

# The Ionization Mechanism of Extraplanar Diffuse Ionized Gas in Low-SFR Galaxies

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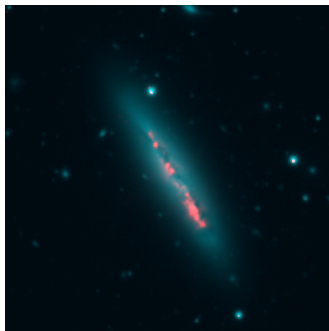
May 25, 2026

- 1 Introduction
  - Extraplanar diffuse ionized gas
  - Ionization sources
- 2 Previous work with eight low-mass edge-on galaxies
  - Sample and data
  - Overview of methods
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- 3 New sample of low-SFR galaxies
  - Sample and data
  - Preliminary analysis

# Ionized gas in galaxies

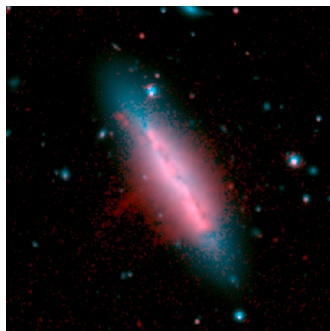
## HII regions

- Around OB star(s) in the thin disk
- Dense ( $10^3 \text{ cm}^{-3}$ )



## Diffuse Ionized Gas (DIG)

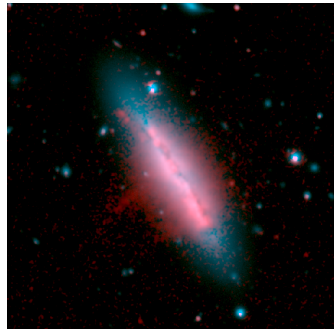
- Spread out and also at large  $z$
- Low-density ( $10^{-1} \text{ cm}^{-3}$ )



Color composite image of ESO157-49 with H $\alpha$  (red) stretched to highlight HII regions (left) and the DIG (right).

## eDIG

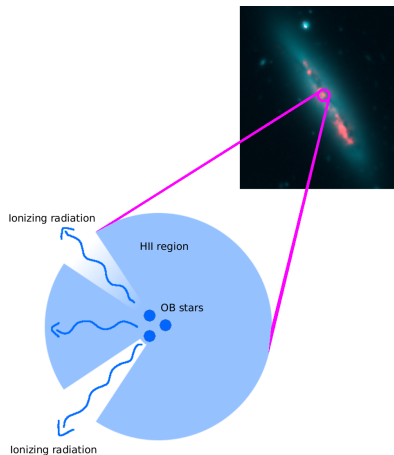
- Is observed up to several kpc above the midplane, far from the ionizing in-plane OB stars
- Has enhanced  $[\text{O III}]/\text{H}\beta$ ,  $[\text{N II}]/\text{H}\alpha$ ,  $[\text{S II}]/\text{H}\alpha$ , and  $[\text{O I}]/\text{H}\alpha$  line ratios compared to HII regions



Source: Rautio et al. 2022

How is it ionized?

# Leaky HII regions



- Standard model:  
Leaky HII regions
- Most ionizing radiation (LyC) of the OB stars absorbed by the HII region
- Some LyC photons escape through empty holes or lower density sections

# Other ionization sources

## Problems with the leaky HII regions model:

- How do the LyC photons find absorption-free pathways up to the heights of kiloparsecs above the midplane?
- Why are line ratios  $[\text{O III}]/\text{H}\beta$ ,  $[\text{N II}]/\text{H}\alpha$ ,  $[\text{S II}]/\text{H}\alpha$ , and  $[\text{O I}]/\text{H}\alpha$  observed to be enhanced in eDIG compared to HII regions; e.g. why is the ionizing spectrum different for eDIG and HII regions?

## Other ionization sources are needed:

# Other ionization sources

## Problems with the leaky HII regions model:

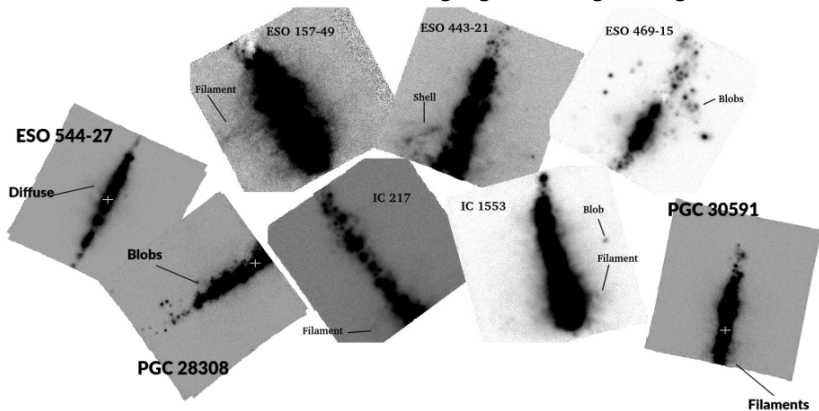
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## Other ionization sources are needed:

- In situ hot low-mass evolved stars (HOLMES, Flores-Fajardo et al. 2011)
- Shocks (e.g. Collins & Rand 2001)

# Eight low-mass edge-on galaxies

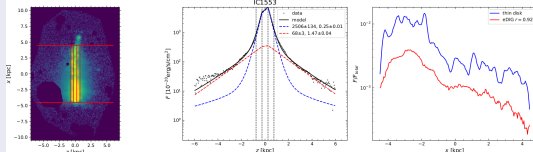
## MUSE data and narrow-band imaging of 8 edge-on galaxies



H $\alpha$  images of the sample galaxies. Produced from the MUSE data-cubes (Comerón et al. 2019) by subtracting the nearby continuum from the H $\alpha$  line. Some eDIG features are indicated.

# Methods

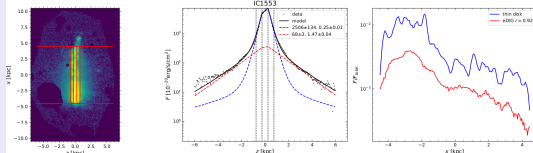
## H $\alpha$ profiles



Source: Rautio et al. 2022

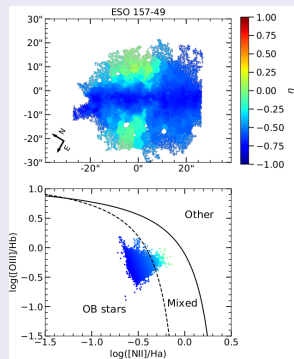
# Methods

## H $\alpha$ profiles



Source: Rautio et al. 2022

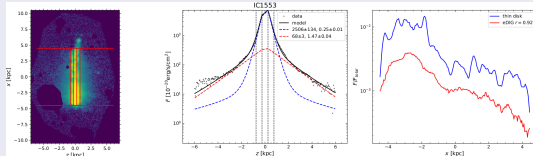
## Emission line diagnostics



Source: Rautio et al. 2022

# Methods

## H $\alpha$ profiles

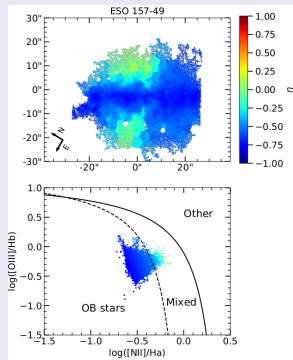


Source: Rautio et al. 2022

## Photoionization modeling

- Cloudy version 23.00 (Chatzikos et al. 2023)
- Fit to emission line ratios over z-axis

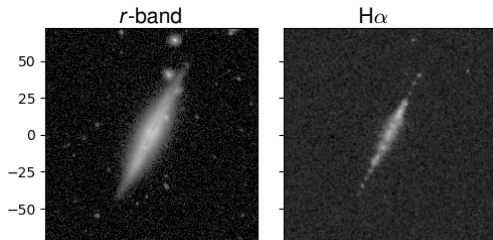
## Emission line diagnostics



Source: Rautio et al. 2022

# Results

Majority of eDIG in our sample galaxies is ionized by radiation escaping from midplane HII regions, and localized shocks



Source: Rautio et al. 2022

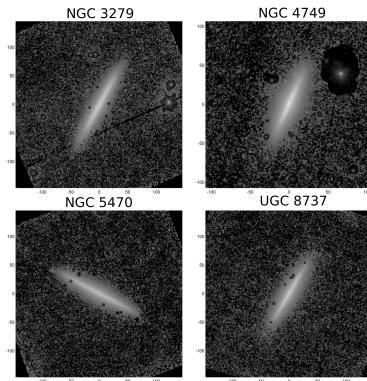
ESO 544-27 is unique in the sample:

- HOLMES driven ionization ( $\sim 20\%$  of eDIG)
- Lowest SFR
- Old stellar population ( $H\alpha/FUV$ )

HOLMES driven ionization is important for low-SFR galaxies?

# Four low-SFR galaxies

- $FUV-NUV > 0.35$  mag,  
 $NUV-[3.6] > 4.3$  mag  
in DAGAL
- $M_T/M_t > 0.4$  in  
Comerón et al. 2018
- Narrow-band  $H\alpha$  observations  
with NOT in 2025
- WEAVE @ WHT observations  
pending



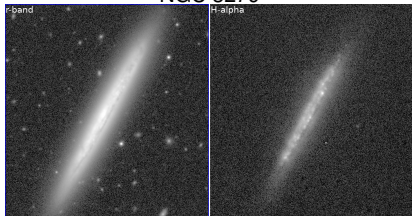
Source: [oulu.fi/astronomy/S4G.PIPELINE4/MAIN/](http://oulu.fi/astronomy/S4G.PIPELINE4/MAIN/)

Sample of 4 edge-on galaxies with less star formation, older stellar populations and more massive thick disks than

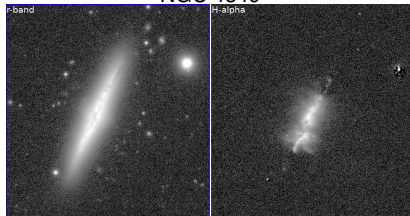
ESO 544-27

# The eDIG in low-SFR galaxies

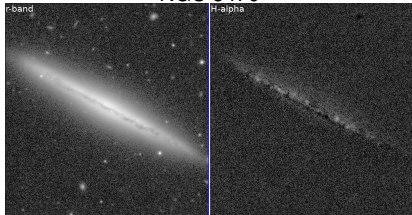
NGC 3279



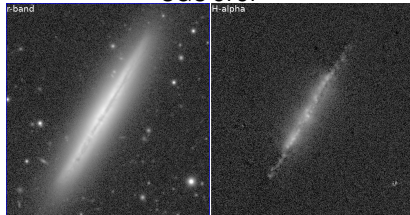
NGC 4849



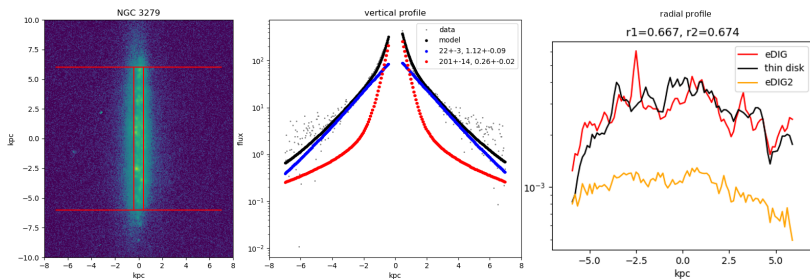
NGC 5470



UGC 8737



# Vertical and radial profiles

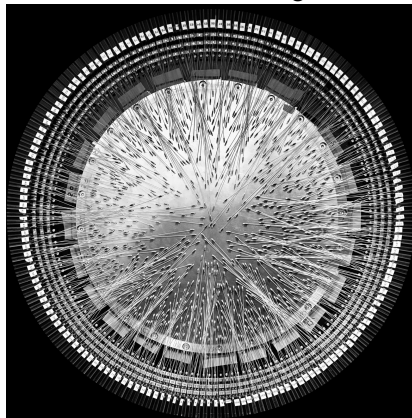


- eDIG scale heights of 1.12 kpc, 0.78 kpc, and 1.19 kpc
- Good correlation between midplane and eDIG radial H $\alpha$  profiles ( $r > 0.5$ )
- No good two disk fit for NGC 5470

## Next steps

- NGC 5470 vertical and radial profiles
- NGC 3379 emission-line diagnostics from MUSE data (GECKOS survey)
- Need WEAVE data for emission-line diagnostics of other galaxies

### A WEAVE fibre configuration



Source: ING & Ruben Sanchez-Janssen

# Summary

- We found evidence for significant ( $\sim 20\%$ ) **HOLMES** driven ionization in the **low-SFR** galaxy ESO 544-27
- To investigate if this is a common feature in low-SFR galaxies, we obtained **NOT** narrow-band  $H\alpha$  imaging of a new sample of four low-SFR edge-on galaxies
- Positive detection of eDIG  $H\alpha$  emission **in all four galaxies**

If you consider this research worthwhile...

# Summary

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PLEASE HIRE ME!

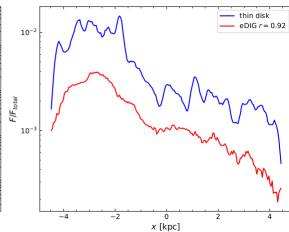
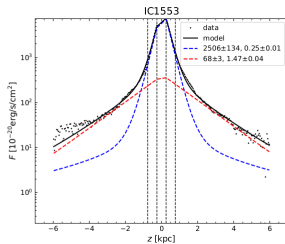
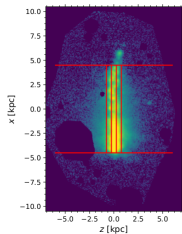
I'm looking for a  
postdoc position :)

[riku.rautio93@gmail.com](mailto:riku.rautio93@gmail.com)

# EXTRA SLIDES

# H $\alpha$ photometry

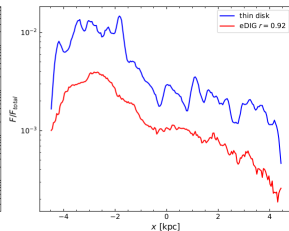
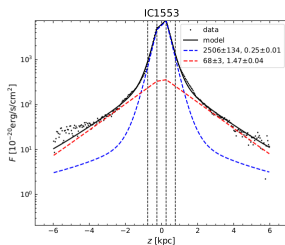
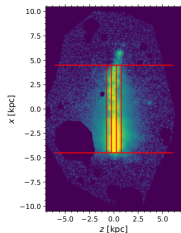
- Obtained with NTT and NOT for five of the sample galaxies (Rautio et al. 2022)
- Double-exponential fit to the vertical H $\alpha$  profile
- Thinner component: quiescent DIG
- Thicker component: disturbed eDIG



Source: Rautio et al. 2022

# H $\alpha$ photometry

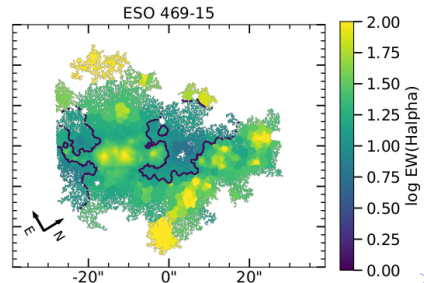
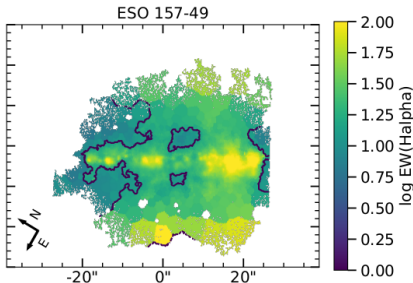
- eDIG scale heights range from 0.63 to 1.53 kpc
- We calculate Pearson correlation between the midplane and the eDIG radial H $\alpha$  profiles
- Some degree of correlation between the eDIG and disk radial profiles in all galaxies ( $r = 0.15$ – $0.92$ )



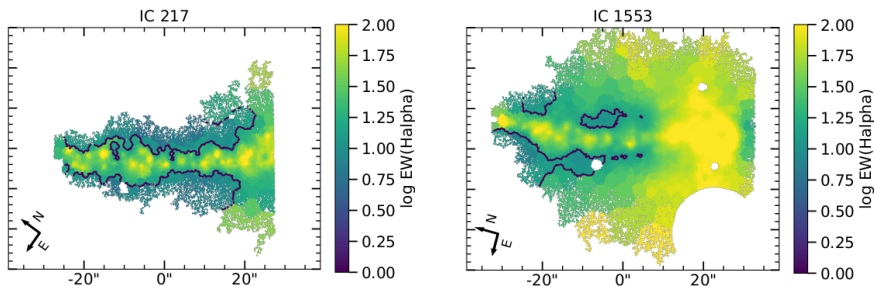
Source: Rautio et al. 2022

# H $\alpha$ equivalent width

- $EW(H\alpha) = L_{H\alpha} / C_{H\alpha}$
- Strong anti-correlation with the age of the ionizing population
- HOLMES dominated ionization:  $\log EW(H\alpha) \lesssim 0.5 \text{ \AA}$
- Mixed OB–HOLMES ionization:  $0.5 \lesssim \log EW(H\alpha) \lesssim 1.1 \text{ \AA}$  (Lacerda et al. 2018)



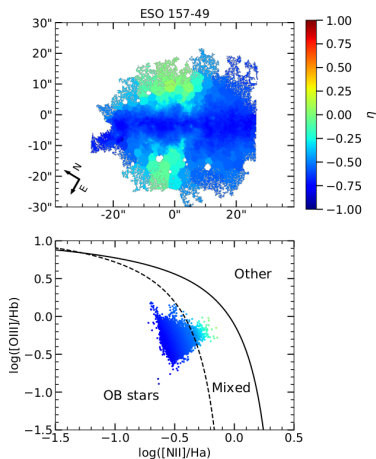
# H $\alpha$ equivalent width



- No HOLMES dominated ionization
- Local OB–HOLMES ionization
- Evolved stars evenly distributed – ionizing power of OB stars must vary locally
- HOLMES ionization anti-correlates with sSFR

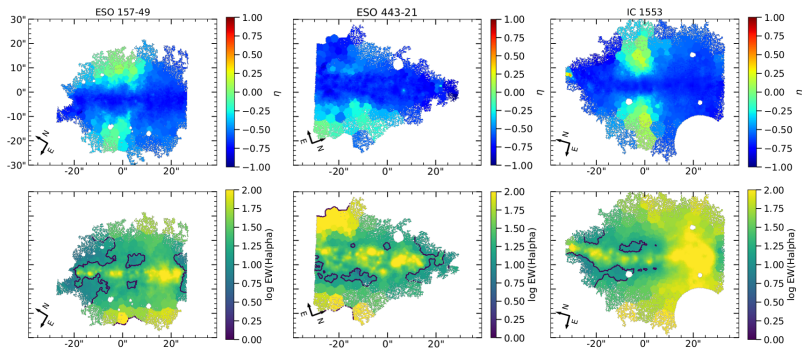
# BPT diagrams

- Diagram using  $[\text{O III}]/\text{H}\beta$  against  $[\text{N II}]/\text{H}\alpha$  line ratios
- Can demarcate OB star ionization, mixed ionization, and other ionization (Kewley et al. 2001, Kauffman et al. 2003)
- The  $\eta$ -parameter is defined as the distance from the demarcation lines so that  $\eta \leq -0.5$  indicates OB stars,  $\eta \geq +0.5$  HOLMES or shocks, and  $-0.5 \leq \eta \leq +0.5$  mixed cause for ionization.



Source: Rautio et al. 2022

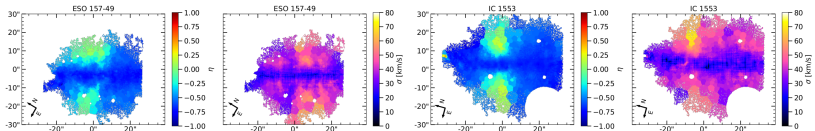
# BPT diagrams



- However, mixed ionization in different areas than the OB–HOLMES ionization For ESO 157-49, ESO 443-21 and IC 1553
- Shock ionization?

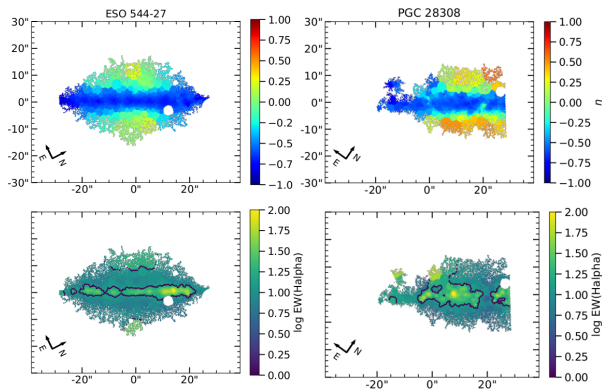
# Velocity dispersion

- Velocity dispersion is enhanced in shock ionized gas (Kewley et al. 2019)
- The eDIG of ESO 157-49, ESO 443-21 and IC 1553 has enhanced velocity dispersion
- The regions of enhanced  $\eta$ -parameter in ESO 157-49, ESO 443-21 and IC 1553 are caused by shock ionization



Source: Rautio et al. 2022

# OB-HOLMES ionization



- BPT diagrams agree with  $\text{EW}(\text{H}\alpha)$  maps for ESO 544-27 and PGC 28308 – non-OB ionization caused by HOLMES?
- However, PGC 28398 has an enhanced velocity dispersion

# Cloudy photoionization code

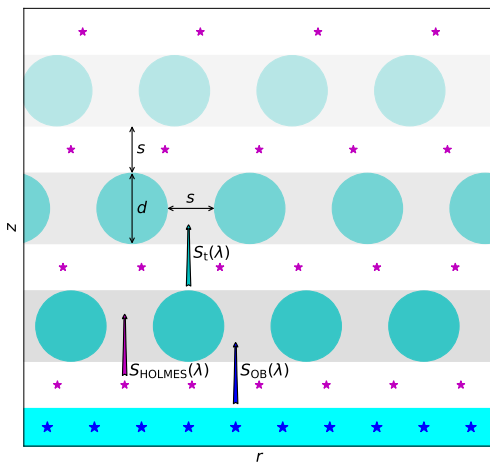
- Cloudy version 23.00 (Chatzikos et al. 2023)
- Simulates physical conditions in interstellar matter
- Takes as input the ionizing spectra and the chemical and physical condition of the cloud
- Predicts the thermal, ionization, and chemical structure of a cloud
- Predicts the observed emission spectrum of a cloud

# Schematic view of the model

Three ionizing sources:

- OB stars (Starburst99, Leitherer et al. 1999)
- HOLMES (Pegase.3, Fioc & Rocca-Volmerange 2019)
- Transmitted radiation

Cloudy is ran once for each cloud layer

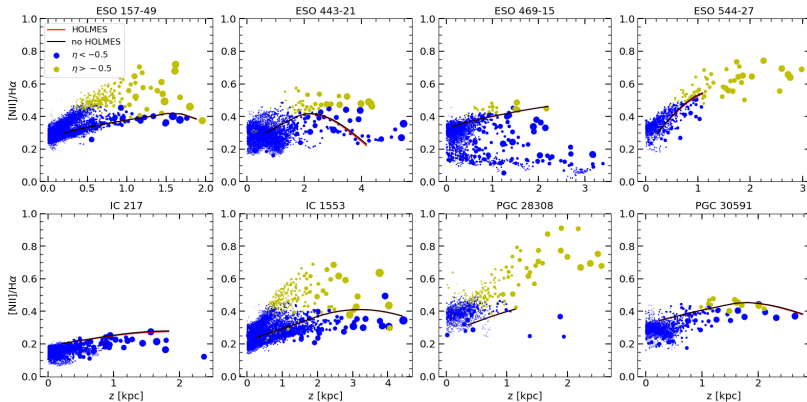


Source: Rautio et al. 2024

# Fitting the model to data

- OB star flux is scaled with measured SFR
- HOLMES flux is scaled with measured thick disk mass
- Gas density profile follows the measured  $H\alpha$  profile
- Metallicity is obtained from the line-ratio data
- Filling factor  $f_V$  and ionization parameter  $U_1$  are left as free parameters

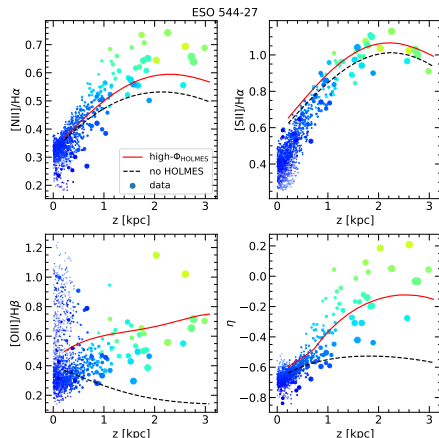
# Best fit model line-ratio profiles



For most of the galaxies, HOLMES make no difference

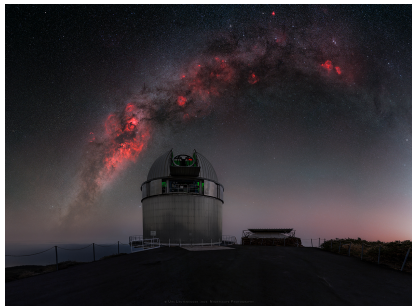
## eDIG of the low-SFR galaxy ESO 544-27

- In the eDIG of ESO 544-27,  $\eta > -0.5$  cannot be explained with leaking OB star radiation alone
- assuming  $1.5\times$  more HOLMES and halved OB star flux we can find a model that reproduces the observed  $\eta > -0.5$
- HOLMES are responsible for  $\sim 20\%$  of the ionizing radiation received by the eDIG of ESO 544-27



Source: Rautio et al. 2024

# Observations



Source: NOT & Urs Leutenegger



- Narrow-band  $H\alpha$  imaging with ALFOSC @ NOT (2.56m)
- Six nights of observations
- Total 10.5 hours of  $H\alpha$  exposure per galaxy\*
- WEAVE @ WHT application

\* if the weather allows!