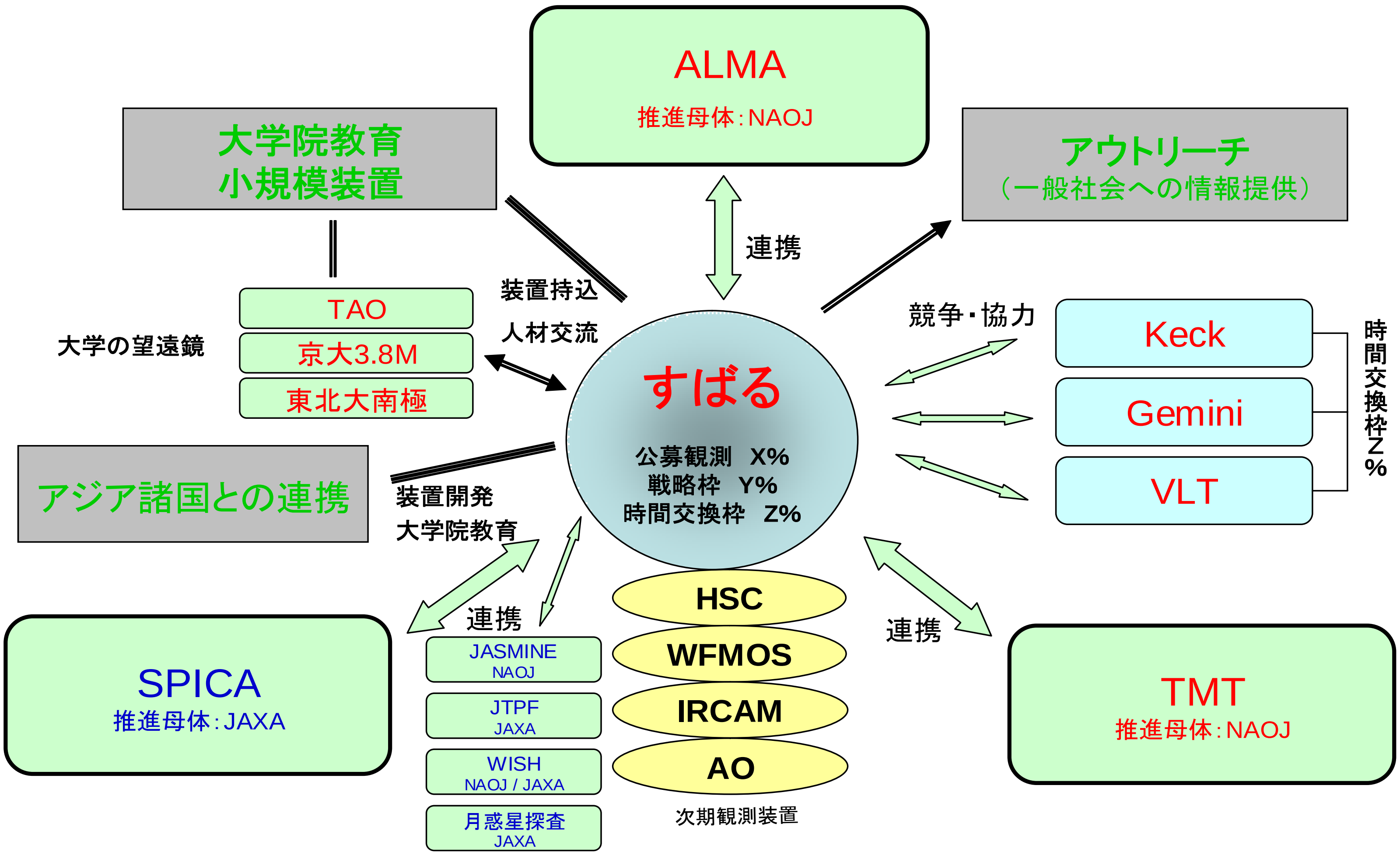
# Galactic Archaeology wishy-washy

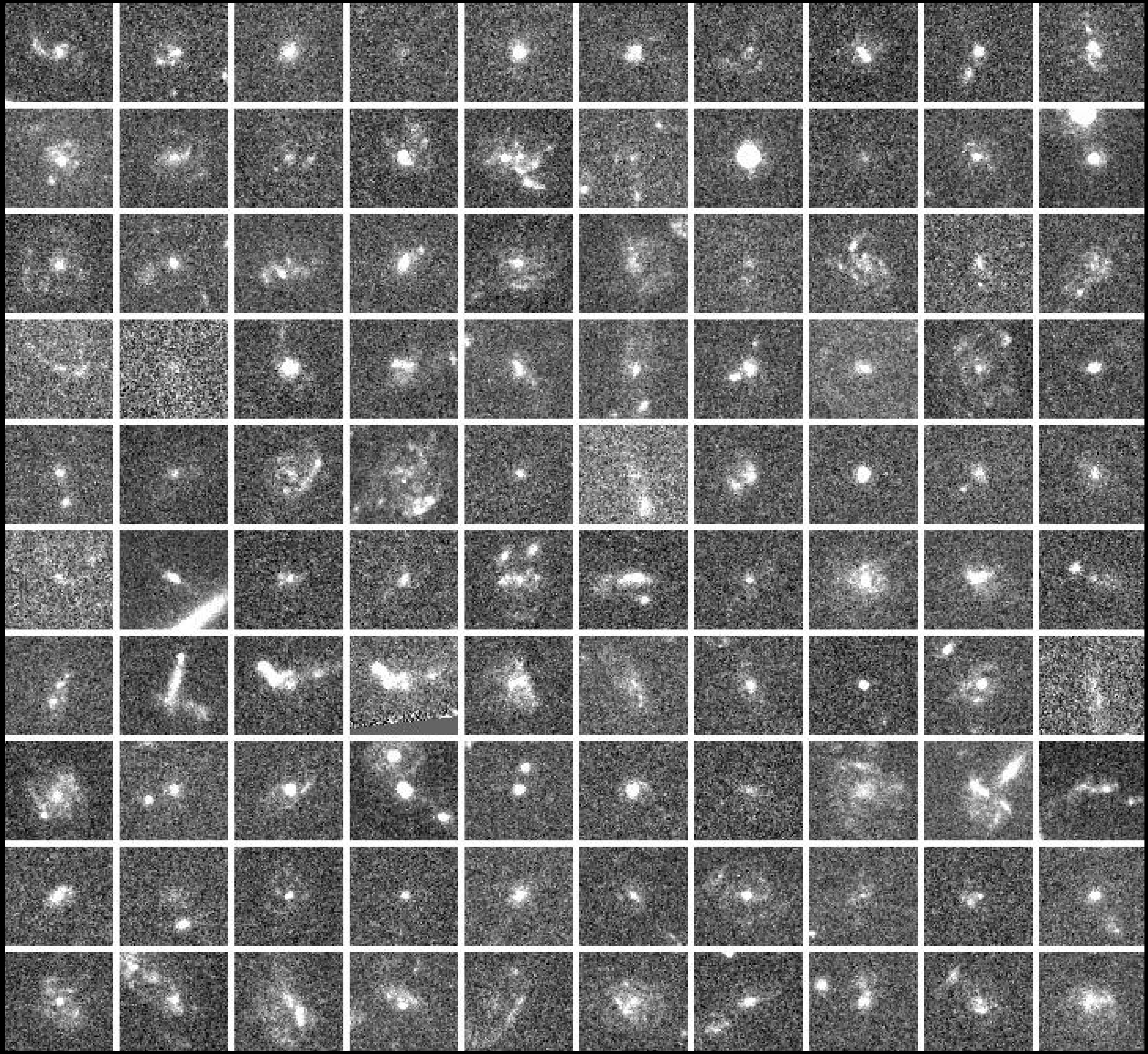
Nobuo Arimoto
NAOJ

光赤外専門委員会への提言　　2009.3.9

# --2020年へのすばるの戦略 "天・地・人"--

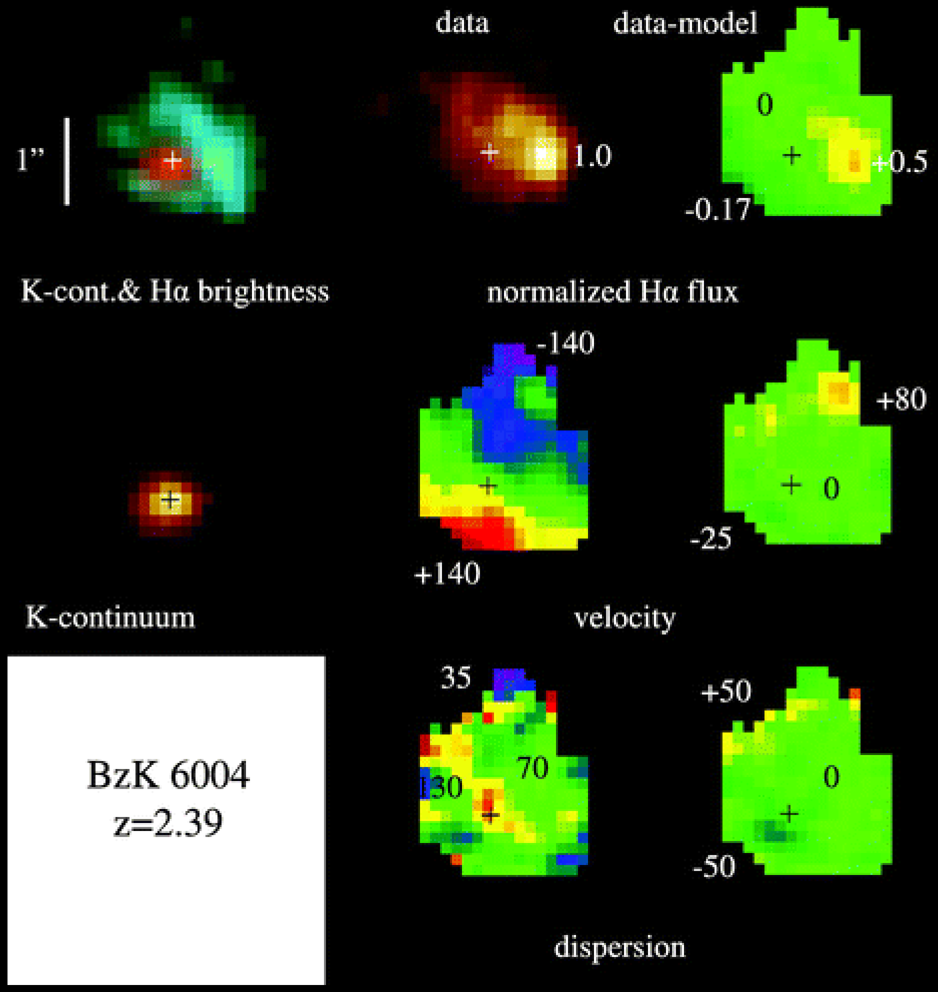
すばる小委員会





# Metabolic sBzK Galaxies

**Genzel et al. (2008, ApJ 687, 59)**



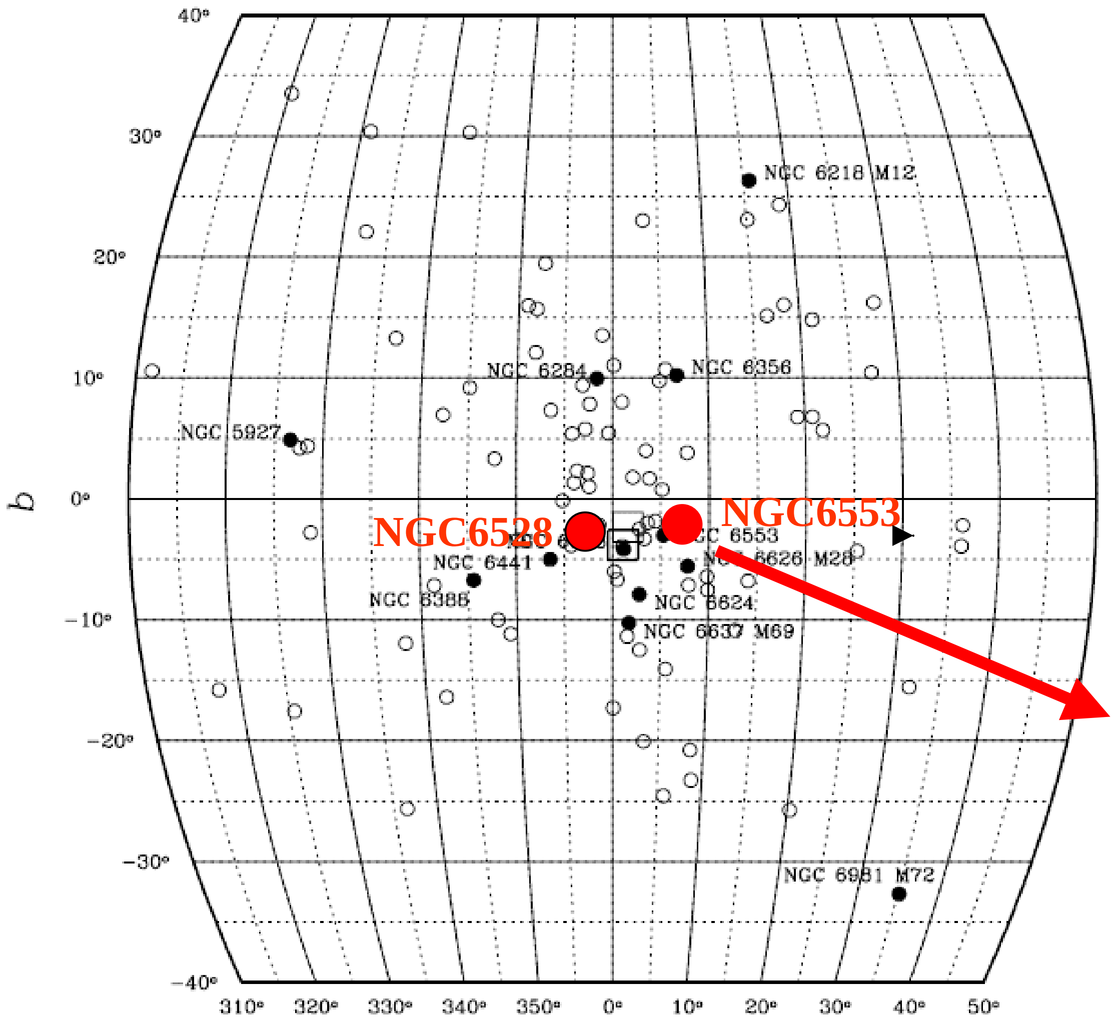

**(D3a6004-3482, z=2.387, Kong et al. 2006)**

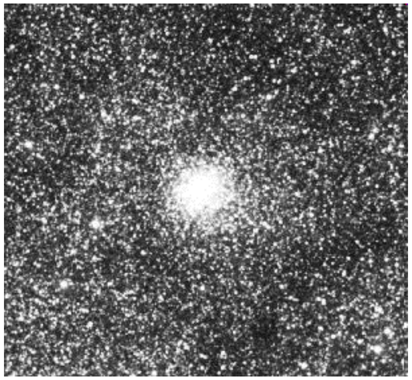
# Salient Features of Metabolic Syndrome

- Rapidly forming, very gas-rich disks will become violently and globally unstable into giant star forming clumps.
- Once fragmentation sets in, the disk evolves rapidly during a short-lived (0.4-1 Gyr) “clump phase”.
- As a result of efficient dynamical friction of the clumps against the background of the rest of the disk, the clumps spiral into the center and form a central bulge and surrounding smooth exponential stellar disk.
- However, the resultant bulge and thick disk stars tend toward a broad range of stellar ages (Noguchi 1999, Immeli et al. 2004, Bournaud et al. 2007).

**Is a Galactic bulge really old?**

# Galactic Bulge Globular Clusters



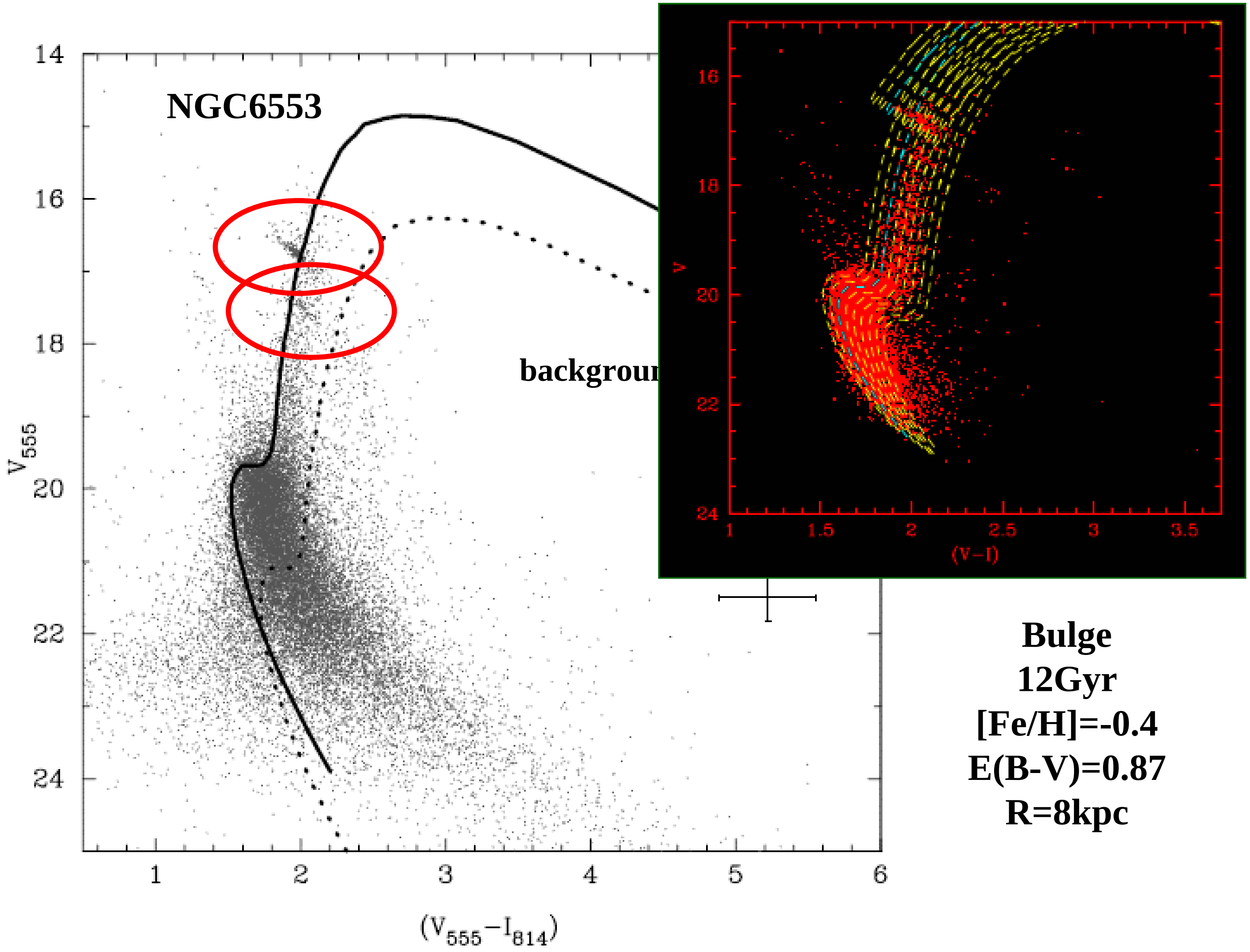



**Puzia et al. (2002) A&A 395, 45**

# Photometry of NGC 6553 (HST)

**Beaulieu et al. (2001) AJ 121, 2618**

**NGC6553**
**12Gyr**
**[Fe/H]=-0.4**
**E(B-V)=0.7**
**$(m\text{-}M)_0$=13.6**




**Bulge**
**12Gyr**
**[Fe/H]=-0.4**
**E(B-V)=0.87**
**R=8kpc**

# Ages of Bulge GCs

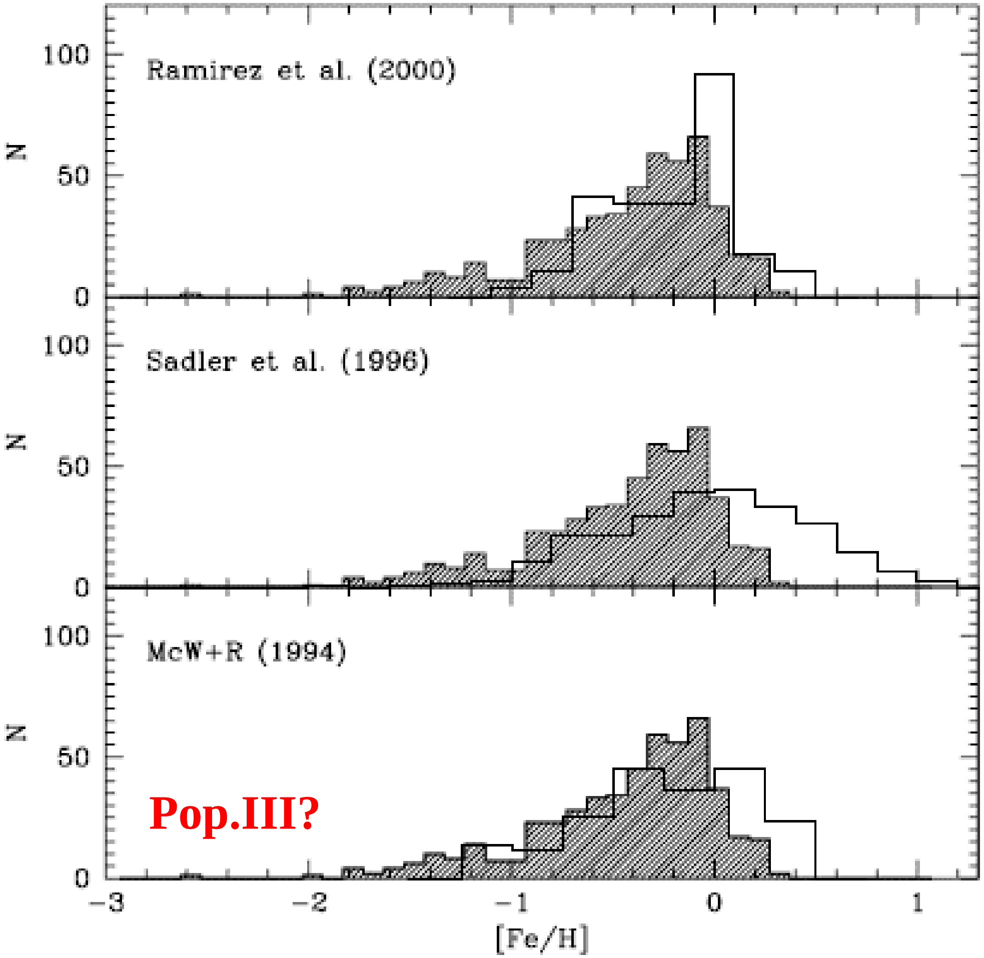
| | | | |
|---|---|---|---|
| NGC6553 | [Fe/H]=0.0 | 12 Gyr | Sagar et al. (1999) |
| | [Fe/H]=0.0 | 12 Gyr | Zoccali et al. (2001) |
| | [Fe/H]=-0.4 | 12 Gyr | Beulieu et al. (2001) |
| NGC6528 | [Fe/H]=0.0 | 13.2 Gyr | Richtler et al. (1998) |
| NGC6624 | [Fe/H]=-0.70 | 14 Gyr | Heasley et al. (2000) |
| NGC6637 | [Fe/H]=-0.70 | 14 Gyr | Heasley et al. (2000) |
| NGC6496 | [Fe/H]=-0.5 | 10 Gyr | Pulone et al. (2003) |
| NGC6352 | [Fe/H]=-0.5 | 10 Gyr | Pulone et al. (2003) |
| 47 Tuc | [Fe/H]=-0.70 | 14 Gyr | Heasley et al. (2000) |

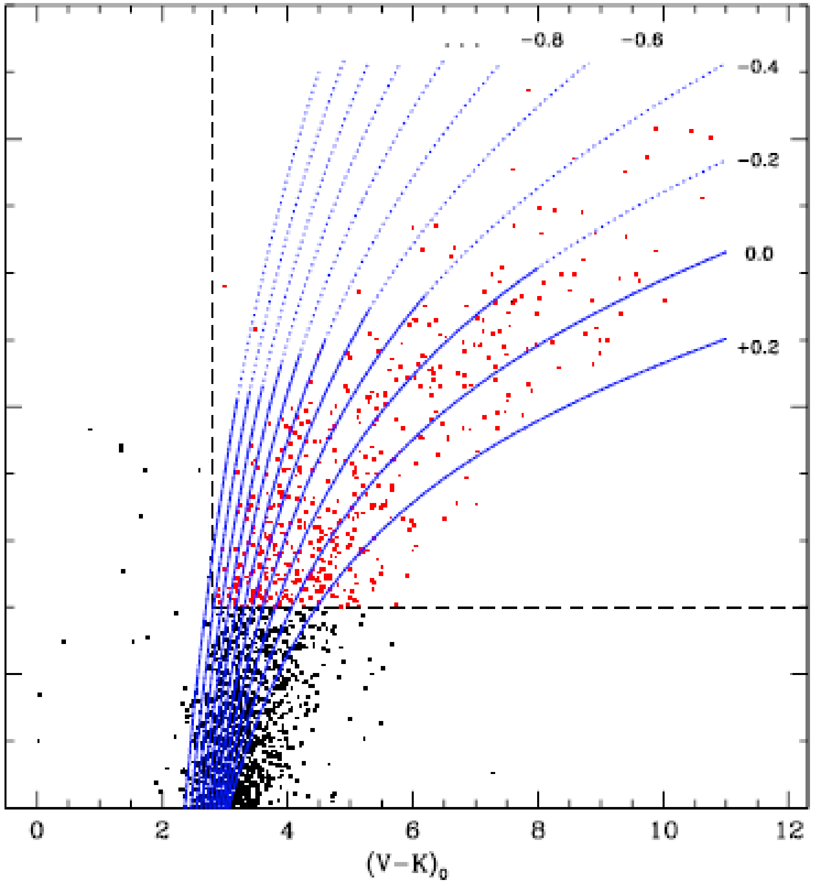
**The luminosity difference between the horizontal branch and the main-sequence turnoff is an effective way of measuring the relative ages (Iben & Renzini 1984).**
**The luminosity difference V(TO-HB) of NGC 6528 and NGC 6553 is at least as large as that of 47 Tuc, which ensures that the two bulge clusters are as old as the metal-poor clusters in the halo, within an uncertainty of a few Gyr.**

**Guarnieri, Renzini & Ortolani (1997) ApJ 477, L21**

# Metallicity Distributions of the Galactic Bulge

**Zoccali et al. (2003) A&A 399, 931**

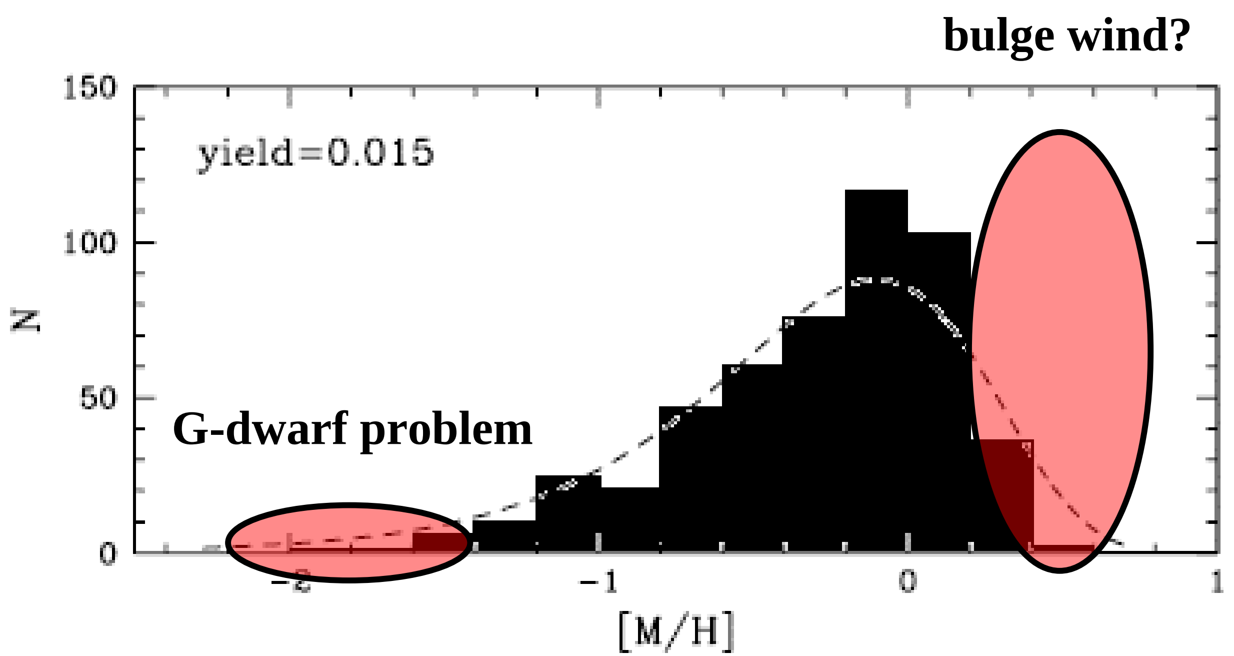



**Photometric Metallicity**

# Metallicity Distributions of the Galactic Bulge

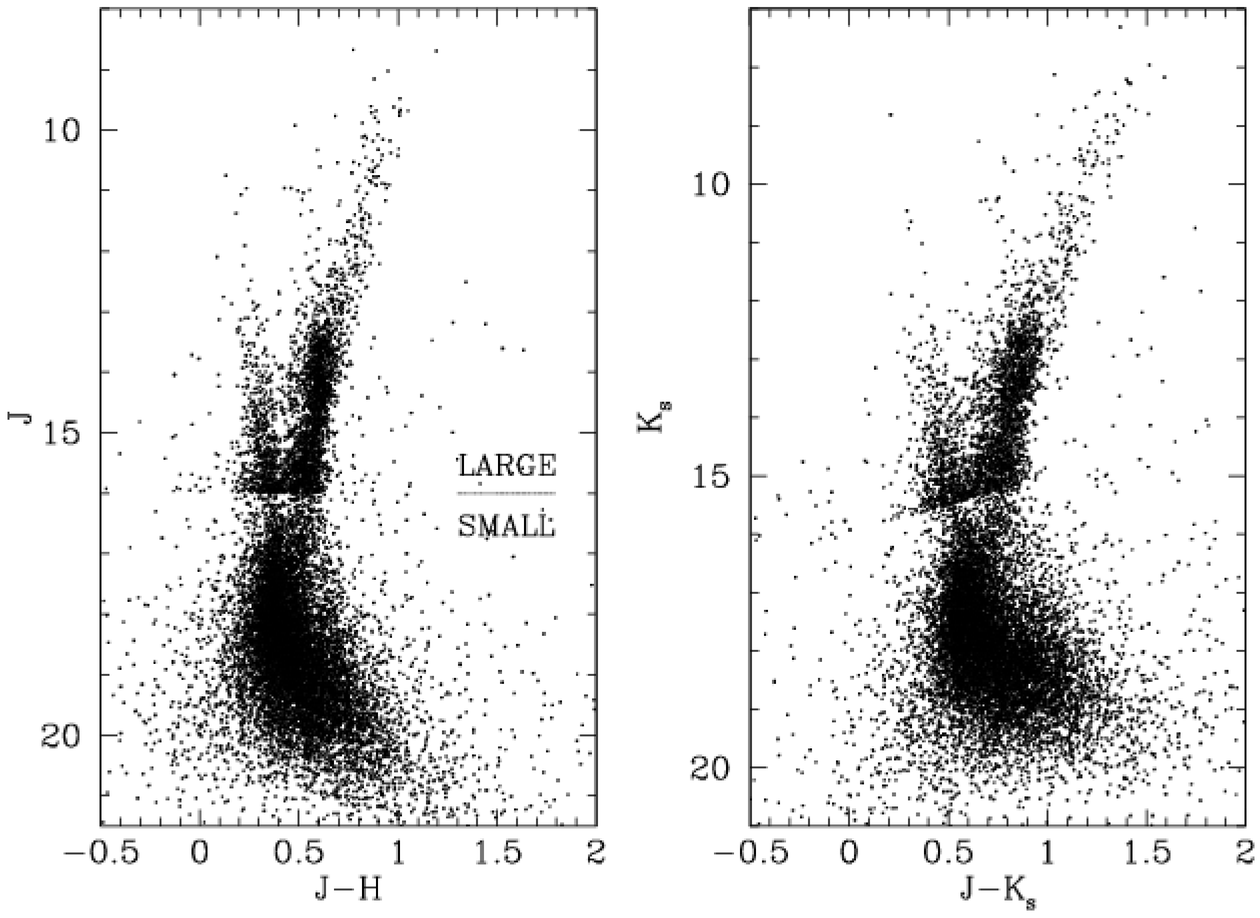
**Zoccali et al. (2003) A&A 399, 931**




**The general shape of the abundance distribution is in fairly good agreement with the Simple Model. The moderate shortage of metal poor stars compared to the Simple Model suggests a G-dwarf problem. The sharp high metallicity cutoff suggests that star formation did not proceed to complete gas consumption (bulge wind?).**

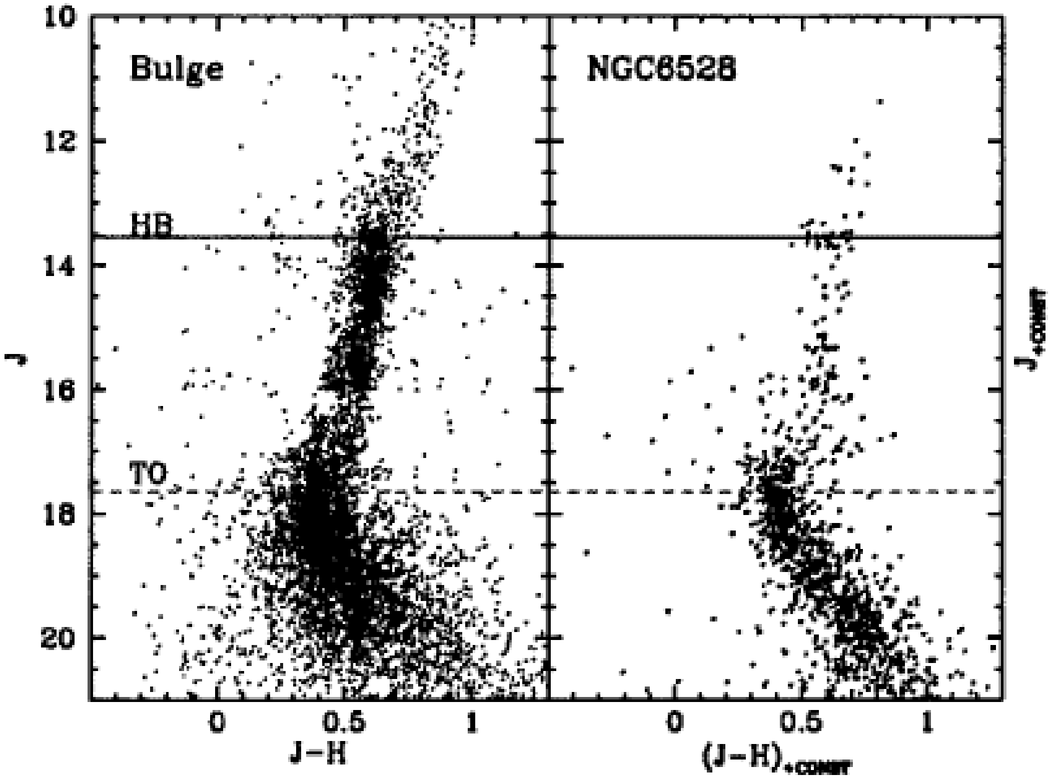
# The Age of the Galactic Bulge

**Zoccali et al. (2003) A&A 399, 931**



# The Age of the Galactic Bulge

**Zoccali et al. (2003) A&A 399, 931**

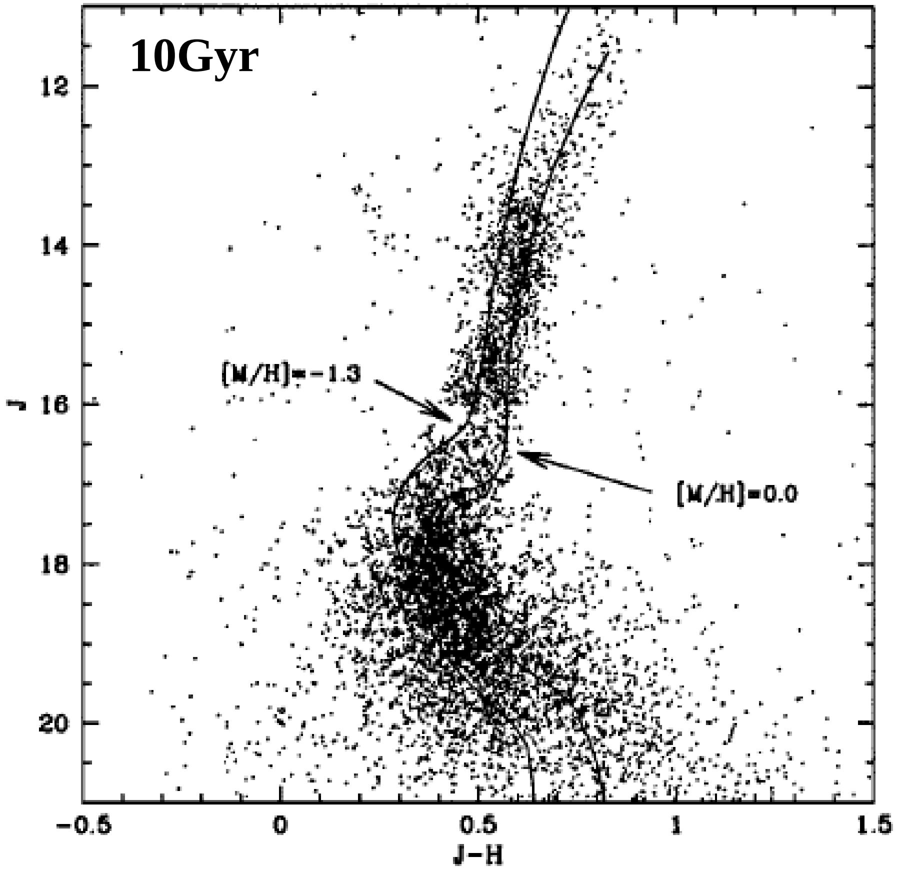


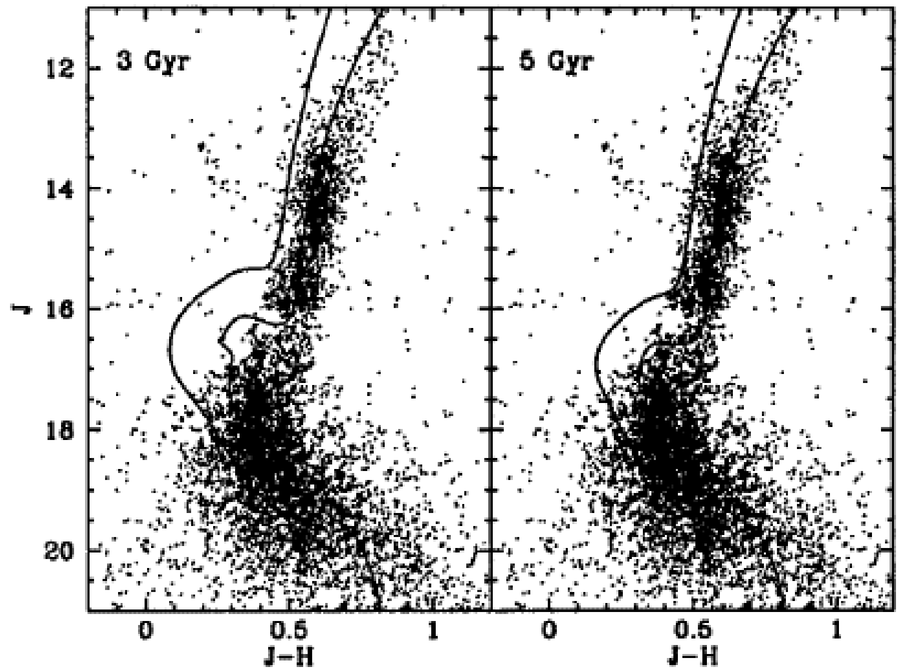

**Δ J(TO-HB)**

**The magnitude difference between the HB clump and the turnoff is virtually identical, ie., the bulk of the bulge stars and NGC6528, NGC6553 are coeval.**

# The Age of the Galactic Bulge

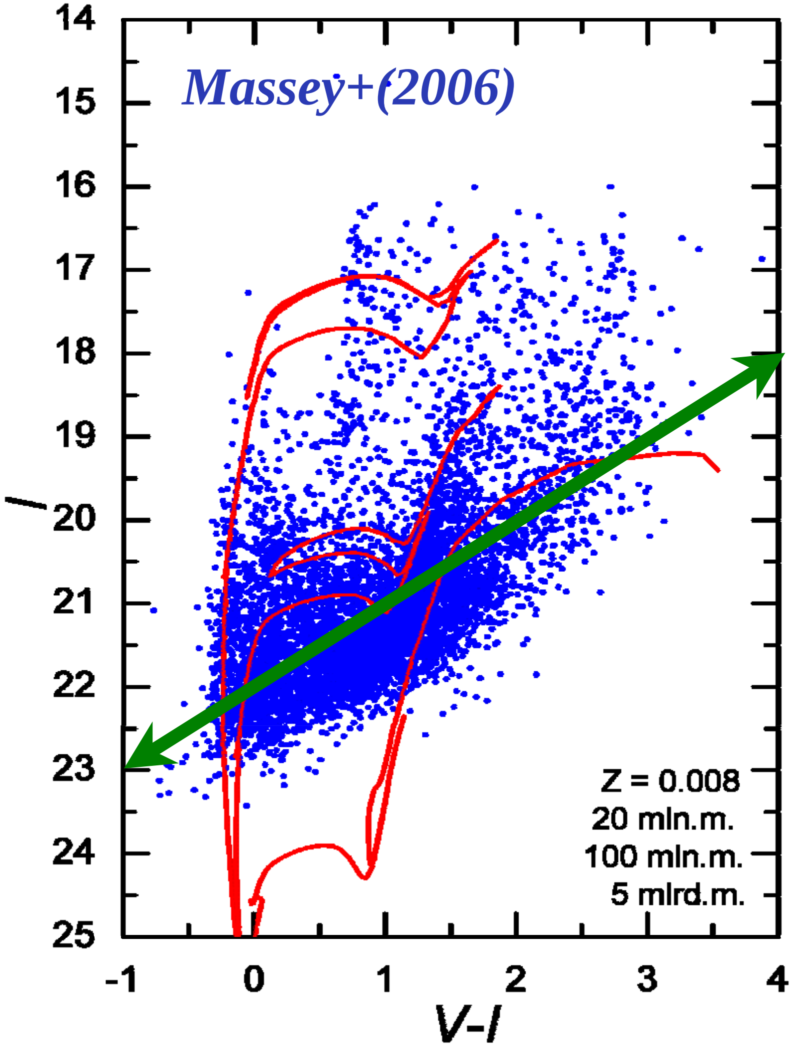
## Zoccali et al. (2003) A&A 399, 931

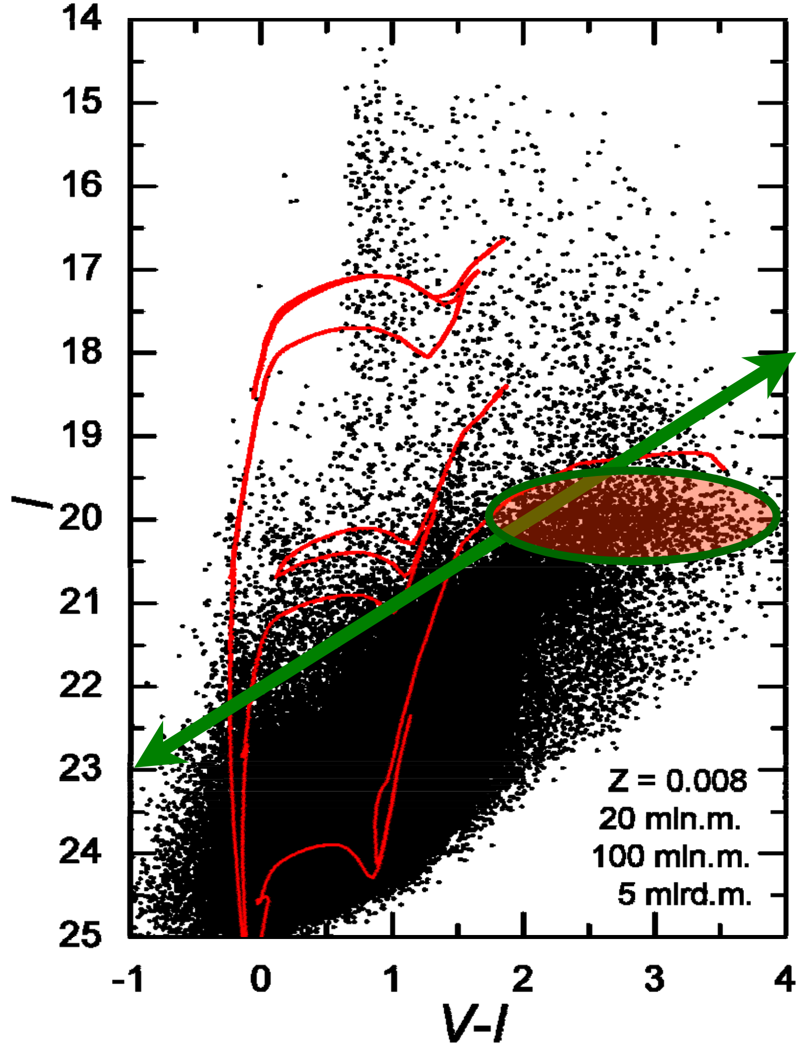



**Wider dispersion in the CMD can be reproduced with 10 Gyr isochrones spanning the full metallicity range of the bulge MDF, while significantly younger ages can be excluded.**

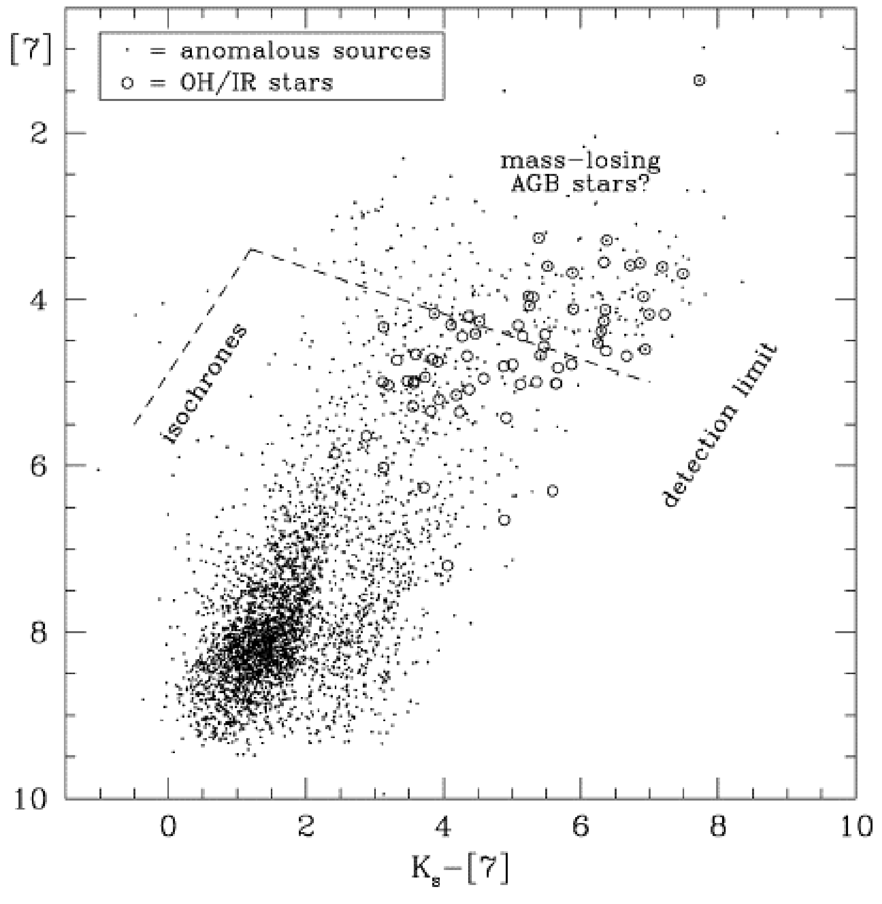
# Intermediate Age Stars (M33)



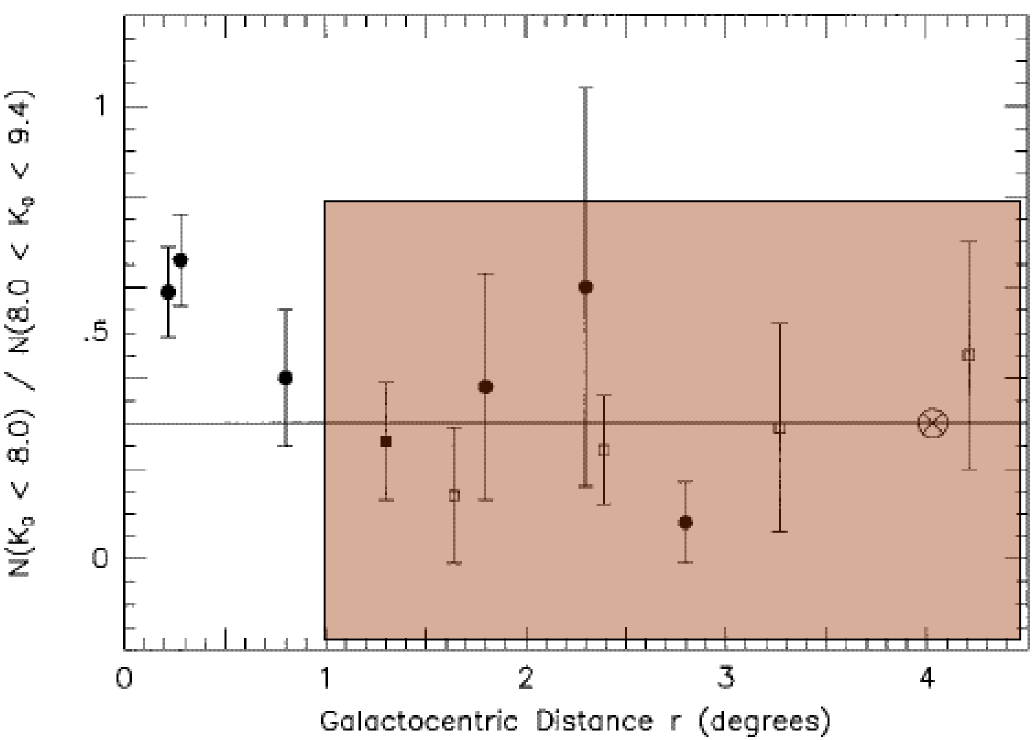
# Young Stars in the Galactic Bulge

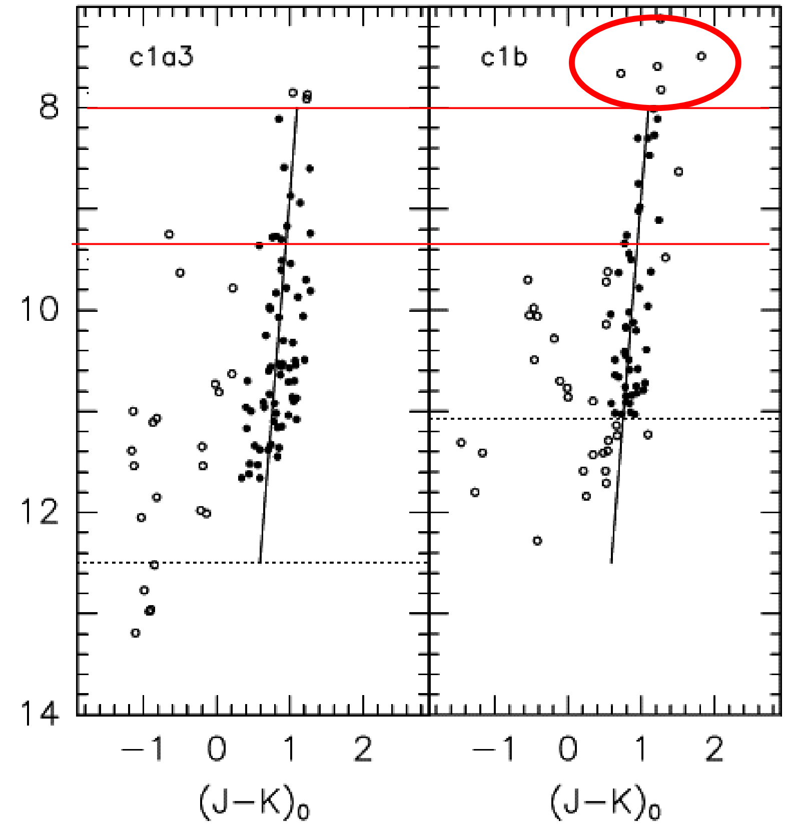
**van Loon et al. (2003) MNRAS 338, 857**



# Young Stars in the Galactic Bulge

## Frogel, Tiede & Kuchinski (1999) AJ 117, 2296

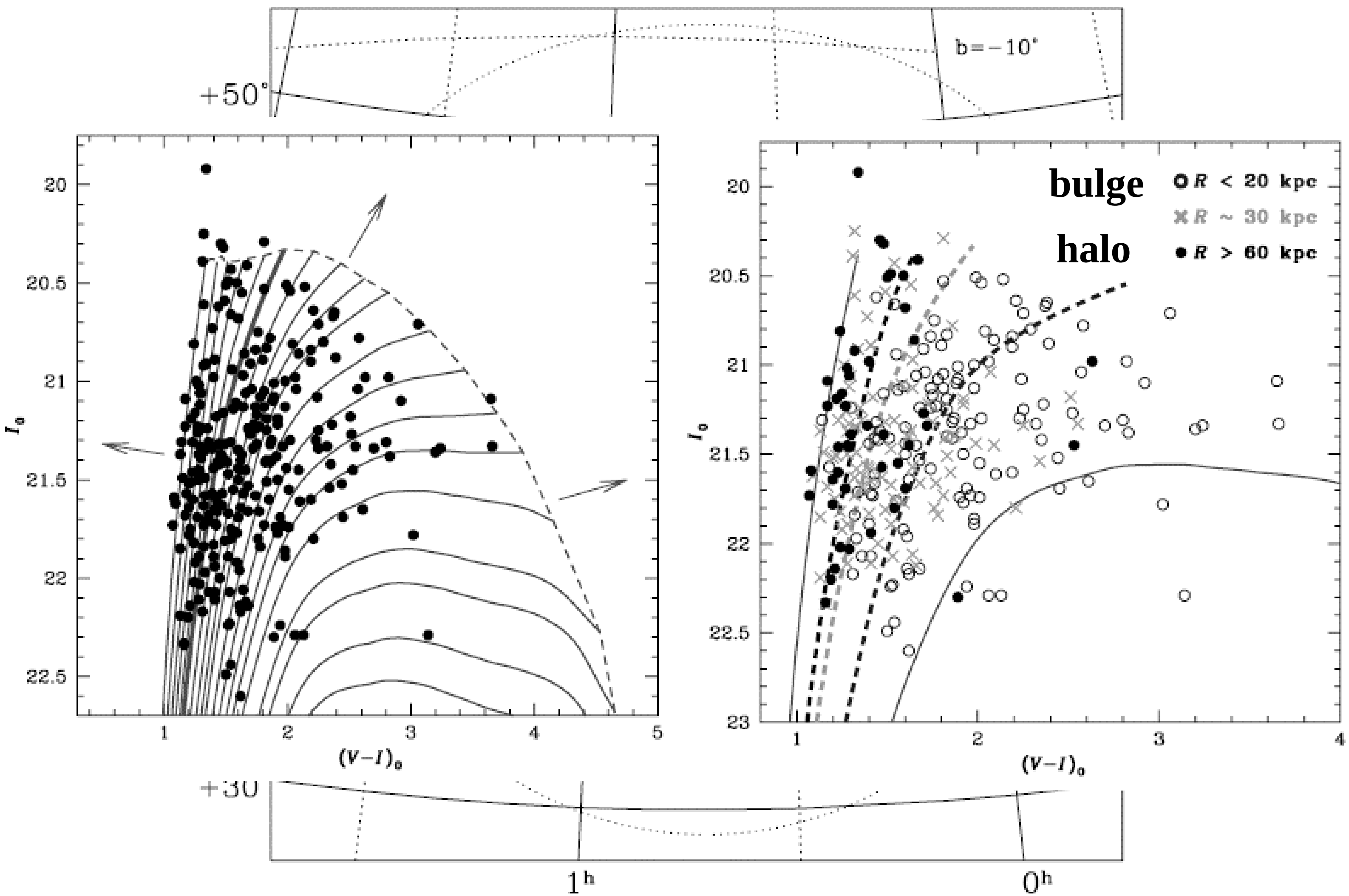



**The young component of the stellar population observed near the Galactic center declines in density much more quickly than the overall bulge population and is undetectable beyond 1 degree from the Galactic center.**

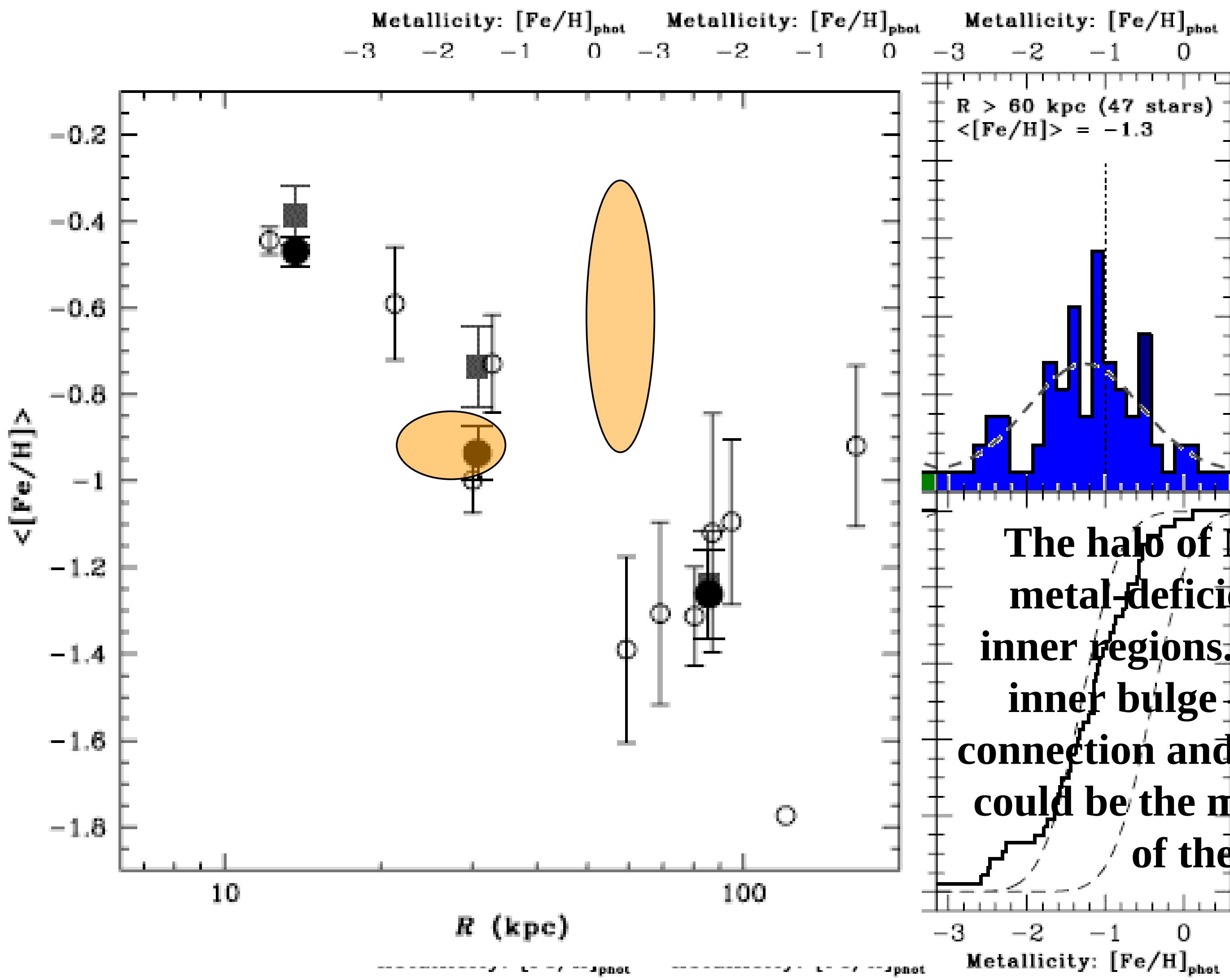
# Halo-Bulge Metallicity of M31 (Keck)

**Kalirai et al. (2006) ApJ 648, 389**



# Halo-Bulge Metallicity of M31 (Keck)

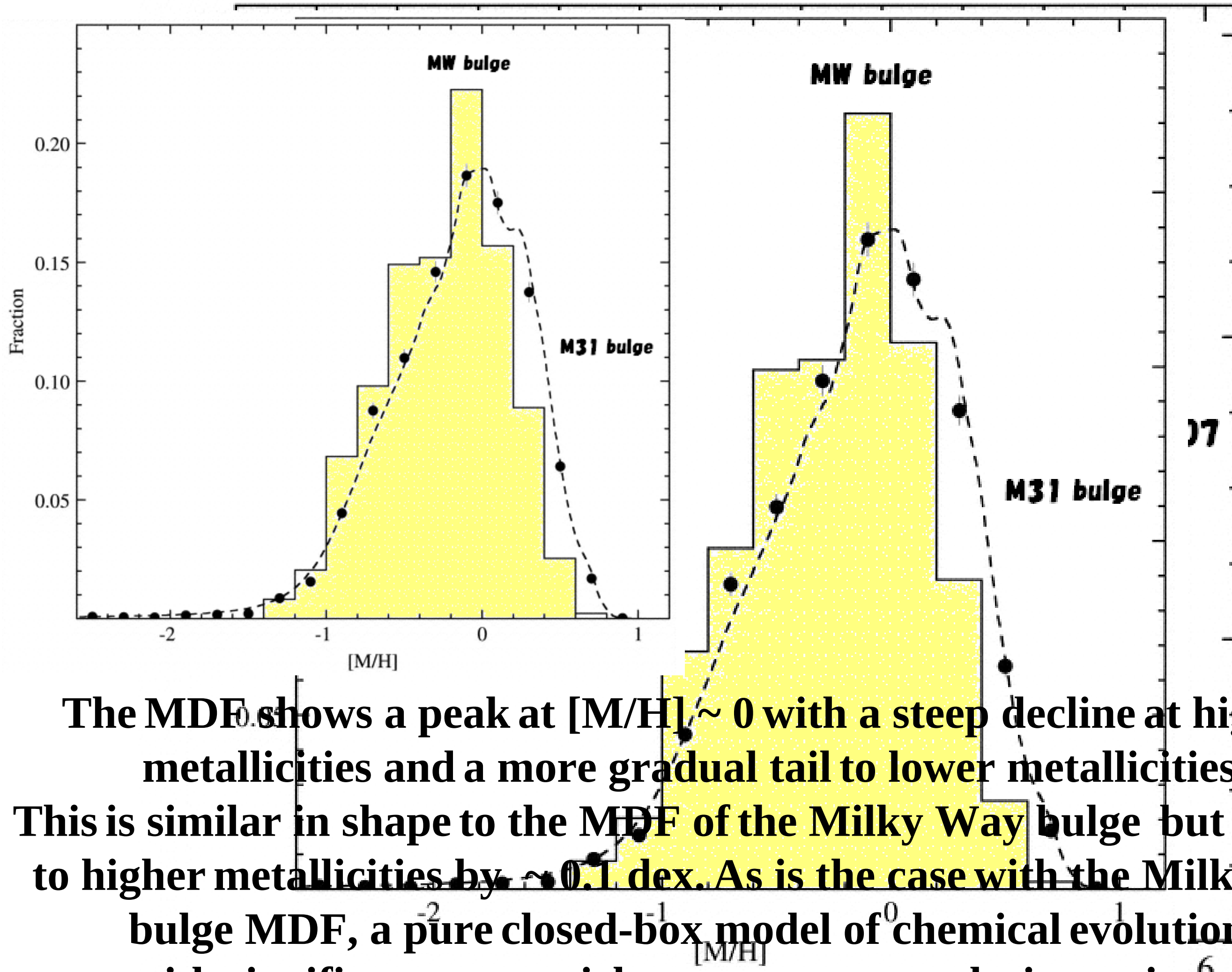
## Kalirai et al. (2006) ApJ 648, 389




**The halo of M31 is more metal-deficient than the inner regions. This suggests inner bulge – outer halo connection and the M31 bulge could be the most inner part of the halo.**

# Metallicity Distribution Function of M31 Bulge

**Sarajedini & Jablonka (2005) AJ 130, 1627**




**The MDF shows a peak at [M/H] ~ 0 with a steep decline at higher metallicities and a more gradual tail to lower metallicities. This is similar in shape to the MDF of the Milky Way bulge but shifted to higher metallicities by ~ 0.1 dex. As is the case with the Milky Way bulge MDF, a pure closed-box model of chemical evolution, even with significant pre-enrichment, appears to be inconsistent with the M31 bulge MDF.**

# Conclusions

- Galactic bulge GCs are virtually coeval and are as old as a halo cluster 47 Tuc (10-14 Gyr).
- Stellar population parameters (age, metallicity, [$\alpha$/Fe]) derived from line indices of bulge GCs are consistent with their CMDs and high dispersion spectroscopic (HDS) analyses.
- Line indices suggest that the Galactic bulge is as old as bulge GCs (10-14 Gyr) and metal-rich ([Fe/H]~-0.3, [M/H]~0, [$\alpha$/Fe]~0.2), which is fully consistent with resolved stellar population analyses and HDSs.
- Young bright AGB (OH/IR) stars exist in the Galactic bulge, but their spatial distribution decays rapidly and disappears beyond 1 degree from the Galaxy centre.
- Age, MDF and [$\alpha$/Fe] of the M31 bulge are very similar to those of Galactic bulge, in particular the shape of MDF suggests that the bulge formed from metal-enriched halo gas and that star formation terminated by a bulge wind before the disk formed.

# Conclusions

- Bulges of spiral galaxies show very prominent correlations of age, metallicity, and [$\alpha$/Fe] with the central velocity dispersion and the maximum rotational velocity, in the sense that less massive bulges tend to have stellar populations of younger (luminosity-weighted) ages, lower (luminosity-weighted) metallicities, and lower [$\alpha$/Fe] ratios, which is somewhat similar to those found for elliptical galaxies.
- The relation between the stellar population gradients and the central velocity dispersion (the bulges with large velocity dispersion can have strong gradient, while those with small velocity dispersion show no significant population gradients) suggests that the stellar population gradients in bulges are gradually built up towards less and less massive bulges.
- The stellar populations of massive bulges formed very rapidly (<1Gyrs) with significant contribution of SNeII enrichment, while less massive bulges form stars more gradually with large contribution of SNeIa enrichment with long lasting star formation or recent secondary star formation.