# Ionized and neutral gas in the XUV discs of nearby spiral galaxies


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*Galaxies in 3D across the Universe* – Vienna – Austria – 7 July 2014

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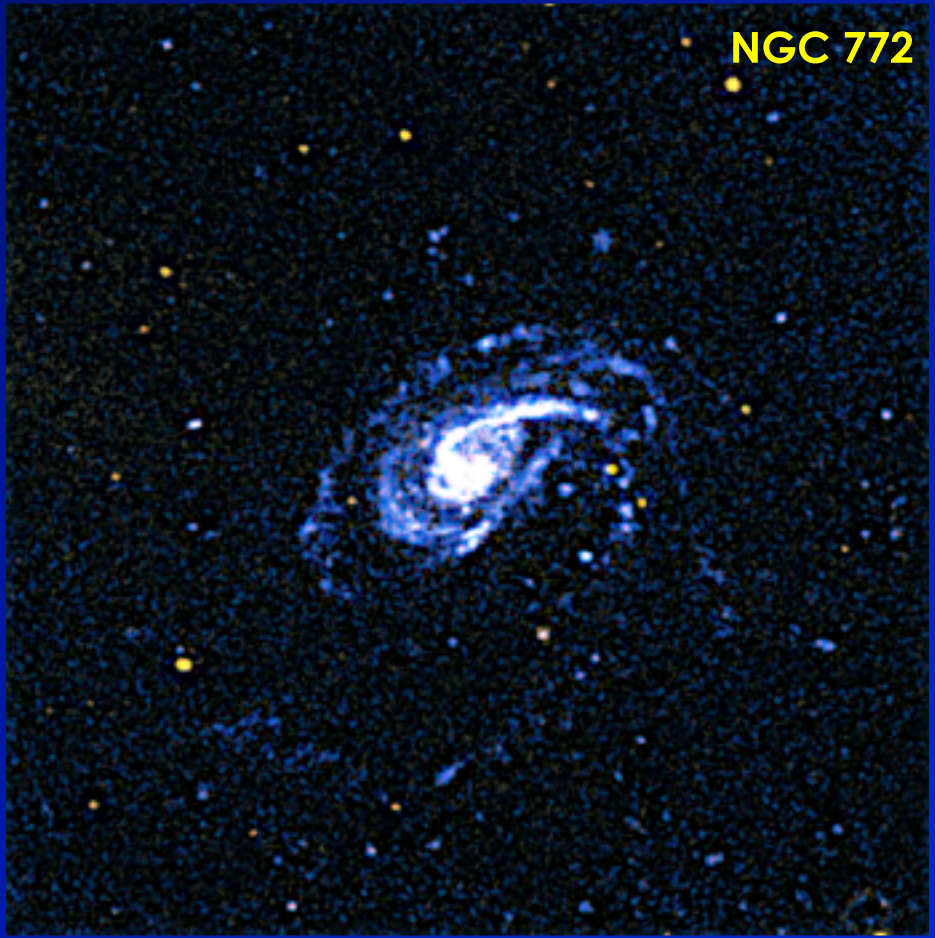
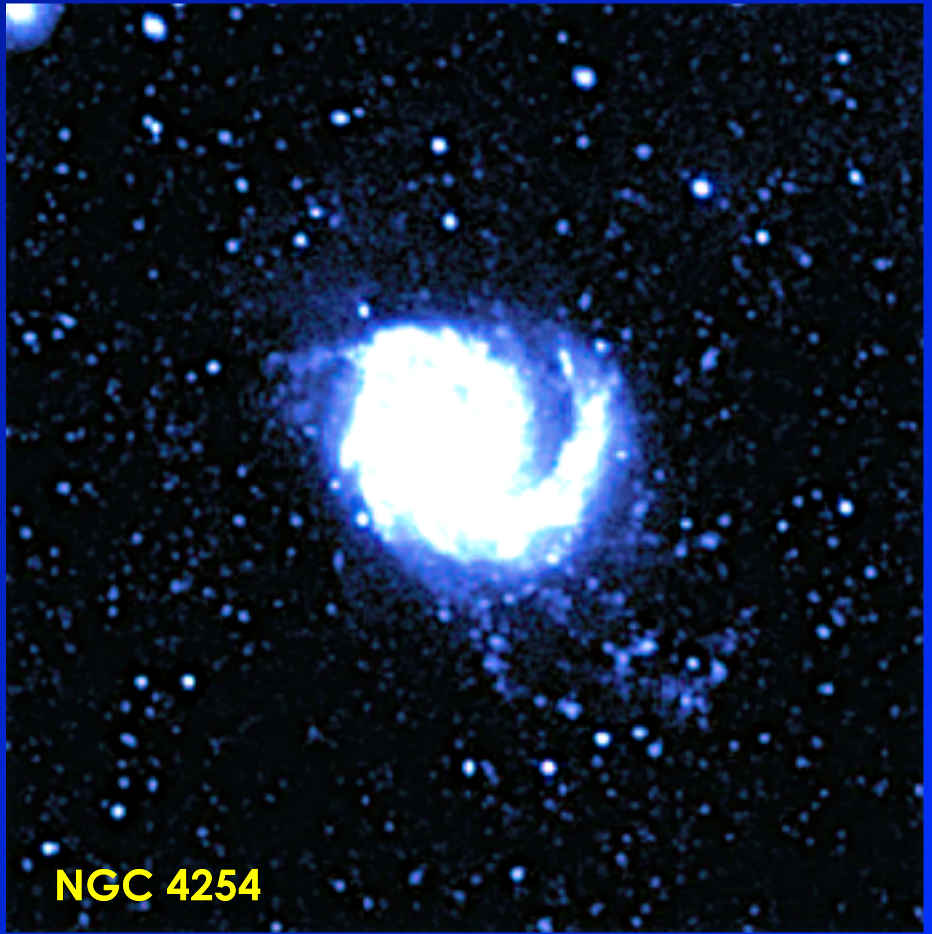
# Extended UV-emission (XUV) in galaxies

- **Discovered using GALEX data.**
  - UV-bright complexes in the outskirsts of nearby spirals
  - Well beyond their $B_{25}$ or $H\alpha$ radius
  - Thilker et al. 2005, 2007
    Gil de Paz et al. 2005, 2007
- **XUV discs seems to exists in 20 - 30 % of the local disc galaxy population.**
  - Zaritsky & Christlein 2007; Thilker et al. 2007; Lemonias et al. 2011.
- **Even found around E/S0 galaxies.**
  - Thilker et al. 2010; Salim & Rich 2010; Moffett et al. 2012; Bresolin 2013.
- **UV-bright complexes are young stellar clusters associated with recent or still on-going star formation.**
  - Gil de Paz 2007, Bresolin et al. 2009, 2012
- **XUV-discs should be embedded in larger HI envelopes, 2X-HI,** (Koribalsky & L-S 2009).



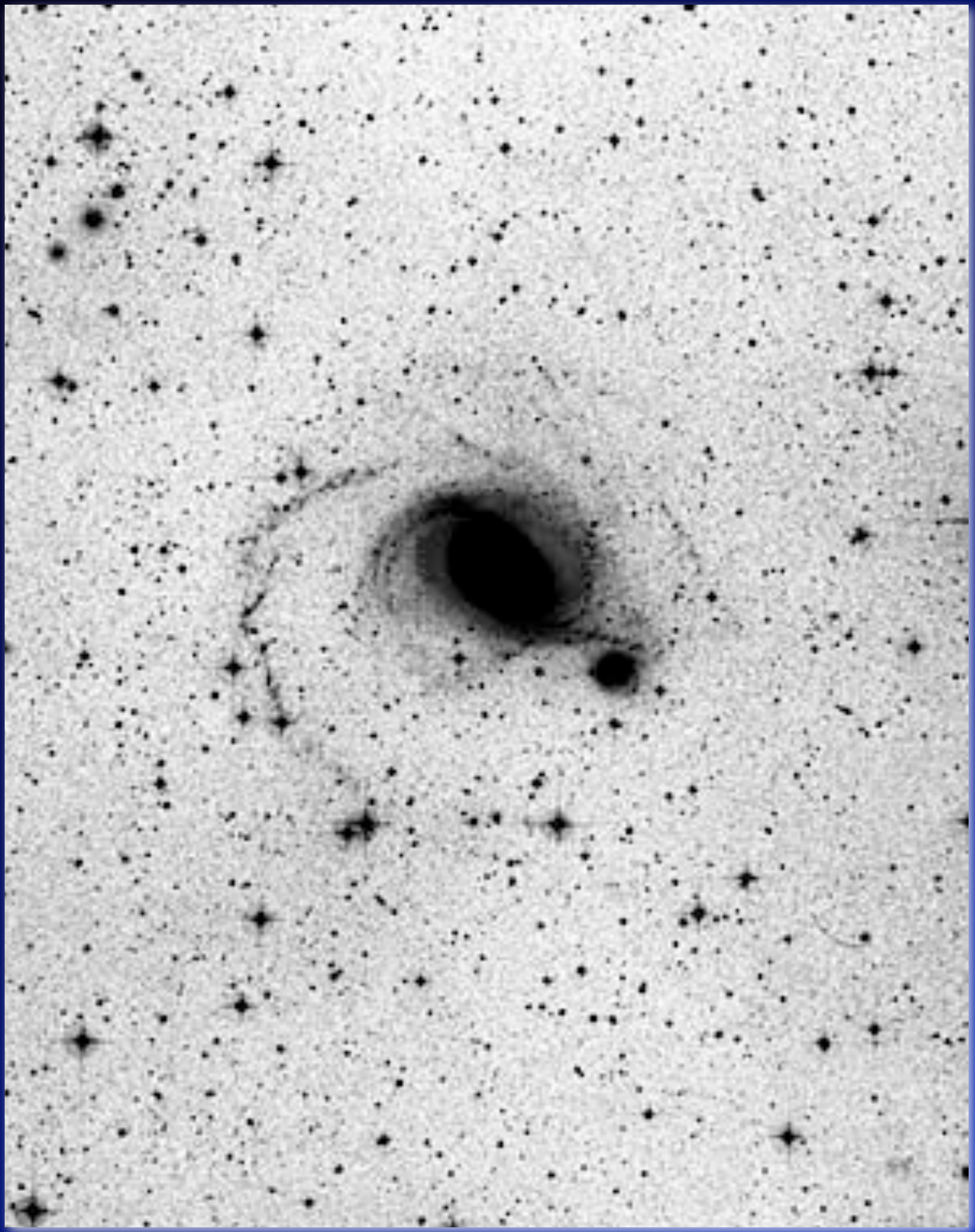

*Thilker et al. 2007*

# The galaxy pair NGC 1512 / 1510

- **NGC 1512:**
  - SB(r)ab, Z ~0.7 Zo
  - D = 9.5 Mpc
  - Bar ~ 3' = 8.3 kpc
  - Ring ~ 3' x 2' = 8.3 x 5.5 kpc
  - Nuclear ring ~ 16" x 12" (740 x 550 pc)
- **NGC 1510:**
  - S0, BCDG, WR, Z~0.2 Zo
  - N enrichment ?
  - 5' = 13.8 kpc from NGC 1512
- Hα images (Meurer et al. 2006) reveal many star forming regions
  - Sizes 2"–5" (90–230 pc)
  - Dozens in the ring
  - NGC 1510
  - But also in external regions with no evident continuum emission!

NGC 1512 / 1510 , B + R + Hα , CTIO data combined by Á.R. L-S.

# NGC 1512/1510 deep optical / UV images



**Deep optical image**

(1.2 UKST, David Malin, priv. com.)

Ángel R. López-Sánchez

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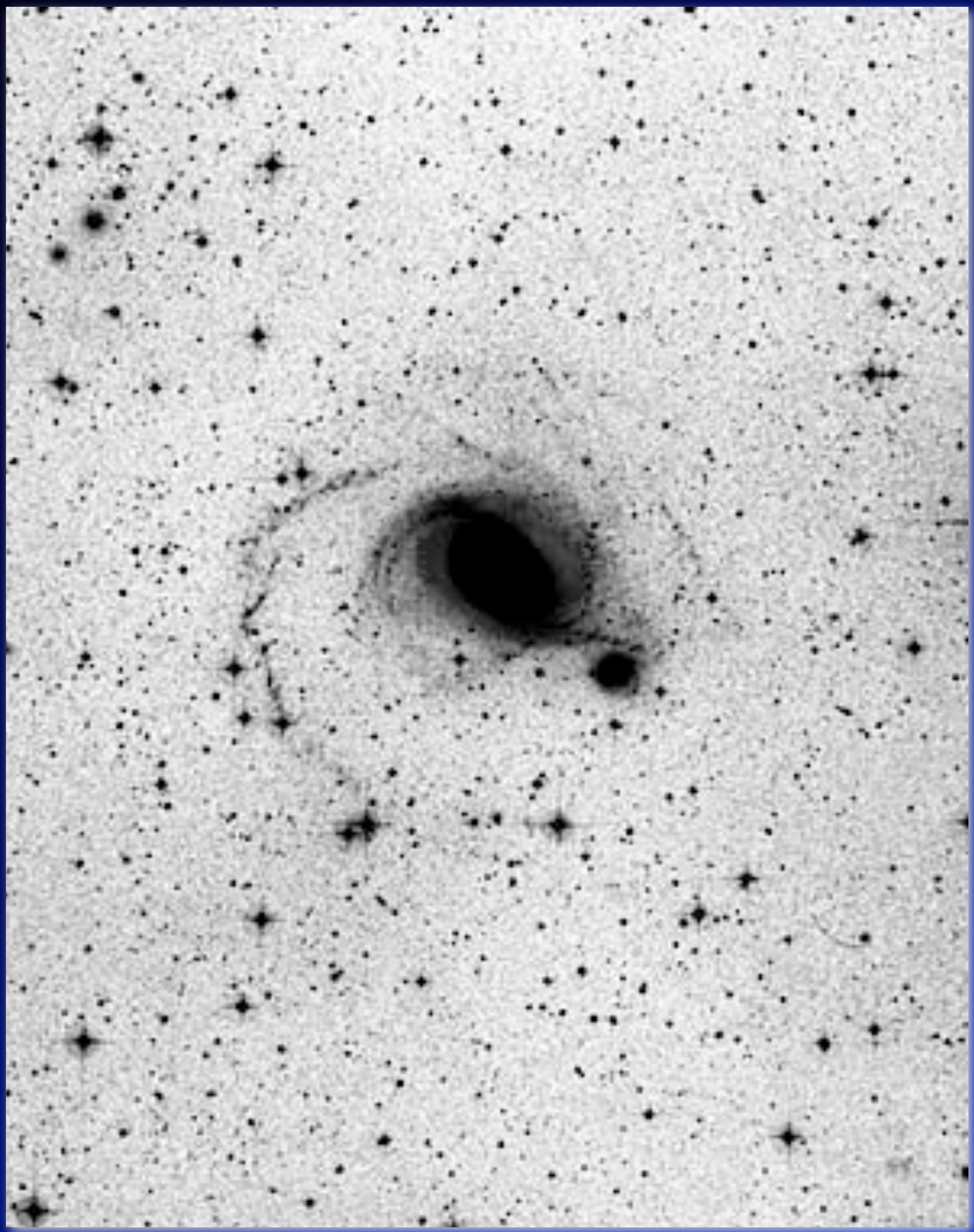

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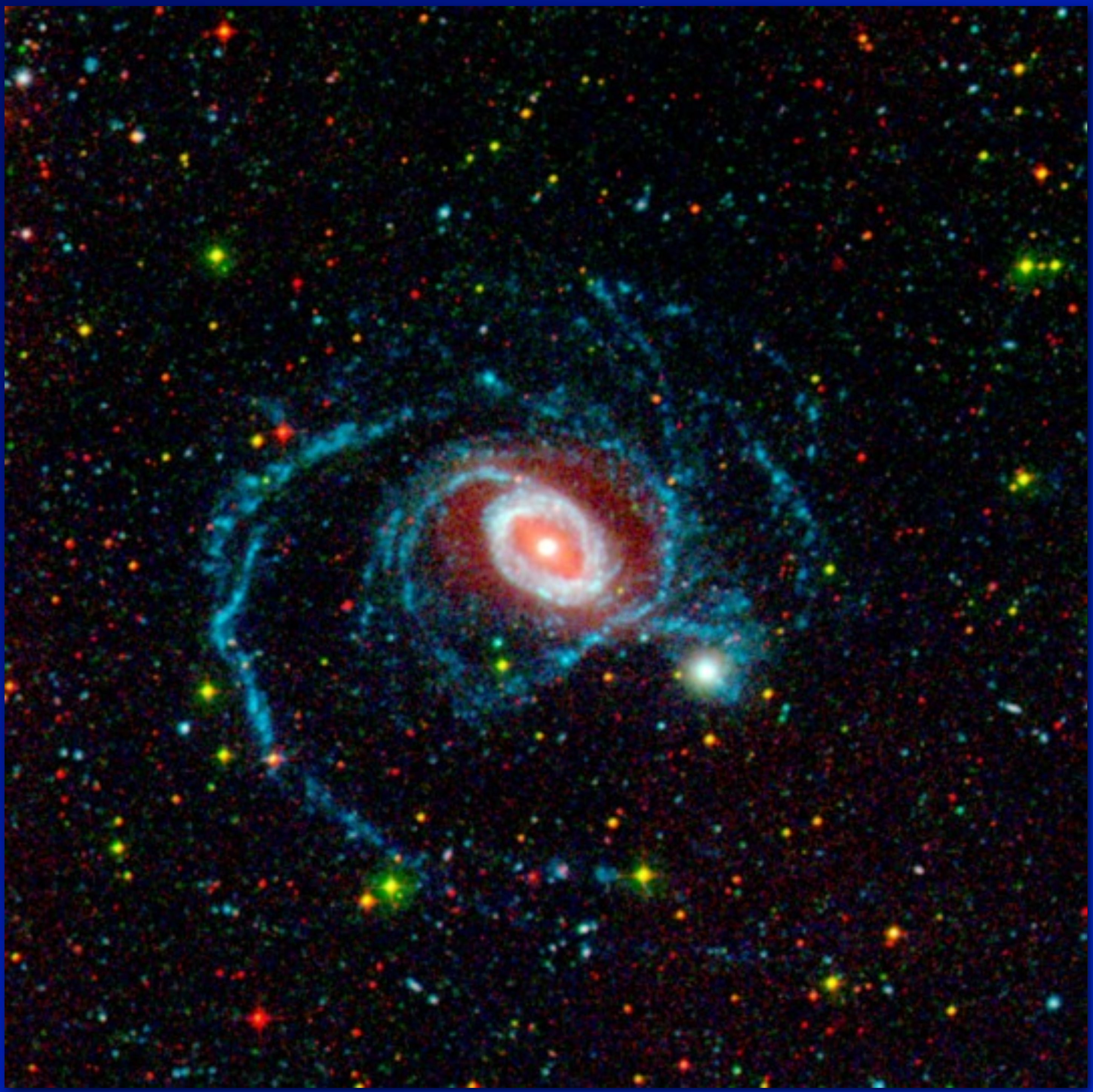

**Deep UV image**

(FUV + NUV, GALEX, Gil de Paz et al. 2007)

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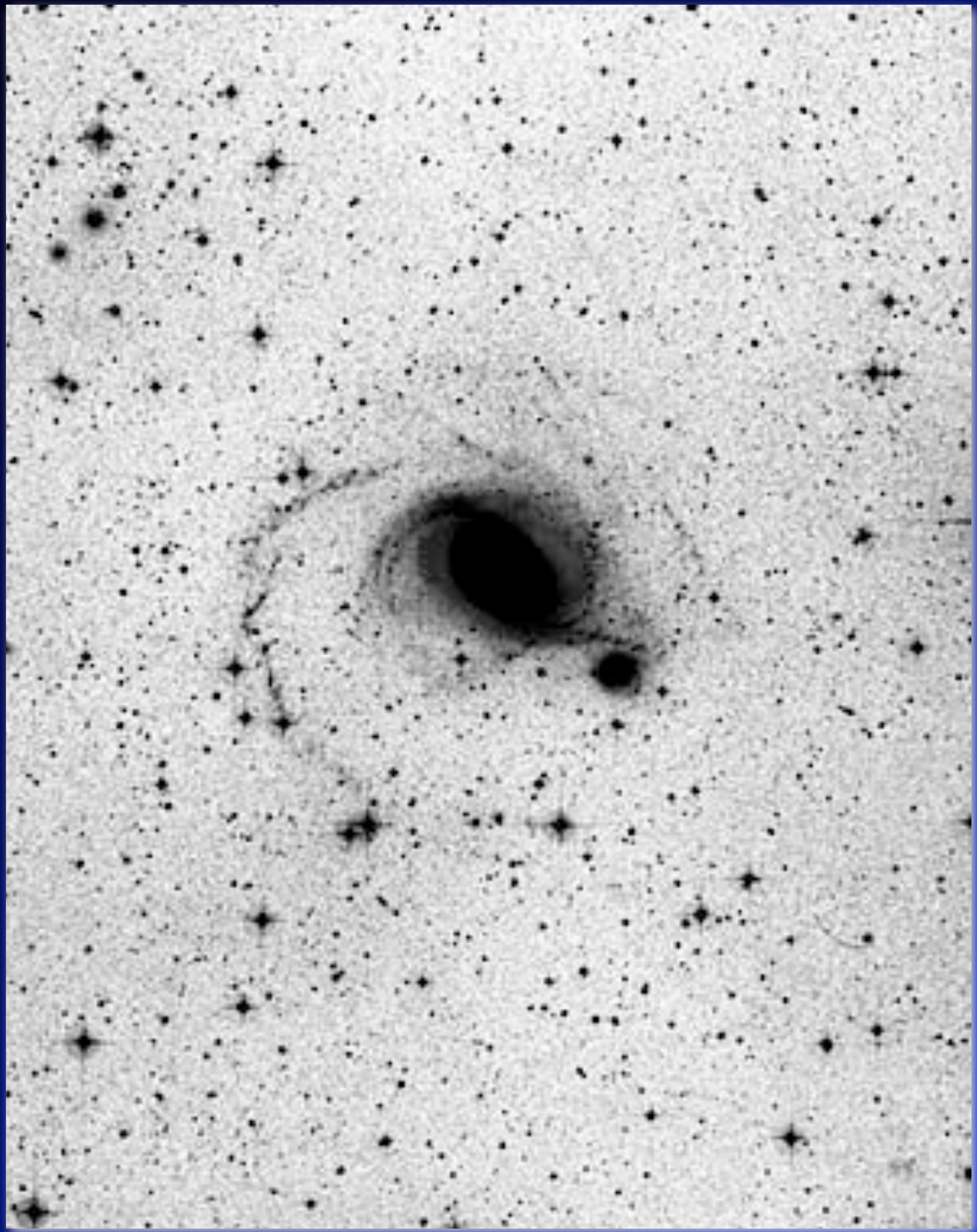

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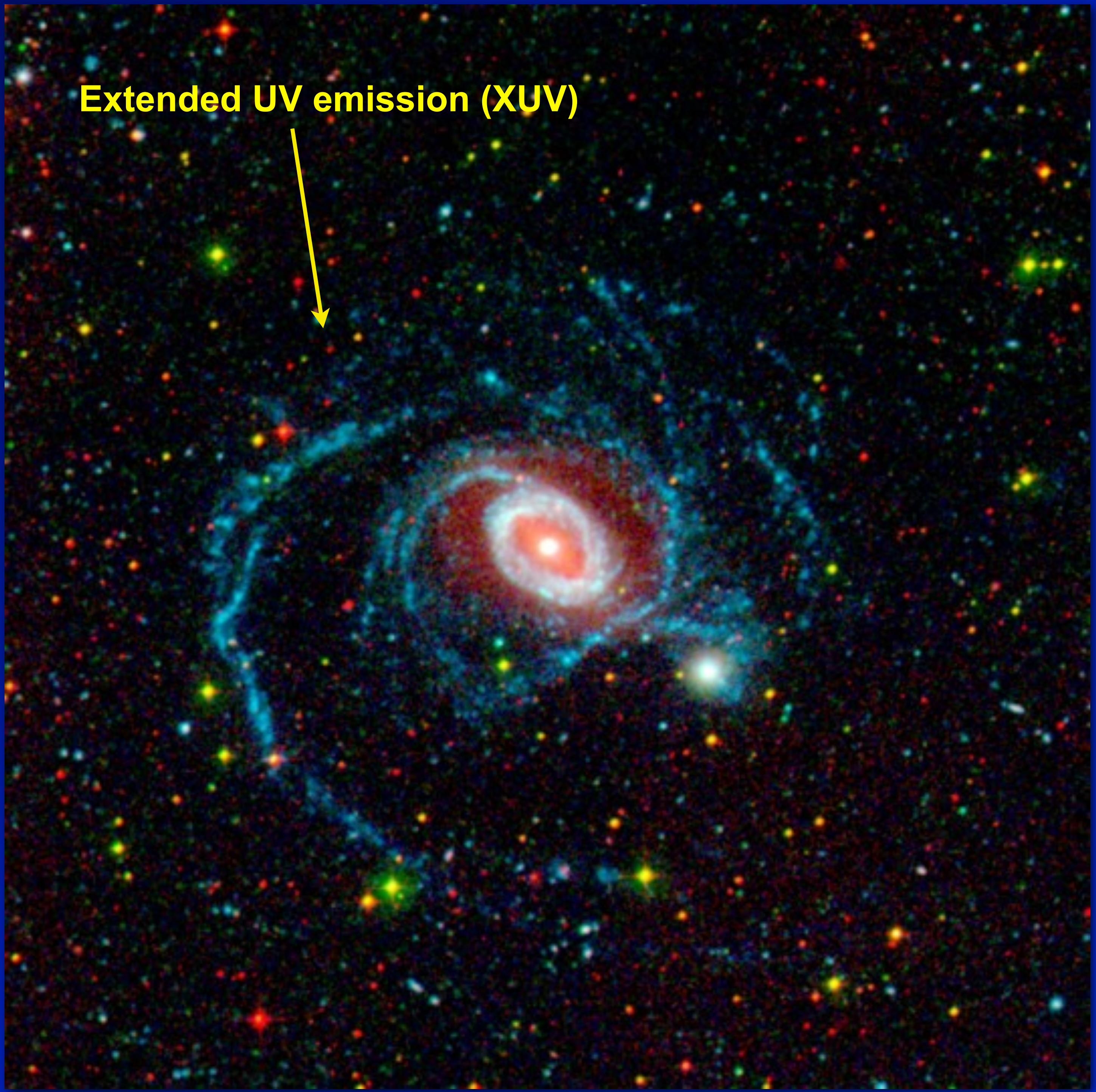


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# Observations of XUV using ATCA + AAT

- HI data from LVHIS, the *Local Volume HI Survey*, P.I. B.S. Koribalski,
  - Koribalski 2008, Koribalski et al. in prep.
  - Australia Telescope Compact Array
  - Deep H I line & 20 cm radio continuum observations for all nearby ($v_{LG}$< 550 km/s, D < 10 Mpc) gas-rich galaxies (HIPASS) with δ < -30º .
- http://www.atnf.csiro.au/research/LVHIS

- Optical data using the 2dF/AAOmega instrument at the 3.9m Anglo-Australian Telescope
  - Use NUV image to select UV-bright regions
  - AAOmega: blue (3700$\lambda$ - 5500$\lambda$) + red spectra (6200$\lambda$ - 7200$\lambda$) simultaneously
  - Main objective: chemical abundances and kinematics of ionized gas

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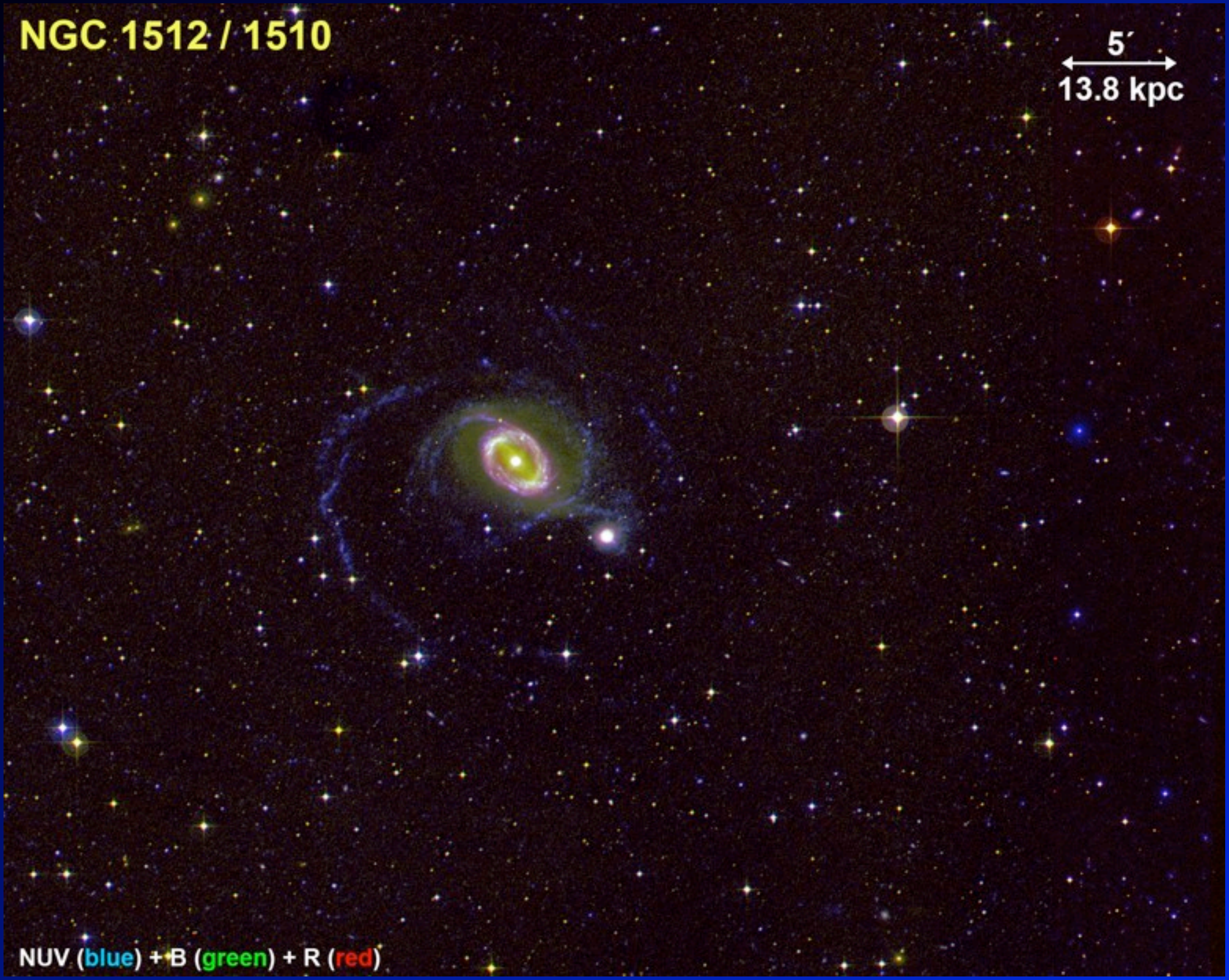
# The HI distribution in the galaxy pair NGC 1512 / 1510




Koribalski & López-Sánchez (2009, MNRAS)

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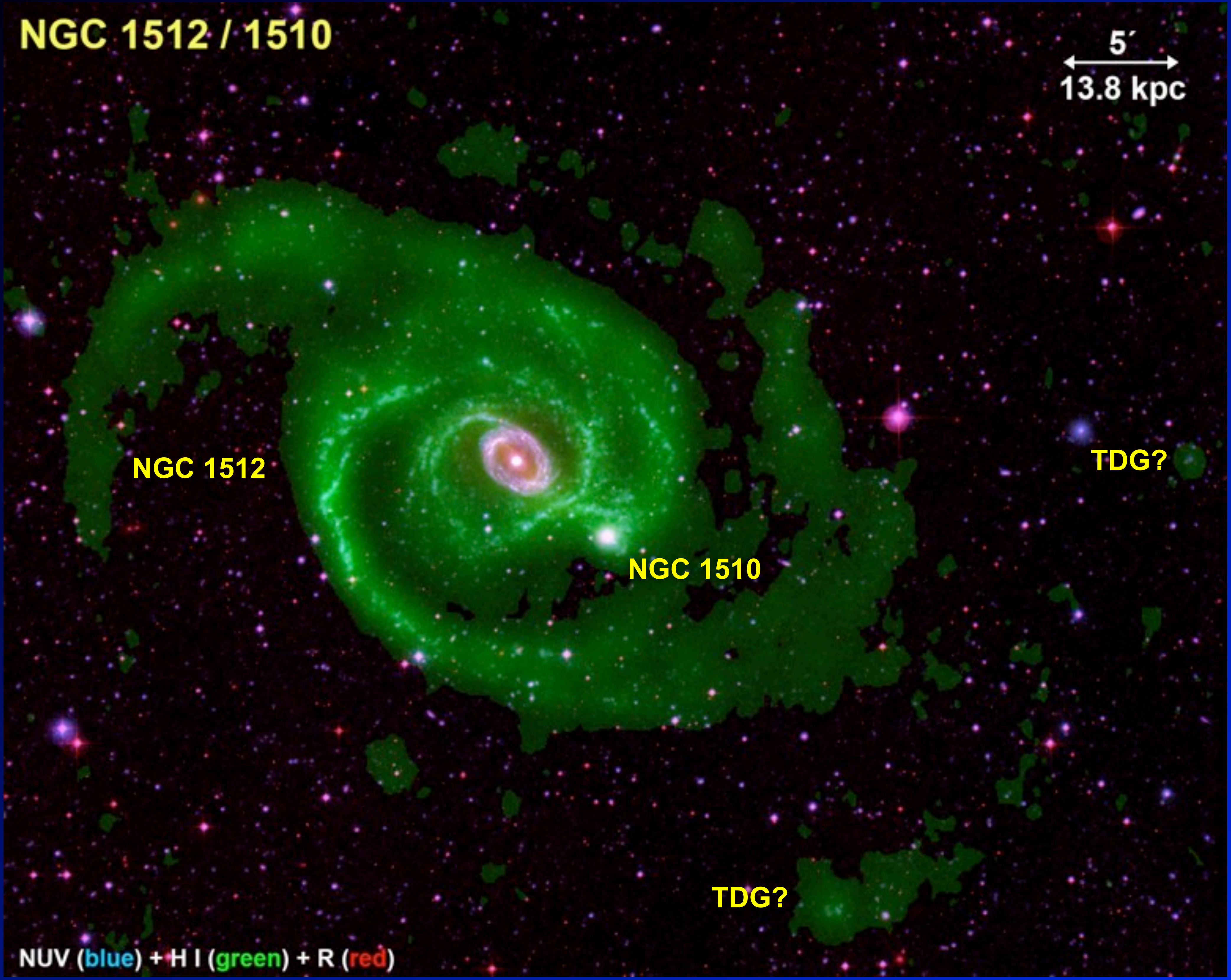
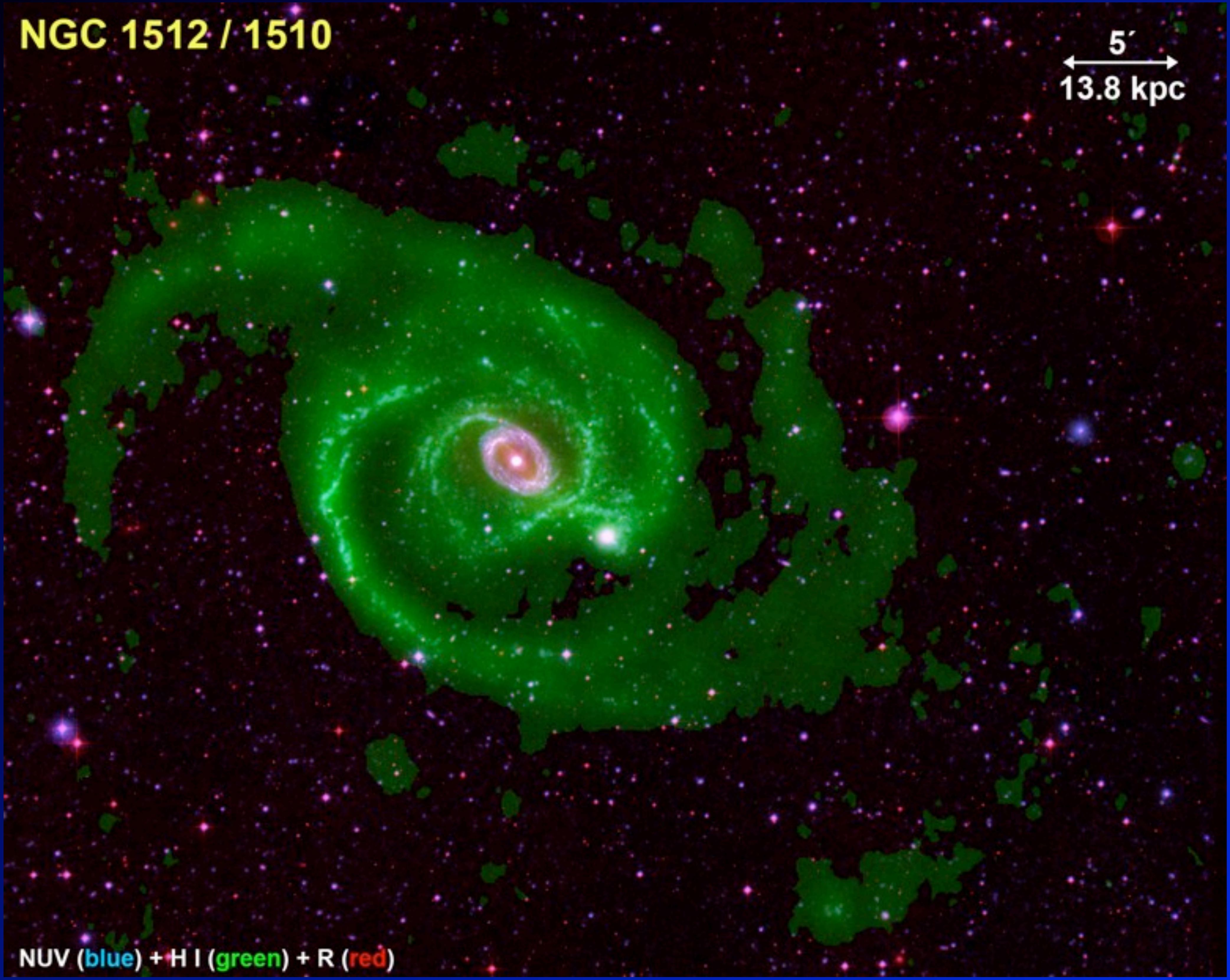



- ATCA observ. using 7 arrays
- Mosaic using 4 pointings
- Total int. time: 3.11 days
- Huge amount of neutral gas!
- Two extended spiral arms
- Two TDG candidates
- NGC 1512:
  - $M_{HI} = 5.7\times10^{9}\ M_\odot$
  - $M_{Dyn} \sim 4 \times 10^{11}\ M_\odot$
  - $M_{HI}/L_B = 1$
- NGC 1510:
  - $M_{HI} \sim 4\times10^{7}\ M_\odot$
  - $M_{HI}/L_B \sim 0.07$

Koribalski & López-Sánchez (2009, MNRAS)

# H I / UV comparison in NGC 1512/1510

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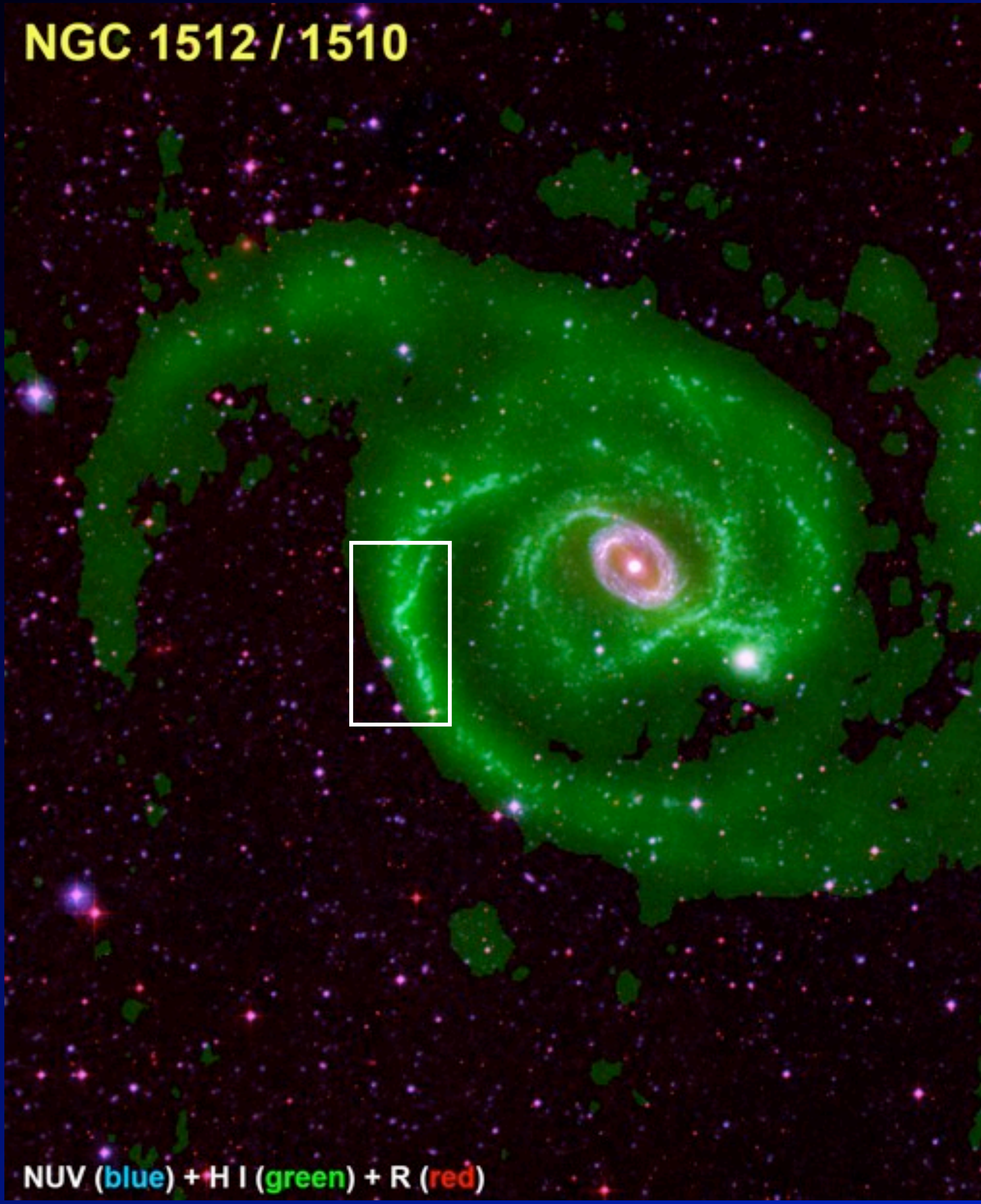


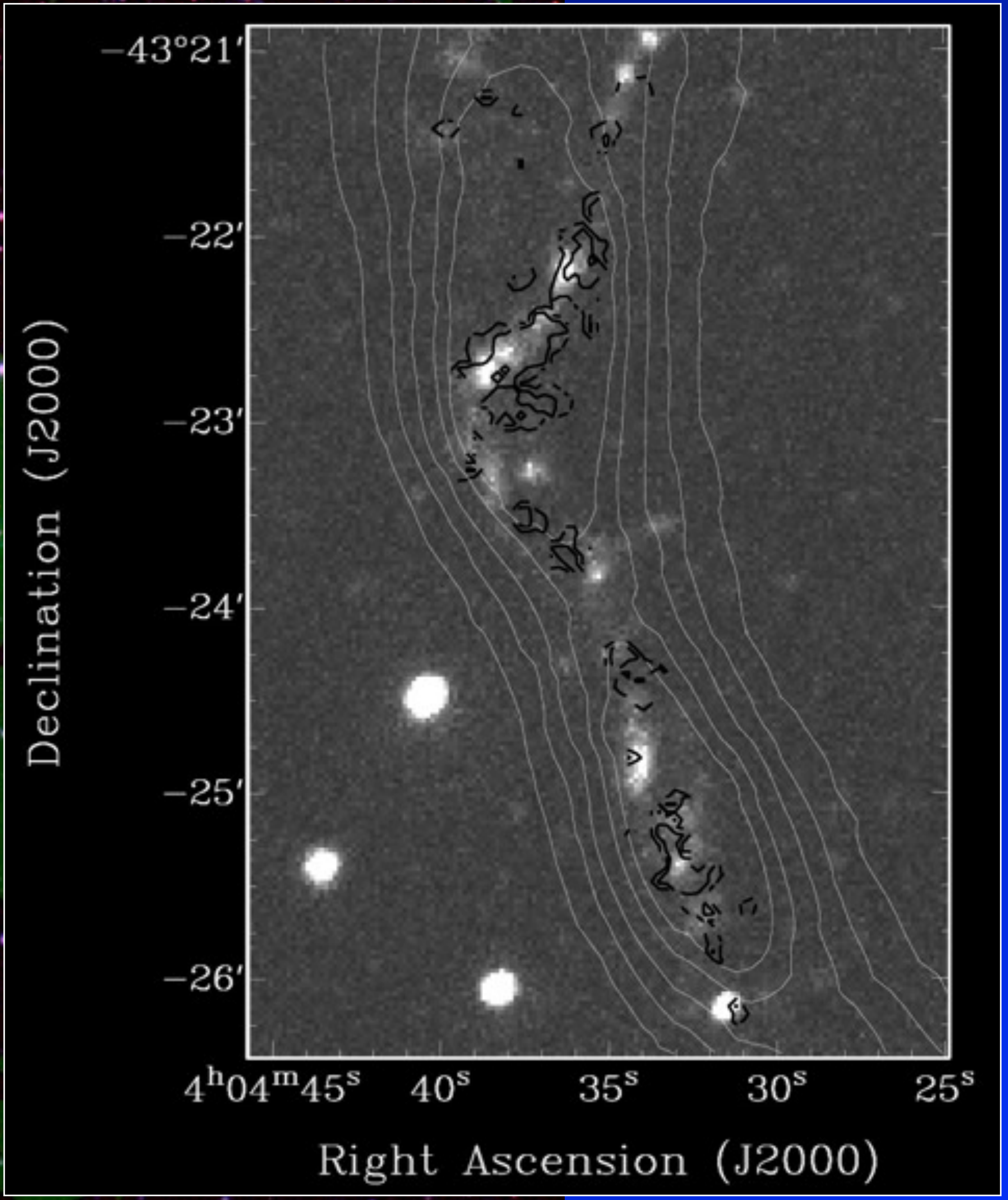


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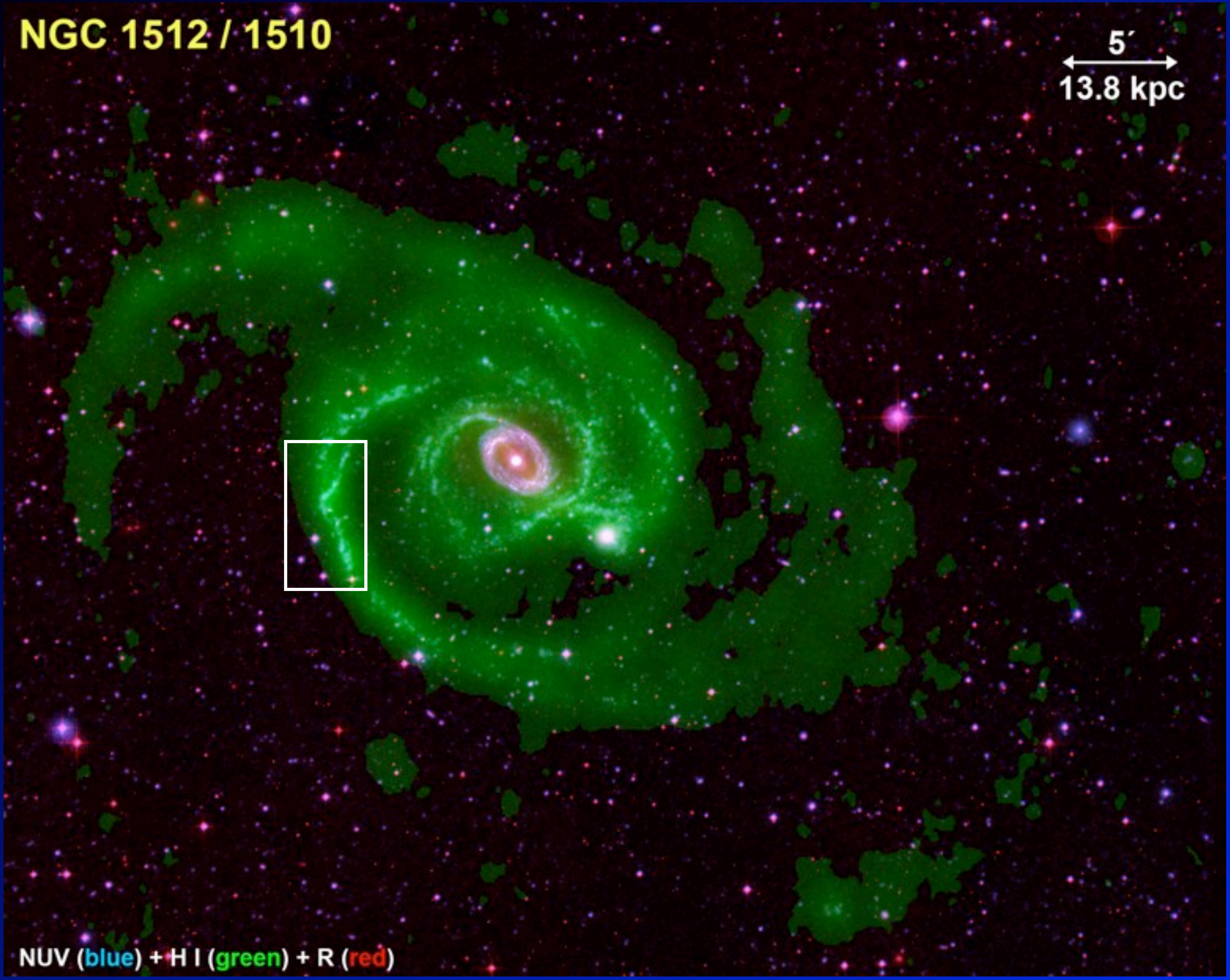


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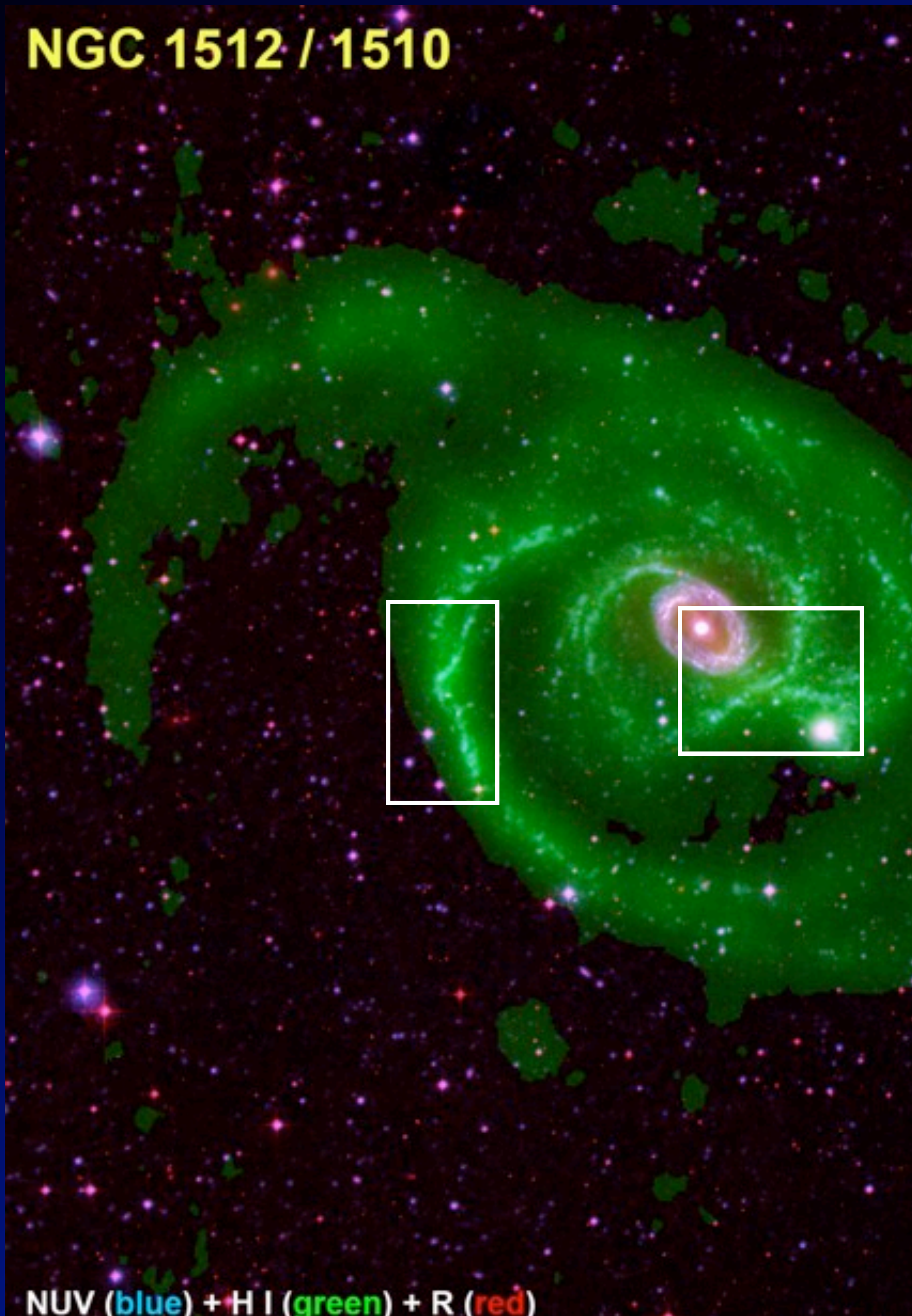
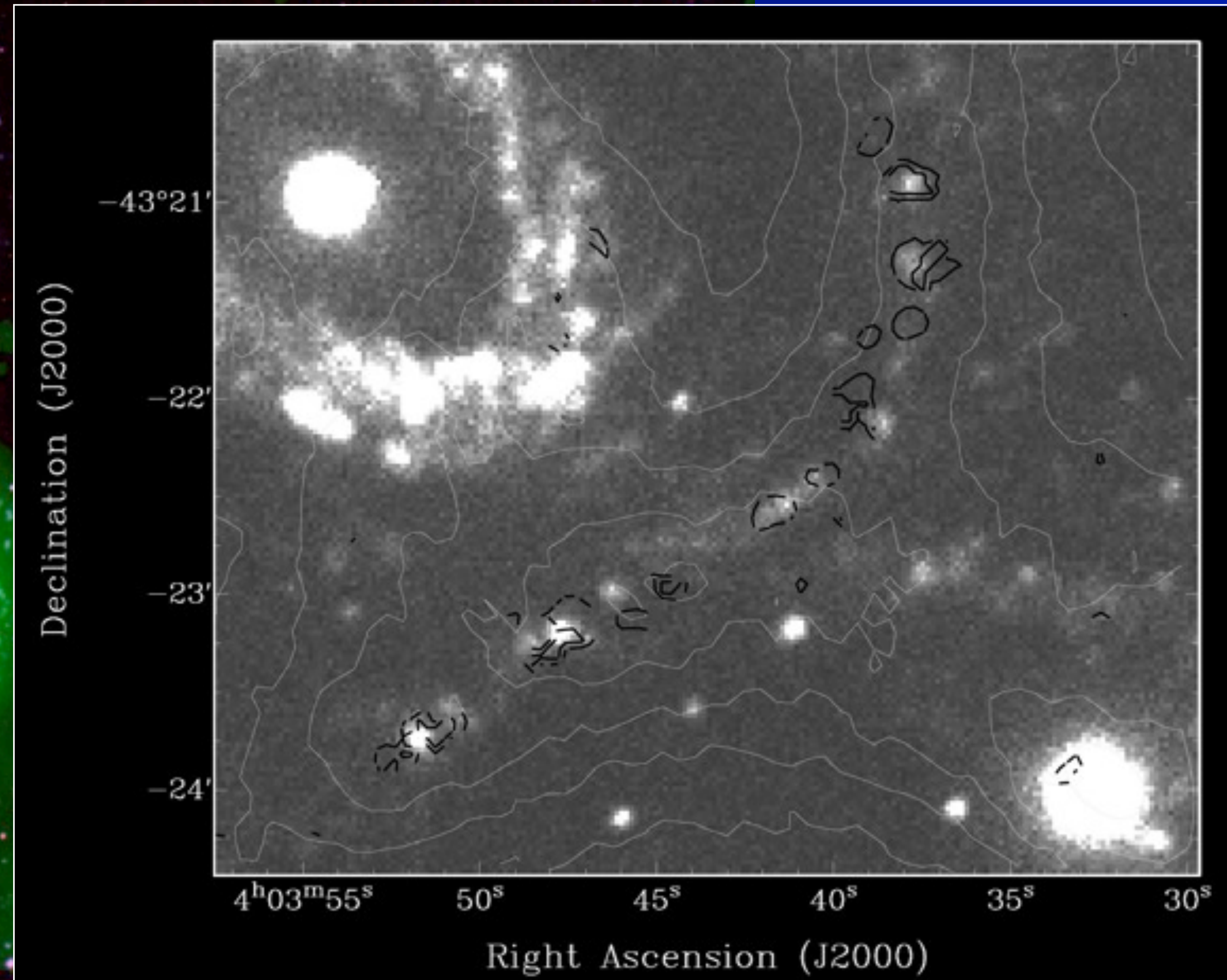
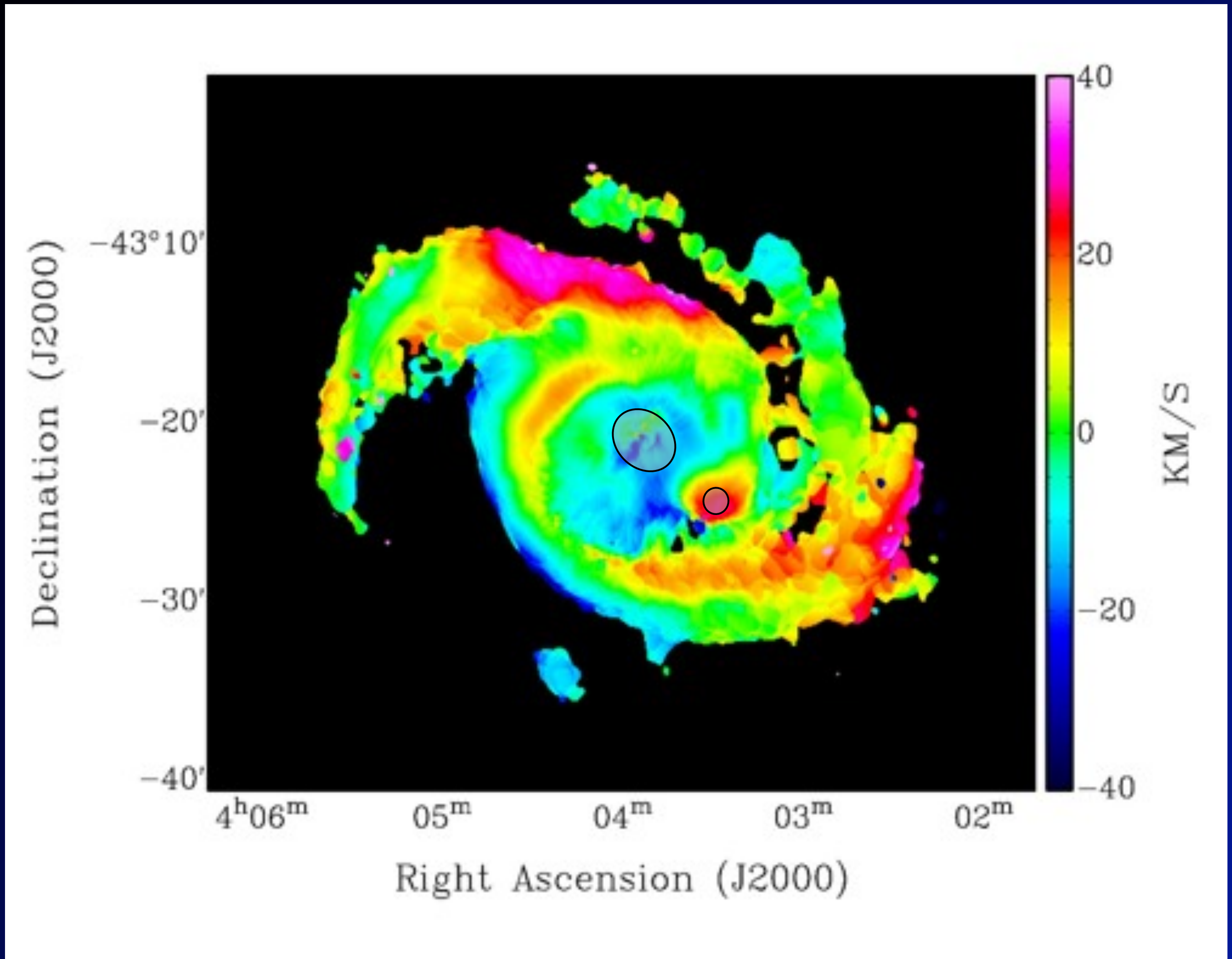


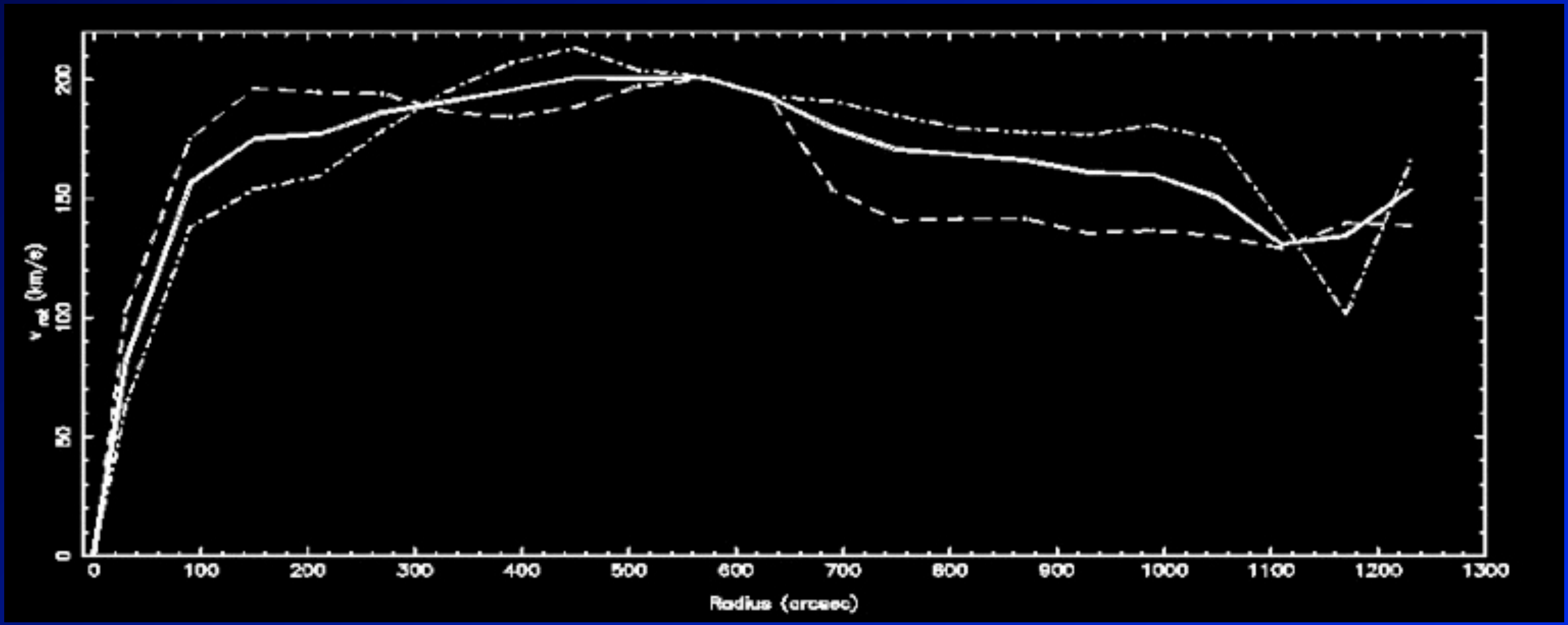

Using **GALEX images**, we derived **UV colors** and **SFRs** in individual UV-bright clusters.

Koribalski & López-Sánchez (2009, MNRAS)



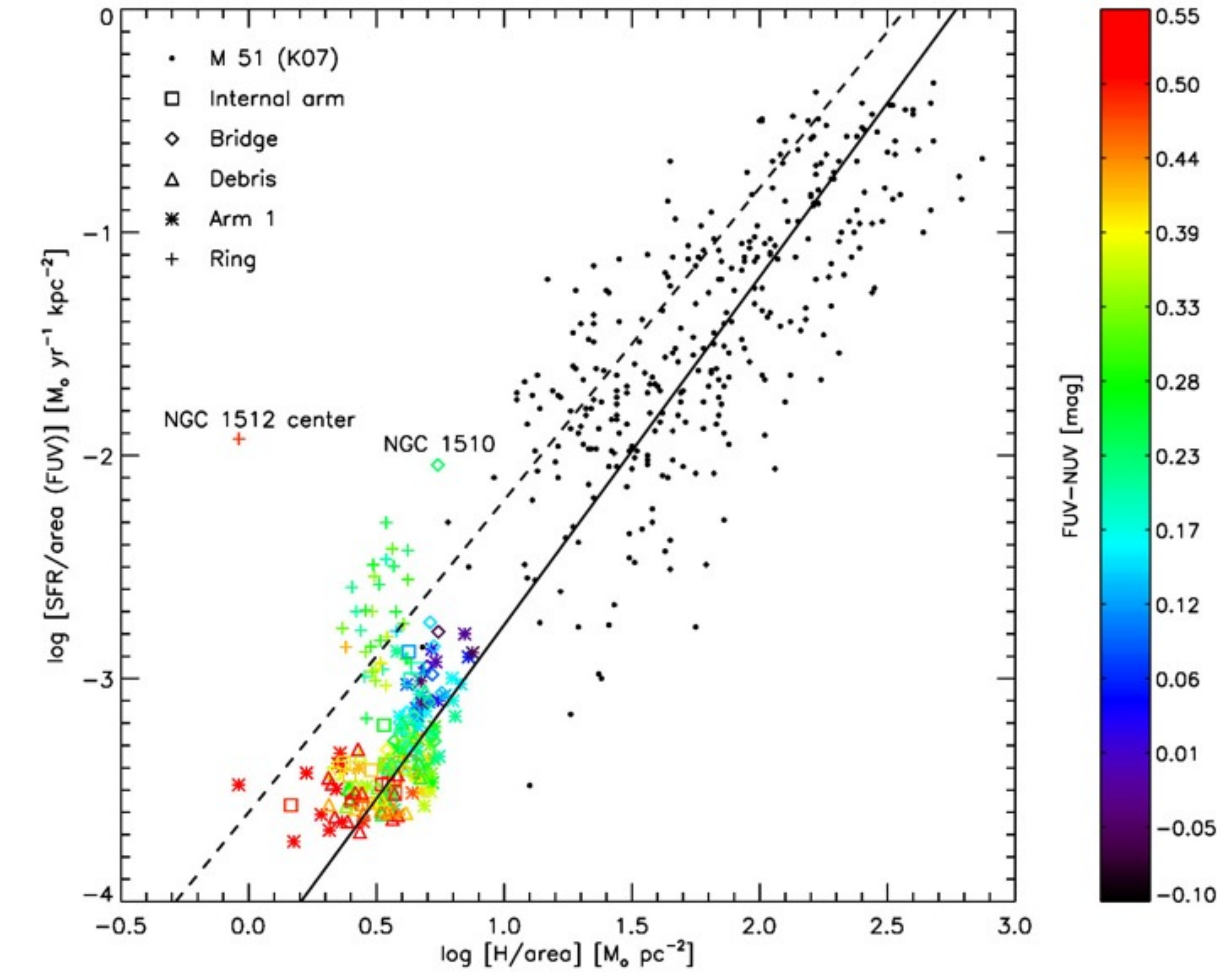

# NGC 1512 / 1510
# Rotation fit and residues

- The velocity field is mainly **rotation**,
- But we found some **discrepances** in the most **external regions** and in the position of **NGC 1510**.
- **Star formation activity** and the external **HI structures** seem to be consequence of the **interaction** that **NGC 1512** and **NGC 1510** are experiencing. **Minor merger ~ 400 Myr**




Koribalski & López-Sánchez 2009, MNRAS.

# Star-formation law in NGC 1512/1510




**Star-forming regions in NGC 1512/1510 follow the Schmidt-Kennicutt relation.**

***Comparison of star-forming regions within different areas with regions in M 51 (Kennicutt et al. 2007, continous line) and relation for dwarf and spiral star-forming galaxies (Kennicutt et al. 1998, dashed line).***

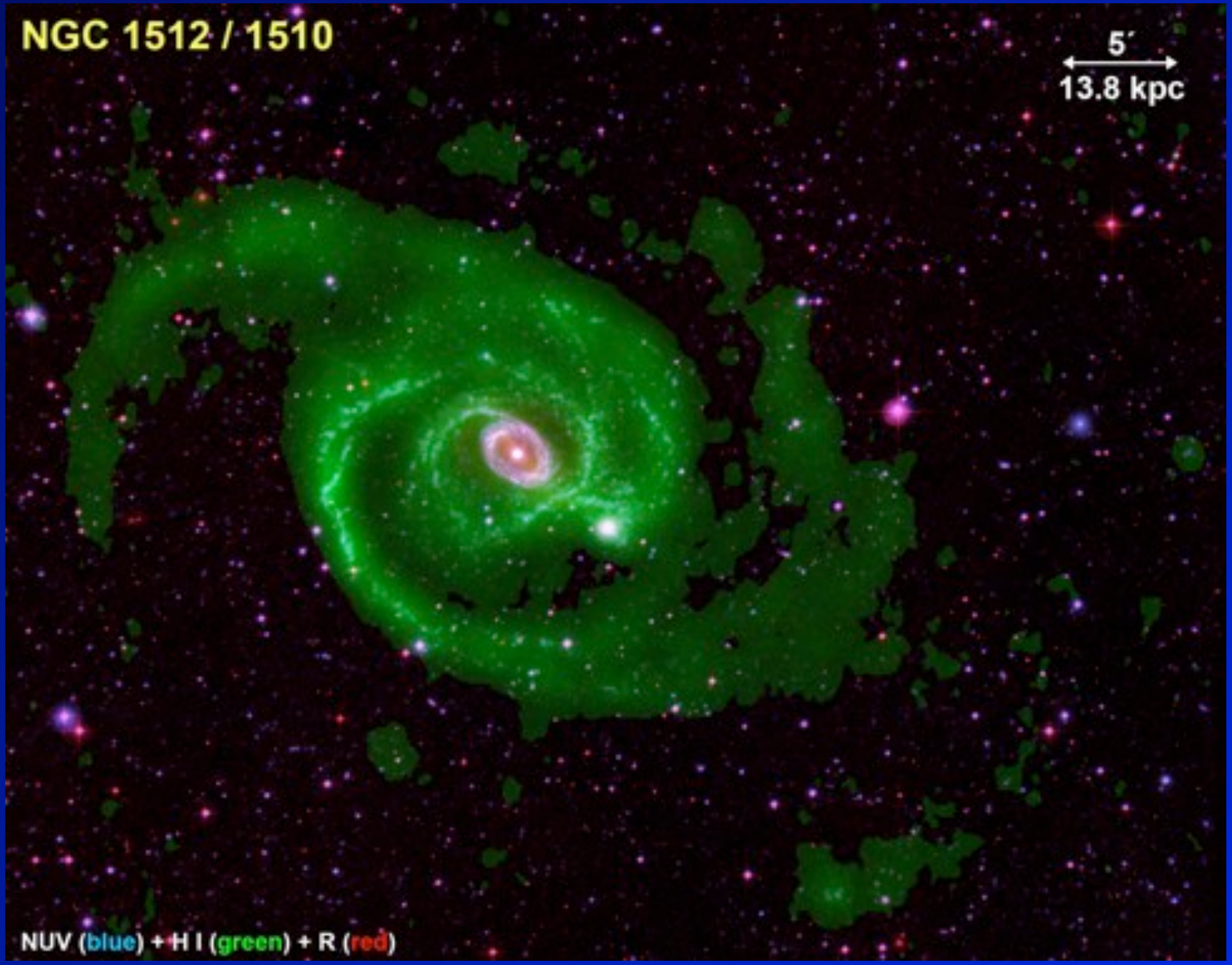
**Same results that Bigiel et al. (2008, 2010a,b) and models by Lagos et al (2013)**

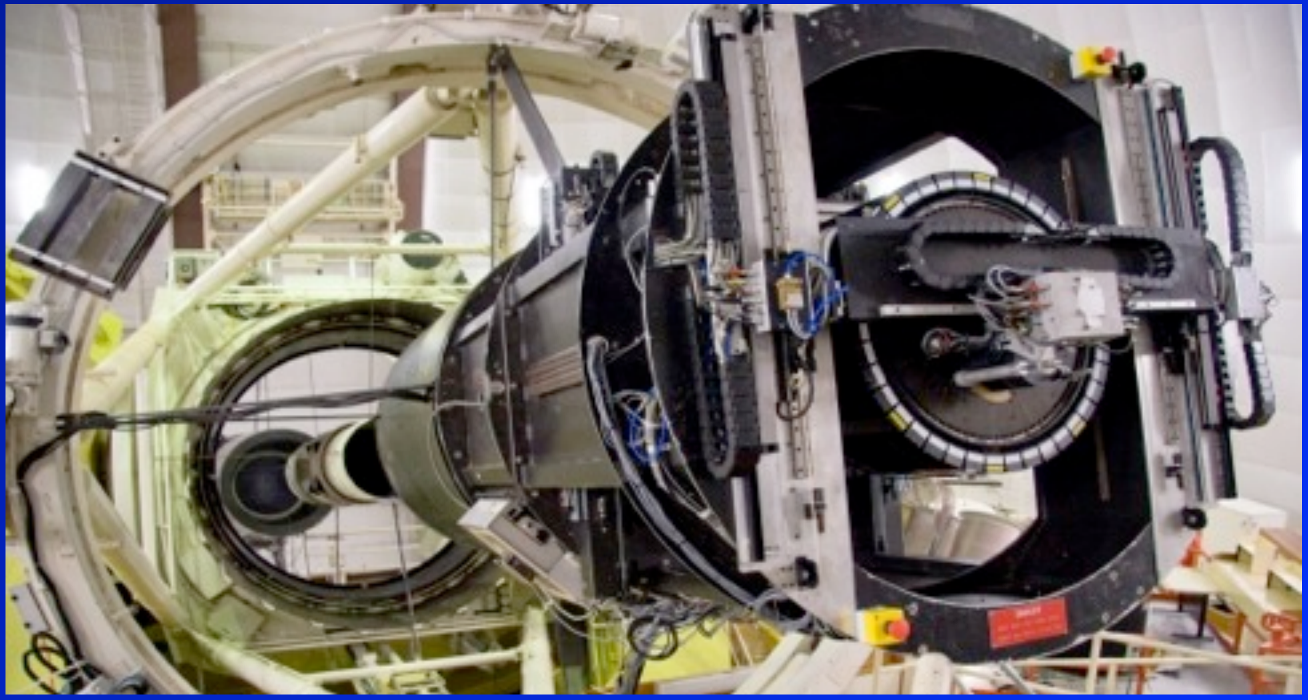
**But see Schrurba et al. (2011) and Charles Lada talk.**

**Koribalski & López-Sánchez (2009, MNRAS)**

# NGC 1512 / 1510 – 2dF/AAOmega @ AAT observations

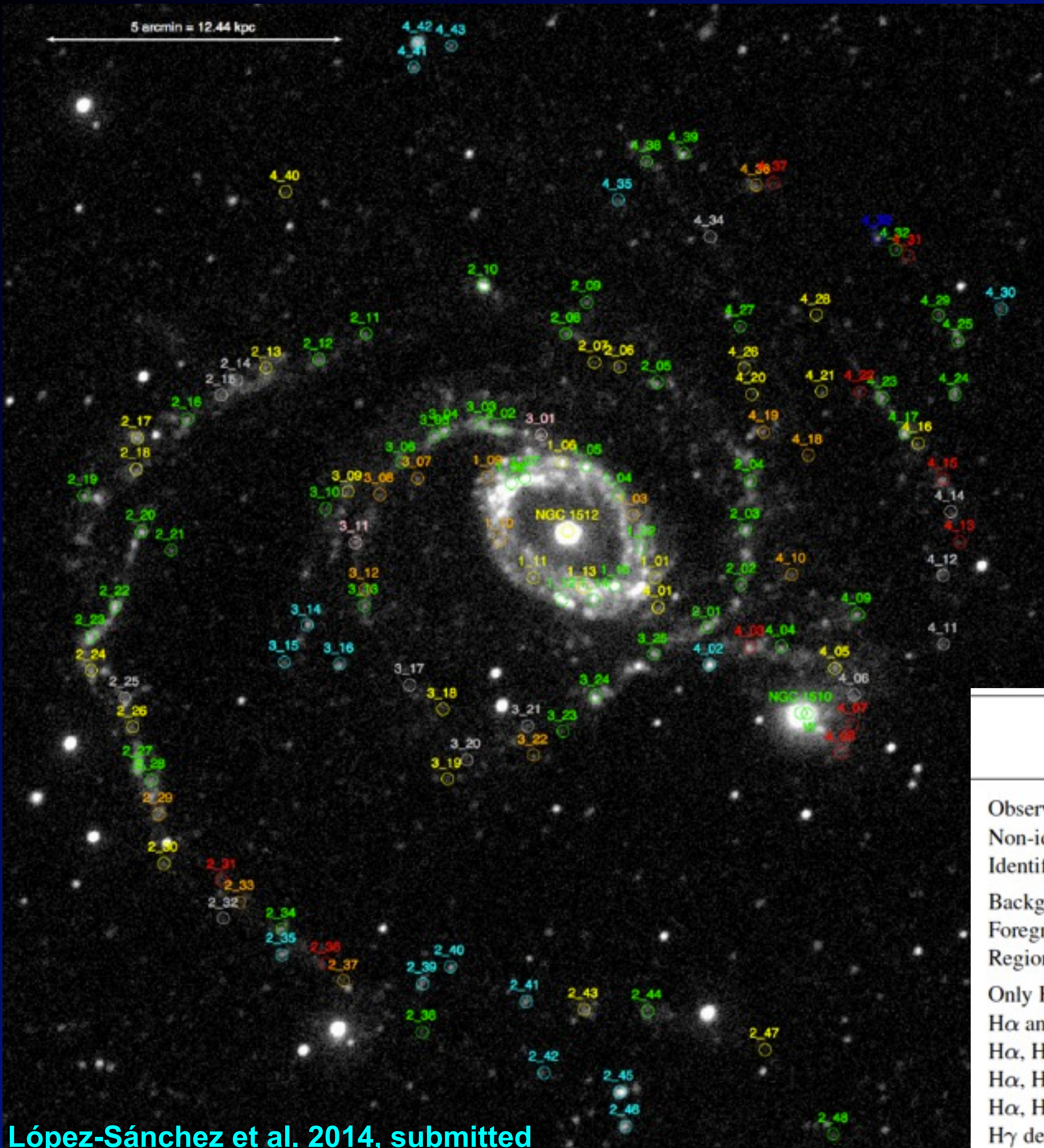
- 3.9m AAT observations using multi-fiber spectrograph 2dF/AAOmega
  - Carried out on 2 - 4 Dec 2008
- Used NUV image to select regions
- 2 plates configurations,
  - 166 UV-bright regions observed
  - 32 regions observed in BOTH plates
- Flux-calibrated spectra
- Science:
  - Hα emission
    - SFR
    - Hα kinematics
  - [N II] / Hα vs. [OIII] / Hβ ratios
    - Excitation mechanism
  - Hα / Hβ and Hγ / Hβ ratios
    - Extinction and Wabs
  - [N II] / Hα, [O III] / Hβ, [O II] / Hβ ratios
    - Chemical abundances of the regions
    - When other lines detected, analyze in detail physical properties and chemical composition of ionized gas
- See Bresolin et al. 2012
- López-Sánchez, Westmeier, Esteban & Koribalski, 2014, submitted!



# Ionized gas in the XUV disc of NGC 1512

- **10%** of the identified targets are **background galaxies**
- **88%** of the UV-bright regions observed in NGC 1512 / NGC 1510 **have ionized gas**!
- Almost **half** of those regions show **Hα, Hβ, [O II], [O III] and [N II] emission.**
- **[O III] λ4363** detected in 4 regions (2 are in NGC 1510)




López-Sánchez et al. 2014, submitted

| | Fibre number | % Total | % Class | Color in Fig. 1 |
|---|---|---|---|---|
| Observed | 164 | 100.0 | ... | ... |
| Non-identified | 11 | 6.7 | ... | red |
| Identified | 153 | 93.3 | ... | ... |
| Background galaxies | 17 | 10.4 | 11.1 | cyan |
| Foreground stars | 1 | 0.6 | 0.7 | blue |
| Regions in NGC 1512/1510 | 135 | 82.3 | 88.2 | ... |
| Only Hα detected | 15 | 9.1 | 11.1 | grey |
| Hα and [N II] | 30 | 18.3 | 22.2 | yellow |
| Hα, Hβ, and [N II] | 6 | 3.7 | 4.5 | pink |
| Hα, Hβ, [N II], and [O III] | 20 | 12.2 | 18.8 | orange |
| Hα, Hβ, [N II], [O III], and [O II] | 64 | 39.0 | 47.4 | green |
| Hγ detected | 51 | 31.1 | 37.8 | ... |

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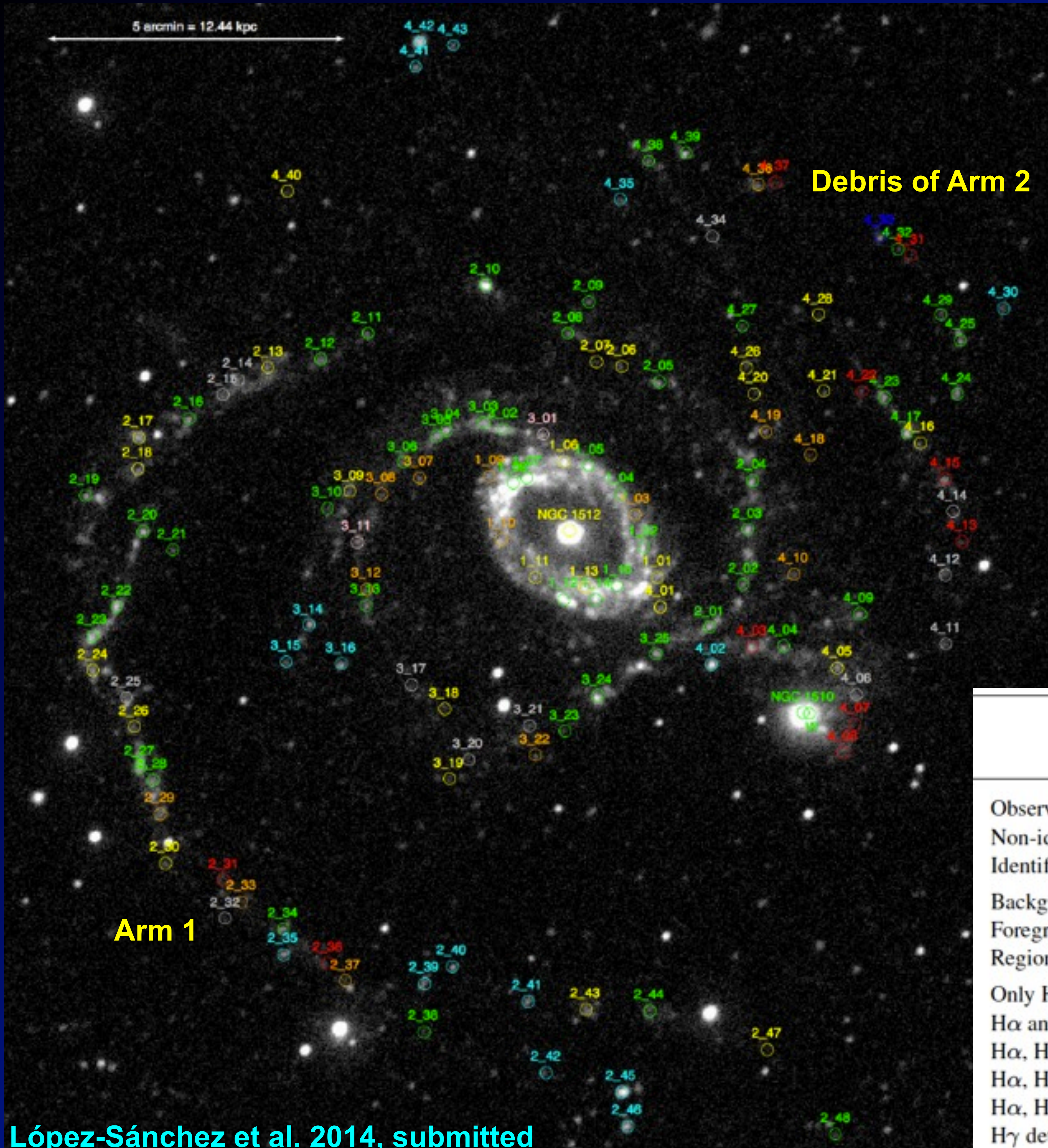


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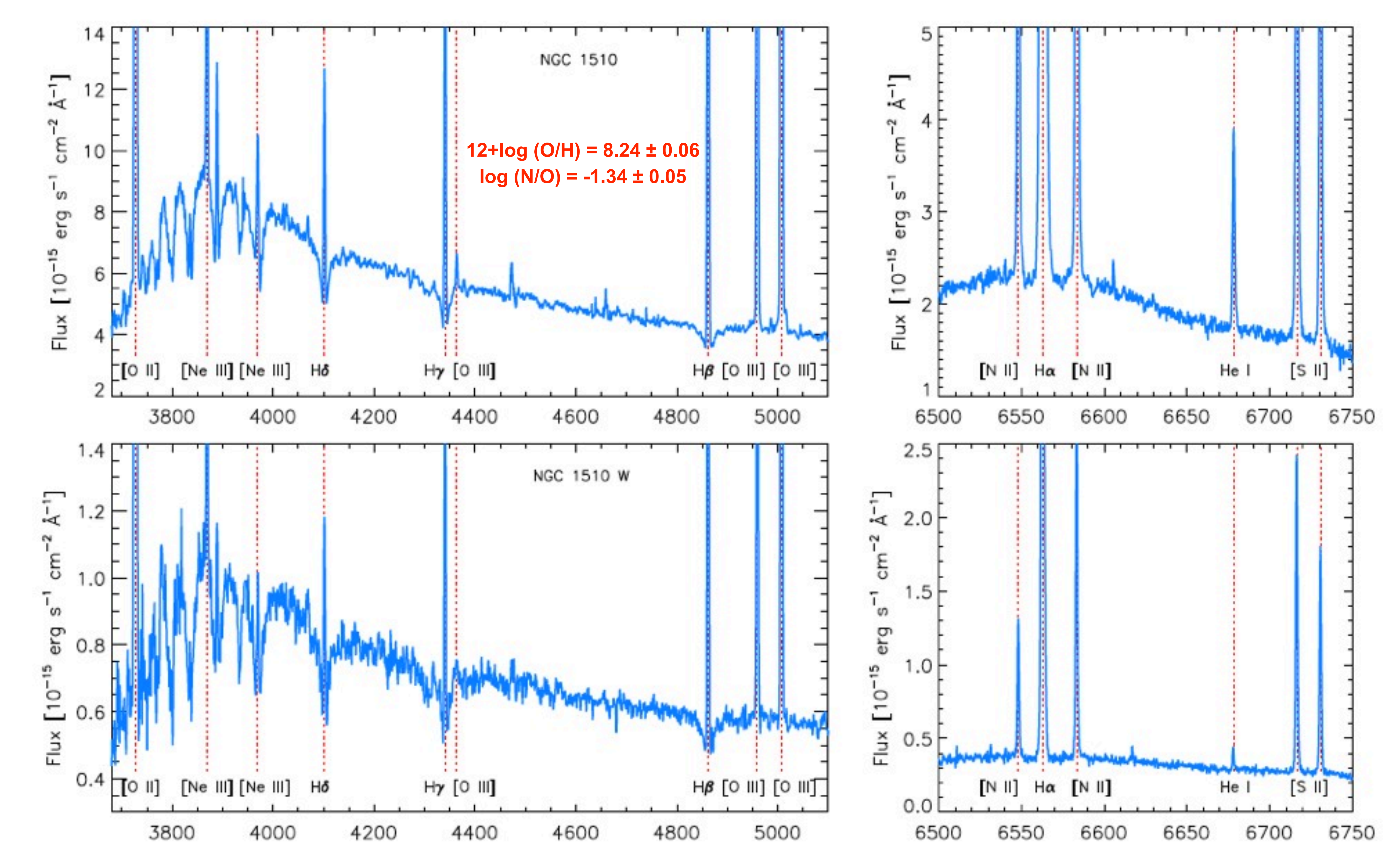
# Examples of the optical spectra of UV-bright regions in NGC 1512

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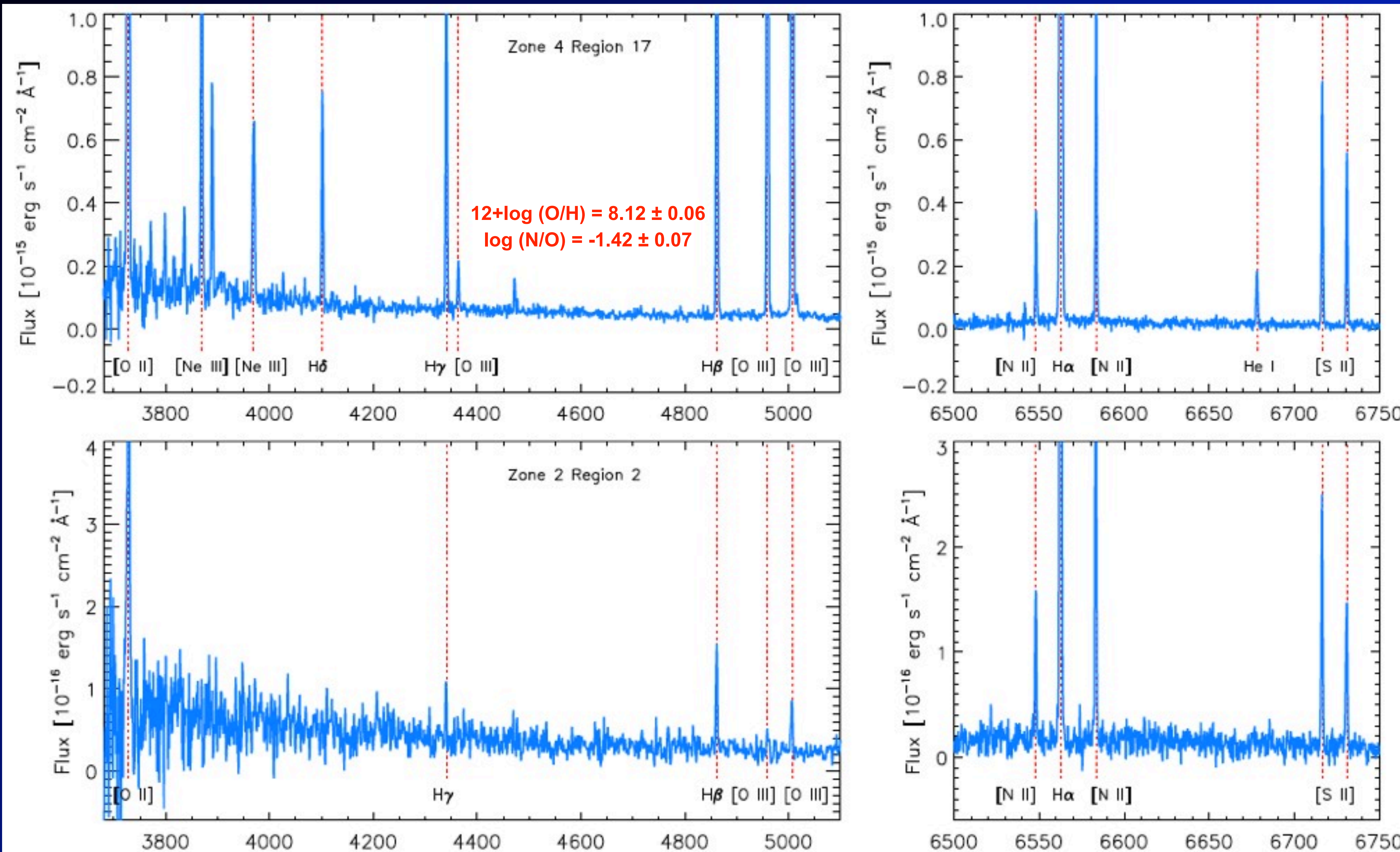
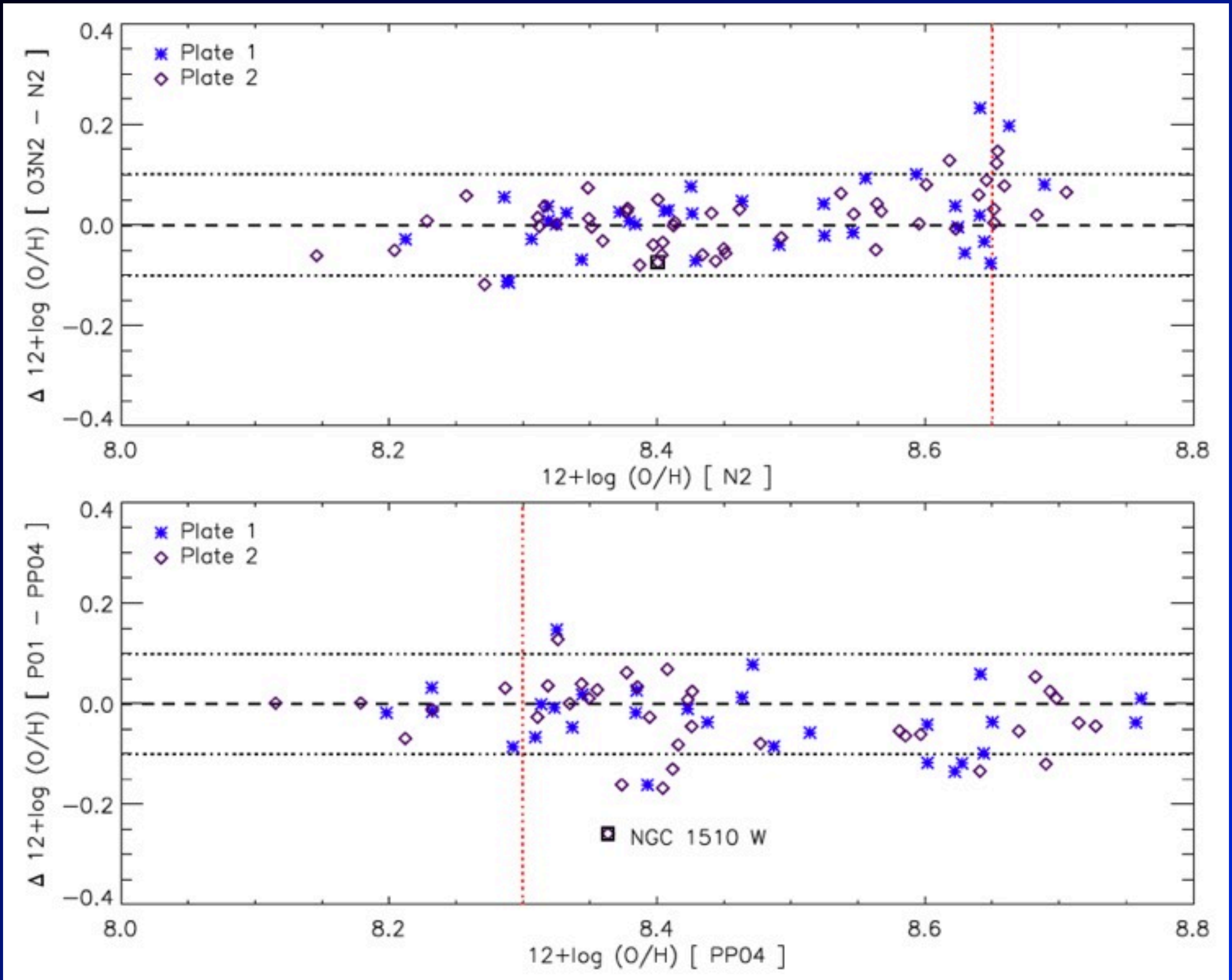



López-Sánchez et al. 2014, submitted

Ángel R. López-Sánchez

# Oxygen abundances in the UV-bright regions of NGC 1512




López-Sánchez et al. 2014, submitted

- **Pagel & Pettini (2004)**

$$N_2 \equiv \log \frac{I([\mathrm{N\,II}])\lambda 6583}{\mathrm{H}\alpha},$$

$$\mathrm{O_3N_2} \equiv \log \frac{[\mathrm{O\,III}]\ \lambda 5007/\mathrm{H}\beta}{[\mathrm{N\,II}]\ \lambda 6583/\mathrm{H}\alpha}.$$

- **Pilyugin (2001)**

$$R_3 = \frac{I([\mathrm{O\,III}])\lambda 4959 + I([\mathrm{O\,III}])\lambda 5007}{\mathrm{H}\beta},$$

$$R_2 = \frac{I([\mathrm{O\,II}])\lambda\lambda 3726, 3729}{\mathrm{H}\beta},$$

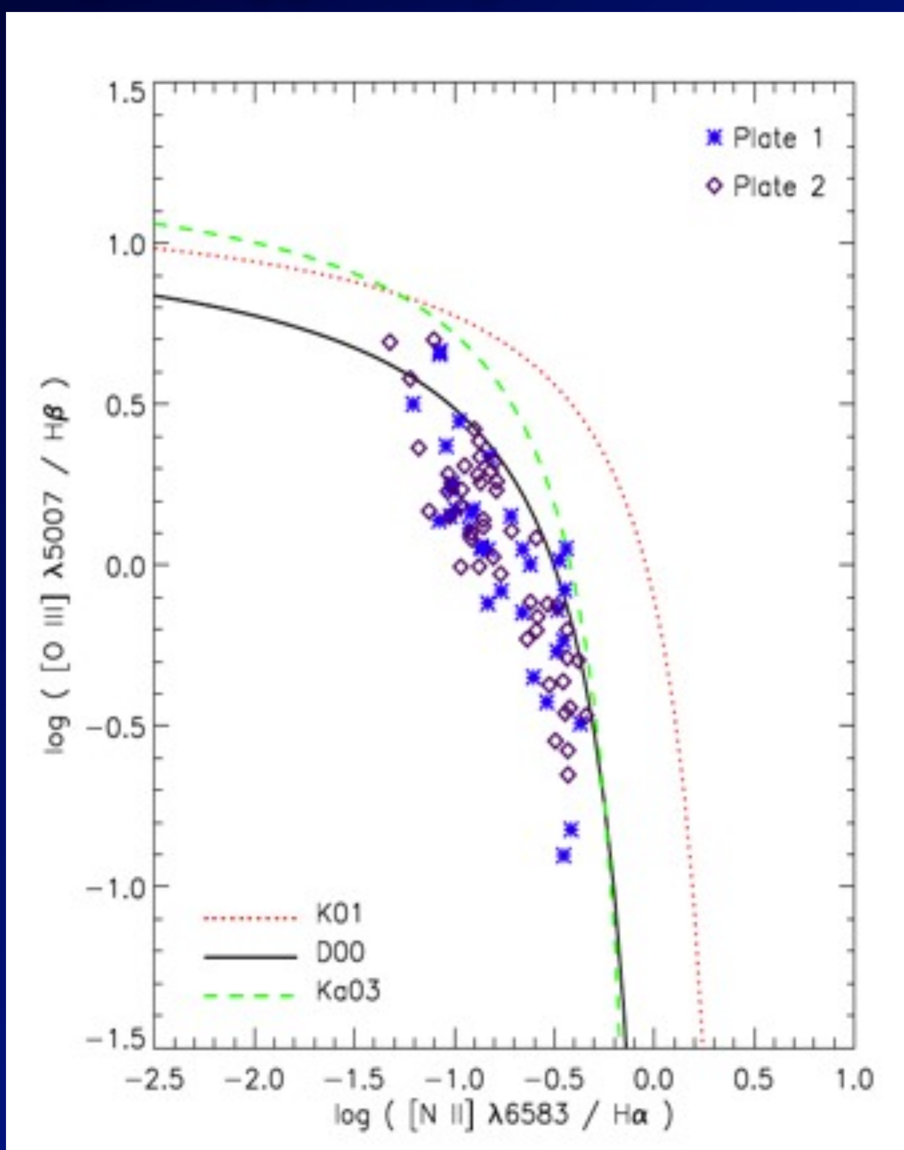
$$R_{23} = R_3 + R_2,$$

$$P = \frac{R_3}{R_{23}},$$

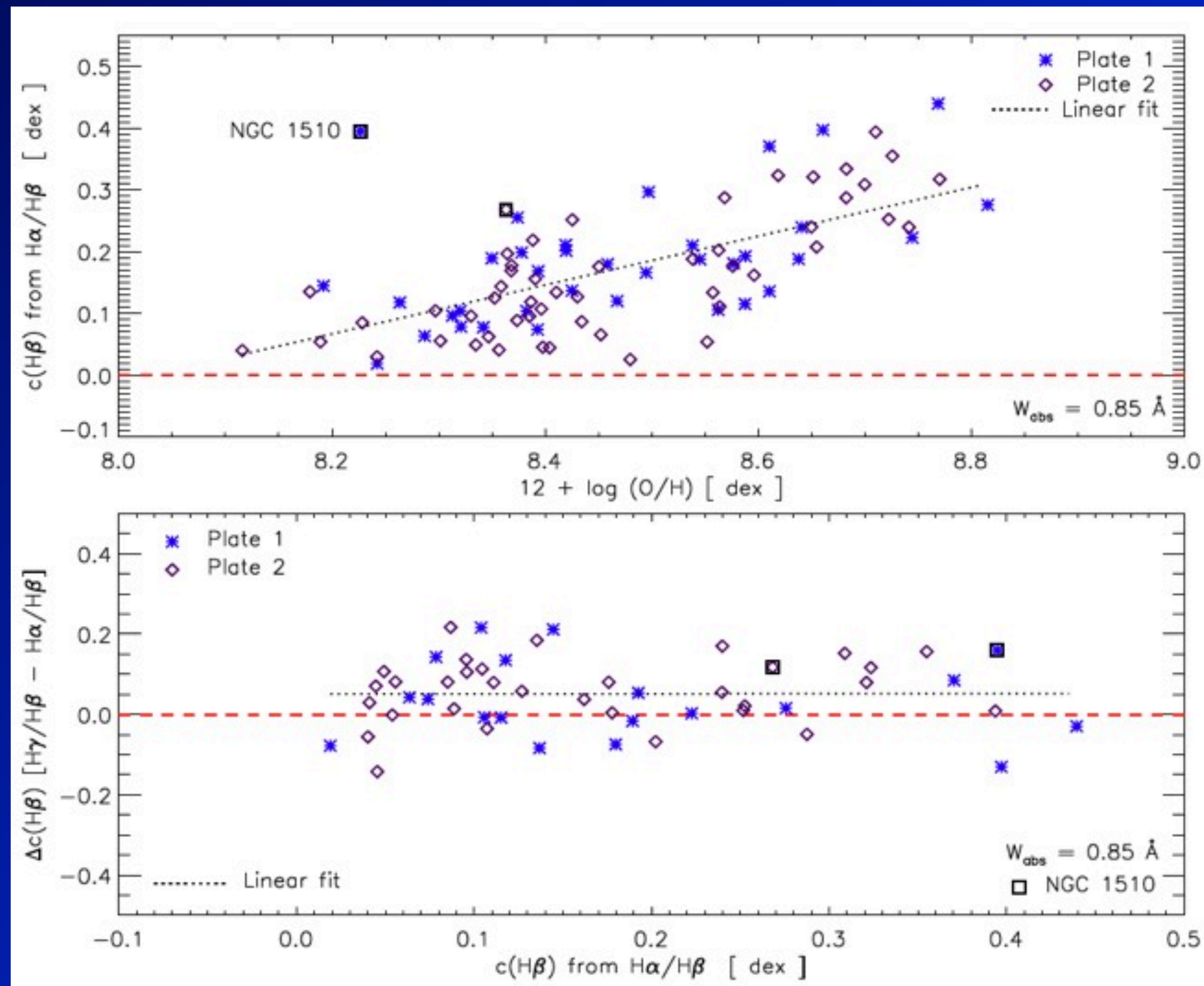
- **See López-Sánchez 2010 and López-Sanchez et al. 2012 for extended discussion about the choice of these calibrators.**
- **Results similar to those found by Bresolin et al. 2012**

# Physical conditions of the ionized gas within the UV-bright regions of NGC 1512

- Diagnostic diagram: **they are HII regions!**
- Reddening: carefully obtained using Hα/Hβ and Hγ/Hβ ratios plus theoretical values for oxygen abundances (see Appendix).

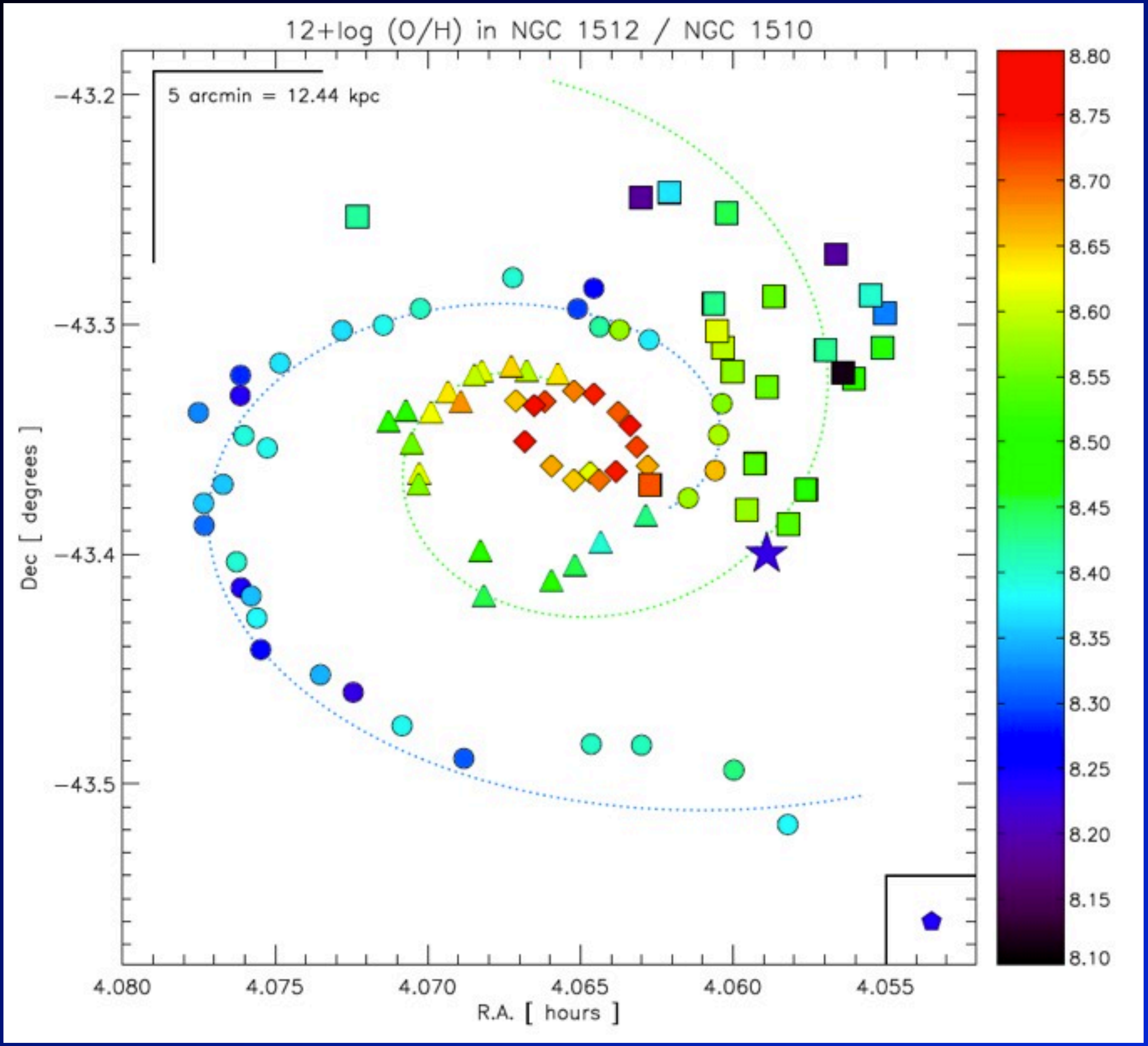



- Just few (1 - 5) massive stars (O7V) can explain the ionization of the gas !
  - In agreement with Gil de Paz et al. 2007.




López-Sánchez et al. 2014, submitted

# NGC 1512 / 1510 oxygen abundance map




12+log (O/H) map in NGC 1512 / 1510 (López-Sánchez et al. 2014, subm.)

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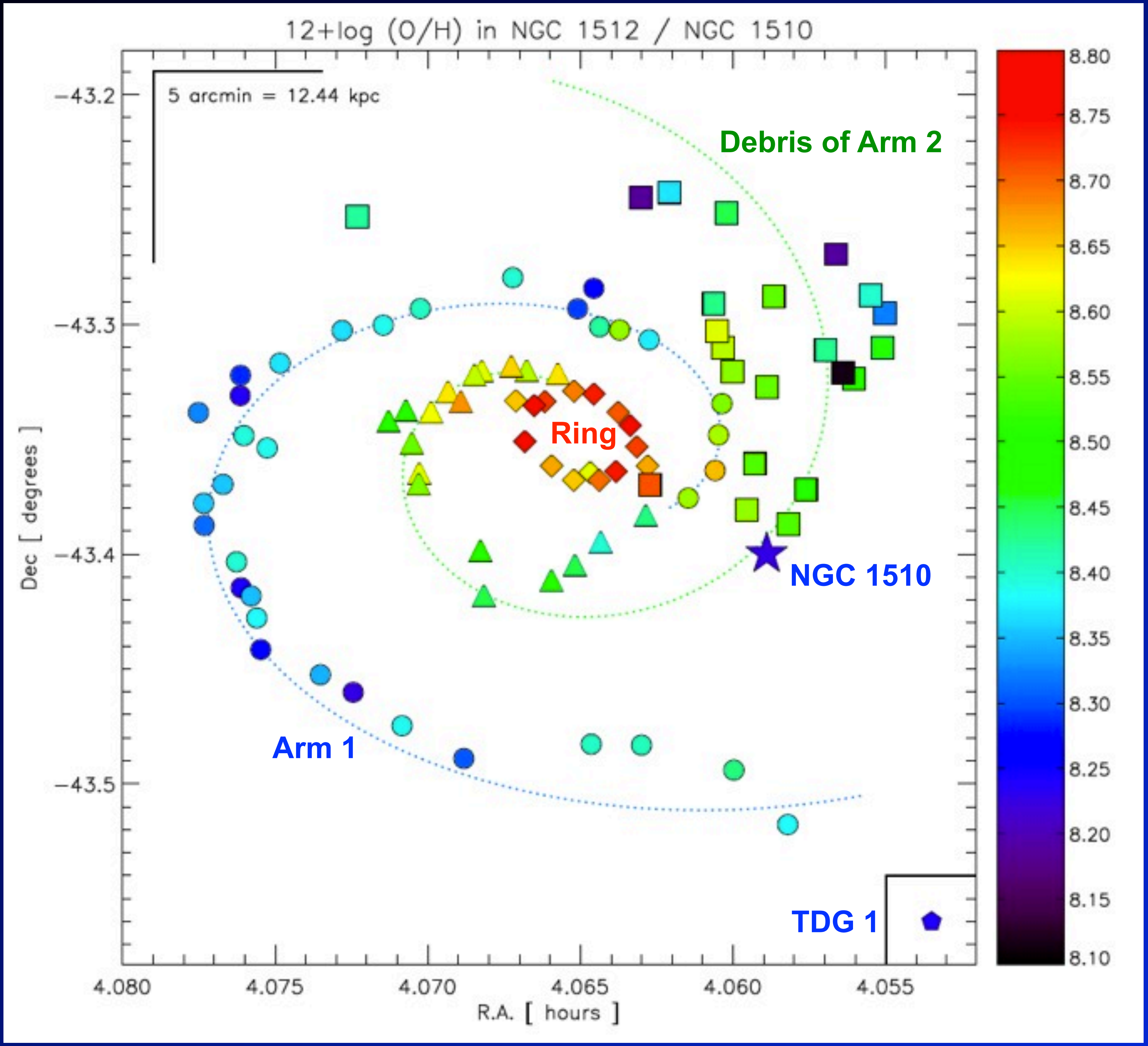


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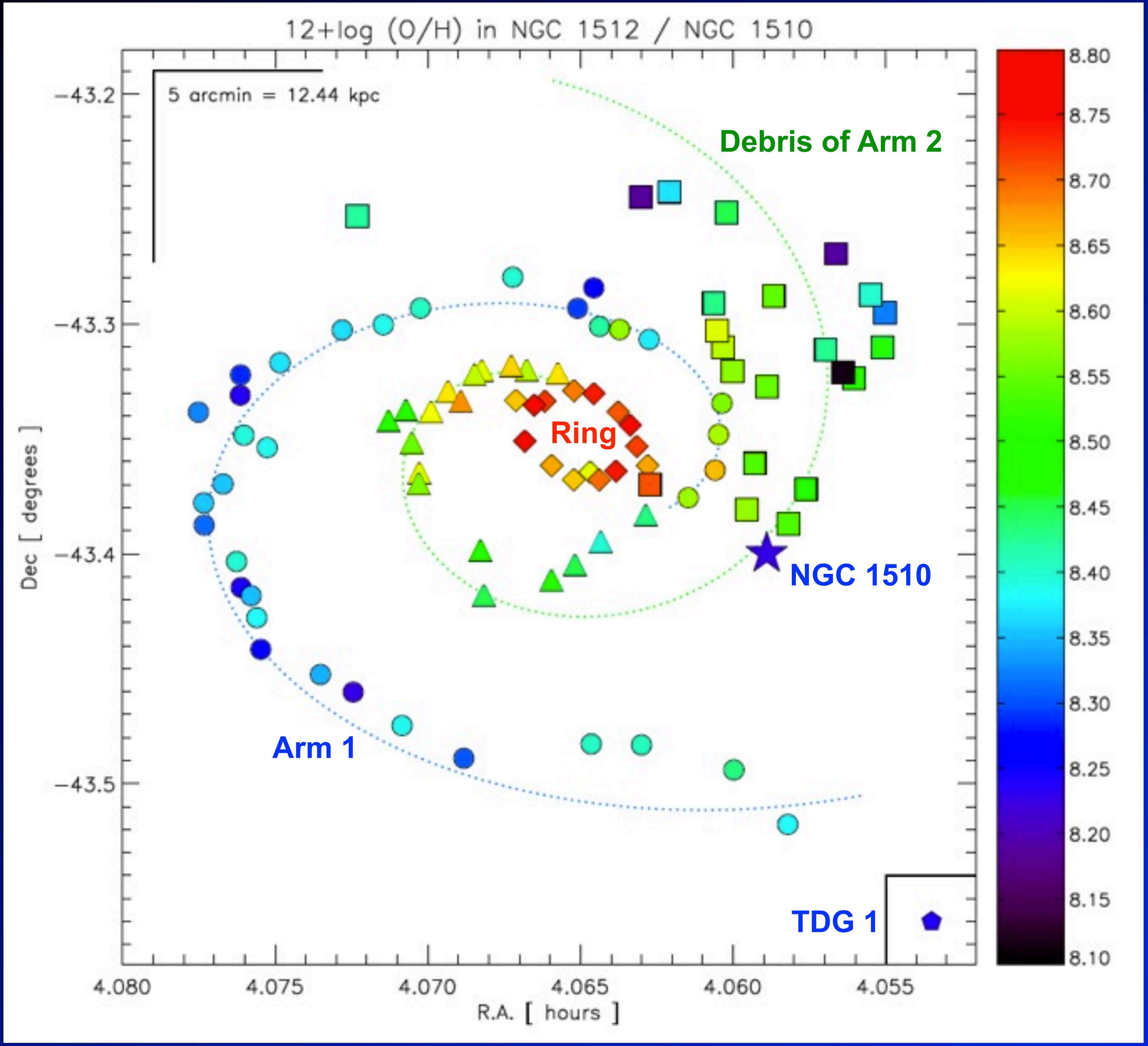


- Ring: 12+log(O/H) ~ 8.71

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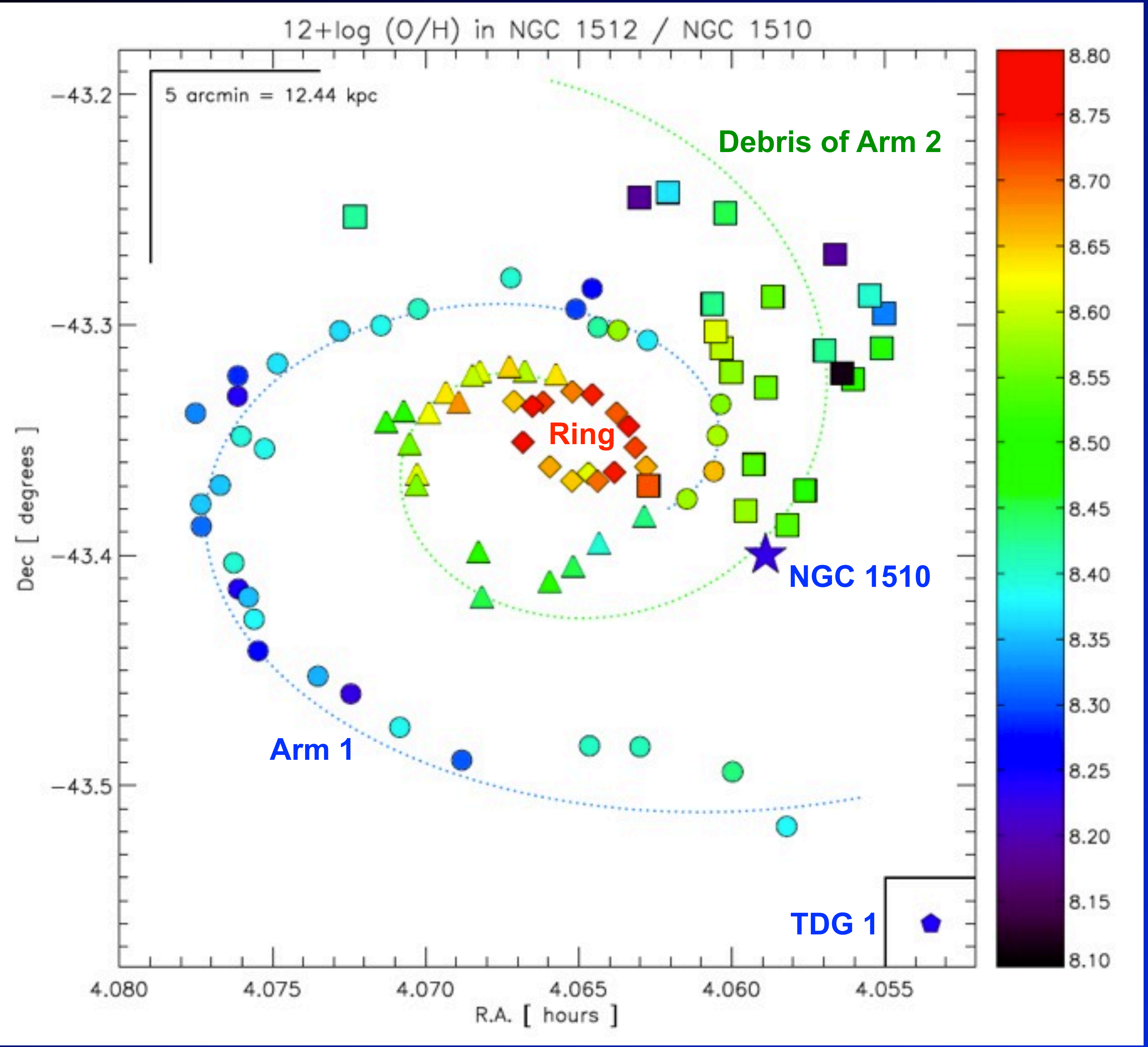


- Ring: 12+log(O/H) ~ 8.71
- Long almost flat abundance gradient through Arm 1, average value ~ 8.35.
  - *Star-formation activity seems to be not important in their recent past.*

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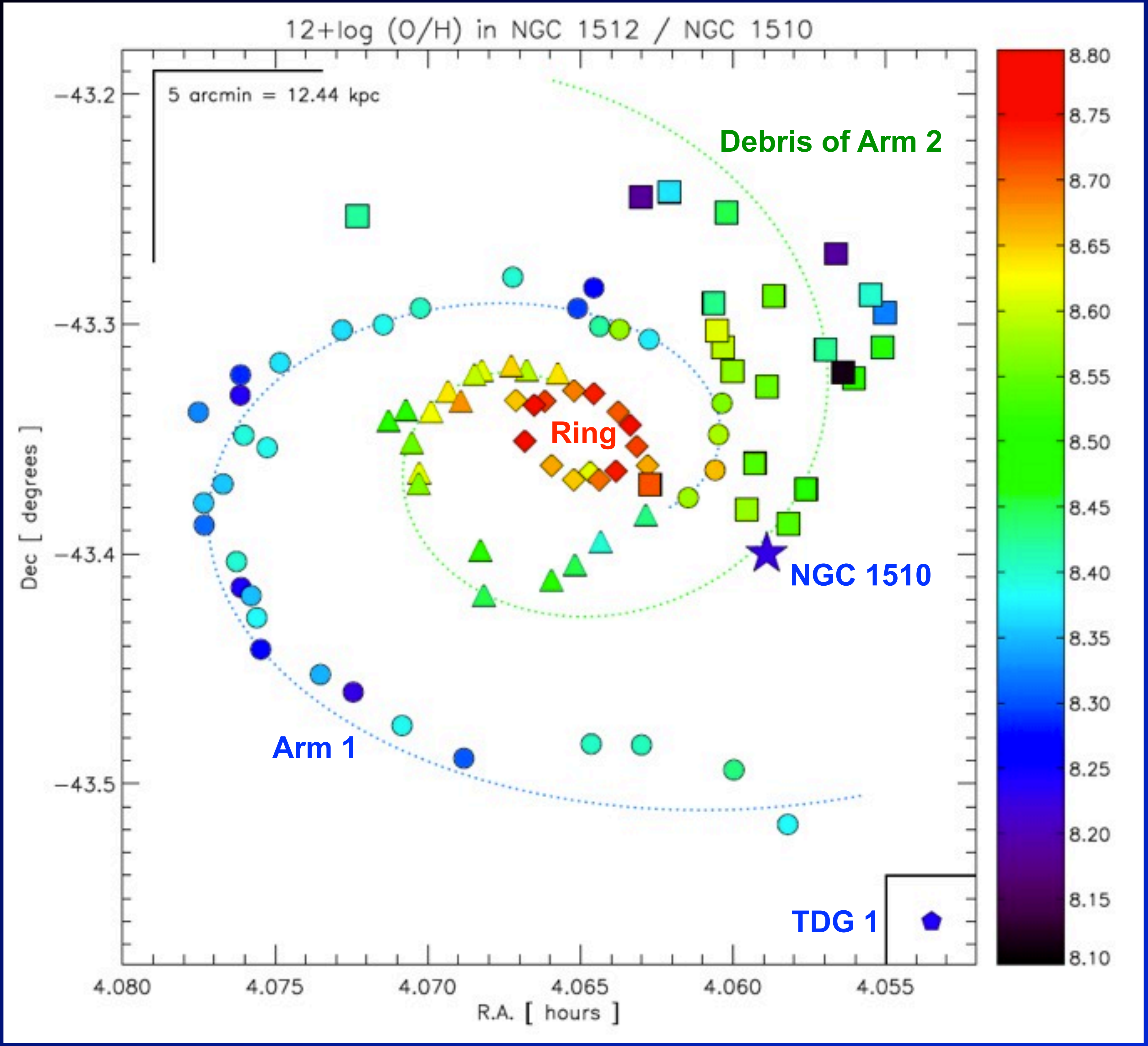


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- Assymetric O/H distribution throughout debris of Arm 2, average value ~ 8.44, but high dispersion (8.71 - 8.12).
  - Interaction processes with NGC 1510 enhanced SF!
  - This confirms results by Kewley et al. (2010) , Rupke et al. (2010) and Werk et al. (2010, 2011) that galaxy interactions flattens the metallicity gradients in galaxies.

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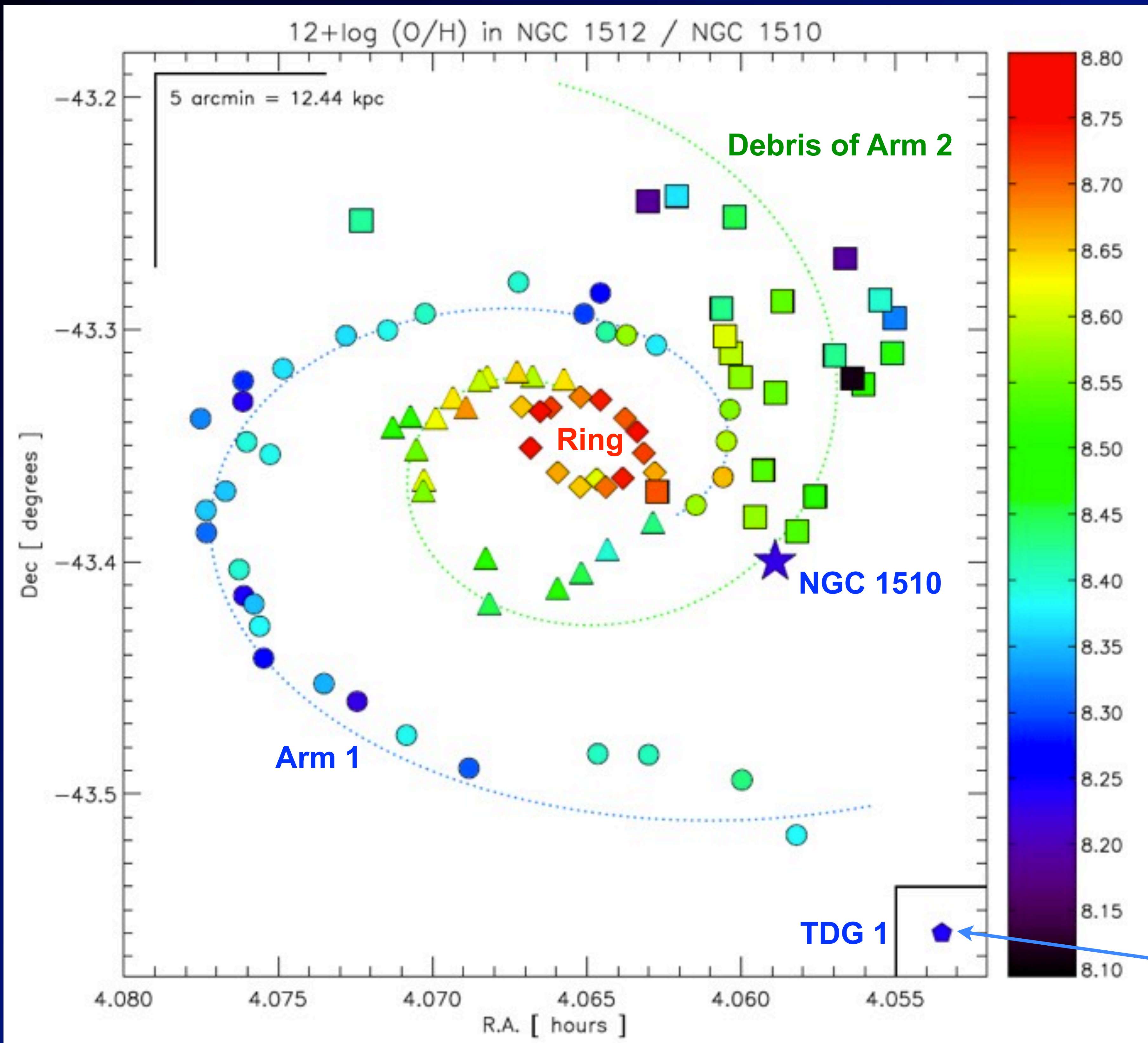


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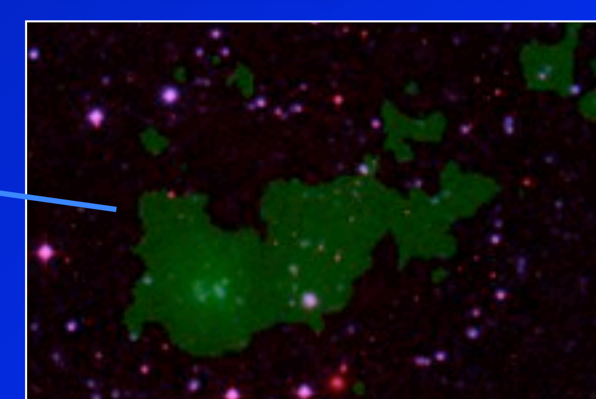
- TDG1 has 12+log(O/H) = 8.24
  - Is it actually a TDG?

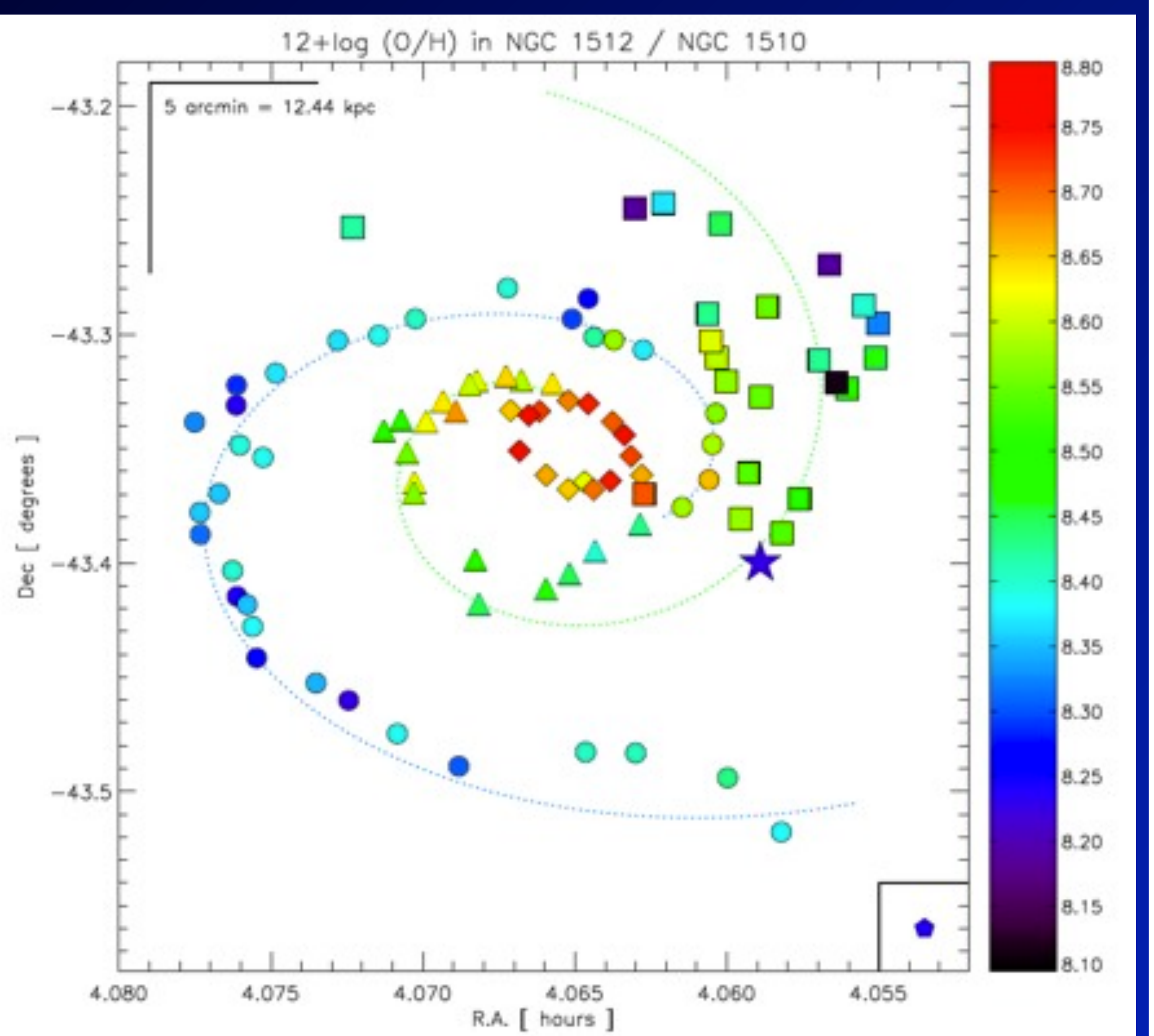


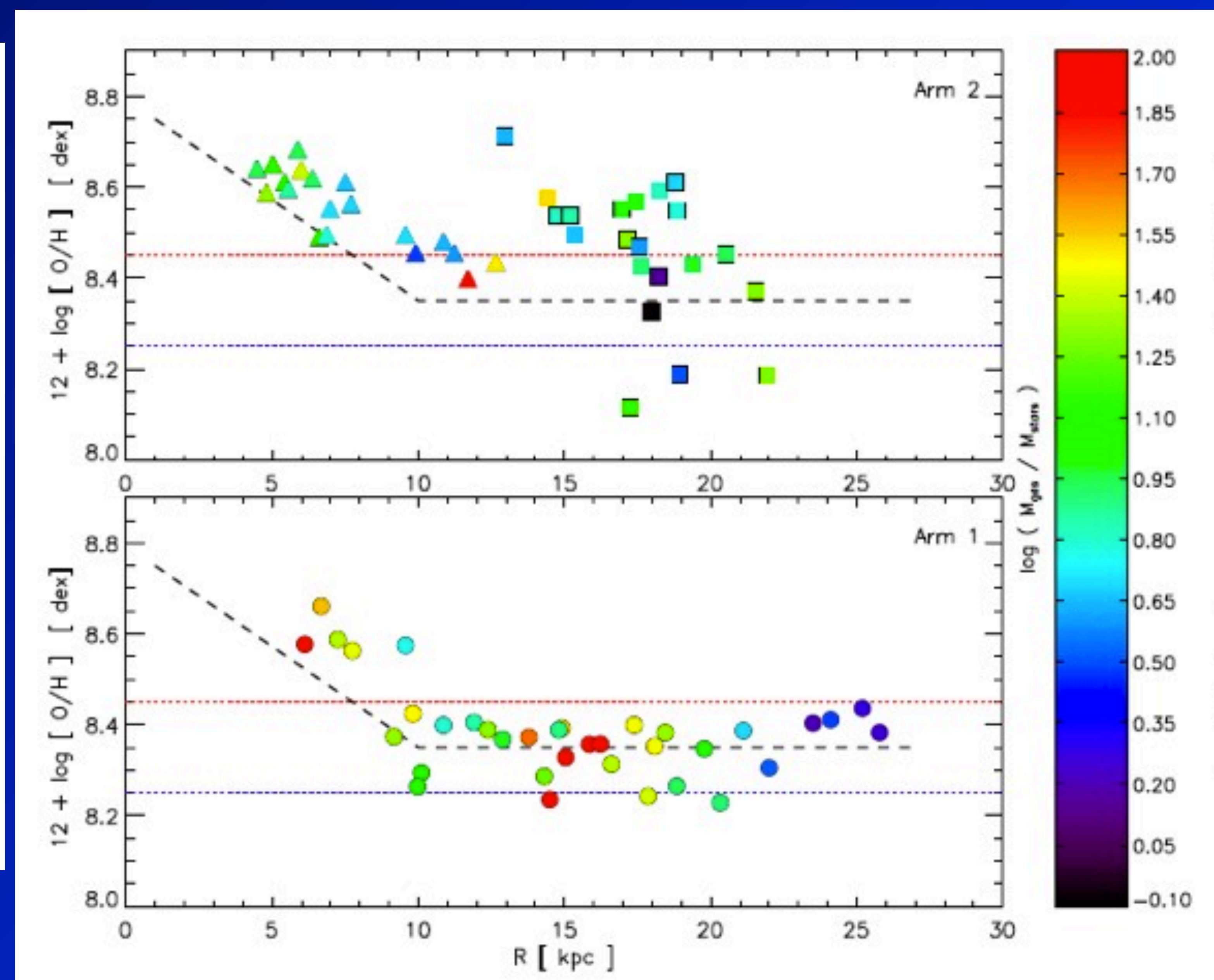
12+log (O/H) map in NGC 1512 / 1510 (López-Sánchez et al. 2014, subm.)

# Metallicity gradients

- Assuming a **radial + azimuthal gradient** along **spiral arms,** the almost undisturbed Arm 1 and the very disturbed Arm 2 are easily identified.
- Similar result plotting the N/O ratio

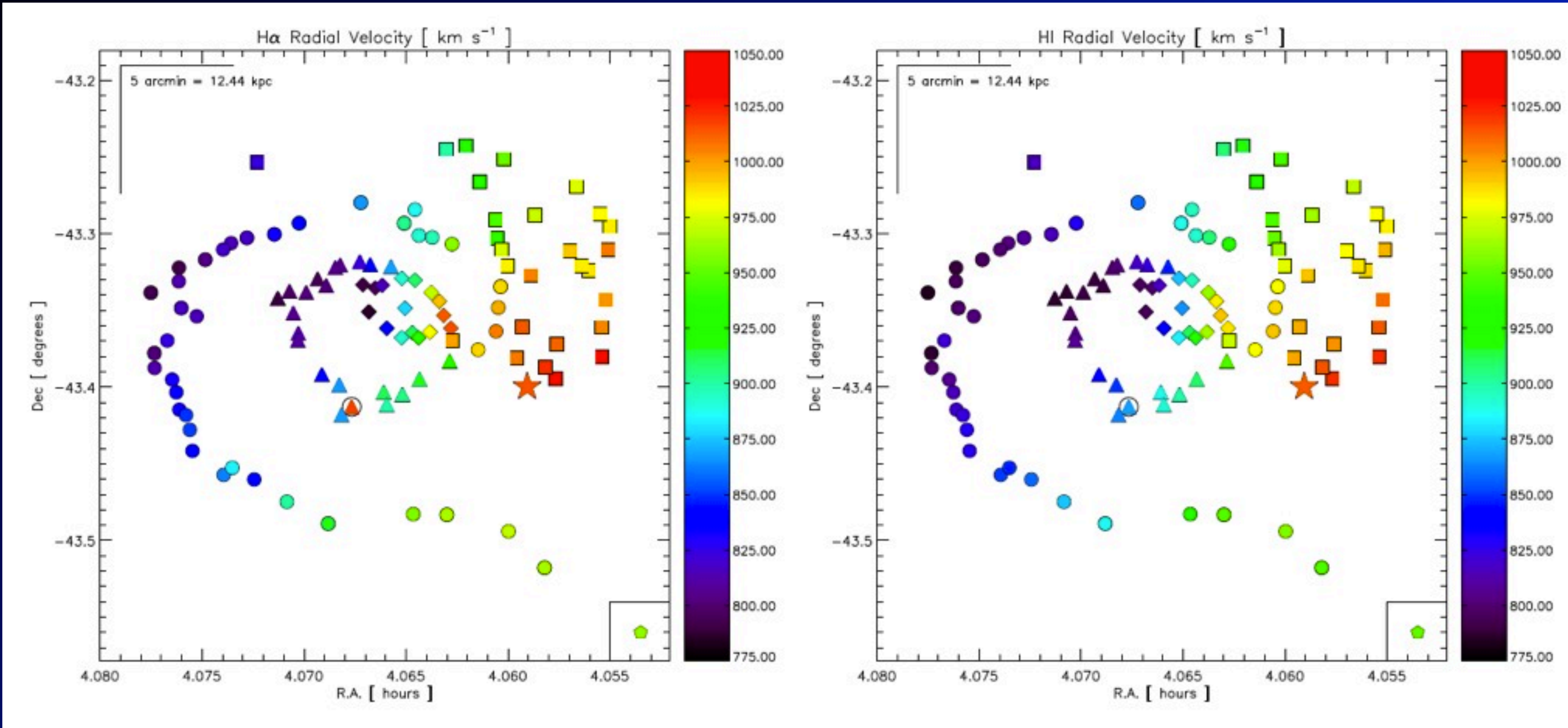
- The flattening of the metallicity gradient in external regions of spiral galaxies was already detected (e.g. Bresolin et al. 2009, 2012; Kewley et al. 2010; Werk et al. 2010, 2011; Sánchez et al. 2014), as it is seen even in the Milky Way (Esteban et al. 2013).




López-Sánchez et al. 2014, submitted

# Kinematics of the ionized gas vs kinematics of the neutral gas




- In general, **excellent agreement between H I and Hα kinematics**
  - This maps traces the kinematics of the system using ionized gas up to 2.8 Re !!!

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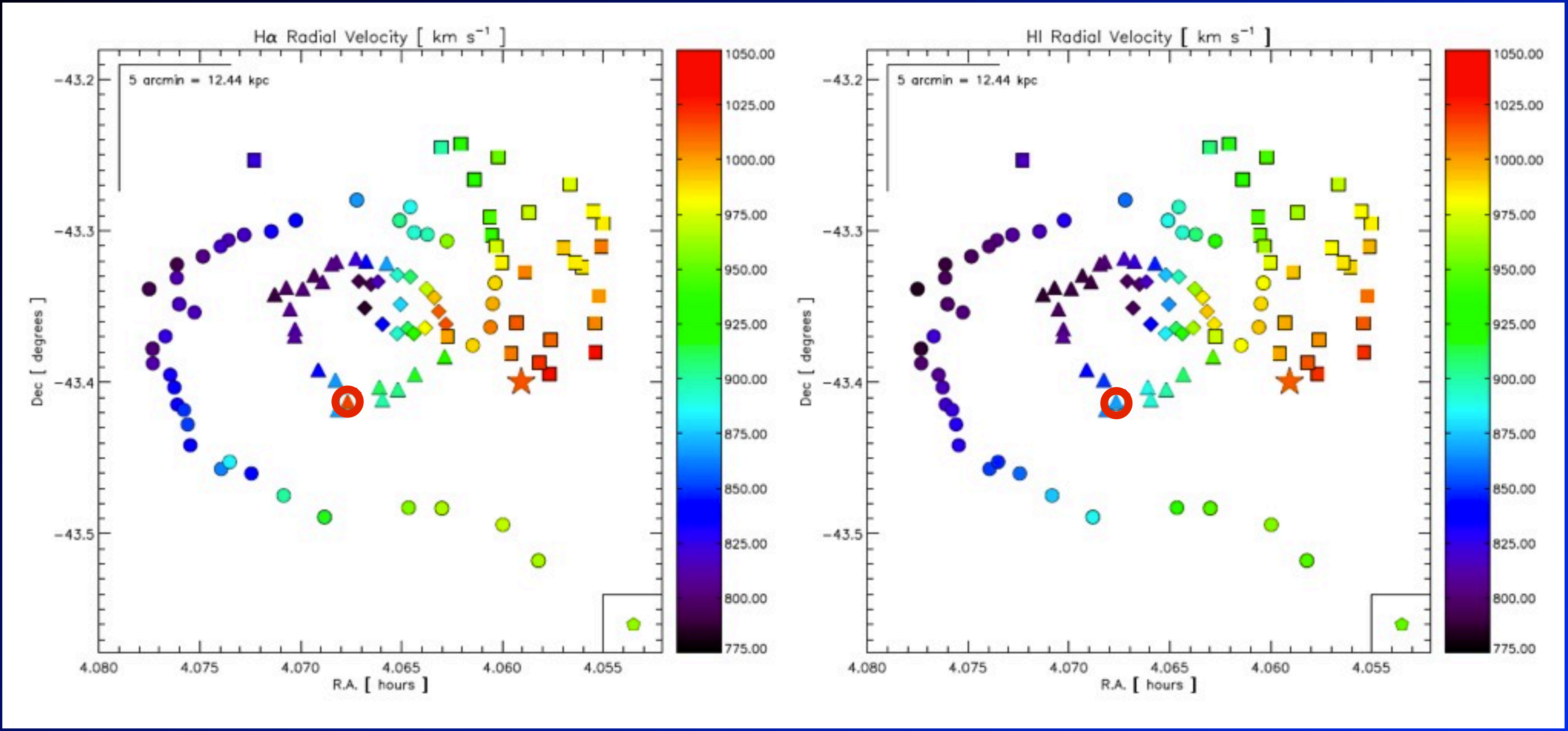
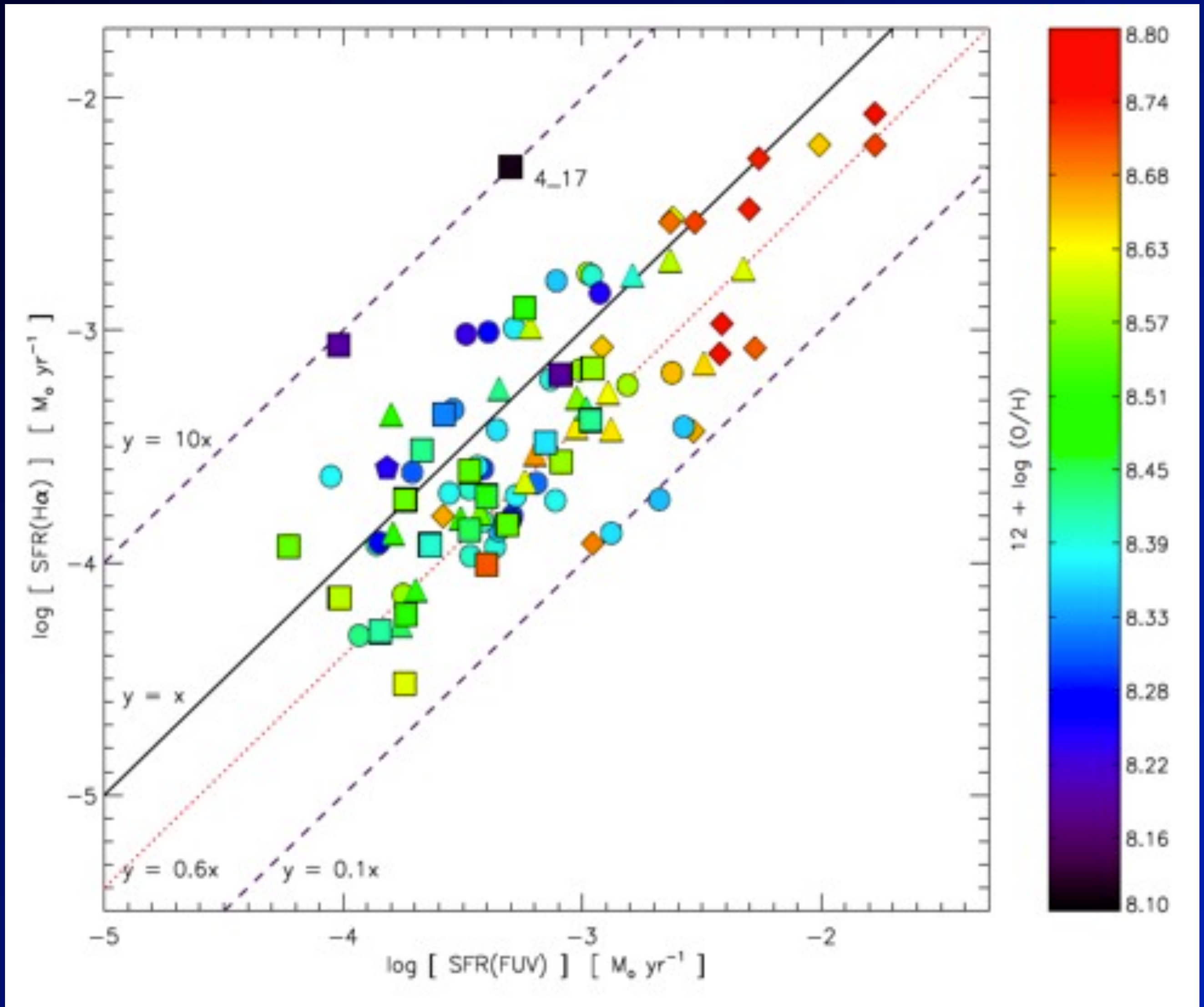



- In general, excellent agreement between H I and Hα kinematics
  - This maps traces the kinematics of the system using ionized gas up to 2.8 Re !!!
- But knot 3_20 shows a difference of 136 km/s between H I and Hα velocities !
  - A careful inspection reveals high Hα dispersion and 12+log (O/H) < 8.1 (8.5 nearby knots) !!
  - Is it an independent dwarf galaxy?

López-Sánchez et al. 2014, submitted

# Star-formation activity and recent star-formation history

- Hα-fluxes using images are only 3.4 - 1.4 times higher than those from 2” fibres. But areas of the knots are 40 - 60 times larger than that!
  - ➡ Ionized emission is very localized within each UV-rich star cluster
- Hα-SFR are systematically lower than FUV-SFR (agrees with Lee et al. 2009, Hunter et al. 2010)

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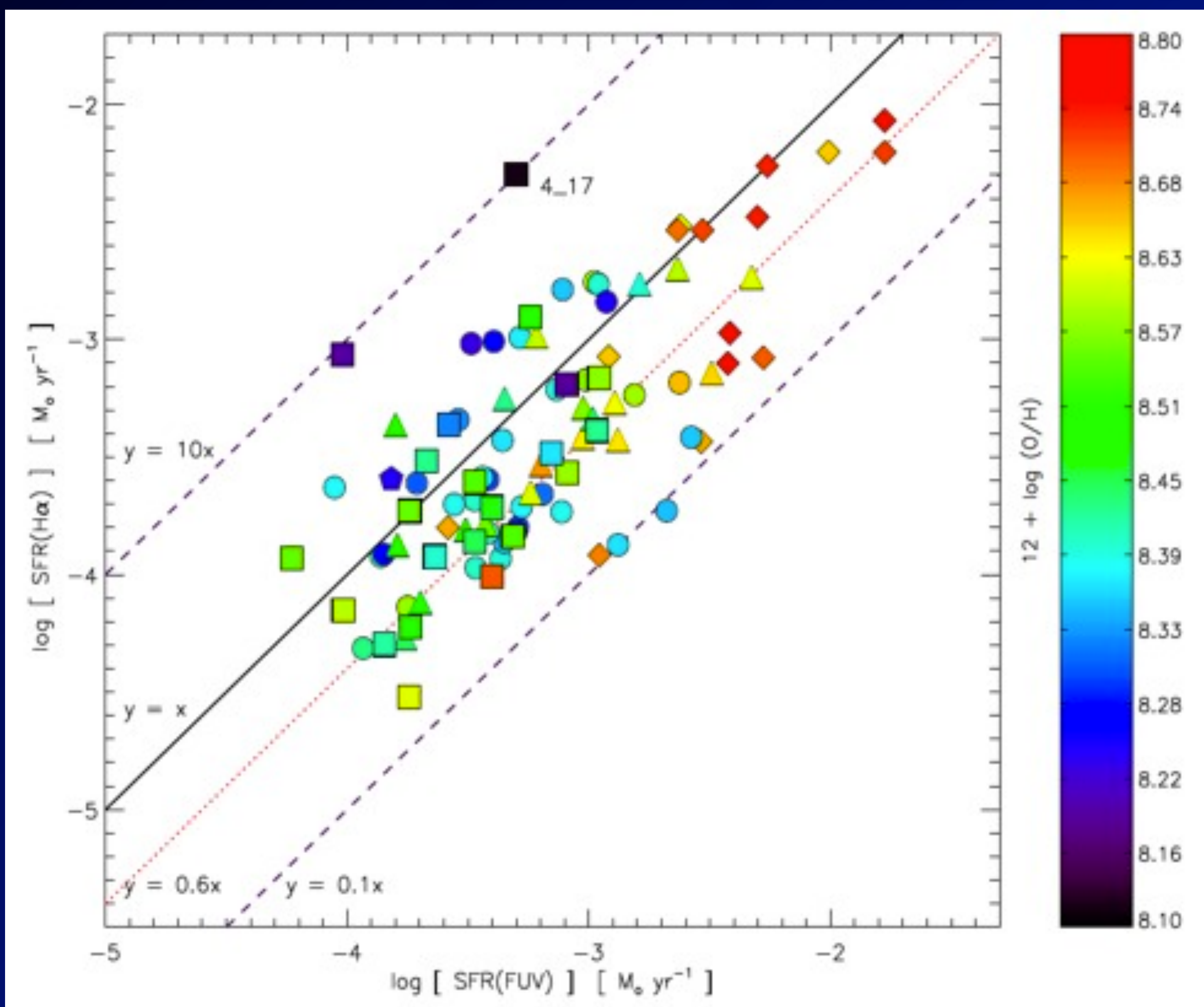
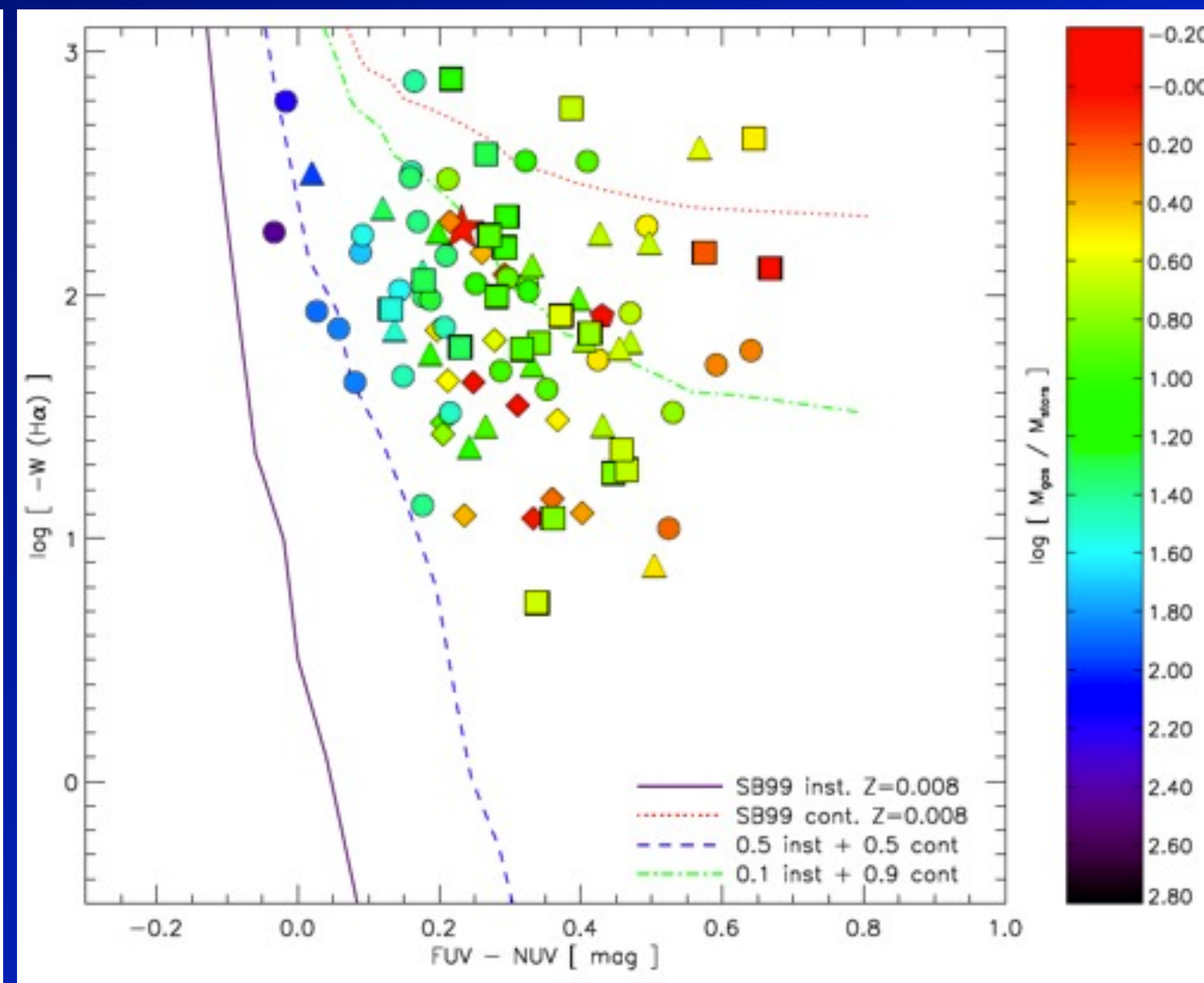


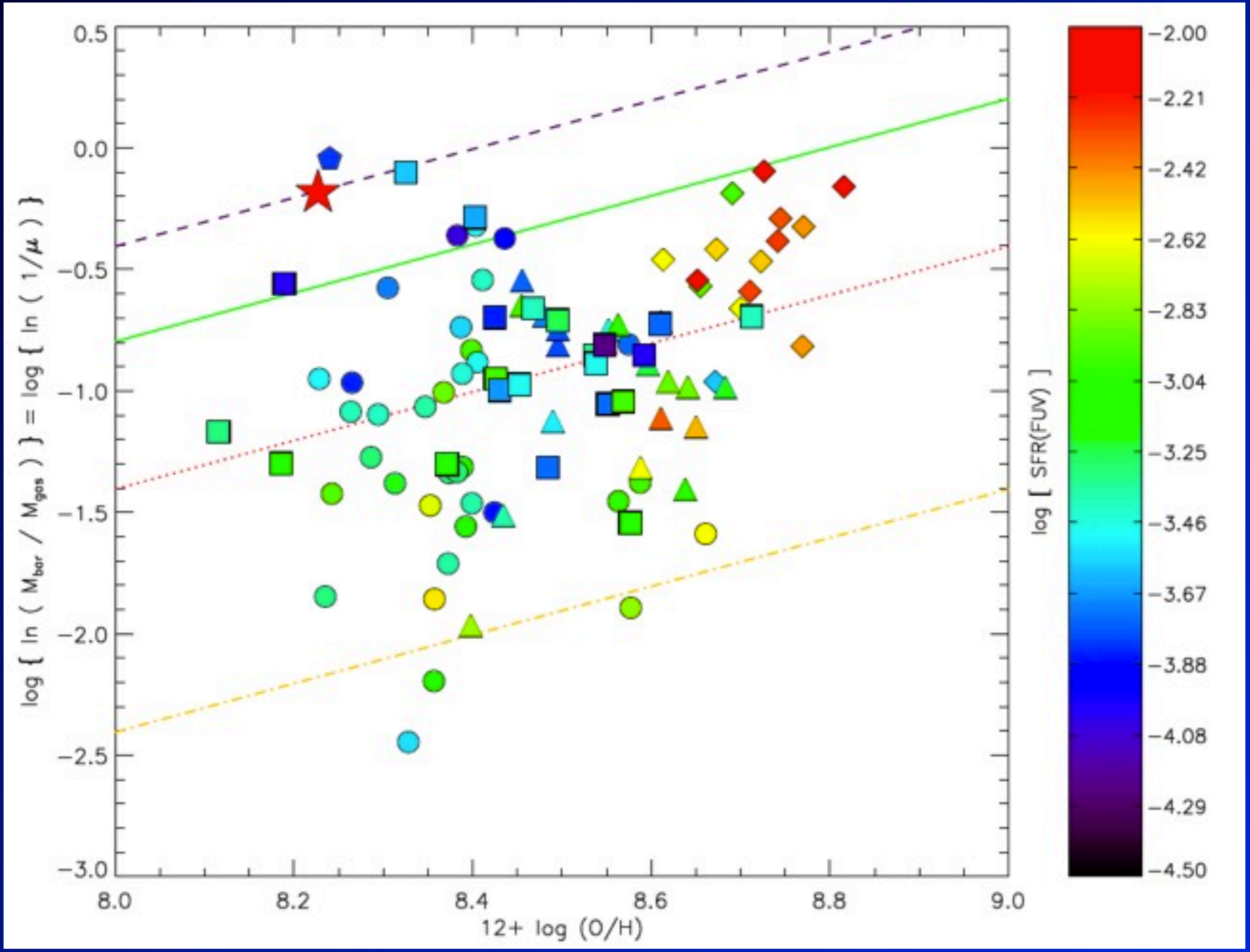

- FUV-based and Hα-based ages DO NOT agree!!
  - ➡ Recent star-formation event (~13 Myr or less) plus an older event (+100 Myr)
  - ➡ Combination of on-going + starburst star-formation

López-Sánchez et al. 2014, submitted

# Comparison with closed box models

- Effective yields in XUV complexes are 1-2 order of magnitude HIGHER than those expected following the theoretical value:
  - ➡ The gas already had a lot of metals before the star-formation started!
- Average effective yields: yo = 0.133 (Arm 1) and 0.049 (Arm 2)
  - ➡ Arm 2 has experienced a larger chemical enrichment that Arm 1

$$Z_O = y_O \ln(1/\mu),$$




$Z_O$ : oxygen mass fraction

$y_O$ : stellar yield by mass

$\mu = M_{gas} / M_{bar}$ : gas mass to baryonic mass ratio

$M_{star}$ : Using UV colours & SB99 models

$y_O$ : 0.0074: theoretical yield of O expected for stars with rotation following Meynet & Maeder (2002) models

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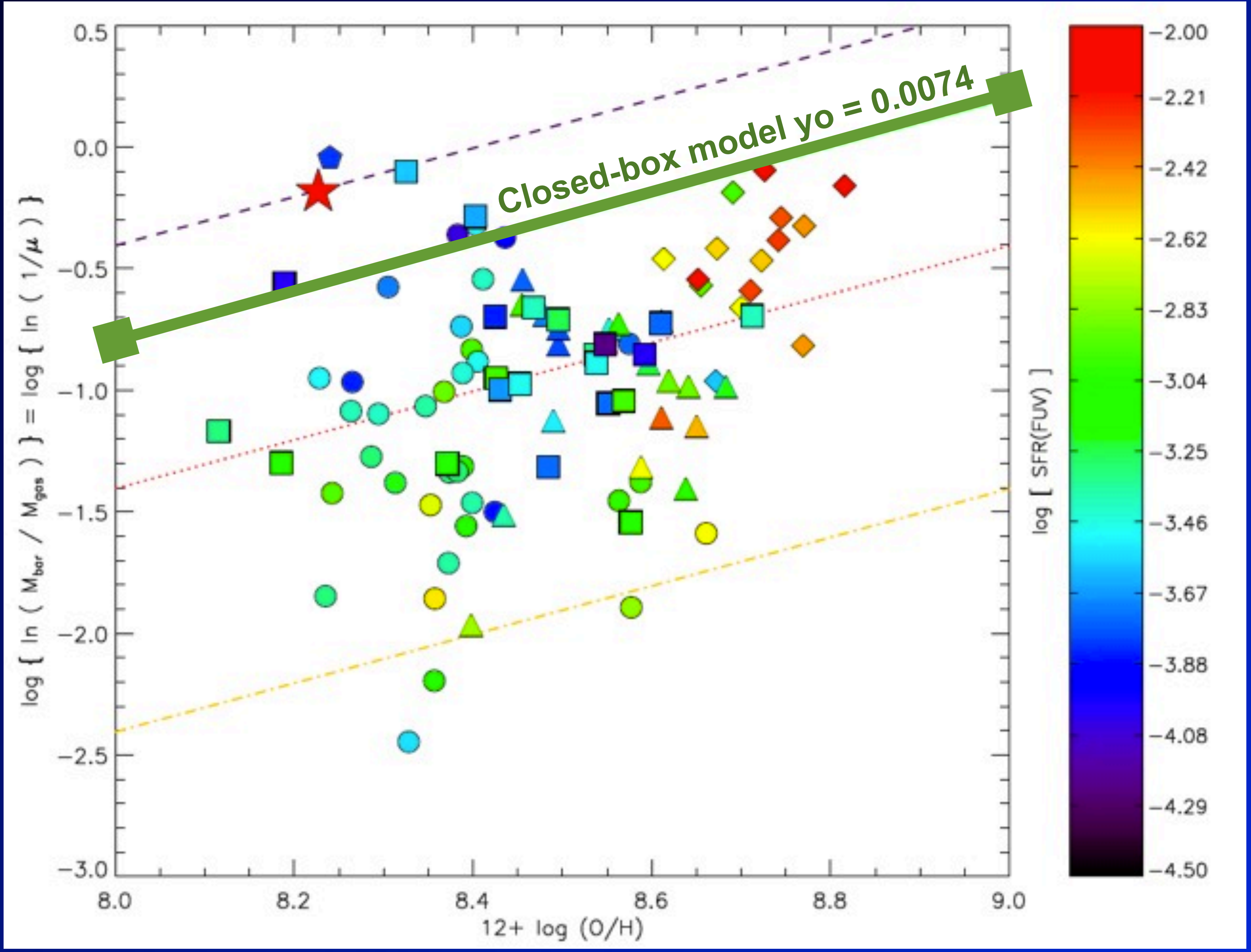


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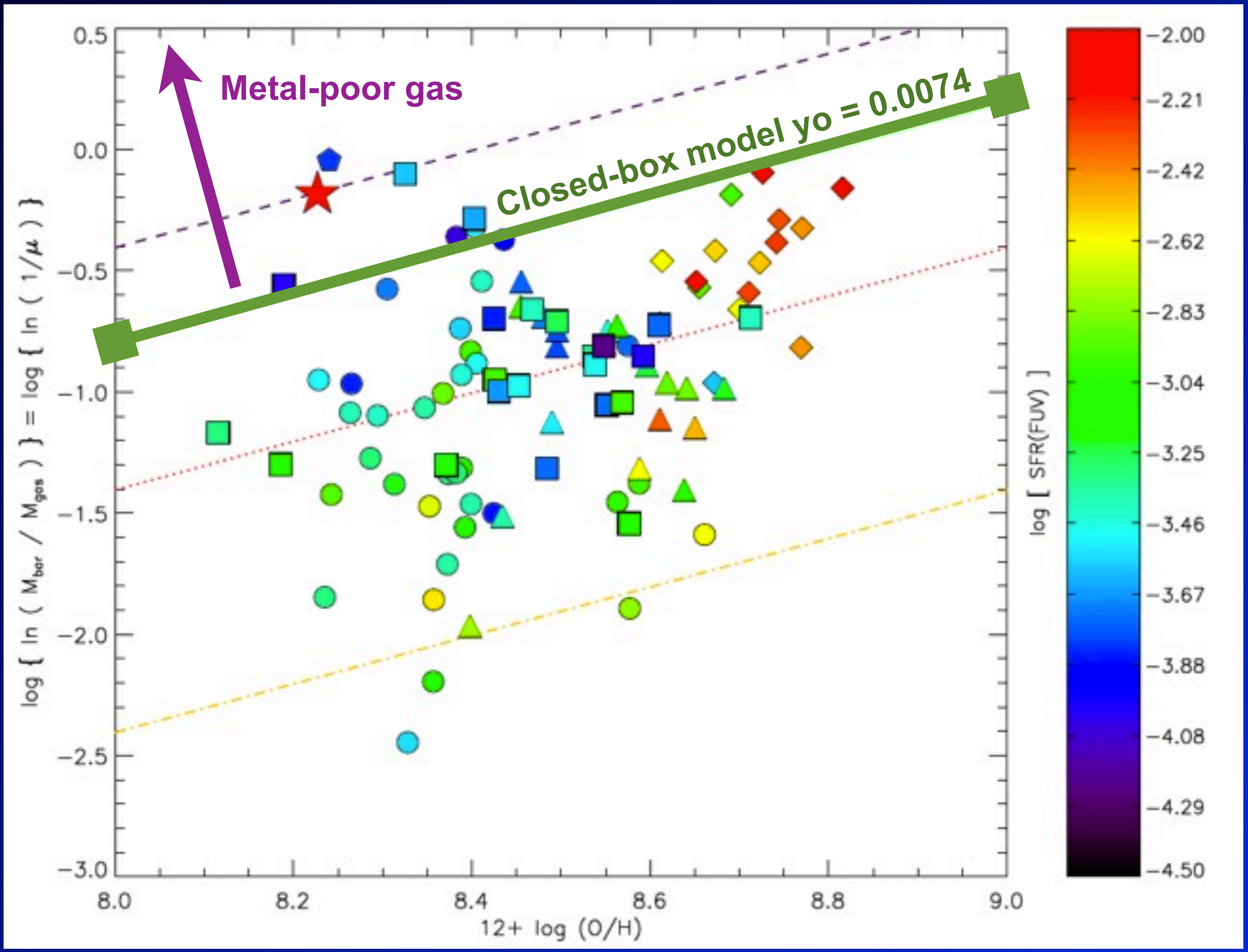


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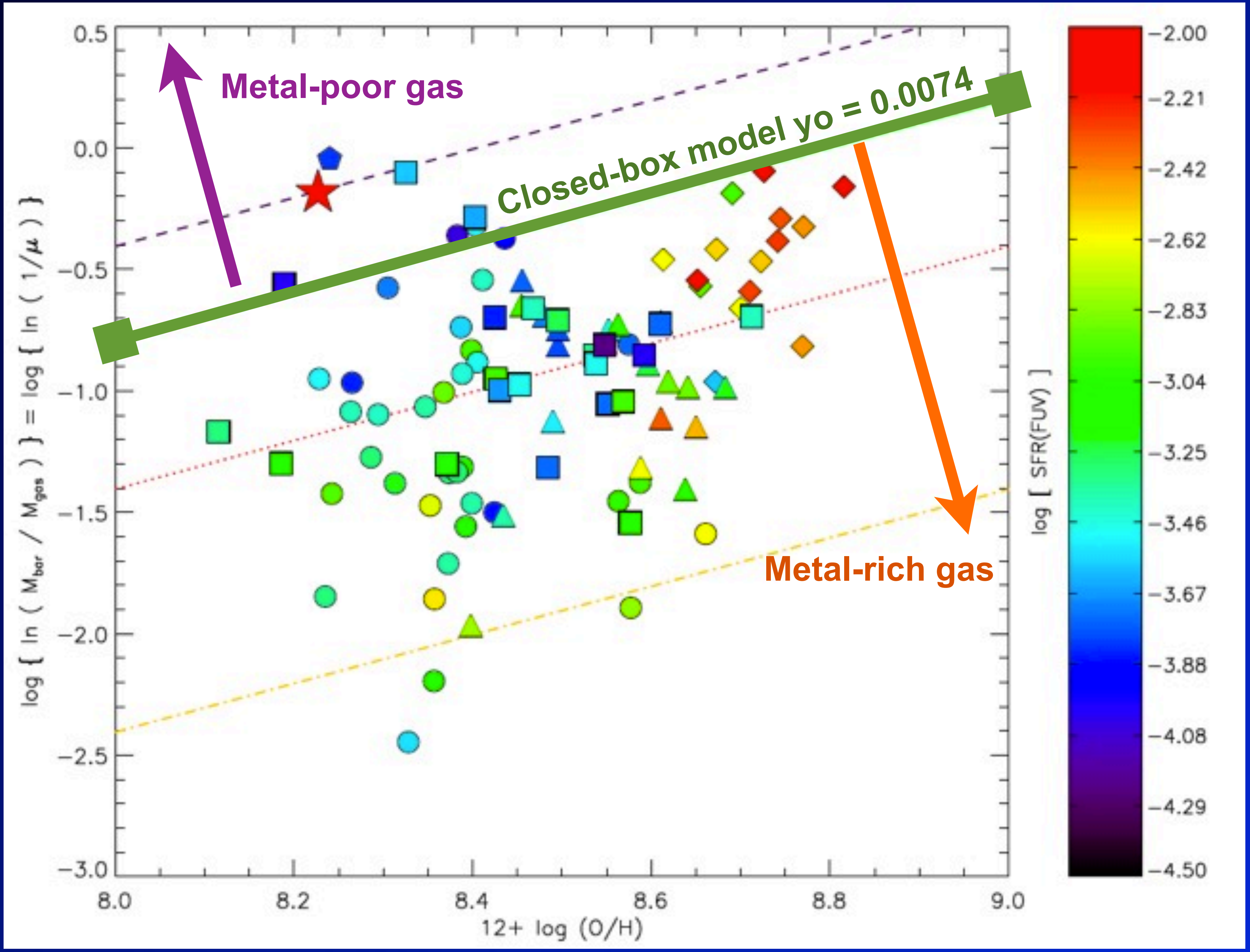


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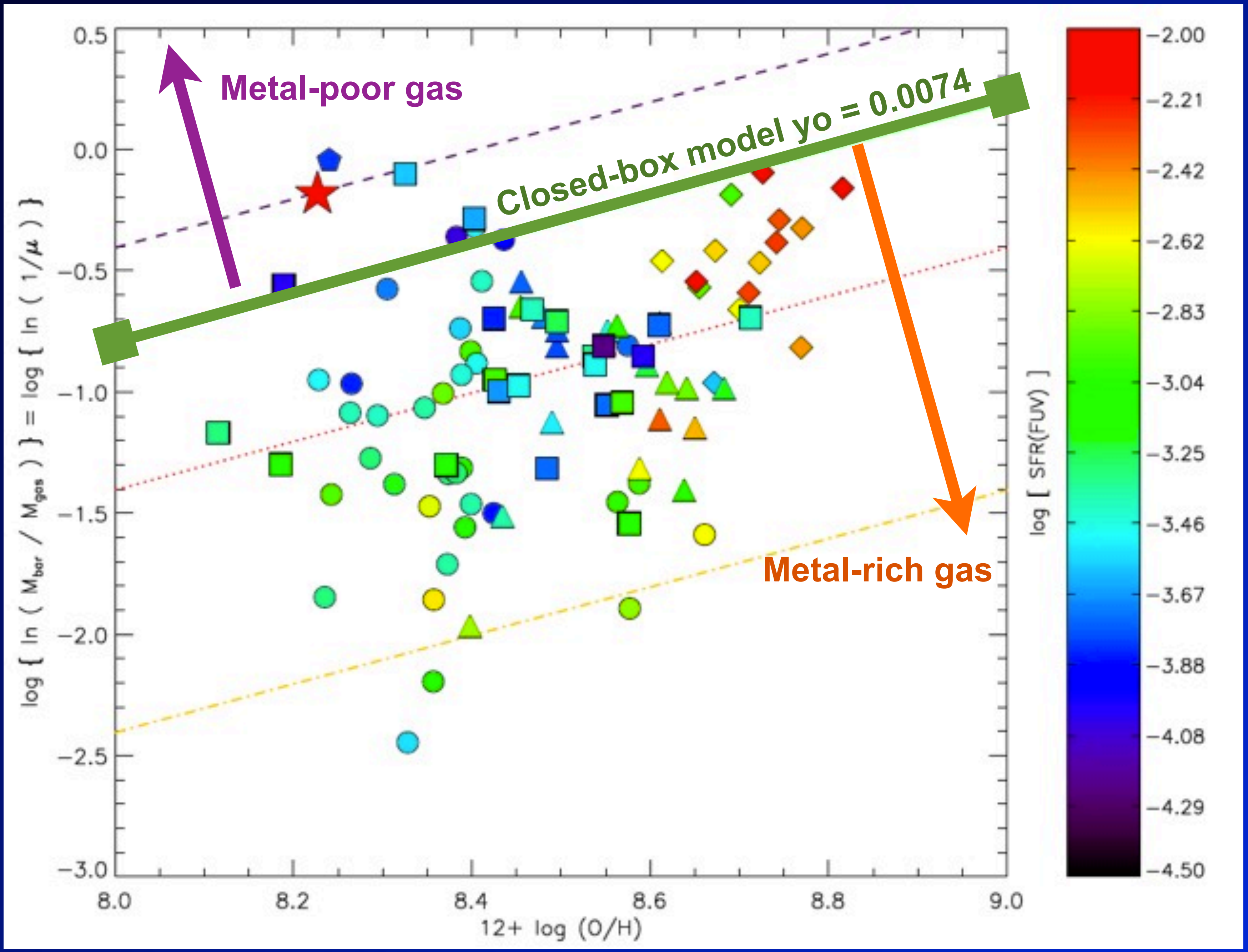


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➡ The UV-bright, young, relatively low metallicity, gas-rich knots should not be defined as TDGs but as tidally-induced star-forming clusters (TSFCs) in the galaxy outskirsts.

➡ As members E and F in HCG 31

# Where are the metals coming from?

## How much enrichment in oxygen ?

$$\Delta\left(\frac{\mathrm{O}}{\mathrm{H}}\right) = \frac{y_{\mathrm{O}} \times \Delta t}{f} \times \frac{\mathrm{SFR}}{M_{\mathrm{H\,I}}},$$

Bresolin, Kennicutt & Ryan-Weber (2012)

- *yo* : *effective yield (computed before)*
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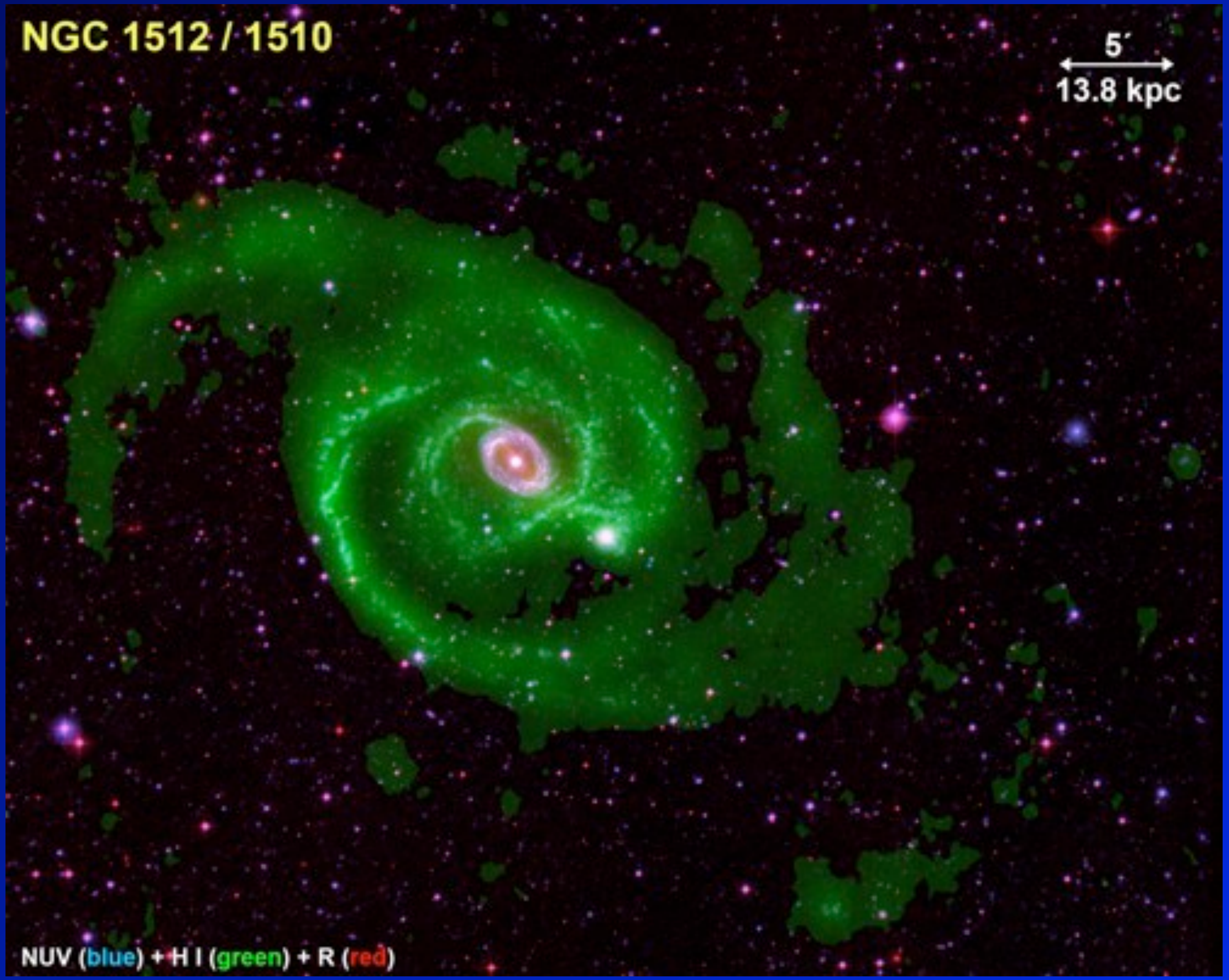

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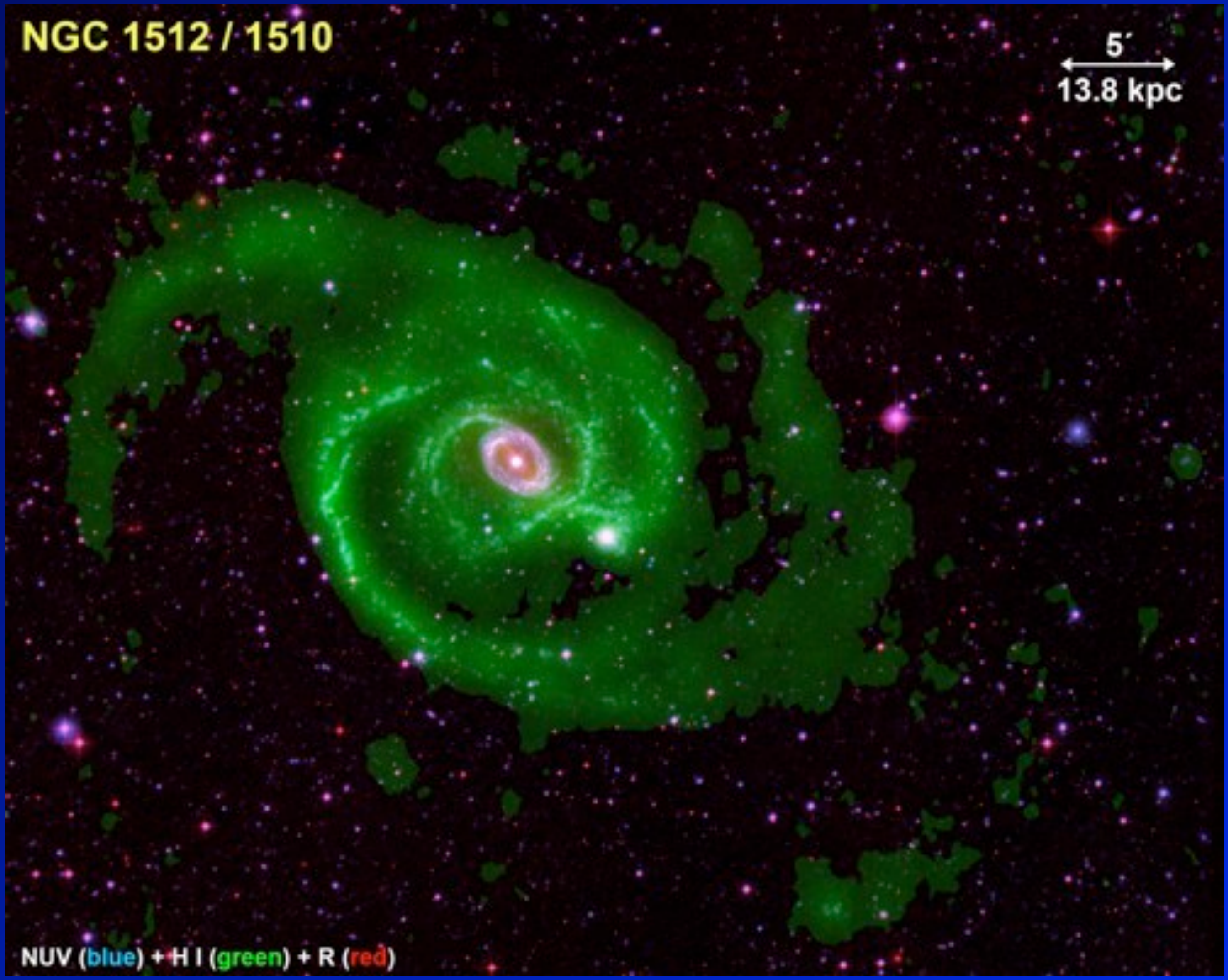

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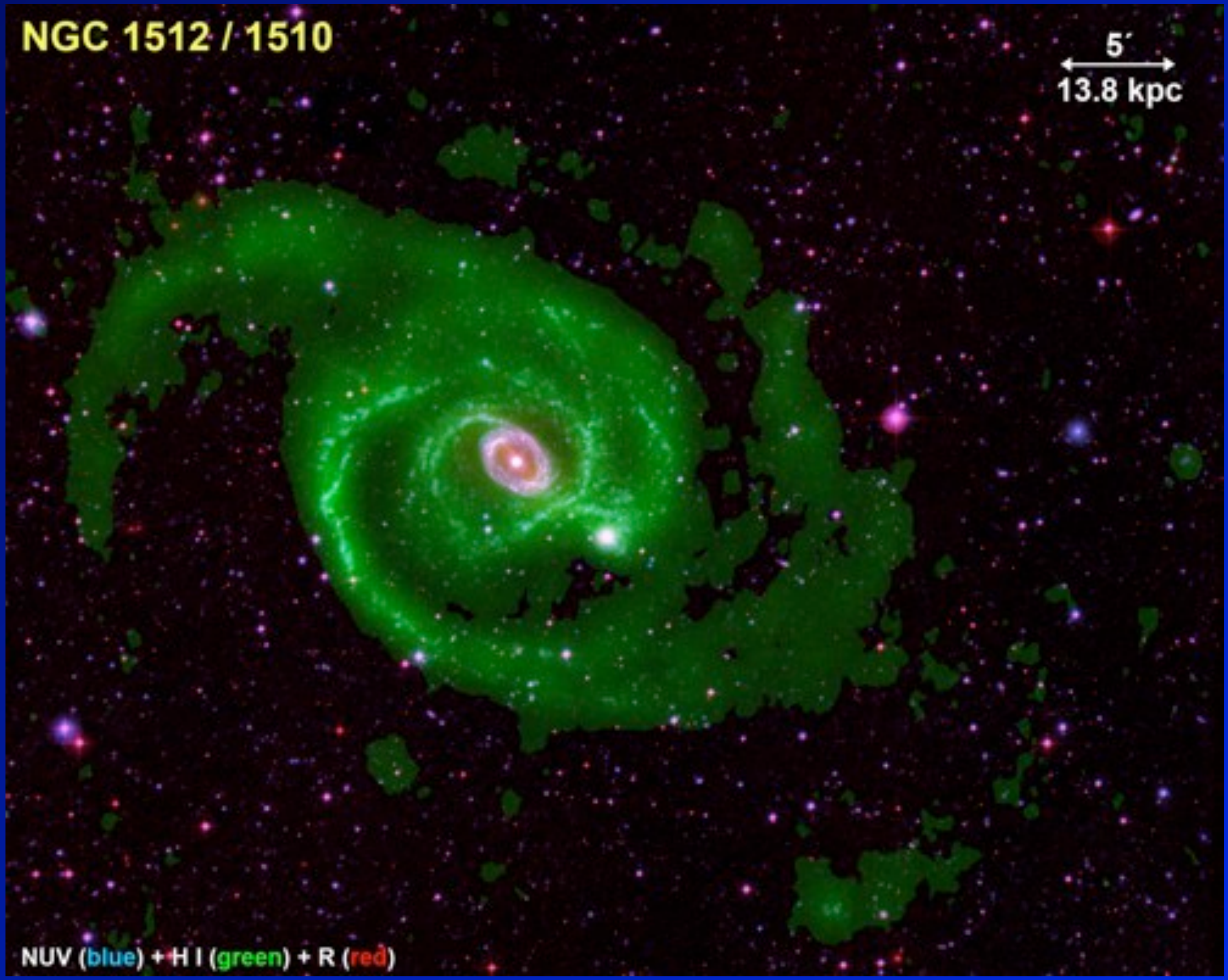


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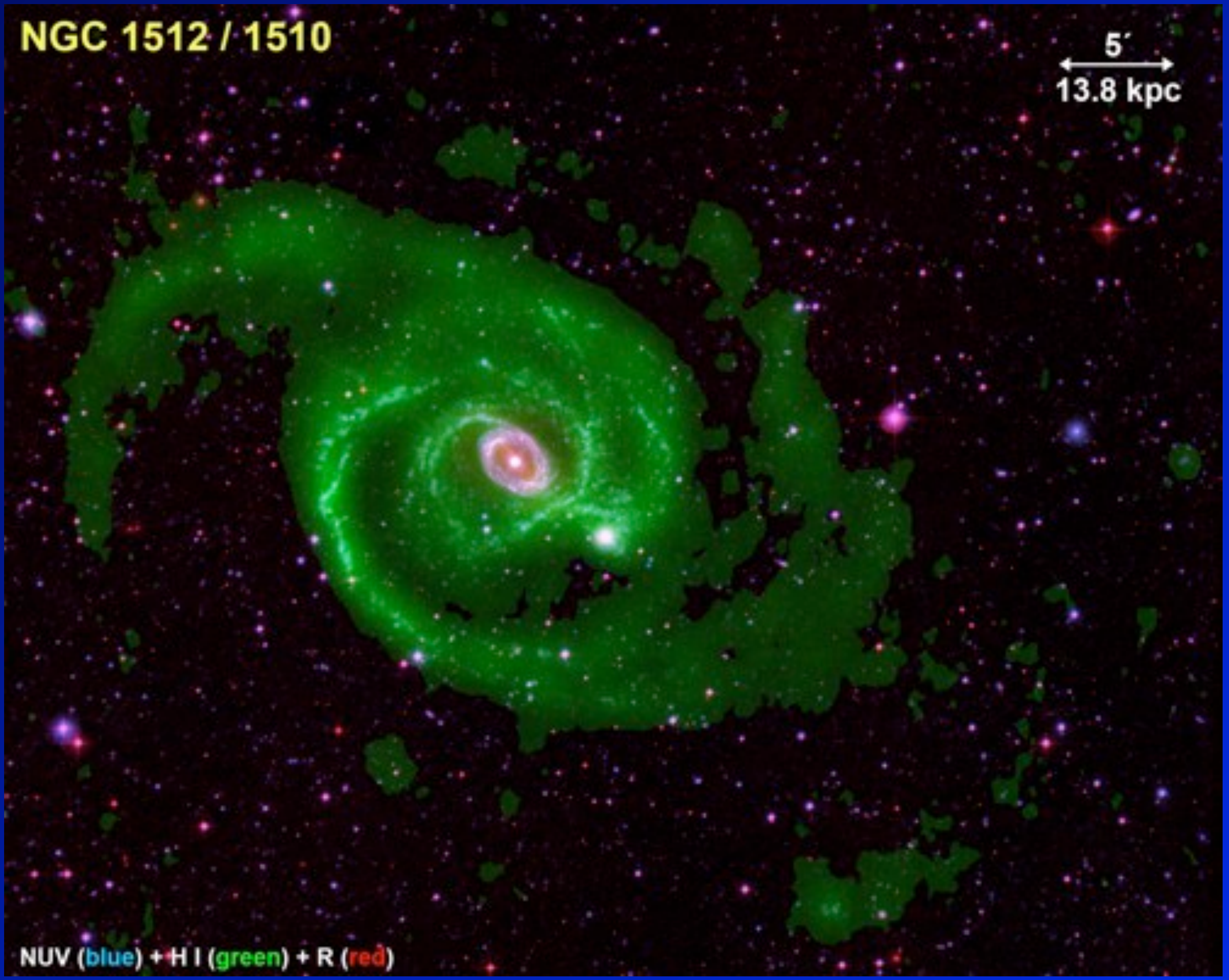


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- **How did those metals get to the huge reservour of HI gas in the outer areas?**

  ➡ **If we put all those metals ( ~ 6.5 × $10^6$ $M_\odot$ of oxygen ) in the galaxy center, the original oxygen abundance of NGC 1512 would be 12+log(O/H) ~ 8.85 (~9.20 in the KD scale). This value is more than 1 order of magnitude higher than that expected following the mass-metallicity relation.**

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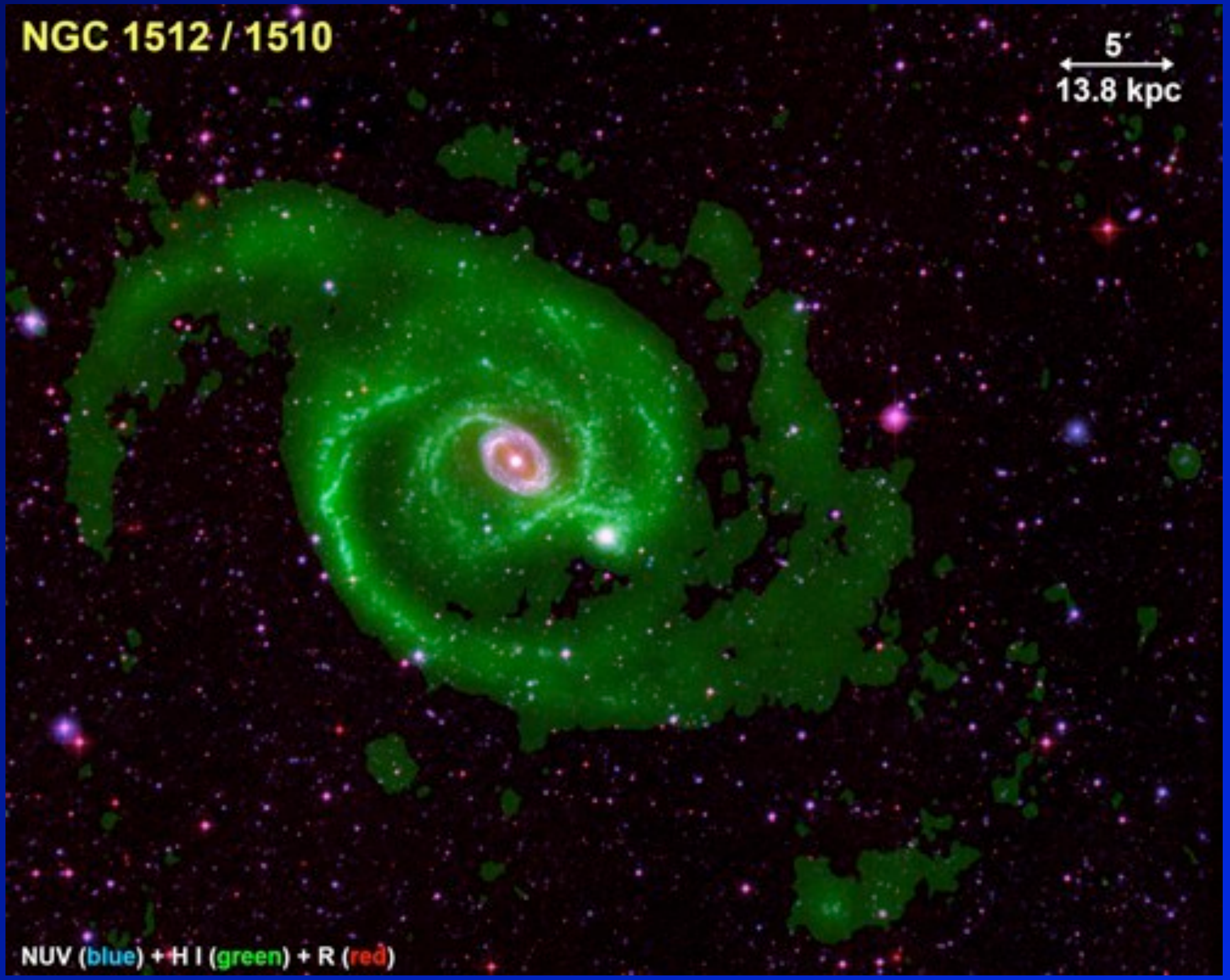


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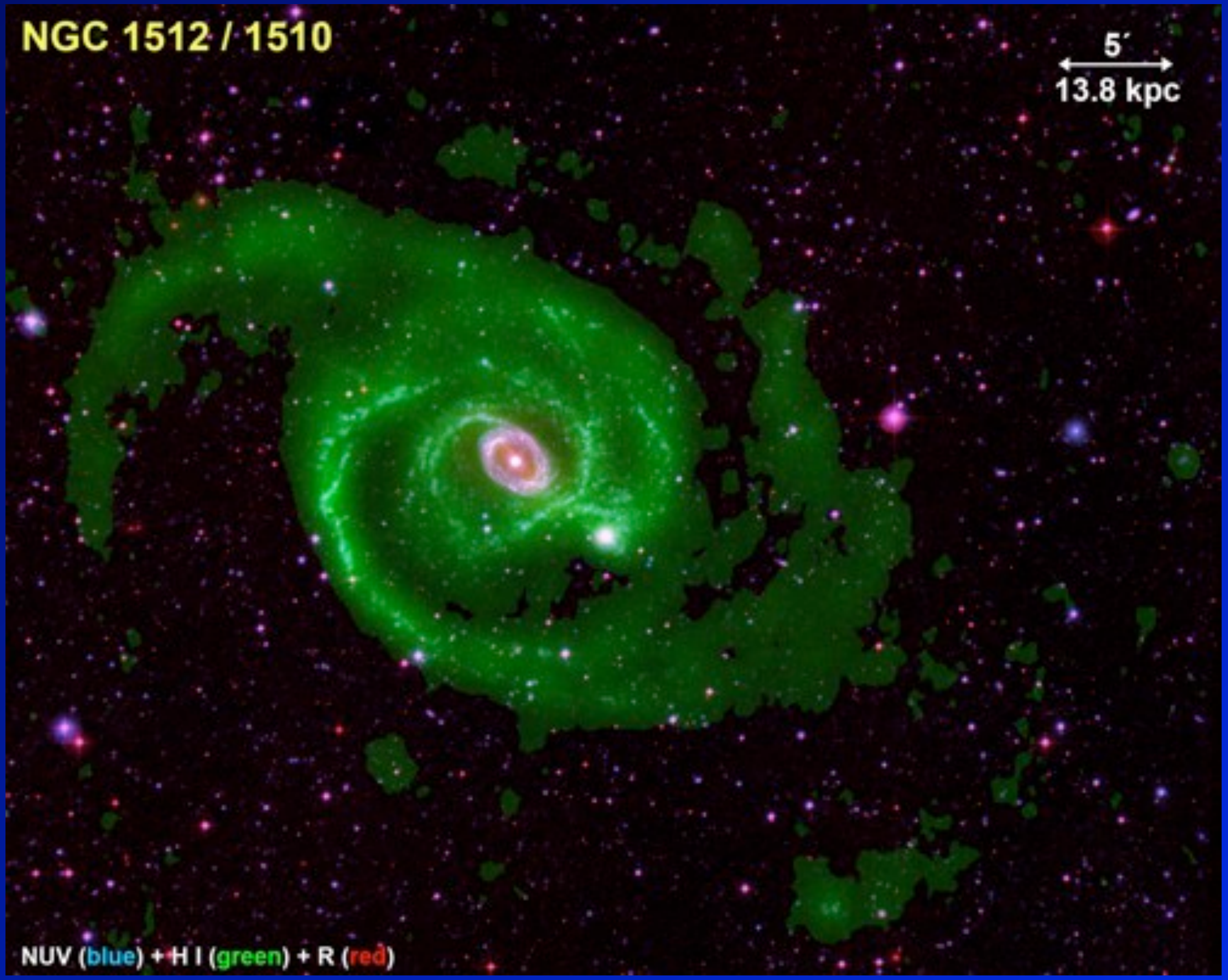
  ➡ **Metals are probably coming from dwarf, low-luminosity, gas-rich galaxies which have been slowly accreted and destroyed into the system.**

# Summary

- Analyses of local SF processes and ISM / IGM interaction in nearby galaxies using HI / UV / optical / MIR data.
  - We need multiwavelength data to get the complete picture!

- There are many things happening in the outskirsts of spiral galaxies.
  - The huge reservour of diffuse gas in the outskirsts of spiral galaxies may be coming from the accretion and destruction of gas-rich low-luminosity dwarf galaxies.
  - Allows us to understand galaxy evolution and test $\Lambda$CDM scenarios.




- Many surprises about galaxy evolution will come from HI surveys (ASKAP, MeerKAT, APERTIF) and from optical IFS surveys (CALIFA, SAMI, MANGA).

  ... BUT EVEN MORE COMBINING BOTH KIND OF DATASETS !!