Unveiling the structure of LSB galaxies with SHARP

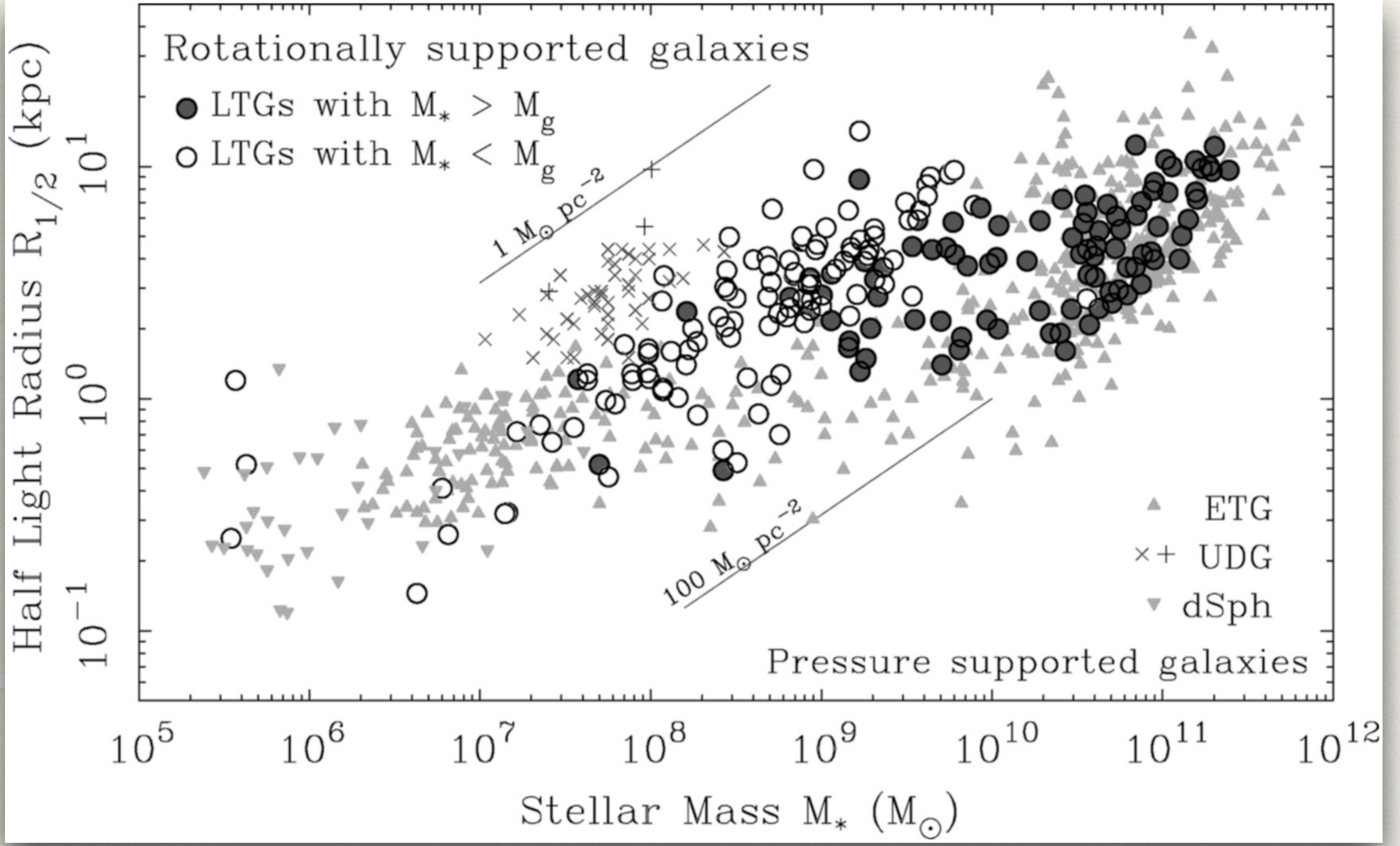
Enrichetta Iodice
INAF-Astronomical Observatory of Capodimonte

Outline of this talk

- Science case: low-surface brightness galaxies
- Lesson learned from IFS for LSB galaxies: the LEWIS project
- What next with SHARP?

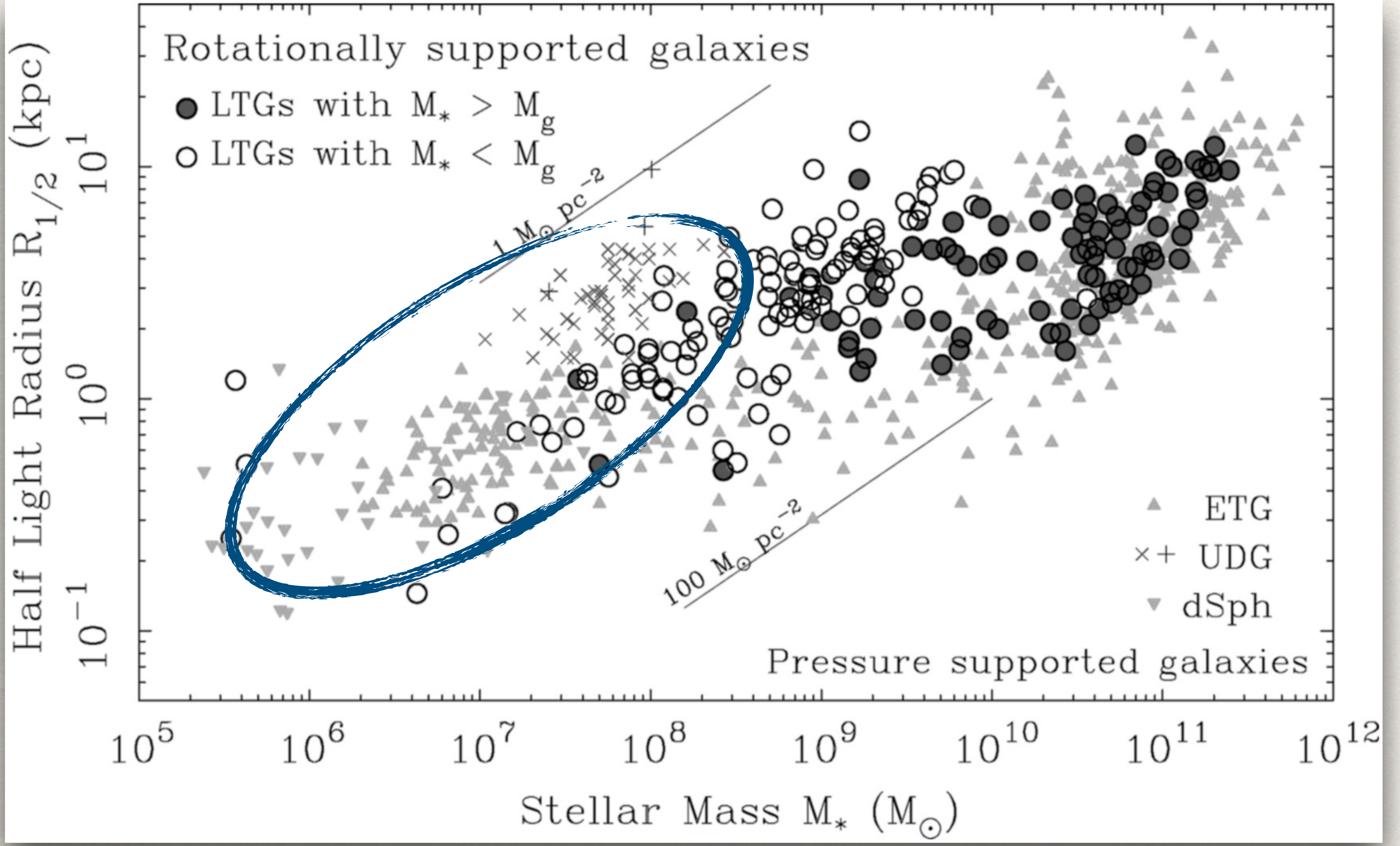
INAF
ISTITUTO NAZIONALE DI ASTROFISICA

Science case: LSB galaxies



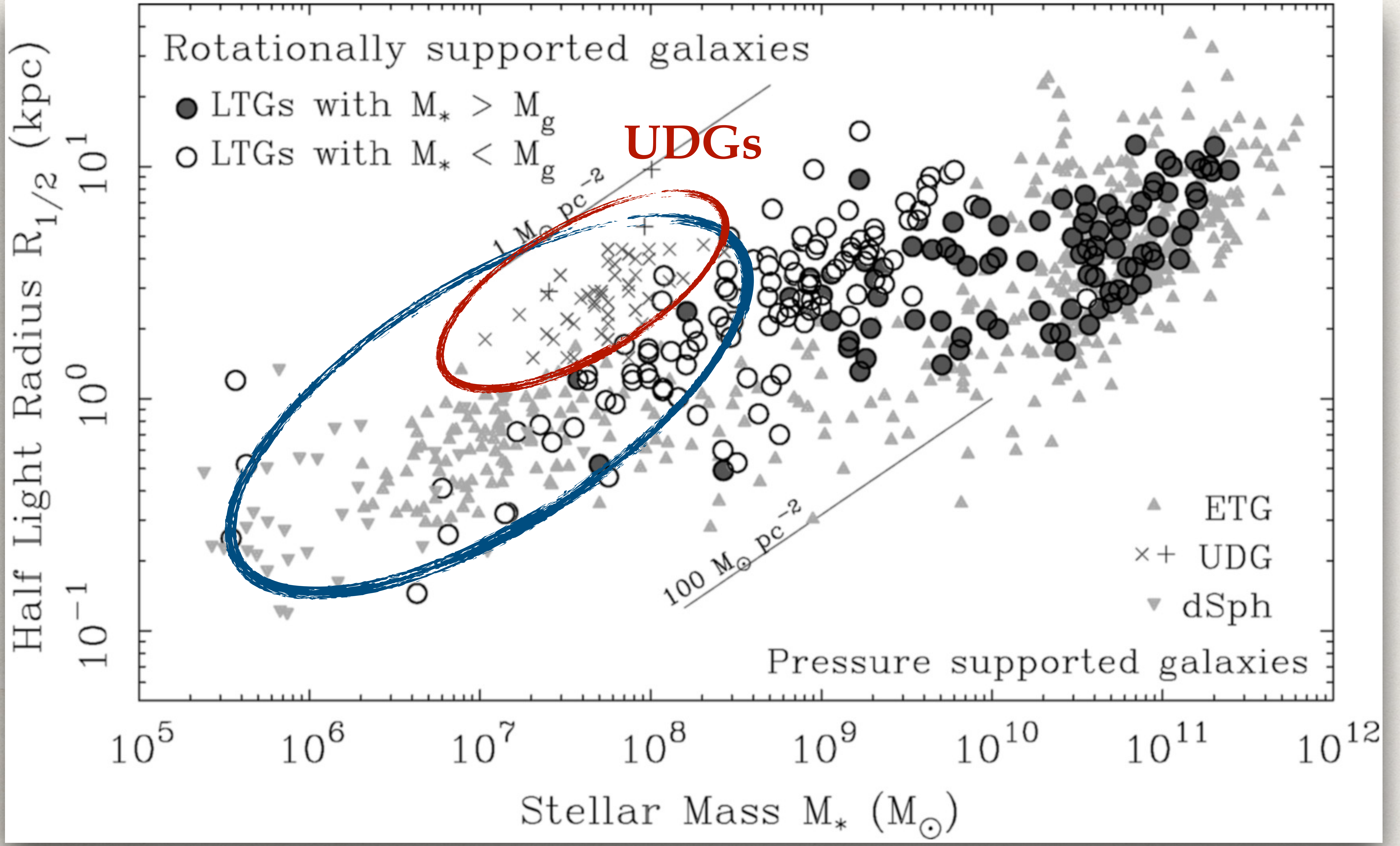
INAF
ISTITUTO NAZIONALE
DI ASTROFISICA

Science case: LSB galaxies



$10^7 < M_* < 10^8\ M_\odot$

Science case: LSB galaxies



$10^7 < M_* < 10^8\ M_\odot$

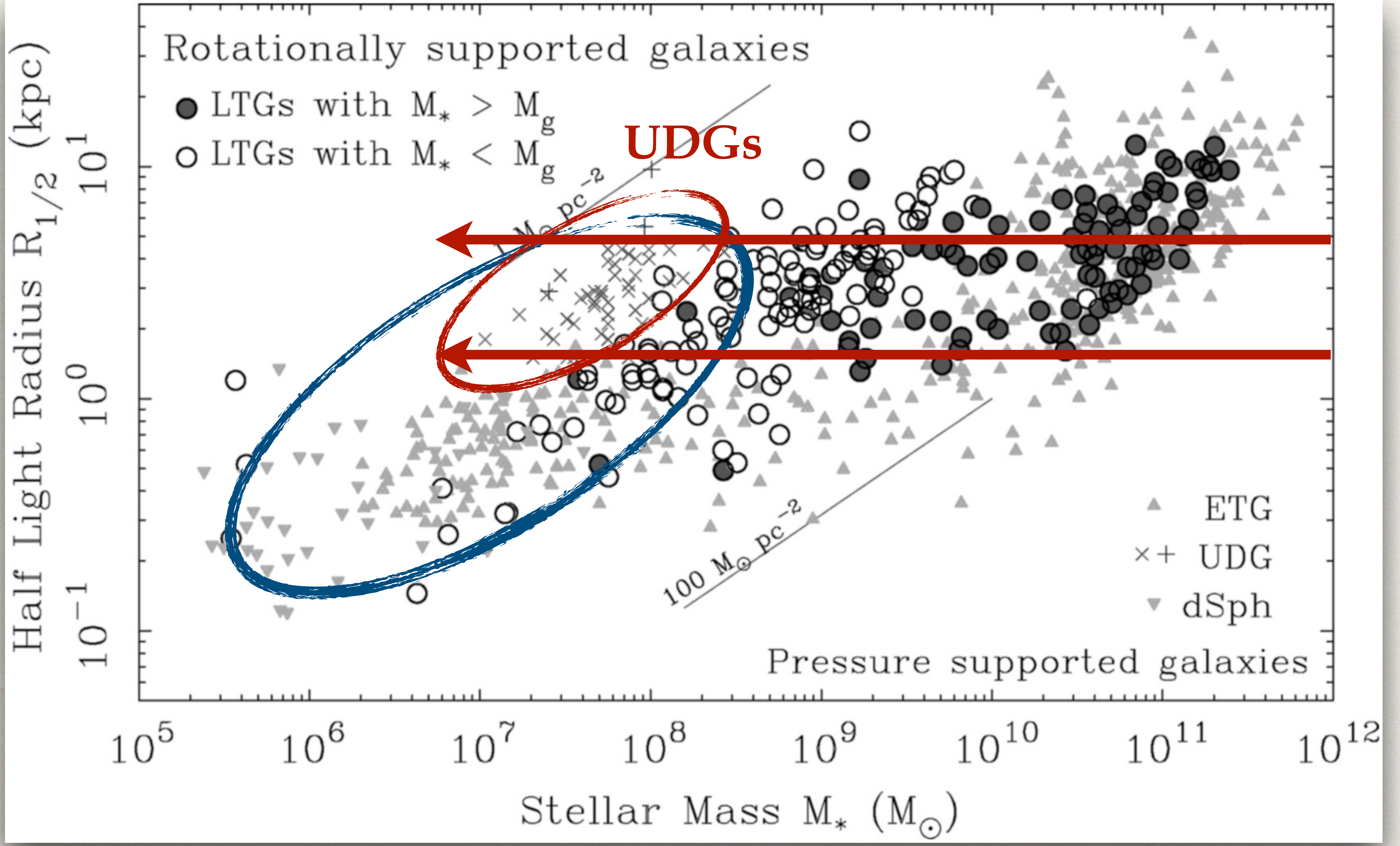
$1.5 \leq Re \leq 4.6$ kpc

$\mu_{0,g} \geq 24$ mag/arcsec^2

$M_* \sim 10^8\ M_\odot$

INAF
ISTITUTO NAZIONALE DI ASTROFISICA

Science case: LSB galaxies



$1.5 \leq Re \leq 4.6$ kpc

$\mu_{0,g} \geq 24$ mag/arcsec^2

$M_* \sim 10^8 M_\odot$

$10^7 < M_* < 10^8 M_\odot$

INAF ISTITUTO NAZIONALE DI ASTROFISICA

Science case: LSB galaxies

Lim et al. 2020

Science case: LSB galaxies

State of the art: observations vs theoretical predictions

Color

Kinematics

Stellar pop

DM content

GCs

INAF
ISTITUTO NAZIONALE
DI ASTROFISICA

Science case: LSB galaxies

State of the art: observations vs theoretical predictions

Color

Kinematics

Stellar pop

DM content

GCs

INAF
ISTITUTO NAZIONALE
DI ASTROFISICA

Science case: LSB galaxies

State of the art: observations vs theoretical predictions

blue population of UDGs in low-density regions ← **Color** → *red and quenched UDGs, in clusters*

Kinematics

Stellar pop

DM content

GCs

INAF
ISTITUTO NAZIONALE DI ASTROFISICA

Science case: LSB galaxies

State of the art: observations vs theoretical predictions

blue population of UDGs in low-density regions ← **Color** → *red and quenched UDGs, in clusters*

Low velocity dispersion ← **Kinematics** → *no rotation ?*

Stellar pop

DM content

GCs

INAF
ISTITUTO NAZIONALE DI ASTROFISICA

Science case: LSB galaxies

State of the art: observations vs theoretical predictions

blue population of UDGs in low-density regions ← **Color** → *red and quenched UDGs, in clusters*

Low velocity dispersion ← **Kinematics** → *no rotation ?*

old systems ~ 9 Gyr metal-poor ($-0.5 \lesssim [M/H] \lesssim -1.5$ dex) ← **Stellar pop** → *younger & star forming*

DM content

GCs

INAF
ISTITUTO NAZIONALE
DI ASTROFISICA

LEWIS

Science case: LSB galaxies

State of the art: observations vs theoretical predictions

blue population of UDGs in low-density regions ← **Color** → *red and quenched UDGs, in clusters*

Low velocity dispersion ← **Kinematics** → *no rotation ?*

old systems ~ 9 Gyr metal-poor ($-0.5 \leq [M/H] \leq -1.5$ dex) ← **Stellar pop** → *younger & star forming*

DM dominated ($M_h \geq 10^{11} M_\odot$) ← **DM content** → *dwarf-like DM ($M_h \sim$ 10-100 $M_\odot$)*

DM-free ← **DM content**

GCs

INAF
ISTITUTO NAZIONALE DI ASTROFISICA

Science case: LSB galaxies

State of the art: observations vs theoretical predictions

Observations		Theoretical predictions
blue population of UDGs in low-density regions	← **Color** →	red and quenched UDGs, in clusters
Low velocity dispersion	← **Kinematics** →	no rotation ?
old systems ~ 9 Gyr metal-poor ($-0.5 \leq [M/H] \leq -1.5$ dex)	← **Stellar pop** →	younger & star forming
DM dominated ($M_h \geq 10^{11} M_\odot$) DM-free	← **DM content** →	dwarf-like DM ($M_h \sim 10\text{-}100\ M_\odot$)
UDGs in Coma: large S_N	← **GCs** →	dwarf-like S_N

INAF
ISTITUTO NAZIONALE DI ASTROFISICA

Science case: LSB galaxies

State of the art: observations vs theoretical predictions

Failed L_* ($M_* \sim 10^{11}\ M_\odot$) galaxies (van Dokkum et al. 2015)

lost gas supply at an early epoch, which prevented the formation of normal, higher surface-brightness systems

UDG is red, quenched, metal poor & old
gas poor
DM dominated

INAF
ISTITUTO NAZIONALE
DI ASTROFISICA

Science case: LSB galaxies

State of the art: observations vs theoretical predictions

Internal processes

External processes

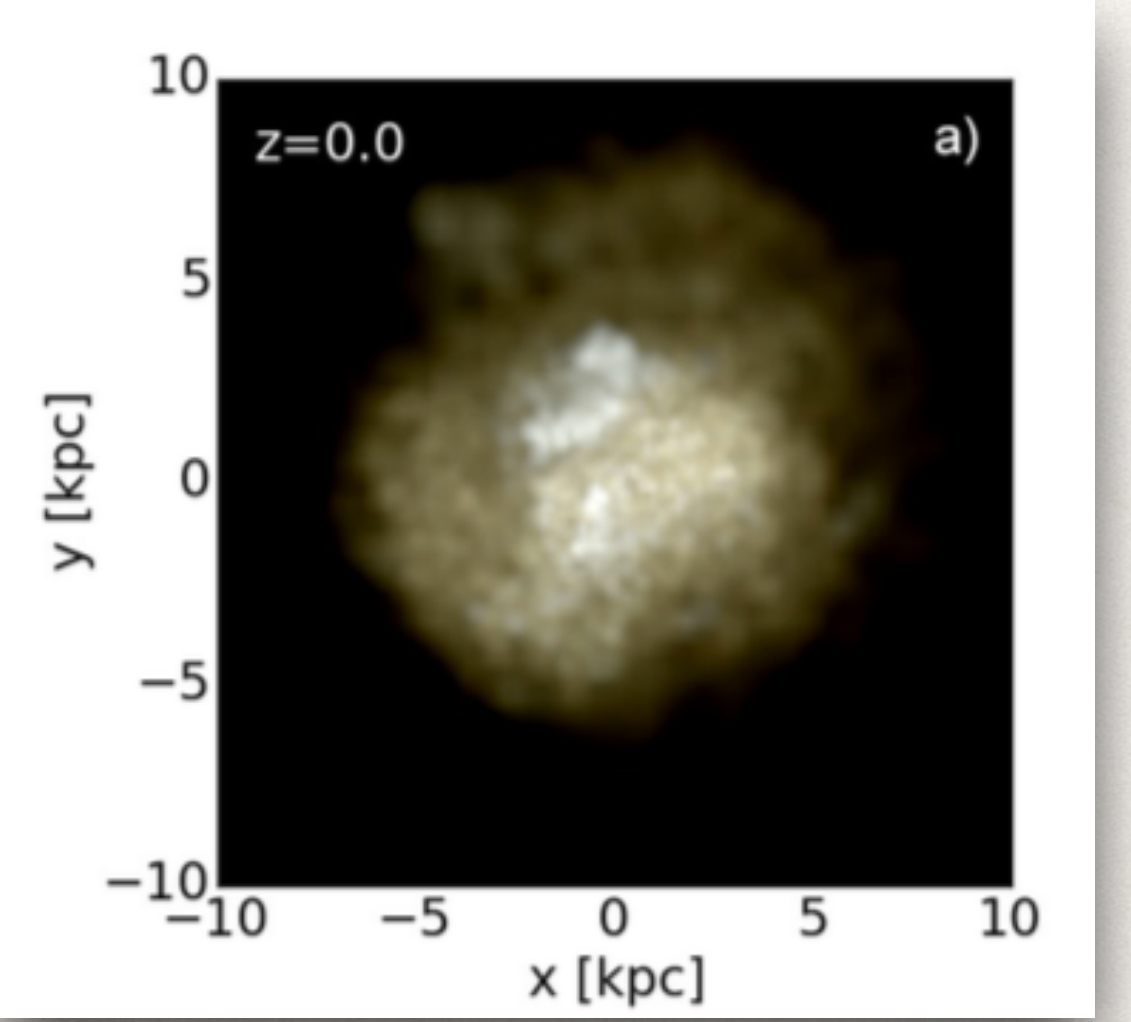
UDGs properties

Science case: LSB galaxies

State of the art: observations vs theoretical predictions

Internal processes

External processes



(Di Cintio et al. 2017; Amorisco & Loeb 2016; Rong et al. 2017; Tremmel et al. 2019)

- *star-formation feedback*
- *high-spin DM halo*

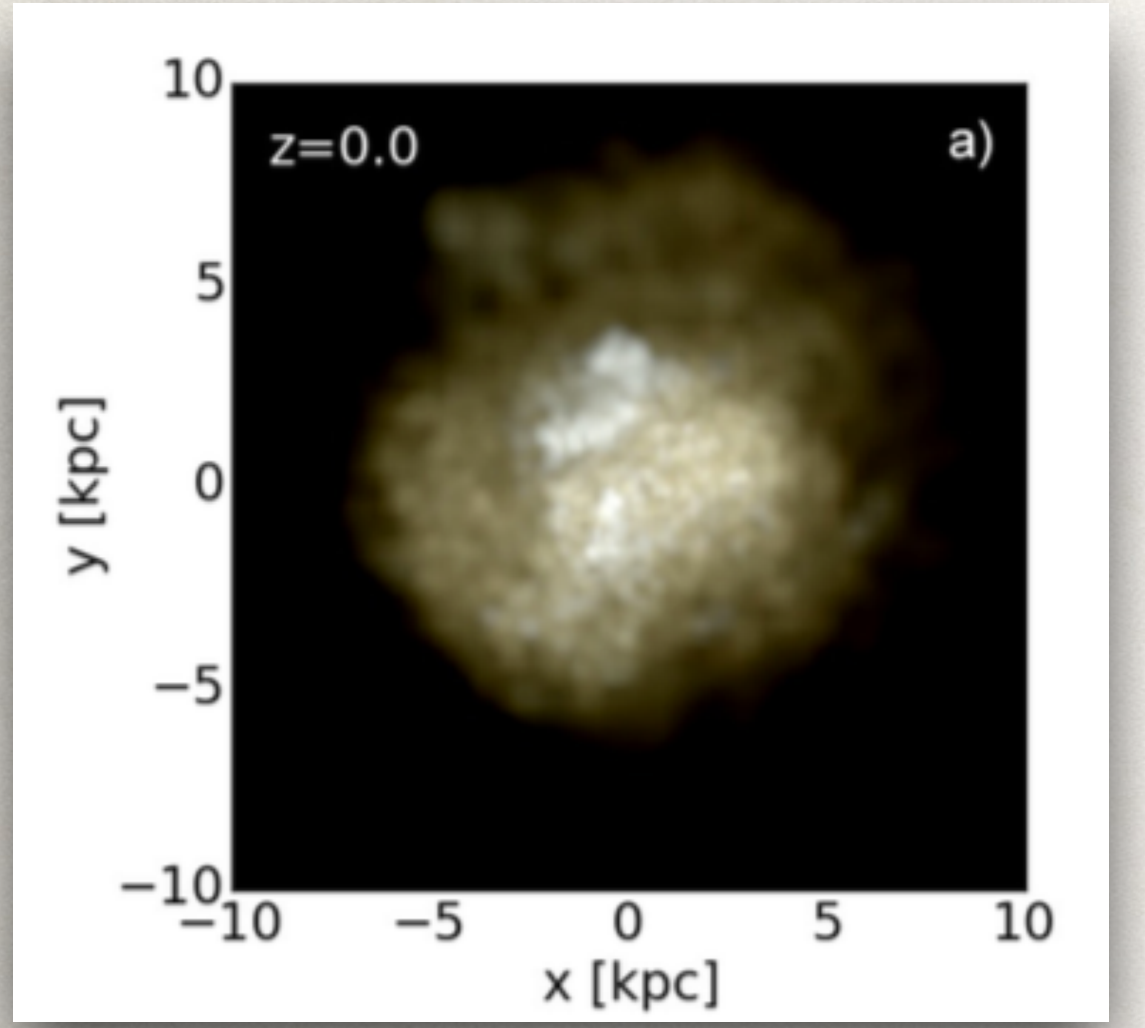
UDGs properties

Science case: LSB galaxies

State of the art: observations vs theoretical predictions

Internal processes

External processes



(Di Cintio et al. 2017; Amorisco & Loeb 2016; Rong et al. 2017; Tremmel et al. 2019)

- star-formation feedback
- high-spin DM halo

UDGs properties

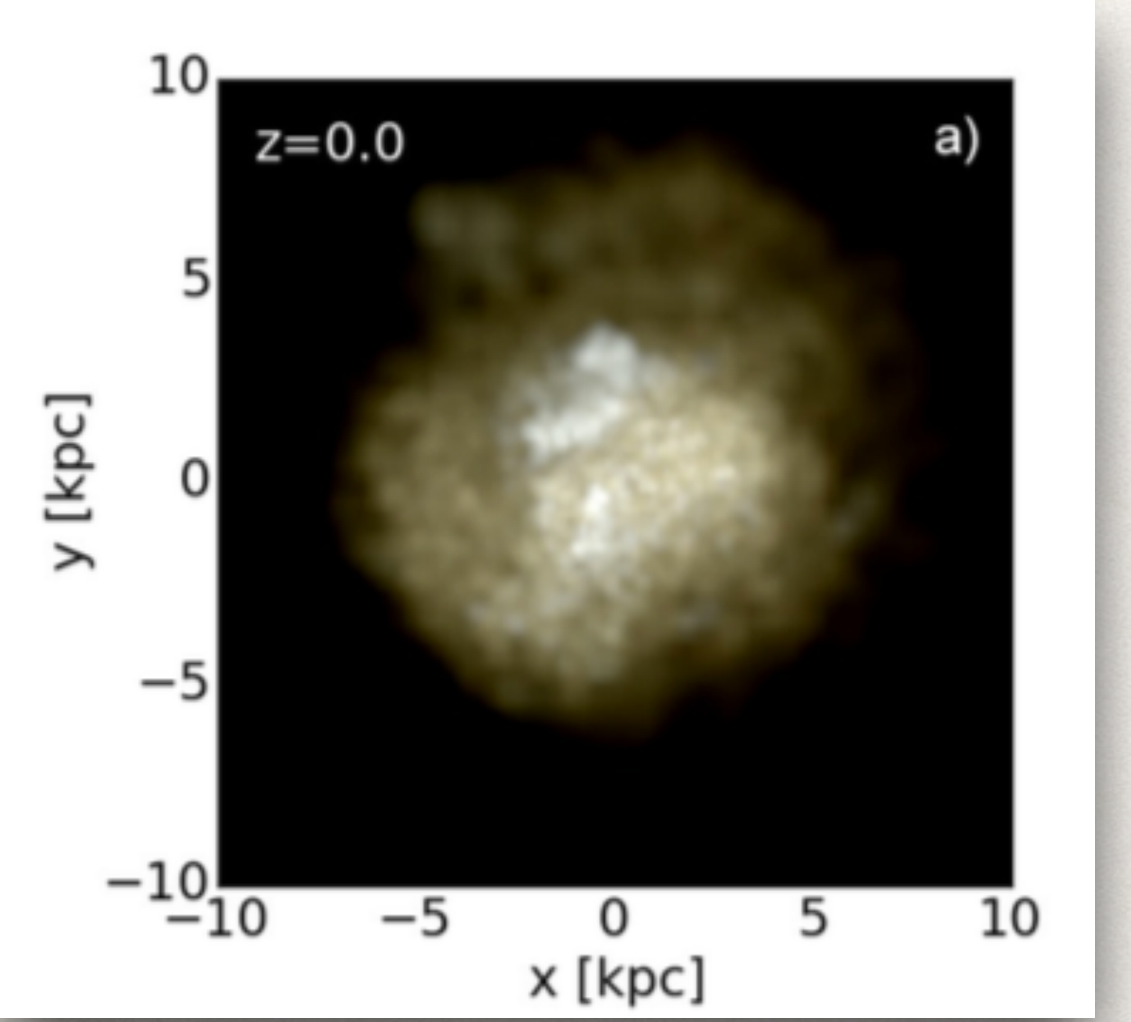
gas-rich
dwarf-like DM halo

INAF
ISTITUTO NAZIONALE DI ASTROFISICA

Science case: LSB galaxies

State of the art: observations vs theoretical predictions

Internal processes



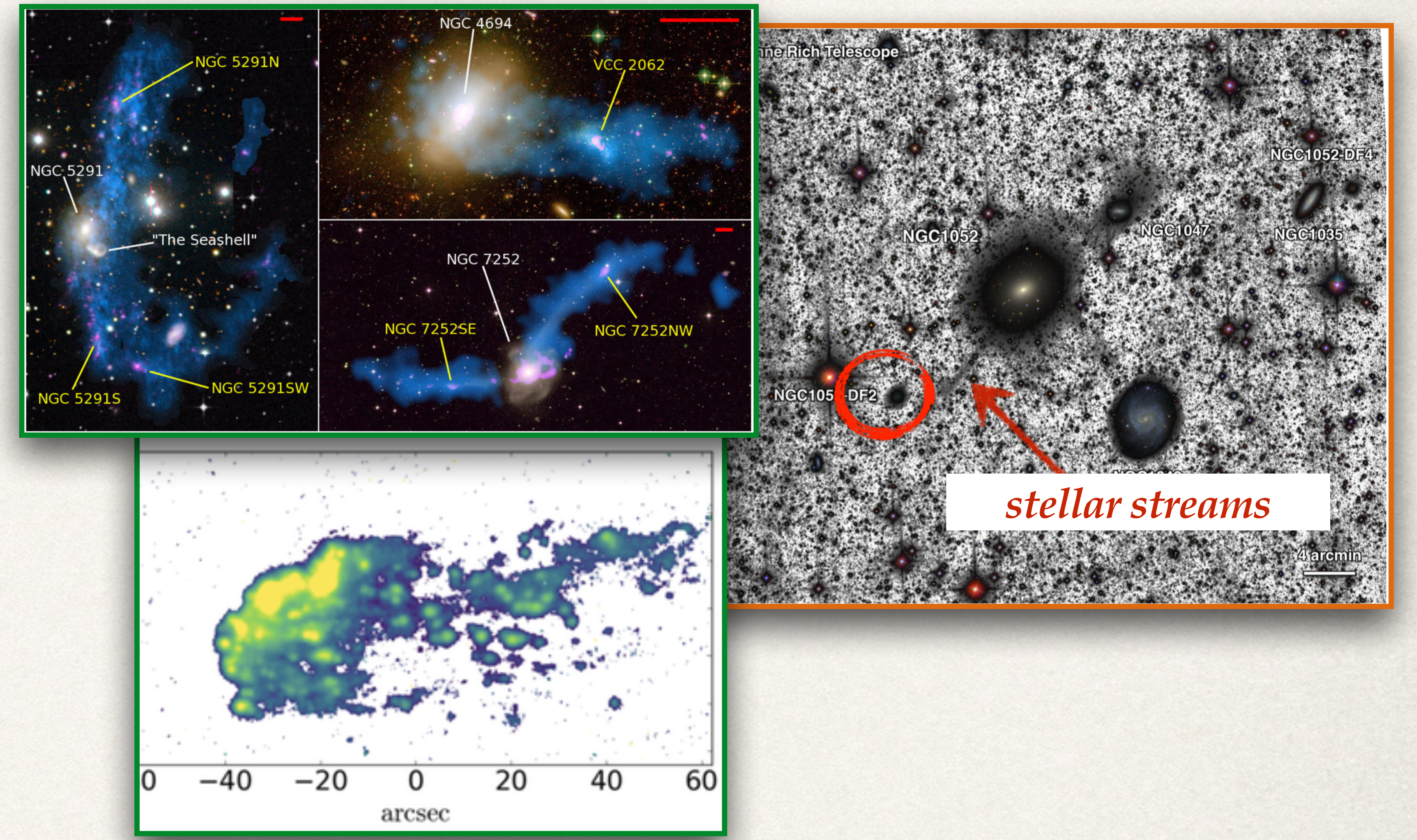
- *star-formation feedback*
- *high-spin DM halo*

(Di Cintio et al. 2017; Amorisco & Loeb 2016; Rong et al. 2017; Tremmel et al. 2019)

gas-rich
dwarf-like DM halo

External processes

- *gravitational interactions & merging*
- *interaction with the environment*



(Lelli et al. 2015; Duc et al. 2014; Ploeckinger et al. 2018; Poggianti et al. 2019; Conselice 2018; Carleton et al. 2021; Bennet et al. 2018; Müller et al. 2019; Silk 2019; Shin et al. 2020; Sales et al. 2020; van Dokkum et al. 2022)

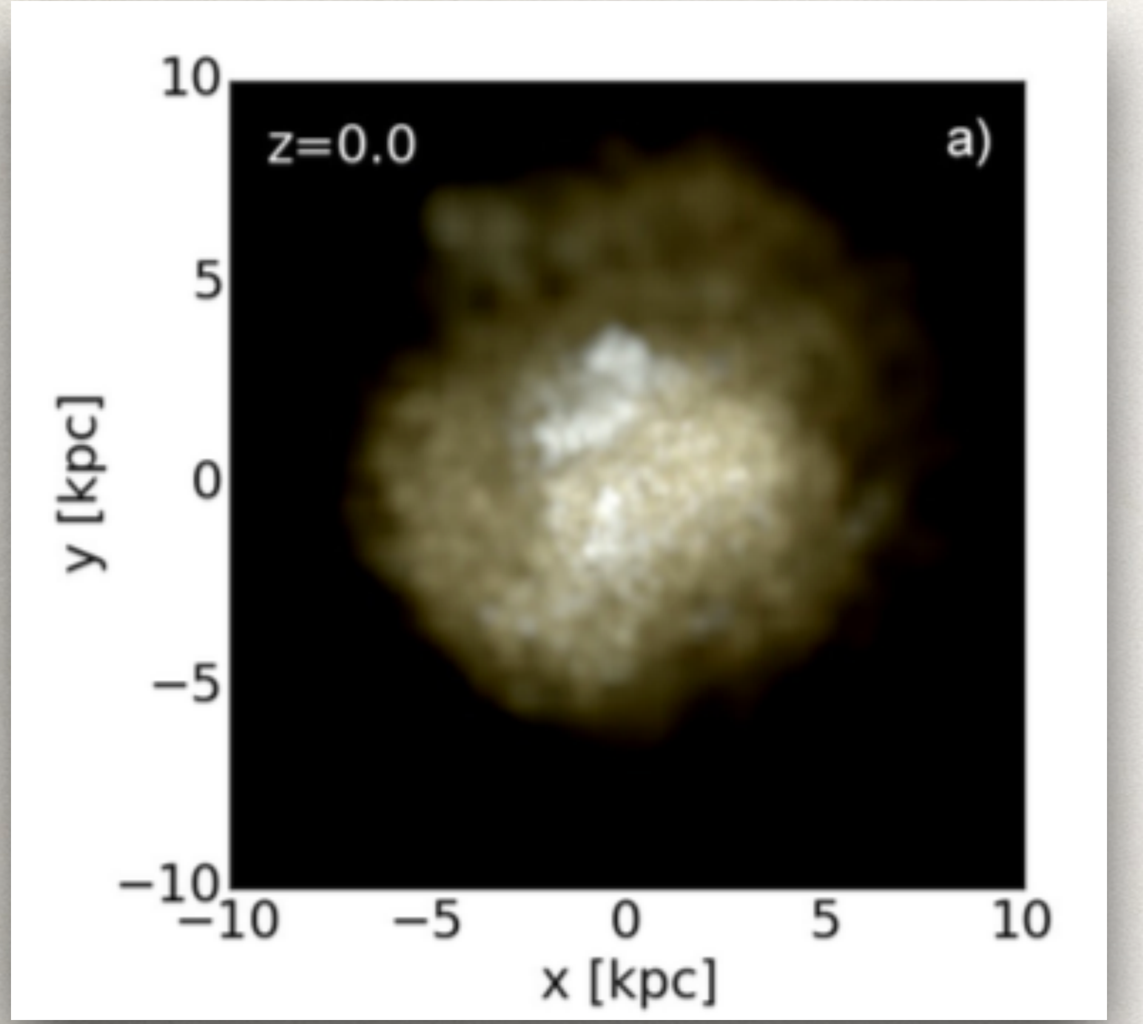
UDGs properties

INAF
ISTITUTO NAZIONALE DI ASTROFISICA

Science case: LSB galaxies

State of the art: observations vs theoretical predictions

Internal processes



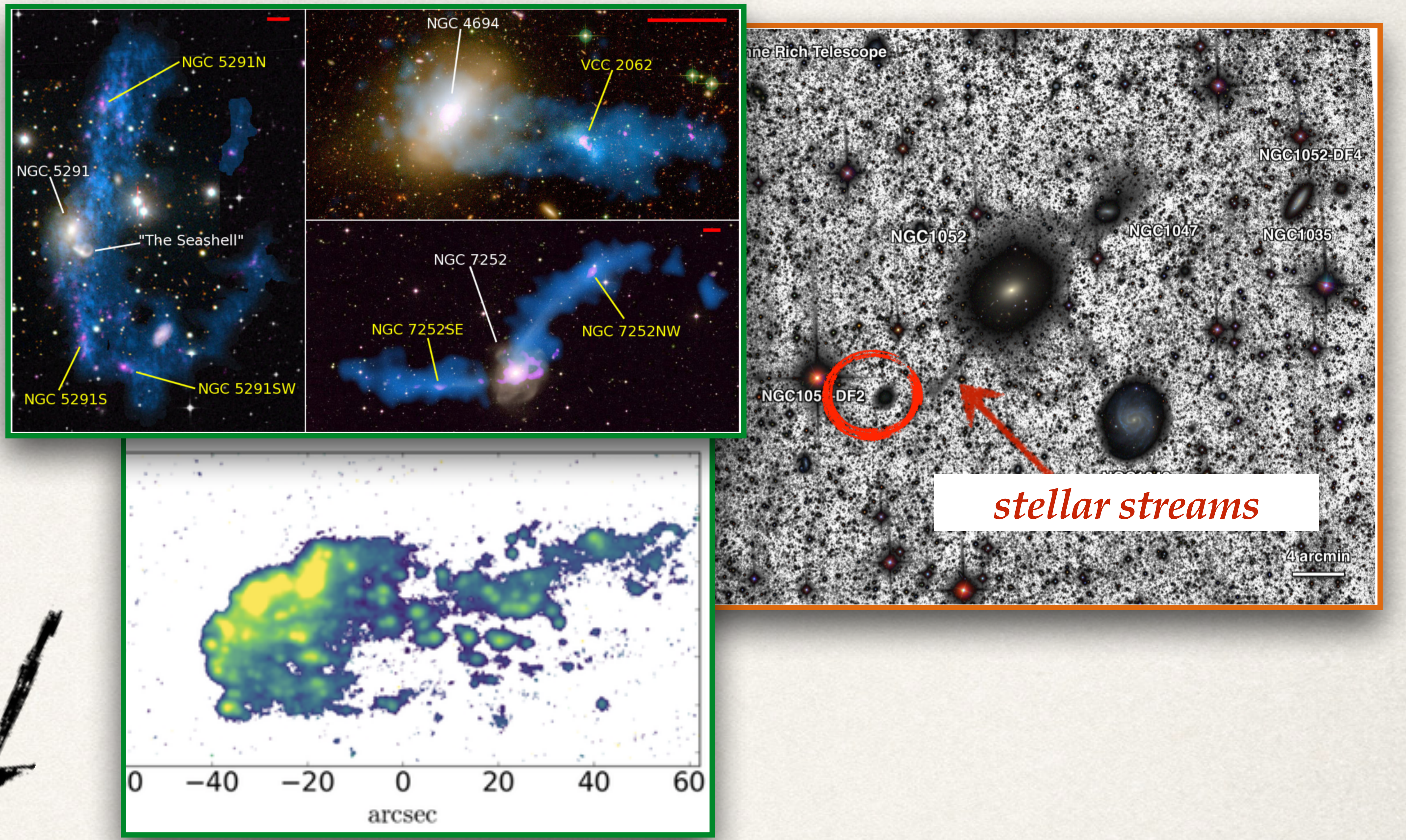
(Di Cintio et al. 2017; Amorisco & Loeb 2016; Rong et al. 2017; Tremmel et al. 2019)

- star-formation feedback
- high-spin DM halo

gas-rich
dwarf-like DM halo

External processes

- gravitational interactions & merging
- interaction with the environment



(Lelli et al. 2015; Duc et al. 2014; Ploeckinger et al. 2018; Poggianti et al. 2019; Conselice 2018; Carleton et al. 2021; Bennet et al. 2018; Müller et al. 2019; Silk 2019; Shin et al. 2020; Sales et al. 2020; van Dokkum et al. 2022)

UDGs properties

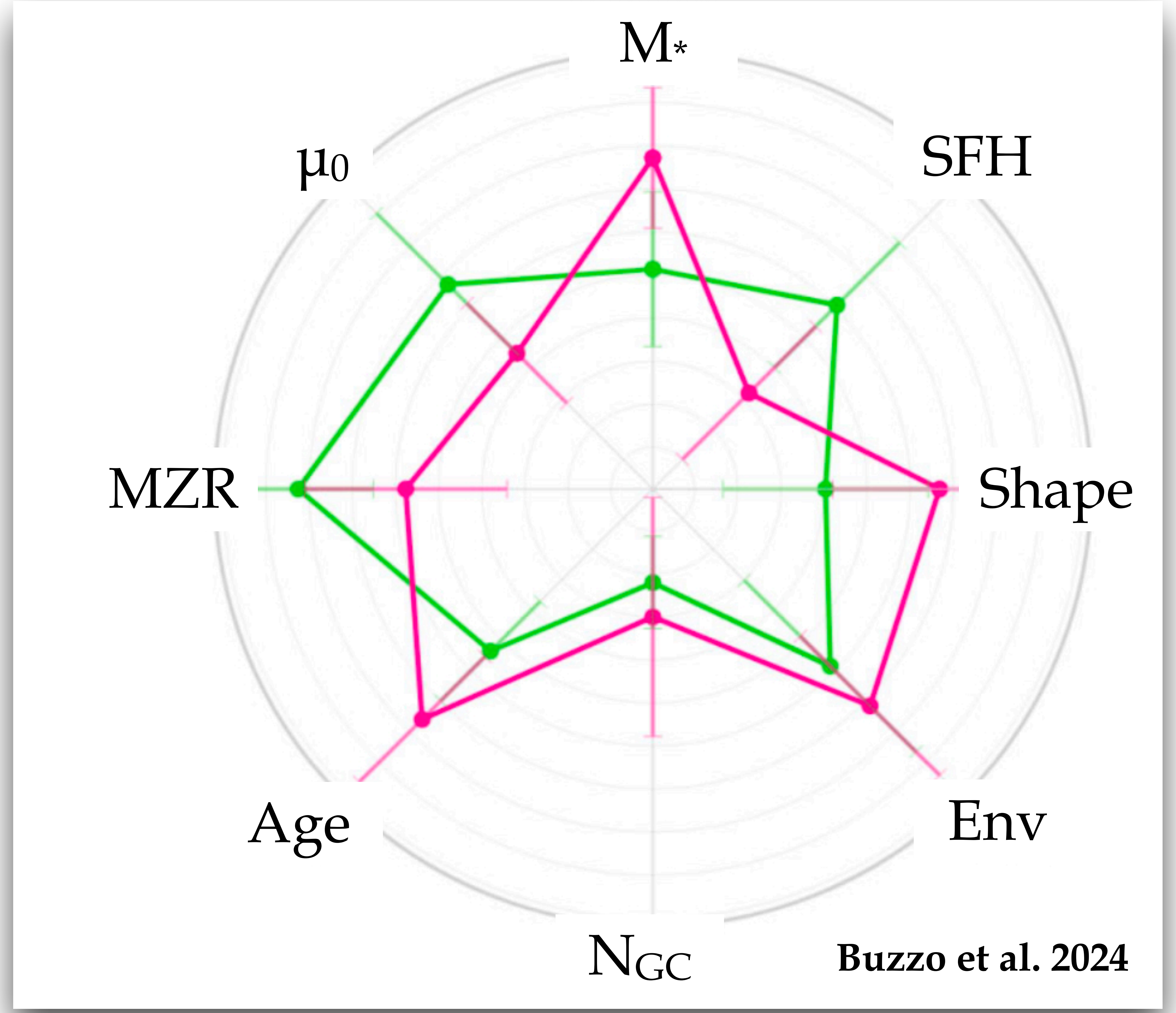
- DM free
- blue, dust, moderate Z/H, SF
- UV emission + gas rich
- gas poor & dwarf-like DM halo

INAF ISTITUTO NAZIONALE DI ASTROFISICA

Science case: LSB galaxies

State of the art: observations vs theoretical predictions

Observables



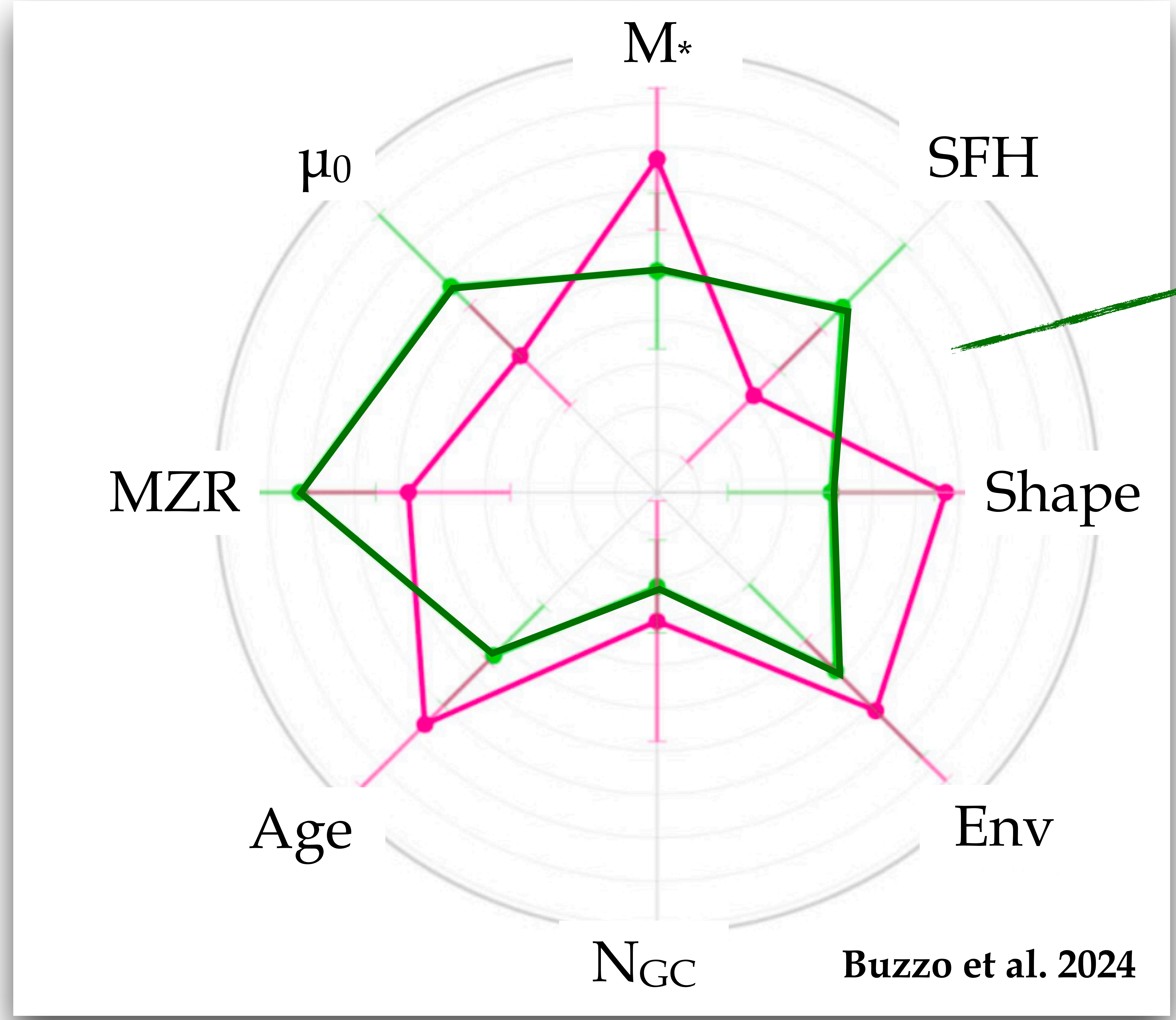
Classes of UDGs

Origin

Science case: LSB galaxies

State of the art: observations vs theoretical predictions

Observables



Classes of UDGs

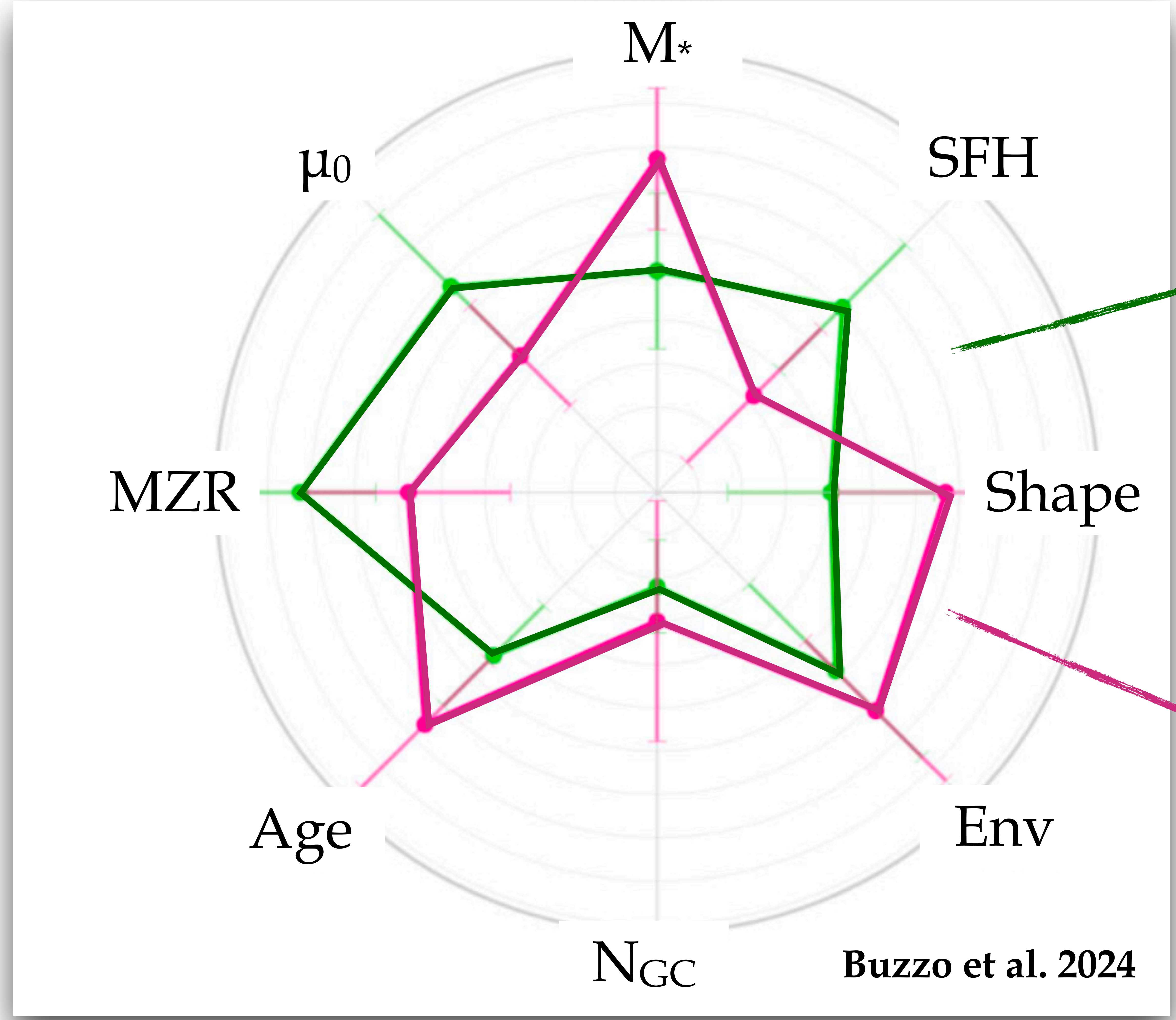
Origin

Dwarf

Science case: LSB galaxies

State of the art: observations vs theoretical predictions

Observables



Classes of UDGs

Puffed-up

Failed

Origin

Dwarf

LTG

Which are the observables to discriminate between UDGs formation channels?

- Structural properties & spatial distribution
- Stellar kinematics (also spatially resolved) —> DM content
- Age & Metallicity —> star formation history
- GCs content —> independent DM tracers

Which are the observables to discriminate between UDGs formation channels?

- Structural properties & spatial distribution
  ➥ ***deep images***
- Stellar kinematics (also spatially resolved) —> DM content
- Age & Metallicity —> star formation history
- GCs content —> independent DM tracers

Which are the observables to discriminate between UDGs formation channels?

- Structural properties & spatial distribution

  ➥ ***deep images***

- Stellar kinematics (also spatially resolved) —> DM content
- Age & Metallicity —> star formation history
- GCs content —> independent DM tracers

  ➥ ***spectroscopy***

Which are the observables to discriminate between UDGs formation channels?

Where we are?

- Structural properties & spatial distribution

  ➥ ***deep images***

- Stellar kinematics (also spatially resolved) —> DM content
- Age & Metallicity —> star formation history
- GCs content —> independent DM tracers

  ➥ ***spectroscopy***

Which are the observables to discriminate between UDGs formation channels?

Where we are?

- Structural properties & spatial distribution

➥ ***deep images***

~3000 UDGs detected
groups & cluster
low statistics in the field

- Stellar kinematics (also spatially resolved) —> DM content
- Age & Metallicity —> star formation history
- GCs content —> independent DM tracers

➥ ***spectroscopy***

Which are the observables to discriminate between UDGs formation channels?

Where we are?

- Structural properties & spatial distribution
  - ➥ ***deep images*** ⟶

~3000 UDGs detected
groups & cluster
low statistics in the field

- Stellar kinematics (also spatially resolved) —> DM content
- Age & Metallicity —> star formation history
- GCs content —> independent DM tracers
  - ➥ ***spectroscopy*** ⟶

~100 UDGs long-slit
< 5 with IFU!

IFS for LSB galaxies: the LEWIS project

Looking into the faintEst With muSe (LEWIS)

- **ESO LP** (P.I. E. Iodice) @ MUSE: 133.5 hrs over P108-P109-P110, 2021-2023

- Targets: a complete sample of UDGs in the Hydra I cluster

INAF
ISTITUTO NAZIONALE
DI ASTROFISICA

IFS for LSB galaxies: the LEWIS project

Looking into the faintEst With muSe (LEWIS)

- **ESO LP** (P.I. E. Iodice) @ MUSE: 133.5 hrs over P108-P109-P110, 2021-2023

- Targets: a complete sample of UDGs in the Hydra I cluster

↓

first homogeneous integral-field spectroscopic survey of UDGs

INAF
ISTITUTO NAZIONALE
DI ASTROFISICA


LEWIS: project plan
science goal: nature of UDGs in Hydra I
cluster membership


LEWIS: project plan
science goal: nature of UDGs in Hydra I
cluster membership
GCs systemic velocities
stellar populations
stellar kinematics

LEWIS: *project plan*

science goal: nature of UDGs in Hydra I

cluster membership

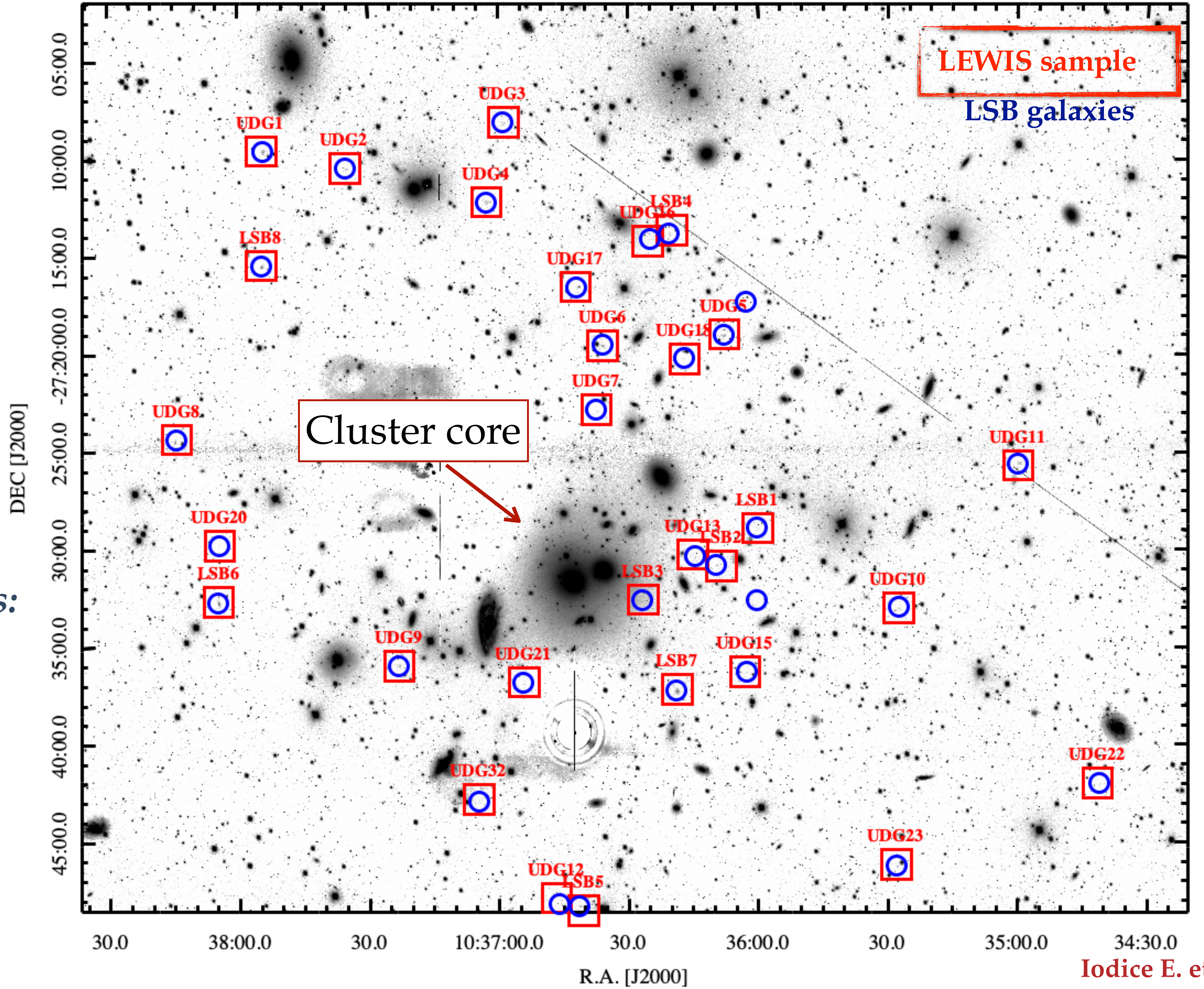
GCs systemic velocities
- confirm membership
- SN & study of the richness
- M_{dyn}

stellar populations
- age & metallicity, SFH
- evolutionary link with dwarfs

stellar kinematics
- M_{dyn}
- DM content *vs* environment

32 LSB galaxies:

24 UDGs
+
8 LSB dwarfs

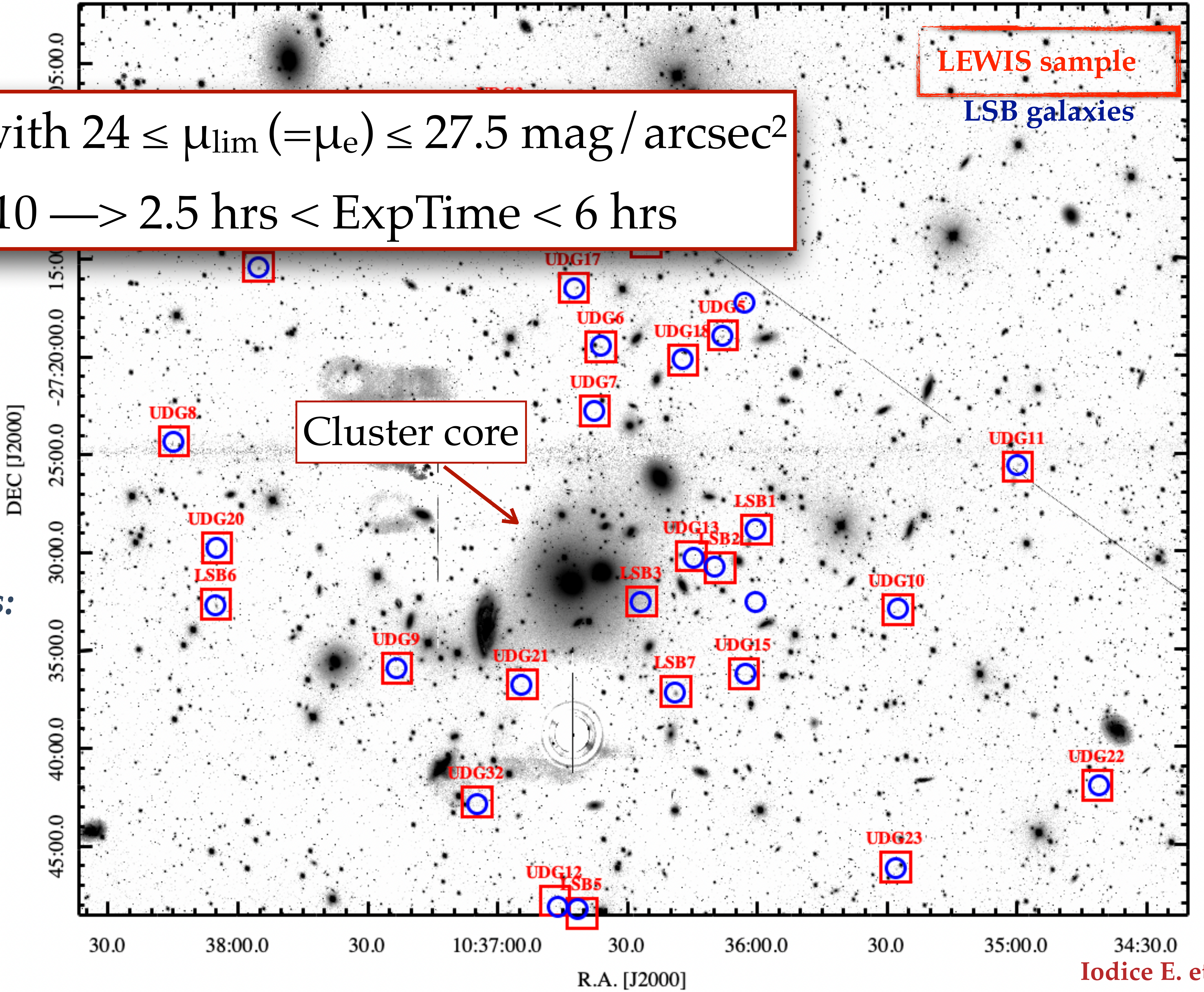


22 UDGs
+
8 LSB

Iodice E. et al. 2023, A&A, 679, 69

30 targets with $24 \le \mu_{lim} (=\mu_e) \le 27.5$ mag/arcsec^2

S/N>10 —> 2.5 hrs < ExpTime < 6 hrs



22 UDGs
+
8 LSB

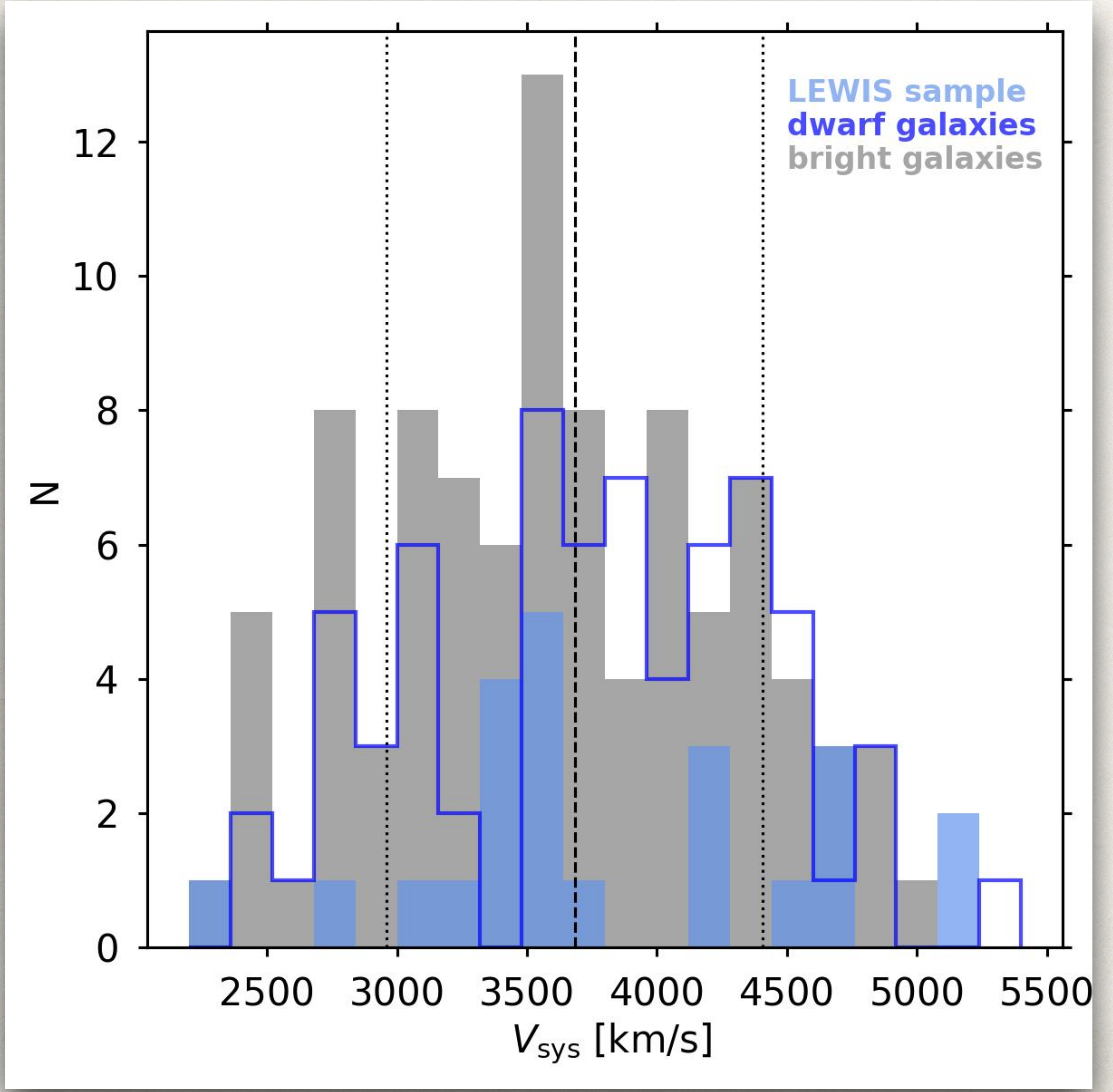
32 LSB galaxies:

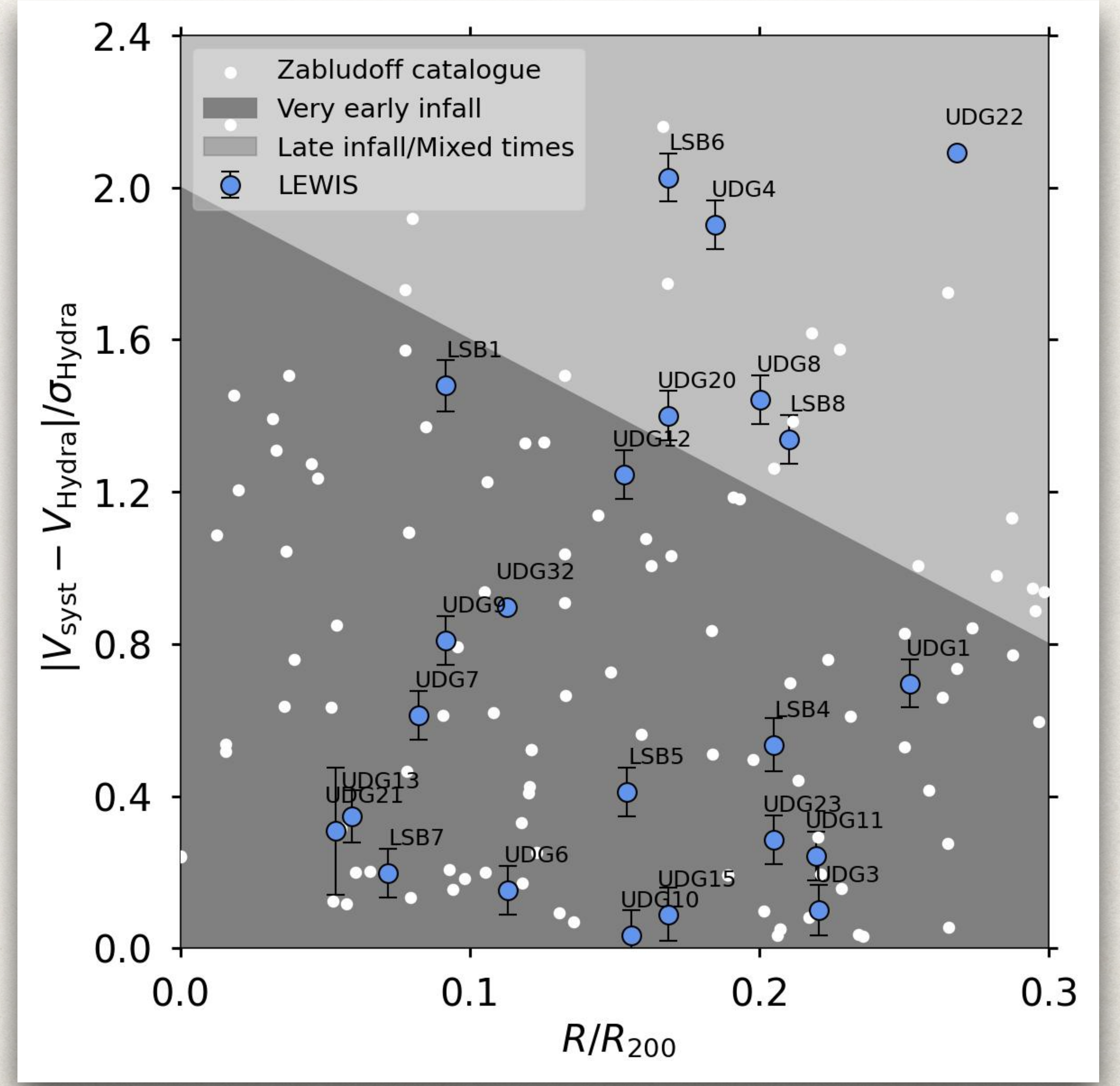
24 UDGs
+
8 LSB dwarfs

Iodice E. et al. 2023, A&A, 679, 69

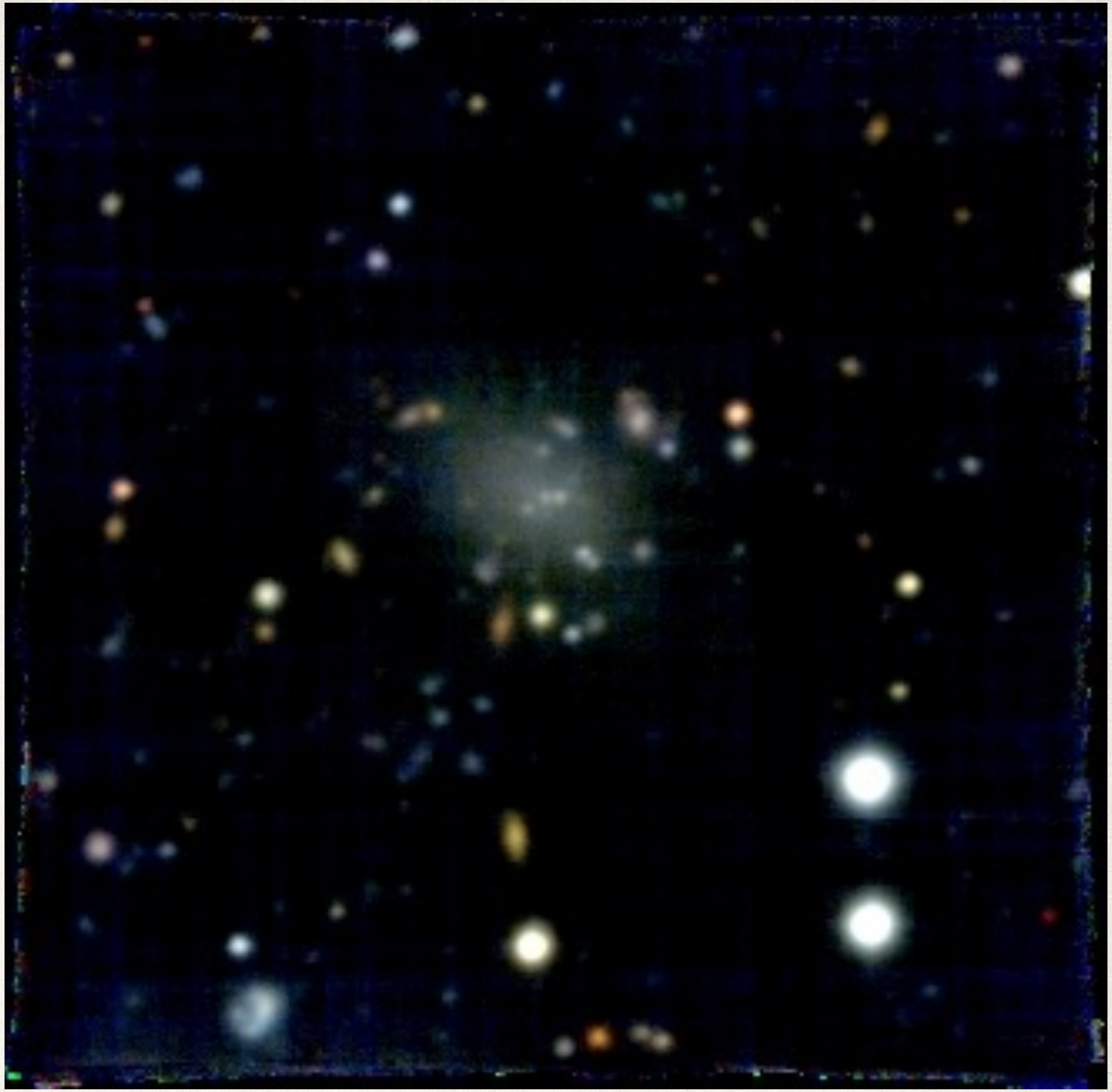
LEWIS: results *On the cluster-membership*

Chiara Buttitta (INAF-OAC) et al. in prep.





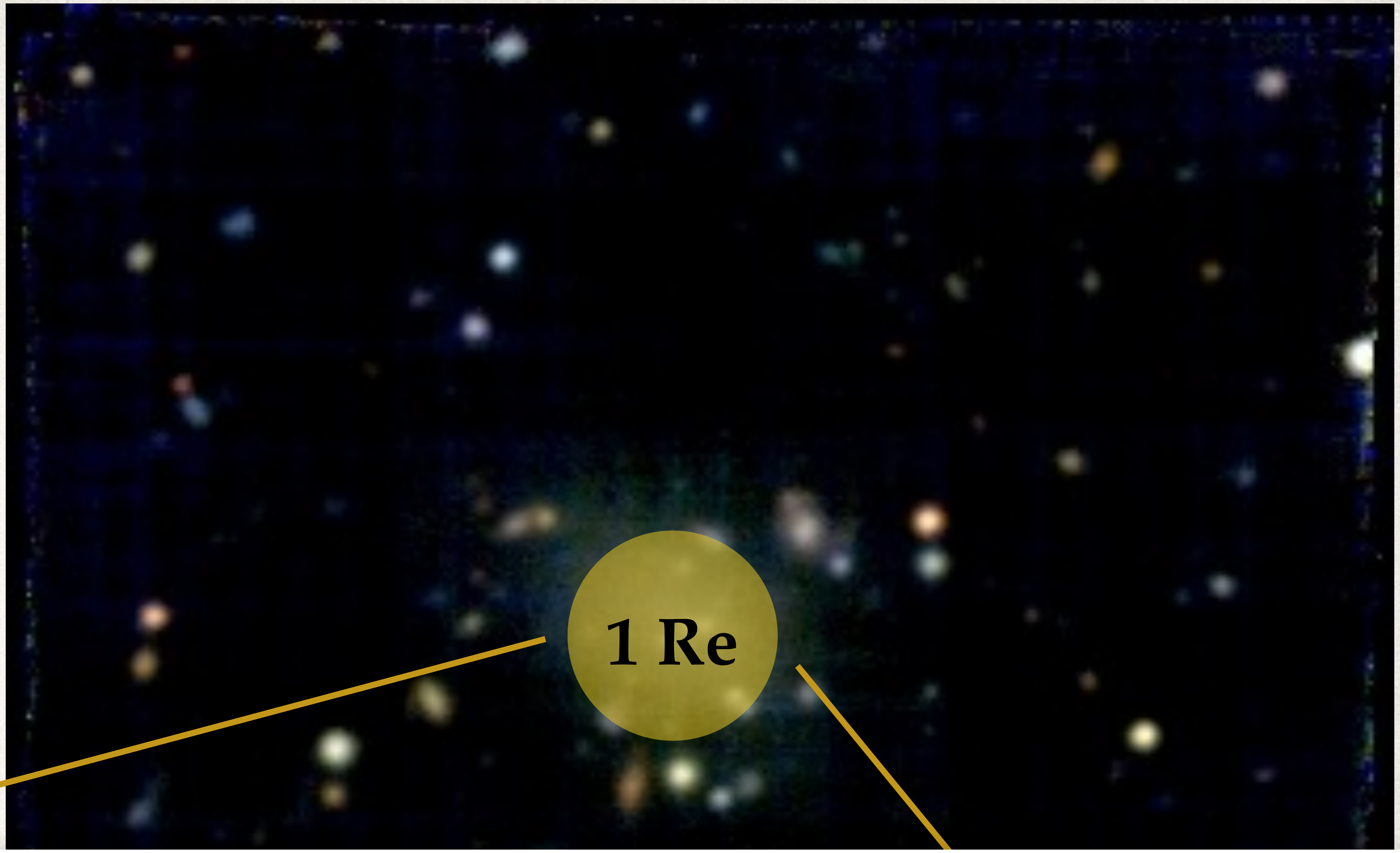
LEWIS: results



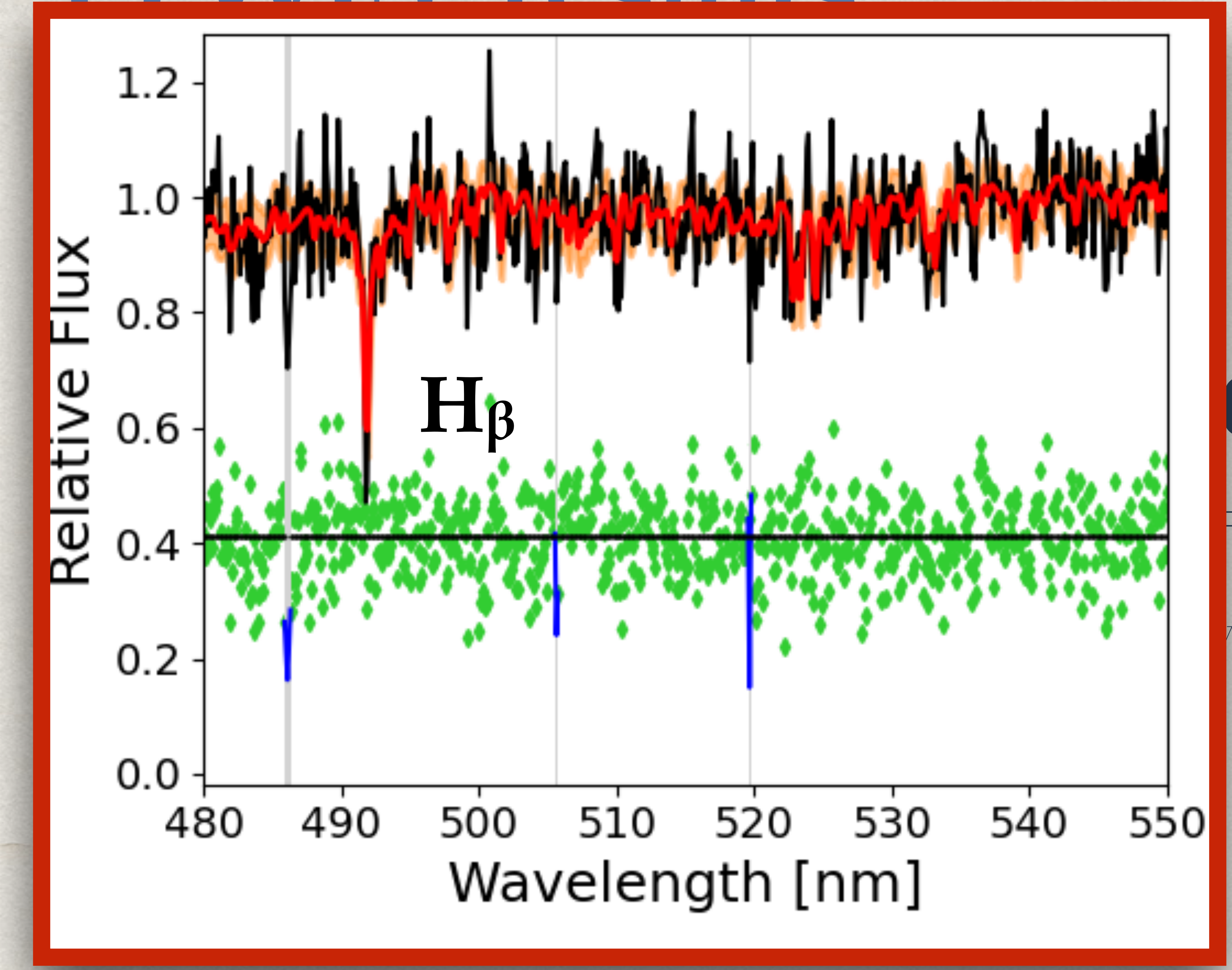
LEWIS: results

- z: 0.01169 ± 0.00002
- Vsys=3507 ± 3 km/s
- RV_{Hydra}: -176 km/s
- σ = 20 ± 8 km/s

ToT Exp T~6hrs - S/N=16



LEWIS: results

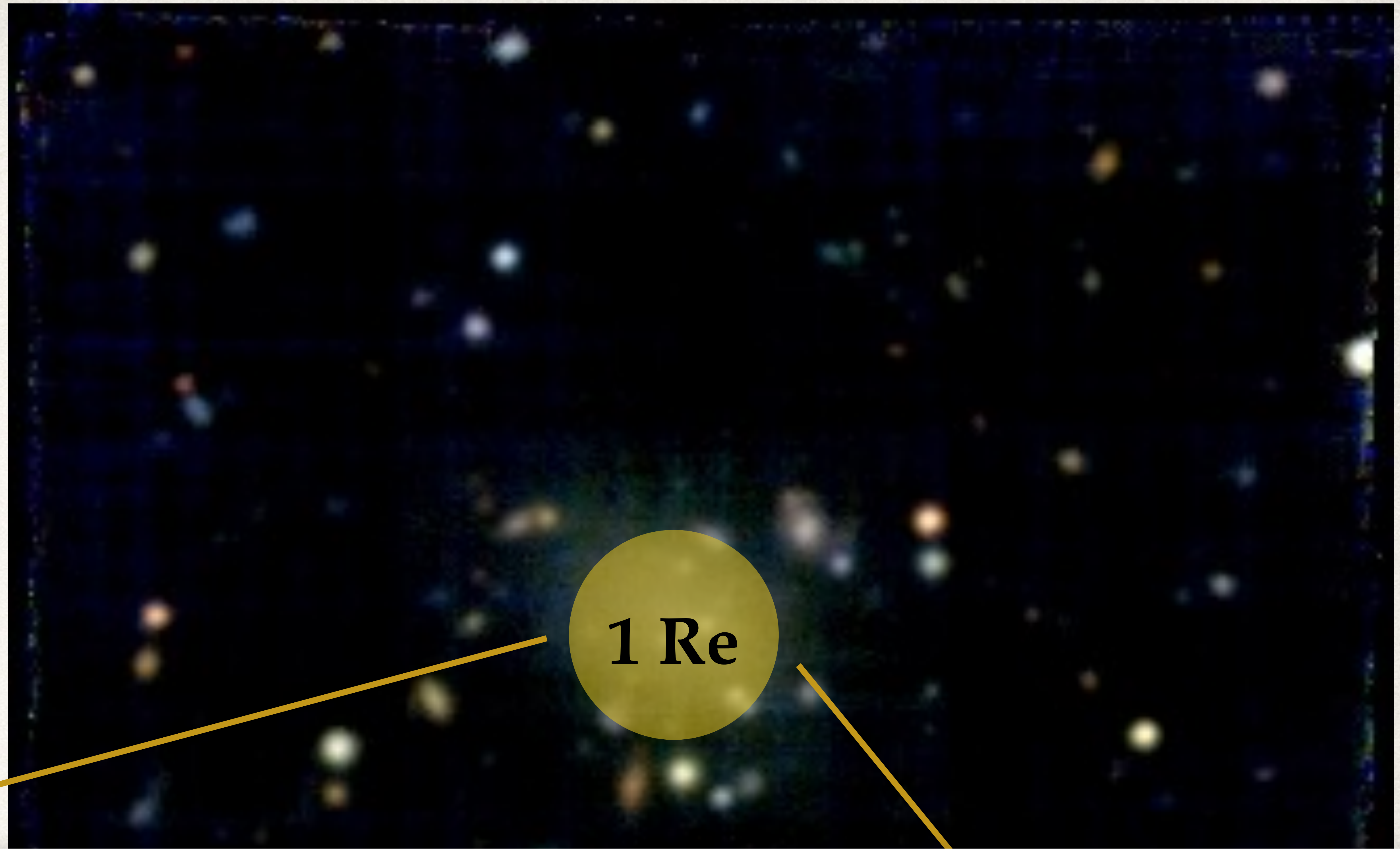


01169 ± 0.00002

=3507 ± 3 km/s

ydra: -176 km/s

0 ± 8 km/s



LEWIS: results

LEWIS: results

LEWIS: results from stellar kinematics

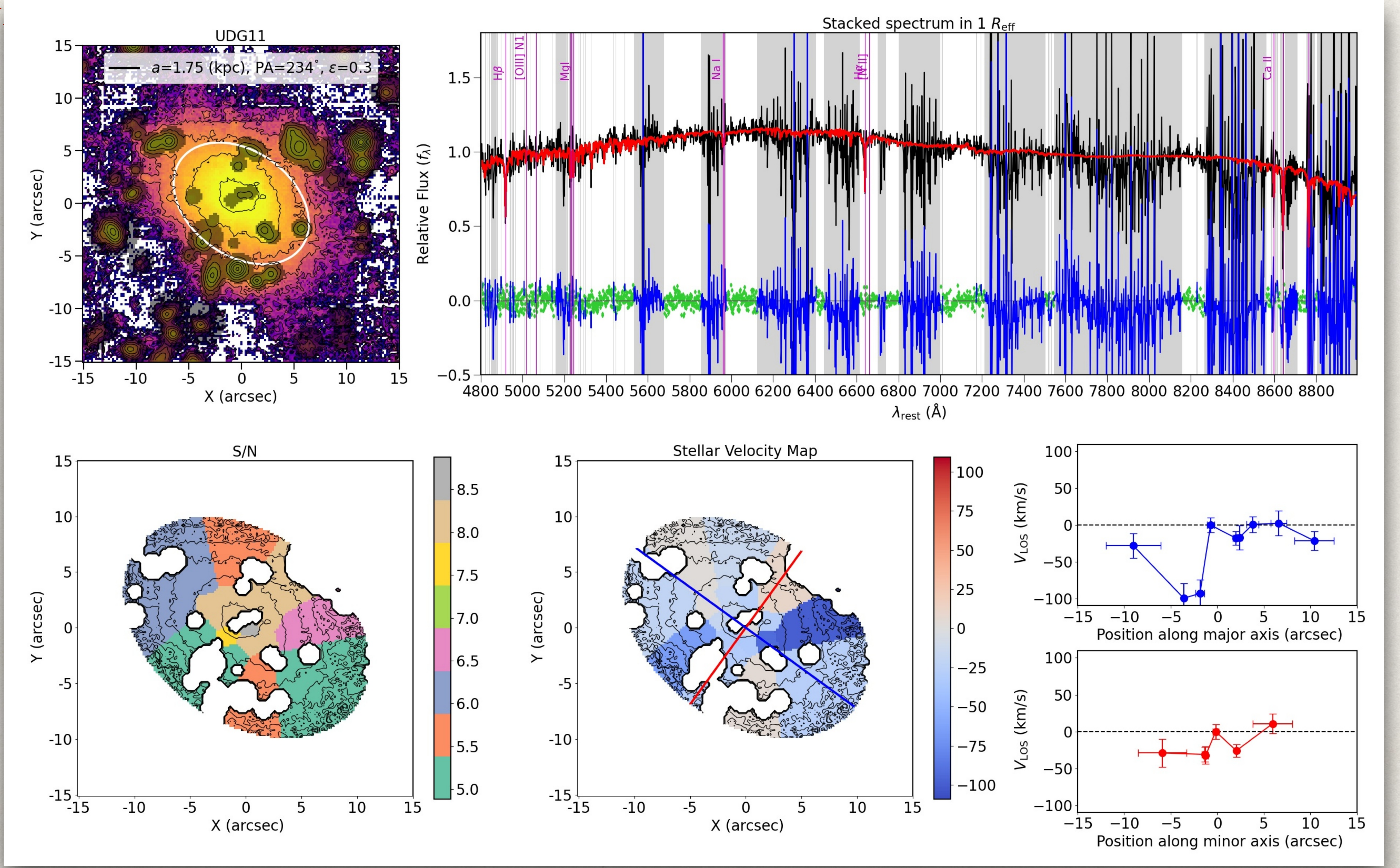
Do UDGs rotate?

Chiara Buttitta (INAF-OAC) et al. in prep.

LEWIS: results from stellar kinematics

Do UDGs rotate?

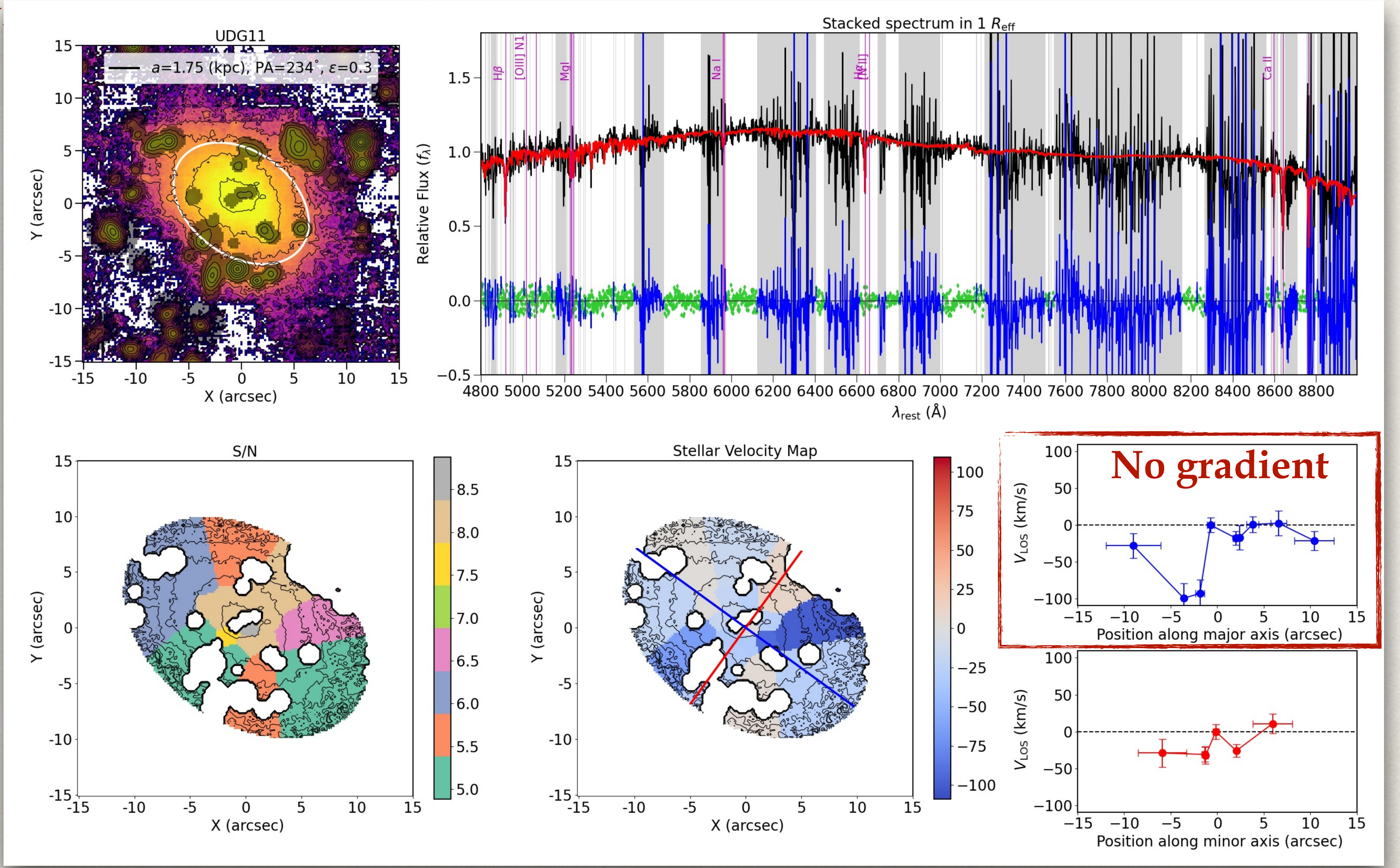
Chiara Buttitta (IN



LEWIS: results from stellar kinematics

Do UDGs rotate?

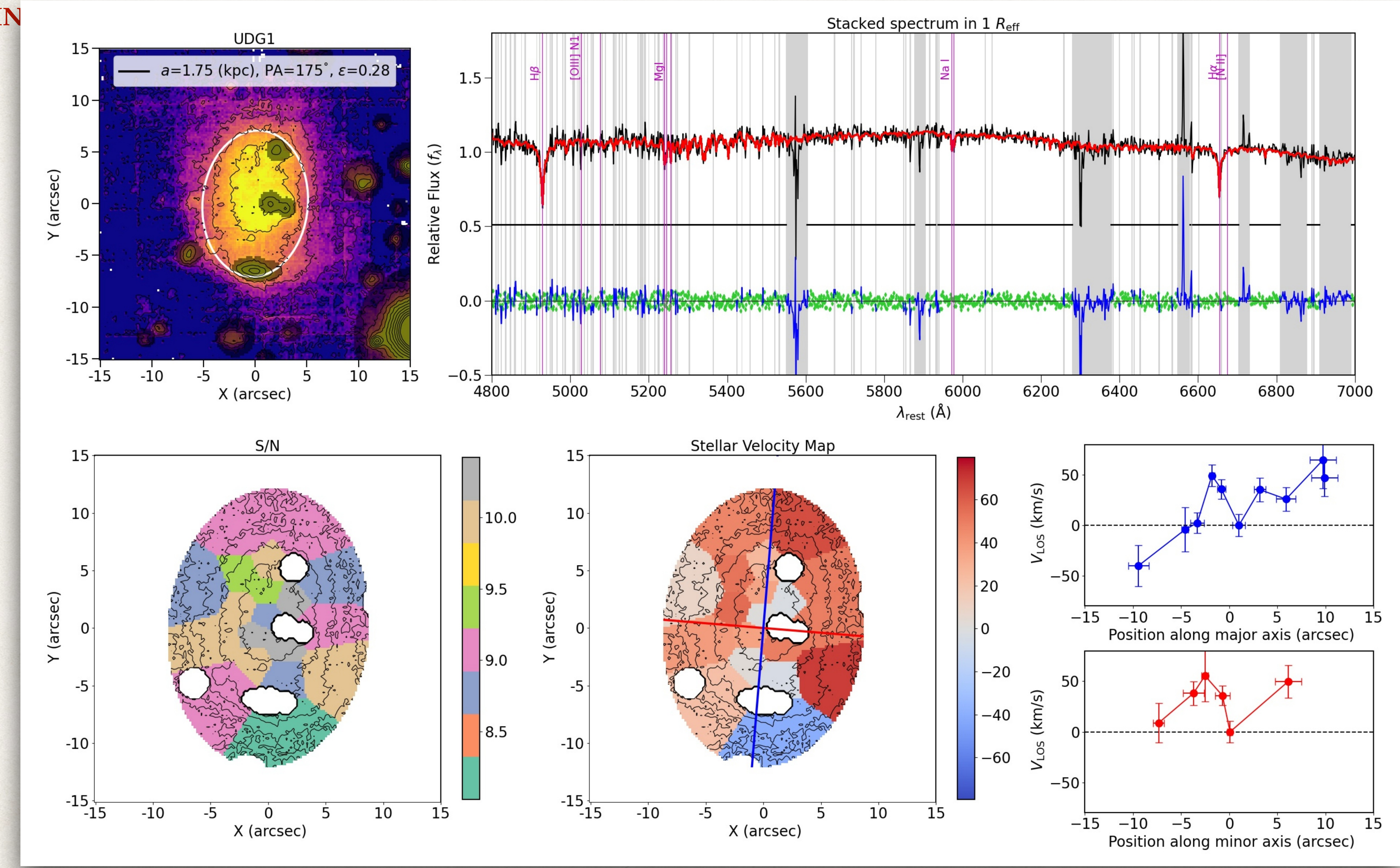
Chiara Buttitta (IN



LEWIS: results from stellar kinematics

Do UDGs rotate?

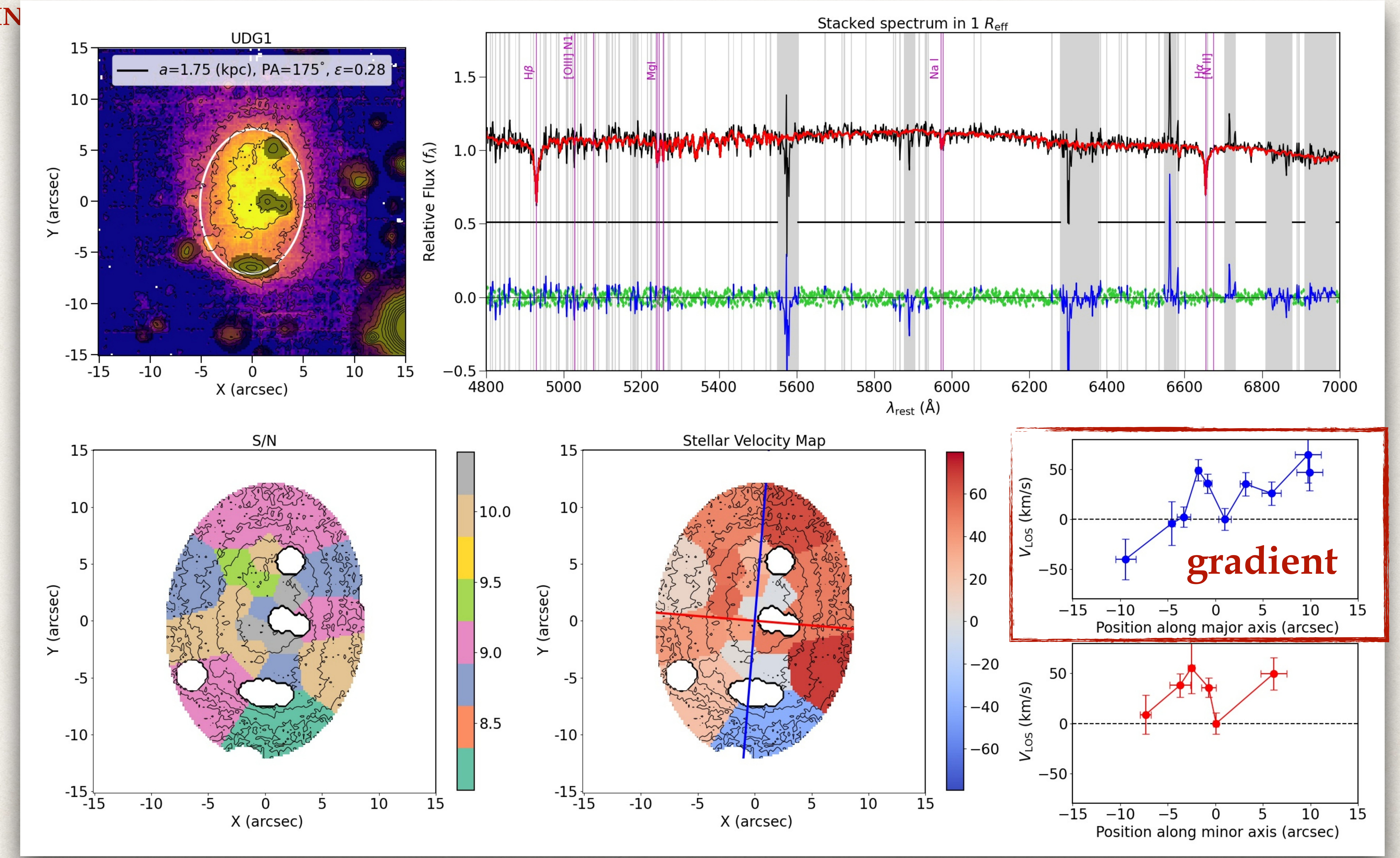
Chiara Buttitta (IN



LEWIS: results from stellar kinematics

Do UDGs rotate?

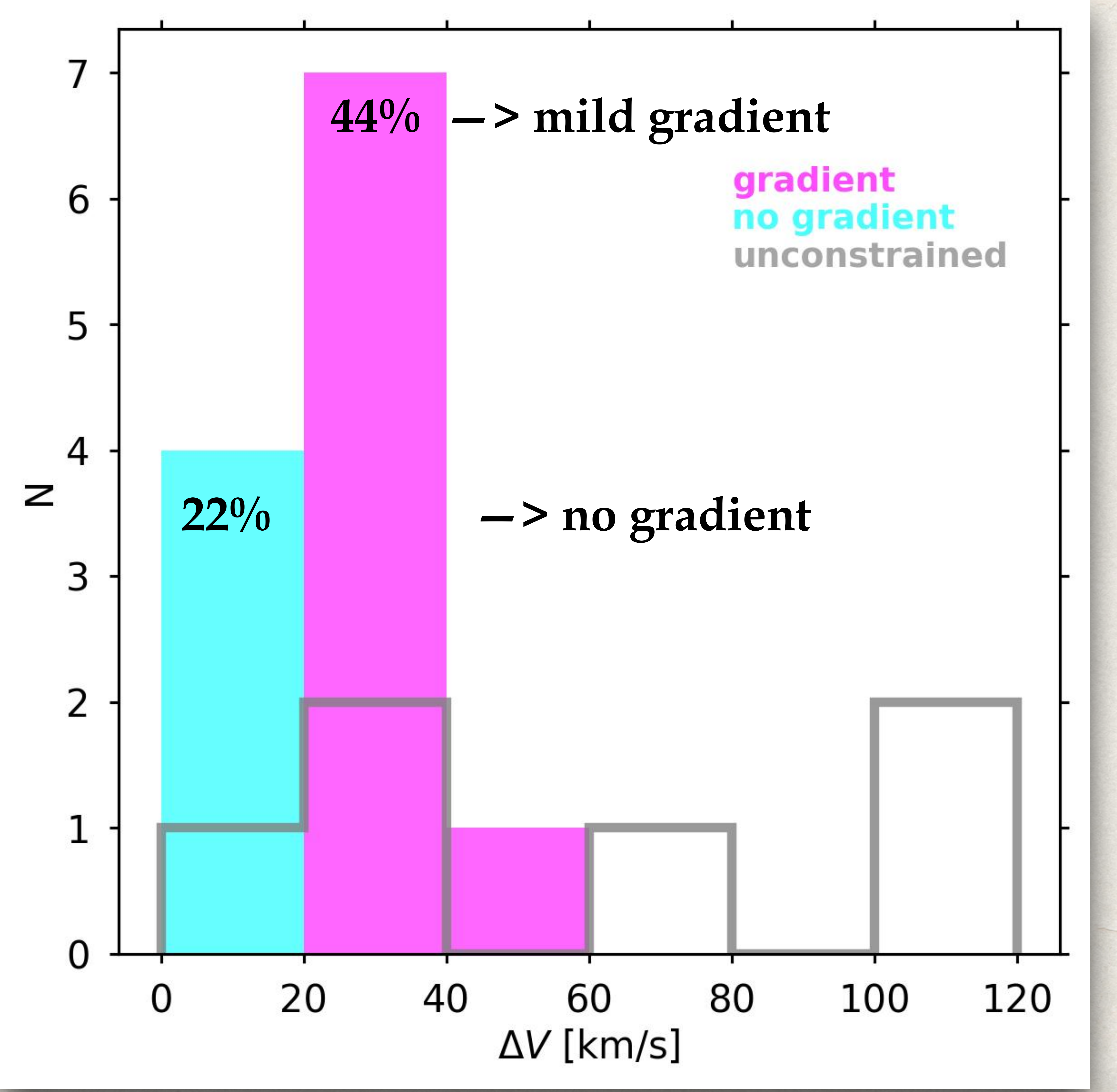
Chiara Buttitta (IN



LEWIS: results from stellar kinematics

Do UDGs rotate?

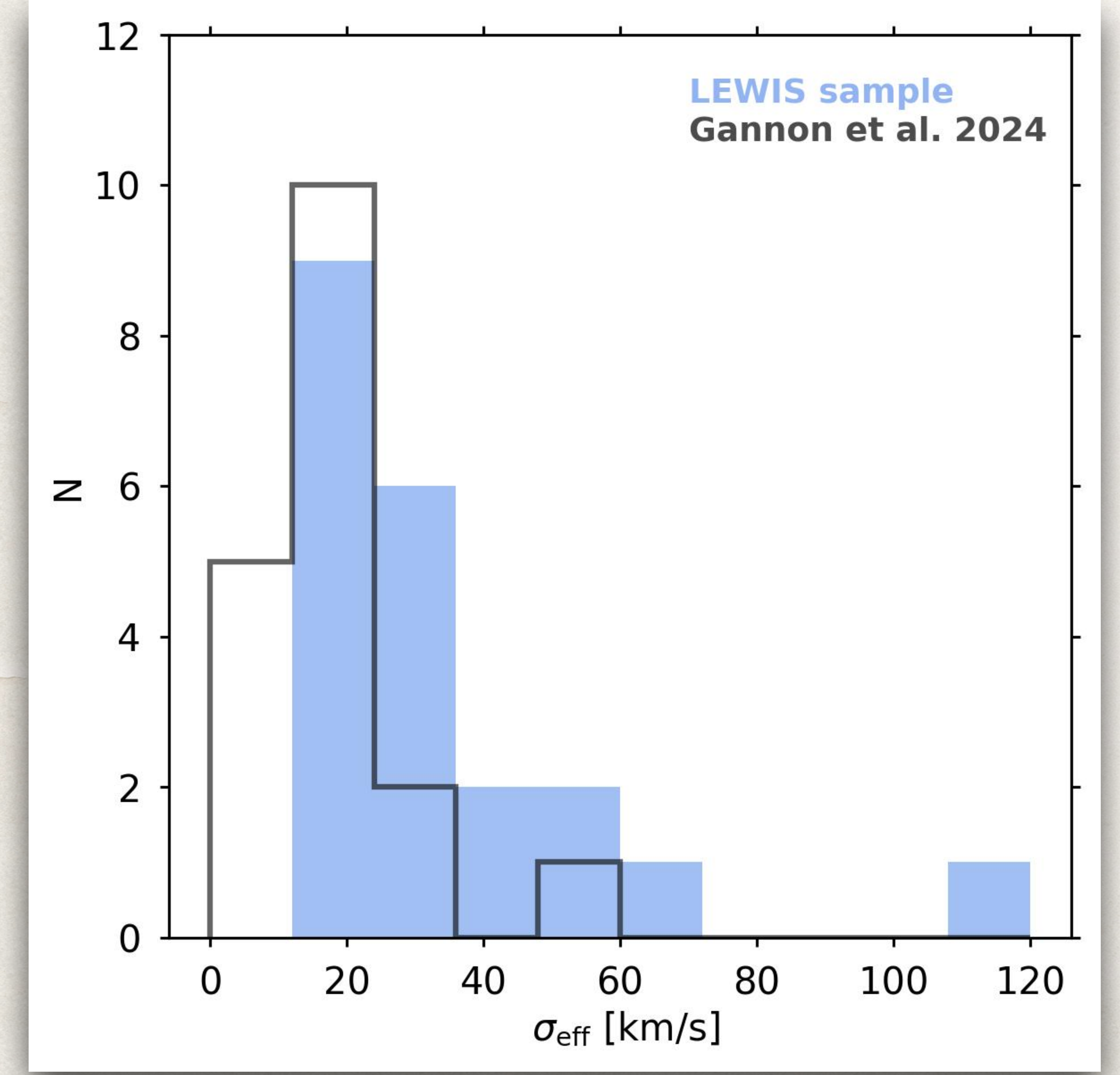
Chiara Buttitta (INAF-OAC) et al. in prep.

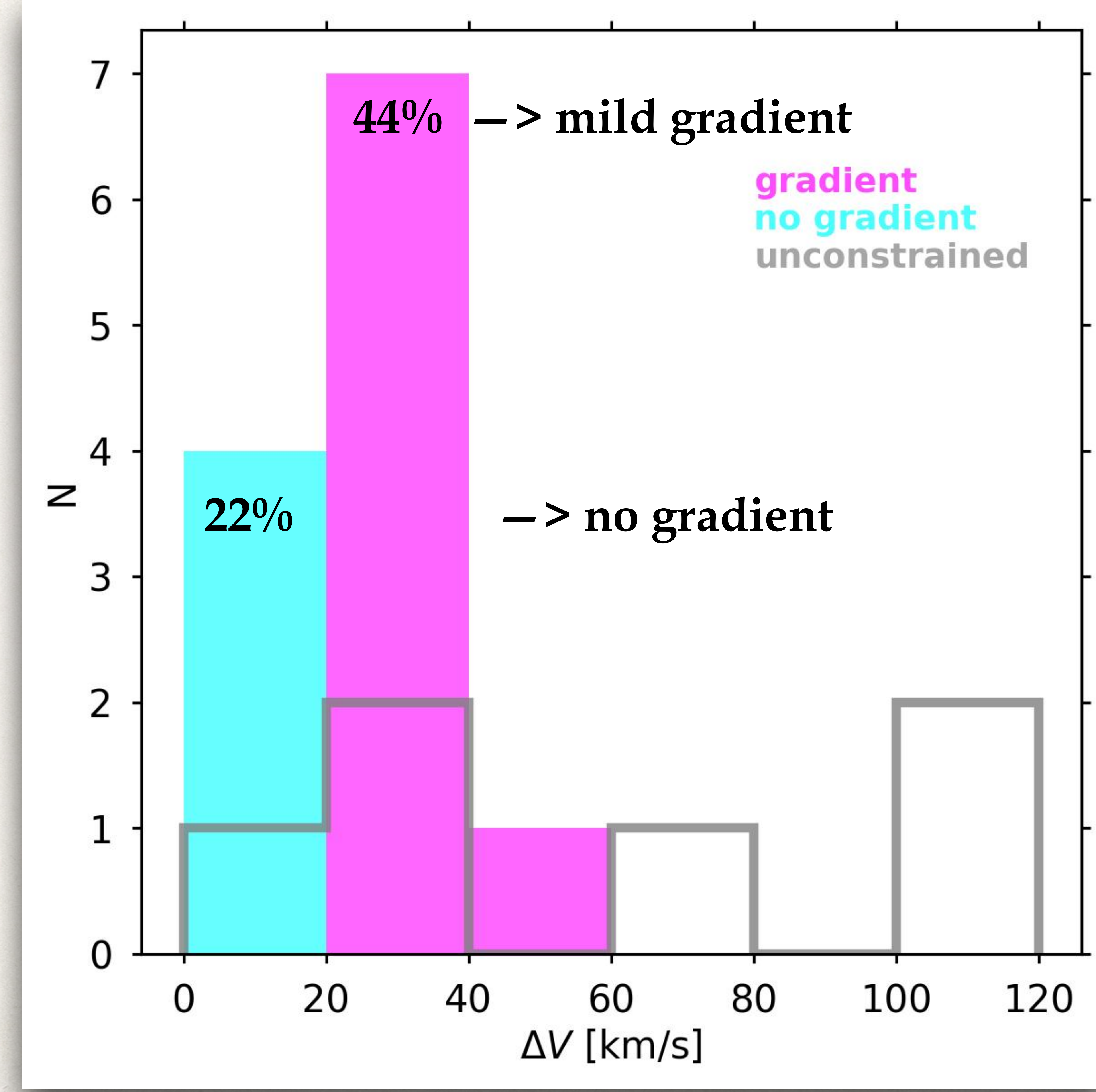


LEWIS: results from stellar kinematics

Do UDGs rotate?

Chiara Buttitta (INAF-OAC) et al. in prep.

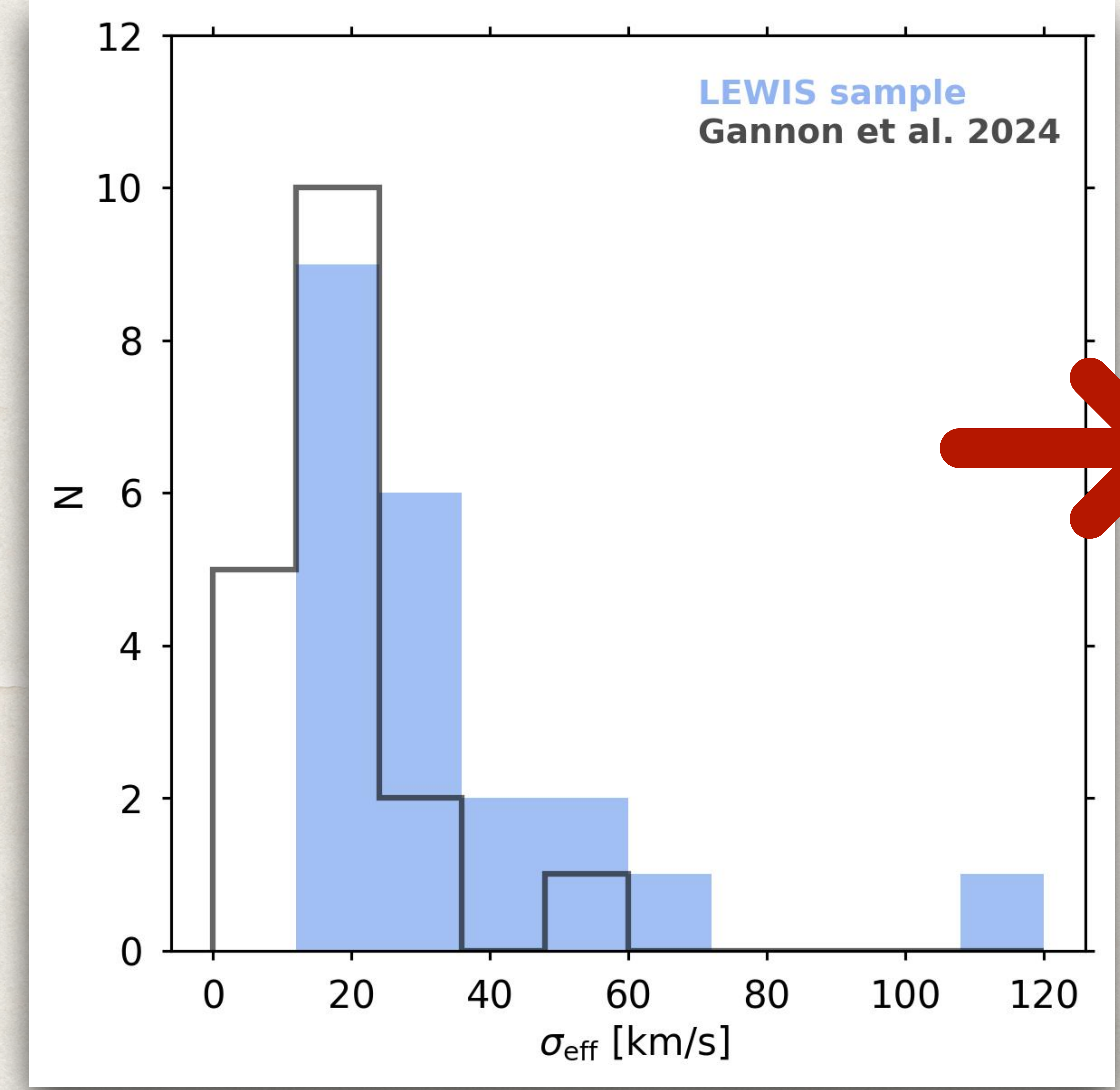


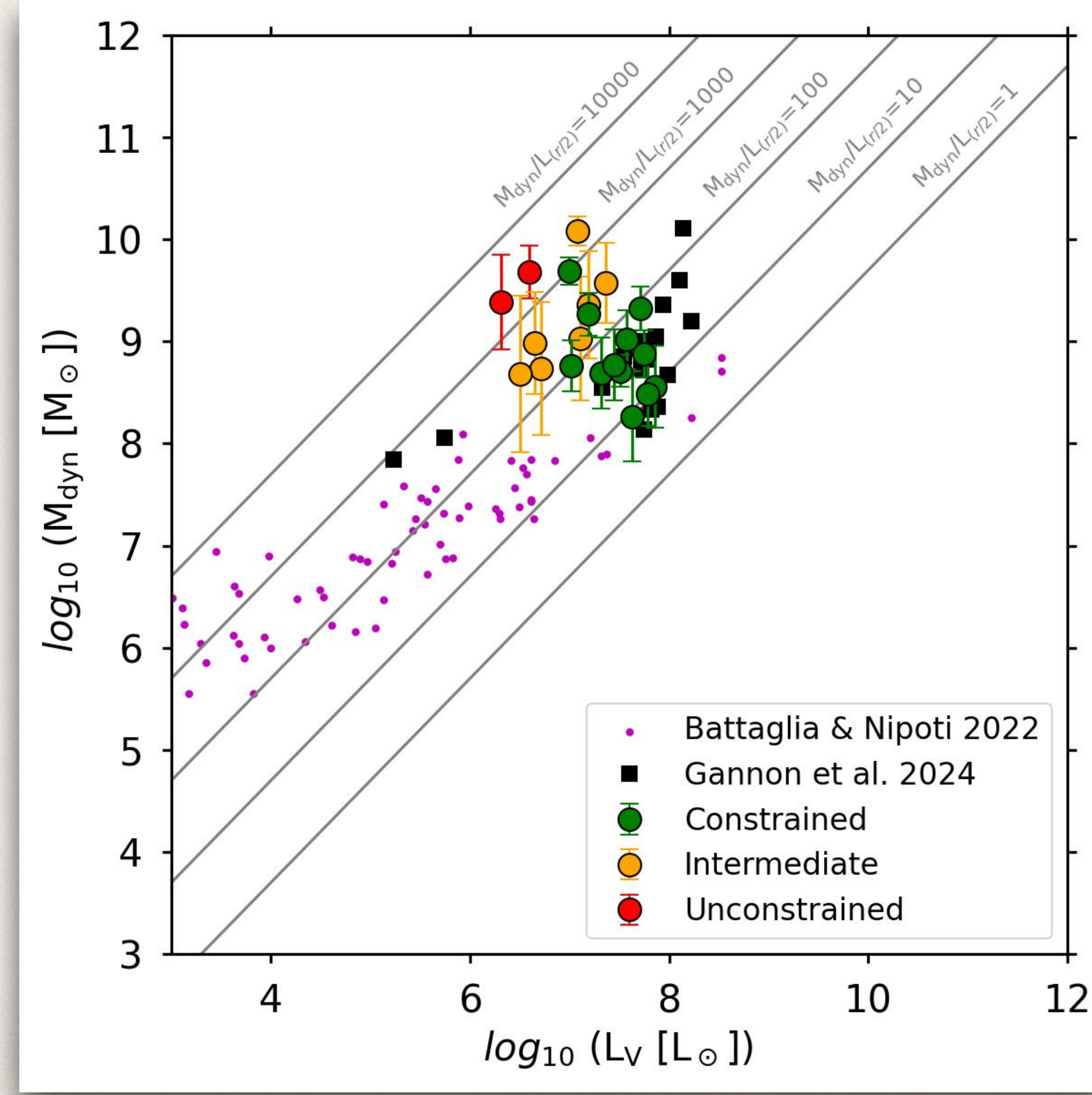


LEWIS: results from stellar kinematics

DM content in UDGs

Chiara Buttitta (INAF-OAC) et al. in prep.

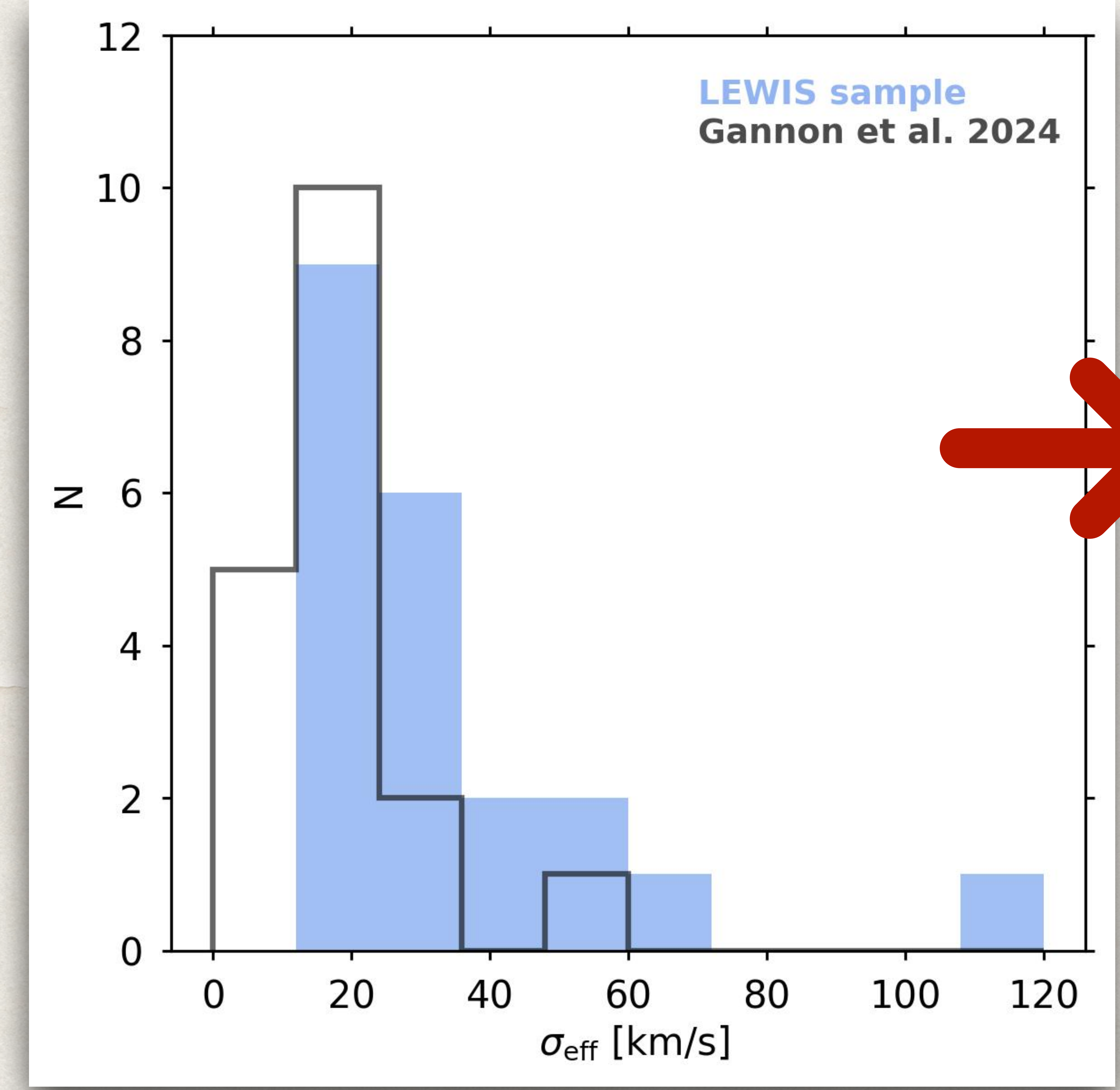


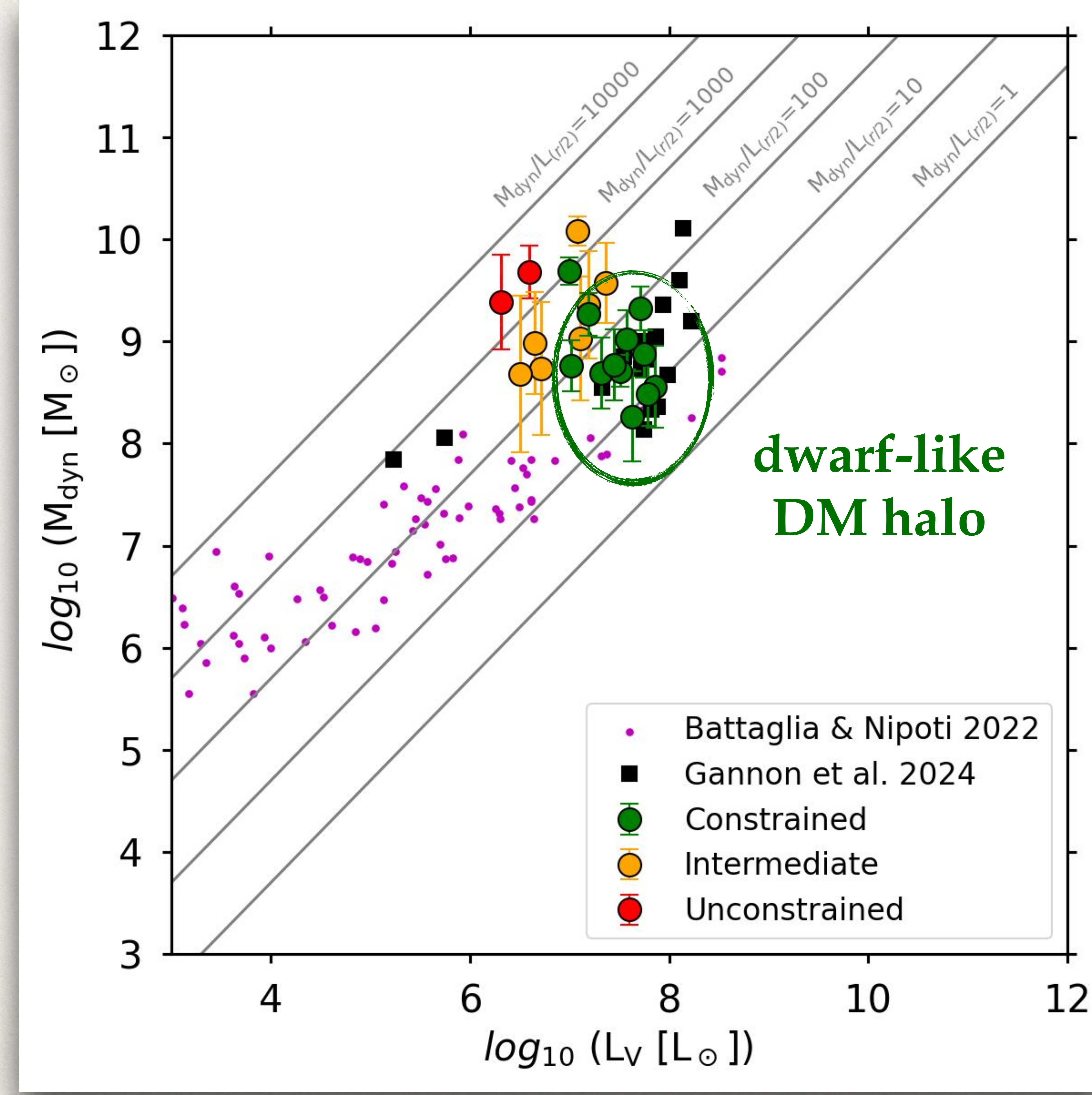


LEWIS: results from stellar kinematics

DM content in UDGs

Chiara Buttitta (INAF-OAC) et al. in prep.



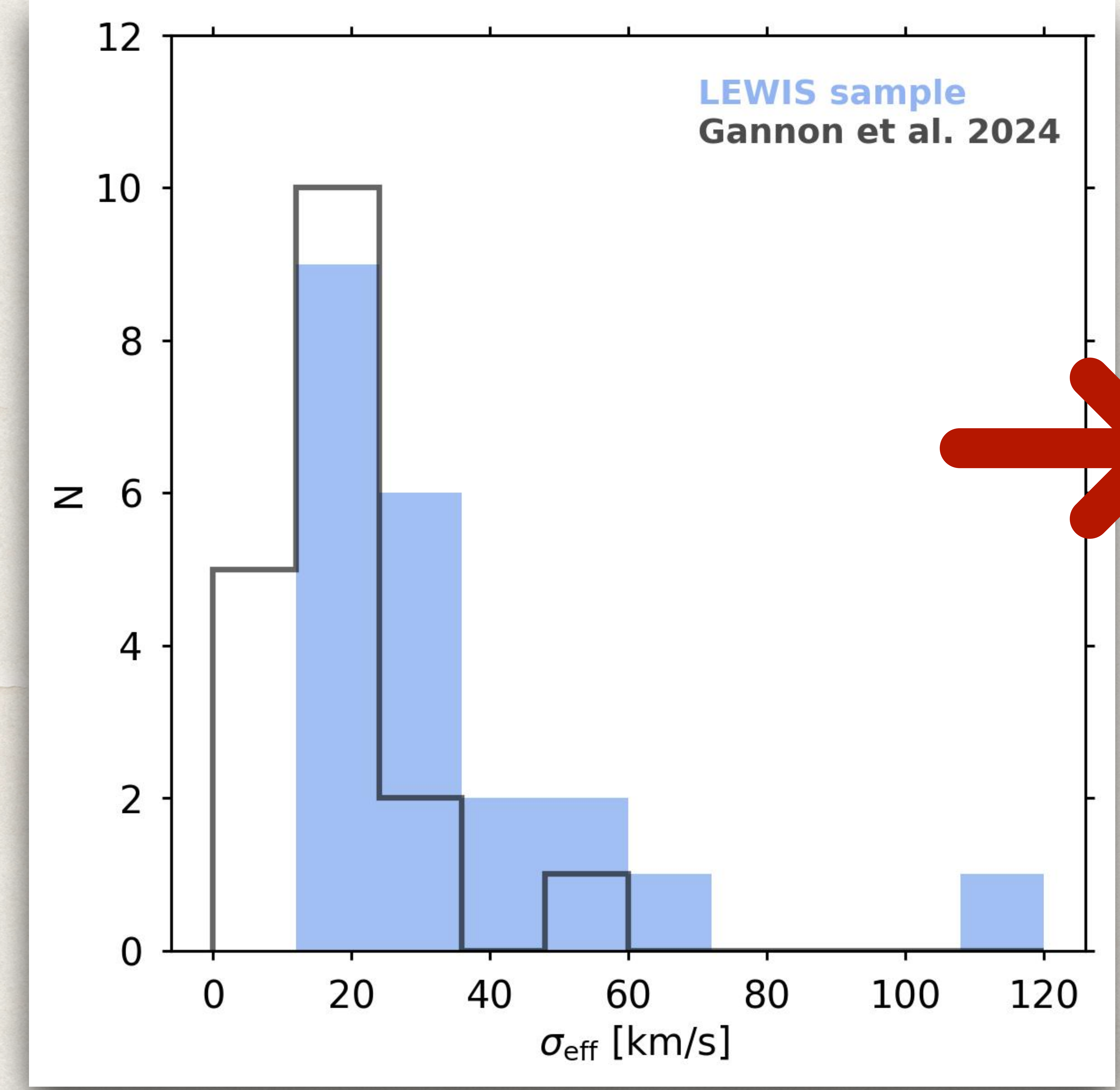


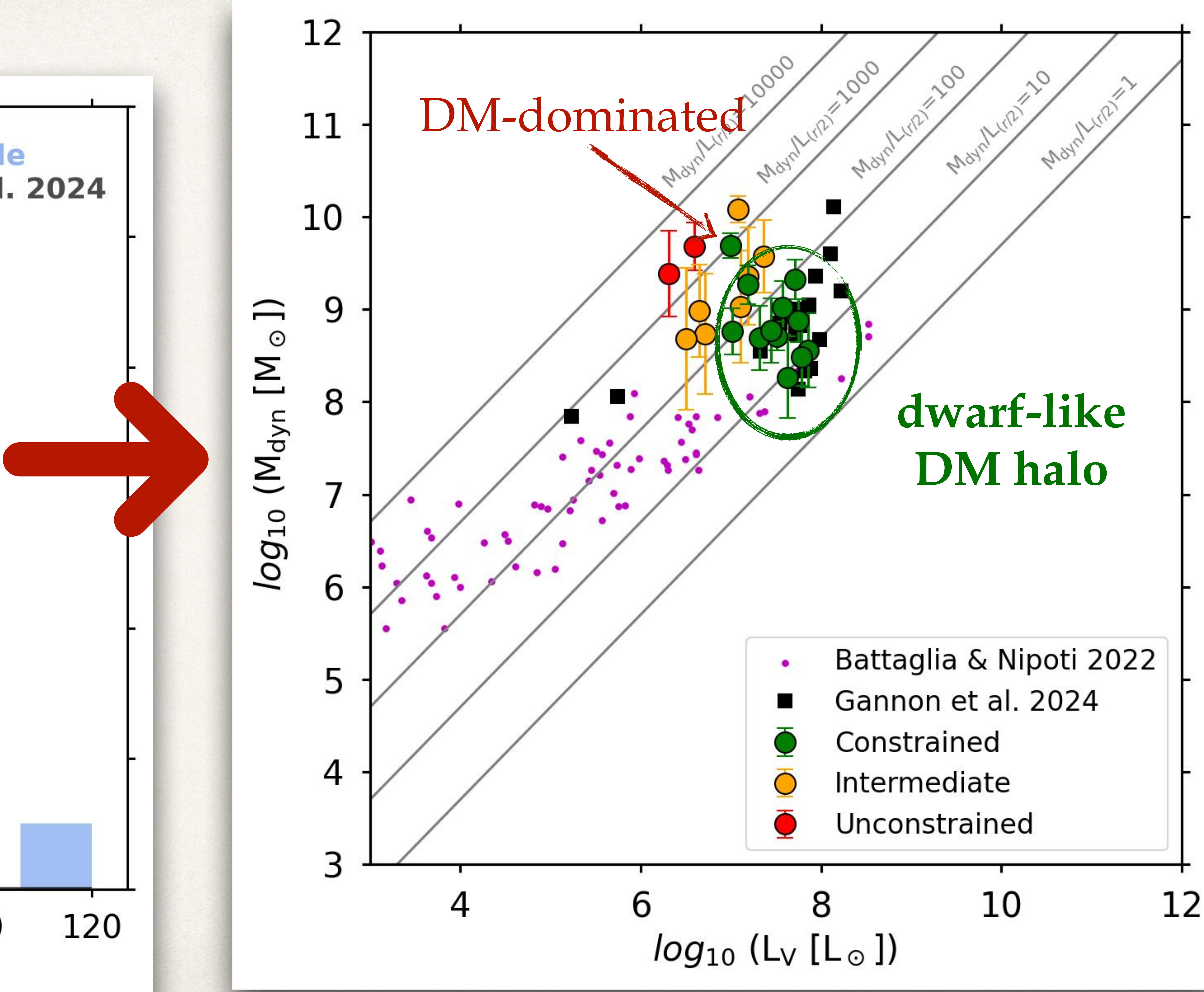
dwarf-like DM halo

LEWIS: results from stellar kinematics

DM content in UDGs

Chiara Buttitta (INAF-OAC) et al. in prep.

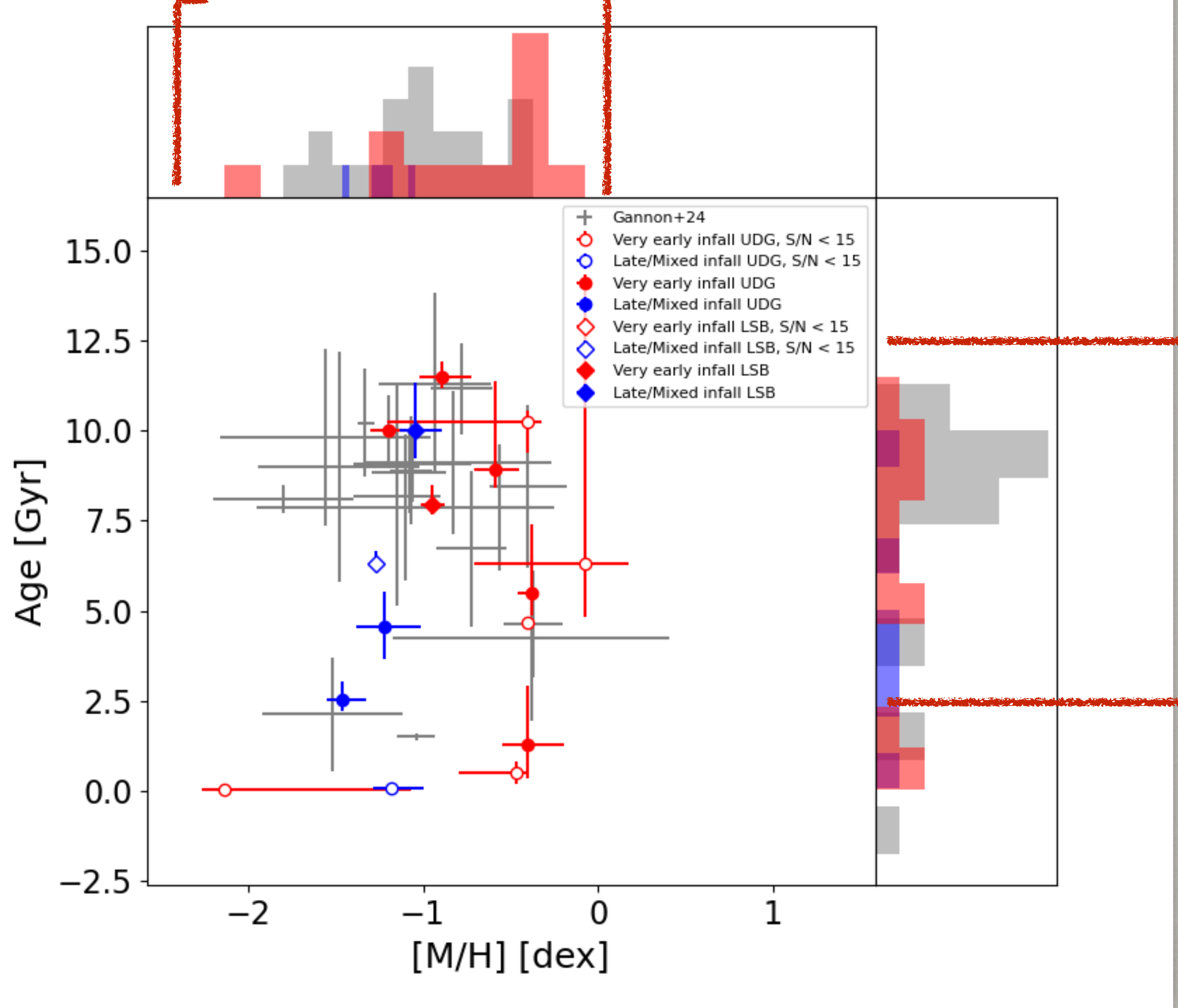




LEWIS: results from stellar population

by Goran Doll (PhD@INAF-OAC & UniNA)

metal poor:
~ -0.29 — -2 dex



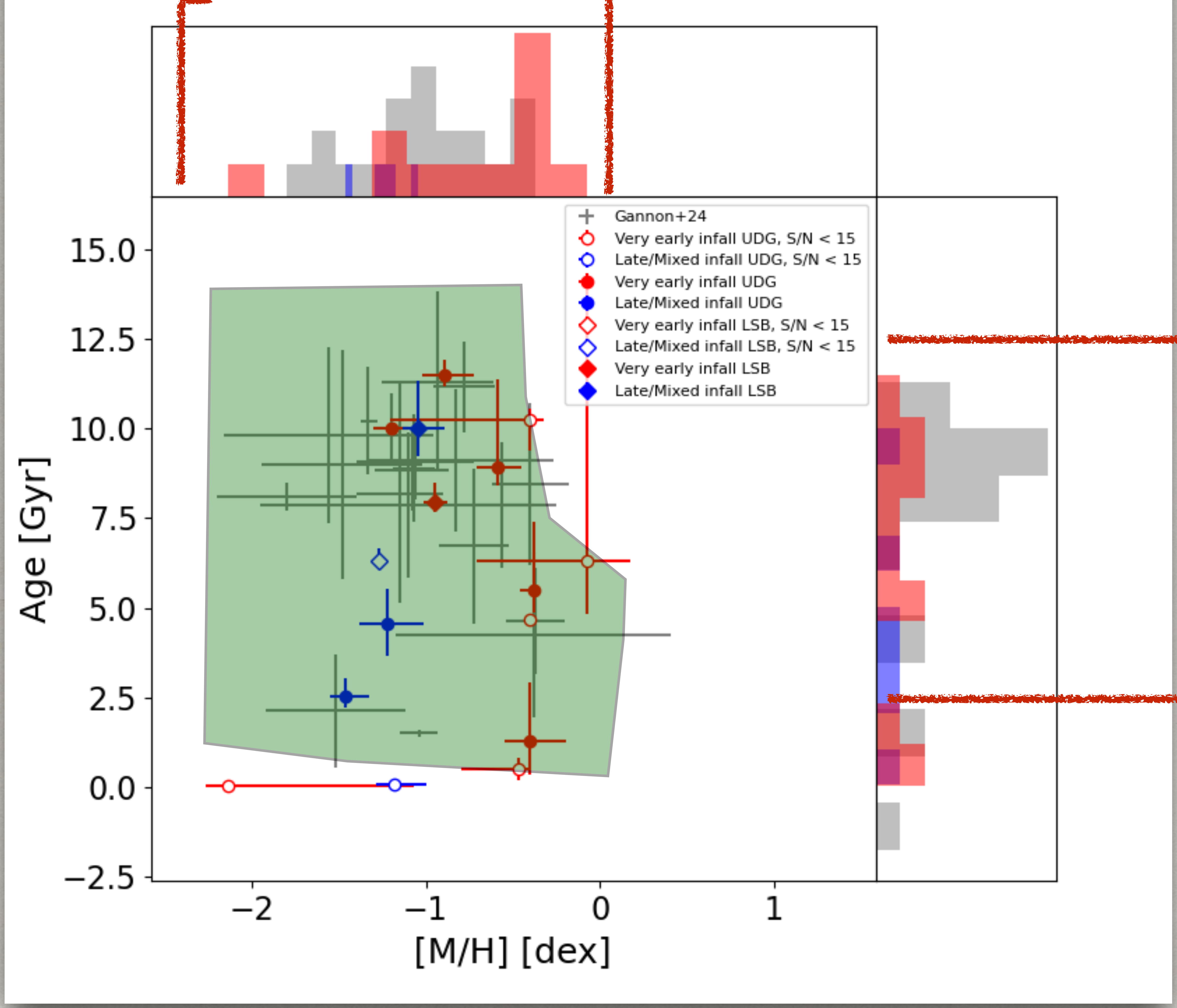
old:
~ 5-10 Gyrs

LEWIS: results from stellar population

by Goran Doll (PhD@INAF-OAC & UniNA)

comparable age & M/H for dwarf galaxies

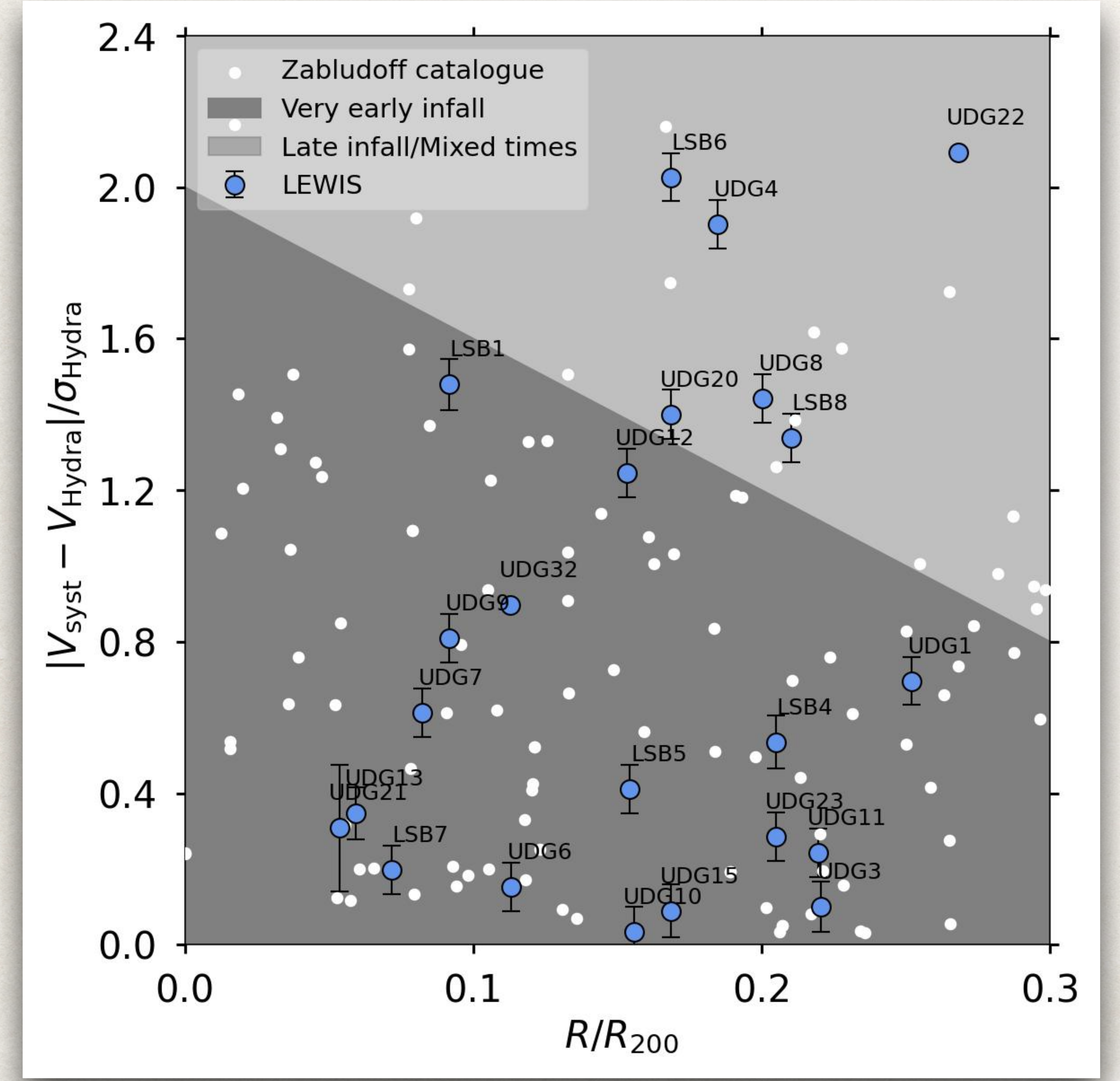
metal poor:
~ -0.29 — -2 dex

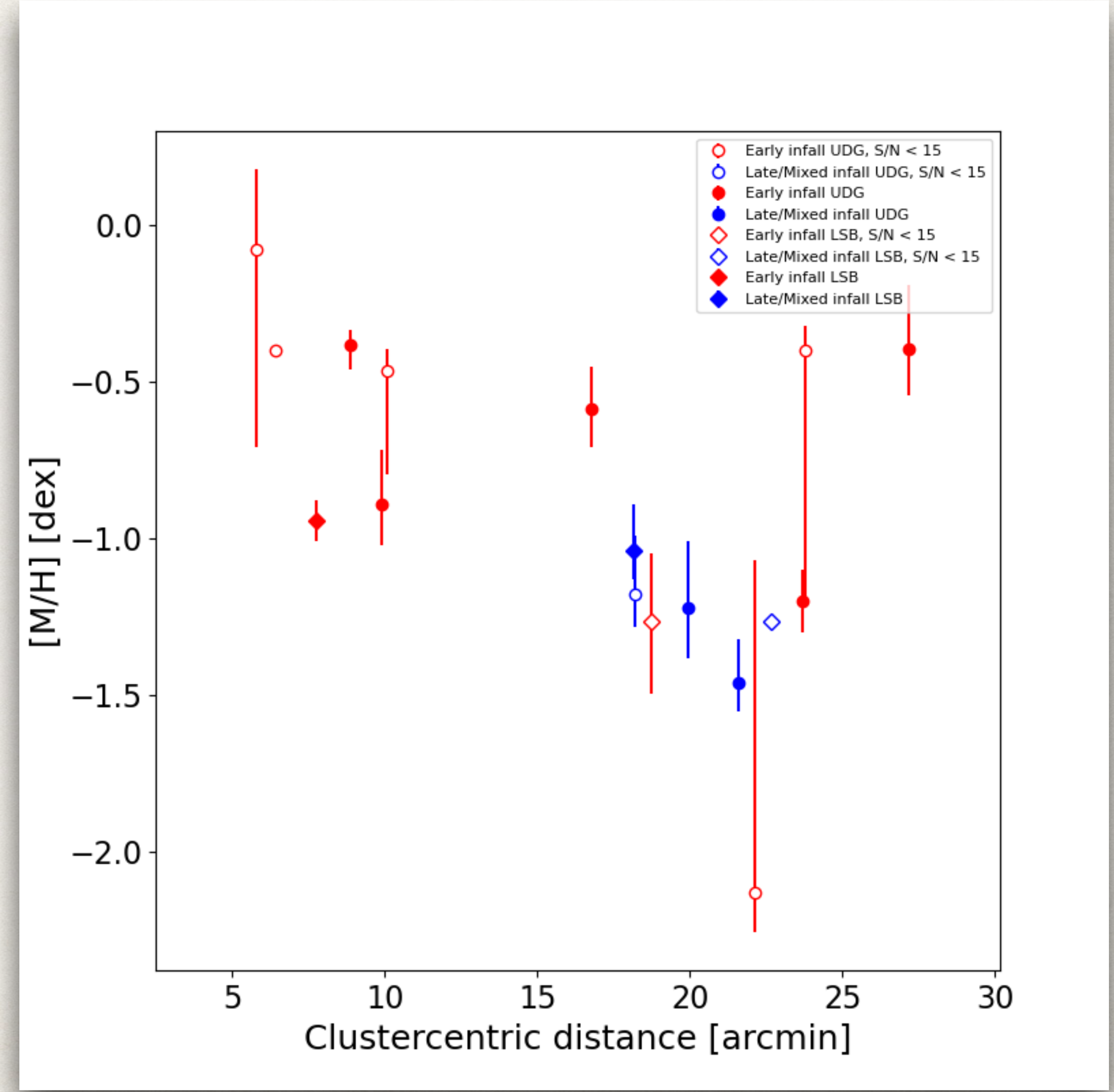


old:
~ 5-10 Gyrs

LEWIS: results from stellar population

by Goran Doll (PhD@INAF-OAC & UniNA)

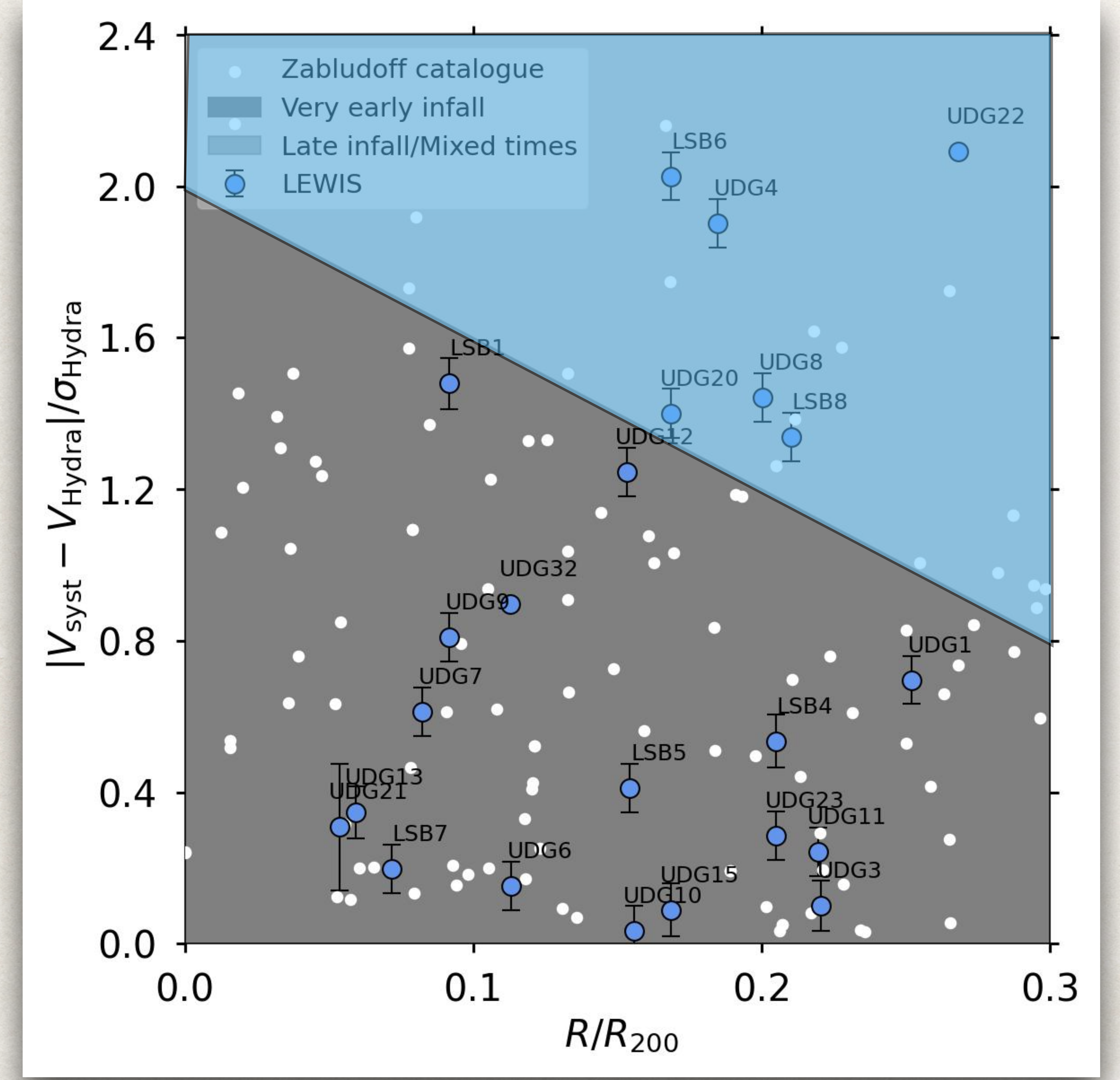


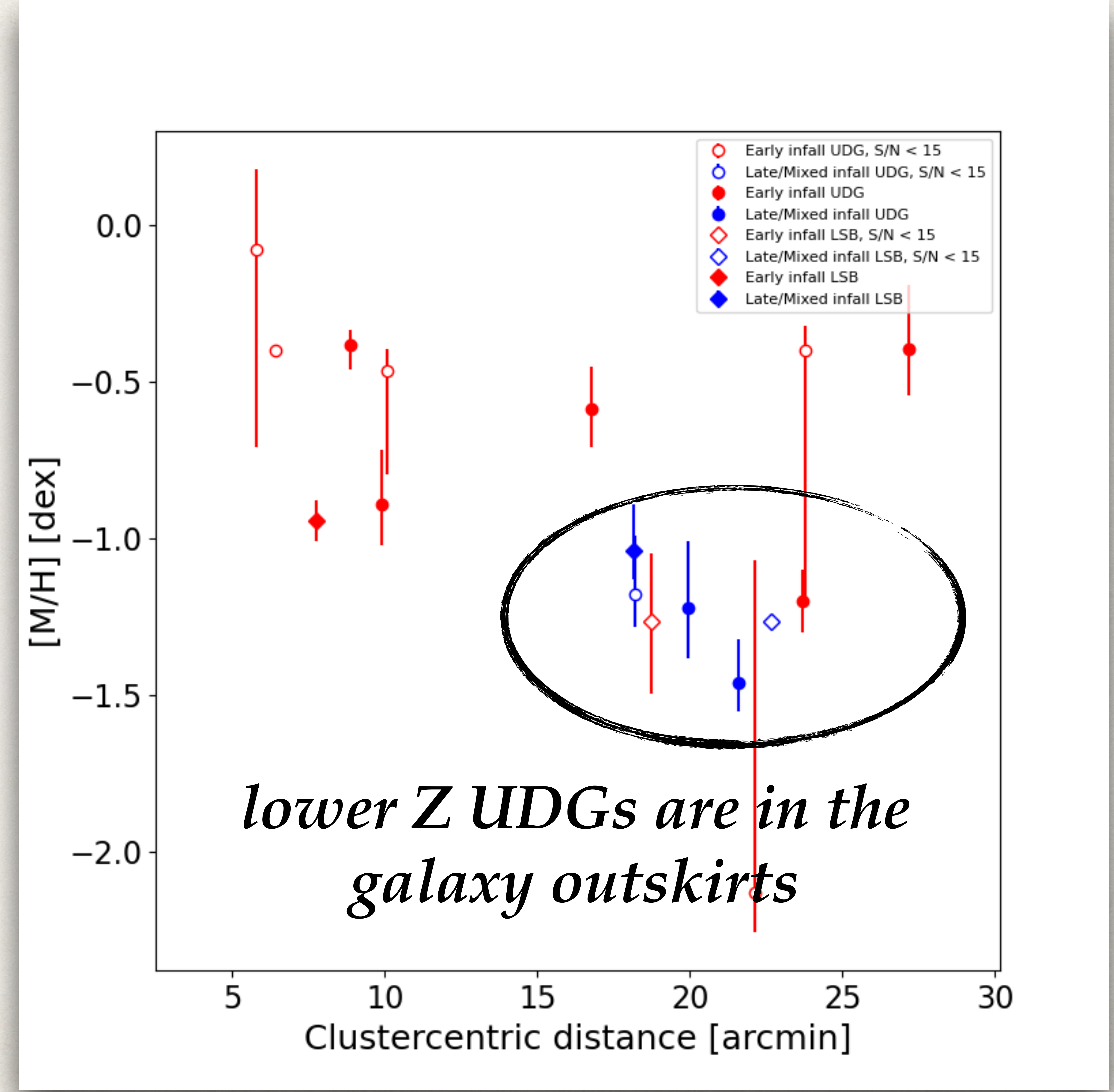


LEWIS: results from stellar population

by Goran Doll (PhD@INAF-OAC & UniNA)

Later infallers





lower Z UDGs are in the galaxy outskirts

IFS for LSB galaxies: lesson learned from the LEWIS project

- Bimodality in the stellar rotation map
- Low velocity dispersion ($\sigma \sim 10 - 40$ km/s)
- Old (5-10 Gys) & metal poor ($-1.3 < [M/H < -0.2]$)
- Bimodal distribution of M/H
- Dwarf-like DM halo ($M_h \sim 10^{10}\ M_\odot$)

Different classes of UDGs in Hydra I cluster

INAF
ISTITUTO NAZIONALE
DI ASTROFISICA

IFS for LSB galaxies: lesson learned from the LEWIS project

- Bimodality in the stellar rotation map → *44% rotation* / *22% no rotation*
- Low velocity dispersion (σ ~ 10 - 40 km/s)
- Old (5-10 Gys) & metal poor (-1.3 < [M/H < -0.2])
- Bimodal distribution of M/H
- Dwarf-like DM halo ($M_h \sim 10^{10}\ M_\odot$)

↓

Different classes of UDGs in Hydra I cluster

INAF
ISTITUTO NAZIONALE
DI ASTROFISICA

LEWIS

IFS for LSB galaxies: lesson learned from the LEWIS project

- Bimodality in the stellar rotation map → *44% rotation* / → *22% no rotation*

- Low velocity dispersion ($\sigma \sim 10$ - 40 km/s) *+ 1 case with high $\sigma \sim 60$ km/s*

- Old (5-10 Gys) & metal poor (-1.3 < [M/H < -0.2])

- Bimodal distribution of M/H

- Dwarf-like DM halo ($M_h \sim 10^{10}\ M_\odot$)

↓

Different classes of UDGs in Hydra I cluster

INAF ISTITUTO NAZIONALE DI ASTROFISICA

LEWIS

IFS for LSB galaxies: lesson learned from the LEWIS project

- Bimodality in the stellar rotation map → *44% rotation* / → *22% no rotation*
- Low velocity dispersion ($\sigma \sim 10$ - 40 km/s) *+ 1 case with high $\sigma \sim 60$ km/s*
- Old (5-10 Gys) & metal poor ($-1.3 < [M/H < -0.2]$) *+ 2 cases with younger age (~1 Gyr) & SF*
- Bimodal distribution of M/H
- Dwarf-like DM halo ($M_h \sim 10^{10}\ M_\odot$)

↓

Different classes of UDGs in Hydra I cluster

INAF
ISTITUTO NAZIONALE
DI ASTROFISICA

IFS for LSB galaxies: lesson learned from the LEWIS project

- Bimodality in the stellar rotation map → *44% rotation* / → *22% no rotation*
- Low velocity dispersion ($\sigma \sim 10$ - 40 km/s) *+ 1 case with high $\sigma \sim 60$ km/s*
- Old (5-10 Gys) & metal poor (-1.3 < [M/H < -0.2]) *+ 2 cases with younger age (~1 Gyr) & SF*
- Bimodal distribution of M/H *– > metal-rich UDGs are "inside" the cluster*
- Dwarf-like DM halo ($M_h \sim 10^{10}\ M_\odot$)

↓

Different classes of UDGs in Hydra I cluster

INAF
ISTITUTO NAZIONALE
DI ASTROFISICA

LEWIS

IFS for LSB galaxies: lesson learned from the LEWIS project

- Bimodality in the stellar rotation map → *44% rotation* / → *22% no rotation*
- Low velocity dispersion ($\sigma \sim 10$ - 40 km/s) *+ 1 case with high $\sigma \sim 60$ km/s*
- Old (5-10 Gys) & metal poor (-1.3 < [M/H < -0.2]) *+ 2 cases with younger age (~1 Gyr) & SF*
- Bimodal distribution of M/H *–> metal-rich UDGs are "inside" the cluster*
- Dwarf-like DM halo ($M_h \sim 10^{10}\ M_\odot$) *+ 1 case DM dominate, i.e. M/L~1000*

↓

Different classes of UDGs in Hydra I cluster

INAF
ISTITUTO NAZIONALE
DI ASTROFISICA

What we still miss

What we still miss

➡ ***statistically significant*** and ***homogeneous imaging*** and ***spectroscopic samples***

What we still miss

➡ ***statistically significant*** and ***<u>homogeneous imaging</u>*** and ***<u>spectroscopic samples</u>***

Euclid

LSST

ELT

INAF
ISTITUTO NAZIONALE
DI ASTROFISICA

What we still miss

➡ *statistically significant* and ***homogeneous imaging*** and ***spectroscopic samples***

Euclid

LSST

ELT

WST?

SHARP?

What we still miss

- ➡ *statistically significant* and ***homogeneous imaging*** and ***spectroscopic samples***

  - Imaging: *Euclid*, *LSST*, *ELT*
  - Spectroscopy: *WST?*, *SHARP?*

- ➡ the ***detection and properties of UDGs beyond the local Universe*** ($z>0.05$)

INAF
ISTITUTO NAZIONALE
DI ASTROFISICA

What we still miss

➡ ***statistically significant*** and ***homogeneous imaging*** and ***spectroscopic samples***

Euclid

LSST

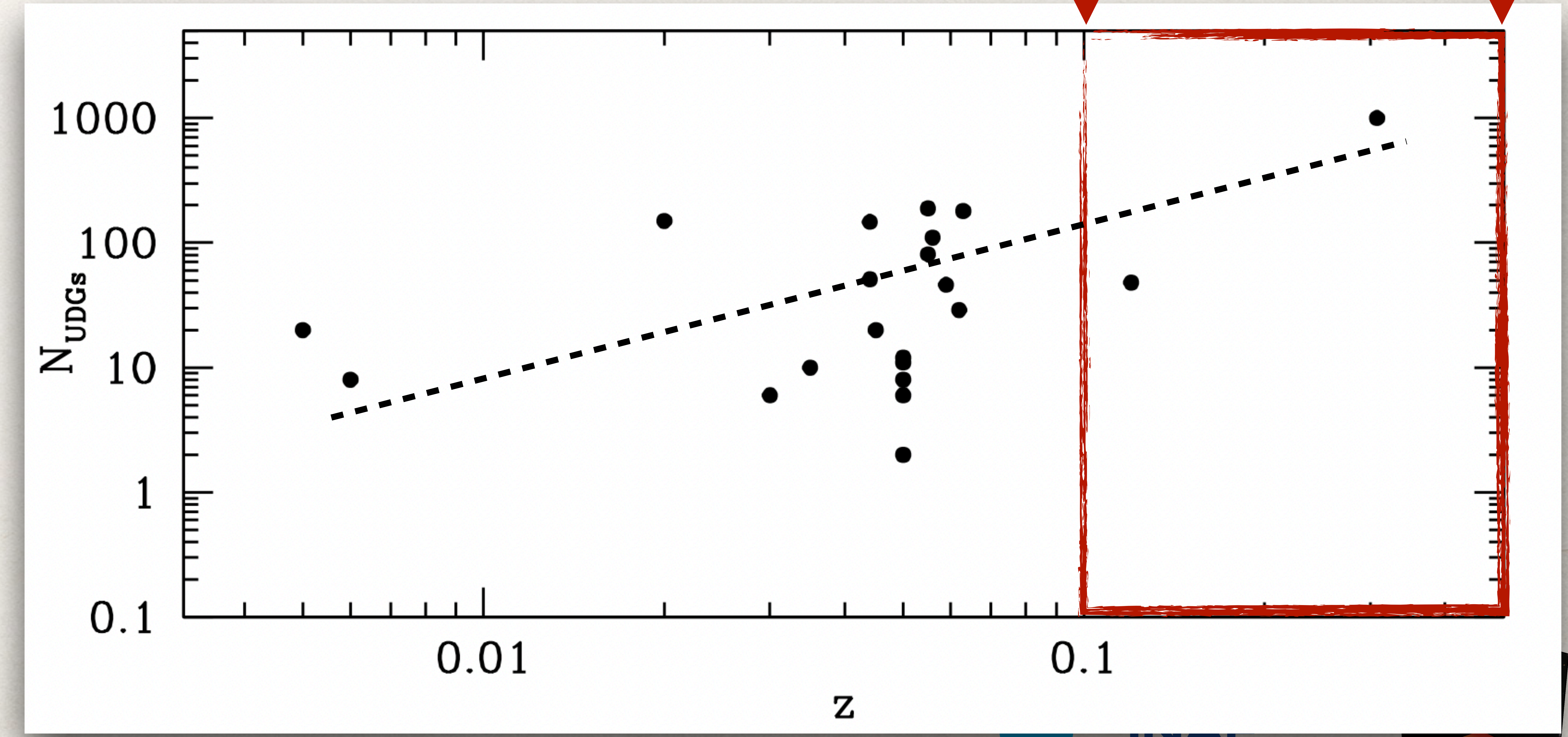
ELT

WST?

SHARP?

➡ the ***detection and properties of UDGs beyond the local Universe*** (z>0.05)

Unexplored redshift range



What we still miss

- *statistically significant* and *homogeneous imaging* and *spectroscopic samples*

Euclid

LSST

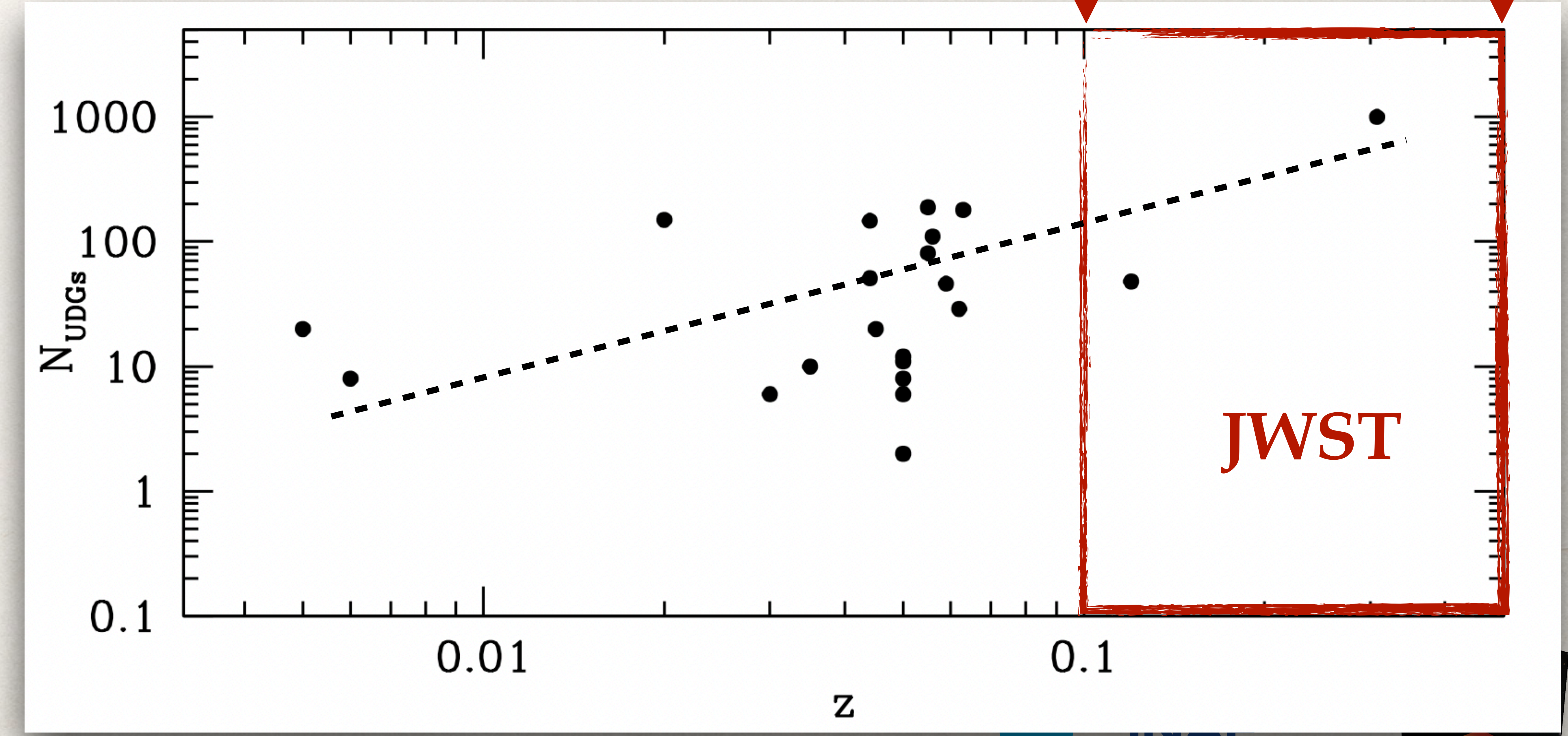
ELT

WST?

SHARP?

- the ***detection and properties of UDGs beyond the local Universe*** (z>0.05)

Unexplored redshift range



What we still miss

➡ ***statistically significant*** and ***homogeneous imaging*** and ***spectroscopic samples***

Euclid

LSST

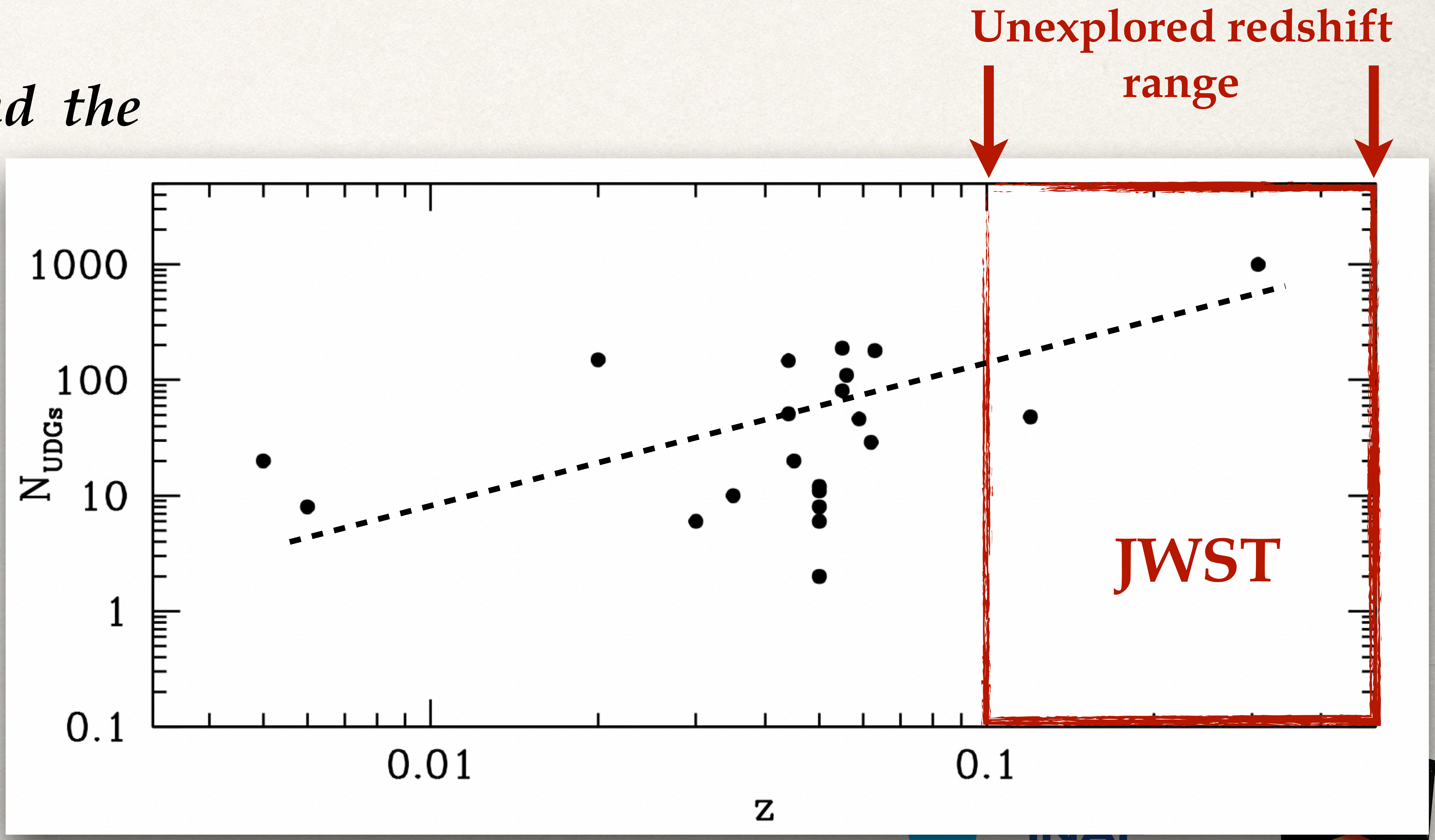
ELT

WST?

SHARP?

➡ the ***detection and properties of UDGs beyond the local Universe*** (z>0.05)

➡ ***dedicated studies*** to map the gas content and star formation signs (***HI, Hα, and UV emissions***)



What we still miss

- ➡ ***statistically significant*** and ***homogeneous imaging*** and ***spectroscopic samples***

Euclid

LSST

ELT

WST?

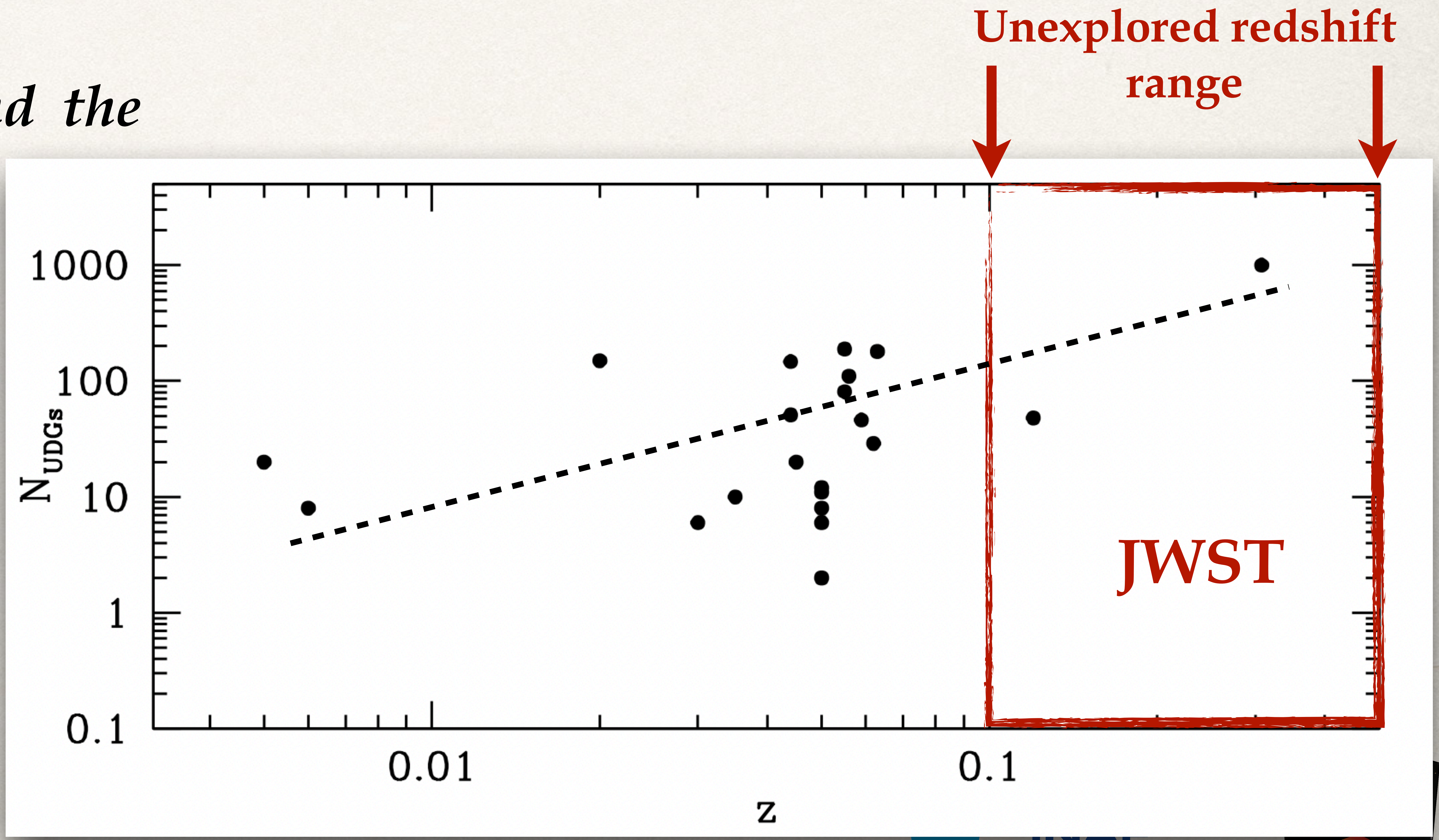
SHARP?

- ➡ the ***detection and properties of UDGs beyond the local Universe*** (z>0.05)

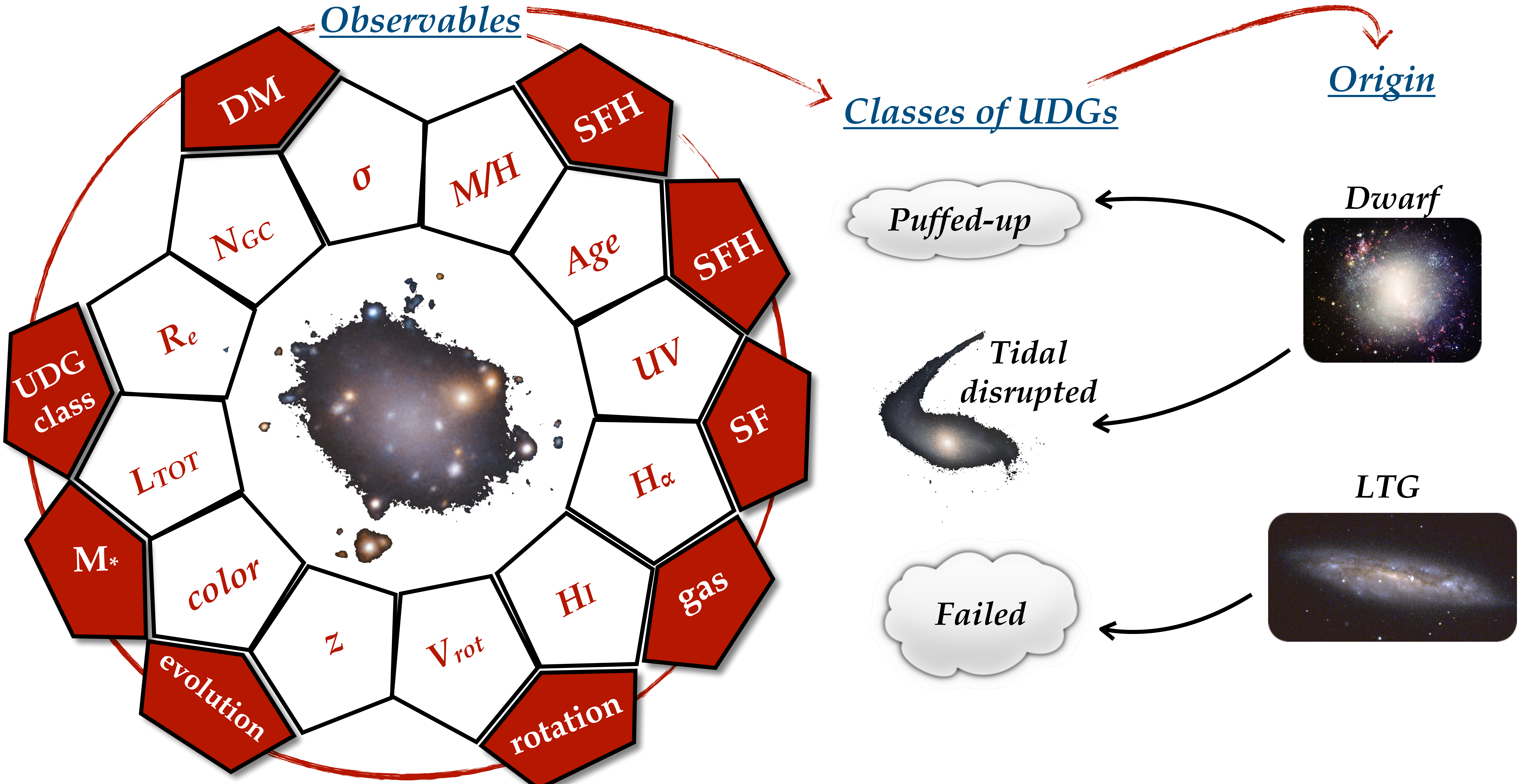
- ➡ ***dedicated studies*** to map the gas content and star formation signs (***HI, Hα, and UV emissions***)

MeerKAT

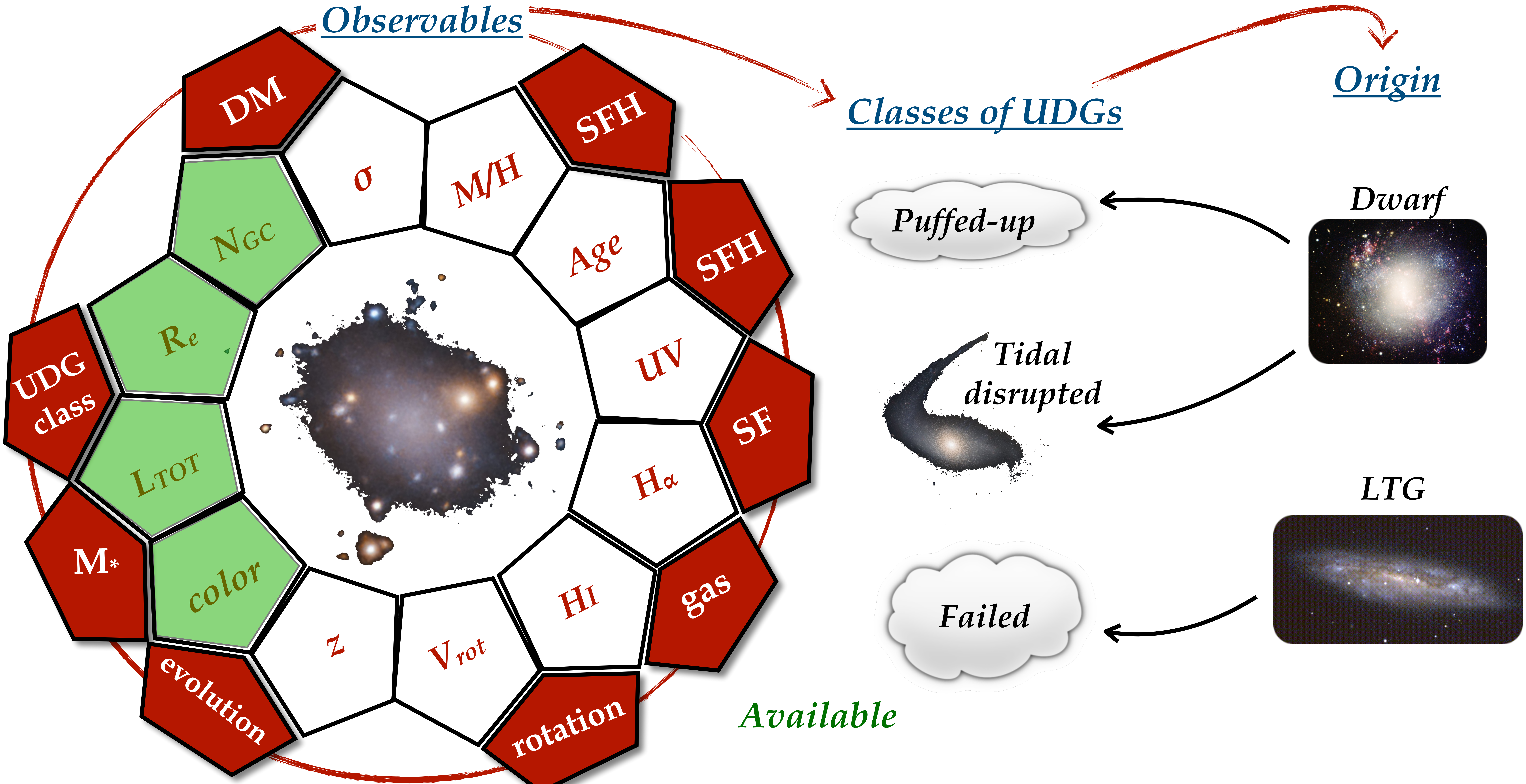
SKA



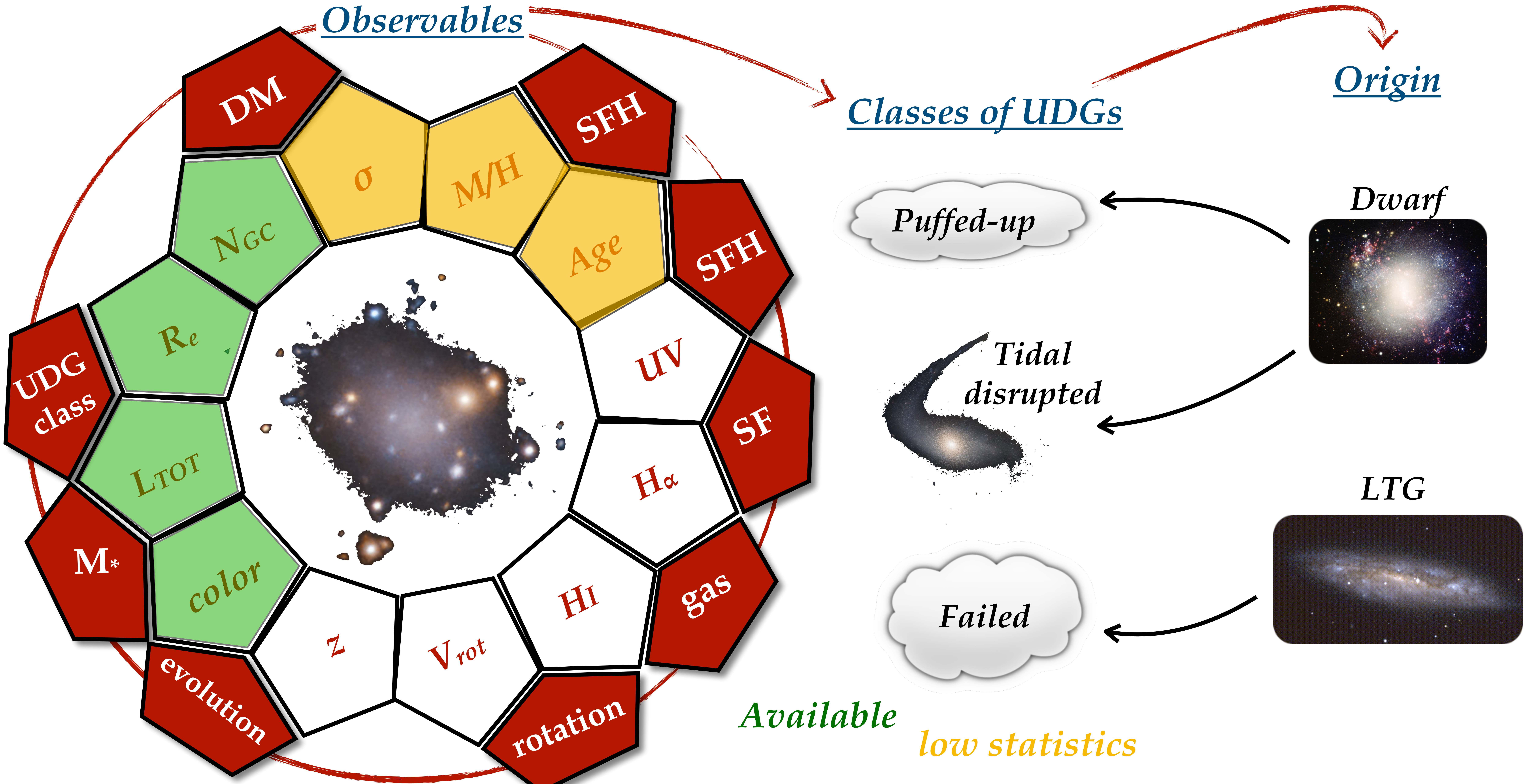
What we still miss



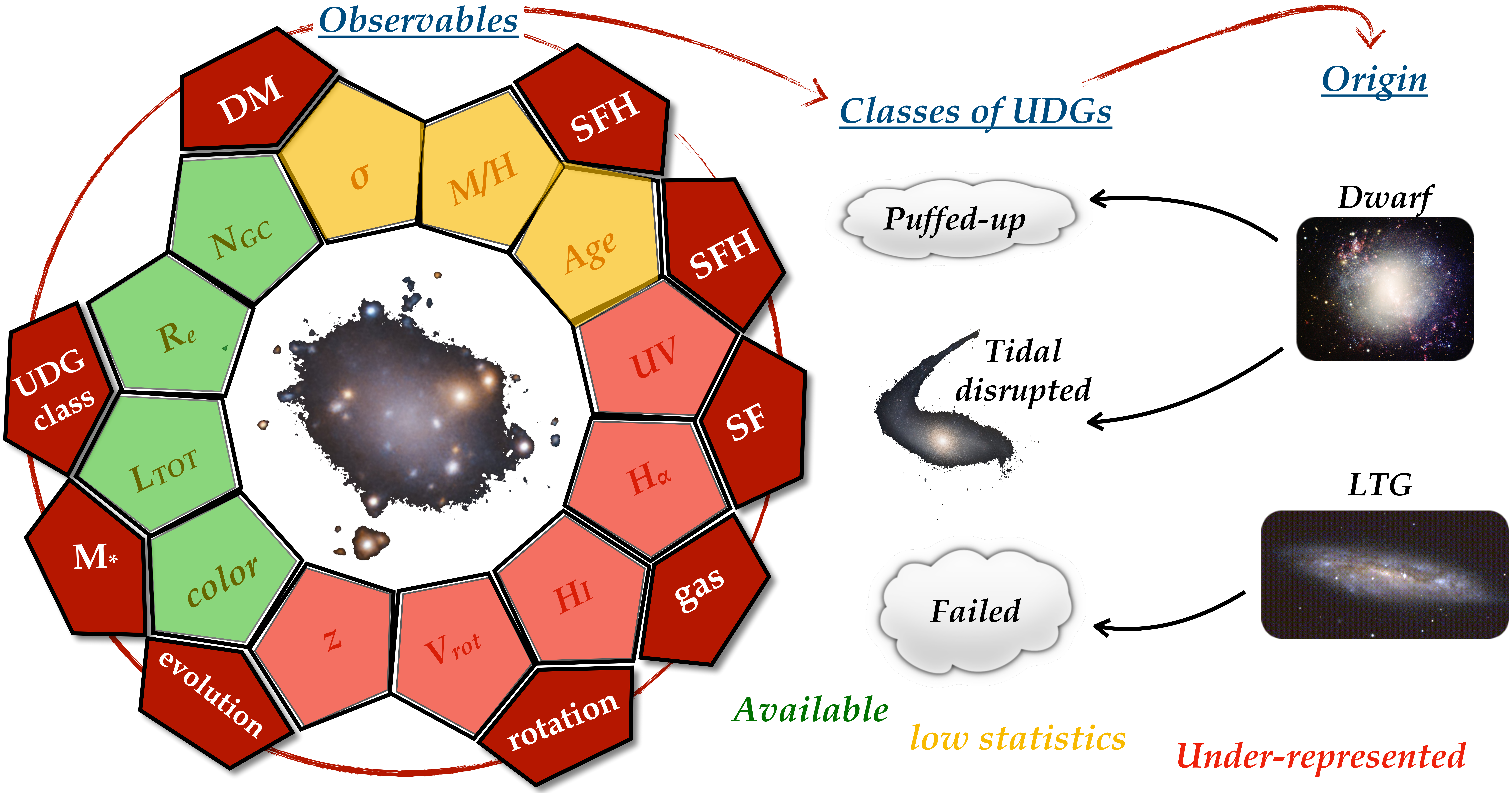
What we still miss



What we still miss



What we still miss



What next with SHARP?
Challenging science for a challenging telescope

- **spectral resolution**: LSB galaxies $M_* \sim 10^{7\text{-}8}\ M_\odot$ => σ~10-30 km/s
- **S/N vs Exp Time:** MUSE@VLT S/N~16 with ExpT~6hrs -> μ_g~28 mag/arcsec^2
- **Combine long-slit with IF**

INAF
ISTITUTO NAZIONALE
DI ASTROFISICA

What next with SHARP?
Challenging science for a challenging telescope

- **spectral resolution**: LSB galaxies $M_* \sim 10^{7\text{-}8}$ $M_\odot$ => σ~10-30 km/s

  ➥ R~20000

- **S/N vs Exp Time:** MUSE@VLT S/N~16 with ExpT~6hrs -> μ_g~28 mag/arcsec^2

- **Combine long-slit with IF**

What next with SHARP?
Challenging science for a challenging telescope

- **spectral resolution**: LSB galaxies $M_* \sim 10^{7-8}\ M_\odot$ => $\sigma \sim 10$-30 km/s
  - ➥ R~20000
- **S/N vs Exp Time:** MUSE@VLT S/N~16 with ExpT~6hrs -> $\mu_g \sim 28$ mag/arcsec^2
  - ➥ ELT: same ExpT —> ~ 3 times larger S/R
- **Combine long-slit with IF**

INAF ISTITUTO NAZIONALE DI ASTROFISICA

What next with SHARP?
Challenging science for a challenging telescope

- **spectral resolution**: LSB galaxies $M_* \sim 10^{7\text{-}8}$ $M_\odot$ => σ~10-30 km/s
  - ➥ R~20000
- **S/N vs Exp Time:** MUSE@VLT S/N~16 with ExpT~6hrs -> μ_g~28 mag/arcsec²
  - ➥ ELT: same ExpT —> ~ 3 times larger S/R
- **Combine long-slit with IF**
  - ➥ LS —> σ (HR spec)
    IF —> 2D kin + GCs

INAF ISTITUTO NAZIONALE DI ASTROFISICA

LEWIS

What next with SHARP?
Challenging science for a challenging telescope

- **spectral resolution**: LSB galaxies $M_* \sim 10^{7\text{-}8}\ M_\odot$ => σ~10-30 km/s
  - ➥ R~20000
- **S/N vs Exp Time:** MUSE@VLT S/N~16 with ExpT~6hrs -> μ_g~28 mag/arcsec^2
  - ➥ ELT: same ExpT —> ~ 3 times larger S/R
- **Combine long-slit with IF**
  - ➥ LS —> σ (HR spec)
    IF —> 2D kin + GCs

SHARP can map the stellar kin & SFH of UDGs at high z

INAF
ISTITUTO NAZIONALE
DI ASTROFISICA

LEWIS

Additional slides

LESSON LEARNED: SN vs σ

LEWIS data are in the LSB regime —> main issue is the S/N of the spectra

several tests to identify the minimum S/N needed for the data to retrieve a reliable value for σ_{LOS}

LESSON LEARNED: SN vs σ

LEWIS data are in the LSB regime —> main issue is the S/N of the spectra

several tests to identify the minimum S/N needed for the data to retrieve a reliable value for σ_{LOS}

based on the E-MILES models, we simulated mock UDG11-like spectra to study how the retrieved quantities from the pPXF fit vary with the SNR

LESSON LEARNED: SN vs σ

LEWIS data are in the LSB regime —> main issue is the S/N of the spectra

several tests to identify the minimum S/N needed for the data to retrieve a reliable value for σ_{LOS}

based on the E-MILES models, we simulated mock UDG11-like spectra to study how the retrieved quantities from the pPXF fit vary with the SNR

I. constructed a synthetic spectrum with log(Age)=10 and [*M*/H]= −1.2

LESSON LEARNED: SN vs σ

LEWIS data are in the LSB regime —> main issue is the S/N of the spectra

several tests to identify the minimum S/N needed for the data to retrieve a reliable value for σ_{LOS}

based on the E-MILES models, we simulated mock UDG11-like spectra to study how the retrieved quantities from the pPXF fit vary with the SNR

I. constructed a synthetic spectrum with log(Age)=10 and $[M/H] = -1.2$

II. convolved the spectrum with MUSE LSF (Bacon+2017)

LESSON LEARNED: SN vs σ

LEWIS data are in the LSB regime —> main issue is the S/N of the spectra

---

several tests to identify the minimum S/N needed for the data to retrieve a reliable value for σ_{LOS}

based on the E-MILES models, we simulated mock UDG11-like spectra to study how the retrieved quantities from the pPXF fit vary with the SNR

I. constructed a synthetic spectrum with log(Age)=10 and $[M/H] = -1.2$

II. convolved the spectrum with MUSE LSF (Bacon+2017)

III. convolved it with varying kernels to simulate different σ_{LOS}

LESSON LEARNED: SN vs σ

LEWIS data are in the LSB regime —> main issue is the S/N of the spectra

several tests to identify the minimum S/N needed for the data to retrieve a reliable value for σ_{LOS}

based on the E-MILES models, we simulated mock UDG11-like spectra to study how the retrieved quantities from the pPXF fit vary with the SNR

I. constructed a synthetic spectrum with log(Age)=10 and $[M/H] = -1.2$

II. convolved the spectrum with MUSE LSF (Bacon+2017)

III. convolved it with varying kernels to simulate different σ_{LOS}

IV. add Poissonian noise with different $5 < S/N < 120$ per pixel

LESSON LEARNED: SN vs σ

LESSON LEARNED: SN vs σ

Minimum S/N to obtain an unbiased value