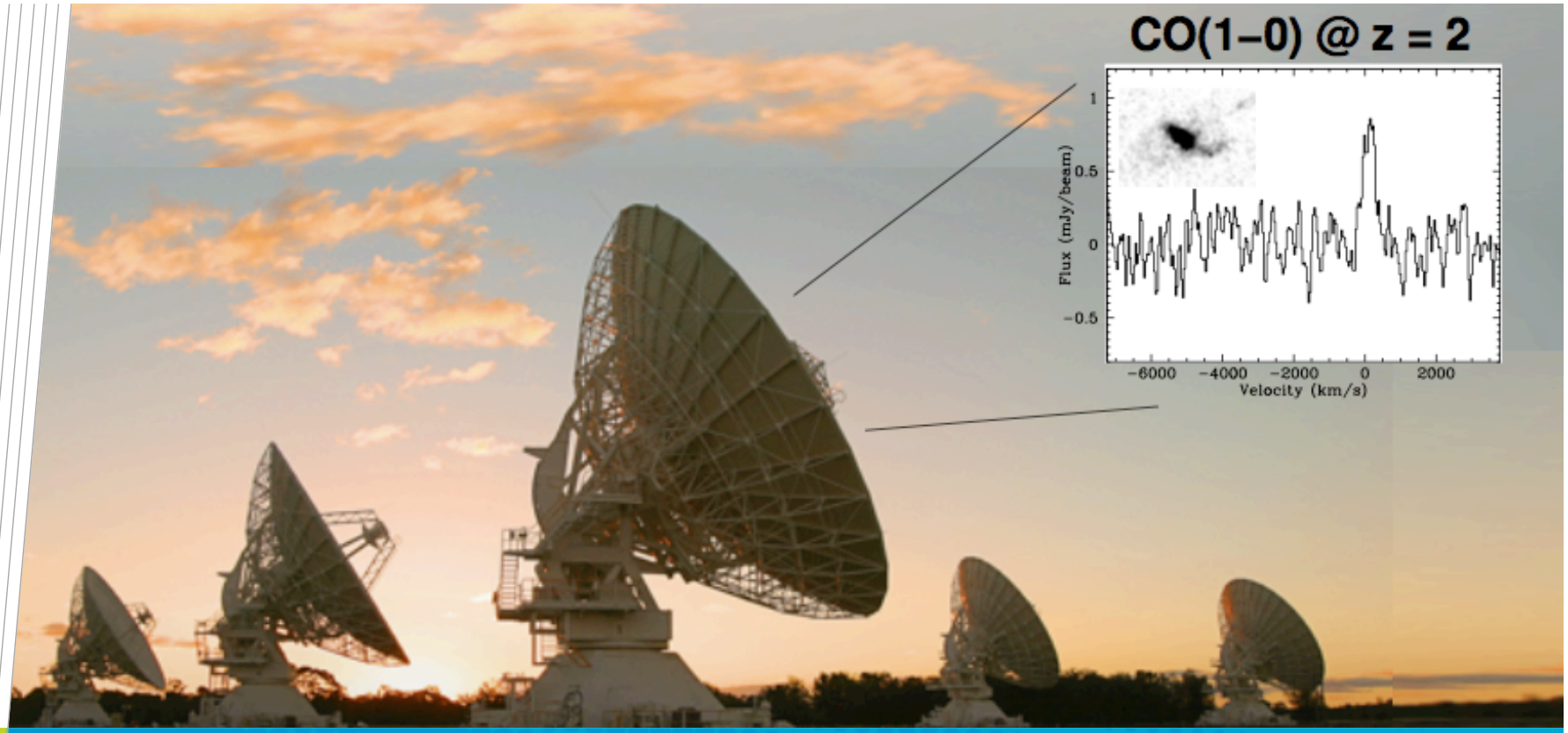


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# CO(1-0) survey of high-z radio galaxies with the Australia Telescope Compact Array

**Bjorn Emonts** *(CSIRO Astronomy & Space Science/ATNF)*

# This talk

- Australia Telescope Compact Array upgrade

  Excellent southern telescope for high-z mm studies

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

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

*Team:*

**Minnie Mao** *(U. Tasmania)*
**Ilana Feain** *(CASS)*
**Ray Norris** *(CASS)*
**George Miley** *(Leiden Obs.)*
**Montse Villar-Martin** *(IAA Granada)*
**Huub Rottgering** *(Leiden Obs.)*
**C. Carilli** *(NRAO)*
**Ron Ekers** *(CASS)*
**Elaine Sadler** *(U. Sydney)*

**J. Holt, G. van Moorsel D.J. Saikia, E. Mahony, J. Stevens, T. Oosterloo, R. Morganti, G. Rees, K. Coppin, M.Wieringa, K. Randall, A. Berciano, C. Tadhunter**

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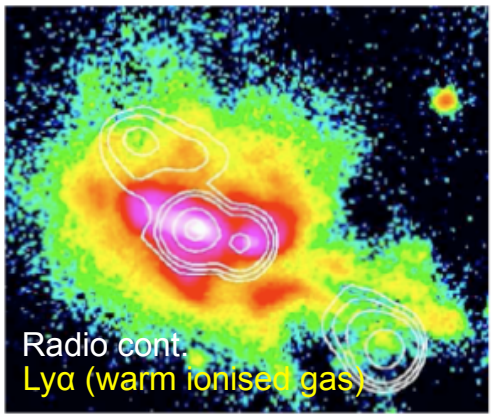
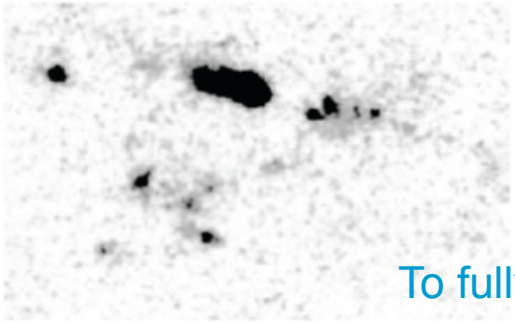
# High-z Radio Galaxies (HzRG)

- Most massive galaxies in Early Universe
  - Central proto-cluster galaxies *(e.g. Venemans et al. 2007)*
    → anchestors of local rich cluster ellipticals
  - Clumpy optical morphology (merging systems) *(Pentericci et al. 2001)*;
  - Radio jets vigorously interact with ISM *(Humphrey et al. 2006)* + alignments jets with UV/optical and 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)**

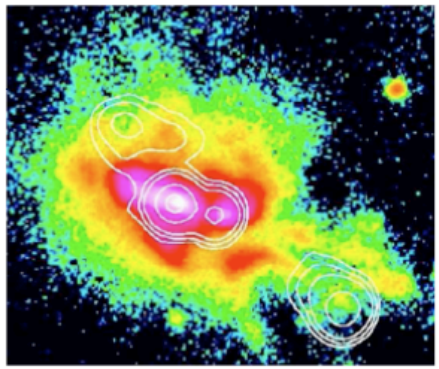
To fully understand HzRGs:
*Holistic approach!*

# Molecular gas in HzRG

- Molecular gas: raw ingredient for star formation
  - $H_2$ virtually invisible -- $^{12}CO$ strong tracer (rotational transitions): CO(1-0) [115 GHz], CO(2-1) [230 GHz], CO(3-2) [345 GHz], CO(4-3) [460 GHz], etc.
  - 1991: First observations of CO at $z > 2$ *(Brown & Vanden Bout 1991)*
- 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 aligned with radio jets *(Klamer et al 2004)*

**4C41.17 ($z$ = 3.8)**

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



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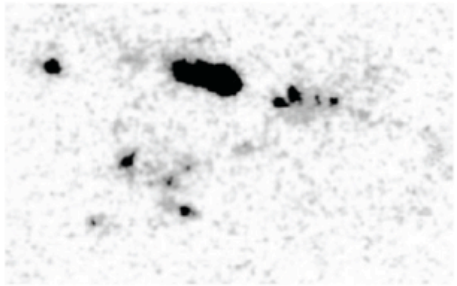
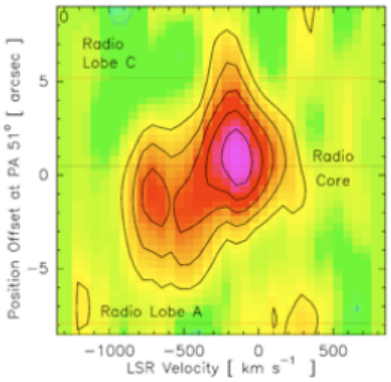


**HST Image, WFPC2 (7000A)**




**CO(4-3)**

*De Breuck et al. (2005)*

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# CO studies of HzRG

- 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 by observations of high-order transitions* *(e.g.Papadopoulos et al. 2000,2001, Greve et al. 2003, 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 (incl low-density, widespread and sub-thermally excited component) – crucial for tracing the overall molecular gas content!*

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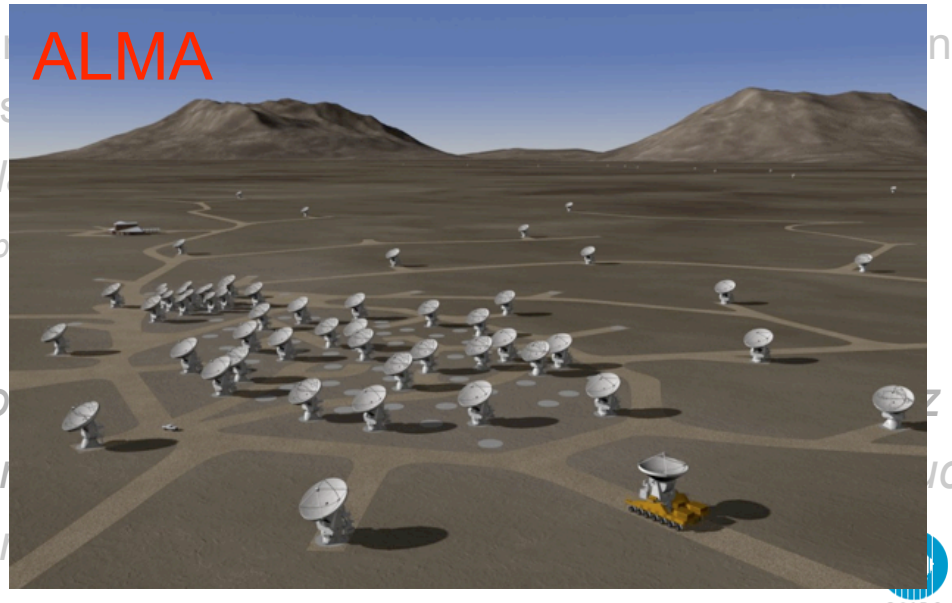
    Only target higher-order CO(*J,J-1*) transition at high-z.
    - High-order transitions: dense a… …n;
    - Low-order transitions: less dens…
      → *large reservoirs of molecul…*
      *order transitions (e.g.Papadop…*
      *Daddi et al. 2010, Carilli et al. 2010,…*

*Ground-transition CO(1-0): mo… …z*
*(incl low-density, widespread a… …ucial*
*for tracing the overall molecular…*

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# CO studies of HzRG

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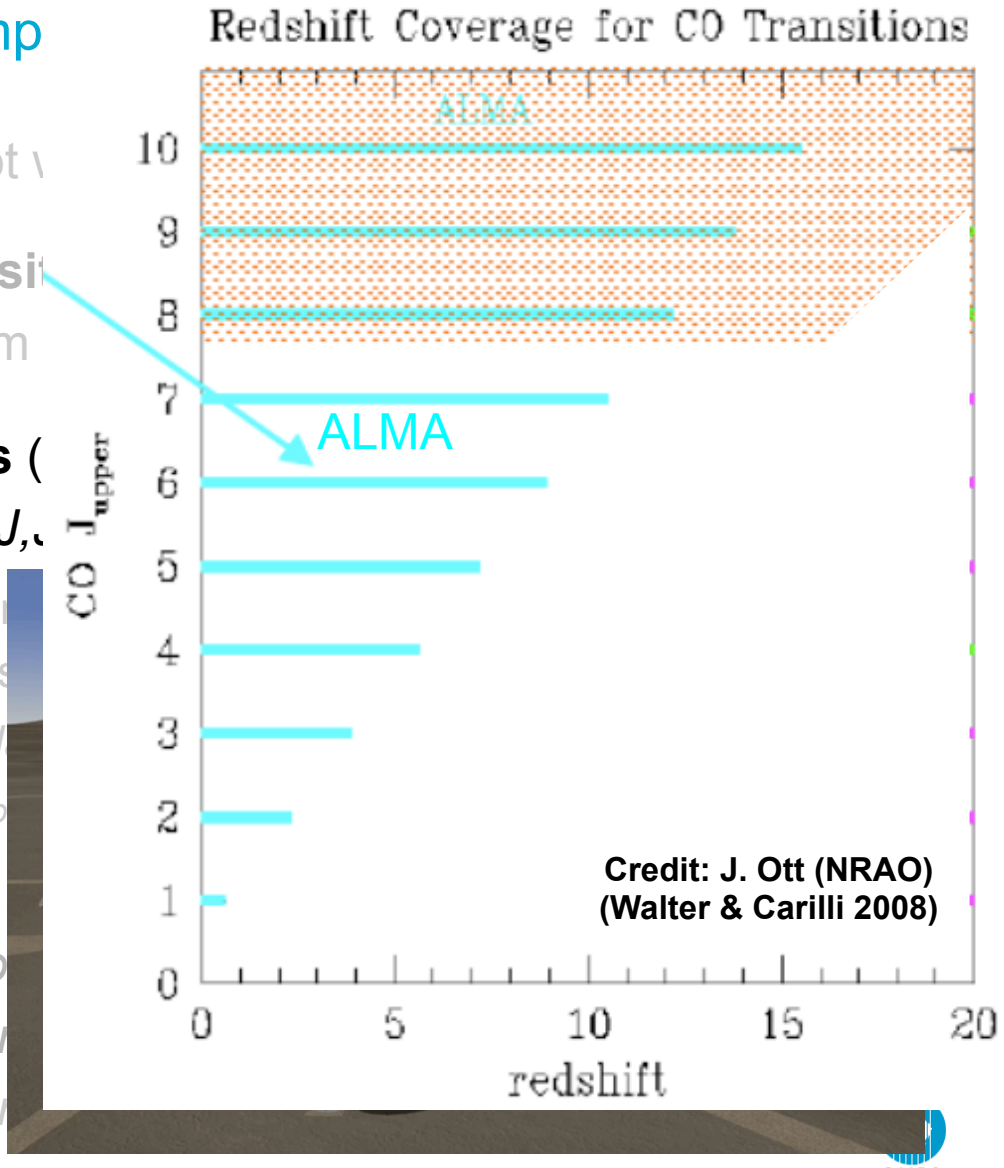

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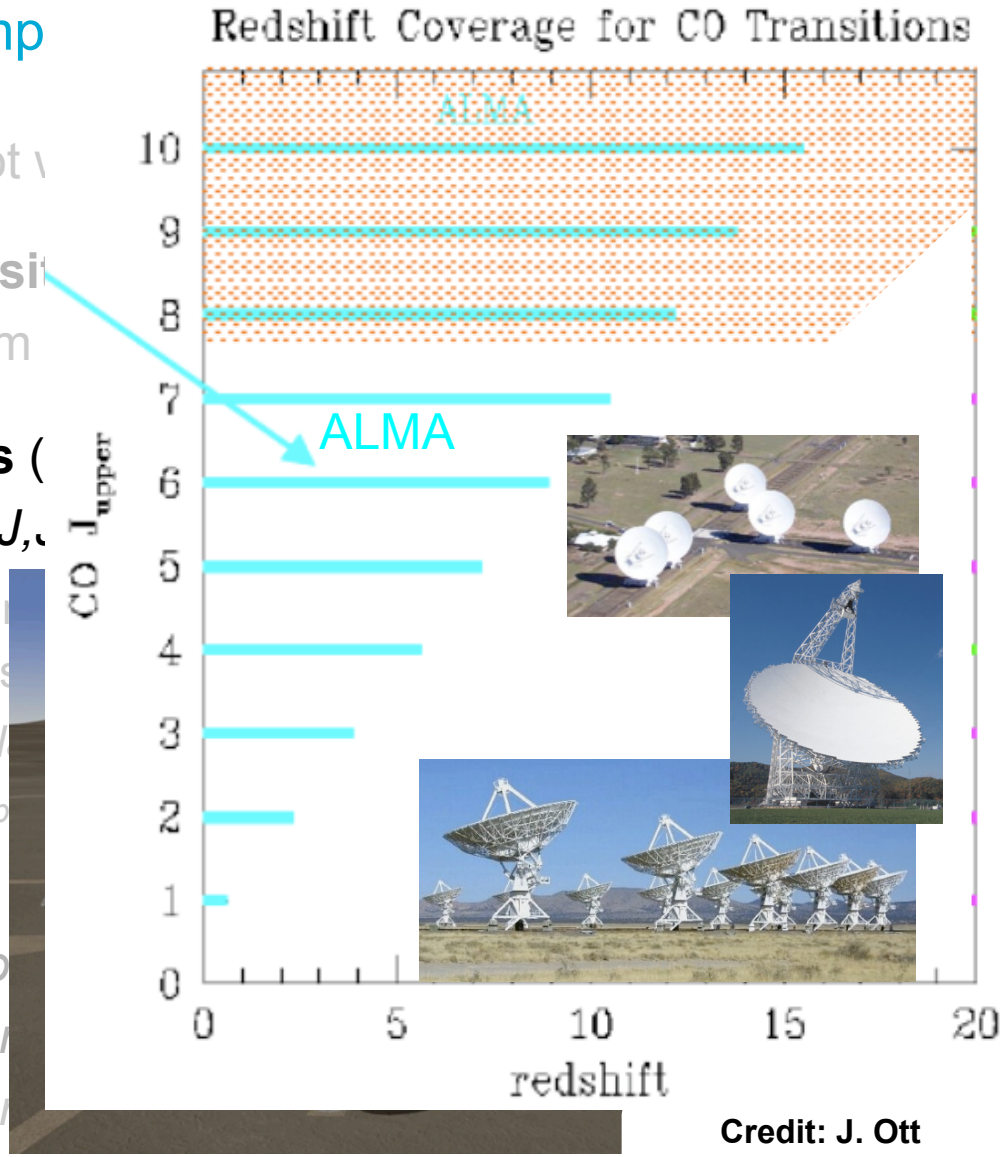


Credit: J. Ott
(Walter & Carilli 2008)

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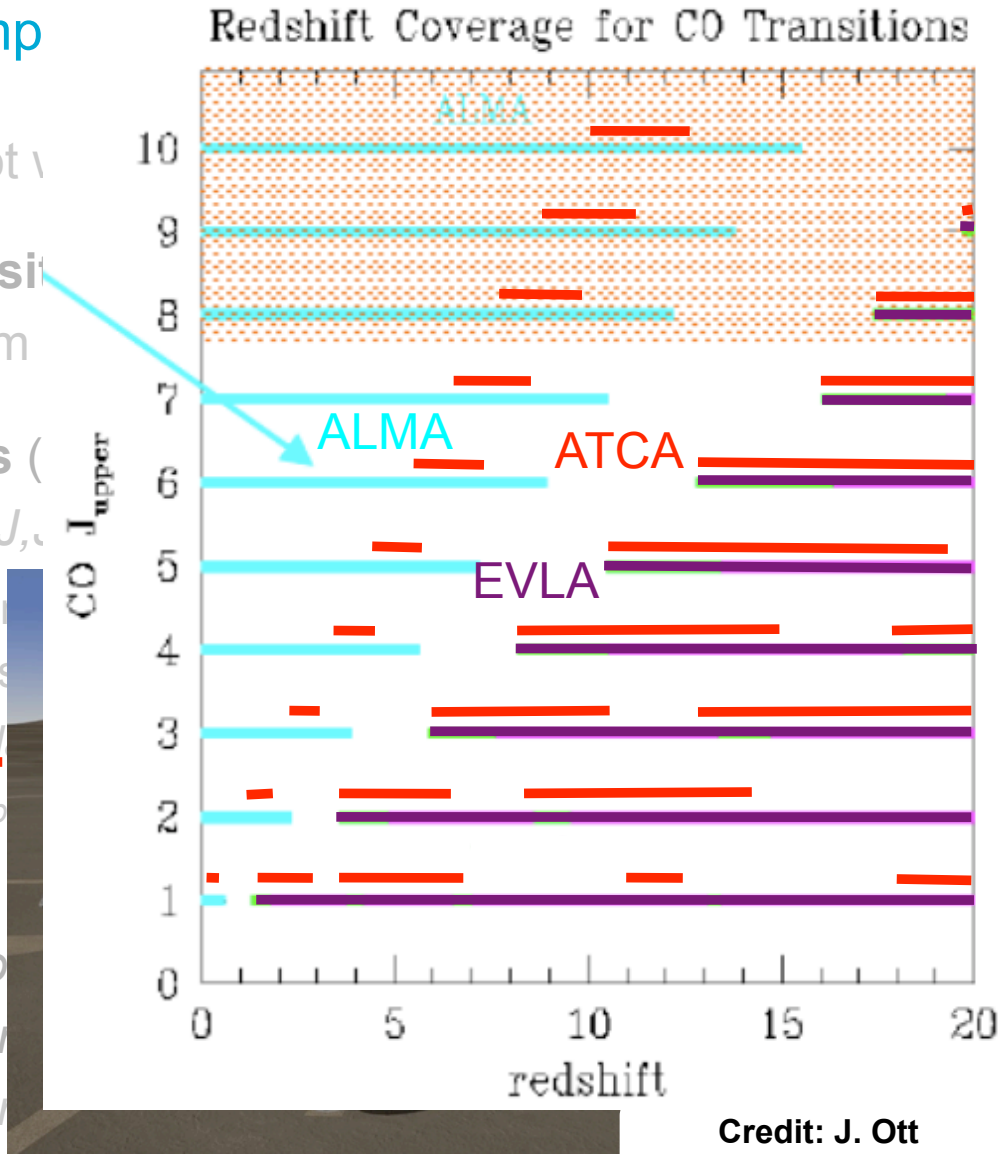


Credit: J. Ott
(Walter & Carilli 2008)

# Australia Telescope Compact Array

- upgraded with *Compact Array Broadband Backend (CABB)* in 2009

• 4 (2x2) GHz bandwidth, 1 MHz coarse res., full stokes

• 16 zoom-windows for high-resolution per band

• Observing frequencies 1.1 - 105 GHz

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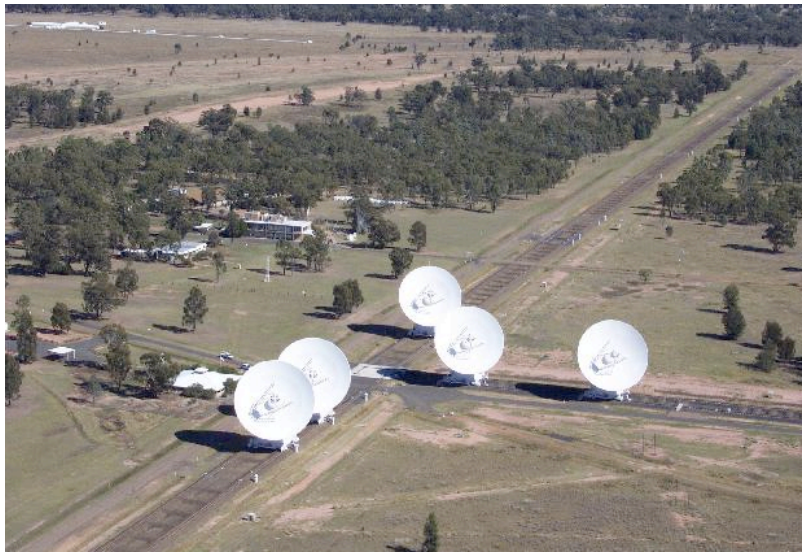
# Australia Telescope Compact Array

- upgraded with *Compact Array Broadband Backend (CABB)* in 2009



• 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*

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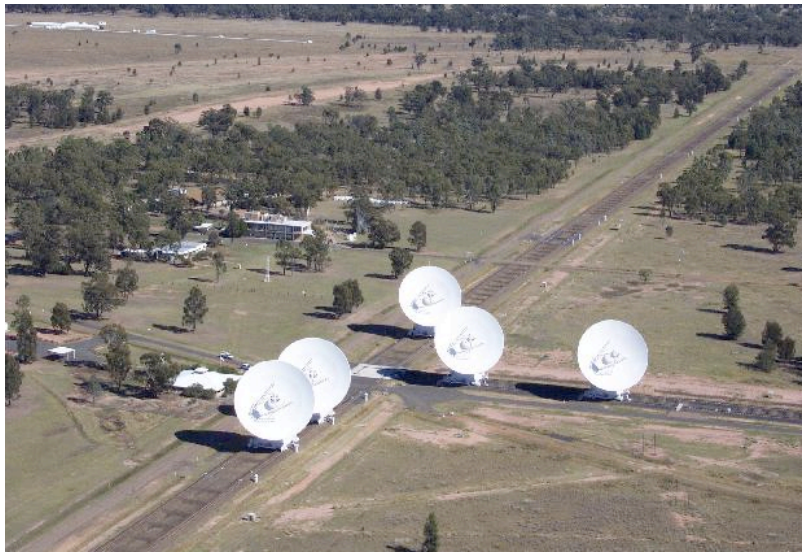
# Australia Telescope Compact Array

- upgraded with *Compact Array Broadband Backend (CABB)* in 2009



- 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.

- EVLA 27 vs ATCA 5/6 dishes;
  ATCA H75: 15 baselines <100m
  EVLA D-array: 41 baselines <100m
  (12% of all baselines)
  → EVLA 'E-array'
- EVLA mm-observations only down to dec ~ -25 deg

**Similar for EVLA/WIDAR in the northern hemisphere**

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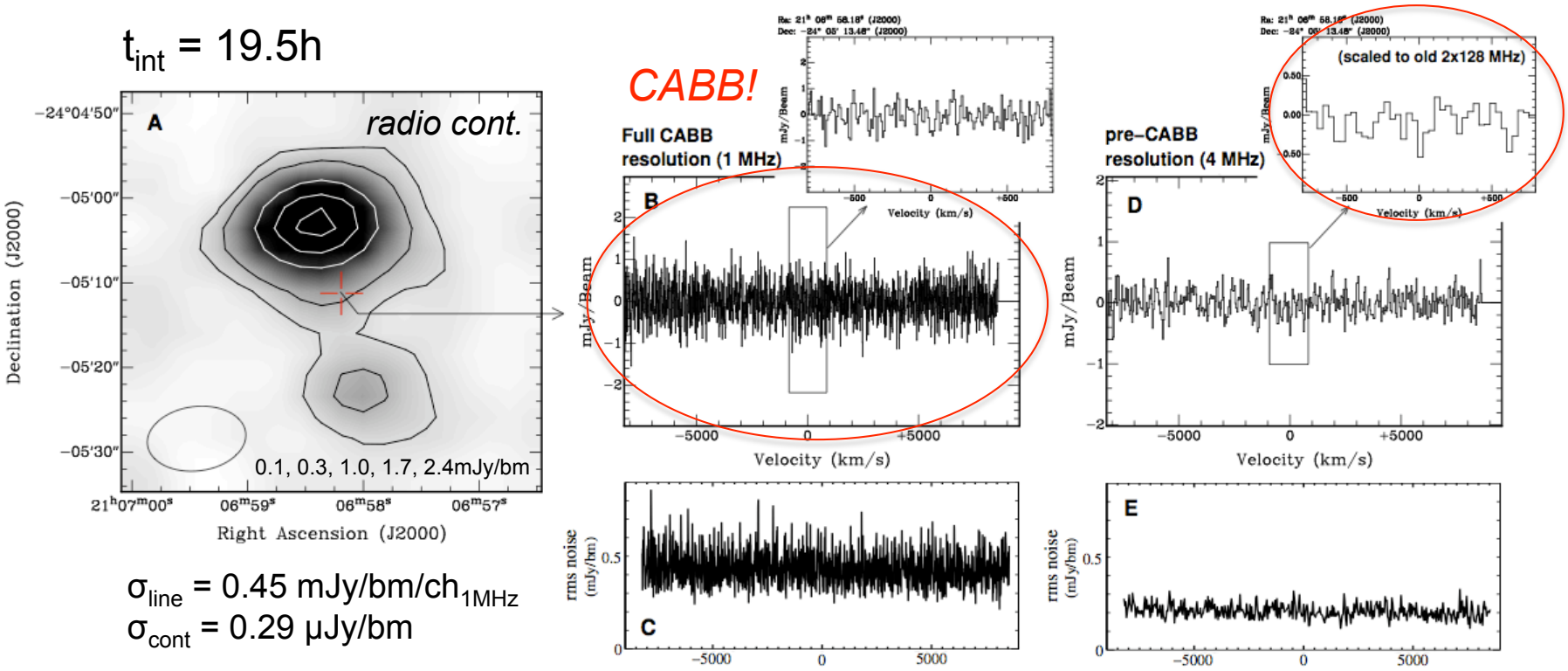
# CO(1-0) survey of HzRG with ATCA/CABB

- Pilot study: **Performance of ATCA/CABB**
  - **MRC 2104-242 (*z* = 2.5)**; $f_{obs}$ = 33 GHz (optimum CABB freq.)
  - Upper limit $\mathbf{M_{H2} < 2 \times 10^{10} M_{sun}}$ ($\alpha[M_{H2}/L_{CO}]$= 0.8)

*pre-CABB*

$t_{int}$ = 19.5h

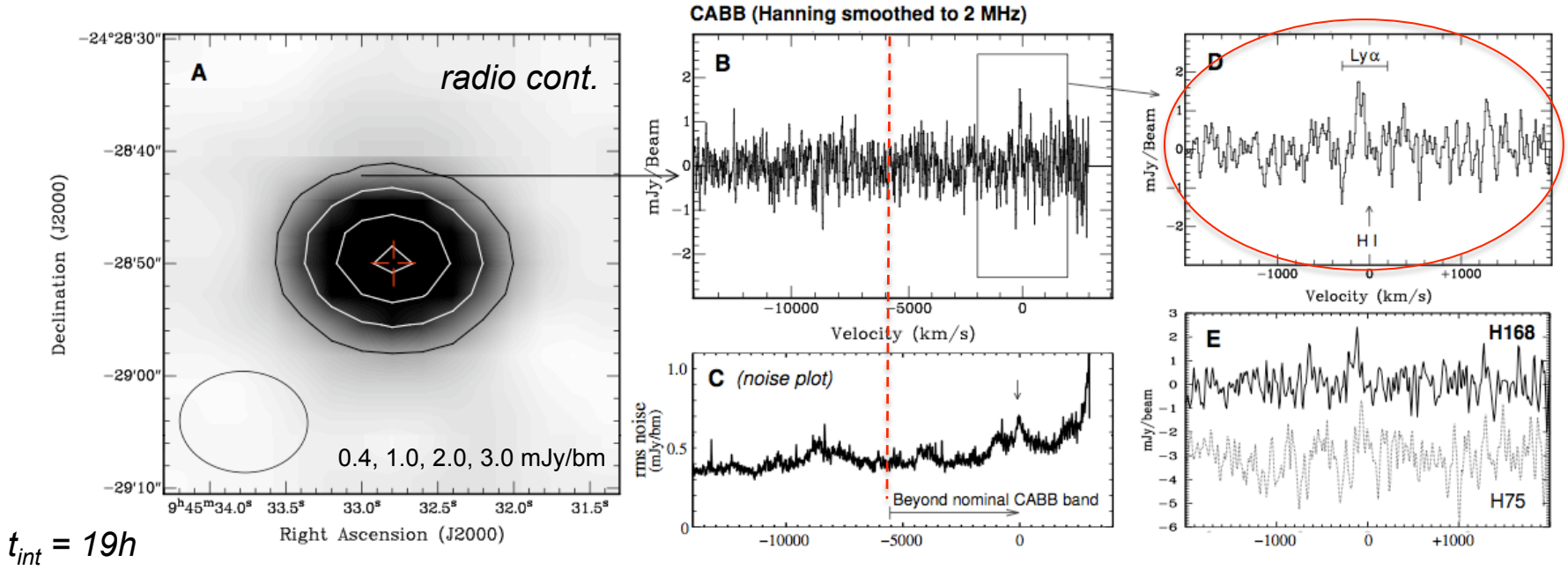



$\sigma_{line}$ = 0.45 mJy/bm/$ch_{1MHz}$
$\sigma_{cont}$ = 0.29 μJy/bm

*Emonts et al. 2011, MNRAS, tmp, 703*

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

- Pilot study: **Performance of ATCA/CABB**
  - **MRC 0943-242 (*z* = 2.9)** – very edge of 7mm band
  - **Tentative off-nuclear detection ($M_{H2}$ = 6 x $10^{10}$ $M_{sun}$; α[$M_{H2}/L_{CO}$]= 0.8)**




$t_{int}$ = 19h

*Emonts et al. 2011, MNRAS, tmp, 703*

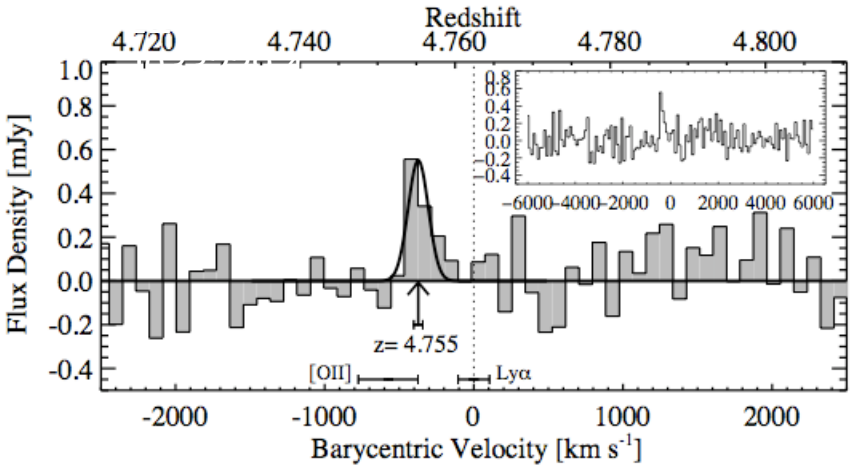
# ATCA/CABB: upgraded in 2009

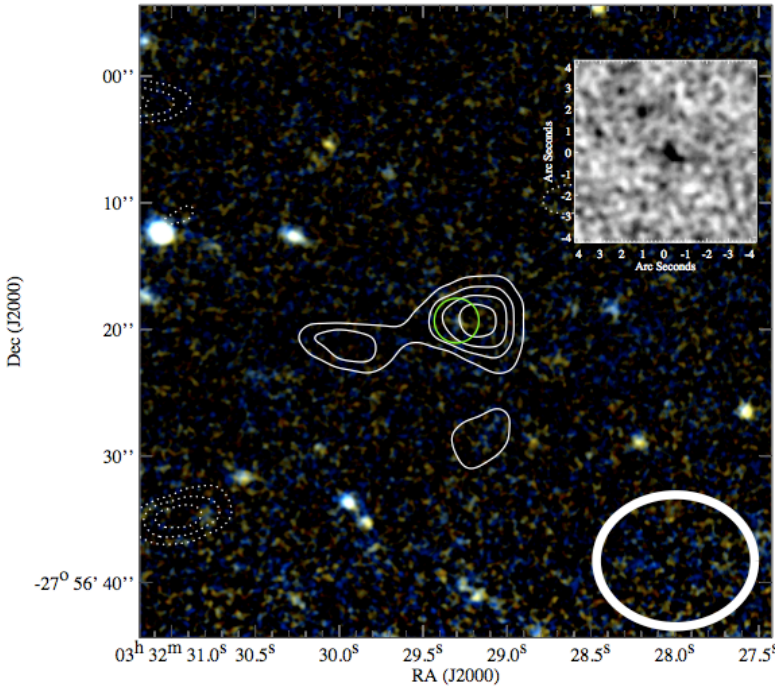
- First high-z CO detection with ATCA/CABB 2 GHz bands:

*Coppin et al. (2011):*

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

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




Talk Kristen Coppin!

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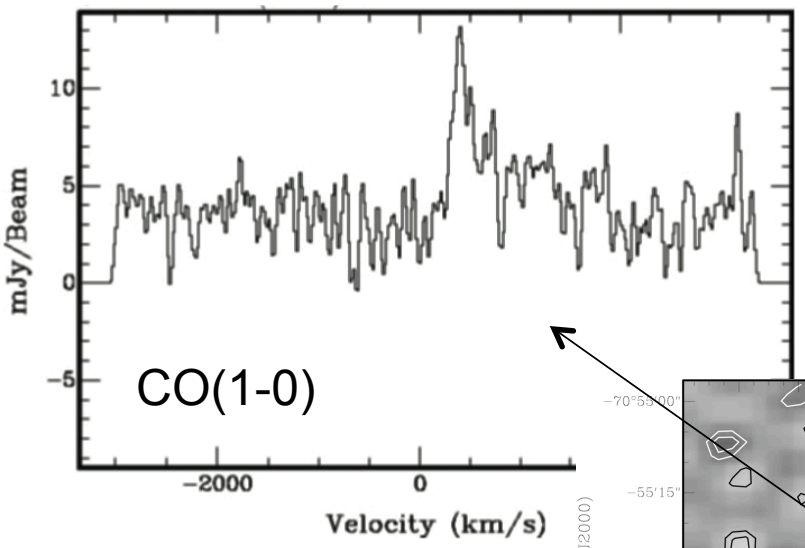
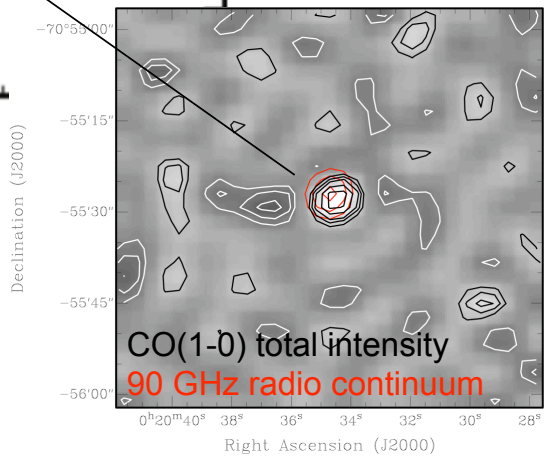
# ATCA/CABB: upgraded in 2009

- CO(1-0) @ 3mm in ULIRG IRAS F00183-7111 ($z$=0.33)

*Norris et al (in prep)*




*Norris et al (2011)*

VLBI:
Compact
powerful
radio source

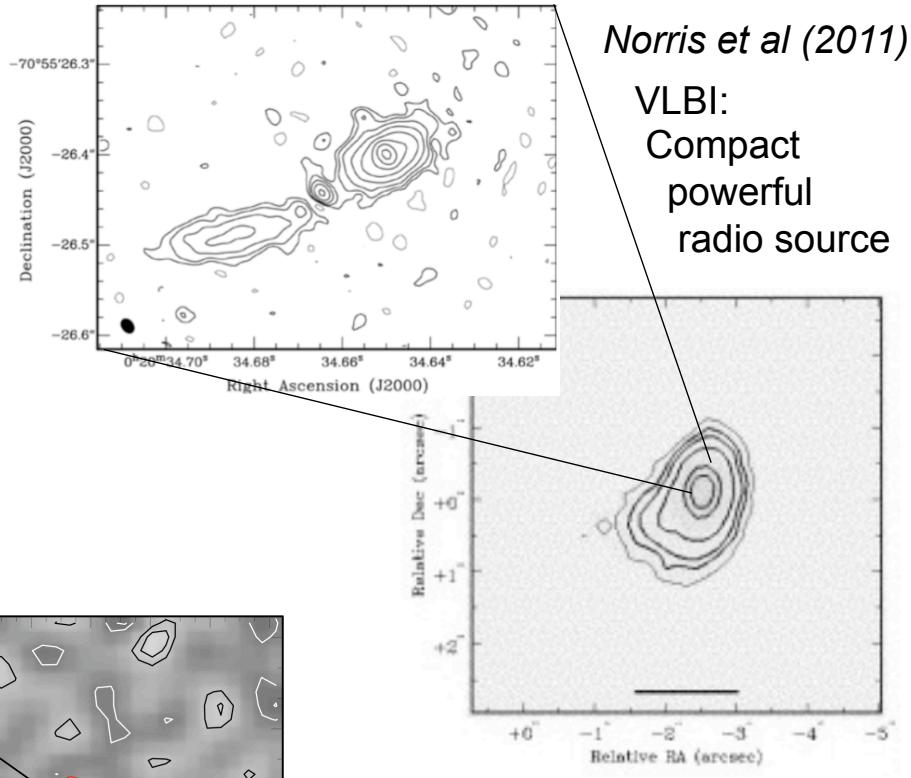



Fig. 1: ISO mid-IR (2.5-11.6μm) image of IRAS F00183-7111 from Rigopoulou et al. (1999).

$M_{H2}$ ~ 2.4 x $10^{10}$ $M_{sun}$

($\alpha[M_{H2}/L_{CO}]$= 0.8)

$L_{IR}$ = 9 x $10^{12}$ $L_{\odot}$

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

- First systematic survey of CO(1-0) in unbiased sample of HzRGs.
- **Sample selection:**

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

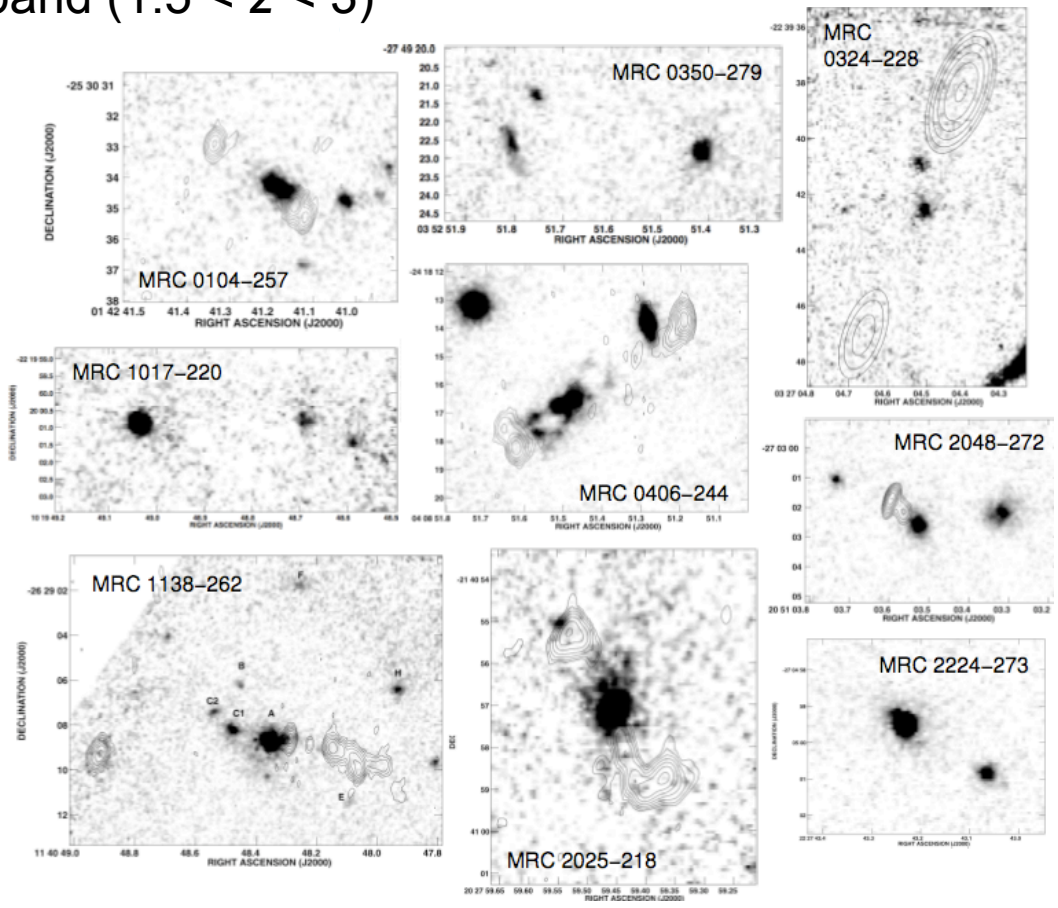
  - observable in ATCA 7mm band ($1.5 < z < 3$)
  - dec < -10
  - HST imaging &

    Spitzer data available

    ⇒ **14 sources**

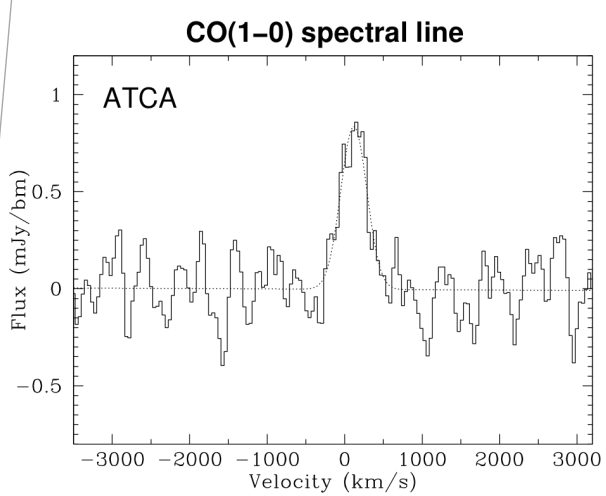
- ***Status:***

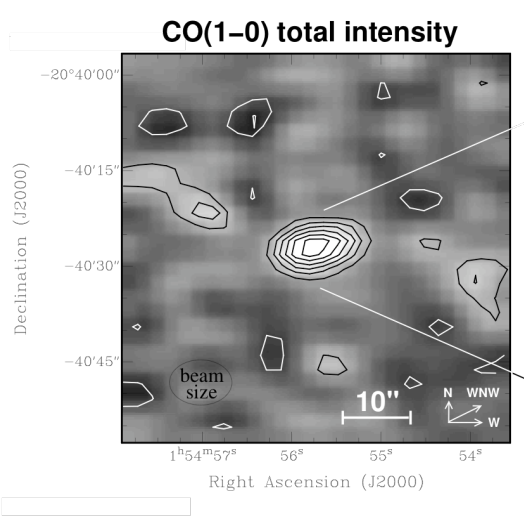
  - *6 sources observed ($t_{int}$ ~15h per source)*
  - *5 sources scheduled in Aug/Sept*

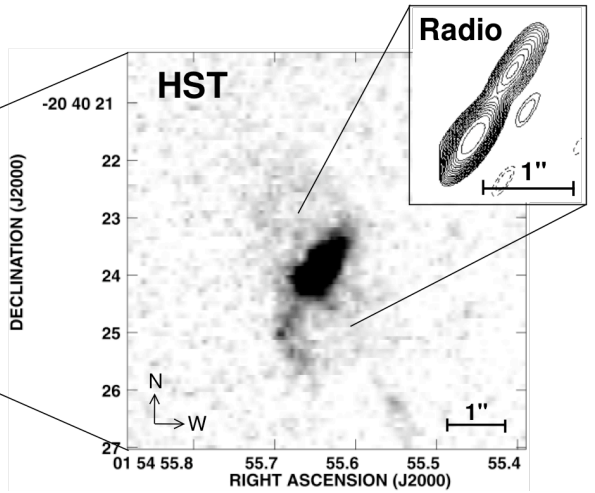


# CO(1-0) survey of HzRG with ATCA/CABB

- CO(1-0) in z=1.92 radio galaxy MRC 0152-209




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

*Pentericci et al. (2000, 2001)*

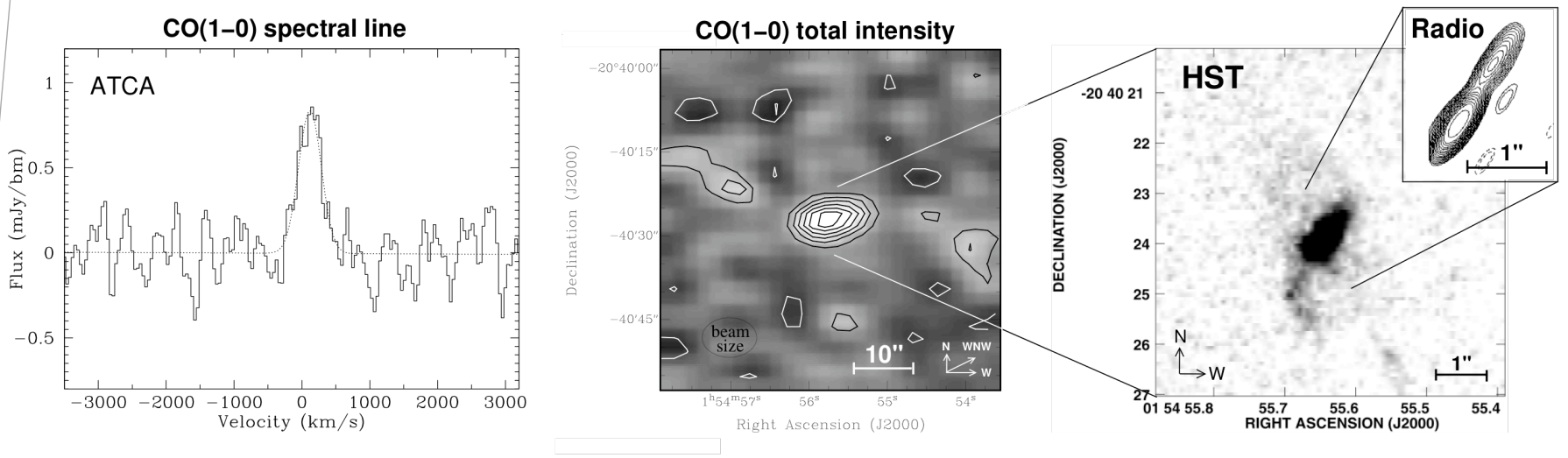
**$M_{H2}$ = 6 x $10^{10}$ $M_s$** ($\alpha[M_{H2}/L_{CO}]$= 0.8)

**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

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

- CO(1-0) in z=1.92 radio galaxy MRC 0152-209

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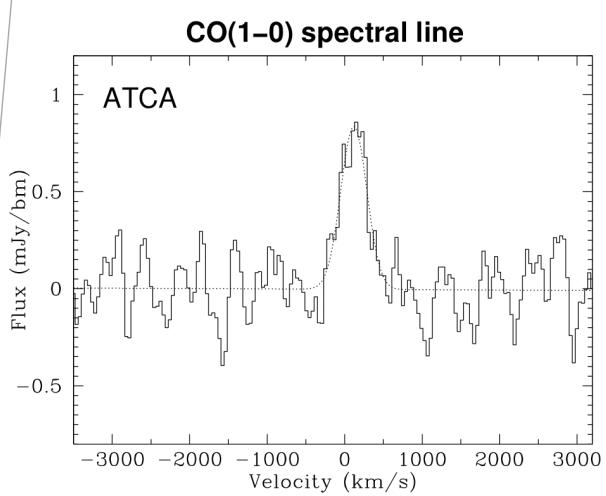
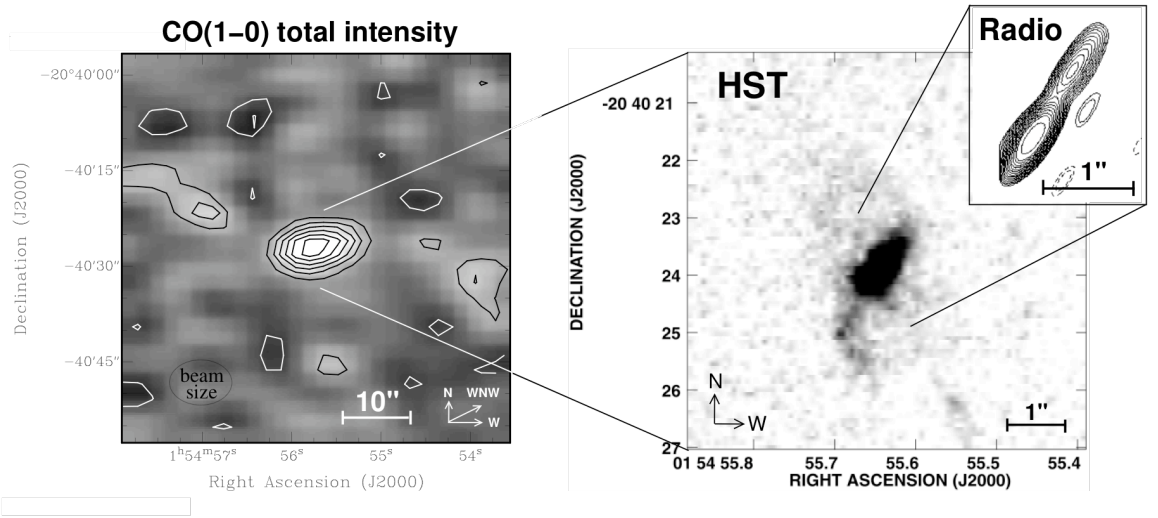
*MRC 0152-209 likely ULIRG that contains large amounts of molecular gas not yet depleted by star formation or radio-AGN feedback.*

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

- CO(1-0) in z=1.92 radio galaxy MRC 0152-209

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$\Delta v$ = 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

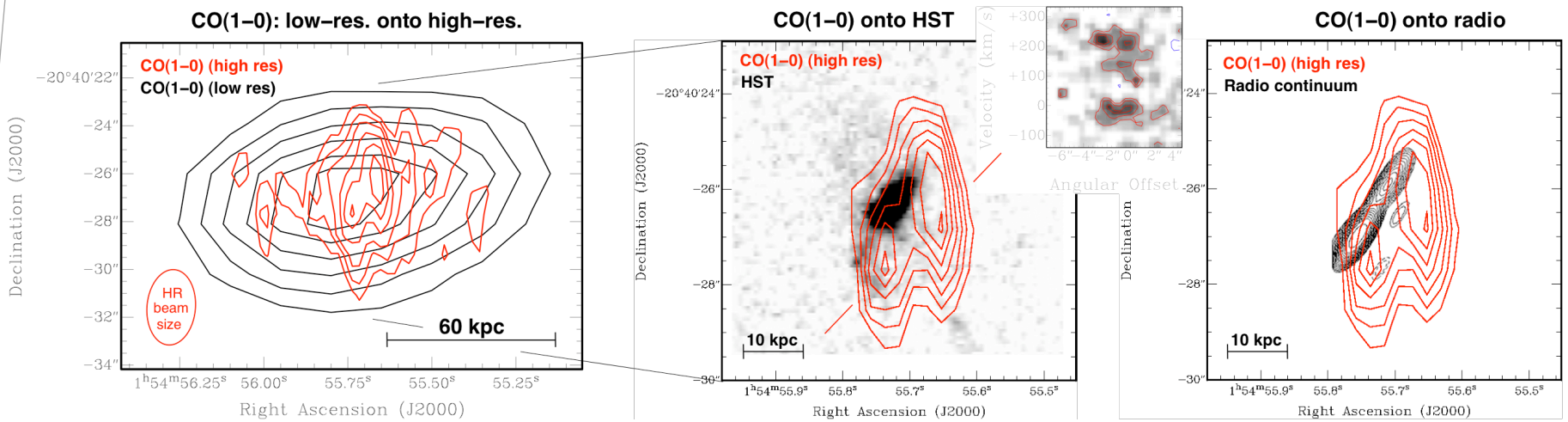
- **Most significant (S/N) CO(1-0) detection in HzRG to date!**
- **Only two other known CO(1-0) detections in HzRG:**
  TN J0924-2201 – z=5.2 (Klamer et al 2005);
  4C60.07 – z=3.8 (Greve et al 2004, Ivison et al 2008).

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

- CO(1-0) in z=1.92 radio galaxy MRC 0152-209

High resolution CO(1-0) follow-up with ATCA + EVLA

**PRELIMINARY RESULTS!**




Cold gas reservoir of ~75 kpc!(?)

CO(1-0) peaks off main body/radio jets, in regions devoid of HST emission!(?)

**ATCA 1.5km array**:
*Only ~13% of high-res data!!*

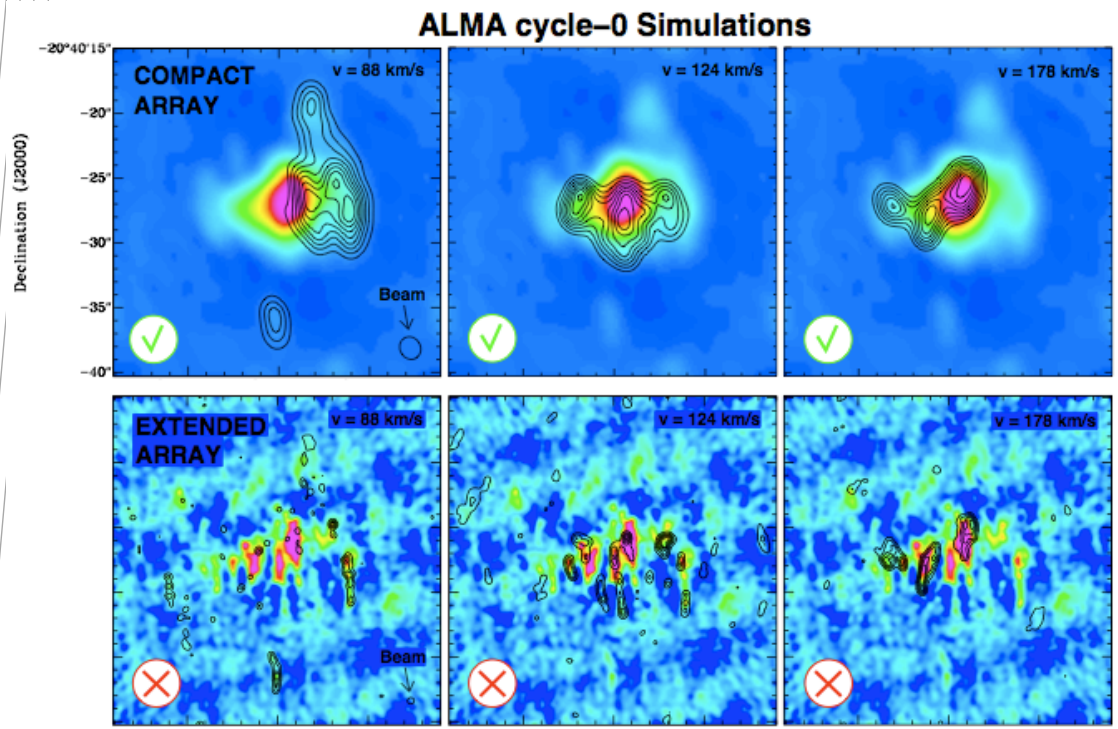
*Emonts & Mao et al. (in prep)*

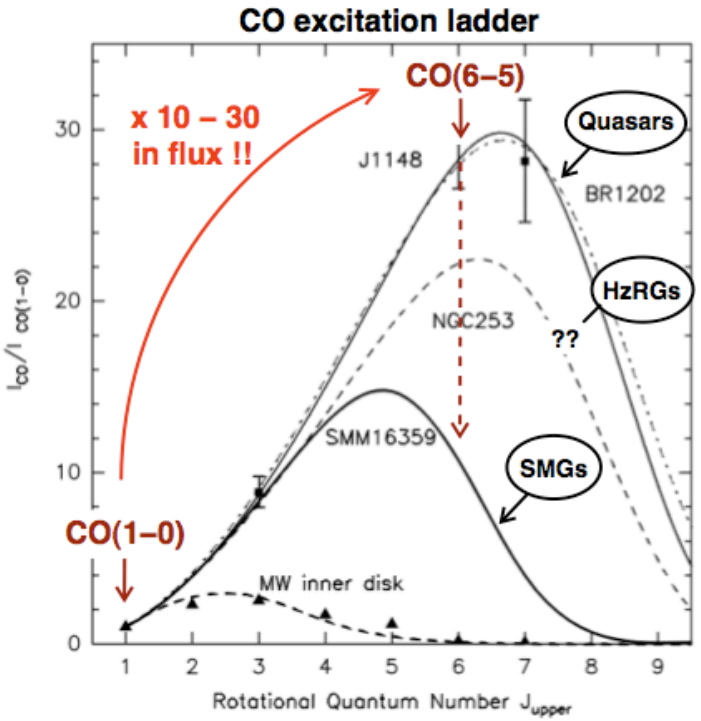
# CO(1-0) survey of HzRG with ATCA/CABB

## ALMA Early Science Proposal

**CO(6-5) observations *dense* molecular gas in MRC 0152-209**

- Match CO(1-0) observations spatially and kinematically
- CO(6-5)/CO(1-0) composition across host galaxy
- Compare with distinct HST features




*Riechers et al (2009)*

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

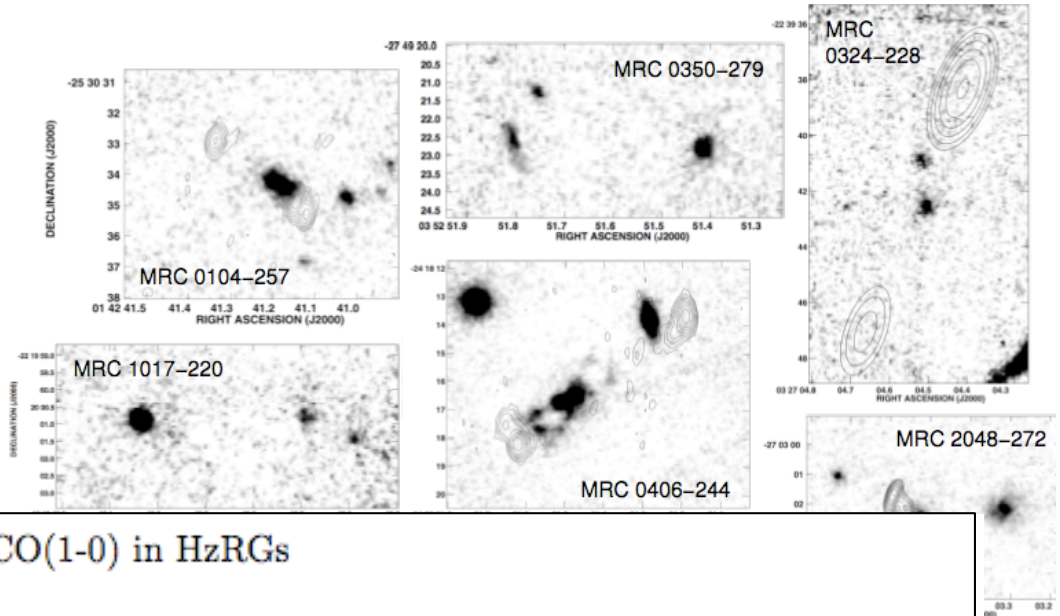
- First systematic survey of CO(1-0) in unbiased sample of HzRGs.

- ***Status** (14 sample sources):*

  - *6 sources observed ($t_{int}$ ~15h per source)*

    *1 detection*
    *1 tentative detection*

  - *5 sources scheduled in Aug/Sept*




Partial sample of CO(1-0) in HzRGs

| Source | $z$ | $LAS_{rs}$ (kpc) | $t_{int}$ (h) | $L'_{CO}$ (K km s$^{-1}$ pc$^2$) | $M_{H2}$ ($M_\odot$) |
|---|---|---|---|---|---|
| MRC 0152-209 | 1.92 | 13 | 15.5 | $6.6 \pm 2.0 \times 10^{10}$ | $5 \pm 2 \times 10^{10}$ |
| MRC 0156-252 | 2.09 | 68 | 11.0 | $< 2.3 \pm 0.7 \times 10^{10}$ | $< 2 \pm 0.6 \times 10^{10}$ |
| MRC 0932-242$^\dagger$ | 2.93 | 30 | 18.3 | $< 7.3 \pm 2.2 \times 10^{10}$ | $< 6 \pm 2 \times 10^{10}$ |
| MRC 2025-218 | 2.63 | 40 | 17.4 | $< 2.5 \pm 0.8 \times 10^{10}$ | $< 2 \pm 0.6 \times 10^{10}$ |
| MRC 2104-242 | 2.49 | 191 | 19.5 | $< 2.6 \pm 0.8 \times 10^{10}$ | $< 2 \pm 0.6 \times 10^{10}$ |
| MRC 2224-273 | 1.68 | $\leq 5$ | 15.3 | $< 1.4 \pm 0.4 \times 10^{10}$ | $< 1 \pm 0.3 \times 10^{10}$ |

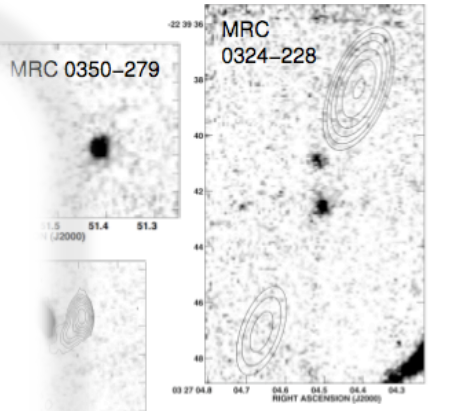
# CO(1-0) survey of HzRG with ATCA/CABB

- First systematic survey of CO(1-0) in unbiased sample of HzRGs.
- ***Status (14 sample sources):***

- **CO(1-0) only detected in compact radio sources, or outside the radio continuum (but low number statistics!)**
  - CO(1-0) – molecular gas least affected by excitation/heating – at radii not affected by radio source??
  - Alignment CO(1-0) with radio jets? *(e.g. Klamer et al 2004)*

- **Compare with ongoing EVLA CO(1-0) surveys:**
  - high-z quasars/qso's *(Riechers et al 2011)*
  - high-*z* submm galaxies *(Ivison et al. 2011, Riechers et al 2011)*
  - high-*z* starforming *BzK* galaxies

  *(Aravena et al. 2010, see also talks by Helmut Dannerbauer, Manuel Aravena, Dominik Riechers)*




| $M_{H2}$ ($M_\odot$) |
|---|
| $5 \pm 2 \times 10^{10}$ |
| $< 2 \pm 0.6 \times 10^{10}$ |
| $< 6 \pm 2 \times 10^{10}$ |
| $< 2 \pm 0.6 \times 10^{10}$ |
| $< 2 \pm 0.6 \times 10^{10}$ |
| $< 1 \pm 0.3 \times 10^{10}$ |

# Conclusions

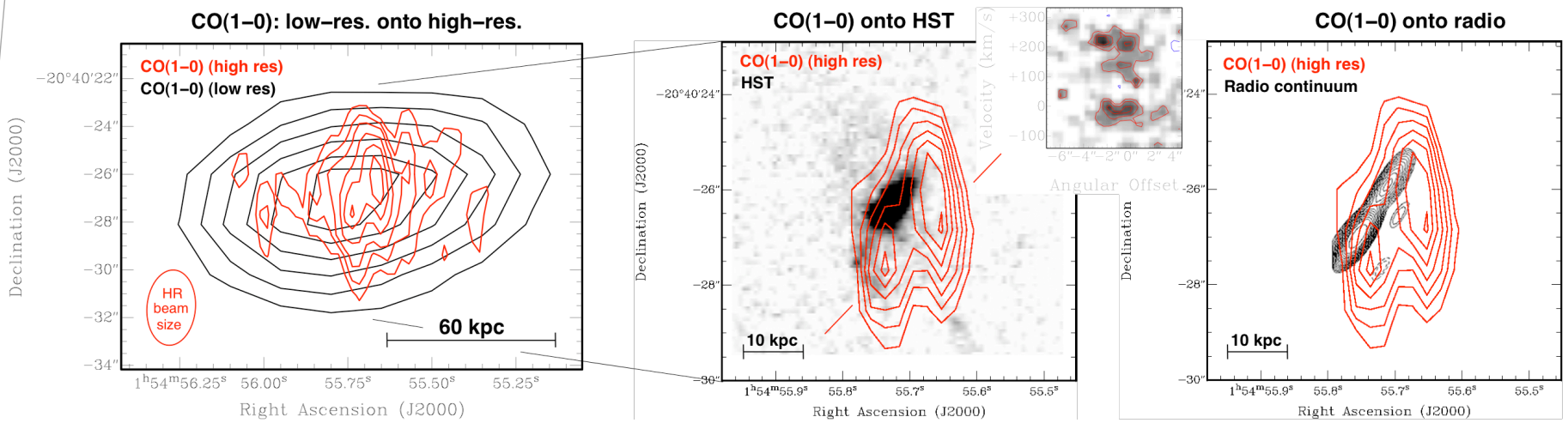
- ATCA/CABB excellent southern instrument for complementary studies of high-z CO with ALMA
  - CO(1-0) observations with ATCA/CABB: most robust tracer for molecular gas at high-z (incl low-density, widespread, sub-thermally excited component).
- Ongoing systematic survey of CO(1-0) in HzRG
  - MRC 0152-209: strongest CO(1-0) signal in HzRG to date
  - Ideal for ALMA observations of high CO transitions of dense molecular gas

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

- CO(1-0) in z=1.92 radio galaxy MRC 0152-209

High resolution CO(1-0) follow-up with ATCA + EVLA

**PRELIMINARY RESULTS!**




Cold gas reservoir of ~75 kpc!(?)

CO(1-0) peaks off main body/radio jets, in regions devoid of HST emission!(?)

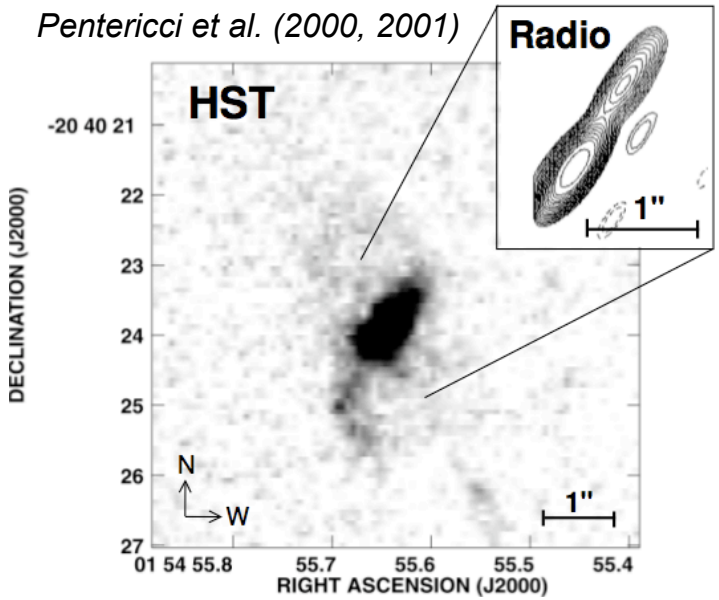
**ATCA 1.5km array**:
*Only ~13% of high-res data!!*

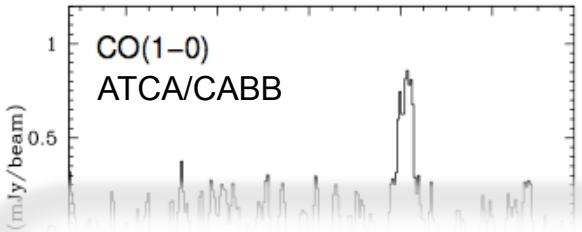
*Emonts & Mao et al. (in prep)*

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

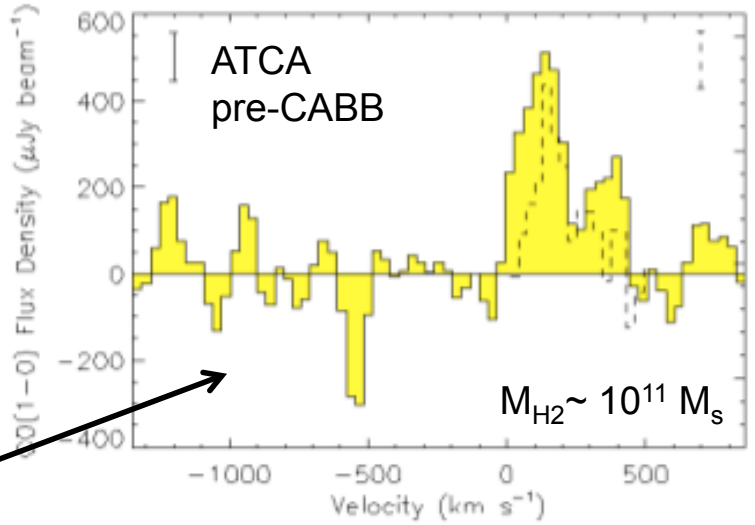
- CO(1-0) in z=1.92 radio galaxy MRC 0152-209

*Pentericci et al. (2000, 2001)*




**TN J0924–2201 (*z* =5.2)**




*Feain et al. (2005)*

- **Most significant (S/N) CO(1-0) detection in HzRG to date!**
- **Only two other known CO(1-0) detections in HzRG**

*Emonts et al.*

$M_s$

8)