Molecular Gas and Star Formation in Jellyfish Galaxies

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Ram pressure and Jellyfish galaxies

The most dramatic way to deprive a galaxy of its fuel for star formation is to directly remove the cold ISM already in its disk

Hydrodynamical

direct interaction between the ISM and the intra-group, or intra-cluster medium (ICM)

- Viscous stripping
- *Ram pressure stripping*
- Thermal evaporation

Gravitational

gravitational pull affecting galaxies while orbiting in groups and clusters

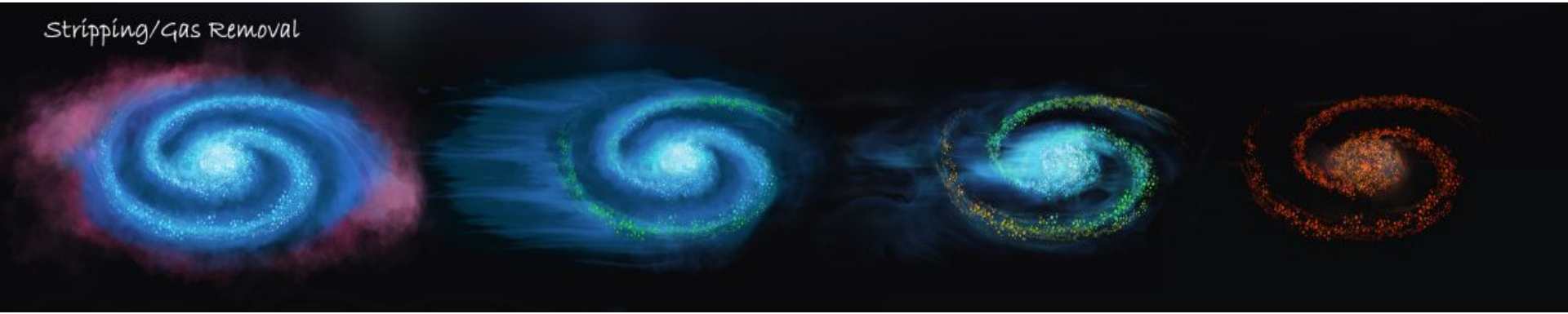


Illustration showing the stripping of the gas, with emphasis on what happens to the cold gas of the ISM (diffuse blue).

Ram pressure and Jellyfish galaxies

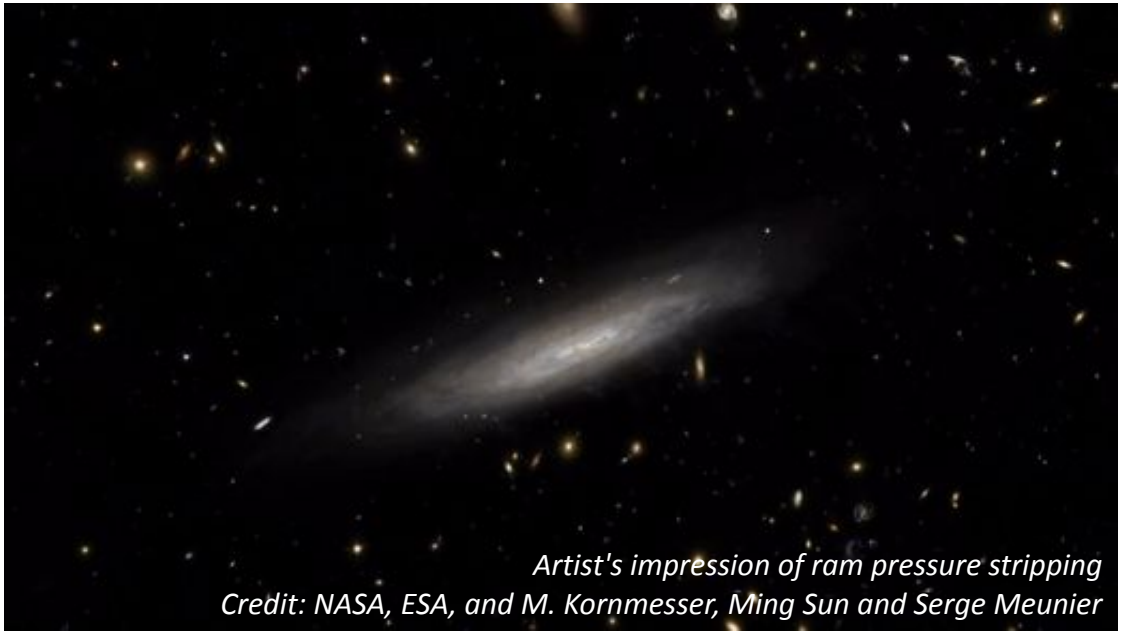
Ram pressure stripping - the removal of the ISM due to the pressure exerted by the ICM while a galaxy is moving through its host halo. (Gunn & Gott, 1972)



Ram pressure stripped galaxies will often have a large trailing tail and because of this they are commonly called

“Jellyfish galaxies”





Artist's impression of ram pressure stripping
Credit: NASA, ESA, and M. Kornmesser, Ming Sun and Serge Meunier

Star formation in galaxies– the Kennicutt-Schmidt Relation

Star formation is the process by which gas in star forming regions collapse and form stars.

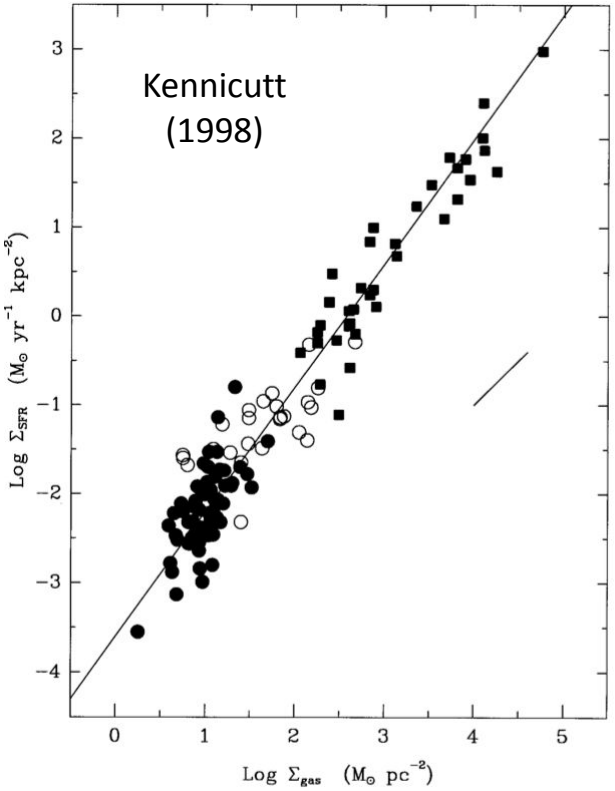
Star formation rate (SFR)

Kennicutt–Schmidt law is an empirical relation between the surface gas density and star formation rate (SFR) in a given region

$$\Sigma_{SFR} = A\,\Sigma_{gas}^{N}$$

const

some positive number



The original Kennicutt-Schmidt diagram.
The relation is shown for normal spiral galaxies (filled circles) and starburst nuclei (squares).

Tracers of molecular gas and SFR

Molecular hydrogen, H2, is the most abundant molecule in the universe.
Star formation is fueled by cold molecular gas (<50K).

Unfortunately cold H2 is not directly observable in emission.

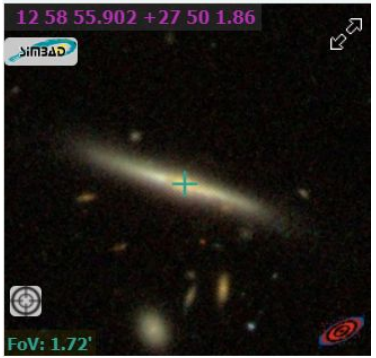
With low energy and critical density CO is easily excited even in cold molecular clouds.
It has thus become the workhorse tracer of the bulk distribution of H2.



The Hα emission line is used as an effective probe of star formation region.
(the Hα emission is a result of the interaction between galaxy-galaxy and tidal interaction occurring within the galaxy groups as the trigger for the massive star formation)

IC3949

IC 3949 is a Lenticular Jellyfish Galaxy in the Coma Berenices constellation.



Credit: SIMBAD

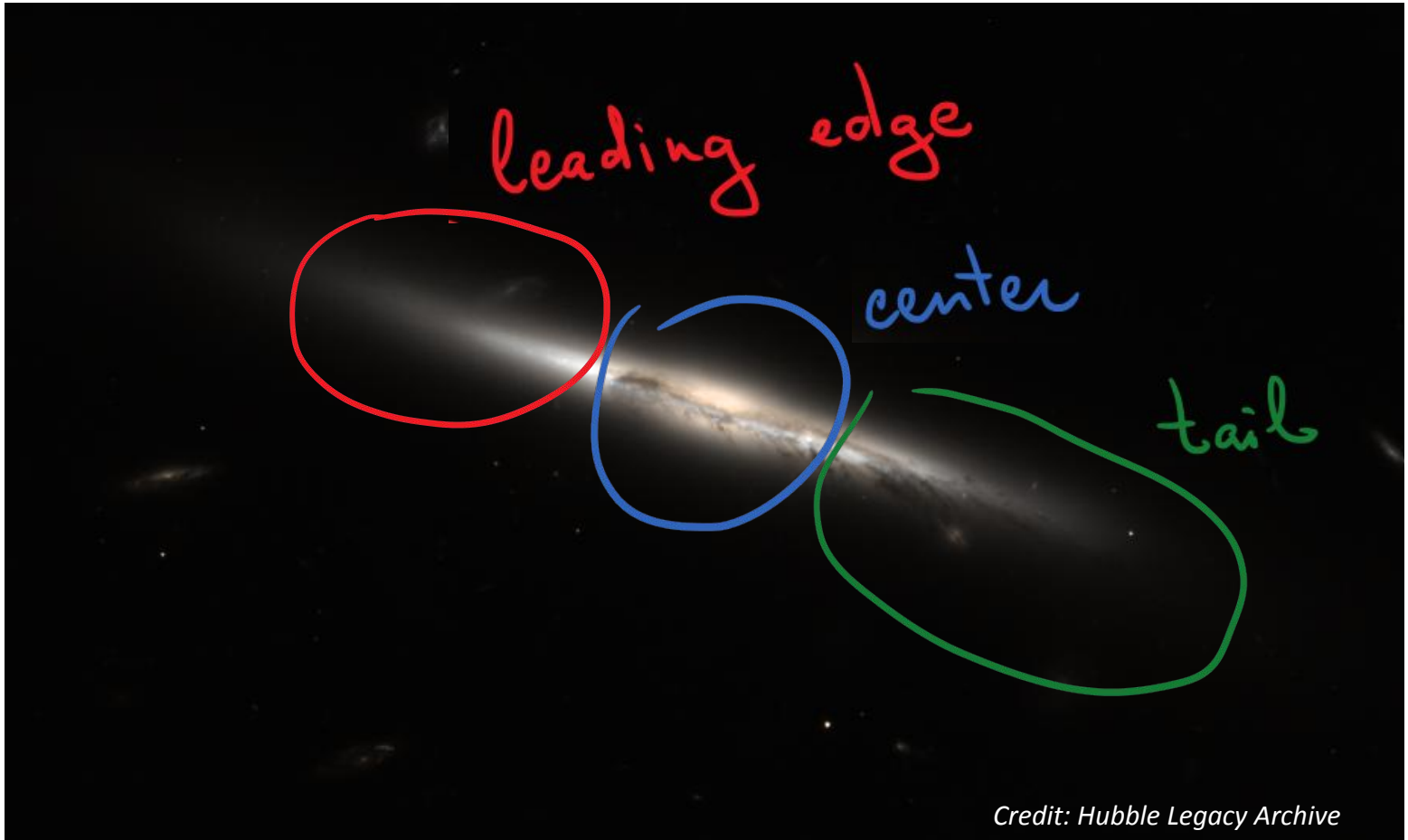
IC3949

IC 3949 is a Lenticular Jellyfish Galaxy in the Coma Berenices constellation.



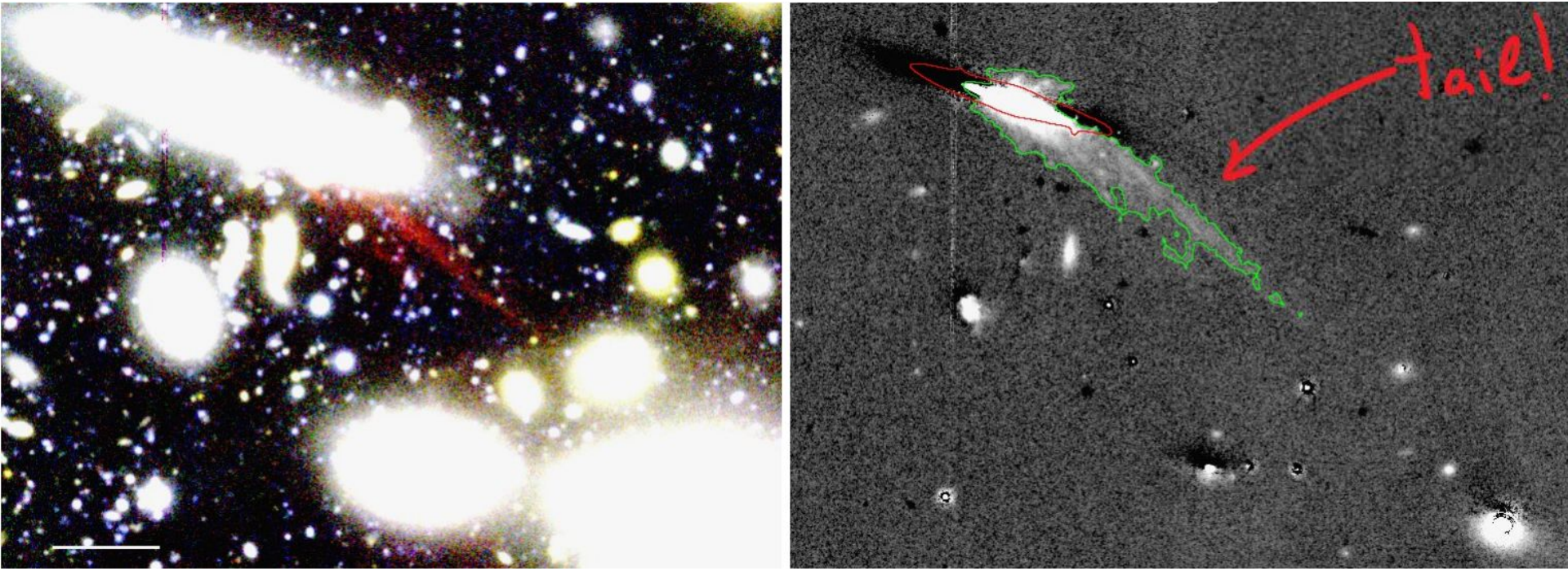
IC3949

IC 3949 is a Lenticular Jellyfish Galaxy in the Coma Berenices constellation.



IC3949

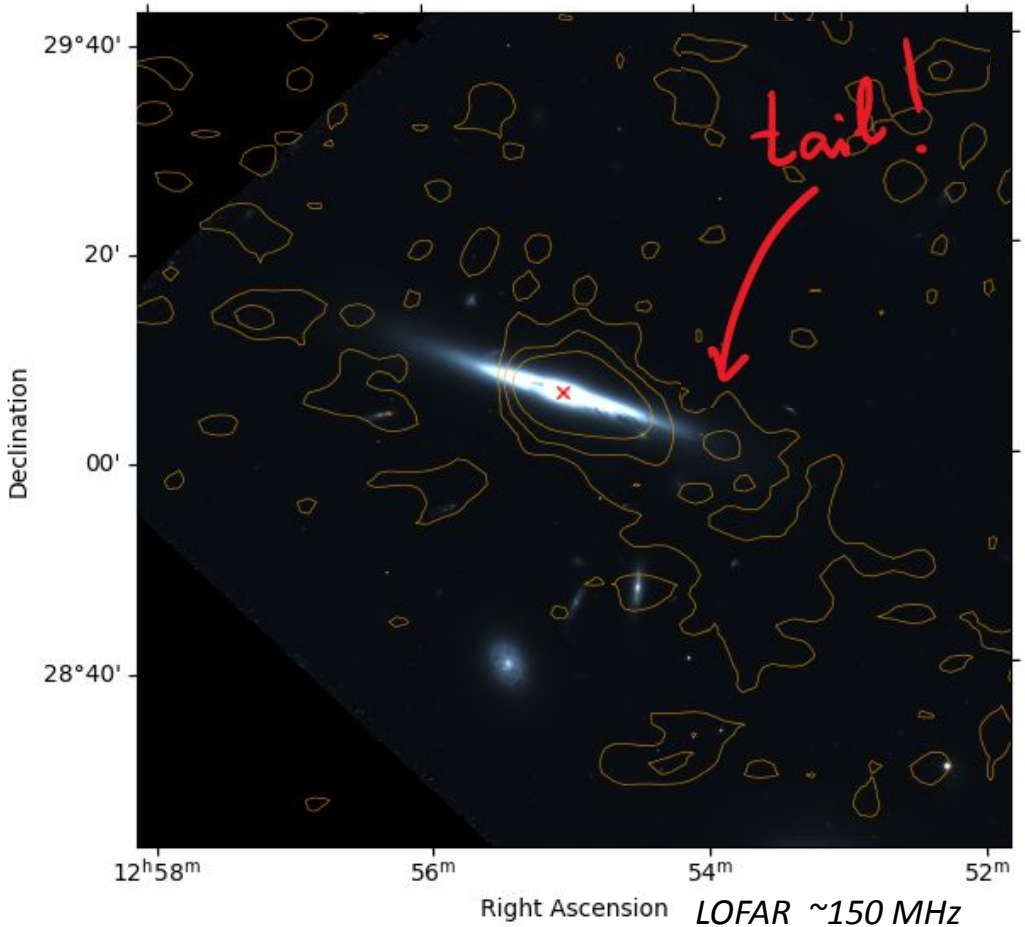
IC 3949 is a Lenticular Jellyfish Galaxy in the Coma Berenices constellation.



Credit: "A dozen new galaxies caught in the act: Gas stripping and extended emission line regions in the Coma cluster" – M. Yagi, M. Yoshida et al. (2010)

IC3949

IC 3949 is a Lenticular Jellyfish Galaxy in the Coma Berenices constellation.



LOFAR ~150 MHz

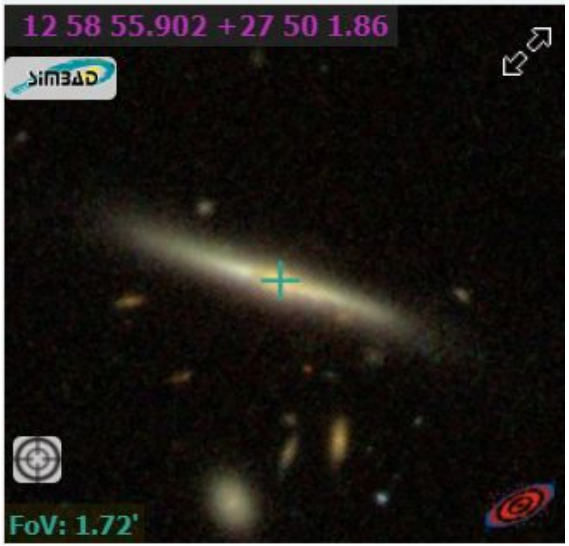
IC3949 and our goal

explore the effect of RPS on the spatial distribution of molecular gas

✔ image molecular line data from ALMA,
(the CO(J=1-0) transition that trace bulk molecular gas and dense molecular gas in galaxies)

explore the relationship between molecular gas and star formation rate

✔ using MaNGA survey image star formation rate across galaxy and build the Kennicutt-Schmidt Relation



Used telescopes and surveys

1. ALMA

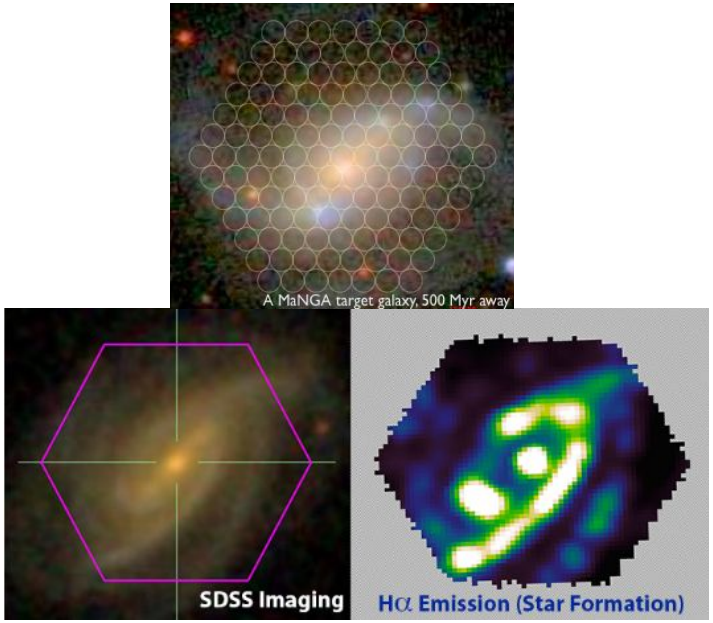
Atacama Large Millimeter/submillimeter Array (ALMA)



CO part

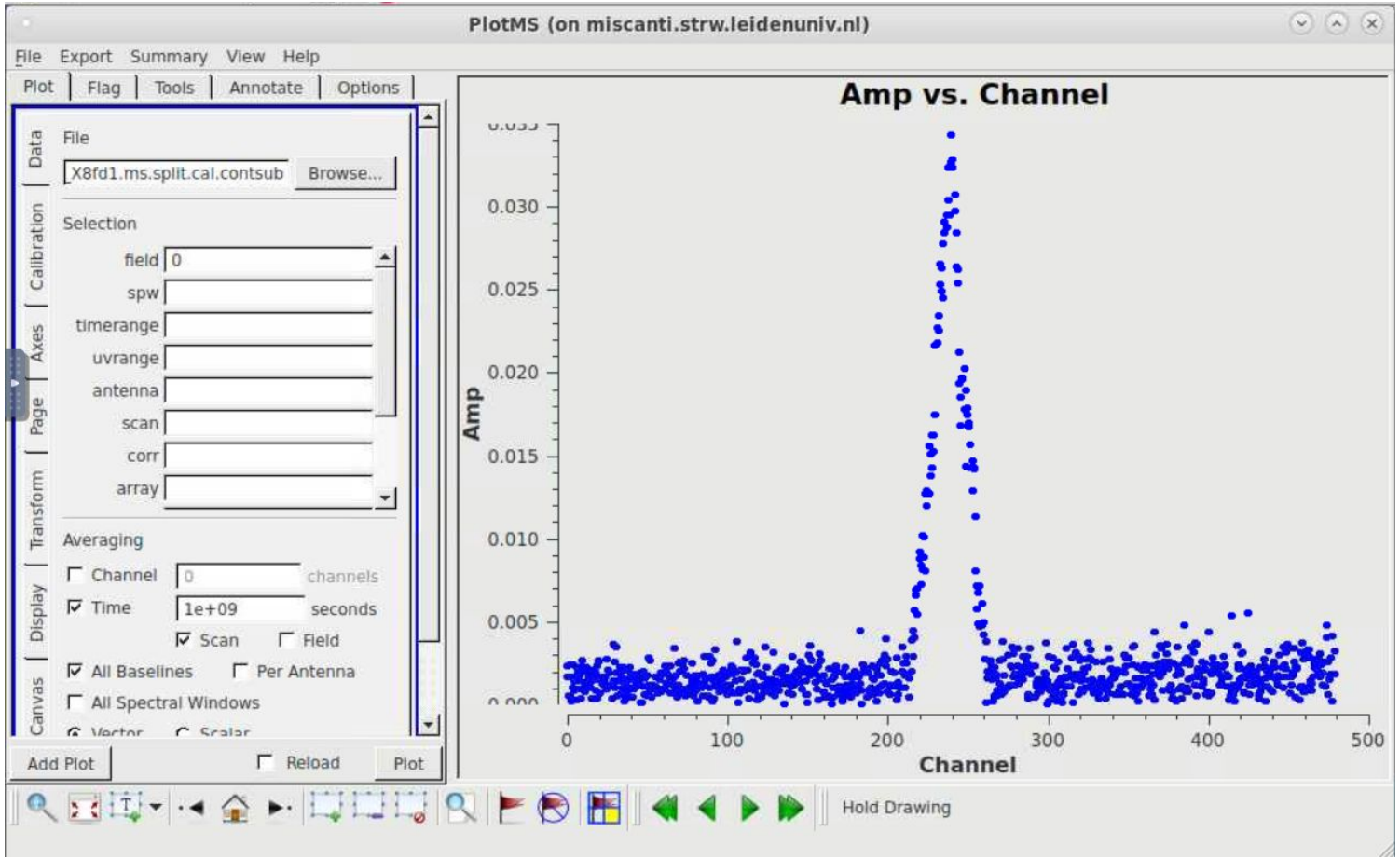
2. MaNGA

Mapping Nearby Galaxies at APO

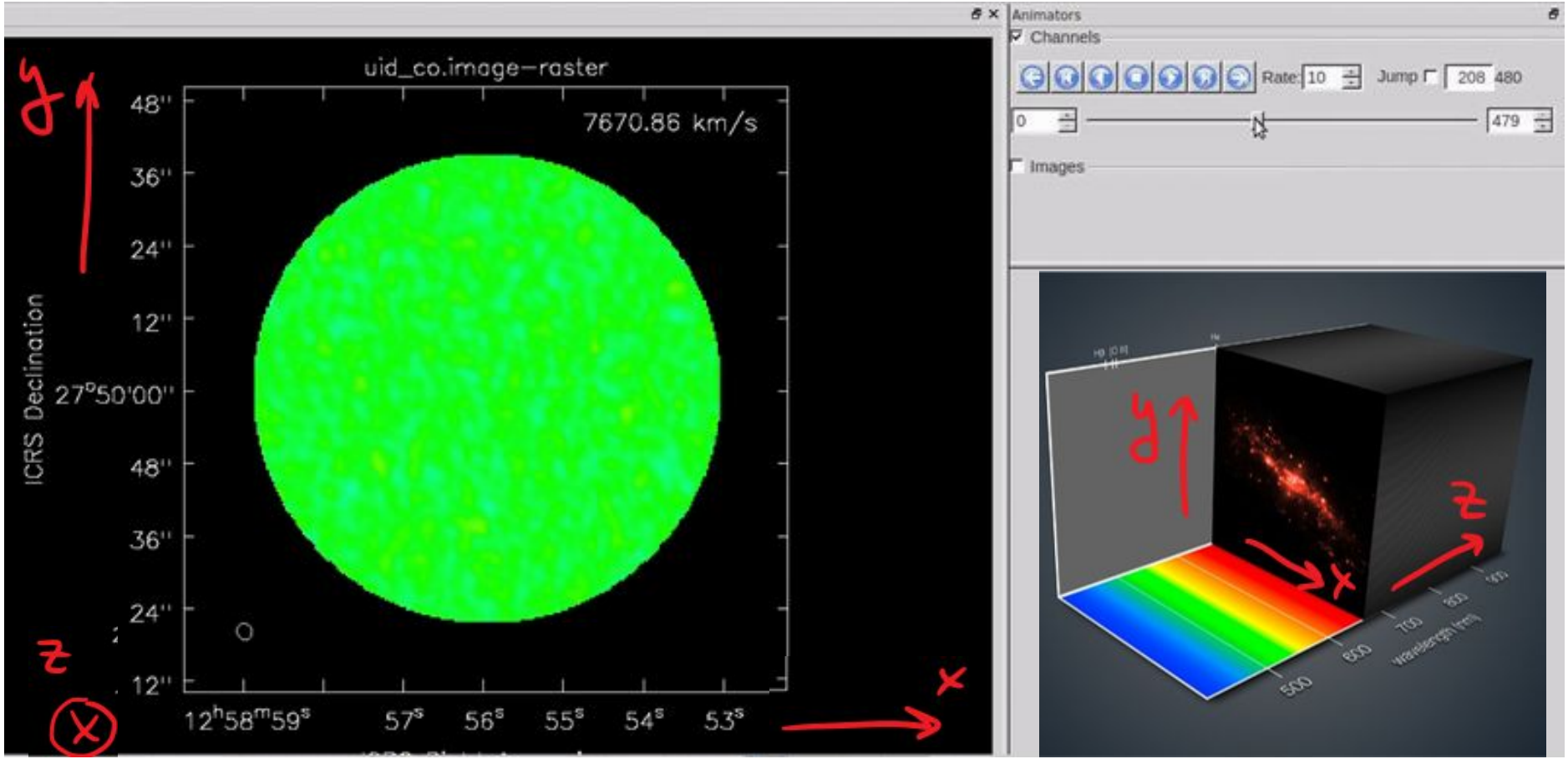


SFR part

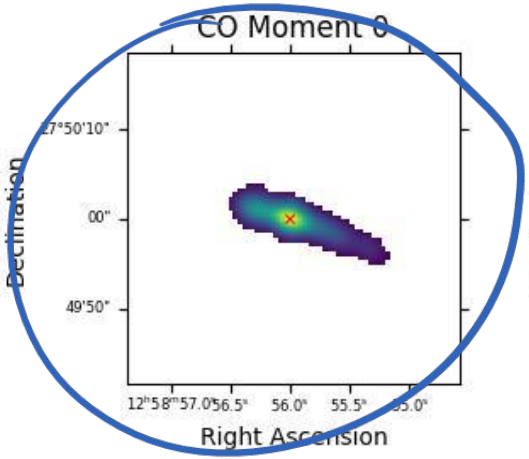
ALMA continuum subtraction .

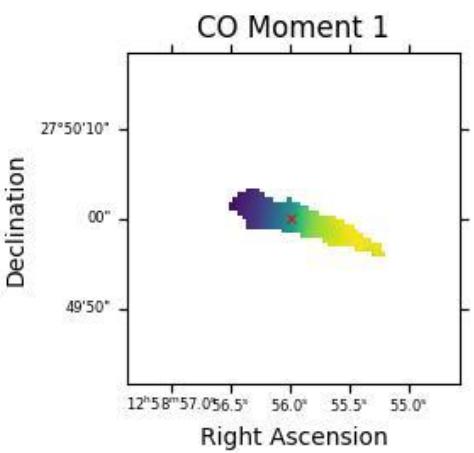


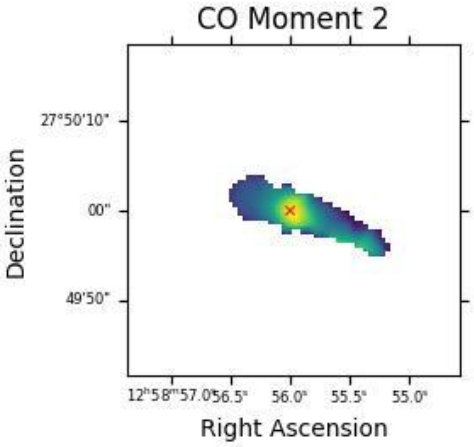
ALMA building the cube

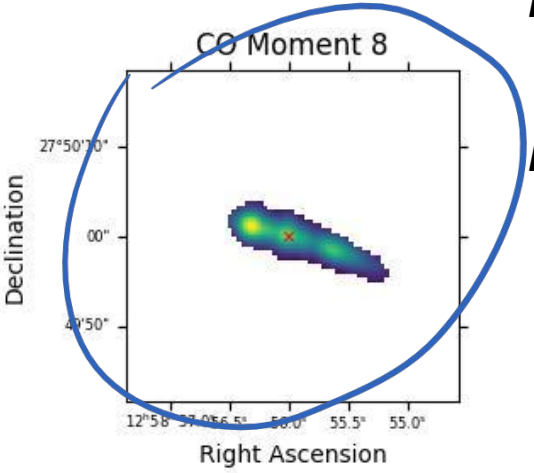


ALMA making moment maps









Moment 0 –
- integrated value of the spectrum

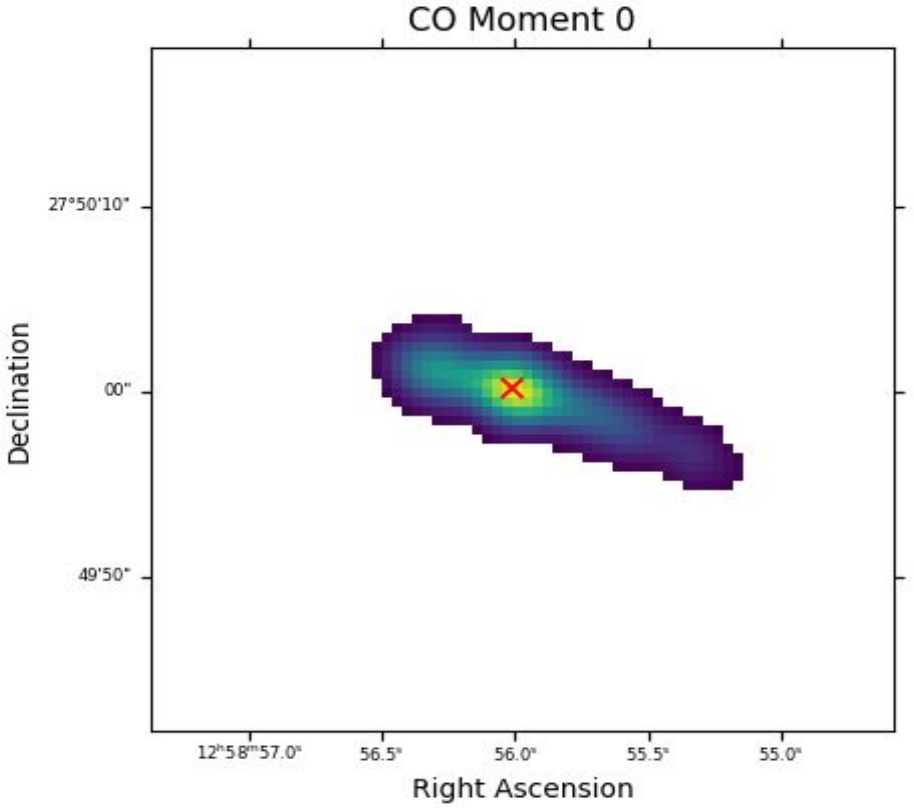
Moment 1 –
- velocity fields

Moment 2 –
- velocity dispersion

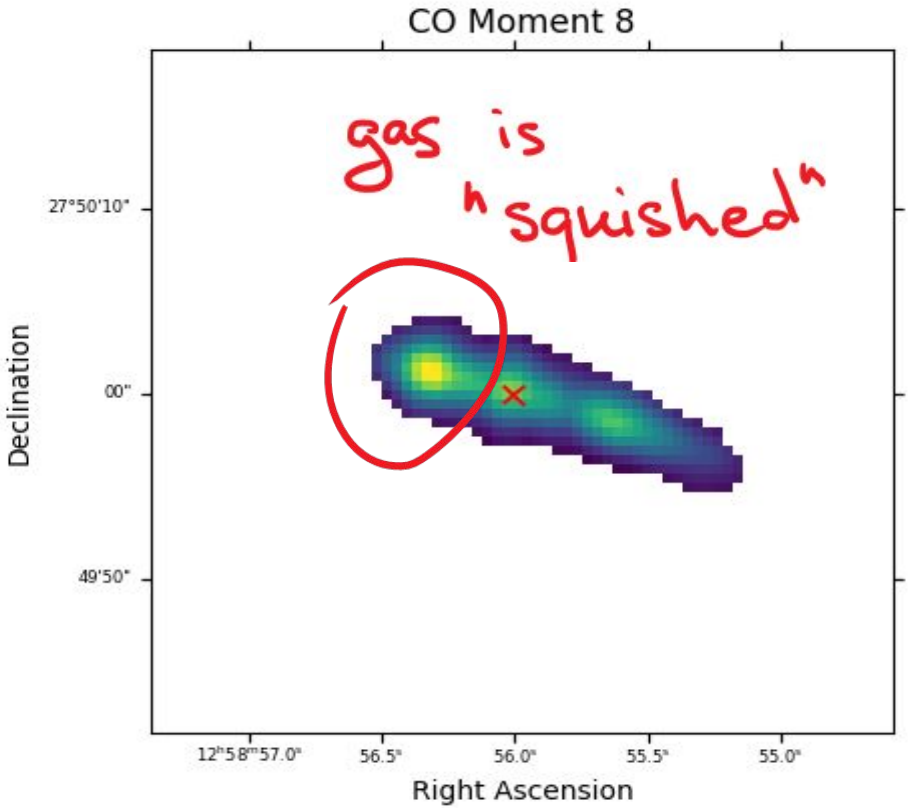
Moment 8 –
- maximum value of the spectrum

ALMA making moment maps

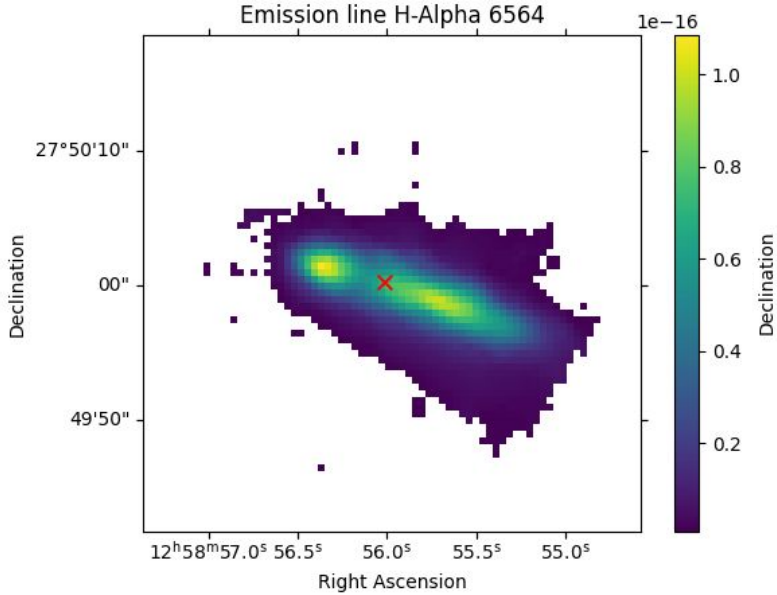
integrated value of the spectrum

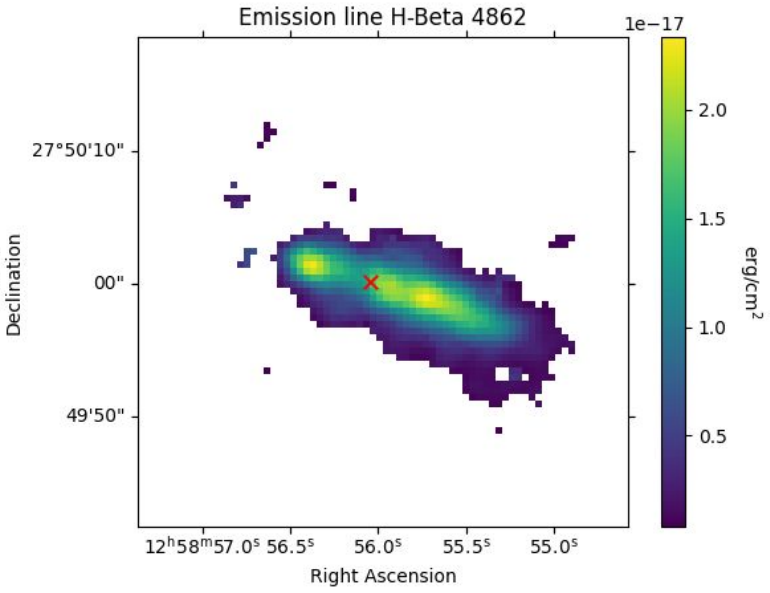


maximum value of the spectrum



MaNGA Hα and Hβ lines





Hα traces massive star formation regions

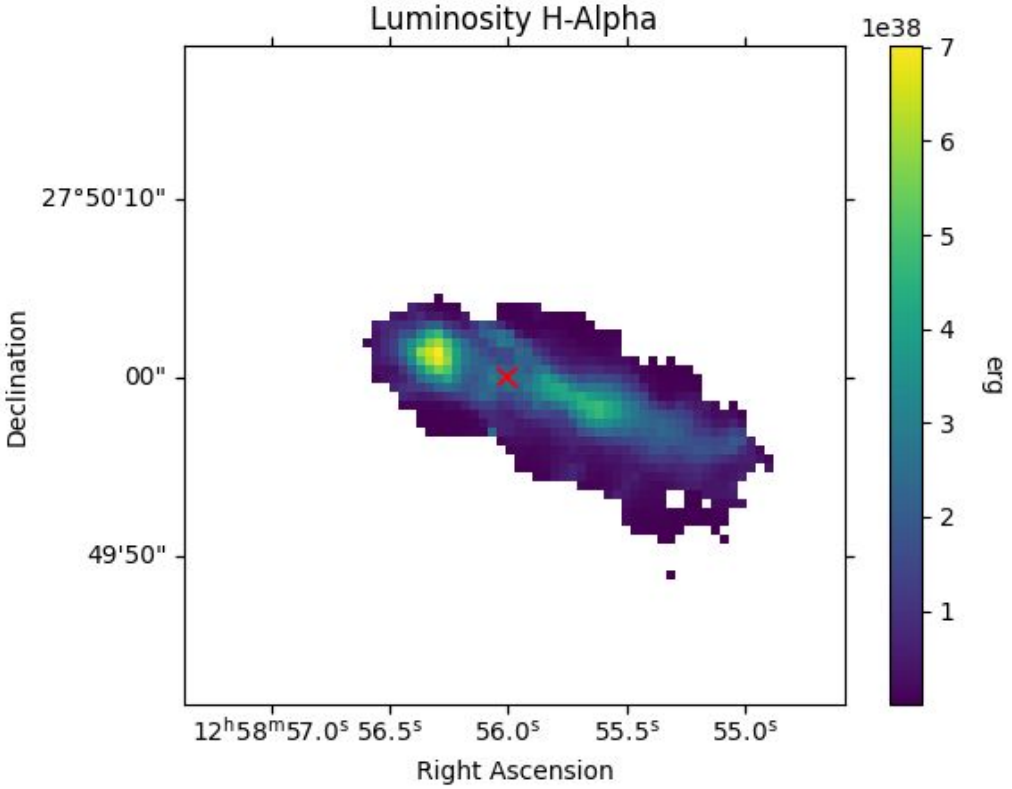
Hβ is used to correct Hα for dust extinctions

$$F_{\lambda,0} \cong F_{\lambda} \cdot \left(\frac{F_{H\alpha}/F_{H\beta}}{F_{H\alpha,0}/F_{H\beta,0}} \right)^{0.76 \cdot \left(\frac{E_{\lambda-V}}{E_{B-V}} + 4.5 \right)}$$

$$\frac{E_{\lambda-V}}{E_{B-V}} \cong -4.61777 + 1.41612 \cdot \lambda^{-1} + 1.52077 \cdot \lambda^{-2} - 0.63269 \cdot \lambda^{-3} + 0.07386 \cdot \lambda^{-4}$$

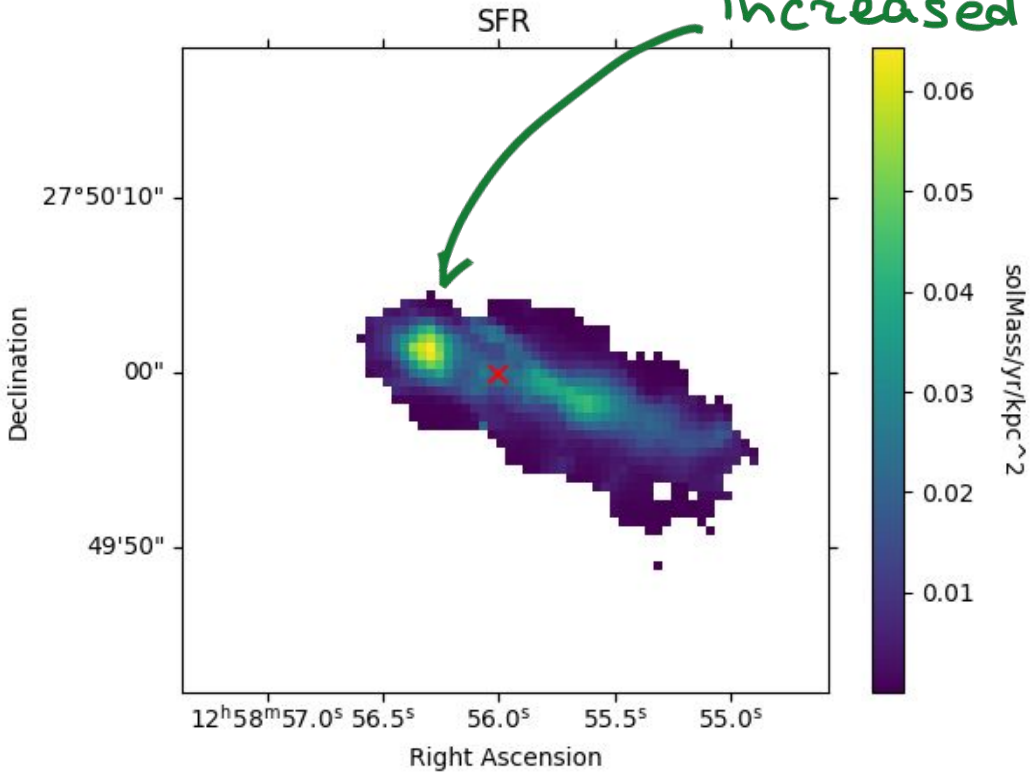
Ref.: "Galaxy Interactions in Compact Groups. I: The Galactic Winds of HCG16" - F.P.A. Vogt, M.A. Dopita, L.J. Kewley (2013)

MaNGA H-Alpha luminosity



$$L = (4\pi D^2) \cdot F$$

Star Formation Rate



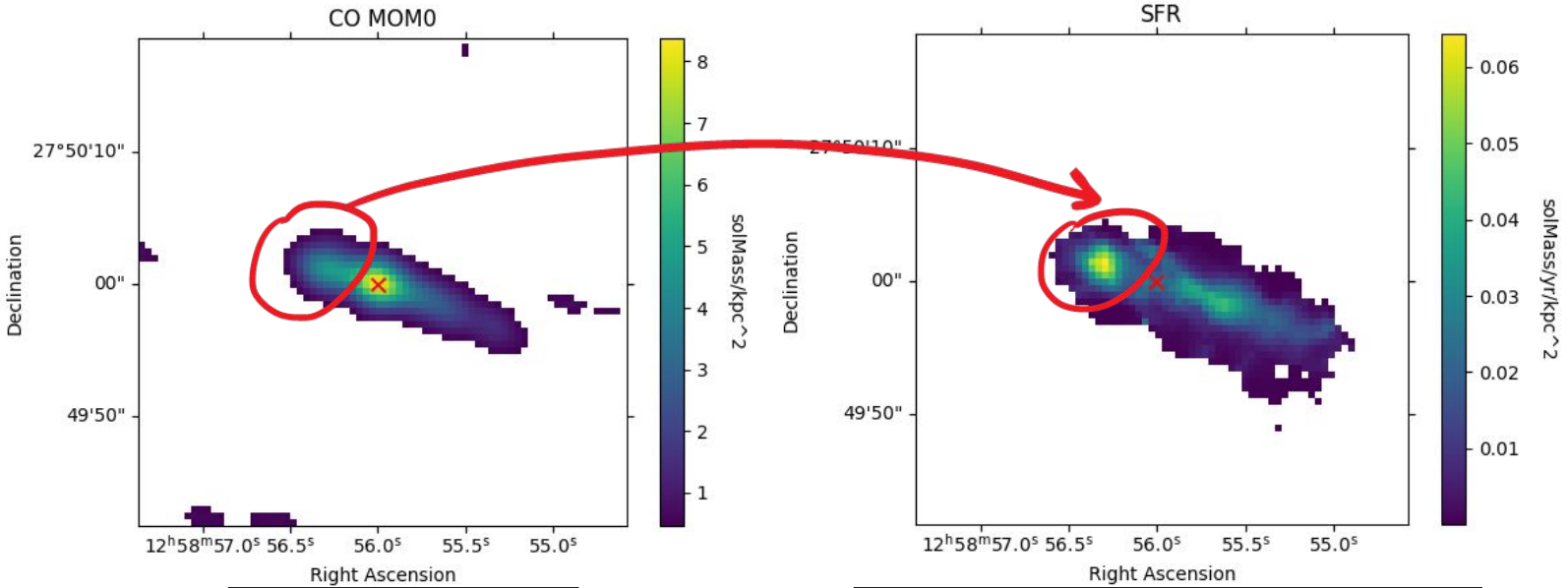
increased SFR on the leading edge

$$\log \dot{M}_*(\mathrm{M}_\odot\ \mathrm{yr}^{-1}) = \log L_x - \log C_x$$

$$\log C_x = 41.27$$

Ref.: "Star Formation in the Milky Way and Nearby Galaxies" – R.C. Kennicutt Jr, N.J. Evans II (2008)
Murphy et al. (2011); Hao et al. (2011)

Depletion time masking, conversion for moment map



MASK: <3*rms

MASK: Hα S/N < 3 and Hβ S/N < 3

Conversion for CO gas into solar masses and molecular gas:

$$M = \alpha_{CO} L(CO) \quad \alpha_{CO} = 4.3\ M_{\odot}\,(K\ km\ s^{-1}\ pc^{2})^{-1} - \text{CO-to-H}_2\ \text{conversion factor}$$

Ref.: "The CO-to-H2 Conversion Factor" – A.D. Bolatto, M. Wolfire, A.K. Leroy (2013)

Depletion time

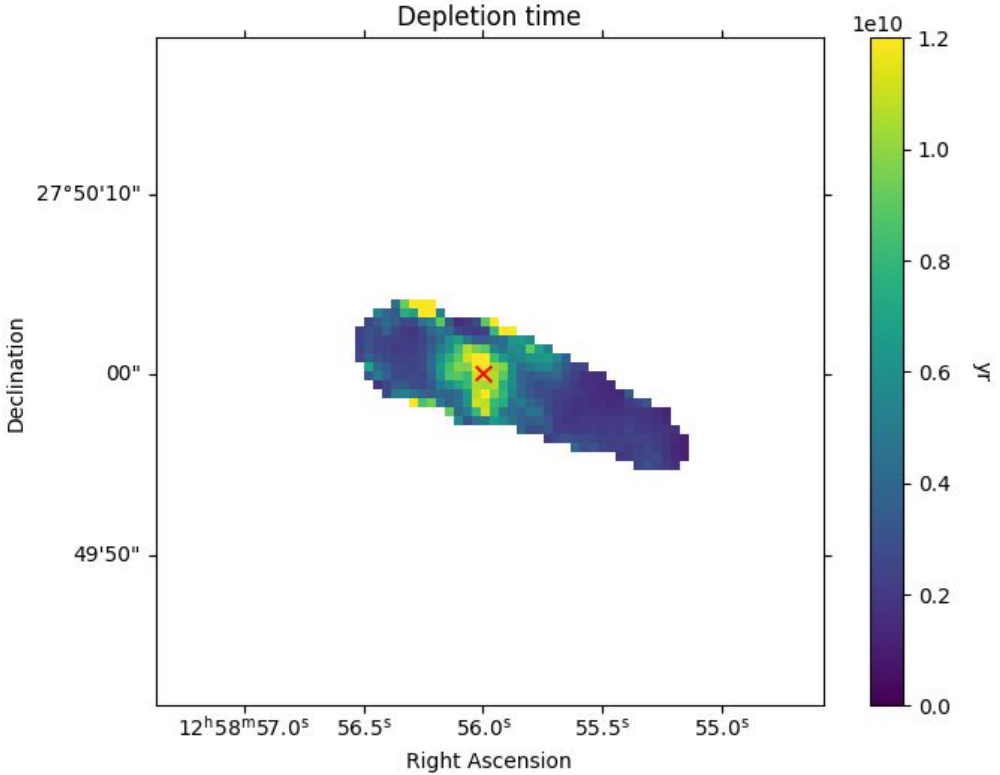
Depletion time - measure of how quickly we expect the molecular gas in a galaxy to be converted into new stars.

<u>The greater depletion time – the slower gas is getting converted to stars.</u>

Result: depletion time is much greater in the center of the galaxy, but overall no difference is noticed in the leading edge => the increase in gas density is “canceled out” by the increase in SFR in the “head” of the galaxy

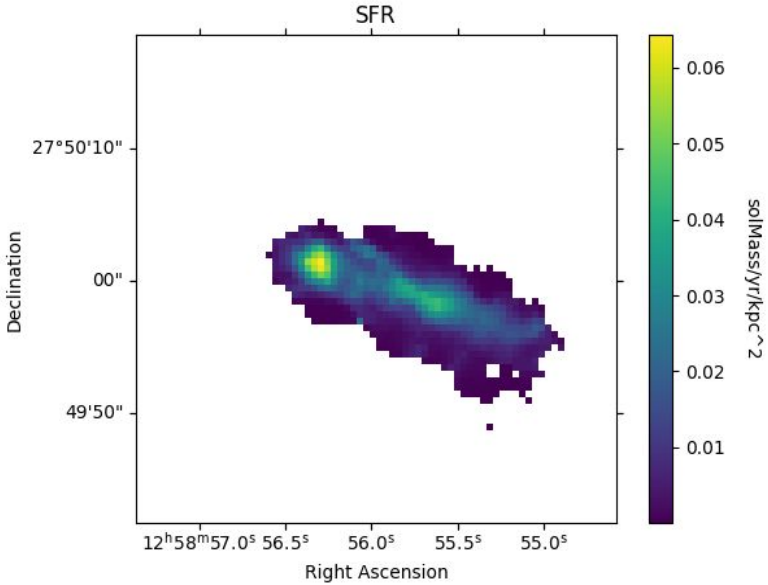
$$\frac{\Sigma_{H_2}}{\Sigma_{SFR}}$$

(surface density of molecular gas) / (SFR surface density)

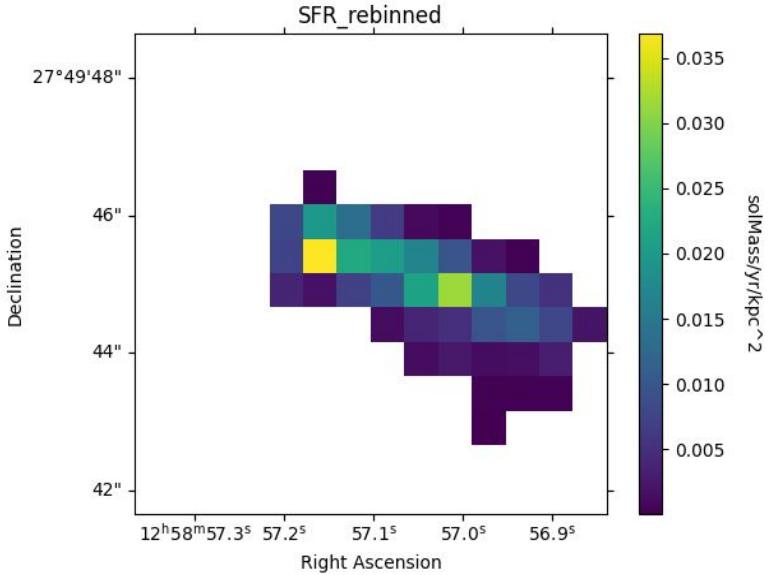


KS relation

Binning

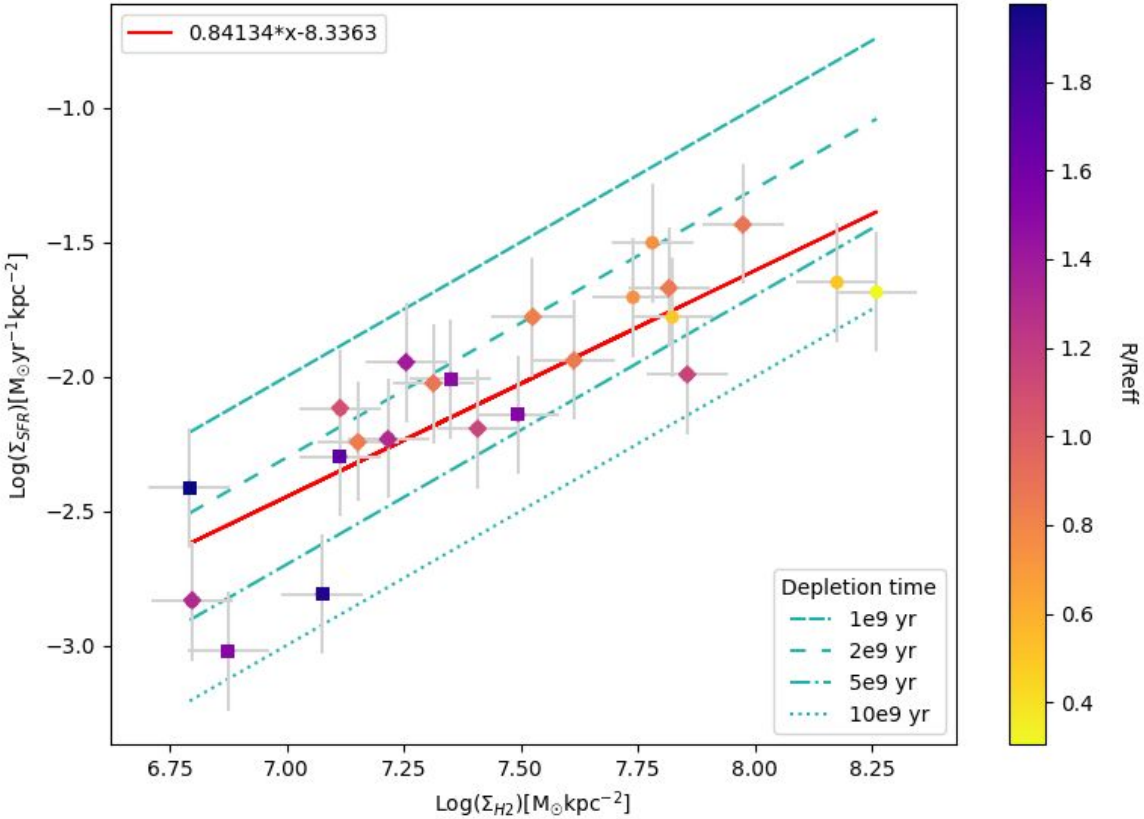


Here pixels within one beam area are correlated (size of the beam is approx. 2.5” and size of the pixel is approx. 0.5”)



Here pixels are roughly beam size and uncorrelated

KS relation

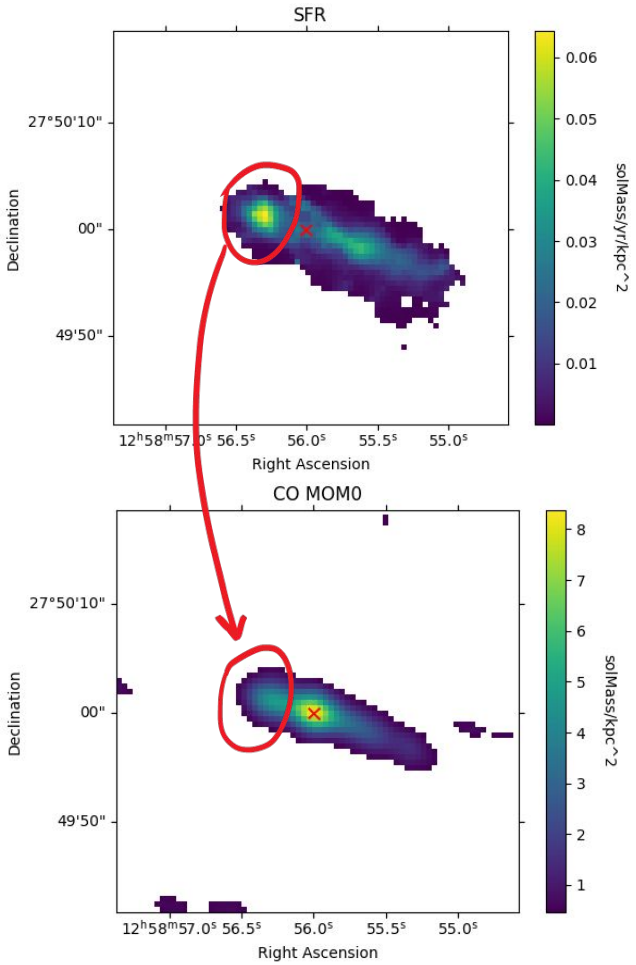


- Red – linear fit
- Blue – lines of constant depletion time
- Color – distance to the center of the galaxy
- Shape –

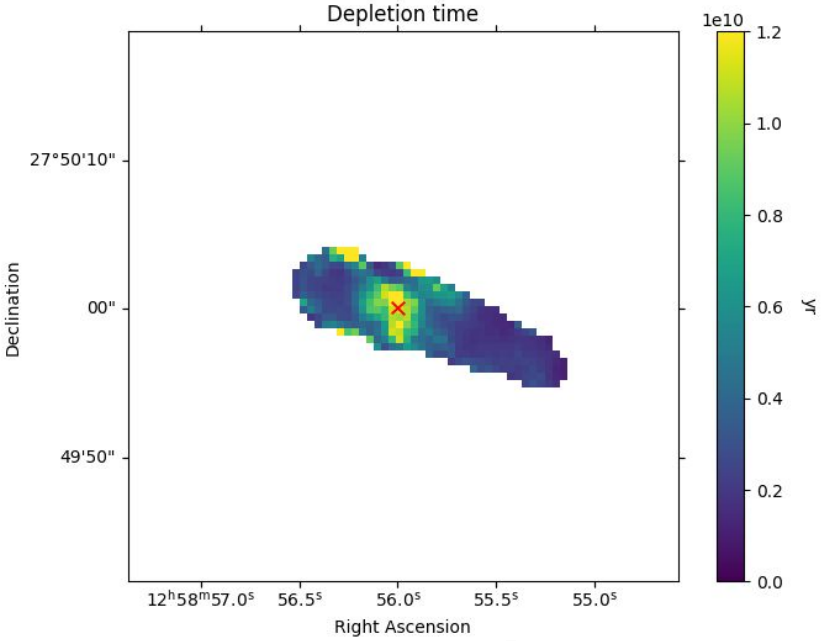
"square" – far side of the galaxy (R/Reff>1.4),
"diamond" – middle (0.8<R/Reff<1.4),
"round" – center (R/Reff<0.8)

- Error – 10% for H2, 25% for SFR (mostly calibration errors)

Conclusions

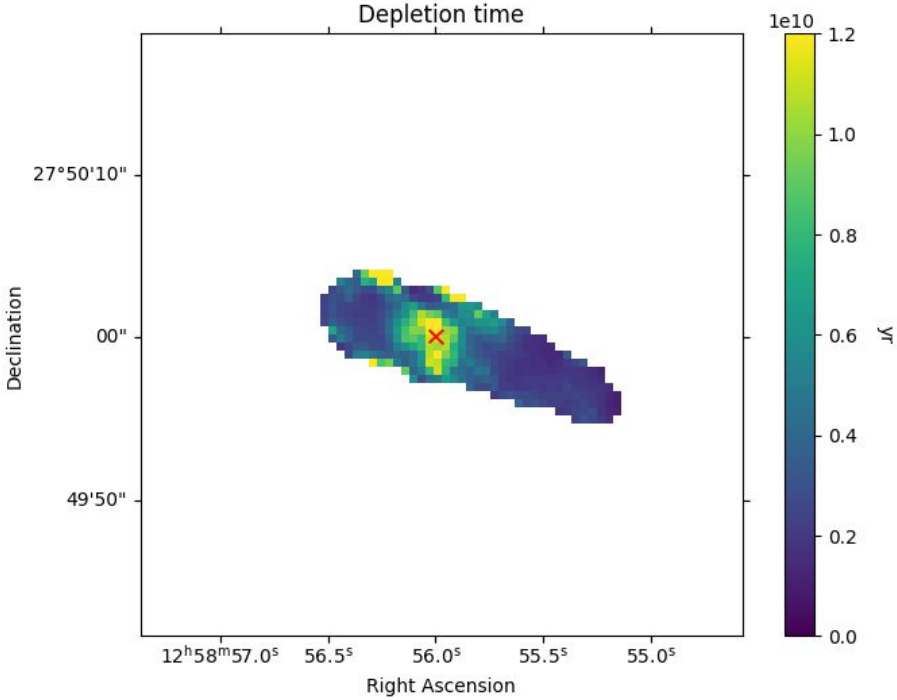


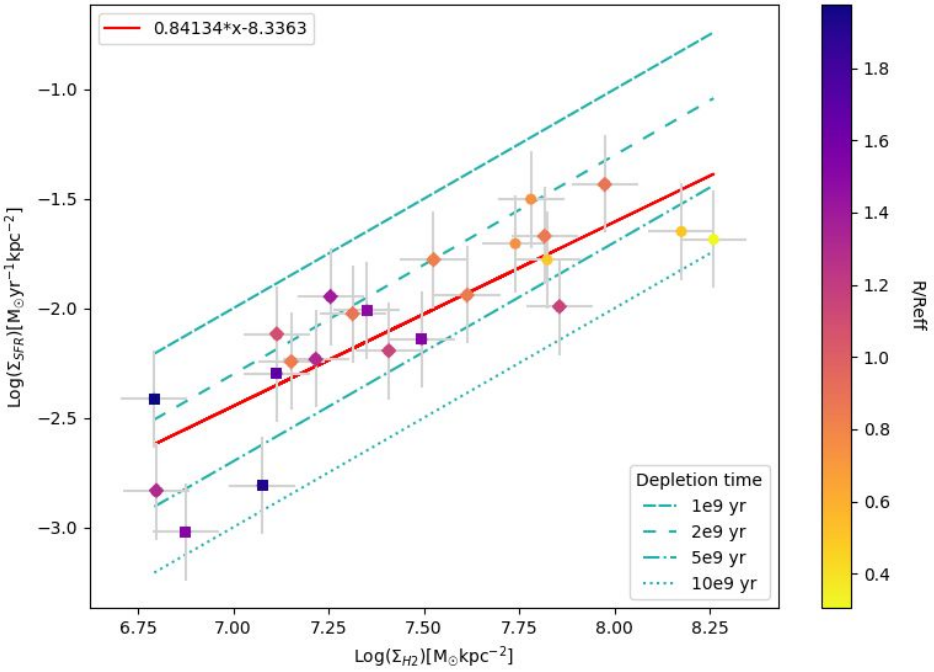
Enhanced star formation on the leading edge of the galaxy, as well as enhanced gas mass.



All this leads to normal star forming relationship and low depletion time.

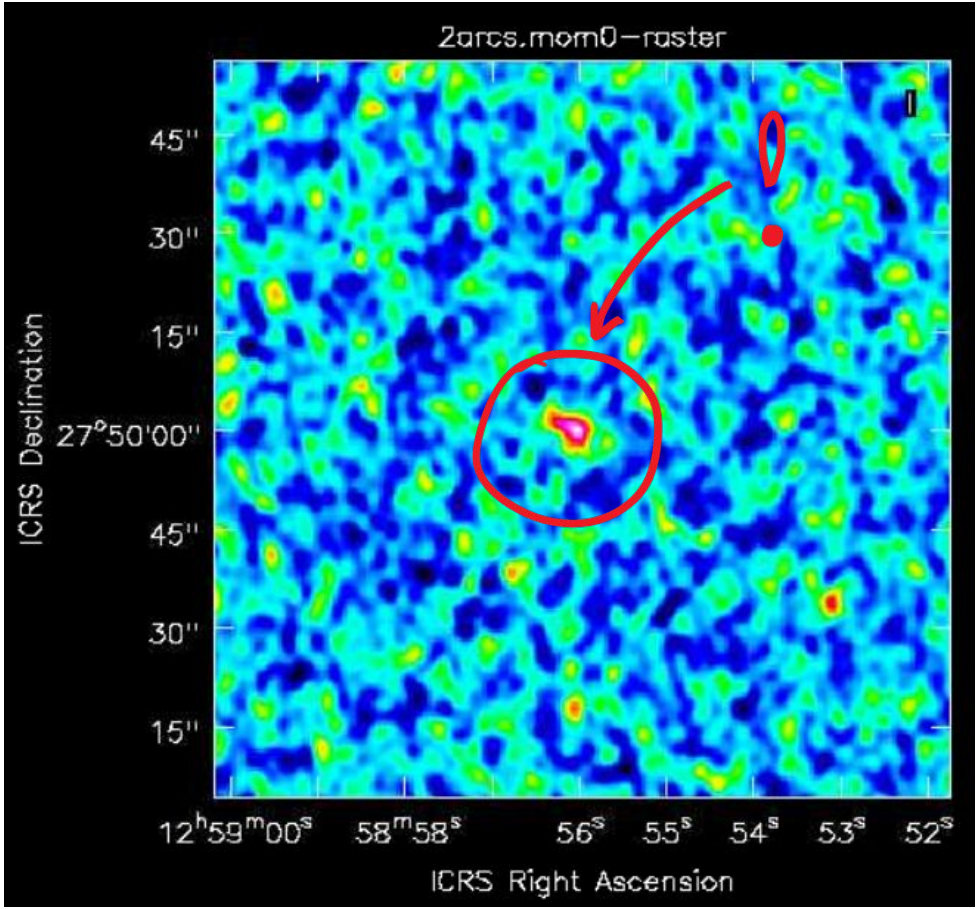
Conclusions





Slightly sublinear KS relation, maybe due to variations in CO conversion factor

Future work



HCN – dense molecular gas


Thank you for your attention!
Any questions?