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The Milky Way Bulge and its X-shaped Structure

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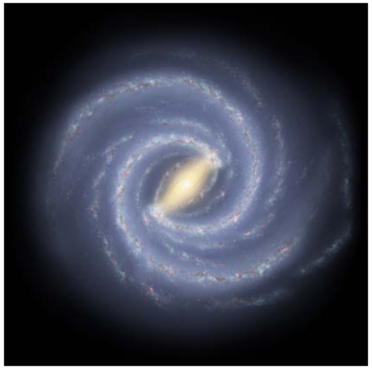
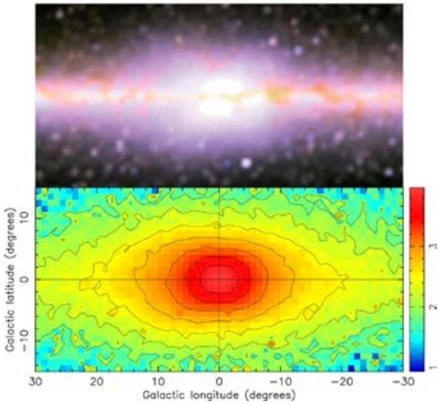




- **“I don't see the true face of Mountain Lushan because I myself am on the mountain.”**
- Since we are located right in the disk of Milky Way, we are at a disadvantageous position to see its full appearance.
- Studying external galaxies could provide hints to understand our own Milky Way

不識廬山真面目
只緣身在此山中
蘇東坡

Bulges

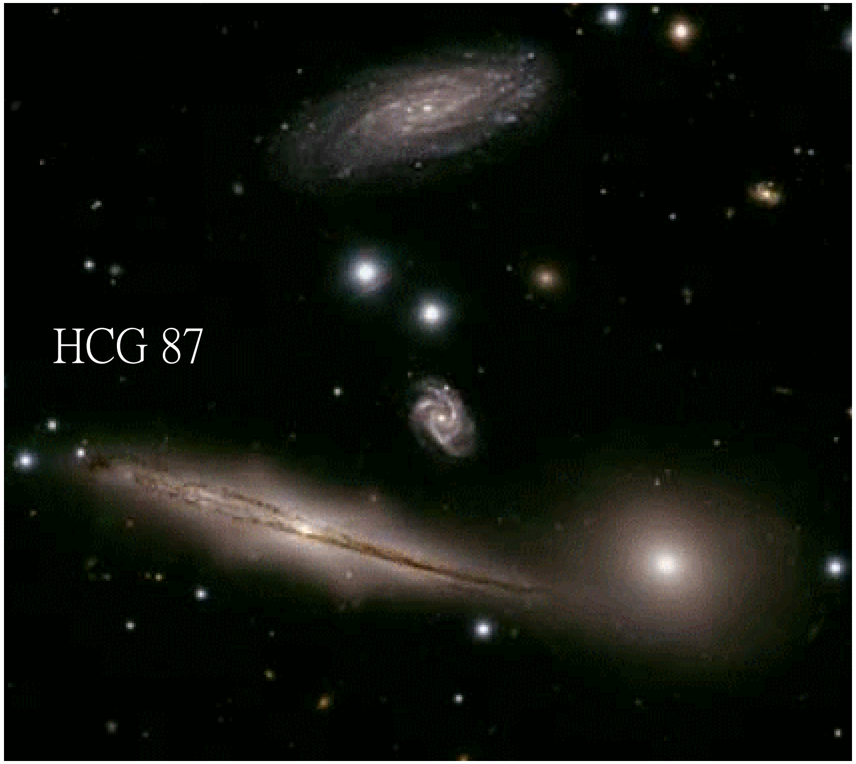
We do not fully understand them yet!

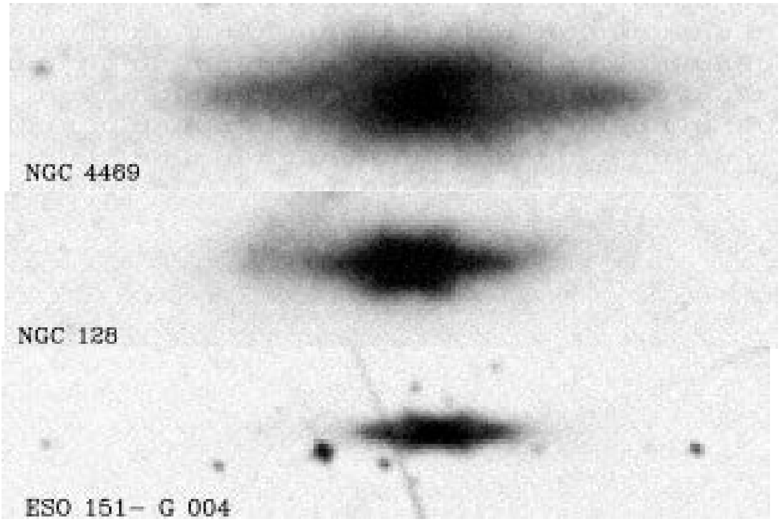
- Classical bulges
  - ≈ Mini-elliptical
  - Major merger-made or made of clumps (Elmegreen et al. 2008)?
  - Sersic n > 2
  - not rotation-dominated

- 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





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

Boxy/peanut-shaped bulges

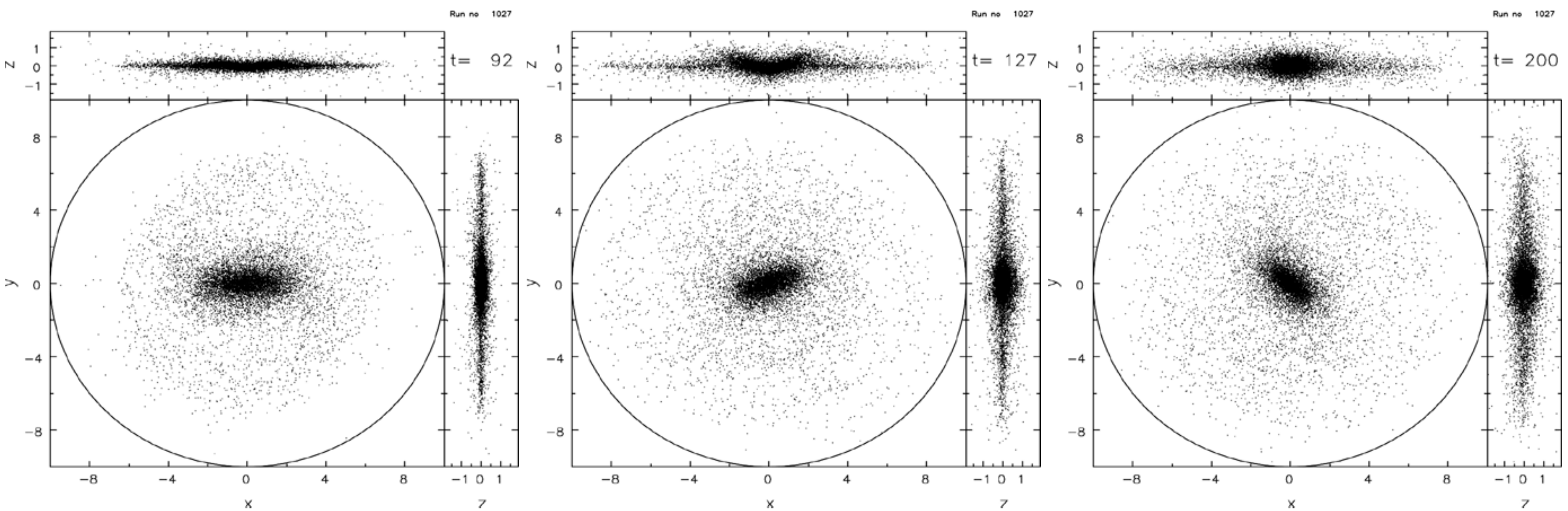
- Most of bulge stars are old (>5 Gyr, Clarkson et al. 2008)
- A wide range of metal abundances (McWilliam & Rich 1994; Fulbright et al. 2006; Zoccali et al. 2008)

Boxy peanut-shaped bulges: side-on bars?

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

    $$\sigma_Z \leq 0.3\sigma_R$$

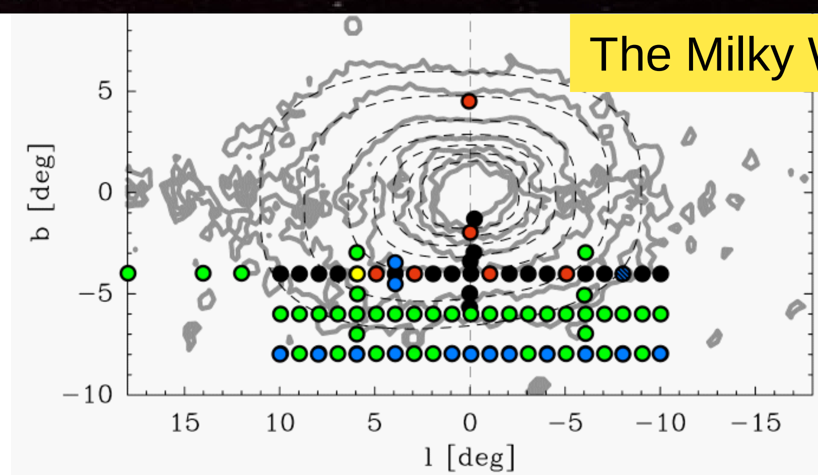
  - Bar formation → buckling instability → saturation → B/PS bulges (e.g. Raha, Sellwood et al. 1991)



Stellar Kinematics of the Bulge

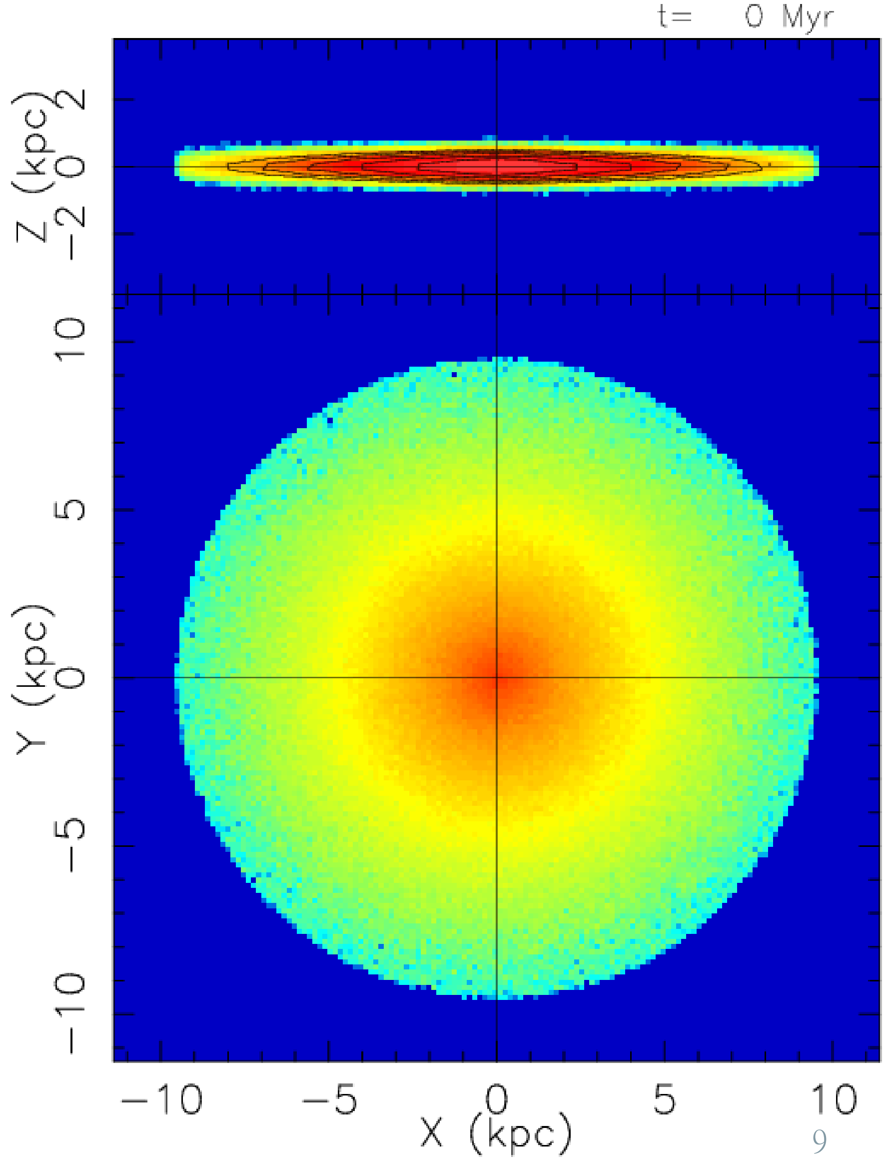
- BRAVA (Bulge Radial Velocity Assay) survey
  - ~10,000 M giants as targets
  - **Stellar kinematics covering the whole Bulge**
- Build a simple dynamical model to explain it

The Milky Way in NIR (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

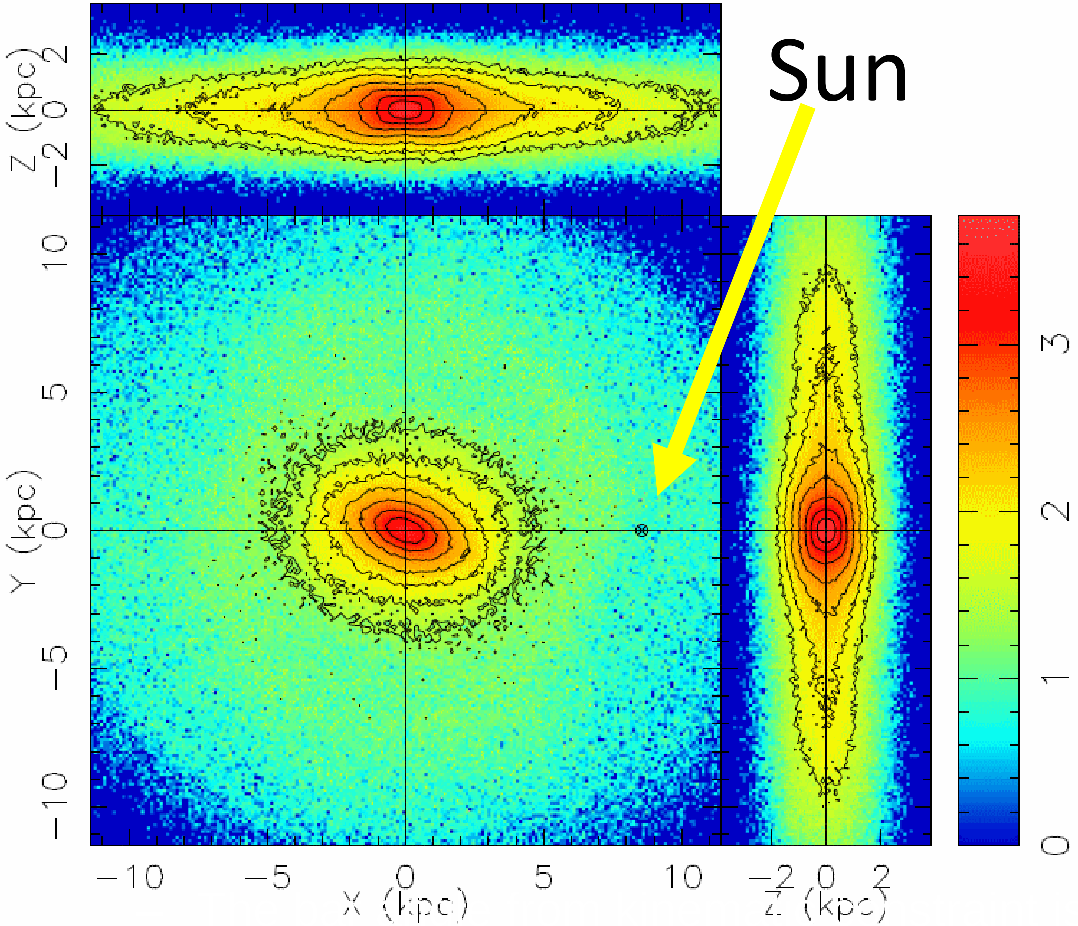


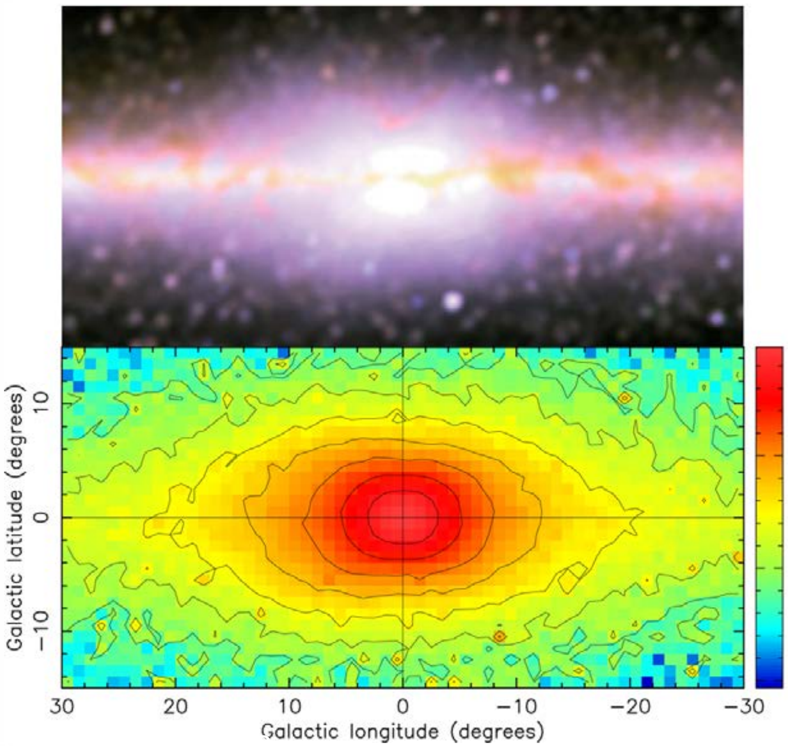
Shen, J., et al 2010, ApJL

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

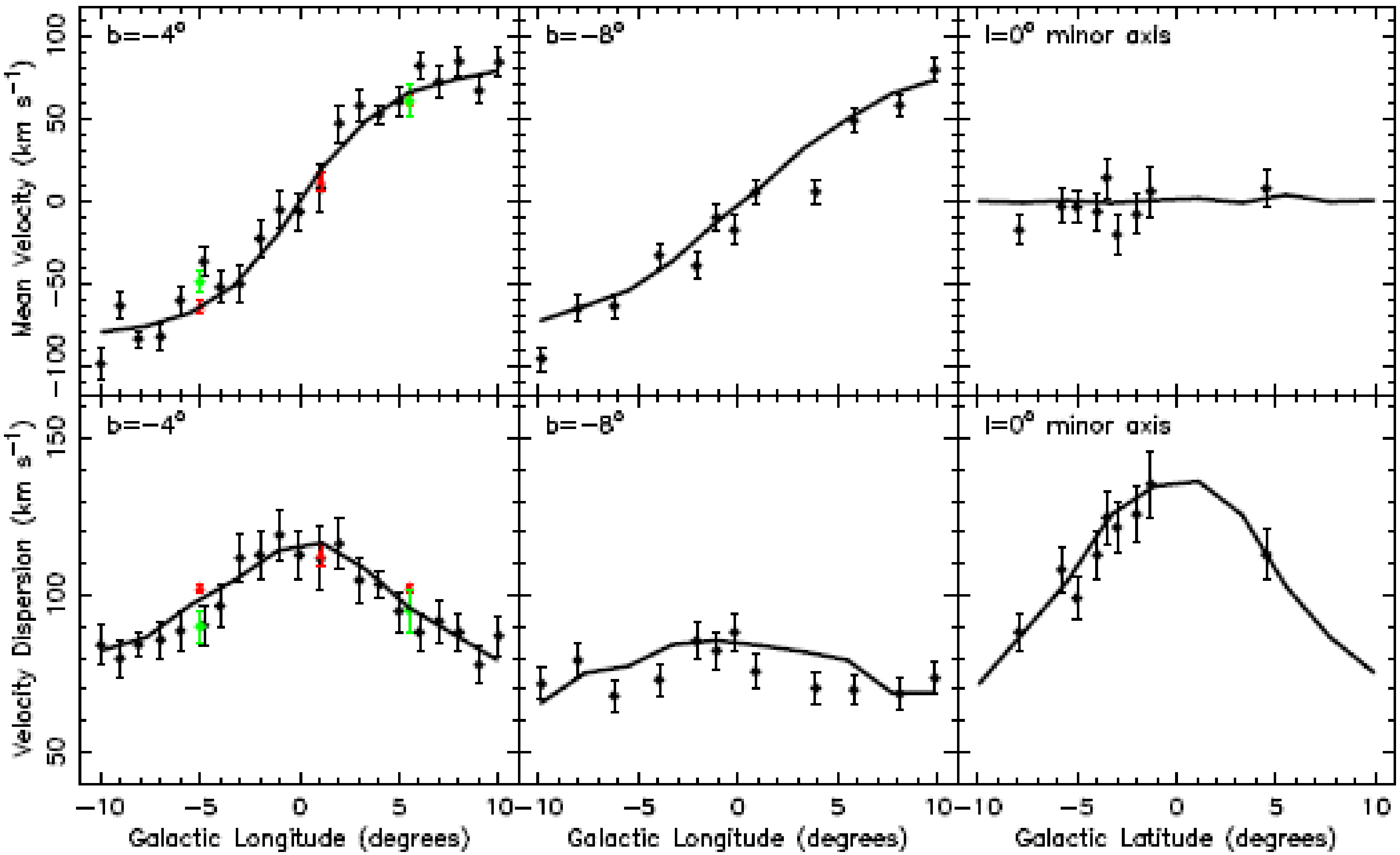




Shen, J., et al 2010, ApJL

Modeling the Milky Way Bulge ---

Match stellar kinematics in all strips strikingly well

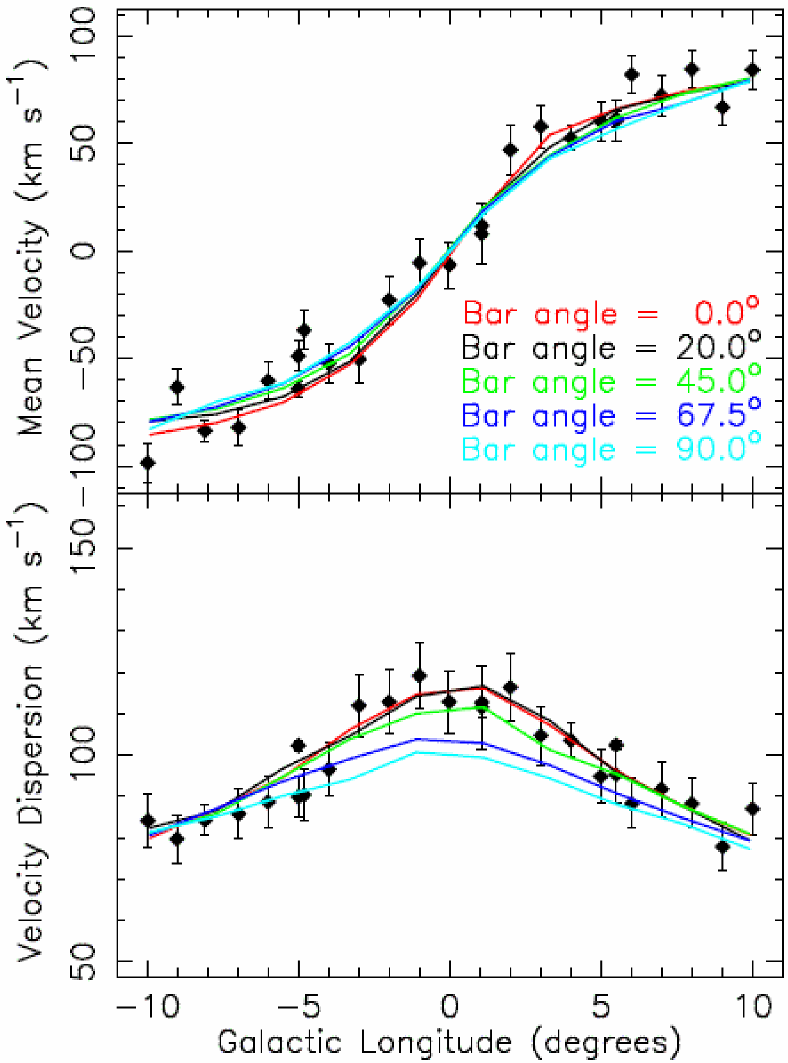


Cylindrical rotation: hard to reproduce with a classical bulge

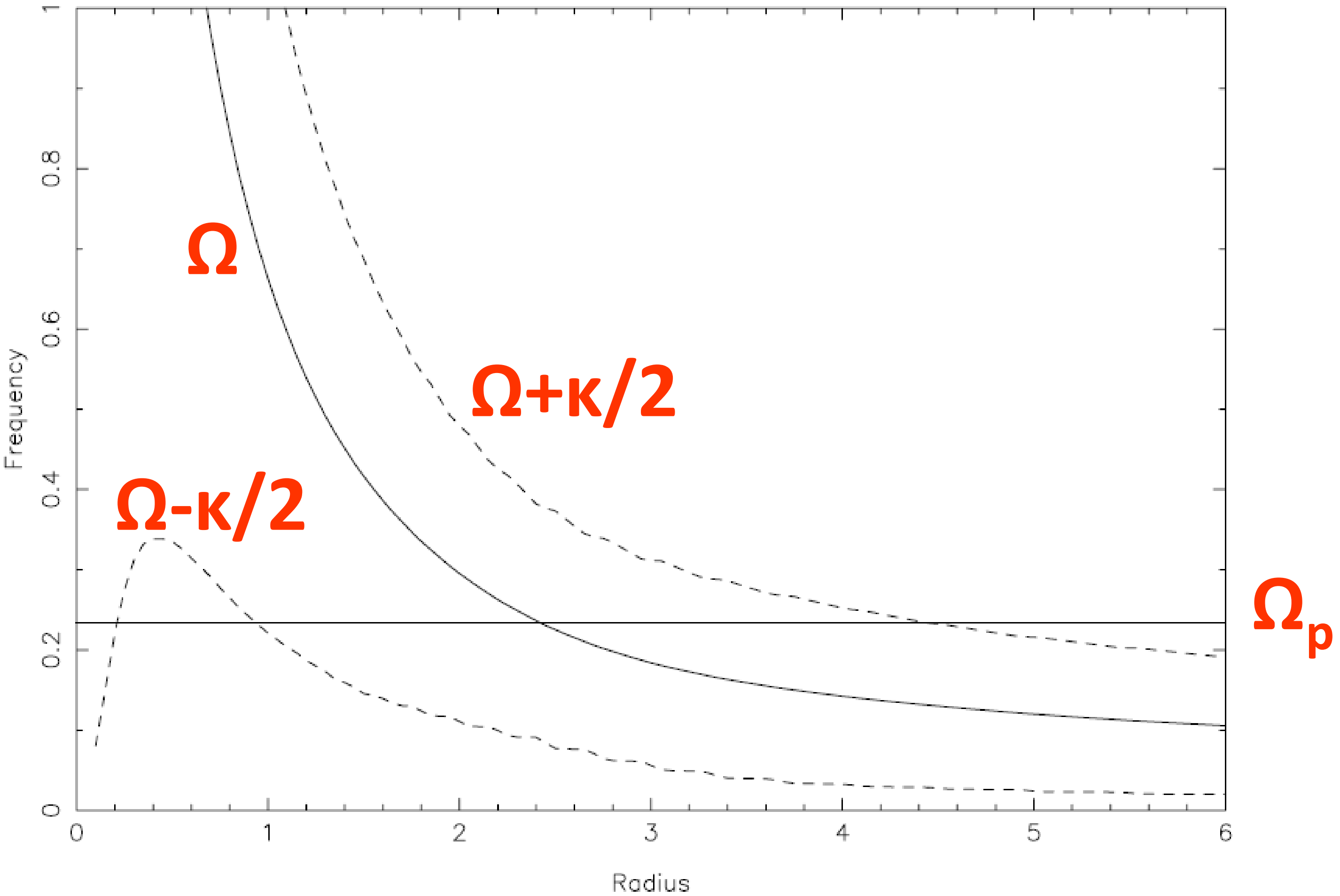
Shen, J., et al 2010, ApJL

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)



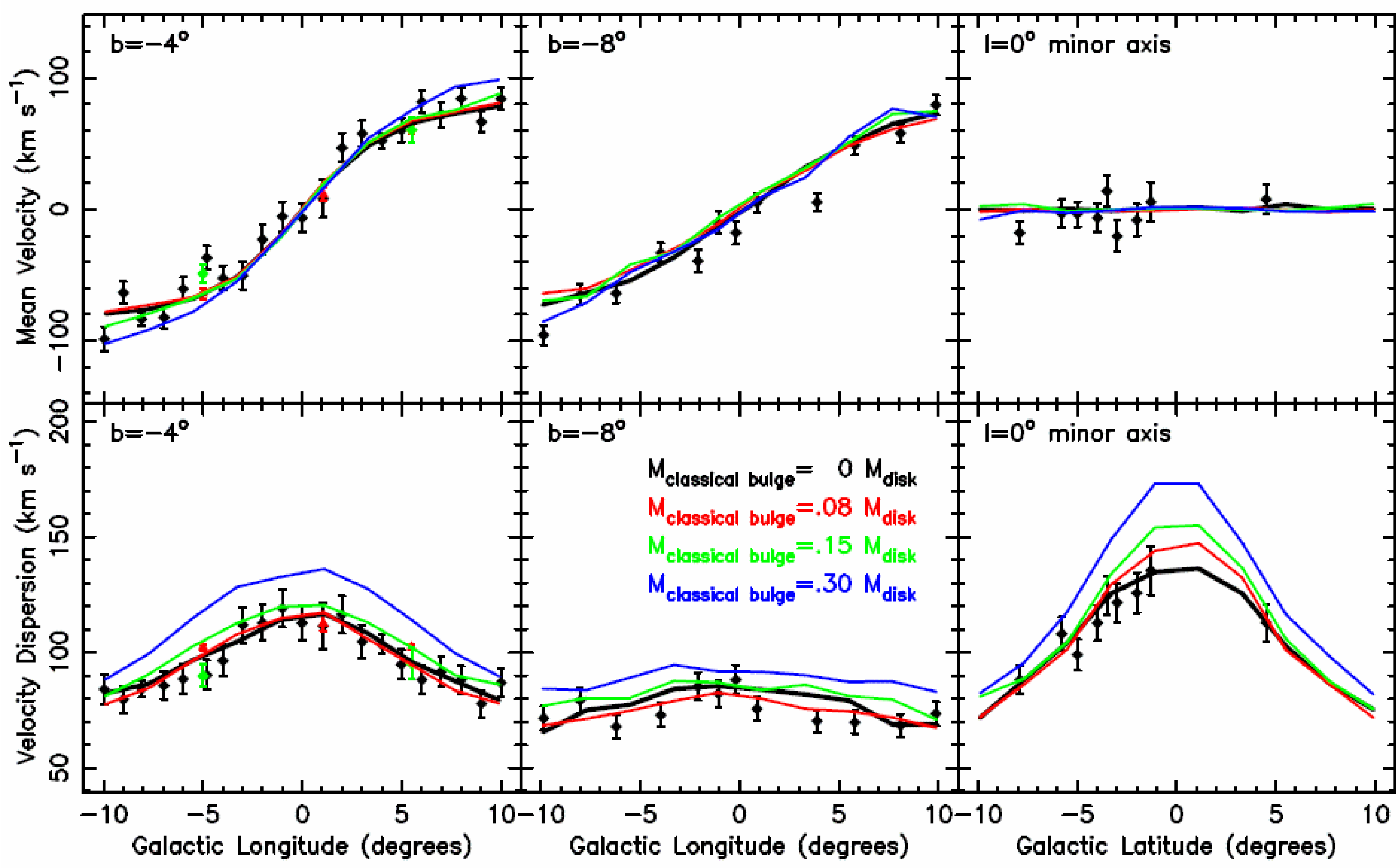
Pattern speed of the MW bar



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!

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)
- **Puzzle of giant pure-disk galaxies:** How can the D.M. halos grow to V_{circ}~220 km/s without letting the mergers that accomplished that growth scramble disks into recognizable classical bulges?
- Major mergers → low angular momentum material will always fall to the center and make a classical bulge, also the disk shape is destroyed.

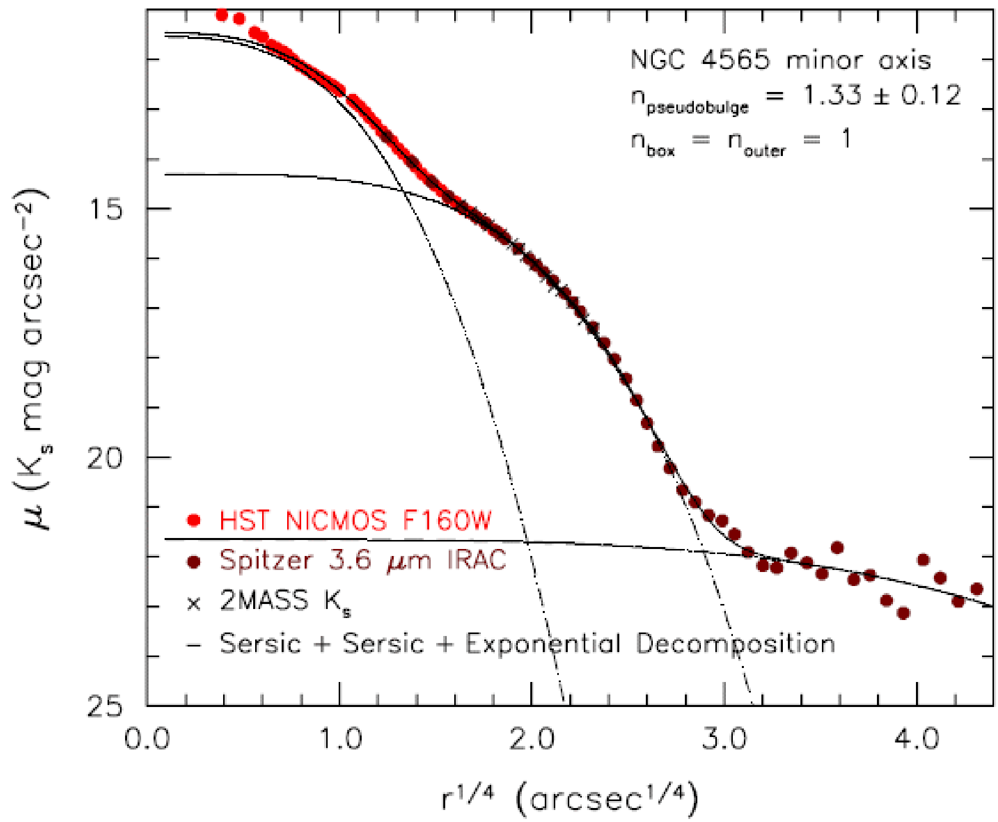
The Milky Way is not special

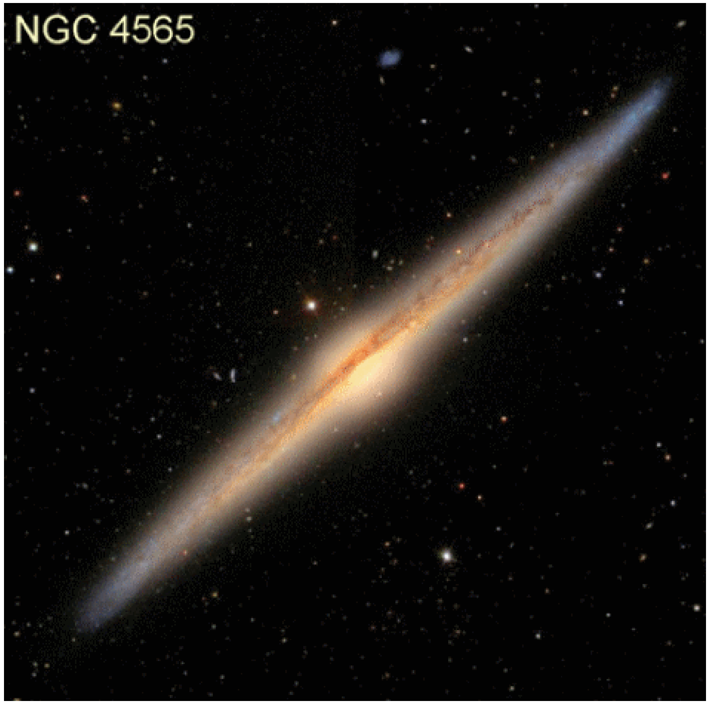
- Our Galaxy is not unusual
  - it is very similar to another giant edge-on galaxy with a boxy bulge, NGC 4565.
  - NGC 4565 does not contain even a small classical bulge component; it is therefore another giant, pure disk galaxy that contains no sign of a merger remnant (Kormendy & Barentine 2010)
- 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 within 8 Mpc from us
- "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."
- From a galaxy formation point of view, galaxies that contain only pseudobulges are pure-disk systems.
- The puzzle of giant pure-disk galaxies 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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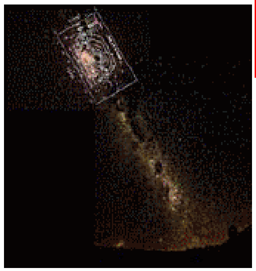
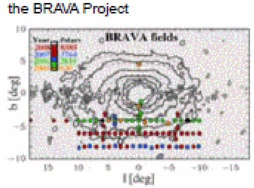


The BRAVA fields are shown in this image montage. For reference, the center of the Milky Way is at coordinates L= 0, B=0. The regions observed are marked with colored circles. This montage includes the southern Milky Way all the way to the horizon, as seen from CTIO. The telescope in silhouette is the 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.

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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.

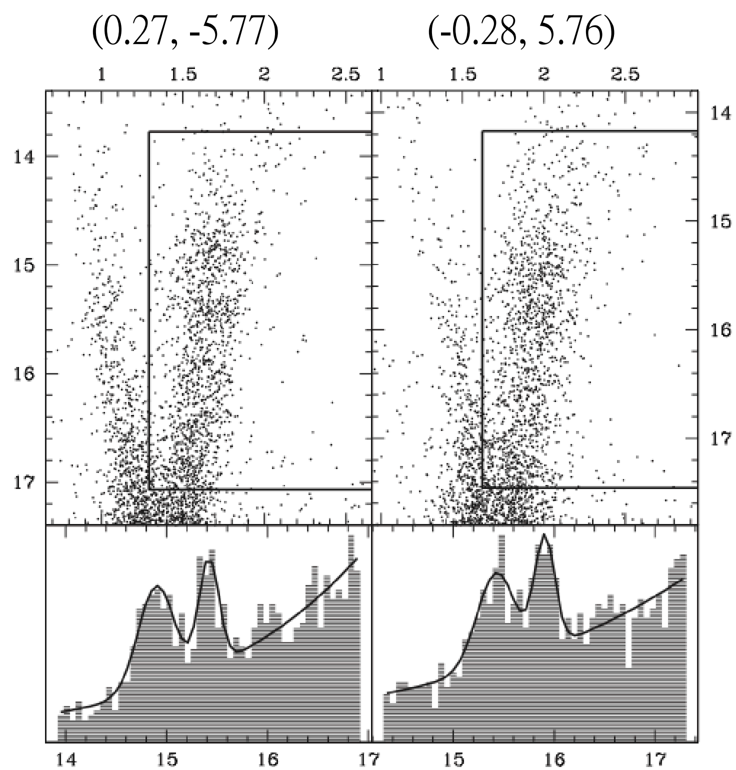
As part of a larger study dubbed BRAVA, for Bulge Radial Velocity Assay, a team assembled by Dr. R. Michael Rich at UCLA, measured the velocity of a large sample of old, red stars towards the galactic center. (See image) They did this by observing the spectra of these stars, called M giants, which allows 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.

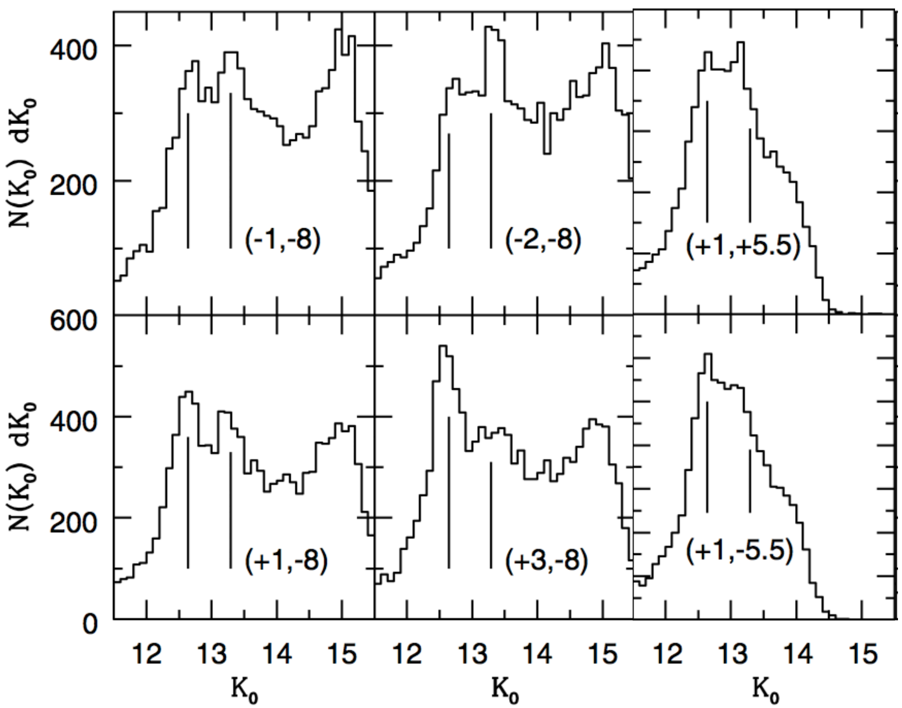
The stellar spectra also allow the team to analyze the chemical composition of the stars. While all stars are composed primarily of hydrogen, with some helium, it is the trace of all the other elements in the periodic table, called "metals" by astronomers, that allow us to say something about the conditions 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

Split Red Clumps in the Galactic Bulge

- Red clump: a good 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)



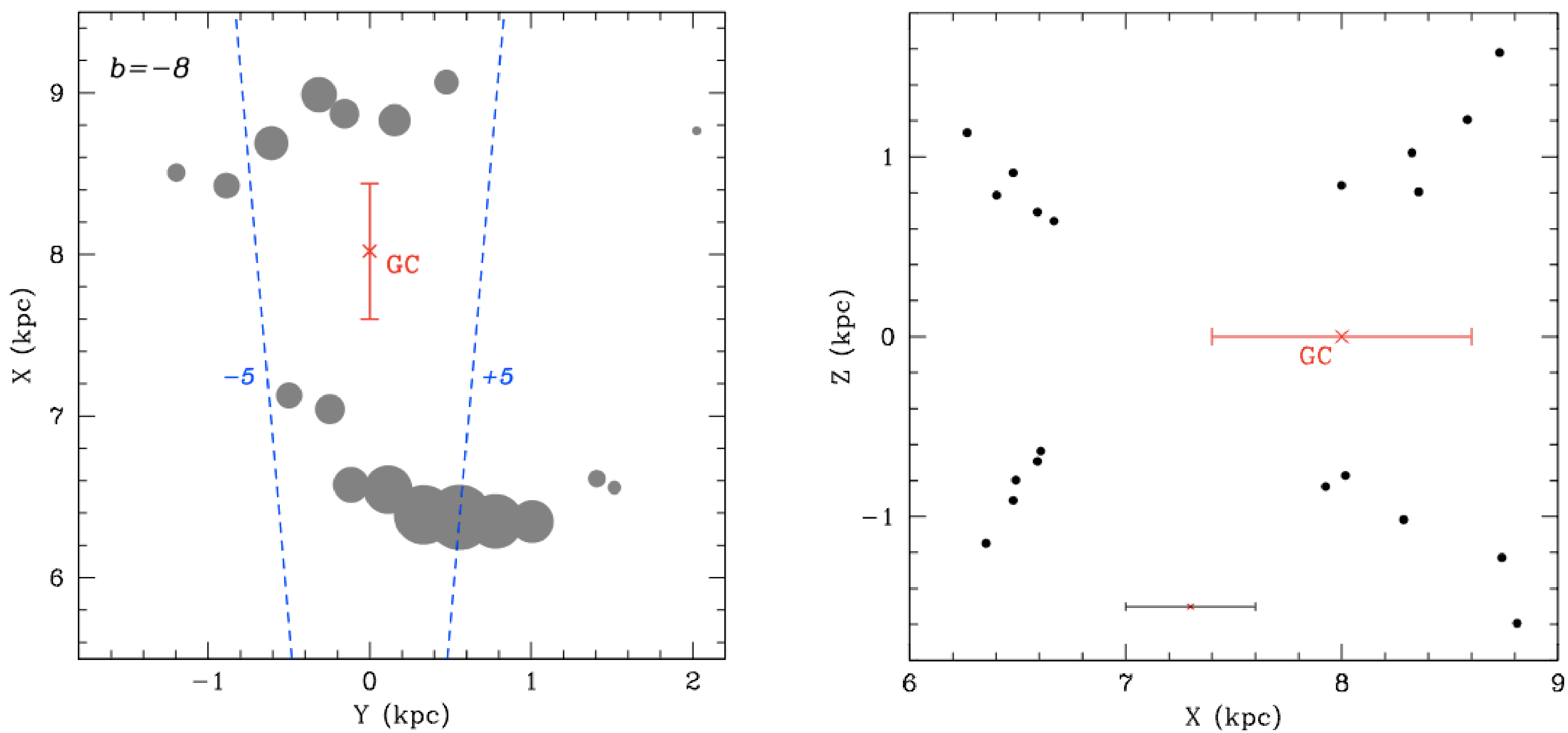
Nataf et al. (2010)



McWilliam & Zoccali (2010)

X-Structure in the Milky Way?

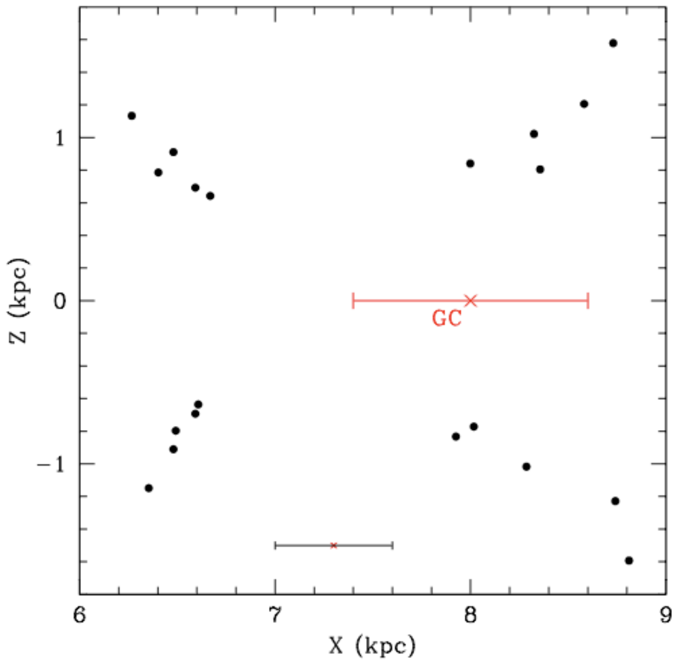
- The full length of the structure is ~2.3 kpc in the radial direction.
- It tilts away from the Sun-GC line by ~ 20°
- "The double peaked RC is **inconsistent** with the tilted bar morphology." (McWilliam & Zoccali 2010)



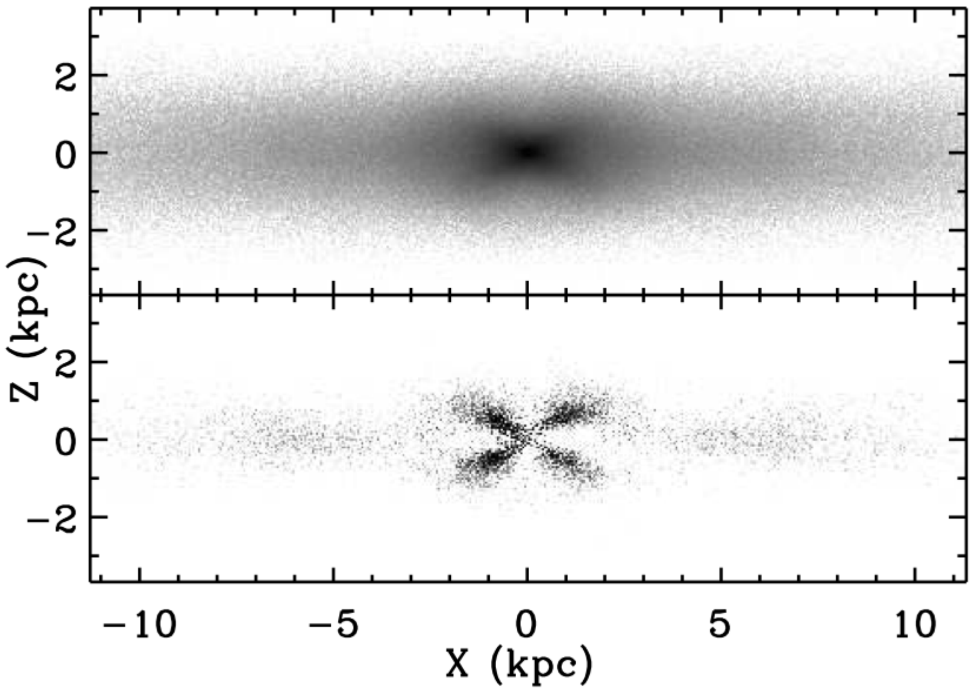
McWilliam & Zoccali (2010)

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



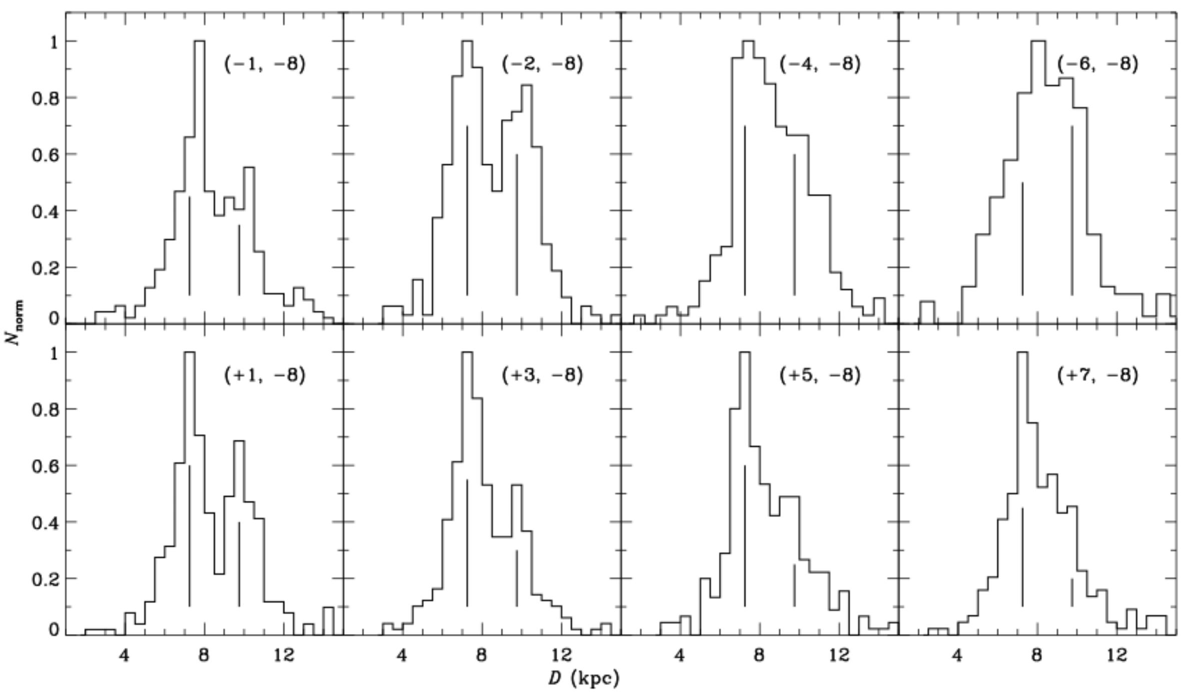
McWilliam & Zoccali (2010)



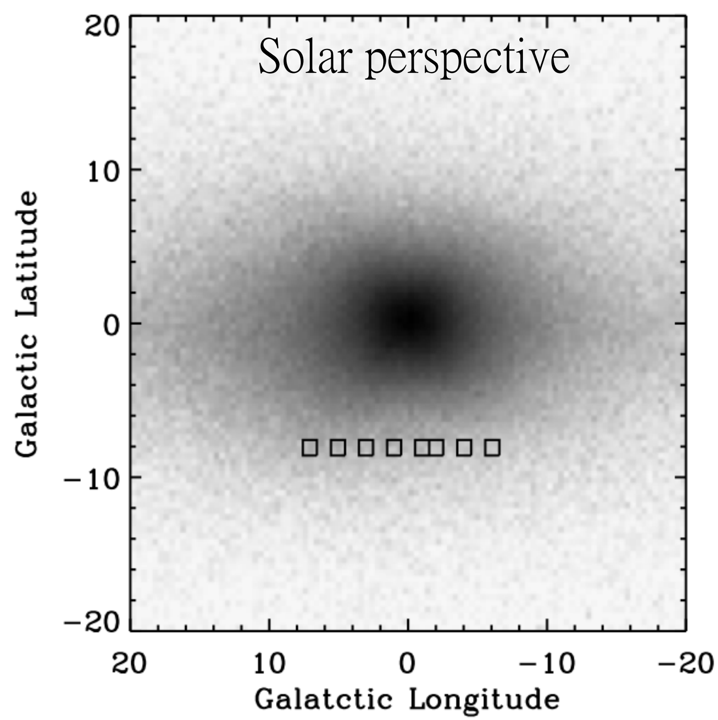
Li & Shen (2012)

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.

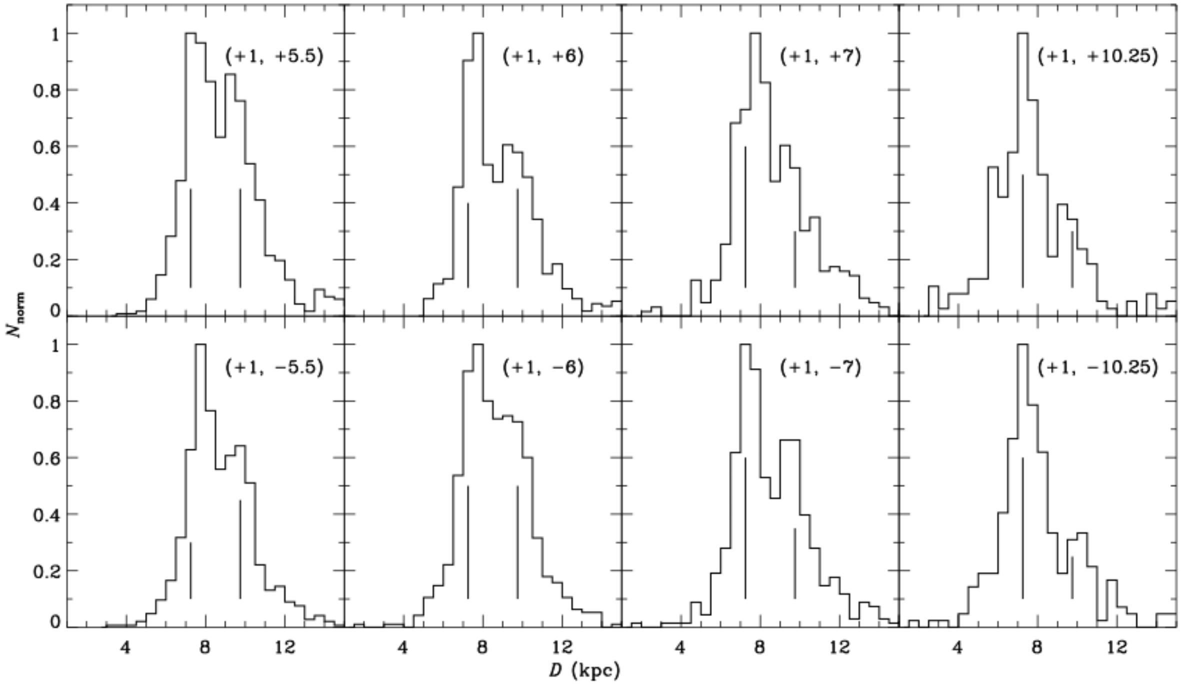


Two vertical lines mark the peak positions in (+1, -8)



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 $b = \pm 10.25°$.



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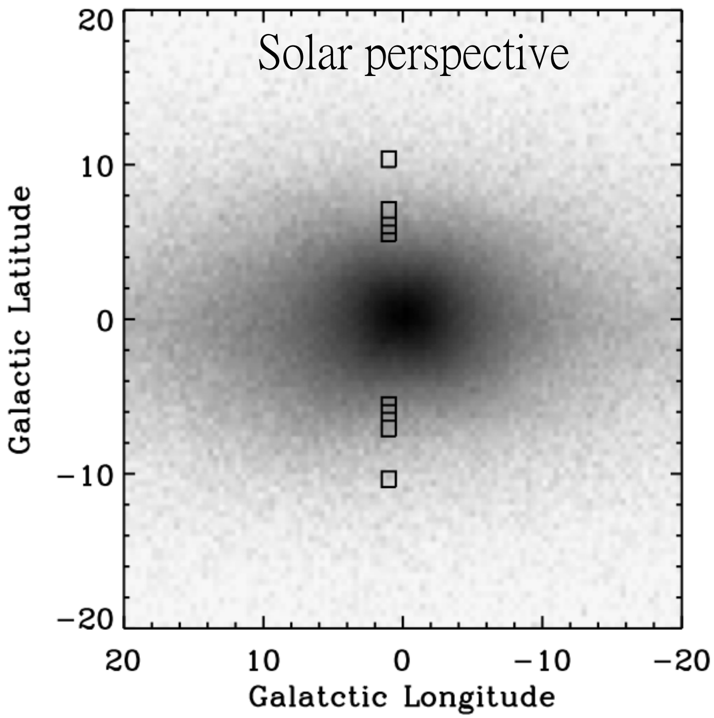
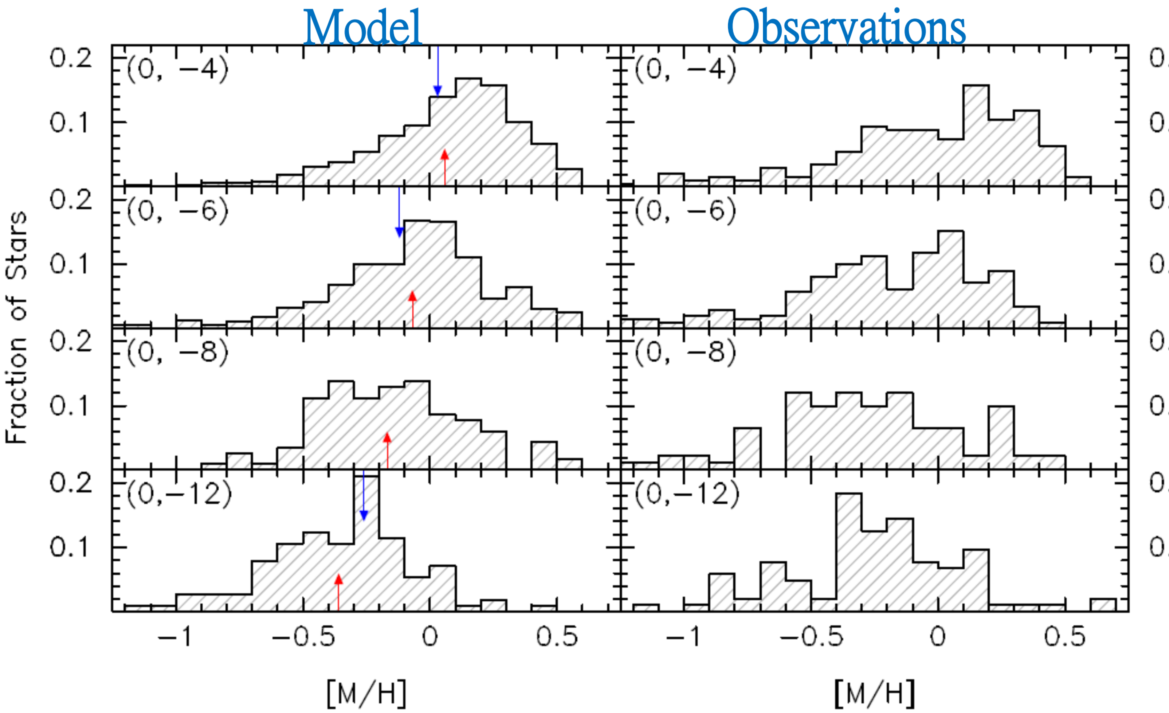


Vertical Metallicity Gradient

- can be reproduced with a secularly evolved bar/boxy bulge model
- not a strong argument for the existence of a classical bulge in the Milky Way.
- Mixing during the bar and buckling instabilities is incomplete, and therefore radial metallicity gradients in the initial disk can transform into gradients in the boxy bulge.



Martinez-Valpuesta & Gerhard (2013)

A similar simple bar model as in Shen et al. (2010)

Summary

- Disk buckles to make boxy / peanut-shaped bulges – main driver shaping the MW bulge
- The MW bulge is consistent with being a bar viewed edge-on
- The formation of giant, pure-disk galaxies like ours is puzzling
- 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
- Many other predictions to compare with observations

Credit: Zhao-Yu Li

Thank you!