# The Extragalactic Universe and its Cosmology

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FCT Fundação para a Ciência e a Tecnologia
MINISTÉRIO DA EDUCAÇÃO E CIÊNCIA

ALMA

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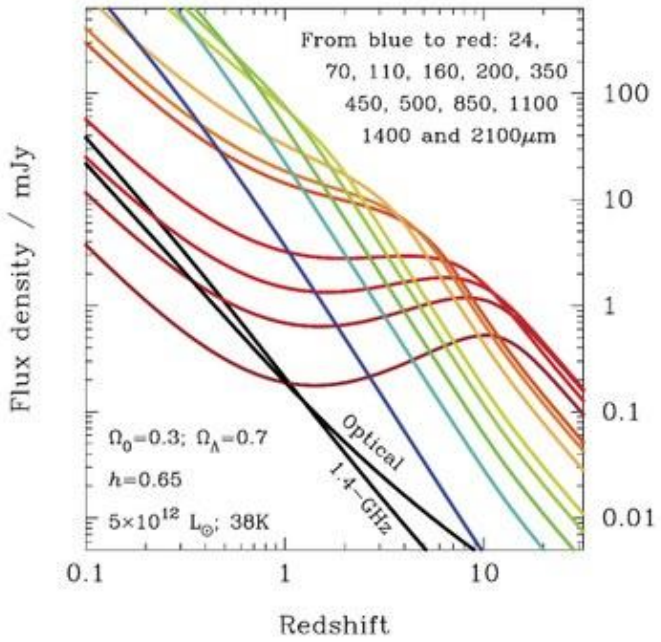
# Summary

- Local Universe (z<0.5)
- High-z Universe (z>0.5 up to z~7)
- Cosmology

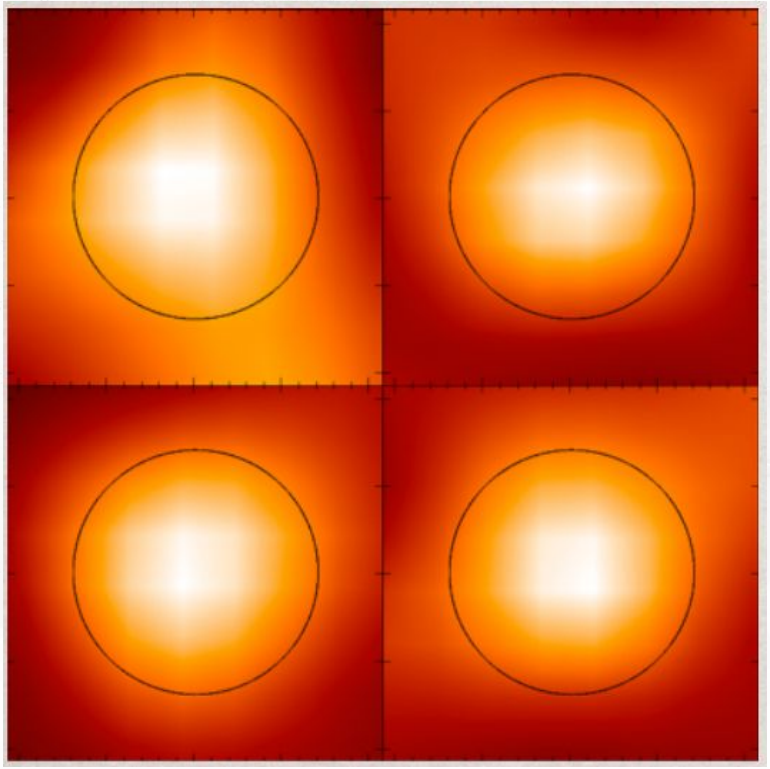
# Why the sub-mm?

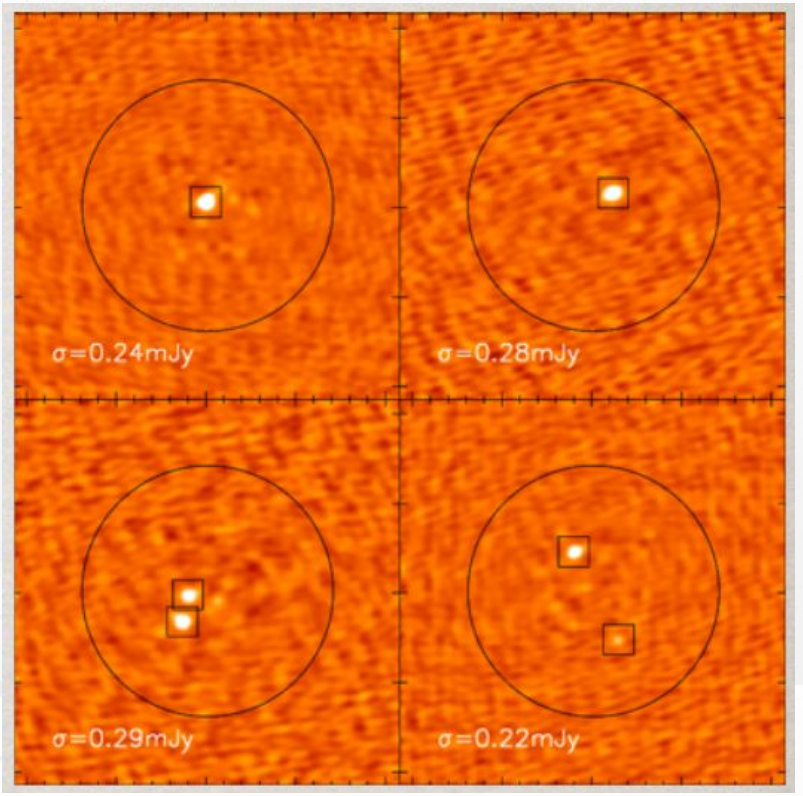
- **~50%** of the UV-optical light produced has been reprocessed by dust (COBE) → FIR-Submm
- Wealth of molecular lines that trace state of gas in the ISM (PDRs, dense regions, shocks, etc)
- **~1000** more dusty SB galaxies than expected (e.g. Chapman+05)
- **Negative** k-correction




Blain+02

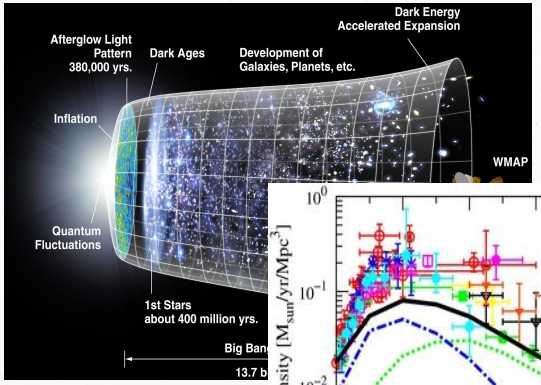
# Why ALMA?

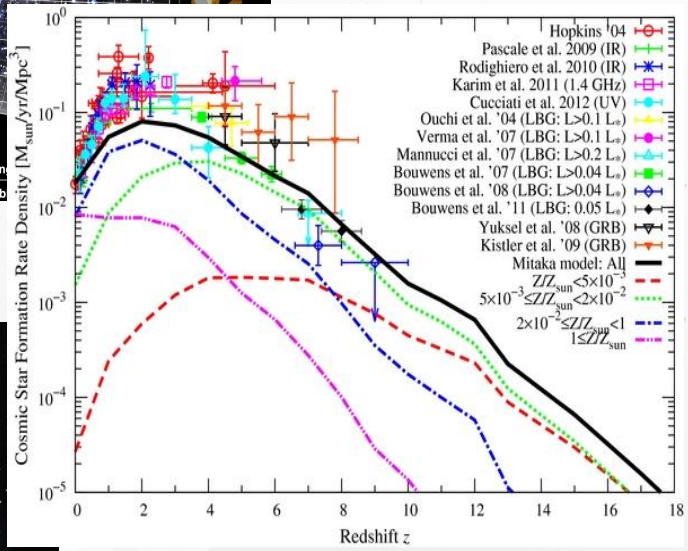




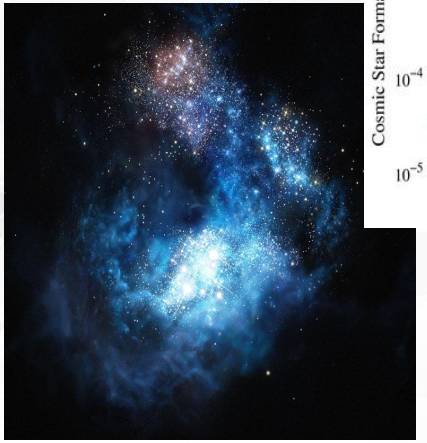
# Challenges:

- Formation & Evolution of galaxies
- *-Formation & accretion history
- Dark ages & The first galaxies




Inoue+ 2013



Sobral+2015

# Cosmology & high-z Universe

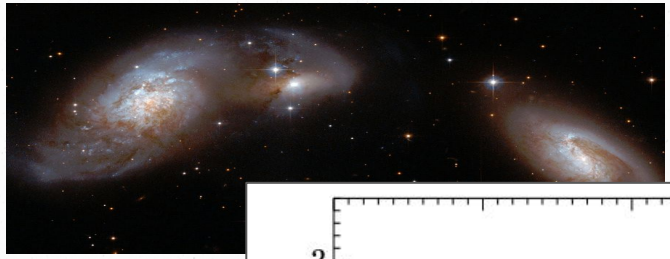
## Challenges with ALMA:

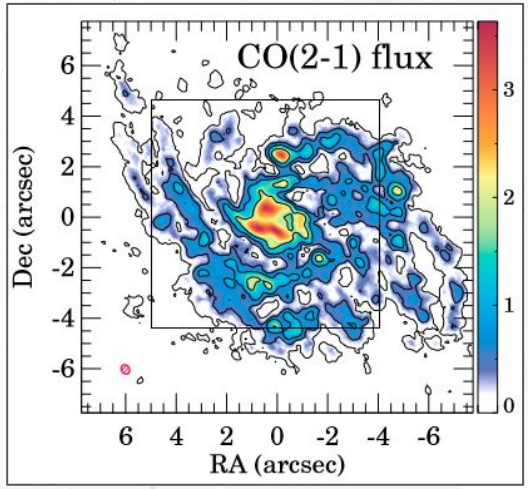
- Finding dust enshrouded *-forming galaxies
- Measuring evolution of dust/gas mass
- Properties of ISM nearby and at high-z
- Interaction between AGN and ISM
- Cosmology using molecular absorption lines

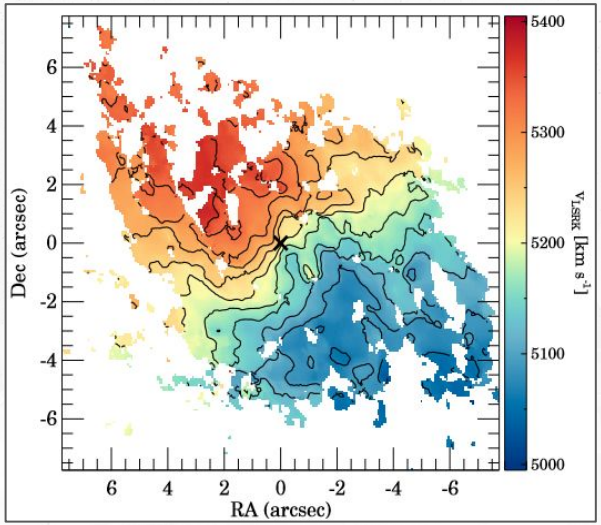
# - Local universe -

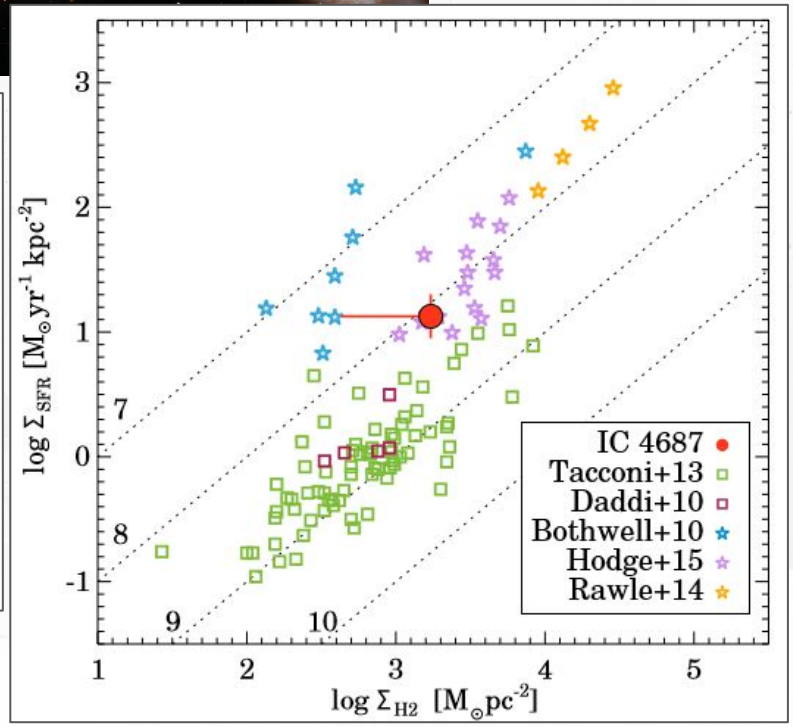
## SF law in local LIRGs

IC 4687, 0.4" (sub-kpc) resolution





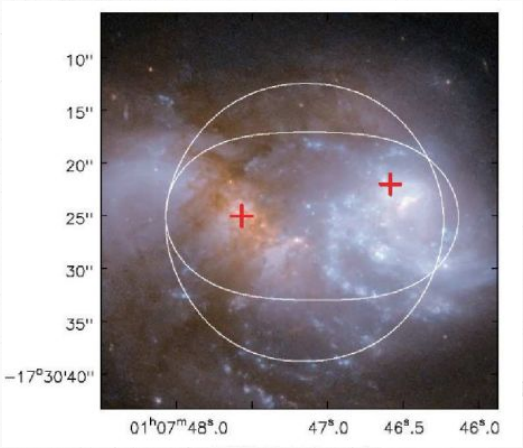



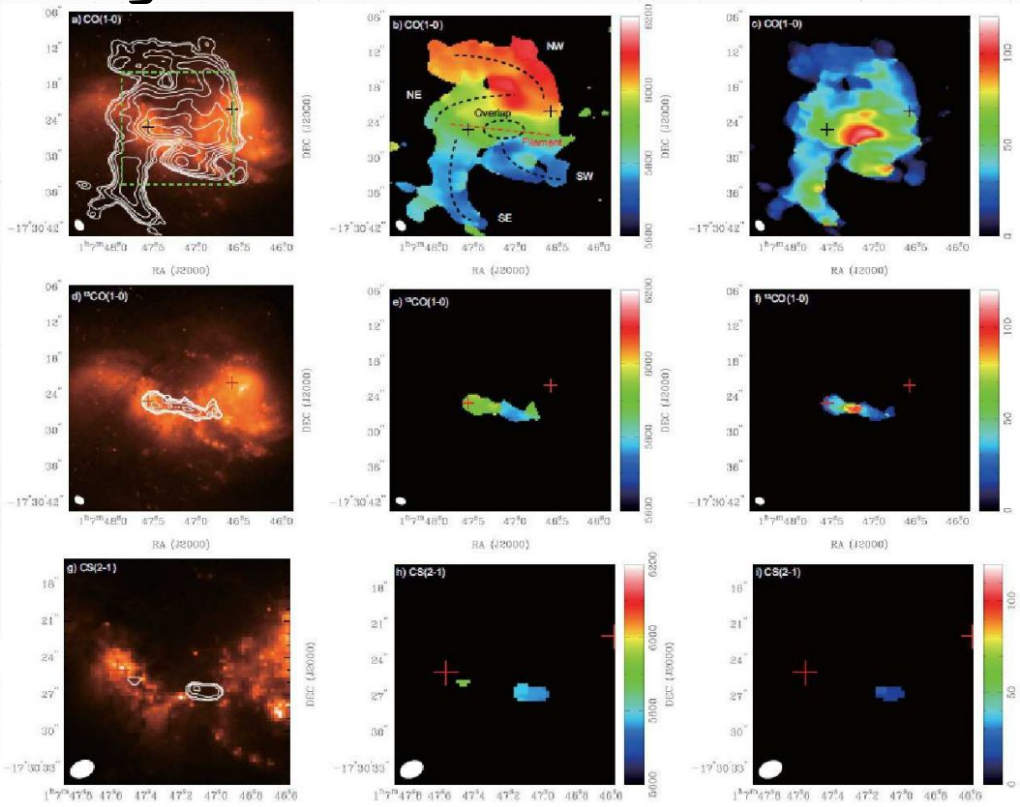




Pereira-Santaella+16

# Multiline Obs of mid-stage merger VV114

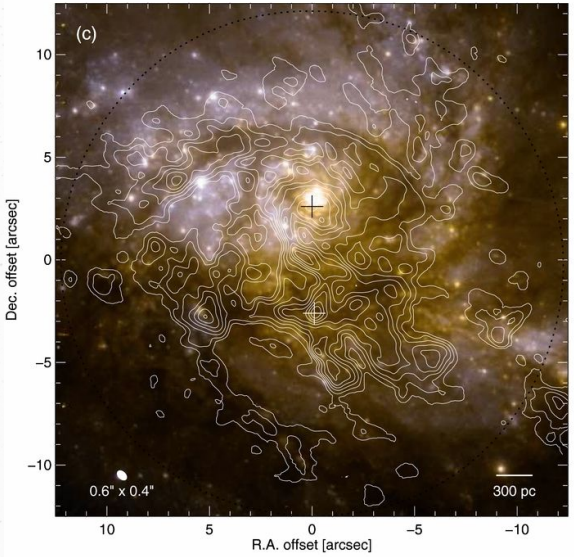
Saito+15

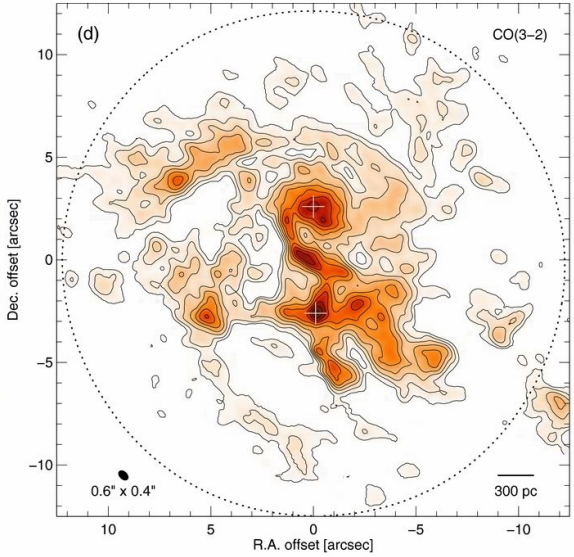


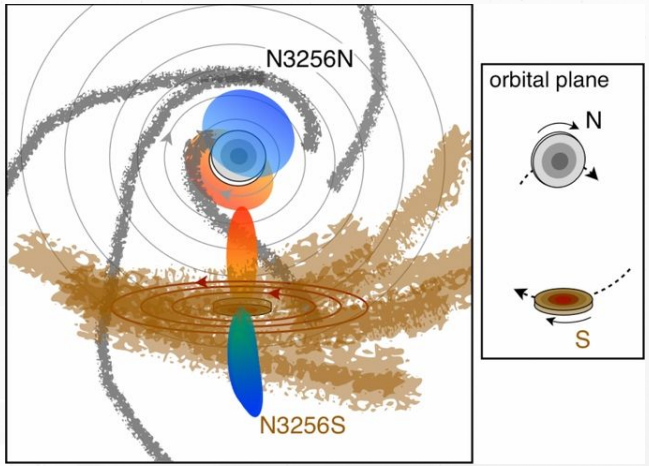




. CO, HCN, HCO+ map on 160-800 pc res.
. Nuclear Starburst/AGN
. Wide-spread dense star-formiing gas
. Shocked gas (merged induced)
. Gas arms without star-formation
. Potential dwarf galaxy formation at tidal tail

# Bi-polar Outflows in NGC5236



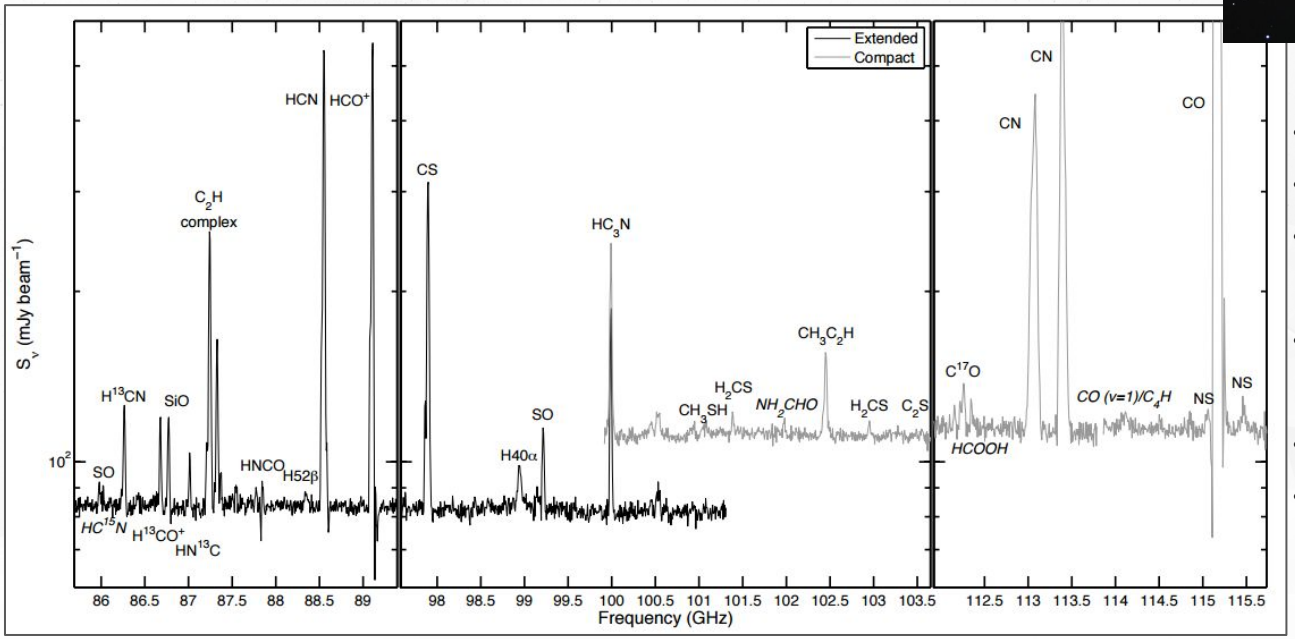




Sakamoto+14

- ALMA (Band3, Band7) + SMA observations
- CO(2-1), (3-2) and HCO+(4-3)
- Merger with large molecular outflow (both nuclei) with 750 km s-1 & 60 M yr$^{-1}$
- Nuclear molecular surface density of >10$^{3}$ M$_{\odot}$ pc$^{-2}$
- Star-formation + AGN contributions

# ISM properties in local galaxies

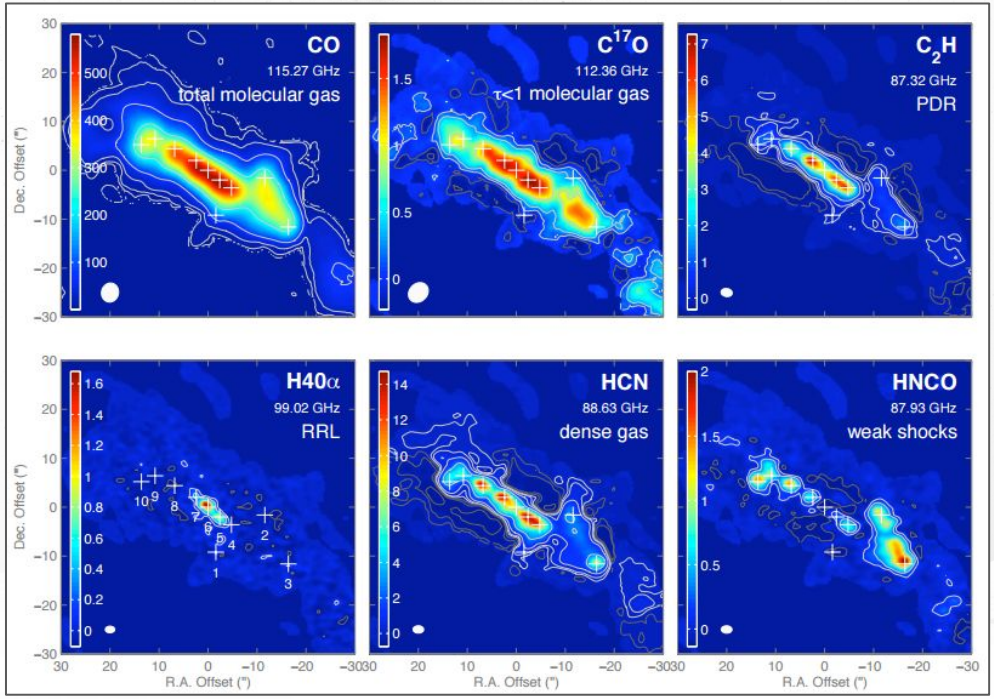
## ALMA multi-line imaging of NGC253 (Meier+15)

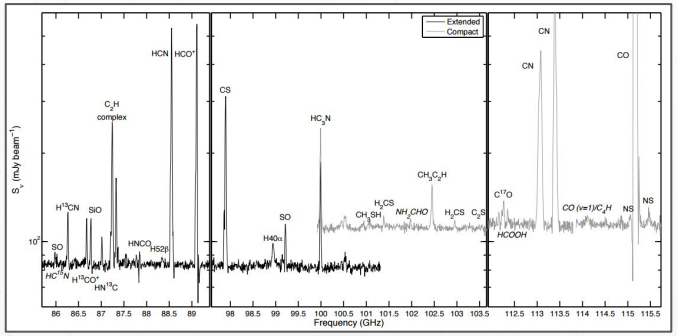


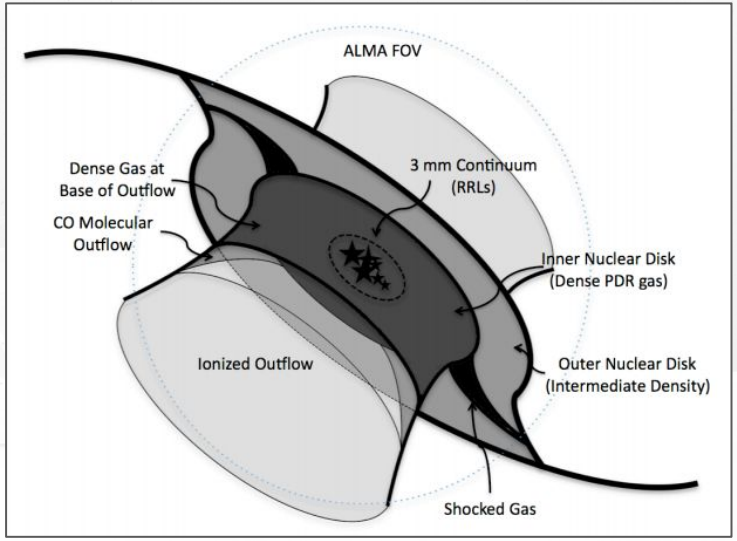

- ~50pc resolution, B3 (3mm)
- 50 detected (27 id) lines
- General view of star formation / feedback
- Strong molecular outflow from starburst
- CO distrib. traces Hα
- Ratio of outflow rate and SFR > 1

# ISM properties in local galaxies

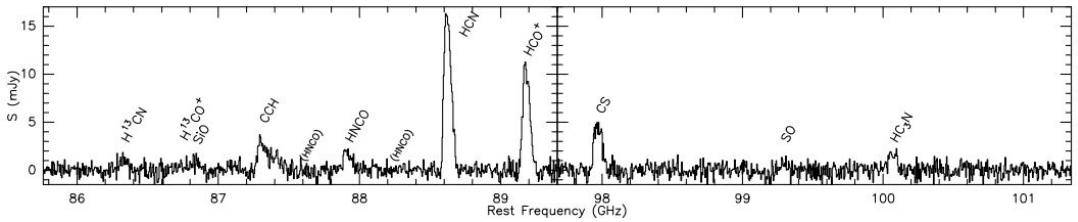
## ALMA multi-line imaging of NGC253 (Meier+15)



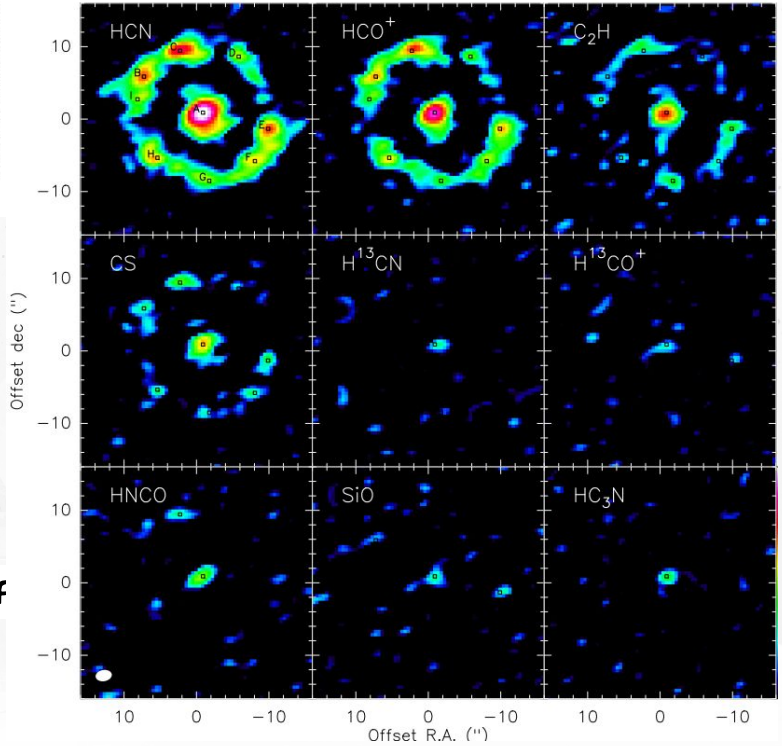
# NGC1067, an ALMA multi-molecule lab




ALMA 3mm , 150pc resolution

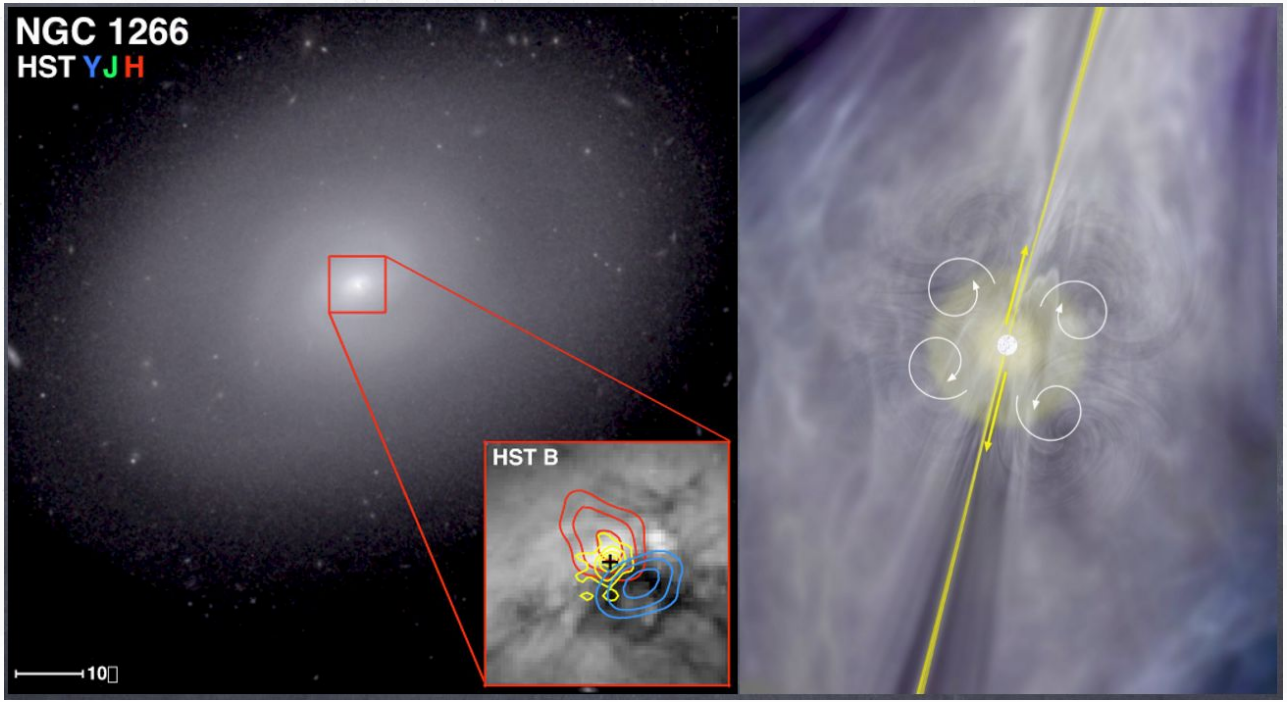
Analysis indicate:

- HCN, HCO+, CCH, CS, HNCO, SiO, HC3N, and SO
- Complex molecular chemistry
- HNCO, SiO and HC3N enhanced around AGN
- HCN/HCO+ and HCN/CS discriminates AGN/SB -> sub-mm BPT diagram (e.g. Izumi et la 2013)
- Different spices probe different physical structures




Martin+15

# SF suppression (the case of NGC-1266)




CARMA + ALMA

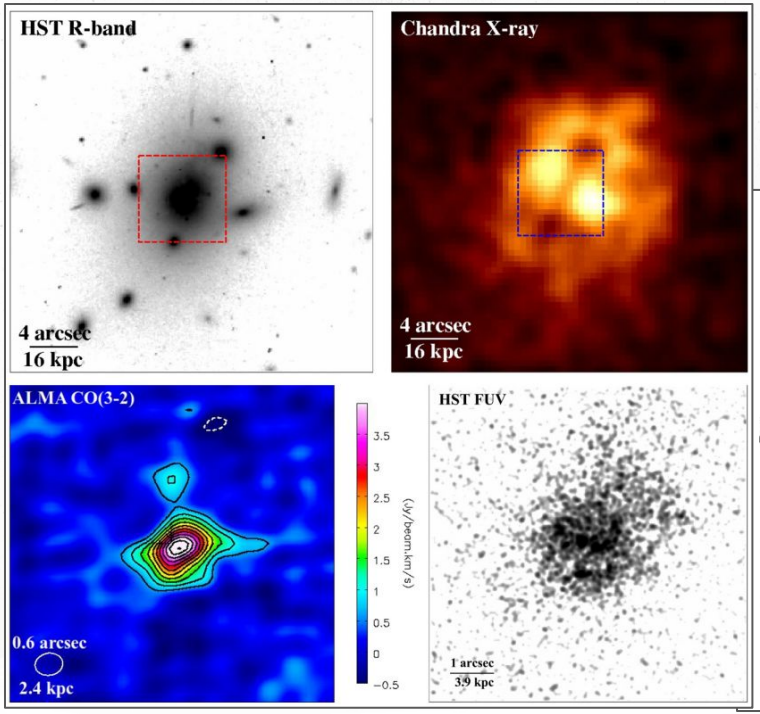
Analysis indicate:

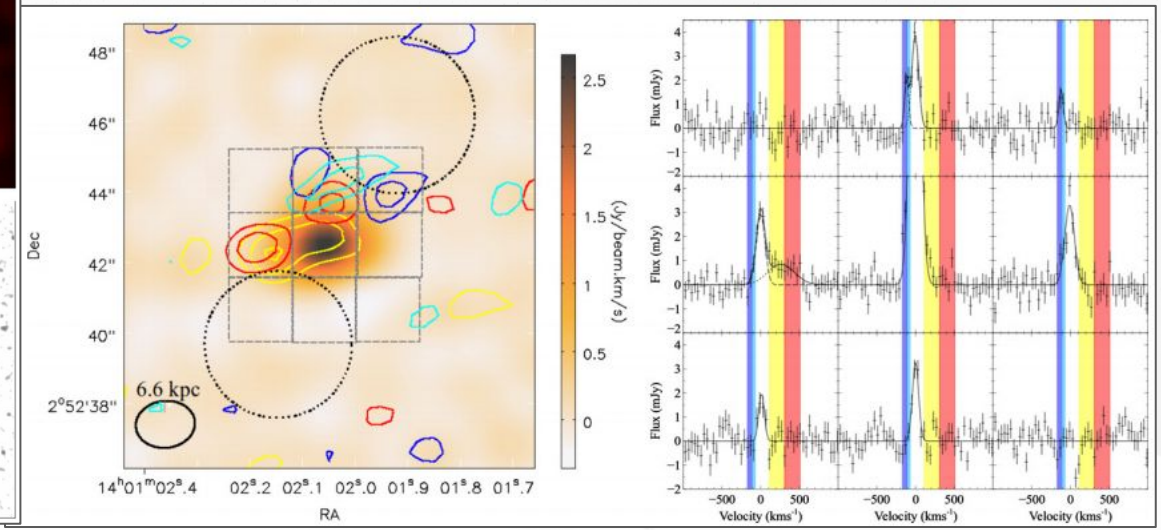
- Outflows
- SF suppressed by ~50 factor
- Too much turbulence
- AGN radio jet maybe responsible

Alatalo+15

# AGN/Host-galaxy interaction

- BGC in Abell 1835 and **SF 100-180 M☐ yr$^{-1}$**
- CO (3-2) and CO (1-0) emission lines
- **~1e10** M☐ molecular gas in **~10 kpc**
- Molecular gas flow of **200 M☐ yr$^{-1}$**



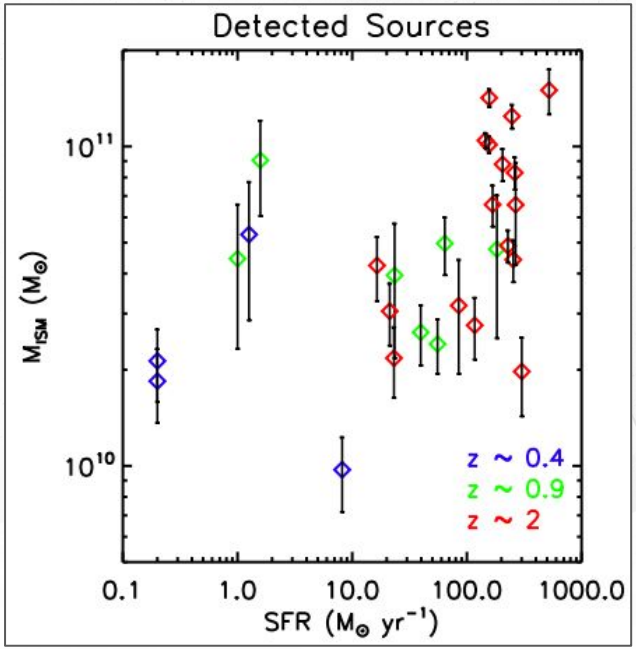



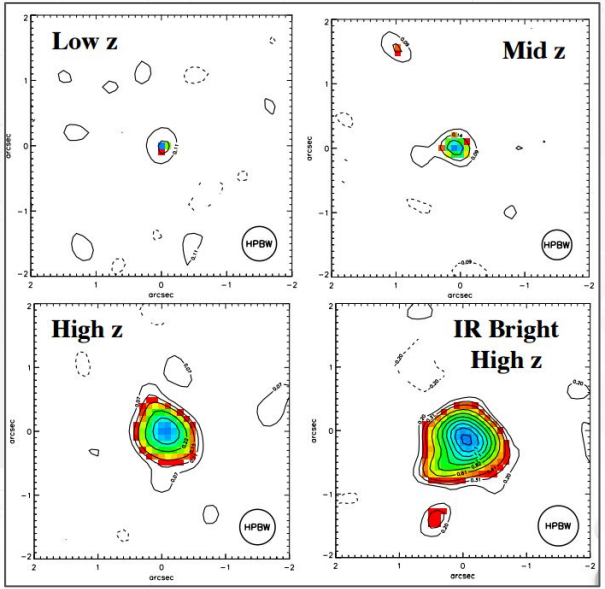

McNamara+14

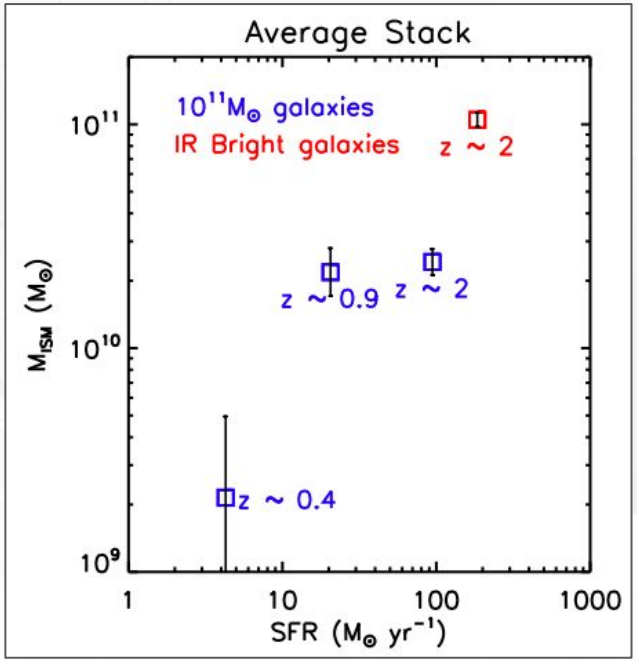
# Evolution of the ISM mass

Scoville+14 ⇒ . Dust Continuum B7 (870mu)

⇒ . 107 galaxies with same M-* ($10^{11}$)



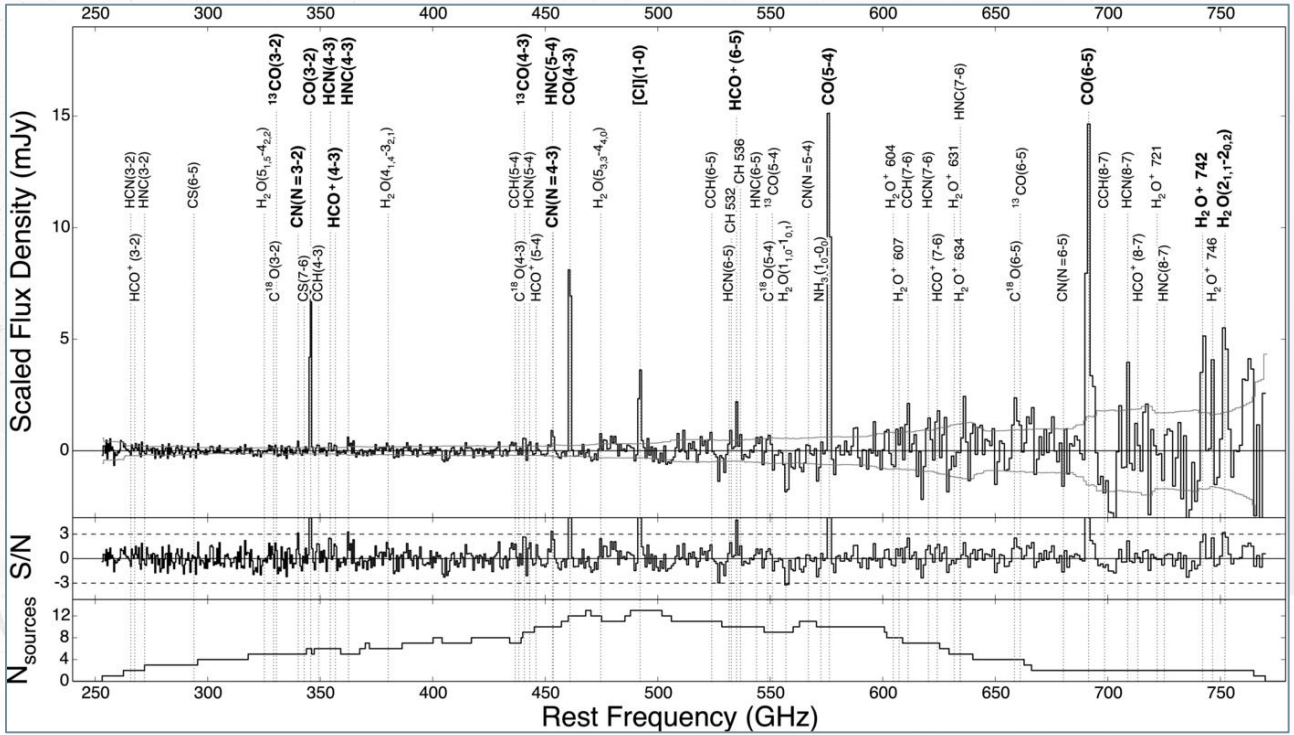



# ISM at high redshift

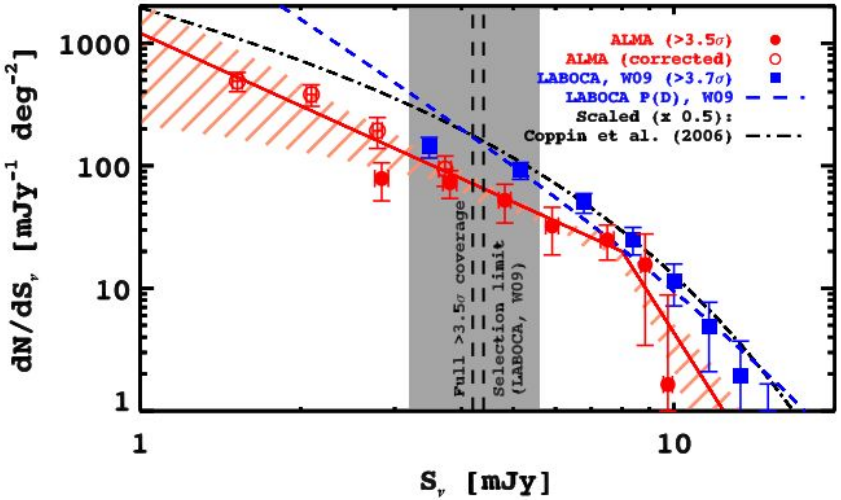
Average rest frame sub-mm spectrum
(Spilker+14)

- ALMA 3mm (Band3)
- **22** dusty SF galaxies
- z=2-5.7

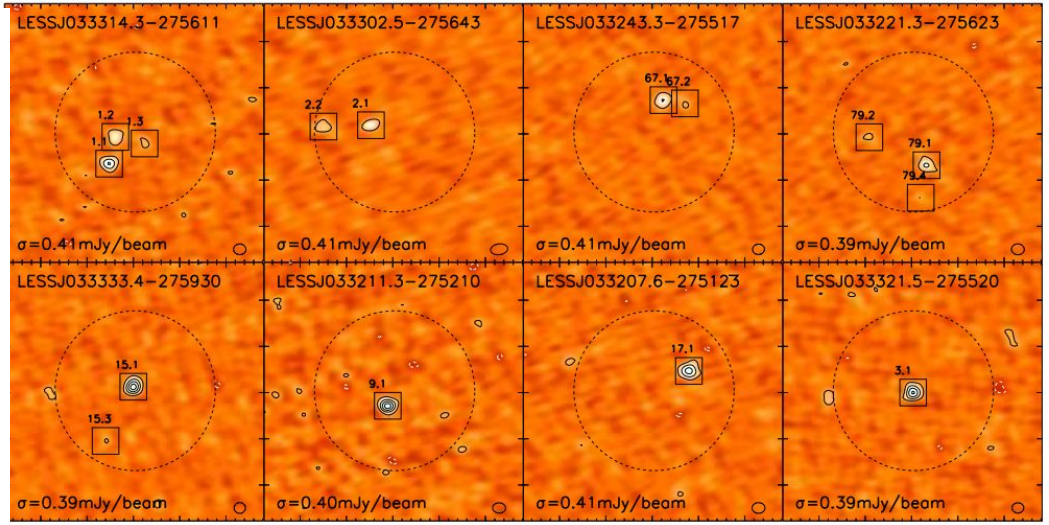


# Search for dusty star-forming galaxies

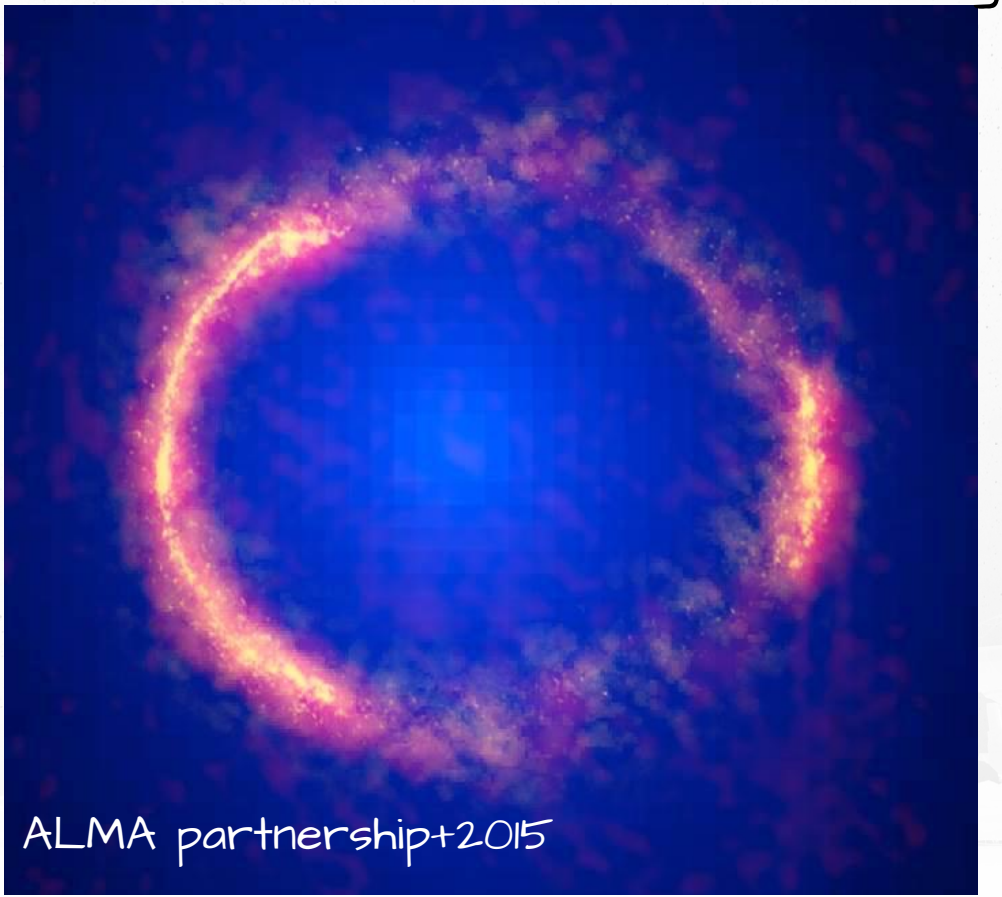
. Band 7 (870μm) continuum observations of 122 SMGs in the ECDFS
. High sensitivity and angular resolution of ALMA for unbiased SMG survey




Karim+13

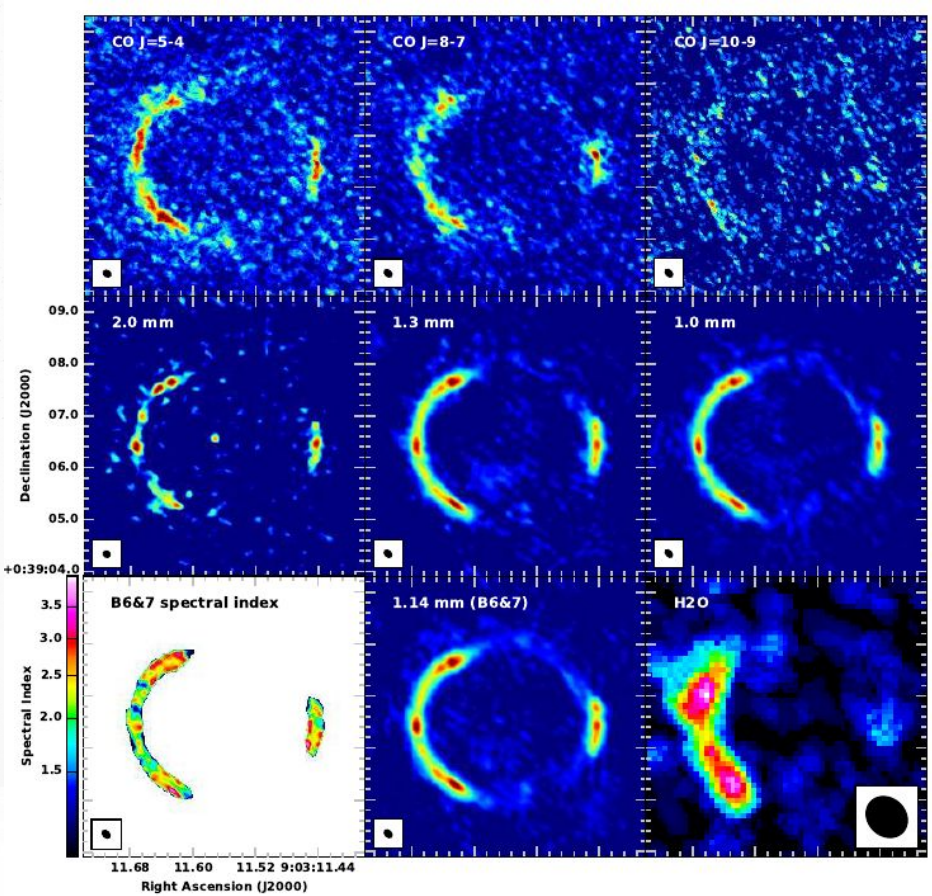


# - High-z universe -




. H-ATLAS 090311.6+003906 (SDP.81)
. ALMA Long Baseline Camp. ~15km
. Continuum at 1.0, 1.3 & 2.0mm
. **23** mas res.→ 180pc at z=3.042

# - High-z universe -




. H-ATLAS 090311.6+003906 (SDP.81)

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. Continuum at 1.0, 1.3 & 2.0mm

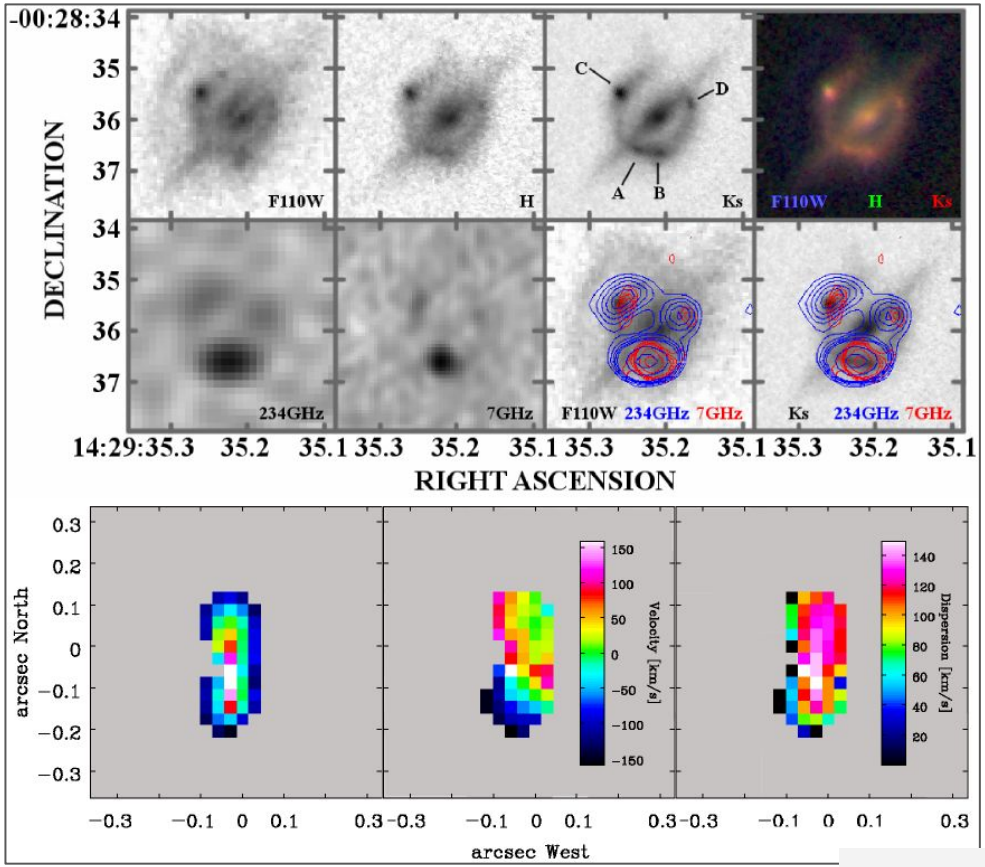
. **23** mas res.→ 180pc at z=3.042

. **CO** J=10-9, J=8-7, J=5-4 & **$H_2O$** ($2_{02}$ - $1_{11}$) line emission

. ~170 mas beam for CO; 0.9" for $H_2O$ (highest-z detection?)

ALMA partnership+15

# - High-z universe -



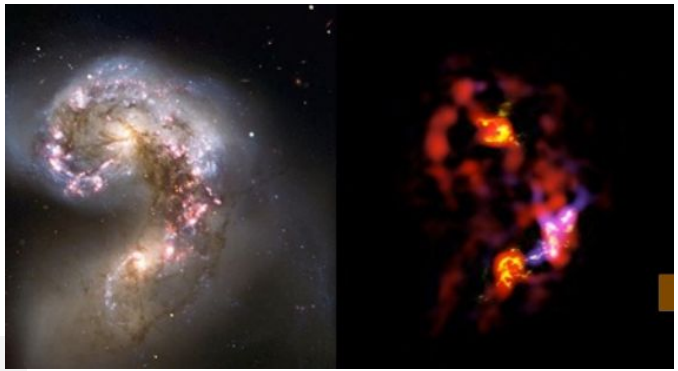

. H-ATLAS, H1429-0028

. ALMA CO (J:4 → 3) transition

. Massive stellar sys. (1.3 x 1e11 $M_\odot$)

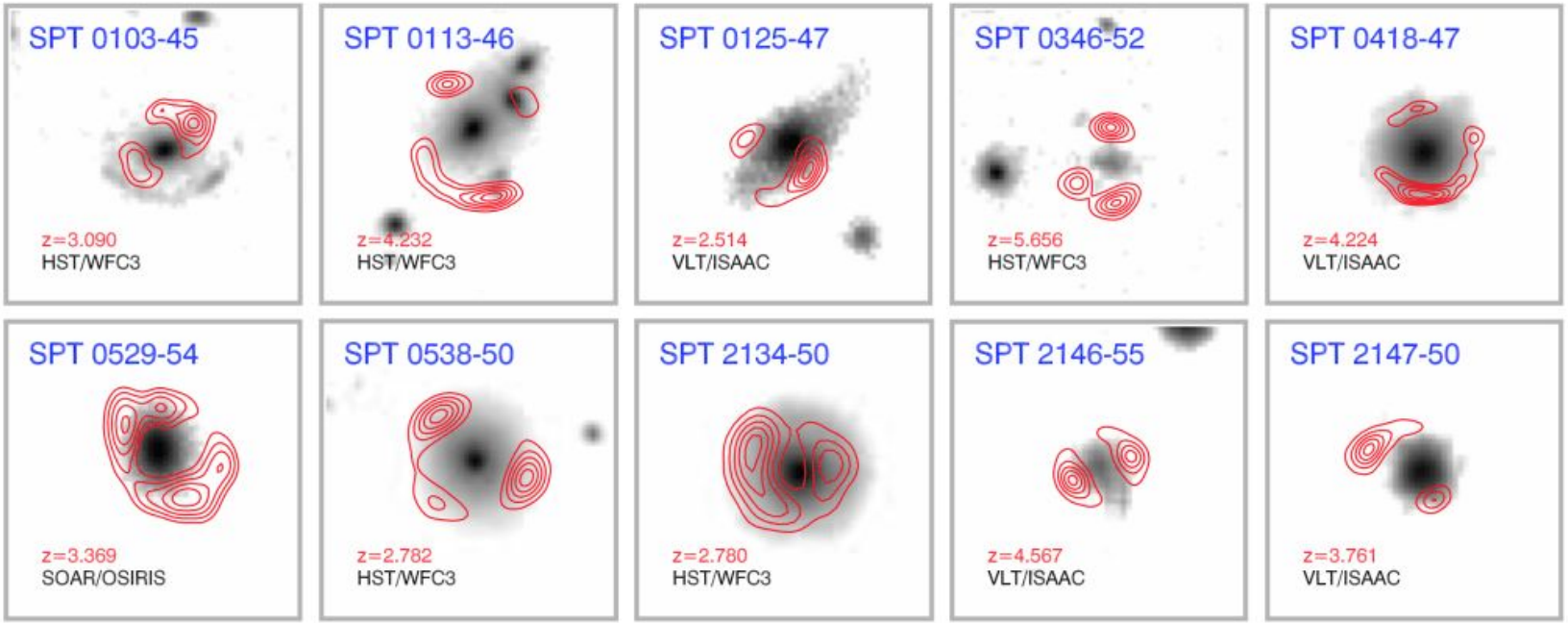
. z = 1,027

. SFR ~400 $M_\odot$ $yr^{-1}$



Messias+2014

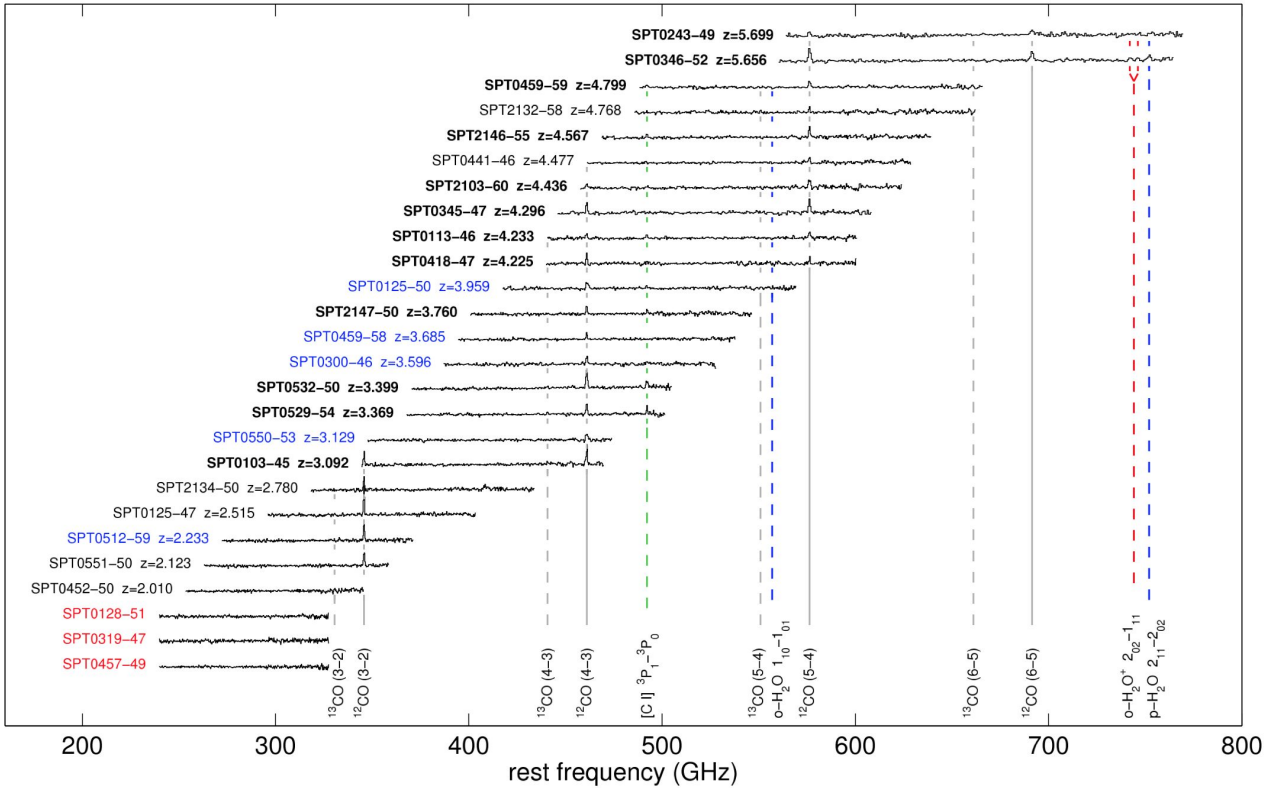
# Dusty SB galaxies




Vieira+13

Target CO emission with ALMA band 3 (3mm). 10/26 at z>4

# Dusty SB galaxies

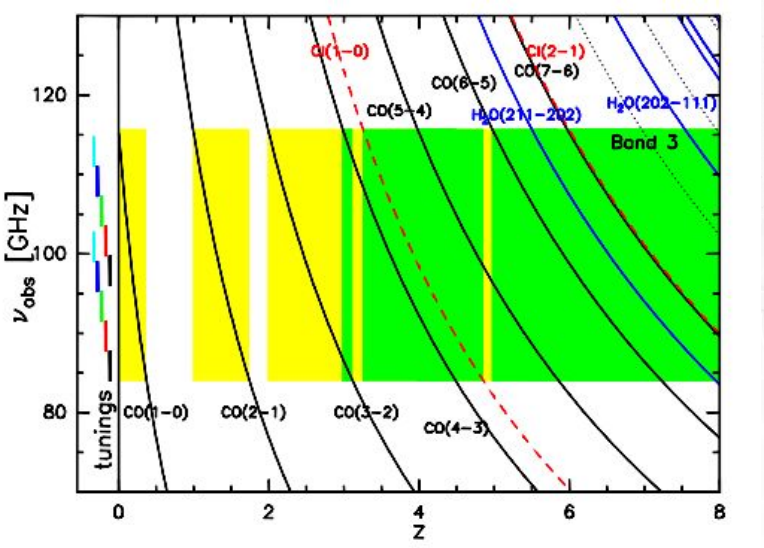


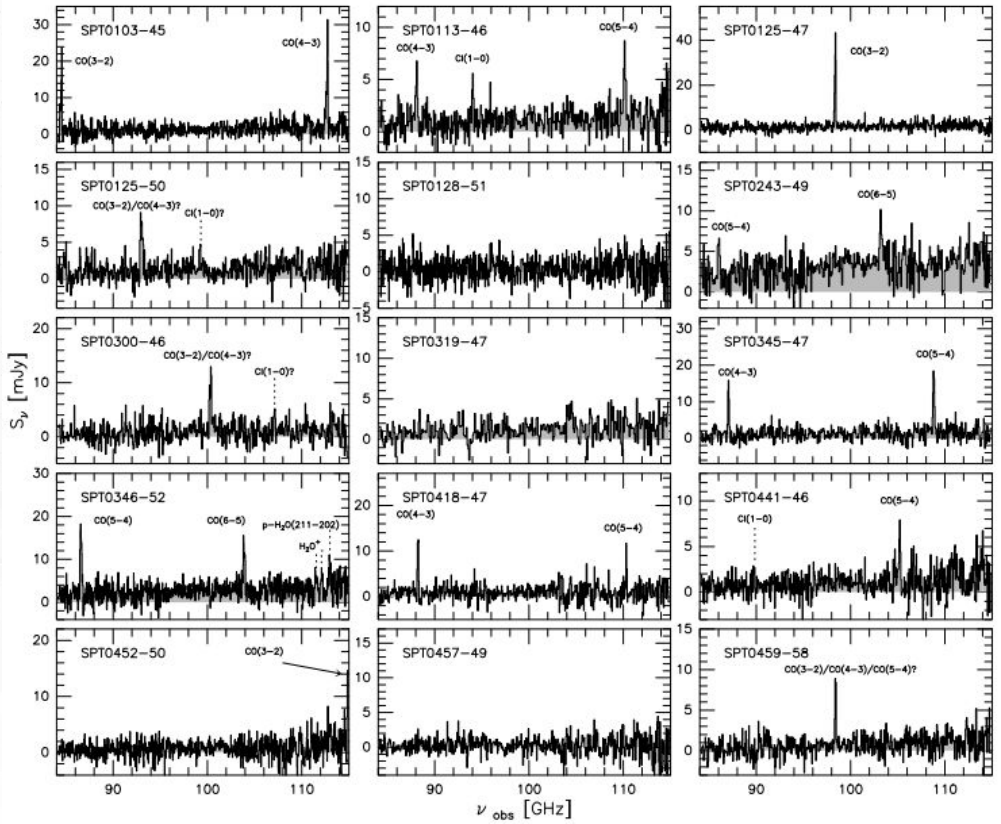

Vieira+13

# - High-z universe -

## Redshift Machine
(e.g. Weiss+13, Vieira+13)

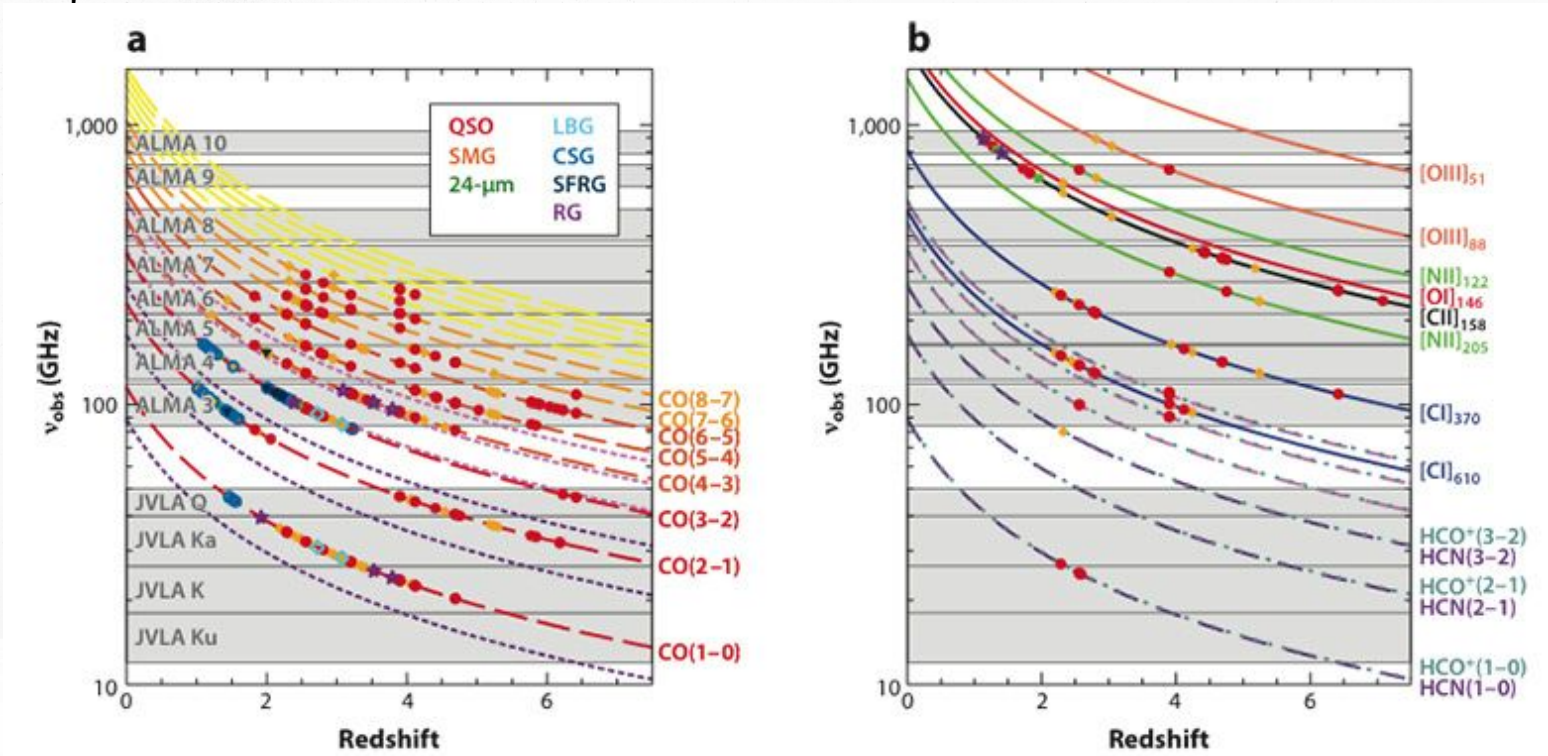
Blind z survey of 26 SPT targets:
90% success (1 line); ~50% secure z



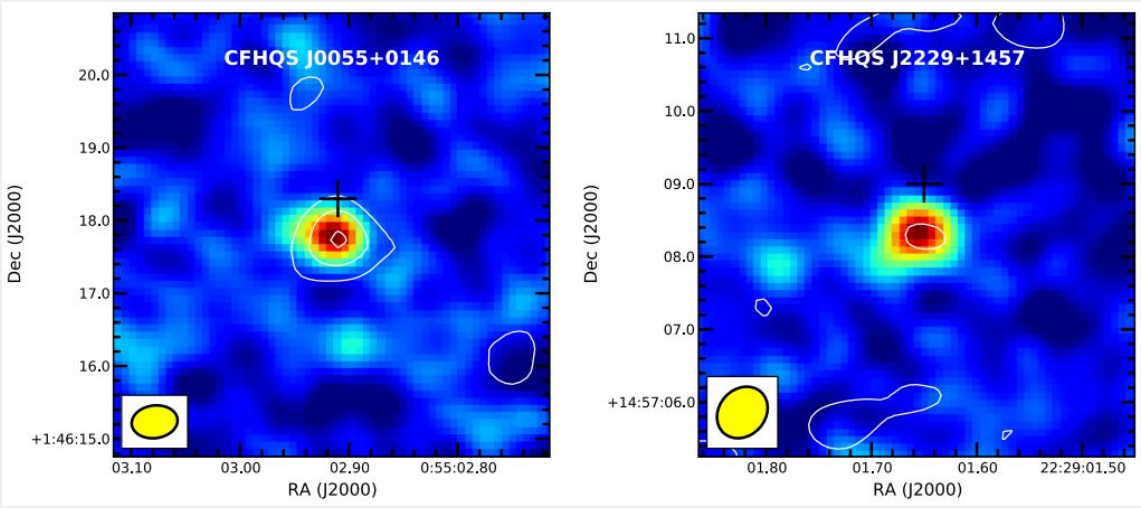
# - High-z universe -

## Redshift Machine
(e.g. Carilli, Walter 2013)

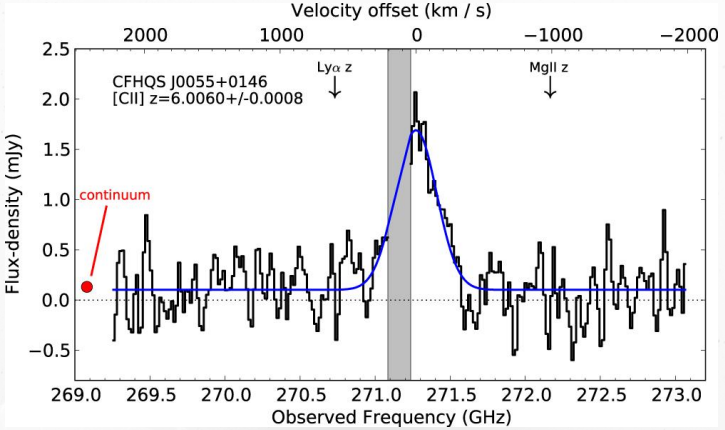


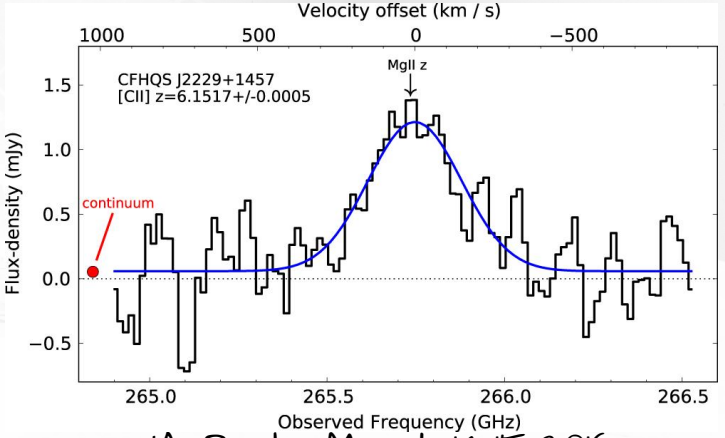
# SFR in high-z QSOs

## 4 QSOs from CFHQS at z6 and BH of $10^8$ M




Willott+13,15



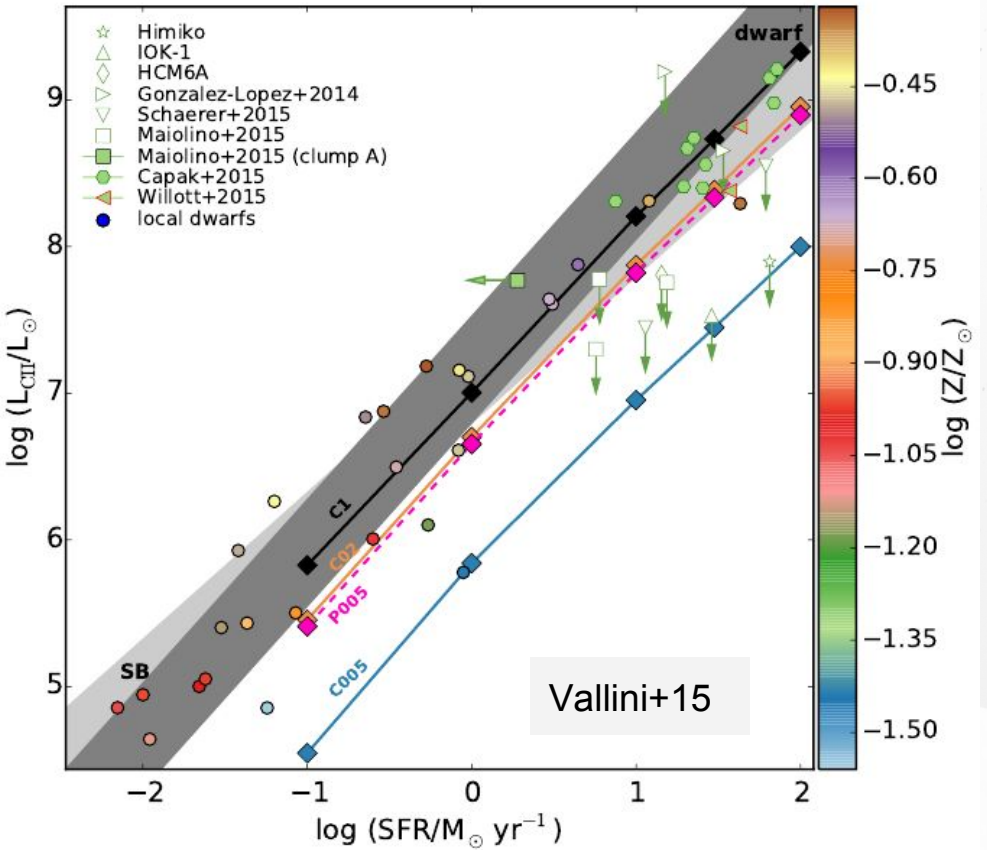



# [CII] 158□ deficiency?

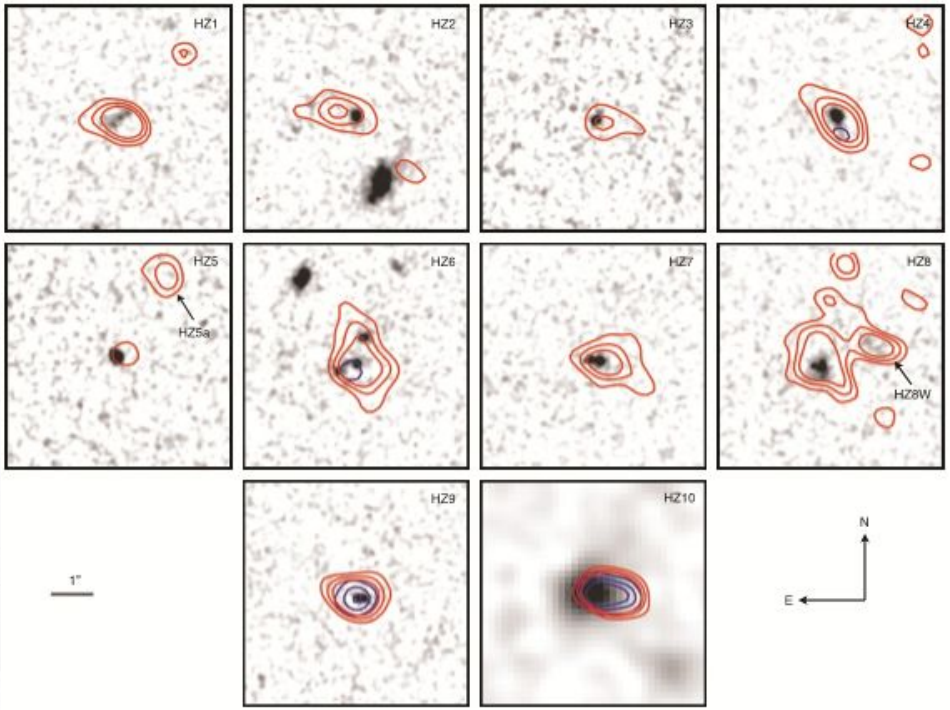
- Detection with modest SFR (50-300 $M_{\odot}$ $yr^{-1}$) @ z~4.5
  (Carilli+2013, Carniani+2013, Williams+2014, Riechers+2014)

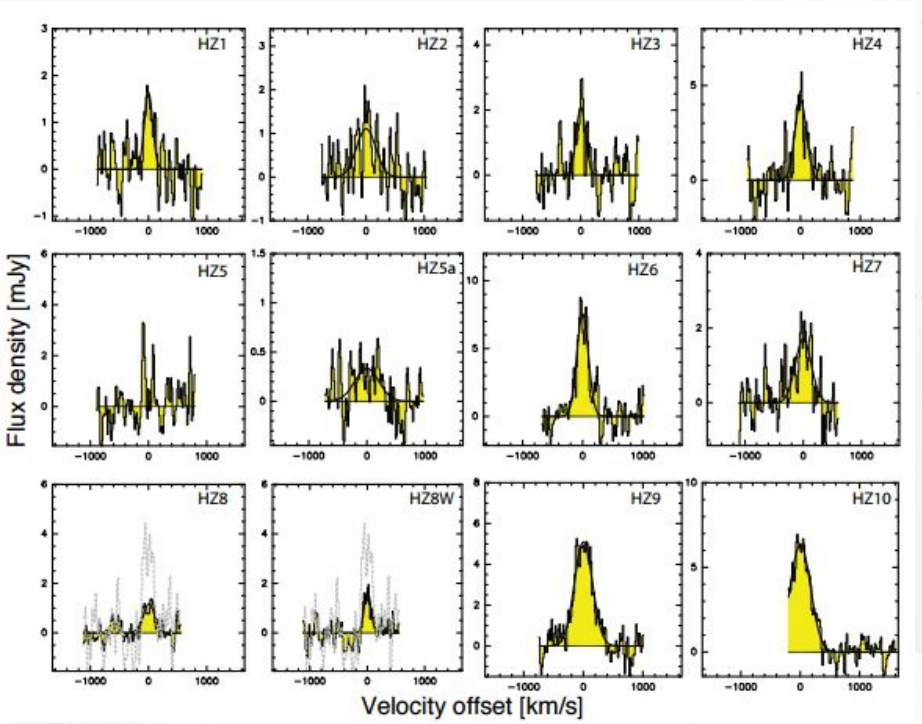
- No detection at normal SFR (~10 $M_{\odot}$ $yr^{-1}$) @ z~6
  (Walter+ 2012, Kanekar+ 2013, Ouchi+2013, Ota+2014, Schaerer+ 2015)

- Detections for z~5-7 LAEs & LBGs
  (Maiolino+15, Willott+15; Capak+15)



# 9 typical (~1-4L*) starforming galaxies ~1 billon yrs after the big bang (z~5-6)



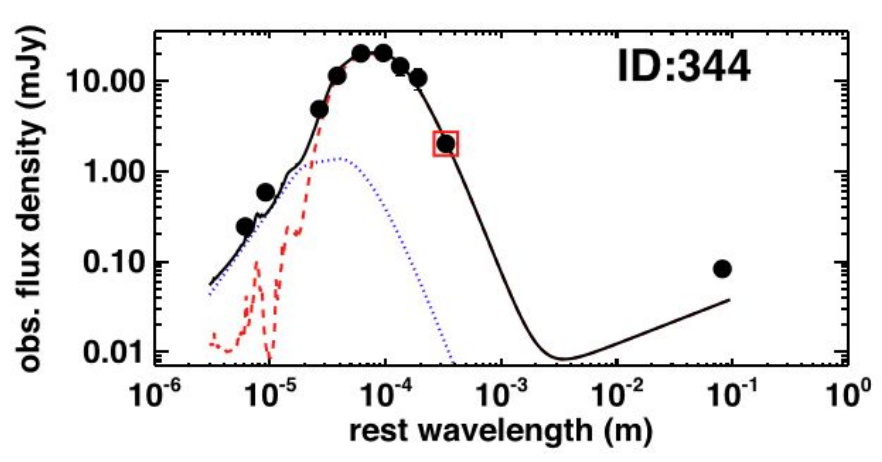




Capak+15

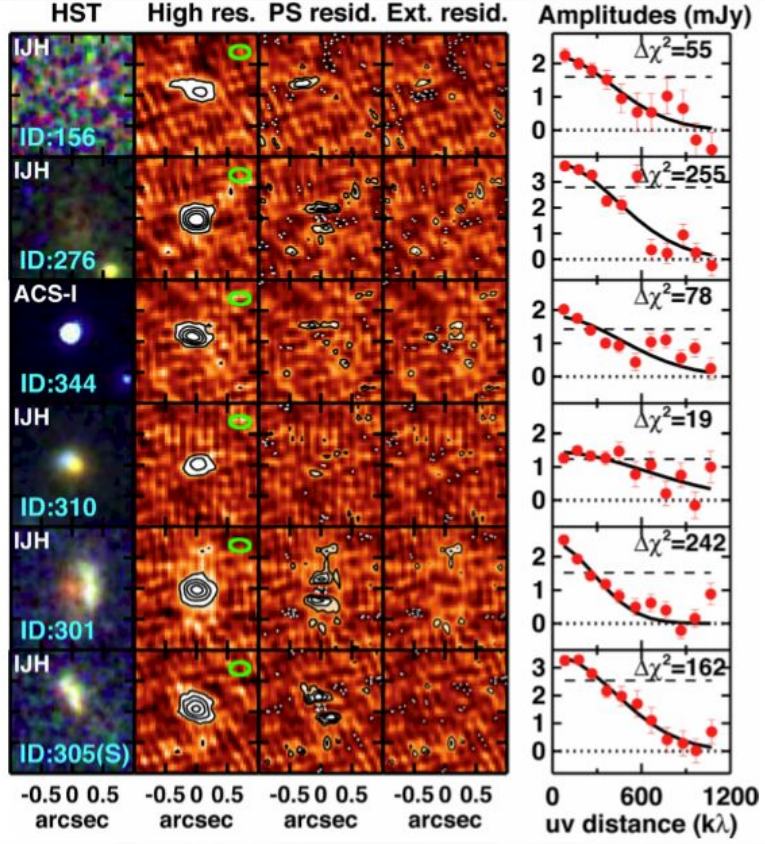
CII [158□m]

# Extended SF on X-ray AGN

5 z≈1.5-4.5 X-ray detected AGN (>$10^{42}$ erg $s^{-1}$)



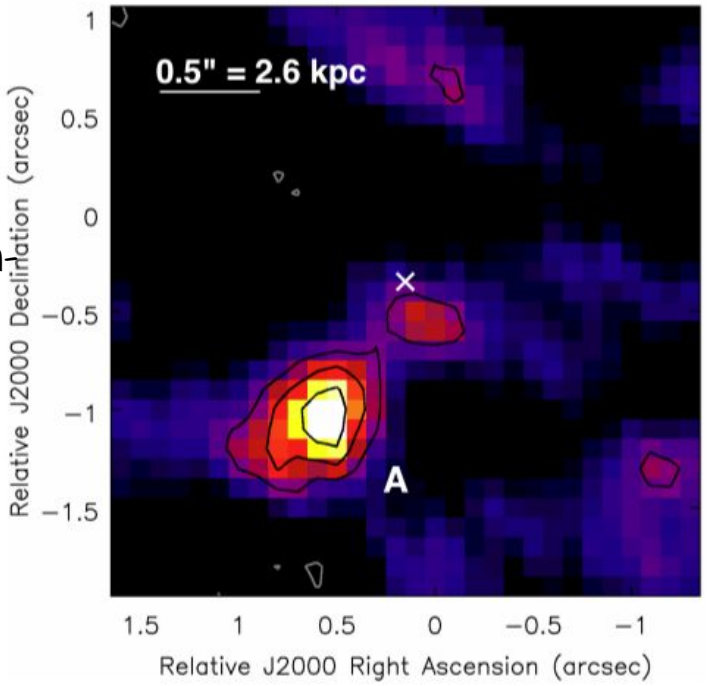

Harrison+16

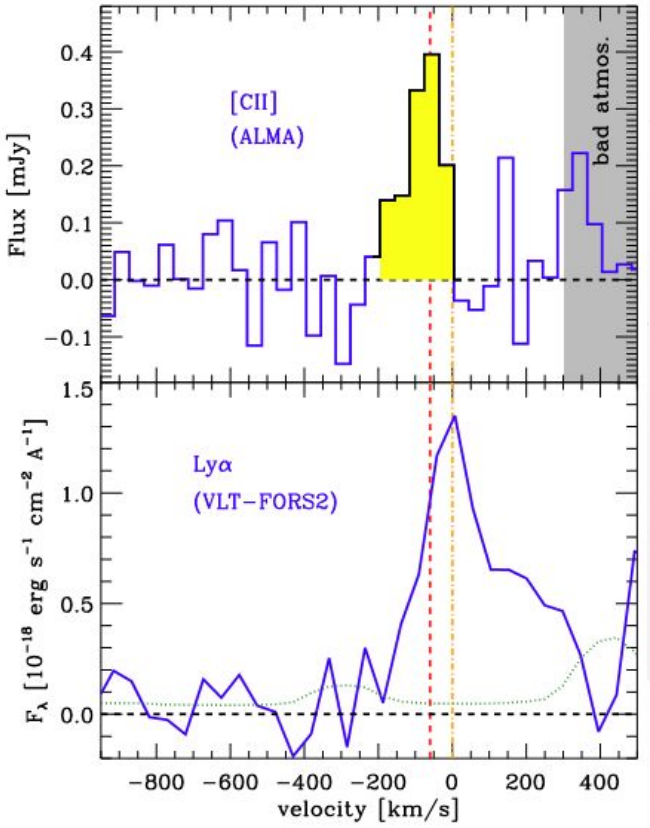


# CII + continuum for 3 LBGs at z~7

. SFR 5-15 M□
. Lyα - CII offset

. CII from external in-falling clumps



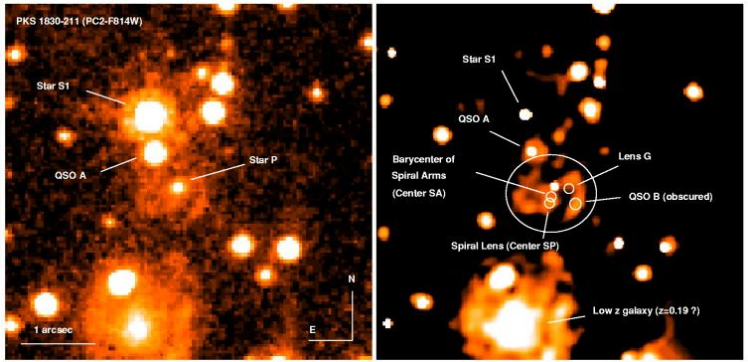

Maiolino+15

# Cosmology with absorption lines

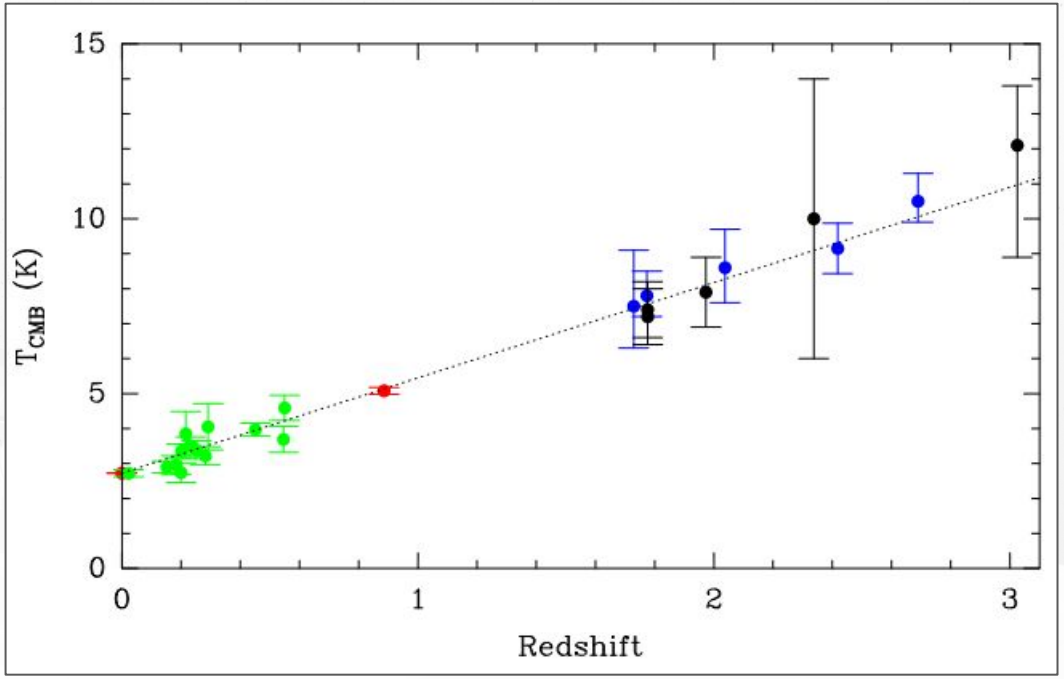
Evolution of... **CMB** Temperature

. Excitation analysis of absorption lines along QSO LOS

**PKS 1830-211**



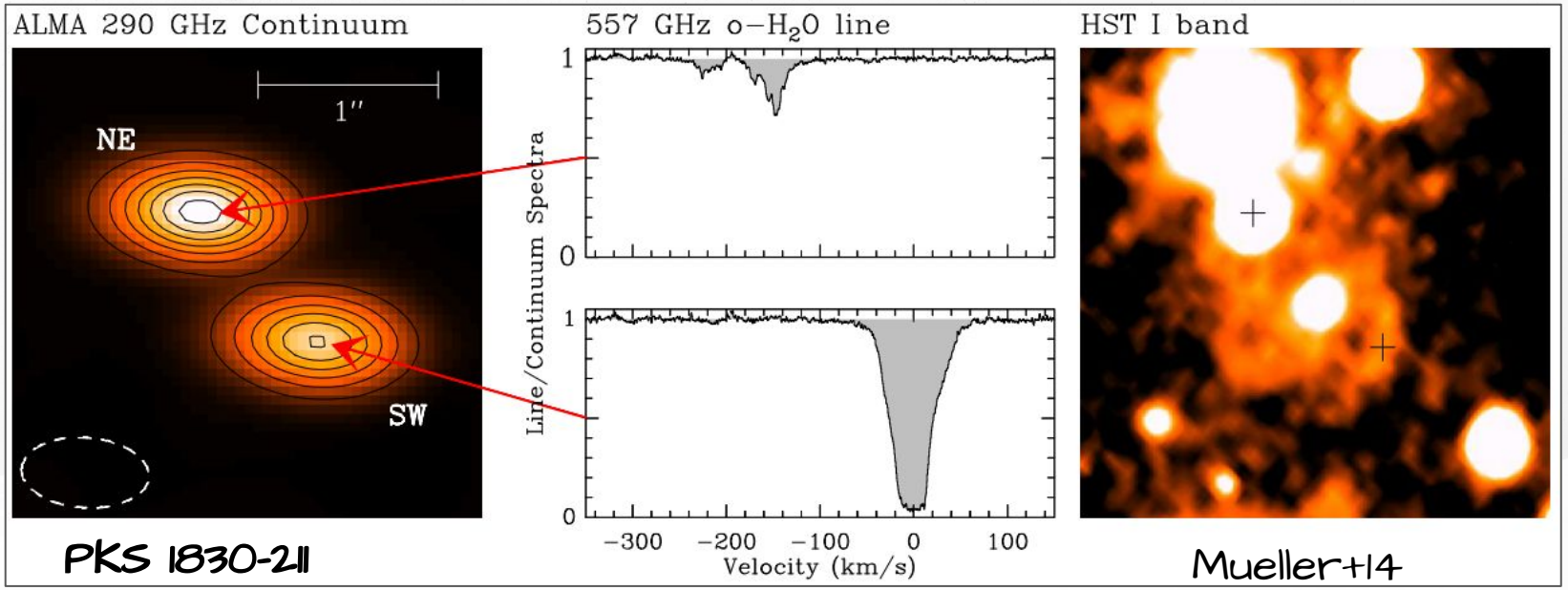

Mueller+12, Noterdaeme+11



# Cosmology with absorption lines

Constraints on the constancy of constants...

Fine structure constant (□), Molecular isotope ratio & $p^+$-to-$e^-$ mass ratio



# THANK YOU!

Mueller+14