Evidence for dark matter in the Milky Way

Astr 511: Galactic Astronomy

Winter Quarter 2015

University of Washington

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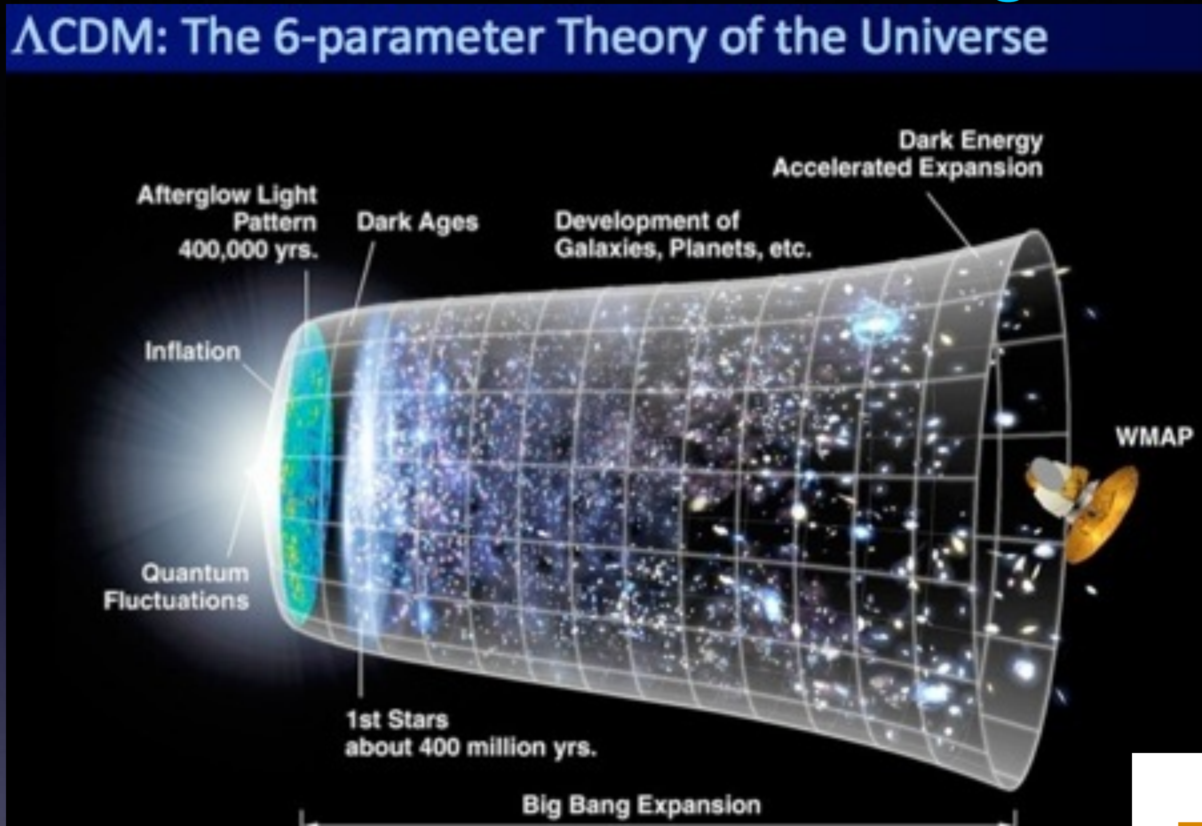
Classical Decomposition of the Milky Way Components

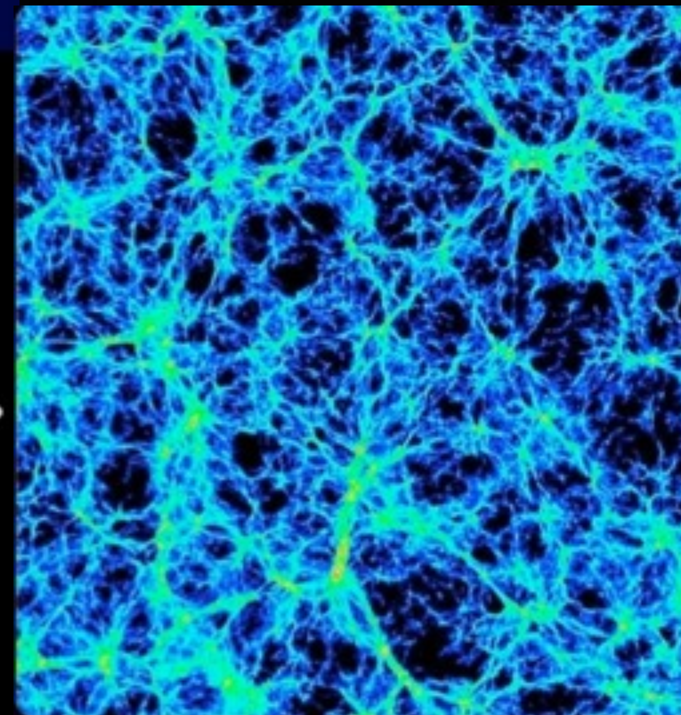
- Thin/thick disk
- Galactic bulge
- Stellar halo

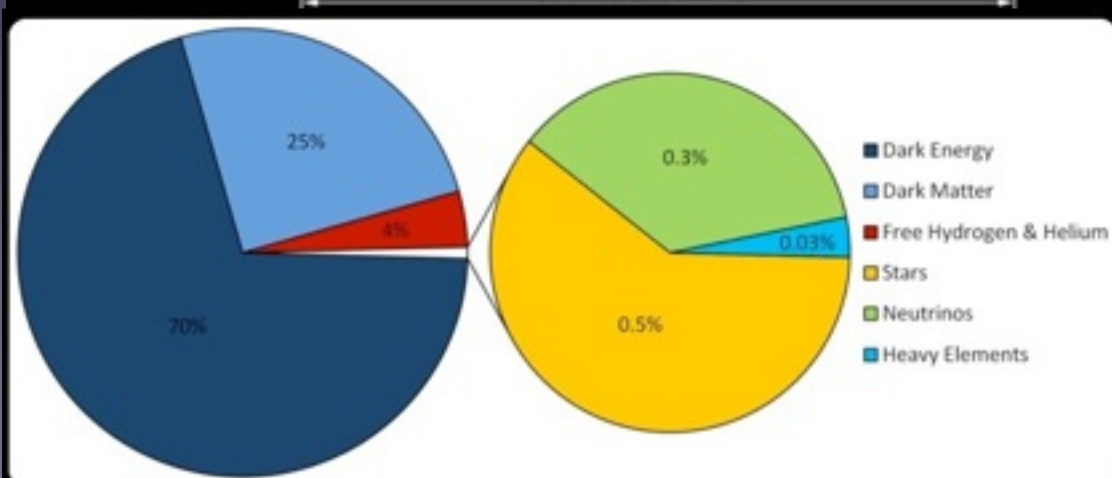
The halo is especially interesting because gravitational potential becomes dominated by the dark matter halo

- Components trace the DM dominated potential
- They are a product of Milky Way formation and evolution

New Cosmological Puzzles

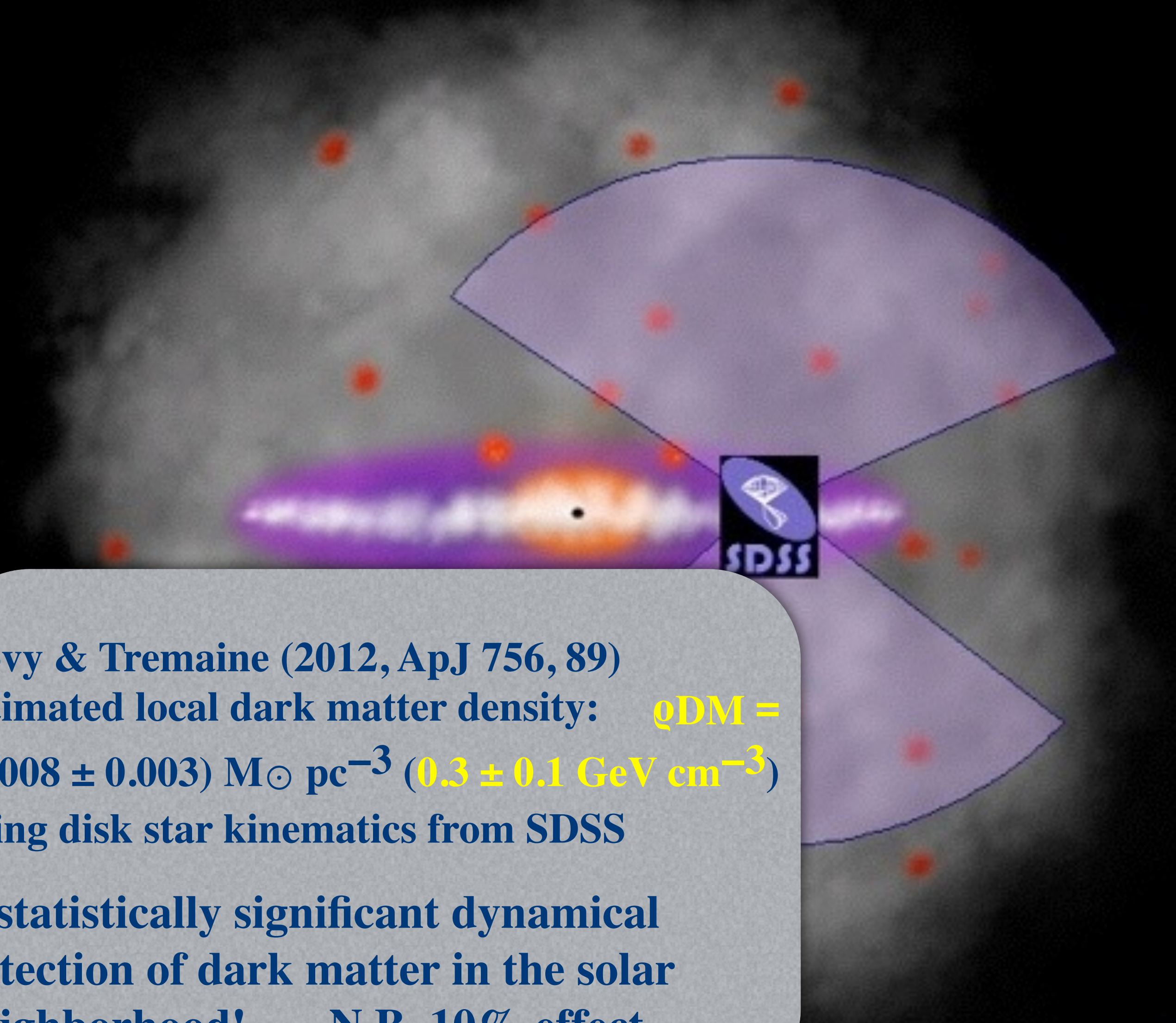






The modern cosmological models can explain all observations, but need to **postulate** dark matter and dark energy (though gravity model could be wrong, too)

Classical Decomposition of the Milky Way Components

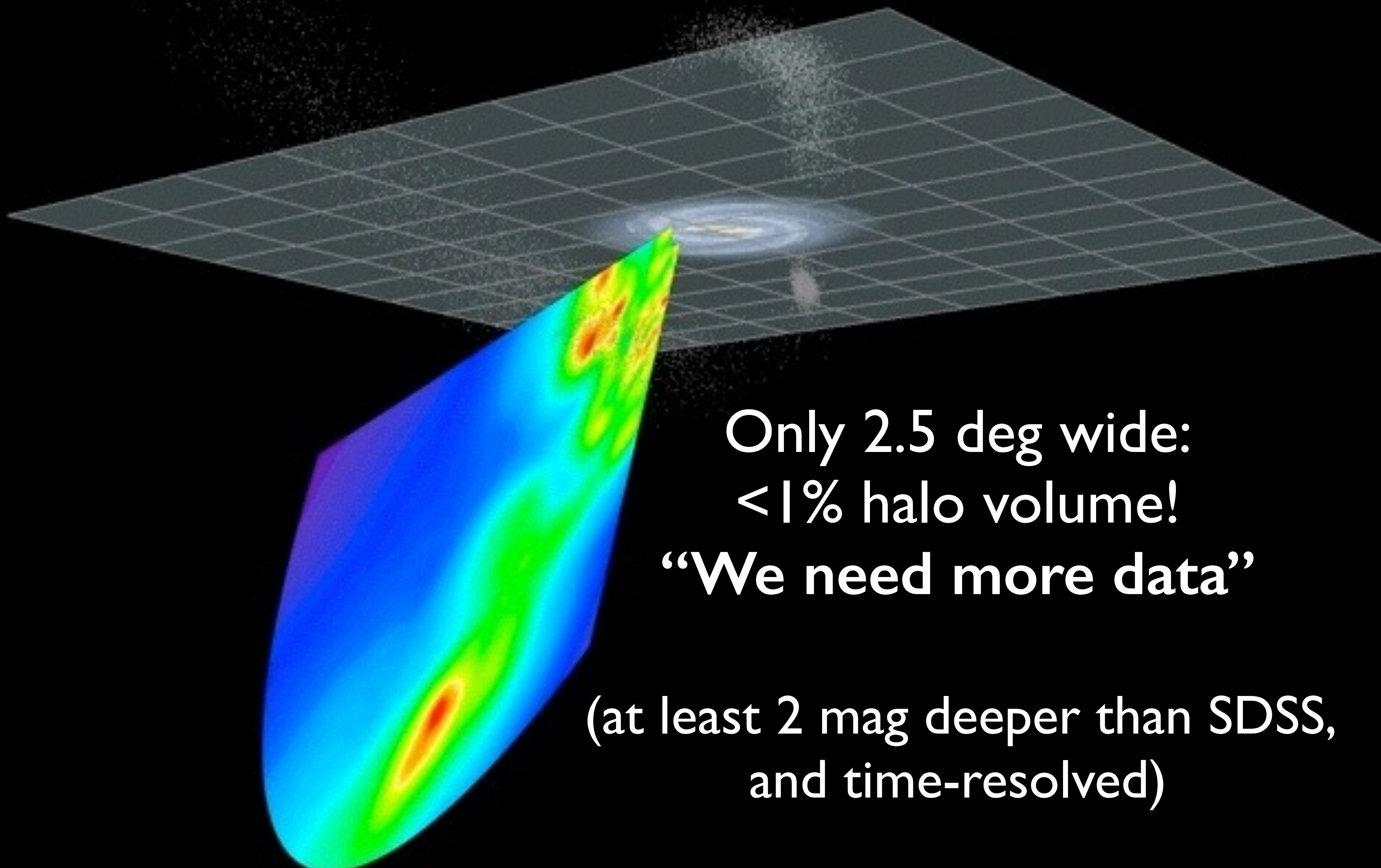


- Thin/thick disk
- Galactic bulge
- Stellar halo

Bovy & Tremaine (2012, ApJ 756, 89) estimated local dark matter density: ϱDM = (0.008 ± 0.003) $M_\odot$ pc^{-3} (0.3 ± 0.1 GeV cm^{-3}) using disk star kinematics from SDSS

A statistically significant dynamical detection of dark matter in the solar neighborhood! N.B. 10% effect

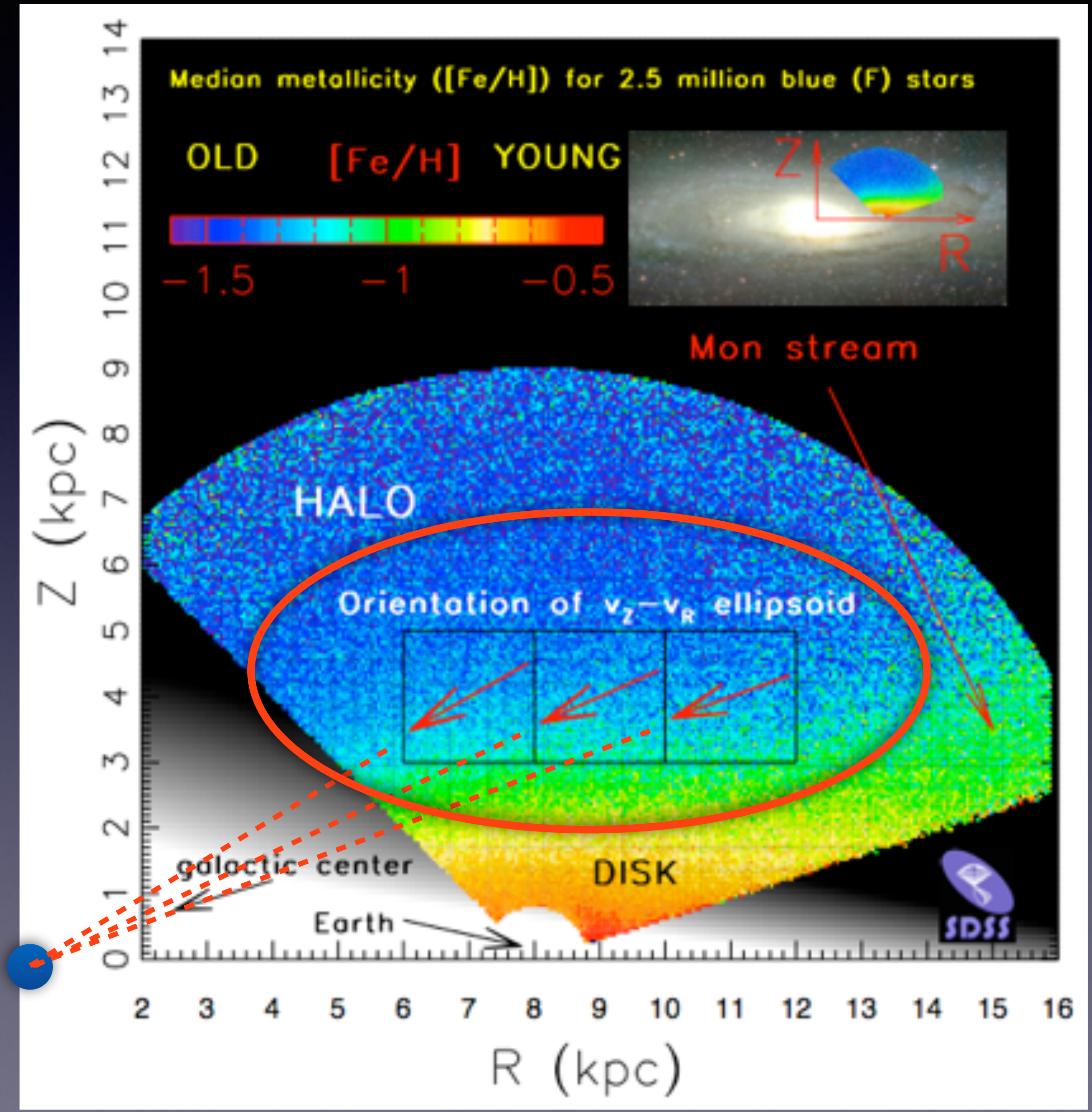
- Components trace the DM dominated potential
- They are a product of Milky Way formation and evolution



Only 2.5 deg wide:
<1% halo volume!
"We need more data"

(at least 2 mag deeper than SDSS,
and time-resolved)

Velocity distribution for (nearby) halo stars

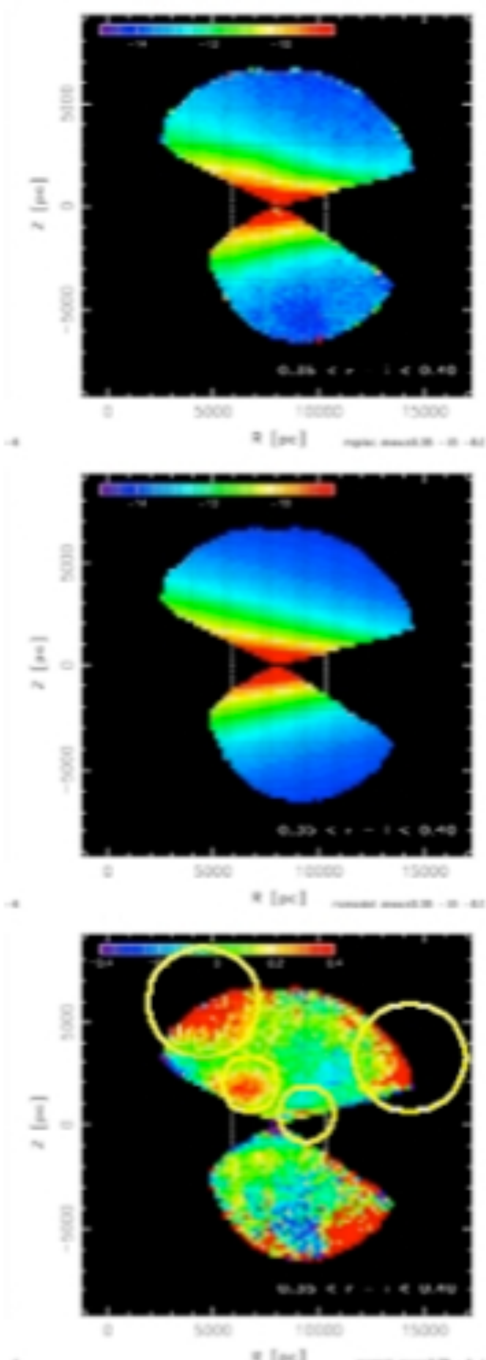


Kinematics of halo stars based on SDSS-POSS proper motions:

velocity ellipsoid is nearly invariant in spherical coordinate system

Bond et al. (2010, ApJ, 716, 1)

Together with the measurement of stellar number density distribution, this finding encodes information about the gravitational potential - including the dark matter contribution!



Dissecting the Milky Way with SDSS

- Panoramic view of the Milky Way, akin to observations of external galaxies; good support for standard Galactic models (with amazing signal-to-noise!)

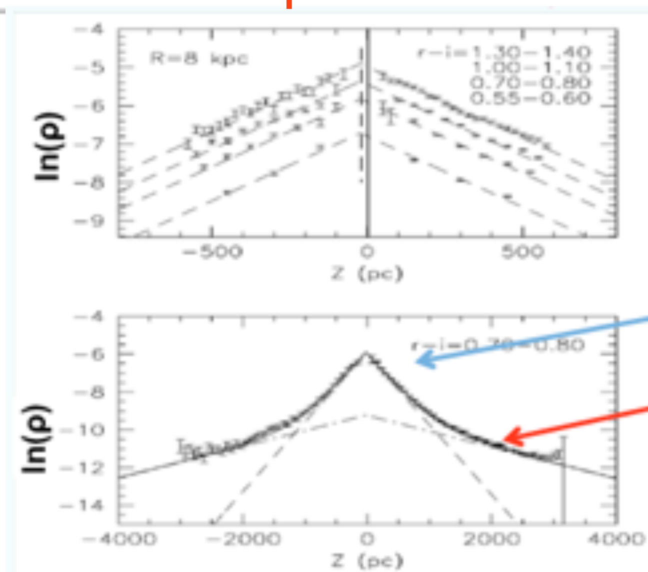
- Removal of obvious clumps
- Fit to least "contaminated" bins
- Exponential disks + halo models

q=0.64

power-law halo

$$\rho(R,Z) = \rho_{thin} e^{-\frac{R-R_{\odot}}{l_{thin}} - \frac{|Z+Z_0|}{h_{thin}}} + \rho_{thick} e^{-\frac{R-R_{\odot}}{l_{thick}} - \frac{|Z+Z_0|}{h_{thick}}} + \rho_{halo} \left(\frac{R_{GC}}{\sqrt{R^2 + (z+z_0)^2 / q^2}} \right)^n$$

2 exponential disks

- 

Thin disk

Two component fit!

Thin disk

Thick disk

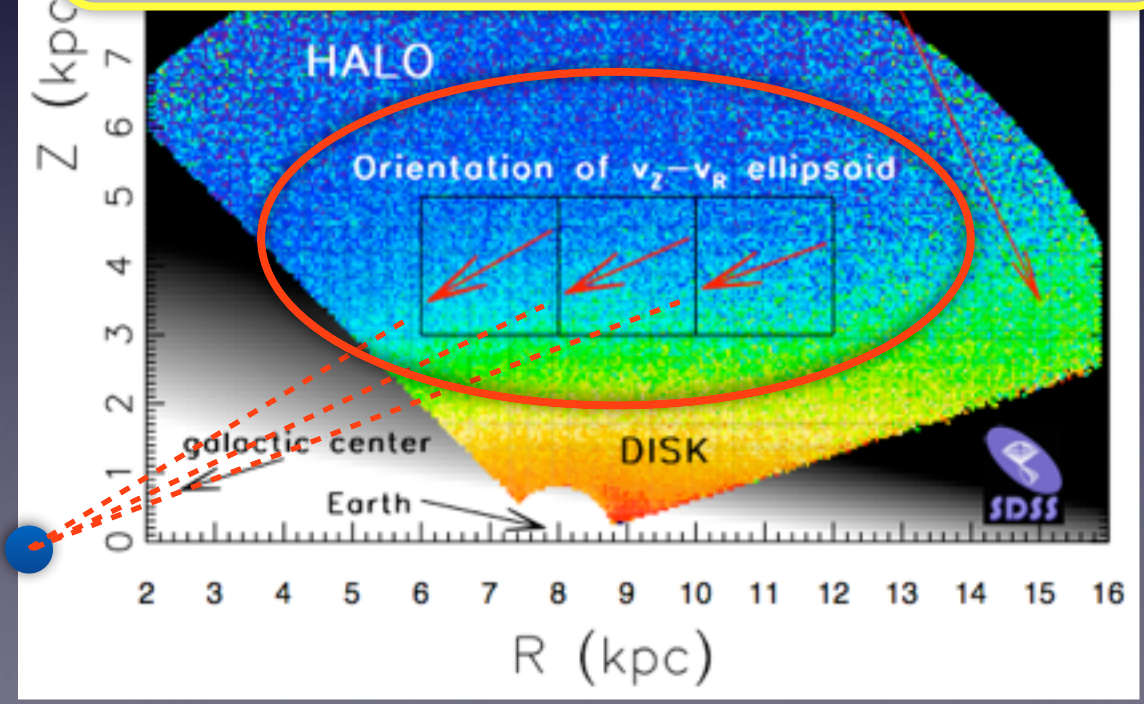
Juric et al. 08

Velocity distribution for (nearby) halo stars

Kinematic data constrain dark matter via Jeans equations

$$a_R = \sigma_{RR}^2 \times \frac{\partial(\ln \nu)}{\partial R} + \frac{\partial \sigma_{RR}^2}{\partial R} + \sigma_{RZ}^2 \times \frac{\partial(\ln \nu)}{\partial Z} + \frac{\partial \sigma_{RZ}^2}{\partial Z} + \frac{\sigma_{RR}^2}{R} - \frac{\sigma_{\phi\phi}^2}{R} - \frac{\overline{v_\phi}^2}{R},$$

$$a_Z = \sigma_{RZ}^2 \times \frac{\partial(\ln \nu)}{\partial R} + \frac{\partial \sigma_{RZ}^2}{\partial R} + \sigma_{ZZ}^2 \times \frac{\partial(\ln \nu)}{\partial Z} + \frac{\partial \sigma_{ZZ}^2}{\partial Z} + \frac{\sigma_{RZ}^2}{R}.$$



Kinematics of halo stars based on SDSS-POSS proper motions:

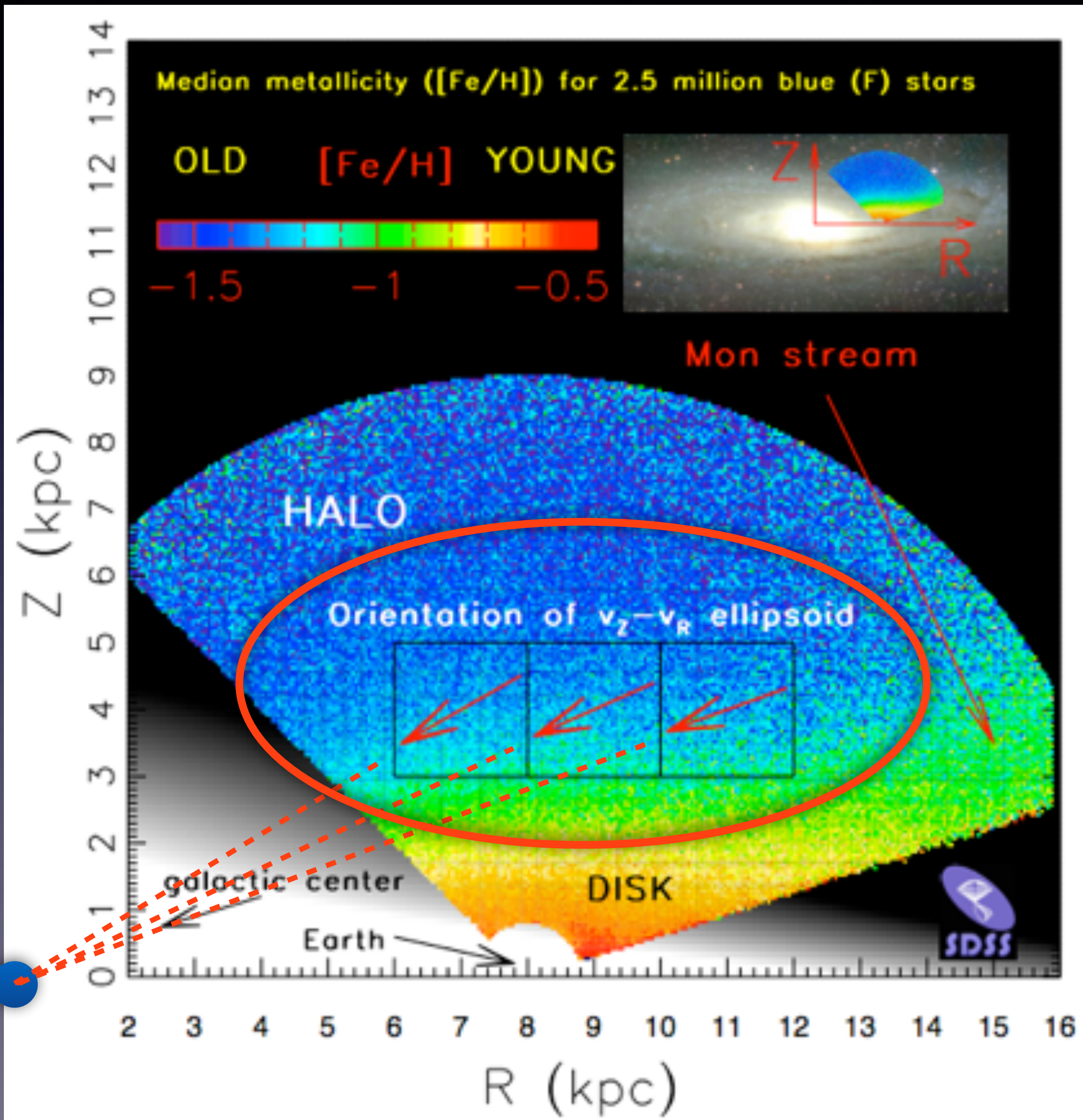
velocity ellipsoid is nearly invariant in spherical coordinate system

Bond et al. (2010, ApJ, 716, 1)

Given stellar distribution from Juric+2008 and stellar kinematics from Bond+2010, we can apply **Jeans equations** and infer the gravitational potential, and ultimately the distribution of dark matter!

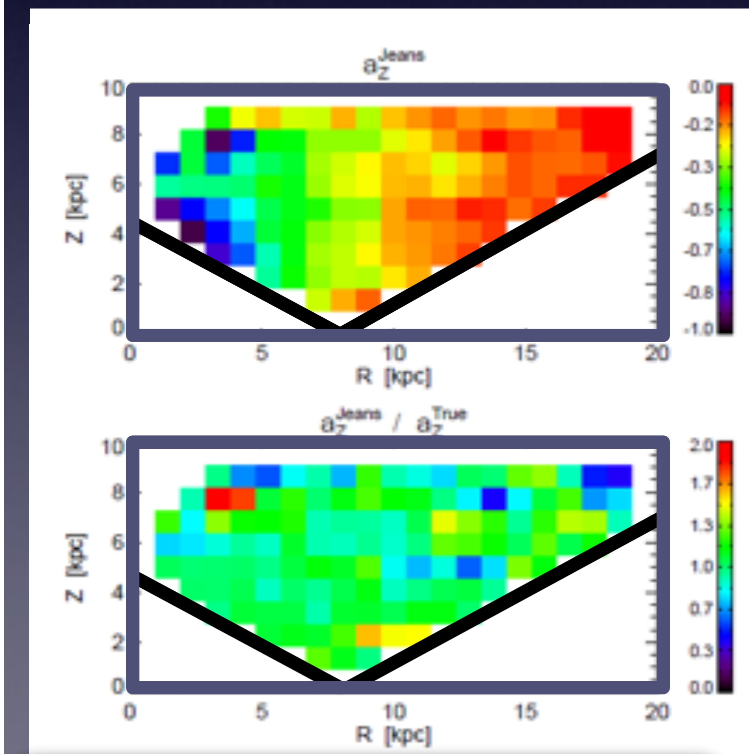
Velocity distribution for (nearby) halo stars

Kinematic data constrain dark matter via Jeans equations



Tests based on a N-body model galaxy (Loebman+2012):

Jeans equations recover the known acceleration with a bias below 10%

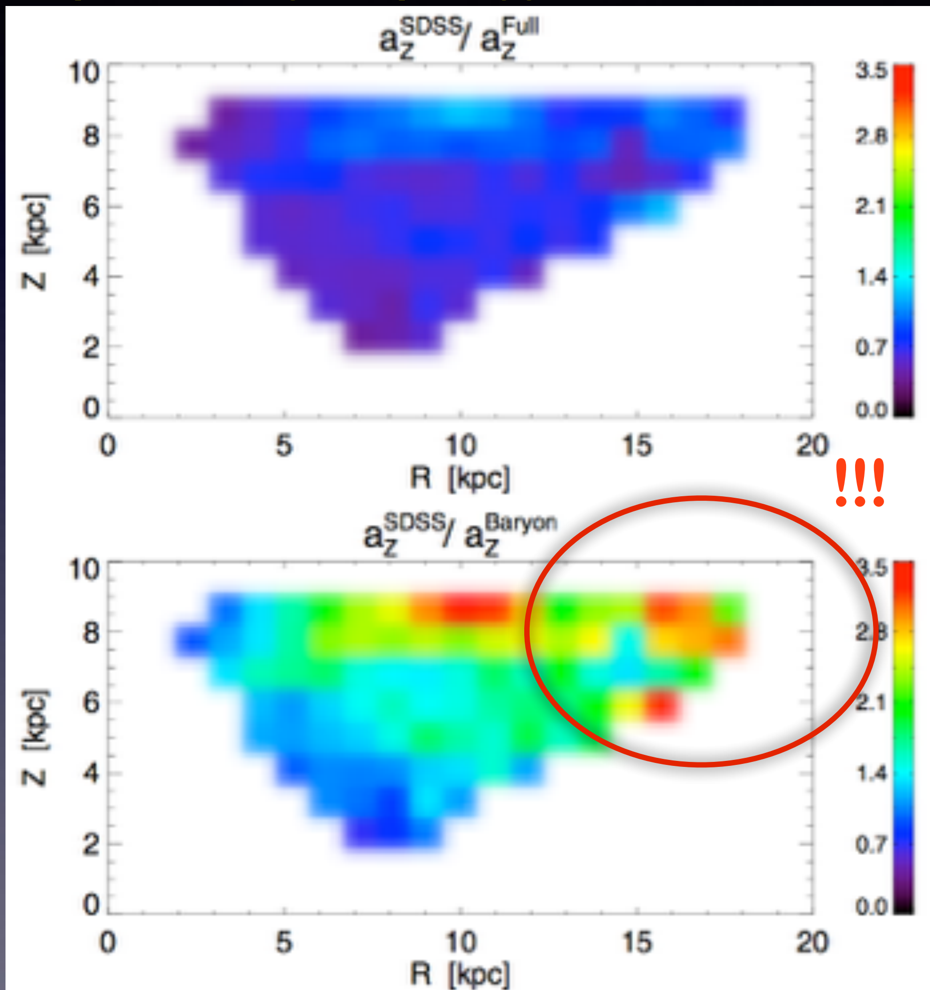


N-body model (Governato et al.)

Velocity distribution for (nearby) halo stars

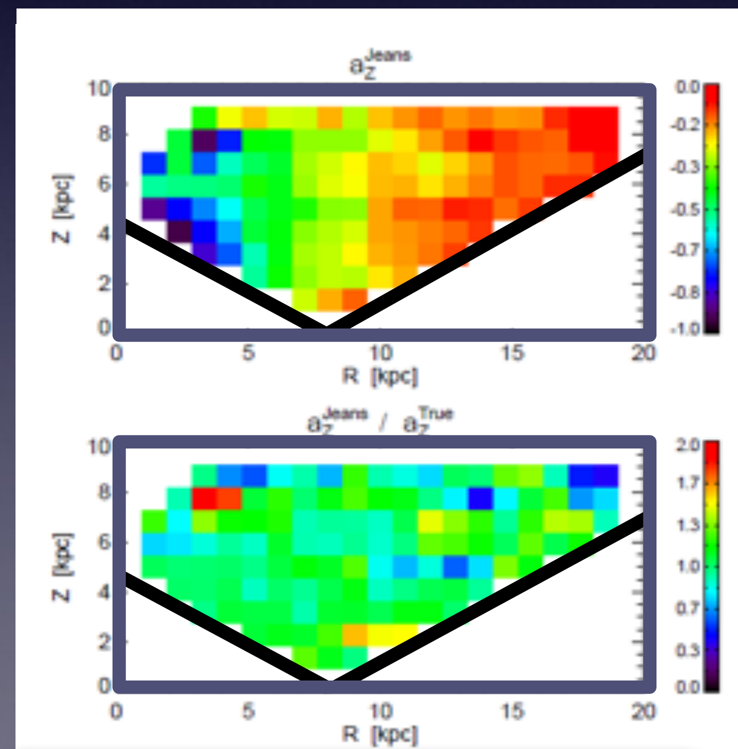
Kinematic data constrain dark matter via Jeans equations

N-body model galaxy suggests dark matter halo:



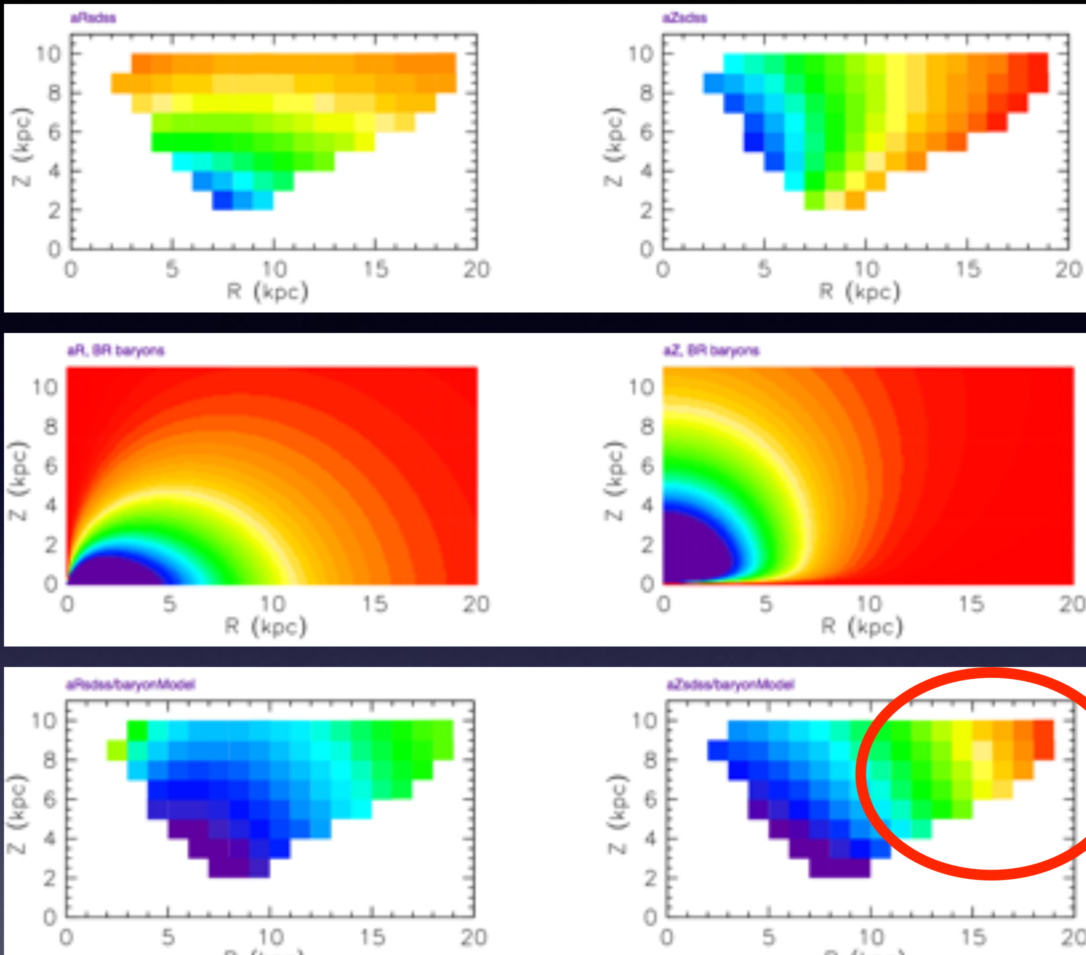
SDSS aZ normalized by model aZ
Top: model with DM; bottom: no DM

Tests based on a N-body model galaxy:
Jeans equations recover the known acceleration with a bias below 10%



N-body model (Governato et al.)

aR aZ



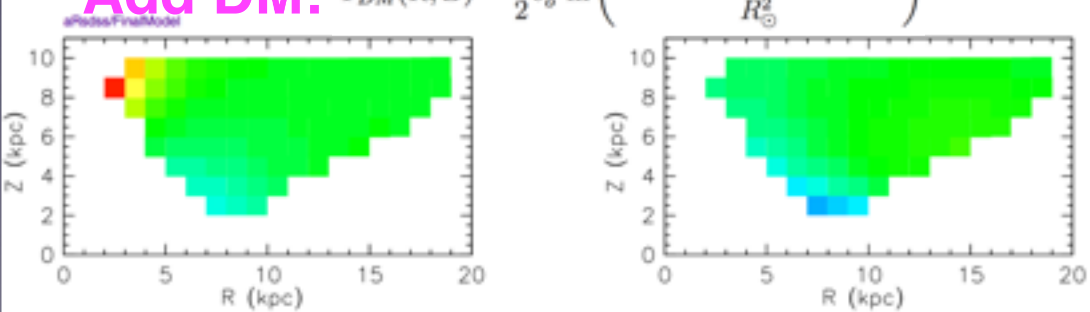
SDSS, halo, total
(Loebman et al. 2012)

Baryons (SDSS, disk)
(Bovy & Rix, 2013)

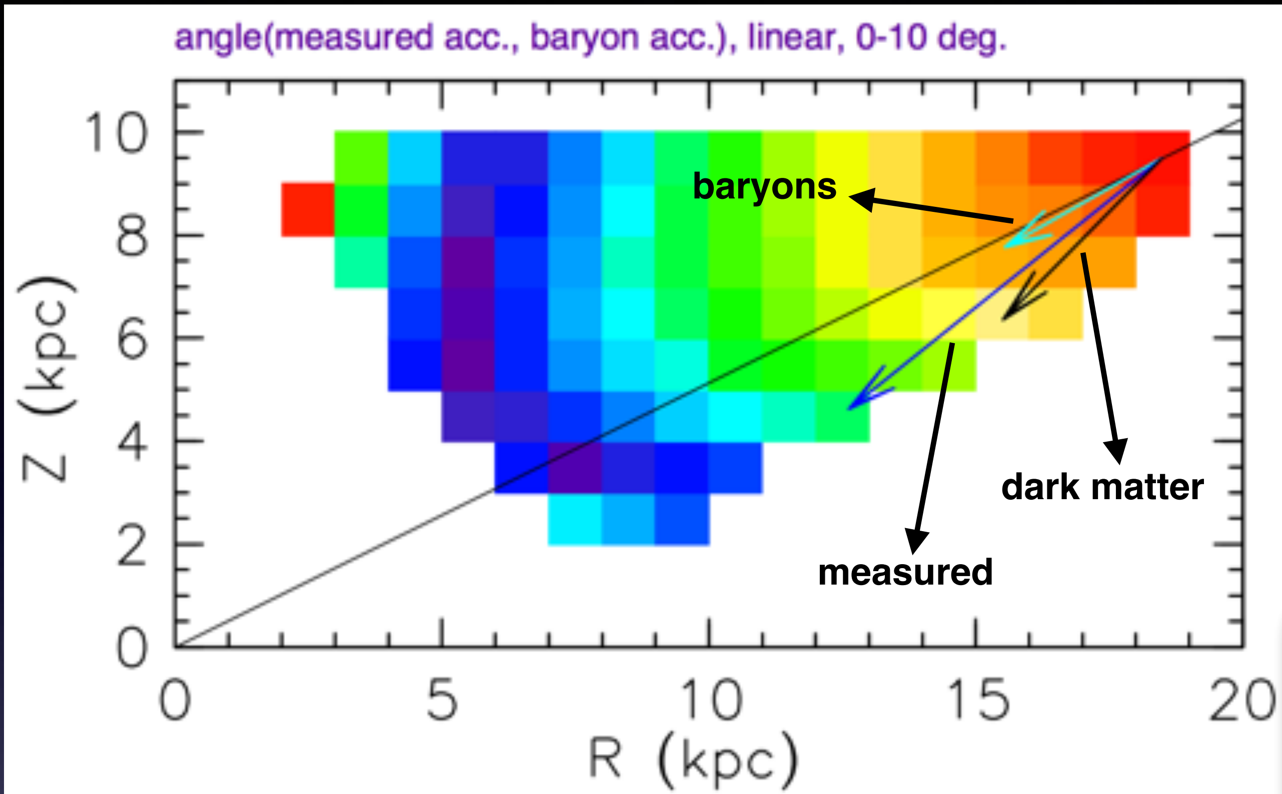
Up to 3 times stronger acc.!

SDSS measured over baryon model

Add DM: $\Phi_{DM}(R,Z) = \frac{1}{2} v_o^2 \ln\left(\frac{R^2 + (Z/q_{DM})^2 + R_{core}^2}{R_\odot^2}\right)$



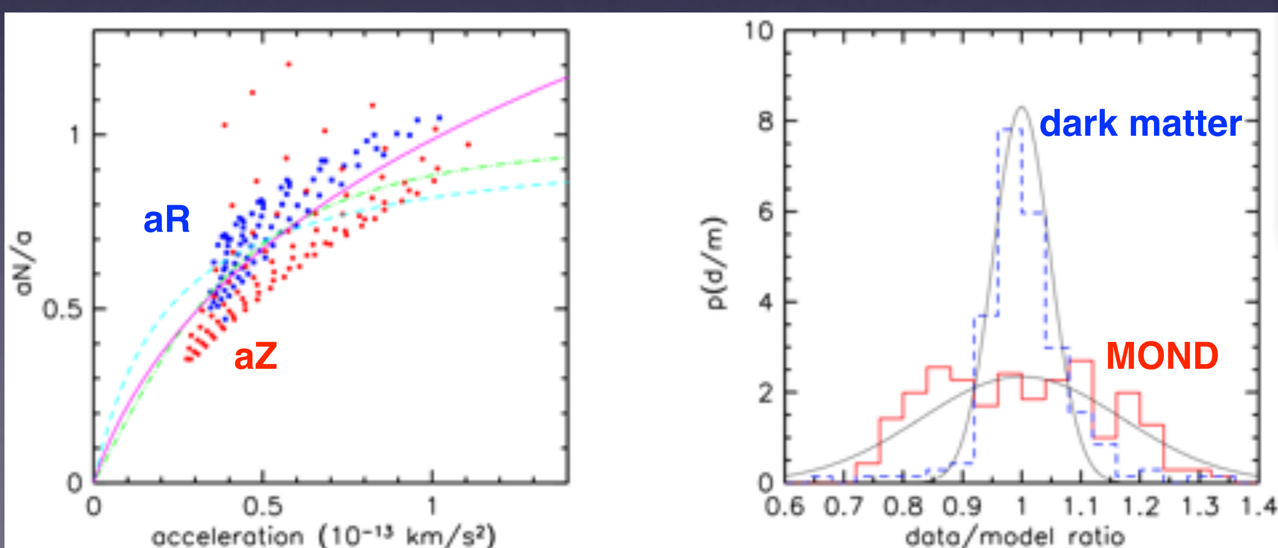
DM halo is oblate!
qPot=0.7±0.1
qRho=0.4±0.1
(Loebman et al. 2014)



Acceler. due to baryons and measured acc. don't point in the same direction:

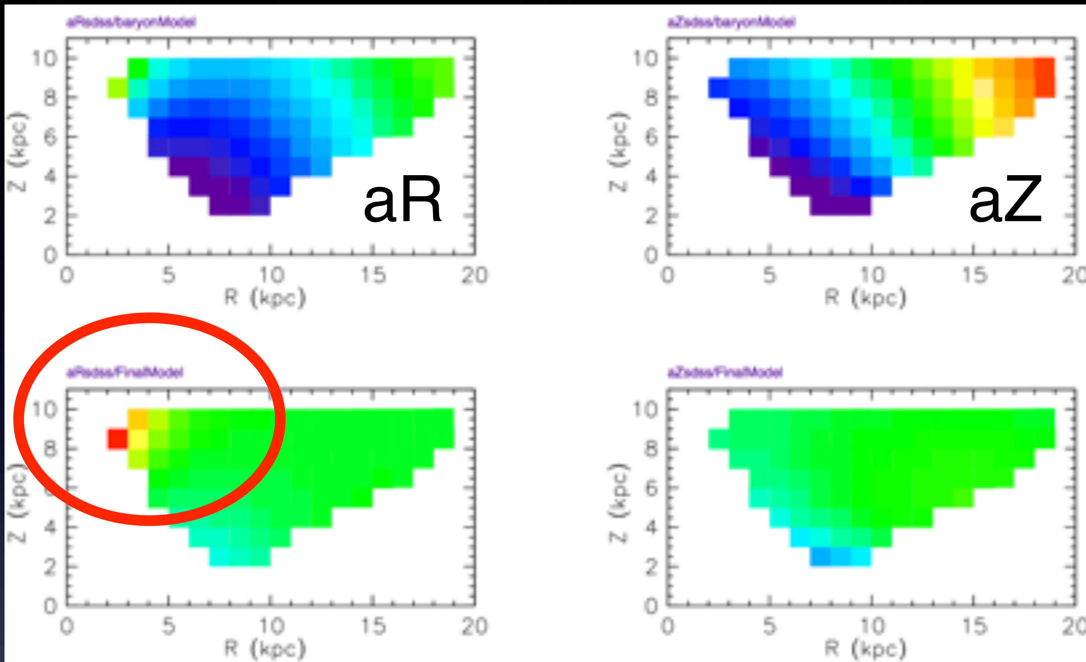
1) DM halo can't be spherical

2) MOND does not work



Strong constraints because of 2D acceleration measurements

Problems (and long-term solutions):



The spherically invariant velocity ellipsoid for halo stars from Bond+10 has

σ_{rr} = 141 km/s

$\sigma_{\theta\theta}$ = 75 km/s

$\sigma_{\varphi\varphi}$ = 85 km/s

with ~ 10 km/s errors.

Add DM:

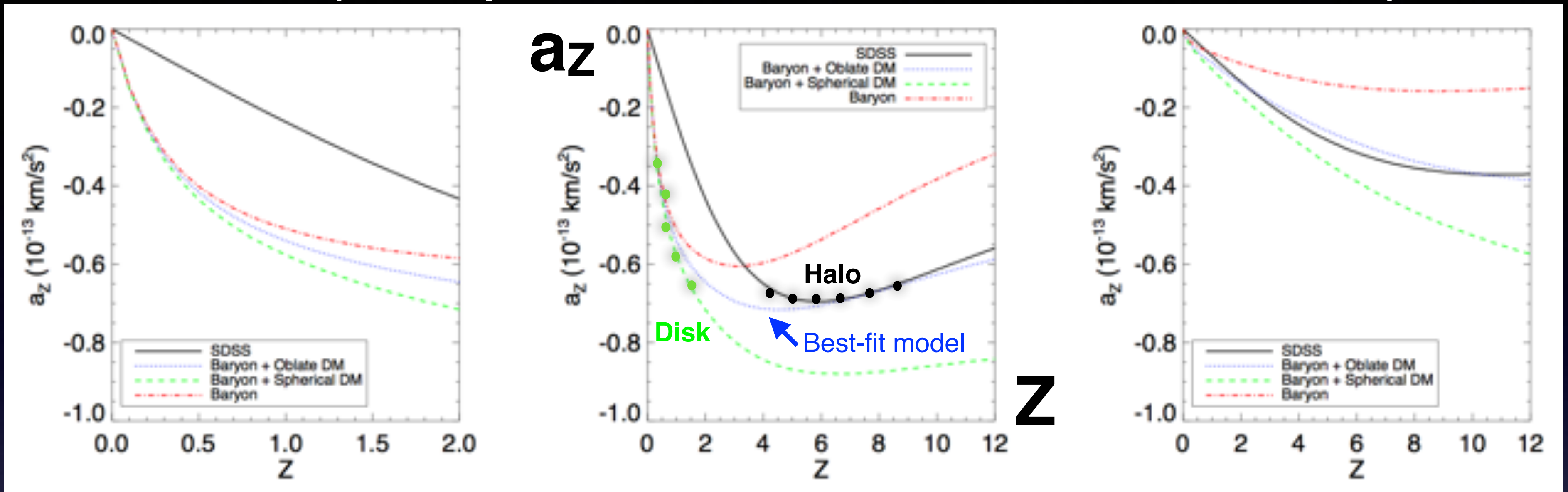
$$\Phi_{DM}(R,Z) = \frac{1}{2} v_o^2 \ln\left(\frac{R^2 + (Z/q_{DM})^2 + R_{core}^2}{R_\odot^2}\right)$$

The BHB sample from Xue et al. has about 100 stars at the right location. Radial velocity errors are ~2-5 km/s. Proper motion based errors are ~180 km/s (without distance errors). With Gaia: about 2 km/s! Need to wait…

Either:

1) this result cannot be extrapolated to the symmetry axis (R=0),
2) or the Milky Way is not axially symmetric

Problems (and possible short-term solutions):



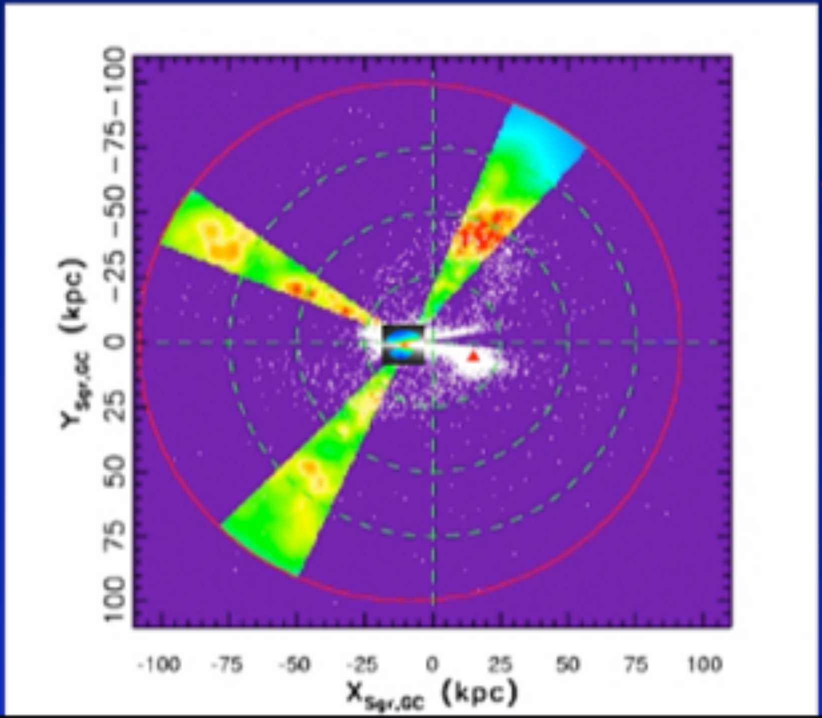
- halo and disk stars should feel the same gravitational potential and have same accelerations derived from Jeans equations…
- but at Z<2 kpc, halo and disk stars differ by a factor of ~2
- this discrepancy could be due to inadequate model for the spatial profile from Juric et al. (2008), or inadequate kinematic model from Bond et al. (2010) (Bovy & Rix results are assumed infallible)
- it turns out that the most plausible resolution is a decrease of the axis ratio for halo stars from q=0.64 at Z>6 kpc to q ~ 0.3 at Z=0
- this could be verified with new SDSS-APOGEE data…

The large blue circle: the ~400 kpc limit of future LSST studies based on RR Lyrae

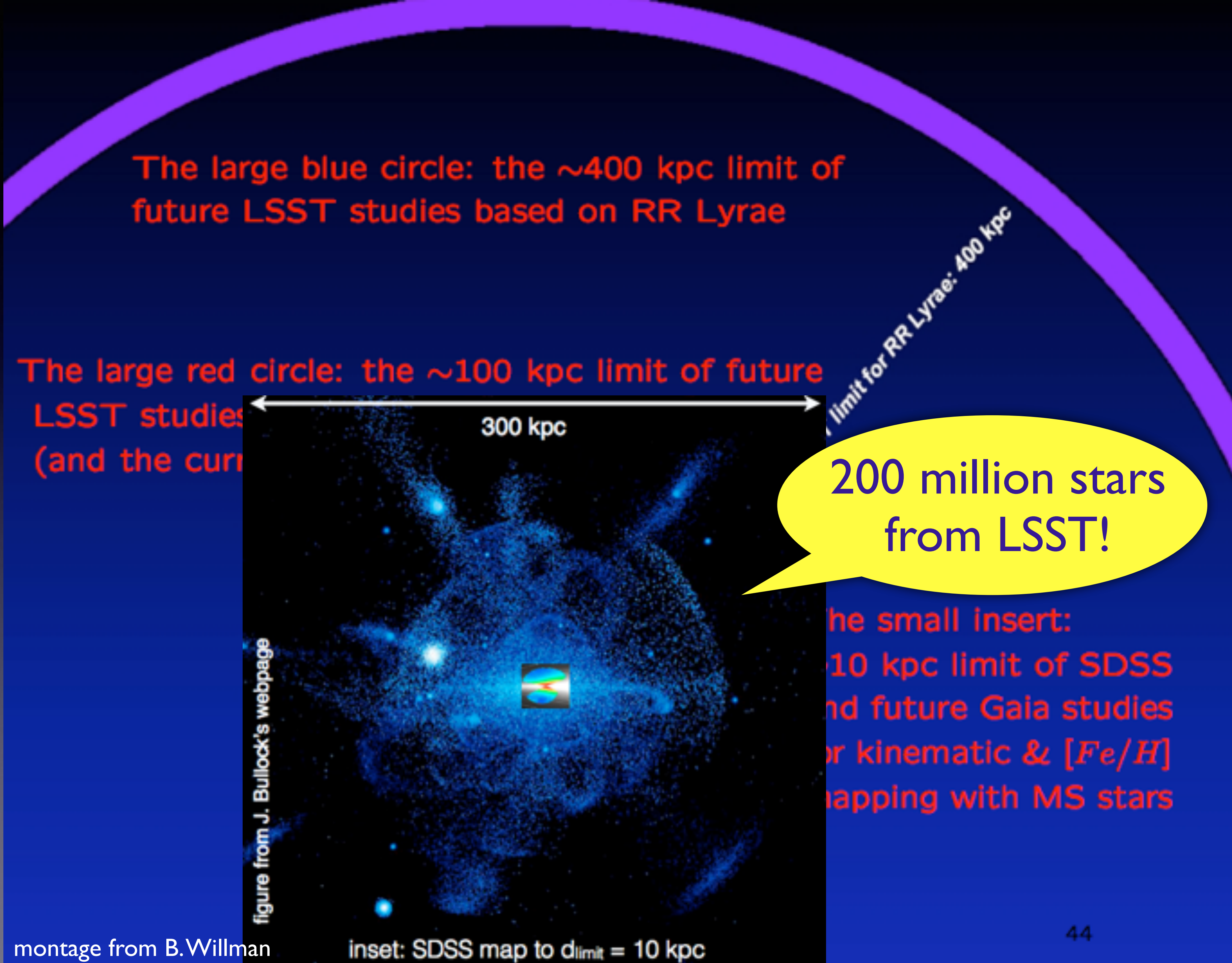
LSST limit for RR Lyrae: 400 kpc

The large red circle: the ~100 kpc limit of future LSST studies based on main-sequence stars (and the current limit for RR Lyrae studies)

6D information from LSST: 3D spatial, 2 velocities, [Fe/H]



The small insert: ~10 kpc limit of SDSS and future Gaia studies for kinematic & $[Fe/H]$ mapping with MS stars


The large blue circle: the ~400 kpc limit of future LSST studies based on RR Lyrae
limit for RR Lyrae: 400 kpc
The large red circle: the ~100 kpc limit of future
LSST studie
(and the curr
300 kpc
200 million stars from LSST!
he small insert:
10 kpc limit of SDSS
nd future Gaia studies
r kinematic & [Fe/H]
apping with MS stars
figure from J. Bullock's webpage
inset: SDSS map to d_limit = 10 kpc
montage from B. Willman
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