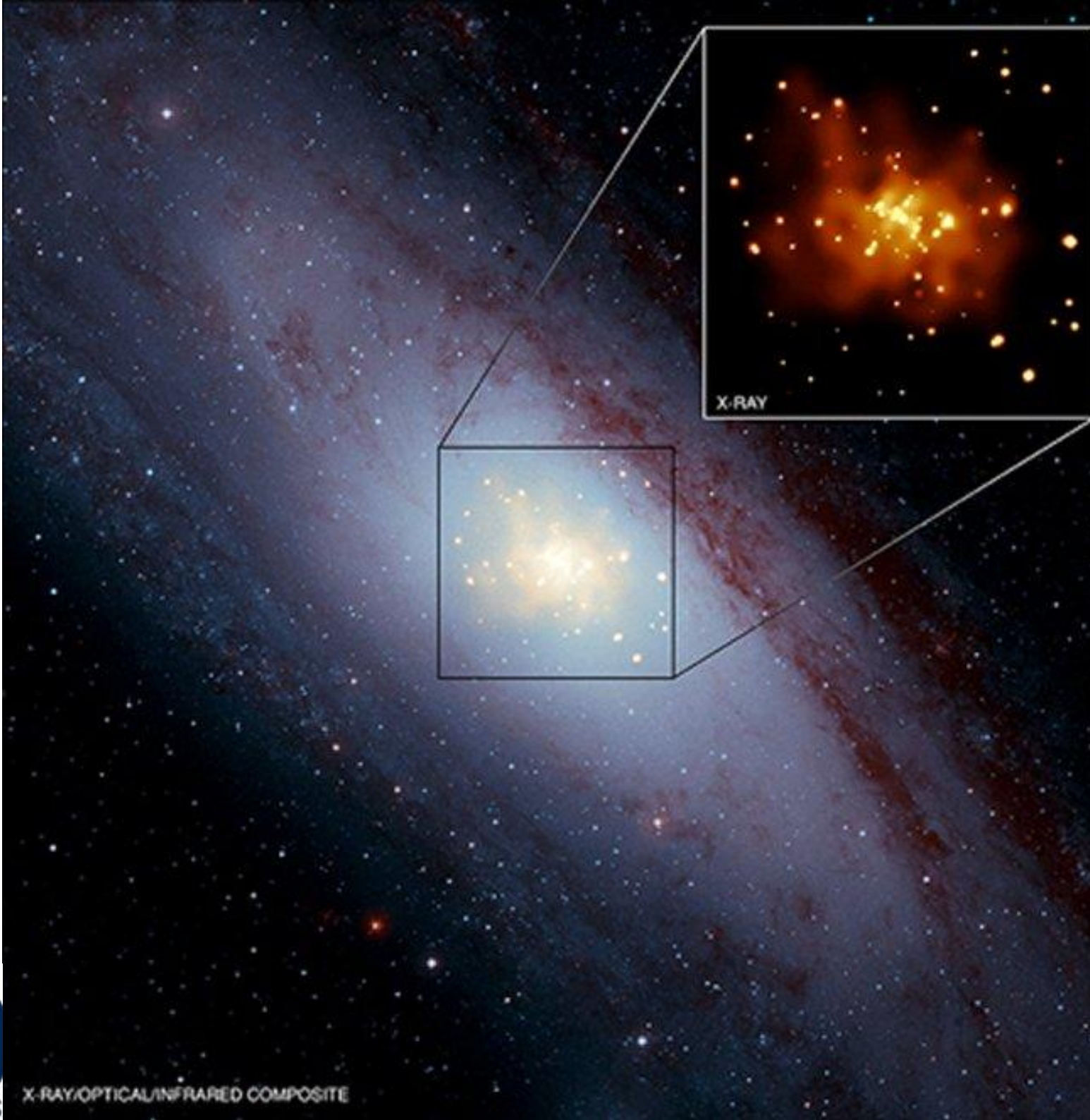# The Bulge of M31

Jeremy Mould
Swinburne University

Schwarzschild
Centennial

How do bulges form ?

Your answer:

- Like elliptical galaxies
- Ask Kormendy & Kennicutt
- We haven't a clue
- ✓ Interesting question, key to understanding the Hubble sequence

Stellar populations clues:

- Age distribution of bulge stars = Star Formation History
- Kinematics
- Chemistry

Note M31 is the nearest relevant object to study (other than the Milky Way)

Freeman 2007

- various kinds of bulges

  - classical, boxy/peanut-shaped, pseudo

  - likely formation mechanisms.

- chemical evolution

- relation between bulges and metal-poor halos
  (often lumped together as spheroids)

- scaling laws for bulges

- input to SAL models.

Pseudobulges

- Internal secular evolution involves the buildup of dense central components in disk galaxies that look like classical merger built bulges but were made slowly out of disk gas

- KK 2004 call these pseudobulges

  - Flatter shapes

  - High v/σ

  - Small σ relative to FJ expectation

  - Bars

  - Exponential SB

# M31 has a classical bulge with pseudobulge trimmings

- A majority of bulges appear rounder than their disks. These include the classical bulges in M31, M81, Sombrero

- Nucleus and bulge of M31 are dynamically independent

   Tremaine and Ostriker 1982

- If B/T > 1/2 , galaxy contains a classical bulge
  - but see Beaton et al 2007 for boxy-bulge
 - And Courteau et al 2007 for structural parameters

Influential Surveys of M31 and its bulge

- ## Mayall 4m and Hale telescopes
  - ### Hodge 1975 The Atlas of Andromeda
  - ### Mould & Kristian1986 & 4SHOOTER
- ## Isaac Newton Telescope
- ## PANDAS
- ## Hubble Space Telescope
  - ### PHAT Dalcanton et al 2012
- ## Keck Telescope
  - ### The SPLASH Survey Gilbert et al,
  - ### Dorman et al 2012,Kinematics of the Inner Spheroid
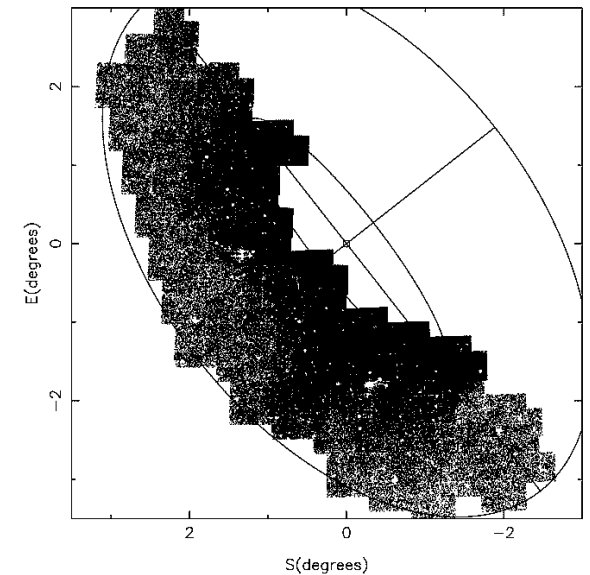
Multiwavelength

IRAC Barmby et al
MIPS, Gordon et al 2006
GALEX Rey et al 2007
21 cm Chemin et al 2009
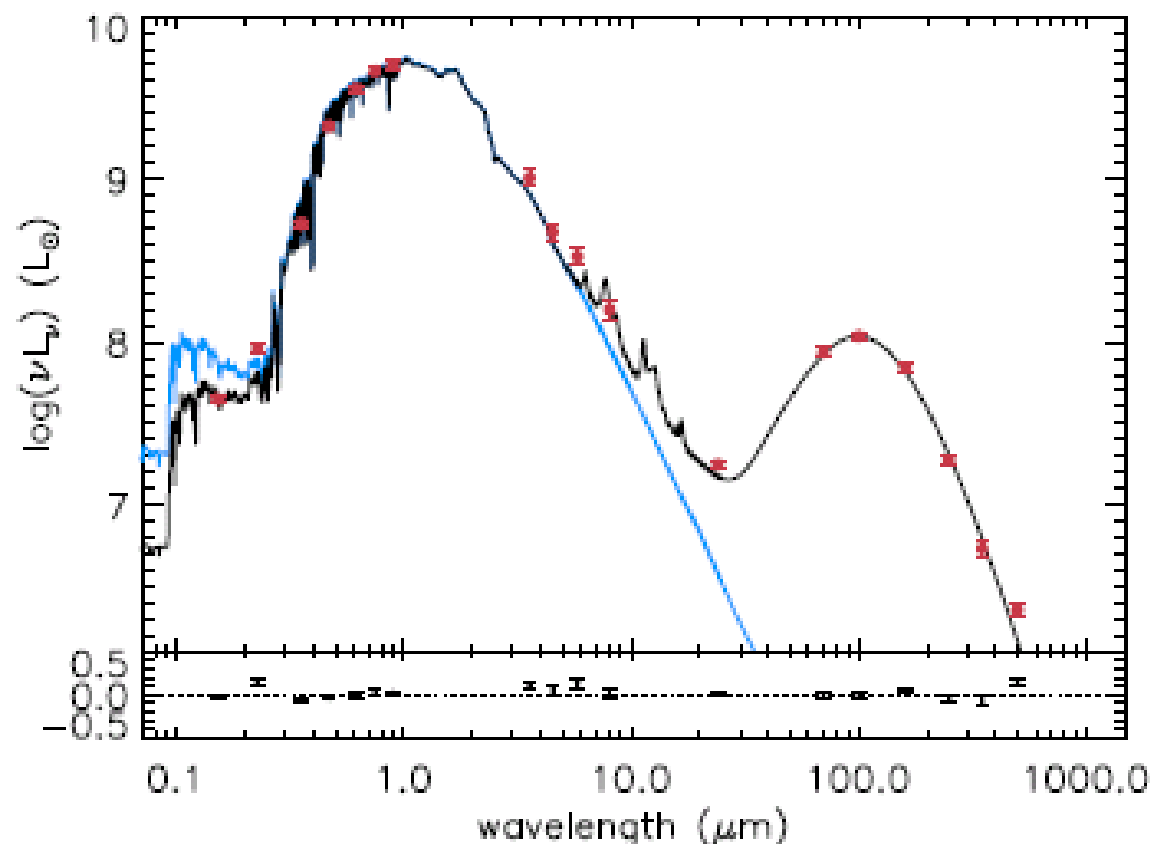Herschel Groves et al 2012
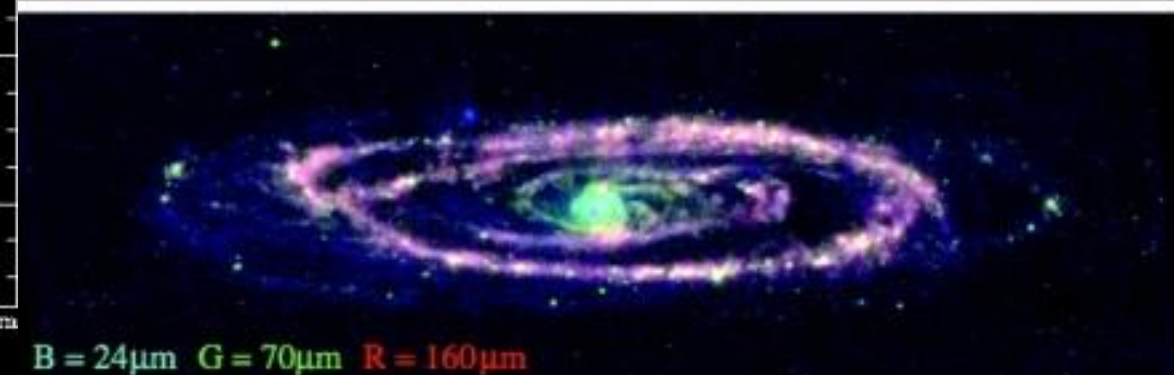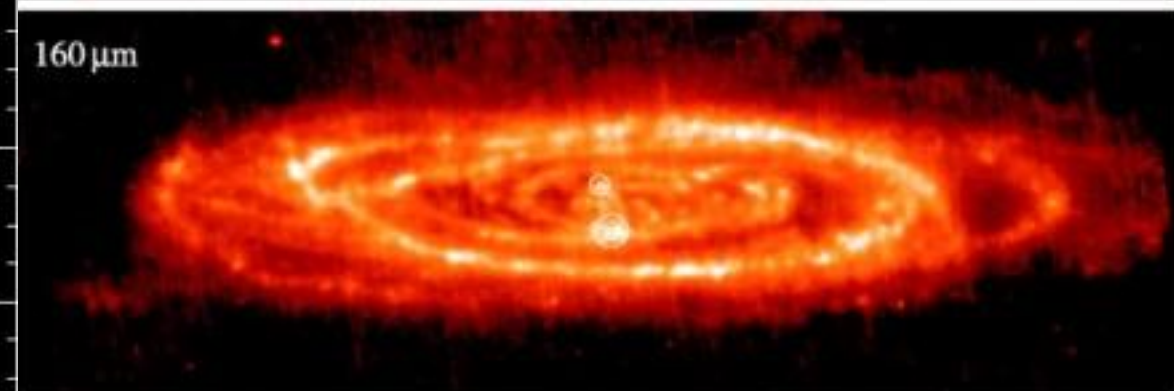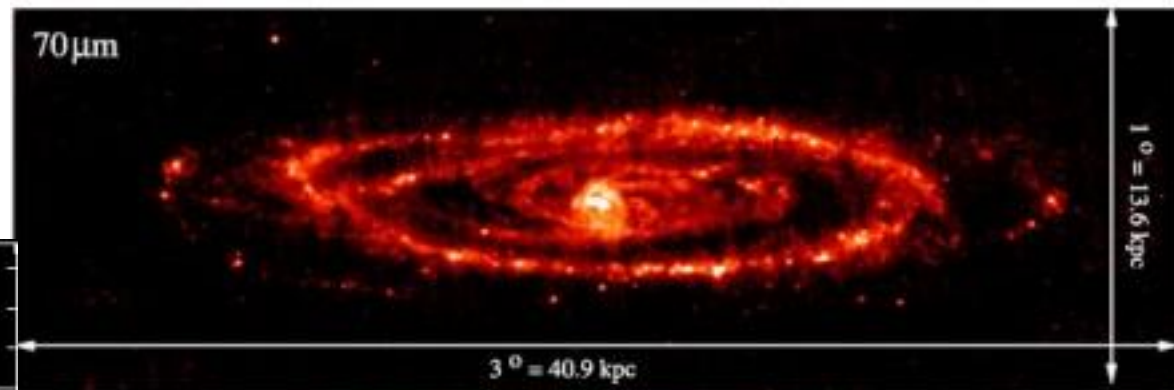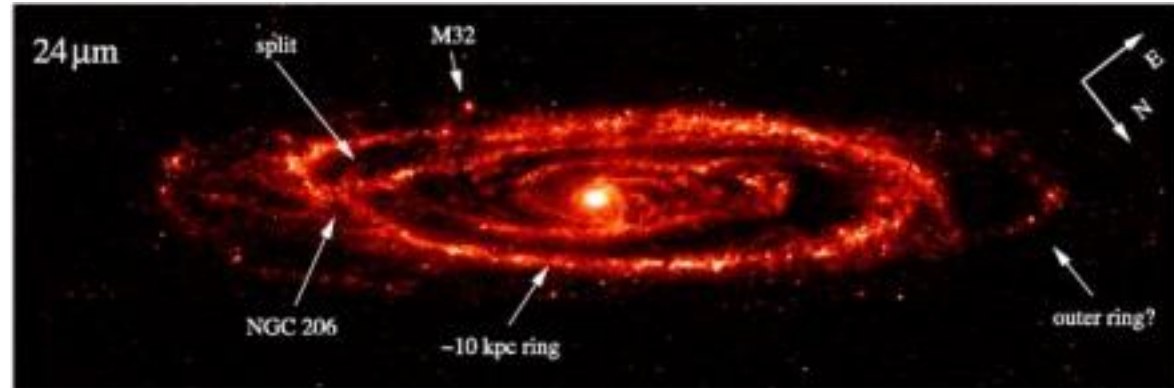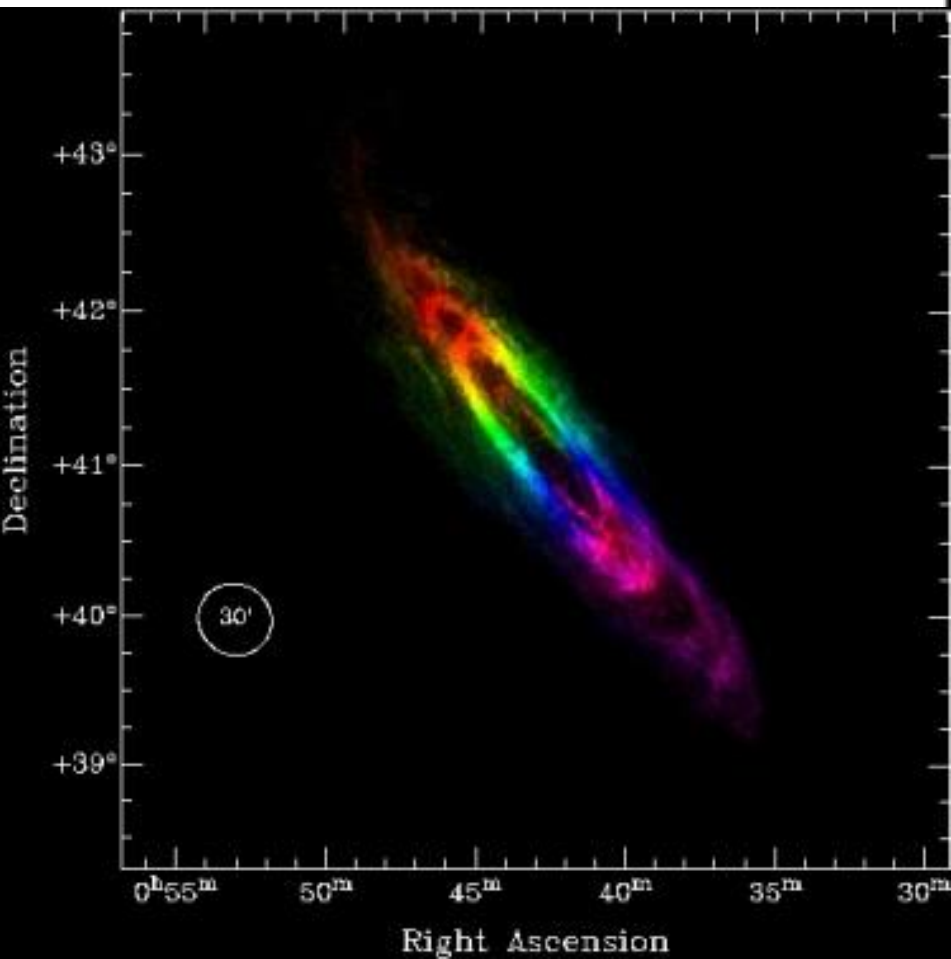
Figure 3. The spectral energy distribution (SED) of the central kpc region of Andromeda, measured within a circle of 1kpc (4.405′) radius from the centre. The fluxes (GALEX FUV and NUV, SDSS *u, g, r, i,* and *z, Spitzer* IRAC and MIPS24, and all six *Herschel* bands) within this aperture are marked by the red points, with the error bars including calibration, sky and noise uncertainties. The black curve shows the best fit model SED from the SED fitting code MAGPHYS (da Cunha et al. 2008), while the blue curve shows the corresponding unattenuated stellar SED from the same model. Below the model SED, the residuals between the observed data and models are shown, with $|\log(L_{obs}/L_{mod})| < 0.1$ dex for all wavelengths except for SPIRE500 μm, where the observed flux is under predicted by ~30%.

Groves et al astro-ph 1206.2925 Herschel

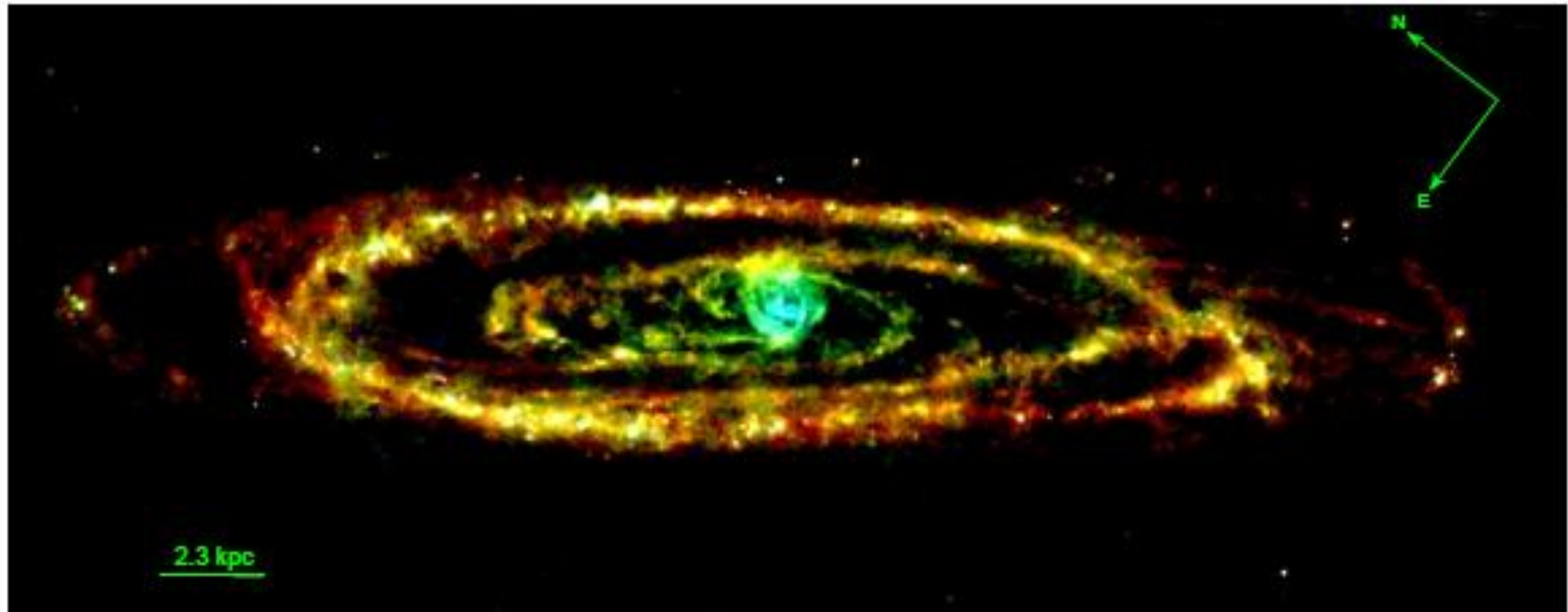**Figure 1.** Far-infrared image of Andromeda using the Herschel bands showing PACS 70 μm (*blue*), PACS 100 μm (*green*), and SPIRE 250 μm (*red*), all convolved to SPIRE 250 μm resolution (from Krause et al., in prep.). All three bands have the same square root scaling from 10 MJy sr^{-1} to 150 MJy sr^{-1}. The angular scale of the image is shown by the 2.3 kpc (10') bar in the lower left.

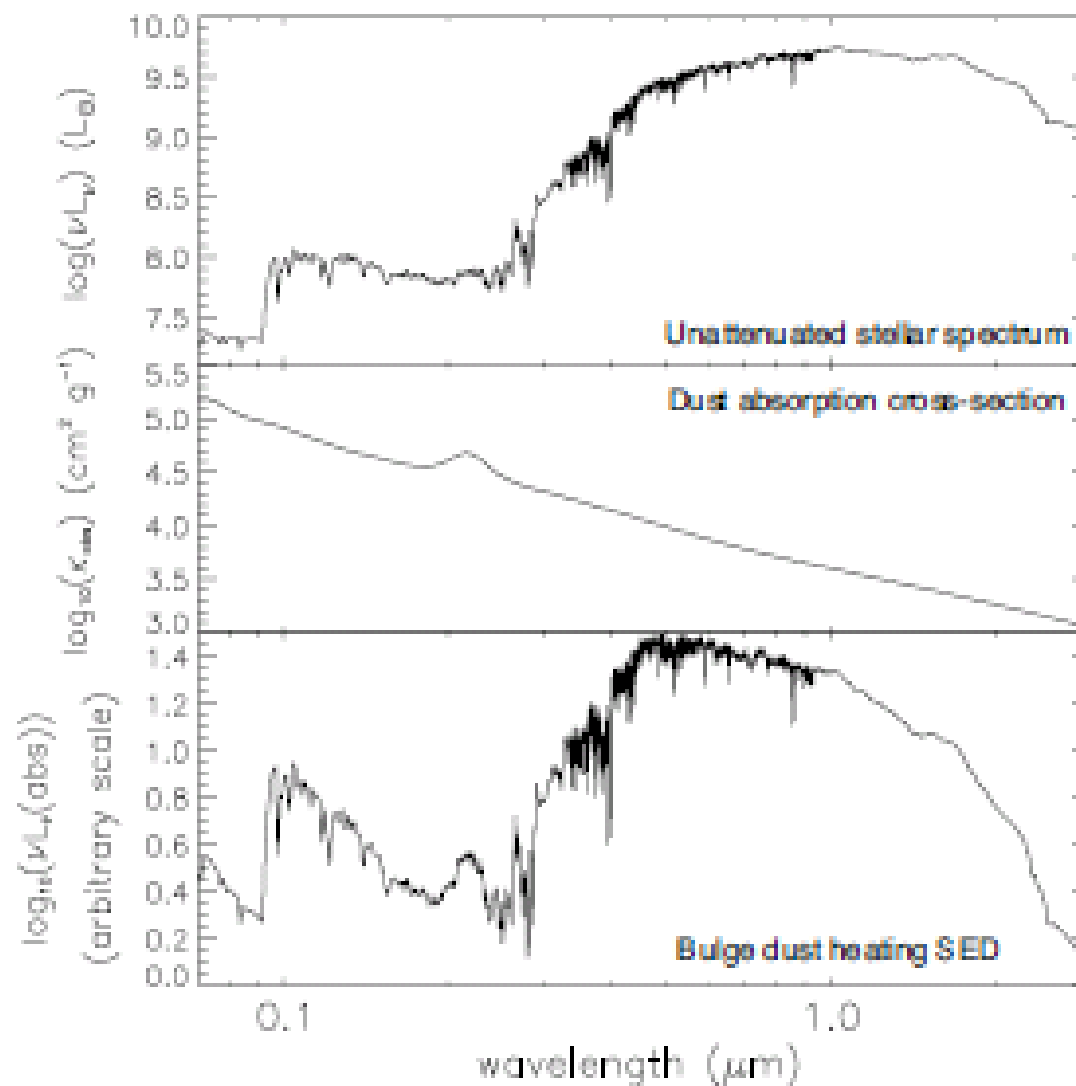Optical stellar light is the main dust heater in the bulge

Figure 8. The energy absorbed by diffuse dust in the bulge of M31. The top panel shows the "unattenuated" bulge UV–NIR SED from the MAGPHYS (da Cunha et al. 2008) model fit to the integrated SED of the central kiloparsecs (blue curve in Figure 3). The middle panel shows the total absorption cross-section per gram of dust for the MW dust model with $R_V = 3.1$ from Draine (2003). The bottom panel shows the product of these, revealing the wavelength distribution of the energy absorbed by dust. The conclusion is that the optical stellar light is the main contributor to the dust heating in the bulge.

Questions about M31's bulge

- What is its star formation history ?

  - continuous or initial burst ?
  - how much of each ?

- What is its chemical enrichment history ?

  - similar to the MW bulge ?

- What is its relation to the other components ?

  - the halo ?
  - the globular cluster system ?
  - the disk ?

Brown 2008

- M31 hosts a traditional bulge that is apparently dominated by stars older than 10 Gyr.

- Deep photometry of the M31 halo shows populations of
  - ancient metal-poor stars
  - one extending to younger ages and high metallicity, apparently due to its active merger history.

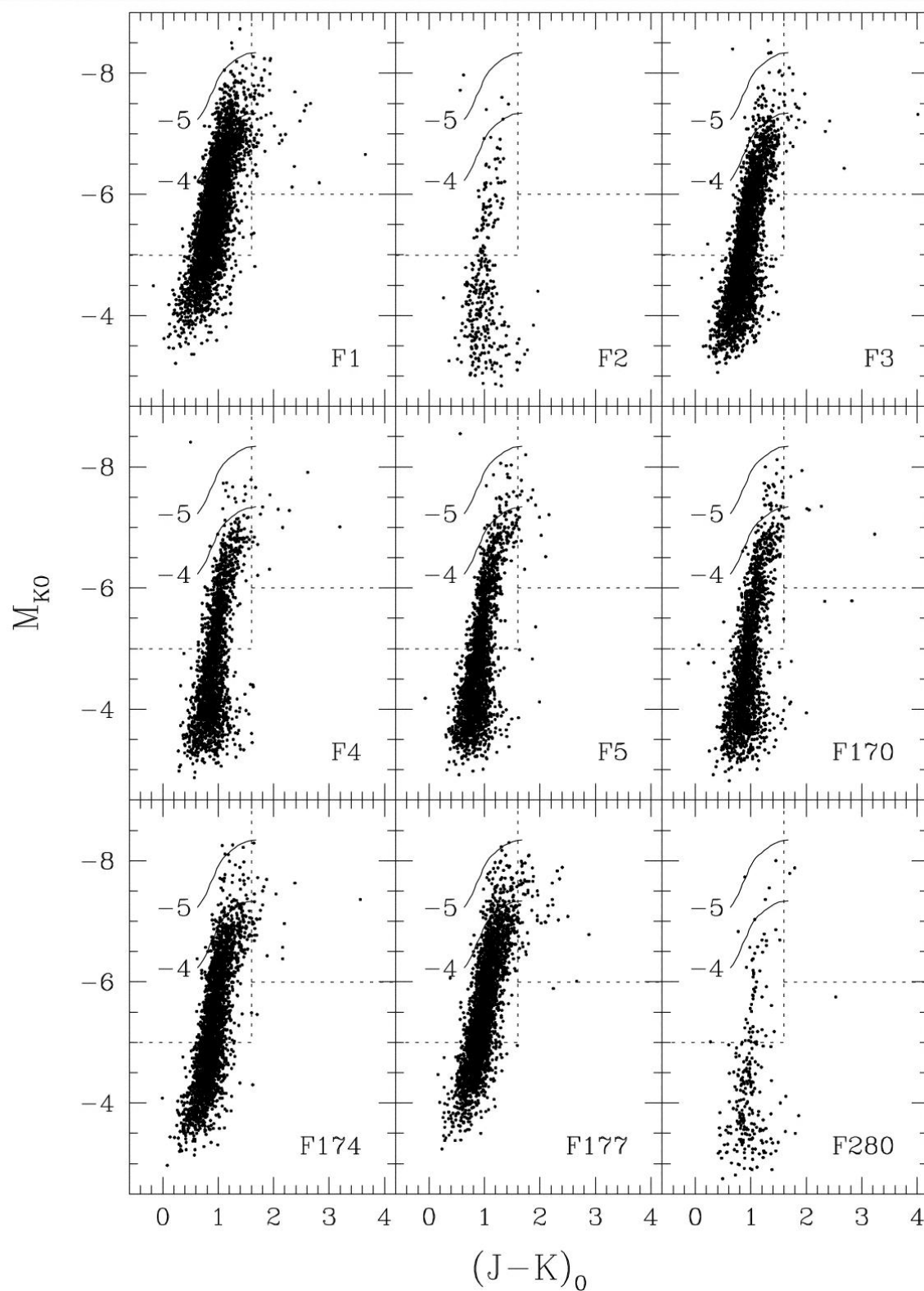# Similarity of the AGB LF M31 inner bulge and Baade's window

Davidge 2001
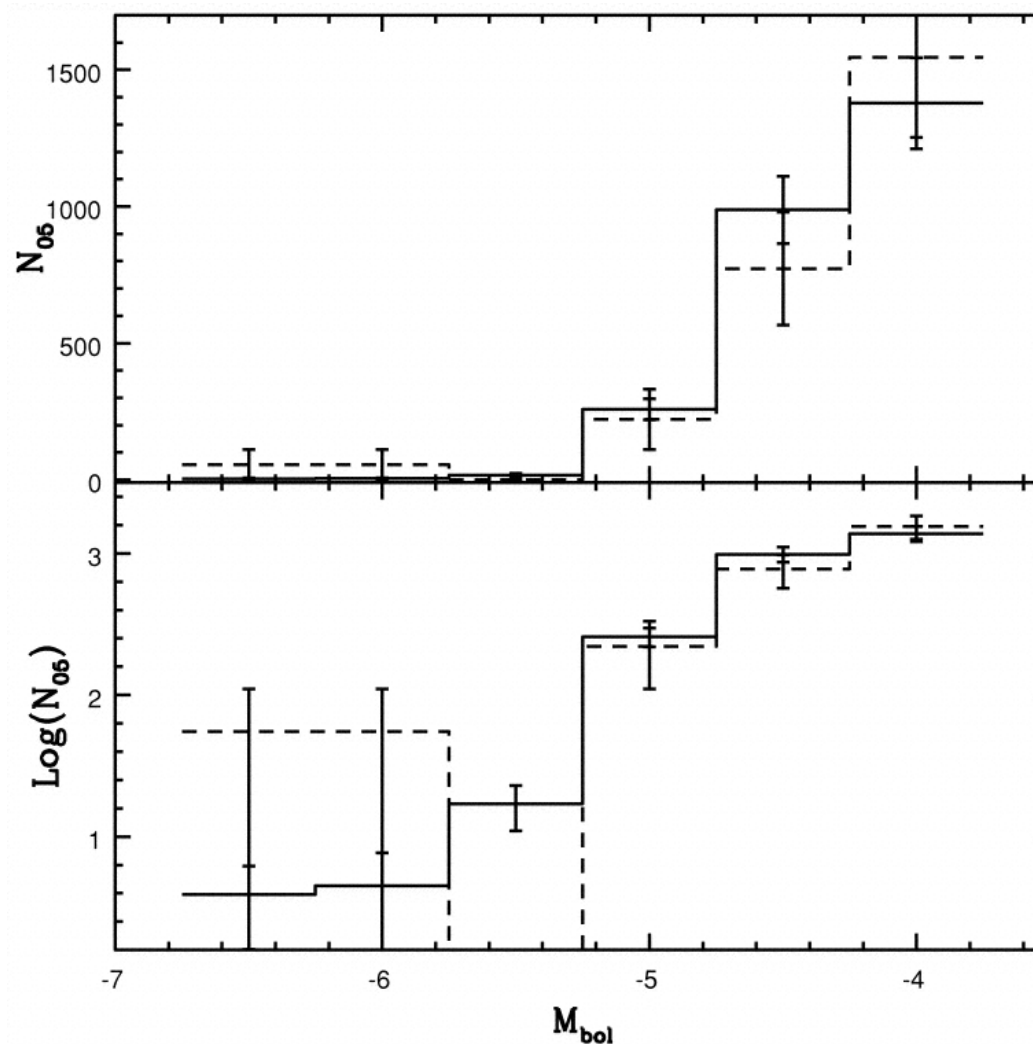
Interpreting the AGB LF
The Mbol = -5 bin is 1 Gyr old stars; the -4.5 bin is 5 Gyr old stars and younger
It is a simple matter to produce plots like the upper one, e.g. assuming a constant SFR.
M31 and MW bulges show a declining SFR from 10 to 1 Gyr. But the stars are not all old.

NICMOS Stephens et al

Dereddened color-magnitude diagrams for each of the nine NIC2 fields. We have drawn lines of constant bolometric magnitude at M_{bol} = -4 and -5, using the bolometric corrections calculated for Baade's window M giants by Frogel & Whitford (1987). The box at upper right in each panel, with $(J-K)_0 > 1.6$ and $M_{K0} < -6$, indicates the region where we expect to find primarily LPVs. The box at upper left in each panel, with $(J-K)_0 < 1.6$ and $M_{K0} < -5$, is the region we use to count nonvariable giants. We have assumed $E(B-V) = 0.22$, giving $E(J-K) = 0.12$ and $A_K = 0.07$.
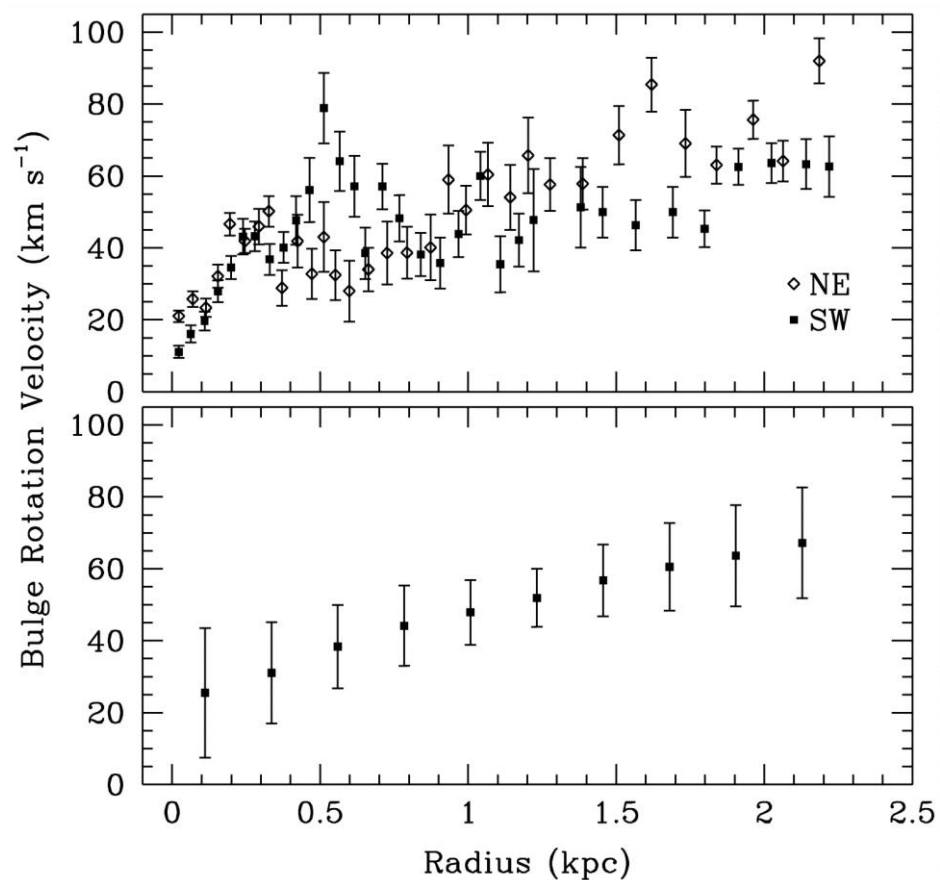
PHAT 1204.0010
B1 = central bulge; B9 = outer bulge
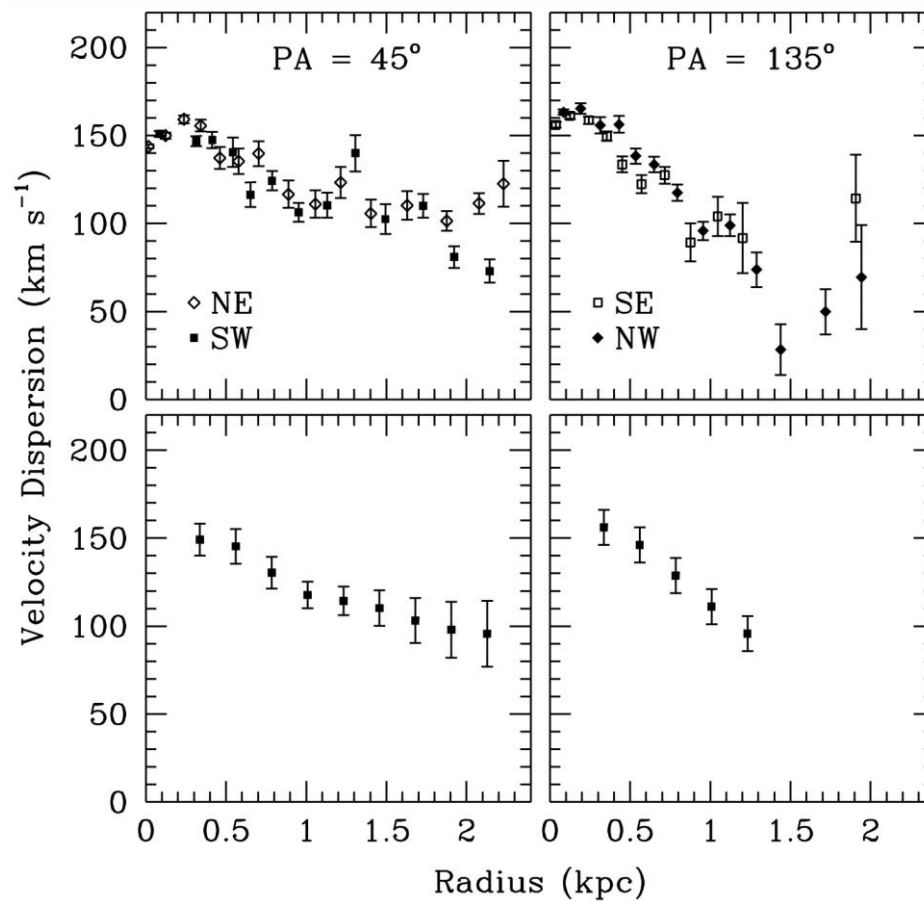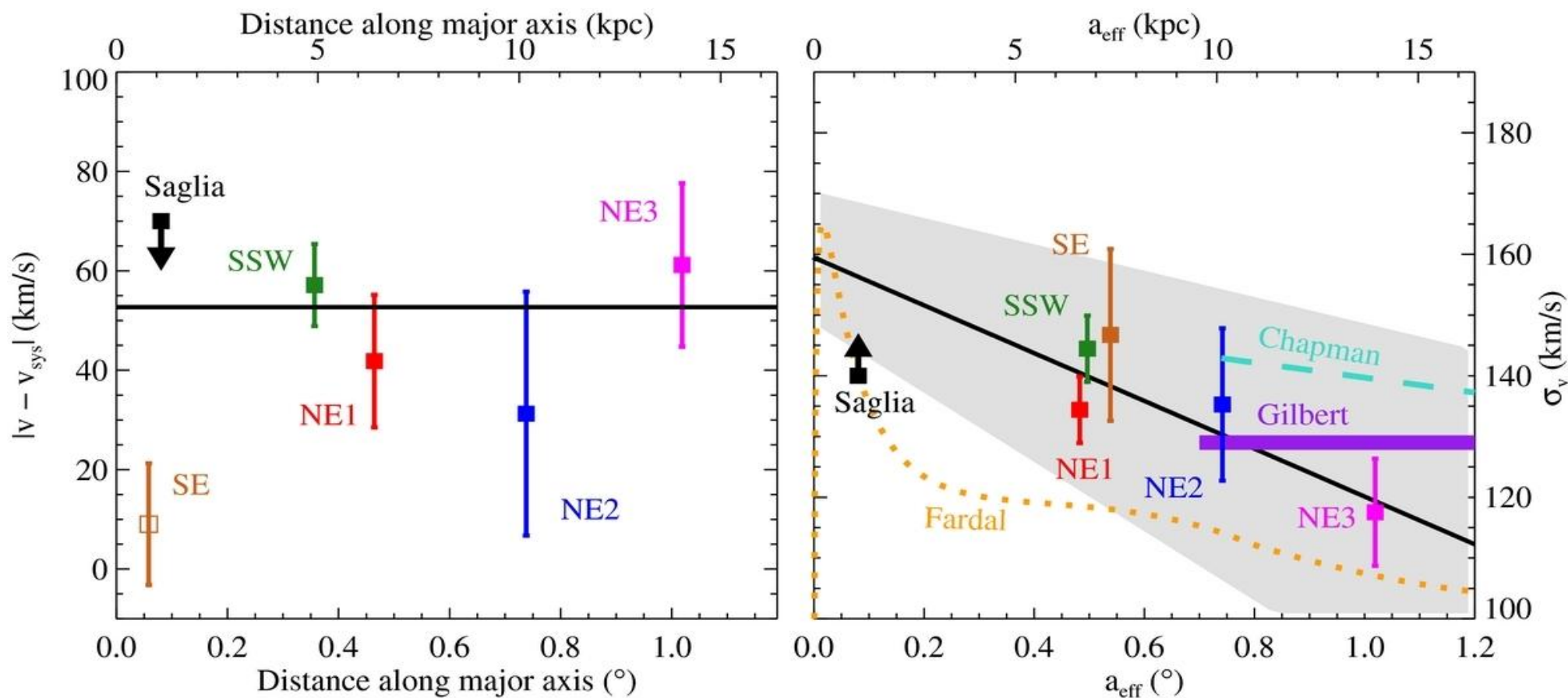
Dalcanton et al.
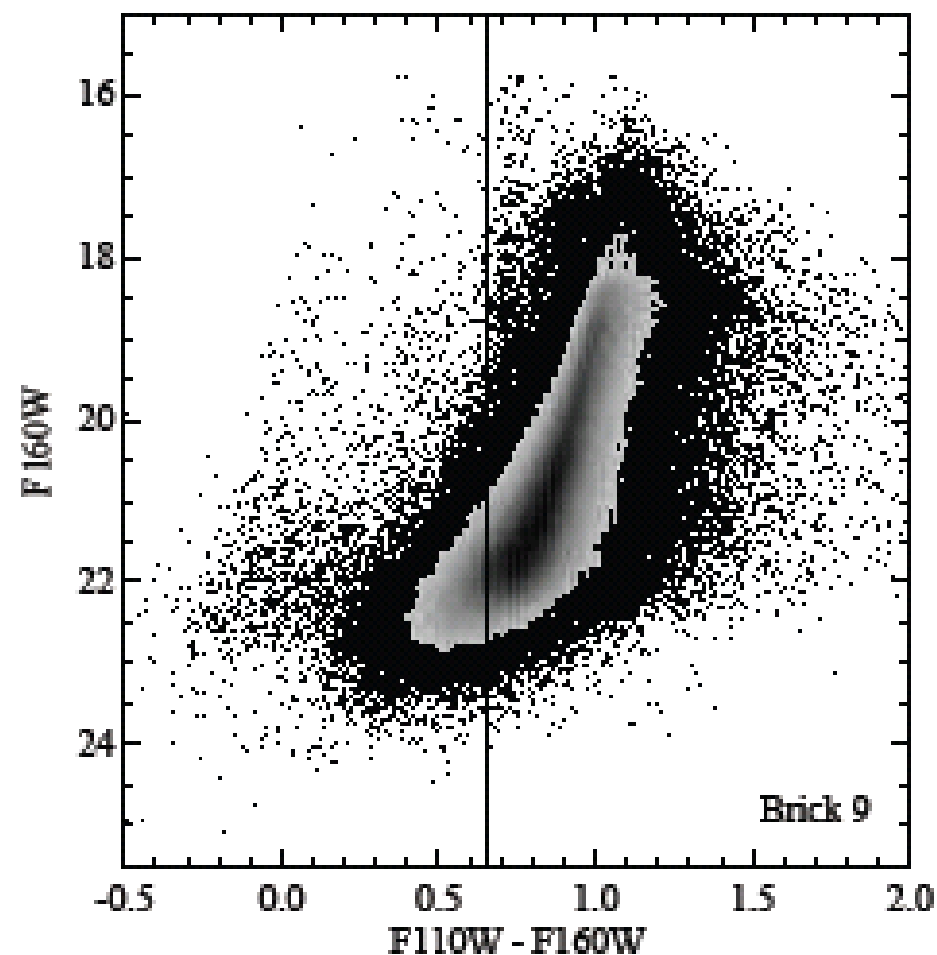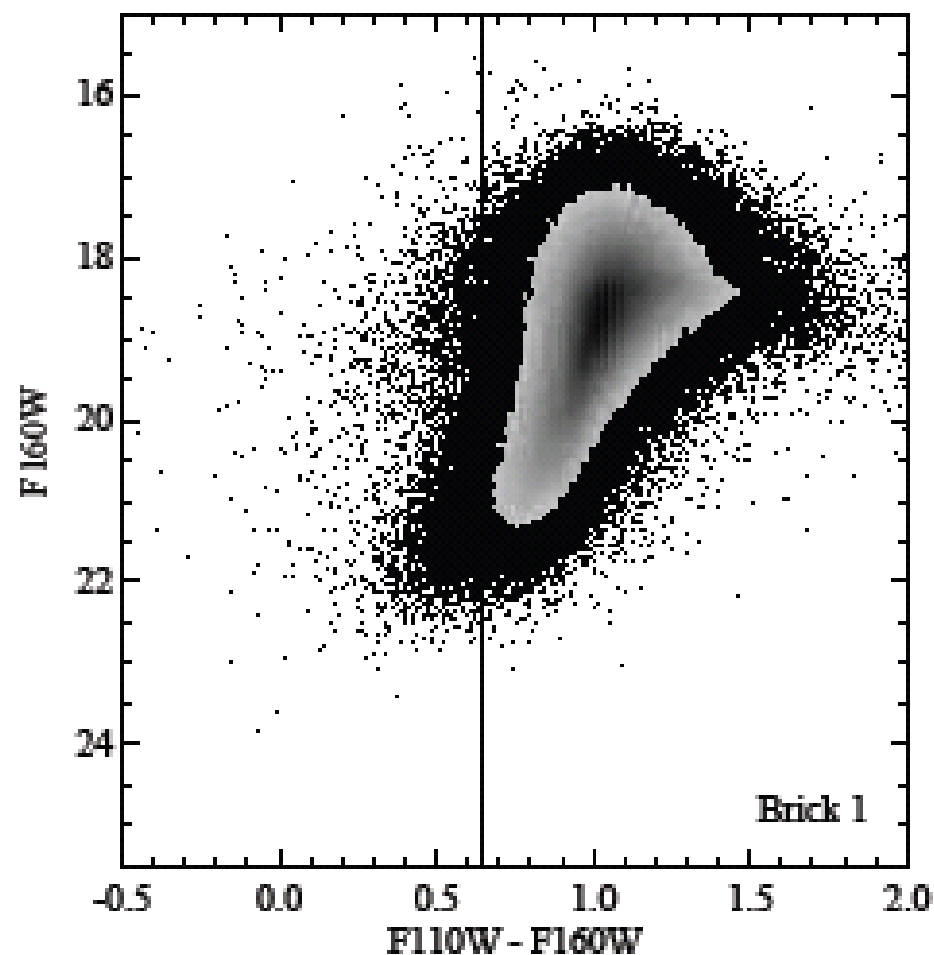
McElroy 1983

Rotation v

Dispersion σ

The best-fit line to our dispersion measurements is shown by the solid black line, with the region within ±1σ of the best-fit line shaded in gray.

Saglia et al 0910.5590

- new optical long-slit data along 6 position angles of the bulge region of M31.

- velocity dispersions of McElroy (1983) are severely underestimated (by up to 50 km/s) and previous dynamical models underestimated the stellar mass of M31's bulge by a factor 2.

- velocity dispersion of M31 grows to 166 km/s,

  thus reducing the discrepancy between the predicted and measured mass of BH at the center of M31.

- kinematic position angle varies with distance, pointing to triaxiality.

Saglia continued

- gas counterrotation near the bulge minor axis
- bulge of M31 is
  - except for the inner arcsecs of the galaxy,
  - uniformly old (>12 Gyr,
  - at solar metallicity with [α/Fe]~0.2 and
  - agreeing with studies of resolved stellar components.
- approx radially constant M/L$_R$ ~ 4,
  - in agreement with stellar dynamical estimates
- In the inner arcsecs the luminosity-weighted age drops to 4-8 Gyr, while the metallicity increases to above 3 times the solar value.

Gilfanov and Bogdan

Unresolved X-ray emission from the bulge of M31 is composed of at least 3 different components:

(i) Broad-band emission from many faint sources – mainly accreting WDs and active binaries, similar to Galactic Ridge X-ray emission of Milky Way.

(ii) Soft emission from ionized gas with t ~ 300 eV and m ~ 4×10^6 $M_\odot$. The gas distribution is significantly elongated along the minor axis suggesting that it may be outflowing perp to disk.

(iii) Hard unresolved emission from spiral arms, most likely associated with protostars and young stellar objects located in the star-forming regions.

Bekki 0912.2476

- major merger event could have formed bulge & rotational kinematics of globular cluster system

- numerically investigate kinematics of GCs

  - GCs in both their disk and halo components.

- GCS formed during major merging rotate

  - maximum rotational velocities of 140 - 170 km/s

  - for a range of orbital parameters of merging

- rotating stellar bar (a boxy bulge) if seen can be formed in models for which the GCSs show strongly rotational kinematics.

Sarajedini & Jablonka 2005
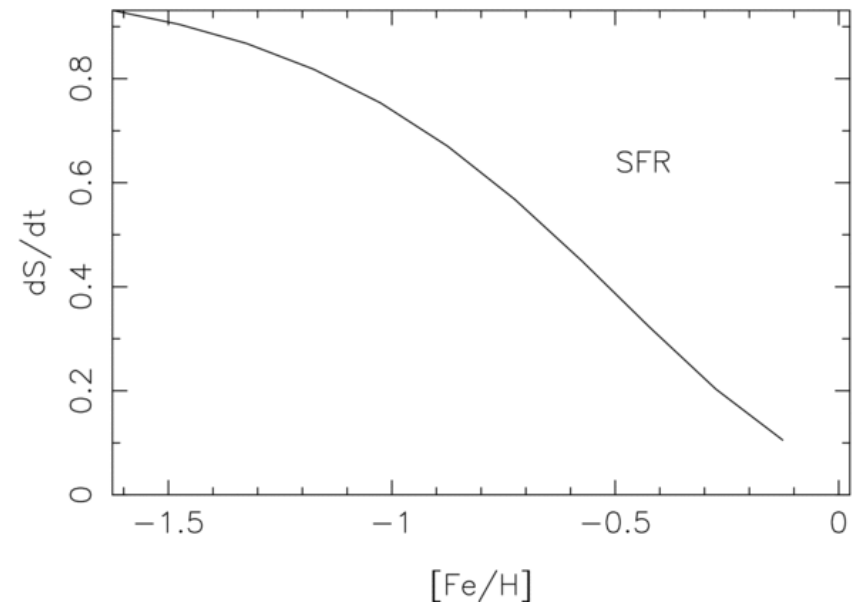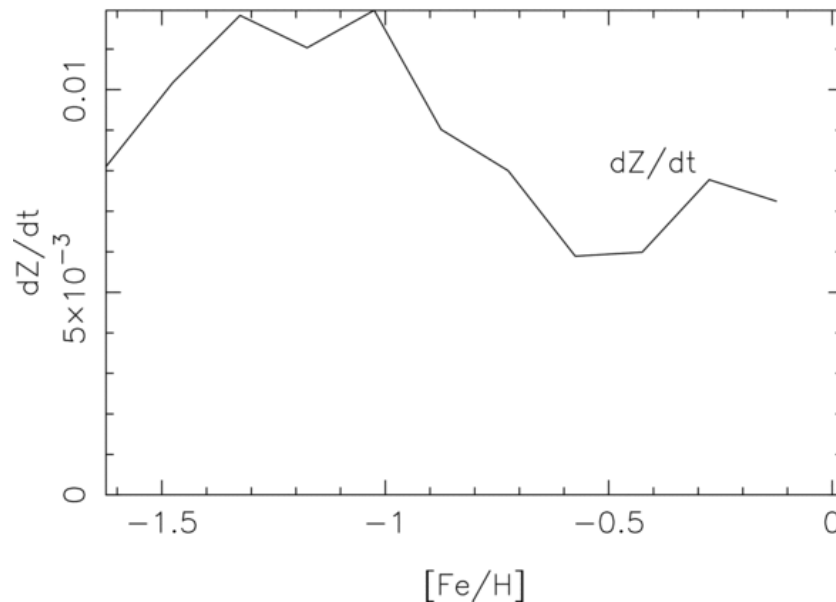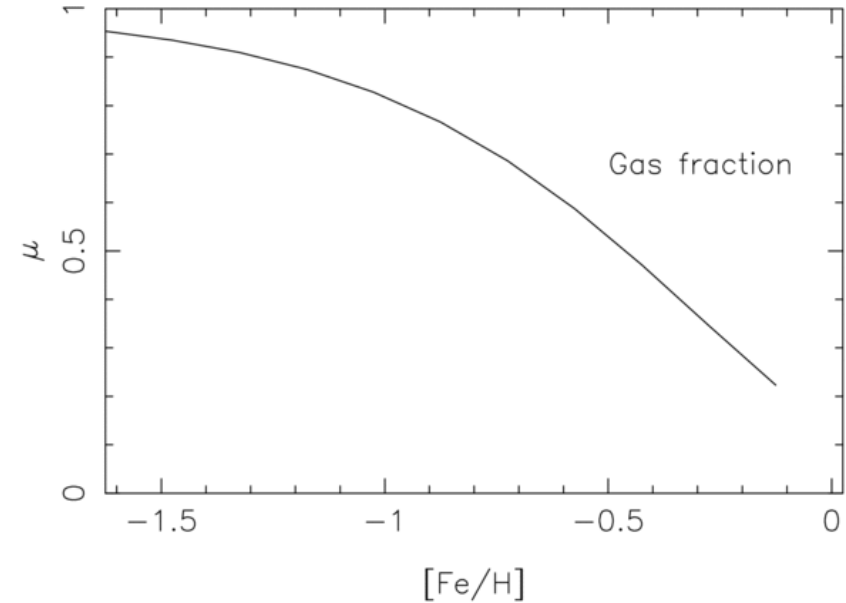

Histogram
= MW
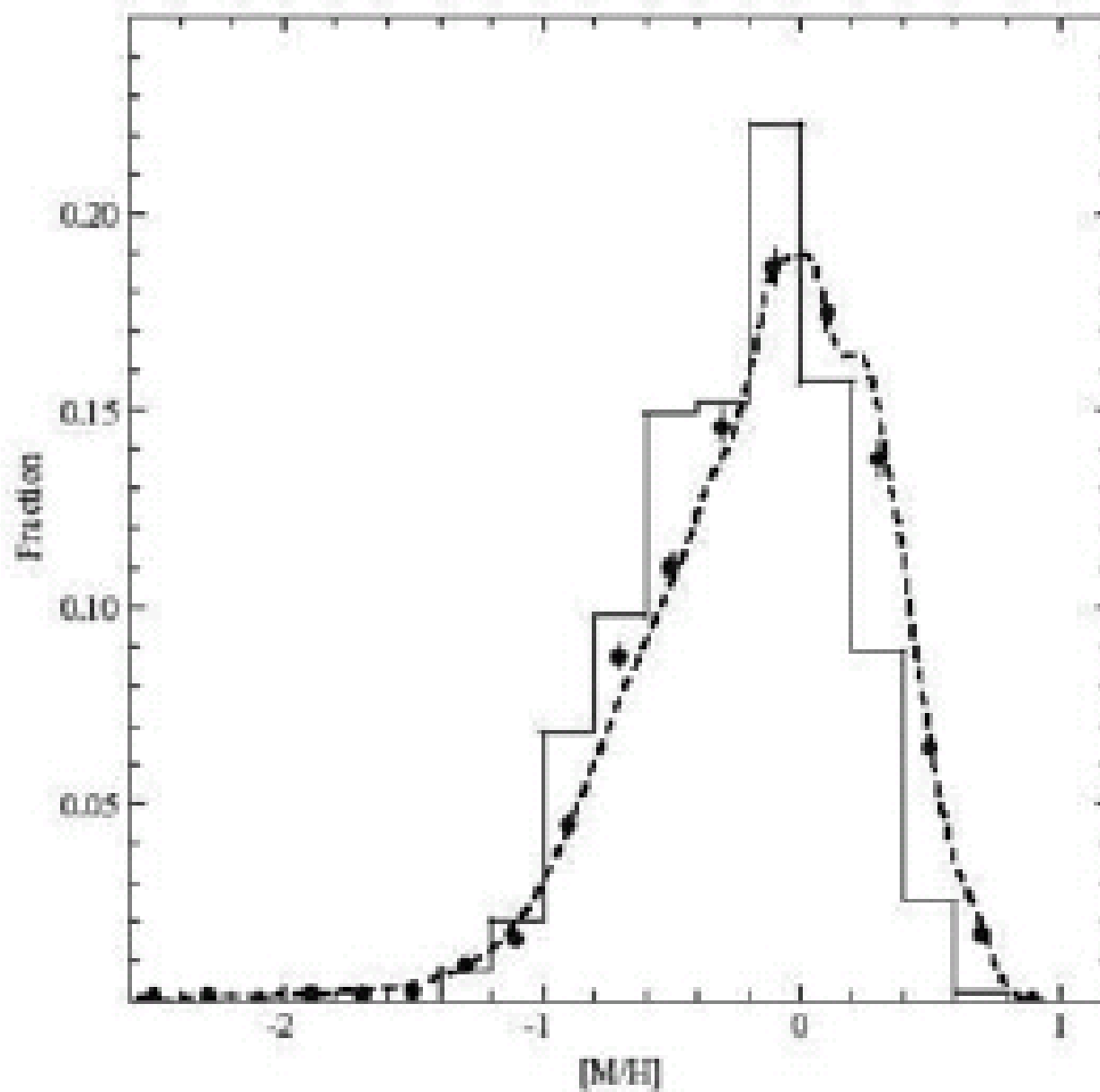
PN chemistry
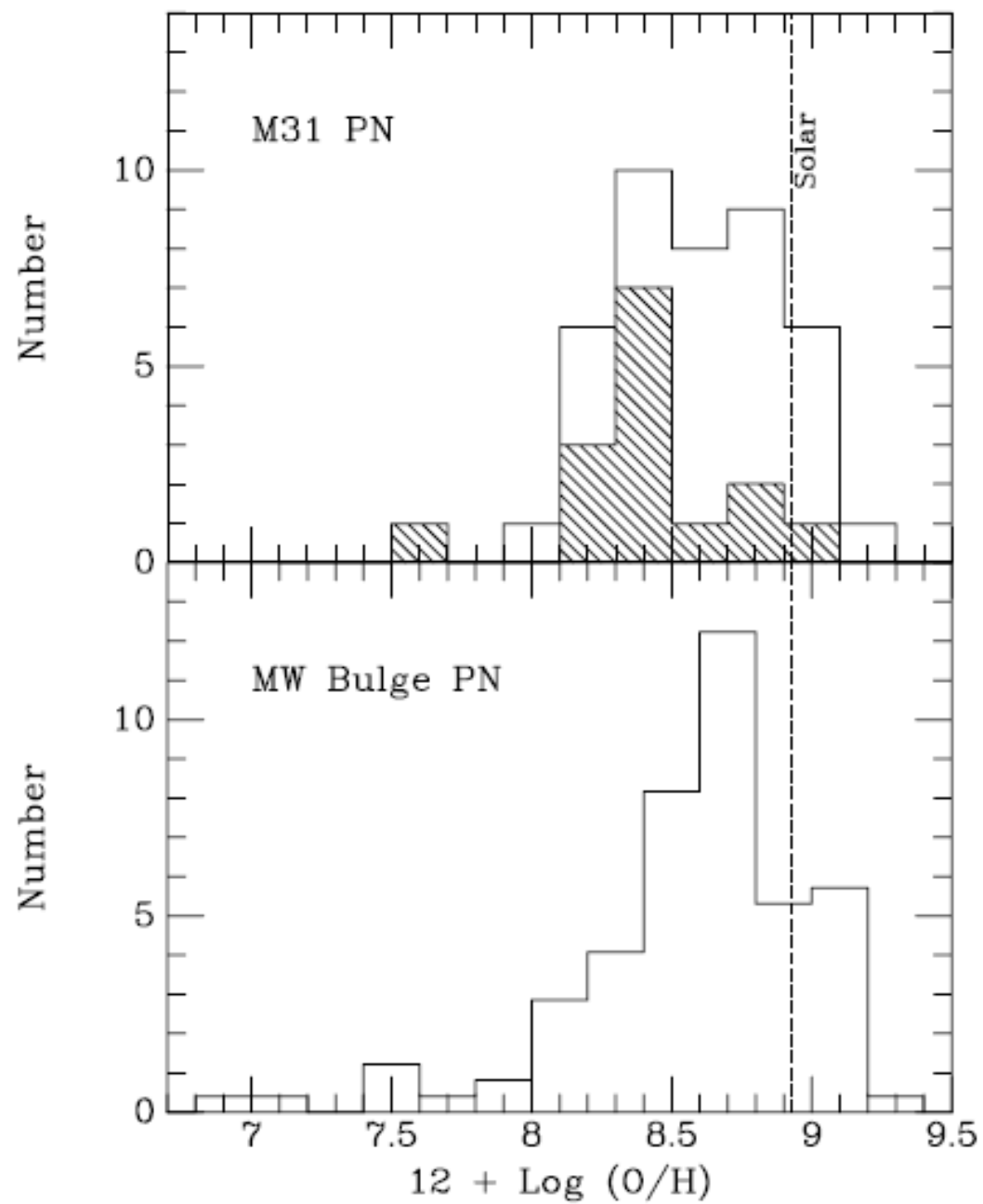
Mould & Spitler 2010 Sombrero

Given any metallicity distribution function, you can obtain the accretion and star formation history.

[Fe/H] is a proxy for time.
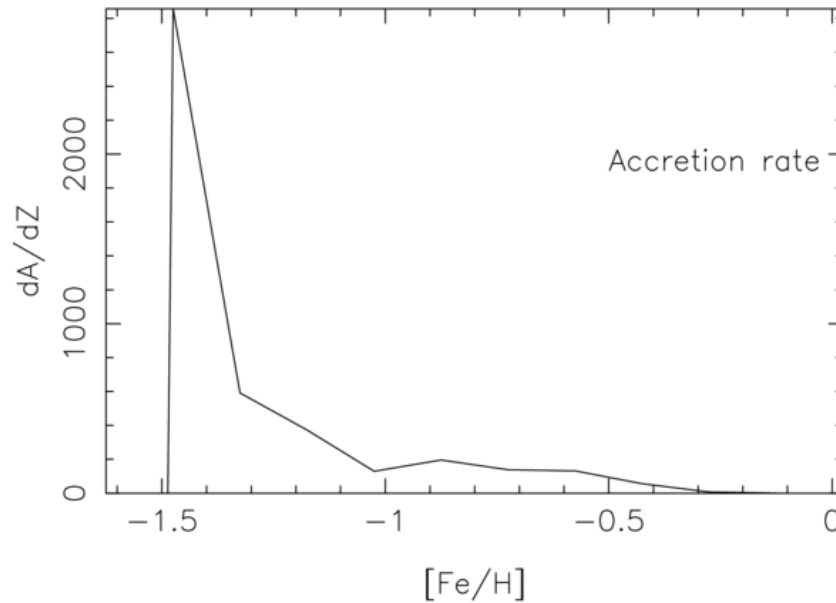
Scaling relations: Pizella et al 2005
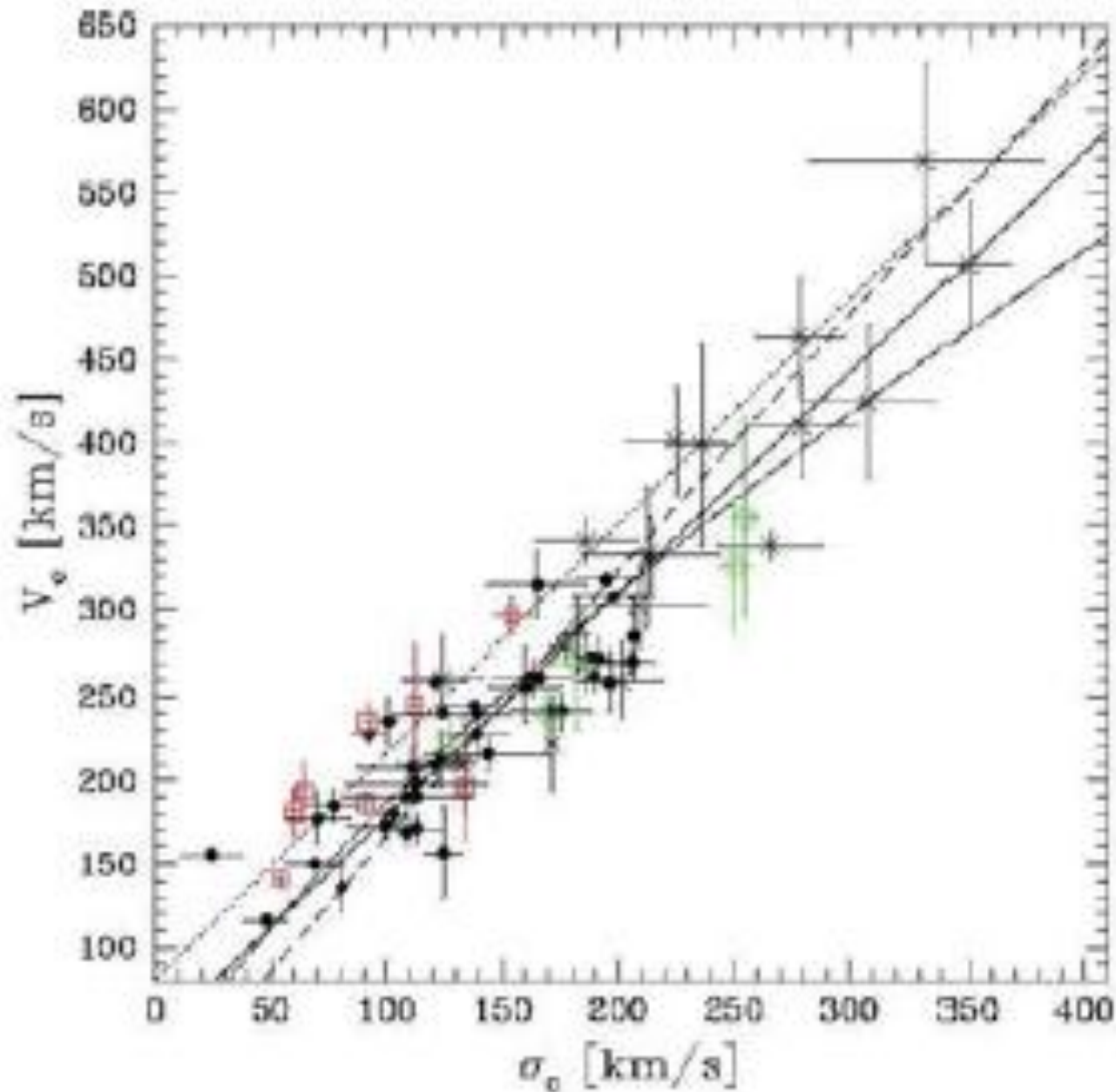
Bulge mass Widrow et al

- The most successful models assume a bulge mass that is nearly a factor of 2 smaller than the oft-quoted value from Kent (1989).

- Our galaxy model with $M_b = 2.5 \times 10^{10} \, M_\odot$ and $M_d = 7 \times 10^{10} \, M_\odot$ provides a good overall fit to observations, yields

  - M/L ratios that are quite acceptable

  - stable against bar formation.

Bulge photometry

Irwin et al Effective *V*- and *i*-band minor-axis profiles shown on a log-log (*left*) and log-linear (*right*) scale. The *V*-band 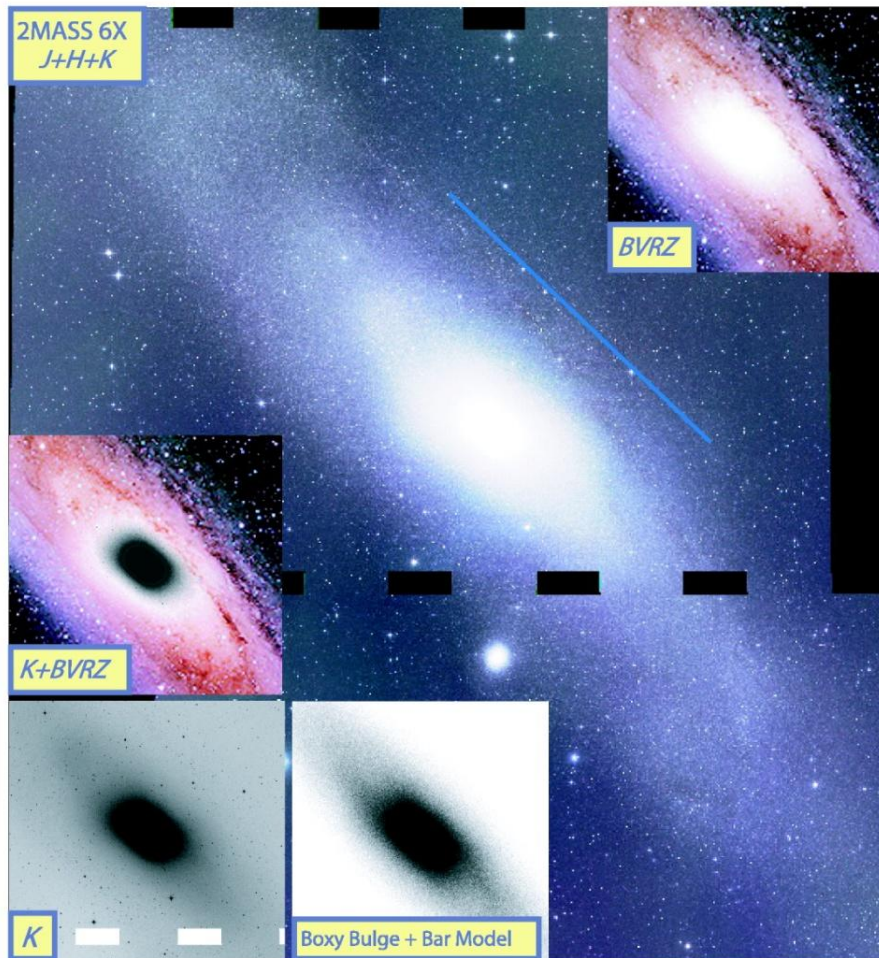profile is illustrated in green and blue, and the *i*-band profile in black and red. The green and black circles are derived from surface photometry, whereas the blue and red points are derived from star counts in the magnitude and color selection boxes described in the text. The error bars reflect a combination of Poissonian and background uncertainties. The green dashed lines show a de Vaucouleurs $R^{1/4}$ law with b_{eff} = 1.4 kpc. The dashed black line in the left-hand panel shows an NFW profile computed with a scale radius of 3.4 kpc and, in the right-hand panel, an exponential profile computed with a scale length of 13.7 kpc.
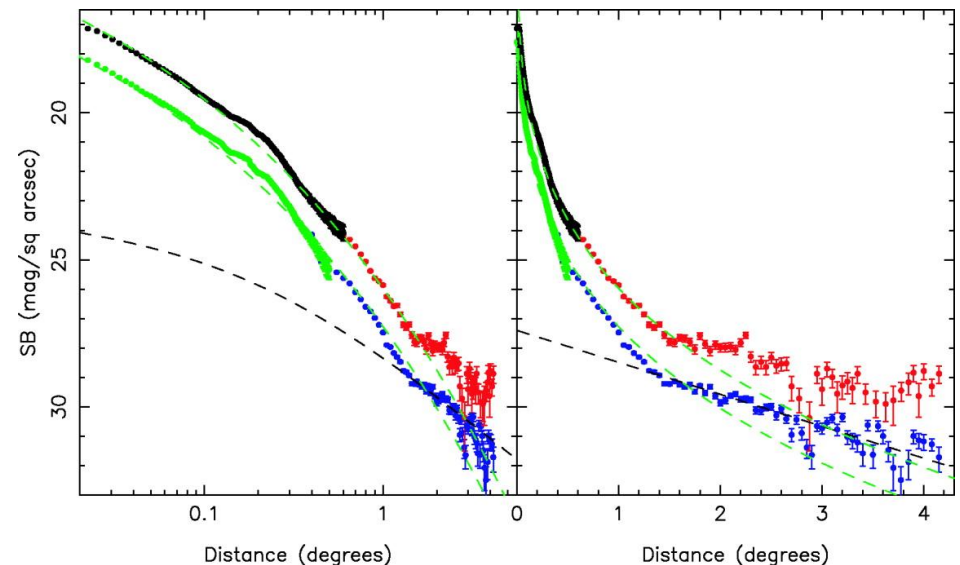
Courteau et al 1106.3564

- basic photometric model for M31 has

  - Sersic bulge with shape index $n = 2.2$ +/- 0.3 and

  - effective radius $R_e = 1.0$ +/- 0.2 kpc,

  - dust-free exp disk, scale length $R_d = 5.3$ +/- 0.5 kpc;

  - parameter errors reflect range of decompositions

- bulge parameter, n,

  - rather insensitive to bandpass effects

  - value suggests a first rapid formation via mergers followed by secular growth from the disk.

M31 RV astro-ph/0506653

- M31 RV is a luminous red variable star that appeared in the bulge of M31 in 1988.

- During outburst, (lasted a few months), it was one of the brightest stars in the Local Group.

- Unlike a classical nova, it was extremely cool during the eruption, and it never became optically thin or exposed a hot, blue source.

- remarkable similarity to V838 Mon, a luminous Galactic variable star that underwent a similar rapid expansion to become a red supergiant,

- outburst mechanism for this new class of luminous transients remains unknown,

Isolating the main sequence

- Why observe giant stars in galaxy halos closer than Virgo, when they are nothing but trouble ?

  - HB anomalies, convective envelopes, mass loss etc

- If you observe 2000 solar luminosities in an old stellar population with a spectrograph or imager

- $N(HB) = 2 \times 10^{-11} \times 2000 \times 10^8 = 4$ stars

- $N(MS) = 4 \times 1.3 \times 10^{10}/10^8 = 500$ stars

  - Fuel Burning Theorem: $n = bLt$ (Renzini)

- There are also subgiants to mask out along with the HB stars (but they are weak in the blue).

Hβ and Ca K

We choose two diagnostics, Hβ and the Ca K line, readily measurable in blue metal poor spectra. We write their line strengths, equivalent widths for example:

$$\beta = \beta(g, T, Z)$$

$$CaK = CaK(g, T, Z)$$

in the usual notation with g = log(gravity), T = log(effective temperature), and Z = log(metal fraction). Expanding around the main sequence turnoff we have

$$\delta\beta = \frac{\partial\beta}{\partial g}\delta g + \frac{\partial\beta}{\partial T}\delta T + \frac{\partial\beta}{\partial Z}\delta Z$$

$$\delta CaK = \frac{\partial CaK}{\partial g}\delta g + \frac{\partial CaK}{\partial T}\delta T + \frac{\partial CaK}{\partial Z}\delta Z$$

For turnoff stars

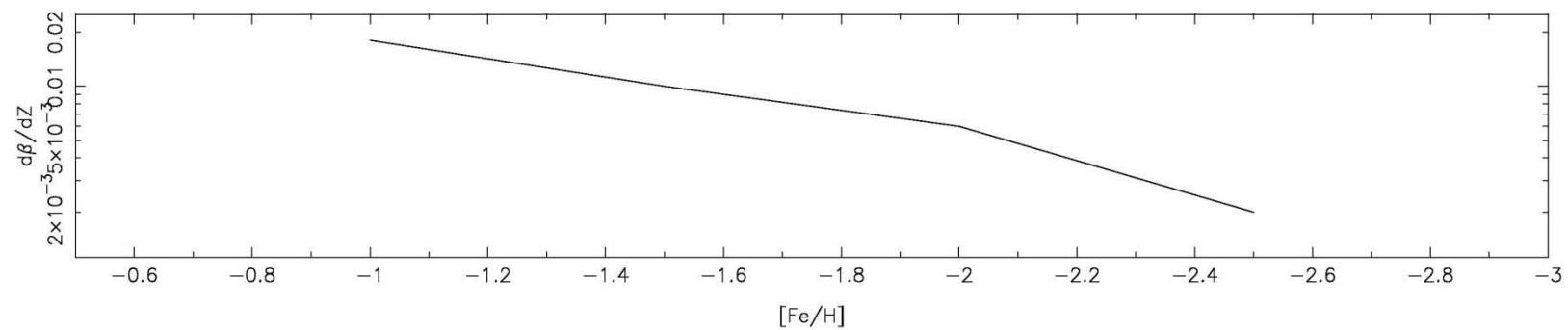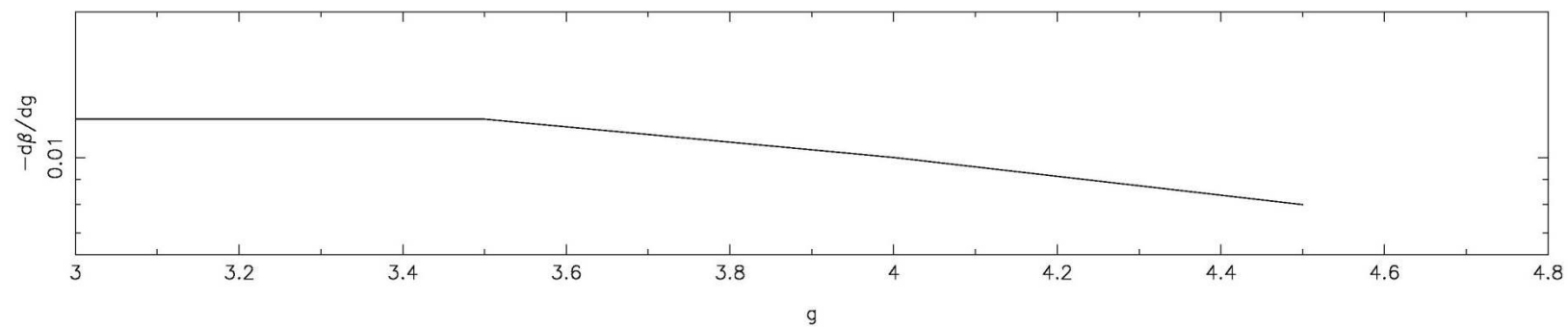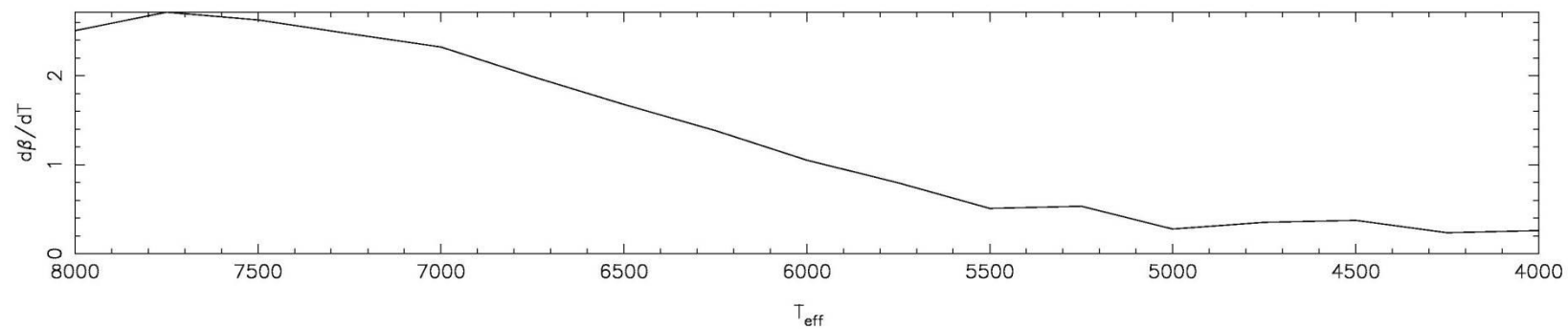$$\delta g = \frac{\partial g}{\partial t}\delta t + \frac{\partial g}{\partial Z}\delta Z$$

$$\delta T = \frac{\partial T}{\partial t}\delta t + \frac{\partial T}{\partial Z}\delta Z$$
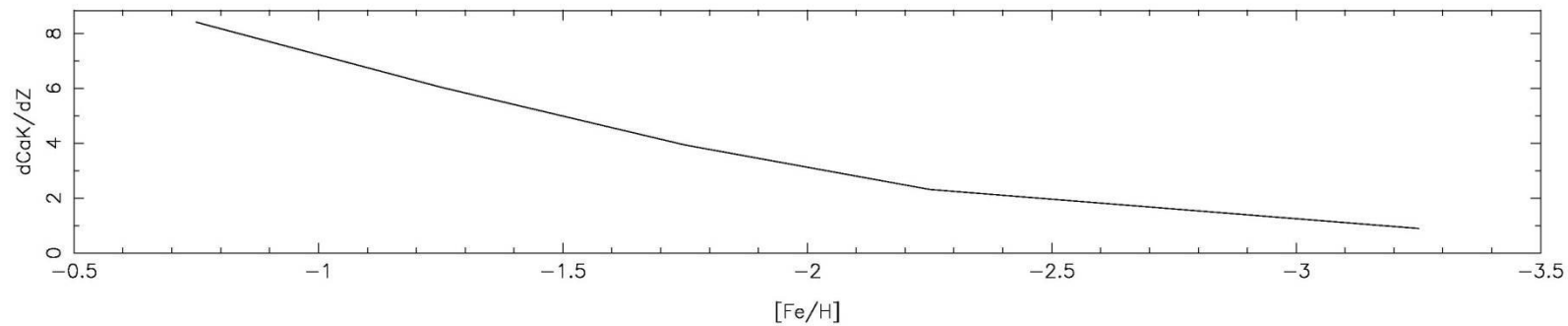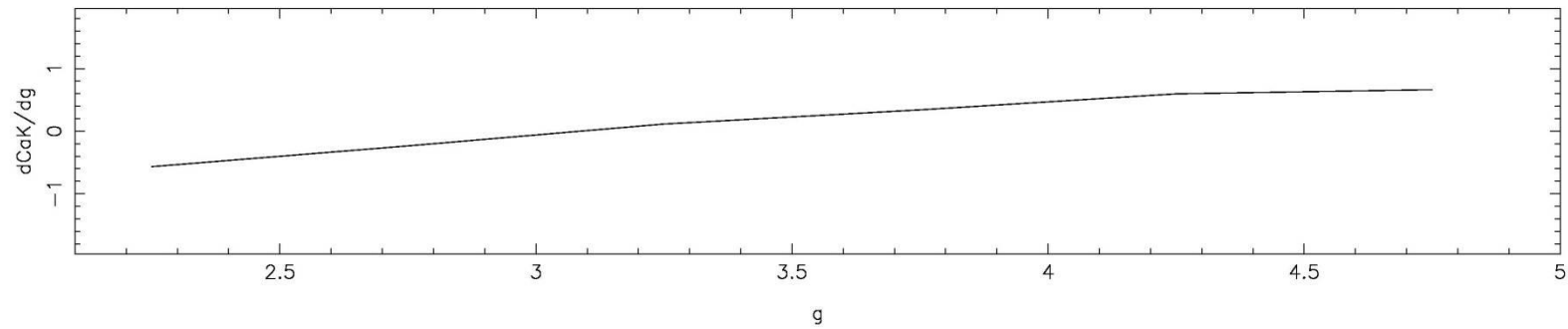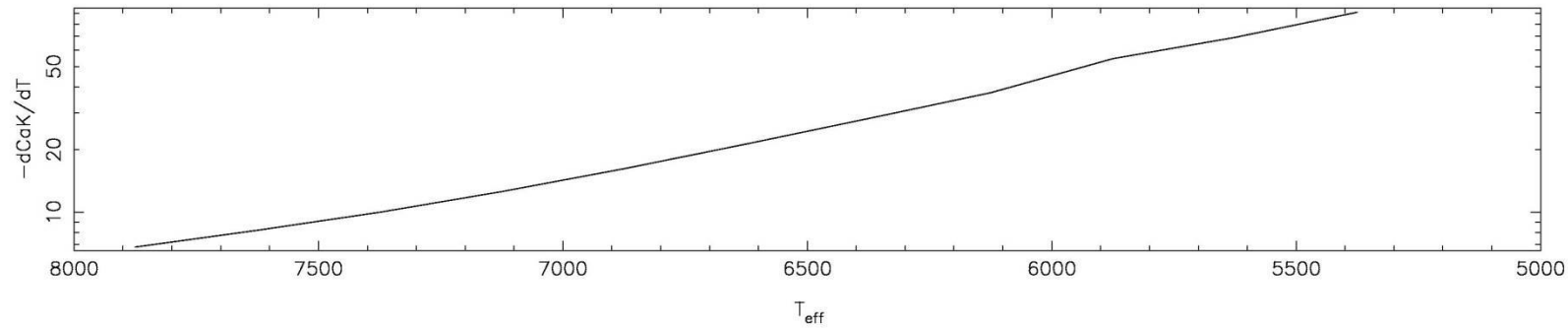
This yields $\delta t = -8\delta\beta$ and

$\delta CaK = 6.1\delta t + 3.1\delta Z$

An error of 0.005 in β implies an error of 1 Gyr in a 12 Gyr population

Hβ from Kurucz models

Ca K from MOOG spectrum synthesis

How many HB stars must be masked?

Many of the galaxies we wish to study in a broad analysis of the formation of the first stars across the Hubble sequence of galaxies are at the distance of the Virgo cluster, where the main sequence turnoff of old stellar populations is at magnitude 35, intractable for current and planned telescopes. However, if we place our 30 meter class telescopes spectrograph slit across the outer parts of NGC 4472, say, and the seeing is good, we can in long exposures recognise individual horizontal branch stars at magnitude 32. If we study the light between these stars and further exclude stars with red colors (subgiants), we have a sample of turnoff stars, which are ideal for age and metallicity study. A quantitative example would be a study of a stellar population at 16 effective radii, 8.3 mag down from the central surface brightness of a de Vaucouleurs profile. If the local surface brightness is 27.5 mag/s^2, a square arcsec would contain 2000 L$_\odot$ at Virgo. This would be composed (by the fuel burning theorem Greggio & Renzini) of some 500 main sequence stars and 4 horizontal branch stars. This is a feasible proposition for a large telescope in natural seeing. Sky subtraction is a challenge at this surface brightness, of course. Working closer to the nucleus would require adaptive optics.

An IFU spectrograph has a significant advantage in this application.

Potential of disintegrated spectra

- Separate measures of mean age and mean metallicity of simple stellar populations
  - distinguish rapid collapse from dwarf merger models
- Initial mass function from FeH Wing-Ford band without contamination from M giants
- Ba/Fe or Ba/Ca ratio would indicate whether the s-process had been active in the extreme halo
- Ca triplet and Paschen lines behave similarly and will be addressable with GSMT AO

Next steps

- Make full main sequence evolutionary synthesis models.

- Effectively this means integrating the present results right down the main sequence

- A trial run on M31 halo with an IFU spectrograph

  - HB stars are B = 25

  - Try μ_B = 24 mag/s^2 *cf* sky = 22 mag/s^2

  - In 1s^2 there is 0.4(24.35-24+5.4) = 2.3 log Lsun

  - In 100s^2 there are 40 HB stars to be masked

  - If you lose 4 fibres for each HB star, that's 160 wasted

How much S/N?

- Take the M31 test case
  - 5000 G2V stars is V = 4.8 + 24.45 − 9.25 = 20 mag
  - $100s^2$ is 21.5 − 5 = 16.5 mag
  - If a 20 mag star yields 10^2 detected photons/A/sec, 16.5 mag of sky yields $10^{0.4} \times 10^3$ /sec
- S/N = $100/(10^{-0.3} \times 100) = 2t^{1/2}$
- S/N = 200 in 10000s, assuming perfect calibration
  - Source surface brightness = 24, Sky = 21.5 mag/s^2

Challenges

- Sky spectrum residuals are solar metallicity

- IFUs have a poor reputation for sky subtraction.

- A differencing scheme involving halo position 1, sky, halo position 2 may be able to cope with this

- The Ba II line at 4554 A is predicted to be 77 mA in a turnoff star at [Fe/H] = -2

  - 100 km/s is 1.5A at 4500A

  - the Ba line will be a 5% dip in the continuum

Summary

- M31 bulge, mostly old stars, some middle aged

  - SFH should be measured in the center and at a radius where a kinematic filter can isolate bulge stars

- Broad metallicity distribution

  - this yields the gas accretion history and SFH

- Maps of mean age and Z are realizable from the turnoff and giant branch respectively

  - either by star counts or disintegrated light

- What was the primary influence on formation?

  - disk, halo, or mergers

There are no formal conference proceedings, but

PASA

is happy to referee
and publish any
speaker's paper