CO(1-0) emission from Quasar Host Galaxies Beyond redshift 4

From Z-Machines to ALMA:
(Sub) Millimeter Spectroscopy of Galaxies

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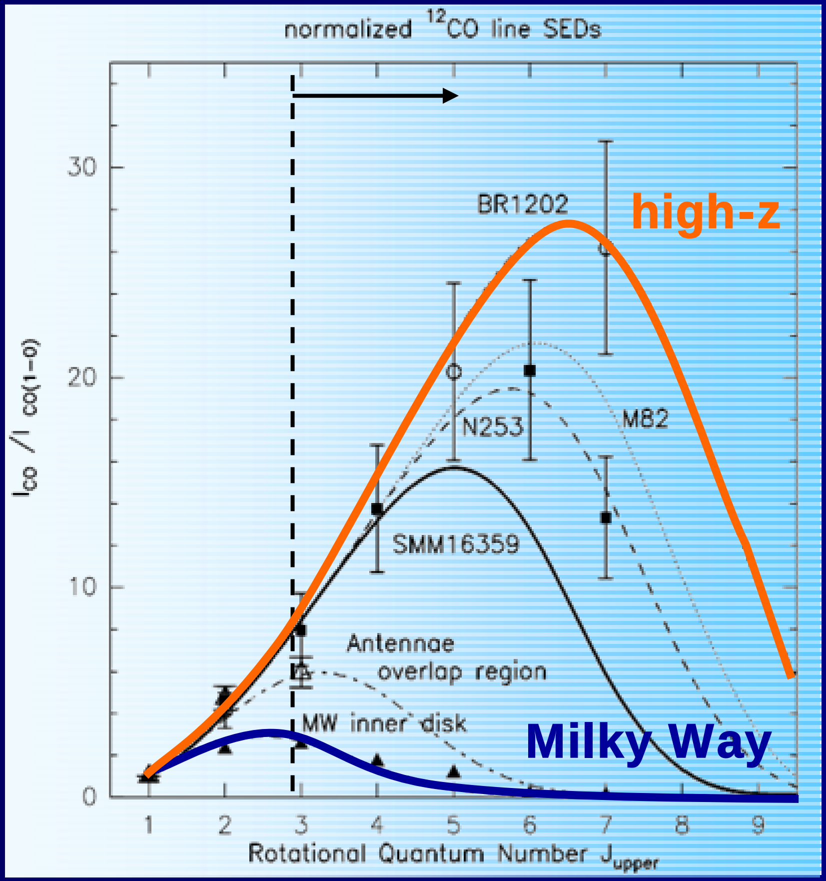
High-z CO Observations



Weiss ea. (2005)

- Typically observed at high-z: CO(3-2) and higher

But:

- These obs would miss a low excitation ‘cold‘ component like e.g. found in the Milky Way

- only CO(1-0) traces full $M(H_2)$

100m Single-dish telescopes

CO(1-0) observations in high-z QSOs are possible in K band

Max-Planck-Institut für Radioastronomie

22 GHz: CO(1-0) @z=4.2

GBT: 1.6 GHz bandwidth (dual polarization)

- 22000 km/s @22GHz ($\Delta z/z=0.09$ @z=4.2)
- Future: Zpectrometer, 14 GHz bandwidth @26-40 GHz

Effelsberg: 500 MHz bandwidth (dual pol.)

- 6000 km/s @22GHz ($\Delta z/z=0.03$ @z=4.2)

⇒ accurate redshift of QSO host not known from optical/IR, but bandwidth large enough to account for difference to CO redshift

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Comparison to **VLA**: 50 MHz bandwidth

- 600 km/s @22GHz ($\Delta z/z=0.003$ @z=4.2)

⇒ **EVLA** – up to 8 GHz bandwidth per pol.

Sample Selection: High-z CO Detections

SMMJ02396-0134	1.062	SMM
Q0957+561	1.414	RLQ
HR10	1.439	ERO
IRAS10214+4724	2.286	QSO
SMMJ16371+4053	2.380	SMM
SMMJ16368+4057	2.385	SMM
53W002	2.394	RG
SMMJ16366+4105	2.450	SMM
SMMJ04431+0210	2.509	SMM
SMMJ16359+6612	2.517	SMM
Cloverleaf	2.558	QSO
SMMJ14011+0252	2.565	SMM
VCVJ1409+5628	2.583	QSO
MG0414-0534	2.639	RLQ
MS1512-cB58	2.727	LBQ
LBQS1230+1627B	2.741	QSO
RXJ0911+0551	2.796	RQQ
SMMJ02399-0136	2.808	SMM

SMMJ04135+10277	2.846	QSO
B3J2330+3927	3.094	RG
SMMJ22174+0015	3.099	SMM
MG0751+2716	3.200	RLQ
SMMJ09431+4700	3.346	SMM
SMMJ13120+4242	3.408	SMM
TNJ0121+1320	3.520	RG
6C1909+722	3.532	RG
4C60.07	3.791	RG
4C41.17	3.796	RG
APM08279+5255	3.911	RQQ
PSSJ2322+1944	4.119	QSO
BRI1335-0417	4.407	QSO
BRI0952-0115	4.434	QSO
BR1202-0725	4.693	QSO
TNJ0924-2201	5.202	RG
SDSSJ1148+5251	6.419	QSO

- List of all detections (1991-2005)

- 1 – 3 mm, mostly CO(3-2), CO(4-3) and higher

see e.g. Solomon & Vanden Bout (2005)

Sample Selection: High-z CO Detections

- -
- Q0957+561 1.414 RLQ
- -
- IRAS10214+4724 2.286 QSO
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- Cloverleaf 2.558 QSO
- -
- VCVJ1409+5628 2.583 QSO
- MG0414-0534 2.639 RLQ
- MS1512-cB58 2.727 LBQ
- LBQS1230+1627B 2.741 QSO
- RXJ0911+0551 2.796 RQQ
- -
- SMMJ04135+10277 2.846 QSO
- -
- -
- MG0751+2716 3.200 RLQ
- -
- -
- -
- -
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- -
- APM08279+5255 3.911 RQQ
- PSSJ2322+1944 4.119 QSO
- BRI1335-0417 4.407 QSO
- BRI0952-0115 4.434 QSO
- BR1202-0725 4.693 QSO
- -
- SDSSJ1148+5251 6.419 QSO

QSOs only!

Sample Selection: High-z CO Detections

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- APM08279+5255 3.911 RQQ
- PSSJ2322+1944 4.119 QSO
- BRI1335-0417 4.407 QSO
- BRI0952-0115 4.434 N QSO
- BR1202-0725 4.693 QSO
- -
- -

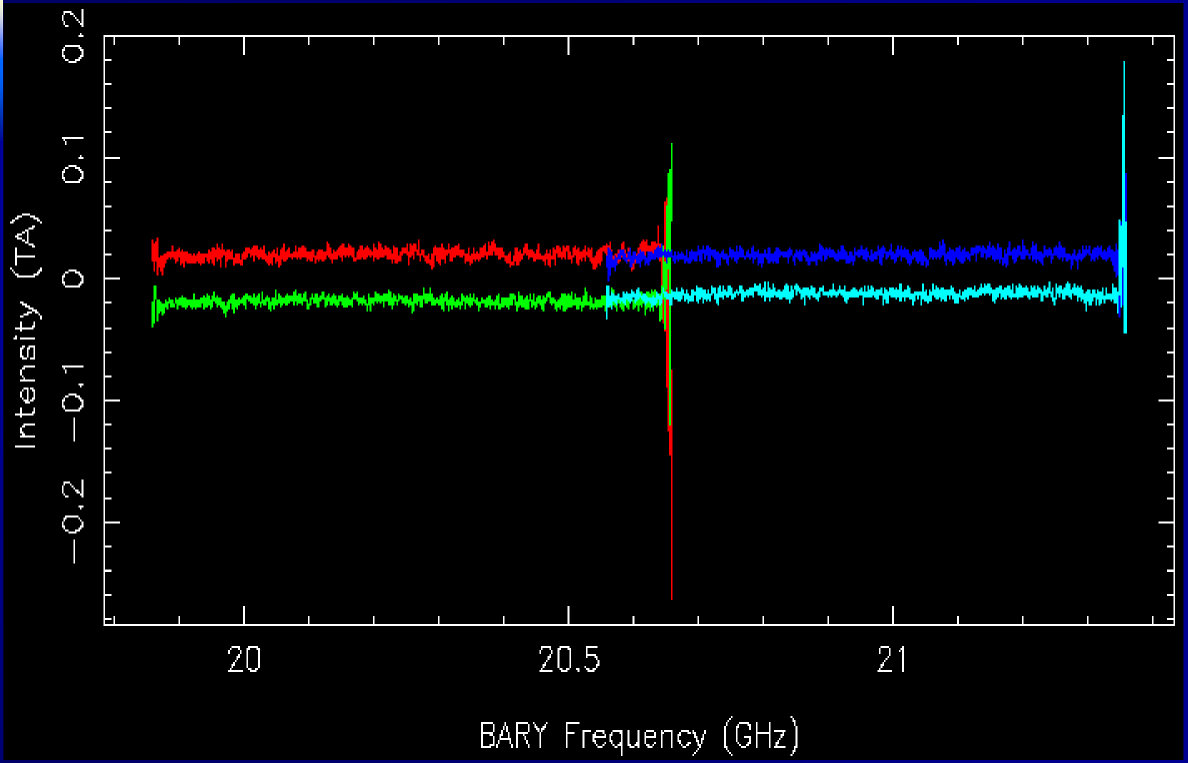
QSOs, CO(1-0) in K band

GBT: Data Quality Assessment

- 90 hours, 3 QSOs in K band
- Position Switched Dual Beam observations
- Mostly excellent winter weather in December 2004:

  T_{sys} = 20-25 K

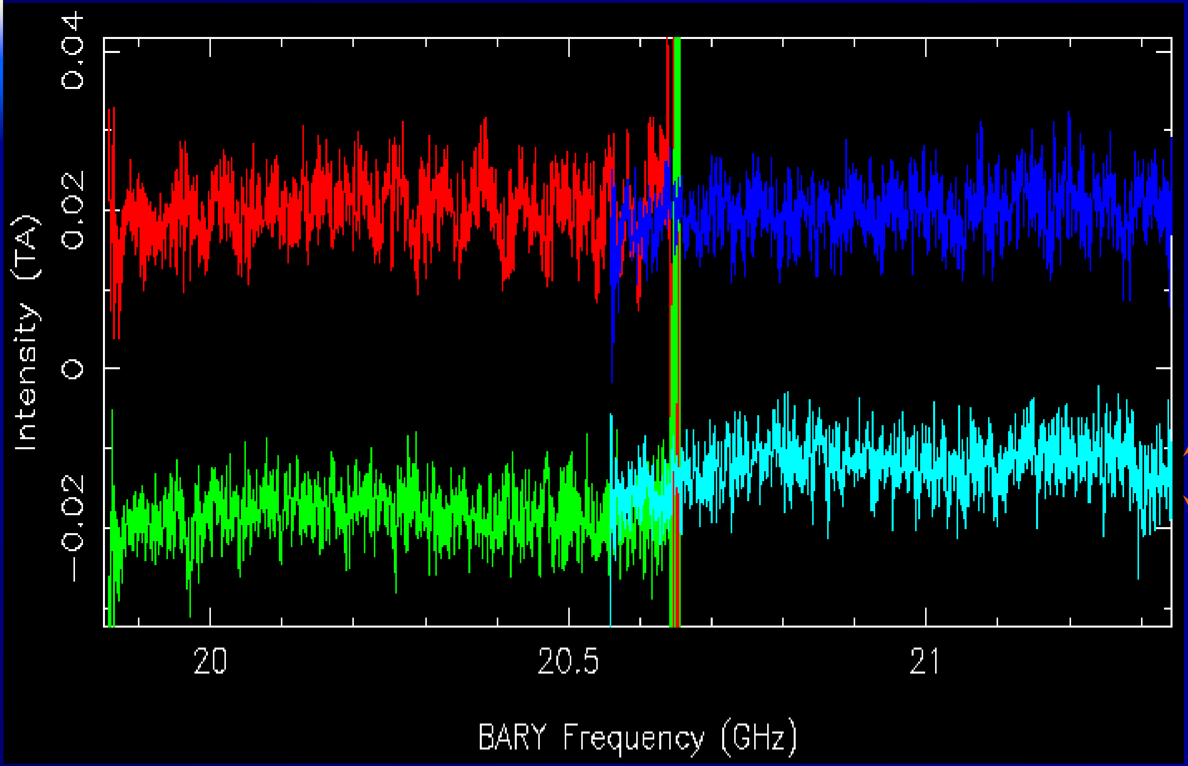
GBT: Data Quality Assessment



Gain: 1.5K/Jy

90 s integration, T_{sys} = 22 K, 1.6 GHz, LL/RR polarization

GBT: Data Quality Assessment

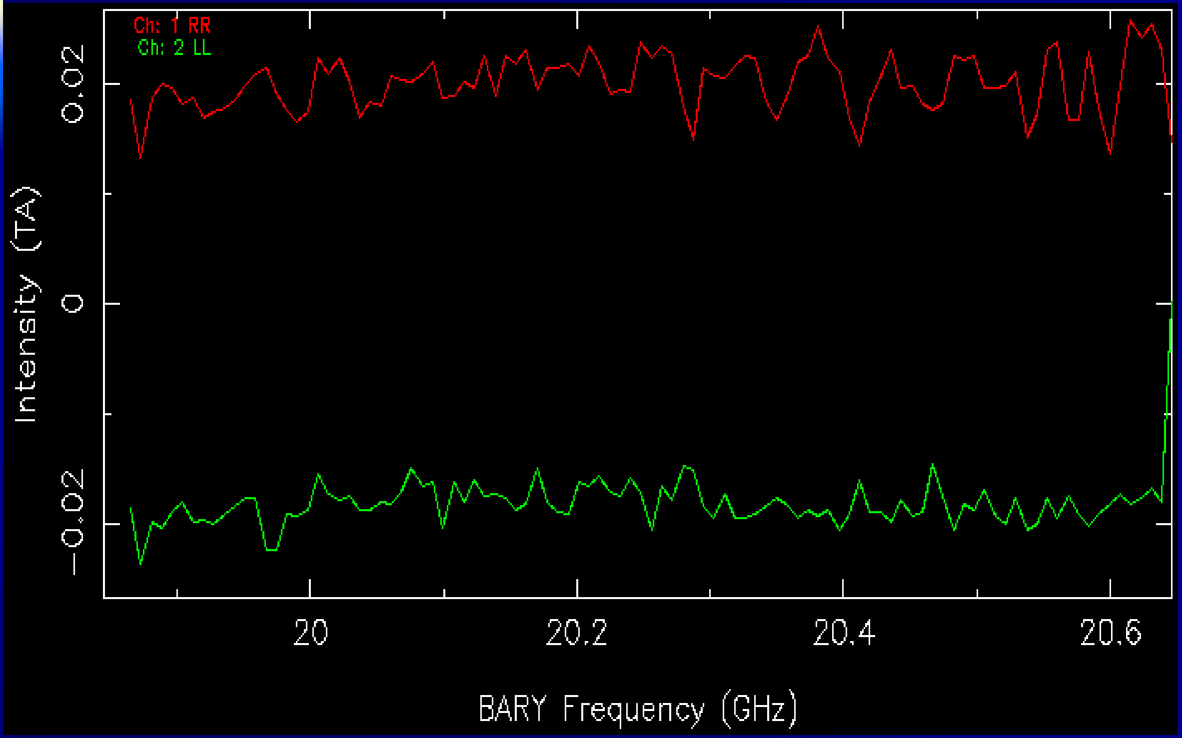


Zoomed in

Gain: 1.5K/Jy

90 s integration, T_{sys} = 22 K, 1.6 GHz, LL/RR polarization

GBT: Data Quality Assessment

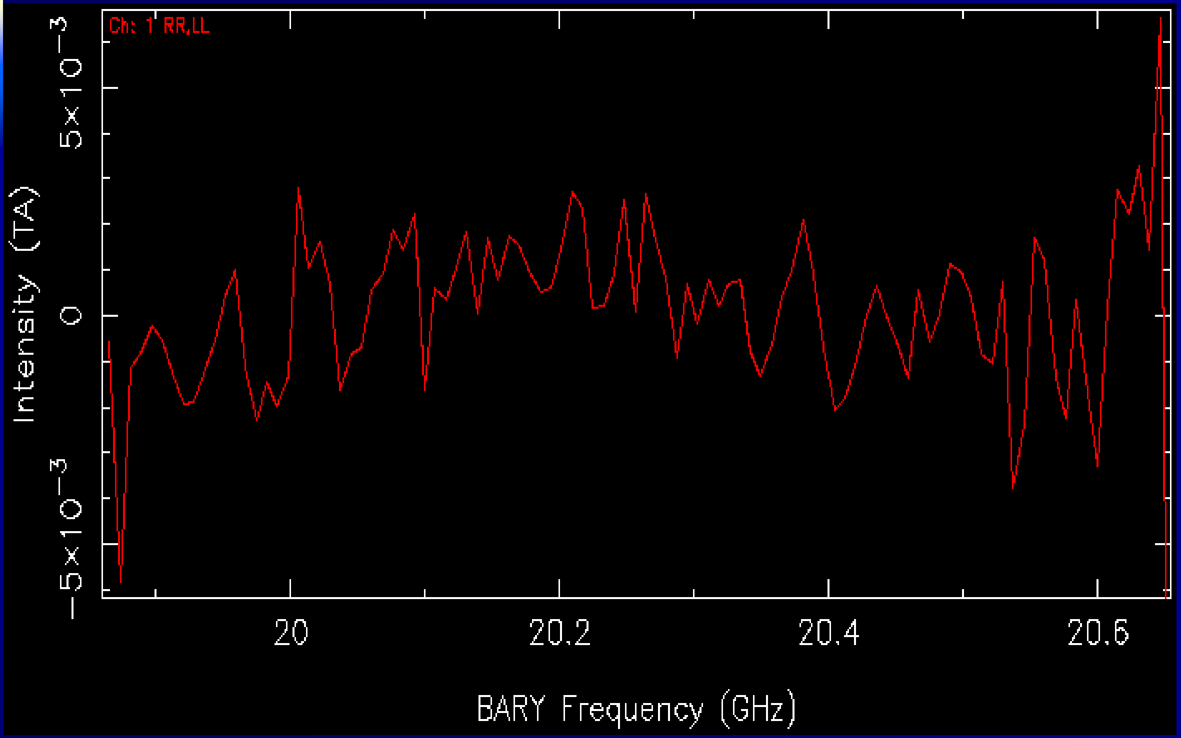


↕ Zoomed in, IF1, Boxcar 20 ch

Gain: 1.5K/Jy

90 s integration, T_{sys} = 22 K, 0.8 GHz, LL/RR polarization

GBT: Data Quality Assessment

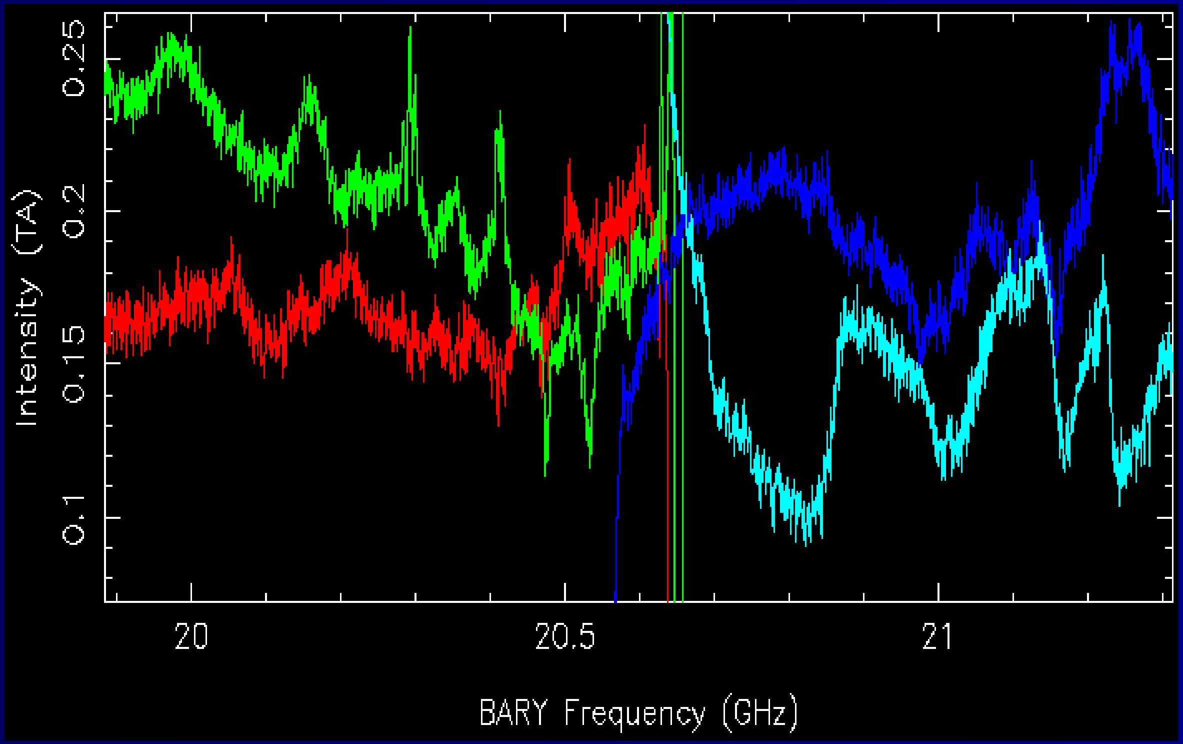


Zoomed in, IF1, Box20, avg. pol.

Gain: 1.5K/Jy

90 s integration, T_{sys} = 22 K, 0.8 GHz, (LL+RR) polarization

GBT Data: The Dark Side

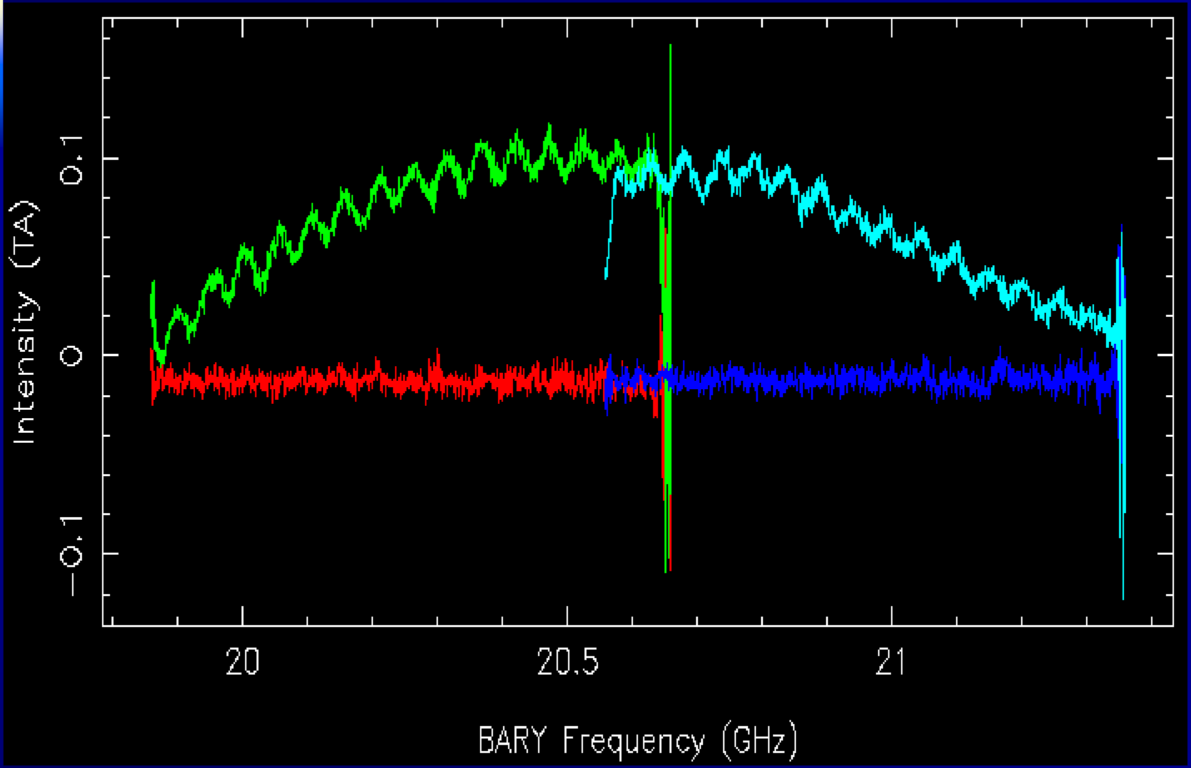


Weather

Gain: 1.5K/Jy

90 s integration, T_{sys} = 40 K, 1.6 GHz, LL/RR polarization

GBT Data: The Dark Side

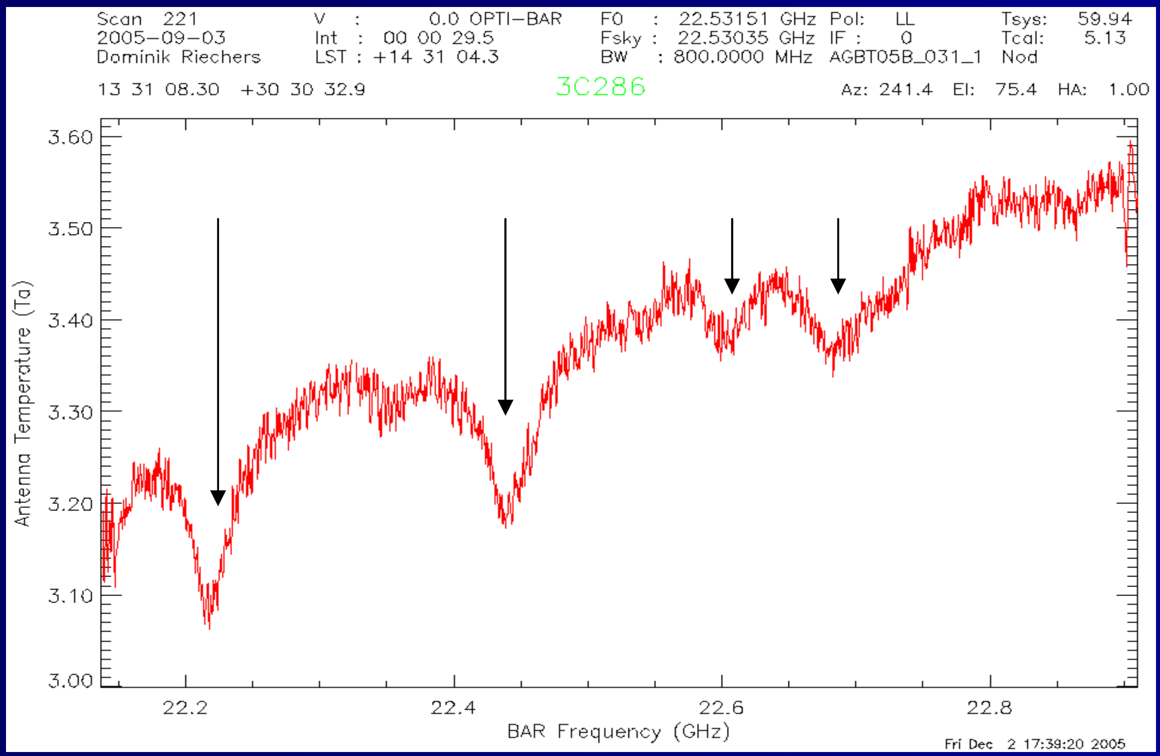


Resonance Features

Gain: 1.5K/Jy

90 s integration, T_{sys} = 40 K, 1.6 GHz, LL/RR polarization

GBT Data: The Dark Side

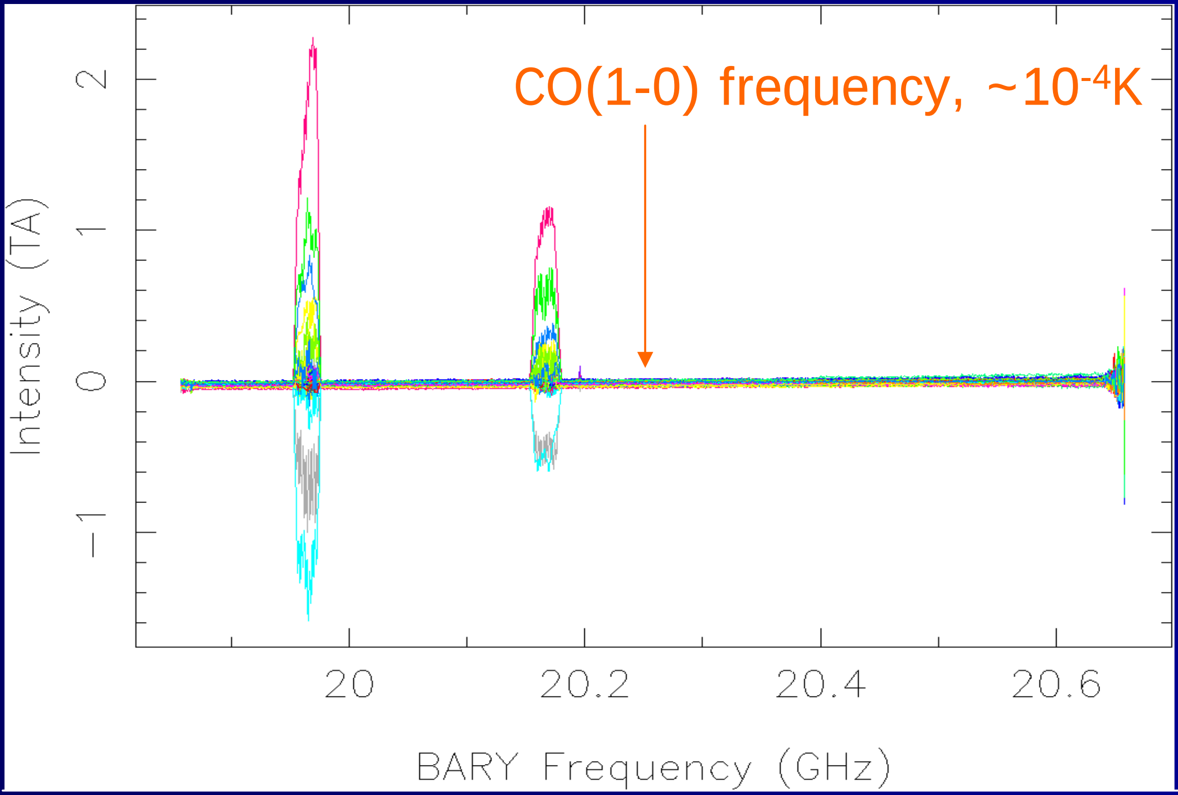


Birdies

Gain: 1.5K/Jy

30 s integration, T_{sys} = 60 K, 0.8 GHz, LL/RR polarization

GBT Data: The Dark Side



Military Satellite

Gain: 1.5K/Jy

20x90 s integration, 0.8 GHz, LL/RR polarization

GBT Data: The Dark Side

- Fixable: Satellite (spectral baselines remain stable)
- Flaggable: Weather, Resonances
- 'Deadly': Birdies

GBT: Data Reduction

aips++

- standard calib (late 2004)
- standard calib (early 2005)
- Bob Garwood's calib
- Ron Maddalena's calib

IDL

- Glen Langston's routines
- GBTIDL

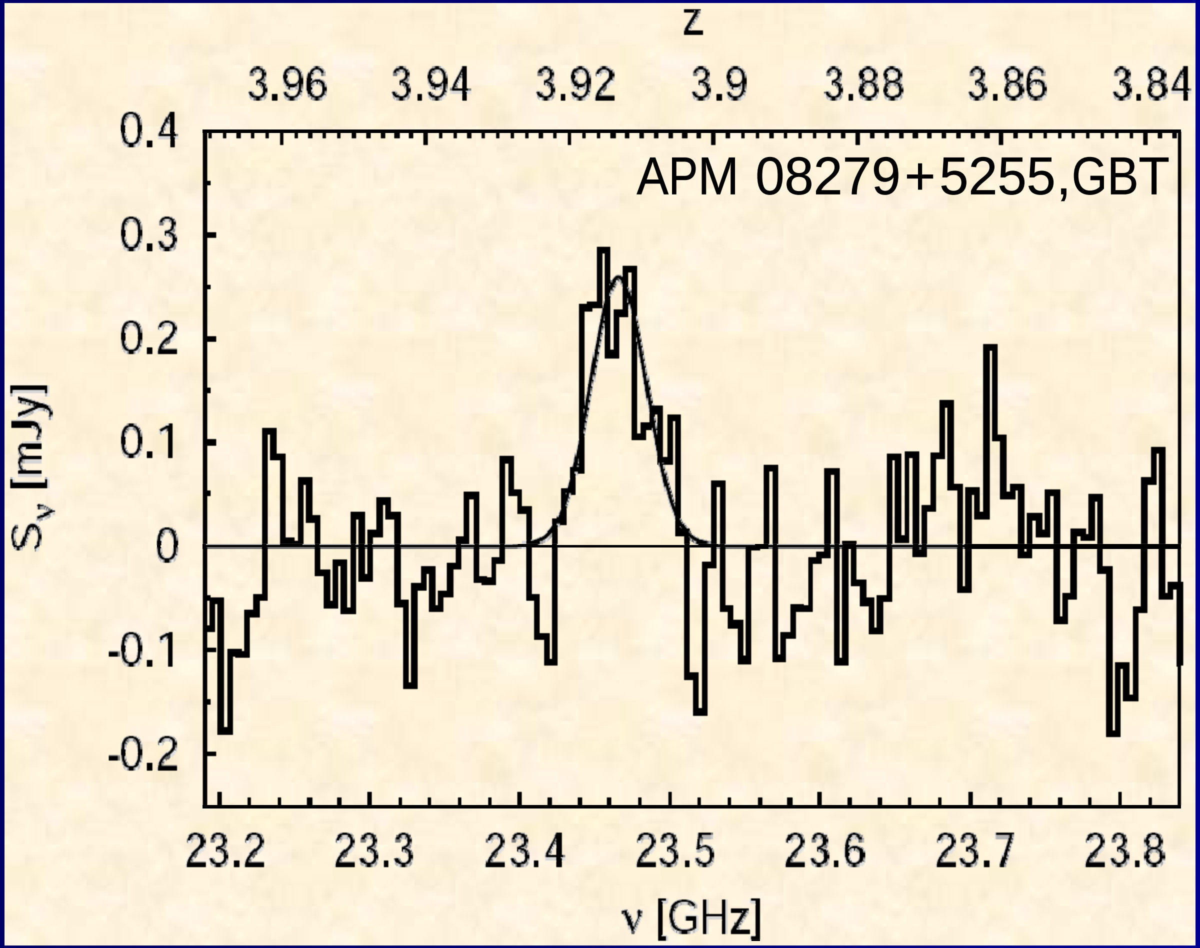
- Vanden Bout, Solomon & Maddalena (2004) scheme

[HCN(1-0) in IRAS F10214+4724 (z=2.3)]

Detection of CO(1-0) @z>4!

CO(1-0): Spectra

APM 08279+5255 (z=3.91)



GBT

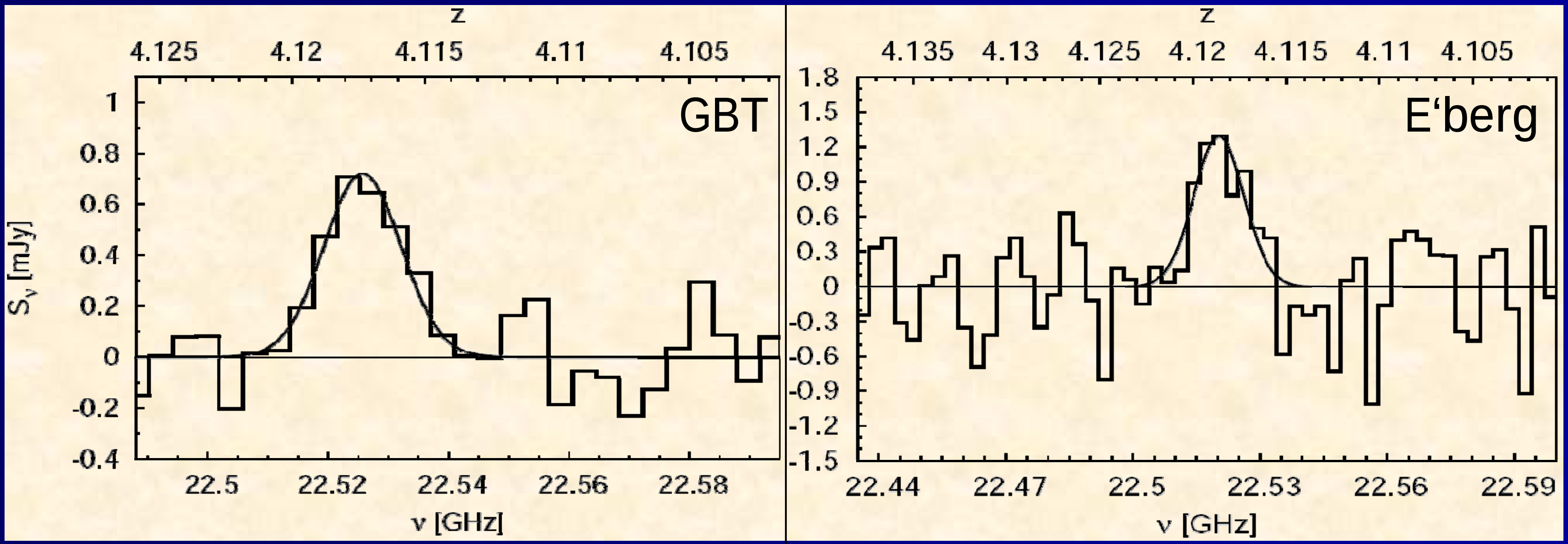
- 35 hours total
- 22 hours on src
- rms: 80 μJy
- 75 km/s res (sm)

- 280 μJy peak
- 560 km/s FWHM

2nd order polynomial fit to spectral baseline subtracted

CO(1-0): Spectra

PSS J2322+1944 (z=4.12)



GBT

- 23 hours total
- 15 hours on src
- rms: 160 µJy
- 52 km/s res (sm)

Effelsberg

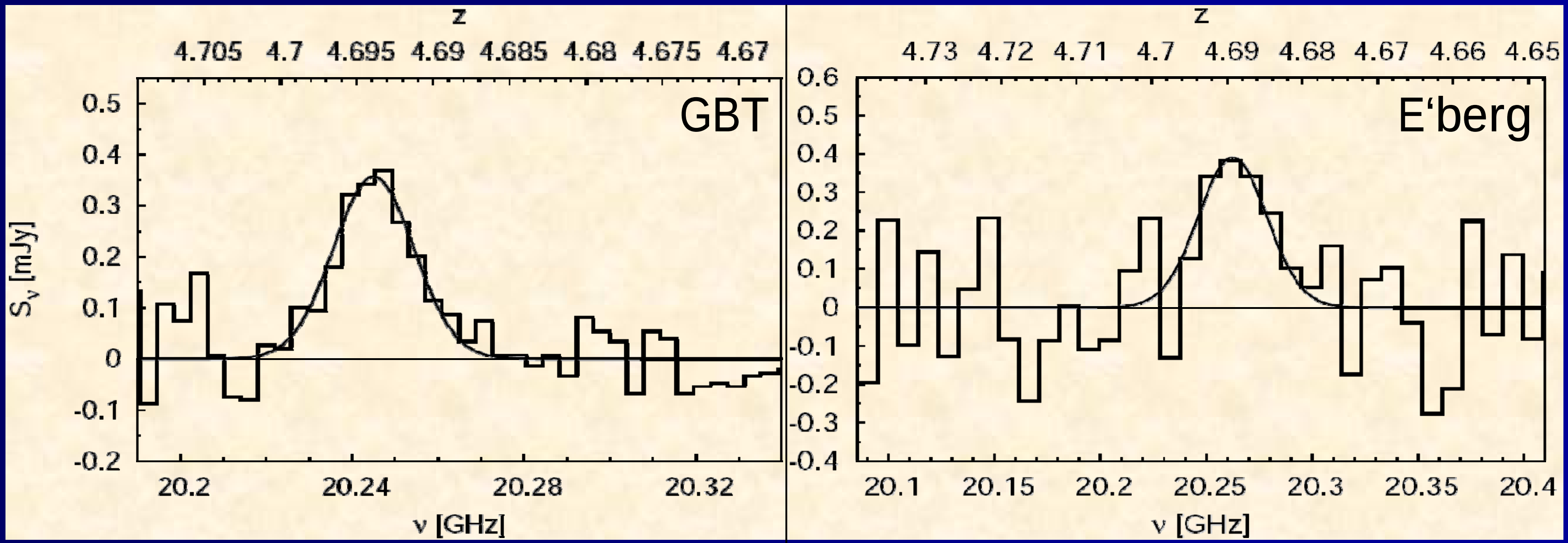
- 20 hours total
- 8 hours on src
- rms: 460 µJy
- 40 km/s res (sm)

- 720 µJy peak
- 202 km/s FWHM

linear fits to spectral baseline subtracted

CO(1-0): Spectra

BR 1202-0725 (z=4.69)



GBT

- 32 hours total
- 20 hours on src
- rms: 70 µJy
- 58 km/s res (sm)

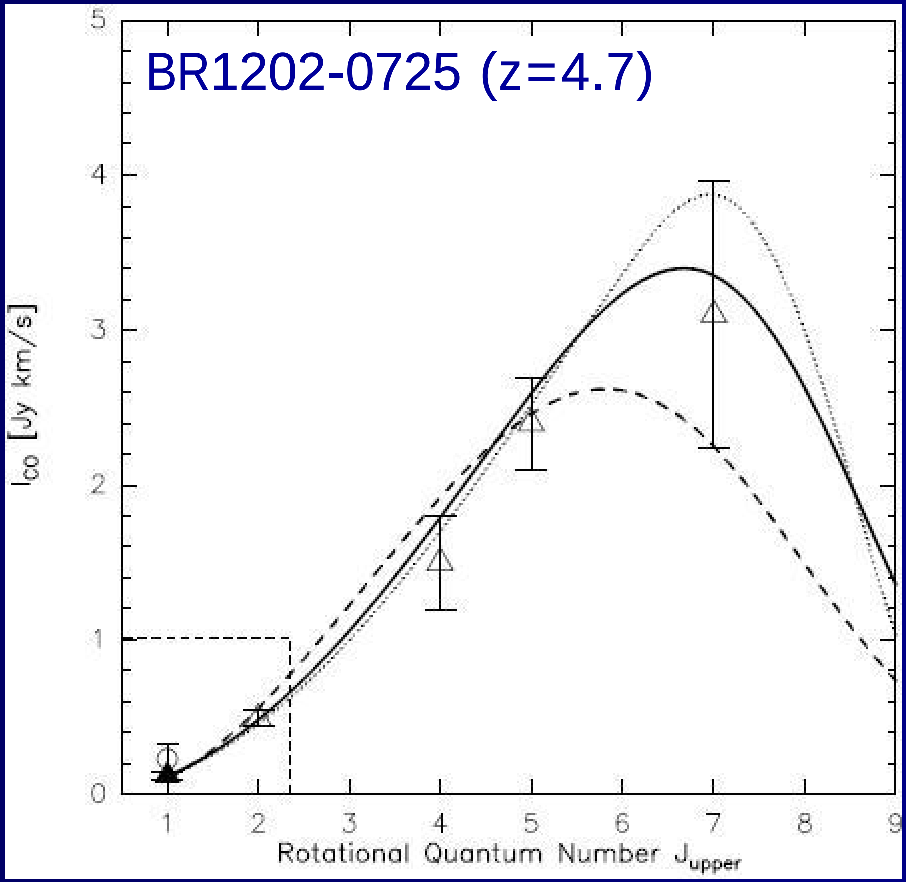
Effelsberg

- 20 hours total
- 8 hours on src
- rms: 160 µJy
- 141 km/s res (sm)

- 360 µJy peak
- 329 km/s FWHM

order 2/1 fit to spec. baseline subtracted

Excitation Conditions



Large Velocity Gradient (LVG) modeling (1 component) on higher-*J* transitions

- T_{kin} = 60 K,
- $n(H_2) = 10^{4.1} cm^{-3}$
- all CO(1-0) flux recovered

⇒ almost fully thermalized ($I_{CO} \sim \nu^2$) up to CO(4-3)

⇒ traces as much gas as CO(1-0)

Summary

- First-time detection of CO @z>4 with 100m single-dish telescopes

- caveat: spectral baselines still limit the detectability

⇒ detection of CO in new, possibly fainter sources very difficult

⇒ requirement for success of observations: the very best weather

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- massive reservoirs of molecular gas: ($M(H_2)$~10^{10} M_0)

- no evidence for additional massive, cold CO(1-0) components which are not visible at high-J CO transitions