The Origin of the Far-UV Excess in Elliptical Galaxies

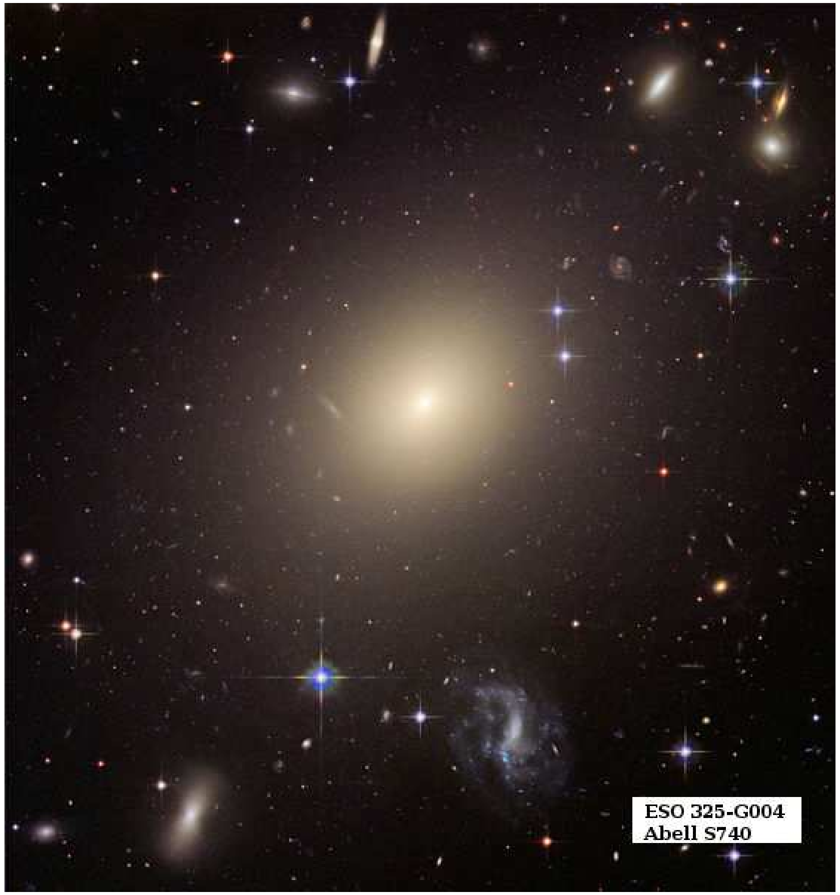
Philipp Podsiadlowski (Oxford),
Zhanwen Han (Kunming),
Anthony Lynas-Gray, David Brown, Kevin Schawinski (Oxford)

(Han, Podsiadlowski & Lynas-Gray, 2007, MNRAS, 380, 1098)

Motivation:

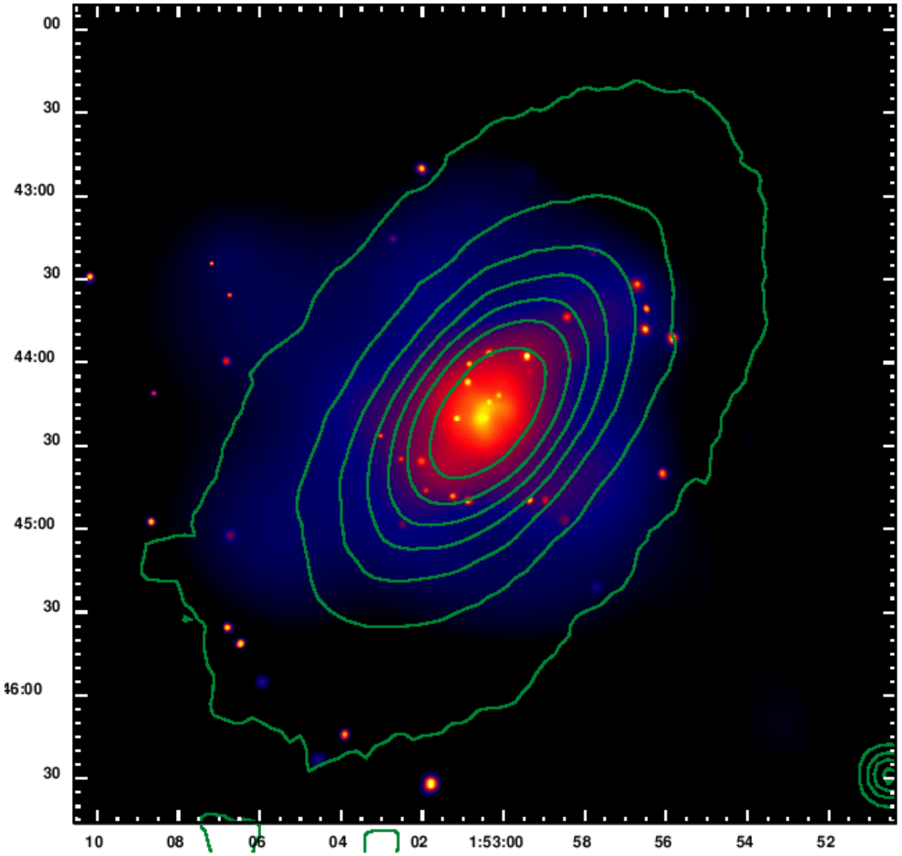
- the discovery of far-UV radiation in "old" elliptical galaxies in 1969 was a major surprise and has remained one of their most enduring puzzles
- however, we 'understand' the origin of the dominant population of old blue objects in the Milky Way:
  hot subdwarfs in binary systems

→ Can these objects explain the far-UV excess in elliptical galaxies?



→ need realistic modeling of stars in external galaxies

The elliptical galaxy NGC 720 (Cetus)



NGC 720 (Chandra) (Jeltema et al. 2003)

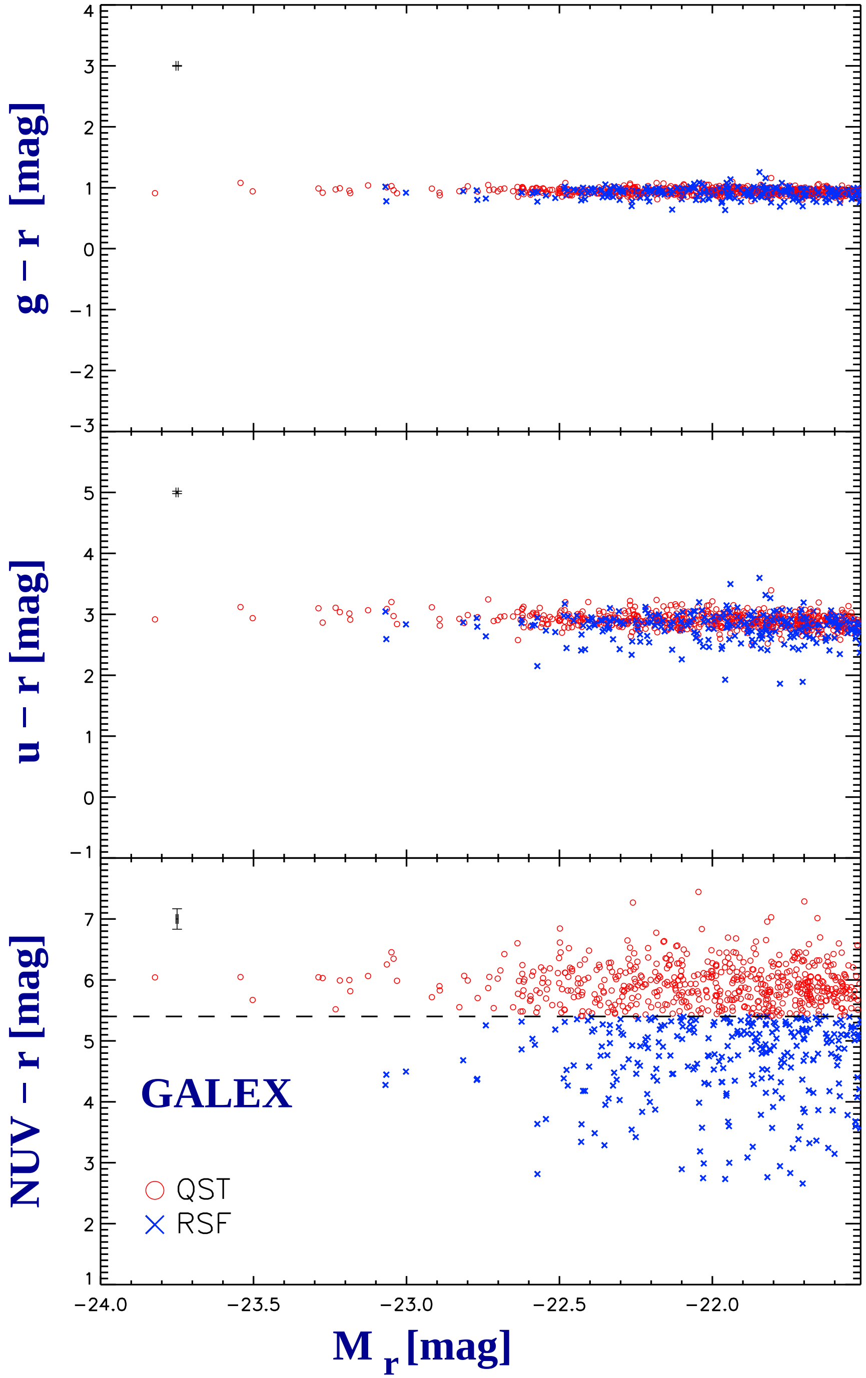
- evidence for a mis-aligned dark matter halo or recent merger activity?
- 9 ultraluminous X-ray sources ($L_X > 10^{39}$ergs/s) → relatively young population?

Evidence for Recent Star Formation (Kaviraj, Schawinski, Yi, Khochfar, Yoon)

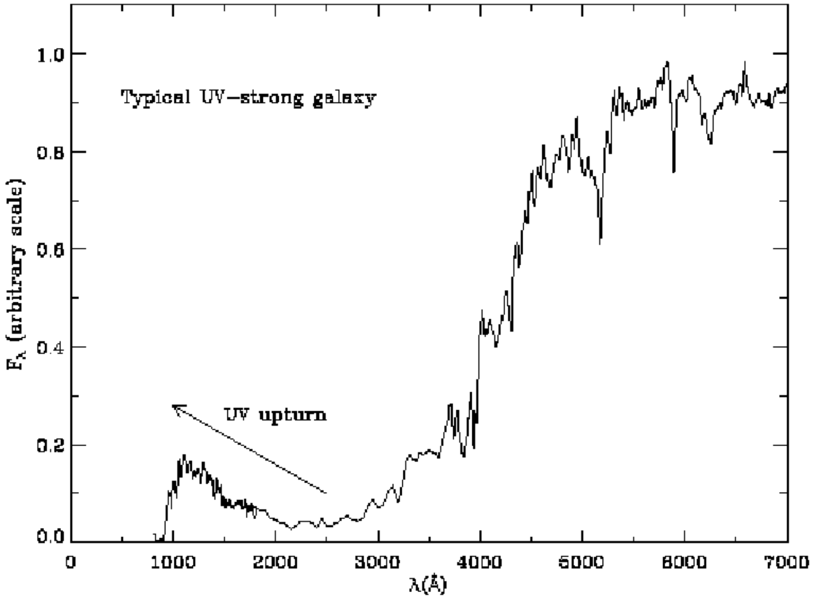
- the $(\mathrm{NUV} - \mathrm{r})$ colour is sensitive to low levels of star formation
- Schawinski et al. 2007:
  - ▷ use GALEX observations of a sample of 839 early-type galaxies from the SDSS $(0.05 < z < 0.1)$

→ $> 30\,\%$ of early-type galaxies show evidence for a low level of star formation $(\lesssim 1\,\%)$ in the last 1 Gyr

Schawinski et al. (2007)



The Far-UV Excess (UVX) in Elliptical Galaxies



- discovered in 1969 by the Orbiting Astronomical Observatory-2 (bulge of M31; Code 1969)
- not expected in an old population without recent star formation
- flux rises towards shorter wavelengths → UV upturn

possible orgin:

- non-thermal radiation from an AGN: no (UVX not centrally concentrated)
- young massive stars: no (UVX smooth, rather than clumpy, no direct evidence for massive stars [HST])

→ the UVX is caused by a population of 'old', hot stars with $T_{\rm eff} \simeq 25000\,$K

Controversy: what is the evolutionary origin of these hot, old stars?

The Low-Metallicity Model
(e.g. Lee 1994)

- low-metallicity old stars have blue-horizontal branches $\rightarrow$ UV excess
- requires large age for the Universe ($\sim 20\,$Gyr)

but: probably not consistent with the metallicity distribution of early-type galaxies (metal-rich!)

- predicts UVX should decreases rapidly with lookback time

The High-Metallicity Model
(e.g. Bressan et al. 1994; Yi et al. 1997)

- increased mass loss for old stars on the RGB causes stars to lose their H-rich envelopes near the tip of the RGB $\rightarrow$ extreme horizontal-branch stars that avoid the AGB
- need metallicity-dependent, enhanced (compared to Reimers) mass loss ($\dot{M}$ increases with Z [plausible]) that varies from star to star (Y?)
- lacks solid physical mechanism for the enhanced mass loss
- predicts UVX should decrease rapidly with lookback time and be strongly dependent on metallicity

The Termination of the AGB and FGB

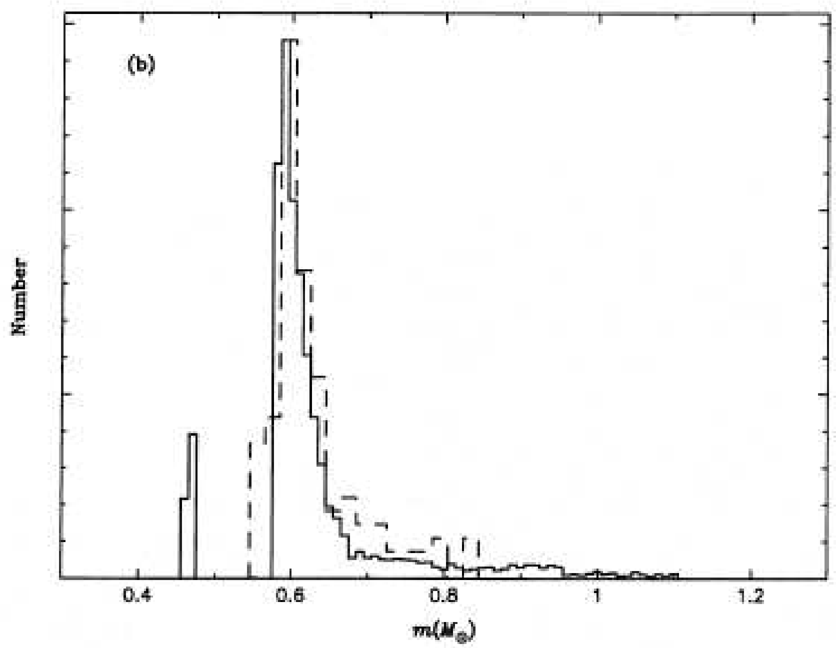
- What terminates the evolution of stars on the asymptotic-giant branch (AGB)?

Paczyński & Ziołkowski (1968) (also Biermann 1938): when the envelope binding energy of the envelope (including recombination energy) becomes positive (i.e. the envelopes become formally unbound)

- not dynamical ejection (radiative losses), but by a superwind in a Mira phase (with $\dot{M} \sim 5 \times 10^{-5}\,M_\odot\,yr^{-1}$) → rapid mass loss → planetary nebula

Han, Ph.P., Eggleton (1994): explains the observed WD mass distribution and the initial–final mass relation of stars without adjustable parameters (!)

- predicts that at high metallicity ($Z \gtrsim Z_\odot$), low-mass stars ($M \lesssim 1\,M_\odot$) reach this point already on the first-giant branch (FGB)



→ stars like the Sun may not ascend the AGB (not presently ruled out)

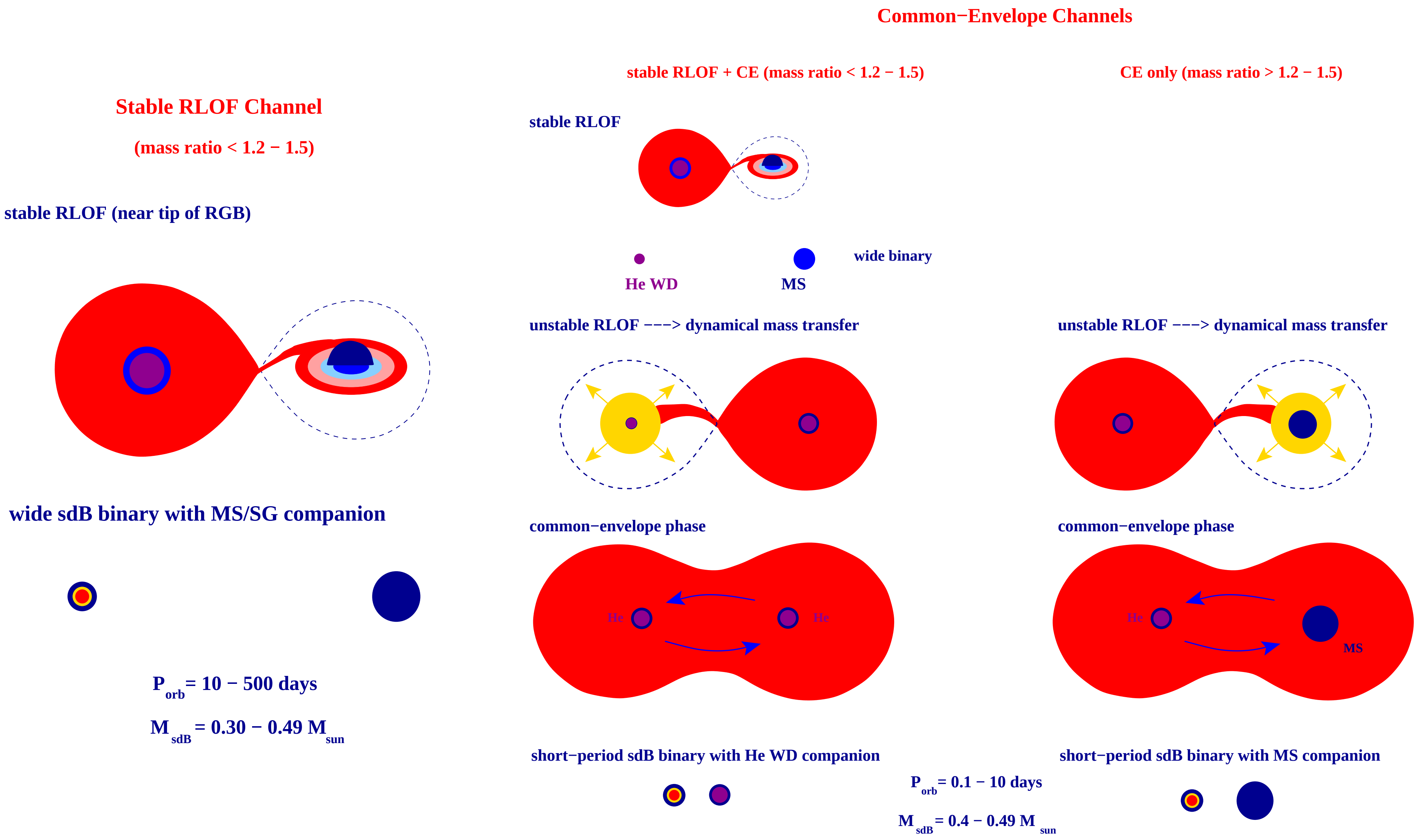
Kaliraj et al. (2007): existence of low-mass white dwarfs ($M = 0.43 \pm 0.06\,M_\odot$) in the old (8 Gyr), super-solar ($[Fe/H] = 0.4$) open cluster NGC 6791 → avoid AGB?

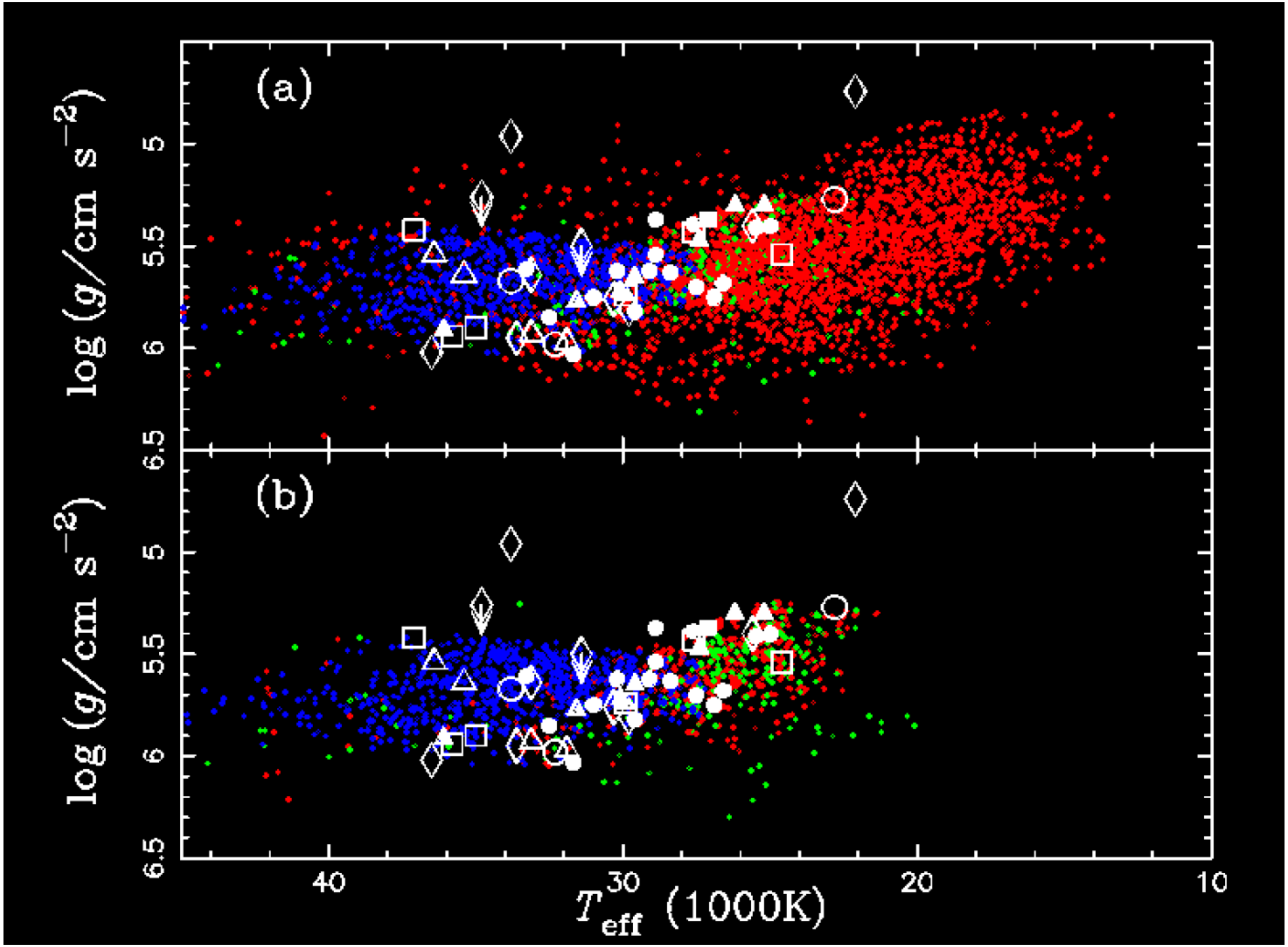
Hot Subdwarfs in the Milky Way

(Han et al. 2002, 2003)

- hot subdwarfs (sdB stars) are helium-core-burning stars (with $\mathrm{M} \simeq 0.5\,\mathrm{M}_\odot$) that have lost most of their envelopes by binary interactions
- prototypical evolution for forming compact binaries
  - ▷ stable Roche-lobe overflow
  - ▷ common-envelope (CE) evolution
  - ▷ binary mergers
- all channels appear to be important (30 %, 40 %, 30 %; Maxted, Heber, Napiwotzki, Green)
- mass transfer must have started near the tip of the red-giant branch (helium burning!)

$\rightarrow$ ideal systems to test/constrain binary evolution

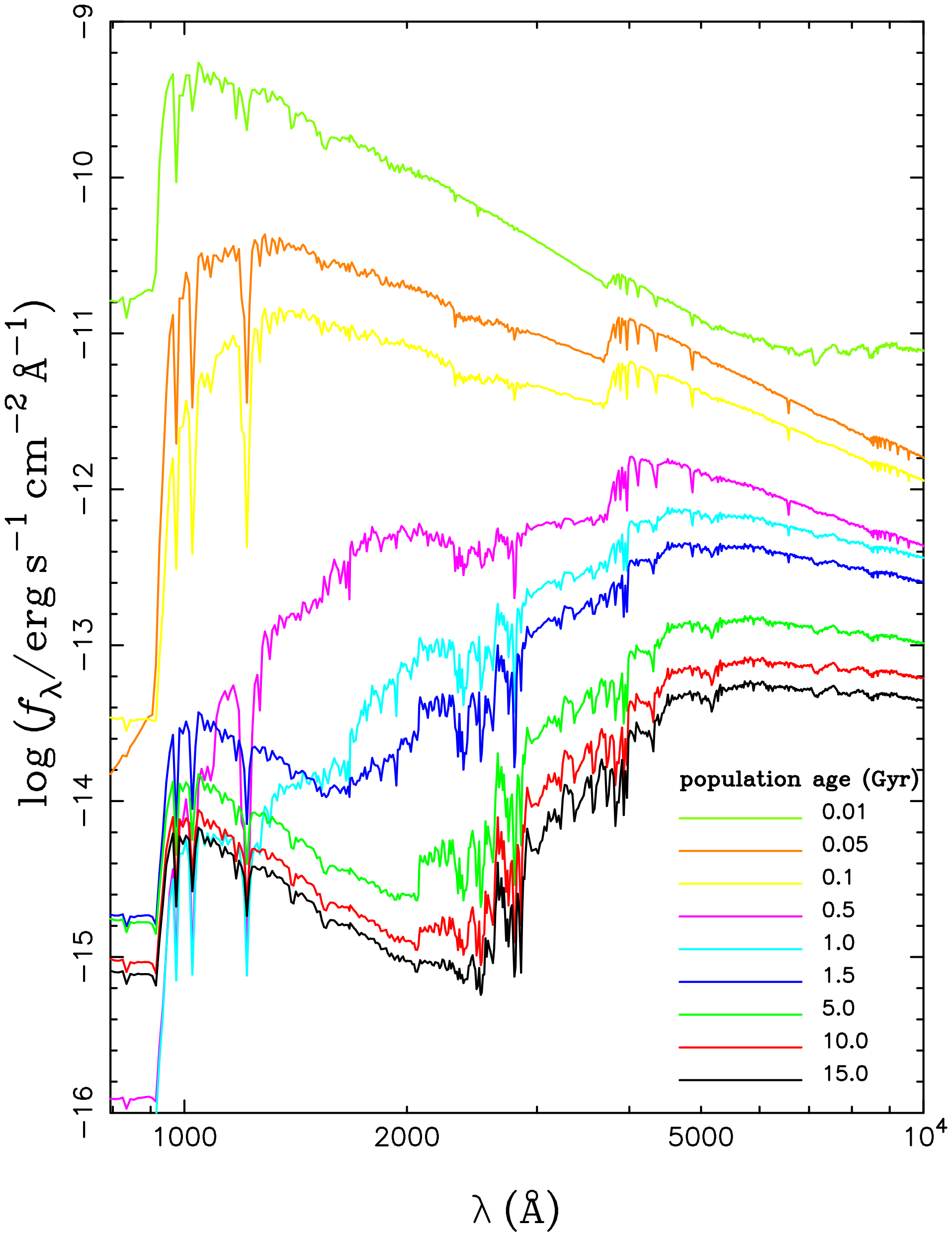

Common−Envelope Channels
stable RLOF + CE (mass ratio < 1.2 − 1.5)
CE only (mass ratio > 1.2 − 1.5)
Stable RLOF Channel
(mass ratio < 1.2 − 1.5)
stable RLOF
stable RLOF (near tip of RGB)
He WD
MS
wide binary
unstable RLOF −−−> dynamical mass transfer
unstable RLOF −−−> dynamical mass transfer
wide sdB binary with MS/SG companion
common−envelope phase
common−envelope phase
He
He
He
MS
P_{orb} = 10 − 500 days
M_{sdB} = 0.30 − 0.49 M_{sun}
short−period sdB binary with He WD companion
short−period sdB binary with MS companion
P_{orb} = 0.1 − 10 days
M_{sdB} = 0.4 − 0.49 M_{sun}


(a)
(b)
log (g/cm s^{-2})
log (g/cm s^{-2})
5
5.5
6
6.5
40
30
20
10
T_{eff} (1000K)

.

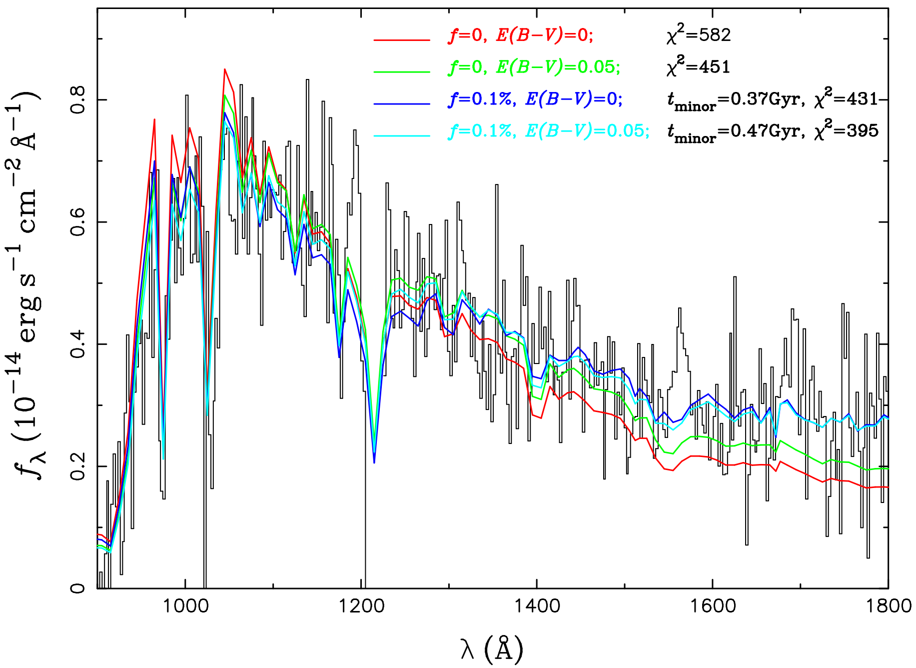
Galaxy Modelling
(single population)
(Han et al. 2007, MNRAS, 380, 1098)

- standard model is the 'best' model to explain hot subdwarfs in the Milky Way
- single stars included by default ('wide binaries')
- add spectral library
  - ▷ hydrogen-rich stars: BaSeL library (Lejeune 1997, 1998)
  - ▷ hot subdwarfs: calculated spectra with ATLAS9 stellar atmosphere code (Kurucz)

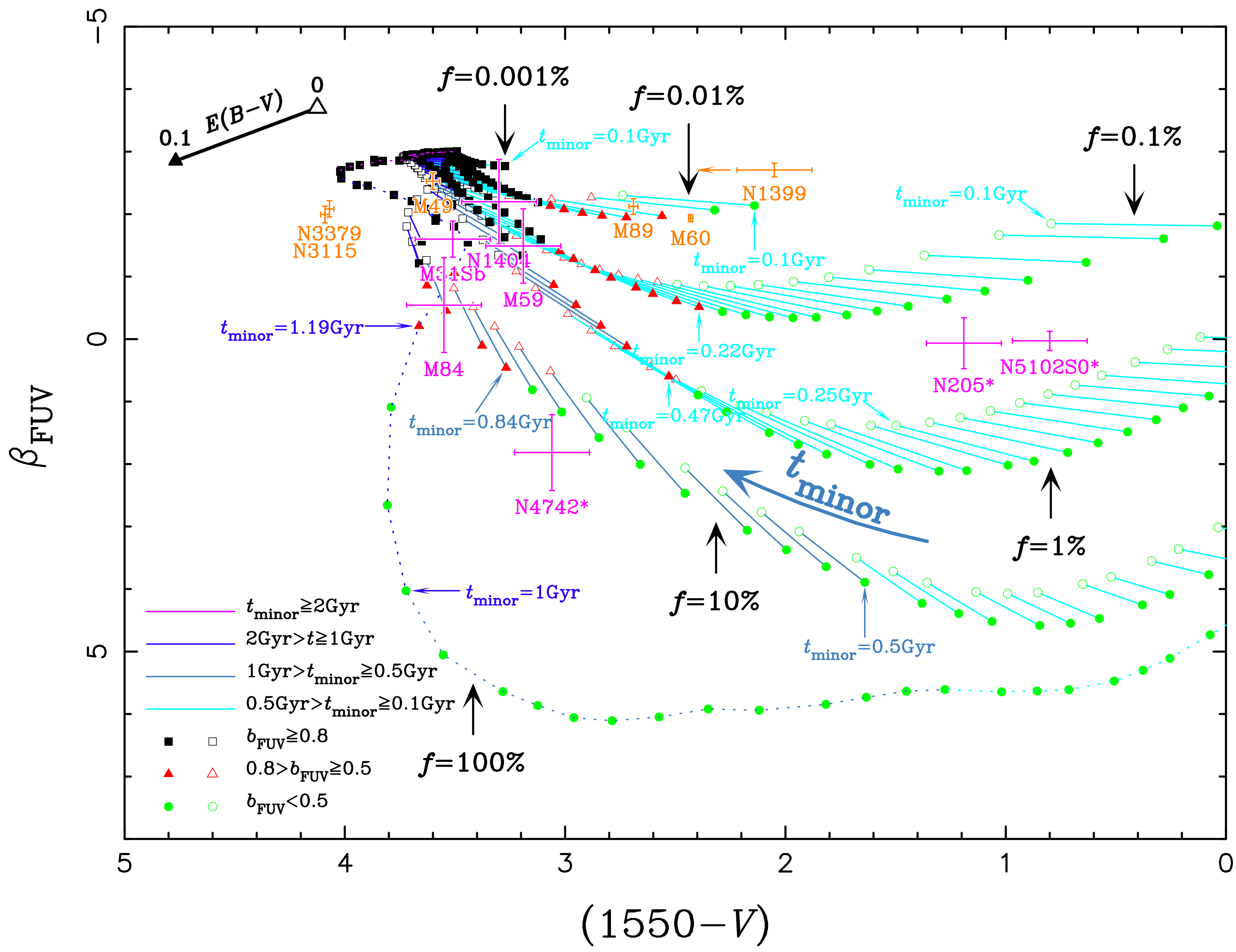


Composite Populations

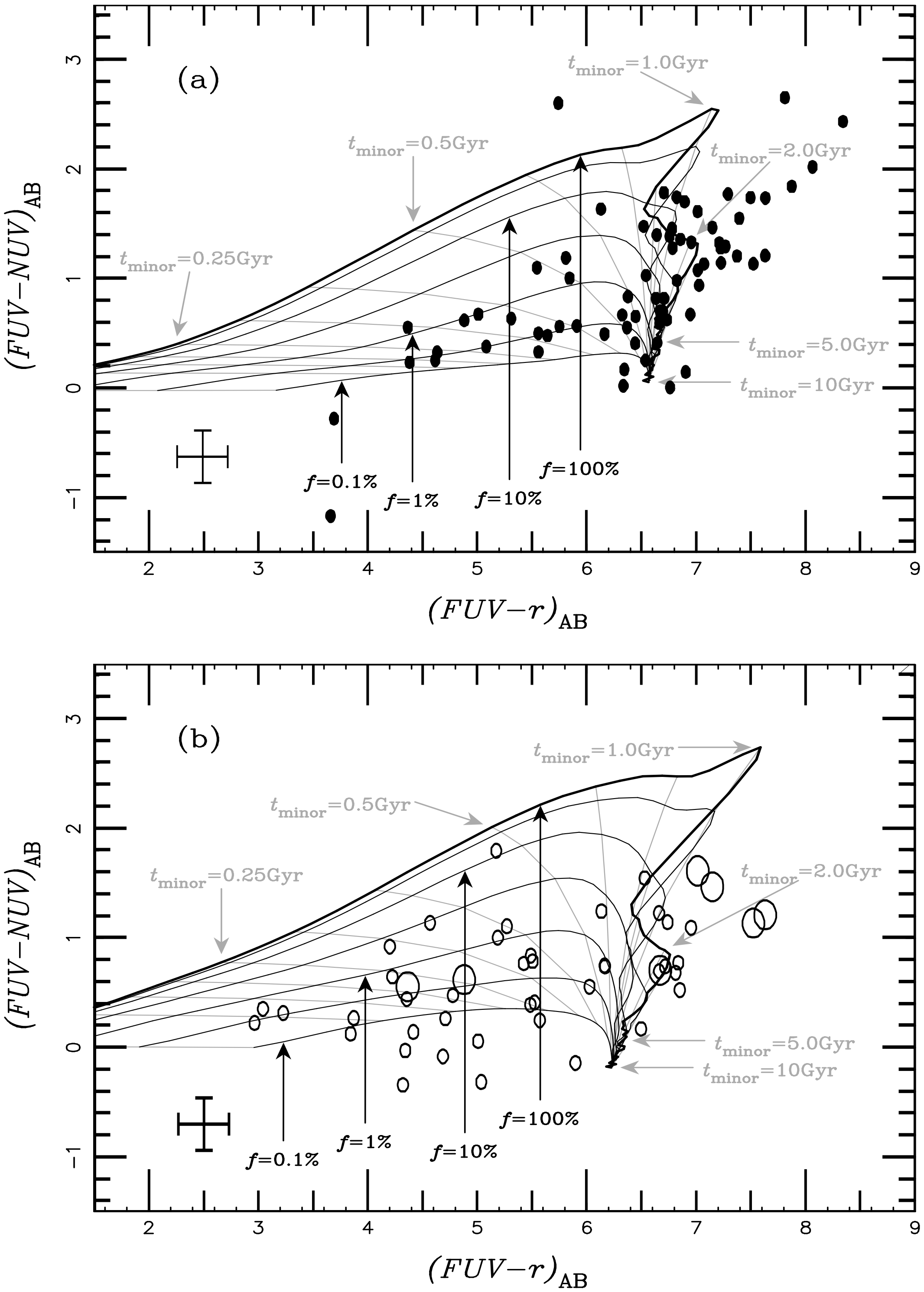
- moderate amounts of recent star formation ($\lesssim 1\,\mathrm{Gyr}$) can affect the UV excess $(1550 - V)$ significantly
- increasing evidence for low-level recent star formation (Schawinksi, Kaviraj, Yi)
- model:
  - ▷ dominant old population: $t_{\mathrm{major}} = 5$, $12\,\mathrm{Gyr}$
  - ▷ minor young population with mass fraction ‘f’ and age t_{minor}
- results:
  - ▷ degeneracy for $t_{\mathrm{minor}} > 1\,\mathrm{Gyr}$
  - ▷ best indicator for young population: slope of spectrum: $f \propto {}^{\mathrm{FUV}}$ (fitted between 1075 and 1750Å)
  - ▷ degeneracy between $E(B-V)$ and f
  - ▷ binary contribution important for most galaxies with UV excess



NGC 3379 (Brown et al. 1997; HUT)



f=0.001%
f=0.01%
f=0.1%
f=1%
f=10%
f=100%
E(B−V)
0.1
0
t_minor=0.1Gyr
t_minor=0.22Gyr
t_minor=0.25Gyr
t_minor=0.47Gyr
t_minor=0.5Gyr
t_minor=0.84Gyr
t_minor=1.19Gyr
t_minor=1Gyr
t_minor
N1399
N3379
N3115
M49
M89
M60
N1404
M31Sb
M59
M84
N205*
N5102S0*
N4742*
t_minor≥2Gyr
2Gyr>t≥1Gyr
1Gyr>t_minor≥0.5Gyr
0.5Gyr>t_minor≥0.1Gyr
b_FUV≥0.8
0.8>b_FUV≥0.5
b_FUV<0.5
β_FUV
(1550−V)



(a)
t_{minor}=1.0Gyr
t_{minor}=0.5Gyr
t_{minor}=2.0Gyr
t_{minor}=0.25Gyr
t_{minor}=5.0Gyr
t_{minor}=10Gyr
f=0.1%
f=1%
f=10%
f=100%
$(FUV-NUV)_{\mathrm{AB}}$
$(FUV-r)_{\mathrm{AB}}$
(b)
t_{minor}=1.0Gyr
t_{minor}=0.5Gyr
t_{minor}=0.25Gyr
t_{minor}=2.0Gyr
t_{minor}=5.0Gyr
t_{minor}=10Gyr
f=0.1%
f=1%
f=10%
f=100%
$(FUV-NUV)_{\mathrm{AB}}$
$(FUV-r)_{\mathrm{AB}}$

The Evolution of the UV Excess

- previous models predict strong evolution of the UV excess with lookback time (old population)
- binary model predicts UV excess for $t > 1\,\mathrm{Gyr}$

$\rightarrow$ moderate evolution with redshift (up to redshift $z \sim 2$)

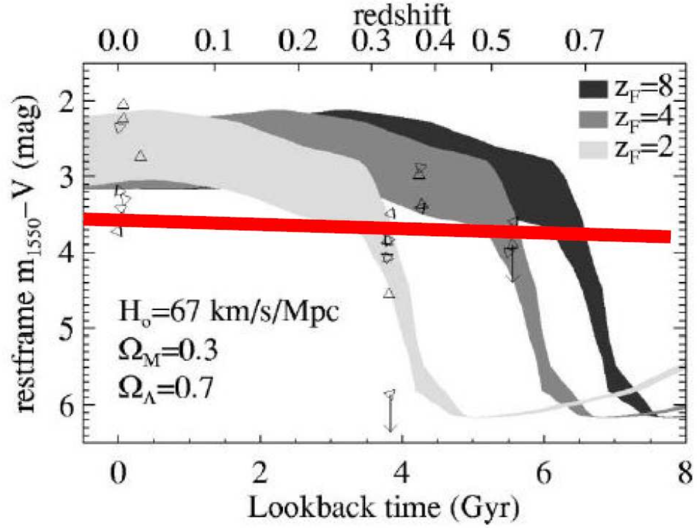
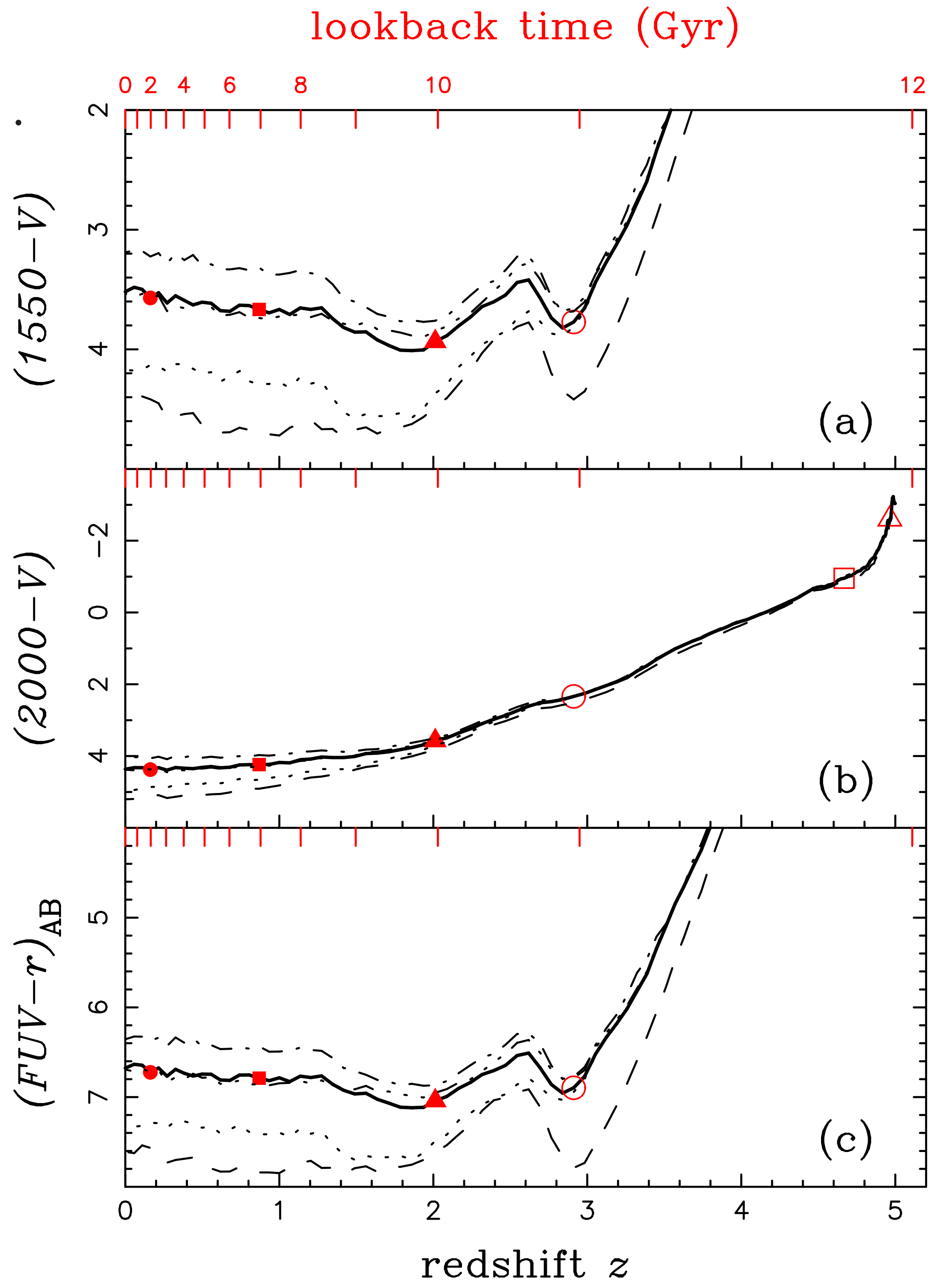
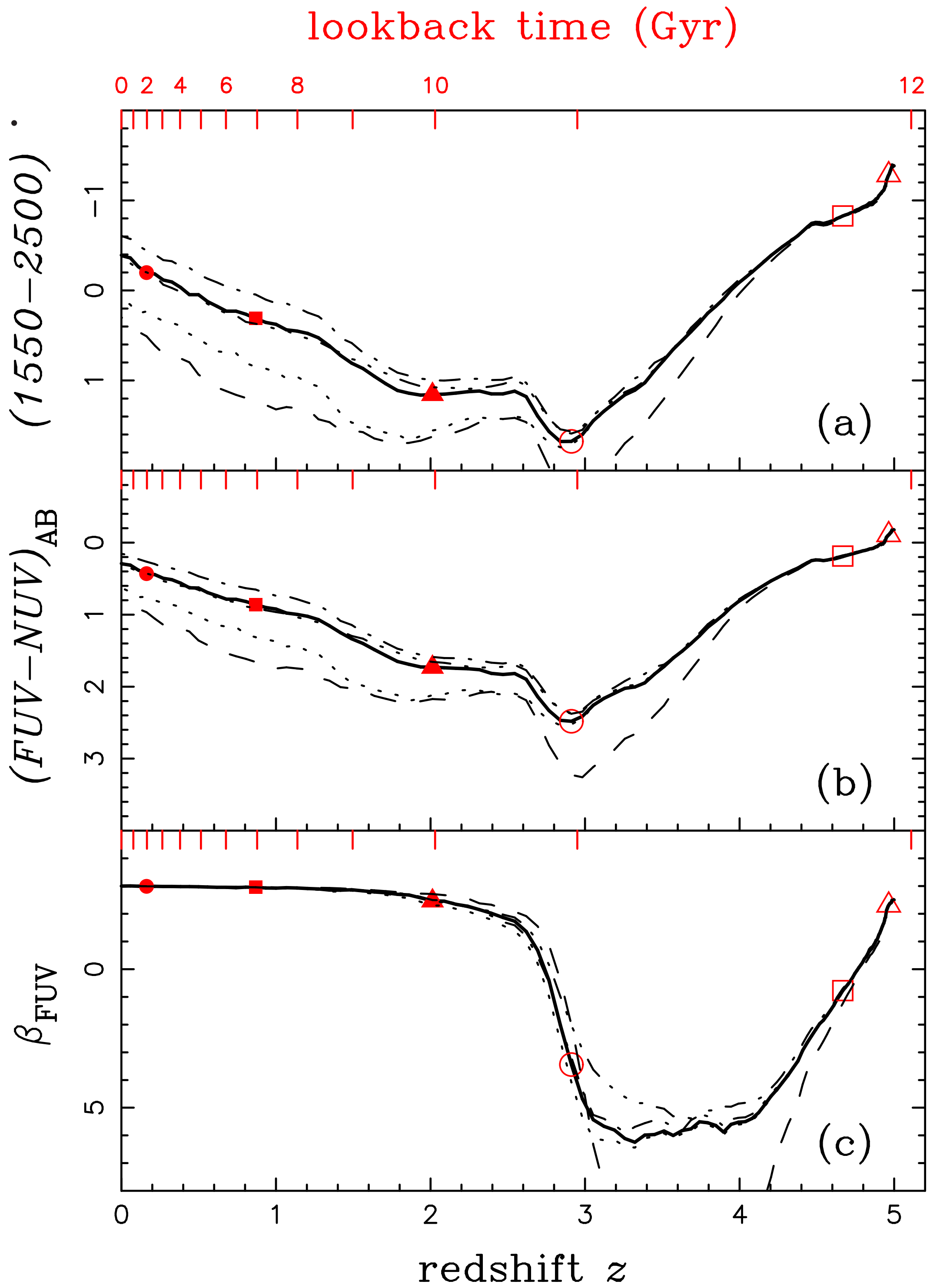


FIG. 2.—Evolution of the rest-frame $m_{1550}-V$ color according to the models of Tantalo et al. (1996; *shaded regions*), assuming a reasonable cosmology and thre… t of UV emi… the spread i… The timing … ical paramet… cent E and S0 galaxies. The statistical uncertainties (Table 1) are small with respect

Brown et al. 2003



lookback time (Gyr)
0 2 4 6 8 10 12
$(1550-V)$
2
3
4
(a)
$(2000-V)$
−2
0
2
4
(b)
$(FUV-r)_{AB}$
5
6
7
(c)
0 1 2 3 4 5
redshift z

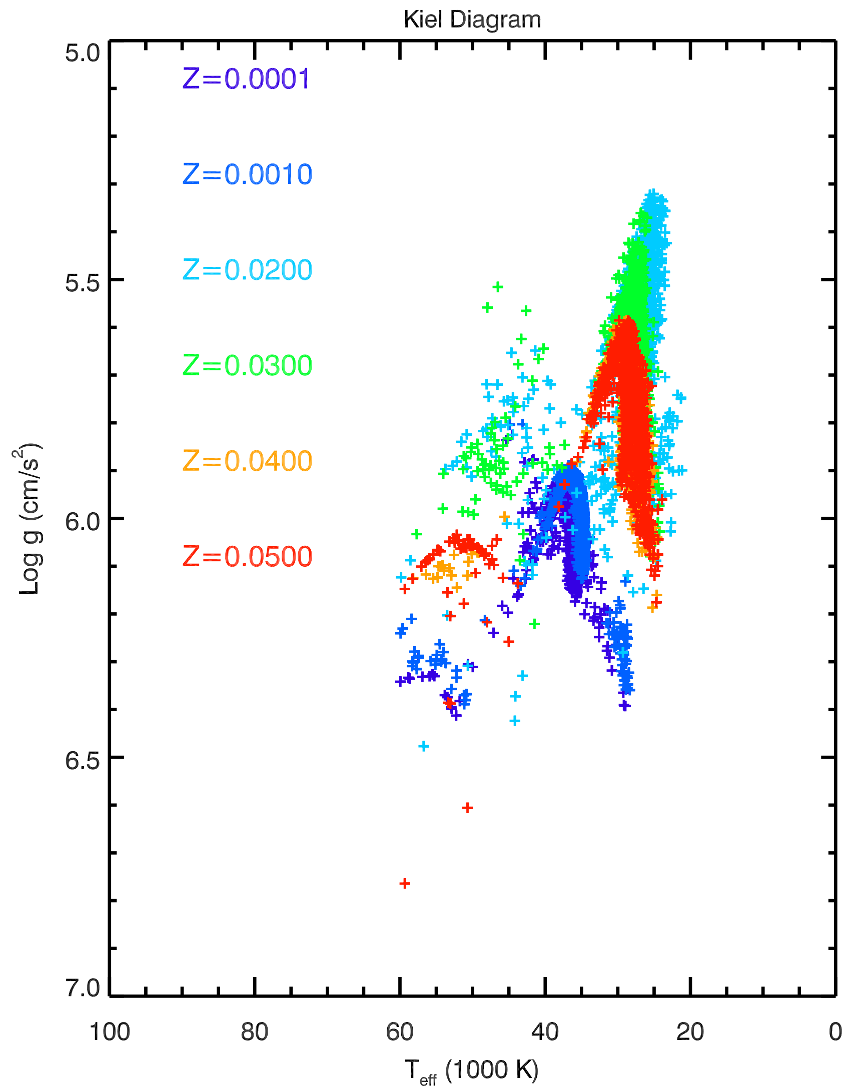


lookback time (Gyr)
0 2 4 6 8 10 12
(1550−2500)
−1
0
1
(a)
(FUV−NUV)AB
0
1
2
3
(b)
βFUV
0
5
(c)
0 1 2 3 4 5
redshift z

The Metallicity Dependence

- expect weak metallicity dependence
  - ▷ binary interaction are not a strong function of metallicity, unlike stellar winds

  but: initial binary properties?
  - ▷ appearance of hot subdwarfs depends on metallicity (David Brown)
  - ▷ more metal-poor subdwarfs are more compact and hence hotter
- Burstein et al. (1988): UVX correlated with metallicity? (from IUE)
- but consistent with GALEX observations? (Rich et al.)



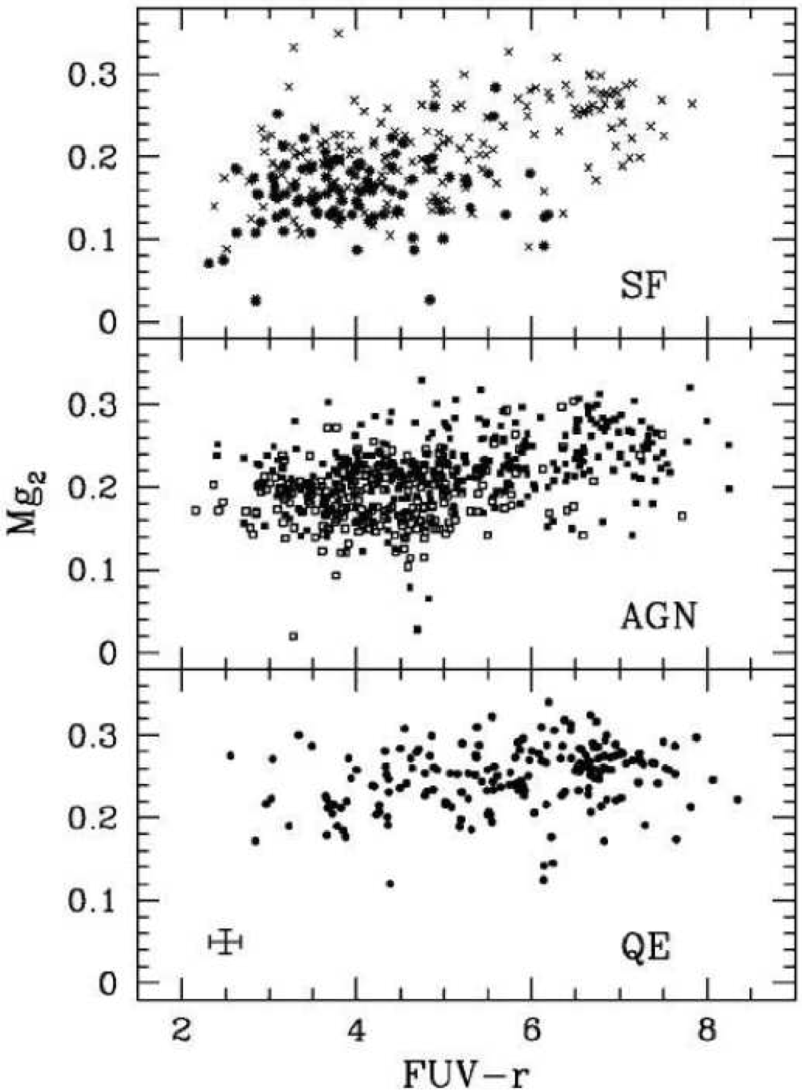


FIG. 1.—Early-type galaxies with both *GALEX* FUV and SDSS spectra, which have been classified according to their emission lines as star-forming, weak star-forming, AGN, AGN/star-forming composite, or quiescent; Mg_2 vs. FUV $- r$. *Top*: Star-forming galaxies. Asterisks indicate well-detected star-forming galaxies; crosses indicate galaxies with star formation detected at low S/N. A large

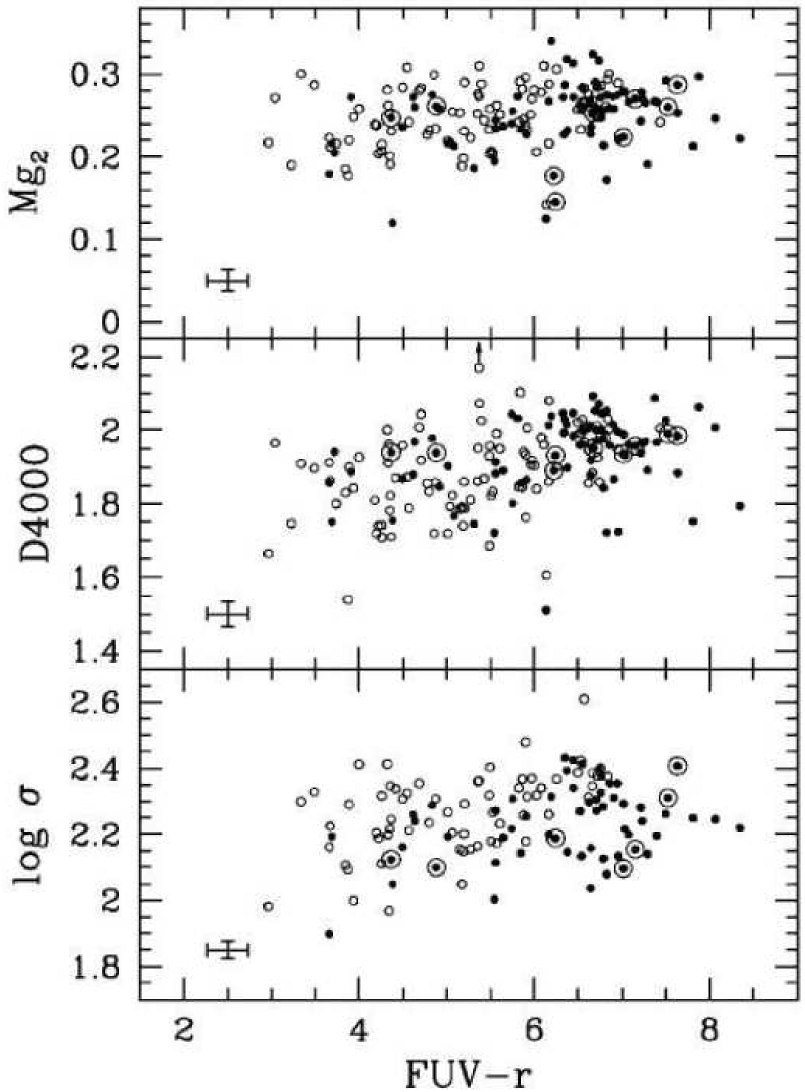
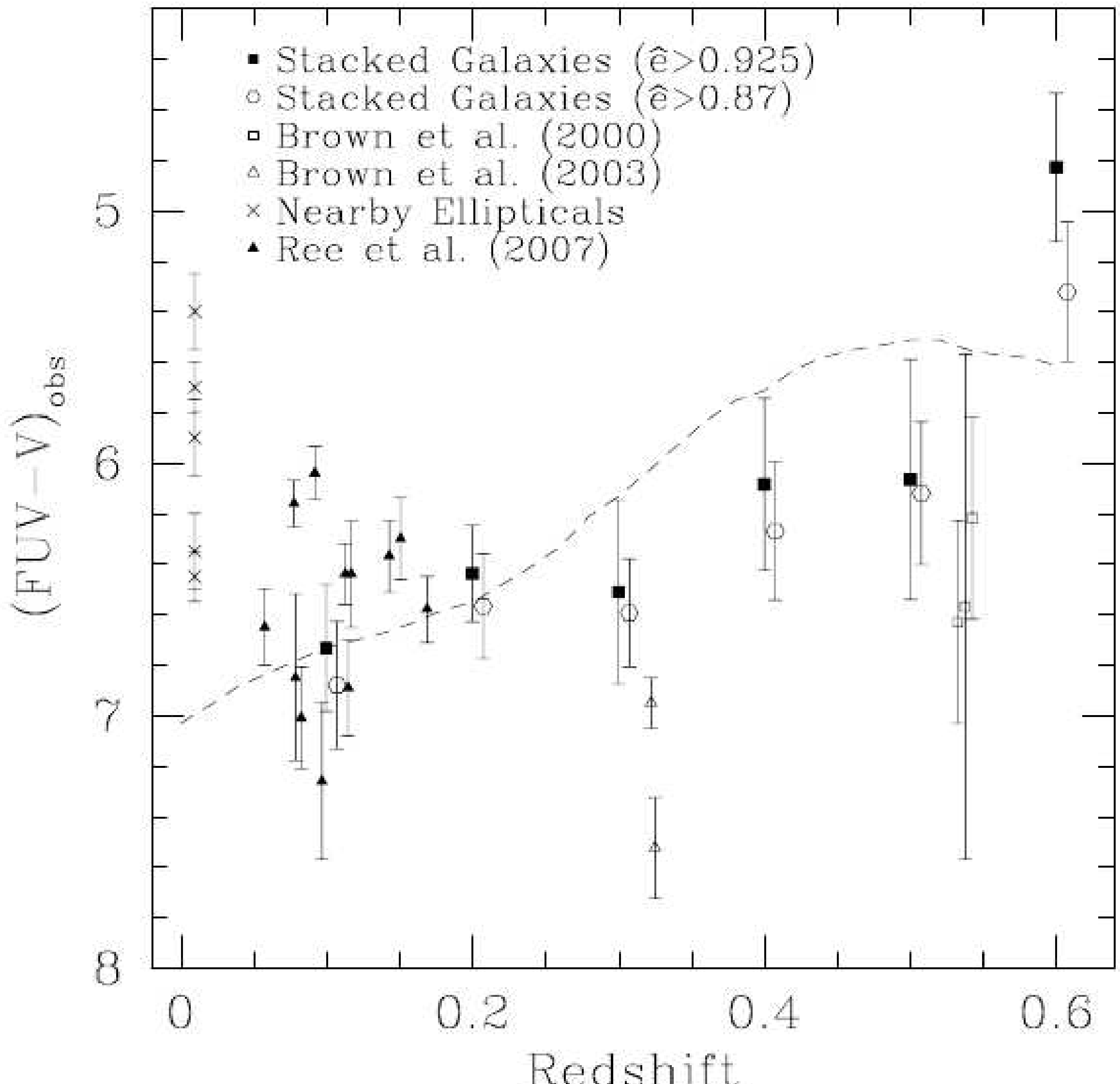


FIG. 2.—Plot of various parameters vs. FUV $- r$ for the 172 quiescent early-type galaxies in our sample. Filled circles indicate $0 < z < 0.1$; open circles indicate $0.1 < z < 0.2$. Circled points indicate membership in the elliptical rich cluster A2670 ($z = 0.076$). These panels show that Mg_2, D4000, and log σ are all weakly correlated with FUV $- r$ color, in contradiction to the trends

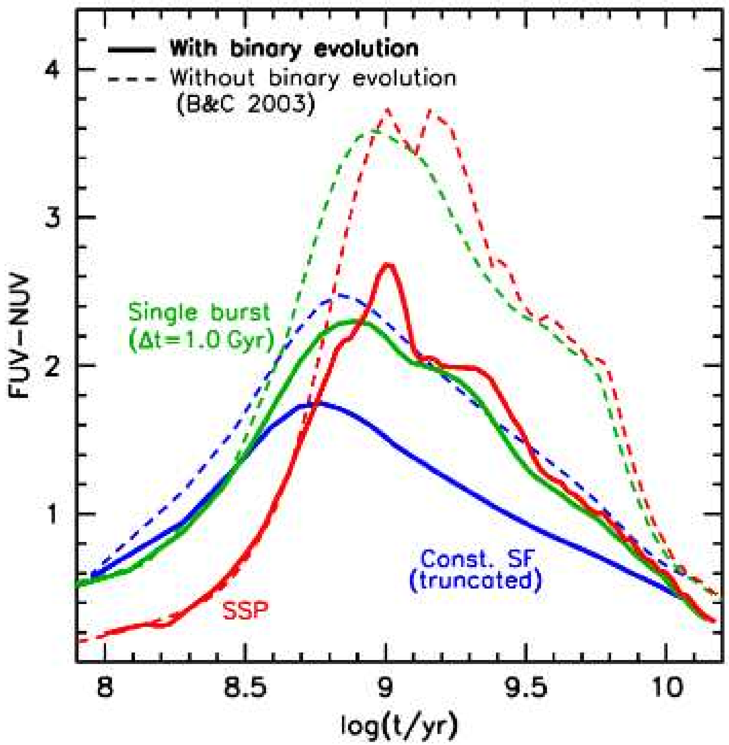
Atlee, Assef & Kochanek (2008)

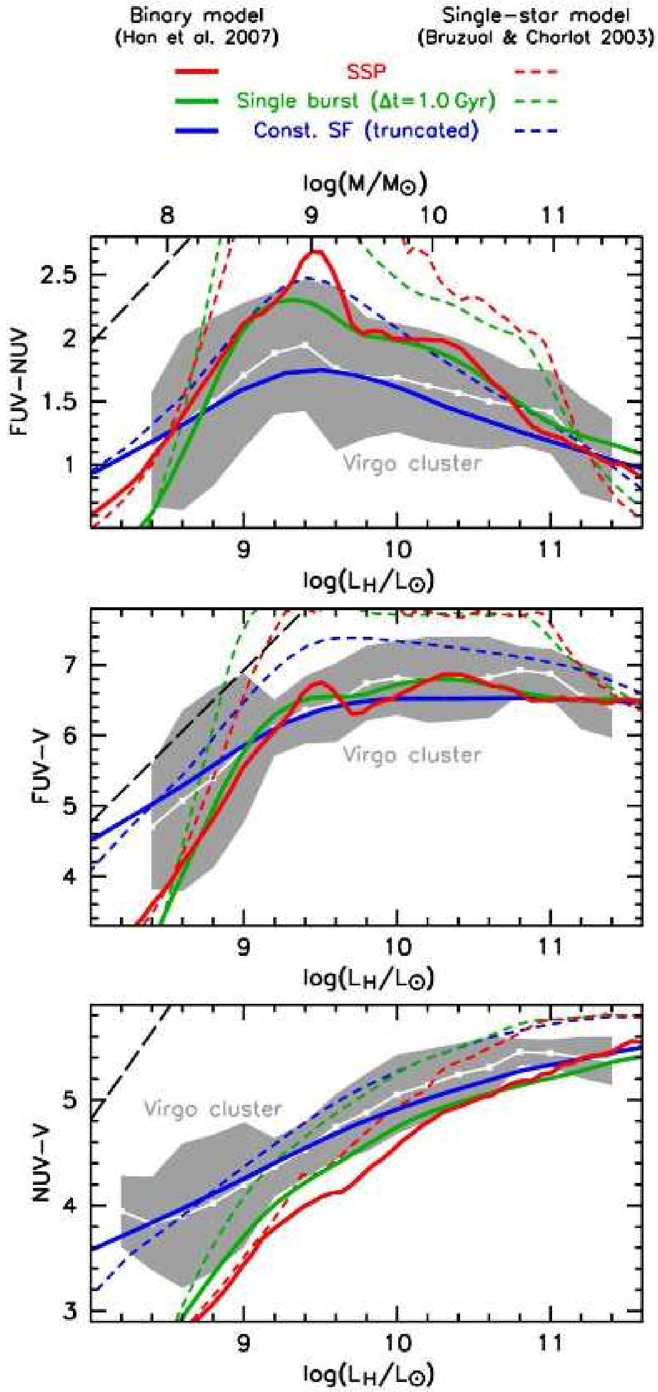
- Galaxy stacking analysis using GALEX deep field survey (Bootes)

→ little evolution up to redshift $z = 0.6$, inconsistent with single-star model, consistent with binary model



Lisker & Han (2008)





- only the binary model can explain the **FUV-NUV colour** as a function of galaxy mass
- reddest colour at 1 Gyr, when hot sdB stars become important

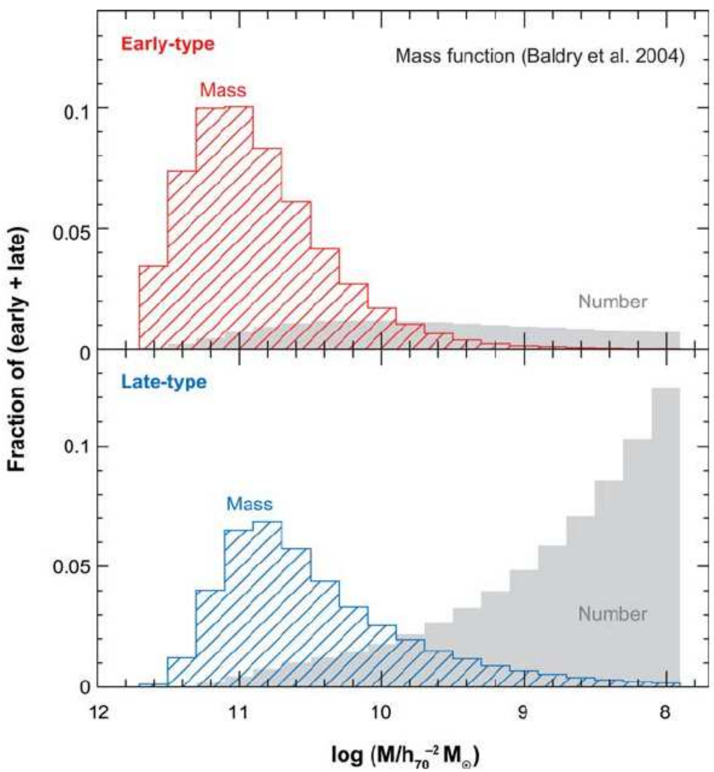
Conclusions

- a binary model can explain most of the main properties of the UV excess
- the model relies only on *a priori* physics and a calibration against a known Galactic population
- any complete model for the UV excess has to include binaries (binaries are not optional!)
- single-star model not ruled out (see Han et al. 1994)
- potential tests:
  - the evolution of the UV excess with redshift
  - the metallicity dependence of the UV excess
- future work:
  - refinement of the model
  - detailed comparison with observations using improved diagnostics
- the inclusion of stars in galaxy modeling has to take into account the known complexities in our own galaxy

Elliptical Galaxies

(e.g. Renzini 2006, ARA&A, 44, 141)

- dominated by an old population of stars
- $\sim 57\,\%$ of the mass in stars is found in elliptical/early-type galaxies
- more than $80\,\%$ of mass is found in massive galaxies (with $\mathrm{M} \gtrsim 3 \times 10^{10}\,\mathrm{M}_\odot$)



Renzini 2006 (from D. Thomas)

Formation Scenarios

- Monolithic Collapse Scenario (Eggen, Lynden-Bell & Sandage 1962)
  - ▷ single rapid global starburst followed by passive evolution

    (disk may form subsequently by accretion of gas from environment)
- Hierarchical Merging Model (Toomre 1977; White & Rees 1978)
  - ▷ spheroids from from mergers of smaller entities

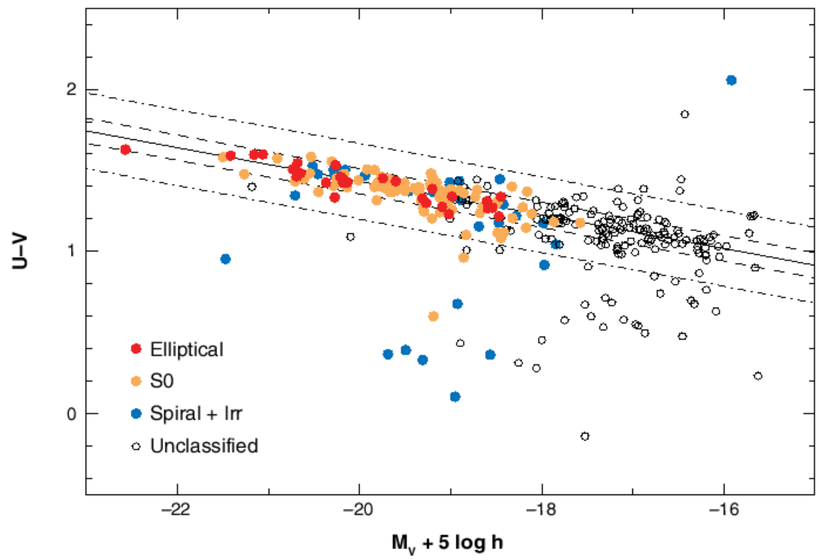
    (disrupting any existing disks)
- modern picture: blurred; evidence for merging, but also evidence for rapid initial starburst from [/Fe] enhancement

The Fundamental Plane

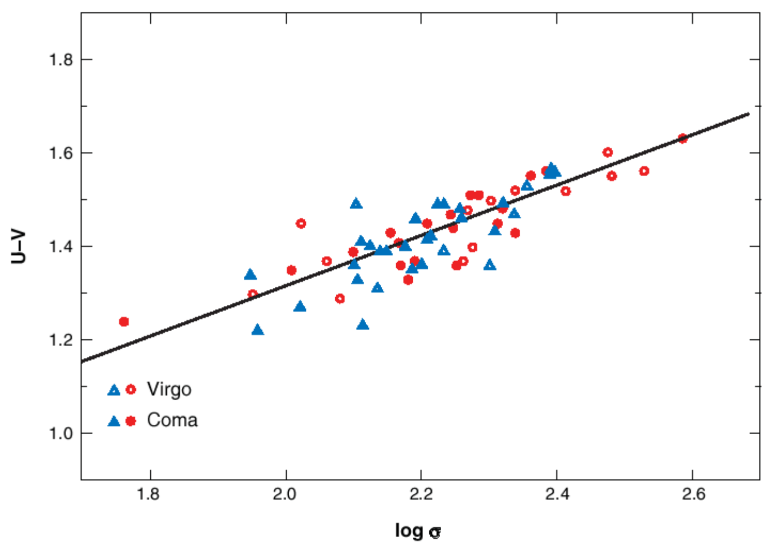
- Early-type galaxies follow both a tight colour–magnitude relation ($U - V$ vs. M_V) and a colour–central velocity relation (($U - V$) vs. relation

$\rightarrow$ defines a fundamental plane with 3 parameters (e.g. effective radius, velocity dispersion, surface brightness)

- suggests a simple, homogeneous picture for early-type galaxies where they
  - ▷ are well-virialized
  - ▷ have similar homologous structure
  - ▷ obey tight age and metallicity constraints

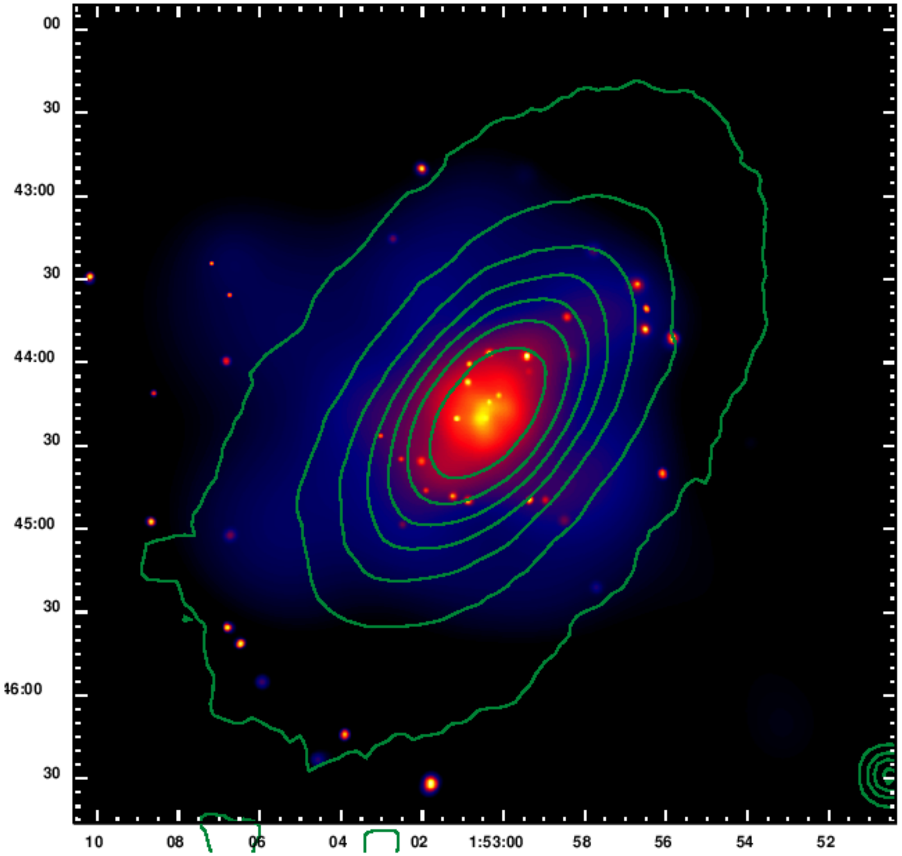


Coma Cluster Bower et al. (1999; after Renzini)



Bower, Lucey and Ellis (1992; after Renzini)

The elliptical galaxy NGC 720 (Cetus)

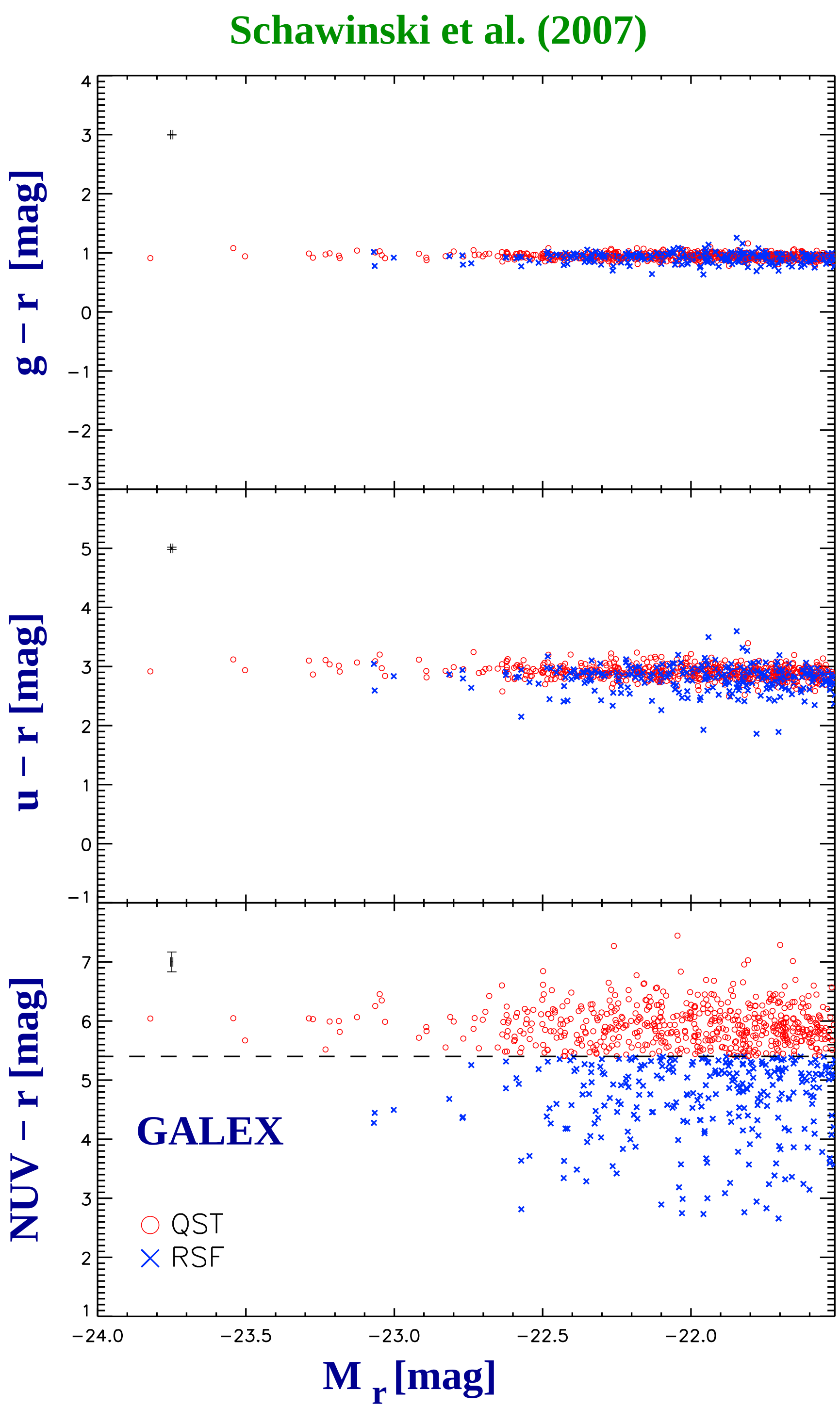


NGC 720 (Chandra) (Jeltema et al. 2003)

- evidence for a mis-aligned dark matter halo or recent merger activity?
- 9 ultraluminous X-ray sources ($L_X > 10^{39}$ergs/s) $\rightarrow$ relatively young population?

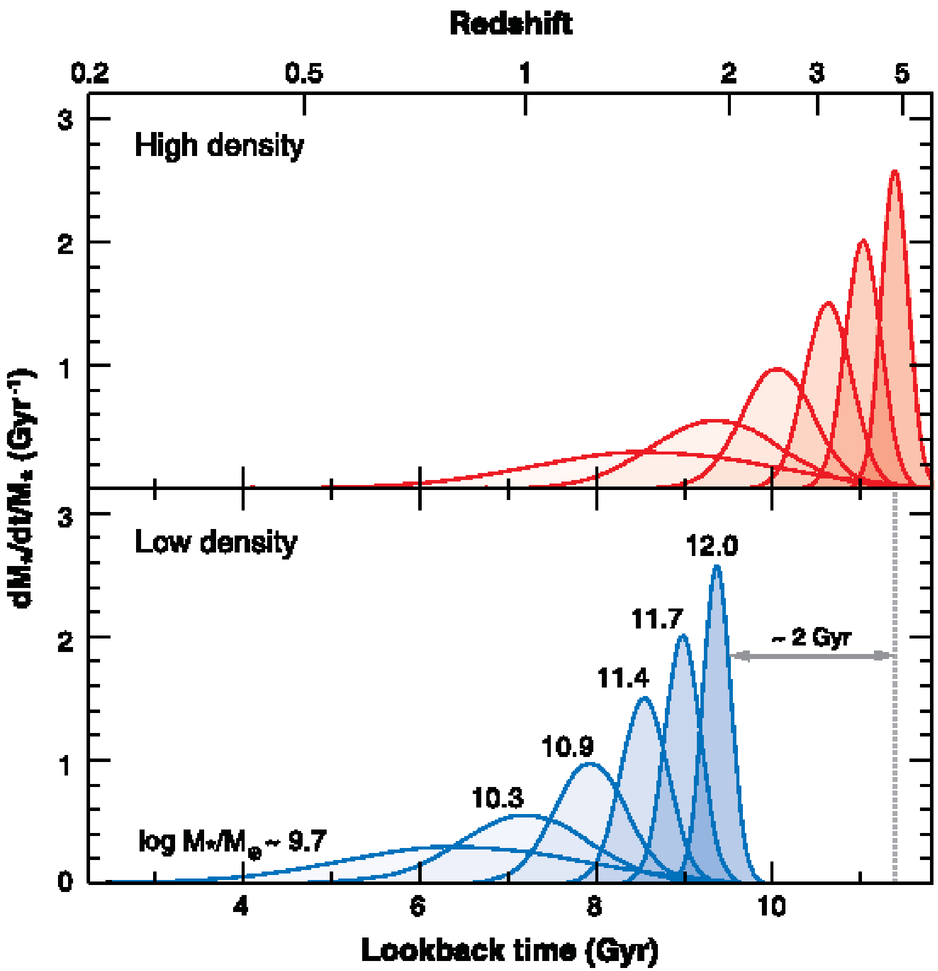
Evidence for Recent Star Formation
(Kaviraj, Schawinski, Yi, Khochfar, Yoon)

- the $(\mathrm{NUV} - \mathrm{r})$ **colour** is sensitive to low levels of star formation
- **Schawinski et al. 2007:**
  - ▷ use **GALEX observations** of a sample of 839 early-type galaxies from the SDSS $(0.05 < z < 0.1)$
  - → $> 30\,\%$ of early-type galaxies show evidence for a **low level of star formation** $(\lesssim 1\,\%)$ in the last 1 Gyr



The Galaxy Downsizing Paradox

- the most massive early-type galaxies form first and more rapidly than lower-mass galaxies
- e.g. galaxy archaeology
  - ▷ study the stellar populations of galaxies in the local Universe to deduce their star-formation histories in the distant Universe
  - ▷ Thomas, Maraston et al. (2005): massive early-type galaxies have formed most of their stars by a redshift $z = 1.5$
  - ▷ $50\,\%$ of all stars in early-type galaxies have formed by a redshift $z = 1$
- not expected in the hierarchical merger model (expect continued mass build-up in the most massive galaxies → paradox)
- what stops star formation?
  - ▷ possibilities: SN feedback in dwarf galaxies, AGN feedback in massive galaxies



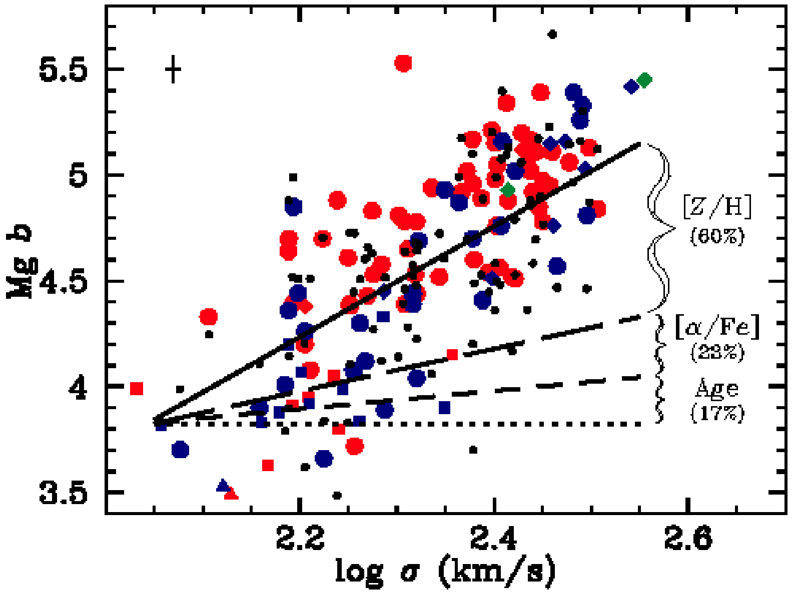
Thomas et al. (2005; from Renzini)

A Chemical Evolution Paradox?

- facts:
  - ▷ the most massive early-type galaxies have super-solar metallicity (~ 2 in Fe; ~ 3 in Mg/O), containing a large fraction of all stars formed to-date
  - ▷ present-day star formation occurs predominantly in small galaxies with low metallicity (e.g. LMC, $Z = 0.5 \times$ solar)

$\rightarrow$ while the total metal content of the Universe increases as the Universe ages, the metallicity in active star-forming regions may decrease with age ($\rightarrow$ paradox)

$\rightarrow$ possible implications for the progenitors of GRB progenitors, SNe Ia (metallicity dependence)



Thomas et al. (2005)