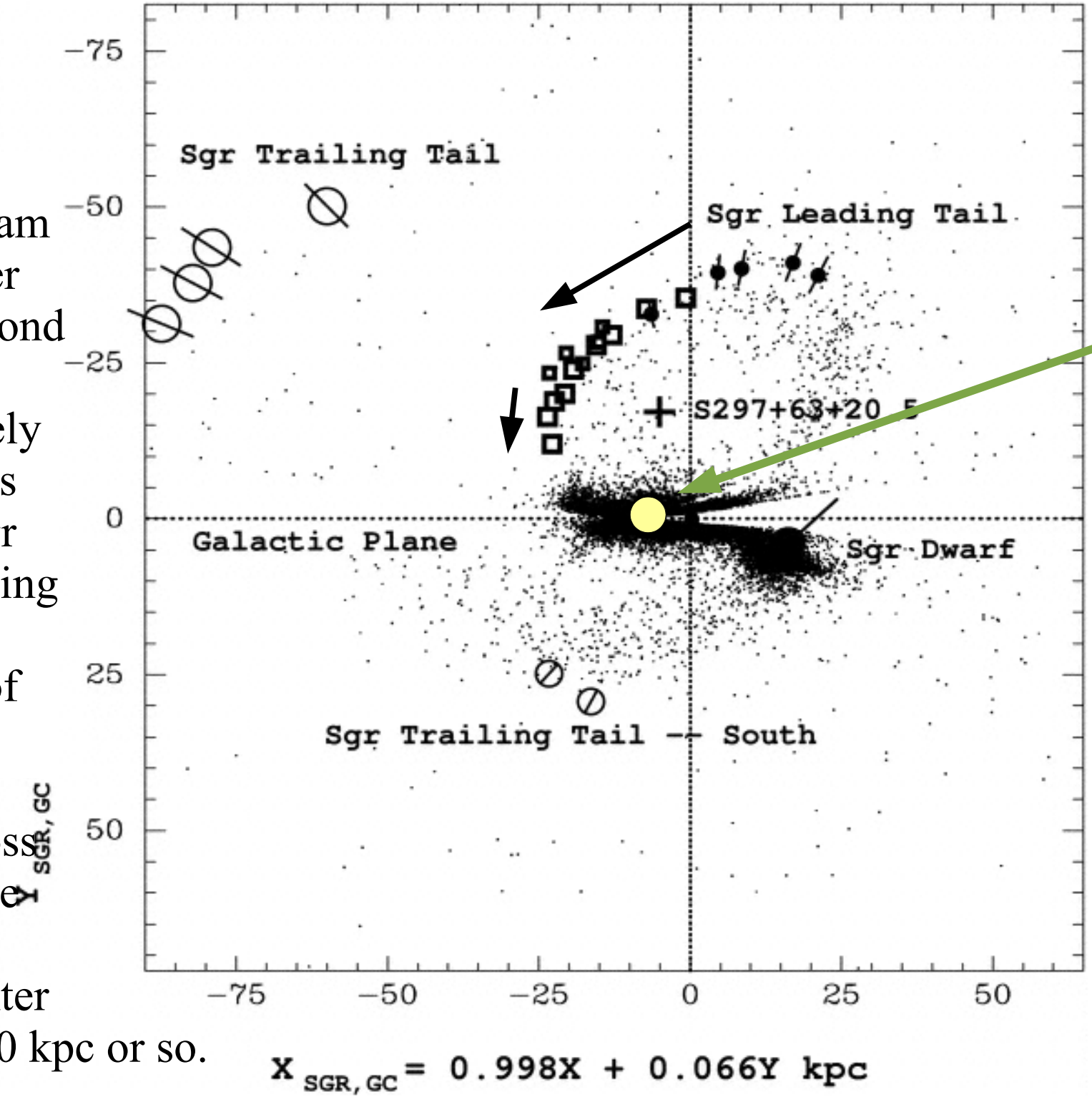
We have SEGUE velocities, we can show that both branches of the Sgr stream are moving in the same direction. i.e. We don't have a leading and trailing tail in the two branches. Both are moving together.



Direction of Motion of Sgr stream.

Yanny, Newberg et al. 2009

We also know that the Sgr stream arcs over and beyond the sun. Relatively few stars from Sgr are 'raining down' on top of the sun. Rather, they cross the plane in the anti-center at X=-20 kpc or so.

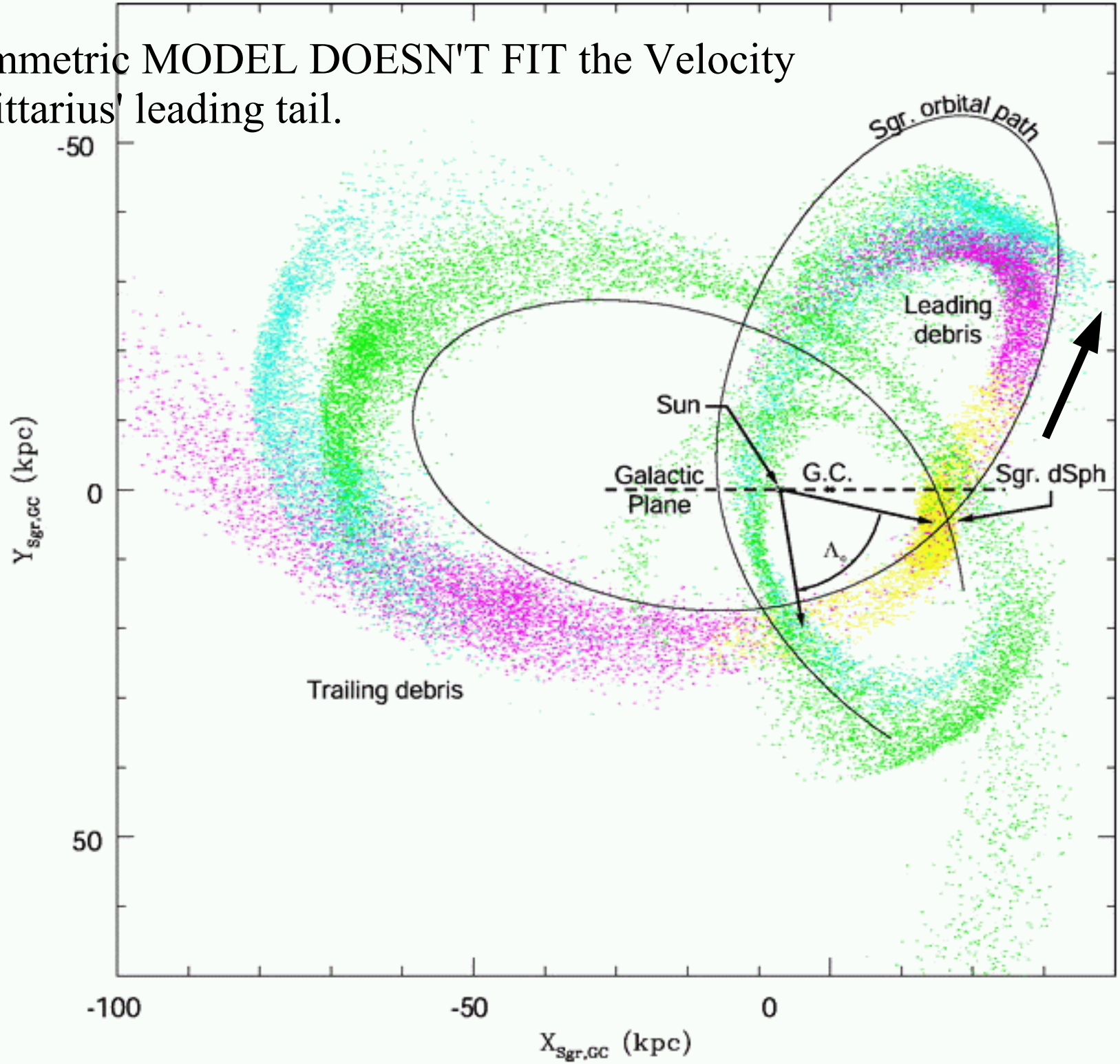


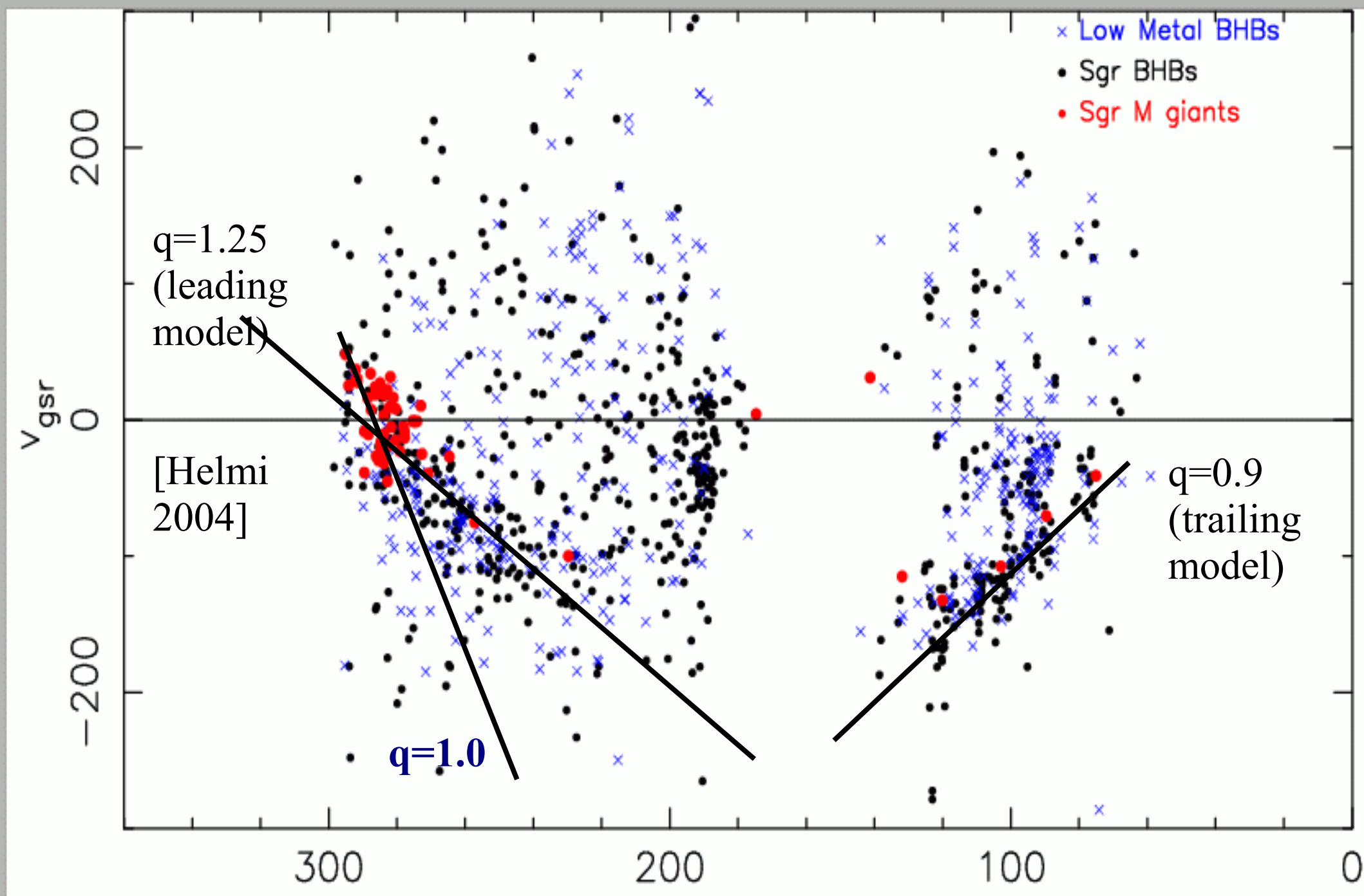
Sun

Thus, there should be no strong Dark Matter lumps due to Sgr at the Sun.

THIS Axisymmetric MODEL DOESN'T FIT the Velocity Data for Sagittarius' leading tail.

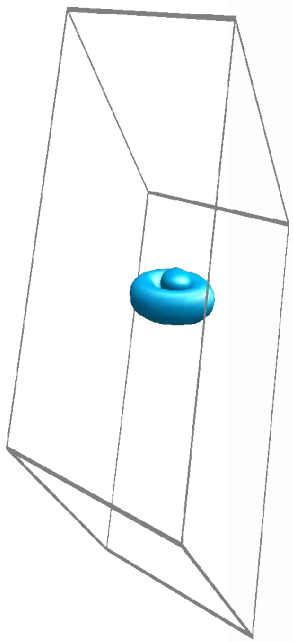
From Law, Johnston and Majewski 2005.

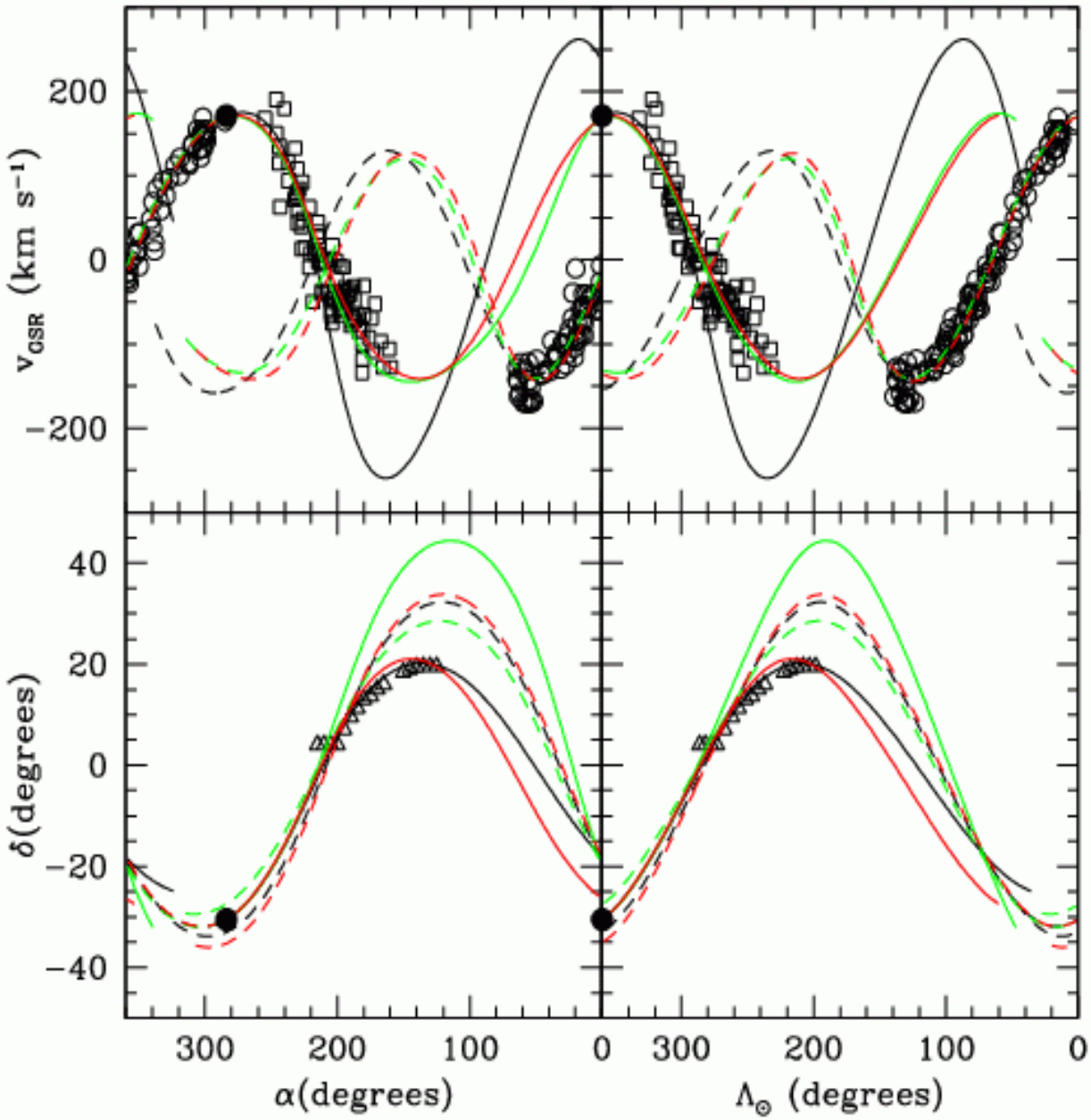




The problem is that the leading tail velocities are 'too flat'. A prolate axi-syn
halo is required for leading tail and an oblate/spherical halo for the trailing.

If you relax the axisymmetric assumption, and give the Milky Way a triaxial halo, rotating about it's middle-length axis, then you can fit both the positions and the velocities simultaneously. (Law, Johnston, Majewski 2009)





The problem is: That solution is unstable, the triaxial halo will tumble and cause all sorts of visible warp effect in the Milky Way disk on short timescales.

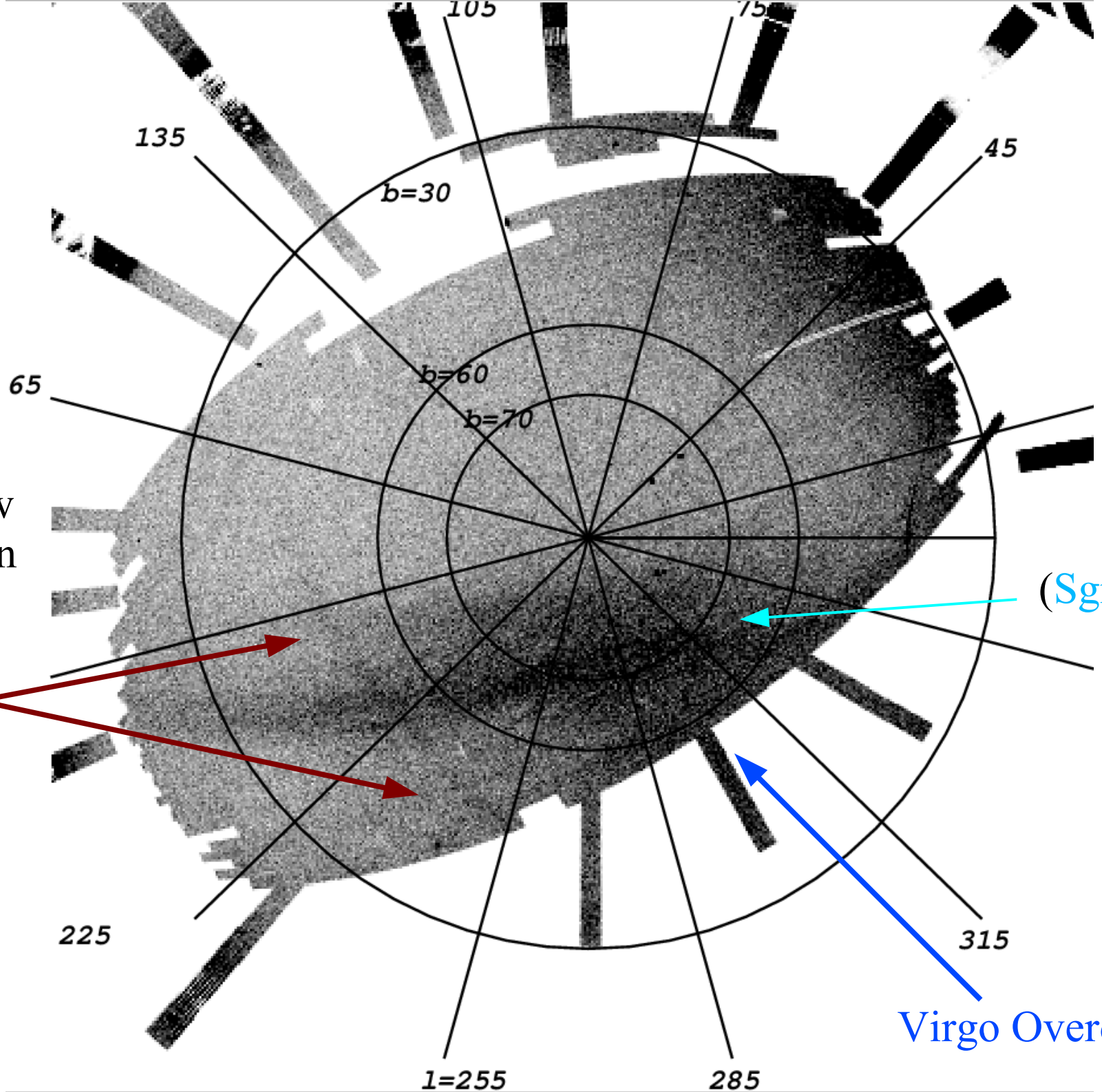
So, after fitting two stream's worth of data,
we find ourselves in the same position as Goldilocks,
having tried out the too small chair and the too big chair...

Grillmair-Dionatos Stream: q_halo=1+/-0.4.
--small range in distances from the sun (Galactic center)
of about 7-10 kpc (at least where we can see it).
Stream is too limited in extent on the sky.

Sagittarius Stream: Too complicated! Big mess on the sky.
Collision? More sophisticated models needed.
Hint that triaxial halo is needed (Law et al 2009),
but that triaxial model rotates about
it's 'middle length axis'...and that is unstable (Binney 1981).

Is there another stream that's `just right'?

....



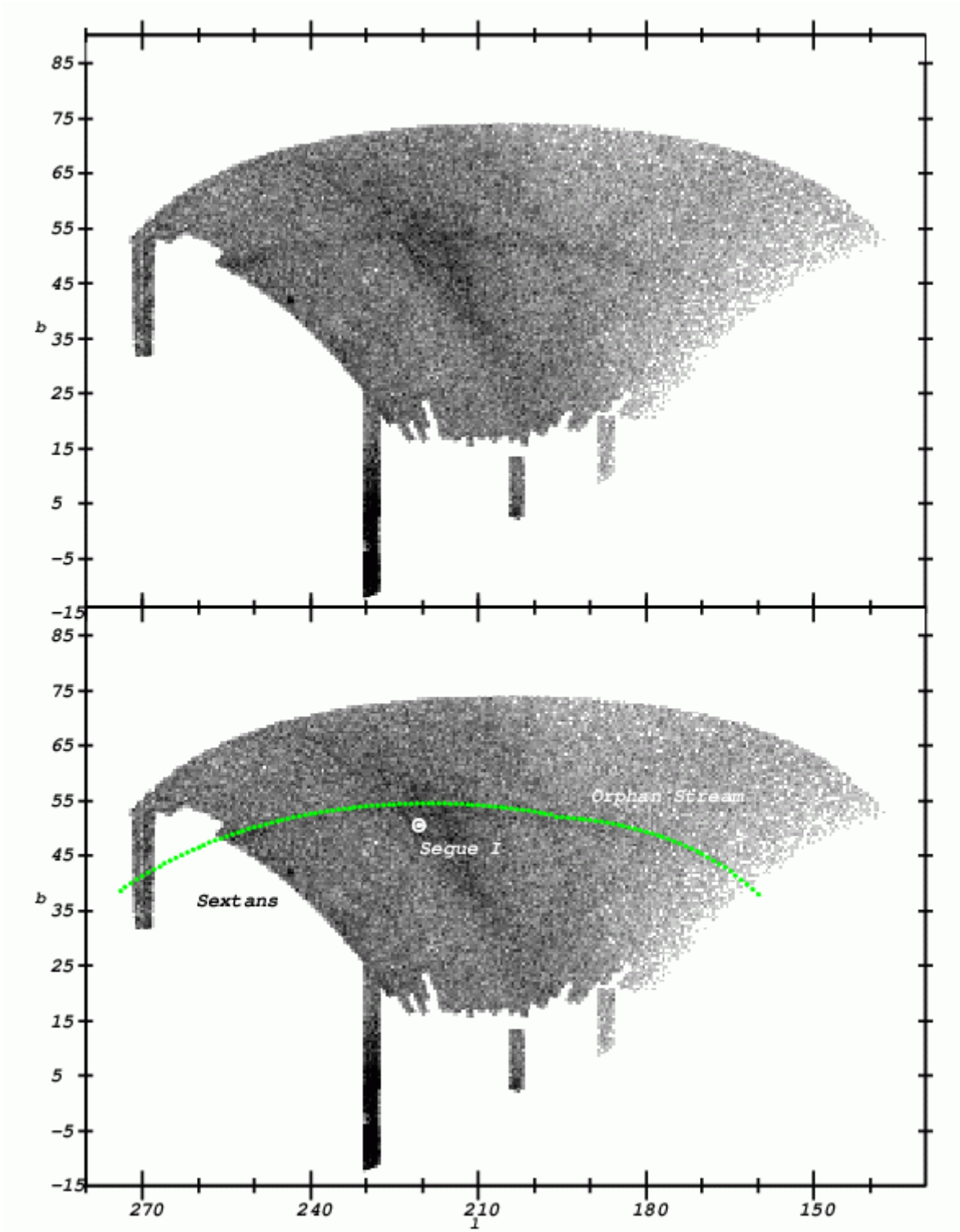
We now focus on the:

Orphan Stream!

(Sgr stream)

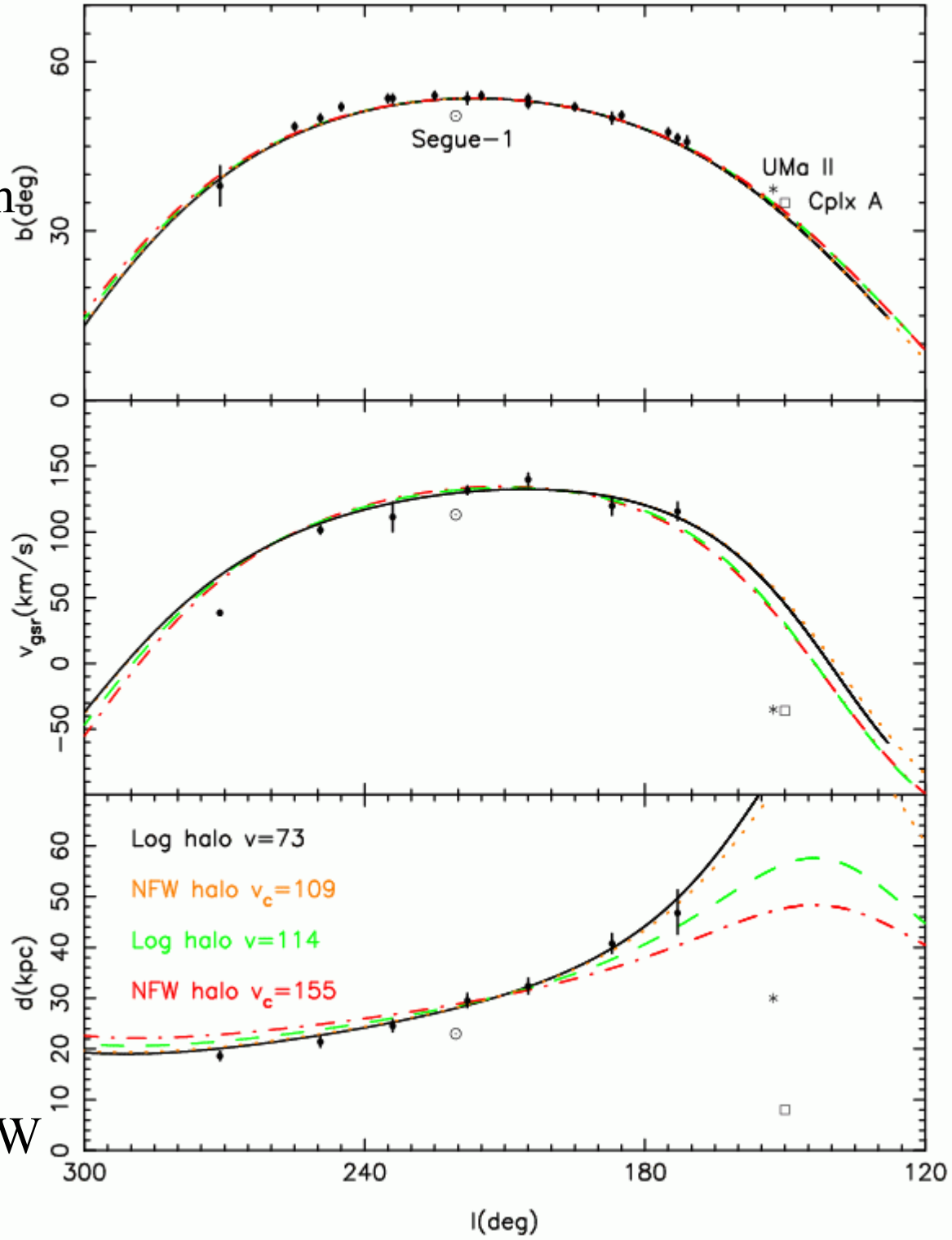
Virgo Overdensity

The Orphan Stream in (l,b) rectangular coordinates.



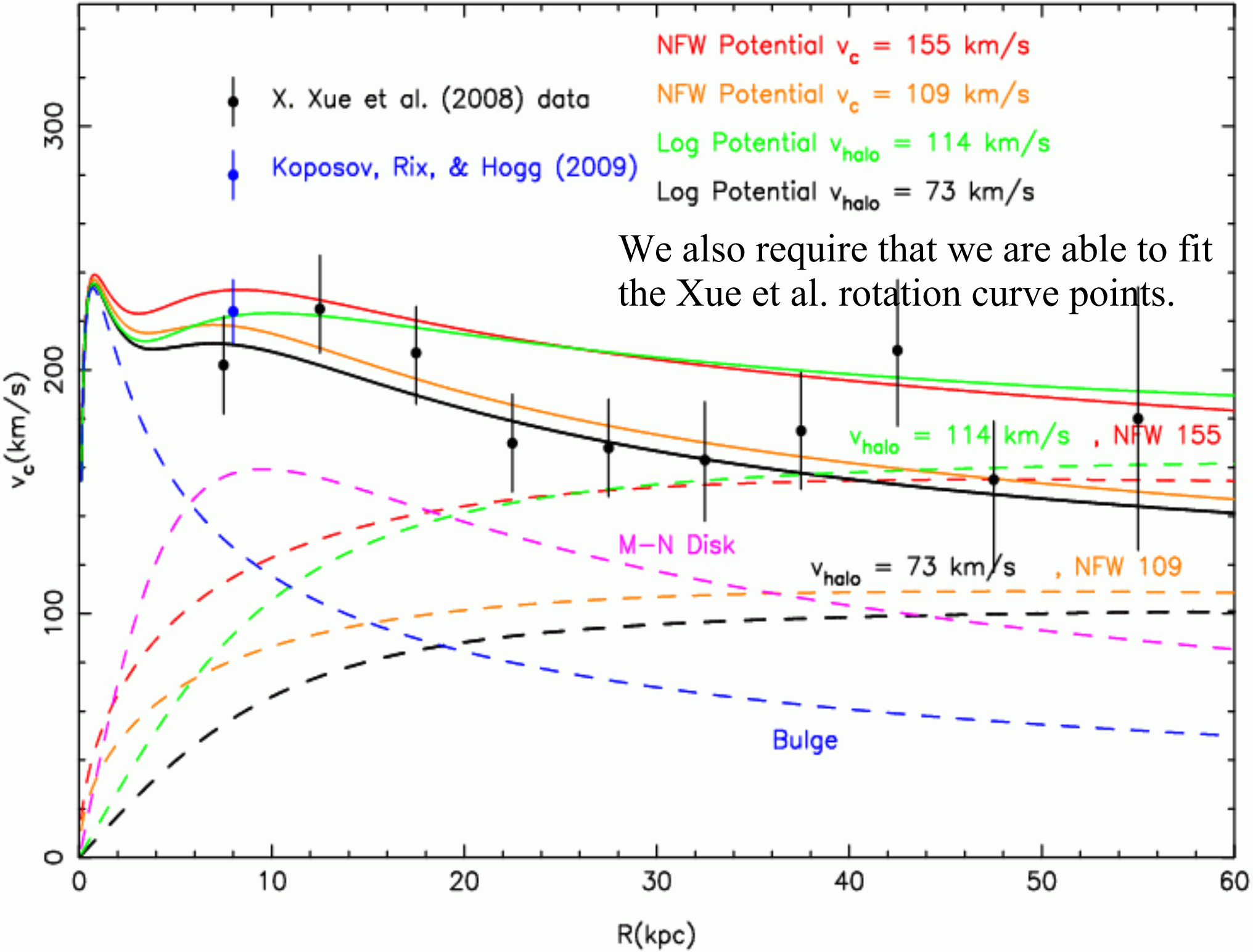
We extract stream member stars along the stream with accurate positions, velocities, and distances:

To these we fit a set of Potential models, varying the strength of the potential and form of the potential (NFW vs. logarithmic)



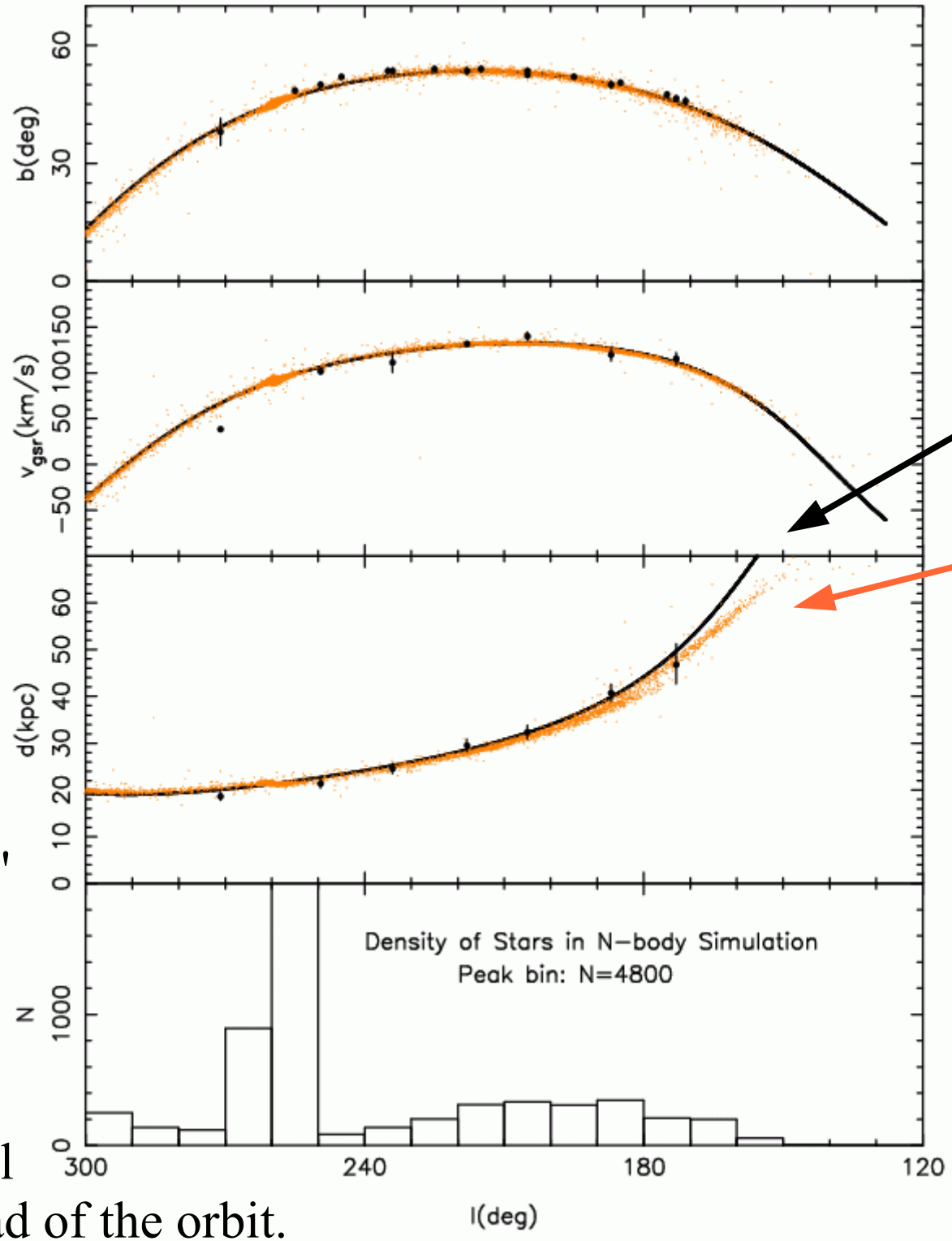
To fit for q, we need streams in different parts of the sky to fit simultaneously. This is future work (Willett et al. 2010 in prep).

Thus, q=1.0 assumed here and not fit.



We also require that we are able to fit the Xue et al. rotation curve points.

Once we have a potential that fits the 'thin narrow orbit', we run an N-body code which tracks the 'finite internal dispersion of the stream's stars' This leads to systematic deviations with distance as the leading tail stars 'droop' ahead of the orbit.



Black 'center of orbit' track

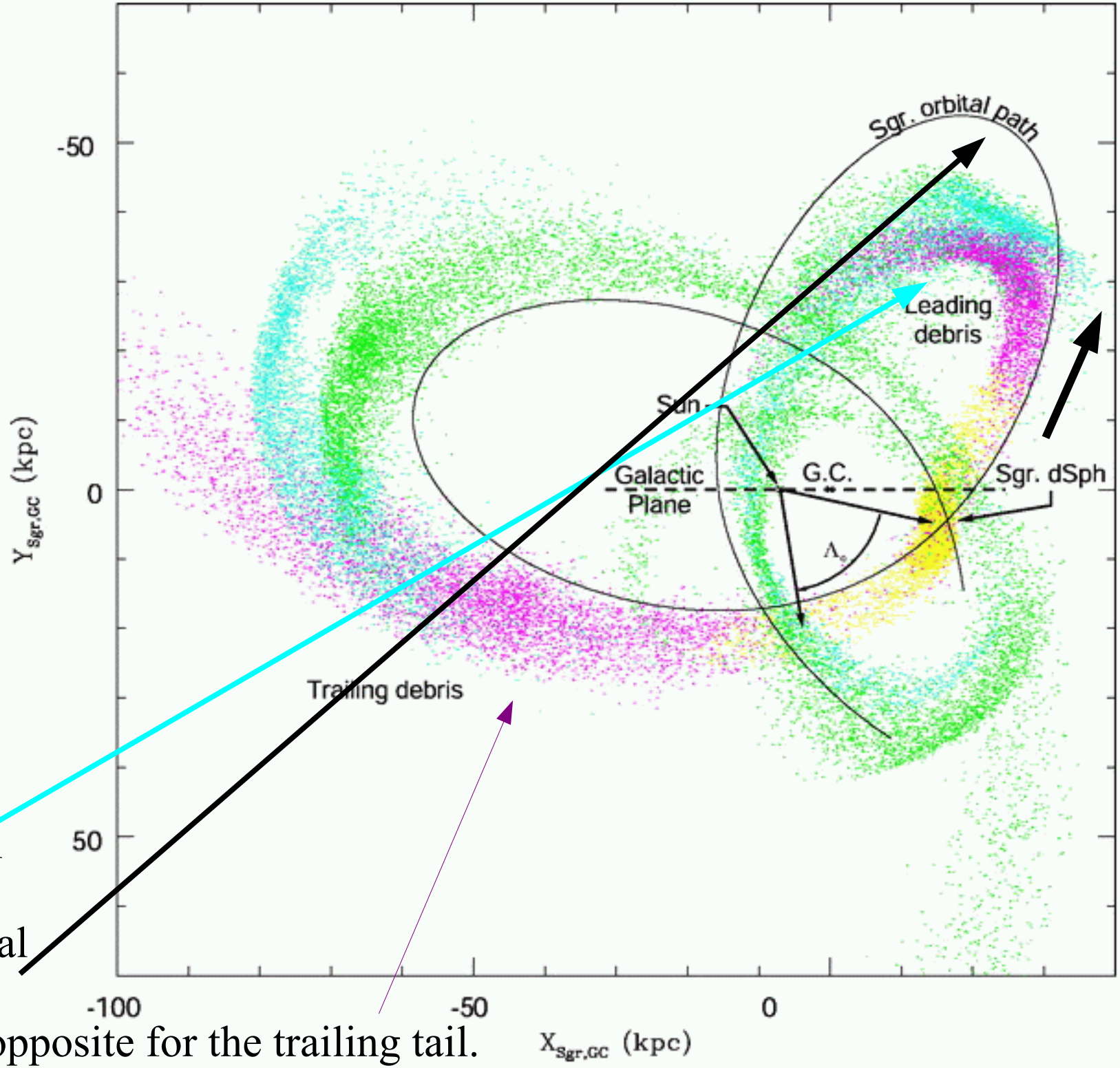
N-body leading tail stars fall 'closer' to G.C.

We also can measure the density of stars along the orbit with the N-body.

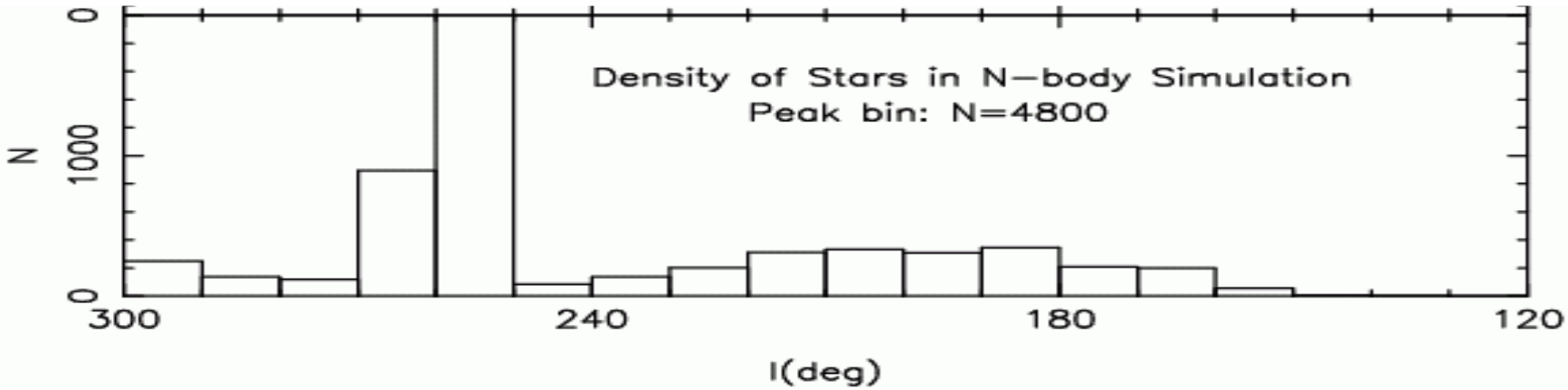
From Law, Johnston and Majewski 2005.

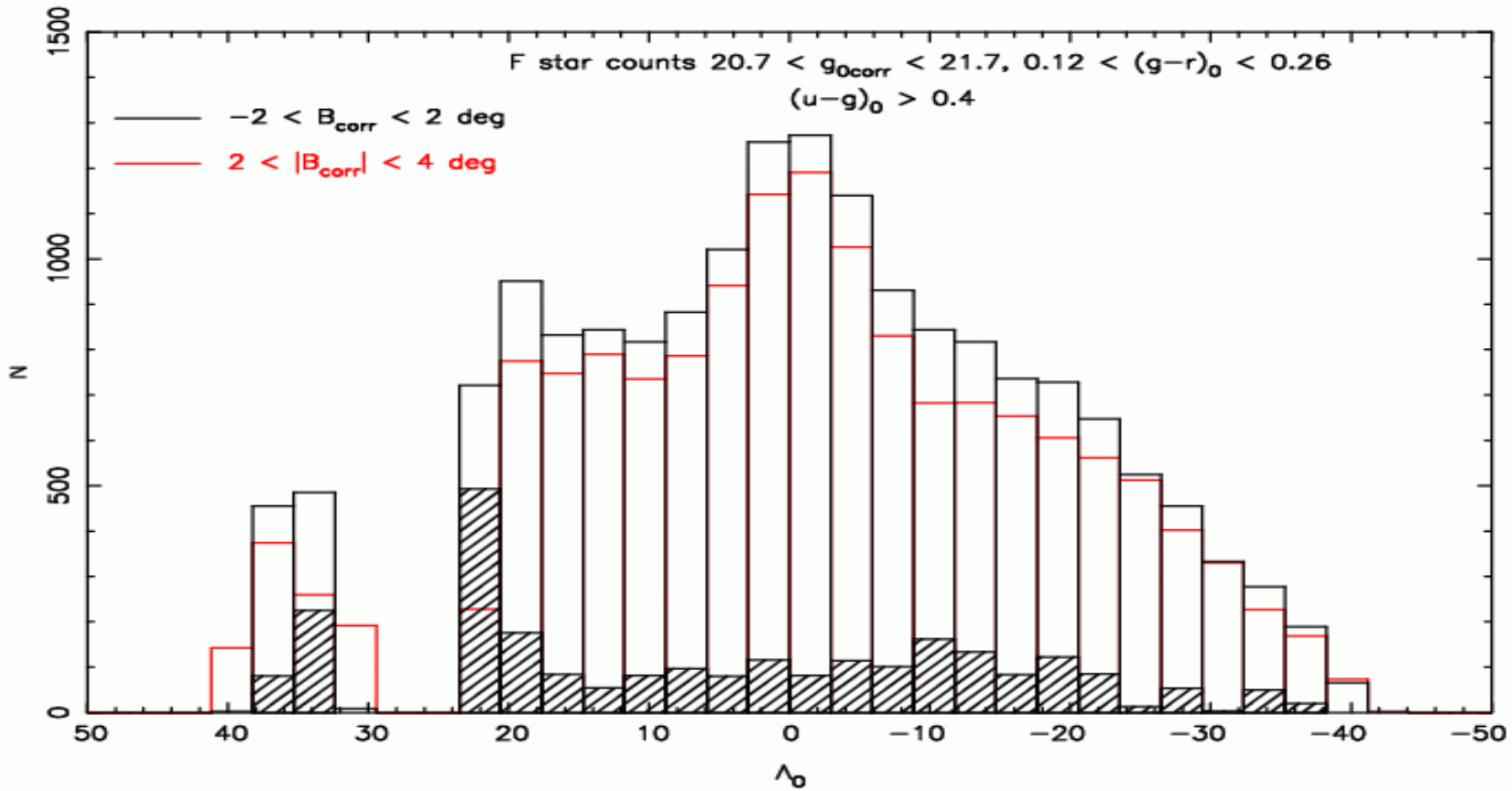
This is for the Sgr stream, but note how the N-body of the leading tail 'droops' in compared with the central orbit.

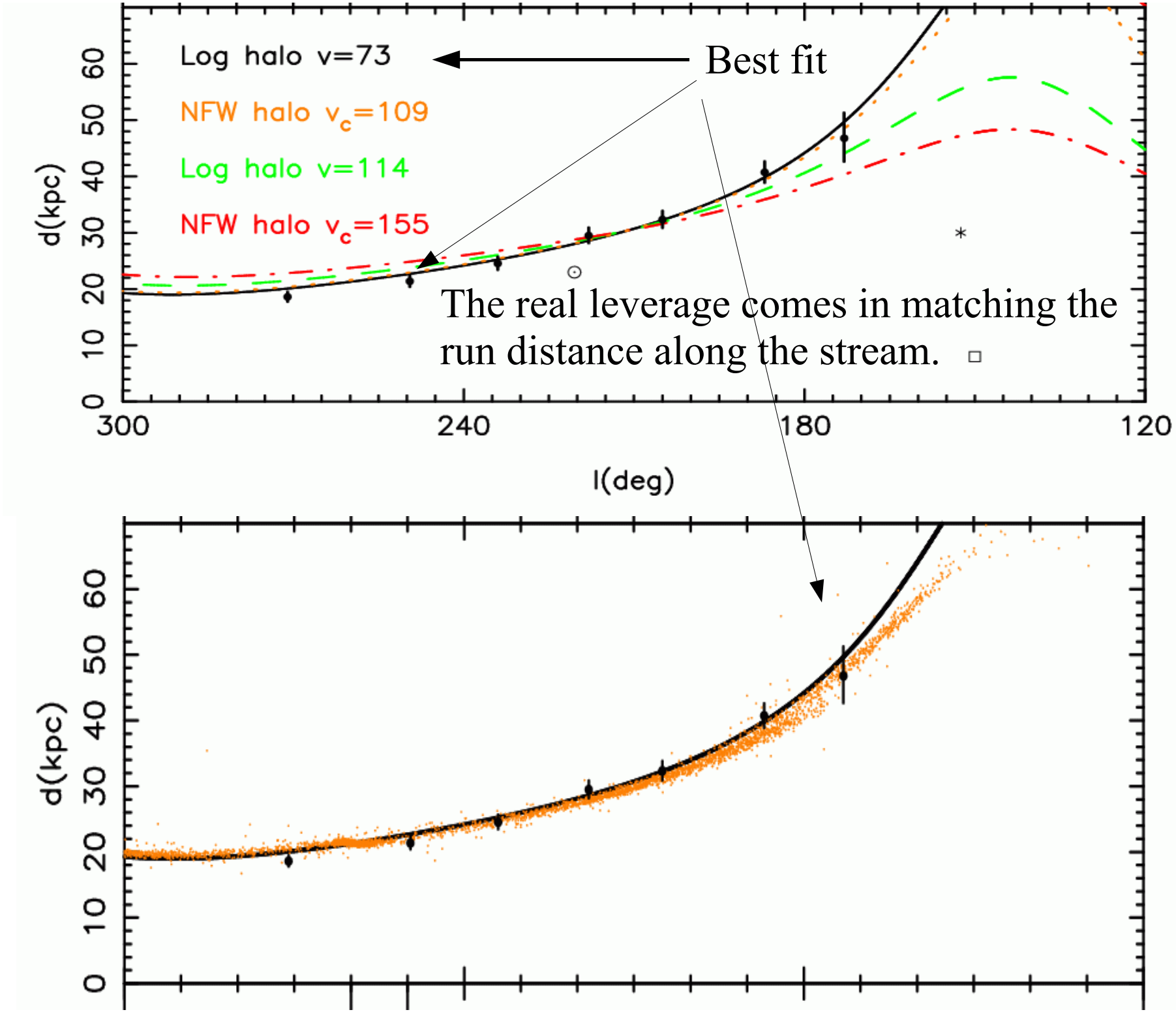
The effect is opposite for the trailing tail.

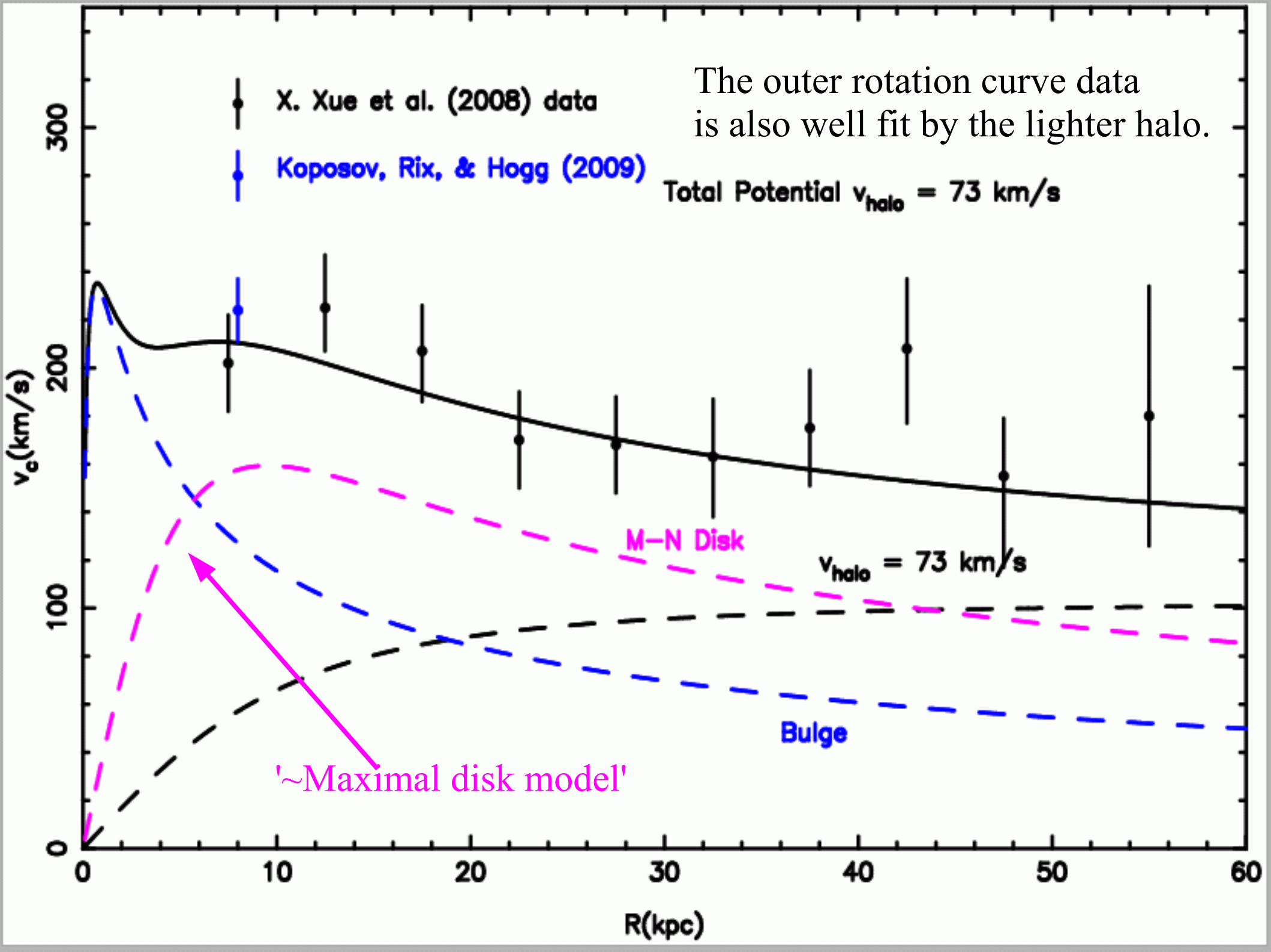


The N-body density match to the data is excellent!






Log halo v=73
NFW halo v_c=109
Log halo v=114
NFW halo v_c=155
Best fit
The real leverage comes in matching the run distance along the stream.
d(kpc)
l(deg)
300
240
180
120
0
10
20
30
40
50
60


The outer rotation curve data
is also well fit by the lighter halo.
X. Xue et al. (2008) data
Koposov, Rix, & Hogg (2009)
Total Potential v_{halo} = 73 km/s
M–N Disk
v_{halo} = 73 km/s
Bulge
'~Maximal disk model'
v_c(km/s)
R(kpc)
0
100
200
300
0
10
20
30
40
50
60

So the new conclusion is:

The Milky Way's dark matter halo component, as probed by the Orphan stream at distances of 20-40 kpc from the Sun (and Galactic center) is about 0.5 to 0.75 as massive than previously thought (though earlier constraints were weak).

The total mass of the Milky Way, out to R= 60 kpc from the Galactic center is about 0.3 Trillion solar masses:

$$M_{\rm total}(R < 60 \text{ kpc}) = 2.65 \times 10^{11} {\rm M}_\odot$$

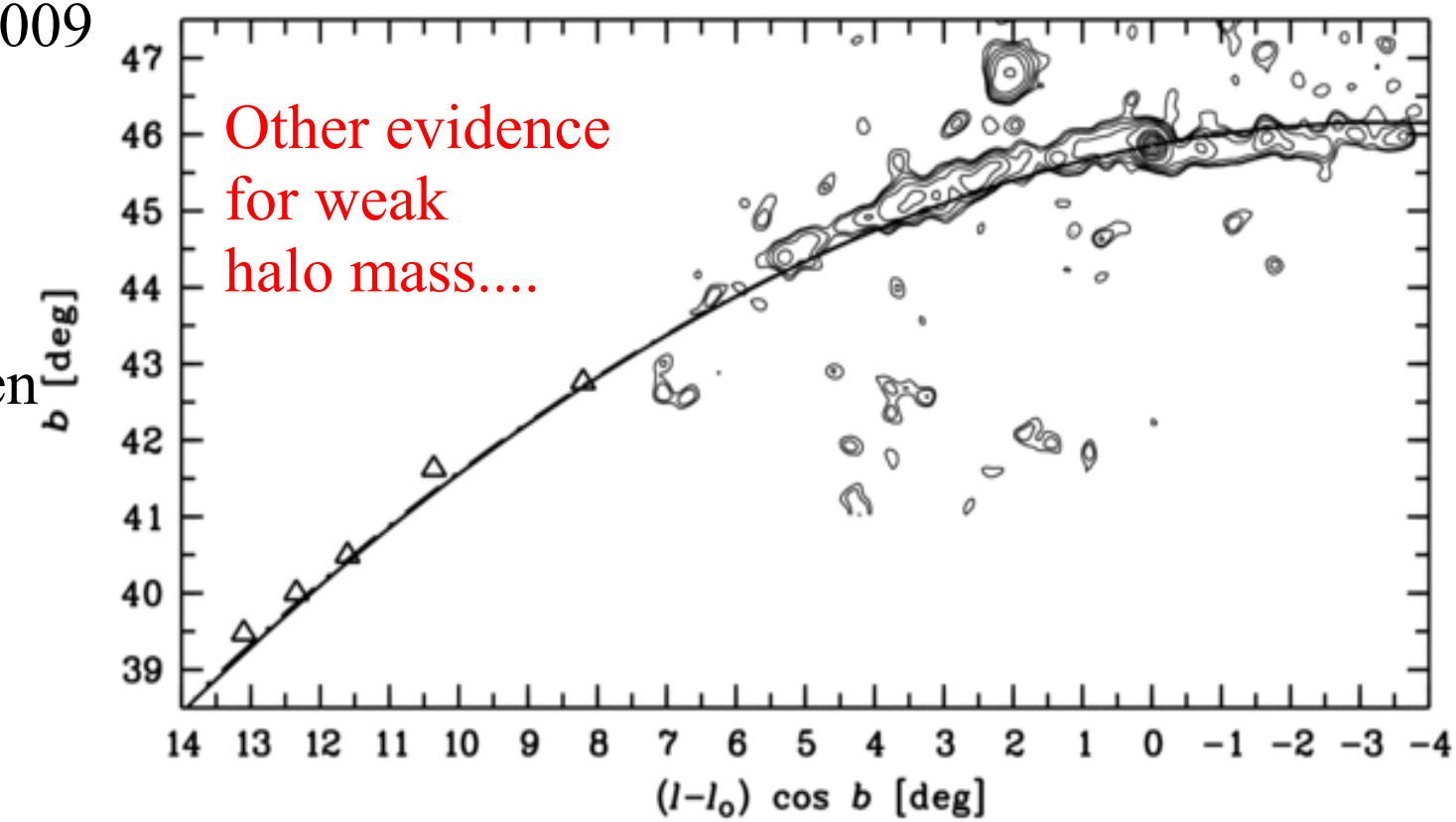
The error bar is significant, about 40% currently, but we hope to reduce that. Still, this is at least a factor of 2 less than most earlier 'Mass of the Galaxy' measurements from PN, HII, LMC orbit, escaping stars estimates (which come in at about 1 Trillion M_sol).

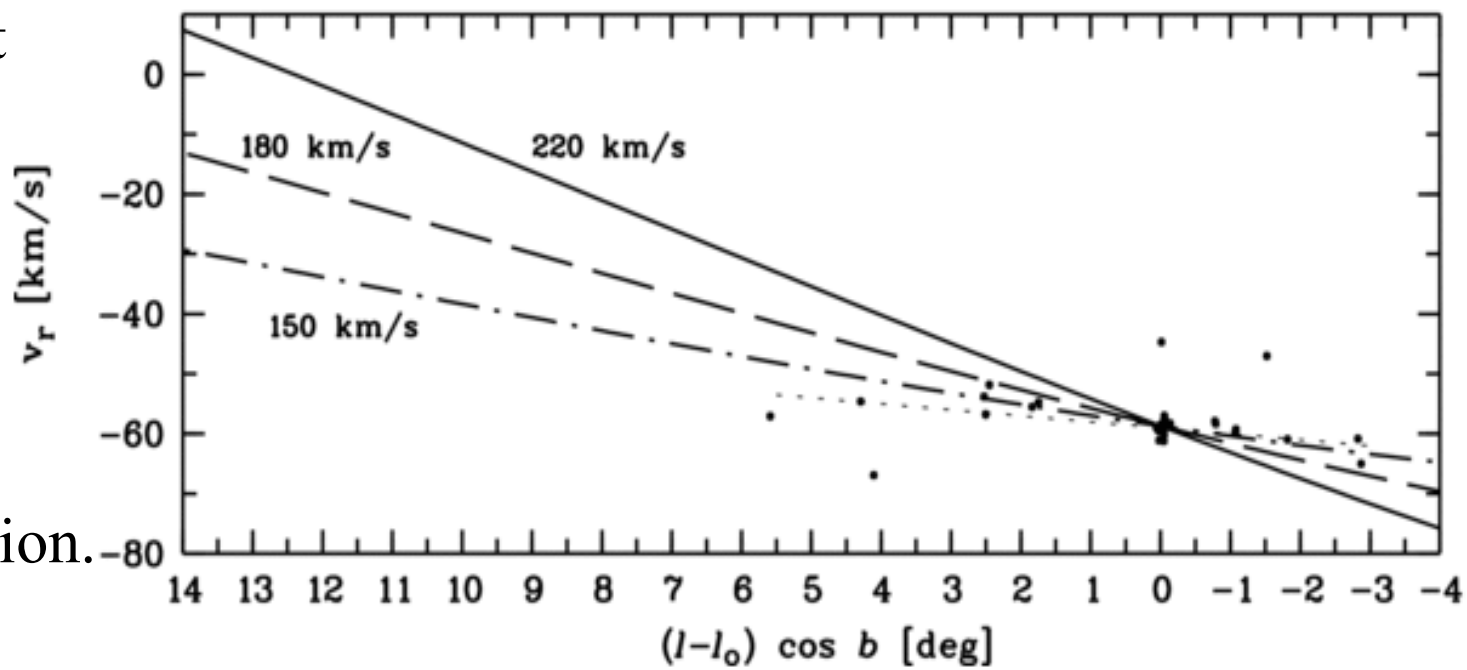
Newberg, Willett, Yanny 2009 ApJ in prep.

Odenkirchen et al. 2009 actually also found data consistent with this very same result (very low dark halo mass) when analyzing the kinematics of the Pal 5 tidal stream.

They attribute it, however, to a geometric effect of the stream's orientation along the line of sight.

We suggest that a lighter halo is the simpler explanation.





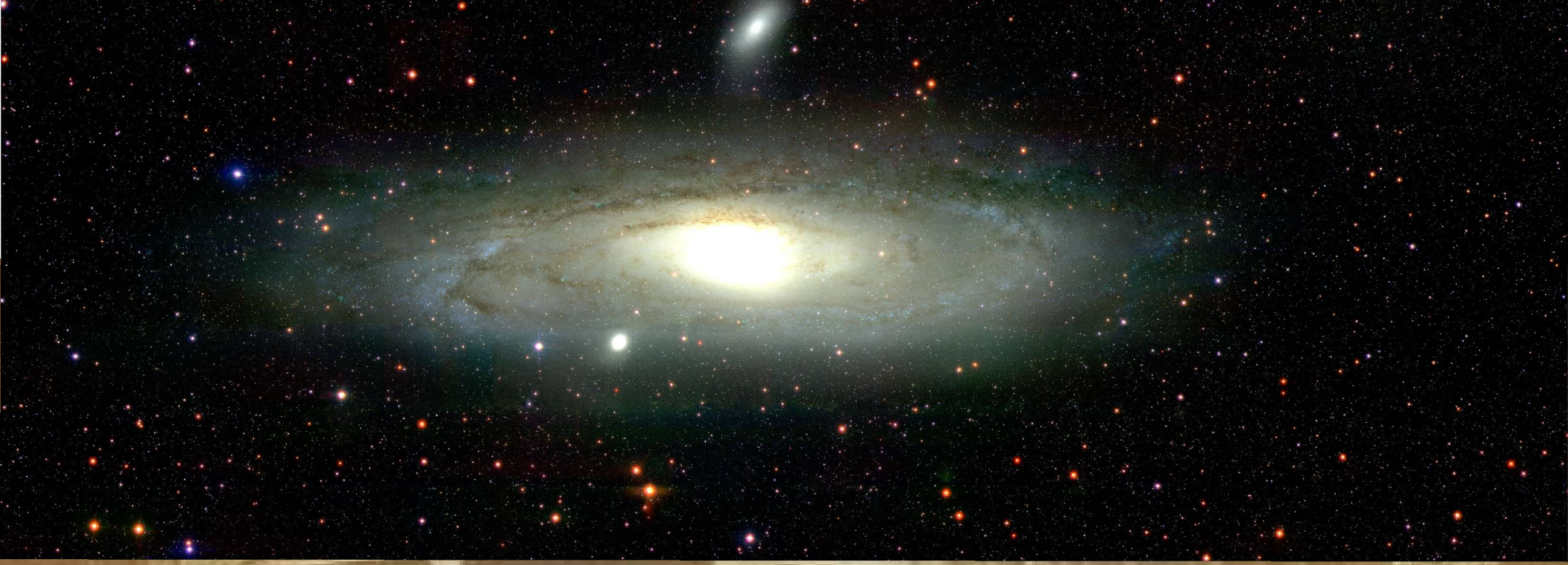
Some Conclusions about the Dark Matter in our Halo from SEGUE data (so far):

•Based on the Orphan stream run of velocity and distance vs. position, the total amplitude of the halo portion of the Galactic potential appears to be somewhat smaller than previously expected, implying as much as a factor of 2 less total mass to the Dark Matter halo.

•Any dark matter enhancement from the Sgr stream in the solar neighborhood is likely to be negligible – The stellar portion of the stream arcs over the sun and passes through the plane at R=20 kpc toward the anti-center (Sun is at R=8 kpc).

•Constraints on 'q' the flattening of the halo are still to come, but they are likely in the range 0.6 < q_density < 1.3, with a nearly spherical halo not ruled out.

•There may be some triaxiality to the halo – but how much, and how it is oriented, is not yet clear. More stream analysis needed!



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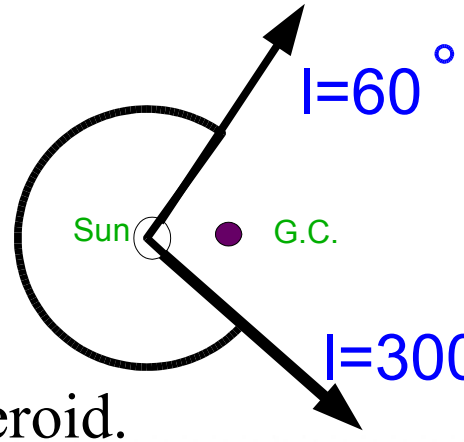
http://www.sdss.org

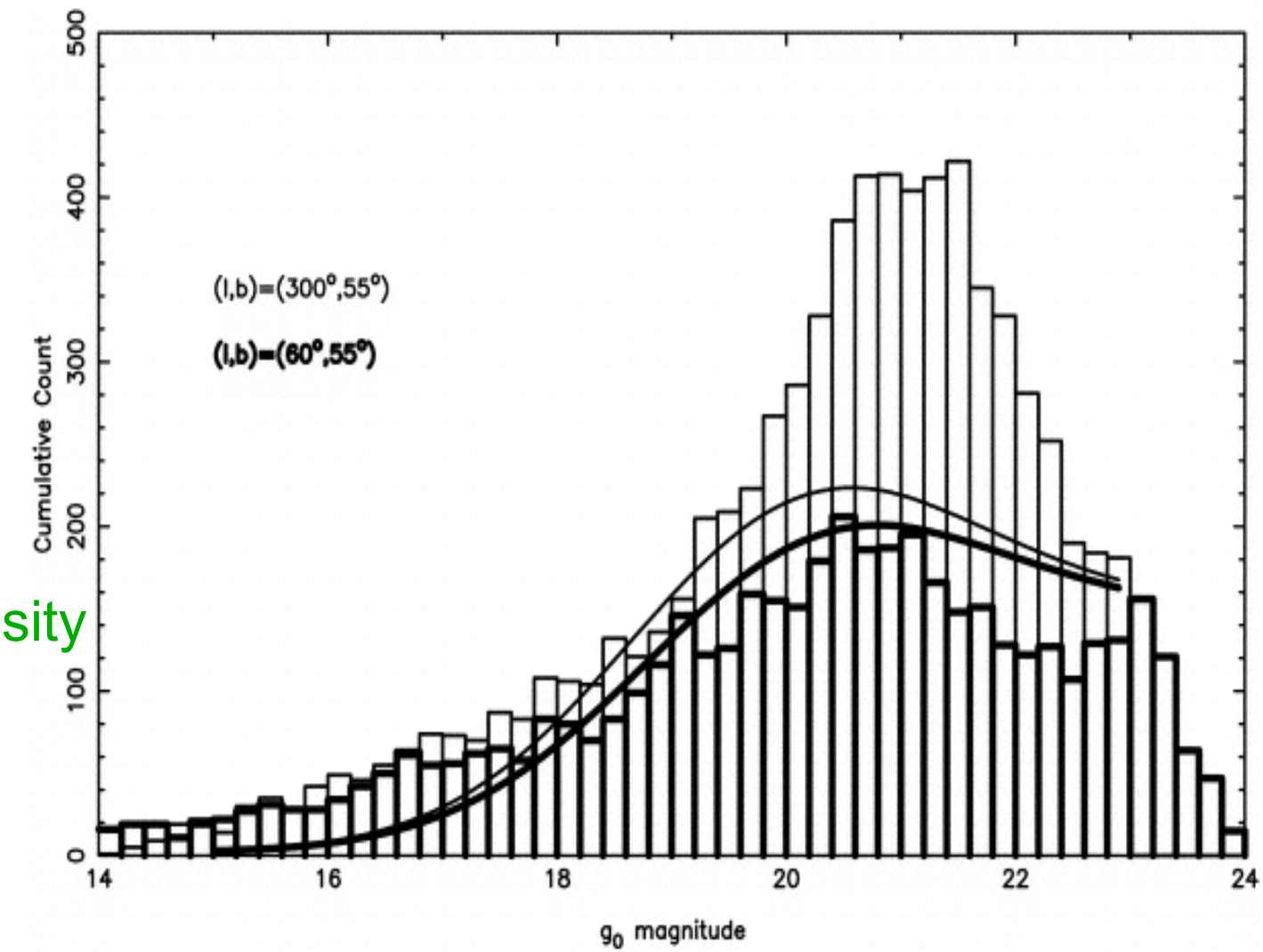
There may in fact be a slightly triaxial dark halo, and there appears to be a triaxial stellar spheroid.

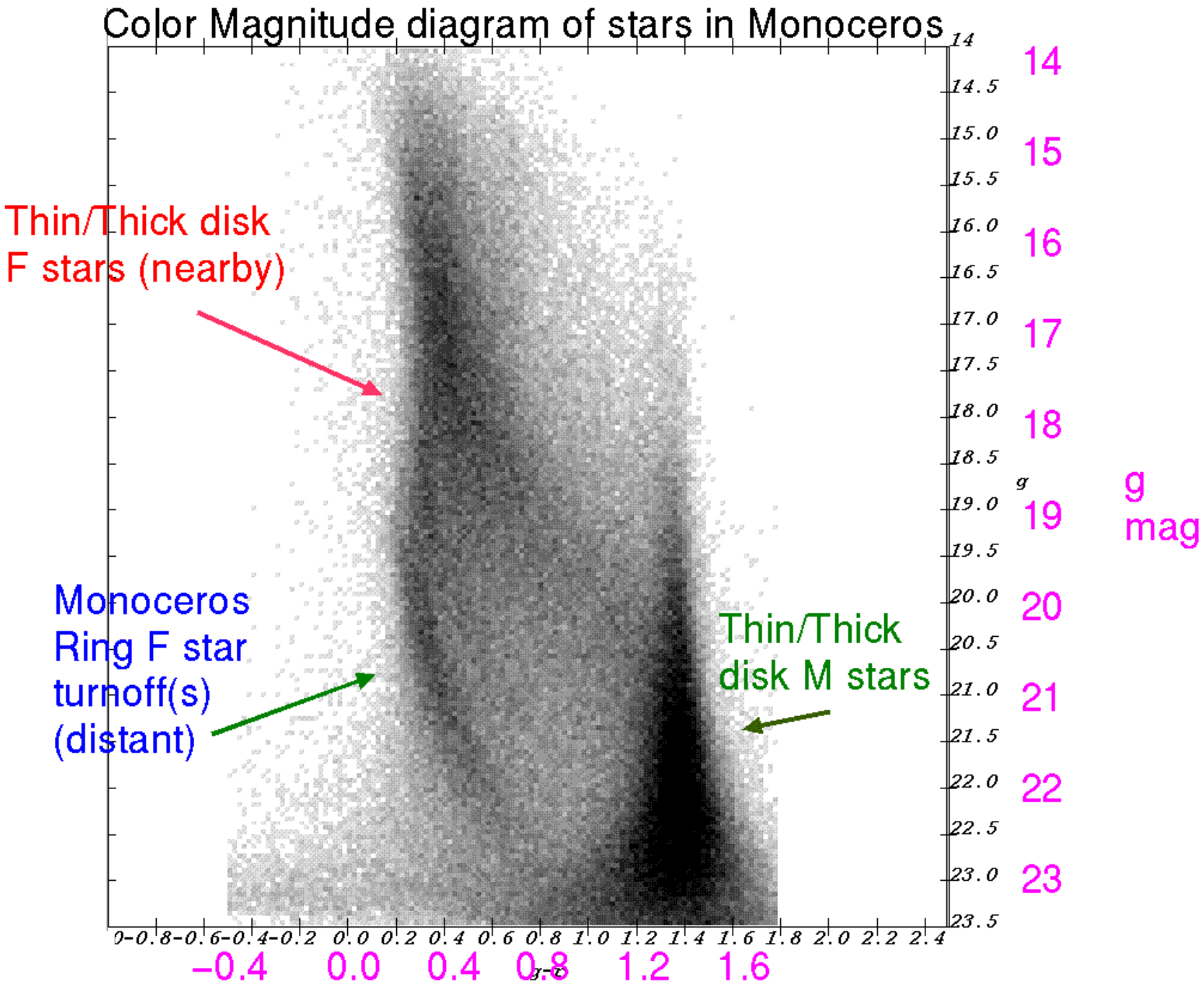


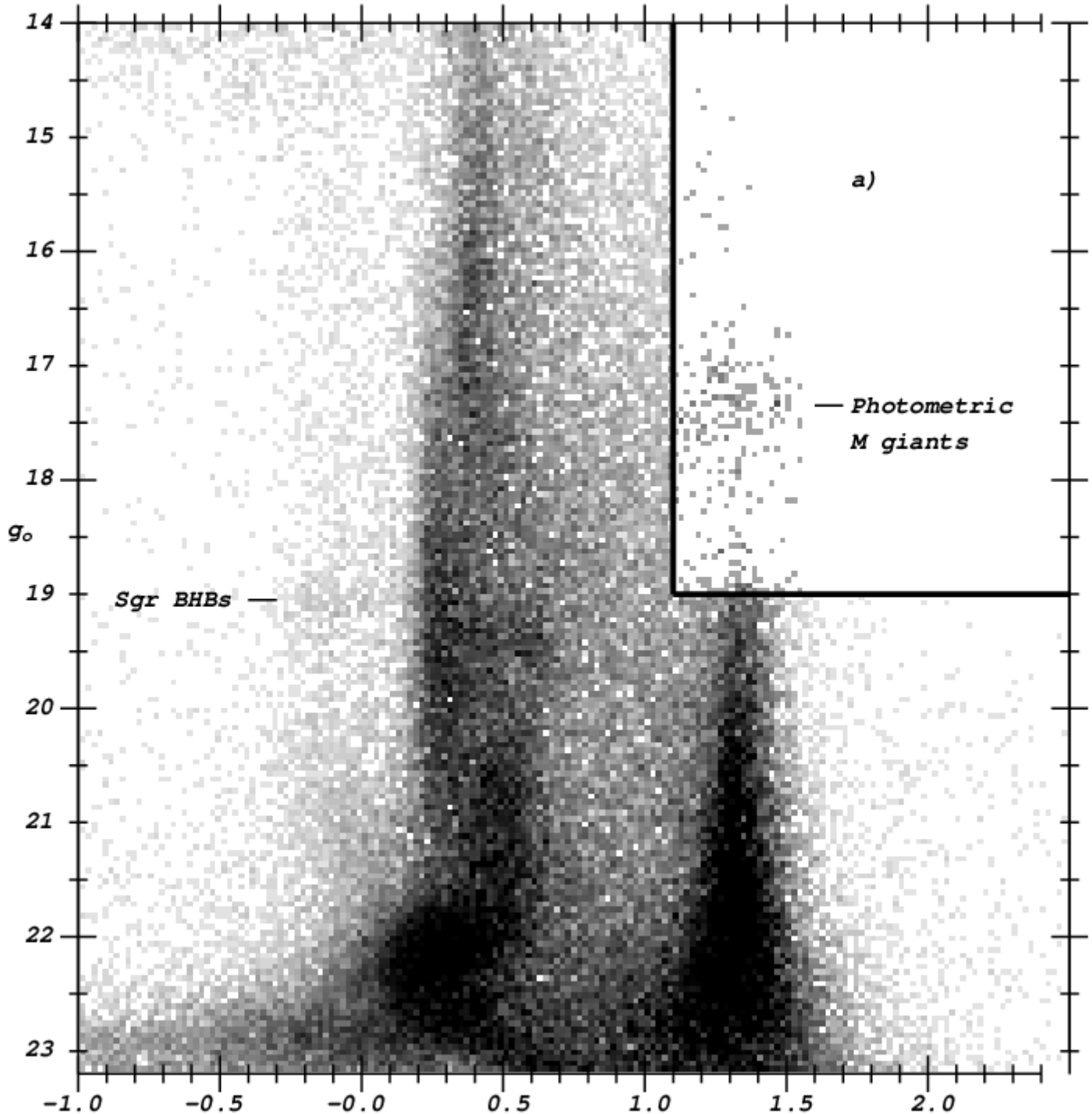
Star counts along two symmetrical sightlines should be the same in an axisymmetric Galaxy.

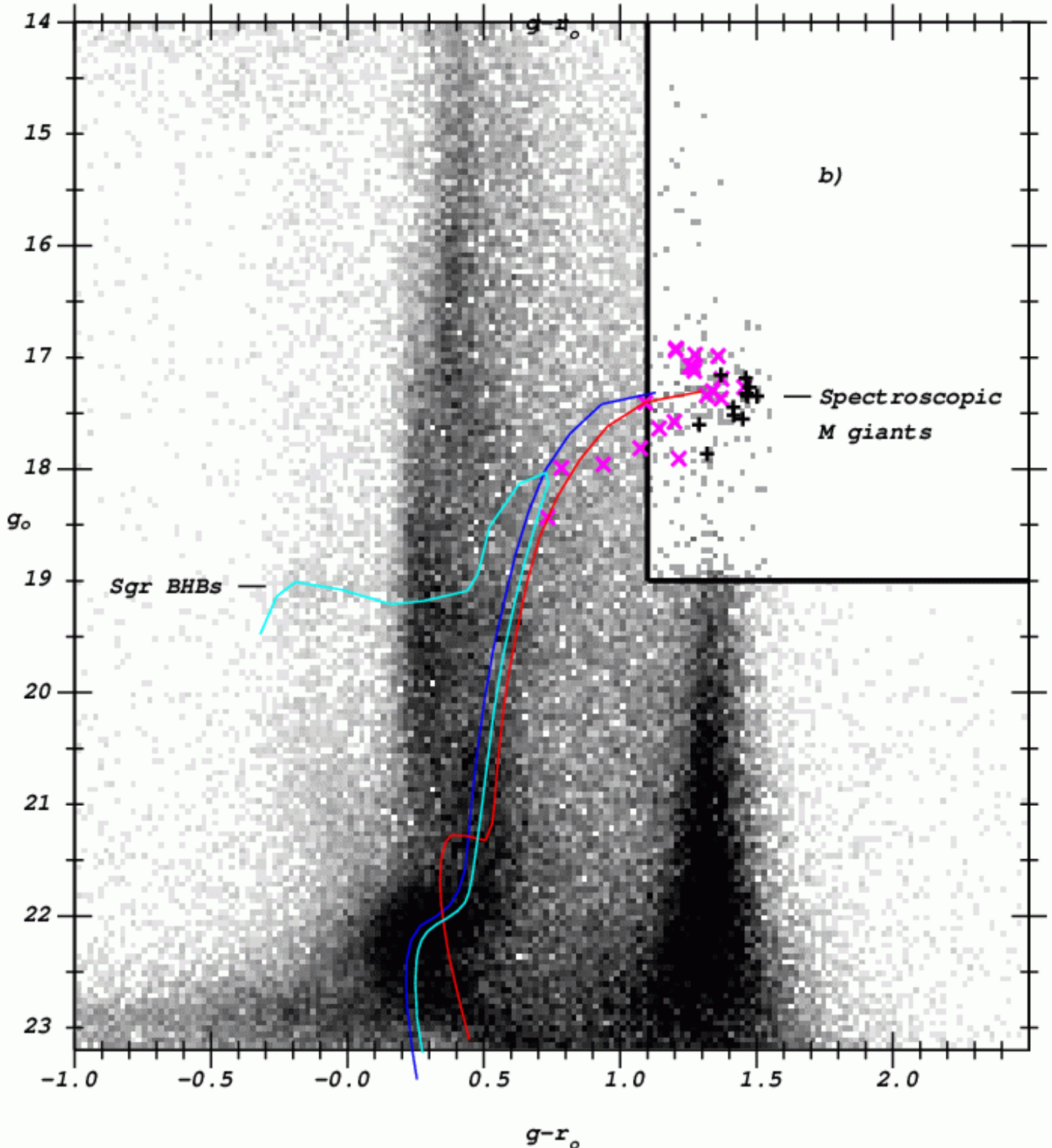
Observations show they are not:

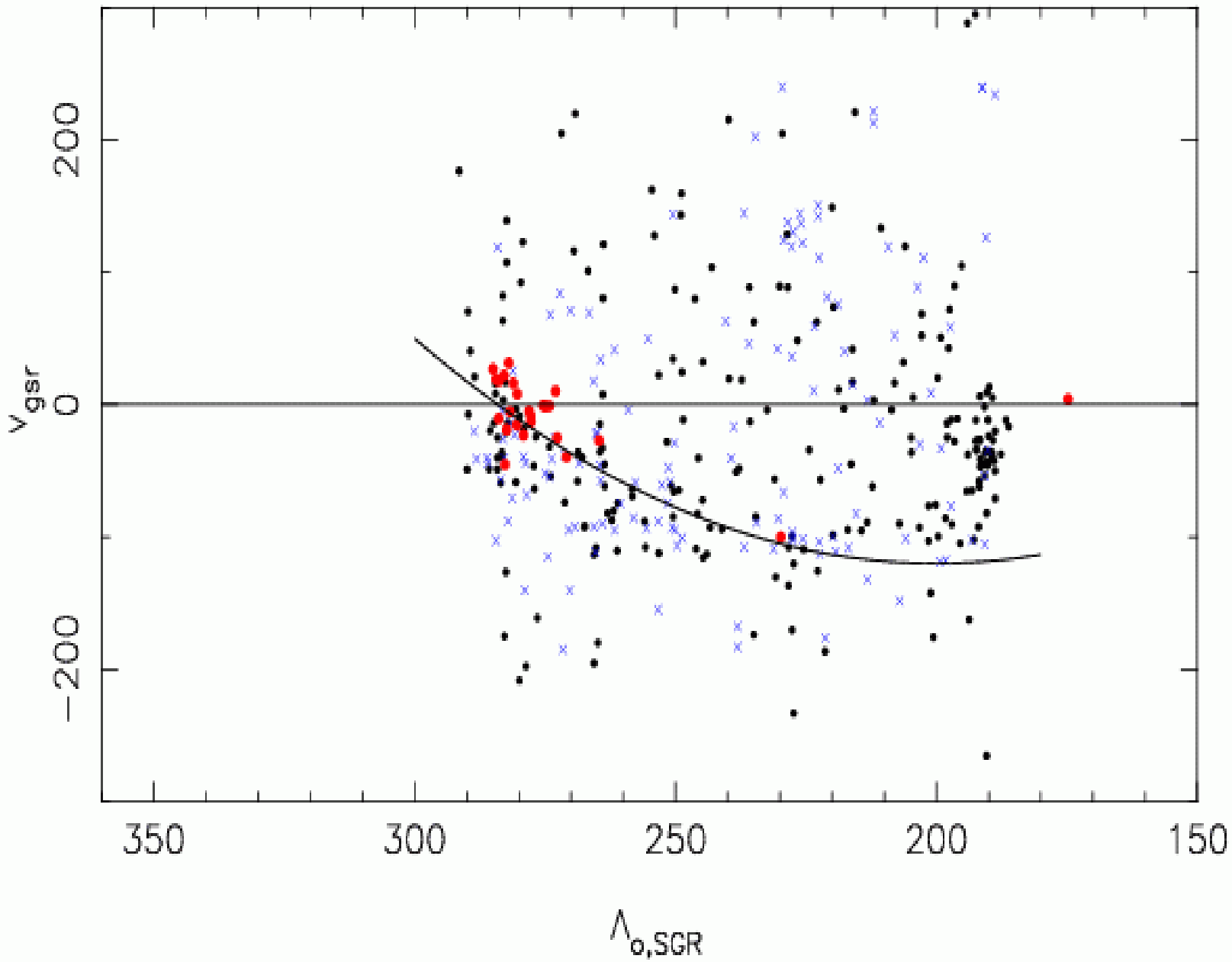
The asymmetry appears to be due to a combination of a triaxial stellar spheroid and sub-structure lumps: Sgr stream and Virgo Overdensity

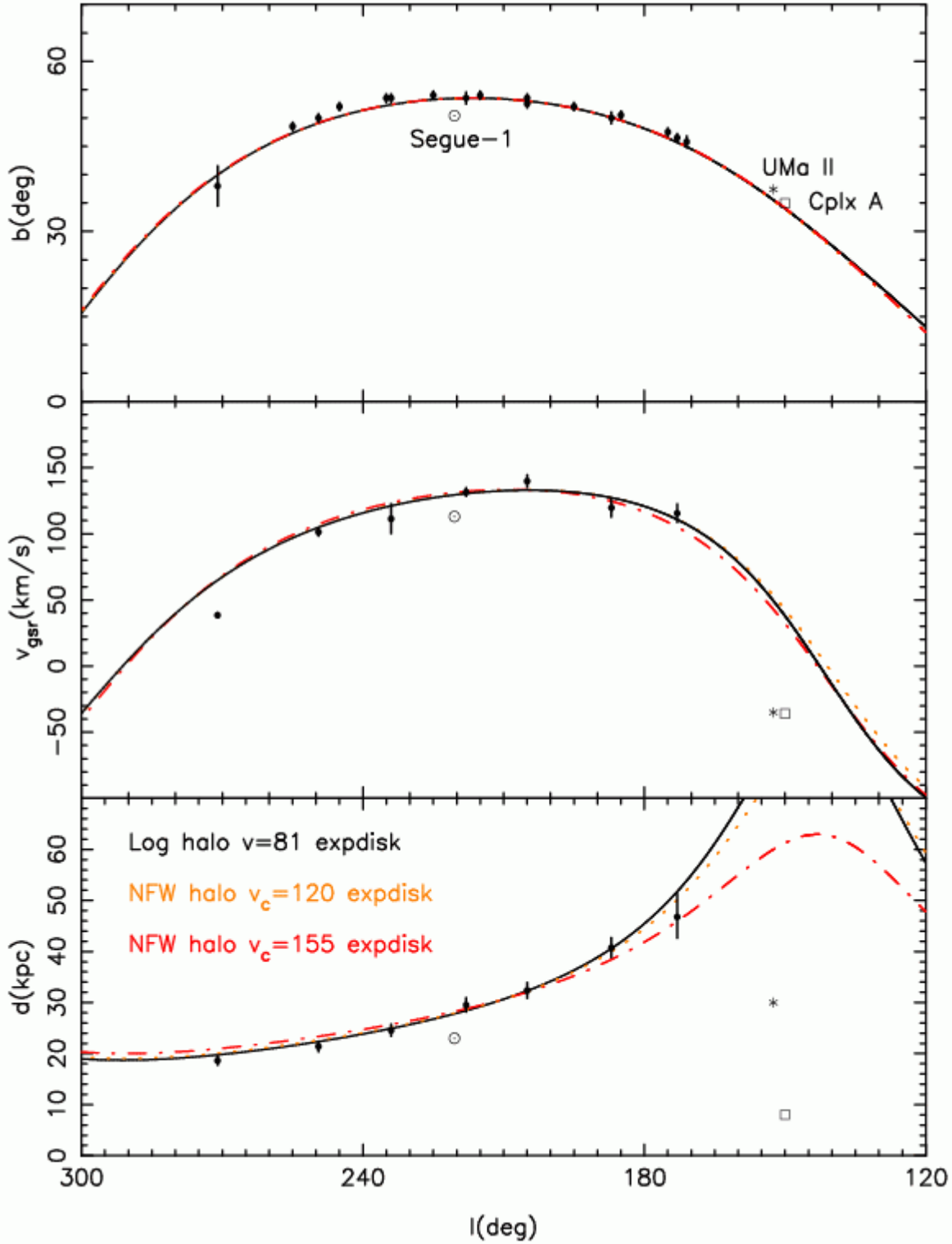


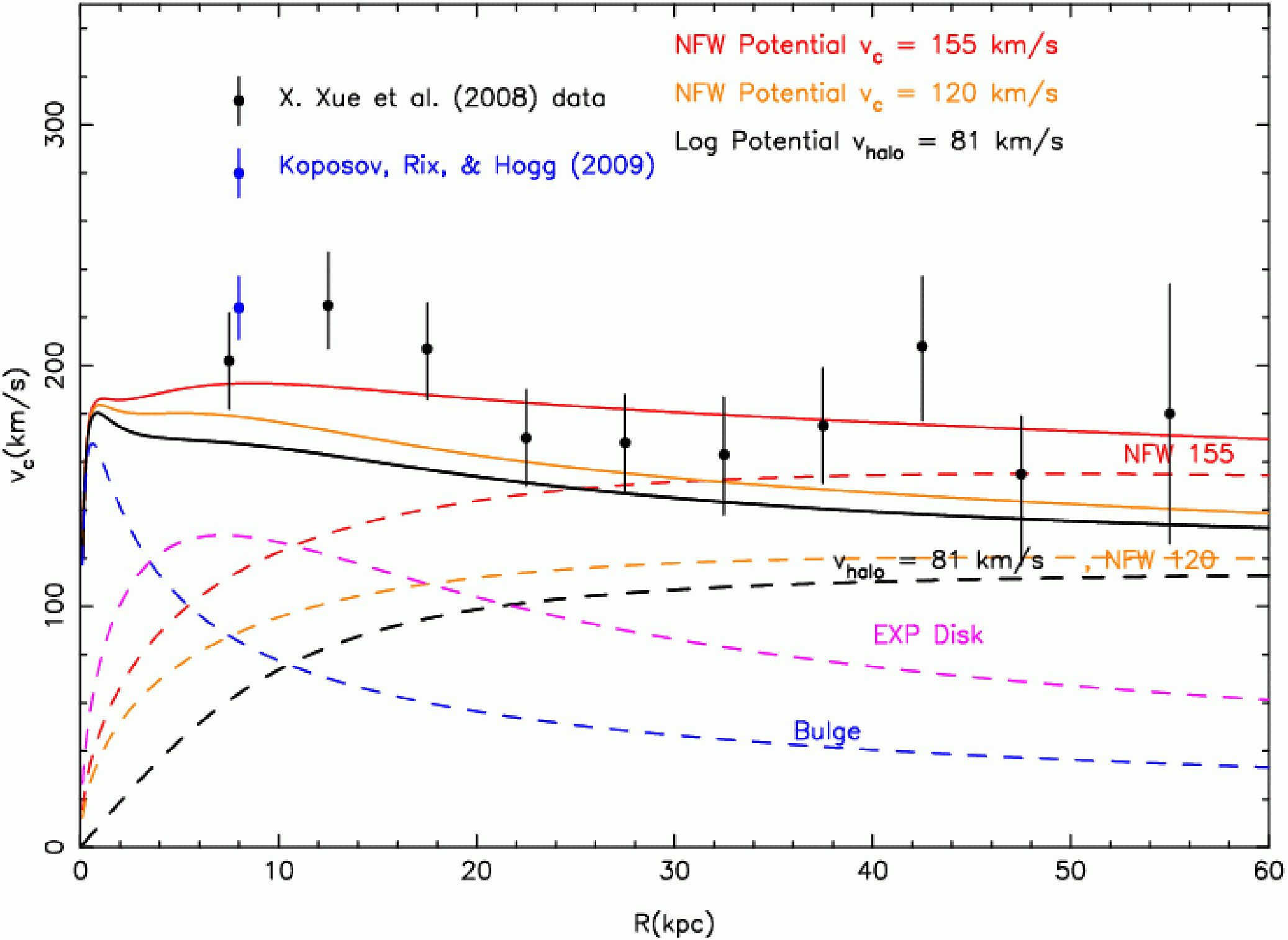

Color Magnitude diagram of stars in Monoceros
Thin/Thick disk
F stars (nearby)
Monoceros
Ring F star
turnoff(s)
(distant)
Thin/Thick
disk M stars
g
g
mag
14
15
16
17
18
19
20
21
22
23
−0.4
0.0
0.4
0.8
1.2
1.6

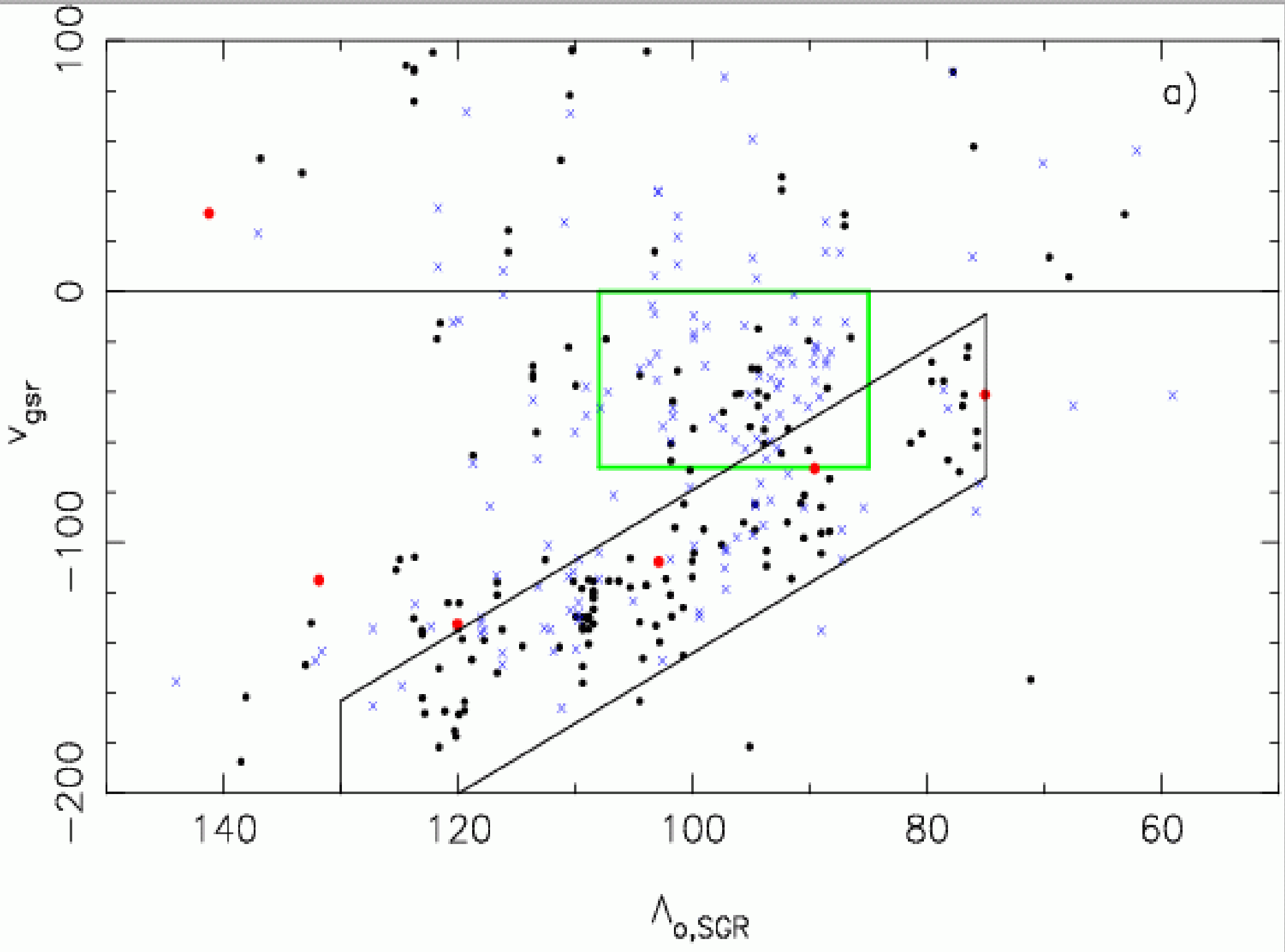

a)
Photometric
M giants
Sgr BHBs
g_o
14
15
16
17
18
19
20
21
22
23
-1.0
-0.5
-0.0
0.5
1.0
1.5
2.0

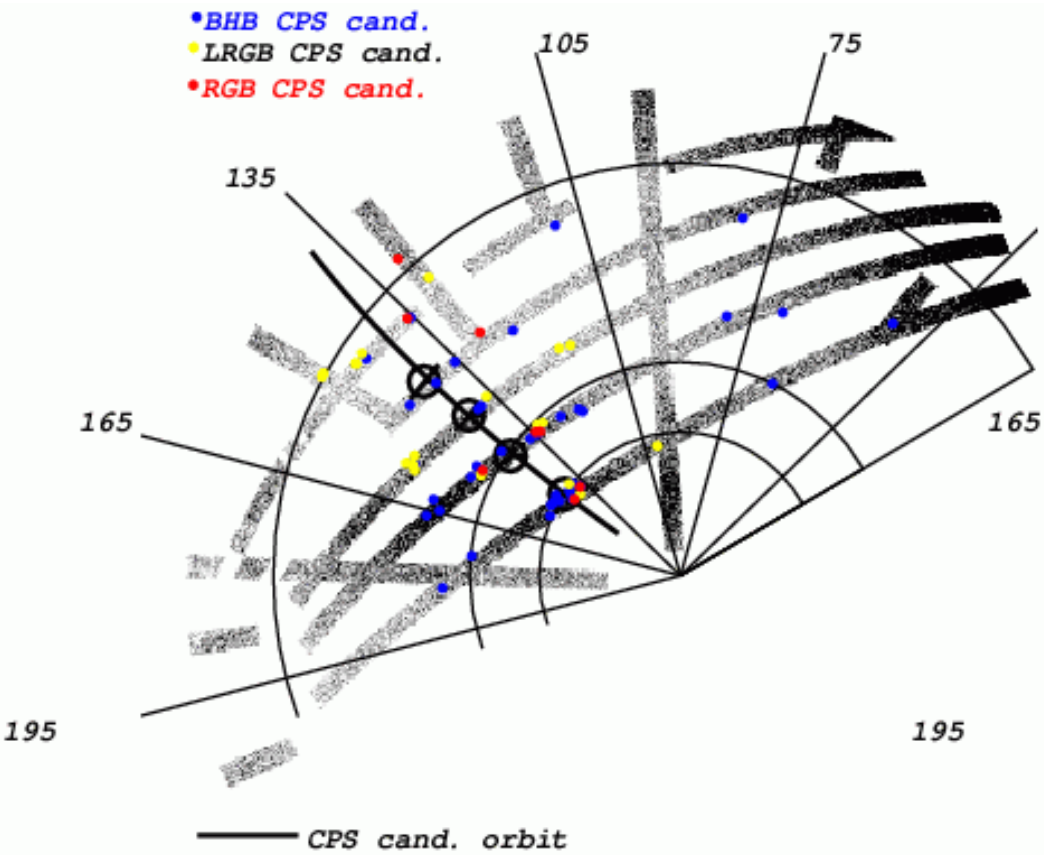

b)
Spectroscopic
M giants
Sgr BHBs
g_o
$g-r_o$
14
15
16
17
18
19
20
21
22
23
-1.0
-0.5
-0.0
0.5
1.0
1.5
2.0

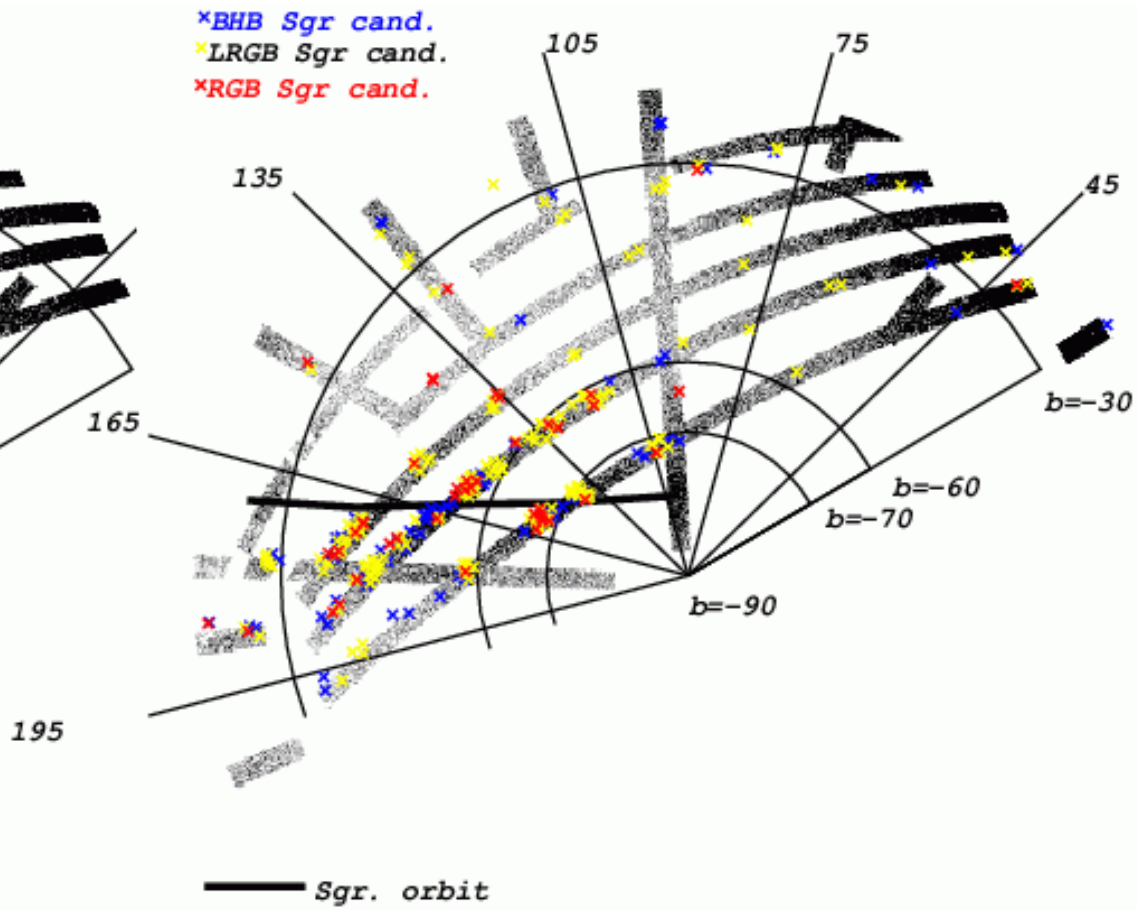

200
0
−200
v_{gsr}
350
300
250
200
150
$\Lambda_{o,SGR}$

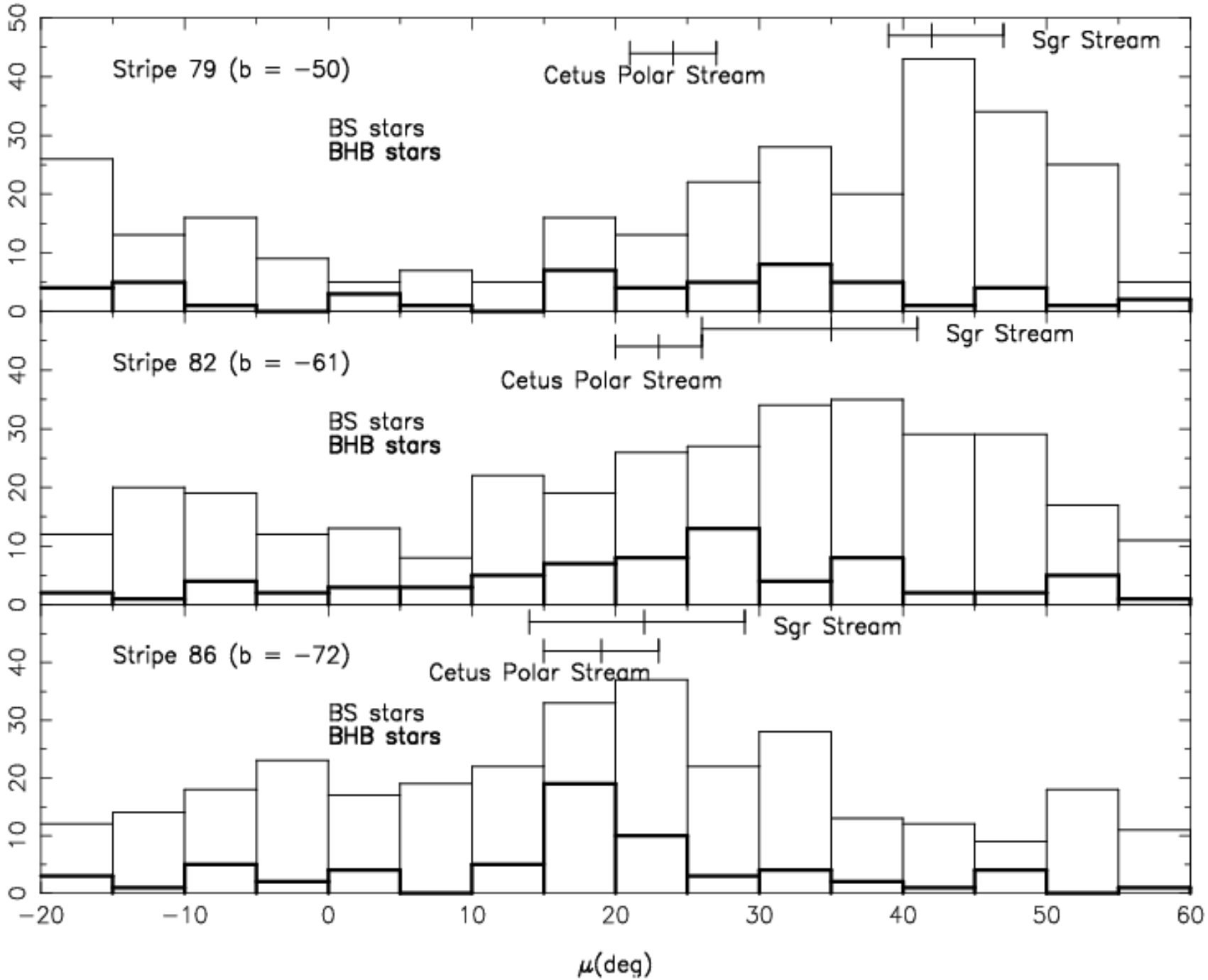

b(deg)
Segue−1
UMa II
Cplx A
v_{gsr}(km/s)
Log halo v=81 expdisk
NFW halo v_c=120 expdisk
NFW halo v_c=155 expdisk
d(kpc)
l(deg)
300
240
180
120


NFW Potential v_c = 155 km/s
NFW Potential v_c = 120 km/s
Log Potential v_{halo} = 81 km/s
X. Xue et al. (2008) data
Koposov, Rix, & Hogg (2009)
NFW 155
v_{halo} = 81 km/s
NFW 120
EXP Disk
Bulge
v_c(km/s)
R(kpc)
0
100
200
300
0
10
20
30
40
50
60


a)
100
0
−100
−200
v_{gsr}
140
120
100
80
60
$\Lambda_{o,SGR}$


BHB CPS cand.
LRGB CPS cand.
RGB CPS cand.
105
75
135
165
195
CPS cand. orbit


BHB Sgr cand.
LRGB Sgr cand.
RGB Sgr cand.
105
75
135
45
165
b=-30
b=-60
b=-70
b=-90
195
Sgr. orbit


Stripe 79 (b = −50)
Cetus Polar Stream
Sgr Stream
BS stars
BHB stars
Stripe 82 (b = −61)
Cetus Polar Stream
Sgr Stream
BS stars
BHB stars
Stripe 86 (b = −72)
Cetus Polar Stream
Sgr Stream
BS stars
BHB stars
0
10
20
30
40
50
−20
−10
0
10
20
30
40
50
60
μ(deg)

$$\rho(r) \sim r^{-2}$$

$$\nabla\Phi^2(r) = 4\pi G\rho(r)$$

$$\Phi(r) \sim log(r)$$

$$v_c(r) \sim \frac{1}{\sqrt{r}}$$

$$F(r) = \frac{v_c^2}{r}$$

$$F = ma$$

$$M(r < R) \sim R$$

$$F = -\nabla\phi$$

$$\mathrm{F(r)} = -\nabla\Phi(\mathrm{r}) = \frac{\mathrm{GM}}{\mathrm{r}^2}$$

$$\Phi(r) = -GM/r$$

$$v_c^2(r) \sim r\frac{d\Phi}{dr} \sim \frac{r}{r} \sim constant$$

$$v_c^2(r) = r\frac{d\Phi}{dr}$$