

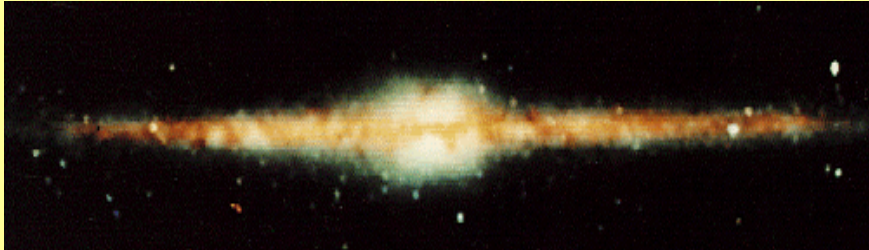
Bulge Formation Models

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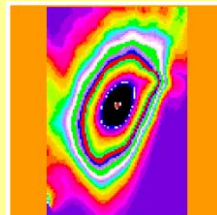
Talk given at 'CTIO: Fifty years of wide field studies in the southern hemisphere: resolved stellar populations in the Galactic bulge and the Magellanic clouds'

Based on work with Inma Martinez-Valpuesta, Kanak Saha



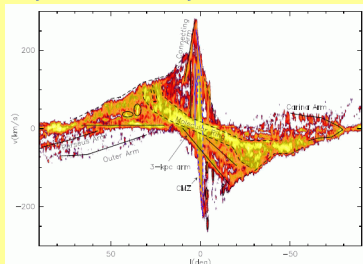
1. The Barred Galactic Bulge

COBE/DIRBE image of inner galaxy:
3D structure in small asymmetries



NIR starcounts from
2MASS, DENIS, etc:
*3D shape from
distance information*

lv-diagrams for atomic and molecular gas
response to barred potential



Artist picture
*of the face-on
Milky Way*
(R.Hurt)

De Vaucouleurs '64, Blitz+Spergel '91, Weiland+'94, Dwek+'95, Binney+'97, Bissantz+OG '02
Stanek+'94,'97, Lopez-Corredoira+'02,'05, Benjamin+'05, Cabrera-Lavers+'07,'08, McWilliam+'10, Gonzalez+'11
Peters '75, Binney, OG+'91, Englmaier+OG'99, Fux'99, Bissantz+'03, Rodriguez-Fernandez+Combes'08, Baba+'10 2

2. *Boxy bulge models from disk instability*

Evolution of isolated disk galaxy in N-body simulations

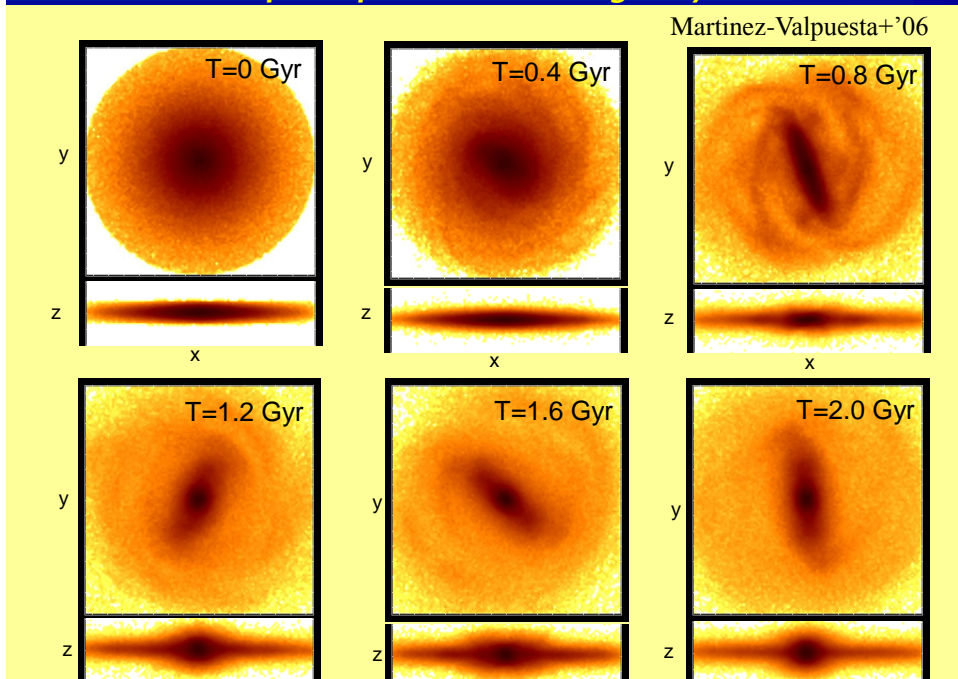
- unstable initial disk (no ILR barrier, cold, self-gravitating) forms a bar
- Bar quickly buckles, resulting in inner boxy bulge
- Bar may then lose angular momentum to the dark matter halo, grow in size, and eventually go through second buckling instability. This results in strongly X-shaped bulge.

e.g.:

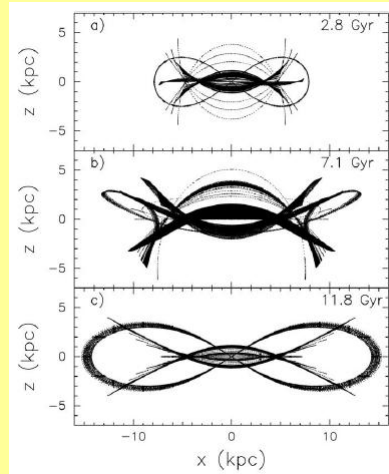
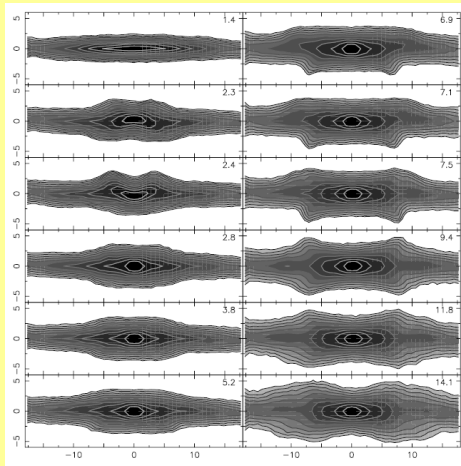
Sellwood '85, '89, Combes+'90, Raha+'91, Debattista+'00,'06, Athanassoula+'02,'03, Martinez-Valpuesta+'06

Disk galaxy evolution within hierarchical cosmology additionally involves mass accretion and outside perturbations. It is now just becoming possible to follow high-resolution, fully cosmological simulations of real disk galaxies from high z to now.

Evolution of a self-consistent disk galaxy simulation



Buckling instability and associated orbits



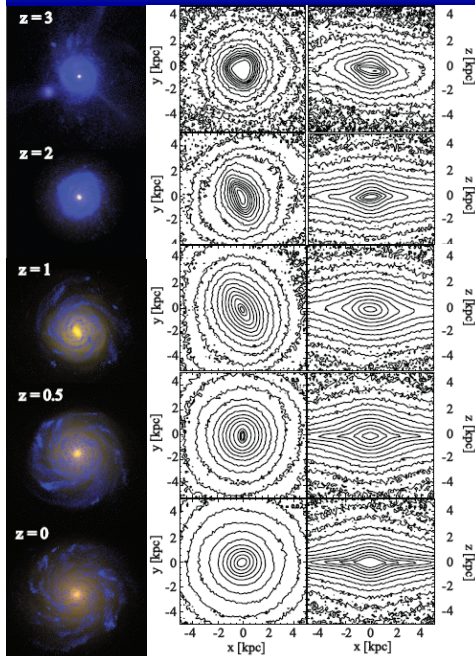
Evolution of N-body model for bar-unstable disk galaxy through first ($T \sim 2.4$ Gyr) and second ($T \sim 7$ Gyr) buckling instability.

Martinez-Valpuesta+'06

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Pseudobulge formation in cosmological simulation



High-resolution zoom-in simulation 'Eris' of 'quiet' halo of $\sim 8 \times 10^{11} M_{\text{sun}}$ from $z=90$ to $z=0$; $m_{\text{DM}} \sim 1 \times 10^5 M_{\text{sun}}$, $m_{\text{sph}} \sim 2 \times 10^4 M_{\text{sun}}$
Guedes +'12

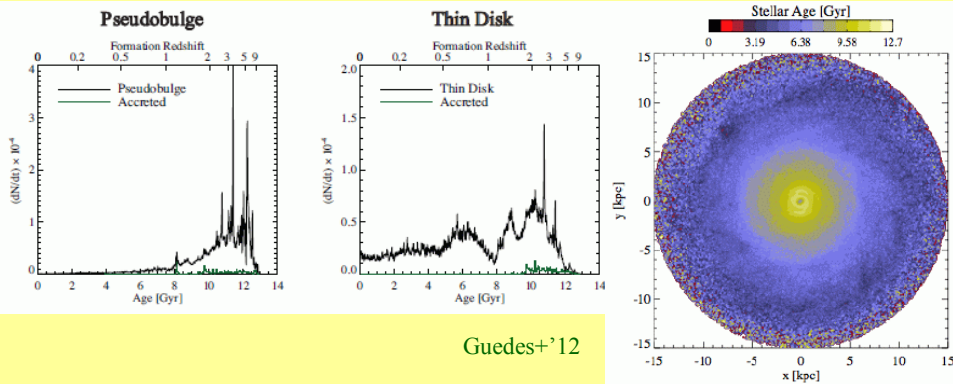
$z > 4$: a bar forms as soon as the disk forms
 $z \sim 3$: several minor mergers destroy the bar
 $z \sim 2$: the bar reforms
 $z < 1$: after another minor merger, the bar weakens steadily
 $z = 0$: negligible bar

Slightly boxy isodensities only at $z=1$; the pseudobulge in this simulation looks mostly like a dissolved 2d bar.

Important point: pseudobulge forms mostly at high-redshift through disk instabilities and minor mergers, on dynamical, not secular time-scales.
Okamoto+'13

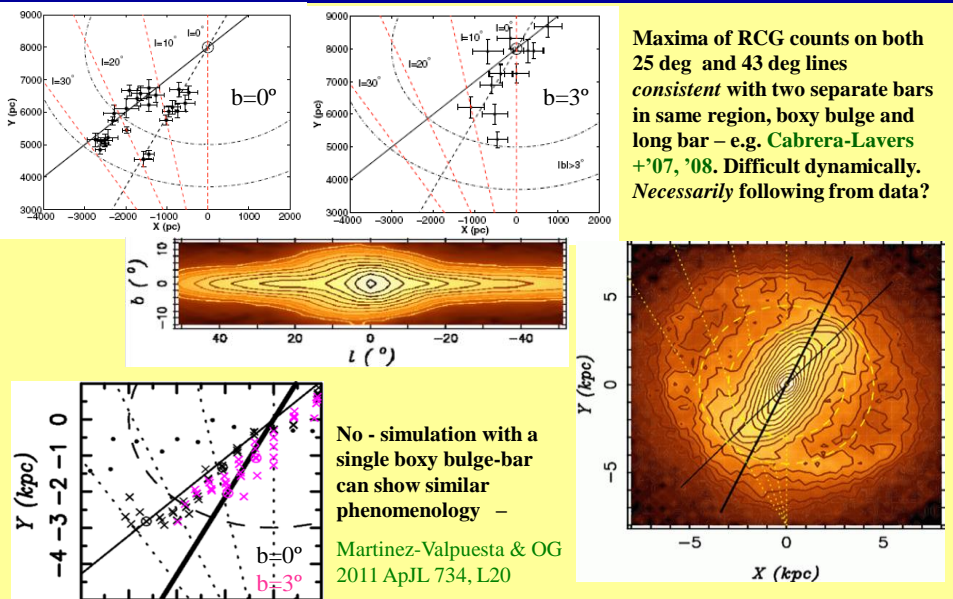
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Old pseudo-bulge formed rapidly



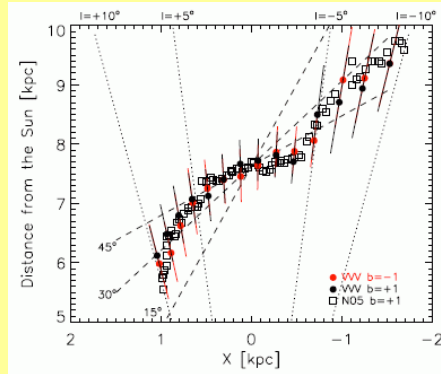
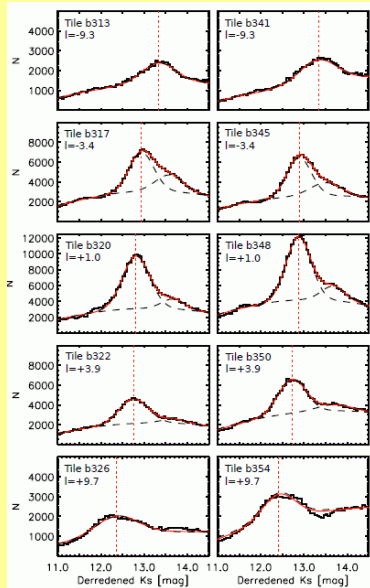
- The pseudobulge is defined as particles inside $R < 2$ kpc and ang.mom. < 0.8 of circular orbit.
 - Most of these pseudobulge particles formed 10-12 Gyr ago, while the disk has a much more uniform formation history.
 - Continuum in mean age from center to outside → pseudobulge is the early, low angular momentum part of the disk which grows from inside out.
 - Since no boxy bulge, not a model for Milky Way but illustrates early formation. Secular evolution simulations of isolated disks neglect the cosmological growth and perturbations.
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The "Long Bar": boxy bulge and misaligned bar?



No separate long bar needed

Inner Galactic bulge traced by VVV

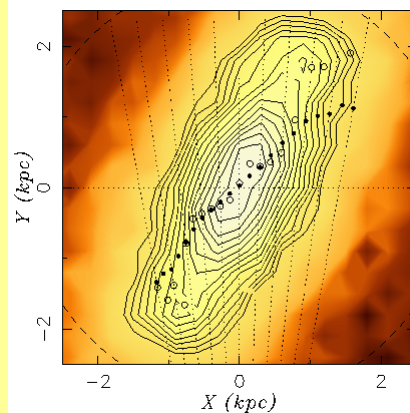
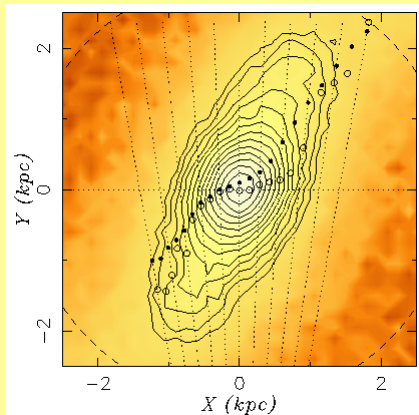


RC magnitude distributions in $l, b = \pm 1^\circ$

“Longitude profiles” (max mag vs l) show structural change within $|\Delta l| \sim 4^\circ$, confirming Nishiyama+’05.

Gonzalez+11b A&A, 534, L14

Milky Way model face-on



Gerhard & IMV ‘12

Isodensity contours rounder and density profile steeper in central 700pc.

Causes flattening of longitude profiles in inner few degrees.

Effect predicted to disappear at higher latitudes where densities more elongated.

Note the volume effect (mag vs density maxima).

No classical bulge or nuclear bar needed to explain these structural properties

The Split Red Clump

Red clump stars from 2MASS show two maxima in their apparent magnitude (distance) distributions, for lines-of-sight near the bulge minor axis and $b > 4$ deg

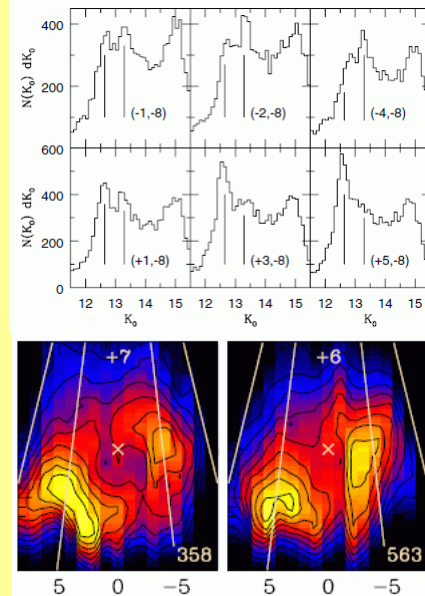
McWilliam+Zoccali'10

Similar results Nataf+'10, Ness+'12

Two peaks seen normalized density slices from 2MASS

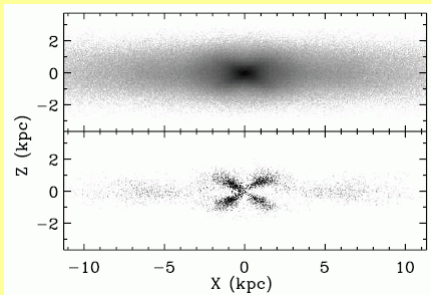
Saito+'11

Explanation: X-shape in barred bulge



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X-shape in boxy bulge



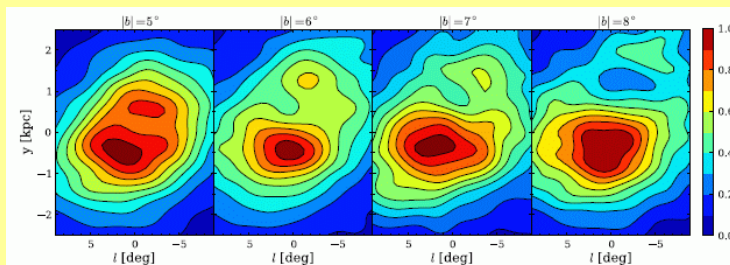
Barred potentials support 2:1:2 vertically symmetric, banana/anti-banana x1-orbits

Visible as X-shapes in N-body models after subtracting mean density (Li+Shen'12)

Densities in vertical slices show double maxima

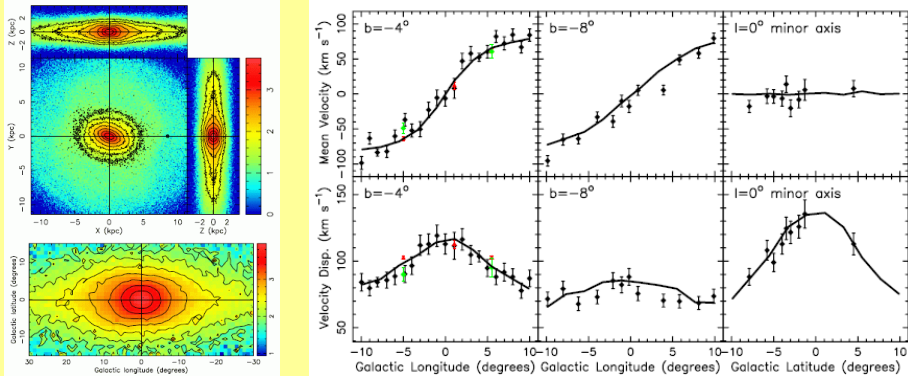
(Ness+'12)

Similar as in 2MASS data (Saito+'11)



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Barred stellar bulge explains all the stellar kinematics from the BRAVA survey

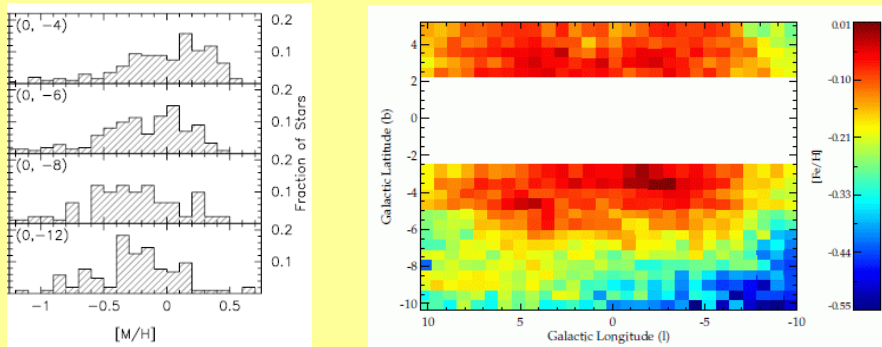


- The BRAVA data for M-giant stars (Howard⁺08) show nearly cylindrical rotation which is well fit by a boxy bulge formed from the disk (Shen⁺10).
- Models from similar simulations with a preexisting classical bulge of 8% (>15%) the *disk* mass worsen the fit (are considered to be ruled out).
- Hence Shen⁺10 conclude the MW originated from an essentially pure disk galaxy.

Is that it?

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Bulge Metallicity Gradients – A Classical Bulge?



- Minor axis metallicity distributions from Zoccali⁺08 and Johnson⁺11 (-8 deg) show clear vertical gradient (loss of metal-rich stars at high b)
- Bulge metallicity map constructed from VVV data (Gonzalez⁺13) indicates comparable radial gradient
- Generally been interpreted as signature of classical bulge, based on merger or collapse models in which the gradient is set up by on-going star formation as the gas settles to the center (e.g., Samland+OG'03). Also, bars tend to mix stars from different radii, erasing gradients (Friedli⁺94)

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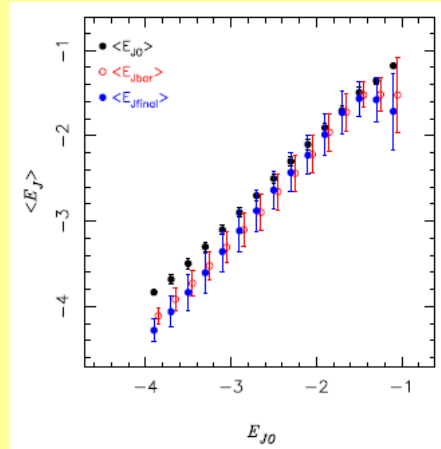
Metallicity Gradients Through Disk Instability

The Galactic bulge is mostly very old (>10 Gyr), therefore the chemical structure of the early disk back then could have been different from that of the Galactic disk today.

In a rapidly evolving disk, radial metallicity gradients are not erased by bar and buckling instabilities:

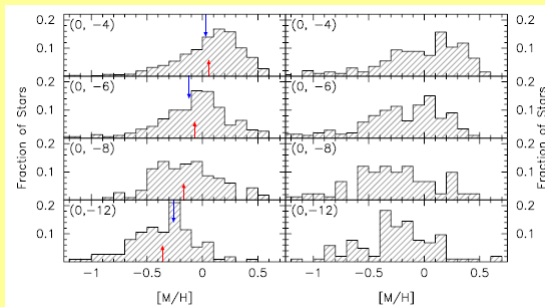
(Jacobi) binding energies scattered by \ll initial range

Martinez-Valpuesta+OG'13

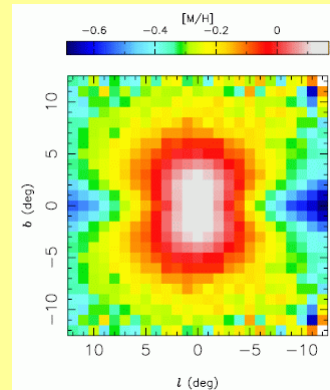


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Metallicity Gradients Through Disk Instability



Final metallicity gradient in the bulge is similar to initial radial gradient in the disk – therefore a pure disk evolution model can be found which approximately reproduces MW bulge metallicities (gradients and longitudinal asymmetries). Metallicity gradients per se do not imply a classical bulge.



Differences to VVV map hint at additional evolutionary processes

Martinez-Valpuesta+OG'13

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3. Classical and composite bulges

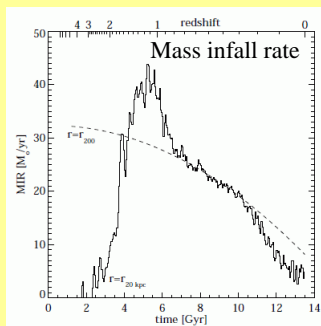
- Classical bulge with mass \sim disk mass often forms in cosmological disk galaxy simulations from (not so) minor mergers. The MW does not have such a bulge.
- However, still possible that the MW contains a composite bulge (lower mass classical plus boxy bulge)
- Such composite bulges have been found in
 - Dissipative collapse models
 - Recent very high-resolution cosmological simulations of disk galaxies

Ortwin Gerhard: Bulge formation models

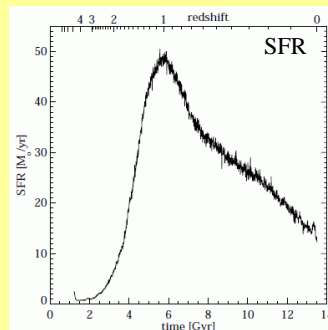
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Dissipative collapse model

- Samland & Gerhard '03 model for dissipative formation of large disk galaxy in $\sim 2 \times 10^{12} M_{\text{sun}}$, spinning ($\lambda=0.05$), DM halo, with accretion history taken from VIRGO –GIF cosmological simulations. Two-phase gas model; foll'g 'Fe', 'Mg'.
- Galaxy formed from inside-out. SFR follows accretion history, with rapid early peak and slower late evolution.
- Resulting bulge consists of at least two stellar populations, one formed in early collapse, and a second formed later in the bar.

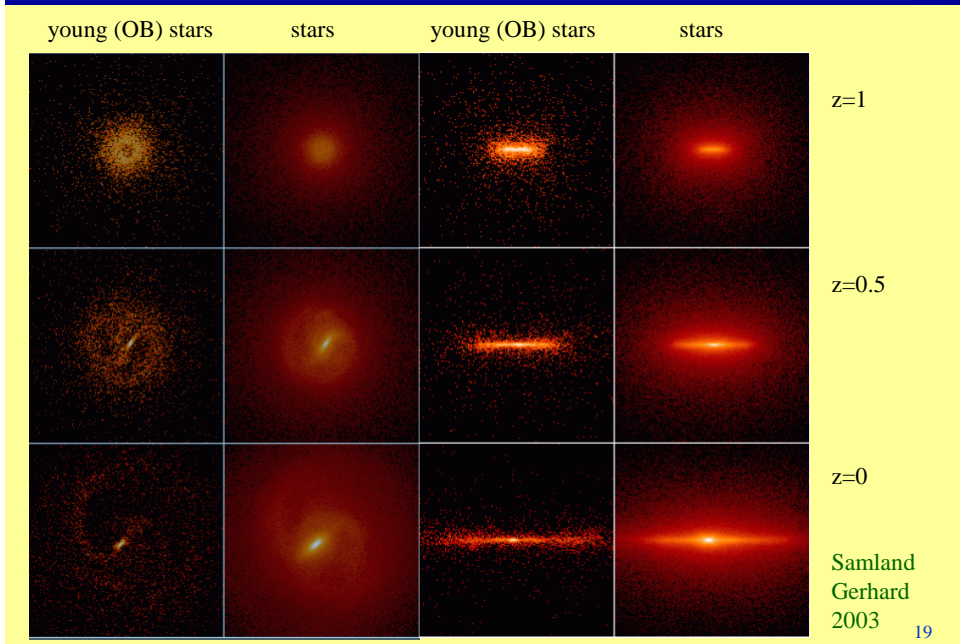


Ortwin Gerhard: Bulge formation models

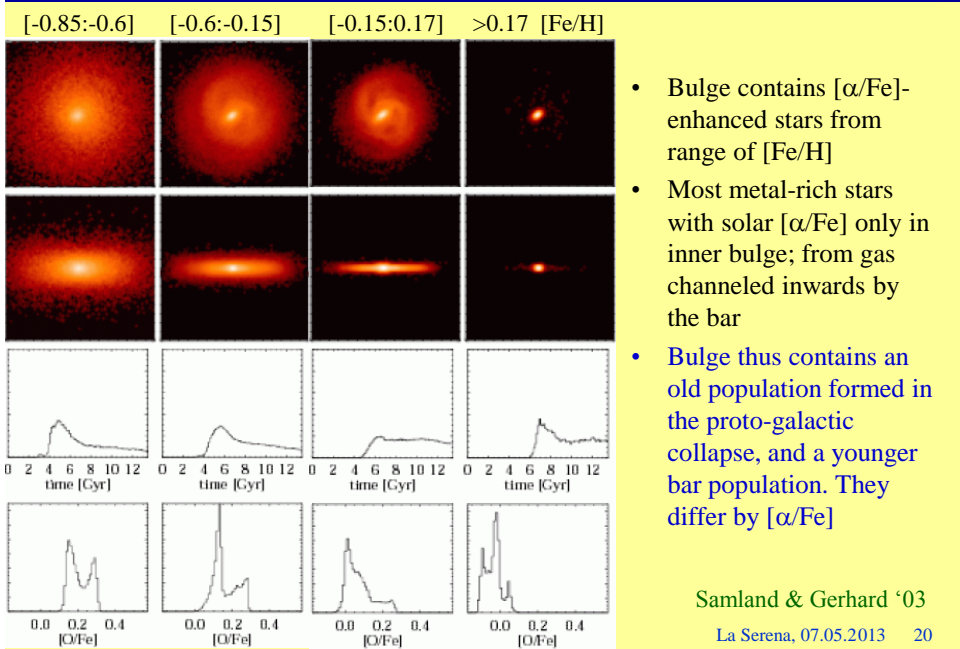


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Build-up of halo-bulge and disk and bar

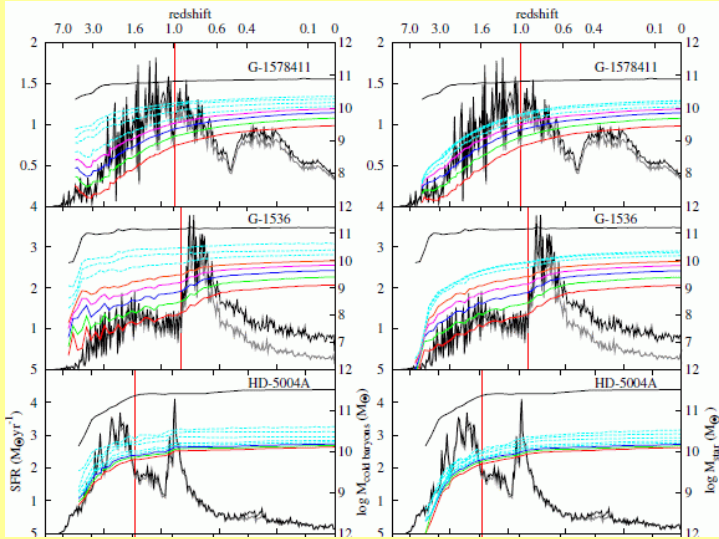


Stars selected by metallicity



Modern cosmological disk galaxy simulations

Comparison of bulges formed in 3/5 recent simulations
 Mass accretion rate star formation rate



- Simulations with diff. codes and feedback models

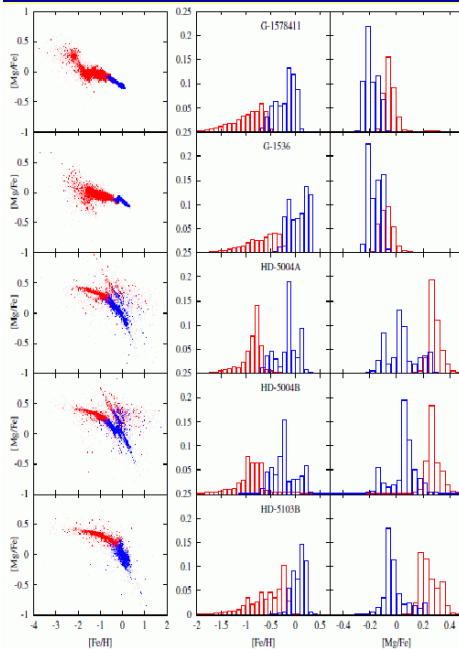
generally

- SFR follows dM
- early starburst collapse phase – later phase with lower SFR driven by disk instabilities and minor mergers
- Hence old and younger stellar population (red vertical line)
 Obreja+’13

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Metallicity and [Mg/Fe] distributions



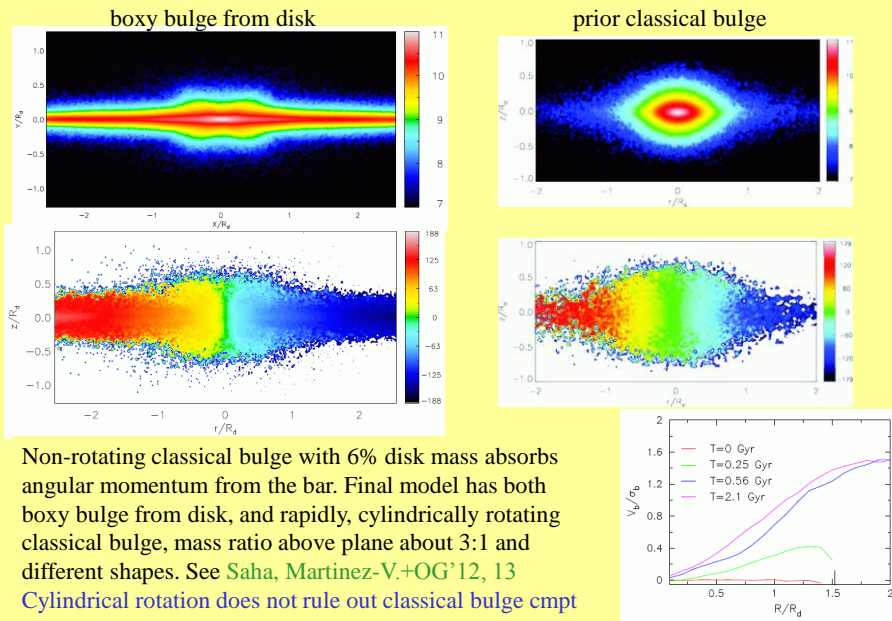
All 5 simulated bulges show similar patterns, although differences in detail:

- Mg vs Fe (left) shows characteristic bend from old merger/collapse → younger bar/disk population
- Old population more metal poor and [Mg/Fe] enhanced, vice-versa for younger population (SNII vs SNIa and collapse)
- Most of the old population forms in disjoint places along filaments at high redshift
- Can associate the rapid phase with a classical bulge, and the late phase with pseudobulge. This classical bulge is different from that formed by late major merger.
- If so, all 5 simulations show both components, with varying mass ratio.

Obreja+’13

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Small classical bulges spun up by the bar can develop cylindrical rotation



Summary – What Next

- Much of the structure and dynamics of the MW bulge can be explained by a boxy bulge made from the disk through bar and buckling instabilities. No convincing evidence yet for a classical bulge in the MW.
- First cosmological simulations of realistic disk galaxies (vs idealized N-body systems) now feasible. Feedback-sensitive but take into account accretion and minor mergers. They suggest that inner disk and bulge could remain dominated by old stars until $z=0$.
- Many of these predict two bulge stellar populations, like dissipative collapse model. One made in a rapid early merger-collapse phase, the other made in later phases through secular processes in the growing disk.
- Is there room for a classical bulge in the MW? Need to look in chemo-dynamics, as it may have been spun-up by the bar.