The Cold Molecular Medium around High-z Radio Galaxies: *Light up the darkness!*

Bjorn Emonts

Centro de Astrobiología (CSIC-INTA), Madrid

M. Lehnert *(IAP)*, P. Guillard *(IAP)*,

M. Villar-Martin *(Centro de Astrobiología)*, R. Norris *(CASS)*, H. Dannerbauer *(IAC)*, *R. Ekers (cass)*, G. van Moorsel *(NRAO)*, M. Mao *(Jodrell Bank)*, C. De Breuck *(ESO)*, G. Miley *(Leiden)*, N. Seymour

H. Röttgering, C. Carilli, L. Pentericci, J. Allison, B. Gullberg, E. Sadler, D. Ceverino, B. Indermuehle, J. Vernet, P. Jagannathan, ***L. Colina, S. Arribas***

Marie Curie Intra-EU Fellowship

MARIE CURIE ACTIONS

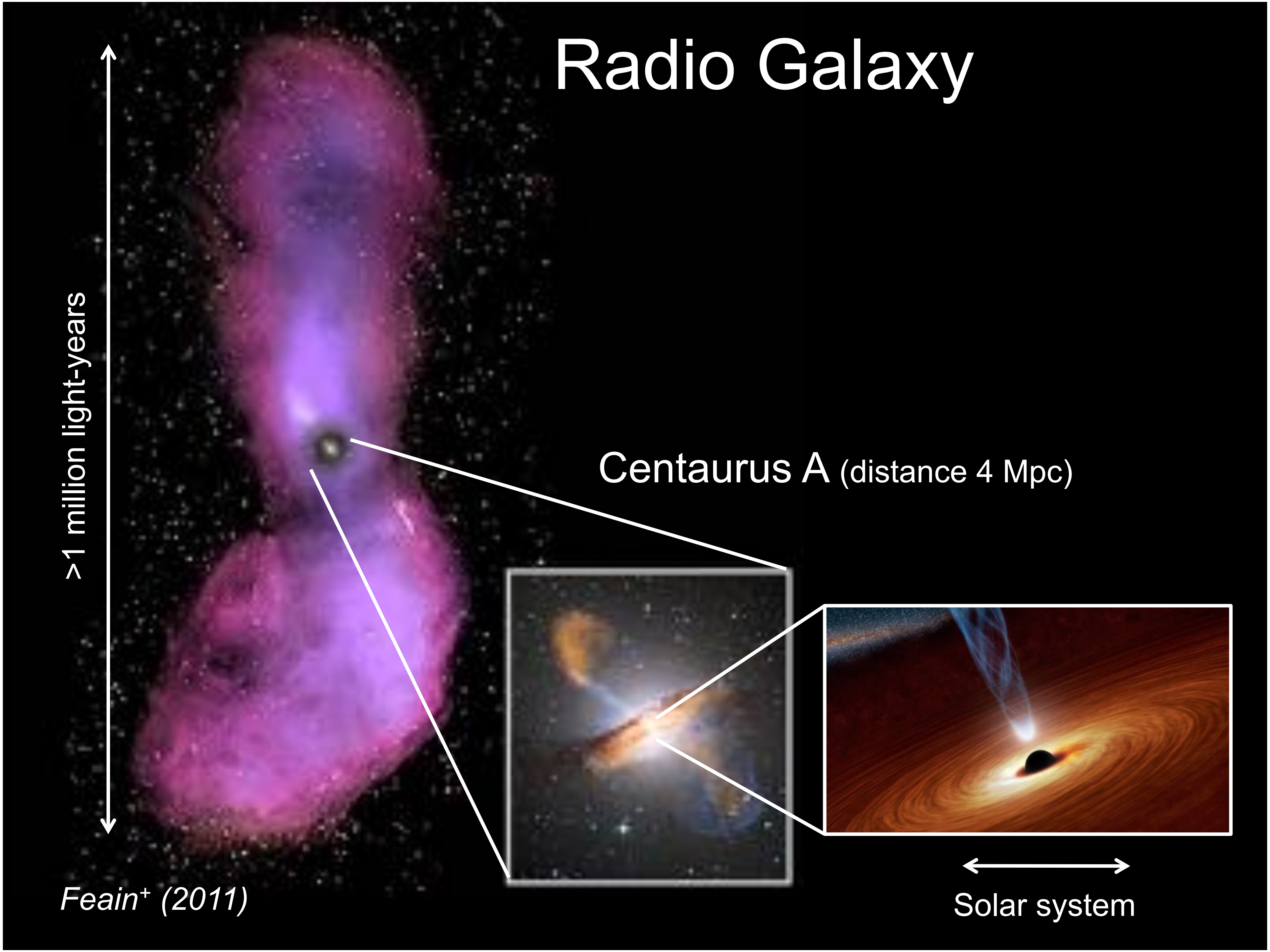
SEVENTH FRAMEWORK PROGRAMME

GOBIERNO DE ESPAÑA CSIC INTA

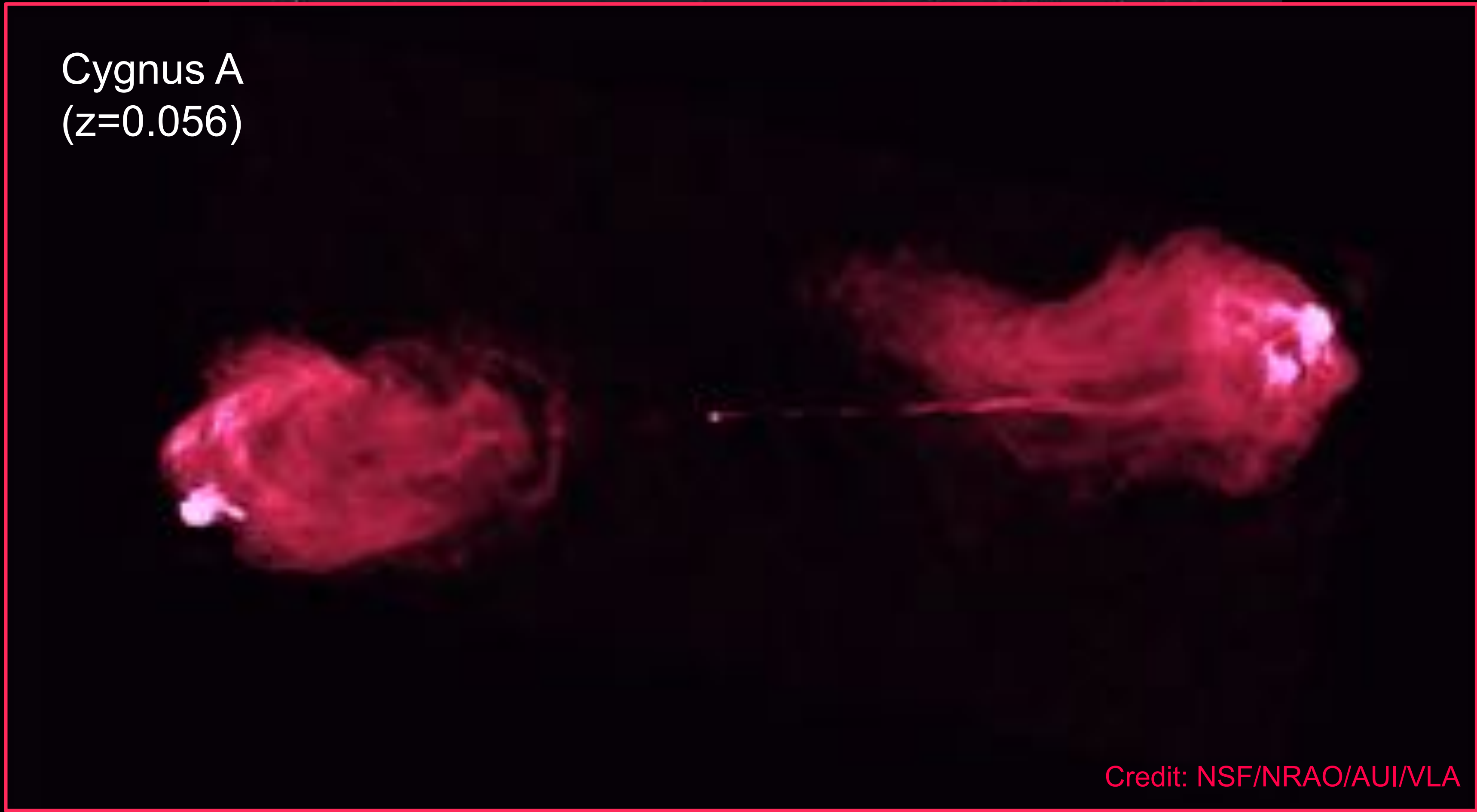
CENTRO DE ASTROBIOLOGÍA

Asociado al NASA Astrobiology Institute

Radio Galaxy



Credit: I. Feain, T. Cornwell, R. Ekers (CSIRO/ATNF); ATCA middle lobe pointing courtesy R. Morganti (ASTRO); Parkes data courtesy N. Junkes (MPIfR); ATCA & Moon photo: S. Amy, CSIRO



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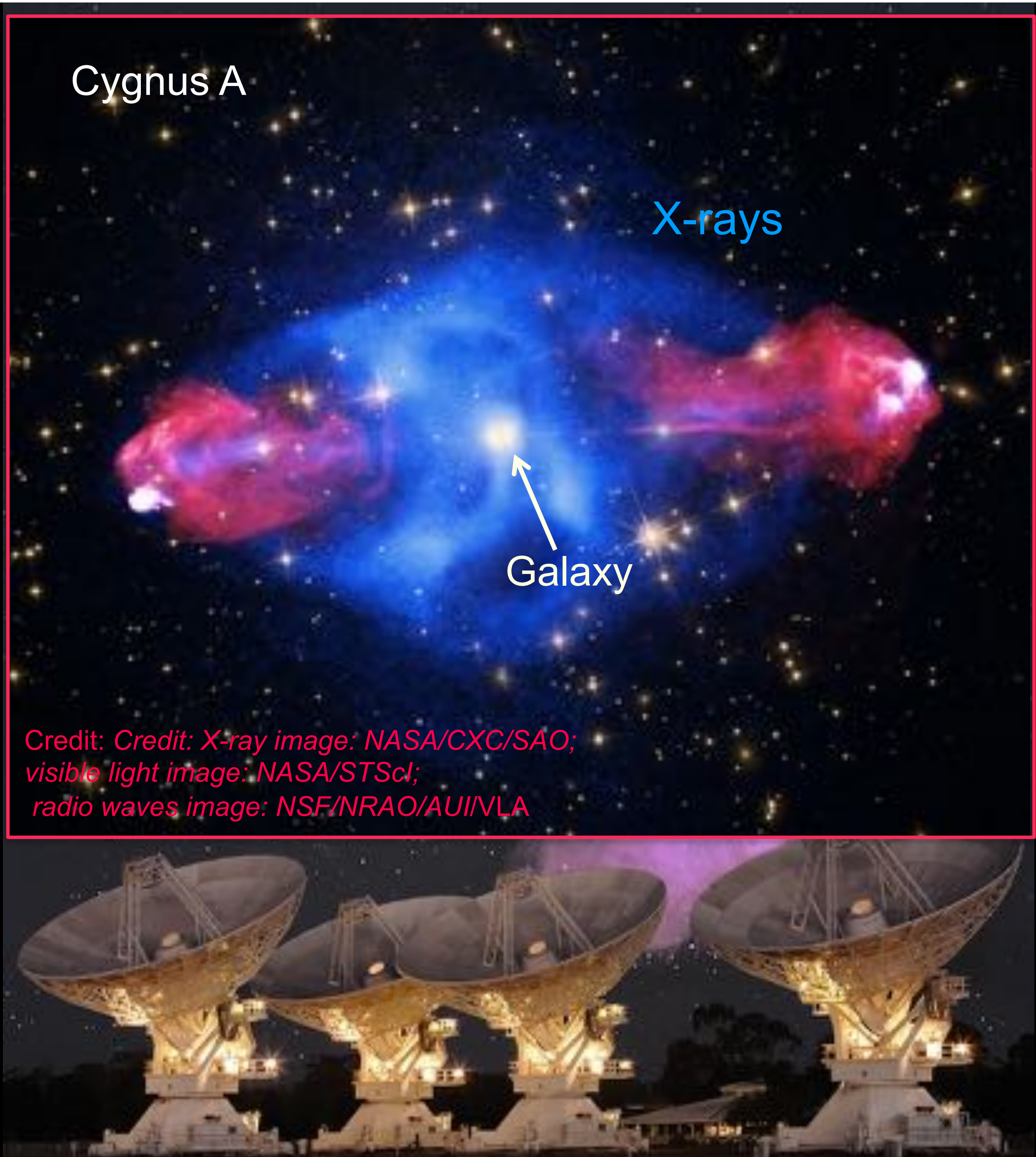

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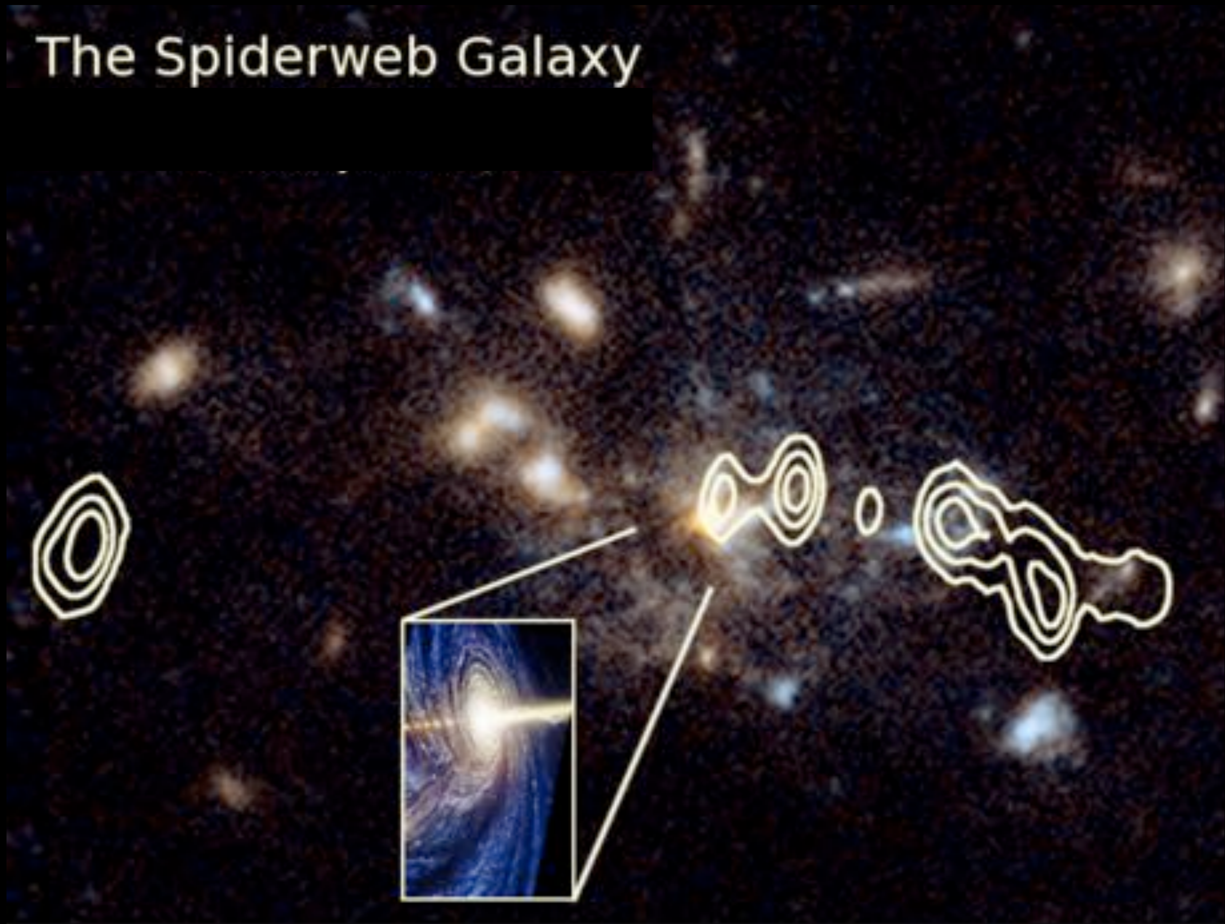
High-z Radio Galaxies

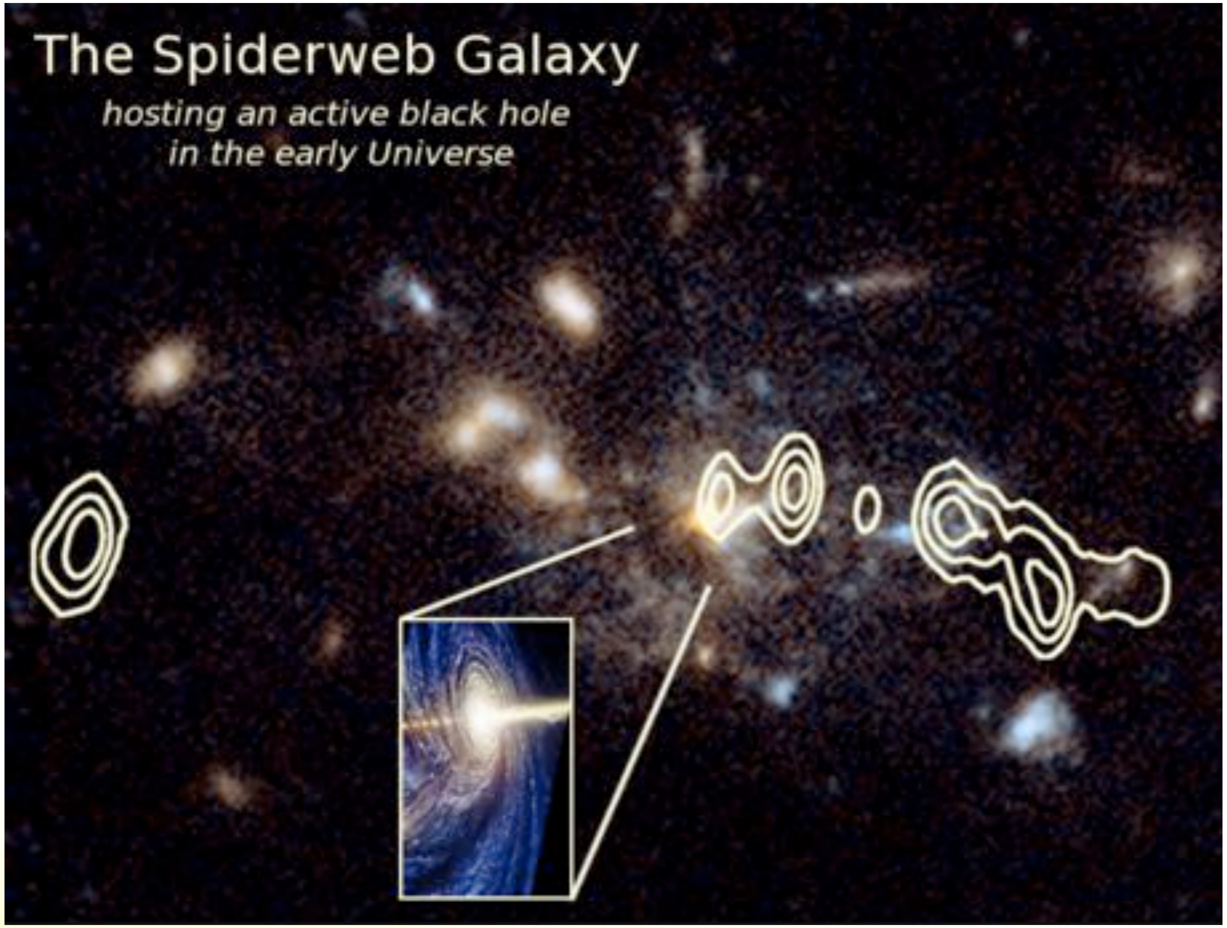


$P_{500\ \mathrm{MHz}} > 10^{27}$ W/Hz

Strong beacons → among best studied high-z objects

High-z Radio Galaxies

- Most massive galaxies in formation
- Very active (high SFR, mergers, jets-gas interactions)
- Central proto-cluster galaxies → *ancestors of giant central cluster ellipticals*



High-z Radio Galaxies

Science question 1

Evolution: How do proto-cluster radio galaxies evolve into giant central cluster ellipticals?

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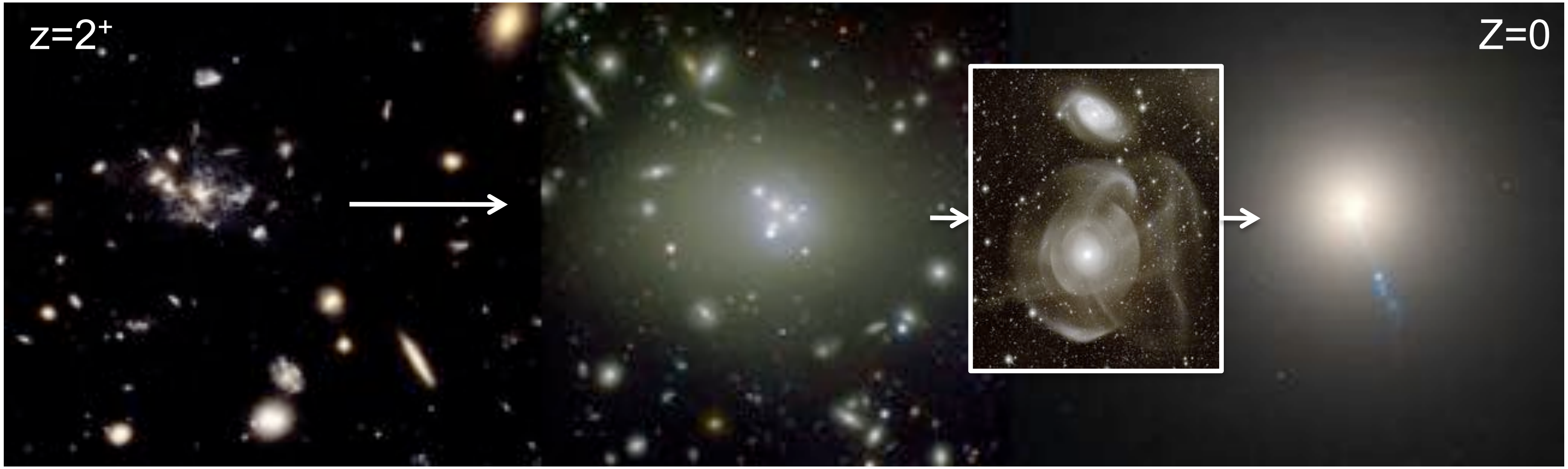


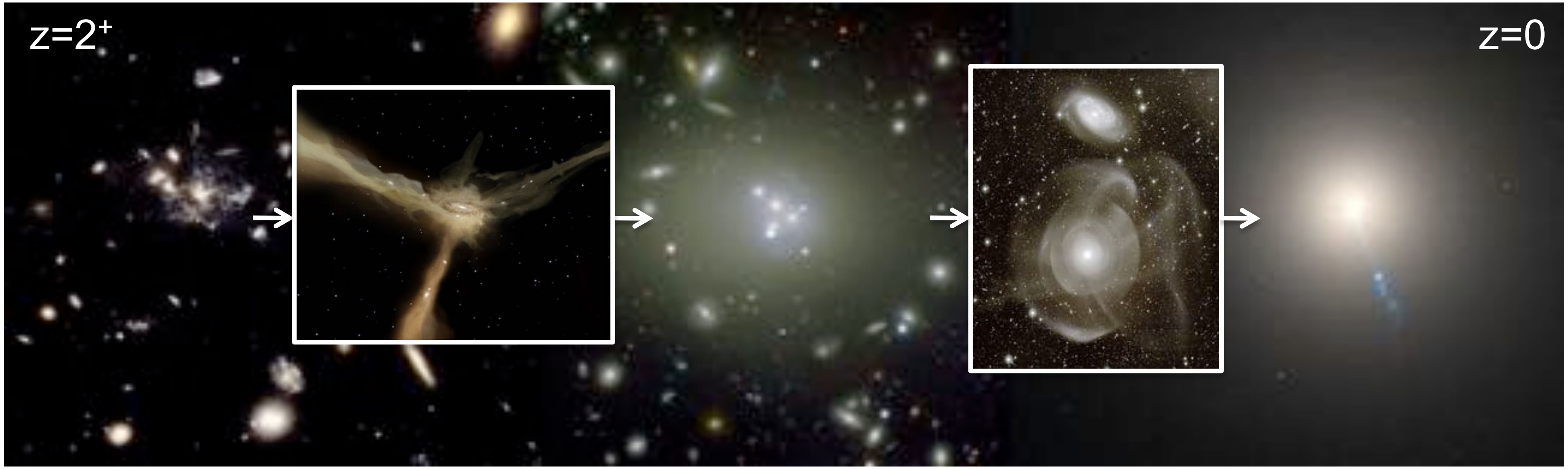
Late phase:

Galaxy mergers

High-z Radio Galaxies

Science question 1

Evolution: How do proto-cluster radio galaxies evolve into giant central cluster ellipticals?



<u>Early phase:</u>

Cold gas accretion

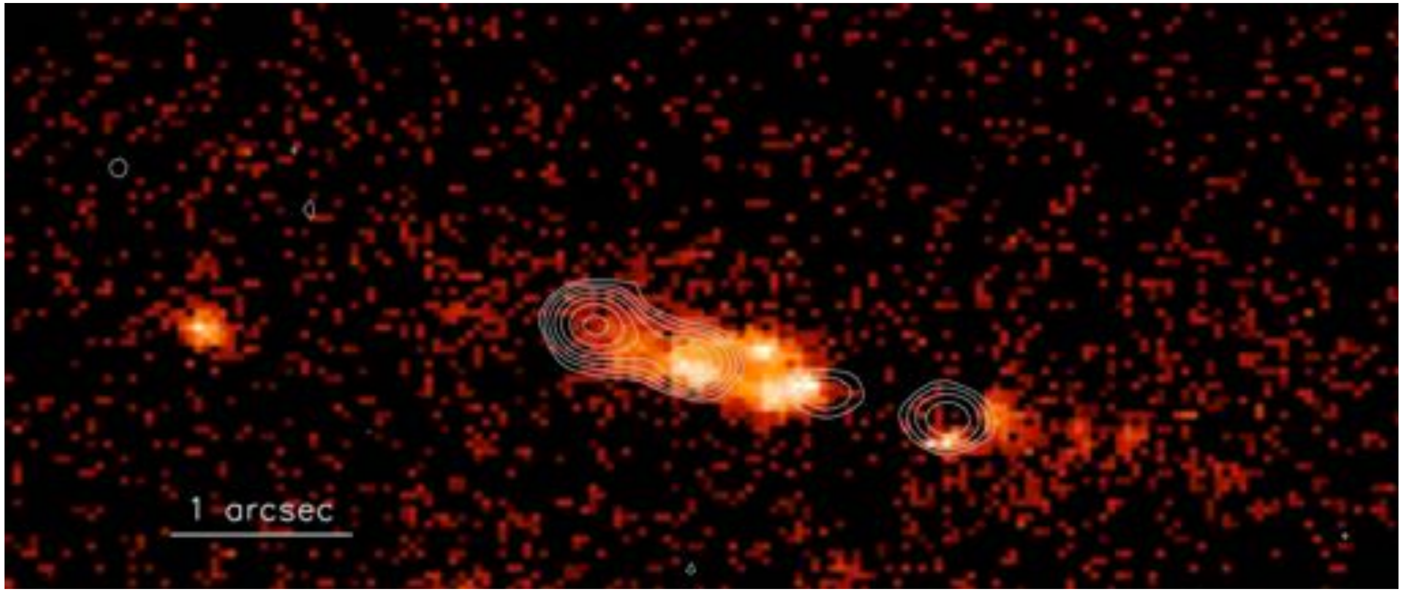
<u>Late phase:</u>

Galaxy mergers

Introduction

Science question 2

Feedback: What feedback to the powerful radio jets
exert onto the (circum-) galactic environment?



Dey et al (1997)

Introduction

Science questions

Evolution: How do proto-cluster radio galaxies evolve into giant central cluster ellipticals?

Feedback: What feedback to the powerful radio jets exert onto the (circum-) galactic environment?

Methods

Carbon-monoxide (CO) → cold molecular gas

raw ingredient for star formation!

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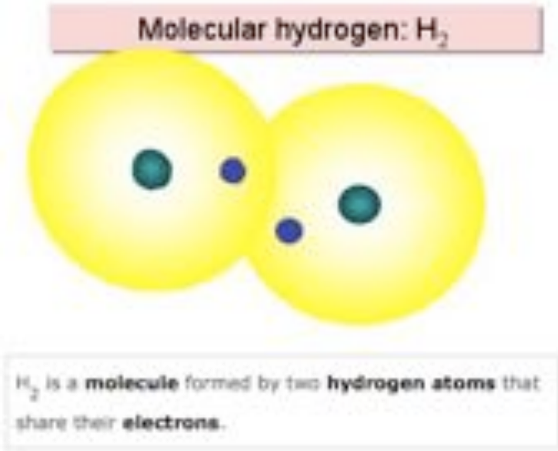
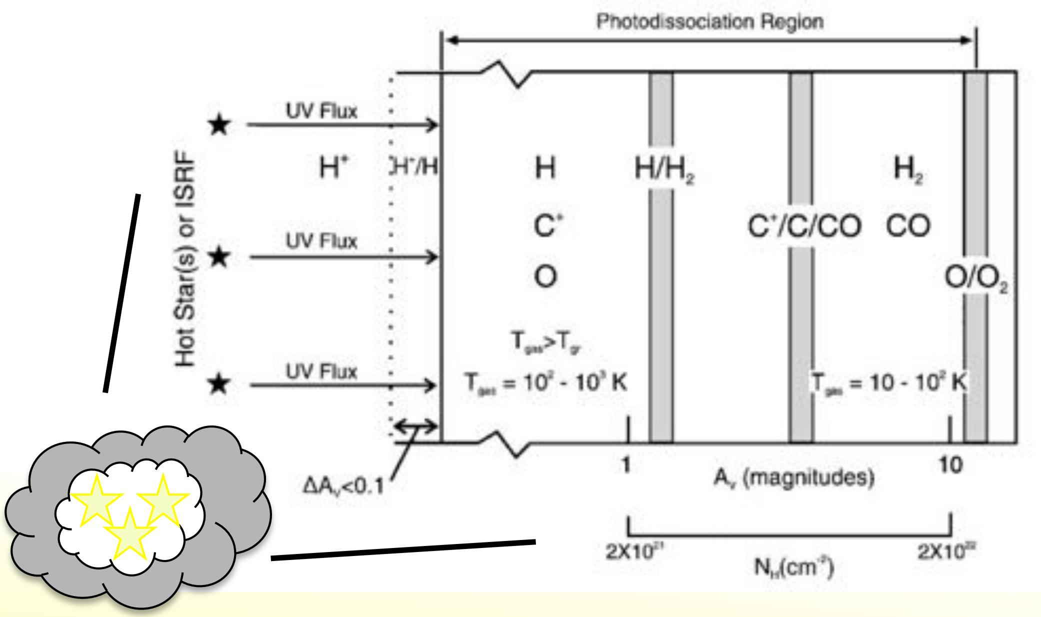
Introduction: molecular gas in HzRGs



H_2 raw ingredient star formation

… but virtually invisible, unless shocked/heated!



^{12}CO good tracer for H_2

- Most abundant after H_2
- Very stable
- Weak dipole moment
  excited by collisions with H_2

Solomon & Vanden Bout (2005)

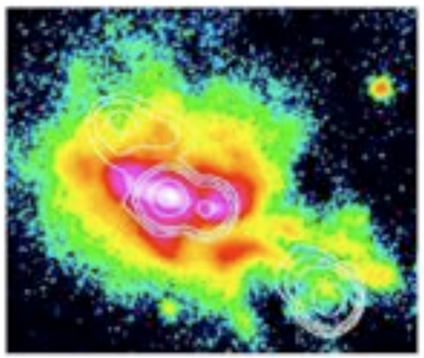
Introduction: molecular gas in HzRGs

CO as tracer for molecular gas in HzRGs

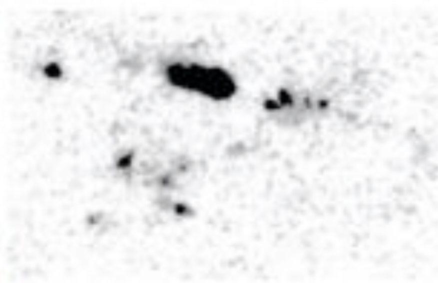
- First (single-dish) surveys failed to detect CO *(Evans+ 1996, van Ojik+ 1997)*
- Since then, CO detected in individual HzRG
  (Miley & De Breuck 2008; also Scoville et al. 1997, Papadopoulos et al. 2000, 2001, Alloin et al. 2000, De Breuck et al. 2003a,b, 2005, Greve et al. 2004, Klamer et al. 2005, Ivison et al. 2008, 2011; Nesvadba et al. 2009; Emonts et al 2011, 2013)
- CO across tens of kpc *(e.g. Papadopoulos et al. 2000)*
  CO in giant Lyα halos *(Nesvadba 2009)*
  CO aligned with radio jets *(Klamer et al 2004)*

4C41.17 (*z* = 3.8)

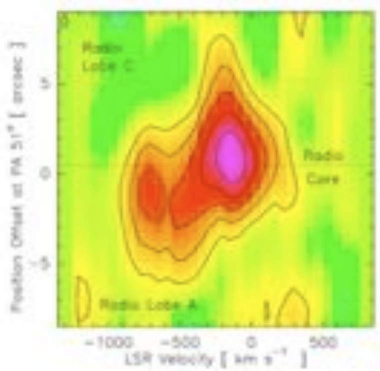
Reuland et al. (2003); Carilli et al (1997)



VLA radio on Keck Lya



HST Image, WFPC2 (7000A)



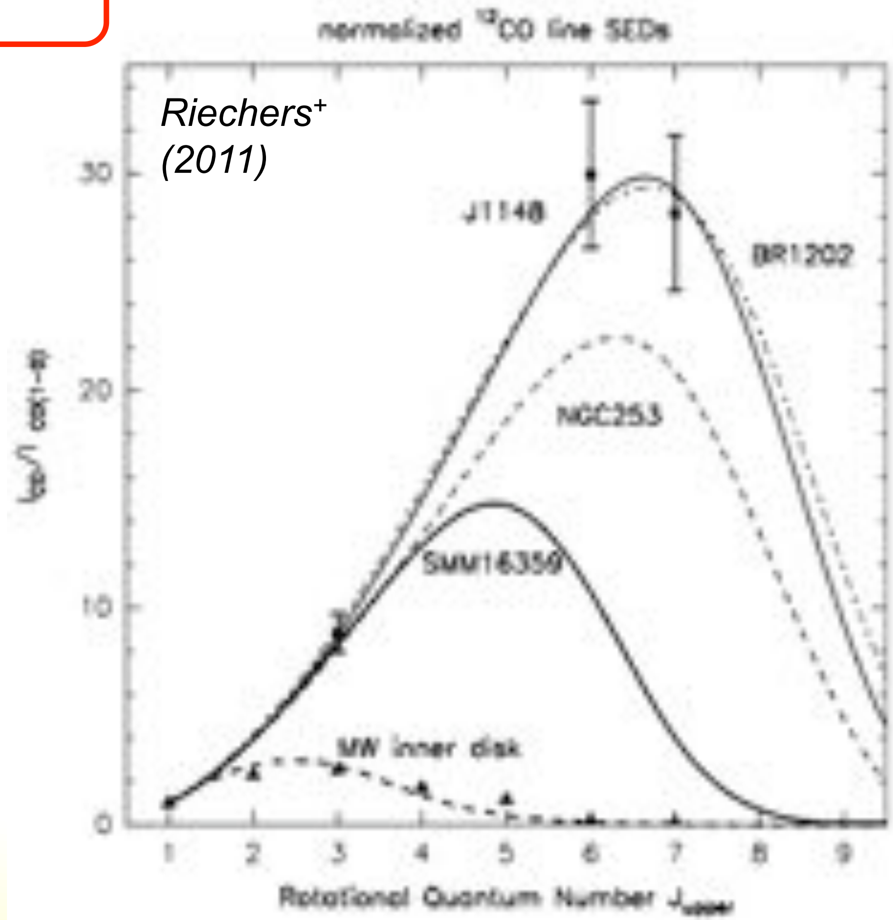
CO(4-3)

De Breuck et al. (2005)

Introduction: molecular gas in HzRGs

CO as tracer for molecular gas in HzRGs

Bias towards high-order CO transitions!



Rotational *J,J-1* transitions:

CO(J=1→0) *115 GHz,*
CO(J=2→1) *230 GHz,*
CO(J=3→2) *345 GHz,*
CO(J=4→3) *460 GHz,*
…

- $n_{crit} \propto J^3$
- CO-ratios:
  Model physical parameters of gas
  (temperature, density and excitation)

Introduction: molecular gas in HzRGs

CO as tracer for molecular gas in HzRGs

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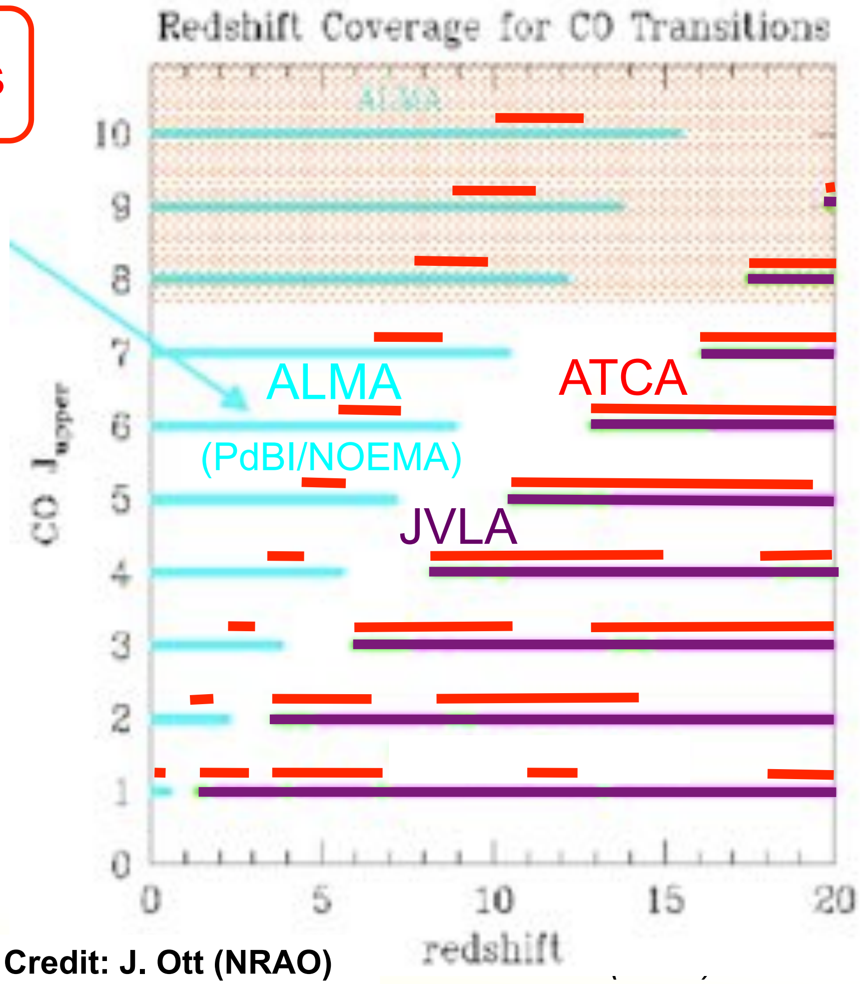
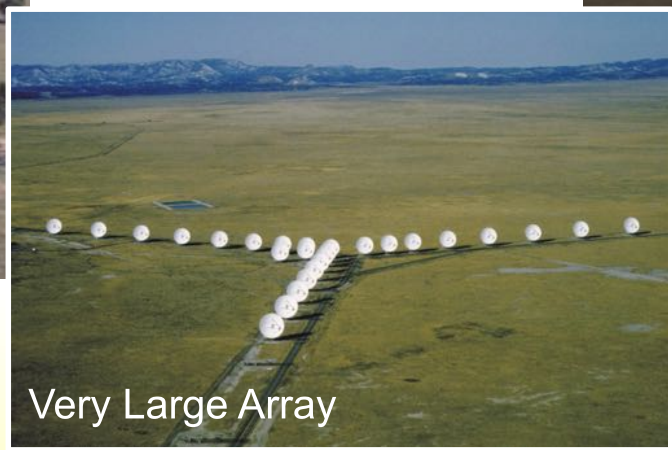


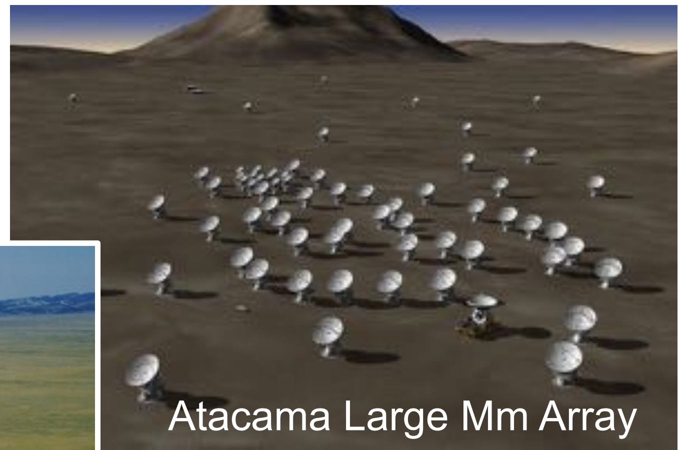
Credit: J. Ott (NRAO) (Walter & Carilli 2008)

This talk

CO in High-z Radio Galaxies

1. *Evolution* of proto-cluster system into giant cluster ellipticals?
2. *Feedback* of powerful radio jets onto circum-galactic environment?





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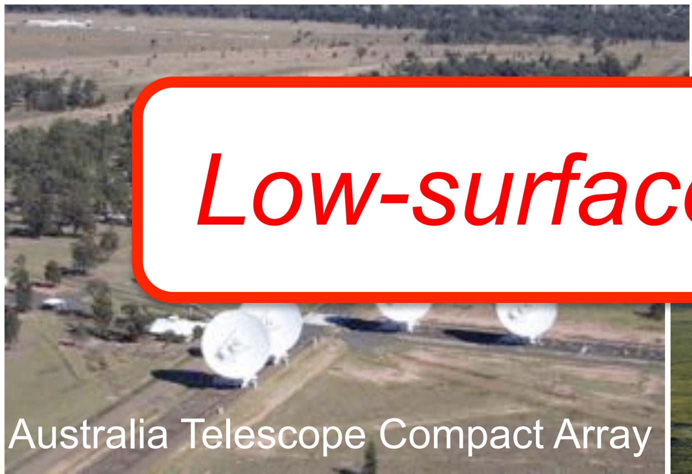

Australia Telescope Compact Array


Very Large Array


Atacama Large Mm Array

Low-surface-brightness sensitivity!

CO(1-0) survey of HzRGs

First systematic survey of CO(1-0) in high-z radio galaxies

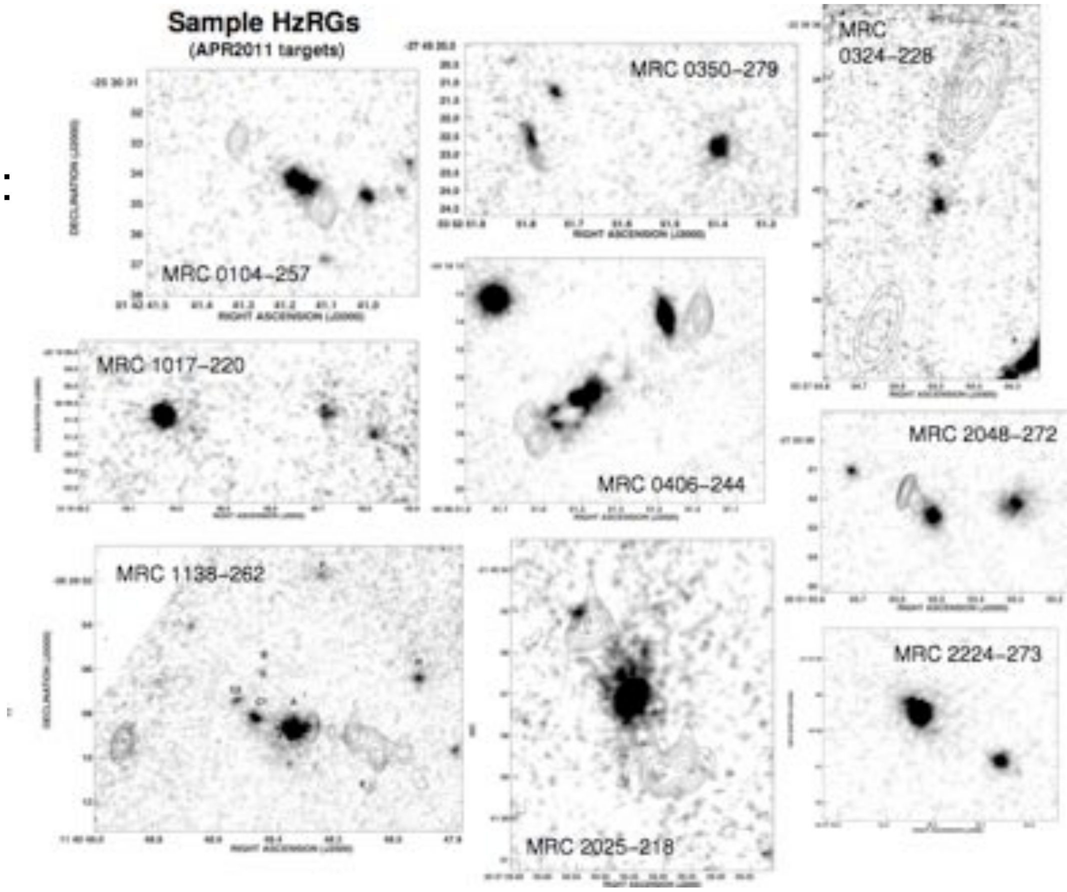
Sample (unbiased in IR/submm):

All HzRGs from MRC catalogue:

- 1.3 < z < 2.8 (ATCA 7mm band)
- dec < -10
- HST & Spitzer data available

13 HzRGs

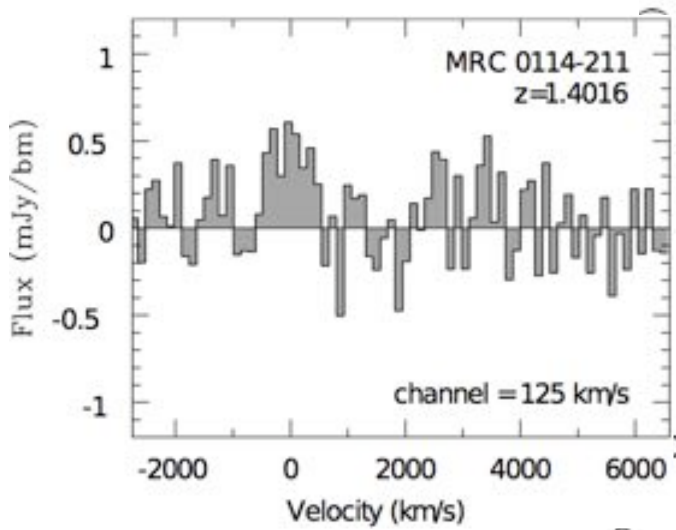
(t_{int} ~15h on-source)

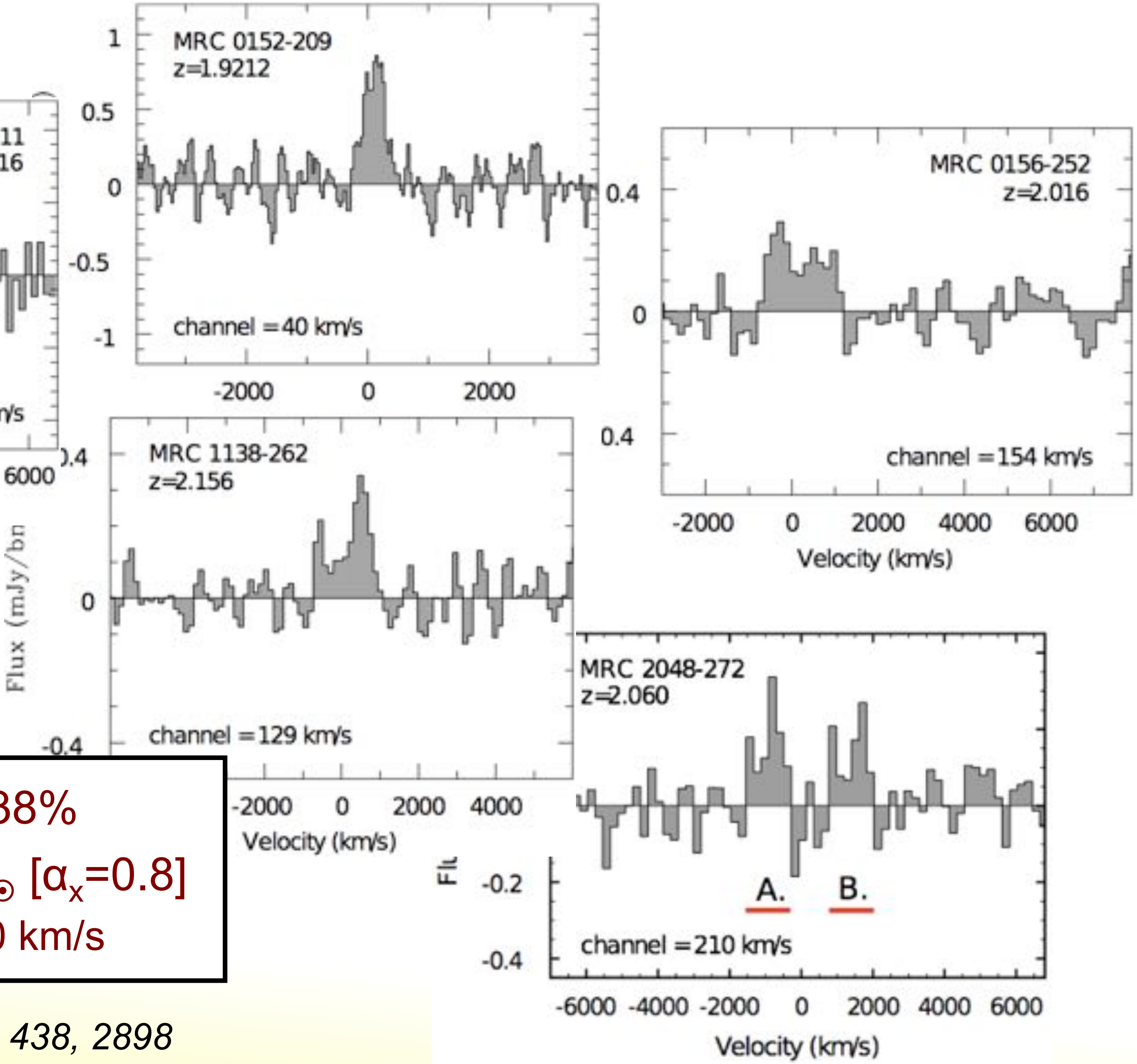


Pentericci+ '01

Emonts et al 2014, MNRAS, 438, 2898

CO(1-0) survey of HzRGs





See Ivison+ 2012 for two Other HzRGs in CO(1-0)

Detection rate 38%

M_{H2} = 4 - 6 × 10^{10} $M_\odot$ [α_x=0.8]

FWZI = 400 - 2000 km/s

Emonts et al 2014, MNRAS, 438, 2898

1. Evolution

esa

www.spacetelescope.org

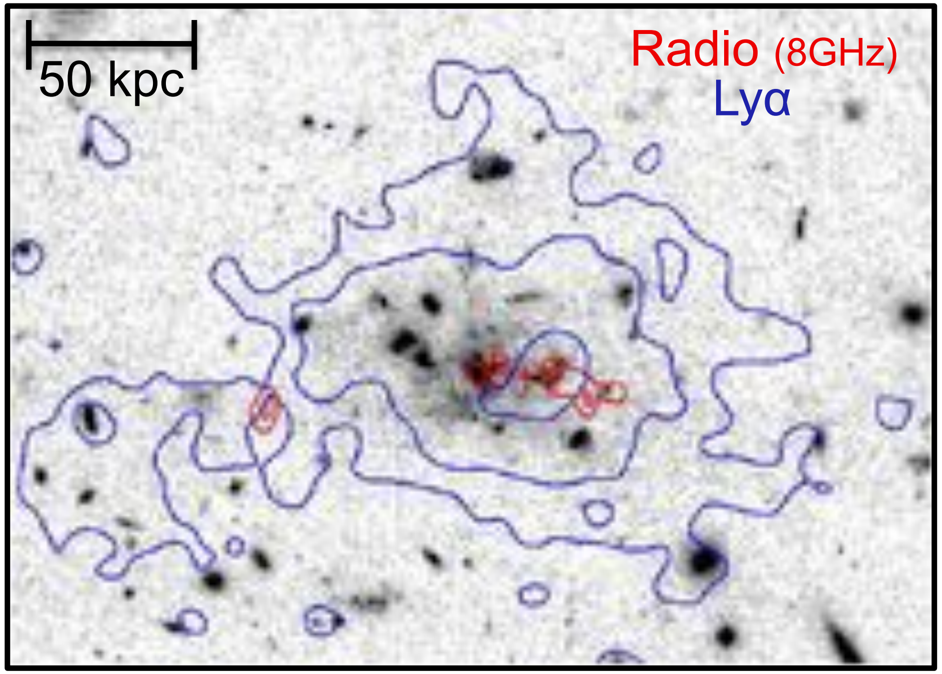
Miley et al. 2006 (Credits: NASA, ESA, George Miley and Roderik Overzier (Leiden Observatory, NL)

"Spiderweb Galaxy"

(MRC 1138-262)

Miley et al. 2006 (Credits: NASA, ESA, George Miley and Roderik Overzier (Leiden Observatory, NL)

Cold molecular IGM



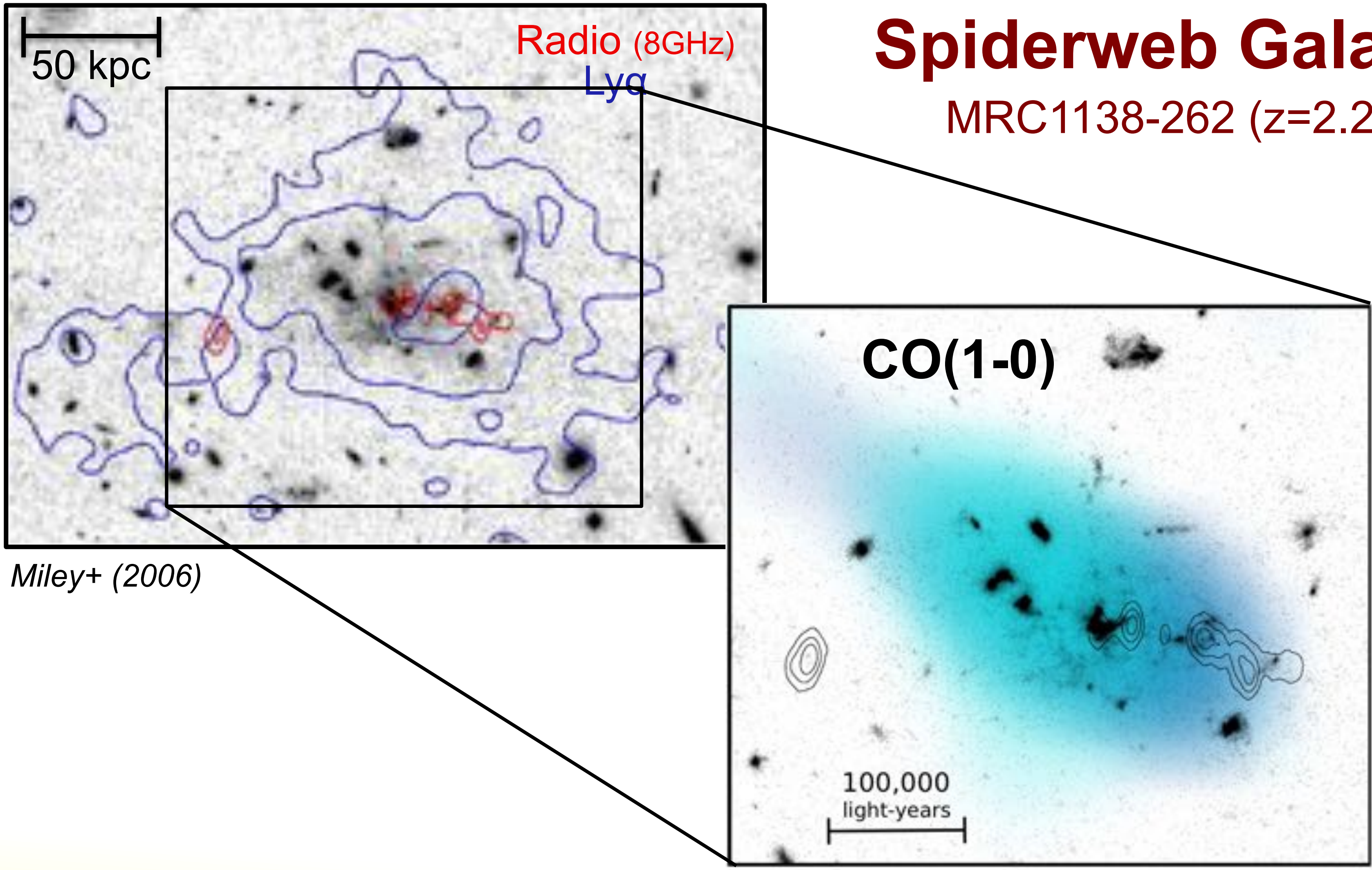
Miley+ (2006)

Spiderweb Galaxy

MRC1138-262 (z=2.2)

- Giant Lyα halo *(Pentericci+ '97, Miley+ '06)*
- SFR 1400 $M_{\odot}$/yr *(Seymour+ '12, Ogle+ '12)*
- Dust & SF widespread *(Stevens+ '03, Hatch+ '09)*

Cold molecular IGM



Miley+ (2006)

Spiderweb Galaxy

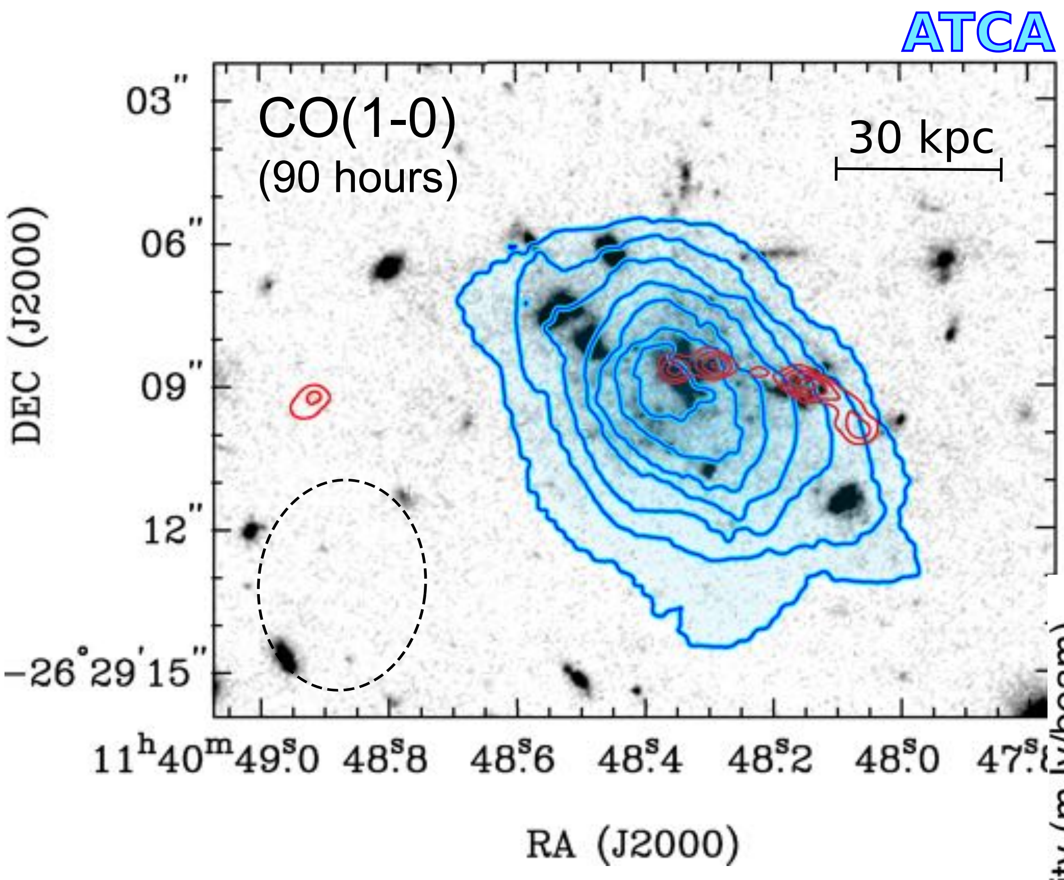
MRC1138-262 (z=2.2)

Australia Telescope Compact Array

(baselines 31-190m)

Emonts et al 2013, MNRAS, 430, 3465

Cold molecular IGM



Spiderweb Galaxy

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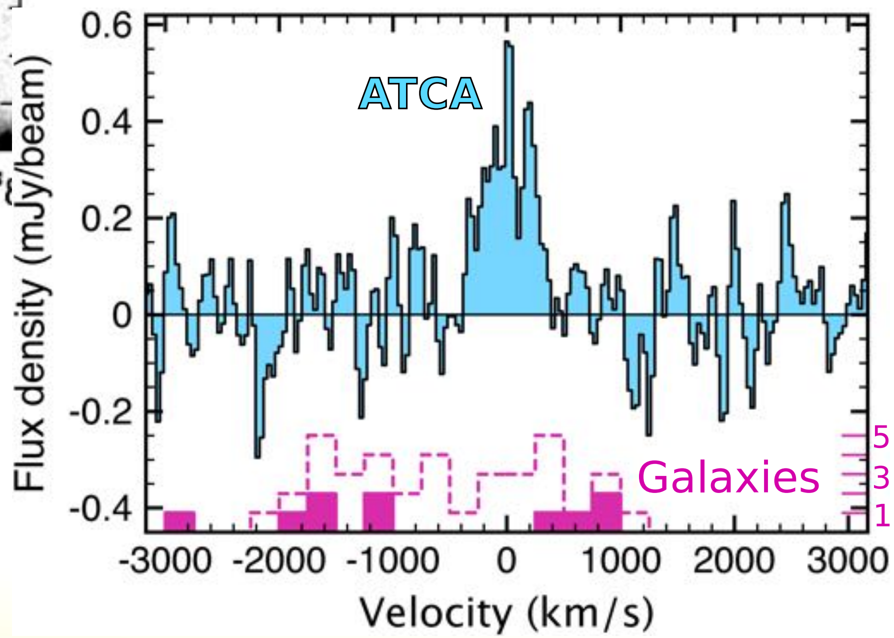
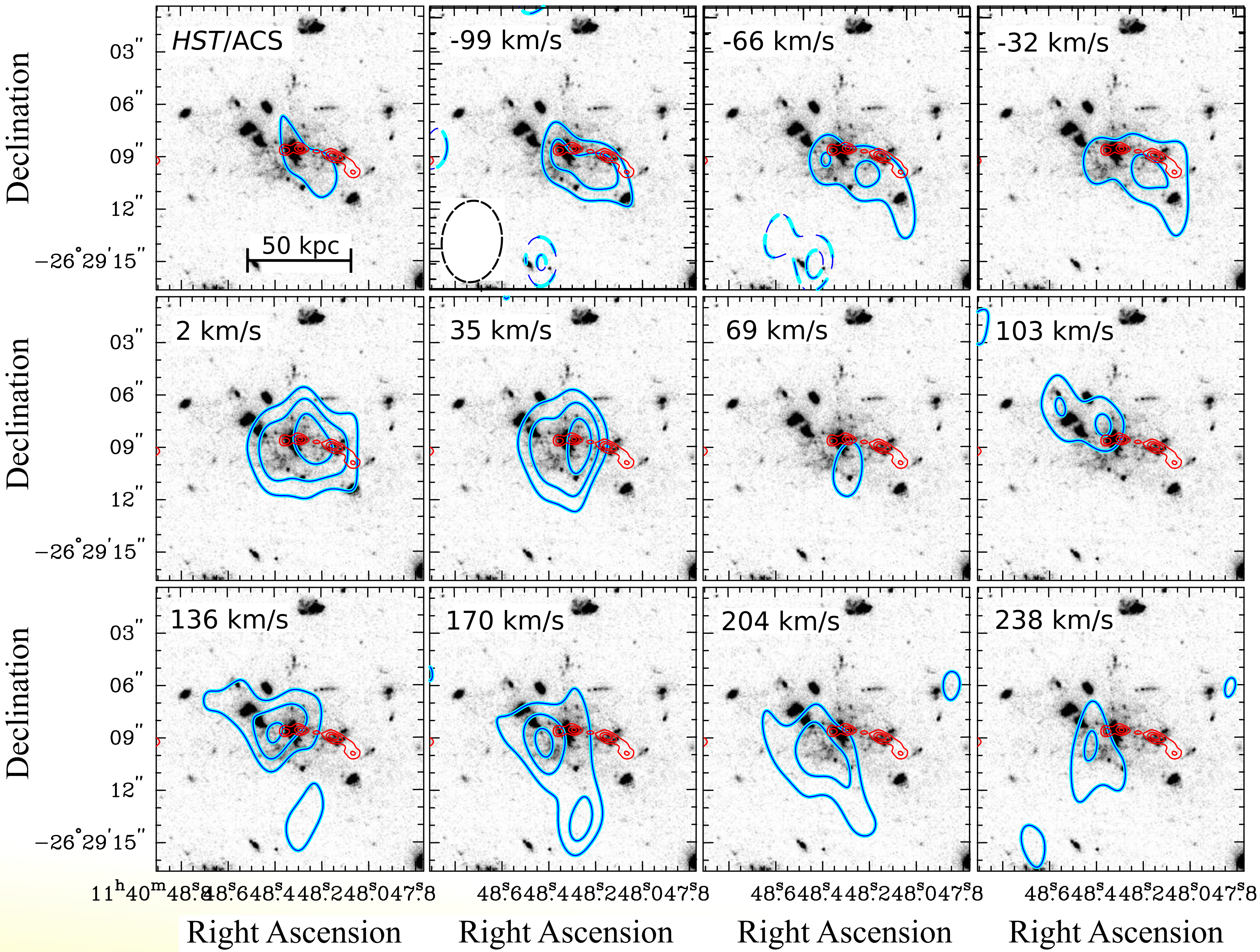


$L'_{CO} = 5.6 \times 10^{10}$ K km/s pc^2

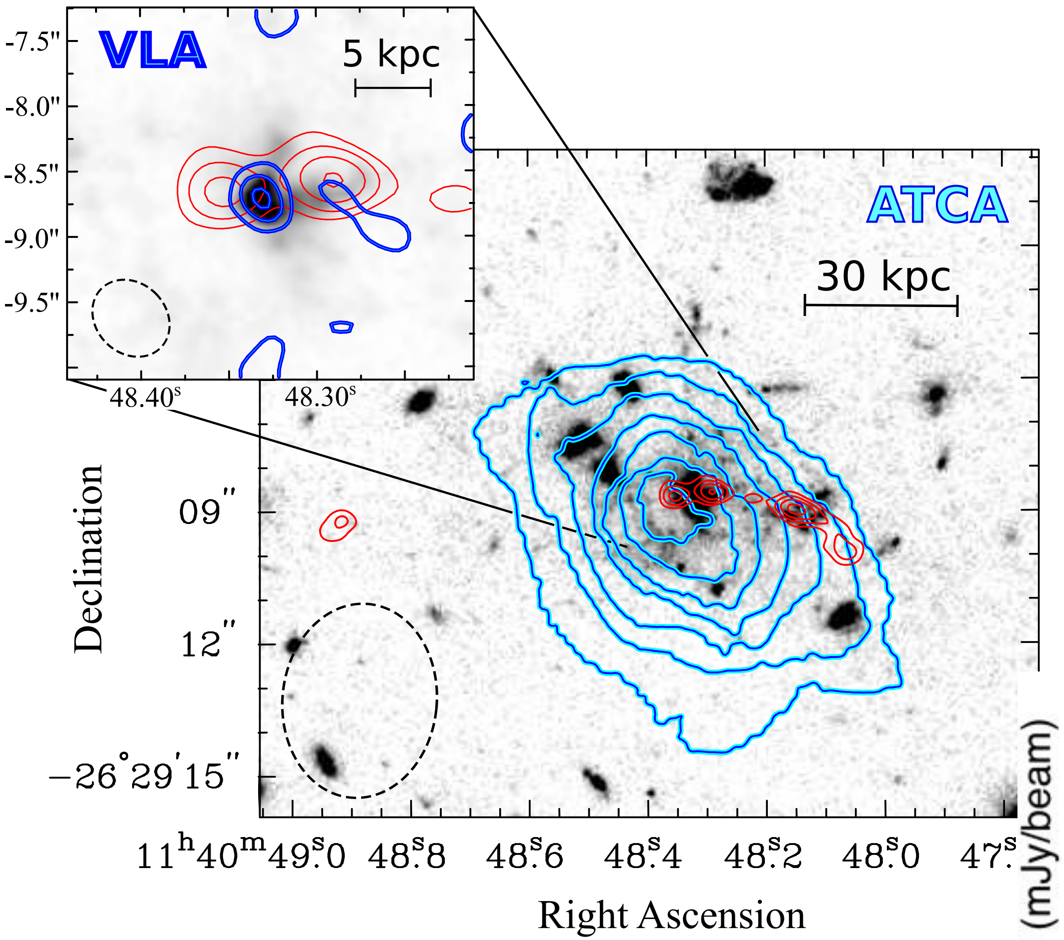
Emonts et al 2016, submitted

Cold molecular IGM



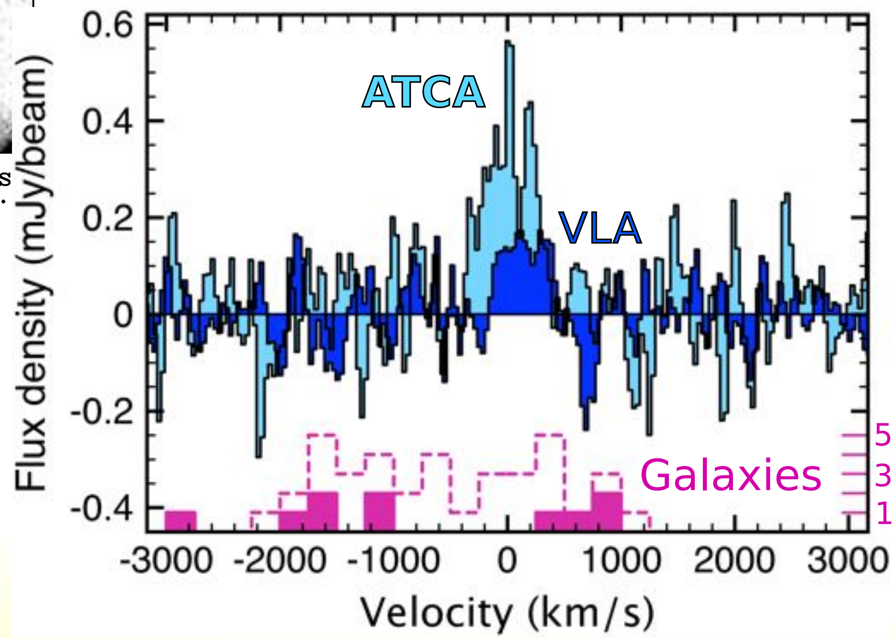
Contour levels: -3.5,-2.5, 2.5, 3.5, 4.5σ

Cold molecular IGM



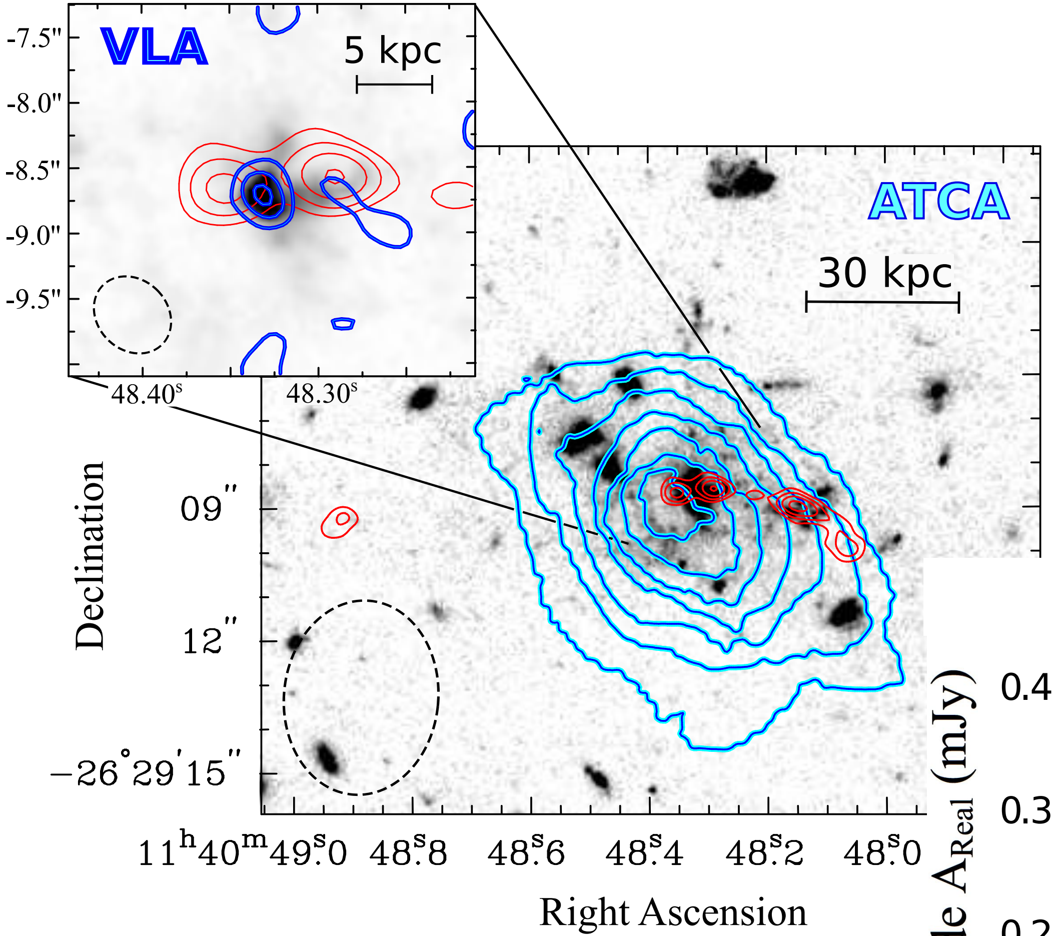
Low-surface-brightness!

VLA sees only ~33% of ATCA flux!!



Emonts et al 2016, submitted

Cold molecular IGM



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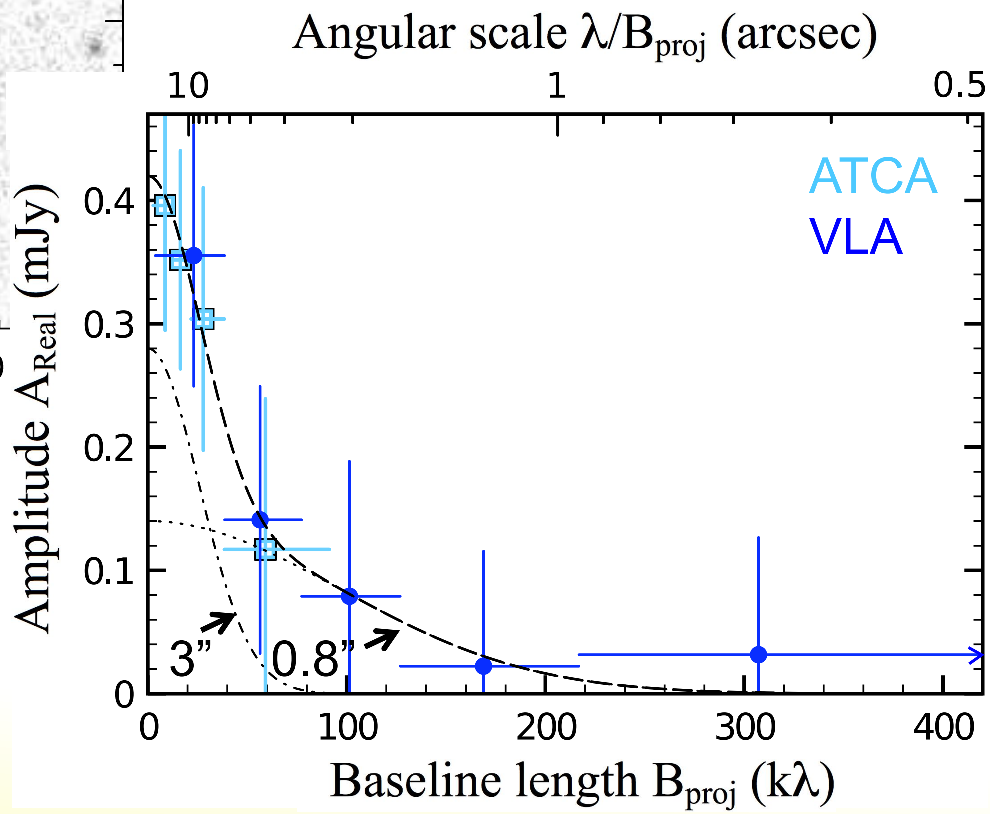
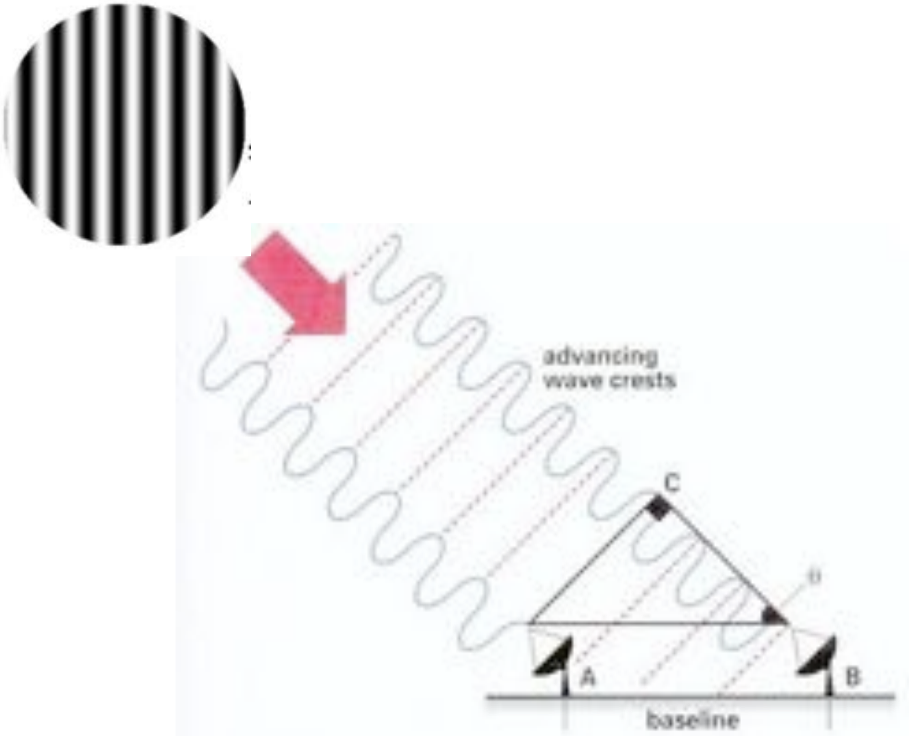


σ_{ATCA} = 0.085 mJy/bm
σ_{VLA} = 0.080 mJy/bm

Emonts et al 2016, submitted

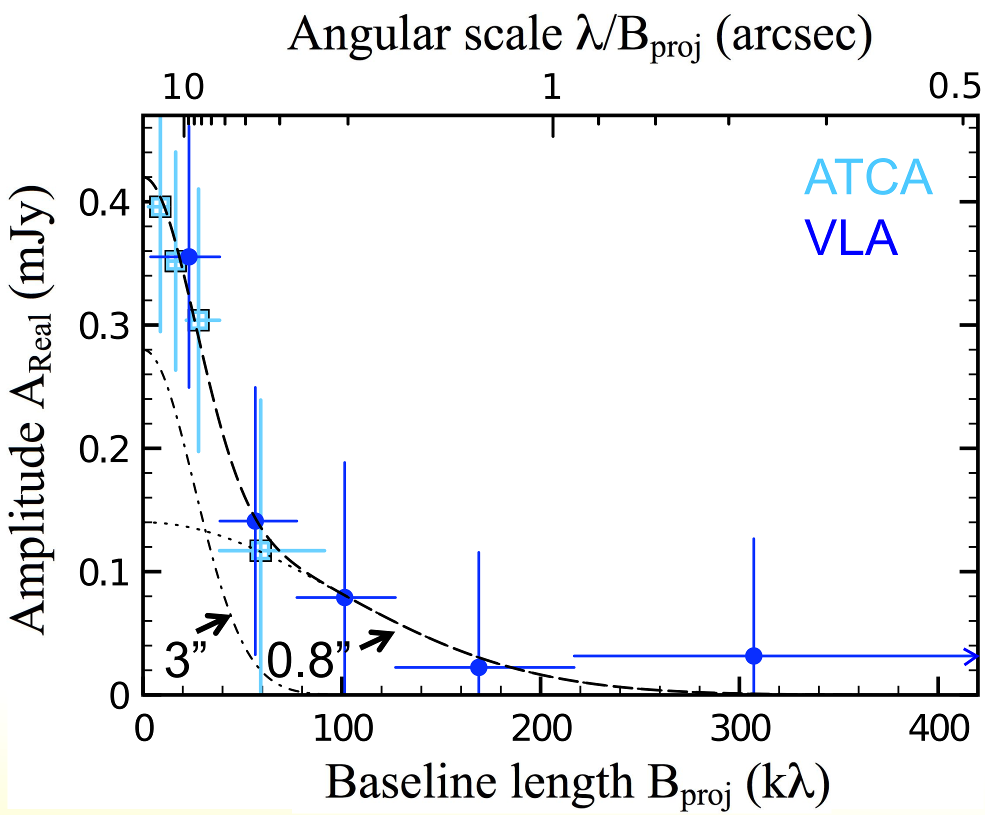
Cold molecular IGM



Signal easily resolved out in mm!

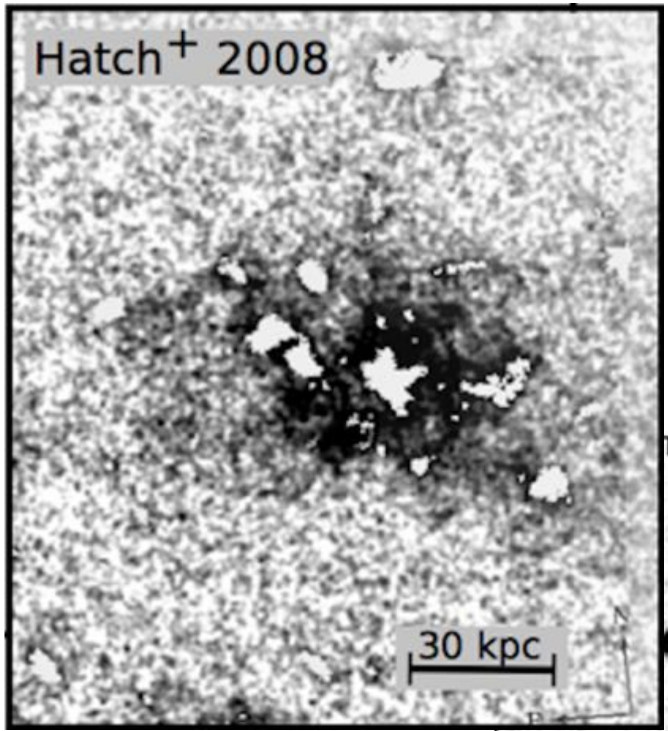
For example, at z=2,
1km baselines resolve out:

- CO(1-0) on >14 kpc scales
- CO(4-3) on >4 kpc scales!



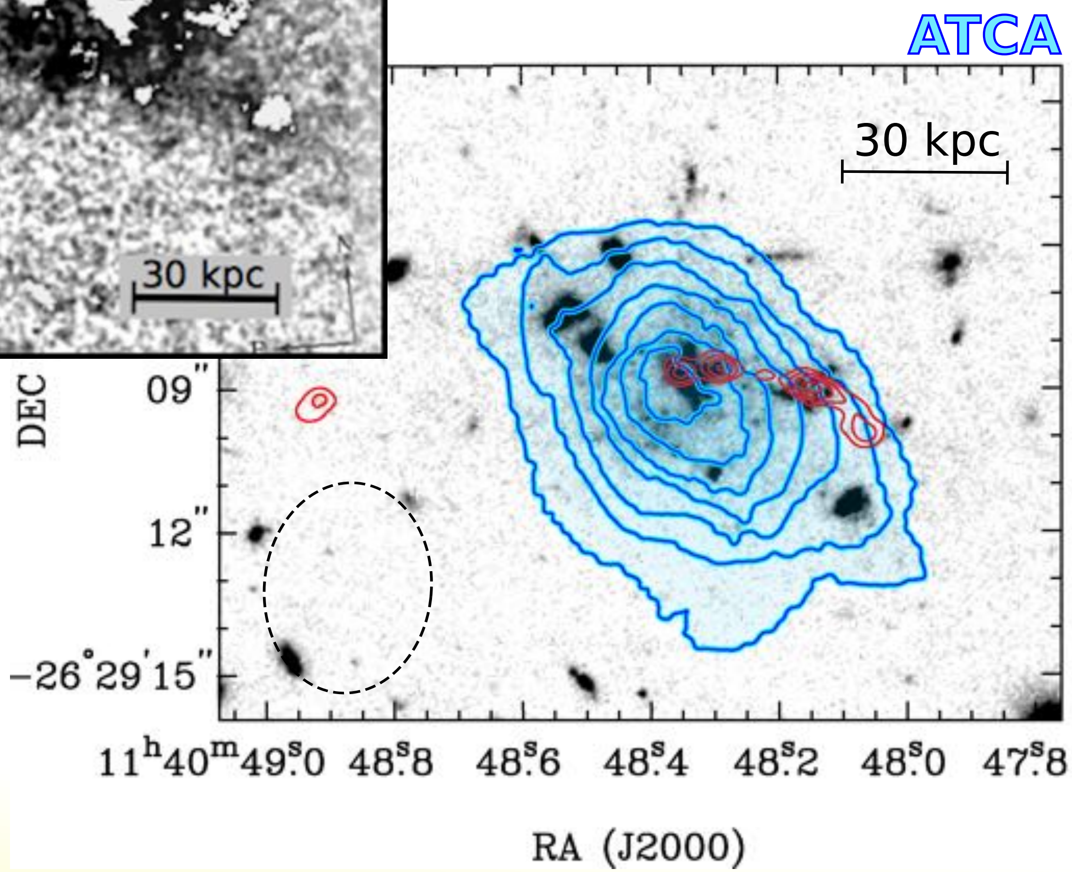
Emonts et al 2016, submitted

Cold molecular IGM



In-situ star formation across the IGM!

SFR_{IGM} ~ 142 $M_\odot$/yr



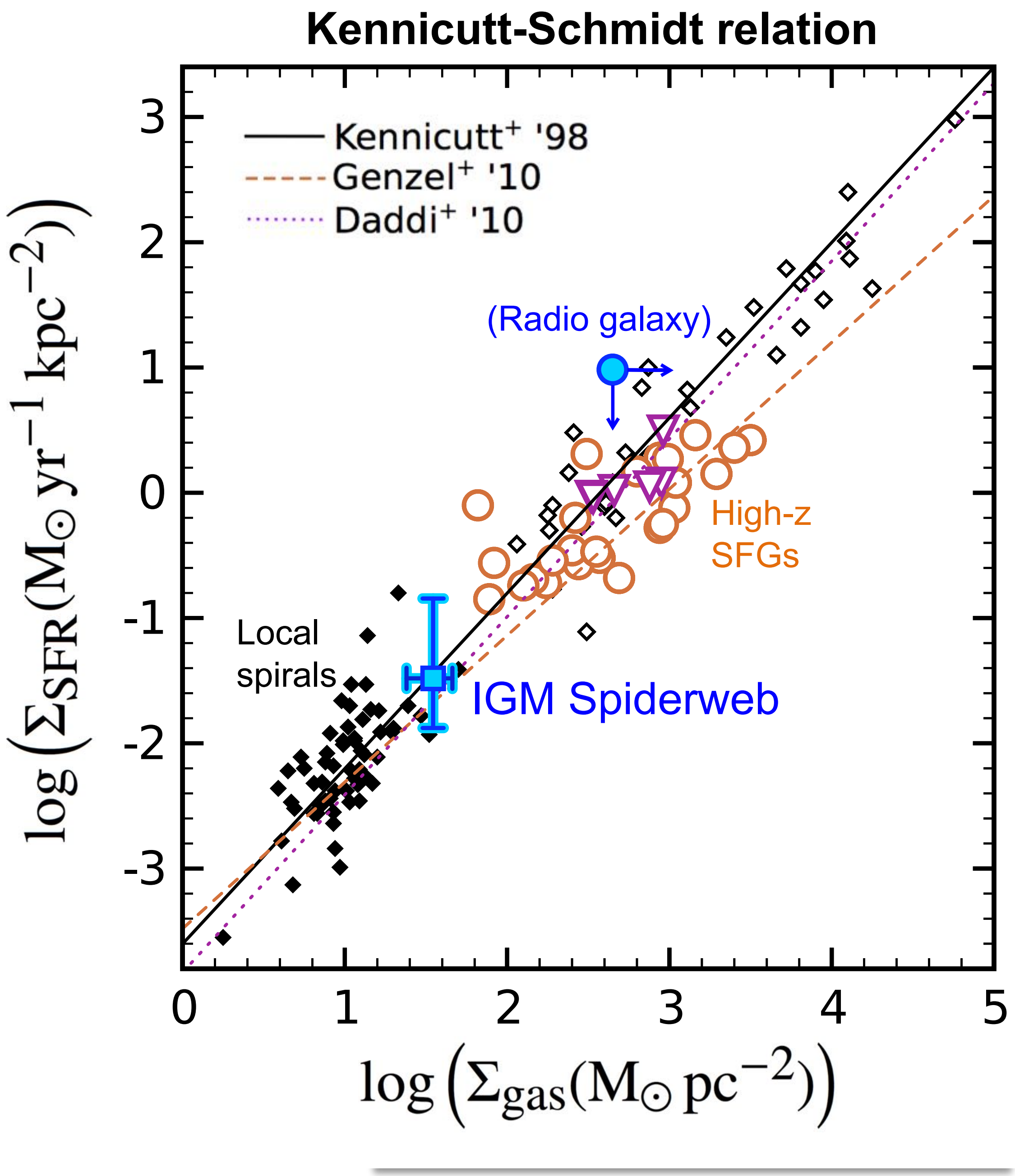
M_{H2}(IGM) =
1.5 x 10^{11} (X_{CO}/4) $M_\odot$

Emonts et al 2016, submitted

Cold molecular IGM

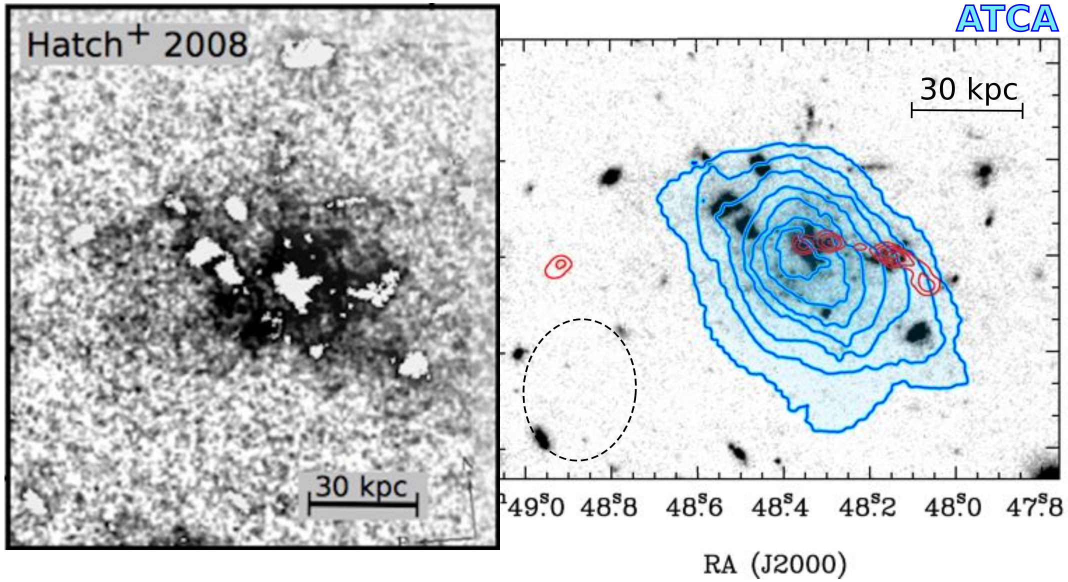
CO(1-0) drives
“in-situ” star formation

Gas depleted by z=1.6
→ stellar halo can age!



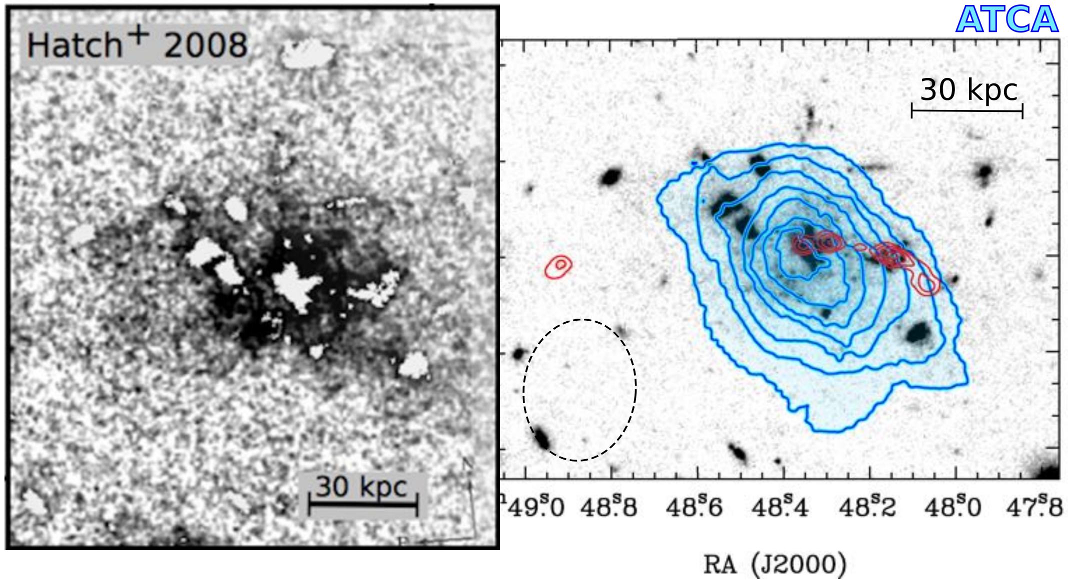
Emonts et al 2016, submitted

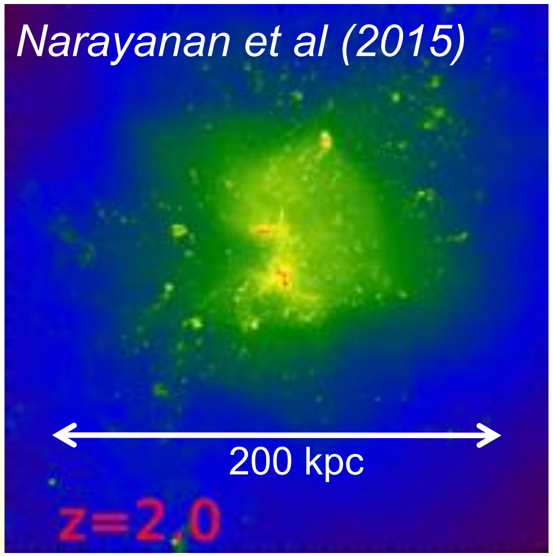
Cold molecular IGM

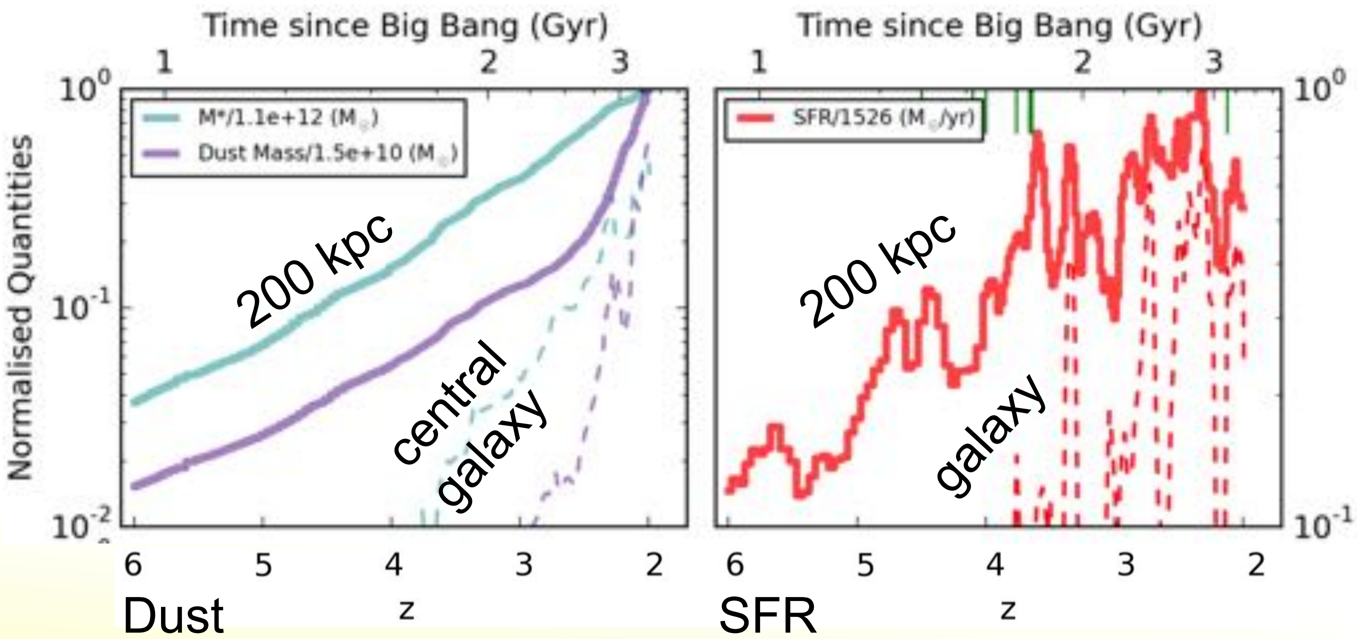


Early assembly of
giant cluster elliptical
out of enriched cold IGM

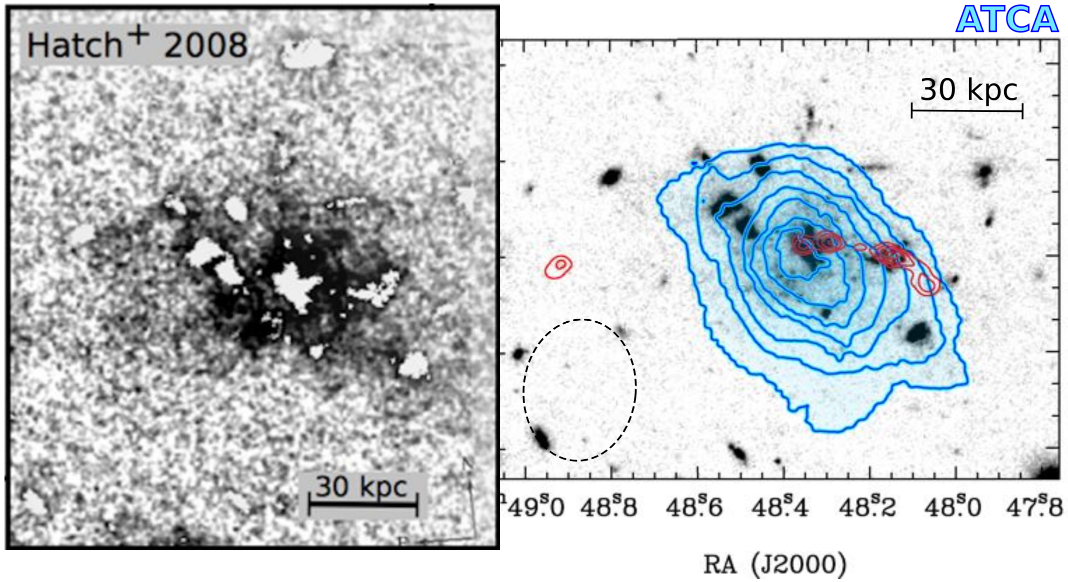
Cold molecular IGM

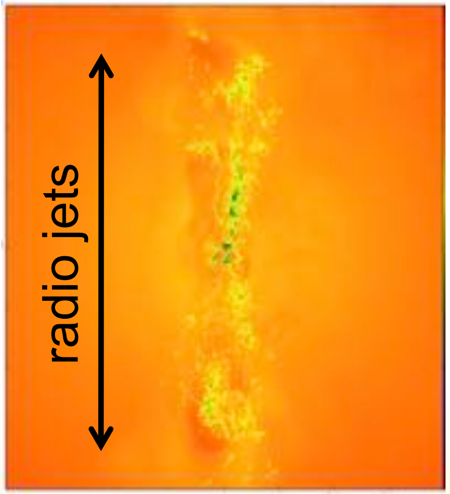


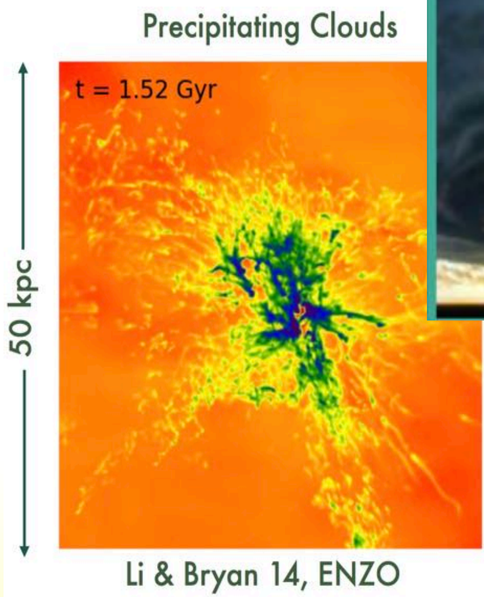




Cold molecular IGM







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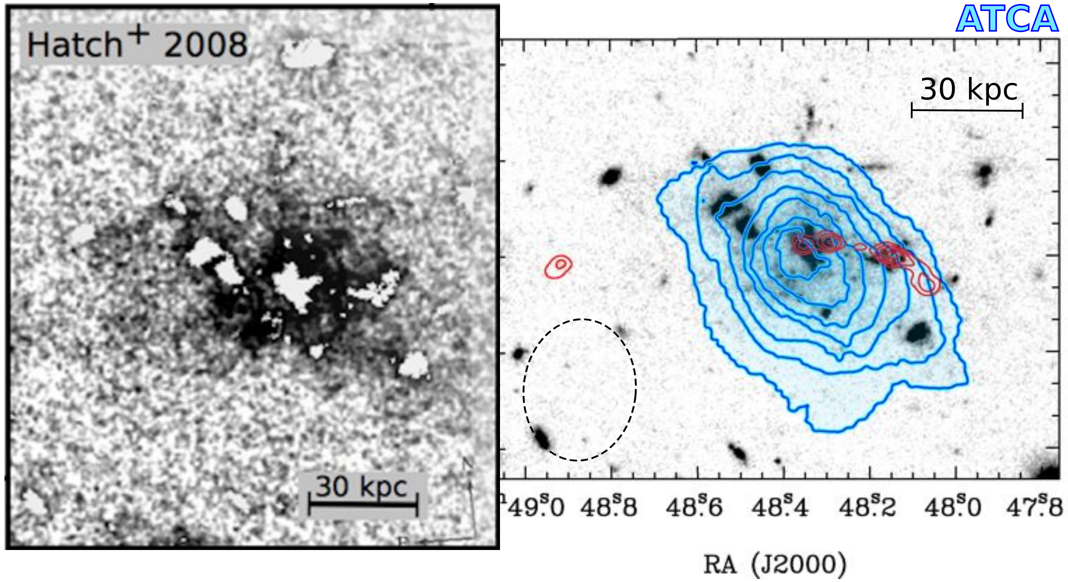
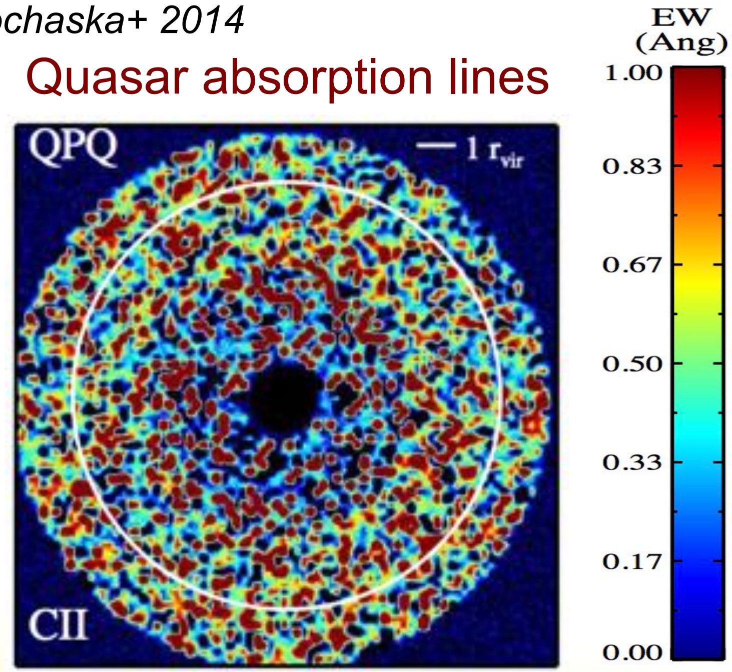
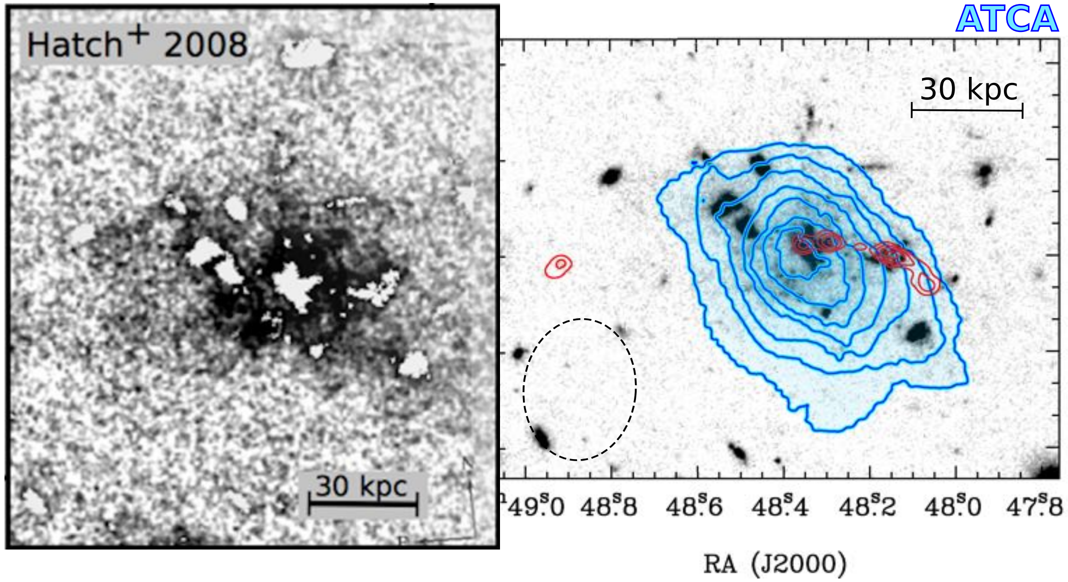


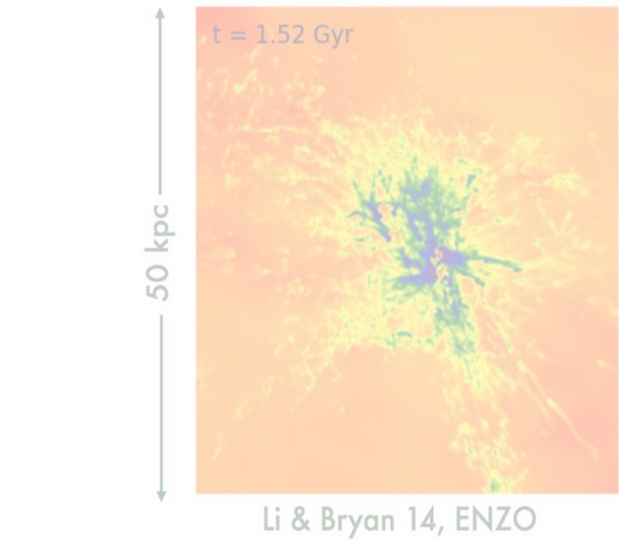
Prochaska+ 2014

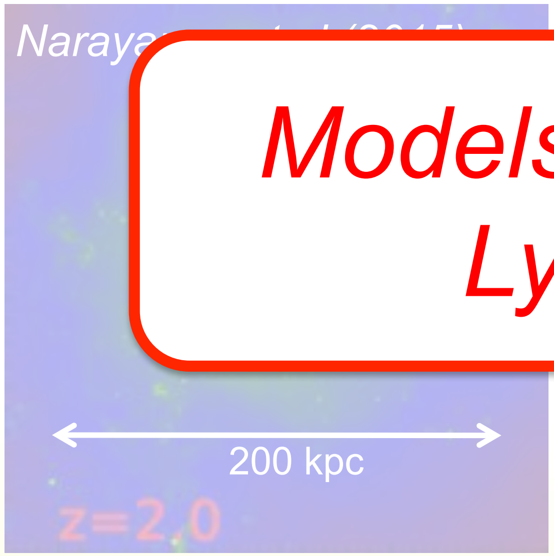
Quasar absorption lines

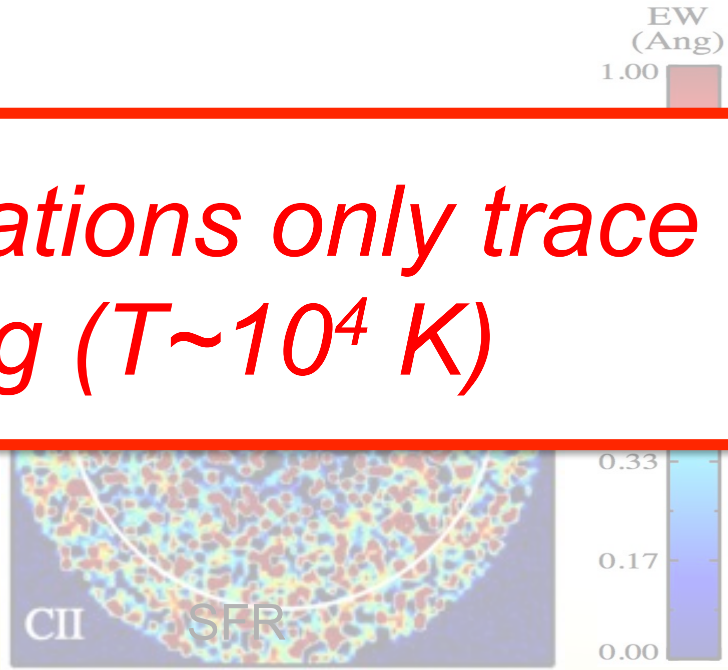


Cold molecular IGM



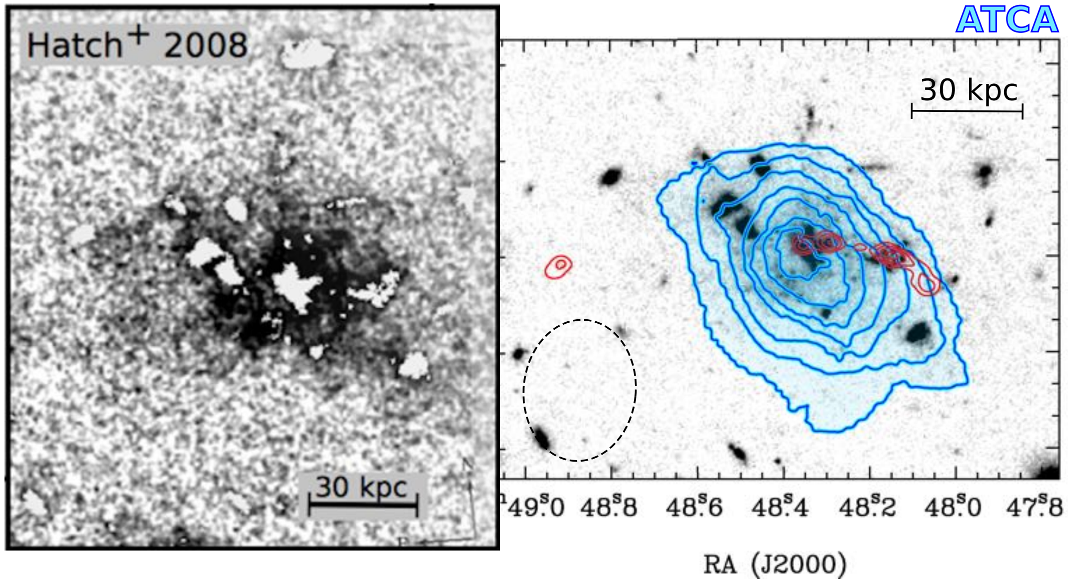






Models/observations only trace Lyα-cooling ($T \sim 10^4$ K)

Cold molecular IGM



Spiderweb Galaxy (z=2):

Early assembly of giant cluster elliptical out of enriched cold IGM

Upcoming:

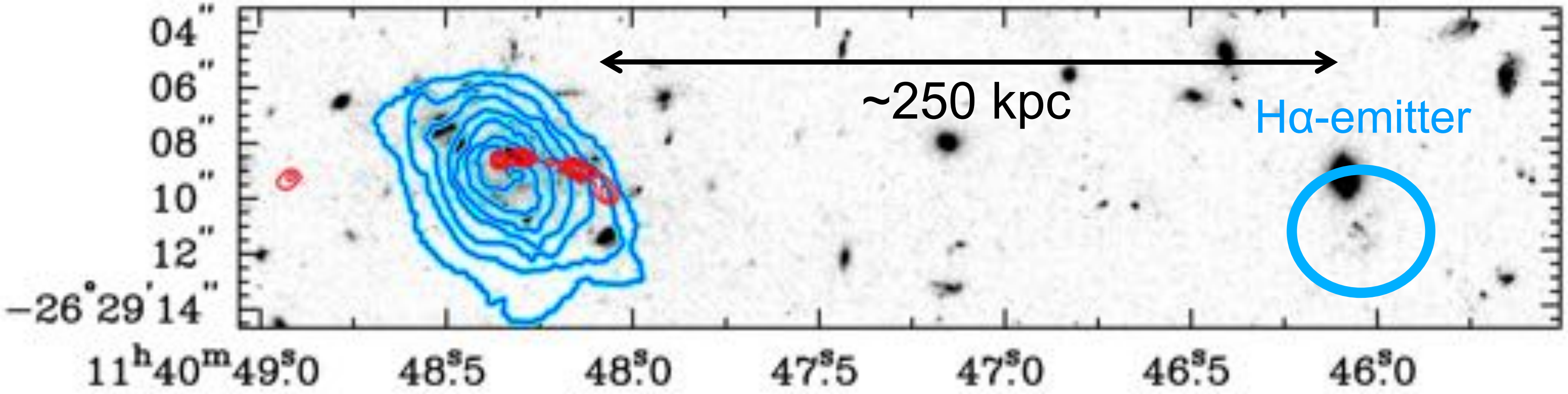
ALMA cycle-3: *low-surface-brightness CI(1-0)+CO(4-3) [col: M. Lehnert]*

VLT-VIMOS (IFU): *Lyα in '3D' (1.5 nights) [col: B. Husemann]*

ATCA: *CO(1-0) environment (100h) [co-PI: H. Dannerbauer]*

VLA: *HI 21cm absorption along jets (experimental P-band) [col: M. Mao & F. Owen]*

Cold molecular IGM

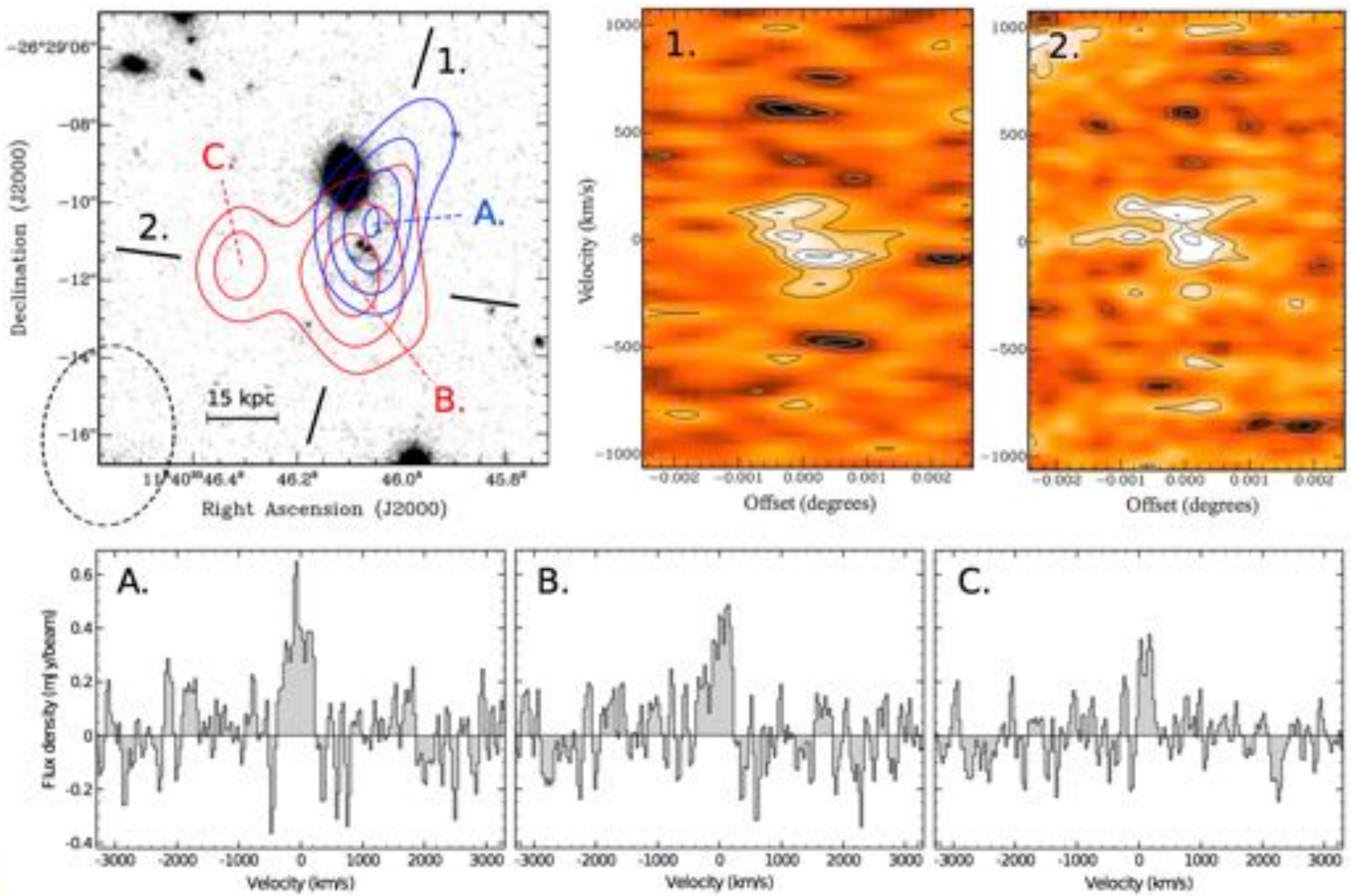


Comparable in molecular gas mass! (M_{H2} ~ 2 x 10^{11} $M_{\odot}$)

Helmut Dannerbauer et al (in prep.)

Cold molecular IGM

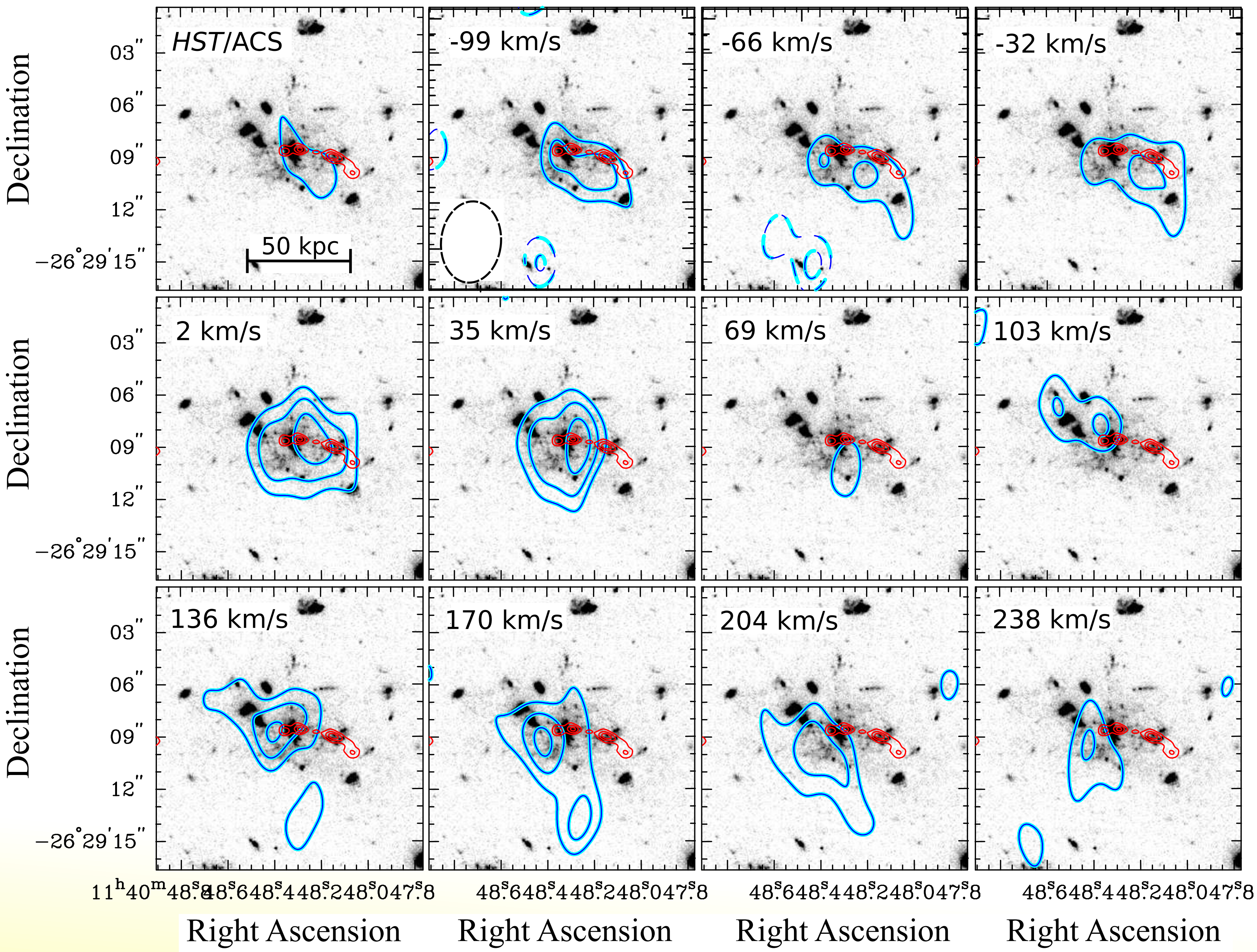
Extended, massive disc in HAE229, only ~250 kpc distance from the Spiderweb! (Δv~1400 km/s)



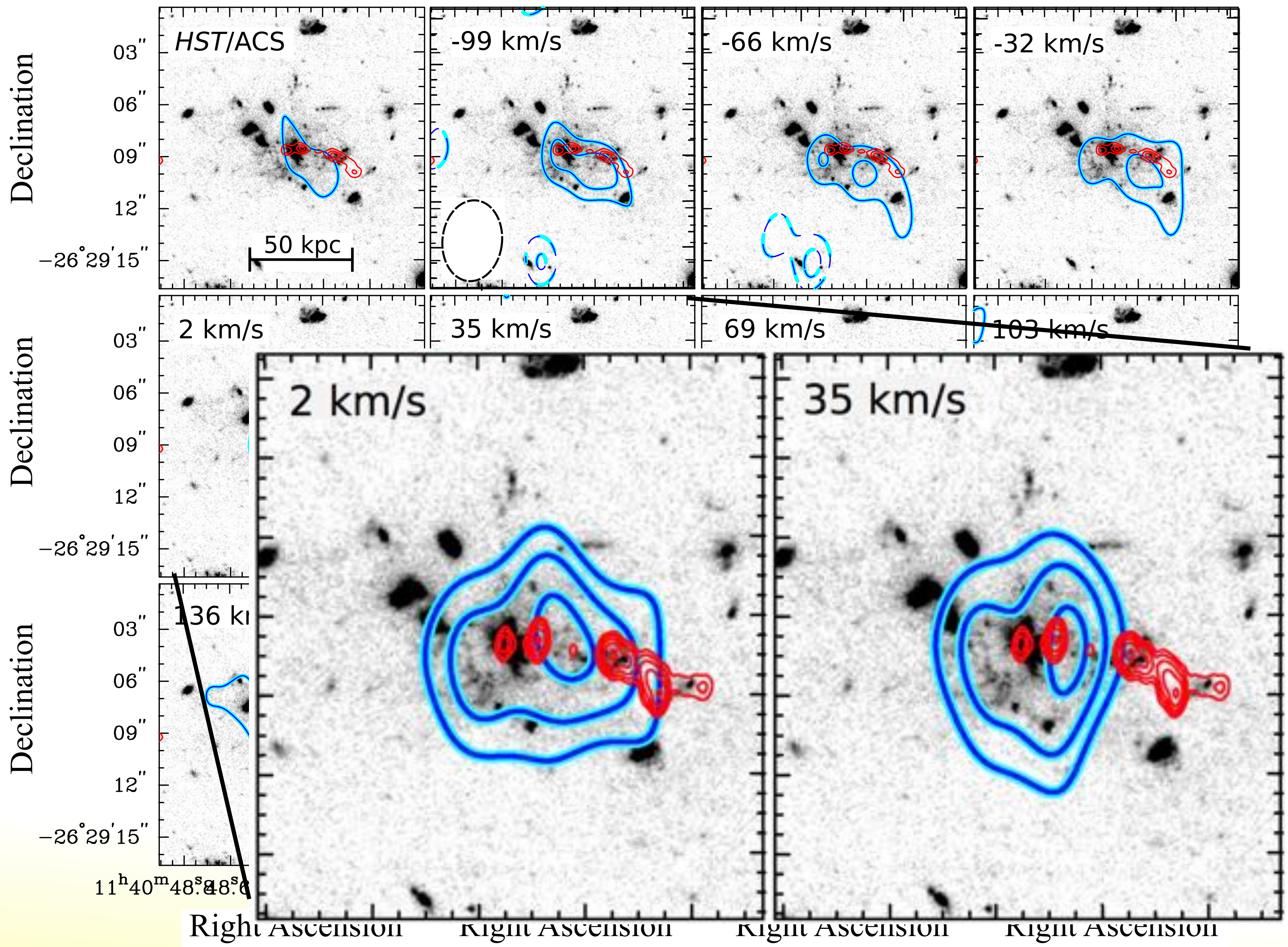
Helmut Dannerbauer et al (in prep.)

2. Feedback

Feedback

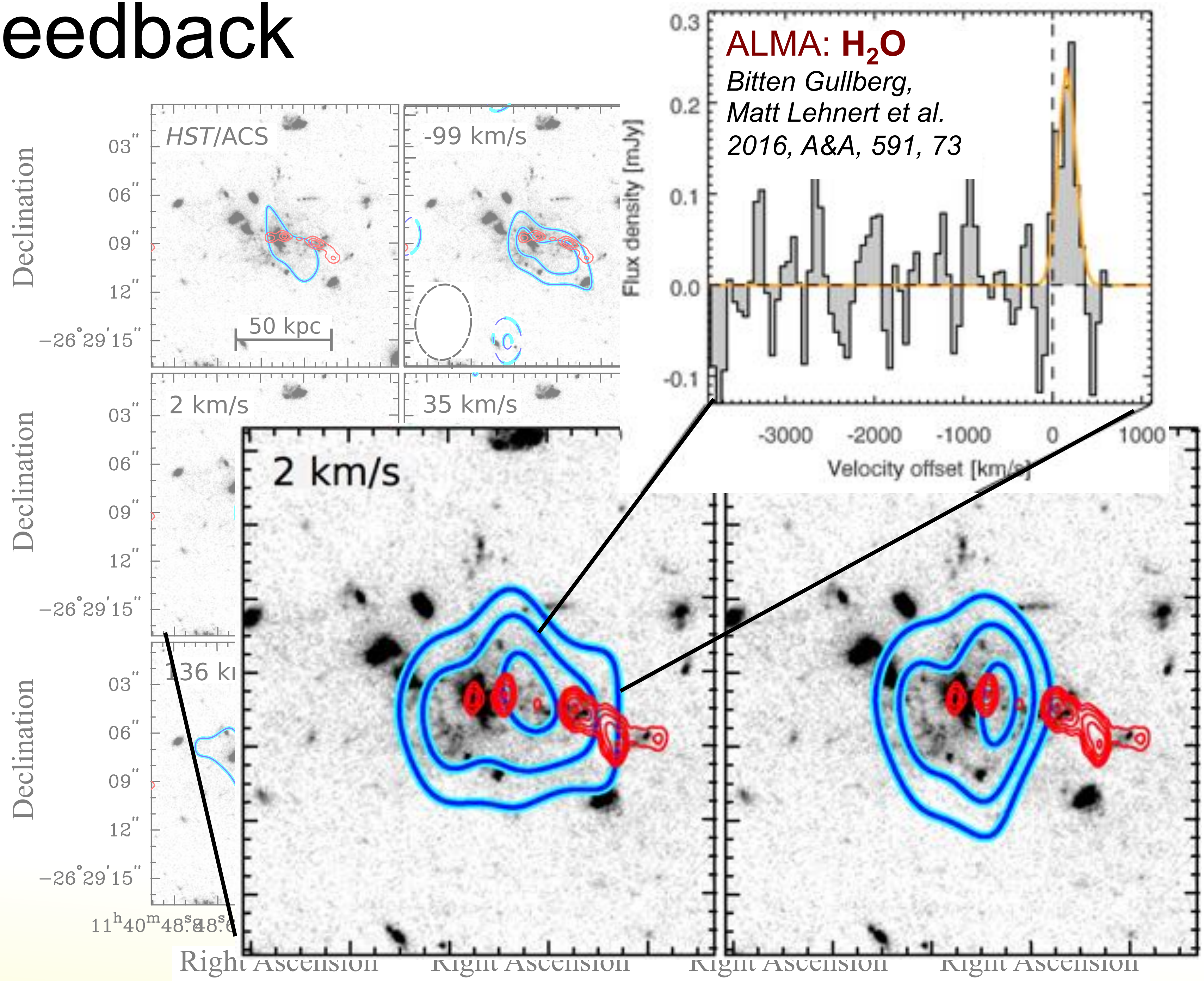

HST/ACS
-99 km/s
-66 km/s
-32 km/s
2 km/s
35 km/s
69 km/s
103 km/s
136 km/s
170 km/s
204 km/s
238 km/s
50 kpc
Declination
03″
06″
09″
12″
−26°29′15″
11h40m48.s8 48.s6 48.s4 48.s2 48.s0 47.s8
Right Ascension

Feedback

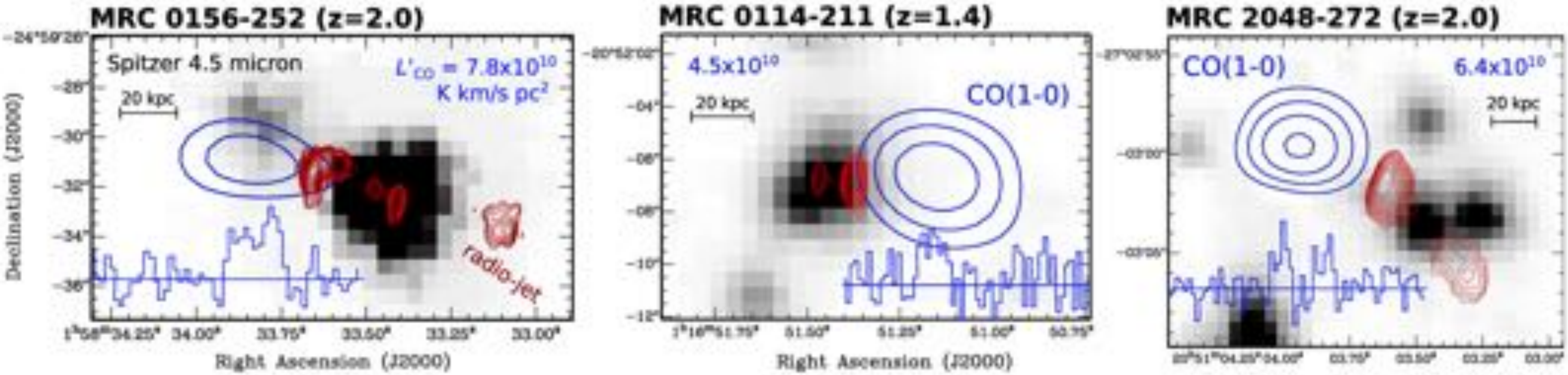


HST/ACS
-99 km/s
-66 km/s
-32 km/s
2 km/s
35 km/s
69 km/s
103 km/s
50 kpc
Declination
03″
06″
09″
12″
−26°29′15″
Right Ascension
2 km/s
35 km/s

Feedback


ALMA: H_2O
Bitten Gullberg,
Matt Lehnert et al.
2016, A&A, 591, 73
Flux density [mJy]
Velocity offset [km/s]
HST/ACS
-99 km/s
2 km/s
35 km/s
50 kpc
Declination
Right Ascension
−26°29′15″
11h40m48.8s

Feedback



Contours; 2.8, 3.5, 4.2, 4.9σ
FWHM ~ 1000 – 3000 km/s

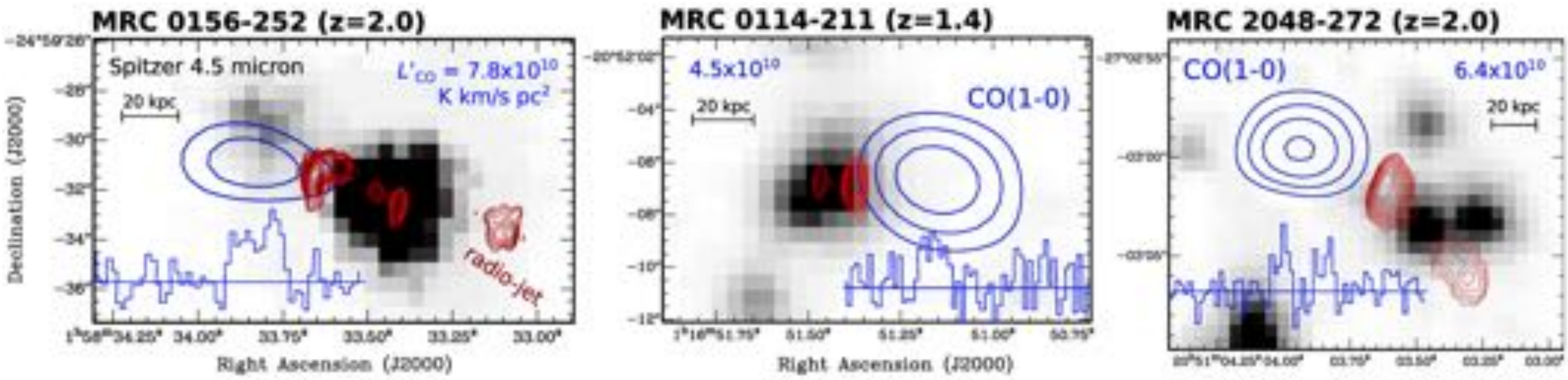
Spitzer data from Galametz[+] 2012

L'_{CO} = 5 – 8 x 10^{10} K km/s pc^2

→ *similar to SMG, but no IR-counterpart (1 mag below L*) !*

Emonts et al 2014 (MNRAS, 438, 2898)

Feedback



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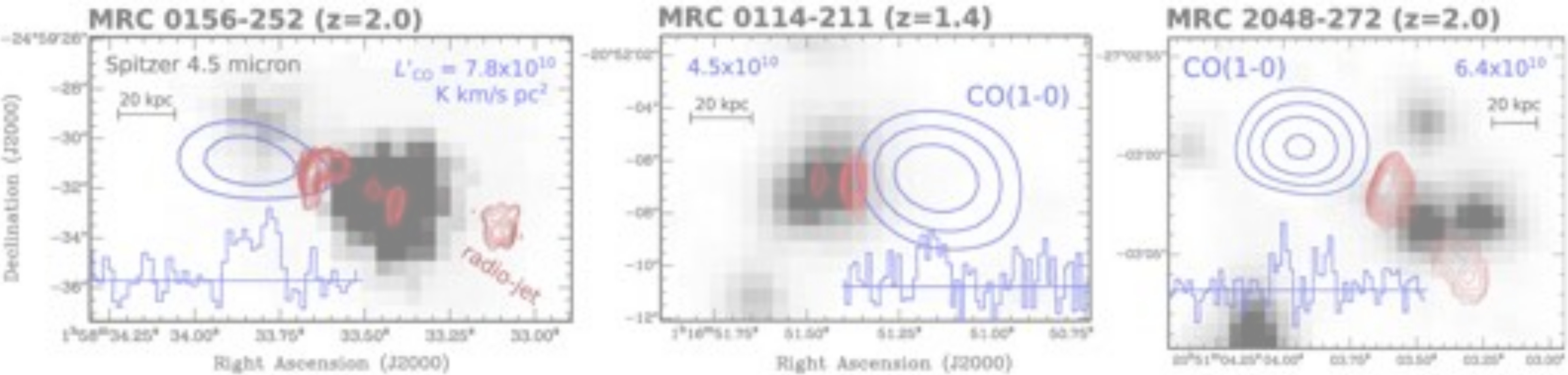
***ALMA cycle-3** data under analysis:*
low-surface-brightness ALMA+ACA observations of CO(2-1) or CO(3-2)

Emonts et al 2014 (MNRAS, 438, 2898)

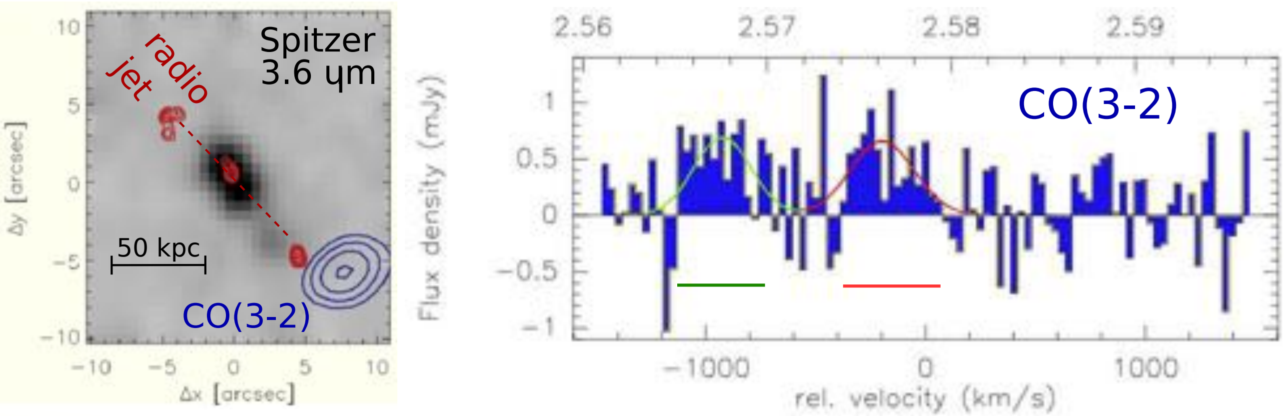
Feedback



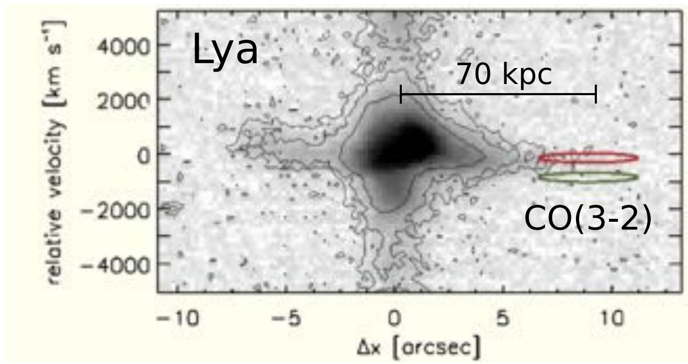
Contours; 2.8, 3.5, 4.2, 4.9σ

Emonts et al (2014)

Nesvadba[+] '09: CO(3-2) in TXS 0828+193 with PdbI (z=2.6)



Villar-Martin[+] '03



Physical properties molecular IGM: CO(1-0) with VLA (observed – D-config)
CI(1-0) with PdbI (observed – D-config)

Conclusions

Cold Molecular Medium in Early Universe

1. Giant molecular halo of enriched cold gas (T~10-100K)
2. Jet-triggered feedback on 100 kpc scales

Models of gas accretion can no longer ignore cold molecular phase

Observations of CO require dedicated instruments for detecting widespread *low-surface-brightness* IGM/ICM

One more thing….

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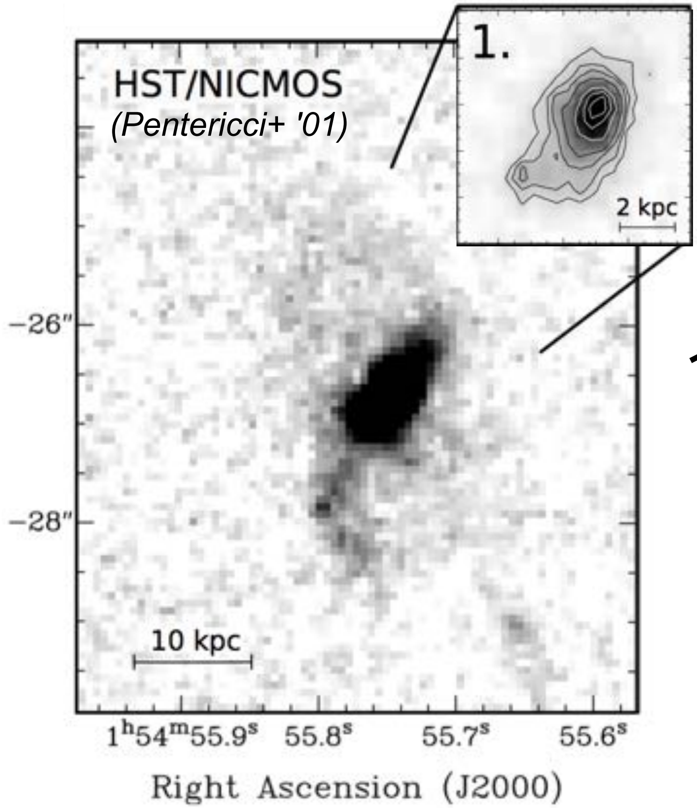
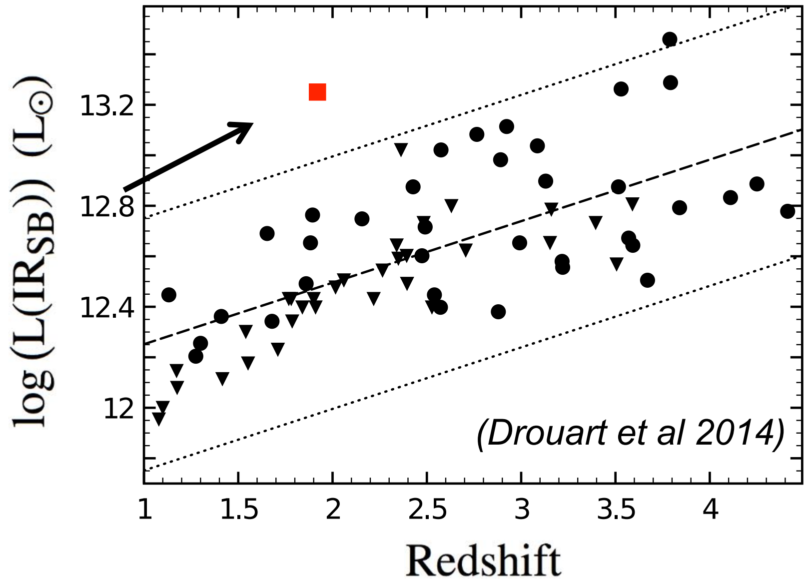
One more thing….

Low-surface-brightness sensitivity





Dragonfly Galaxy

MRC 0152-209 (z=1.9)

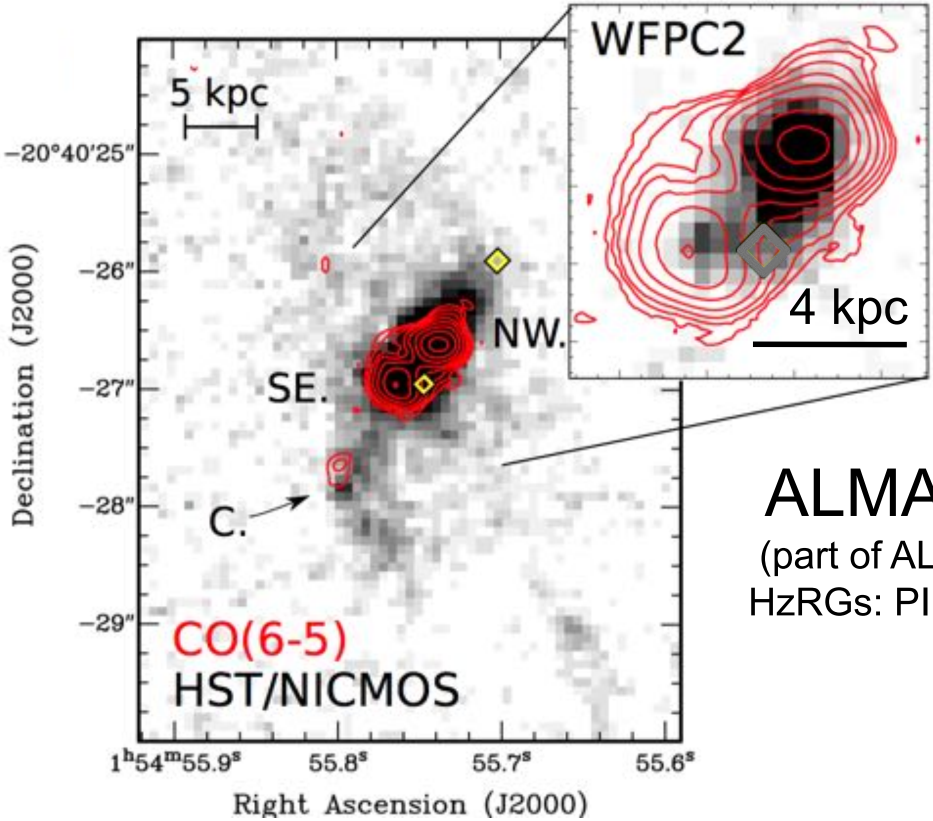
HyLIRG

L_{IR}(SB) ~ 2 x 10^{13} $L_\odot$

SFR = 3000 $M_\odot$/yr !

Emonts et al 2015b, A&A, 584, 99
Emonts et al 2015a, MNRAS, 451, 1025
Emonts et al 2011, ApJL, 734, 25

Low-surface-brightness sensitivity



Triple merger!

ALMA cycle-2

(part of ALMA sample of HzRGs: PI C. De Breuck)

Emonts et al 2015b, A&A, 584, 99

Emonts et al 2015a, MNRAS, 451, 1025

Emonts et al 2011, ApJL, 734, 25

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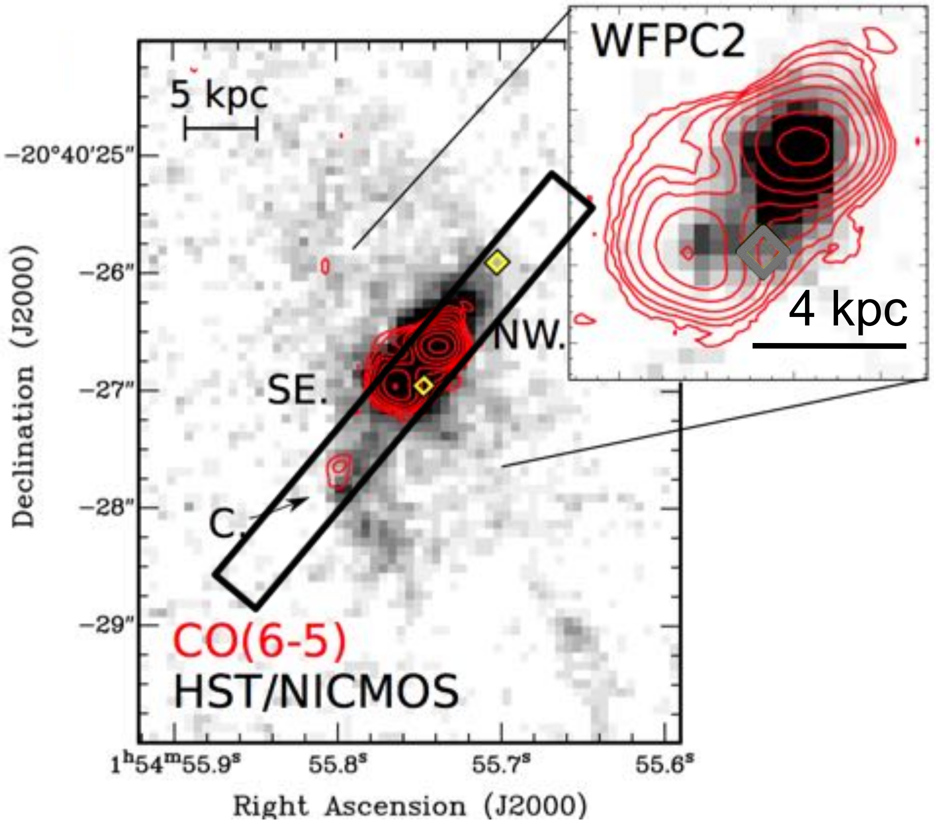
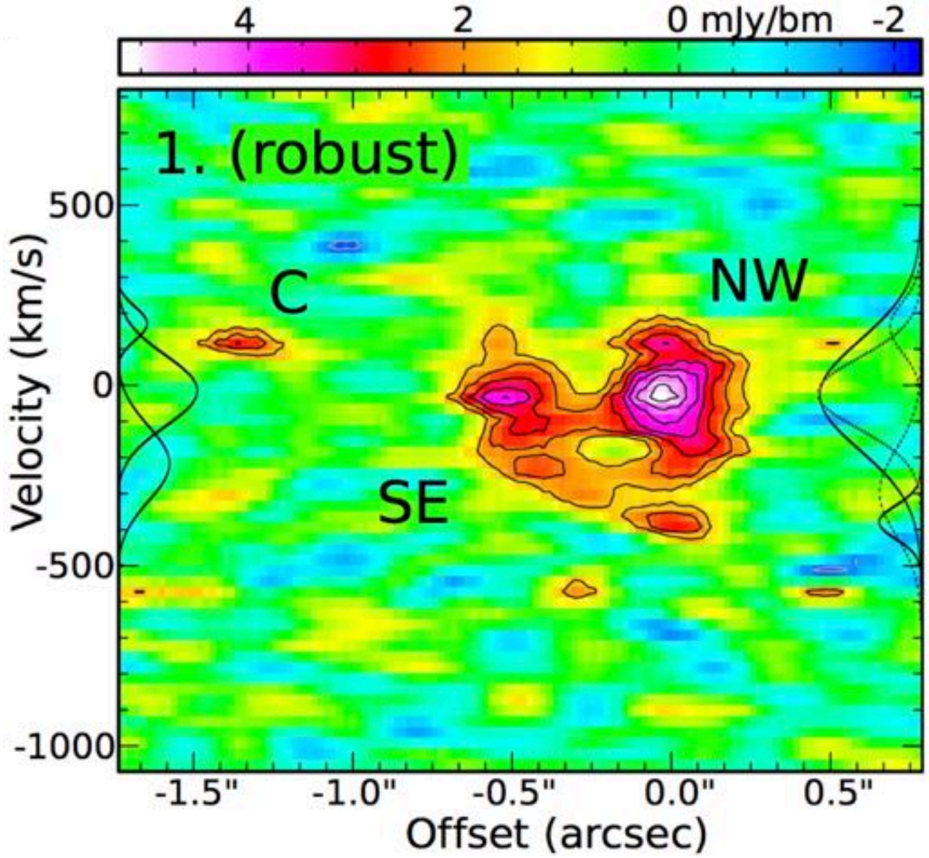
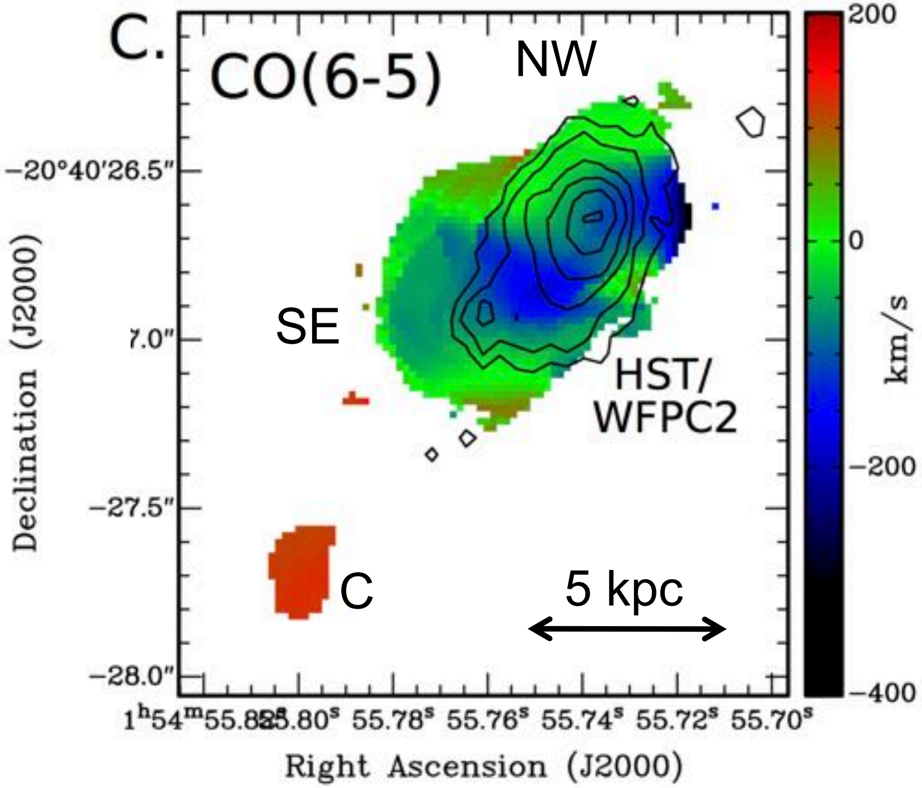




Gas re-distributed at rate approaching SFR (1200 – 3000 $M_{\odot}$/yr)

Emonts et al 2015b, A&A, 584, 99
Emonts et al 2015a, MNRAS, 451, 1025
Emonts et al 2011, ApJL, 734, 25

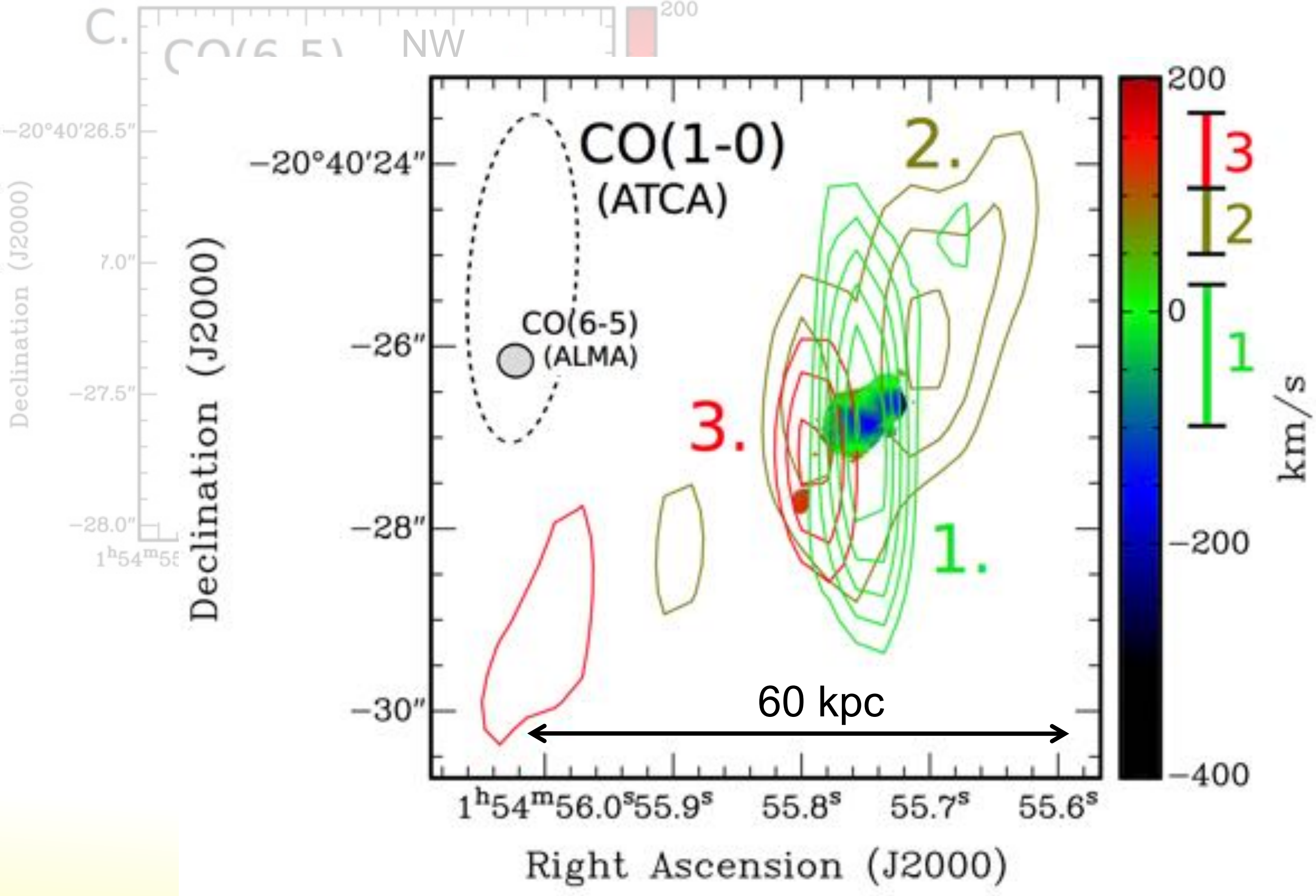
Low-surface-brightness sensitivity



ALMA high-J CO: starburst/AGN

Emonts et al 2015b, A&A, 584, 99

Low-surface-brightness sensitivity



Emonts et al 2015b, A&A, 584, 99

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