Blue Compact Dwarf Galaxies

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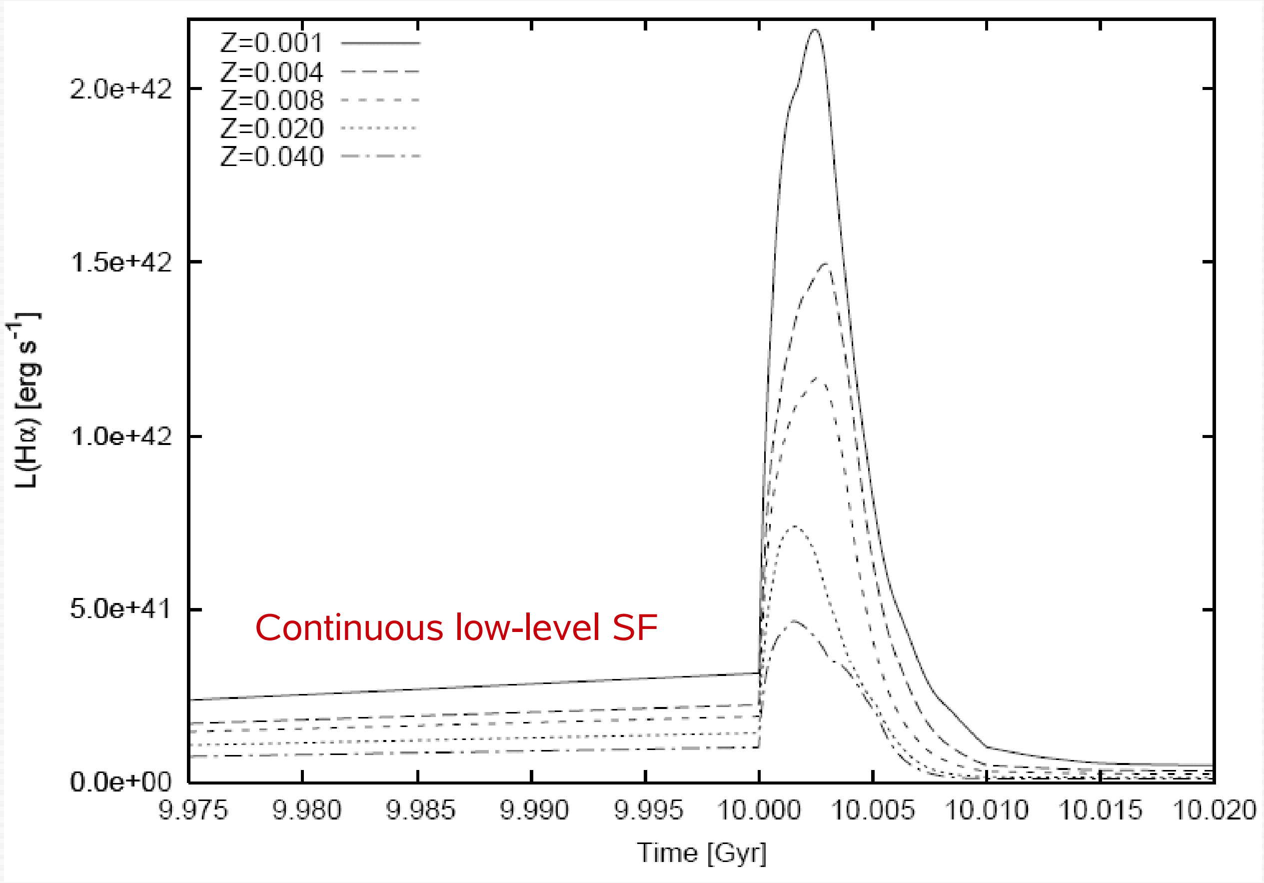
BCDs: Star Formation Rate (**SFR**)

- SFR indicators: Hα, UV and radio continuum luminosity
- Derived SFRs between 0.05 and 0.5 $M_\odot$/year
- A cautionary note: the SFR calibration is based on the assumption that star formation is continuous and at constant rate over $\geq$100 Myr … but

Starburst

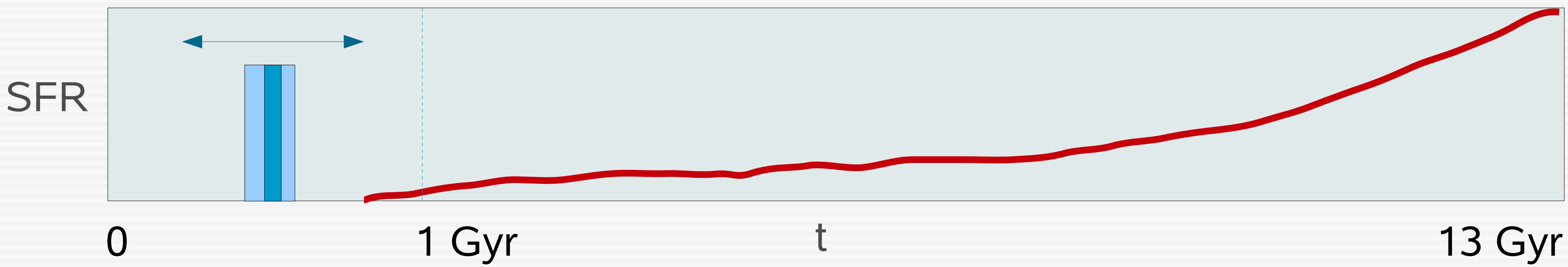


Weilbacher & Fritze von Alvensleben (2001)

L(Hα) depends on
- starburst age
- metallicity

BCDs: Burst parameter ***b*** and Star Formation History (SFH)

- evolutionary synthesis: a SFH is assumed.
  old+young stellar population with e.g.
  old ✶: constant or exponentially decreasing SFR with varying e-folding τ
  young ✶: constant SFR over 5.e+6 ... 1.e+8 yr, starting at t_0 (t_0<0.1 Gyr)
  Output: synthetic spectral energy distribution (SED) and colors → comparison with observations → variation of the initial SFH → match between synthetic and observed SED.



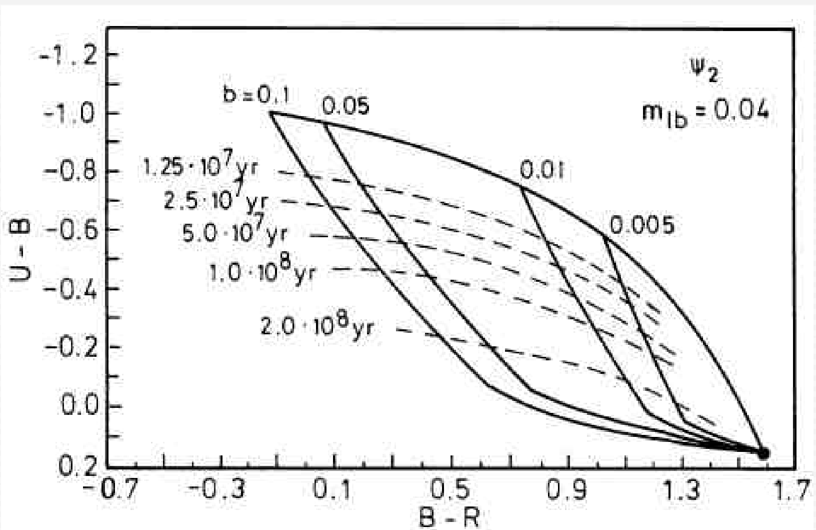
- Different models (after Tinsley 1968), incl. Krüger et al. (1991,1995), Guseva et al. (2001,2004), Mas-Hesse & Kunth 1999, Westera et al. 2004, Zackrisson et al. 2008 etc.) with emphasis on various observables, such as e.g. integral colors and/or the SED slope, equivalent widths of Balmer absorption lines, 4000 Å break, H+K(Ca) index
- **Problem:** uniqueness of the best-fitting solution.

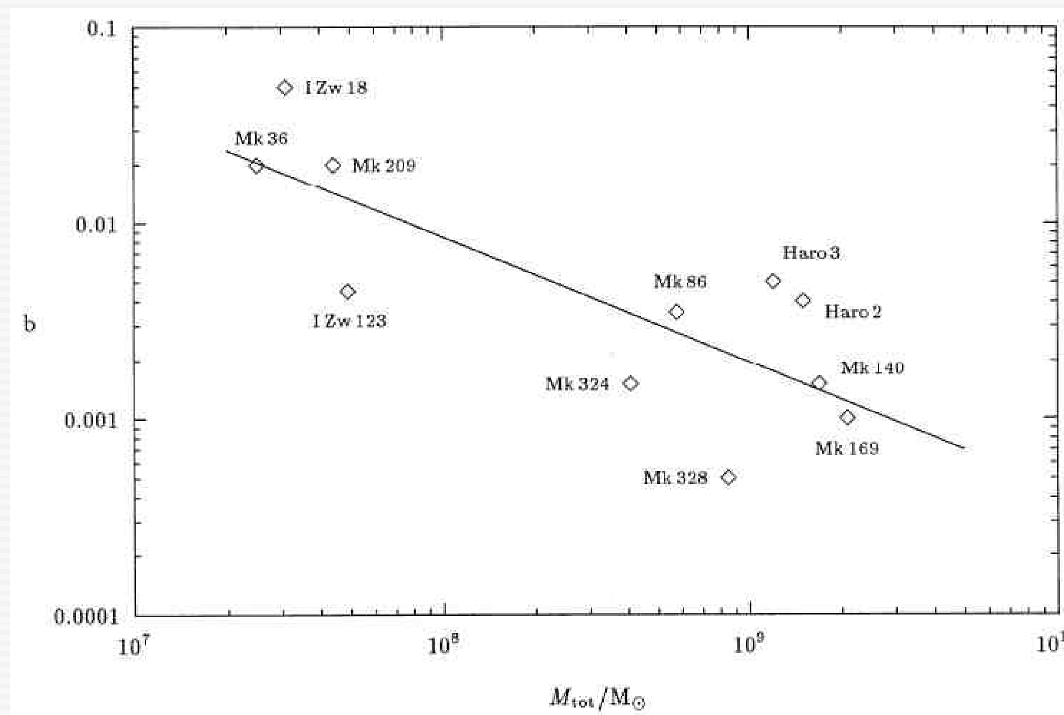
Evolutionary Synthesis models of the integral colors of BCDs

- burst parameter

  b(%) = mass of the stars formed in the current burst / mass of the stars ever formed

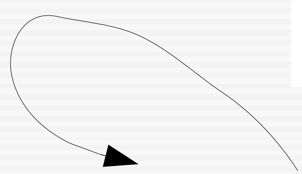
- Method: photometric evolutionary synthesis models (reproducing the integral colors U-B, B-V, V-R etc.)
- Basic assumption: old (10 Gyr) stellar host + recent burst
- b parameter in the range between 0.1% and 5%
- Comparable b values derived from chemical evolutionary synthesis models (e.g. Recchi et al. 2001) and optical-UV evolutionary spectral synthesis models (Mas-Hesse & Kunth 1999).





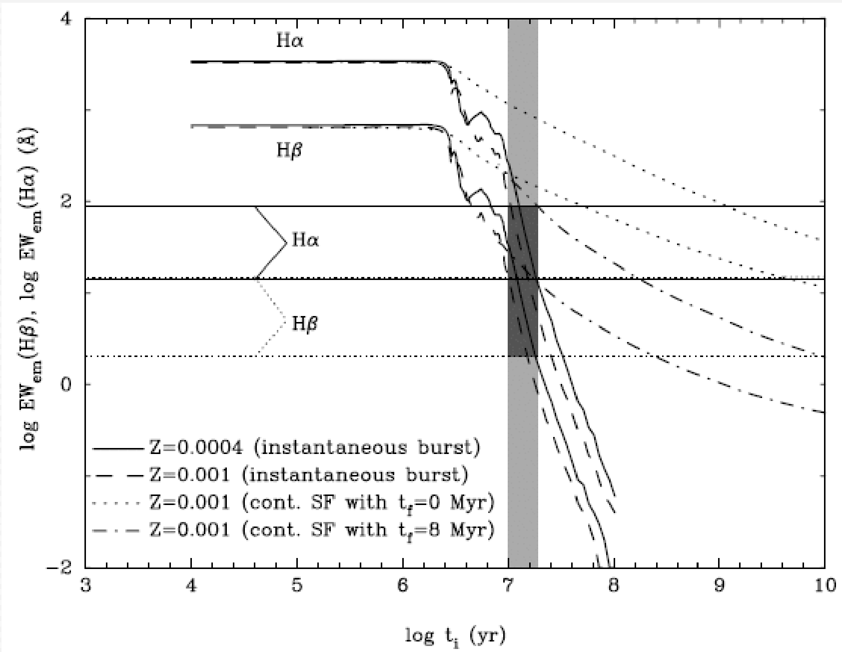
Krüger et al. (1995)

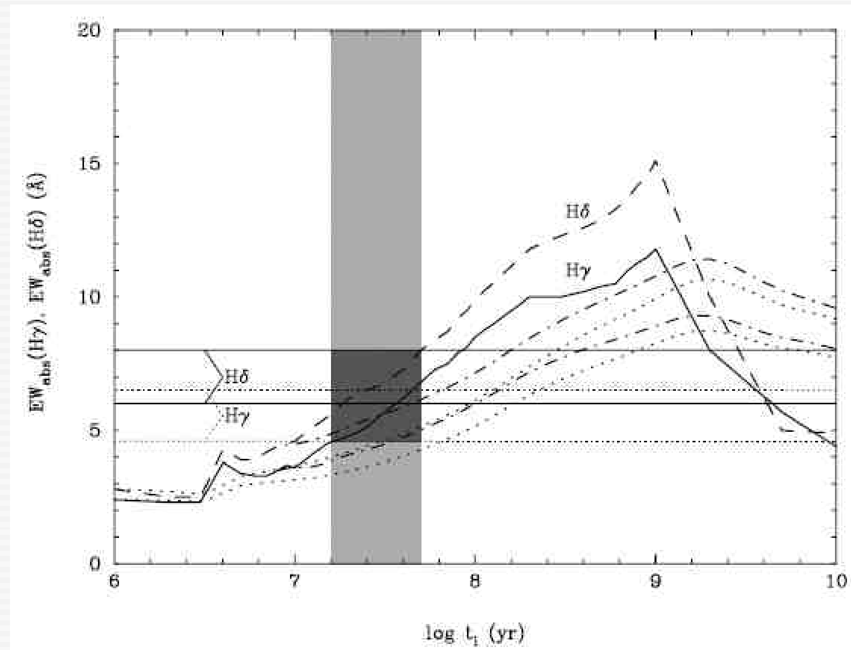
„Loops“ on two-color diagrams with an amplitude proportional to the burst parameter b (in addition, to e.g. the Initial Mass Function)



$t=t_1$ $t=0$

Evolutionary Synthesis models of the integral colors, SED slope, equivalent widths of Balmer absorption lines + intrinsic extinction



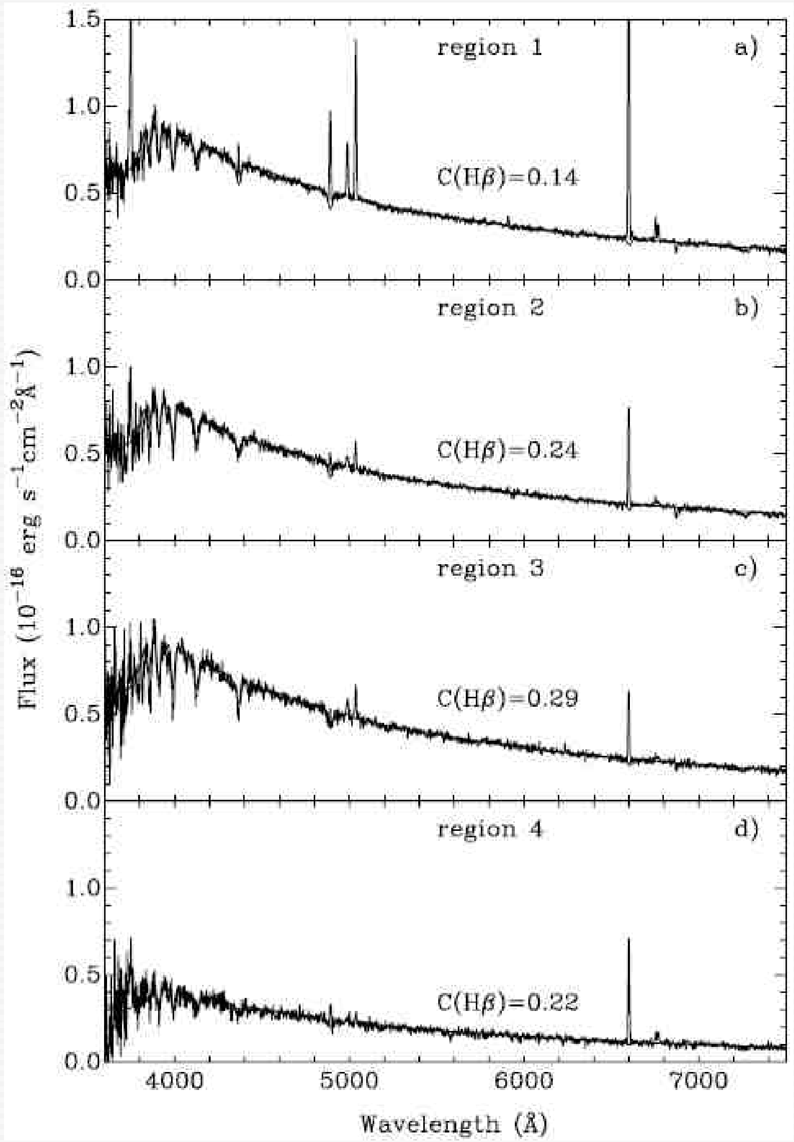


Guseva et al. (2001)

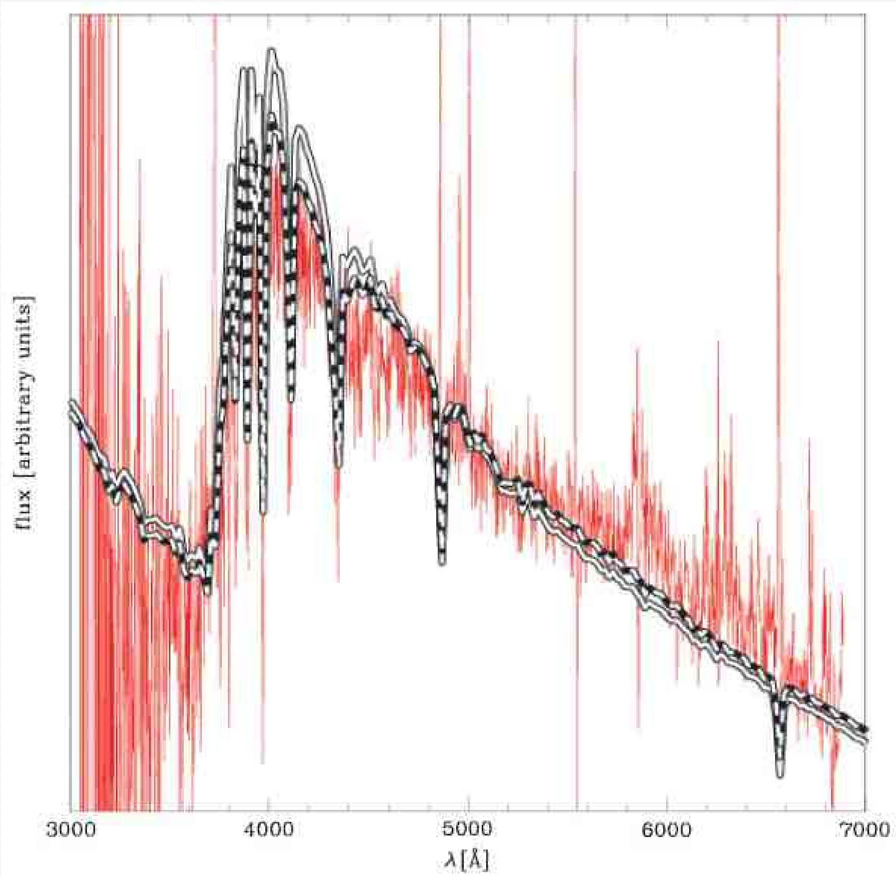
Search for a SFH which approximates the observed equivalent widths of both Ha+Hb (in emission) and Hg+Hd (in absorption), in addition to the SED slope and colors.
Self-consistent determination of intrinsic extinction

- EWs **do not depend** on intrinsic extinction
- The slope and colors of the SED **depends** on extinction

Evolutionary Synthesis models of the integral colors, SED slope, equivalent widths of Balmer absorption lines + intrinsic extinction



Guseva et al. (2001)



Westera et al. (2004)

BCDs: Burst parameter ***b*** and Star Formation History (SFH)

- population synthesis: decomposition of the observed SED in a set of Single Stellar Populations **(SSPs)** with different ages and metallicities
a) no assumption about the SFH
b) for example, input SSP library with 3 metallicities $\times$ 50 ages

- Output: t- and z-distribution of SSPs & intrinsic extinction,
  luminosity-weighted and mass-weighted stellar age and metallicity,
  burst parameter *b*.

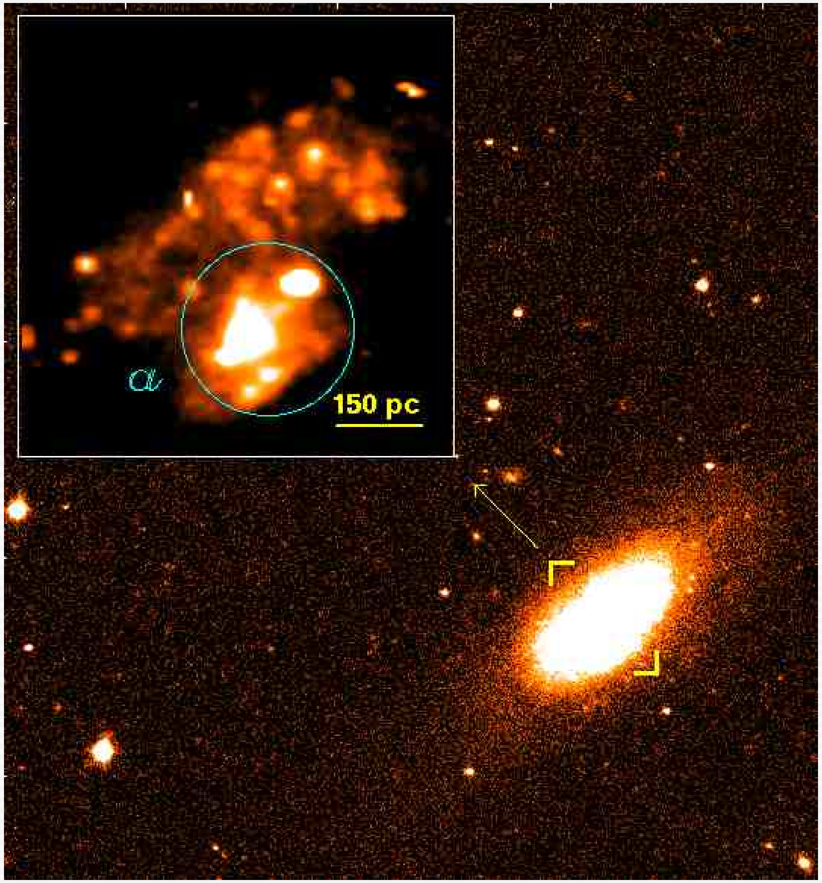
- **Example**:
  Asari et al. (2007) for SDSS galaxies, based on *Starlight* (Cid Fernandez et al. 2004)

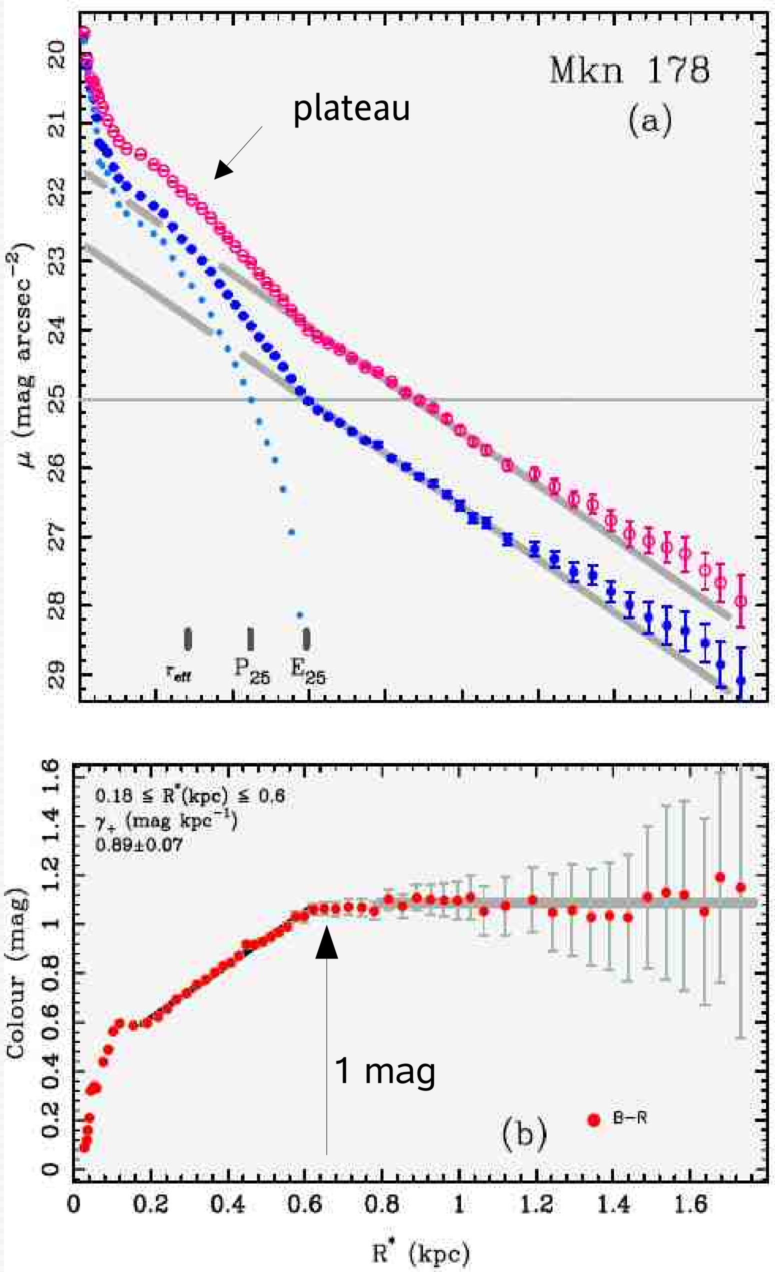
- **Warning**: spectral synthesis will not work for galaxies with strong ionized gas emission

The photometric structure of BCDs

BCDs: photometric structure I

Mrk 178





- A single fitting law (e.g. Sersic) cannot fit the surface brightness profiles **(SBPs)** of BCDs
- SBP decomposition in (at least) two components: **old** host galaxy and **young** star-forming component
- Large colour gradients within the star-forming component ($R^* \leqslant P_{25}$) are typical for BCDs

Papaderos et al. (2002)

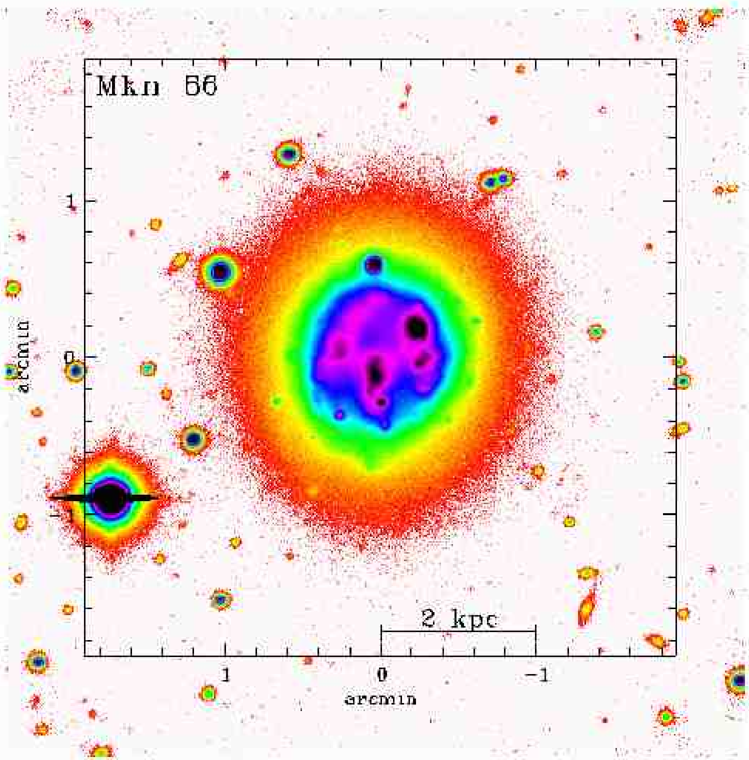
Profile decomposition

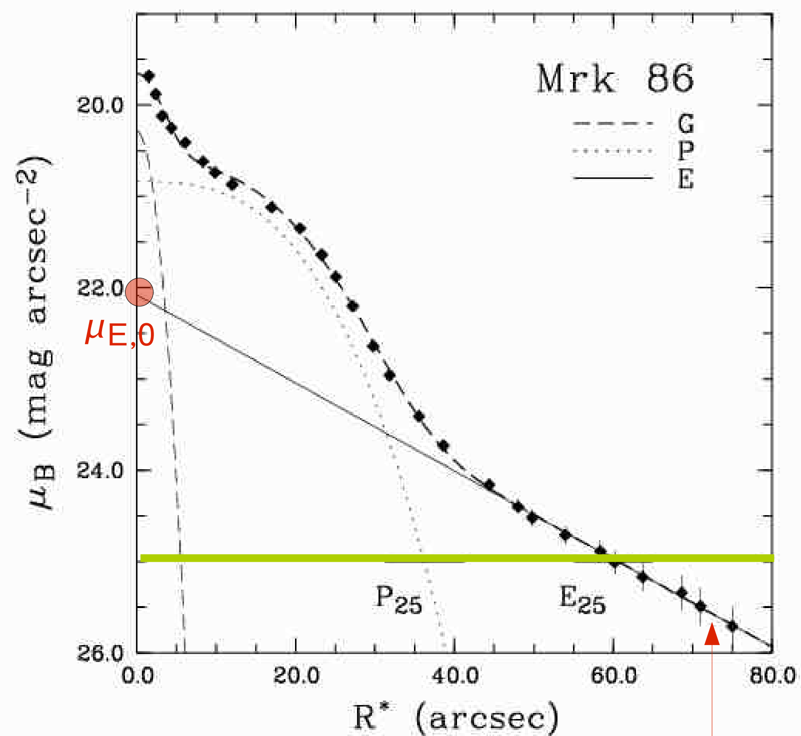
Gaussian component (G)

$I_G = I_{G,0} \exp\left[-0.5\,(R^*/\gamma)^2\right]$

"Plateau" component (P)

$I_P = I_{P,0} \exp\left[-(R^*/\beta)^\eta\right]$





Papaderos et al. (1996a)

Optical structure of BCDs - Parameters

Starburst component: radial extend, luminosity & mass contribution, SF history, mass fraction of young compact clusters

Host galaxy: structural properties (e.g. profile slope, exp. scale length, formation history, color+age gradients, kinematics ..)

Low-surface brightness (LSB) host galaxy (E)

$I_E = I_{E,0} \exp\left[-(R^*/\alpha)\right]$

$\mu \equiv -2.5 \log I_E + \text{constant} = \mu_{E,0} + 1.086\,(R^*/\alpha)$

$\mu_{E,0}$: Central surface brightness of the LSB host

α : exponential scale length

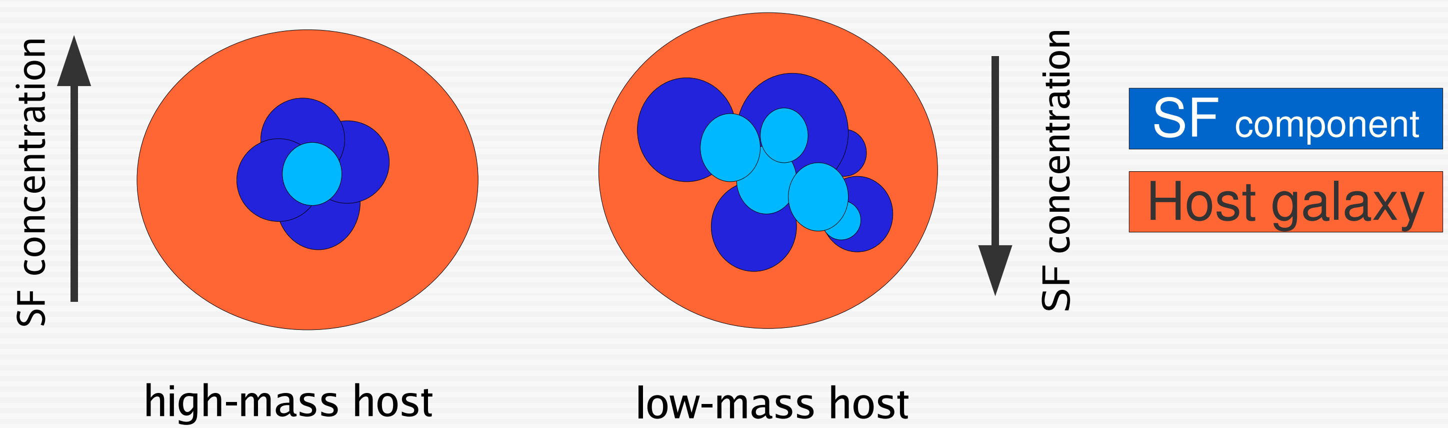
BCDs: photometric structure II

Loose & Thuan (1986ab), James (1993), Papaderos et al. (1996ab), Telles et al. (2007), Cairos et al. (2001a,b, 2003), Noeske et al. (2000,2003,2005), Bergvall & Östlin (2002), Gil de Paz et al. (2003,2005), Lee et al. (2004), Gil de Paz & Madore (2005), Vaduvescu et al. (2005), Caon et al. (2005), Makarova et al. (2009), Amorin et al. (2007,2009), Sung et al. (2008), Micheva et al. (2009)

- Surface photometry: down to $\mu \simeq 26.5$ B mag arcsec^{-2}
- Color contrast between the **old** host galaxy and **young** star-forming component (Δ(B-R) of up to 1 mag) with radial color gradients of up to 2 (B-R) mag kpc^{-1}
- BCD host galaxy can be approximated in its outer part by an exponential fitting law over 3-5 exponential scale lengths α.
  Alternatively, or in addition: Sersic law with a shape parameter $\eta \approx 1$
  (Noeske et al. 2003, Cairos et al. 2003, Caon et al. 2005),
  modified exponential distribution (Papaderos et al. 1996),
  hyperbolic secant distribution (Vaduvescu et al. 2005),

Spatial extent of the star-forming component

- Radius of the star-forming component R_{SF} (P96) : $R_{SF} \simeq 2\alpha_{host}$
- A starburst requires a minimum stellar density of $\rho_* \geq 1\ M_\odot\ pc^{-3}$ in the host galaxy, i.e. compact underlying host galaxy (P96, Noeske et al. 2003, Gil de Paz & Madore 2005)
- Degree of concentration of star forming activities $\propto$ mass of the host galaxy → **mass-morphology relation for BCDs**



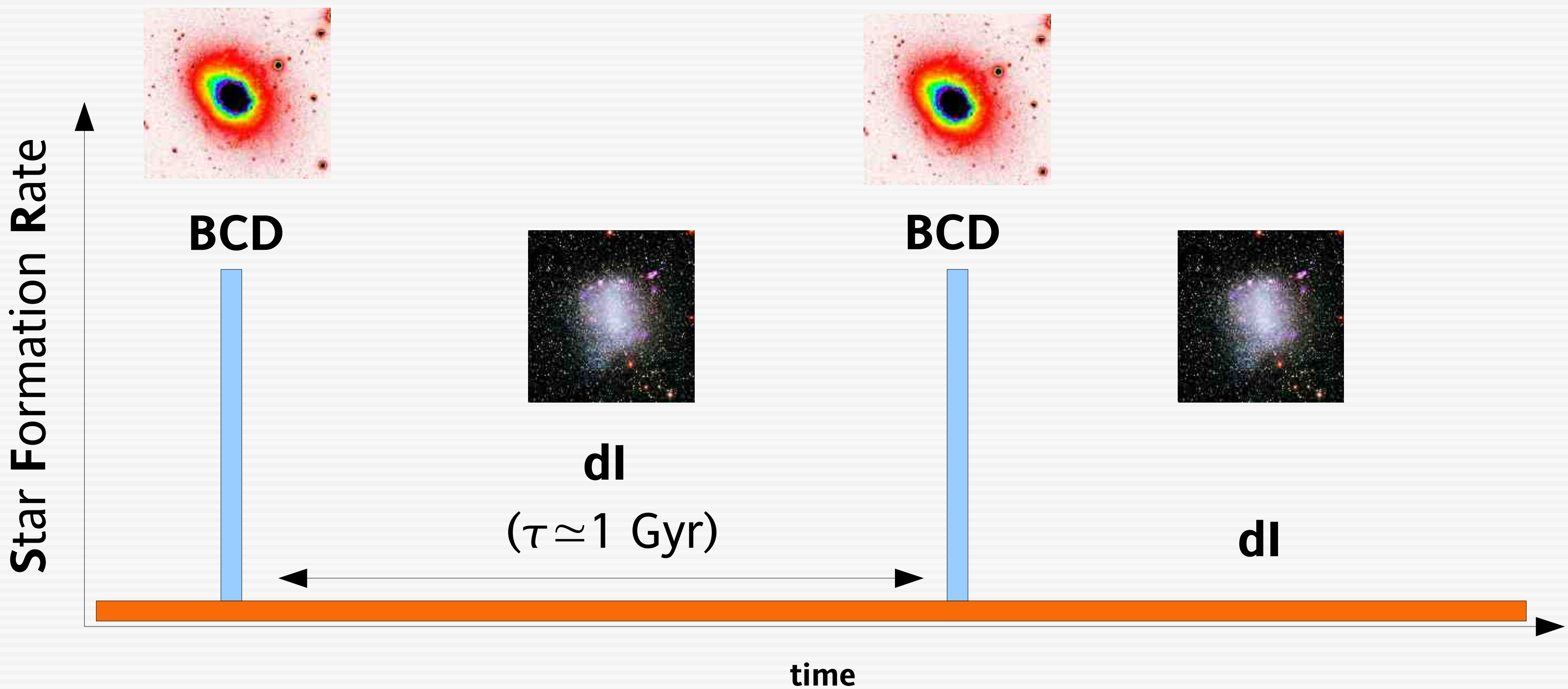
- Star forming activities in BCDs are (partly) regulated by the gravitational potential of the stellar LSB host $\longrightarrow$
- ? does Dark Matter dominate within the Holmberg radius of BCDs?

Evolutionary connections between BCDs and dIs

P. Papaderos

Evolutionary links between BCDs and dIs (?)

The “standard” dI↔BCD evolutionary scenario



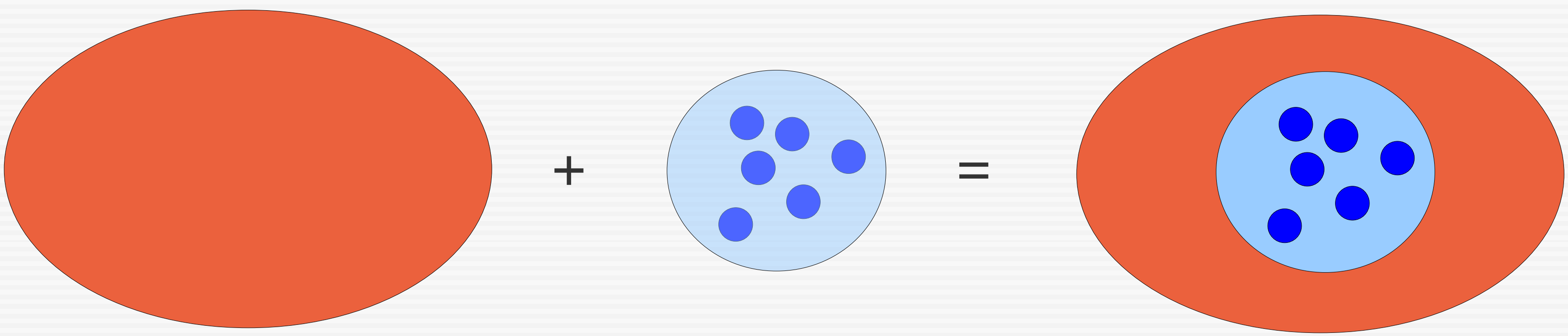
why starburst?

- gas consumption timescale ($\simeq M_{gas}/SFR$)
- timescale for gas cooling & replenishment
- evolutionary & population synthesis models
- ratio BCDs/dIs ~ 1/28

Thuan et al. (1991)
Krüger et al. (1994)
Mas-Hesse & Kunth (1999)
Sanchez-Almeida et al. (2008)

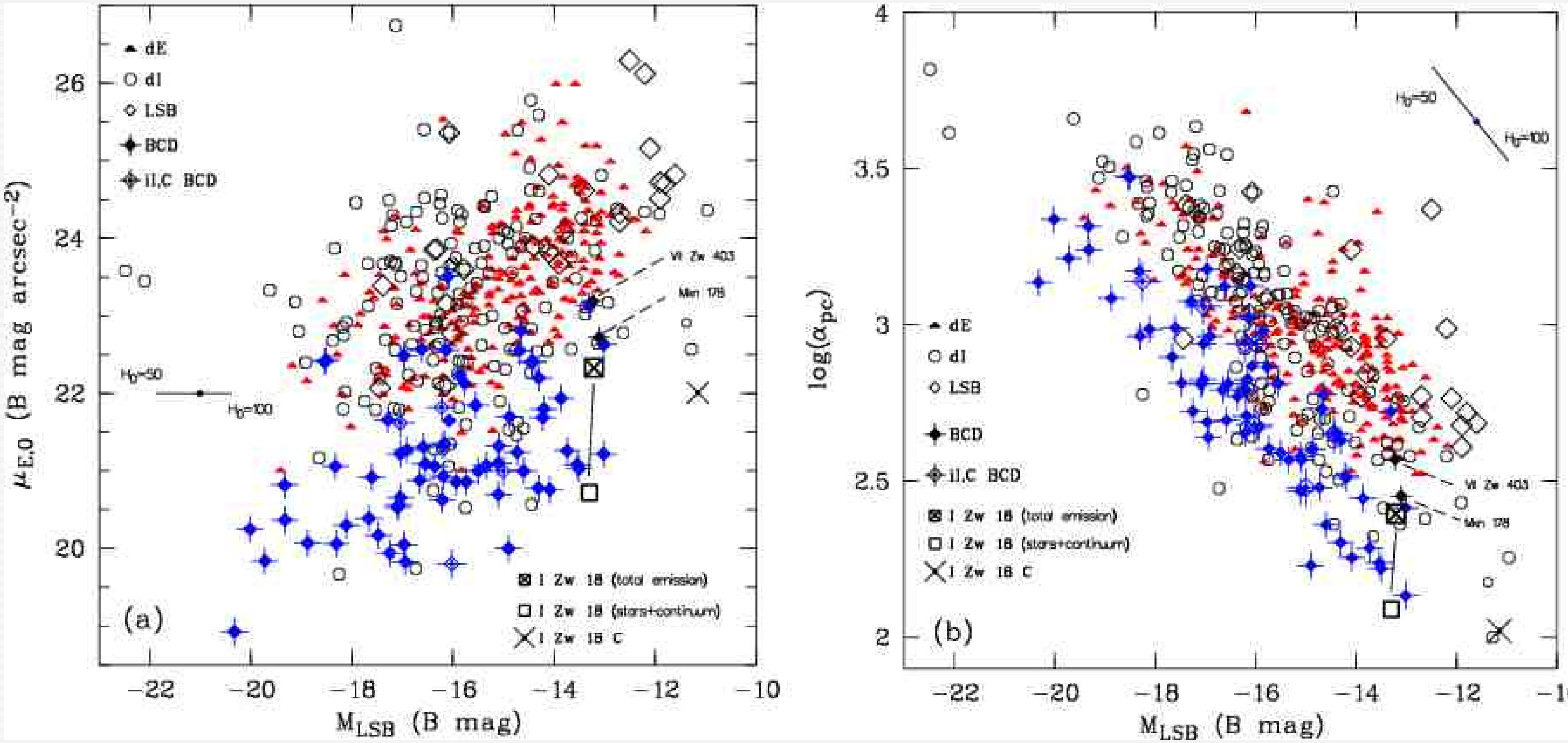
Evolutionary links between BCDs and dIs (?)

Working hypothesis: if BCDs and dIs represent one and the same type of dwarf galaxy seen, respectively, in an active (starburst) and quiescent (inter-burst) phase, then BCDs and dIs must be indistinguishable from one another in the structural properties ($\mu_{E,0}$ and α at a given M_B) of their host galaxy.



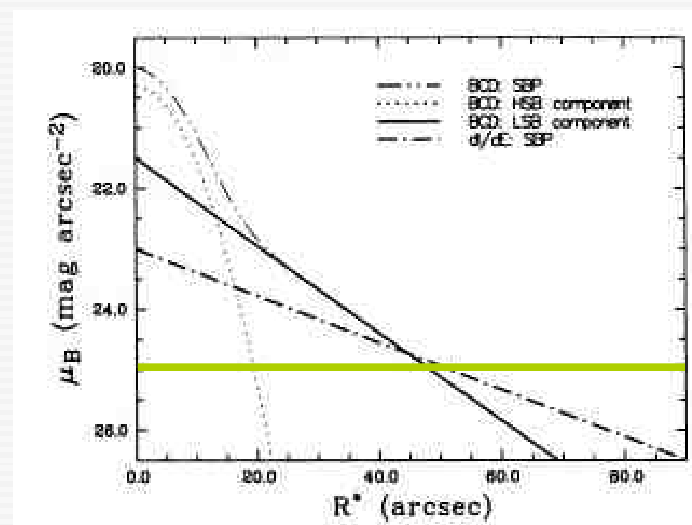
Dwarf irregular + Starburst = Blue Compact Dwarf

Evolutionary links between BCDs and dIs (?)



Papaderos et al. (1996,2002)

- at equal absolute B magnitude, the host galaxy of a BCD is on average more compact than a dI (or a dE). (Papaderos et al. 1996, Gil de Paz & Madore 2005)
- $\Delta\mu_{E,0} \geq$ 2 mag and $\alpha_{BCD}/\alpha_{dI} \leq$ 0.5
- → The central stellar density of the host galaxy of the BCD host is $\geq$**10** higher than that in dIs.
- BCDs have a $\geq 5\ \Sigma_{HI}$ than dIs (Wednesday, May 5th)
- Revision of the "standard" dI↔BCD evolutionary scenario for dwarf galaxies?



Evolutionary links between BCDs and dIs (?)

Hypotheses

- a) bimodal dwarf galaxy distribution (☹)

- b) dynamical (structural) dI↔BCD evolution due to gas infall *prior to* the starburst and subsequent gas ejection *during/after* the starburst.

  Possible only if Dark Matter **does not** dominate the mass within the Holmberg radius (P96).

dark-to-luminous mass ratio

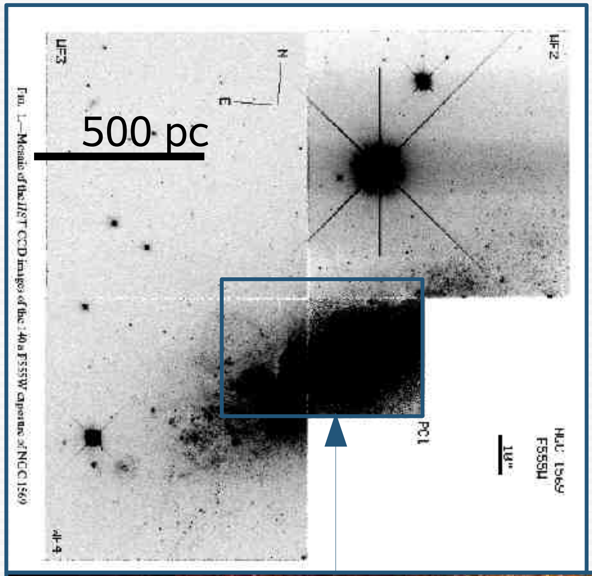
$$\psi(Ri_{Ho}) = M_{DM} / M_L < 1$$

Evolutionary links between BCDs and dIs (?)

$$\frac{R^{\mathrm{f}}}{R^{\mathrm{i}}} = \frac{M^{\mathrm{i}}}{M^{\mathrm{f}}} = (1+\mathscr{F})^{-1}$$

Hills (1980)

$$\mu^{\mathrm{f}}_{\mathrm{E},0} = \mu^{\mathrm{i}}_{\mathrm{E},0} + 5\log\left(\frac{\alpha^{\mathrm{f}}}{\alpha^{\mathrm{i}}}\right) = \mu^{\mathrm{i}}_{\mathrm{E},0} - 5\log\left(\frac{M^{\mathrm{f}}}{M^{\mathrm{i}}}\right)$$



Hunter et al. (2000)

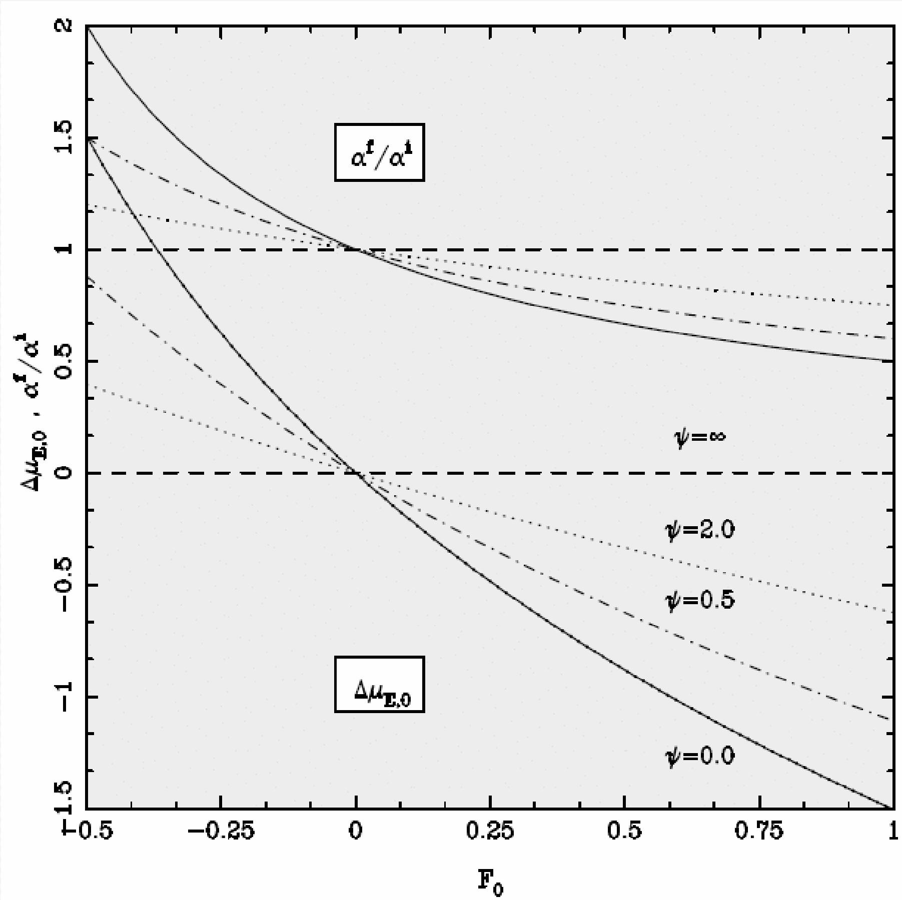
Conversely, if **(ψ <1)** then the reverse scenario is also feasible, i.e. gas infall from the halo can lead to an

adiabatic contraction

of the stellar host galaxy, possibly moving a dI into the parameter space typically occupied by BCDs.

Therefore when starburst activity is initiated (BCD phase) both gas and stars are much more centrally concentrated than during the quiescent interburst phase (dI phase).

Adiabatic contraciton & expansion of the host galaxy



← Variation of the central surface brightness $\Delta\mu_{E,0} = \mu^f_{E,0} - \mu^i_{E,0}$ and the exponential scale length α^f/α^i of the underlying stellar LSB component as a function of the fractional luminous mass $\mathcal{F}_0 = (\Delta M_{Gas}/M^i_L)$ removed from or accreted onto it, for initial dark-to-luminous mass ratios $\psi^i = M_{DM}/M^i_L$ equal to 0, 0.5, 2.0 and ∞.

with

$F_0 = \Delta M_{gas}/M_L$

gas ejection: $F_0 < 0$

gas infall : $F_0 > 0$

$M_L = M_\star + M_{gas}$

dark-to-luminous mass ratio

$\psi(R^i_{Ho}) = M_{DM} / M_L$

For

$$\xi = 1 + \frac{\mathcal{F}_0}{1+\psi^i_{R_{Ho}}}$$

$$\Delta\mu_{E,0} = -5\,\log(\xi)$$

and

$$\frac{\alpha^f}{\alpha^i} = \xi^{-1}$$

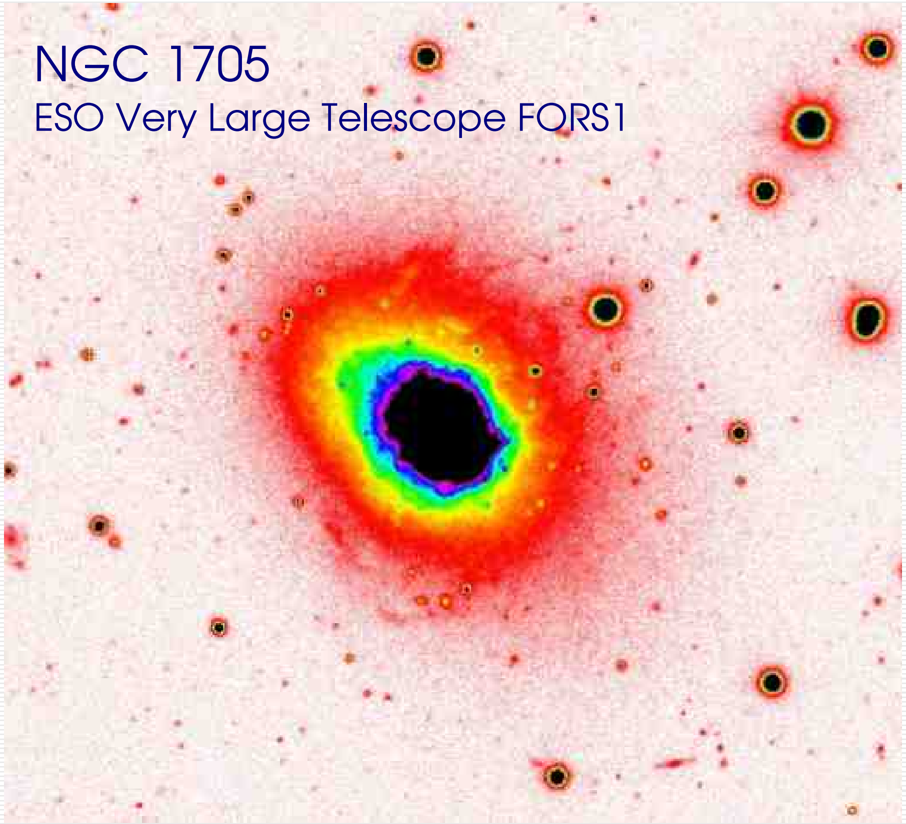
Summary

The evolutionary links between BCDs and dIs are not yet understood.

Critical observational test: determination of

$\psi(Ri_{Ho})$ and its time evolution

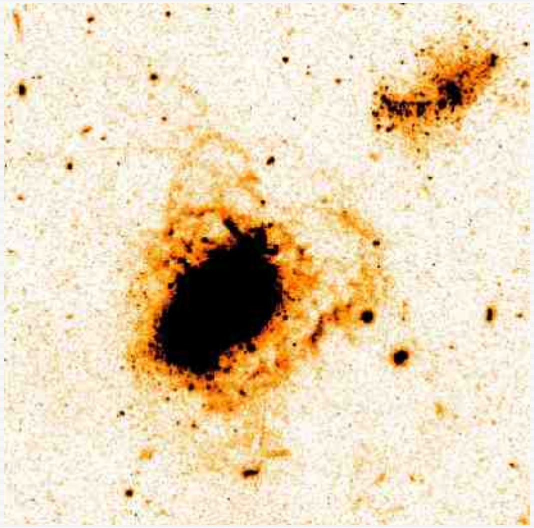
In >95% of the BCD population in the local universe
starburst activity takes place
within an <u>old</u> <u>regular</u> host galaxy



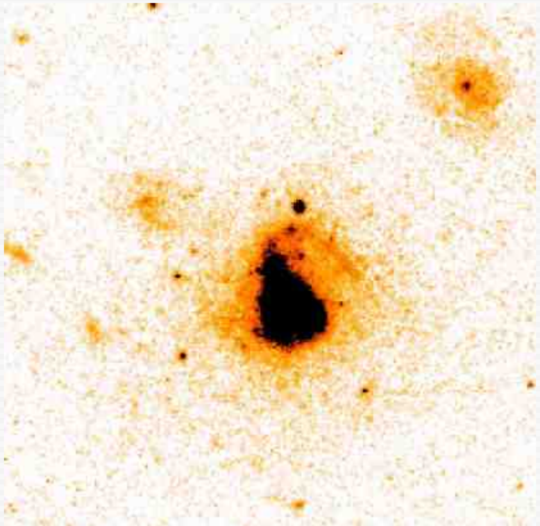
There are very few exceptions!

Extremely metal-deficient **BCD**s: **XBCDs**

Young galaxy candidates in the nearby Universe?

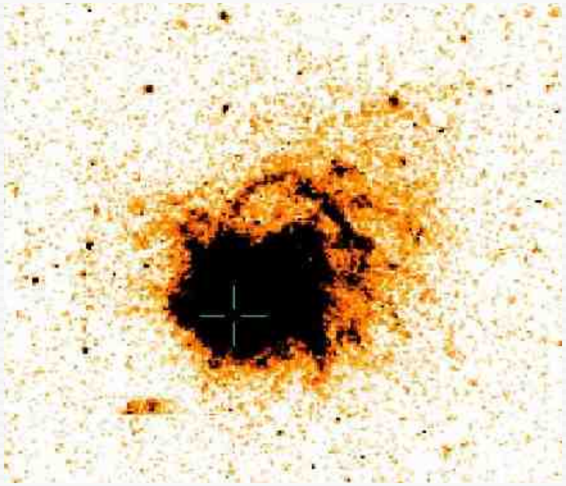


Papaderos et al. (2002)

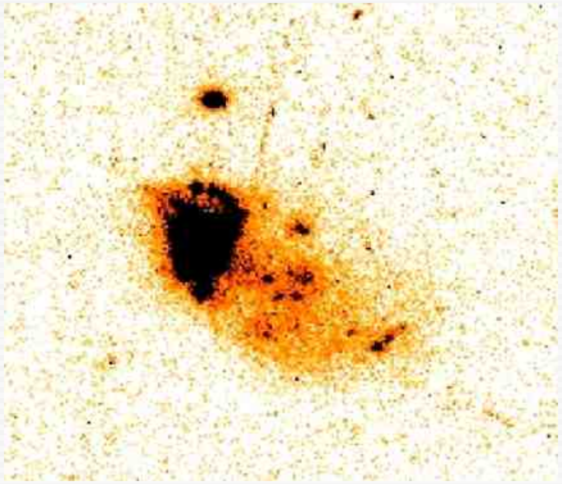


Guseva, Papaderos, Izotov et al. (2004)

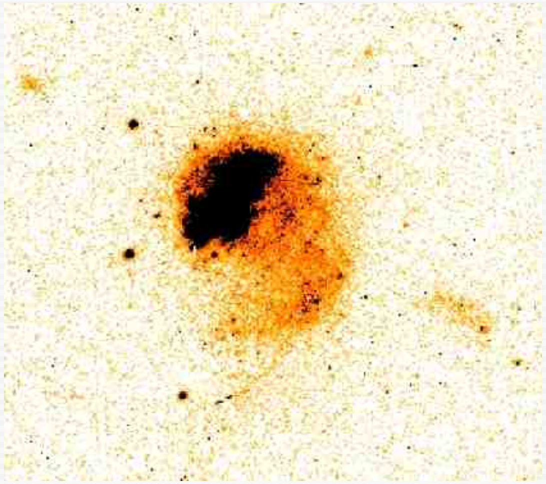
- no evidence for a dominant old stellar population
- irregular morphology and intense star-forming activity
- extremely metal-deficient ($Z_\odot/43 \leq Z \leq Z_\odot/3$)
- extremely rare (1% of the BCD-population; only 15 XBCDs discovered by the end of the last millenium)



Thuan et al. (1997), Papaderos et al. (1998)



Fricke et al. (2001)



Papaderos et al. (1999,2007)

Evolutionary status

- ~10 XBCDs studied in some detail with surface photometry and evolutionary synthesis models
  - ∃ stellar host galaxy with a Holmberg diameter of few 100 pc → do not currently form their first stellar generation
  - However – *contrary to normal BCDs* - the colors of the host galaxy (*in regions with weak nebular emission, or after subtraction of nebular emission*) are very blue (V-I=0.1 … 0.5 mag)
  - for standard SFHs (exp. SFR with an e-folding time of 1-3 Gyr) such colors imply that ½ of the stellar mass has formed during the last 0.5 – 4 Gyrs
- → several XBCDs are **cosmologically young** objects

Why to study XBCDs?

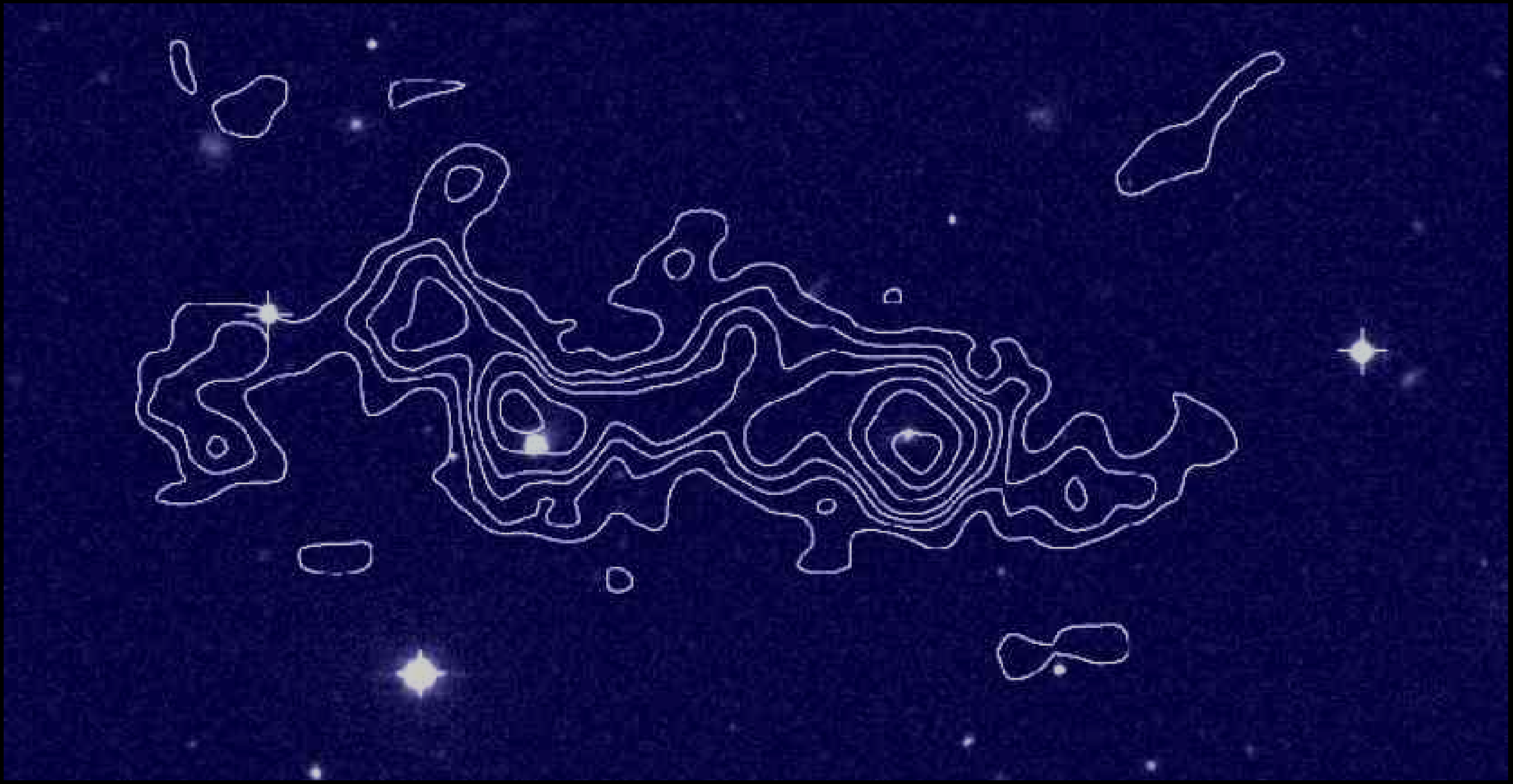
Star formation and feedback processes under chemical conditions similar to those in high-redshift protogalaxies

- properties of massive low-metallicity stars
- cooling efficiency of the hot, X-ray emitting plasma

Dynamical build-up and early chemical and spectrophotometric evolution of low-mass galaxies

- dynamical processes (e.g. monolithic collapse, inside-out, SF propagation, merging of smaller units?)
- observational constraints to numerical simulations of dwarf galaxy formation

The pair of XBCDs SBS 0335-052 E&W



Pustilnik et al. (2001)

SBS 0335-052: HI cloud with a projected size of 70×20 kpc; mass of ~10^9 $M_\odot$

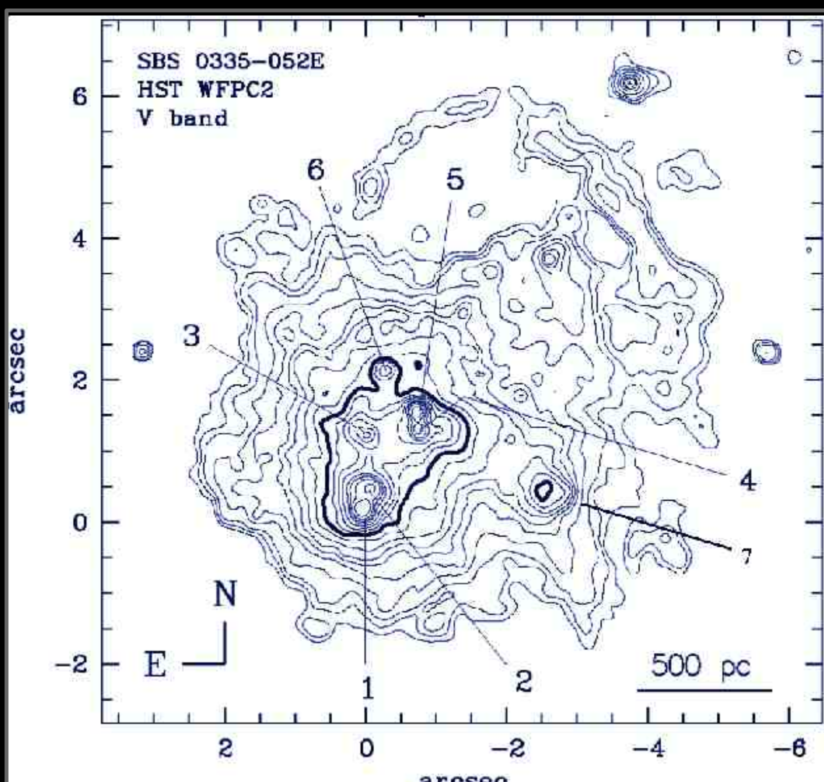
SBS 0335-052: formation

- Study of the V-I color and spatial distribution of stellar clusters using HST data

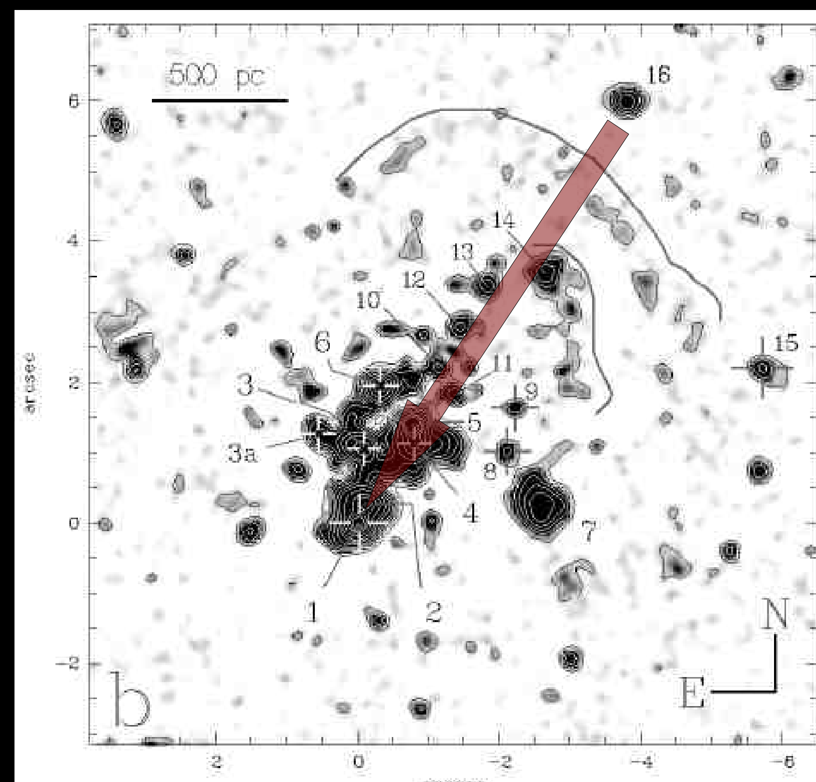
→

- galaxy is forming in a propagating mode from northwest to southeast with a mean velocity of ~20 km/s.

Papaderos et al. (1998)



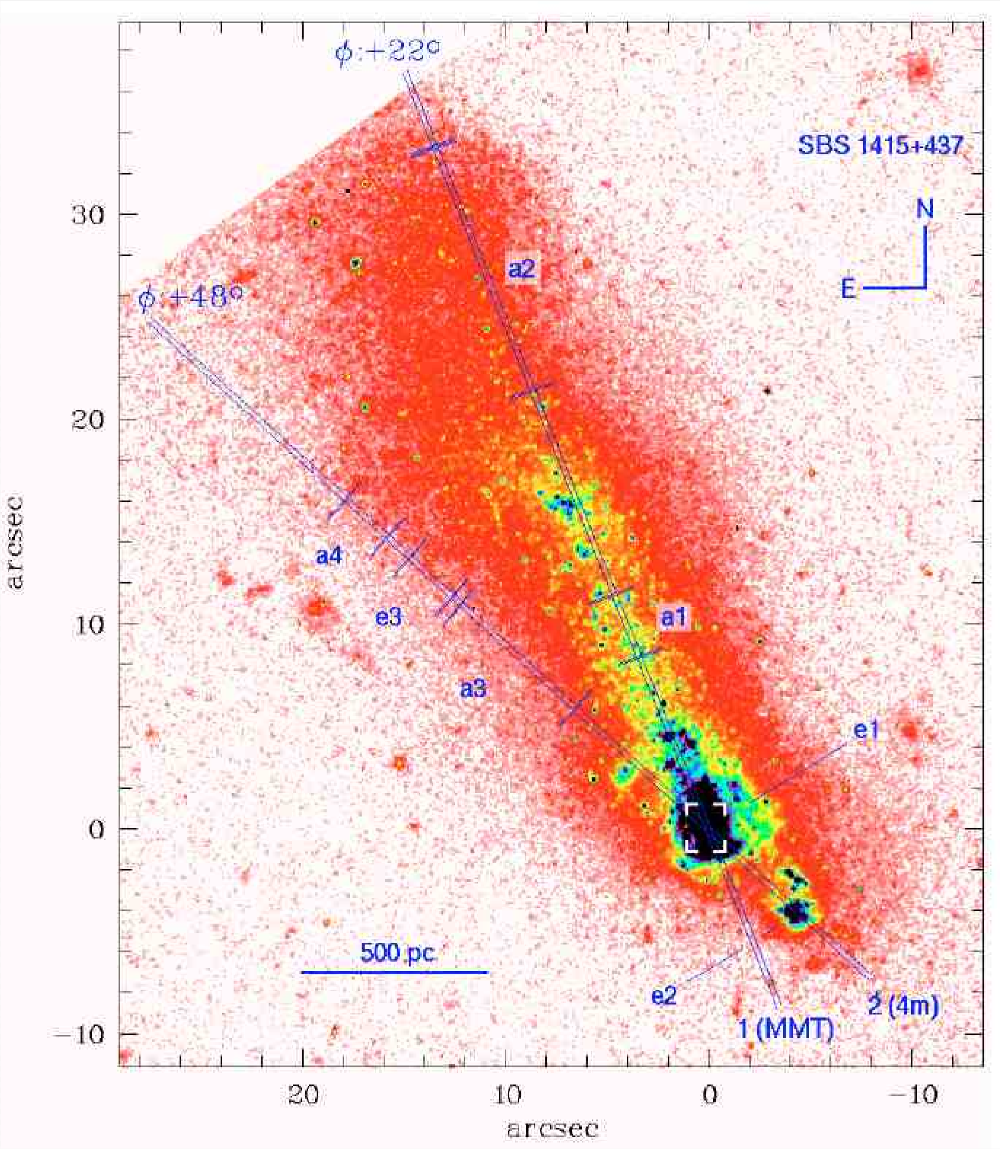
HST/WFPC2, V band



HST/WFPC2, I band, unsharp masked

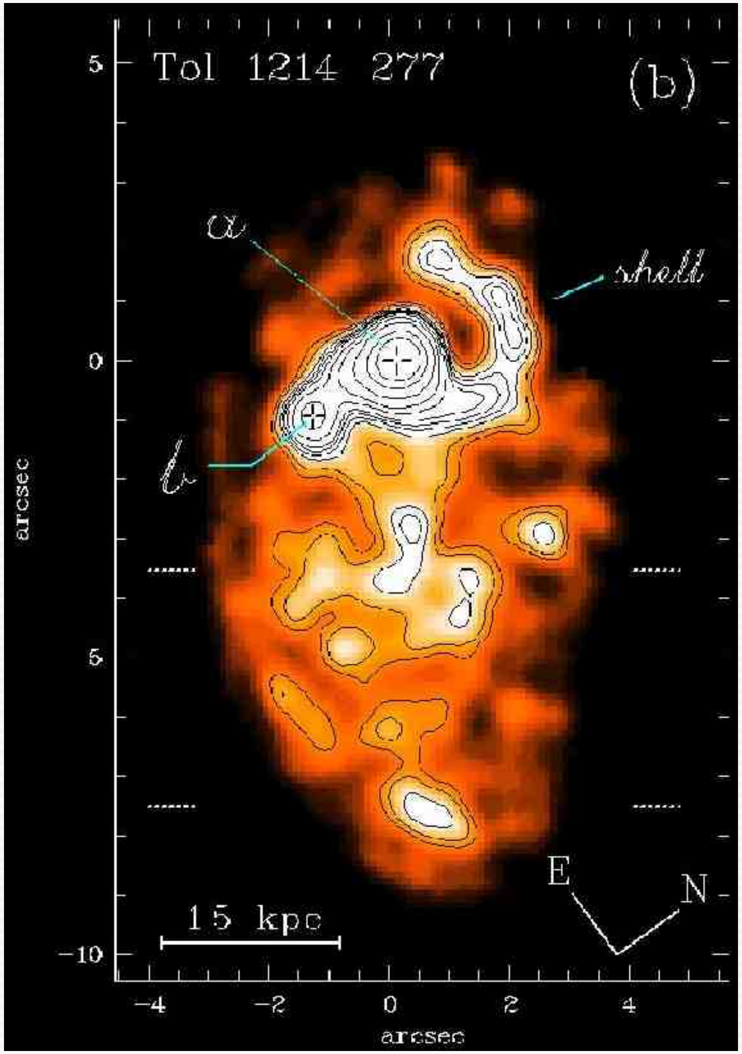
… other examples of XBCD formation through propagation

SBS 1415+437



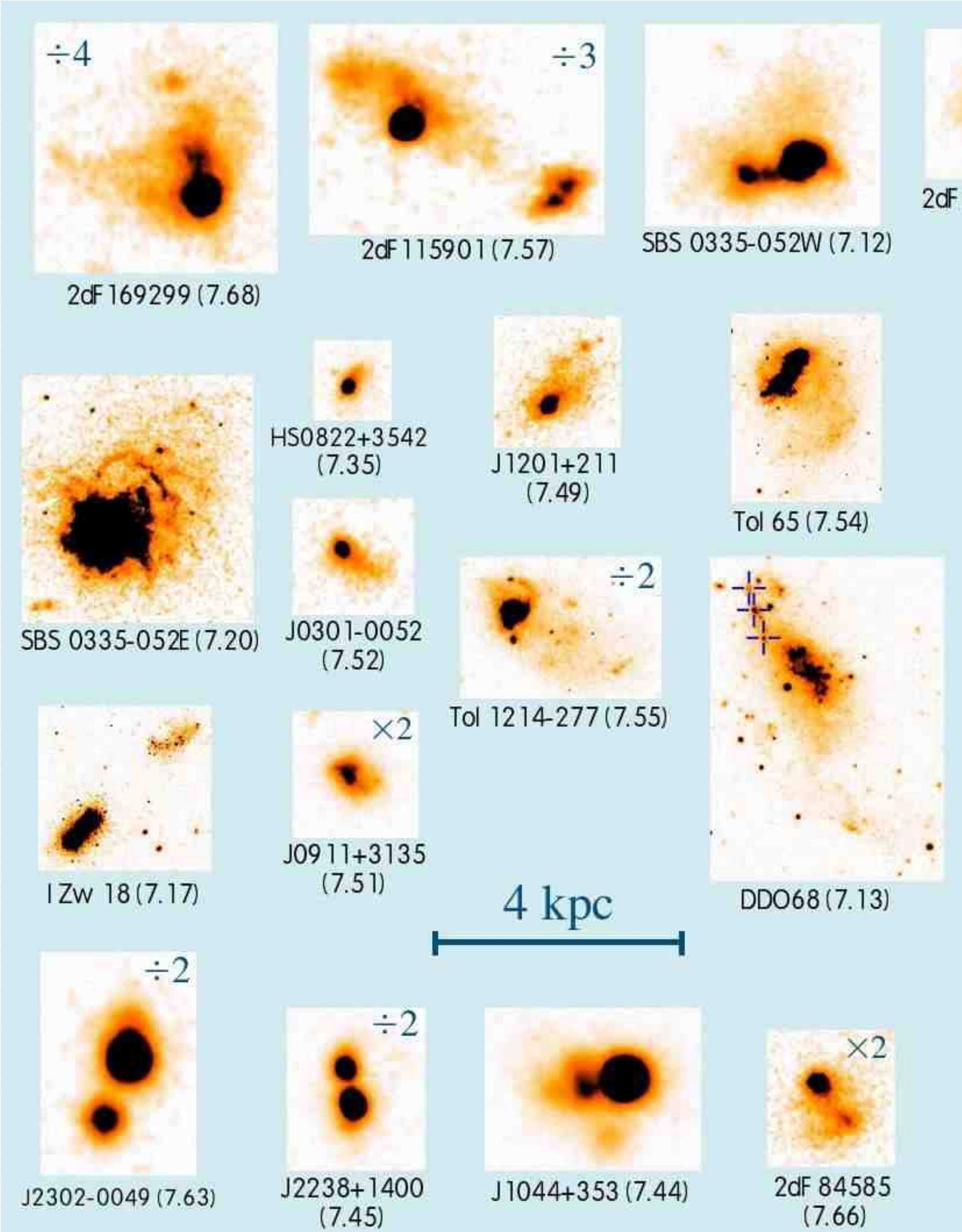
Guseva et al. (2003)

Tol 1214-277



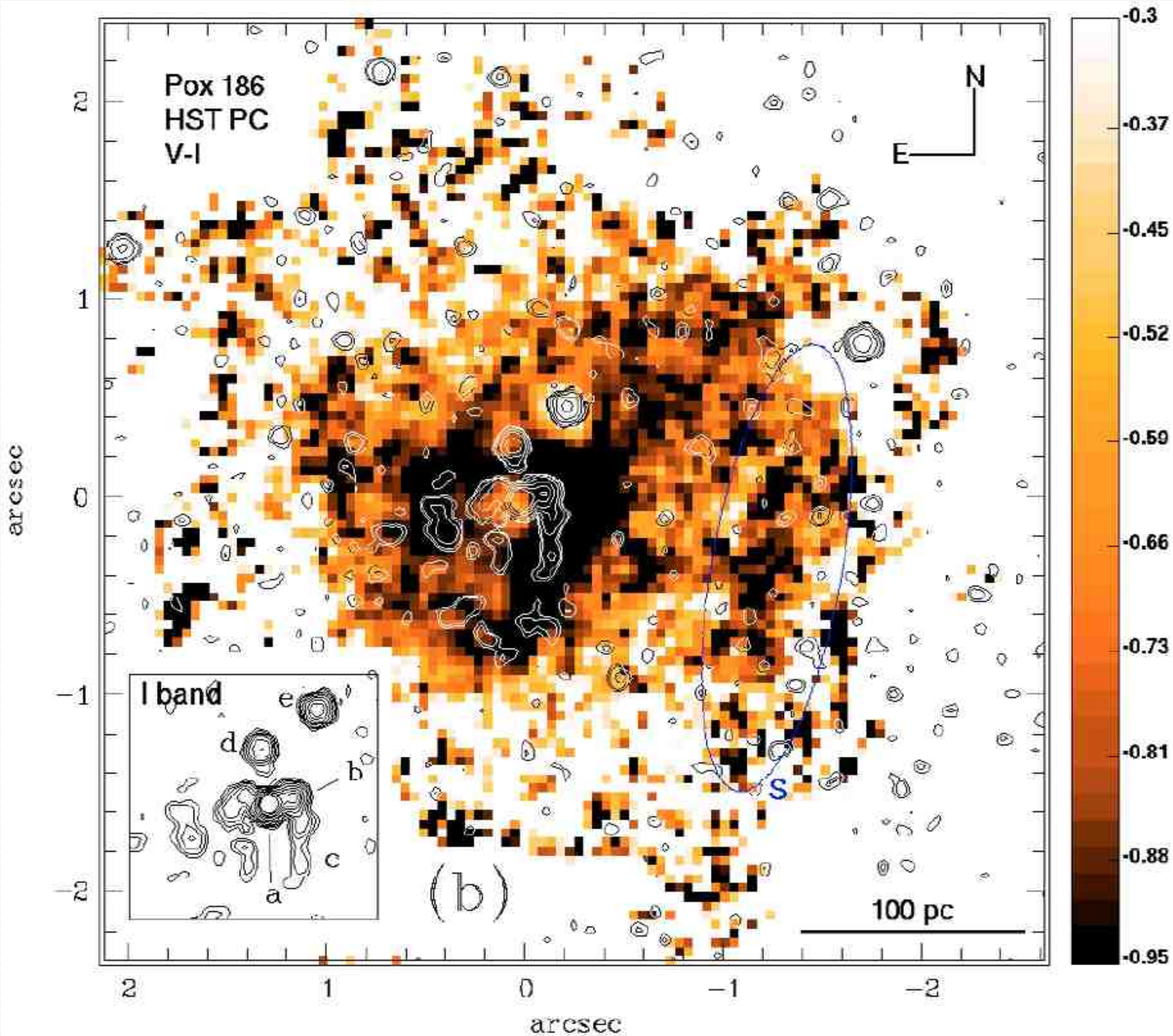
Fricke et al. (2001)

Morphology of XBCDs



Most XBCDs are characterized
by irregular or cometary
morphology
(contrary to the main class
of more metal-rich, old BCDs)

Ionized gas emission in XBCDs

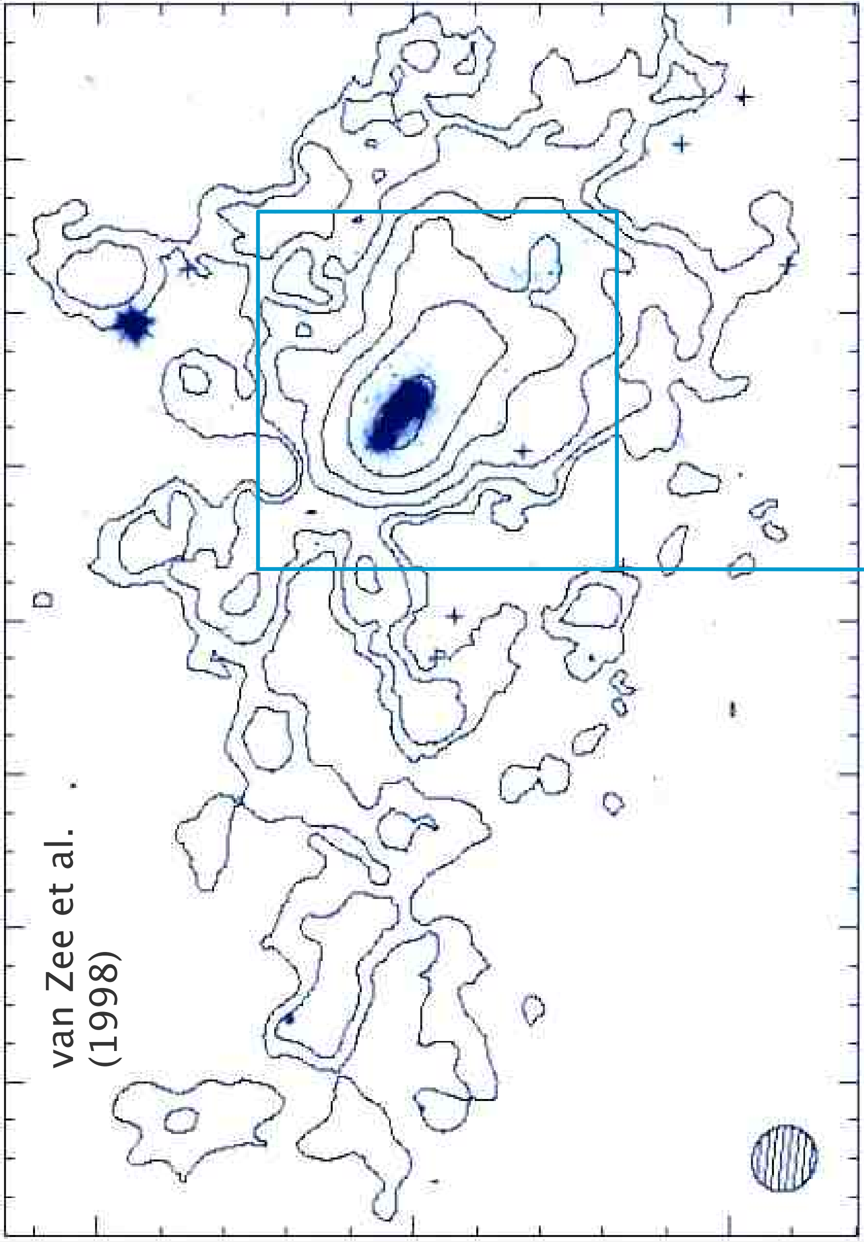


Guseva et al. (2004)

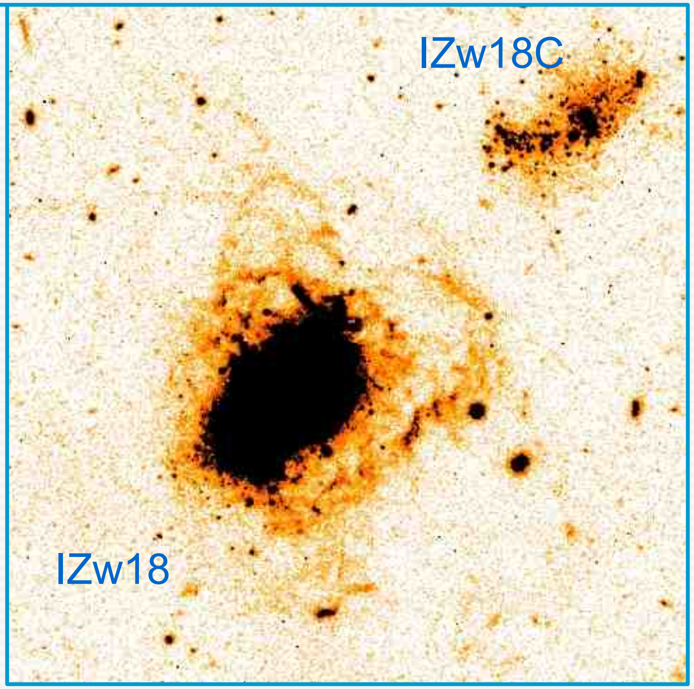
- Several XBCDs show intense nebular emission (EW > 1000 Å), 0.1-1 kpc away from their SF regions
- Typical signatures: very blue (-0.5 .. -1 mag) V-I and R-I and moderately red (0.4 ... 0.6) B-R and V-R colors
- Corrections for ionized gas emission are necessary for age-dating of stellar populations using colors and/or color magnitude diagrams

I Zw 18 – the prototypical XBCD

(Z=Z$_\odot$/30, D=15 Mpc)

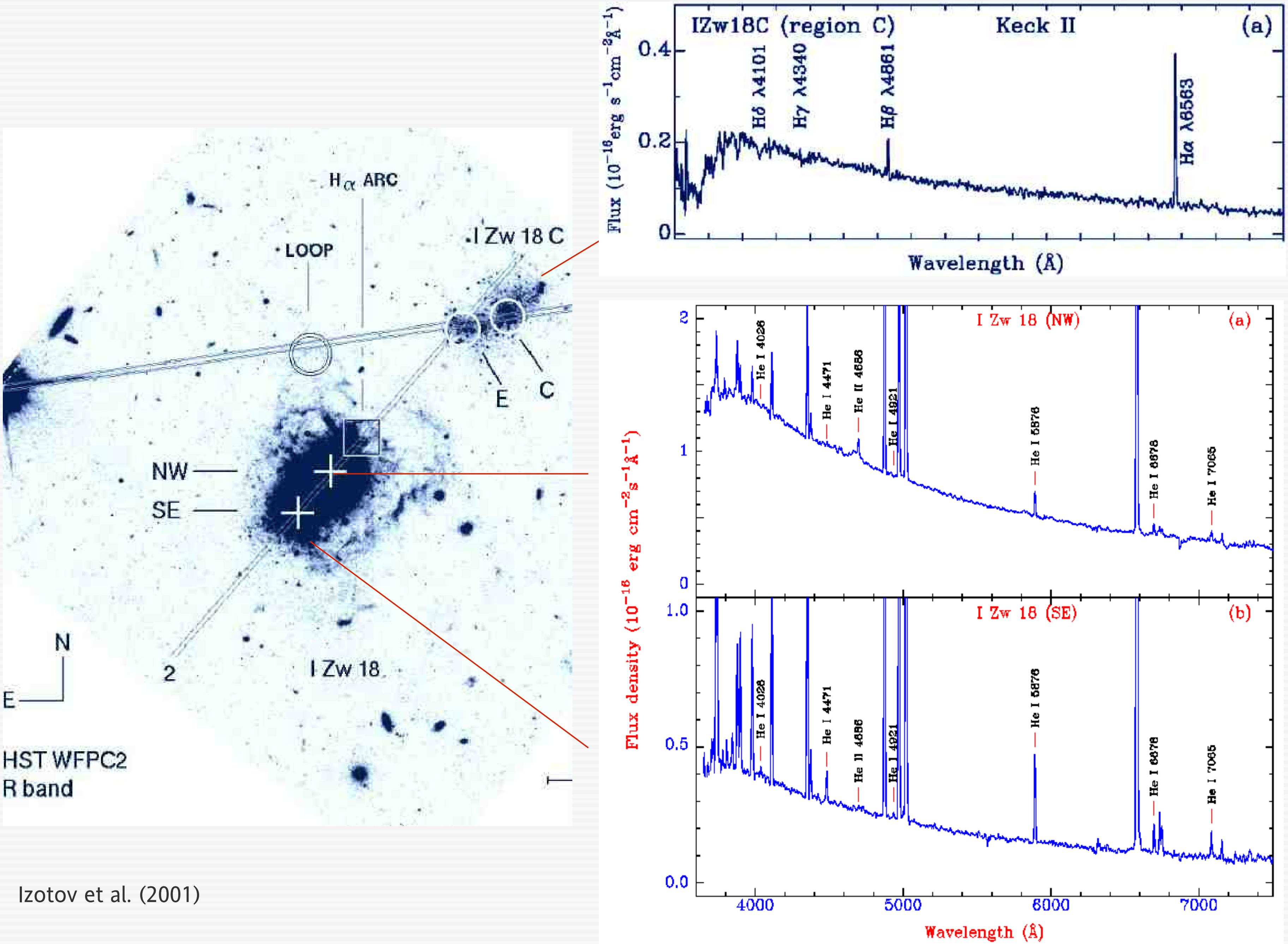


21cm VLA map



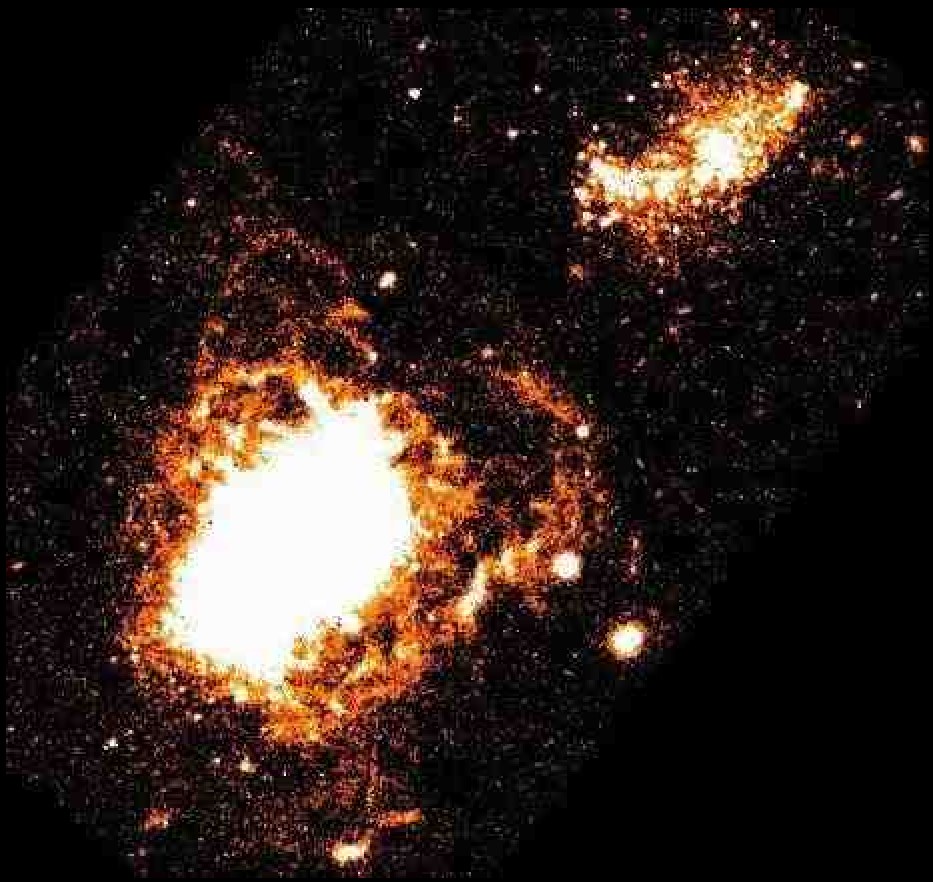
Optical HST exposure

I Zw 18 – the prototypical XBCD

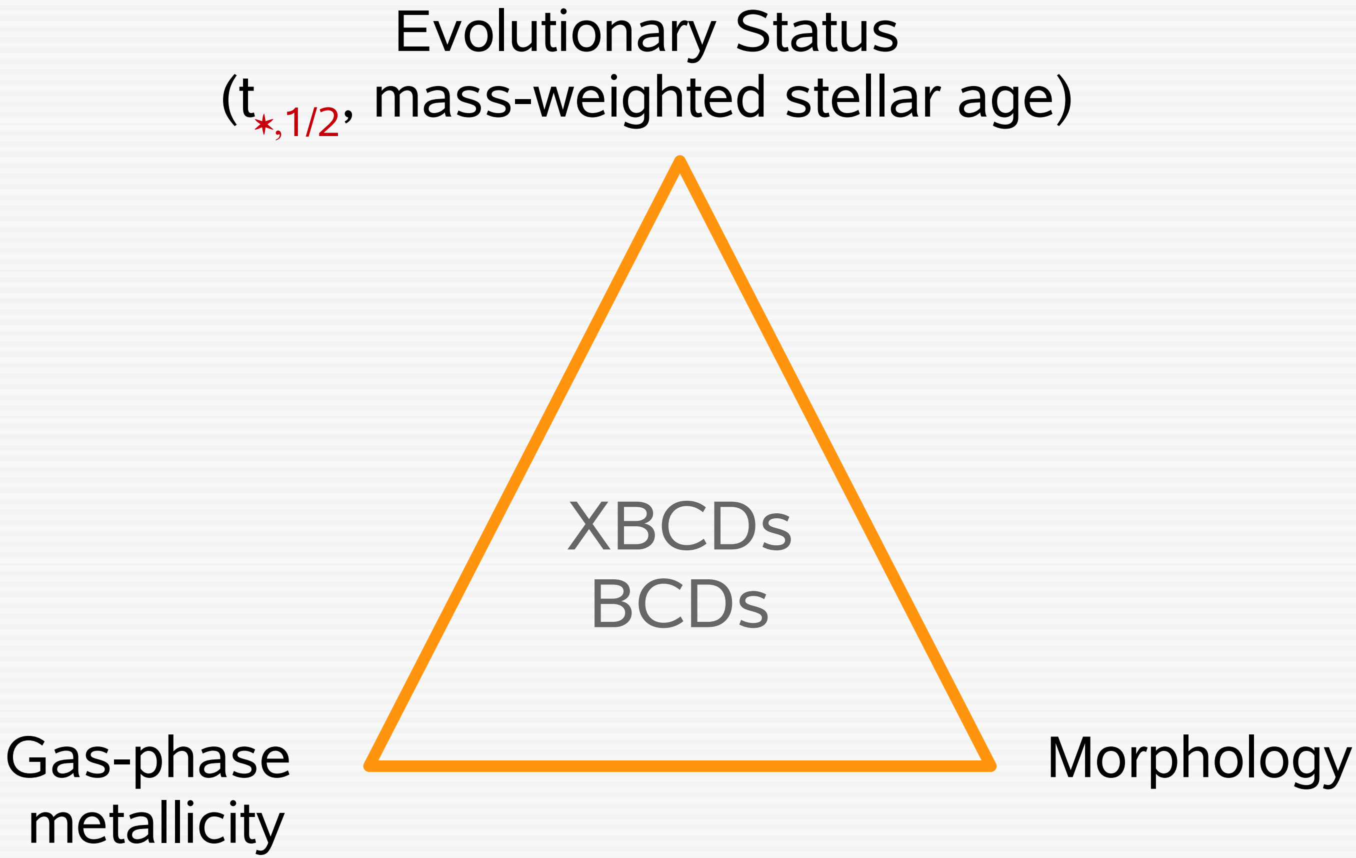


Izotov et al. (2001)

I Zw 18: a dwarf galaxy surrounded by an extended ionized gas halo



Papaderos et al. (2001)



+ mass & environment

Summary

- The number of XBCDs ($7.0 \leq 12+\log(O/H) \leq 7.6$) has dramatically increased in the last decade (~60 XBCDs currently known). Very few XBCDs have been studied in detail so far.

- All XBCDs studied have a stellar host galaxy, i.e. none of these systems forms its first stellar generation

- However, XBCDs are cosmologically young ($M_{\star,old}/M_{\star,0.5\text{-}4\,Gyr} \leqslant 1/2$). Studies of XBCDs may yield important insights into the main processes driving dwarf galaxy formation.

- IFU spectroscopic studies will permit a major step forward in our understanding of XBCD/BCD evolution.

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