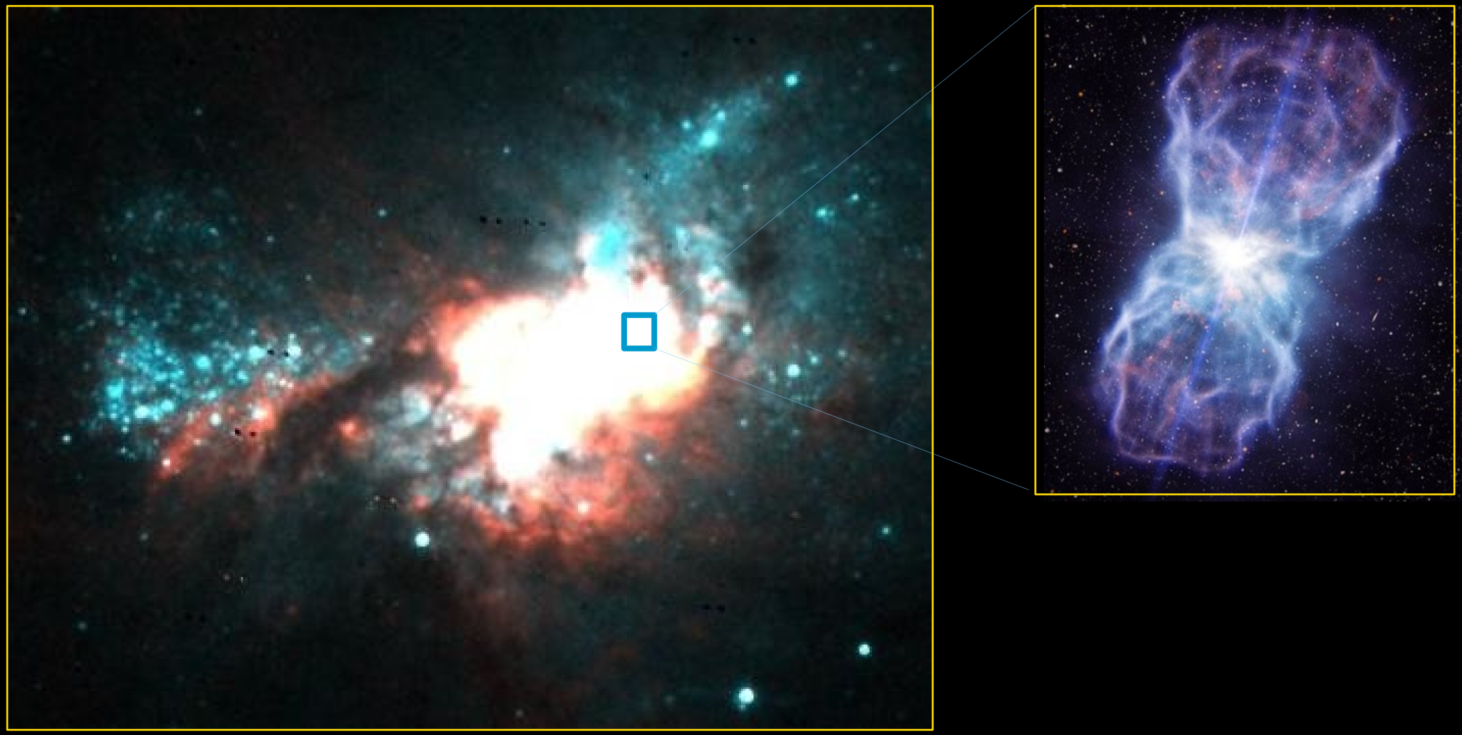


Extremely metal-poor (star-forming) galaxies (in the nearby universe)

Polychronis Papaderos
Centro de Astrofísica da Universidade do Porto

Galaxies meet GRBs ● Cabo de Gata ● September 2013

Metal poor ($12+\log(O/H) \lesssim 8.6$) and extremely metal-poor (XMP) galaxies ($12+\log(O/H) \lesssim 7.6$)

Note: recent revisions of the solar metallicity ($Z_\odot$): 12+log(O/H)

8.76 (Caffau et al. 2008)
8.65 (Asplund et al. 2005)
8.92 (Anders & Grevesse 1989)

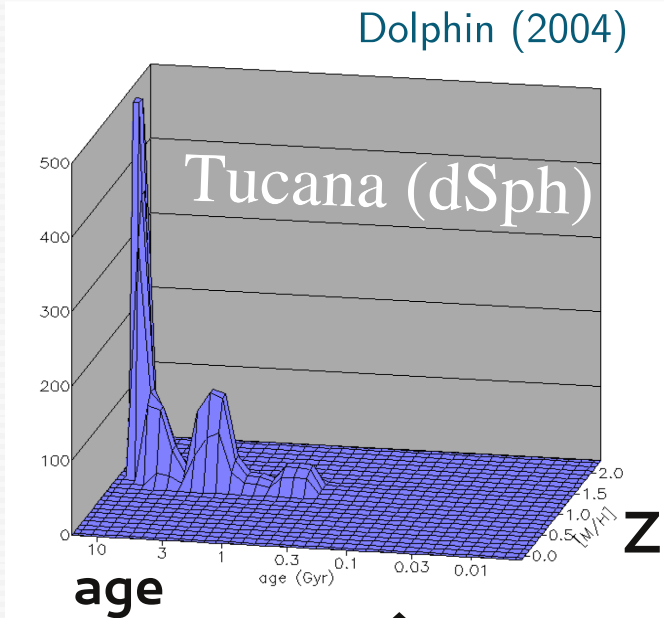
Sub-solar metallicity galaxies span a broad range in

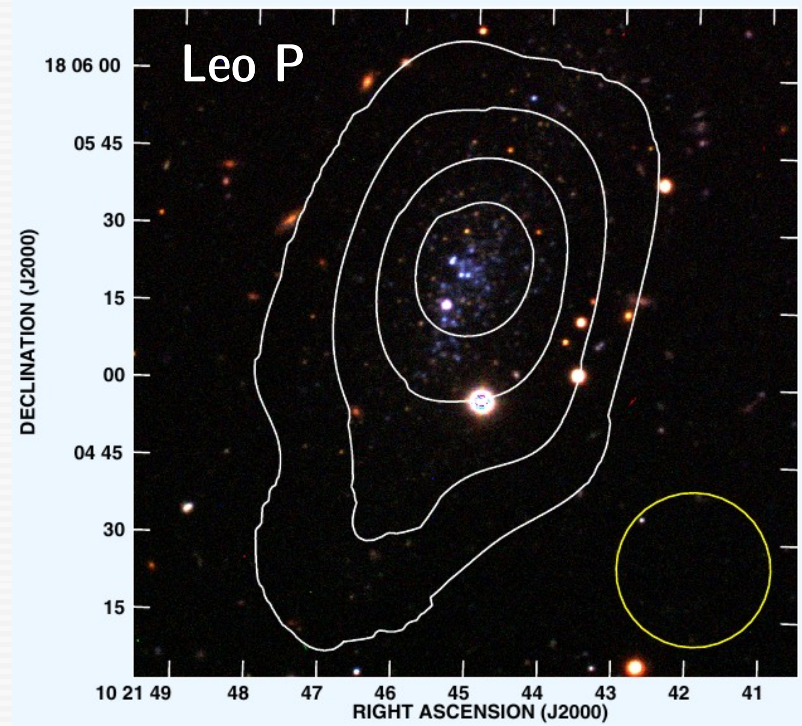
star formation rate (**SFR**),
specific SFR (**sSFR**),
SFR surface density (**ΣSFR**) and
mean surface brightness (**<μ>**)

sSFR
ΣSFR
<μ>

Low-surface brightness, low-sSFR metal poor galaxies

sSFR
ΣSFR
<μ>



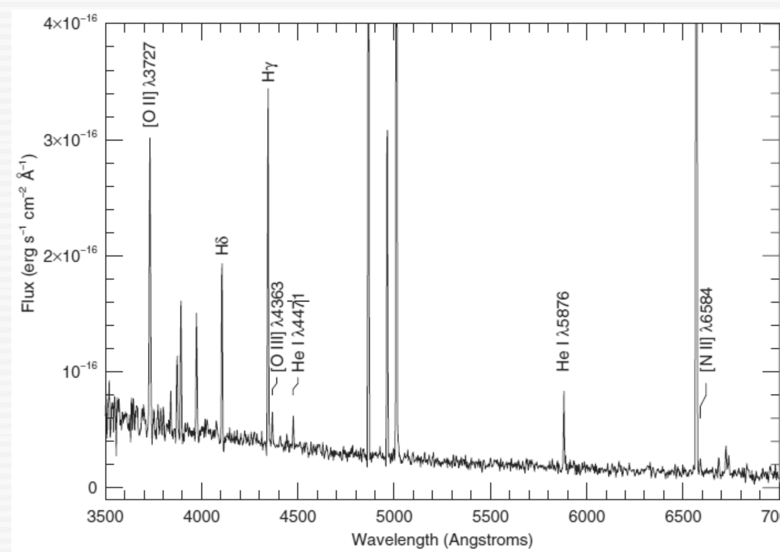


Giovanelli et al. (2013)

- Dwarf spheroidals (dSph) and *transition galaxies*
- a few nearby dwarf irregulars with a very low <μ> and large M(HI)/L_B ratio

(*retarded, slowly-cooking, dark*)

- Blue low-surface brightntess (LSB) galaxies (and the outskirts of late-type disks)

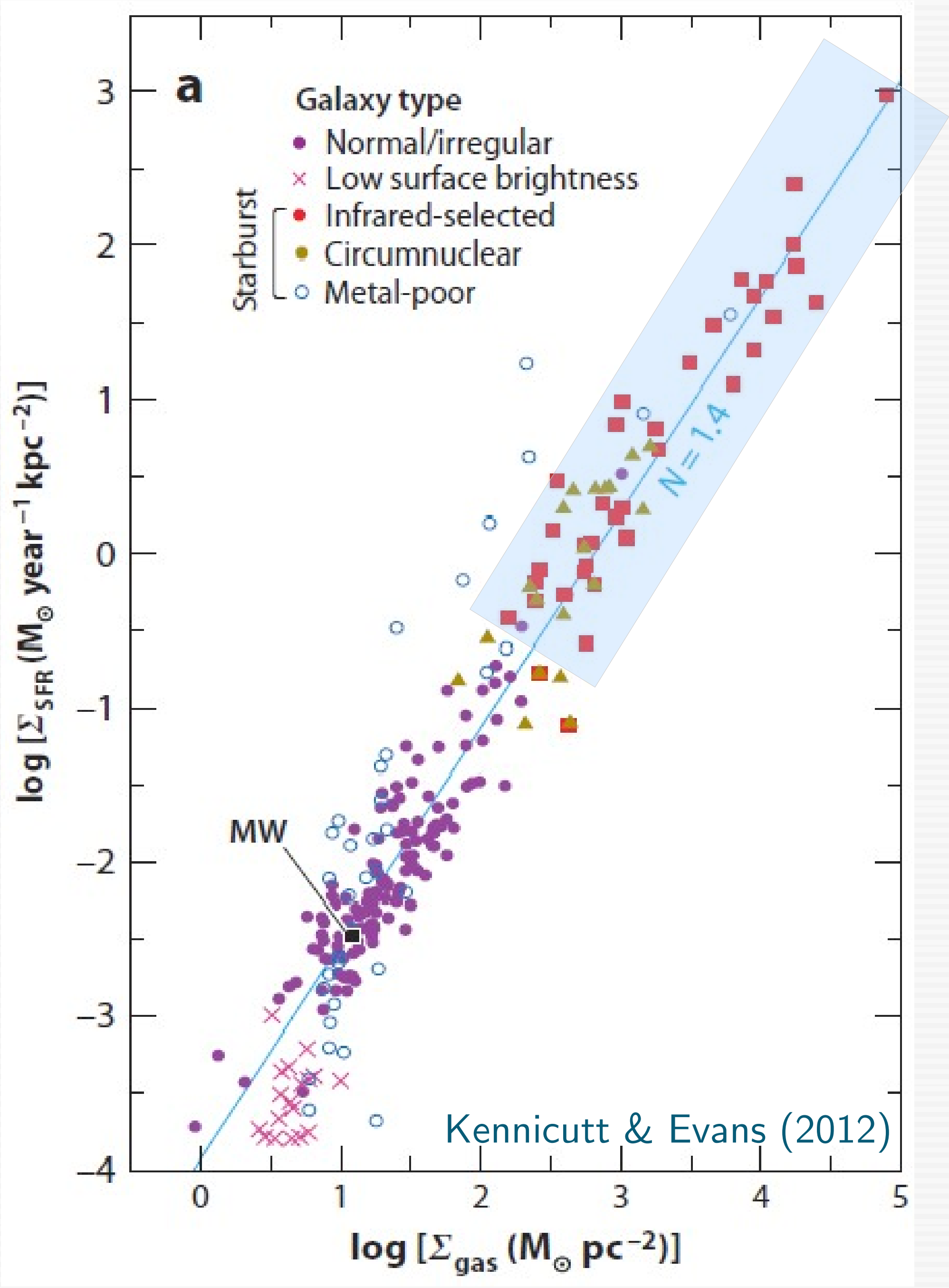


Skillman et al. (2013)

see, e.g. Mateo (1998), McConnachie (2012), Bergvall (2012)

High-surface brightness, high-sSFR metal poor galaxies

sSFR
ΣSFR
<μ>



High-surface brightness, high-sSFR metal poor galaxies

ΣSFR
sSFR
<μ>

$\lesssim 10^{-8}$ yr^{-1}

- Blue compact dwarf (BCD) galaxies (low-mass & high-compactness subset of HII galaxies)

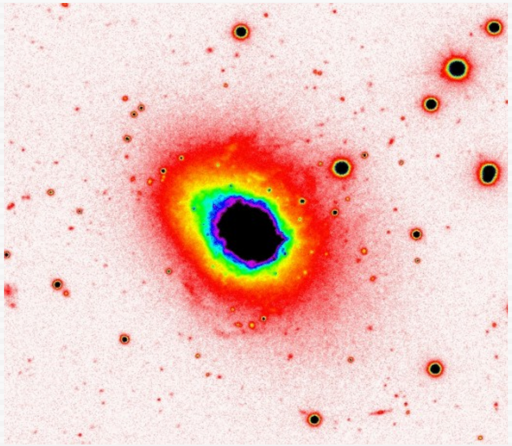
  $M_\ast \approx$ a few $10^8\ M_\odot$; $Z_O \simeq 8.1$

- Luminous blue compact galaxies (BCGs)
  - LBCGs
  - CNELGs
  - green peas

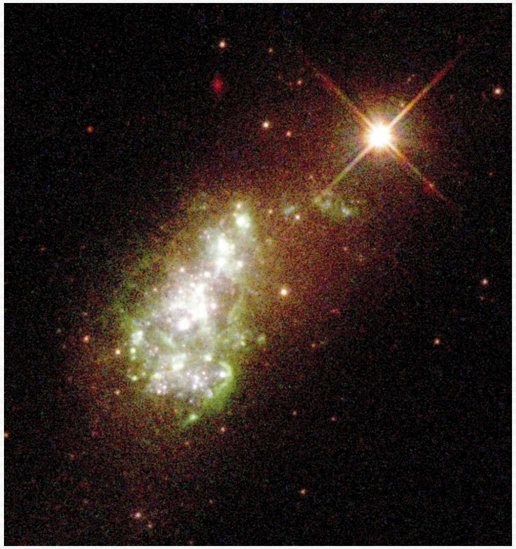
  $M_\ast \approx$ a few $10^9\ M_\odot$; $Z_O \lesssim 8.5$

- XMP BCDs (XBCDs)

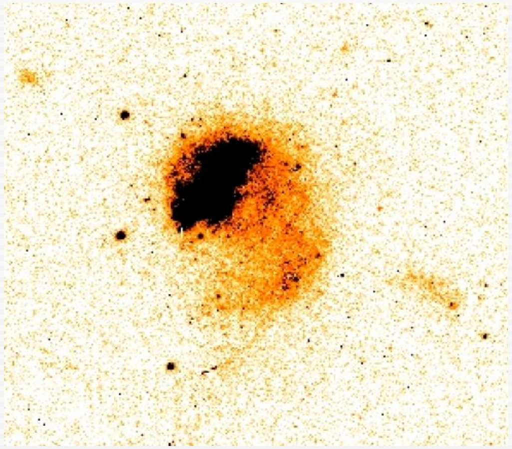
  $M_\ast \approx 10^7\ M_\odot$; $Z_O \lesssim 7.6$



Papaderos et al. (1996)

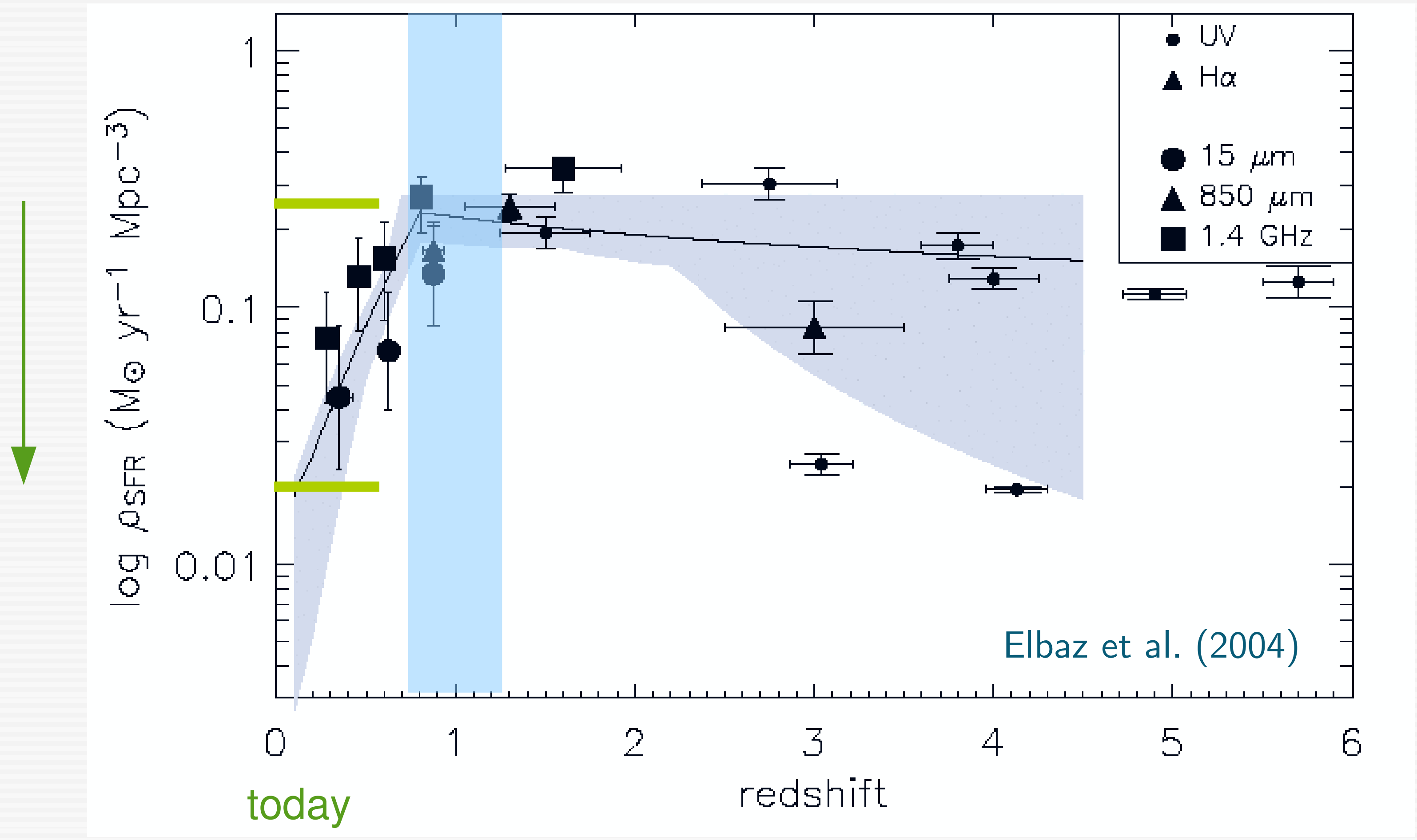


Östlin et al. (2003)



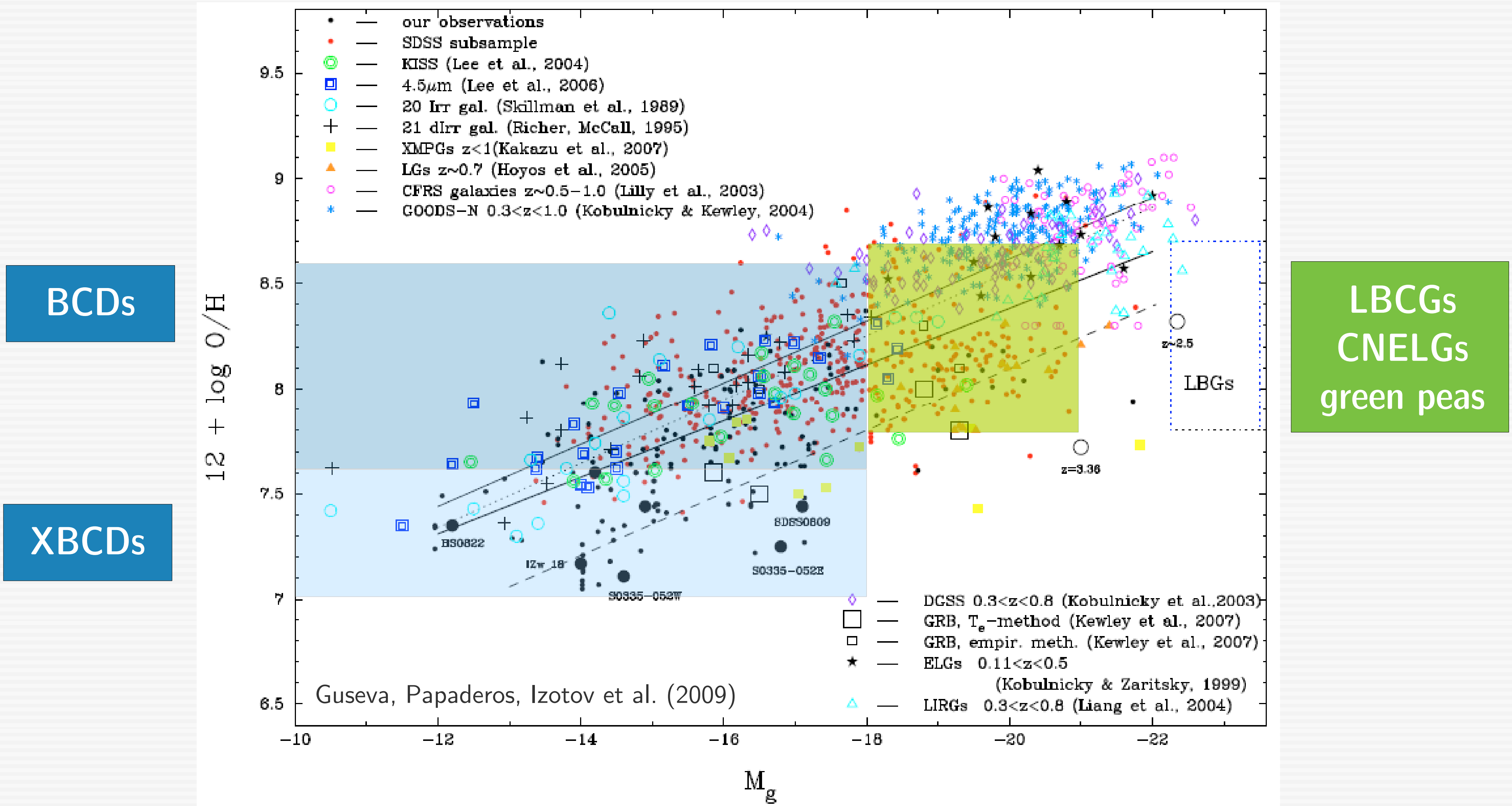
Papaderos et al. (1999)

Evolution of the cosmic SFR density



Low-mass starburst galaxies (BCDs/LBCGs) account for ~40% of the cosmic of SFR density at z~1 (Guzman et al. 1998)

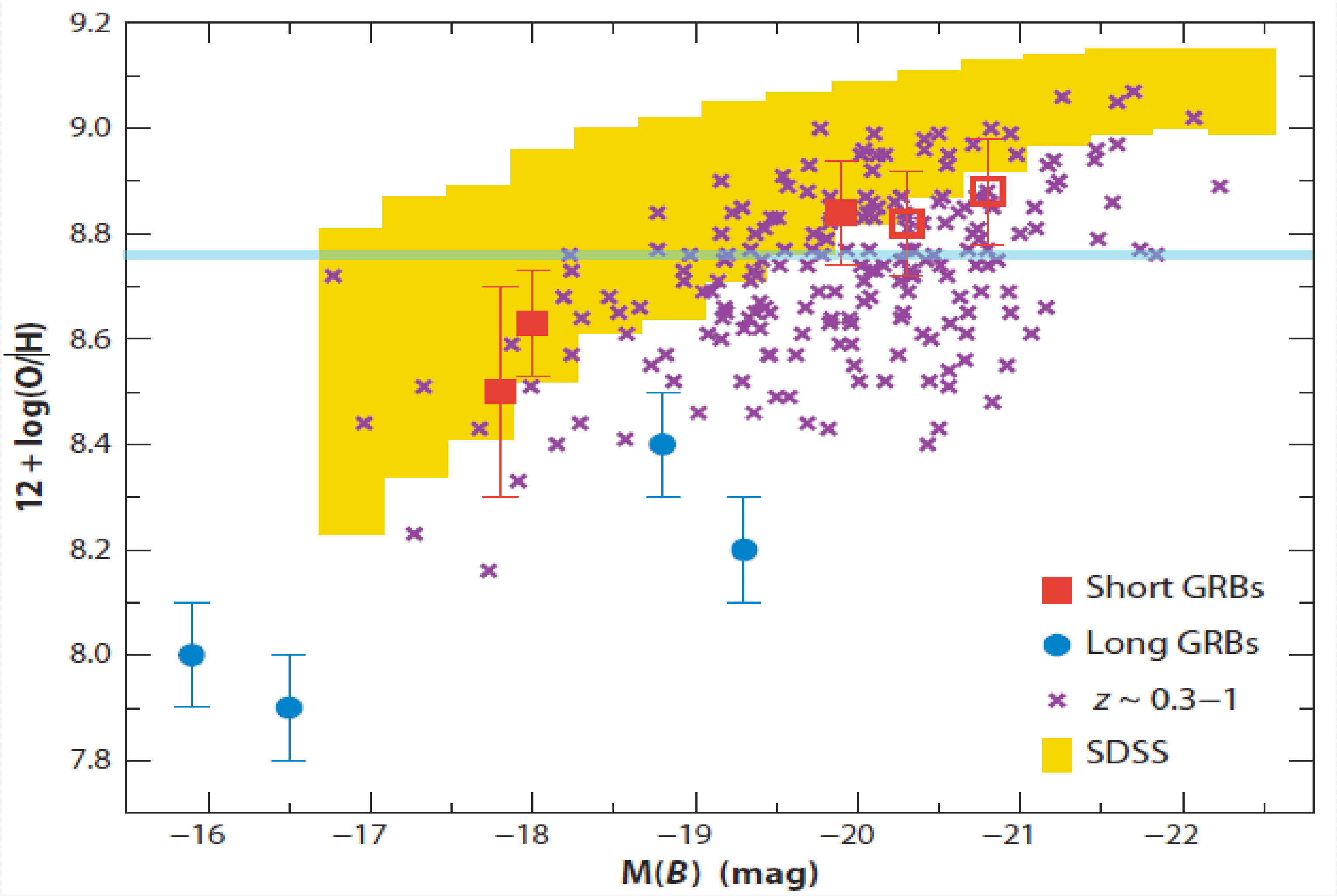
Luminosity-Metallicity (T_e based) relation for emission-line galaxies



- XMP BCDs (XBCDs) are very rare in the nearby Universe (<1% of the BCD population; ~15 systems identified by the end of the past millennium, cf Kunth & Östlin 2000); meanwhile ~90 further XBCDs discovered, mainly from SDSS data (e.g., Izotov et al. 2006, Papaderos et al. 2006, Guseva et al. 2009; recent compilation of literature data in Moralez-Luis et al. 2011 and Filho et al. 2013)

- only very few XBCDs/XBCGs known at higher-z (e.g. Kakazu et al. 2007, Kewley et al. 2007, Atek et al. 2011)

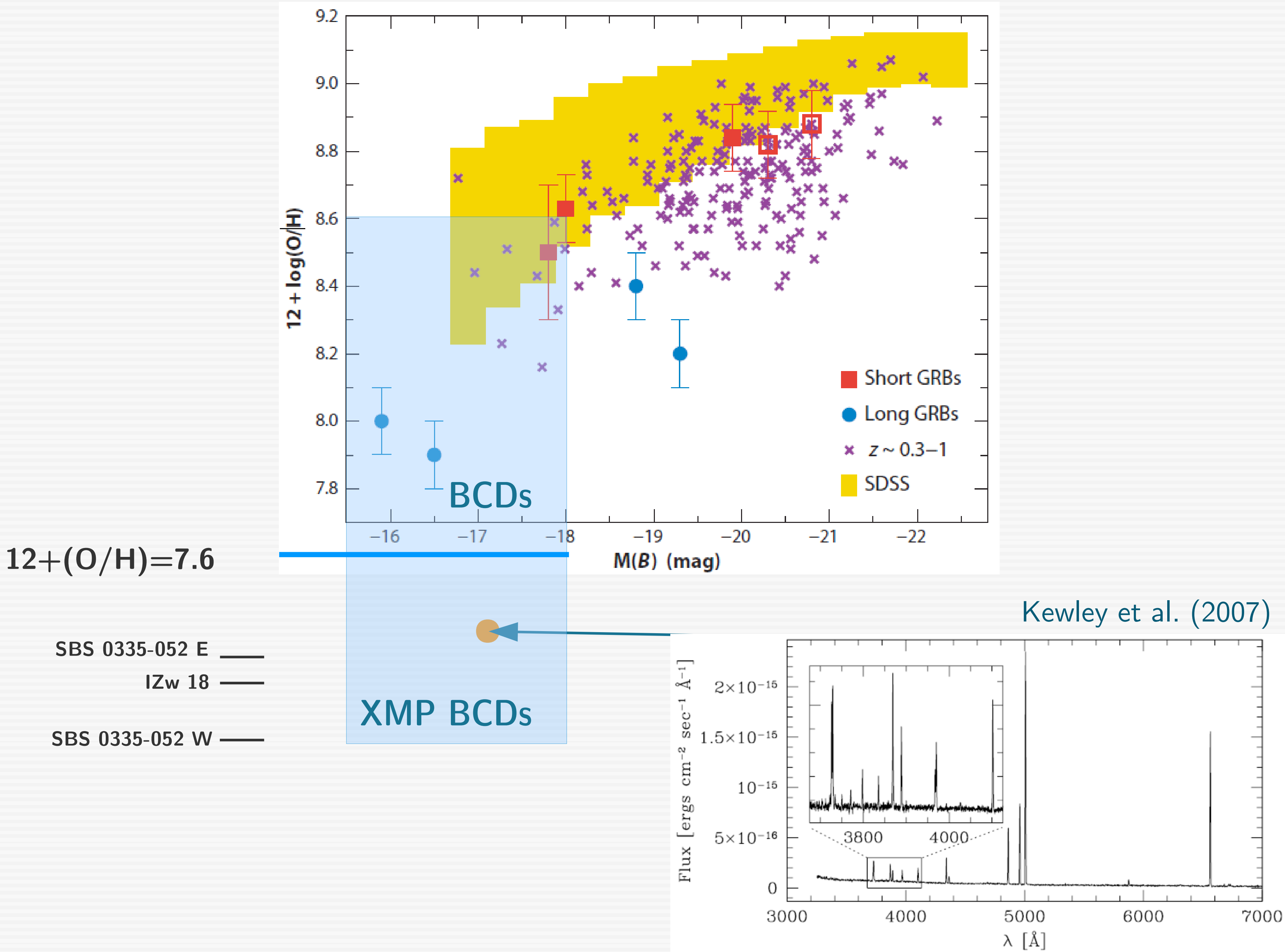
Metallicity distribution of GRB hosts



$Z_\odot$

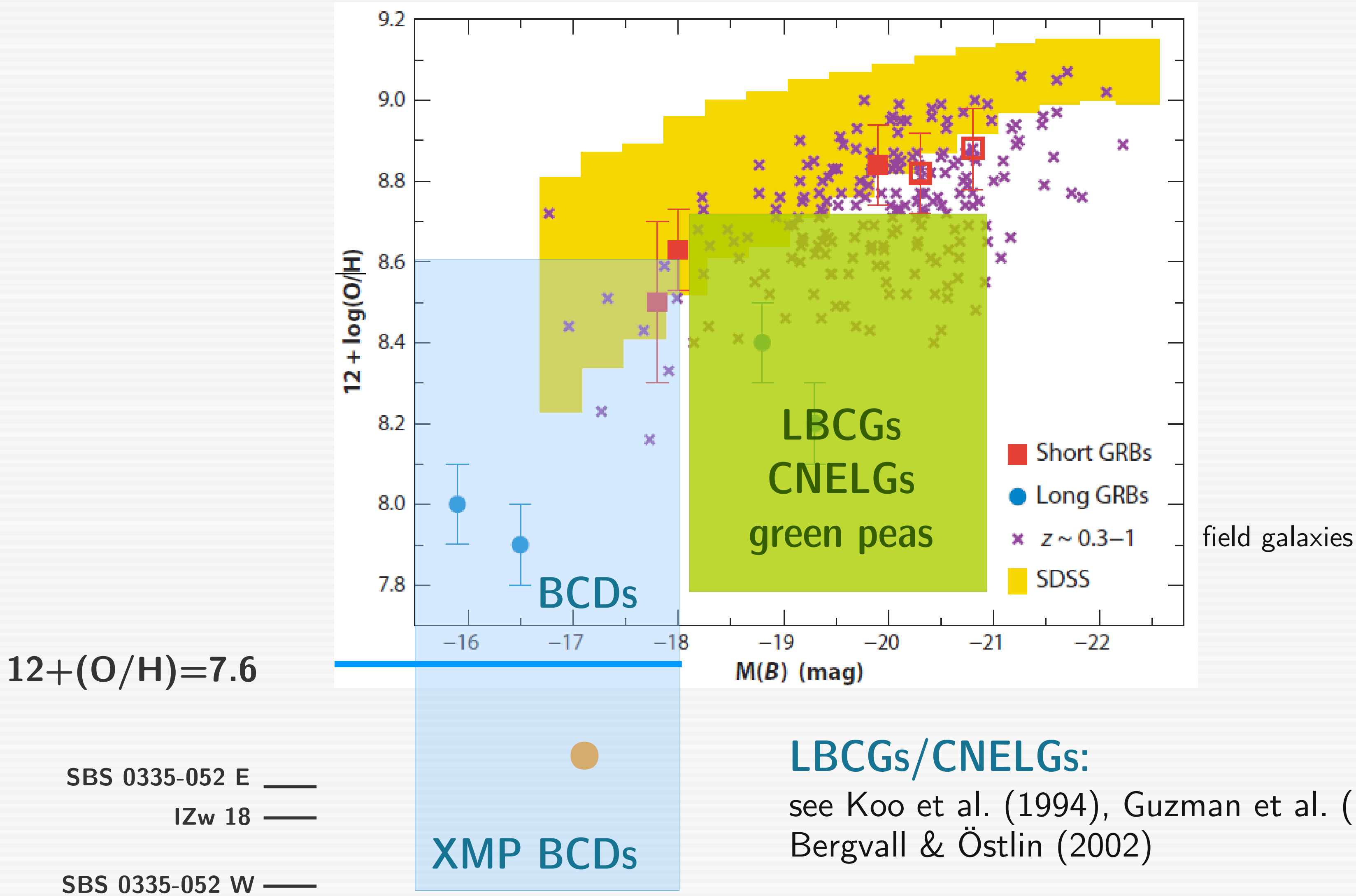
Gehrels, Ramirez-Ruiz & Fox (2009)

Gehrels, Ramirez-Ruiz & Fox (2009)



SDSS 0809+1729: M_B=-17.1, 12+log(O/H) = 7.44

Gehrels, Ramirez-Ruiz & Fox (2009)



LBCGs/CNELGs:

see Koo et al. (1994), Guzman et al. (1996/98), Bergvall & Östlin (2002)

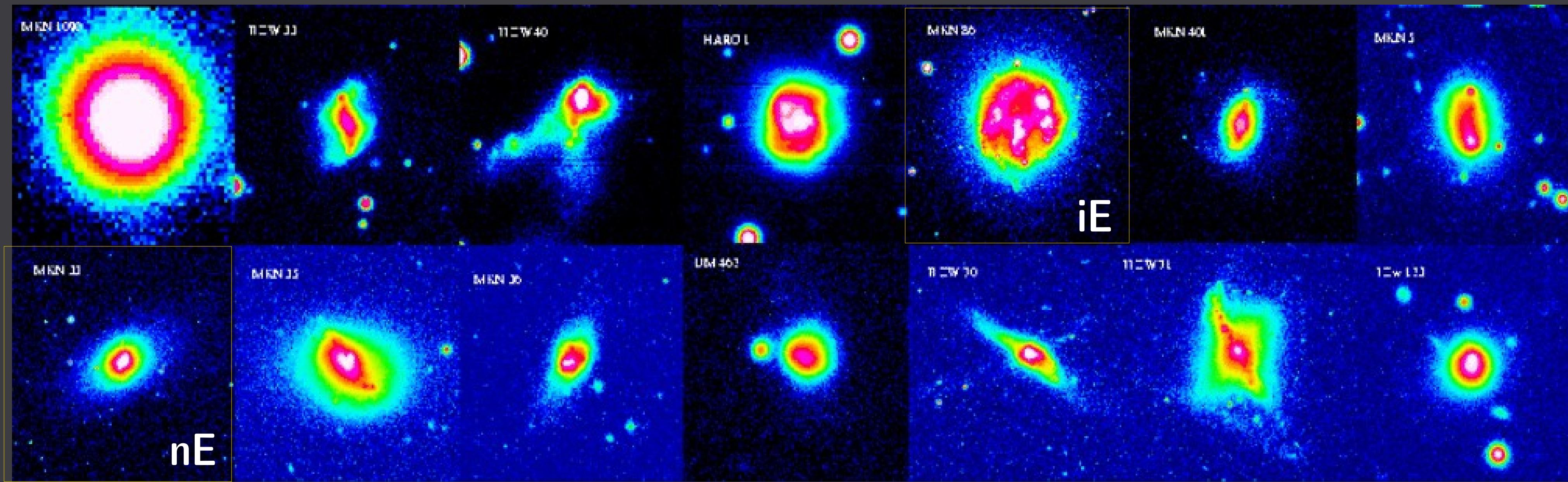
Green peas

see Cardamone et al. (2009), Amorin et al. (2010/12), Izotov et al. (2011)

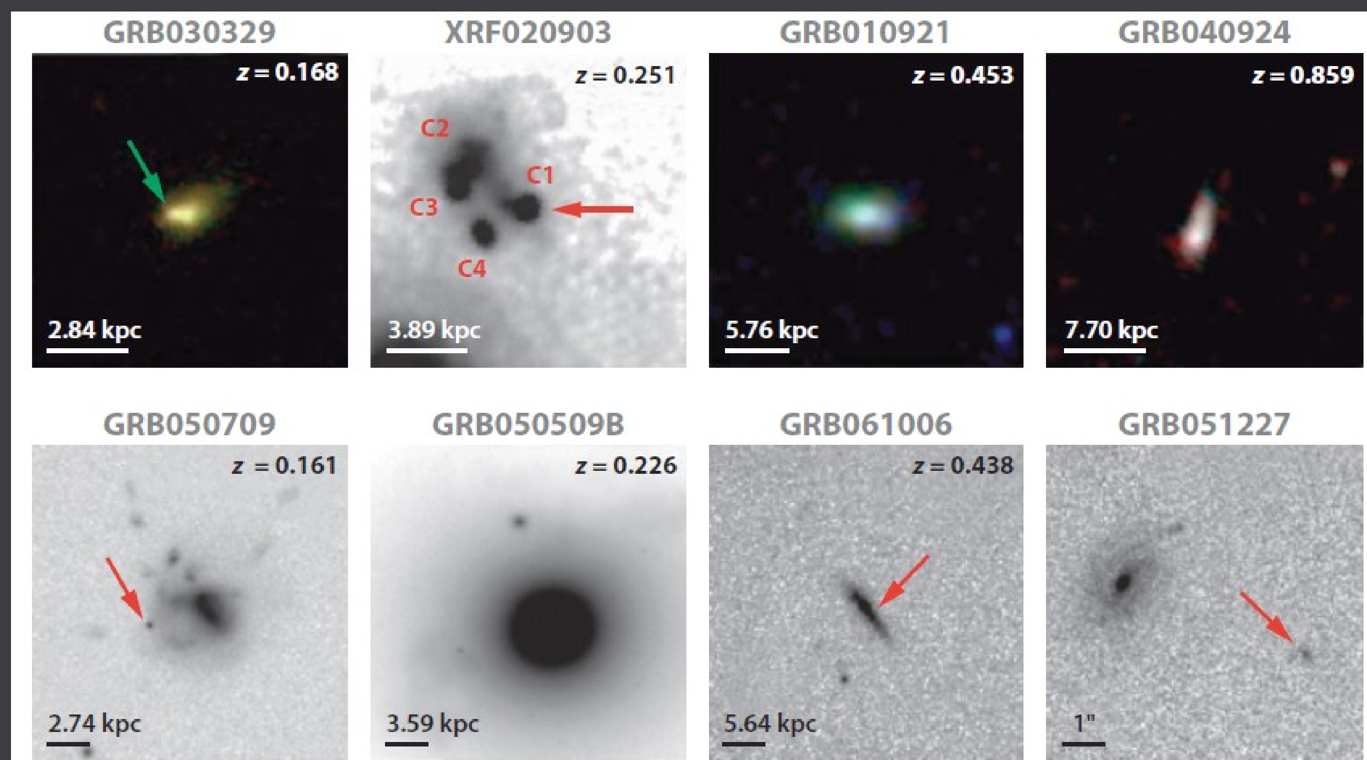
Green peas (=LBCGs=CNELGs) are structurally similar to BCDs, i.e. earlier phases of BCD evolution (1-6 Gyr ago) ← Enrique's and Ricardo's presentation

BCDs/BCGs vs GRB hosts

5 kpc

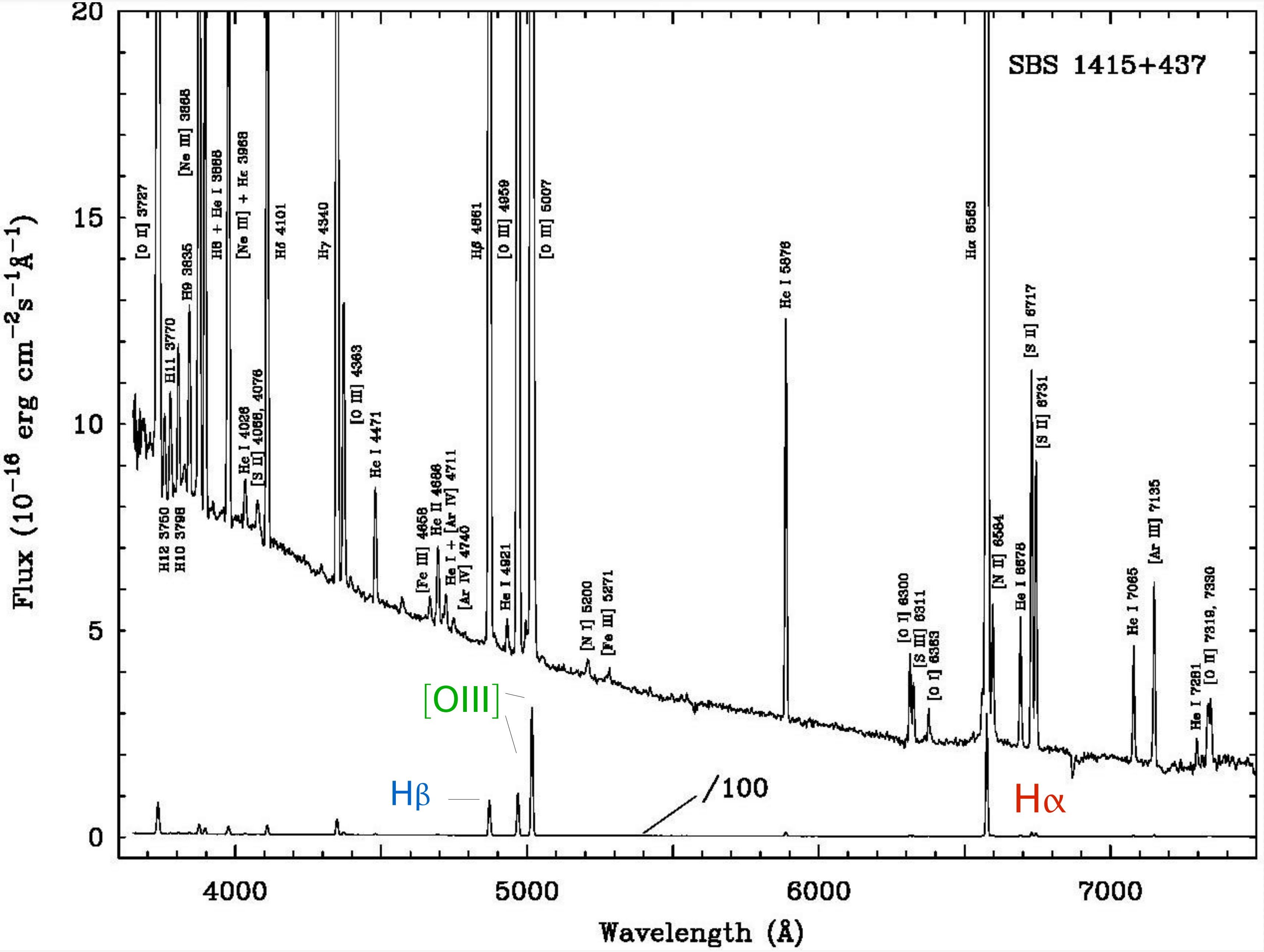


Cairós et al. (2001)

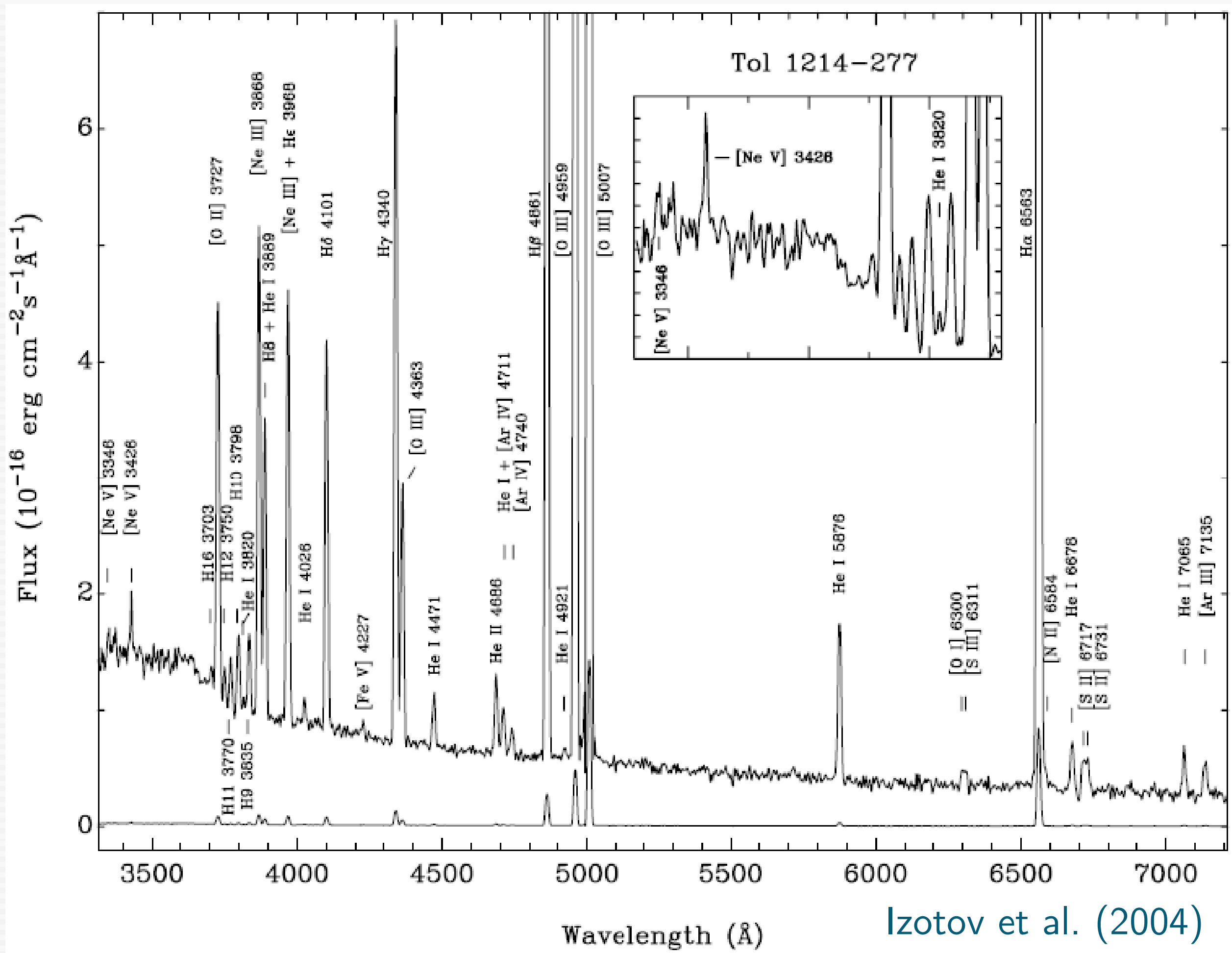


Many GRBs are hosted by sub-L⋆, low-metallicity starburst environments

Gehrels, Ramirez-Ruiz & Fox (2009)


SBS 1415+437
Flux (10^{-16} erg cm^{-2}s^{-1}Å^{-1})
Wavelength (Å)
[OIII]
Hβ
Hα
/100

High-excitation emission lines in (extremely metal-poor) BCDs



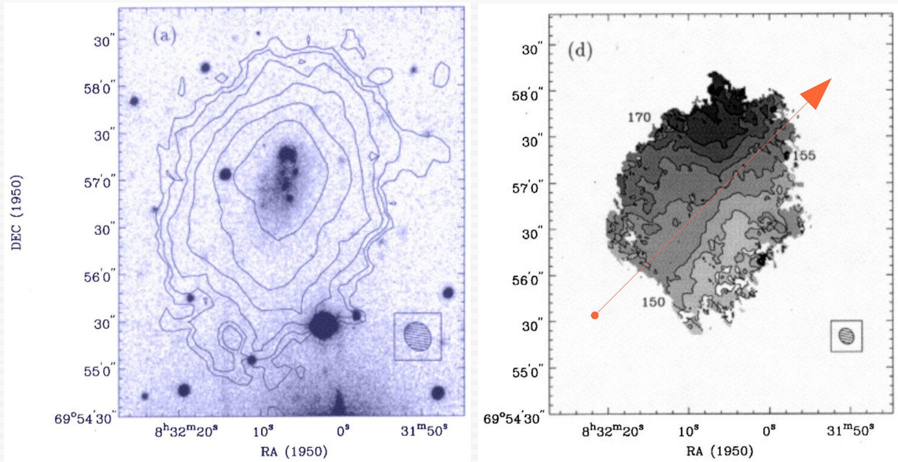
Izotov et al. (2004)

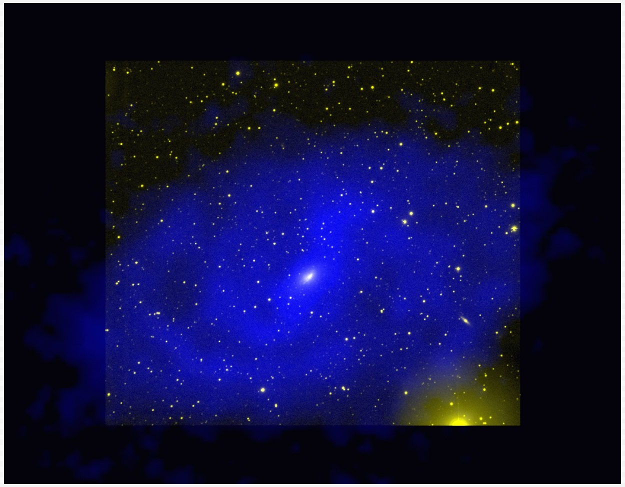
- [Ne V] λ3426 Å emission, implying the presence of hard ionizing radiation with λ<228 Å (≙7.14 Ryd)
- Also other high-excitation lines detected (e.g. [Fe V] λ4227 Å) along with
- strong He II λ4686 Å (≈ 5% of Hβ intensity)
- Lyα equivalent width of ~80 Å (!) (Thuan & Izotov 1997)

See also presentations by D. Szesci, E. Perez-Montero, C. Kehrig, R. Amorin, D. Miralles and M. Pakull

Properties of the HI component in BCDs

UGC 4483

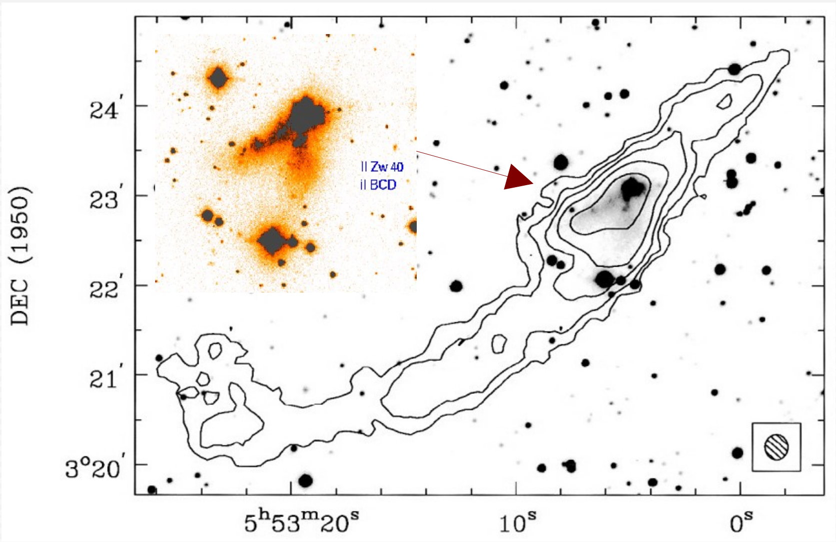


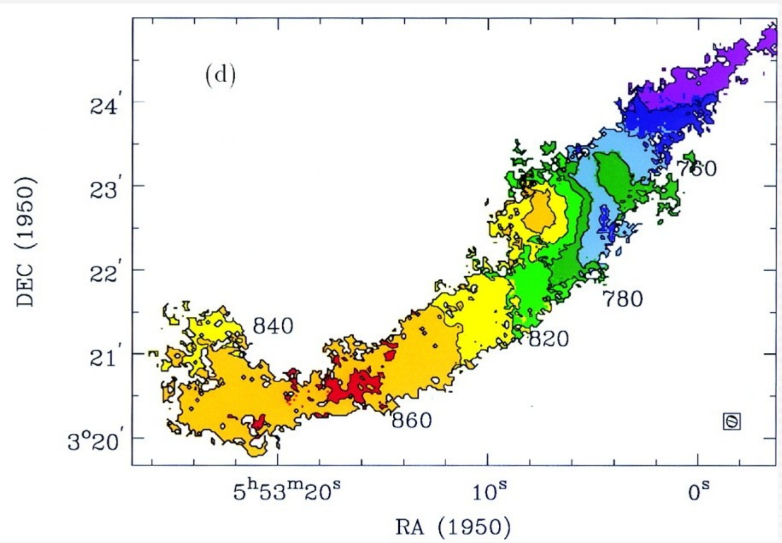


NGC 2915

van Zee et al. (1998)

II Zw 40



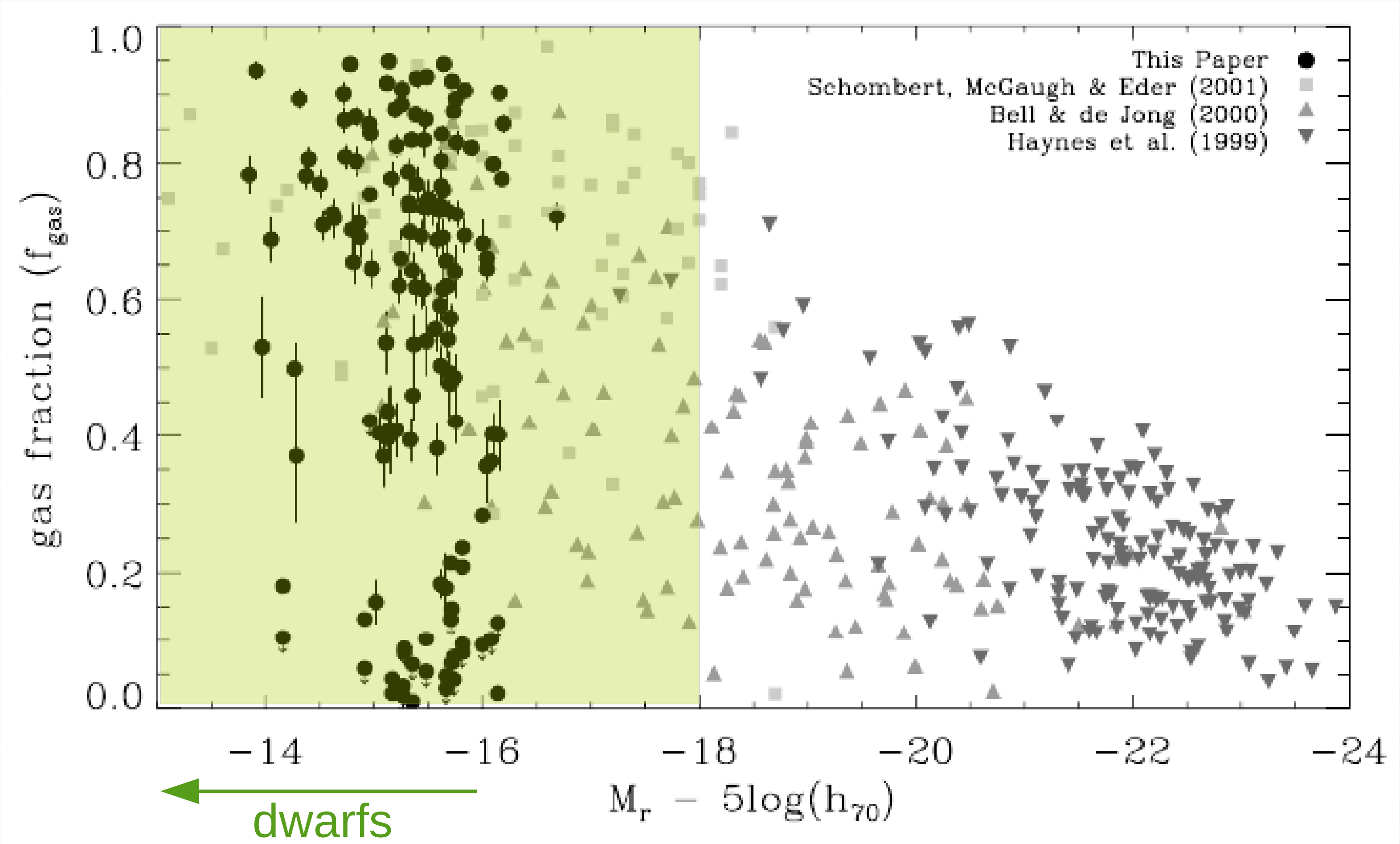


mass ratio: typically $M_{HI}=(0.1\text{-}1)\times10^9\ M_\odot$, M_{Gas}/M_T: 0.3-0.9, $M_T/L_B=2\text{-}6$

$$\frac{\text{HI radius}}{\text{optical radius}} \sim 3\ldots10$$

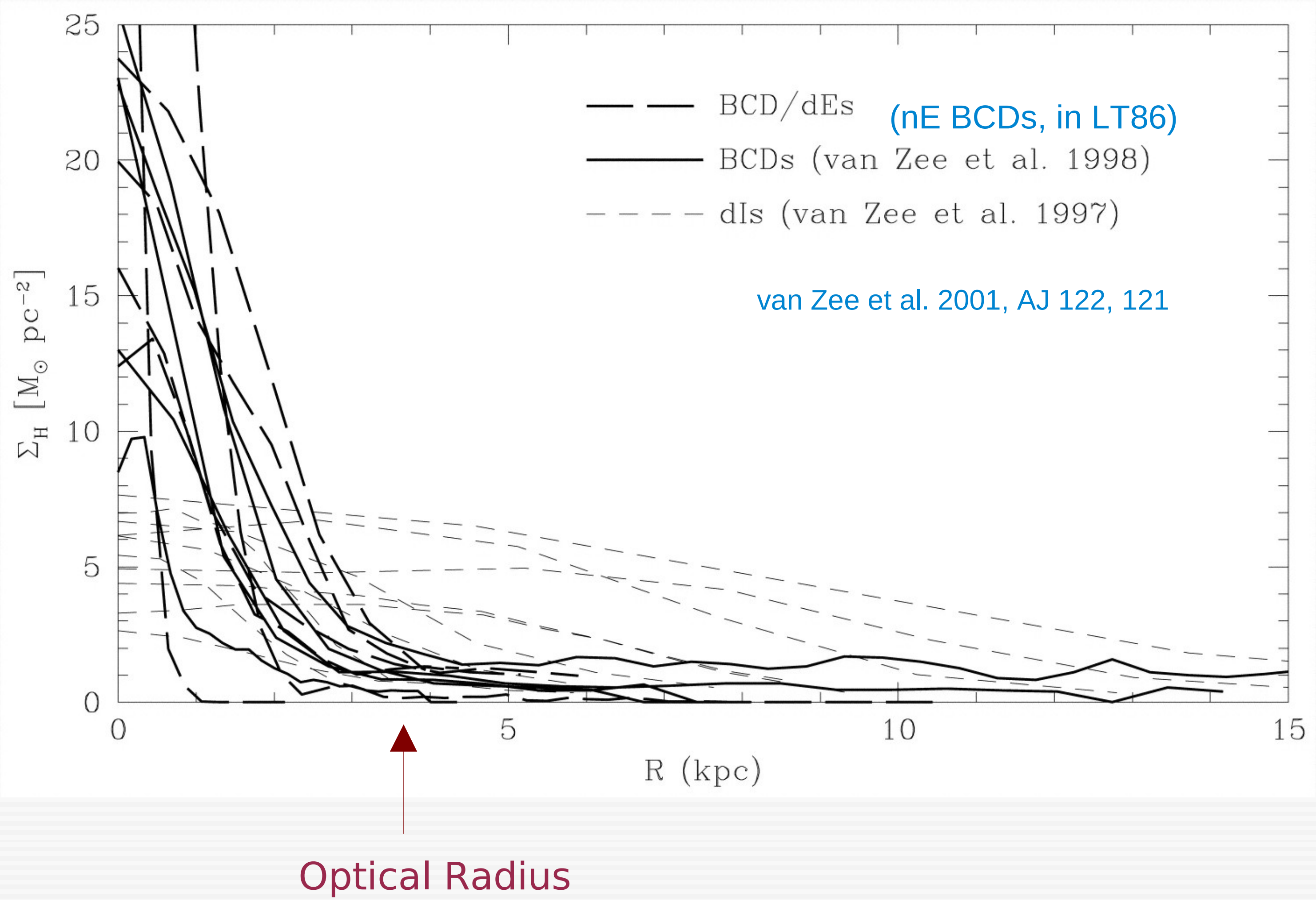
Gas fraction as a function of absolute magnitude

typically $M(\text{HI}+\text{He})/M(\star+\text{gas}) > 0.4$



Geha et al. (2006)

Comparison of the radial HI surface density distribution in BCDs and quiescent (low-SFR, low-sSFR) late-type dwarfs (dwarf irregulars - dIs)



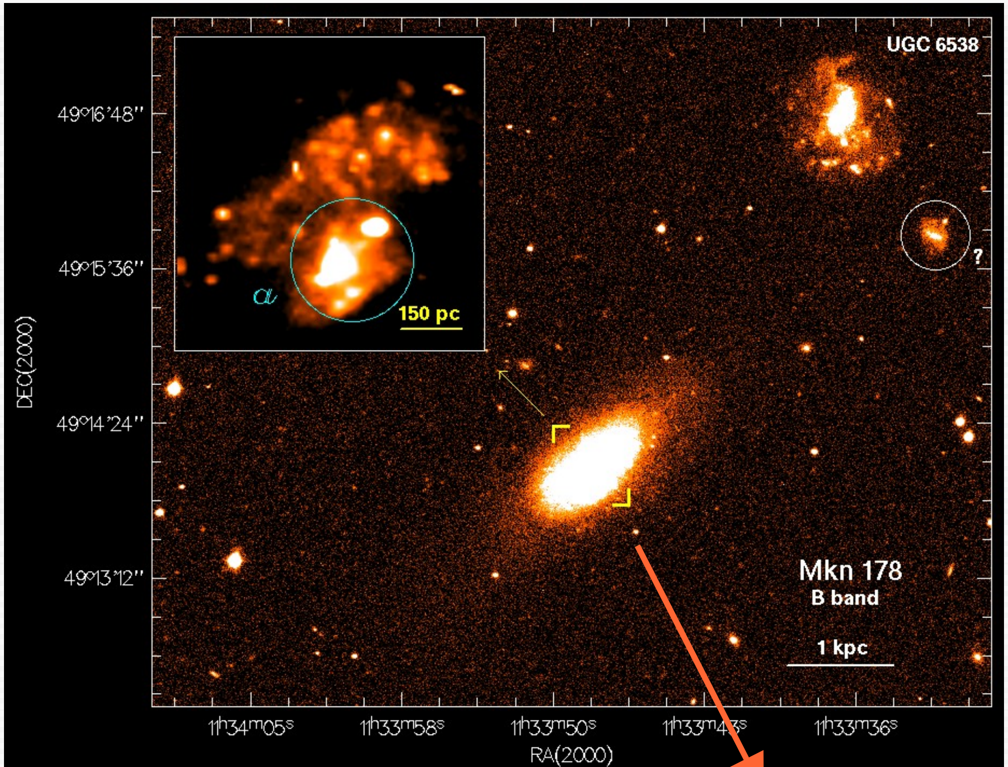
BCDs are more compact than dIs with respect to their HI distribution

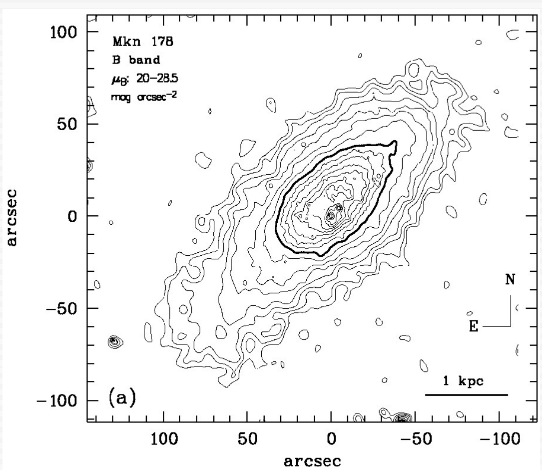
$$\Sigma_{HI}(\text{BCDs}) \sim 5 \times \Sigma_{HI}(\text{dIs})$$

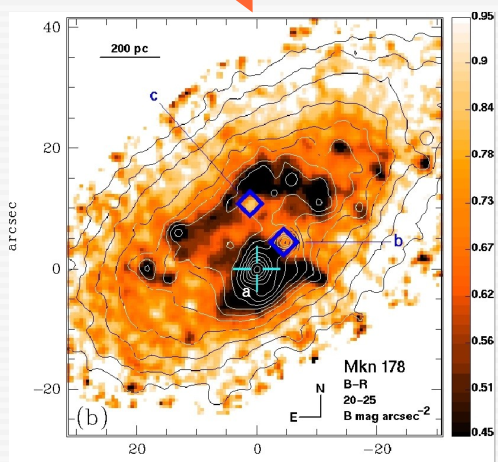
See also Taylor et al. (1995), Simpson & Gottesmann (2003)

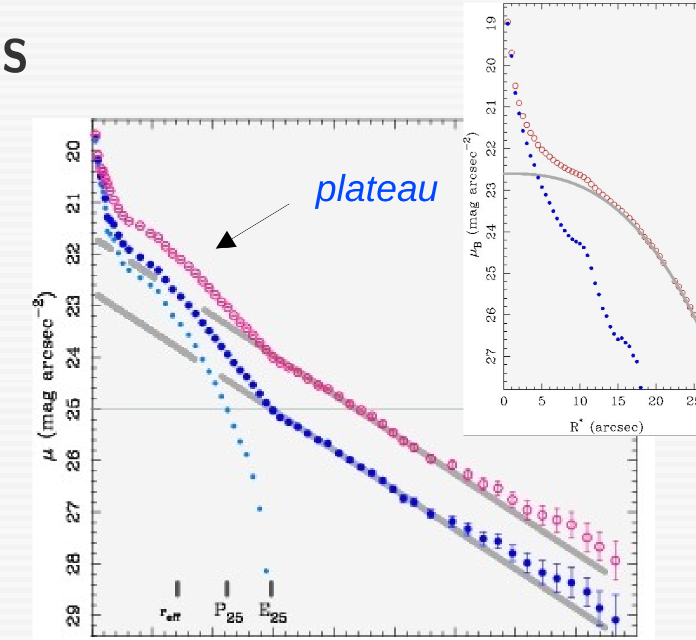
Structural properties of BCDs & BCGs

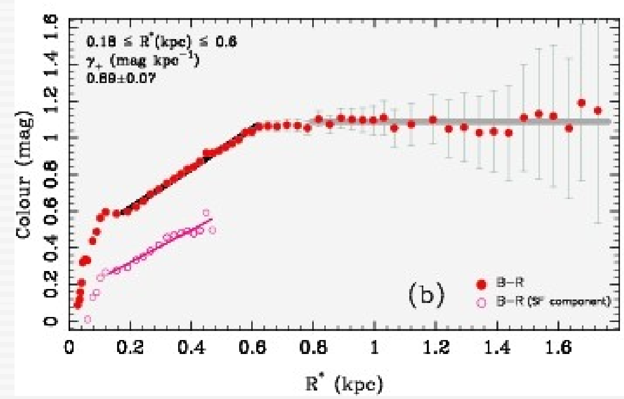
Papaderos et al. (2002)











P_{25}, E_{25}: isophotal radius of the star-forming and LSB component

line-of-sight intensity contribution of the SF component: <40% at **P_{25}**, 4% at **E_{25}**

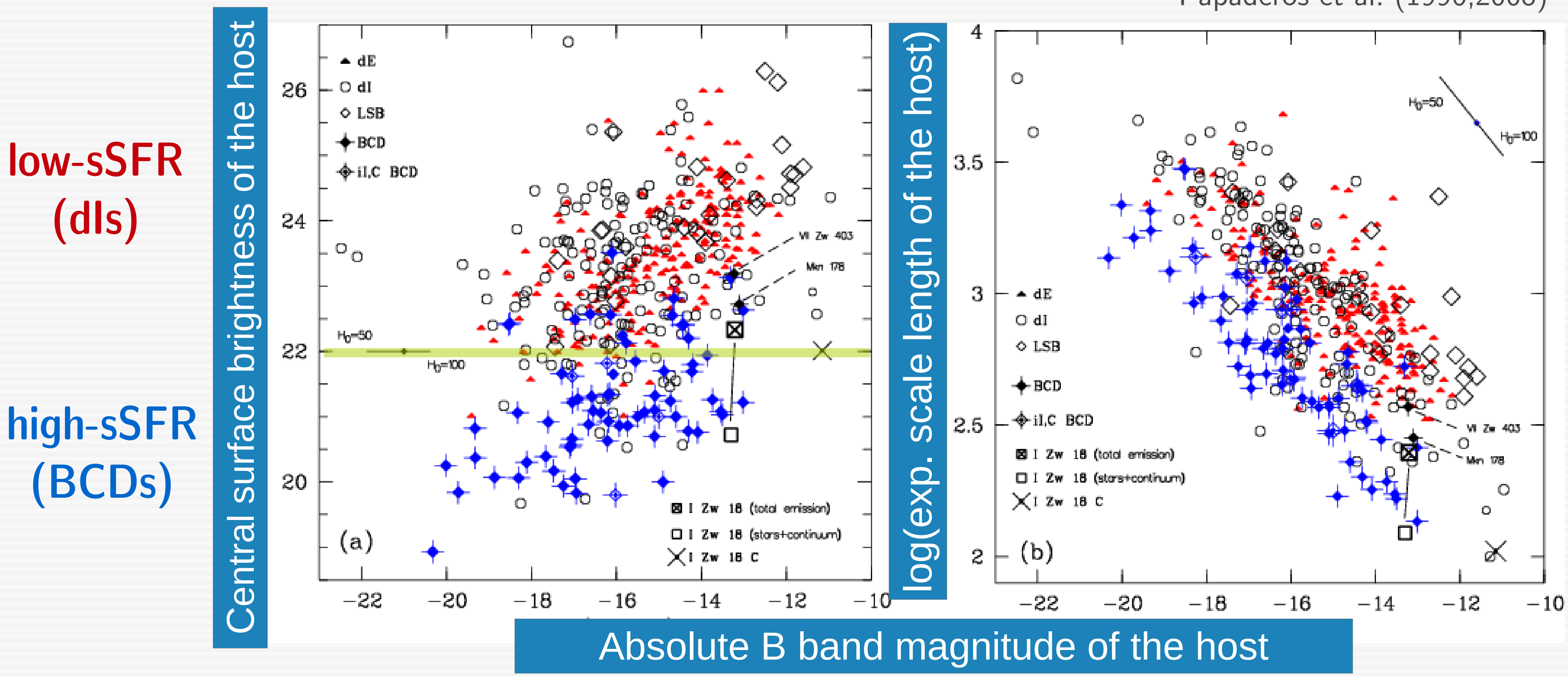
D = 4 Mpc
M_B=-13.9 mag

Mkn 178

← Carolina's presentation

Starburst activity in low-mass galaxies occurs preferentially in compact, high-stellar density ($\rho_\star$) hosts

Papaderos et al. (1996,2008)

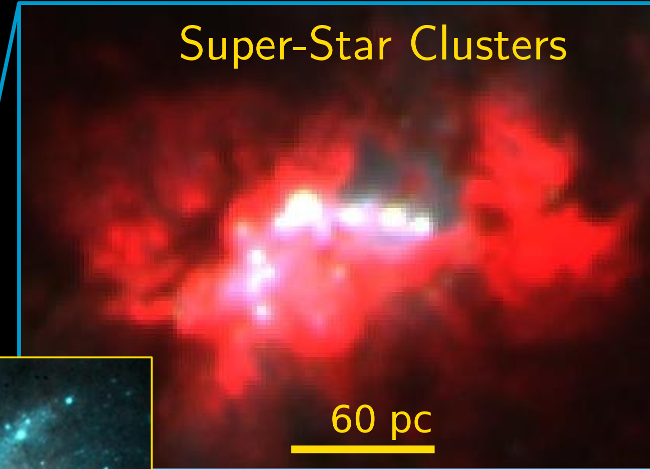


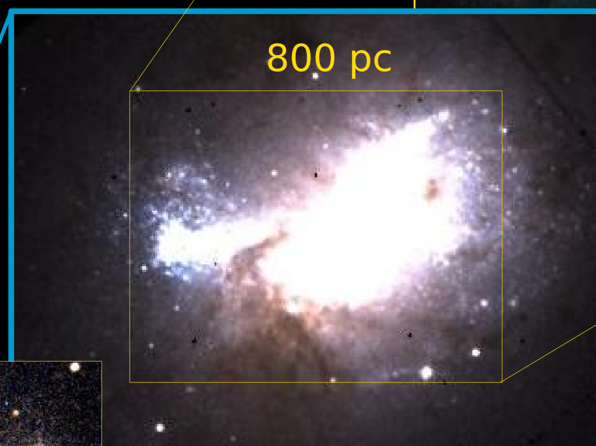
- Central $\rho_\star$ of the BCD host galaxy is ~10 × higher than in (low-sSFR) dIs
- The density of the local stellar background (and the form of the gravitational potential it produces) is one of the parameters regulating star-forming activity in <u>triaxial low-mass late-type galaxies.</u>

Starburst activity in BCDs

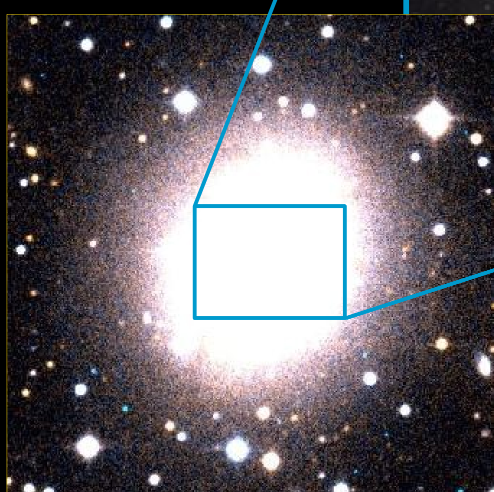
Henize 2-10

- Nearby (D=8.7 Mpc) BCD
- Starburst since 10^7 yr
  (Conti & Vacca 1996,
  Papaderos & Fricke 1998)
- Prominent Wolf-Rayet features





Papaderos et al. (2006)



Star formation in BCDs

a) diffuse component consisting of low-mass stellar clusters ($\simeq 10^{2}$ – a few 10^3 $M_\odot$)

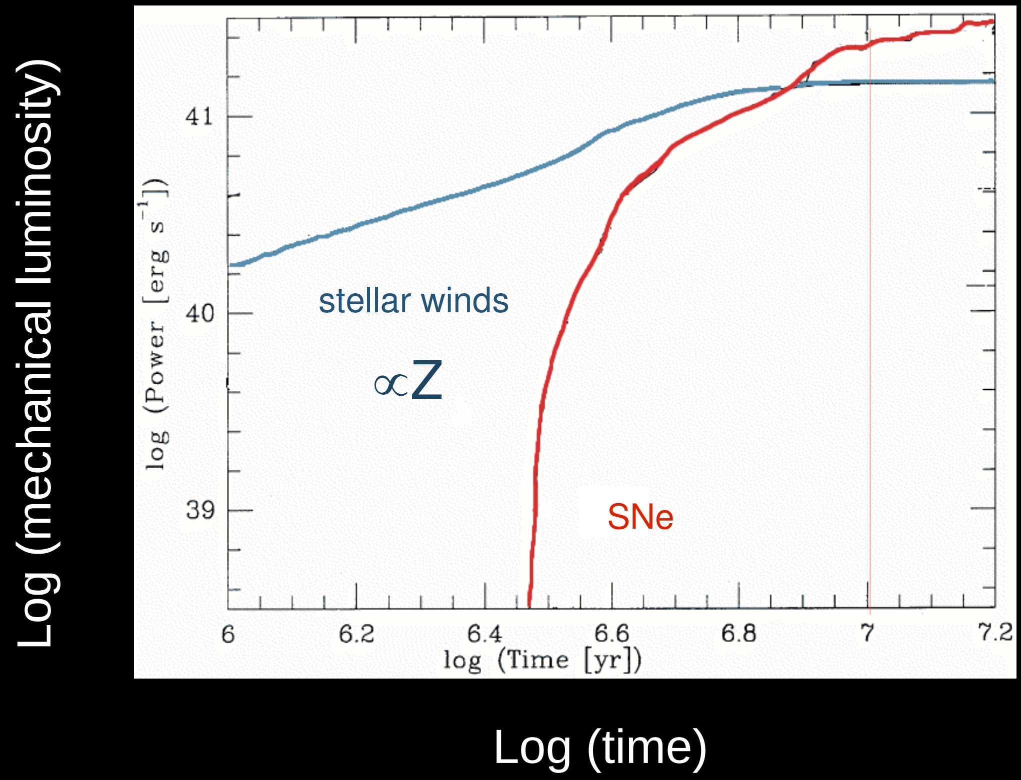
b) luminous, very compact stellar clusters ($\simeq 10^4$ $\mathbf{M_\odot}$) all through to "Super-Star Clusters" (SSCs) with mass: up to 10^5 $M_\odot$!
radius: 3-10 pc
density: up to 10^4 $M_\odot$ pc^{-3}

Nearly coeval star formation on spatial scales of ~1 kpc

Henize 2-10: Hα supershells and large-scale gas outflows

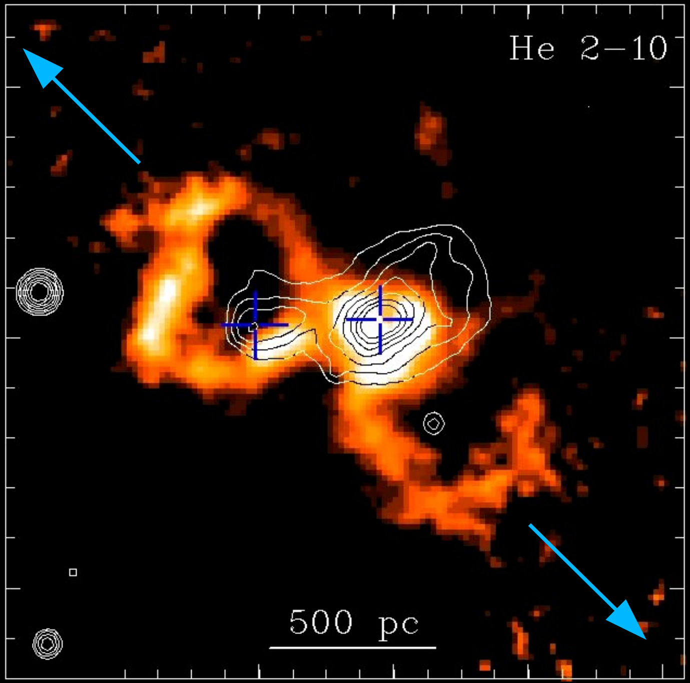
a)

Leitherer et al. (1992)



Papaderos & Fricke (1998)

b)



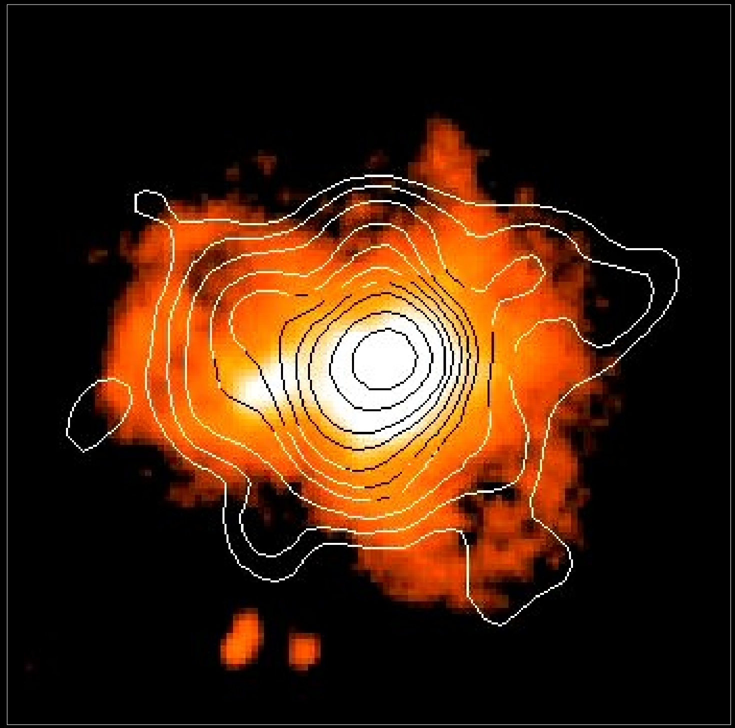
Hα equivalent width map

a) mechanical luminosity as a function of time for a Star Formation Rate of 1 $M_\odot$ yr^{-1}
Luminosity Power at $t=10^7$ yr : 4×10^{41} erg s^{-1}
(total energy injected into the ISM: 4.5×10^{55} erg)

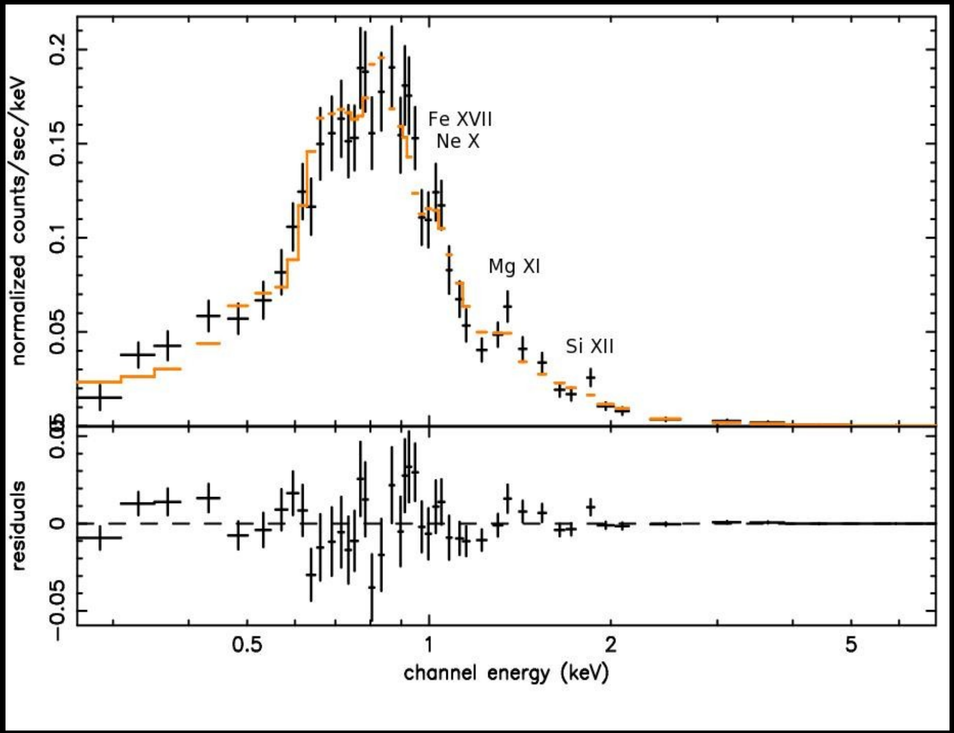
b) observations: gigantic bipolar outflow of hot and metal-enriched gas from the starburst component, expanding with velocities of $\gtrsim$200 km s^{-1} into the ambient interstellar medium.

Henize 2-10: Hα supershells and large-scale gas outflows

Papaderos & Fricke (1998)



X-ray contours (ROSAT HRI) overlaid with a continuum-subtracted Hα map.

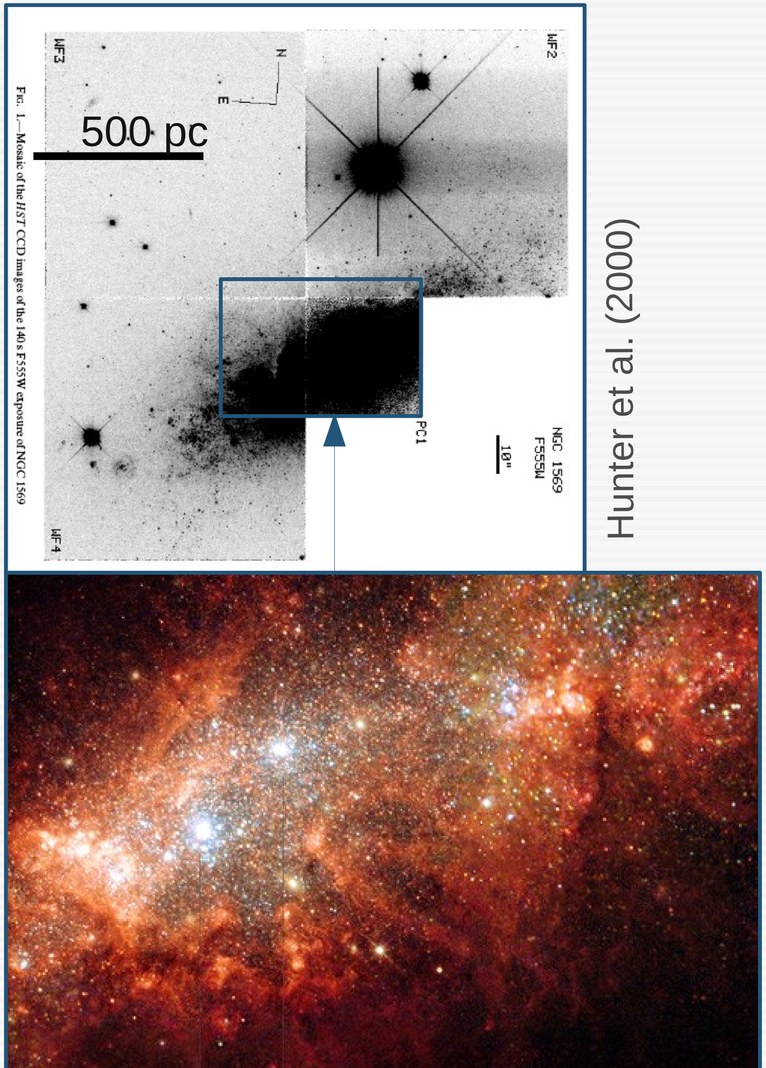


XMM-Newton X-ray spectrum (0.25-6 keV)

- Thermalization of the ISM (hot (10^7 K) X-ray emitting gas)
- Expansion into the ambient ISM and ejection into the halo (and possibly beyond): **galactic outflows**
- Chemical enrichment of the interstellar and intergalactic medium.
- Lyman continuum photon escape and the reionization of the universe

BCDs: starburst-driven mass ejection into halo

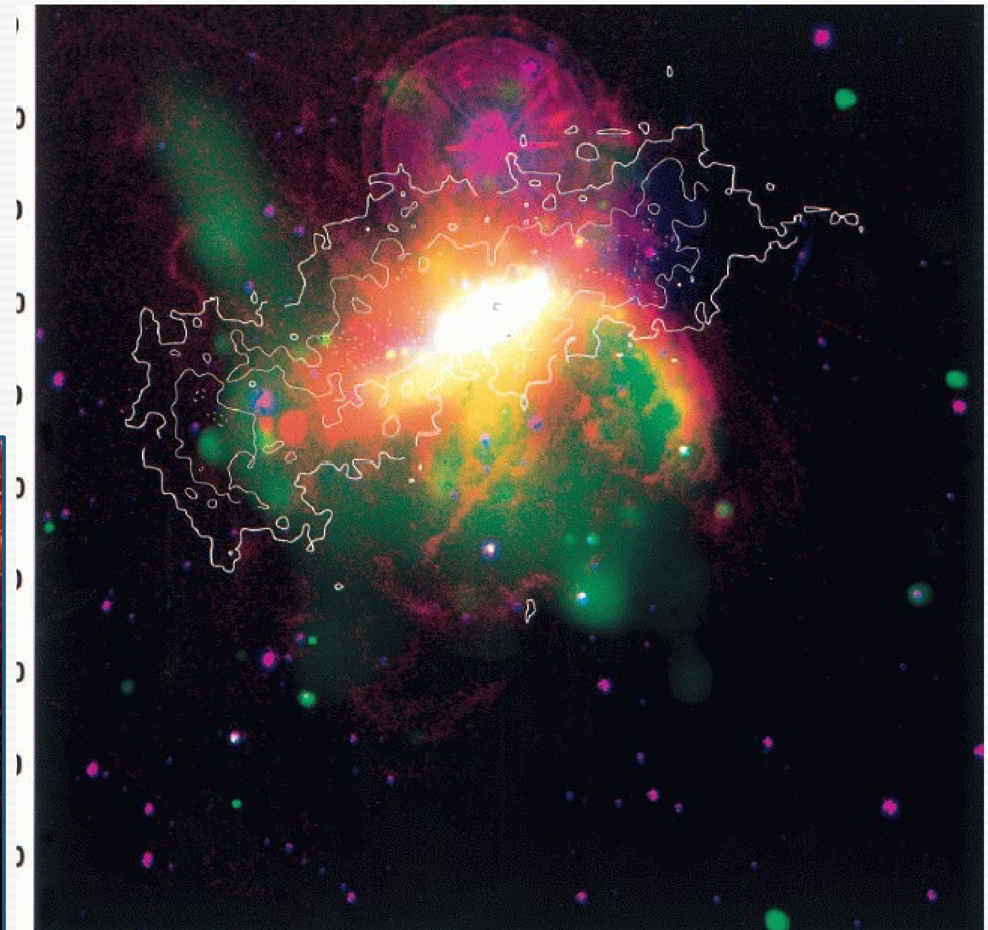
NGC 1569



Hunter et al. (2000)

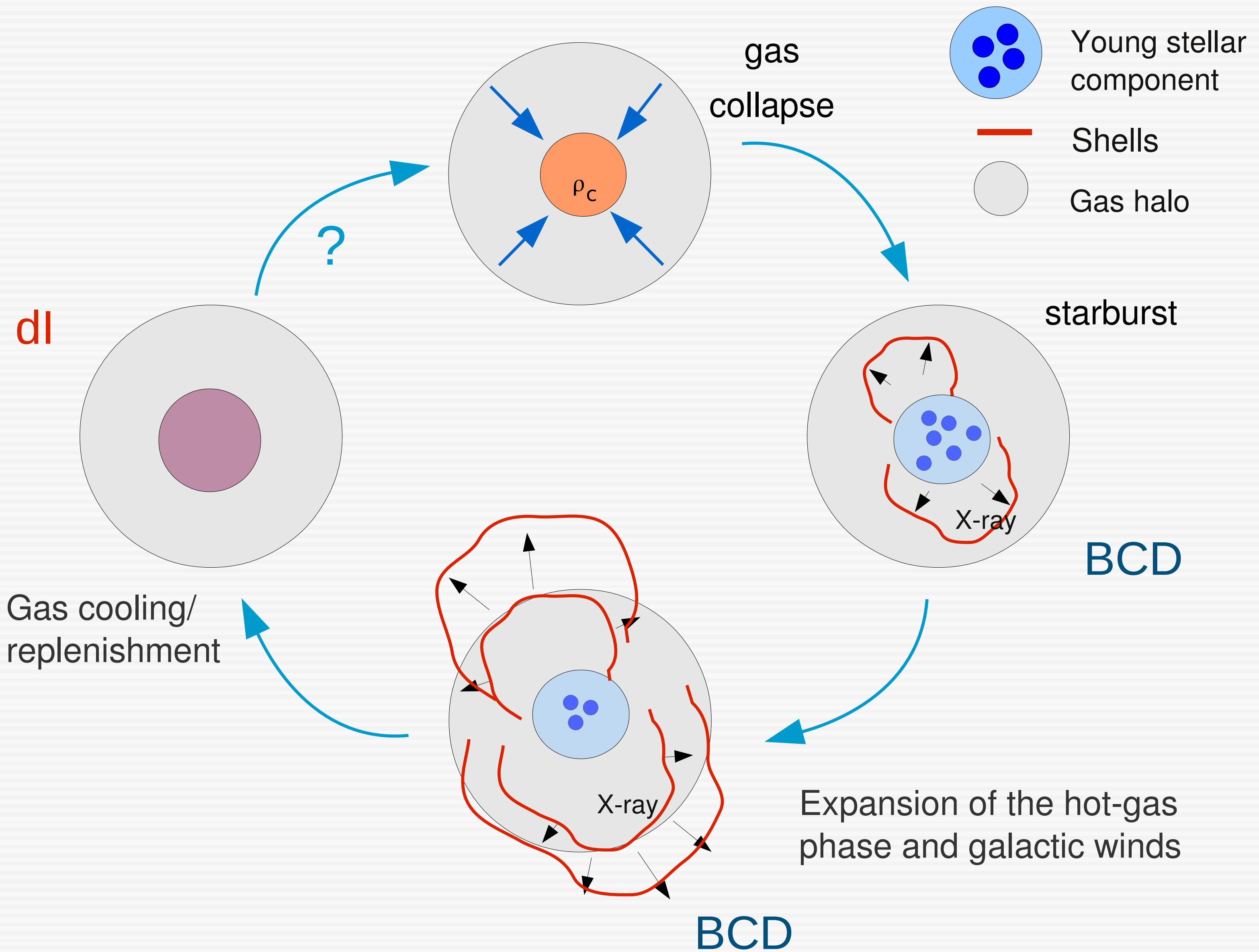
Super-Star Clusters

Martin et al. (2001)

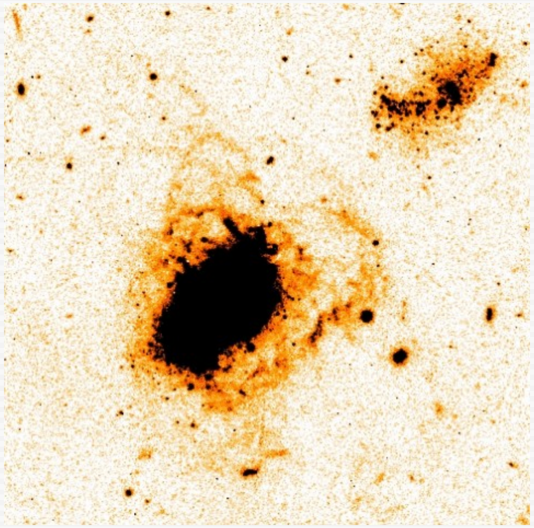


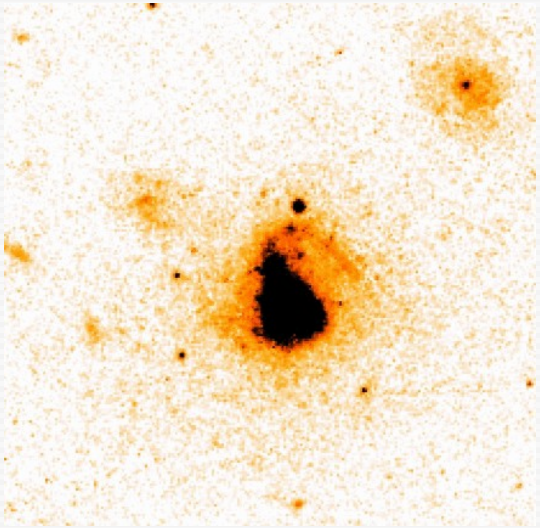
HI   Hα   X-ray

Chronology of a starburst in a dI/BCD

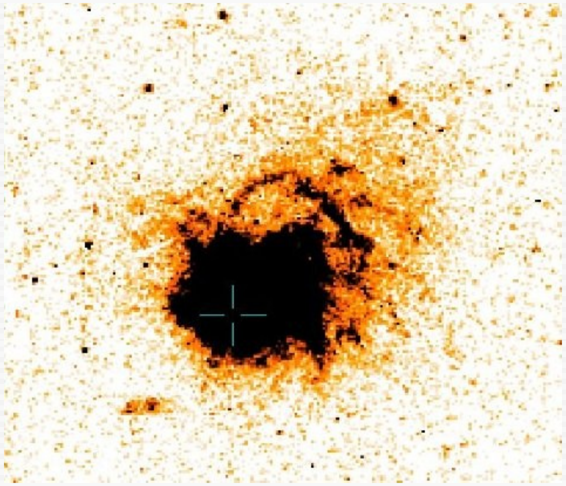


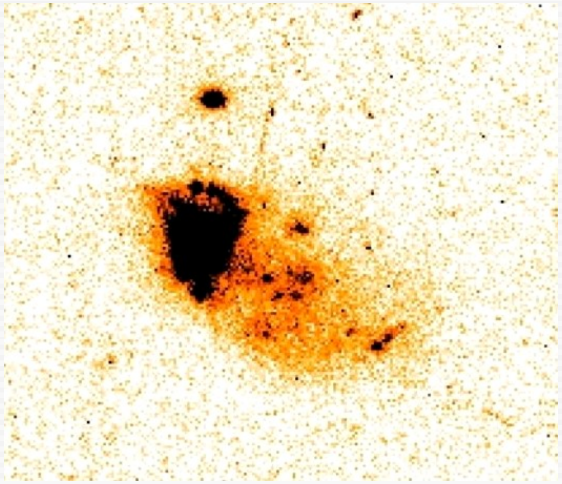
Extremely metal-poor (XMP) BCDs: XBCDs
Young galaxy candidates in the nearby universe?

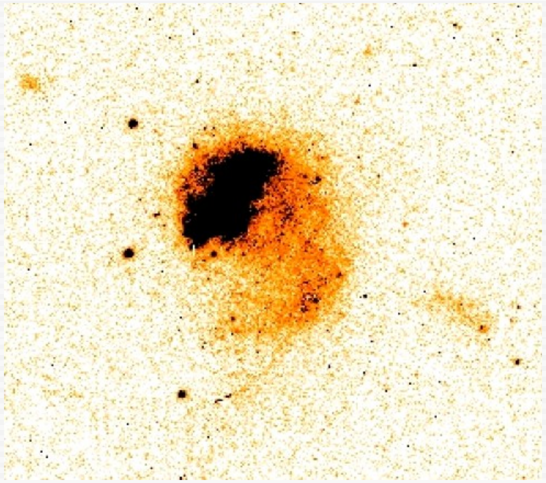

Papaderos et al. (2002)


Guseva, Papaderos, Izotov et al. (2004)

- Gas-phase metallicity: $7.0 \lesssim 12+\log(\mathrm{O/H}) \lesssim 7.6$
- No evidence for a dominant old stellar population (>50% of $M\star$ formed in the past 1-3 Gyr)
- Irregular morphology, with a a remarkably large fraction of **cometary** systems

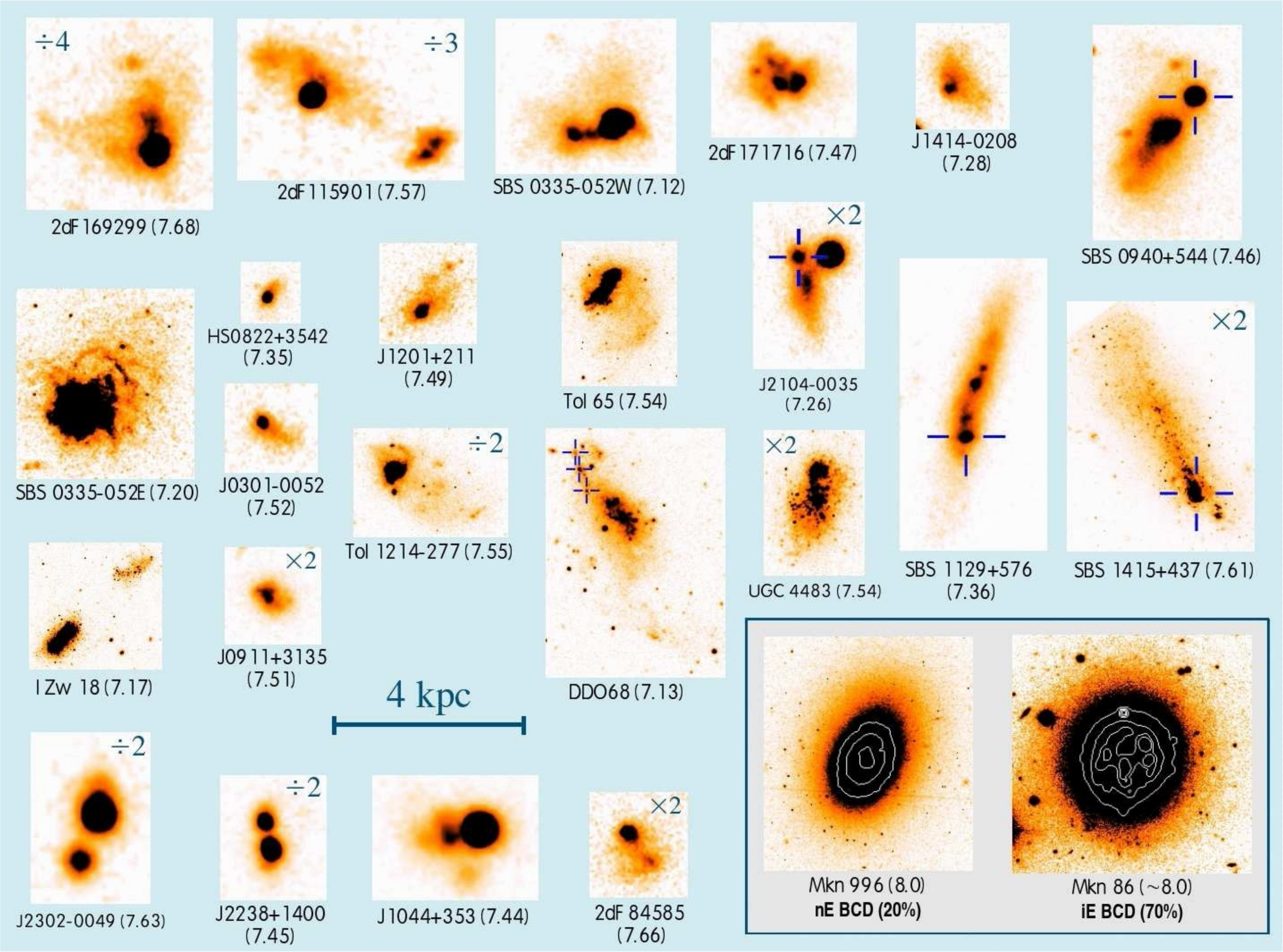

Thuan et al. (1997), Papaderos et al. (1998)


Fricke et al. (2001)


Papaderos et al. (1999,2007)

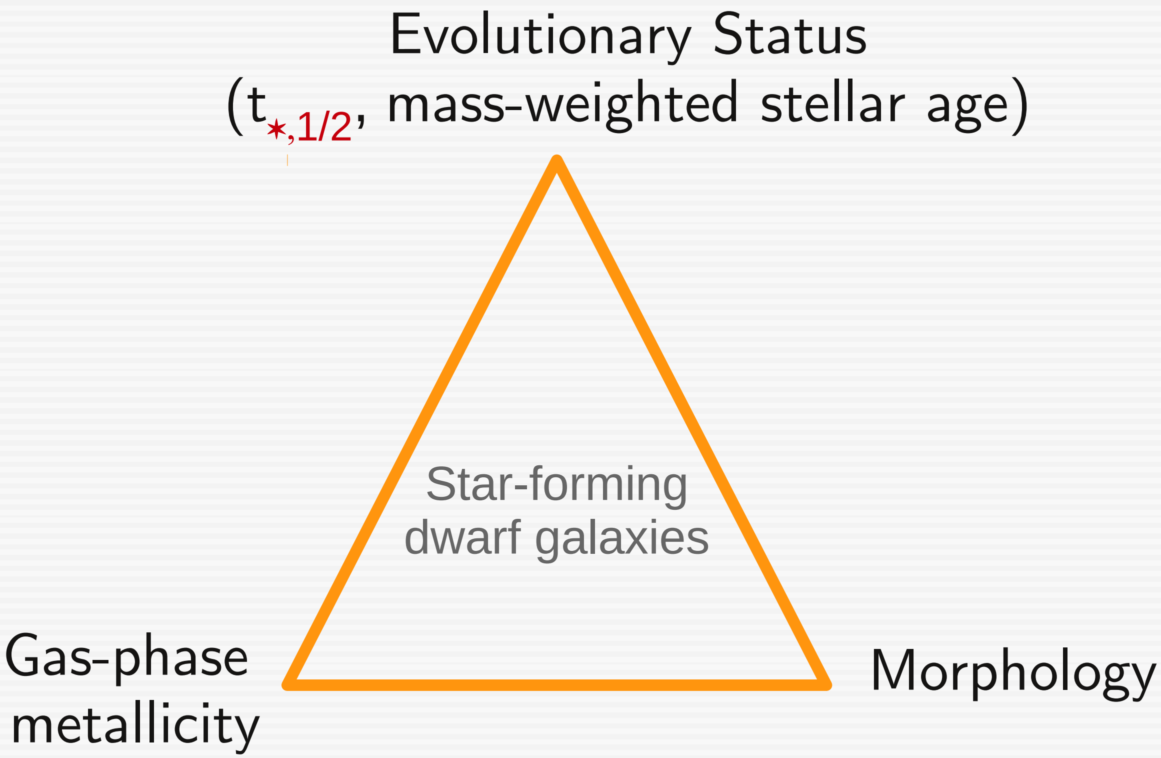
Morphological comparison of BCDs and XBCDs

XBCDs



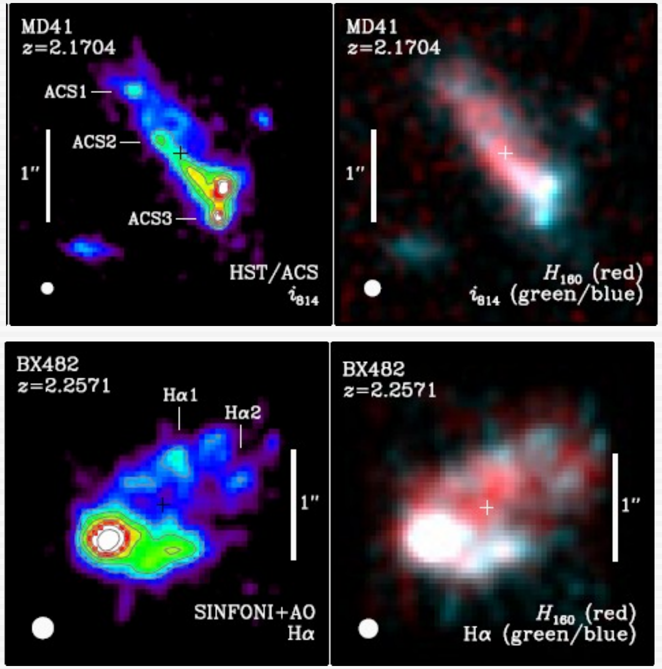
BCDs

Papaderos et al. (2008)



See, e.g. Lehnert et al. (2013) and Matt's presentation →

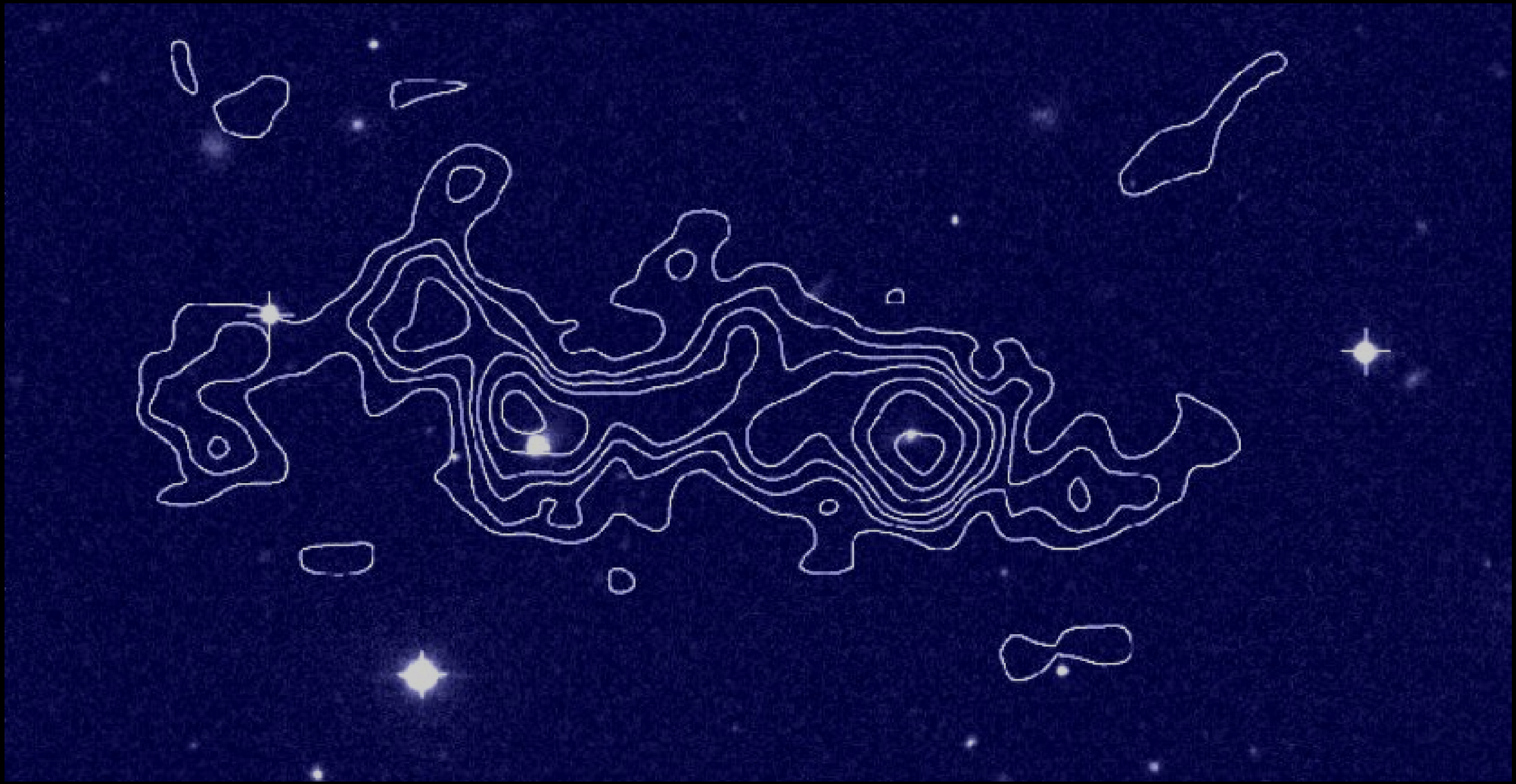
Cometary (or tadpole) massive galaxies at high redshift



Förster-Schreiber et al. (2011)

Pairwise XBCD formation

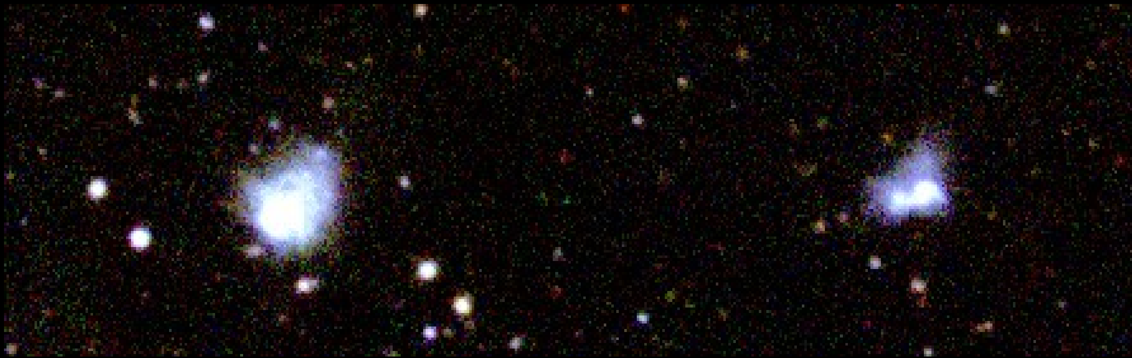
Example: the XBCD pair SBS 0335-052 E&W



Pustilnik et al. (2001)

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

SBS 0335-052 E: formation through propagating star formation

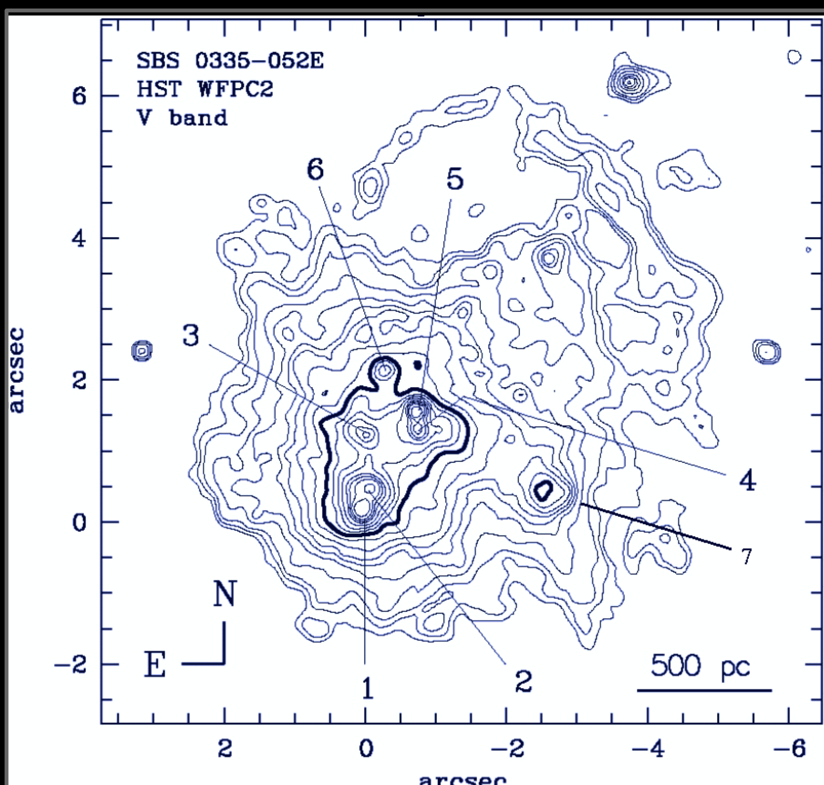


- Study of the V-I color and spatial distribution of stellar clusters using HST data

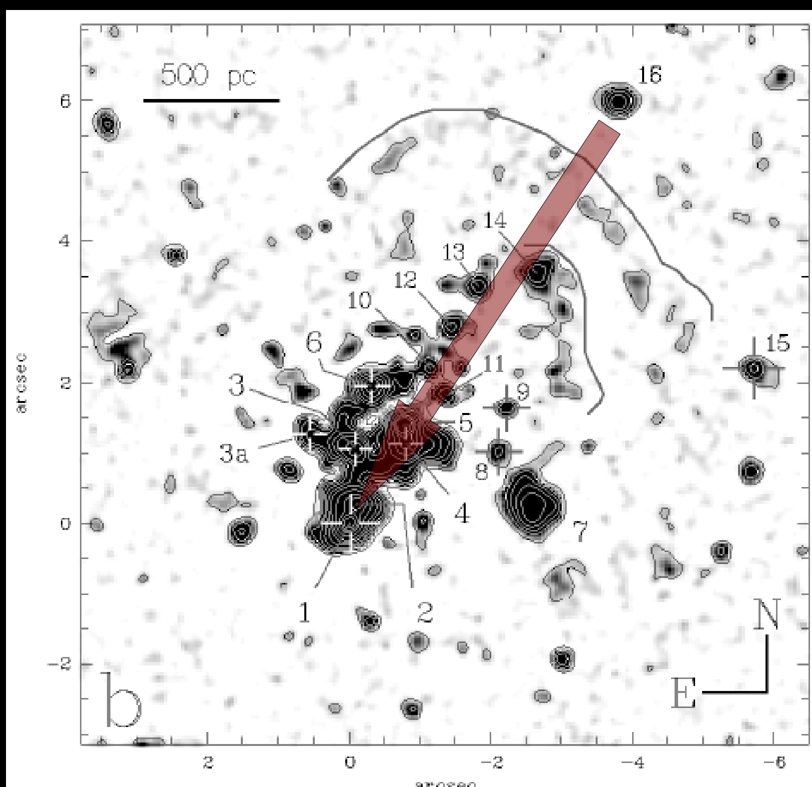
→

- galaxy formation in a propagating mode from NW to SE with a mean velocity of ∼20 km/s.

Papaderos et al. (1998)



HST/WFPC2, V band



HST/WFPC2, I band, unsharp masked

Strong & extended nebular emission in XBCDs

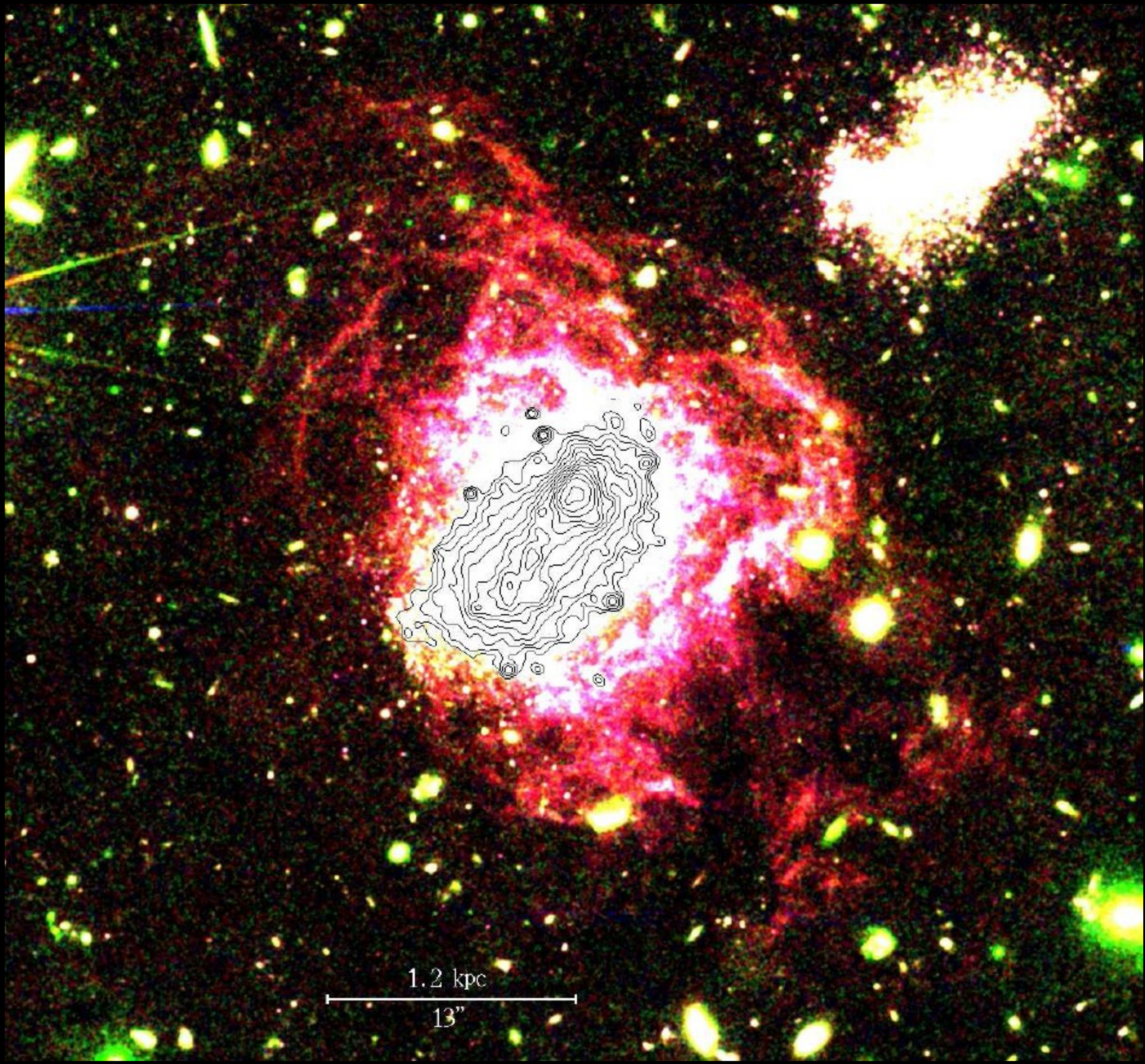
Example: I Zw 18 (the prototypical XBCD)

- 2D subtraction of nebular line emission using HST WFPC2 [OIII]5007 and Hα narrow band images (Papaderos et al. 2002) leads to complete removal of the lower-surface brightness (LSB) envelope of I Zw 18

The LSB envelope of I Zw 18 is entirely due to extended nebular emission

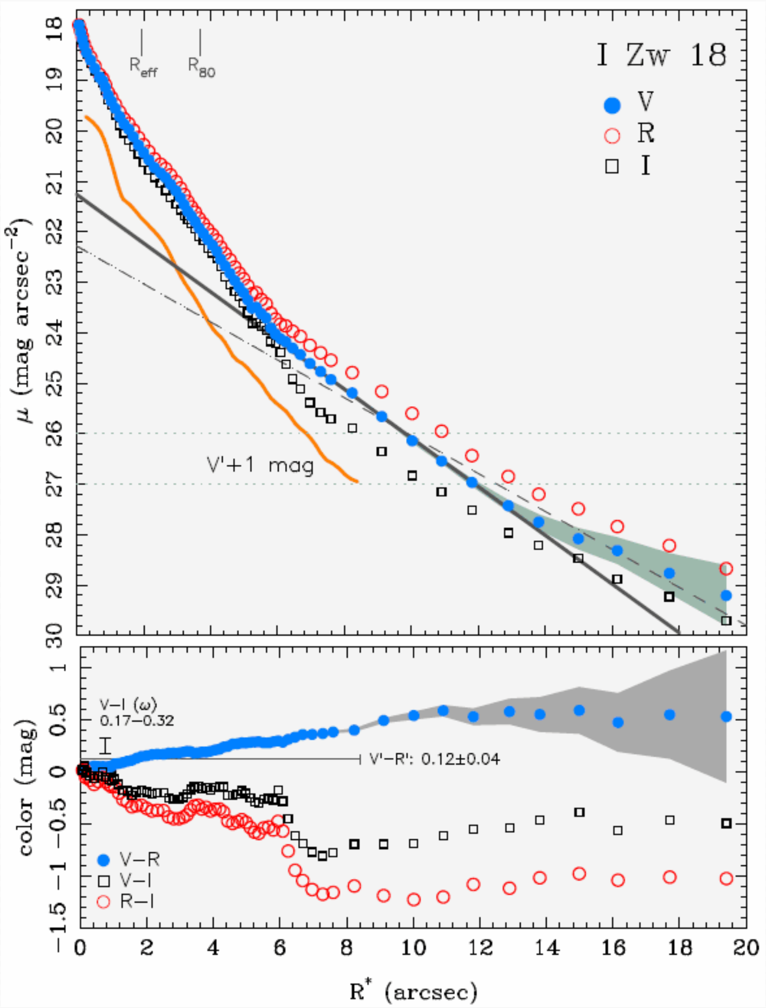
- Very deep HST ACS imaging down to $\mu \simeq 30$ mag/arcsec^2 (Papaderos & Östlin 2012) shows that the nebular envelope of I Zw 18 reaches out to R $\simeq$ 2.6 kpc

The nebular halo of I Zw 18 extends out to 16 exponential scale lengths of the stellar component and contributes $\gtrsim$1/3 of the total R band luminosity



Papaderos & Östlin (2012)

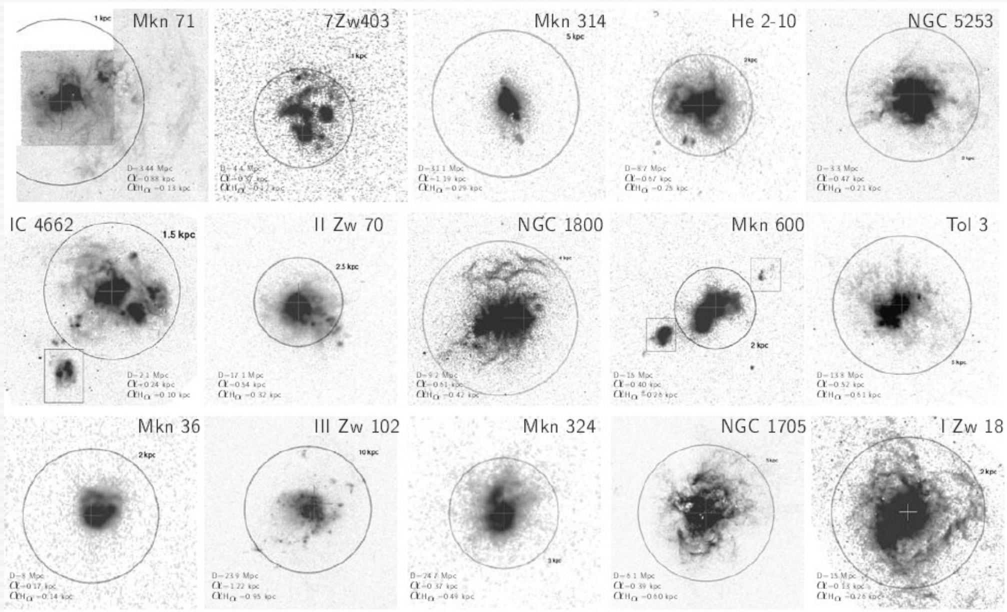
I Zw 18: surface brightness and color profiles

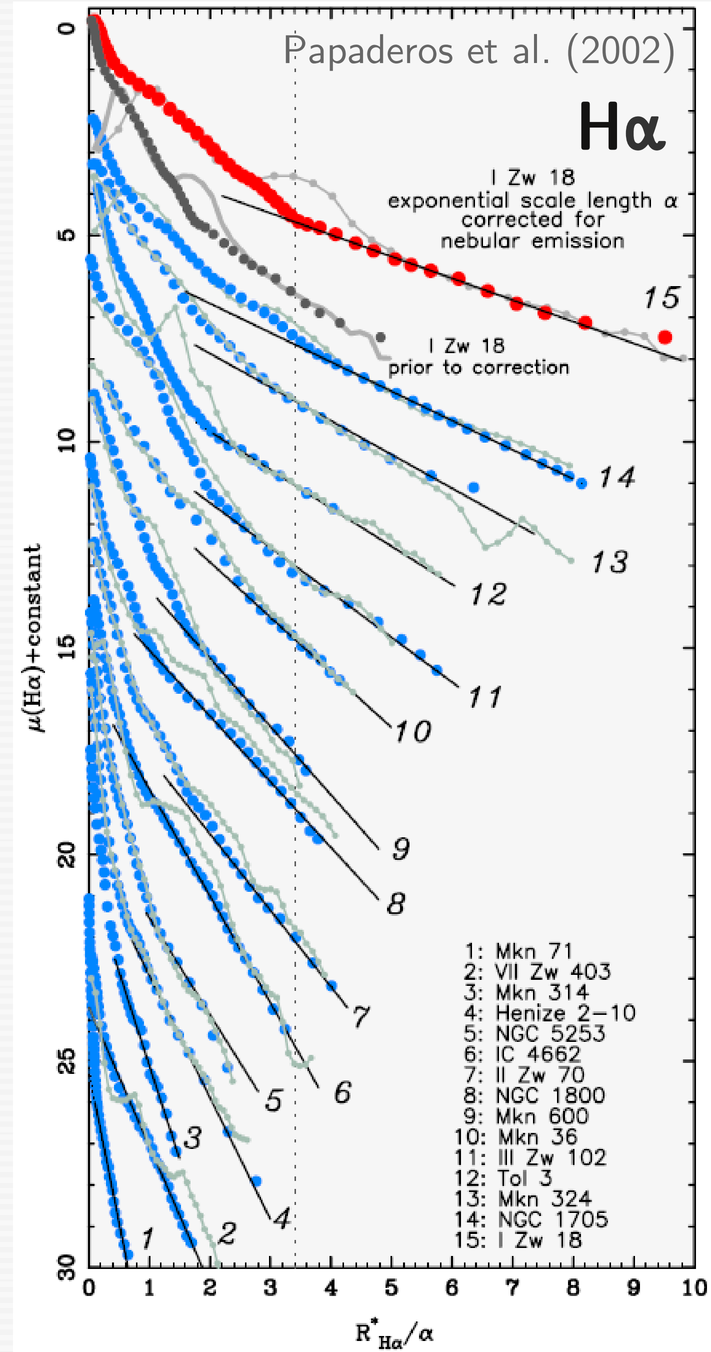


Papaderos & Östlin (2012)

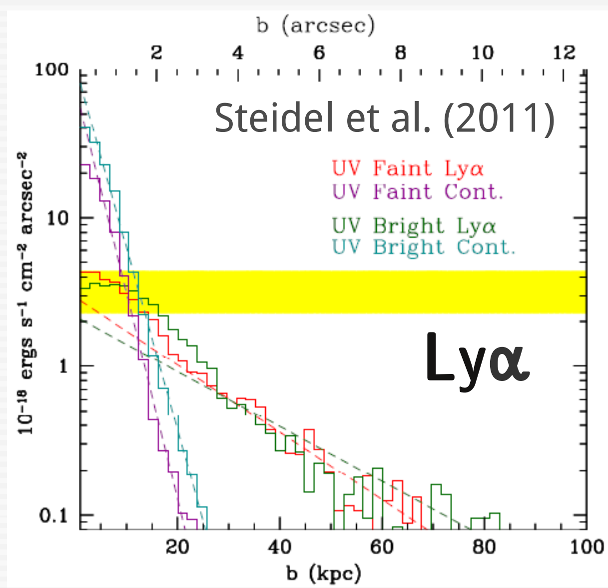
- V-R and B-R relatively red (0.5…0.6 mag) whereas V-I and R-I extremely blue (-0.7 and -1.2 mag)
- There is no stellar population, regardless of SFH, age and metallicity, that can reproduce the observed combination of colors in the LSB envelope of I Zw 18.
- Such colors can readily be explained by nebular emission.

Extended nebular emission in high-sSFR galaxies has an <u>exponential</u> outer slope





- An exponential profile in a distant high-sSFR galaxy is not compeling evidence for an evolved underlying stellar disk.



- Exponentiality is (probably) also a generic property of Lyman α halos