A new mechanism for the formation of PRGs

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Galaxy formation in CDM model

The hierarchical merger–dominated picture of galaxy formation is based on the cold dark matter model:

Formation and evolution of galaxies

Assembly of matter through accretion & merger

Conversion of matter into stars

Cold Dark Matter scenario

Galaxy formation in CDM model

The gas fraction is a key parameter in the physics of gravitational interactions.

Galaxies can get their gas through several interacting processes, such as smooth accretion, stripping and accretion of primordial gas.

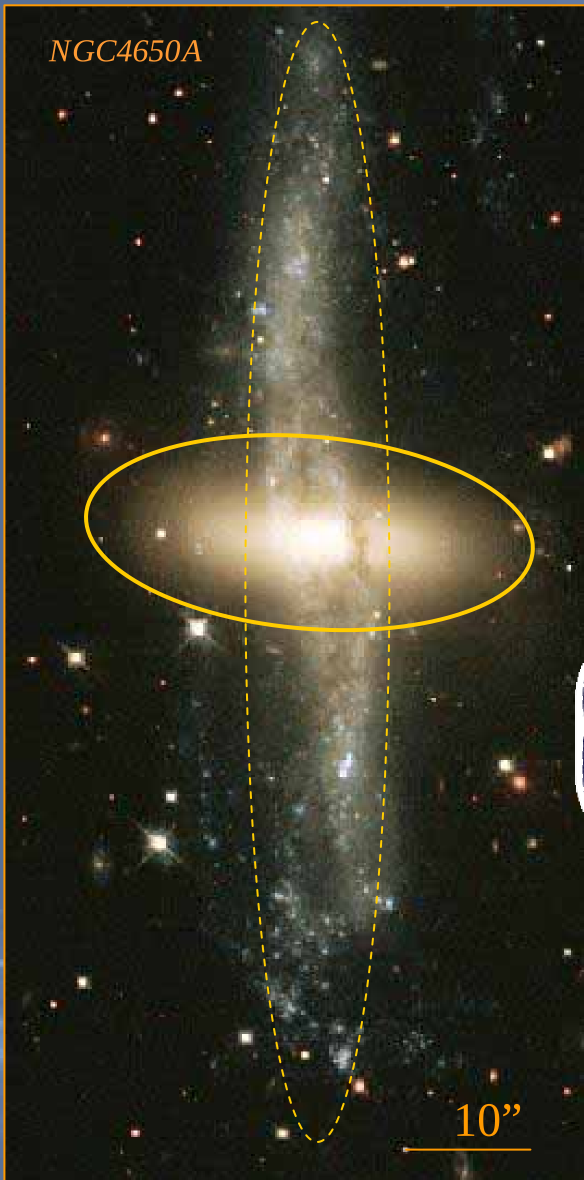
Recent theoretical works have argued that the accretion of external gas from cosmic web filaments, with inclined angular momentum, might be the most realistic way by which galaxies get their gas.

The relative share of all processes depends on the environments and it drives many morphological features (bars, polar rings and so on).

Polar Ring Galaxies

“The discovery of PRGs has provided an unexpected but very welcome opportunity to study galaxies in a new way”

B. Whitmore (1991)



PRGs are peculiar object composed by a central spheroidal component, the **host galaxy (HG)** surrounded by an outer **ring** made up by gas, stars and dust, which orbits in a nearly perpendicular plane to the equatorial one of the central galaxy

The unique geometry allows to study

- ***galaxy interactions and merging***
- ***3D shape of dark matter halos***

Polar Ring Galaxies

According to the ring morphology, PRGs can be divided into two broad classes (Whitmore et al., 1990):

☆ Narrow PRG

Polar Ring Galaxies

According to the ring morphology, PRGs can be divided into two broad classes (Whitmore et al., 1990):

☆ Wide PRG

Polar Ring Galaxies

According to the ring morphology, PRGs can be divided into two broad classes (Whitmore et al., 1990):

☆ Multiple rings

Polar Ring Galaxies

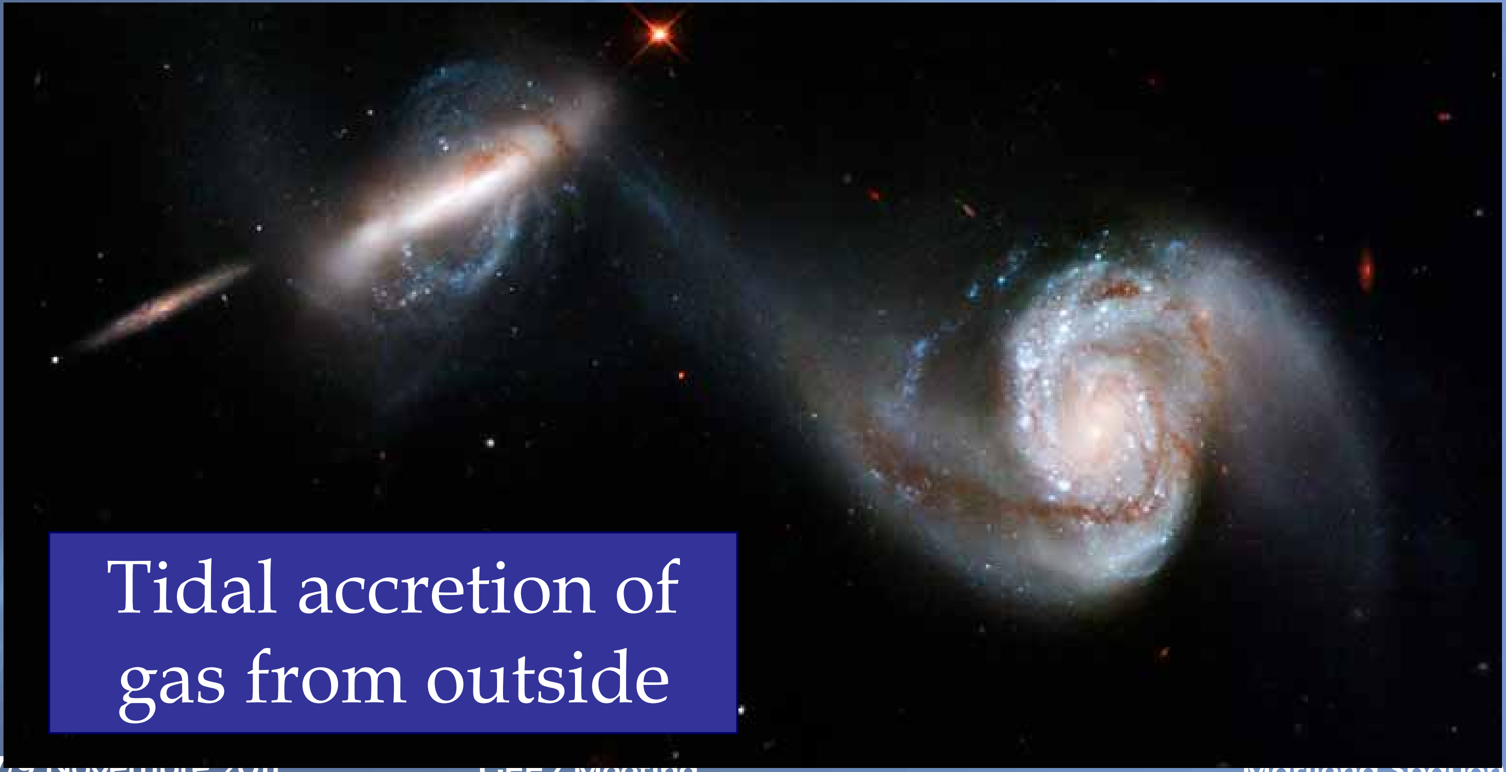
According to the ring morphology, PRGs can be divided into two broad classes (Whitmore et al., 1990):

☆ Low inclination ring

How might PRGs forms?

The two possible formation scenarios for PRGs, proposed till some years ago, involve the interaction of two galaxies (Bekki 1998; Bournaud & Combes 2003)

Tidal accretion of gas from outside



Tidal accretion of gas from outside

How might PRGs forms?

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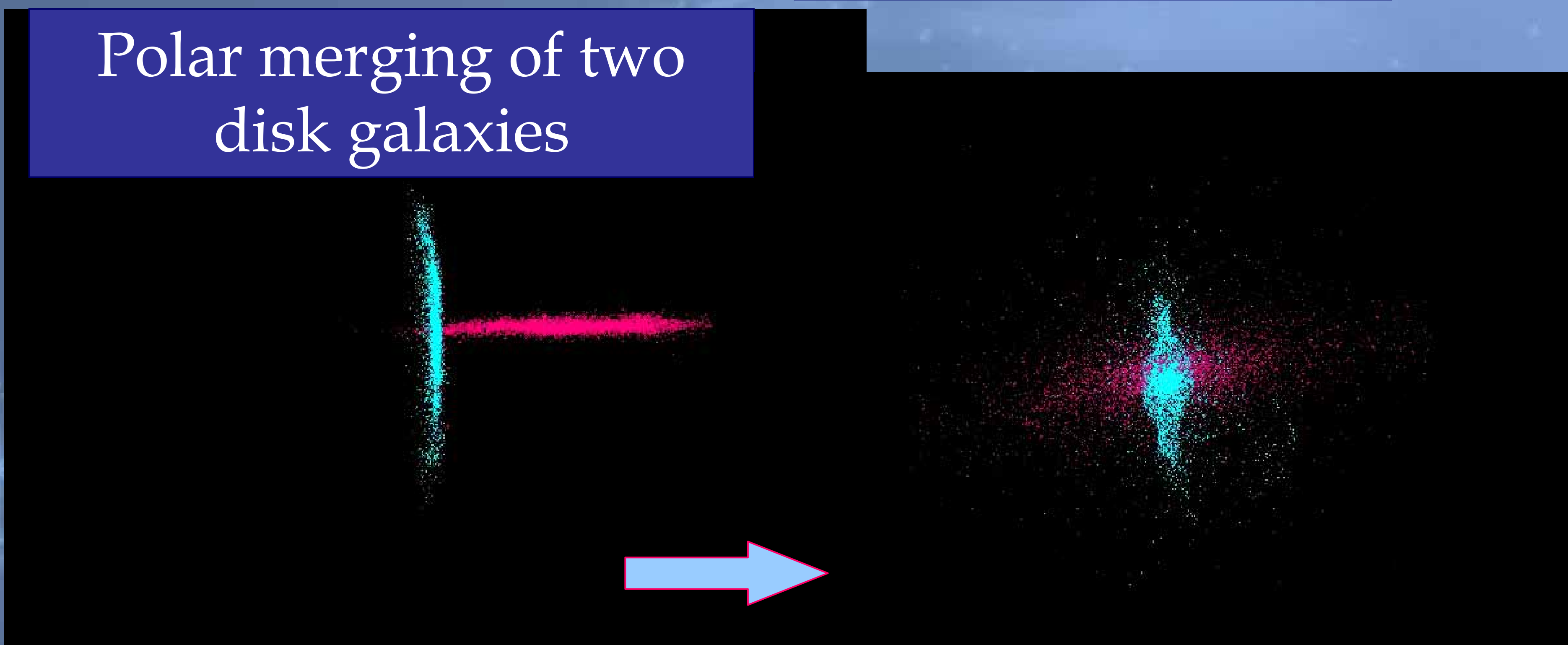
Polar merging of two disk galaxies



How might PRGs forms?

The two possible formation scenarios for PRGs, proposed till some years ago, involve the interaction of two galaxies (Bekki 1998; Bournaud & Combes 2003)

Tidal accretion of gas from outside	Polar merging of two disk galaxies

Both scenarios are able to account for:

☆ the main morphologies observed for PRGs

☆ a central HG similar to an early-type system

How might PRGs forms?

The two possible formation scenarios for PRGs, proposed till some years ago, involve the interaction of two galaxies (Bekki 1998; Bournaud & Combes 2003)

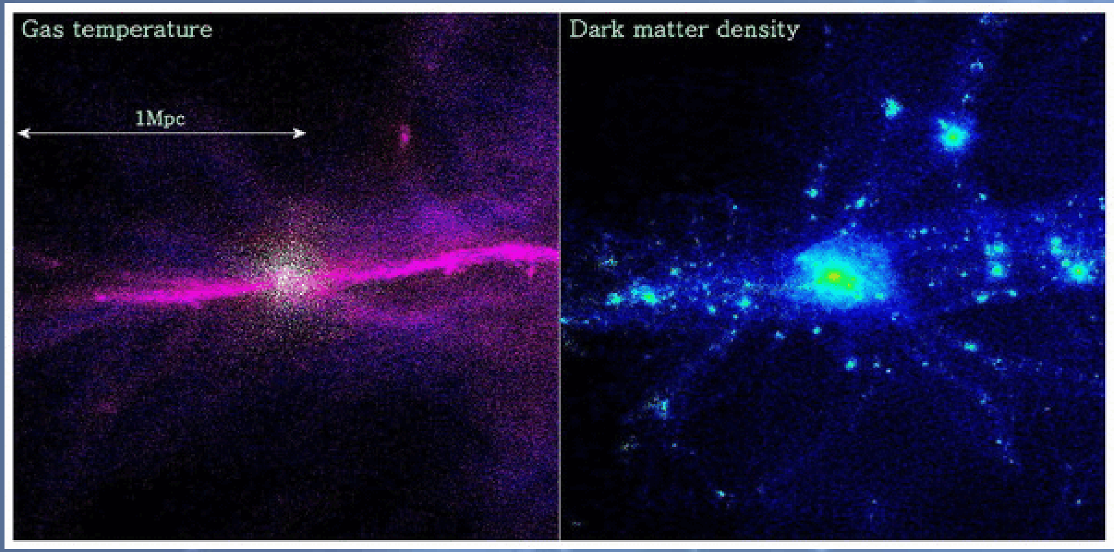
Tidal accretion of gas from outside	Polar merging of two disk galaxies

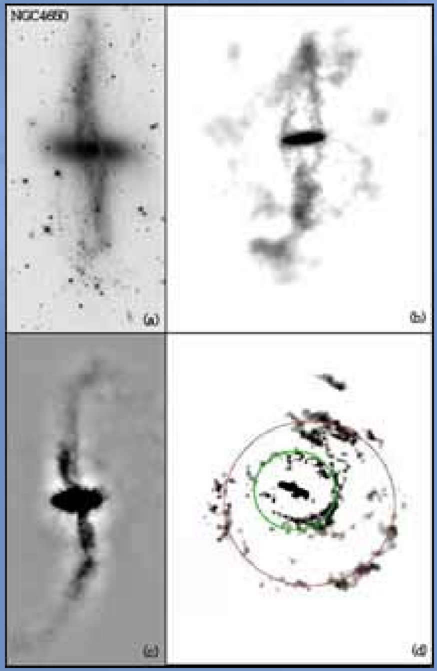
☆ The accretion scenario fails in reproducing extended disk-like polar structures with a total baryonic mass comparable with (or even larger!) that in the HG.

☆ The merging scenario fails to form massive polar disk around a rotationally supported HG.

A new mechanism for the formation of PRGs: the cold accretion

PRGs can be formed through cold gas accretion along a filament, extended for ~1Mpc, into the virialized dark matter halo (Macciò et al. 2006)

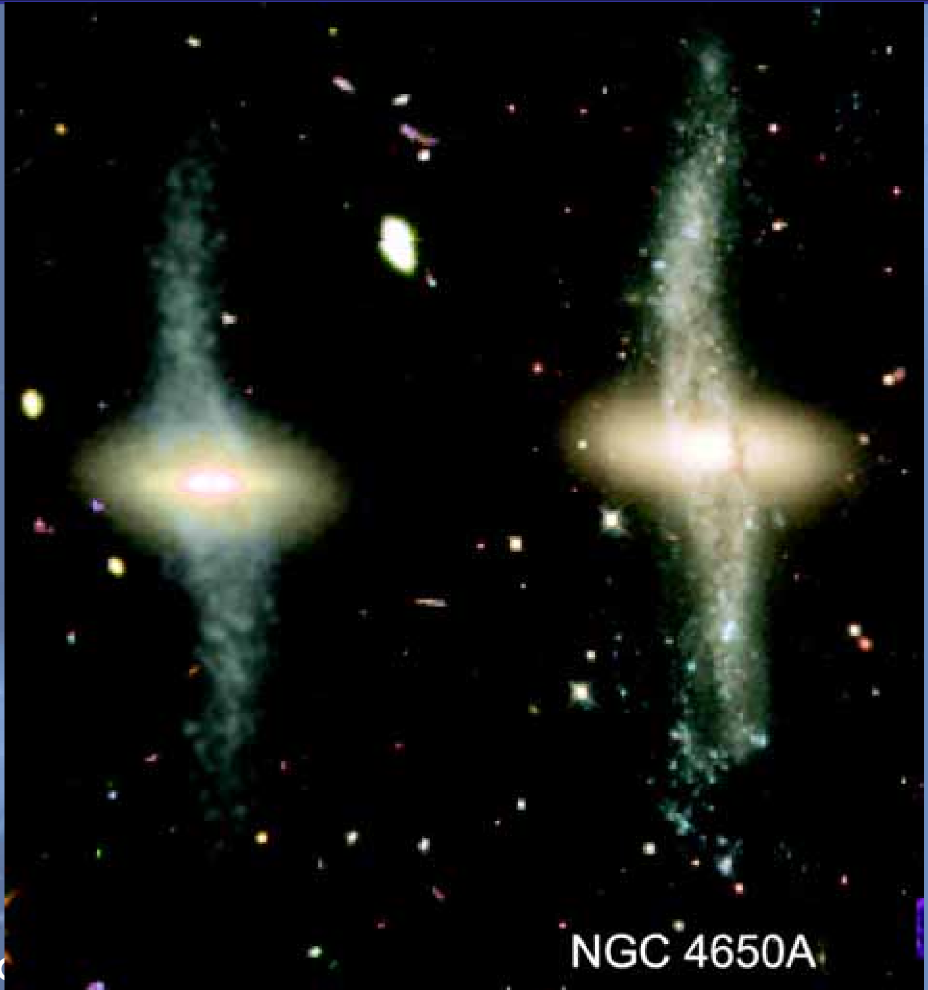




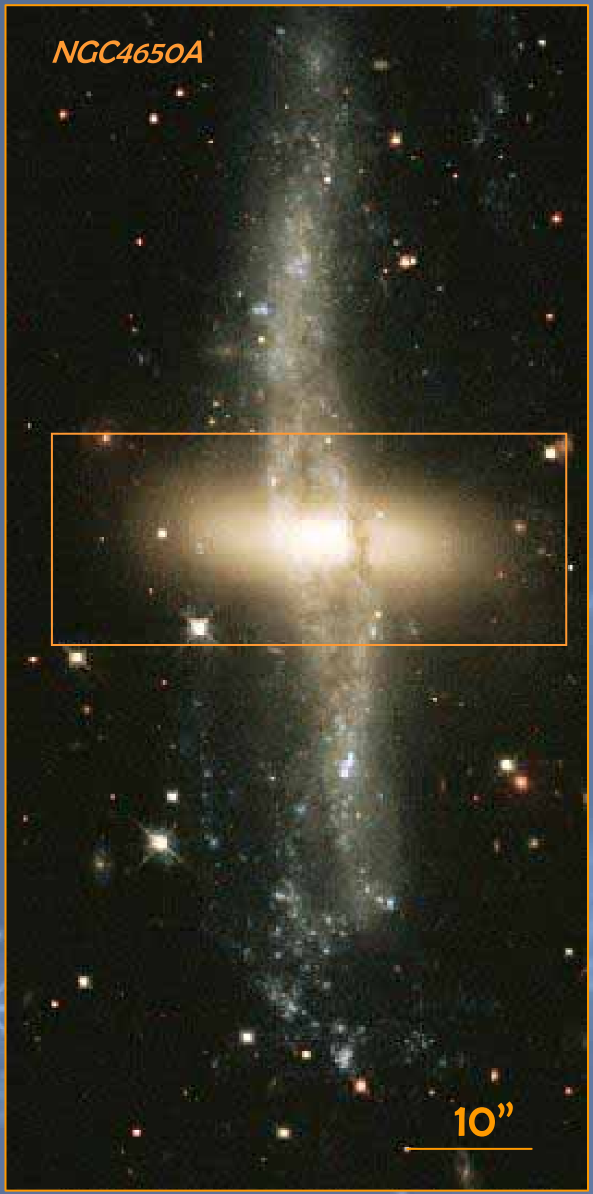
If the polar disk forms by accretion from cosmic web filaments of external cold gas, we expect metallicities similar to those of same-mass late-type galaxies.

A new mechanism for the formation of PRGs:

High-resolution cosmological simulations by Brook et al (2008) showed that polar disk galaxies can be considered as extreme examples of angular momentum misalignment



The Polar disk galaxy NGC4650A

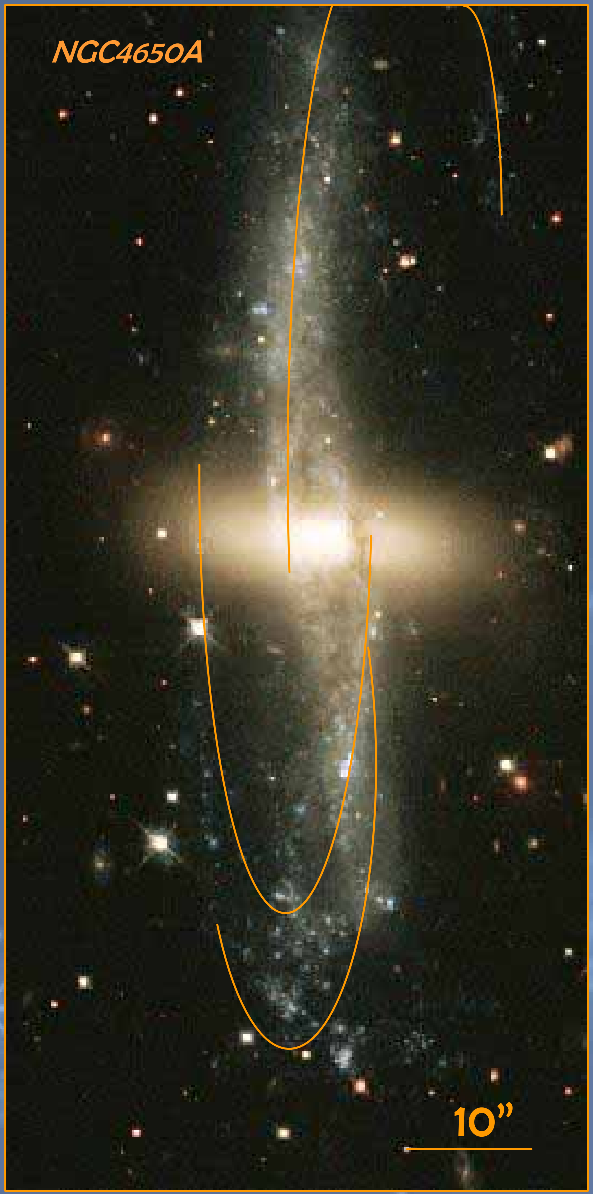


The central spheroid

☆ exponential luminosity profile and a very bright nucleus

☆ stars rotate in a disk, V_{max} ~ 80 – 100 km/s at 20 arcsec

The Polar disk galaxy NGC4650A



The polar structure

☆ Very young age (~1 Gyr) and star formation

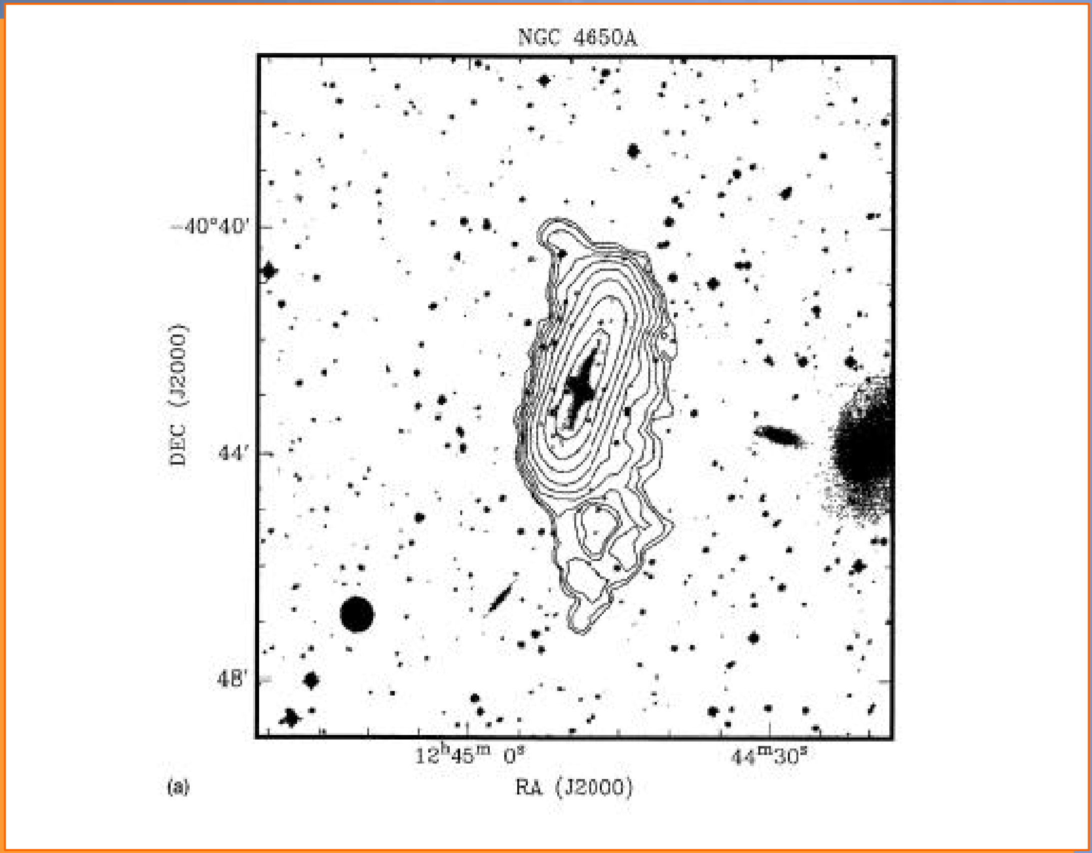
☆ Stars and gas are distributed in a disk

☆ Polar disk and luminous spheroid coexist at small radii

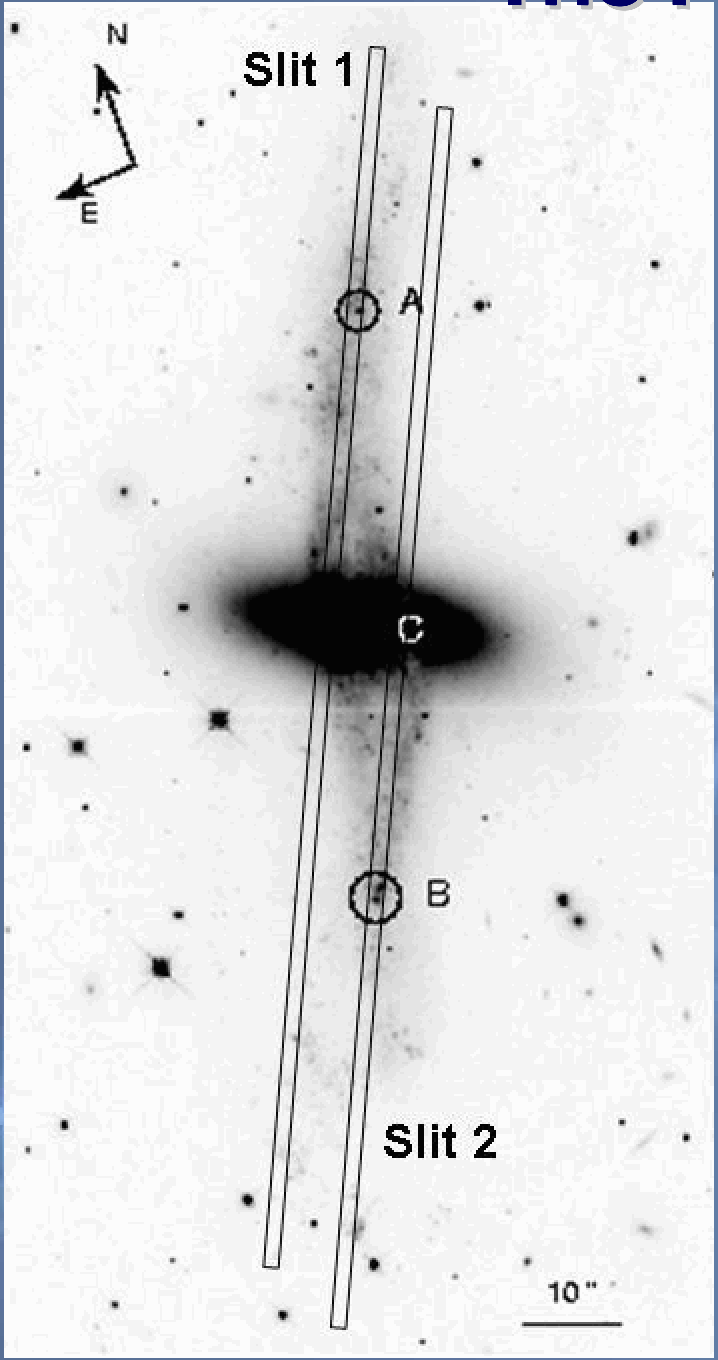
☆ High HI mass (~8 x 10^9 $M_\odot$)

The Polar disk galaxy NGC4650A

The HI is all associated to the polar structure, it extends about 4 times than the optical disk, ~ 40 kpc



The Polar disk galaxy NGC4650A



We have obtained high resolution spectroscopy with FORS2@VLT (78.B-0580 & 079.B-0177), to study the abundance ratios and metallicities of the HII regions associated to the polar disk in NGC4650A

Spectra Wavelength ranges:

3300 - 6210 Å → OII[3727], OIII[4363], OIII[4959,5007], H_{β}[4861]

5600 – 11000 Å → SII[6717,6731], H_{α}[6563], SIII[9068,9532]

Methods

☆ Empirical methods

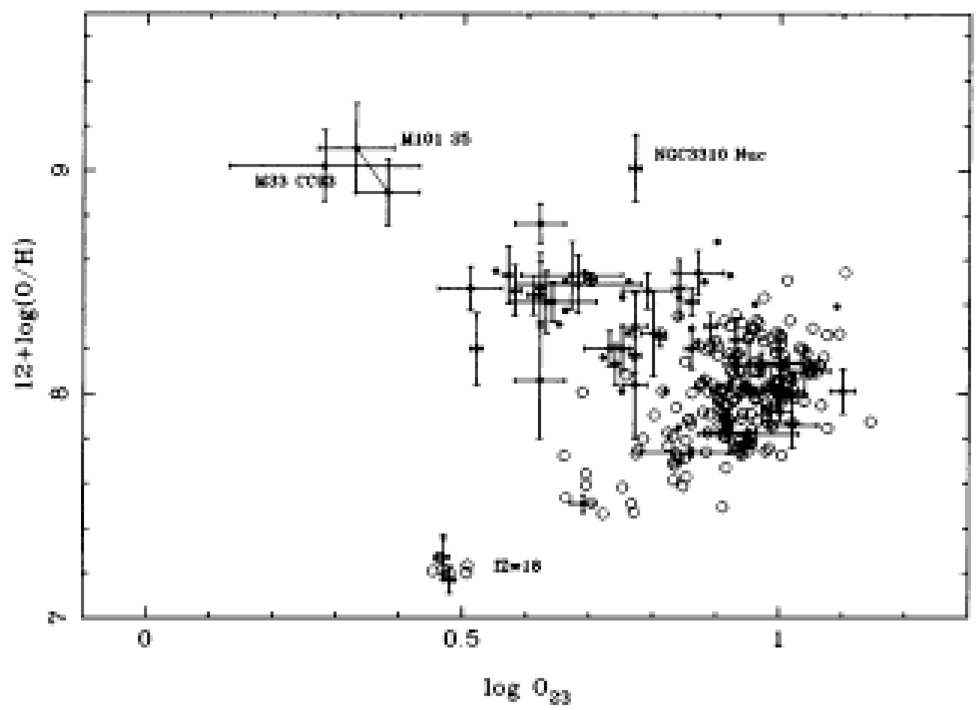
$$12 + \log(O/H) \approx f\left(R_{23} = \frac{[OII]\lambda 3727 + [OIII]\lambda 4959 + \lambda 5007}{H_\beta}\right)$$

(Pagel et al. 1979)

$$12 + \log(O/H) \approx f\left(S_{23} = \frac{[SII]\lambda 6717 + \lambda 6731 + [SIII]\lambda 9069 + \lambda 9532}{H_\beta}\right)$$

(Diaz et al. 2000)

Methods



$$12 + \log\left(\frac{O}{H}\right) = 1.53 \log S_{23} + 8.27$$

Diaz & Perez-Montero 2000, MNRAS, 312, 130

Methods

☆ Direct methods

$$12 + \log(O/H) \approx f\left(\frac{[OIII]\lambda 4959 + \lambda 5007}{H_\beta}, \frac{[OII]\lambda 3727}{H_\beta}, t_3, t_2, N_e\right)$$

(Osterbrock 1989)

The electron temperature is the fundamental parameter to directly derive the chemical abundances in the star-forming regions of galaxies.

For HII galaxies we assume a two-zone model with a low ionization zone, where the OII, NII, NeII and SII lines are formed, and a high ionization zone where the OIII, NIII, NeIII and SIII lines are formed.

Photoionization models are then used to relate the temperature of the low ionization zone t_2 to t_3, the temperature of the high ionization zone → O/H = OII/H + OIII/H

Metallicity & SFR

$$12 + \log\left(O/H\right)_{sun} = 8.83 = A_{sun}$$

$$Z_{sun} = 0.02$$

$$Z_{N4650A} \approx KZ_{sun}$$

$$K = 10^{\left[A_{N4650A} - A_{sun}\right]}$$

$$SFR = 7.9 \times 10^{-42} \times L(H_{\alpha})$$

Kennicutt (1998)

$$SFR(t) = 2M_{*}\tau^{-1}\left[1 - \left(t/\tau\right)\right]$$

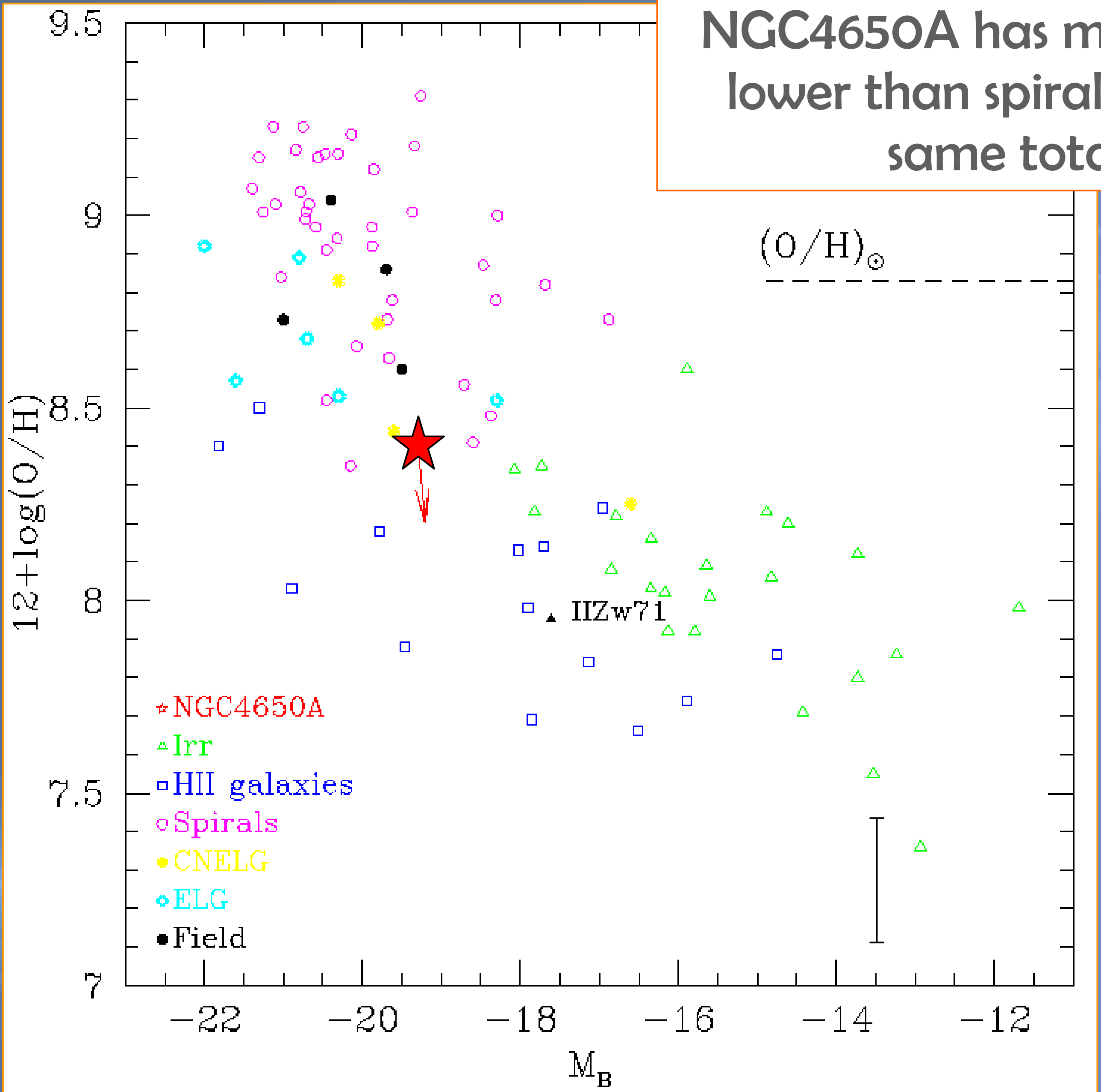
Bruzual & Charlot (2003)

$$12 + \log(O/H) = -1.492 + 1.847\log(M_{*}) - 0.08026(\log M_{*})^{2}$$

Tremonti et al. (2004)

Main results

NGC4650A has metallicity ($Z = 0.2\ Z_{\odot}$) lower than spiral galaxy disks of the same total luminosity



Marilena Spavone

Main results

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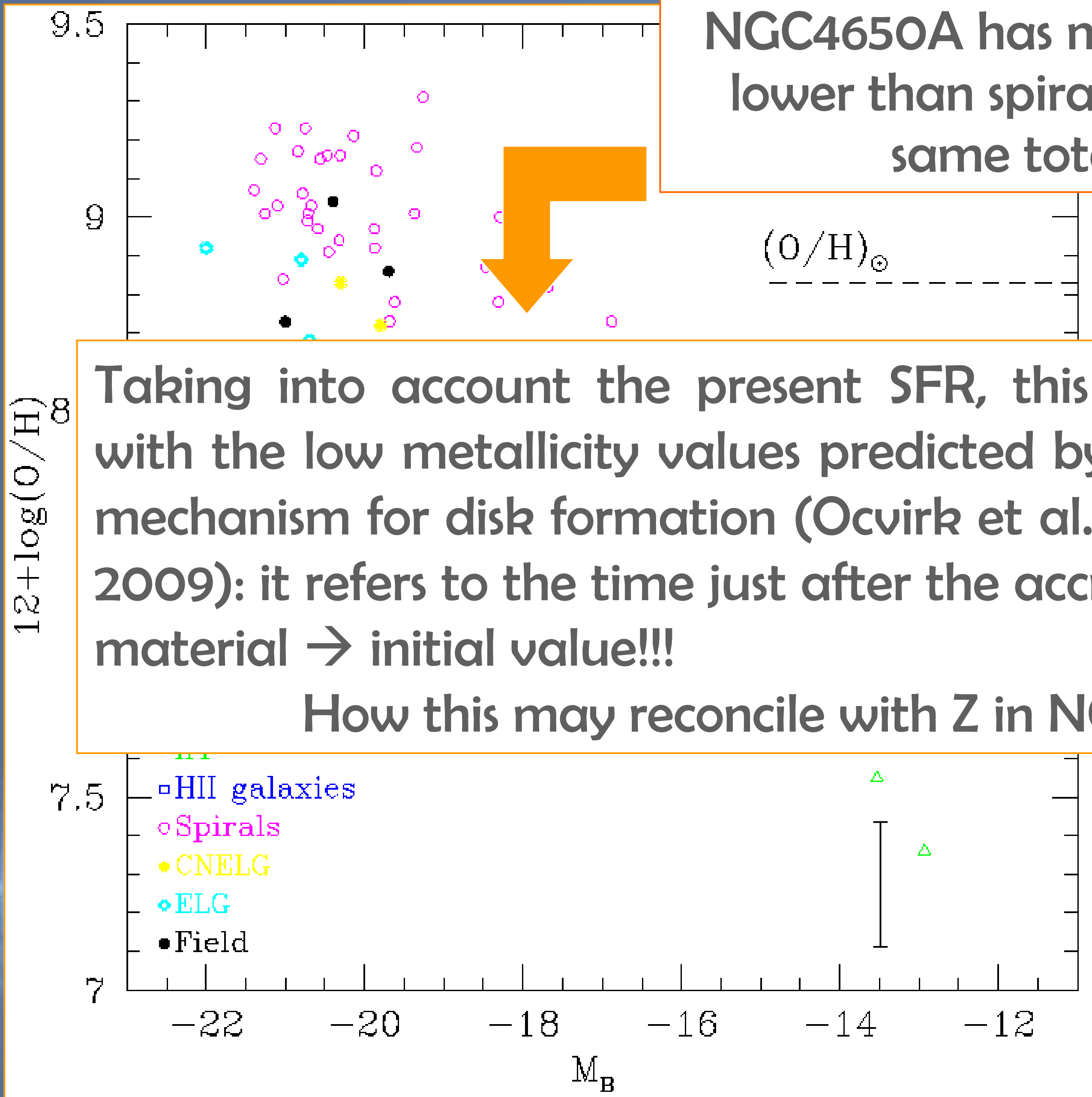
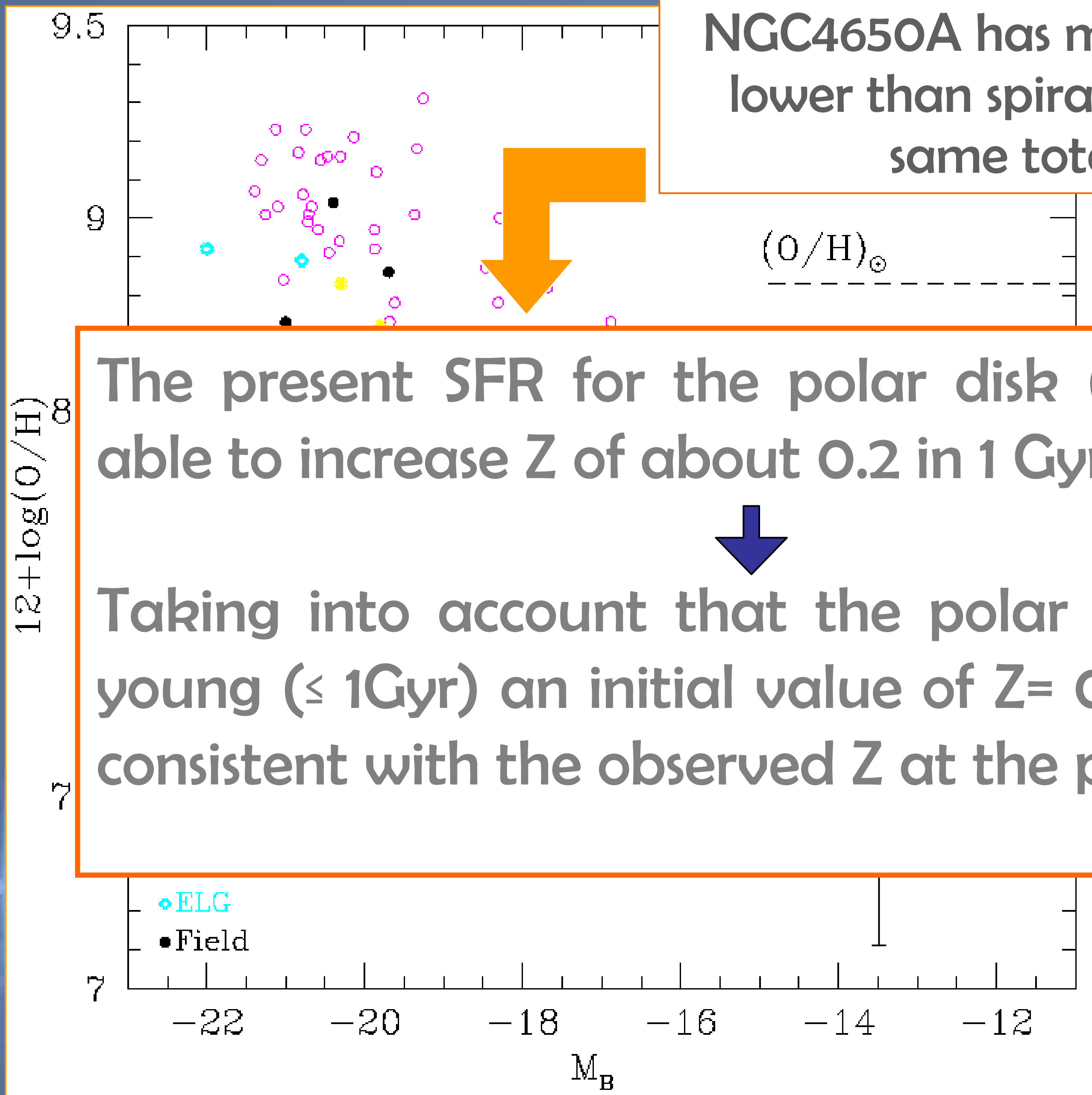


Taking into account the present SFR, this value is consistent with the low metallicity values predicted by the cold accretion mechanism for disk formation (Ocvirk et al. 2008; Agertz et al. 2009): it refers to the time just after the accretion of misaligned material → initial value!!!

How this may reconcile with Z in NGC4650A?

Main results

NGC4650A has metallicity (Z= 0.2 $Z_\odot$) lower than spiral galaxy disks of the same total luminosity



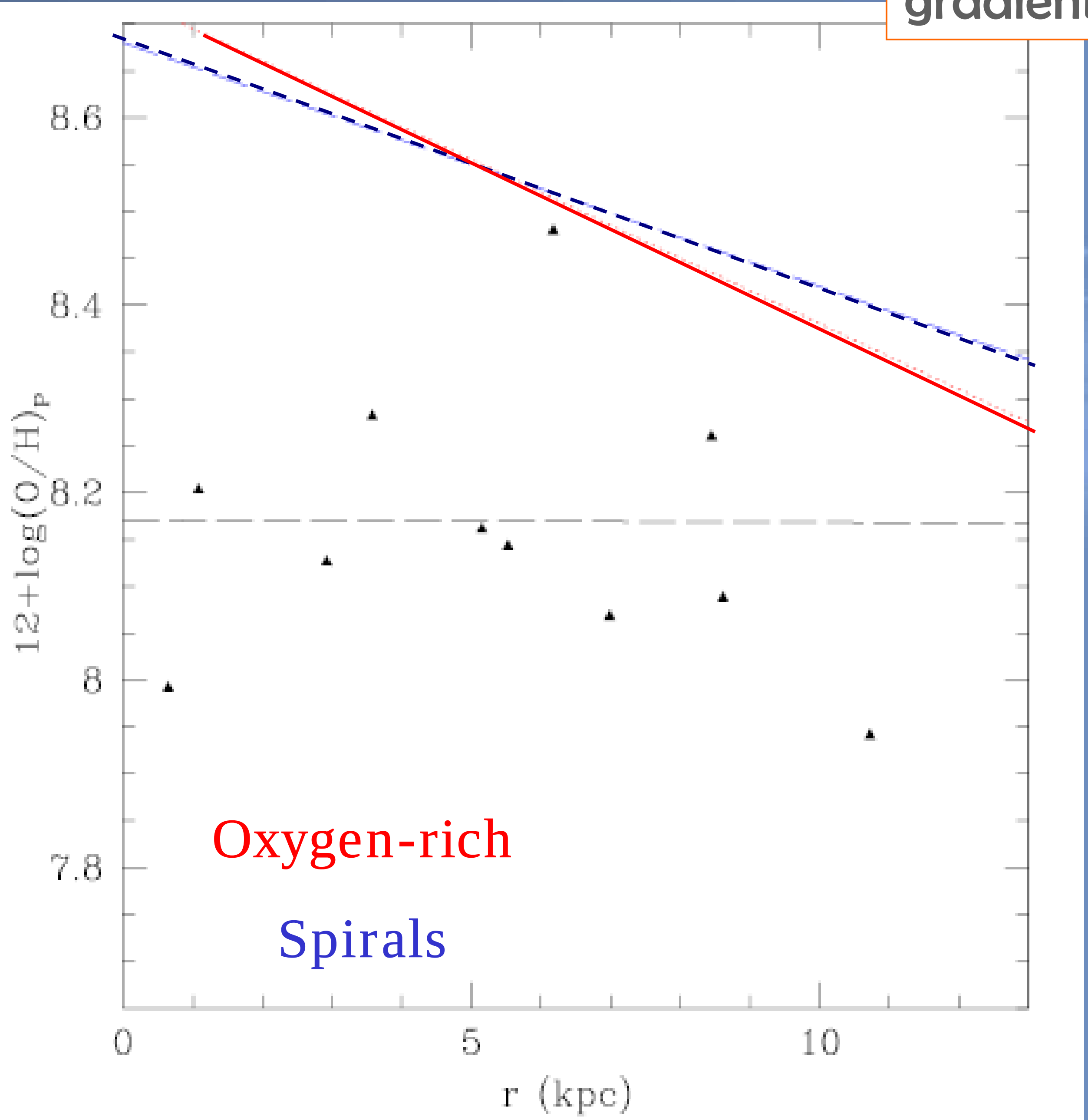
The present SFR for the polar disk (≈0.06 $M_\odot$/yr) is able to increase Z of about 0.2 in 1 Gyr

↓

Taking into account that the polar structure is very young (≲ 1Gyr) an initial value of Z= 0.1 $Z_\odot$ turns to be consistent with the observed Z at the present time

Main results

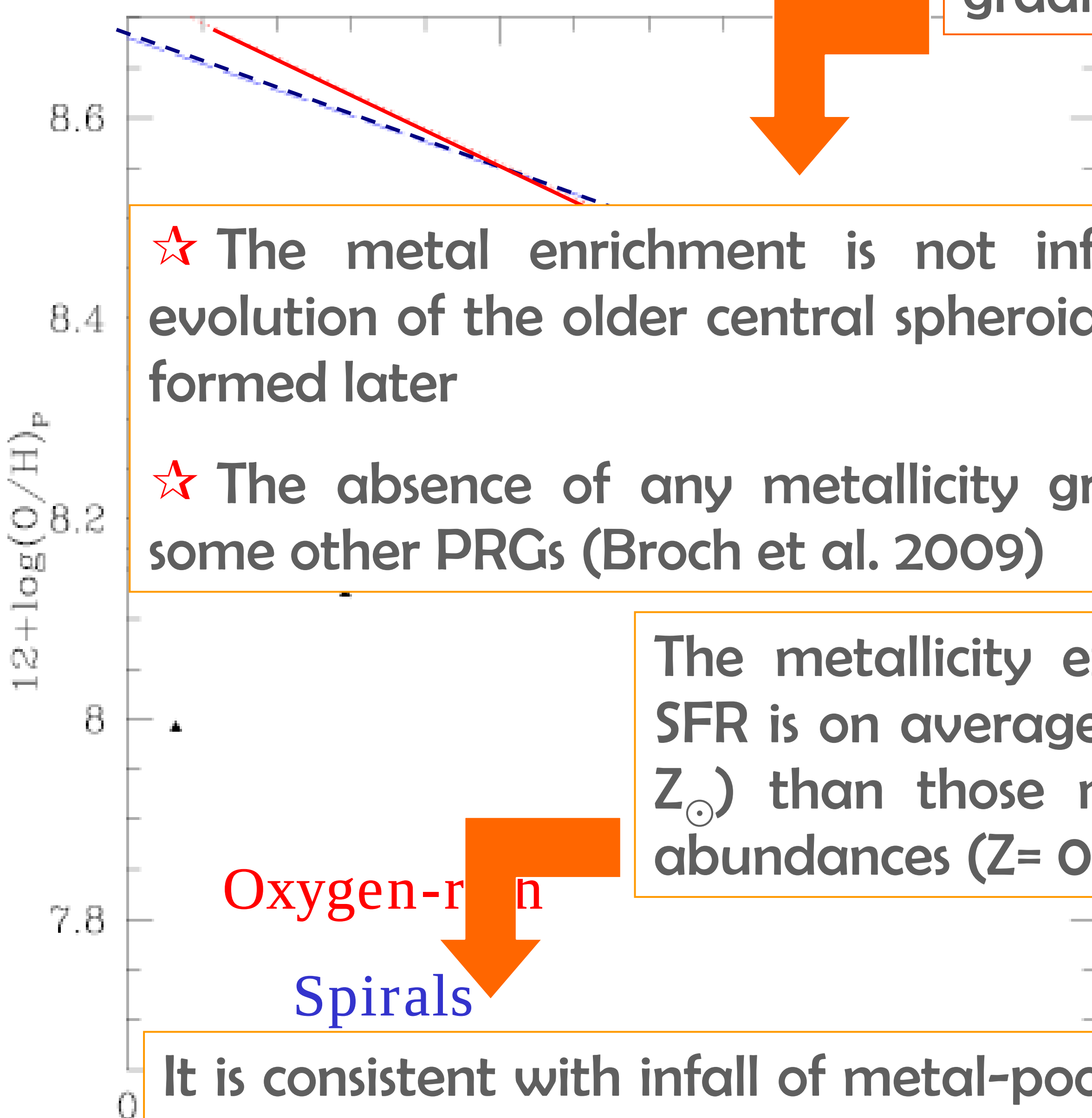
Absence of any metallicity gradient along the polar disk



Marilena Spavone

Main results

Absence of any metallicity gradient along the polar disk



☆ The metal enrichment is not influenced by the stellar evolution of the older central spheroid and, thus, the disk was formed later

☆ The absence of any metallicity gradient is also found in some other PRGs (Broch et al. 2009)

The metallicity expected for the present SFR is on average higher ($1.02\ Z_\odot \leq Z \leq 1.4\ Z_\odot$) than those measured from element abundances ($Z = 0.2\ Z_\odot$)

It is consistent with infall of metal-poor gas from outside which is still forming the disk

Main results

The low metallicity measured for NGC4650A confirmed that the tidal accretion scenario is unable to account the observed properties:

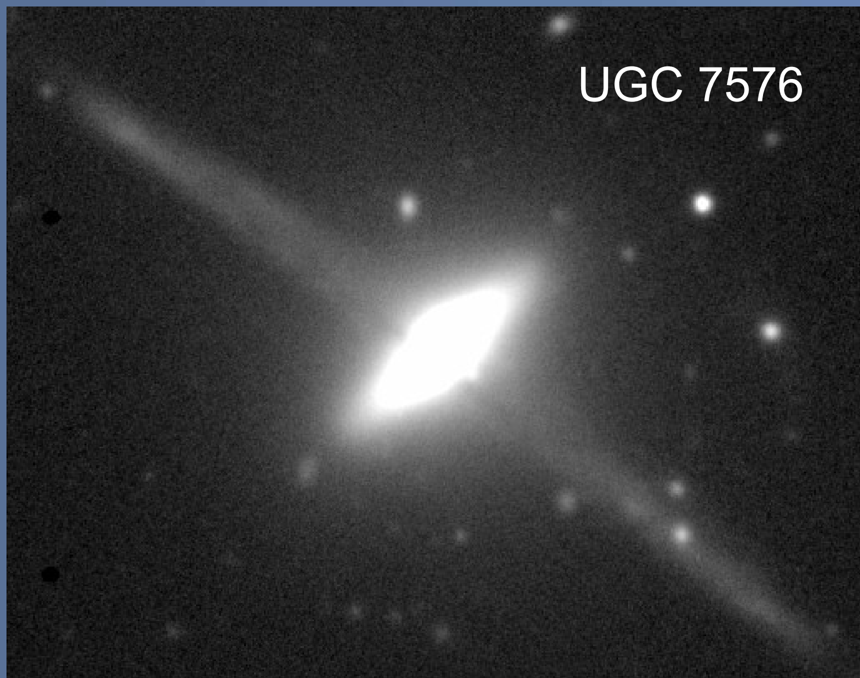
It is lower than the typical values of Z observed in the outer and more metal-poor regions of spiral galaxies (Bresolin et al. 2009)

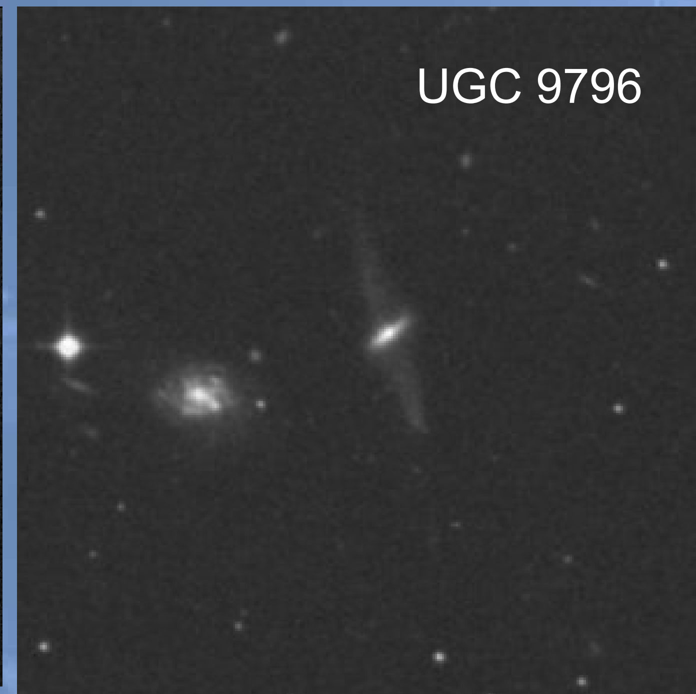
Moreover, the total amount of the accreted gas is about 10% of the gas in the donor galaxy. In NGC4650A

$$M_B^{PD} \sim 12 \times 10^9\, M_{sun} > M_B^{HG} \sim 5 \times 10^9\, M_{sun}$$

Spavone M., Iodice E., Arnaboldi M., Gerhard O., Saglia R. and Longo G., 2010, ApJ, 714, 1081

What about other PRGs?





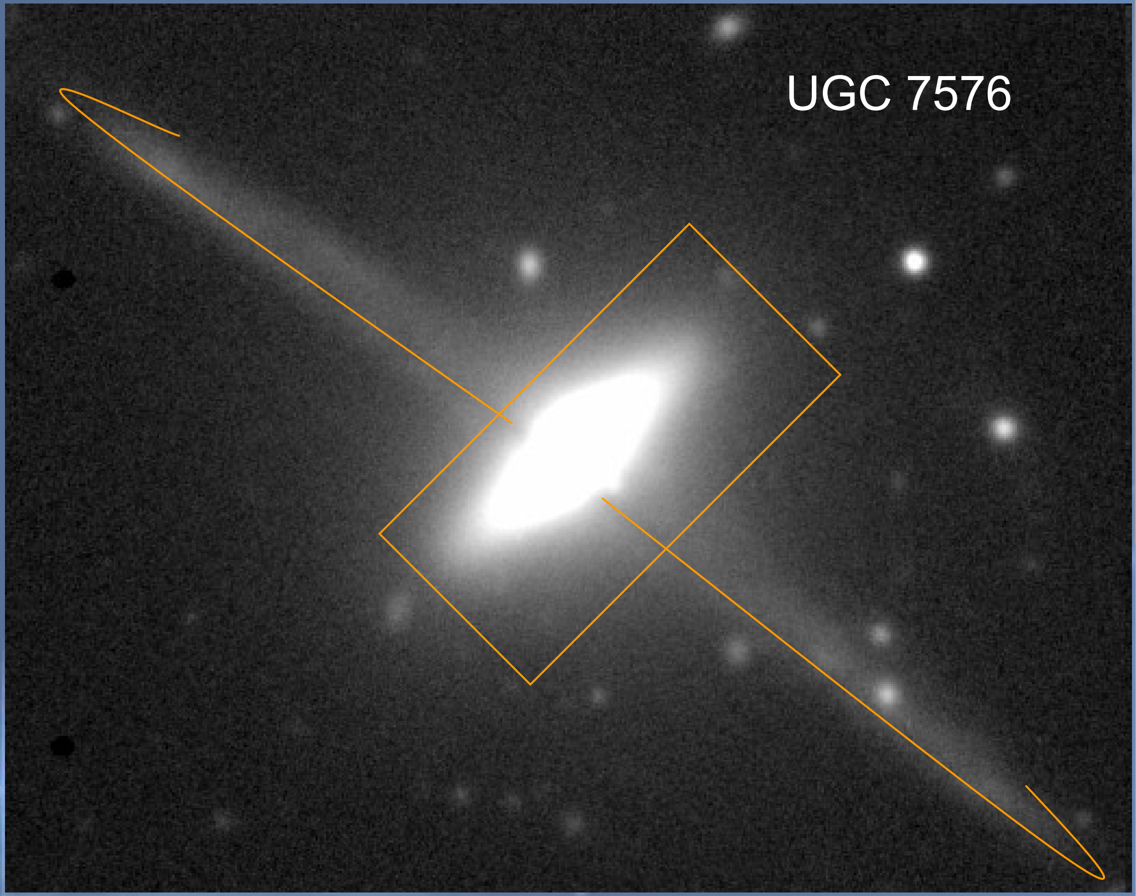
Accepted proposal at TNG telescope.

Global properties of UGC7576 and UGC9796 compared to those observed for NGC4650A.

Parameter	UGC7576	UGC9796	NGC4650A
R.A. (J2000)	12h27m41.8s	15h15m56.3s	12h44m49.0s
Decl. (J2000)	+28d41m53s	+43d10m00s	-40d42m52s
Helio. radial velocity	7022 km/s	5406 km/s	2880 km/s
Redshift	0.02342	0.01832	0.009607
Distance	94 Mpc	72 Mpc	38 Mpc
Central galaxy			
M_B	-19.15	-17.93	-18.83
B-V	+0.84	+0.92	+0.78
V-R	+0.46	+0.55	
Polar structure			
M_B	-17.5	-17.0	-17.0
$M(HI)(M_\odot)$	2.7×10^9	2.6×10^9	8.0×10^{9a}
$M(HI)/L_B$	0.6	1.5	4
B-V	$+0.70^b$	$+0.57^b$	$+0.26^c$
μ_B	24.3	24.5	22.6
R_{25}	13.6	10.8	7.0
r_{max}	40″	60″	40″

The polar ring galaxy UGC7576

Kinematically confirmed Polar Ring Galaxy (Whitmore et al. 1990)



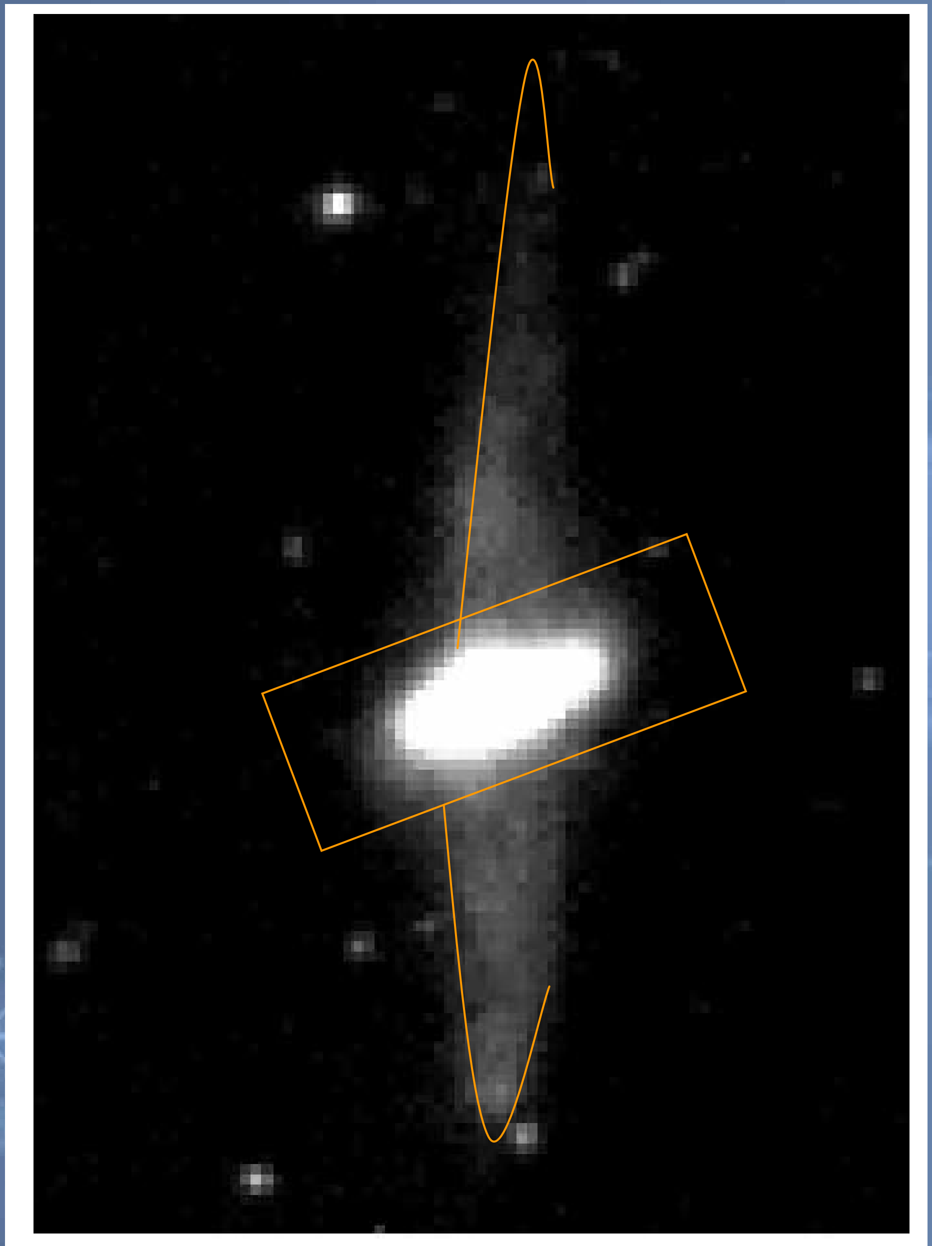
The polar structure

- ☆ More similar to a ring rather than a disk
- ☆ A narrow polar ring crossing the center of the HG
- ☆ Warping of the ring

The central spheroid

- ☆ Main body with elliptical isophotes
- ☆ High rotational velocity (~ 212 km/s)

The polar ring galaxy UGC9796



The polar structure

☆ Non-polar PRG

☆Rotating disk rather than a ring

☆ Warping of the disk

The central spheroid

☆ S0, rotationally supported

☆ High rotational velocity (~ 157 km/s)

Methods

The P-method

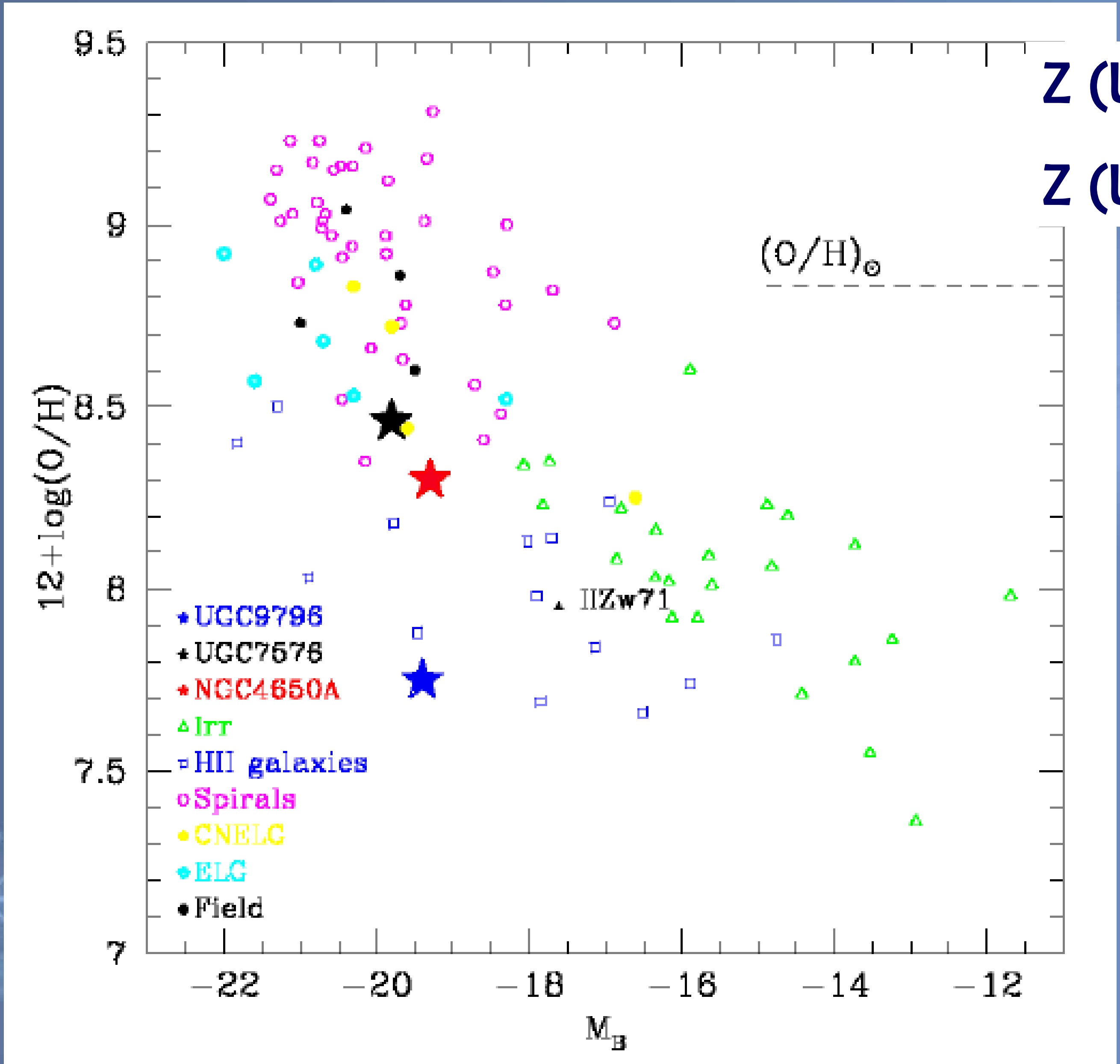
Pilyugin (2001) realized that for fixed oxygen abundances the value of X23=logR23 varies with the excitation parameter P=R3/R23, where R3=OIII[4959 + 5007]/Hß and proposed that this latter parameter could be used in the oxygen abundance determination.

$$R_{23} = \frac{[OII]\lambda 3727 + [OIII]\lambda 4959 + \lambda 5007}{H_{\beta}}$$

(Pagel et al. 1979)

$$12 + \log(O/H)_P = \frac{R_{23} + 54.2 + 59.45P + 7.31P^2}{6.07 + 6.71P + 0.371P^2 + 0.243R_{23}}$$

Results

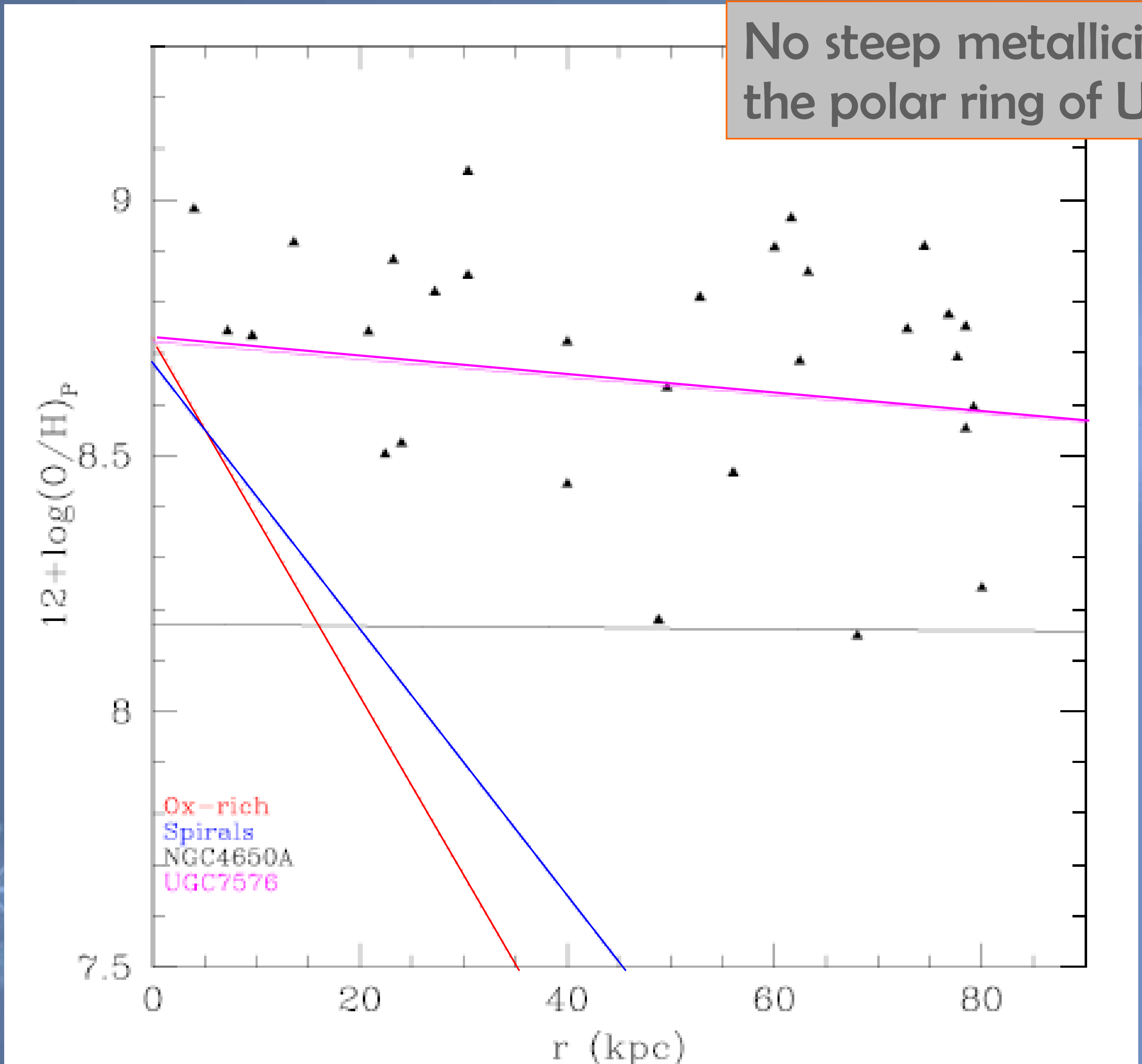


Z (UGC7576) = 0.4 Z⊙

Z (UGC9796) = 0.1 Z⊙

Both PRGs have metallicities lower than spiral galaxy disks of the same total luminosity.

Results



No steep metallicity gradient along the polar ring of UGC7576

Mass-Metallicity relation

$$SFR = 7.9 \times 10^{-42} \times L(H_\alpha)$$

Kennicutt (1998)

Given the absence of star-forming clumps we use an exponentially declining SFR, started at t_0 = 8 Gyrs and with a decay timescale τ = 2 Gyrs:

$$SFR(t) = M_* \tau^{-1} \exp\left[-(t - t_0)/\tau\right]$$

Bruzual & Charlot (2003)

$$12 + \log(O/H) = -1.492 + 1.847 \log(M_*) - 0.08026(\log M_*)^2$$

Tremonti et al. (2004)

Results

The metallicity expected for the present SFR are

UGC7576	UGC9796
$0.5\ Z_\odot \leq Z \leq 1\ Z_\odot$	$0.05\ Z_\odot \leq Z \leq 0.45\ Z_\odot$

↓ UGC7576: On average higher than those measured from element abundances ($Z= 0.4\ Z_\odot$)

↓ UGC9796: On average consistent with those measured from element abundances ($Z= 0.1\ Z_\odot$)

Results

Key parameters for formation scenarios

PRG	M_B^{HG}	M_B^{PD}	V_{eq}	V_{eq}/V_{PD}	σ_0	v/σ	Z_{est}	Z_{exp}
UGC7576	7.9×10^9	2.9×10^9	212	0.96	116	1.8	0.4	$0.5 \div 1$
UGC9796	1.0×10^{10}	3.0×10^9	157	1.08	73	2.15	0.1	$0.05 \div 0.45$
NGC4650A	5.0×10^9	12×10^9	90	0.75	70	1.28	0.2	$1.02 \div 1.4$

Baryonic mass

Kinematics

Metallicity & SFR

Results

Key parameters for formation scenarios

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NGC4650A	5.0×10^9	12×10^9	90	0.75	70	1.28	0.2	1.02 1.4

The *merging scenario* is ruled out for both UGC7576 and UGC9796 due to the high maximum rotation velocity in the equatorial plane

Results

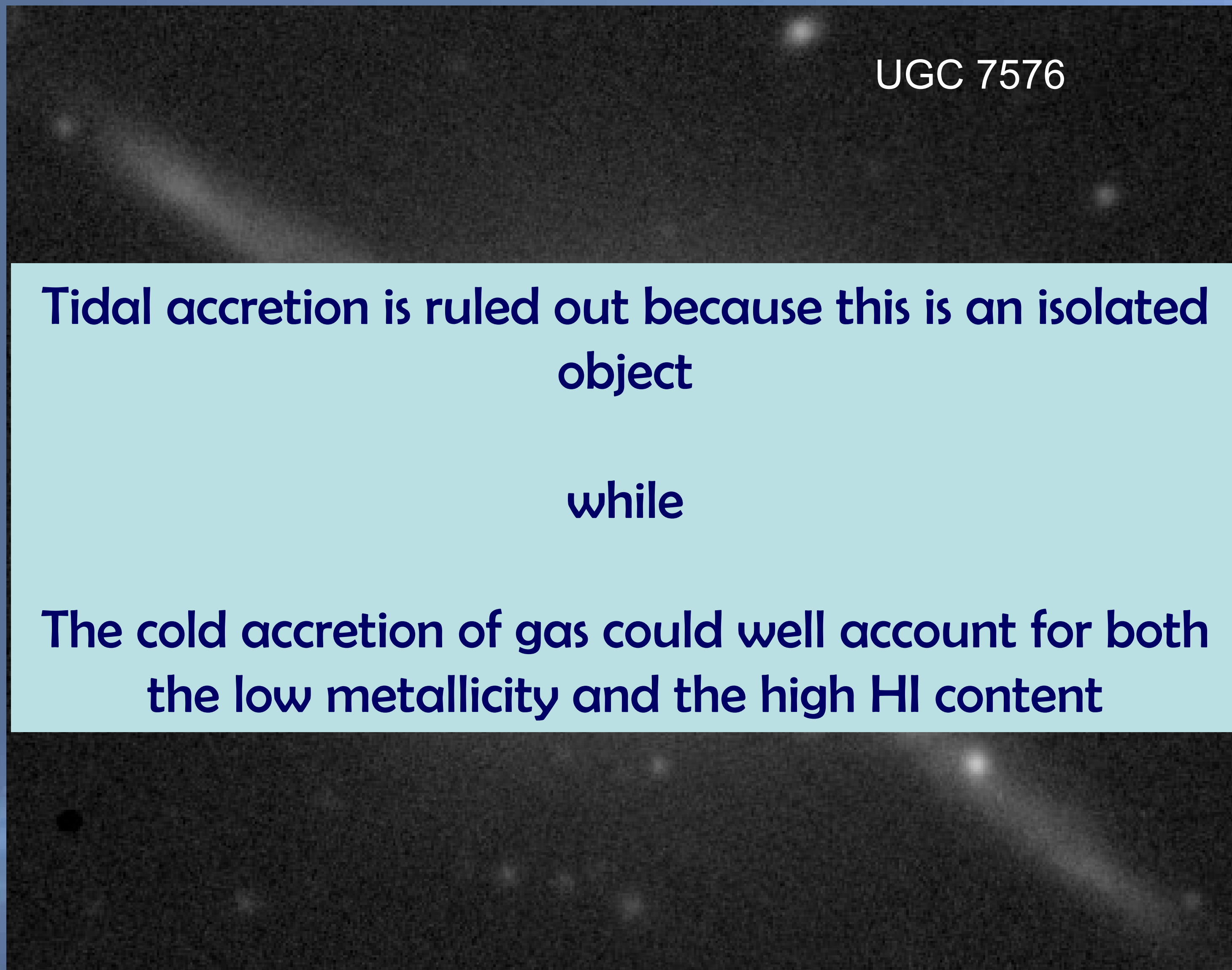
Key parameters for formation scenarios

PRG	M_B^{HG}	M_B^{PD}	V_{eq}	V_{eq}/V_{PD}	σ_0	v/σ	Z_{est}	Z_{exp}
UGC7576	7.9×10^9	2.9×10^9	212	0.96	116	1.8	0.4	0.5 1
UGC9796	1.0×10^{10}	3.0×10^9	157	1.08	73	2.15	0.1	0.05 0.45
NGC4650A	5.0×10^9	12×10^9	90	0.75	70	1.28	0.2	1.02 1.4

The high baryonic mass, the large extensions of the polar structures and the low metallicity in UGC7576 and UGC9796 are not accounted for the formation of PRGs through the *tidal disruption of a dwarf galaxy*

Results

Tidal versus Cold accretion



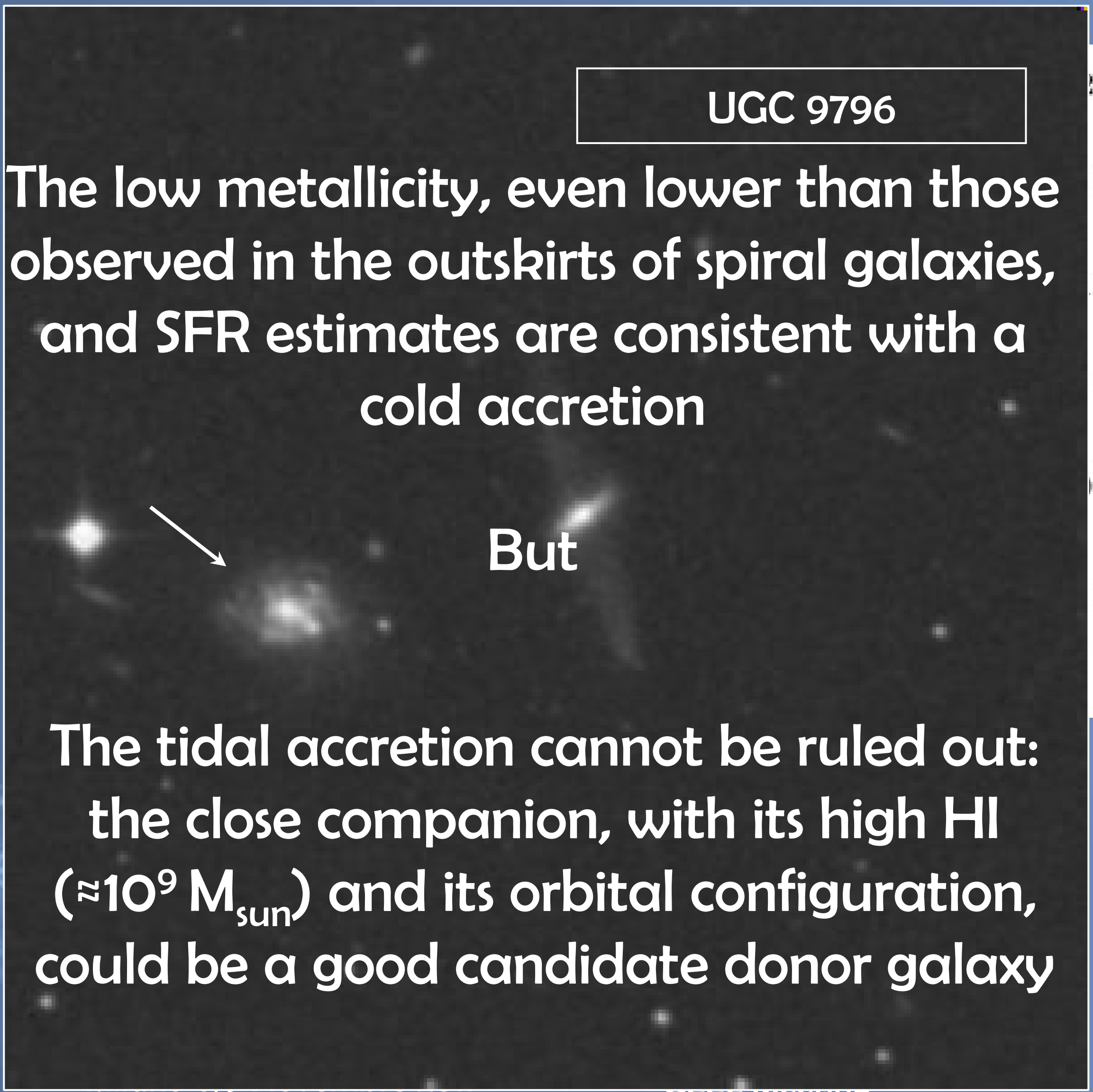
Tidal accretion is ruled out because this is an isolated object

while

The cold accretion of gas could well account for both the low metallicity and the high HI content

Results

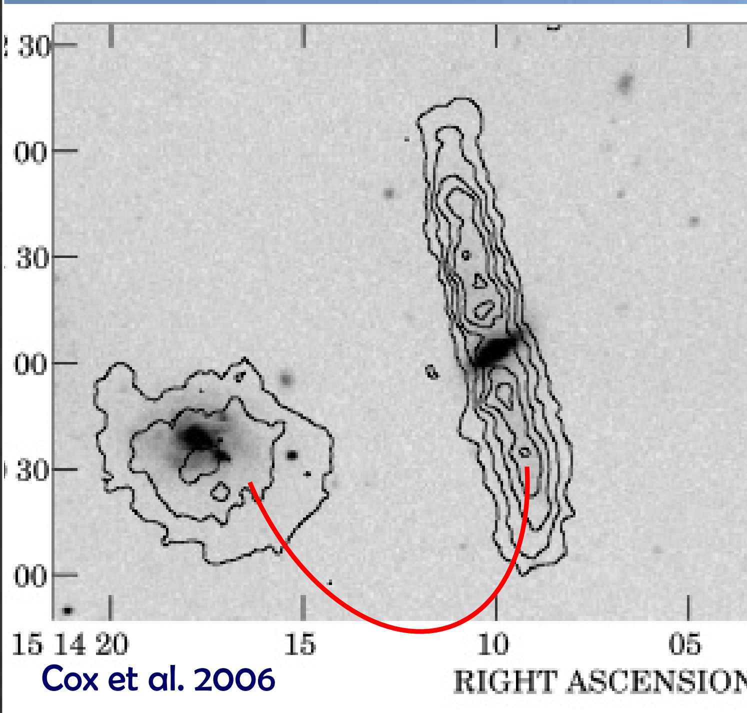
Tidal versus Cold accretion



The low metallicity, even lower than those observed in the outskirts of spiral galaxies, and SFR estimates are consistent with a cold accretion

But

The tidal accretion cannot be ruled out: the close companion, with its high HI ($\approx 10^9 M_{sun}$) and its orbital configuration, could be a good candidate donor galaxy



Cox et al. 2006

Summary and conclusions

Spavone M., Iodice E., Arnaboldi M., Longo G., and Gerhard O., 2011, A&A, 531, 21.

- Chemical abundances of the HII regions of the polar structures have been used to estimate the metallicities of the PRGs
- Present and expected SFR have been estimated
- Both PRGs have metallicities lower than spirals of same total luminosity
- UGC7576 has no close companion, so we can rule out the tidal accretion from a donor galaxy as well as the merging with a dwarf galaxy
- For UGC9796 we can exclude the merging scenario because of the high mass ratios required to form a similar polar disk. However there are 5 close companion galaxies, so both the tidal and cold accretion are plausible.

Follow up

TNG proposal submitted:

Name	α	δ	Info
IC689	01 23 48	33 03 19	Wide PRG
NGC442	01 14 39	-01 01 14	Narrow PRG
NGC660	01 40 21	13 23 18	Multiple
NGC7468	23 02 59	16 36 19	Inner PD

ESO proposal submitted:

Name	α	δ	Info
A0136	01 38 55	-07 45 56	Wide PRG
ESO415	02 28 20	-31 52 52	Narrow PRG
ARP230	00 46 24	-13 26 32	Narrow PRG
ESO235	21 06 28	-48 07 16	Wide PRG
ESO603	22 51 22	-20 14 50	Narrow PRG
ESO474	00 47 07	-24 22 14	Multiple
AM2020	20 23 55	-50 39 07	Narrow PRG

Thank you