High-z proto-cluster radio galaxies

and the search for molecules in the early Universe

Bjorn Emonts

CSIRO ASTRONOMY & SPACE SCIENCE / ATNF

This talk

- Molecular gas at high redshifts

  Introduction on the search for molecular in the early Universe

- Australia Telescope Compact Array

  Excellent southern telescope for high-z mm studies/complement to ALMA

- CO(1-0) survey of high-z radio galaxies (HzRGs) with ATCA

  First sample results: - *Widespread CO(1-0) in MRC 0152-209 and Spiderweb Galaxy*

  - *Potential link between CO(1-0) content and radio source size*

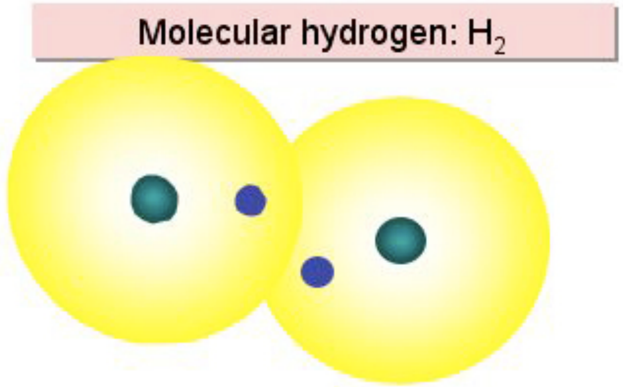
CO-investigators:

Ilana Feain *(CASS)*
Ray Norris *(CASS)*
Huub Rottgering *(Leiden Obs.)*
Montse Villar-Martin *(CAB-INTA)*
George Miley *(Leiden Obs.)*
Minnie Mao *(NRAO)*
Nick Seymour *(CASS)*
Elaine Sadler *(U. Sydney)*
Ron Ekers *(CASS)*

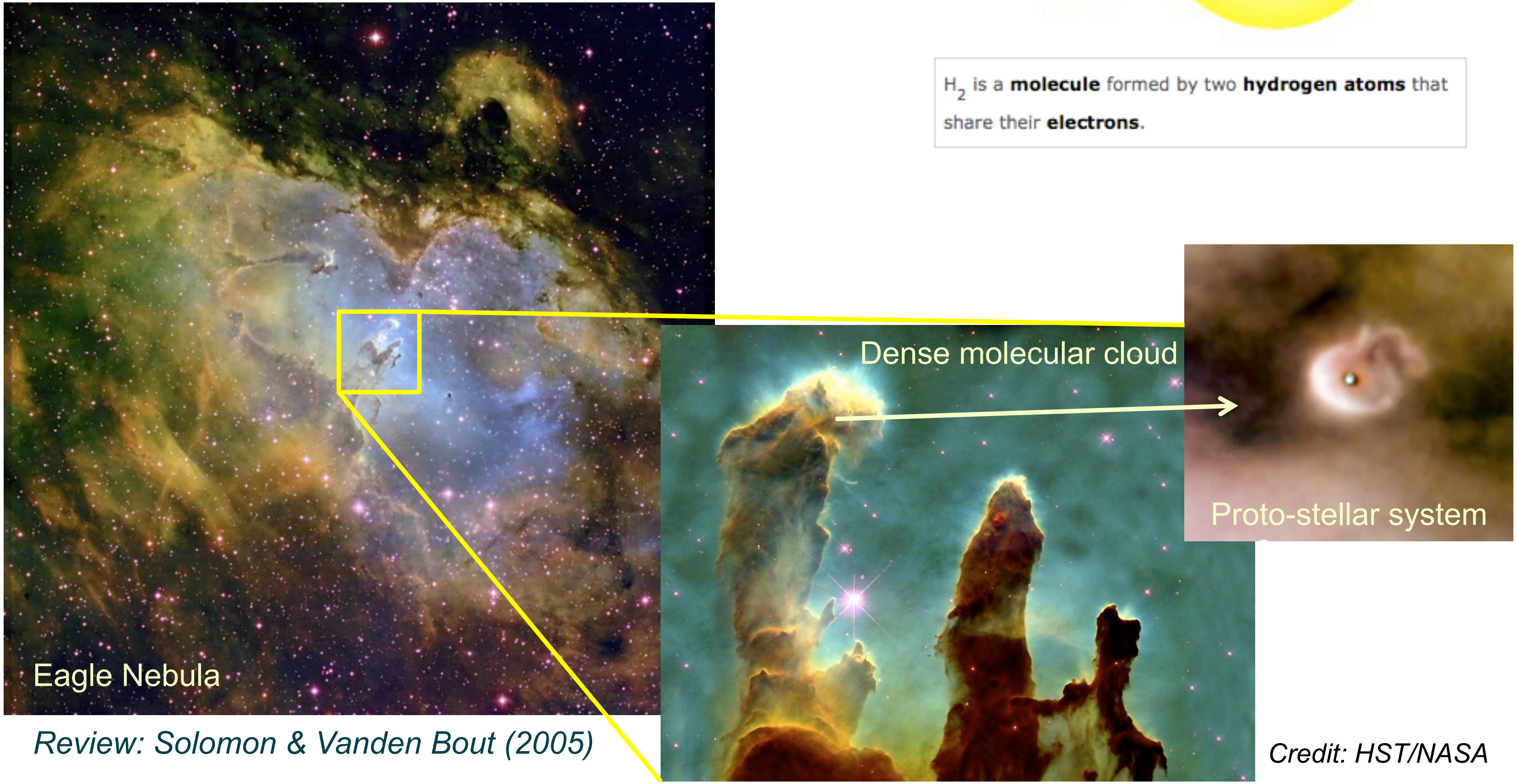
E. Mahony, C. Carilli, G. van Moorsel, J. Stevens, L. Pentericci, A. Stroe, T. Oosterloo, R. Morganti, G. Rees, D.J. Saikia, M.Wieringa, K. Randall, C. Tadhunter.

Molecular hydrogen

- H_2 Raw ingredient for star formation
  - Made in the presence of dust
  - Dominates clouds where $n > 100\ cm^{-3}$



H_2 is a **molecule** formed by two **hydrogen atoms** that share their **electrons**.



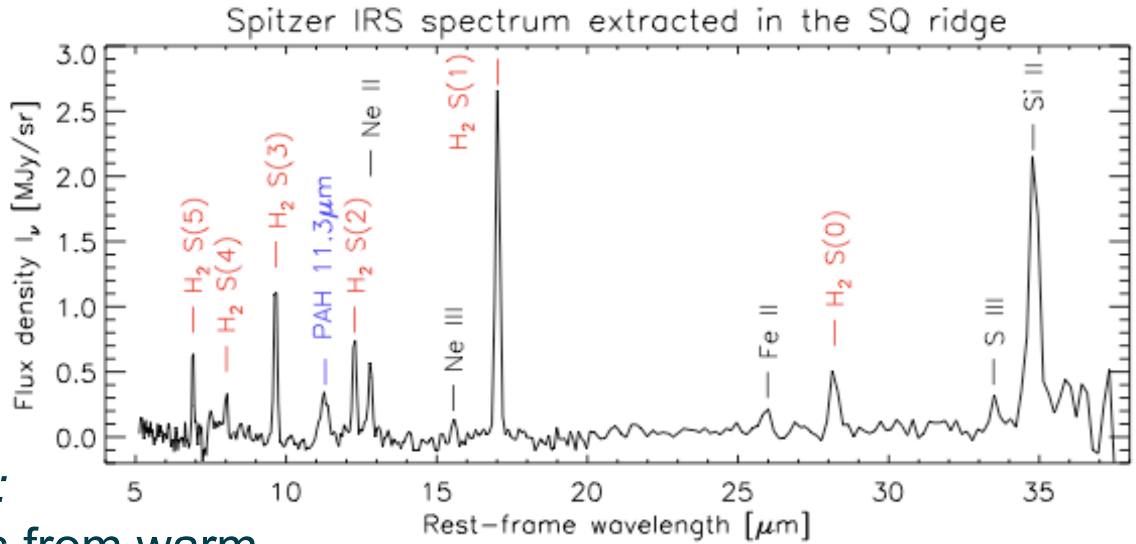
Review: Solomon & Vanden Bout (2005)

Credit: HST/NASA

Molecular hydrogen

- H_2 Raw ingredient for star formation

- H_2 virtually invisible
  (strongly forbidden lines)
  Unless shocked or heated to high temp!



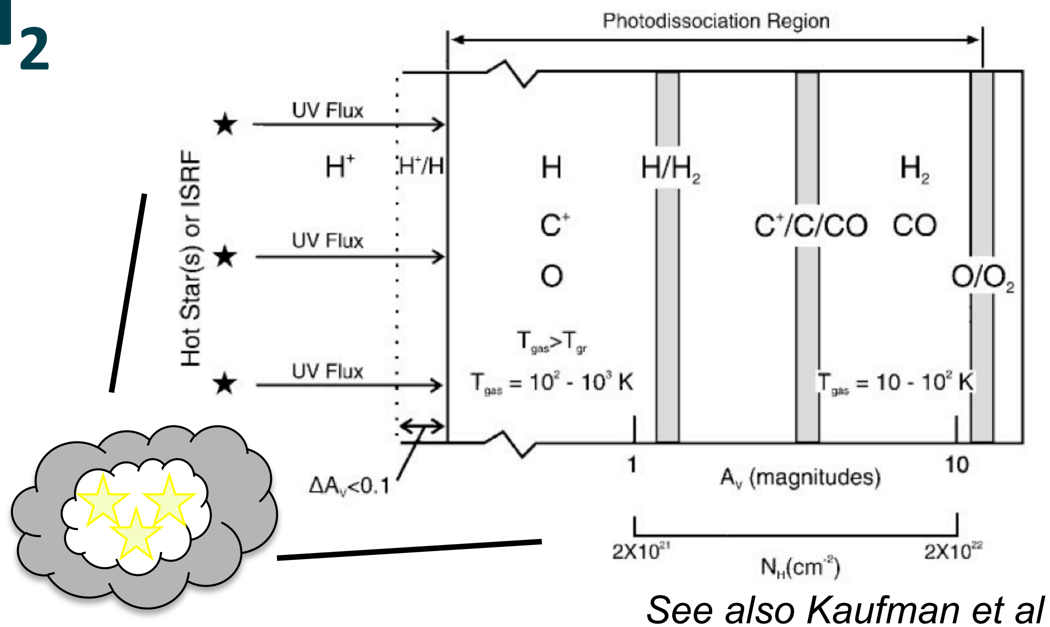
Spitzer:
H_2 lines from warm molecular gas ($10^{2\text{-}3}$ K)

Guillard et al (2010)

- Cold H_2: ^{12}CO strong tracer

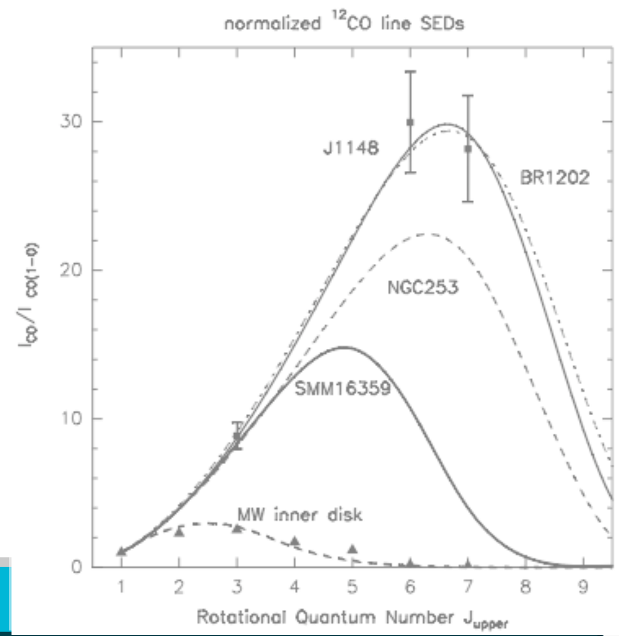
CO as tracer for H_2

- ^{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)



See also Kaufman et al (1999)

- Rotational *J,J-1* transitions:
  CO(1-0) *[115 GHz]*, CO(2-1) *[230 GHz]*,
  CO(3-2) *[345 GHz]*, CO(4-3) *[460 GHz]*, etc.
  - n_{crit} [substantial thermal excitation] $\propto J^3$
  - Line-intensity ratios of transitions →
    Model physical parameters of gas: temperature, density and excitation



Riechers et al (2011)

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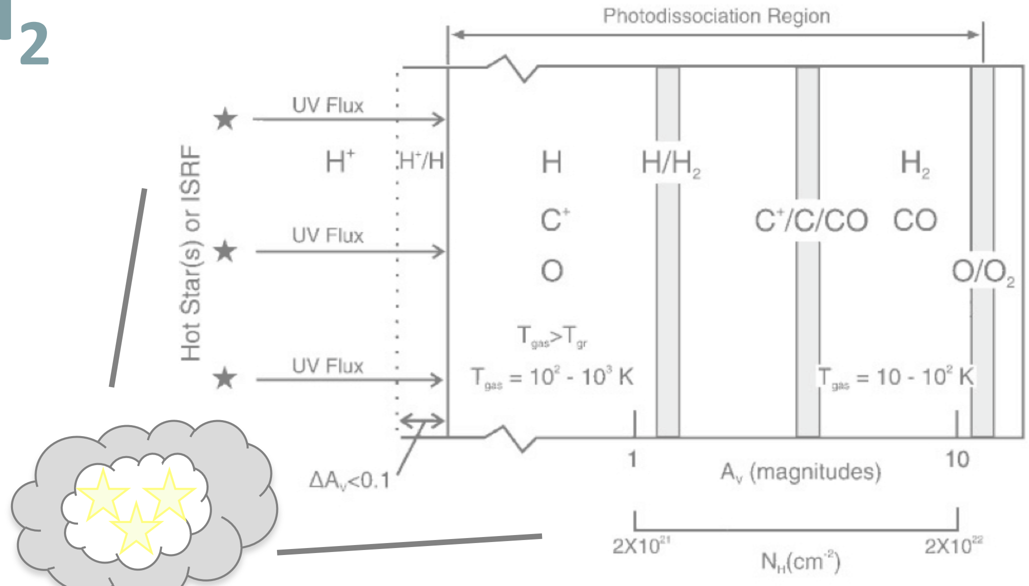

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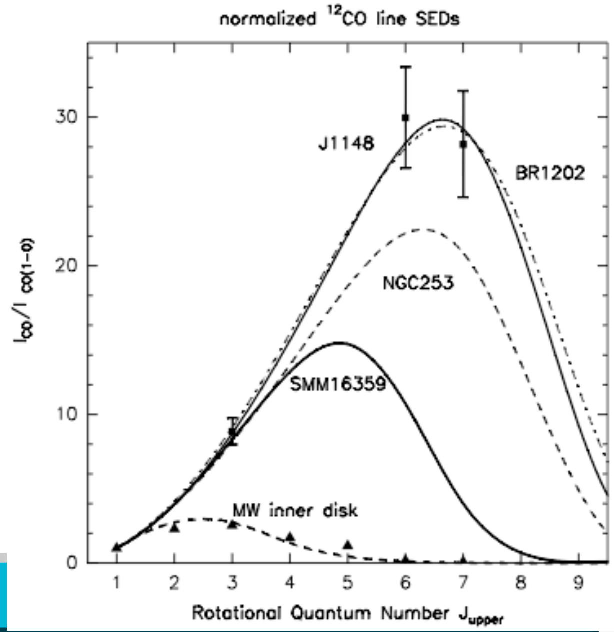


Riechers et al (2011)

CO as tracer H_2 at high-*z*

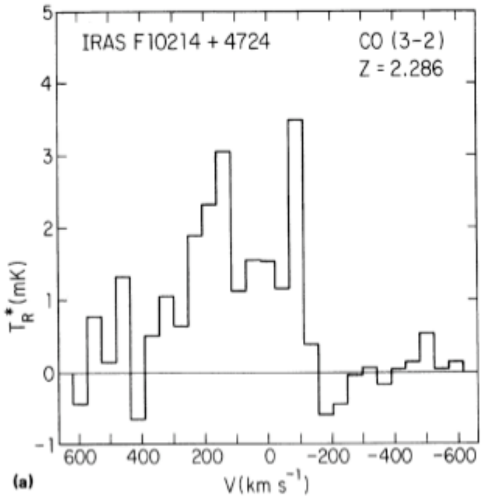
- 1991: First CO detection *z* > 2

  (Brown & Vanden Bout 1991, Kawabe et al 1992)

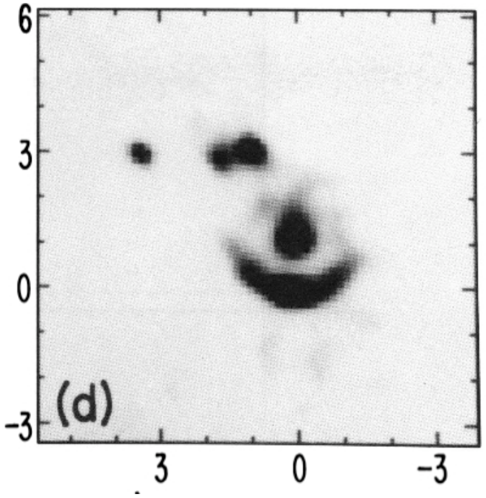
  IRAS F10214 + 4724 (*z* = 2.286)

  Extreme IRAS infra-red luminosity
  Rowan-Robinson et al. (1991)

  Later turned out to be lensed 10×
  (M_{H2} ~ 10^{10} $M_{\odot}$)

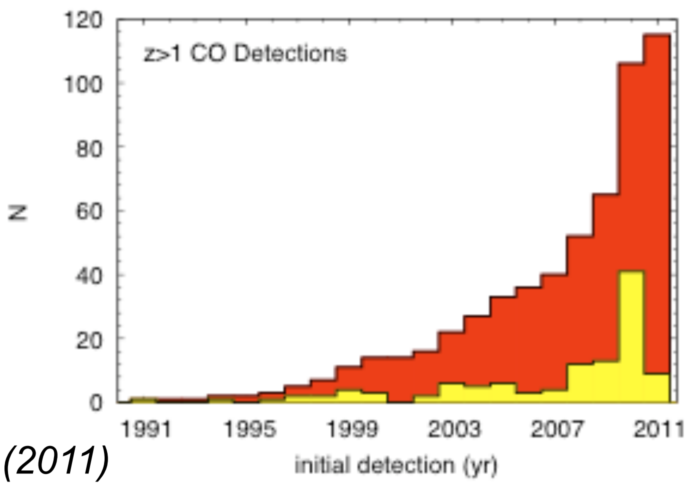


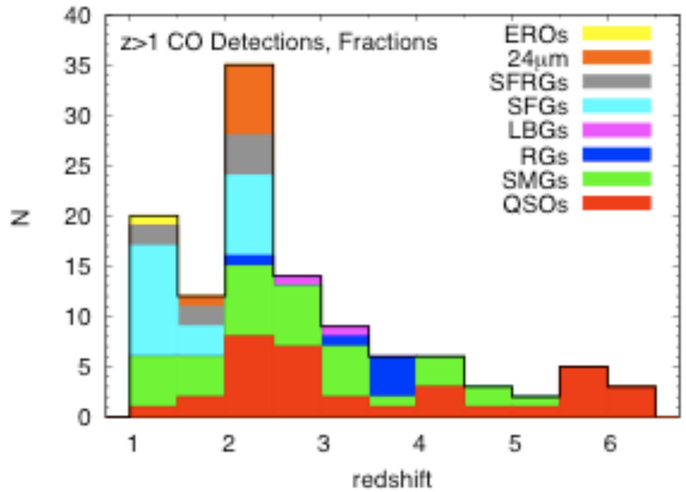
(Brown & Vanden Bout 1991)



Matthews et al (1994)

- Since then….





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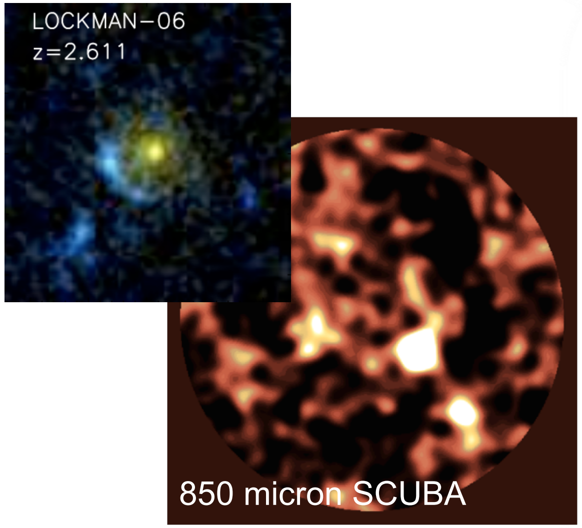
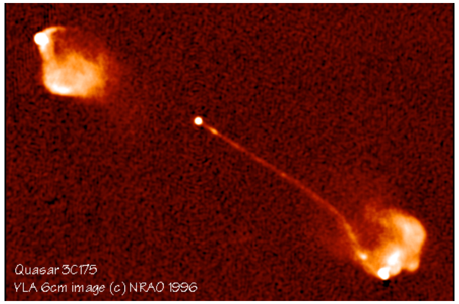
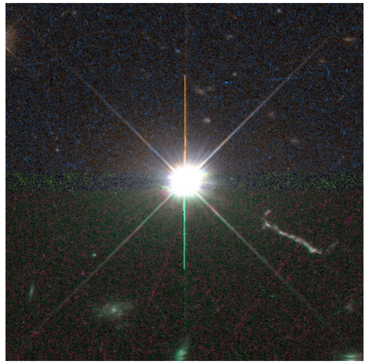


SMGs (Submm Galaxies)

Dusty ULIRG-type starbursts



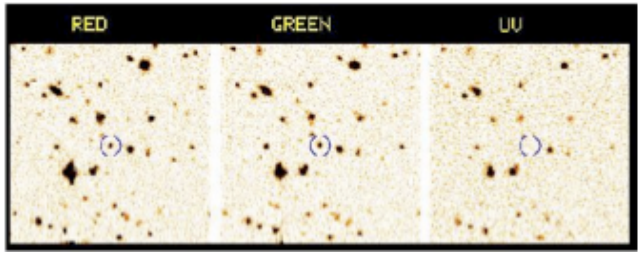
HzRG (High-z Radio Galaxy)

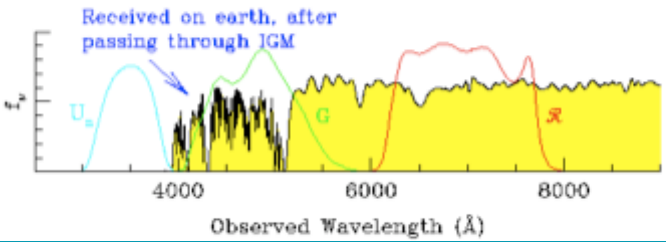


- *Radio-quiet:* QSO (quasi-stellar object)
- *Radio-loud:* quasar (quasi-stellar radio source)

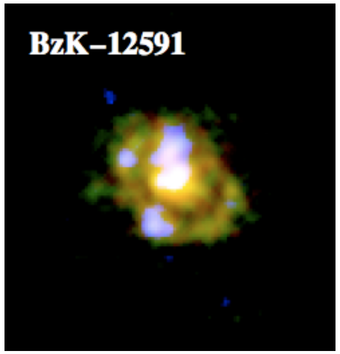
SELECTION METHOD!

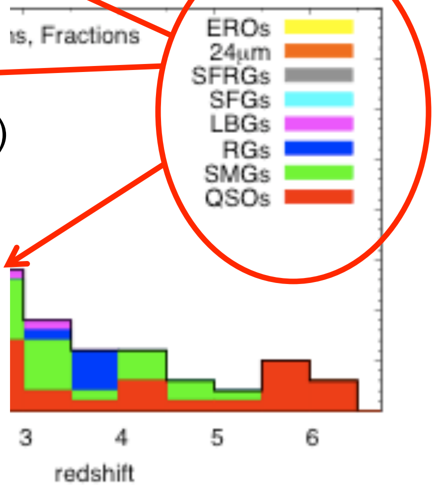
LBGs (Ly-break Galaxies)

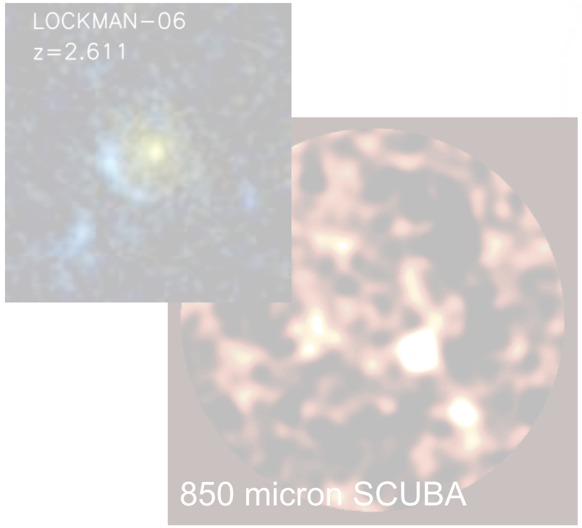




BzK (SF Disk Galaxies)







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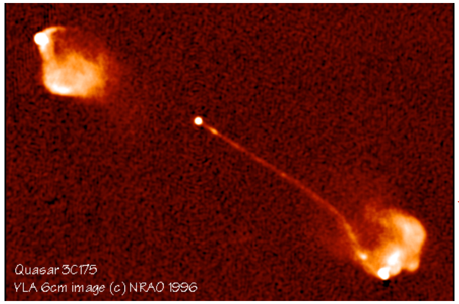
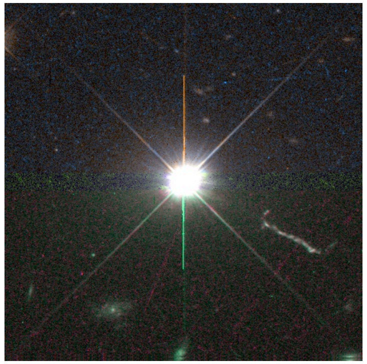


HzRG (High-z Radio Galaxy)

Edge-on – AGN-light blocked by torus

ORIEN-
TATION



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Face-on – look into AGN

SELECTION METHOD!

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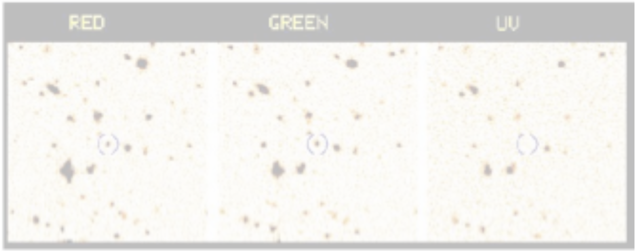

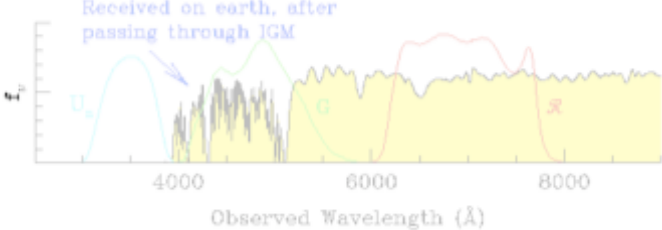

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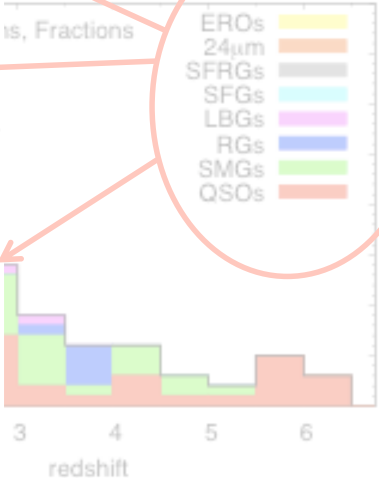
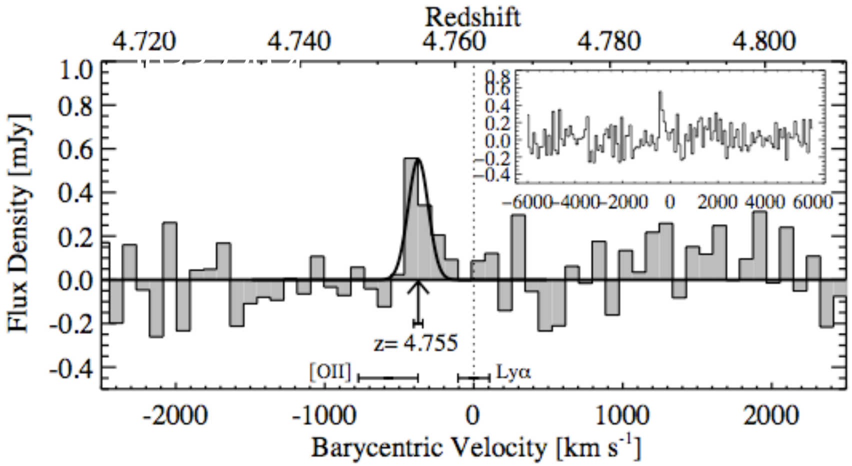


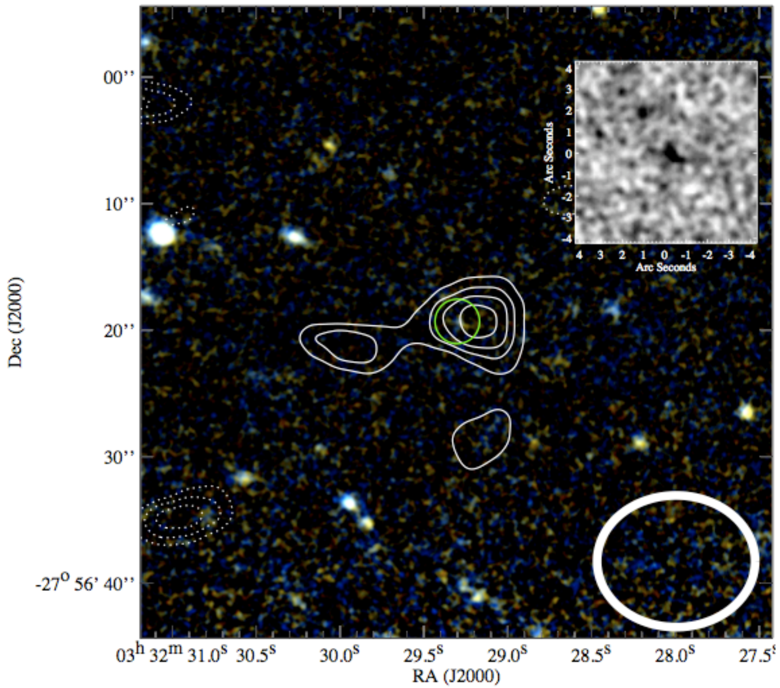
(Random) examples high-z CO

Coppin et al. (2011):

CO(2-1) in submm-galaxy at z=4.8

M_{H2} = 1.6 x 10^{10} M_{sun} (α[M_{H2}/L_{CO}]= 0.8)





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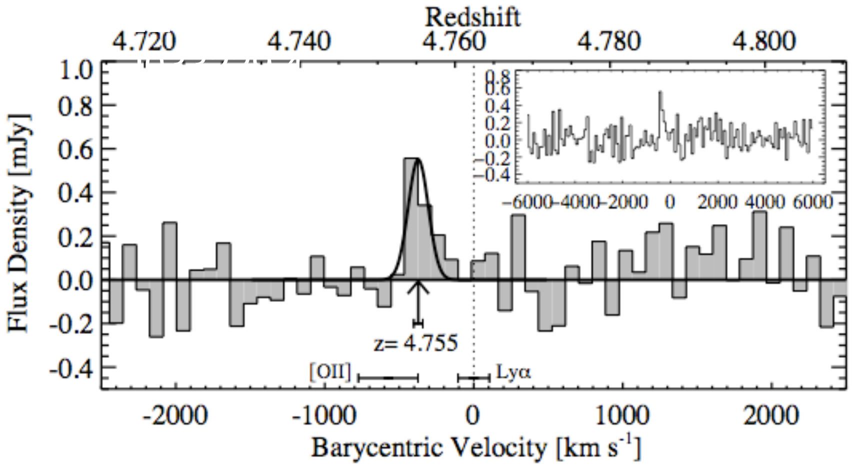
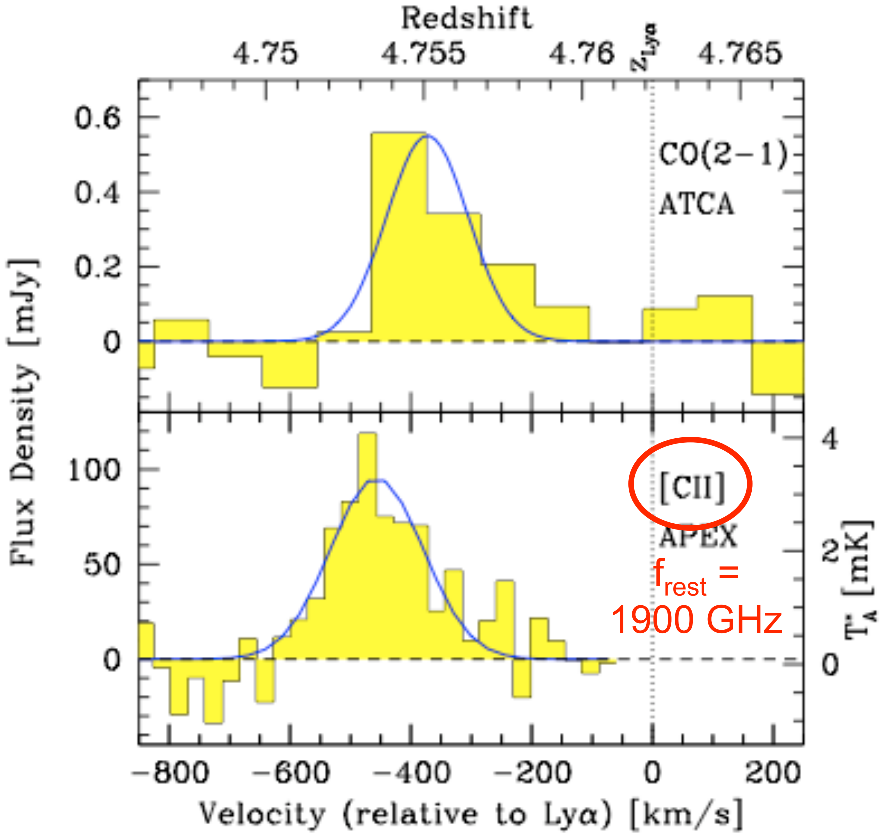
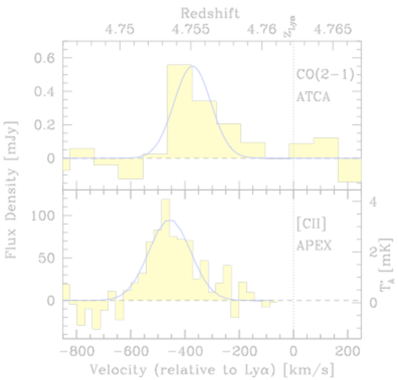




De Breuck et al (2011)

C II luminosity 10,000× stronger than CO(1-0)!!

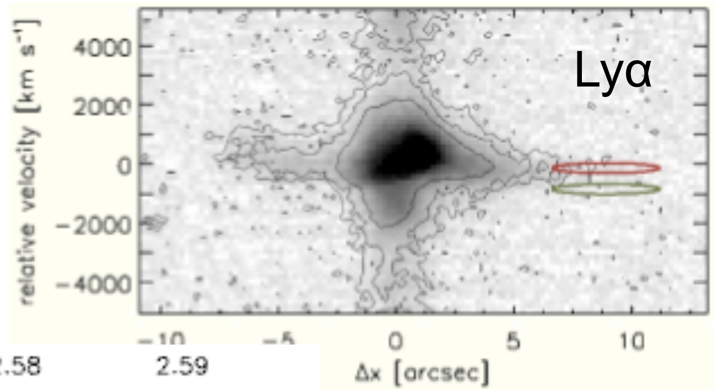
(Random) examples high-*z* CO

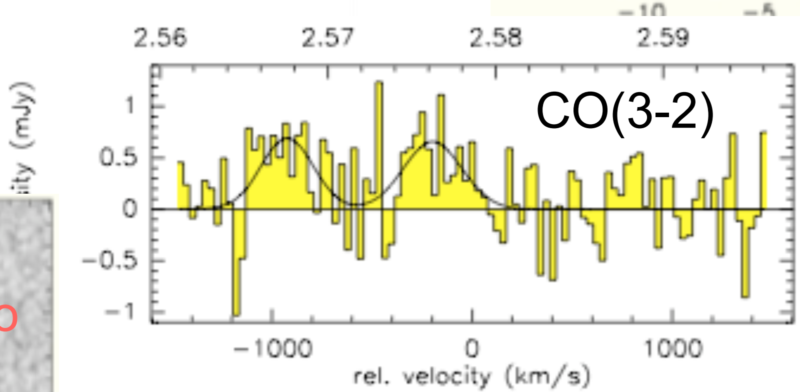


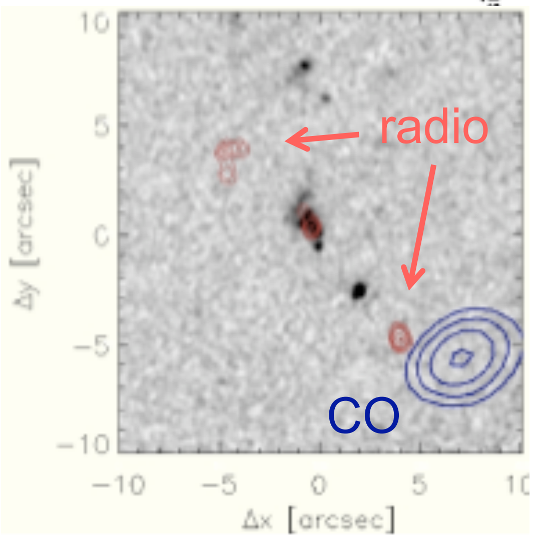
Coppin et al. (2011)
De Breuck et al (2011)

Nesvadba et al (2009)

High-z radio galaxy
TXS 0828+193
(z = 2.6)

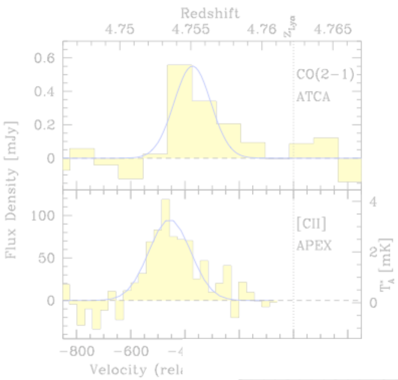






CO(3-2) in halo, just outside radio source

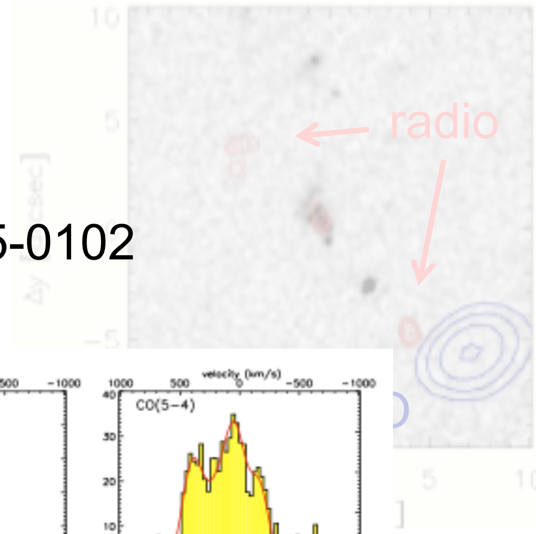
(Random) examples high-z CO



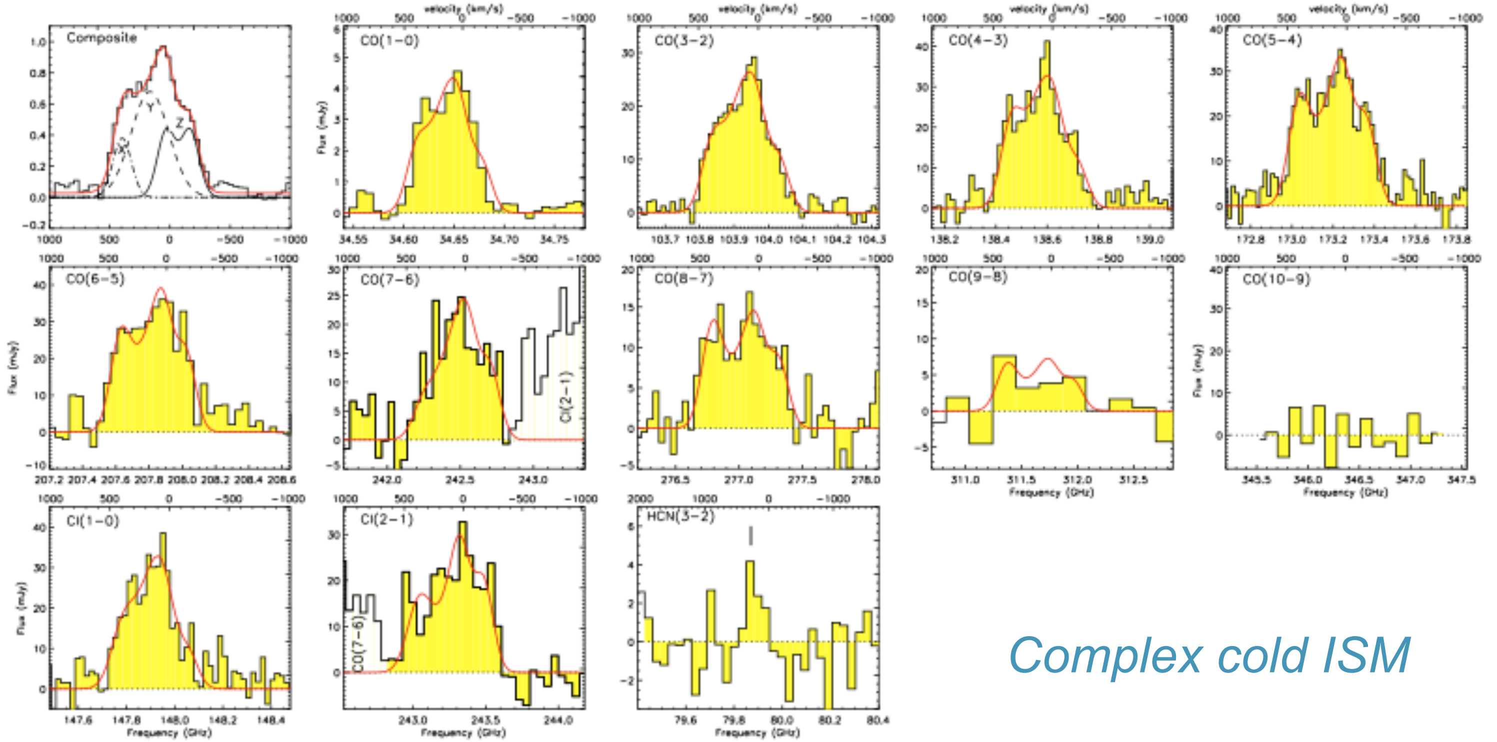
Coppin e
De Breu

Danielson et al (2010)

z= 2.3 submillimetre galaxy SMM J2135-0102
Lensed: factor 32.5



l (2009)



Complex cold ISM

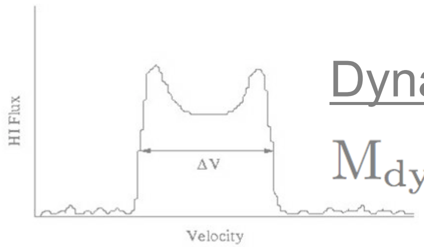
CO properties

- CO(1-0) as robust H2 tracer:

H2 mass:

$$L'_{\rm CO} = 3.25 \times 10^7 \left(\frac{\int_v S_{\rm CO}\delta v}{\rm Jy\ km/s}\right)\left(\frac{D_L}{\rm Mpc}\right)^2\left(\frac{\nu_{\rm rest}}{\rm GHz}\right)^{-2}(1+z)^{-1}$$

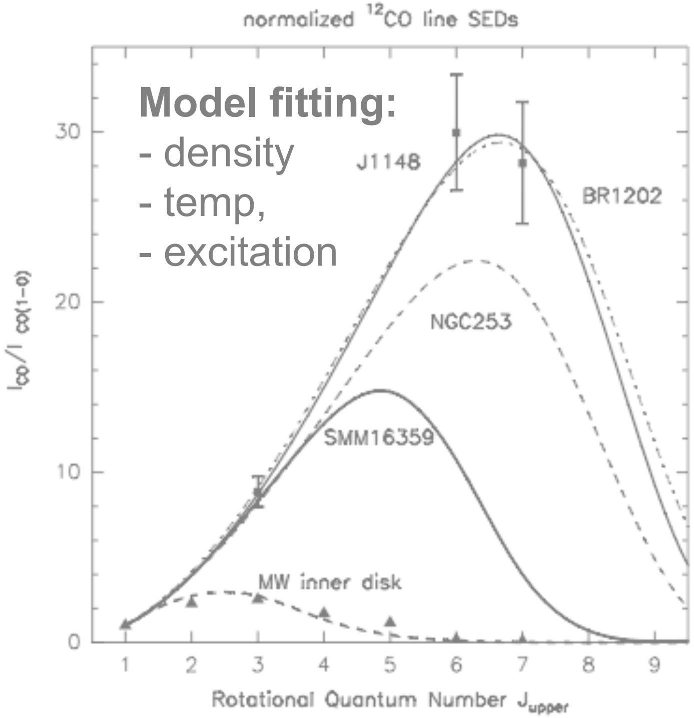
$M_{H2} = X_{CO}\, L'_{CO}$ (X_{CO} = 0.8 [ULIRGs] – 5 [Milky Way])



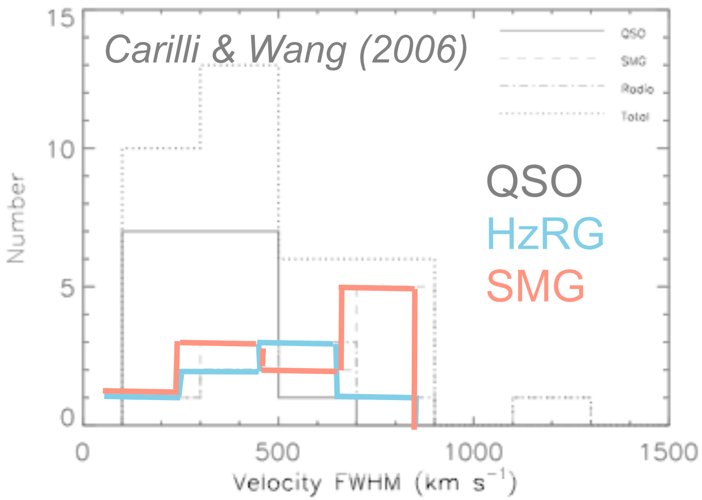
Dynamical mass:

$$M_{\rm dyn} = Rv^2/G \cdot \sin^{-2} i$$

Excitation:



CO(*J*,*J*-1): *J* ⟶



Line width:

Differences between QSOs, HzRGs, SMGs?

(edge-on CO disc, face-on CO disc, merger?)

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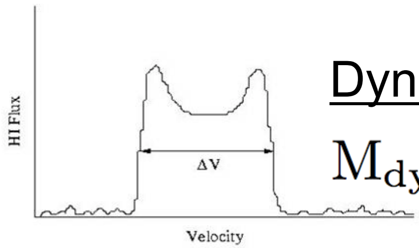

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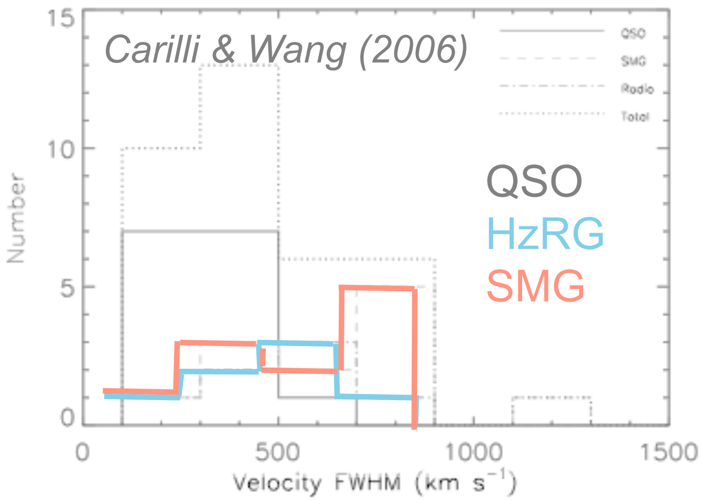

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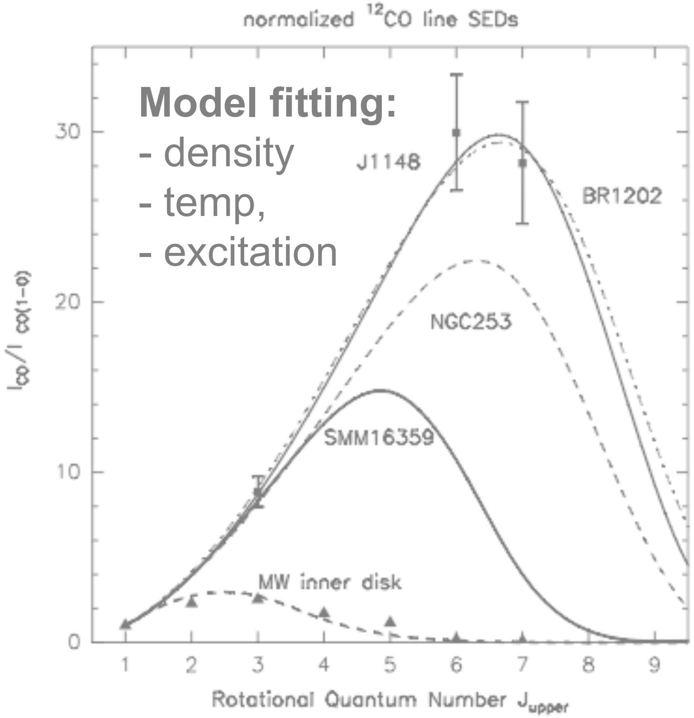

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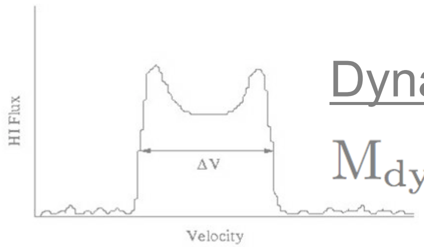

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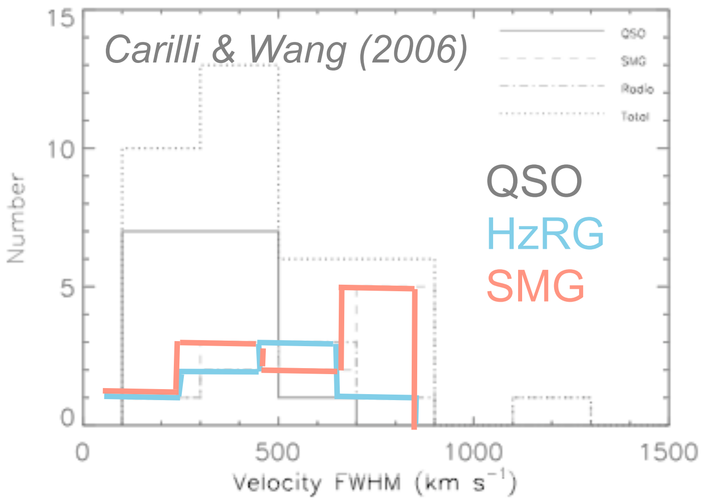

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Differences betw

(edge-on CO disc, i

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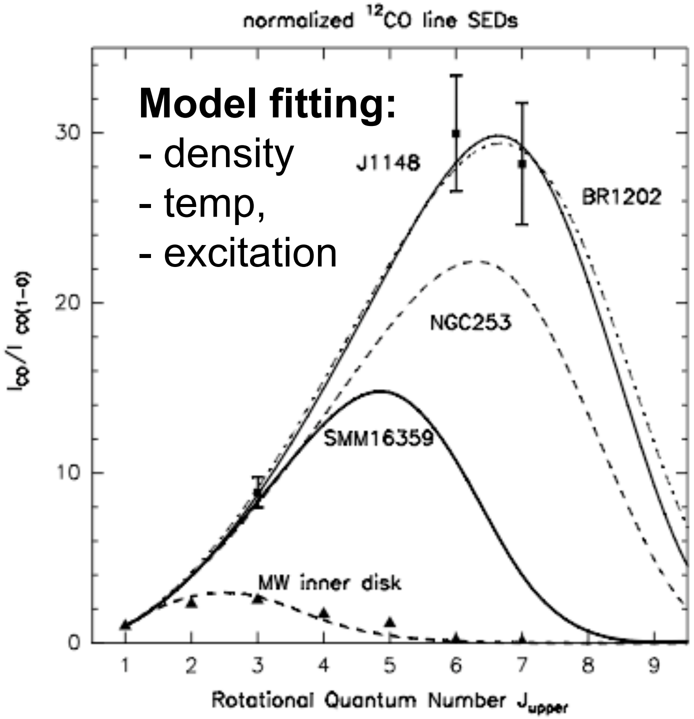

CO(*J*,*J*-1): *J* ⟶

Quasars in thermal excitation
Riechers et al (2011)

SMGs, BzK galaxies -- large reservoirs of sub-thermally excited gas
(Ivison et al 2011, Carilli et al 2010, Dannerbauer et al 2009)

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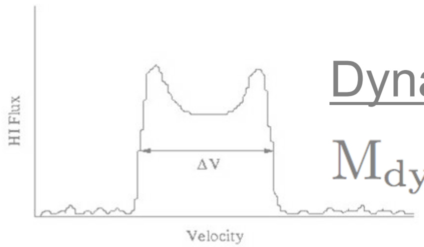

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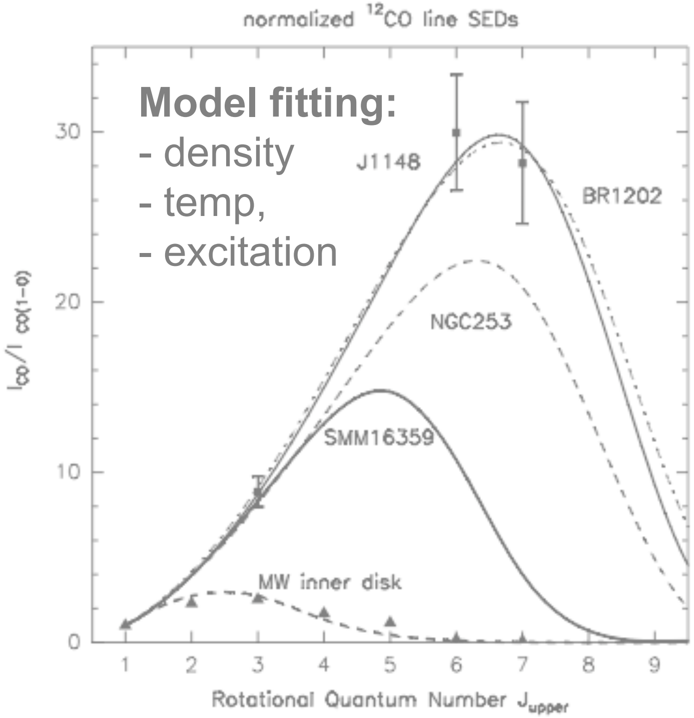

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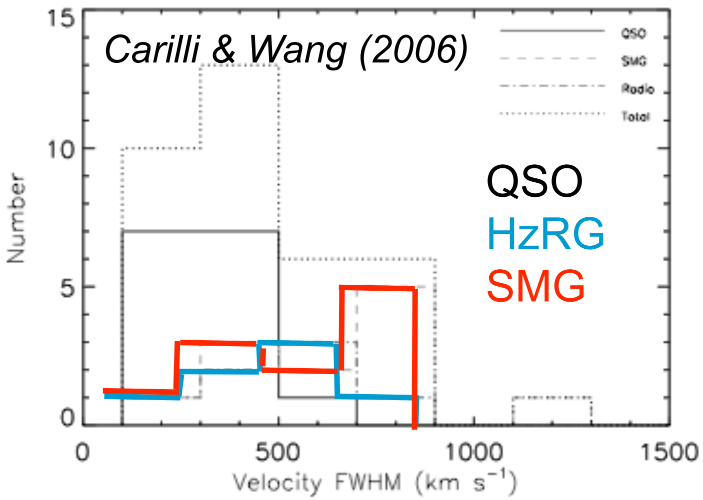

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High-z galaxies: CO limitations

Major limitations plagued comprehensive studies of high-*z* CO:

- **Limited bandwidth,** often not wider than CO signal or *z*-accuracy;
- **Limited collecting area/sensitivity**, requiring long integration times (pre-selection on IR or submm flux);
- **High observing frequencies** (>100 GHz) of mm observatories: Only target higher-order CO(*J,J-1*) transition at high-z.
  - High-order transitions: dense and thermally excited gas in starburst/AGN region;
  - Low-order transitions: less dense, widespread, sub-thermally excited gas;

  → *large reservoirs of molecular gas missed in high-order CO observations*

  (e.g.Papadopoulos et al. 2000,2001, Riechers et al. 2010, Daddi et al. 2010, Carilli et al. 2010, Ivison et al. 2010, 2011)

Ground-transition CO(1-0): most robust tracer for molecular gas at high-z

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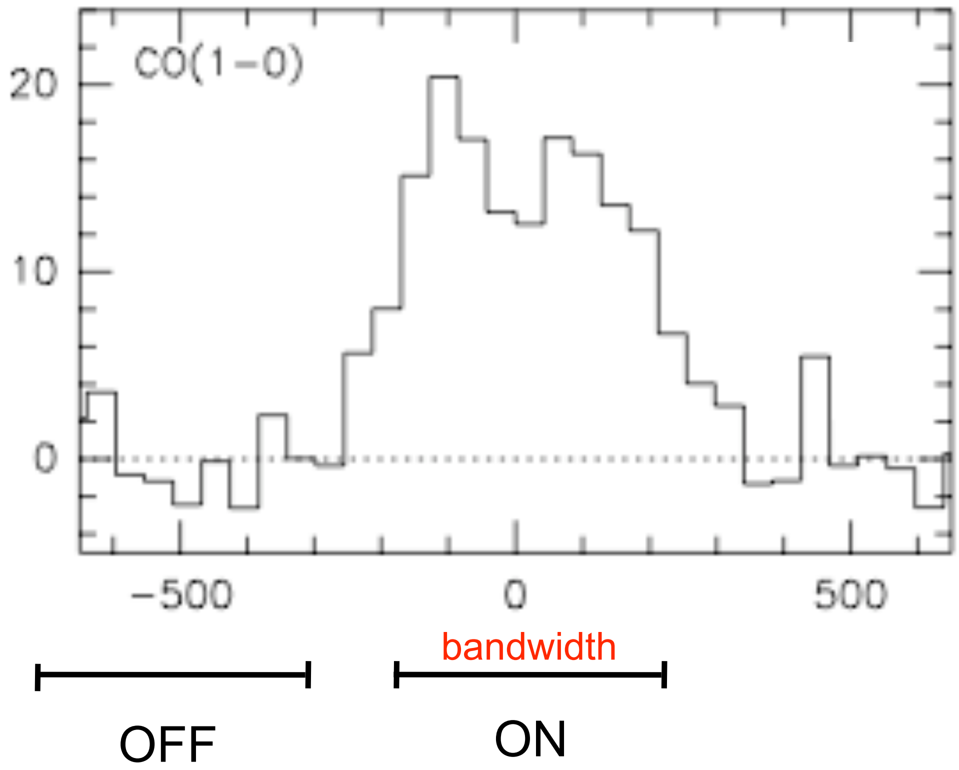
Ground-transition CO(1-0): most r



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- **High observing frequencies** (>100 GHz) of mm observatories: Only target higher-order CO(*J,J-1*) transition at high-z.
  - High-order transitions: dense and thermally excited gas in starburst/AGN region;
  - Low-order transitions: less dense, widespread, sub-thermally excited gas;

  → *large reservoirs of molecular gas missed in high-order CO observations*

  (e.g.Papadopoulos et al. 2000,2001, Riechers et al. 2010, Daddi et al. 2010, Carilli et al. 2010, Ivison et al. 2010, 2011)

Ground-transition CO(1-0): most robust tracer for molecular gas at high-z

High-z galaxies: CO limitations

Major limitations plagued comprehensive studies of high-*z* CO:

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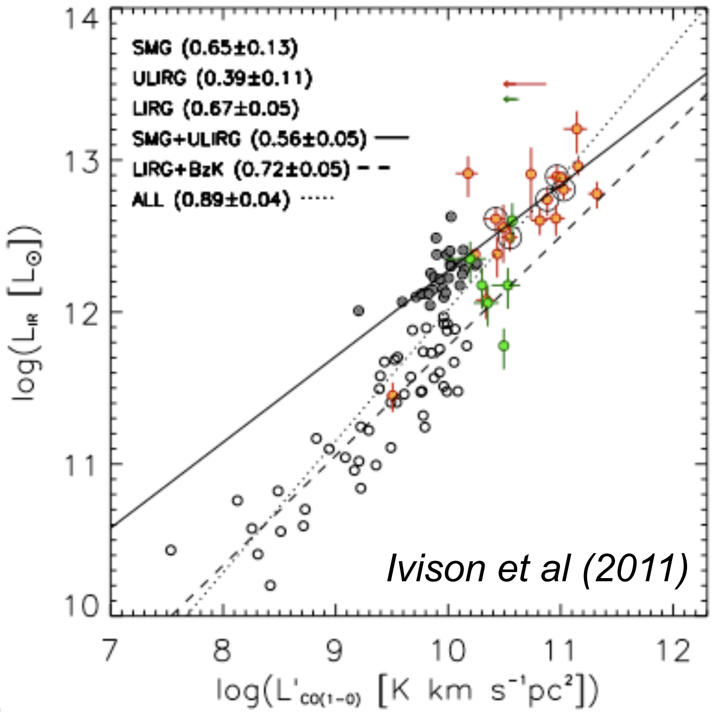
- **Limited collecting area/sensitivity**, requiring long integration times (pre-selection on IR or submm flux);
- **High observing frequencies** (>100 GHz)

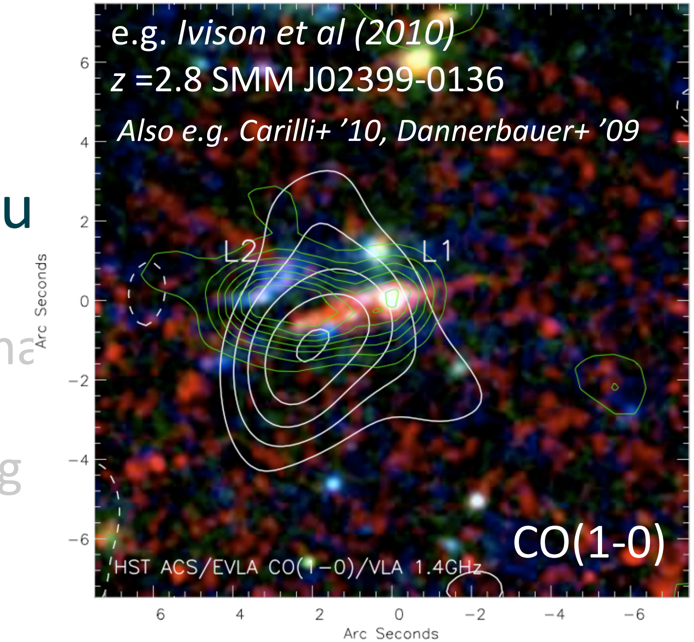
Strong correlation between L'_{CO} and L_{FIR}.

e.g. *Evans et al 2005* (low-z),
Ivison et al 2011, Greve et al 2005 (high-z SMGs)

Likely reflects the Schmidth-Kennicutt relation between star formation rates and gas reservoir *(Schmidt 1959; Kennicutt 1998)*.



High-z galaxies: CO limitations



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  - Low-order transitions: ... d gas;

  → *large reservoirs of m*

  (e.g.Papadopoulos et al. 2000,2001 ... al. 2010, 2011)

Thing of the past...

- **ATCA** 4 GHz
- **EVLA** 8 GHz
- **IRAM/PdbI** 3.6 GHz
- **CARMA** 4 GHz
- **GBT** 10.5 GHz
- **ALMA (ES)** 8 GHz
- ....

Ground-transition CO(1-0): most robust tracer for molecular gas at high-z

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Figure 1: *Nineteen antennas at the ALMA high site, the AOS, in September 2011. (Photo W. Garnier © ALMA (ESO/NAOJ/NRAO))*

Ground-transition CO(1-0): mos

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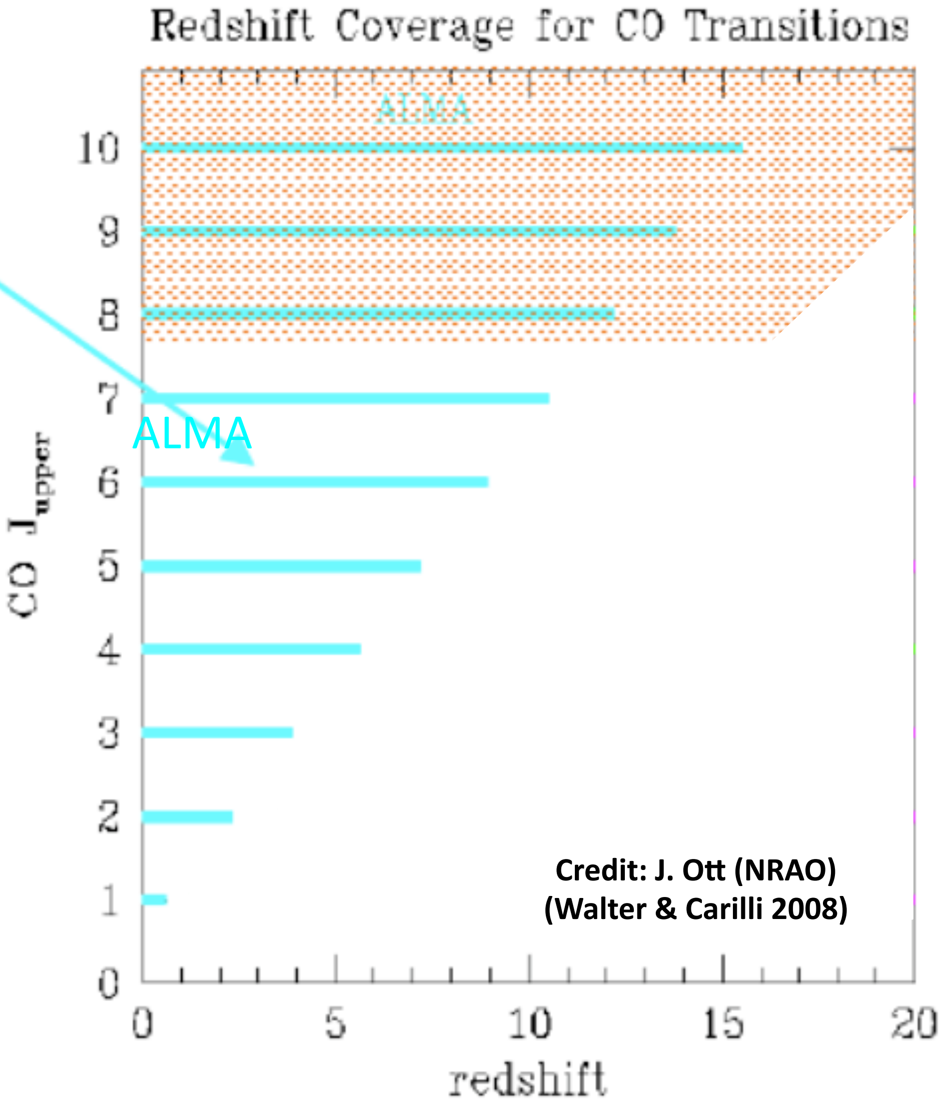

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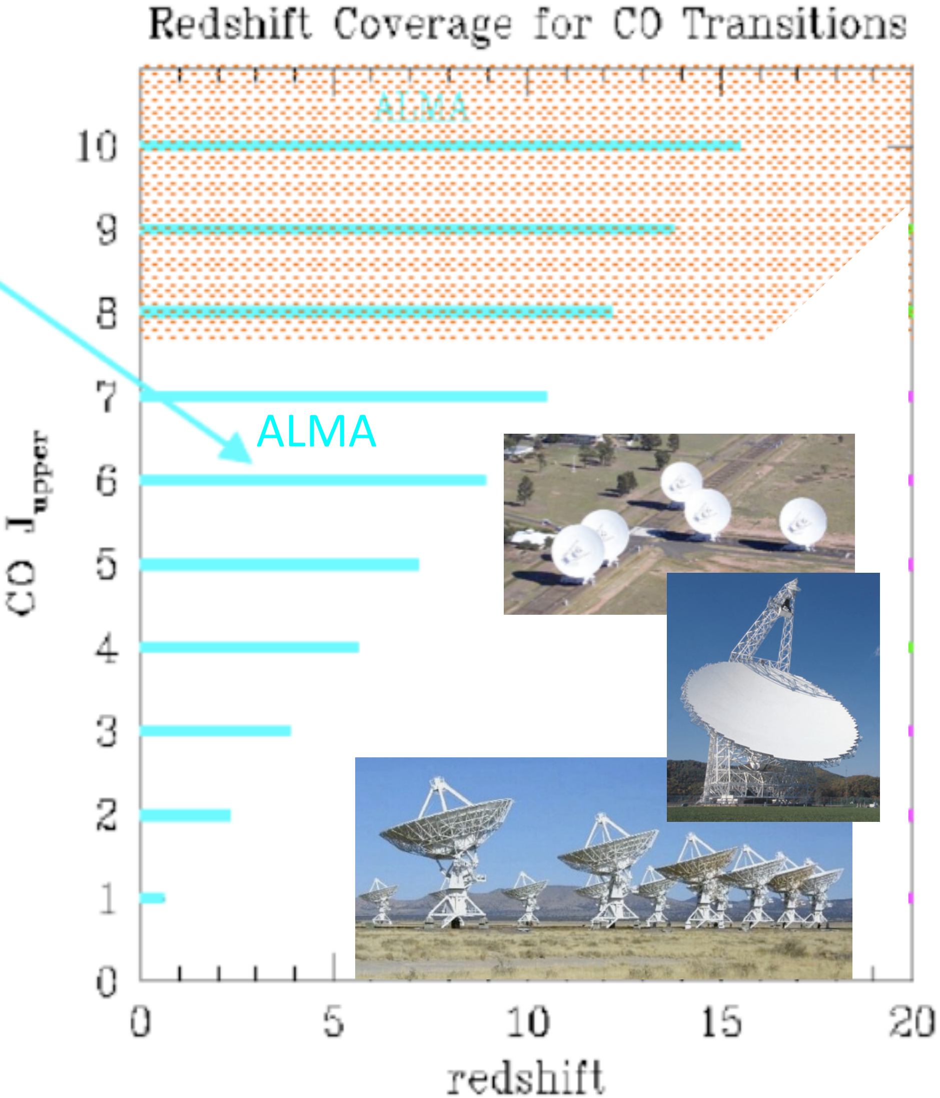

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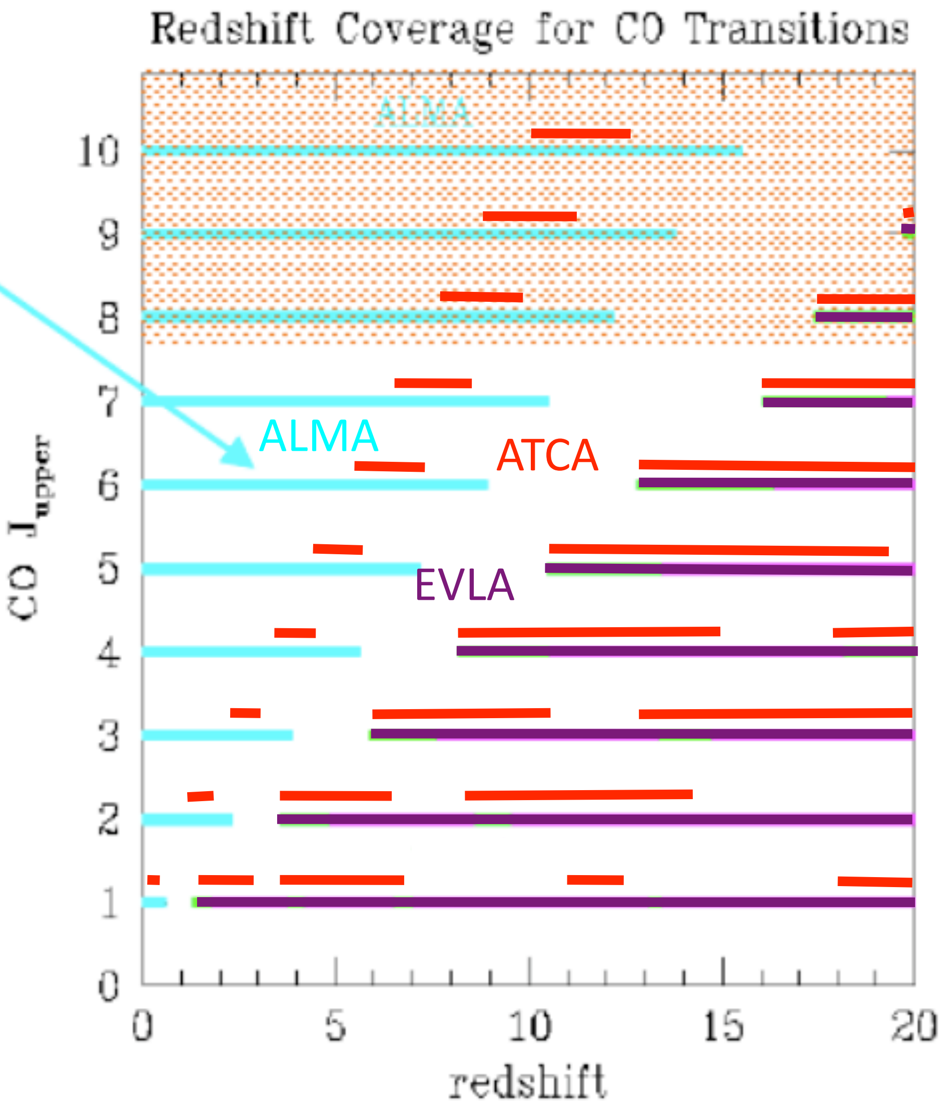
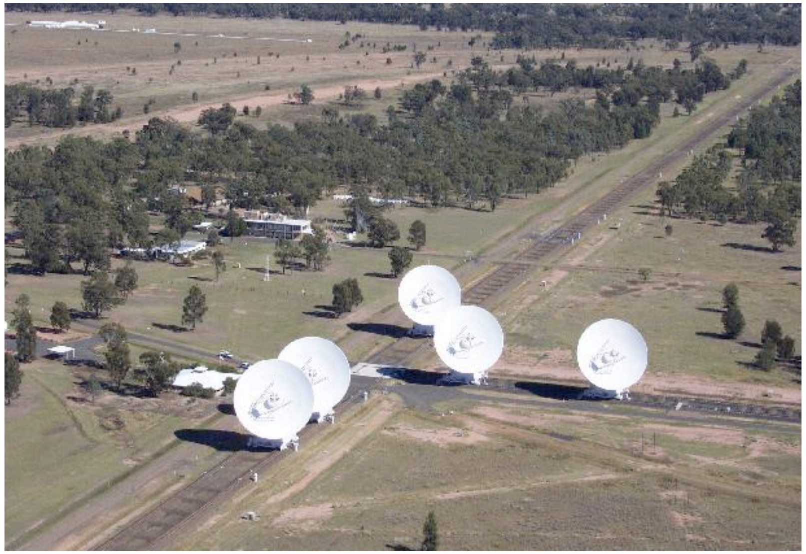


Australia Telescope Compact Array

- *Compact Array Broadband Backend (CABB)*

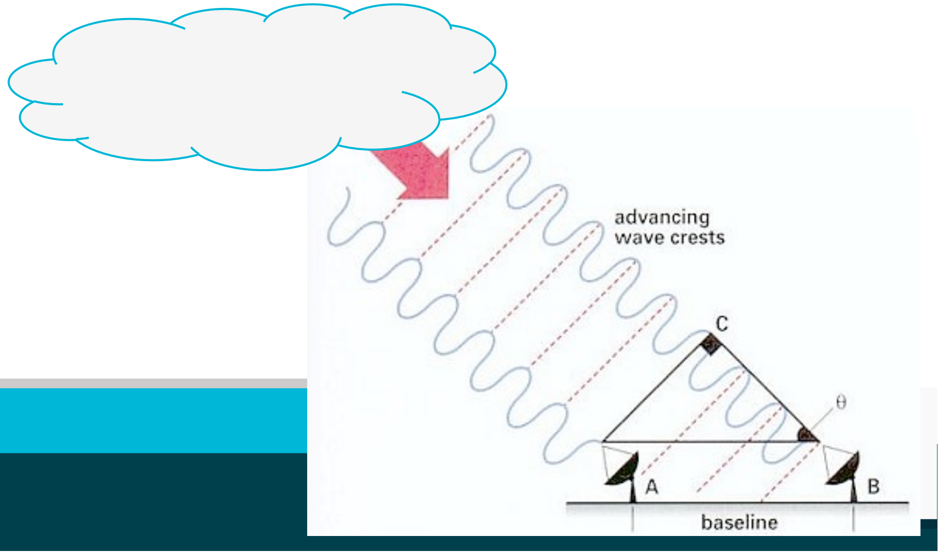


- 4 (2x2) GHz bandwidth, 1 MHz coarse res., full stokes
- mm observing frequencies
  3mm (84-105 GHz)
  7mm (30-50 GHz)
  15mm (16-25 GHz)
- Hybrid array configurations
  baselines as short as 31m.

Example: at f_{obf} = 40 GHz (7mm band)

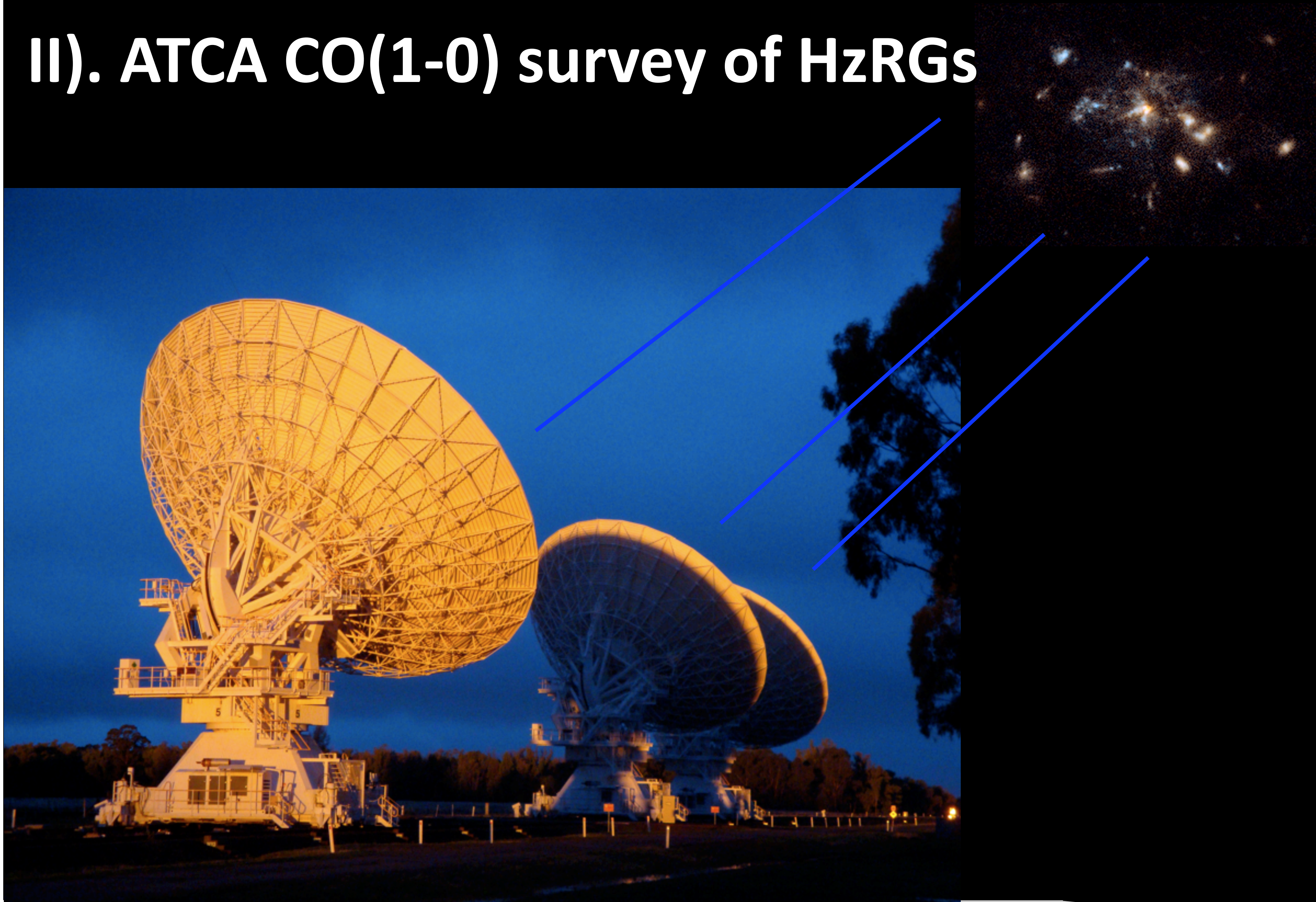
↓

15,000 km/s per 2 GHz, Δv ~ 7.5 km/s



Wilson et al (2011)

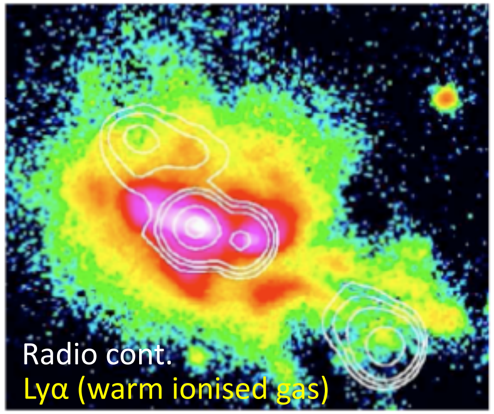
II). ATCA CO(1-0) survey of HzRGs



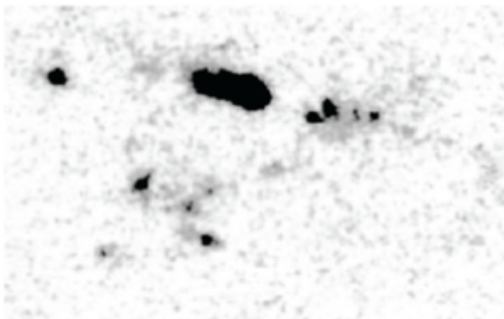
High-z Radio Galaxies (HzRG)

- Most massive galaxies in Early Universe
  - Central proto-cluster galaxies *(e.g. Venemans et al. 2007)*
    → ancestors of local rich cluster ellipticals
  - Very active systems:
    - *Clumpy optical morphology (merging star forming systems) (Pentericci et al. 2001);*
    - *Radio jets vigorously interact with ISM (Humphrey et al. 2006) + alignments jets with UV/optical and possibly CO (Chambers et al 1987; McCarthy et al. 1978; Klamer et al. 2004).*
- Among best studied high-z objects
  - Strong radio continuum beacon for tracing faint host galaxy/proto-cluster;
  - Optical quasar-core generally shielded by torus

4C41.17 (z = 3.8)
(Reuland et al. 2003)



VLA radio on Keck Lya



HST Image, WFPC2 (7000A)

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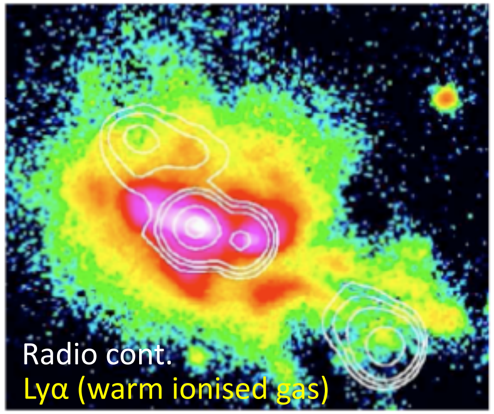

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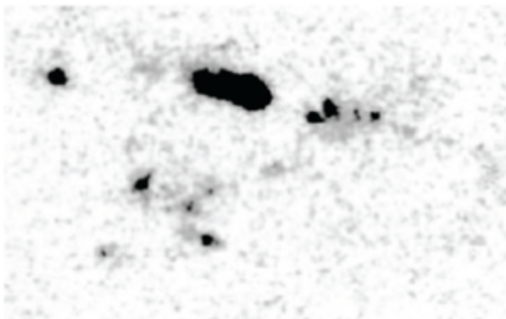


HST Image, WFPC2 (7000A)

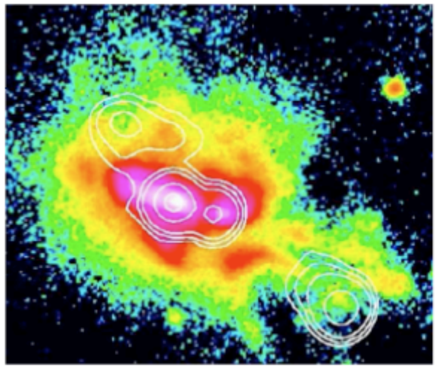
Molecular gas in HzRG

- CO as tracer for molecular gas in HzRGs
  - First (single-dish) surveys failed to detect CO *(Evans et al 1996, van Ojik et al 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)*
  - CO found on scales of tens of kpc *(e.g. Papadopoulos et al. 2000)* in giant Lyα halos *(Nesvadba 2009)* and perhaps aligned with radio jets *(Klamer et al 2004)*

All individual objects, often selected on high IR luminosity!

4C41.17 (z = 3.8)

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



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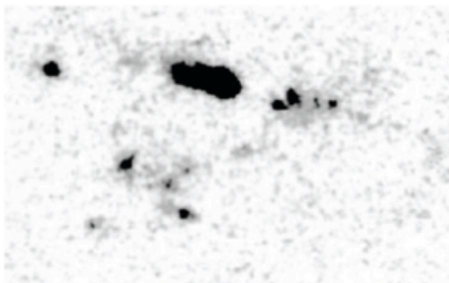

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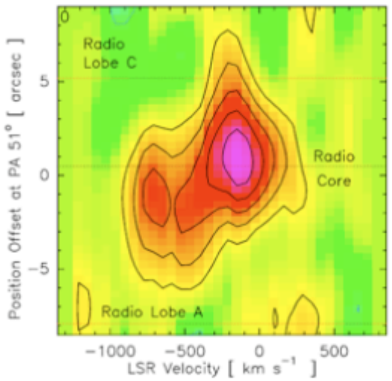


CO(4-3)

De Breuck et al. (2005)

CO(1-0) survey of HzRG with ATCA/CABB

First systematic survey of CO(1-0) in representative sample of HzRGs

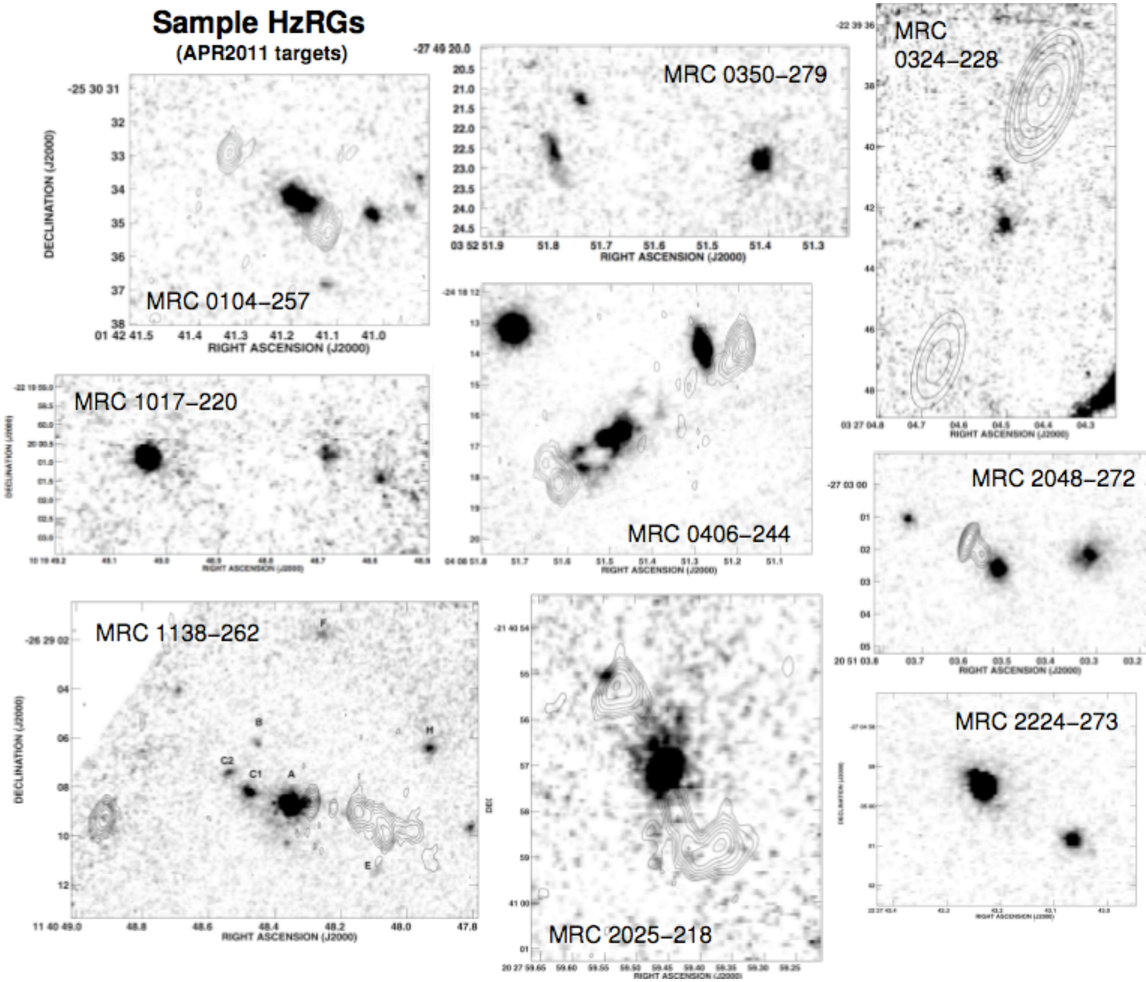
- **Sample selection:**

  All HzRGs from MRC catalogue (*unbiased in IR, submm, etc*):

- observable in ATCA 7mm band *(1.3 < z < 3)*
- dec < -10
- HST imaging & Spitzer data available

  ➔ ***14 sources***

- t_{int} ~15h average per source



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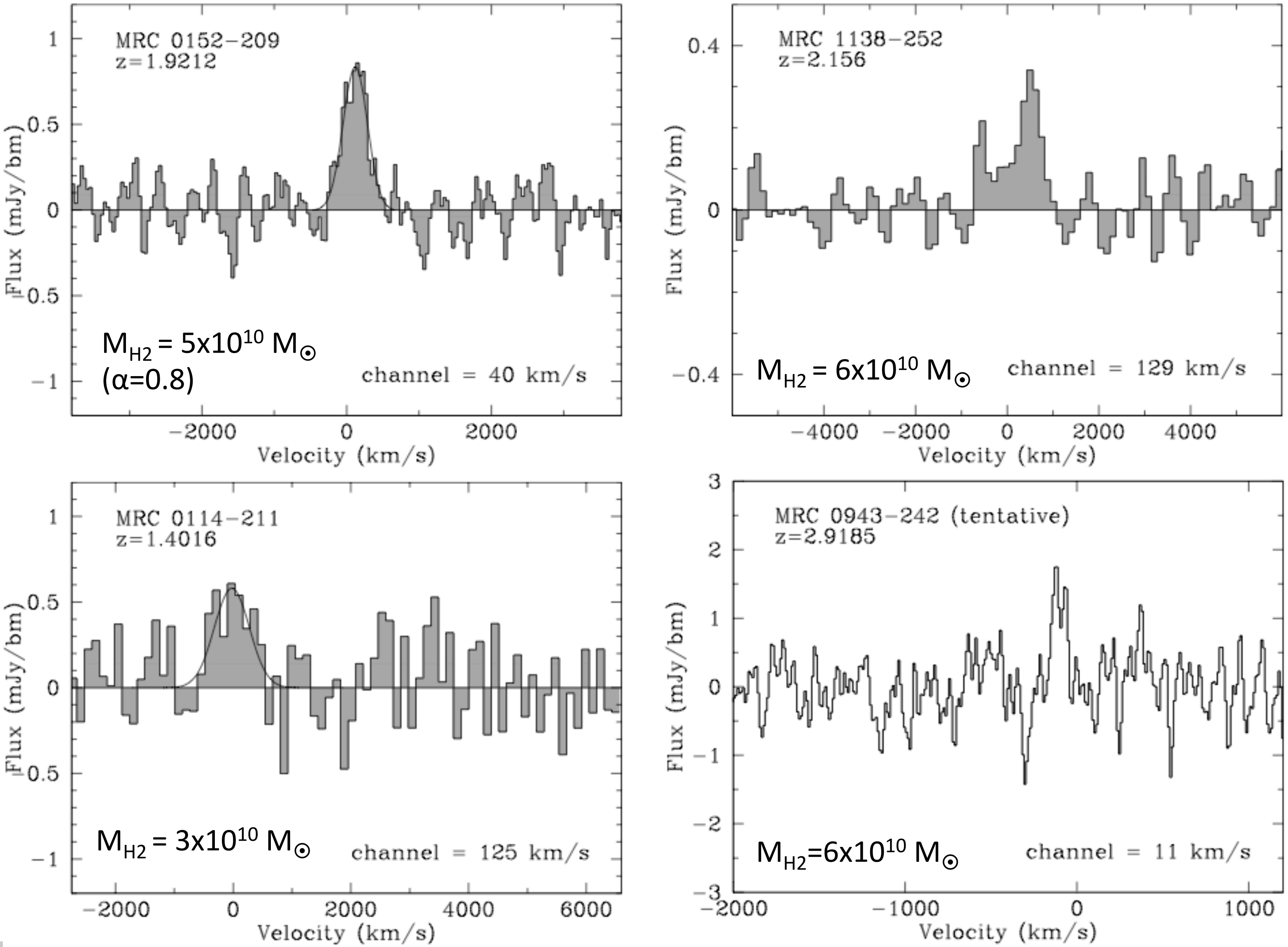

Emonts et al (2011a,b)

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

"Spiderweb" proto-cluster

z = 2.156

(23% of age Universe)

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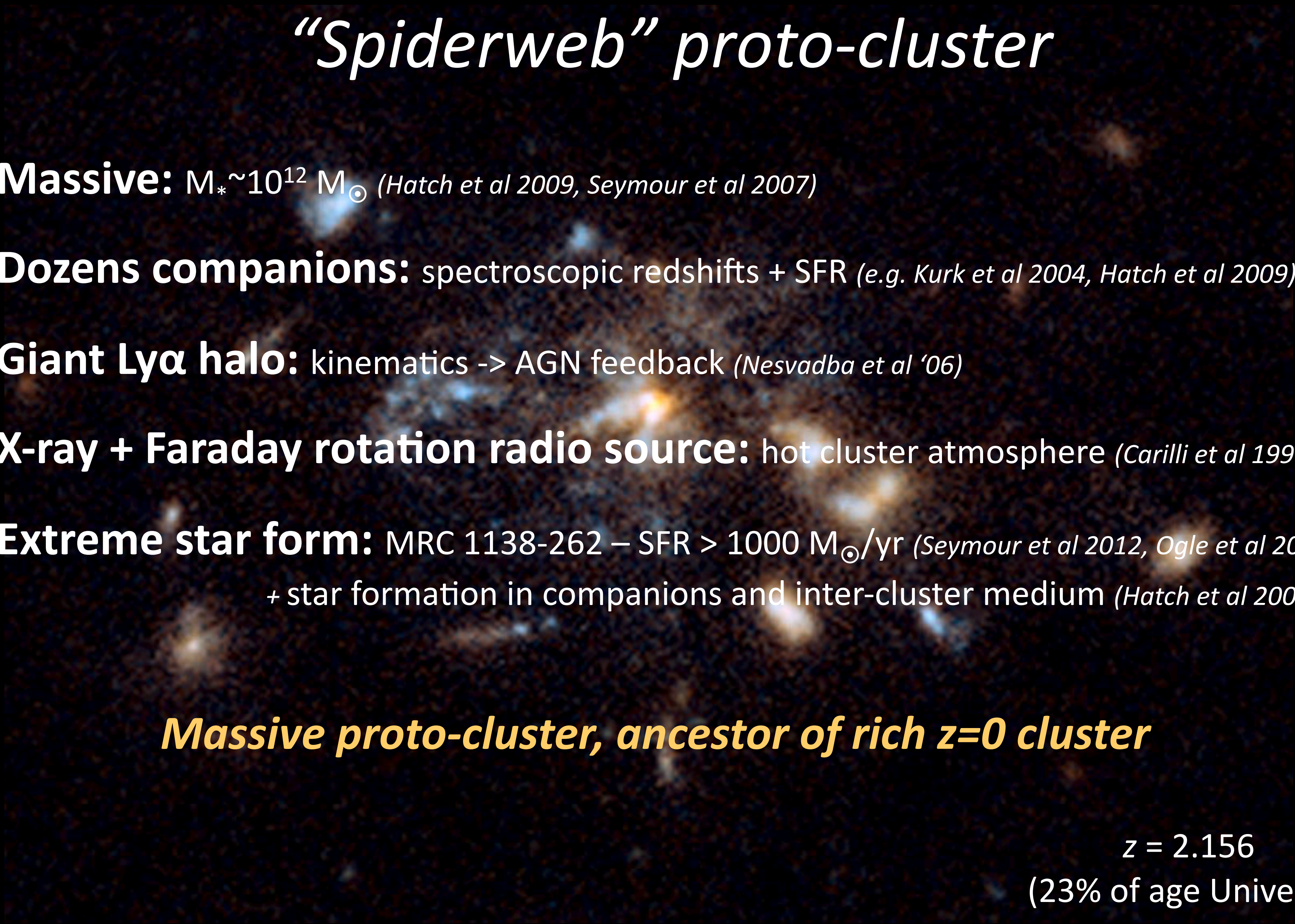

- **Massive:** M_*~10^{12} $M_\odot$ *(Hatch et al 2009, Seymour et al 2007)*
- **Dozens companions:** spectroscopic redshifts + SFR *(e.g. Kurk et al 2004, Hatch et al 2009)*
- **Giant Lyα halo:** kinematics -> AGN feedback *(Nesvadba et al '06)*
- **X-ray + Faraday rotation radio source:** hot cluster atmosphere *(Carilli et al 1997)*
- **Extreme star form:** MRC 1138-262 – SFR > 1000 $M_\odot$/yr *(Seymour et al 2012, Ogle et al 2012)*
  \+ star formation in companions and inter-cluster medium *(Hatch et al 2009)*

Massive proto-cluster, ancestor of rich z=0 cluster

z = 2.156
(23% of age Universe)

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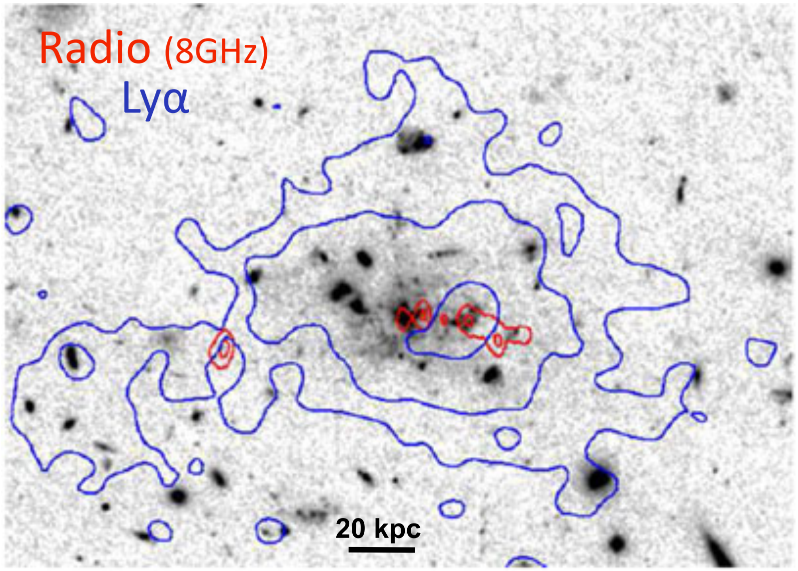
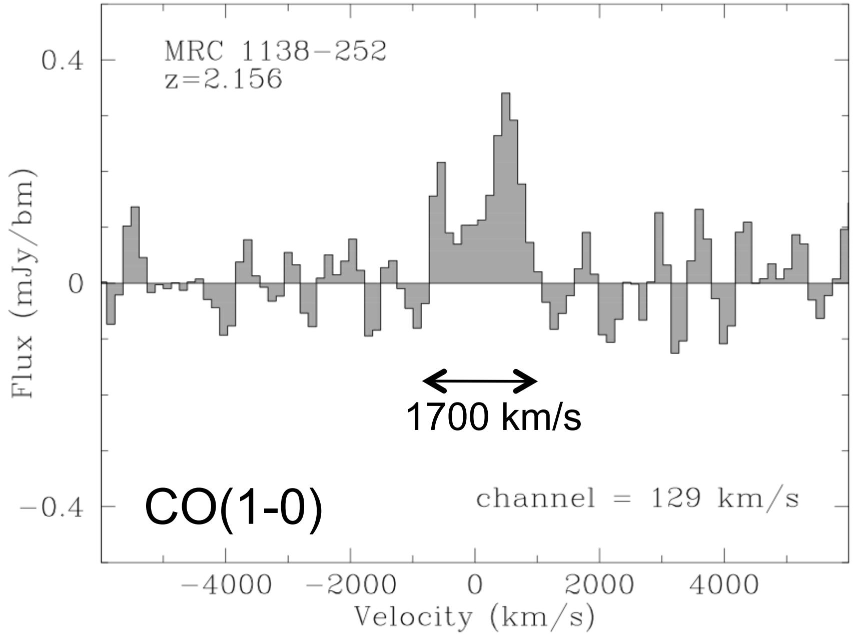
CSIRO

"Spiderweb" proto-cluster



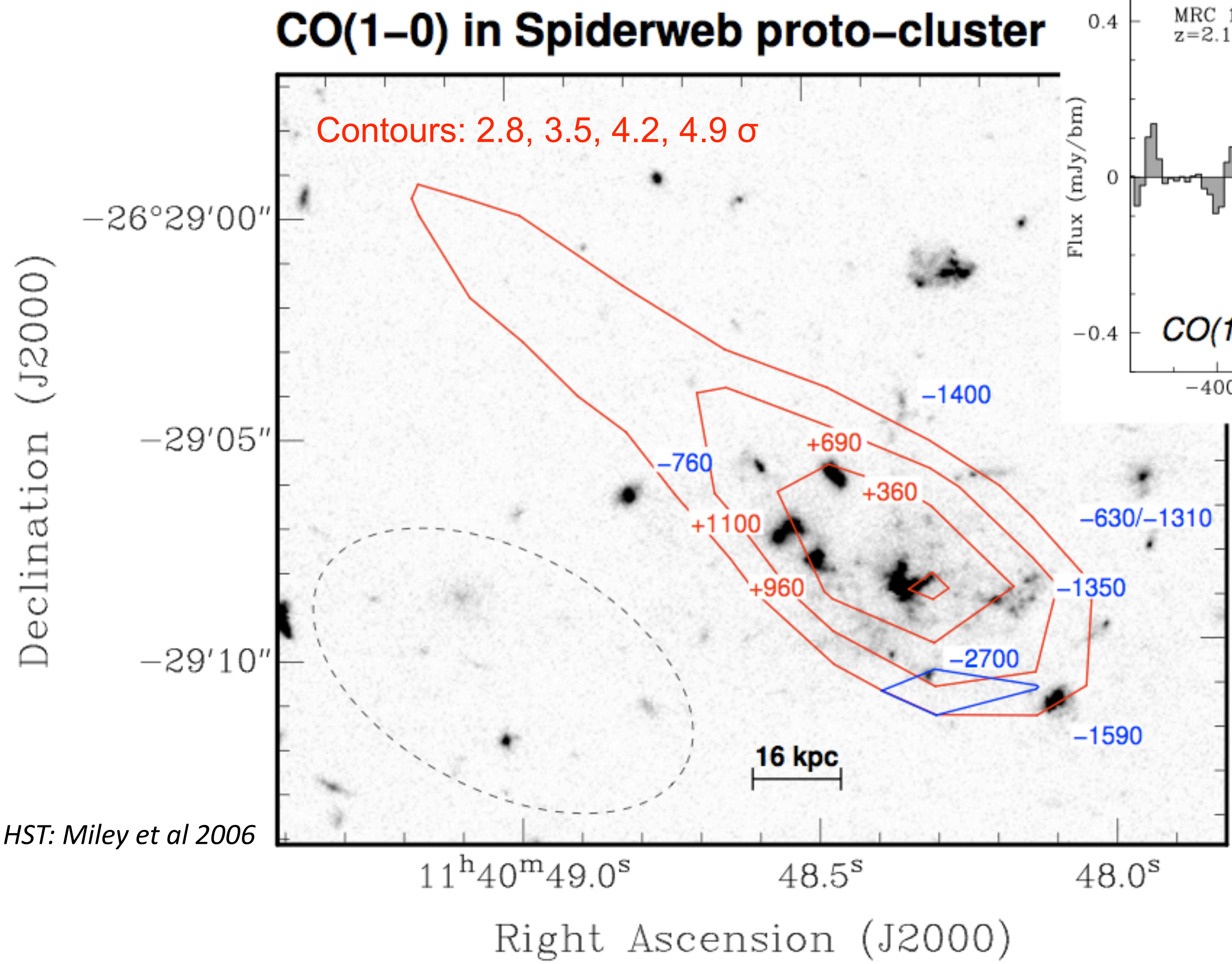
Pentericci et al 1997/2000
Miley et al 2006

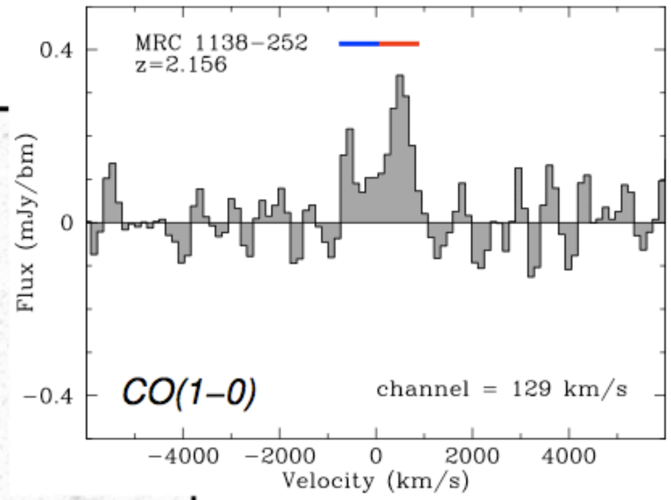


Emonts et al 2012 (in prep)

- **Cold molecular gas CO(1-0): $M_{H2} = 6 \times 10^{10}\ M_{\odot}$ [α_x=0.8]**
- Warm molecular gas H_2: $M_{H2} \leq 10^9\ M_{\odot}$ (*Spitzer; Ogle et al 2012*)

"Spiderweb" proto-cluster



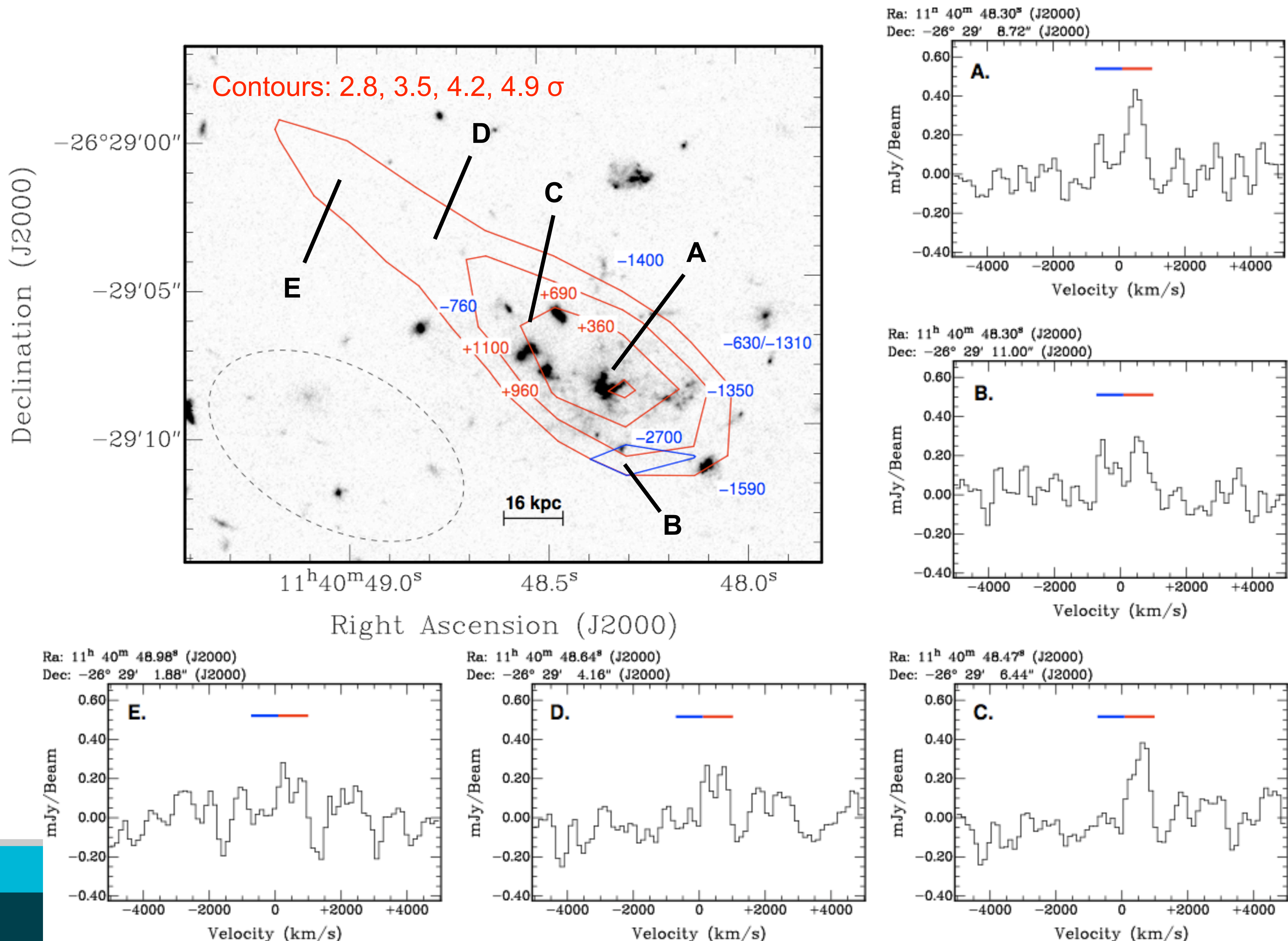


HST: Miley et al 2006

H75 + H168 array

Emonts et al 2012 (under review by team)

"Spiderweb" proto-cluster



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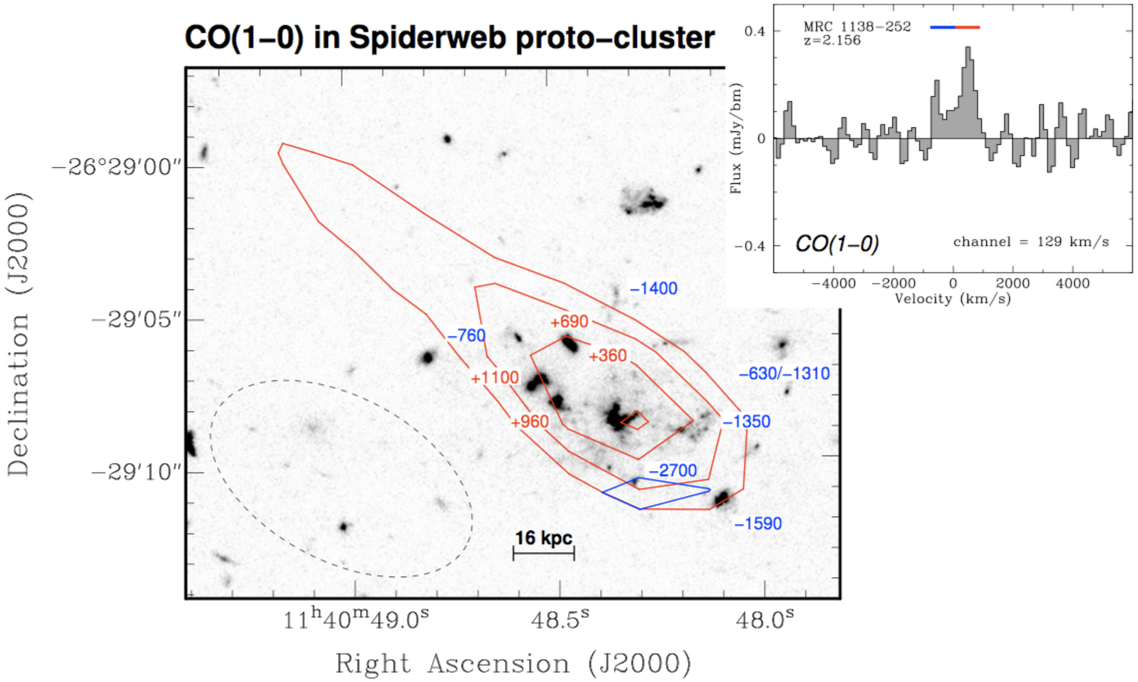
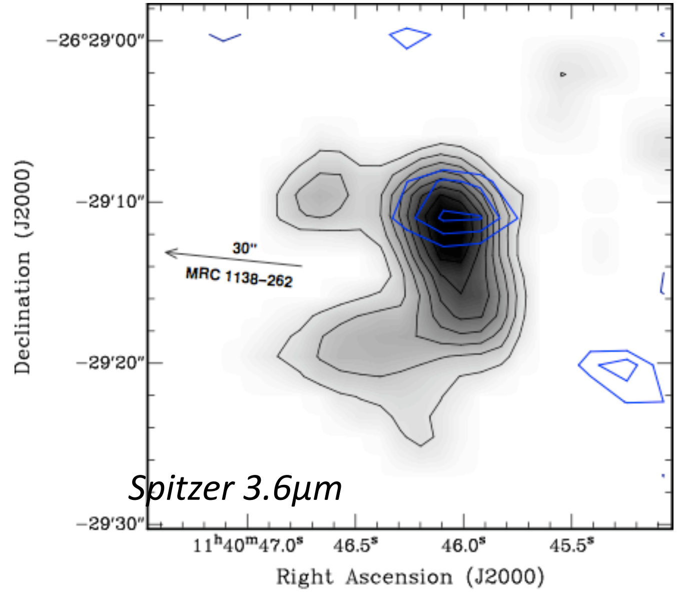
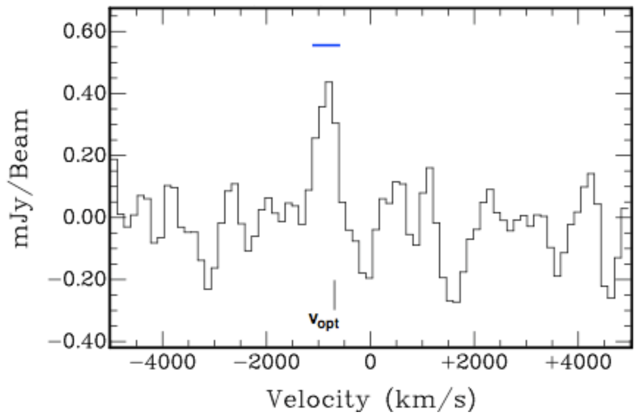


IR-bright companion HAE229
(280 kpc west of Spiderweb Galaxy)



- MRC 1138-262: M_{H2} = 6 × 10^{10} $M_\odot$ [α_x=0.8]
  - Up to ~40% of CO(1-0) could be in proto-cluster!
  - SFR ~ 1400 $M_\odot$/yr (Seymour e.a. 2012) → $t_{depletion}$ ≥ 41 Myr
    Short active phase of rapid mass buildup!

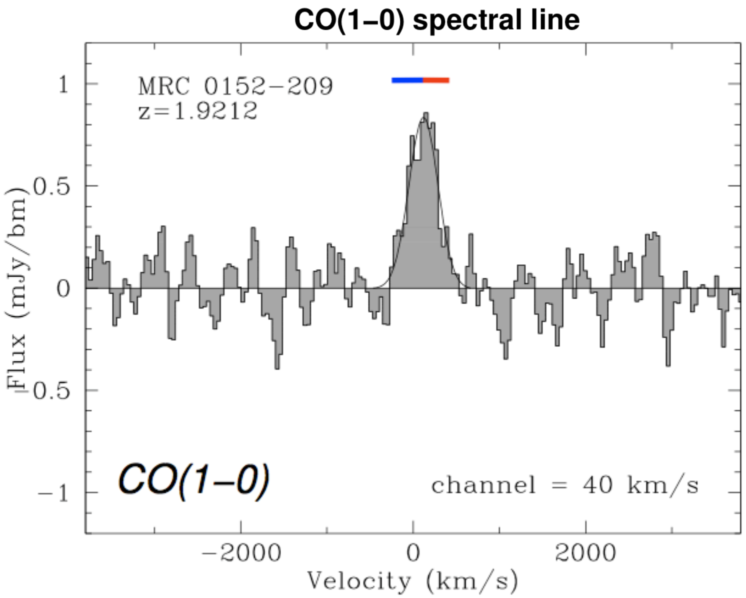


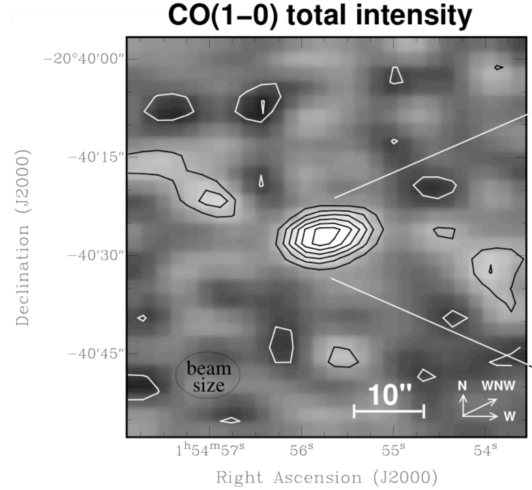
- HAE 229: M_{H2} = 3 × 10^{10} $M_\odot$ [α_x=0.8]

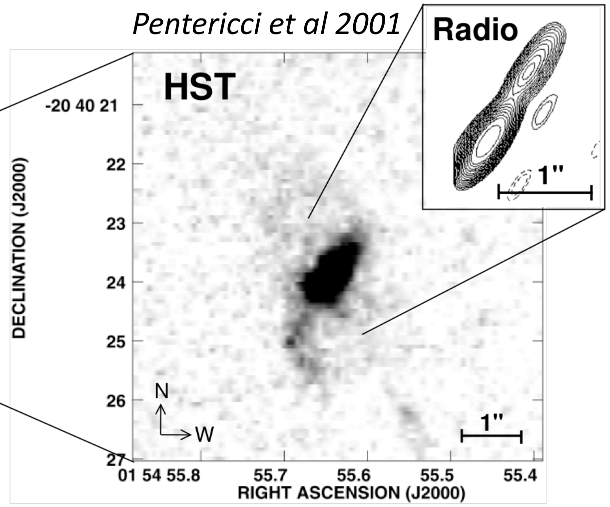
MRC 0152-209: strongest CO(1-0) to date

MRC 0152-209
(z=1.92)

Emonts et al. 2011a, ApJ, 734, L25







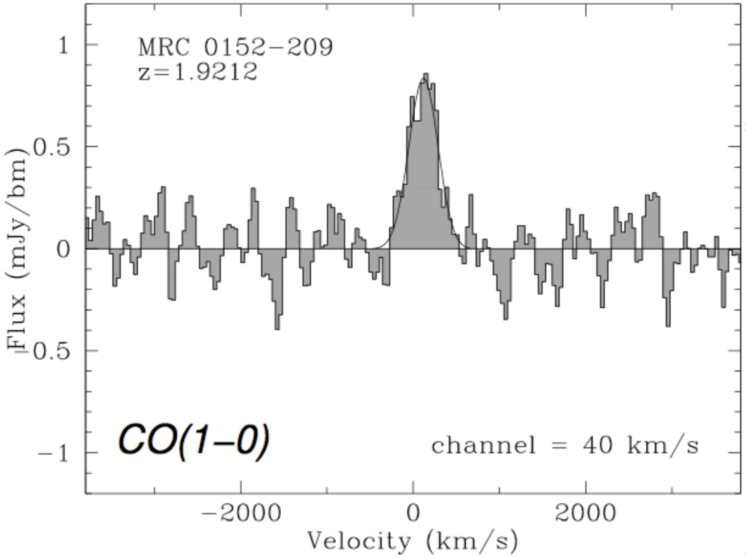
M_{H2} = 6 x 10^{10} M_s ($\alpha[M_{H2}/L_{CO}]$= 0.8)
Δv = 400 km/s

$L_{IR} \leq 7.9 \times 10^{12}\ L_{\odot}$ ($L_{IR}/L'_{CO} \leq 120$);
SFR ≤ 1362 $M_{\odot}$/yr -> $t_{depl} \leq 39$ Myr

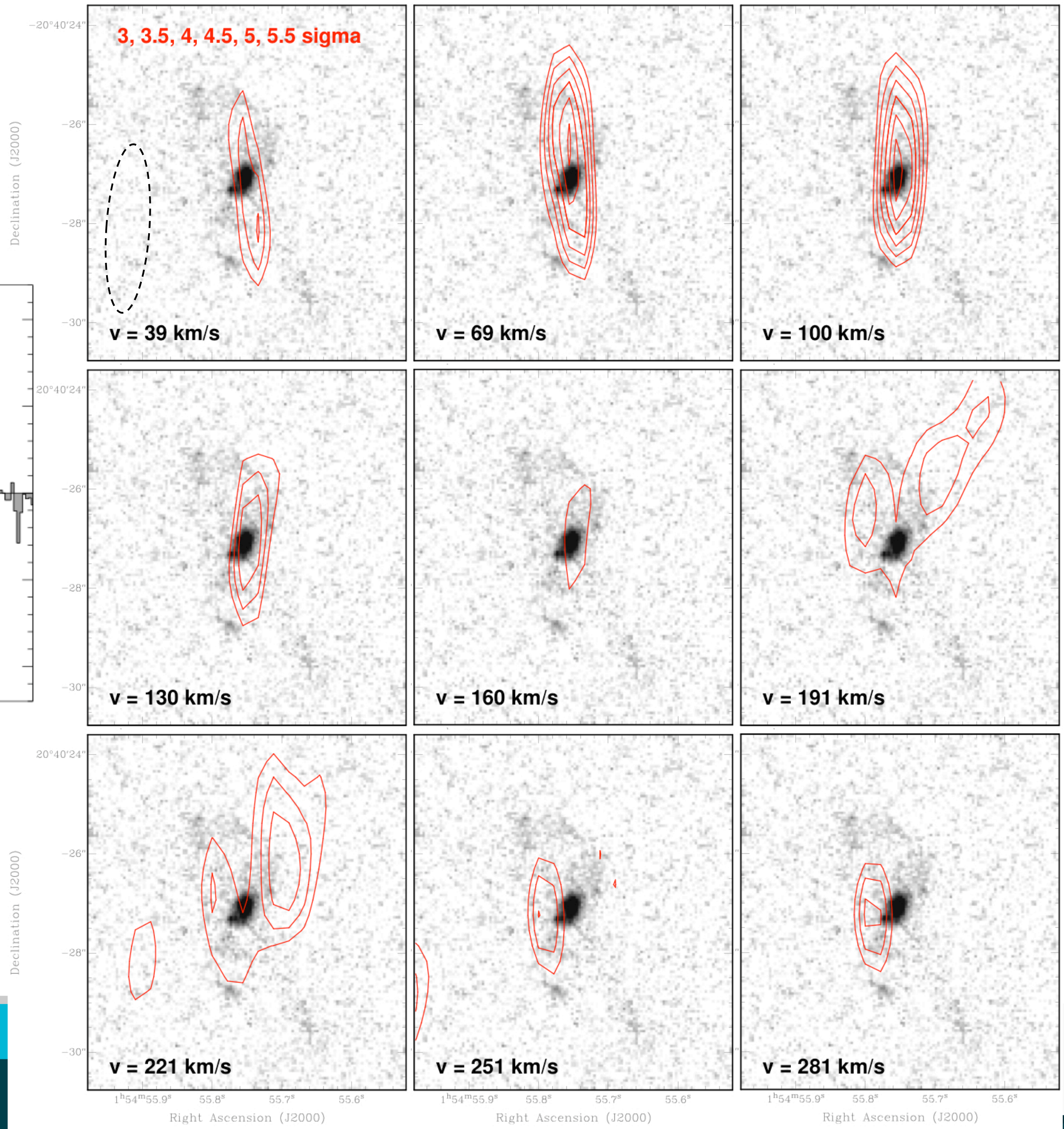
IR-bright `starbursting' merger-system that contains large amounts of molecular gas not yet depleted by star formation or radio-AGN feedback.

MRC 0152-209: strongest CO(1-0) to date

MRC 0152-209
(z=1.92)



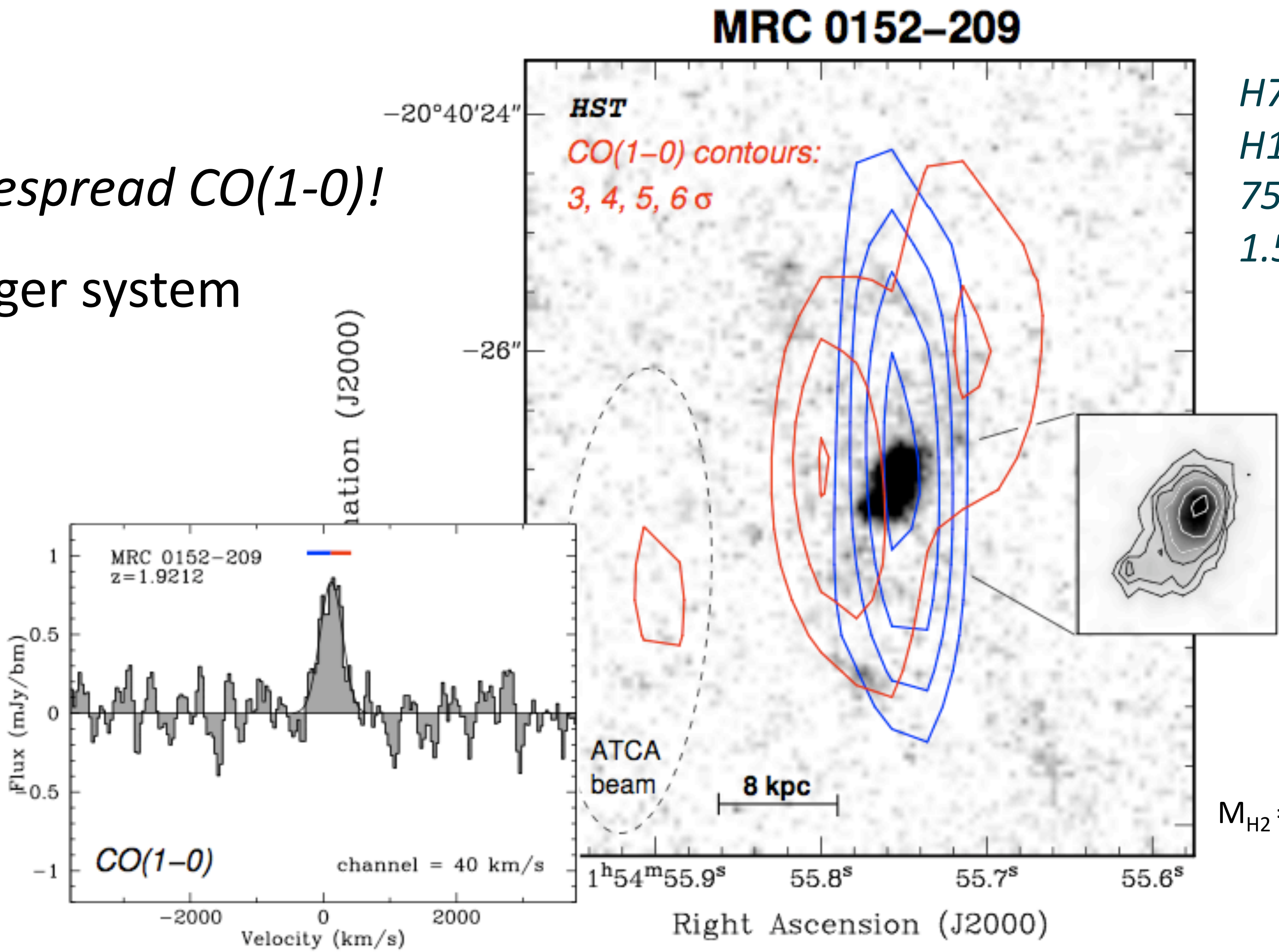
ATCA high-res follow-up: extended (750m + 1.5k) arrays →



Emonts et al (2011a)

MRC 0152-209: strongest CO(1-0) to date

- *Widespread CO(1-0)!*
- Merger system

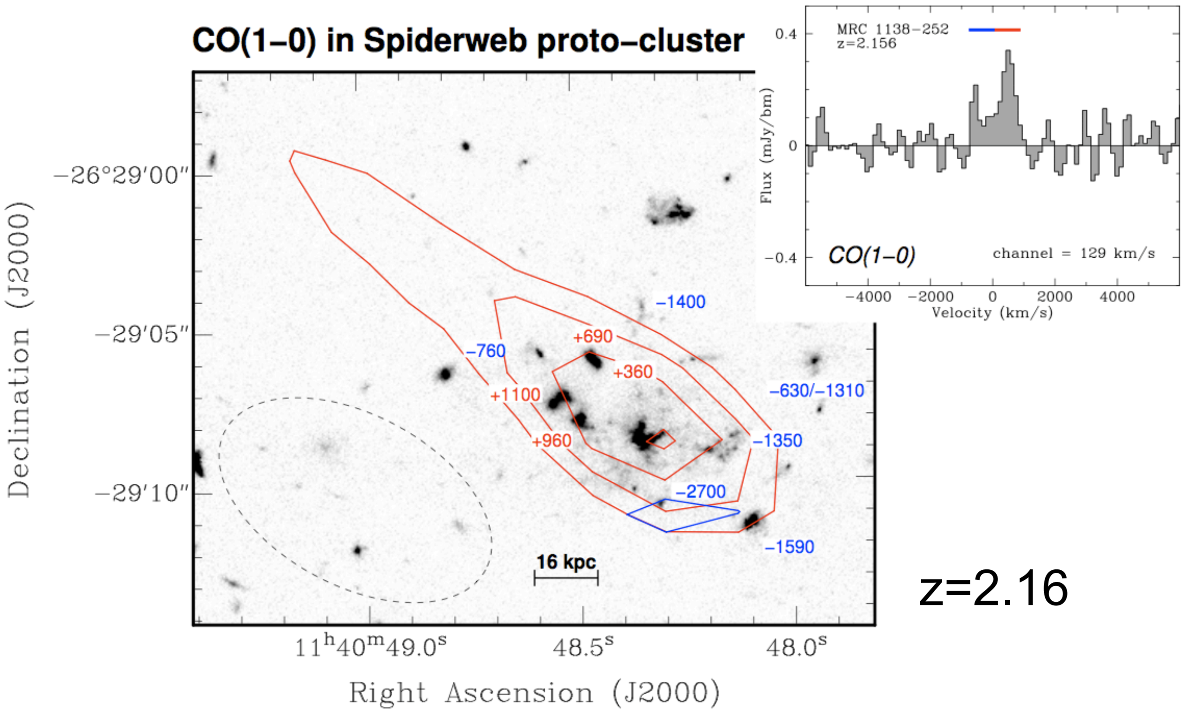


H75+
H168+
750m+
1.5k

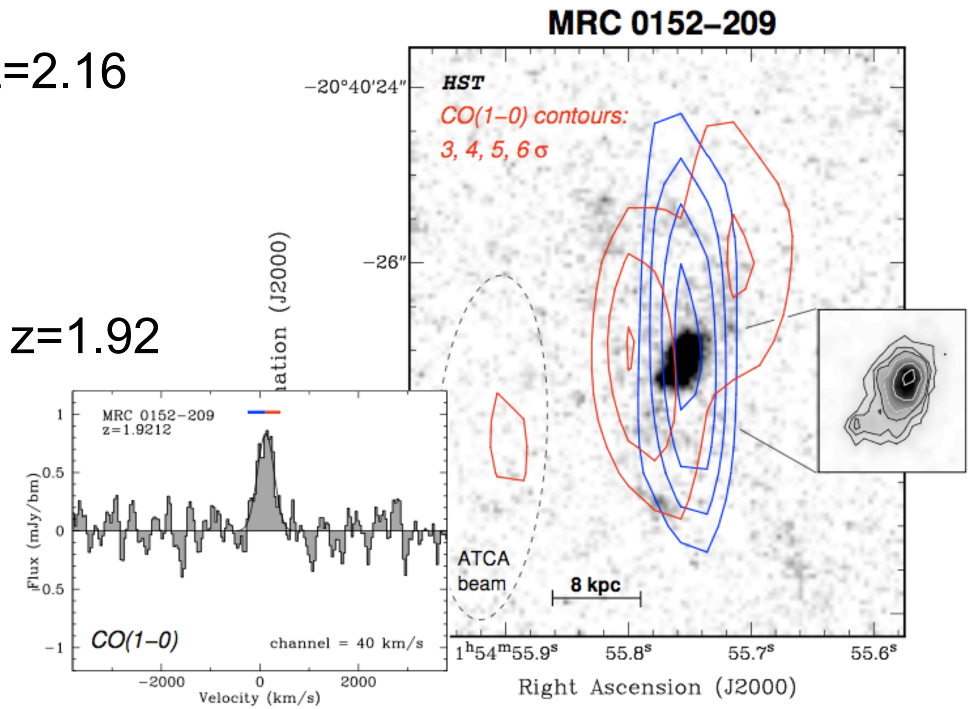
$M_{H2} = 5 \times 10^{10}\ M_{\odot}$

Emonts et al (2011a)

CO(1-0) in two HzRGs



z=2.16

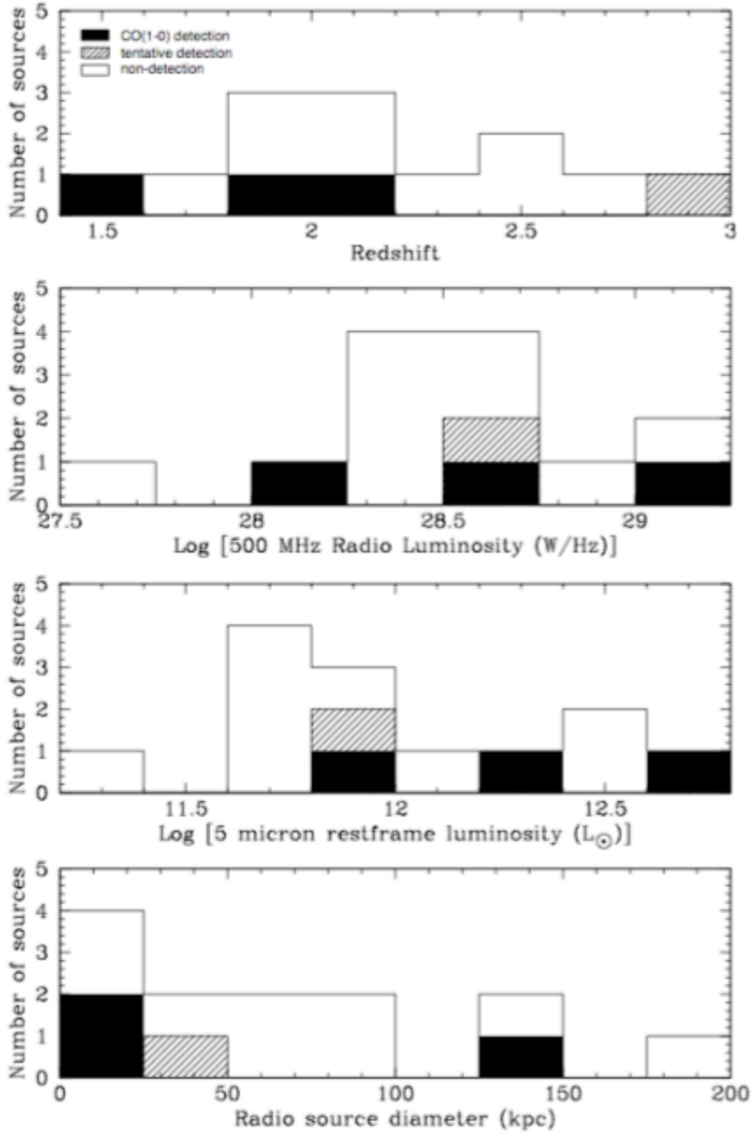


z=1.92

CO(1-0) → bulk of star forming gas

+ *widespread* component

CO(1-0) survey of HzRGs with ATCA/CABB



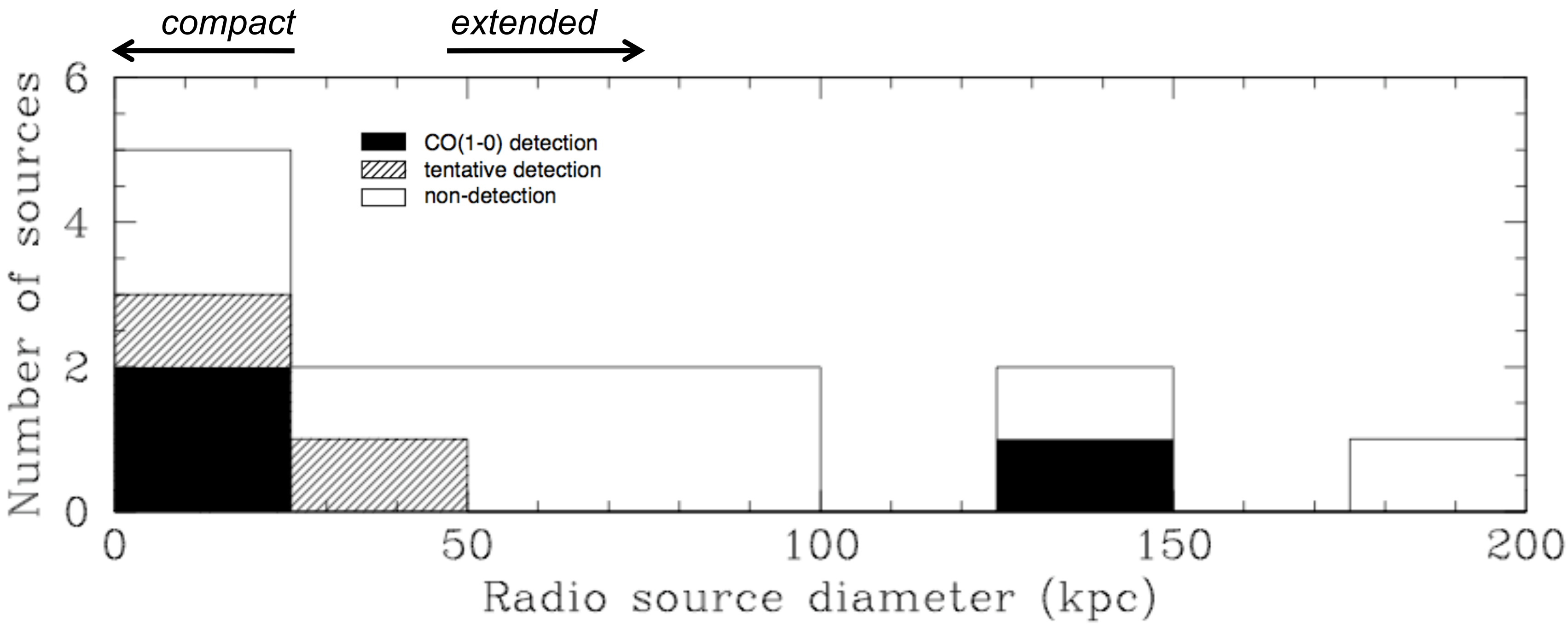
To do next:
compare CO(1-0) content with properties HzRGs

Emonts et al (in prep)

CSIRO

CO(1-0) survey of HzRGs with ATCA/CABB

50% of small (<25 kpc) vs. 14% of extended (>50 kpc) radio sources detected in CO(1-0)

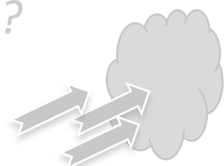


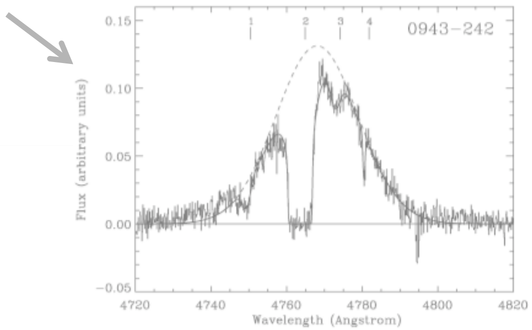
Similar trend in Lyα absorption of neutral hydrogen gas *(van Ojik e.a. 1997)*

Physical link between propagating radio jets and cold gas content?

- small radio sources constrained by large amounts of cold gas?

- propagating jets influence gas properties?





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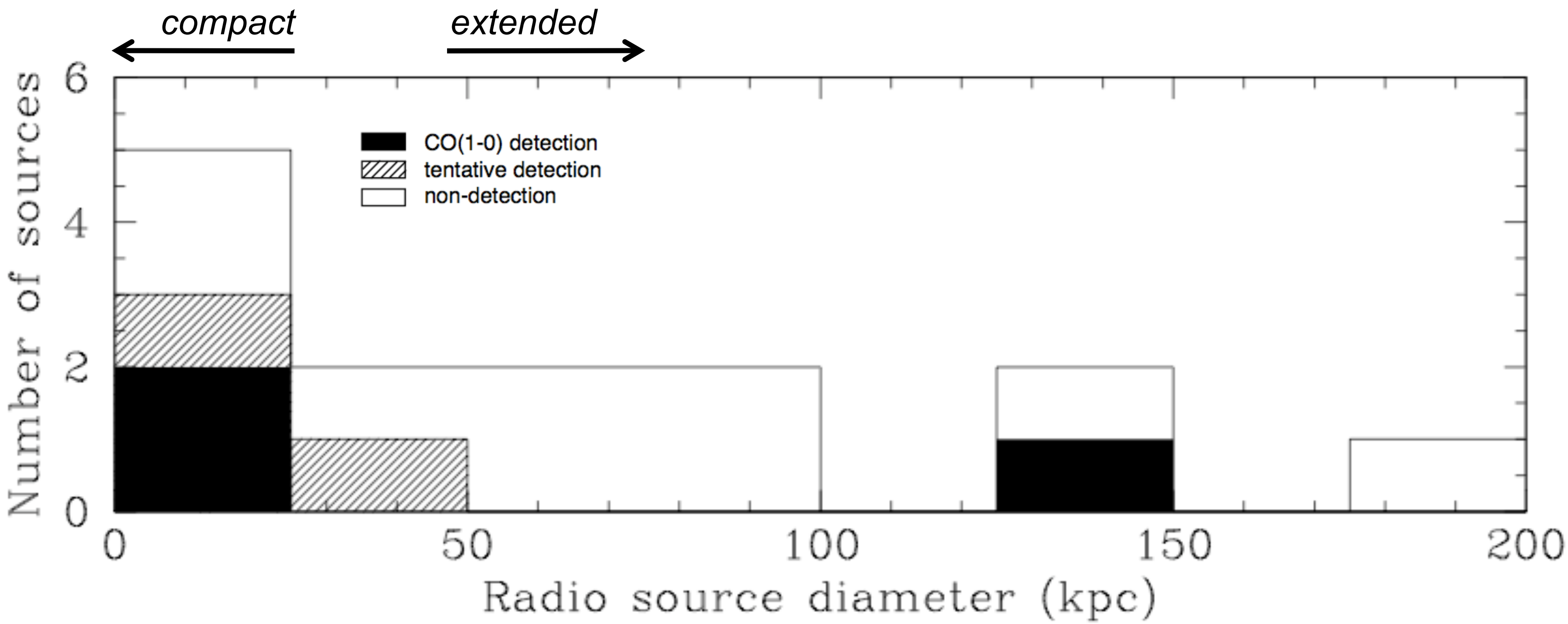

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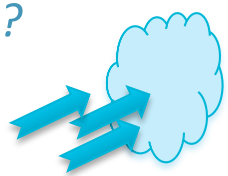
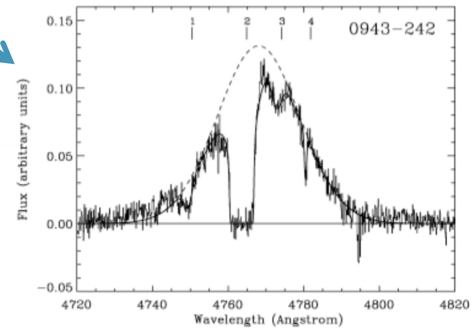
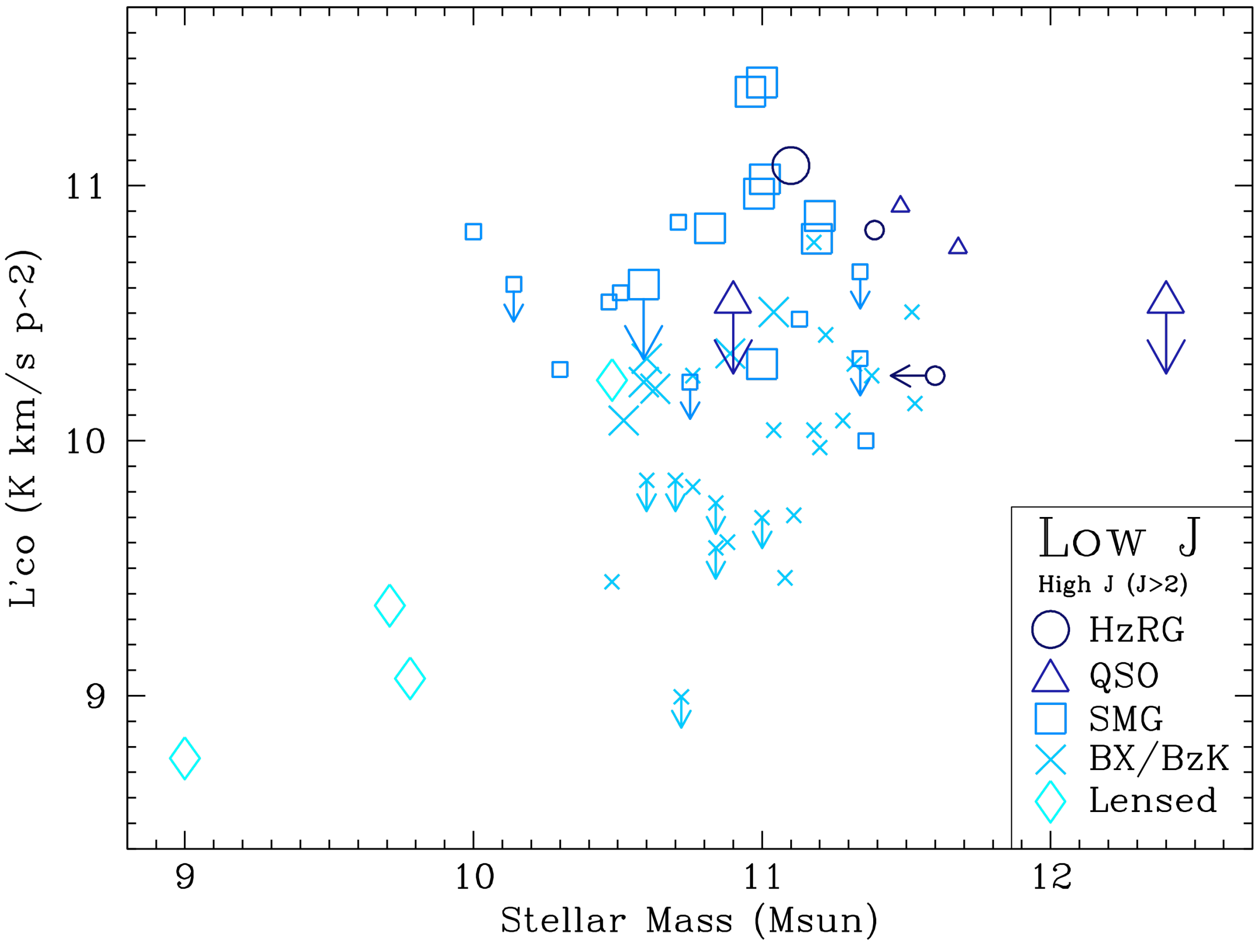
- propagating jets influence gas properties?





CO(1-0) survey of HzRG with ATCA/CABB

To do next: compare CO(1-0) content HzRGs with other high-z galaxies

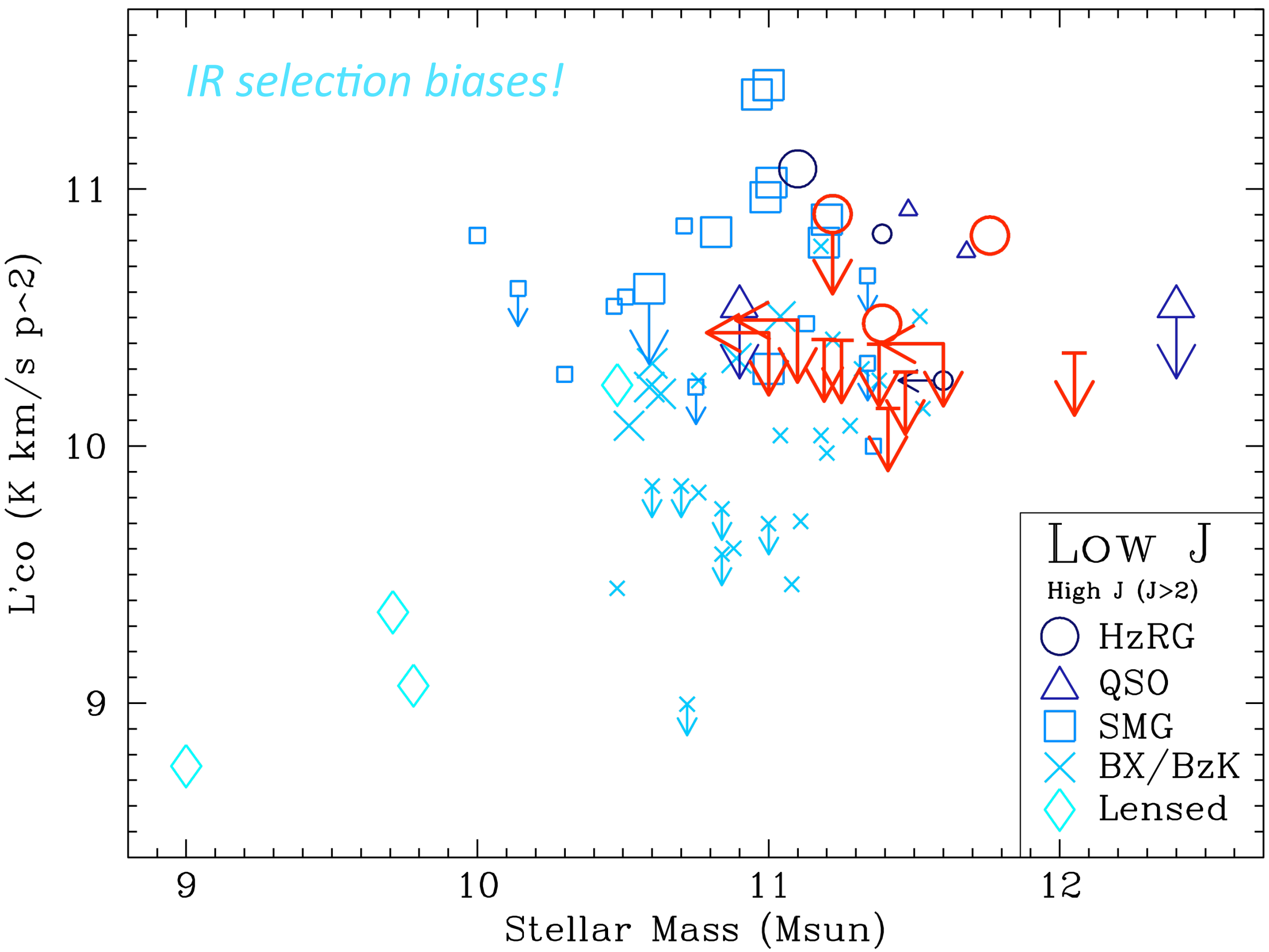


Post 2005 data:

Lacy+ '11, Martinez-Sansigre+ '11, Polletta+ '11, Greve+ '04,'05, Hainline+ '11, Ivison+ '10,'11, Riechers+ '10,'11, Coppin+ '10, Johansson+ '11, Kneib+ '04,'05, Danielson+ '10, Swinbank+ '10, Tacconi+ '08,'11, Daddi+ '10, Aravena+ '10, De Breuck+ '05, Klamer+ '05, Nesvadba+ '09

CO(1-0) survey of HzRG with ATCA/CABB

To do next: compare CO(1-0) content HzRGs with other high-z galaxies



Post 2005 data:

Lacy+ '11, Martinez-Sansigre+ '11, Polletta+ '11, Greve+ '04,'05, Hainline+ '11, Ivison+ '10,'11, Riechers+ '10,'11, Coppin+ '10, Johansson+ '11, Kneib+ '04,'05, Danielson+ '10, Swinbank+ '10, Tacconi+ '08,'11, Daddi+ '10, Aravena+ '10, De Breuck+ '05, Klamer+ '05, Nesvadba+ '09

"The search for molecules in the early Universe"

Figure 1: *Nineteen antennas at the ALMA high site, the AOS, in September 2011. (Photo W. Garnier © ALMA (ESO/NAOJ/NRAO))*

Conclusions

- Australia Telescope Compact Array
  - Excellent southern telescope for high-z mm studies
  - Observing frequencies <50 GHz excellent compliment to ALMA

- CO(1-0) survey of high-z radio galaxies (HzRGs) with ATCA
  - CO(1-0) in HzRGs: first sample results:
    - *Widespread CO(1-0) in MRC 0152-209 and Spiderweb Galaxy*
    - *Potential link between CO(1-0) content and radio source size*

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Thank you