EANAM5 (Oct. 29, 2012 @Kyoto)

Structures, Dynamics, and Formation of the Milky Way:

A Narrow Perspective

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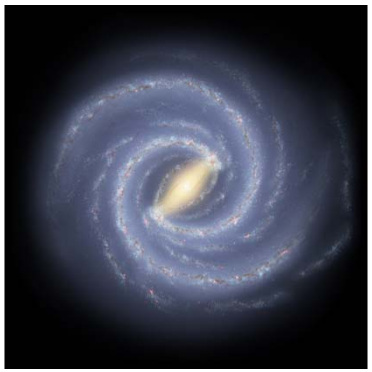
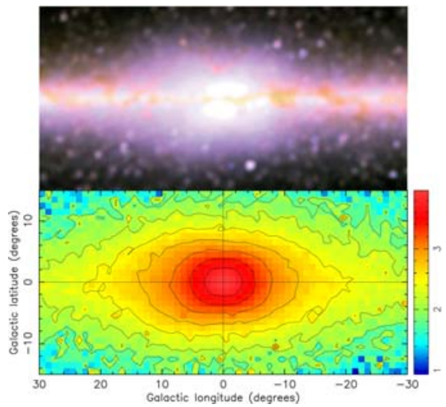





不識廬山真面目
只緣身在此山中
蘇東坡

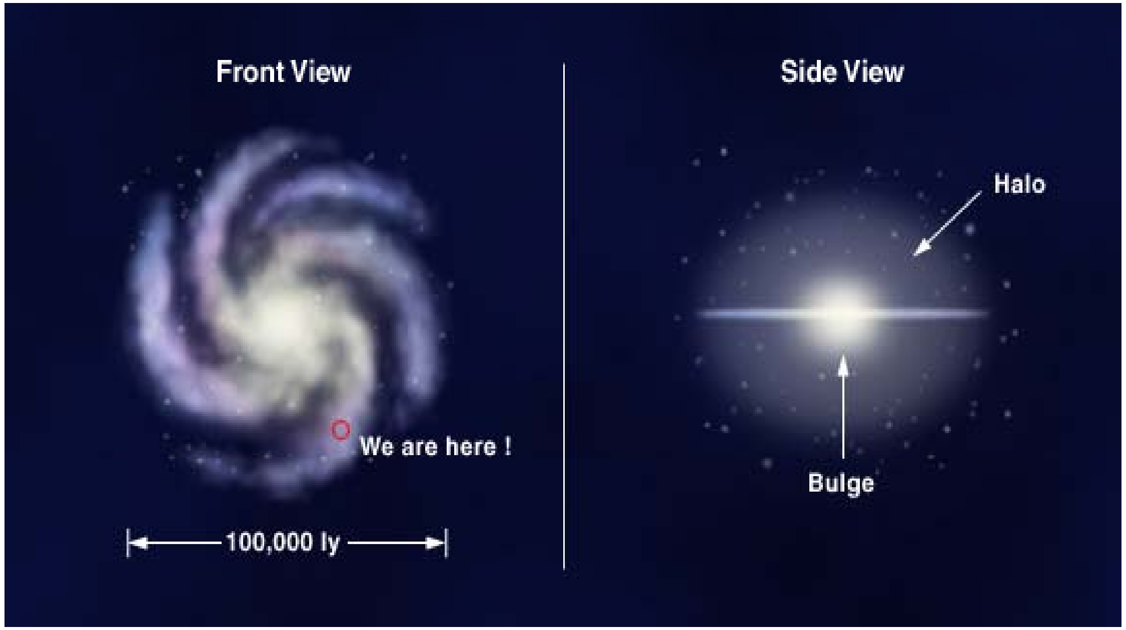
Outline

There is no place like home!

- Global properties
- Components
- Spiral structure
- Bars in general
- MW's Bulge/Bar
  - Classical vs. pseudo bulges
  - Milky Way's bulge
  - New developments
    - X-shaped structure

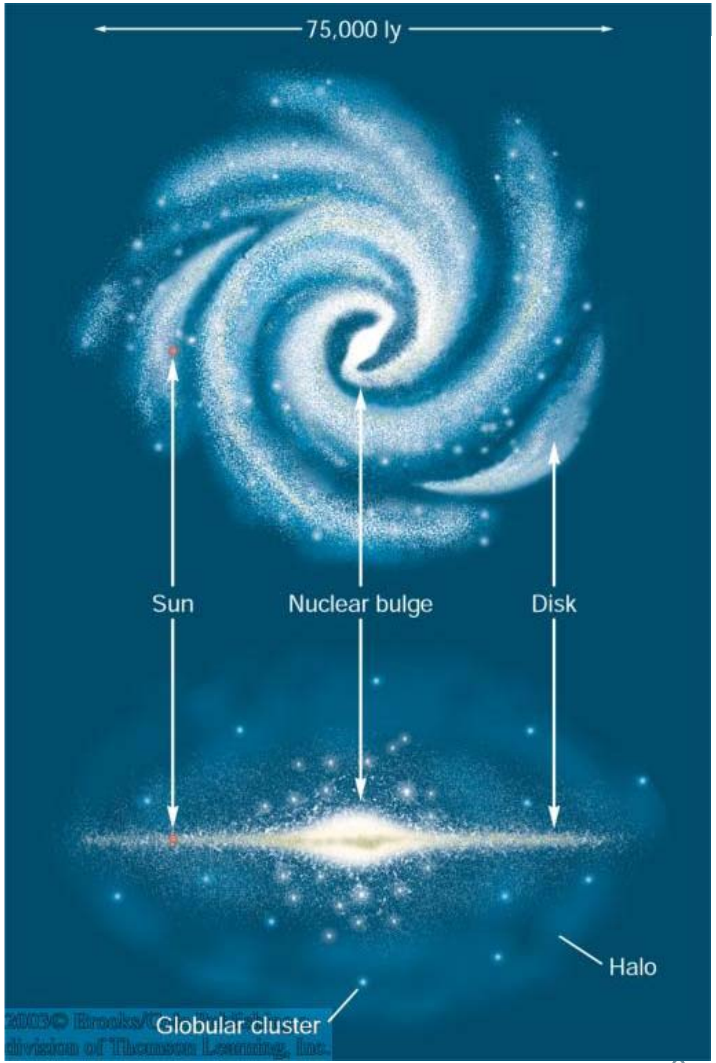
Components of the MW

- Disk
  - Thin disk
  - Thick disk
- Bulge / Bar
- Halo
  - Dark matter
  - Stellar
  - Gas
- Spiral structure



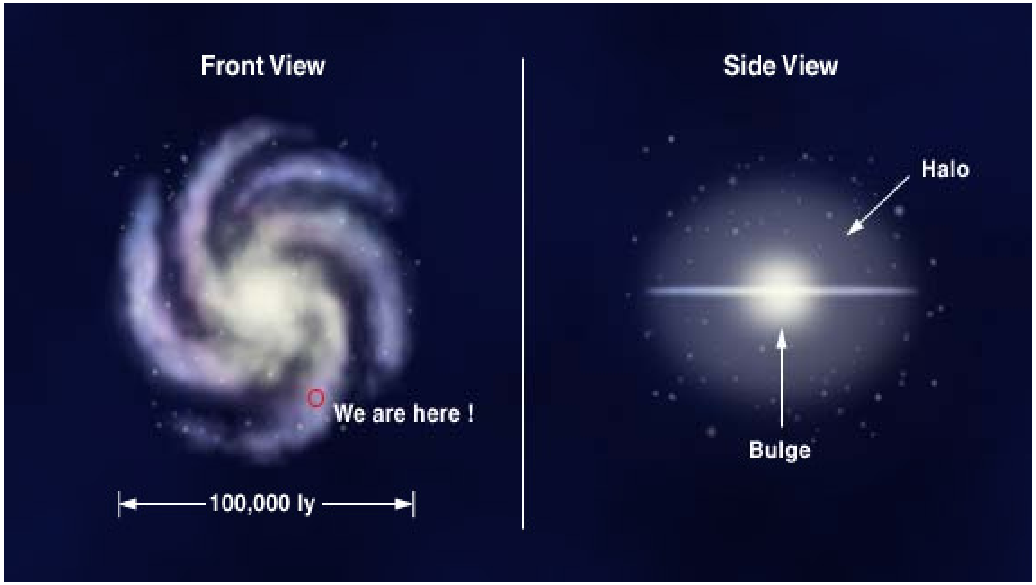
Global properties of the MW

- $R_d \sim 2.5 \pm 0.5$ kpc
- $L_{tot} \sim 3X10^{10} L_\odot$
  - $M_I = -22.7$
  - Disk 85% vs. Bulge 15%
- $M_{disk} \sim 5X10^{10} M_\odot$
  - (Flynn et al 2006)
- M_{tot} (R) ~ R(kpc) X $10^{10} M_\odot$
- Disk stellar $(M/L)_R \sim 2 (M/L)_\odot$
- SMBH ~ $4 X 10^6 M_\odot$
- Hubble type: SBbc



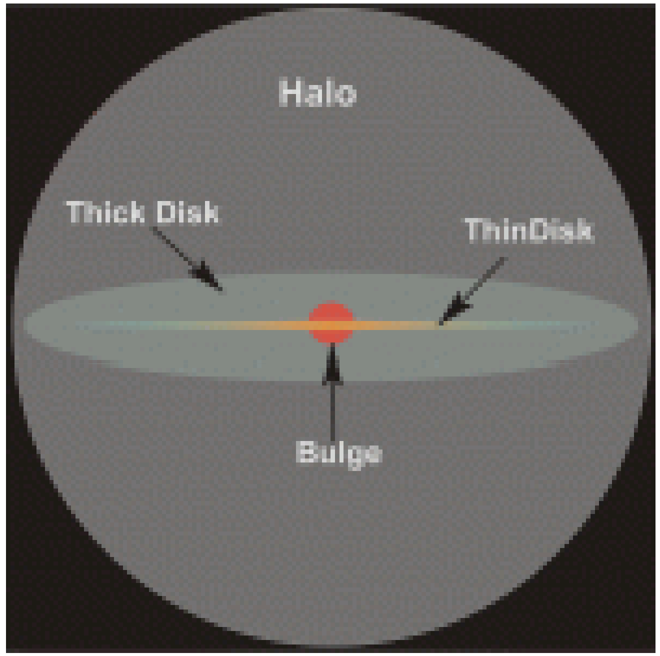
Solar neighborhood properties

- $R_\odot$ ~ 8.0-8.5 kpc
- V_{circ} ~ 220-245 km/s ?
- Disk ρ ~ 0.1 $M_\odot pc^{-3}$
- Disk Σ ~ 50 $M_\odot/pc^{-2}$
- Disk thickness ~ 500 pc
- Rotation period ~ 220 Myr
- Vertical period ~ sqrt(4*pi*Gρ)~90 Myr



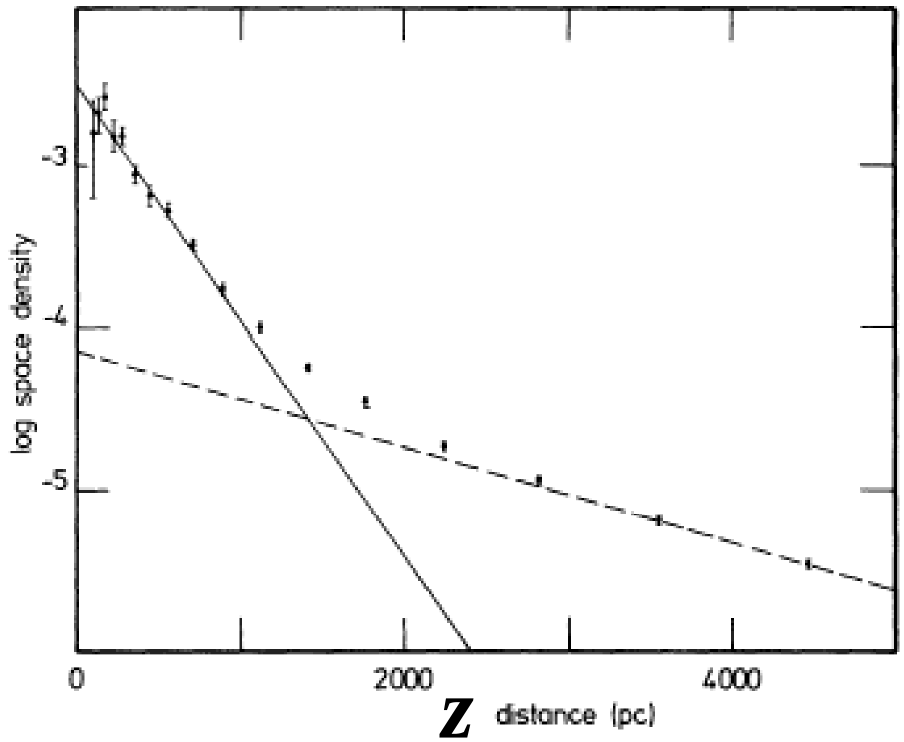
Component: thin disk

- Scale-height ~ 300pc
- Continuous on-going star formation for 10Gyr
- Wide range of ages
- Metal-rich
  - >~ solar metallicity



Component: thick disk

- Scale-height ~ 1 kpc
- Stars older; metal-poorer; alpha elements enhanced
- Surface density ~ 7% of that of the thin disk
- At midplane, thin/thick stars ~ 50:1
- Created by thickening by an encounter with a smaller galaxy?
  - Quillen & Garnett 2001
- Is it really a distinct thick disk, or just a *thicker disk component*? (Bovy et al. 2012)



Gilmore & Reid (1983)

Component: stellar halo

- Spherical
- About 1% of the total stellar mass
- Very metal-poor; $0.02Z_{\odot}$
- Little mean rotation
- $\rho \sim r^{-3}$
- Debris of disrupted stellar systems, globular clusters and small satellites?
- Inner (<30kpc): in situ star formation? (Font et al. 2011)

Component: gas halo

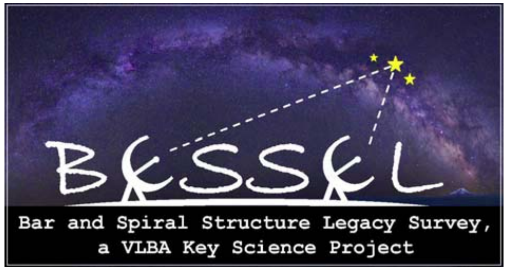
- Massive gaseous halo?
- Ionized hydrogen at $>10^6$K, extends for 100s kpc
  - Shull et al (2009); Gupta et al (2012)
- The missing baryons?
  - Mass comparable to stars? $>10^{10}\,M_\odot$
- Reservoir of gas to cool and fall into the Galaxy
  - Observed high-speed clouds (HVCs)?
  - Stuff in and out: same things?
- To be confirmed in follow-ups

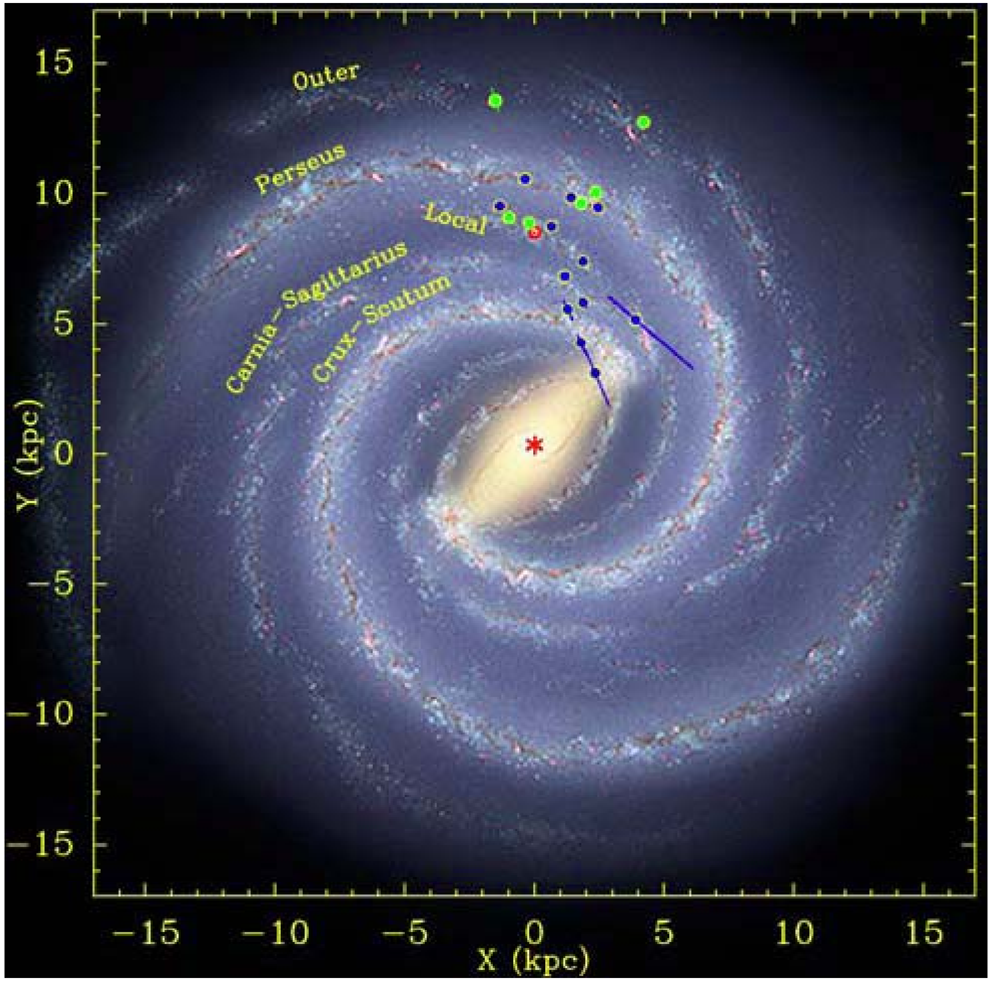
Component: dark matter halo

- The least well understood
  - Shape: spherical or triaxial?
- Mass & Size
  - Kinematics of distant GCs and nearby galaxies
  - Wilkinson & Evans (1999): $2X10^{12}\ M_{\odot}$; r_{half} ~ 100 kpc
  - Xue et al. (2008): blue horizontal-branch halo stars; $1X10^{12}\ M_{\odot}$
  - Bovy et al. (2012): $0.85X10^{12}\ M_{\odot}$
- M_{tot} (R) ~ R(kpc) X $10^{10}\ M_{\odot}$

Component: spiral arms

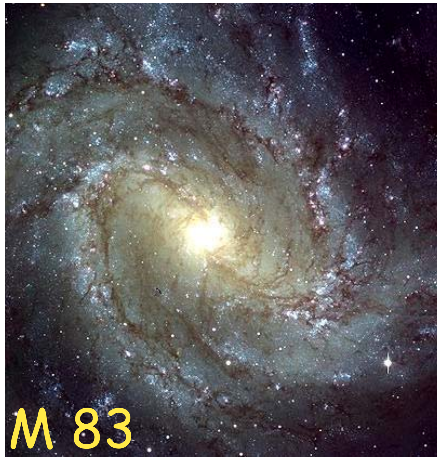
- Very uncertain
- How many arms
  - only two major stellar arms?: the Perseus arm and the Scutum-Centaurus arm (Benjamin et al. 2008)
- BeSSel project





Spiral structure

Contrast global and flocculent spiral structures



Flocculent spiral structure

- Easy to understand
  - Differential rotation; strong shear
  - "*Spiral structures are quite natural. Every structural irregularity is likely to be drawn out into a part of a spiral*" (Oort 1962)

Global “grand-design” spirals

- Fact: observed spiral arms are always **trailing**
- The winding problem
  - Not material arms
- They are density waves
  - Lin & Shu 1964
- Some of them are clearly driven by tidal interactions or perhaps bars

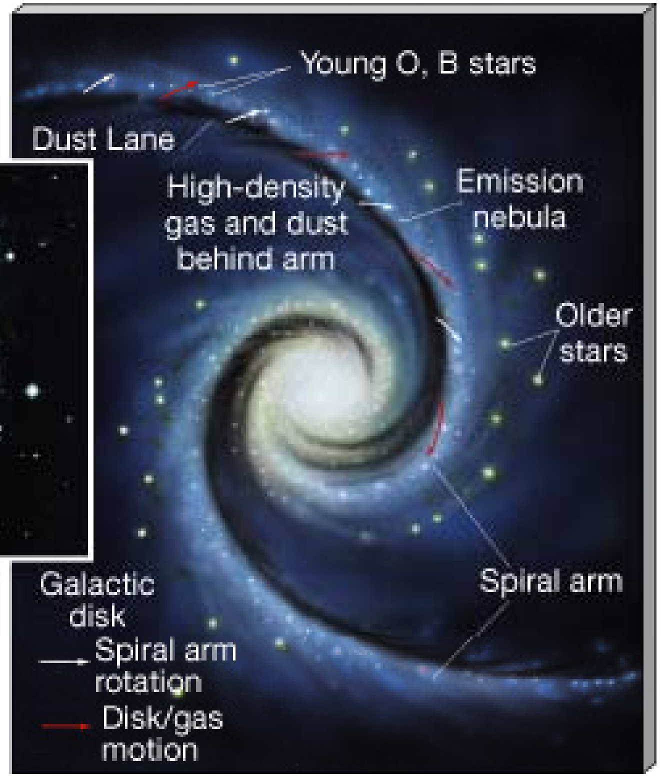
Self-excited global spirals

- Quasi-steady modes
  - Lin & Shu
  - Persistence problem: group vel. not 0
  - Anti-spiral theorem (Lynden-Bell & Ostriker 1967):
    - non-steady
    - dissipational
- Short-lived, transient, recurrent
  - Today's grand-design spirals have not been in place in HDF.
  - Swing amplifying of unsmooth distribution func. (see Sellwood 2010)

If a steady-state solution of a time-reversible set of equations has the form of a trailing spiral, then there must be an identical solution in the form of a leading spiral

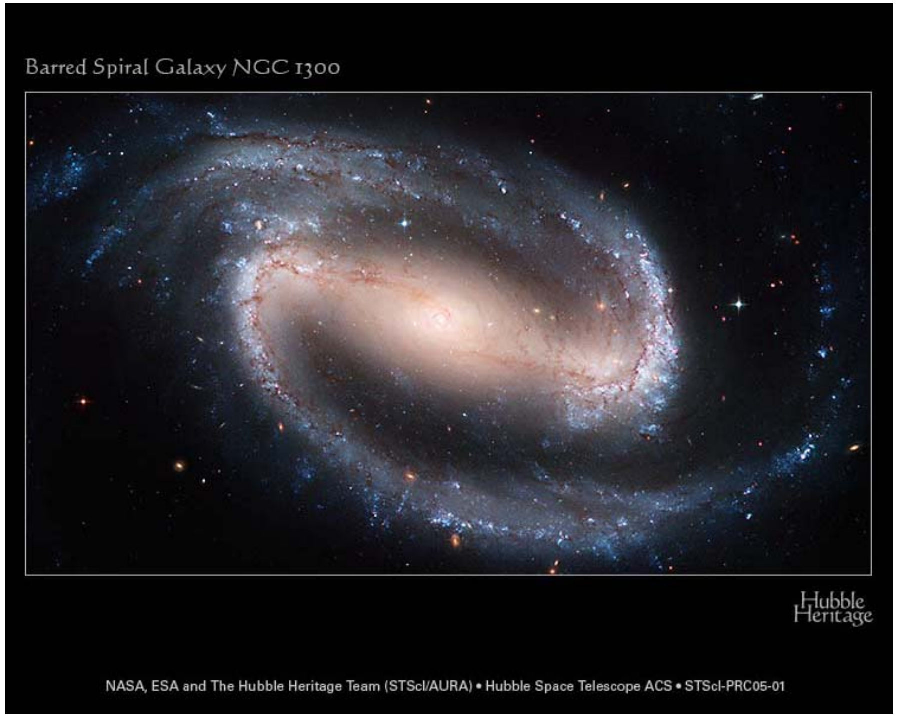
Testing spiral structure theories

- Expect to find a progression:
  - cold HI gas and CO
  - H_2 and 24-μm emission from stars forming in clouds
  - the UV emission of fully formed and unobscured stars.
- Both theories can have density waves surviving much longer than the T_{SF}
- Foyle et al. 2011: no systematic offsets
  - Observational evidence against long-lived spiral arms in galaxies?



Barred galaxies

- Bars: elongated cigar-shaped features in disk
- Composed of old stars
  - Easier to detect bars in near infrared
- Ubiquitous: ~ 2/3 of disk galaxies are barred
  - Latest NIR survey (Eskridge et al. 2000)
  - More normal than "normal" disk galaxies!
- Bar pattern rotates rapidly



Impact of bars on galaxy evolution

- Strongest internal disturber: influence disk, bulge, and dark matter halo
- Drive gas flow inward
- Ignite circum-nuclear starbursts
- Build up pseudo-bulges
  - Different from classical bulges
  - Secular evolution (Kormendy + Kennicutt 2004)
- Bars exchange angular momentum with dark matter halos via dynamical friction
- Understanding bars is an integral part of understanding galaxy formation and evolution.

Making bars in simulations

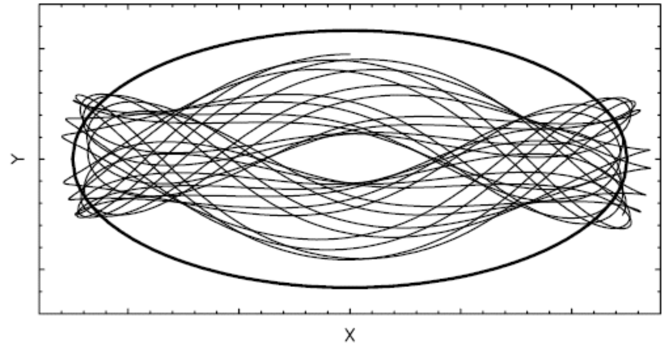
- Spontaneous bar instability
  - if ordered rotation dominates over random motion in the initial disk (dynamically “cold”)

(Hohl 1971, Sellwood 1981)

- Tidally-induced (e.g. Noguchi 1996)
- Formation of real bars may be more sophisticated
  - Still lots of questions
  - Halo properties are important
  - Why 2/3 are barred?

Dynamics of bars

- Bars are made of elongated x_1 orbits
  - x_1 are analogous to z-axis tubes
  - but very elongated



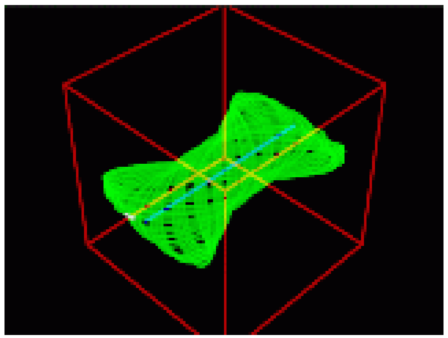
- They are nearly resonant (ILR) orbits that would precess exactly together like if $\Omega_p = \Omega - \kappa/2$

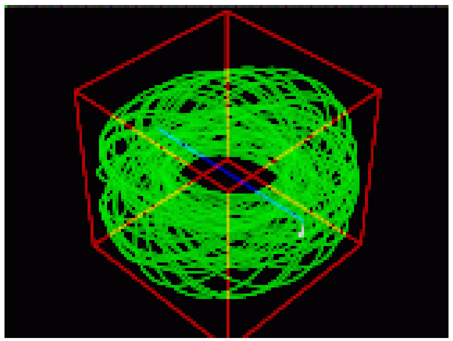
- Since $\Omega - \kappa/2$ is not quite constant with R, it is the job of self-gravity to force the orbits precess exactly together.

Bars & ellipticals: *fundamentally different!*

- Bars are tri-axial because of **too much** angular momentum
- Giant ellipticals are tri-axial because of **too little** angular momentum
  - Supported by random motions
  - Mostly boxy orbits
  - Angular momentum is provided in z-axis tube orbits (not very elongated)

Boxy Orbits





z-axis tubes

Credit: J. Barnes

Bulges

We do not fully understand them yet!

- Classical bulges
  - ≈ Mini-elliptical
  - Merger-made
  - Sersic n > 2
  - not rotation-dominated

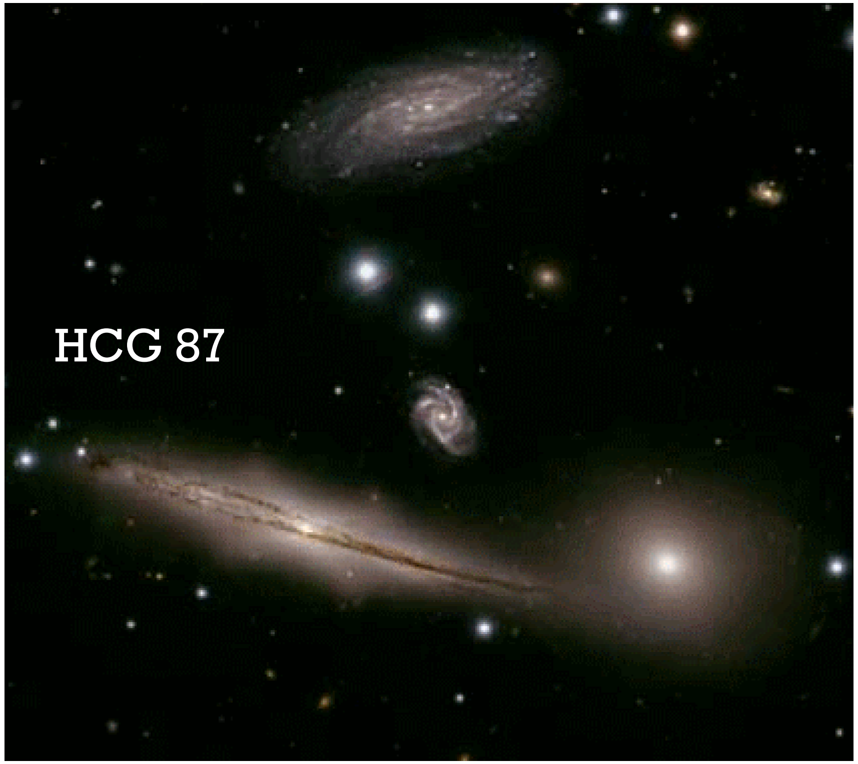
- Pseudo-bulges
  - Extra light at small R; central thick comp.
  - Formed from disk by internal secular processes
  - Retain some memory of their disk origin
  - Rotation dominated
  - Young stars, gas, dust
  - Sersic index 1-2
  - Including "**boxy bulges**"

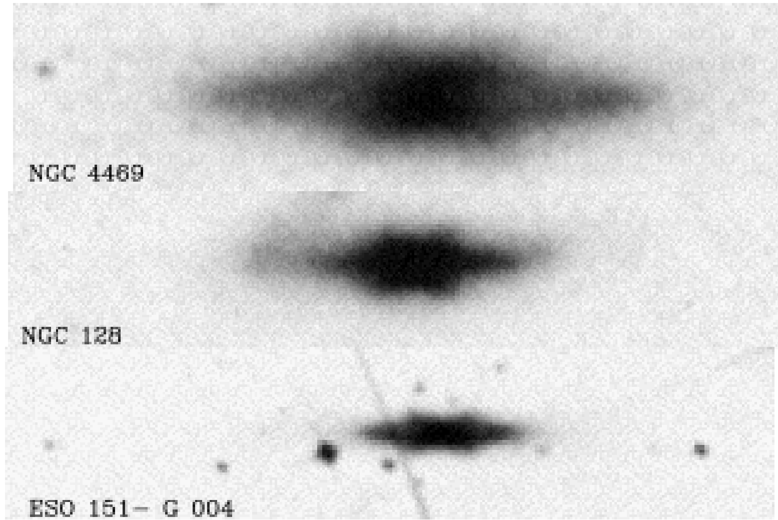
Kormendy & Kennicutt (ARAA, 2004)

Boxy/peanut-shaped bulges

- Most of bulge stars are old (>5 Gyr, Clarkson et al. 2008)
- A wide range of metal abundances (McWilliam & Rich 1994; Fulbright et al. 2006; Zoccali et al. 2008)

Boxy/peanut-shaped bulges





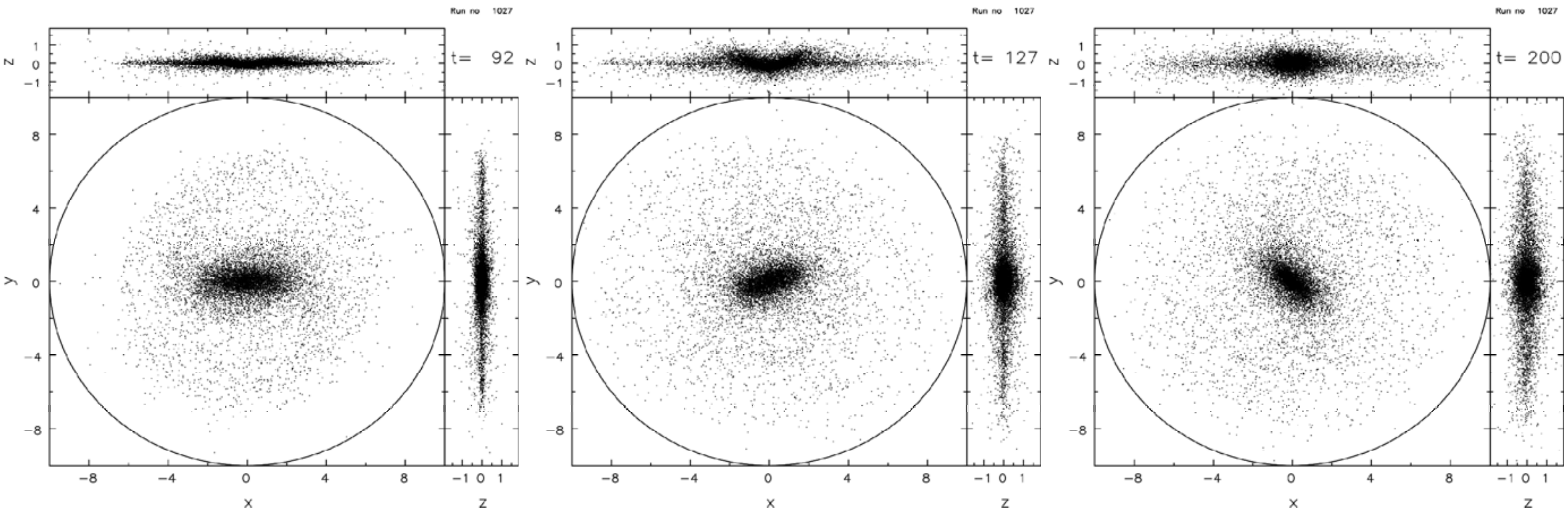
- ~45% edge-on disks have peanut-shaped bulges (Lutticke et al. 2000)
  - Comparable to the fraction of bars

Boxy peanut-shaped bulges: side-on bars?

- Simulation of bended/thickened bars
  - Buckling/firehose instability (Toomre 1966)

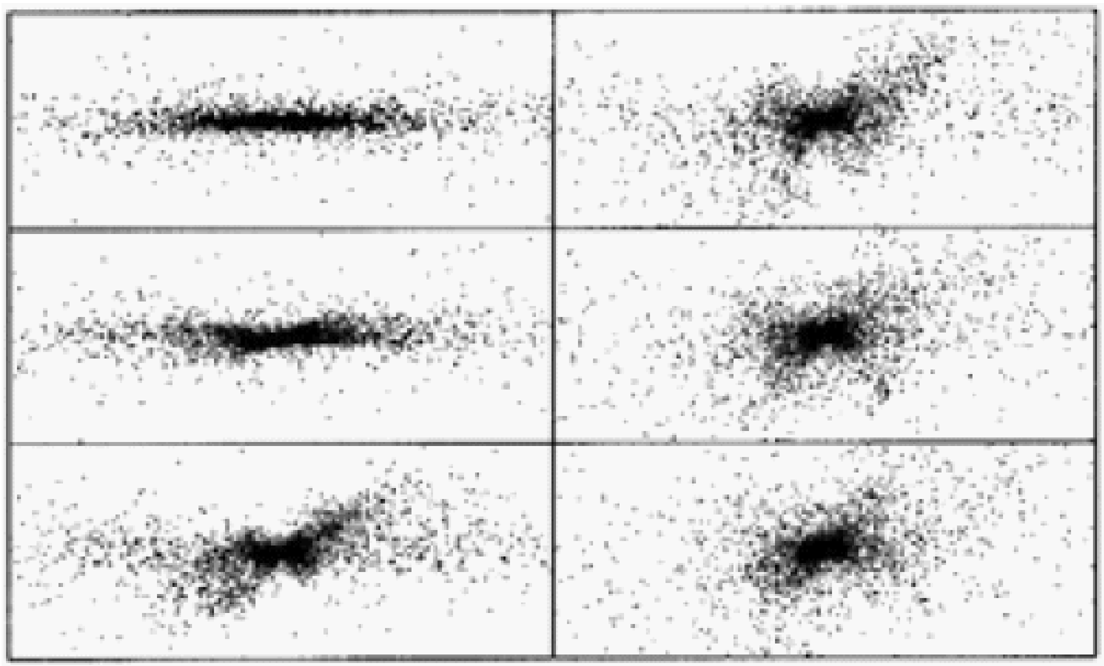
    $$\sigma_Z \leq 0.3\sigma_R$$

  - Bar formation → Buckling instability → saturation → B/PS bulges (e.g. Raha, Sellwood et al. 1991)



Buckling instability and ellipticals

- Possible explains why there are no ellipticals more elongated than E6 or E7, corresponding to a maximum axis ratio of about 3:1.
- Sufficiently thick → low κ_z → disturbances damped

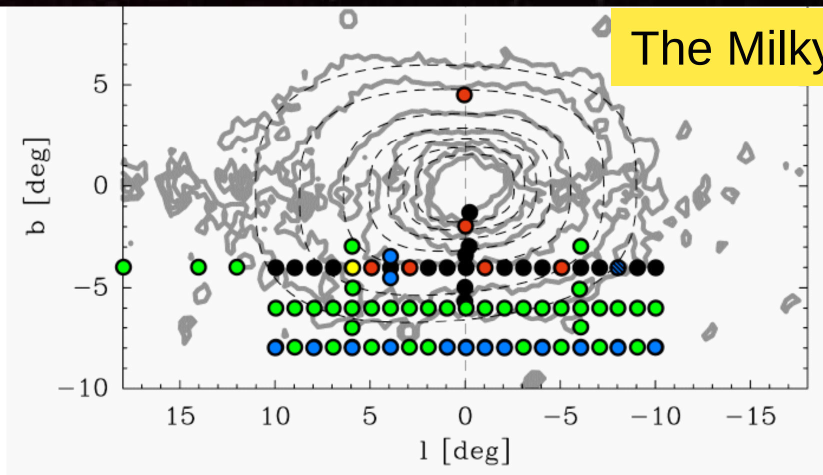


Merritt & Hernquist 1991

Stellar Kinematics of the Bulge

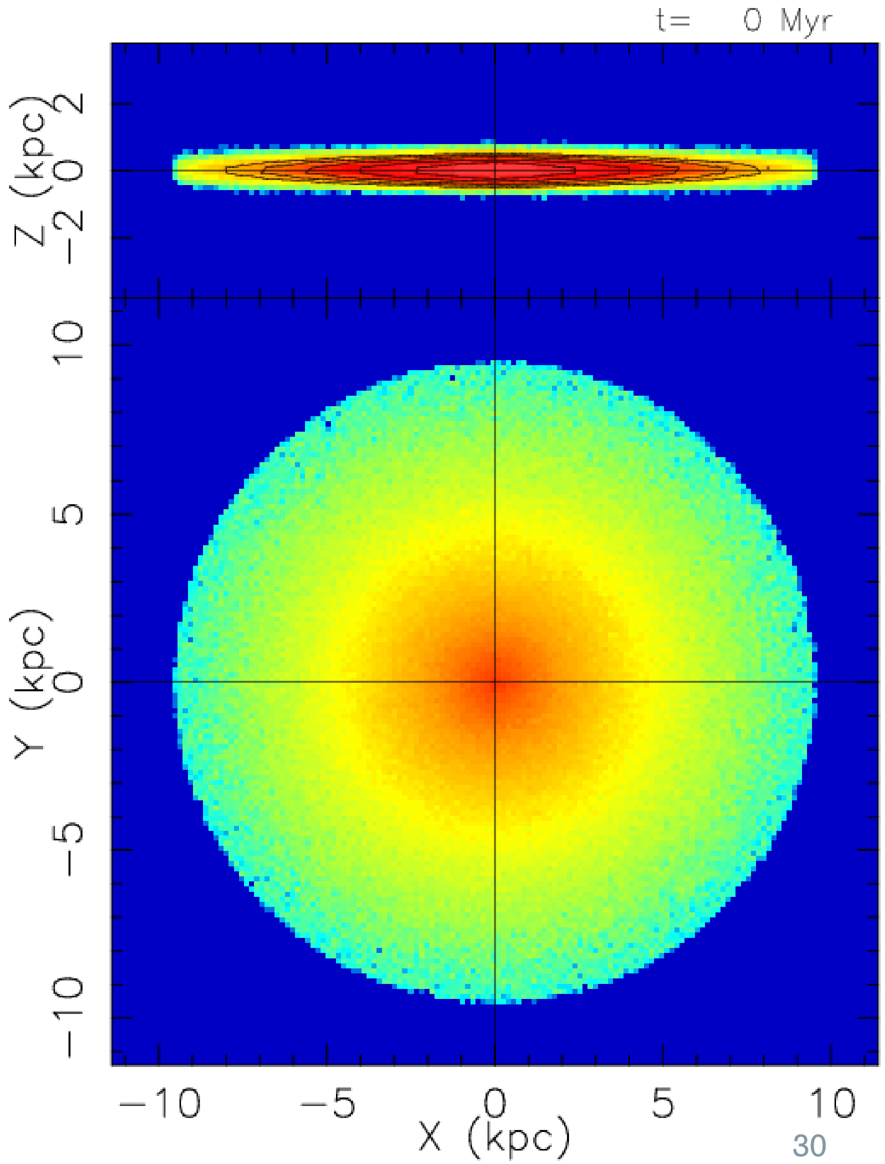
- BRAVA (Bulge Radial Velocity Assay) survey
  - ~10,000 M giants as targets
  - **Stellar kinematics covering the whole Bulge**
- Build a simple dynamical model to explain it

The Milky Way in IR (COBE)



Modeling the Milky Way Bulge

- A simple model of the Galactic bulge matches the BRAVA data extremely well in almost all aspects:
  - *b* = -4° major axis
  - *b* = -8° degree major axis
  - *l* = 0° degree minor axis
  - Surface density

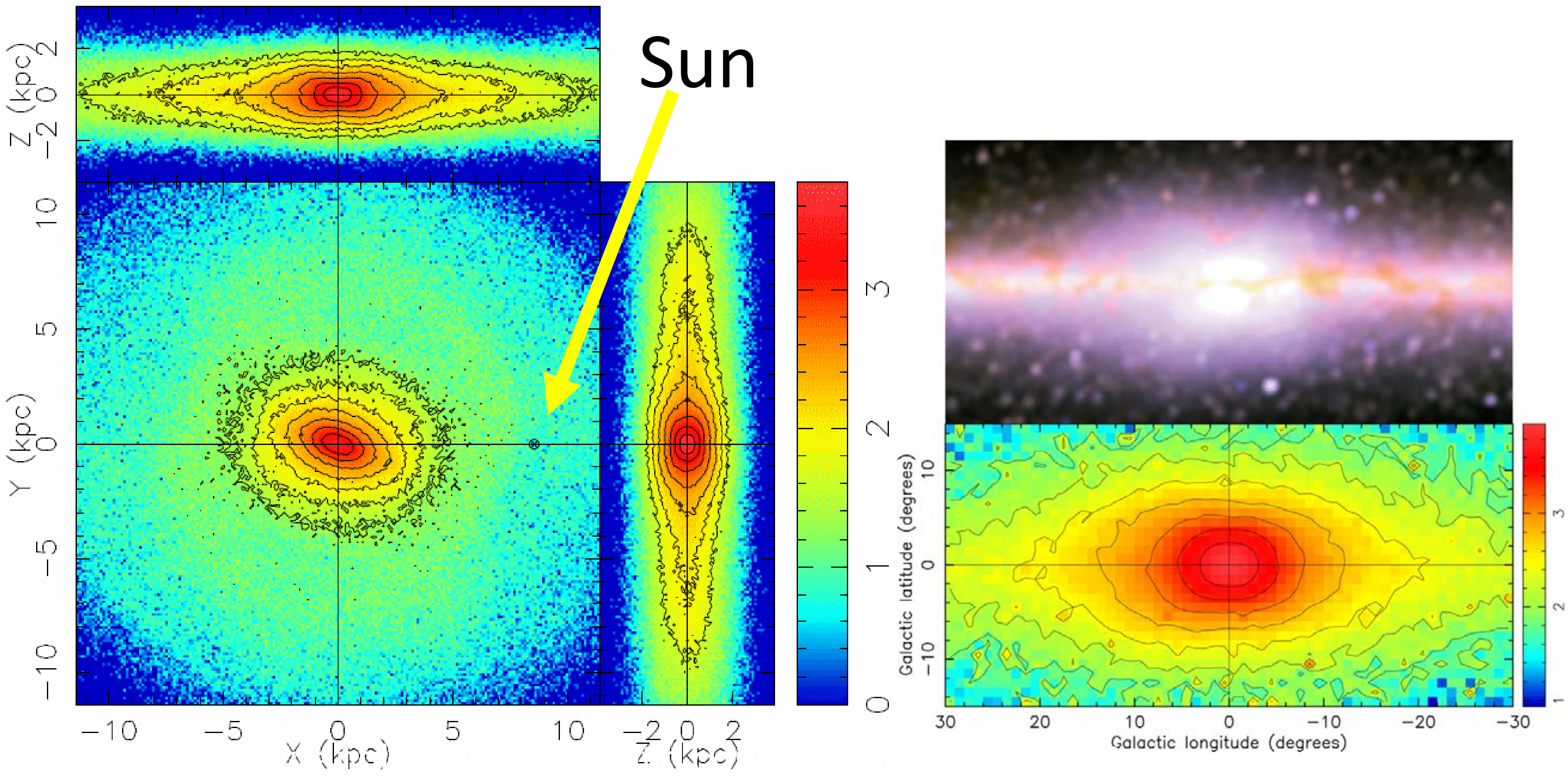


Shen, J., et al 2010, ApJL

Power of simplicity

- High resolution *N*-body simulations with millions of particles
- Cold massive disk, initial Q ~ 1.2
- A pseudo-isothermal rigid halo with a core which gives a nearly flat rotation curve of ~220 km/s from 5 to 20 kpc
- Inside solar circle, M_{disk}/M_{halo} ~ 1.5, max disk
- A good starting point

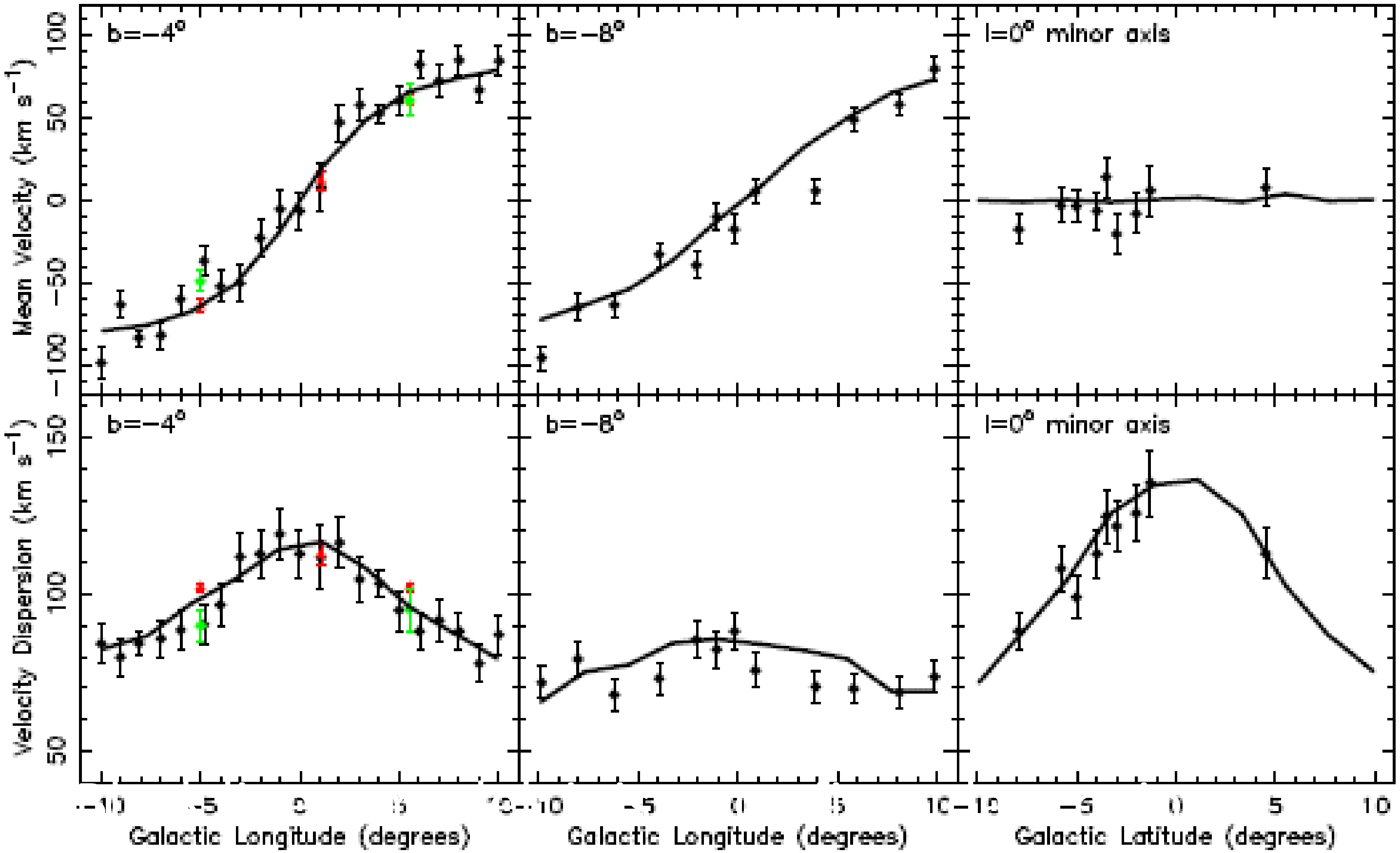
Modeling the Milky Way Bulge ---
Surface Brightness Map



Shen, J., et al 2010, ApJL

Modeling the Milky Way Bulge ---

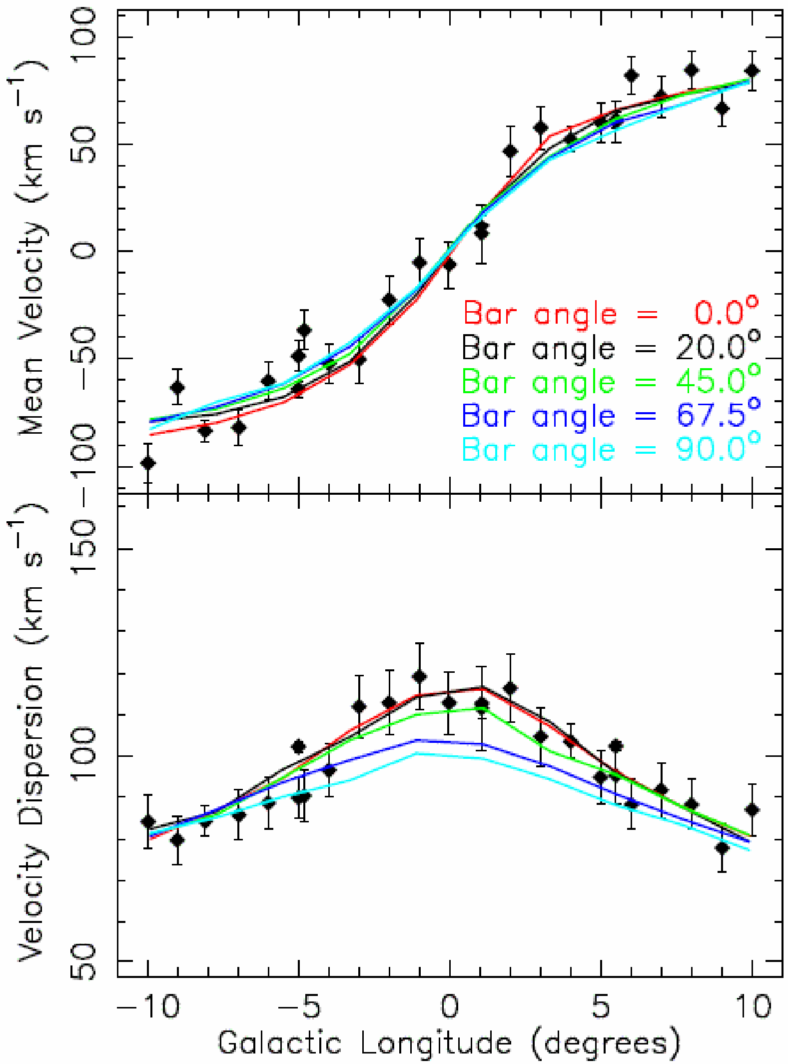
Match stellar kinematics in all strips strikingly well



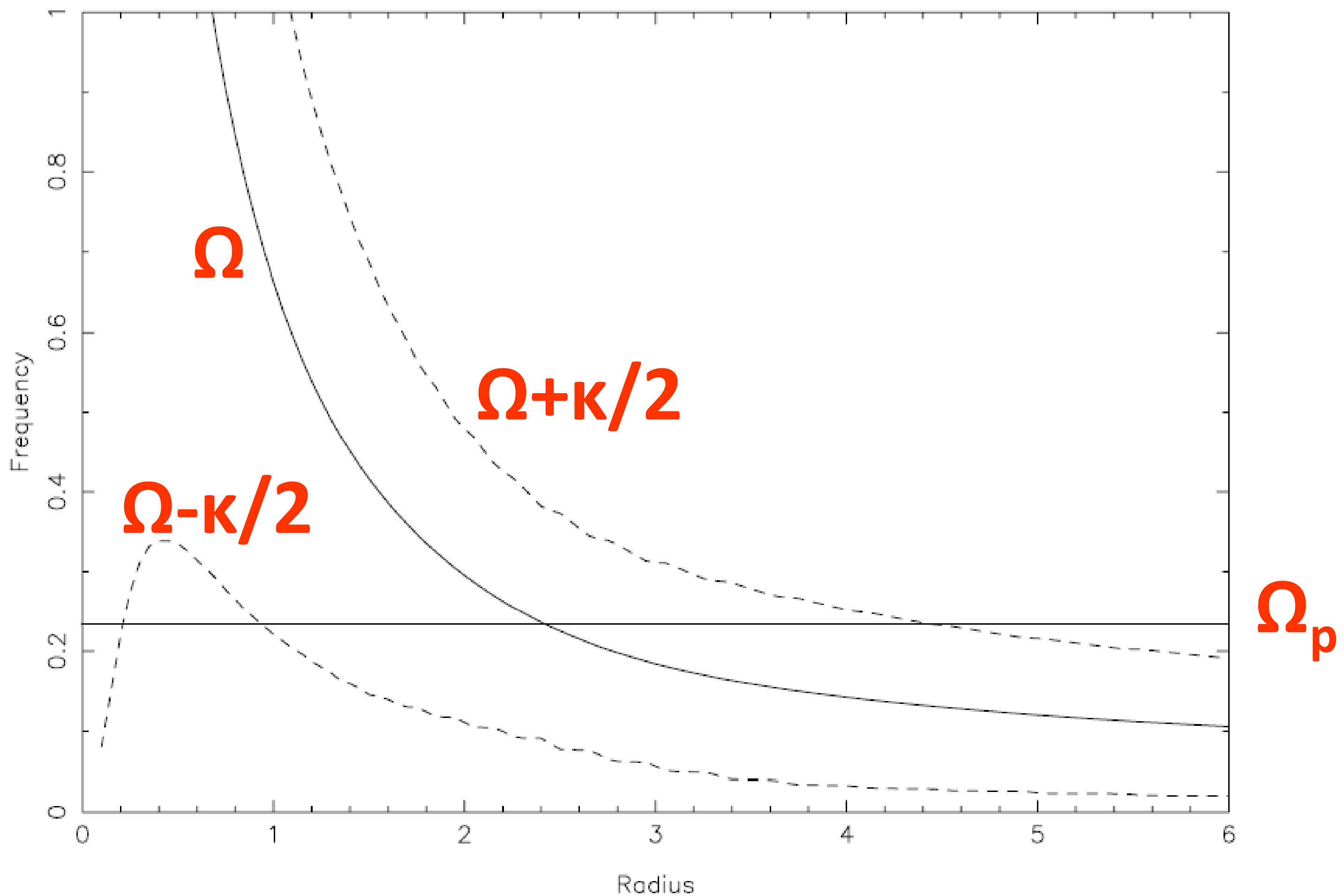
Shen, J., et al 2010, ApJL

Modeling the Milky Way Bulge ---
Constraining the Bar Angle

- Bar angle consistent with other studies of star counts and surface brightness (Stanek et al. 1997; Bissantz & Gerhard 2002)



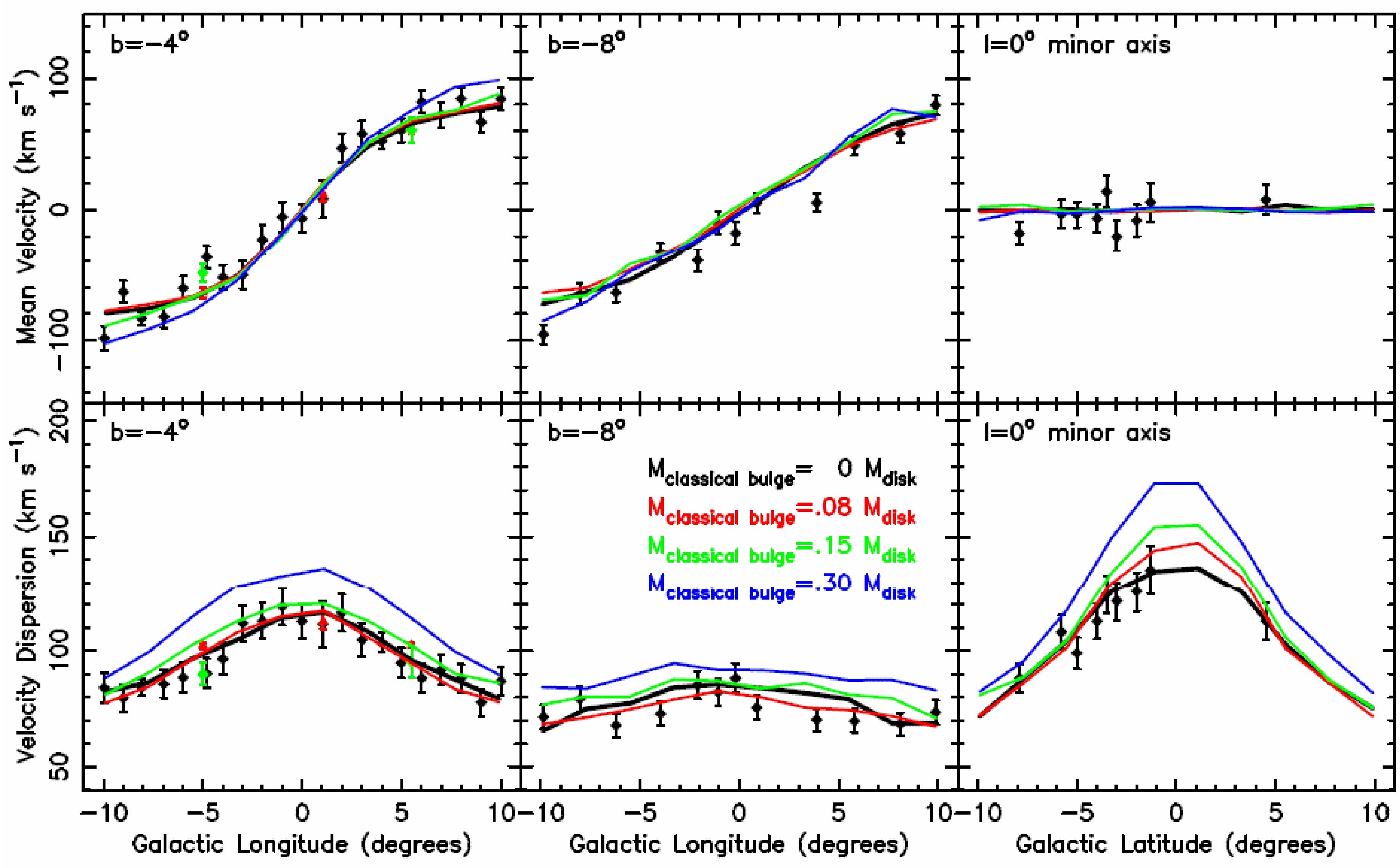
Pattern speed of the MW bar



Pattern speed ~ 40 km/s/kpc

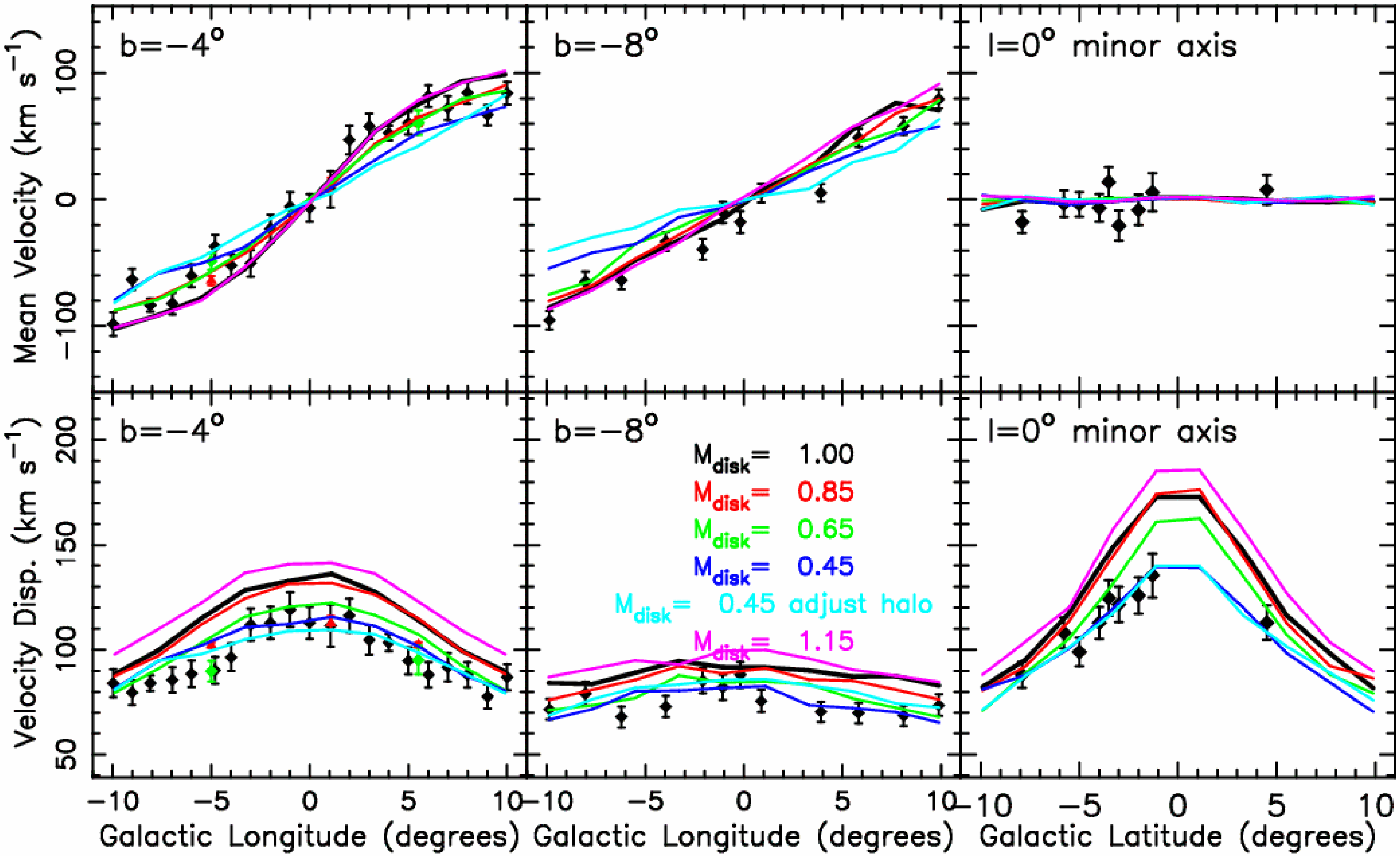
R_{CR}~ 4.5kpc; R_{CR} /R_{bar} = 1.15

A Significant Classical Bulge is Excluded



The data excludes a pre-existing classical bulge with mass >~ 10% Mdisk; the MW is nearly a pure-disk galaxy!

A Significant Classical Bulge is Excluded



Even if we re-adjust the disk, it does not help much

The Milky Way as a pure-disk galaxy

- The bulge is simply the bar viewed edge-on; it is part of the disk, not a separate component.
- A significant merger-made classical bulge is excluded, **so our MW is an nearly pure-disk galaxy**
- Milky Way has a quiescent merger history (Hammer et al 2007)
- **No prominent classical bulge → no significant mergers → how do giant pure-disk galaxies grow so massive?**
- Too many significant mergers → destroy disk shape

- **Is our Milky Way special?**

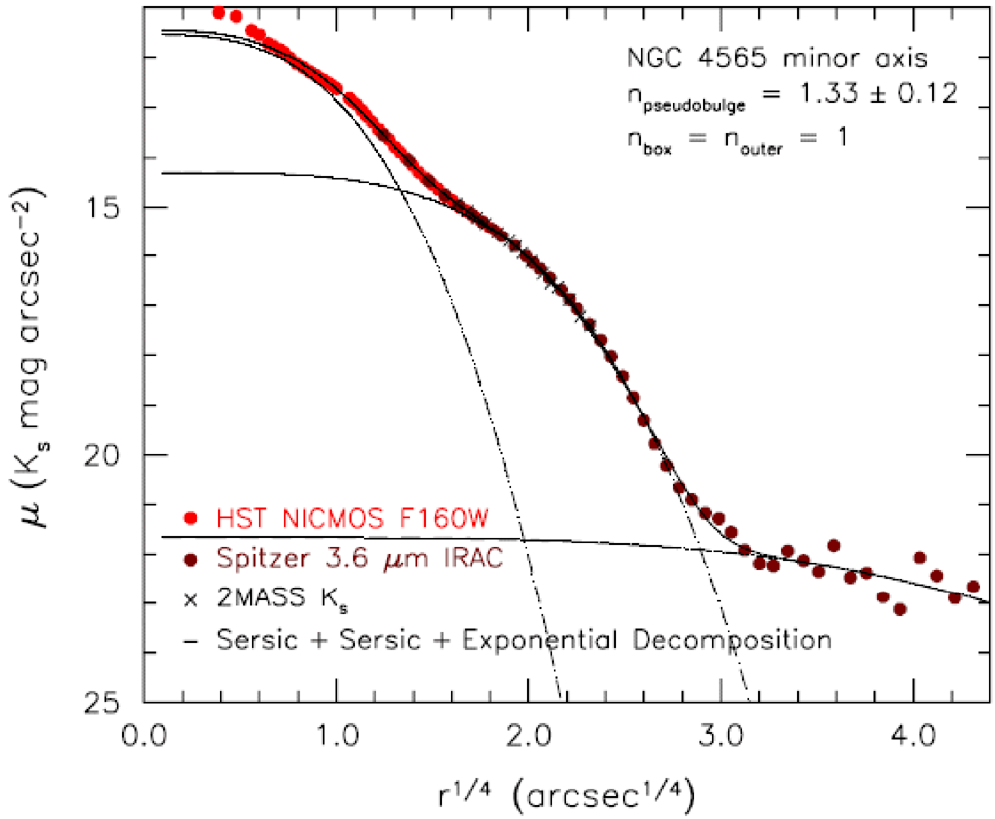
The Milky Way is not special

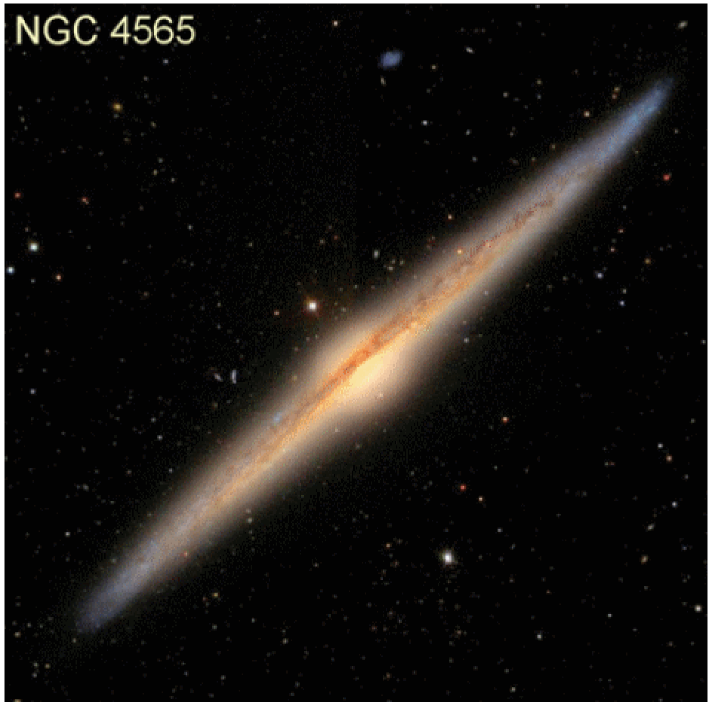
- Quote from our paper: "Our Galaxy is not unusual: it is very similar to another giant edge-on galaxy with a boxy bulge, NGC 4565. Kormendy & Barentine (2010) recently showed that NGC 4565 does not contain even a small classical bulge component and that it is therefore another giant, pure disk galaxy that contains no sign of a merger remnant. In fact, giant, pure-disk galaxies are common in environments like our own that are far from rich clusters of galaxies (Kormendy et al. 2010)."

Shen, J., et al 2010, ApJL

NGC 4565: another giant pure-disk galaxy

- Vcirc~255km/s
- PB/T ~ 0.06; as opposed to "B/T" ~ 0.4





Kormendy & Barentine 2010

Many nearby spirals are nearly bulge-less

- inventory the galaxies in a sphere of radius 8 Mpc centered on our Galaxy

- "We find that at least 11 of 19 galaxies with $V_{circ} > 150$ km s^{-1}, including M101, NGC 6946, IC 342, and our Galaxy, show no evidence for a classical bulge. Four may contain small classical bulges that contribute 5%–12% of the light of the galaxy. Only four of the 19 giant galaxies are ellipticals or have classical bulges that contribute ~1/3 of the galaxy light."

- This problem is a strong function of environment
  - the Virgo cluster is not a puzzle, because more than 2/3 of its stellar mass is in merger remnants
  - it is a puzzle in the field but not in rich clusters

Kormendy et al. 2010, ApJ

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FOR IMMEDIATE RELEASE: Monday, December 19, 2011
RELEASE NO: NOAO 11-09

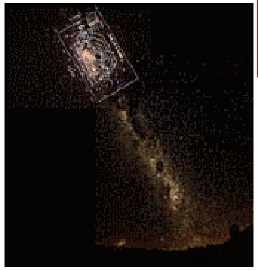
NOAO: New Insight into the Bar in the Center of the Milky Way

It sounds like the start of a bad joke: do you know about the bar in the center of the Milky Way Galaxy? Astronomers first recognized almost 80 years ago that the Milky Way Galaxy, around which the sun and its planets orbit, is a huge spiral galaxy. This isn't obvious when you look at the band of starlight across the sky, because we are inside the galaxy: it's as if the sun and solar system is a bug on the spoke of a bicycle wheel. But in recent decades astronomers have suspected that the center of our galaxy has an elongated stellar structure, or bar, that is hidden by dust and gas from easy view. Many spiral galaxies in the universe are known to exhibit such a bar through the center bulge, while other spiral galaxies are simple spirals. And astronomers ask, why? In a recent paper Dr. Andrea Kunder, of Cerro Tololo Inter-American Observatory (CTIO) in northern Chile, and a team of colleagues have presented data that demonstrates how this bar is rotating.

As part of a larger study dubbed BRAVA, for Bulge Radial Velocity Assay, a team assembled by Dr. R. Michael Rich at UCLA, measured the velocity of a large sample of old, red stars towards the galactic center. (See image) They did this by observing the spectra of these stars, called M giants, which allows the velocity of the star along our line of sight to be determined. Over a period of 4 years almost 10,000 spectra were acquired with the CTIO Blanco 4-meter telescope, located in the Chilean Atacama desert, resulting in the largest homogeneous sample of radial velocities with which to study the core of the Milky Way. Analyzing the stellar motions confirms that the bulge in the center of our galaxy appears to consist of a massive bar, with one end pointed almost in the direction of the sun, which is rotating like a solid object. Although our galaxy rotates much like a pinwheel, with the stars in the arms of the galaxy orbiting the center, the BRAVA study found that the rotation of the inner bar is cylindrical, like a toilet roll holder. This result is a large step forward in explaining the formation of the complicated central region of the Milky Way.

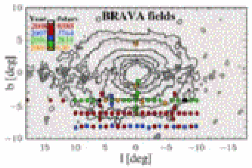
The full set of 10,000 spectra were compared with a computer simulation of how the bar formed from a pre-existing disk of stars. Dr. Juntai Shen of the Shanghai Observatory developed the model. The data fits the model extremely well, and suggests that before our bar existed, there was a massive disk of stars. This is in contrast to the standard picture in which our galaxy's central region formed from the chaotic merger of gas clouds, very early in the history of the Universe. The implication is that gas played a role, but appears to have largely organized into a massive rotating disk, that then turned into a bar due to the gravitational interactions of the stars.

The stellar spectra also allow the team to analyze the chemical composition of the stars. While all stars are composed primarily of hydrogen, with some helium, it is the trace of all the other elements in the periodic table, called "metals" by astronomers, that allow us to say something about the conditions under which the star formed. The BRAVA team found that stars closest to the plane of the Galaxy have a lower ratio of metals than stars further from the plane. While this trend confirms standard views, the BRAVA data cover a significant area of the bulge that can be chemically fingerprinted. By mapping how the metal content of stars varies throughout the Milky Way, star



The BRAVA fields are shown in this image montage. For reference, the center of the Milky Way is at coordinates L= 0, B=0. The regions observed are marked with colored circles. This montage includes the southern Milky Way all the way to the horizon, as seen from CTIO. The telescope in silhouette is the CTIO Blanco 4-m. (Just peaking over the horizon on the left is the Large Magellanic Cloud, the nearest external galaxy to our own.)

Image Credit: D. Talent, K. Don, P. Marenfeld & NOAO/AURA/NSF and the BRAVA Project



BRAVA Data.

Science Contact

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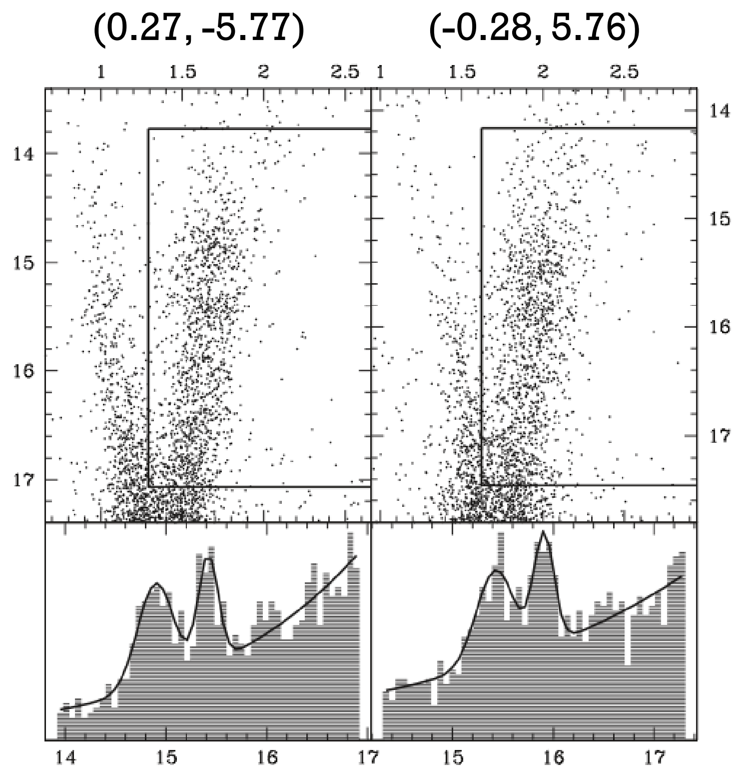
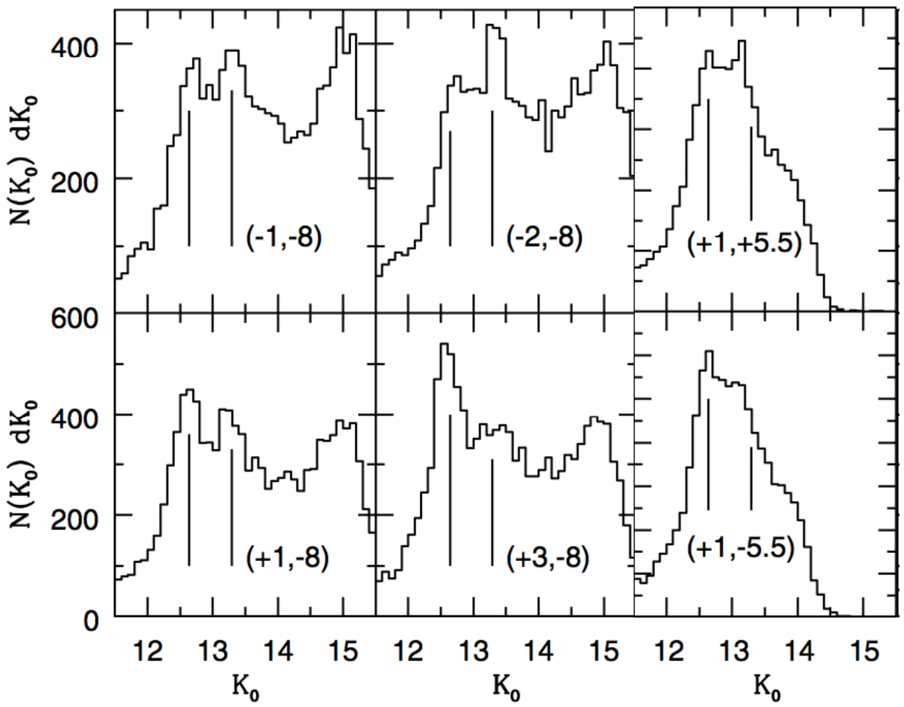
Split Red Clumps in the Galactic Bulge

- Red clump: a standard candle
- Along different lines of sight toward the Galactic bulge, red clumps split into two groups (McWilliam & Zoccali 2010; Nataf et al. 2010; Saito et al. 2011)



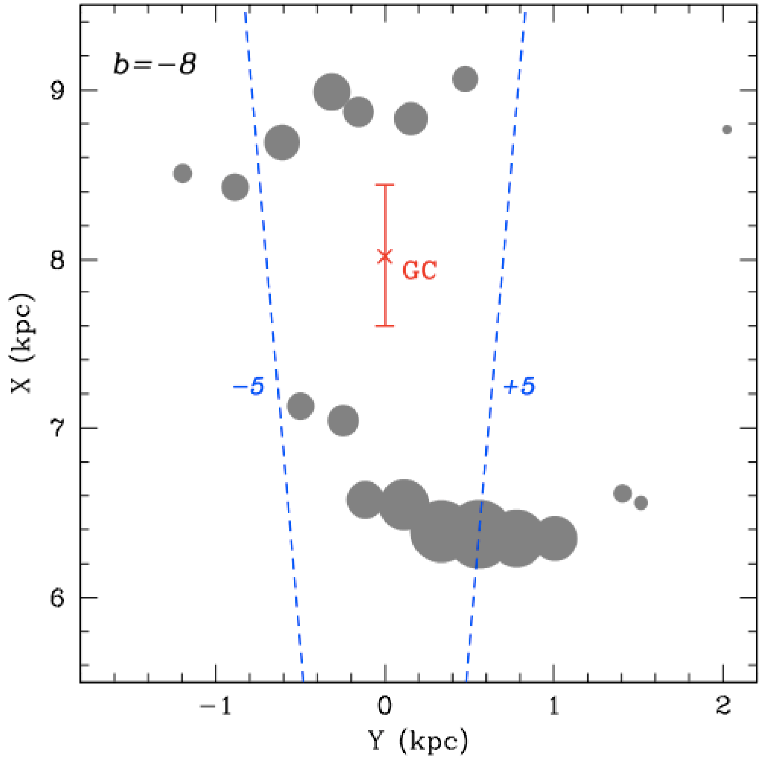
Nataf et al. (2010)

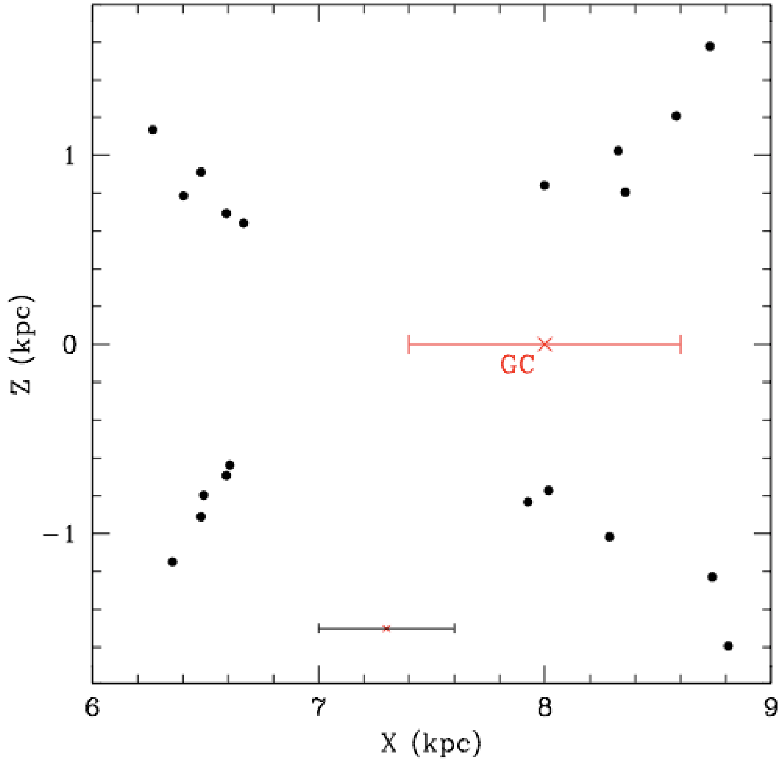


McWilliam & Zoccali (2010)

X-Structure in the Milky Way?

- The full length of the structure is about 2.3 kpc in the radial direction.
- It tilts away from the Sun-GC line by ~ 20°
- "The double peaked RC is **inconsistent** with the tilted bar morphology." (McWilliam & Zoccali 2010)

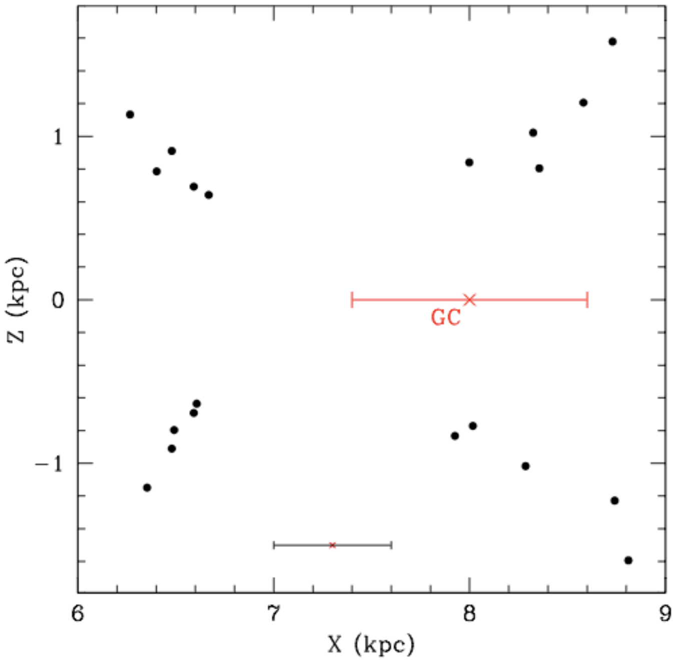




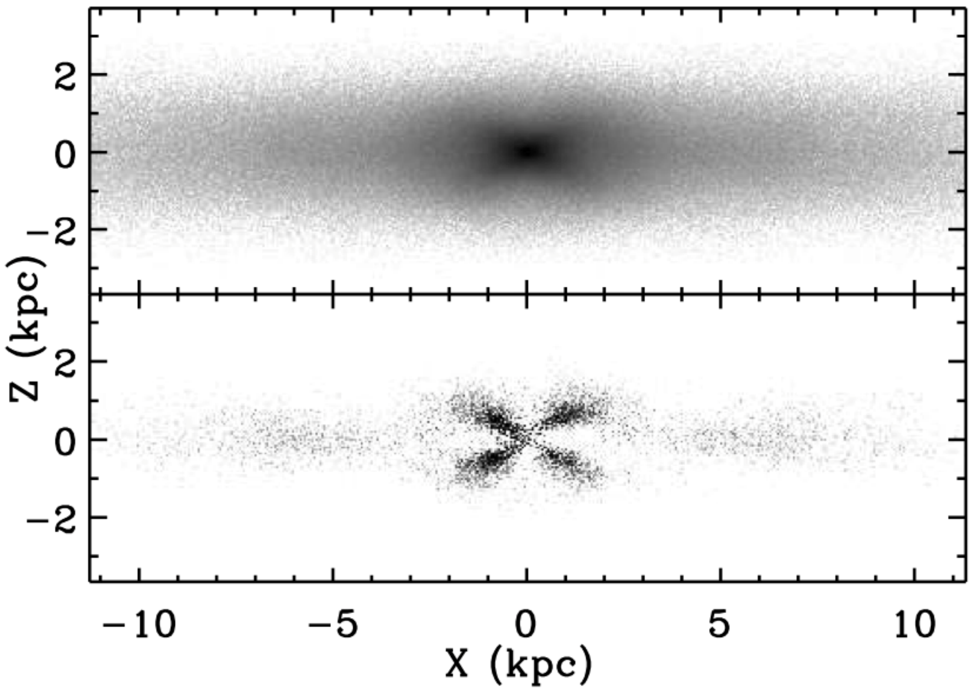
McWilliam & Zoccali (2010)

X-Structure in our model

- End-to-end separations in the radial and vertical directions are roughly 3 kpc and 1.8 kpc, respectively.
- Contribute ~7% of the boxy bulge light
- Orbits trapped around the vertically-extended x_1 family



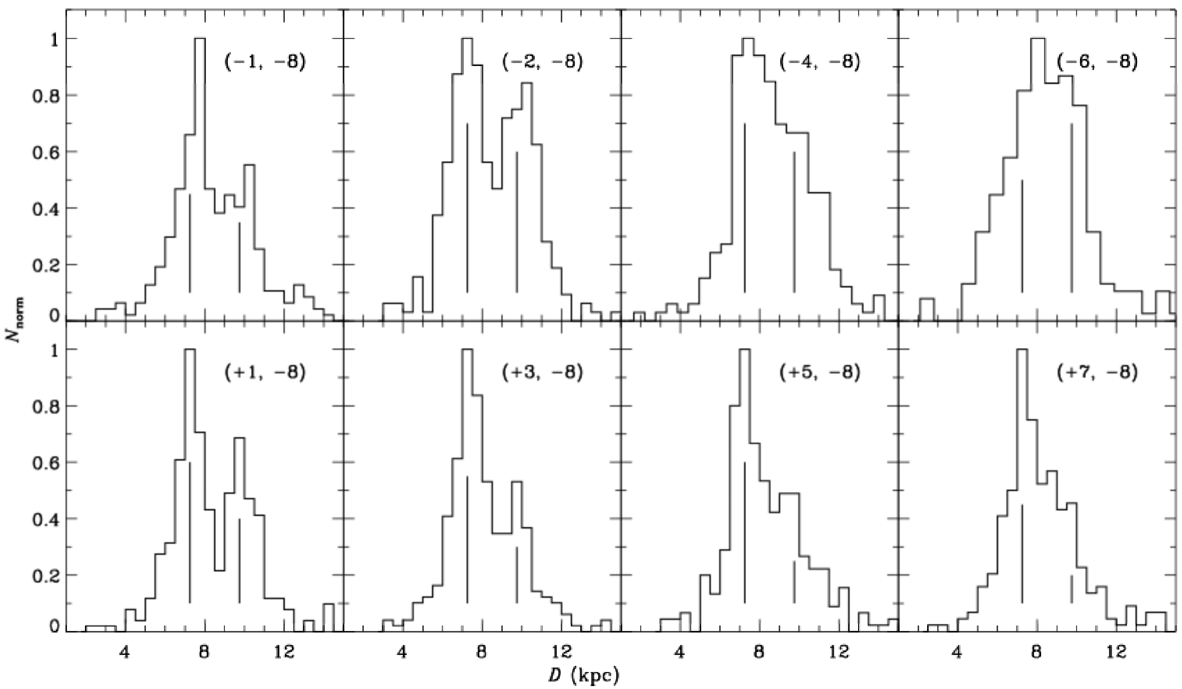
McWilliam & Zoccali (2010)



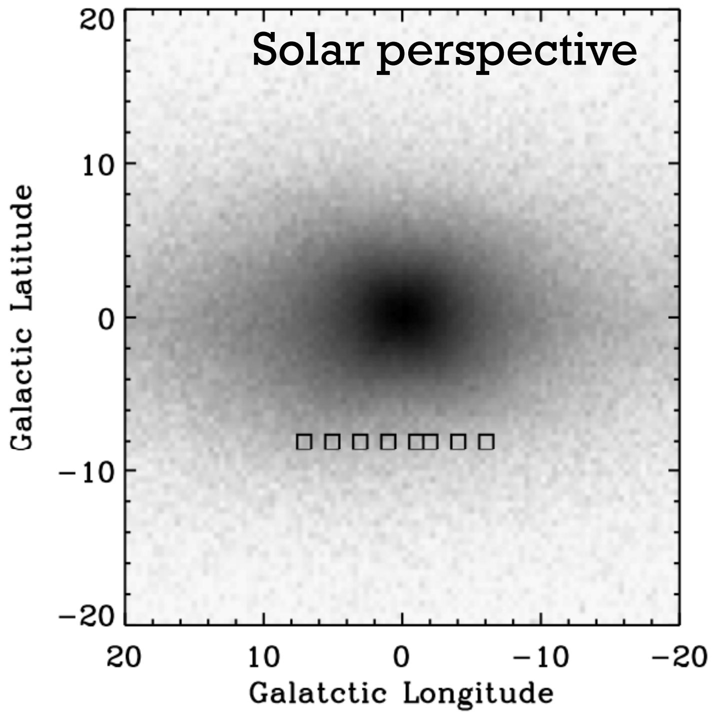
Li & Shen (2012)

Comparison with Observations

- As the longitude decreases, the peak at large distance becomes stronger with more distant particles.
- The separation between the two peaks is roughly constant at different longitudes as in MZ10.

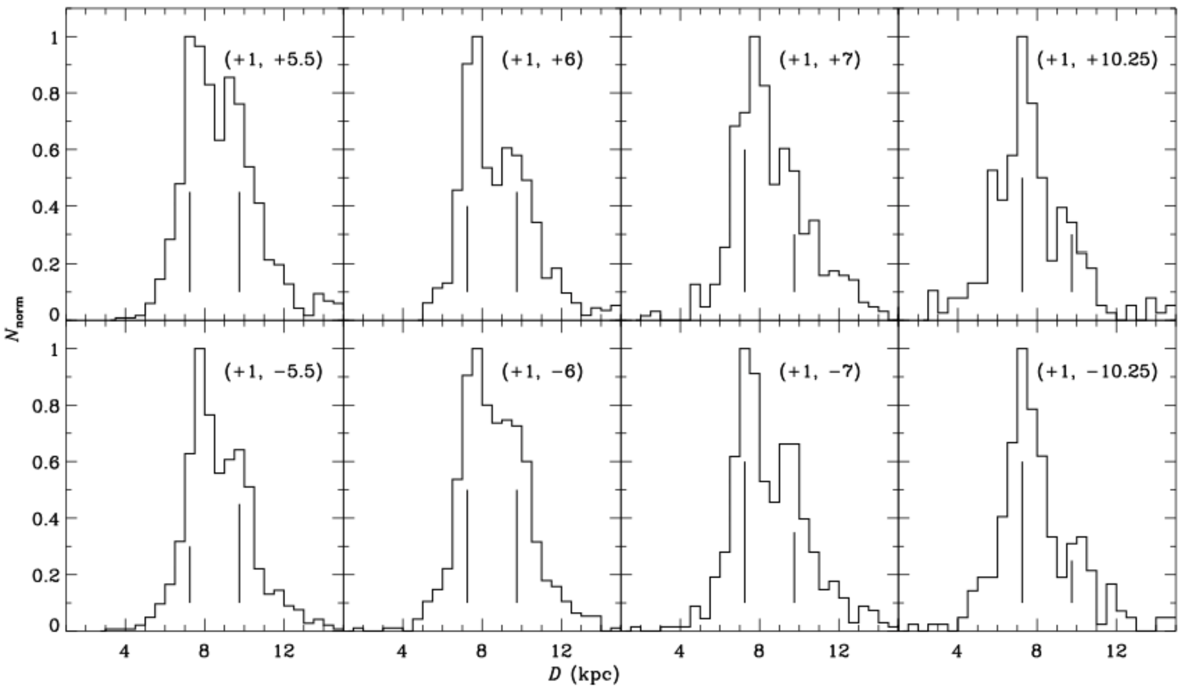


Two vertical lines mark the peak positions in (+1, -8)

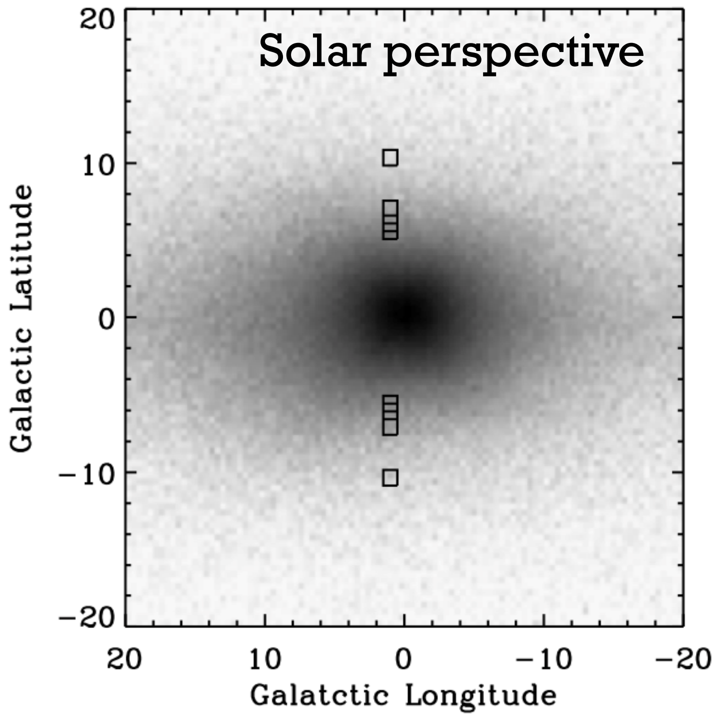


Comparison with Observations

- As the latitude decreases, the separation between the two peaks also decreases.
- The separation increases from ~2 kpc at $b = \pm 5.5°$ to ~3 kpc at $b = \pm 10.25°$.



Two vertical lines mark the peak positions in (+1, -8)



Future work

- Vertical metallicity gradient (Zoccali 2008)
  - resonant heating of stars that scatter off the bar (Pfenniger & Norman 1990)? Most metal-poor stars (~ oldest), then they have been scattered for the longest time (reach the greatest heights).
  - Allow a small classical bulge?
  - Other bulge formation scenarios? (Bekki & Tsujimoto 2011, Inoue & Saitoh 2012)
- More sophisticated models (e.g. Agertz et al. 2010; Guedes et al. 2011)

Summary

- Studies of MW help us understand the properties galaxies in general
- Spiral structure
  - probably re-occurring transient features
- Bar/Bulge
  - Disk buckles to make boxy / peanut-shaped bulges – main driver of shaping the MW bulge
  - The MW bulge is consistent being a bar viewed edge-on
  - Many bulges are pseudo-bulges made from disks
  - The standard galaxy formation picture needs to be improved to explain giant pure-disk galaxies, like our own MW

- There is an **X** in the MW bulge! Its properties qualitatively match obs.
- It formed at least a few Gyrs ago
- Further evidence that MW bulge formation is shaped mainly by internal dynamical instabilities

Credit: Zhao-Yu Li