# Tracing the physics of the neutral and ionized ISM with the HI-MaNGA survey

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# Acknowledgments


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Stark et al. 2021, MNRAS,

HI-MaNGA team

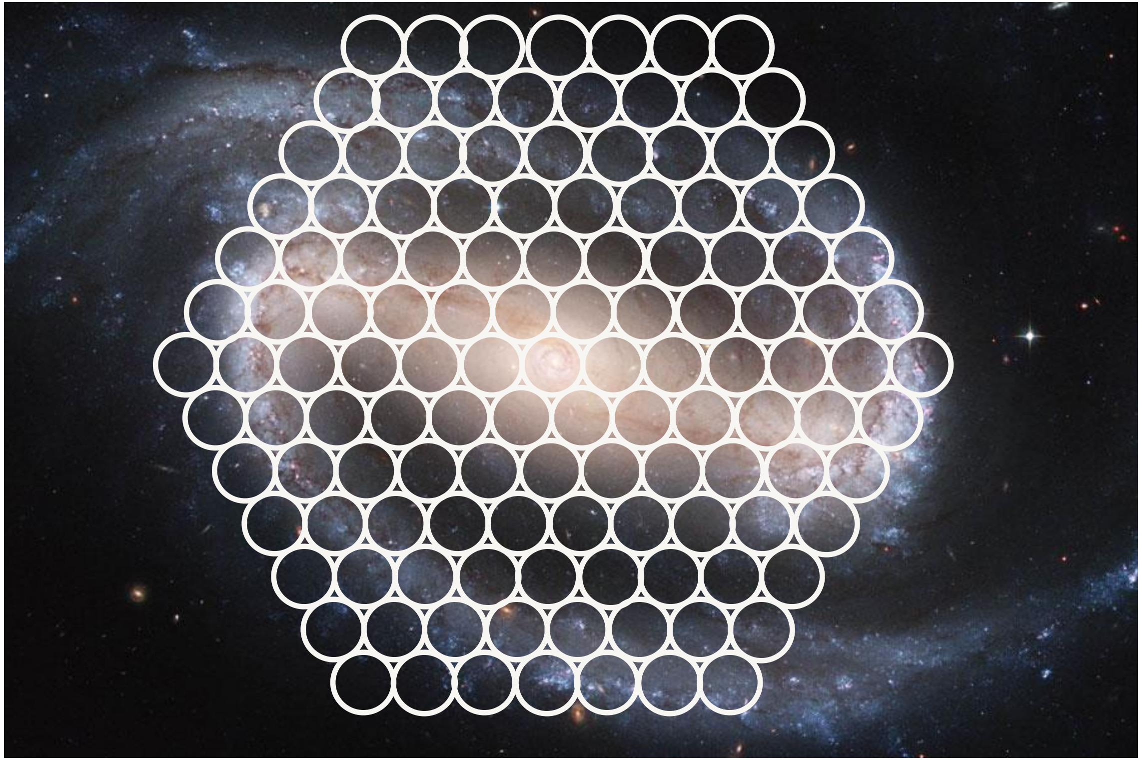
The MaNGA team

# Today's Talk

- The MaNGA and HI-MaNGA surveys: overview
- HI content vs. ISM diagnostics
- HI content - single emission line scaling relations

# The HI-MaNGA survey

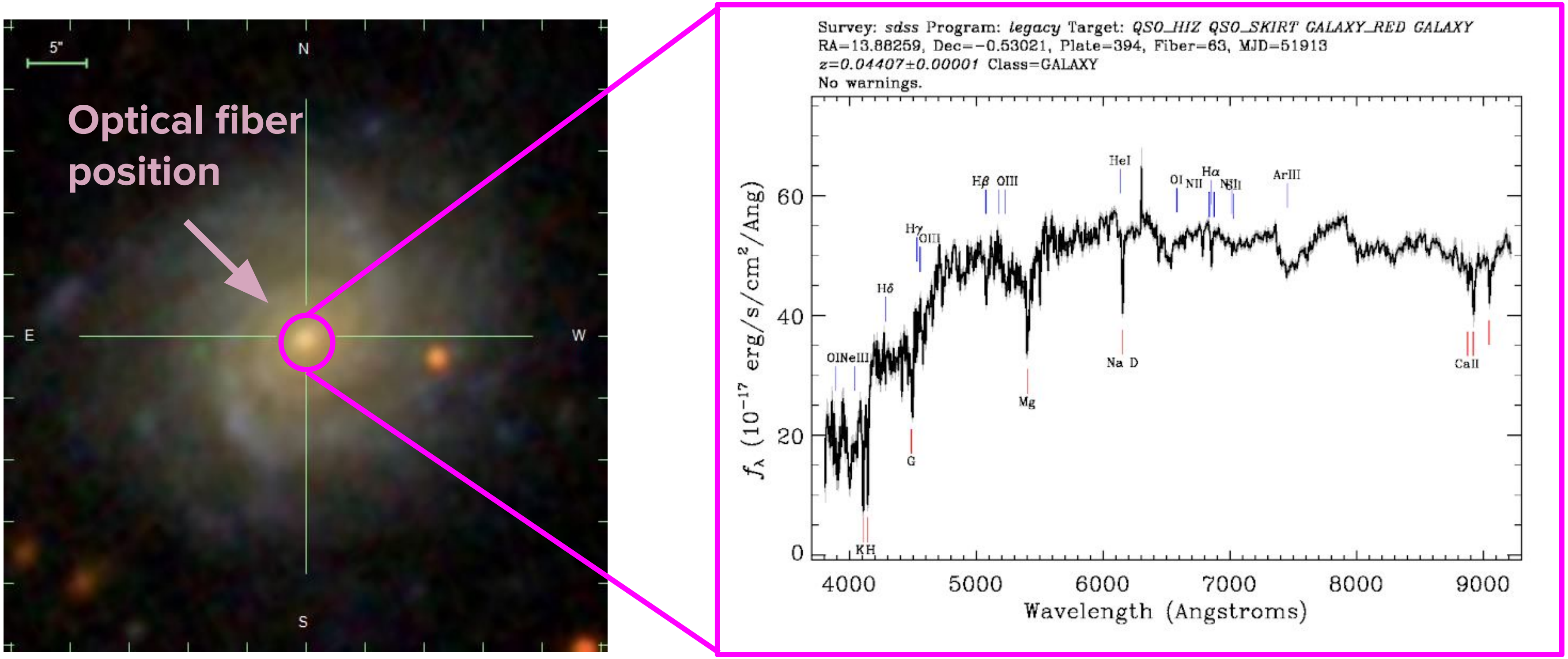
# What is MaNGA ? (Mapping Nearby Galaxies at APO)



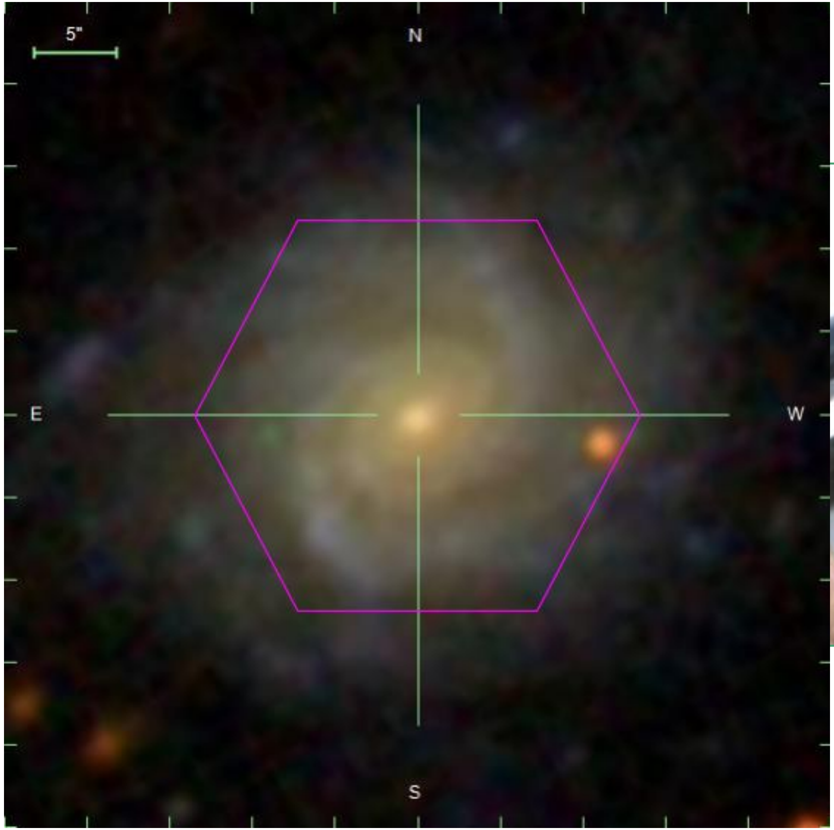
- Optical spectroscopy of nearby galaxies ($0.025<z<0.15$)
- Part of SDSS-IV
- IFU survey (spectral maps)
- Observations 2014-2020
- ~10k galaxies

# Legacy SDSS optical spectroscopy

Previous optical galaxy spectra from SDSS – single fibres

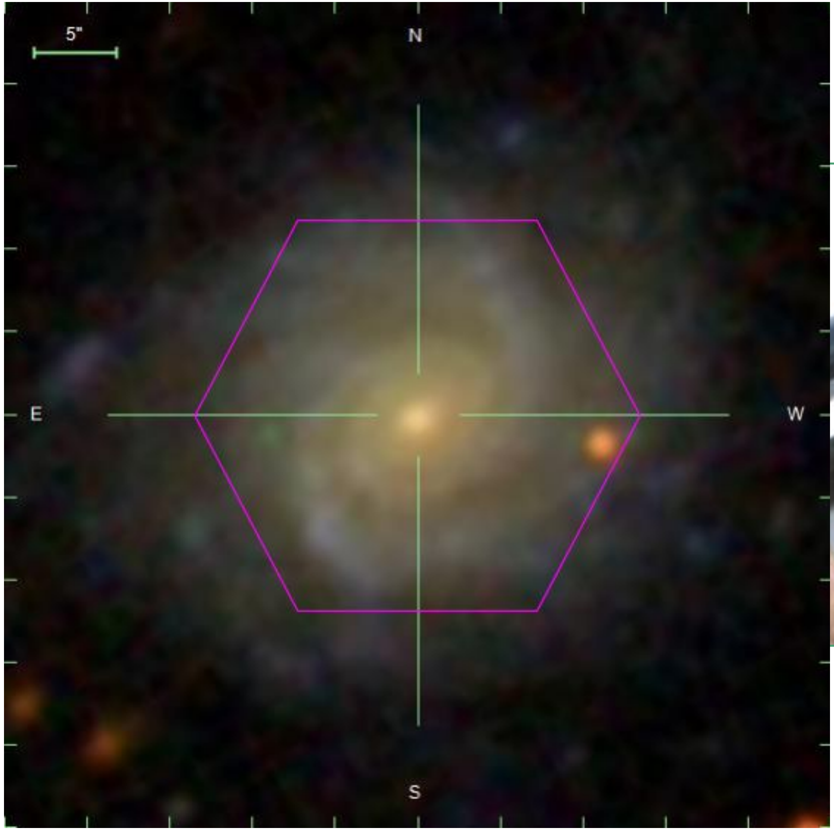


# Mapping Nearby Galaxies at APO (MaNGA)

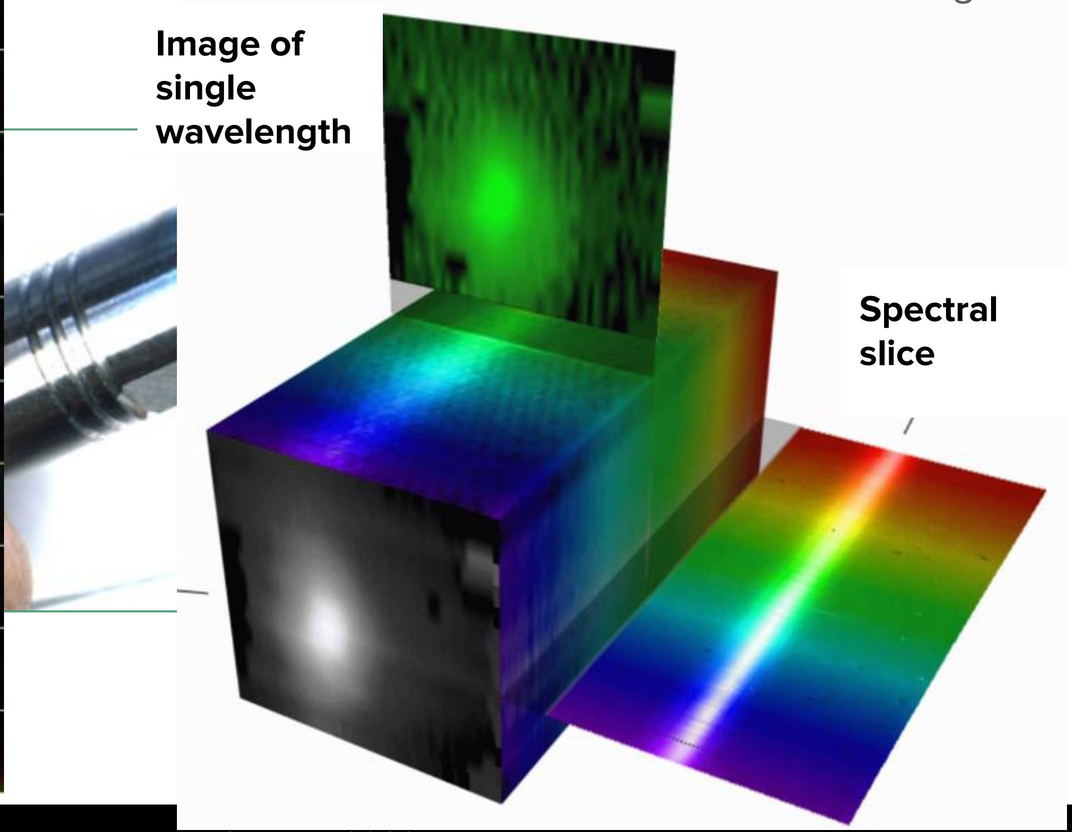



MaNGA – 19 to 127 resolution elements in a hexagon

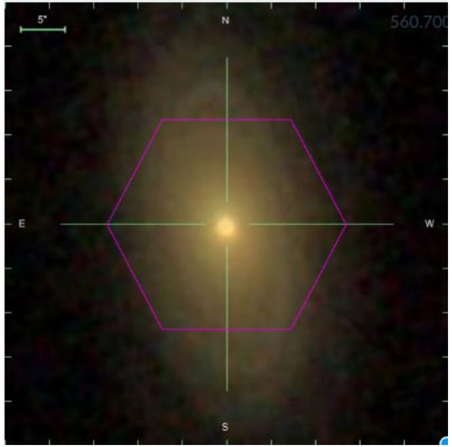
# Mapping Nearby Galaxies at APO (MaNGA)



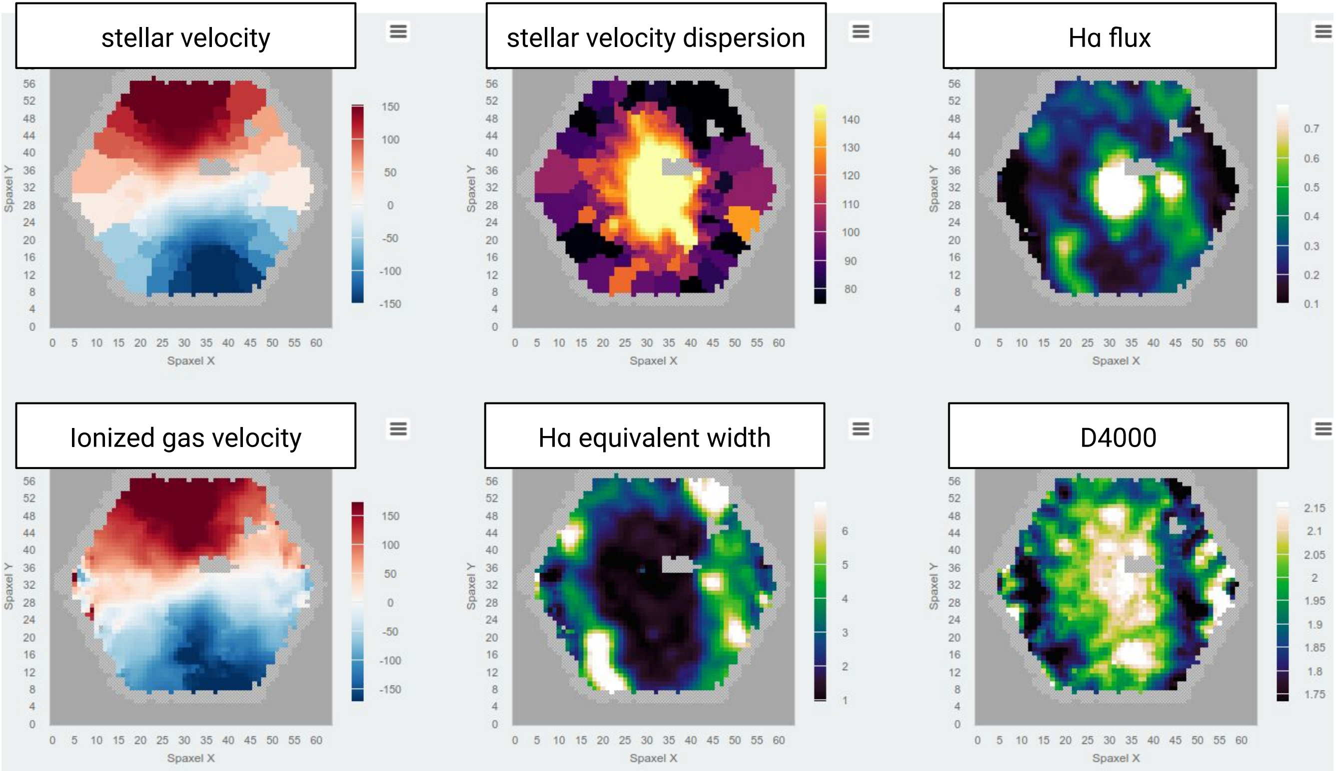

MaNGA – 19 to 127 resolution elements in a hexagon



# 2D maps of spectral features



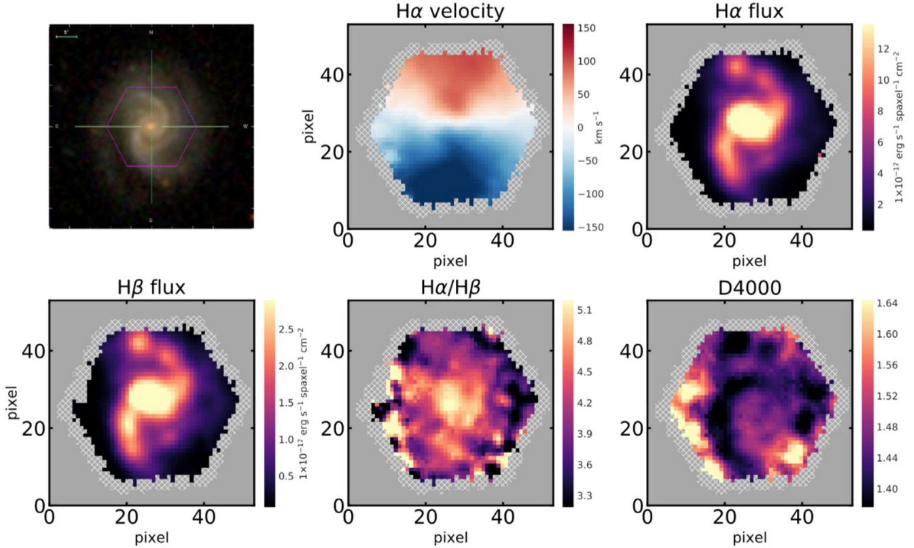

https://sas.sdss.org/marvin/



# HI-MaNGA: builds on MaNGA's key questions

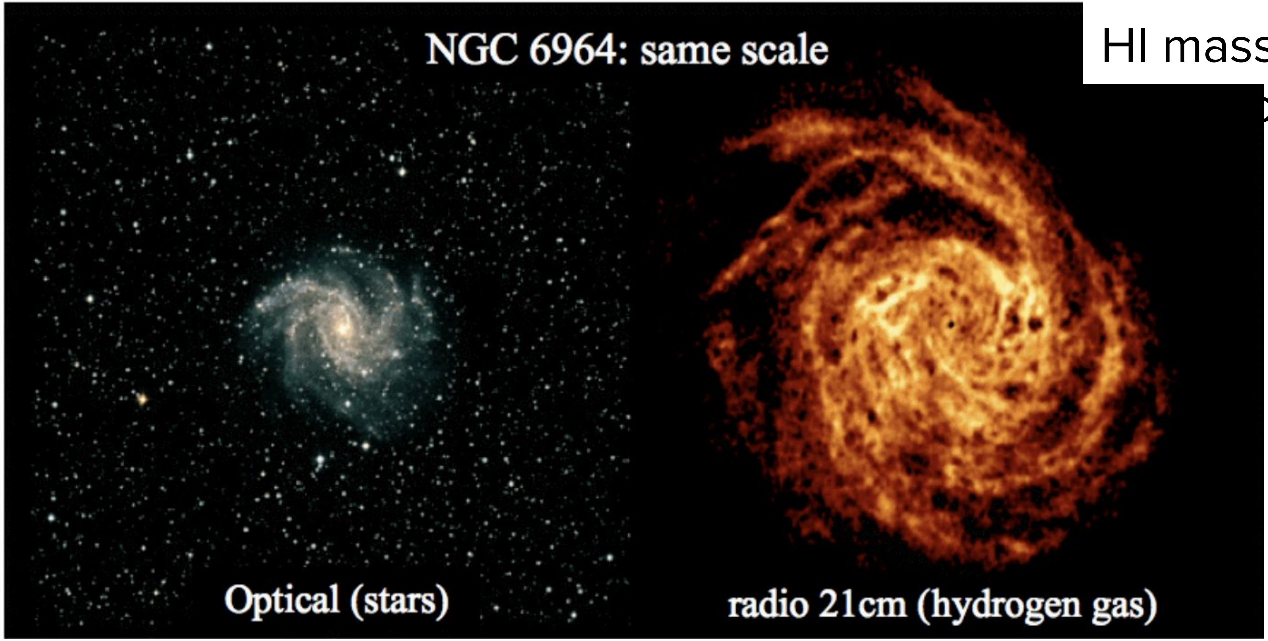
BIRTH
GROWTH
DEATH

} OF GALAXIES

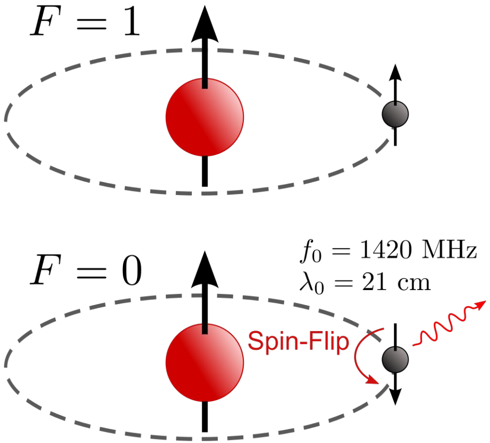



- **How does gas accretion drive growth?**
- **What quenches star formation?**
- **How is angular momentum distributed among different galaxy components?**
- **How do various galaxy components assemble and influence one another?**

# Neutral Atomic Hydrogen, HI: (typically) the dominant cold gas phase in galaxies

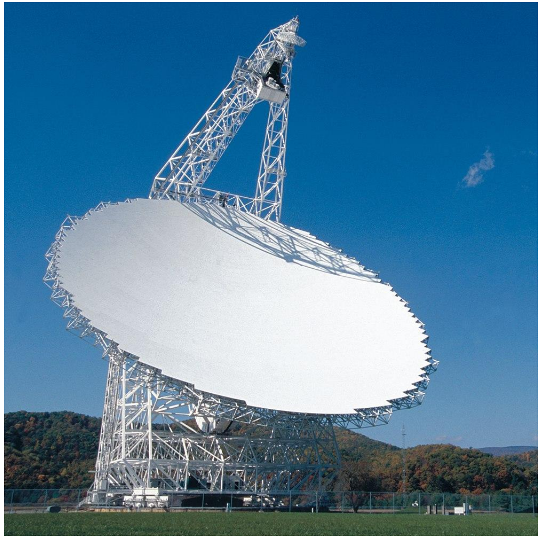



HI mass ∝ (21cm flux) ×
ce)$^2$

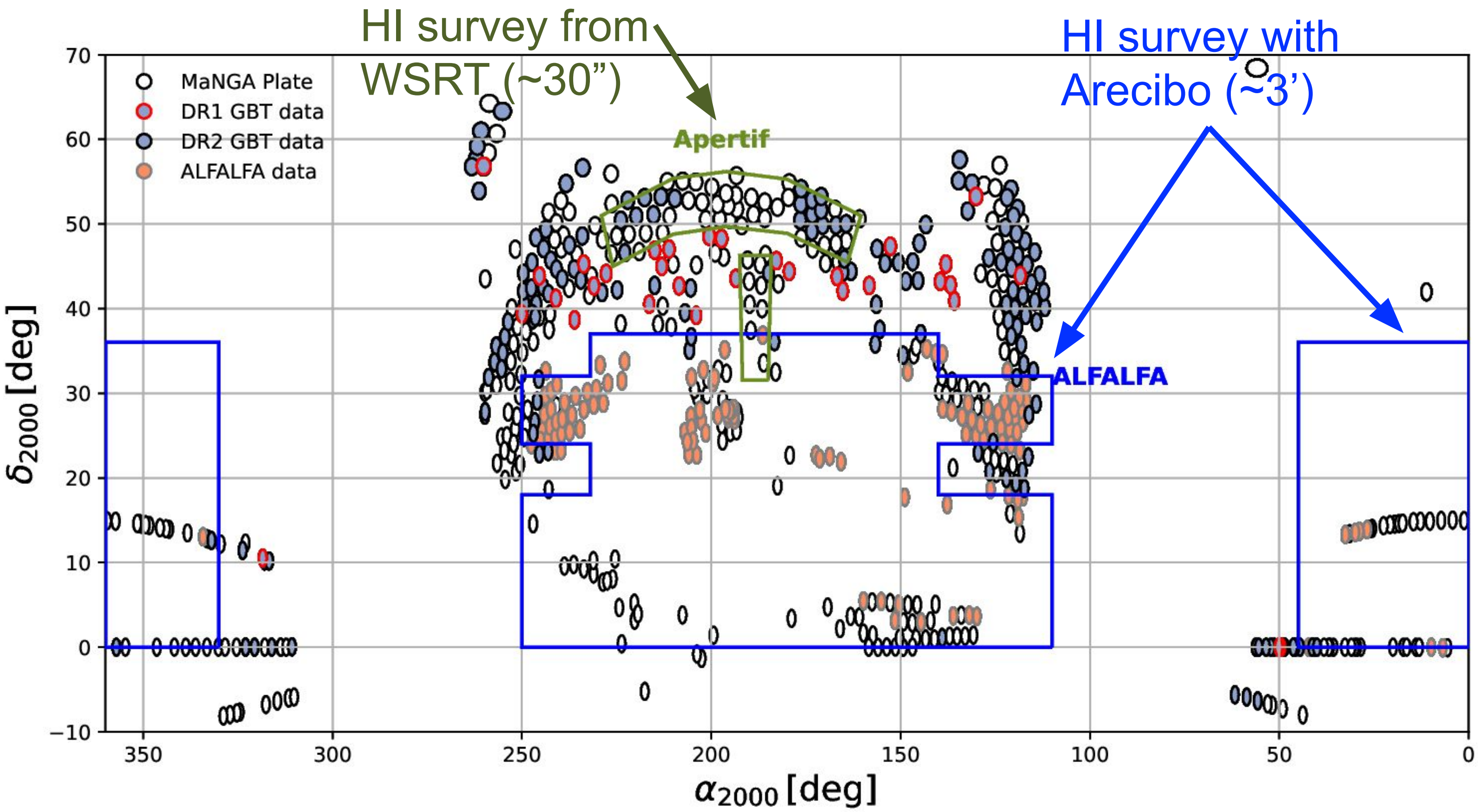


# HI-MaNGA: builds on MaNGA's key questions

PI: Karen Masters (Haverford College)
Add cold gas (**neutral atomic hydrogen, HI)** content information with GBT
- crucial to trace full baryonic content and information on angular momentum
- MaNGA's strength is numbers – need to match with HI data

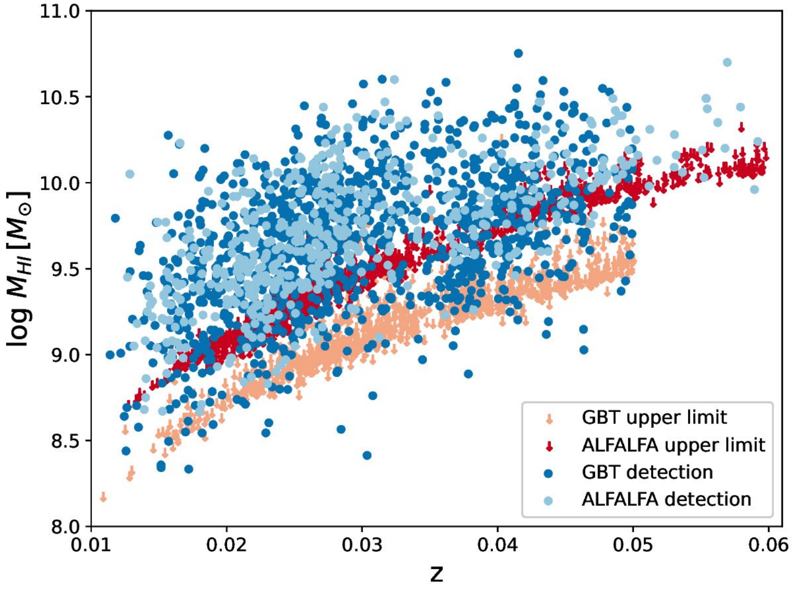

Green Bank Telescope

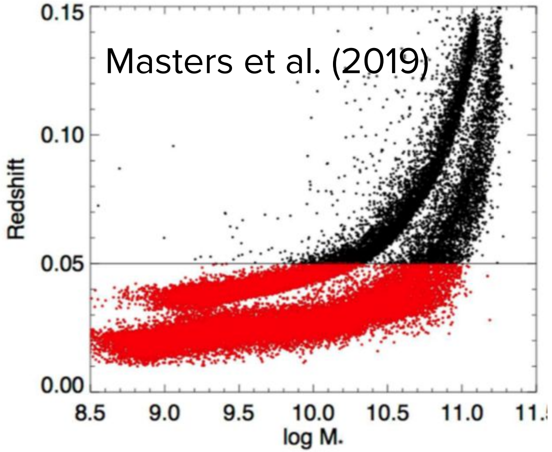
# Second data release sky coverage -- 3818 observations

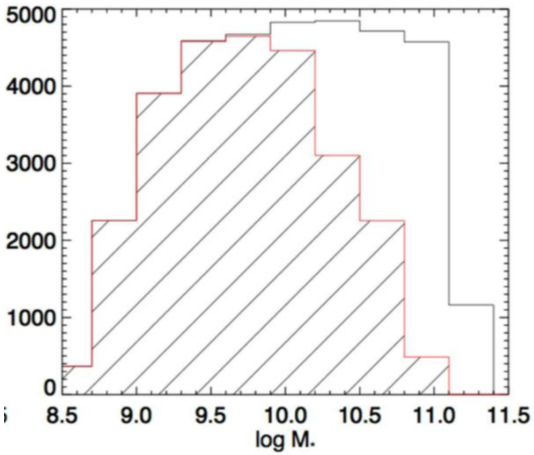


# GBT Observing

- Depth to match ALFALFA (really a bit deeper)
- No selection on color/morphology
- Require z<0.05 (70% of MaNGA) ➡ leads to bias against the most massive galaxies

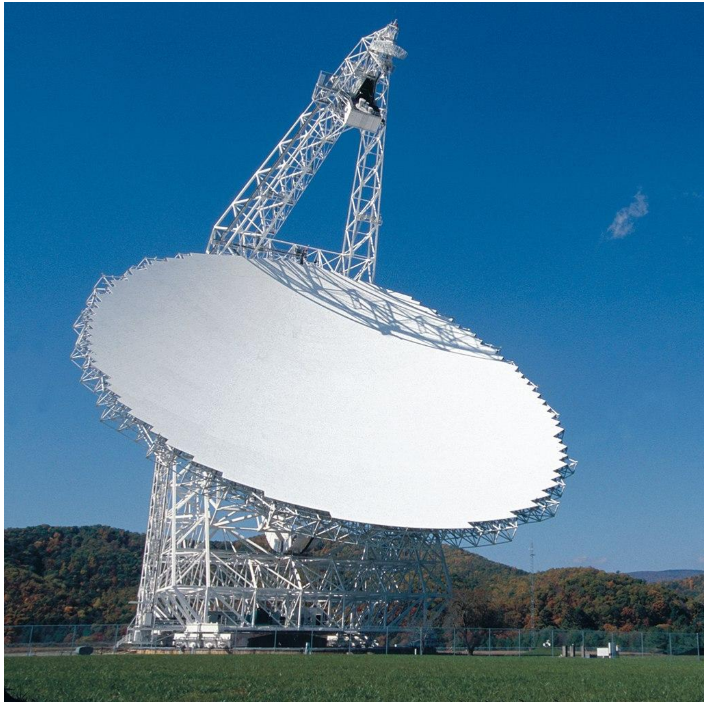


# Observing so far

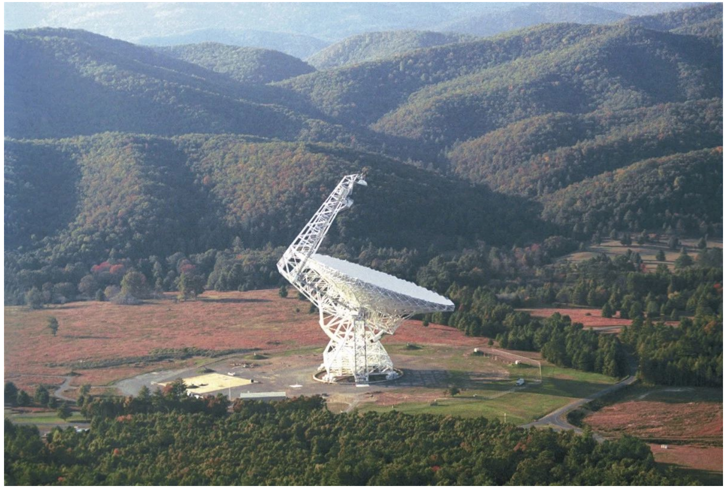
- **16A: 193 hours (filler time, Feb 2016-2017)**
  - 331 galaxies
  - Released in Masters et al. (2019)
- **17A: 1080+194 hours (Dec 2017-Feb 2019)**
  - 2159 galaxies
  - **Released in Stark et al. (2021)**
- **19A: 199 hours (Feb – Apr 2019)**
  - 352 galaxies
  - Reduction in progress
- **20B: 580 hours (ongoing)**
  - ~968 more galaxies
- **21B: …let's see what the TAC says…**

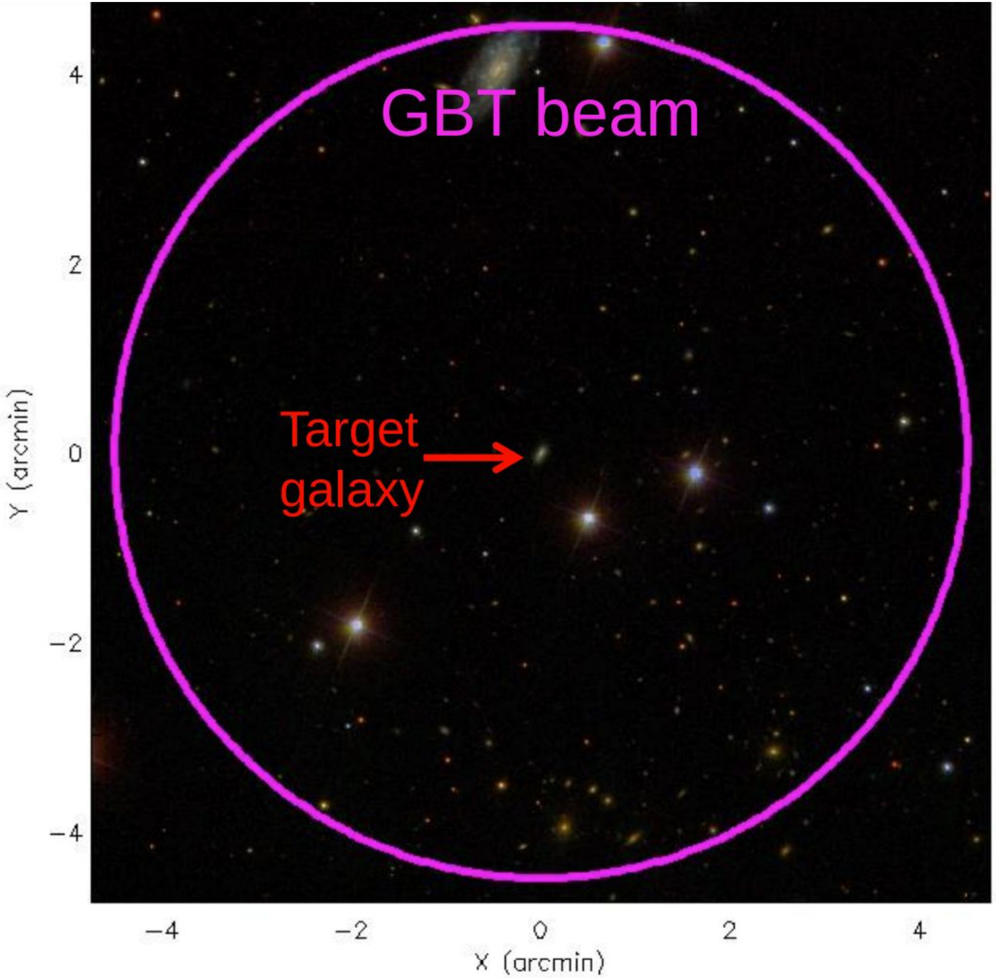


Latest products available at https://greenbankobservatory.org/science/gbt-surveys/hi-manga/ (just Google "himanga gbt")

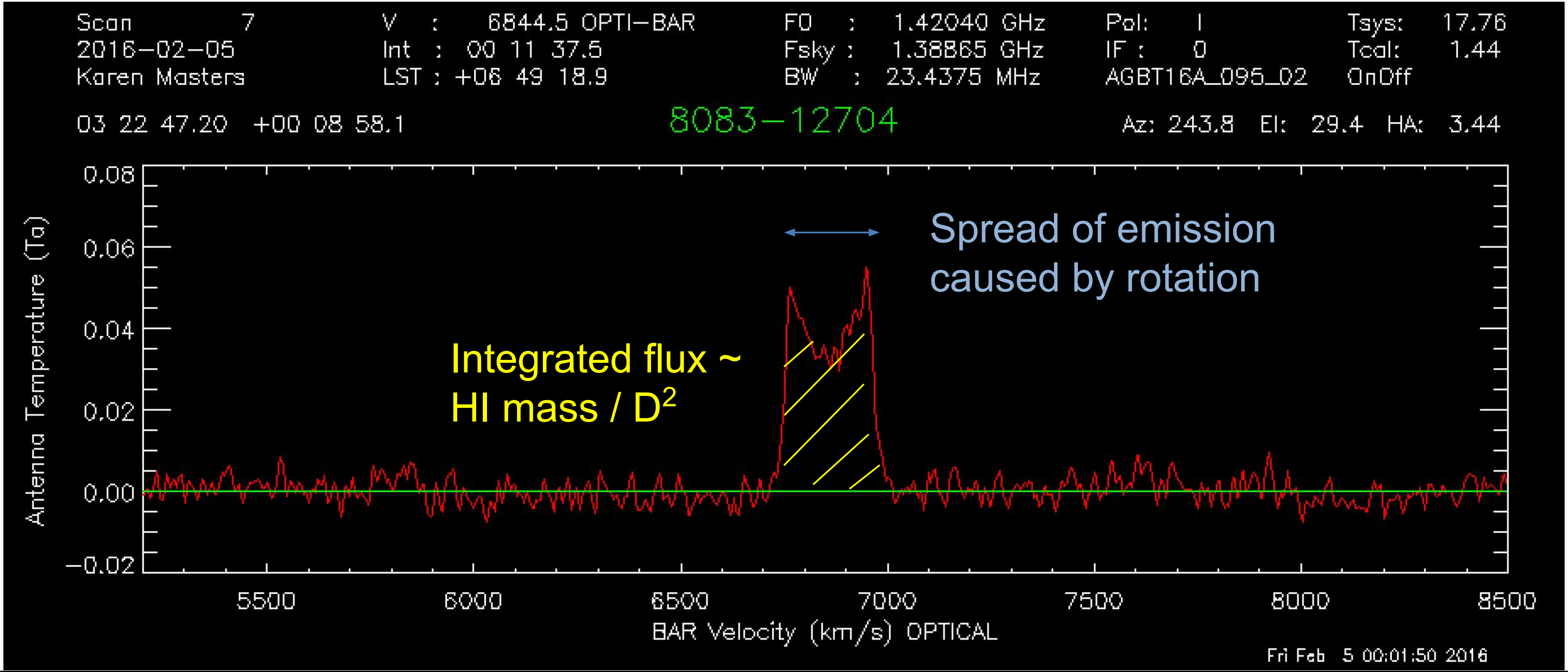
Reminder: We're not making HI images, but we do have large number statistics

**Dish diameter D = 100m**
**$\lambda$ = 21cm**
**Ang. res. $\Theta \approx \lambda/D$ = 9 arcmin**





# Key data products: HI mass and linewidth

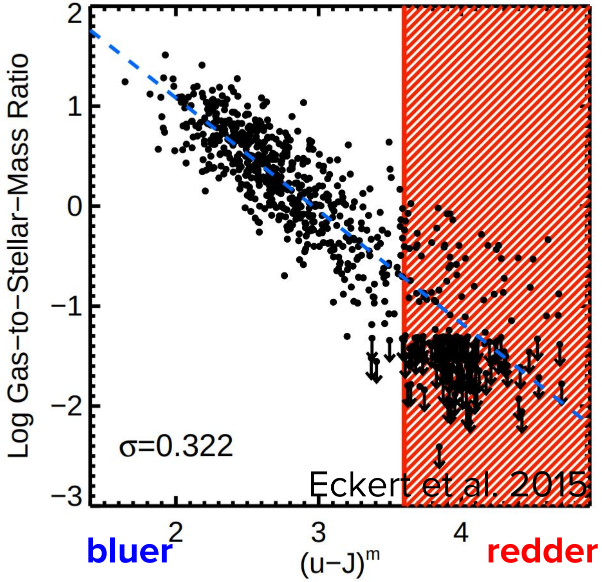


# Relation between interstellar medium (ISM) properties and HI-to-stellar mass ratio

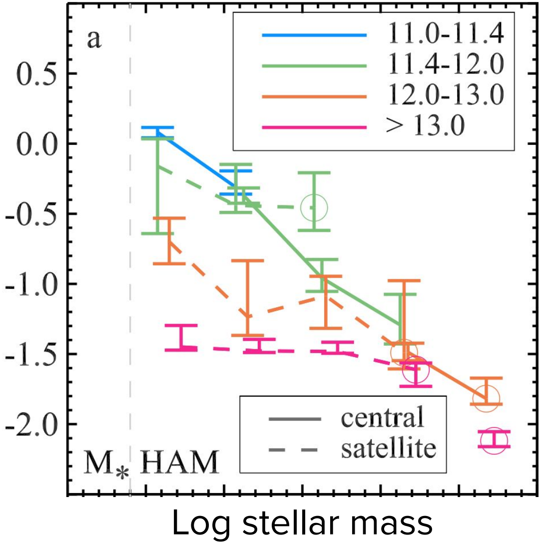
# Global HI in galaxies: What we know

- Typically most common phase of cold gas in galaxies
- Cold gas reservoir -- provides fuel needed for star formation
- Total gas (HI) fraction related to:

galaxy color

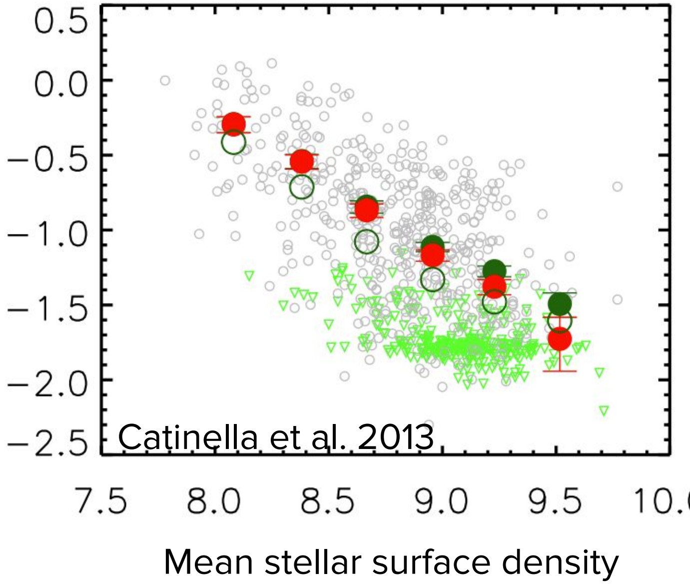



mass and environment




Stark et al. 2016

galactic structure



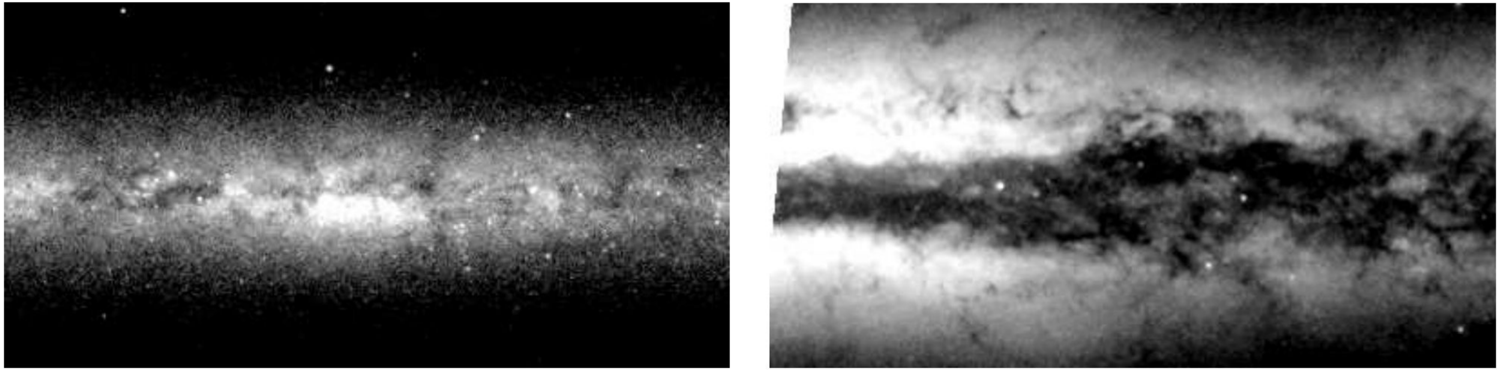
# The ISM in galaxies: broad trends

**Low stellar mass/high HI fraction**

- Lower metal content
- More stable against collapse (more diffuse gas)
- Less efficient star formers (SFR per cold gas)

**High stellar mass/low HI fraction**

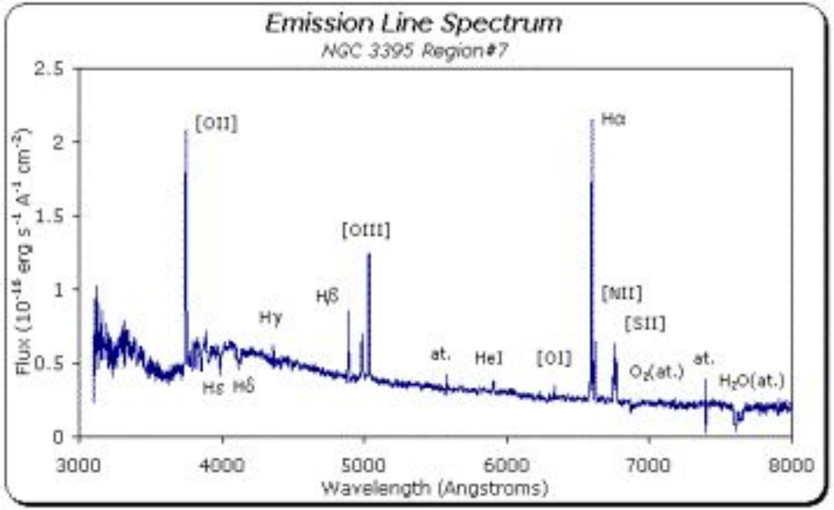
- Higher metal content
- Unstable against collapse (more dense gas)
- More efficient star formers (SFR per cold gas)



Dalcanton et al. (2004) -- weak/strong dust lines reflect stable/unstable disks

# Optical emission lines tell us more about ISM conditions

- Metallicity
- Pressure/density
- Ionizing radiation properties (e.g. from star formation vs. evolved stars vs. active galactic nuclei, hard/soft ionizing spectra)
- Other ionizing sources (e.g. shocks)




***Do these vary significantly between gas-rich and gas-poor galaxies? Do they help explain SF behavior?***

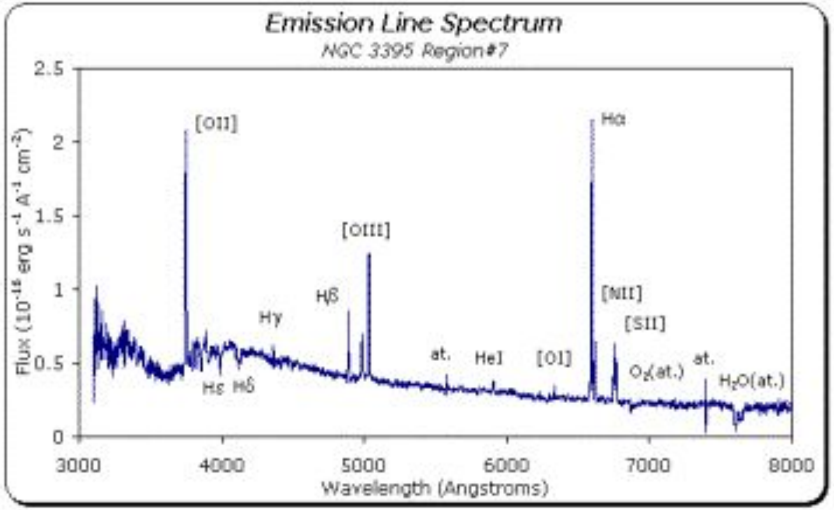
Need:

(1) optical spectroscopy covering all (or a large portion) of the disks of galaxies ← **MaNGA survey**

(2) gas mass estimates ← **HI-MaNGA survey**

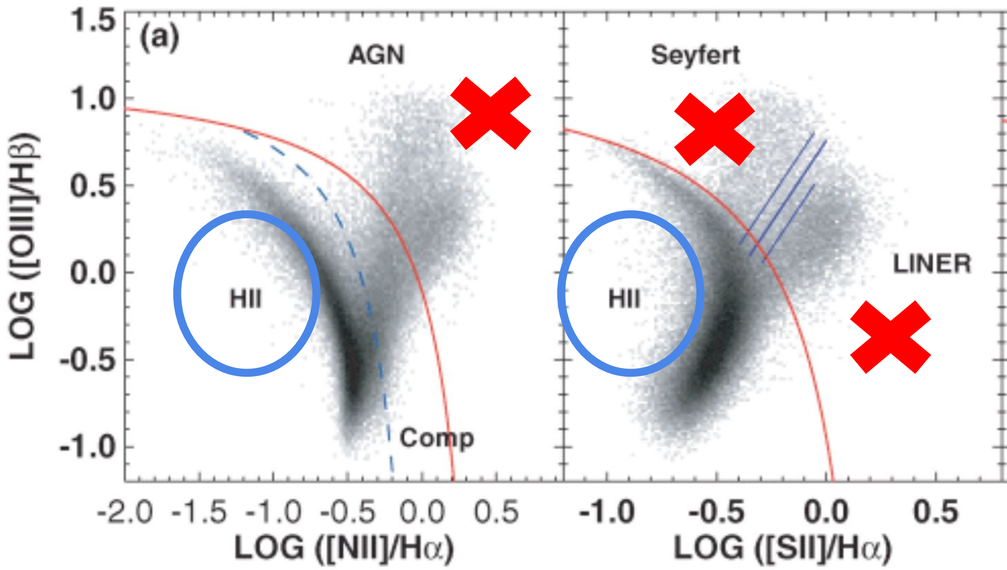
# ISM Diagnostics

- **Equivalent width, EW** (line flux normalized by stellar continuum)
- **Electron density**
  - From [SII] doublet
- **Metallicity, 12+log (O/H)**
  - From [NII]/[OII] ratio
- **Ionization parameter** (ratio of ionizing photons to particle density)
  - From metallicity and [OIII]/[OII]
- **Low ionization lines**, [NII]/Hα, [SII]/Hα, [OI]/Hα (sensitive to hardness of ionizing spectrum, shocks, diffuse ionized gas, metallicity)
- **Hα surface brightness,** $\mu_{H\alpha}$ (traces relative contribution of ***diffuse ionized gas, DIG***)



# Sample and Analysis

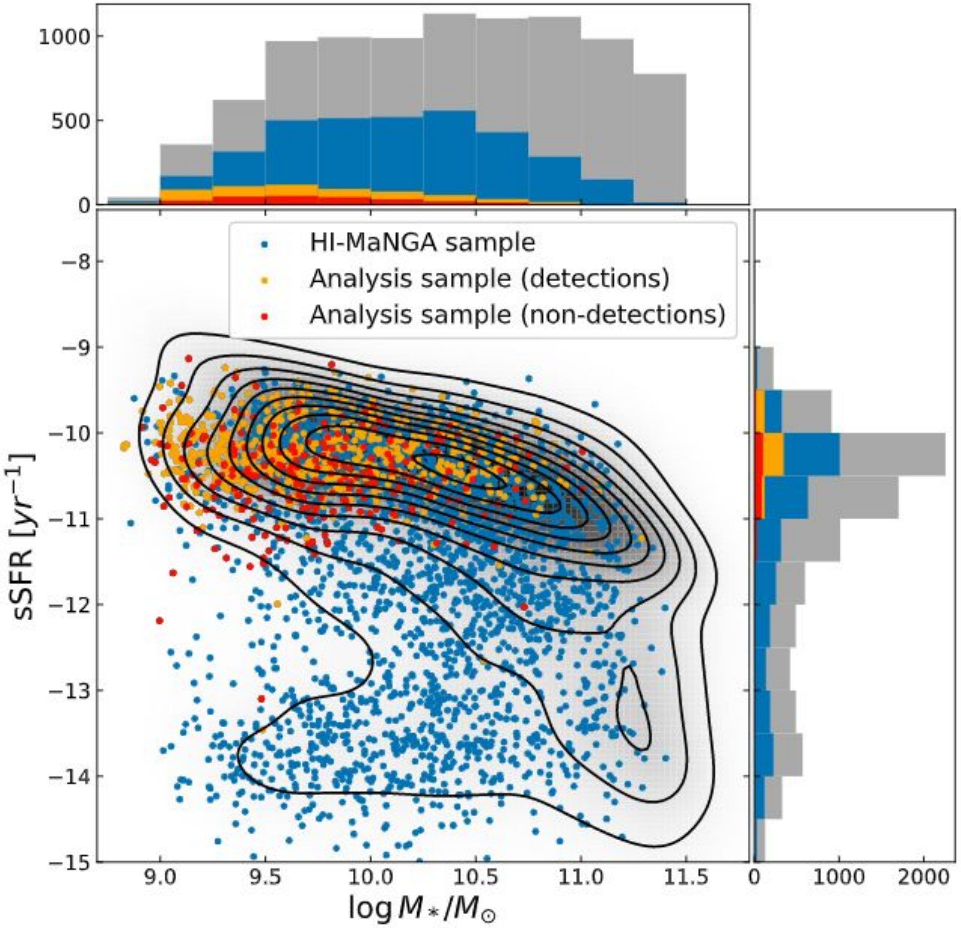
- Parent HI-MaNGA catalog (3818 galaxies; GBT + ALFALFA data)
- Subselect MaNGA Primary+ sample (⅔ of MaNGA with spectral coverage out to appox. 1.5Re)
- Star forming galaxies only (no AGN)



# Sample and Analysis

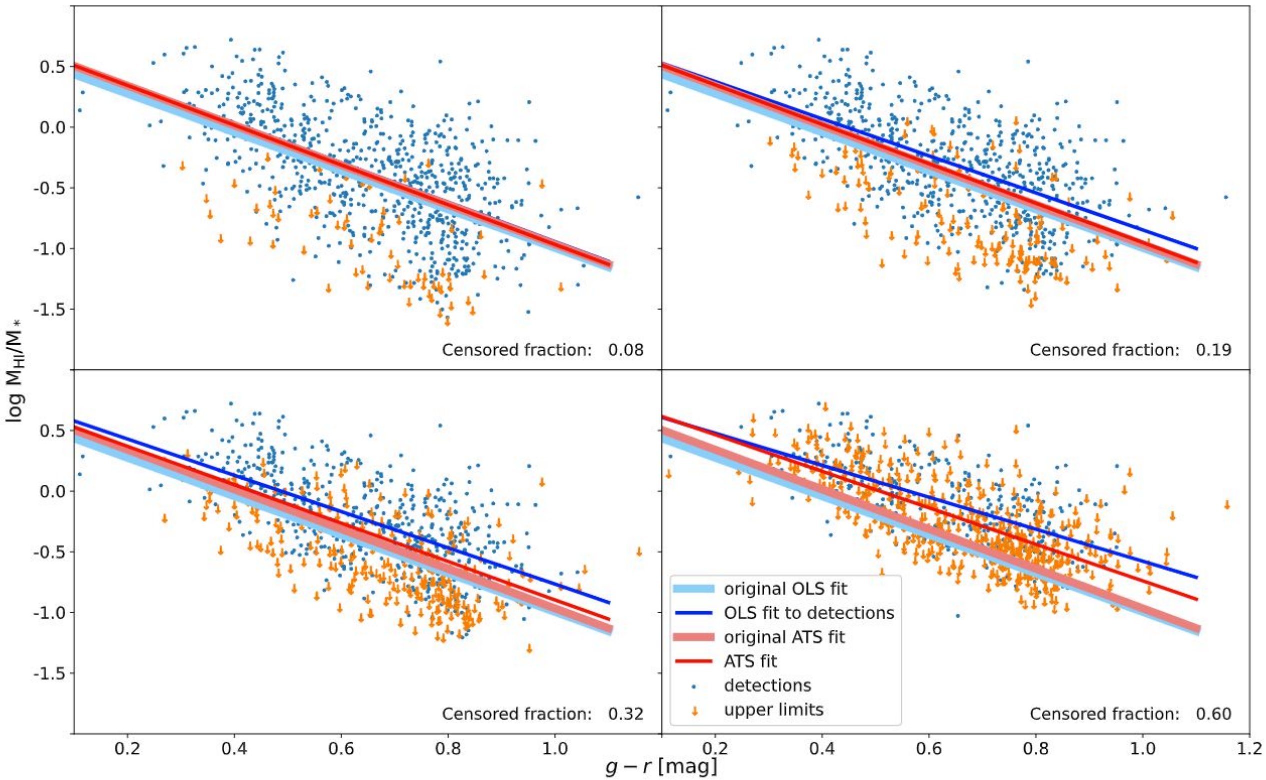
- Parent HI-MaNGA catalog (3849 galaxies; GBT + ALFALFA data)
- Subselect MaNGA Primary+ sample (⅔ of MaNGA with spectral coverage out to appox. 1.5Re)
- Star forming galaxies only (no AGN)

- **Final sample of 836 galaxies**
- Emission line properties measured within the half-light radius, $R_e$



# Treatment of upper limits

- 30% of analysis sample are HI non-detections
- ***Modified Kendall's τ*** *for correlation tests*
- ***Akritas-Theil-Sen estimator*** (ATS, Akritas et al. 1995) used for and linear fitting
  - Robust in presence of upper limits

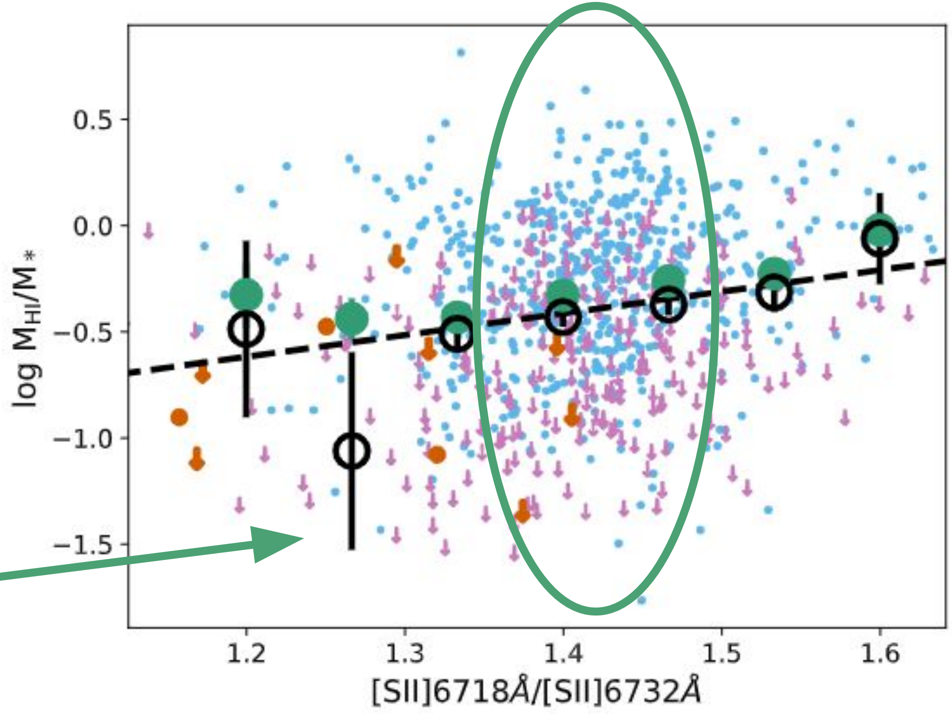


# HI fraction and ISM conditions

No strong trends (|$\tau$| <0.1) with mean:

- **electron density ([SII] doublet ratio)**
- ionization parameter, q
- Hα surface brightness, $\mu_{H\alpha}$

**[SII] ratio mostly saturated; consistent with $n_e$ < 100-200 cm$^{-2}$**



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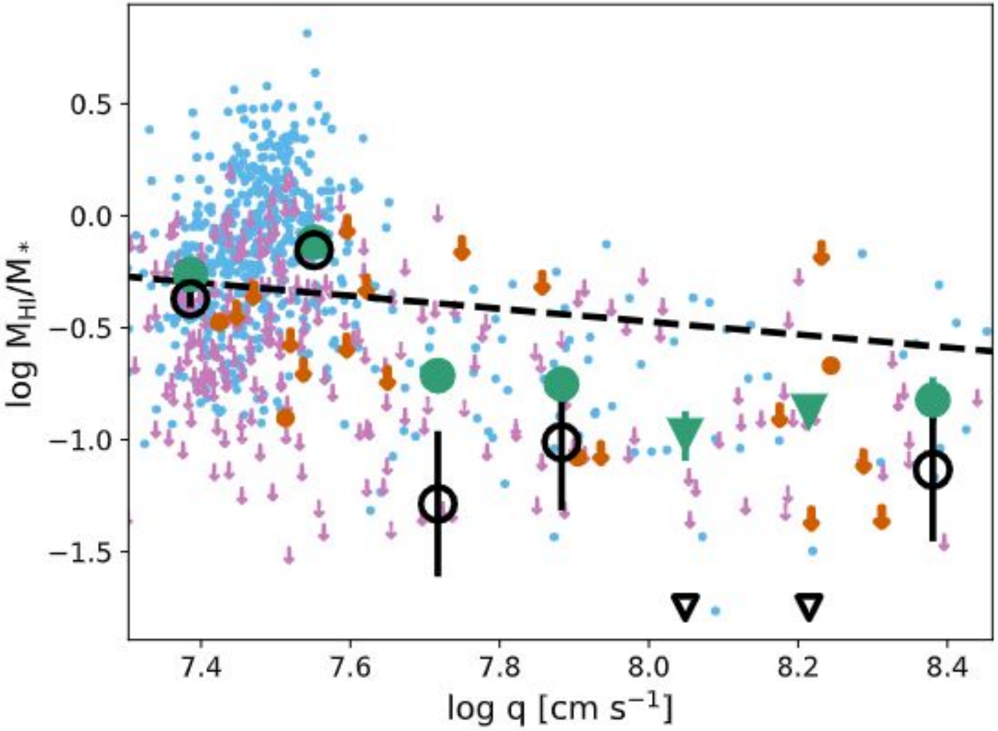

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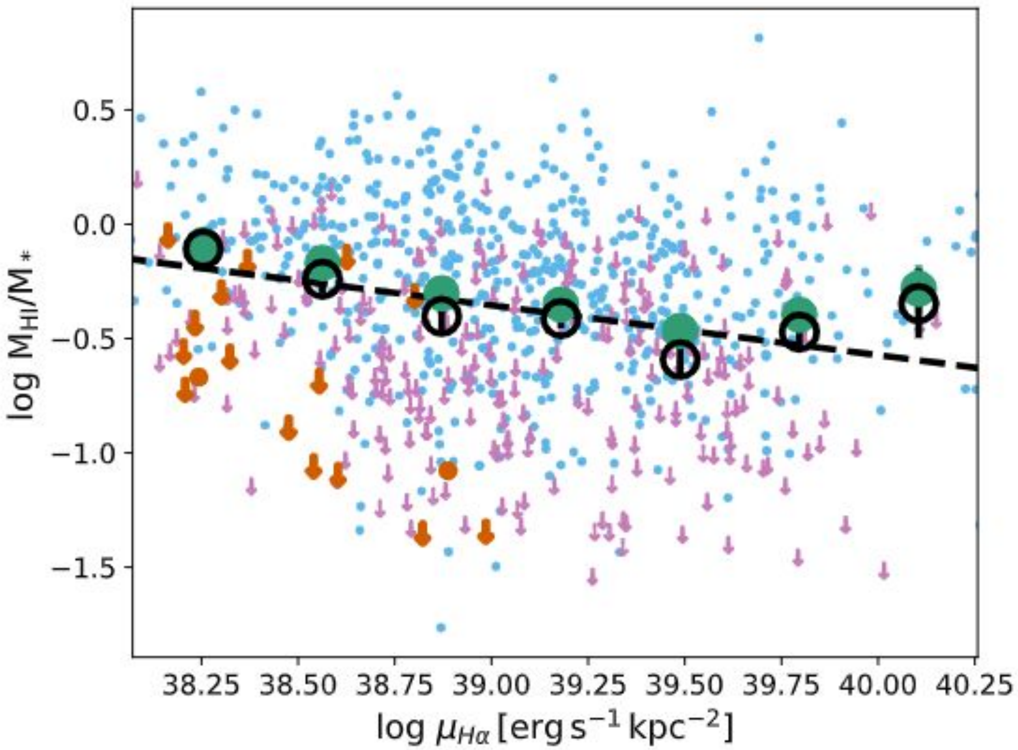
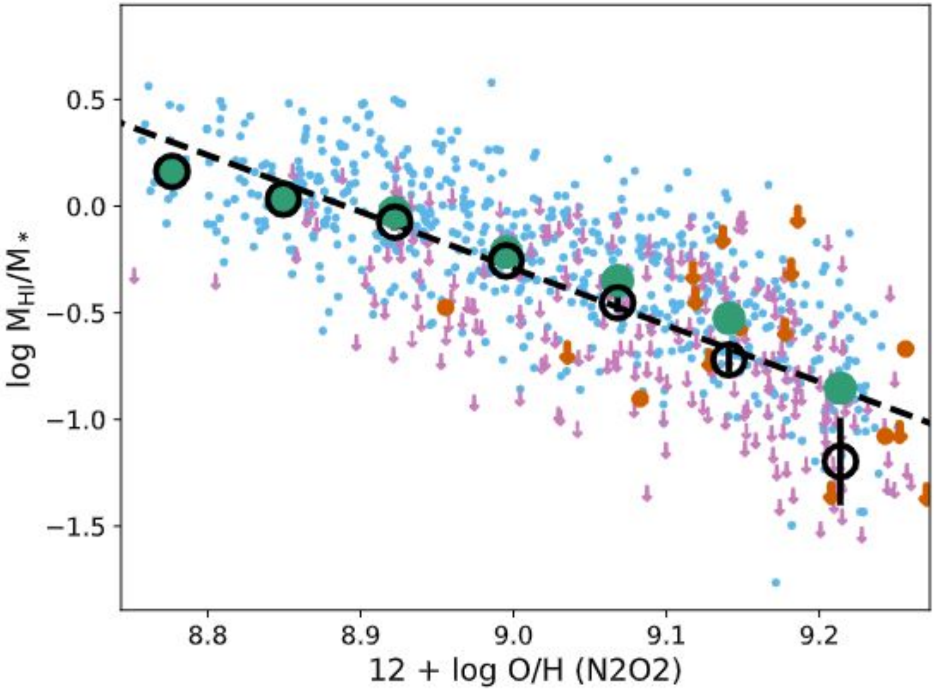


# HI-content and gas-phase metallicity

Strong anti-correlation ($\tau$=-0.45) with mean gas-phase metallicity

Consistent with previous studies

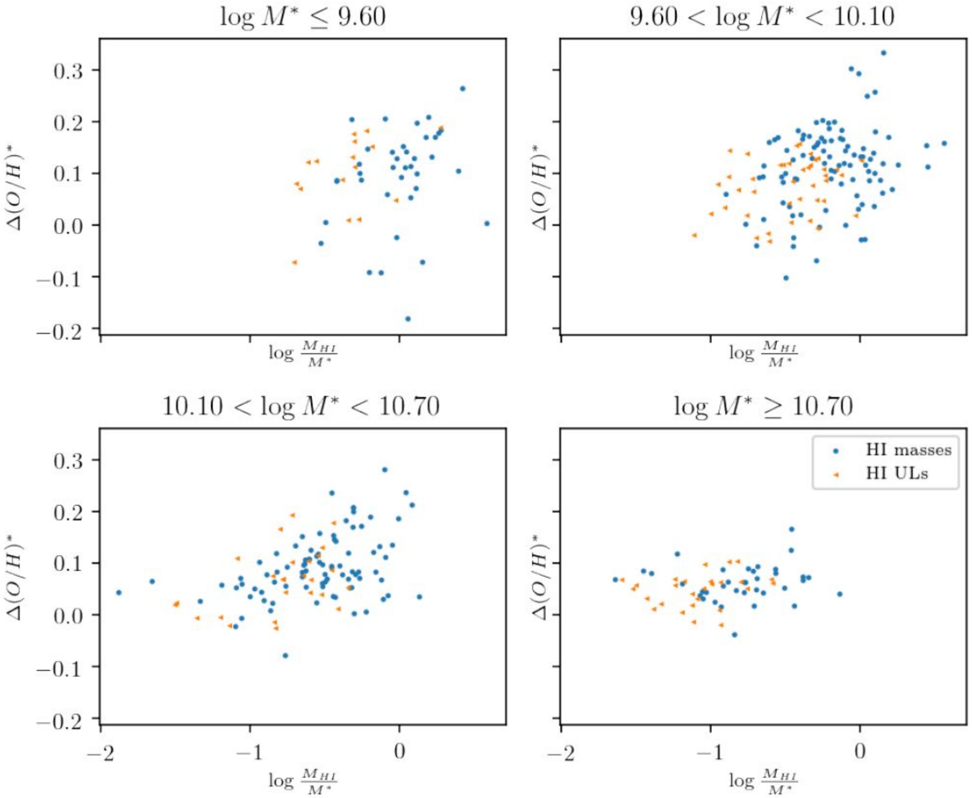
*(also keep an eye out for a paper by Zach Pace on how HI content and metallicity gradients imply regular gas inflow for low-mass galaxies!)*



# HI-content and gas-phase metallicity

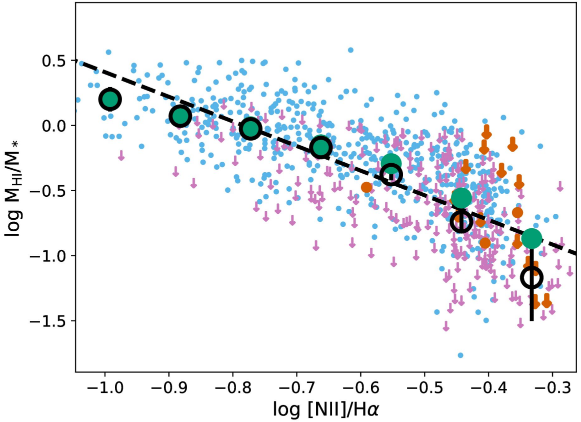
Pace et al. (2021): steep gas-phase metallicity **gradients** and high metallicity **dispersion** correlate with HI fraction at log $M_{*}$<10.7 $M_{\odot}$

Consistent with a gas inflow model (impulsive asymmetric inflows, not smooth, steady, and global)

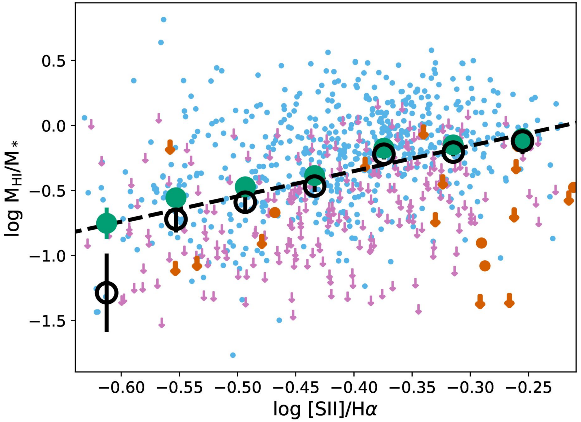


# HI content and low ionization lines

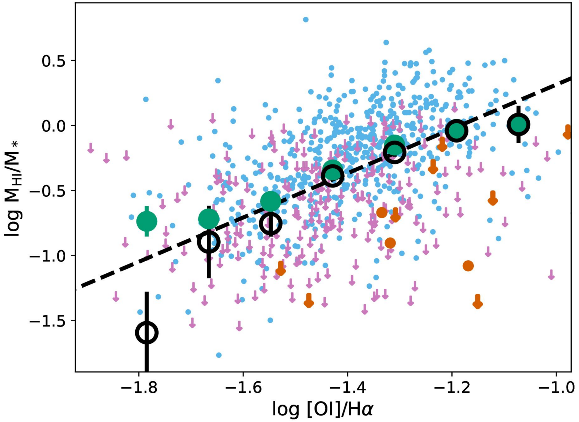
**Strong trends (|$\tau$|=0.15-0.45) with [NII]/Hα, [SII]/Hα, [OI]/Hα** arise in partially ionized regions (e.g. outer edges of SFing nebula), enhanced in diffuse ionized gas (DIG), sensitive to excitation by hard ionizing spectrum, shocks, ***and metallicity.***




log [NII]/Ha



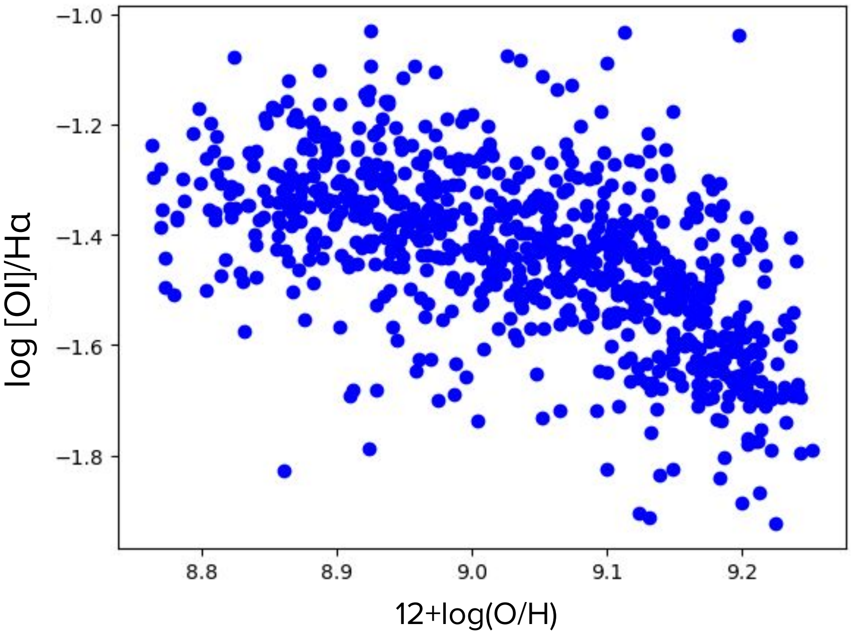

log [SII]/Ha

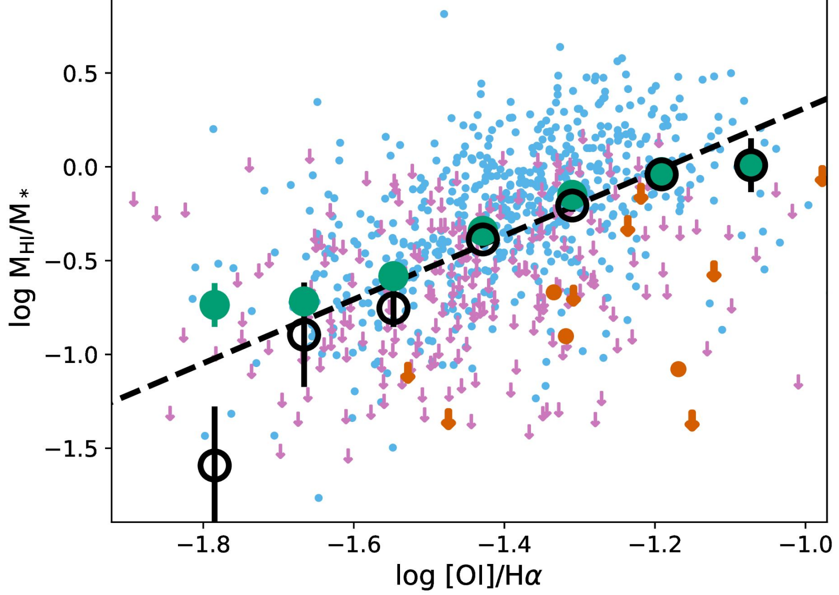



log [OI]/Ha

# HI content and [OI]/Hα

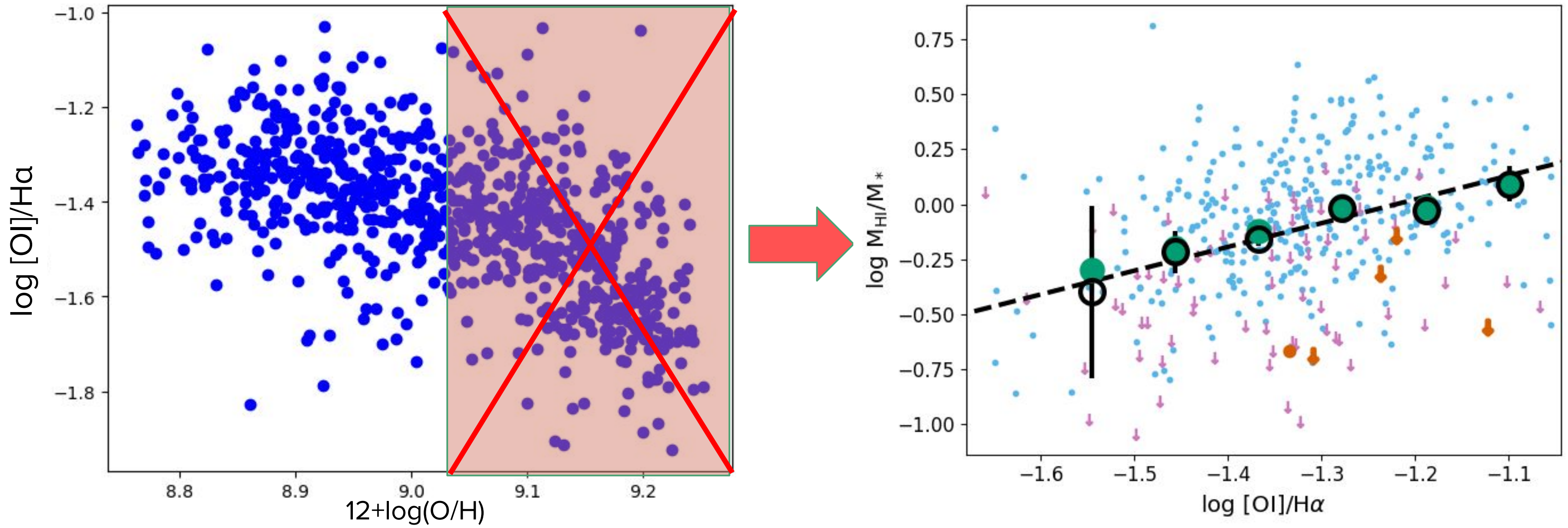
Trend driven by metallicity?



# HI content and [OI]/Hα

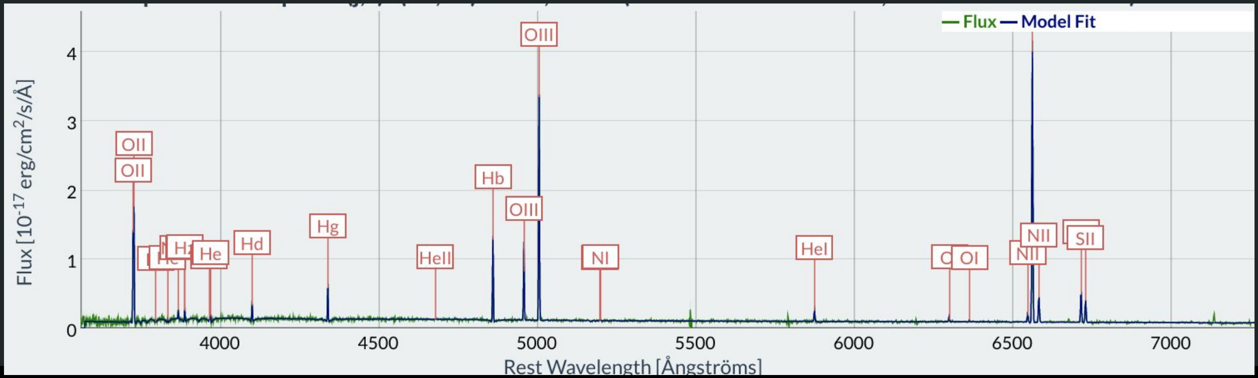
Isolate region of [OI]/Hα which is not strongly metallicity dependent ➔ ***HI fraction vs. [OI]/Hα correlation persists*** (though weaker, $\tau$=0.25)



# Recap so far

- Mean electron density, ionization parameter, and Hα surface brightness not do not vary significantly with HI fraction
- $M_{HI}/M_\star$ strongly correlates with metallicity (consistent with previous studies)
- $M_{HI}/M_\star$ positively correlated with [OI]/Hα, even after removing metallicity dependence
  - More gas rich galaxies may have harder ionizing fields, more shock heating, and/or larger DIG fractions

# HI-to-stellar mass ratio and optical line scaling relations

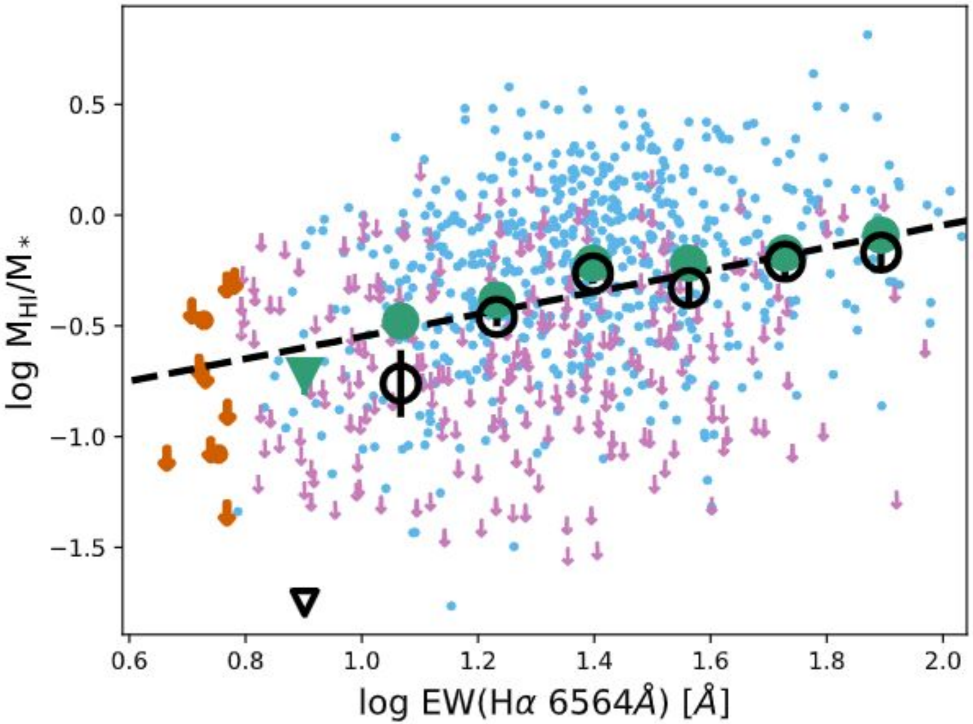


# HI fraction and Hα equivalent width

EW(Hα) ~ SFR/M* (specific star formation rate, sSFR)

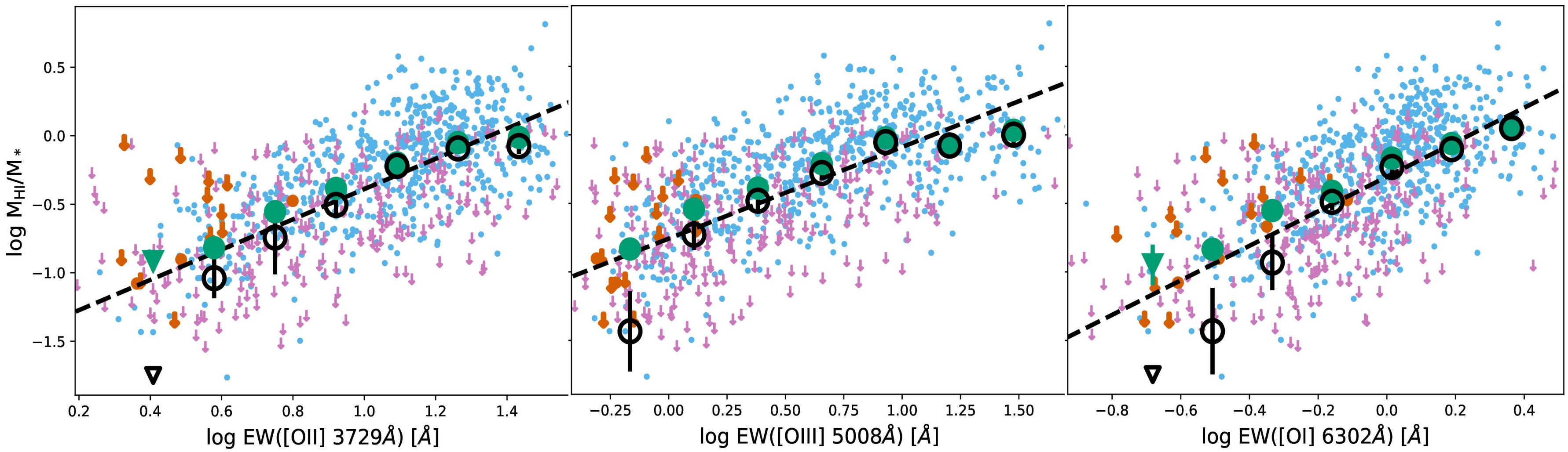
Weak correlation ($\tau$=0.15)

**Implication: star formation (measured over short timescales) weakly related to HI reservoir**



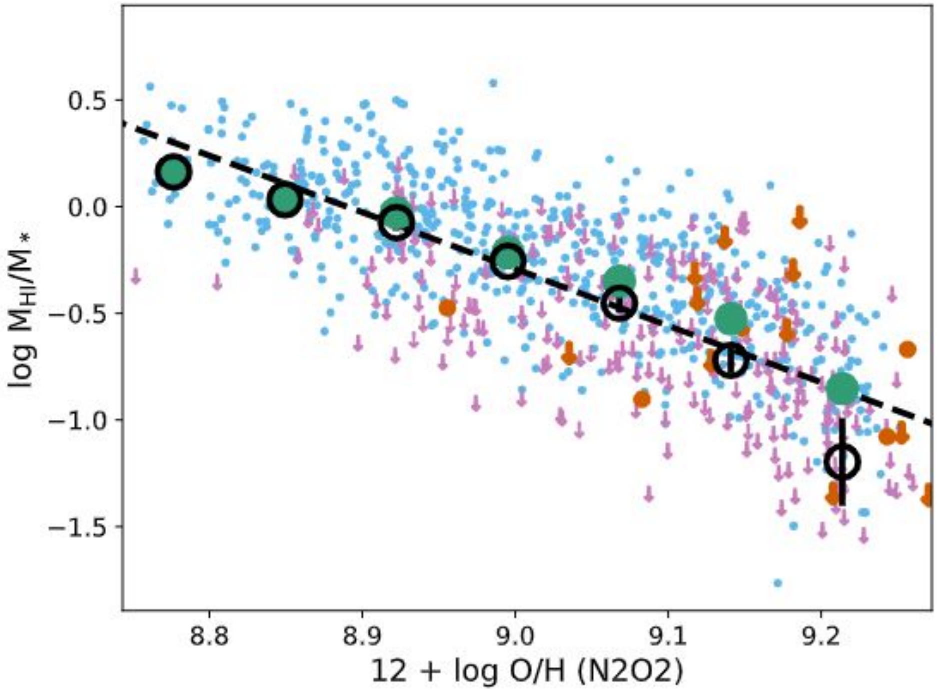
# HI Fraction and Oxygen Equivalent Width

[OII] 3729, [OIII] 5008, and [OI] 6302 EW show strongest correlations ($\tau$=0.4) with HI-to-stellar mass ratio



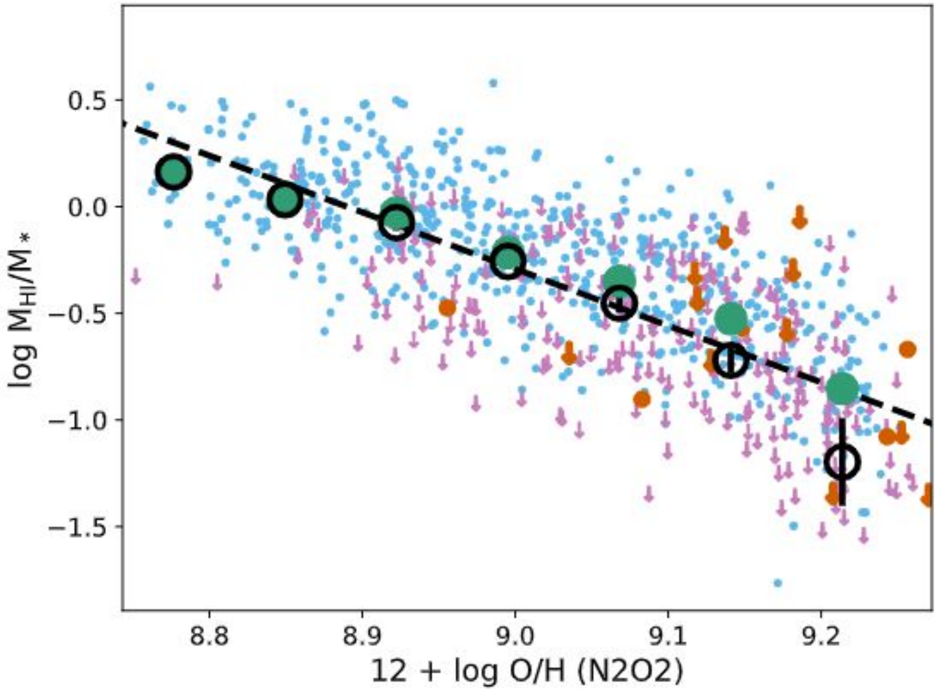
# Why does HI content correlate so well with EW(O)?

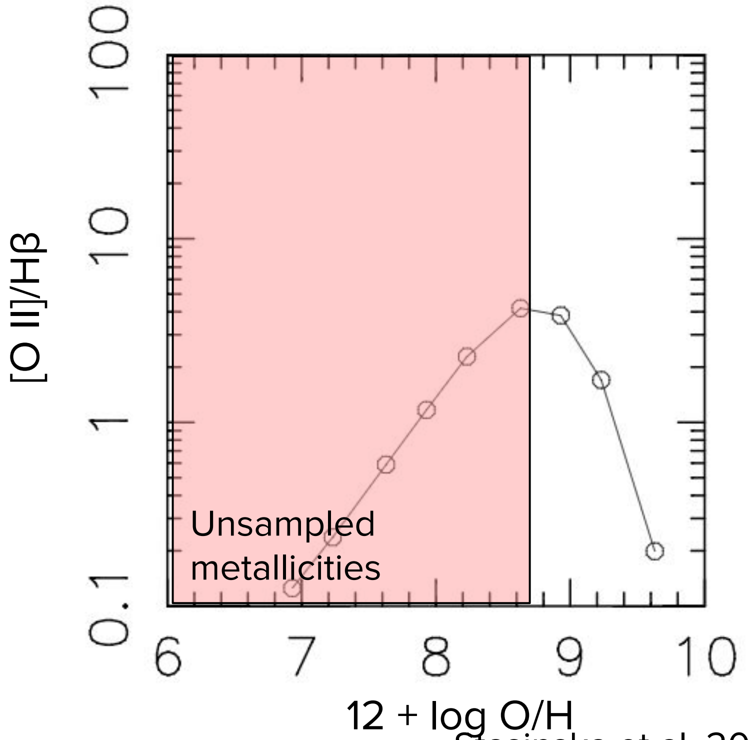
Recall this relationship...



# Why does HI content correlate so well with EW(O)?

Recall this relationship...and how oxygen line emission scales with metallicity




Stasinska et al. 2002

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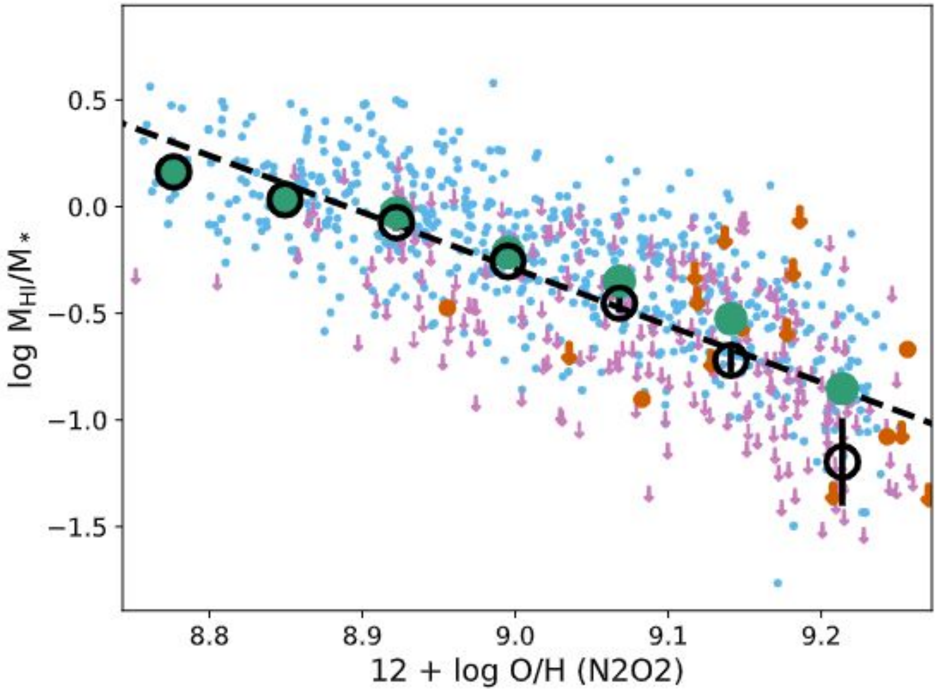


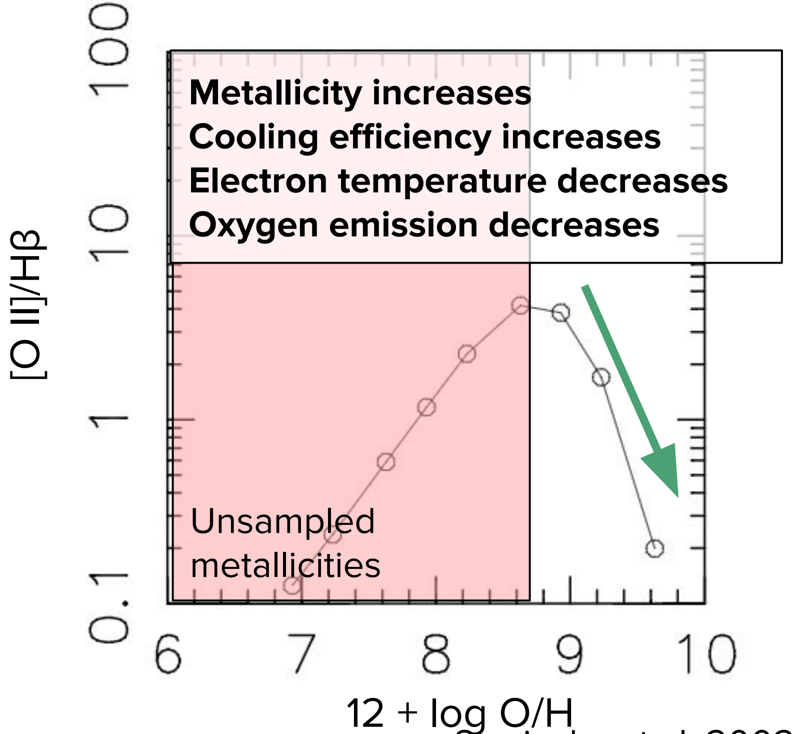


Stasinska et al. 2002

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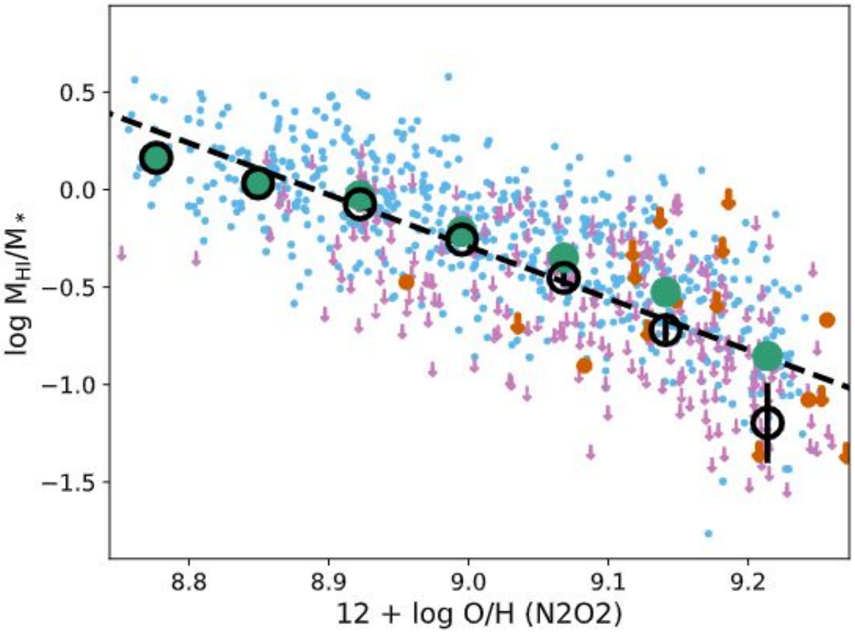
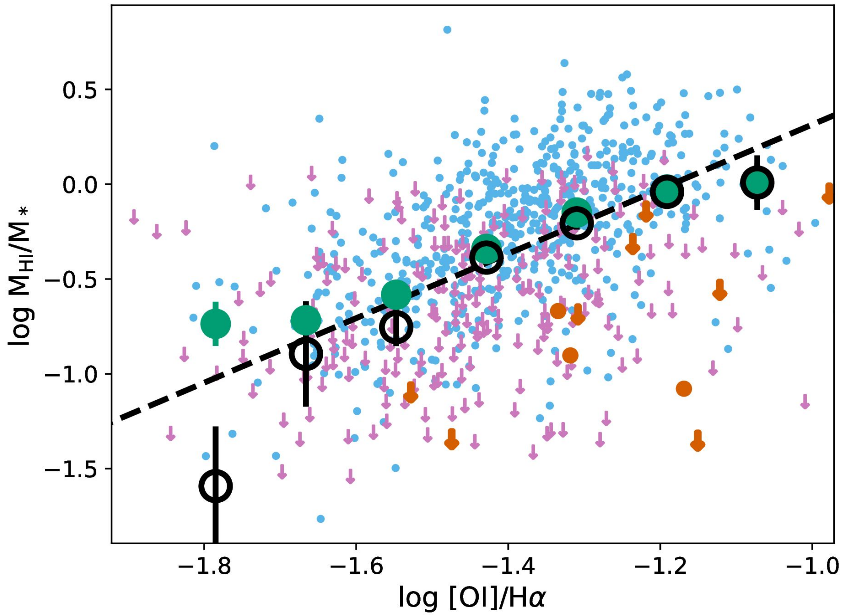
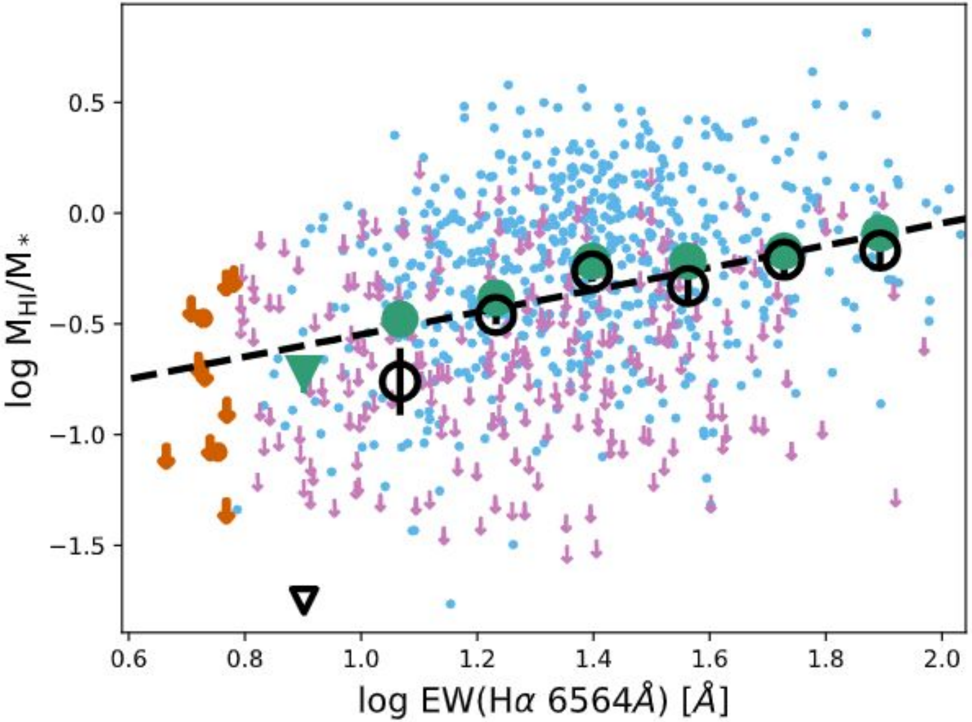
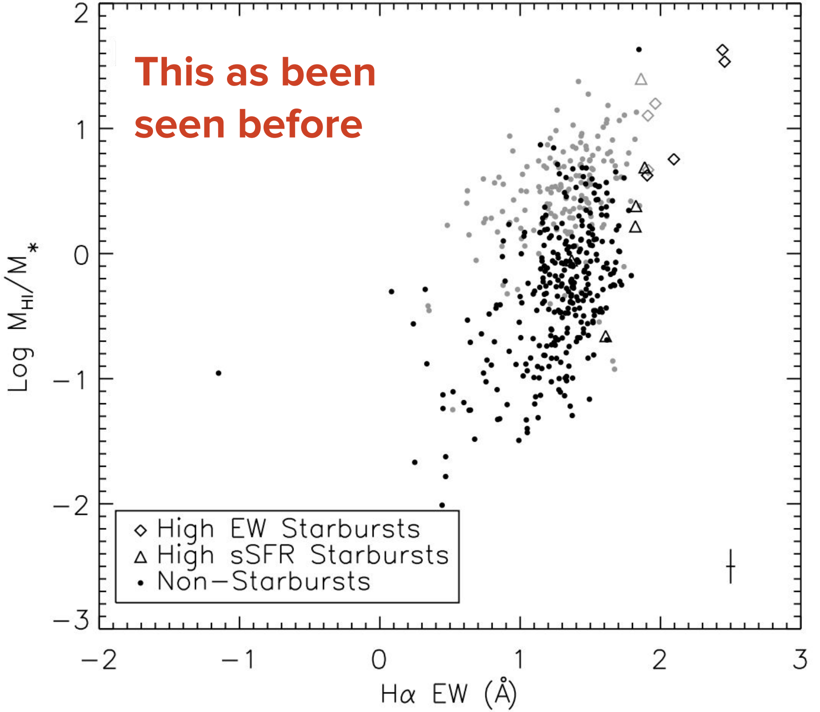


# Why is EW(Hα) so poorly correlated with HI fraction?

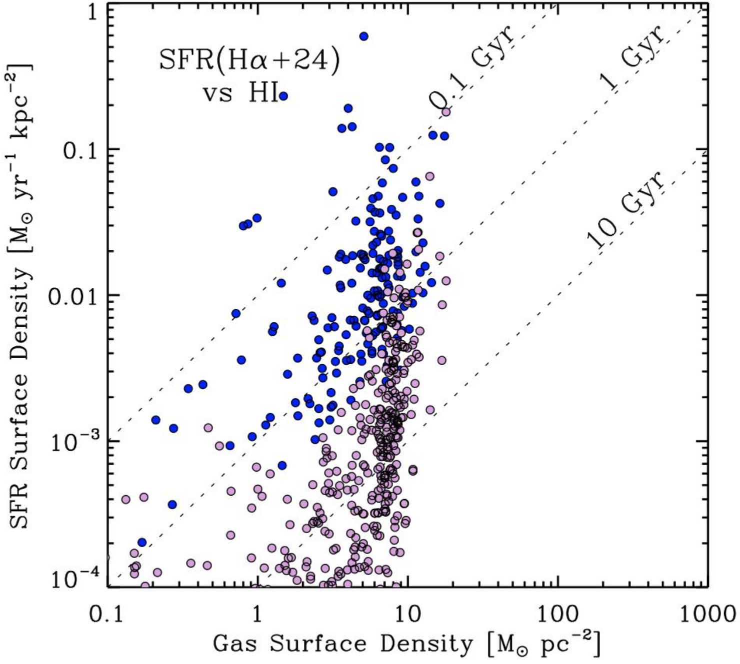



Jaskot et al. (2015)

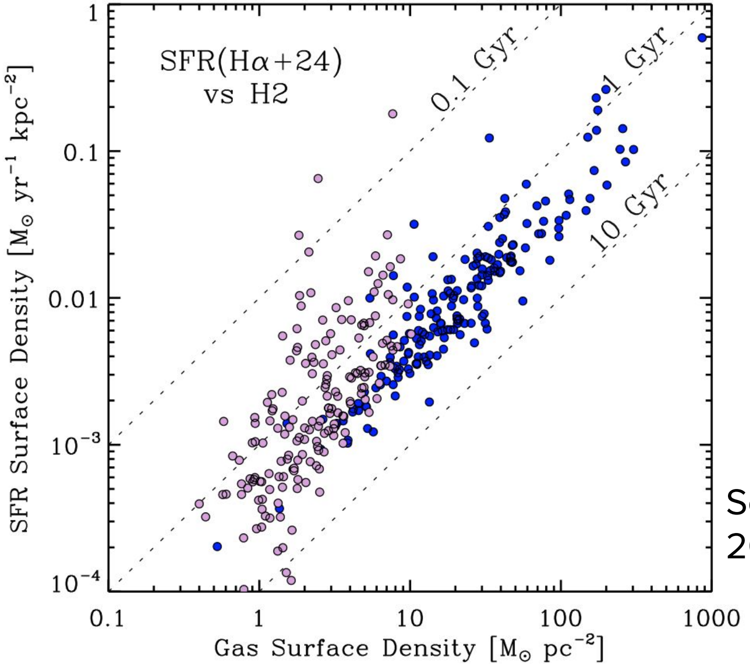


# Insight from spatially resolved gas/SFR data

## SFR vs. HI




## SFR vs. $H_2$



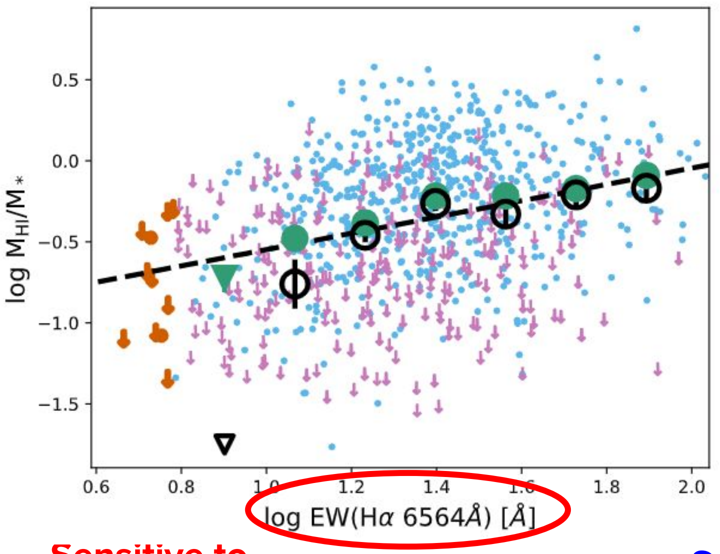

Schruba et al. 2011

# But HI fraction correlates well with other sSFR indicators

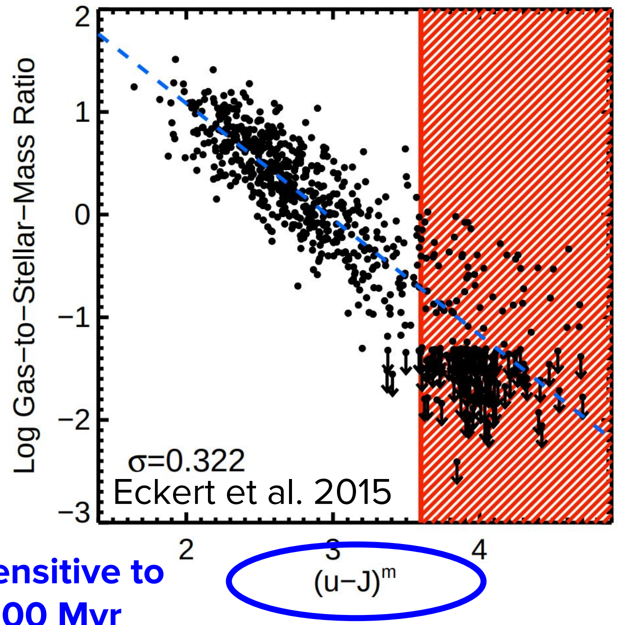
HI-to-stellar mass ratio correlates poorly with EW(Hα) but strongly with NUV-NIR color (***both are specific SFR tracers***)

Why is HI vs. color so much tighter?

- Dust? (Jaskot et al. 2015) - no
- Aperture effects? - no
- Scatter in Hα-to-SF calibration? - maybe a bit
- SF tracer timescales?

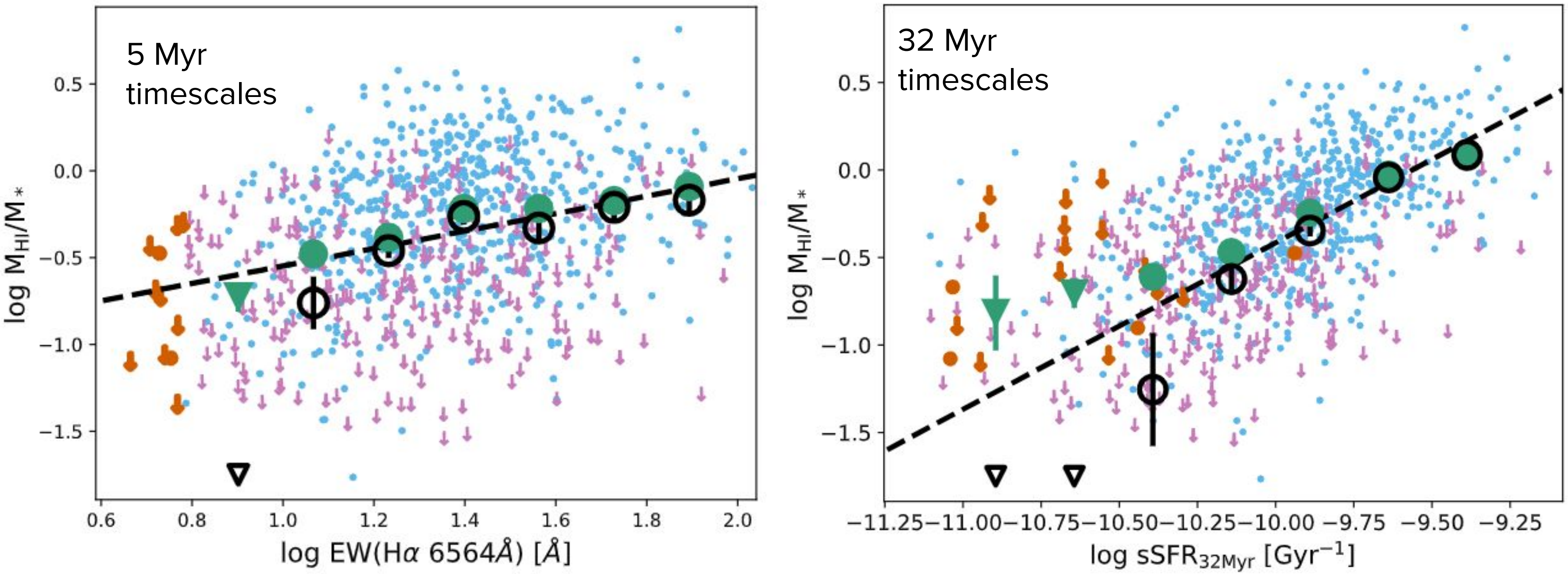



**Sensitive to ~5Myr timescales**




**Sensitive to >100 Myr timescales**

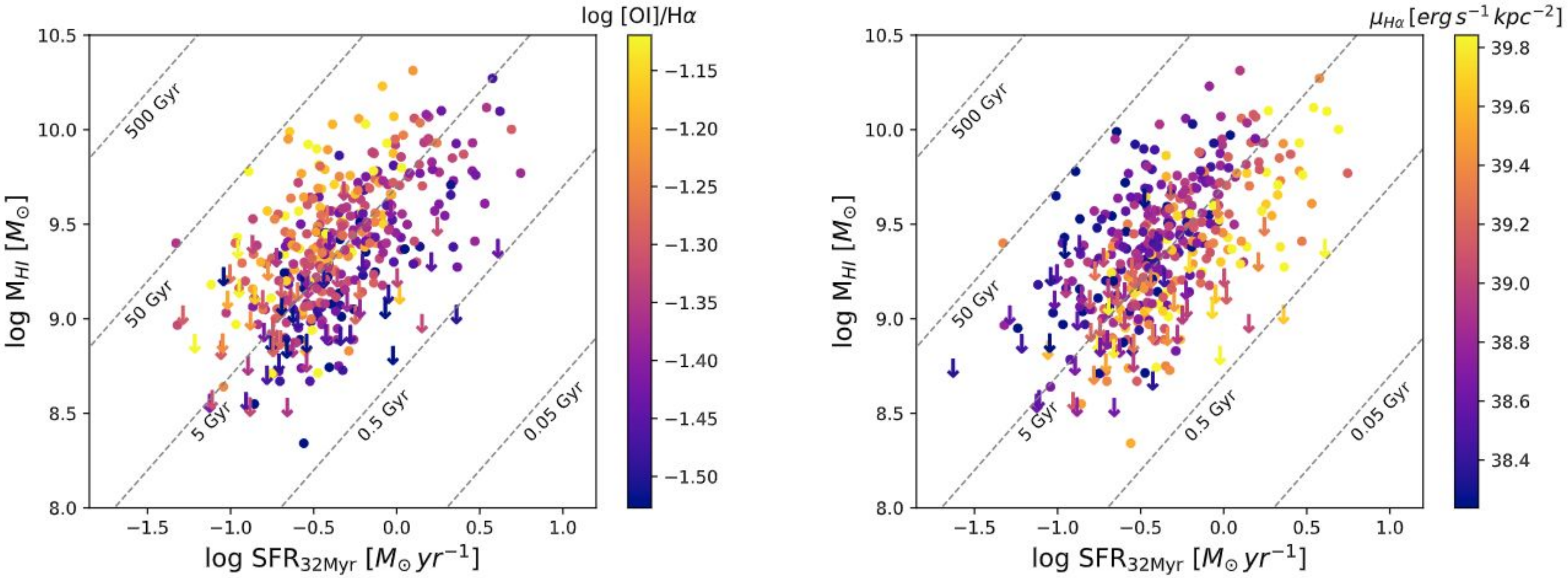
# HI *sustains* long term-averaged SF



# Understanding the scatter: long HI depletion time associated with elevated [OI]/Hα and depressed Hα surface brightness

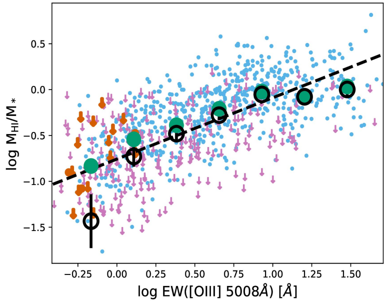
**Larger fraction of diffuse gas (and/or shock heating)?**

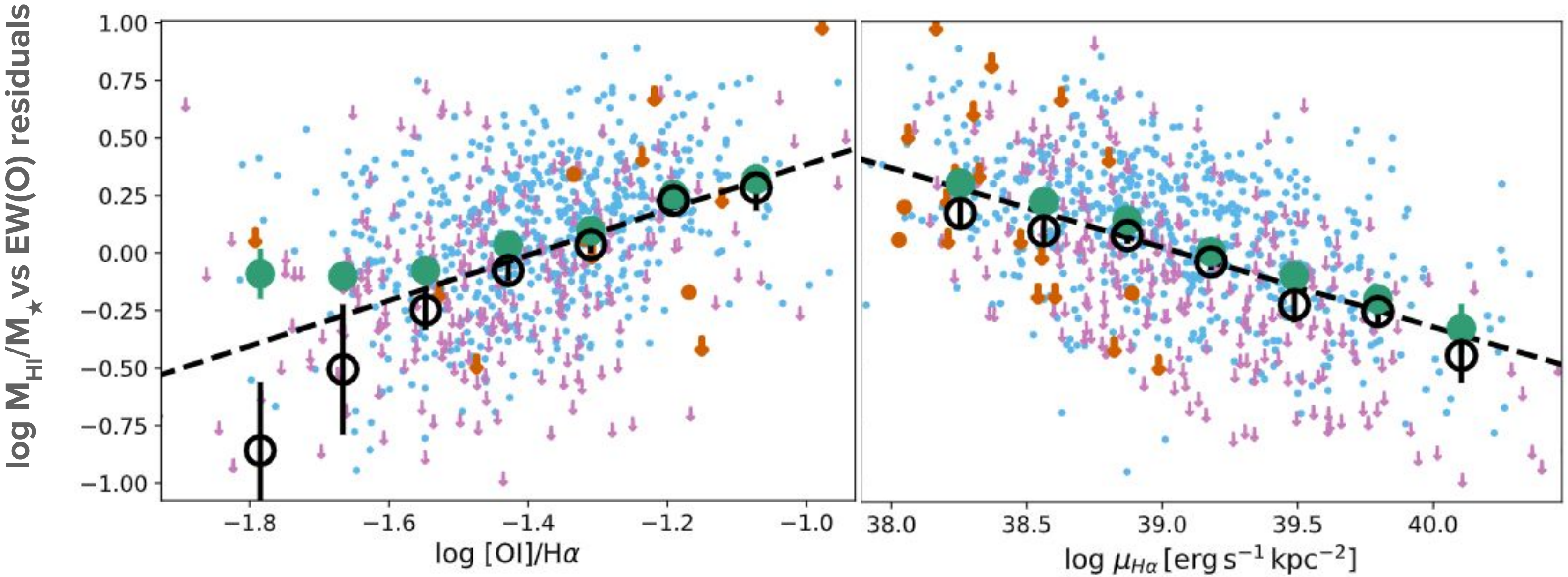
***Harder to form dense molecular clouds and stars?***



# Diffuse gas/shock heating impacts other relations too

[OI]/Hα and $\mu_{H\alpha}$ correlates with residuals of MHI/M* vs EW(O)



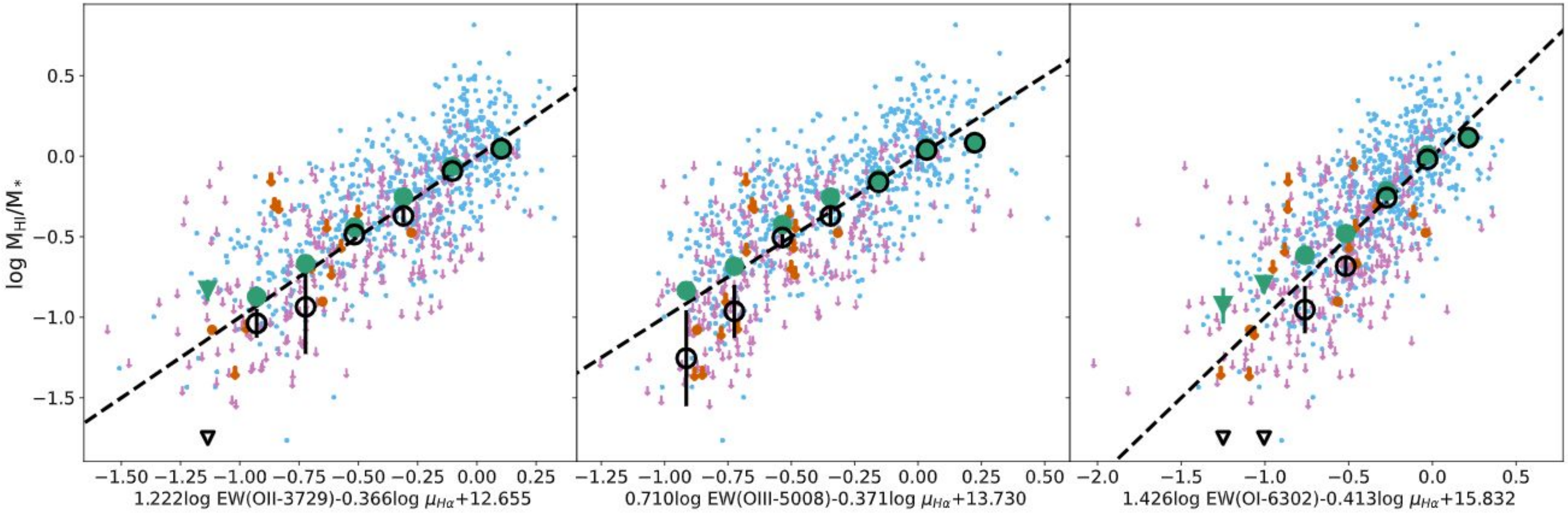
# Summary

- HI-MaNGA is obtaining HI data for all z<0.05 MaNGA galaxies
- **$M_{HI}/M_*$ correlates with [OI]/Hα** → consistent with more gas-rich galaxies having harder ionizing fields, more shock heating, and/or larger DIG fractions
- **$M_{HI}/M_*$ is well-correlated with EW([OI,II,III])** → A likely result of the $M_{HI}/M^*$-metallicity relation
- **$M_{HI}/M_*$ is poorly correlated with EW(Hα)** → Weak connection between HI and SF on short timescales, but tighter when SF averaged over longer timescales
- **Long HI depletion times coincide with enhanced [OI]/Hα and depressed Hα surface brightness** → consistent with more DIG → may imply larger amounts of diffuse HI, so less HI in conditions conducive to $H_2$ cloud formation
  - Scatter in $M_{HI}/M_*$ vs. EW(O) relation also correlates with [OI]/Hα and Hα surface brightness

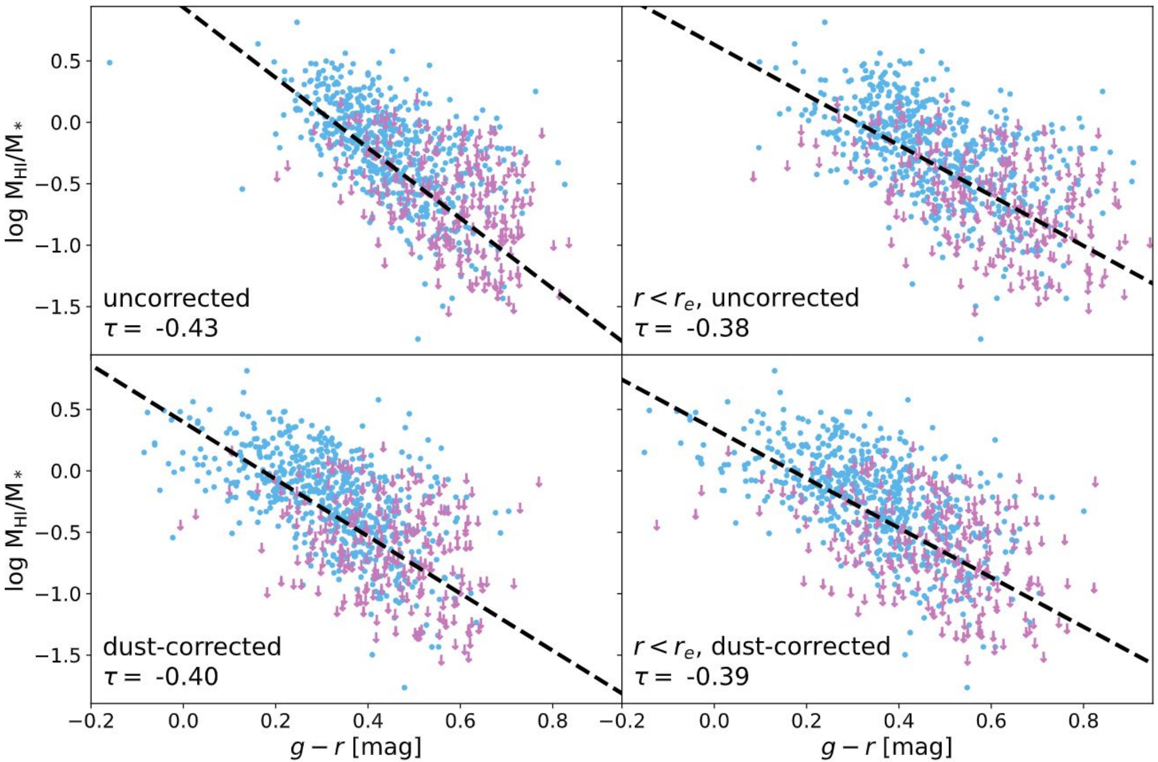
**Thank you!**

# Backup slides

# Multi-parameter scaling relations



# Aperture/extinction-correction tests



# Photometric gas fractions instead