IAU Division H Meeting (Aug. 07, 2015 @Honolulu)

The Milky Way Structure

In the Context of the Local Group

A narrow perspective

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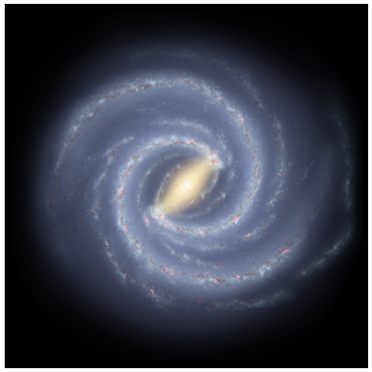
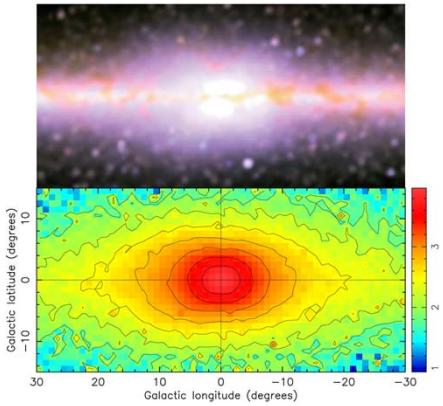
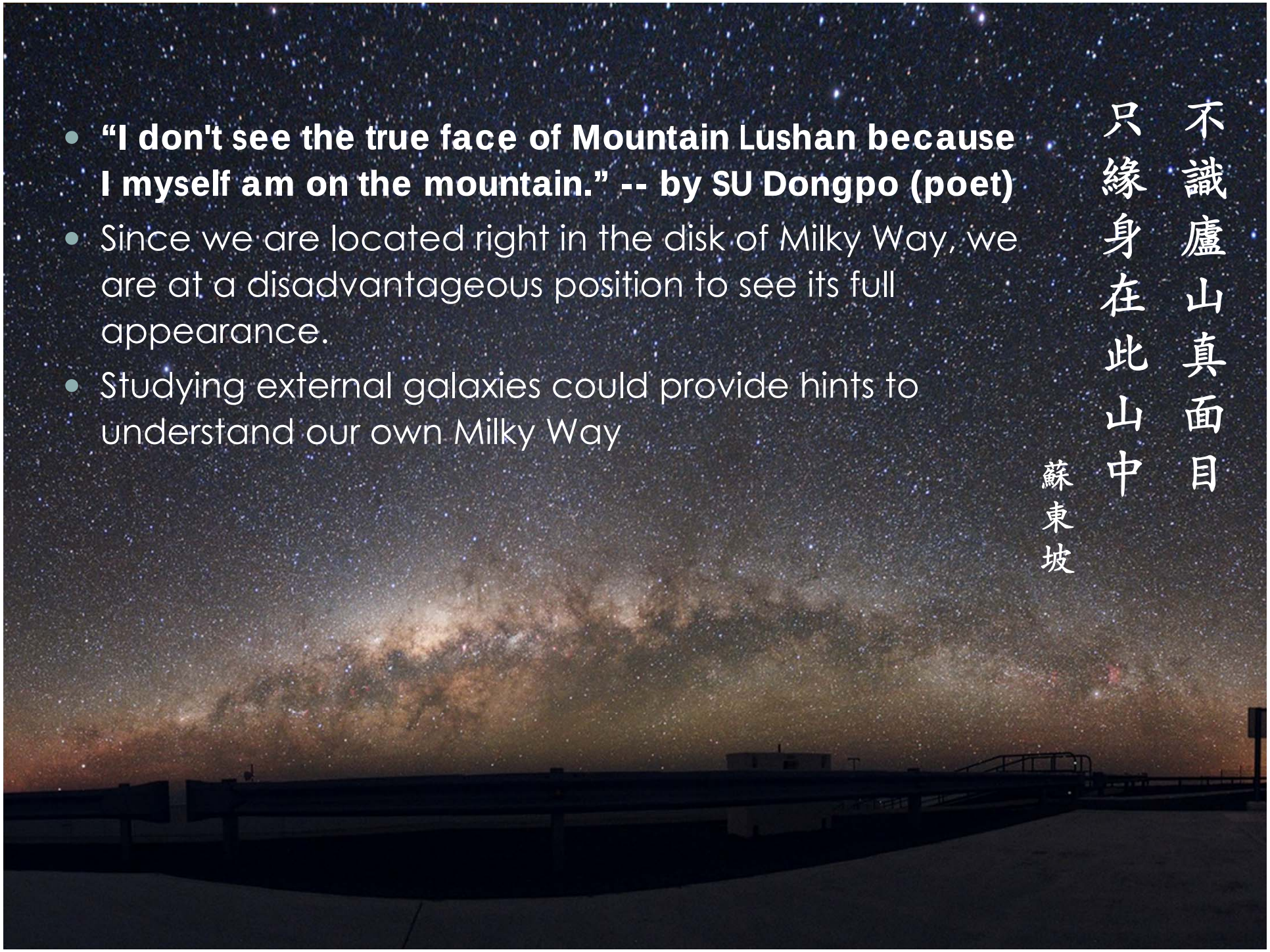




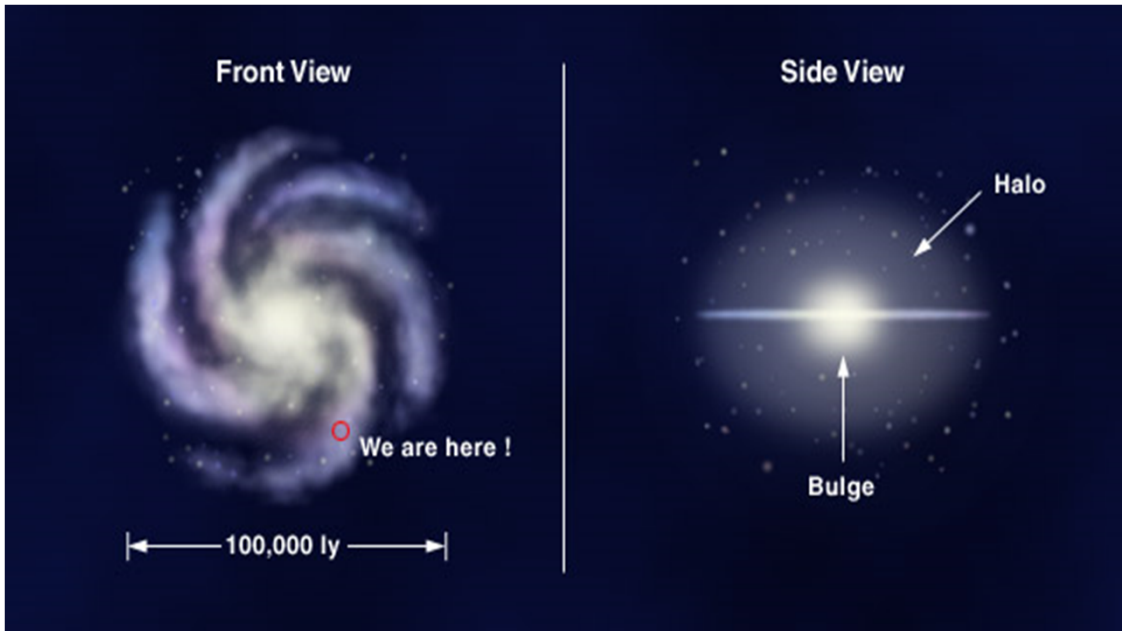
- **“I don't see the true face of Mountain Lushan because I myself am on the mountain.” -- by SU Dongpo (poet)**
- Since we are located right in the disk of Milky Way, we are at a disadvantageous position to see its full appearance.
- Studying external galaxies could provide hints to understand our own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

不識廬山真面目
只緣身在此山中
蘇東坡

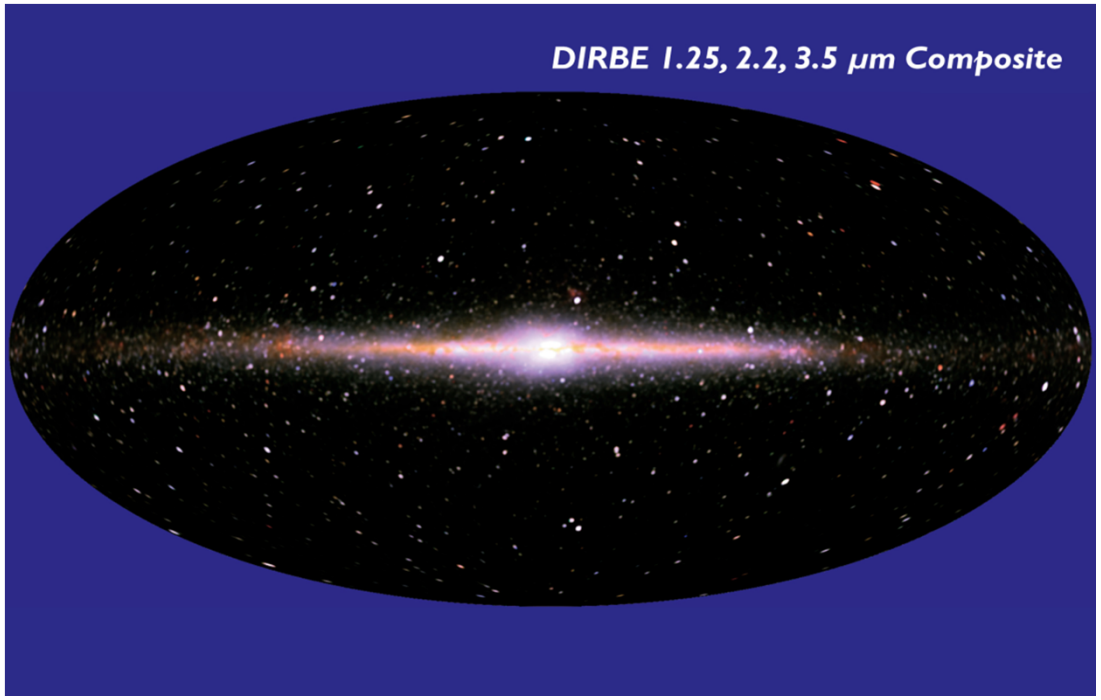


Defining characteristics of a spiral galaxy

- Three largest members of the Local Group: MW, M31, M33
  - Bulge (bar)
  - Disk (& spirals)
  - Halo (IAUS 317)



Milky Way's bulge



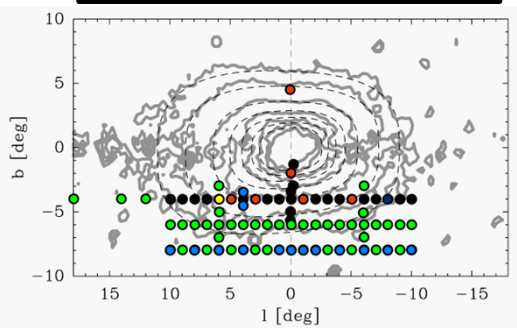
Weiland et al. 1994;
Dwek et al. 1995

- Obscured by dust; boxy shaped; asymmetric about minor axis
- Most of bulge stars are old (>5 Gyr, e.g. Clarkson et al. 2011)
- A wide range of metal abundances (McWilliam & Rich 1994; Fulbright et al. 2006; Zoccali et al. 2008; Hill et al. 2011)

Dynamical modeling of the MW Bulge

- Classical picture: bulges are formed in the dynamical violence of major mergers

BRAVA survey results as model constraints



→

Build a simple fully-evolutionary N-body model of the MW bulge

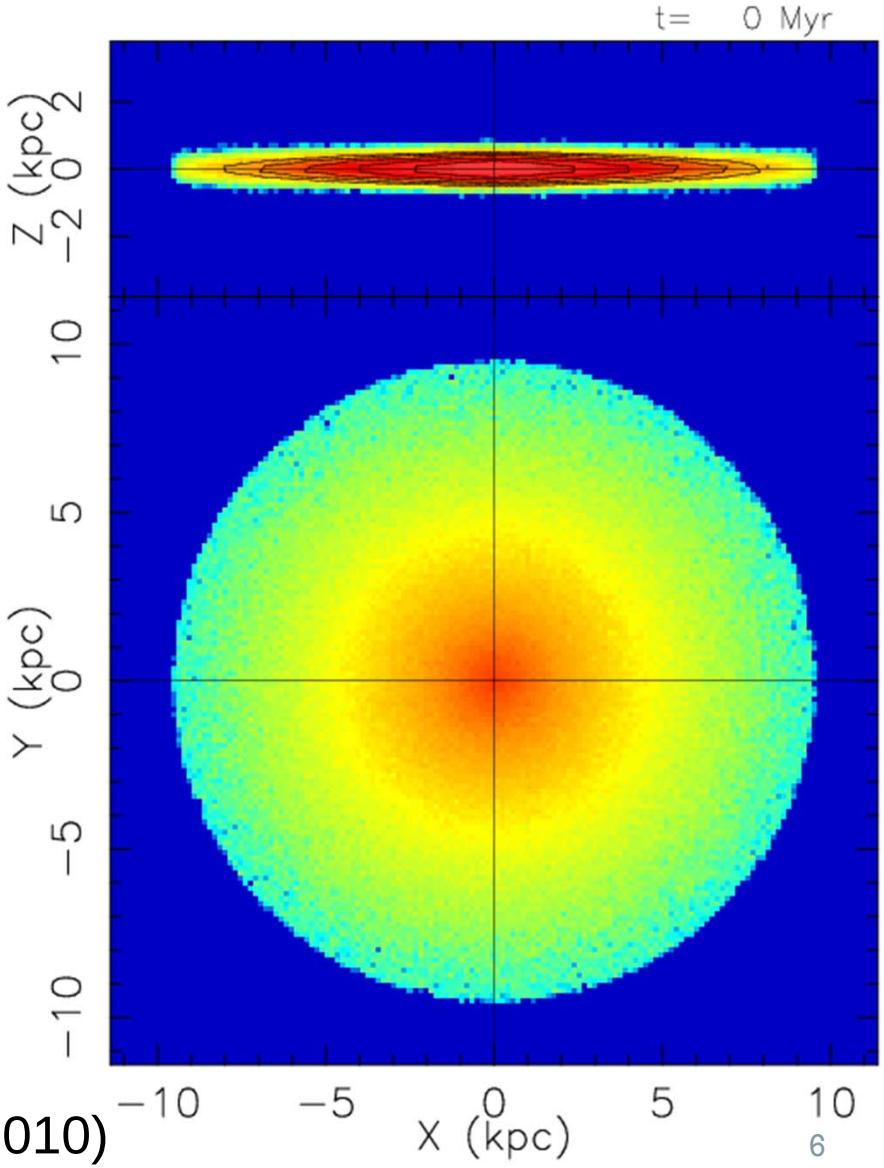
→

Infer the formation history of the MW; and examine the classical picture

BRAVA: Rich+ 2007; Howard+ 2009; Kunder+ 2012

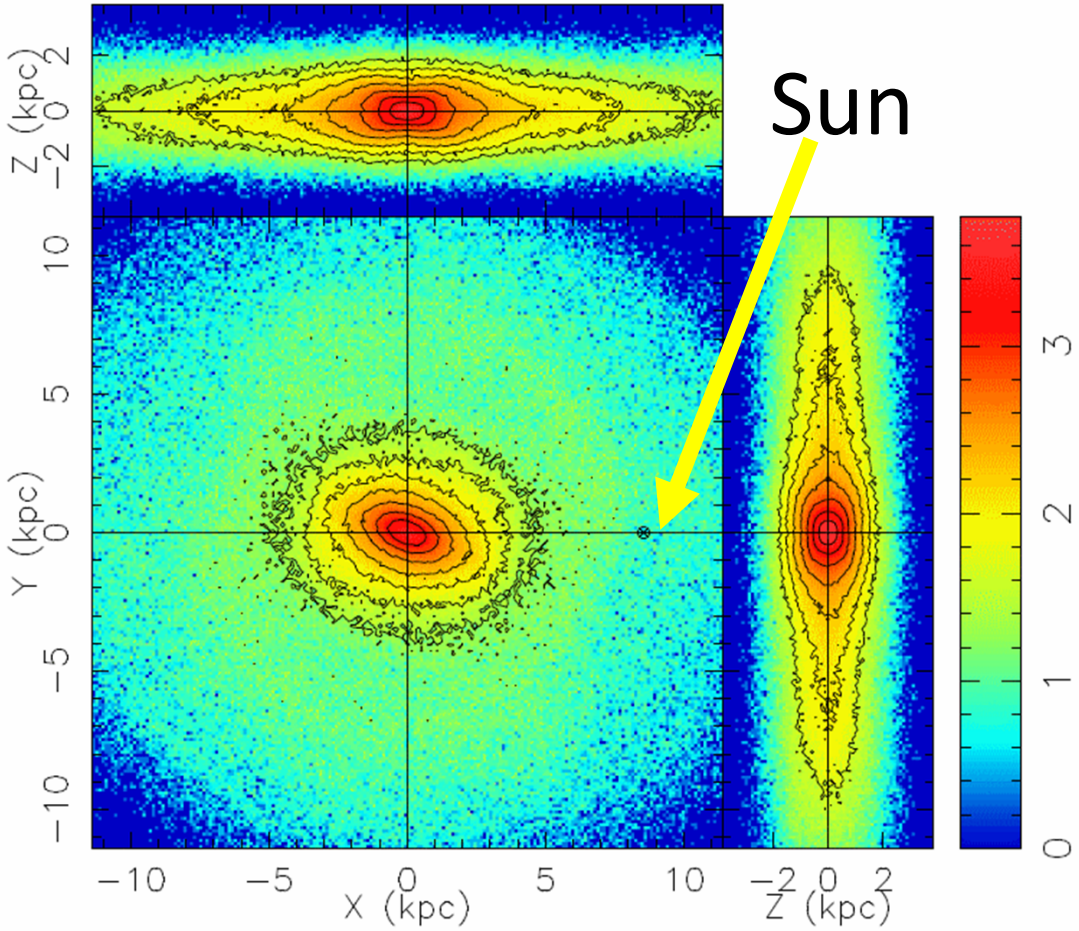
Modeling the Milky Way Bulge

- A very simple model is highly successful
  - match the stellar kinematics extremely well
  - Vertical metallicity gradient
- ***Physical mechanism: a tale of two instabilities!***
  - **Bar-forming instability** (in-plane) → **buckling instability** (vertical) → saturation → boxy bulge
- Boxy bulge ≈ edge-on bar

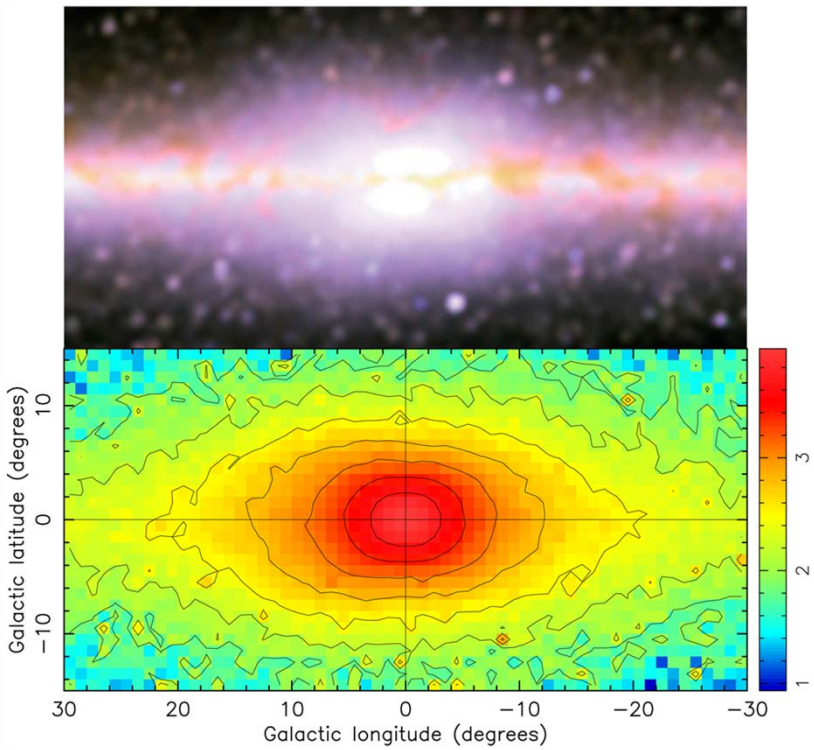


Shen et al. (2010)

Modeling the Milky Way Bulge ---
Surface Brightness Map



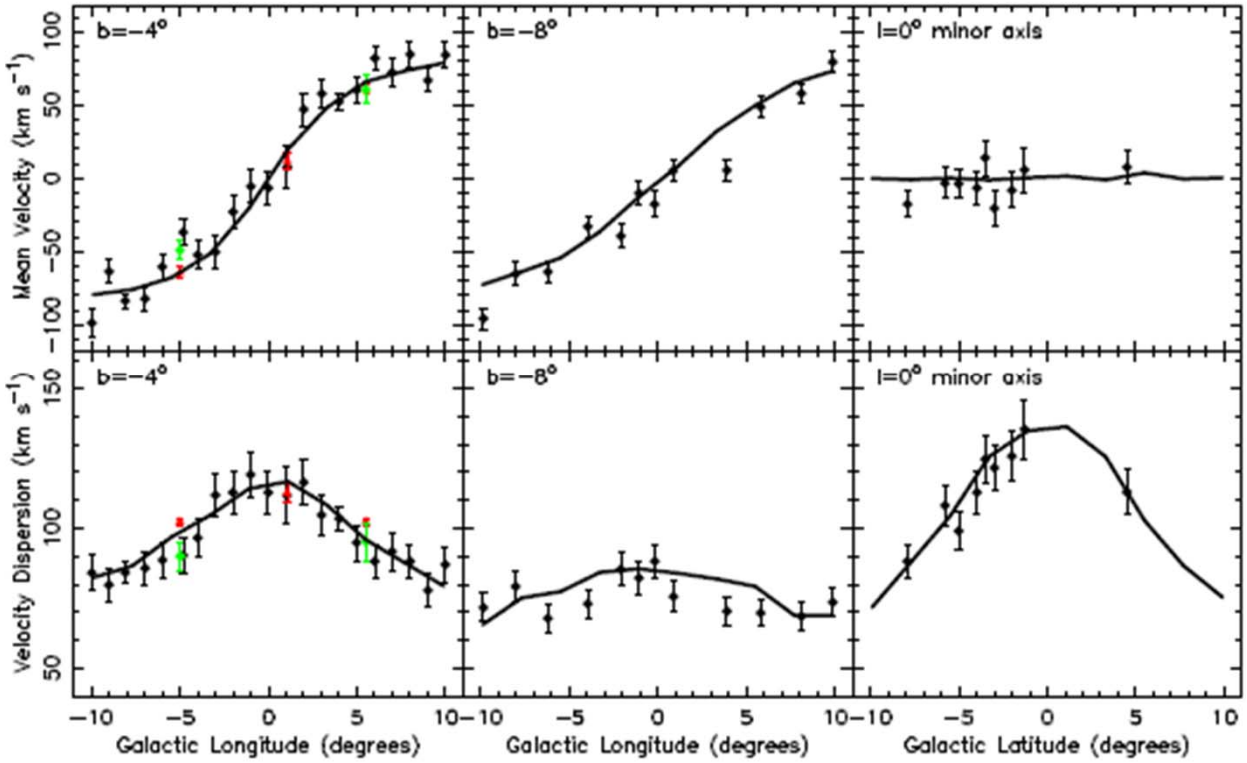
Shen et al (2010)



Other dynamical properties of the bar (pattern speed, bar angle, axial ratio, bar length) are also consistent with other independent studies

Successes of the simple model:

Match stellar kinematics in all strips strikingly well



Shen, J., et al (2010)

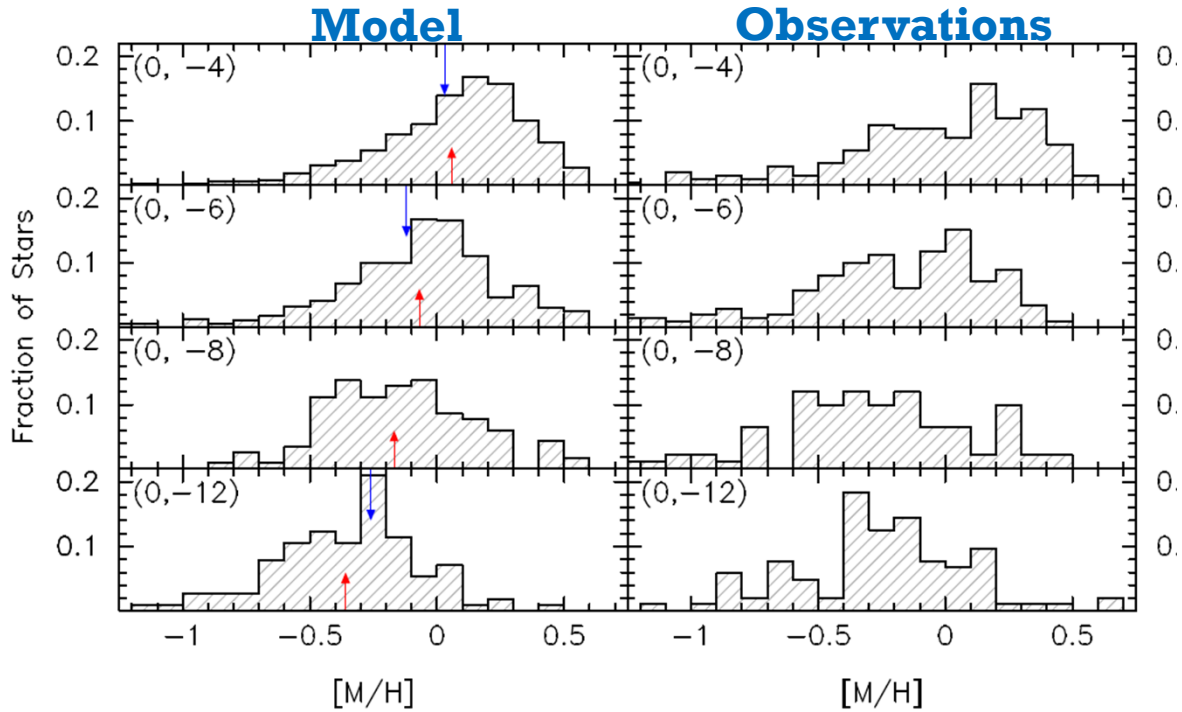
Kunder+ 2012

See also ARGOS results (Ness et al. 2013a,b)

- Cylindrical rotation: rotation independent of height
- Classical bulge is small
  - Consistent with its relatively small BH mass and quiet merger history (Hammer+ 2010)

Successes of the simple model:
Vertical metallicity gradient

- A vertical metallicity gradient can still be generated even after the violent buckling!

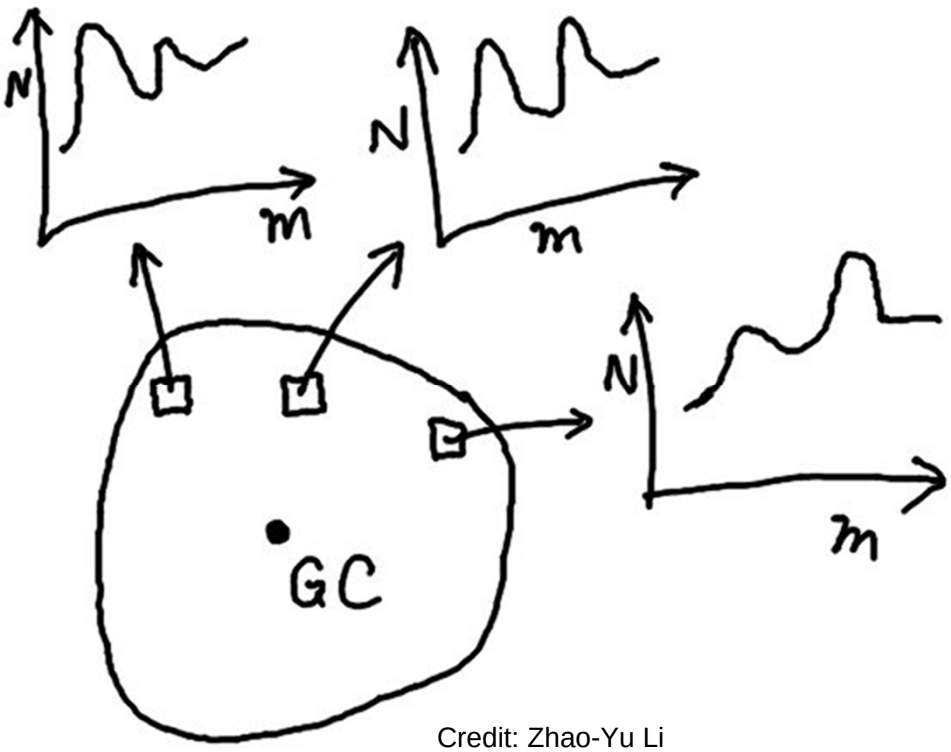


Martinez-Valpuesta & Gerhard (2013)

Similar simple bar model to Shen et al. (2010)

Intriguing X-shaped structure in MW Bulge

- A major obs. discovery
- Red clumps: a good standard candle
- Along different lines of sight toward the Galactic bulge, red clumps split into two groups



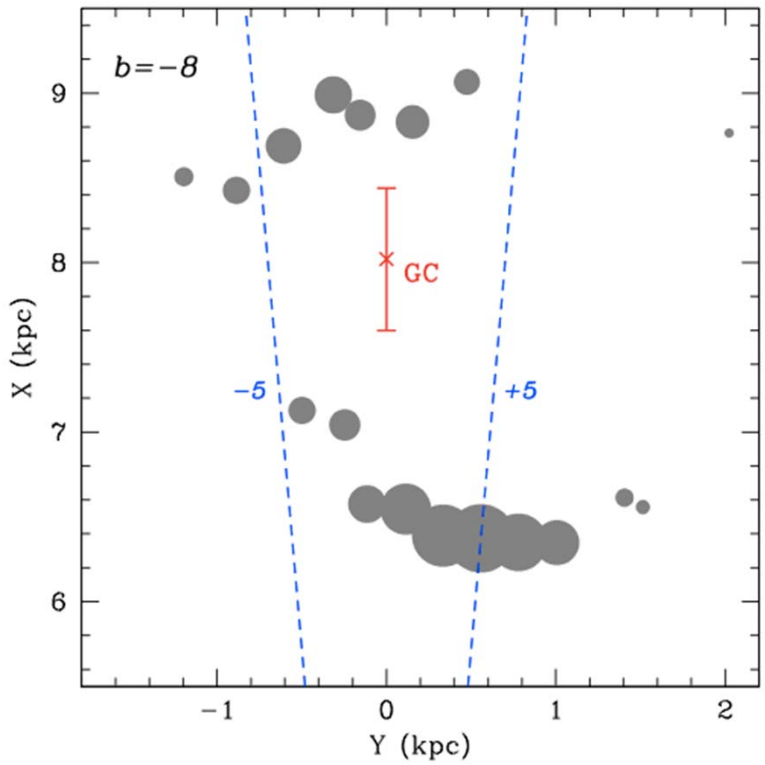
Credit: Zhao-Yu Li

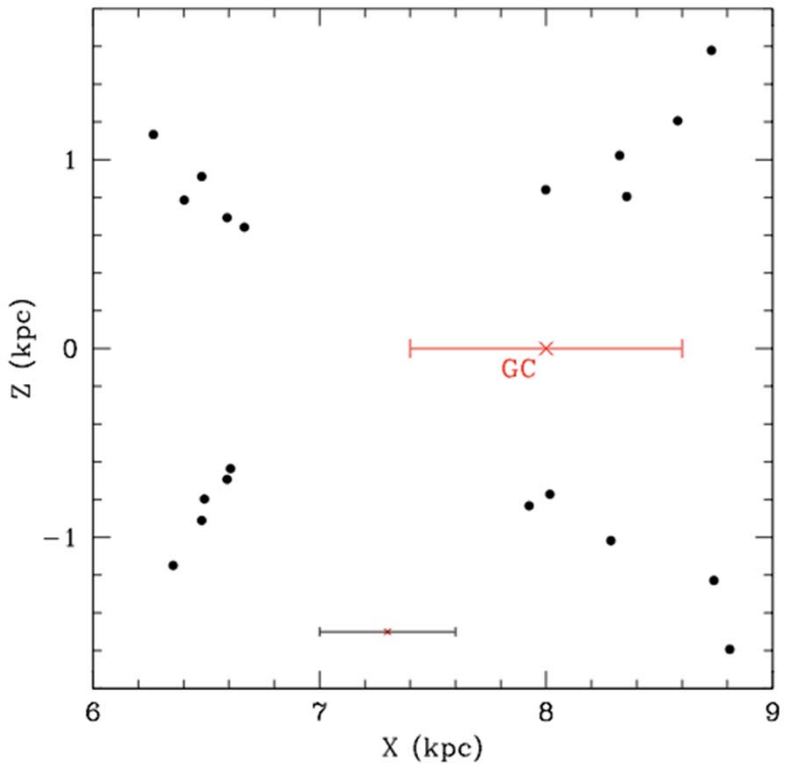
Stars are distributed in a vertical X-shape?

McWilliam & Zoccali (2010)
Nataf et al. (2010)

Intriguing X-Structure in the MW?

- 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)

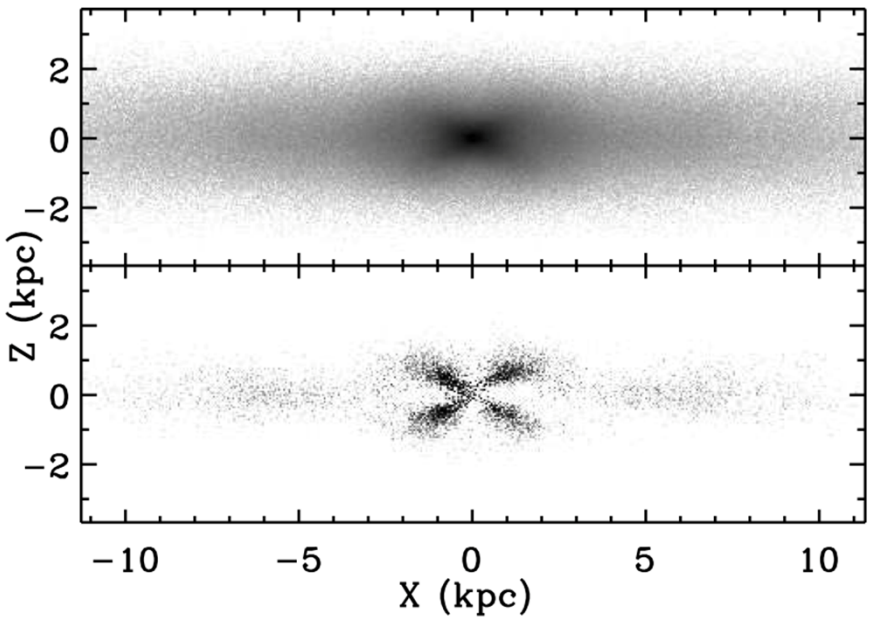




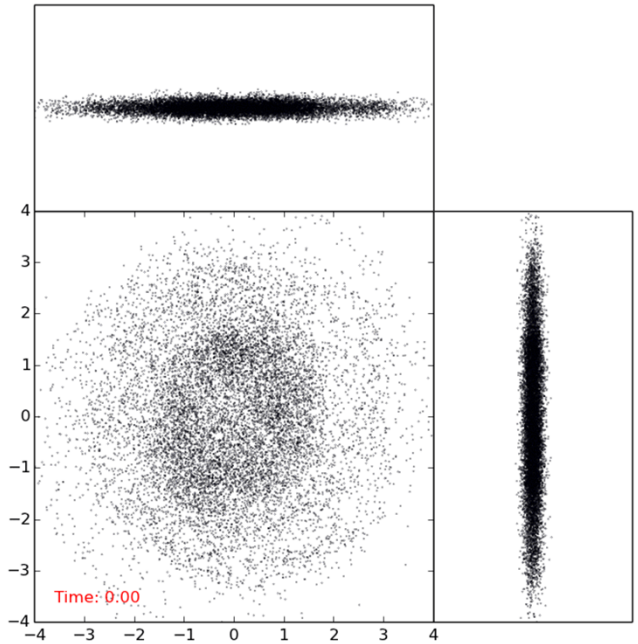
McWilliam & Zoccali (2010)

X-structure in our model

- The same model matches observations reasonably well
- The X is a natural consequence of the buckling instability
- The X must have formed at least a few Gyrs ago
- Further evidence that **MW bulge formation is shaped mainly by internal dynamical instabilities**, instead of mergers
- Major orbital families supporting the X-shape?
  - Banana? Brezel? Others? (Portail et al. 2015, Qin et al. in prep)



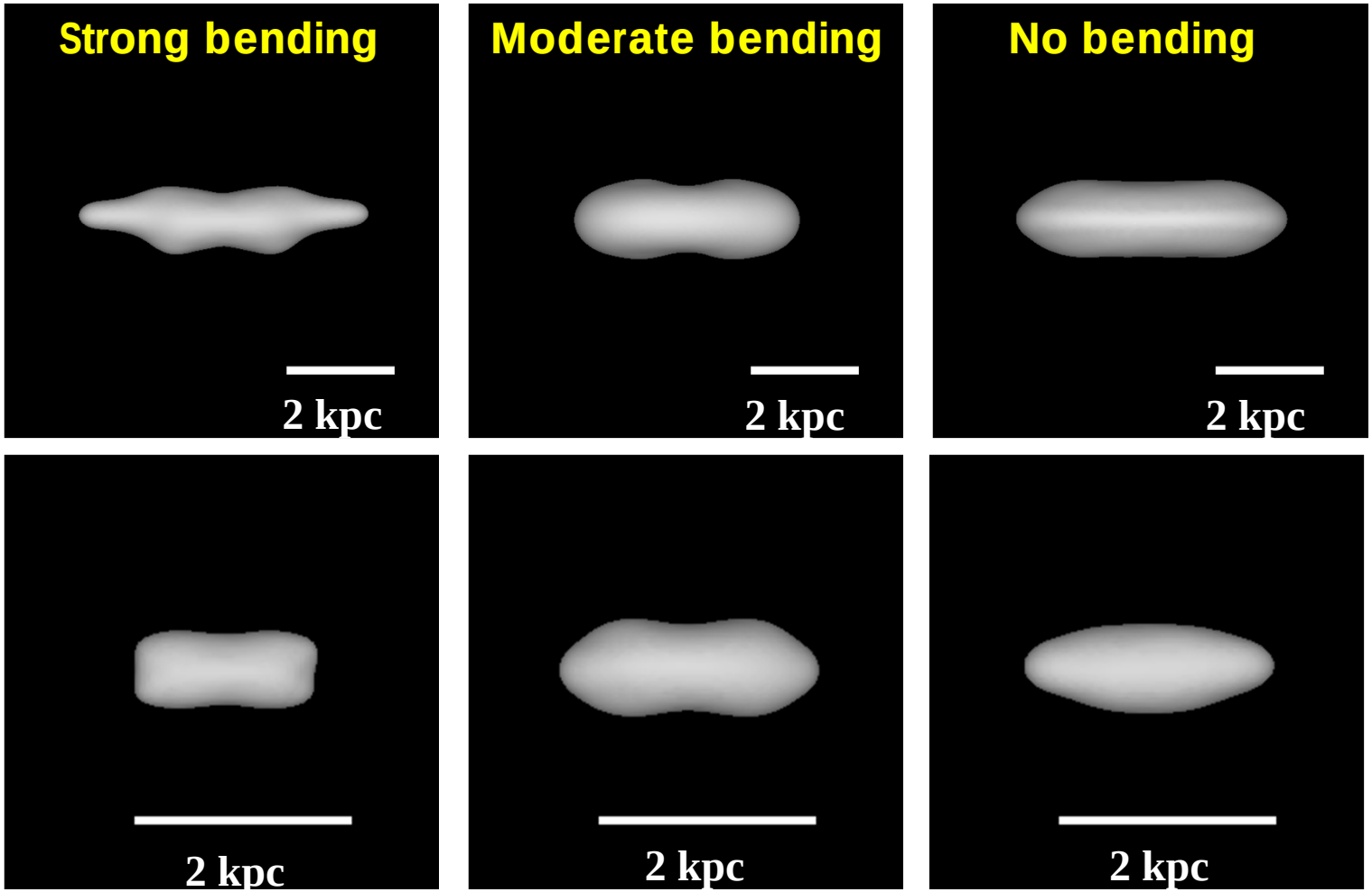
Li & Shen (2012); also Ness et al. (2012)



3D structure of the X-shape

- A buckled bar = outer thin part + peanut + inner box
- A reflection of the central peanut?

Li & Shen (2015, in prep)

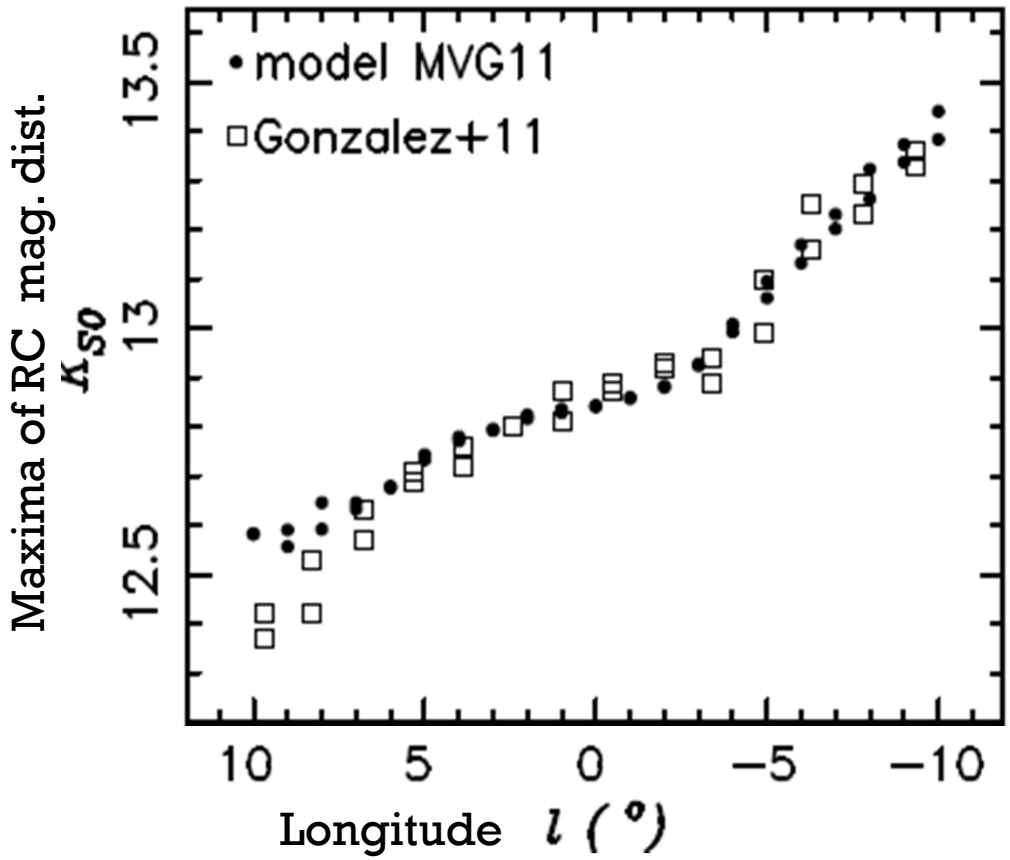


More than one bar in the MW?

- Bar/boxy bulge
  - Bar angle 20-30°; length ~ 4kpc
  - Gerhard 2002; Shen+ 2010; Cao+ 2013; Wegg+ 2013, Pietrukowicz+ 2014 and many others
- Separate long planar bar? (Benjamin et al. 2005 ; Cabrera-Lavers et al. 2007); ~ 45°; length ~4.5 kpc
  - Angle offset is dynamically puzzling, given similar sizes
- Explained by a single coherent bar structure?
  - a boxy bulge and a planar thin bar continuation (Athanassoula 2005; Li & Shen 2015)
  - leading ends of the bar, and due to volume effect in star counts (Martinez-Valpuesta & Gerhard 2011)
  - supported by new analysis (Wegg et al. 2015)
    - Long bar angle ~ 30°
    - Bar length is still a bit uncertain: 4-5kpc

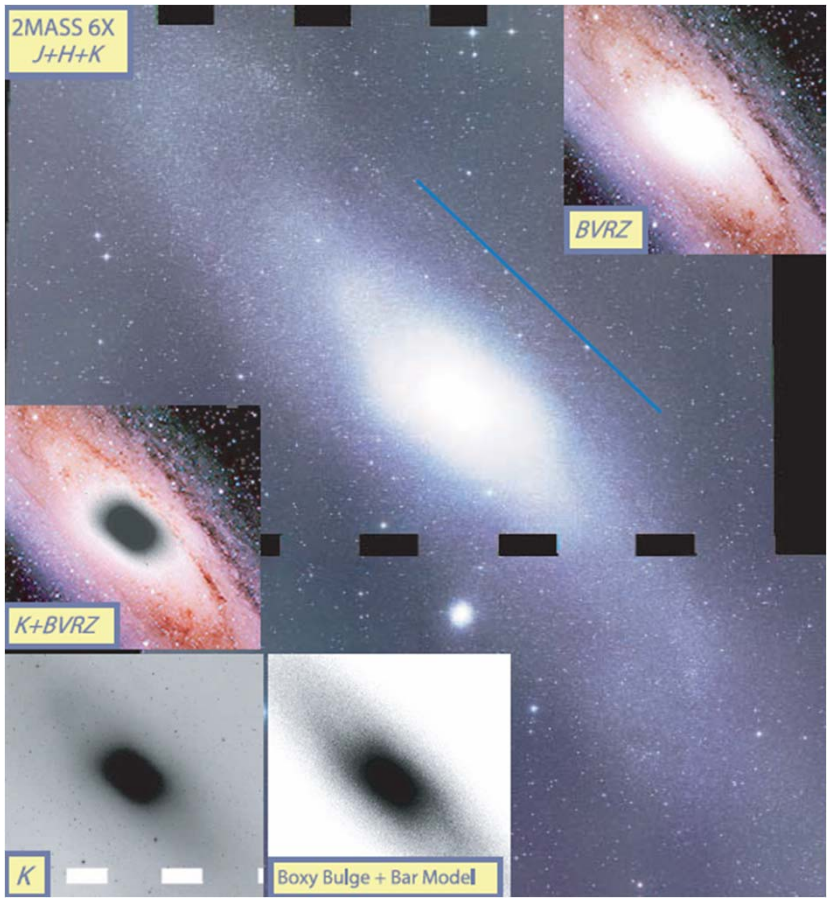
More than one bar in the MW?

- A nuclear bar?
  - Nishiyama et al. 2005; Gonzalez et al. 2011
  - Red clump as a standard candle
  - Clear change of slope in the red clump longitude profiles at $|l|=4^{\circ}$
- May still be explained by a single bar
  - Slope change is caused by transition from highly-elongated to nearly axisymmetric (Gerhard & MV et al. 2012)



M31's bulge

- Hybrid/composite
  - Requires a boxy bar/bulge + classical bulge (Athanassoula & Beaton 2006, Beaton+ 2007)
- Its ring-like structure could be near the OLR of the bar
  - Like an outer ring as often observed in barred galaxies
- More detailed modeling is desired with new star+gas kinematical data
  - Opitsch M., in prep

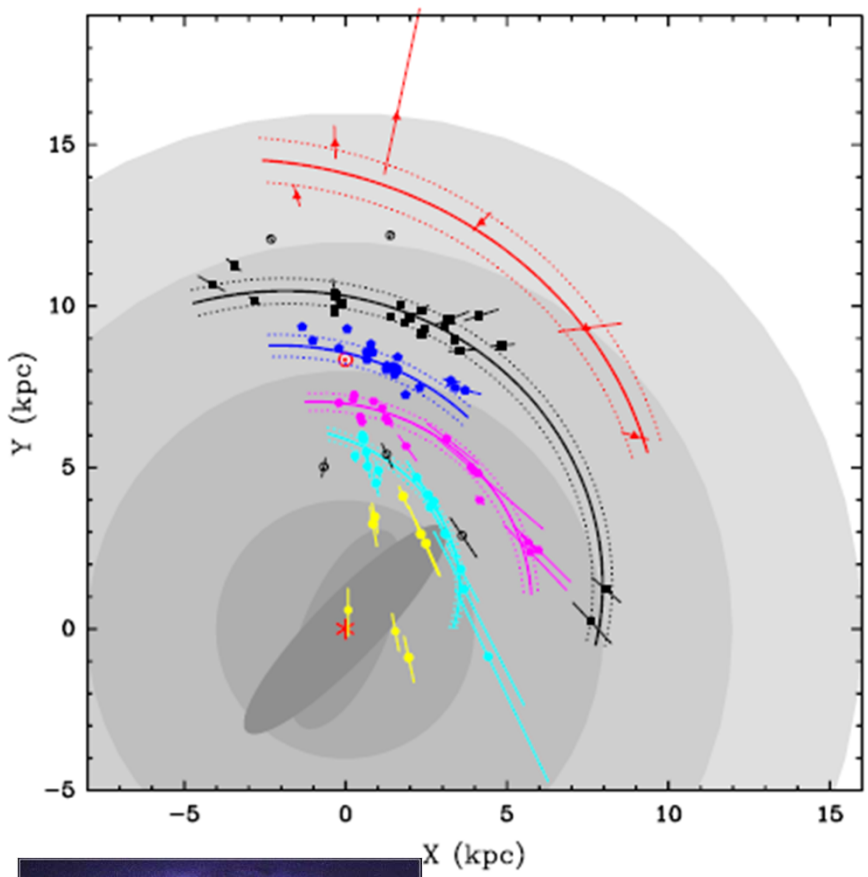


M33

- Nearly bulgeless, classical or pseudo
  - a small nucleus
- SAc - SAd
- Why unbarred?
  - It is actually easier to form a bar than not to
  - Slowly rising rotation curve
  - Puzzling: DM dominates over visible matter?

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
  - Use masers associated with young high-mass stars
  - 4 + the local arm

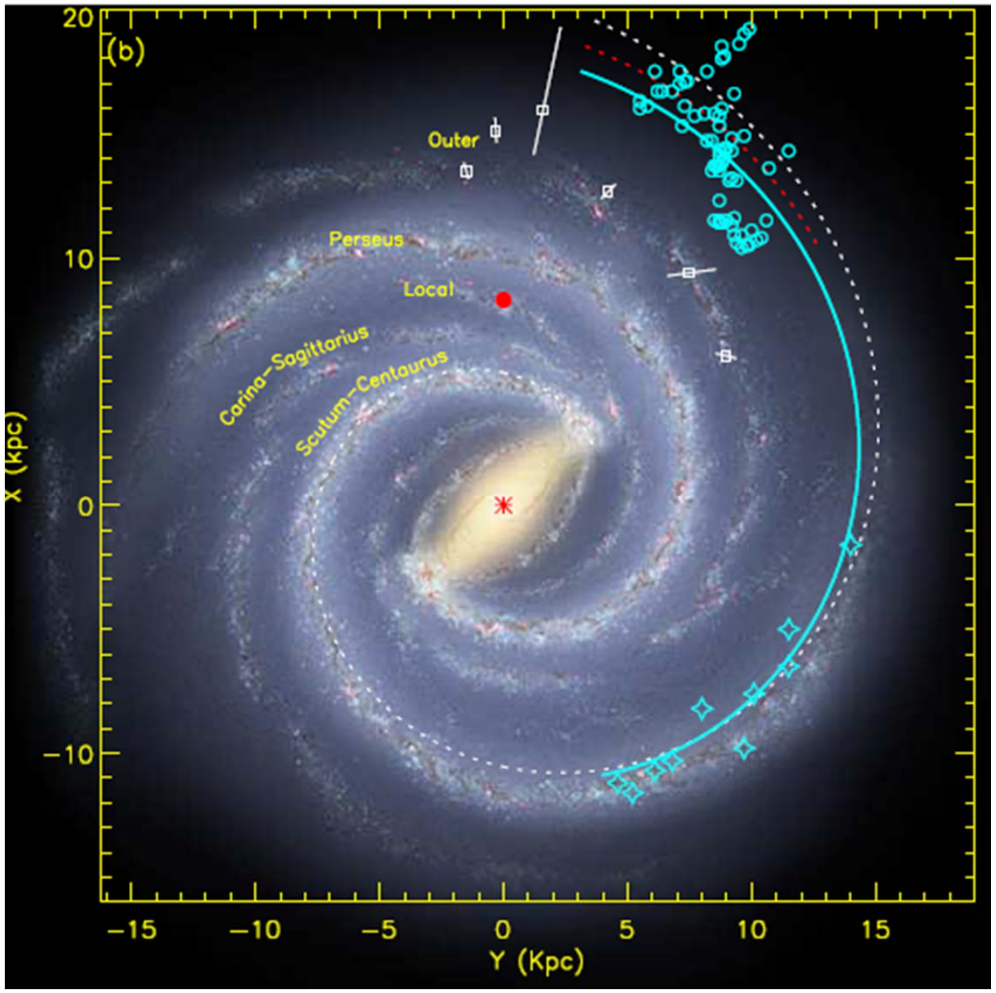


Reid et al. 2014

BESSEL
Bar and Spiral Structure Legacy Survey,
a VLBA Key Science Project

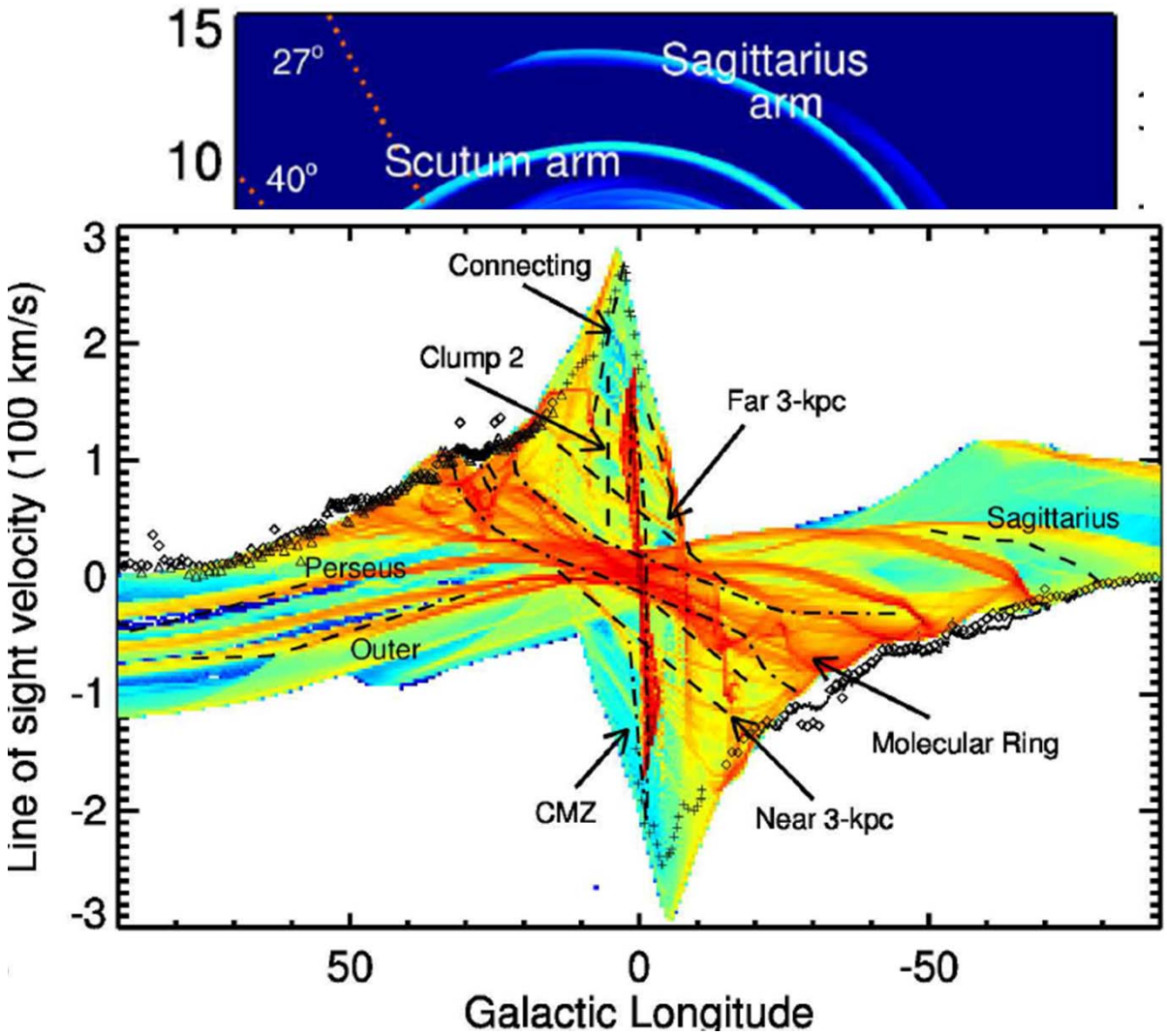
Spiral arms

- New sections of arms are still being discovered …
- Combining HI from the Canadian Galactic Plane Survey (CGPS) and CO from the Milky Way Imaging Scroll Painting (MWISP) project



Sun, Y et al. (2015)
Dame & Thaddeus (2011)

The gas features in the MW



- Gas studied with the l-v diagram (e.g. Burton &Liszt 1993; Dame et al. 2001)

- Li, Z., Gerhard, JS+ 2015, in prep.

- CMZ≈ the nuclear ring

- To constrain the bar and spiral pattern speeds

Summary

- MW bulge ≈ the central part of edge-on bar
- MW bulge/bar contains a X-shaped structure (peanut-shaped), so does the M31
- Boxy bulge is the natural outcome of two dynamical instabilities
  - Why M33 unbarred?
- Boxy bar, long planar bar, and nuclear bar may all belong to the same coherent bar structure
- Gas features may be understood and used to constrain the properties of the MW bar and spiral patterns
- Future is bright with many upcoming large surveys (APOGEE2, *Gaia*, etc.)