Highly excited CO lines in quasars at z>6

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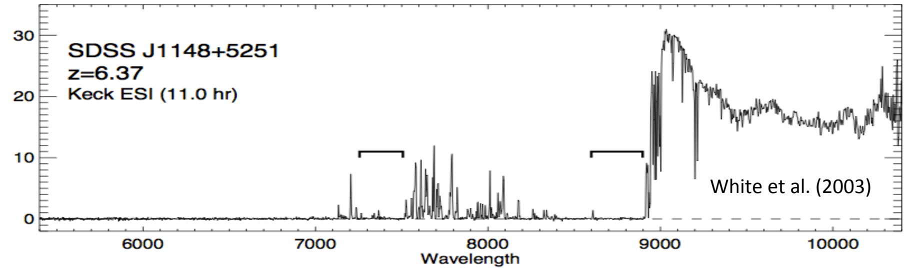
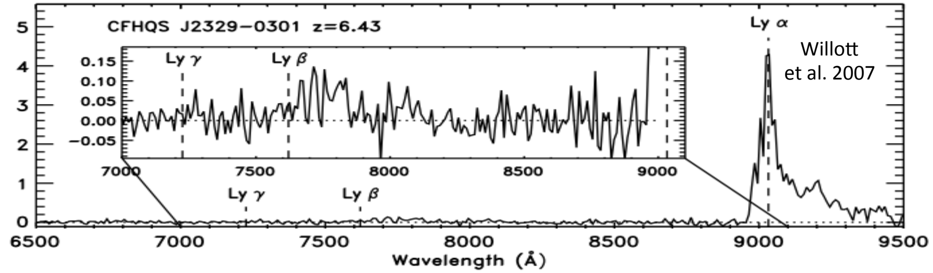
"Terzo Workshop sull'Astronomia Millimetrica in Italia", Bologna, 20th January 2015

Observations of (more than 60!) z ≥ 6 quasars

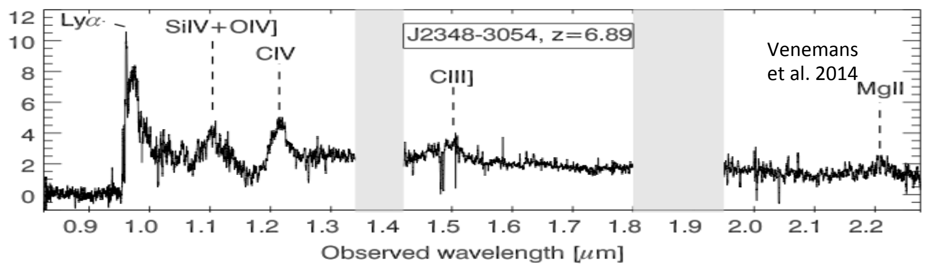
Sloan Digital Sky Survey
(SDSS, Fan et al. 2001/2003/2006)



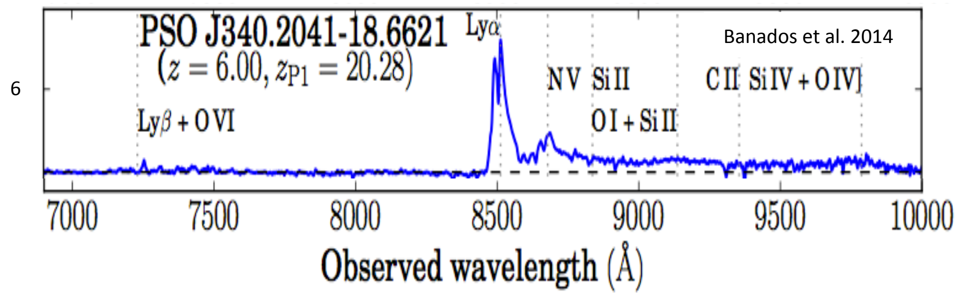
Canada-France High-z Quasar Survey
(CFHQS, Willott et al. 2005/2009/2010)



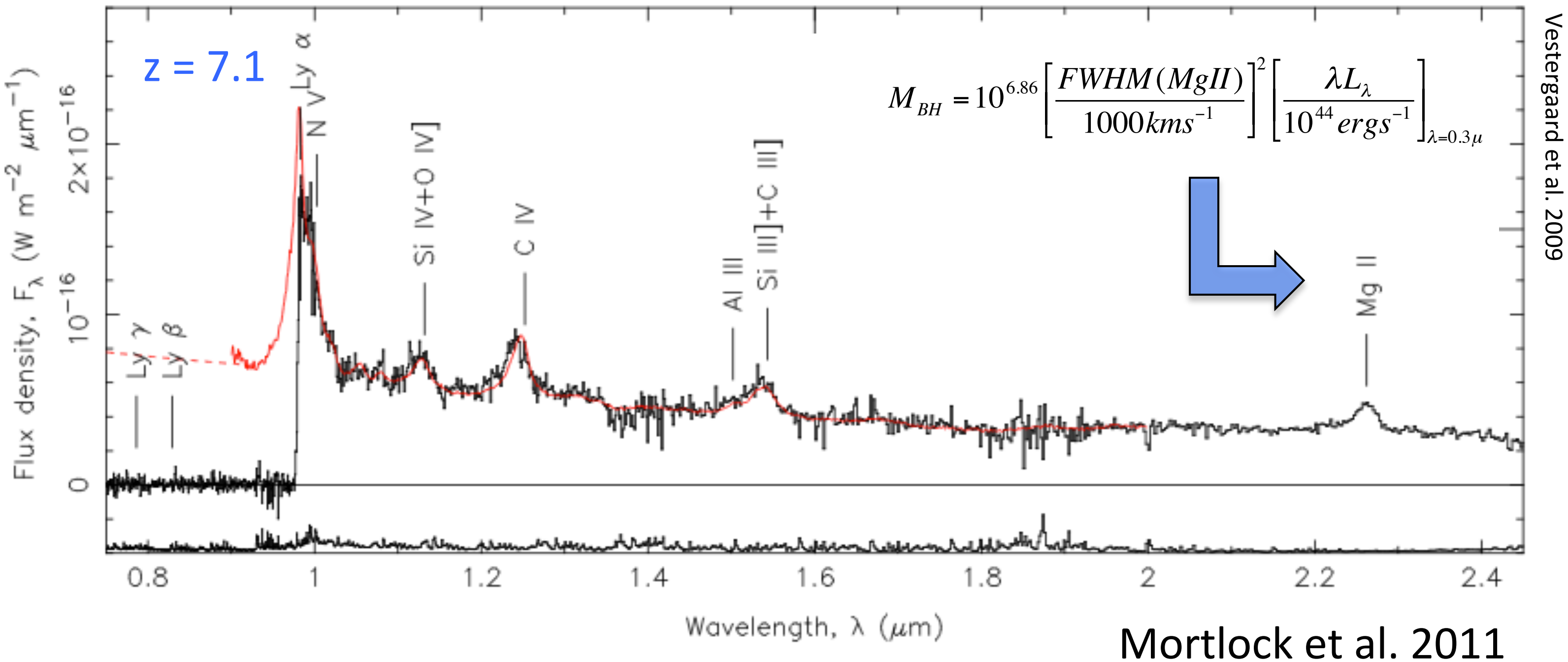
Visible and Infrared Survey Telescope
for Astronomy Kilo-degree INfrared Galaxy
(VIKING, Venemans et al. 2014)



Panoramic Survey Telescope
And Rapid Response System 1
(PanSTARRS1, Banados et al. 2014)



Black hole mass in high redshift quasars



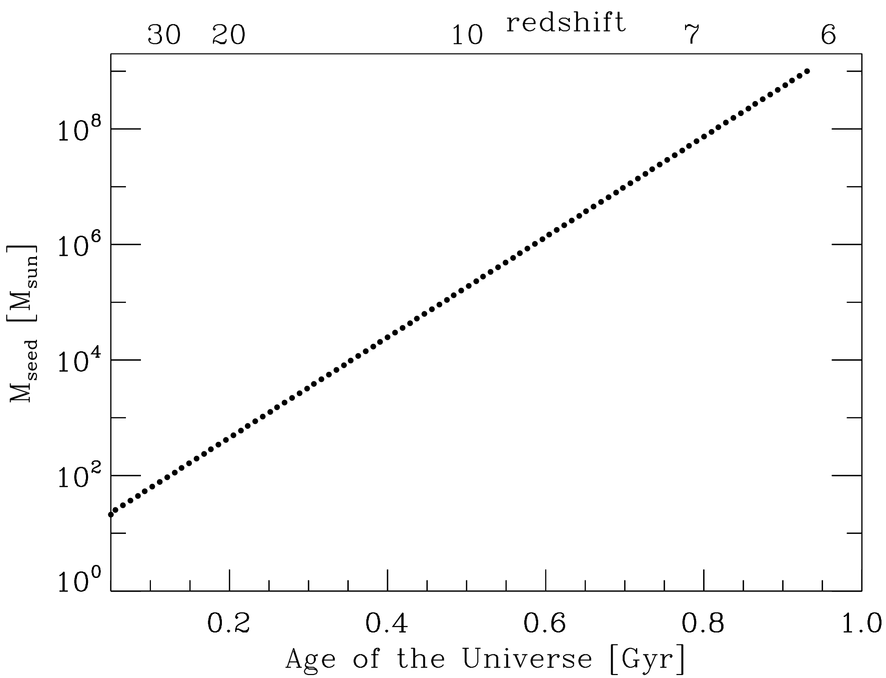
Mortlock et al. 2011

Tens of z ≈ 6 quasars

(e.g. Barth et al. 2003; Willott et al. 2003; Jiang et al. 2007; Priddey et al. 2003; Wang et al. 2010)

$$M_{BH} = (0.2 - 3.4) \times 10^9 M_{sun}$$

Possible pathways for the origin of SMBH seeds



Assumptions:

The BH is radiating at L_{EDD} for all the time spent accreting

$$\varepsilon = 0.1$$

$$\dot{M}_{BH} = \frac{(1-\varepsilon)L_{EDD}}{\varepsilon c^2}$$

e.g. Volonteri (2010)

Possible pathways for the origin of SMBH seeds

(1) PopIII remnants

collapse of primordial stars
(M_{PopIII}≈100 M_{sun})
in DM minihalos
(M_{DM}≈10^6 M_{sun})

z≈20-30

(2) Compact nuclear star clusters

Star collisions can lead
to the formation of VMSs
in H_2-cooling halos
(T_{vir}<10^4 K)

z ≈10-20

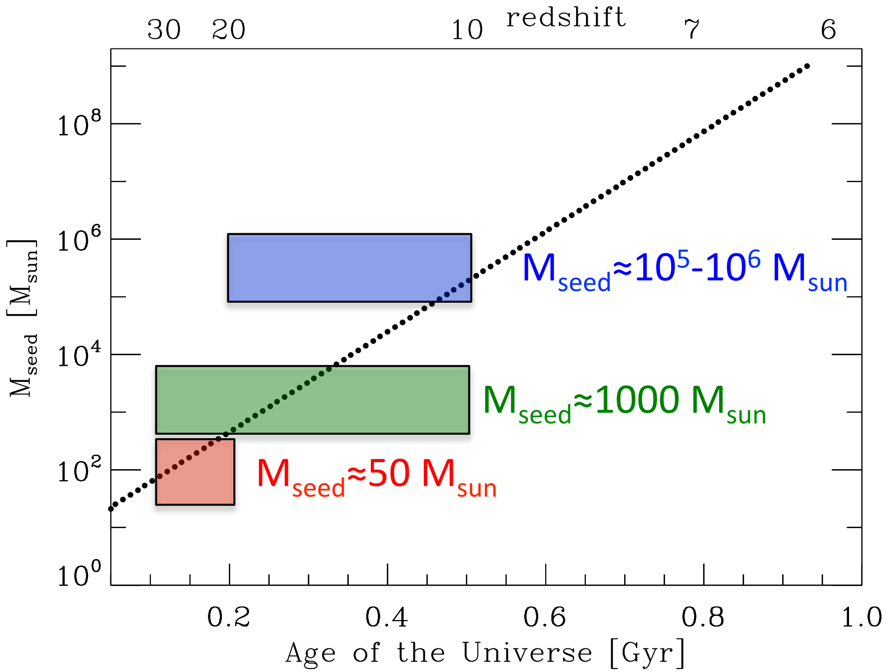
(3) Direct Collapse Black Holes

Primordial gas
irradiated by LW radiation
in atomic-cooling halos
(T_{vir}>10^4 K)

z > 10

(e.g. Haehnelt & Rees 1993;
Begelman et al. 2006;
Yue et al. 2013)

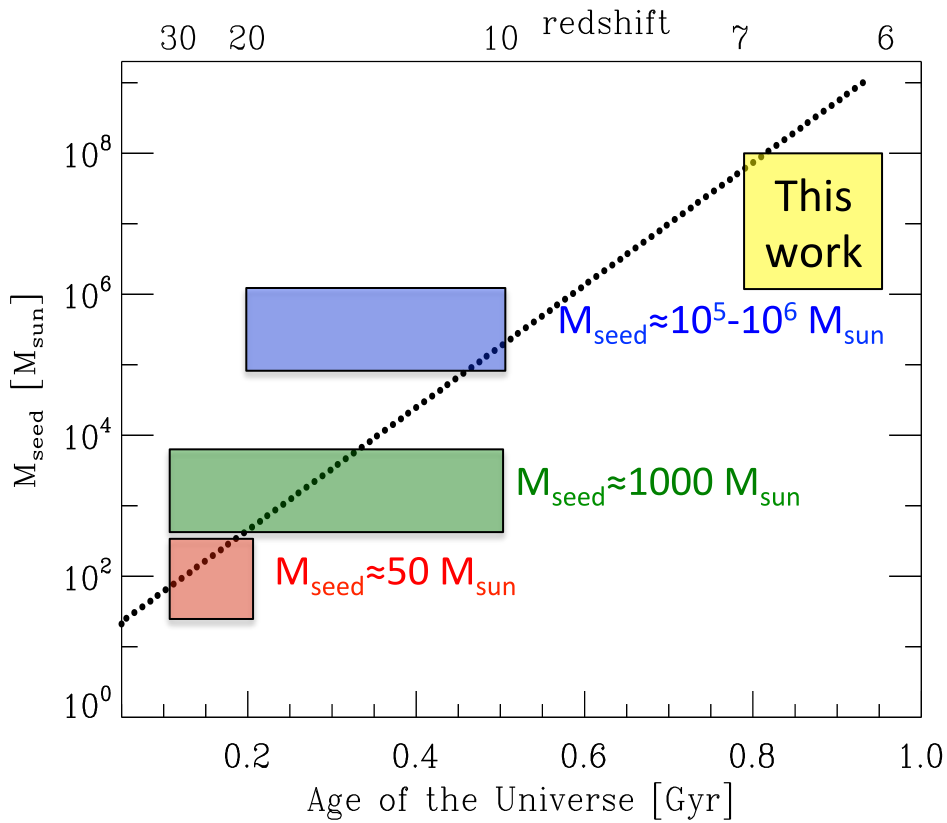
(e.g. Tegmark et al. 1997;
Madau & Rees 2001;
Palla et al. 2002)



(e.g. Schneider et al. 2006;
Clark et al. 2008;
Devecchi et al. 2012)

e.g. Volonteri (2010)

Constraints on the possible pathways for the origin of SMBH seeds…



$M_{seed} \approx 10^6$-10^8 M_{sun}

Gallerani et al. (2014)

through rest frame FIR emission lines

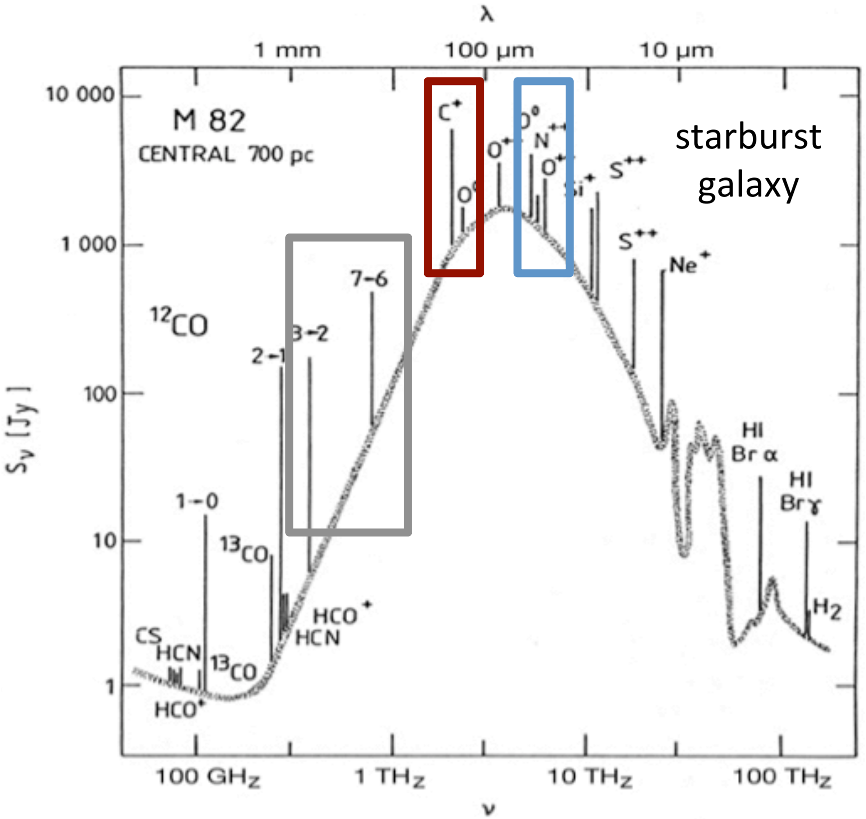
Rest frame FIR emission lines

Fine structure transitions from atomic species (C and N)
and rotational lines from the carbon monoxide molecule (CO)

(e.g. [CII] ($^2P_{3/2}$-$^2P_{1/2}$) @158 μm; [NII] ($^3P_1$-$^3P_0$) @205 μm; CO (J-J-1) @ J × 115 GHz)

- Major coolants of the inter-stellar medium in star forming galaxies
- The strongest emission lines in most galaxies ($L_{[CII]}$ ~ 0.1-1% L_{FIR})
- **Unaffected by dust extinction (r_{dust} ≤ 0.1 μm)**
  Allow to detect dust obscured sources
  (e.g. Gallerani et al. 2012)

  Black hole growth at early epochs may happen in dusty host galaxies
  (e.g. Valiante et al. 2014)



(e.g. Stacey 1993)

- At z > 4 the [CII] emission line is redshifted into the mm

The Plateau de Bure Interferometer

Array of 6 antennas
15 m diameter
→
NOEMA 12 antennas
(2018)

located at 2550 m altitude
in the French Alps

operated by IRAM
(Grenoble)

Technical properties:

WAVELENGTH COVERAGE
(0.8 mm < λ < 3 mm)
(370 GHz > ν > 80 GHz)

ANGULAR RESOLUTION
(0.35'' < R < 0.8'')

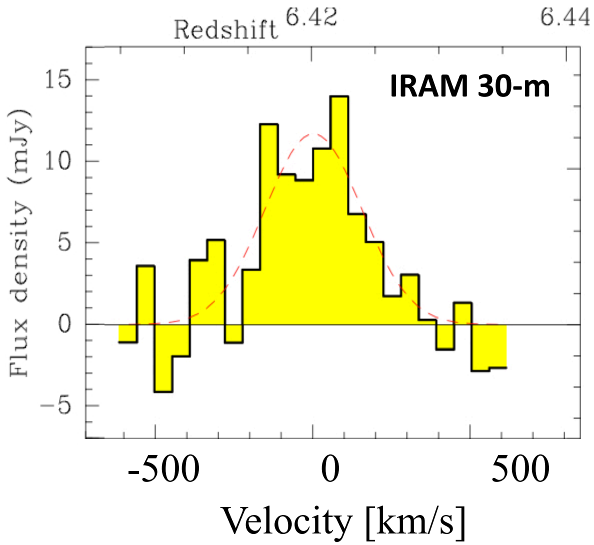
1" = 5.5 kpc @ z=6.4

The case of:

SDSS 1148 at z=6.4

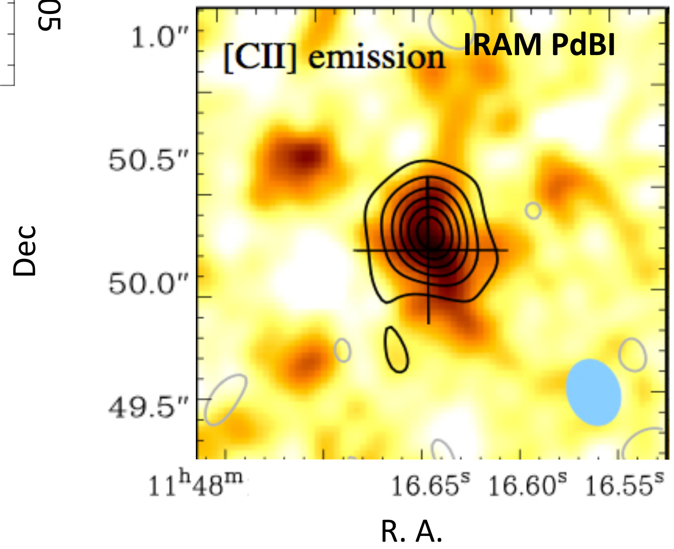
SDSS J1148 + 5251: RECORDS HOLDER at z=6.4

FIRST [CII] DETECTED



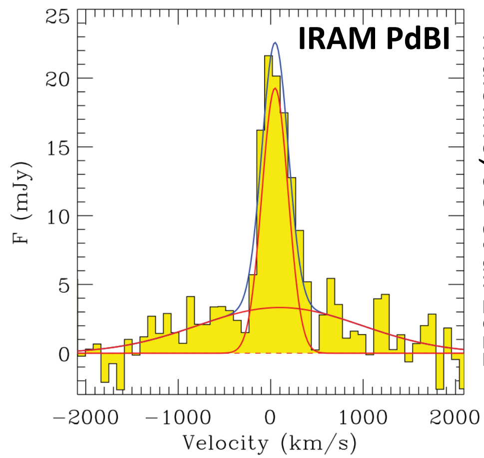
Maiolino et al. 2005

FIRST [CII] RESOLVED



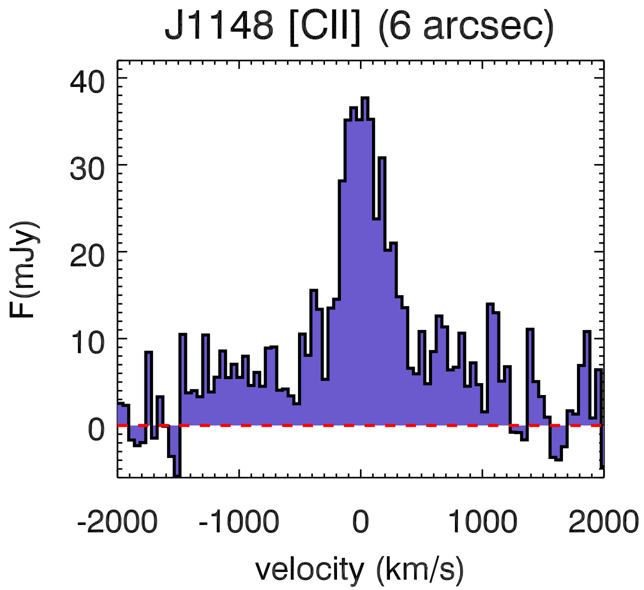
Walter et al. 2009

FIRST POWERFUL OUTFLOW



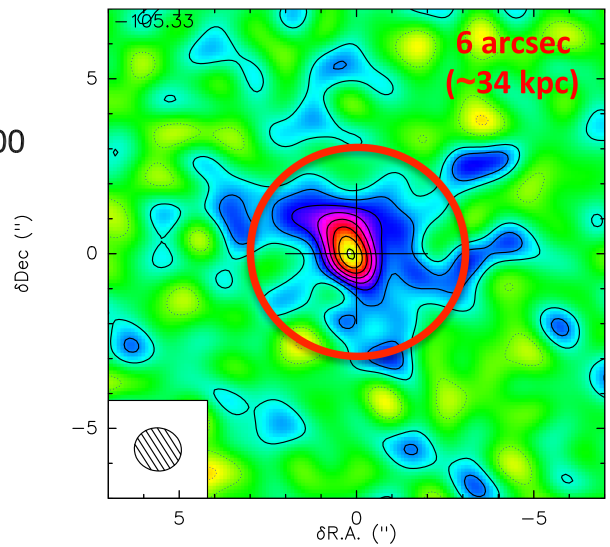
Maiolino, SG et al. 2012

SDSS J1148 + 5251: RECORDS HOLDER at z=6.4

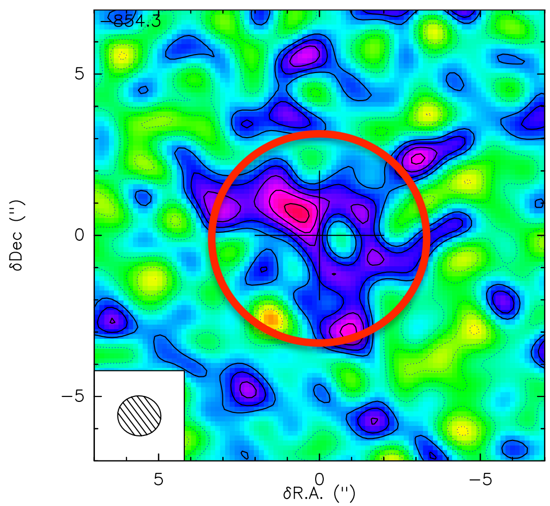


NEW surprising results from the PdBI !!!

Total
(core+ouflow)



Outflow



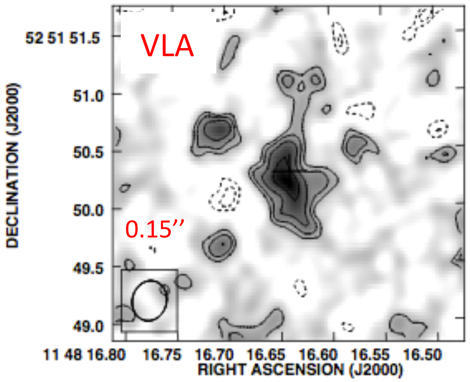
[CII] emission and outflowing gas up to 20-30 kpc

Cicone et al. (2014)

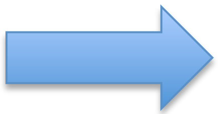
The core contains
an extended component
> 20 kpc large !!!

Gigantic outflow extend
up to > 30 kpc !!!

CO observation in J1148



Walter et al. (2003/2004)



The molecular gas

$M_{H2} \approx 2 \times 10^{10}\ M_{sun}$

is enclosed within a radius

$R_{H2} \approx 2.5$ kpc

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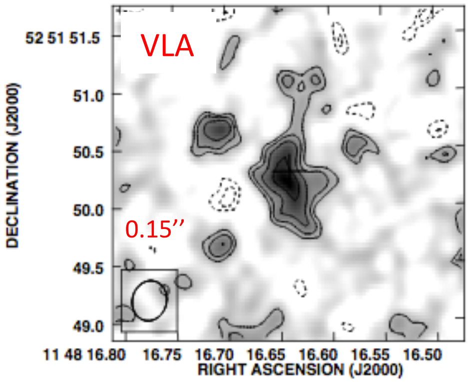

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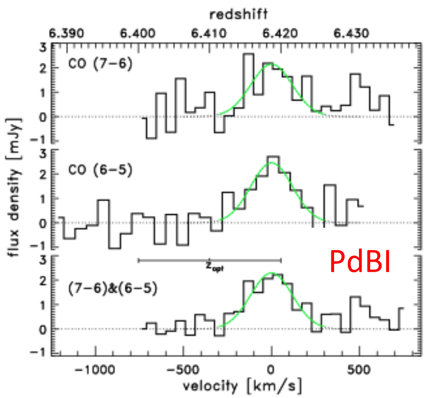
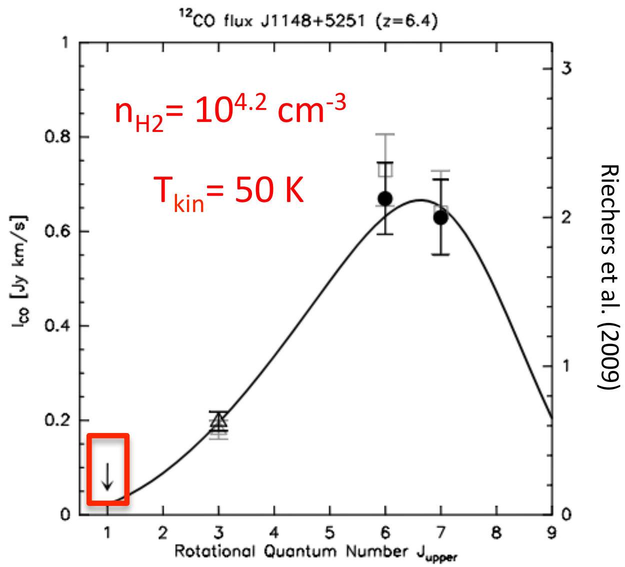


Bertoldi et al. (2003)

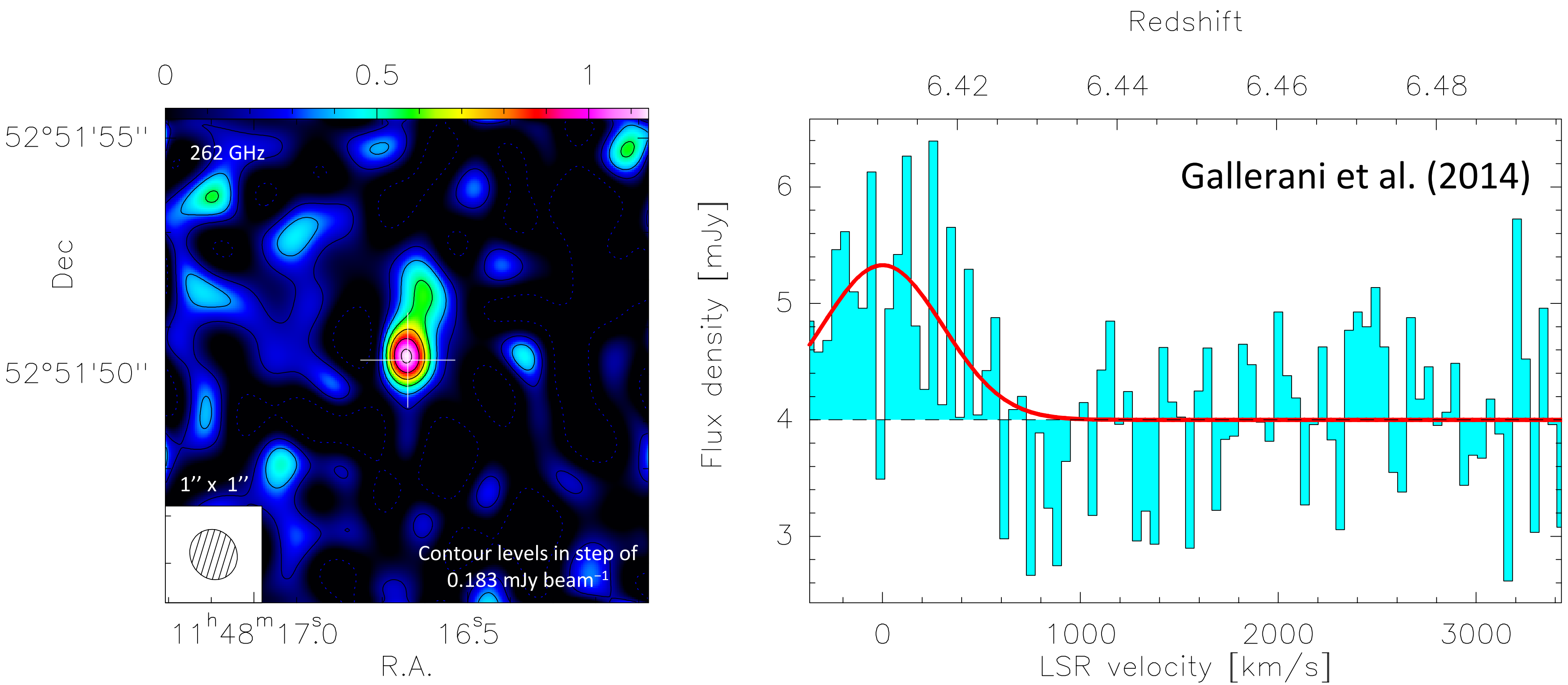
CO SLED

(Spectral Line Energy Distribution)



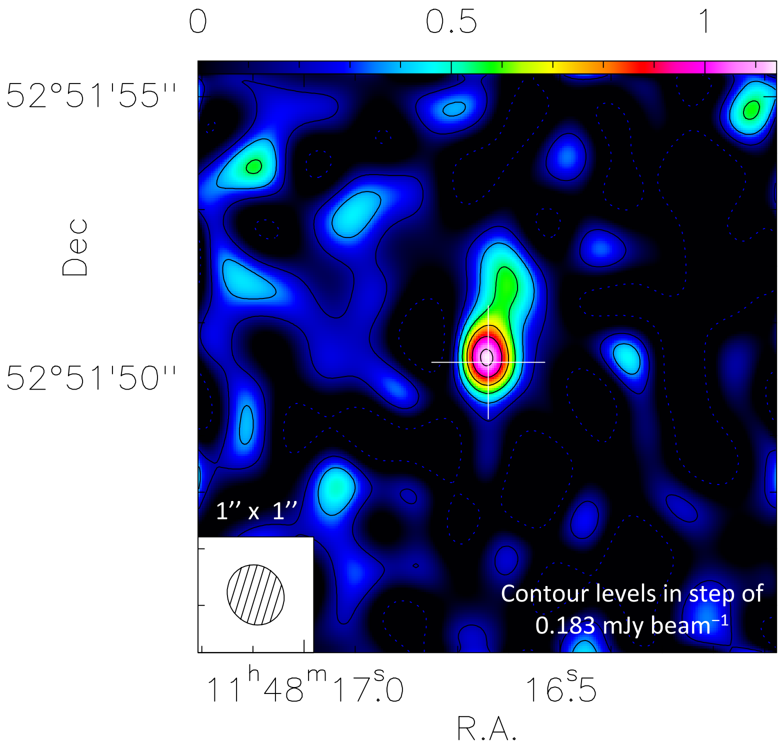
Effelsberg
100 m telescope

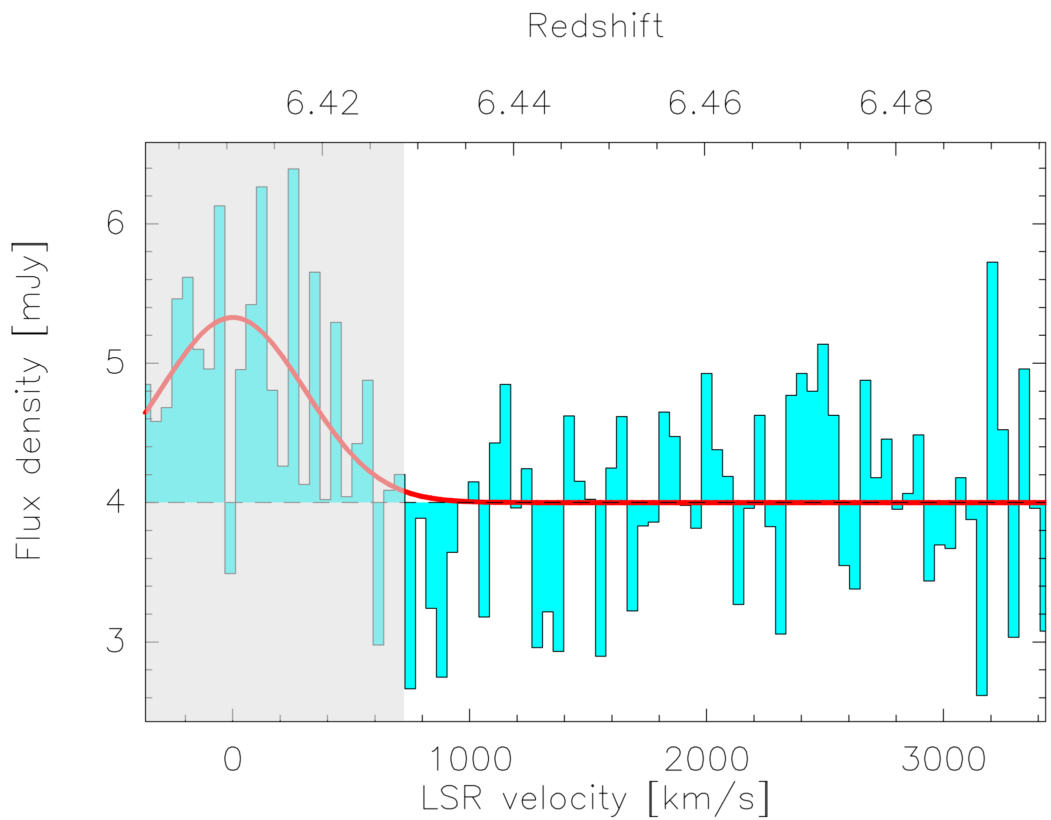
Strong emission serendipitously detected in J1148



6.2σ detection

First detection of the CO(17-16) line at high-z!





observing time: 20 hr

Gallerani et al. (2014)

263 < ν_{obs} [GHz]< 264

$z_{[CII]}$ =6.4189

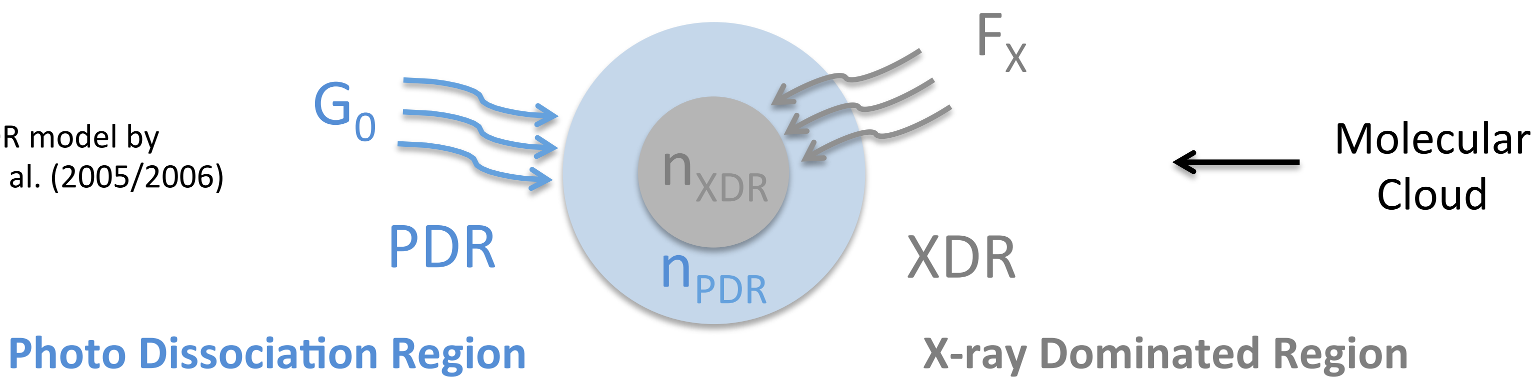
(Maiolino et al. 2005)

1951 < ν_{RF} [GHz]< 1959

CO(17-16)

Modelling the molecular clouds in J1148

PDR/XDR model by
Meijerink et al. (2005/2006)



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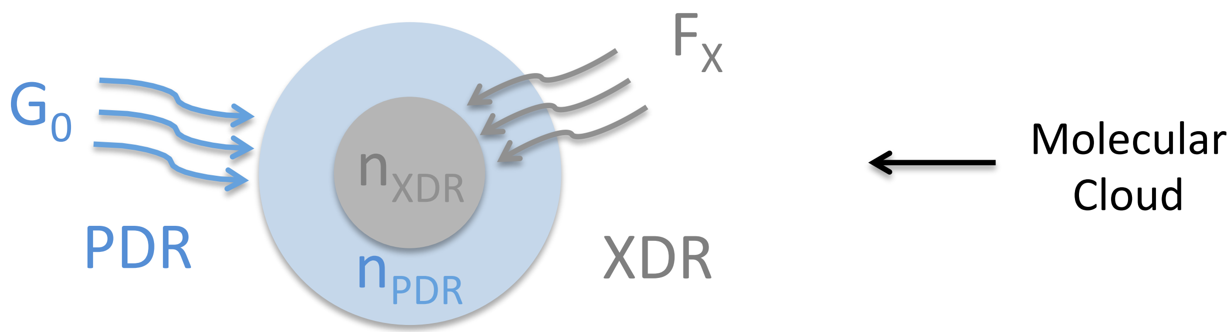
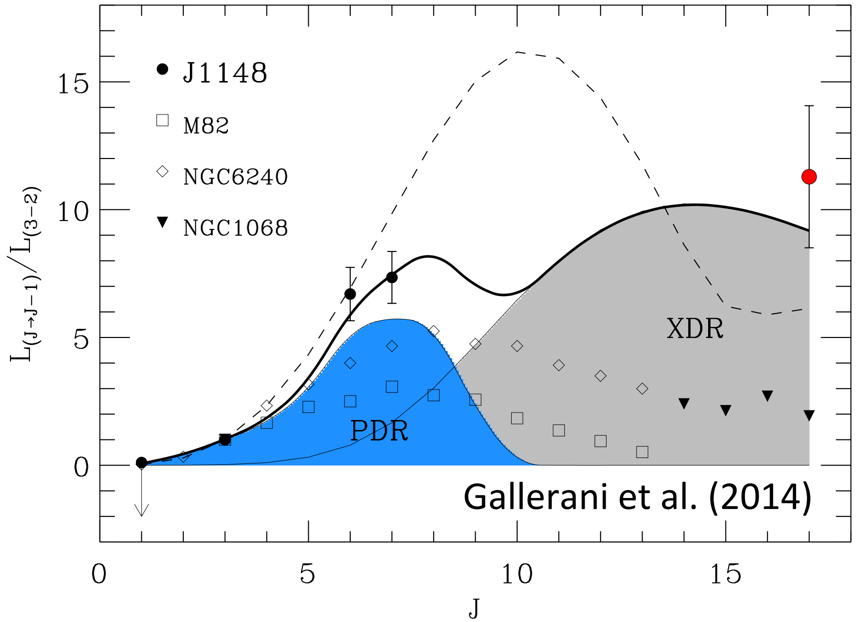


$n_{XDR} = 10^{4.25}$ [cm^{-3}]

$F_X = 160$ [erg s^{-1} cm^{-2}]

$n_{PDR} = 10^{3.25}$ [cm^{-3}]

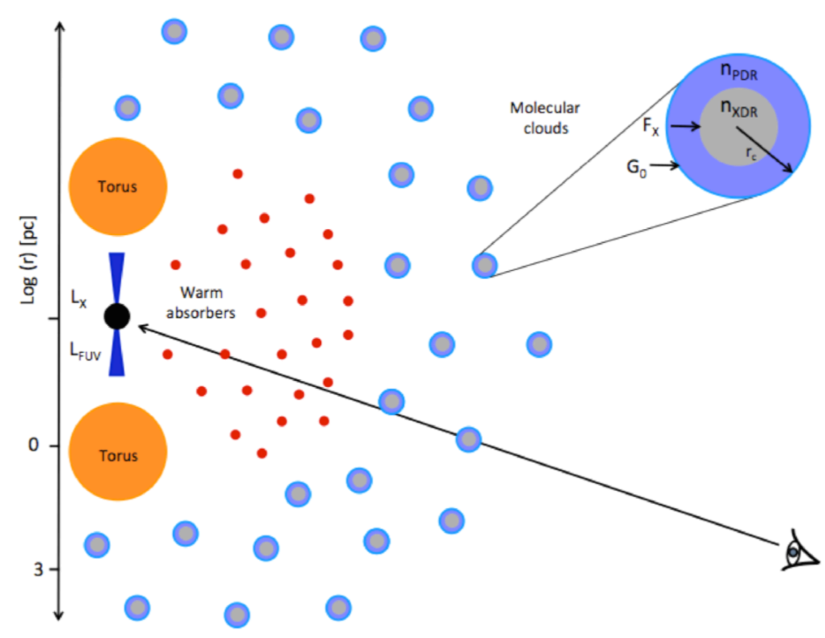
$G_0 = 10^4$

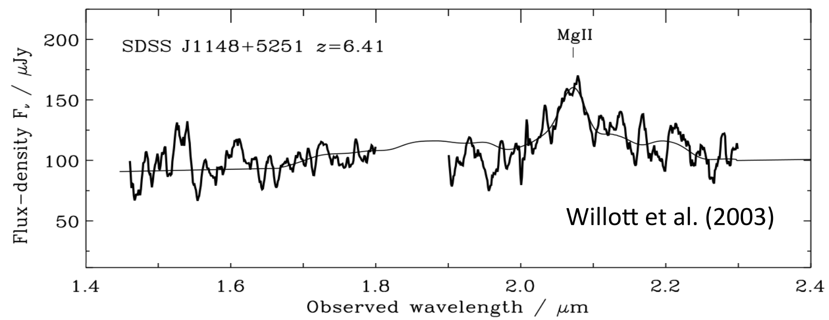


PDR and XDR models by Meijerink et al. (2005/2006)

High-J CO lines as proxies of AGN activity

Predictions on the X-ray flux of SDSS J1148 at z=6.4





$$M_{H2} = 2\times10^9 M_{sun} \qquad M_{BH} = 3\times10^9 M_{sun}$$

$$F_X^{obs} = \frac{L_X}{4\pi d_L(z)^2}\exp[-\tau_X]$$

Photo-electric optical depth by Morrison & McCammon 1983

$$F_X^{soft} \sim 7\times10^{-15}[erg\ s^{-1}cm^{-2}] \qquad F_X^{hard} \sim 3\times10^{-14}[erg\ s^{-1}cm^{-2}]$$

Prospects for detecting SMBH ancestors

$z \approx 6$

$M_{BH} \approx 10^9 M_{sun}$

$M_{H2} \approx 10^{10} M_{sun}$

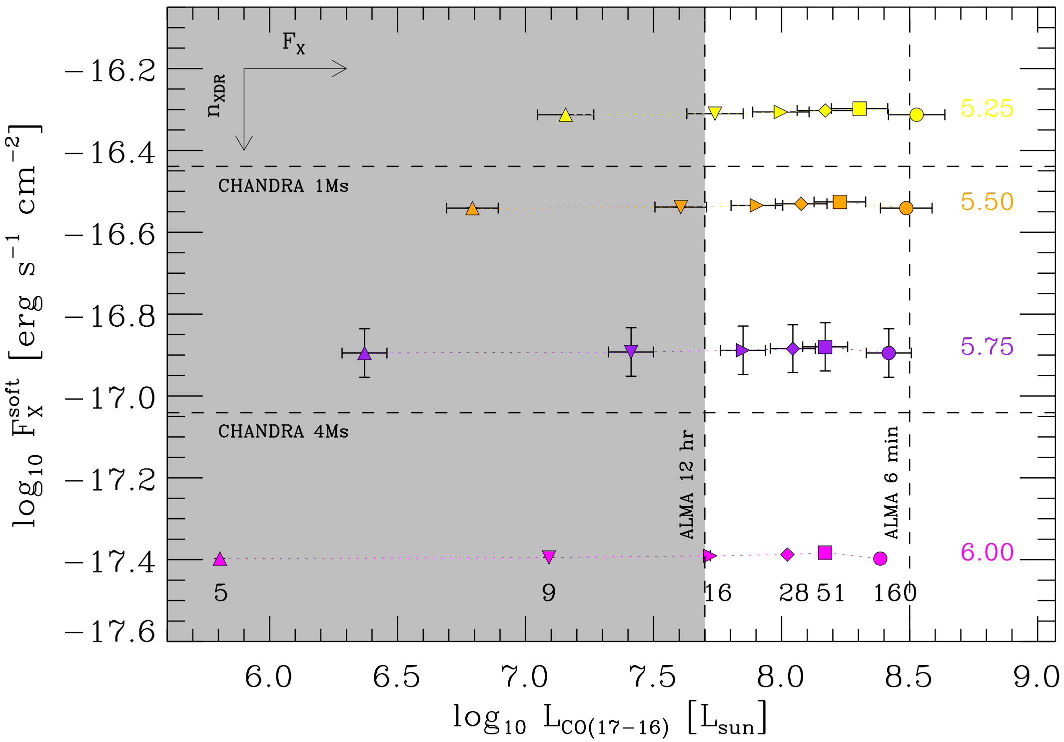
$r_{H2} \approx 2.5\ kpc$

$z \approx 7$

$M_{BH} \approx 10^6 M_{sun}$

$M_{H2} \approx 10^7 M_{sun}$

$r_{H2} \approx 0.3\ kpc$



Gallerani et al. (2014)

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$M_{H2} \approx 10^7 M_{sun}$

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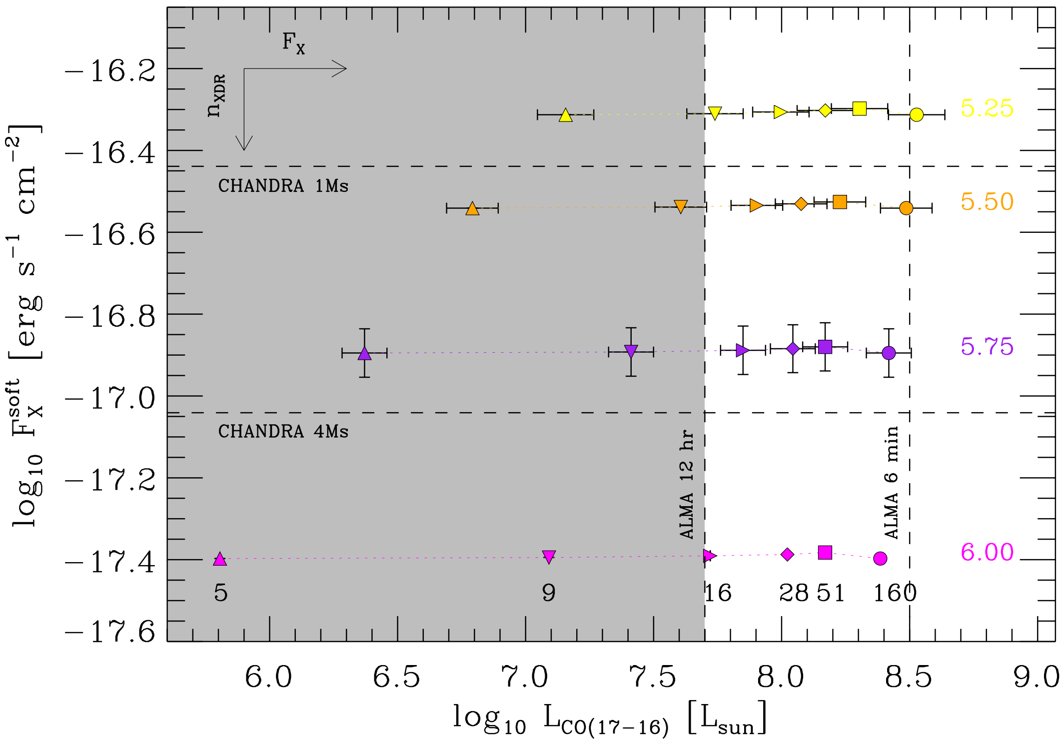
Undetected/obscured

$N_H \geq 10^{24} cm^{-2}$

(e.g. Comastri 2004)

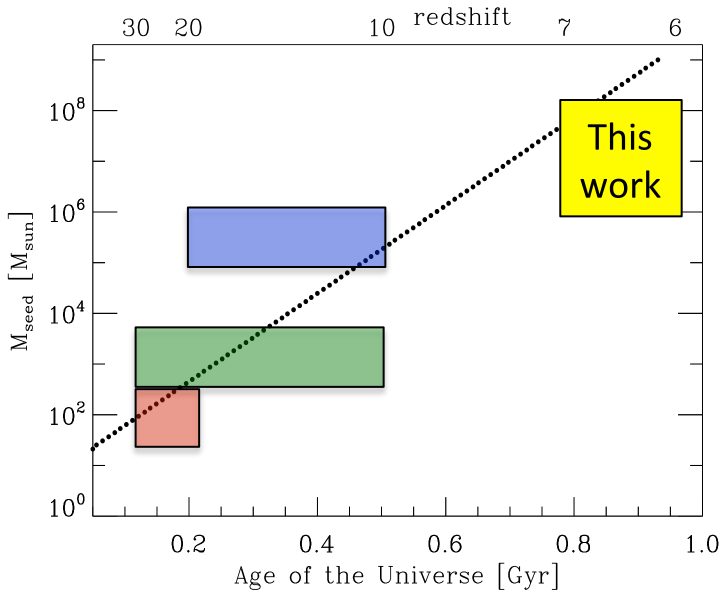


Gallerani et al. (2014)

In X-ray observations of z ≈ 6 quasar the typical flux detection limit is ≈ 10^{-15}erg s^{-1} cm^{-2}

(Shemmer et al. 2006; Page et al. 2013)

Prospects for detecting SMBH ancestors



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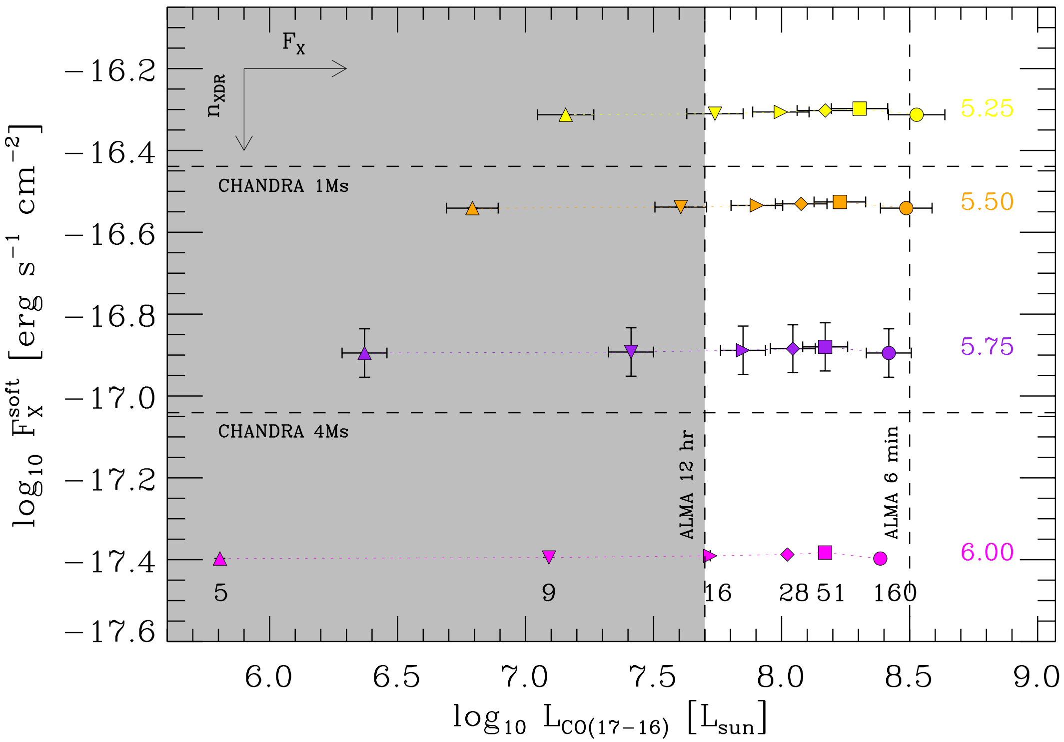
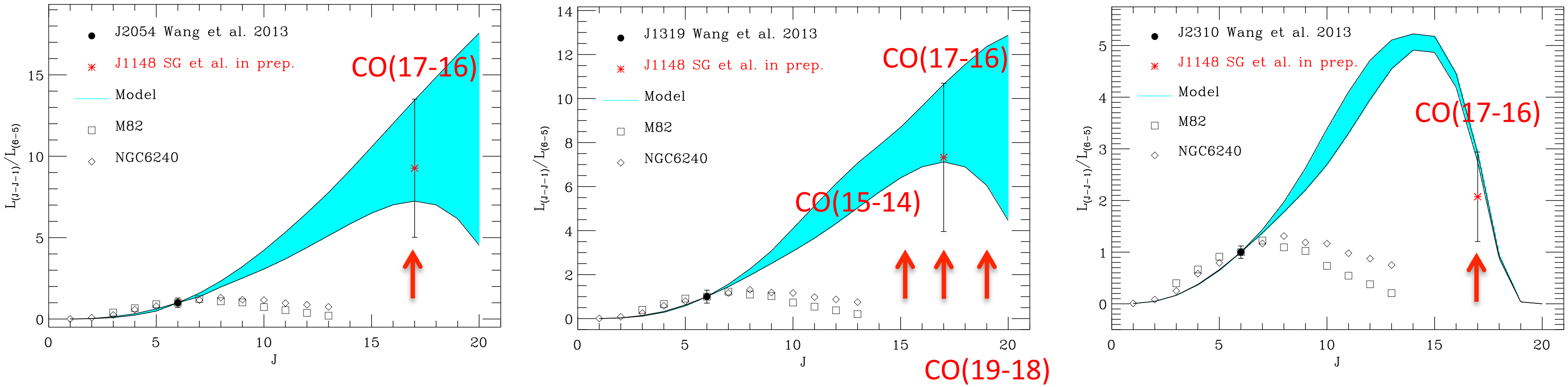


Gallerani et al. (2014)

High-J CO lines are powerful probes of SMBH ancestors

ALMA Cycle 2 proposal

Detection of high-J CO lines in other z≈6 quasars…



… already detected in [CII] with ALMA and in the CO(6-5) and dust continuum emission with PdBI

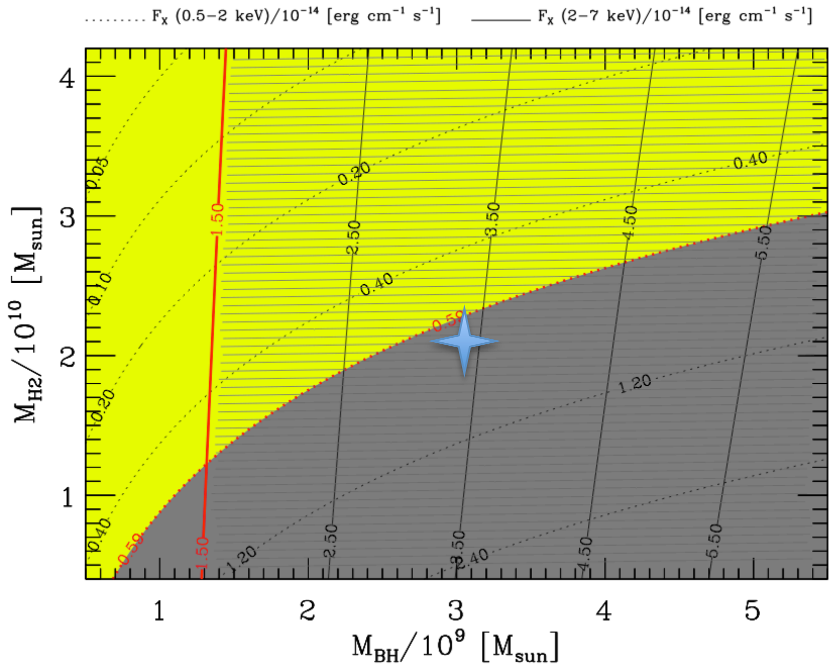
(Wang et al. 2013)

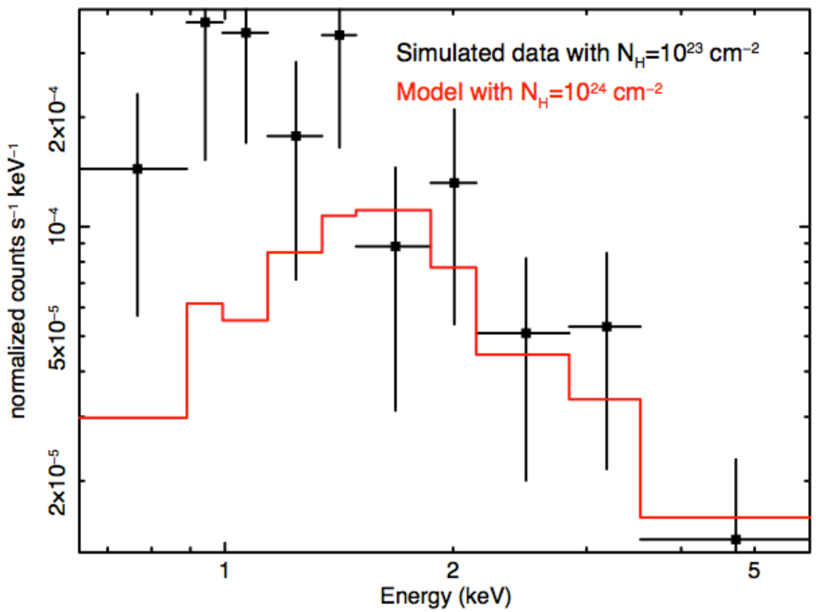
We request **only 4.3 hr to detect 5 high-J CO lines** at 5σ

FILLER PROJECT

Chandra proposal

Constraints on M_{BH} and M_{H2} from X-ray observations





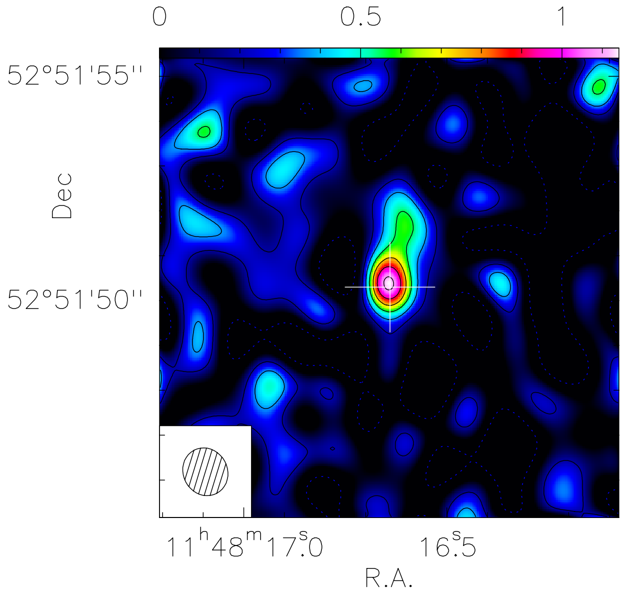
80 ks of CHANDRA observing time will be used to check our predictions

PI: S. Gallerani

CoI: E. Piconcelli; L. Zappacosta; A. Ferrara; R. Maiolino; R. Neri; C. Feruglio; F. Fiore

SUMMARY

- **First detection** of the **CO(17-16)** emission line at z=6.4

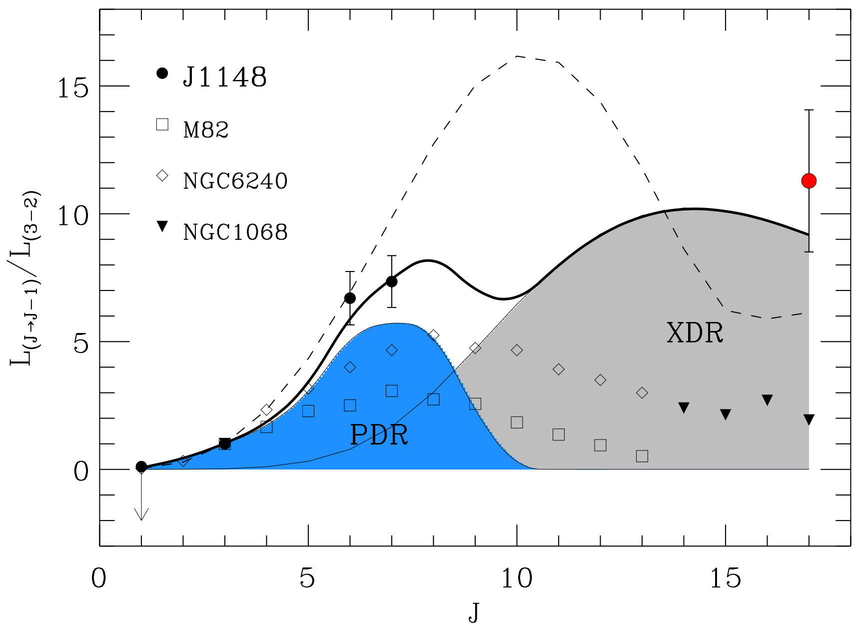


Galleroni et al. (2014)

SUMMARY

- **First detection** of the **CO(17-16)** emission line at z=6.4

- COSLED fit requires **strong contribution from XDRs**



Gallerani et al. (2014)

SUMMARY

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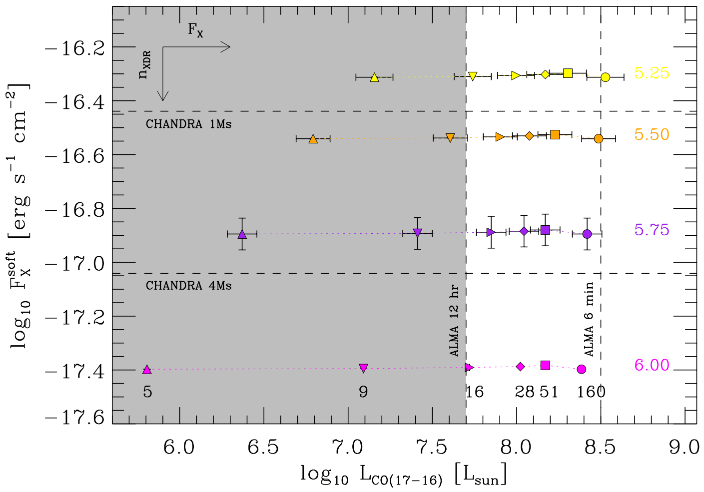
- COSLED fit requires **strong contribution from XDRs**
- **X-ray vs millimeter detectability** of high-z quasars

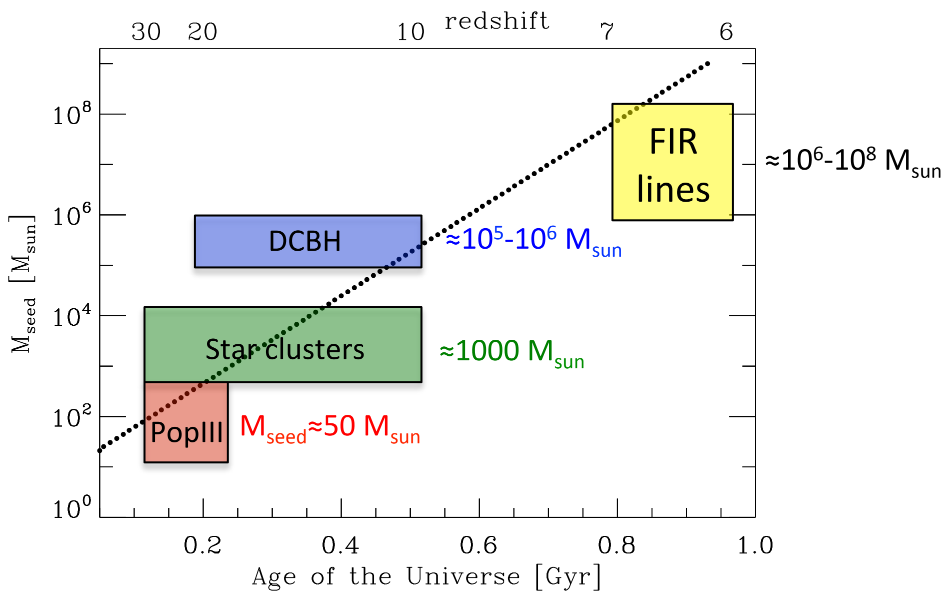


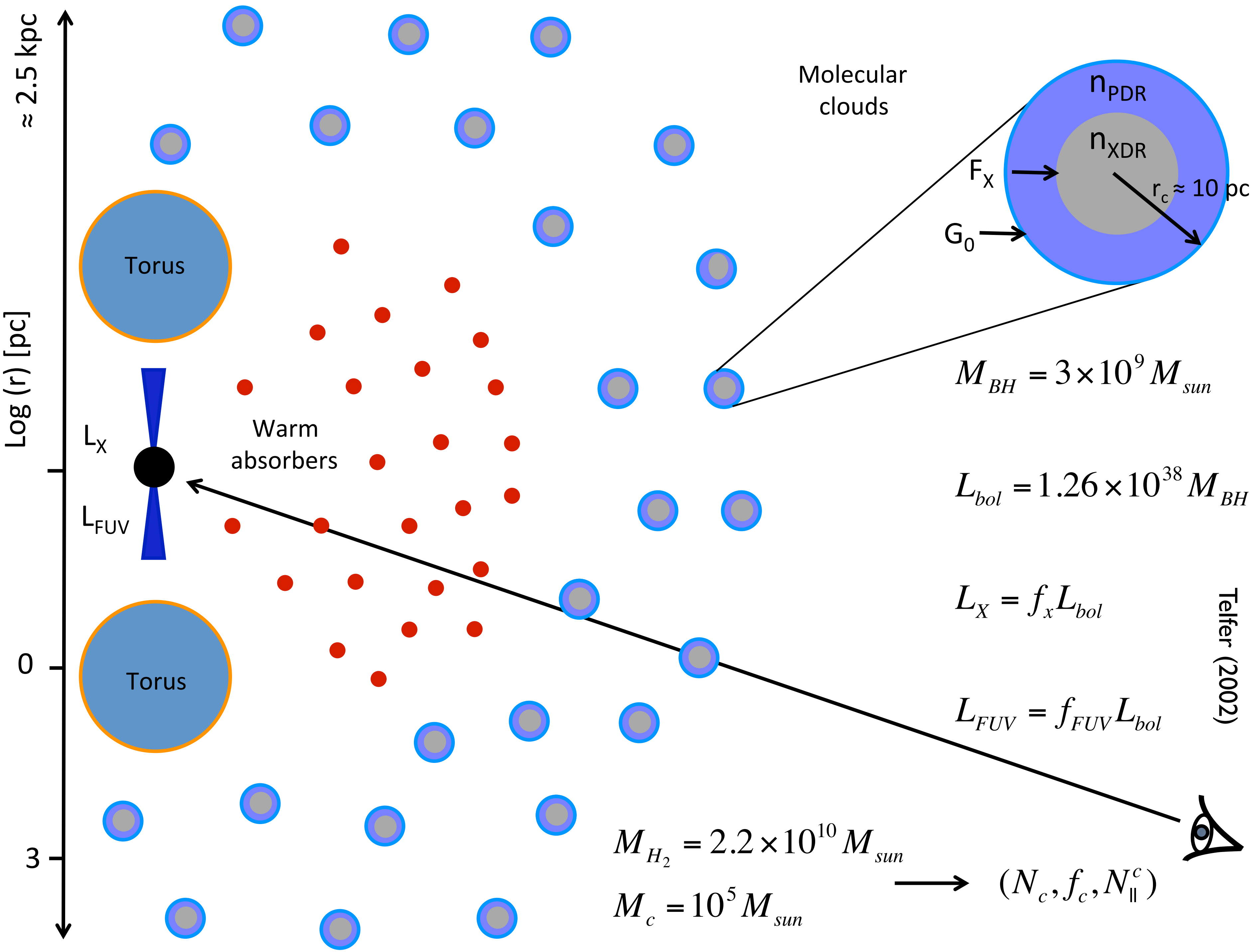
Gallerani et al. (2014)

CONCLUSION

- **First detection** of the **CO(17-16)** emission line at z=6.4
- COSLED fit requires **strong contribution from XDRs**
- **X-ray vs millimeter detectability** of high-z quasars

High-J CO lines are promising tools for detecting (dust-obscured) SMBH ancestors at z > 6





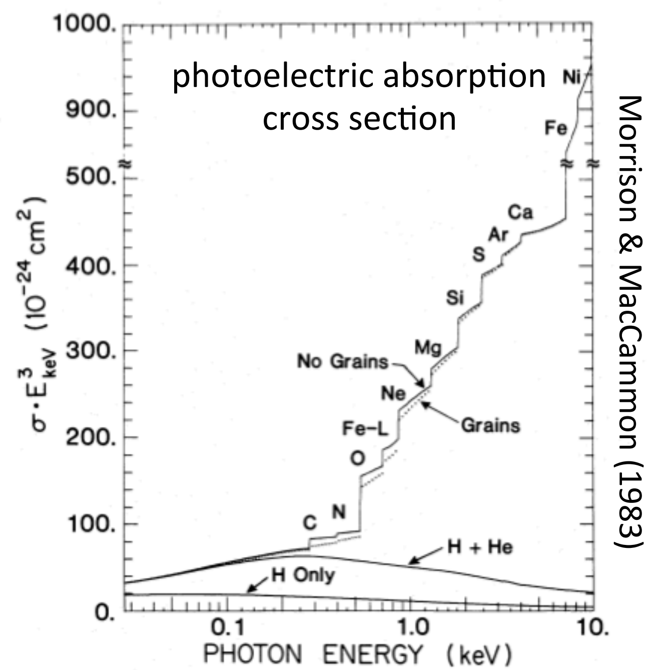
≈ 2.5 kpc
Log (r) [pc]
0
3
Torus
Torus
L_X
L_{FUV}
Warm absorbers
Molecular clouds
n_{PDR}
n_{XDR}
F_X
G_0
$r_c \approx 10$ pc
$M_{BH} = 3\times10^9 M_{sun}$
$L_{bol} = 1.26\times10^{38} M_{BH}$
$L_X = f_x L_{bol}$
$L_{FUV} = f_{FUV} L_{bol}$
Telfer (2002)
$M_{H_2} = 2.2\times10^{10} M_{sun}$
$M_c = 10^5 M_{sun}$
$(N_c, f_c, N_{\parallel}^c)$

Predictions for CHANDRA soft band (0.5<E<2 keV)

$$F_X^{obs} = \frac{L_X}{4\pi d_L(z)^2}\exp[-(\tau_X^{warm} + \tau_X^{ISM})]$$

$$\tau_X^{ISM} = N_{\parallel}^c \sigma_X^{obs} N_H^c$$

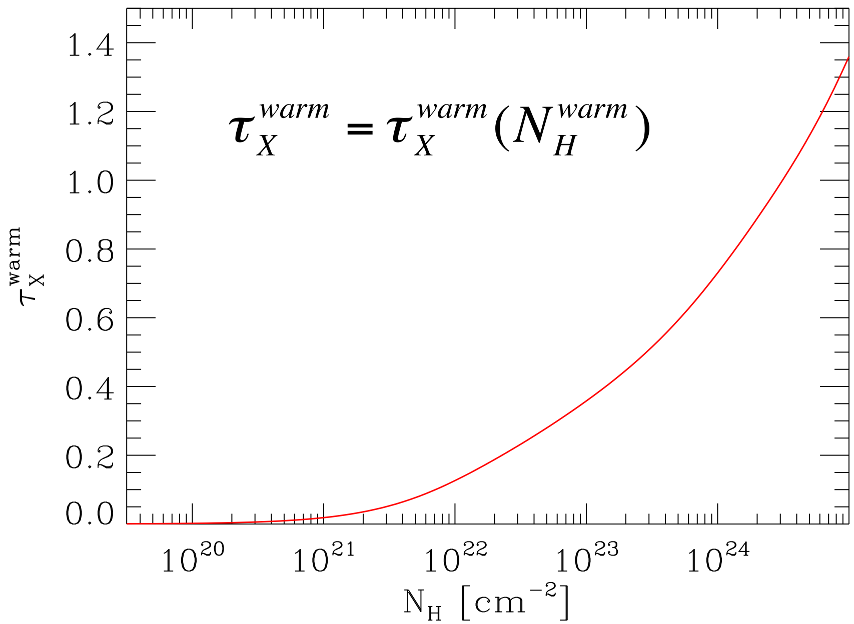
$$\tau_X^{warm} = \sigma_X^{\text{int}} N_H^{warm}$$

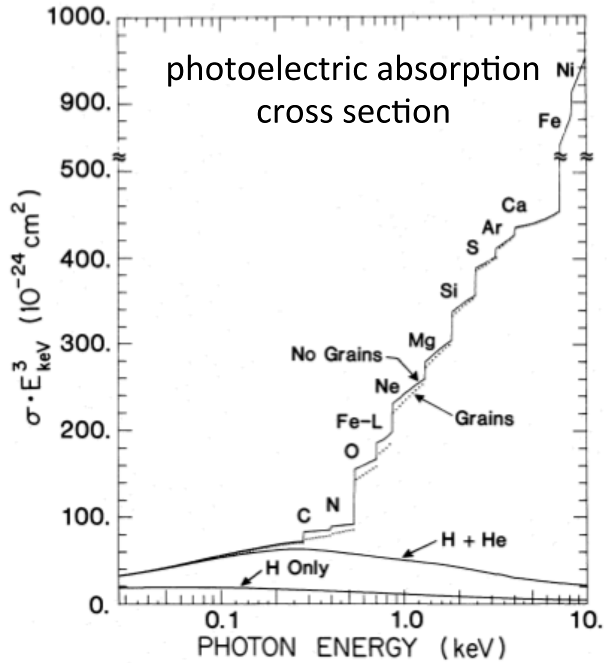


Predictions for CHANDRA soft band (0.5<E<2 keV)

$$G_0 = G_0^{QSO}\left(1+\frac{G_0^*}{G_0^{QSO}}\right) = \frac{L_{FUV}}{4\pi d_c^2}\exp[-\sigma_{FUV}N_H^{warm}]\left(1+\frac{G_0^*}{G_0^{QSO}}\right)$$

$$F_X = \frac{L_X}{4\pi d_c^2}\exp[-(\tau_X^{warm}+\sigma_X N_H^{PDR})]$$

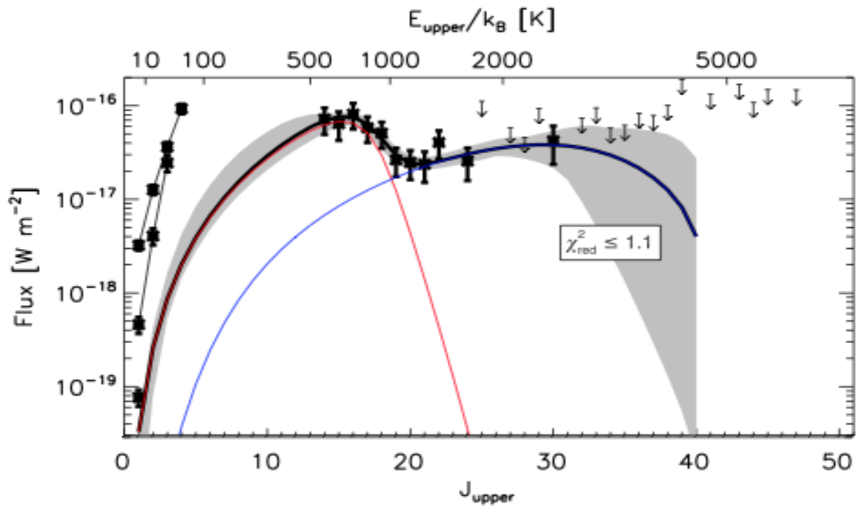


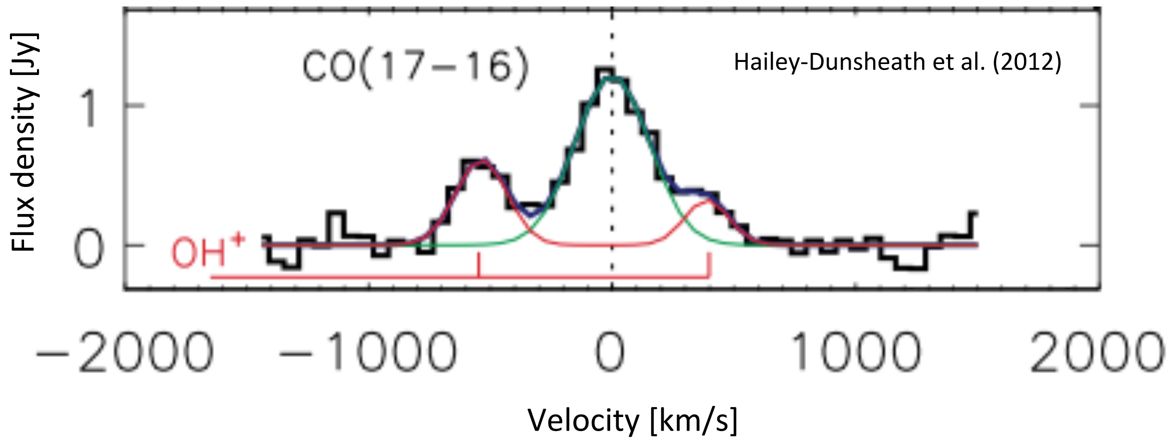


Morrison & MacCammon (1983)

First detection of the CO(17-16) line

NGC1068, a local Seyfert 2 Galaxy
detected up to
the **CO(30-29) transition**





Line complex of
CO(17-16) and **OH+**
transitions

$F_{CO(17\text{-}16)} \approx 65\%\ F_{total}$

About the OH+ contamination