Far infrared emission lines in high redshift quasars

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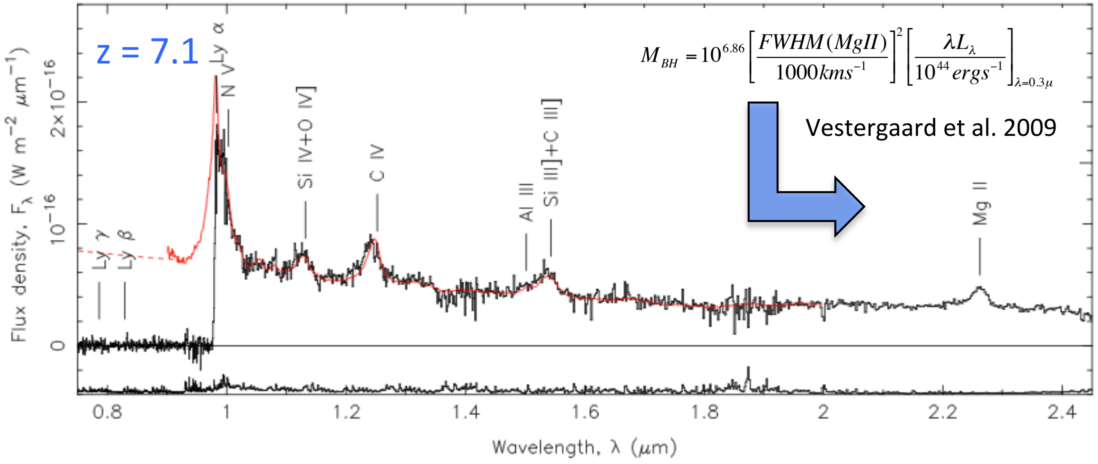
in collaboration with:

A. Ferrara, R. Maiolino, R. Neri

"Where Black Holes and Galaxies meet", Trieste, 23rd June 2014

Black hole mass in high redshift quasars

Mortlock et al. 2011



$$M_{BH} = 10^{6.86}\left[\frac{FWHM(MgII)}{1000\,kms^{-1}}\right]^2\left[\frac{\lambda L_\lambda}{10^{44}\,ergs^{-1}}\right]_{\lambda=0.3\mu}$$

Vestergaard et al. 2009

Tens of z ≈ 6 quasars

$$\boxed{M_{BH} = (0.2-3.4)\times10^9 M_{sun}}$$

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

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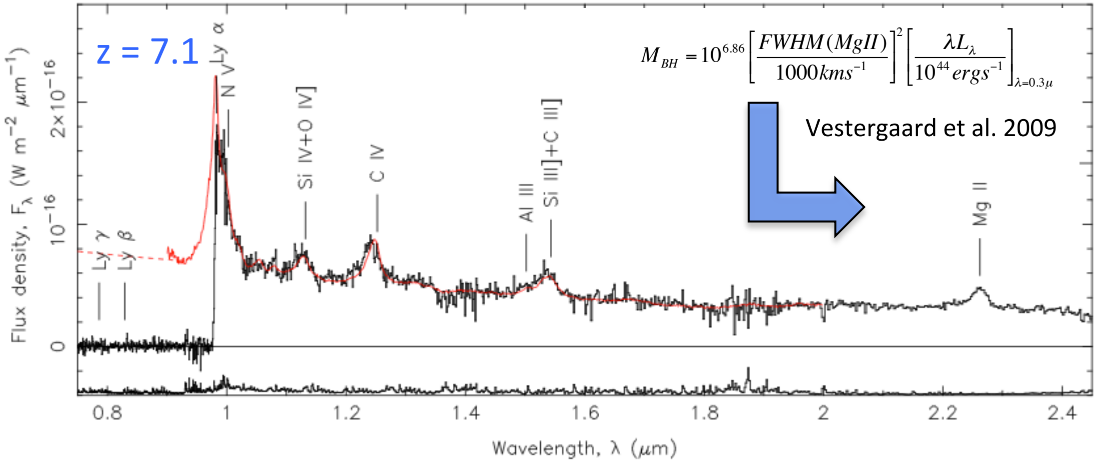

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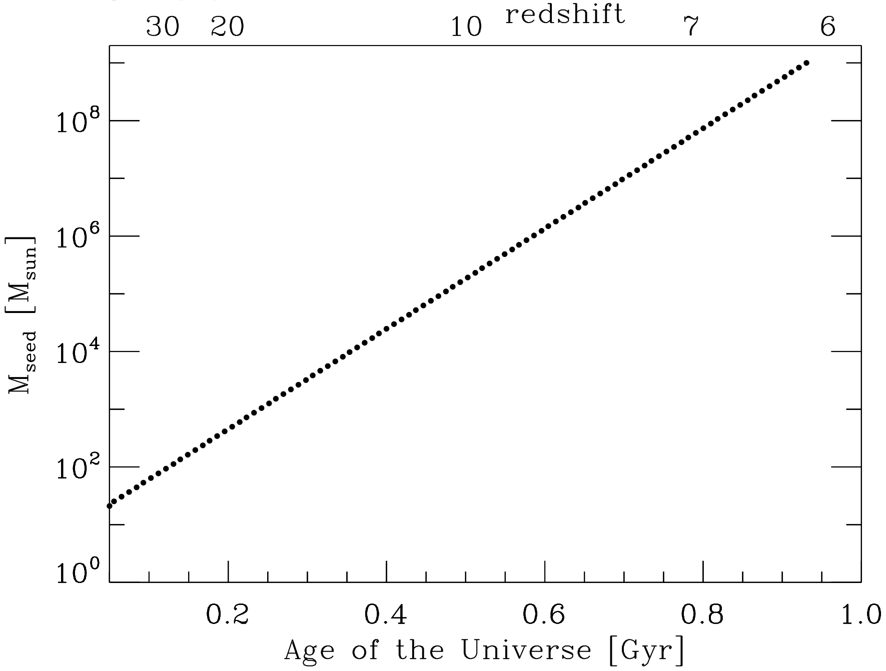
Assumptions:

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

$$\varepsilon = 0.1$$



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

Possible pathways for the formation of SMBH

(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

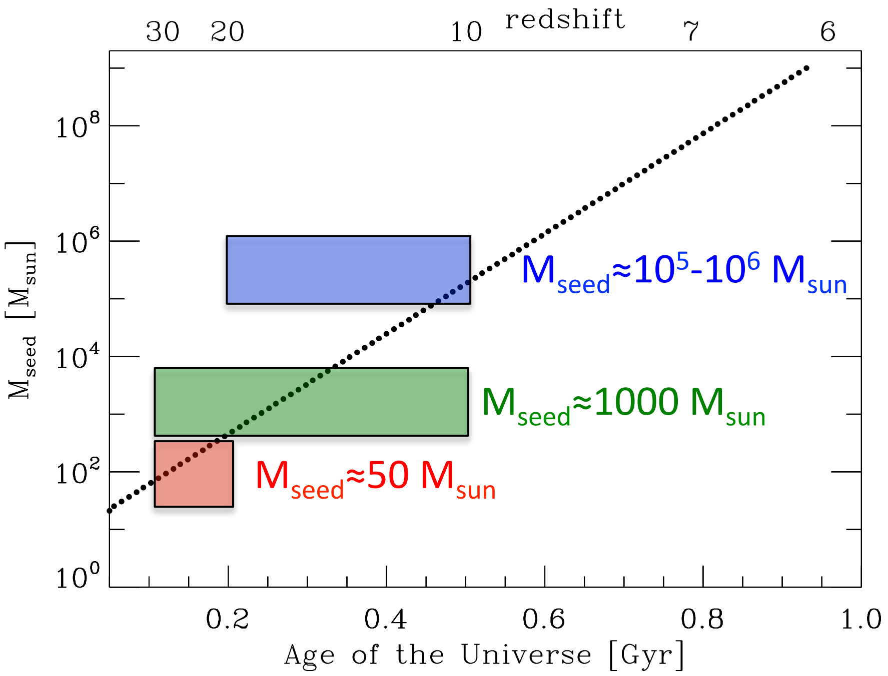
(3) Direct Collapse Black Holes

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

z > 10

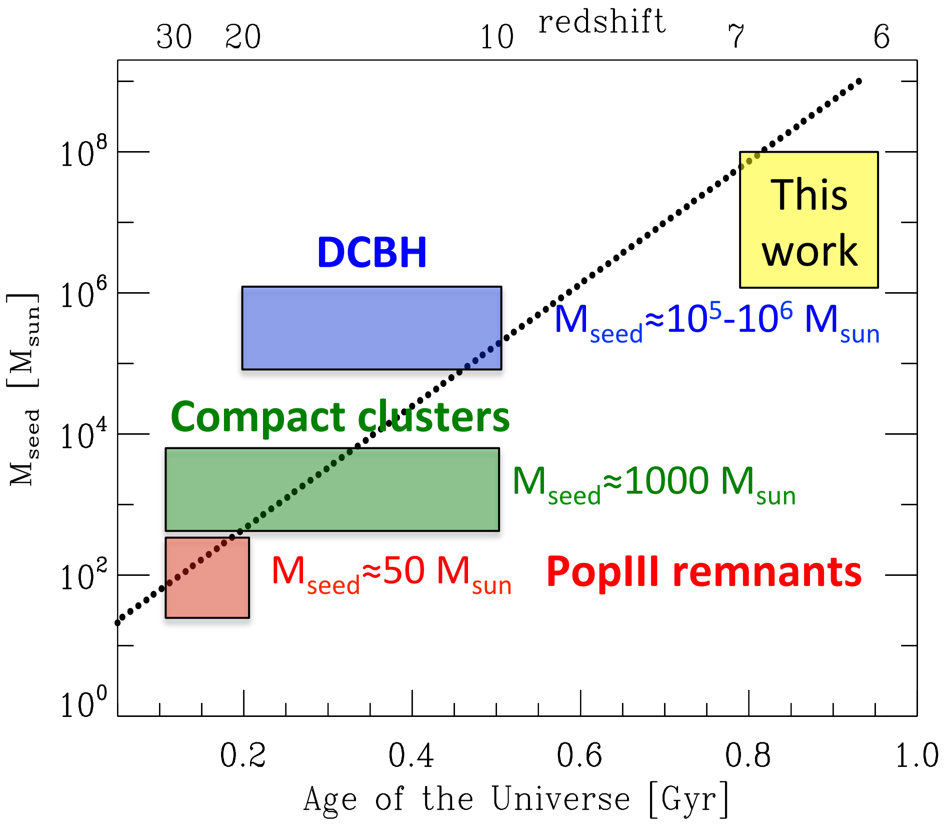
(e.g. Haehnelt & Rees 1993;
Begelman et al. 2006;
Yue et al. 2013)

(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)

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



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

Gallerani et al. (2014)
arXiv1409.4413

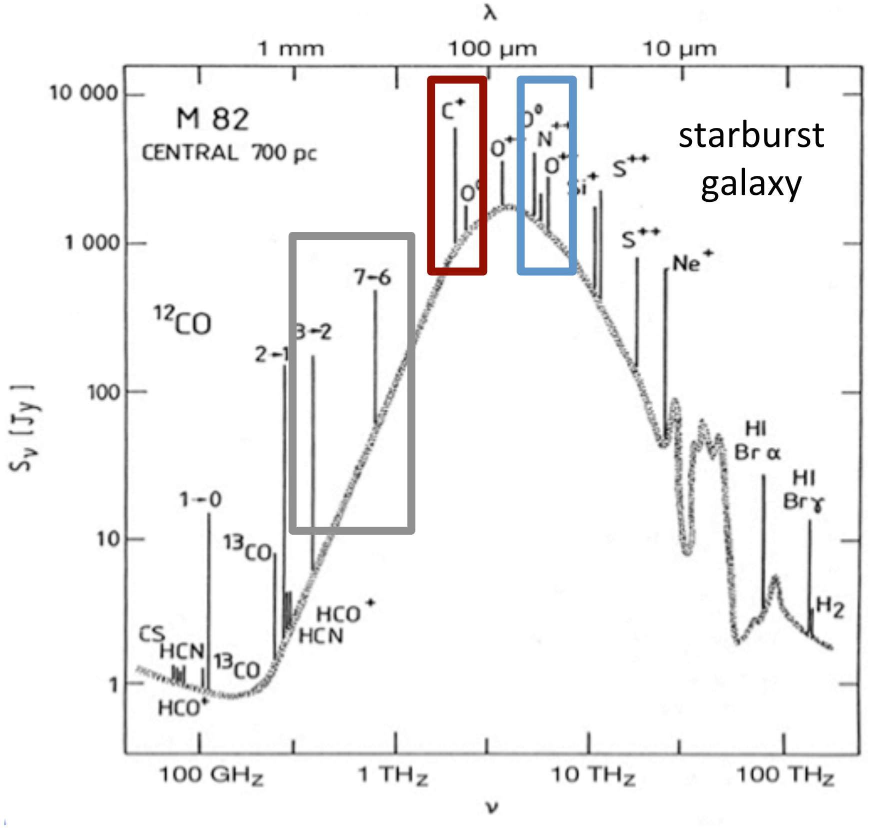
Accepted for publication in MNRAS Letter

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)



(e.g. Stacey 1993)

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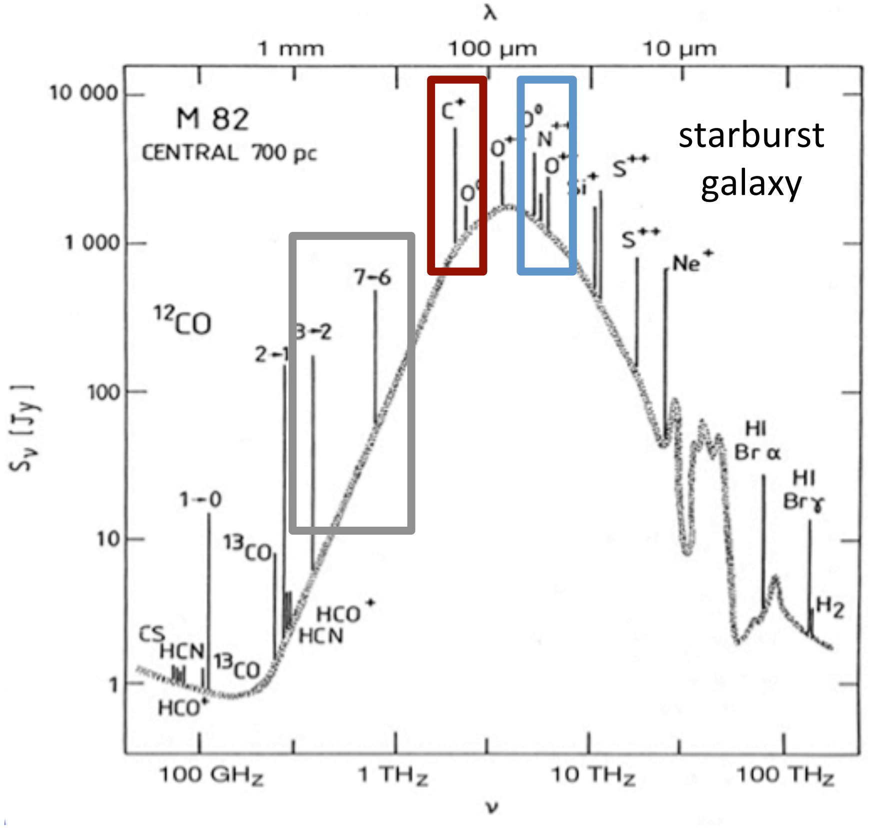
- Major coolants of the inter-stellar medium in star forming galaxies
- The strongest emission lines in most galaxies ($L_{[CII]} \sim 0.1$-$1\%\ L_{FIR}$)



starburst galaxy

(e.g. Stacey 1993)

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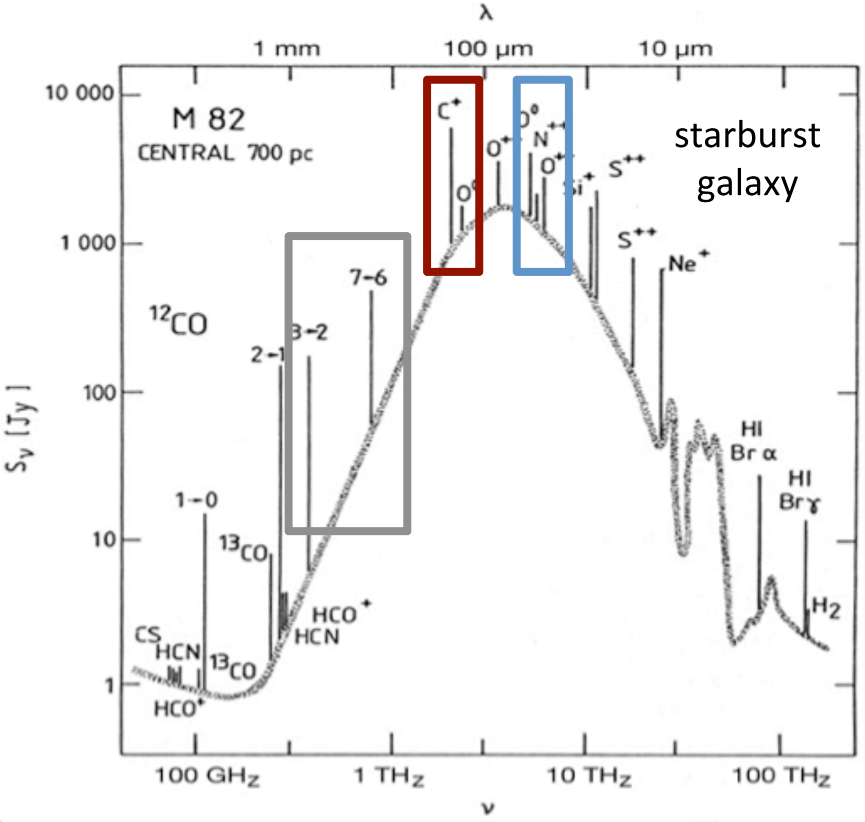
- Major coolants of the inter-stellar medium in star forming galaxies
- The strongest emission lines in most galaxies ($L_{[CII]}$ ~ 0.1-1% L_{FIR})
- **Unaffected by dust extinction (r_{dust} ≤ 0.1 µm)**
  Allow to detect dust obscured sources
  (e.g. Gallerani et al. 2012)

  Black hole growth at early epochs may happen in dusty host galaxies
  (e.g. Treister et al. 2013; Valiante et al. 2014)



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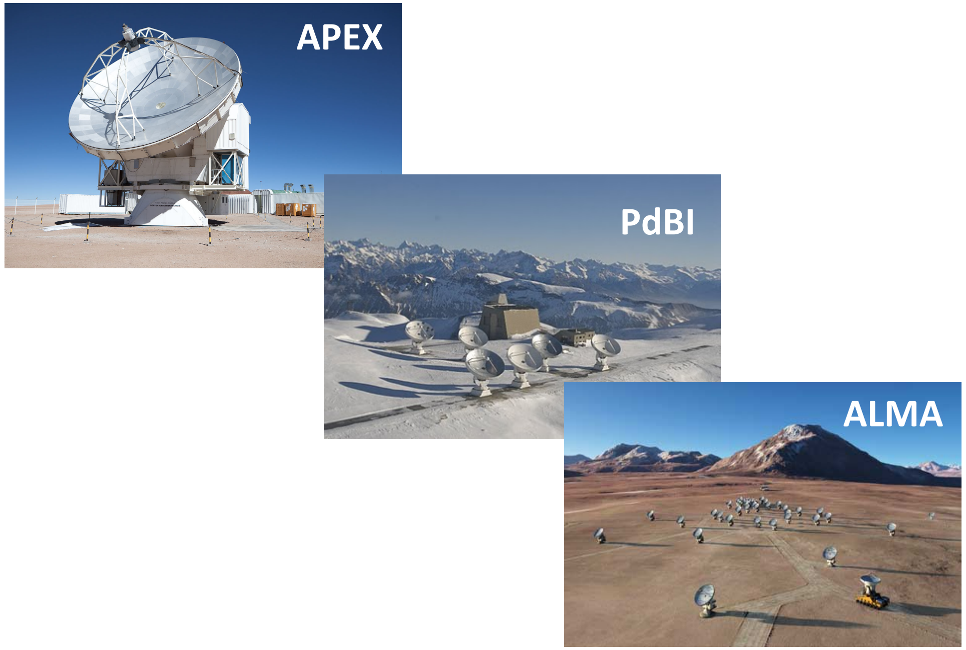
- Major coolants of the inter-stellar medium in star forming galaxies
- The strongest emission lines in most galaxies
- Unaffected by dust extinction
- At z > 4 the [CII] emission line is redshifted into the mm



Thanks to current powerful millimeter facilities
(e.g. APEX, PdBI, ALMA, NOEMA)
they are considered promising tools
to detect high-z star forming galaxies and characterize their ISM

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'')

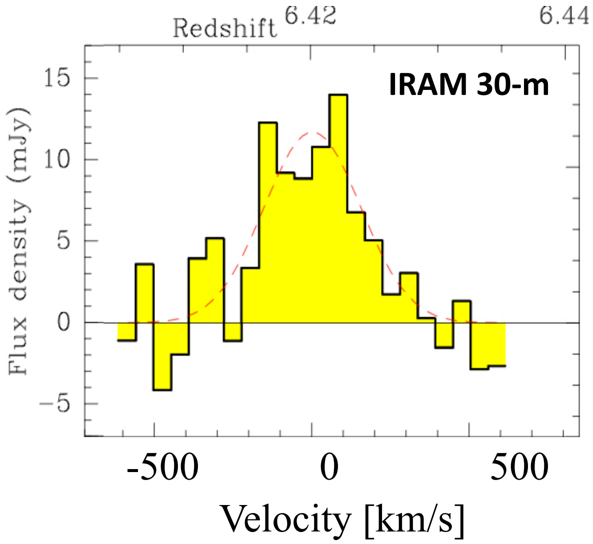
1" = 5.5 kpc @ z=6.4

The case of:

SDSS J1148 at z=6.4

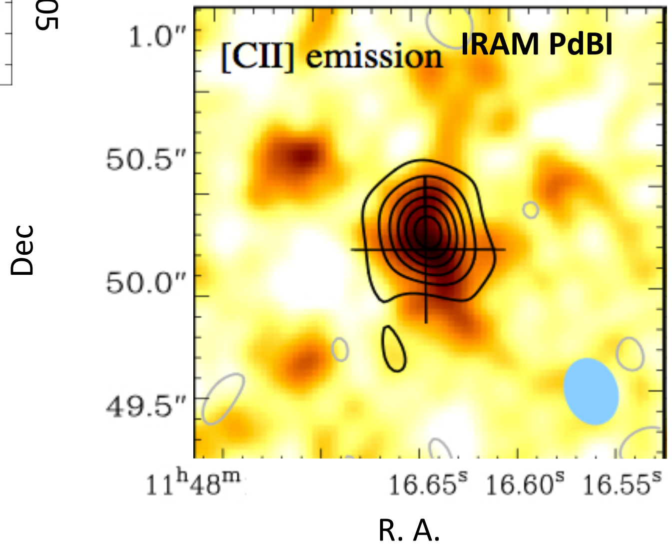
SDSS J1148 + 5251: RECORDS HOLDER at z=6.4

FIRST [CII] DETECTED



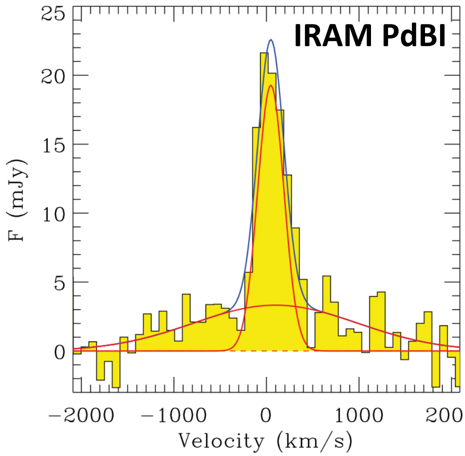
Maiolino et al. 2005

FIRST [CII] RESOLVED



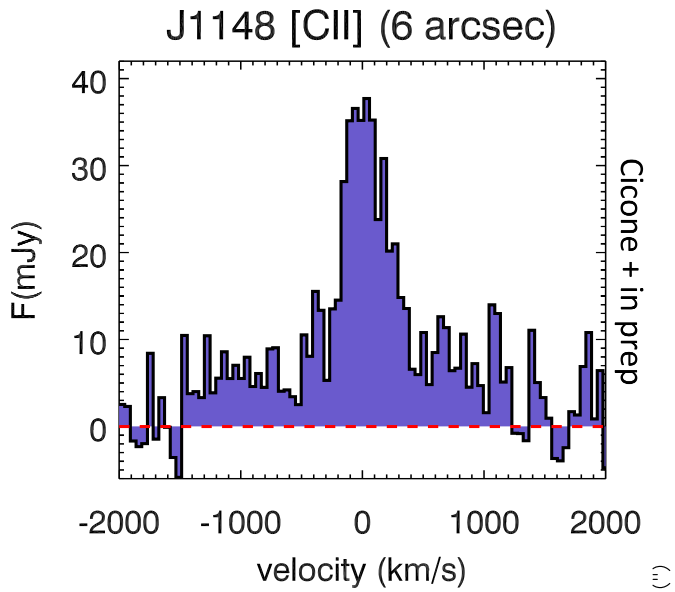
Walter et al. 2009

FIRST POWERFUL OUTFLOW



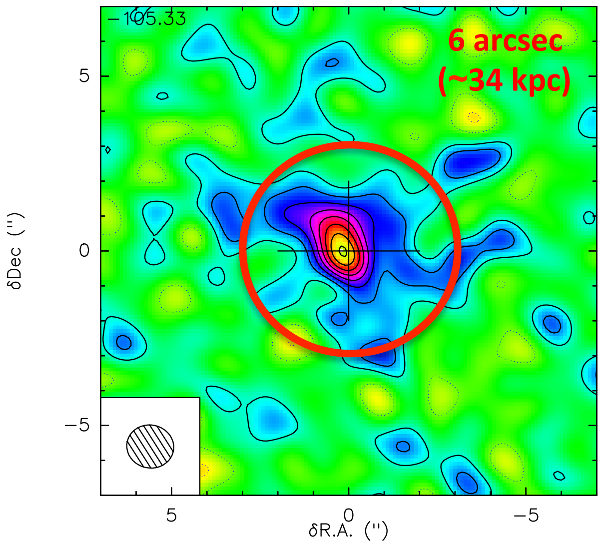
Maiolino, SG et al. 2012

SDSS J1148 + 5251: RECORDS HOLDER at z=6.4



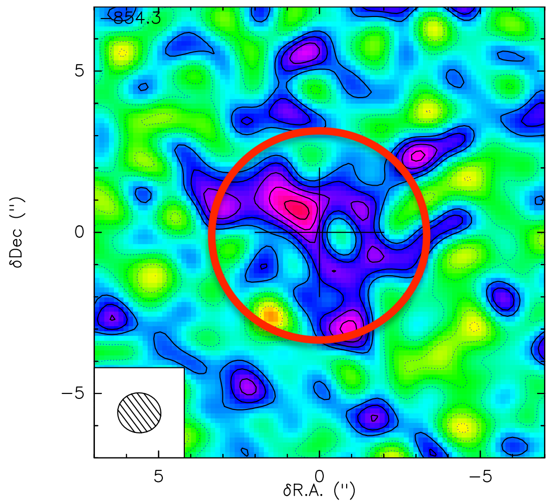
[CII] emission
and outflowing gas
up to > 20-30 kpc

Total
(core+ouflow)



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

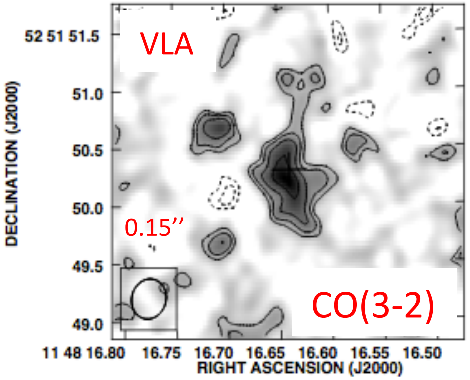
Outflow



Gigantic outflow extend
up to > 30 kpc !!!

Cicone et al. (2014)
arXiv.1409.4418

CO observation in J1148



Walter et al. (2003/2004)

The molecular gas

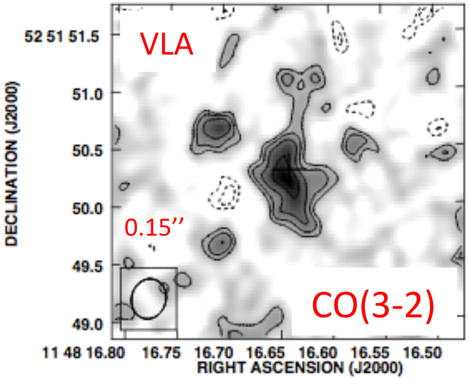
$M_{H2} \approx 2 \times 10^{10}$ M_{sun}

is enclosed within a radius

$R_{H2} \approx 2.5$ kpc

(but see also the **Valiante**'s talk)

CO observation in J1148



VLA

0.15″

CO(3-2)

Walter et al. (2003/2004)

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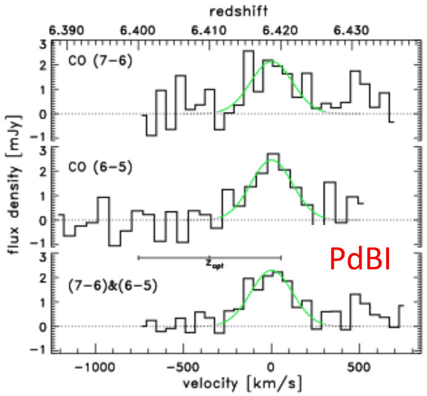
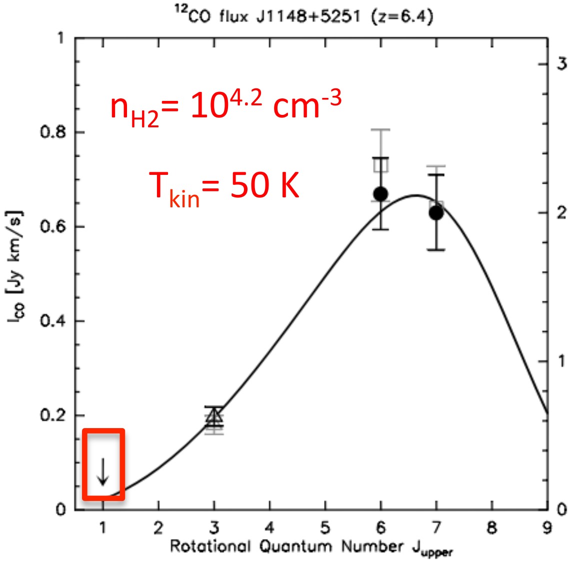


PdBI

Bertoldi et al. (2003)

CO SLED

(Spectral Line Energy Distribution)



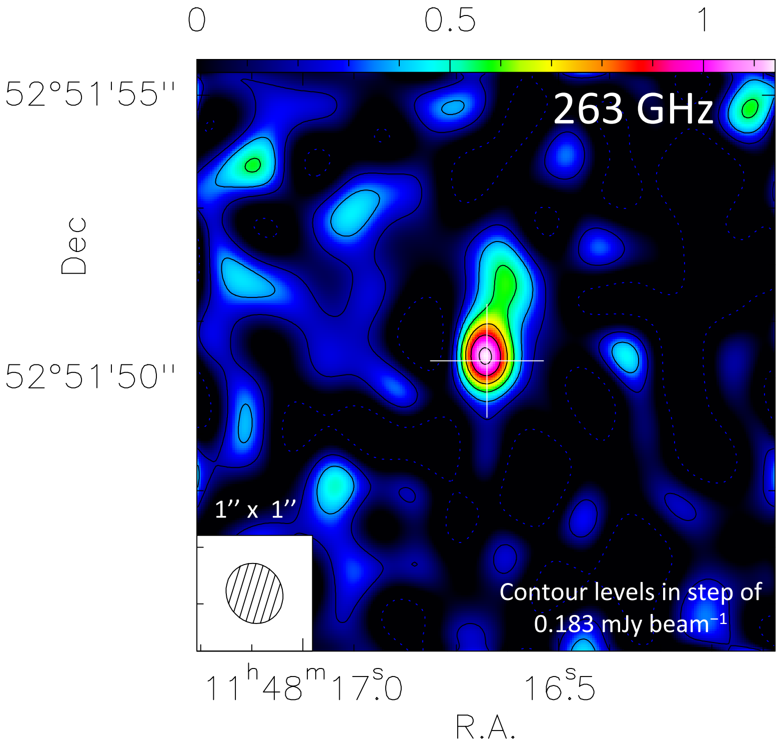
$n_{H2} = 10^{4.2}\ cm^{-3}$

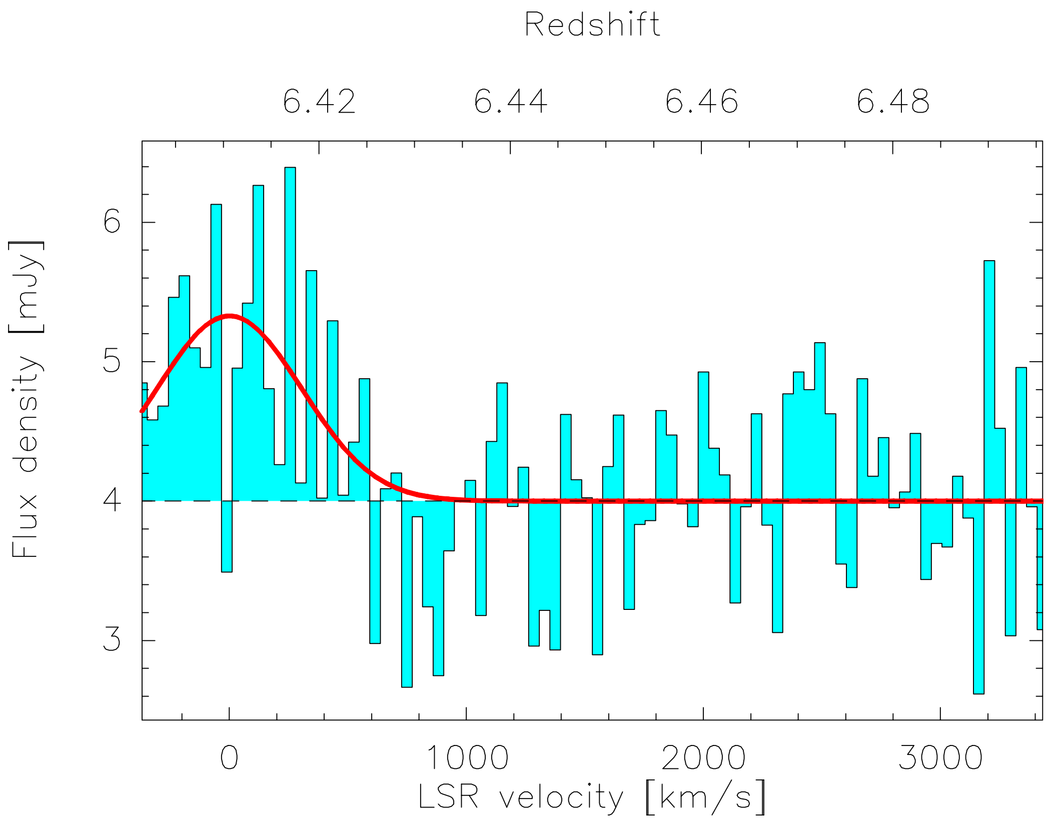
$T_{kin} = 50$ K

Riechers et al. (2009)

Effelsberg
100 m telescope

Strong emission serendipitously detected in J1148

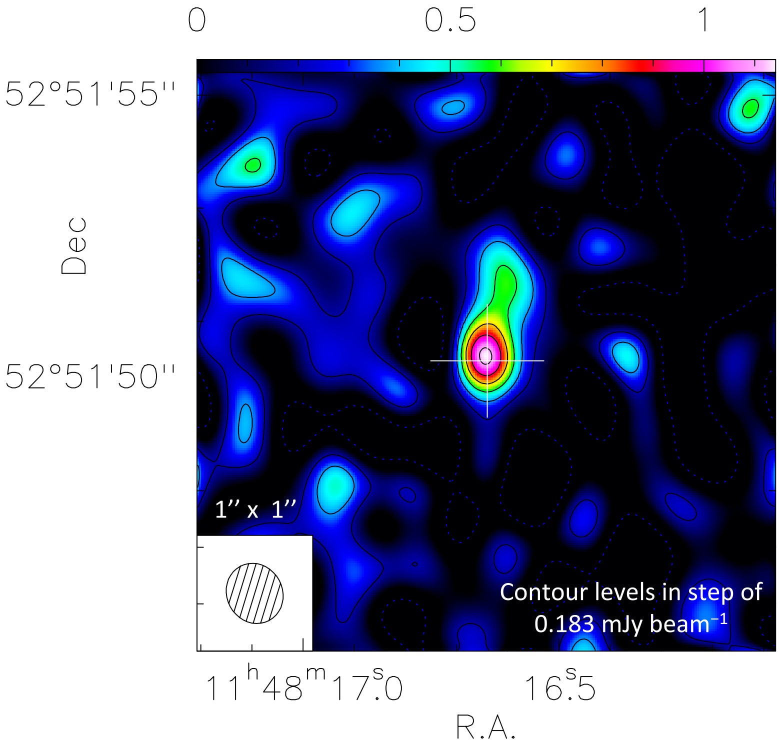


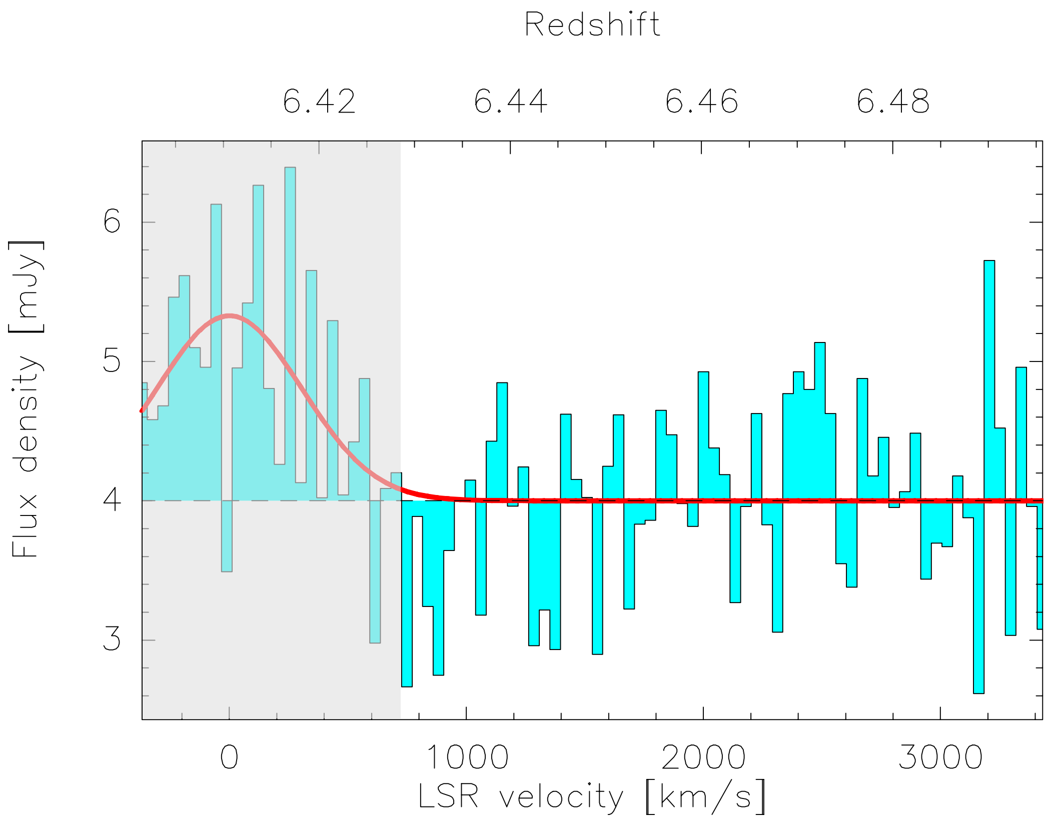


Gallerani et al. (2014)

6.2σ detection

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





Gallerani et al. (2014)

$263 < \nu_{obs}$ [GHz]< 264

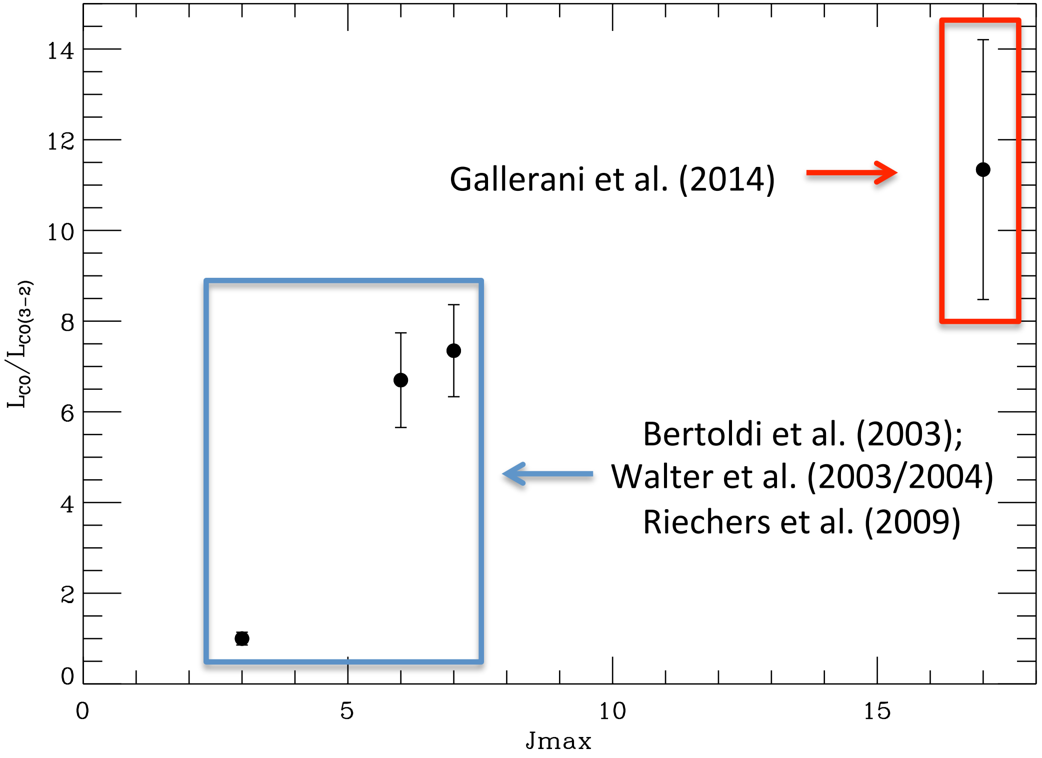
$z_{[CII]} = 6.4189$

(Maiolino et al. 2005)

$1951 < \nu_{RF}$ [GHz]< 1959

! CO(17-16) !

Observed COSLED in J1148



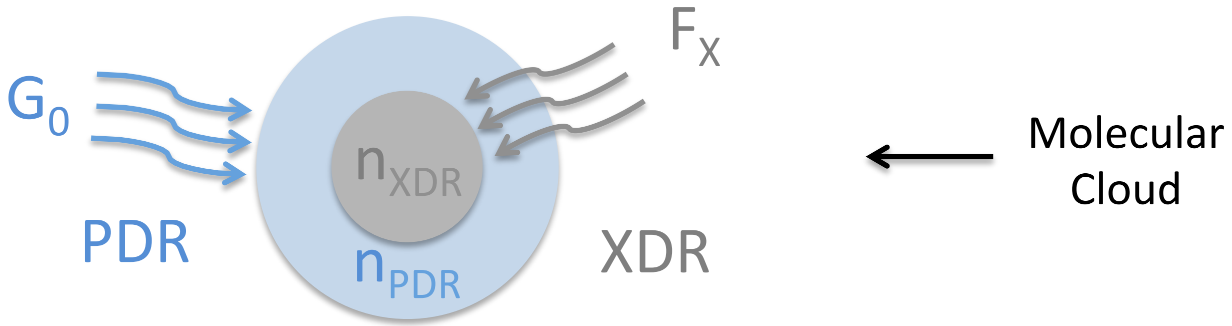
Gallerani et al. (2014)

Bertoldi et al. (2003);
Walter et al. (2003/2004)
Riechers et al. (2009)

The most excited CO rotational transition ever detected in such distant galaxies

Modelling the molecular clouds in J1148

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



G_0

F_X

n_{XDR}

n_{PDR}

PDR

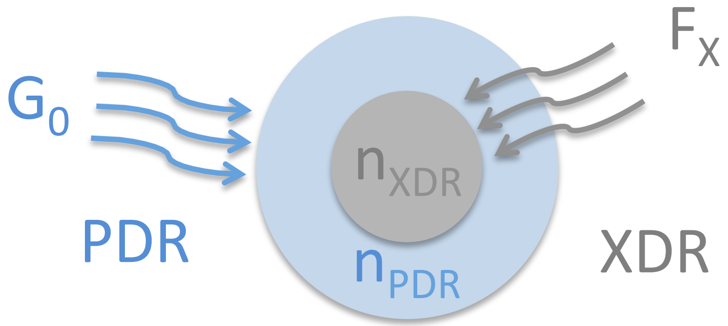
XDR

Molecular
Cloud

Photo Dissociation Region

X-ray Dominated Region

Modelling the molecular clouds in J1148



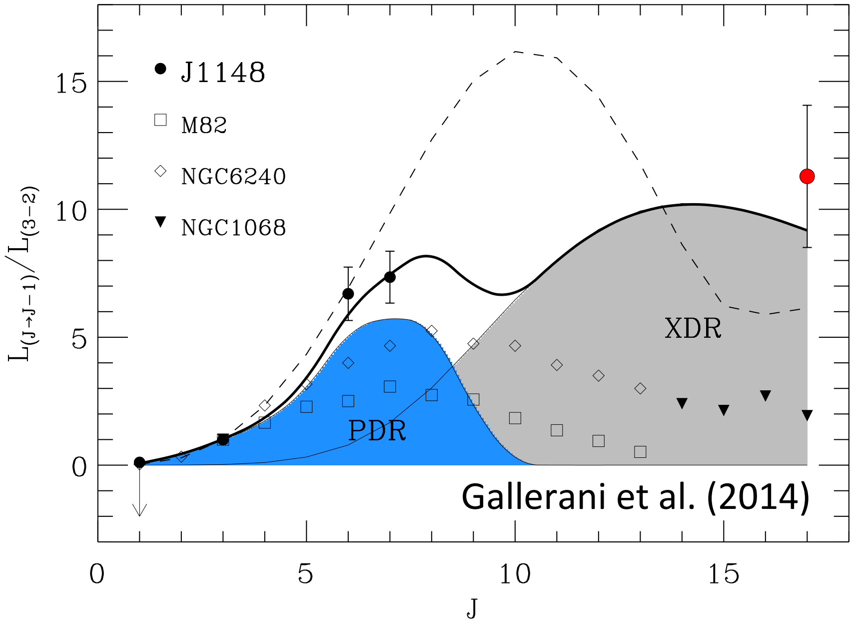
Molecular Cloud

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

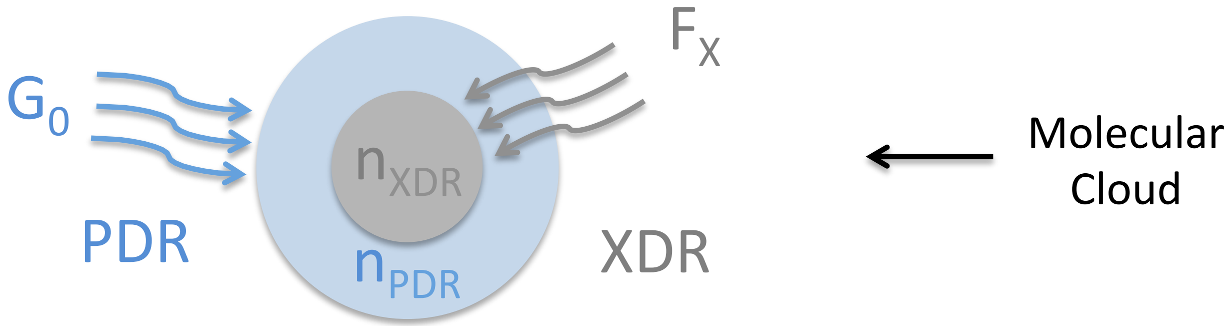


Gallerani et al. (2014)

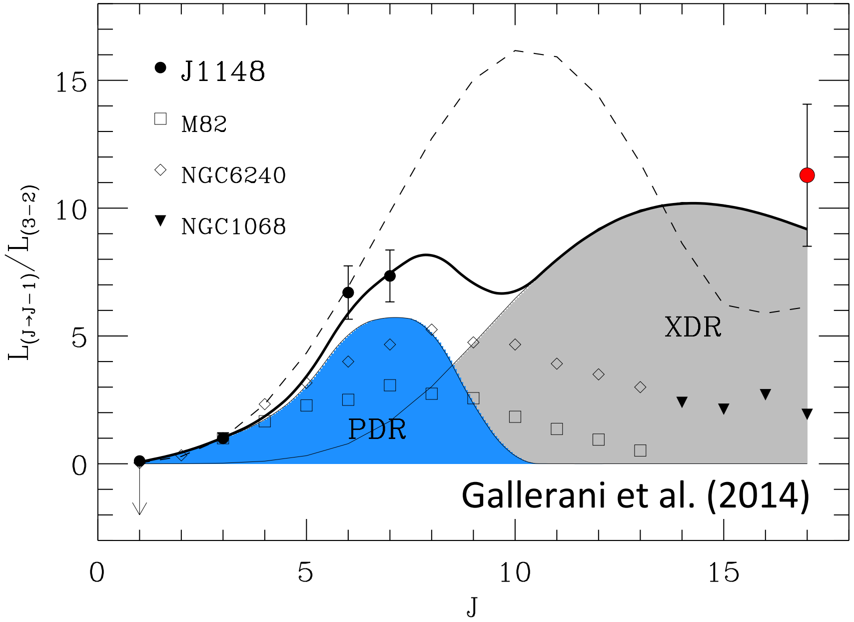
PDR and XDR models by Meijerink et al. (2005/2006)

… is perfectly consistent with the observed COSLED!

Modelling the molecular clouds in J1148



Molecular Cloud



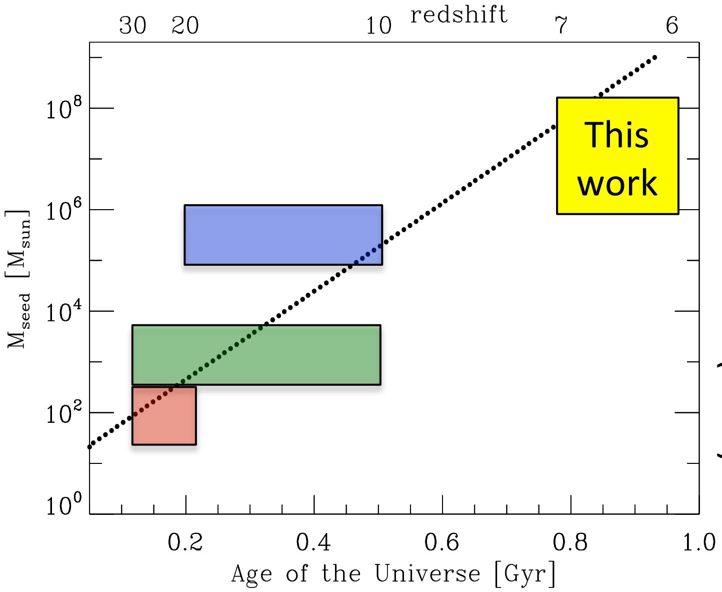
Gallerani et al. (2014)

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

See also Schleicher et al. (2009)

High-J CO lines are powerful probes of AGN activity

Prospects for detecting SMBH ancestors



This work

Gallerani et al. (2014)

Prospects for detecting SMBH ancestors

$z \approx 6$

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

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

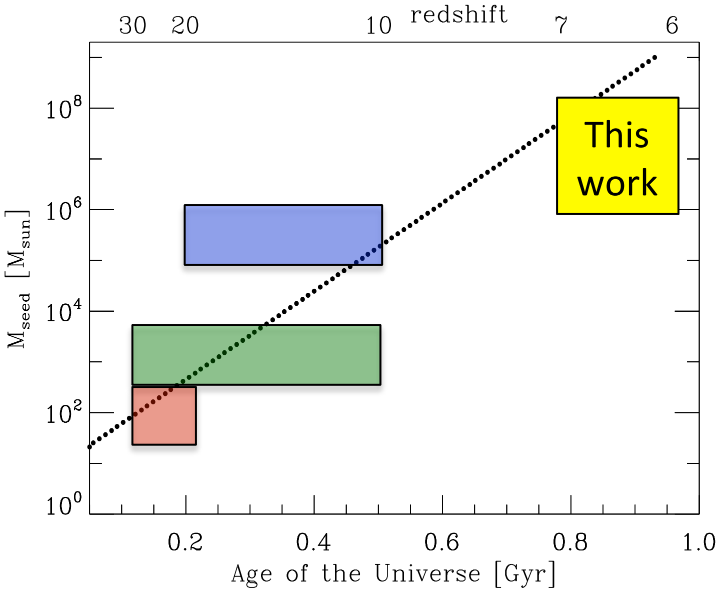
$r_{H2} \approx 2.5\ kpc$

↓

$z \approx 7$

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

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



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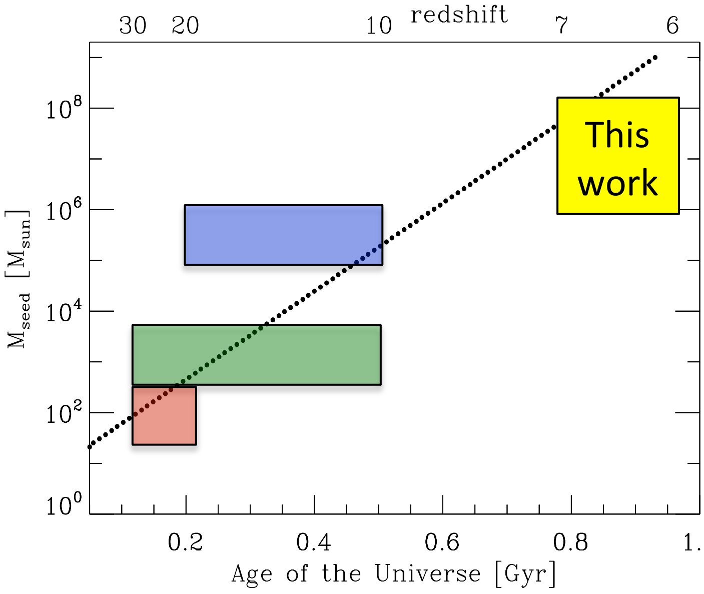

Gallerani et al. (2014)

$$r_{H2} = \frac{\lambda}{\sqrt{2}} r_{vir}$$

$M_{BH} - \sigma$ → $v_{circ} \approx 80\ km/s \Leftrightarrow r_{vir} \approx 10\ kpc$ → $r_{H2} \approx 0.3\ kpc$

Gultekin et al. (2014)

$\lambda = 0.04$

Prospects for detecting SMBH ancestors

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↓

$z \approx 7$

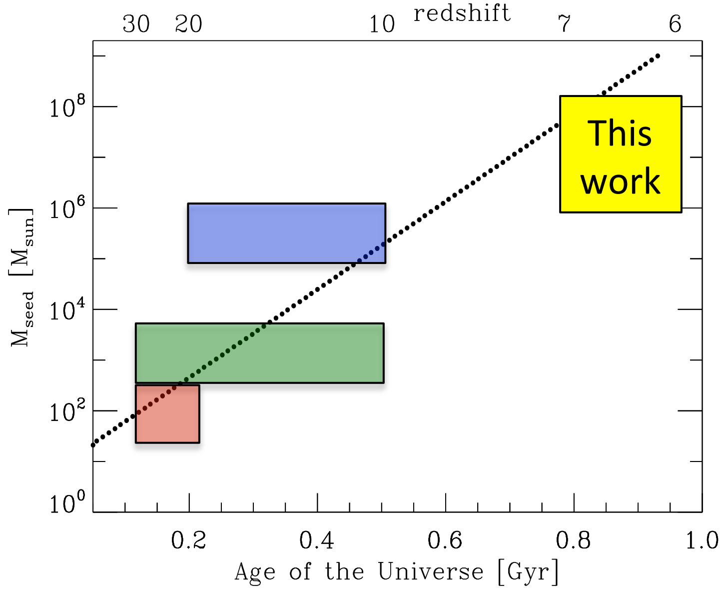
$M_{BH} \approx 10^{6} M_{sun}$

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

$r_{H2} \approx 0.3\ kpc$

Undetected/obscured

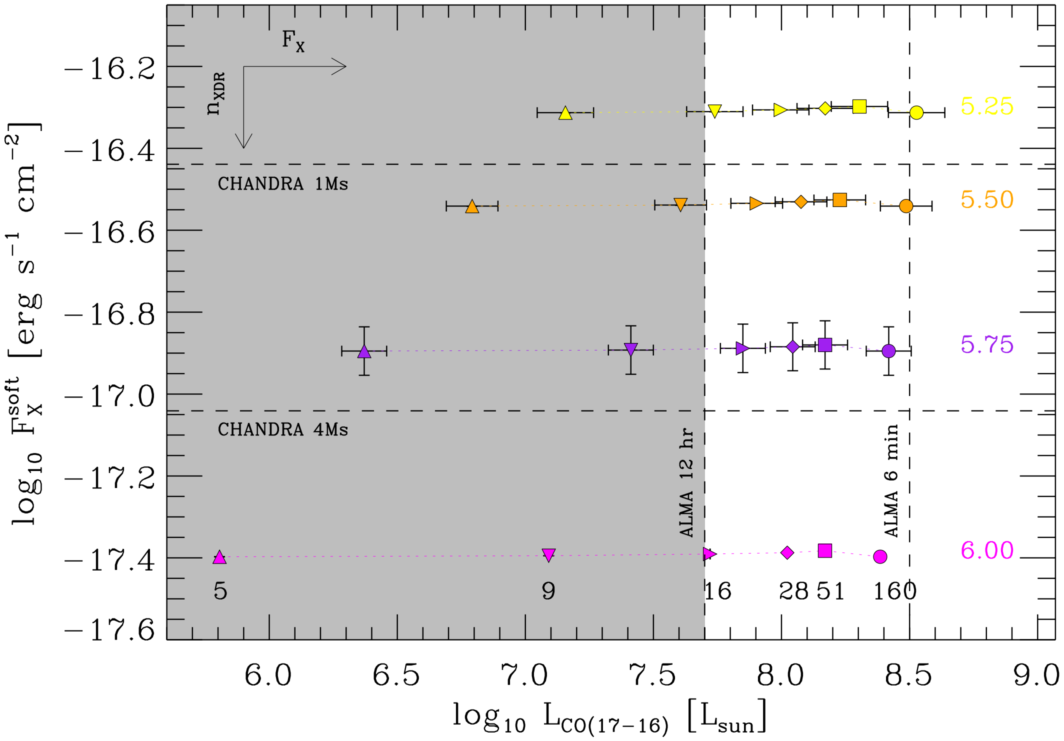
$N_{H} \geq 10^{24} cm^{-2}$

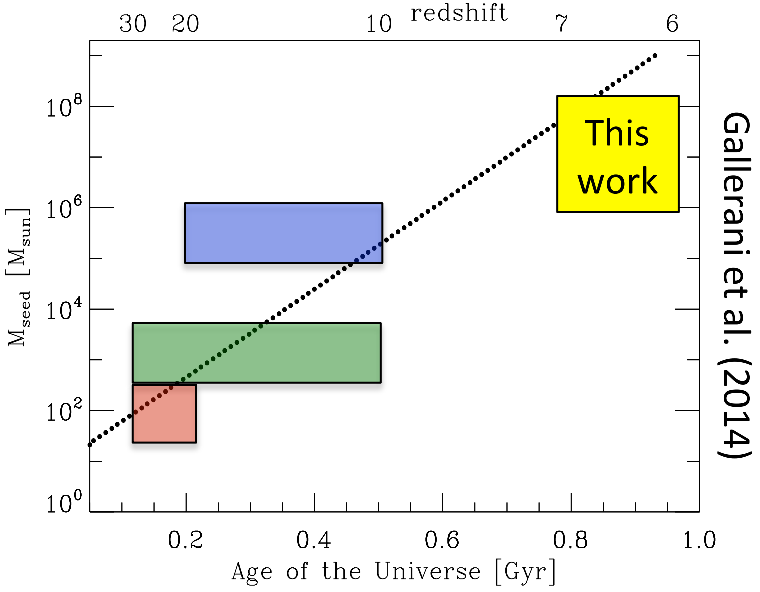


Gallerani et al. (2014)

Prospects for detecting SMBH ancestors

CHANDRA vs ALMA detectability





Prospects for detecting SMBH ancestors

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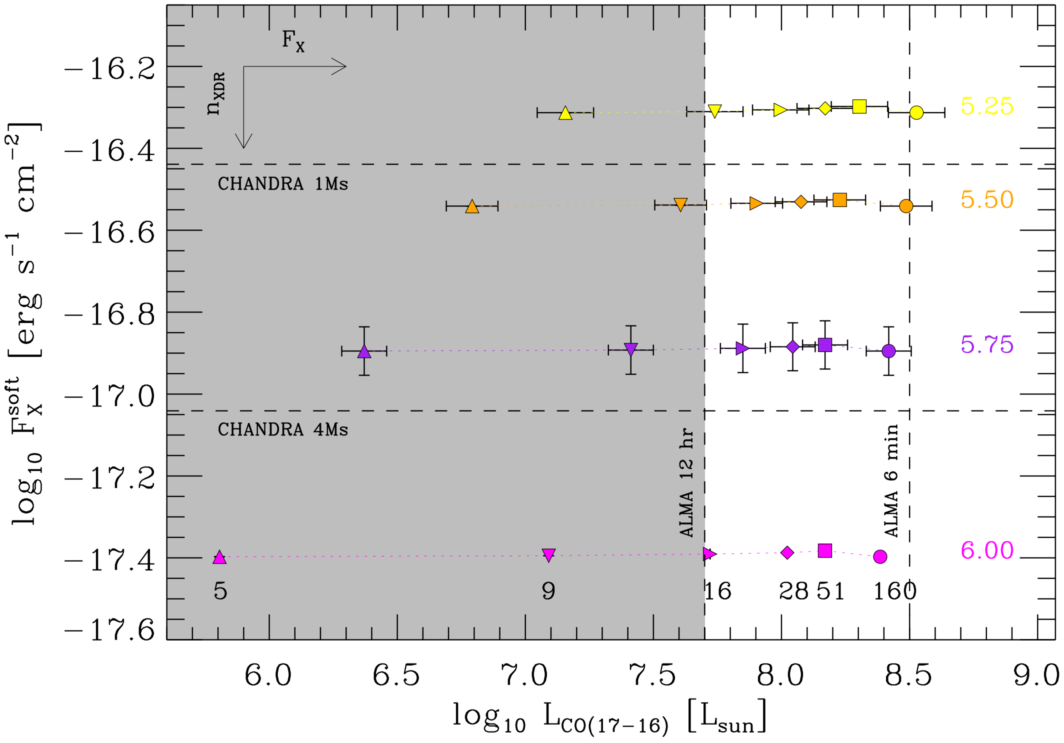
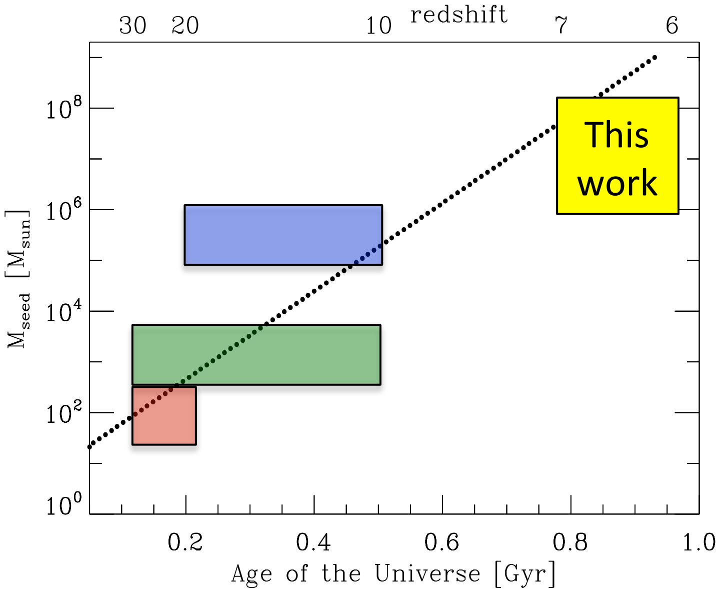




Gallerani et al. (2014)

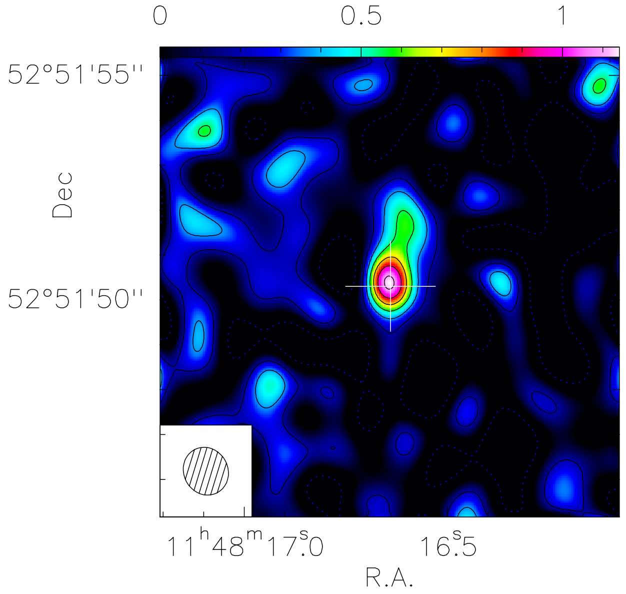
In X-ray observations in $z \approx 6$ quasar

the typical flux detection limit of is $\approx 10^{-15}$erg s^{-1} cm^{-2}

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

SUMMARY

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

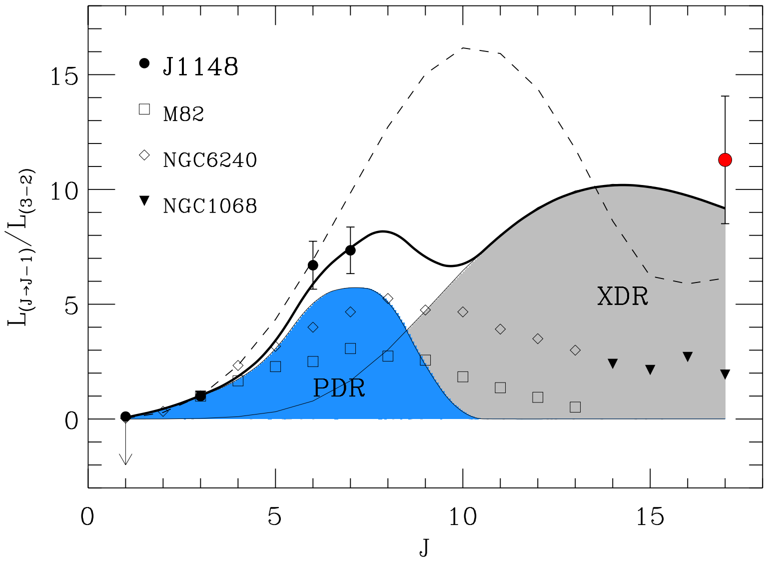


Gallerani et al. (2014)
arXiv1409.4413

Accepted for publication
in MNRAS Letter

SUMMARY

- **First detection** of the **CO(17-16)** emission line at z=6.4
- Observed **COSLED** requires **strong contribution from XDRs**



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

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- **X-ray vs millimeter detectability** of high-z quasars

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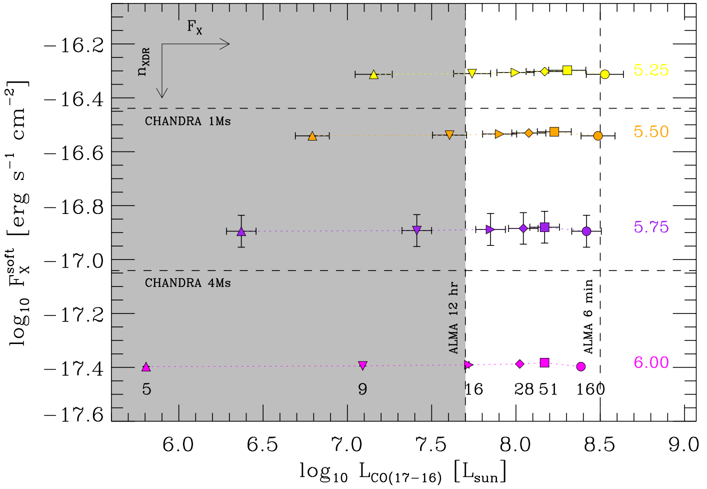

CONCLUSION

- **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

Gallerani et al. (2014)
arXiv1409.4413

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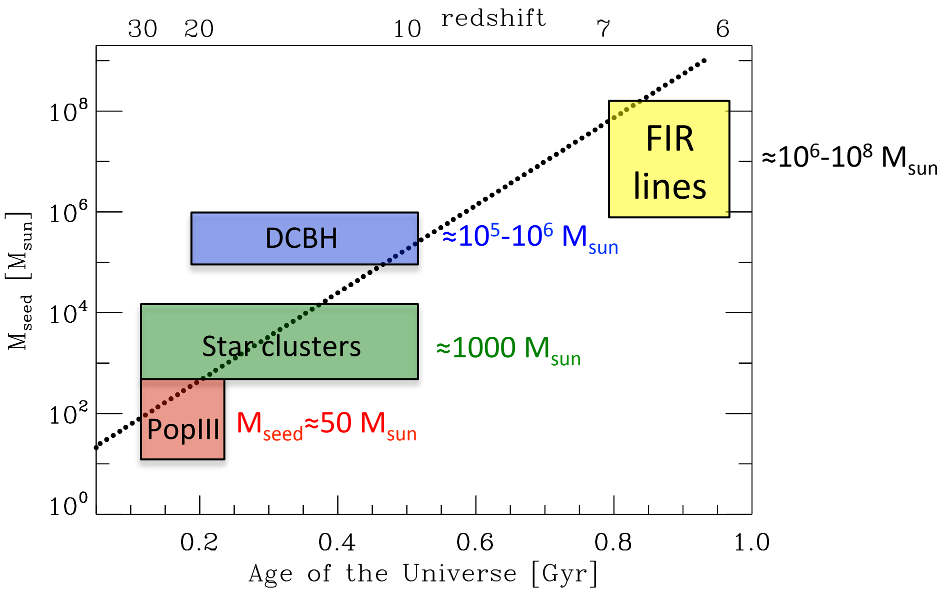
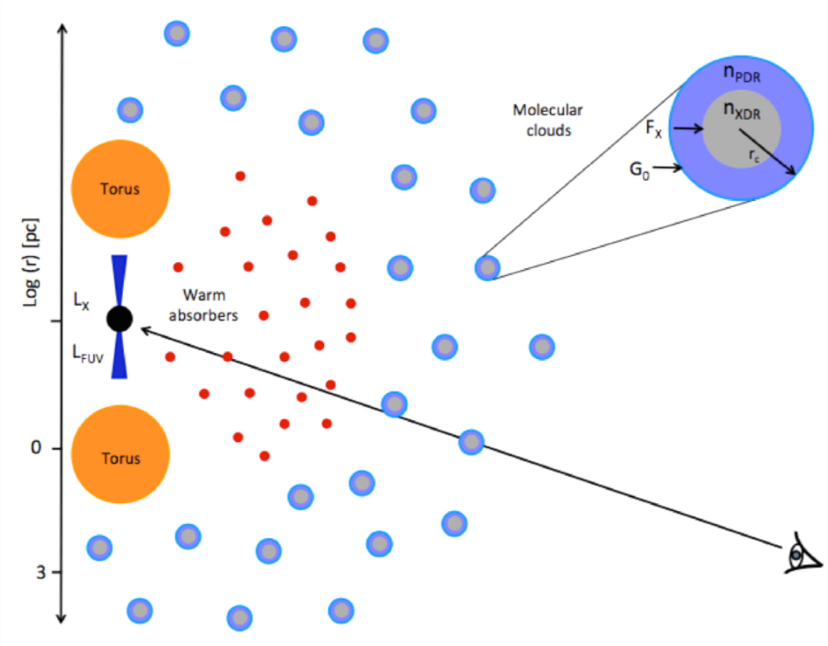
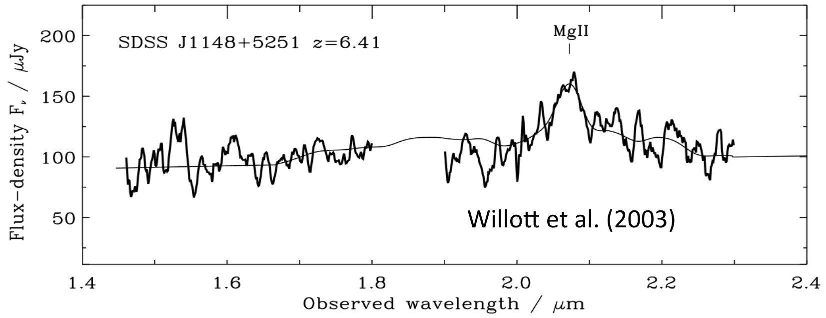


X-ray observations of SDSS J1148 at z=6.4





$$M_{BH} = 3\times 10^{9} M_{sun} \qquad L_X \propto M_{BH}$$

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

Predictions for X-ray observations

$$F_X^{soft} = 7\times 10^{-15}[erg\ s^{-1}cm^{-2}] \qquad F_X^{hard} = 3\times 10^{-14}[erg\ s^{-1}cm^{-2}]$$

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

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