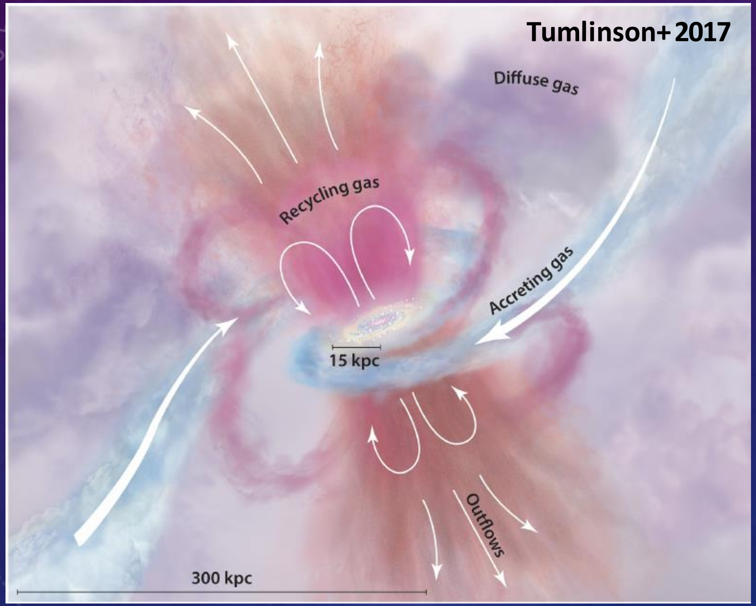
THE IMPACT OF OUTFLOWS ON GALAXIES AND HALOS OVER COSMIC TIME



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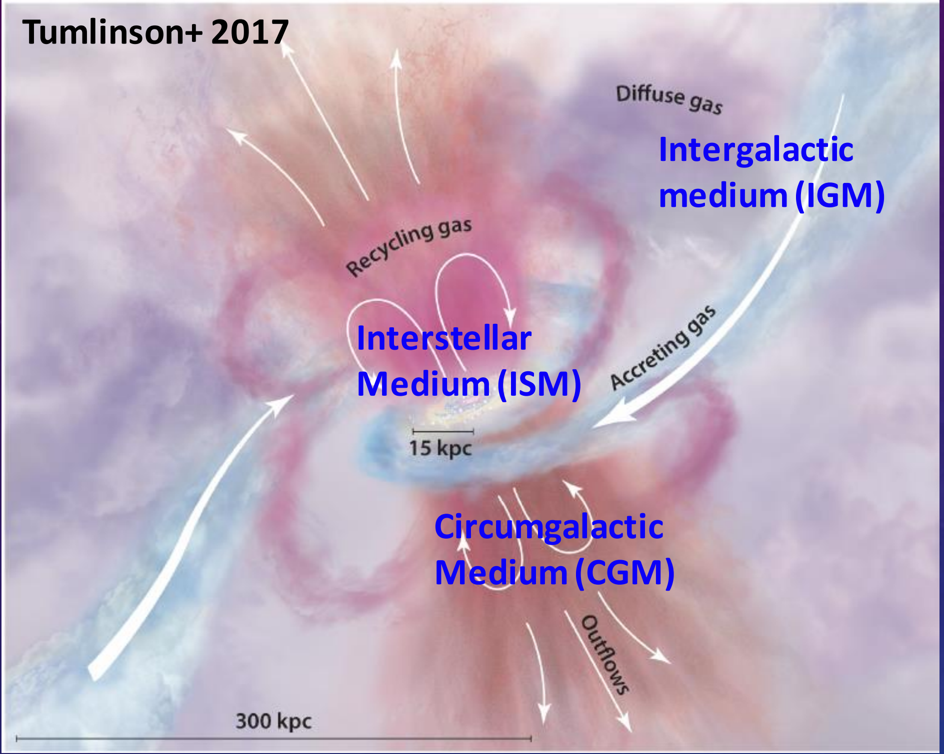
COLLOQUIUM, UNIVERSITY OF MELBOURNE, AUGUST 4, 2021

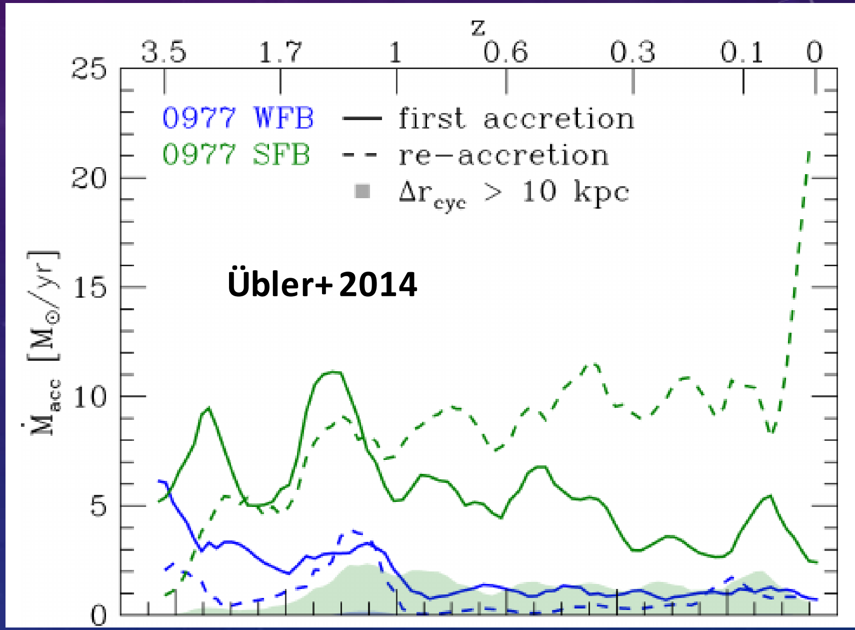
SWINBURNE UNIVERSITY OF TECHNOLOGY

ASTRO 3D

OUTFLOWS: A KEY COMPONENT OF THE BARYON CYCLE



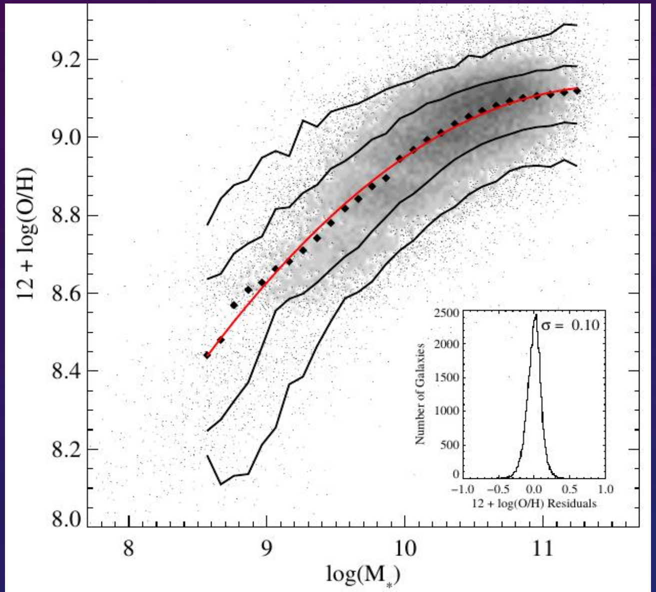
Outflows transport mass, metals and energy from galaxies to the CGM



Simulations suggest that material ejected in outflows is the dominant source of accretion at low redshift

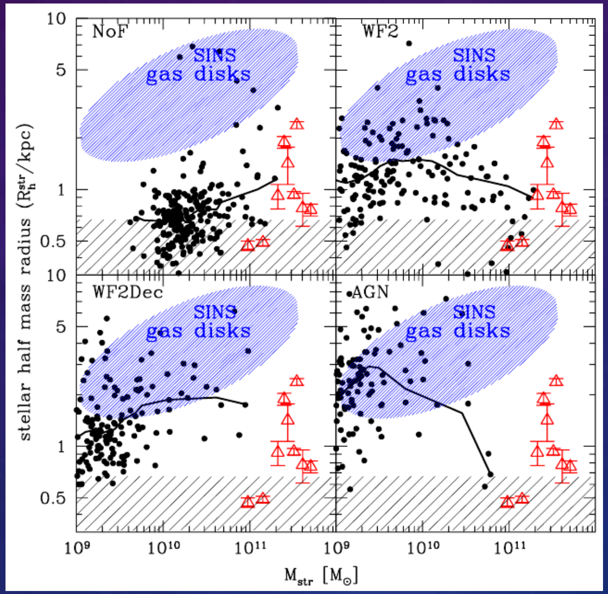
OUTFLOWS SHAPE THE PROPERTIES OF GALAXIES

Mass-Metallicity Relation



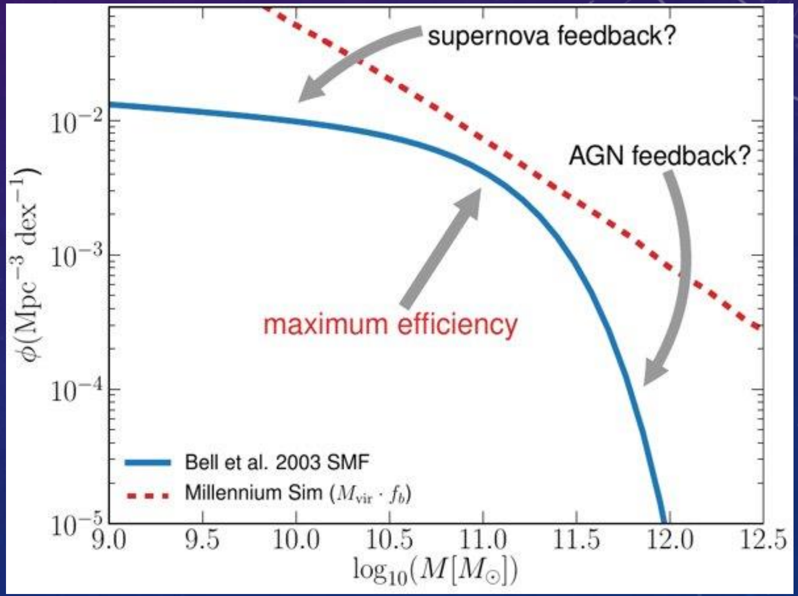
Tremonti+ (2004)

Disk Sizes



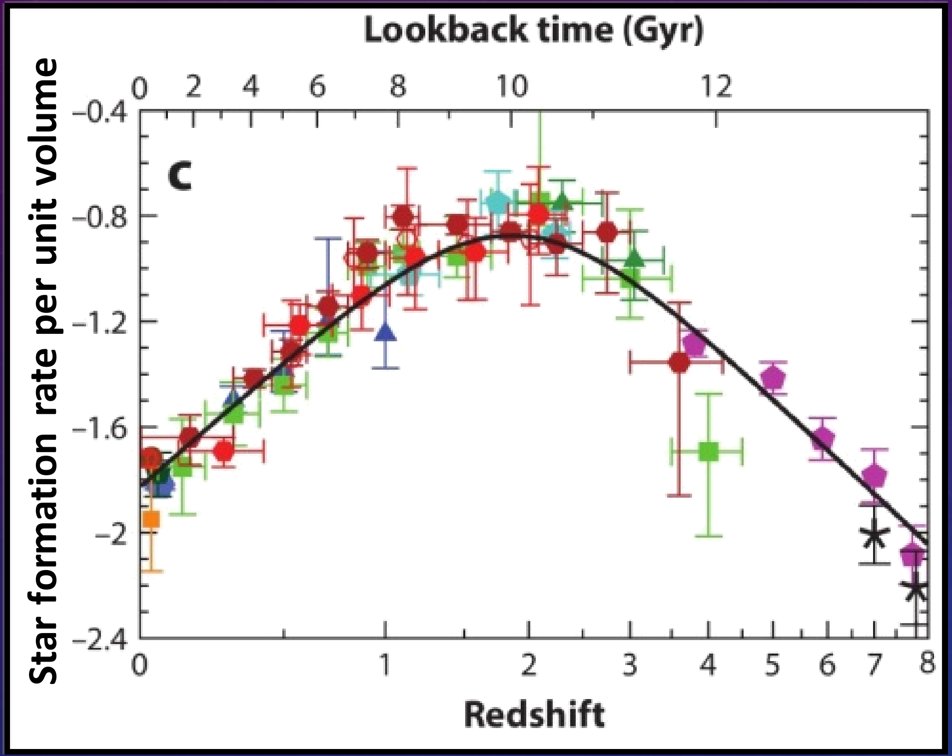
Sales+ (2010)

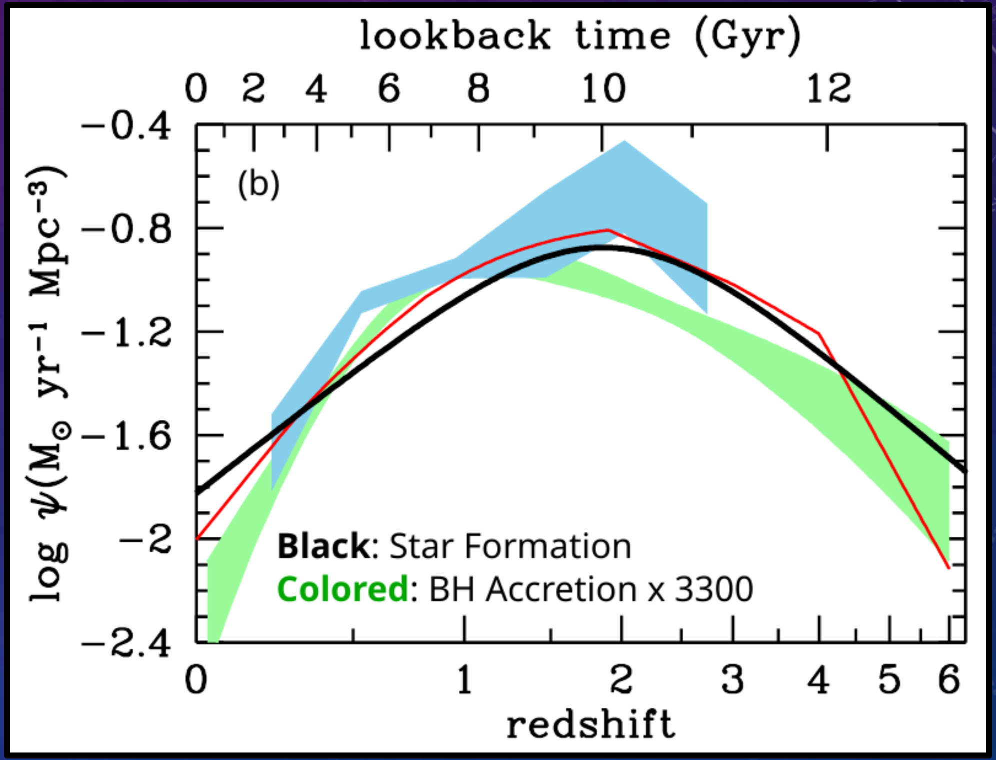
Galaxy Formation Efficiency



Mutch+ (2013)

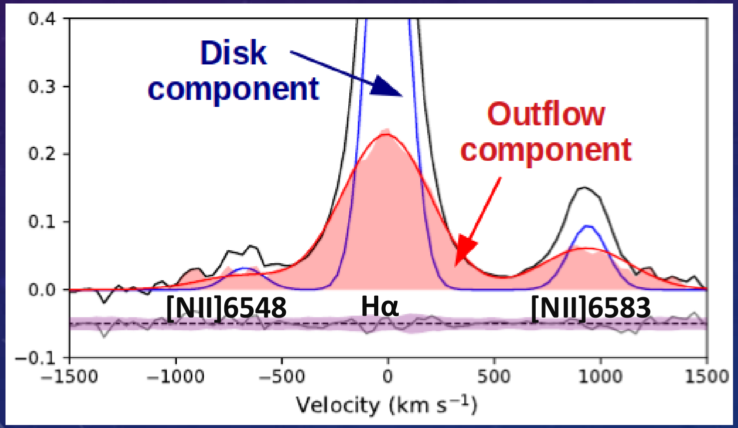
COSMIC NOON: THE PEAK EPOCH OF OUTFLOWS





Madau & Dickinson (2014)

MEASURING OUTFLOW PROPERTIES



Outflow Velocity ($v_{outflow}$) = $\Delta v + 2\sigma_{outflow}$

Mass outflow rate $\propto$ (L[$H\alpha_{outflow}$] / n_e) x $v_{outflow}$ / $r_{outflow}$

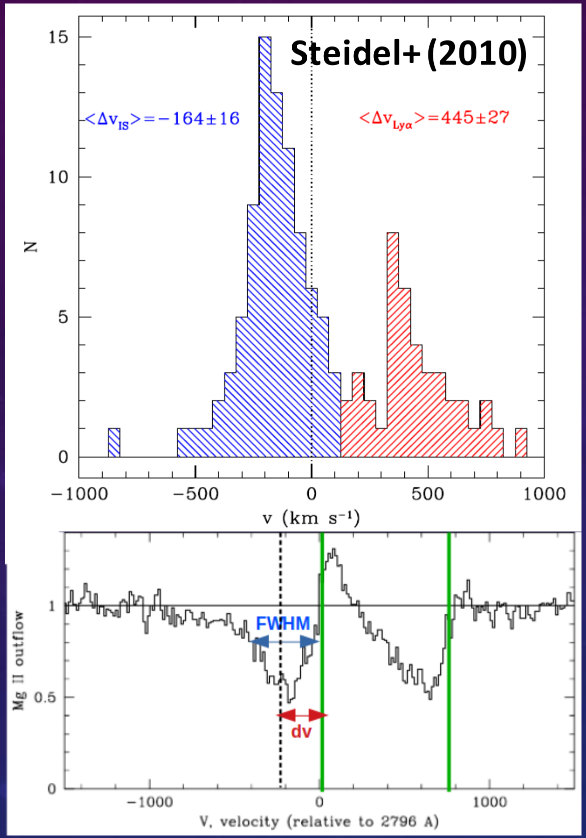
Electron density in the outflow

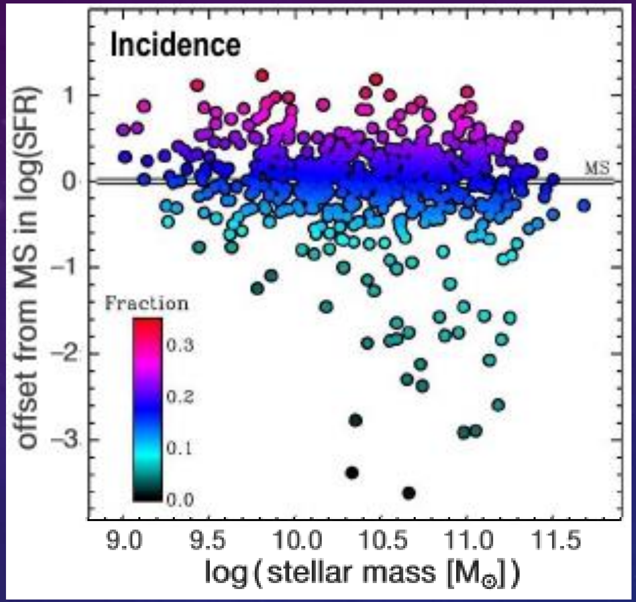
Radial extent of the outflow

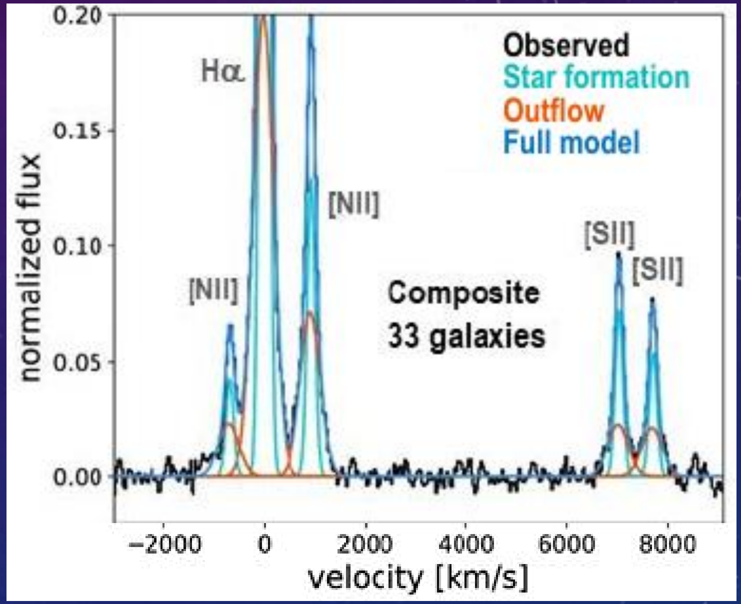
Mass loading factor (η) = mass outflow rate / SFR

SFR $\propto H\alpha_{disk}$

PROPERTIES OF STAR-FORMATION-DRIVEN OUTFLOWS



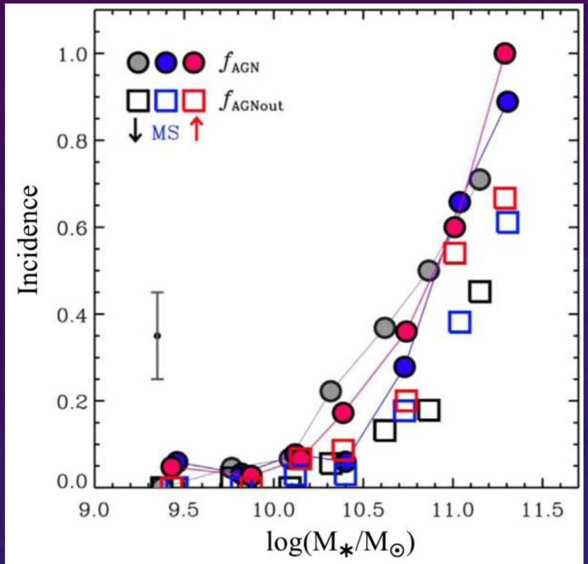


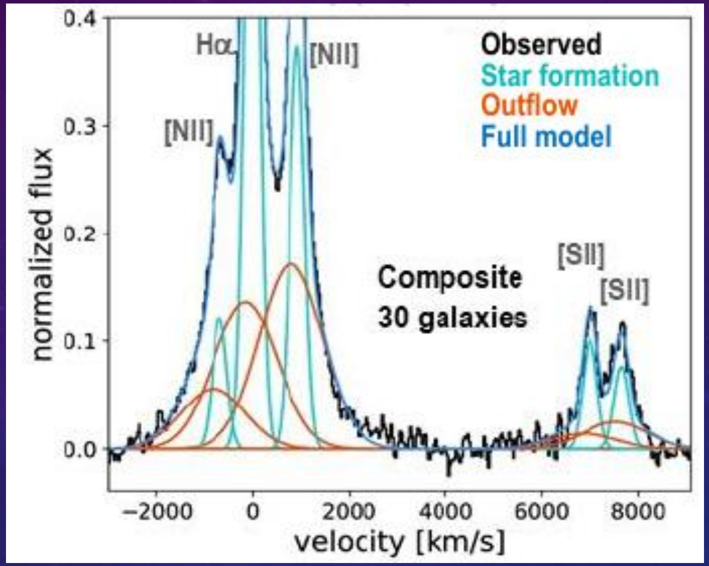


Förster Schreiber, Übler, *RLD* et al. (2019)

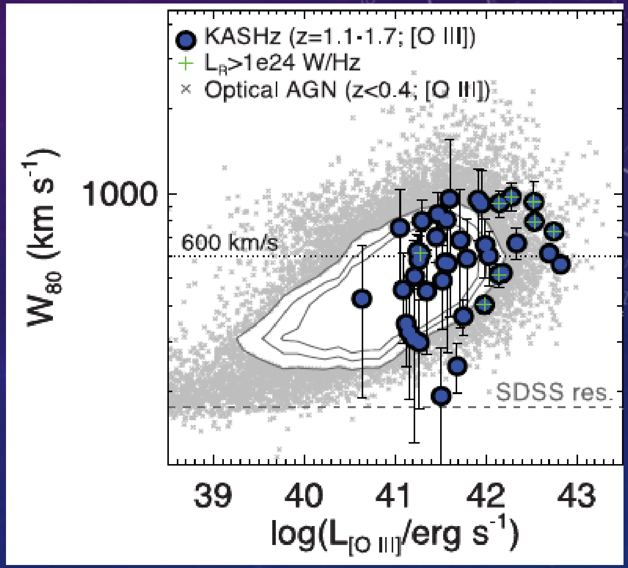
Prevalent **above the main sequence,** with typical velocities of **300-500 km/s.**

PROPERTIES OF AGN-DRIVEN OUTFLOWS





Förster Schreiber, Übler, *RLD* et al. (2019)



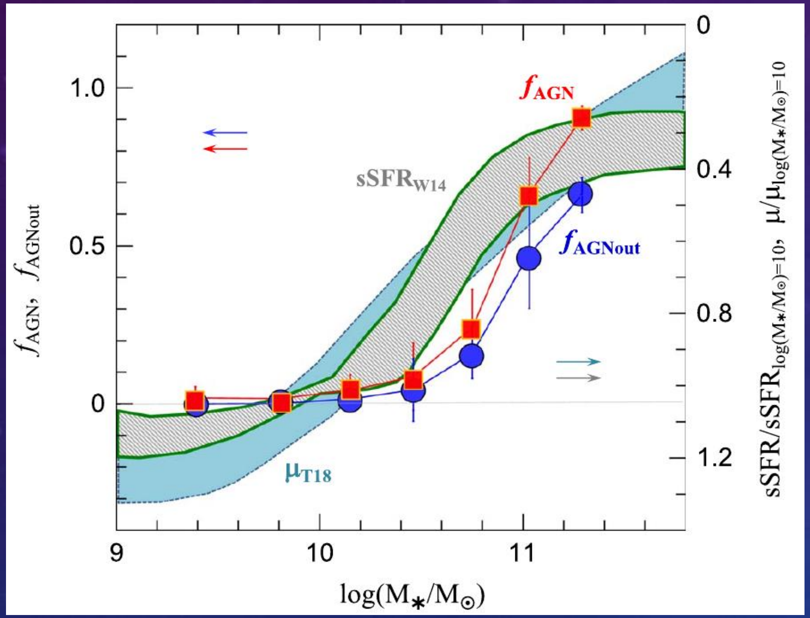
Harrison et al. (2016)

Prevalent at **high stellar masses**.

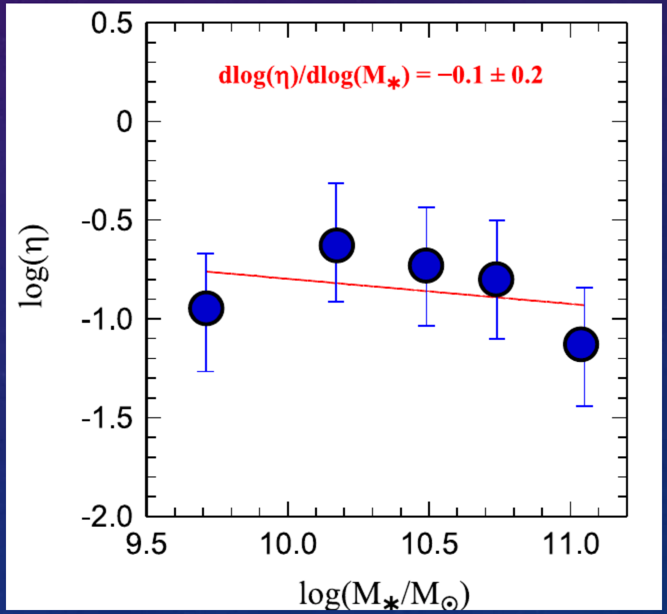
Outflow velocity increases with AGN luminosity. Typical maximum velocities of **1000-2000 km/**s.

OUTFLOWS AT COSMIC NOON: IMPACT ON GALAXY EVOLUTION

AGN-driven



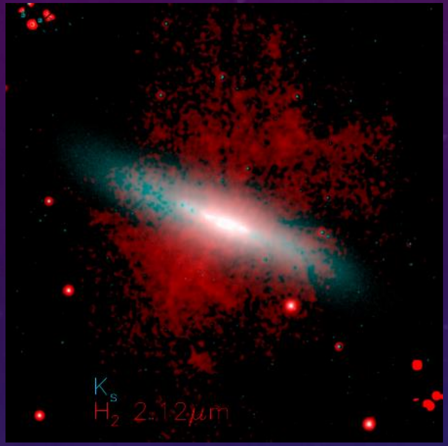
Star-formation-driven



Förster Schreiber, Übler, *RLD* et al. (2019)

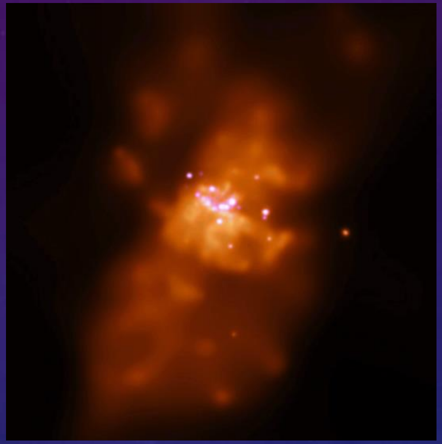
OUTFLOWS ARE INTRINSICALLY MULTI-PHASE PHENOMENA

M82

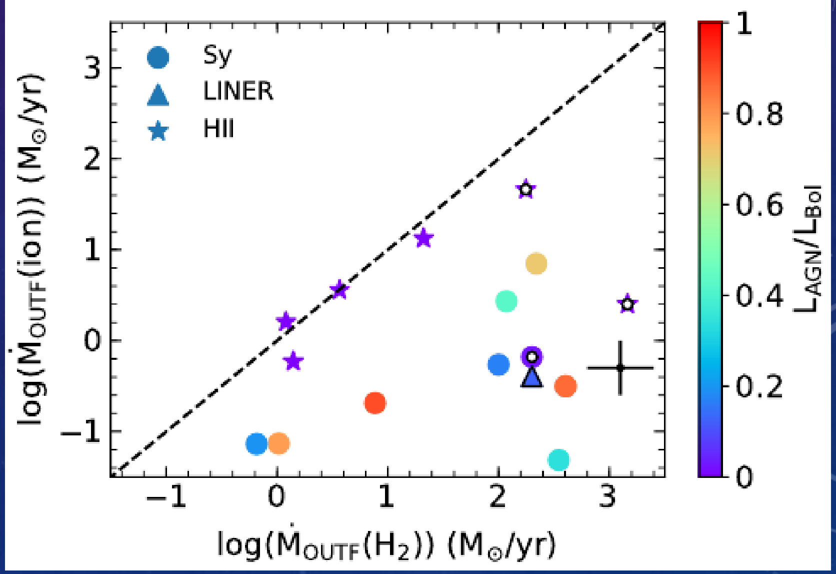


Warm molecular gas

Ionized gas



Hot (X-ray) gas

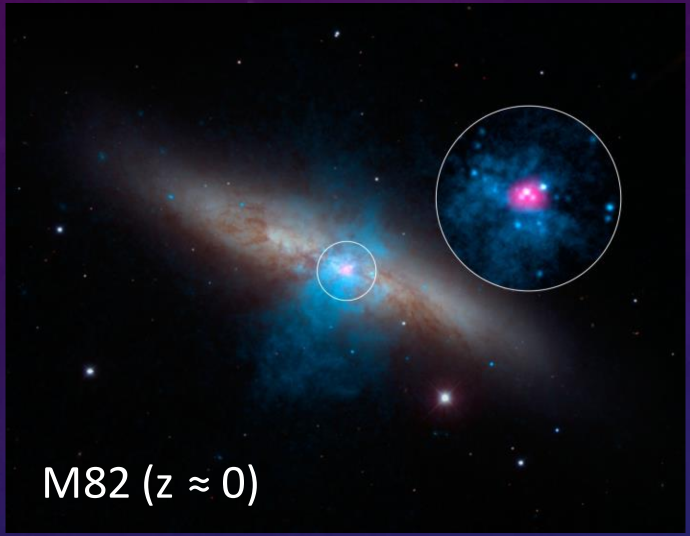


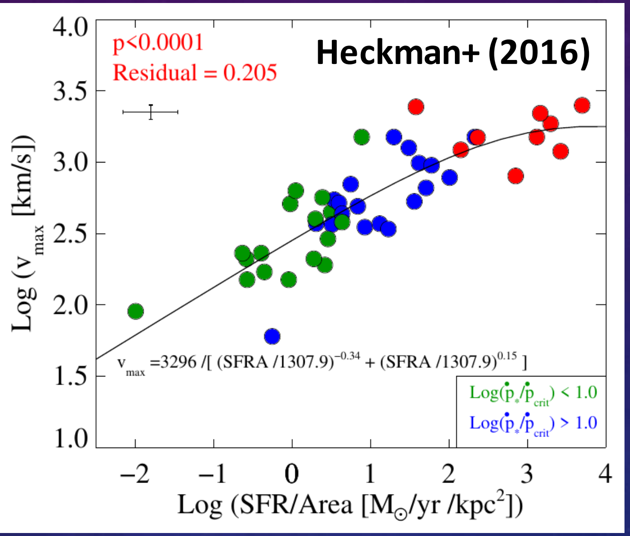
Fluetsch+ (2019)

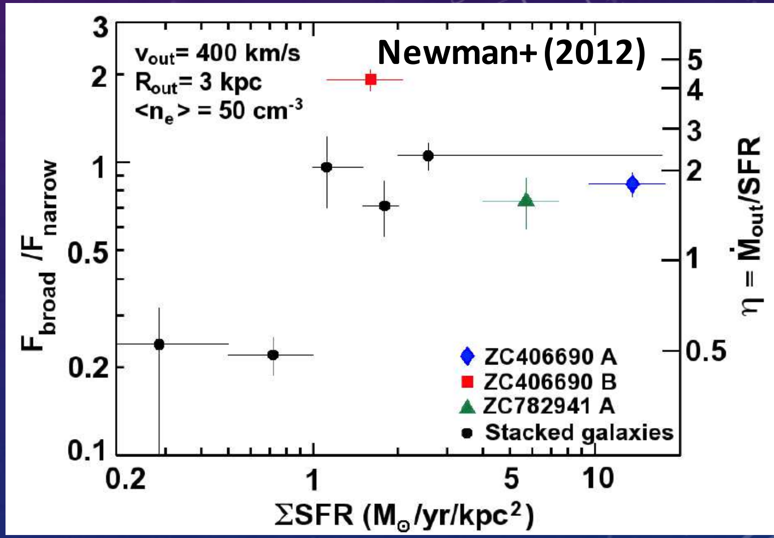
OUTLINE

- Spatially resolved studies of galactic winds at cosmic noon
  - Constraining models of star-formation-driven outflows
  - Observations of AGN feedback on circumnuclear to circumgalactic scales
- Investigating the production and transport of metals in the early Universe using measurements of the CGM at $z > 5.5$

IMPORTANT TO RESOLVE OUTFLOWS ON KILOPARSEC SCALES

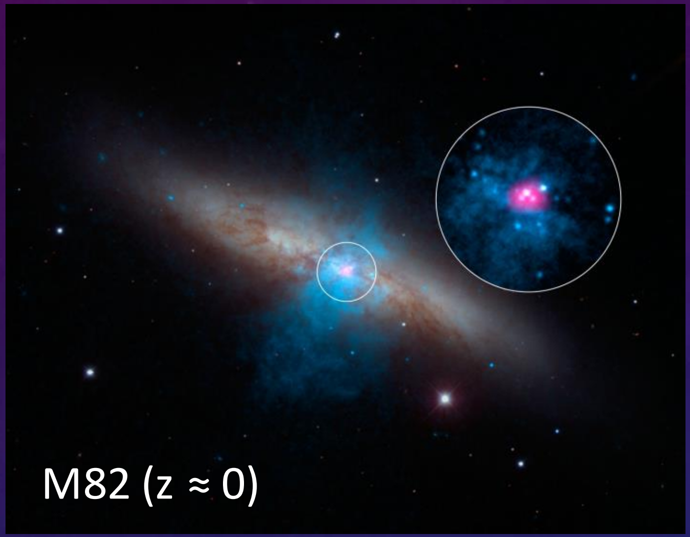


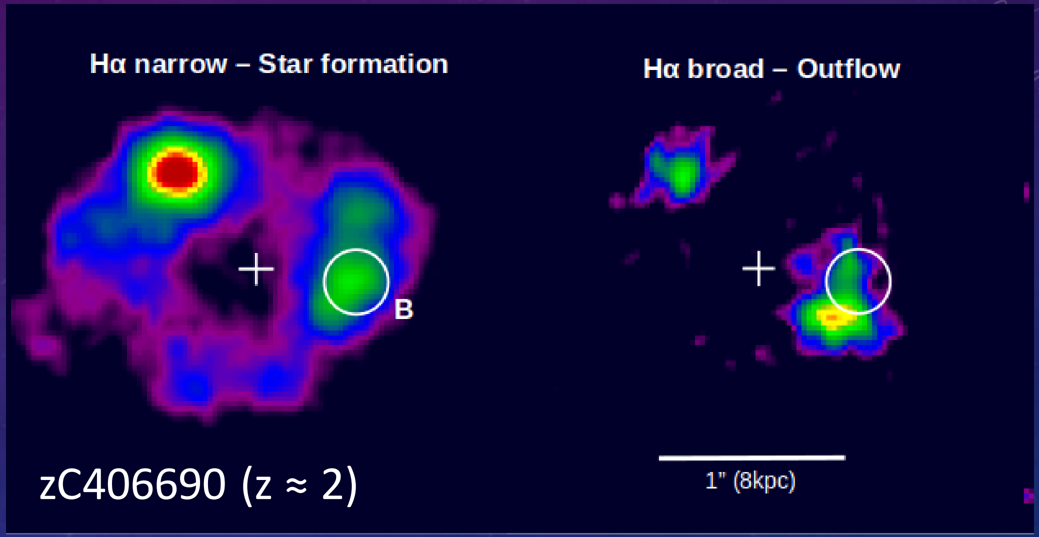




- Outflows launched from regions of concentrated star formation
- Higher star formation rate surface density (Σ_{SFR}) = greater outward force

IMPORTANT TO RESOLVE OUTFLOWS ON KILOPARSEC SCALES

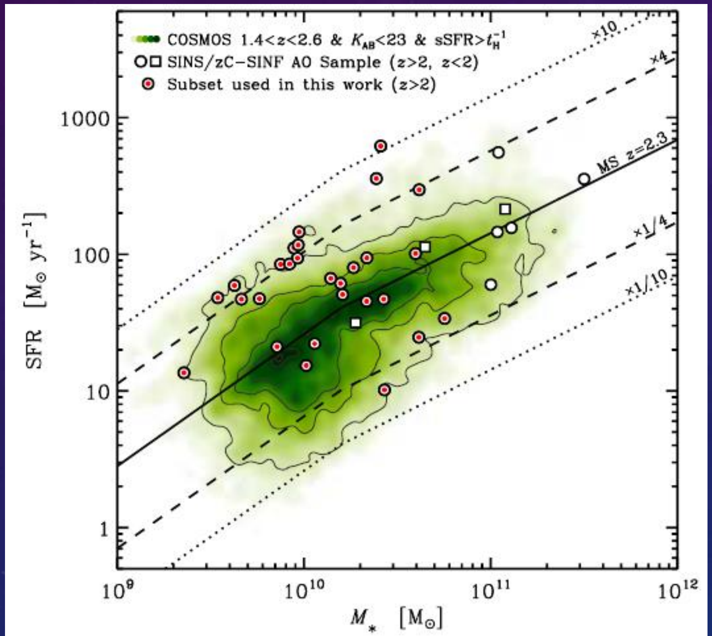


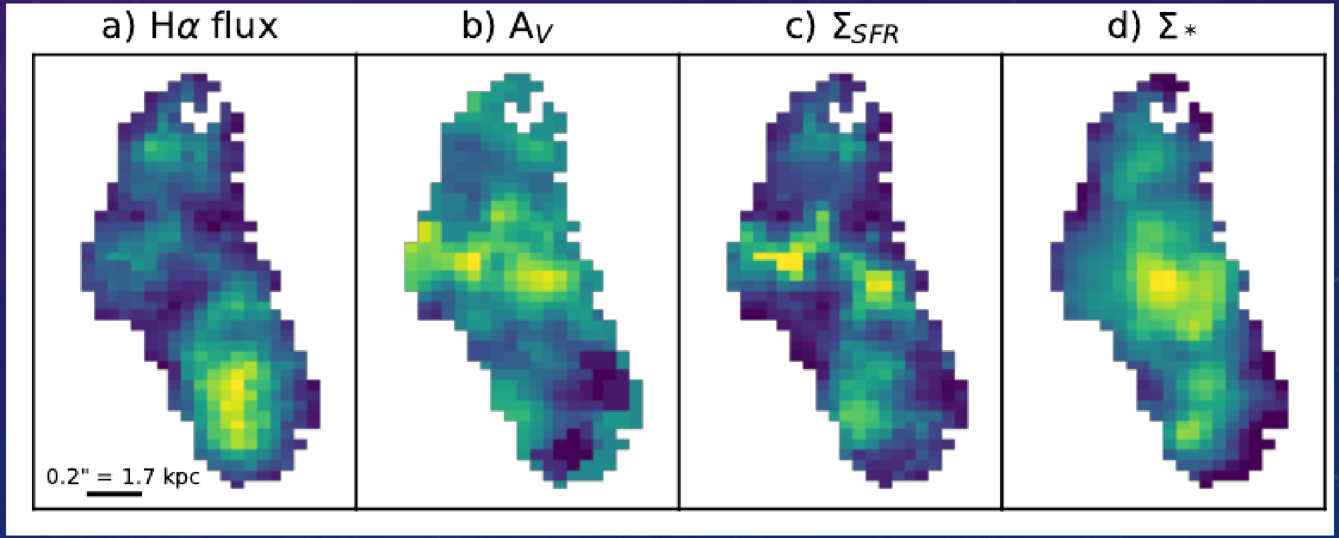


- Outflows launched from regions of concentrated star formation
- Important to investigate relationship outflow properties and resolved physical properties, on 1-2 kpc scales

THIS STUDY

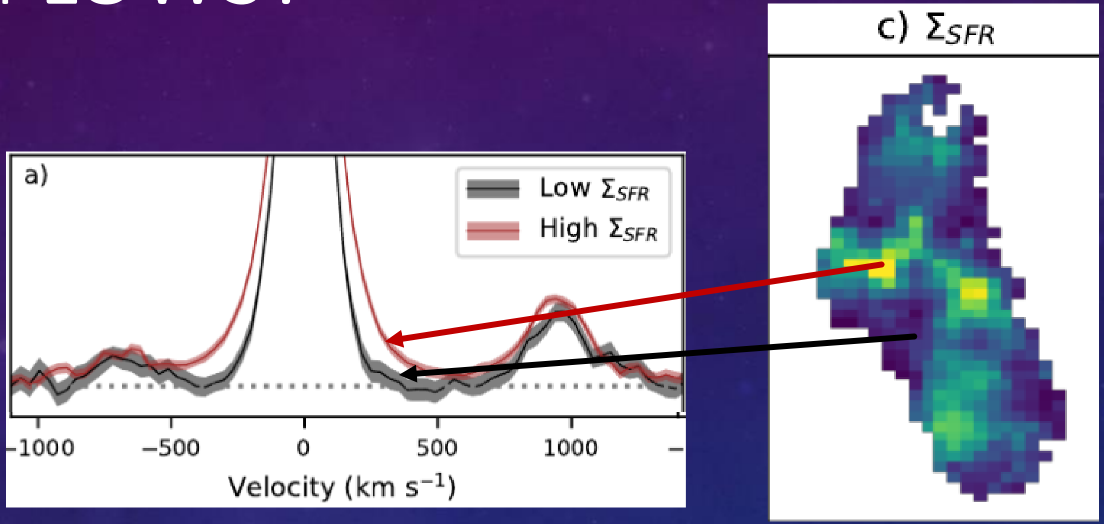
28 normal star forming galaxies at z = 2-2.6, observed with SINFONI+AO to obtain flux and kinematic maps at 1-2 kpc resolution





RLD, Förster Schreiber, Übler et al. (2019)

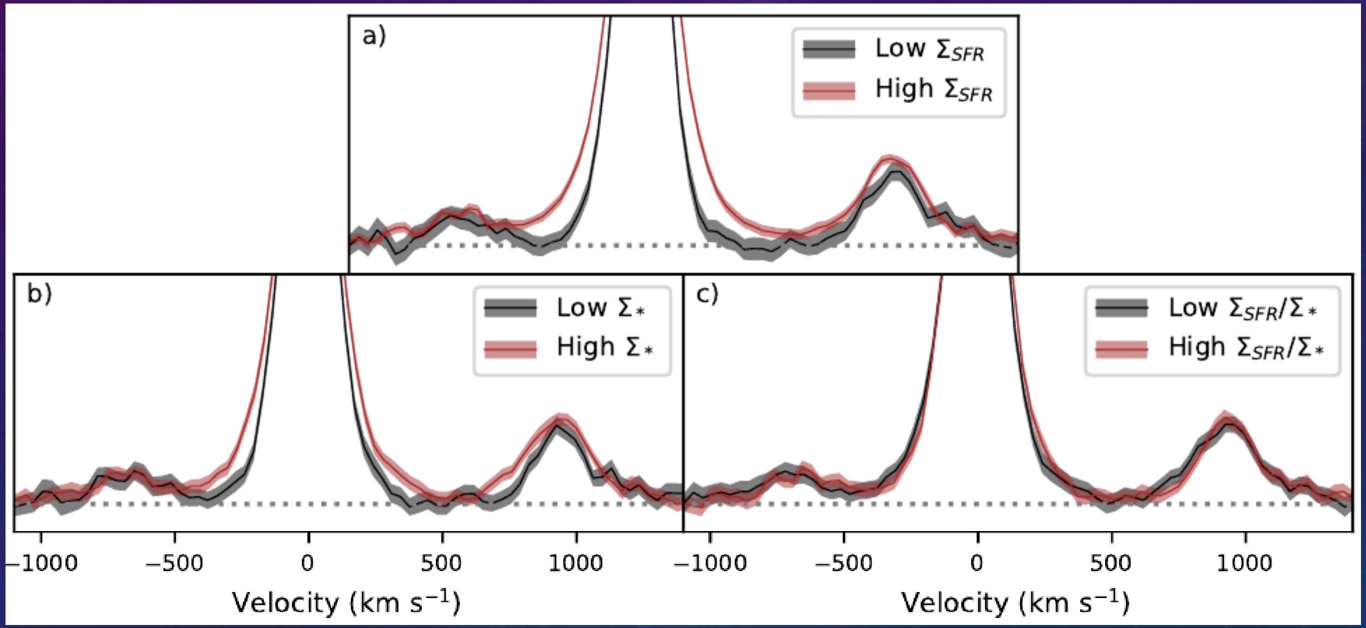
WHICH PROPERTY IS MOST CLOSELY RELATED TO THE PRESENCE OF OUTFLOWS?



Prominent broad base in high Σ_{SFR} spaxels but not in low Σ_{SFR} spaxels → Σ_{SFR} closely related to outflow driving

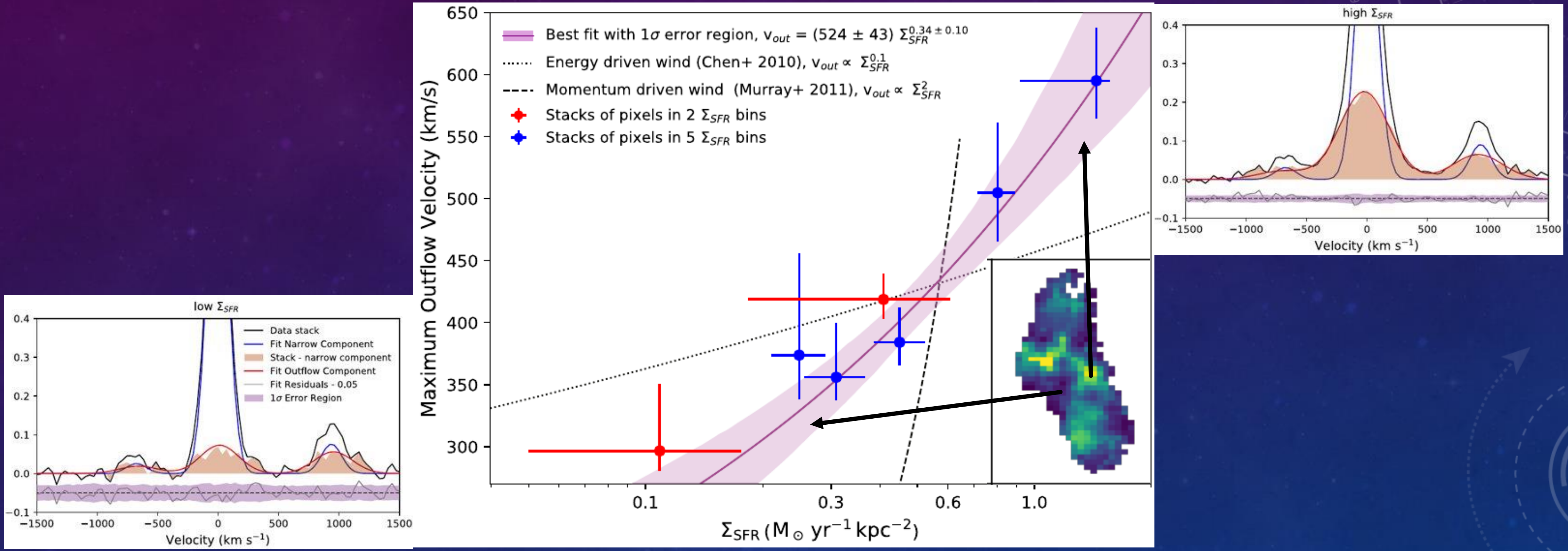
RLD, Förster Schreiber, Übler et al. (2019)

WHICH PROPERTY IS MOST CLOSELY RELATED TO THE PRESENCE OF OUTFLOWS?



RLD, Förster Schreiber, Übler et al. (2019)

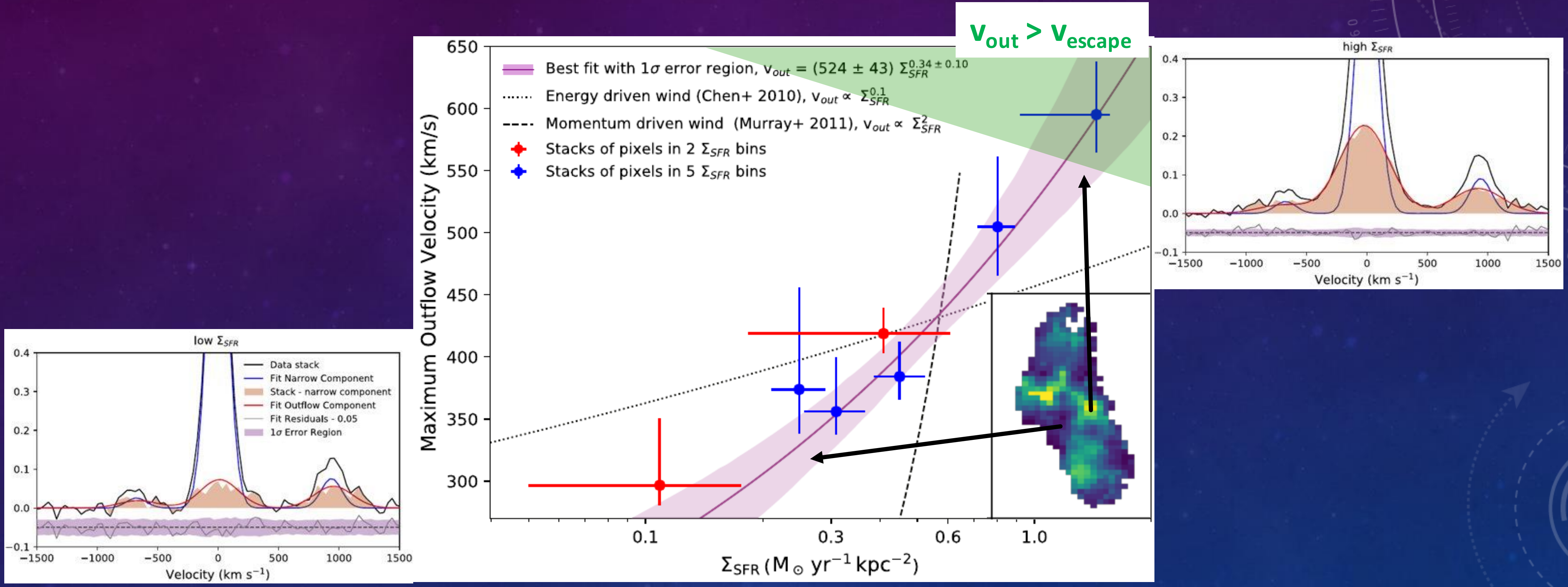
ENERGY- OR MOMENTUM-DRIVEN WINDS?



Regions with more concentrated star formation drive faster outflows.
Measured scaling lies between predictions from energy driven and momentum driven models.

RLD, Förster Schreiber, Übler et al. (2019)

CAN OUTFLOWING MATERIAL ESCAPE THE HALOS?

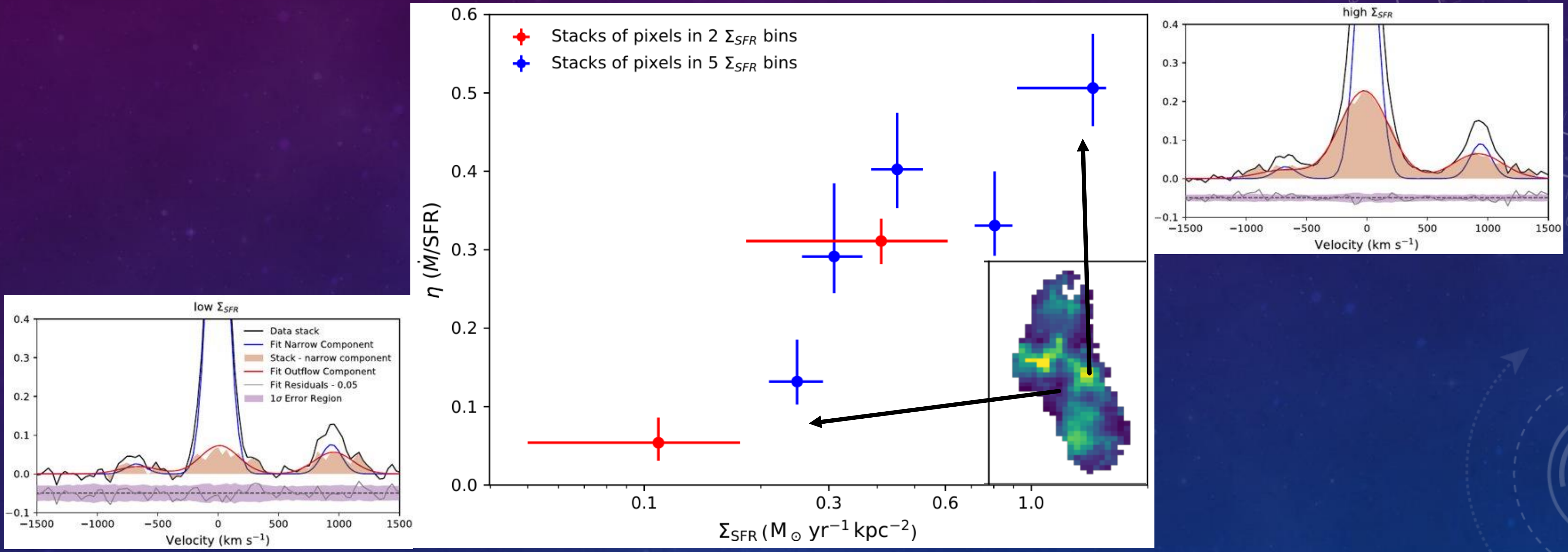


Only material expelled from highest Σ_{SFR} regions is likely to exceed the halo escape velocity

RLD, Förster Schreiber, Übler et al. (2019)

MASS LOADING FACTOR

Mass loading factor (η) = mass outflow rate / SFR

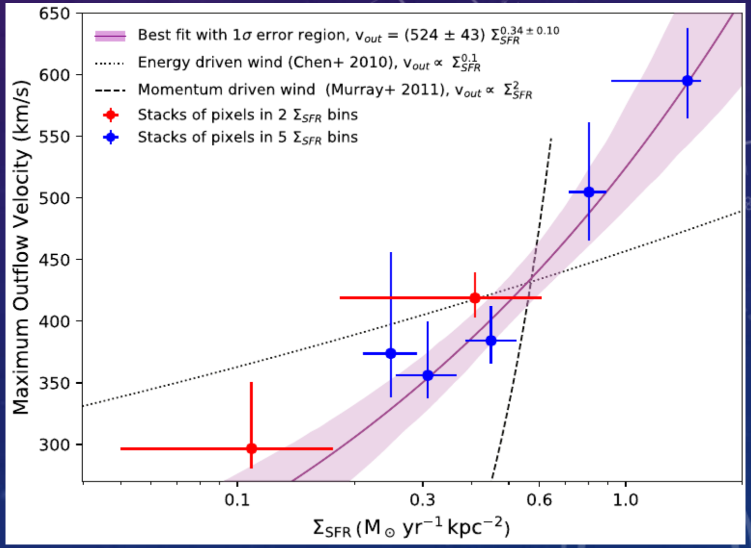


Higher Σ_{SFR} regions are associated with higher mass loading factors and/or more frequent outflows

RLD, Förster Schreiber, Übler et al. (2019)

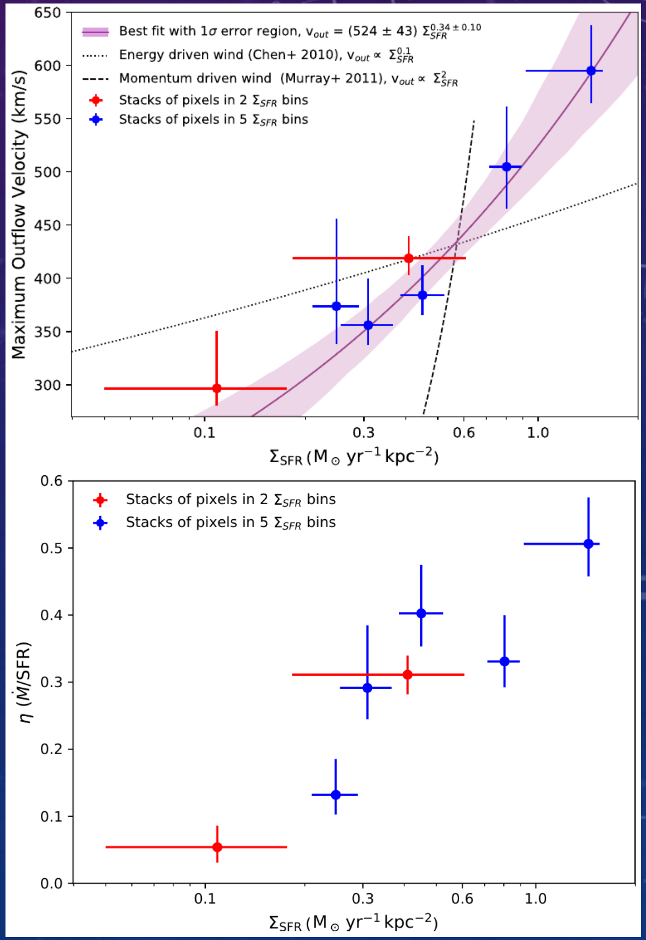
FOLLOW-UP QUESTIONS

- Investigate why the measured Σ_{SFR} - $v_{outflow}$ relation lies in between the predictions of the energy-driven and radiation-pressure-driven models
  - Investigate what drives the scatter in outflow properties at fixed local Σ_{SFR}
  - Construct Σ_{SFR} scaling relations within individual galaxies and examine whether the slope of the Σ_{SFR} - $v_{outflow}$ relation correlates with (global) galaxy properties
- Being investigated using KCWI data for local starburst galaxies from the DUVET survey (Fisher, Reichardt-Chu)



SUMMARY – STAR FORMATION DRIVEN OUTFLOWS

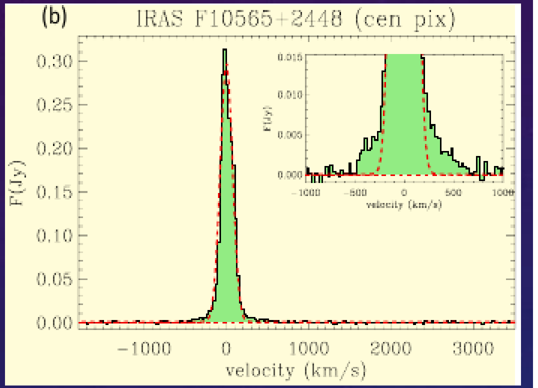
- Outflow velocity and mass loading factor are positively correlated with Σ_{SFR} on scales of 1-2 kpc
- Only material launched from the highest Σ_{SFR} regions can escape; the rest will be re-accreted in 1-2 Gyr
- The slope of the Σ_{SFR}-v_{out} relation suggests that both mechanical (supernovae) and momentum (radiation pressure) driving are active in z≈2 star-forming galaxies



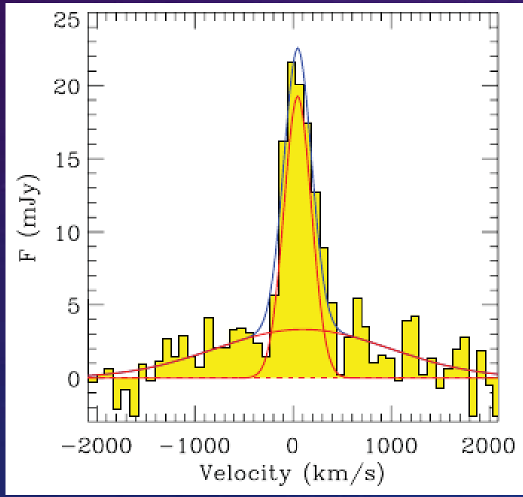
RLD, Förster Schreiber, Übler et al. (2019)

ROLE OF AGN-DRIVEN OUTFLOWS IN STAR FORMATION QUENCHING

Ejection of large amounts of neutral/molecular gas

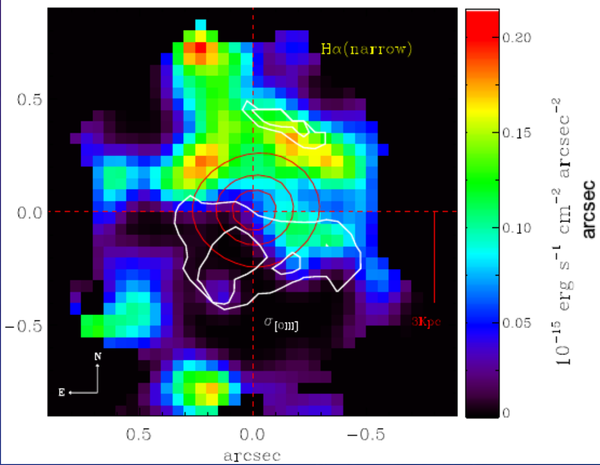


Cicone et al. (2014)

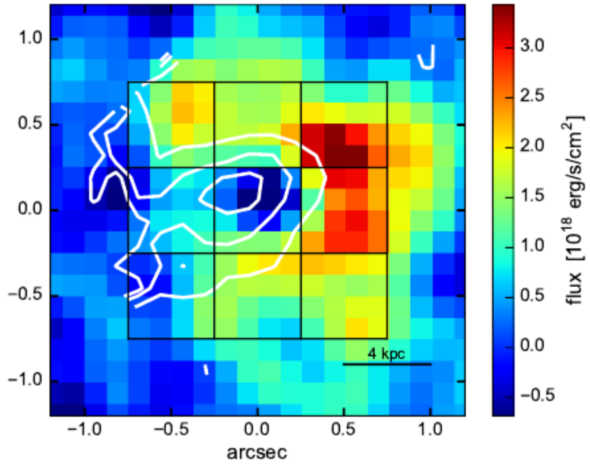


Maiolino et al. (2012)

Local instantaneous suppression of star formation by outflows?



Cano-Diaz et al. (2012)



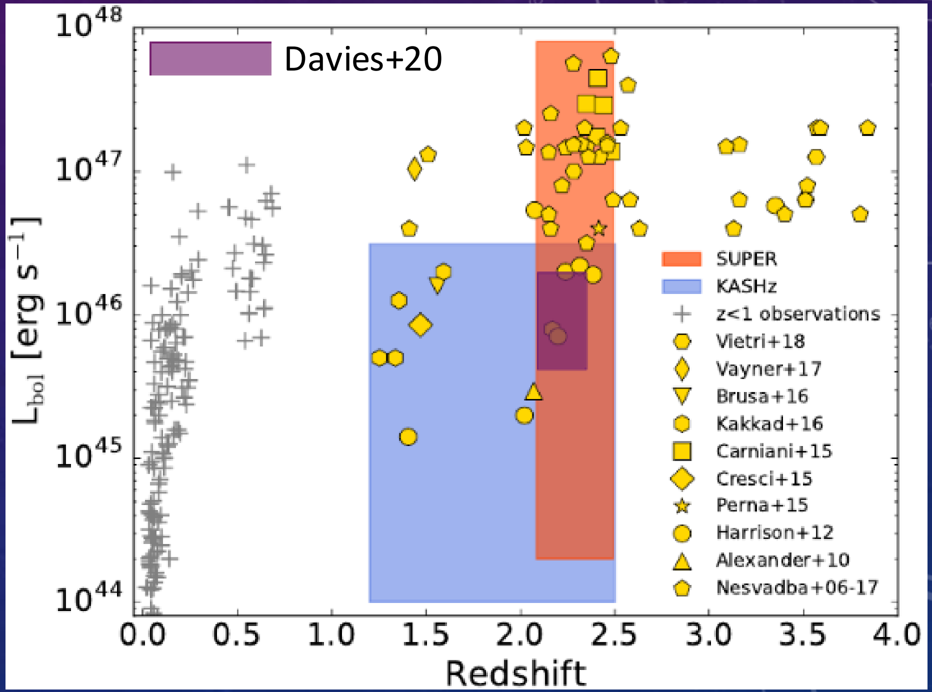
Carniani et al. (2016)

(But see Scholtz+ 2020)

THIS STUDY

Question: How do AGN-driven outflows influence the properties of the surrounding gas as they move through galaxies and halos?

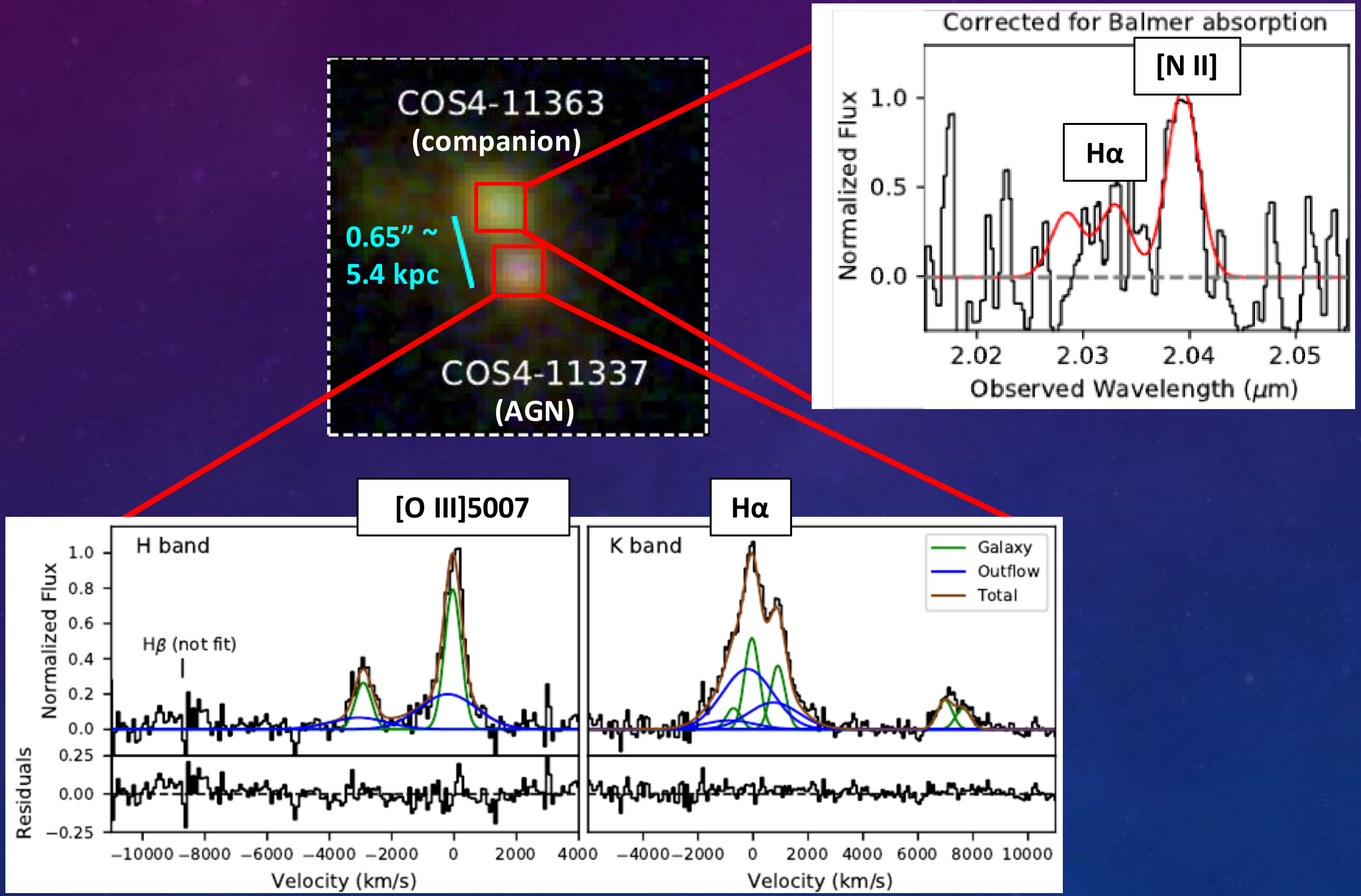
- Select 3 z≈2 galaxies with AGN-driven outflows that have different spatial extents and may therefore be at different stages of outflow evolution
- Used deep SINFONI-AO observations (5-20h on source) to map outflows and ISM properties across the galaxies
- Included ancillary data from HST and ALMA to study the evolutionary stages of the host galaxies



Circosta+ 2018

RLD, Förster Schreiber, Lutz et al. 2020

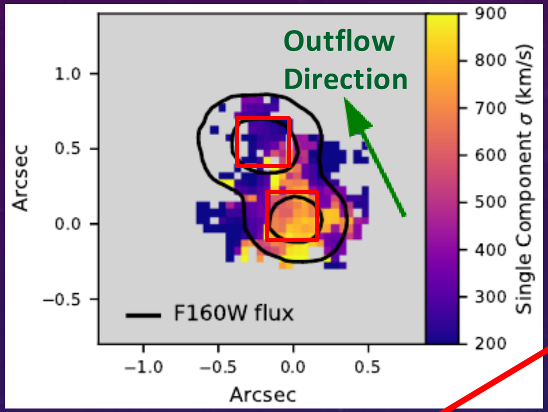
COS4-11337: AN OUTFLOW INTERACTING WITH A COMPANION?

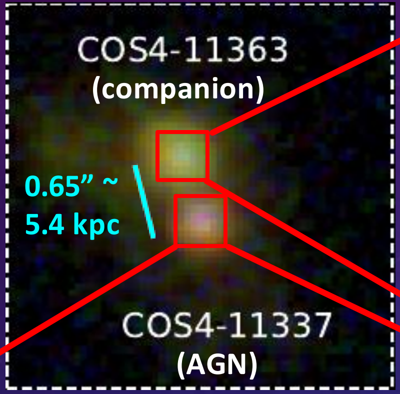


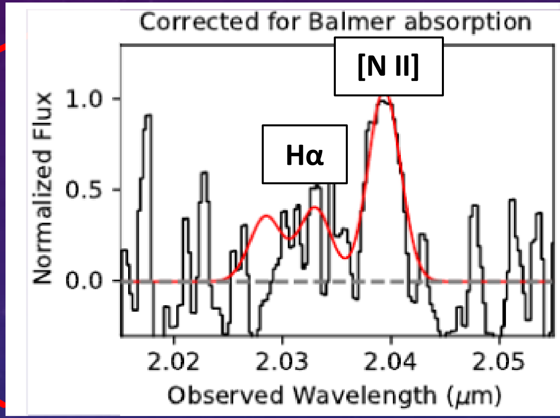
- Strong shocks?
- Star formation truncated abruptly ~100 Myr ago
- Below the main sequence

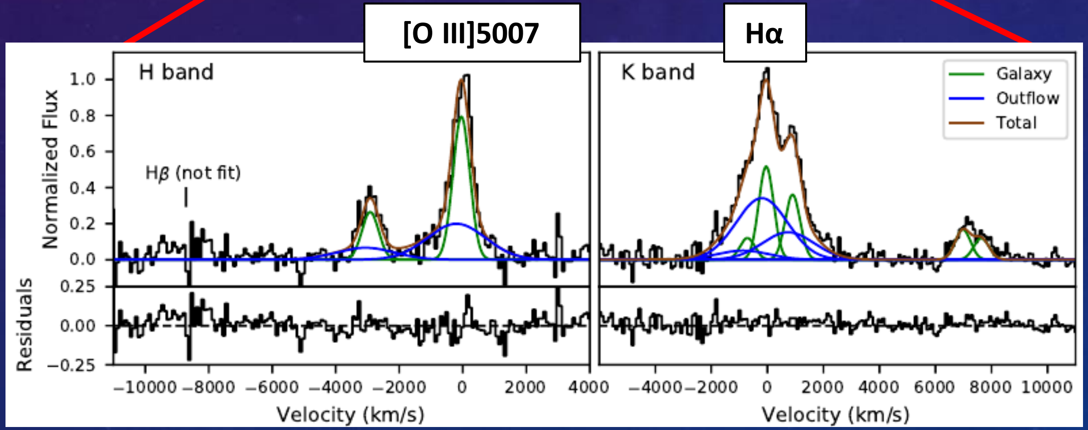
RLD, Förster Schreiber, Lutz et al. 2020

COS4-11337: AN OUTFLOW INTERACTING WITH A COMPANION?







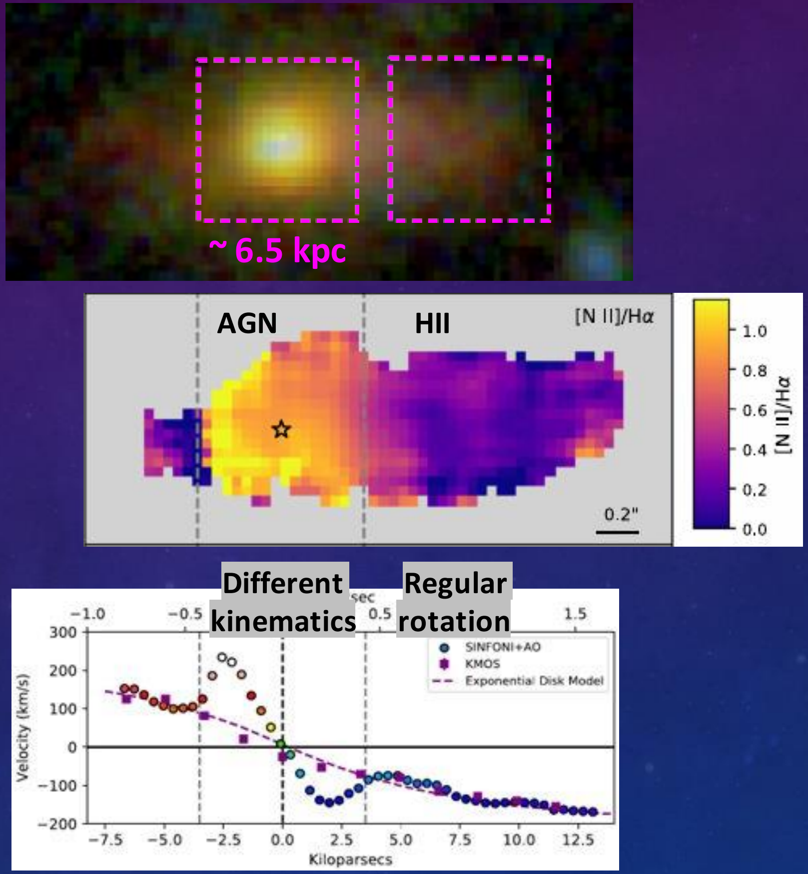


- Strong shocks?
- Star formation truncated abruptly ~100 Myr ago
- Below the main sequence

Outflow impacting gas on circumgalactic scales?

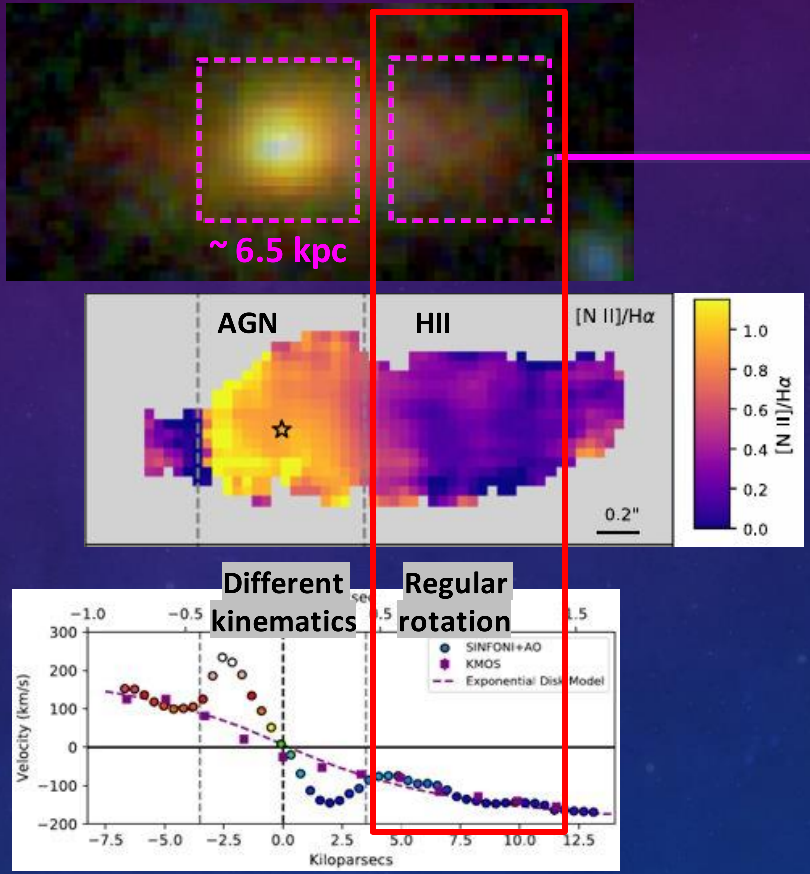
RLD, Förster Schreiber, Lutz et al. 2020

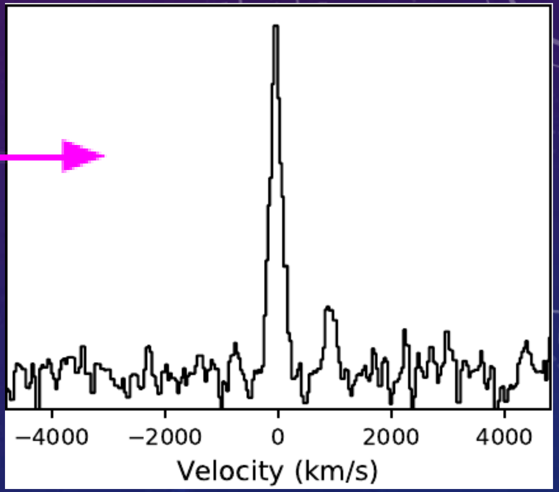
K20-ID5: A POWERFUL GALAXY-SCALE OUTFLOW



RLD, Förster Schreiber, Lutz et al. 2020

K20-ID5: A POWERFUL GALAXY-SCALE OUTFLOW

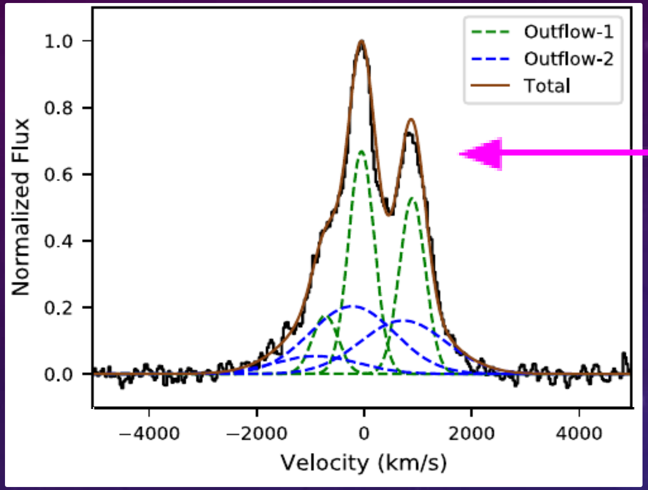




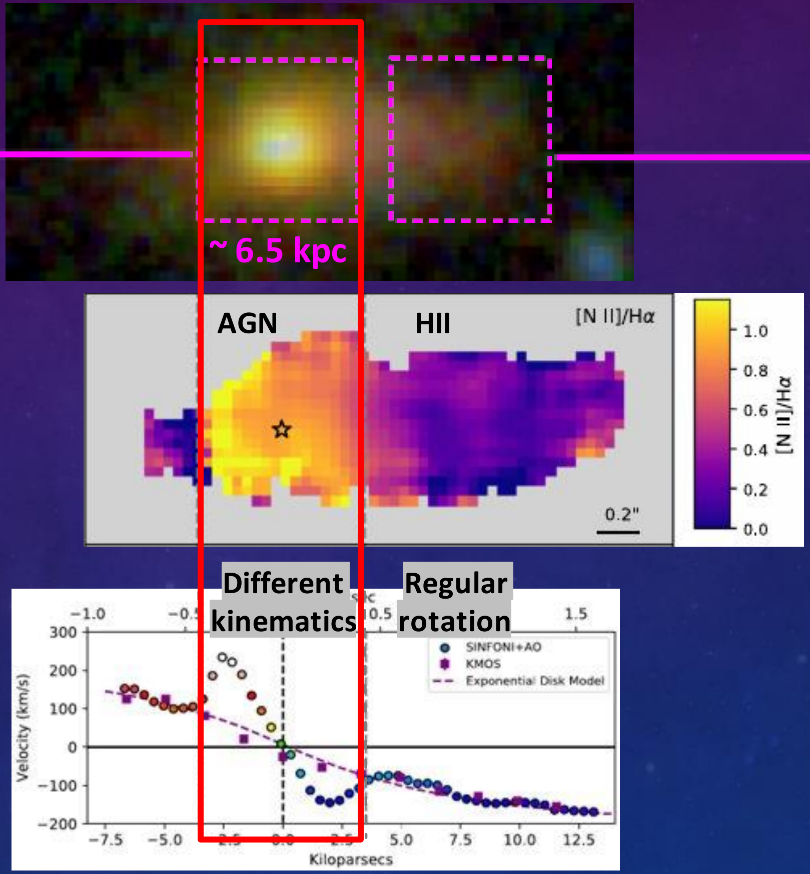
- Rotating
- Narrow emission lines
- Small [NII]/Hα = Star Formation

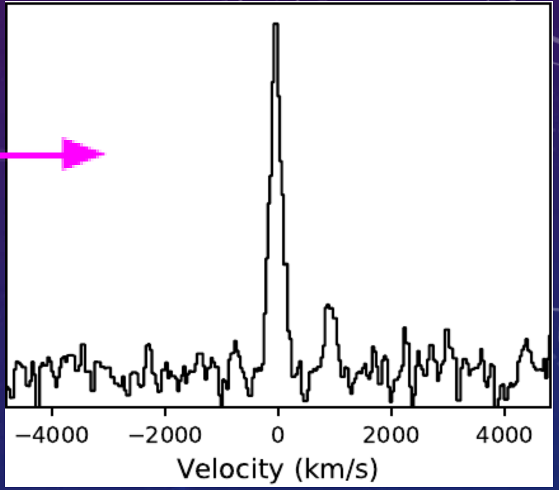
RLD, Förster Schreiber, Lutz et al. 2020

K20-ID5: A POWERFUL GALAXY-SCALE OUTFLOW



- Different kinematics
- Broad emission lines
- Large [NII]/Hα = AGN

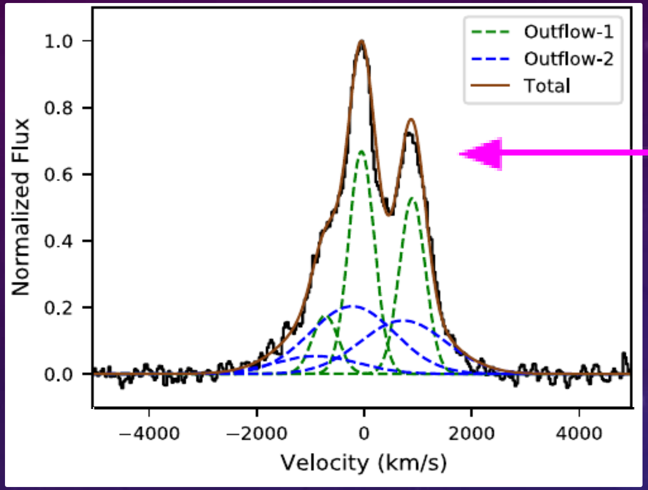


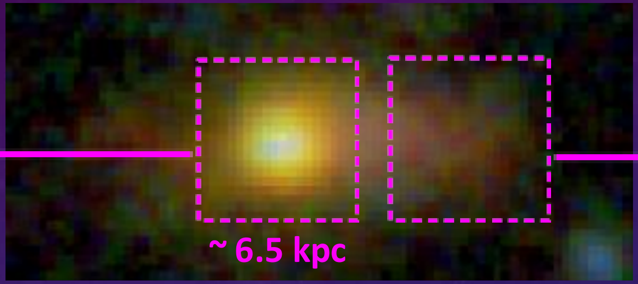


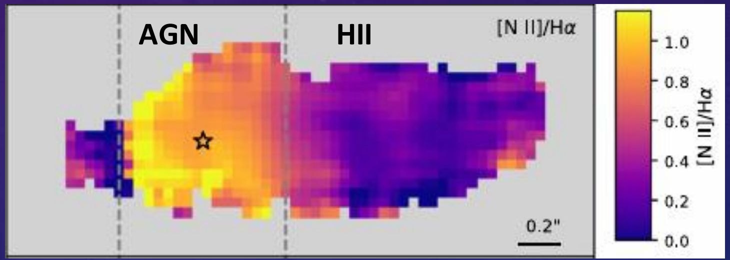
- Rotating
- Narrow emission lines
- Small [NII]/Hα = Star Formation

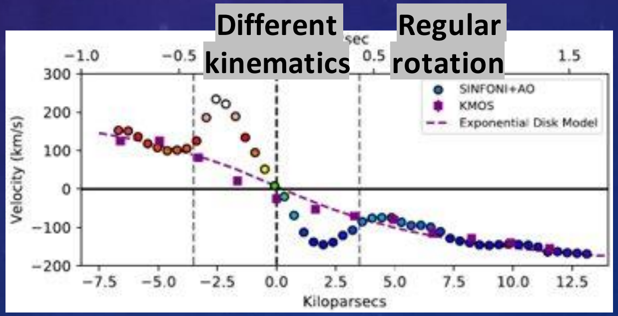
RLD, Förster Schreiber, Lutz et al. 2020

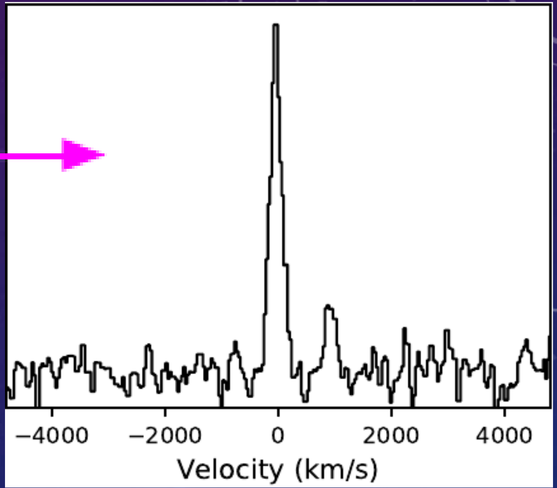
K20-ID5: A POWERFUL GALAXY-SCALE OUTFLOW









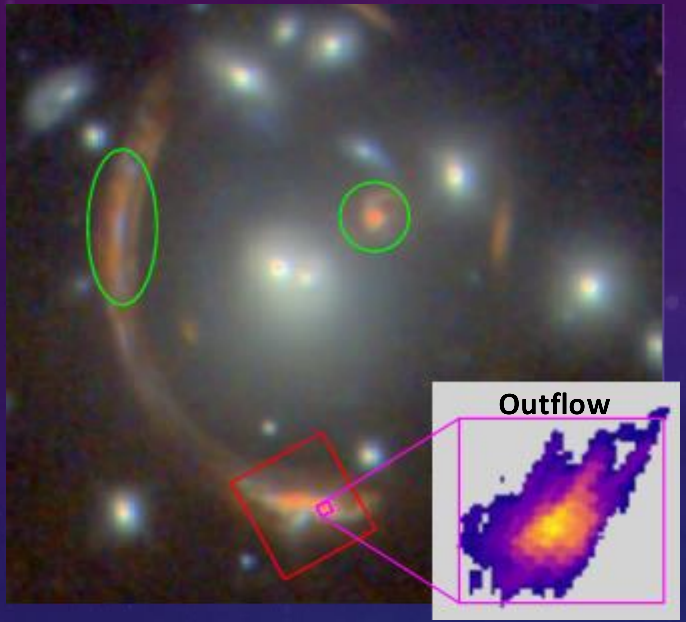


- Different kinematics
- Broad emission lines
- Large [NII]/Hα = AGN
- **Outflow found only within the galaxy**

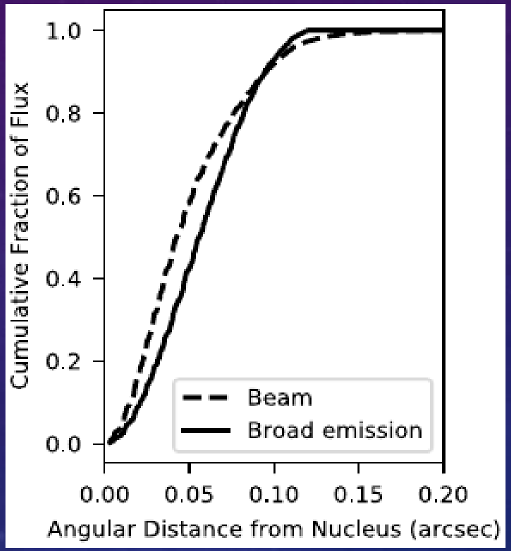
- Rotating
- Narrow emission lines
- Small [NII]/Hα = Star Formation

RLD, Förster Schreiber, Lutz et al. 2020

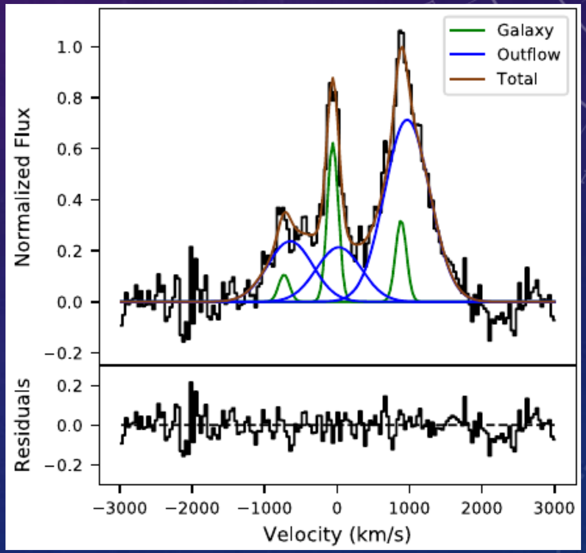
J0901: A HUNDRED-PARSEC-SCALE NUCLEAR OUTFLOW



Marginally resolved



Low outflow velocity

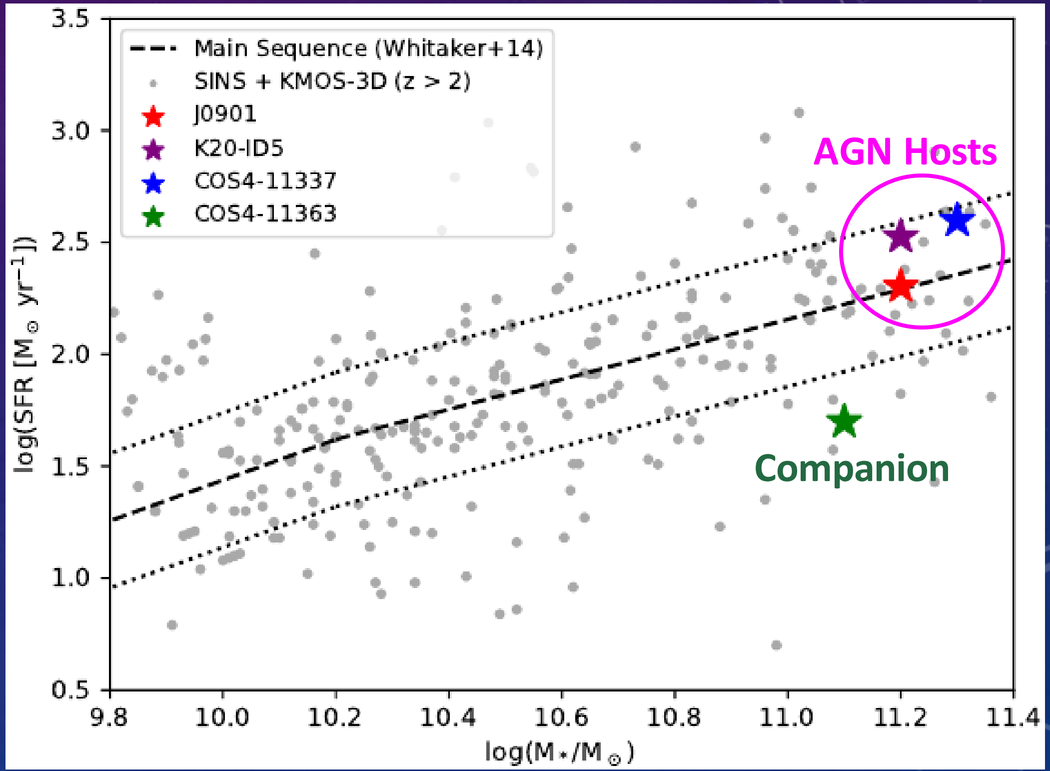


Outflow has not moved beyond the circumnuclear region

RLD, Förster Schreiber, Lutz et al. 2020

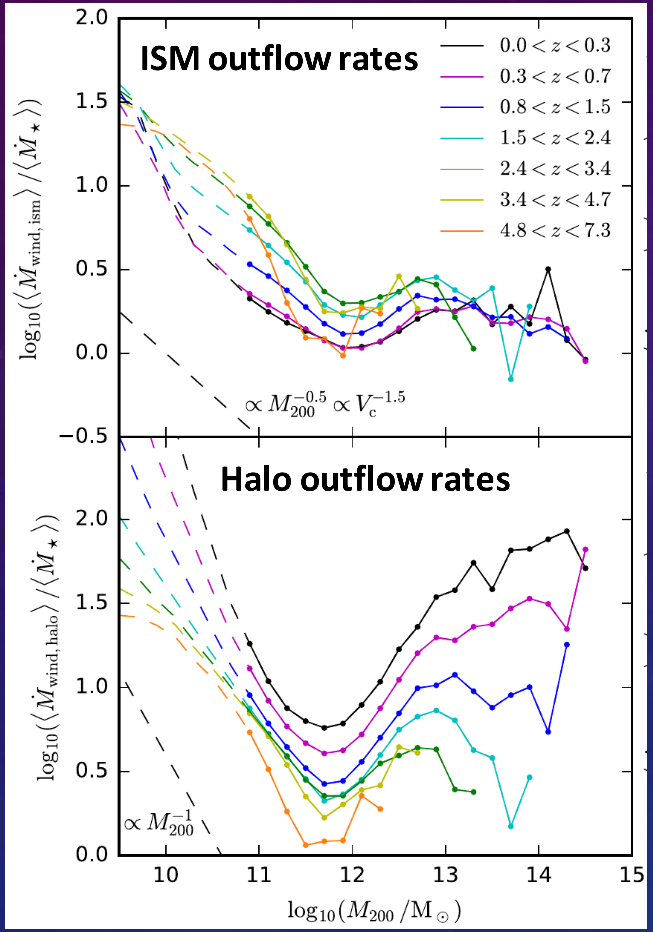
IMPACT ON STAR FORMATION

- Outflows have no impact on instantaneous rate of star formation in the host galaxies.
- Could the kinetic energy of the outflows heat the gas enough to prevent replenishment of the molecular gas reservoir?

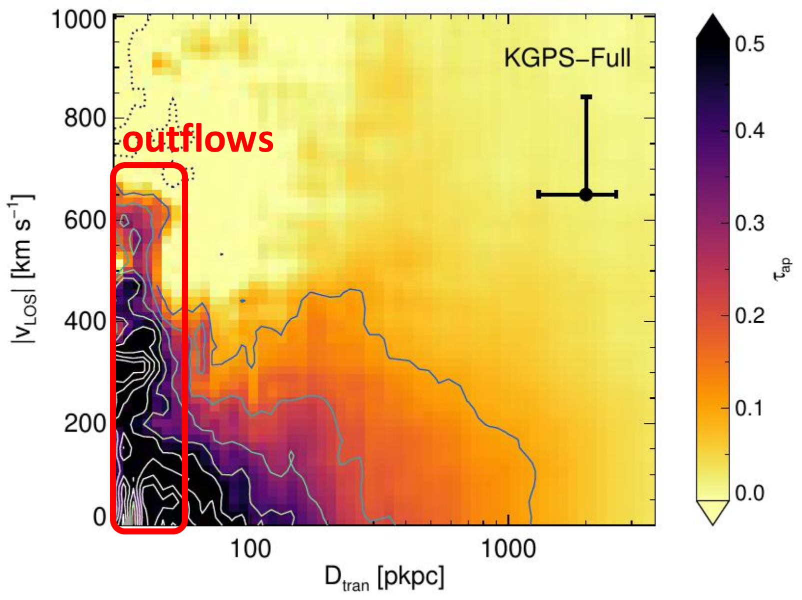


RLD, Förster Schreiber, Lutz et al. 2020

QUENCHING DUE TO REMOVAL OF GAS FROM THE CGM?



Mitchell et al. (2020)

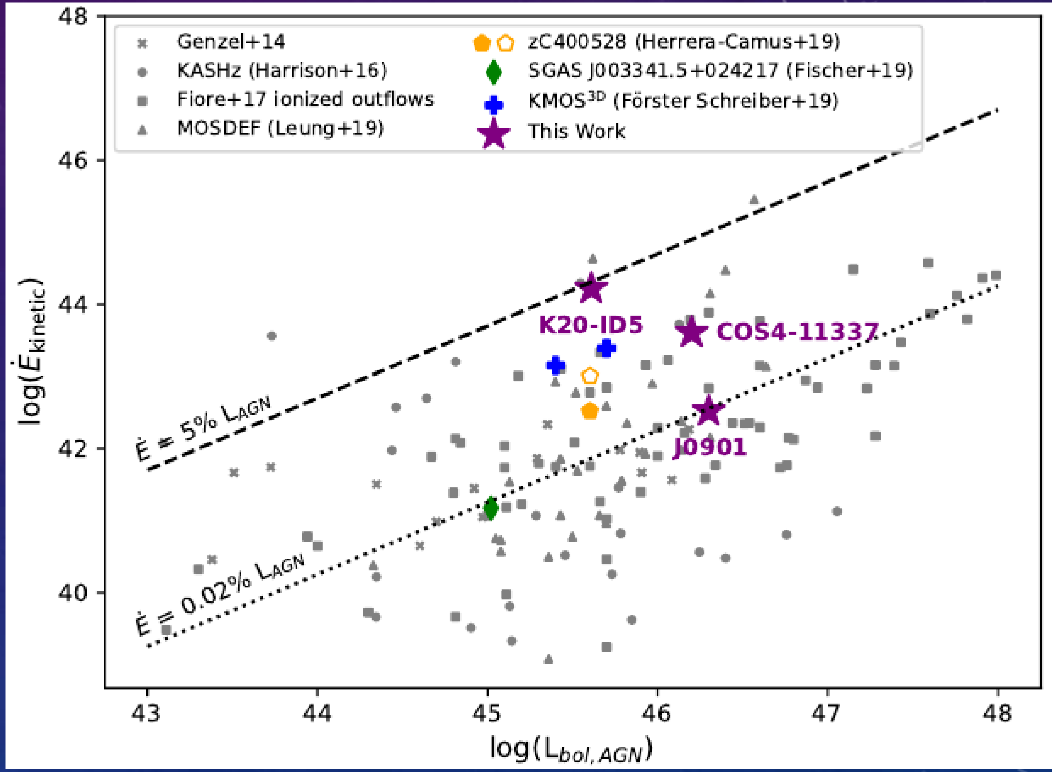


Chen et al. (2020)

RLD, Förster Schreiber, Lutz et al. 2020

COUPLING BLACK HOLE GROWTH AND STAR FORMATION

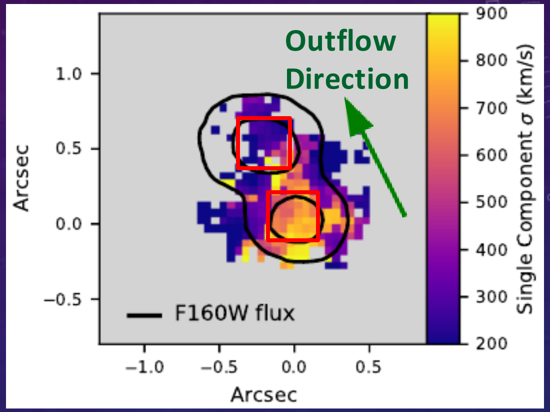
- Outflow kinetic power generally too low to explain M-σ relation. Possible explanations include:
  - Majority of outflow kinetic power in other gas phases?
  - AGN variability? (e.g. Zubovas & Nardini 2020)
  - Inefficient coupling between hot wind and outflow?
  - M-σ relation driven by torque-limited accretion rather than outflows? (e.g. Anglés-Alcázar et al. 2013)

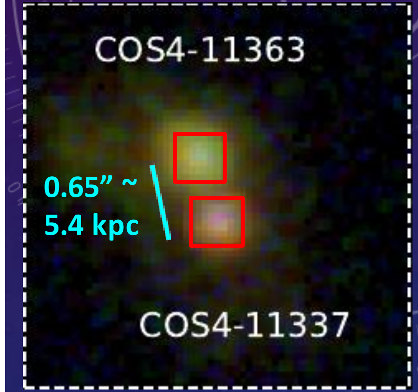


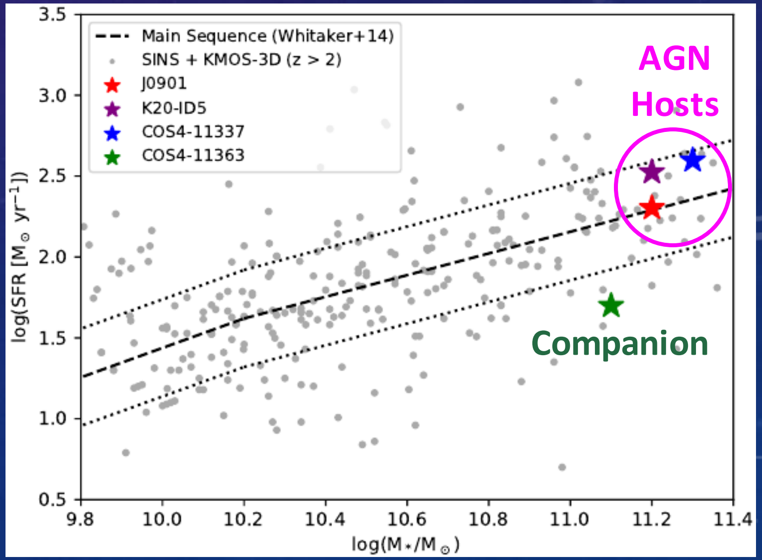
RLD, Förster Schreiber, Lutz et al. 2020

SUMMARY – AGN-DRIVEN OUTFLOWS

- During successive stages of evolution outflows can transfer energy to gas on nuclear, galactic and circumgalactic scales
- We find possible evidence for an outflow quenching star formation in a companion galaxy
- All 3 AGN host galaxies in our study lie on the main sequence – will the outflows suppress star formation on longer timescales?
- In general, the kinetic powers of AGN-driven ionized outflows appear to be too low for them to be the primary driver of the M-σ relation.



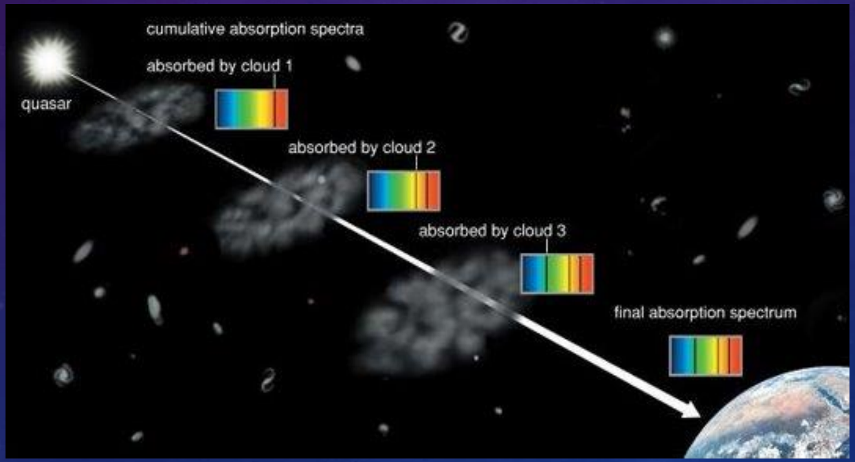


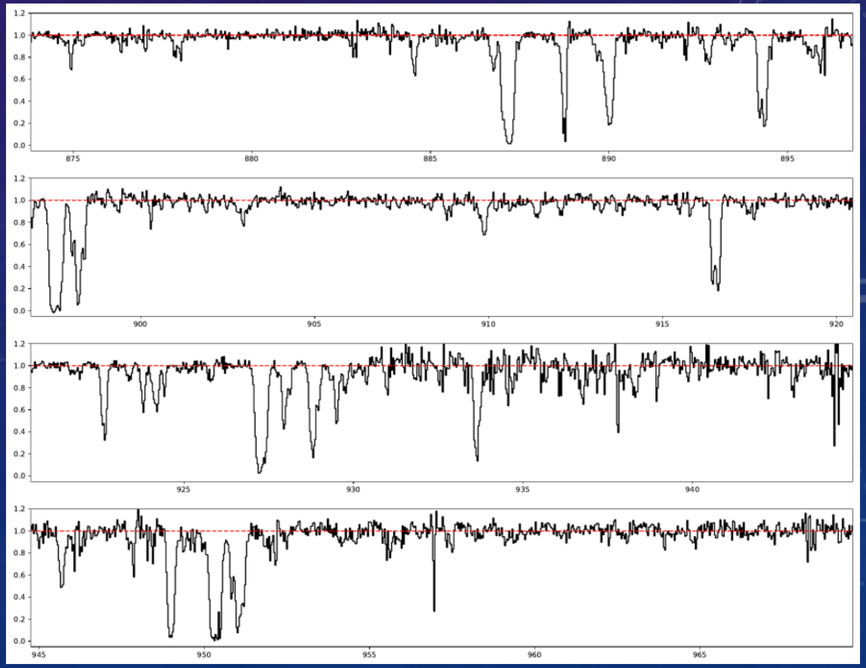


RLD, Förster Schreiber, Lutz et al. 2020

THE PRODUCTION AND TRANSPORT OF METALS IN THE EARLY UNIVERSE

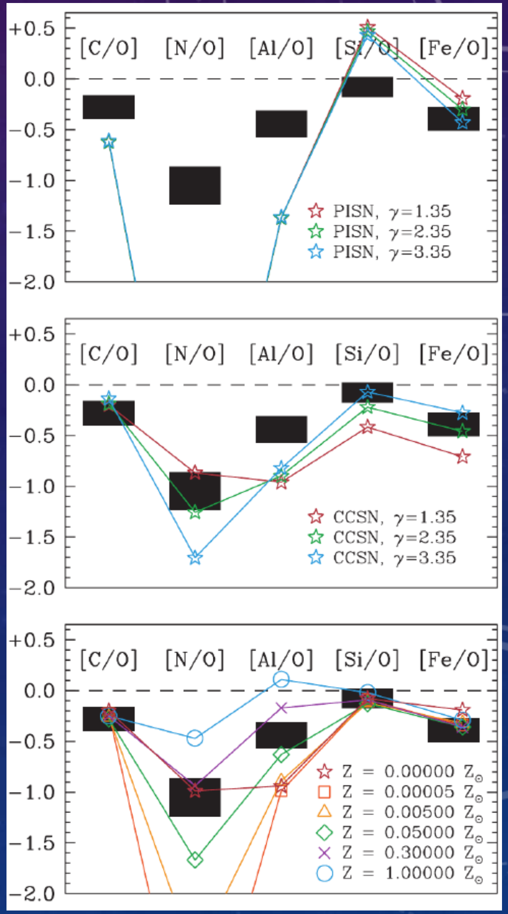
- Absorption lines allow us to probe gas that is far too faint to detect in emission





SEARCHING FOR EVIDENCE OF POPULATION III STARS

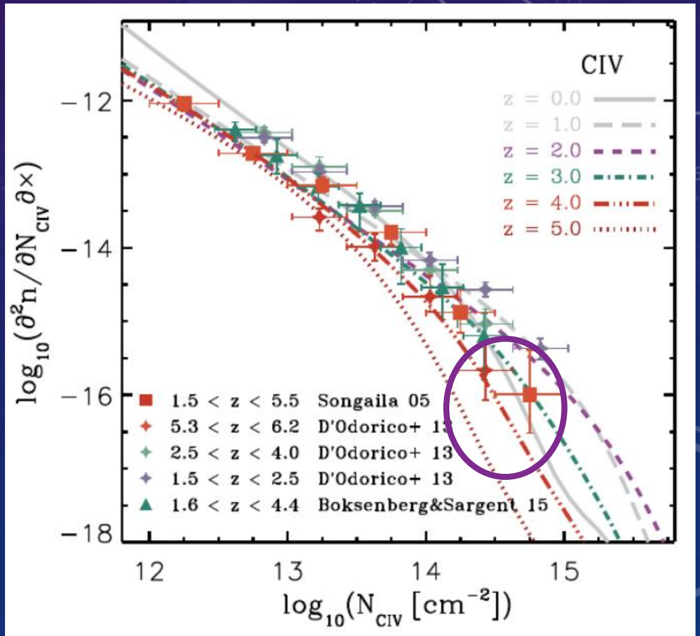
- Population III stars cannot be observed directly, but the yields of stellar and supernova nucleosynthesis reflect the masses and metallicities of the progenitor stars
- We can use this to search for very-metal-poor systems enriched by a single generation of Pop III stars
- If we do not find any such regions at z≈6, it would place strong lower limits on the minimum formation redshifts of the first stars



Cooke et al. (2011)

CONSTRAINING THE PROPERTIES OF OUTFLOWS IN THE EARLY UNIVERSE

- Measurements of the chemical composition of the CGM provide valuable constraints on feedback models
  - Outflows transport metals from the ISM to galactic halos
  - Different feedback models predict very different CGM properties
- Make improved measurements and compare to different simulations to determine what types of feedback can reproduce the observed properties of both galaxies and circumgalactic environments



Rahmati et al. (2016)

Z≈6: A PERIOD OF TRANSITION IN CGM PROPERTIES

What drives the decrease in the cosmic mass density of C IV at z > 5.5?

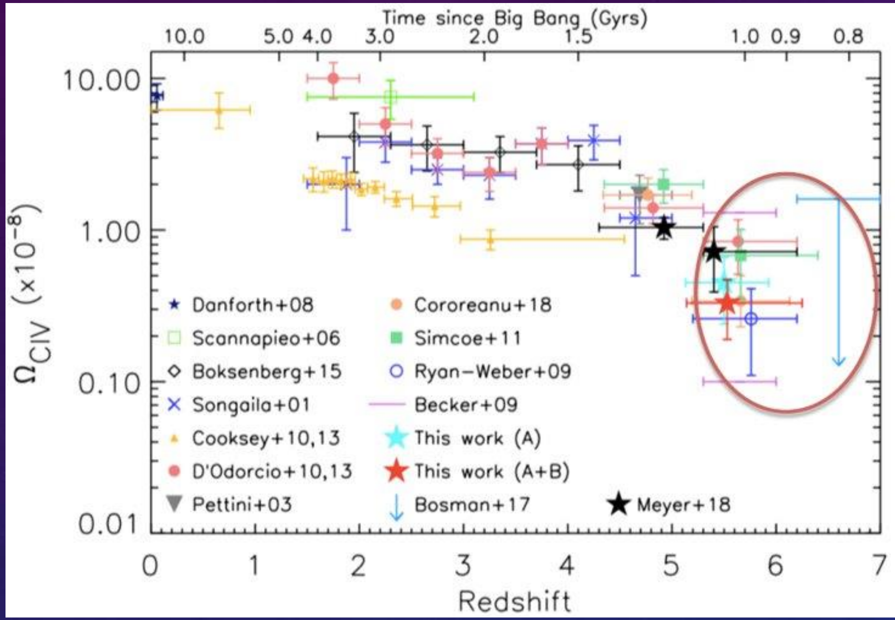
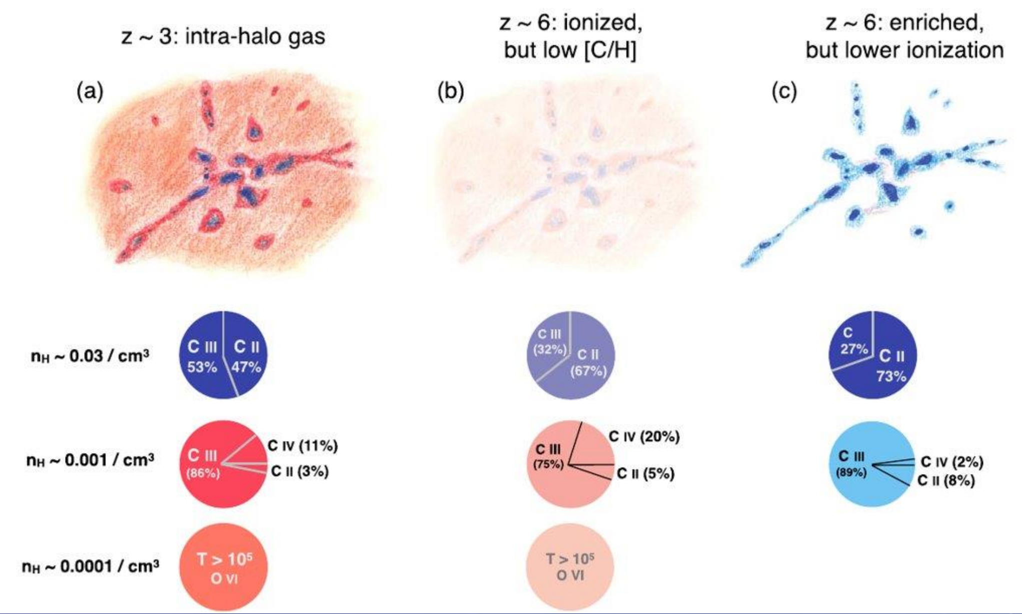


Figure credit: Emma Ryan-Weber

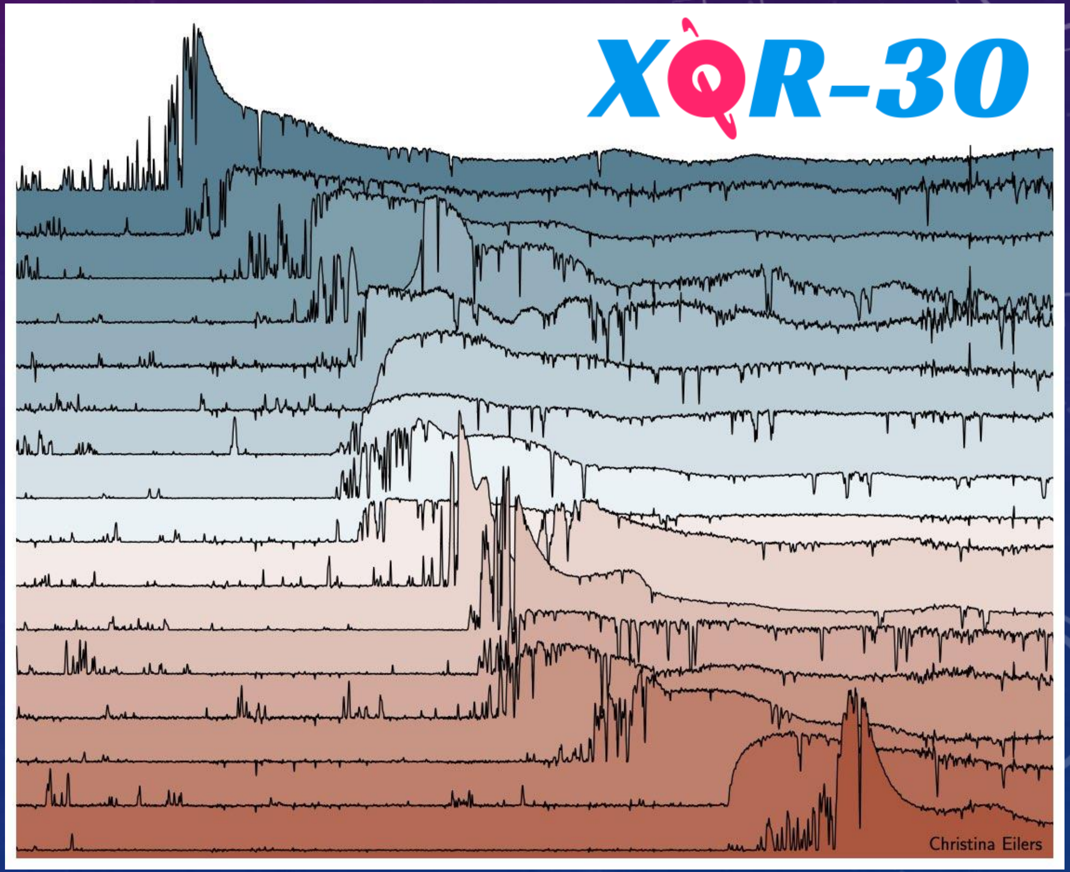


Cooper et al. (2019)

Need better statistics to reduce errors and determine the cause of the transition!

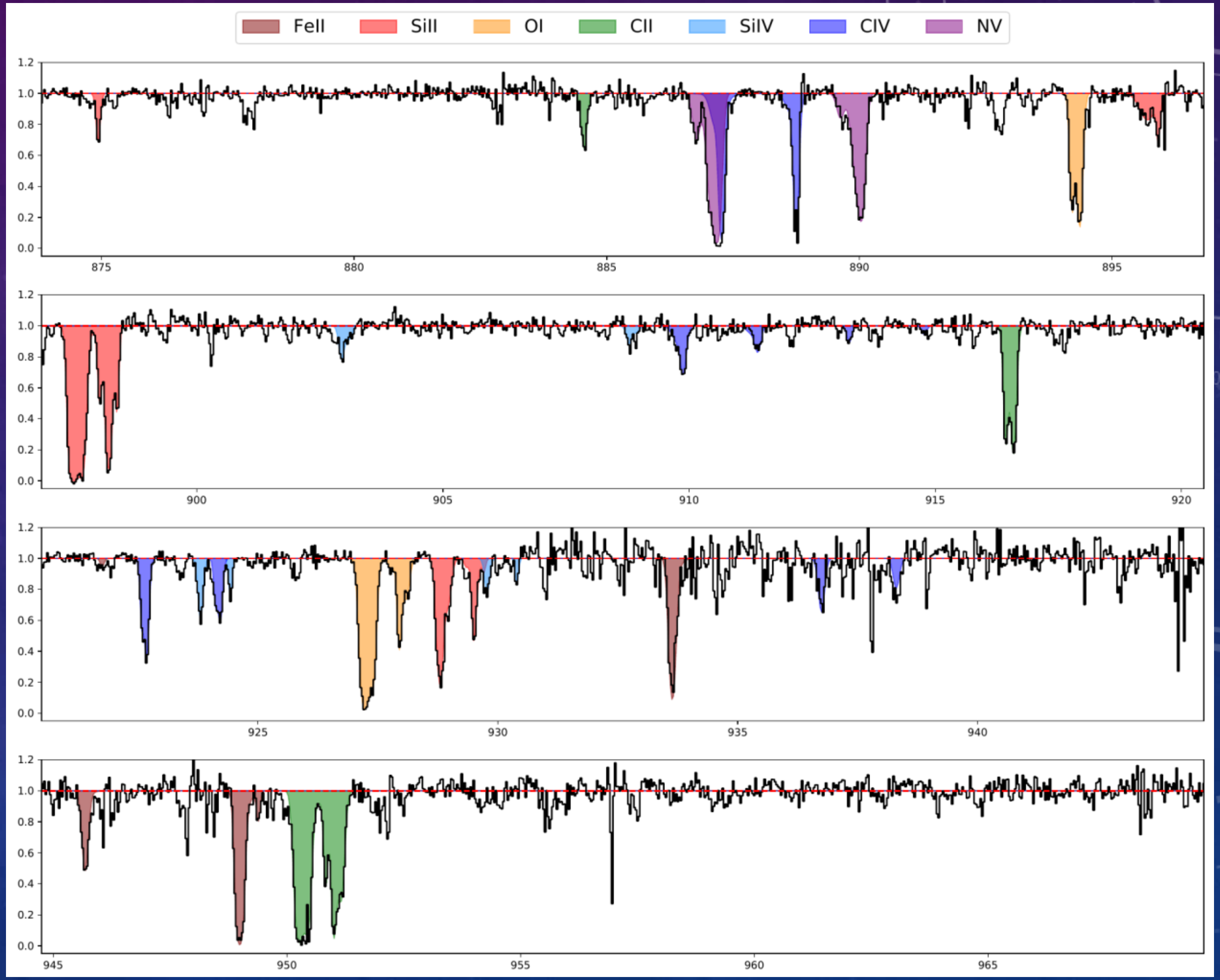
XQR-30

- X-Shooter large program (PI: V. D'Odorico)
- High S/N spectra of 30 QSOs at 5.8 < z < 6.6
- 3 key science areas
  - Better constraining the endpoint of reionization
  - Chemical enrichment, feedback and ionizing sources
  - Quasars and their environments in the early Universe
- *Ultimate sample of high quality z~6 quasar spectra*



PRODUCING THE METAL ABSORBER CATALOG

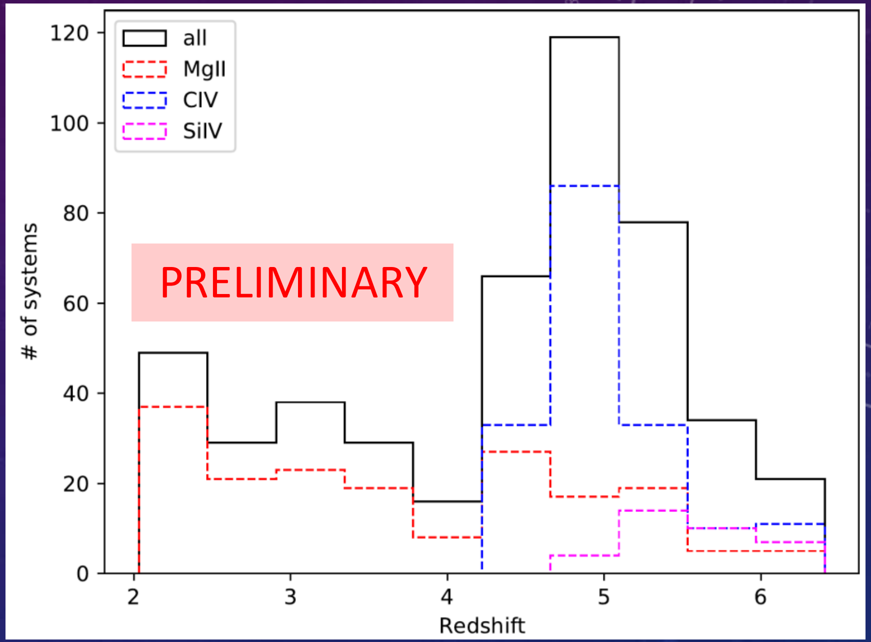
- Key requirement for statistical studies
- Use an automated pipeline to search for candidate absorbers in MgII, FeII, CII, CIV, SiIV and NV
- All visually identifiable lines recovered
- *Absorption line catalog will be publicly released!*



RLD, XQR-30 team *in prep*.

ABSORBER STATISTICS

≥ 500 absorption systems spanning $2 < z < 6.5$



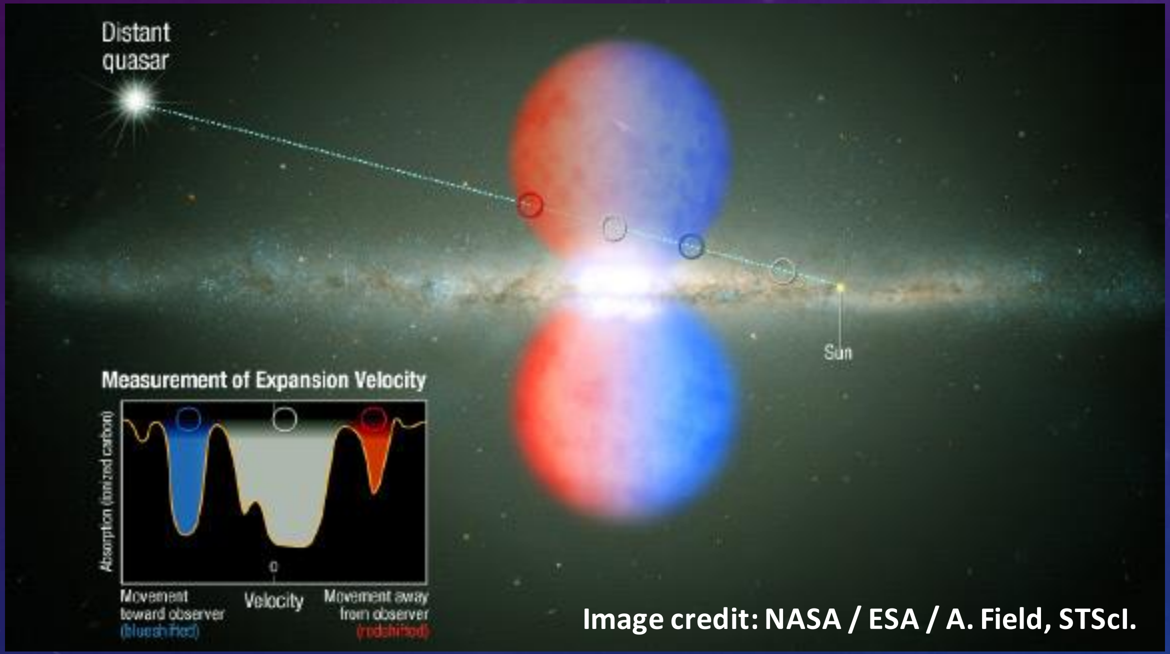
Measurements across a wide redshift range derived using consistent data and analysis: *Key sample for evolutionary studies of metal absorbers from the end of reionization to the peak epoch of star formation*

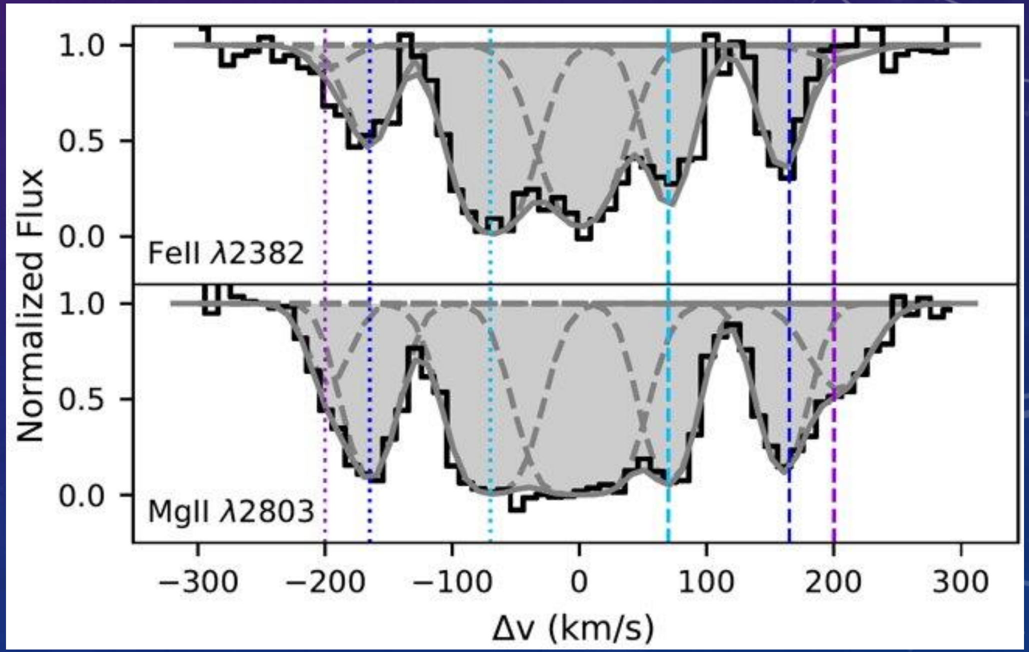
Completeness statistics to be released with the catalog

RLD, XQR-30 team *in prep.*

MULTIPHASE OUTFLOW STUDIES

Combine information from emission line and absorption line tracers to gain unique insights into the long-term evolution of outflows





OVERALL SUMMARY

- The (average) properties of star-formation driven outflows are governed by Σ_{SFR}, and the slope of the Σ_{SFR}-v_{out} relation suggests that both mechanical energy driving and radiation pressure driving are active in star-forming galaxies at $z \approx 2$.
- AGN-driven outflows transfer energy to gas on nuclear to circumgalactic scales, but we find no evidence for instantaneous suppression of star formation. Further investigation is required to determine whether AGN-driven outflows could quench star formation on longer timescales.
- By measuring the properties of metal absorbers at $z > 5.5$ in XQR-30, we will:
  - Constrain the shape of the UV background and the sources of reionization
  - Test models of CGM enrichment by stellar feedback
  - Search for evidence of Pop III stars