Do Blue Compact Galaxies Have Red Halos?

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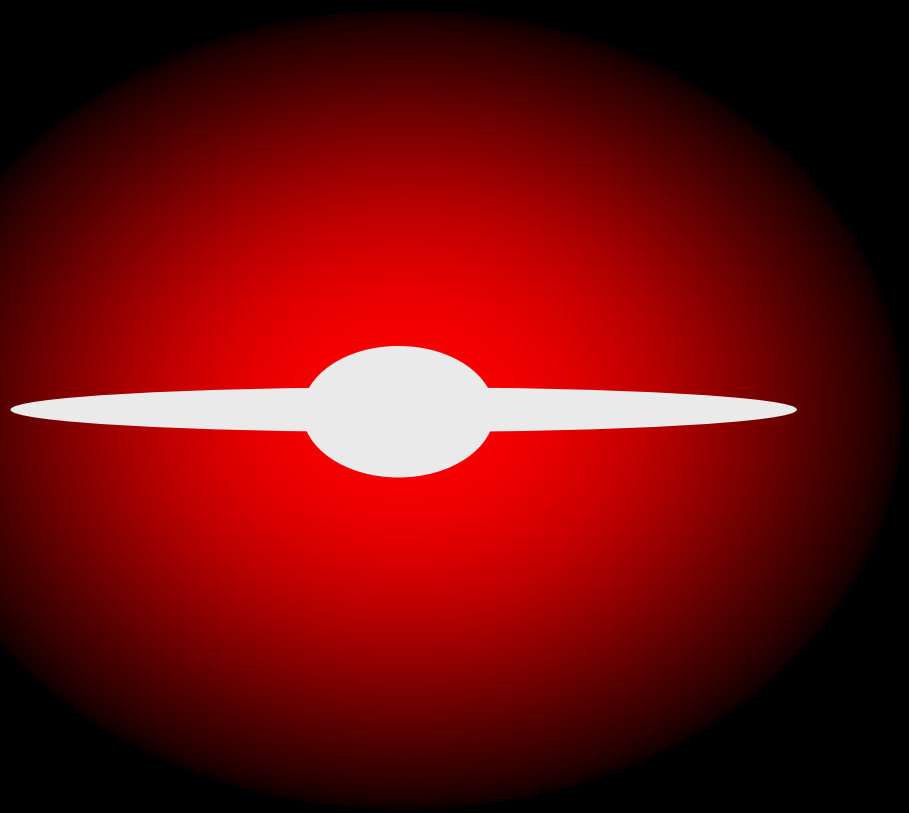
Outline

- The red halos of galaxies
  - The red halo project
  - Red halo stars = missing baryons?
  - Current constraints on red halo populations
- Blue Compact Galaxies
  - The case for red halos around BCGs
  - New model results
  - Observational challenges

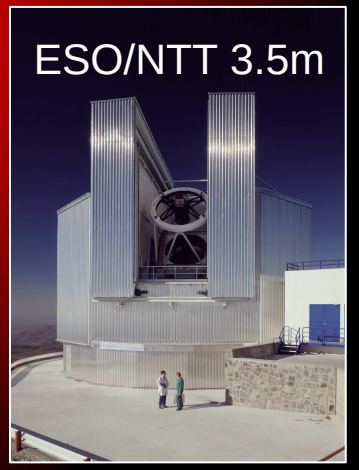
Red halos

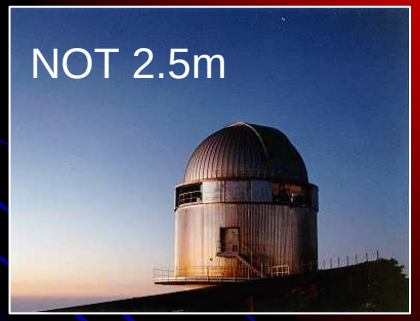


Early detections:

- Edge-on disk galaxy NGC 5907 (Sackett et al. 1994, Nature, 370, 441; Rudy et al. 1997, Nature 387, 159)
- cD-galaxy in A 3284 (Molinari et al. 1994, A&A 292, 54)

The Red Halo Project





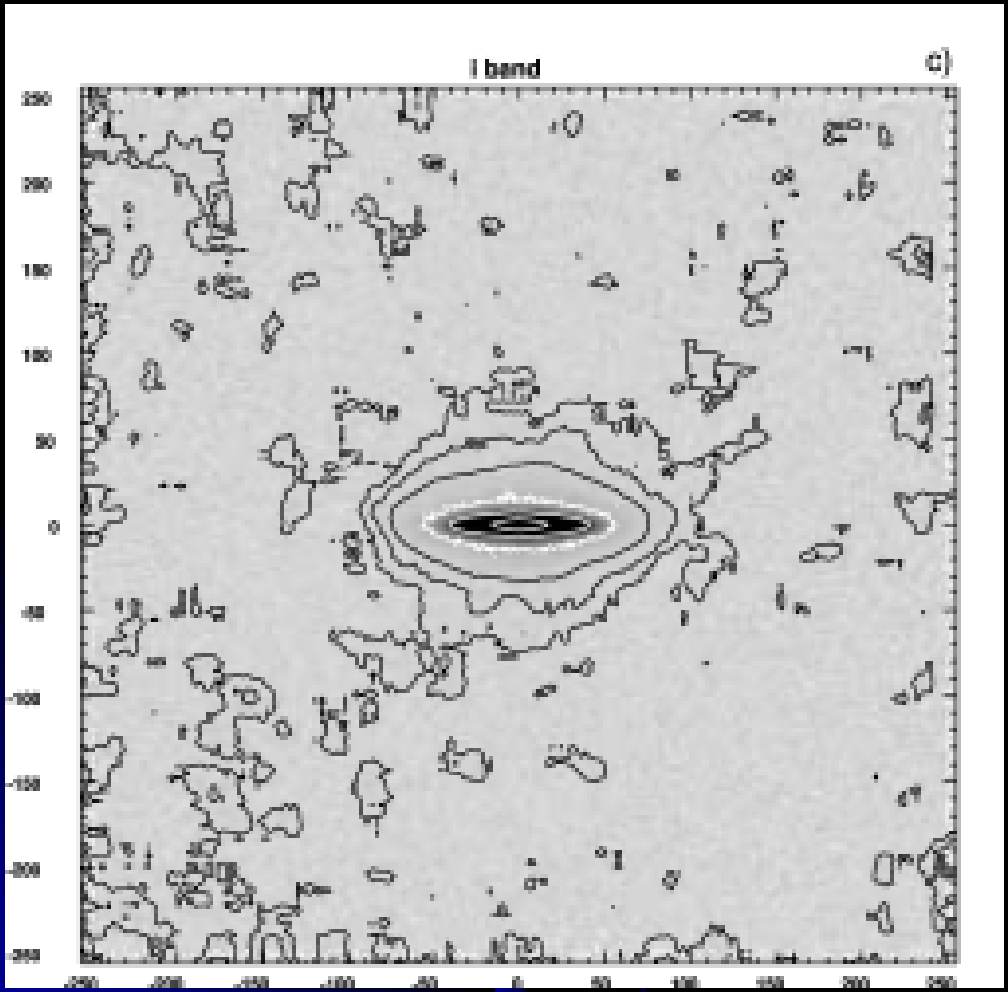
Team members:

- Erik Zackrisson
- Nils Bergvall
- Chris Flynn
- Genoveva Micheva
- Göran Östlin
- Brady Caldwell
- Elisabet Leitet
- Polychronis Papaderos
- Joseph Silk
- Kai Noeske

Ongoing searches

- Observational searches for red halos of:
  - Elliptical galaxies
  - Post-starburst galaxies
  - Local Group dwarf galaxies
  - Tidal dwarf galaxies
  - A larger sample of BCGs

Halos of Edge-On Disk Galaxies in the SDSS I

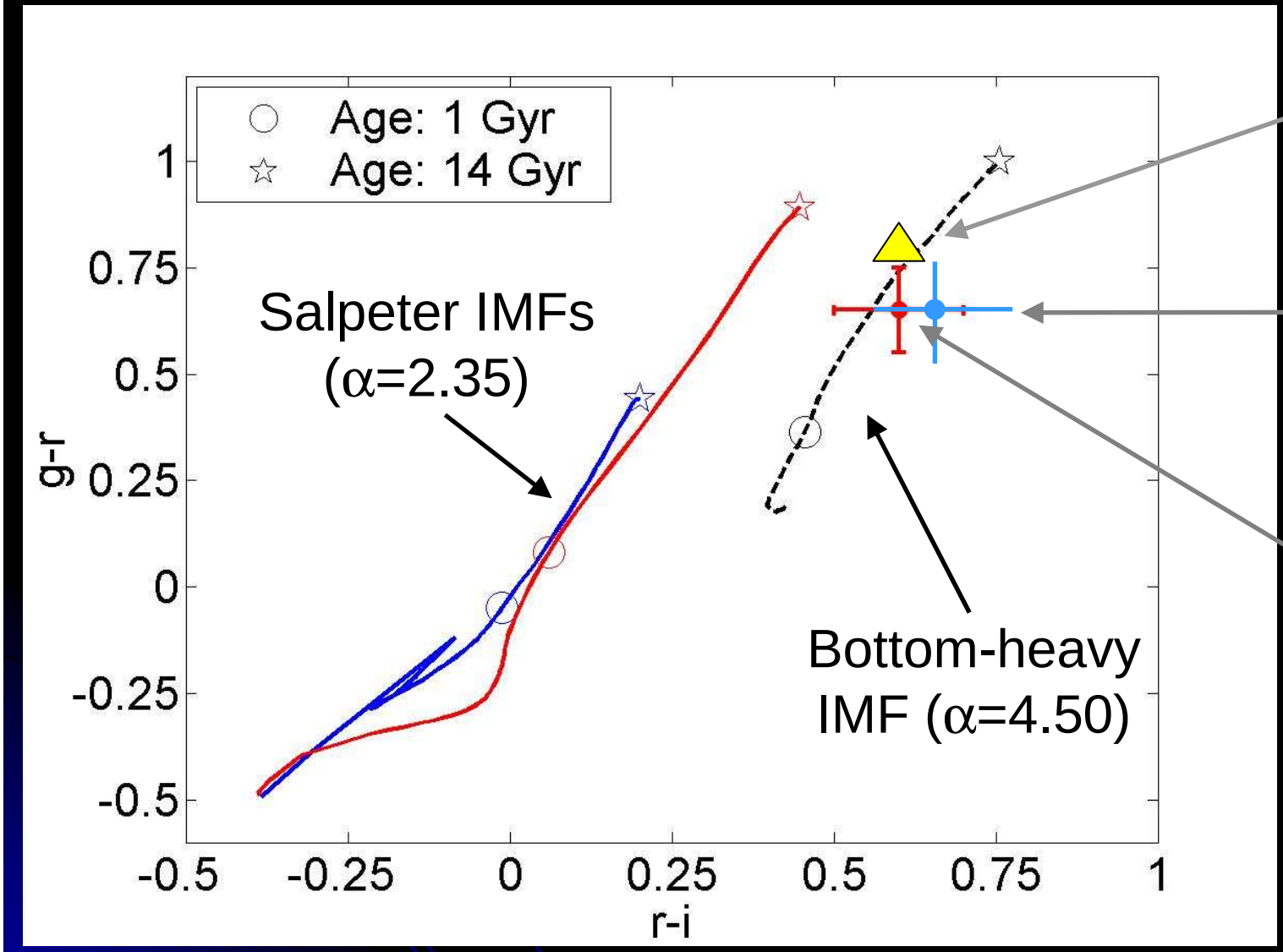


High surface brightness disks
Zibetti et al. (2004, MNRAS, 34, 556)

Low surface brightness disks
Bergvall et al. (2008, in prep.)

Red halos detected at
$\mu_g \geq 28$ mag arcsec^{-2}

Halos of Edge-On Disk Galaxies in the SDSS II



Halo of NGC 5907

Bergvall et al. (2008) halo

Zibetti et al. (2004) halo

$$\frac{dN}{dM} \propto M^{-\alpha}$$

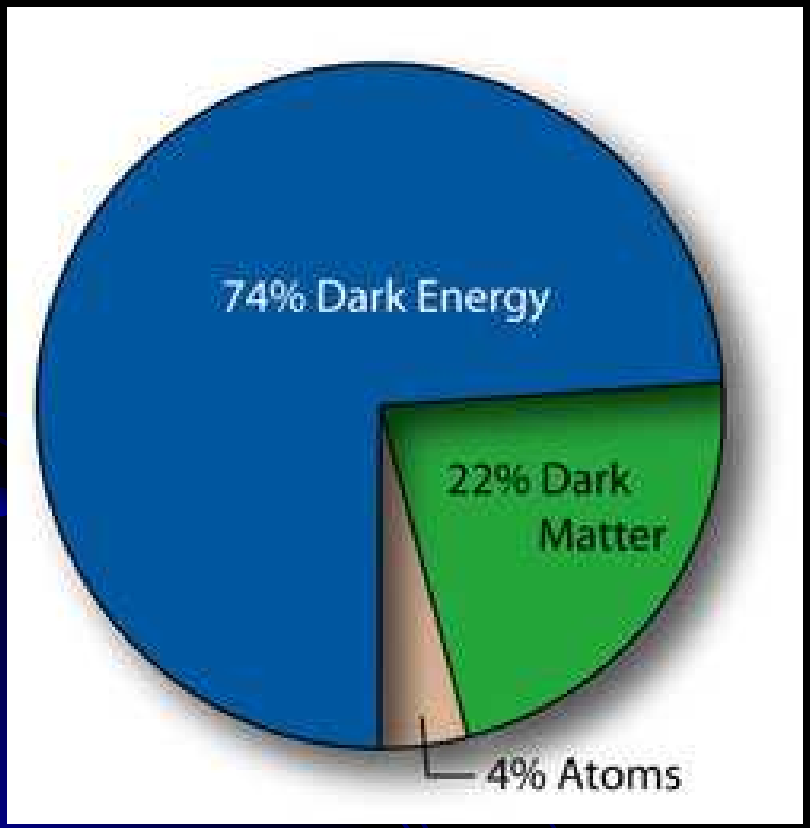
A bottom-heavy IMF with α=4.50 explains the observations (Zackrisson et al. 2006, ApJ, 650, 812)

Red halo stars as dark baryons

- A stellar pop with dN / dM $\propto$ $M^{-4.50}$ IMF has mass-to-light ratio: $M/L_B > 40 \rightarrow$ Effectively baryonic dark matter
- Very small contribution to overall light (1-10 %), yet substantial contribution to baryonic mass
- Can be detected in integrated light because it happens to be more extended than normal stellar populations of galaxies
- But note: Non-baryonic CDM still dominates the overall dark halo mass of large galaxies like the Milky Way

Zackrisson et al. (2006, ApJ, 650, 812)

Baryonic & Non-Baryonic Dark Matter I

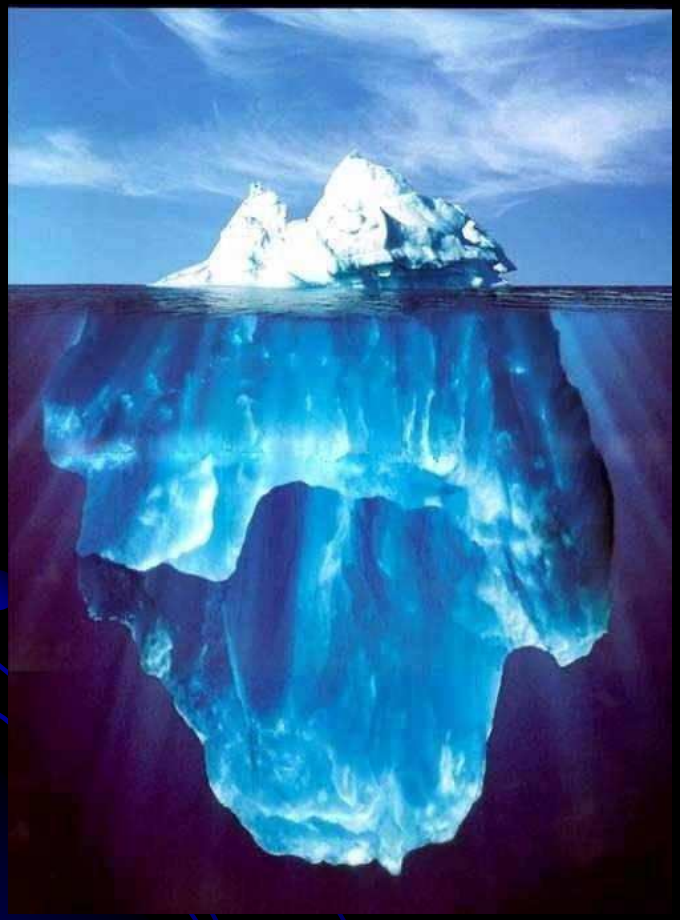


Not a completely fair representation!

~1/3-2/3 of the baryons are still missing at z<1

Fukugita (2004)
Fukugita & Peebles (2004)
Nicastro et al. (2005)
Bregman (2007)
Prochaska & Tumlinson (2008)

Baryonic & Non-Baryonic Dark Matter II



9±3% Dark baryons

$\Omega_{BDM} \approx 0.015\text{-}0.031$

91±3% Non-baryonic DM

(Cold Dark Matter)

$\Omega_{CDM} \approx 0.23$

The Matter Sector

Baryonic & Non-Baryonic Dark Matter III

But ~9 % is damn small…

Why bother with that stuff?

- Potentially very important implications for galaxy evolution ($\Omega_{\text{bar, DM}} \approx 6\text{-}12 \times \Omega_{\text{stars}}$)
- Spatial distribution may be very different from that of CDM $\rightarrow$
  - Subdominant on large scales, but not necessarily on small
  - May interfere with CDM tests on subgalactic scales (core/cusp issue, subhalos, tidal dwarfs)

Where are the Dark Baryons Hiding?

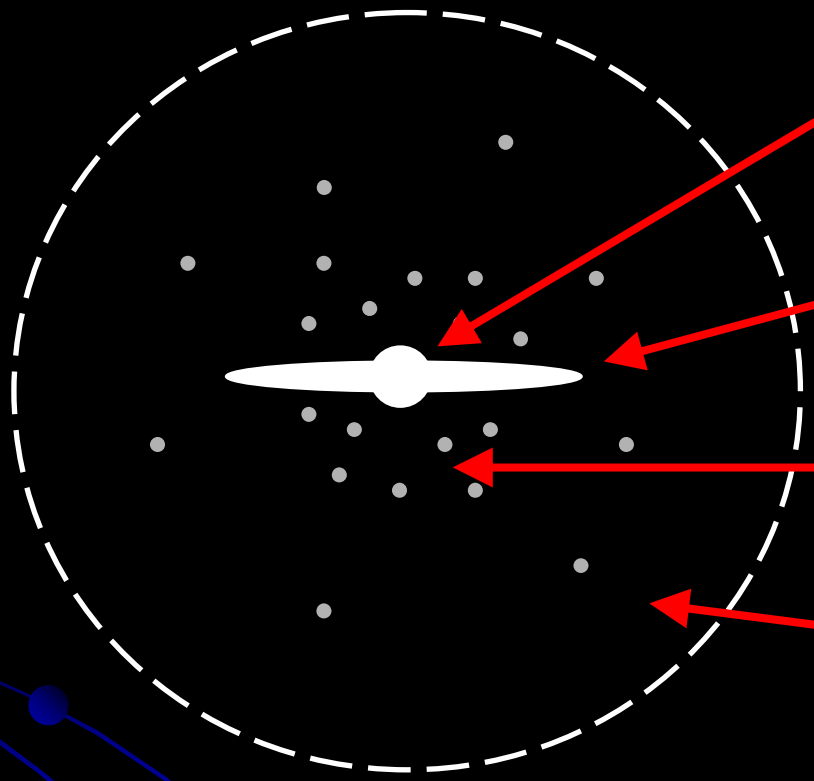
- Warm/hot intergalactic medium
- Hot gas around galaxies

Favoured by simulations
Cen & Ostriker ’99
Davé et al. ’01
Maller & Bullock ’04
Fukugita & Peebles ’06
Sommer-Larsen ’06

- Cold gas ← Favoured by observations of tidal dwarf galaxies
Bournaud et al. ’07

- Faint stars ← Favoured by observations of red halos (and possibly microlensing)

Missing Baryons in The Milky Way



Milky Way Bulge
$M \sim 2 \times 10^{10}\ M_{solar}$

Milky Way disk(s)
$M \sim 6 \times 10^{10}\ M_{solar}$

Stellar halo
$M \sim 10^{9}$ Msolar

Dark halo
$M \sim 10^{12}$ Msolar

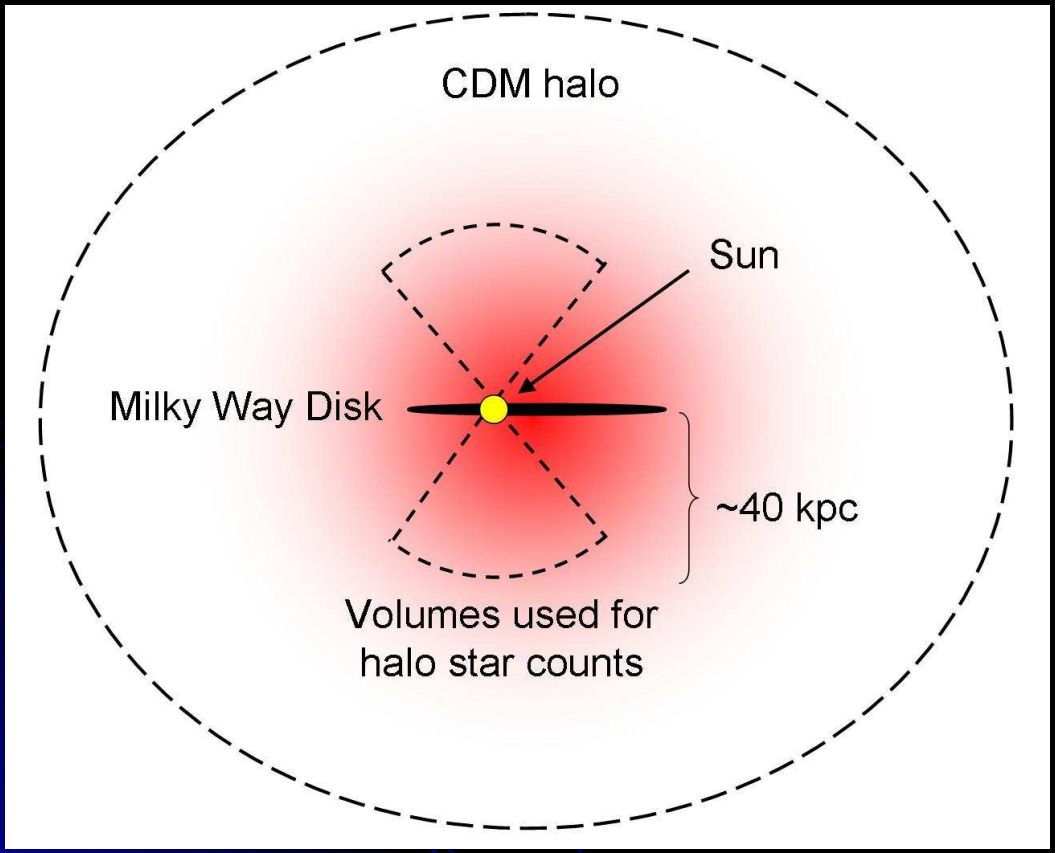
Crain et al. (2007) & WMAP 5-yr results $\rightarrow$
Baryonic mass $\sim 15 \times 10^{10}\ M_{solar}$ expected within R_{vir}
Only $\sim 8 \times 10^{10}\ M_{solar}$ identified

We are missing a few times $10^{10}\ M_{solar}$ of baryonic material!

Constraints from Direct Star Counts

Observed red halo properties and $\alpha = 4.50$ IMF

$\rightarrow M_{red} \sim$ few times 10^{10} Msolar inside R_{vir}. Great!

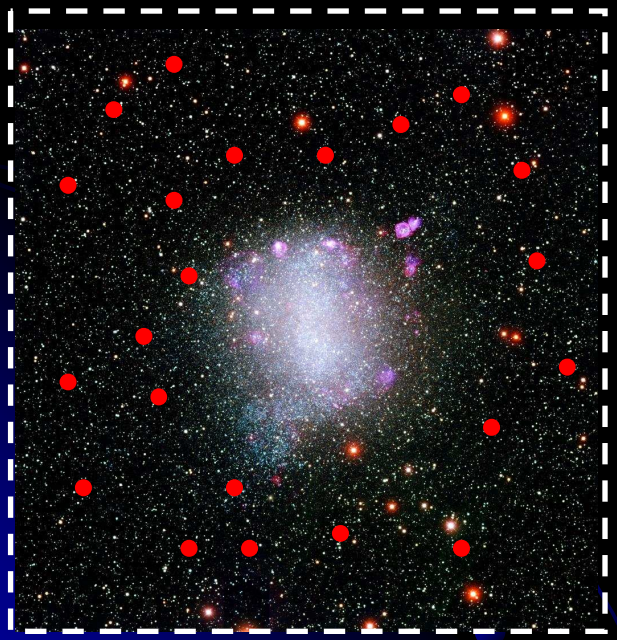


But: Smooth red halo of low-mass stars ruled out by HST star counts $\rightarrow$ Red halo stars would have to be highly clustered

Zackrisson & Flynn 2008 (ApJ, in press, arXiv0809.2991)

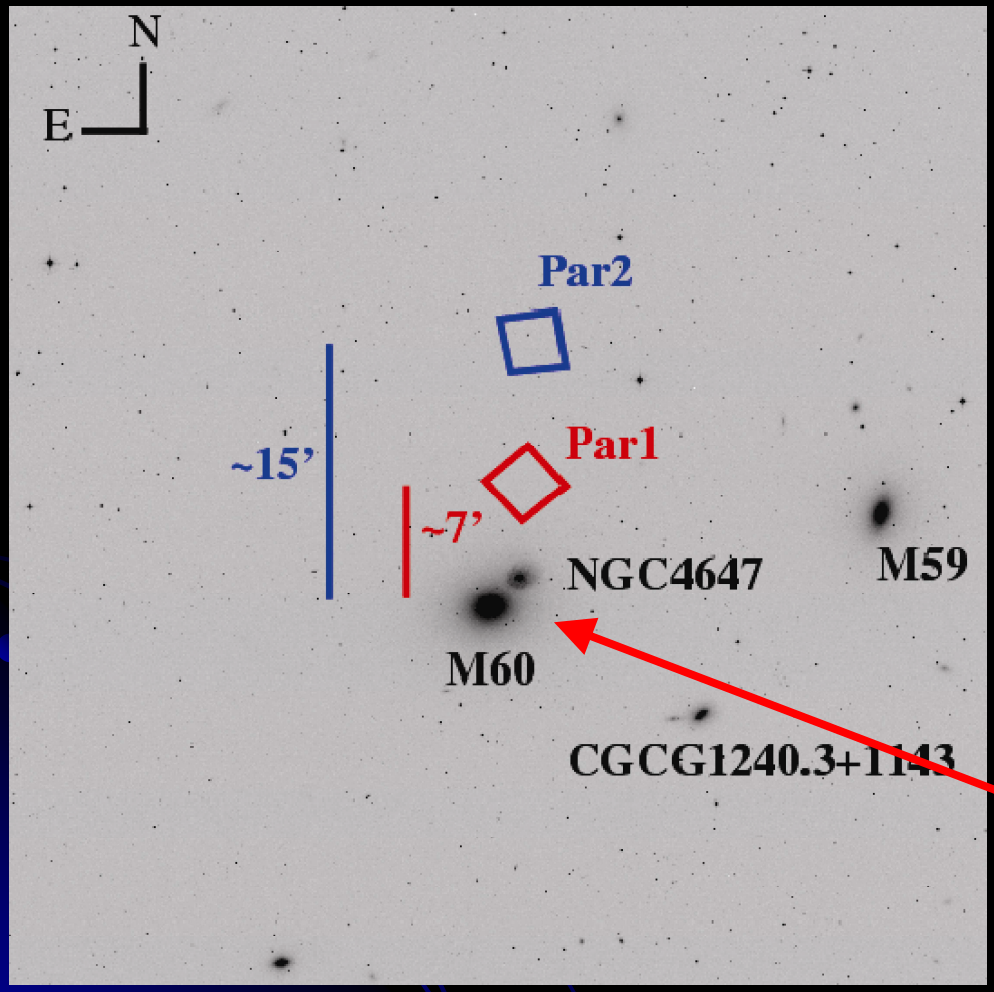
Observable Consequences of Clusters of Low-Mass Stars

Deep, high-resolution observations of nearby halos should unravel point-sources with luminosities of single red giants but very strange colours



- Mass ~10^5 Msolar ('Dark Globulars')
  $\rightarrow$ M_I ~-4 (Typical TRGB luminosity)
- Could be ~10^5 such objects in Milky Way-sized halo
- Would evade all dynamical constraints (Kerins '97; Carr & Sakellariadou '99)

M60 – A Rosetta Stone for Red Halos?



Serendipitous discovery of extremely red objects in the halo of M60, while using the HST to search for z~6 galaxies

The colours of these objects do not match any known type of star!

M60
~14 Mpc away

Yan et al. 2008, ApJ, 675, 136

What about blue compact galaxies?

ESO 338-IG04 (HST)

What is out here?

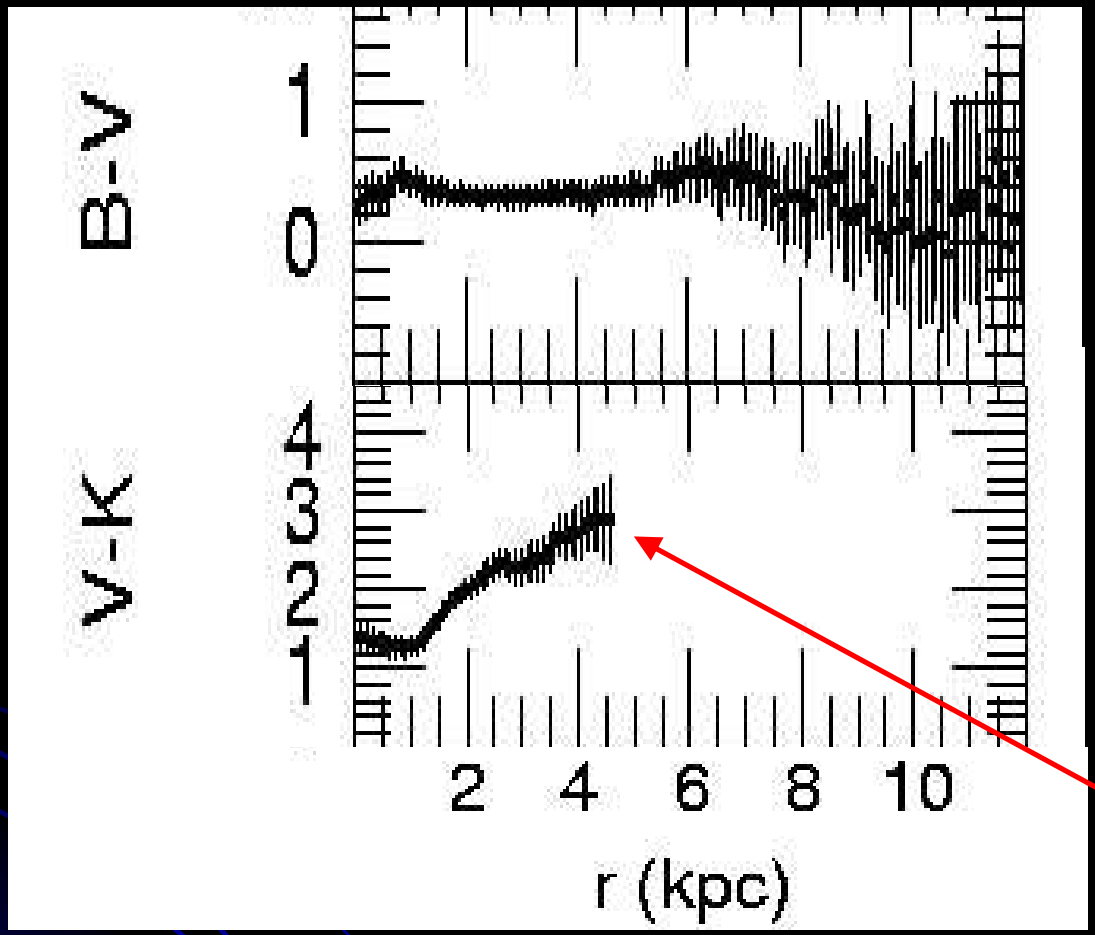
Host?

Progenitor?

Envelope?

Halo?

Red halos around BCGs I



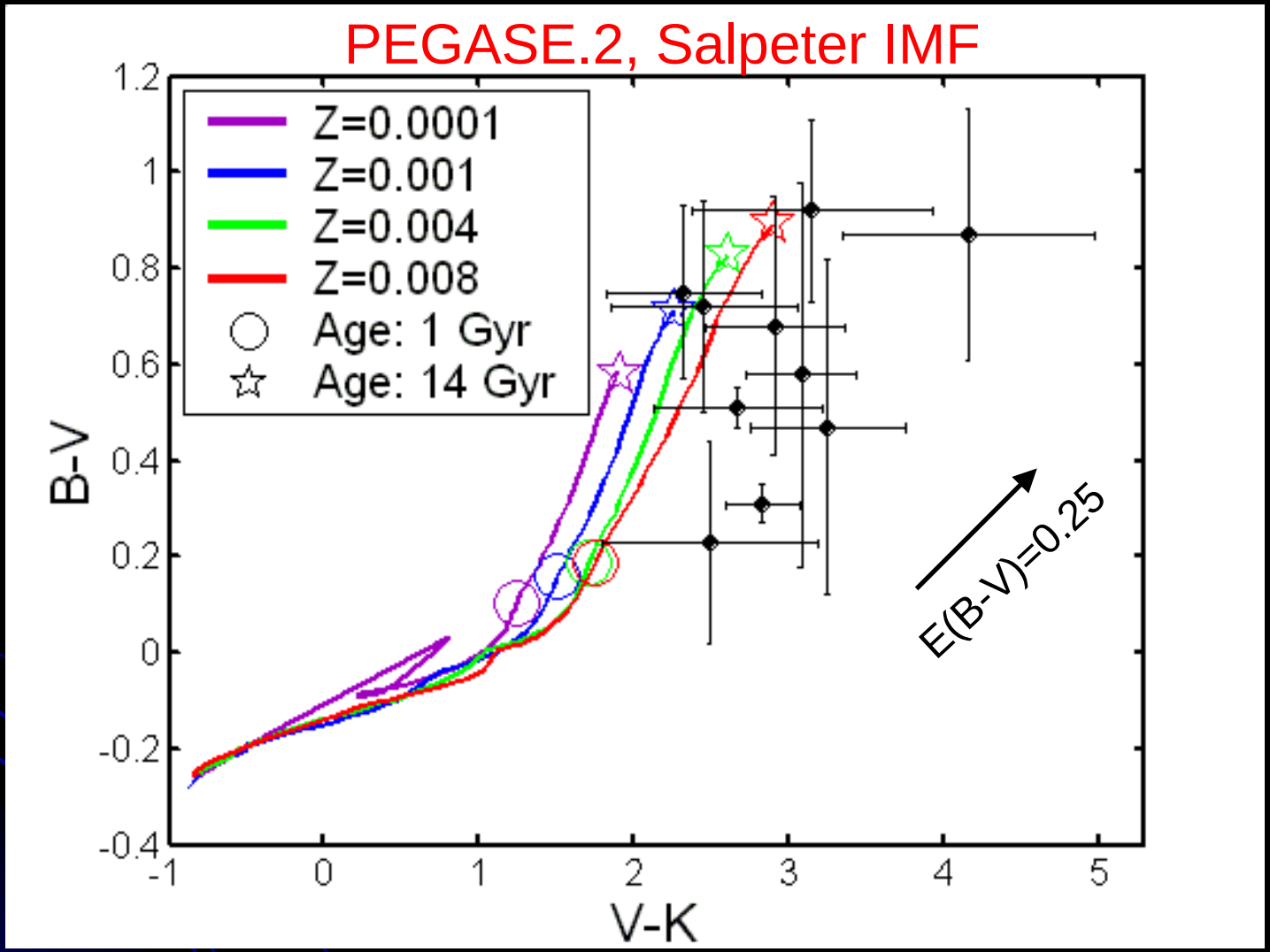
Surface photometry down to $\mu_K \sim 23$ mag arcsec^{-2}

Bergvall & Östlin 2002, A&A 390, 891

Very red!

Expected signature of bottom-heavy IMF:
Flux excess in I-band and redward
Detectable in (for example): V-I, R-I, V-J, V-H, V-K
But not in: B-V, V-R, J-H, H-K

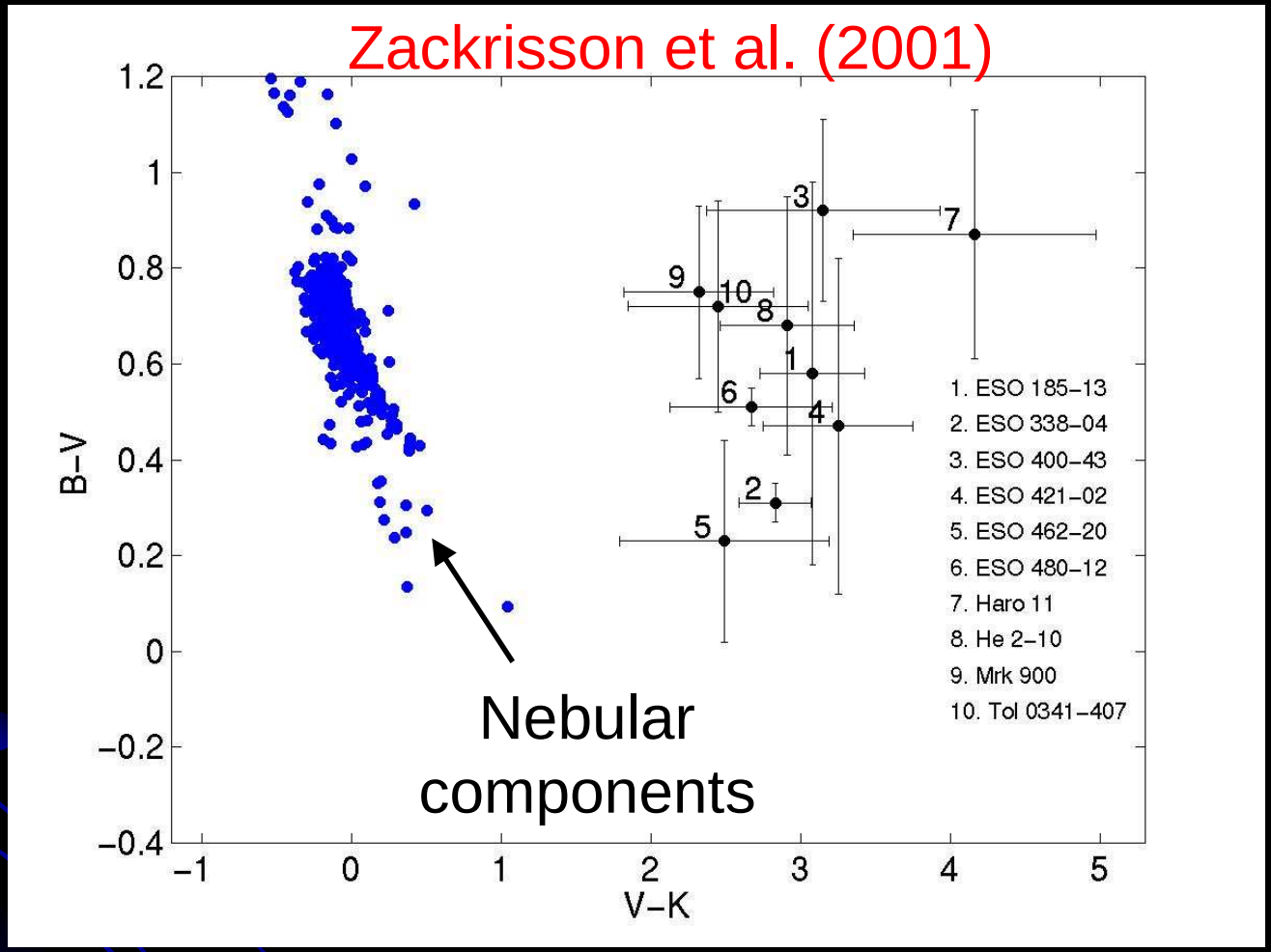
Red halos around BCGs II



A low-metallicity, Salpeter-IMF population won't do!

Bergvall & Östlin (2002), Zackrisson et al. (2006)

Red halos around BCGs III

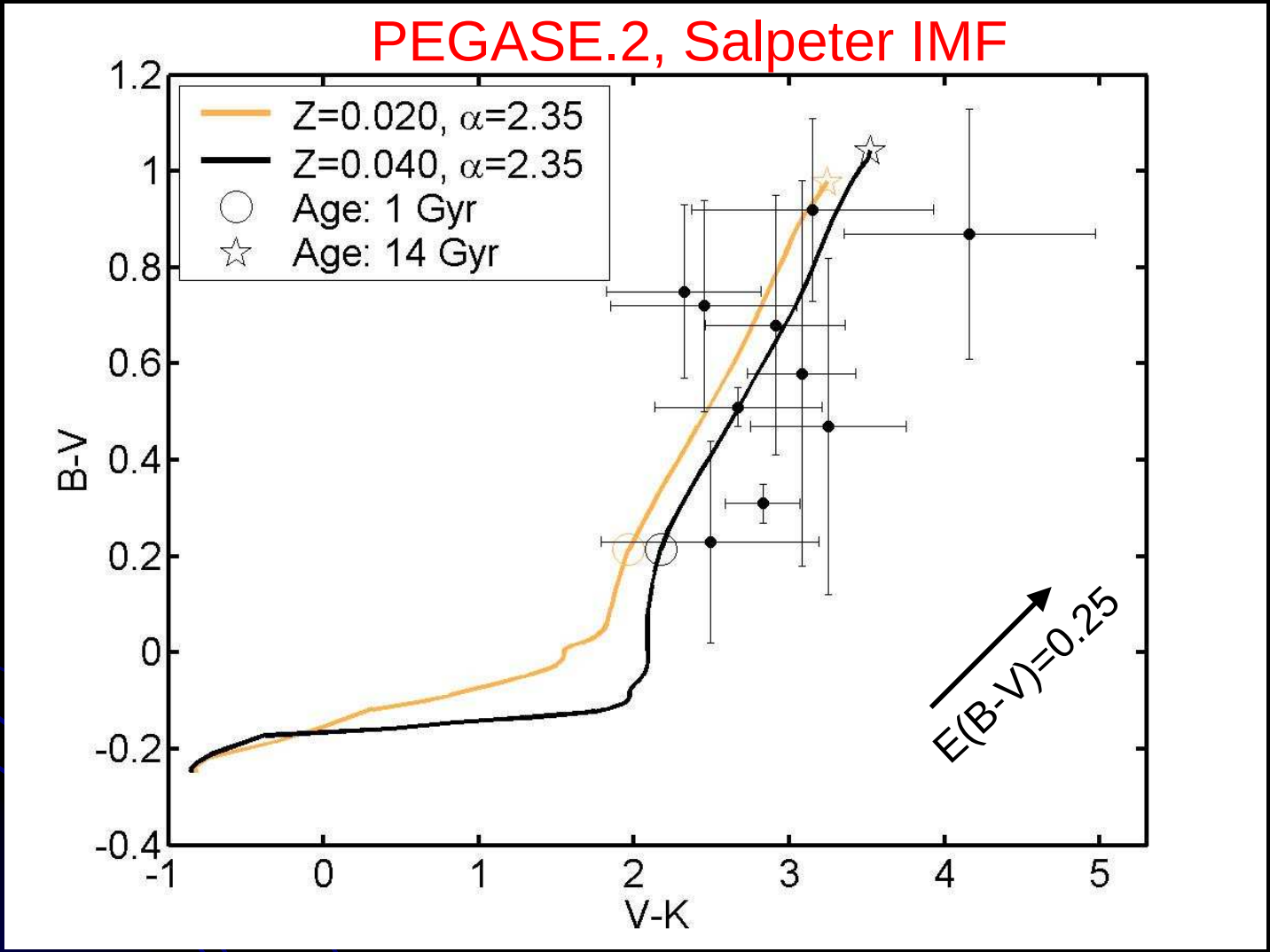


Nebular emission won't do!

Correcting for this would just make the halo even redder…

Bergvall & Östlin (2002), Zackrisson et al. (2006)

Red halos around BCGs IV

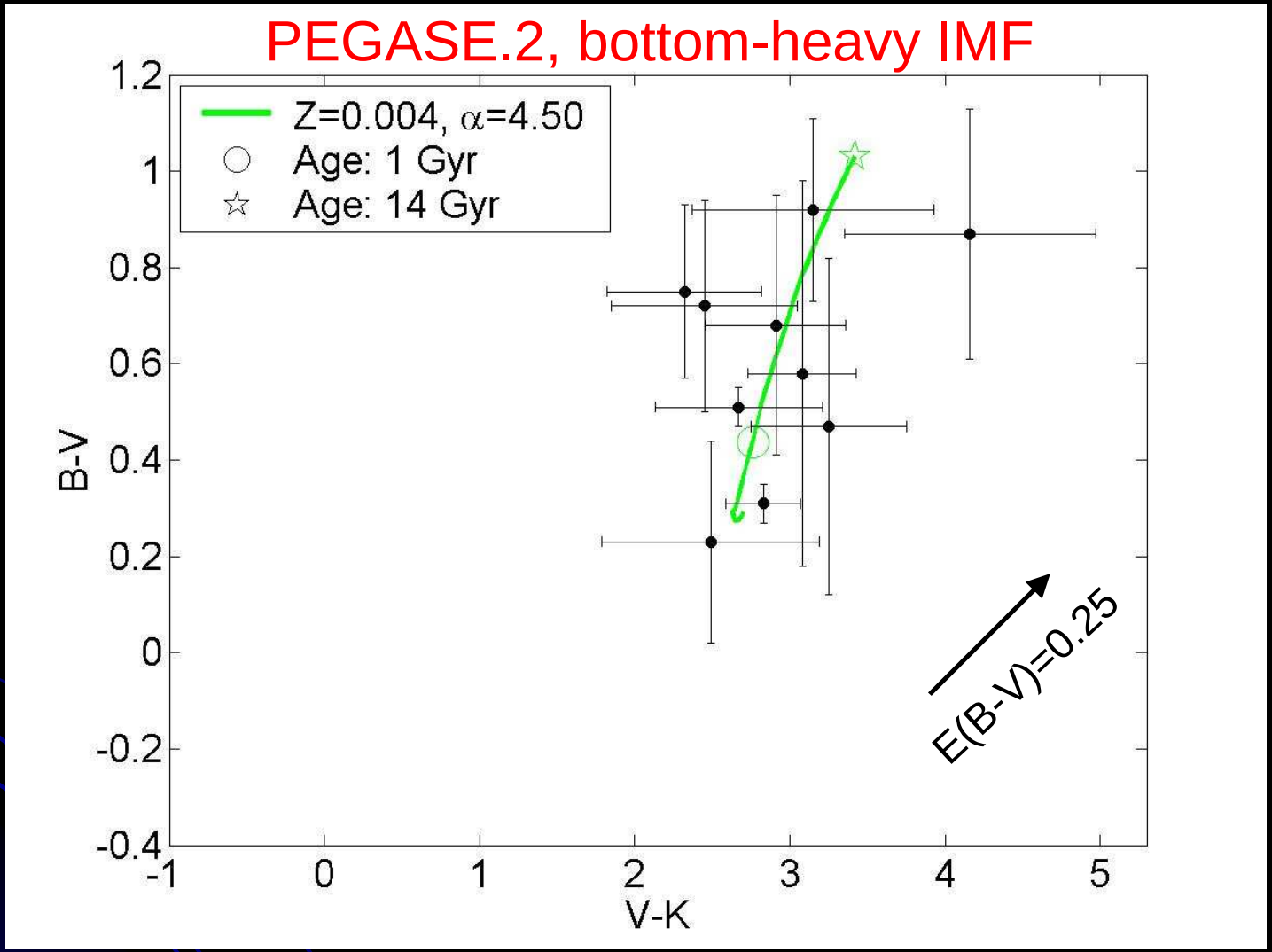


A Salpeter-IMF population with very high metallicity will do!

But note: measured metallicities are low…

Bergvall & Östlin (2002), Zackrisson et al. (2006)

Red halos around BCGs V

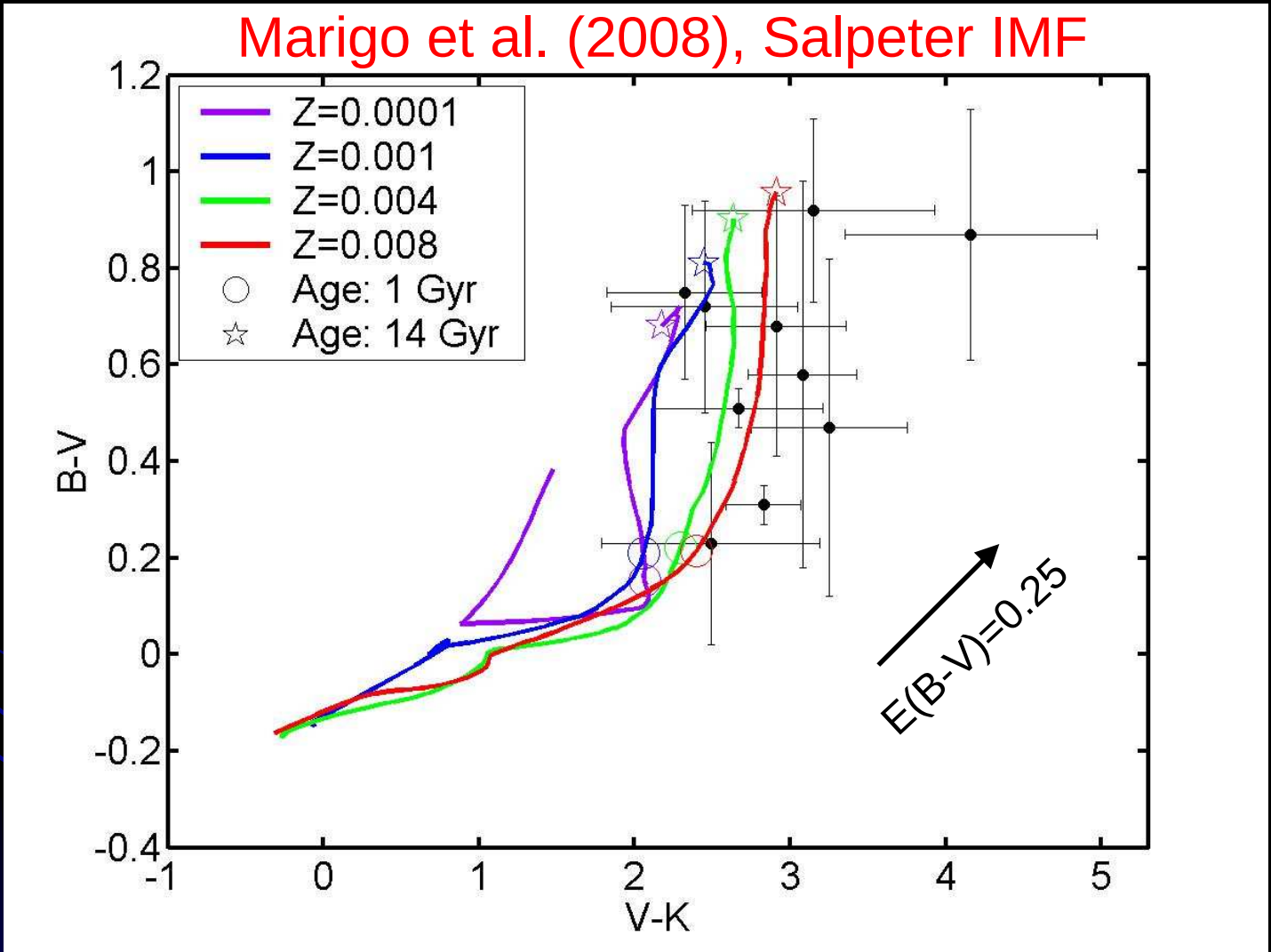


A bottom-heavy IMF population with low metallicity will do!

Note: the α=4.50 IMF works here as well!

Zackrisson et al. (2006)

Recent updates in spectral synthesis



Improved treatment of TP-AGB →

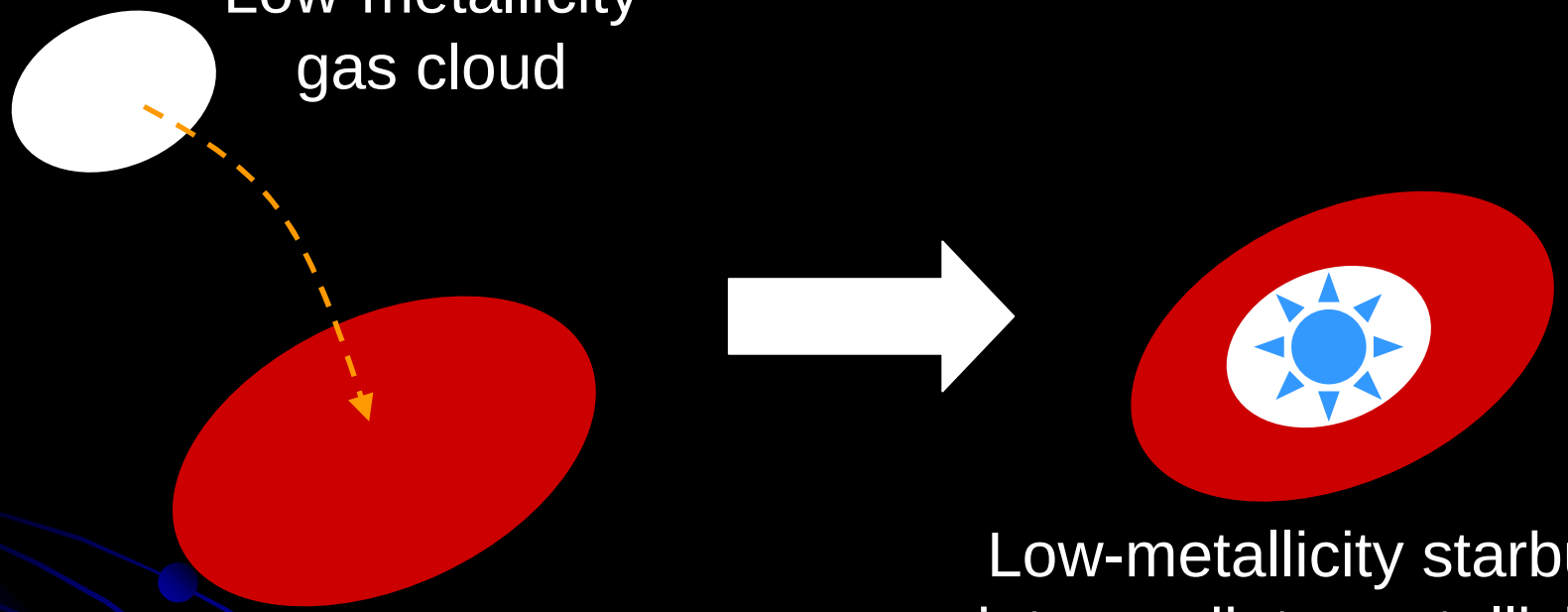
A Salpeter-IMF population with Z≤0.008 (and a bit of dust) does OK!

Normal IMF and intermediate metallicity?

- $Z \leq 0.5$ Zsolar explains the *BVK* colours of the majority of hosts
- Normal IMF $\rightarrow$ Most objects in this sample would have $M_{stars} \sim 10^9$-10^{10} Msolar
- M-Z relation (Panter et al. 2008) $\rightarrow$
  - Z~0.5 Zsolar not remarkable for 10^{10} Msolar
    Z~0.5 Zsolar is high for 10^9 Msolar, but not unheard of (e.g. Peeples et al. 2008)

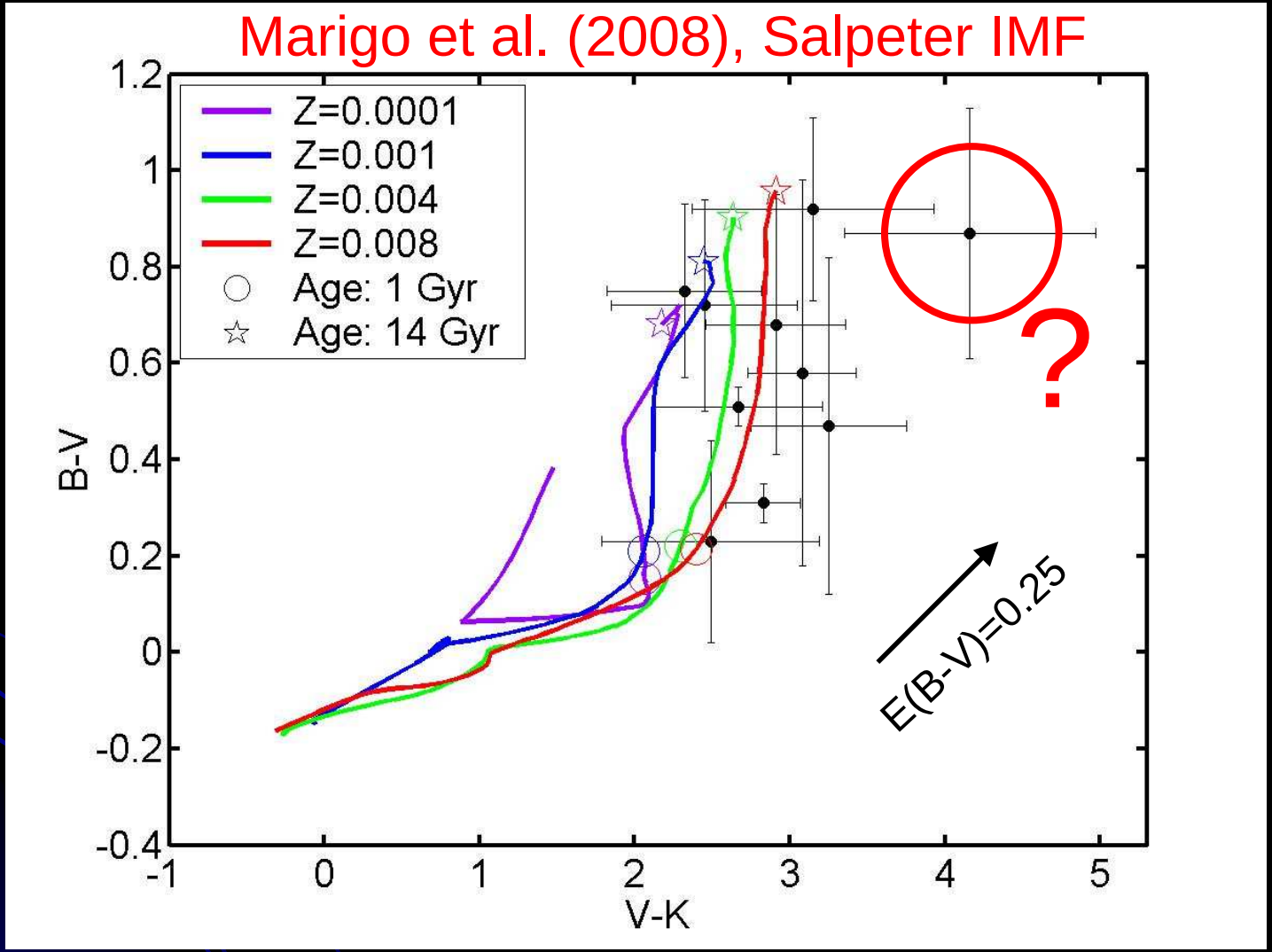
But why is $Z_{gas} < Z_{host}$?

A possible formation scenario



Note: This requires Z(r) trend opposite
of that predicted by the Bekki (2008) simulation

What about Haro 11?



Outlier because of large error bars or genuine red halo?

See Micheva's talk!

Observational challenges of deep surface photometry: Sky subtraction

Red halos typically turn up at:

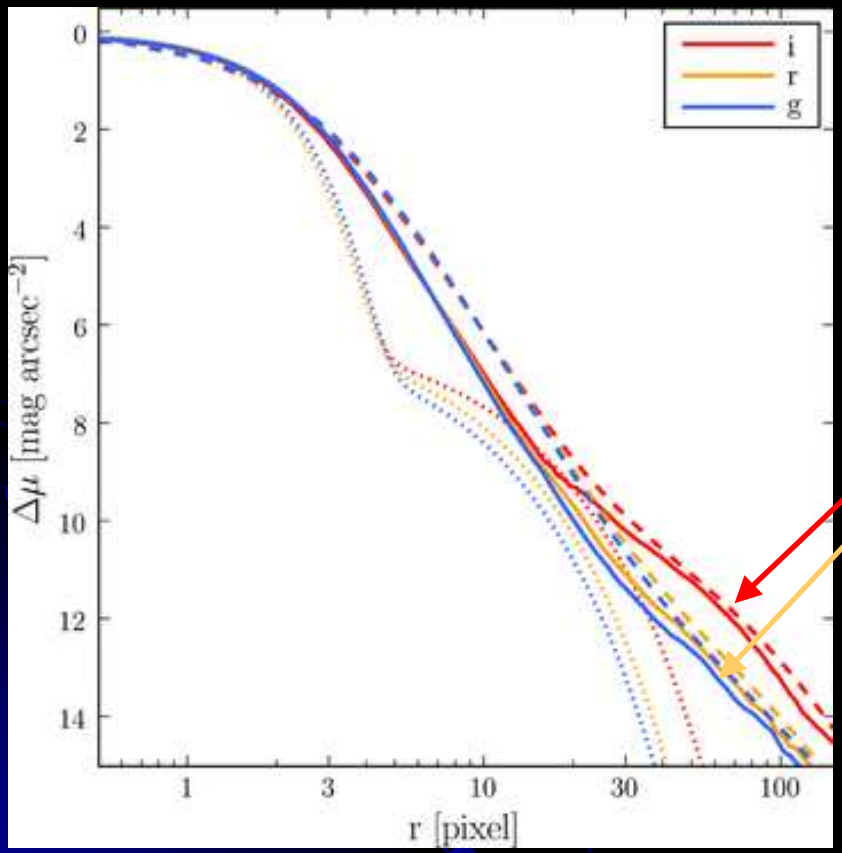
- $\mu_{V \text{ or } g} \sim 27\text{-}28$ mag arcsec^{-2} 100-300 times fainter than sky
- $\mu_{i \text{ or } I} \sim 26\text{-}27$ mag arcsec^{-2} 300-600 times fainter than sky
- $\mu_K \sim 23$ mag arcsec^{-2} ~10000 times fainter than sky

The sky must be subtracted with excruciating accuracy!

All kinds of tests are in progress to check the reliability of the reduction methods used – see Micheva's talk

Observational challenges of deep surface photometry: Instrumental scattering

Red wing of the SDSS PSF



Red wing → spuriously red *r-i* for small objects

De Jong (2008) argues that this effect explains the red excess seen in the halo of stacked SDSS disks.

Our analysis (Bergvall et al., in prep) → *No!*

Mundane explanations I

- Dust reddening?

  Balmer decrement of BCGs $\rightarrow$ No!

  Red halo colours also incompatible with standard reddening vector

- Extended red emission (from dust) in the i-band?

  Possibly, but would imply different explanations for excesses seen in I-band and K-band

- Dust emission in the K-band?

  ISO observations of BCGs $\rightarrow$ No!

Mundane explanations II

- Spectral synthesis problems?

  In the I-band, BC03, Pegase2, Zackrisson et al. (2001), Maraston (2005), Li & Han (2007) and Marigo et al. (2008) models all confirm that extreme stellar population properties are required.

- Sky subtraction problems?

  Tests with synthetic galaxies underway

  Effects associated with extragalactic background light (Zackrisson et al., in preparation) – See Micheva's talk

- Some instrumental effect ?

  Same red excess seen with different telescopes and instruments. No similar red halos seen around stars $\rightarrow$ No!

Red halo stars as MACHOs

Characteristic mass of red halo stars: M ~ 0.1-1 M_{solar}

Can this explain the MACHO microlensing events?

MACHOs contribute <10% to the mass of dark halos

e.g. Tisserand et al. 2007 (LMC/SMC)

…but there still appear to be halo microlensing events that are difficult to reconcile with known stellar populations

Alcock et al. 2000 (LMC)

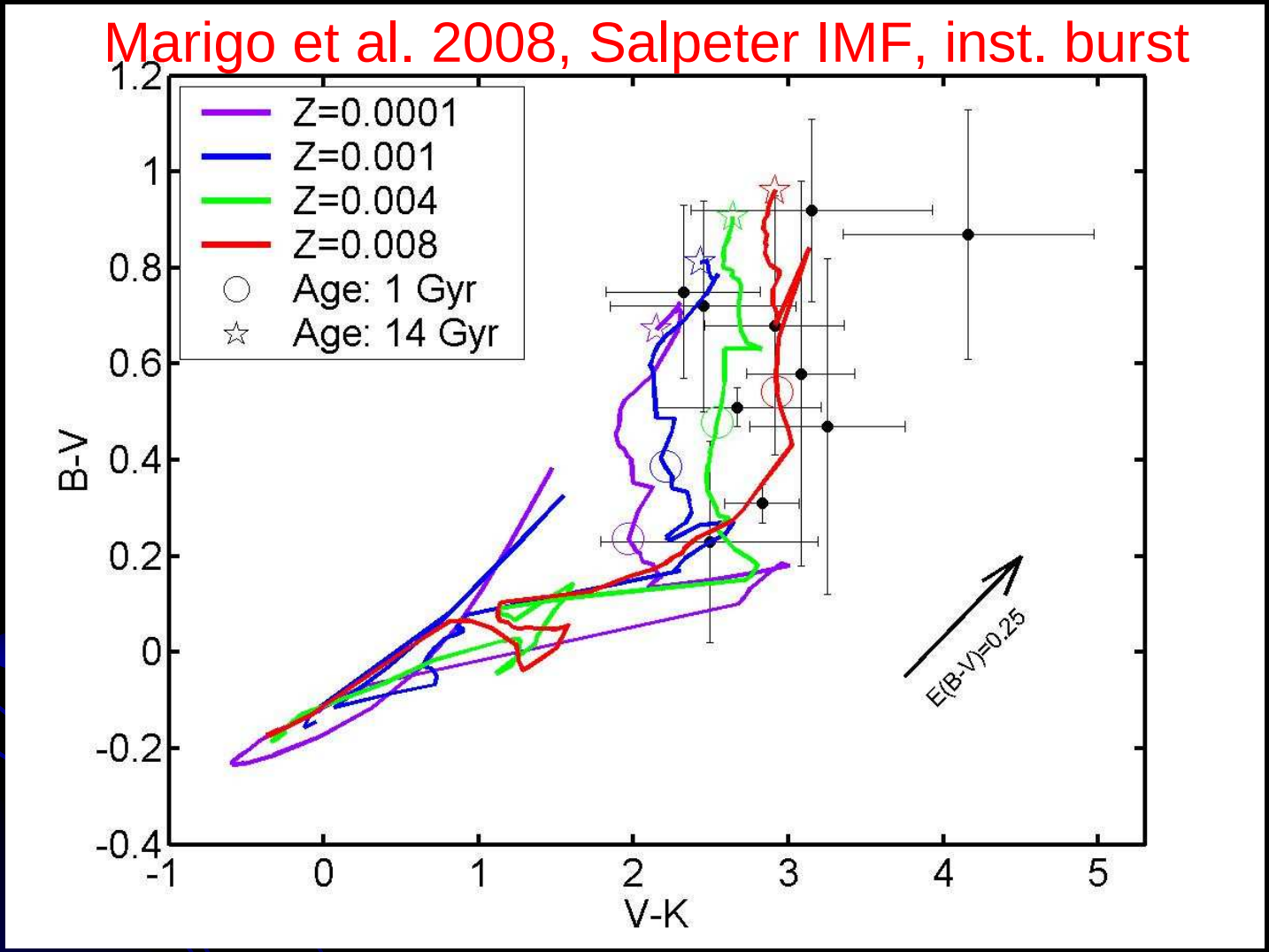
Calchi-Novati et al. 2005 (M31)

De Jong et al. 2006 (M31)

Riffeser et al. 2008 (M31)

Recent updates in spectral synthesis

Marigo et al. 2008, Salpeter IMF, inst. burst



Summary

- Red halos of low-mass stars: possible reservoirs for some of the missing baryons
- But: Claims of red halos around BCGs questionable
- Most recent models $\rightarrow$ Normal IMF and intermediate metallicity does OK
- Haro 11 is the only obvious outlier