First detection of a THz water maser in NGC7538-IRS1

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Herpin et al. (2017)

Outlines

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(II): maser theory predictions

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A-Motivation (I): High-mass star formation


ESA/PACS/SPIRE/Thomas Preibisch, Universitäts-Sternwarte München, Ludwig-Maximilians-Universität München, Germany

Huge luminosity
⇒ radiative pressure stops accretion

⟹ ***How to accumulate a large amount of mass infalling*** **within a single entity despite radiation pressure?**

⟹ **Models considering a protostar-disk system** (e.g. *Krumholz et al. 2005, Kuiper et al. 2010, 2015*). Disk accretion and protostellar outflows enable the accretion process to continue for longer times and then to reach final star masses above the upper mass limit of spherically symmetric accretion.

Two main theoretical scenarios, both requiring the **presence of a disk** and **high accretion rates**:
(a) ***turbulent core model*** with a monolithic collapse scenario (*Tan & McKee 2002, McKee & Tan 2003*);
(b) ***competitive accretion model*** involving the formation of a cluster (*Bonnel & Bate 2006*)

A-Motivation (I): High-mass star formation

How could water help?

➡ **Water is abundant**: while in cold regions water is mostly found as ice on dust grains, at temperatures $T > 100\ K$ the gas-phase water abundance increases by several orders of magnitudes as the ice evaporates (*Fraser et al. 2001;Aikawa et al. 2008*) $\Longrightarrow X_{in} = a\ few 10^{-4}$

Partly confirmed by ISO and SWAS (*Helmich et al. 1996, Snell et al. 2000*):

$X_{in} = 2{-}6 \times 10^{-5}$, $X_{out} = 0.8{-}13 \times 10^{-9}$

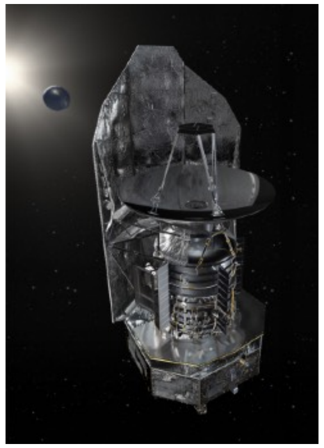
➡ water might help cooling

➡ **to discriminate between models?**

Turbulent core model implies supersonic turbulence in the protostellar envelope, while the competitive accretion model predicts subsonic cores, but still embedded in a supersonic envelope.

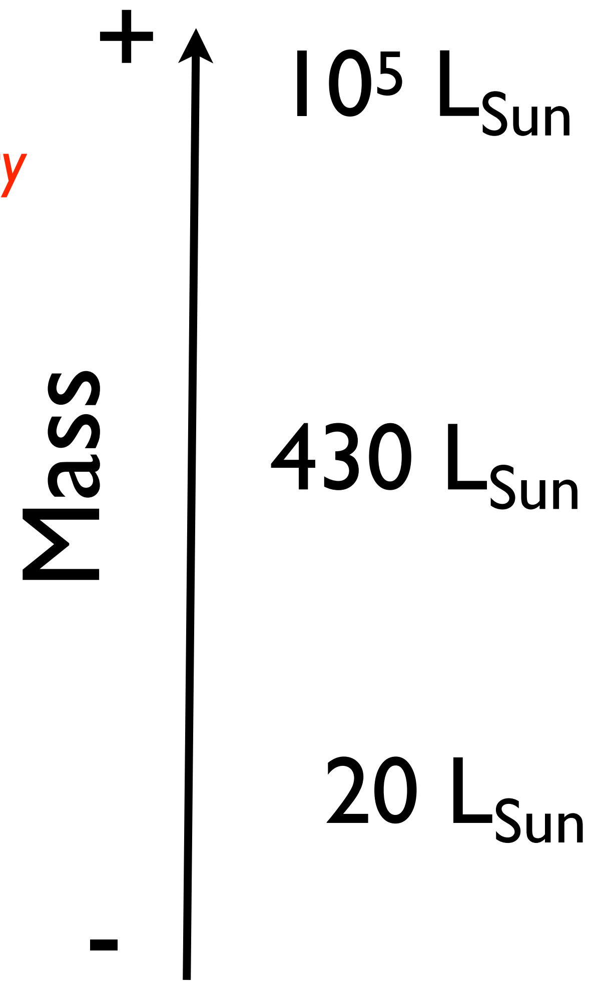
➡ water = probe of the gas dynamics

A-Motivation (I): High-mass star formation



Herschel Space Observatory

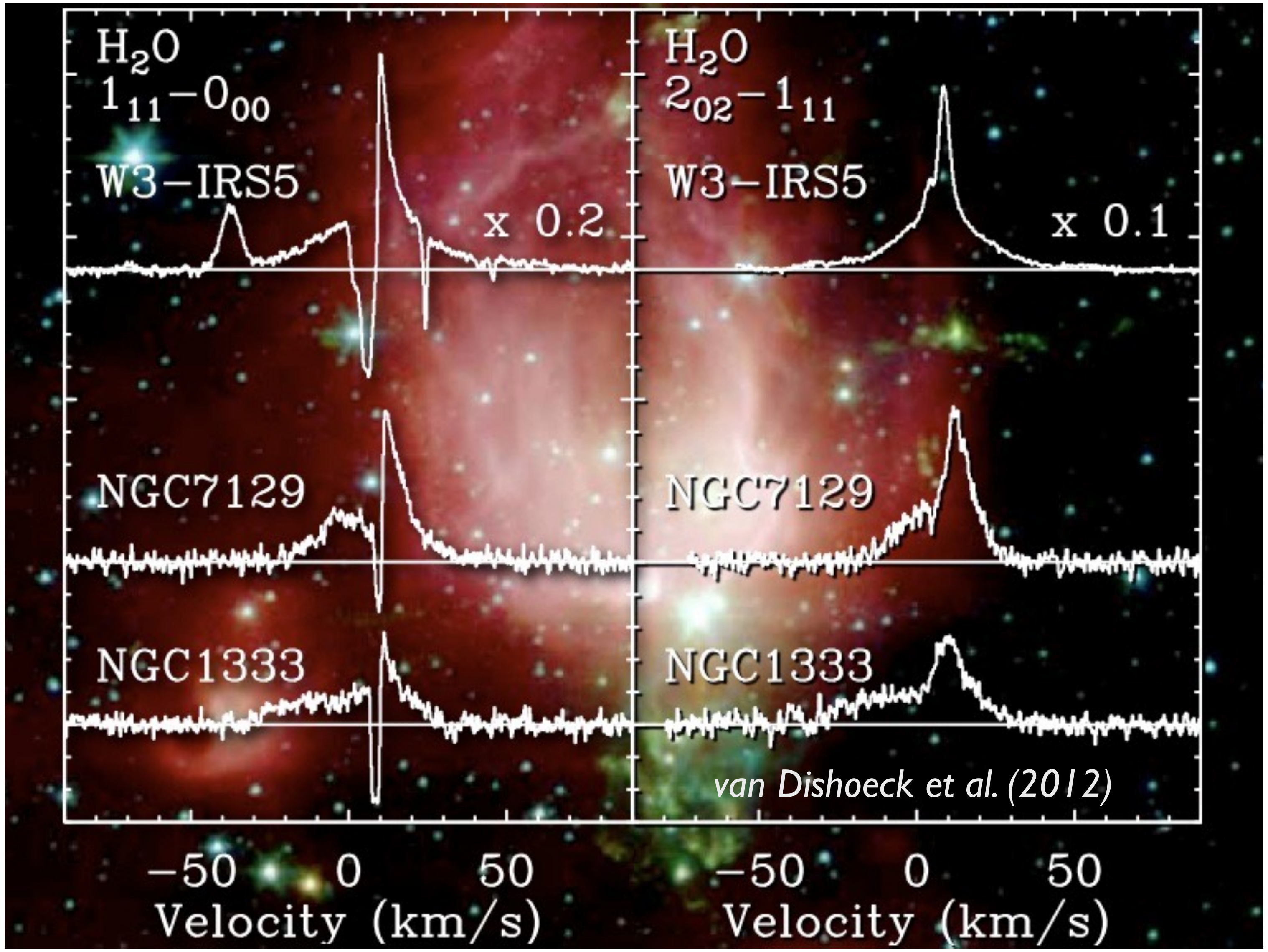
→ Studying the star formation though the water lines observations with HIFI et PACS
= WISH GT-KP (*van Dishoeck et al. 2011*)



$10^5\ L_{Sun}$

$430\ L_{Sun}$

$20\ L_{Sun}$



van Dishoeck et al. (2012)

A-Motivation (I): High-mass star formation *WISH results*

HIFI line modelling (*Herpin et al. 2012, 2016*)
⟹ **Inner water abundances below the predicted abundance** from *Fraser et al. (2001)*
⟹ **Why?**

- **Do we probe deep enough? *We think so…***
- **Is our model guilty? *Could be***…Simplified 1D-model. ⟹ LIME (3D) on-going modeling
- **Dynamical reasons? *Maybe***, *no correlation* is found between χ_{in} and the turbulent velocity or outflow, but correlation with the infall/expansion velocity.

⟹ larger infall or expansion velocities generate shocks that will sputter water out of the dust grain mantles.

A-Motivation (II): Maser theory predictions

Since the end of the HSO, *only SOFIA allows to observe water in the THz frequency range.*

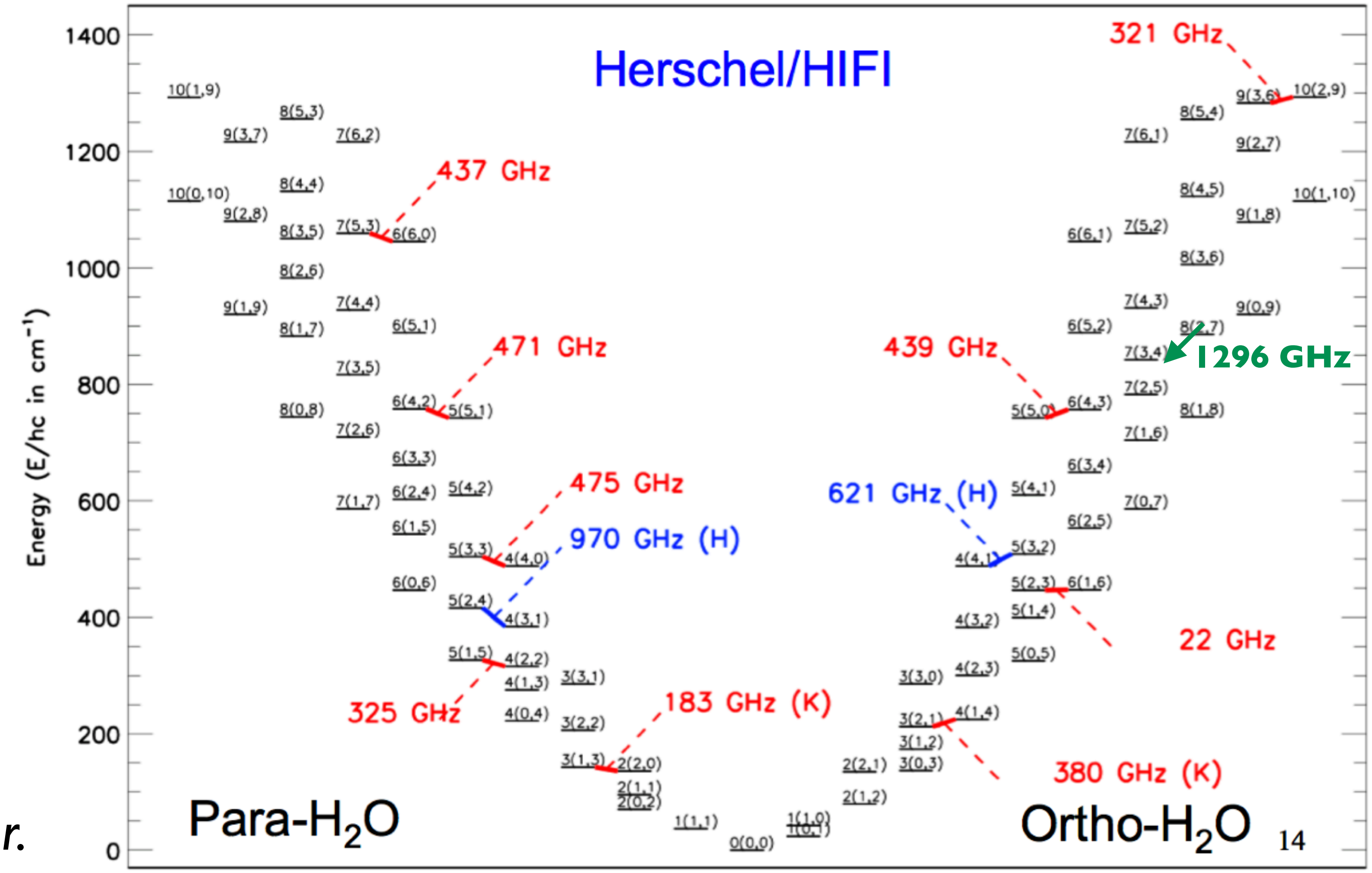
Some of the **THz water lines could be masing** (e.g. *Neufeld & Melnick 1991, Gray et al. 2016*):

one, **o-H2O transition, $8_{2,7} - 7_{3,4}$ at 1296.41 GHz**, could be observed at the flying altitude of the SOFIA observatory (transmission ≃ 62%); others are absorbed by the remaining atmosphere.

E_{up} (1296)=1274 K

⟹ **can probe the gas deep enough into the inner layers of the hot core.**

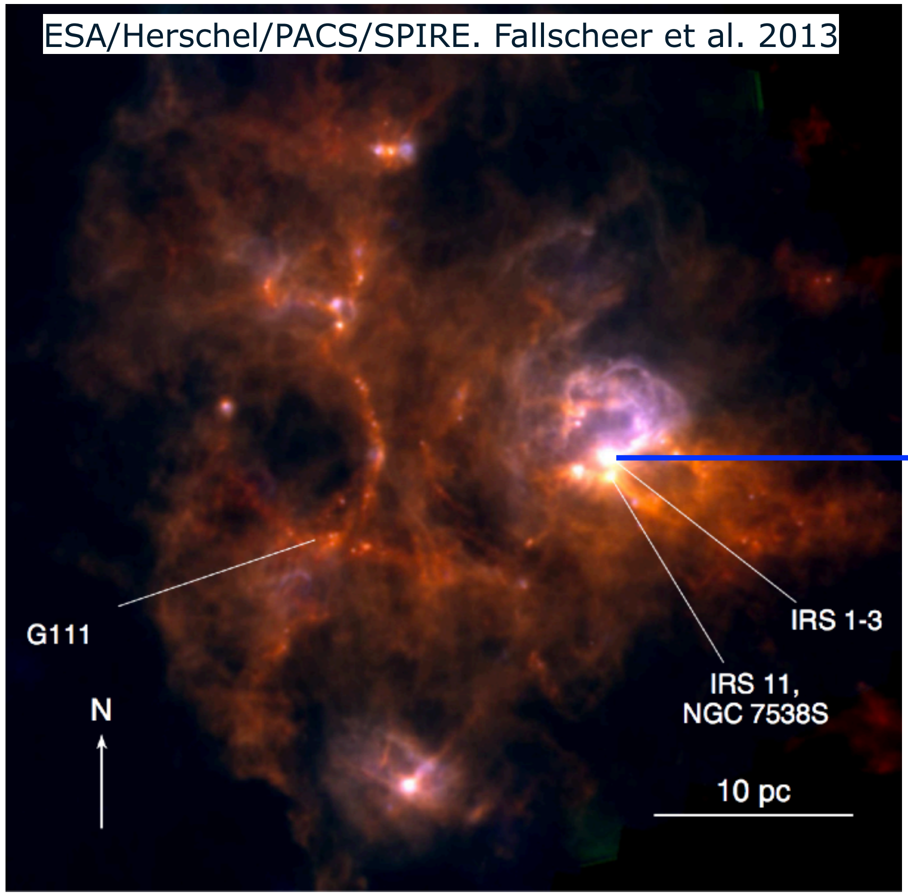
Neufeld et al. (2017): first detection of the $8_{2,7} - 7_{3,4}$ masing line toward an evolved star.

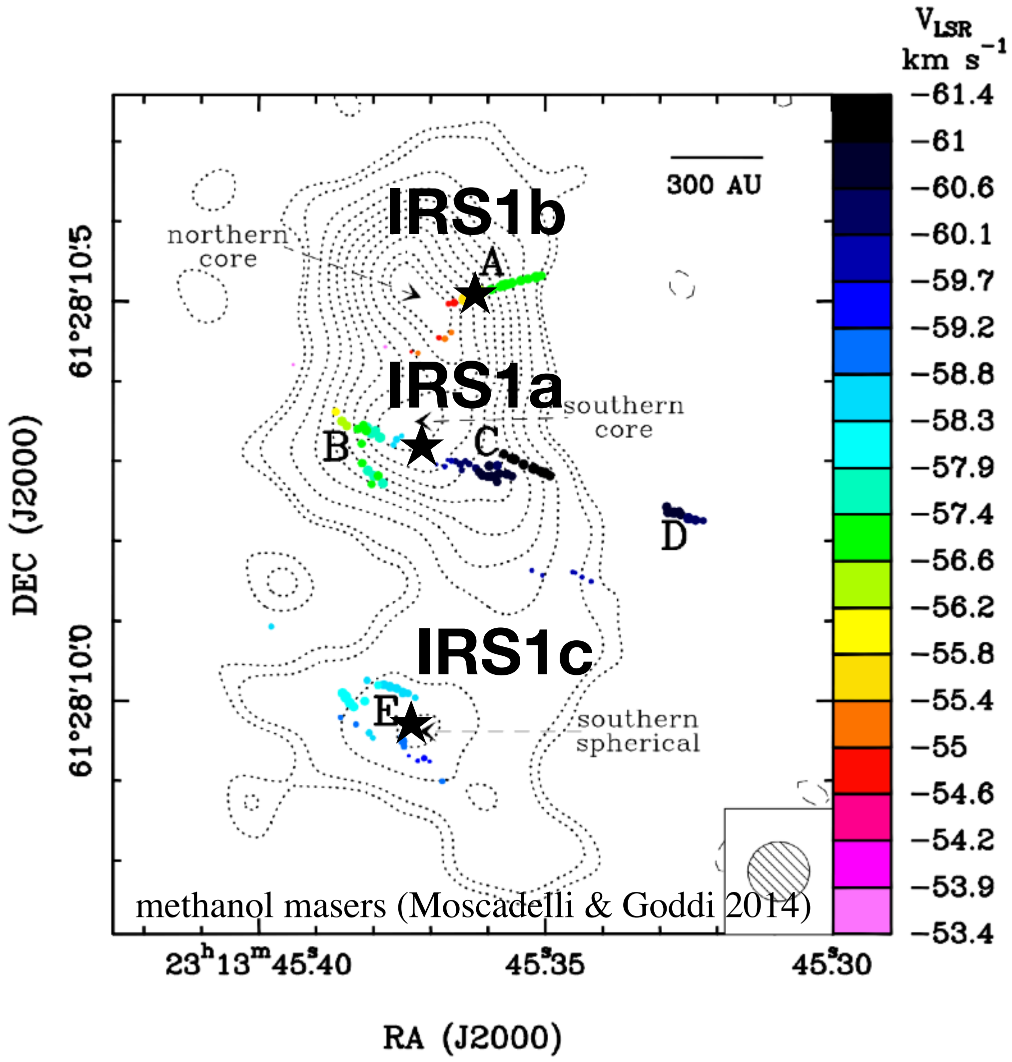


From Neufeld's SOFIA talk (2017)

B-NGC7538-IRS1, a complex massive star-forming object

relatively nearby (2.65 kpc) **UCHII object** ($L \approx 1.3 10^{5} L_{sol}$) in the massive star-forming region NGC7538 **surrounded by a molecular hot core.** 22 GHz maser + strong thermal water lines


ESA/Herschel/PACS/SPIRE. Fallscheer et al. 2013



methanol masers (Moscadelli & Goddi 2014)

NGC7538- IRS1

= strongest and main concentration of the 22 GHz H_2O maser features (*Kameya et al. 1990; Surcis et al. 2011*).

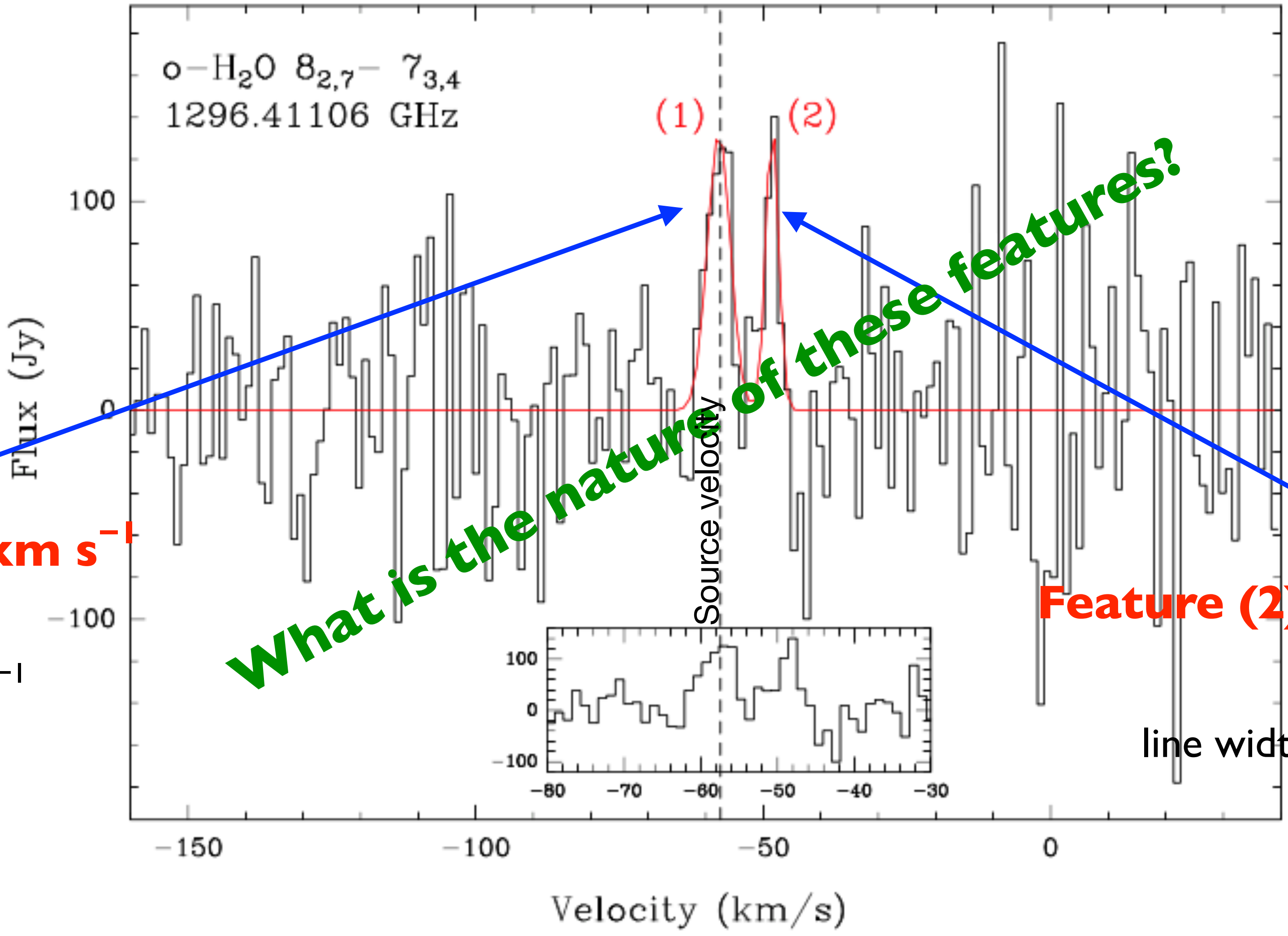
= three individual high-mass YSOs within 1600 AU:

- **IRS1a = the most massive YSO**, with ~25 M⊙ and a quasi-Keplerian disk of ~1 M⊙,
- **IRS1b = less massive (a few M⊙)** object + massive (≤ 16 M⊙) thick disk,
- **IRS1c**, is likely to be a massive YSO as well.

C-Observations

SOFIA Cycle 3 on 2015 December 9, using **GREAT**.

Smoothed to 1.13 km s^{-1}, **rms = 90 mK**



What is the nature of these features?

Feature (1) at -57.7±0.6 km s^{-1}

S/N ratio 5.5

line width = 4.7 (±1.3) km s^{-1}

Feature (2) at -48.4±0.5 km s^{-1}

S/N ratio 3.2

line widths = 2.6 (±1.3) km s^{-1}

- **feature (1): velocity and line width comparable** to CS **thermal lines** *(van der Tak et al. 2000)* or OH with SOFIA *(Csengeri et al. 2012)*.
- **feature (2):** at a **velocity different** from the source velocity + **narrower** by a factor of 2.

D-Maser or not maser?

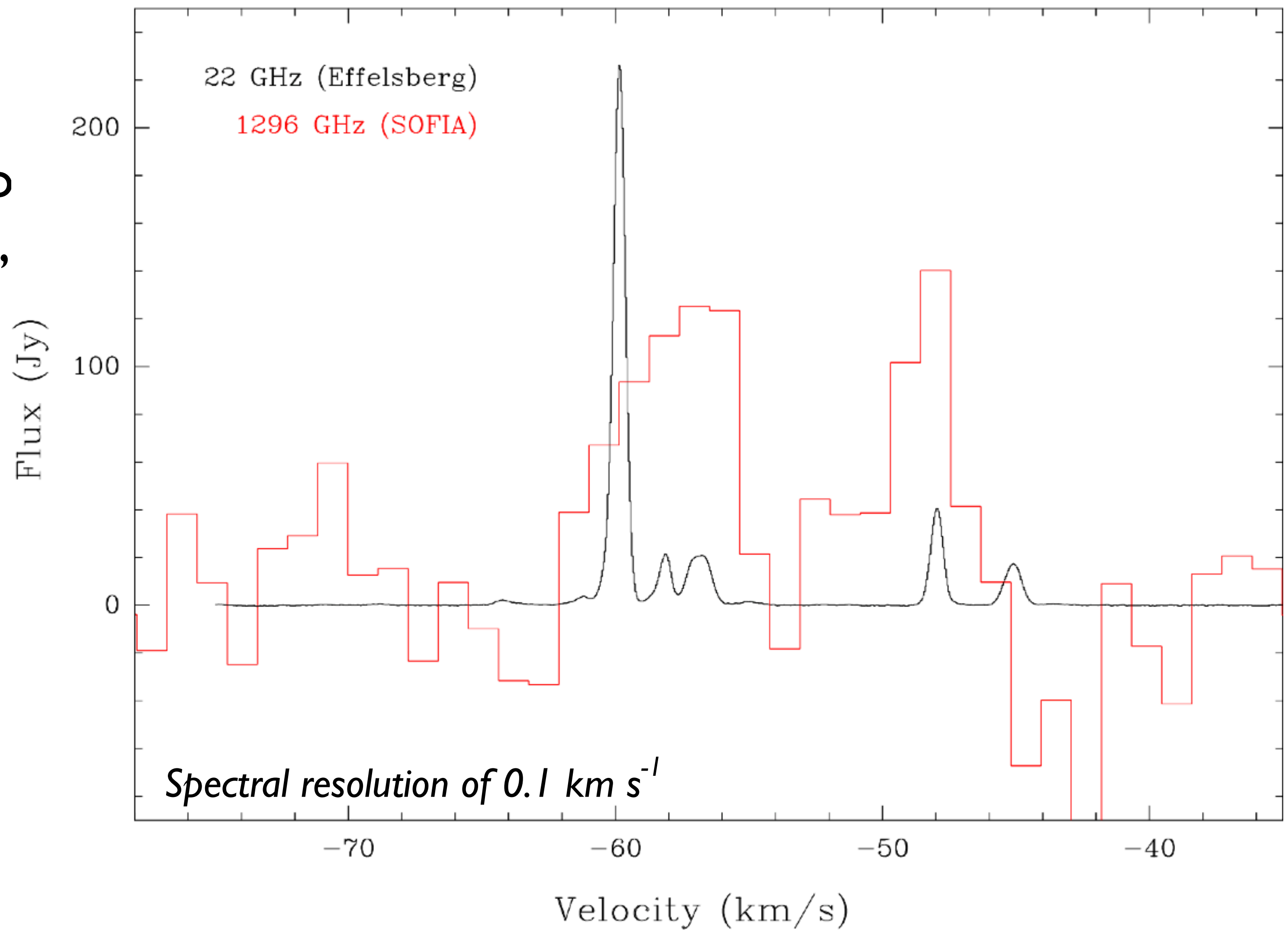
Effelsberg 22GHz maser observations

In order **to constrain the maser models** and because of the variability of the maser emission, **nearly contemporaneous observations of the o-H_2O $6_{16} - 5_{23}$ transition** (22 GHz) were carried out on 2015 December 11 with the MPIfR-100 m telescope ($\Theta \simeq 39''$)

Two main groups of lines:

- one made of three strong lines close to the source velocity ~ −(56 − 60) km/s),
- another group with two lines centred at -45.1 and -48 km/s

All lines are narrow ($\leq$ 1km s^{-1})



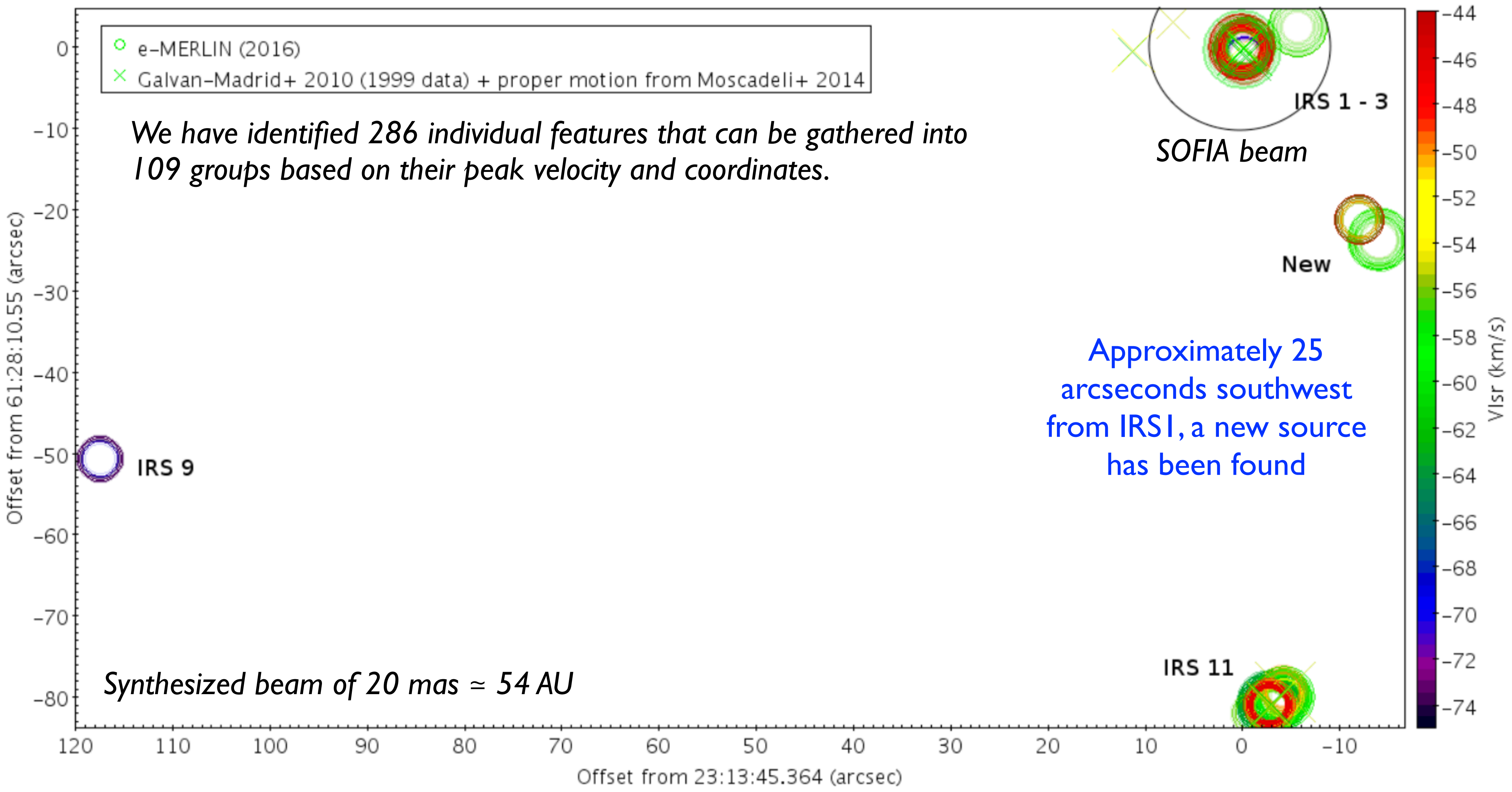
Spectral resolution of 0.1 km s^{-1}

Question: are all of these Effelsberg maser components associated with IRS1-3?

D-Maser or not maser?

e-MERLIN 22GHz maser observations

Maser positions consistent with *Galván- Madrid et al. (2010)*, taking into account the proper motions from *Moscadelli & Goddi (2014)*.



We have identified 286 individual features that can be gathered into 109 groups based on their peak velocity and coordinates.

Approximately 25 arcseconds southwest from IRS1, a new source has been found

Synthesized beam of 20 mas ≃ 54 AU

Positions of individual maser components with a relative accuracy ~ 1 AU.

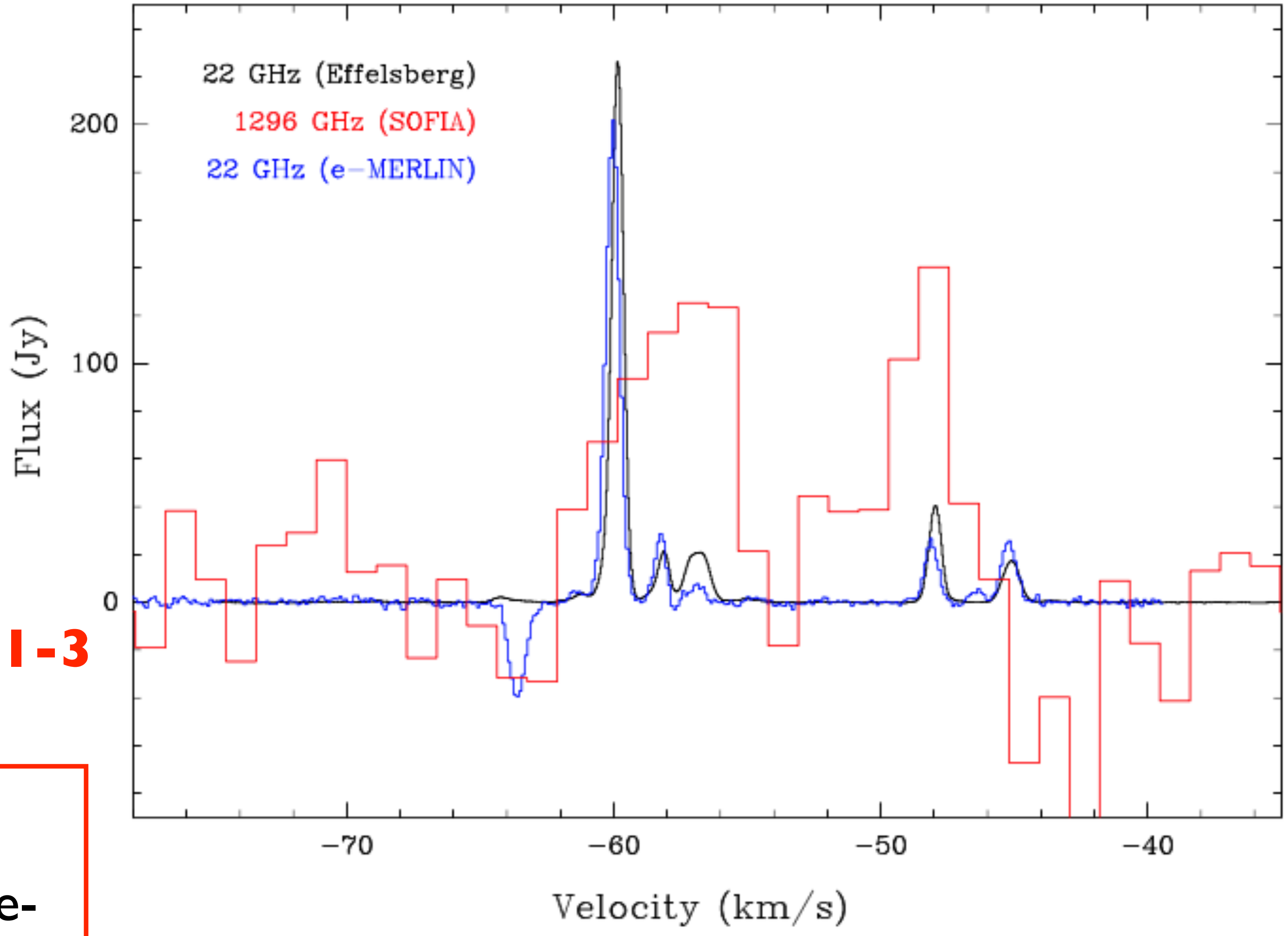
Astrometric position accuracy is a few tens of mas. Spectral resolution of 0.105 km/s.

e-MERLIN 22GHz maser observations

The total size of the image around IRS1-3 (12" comparable to the SOFIA beam at 1.3 THz) was used to **synthesize the e-MERLIN 22 GHz spectrum**,

⟹ **to compare with the line profile obtained at Effelsberg**

Both line profiles are very similar, except for the apparently negative feature in the -63.5 to -64 km s^{-1} velocity range, which is due to residual side-lobes arising from strong IRS11 emission in this velocity range.

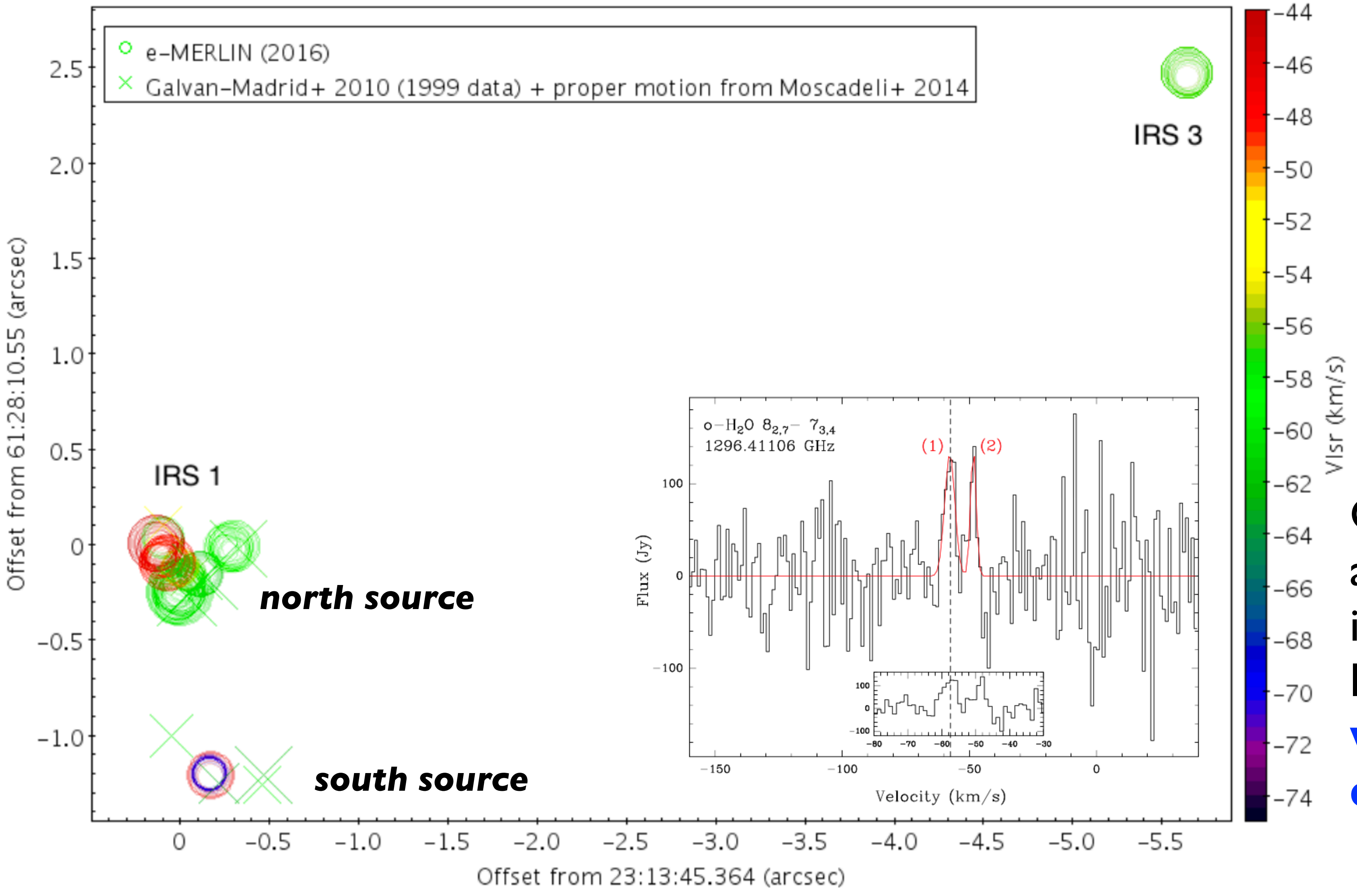


⟹ **all of the Effelsberg maser components are associated with IRS1-3**

⟹

- flux density scale ok
- maser variability over this short time-period (four months) is not significant
- entire flux is detected

e-MERLIN 22GHz maser observations: zoom



IRS1 is made of what *Surcis et al. (2011)* called the ***north source*** (the main source) and the ***south source.***

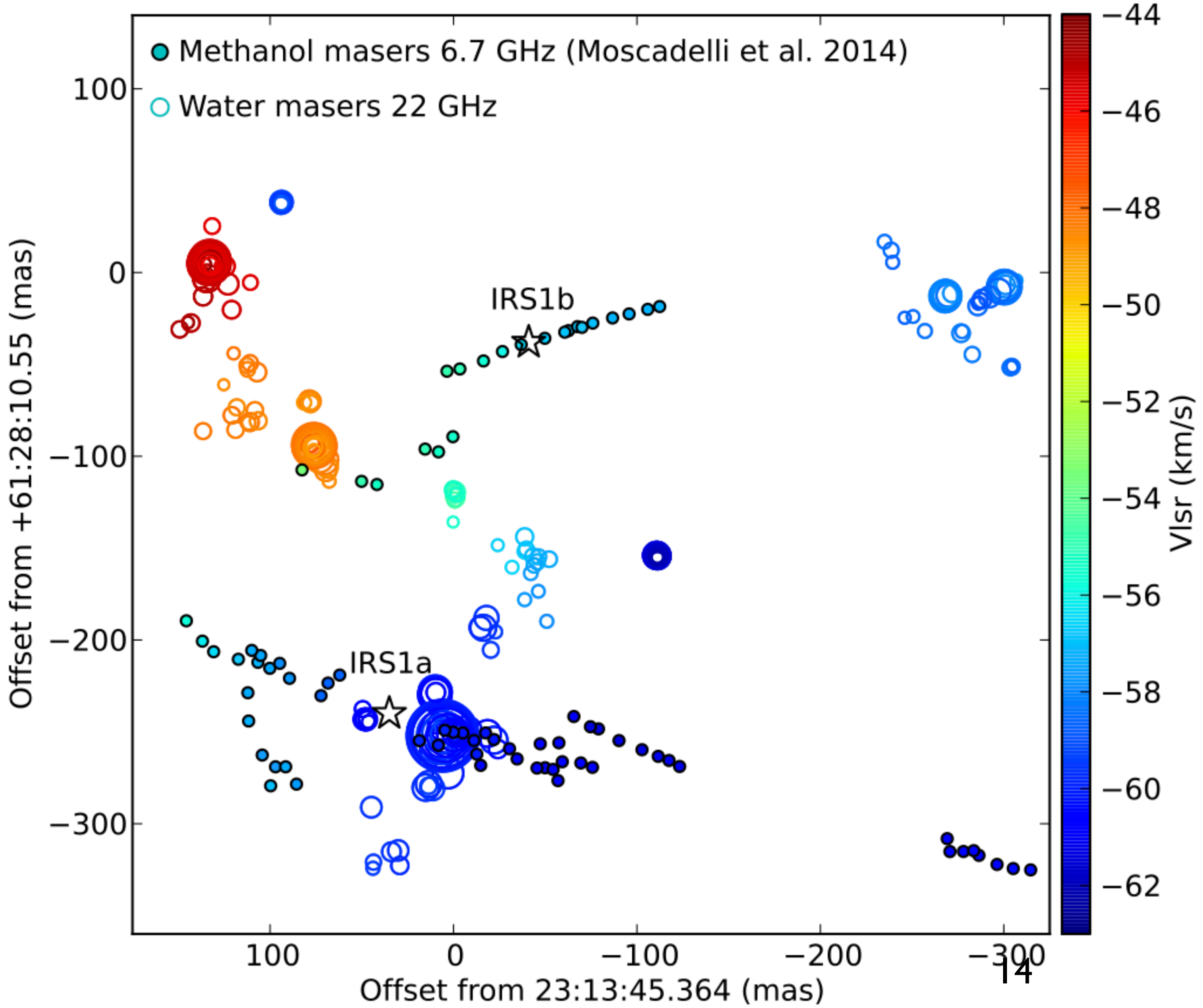
Considering the SOFIA beam size and the size of the e-MERLIN image (primary beam) toward IRS1-3, **the detected THz water emission can only originate from IRS1-3**

We can infer that:

- **water in IRS1 north or IRS3 can give rise to feature (1),**
- only **IRS1 North** exhibits maser emission at velocities (~ −48 km/s) similar to **feature (2)**

e-MERLIN 22GHz maser observations: zoom (2)

- large group of masers within ±3 km s^{-1} from the main source LSR velocity, concentrated very close to IRS1a plus several spots spread in the northwest.
- group of redshifted masers whose LSR velocity is between -45 and -48 km s^{-1}, north of IRS1a, aligned along a NE-SW direction.



Maser spots at velocities similar to THz **feature (2) emission are located 0.2" northeast of IRS1a and 0.1" east of IRS1b.**

⟹ similar beam dilution of the two maser features is obtained with the Effelsberg 22 GHz beam.

⟹ sizes of the emitting regions for maser features around -48 and -58 km/s are comparable, but not spatially coincident.

D-Maser or not maser?
⟹ thermal modeling

What do HIFI water lines observations tell us?

- All components at velocity similar to THz feature (1), ~ −57 km s^{-1}
- No emission is detected at -48 km s^{-1}

⟹ **non-thermal origin of this emission.**

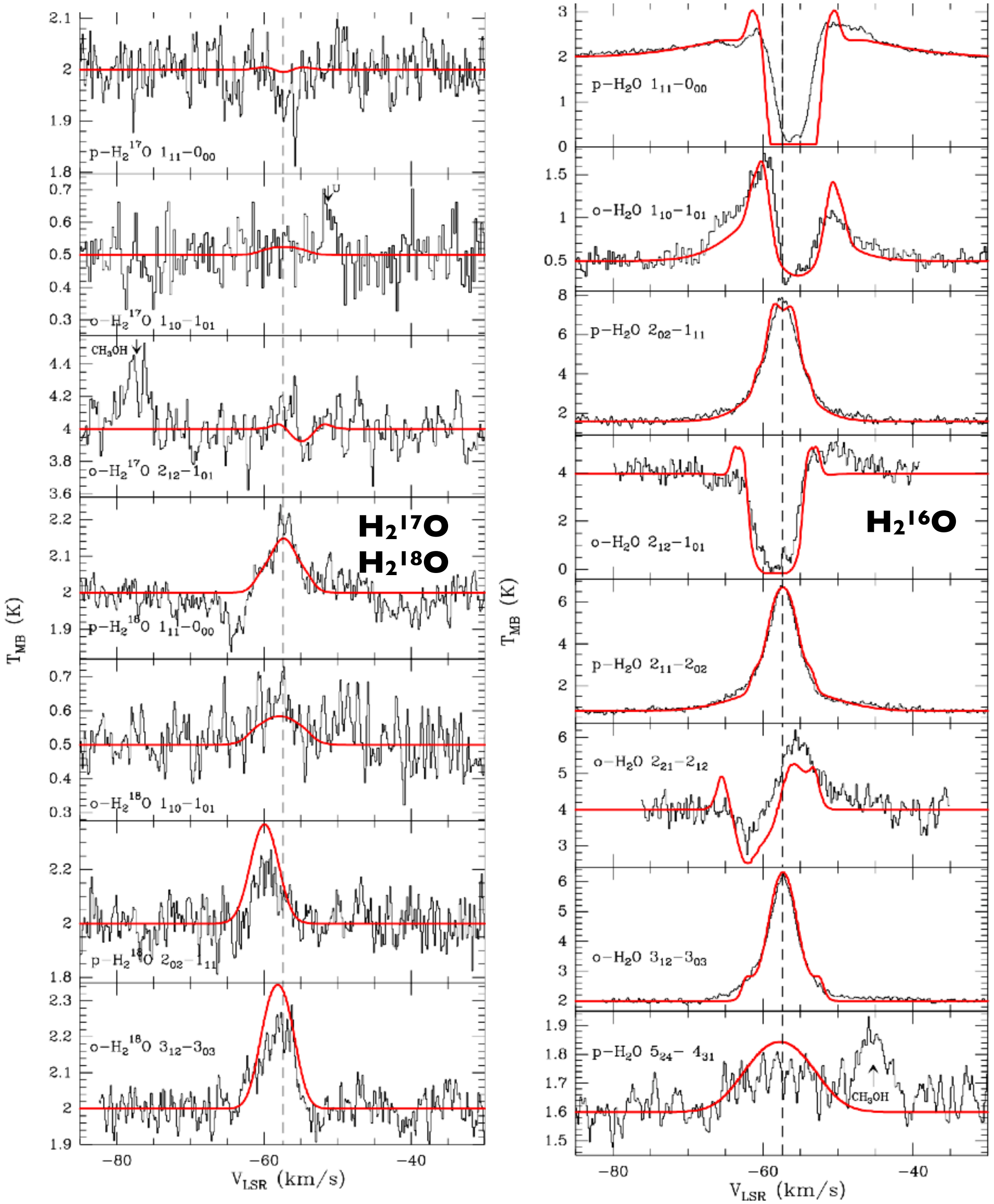
We model all water line profiles in a single spherically symmetrical model (see *Herpin et al. 2012, 2016*) using RATRAN with:

- lines @ −57.4 ± 0.5 km/s
- no infall
- outflow
- V$_{turb}$= 1.5- 2.5 km s^{-1}

⟹ **Water abundance jump in the inner envelope:**

X(H_2O)$_{inner}$=8 x 10^{-6} (> 100 K)

X(H_2O)$_{outer}$=2 x 10^{-8}



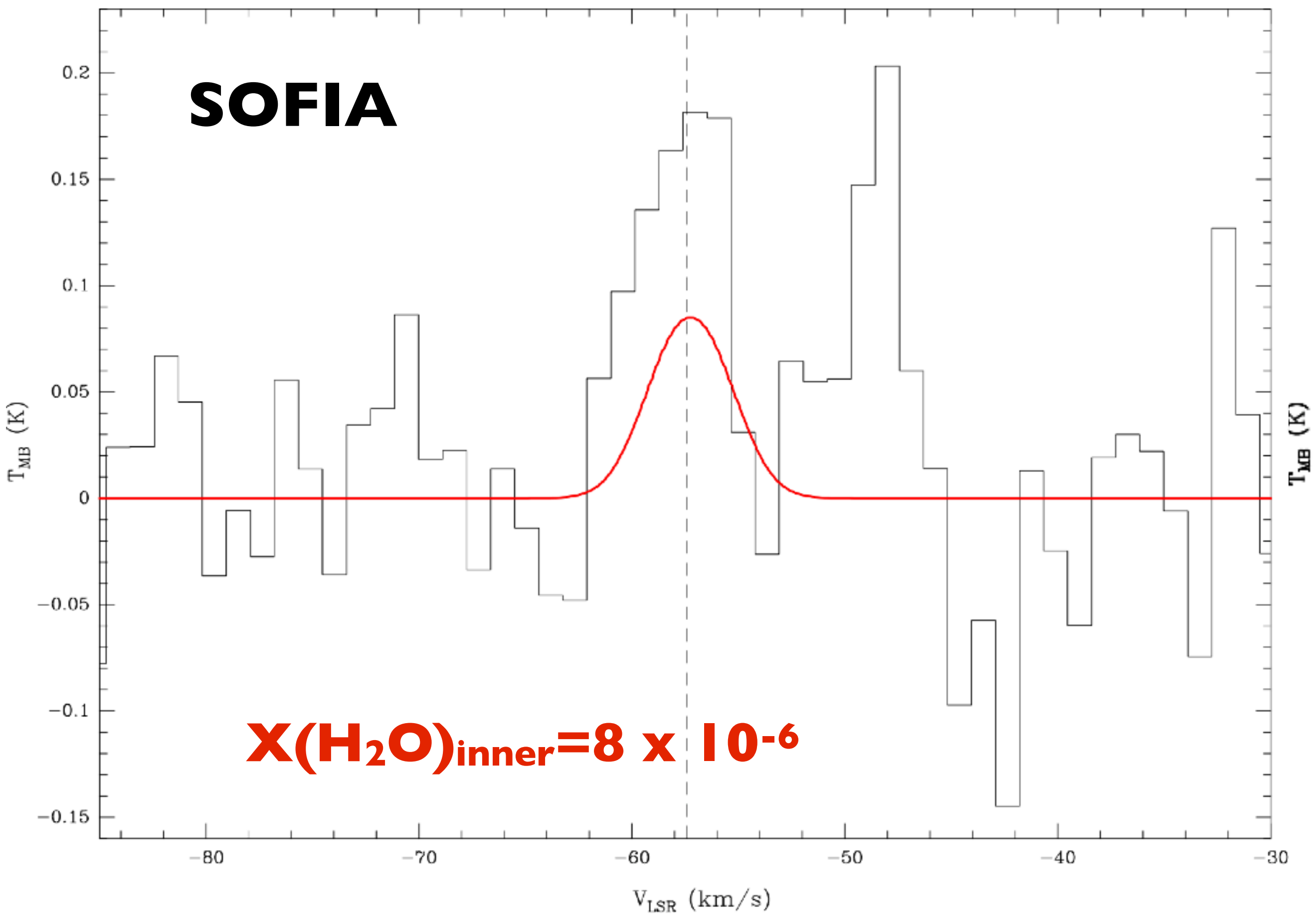
Herschel H_2O line: impact on THz line

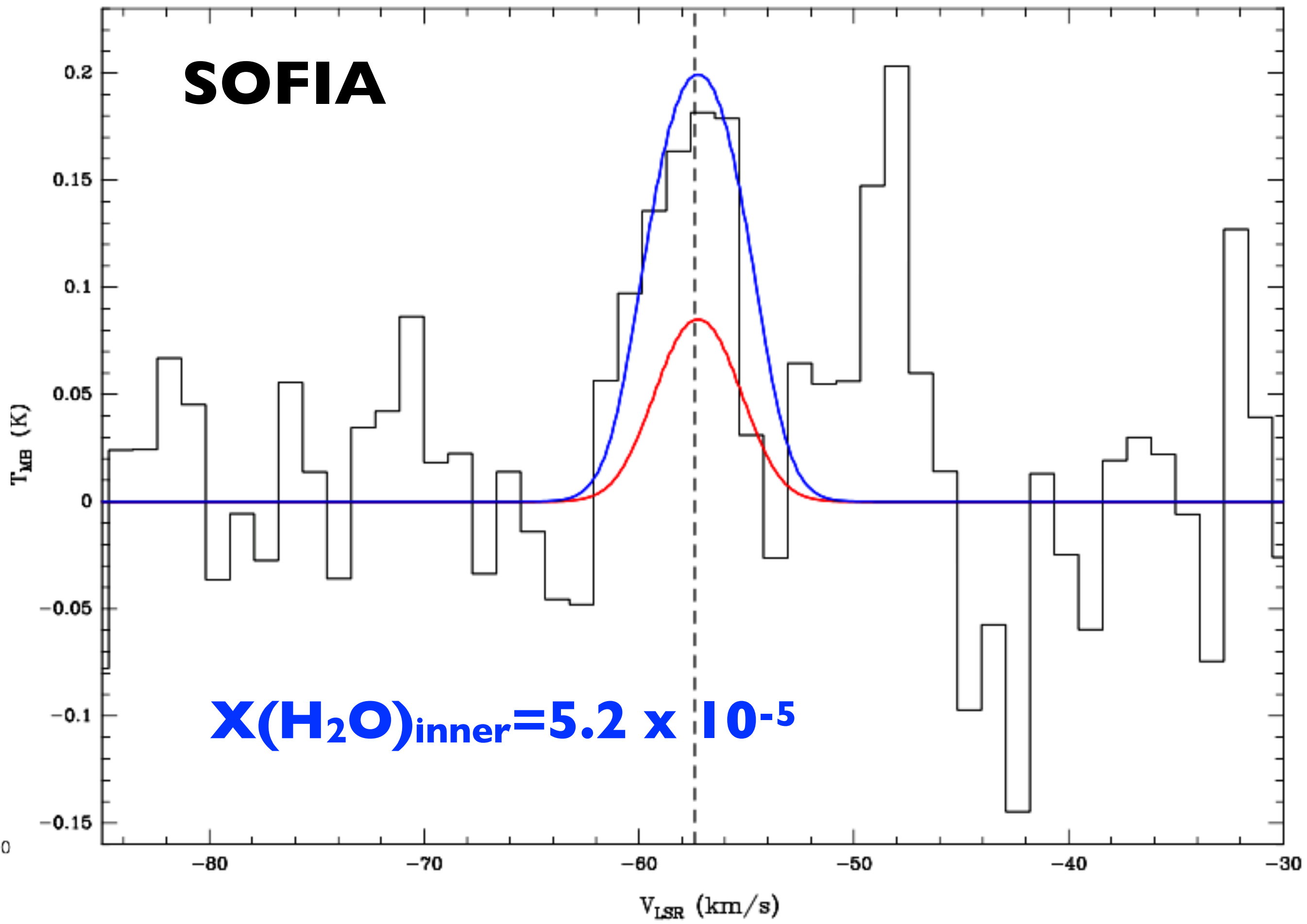
«HIFI» abundances applied to SOFIA feature (1) line model (o-H2O $8_{2,7} - 7_{3,4}$), with v_{turb} = 2.5 km/s

⟹ we do not reproduce the observed SOFIA line (I),

⟹ **feature (1) perfectly reproduced with an increased water inner abundance**.

Also successfully applied to the $H_2{}^{18}O$ $3_{13} - 2_{20}$ line (E_{up} ≃200 K), observed by *van der Tak et al. (2006)*.





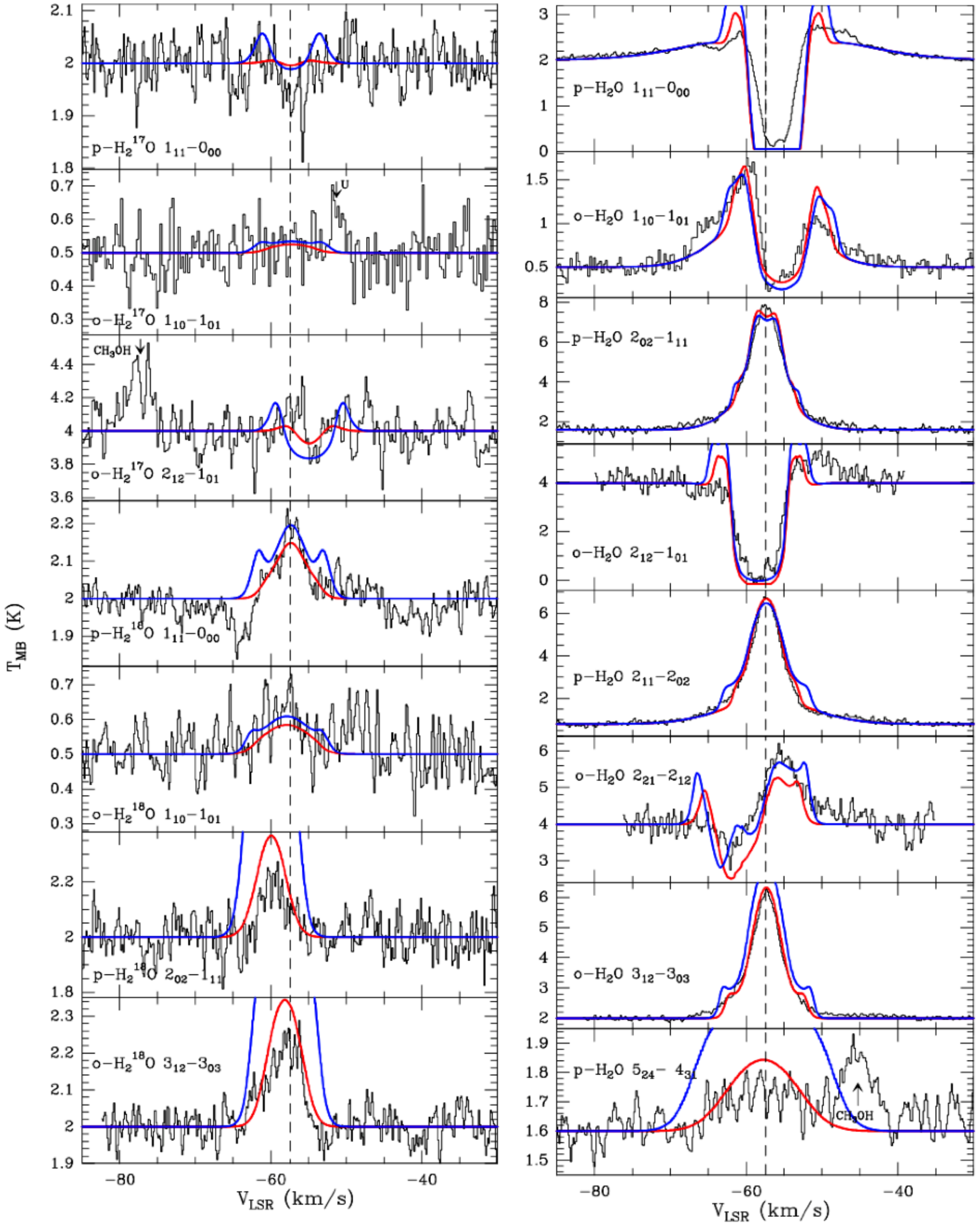
« SOFIA » water abundance applied to HIFI lines

Result is less satisfactory. Why?

- limitations of our symmetrical 1D model?
- **SOFIA $8_{2,7} - 7_{3,4}$ line emanates from the inner part of the hot core**, while the water lines observed with HIFI are from somewhat cooler regions farther out.
- *non-thermal effects*: model could miss a non-thermal contribution at 1296 GHz, on the order of 50%.

$\Longrightarrow$ if purely thermal, $M(H_2O)_{total} = 10^{-3}\ M_\odot$ to be compared with $2 \times 10^{-4}\ M_\odot$ in the case of a non-thermal contribution

But still low contribution of water cooling to the total far-IR gas cooling (*Karska et al. 2014; Herpin et al. 2016*)



$X(H_2O)_{inner} = 8 \times 10^{-6}$

$X(H_2O)_{inner} = 5.2 \times 10^{-5}$

D-Maser or not maser? ⟹ maser modeling

Line intensity ratios

⟹ physical conditions leading to these maser emissions (models *Gray et al. 2016*).

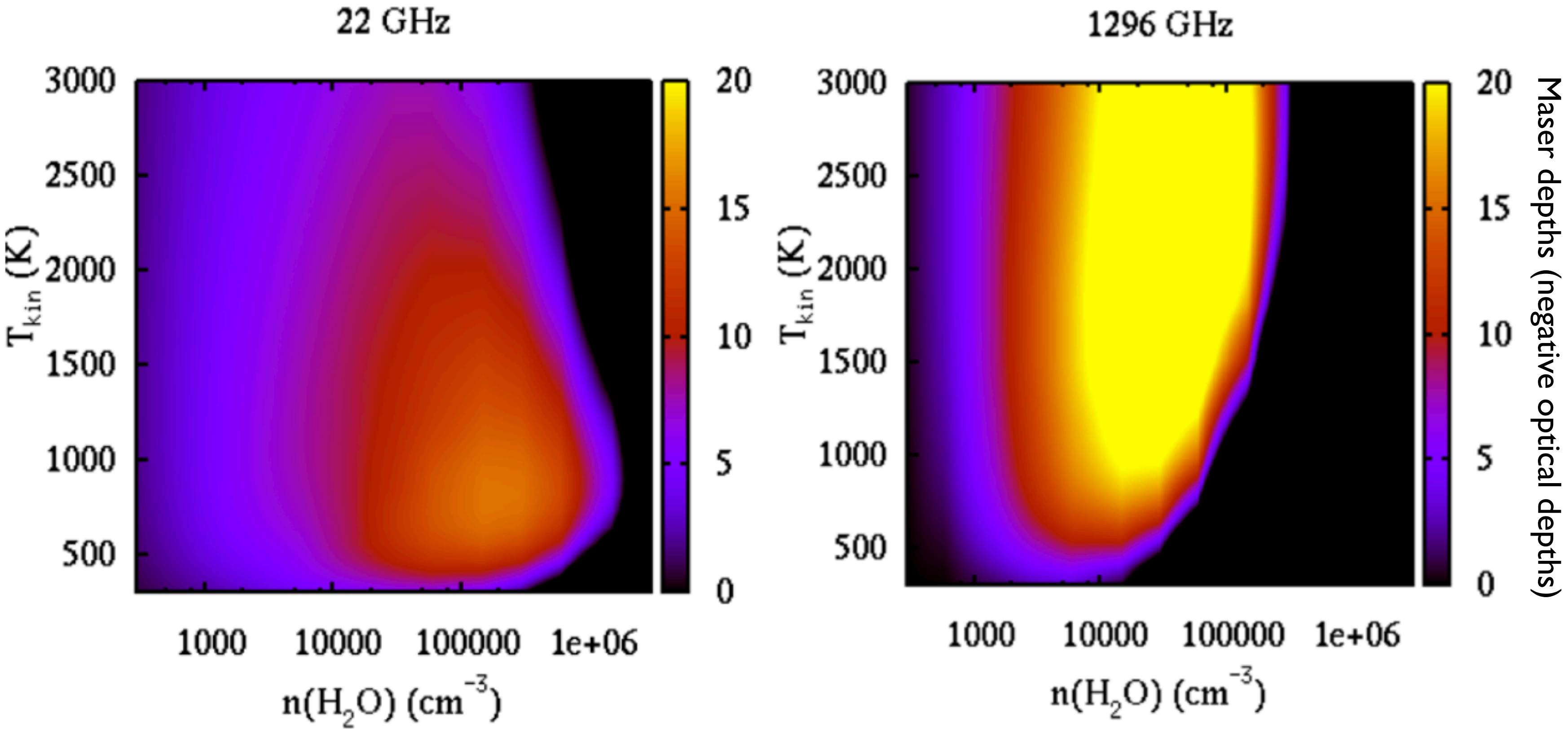
Line intensity ratios are less dependent on the cloud geometry + in the saturated regime tend to be independent of the exact ratio of the beaming angles, which should then be close to one.

Significant overlap between conditions supporting the 22 GHz and 1296 GHz masers:

T_K> 500 K

n(o-H_2O)=10^4 - 2×10^5 cm^{-3}

(i.e., $nH_2 \sim 3\times10^9 - 6\times10^{10}$ cm^{-3})



Compared to the 22 GHz inversion, the 1296 GHz inversion is biased toward higher values of T_K and it is lost with increasing dust temperatures

⟹ ***low value of T_{dust}, around 50 K, is preferred***.

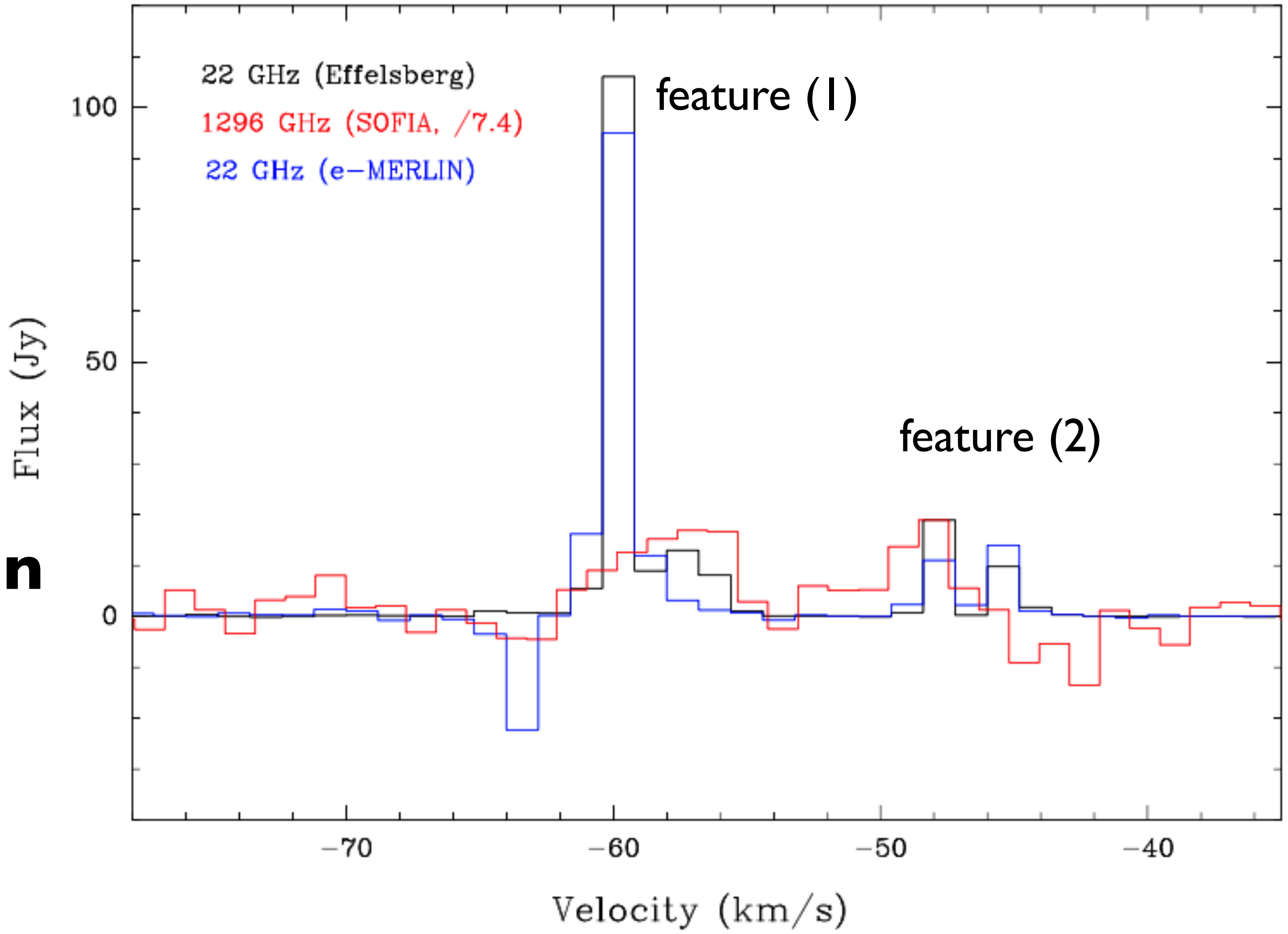
D-Maser or not maser? ⟹ lines ratios

Assuming *Tdust* = 50 K, Gray et al. (2016) **predicted τ(1296)/τ(22) ~ 1.9**

⟹ flux density and brightness temperature at 1296 GHz can be several times that at 22 GHz.

We derive the ***line peak ratios*** from spectra smoothed to the same spectral resolution. We ***cannot directly estimate the brightness temperature*** of the 1296 GHz emission since its spatial extent is unknown.

⟹ **S(1296)/S(22) = 1.2 and 7.4 for features (1) and (2)**, respectively



⟹ **feature (2) is definitely much brighter in the 1296 GHz line than at 22 GHz.**

This is ***in agreement with maser conditions suggested from the 1.9 opacity ratio above.***

D-Maser or not maser? Conclusion

Assuming that the 1296 and 22 GHz emissions have a similar spatial extent, and using the e-MERLIN resolution of 20 mas as an upper limit to the beamed size of maser spots:

***Tb (1296)* of at least 10^9 K**

⟹ strongly suggests, but does not prove, the maser nature of this emission.

+ feature (2) nearly 2.5 times narrower than feature (1)

⟹ feature (2) water emission is likely a maser.

Observations with some instrument that has much higher spatial resolution at 1296 GHz would be the only way to unambiguously prove it is a maser.

E-NGC7538-IRS1 geometry

THz water feature (1) consistent with thermal excitation, while feature (2) is masing.

Different physical conditions, i.e. a different spatial origin, could explain these different behaviours:

⟹ the -48 km/s 22 GHz maser spots located close to the IRS1b source, while the -57 km/s spots are associated with the IRS1a source.

- ***option (1):*** ***higher dust temperature*** in the "-57 km/s" region?

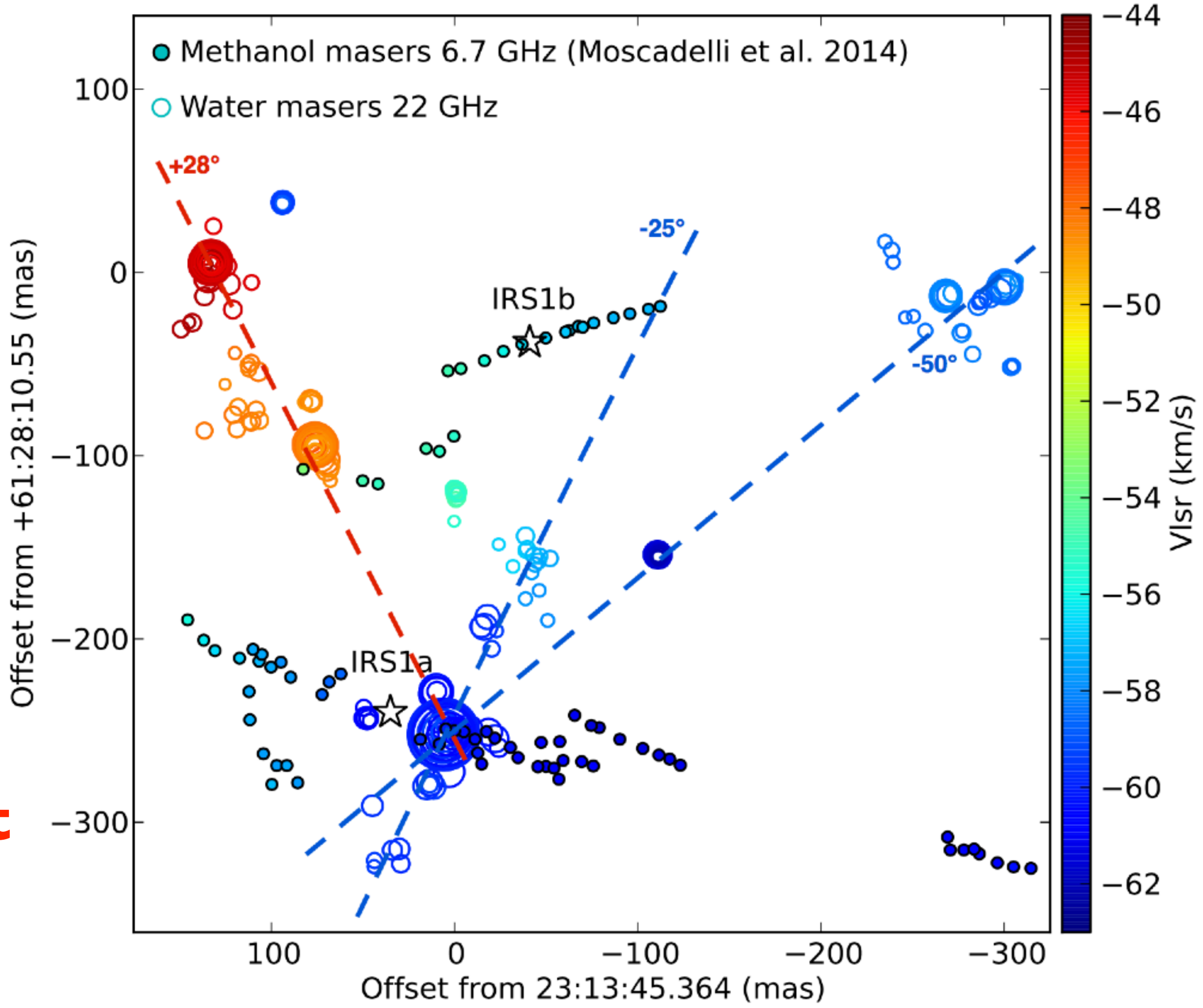
Moscadelli & Goddi (2014): gas surrounding IRS1b has a lower temperature than the gas observed toward IRS1a, which is a more massive and evolved YSO.

⟹ *the higher temperature in IRS1a might be less suitable for water maser emission at 1296 GHz.*

- ***option (2):*** more likely, ***IRS1a could collisionally quench the maser if the number density is too high***.

$n_{crit}(1296) = 5 \times 10^7\ cm^{-3}$ at T=50 K.

⟹ gas in the core of IRS1a is so dense that it begins to quench the maser action.

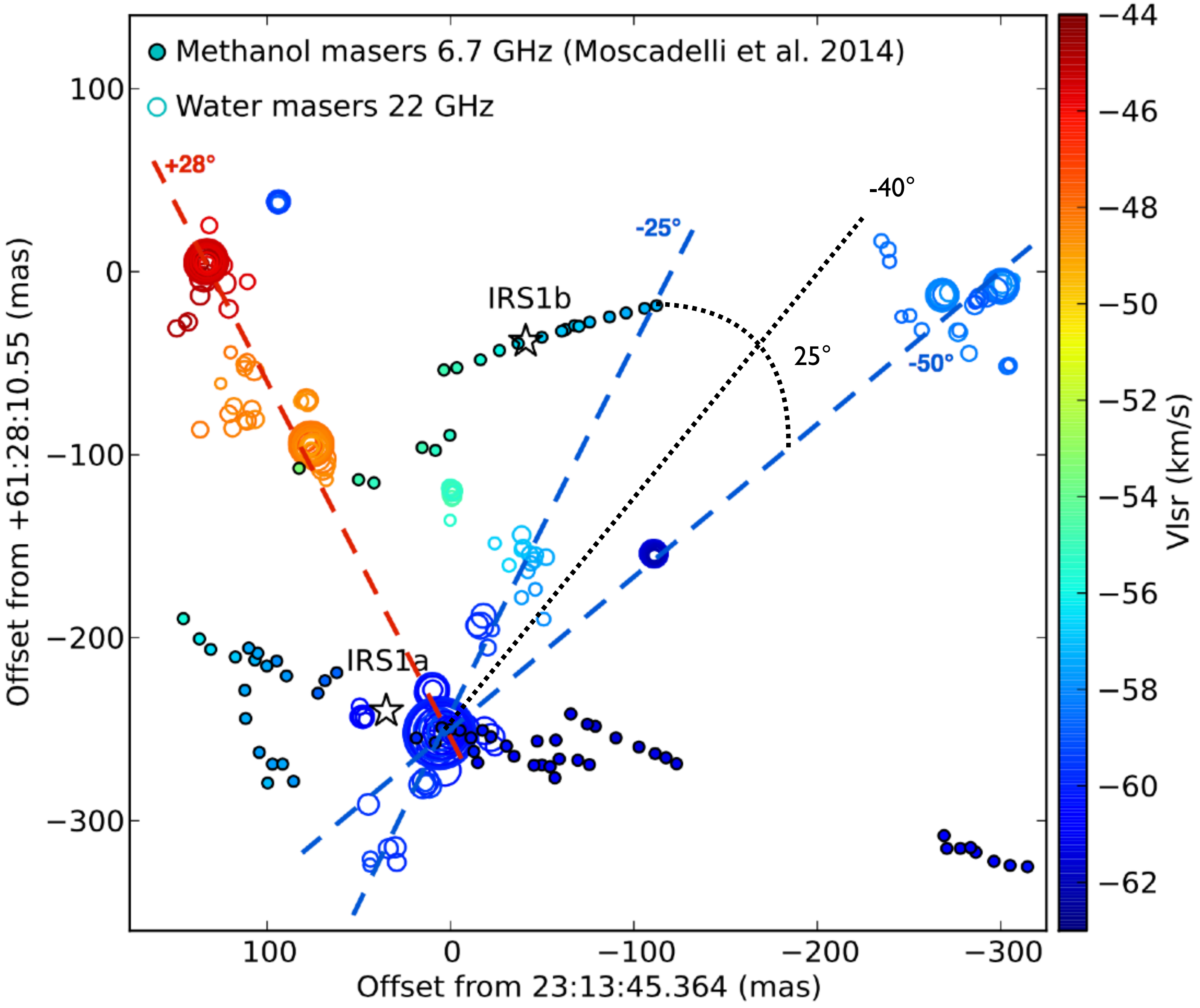


E-NGC7538-IRS1 geometry

“blue” H_2O maser spots

- strongest "blue" (i.e., $v \le -56$ km s^{-1}) maser spots are associated with IRS1a,
- others are distributed roughly along a line with *PA* = −25° and another with *PA* = −50°.

Some similar linear distribution with *PA* = −52° was seen by *Surcis et al. (2011)*, almost aligned with the CO NW-SE outflow from IRS1a with *PA* = −40° (e.g. *Kameya et al. 1990*). Proposed that the water masers are pumped by a shock caused by the interaction of the outflow with the infalling gas.



⟹ H_2O maser spots might either trace the cavity of the outflow, i.e., a cone with an opening angle of ~ 25° and *PA* ≃ −40°, or trace two different outflows originating from IRS1a, the outflow at *PA* = −25° being almost perpendicular to the disk.

E-NGC7538-IRS1 geometry

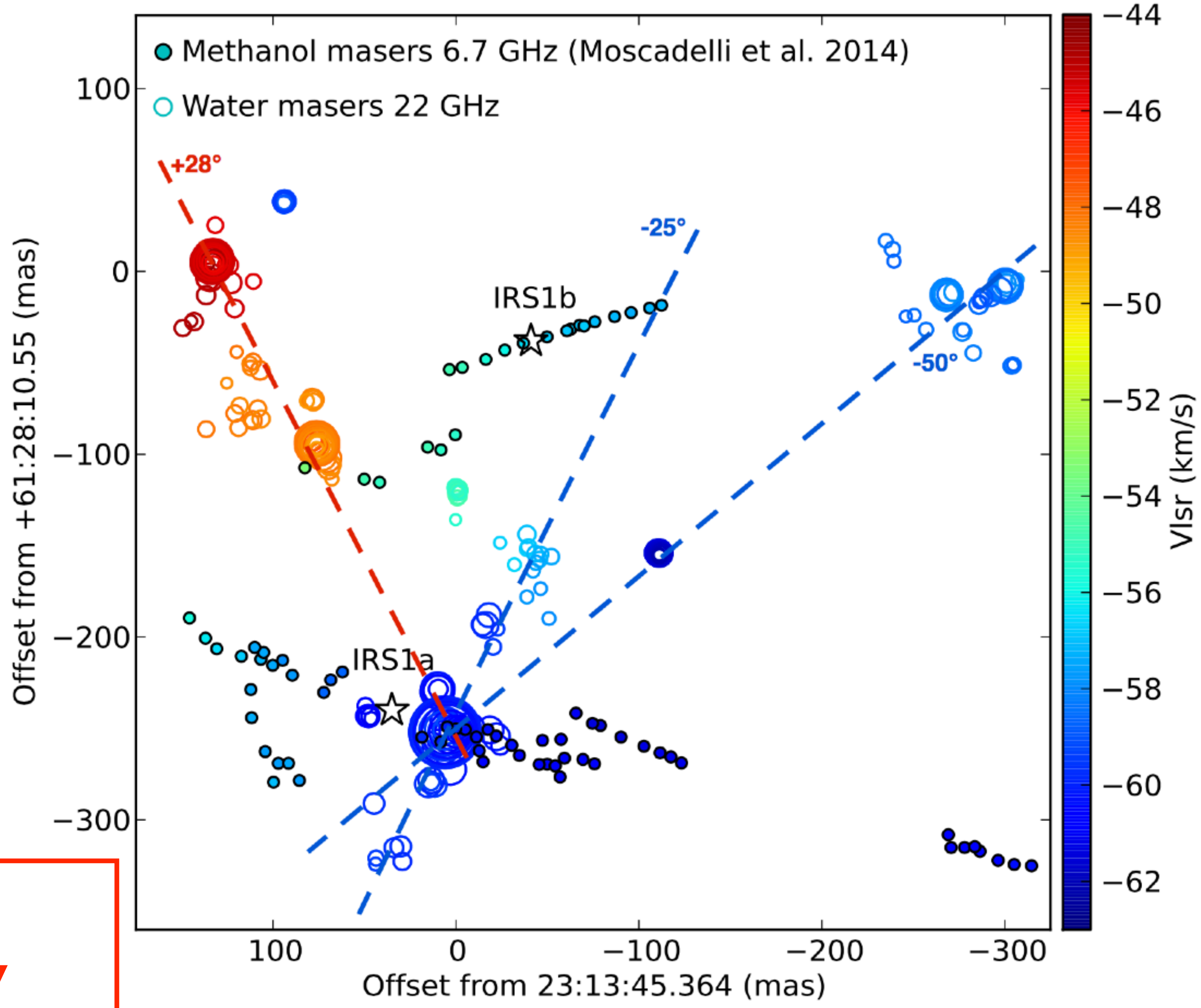
“red” H_2O maser spots

located NW from IRS1a and W from IRS1b + distributed **along a line with *PA* ≃ +28°**, i.e., NE-SW, which can be associated with the outflow observed by *Beuther et al. (2013)* with *PA* ≃ 40°.

Moscadelli & Goddi (2014), and *Zhu et al. (2013)*: velocity gradient in the same direction with line emission at velocities similar to our feature (2) emission.

= outflow driven by IRS1b that is collimated by its rotating disk.

⟹ THz feature (2) is a maser, not associated with IRS1a, and is pumped by shocks that are driven by the IRS1b outflow



Thanks for your attention