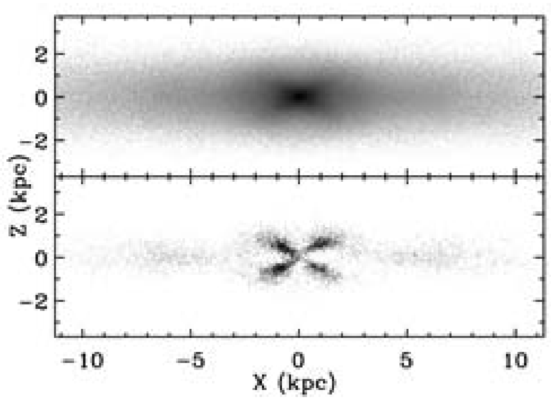
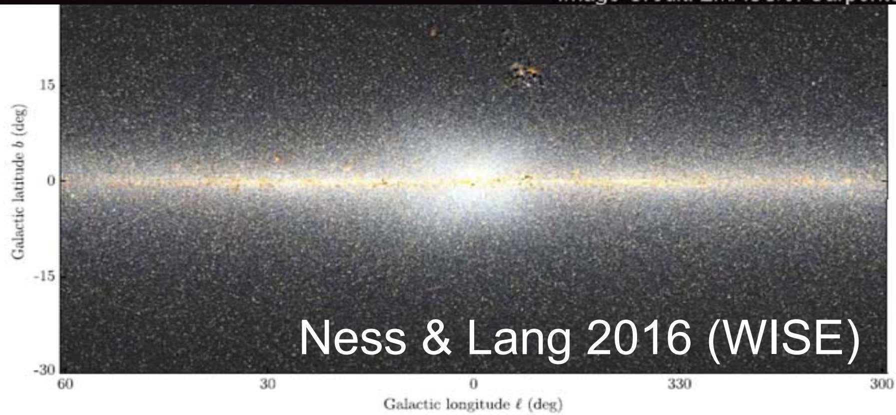
Dynamical modelling of the Milky Way Bar/Bulge

Juntai Shen (Shanghai Astro. Obs.)
沈俊太(上海天文台)



Milky Way's bulge

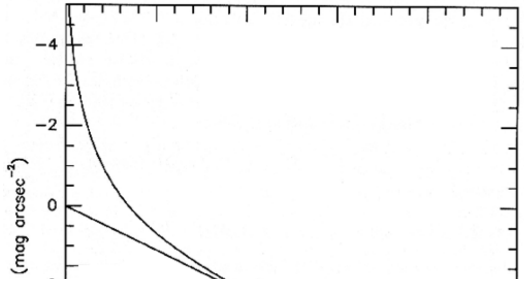


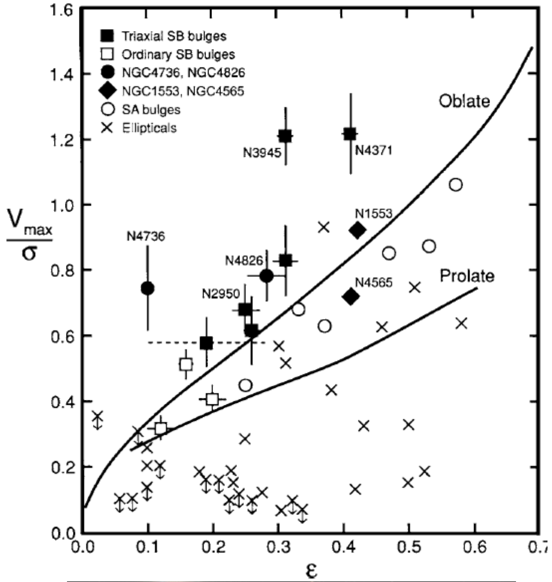
- **Morphology**
  - **Obscured by dust**
  - **Boxy shaped**
  - **asymmetric**

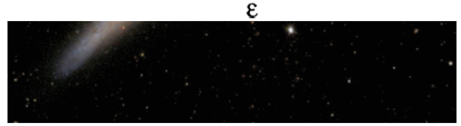
- **Most bulge stars are old (>5 Gyr)**
  Barbuy+ (2018); see Valenti's talk
- **A wide range of metal abundances**
  (McWilliam & Rich 1994; Fulbright+ 2006; Zoccali+ 2008, 2017; Bensby + 2010 2012, Rojas-Arriagada+2017)

Bulges: external perspective

- A disk galaxy = “bulge” + disk
  - 1st order approx.
- But how to define a bulge?
  - Bulge ≈ roundish thing in the middle of a disk
  - Morphology / Photometry
    - Face-on: bulge=extra light in the center
    - Edge-on: bulge=brighter and thicker center
  - Kinematics
    - Rotation vs. random motions
- Surrogate definition is easy, but what they are physically?



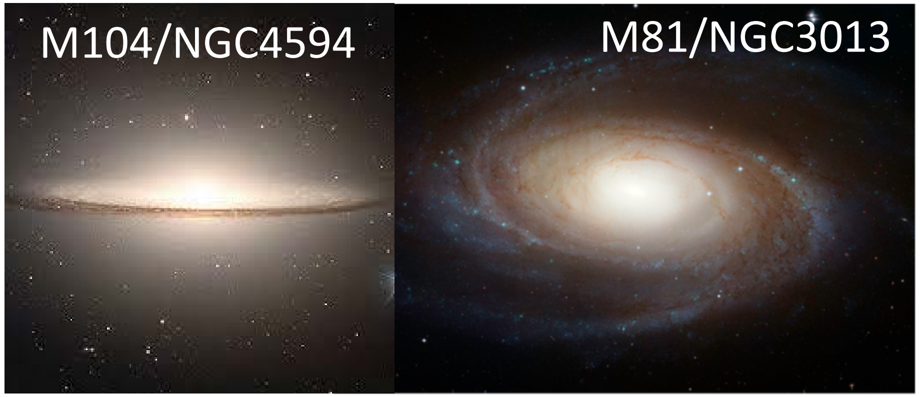




Bulge types

Kormendy & Kennicutt (ARAA, 2004)
Athassoula (2008)

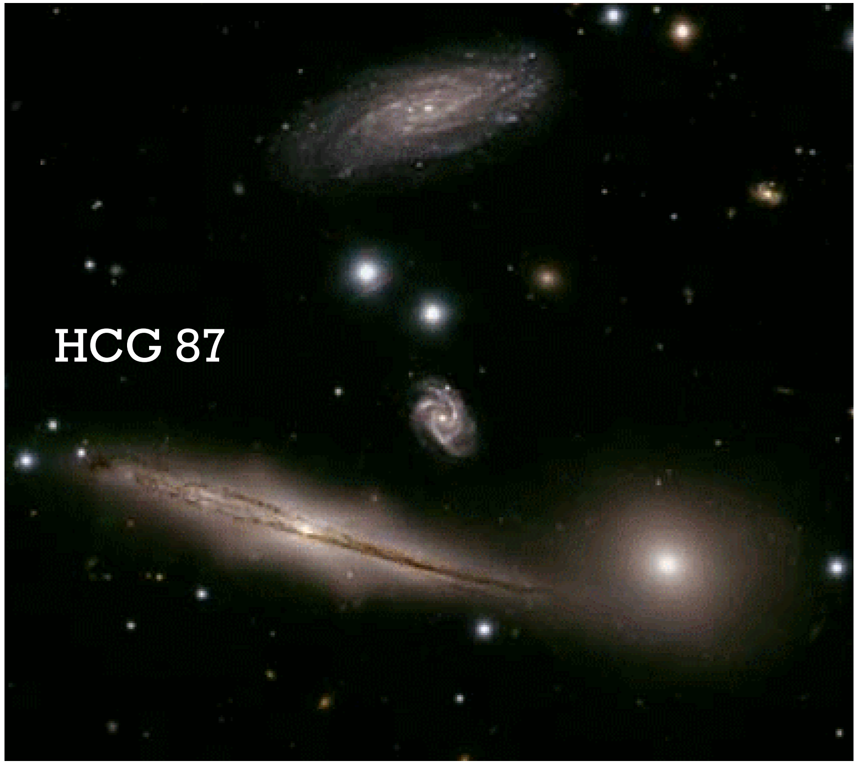
- **Classical bulges**
  - ≈ Mini-elliptical
  - Merger-made; or merging clumps
  - Sersic n > 2
  - not rotation-dominated
  - F.P. (R, L, Σ) defined by Es

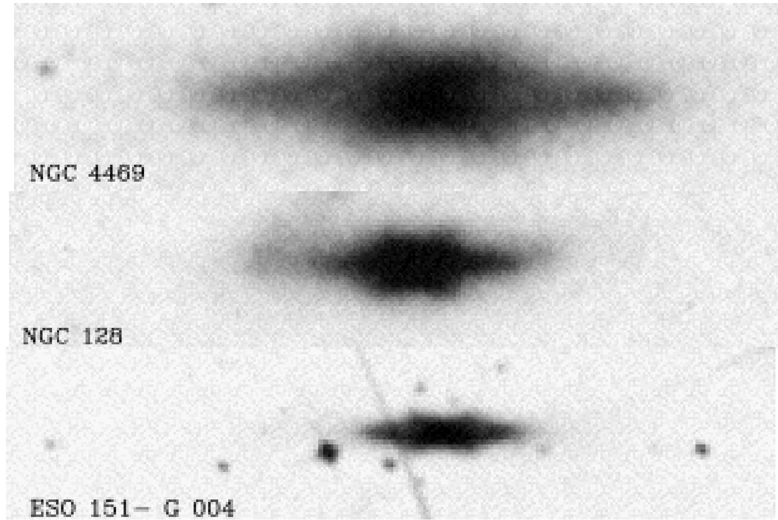


- **Pseudo-bulges**
  - Formed from disk by internal secular processes
  - Rotation dominated
    - memory of disk origin
  - Young stars, gas, dust
  - Sersic index 1-2
  - Including "**boxy bulges**"?

Physical path clear, but classification is hard!

Boxy/peanut-shaped bulges

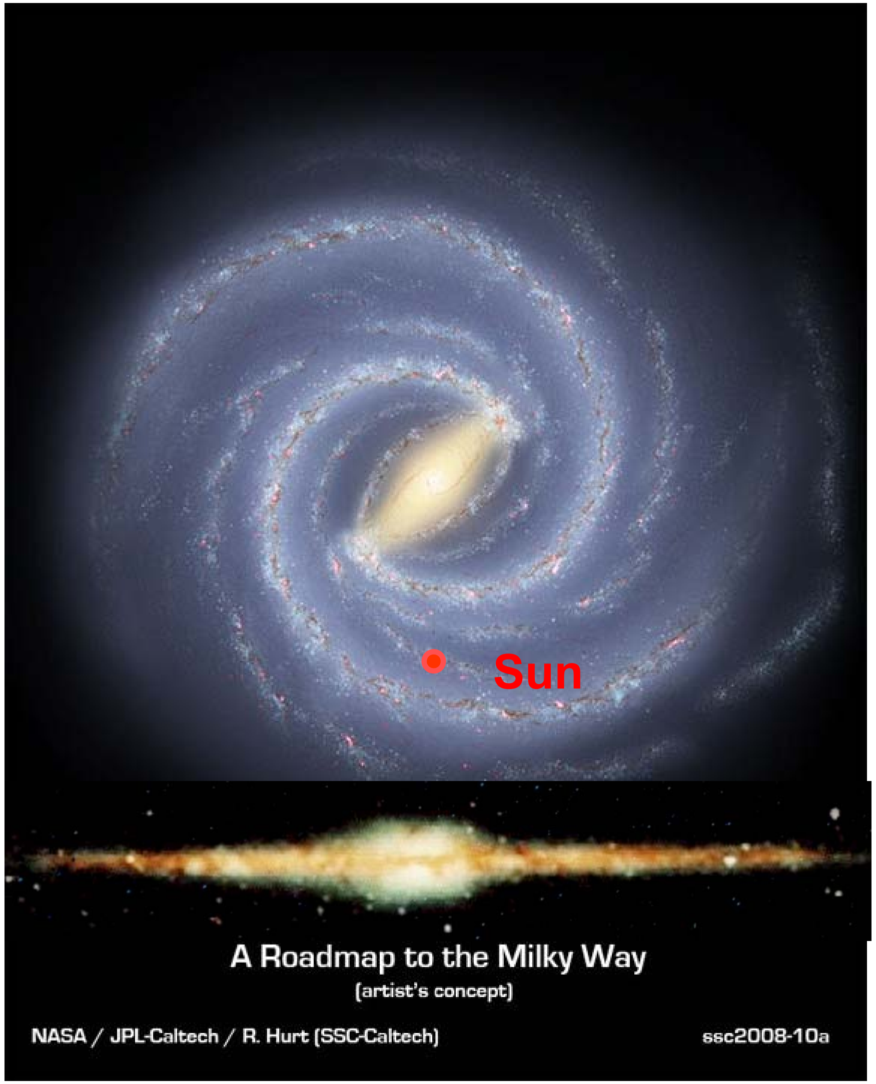




- ~45% of edge-on disks have peanut-shaped bulges (Lutticke et al. 2000)
  - Comparable to the fraction of bars

MW bulge ≈ MW bar?

- Hints of MW bar
  - non-circular motions of gas
  - Stellar photometry
- Bulge ≈ bar seen nearly end-on (20-30°)
- Recent surveys + dynamical modelling
  - BRAVA; ARGOS; APOGEE; GIBS; VVV; Gaia-ESO (Kunder+2012; Ness+2013ab; Zoccali+2014, 2017)

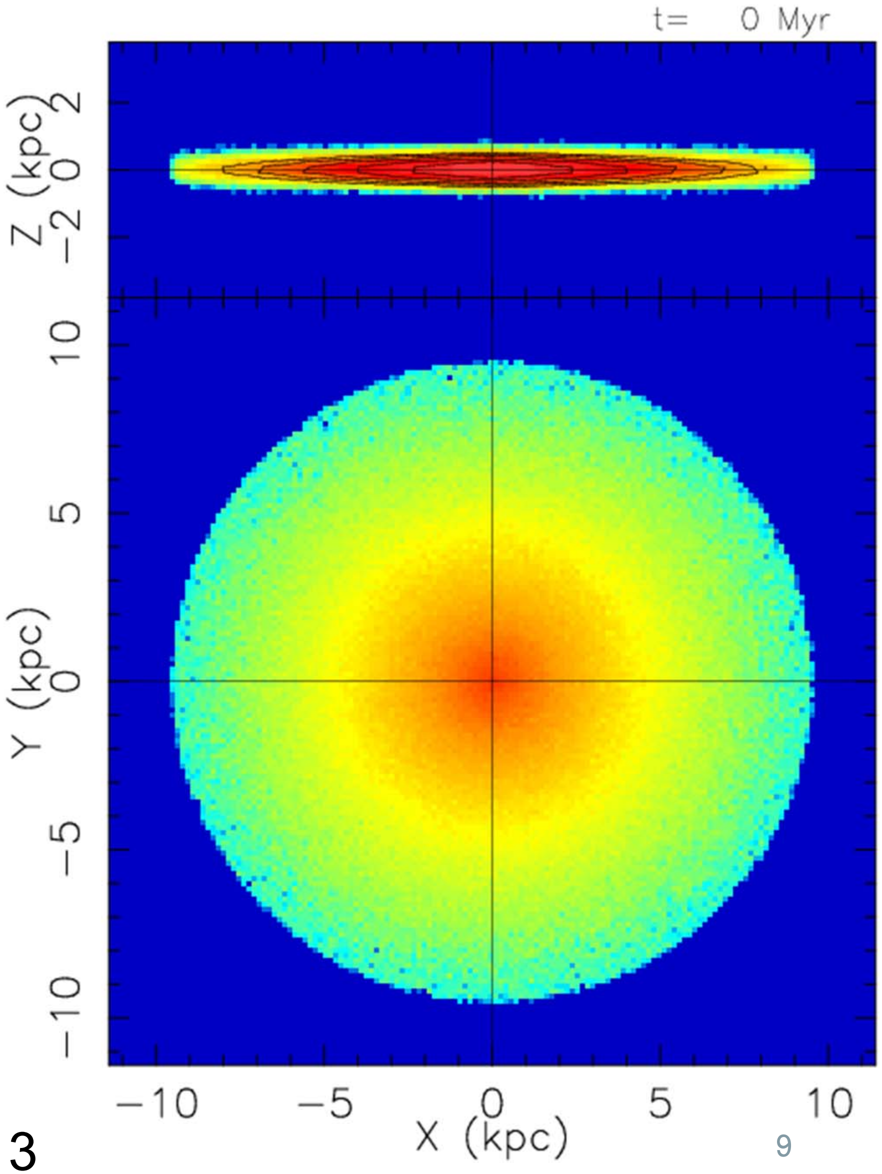


Modelling the bulge formation

- Hydrodynamical models in cosmo. setup is complicated *(Sandro Tacchella's nice review)*
  - Sub-grid physics is still quite uncertain
  - Expensive: may get appealing results but hard to separate out the physics involved
- Simpler models still has its advantages
  - Fewer free parameters
  - Easier to explore the parameter space extensively
  - Isolate out the individual physical effect in play
  - Understand what effect is caused by which physical process
  - Help quantitative comparison with obs.
- Simple models can be a starting point
  - Add in more complicated processes step by step
  - We gradually unravel how Nature works
  - Complementary approach

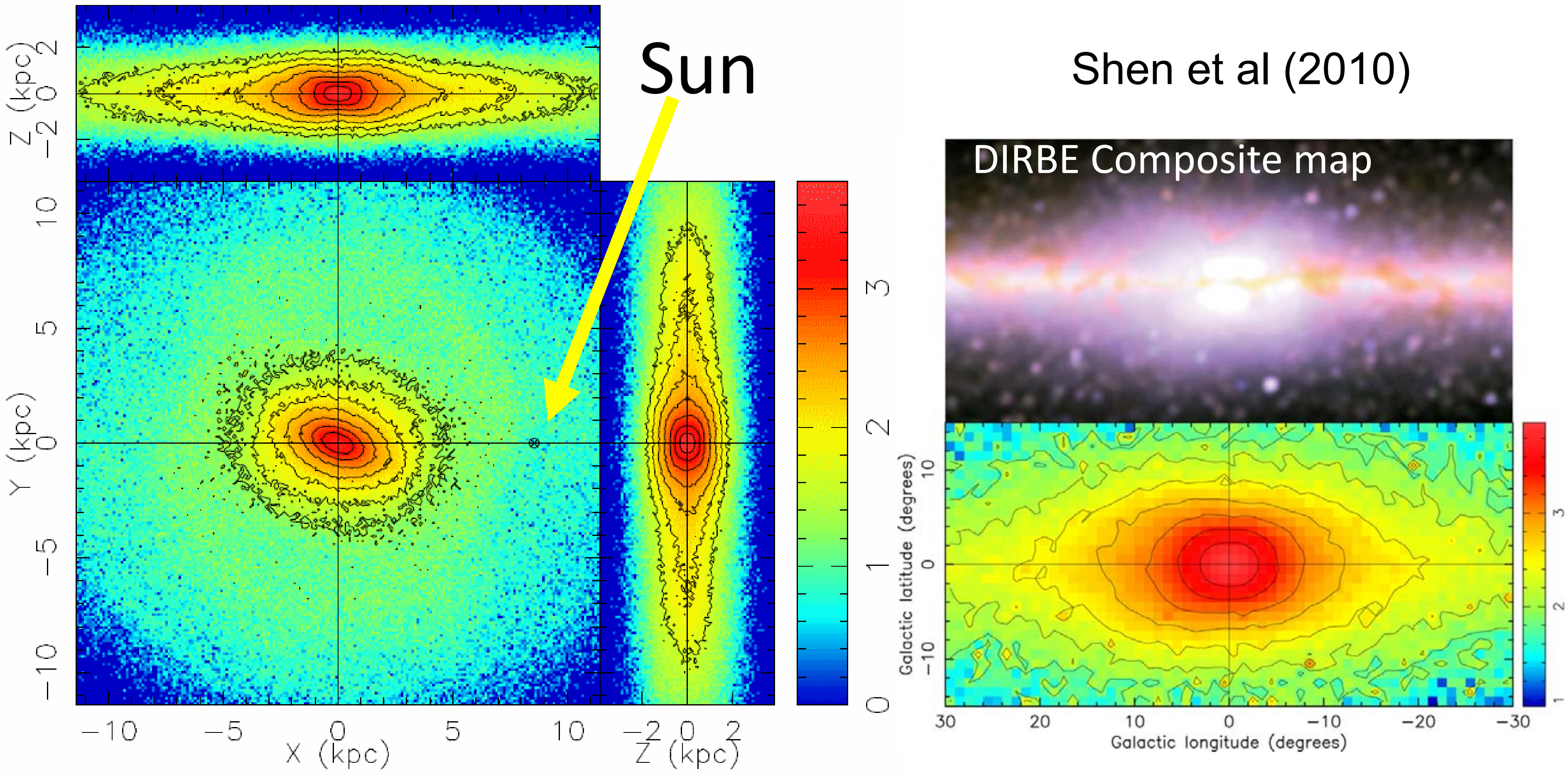
MW bulge as a buckled bar

- A simple model can match survey data very well in many aspects
- ***Physical mechanism: a tale of two instabilities!***
    - **Bar-forming instability** (in-plane) → **buckling instability** (vertical) → saturation → boxy bulge
- Boxy bulge = edge-on bar
- Instability of a precursor disk, instead of major mergers



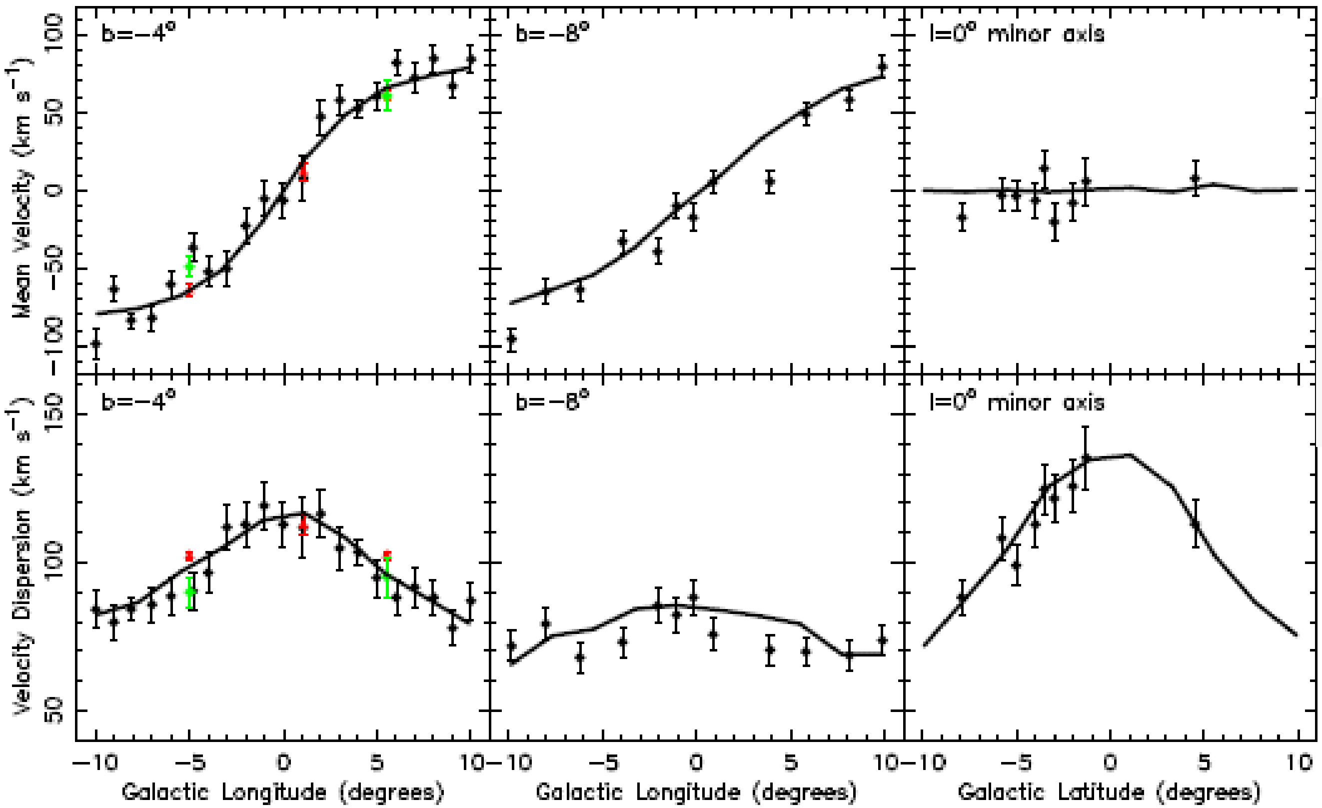
Shen+ 2010; Ness+ 2013

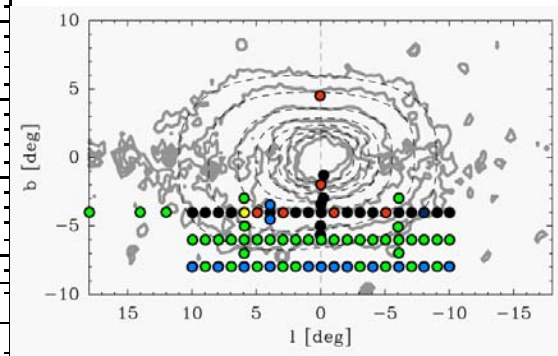
Surface Brightness Map



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

Match stellar kinematics strikingly well





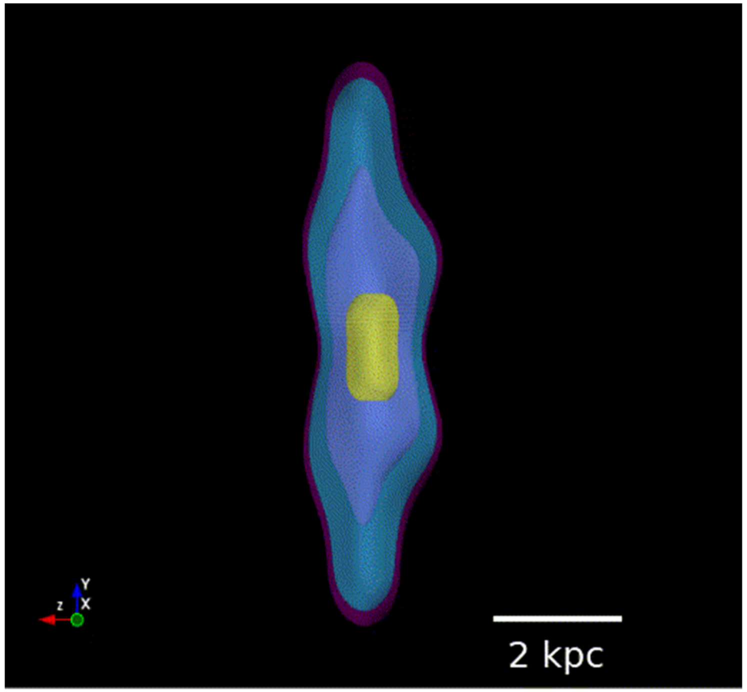
Shen+ (2010)

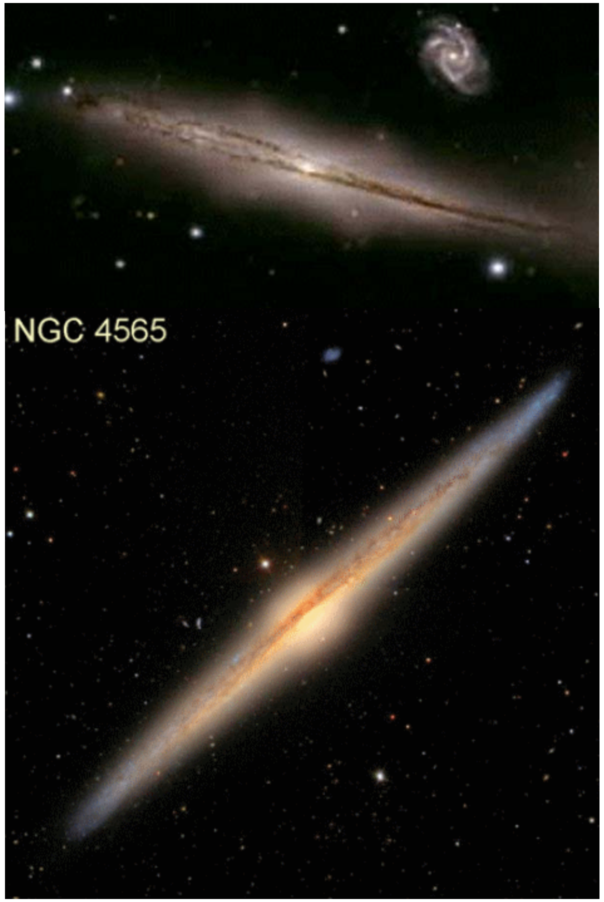
See also
Kunder+ 2012
Ness+ 2013a,b
Zoccali+ 2014

- **Cylindrical rotation**: const. rotation regardless of height
- Hard to reproduce with a classical bulge

Boxy peanut-shaped bulge

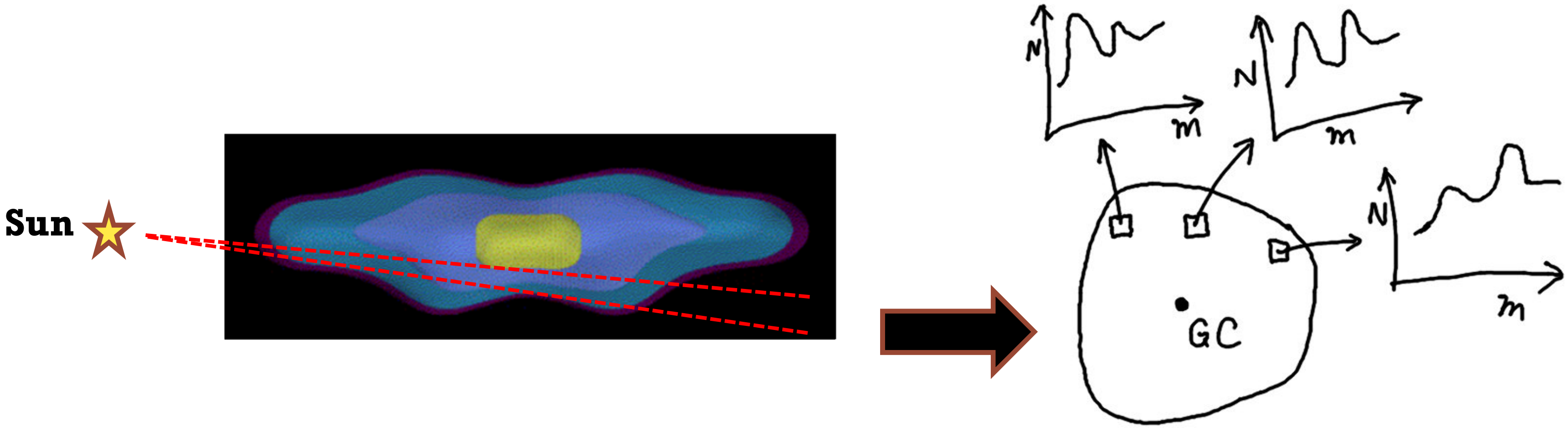
- Peanut naturally predicted by a buckled bar (Raha+91; Combes+1991)
- A buckled bar = central peanut + outer thin part
- Long thin bar in MW (Benjiamin+ 2005; Cabrera-Lavers+2007; Wegg+2015)
- Also seen in external galaxies





Li & Shen (2015)

Peanut → bimodal dist. of stars



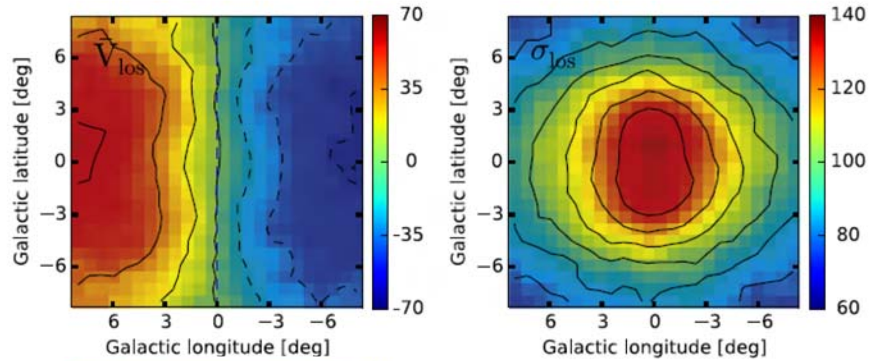
McWilliam & Zoccali (2010) Nataf et al. (2010) Saito+ (2011) Li & Shen (2012)

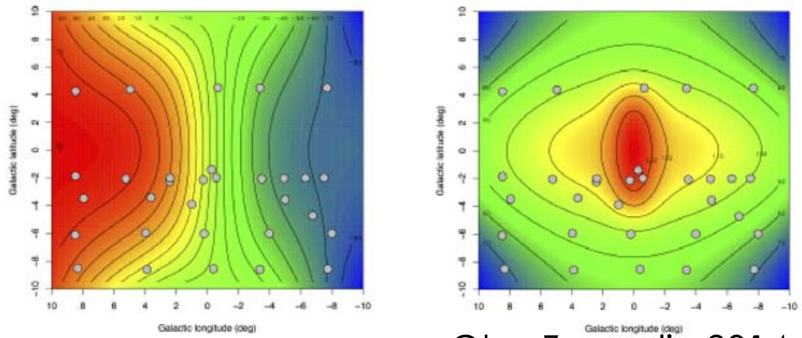
- Red clumps (RC): a good standard candle? also competing view by Y.-W. Lee
- Along different lines of light, distance of RC splits into two groups
  - "X-shaped" structure
  - Also seen in proper motions (Clarke+, in prep)
- X-shape: a reflection of the central peanut? (Li & Shen 2012, 2015)
- Further evidence that **MW bulge formation is shaped mainly by internal dynamical instabilities**, instead of mergers

Predictions on kinematics of X-shape

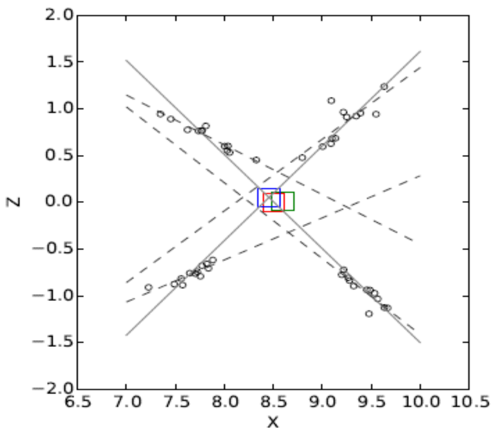
- Make model predictions on the kinematic properties of the bulge and the X-shape
  - R.V. and proper motion
  - Consistent with most of recent obs. (Vasquez+ 2013; Zoccali+ 2014)
  - Will be further cross-checked by upcoming large surveys like *Gaia* etc.
- Test using the stars' spatial distribution to determine R_{GC} (Gardner et al. 2014)

Model: Qin, Shen et al., 2015



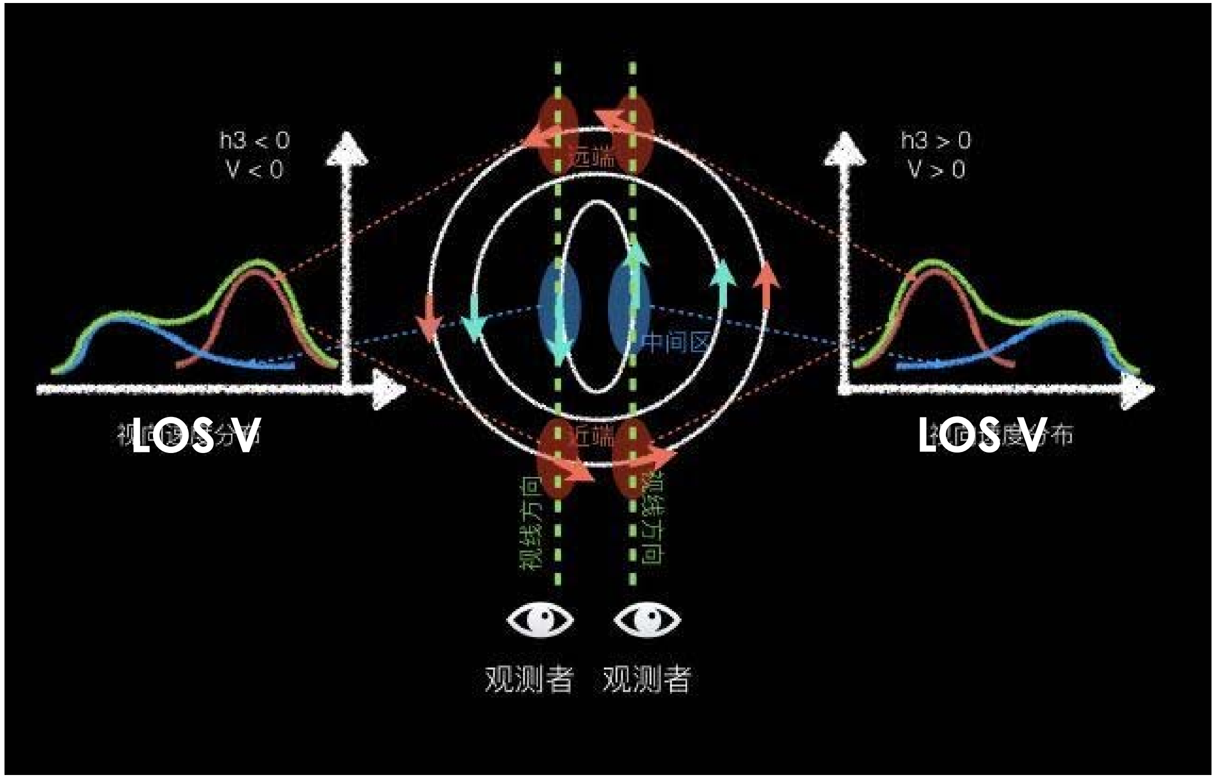


Obs. Zoccali+ 2014



Skewness of LOSVD

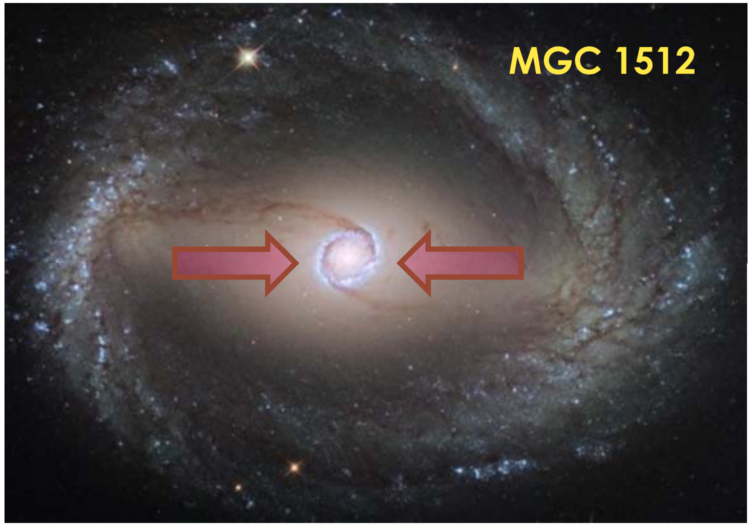
- Correlation btw. **skewness** (h_3) and **mean velocity**
- Also seen in external peanut-shaped bulges
- Indication of a end-on bar

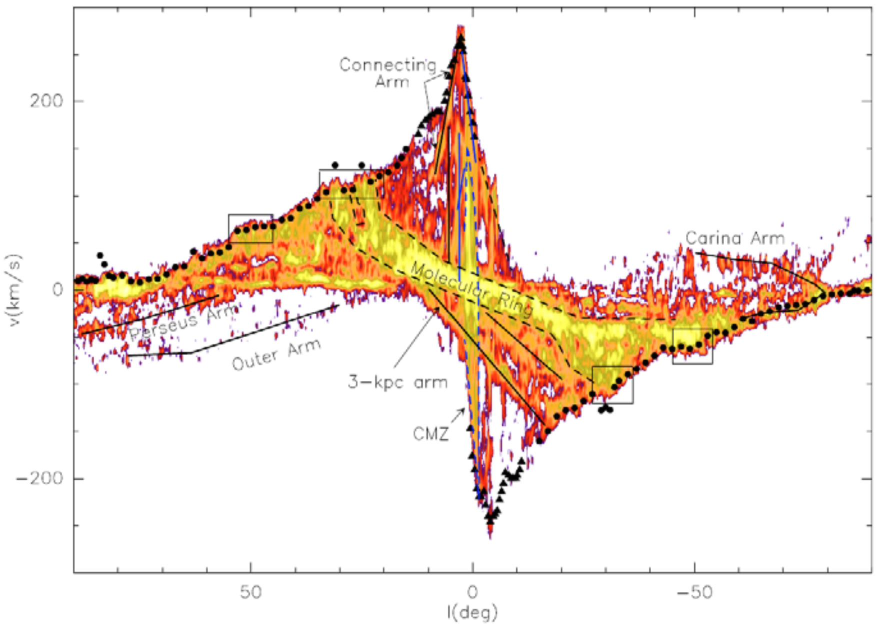


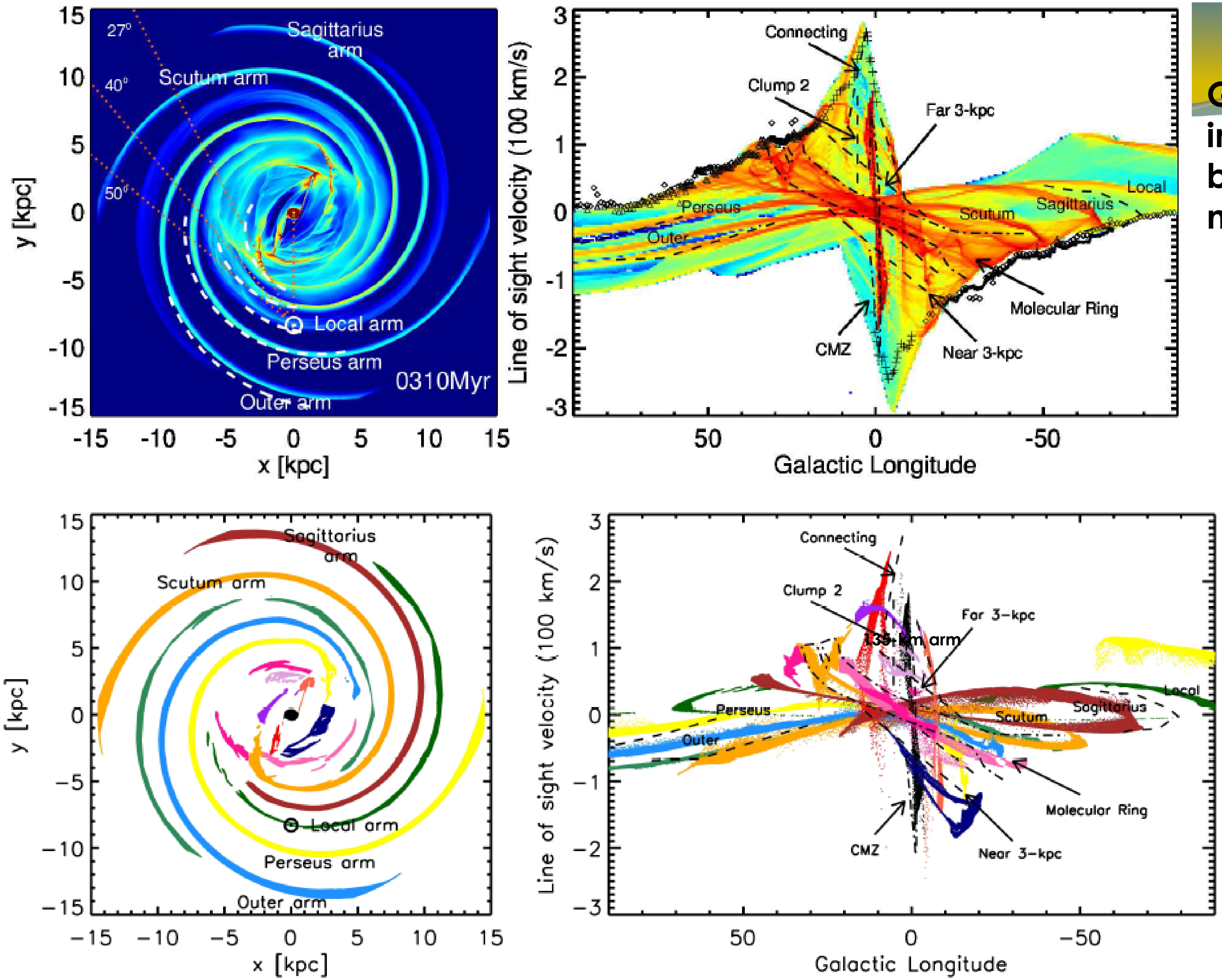
APOGEE: Zasowski+ 2016; Zhou+2017, Bureau & Athanassoula 2006; Li+ 2018

Gas features in the MW

- Simple bar models can also explain the gas features
- Gas is NOT always driven right to center, often forming a **nuclear ring**
  - Physical mechanism understand
  - Low-res hydro models do not always reproduce obs.
- The best-fitting **bar+spirals** model can reproduce most gas features in the observed l-v diagram (Li, Z. et al. 2016)
  - Base potential: M2M modeling results of VVV red clump giants (Portail + 2015)







Gas flow model in the best-fitting model

Ω_b = 33km/s/kpc

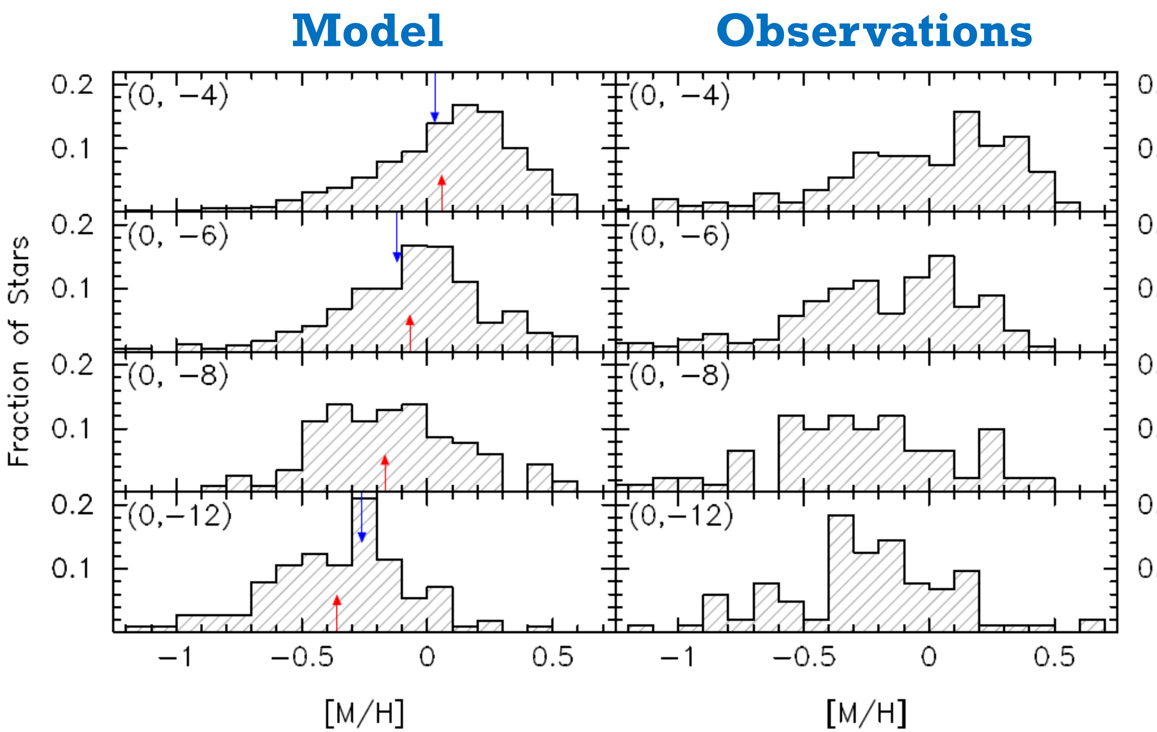
Ω_s = 23km/s/kpc

- **MW's nuclear ring is the Central Molecular Zone (CMZ)**
- **Gas is being driven towards CMZ**

Li Z., Gerhard, JS + (2016)

Vertical Metallicity Gradient

- More metal-poor stars at increasing height
- Strong argument against bulge as a buckled bar?
- A vertical gradient can still be generated even after the violent buckling!
  - Purely dynamical: **Initial radial gradient is transformed into the final vertical one**
  - Reason: different region of the bar/disk is heated vertically differently

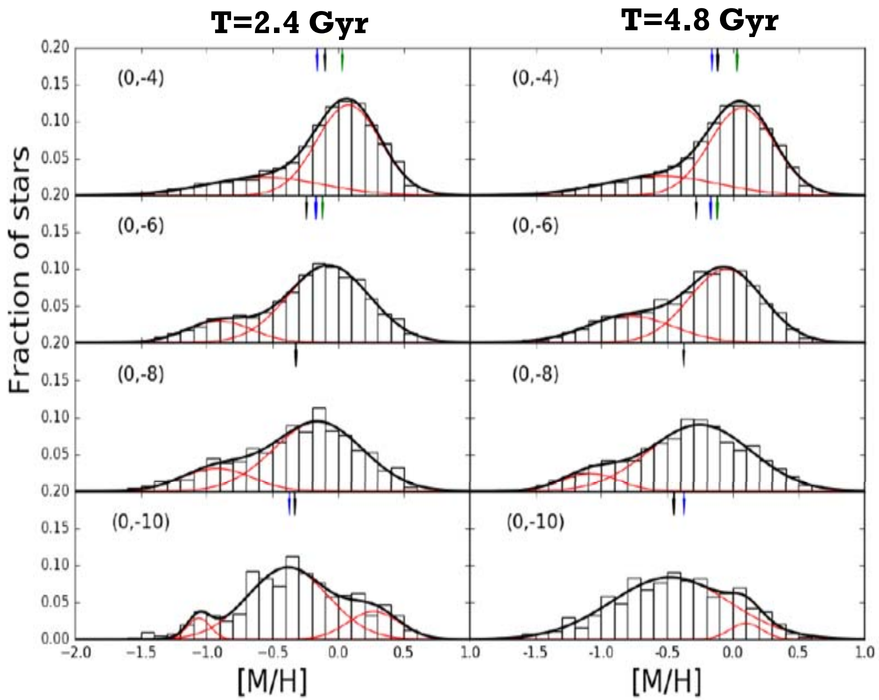


Martinez-Valpuesta & Gerhard (2013)

Liu Z. & JS (2019, in prep)

MDF in our model

- tag to each star w/ fixed [Fe/H] in Shen+ 2010 model
  - Initial **radial** gradient: predicted by inside-out formation scenario of early disks
  - high-z disk obs. (Jones+ 2013) (a_R = −0.3 dex kpc^{-1})
- Stable MDF after buckling
  - Final gradient ~ 0.04 dex/deg (similar to Gonzalez+13)
- Multiple sub-pop signature
  - not necessarily indicate different dynamical origins

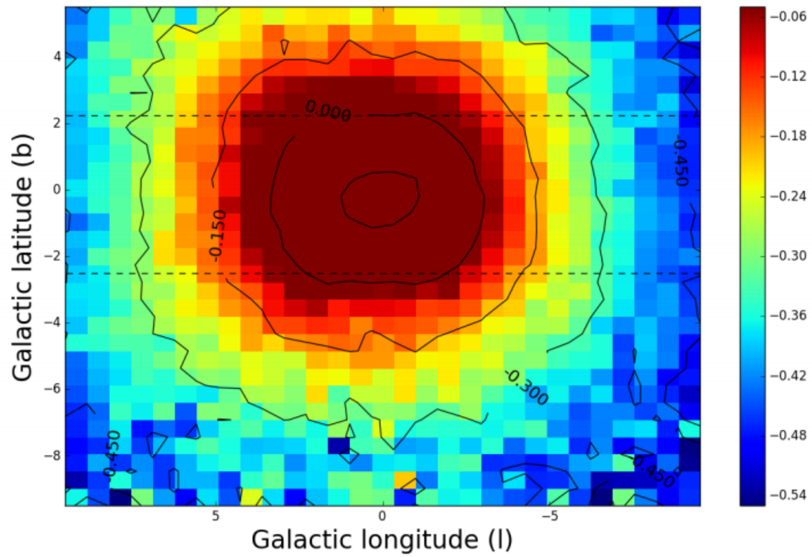


Liu Z. & JS (2019, in prep)

Arrows:
Blue: our model
Red: Gaia-ESO (Rojas-Arriagada+14)
Green: Zoccali.2008

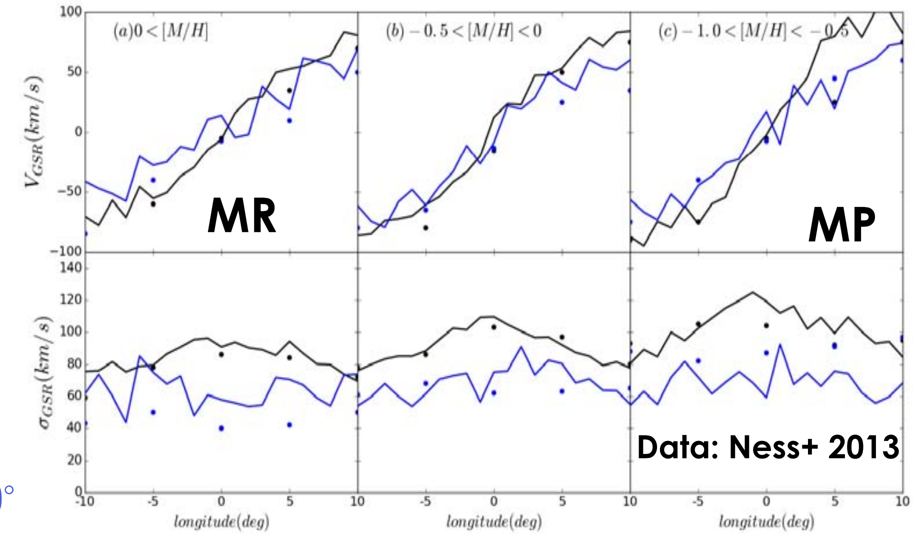
MDF in our model

- Full metallicity map



- Metal-poor stars: slower rotation, larger dispersion
  - Chemo-kinematic relation (talk by Alvaro, Ness+ 13, Johnson+13; Zoccali+16; Clarkson+18)
- Simple models with chemical tag give qualitative trend

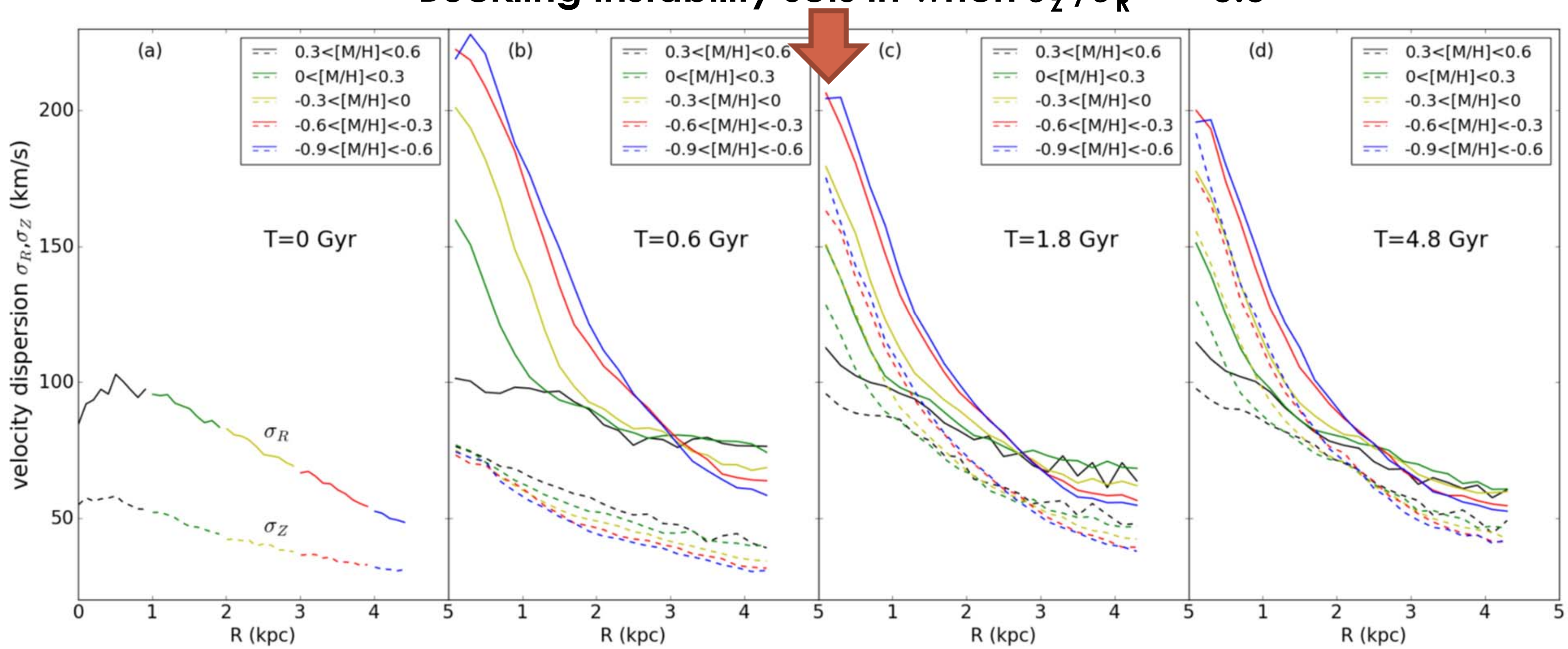
Black: b=−5°
Blue: b=−10°



Pure dynamical mechanism

- **Initial radial gradient is transformed into the final vertical one**
- The outer (more metal-poor) particles move inward and got vertically heated the most in the bar formation and buckling event, than the initially inner particles.
- Gradient is established in a 2-step process (bar formation and subsequent buckling).

Buckling instability sets in when σ_z / σ_R < ~ 0.5



Initial disk

Bar formed; pre-buckling (radial heating only)

Post-buckling (vertical heating)

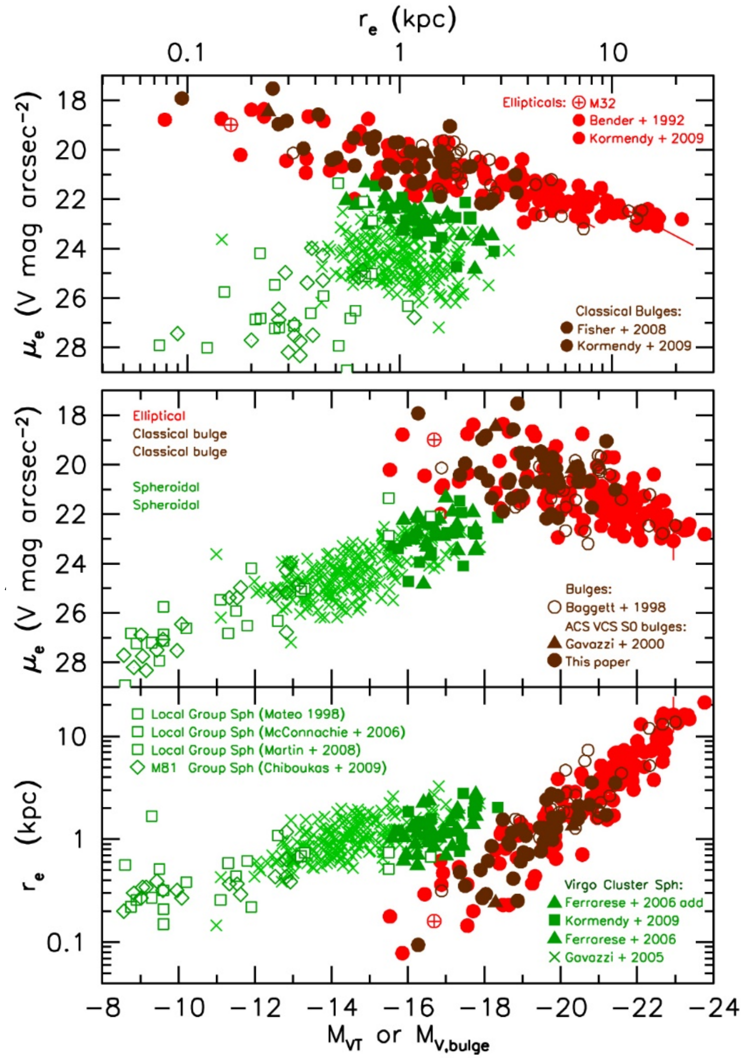
Final quasi-steady

Comparison with other scenarios

- Less parameters to fine-tune
- The 2-disk and 3-disk scenario may improve the match further
  - Bekki & Tsujimoto 2011; Di Matteo+15; Fragkouti+ 2017
- Debattista+17: somewhat similar, but there stars largely formed in-situ, not from the mass redistribution as in our model
- Main weakness: MP stars tend to show a stronger X than MR? (opposite to Ness+ 2012, Uttenthaler+13)
- **Basic mechanism must be in action in other more advanced models**
  - A simple stellar disk with a radial gradient → buckled bar with a vertical gradient (Martinez-Valpuesta & Gerhard 13, Liu & JS 2019)
  - Need to compare these models to better understand the differences better
    - Maybe initial radial gradient even weaker? Or something else

No classical bulge?

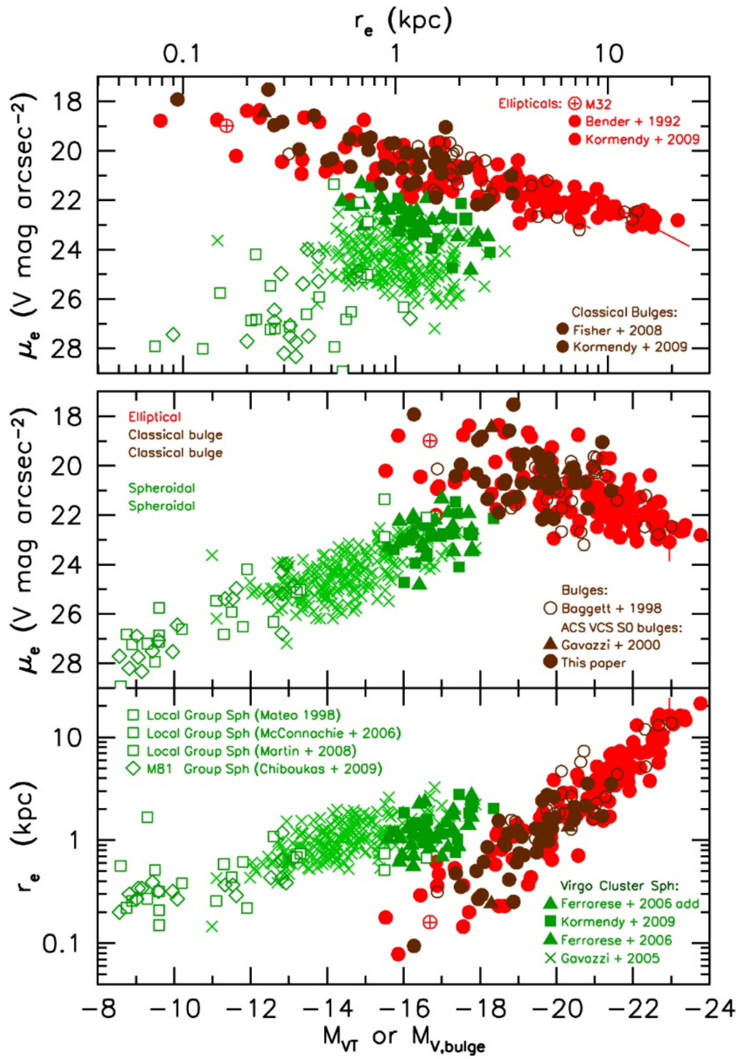
- What is a classical bulge?
  - Old? Spherioidal shape? Non-rotating?
- Classical bulges ≈ Mini-ellipticals
- "fundamental plane" of ellipticals: a tight relation of (size, luminosity, surface brightness)
- No freedom to tinker classical bulge profiles to make them easy to hide.



Kormendy & Bender 2016

No classical bulge?

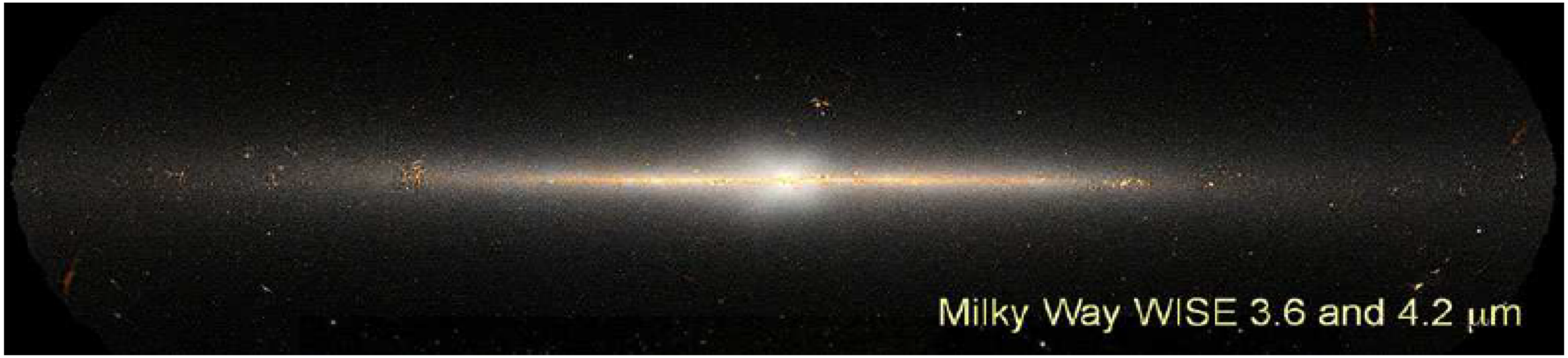
- A smaller CB → higher central surface brightness, much denser than a star cluster (4.2pc) or disky pseudo- bulge (~45pc)
  - if B/T = 0.02, corresponding to $M_V \approx$ -16.3 (M32: -16.7)→ r_e~100–200 pc (dense & large)
  - ***The fact that we can detect the NSC shows that the MW contains almost no 1%M$_*$ classical bulge***, otherwise we would only see a dense classical bulge (Kormendy & Bender 2018)
- For a ~10% M$_*$ CB
  - Inconsistent with kinematics (S10)
  - Surface brightness steeply rising?
  - Inconsistent with COBE results: exponential minor-axis profile of MW

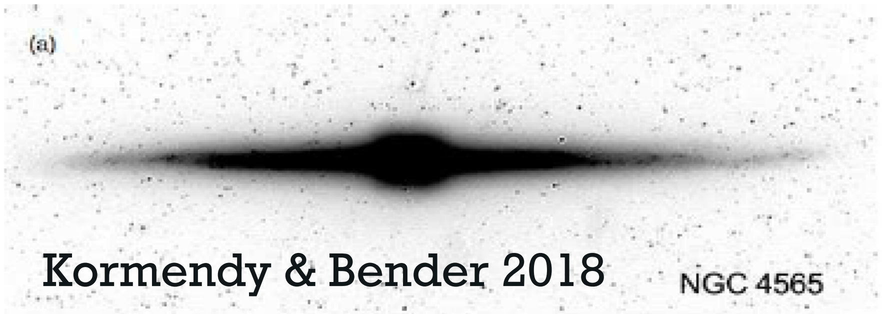


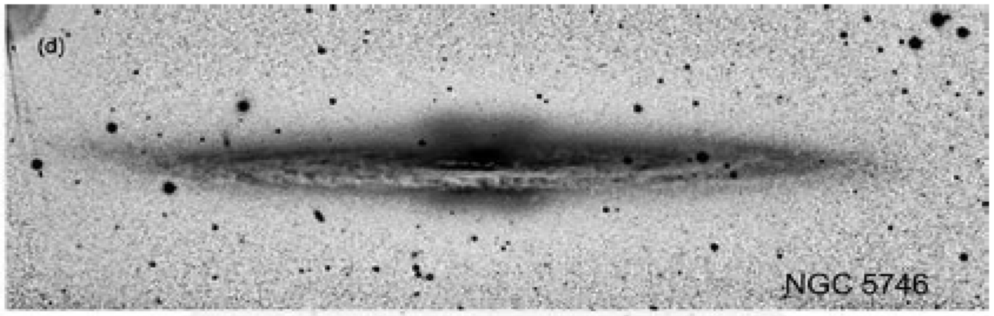
Kormendy & Bender 2016

Is MW typical?

- See Oscar Gonzalez's talk Friday
- All three are giant, SBb – SBbc galaxies
- Structural analogs of MW
- also made of old and alpha-enhanced stars.
  - It is not rare that the formation of stars that now live in bars finished quickly and early







Virtues of simple disk instability model

- Simplicity, few parameters to tweak
- Physical mechanism well understood
- Despite its simplicity, it ties together several isolated results in a coherent picture, cemented by a fully-evolutionary N-body model in which the bar evolves naturally and without much fine-tuning
  - Morphology match
  - Beautiful match to full kinematics (cylindrical rotation)
  - Photometric/kinematic bar angle
  - Bar length & bar pattern speed
  - Boxy peanut-shaped / X-shape (also common in other galaxies)
  - h_3-V correlation
  - Quantitative gas features in MW l-v diagram
  - SMBH under-massive relative to M_{BH}-σ relation
  - Vertical metallicity gradient, a lot of room to improve
- A physically-motivated starting point
  - To incorporate more complexities

See review by **Shen & Li (2016), Springer book chapter**

Puzzles to be understood

- Truly peanut-shaped ("X") bar or helium enhanced multiple stellar population phenomenon? Or both?
- No a significant classical bulge component?
  - Shen+2010; Saha & Gerhard 2013; Kormendy & Bender 2018
  - Metal-poor RRL and cepheids are extrapolation of the inner halo into the bulge region?
- thick disk(s) is needed to explain full metallicity map?
  - Bekki & Tsujimoto 2012; Di Matteo+ 2015; Fragkouti+ 2017
- When and how is the precursor disk formed: could still be made in a gas-rich merger very early on? (Athanassoula + 2017), or merging clumps? (Elmegreen+ 2008; Inoue & Saitoh 2012; also Debattitsa's talk)
  - When & How the bulge stars were mapped
  - morphology-chemistry-kinematics
- X-shape only show up in metal-rich stars, not metal-poor?
  - Hill+ 2011; Ness+ 2012; Uttenthaler+ 2012, ...
  - Kinematic fractionation (Debattista+ 2017)
- High-V cold peaks in some fields of the bulge/disk?
  - Nidever+ 2011; Zasowski+ 2016; Zhou+2017
- *How can Gaia help?*

Slides for Alvio & Ivo

- When did the bar form?
  - Assembly of bar structure definitely younger than most stars in MW bar/bulge
  - > a few Gyr ago (top-bottom symmetry of X-shape, if too recently then many young stars will scattered/kicked into the high latitutes of the MW bulge)
  - Hints from its dynamical influence to the MW disk
    - e.g. phase-mixing feature in phase space, Antoja+ 18
- Is there a classical bulge ?
  - Bulge RRL: inward extension of the Galactic metal-poor stellar halo? (e.g. Minniti+ 1996, Perez-Villegas+ 2017, Andrea Kunder's talk)
- Is MW a typical barred galaxy?
  - Probably yes
- What fraction of bulge is in the bar?
  - Now: most (some may be captured by bar in the past)

IAUS 353

- 2019.7.1-5
- Dynamics focused
- 70-yr birthday of Jerry Sellwood
- See poster in hallway
- Website is working fine, but inaccessible from this hotel mysteriously

Thank you!