Resolving the molecular gas in the host galaxy of a gravitationally lensed quasar

Taipei, 2015

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(arXiv:1303.3707

arXiv:1303.6110)

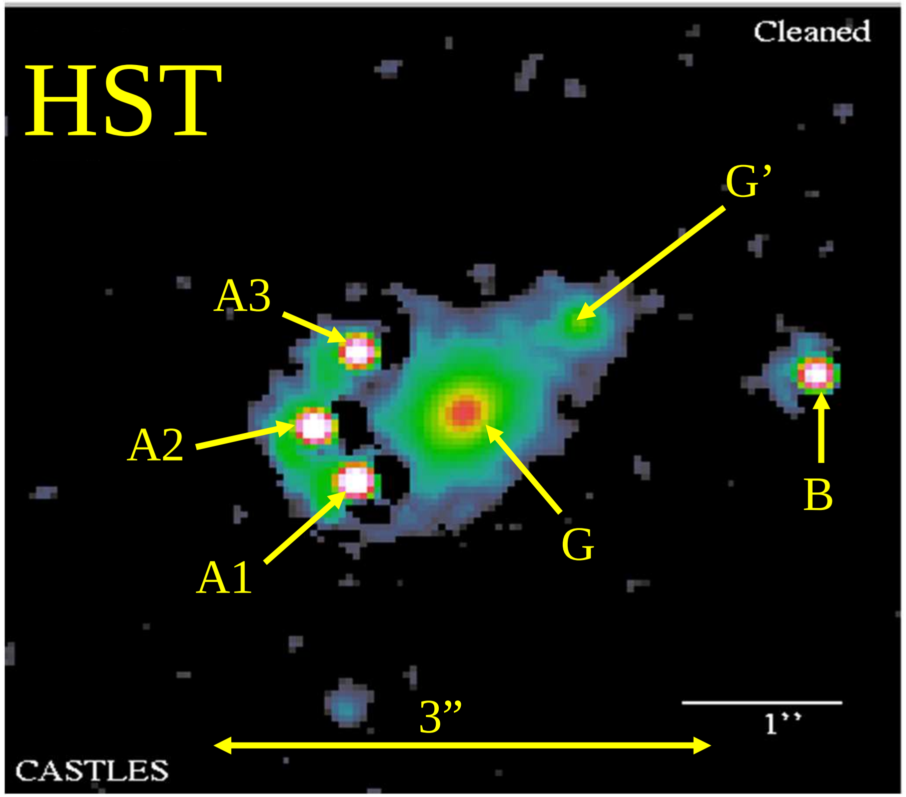
Astrophysics motivation

High redshift (z) galaxies tell us about galaxy formation and star formation in the early Universe.

As a light amplifier, strong gravitational lensing makes it possible to observe far away galaxies that would be otherwise too faint to be detected.

High z values shift the frequencies of molecular lines to the millimeter region, accessible to modern radio telescopes and interferometer arrays.

RX J0911



Four quasar images observed by HST in the visible and near infrared lensed by a galaxy G. A galaxy cluster and a satellite galaxy also contribute to lensing. The quasar is at a redshift of z=2.8 (backlook of 11.3 Gyr!) while the lens is at z=0.8.

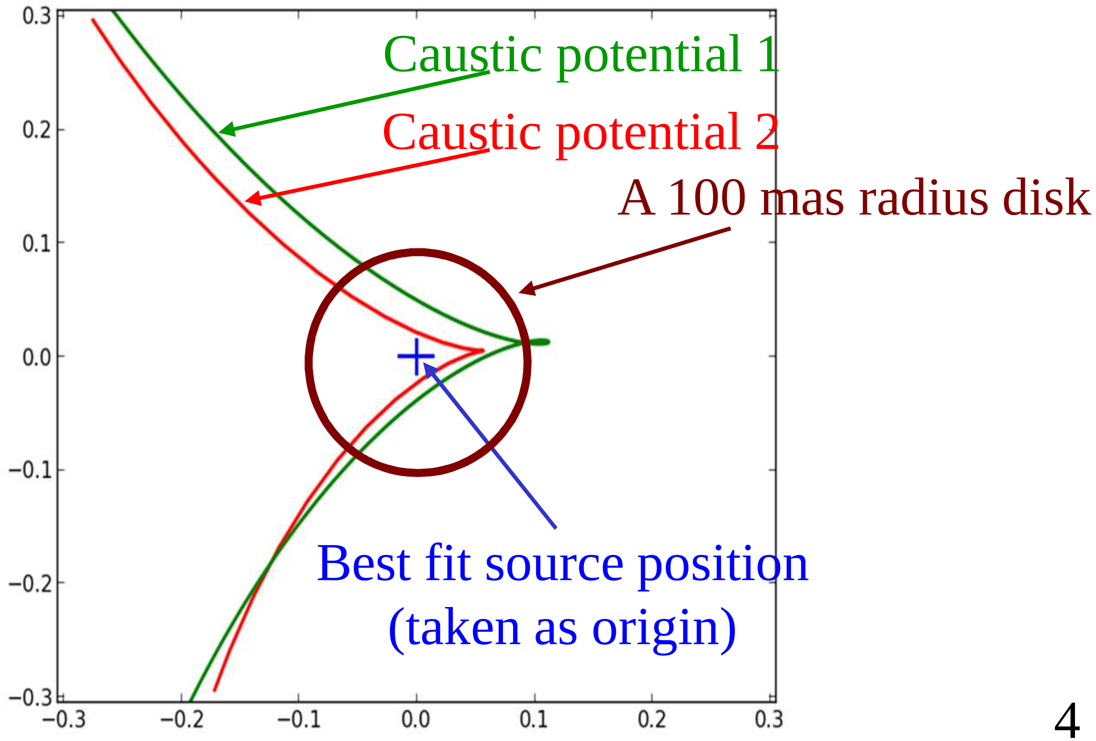
To obtain an estimate of systematic uncertainties attached to the modeling of the lensing mechanism, we use two different potentials.

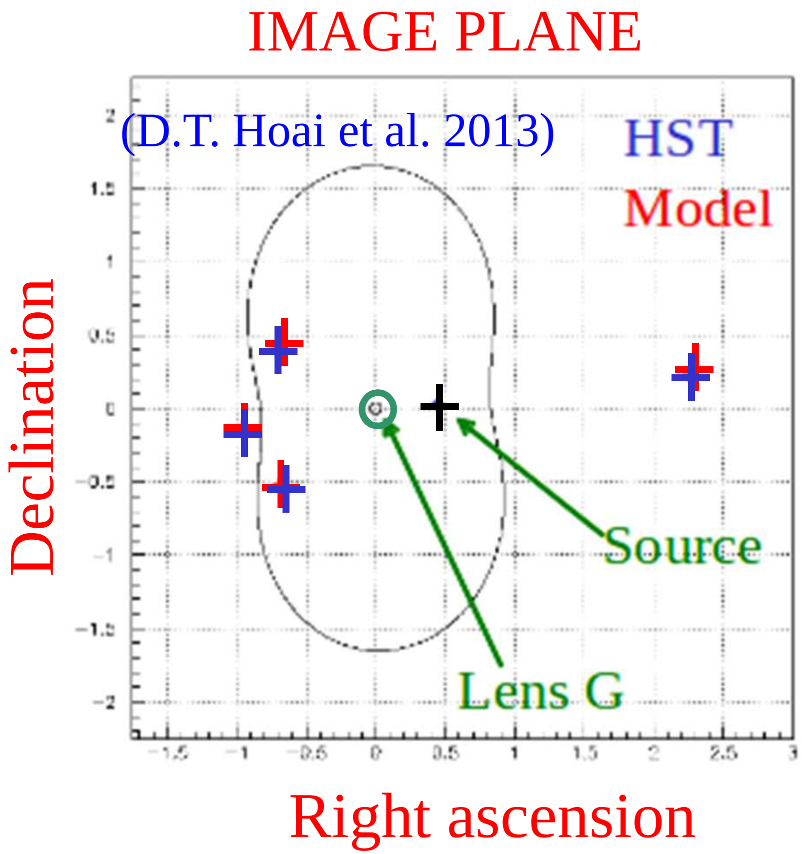
Potential 1: an elliptical main lens & an external shear (mimic the influence of the satellite galaxy and of the galaxy cluster). We develop a code to solve the lens equation explicitly.

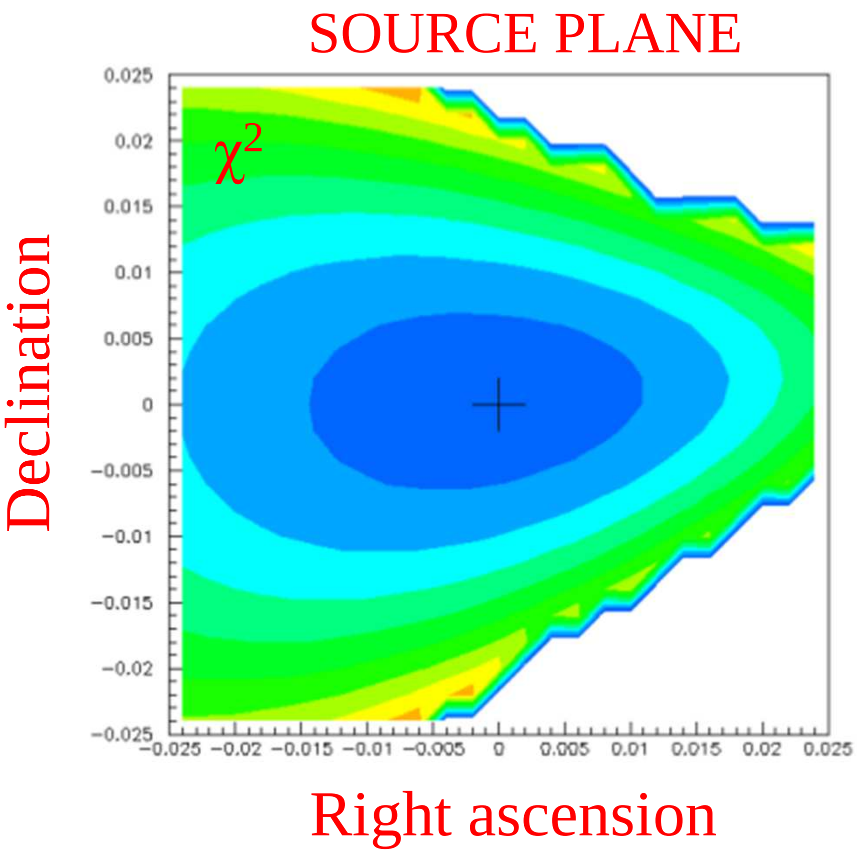
Potential 2: three terms describing separately the effect of the main lens, of the satellite galaxy and of the cluster. We use a public code: LENSTOOL.

The potential parameters are defined from fits to the HST QSO point source.

(P.T. Anh Phd thesis)

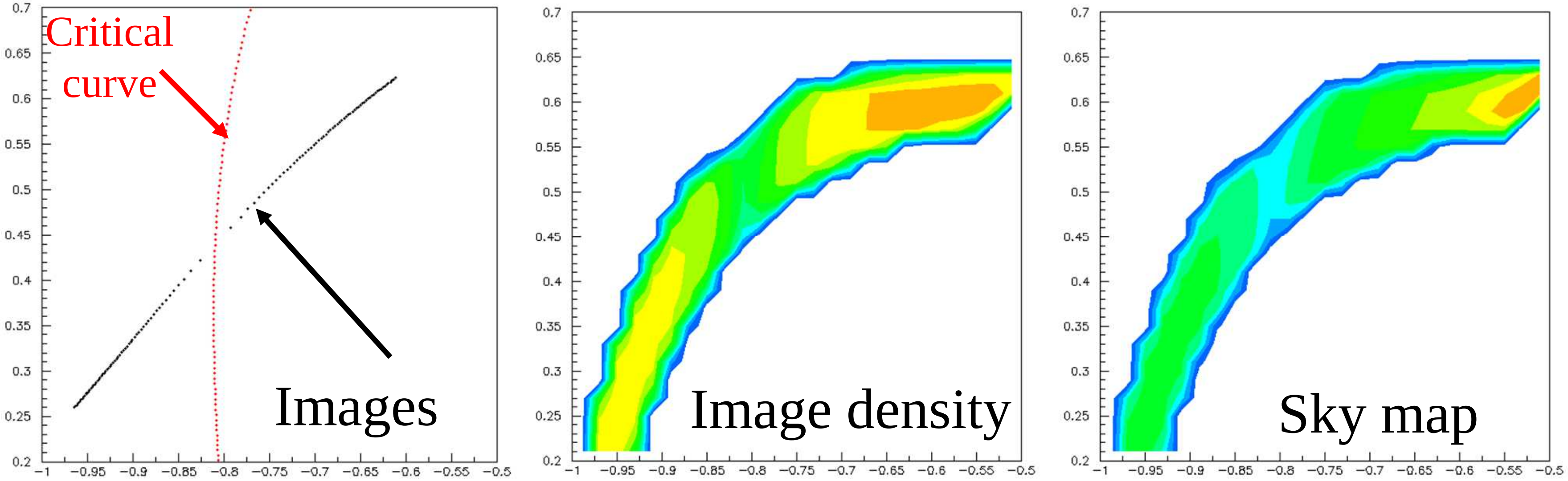






Good fits are obtained to the observed image positions. Three of the images are very close to the line where magnification is infinite (critical line), meaning that the source is very close to its partner in the sky, the caustic.

(P.T. Anh Phd thesis)



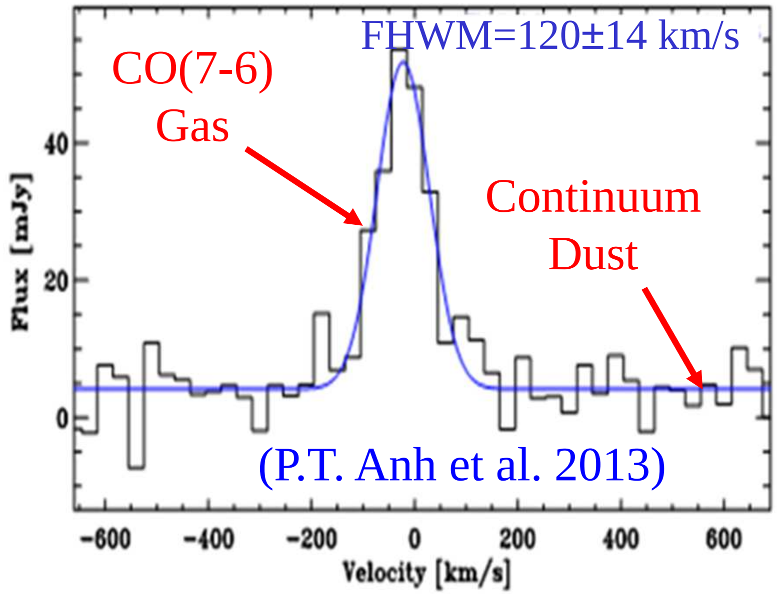
Magnifications are very sensitive to the position of the source with respect to the caustic where magnifications are infinite.

RX J0911 is very close to the caustic, its images are close to the critical curve. The host galaxy overlaps the caustic with part of it giving 2 images and part of it giving 4 images and magnifications varying significantly across the galaxy.

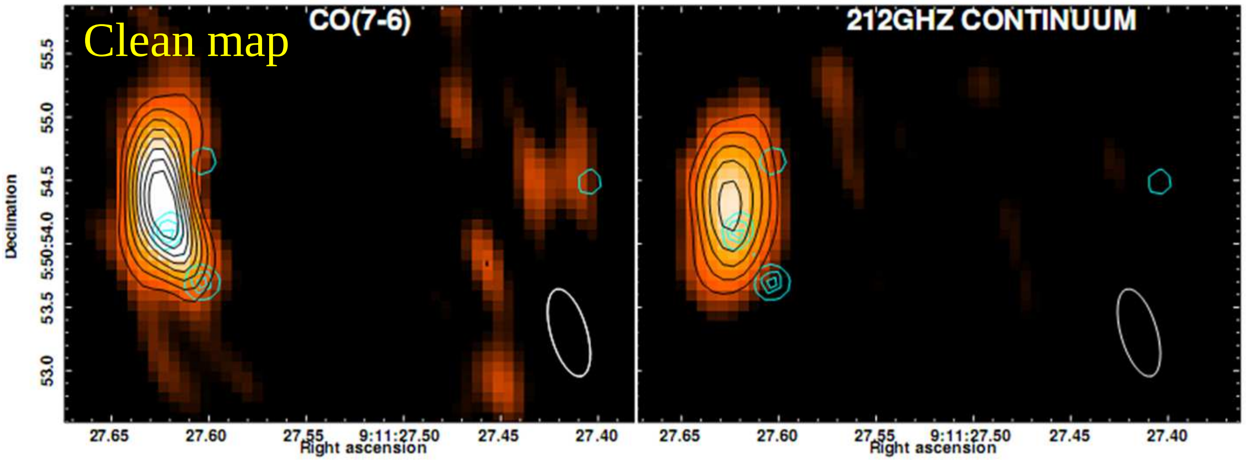
Data are CO(7-6) line (tells us about the gas) and underlying continuum (tells us about the dust) of the host galaxy of RX J0911.

The interferometer data (six antennas) measure intensities of the Fourier transform of the source (called uv plane).

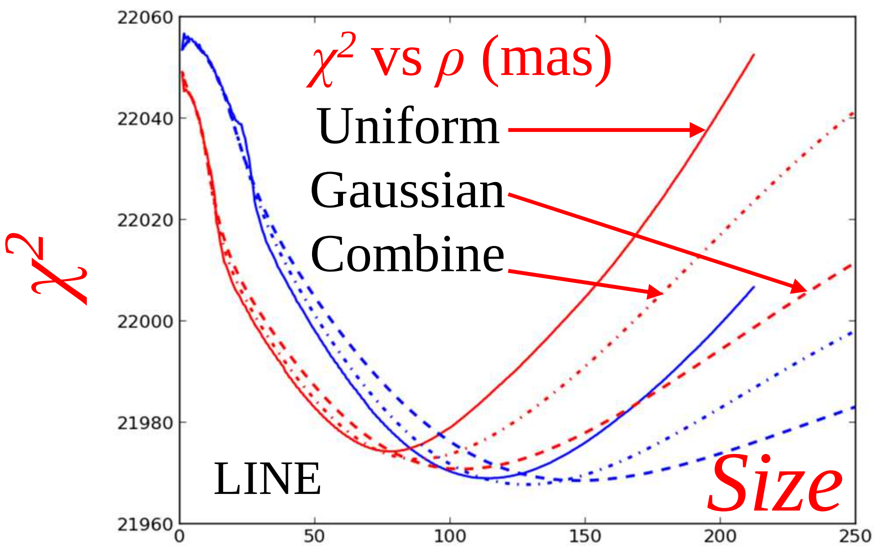
Much of the adjusting of the model parameters modeling is done in the uv plane.

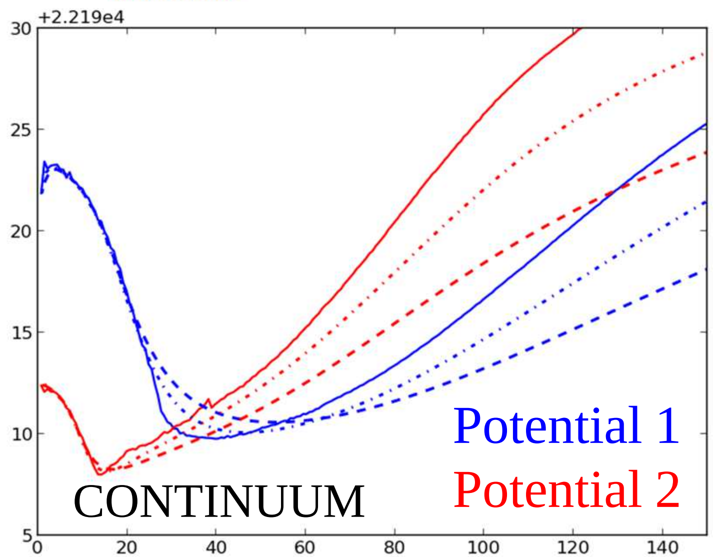


A model of the source and of the lens is used to create model images in the sky plane. They are then Fourier transformed to the *uv*-plane where they are compared with observation. A χ^2 is calculated, which provides a measure of the quality of the fit.



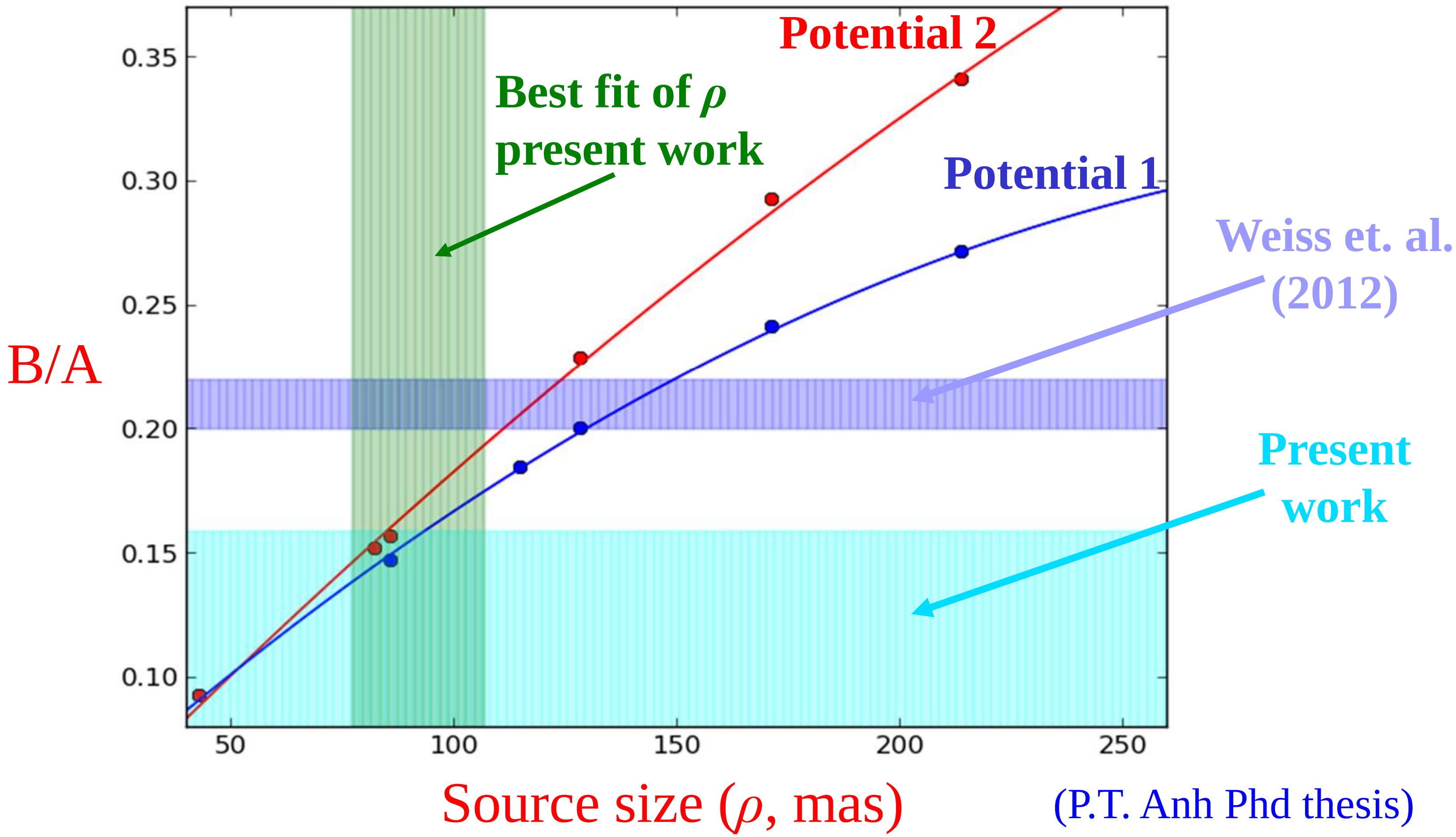
(P.T. Anh et al. 2013)





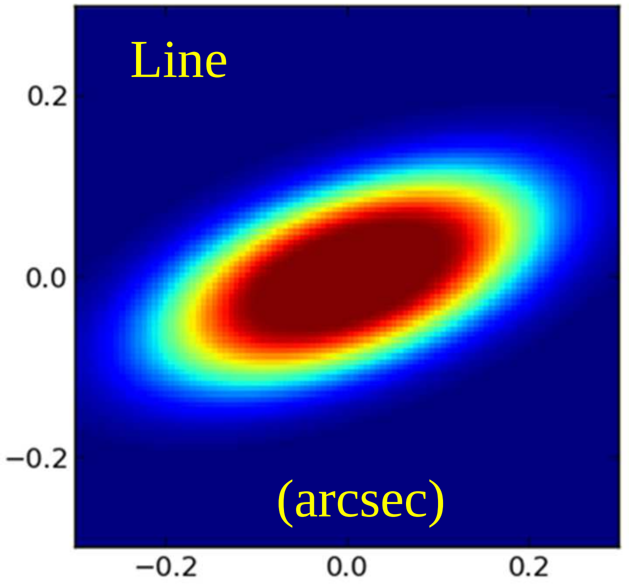
We measure the size of the source: ρ=106±15 mas (7 s.d. away from a point source) for the line and ρ=32±16 mas (2 s.d., barely resolved) for the continuum.

A brightness is very sensitive to source geometry but B brightness is not. Therefore a measurement of the B/A ratio provides an independent estimate of the source size.

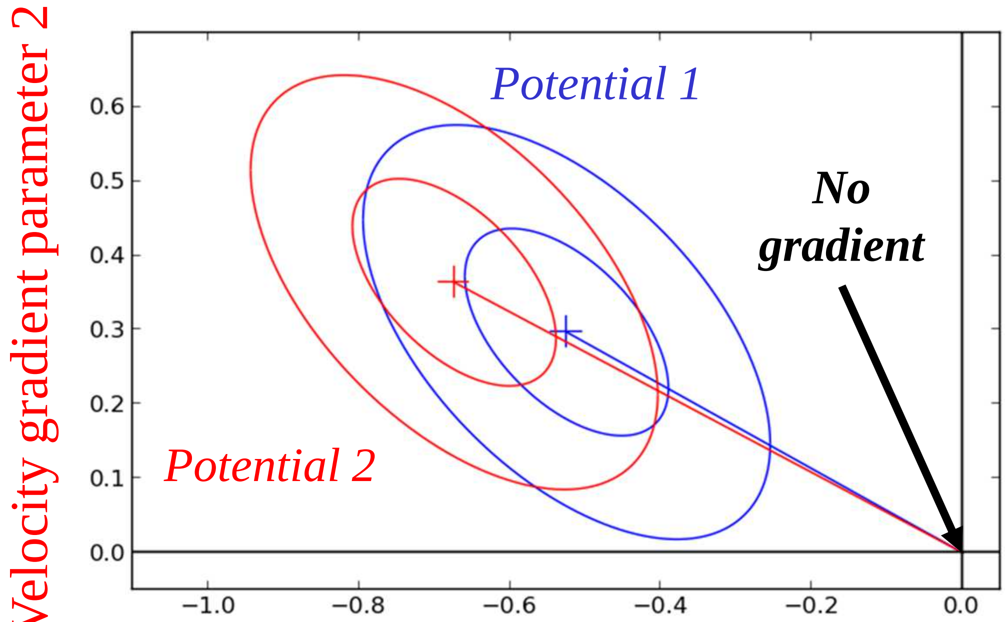


(P.T. Anh Phd thesis)

We find evidence for ellipticity with major/minor axis 2.6±0.8 and a position angle of 111°±9°.
We also find that the velocity depends on the position of the source in the galaxy, probably associated with rotation, a zero velocity gradient is rejected to within 4.5 standard deviations.



Sky map of the source galaxy



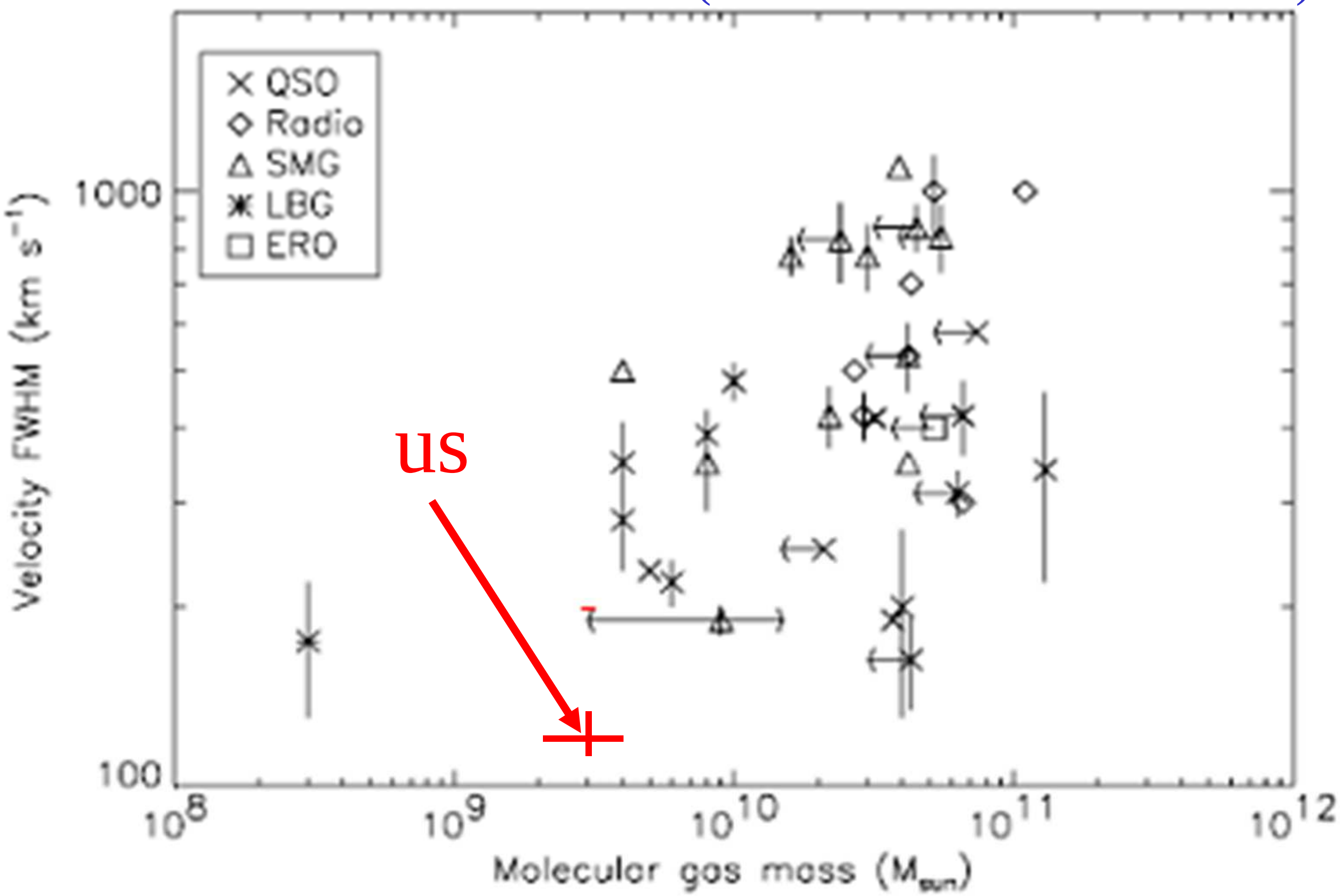
Velocity gradient parameter 1

RX J0911 results

Lens potential	**P1**	**P2**	**Retained**
Magnification (point source)	17.4	35.9	26±10
Magnification (line)	9.4±0.7	16.0±1.1	12±4
Magnification (continuum)	15.4±2.2	33.9±4.8	24±10
$L'_{CO(7\text{-}6)}$ [10^9 K km s^{-1} pc^2]	3.9±0.8	2.3±0.5	3.1±1.0
$L'_{CO(1\text{-}0)}$ [10^9 K km s^{-1} pc^2]	4.9±1.0	2.9±0.6	3.9±1.3
Continuum [mJy]	0.31±0.08	0.14±0.04	0.20±0.09
M_{H2} [10^9 M_{Sun}]	3.9±0.8	2.3±0.5	3.1±1.0
SFR [M_{Sun}/yr]	~360	~160	~230
Depletion rate [10^7 yr]	1.1	1.4	1.3
Dust mass [10^8 M_{Sun}]	~1.3	~0.6	~0.8
M_{dyn} [10^9 M_{Sun}]	4.7±1.4	4.7±1.4	4.7±1.4
ρ *(line) [arcsec]*	115±13	81±9	106±15
ρ *(continuum) [arcsec]*	51±15	24±10	39±18

(Solomon & Vanden Bout 2005)

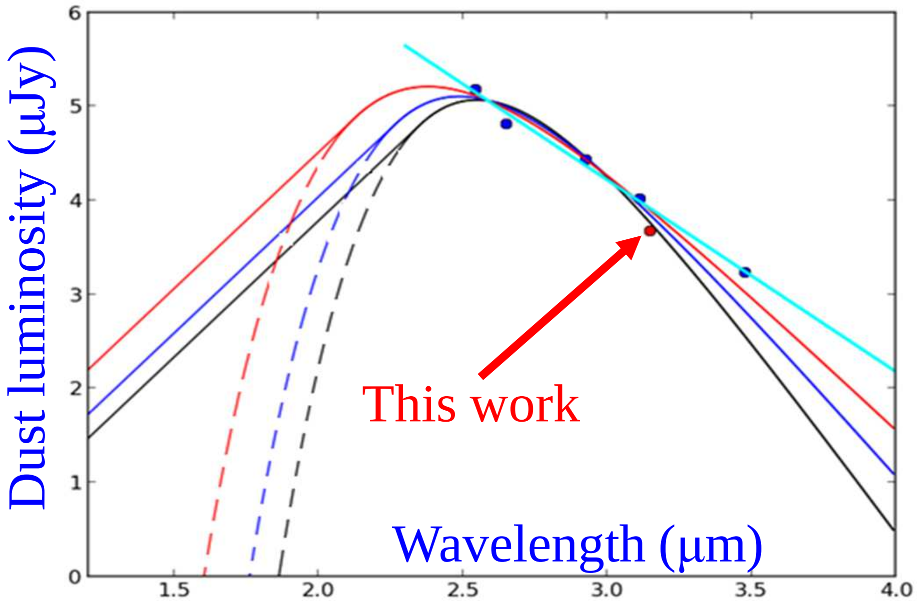
FWHM measures dynamical mass



Measured from the luminosity

Even with the large magnification uncertainty (nearly halved when using potential 1 rather than potential 2), the molecular gas mass estimated from the line luminosity is quite small in comparison with other quasar hosts and lies at the low end of their observed range. The vey narrow line width confirms this estimate.

Dust luminosity



$$f_\nu = \nu^{3+\beta}/\{exp(h\nu/kT_d)\text{-}1\}\ (\nu<\nu_0)$$
$$= A_0\nu^{-\alpha}\ (\nu>\nu_0)$$

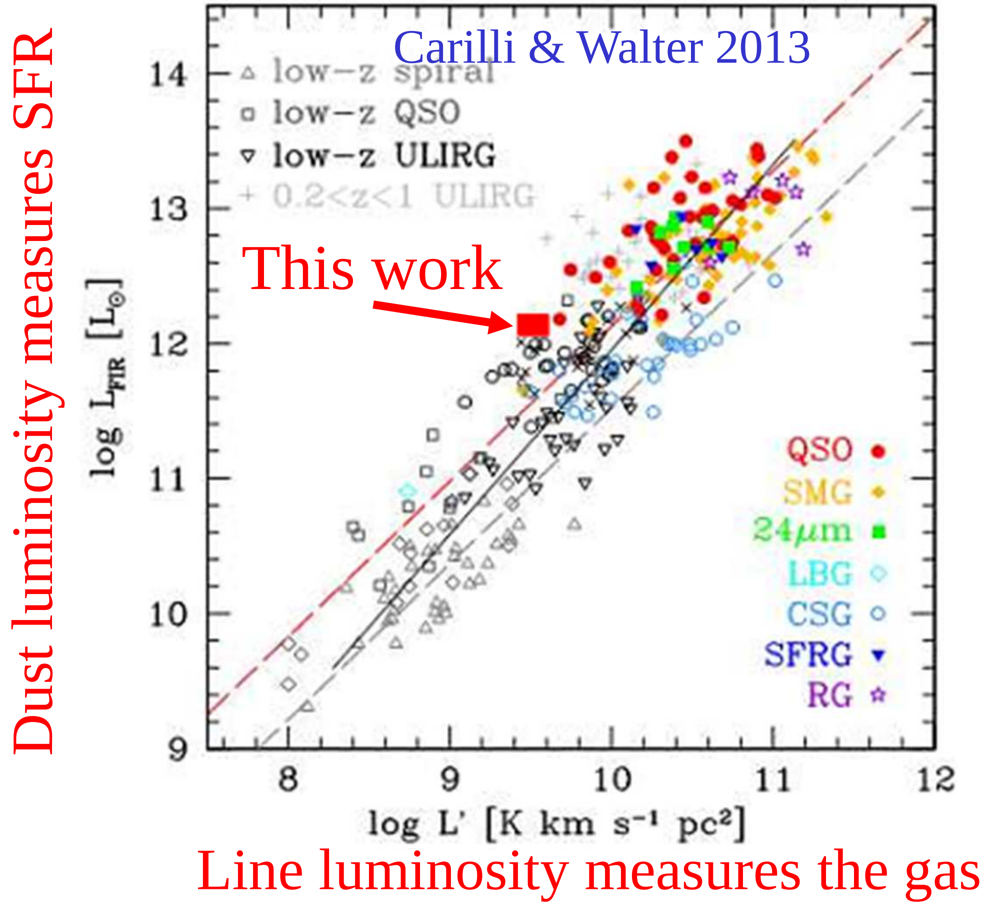
The data are unable to fix the parameters. They only allow to evaluate β when T_d is known (or conversely). They are completely insensitive to α.

We use $\alpha = 2.9$, $\beta = 1.5$ and $T_d = 40$ K

Using a magnification of 24 we derive a FIR (8-1000 µm) luminosity of ~13 $10^{11} L_{Sun}$ and a star formation rate $L_{FIR}/(5.8\ 10^9 L_{Sun})$ of ~2 10^2 M_{Sun}/yr, corresponding to a depletion time M_{H2}/SFR ~10^7 years, independent of magnification and consistent with typical QSO values.

The RX J0911 star formation efficiency is on the high side of all galaxies of similar gas mass, whether low-z or high-z, and both CO and FIR luminosities are at the low end of the high-z population.

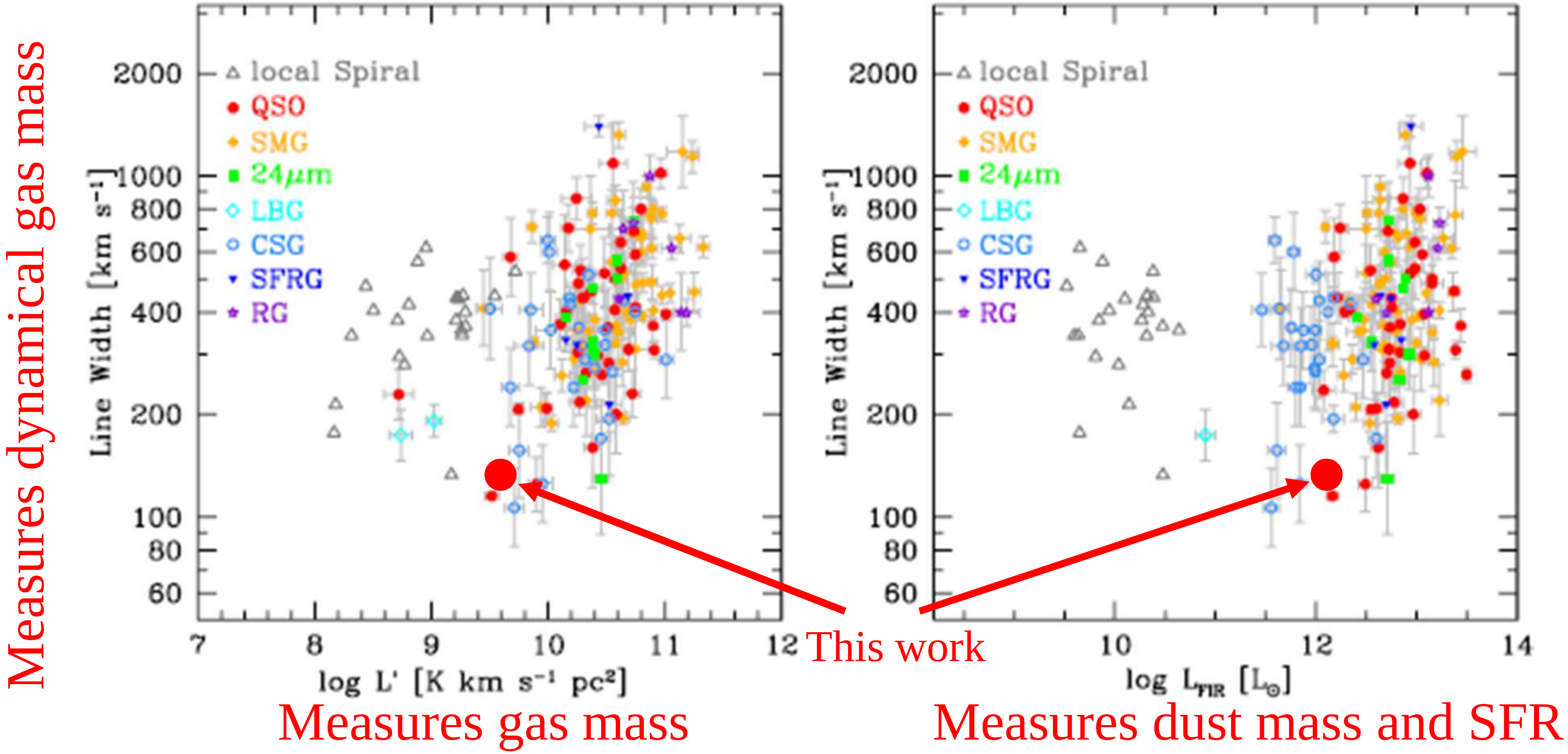
L_{FIR}/L_{CO} is higher (~ 3) than the correlation found in Submillimeter Galaxies (SMGs, Bothwell 2013).



This is consistent with the scenario according to which there is an evolution from SMG to QSO with the SMG forming less stars for the same amount of gas (probably due to a phase of cold gas accretion).

CO line width & luminosity

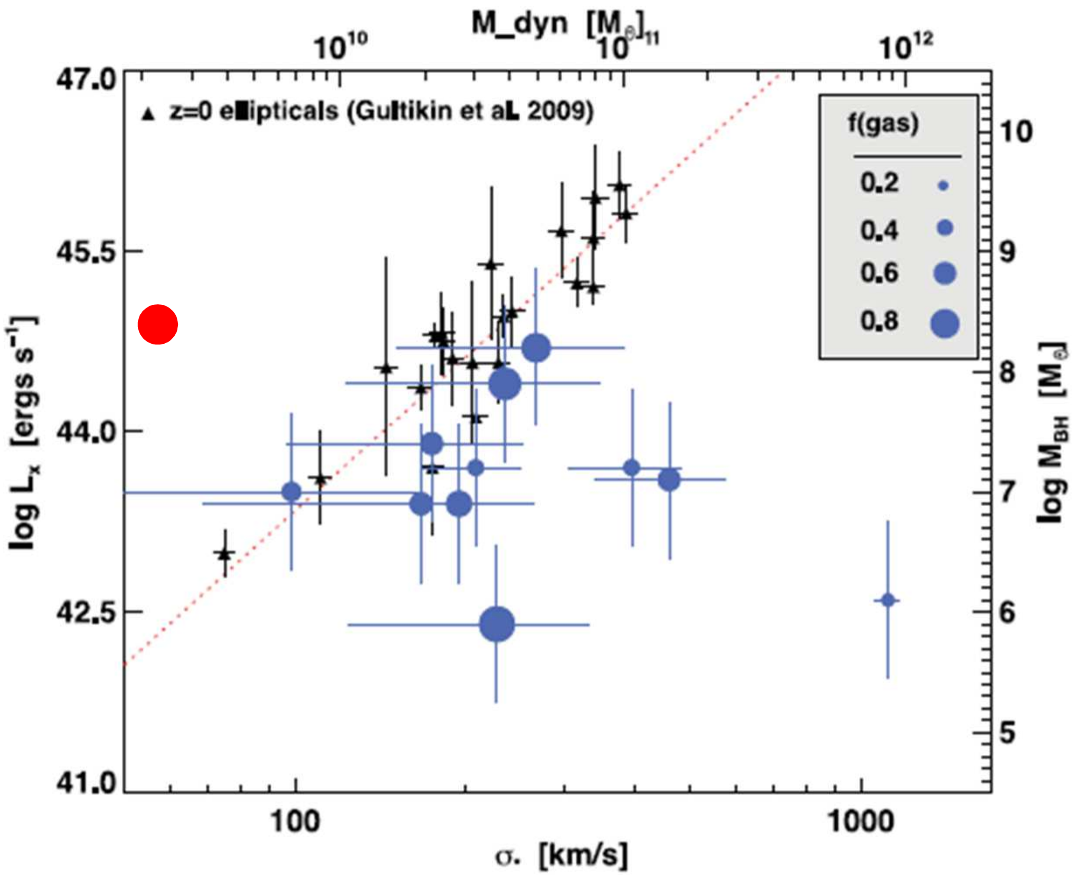
Carilli & Walter 2013



RX J0911 has an outstandingly small line width, which could be interpreted as a rotating disk seen face on. However, the aspect ratio we found points to a significant inclination (70 degrees) and the low dynamical mass we derive with this inclination is consistent with the relatively low molecular gas mass. Hence, our interpretation is that RX J0911 resides in a relatively small galaxy (when compared to other high-z quasars).

(Bothwell et al. 2013)

X-ray luminosity
measures Black Hole mass



Dynamical mass

The dynamical mass is also abnormally low when compared with host galaxies having a similar central black hole mass (measured by the X-ray luminosity).

Summary

- While the gas of the host galaxy of the quasar has been clearly resolved (7 standard deviations away from point source), the dust content has been only barely (2 s. d.).

- Two models of the lensing mechanism have been used to evaluate the importance of systematic effects.

- Evidences for an important ellipticity (aspect ratio of ~2.6) and for a velocity gradient have been given at the level of respectively 3.3 and 4.5 standard deviations.

Summary (2)

- The properties of the gas, low mass and small velocity dispersion, place RX J0911 on the low side of the z~>1 quasar host population. The RX J0911 star formation efficiency is on the high side of all galaxies of similar gas mass, whether low-z or high-z and both CO and FIR luminosities are at the low end of the high-z population. It is as if RX J0911 had exhausted much of its gas after a period of intense star formation.

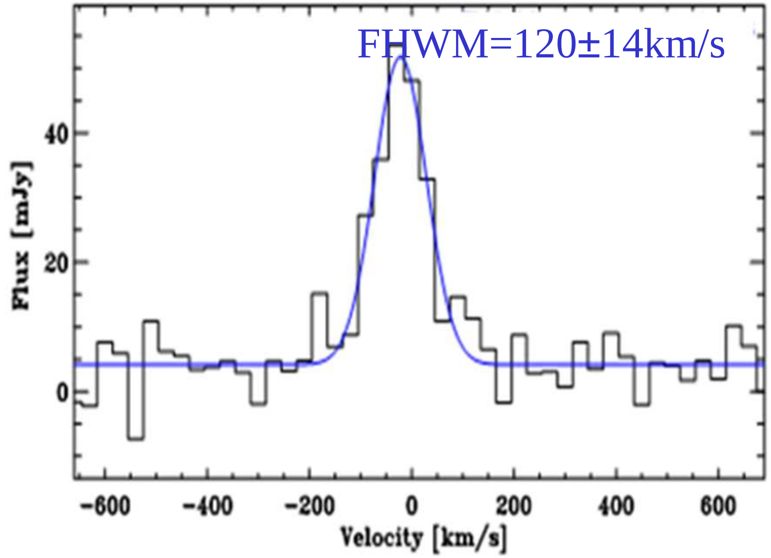
- In the future, ALMA will allow for higher sensitivity and better resolution data than analyzed here.

This work was performed in part in Ha Noi (VATLY/INST) and in part in Toulouse (IRAP) in the framework of a joint supervision agreement between the two laboratories.

I am grateful to the National Astronomical Observatory of Japan (NAOJ), French Embassy for a fellowship, and to the World Laboratory, the Institute for Nuclear Science and Technology and NAFOSTED for financial support.

CO luminosity to molecular gas mass

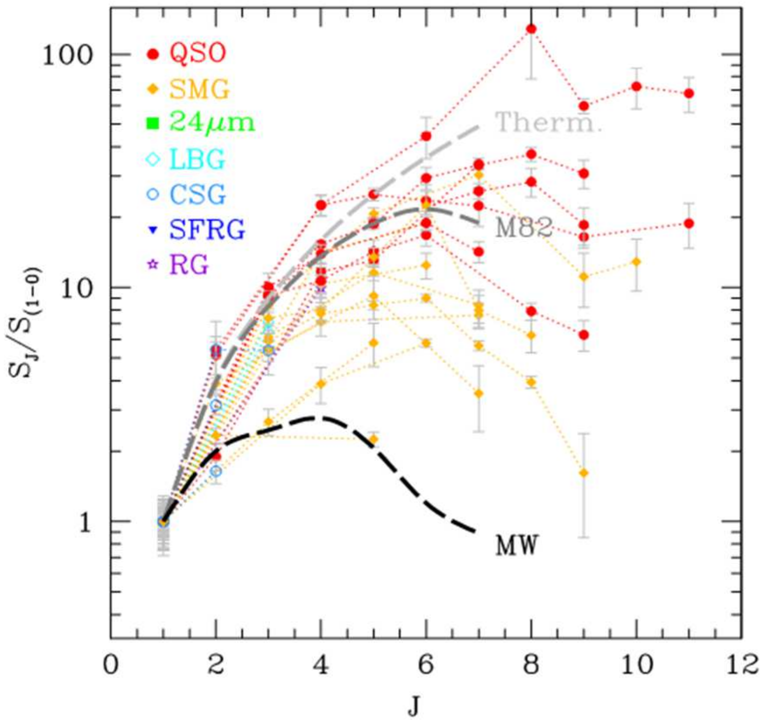
$L'_{line}=3.25\ 10^7 S_{line}\Delta v D_L^2(1+z)^{-3}\nu_{obs}^{-2}$



From CO(7-6) to CO(1-0): 25% correction

From CO(1-0) to H2 and gas: α_{CO} 0.8 M_{sun} (K km/spc^2)$^{-1}$

The main uncertainty comes from magnification M_{gas} ~ 2 to 4 10^9 M_{Sun}



Dynamical mass:

$M_{dyn}=R\Delta V^2 G^{-1} \sin^{-2} i$ where R is the radius of the disk, ΔV the FWHM of the line, G the gravity constant and i the inclination angle.

$M_{dyn}= (4.7\pm1.4)10^9\ M_{Sun}$