

# *Integral-field spectroscopy of UDGs with MUSE*

The LEWIS project



*Exploring the low-surface brightness  
universe with MUSE*

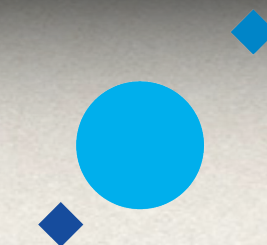
**E. Iodice, INAF (PI)**

**M. Hilker, ESO (co-PI)**

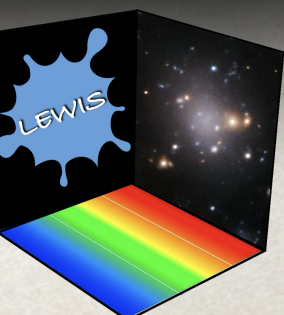
*M. Arnaboldi (ESO), C. Buttitta (INAF), M. Cantiello (INAF), E.M. Corsini (Univ. Padova), G. D'Ago (Cambridge),  
G. Doll (Univ. Naples & INAF), J. Falc n-Barroso (IAC), K. Fahrion (Univ. Vienna), D. Forbes (Swinburne Univ. of Technology),  
M. Gullieuszik (INAF), J. Hartke (Turku Univ.), A. La Marca (Univ. of Groningen), F. Lohmann (ESO), S. Mieske (ESO), M.  
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*Enrichetta Iodice*

*INAF-Astronomical Observatory of Capodimonte*



**INAF**  
ISTITUTO NAZIONALE  
DI ASTROFISICA





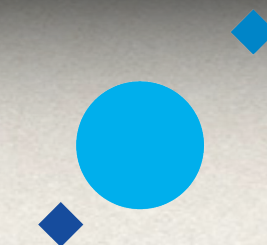
# *Looking into the faintEst With muSe (LEWIS)*

on the nature of the ultra-diffuse galaxies in the Hydra I cluster

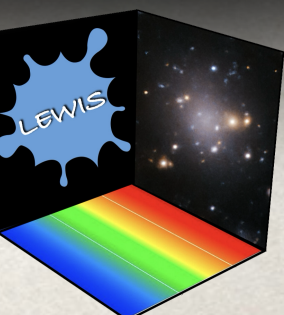
- ❖ **ESO LP @ MUSE:** 133.5 hrs over P108-P109-P110, 2021-2023
- ❖ Targets: a complete sample of UDGs in the **Hydra I cluster**



first homogeneous integral-field spectroscopic survey of UDGs

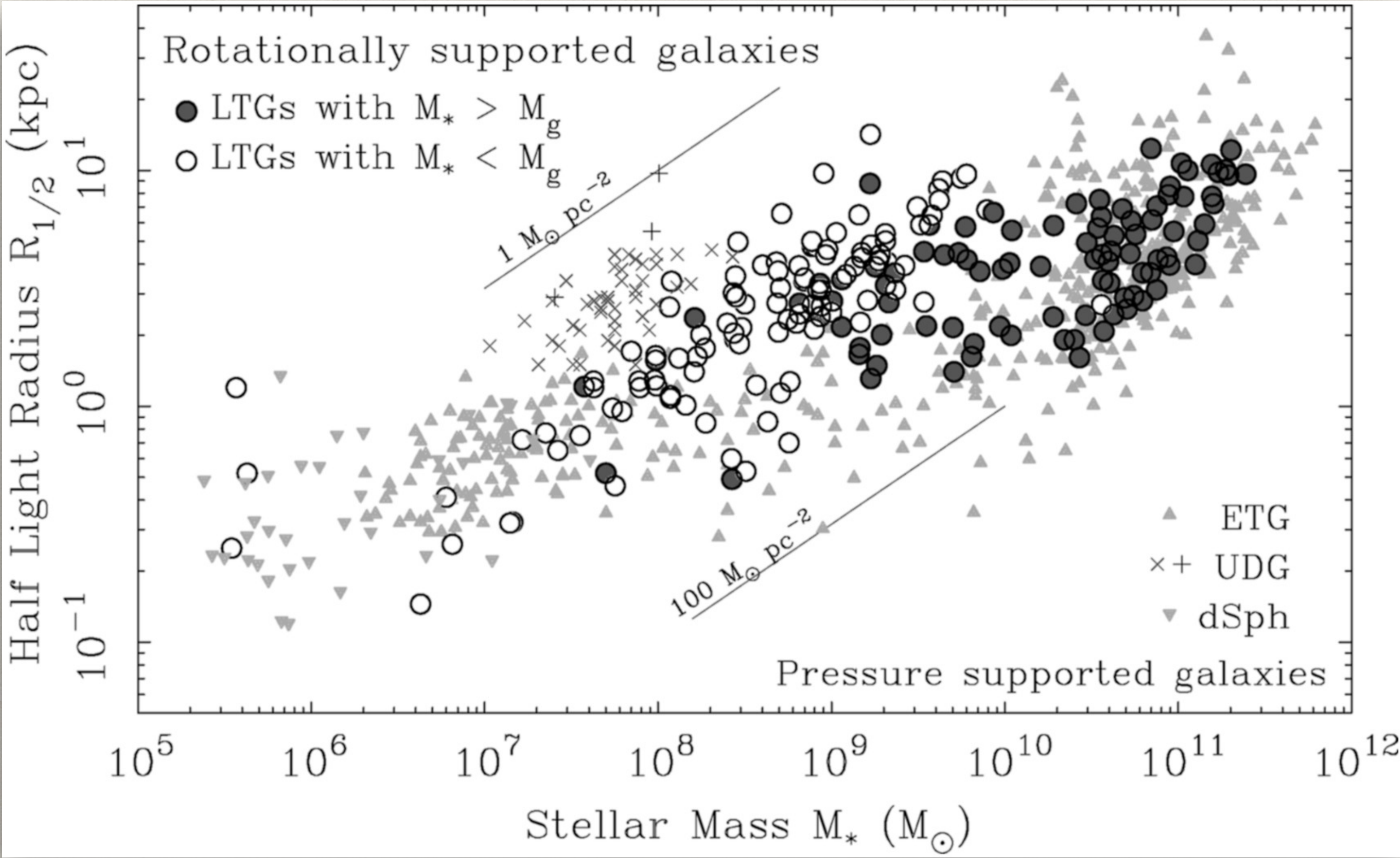


**INAF**  
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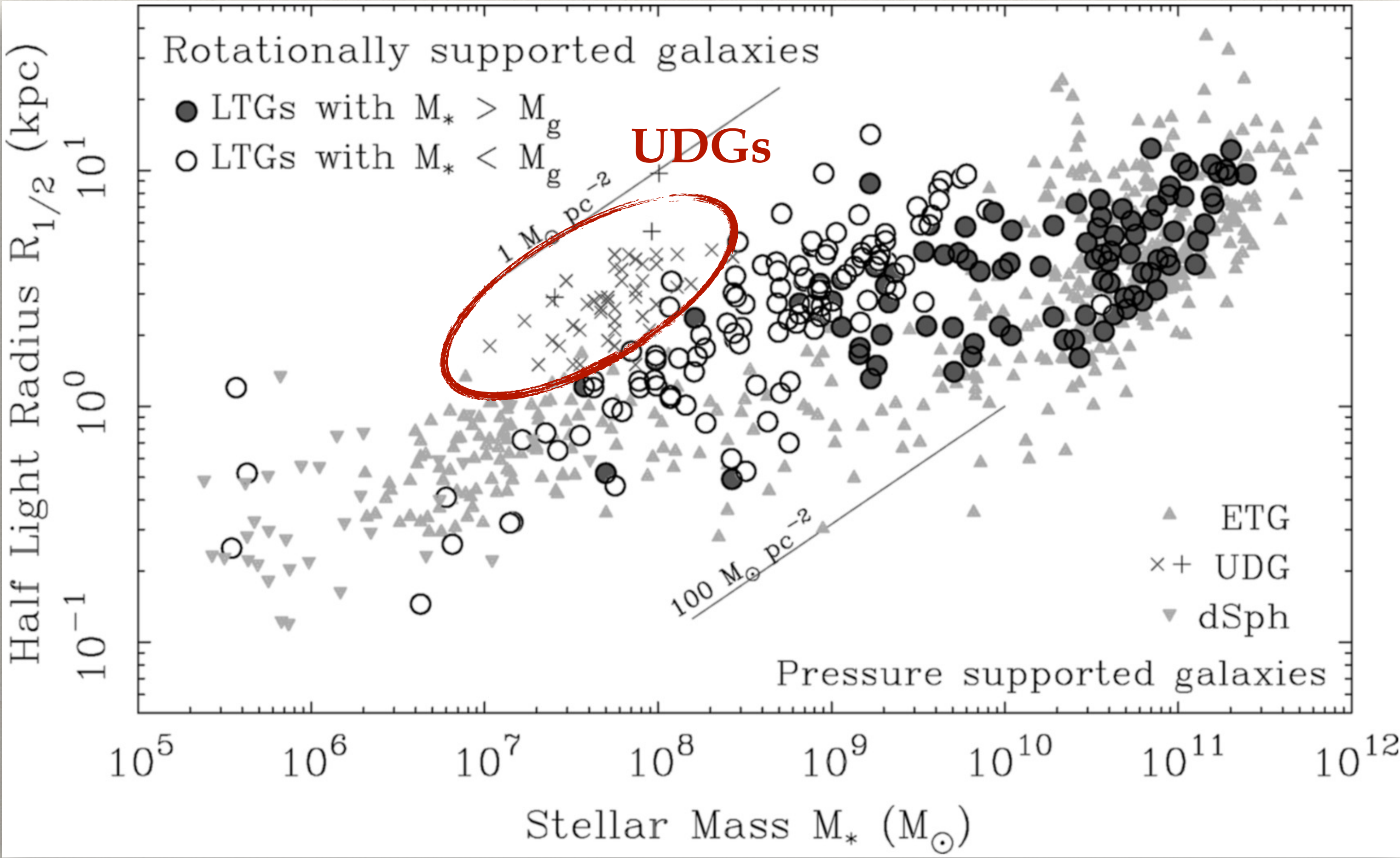


# Science case: UDGs





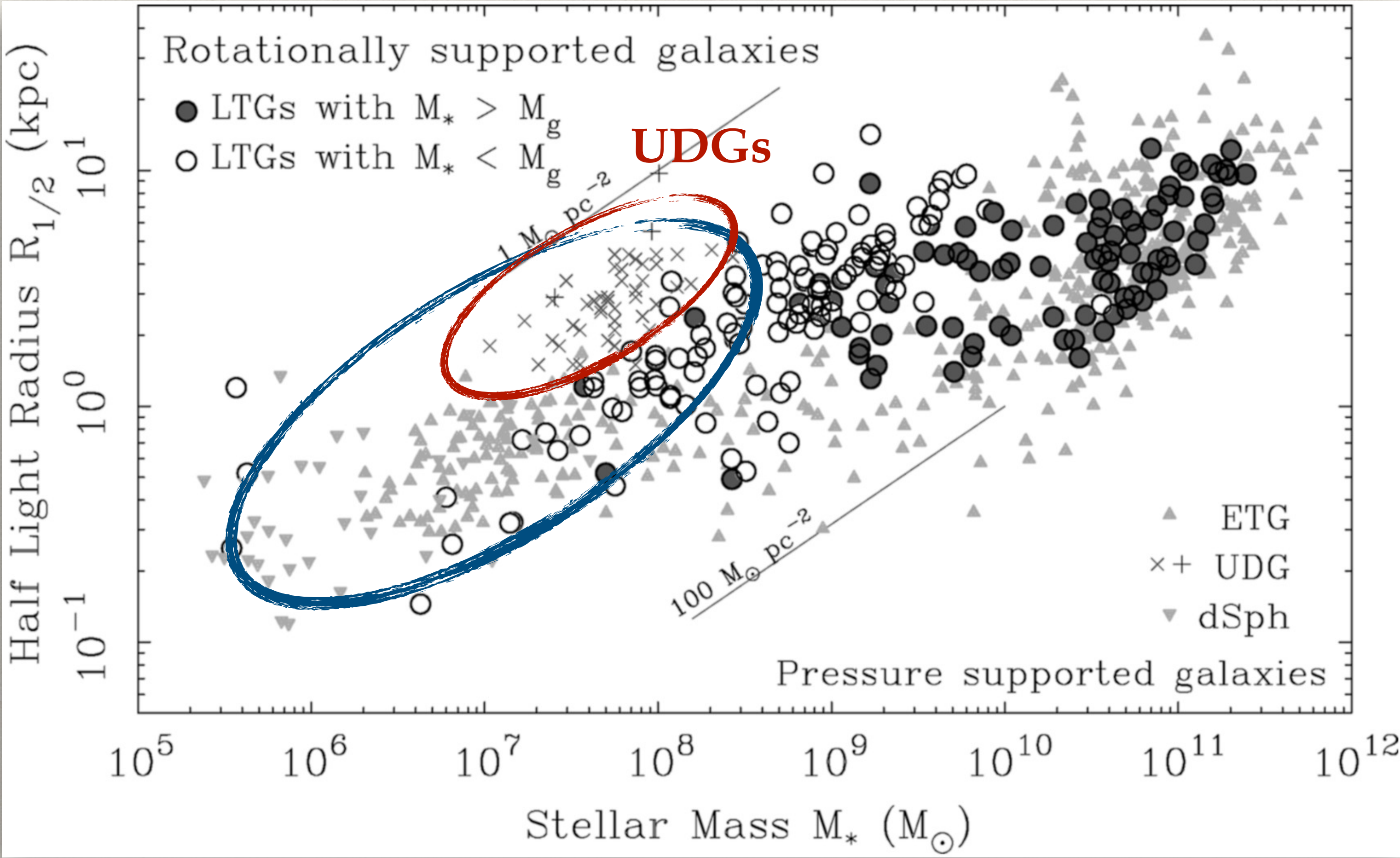
# Science case: UDGs



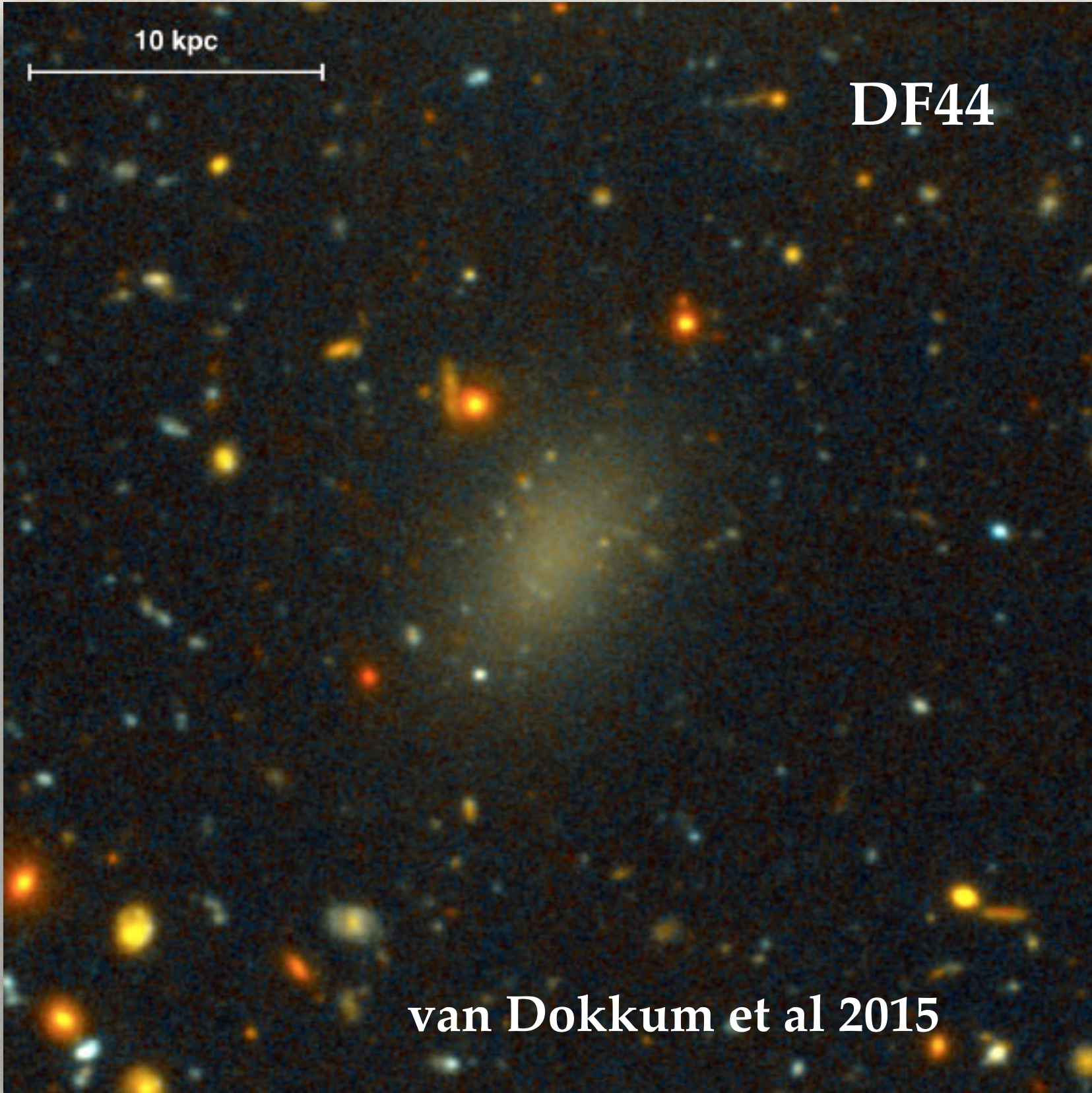
$1.5 \leq R_e \leq 4.6 \text{ kpc}$   
 $\mu_{0,g} \geq 24 \text{ mag/arcsec}^2$   
 $M_* \sim 10^8 M_\odot$



# Science case: UDGs



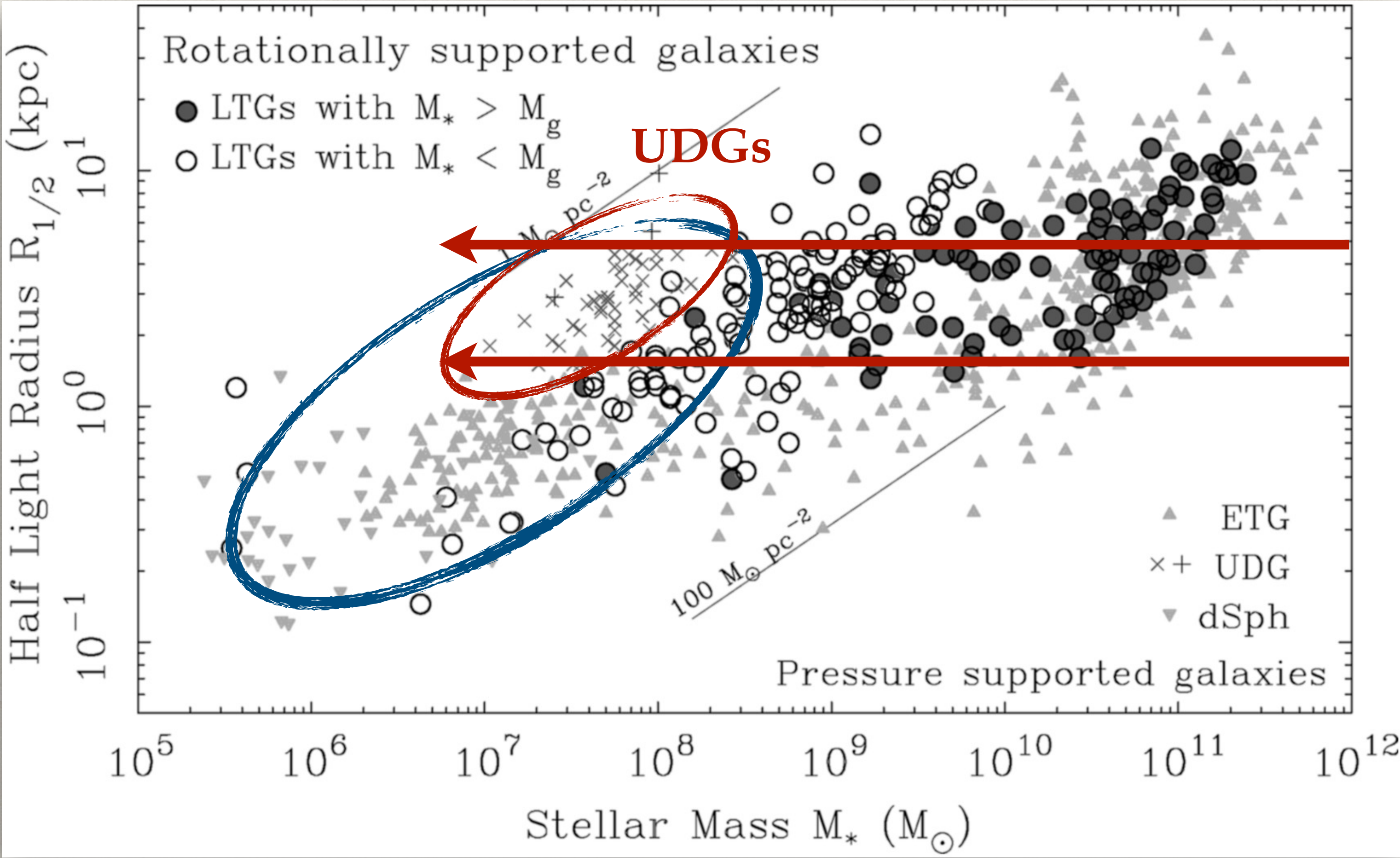
$10^7 < M_* < 10^8 M_\odot$



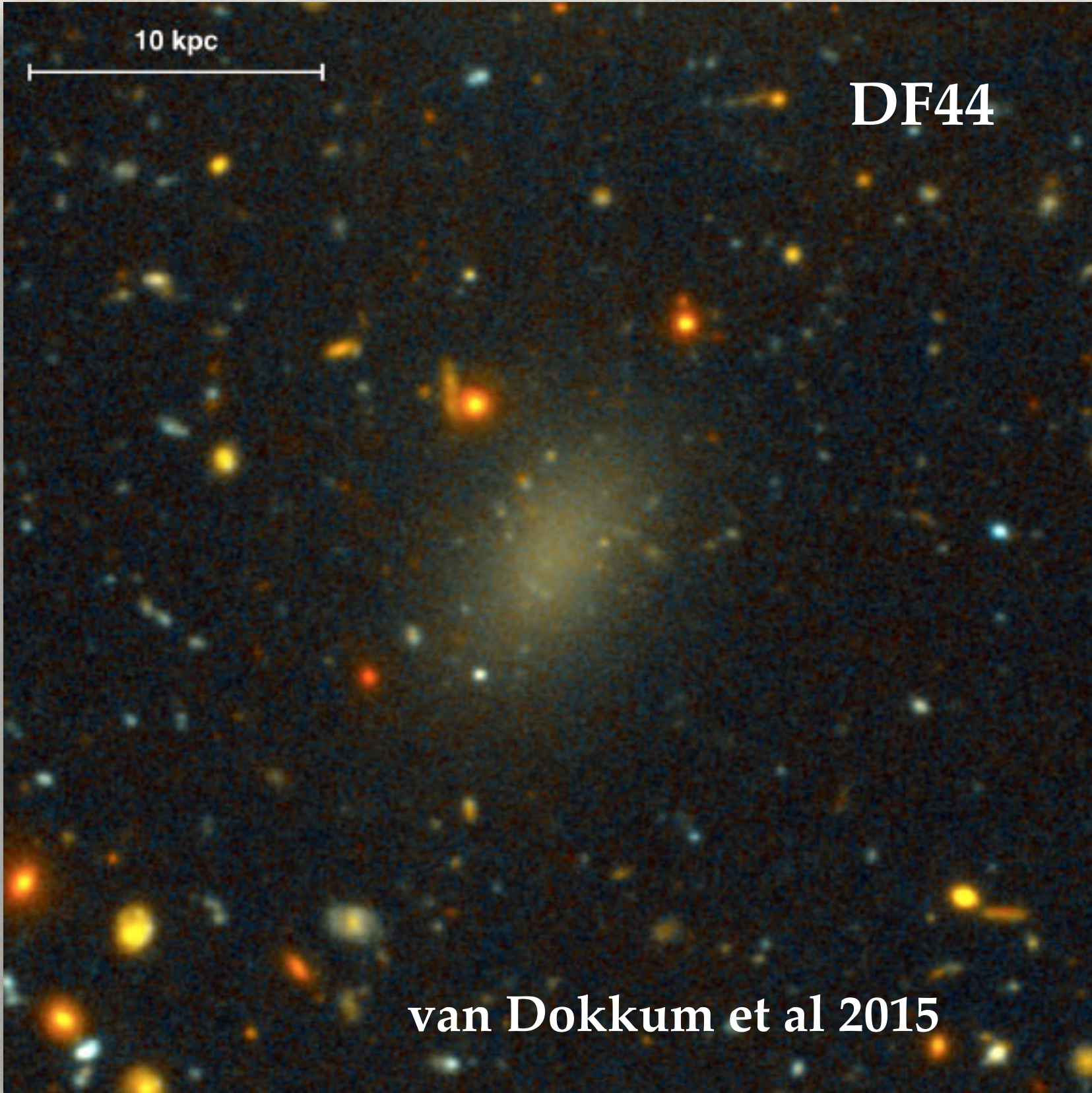
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# *State of the art: observations vs theoretical predictions*

**Color**

**Kinematics**

**Stellar pop**

**GCs**

**DM content**



# State of the art: **observations** vs theoretical predictions

*blue population of UDGs  
in low-density regions*



*red and quenched UDGs,  
in clusters*

**Kinematics**

**Stellar pop**

**GCs**

**DM content**



# State of the art: **observations** vs theoretical predictions

*blue population of UDGs  
in low-density regions*



*red and quenched UDGs,  
in clusters*

*Low velocity dispersion*



*no rotation ?*

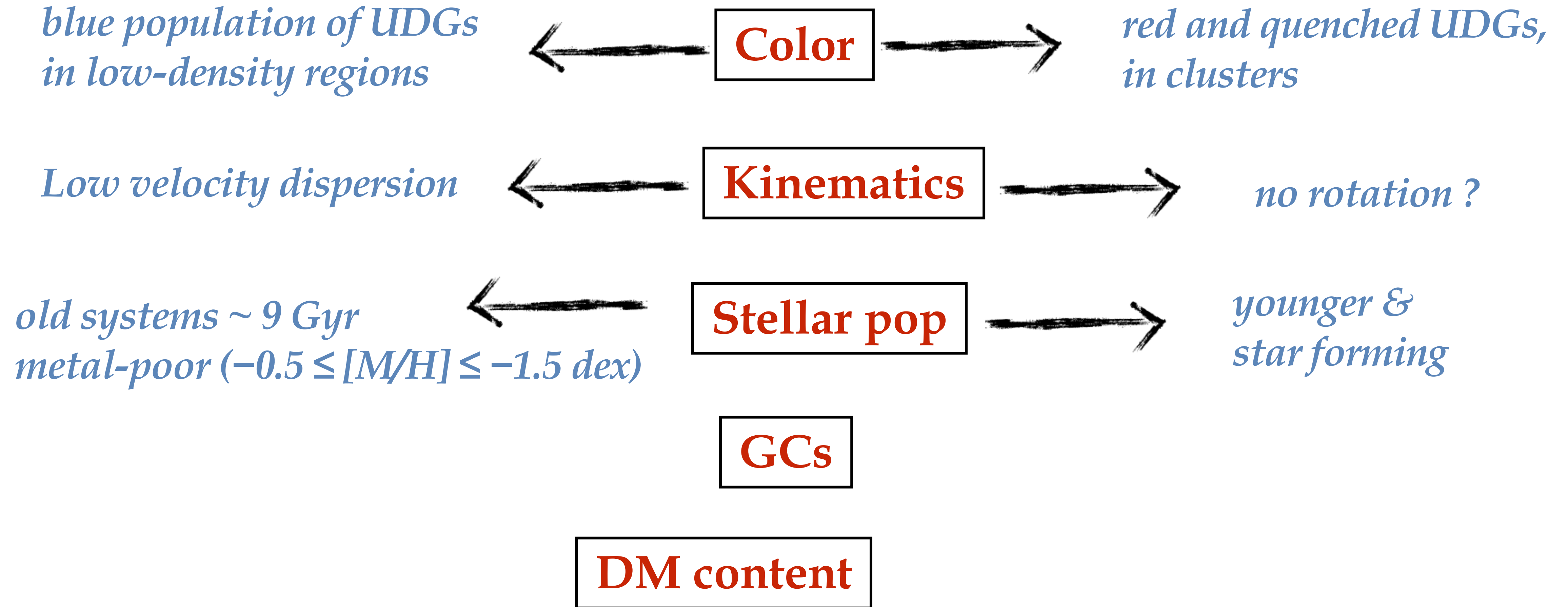
**Stellar pop**

**GCs**

**DM content**

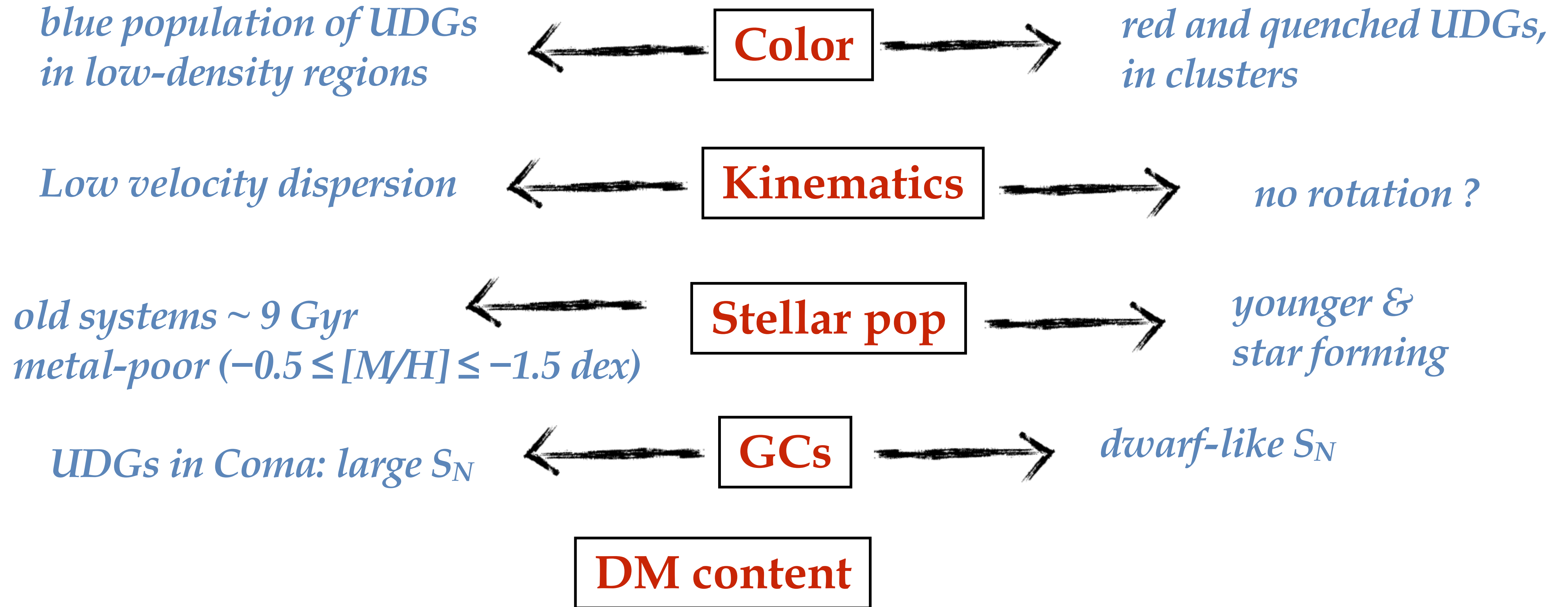


# State of the art: **observations** vs theoretical predictions



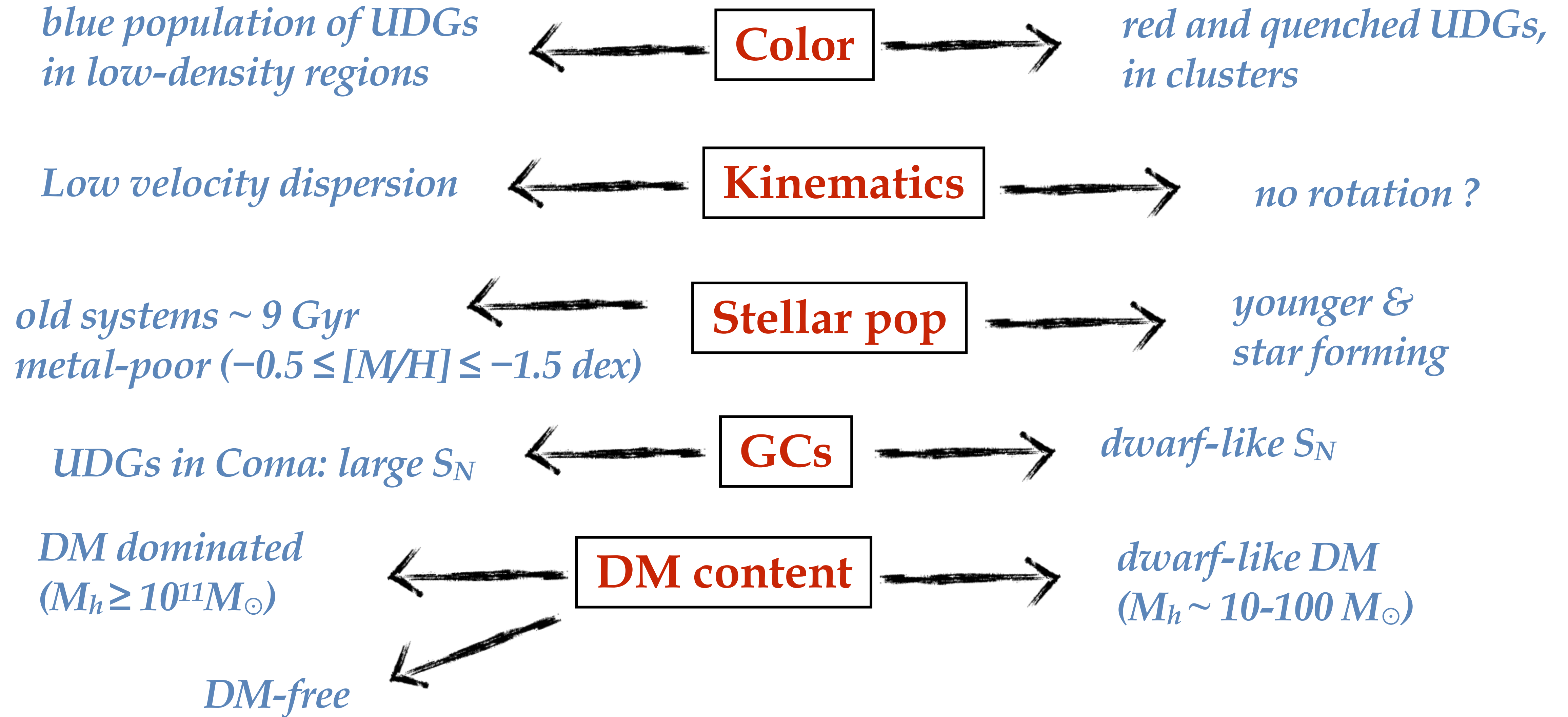


# State of the art: **observations** vs theoretical predictions



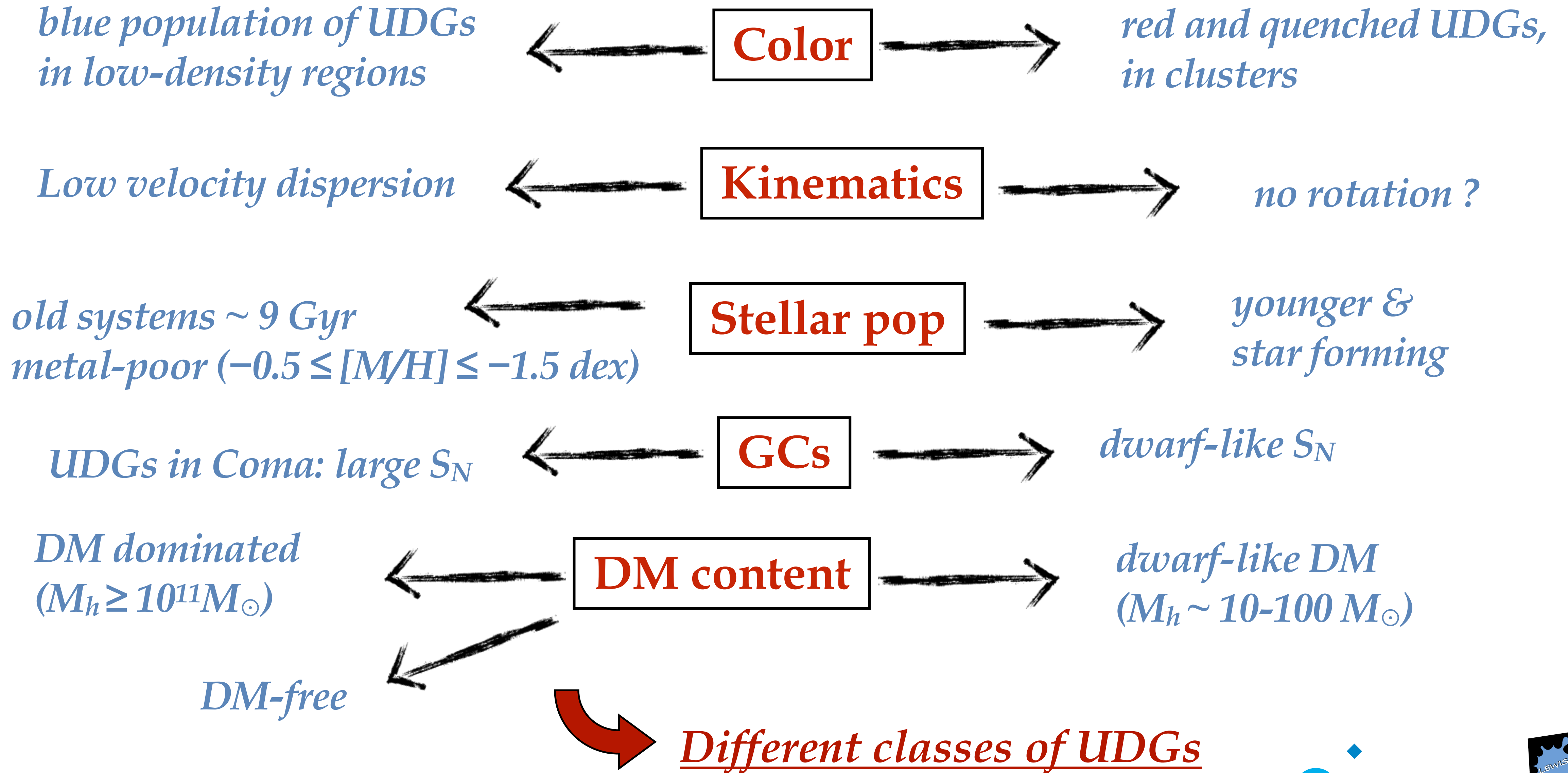


# State of the art: **observations** vs theoretical predictions





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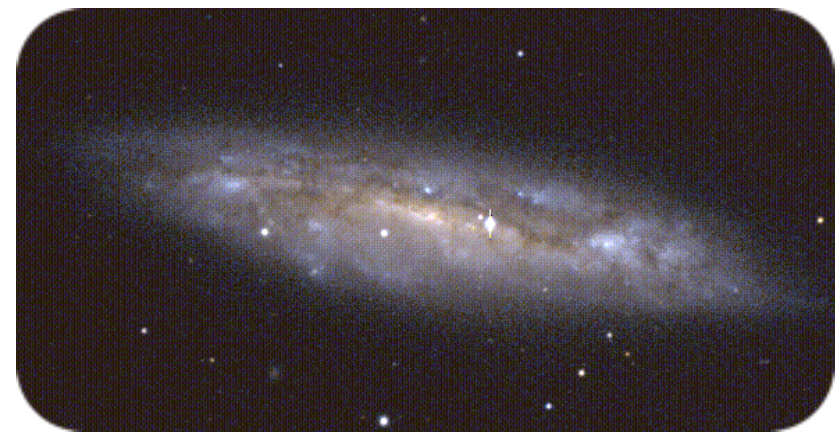


# *State of the art: observations vs theoretical predictions*

**Failed  $L_*$  ( $M_* \sim 10^{11} M_\odot$ ) galaxies**

**(van Dokkum et al. 2015)**

HSB systems  $\rightarrow$  lost gas supply at an early epoch



***UDGs properties***

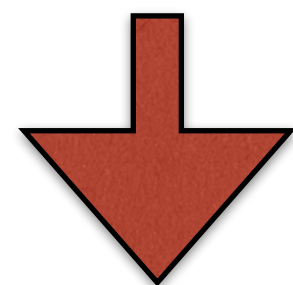
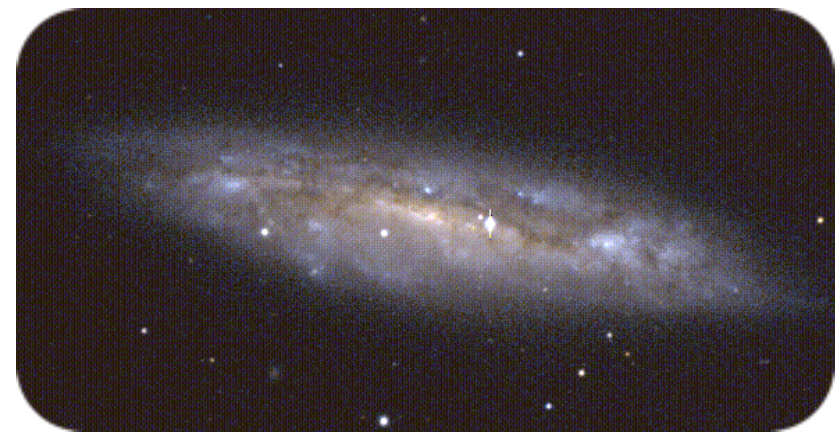


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***UDGs properties***

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

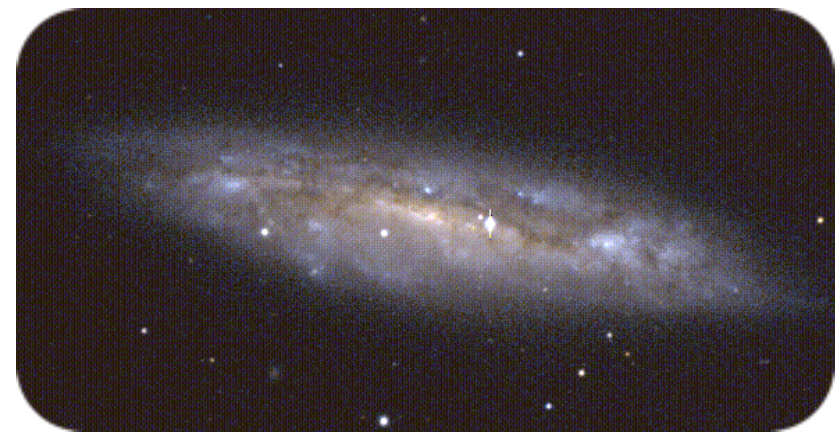


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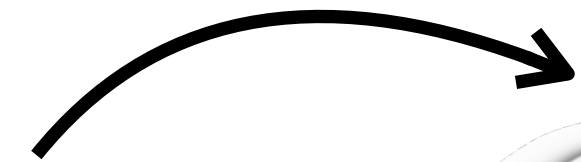
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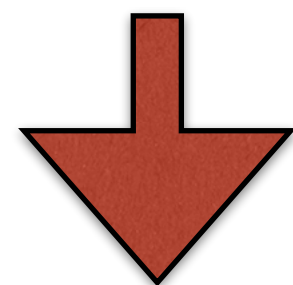


*Failed*

**Puffed-up dwarfs**



*Puffed-up*



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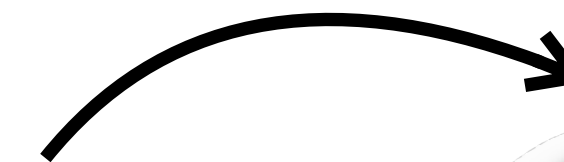
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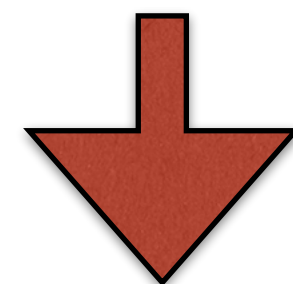


**Internal  
processes**



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

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



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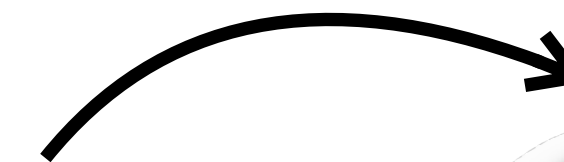
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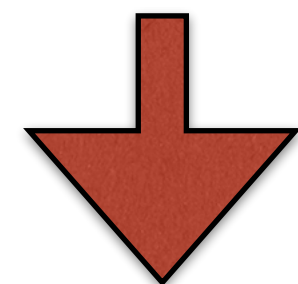
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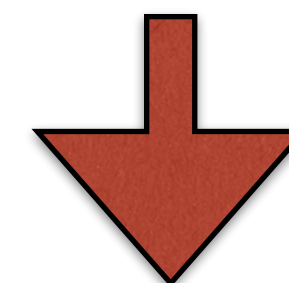
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**gas-rich  
dwarf-like DM halo**



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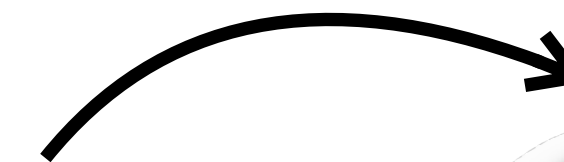
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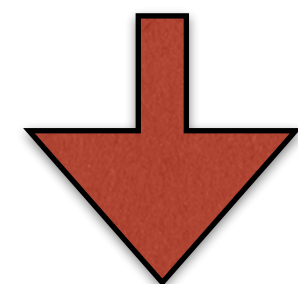
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**External processes**

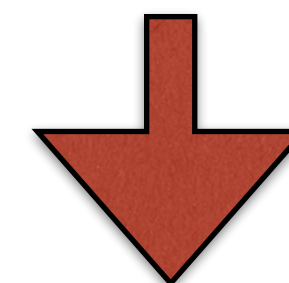
- ▶ interaction with environment

(Bennet+2018; Müller+2019; Sales+2020 )



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**gas-rich  
dwarf-like DM halo**

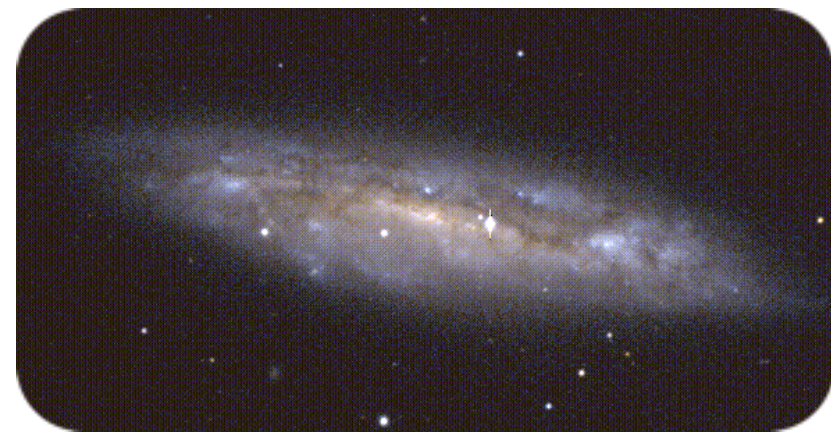


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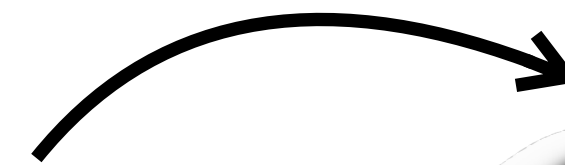
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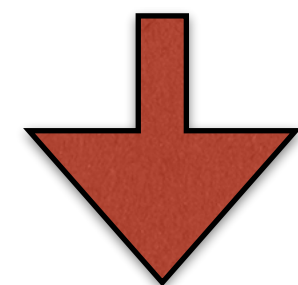
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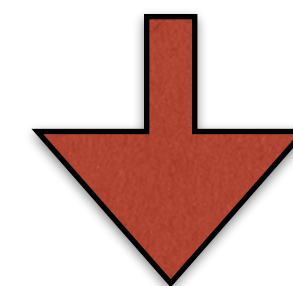
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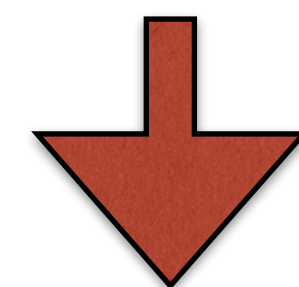


**UDGs properties**

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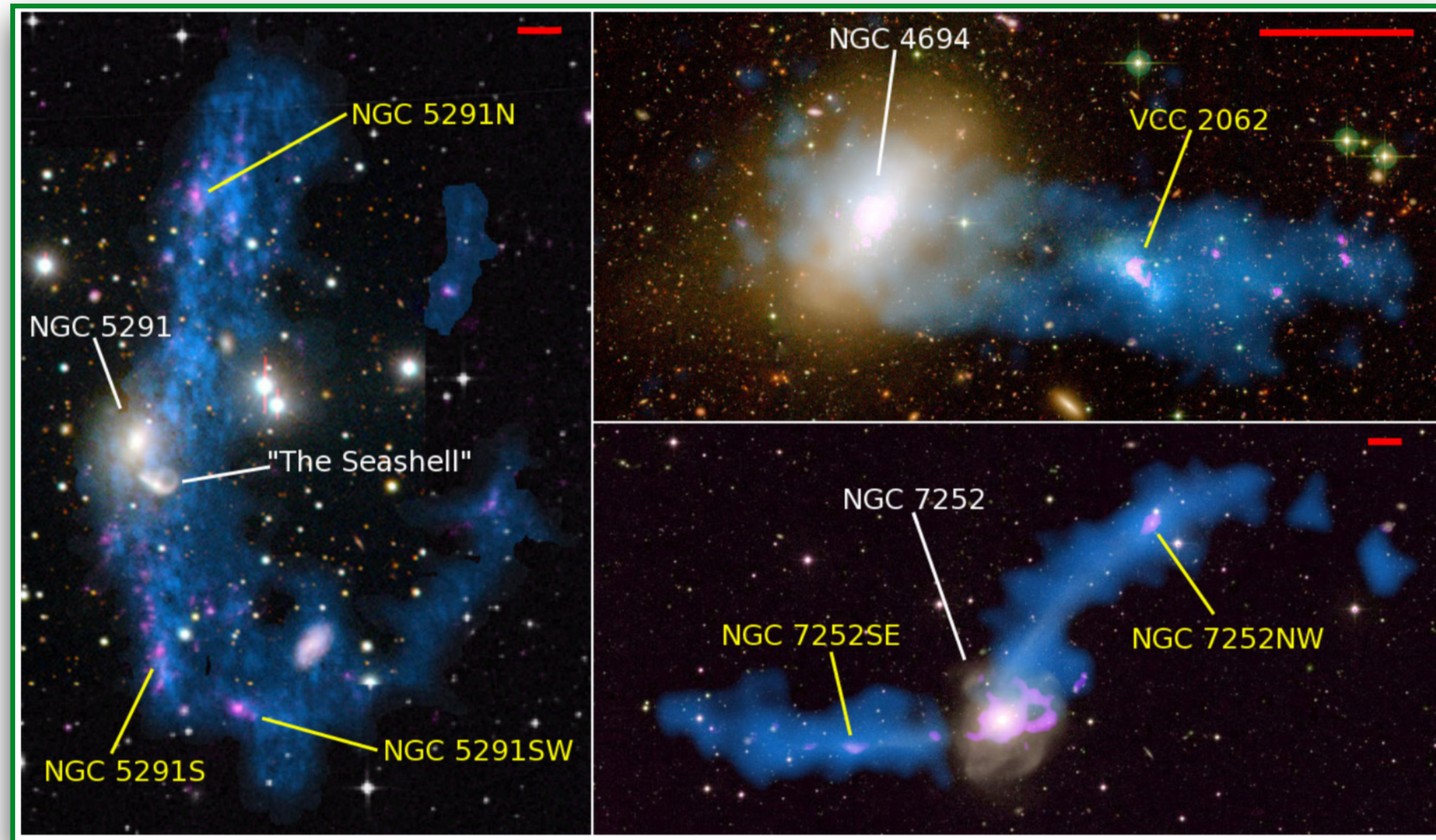
**gas-rich  
dwarf-like DM halo**



**gas-poor  
DM & Z function of  
the environment**



# *State of the art: observations vs theoretical predictions*

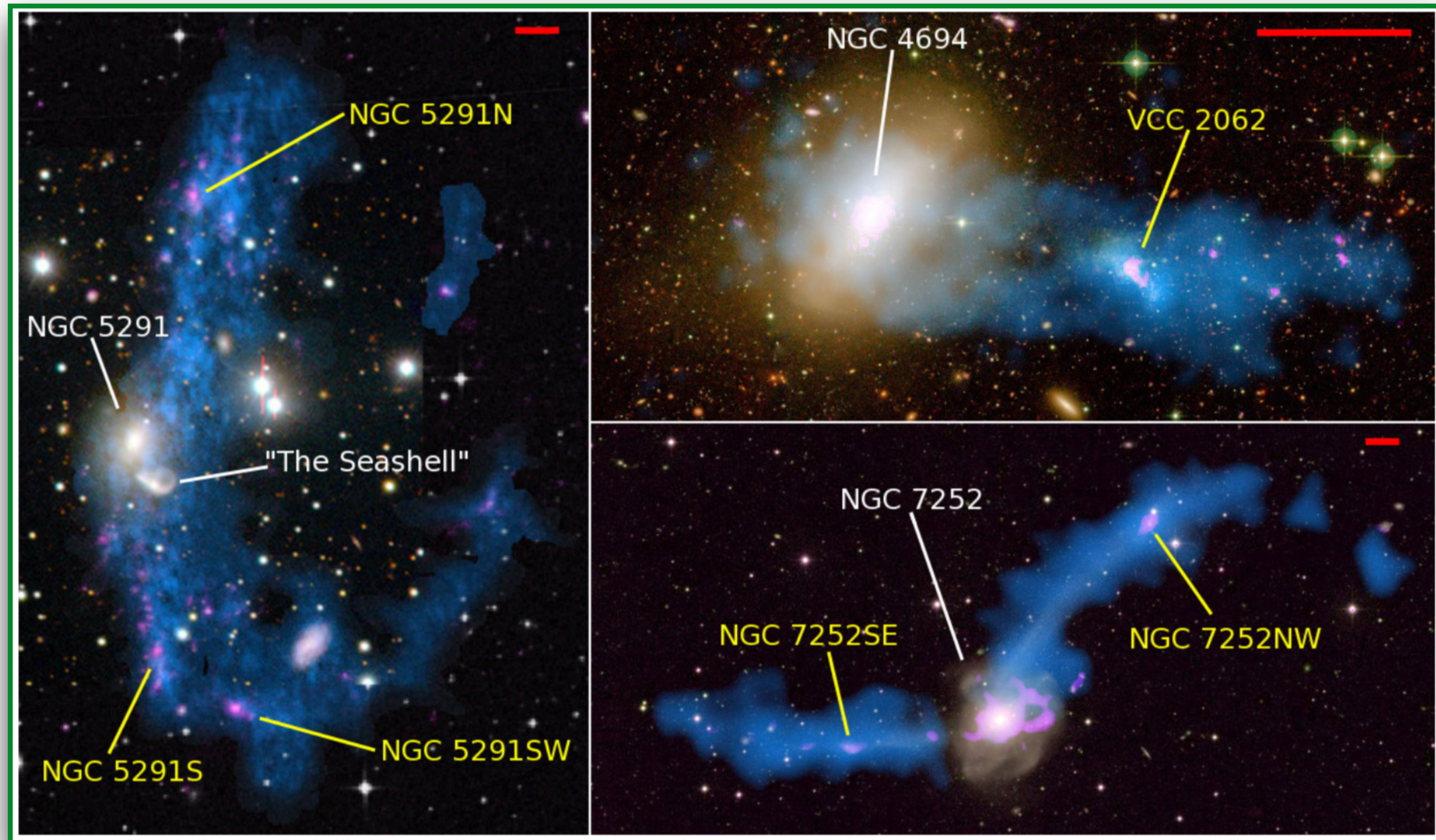


## *Tidal-UDGs*

(Lelli+2015; Duc+2014;  
Ploekinger+2018)

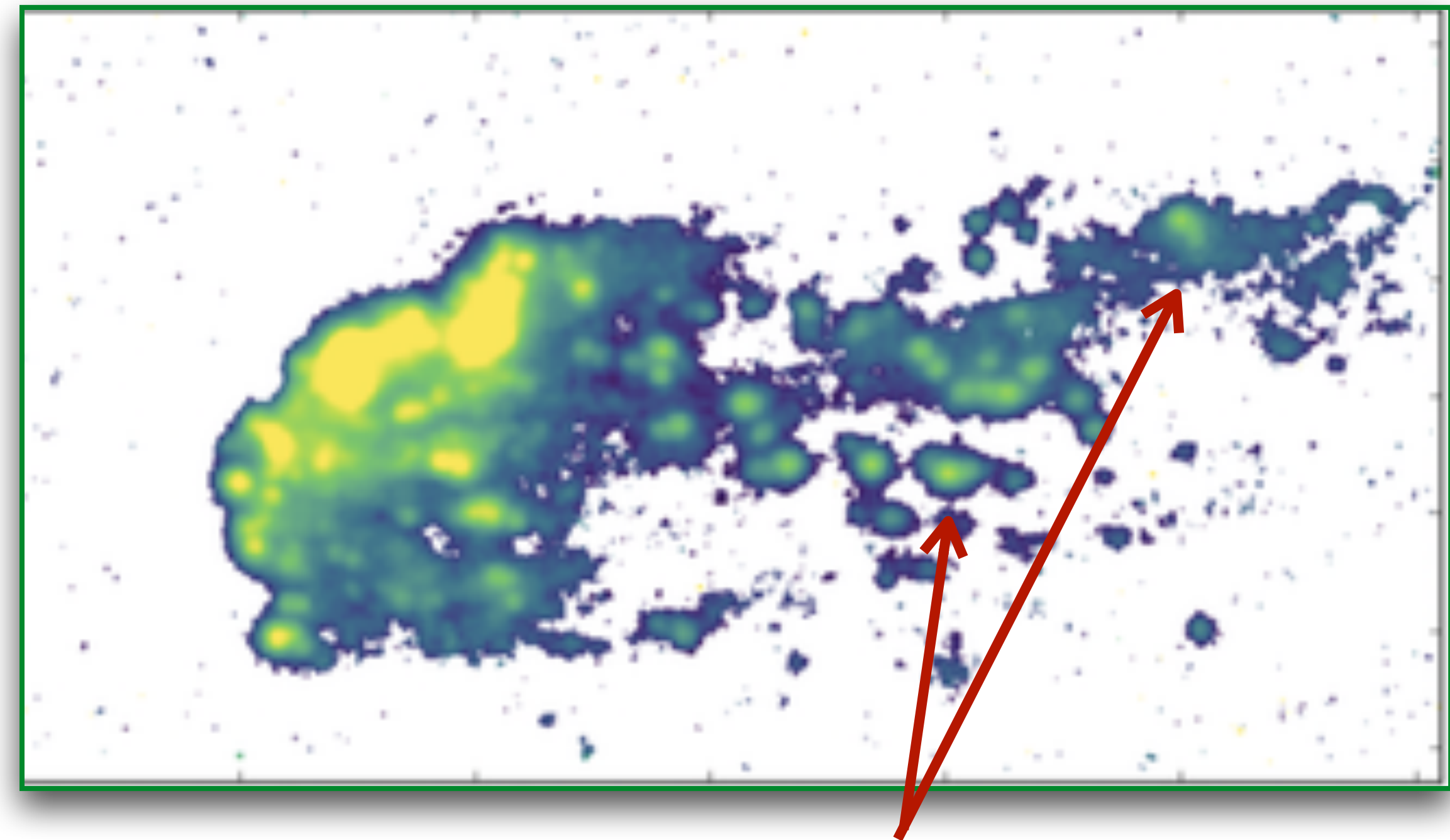


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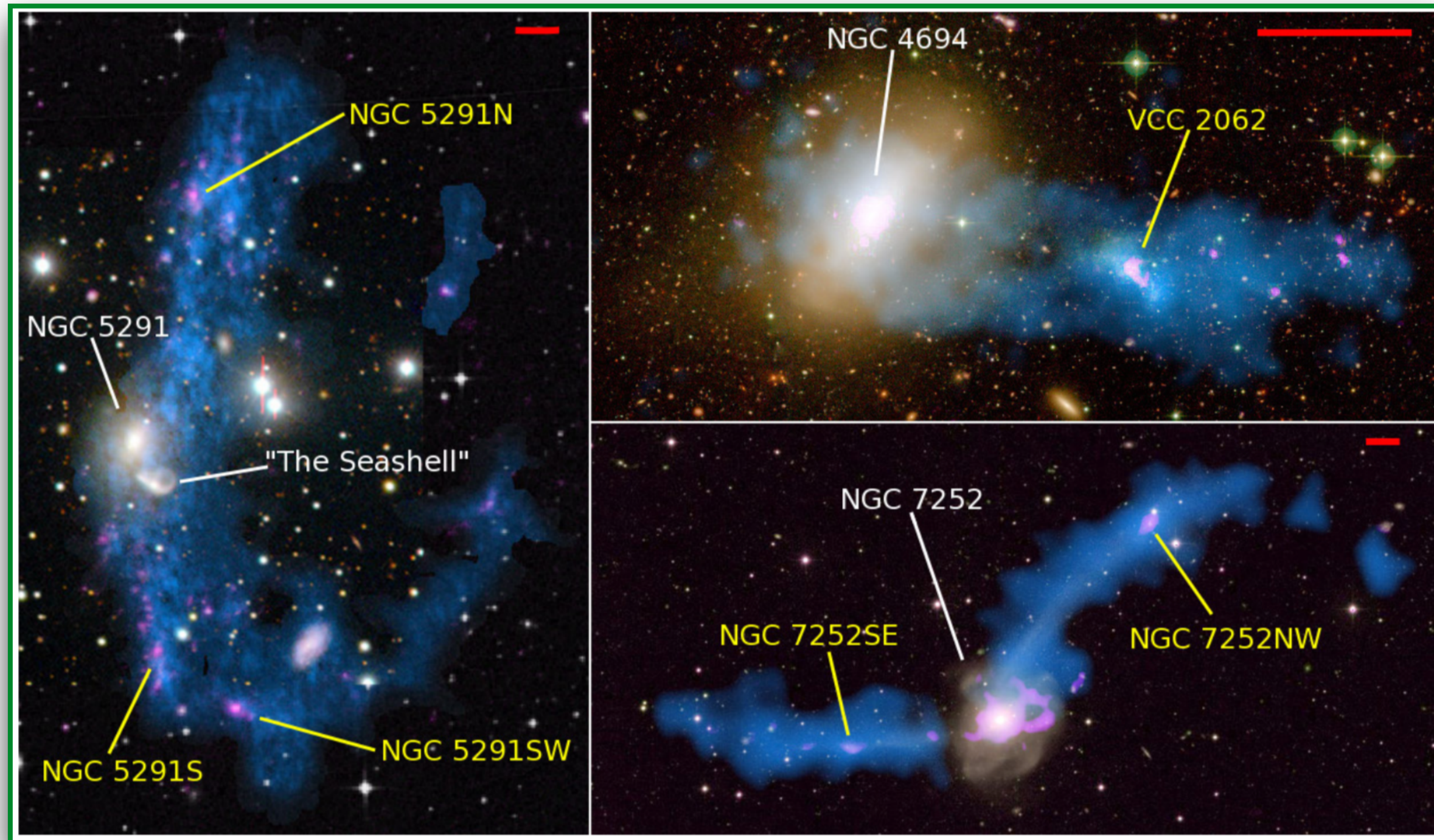


*UDGs from gas clumps in  
Jelly-fish galaxies*

(Poggianti+2019)

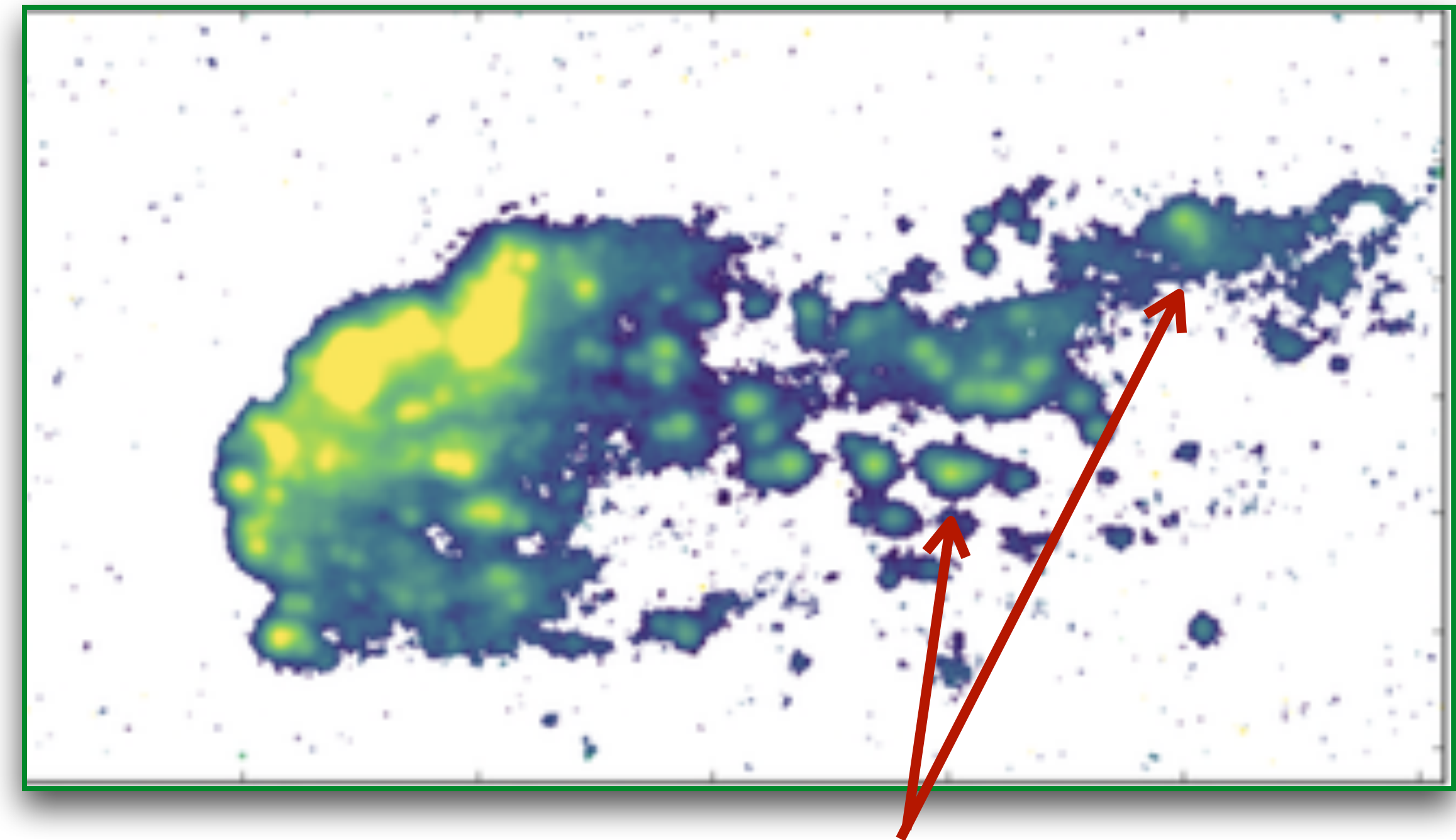


# State of the art: observations vs theoretical predictions



## *Tidal-UDGs*

(Lelli+2015; Duc+2014;  
Ploekinger+2018)



*UDGs from gas clumps in  
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(Poggianti+2019)

## *UDGs properties*

- ▶ DM free
- ▶ blue, dust, moderate Z/H, SF
- ▶ UV emission + gas rich



# *Which are the observables to discriminate between UDGs formation channels?*

---

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



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↳ **deep images**
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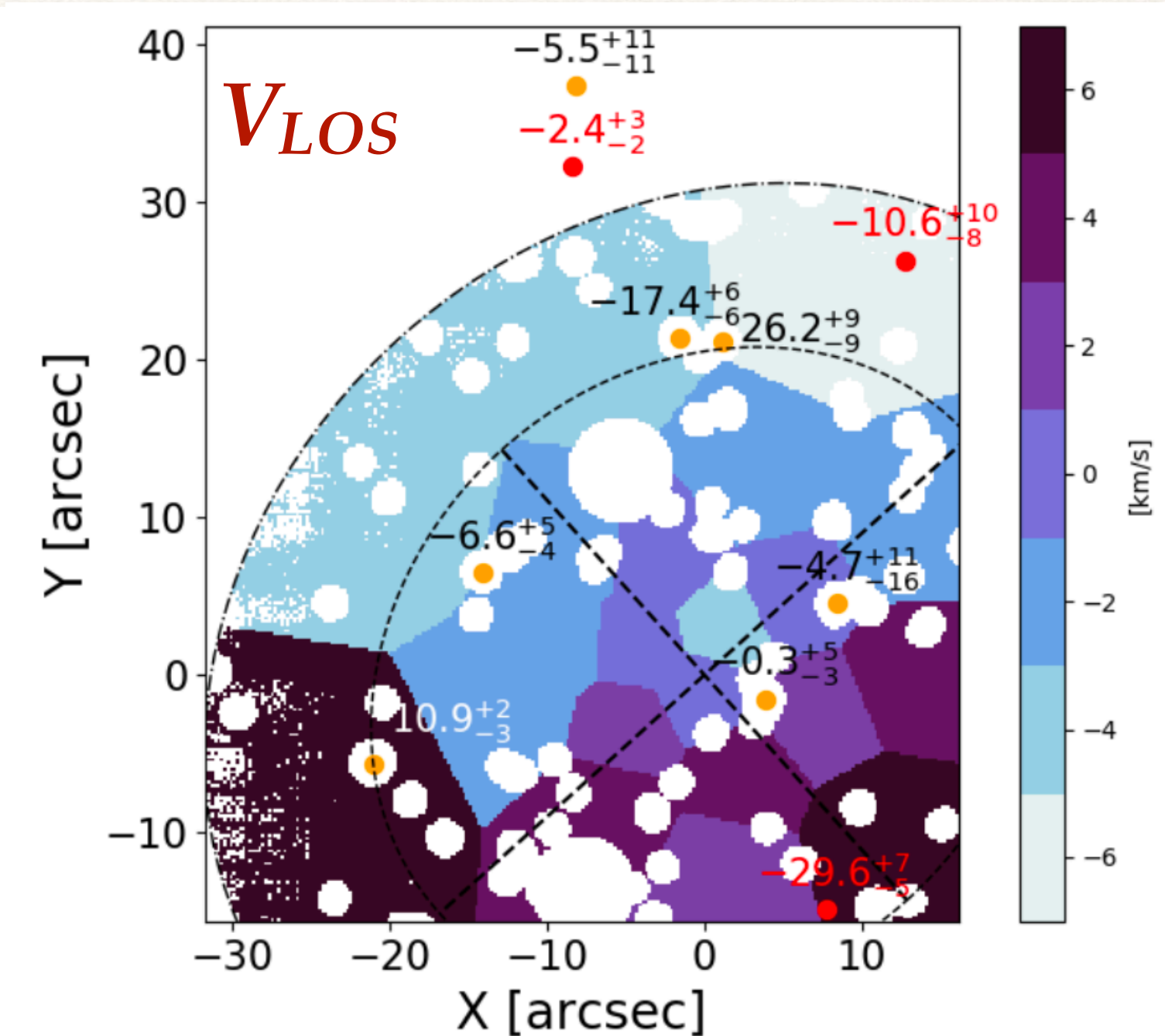
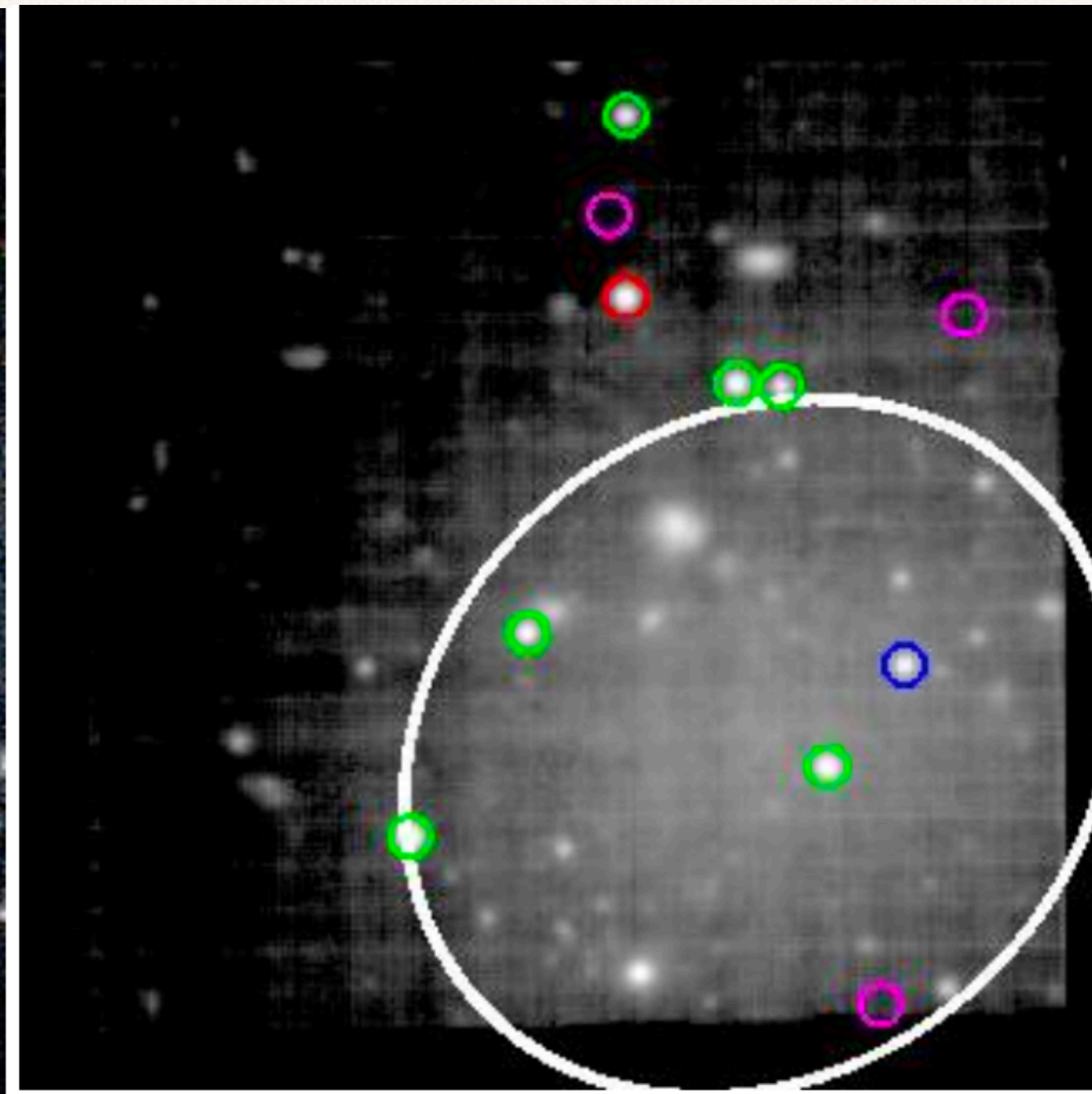
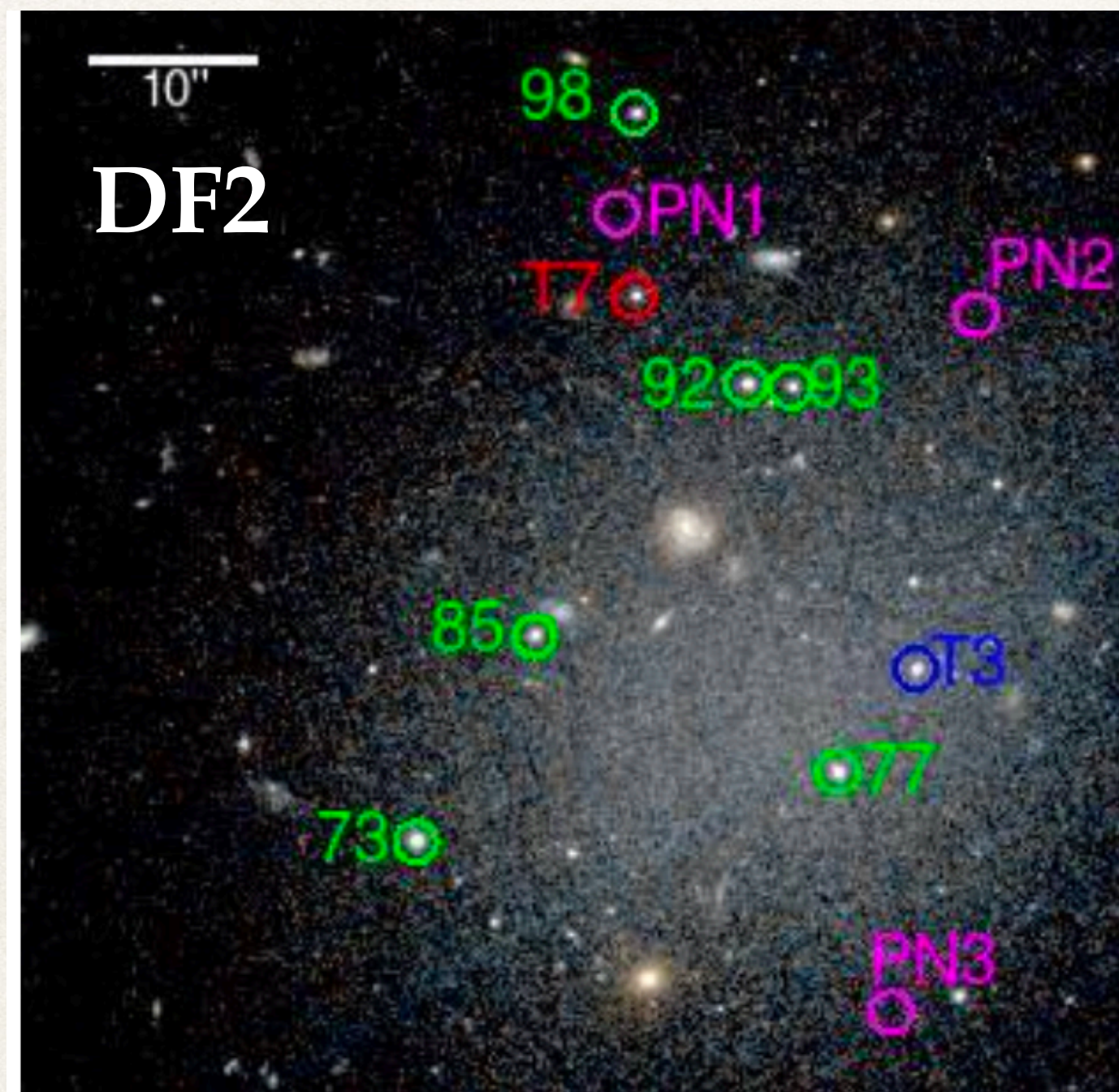
↳ **spectroscopy**



# *Which are the observables to discriminate between UDGs formation channels?*

1<sup>st</sup> IFU data for UDG DF2: MUSE

Emsellem+2019



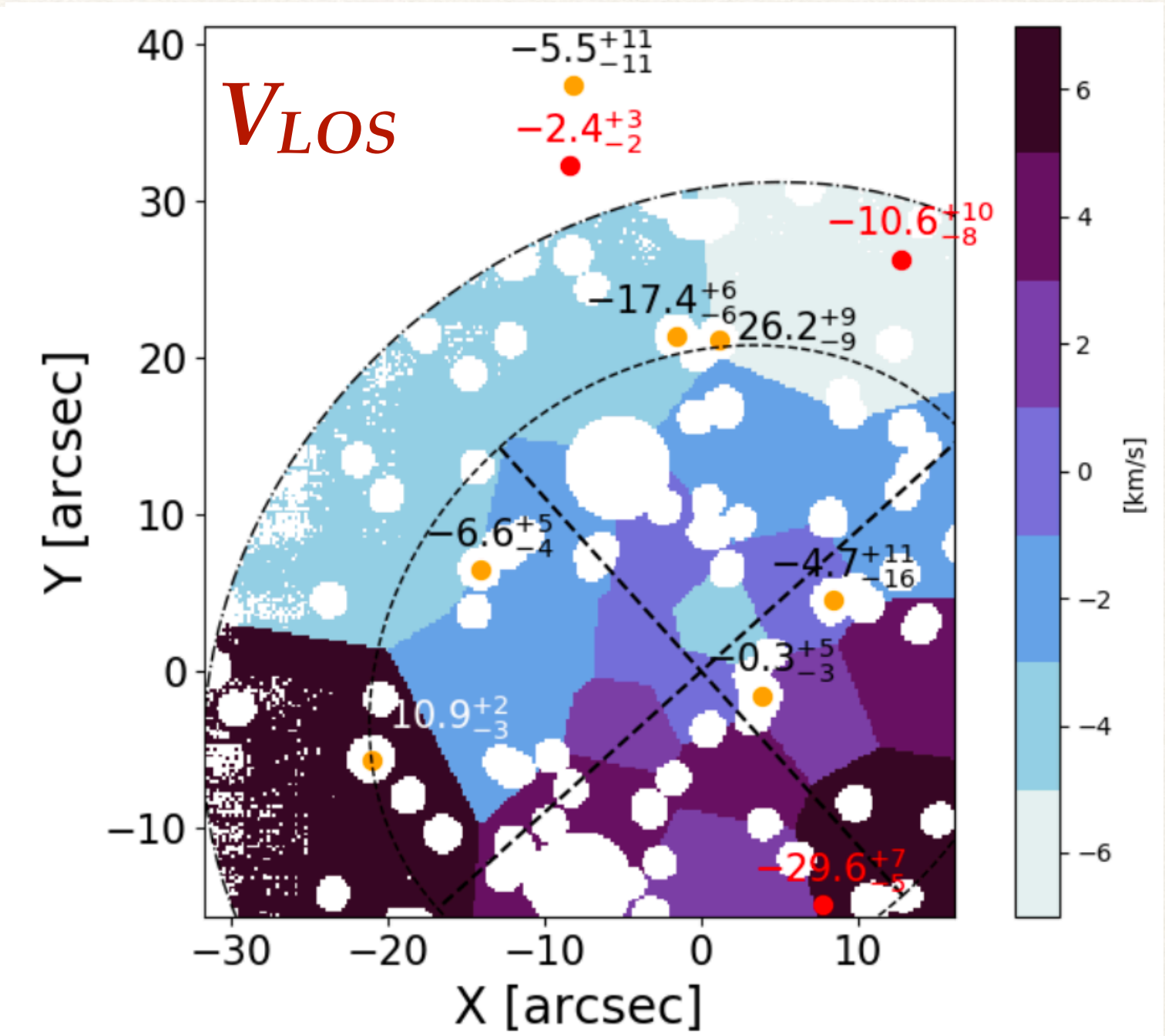
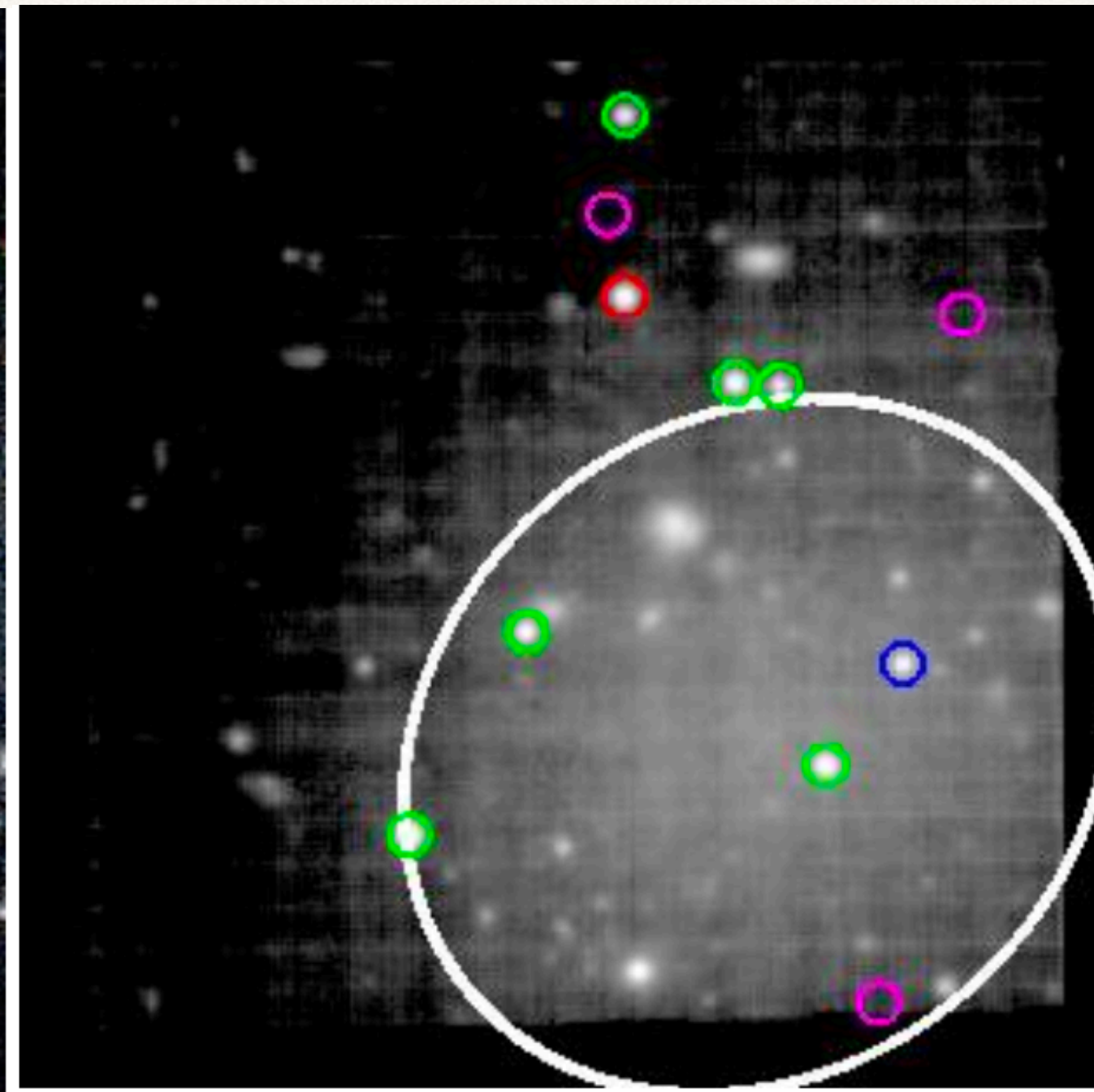
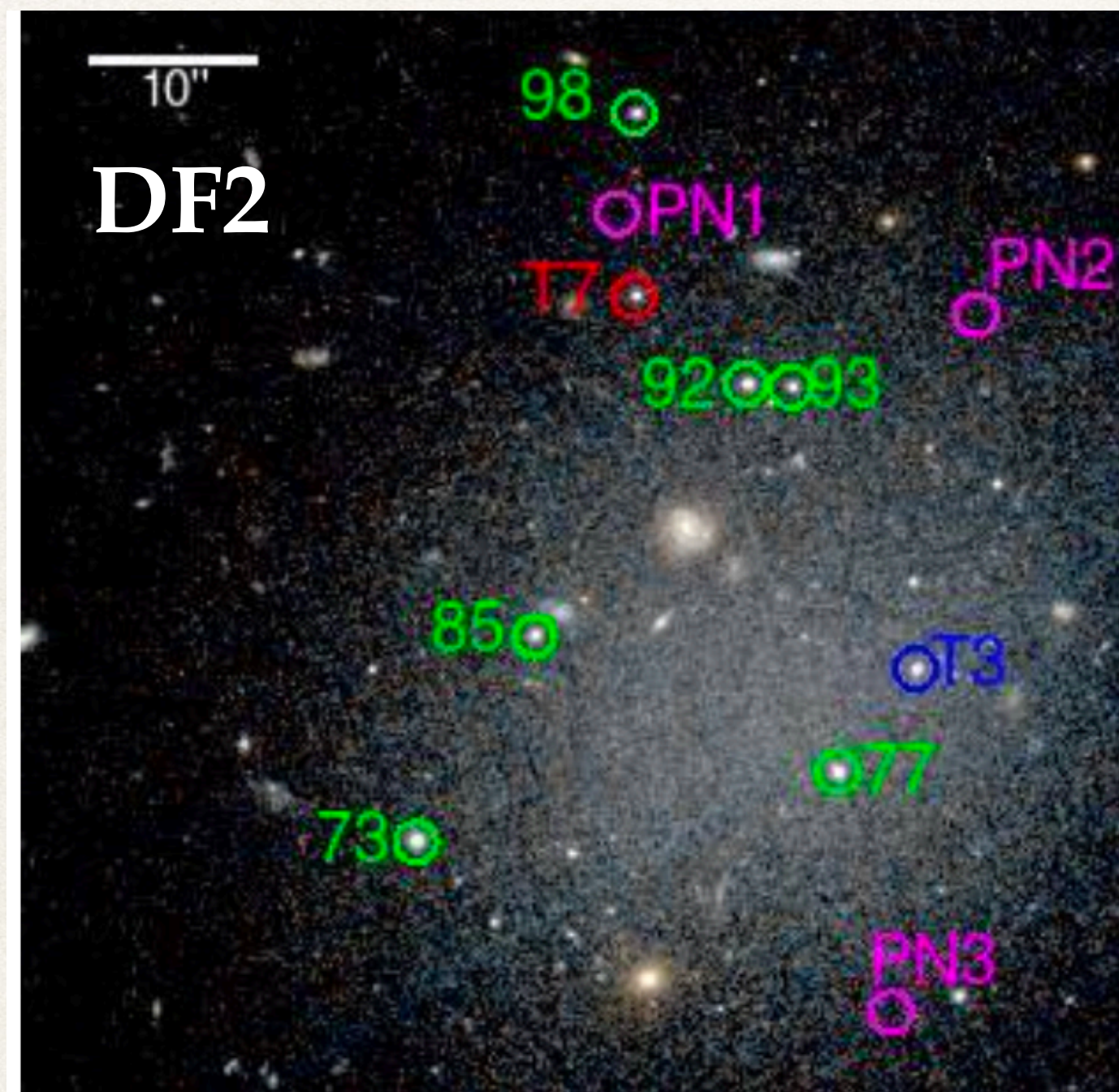
➡ spectroscopy



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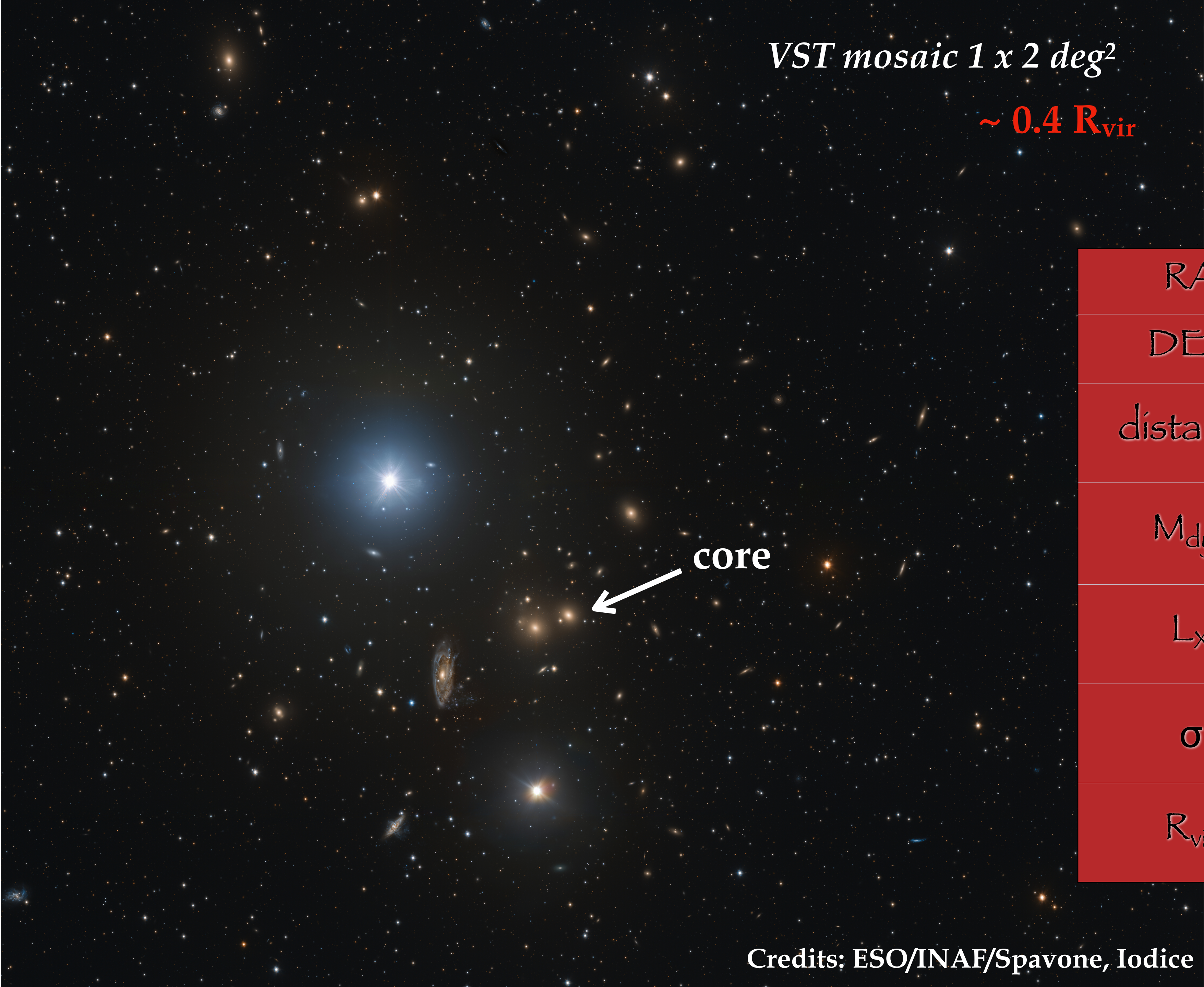
1<sup>st</sup> IFU data for UDG DF2: MUSE

Emsellem+2019



➔ **LEWIS**





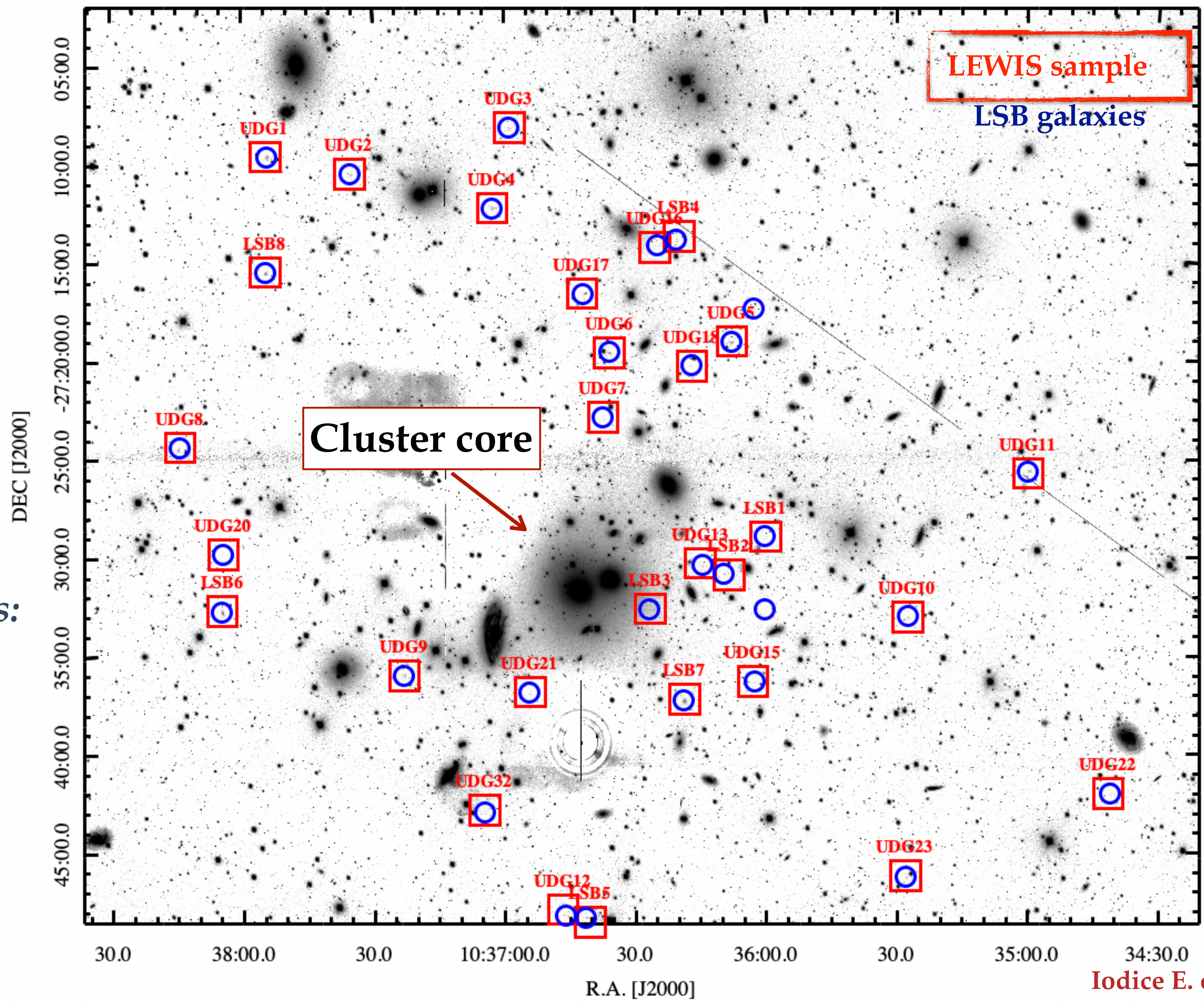
# Target:

## Hydra I cluster

RA	10h 36m
DEC	-27d 31m
distance	51 Mpc (Christlein et al. 2003)
M <sub>dyn</sub>	2 x 10 <sup>14</sup> M <sub>⊙</sub> (Girardi et al. 1998)
L <sub>x</sub>	2 x 10 <sup>43</sup> erg/s (Yamasaki et al. 2005)
σ	690 km/s (Lima-Dias et al. 2020)
R <sub>vir</sub>	1.6 Mpc



32 LSB galaxies:  
24 UDGs  
+  
8 LSB dwarfs



22 UDGs  
+  
8 LSB

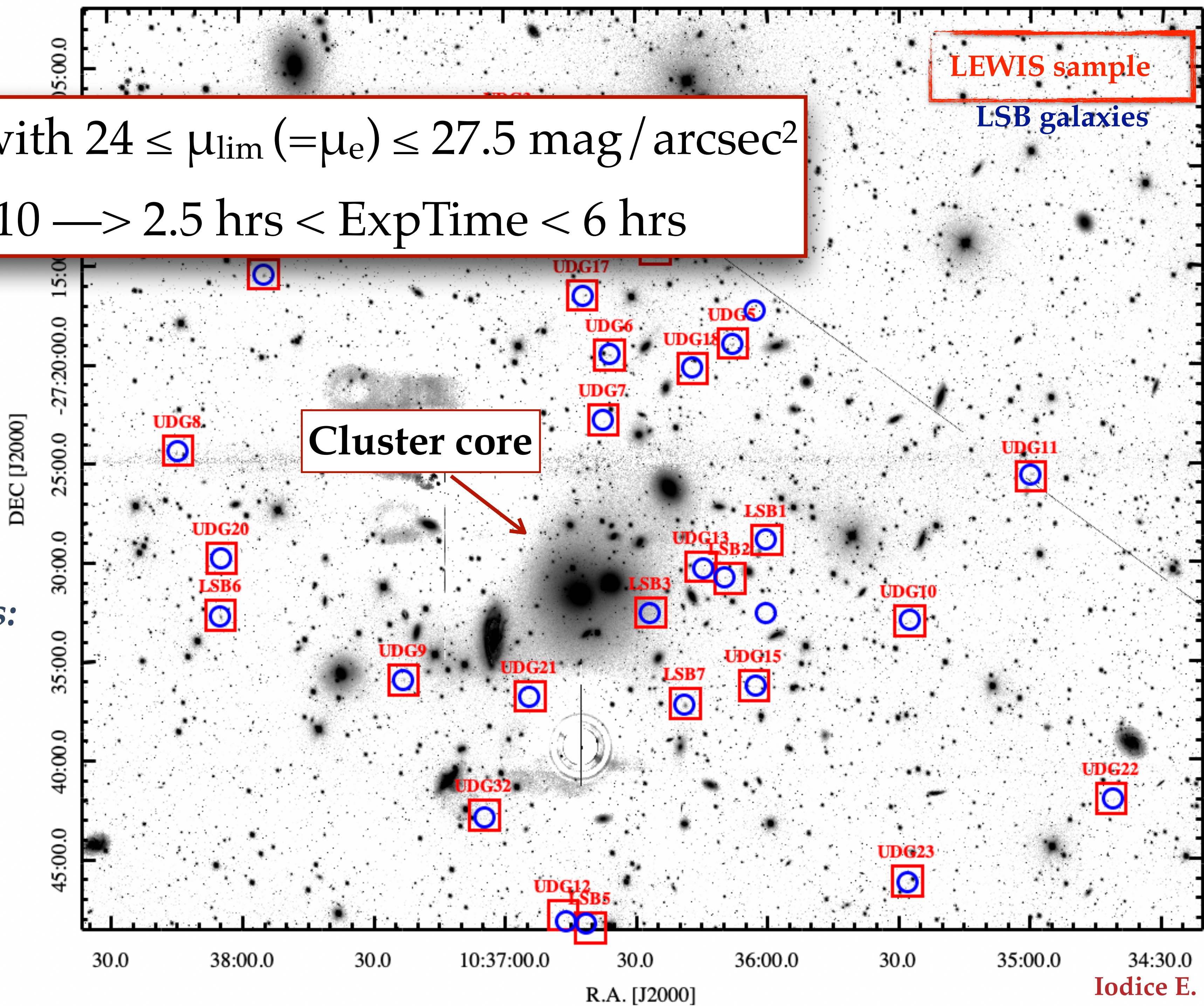


30 targets with  $24 \leq \mu_{\text{lim}} (= \mu_e) \leq 27.5 \text{ mag / arcsec}^2$   
 $S/N > 10 \longrightarrow 2.5 \text{ hrs} < \text{ExpTime} < 6 \text{ hrs}$

LEWIS sample  
 LSB galaxies

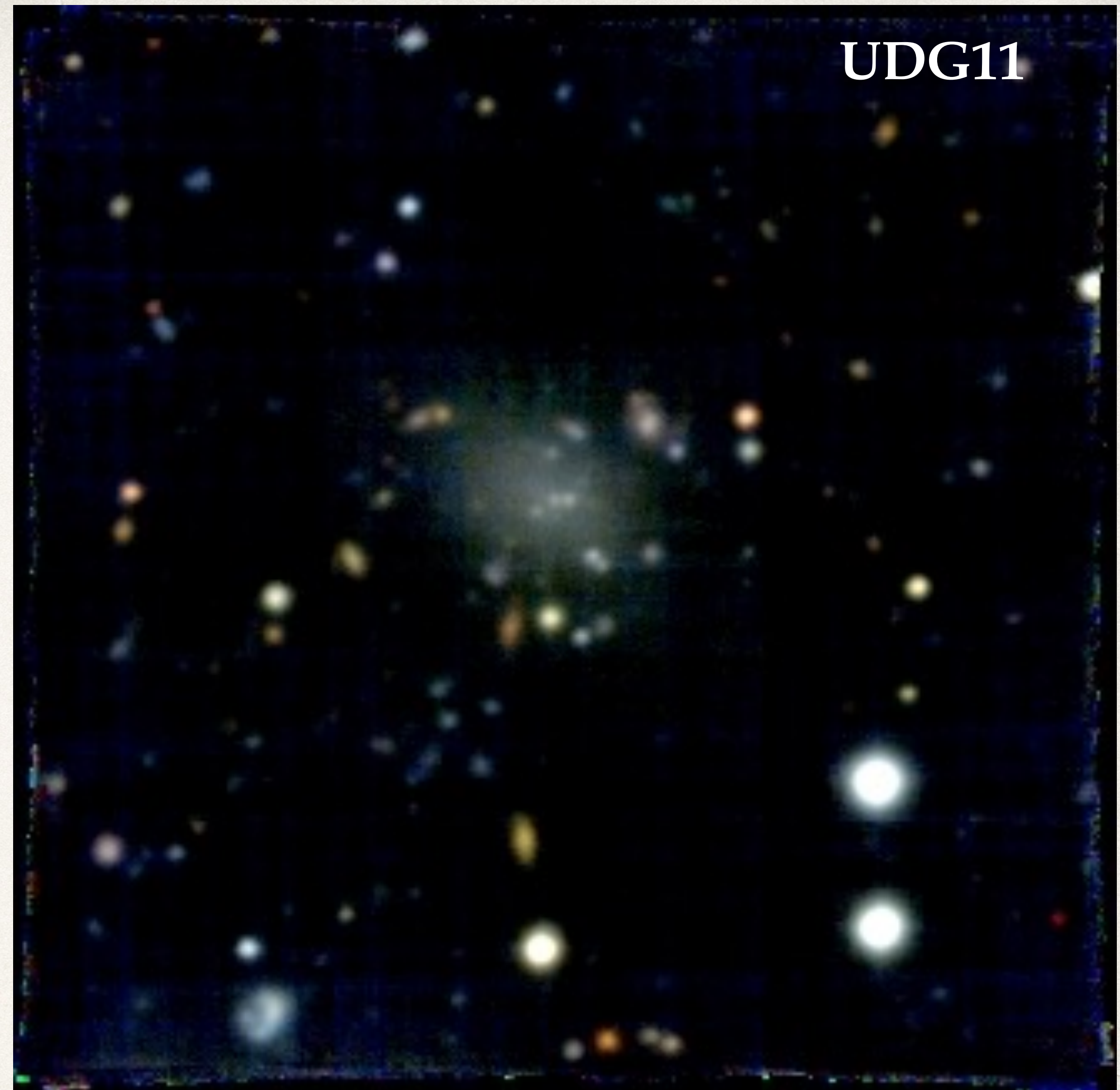
22 UDGs  
 +  
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32 LSB galaxies:  
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# *UDG spectra*



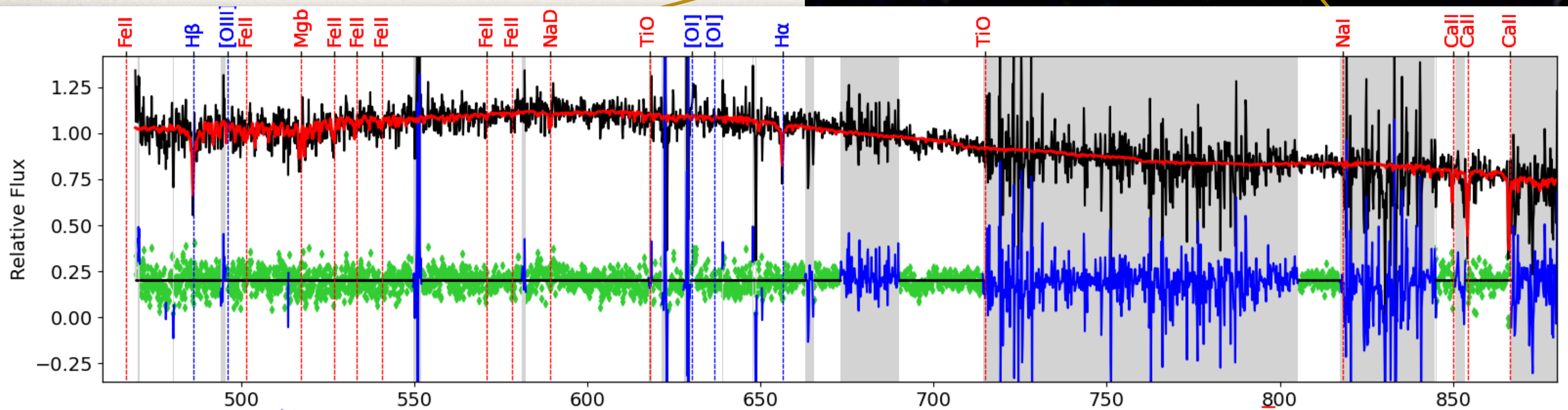


# *UDG spectra*

UDG11

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

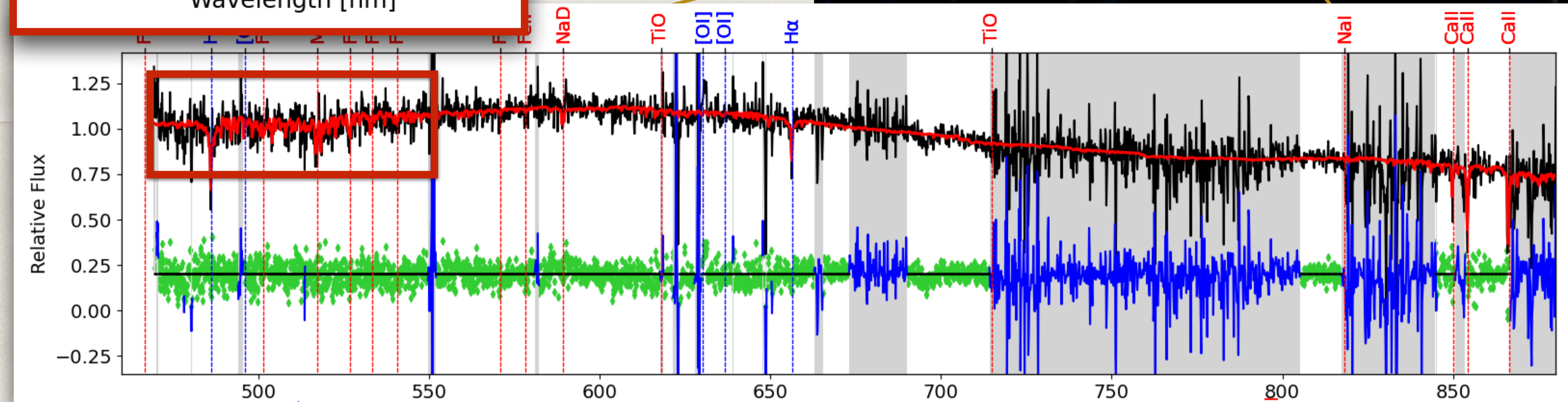
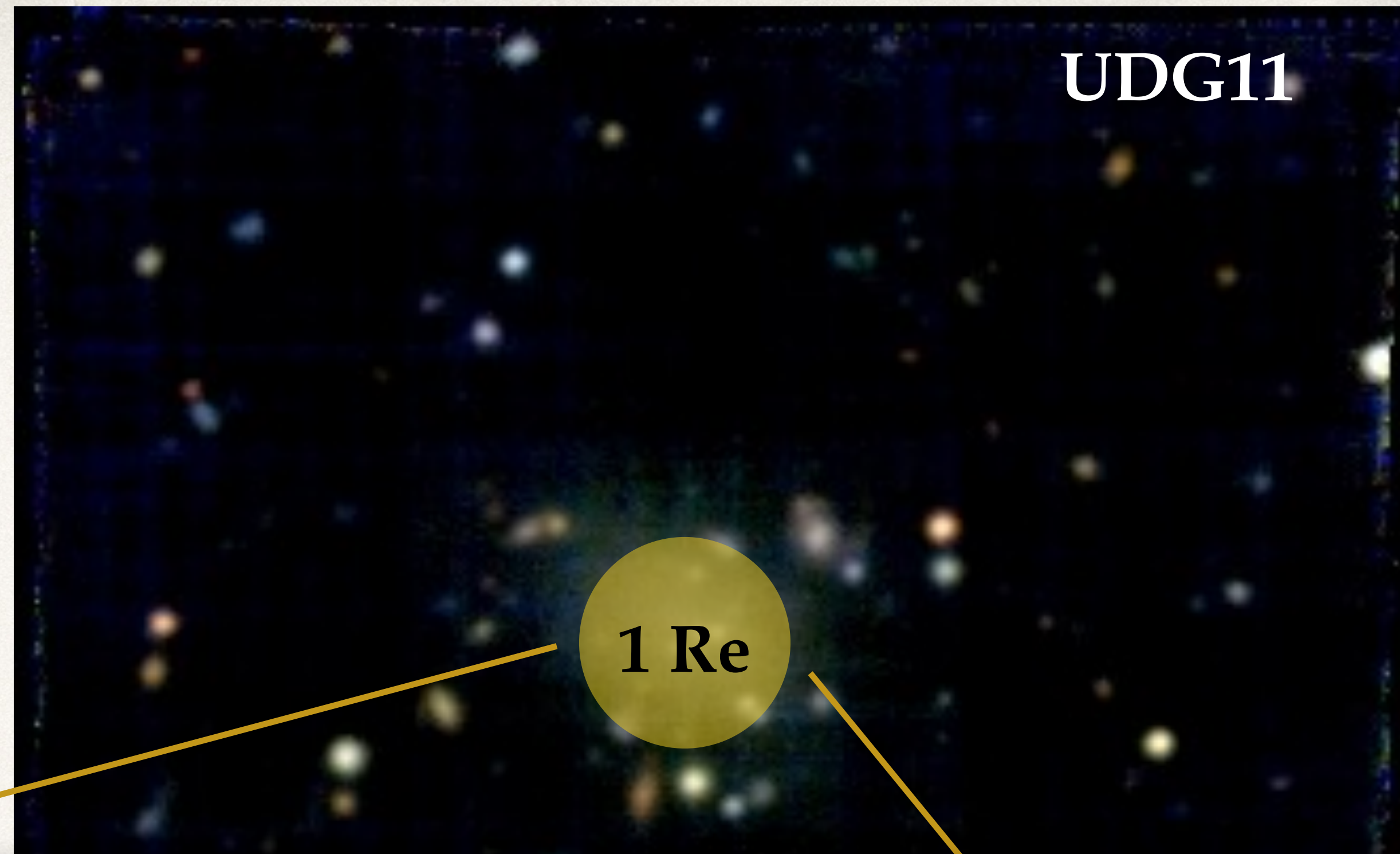
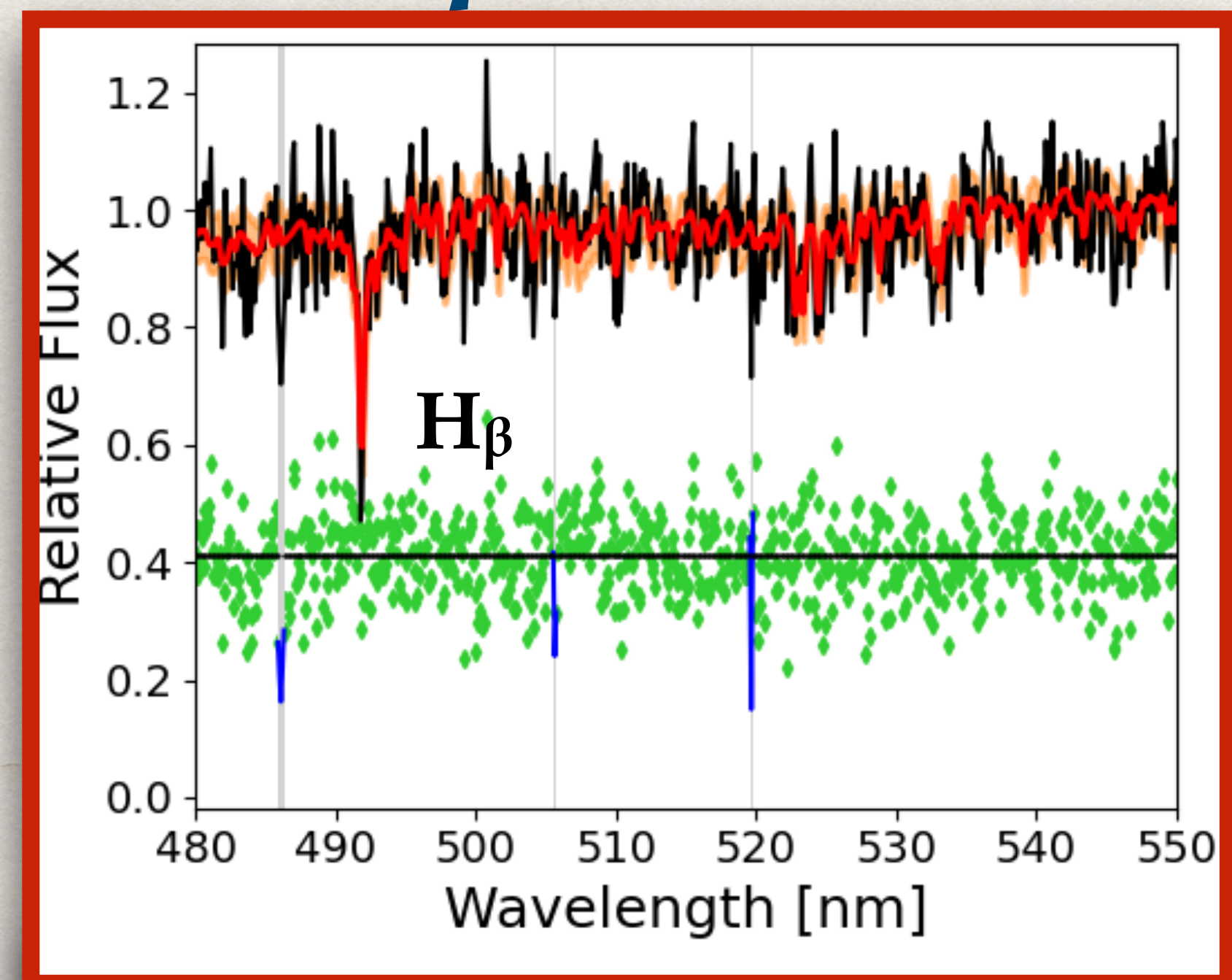
1 Re





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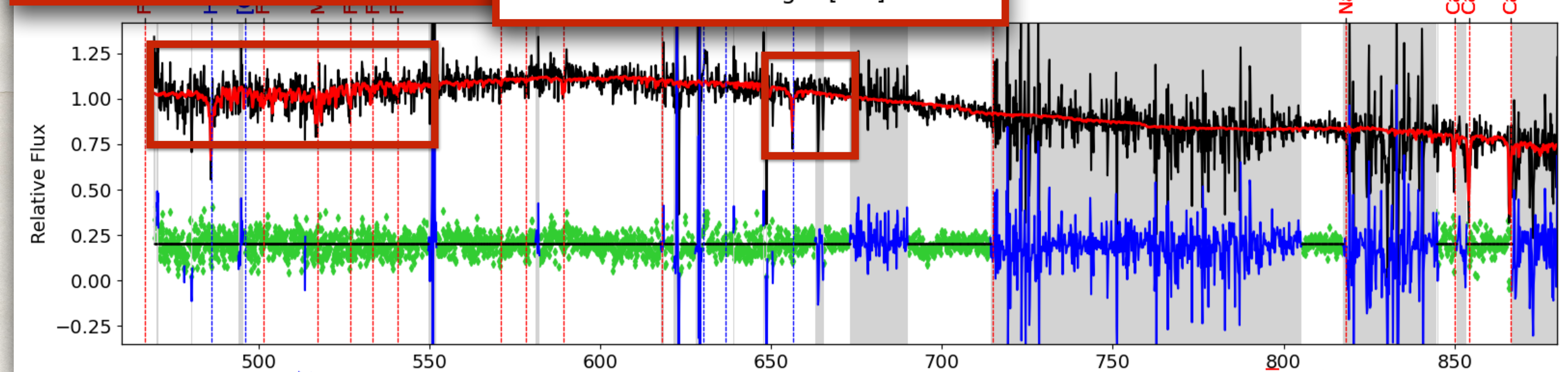
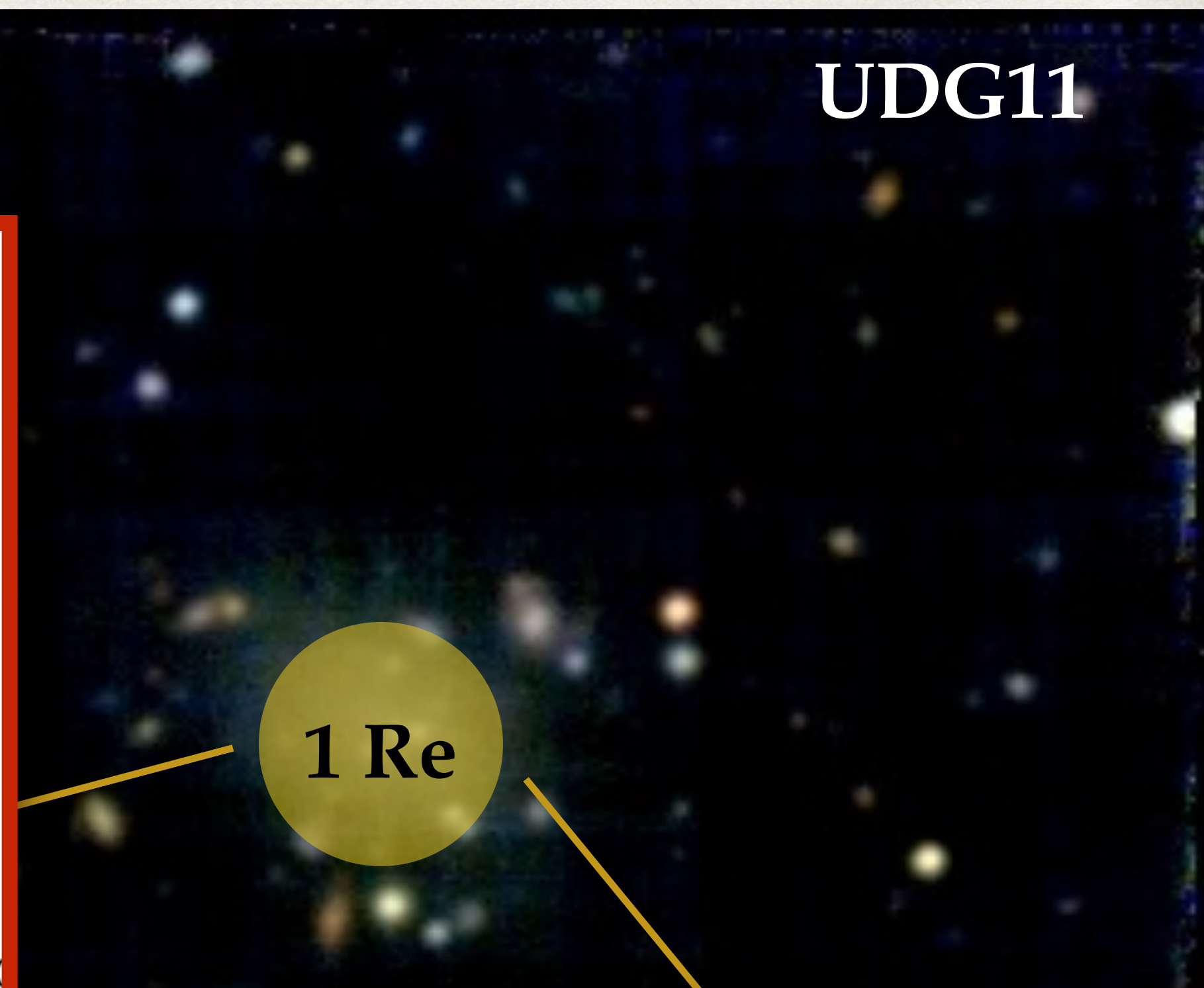
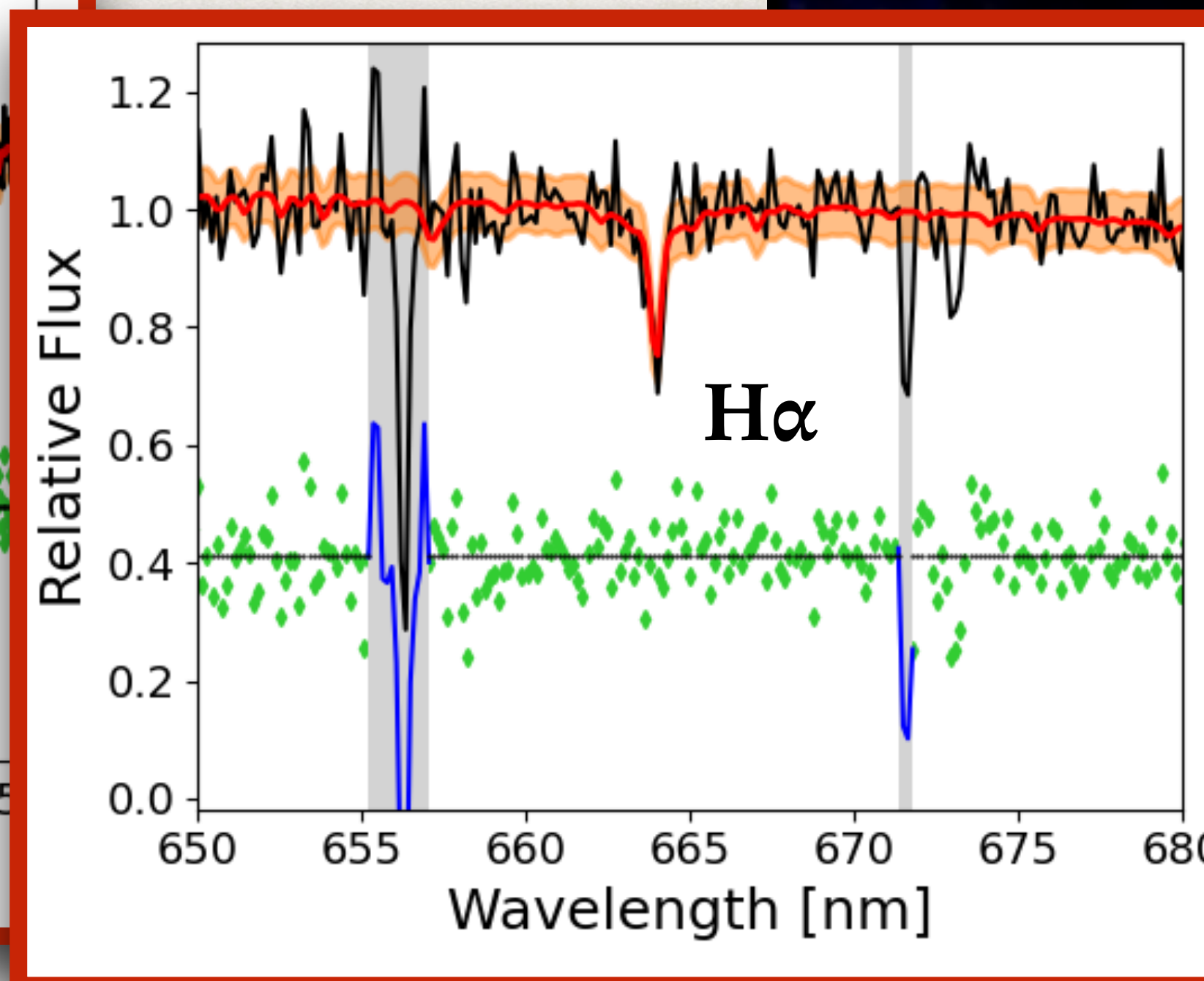
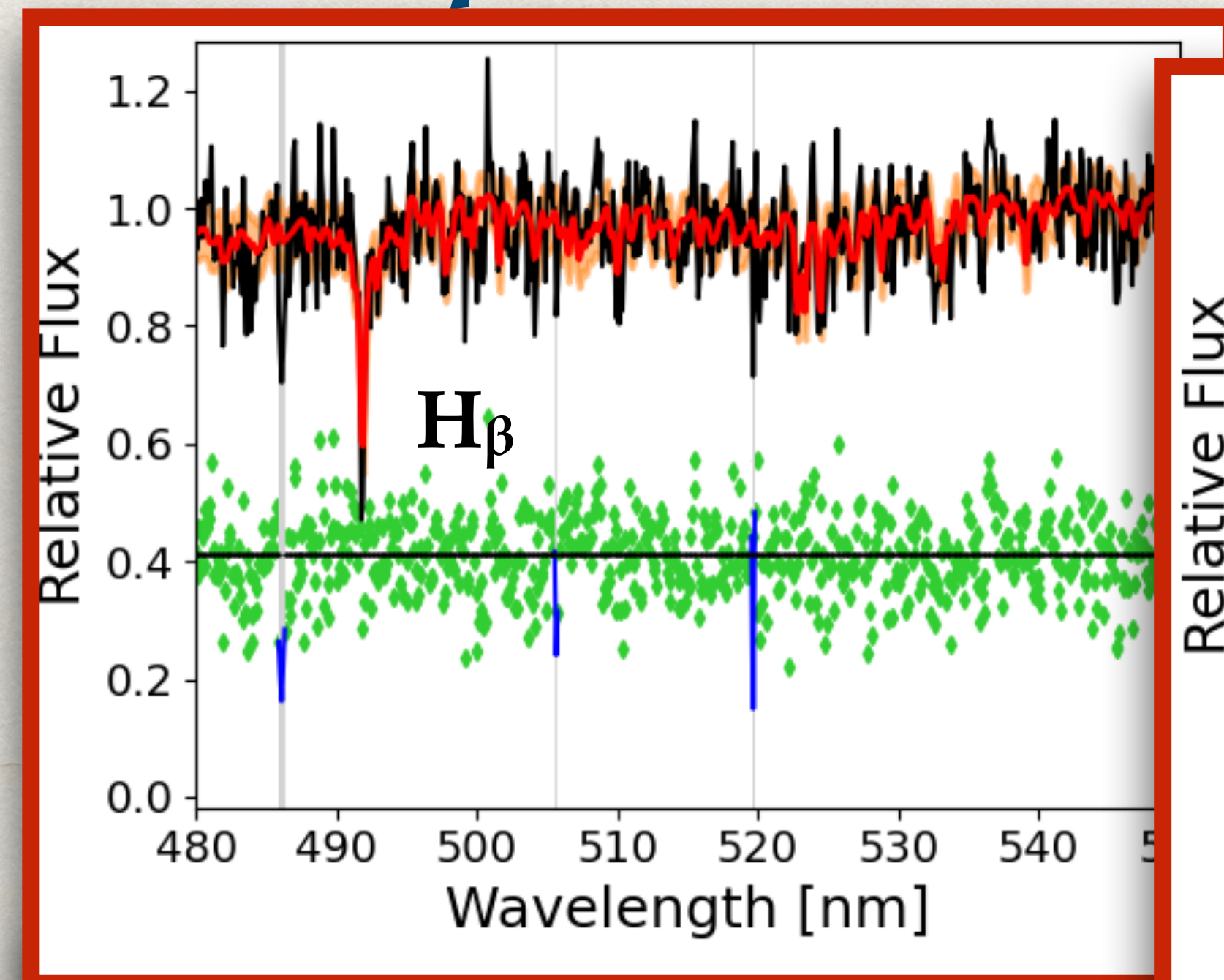
UDG11





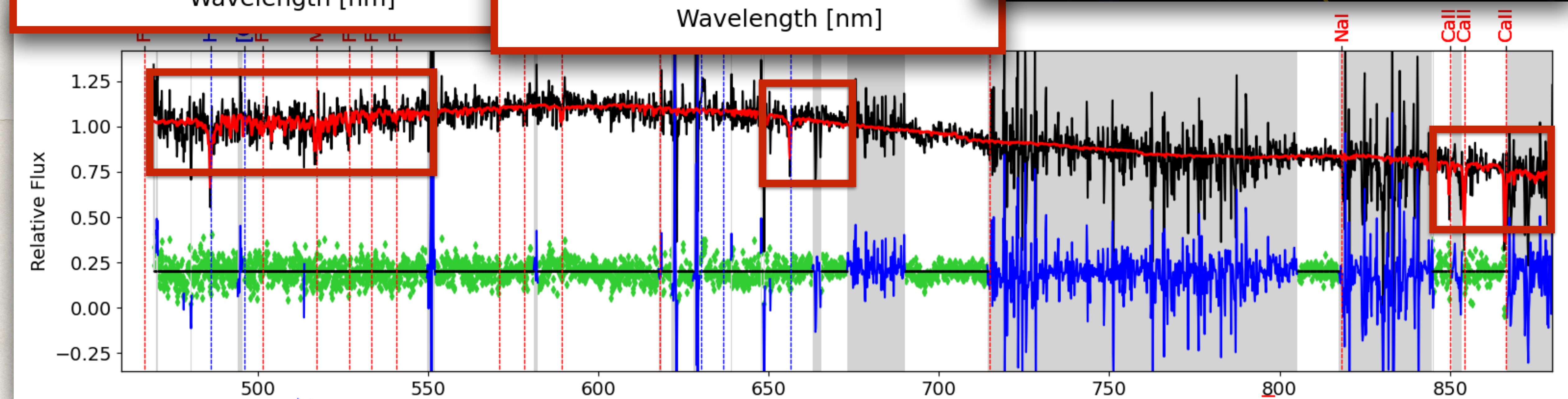
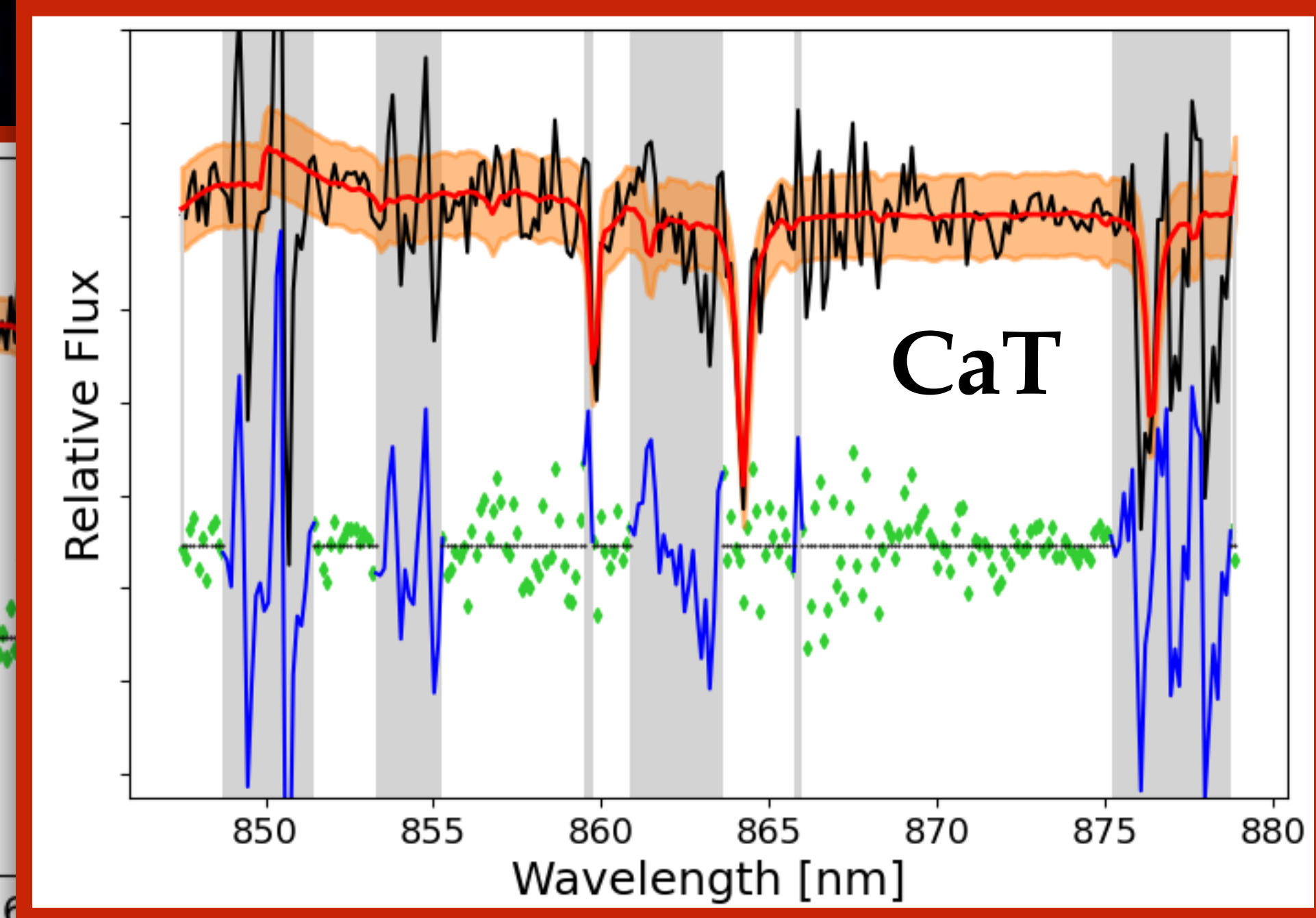
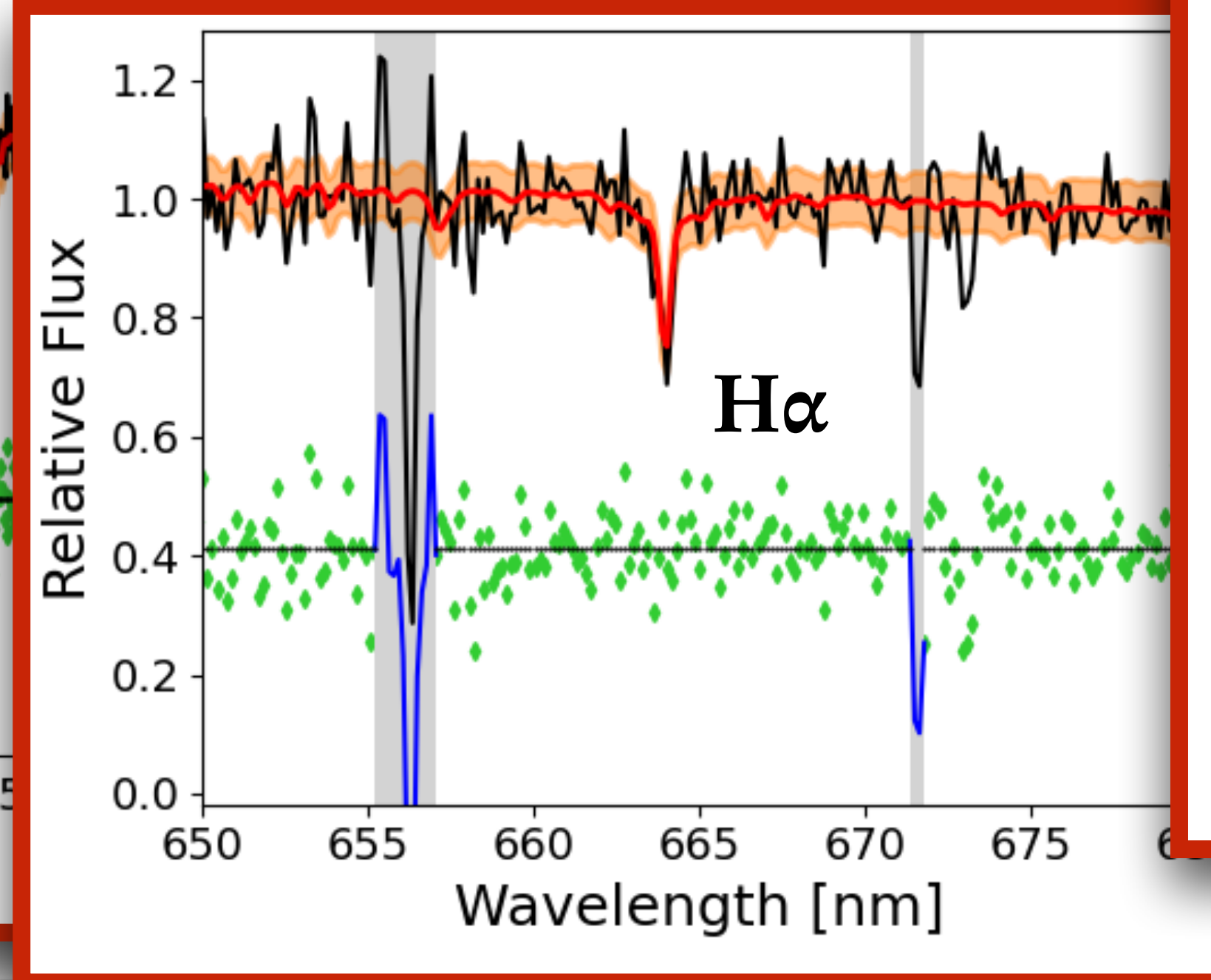
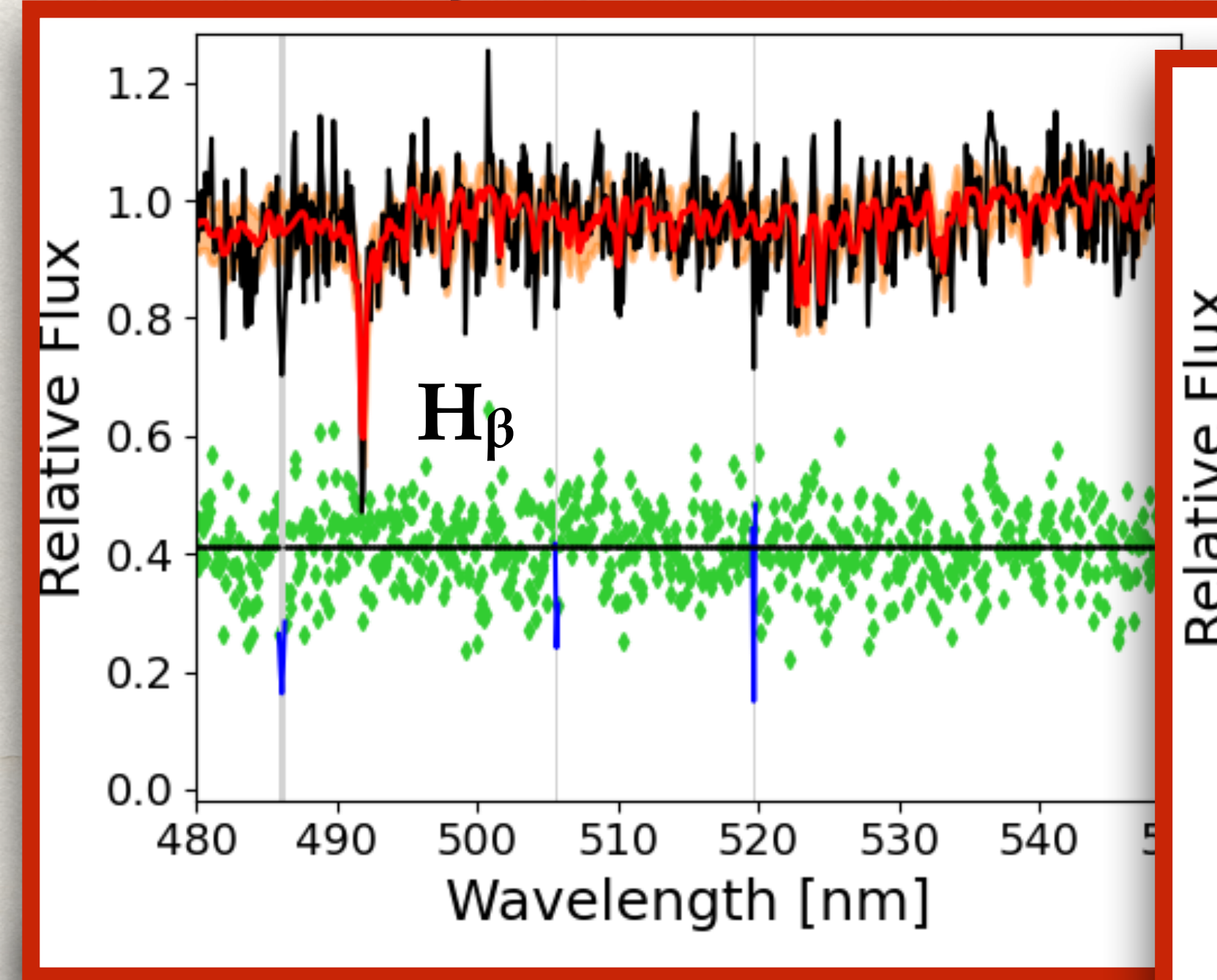
# UDG spectra

UDG11





# UDG spectra





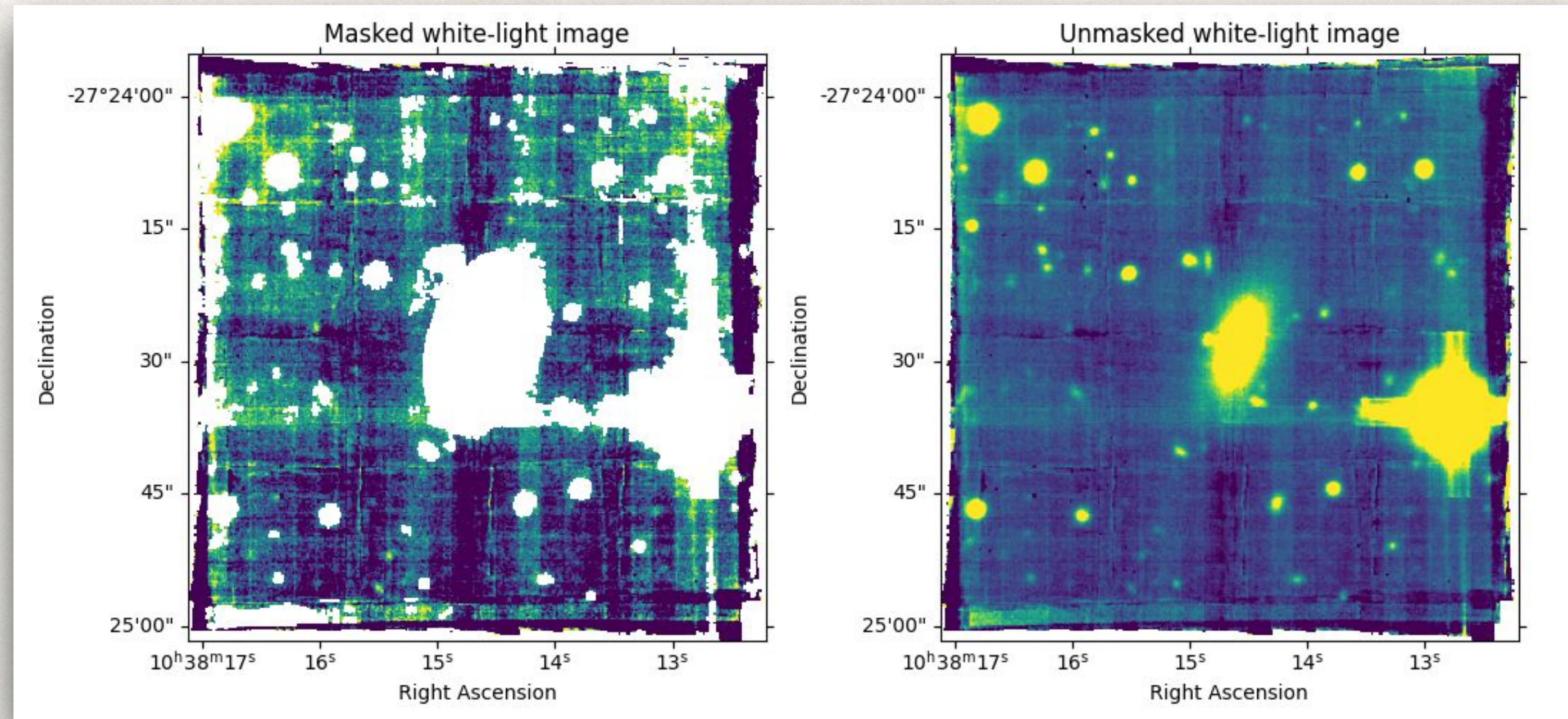
*Challenges: lesson learned from LEWIS*



# Challenges: lesson learned from LEWIS

## I. Improved data reduction

—> *ad hoc mask to improve the estimate of the sky*

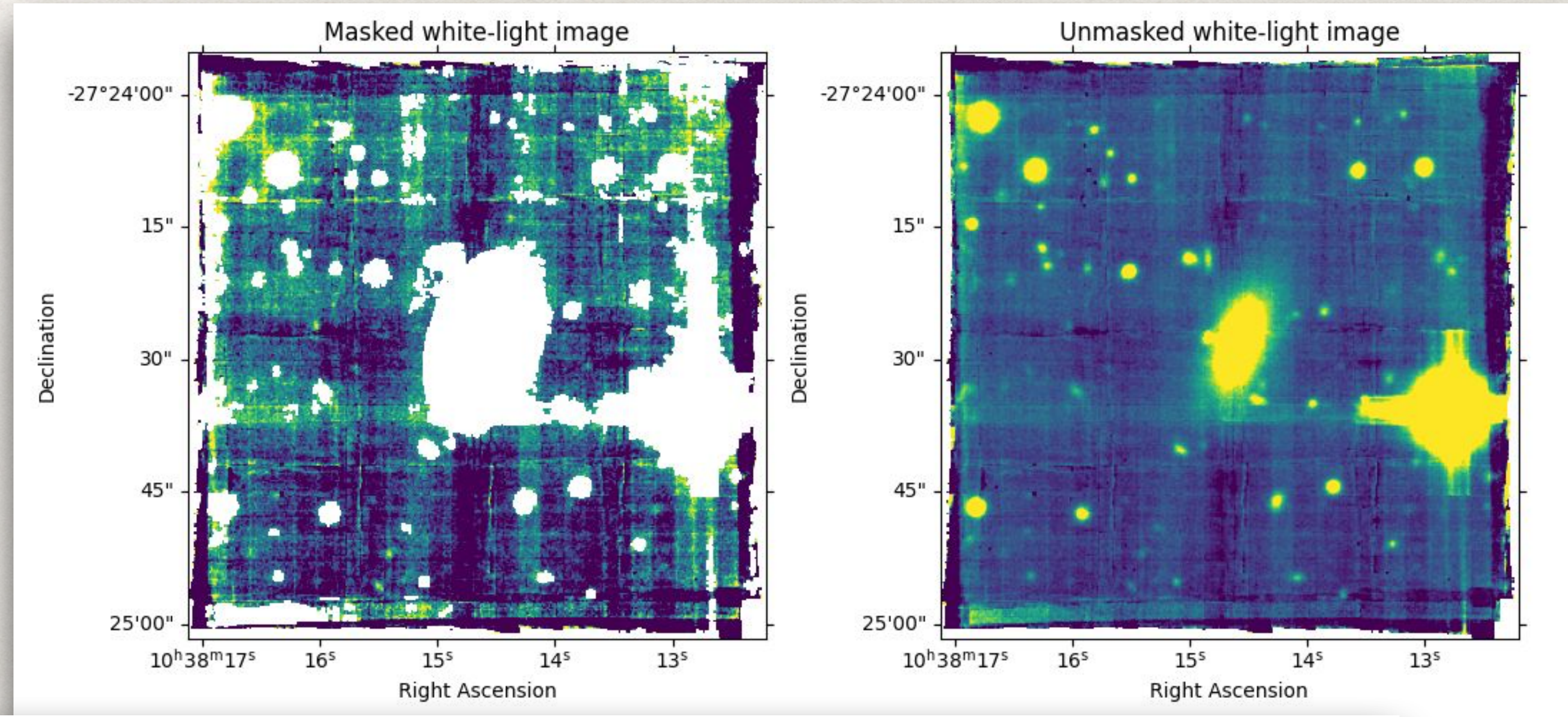




# Challenges: lesson learned from LEWIS

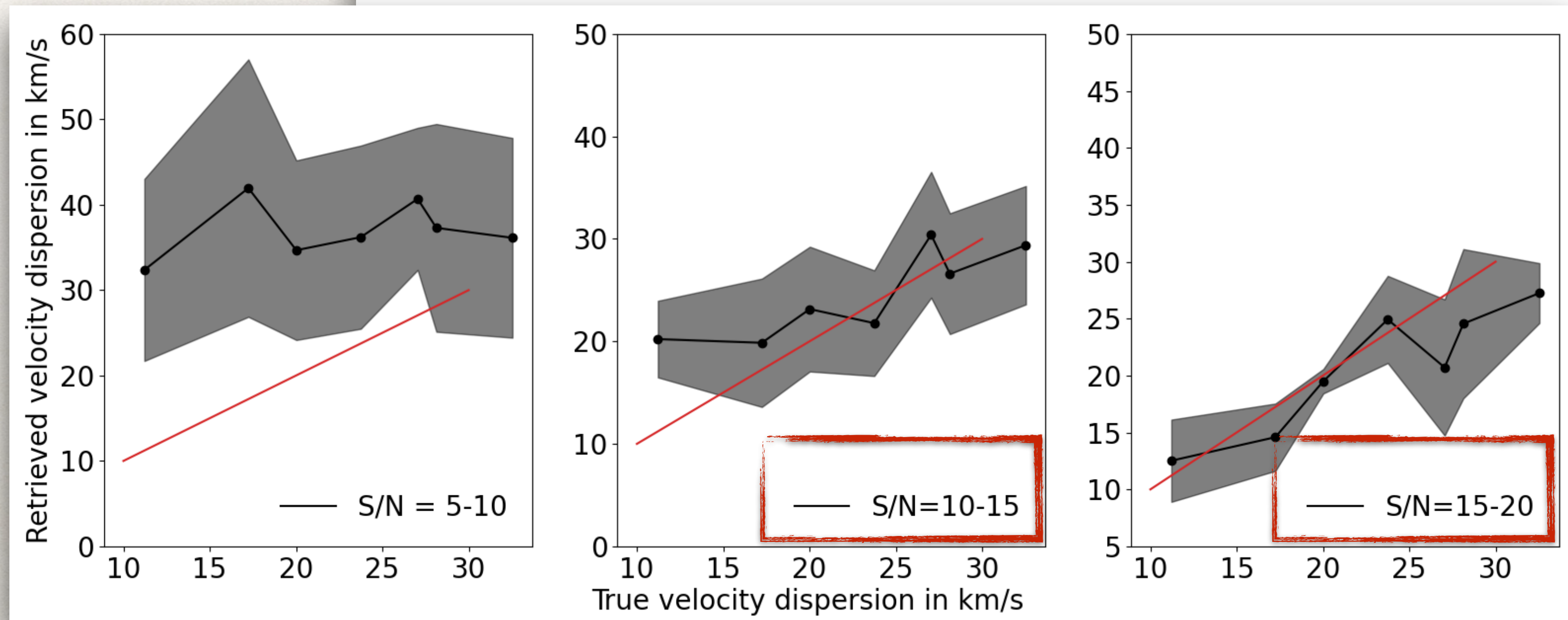
## I. Improved data reduction

—> *ad hoc mask to improve the estimate of the sky*



## II. Minimum $S/N > 10-15$

—> *to retrieve an unbiased value for  $\sigma_{LOS}$*





# *Groundbreaking results from LEWIS*

## **I. Stellar kinematics: *do UDGs rotate?***

Chiara Buttitta+2024,  
A&A sub.



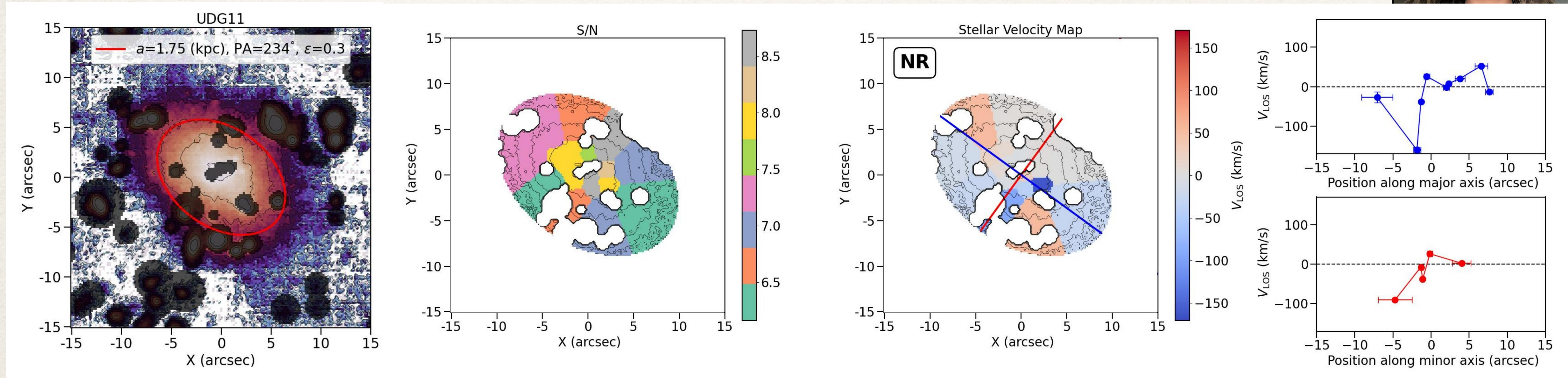


# Groundbreaking results from LEWIS

Chiara Buttitta+2024,  
A&A sub.



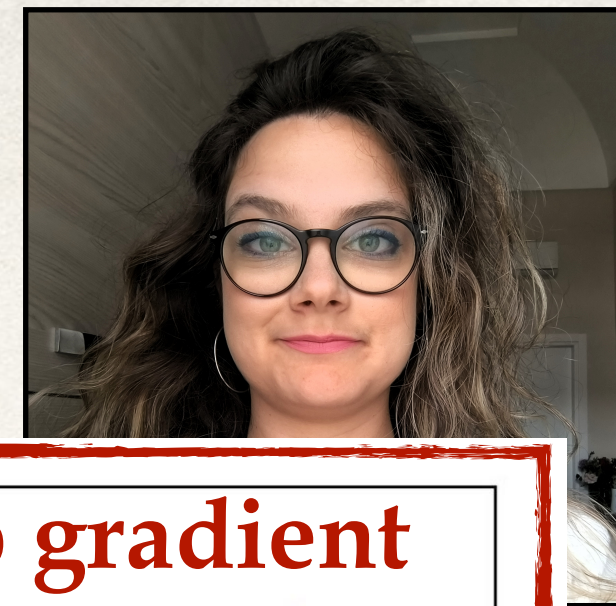
## I. Stellar kinematics: *do UDGs rotate?*



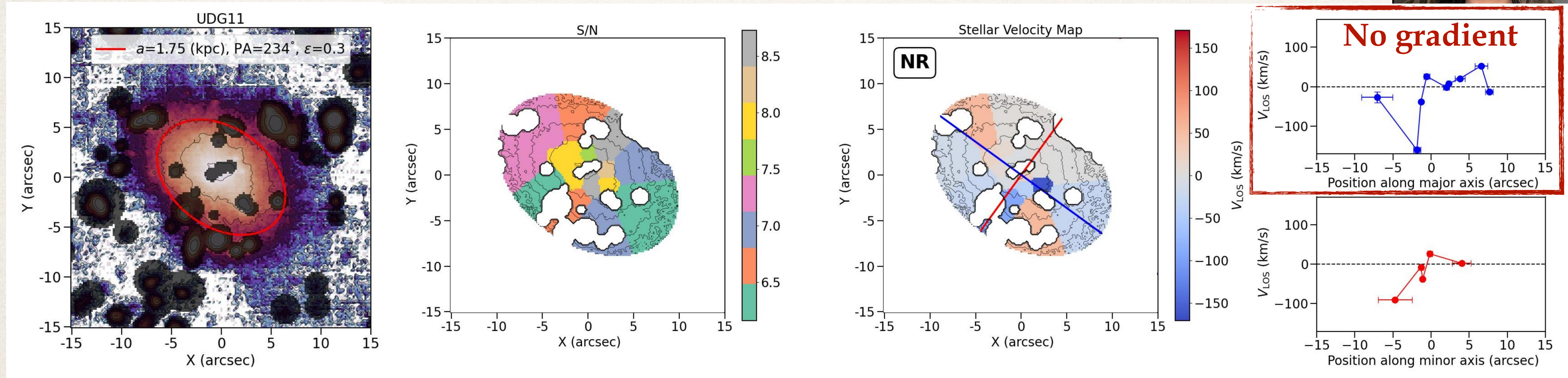


# Groundbreaking results from LEWIS

Chiara Buttitta+2024,  
A&A sub.



## I. Stellar kinematics: *do UDGs rotate?*



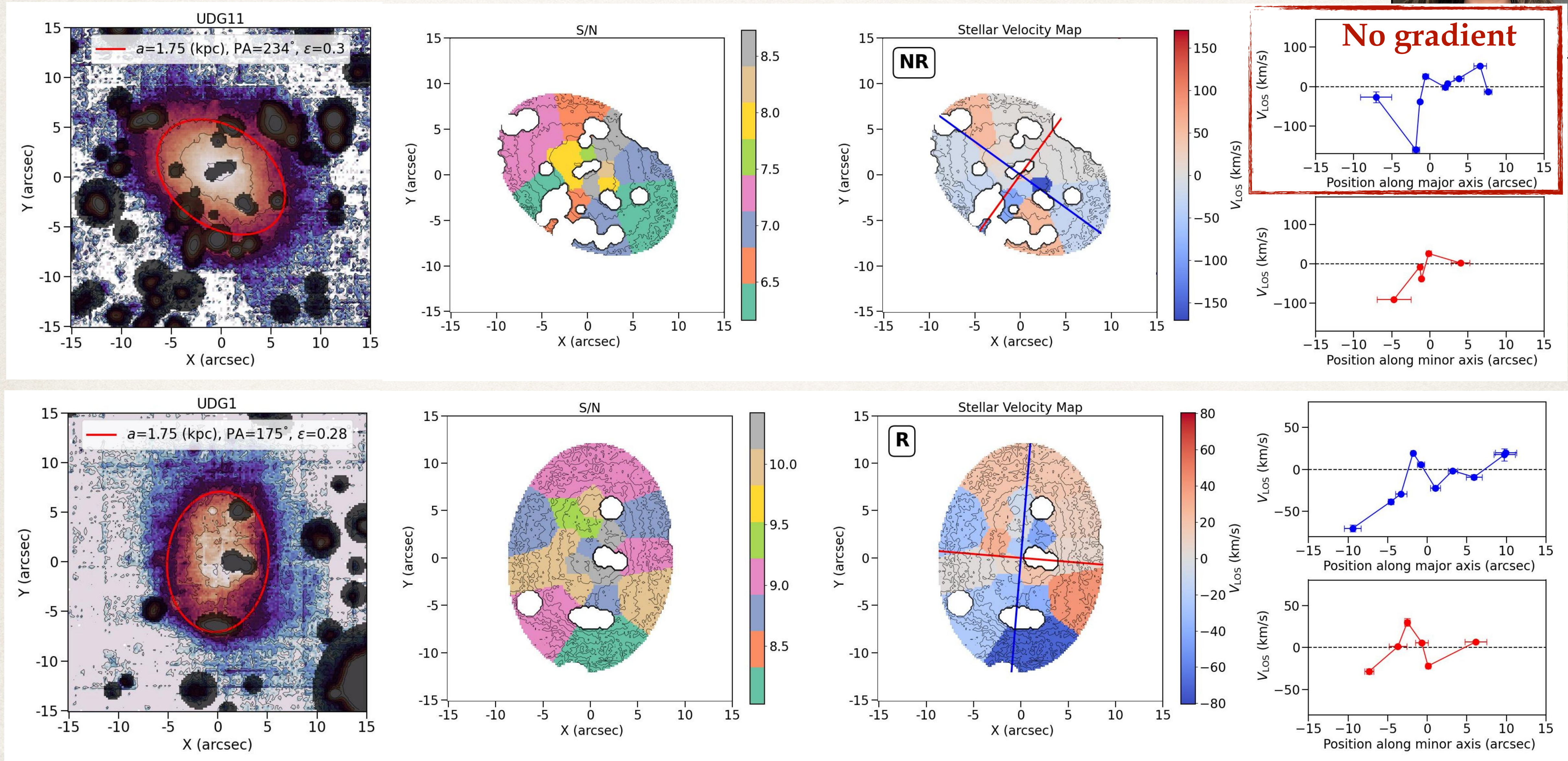


# Groundbreaking results from LEWIS

Chiara Buttitta+2024,  
A&A sub.



## I. Stellar kinematics: *do UDGs rotate?*



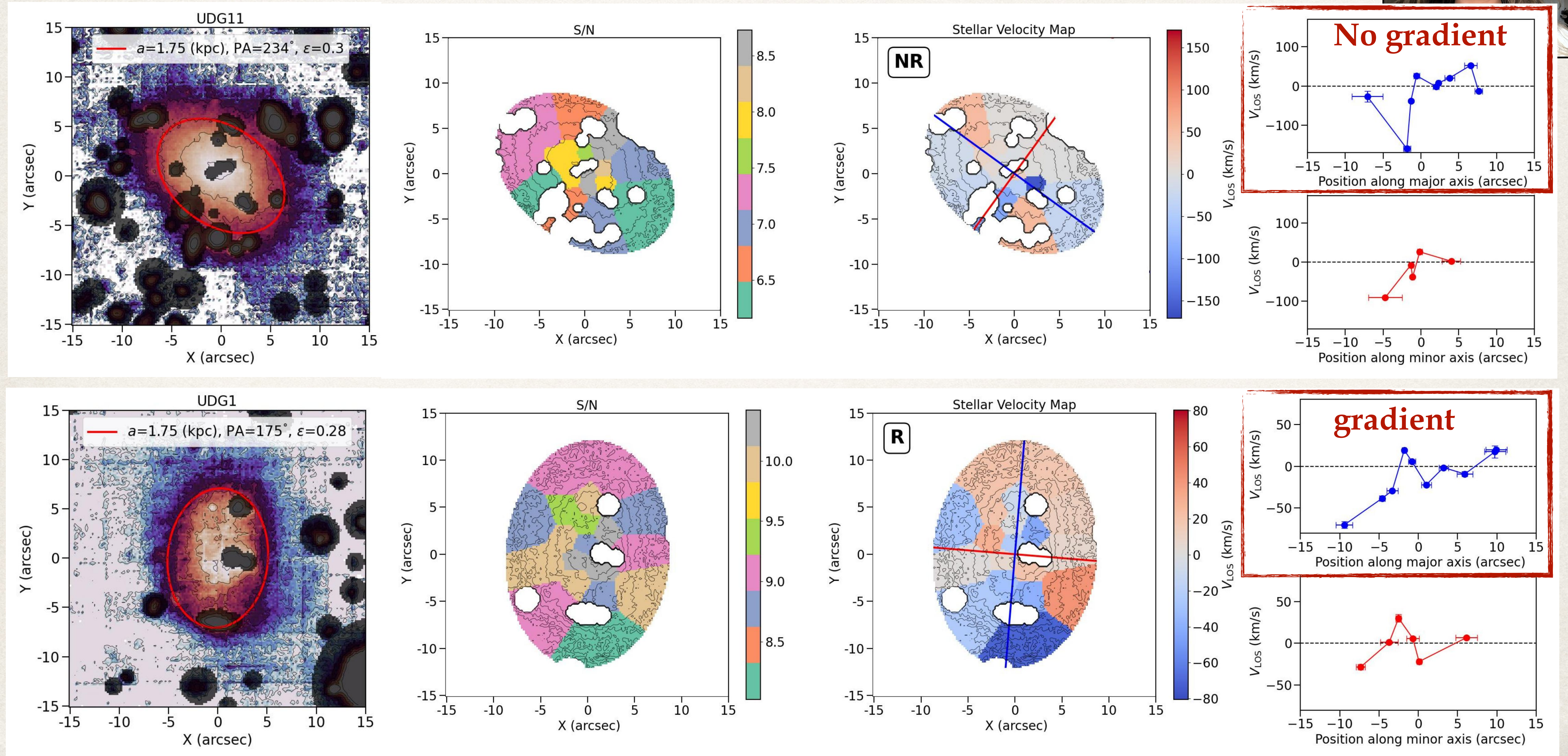


# Groundbreaking results from LEWIS

Chiara Buttitta+2024,  
A&A sub.



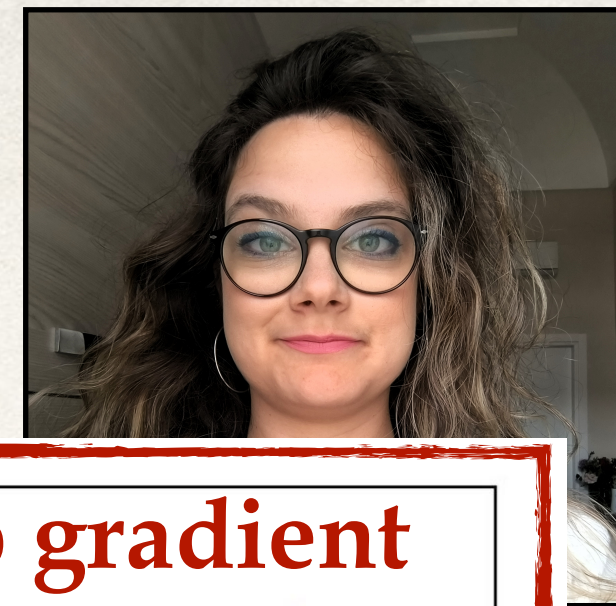
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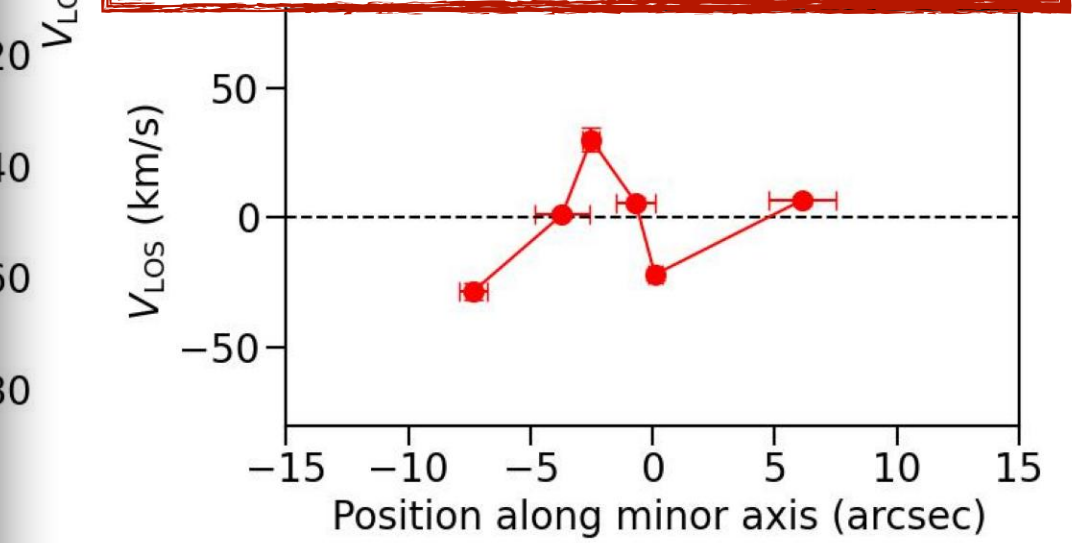
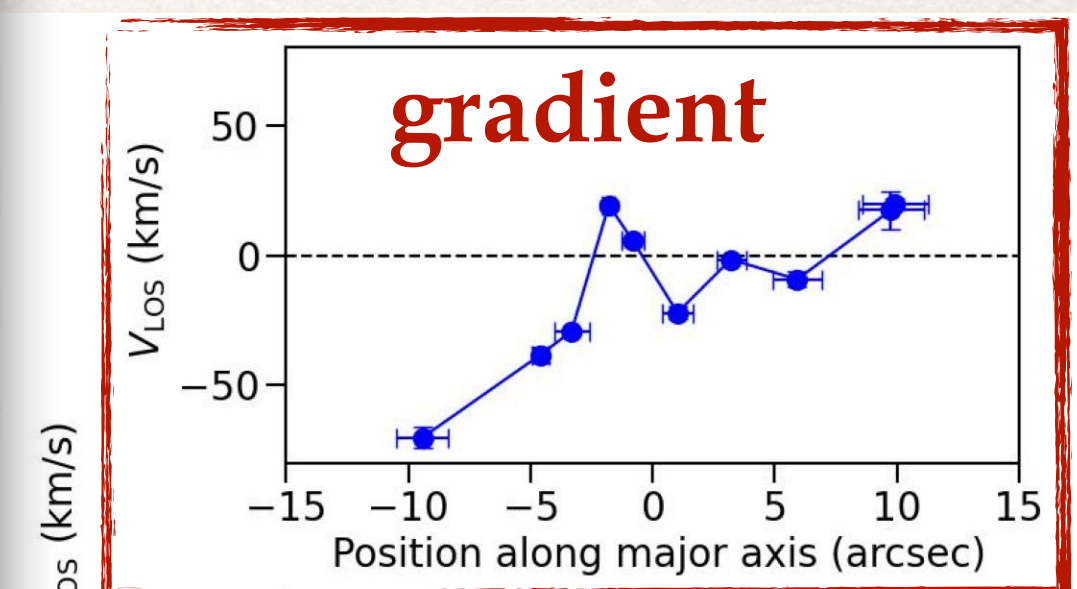
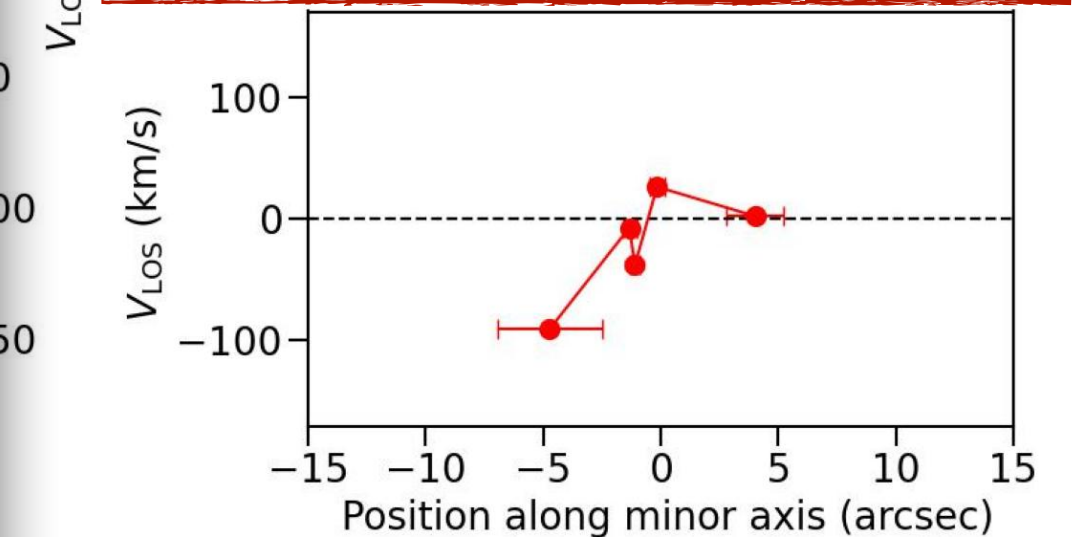
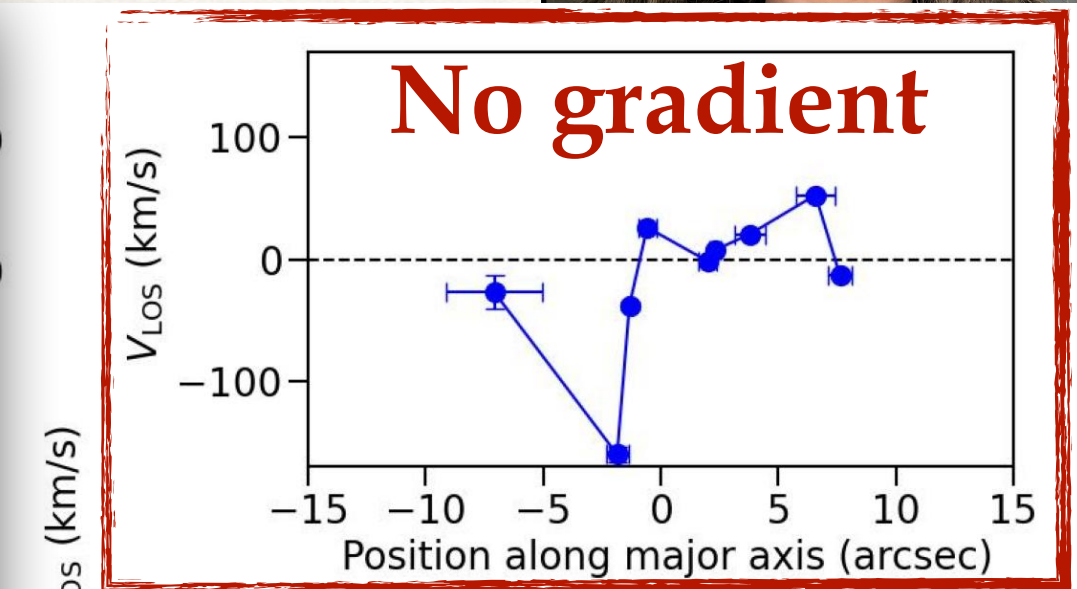
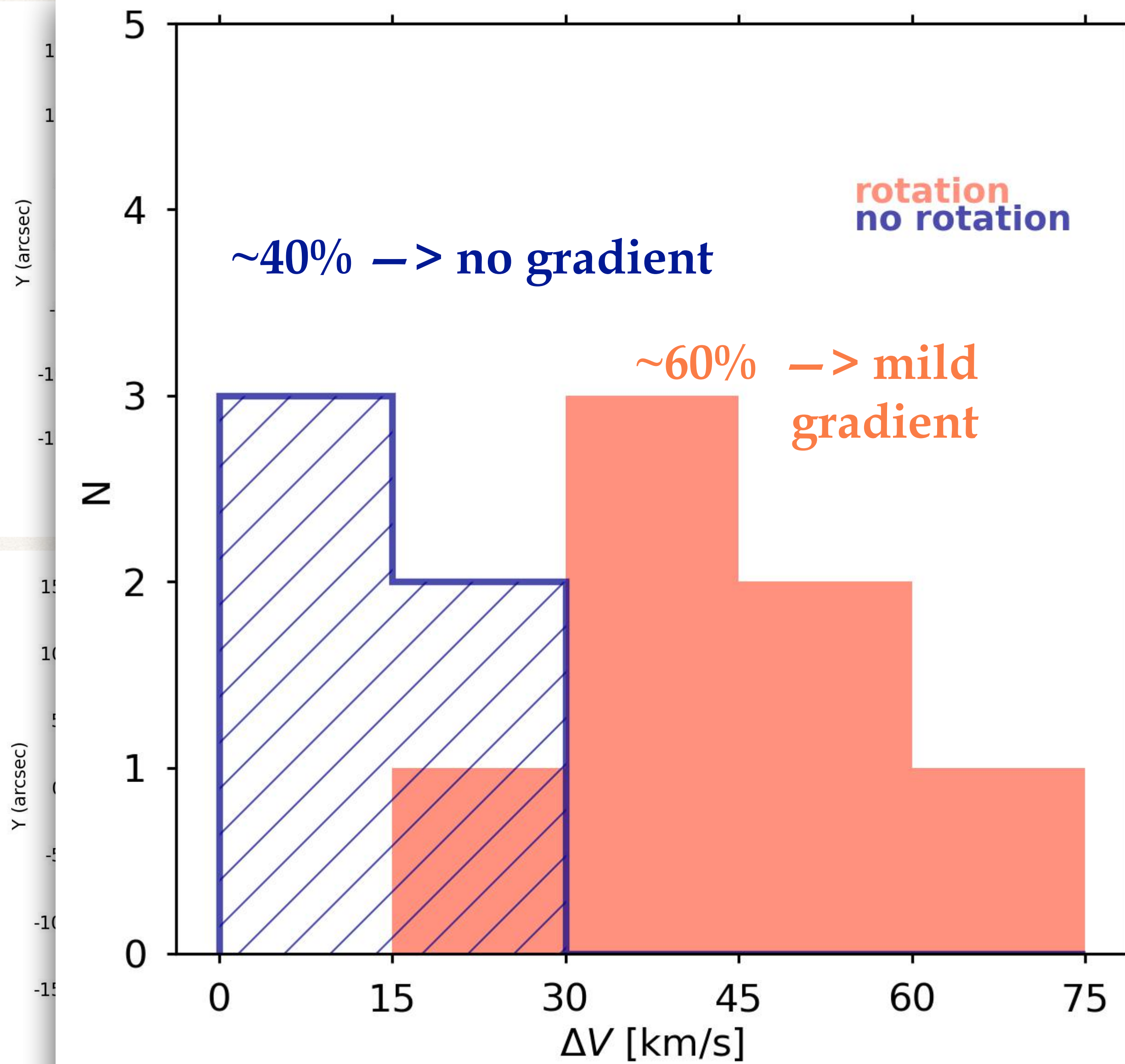
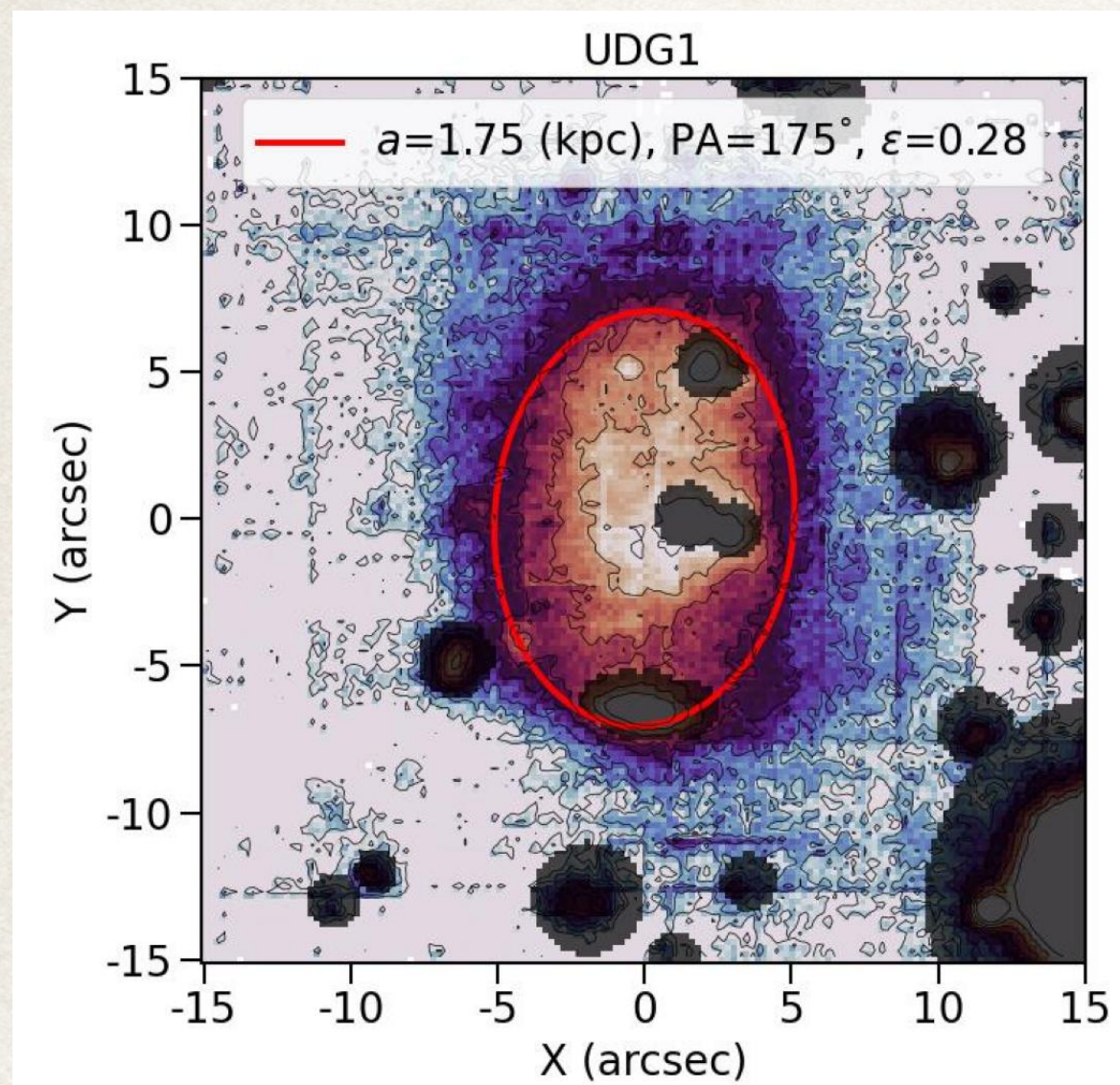
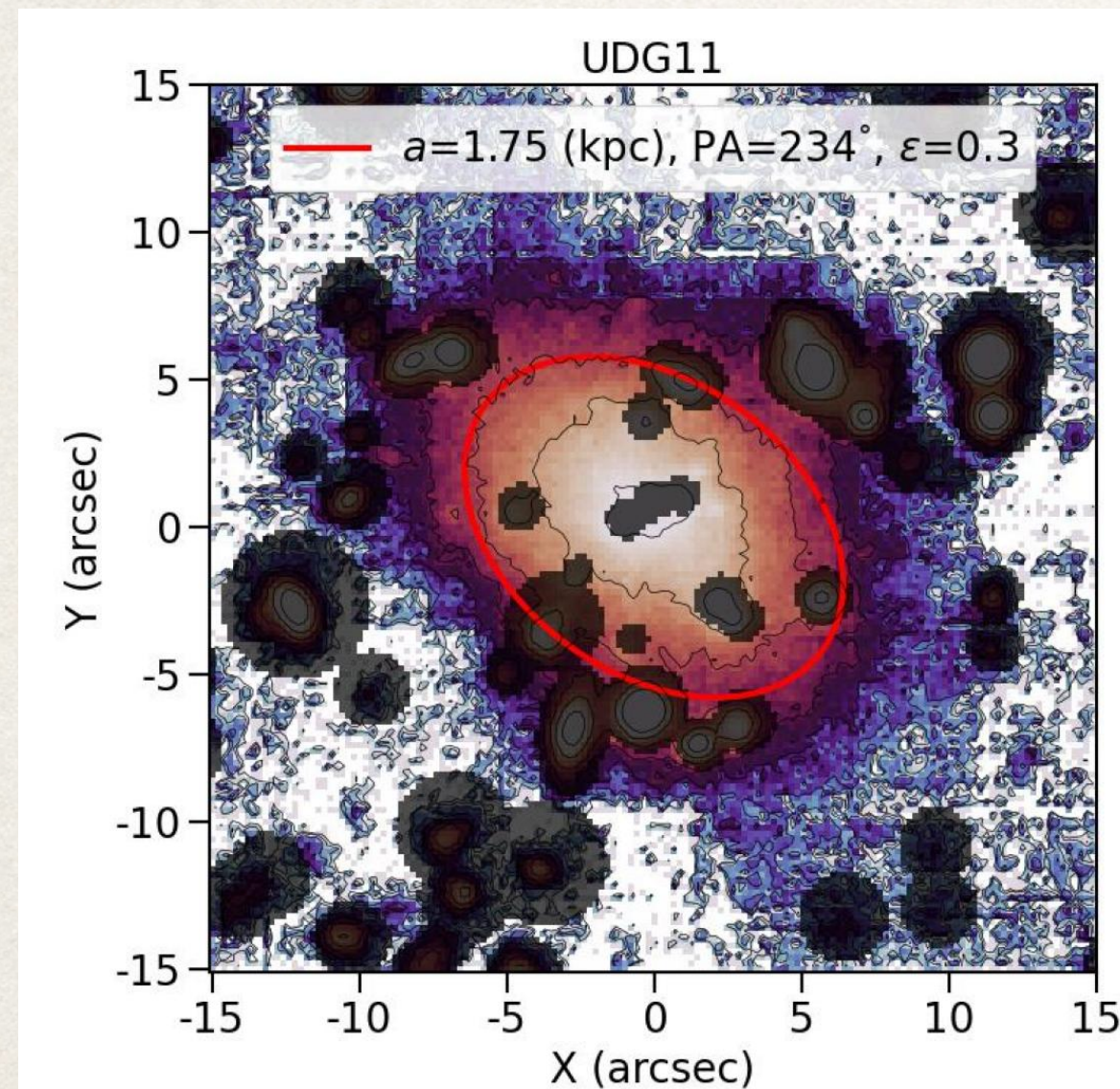


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Chiara Buttitta+2024,  
A&A sub.



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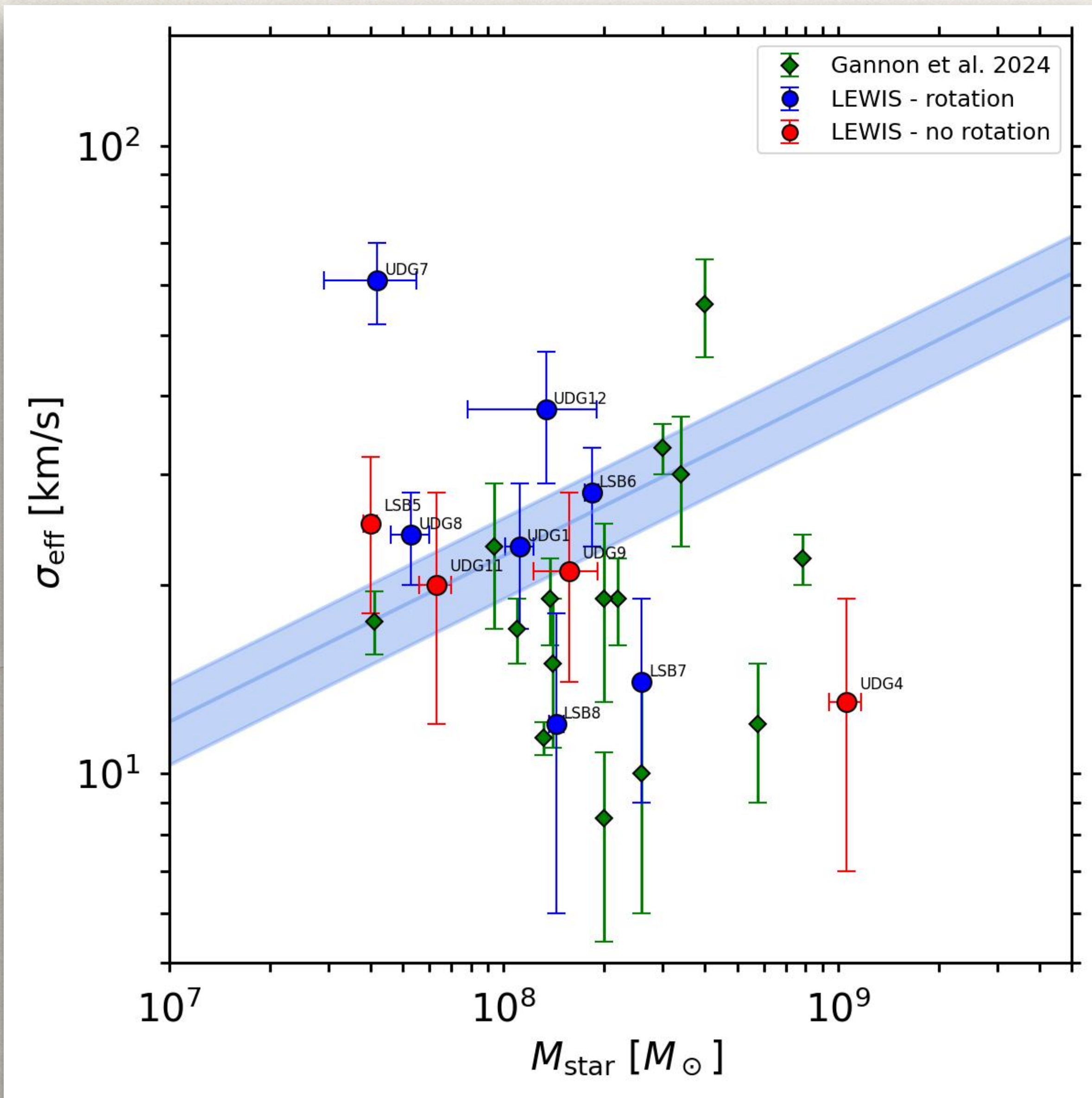


# Groundbreaking results from LEWIS

Chiara Buttitta+2024,  
A&A sub.



## II. DM content in UDGs



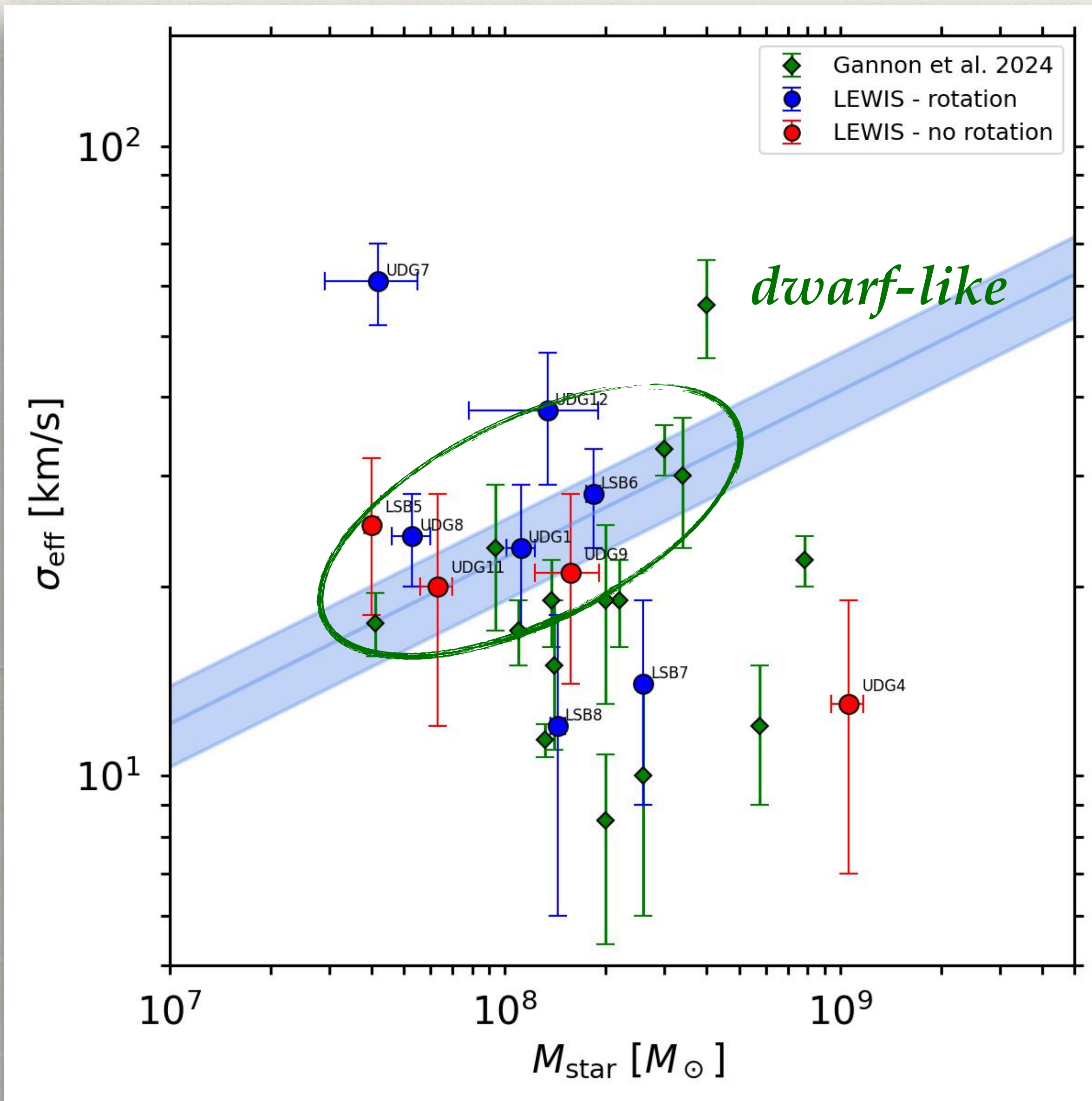


# Groundbreaking results from LEWIS

Chiara Buttitta+2024,  
A&A sub.



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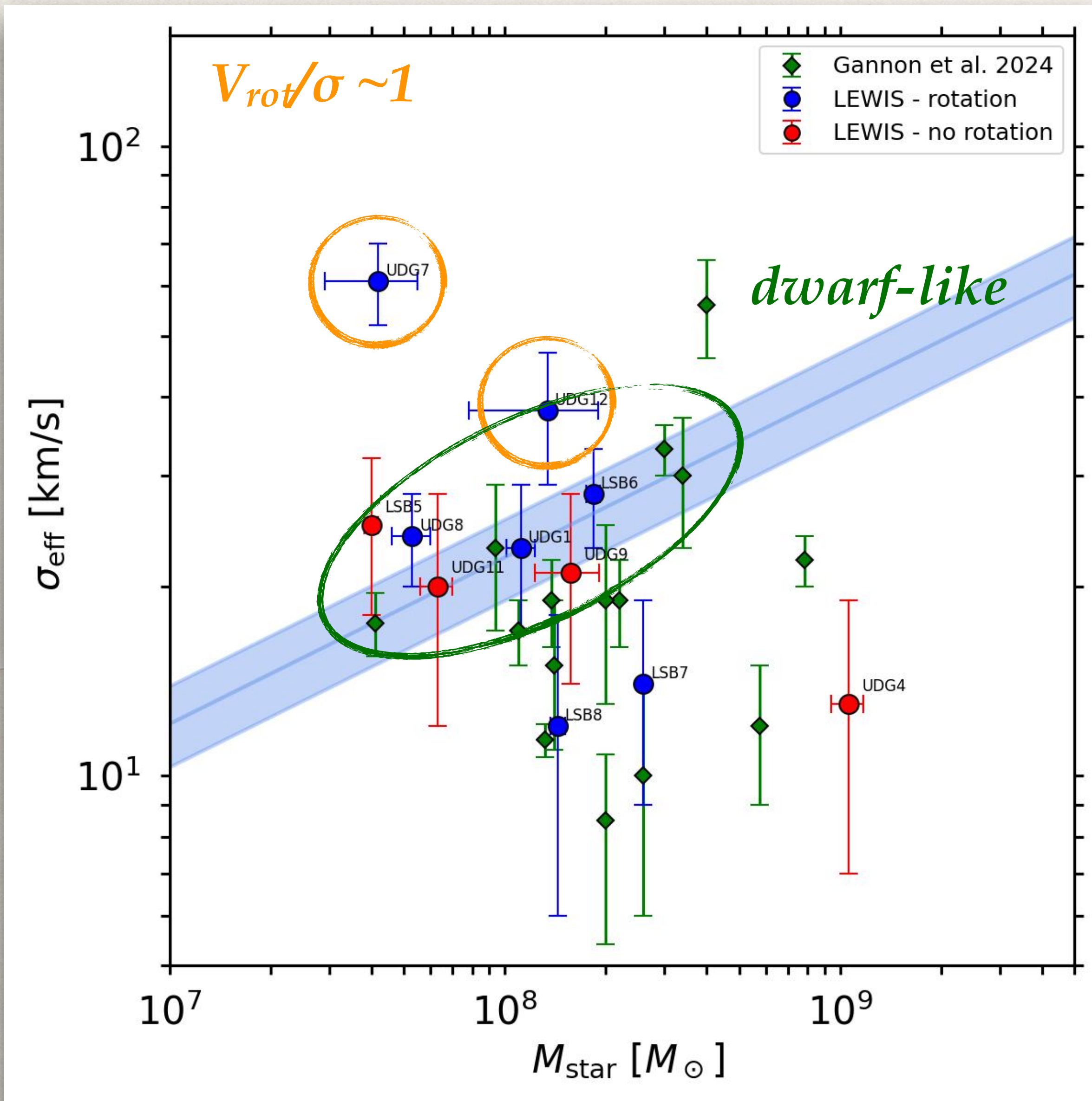


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A&A sub.



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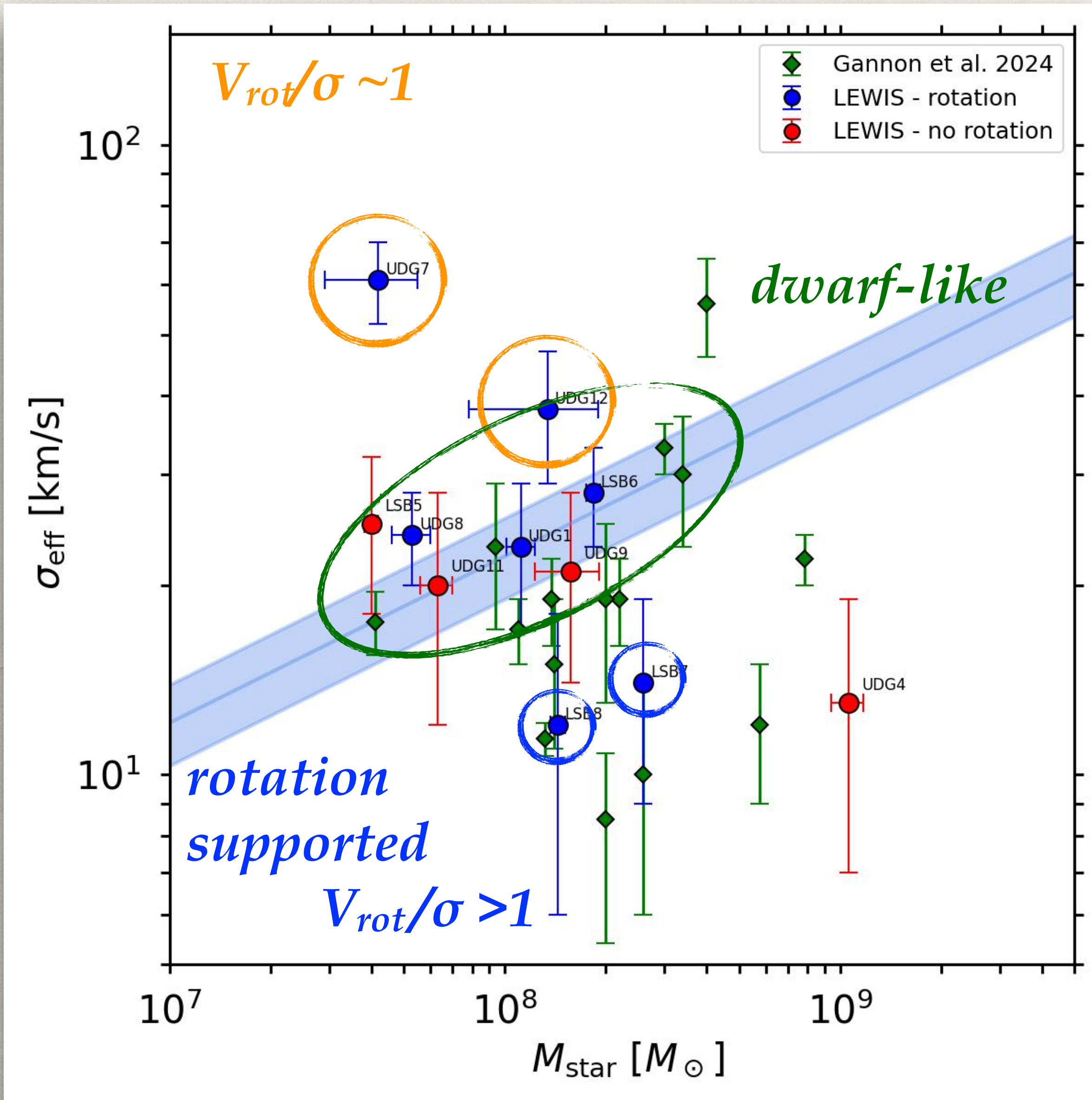


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A&A sub.



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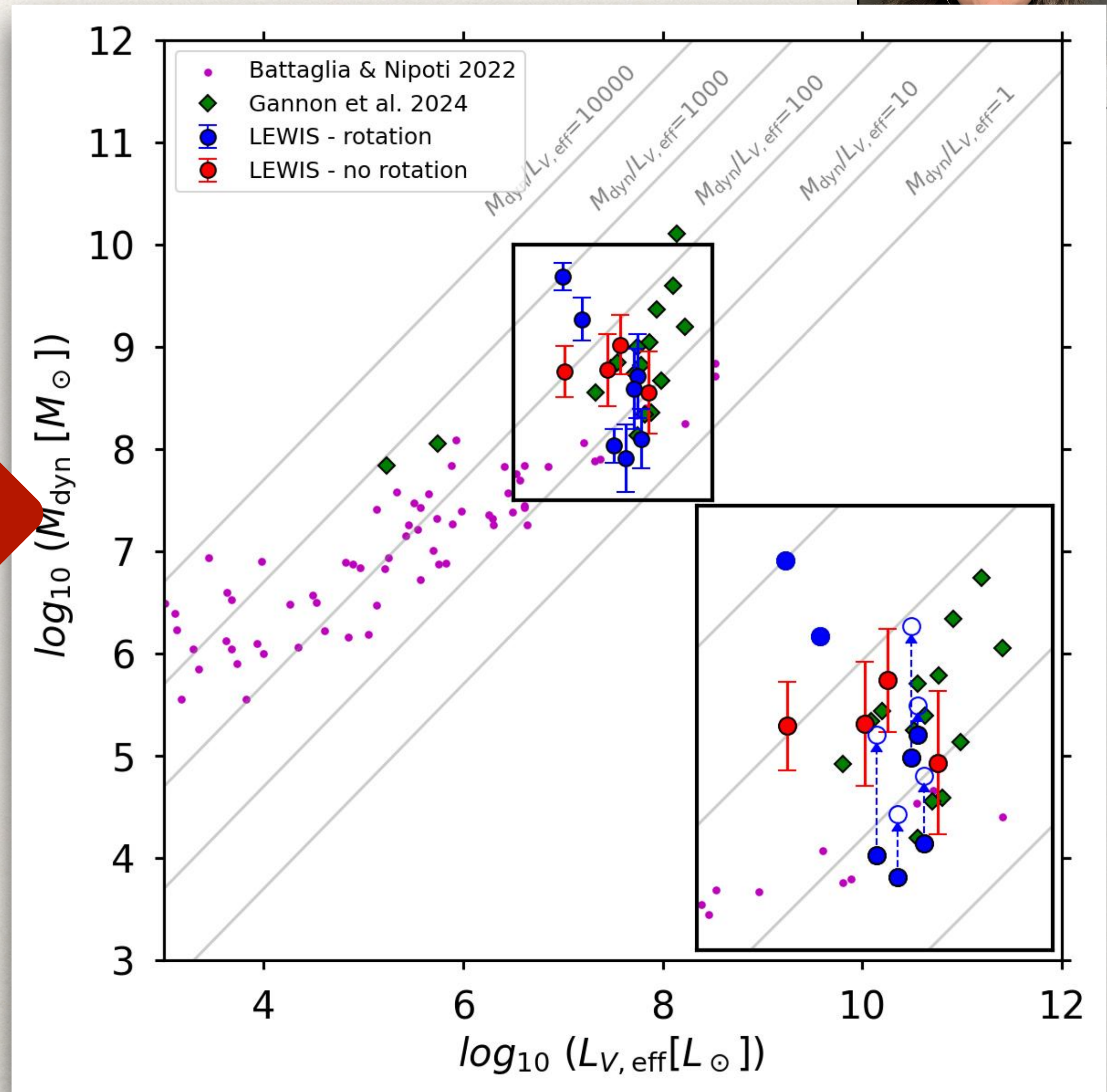
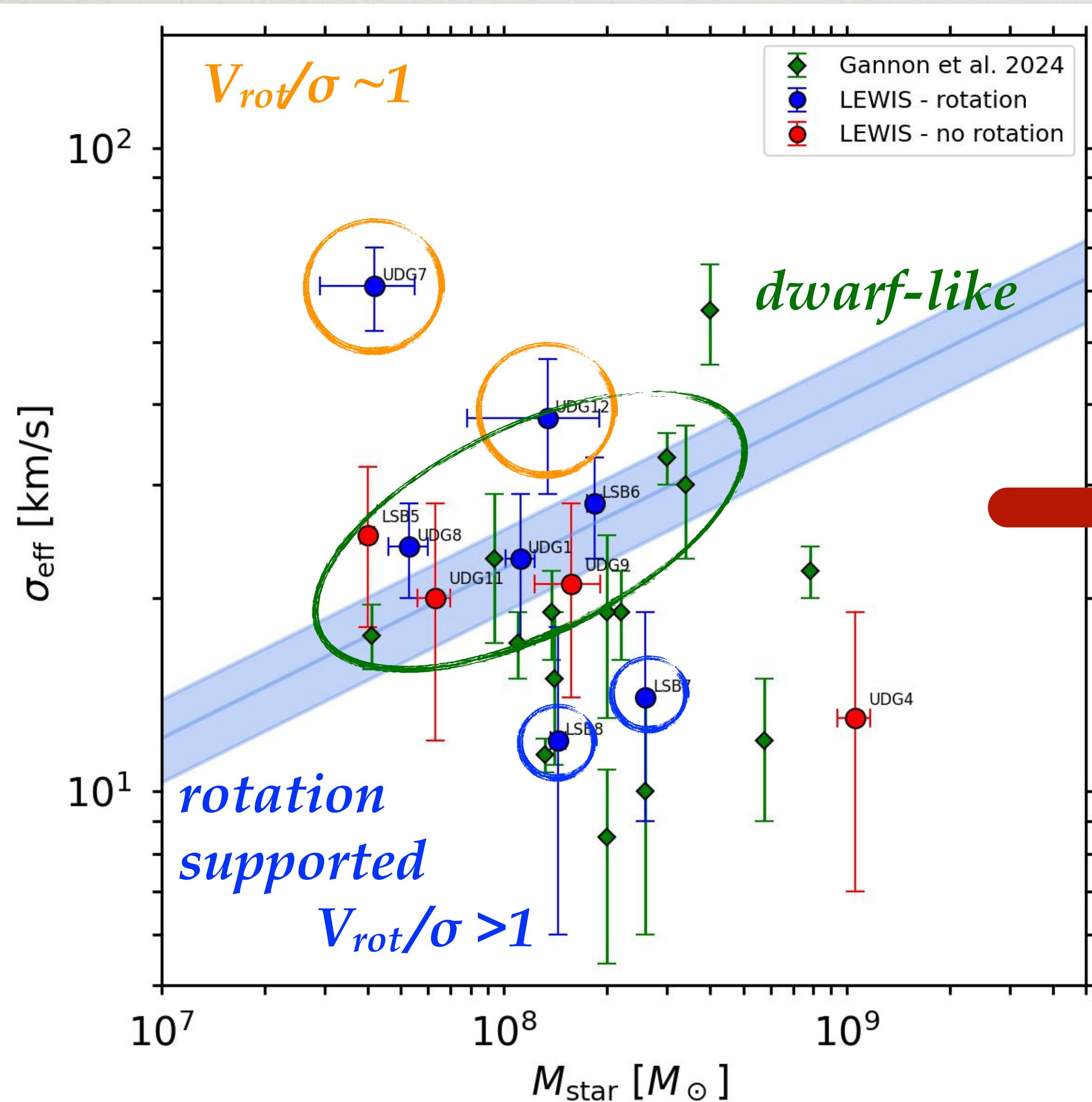


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A&A sub.



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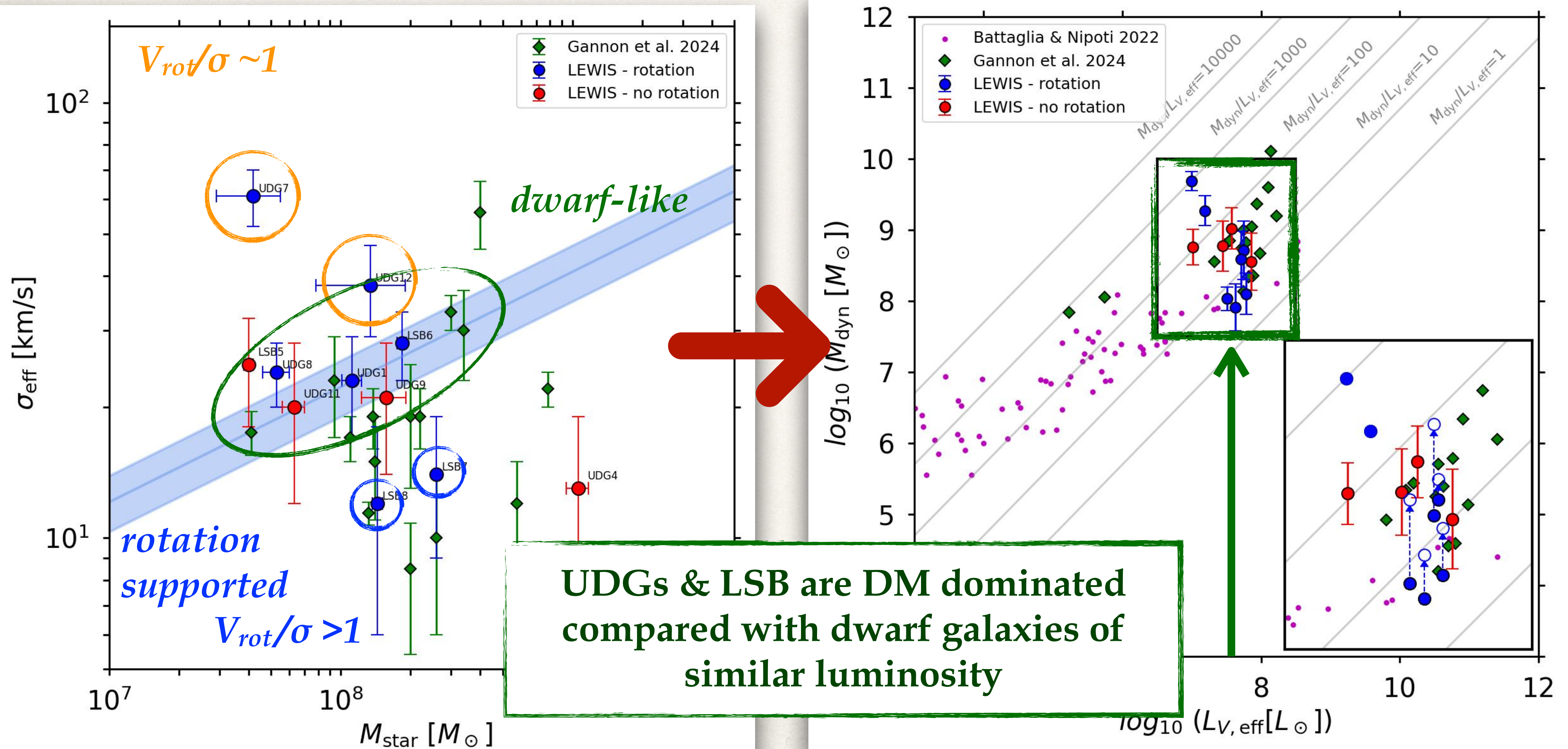


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A&A sub.



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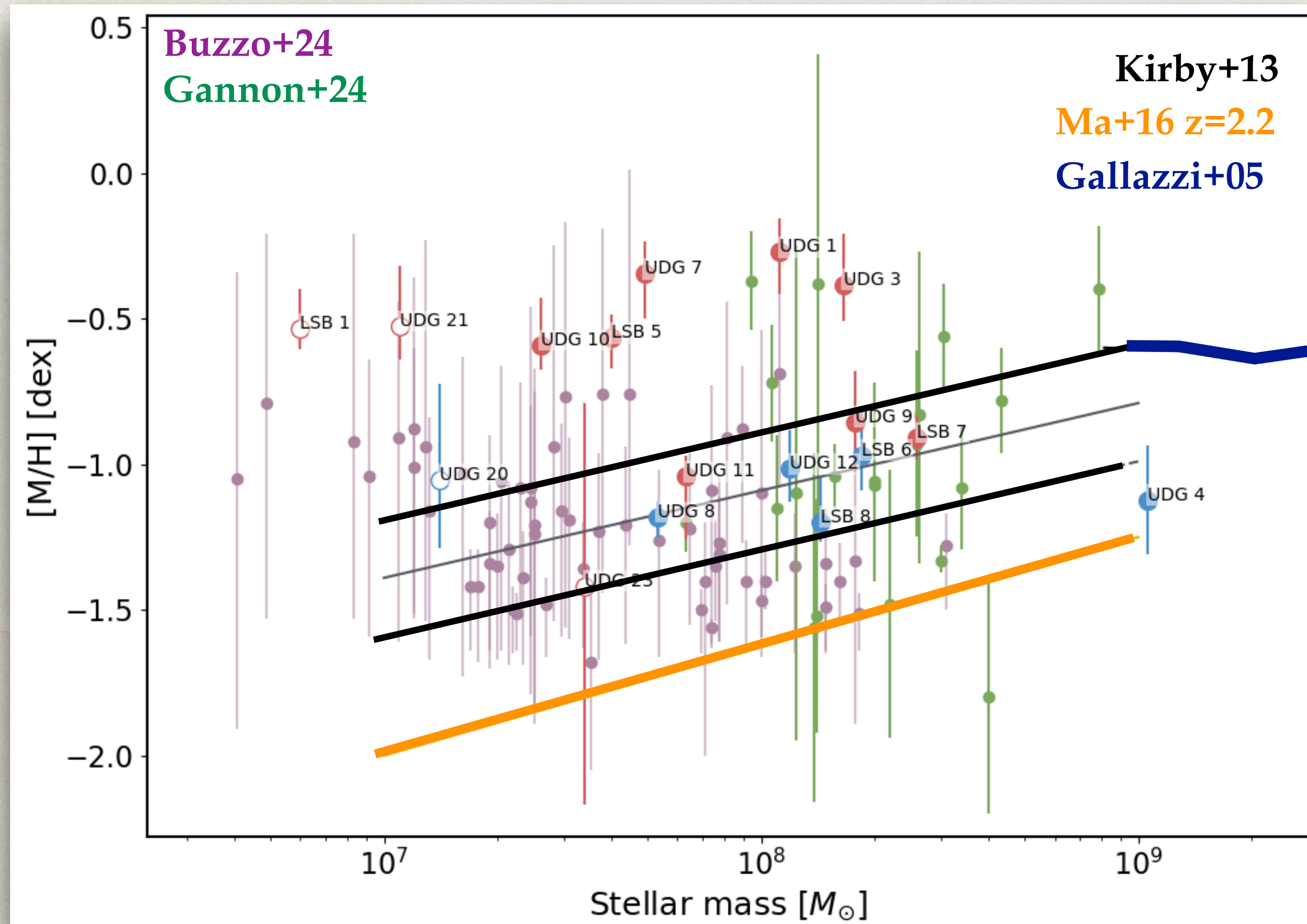


# Groundbreaking results from LEWIS

Goran Doll+2024,  
in prep.



## III. Stellar populations of UDGs



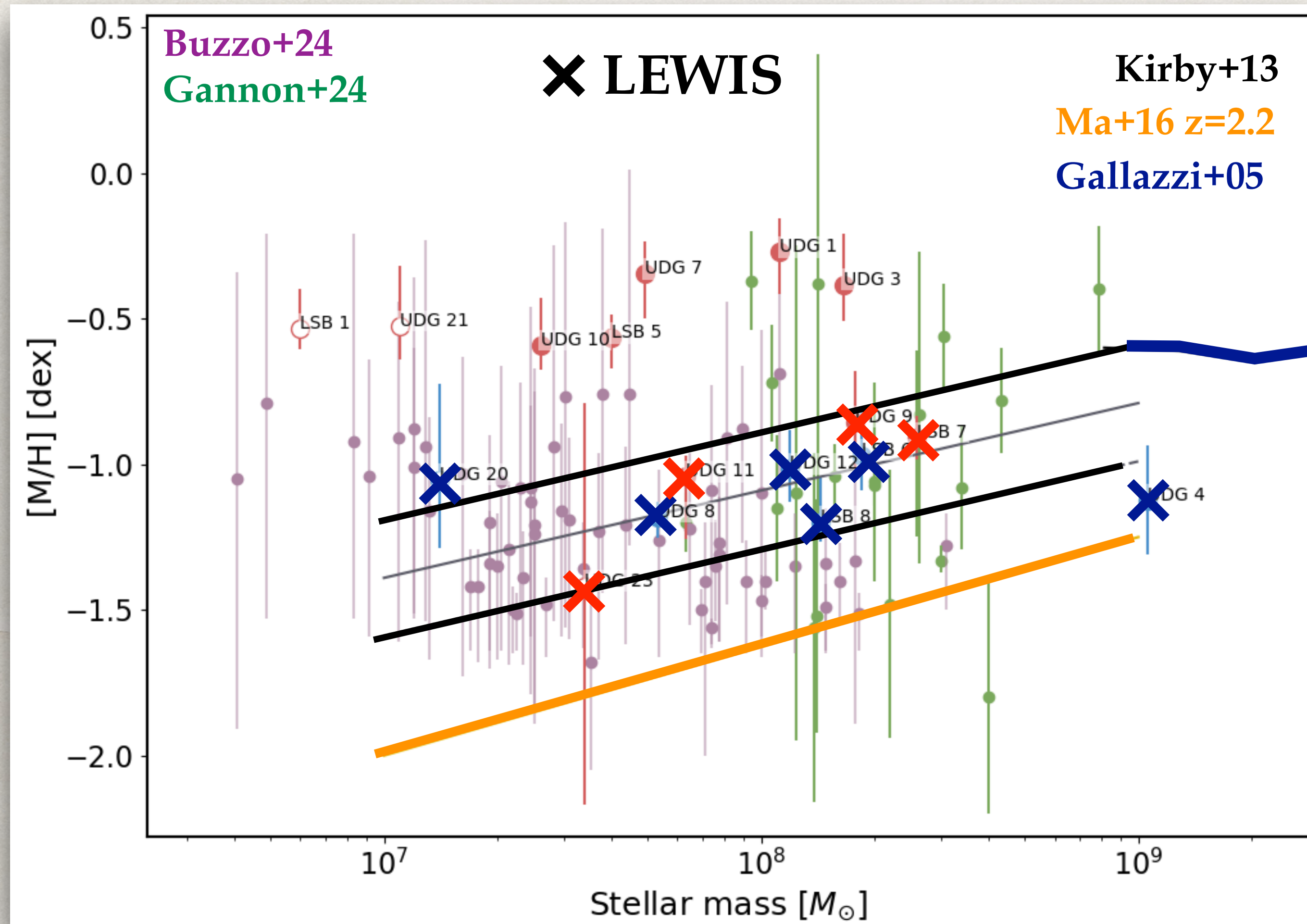


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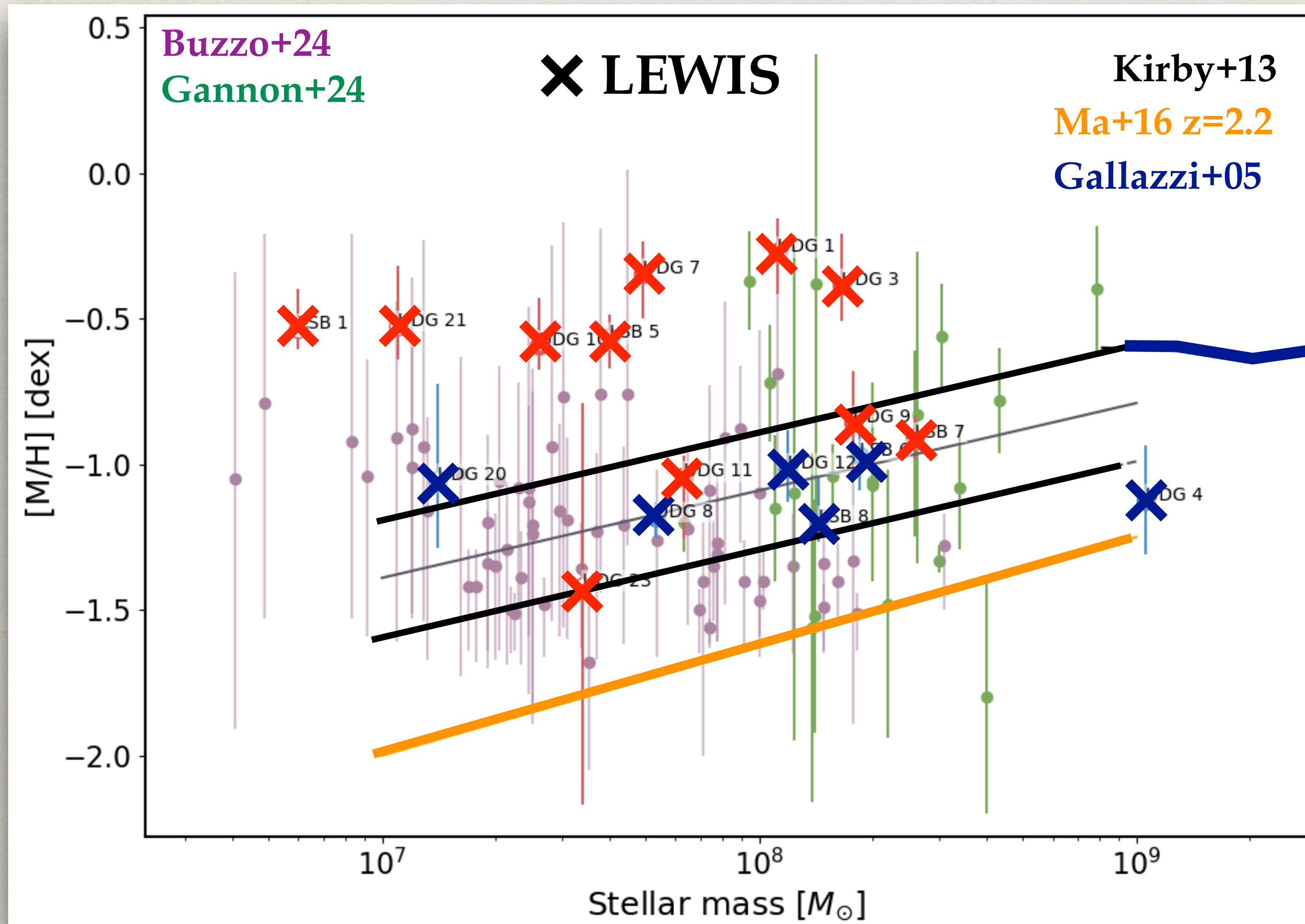


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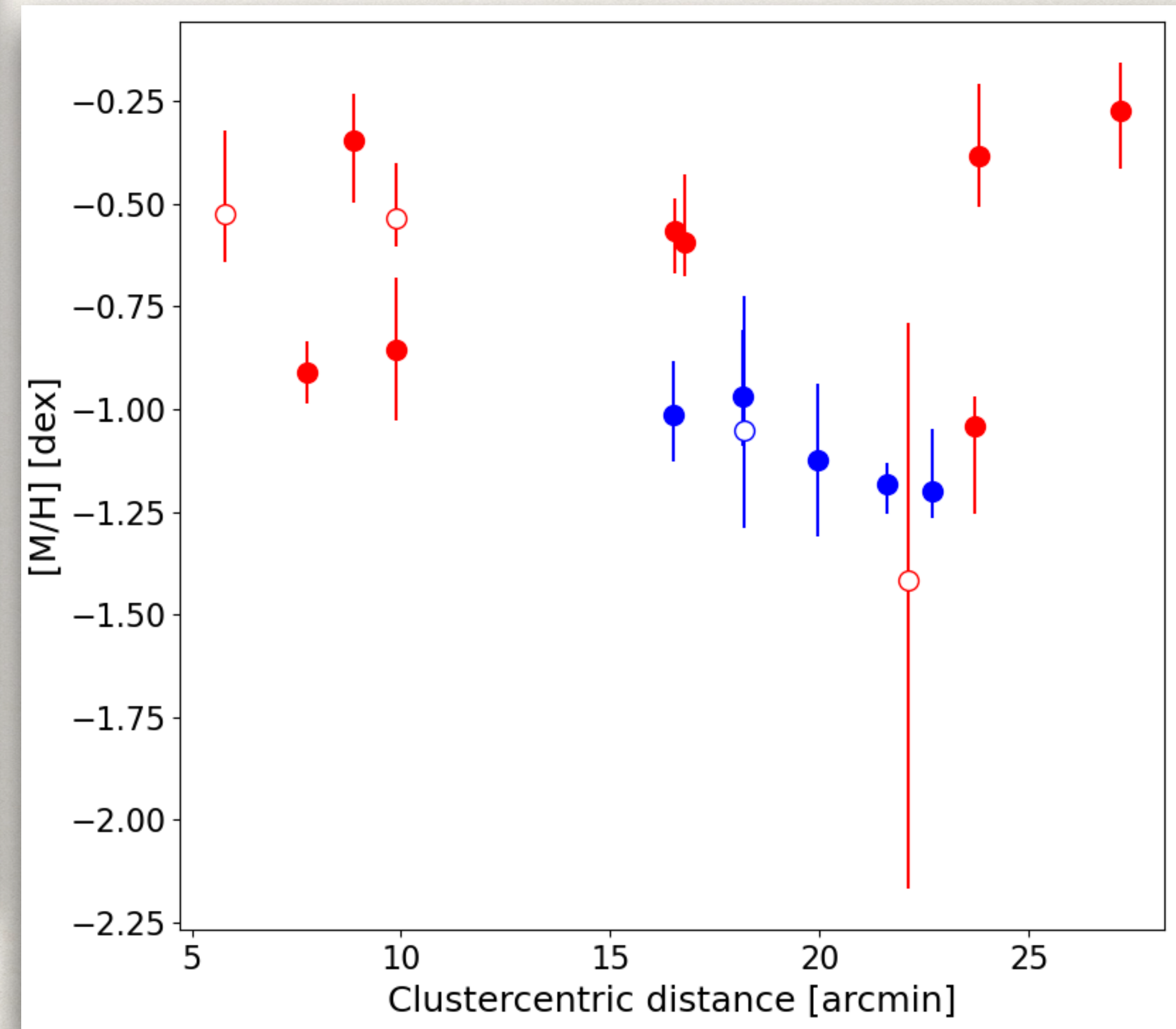
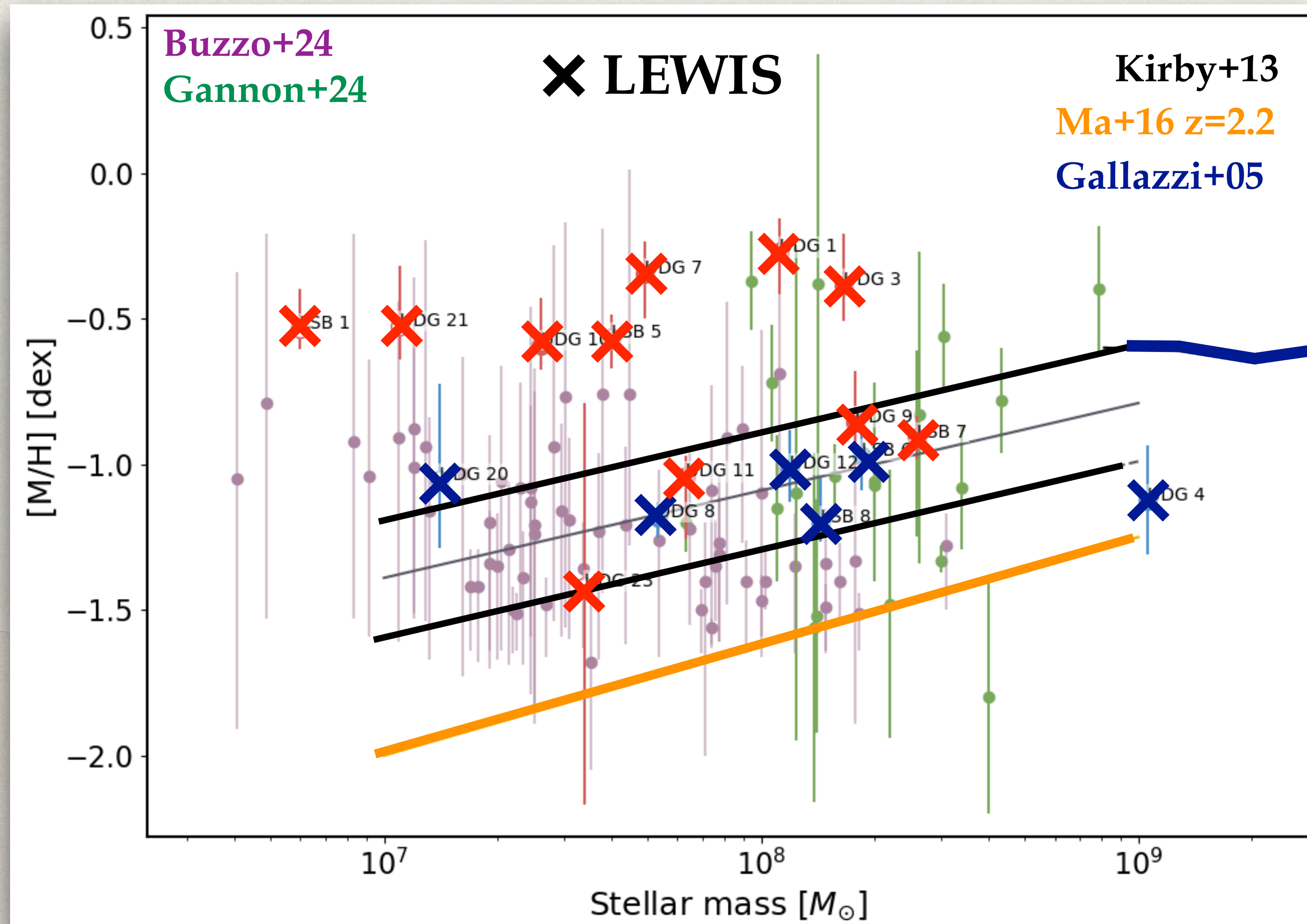


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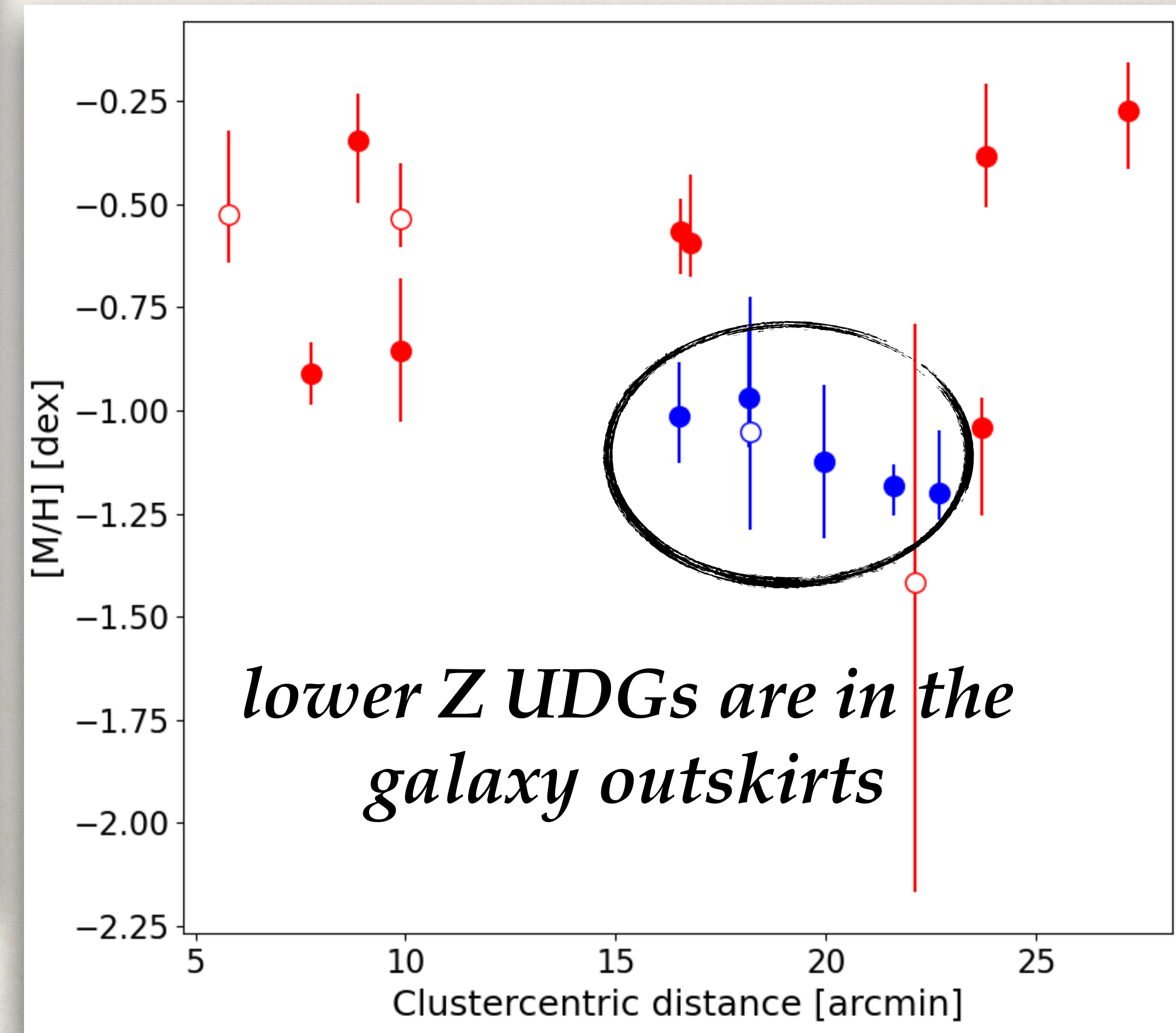
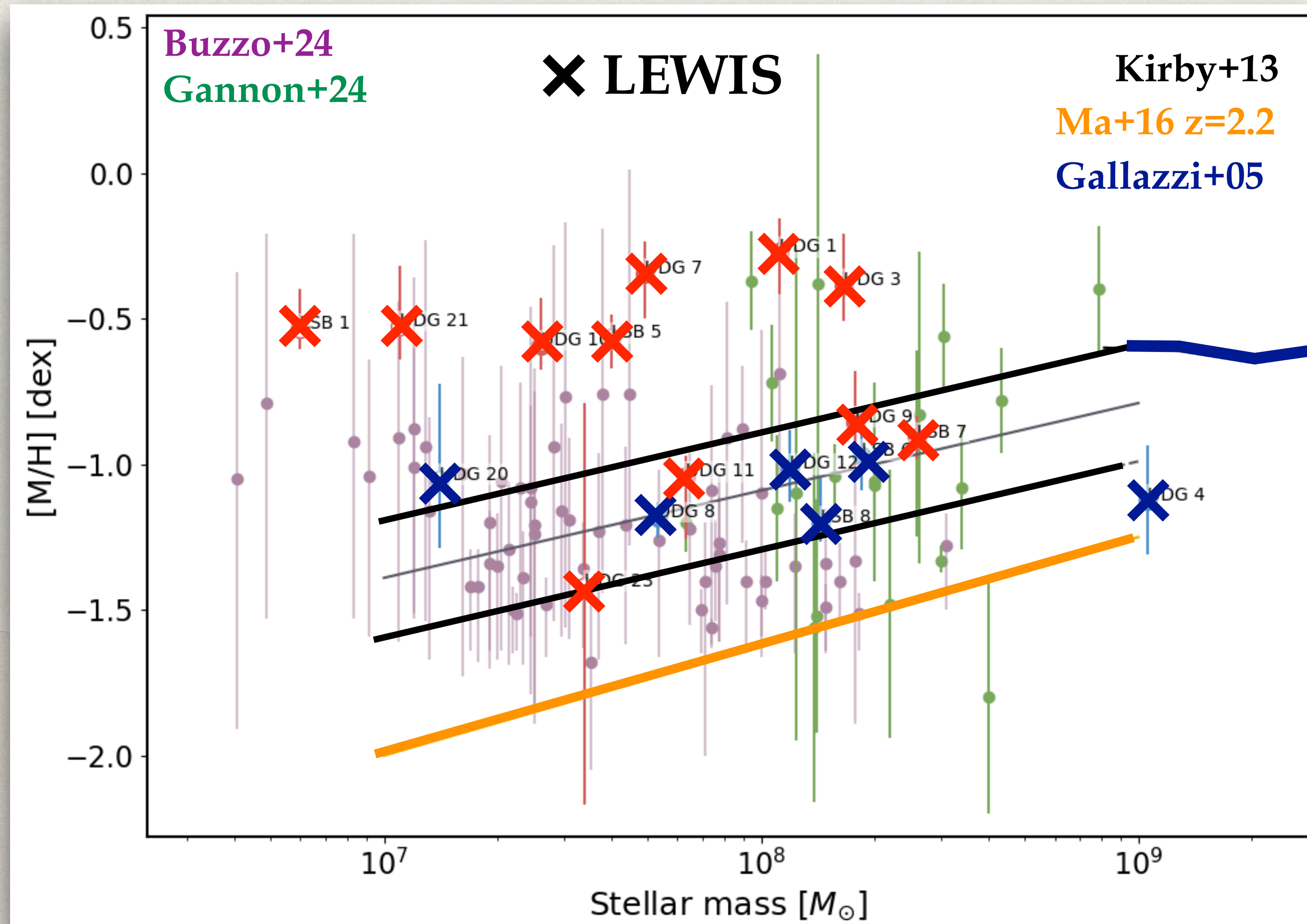


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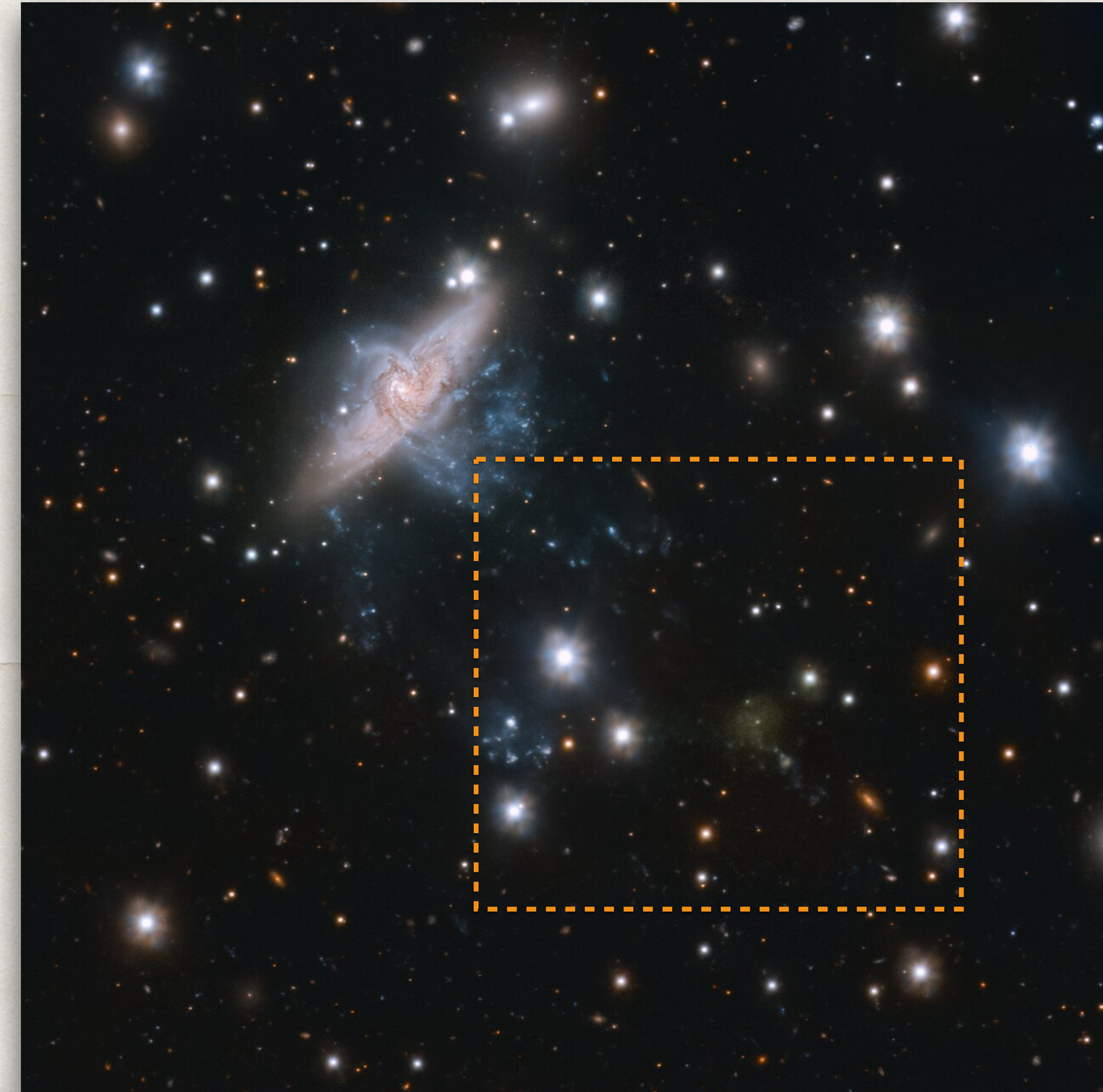


# *Groundbreaking results from LEWIS*

Johanna Hartke+2024,  
A&A sub.



## IV. On the formation channels for UDGs



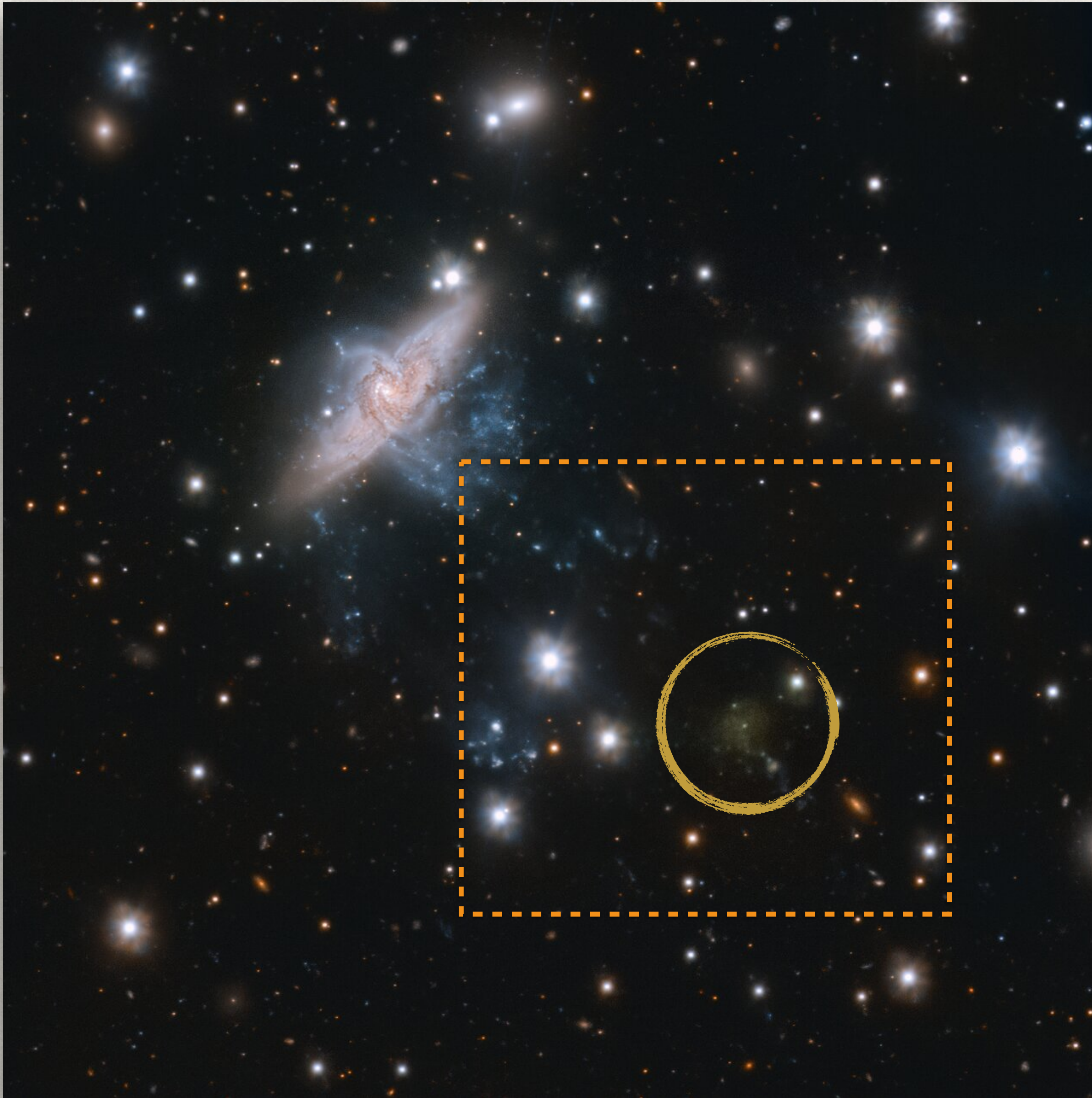


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A&A sub.



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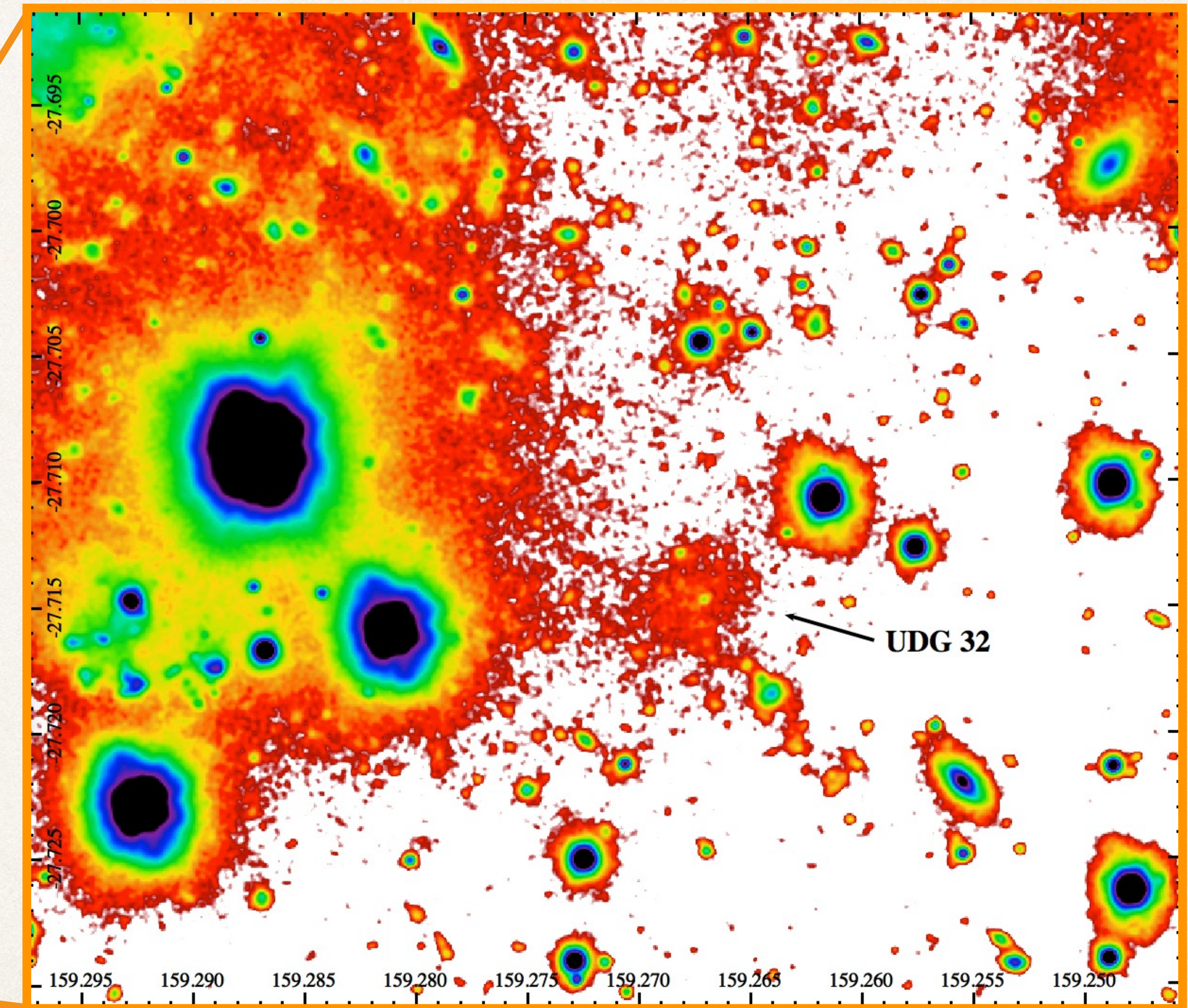
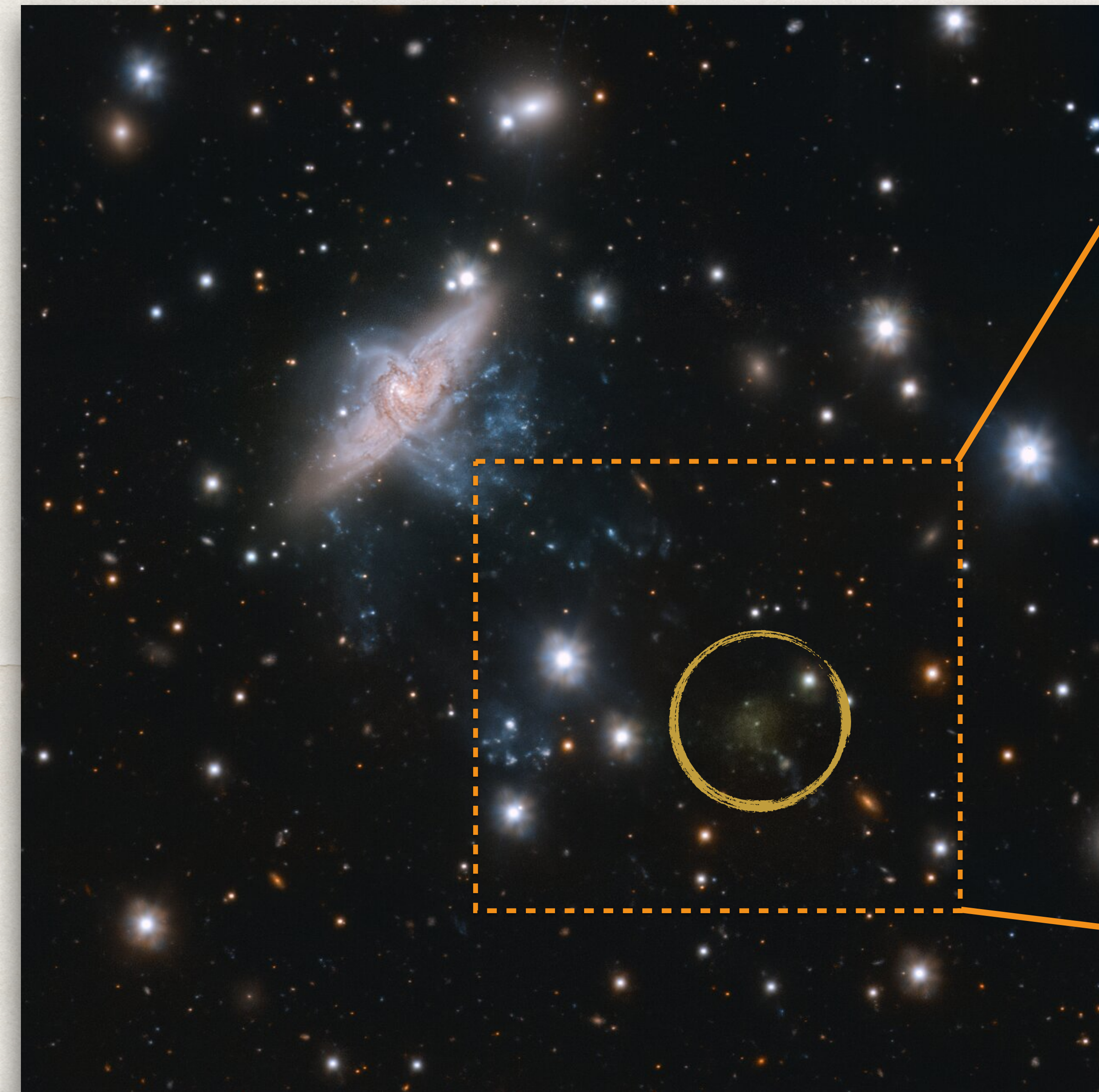


# Groundbreaking results from LEWIS

Johanna Hartke+2024,  
A&A sub.



## IV. On the formation channels for UDGs



$$\mu^0_g = 26 \pm 1 \text{ mag/arcsec}^2$$

$$R_e \sim 4 \pm 1 \text{ kpc}$$



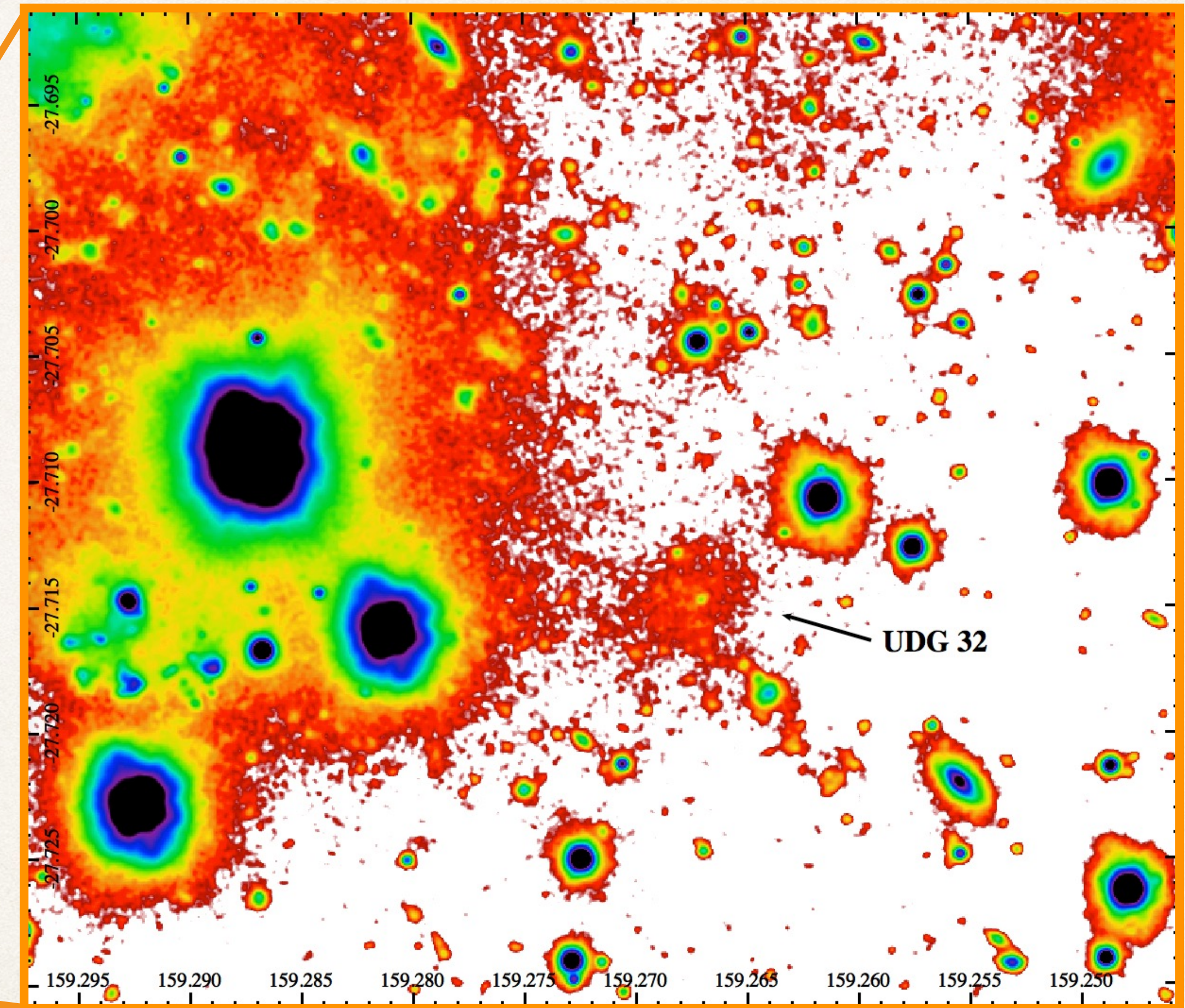
# Groundbreaking results from LEWIS

Johanna Hartke+2024,  
A&A sub.



## IV. On the formation channels for UDGs

*Is UDG32 formed from the RPS gas clumps?*



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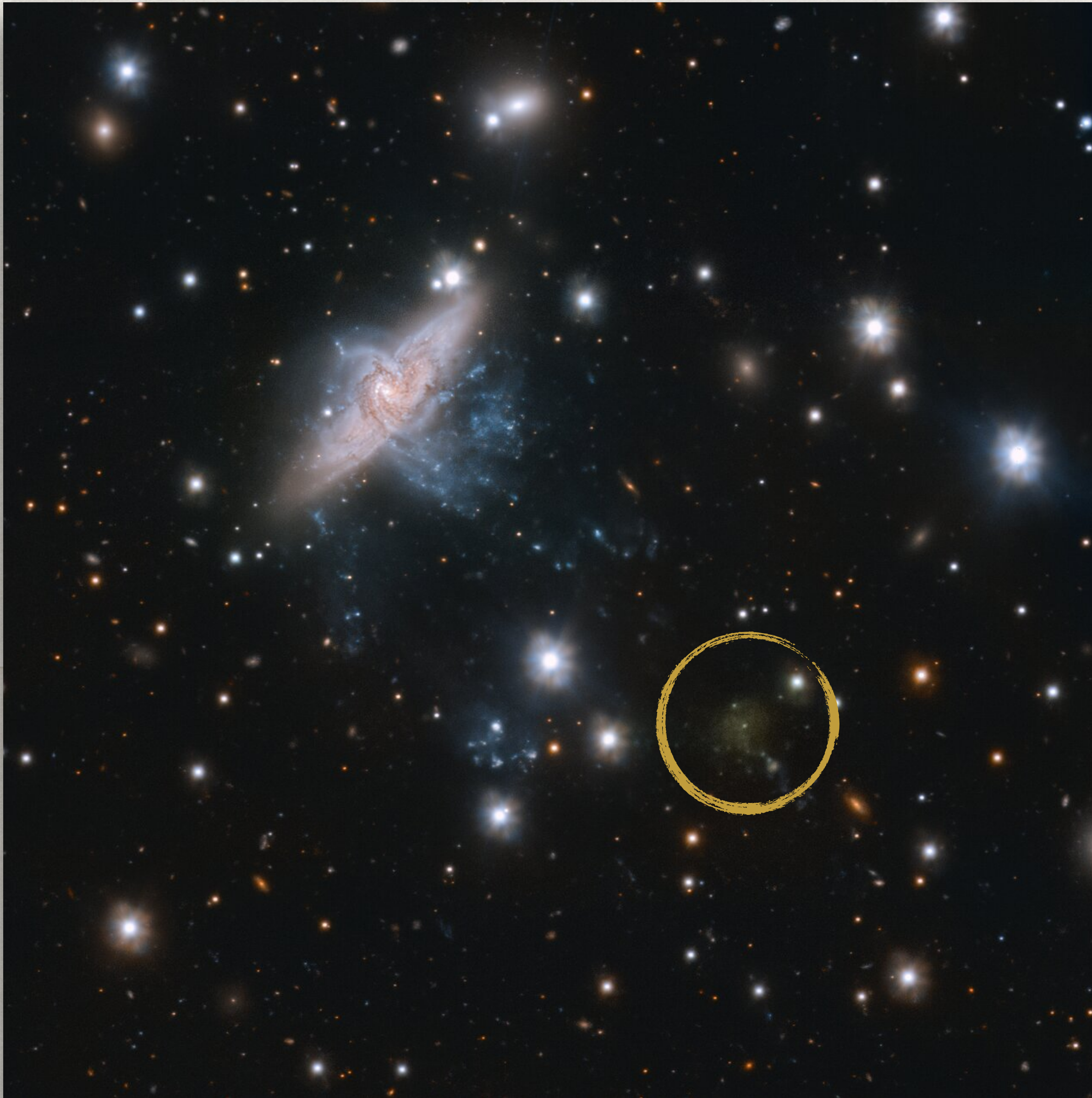
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Johanna Hartke+2024,  
A&A sub.



## IV. On the formation channels for UDGs

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# Groundbreaking results from LEWIS

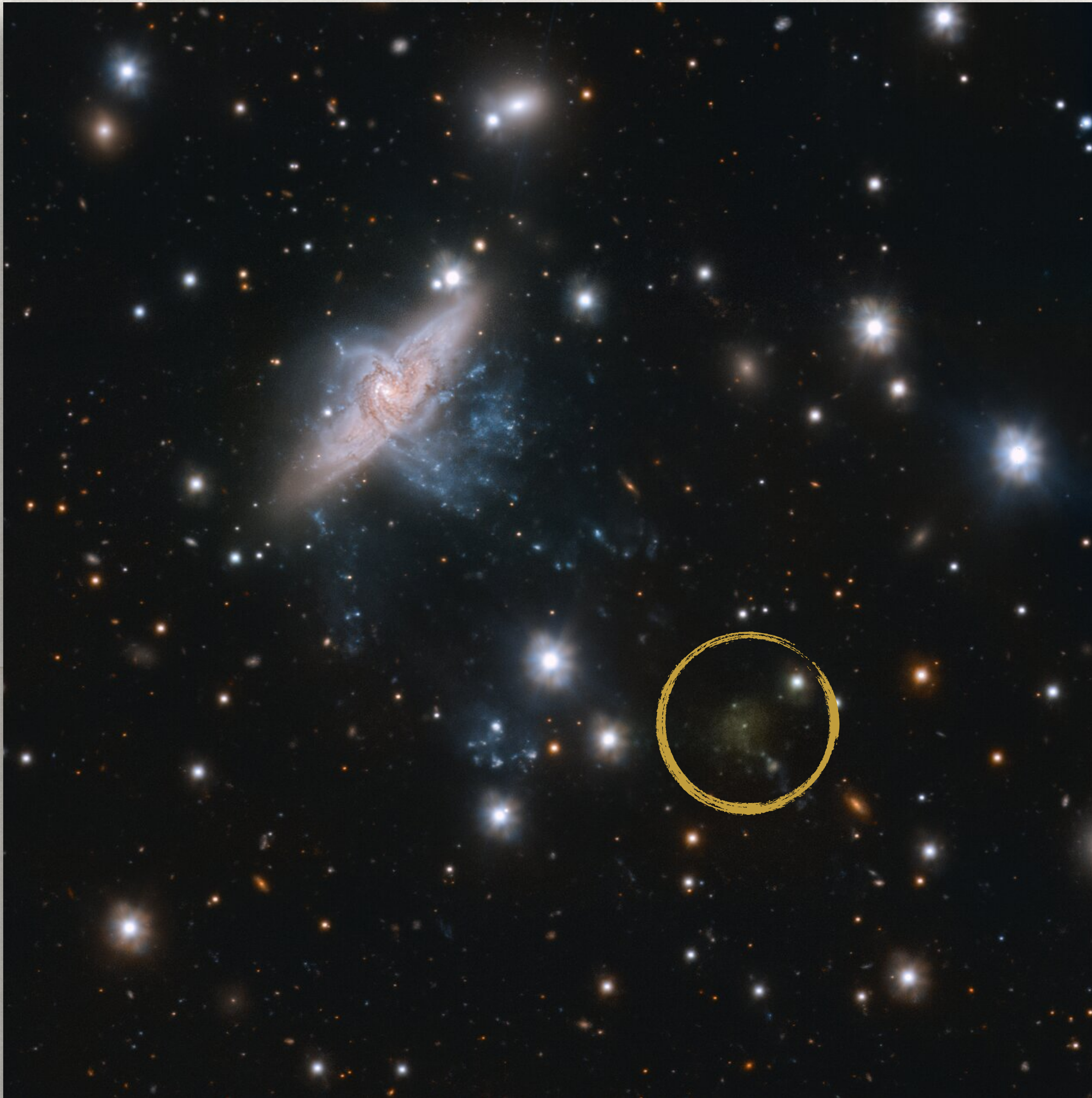
Johanna Hartke+2024,  
A&A sub.



## IV. On the formation channels for UDGs

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Expected properties:





# Groundbreaking results from LEWIS

Johanna Hartke+2024,  
A&A sub.

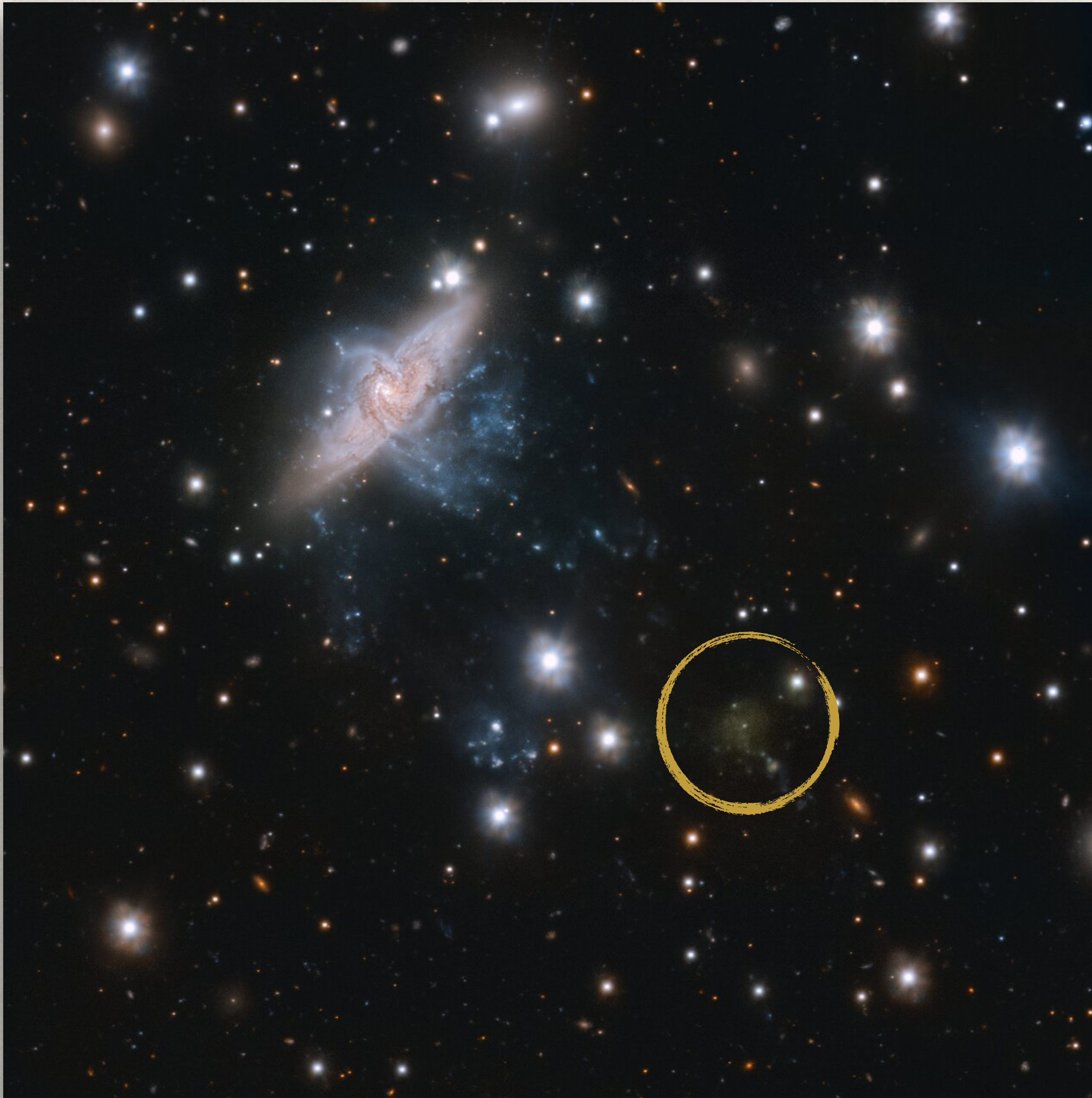


## IV. On the formation channels for UDGs

*Is UDG32 formed from the RPS gas clumps?*

**Expected properties:**

► *co-spatial with filaments*





# Groundbreaking results from LEWIS

Johanna Hartke+2024,  
A&A sub.

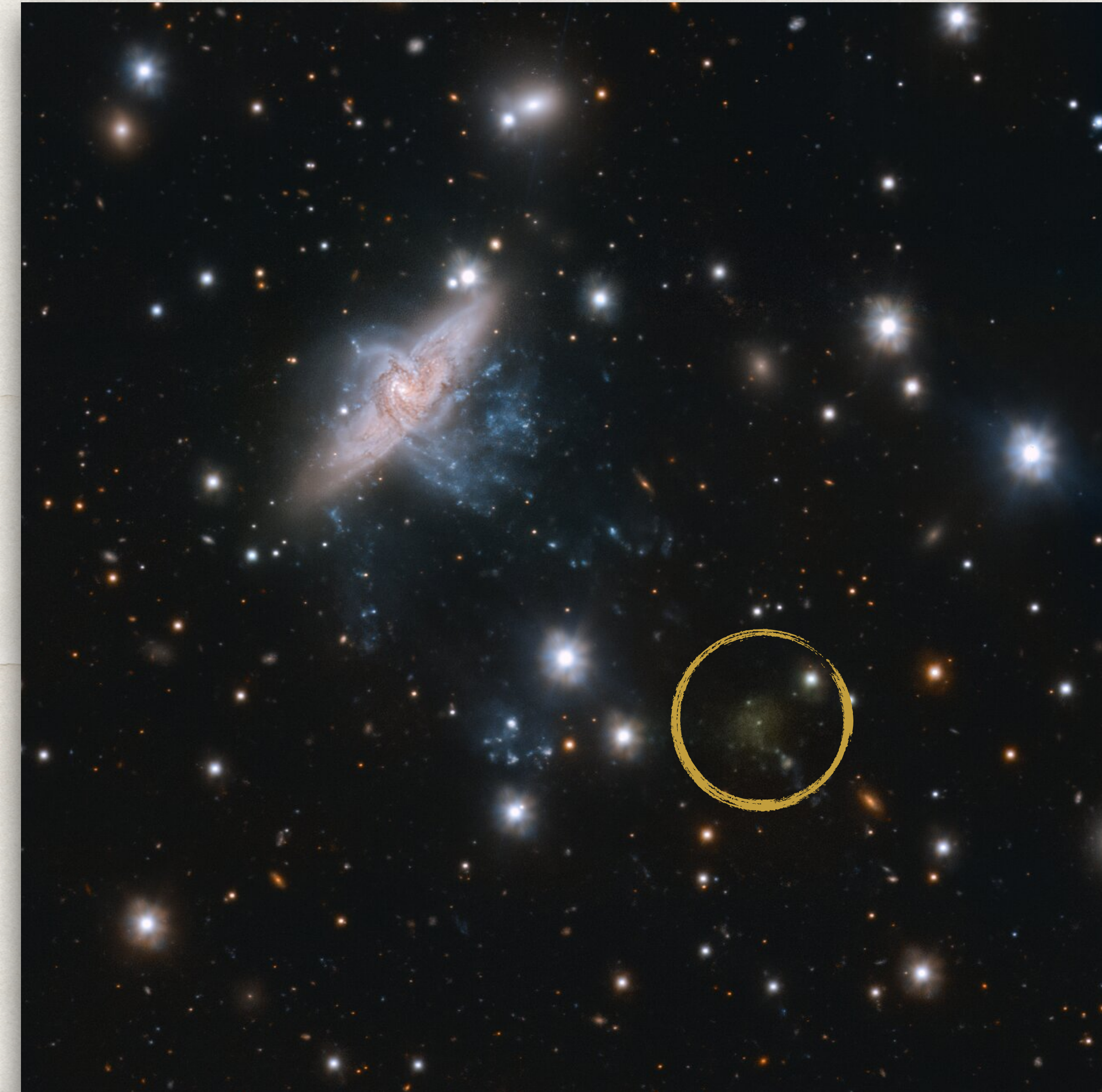


## IV. On the formation channels for UDGs

*Is UDG32 formed from the RPS gas clumps?*

**Expected properties:**

- ▶ *co-spatial with filaments*
- ▶ *younger age & higher  $Z$  than typical UDGs*





# Groundbreaking results from LEWIS

Johanna Hartke+2024,  
A&A sub.

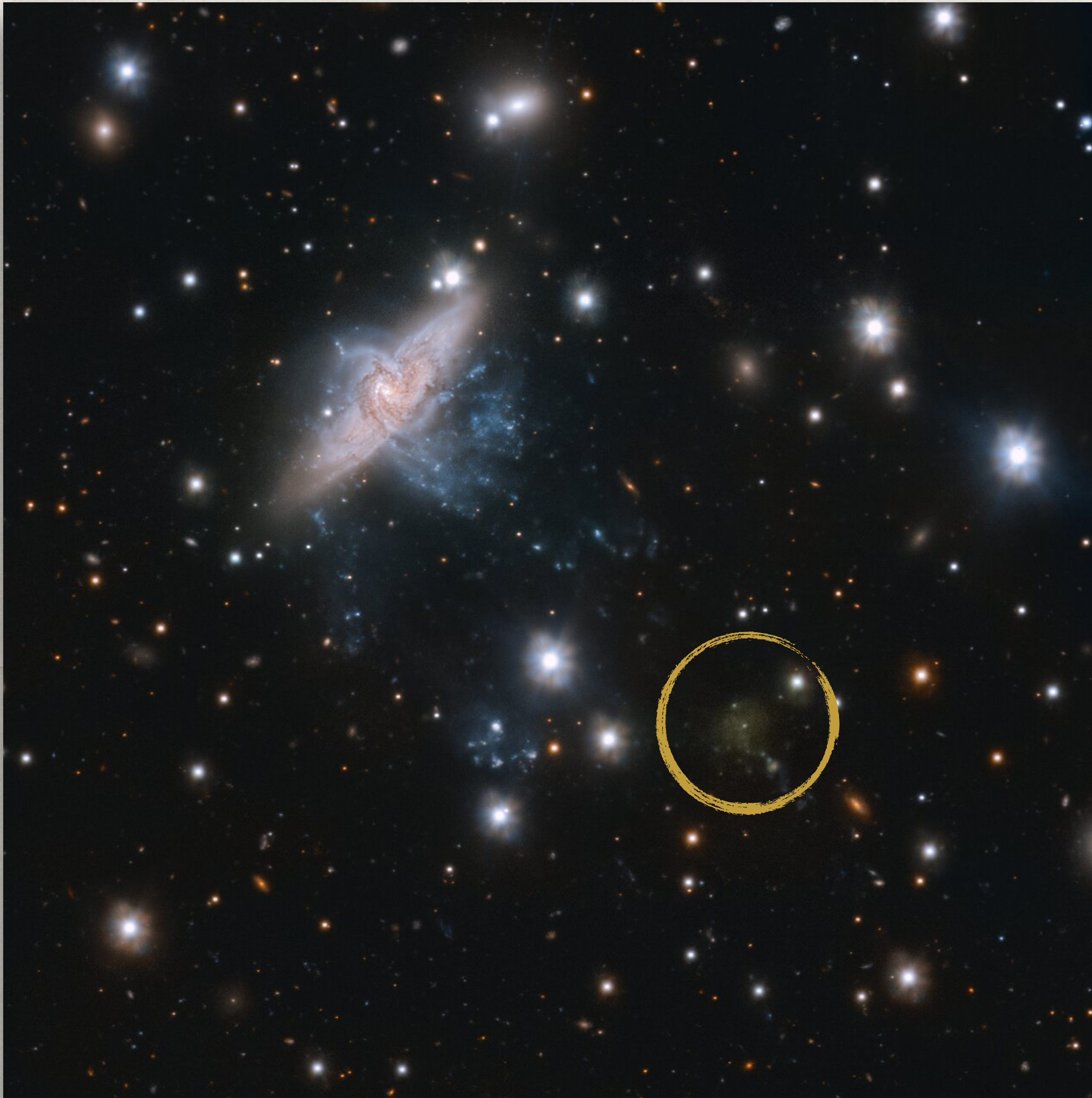


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*Is UDG32 formed from the RPS gas clumps?*

### Expected properties:

- ▶ *co-spatial with filaments*
- ▶ *younger age & higher  $Z$  than typical UDGs*
- ▶ *DM free*





# Groundbreaking results from LEWIS

Johanna Hartke+2024,  
A&A sub.



## IV. On the formation channels for UDGs

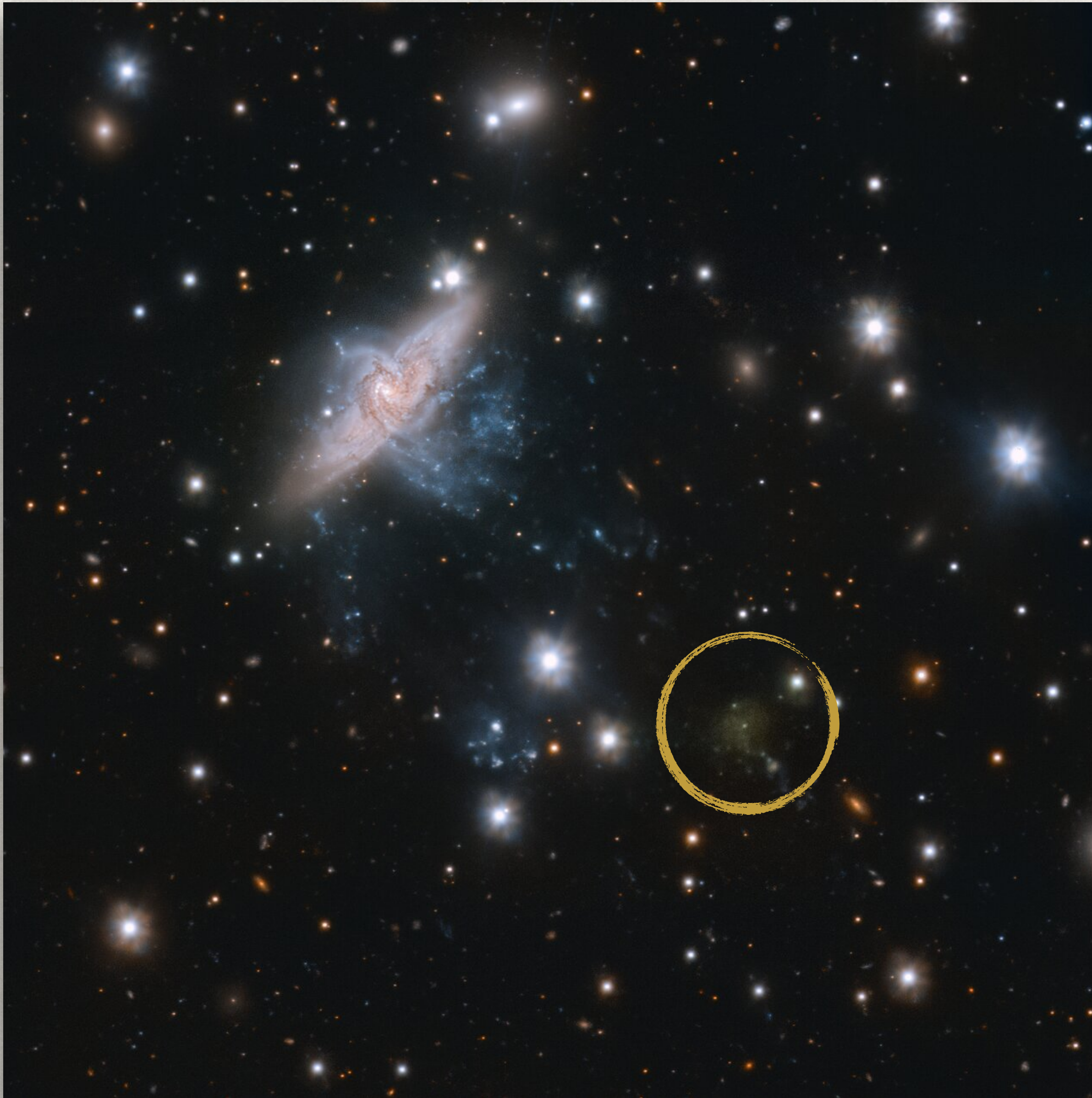
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*from MUSE  
with LEWIS*





# Groundbreaking results from LEWIS

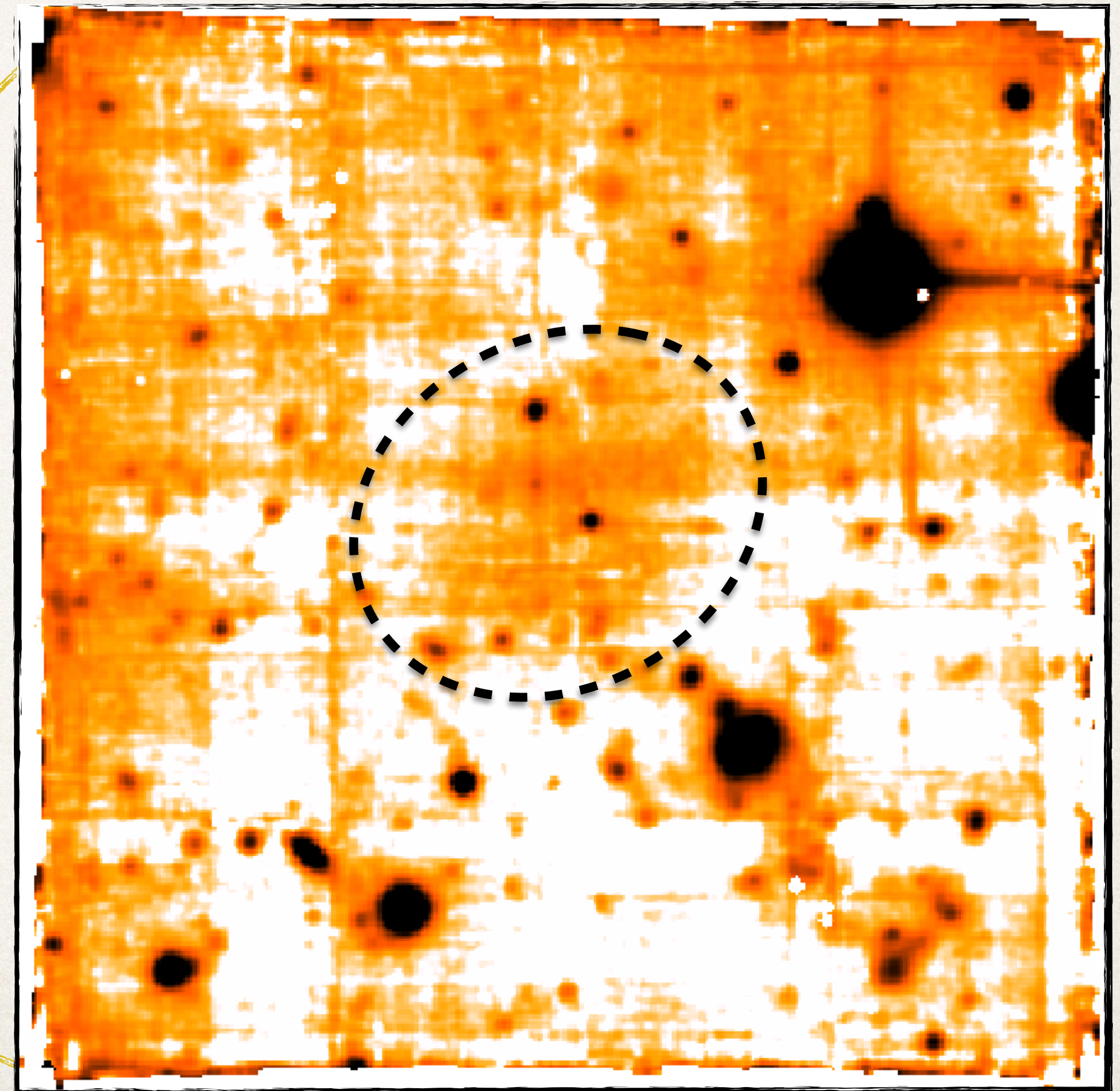
Johanna Hartke+2024,  
A&A sub.



## IV. On the formation channels for UDGs

*Is UDG32 formed from the RPS gas clumps?*

*UDG32 observed with MUSE*





# Groundbreaking results from LEWIS

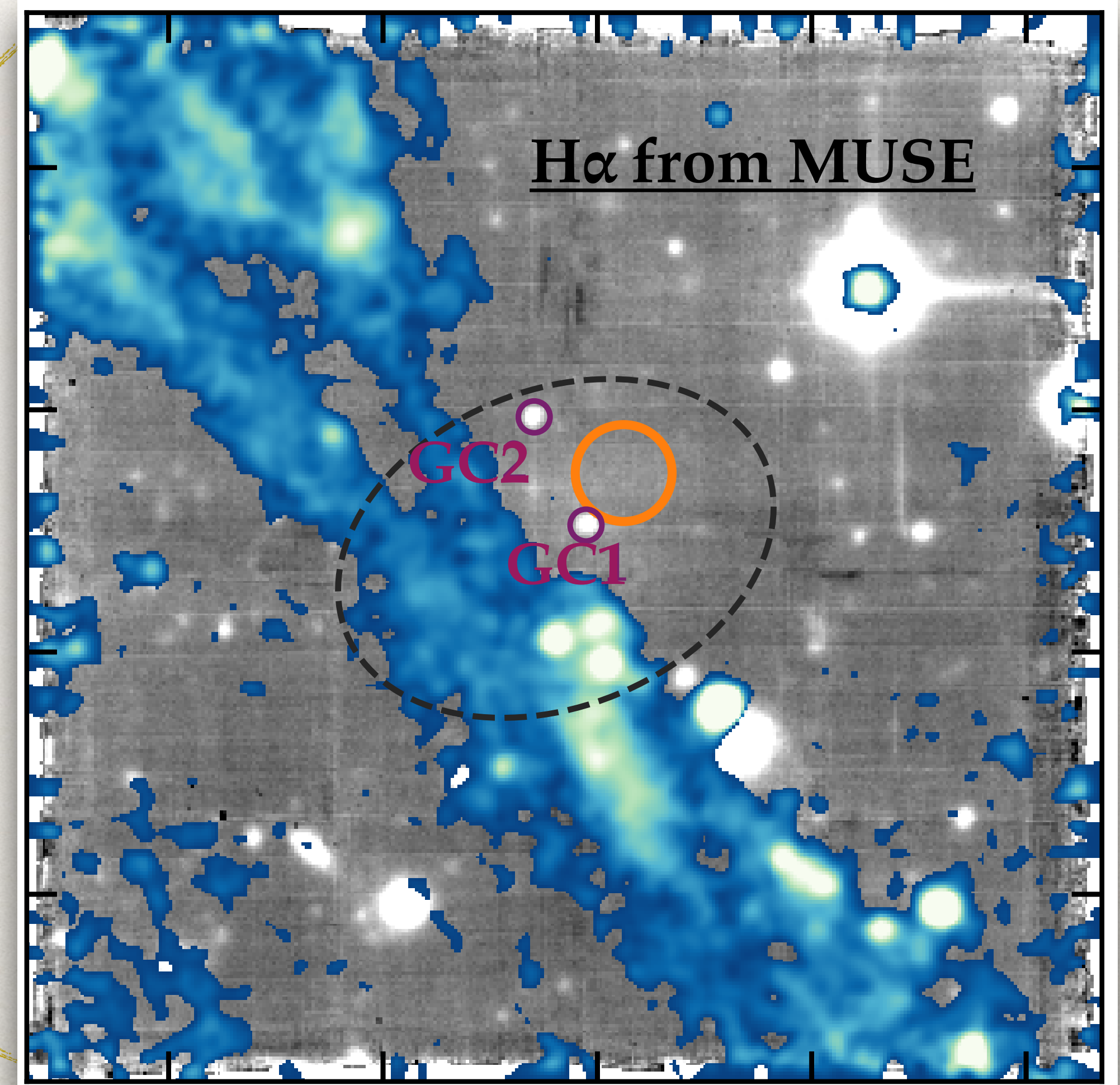
Johanna Hartke+2024,  
A&A sub.



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*UDG32 observed with MUSE*





# Groundbreaking results from LEWIS

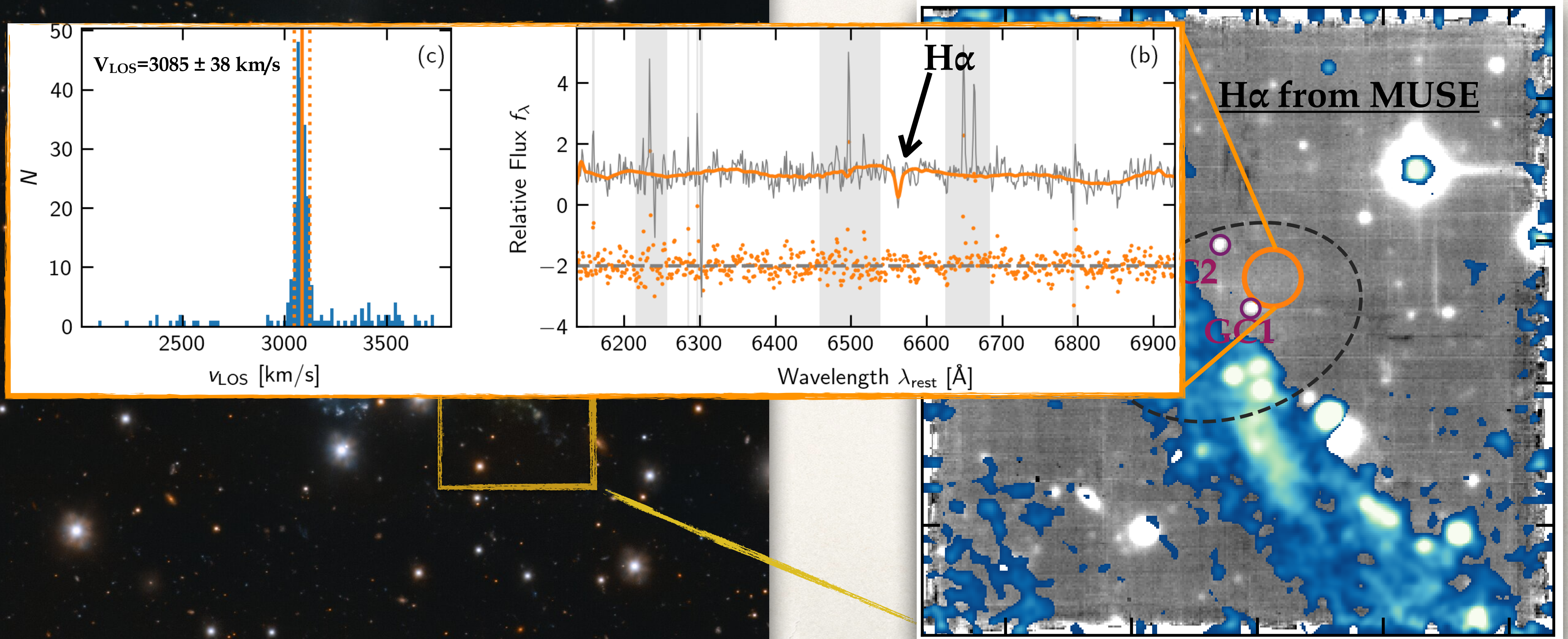
Johanna Hartke+2024,  
A&A sub.



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*UDG32 observed with MUSE*





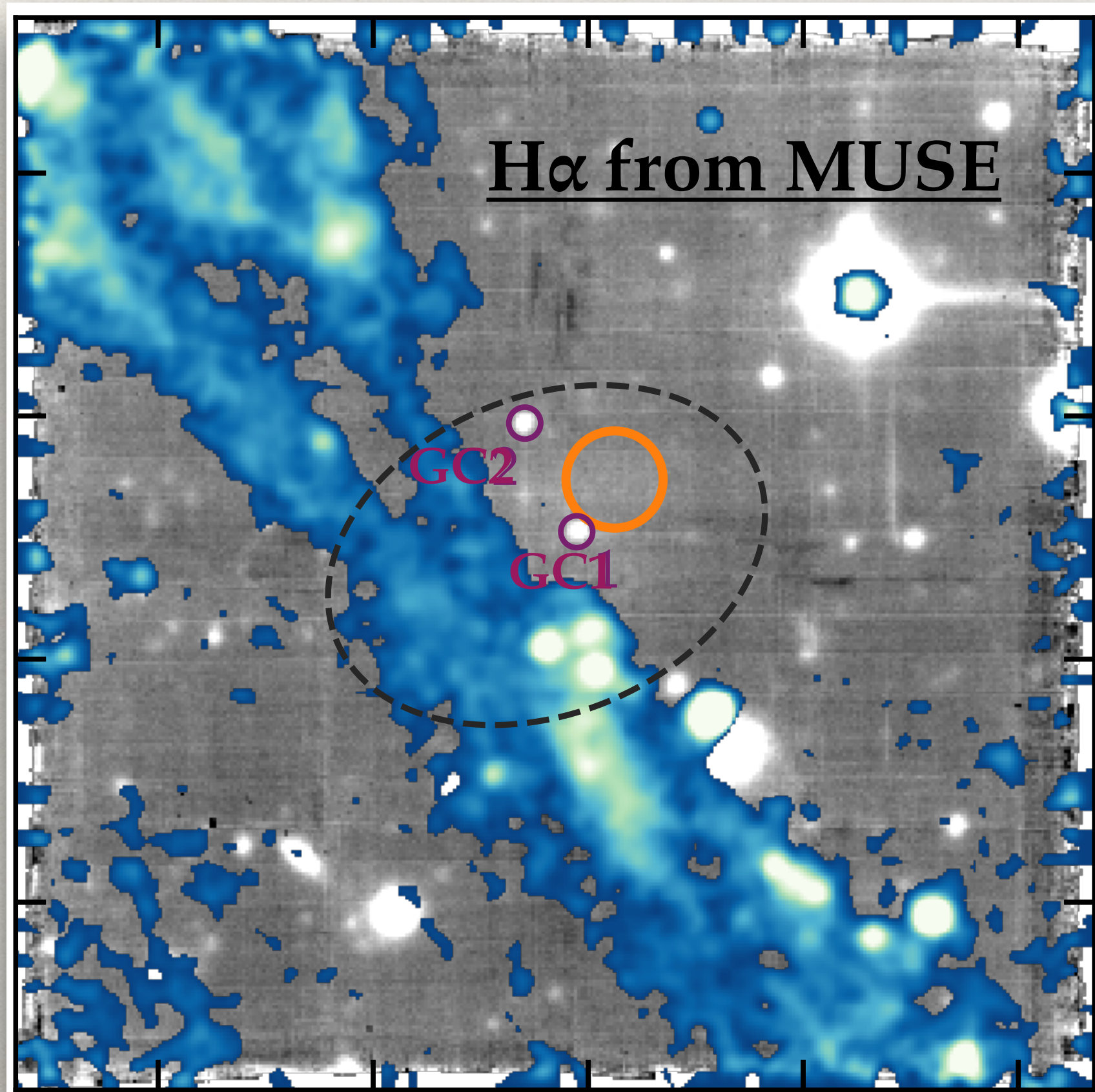
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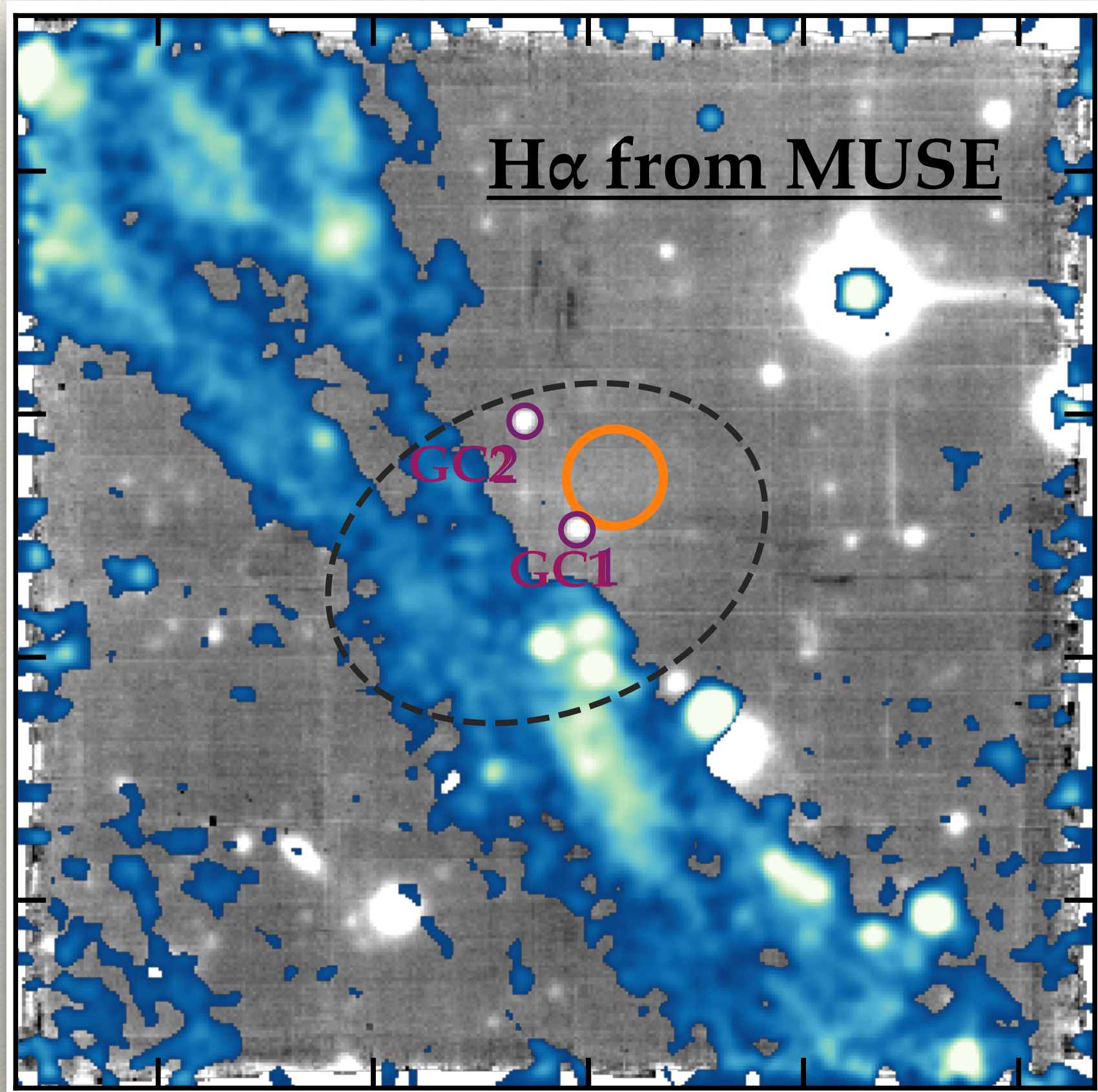
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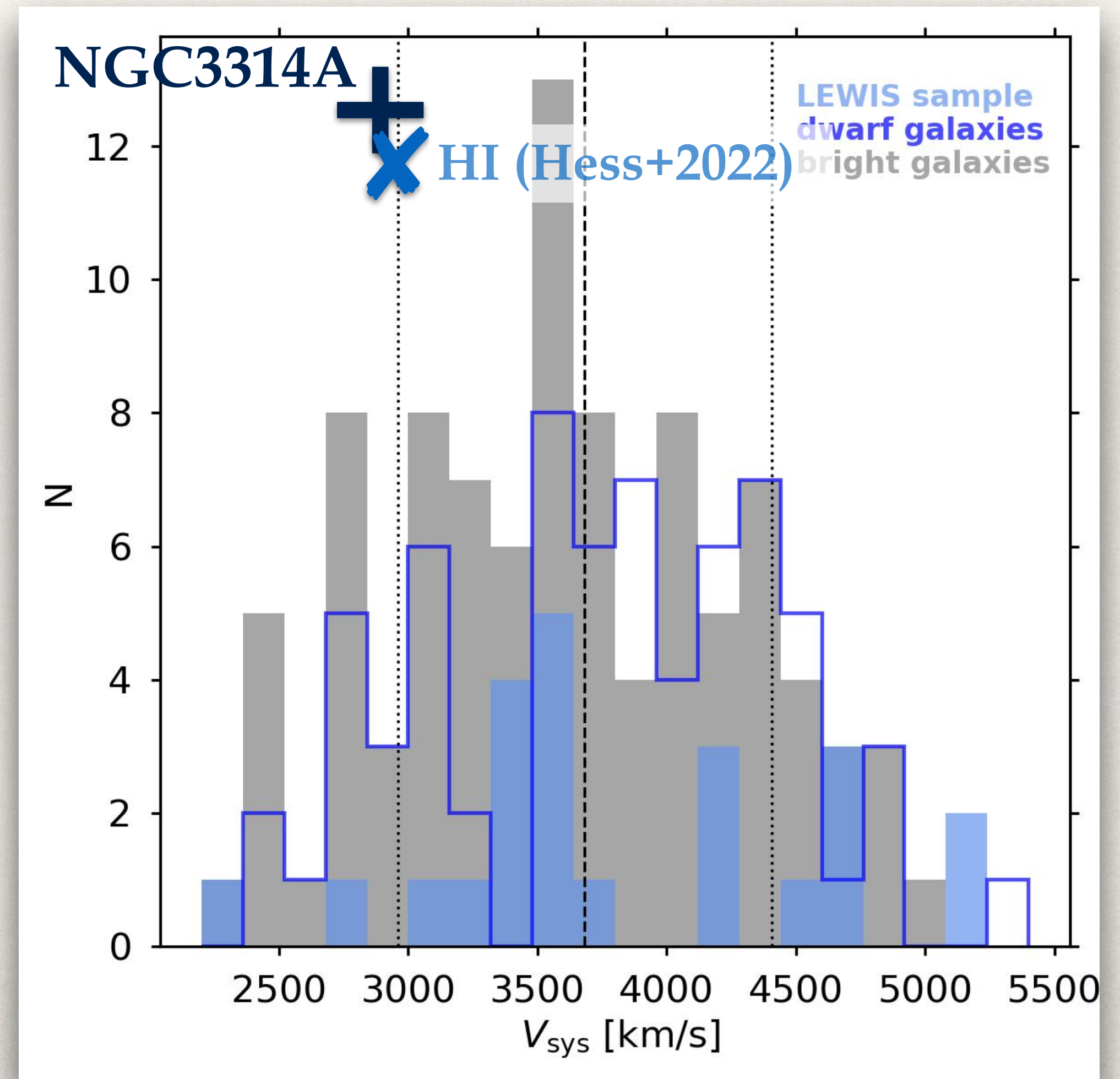
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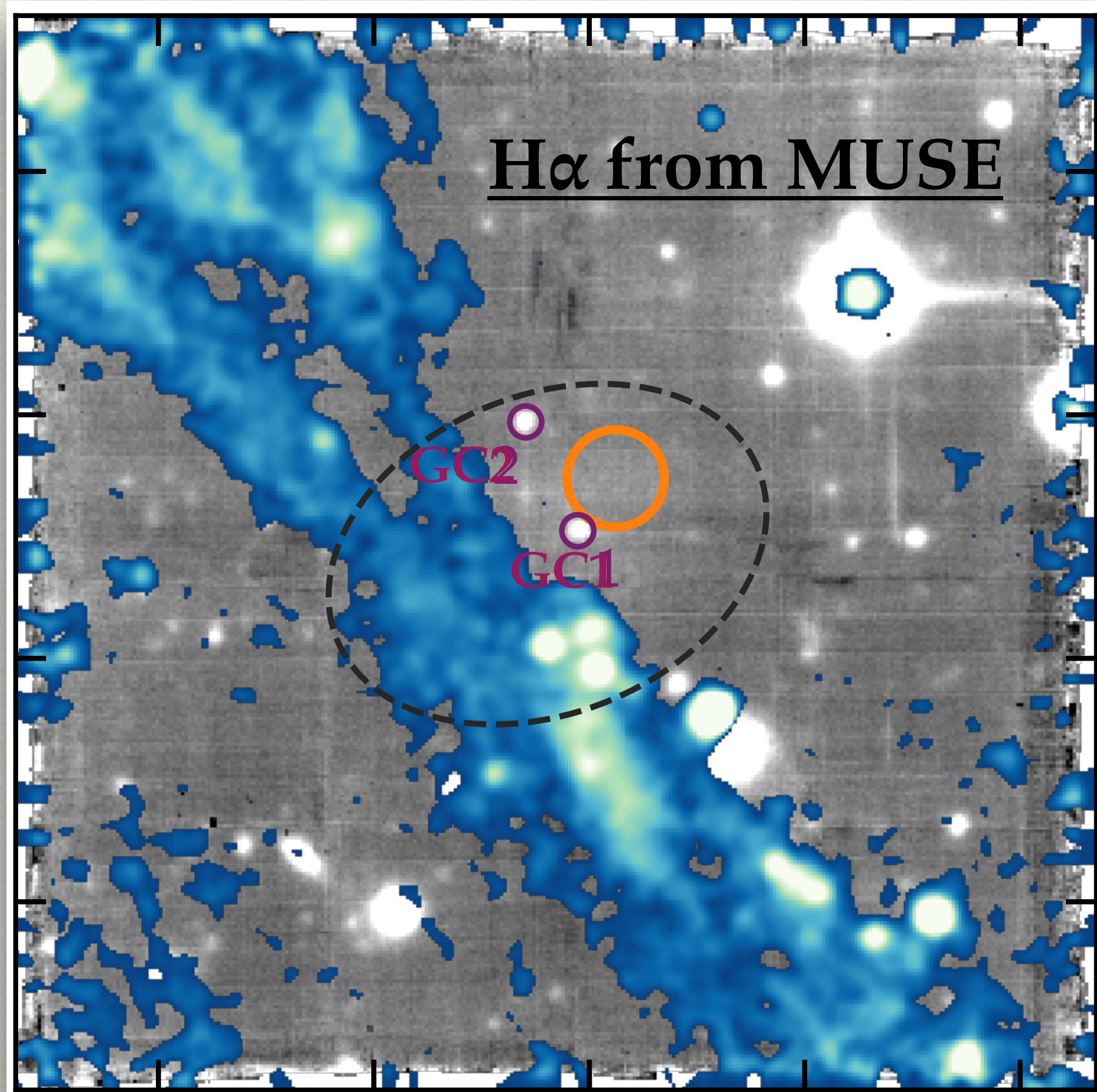
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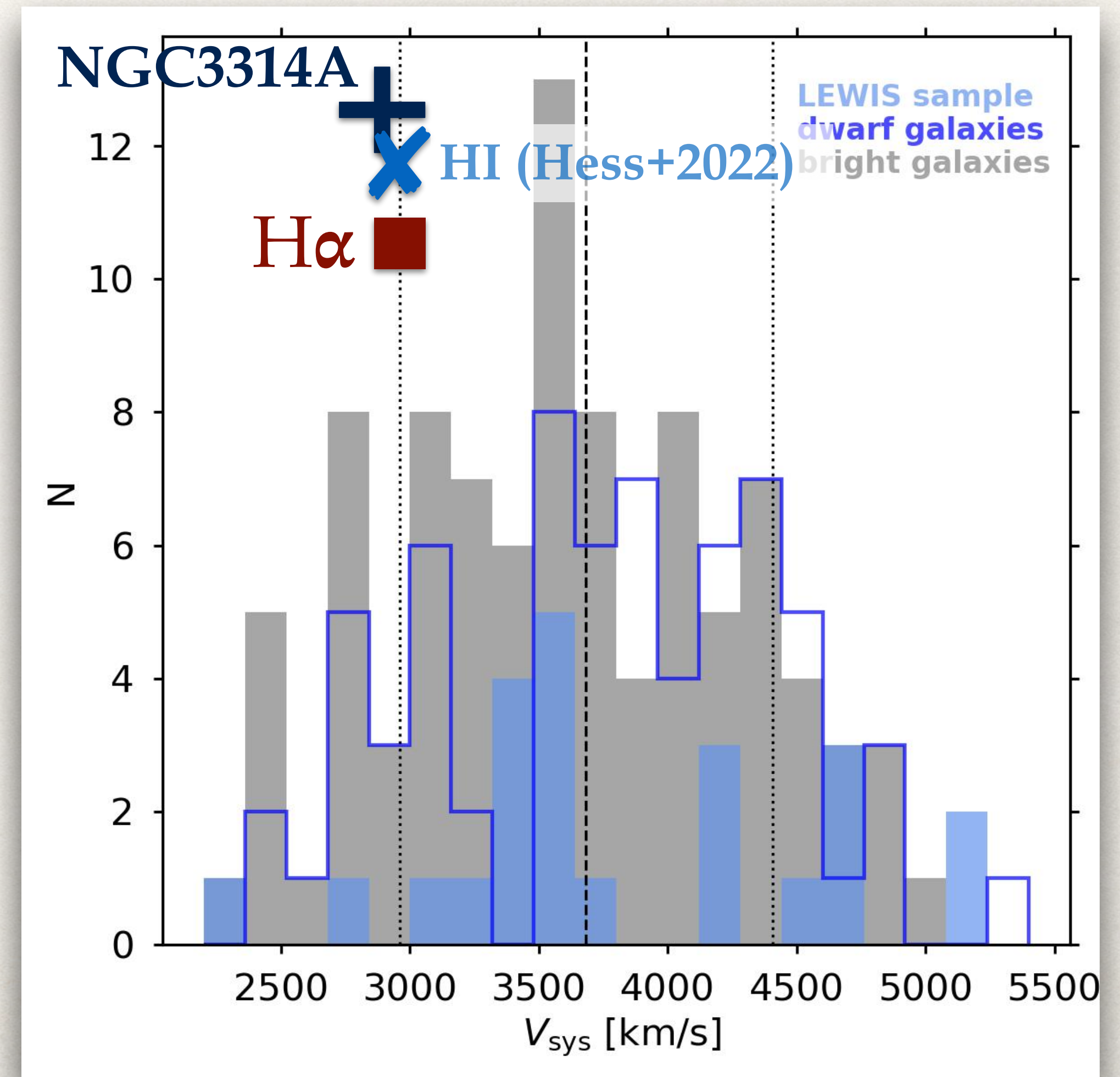
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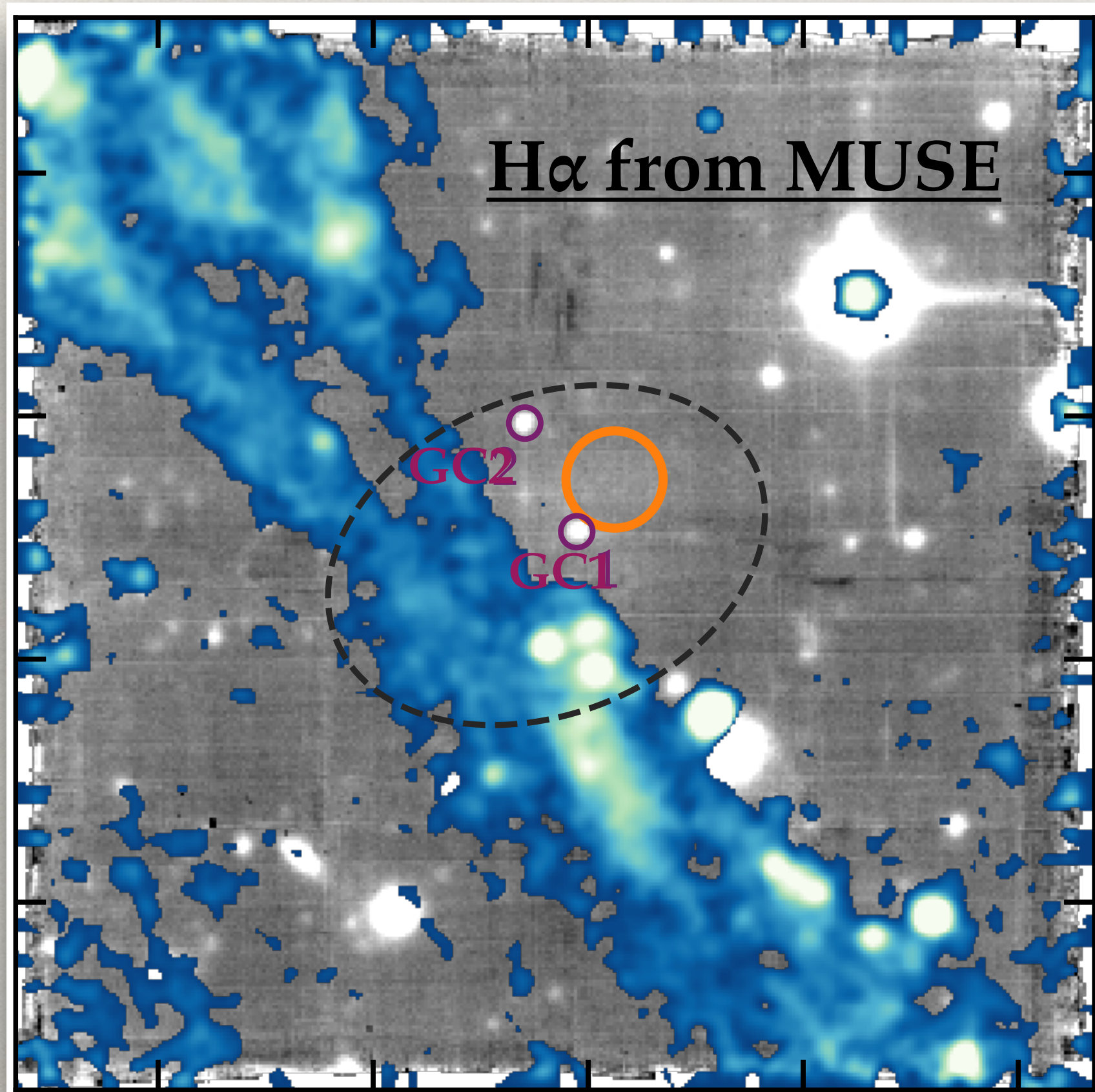
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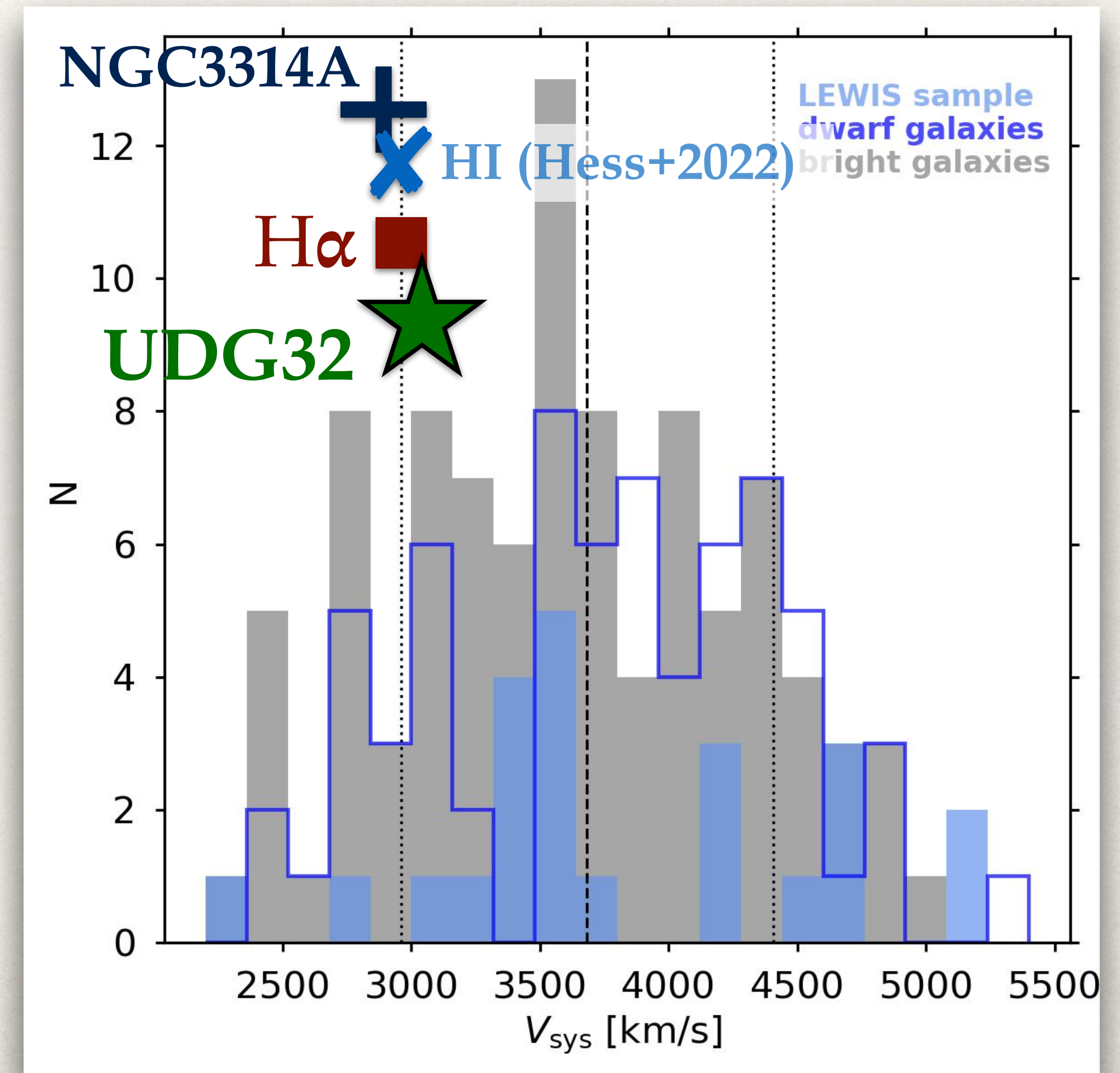
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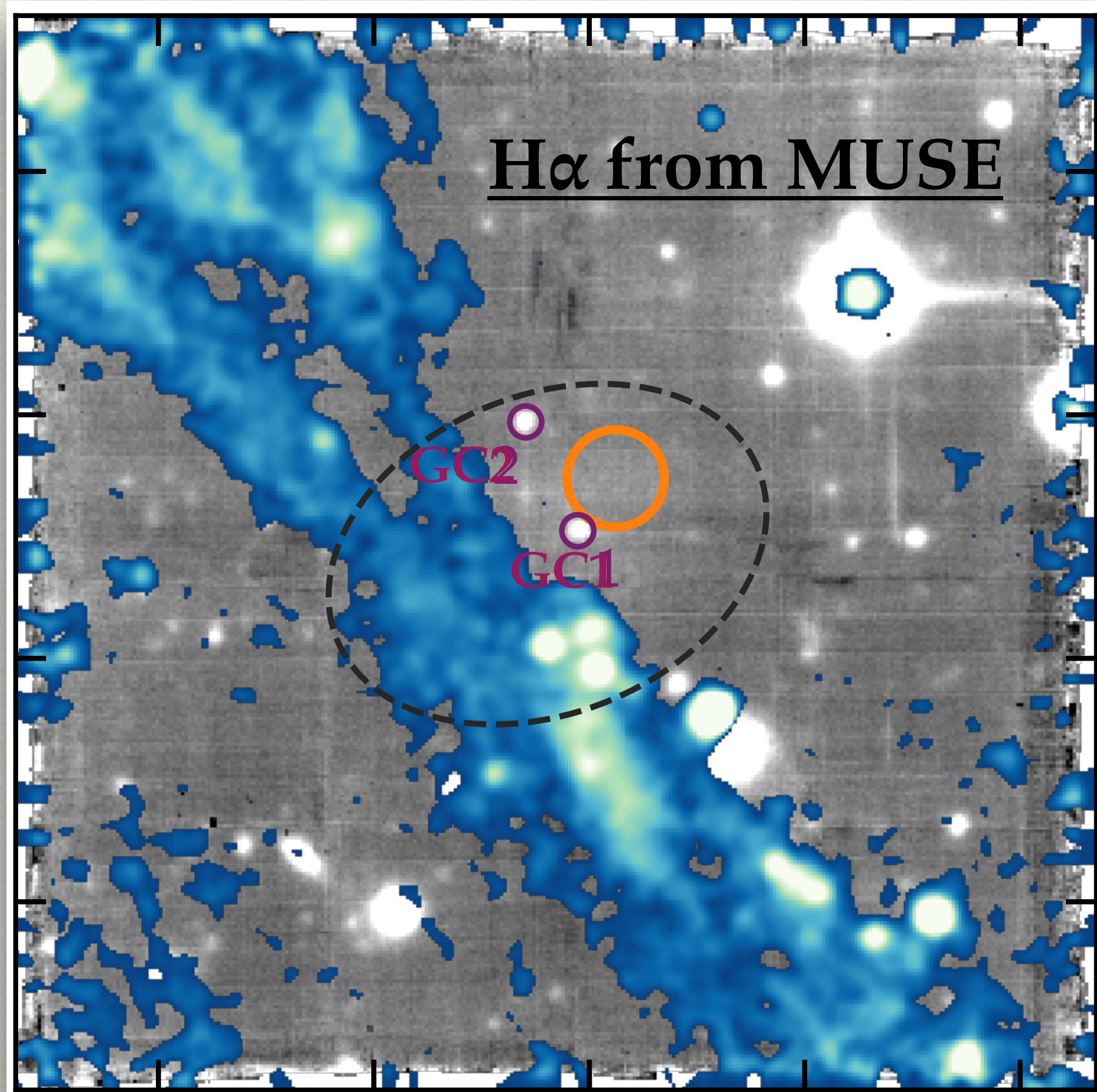
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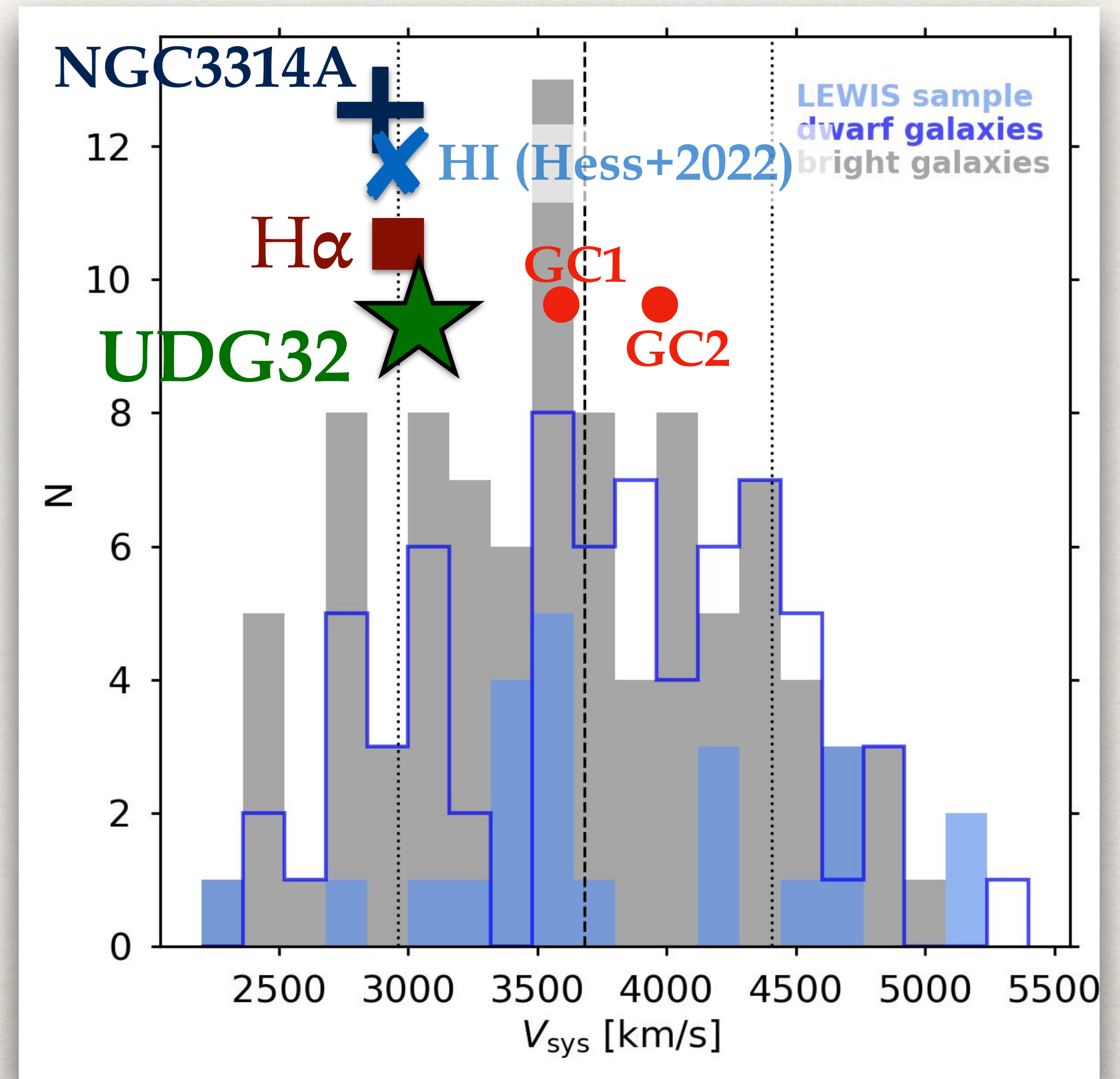
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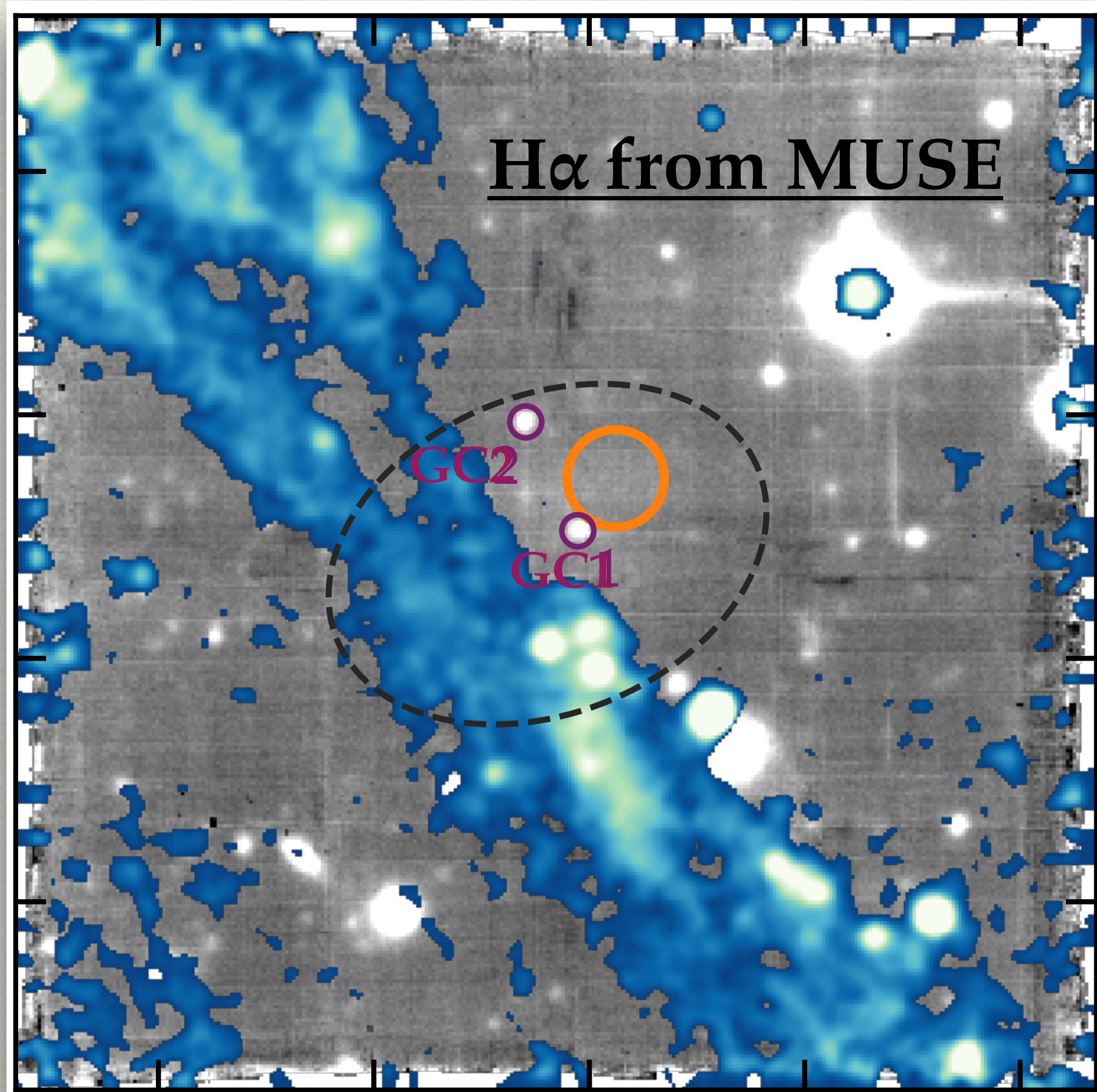
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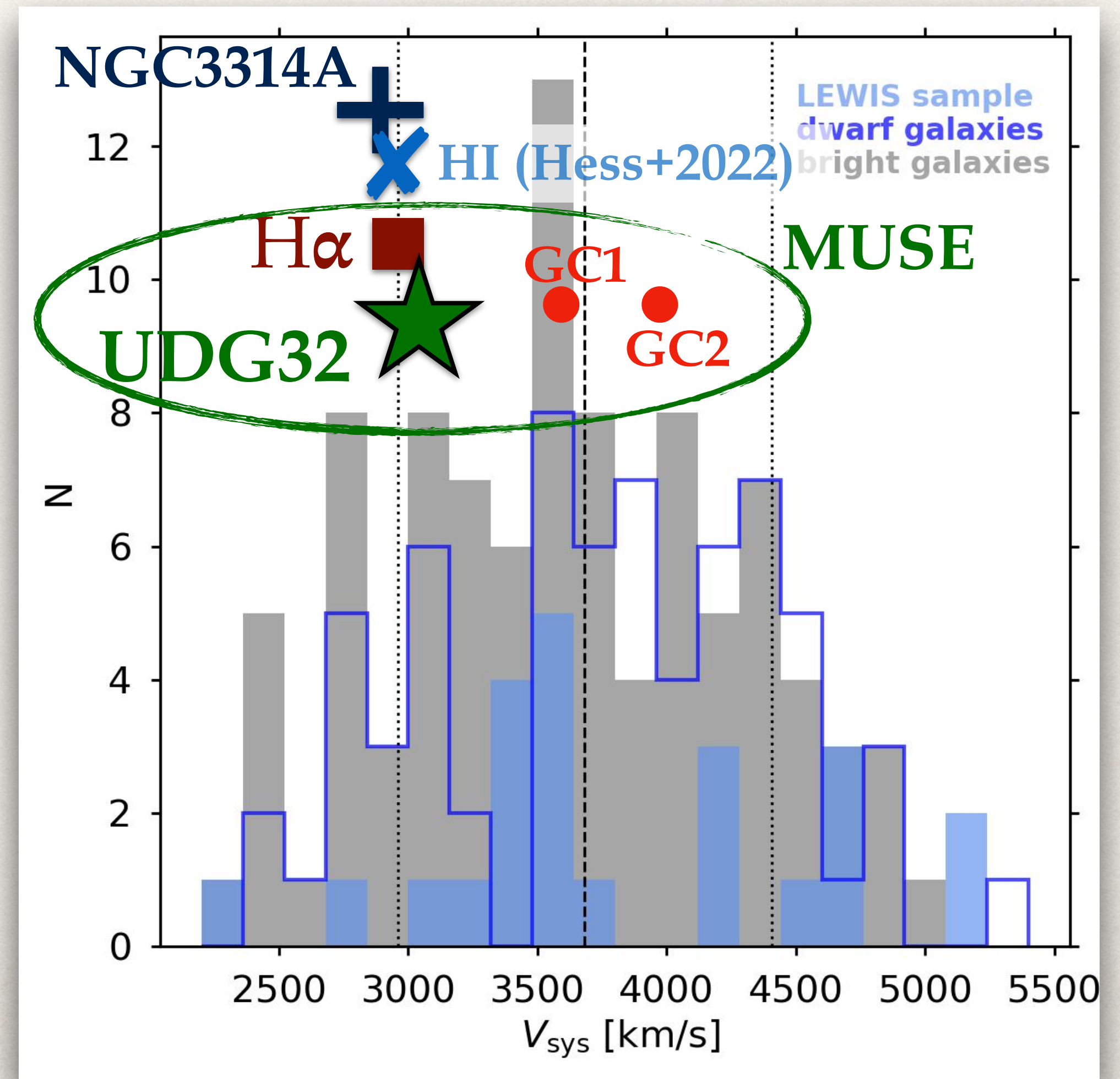
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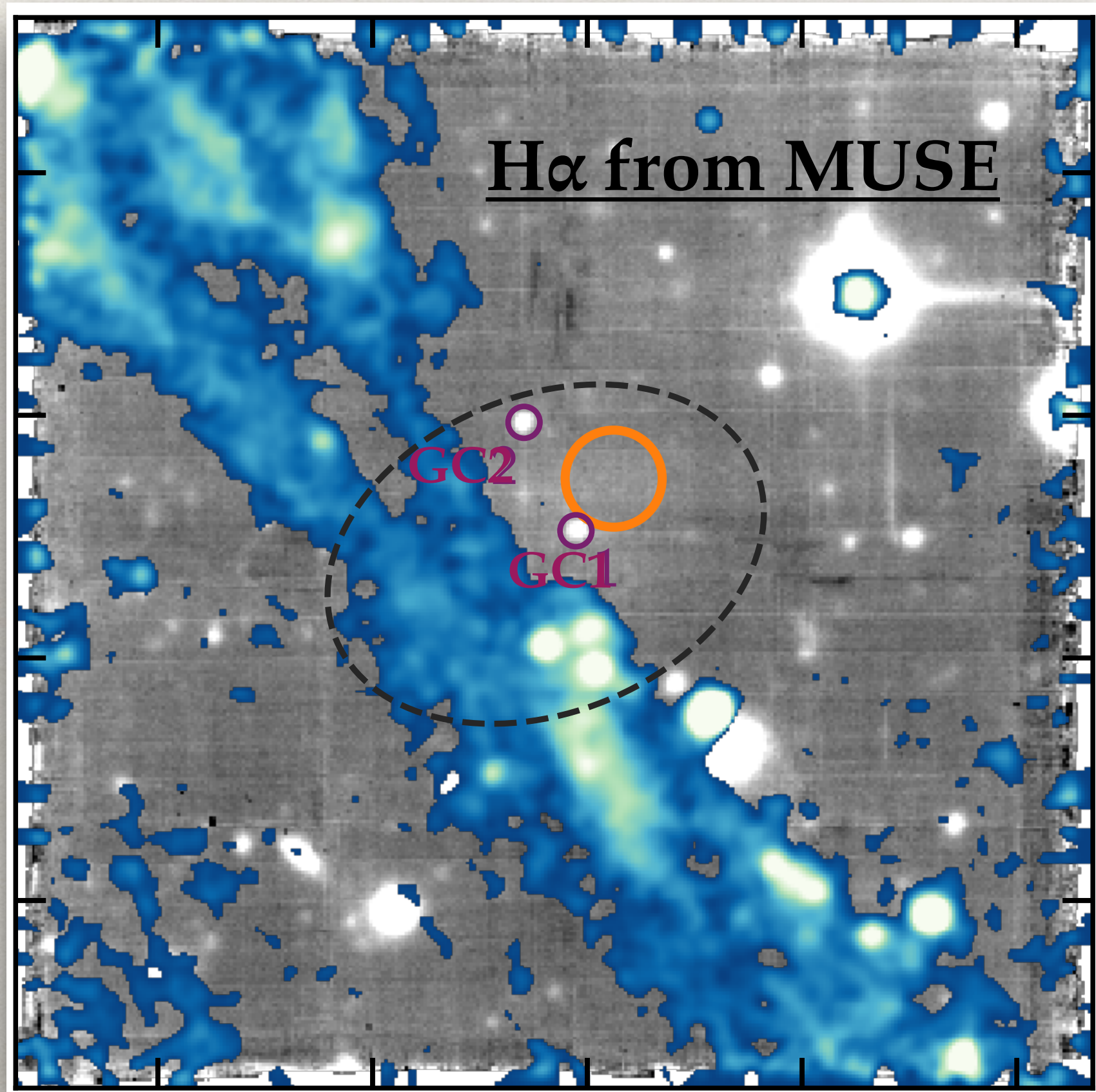
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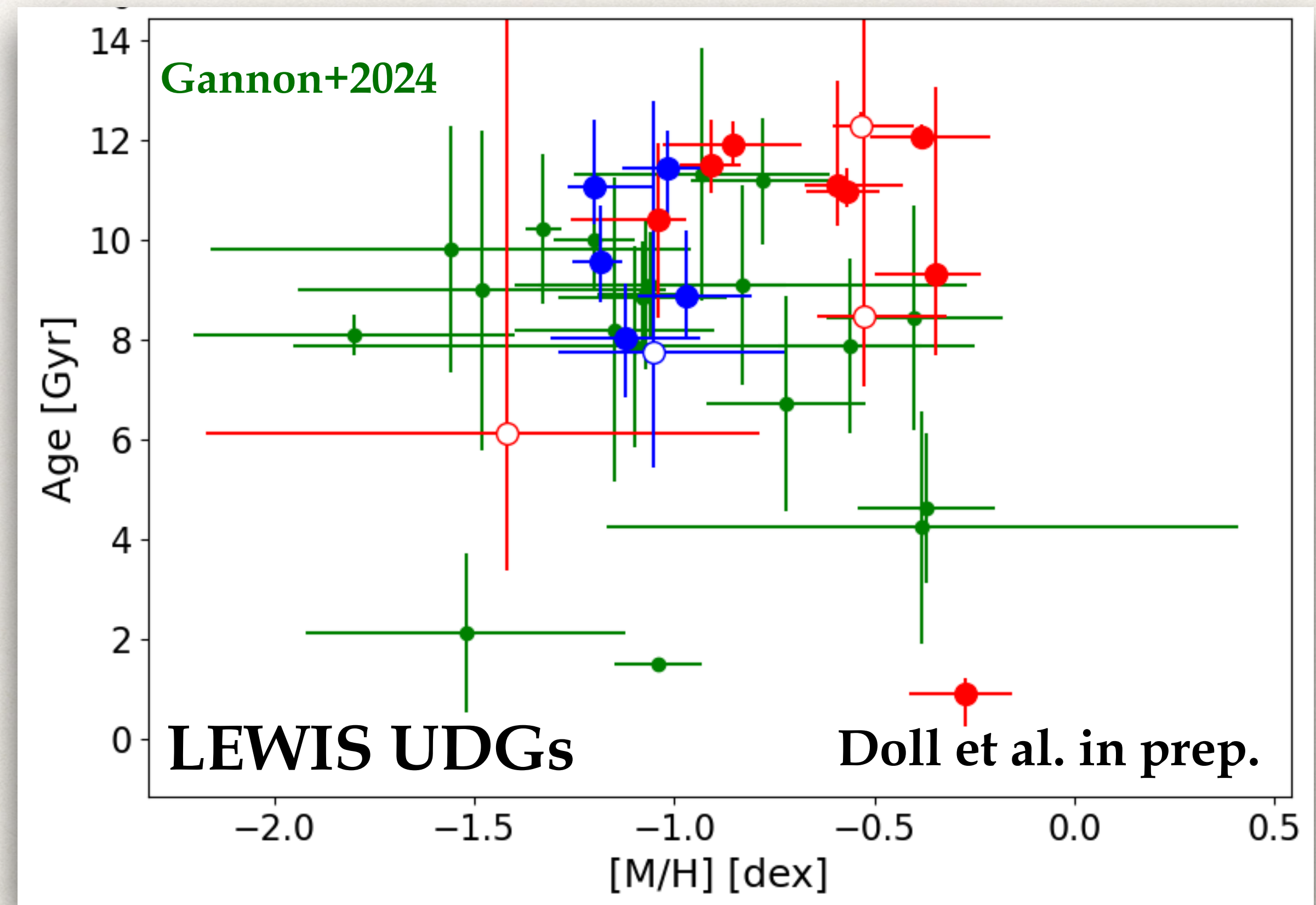
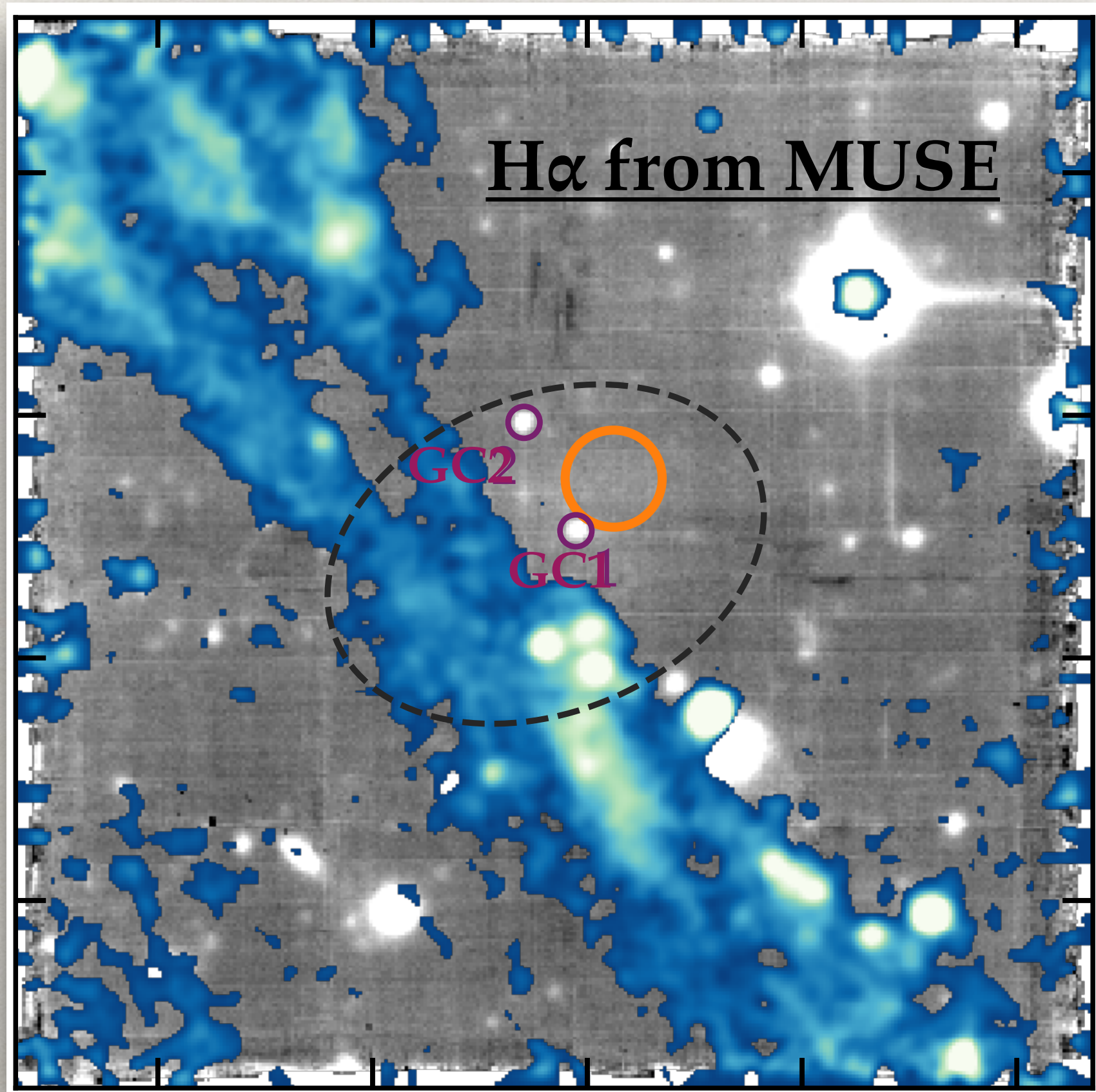
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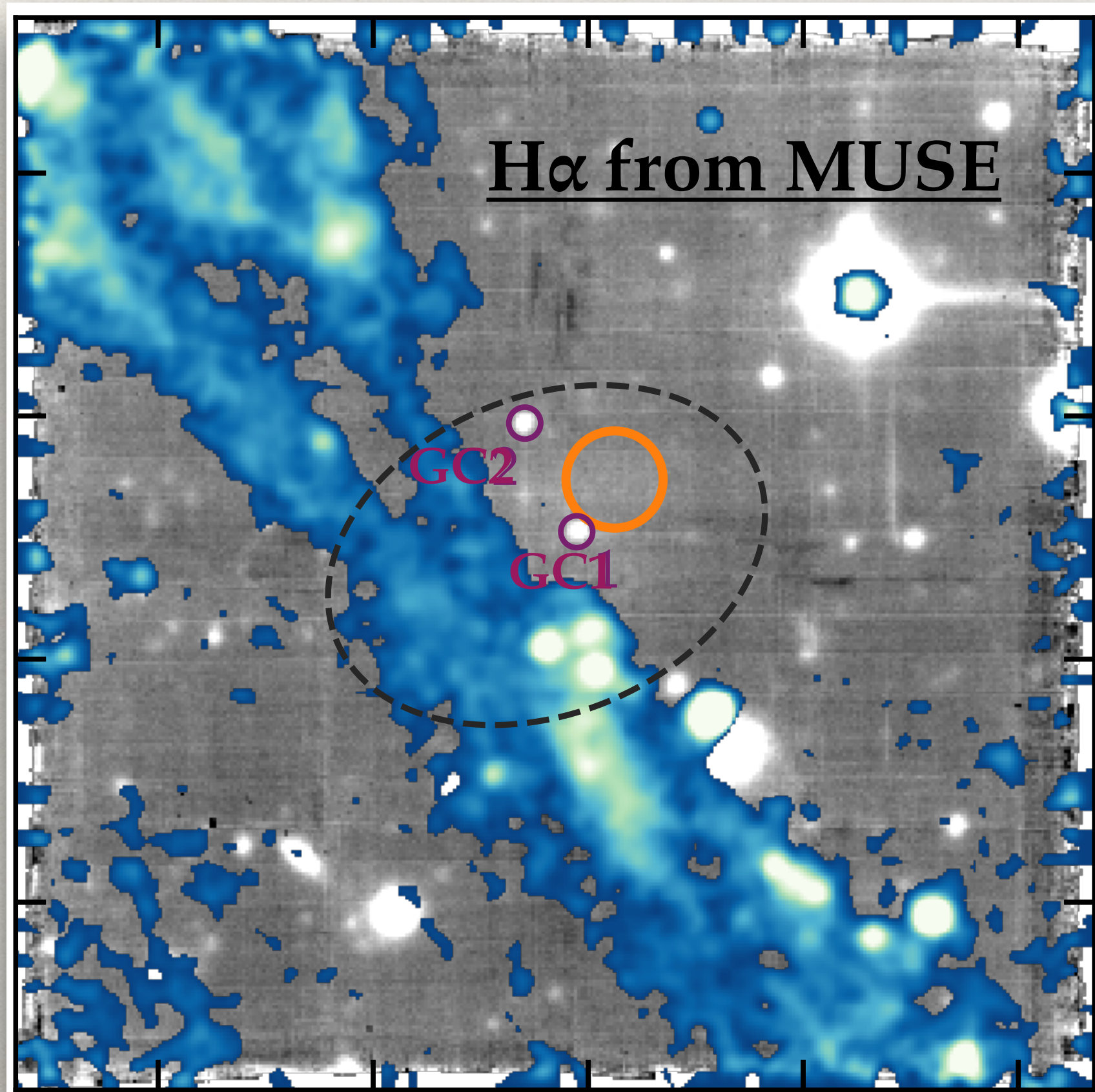
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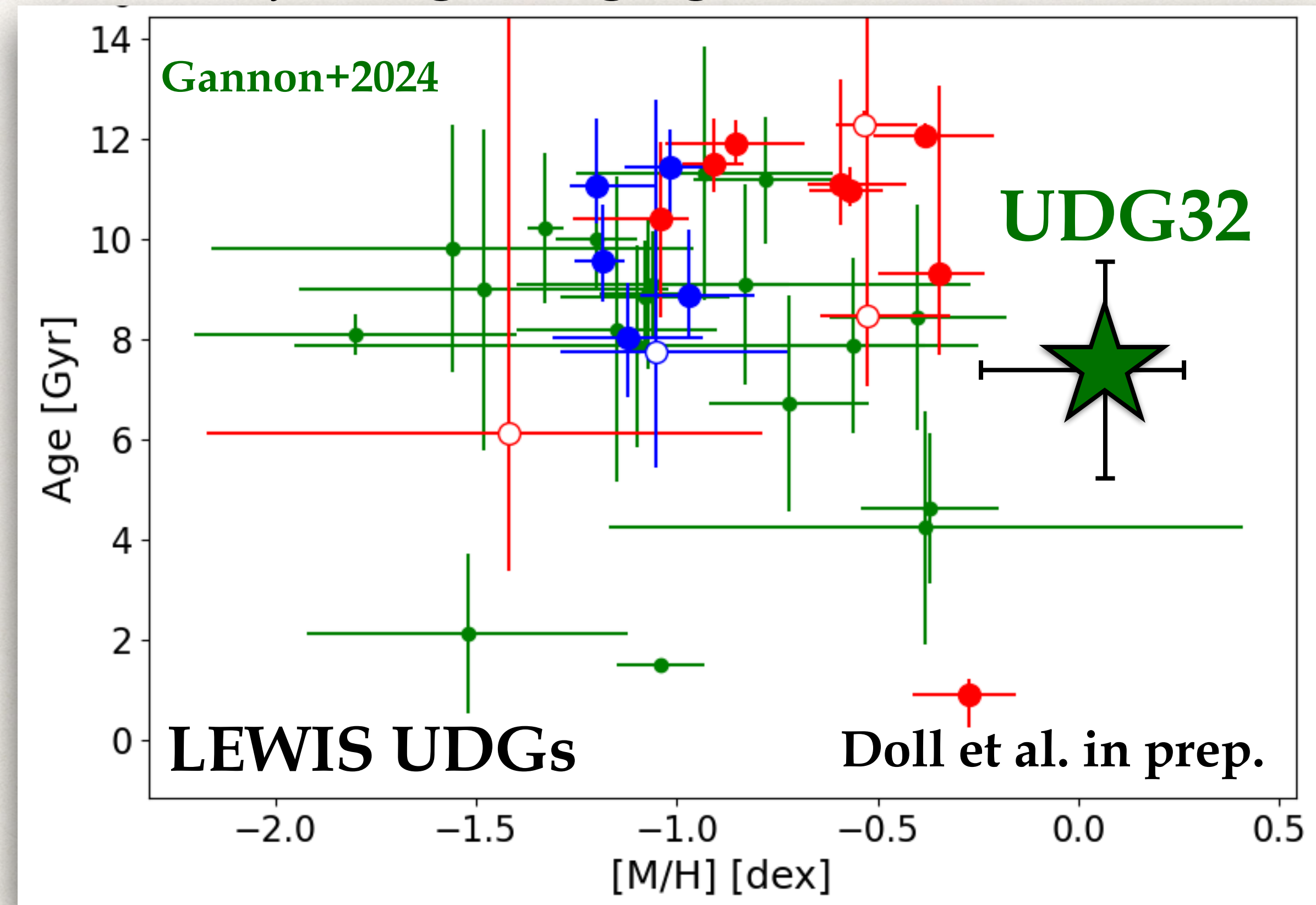


## IV. On the formation channels for UDGs:

*is UDG32 formed from the RPS gas clumps?*



*SED fitting using ugri DECam*



### Expected properties:

- ▶ *co-spatial with filaments* ✓
- ▶ *younger age & higher Z than typical UDGs* ✓
- ▶ *DM free*

Age =  $7.7 \pm 3$  Gyr  
[M/H] =  $0.07 \pm 0.2$  dex



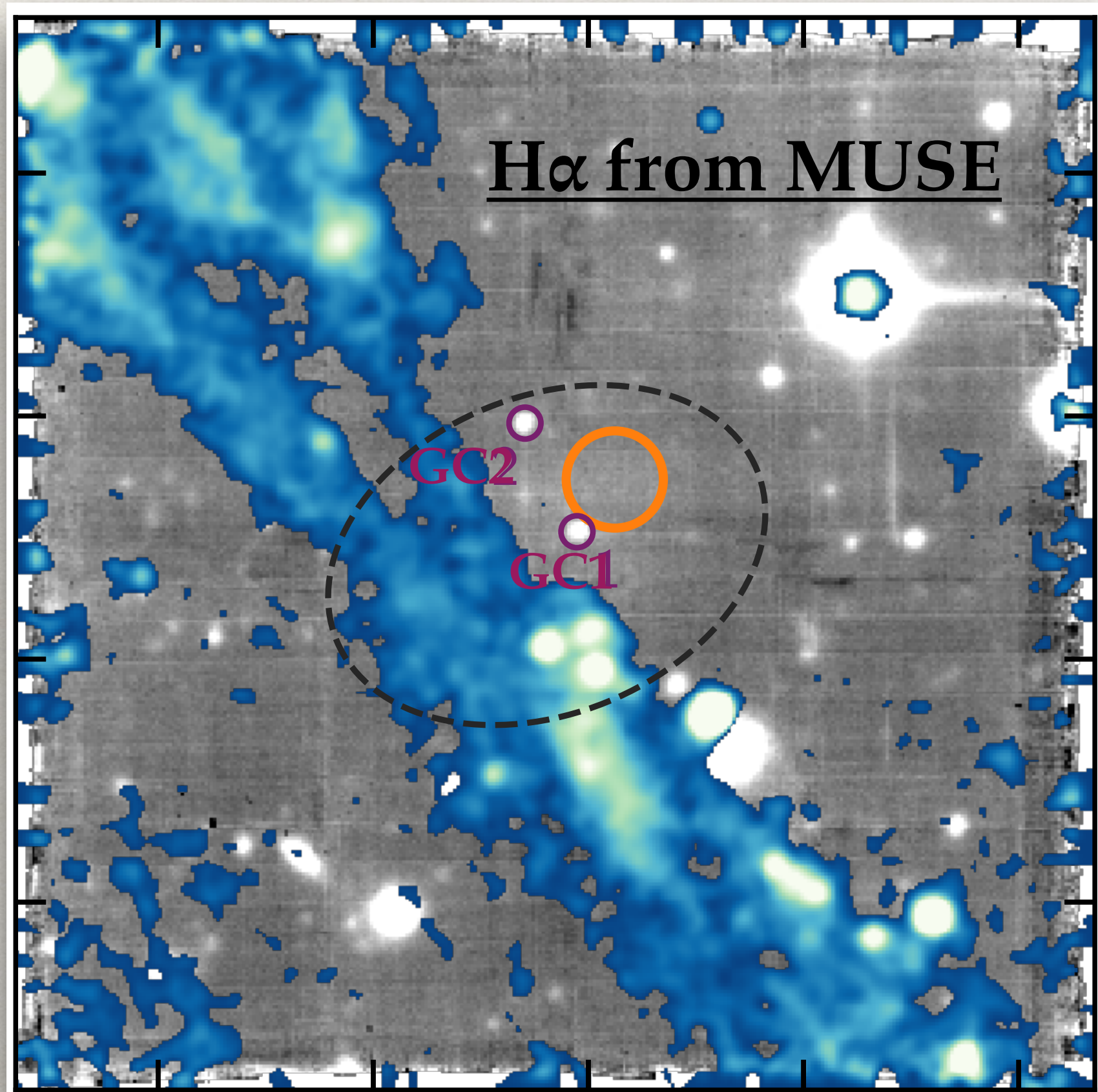
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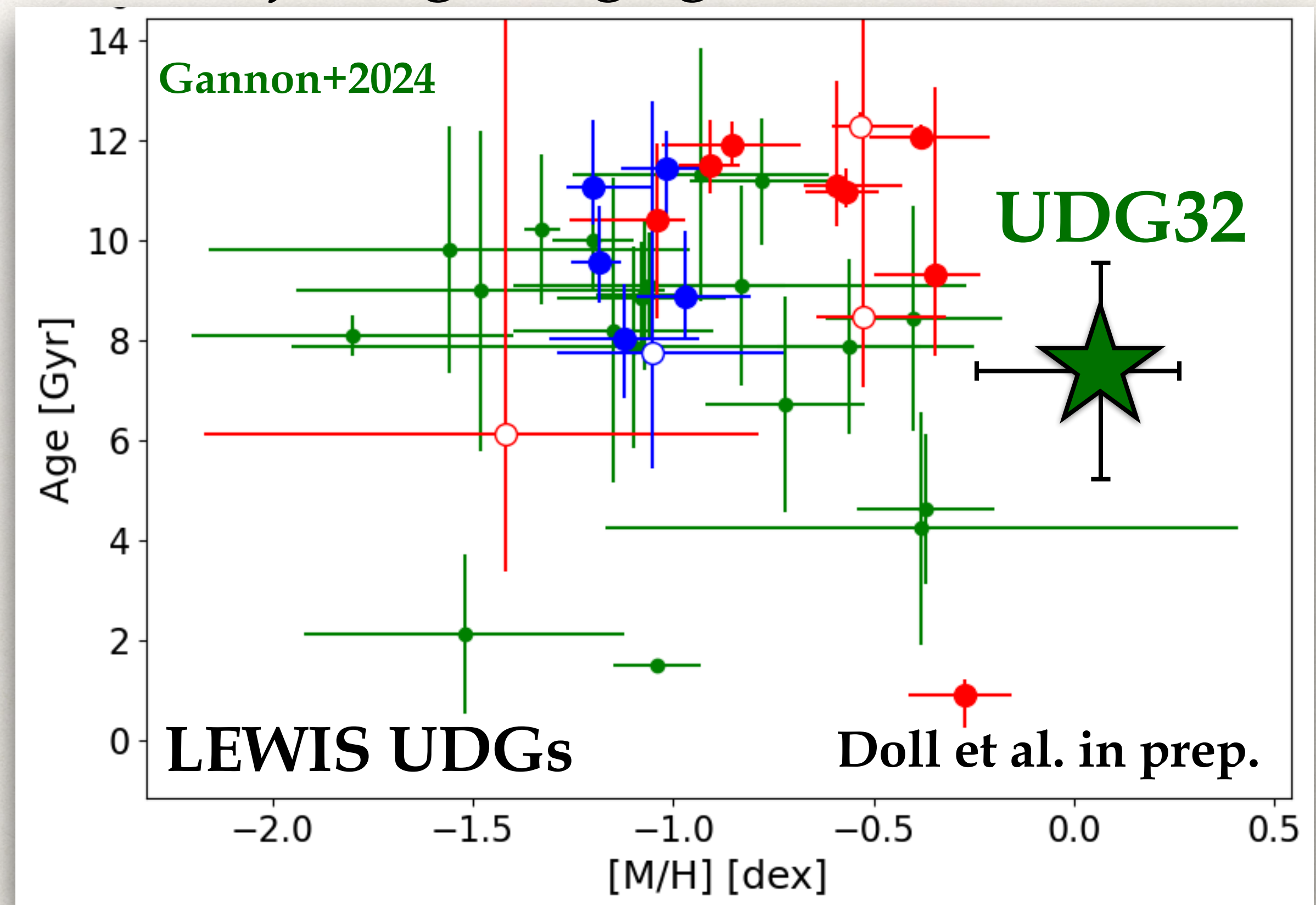


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Age =  $7.7 \pm 3$  Gyr  
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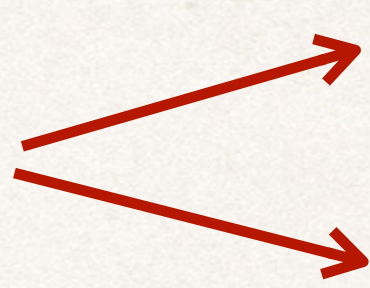


# *Summary & future perspectives*

- Bimodality in the stellar rotation map
- Few UDGs have a dwarf-like DM halo ( $M_h \sim 10^{10} M_\odot$ )
- Bimodal distribution of M/H

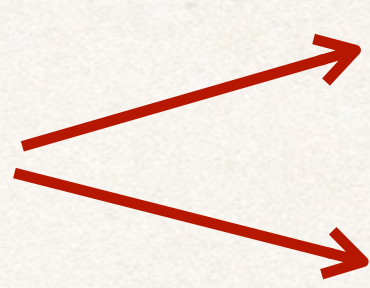


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- Bimodality in the stellar rotation map 
  - 60% rotation*
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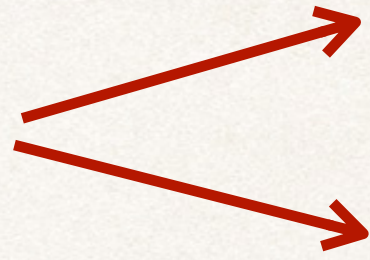


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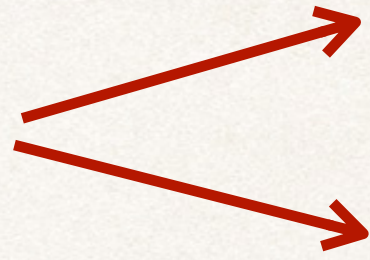


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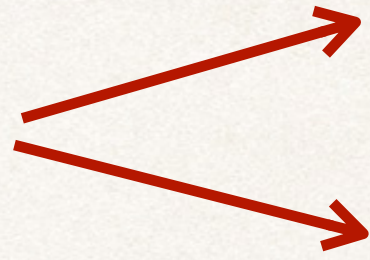
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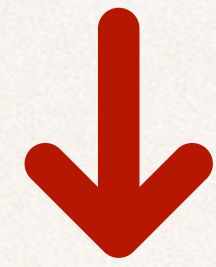


**Different classes of UDGs in Hydra I cluster**

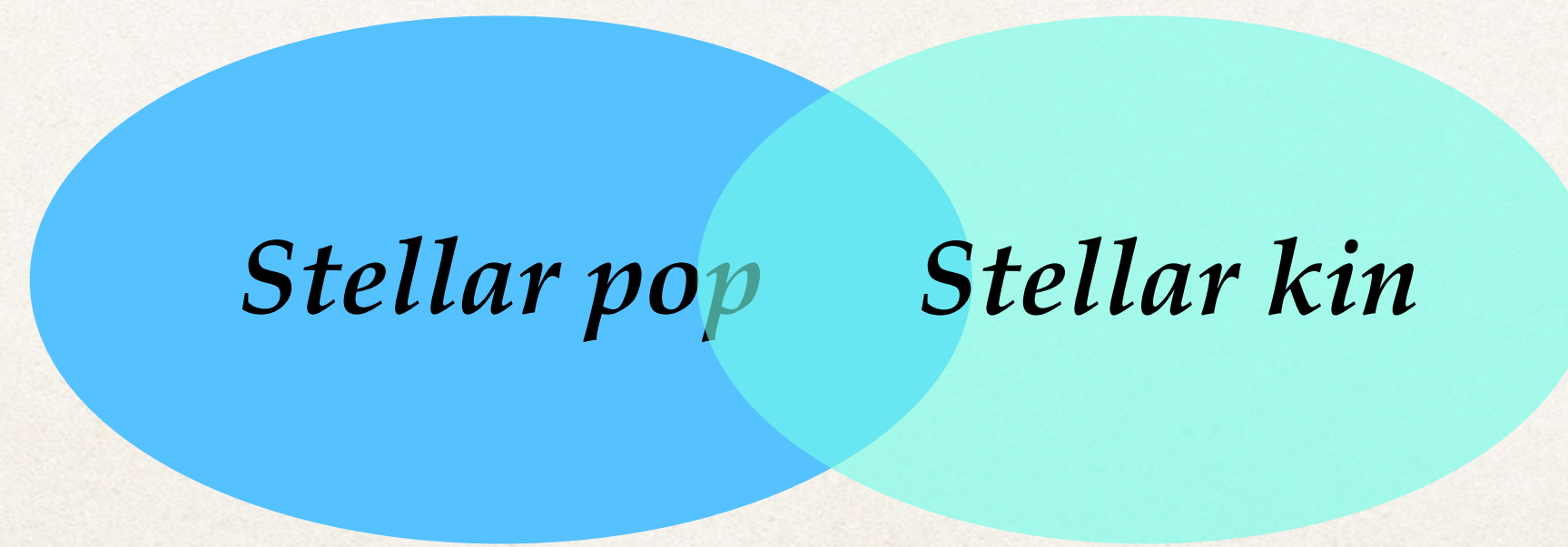


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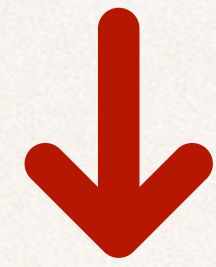
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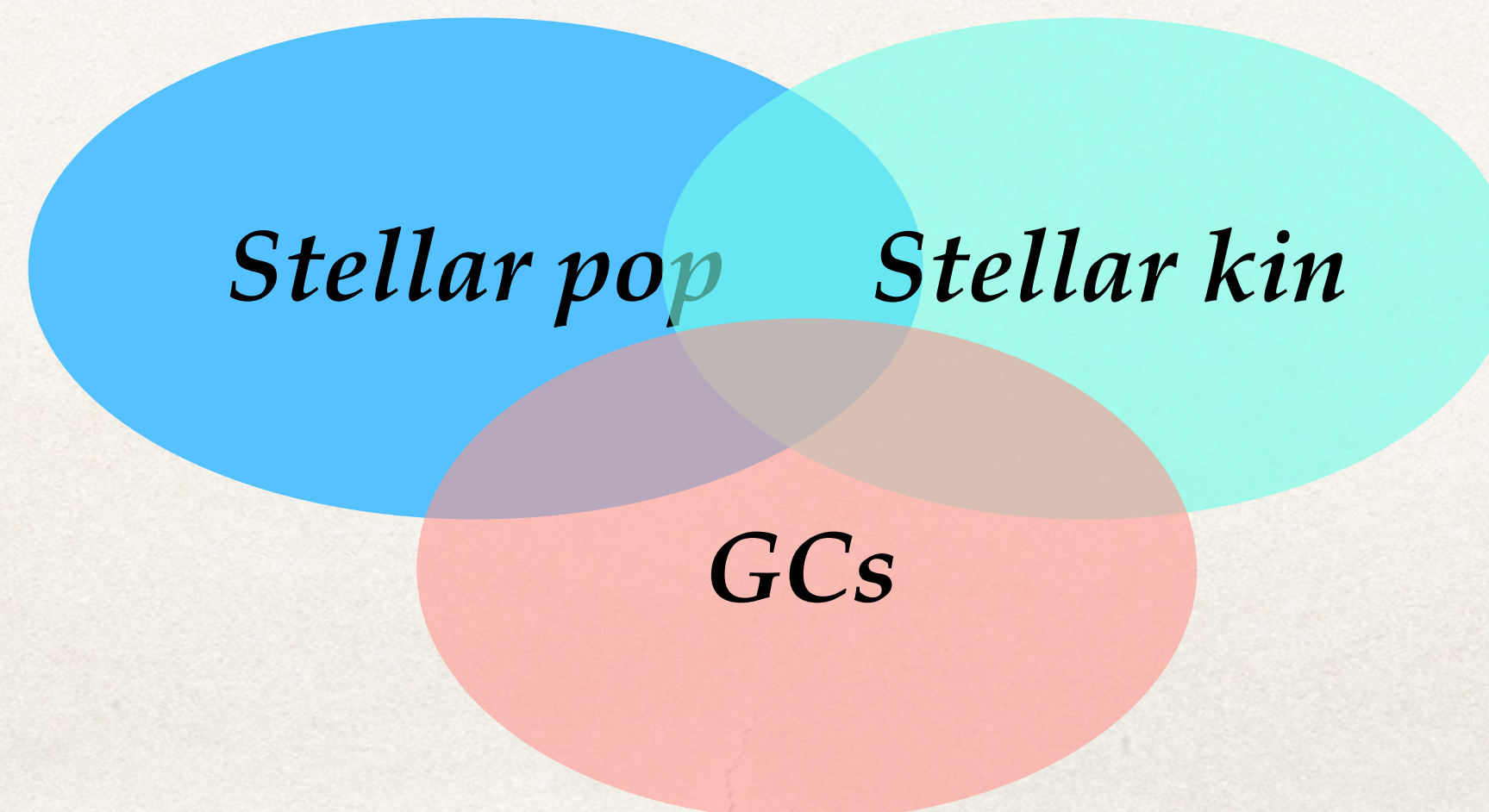


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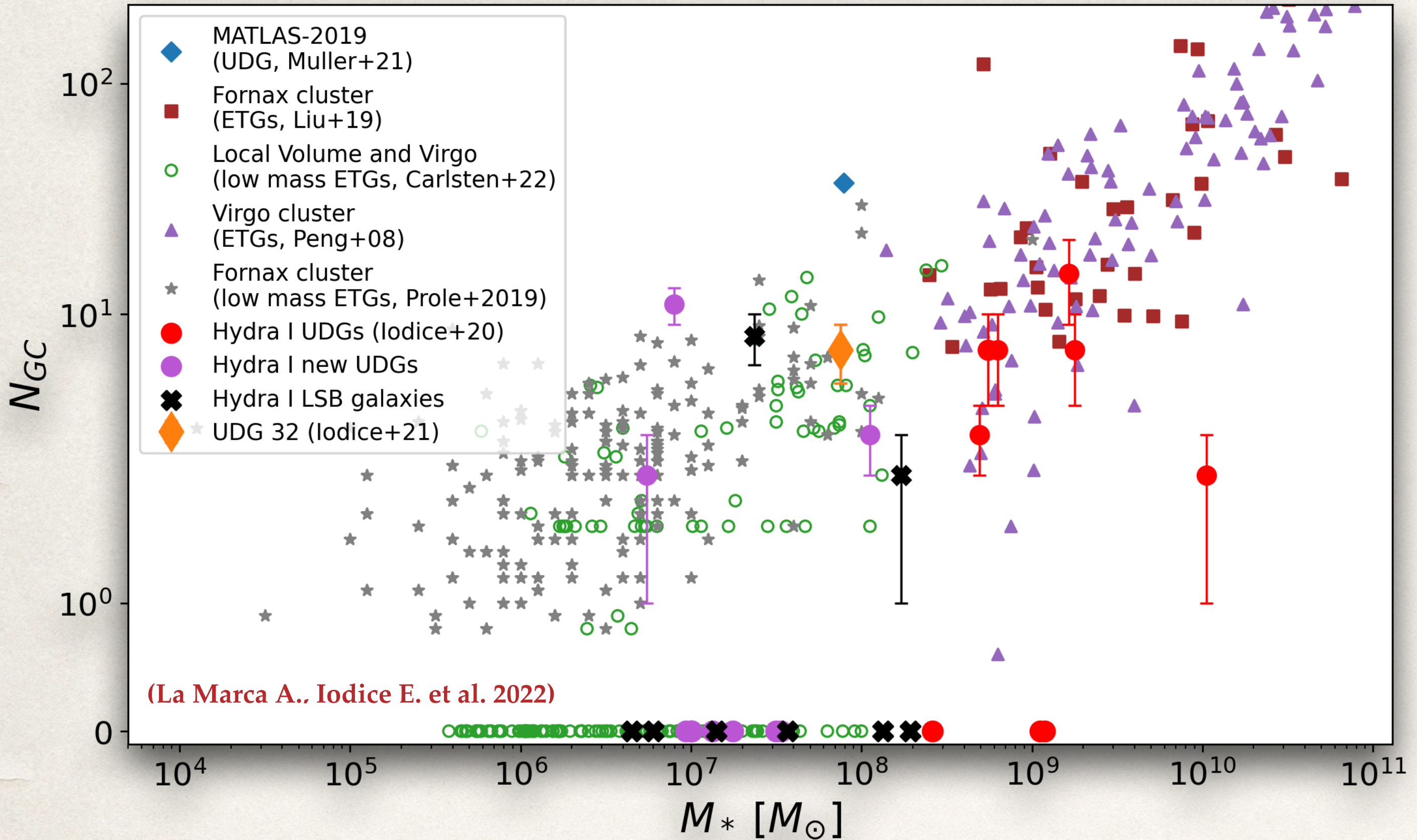


# GCs in Hydra I UDGs

Marco Mirabile  
in prep.



a handful of UDGs (12) in LEWIS have GCs  
( $2 \leq N_{GC} \leq 11$ )



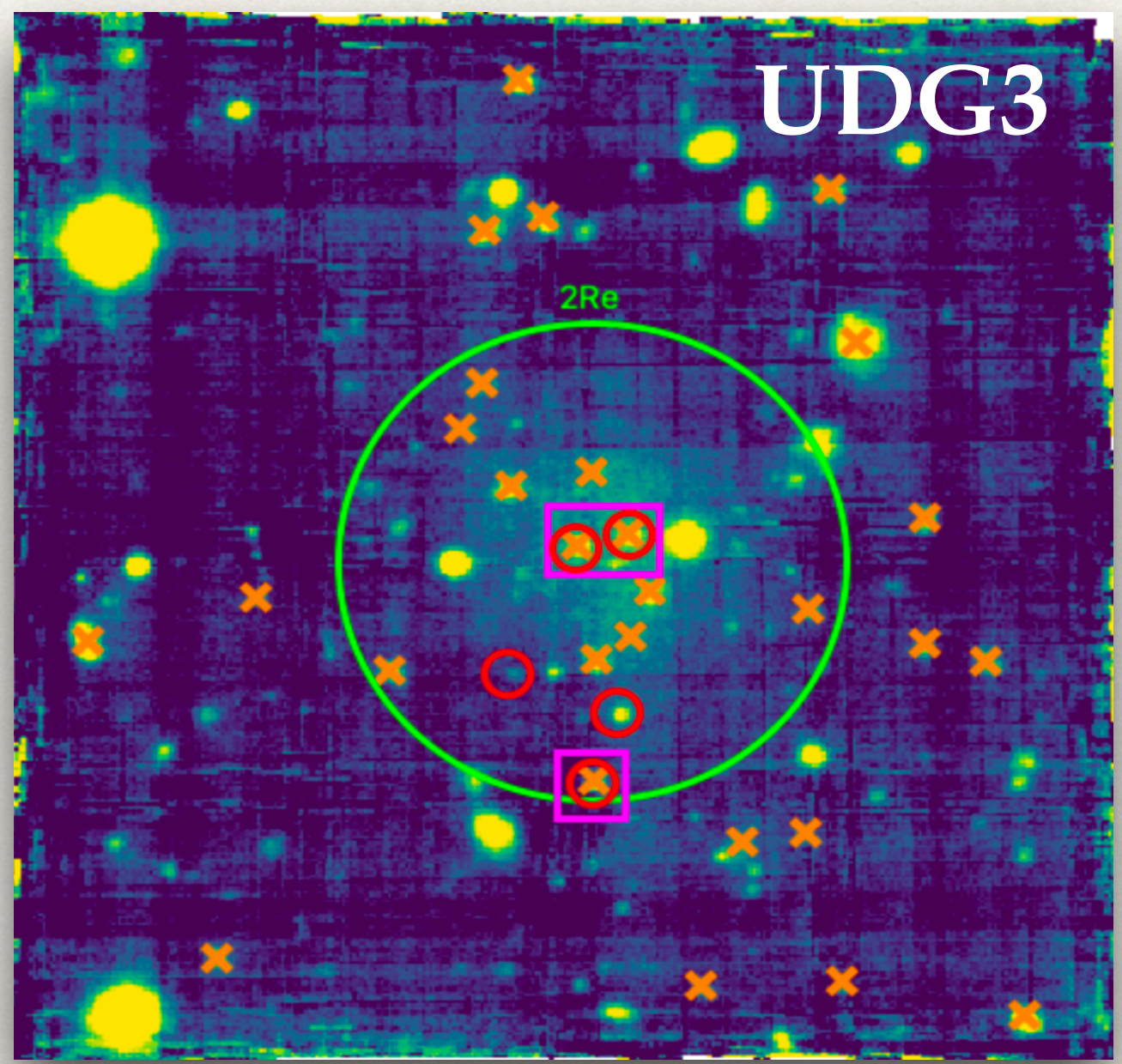
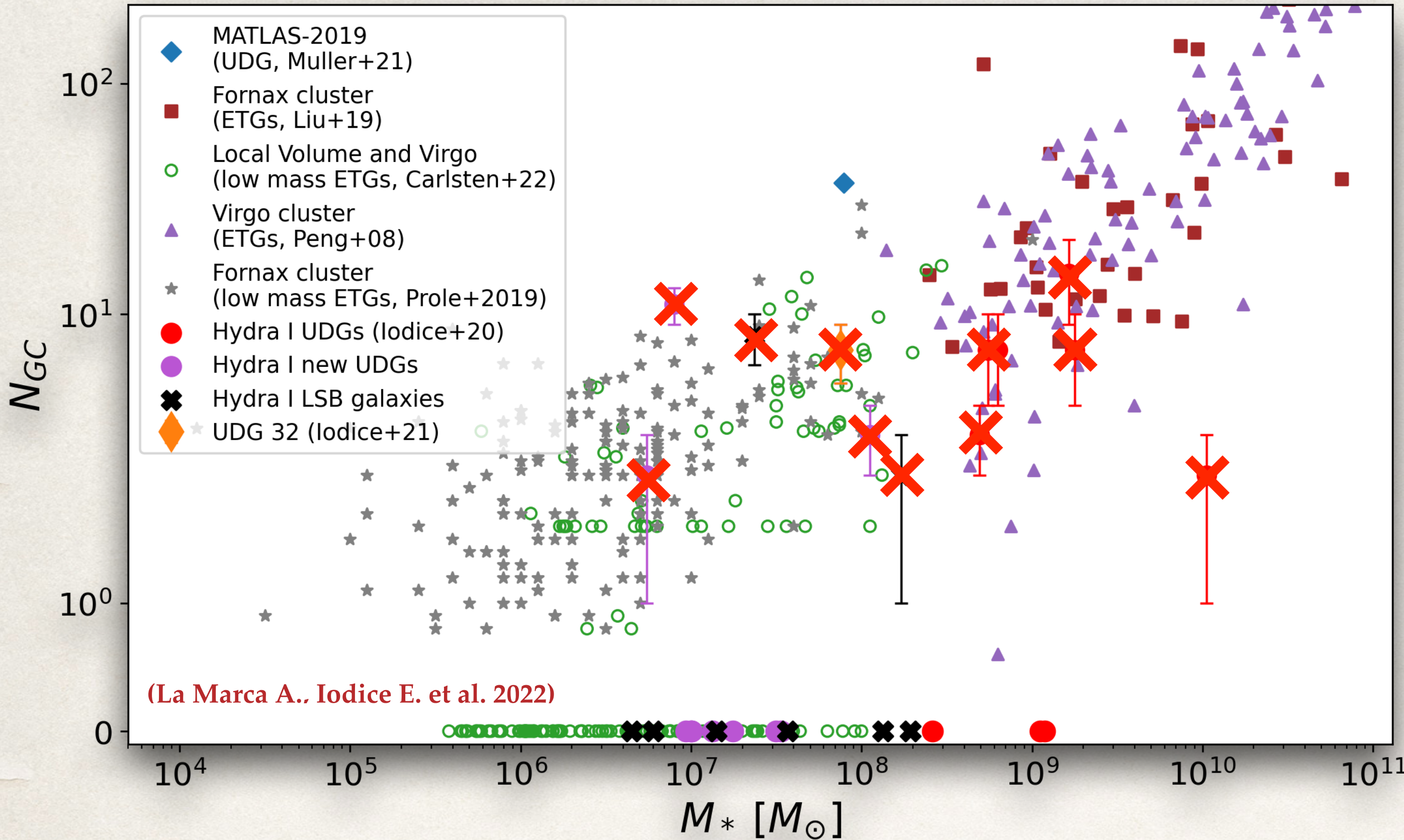


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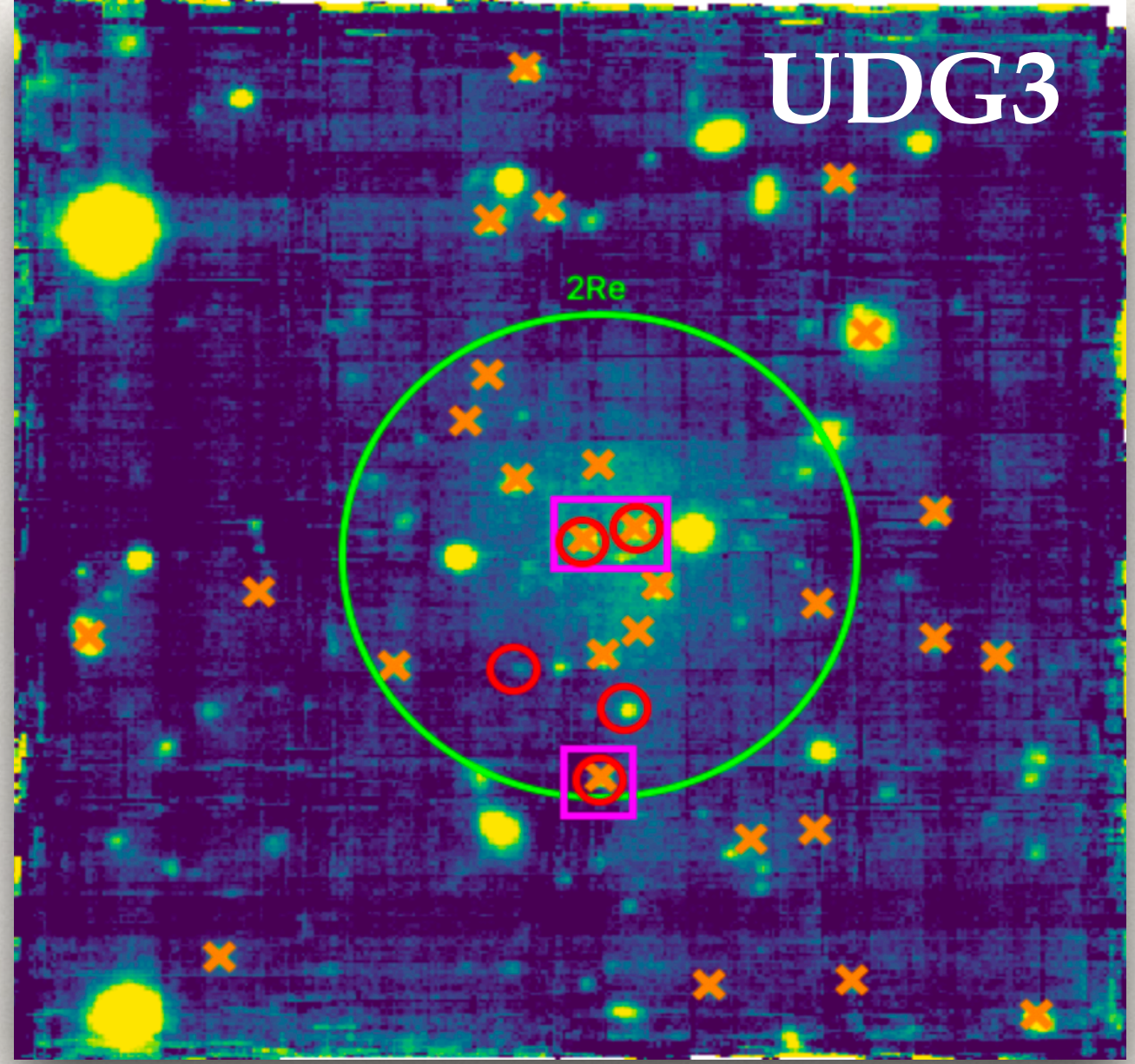
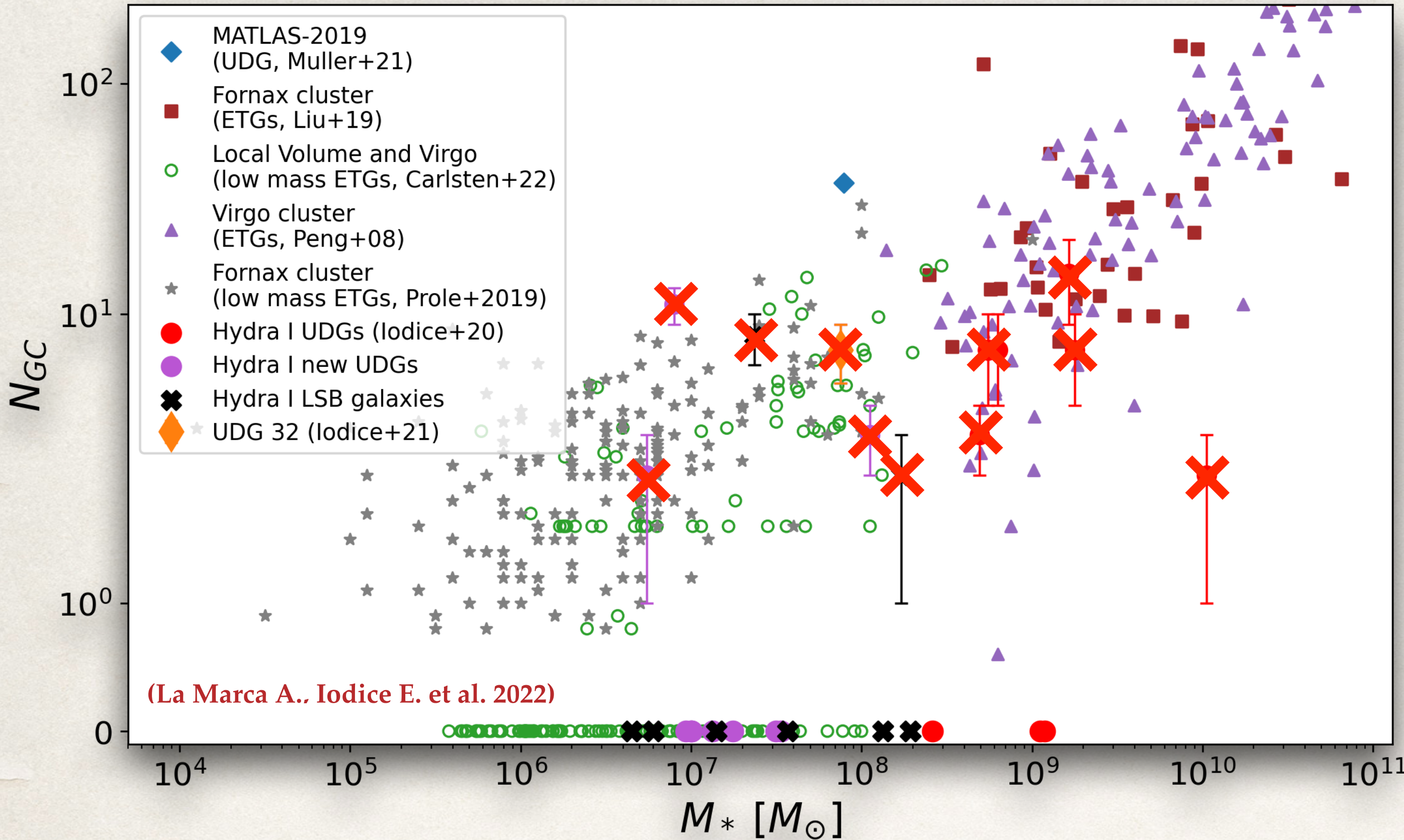


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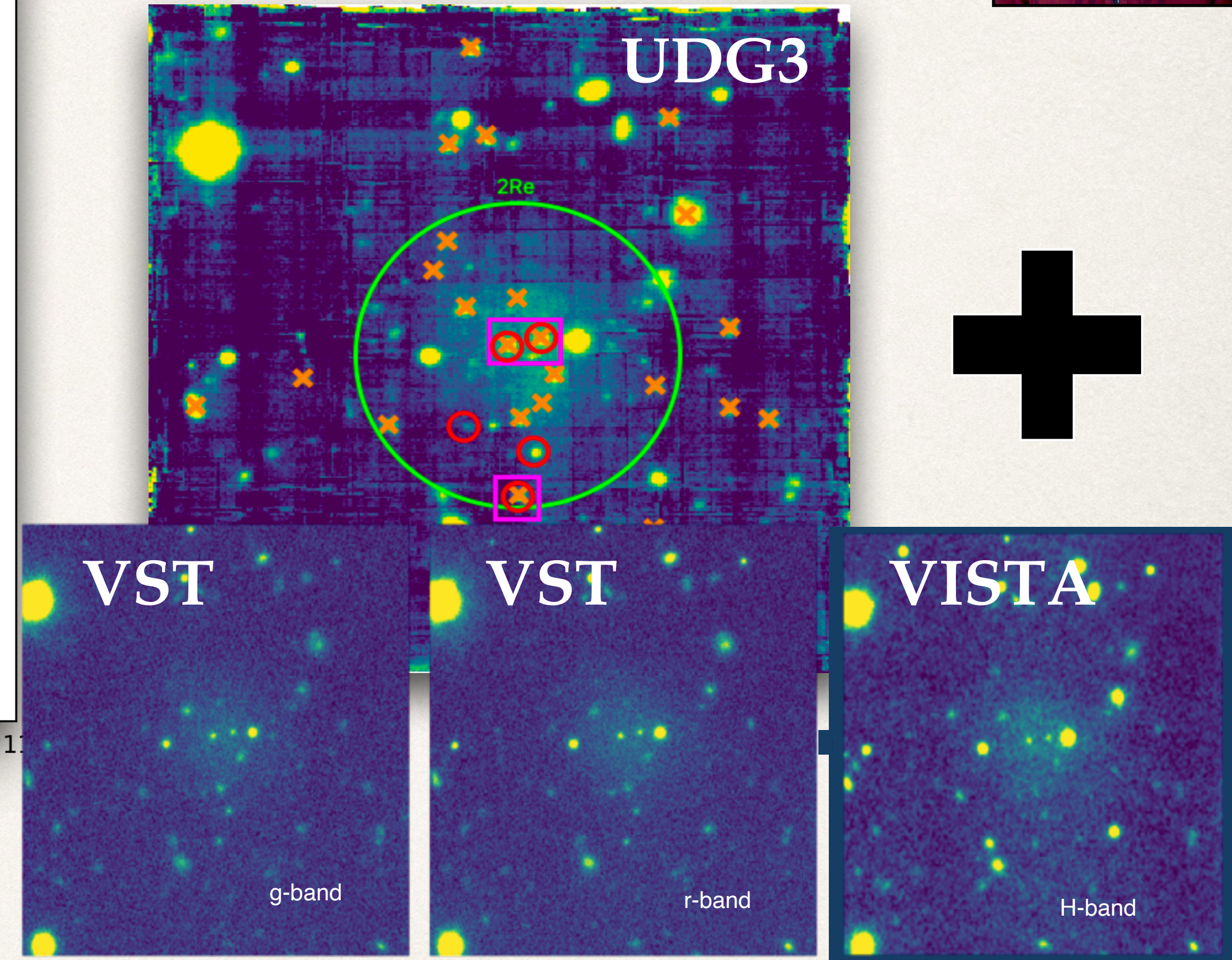
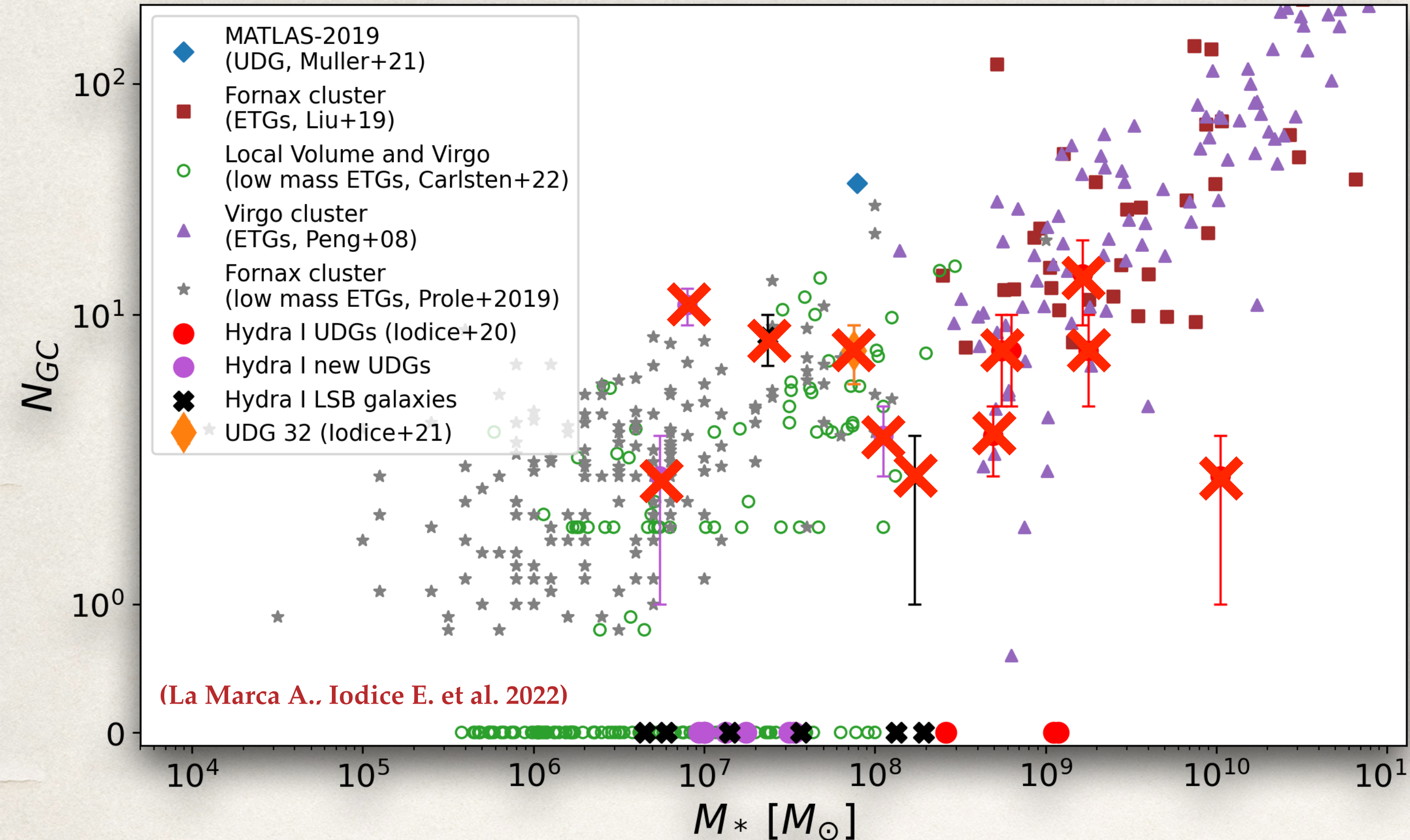


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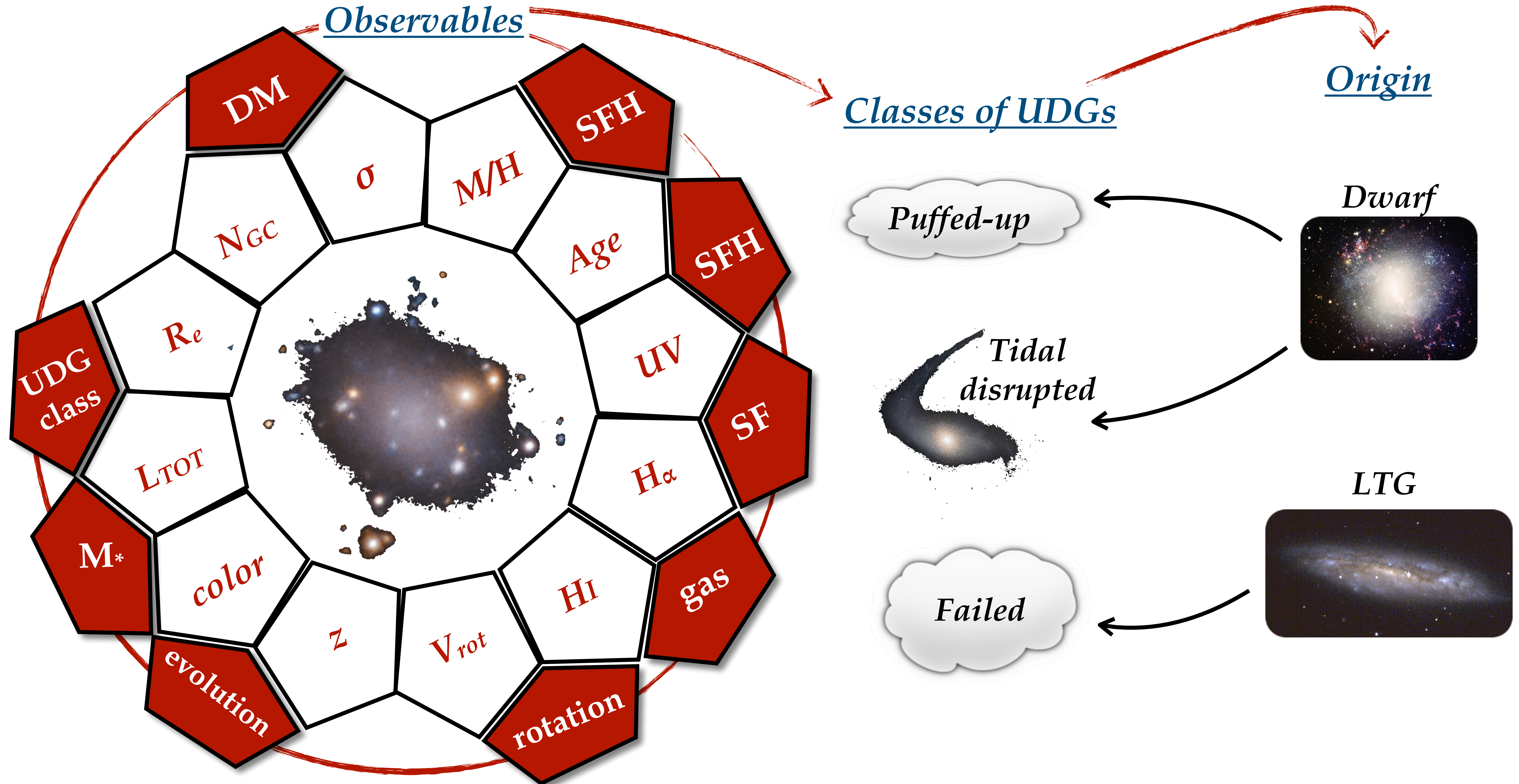
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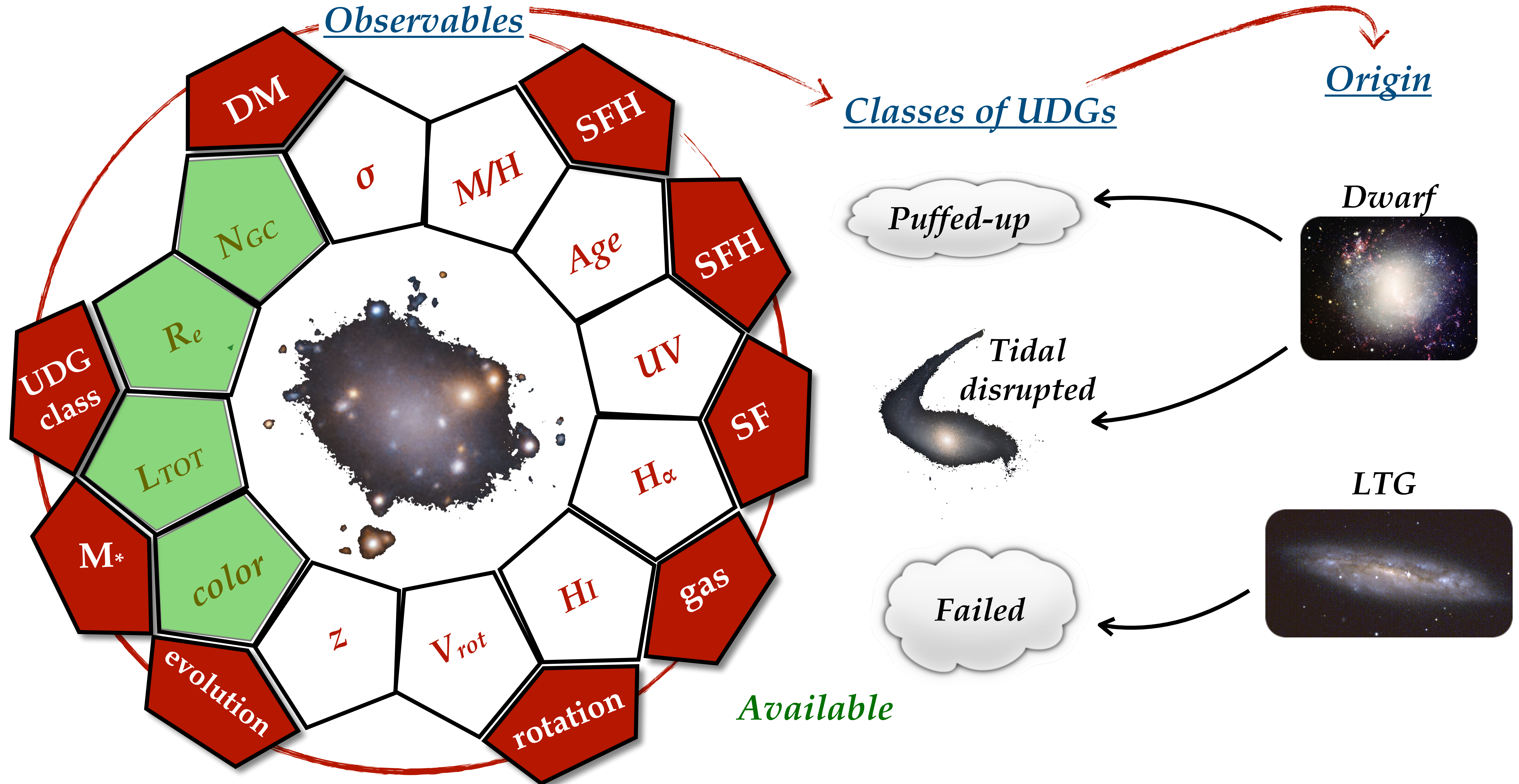


# *What we still miss: future perspectives*



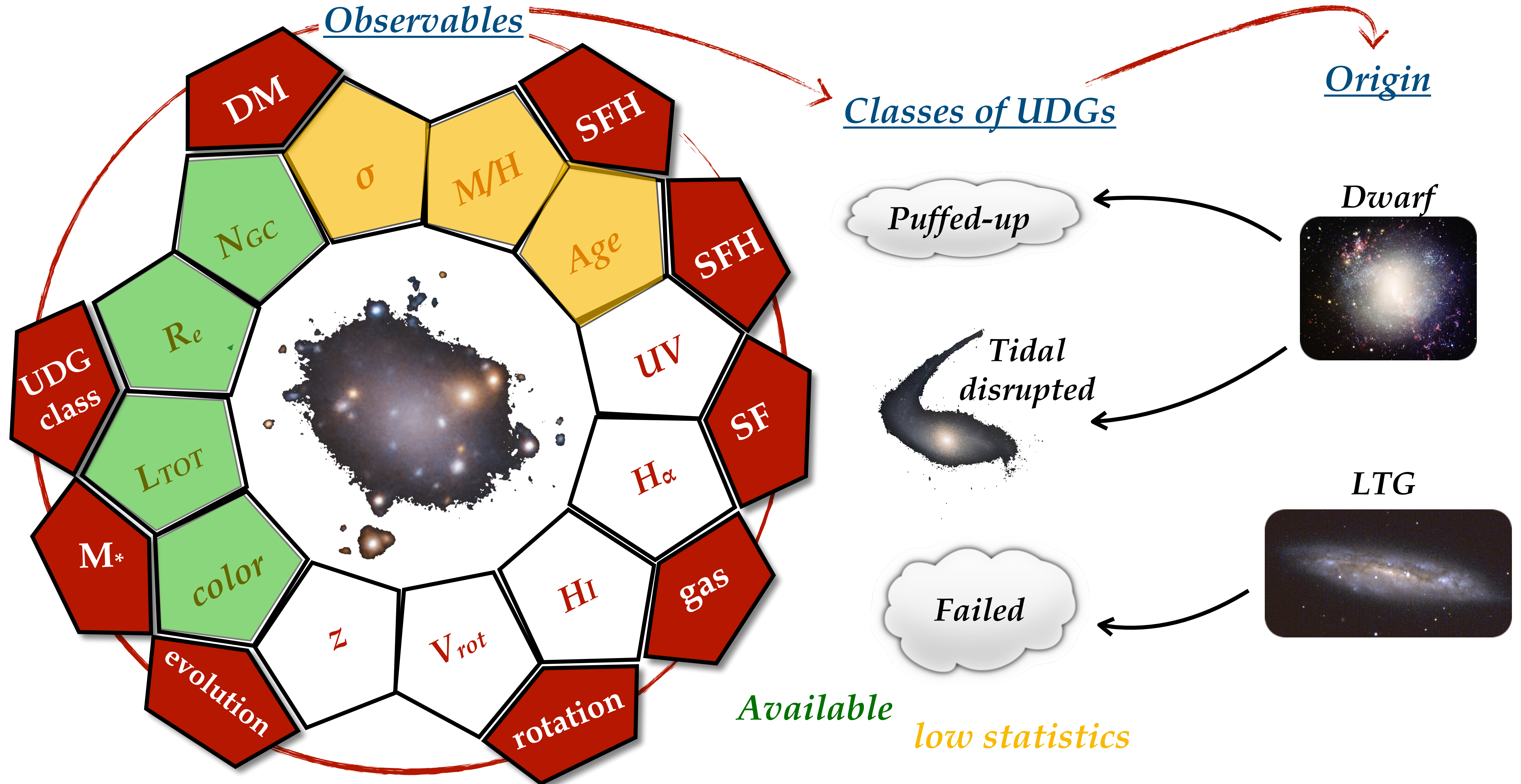


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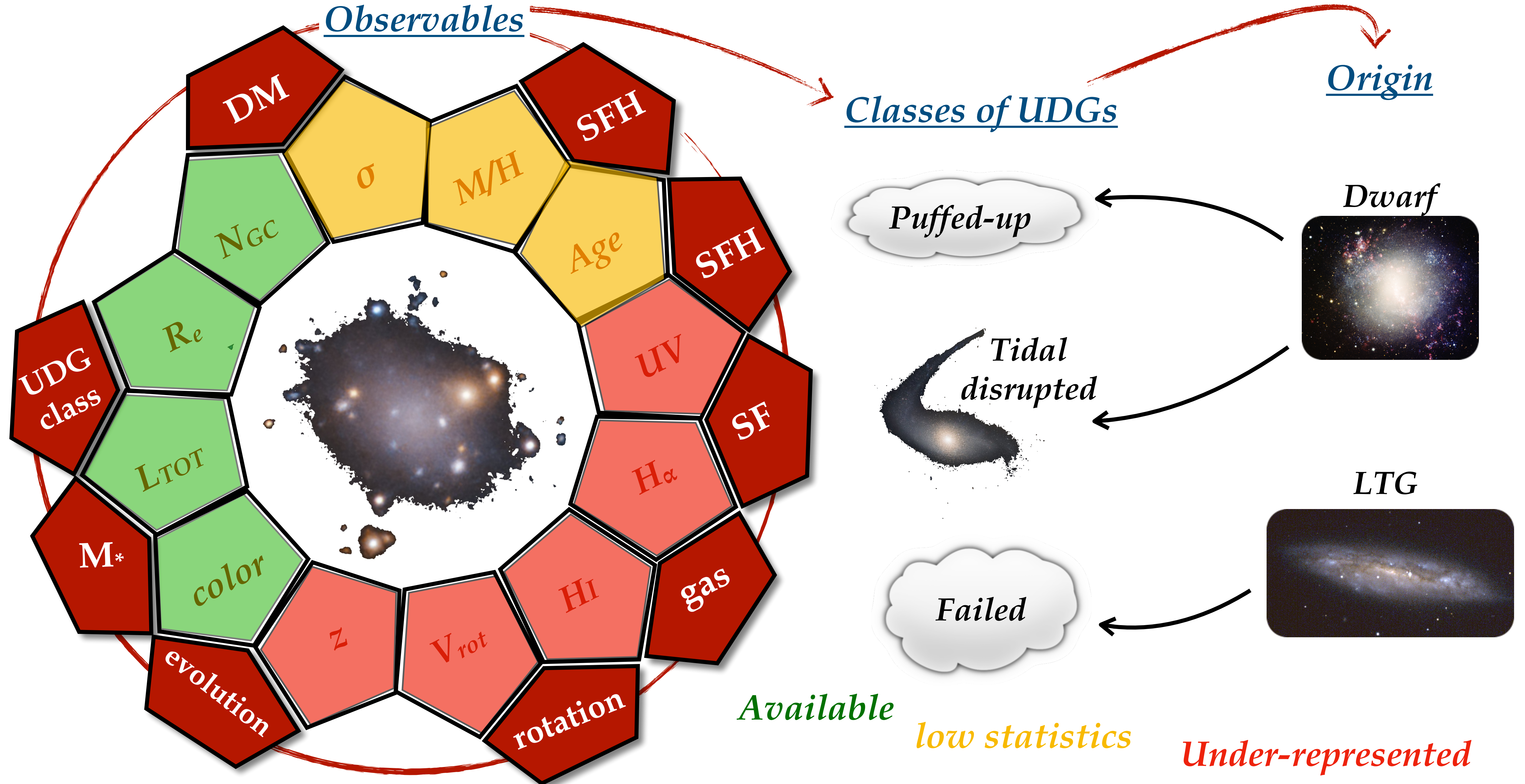


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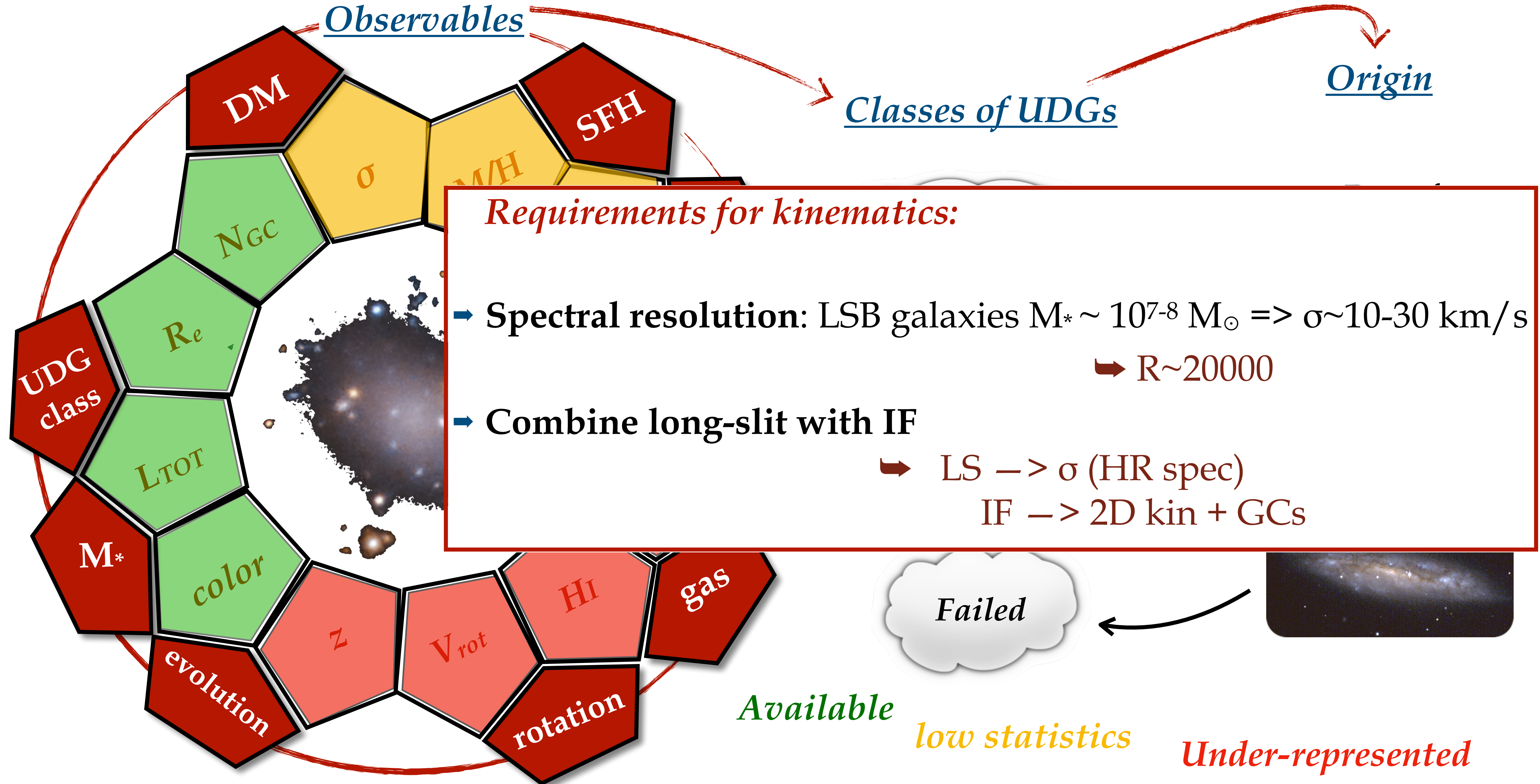


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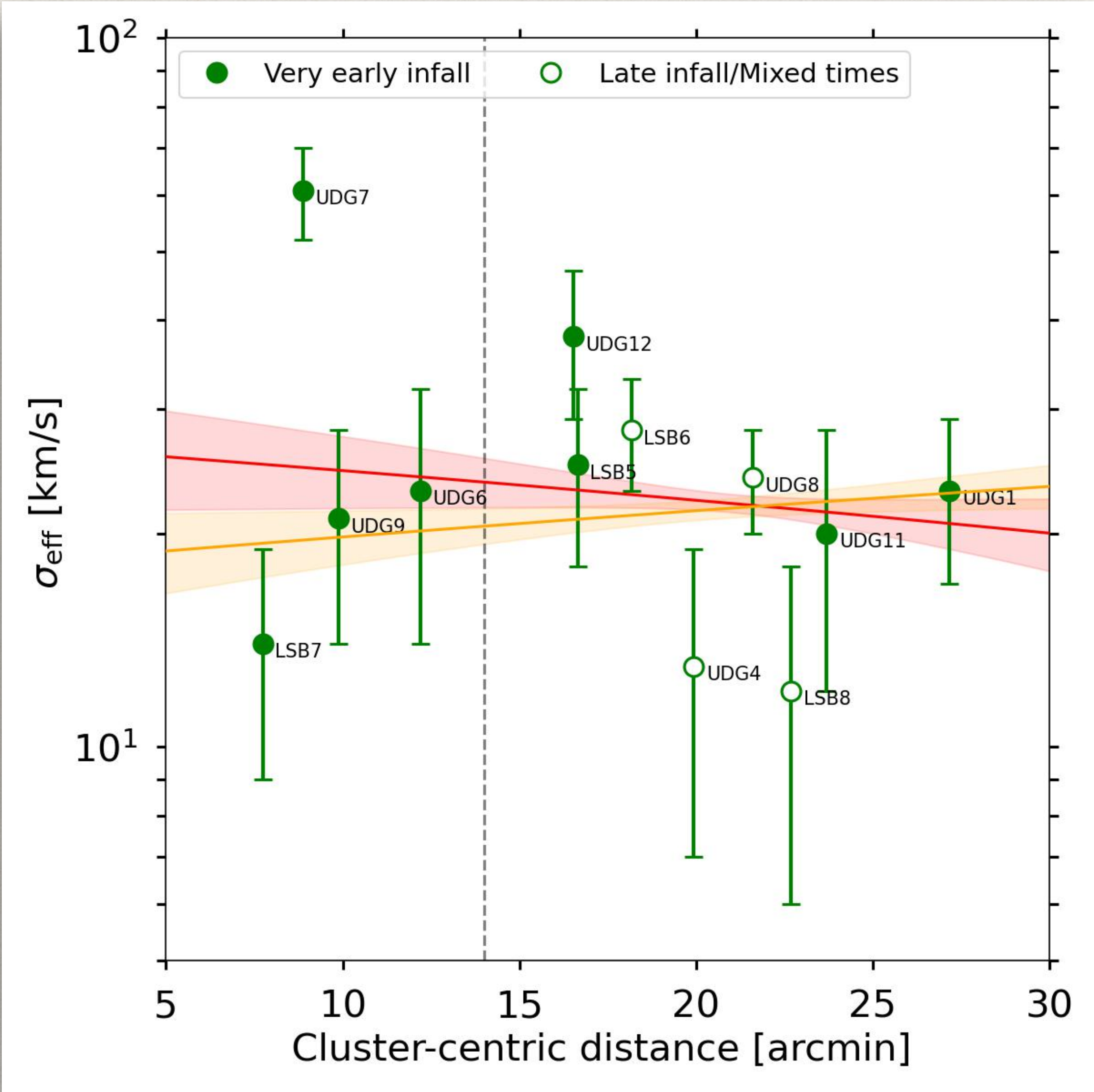
**Additional slides**



# LEWIS: results from stellar kinematics

*Cluster-centric trends*

Chiara Buttitta (INAF-OAC) et al., 2024, A&A sub.

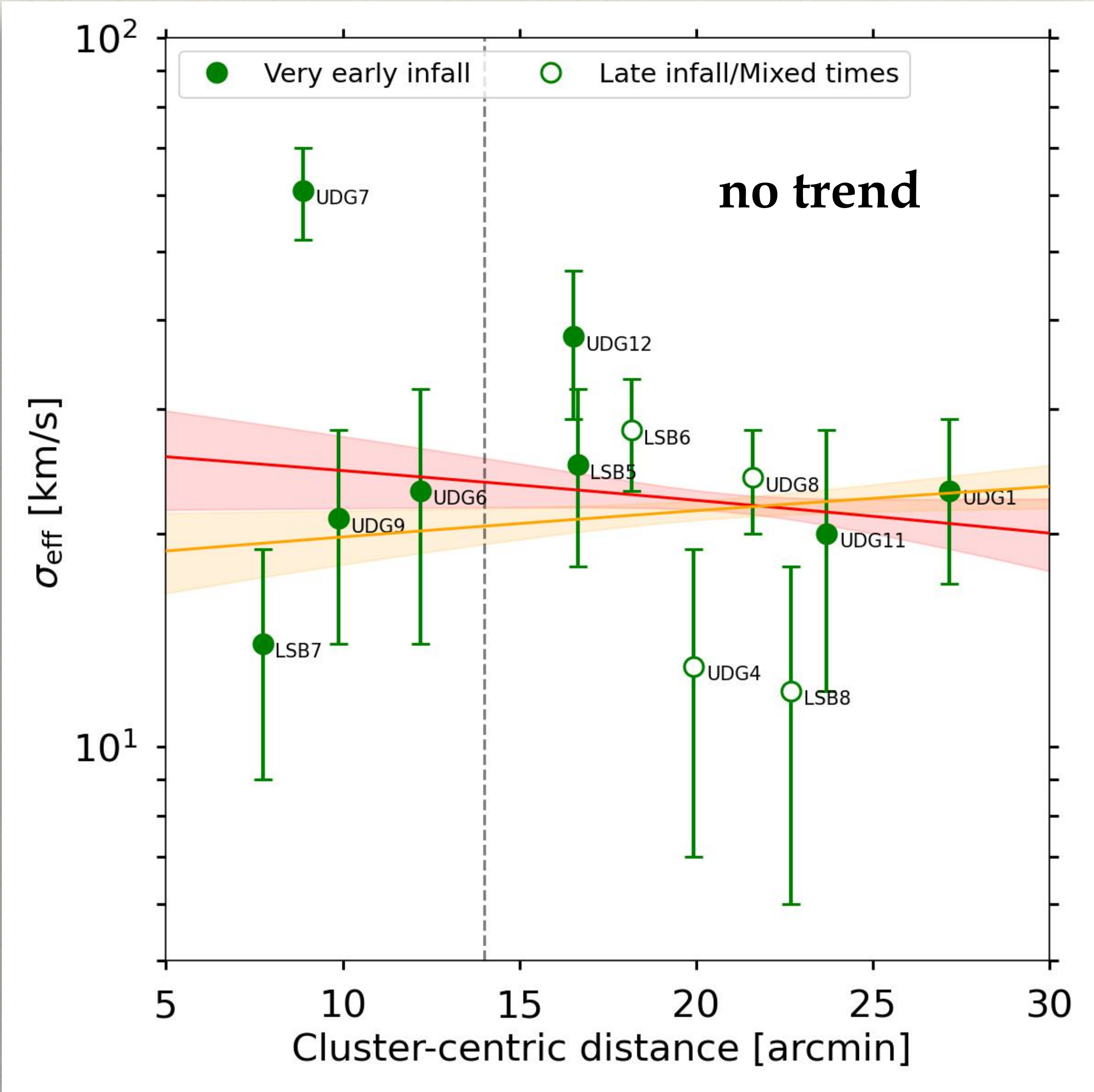




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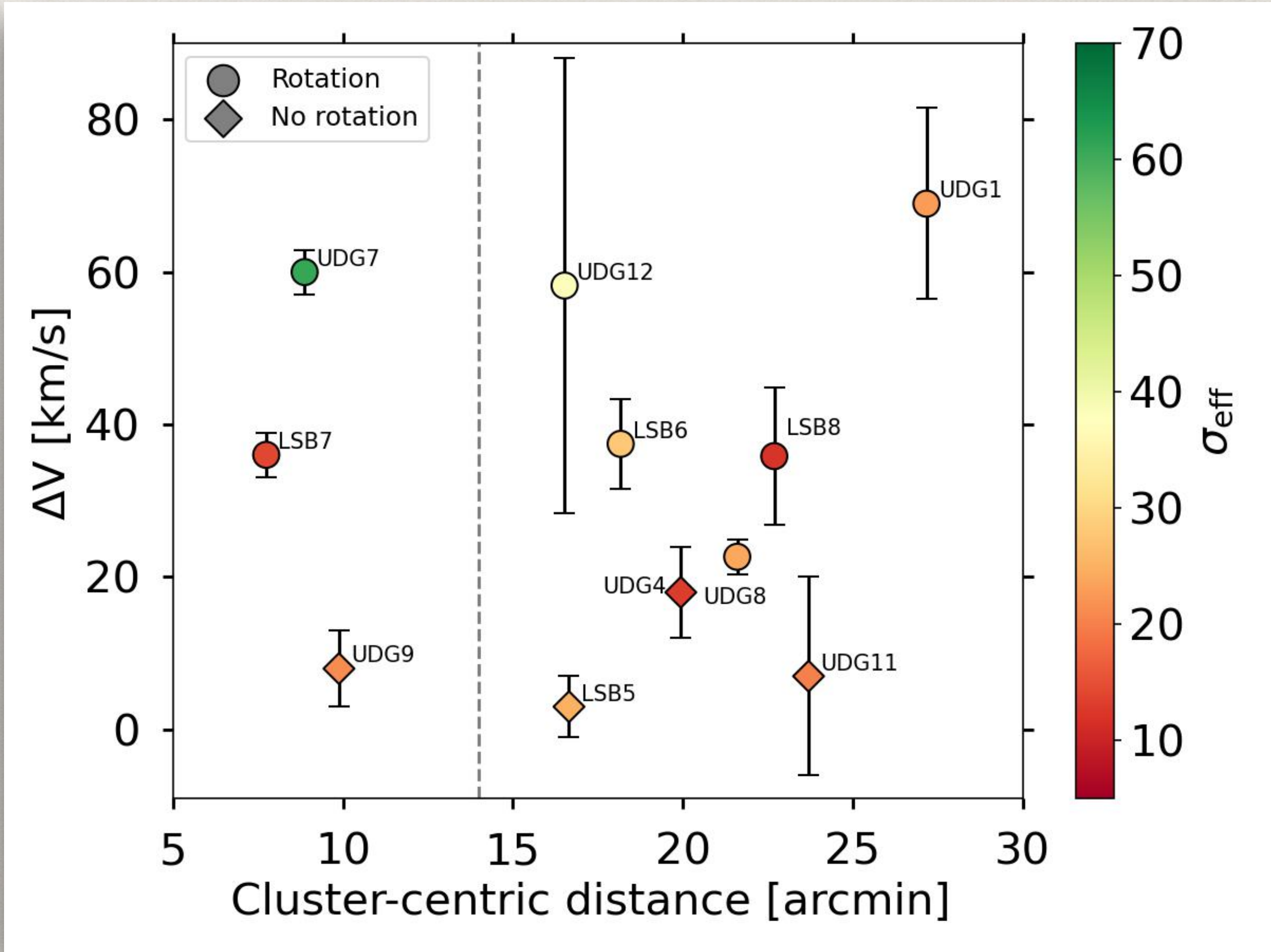
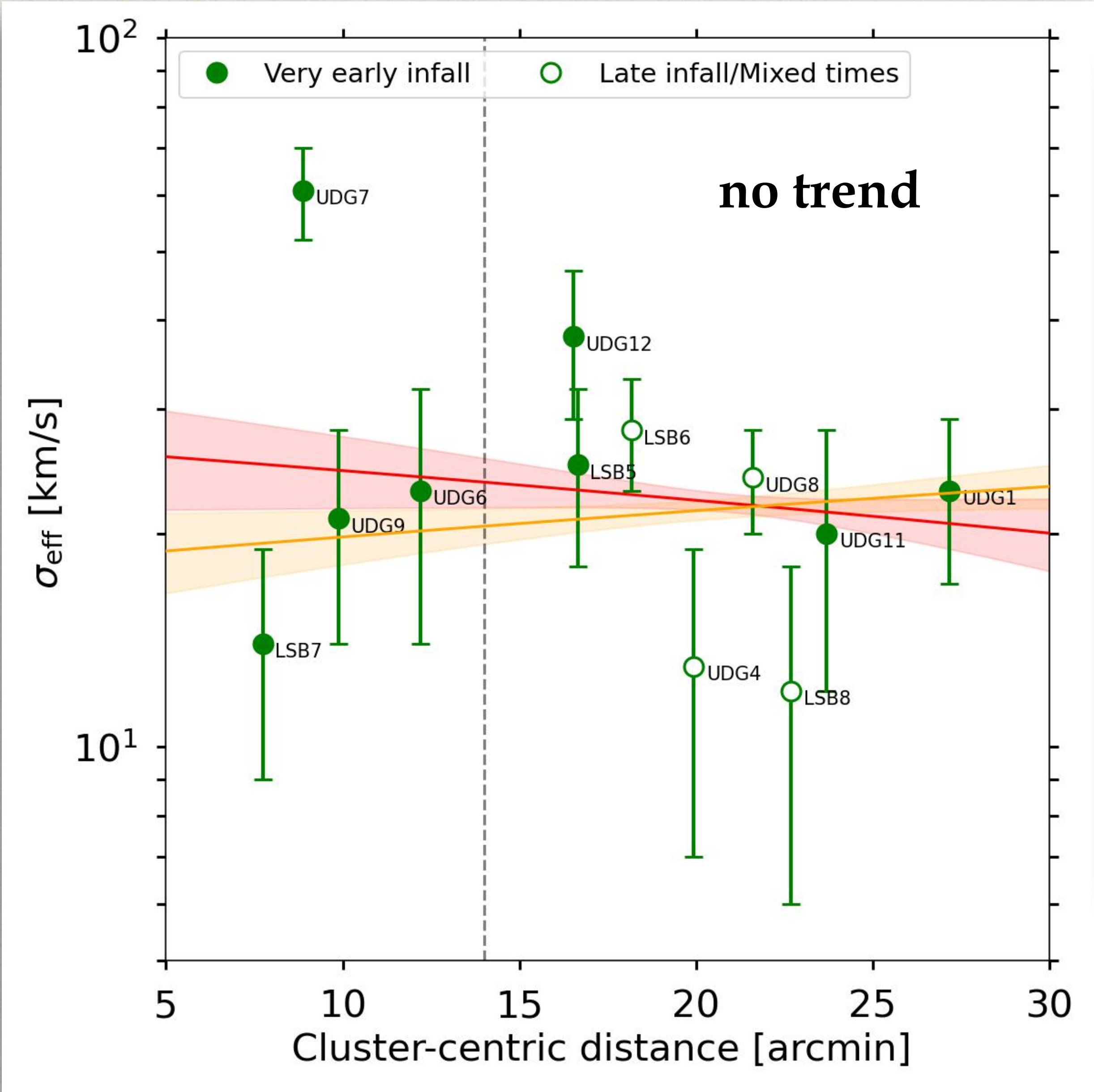




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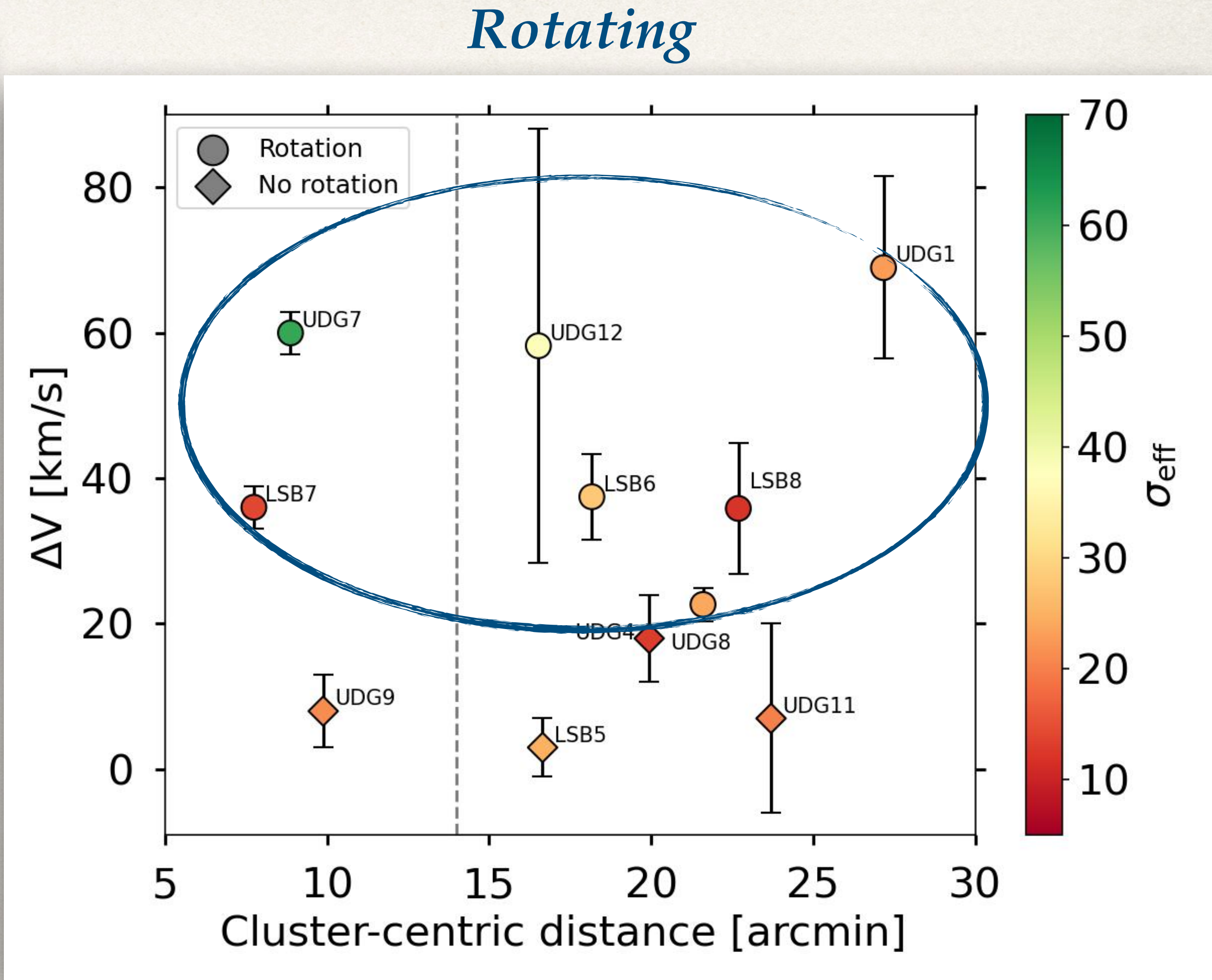
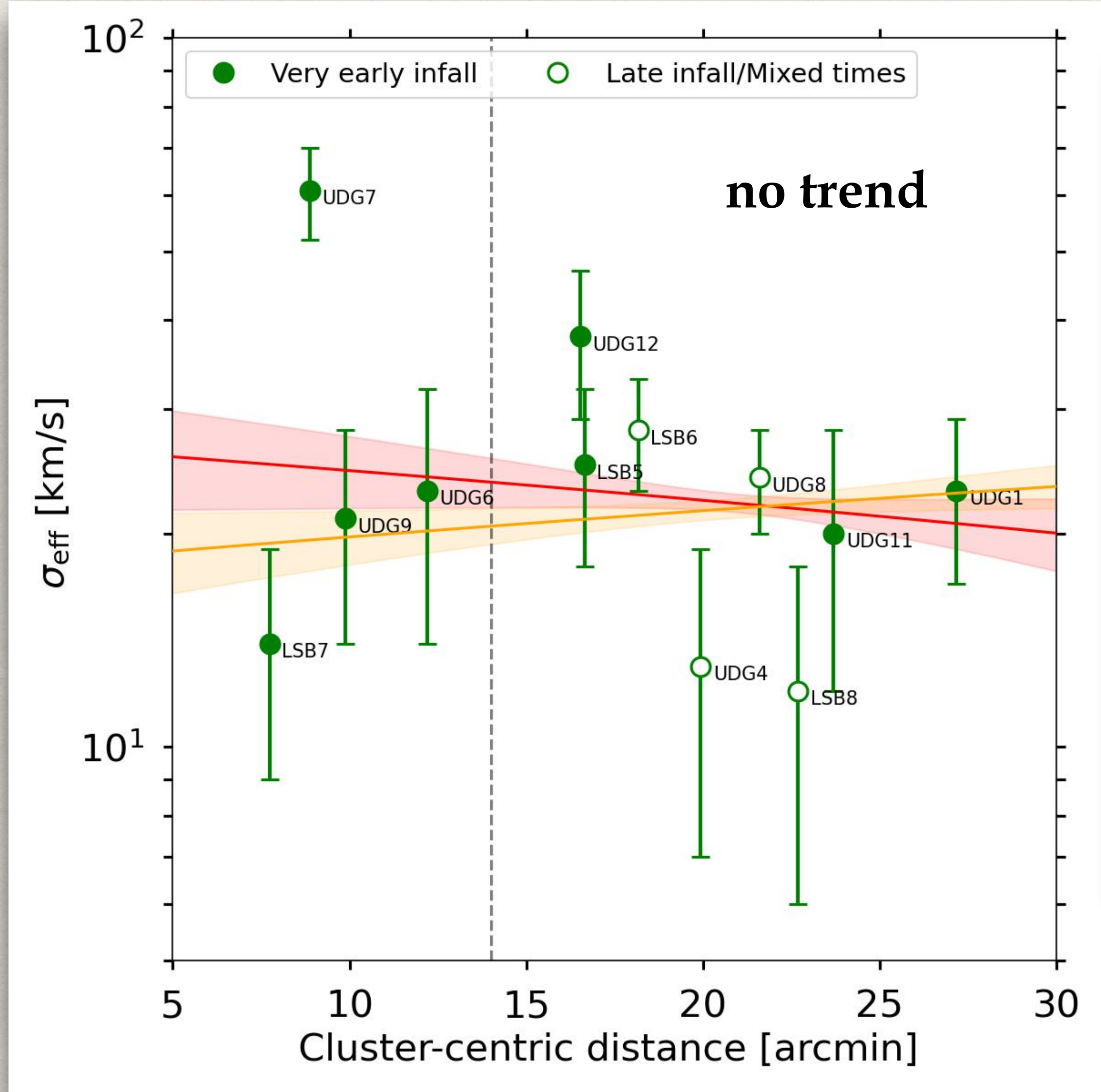




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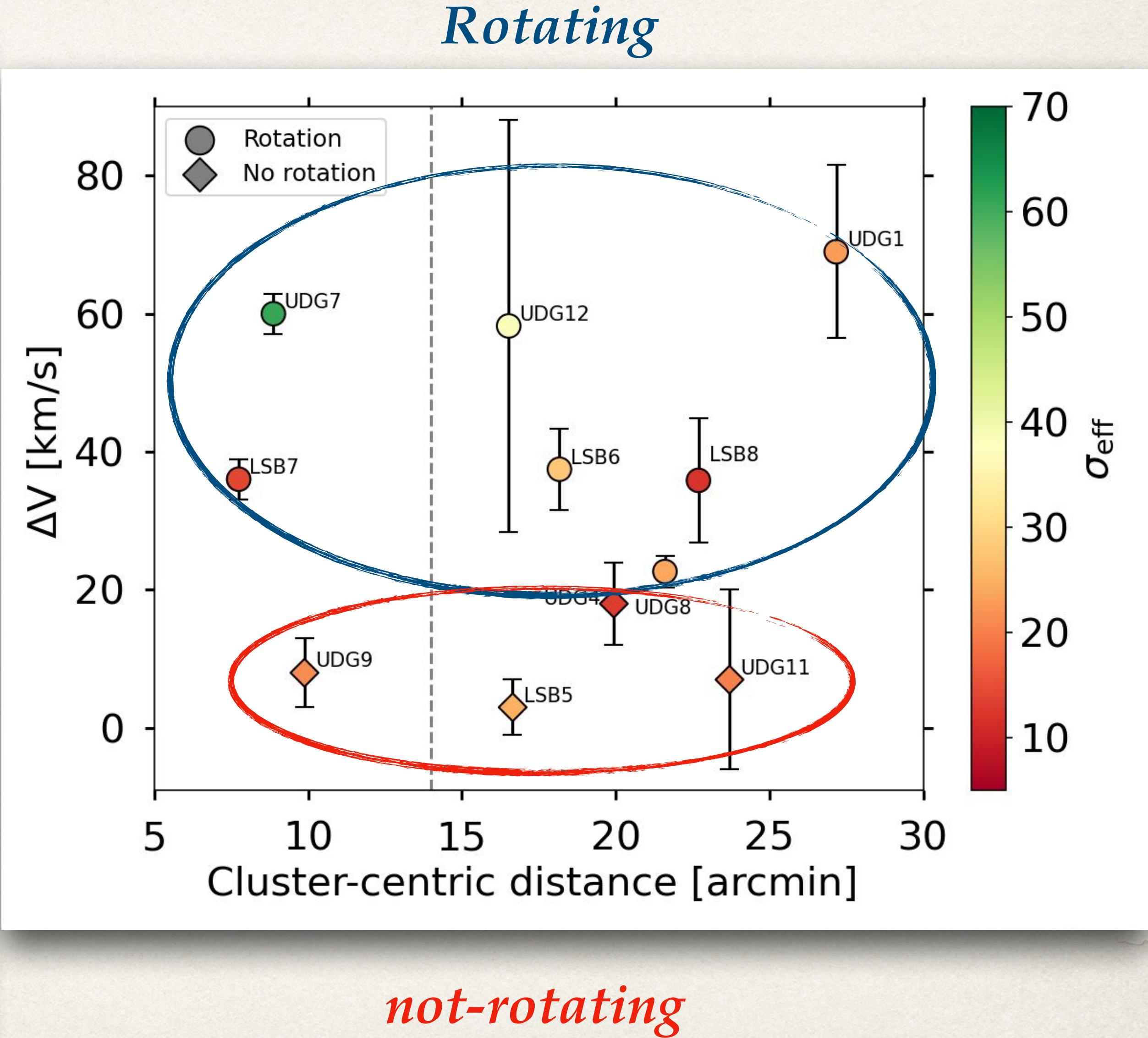
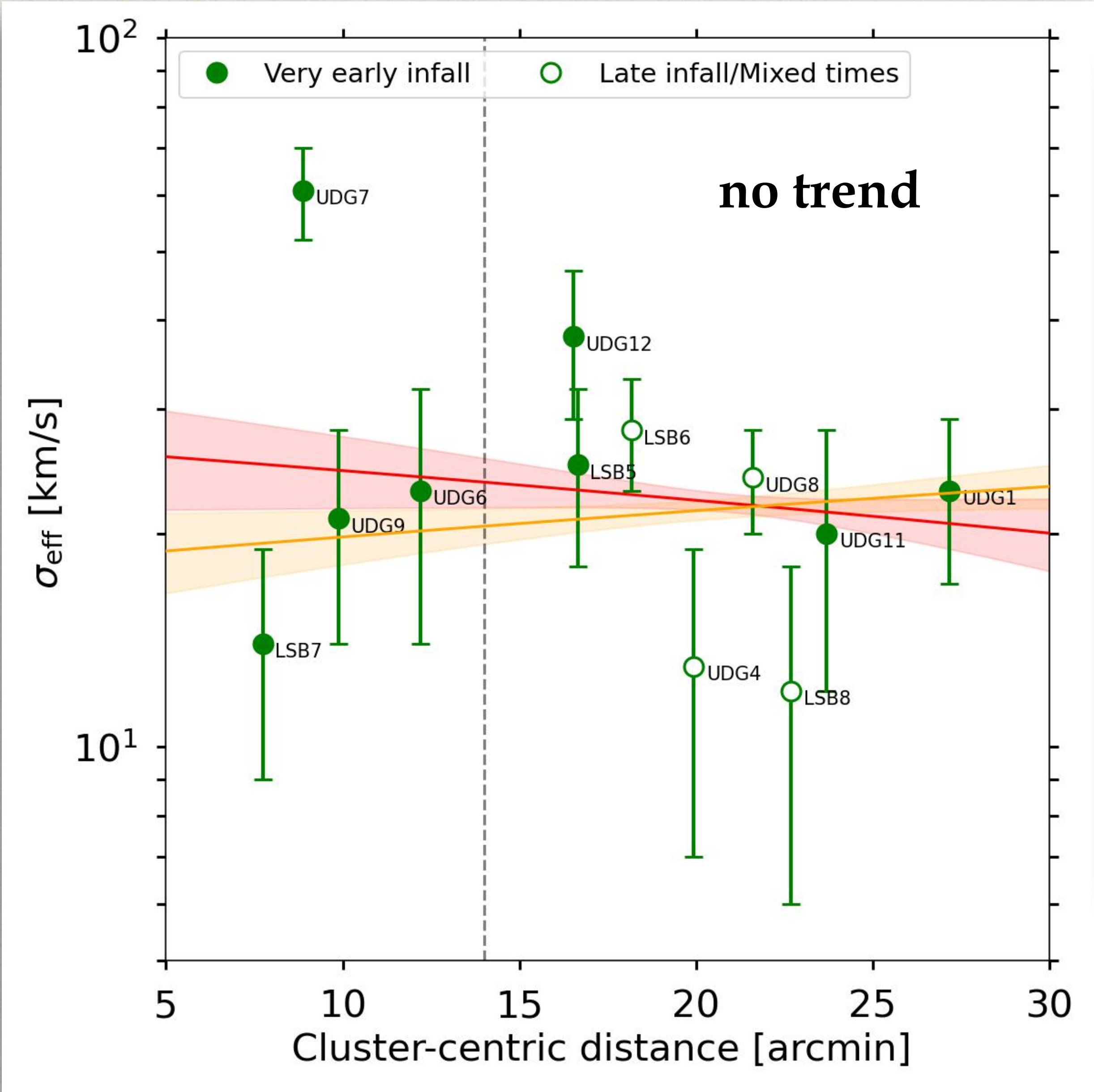




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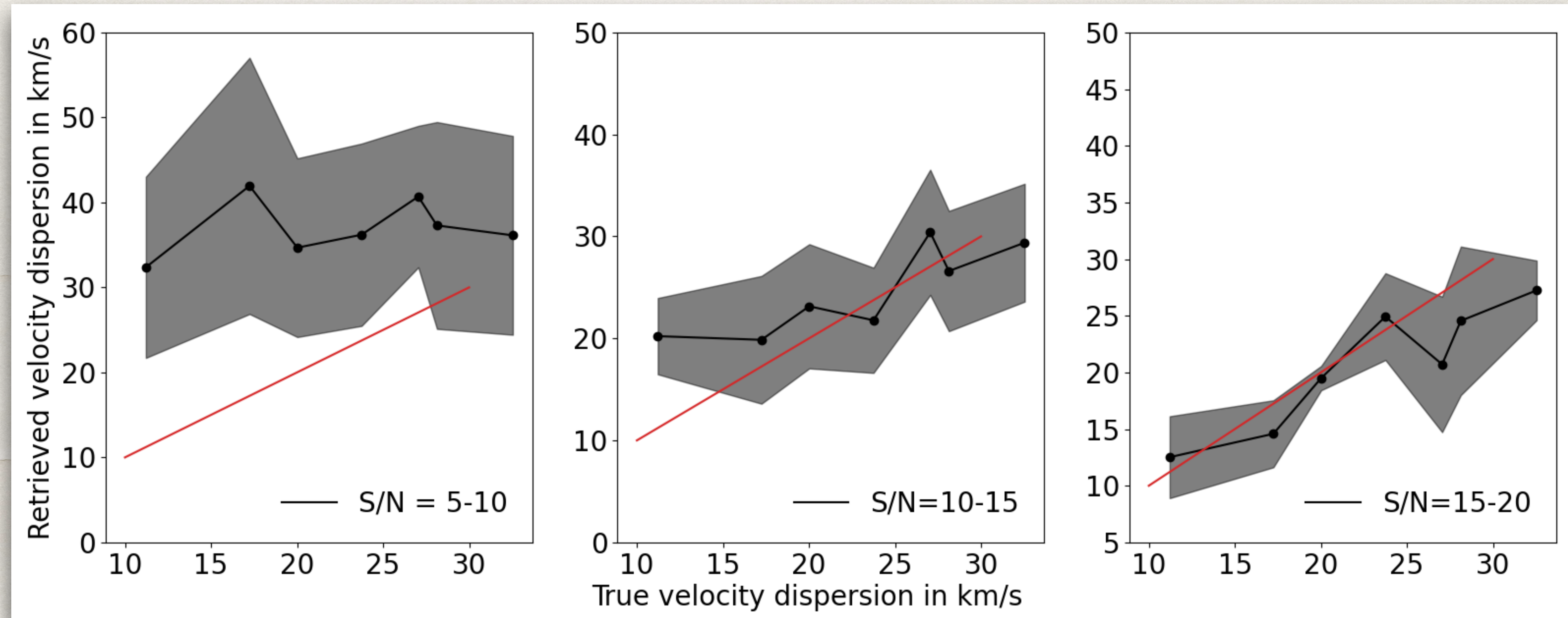
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- IV. add Poissonian noise with different  $5 < S/N < 120$  per pixel

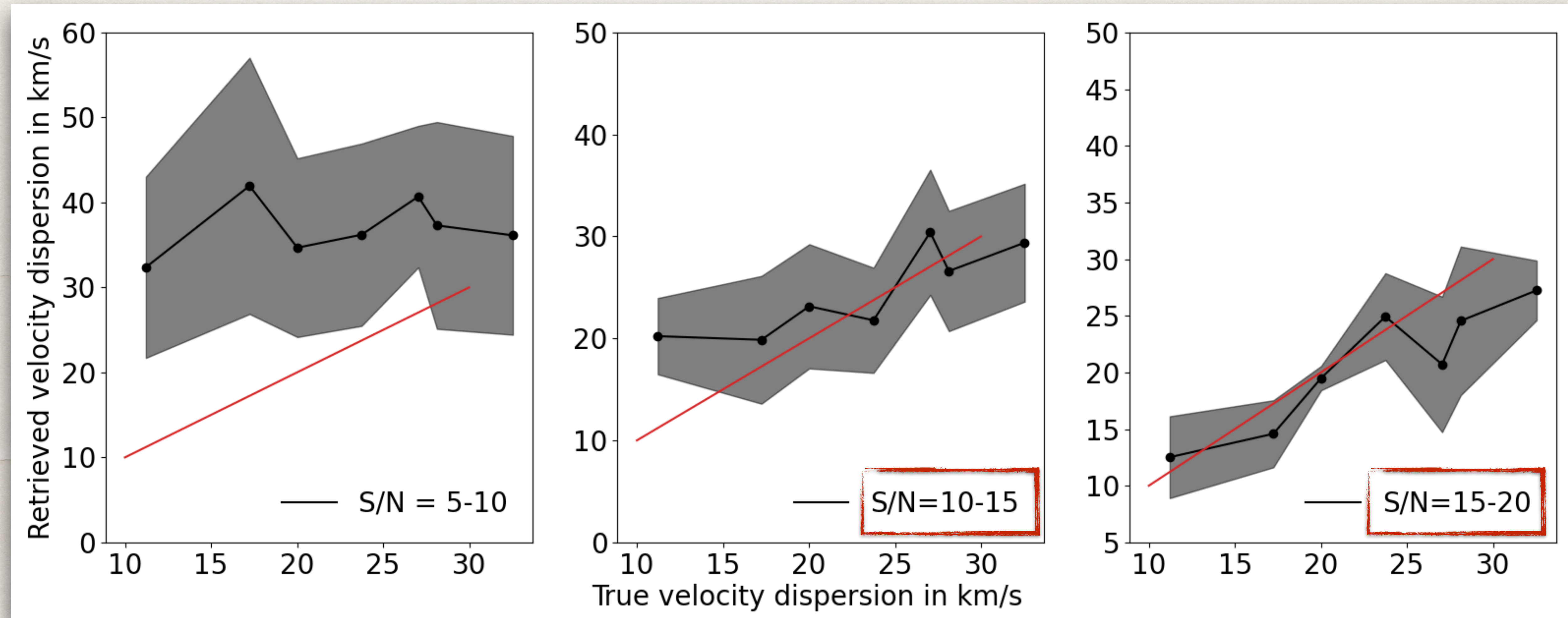


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Minimum  $S/N$  to obtain an unbiased value