Auto-consistent metallicity and star formation history of Blue Compact Dwarf Galaxies:

NGC 6789 as a pilot study

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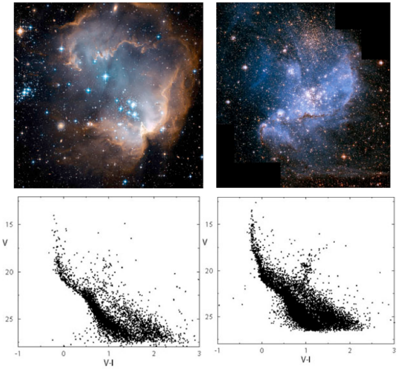
Enrique Pérez Montero (IAA)

Star Formation Histories

Color-magnitude diagram (CMD)



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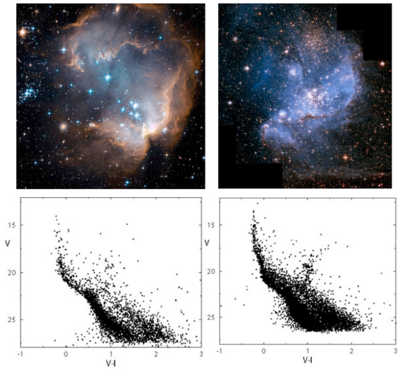
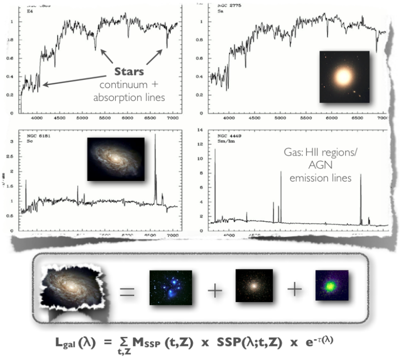


Spectral fitting methods



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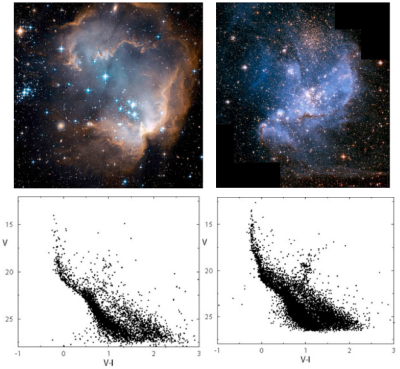

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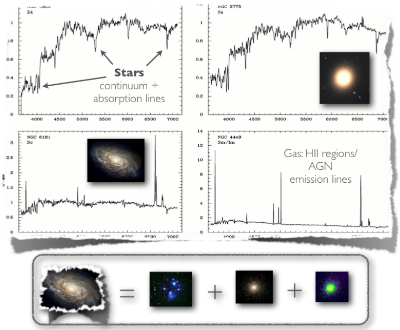

$$L_{gal}(\lambda) = \sum_{t,Z} M_{SSP}(t,Z) \times SSP(\lambda;t,Z) \times e^{-\tau(\lambda)}$$

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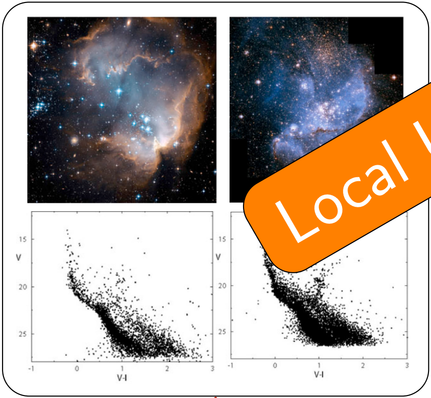

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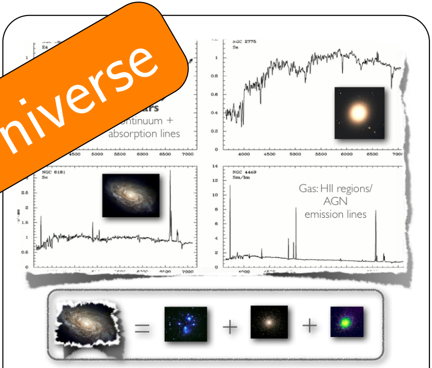

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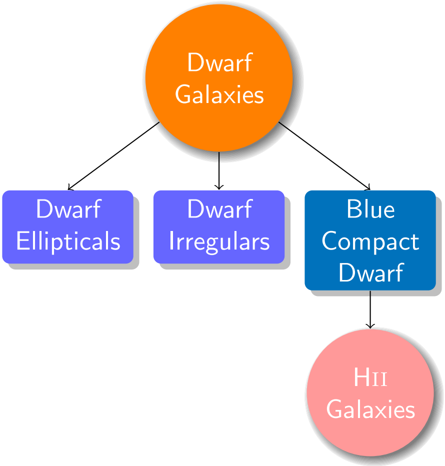
Blue Compact Dwarf Galaxies (BCD)



- Diameter: 2 - 5 kpc
- Mass: 1/10 - 1/100 of the mass of the Milky Way
- Very few are strongly interacting/merging systems
- Evenly distributed in space
- Intense star-forming activity in a spatial scale $\sim$ 1 kpc

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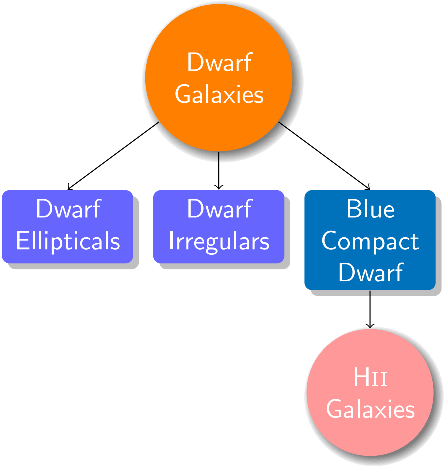

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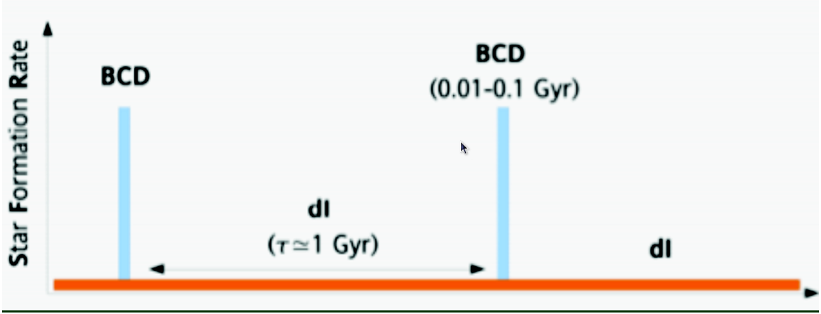
The SFH (Star Formation History) of BCDs

Most of them present old stellar populations, although there is a discrepancy about a continuous SFR or recursive episodes of star formation[1]



[1] Terlevich (2004), Sánchez-Almeida et al. (2008)

Low metallicity and SFR

Reconcile low observed metallicity in BCDs with the relatively high SFR.

Possible mechanisms[2]:

1. Variations in the initial mass function (IMF)
2. Accretion of metal-poor gas
3. Galactic winds powered by supernovae explosions

Numerical models → Last mechanism is the most simple to reproduce the observed properties[3]

[2] Matteucci & Chiosi(1983)
[3] Tolstoy, Hill & Tosi 2009

Pilot project

Methods, techniques, data:

- Photometry: Integrated & Resolved → Properties, CMD, Star Formation History (SFH)
- Spectrophotometry: **Metallicity**, **gas properties**, SFH
- Photoionization Models

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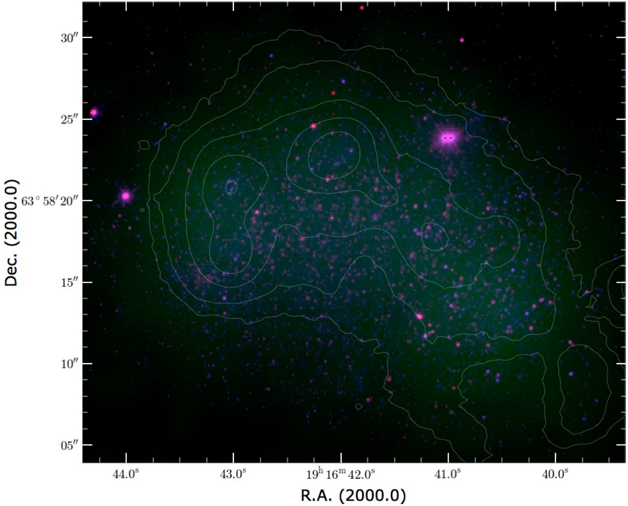
Present-day abundances

Let's put it all together!

The nearest BCD: NGC 6789

814W ⊕ FUV ⊕ 555W ⊕ Hα contours



3.6 Mpc $\rightarrow$
(m-M) $=$ 27.80

(Drozdovsky et al. 2001)

Observations

- ISIS@4.2m-WHT at Roque de los Muchachos
- Double-beam spectrograph

Slit position	Spectral range (Å)	Disp. (Å px^{-1})	FWHM (Å)	Spatial res. ($''$ px^{-1})	Exposure Time s
S1	3670-5070	0.45	1.0	0.2	4×900
S1	5500-7800	0.86	3.5	0.2	2×900, 1×300
S1	7600-9900	0.86	3.5	0.2	2×900
S2	3670-5070	0.45	1.0	0.2	5×900
S2	5500-7800	0.86	3.5	0.2	2×900, 1×300
S2	7600-9900	0.86	3.5	0.2	2×900

- Airmass ~ 1.3
- Sky subtraction $\rightarrow$ strong residuals $\rightarrow$ 7600-9900Å unusable

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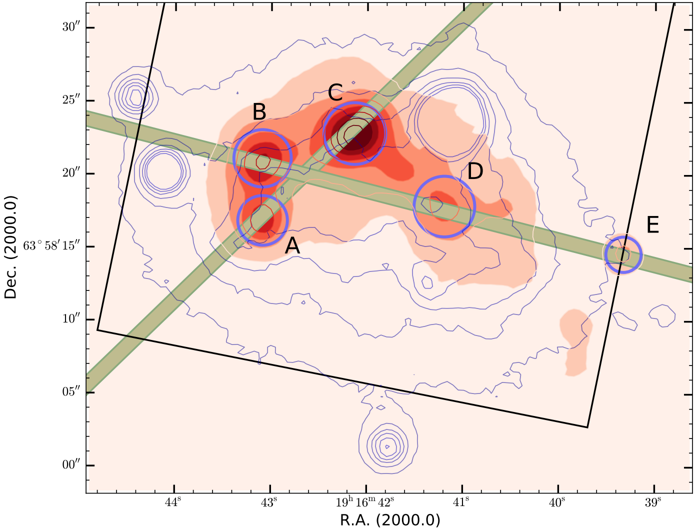
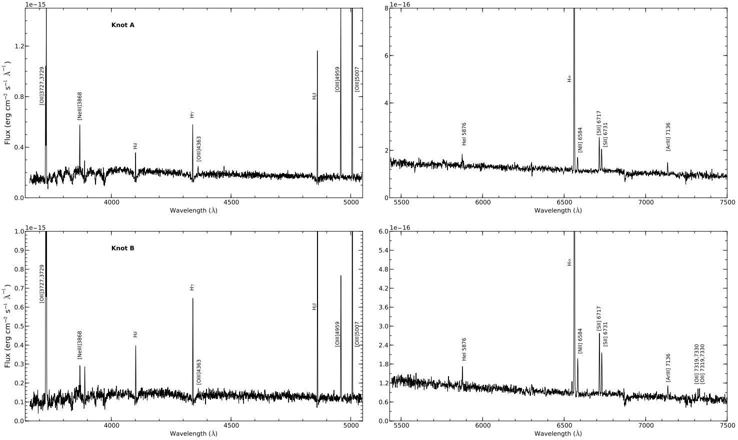
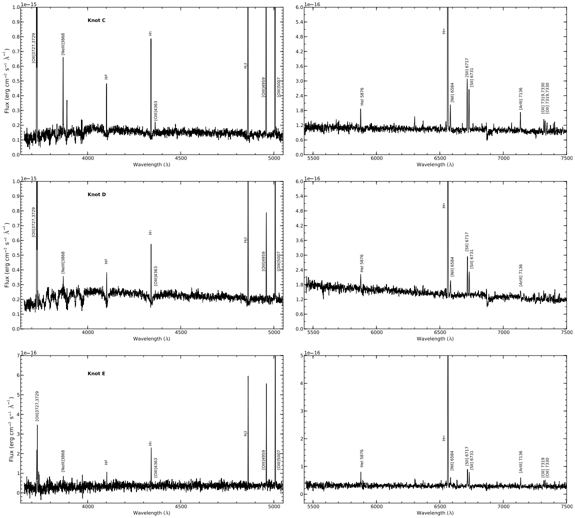
Slit Positions



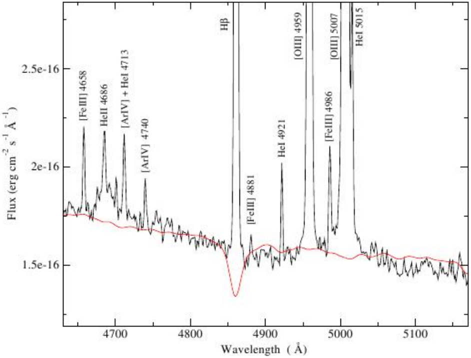
Spectra: Knots A & B



Spectra: Knots C, D & E



Subtraction of the underlying population



STARLIGHT[4]

SSPs[5]

- $Z = 0.001 \oplus 0.004$
- $\cap$
- Ages: SFH from CMD

[4] Cid Fernandes et al. (2004,2005)

[5] Bruzual & Charlot (2003)

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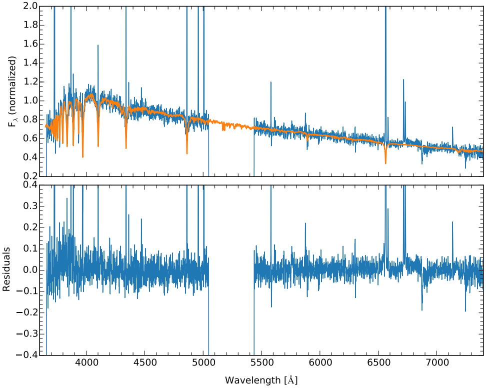


Knot A

STARLIGHT[4]

SSPs[5] { Z = 0.001 ⊕ 0.004 ∩ Ages: SFH from CMD }

4 Cid Fernandes et al. (2004,2005)
5 Bruzual & Charlot (2003)

Reddening correction

Knot	c(Hβ)	A(V)
NGC6789-A	0.12 $\pm$ 0.02	0.26 $\pm$ 0.04
NGC6789-B	0.10 $\pm$ 0.02	0.21 $\pm$ 0.04
NGC6789-C	0.11 $\pm$ 0.02	0.24 $\pm$ 0.04
NGC6789-D	0.12 $\pm$ 0.02	0.26 $\pm$ 0.04
NGC6789-E	0.47 $\pm$ 0.06	1.00 $\pm$ 0.10

c(Hβ) calculation

- Reddening coefficient c(Hβ) for each fiber spectrum
- Balmer decrement derived from Hα,Hβ,Hδ,Hγ compared to the theoretical value expected for case B recombination[6]
- Cardelli et al. (1989) extinction law

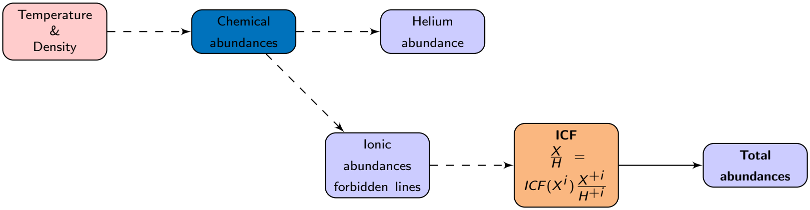
[6] Storey & Hummer (1995)

Electron densities and temperatures

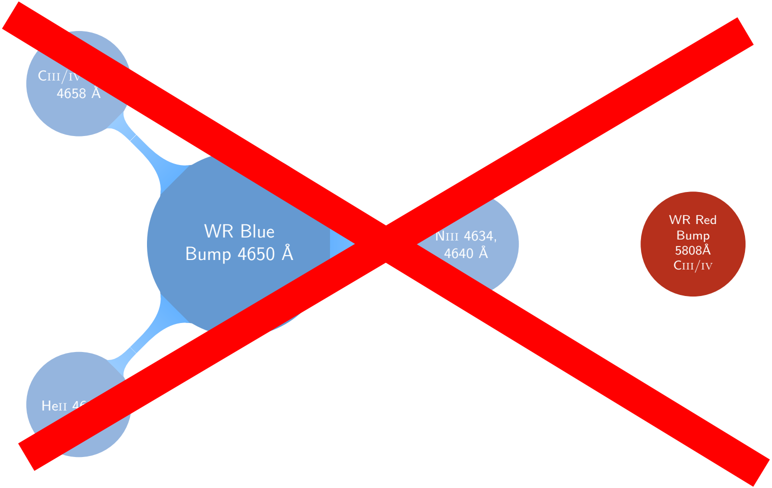
Densities units in cm^{-3} and temperatures in 10^4 K.

	NGC 6789-A	NGC 6789-B	NGC 6789-C	NGC 6789-D	NGC 6789-E
n([SII])	80:	60:	60:	90:	300:
n([OII])	60:	70:	60:	70:	250:
t([OIII])	1.44 ± 0.05	1.36 ± 0.10	1.44 ± 0.05	1.30 ± 0.15	1.16 ± 0.18
t([OII])	1.35 ± 0.06[a]	1.18 ± 0.10	1.41 ± 0.08	1.21 ± 0.10[a]	1.33 ± 0.25
t([SIII])[b]	1.38 ± 0.16	1.30 ± 0.19	1.38 ± 0.16	1.22 ± 0.24	1.06 ± 0.25

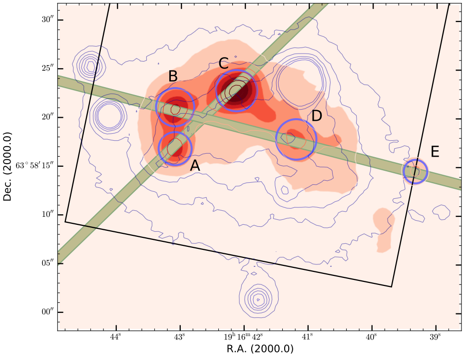
[a] From a relation with T([OIII]) based on photoionisation models
[b] From an empirical relation with T([OIII])



NO Wolf-Rayet stellar population detected



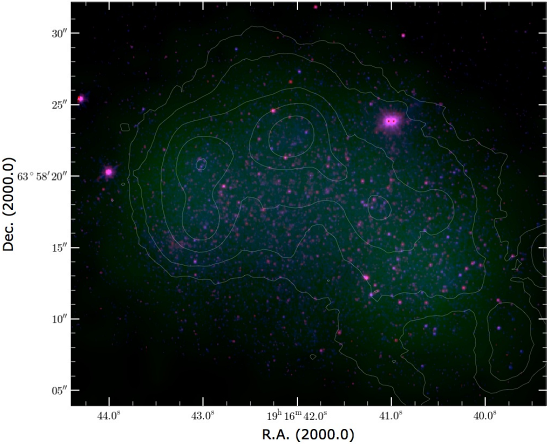
Hα: Defining regions



- Palomar/Las Campanas atlas[7]: Hα $\oplus$ BVR
- Elliptical apertures in Hα up to isophote at 50% of the peak ofr each knot
- NGC 6789 size (Hα): major axis $\approx$ 740 pc $\otimes$ minor axis $\approx$ 560 pc (isophote at 3σ over sky background)

7 Gil de Paz et al. 2003

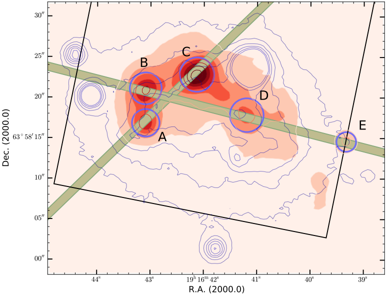
GALEX



- FUV and NUV from the Nearby Galaxies Survey (NGS)
- FUV and NUV flux measured on the Hα-defined ellipses

Hα and GALEX properties

	NGC 6789-A	NGC 6789-B	NGC 6789-C	NGC 6789-D	NGC 6789-E
log F(Hα) (erg/s/cm^2)	-13.96 $\pm$ 0.03	-13.85 $\pm$ 0.03	-13.69 $\pm$ 0.03	-14.03 $\pm$ 0.03	-14.17 $\pm$ 0.03
log L(Hα) (erg/s)	37.23 $\pm$ 0.02	37.34 $\pm$ 0.02	37.50 $\pm$ 0.03	37.17 $\pm$ 0.02	37.02 $\pm$ 0.01
Radius (pc)	30	34	37	36	21
FUV (mag)	20.00 $\pm$ 0.14	20.00 $\pm$ 0.16	20.18 $\pm$ 0.20	19.71 $\pm$ 0.15	21.24 $\pm$ 0.04
NUV (mag)	19.86 $\pm$ 0.08	19.69 $\pm$ 0.09	19.86 $\pm$ 0.10	19.68 $\pm$ 0.09	21.18 $\pm$ 0.01
FUV - NUV (mag)	0.14 $\pm$ 0.16	0.28 $\pm$ 0.19	0.31 $\pm$ 0.22	0.03 $\pm$ 0.18	0.06 $\pm$ 0.04



- Brightest in Hα: Knot C
- A-D (brightest knots) have similar UV luminosities
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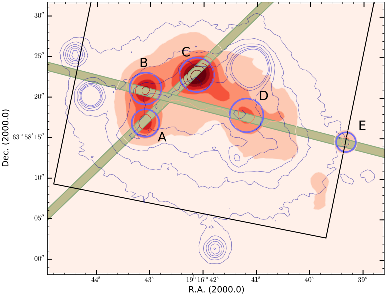

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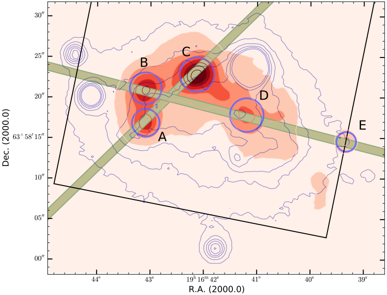

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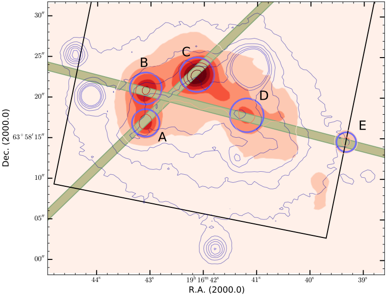

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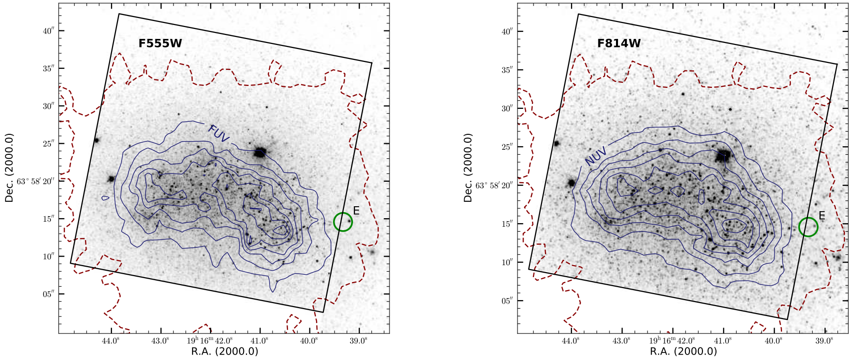
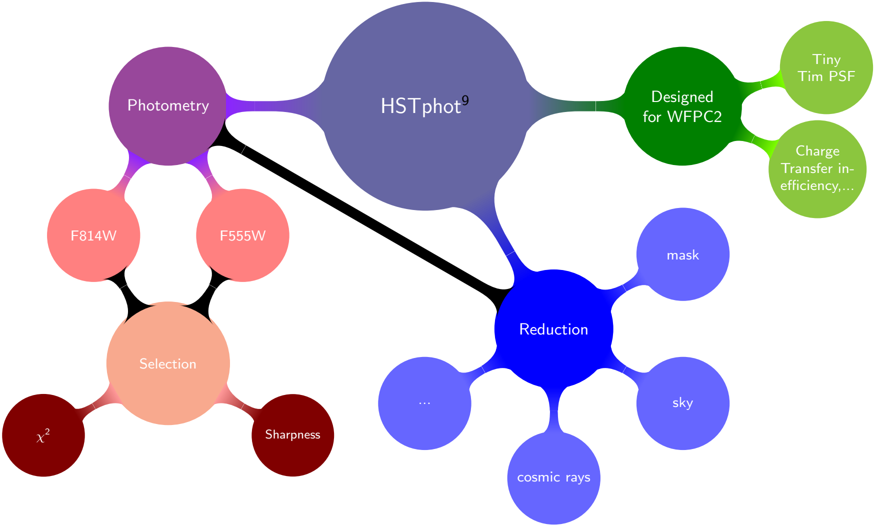
WFPC2 images



- Retrieved from HST archive
- NGC6789[8] at the PC → 0.″046 pixel^{-1} → **0.80 pc pixel^{-1}**

[8] (m-M)=27.80 (Drozdovsky et al. 2001)

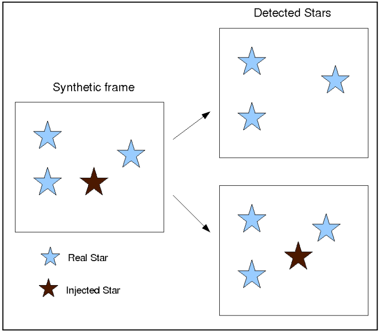
WFPC2 Stellar Photometry



[9] Dolphin (2000)

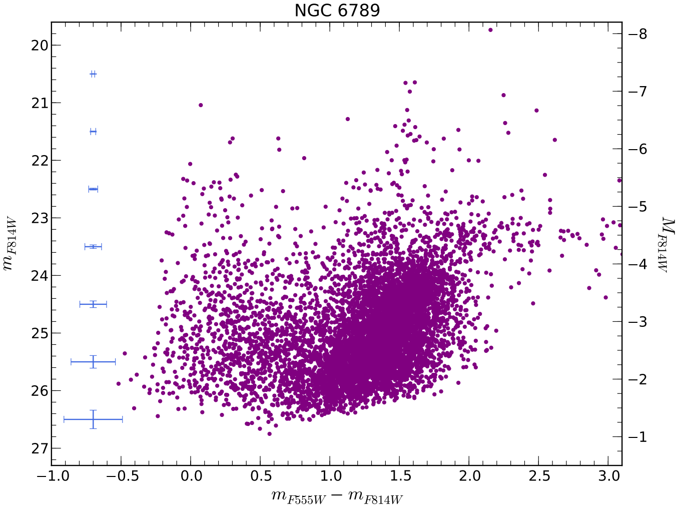
Completeness

- Due to two factors:
  - Overlapping of stellar profiles in crowded regions
  - Background noise
- Best way to account for completeness: to add artificial stars and to subject them to the same photometric analysis as real stars
- Add less than 10% of the numer of real stars to avoid overcrowding effects → **60000 fake stars**
- Completeness table: recovered injected stars and injected stars which have not been paired
- Completeness factor per each magnitude bin: $\frac{\textit{recovered stars}}{\textit{injected stars}}$



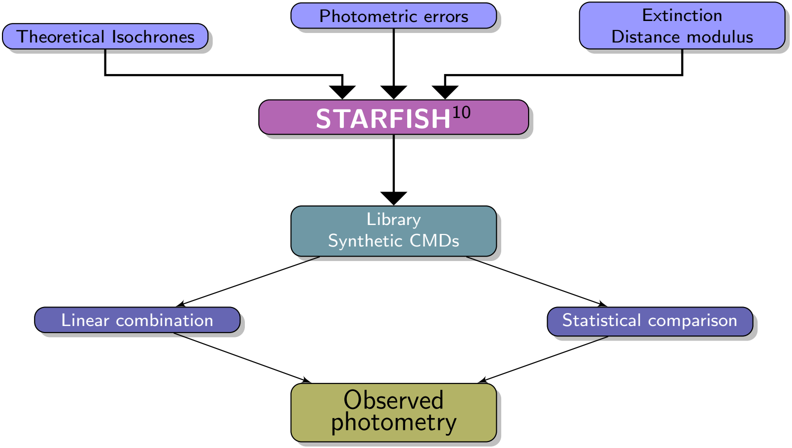
50% COMPLETENESS		
	F555W	F814W
MAG	26.9	25.6

NGC 6789 Color-Magnitude Diagram



CMD of NGC6789 ($\sim$ 7000 stars) with average photometric uncertainties per magnitude bin

Star Formation History: STARFISH



[10] Harris & Zaritsky (2001,2002)

STARFISH and SFHs

- Theoretical isochrones (Marigo et al. 2008) in the range: 1 Myr-14 Gyr
- Metallicity Z = {0.001, 0.004} → same as in STARLIGHT libraries[11]
- Salpeter IMF: -1.35 from 0.1-100 $M_\odot$ → CMD does not contain stars with masses < 1 $M_\odot$

- Distance Modulus[12] (m-M) = 27.80 ± 0.13 ± 0.18
- Galatic extinction[13] A_V = 0.212

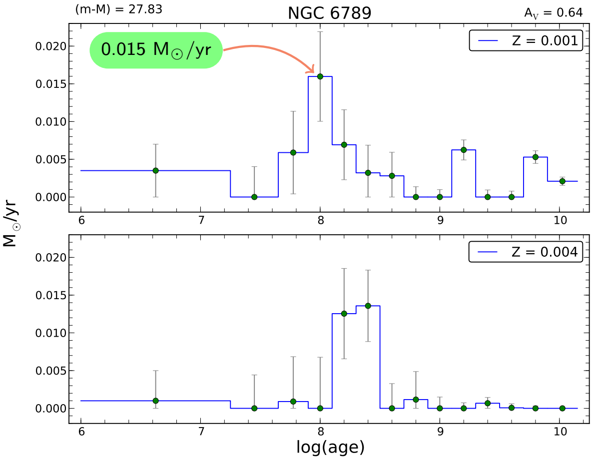
→

- Build a set of models to explore the space of parameters and get best (m-M) **and** A_V
- Steps of 0.01 in distance modulus and extinction
- Error evaluation → Generate a series of synthetic CMDs using the best-fitting SFR and find a correspondece between ther χ^2_{min} and the confidence level of significance

[11] Bruzual & Charlot 2003
[12] Drozdovsky et al. 2001, tip RGB
[13] Schlegel et al. 1998

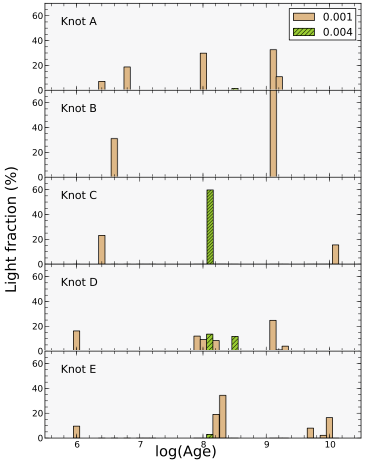
NGC 6789 Star Formation History (SFH)

$(\text{m-M}) = 27.83 \pm 0.06 \otimes A_V = 0.64 \pm 0.08$

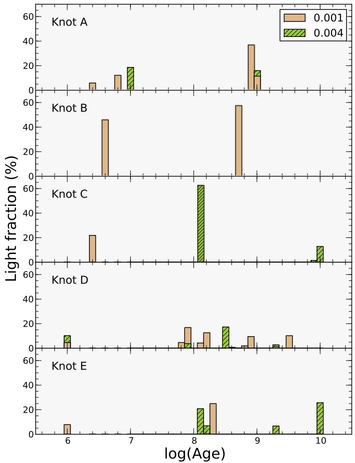


STARLIGHT SFH

CMD-constrained



Free



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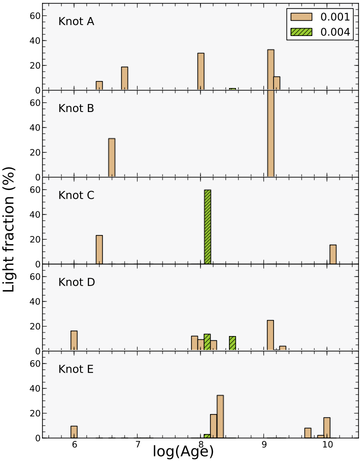
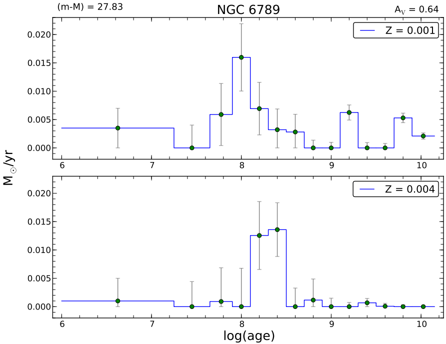




STARLIGHT derived properties

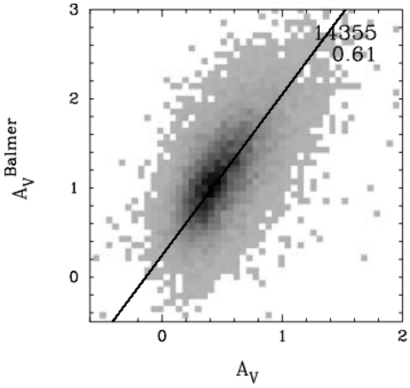
ID	A(V) (mag)	log M_*	log M_{ion*}	EW($H\beta$)$_c$ (Å)
Knot A	0.4	5.34	3.69	23
	0.4	5.35	3.81	19
Knot B	0.3	5.26	3.16	30
	0.7	5.22	3.68	30
Knot C	0.7	6.00	4.03	49
	0.6	5.97	3.95	51
Knot D	0.5	5.42	3.79	24
	0.5	5.51	3.66	24
Knot E	0.7	5.16	2.71	84
	0.5	5.21	2.47	95

- Presence old populations confirmed by presence Ca II K λ 3933 Å and Ca II H λ 3968 Å
- 80% coming from the old population
- Little difference in the fitted spectra between the constrained case and the free one

STARLIGHT (Average)	StarFish	Balmer
0.52 $\pm$ 0.16	0.64 $\pm$ 0.08	0.24 $\pm$ 0.04 (A-D)
		0.47 $\pm$ 0.06 (E)

STARLIGHT derived properties

Cid Fernandes et al. (2005)



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		0.47 $\pm$ 0.06 (E)

Helium Abundance

	NGC 6789-A	NGC 6789-B	NGC 6789-C	NGC 6789-D	NGC 6789-E
He^+/H^+ (4471)	0.077 ± 0.011	0.080 ± 0.015	0.079 ± 0.013	0.076 ± 0.014	0.082 ± 0.015
He^+/H^+ (5876)	0.075 ± 0.011	0.071 ± 0.013	0.072 ± 0.012	0.076 ± 0.015	0.073 ± 0.016
He^+/H^+ (6678)	...	...	0.071 ± 0.013	...	...
He^+/H^+ (7065)	...	...	0.074 ± 0.016	...	...
He^+/H^+	0.076 ± 0.010	0.075 ± 0.012	0.074 ± 0.009	0.076 ± 0.011	0.077 ± 0.011
He^{2+}/H^+ (4686)	...	...	0.0023 ± 0.0006	...	...
He/H	...	...	0.076 ± 0.009	...	...

Helium abundance similar all knots and to other BCDs

Metal content

	NGC 6789-A	NGC 6789-B	NGC 6789-C	NGC 6789-D	NGC 6789-E
$12 + \log(O^{+}/H^{+})$	7.43 ± 0.04	7.82 ± 0.11	7.42 ± 0.07	7.73 ± 0.11	7.16 ± 0.23
$12 + \log(O^{2+}/H^{+})$	7.63 ± 0.04	7.28 ± 0.07	7.59 ± 0.04	7.41 ± 0.13	7.68 ± 0.17
$12 + \log(O/H)$	7.84 ± 0.04	7.93 ± 0.10	7.81 ± 0.05	7.90 ± 0.12	7.80 ± 0.18
$12 + \log(N^{+}/H^{+})$	6.03 ± 0.04	6.37 ± 0.07	6.08 ± 0.06	6.22 ± 0.07	5.85 ± 0.16
$ICF(N^{+})$	3.57	1.57	4.57	1.97	4.09
$12 + \log(N/H)$	6.58 ± 0.04	6.57 ± 0.07	6.74 ± 0.06	6.51 ± 0.07	6.50 ± 0.16
$\log(N/O)$	-1.26 ± 0.06	-1.37 ± 0.12	-1.07 ± 0.08	-1.38 ± 0.14	-1.30 ± 0.24
$12 + \log(S^{+}/H^{+})$	5.70 ± 0.03	5.91 ± 0.07	5.75 ± 0.05	5.83 ± 0.07	5.70 ± 0.14
$12 + \log(S^{2+}/H^{+})$	5.88 ± 0.16	6.14 ± 0.23	6.09 ± 0.16	6.35 ± 0.30	...
$ICF(S^{+} + S^{2+})$	1.11	1.01	1.24	1.01	7.64
$12 + \log(S/H)$	6.20 ± 0.11	6.35 ± 0.18	6.41 ± 0.11	6.48 ± 0.25	6.58 ± 0.14
$\log(S/O)$	-1.64 ± 0.12	-1.58 ± 0.20	-1.41 ± 0.12	-1.41 ± 0.27	-1.22 ± -0.25
$12 + \log(Ne^{2+}/H^{+})$	7.00 ± 0.06	6.77 ± 0.10	7.00 ± 0.06	6.68 ± 0.17	6.75 ± 0.20
$ICF(Ne^{2+})$	1.39	1.61	1.28	2.07	1.22
$12 + \log(Ne/H)$	7.14 ± 0.06	6.98 ± 0.10	7.11 ± 0.06	7.00 ± 0.17	6.82 ± 0.20
$\log(Ne/O)$	-0.70 ± 0.07	-0.95 ± 0.14	-0.70 ± 0.08	-0.90 ± 0.21	-0.96 ± 0.27
$12 + \log(Ar^{2+}/H^{+})$	5.67 ± 0.08	5.56 ± 0.12	5.56 ± 0.09	5.63 ± 0.17	5.70 ± 0.19
$ICF(Ar^{2+})$	1.12	1.21	1.15	1.14	1.10
$12 + \log(Ar/H)$	5.72 ± 0.08	5.64 ± 0.12	5.62 ± 0.09	5.68 ± 0.17	5.74 ± 0.19
$\log(Ar/O)$	-2.12 ± 0.09	-2.28 ± 0.16	-2.19 ± 0.10	-2.22 ± 0.21	-2.06 ± 0.22

- ICFs estimated from tailored photoionisation models
- t([O III]) between 13000 - 14300 K
- Knot C, brightest in Hα, has in average higher temperatures

Metal content

NGC 6789 [12 + log(O/H)] ≈ 7.80-7.93

	NGC 6789-A	NGC 6789-B	NGC 6789-C	NGC 6789-D	NGC 6789-E
log(N/O)	-1.26 ± 0.06	-1.37 ± 0.12	-1.07 ± 0.08	-1.38 ± 0.14	-1.30 ± 0.24

- At low metallicity, most part of nitrogen has a primary origin and constant log(N/O) is observed
- NGC 6789 N/O ratio is sensibly higher (range -1.38 -1.26; -1.07 for knot C) that values for other low metallicity BCDs (around -1.6) → **Different evolutionary and excitation properties**

Overabundance

Fall of pistine gas?

Metal content

NGC 6789 $[12 + \log(O/H)] \approx 7.80$-$7.93$

	NGC 6789-A	NGC 6789-B	NGC 6789-C	NGC 6789-D	NGC 6789-E
log(N/O)	-1.26 ± 0.06	-1.37 ± 0.12	-1.07 ± 0.08	-1.38 ± 0.14	-1.30 ± 0.24

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Overabundance

Fall of pistine gas?

Dust absorption

- To fit the observed EW(Hβ) it is necessary to get an estimation of the dust absorption factor:

$$Q(H) = f_d \times Q_{obs}(H)$$

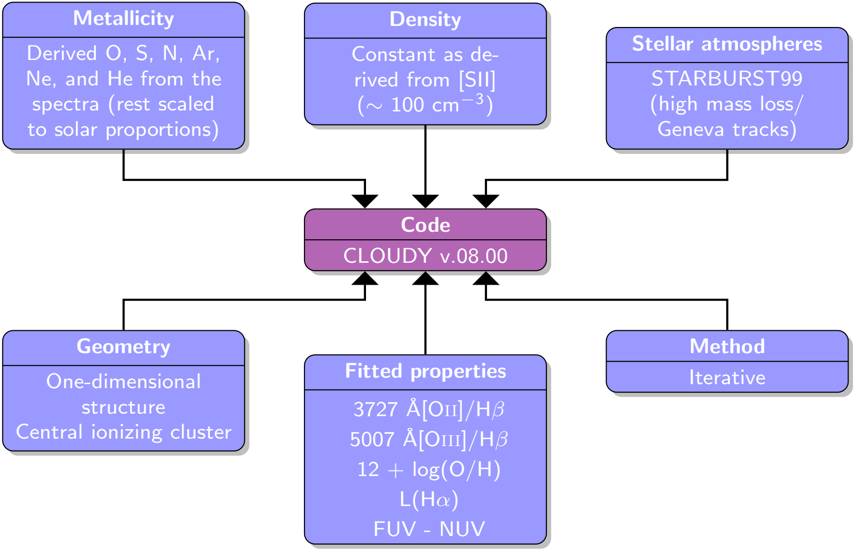
The inclusion of dust allows to fit the measured electron temperature $\Rightarrow$ reproduce thermal balance in the gas[14]

- Free parameters: amount of dust, radius, and filling factor
- Age of the burst limited to the range 1-10 Myr: initial guesses of f_d $\Rightarrow$ calculate age of cluster and Q(H) to match observed values

CLOUDY $\Rightarrow$ Fit observed properties

14 Pérez-Montero & Díaz (2007)

CLOUDY Parameters



Cloudy Results

	NGC 6789-A		NGC 6789-B		NGC 6789-C		NGC 6789-D		NGC 6789-E	
	Mod.	Obs.	Mod.	Obs.	Mod.	Obs.	Mod.	Obs.	Mod.	Obs.
log L(Hα) (erg/s)	37.32	37.23 $\pm$ 0.02	37.34	37.34 $\pm$ 0.02	37.51	37.50 $\pm$ 0.03	37.18	37.17 $\pm$ 0.02	37.03	37.02 $\pm$ 0.01
Radius (pc)	7	30	33	34	22	37	10	36	5	21
FUV-NUV (mag)	0.17	0.14 $\pm$ 0.16	0.28	0.28 $\pm$ 0.19	0.30	0.31 $\pm$ 0.22	0.22	0.03 $\pm$ 0.18	0.10	0.06 $\pm$ 0.04
I([OII]/I(Hβ)	2.30	2.34 $\pm$ 0.15	3.33	3.16 $\pm$ 0.20	2.35	2.51 $\pm$ 0.16	3.05	3.14 $\pm$ 0.20	1.09	1.06 $\pm$ 0.04
I([OIII]/I(Hβ)	3.82	3.76 $\pm$ 0.17	1.47	1.48 $\pm$ 0.07	3.45	3.44 $\pm$ 0.15	1.72	1.73 $\pm$ 0.08	2.30	2.26 $\pm$ 0.20
12+log(O/H)	7.93	7.84 $\pm$ 0.04	7.82	7.93 $\pm$ 0.10	7.79	7.81 $\pm$ 0.05	7.77	7.90 $\pm$ 0.12	7.64	7.80 $\pm$ 0.18
-EW(Hβ (Å)	21	23	30	30	48	49	29	24	80	84
Age (Myr)	5.4	...	4.2	...	3.5	...	5.2	...	3.9	...
Dust-to-gas ratio	0.026	...	0.34	...	0.12	...	0.15	...	0.015	...
Abs. factor (f_d)	5.34	....	7.28	...	8.21	...	4.37	...	2.23	...

- Properties generally well fitted, assuming different geometries and dus-to-gas ratios
- f_d correlates better with FUV-NUV than with the reddening constant $\longrightarrow$ complex inner dust structure
- Ages in the range 3.5-5.4 Myr

Mass

NGC 6789 Mass

ID	log Q(H^0) (erg/s)	log M_{burst} ($M_\odot$)	log M(HII) ($M_\odot$)	log SFS ($M_\odot$)	SFR (10^{-3} $M_\odot$/yr)
Knot A	49.94	3.82	3.45	4.34	1.04
Knot B	50.09	3.65	3.60	4.32	1.47
Knot C	50.31	3.69	3.82	4.54	2.44
Knot D	49.69	3.52	3.20	4.09	0.59
Knot E	49.25	2.73	2.76	3.48	0.21
NGC 6789[a]	51.49	···	5.00	5.89	36.97

- Ionized mass of HII → $M_{H+} = Q(H^0)\,\frac{m_p}{n_e\,\alpha_B}$
- Ionizing cluster masses → $Q(H^0)$ ⊕ ages ⊕ SB99 → similar to STARLIGHT
- SFS & SFR from Otí-Floranes & Mas-Hesse (2010)

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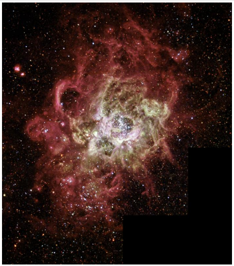

NGC 604

Mass

NGC 6789 Mass

ID	log Q(H^0) (erg/s)	log M_{burst} ($M_\odot$)	log M(HII) ($M_\odot$)	log SFS ($M_\odot$)	SFR (10^{-3} $M_\odot$/yr)
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NGC 5471

Mass

NGC 6789 Mass

ID	log Q(H^0) (erg/s)	log M_{burst} ($M_\odot$)	log M(HII) ($M_\odot$)	log SFS ($M_\odot$)	SFR (10^{-3} $M_\odot$/yr)
Knot A	49.94	3.82	3.45	4.34	1.04
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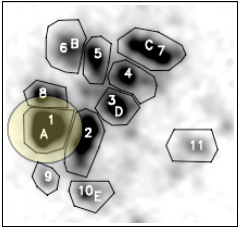

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Summary pilot project: NGC 6789

CMD SFH

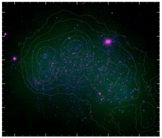
Bursty SFH with a peak in the last 100 Myr

Spectra

Low abundance (7.80-7.93)
Higher N/O value → Infall?

Spectra SFH

Simultaneous resolved stellar photometry and optical spectroscopy provide accurate constraint to age-metallicity extinction degeneracy of these parameters



Photoionisation models

Optical-UV photometry, emission-line ratios & EW(Hβ) fits → age (3-6Myr), masses (10^5 $M_\odot$) and dust properties.

Dust absorption factors correlate with FUV-NUV

Auto-consistency

Combination of observational and model techniques leads to a better (yet complex) and auto-consistent study of nearby galaxies

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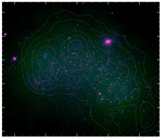

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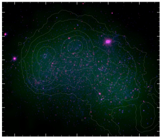

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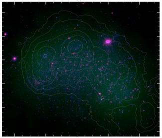

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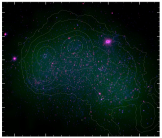

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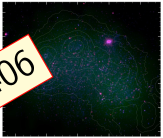
MNRAS 2012, 423, 406



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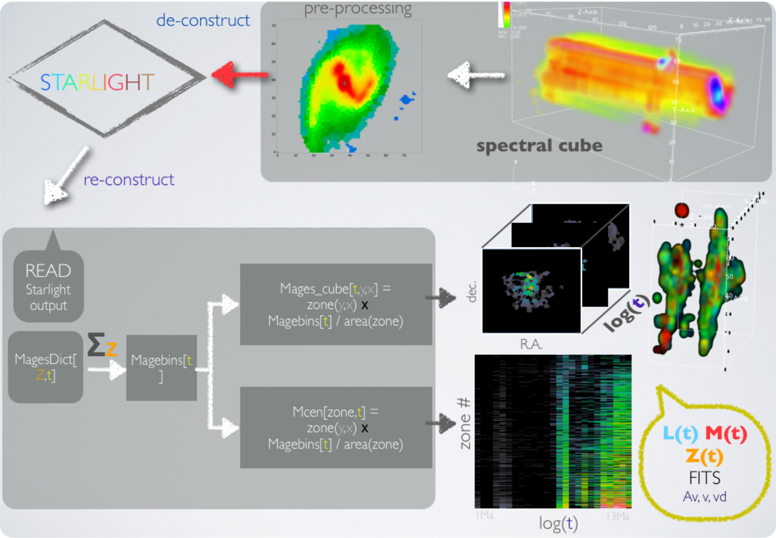
2D Star formation histories: 3D data



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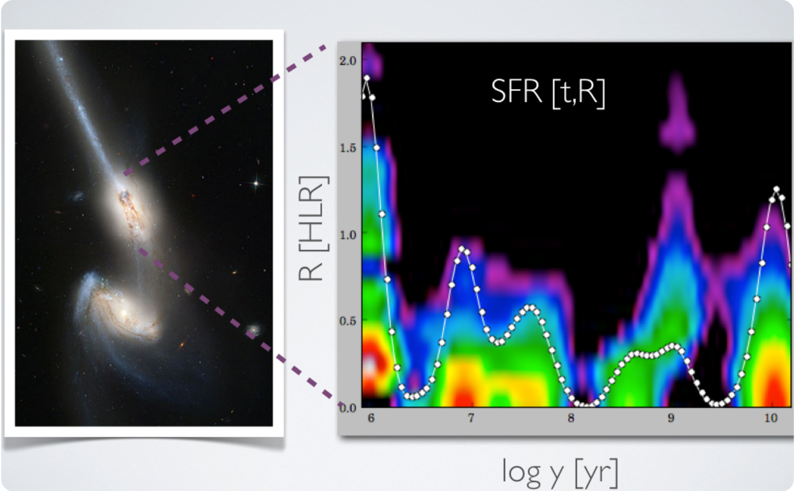


Main Project

IFU observations of Local Universe BCDs (< 6 Mpc)

All objects with **HST data** and at least 2 filters (CMD $\rightarrow$ SFH)

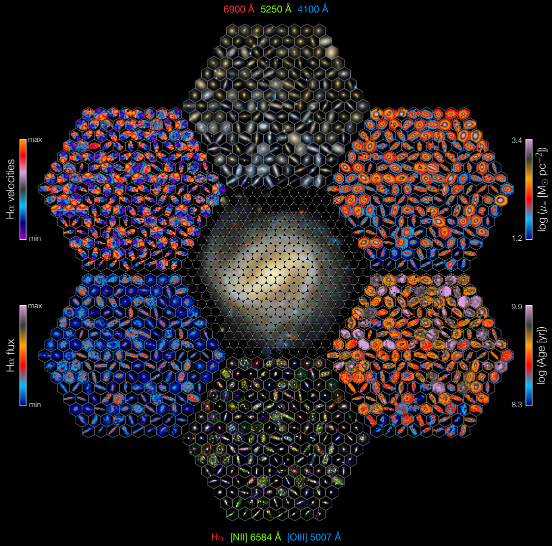
PPak @ CAHA
PI: García-Benito

- NGC 1569
- UGC 4483
- VII Zw 403
- UGCA 290

MUSE @ VLT
PI: García-Benito

- NGC0625
- NGC1705
- NGC2915
- NGC3125
- NGC5253
- UGC9128
- IIZw40
- ESO154-023

CALIFA Second Public Data Release (DR2)



califa.caha.es

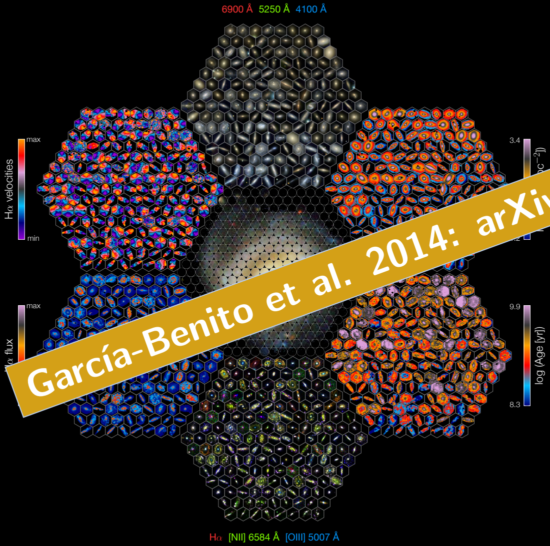
200 galaxies

400 datacubes:

- V500: 3745-7500 Å (6.0Å)
- V1200: 3650-4840 Å (2.3Å)

PSF 2.5″

CALIFA Second Public Data Release (DR2)



García-Benito et al. 2014: arXiv:1409.8302

califa.caha.es

…axies

400 datacubes:

V500: 3745-7500 Å (6.0Å)

V1200: 3650-4840 Å (2.3Å)

PSF 2.5″

Auto-consistent metallicity and star formation history of Blue Compact Dwarf Galaxies:

NGC 6789 as a pilot study

Rubén García-Benito

Instituto de Astrofísica de Andalucía