Hot and cold running water: understanding evolved star winds

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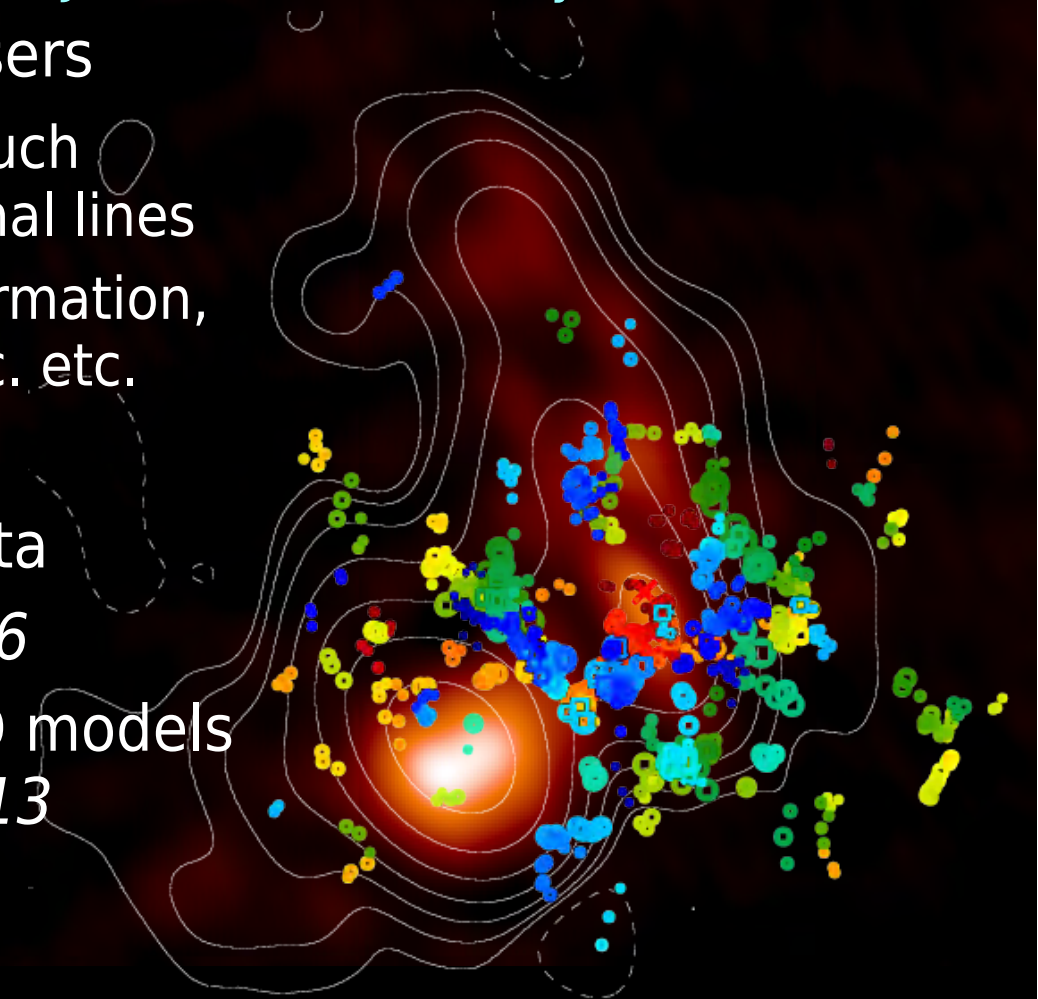
A. Baudry, L. Decin, M.D. Gray, E.M.L. Humphreys, I. Marti-Vidal, A. Sobolev, W. Vlemmings, J.A. Yates and many more

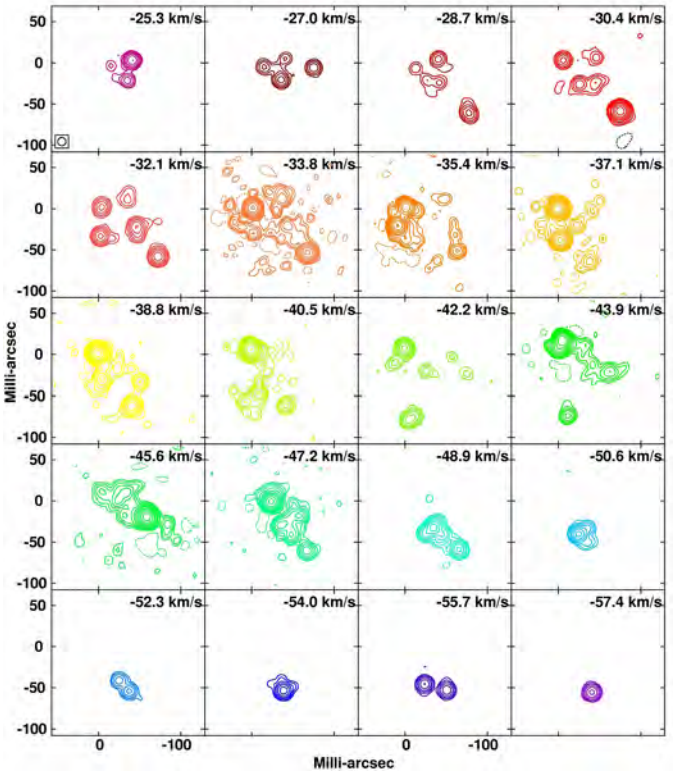
- Modelling multiple masers
- Physical conditions on much smaller scales than thermal lines
- Changes due to dust formation, clumping (shielding) etc. etc.
- VY CMa ALMA SV data
- (e-) MERLIN 22 GHz data
- Maser models *Gray+'16*
- *Herschel* etc.-based 1D models *Decin+07, Matsuura+13*

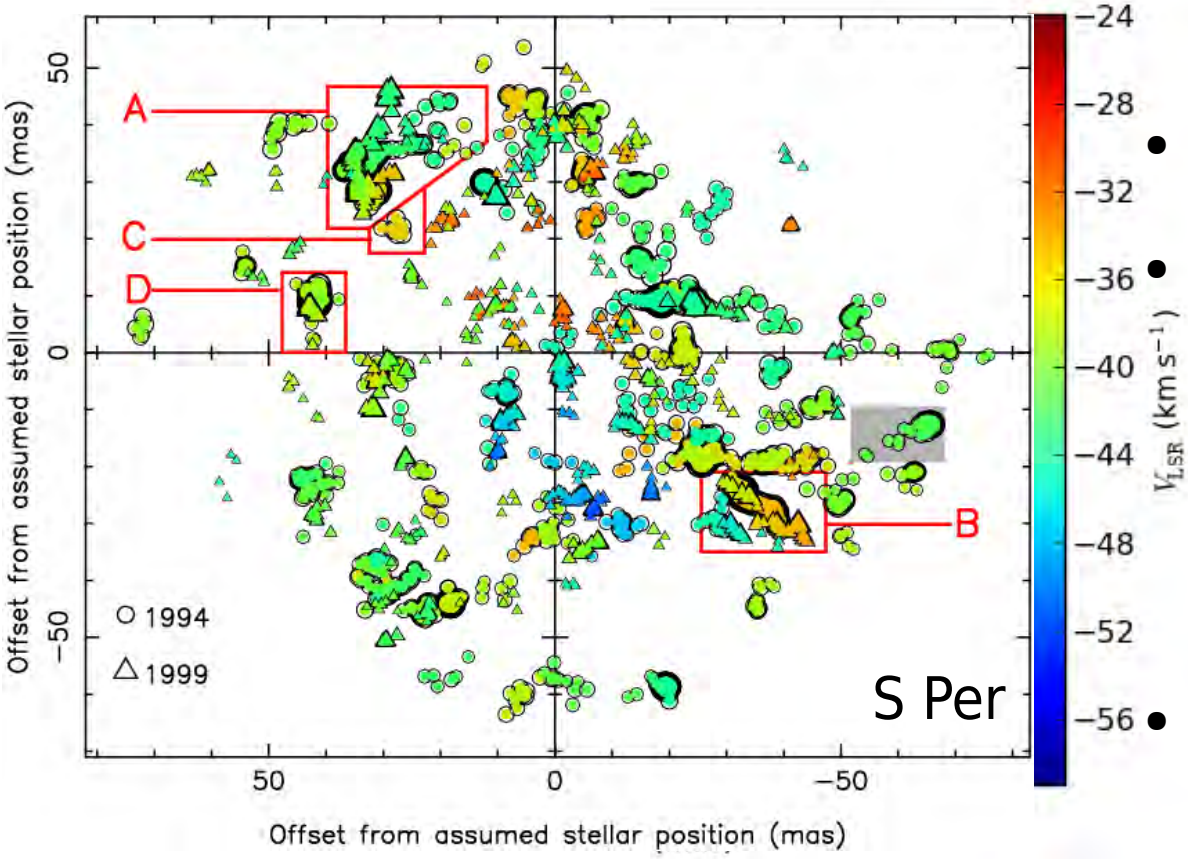


EUROPEAN ARC
ALMA Regional Centre || UK

Terminology/observations

- Individual channel **components:**
- Fit 2-D Gaussians, FWHM = *s*
  - Uncertainty $\sigma_{pos} \propto$ (beamsize)/(S.N.R.)
- Series make **features** (e.g. **A - D**:
  - Provides 'true' **cloud** size *L*





- θ_B<(few)100 mas resolve *L*
- $\theta_B \lesssim$ 25 mas also resolve *s*
  - Beaming angle $\Omega = s^2/L^2$
    - Shocked slab v. quiescent clouds (*Richards+10*)
    - Accurate T_b
- $\theta_B \lesssim$ 5-10 mas resolve out
  - (limits depend on line *E*)

Terminology/observations

- Individual channel **components:**
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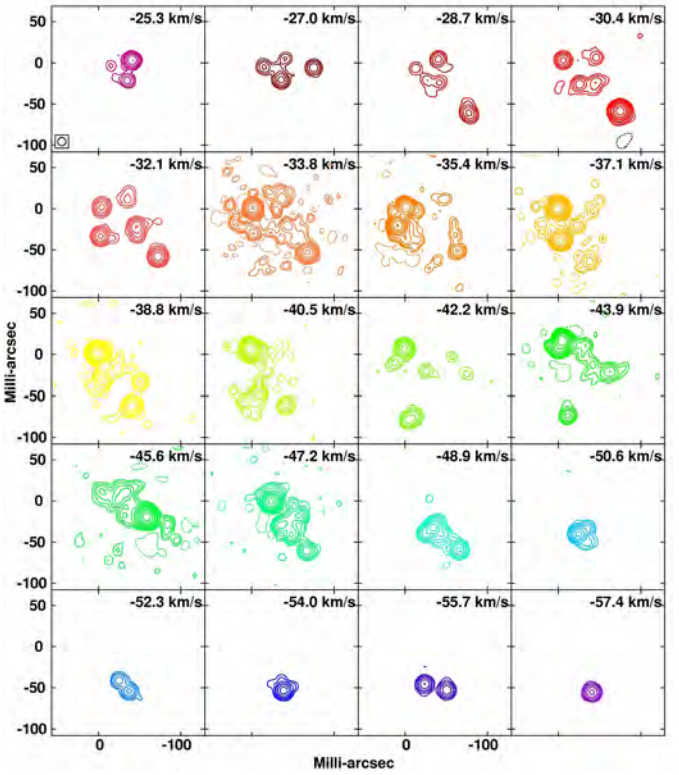
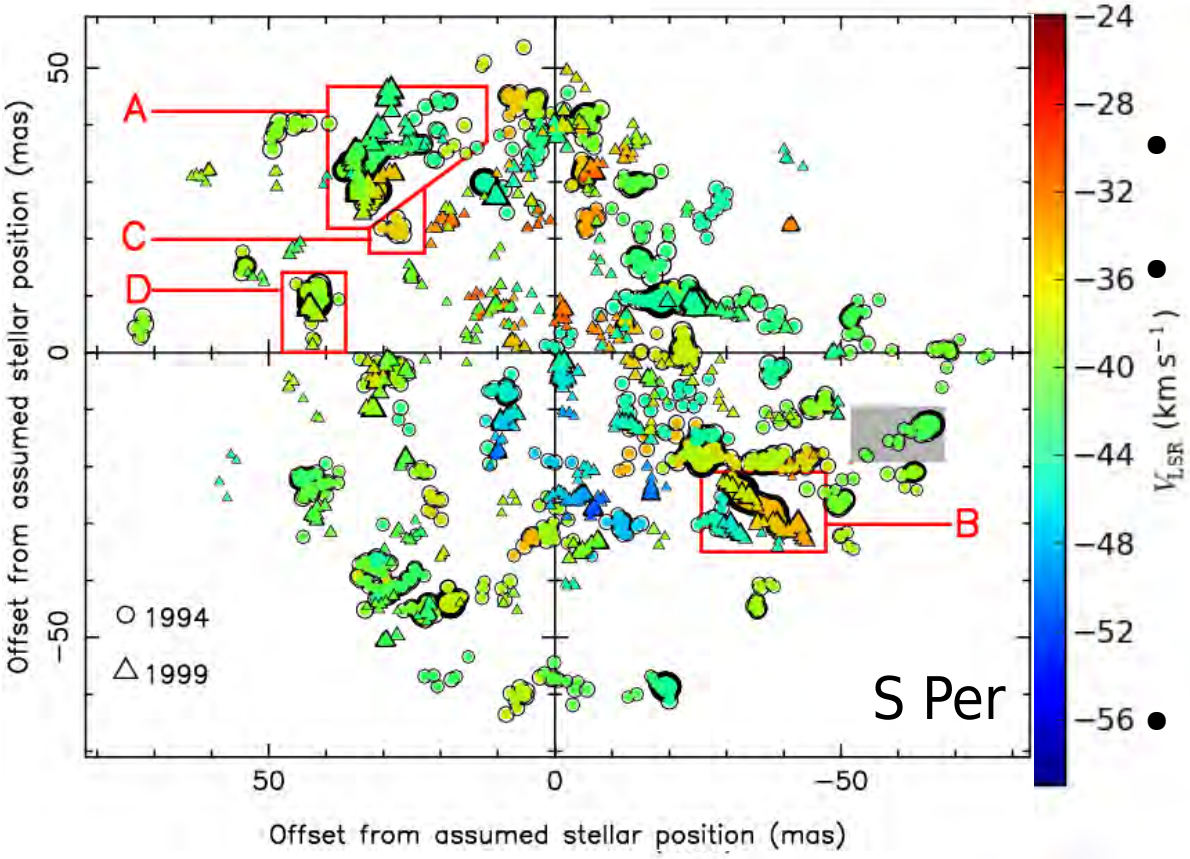
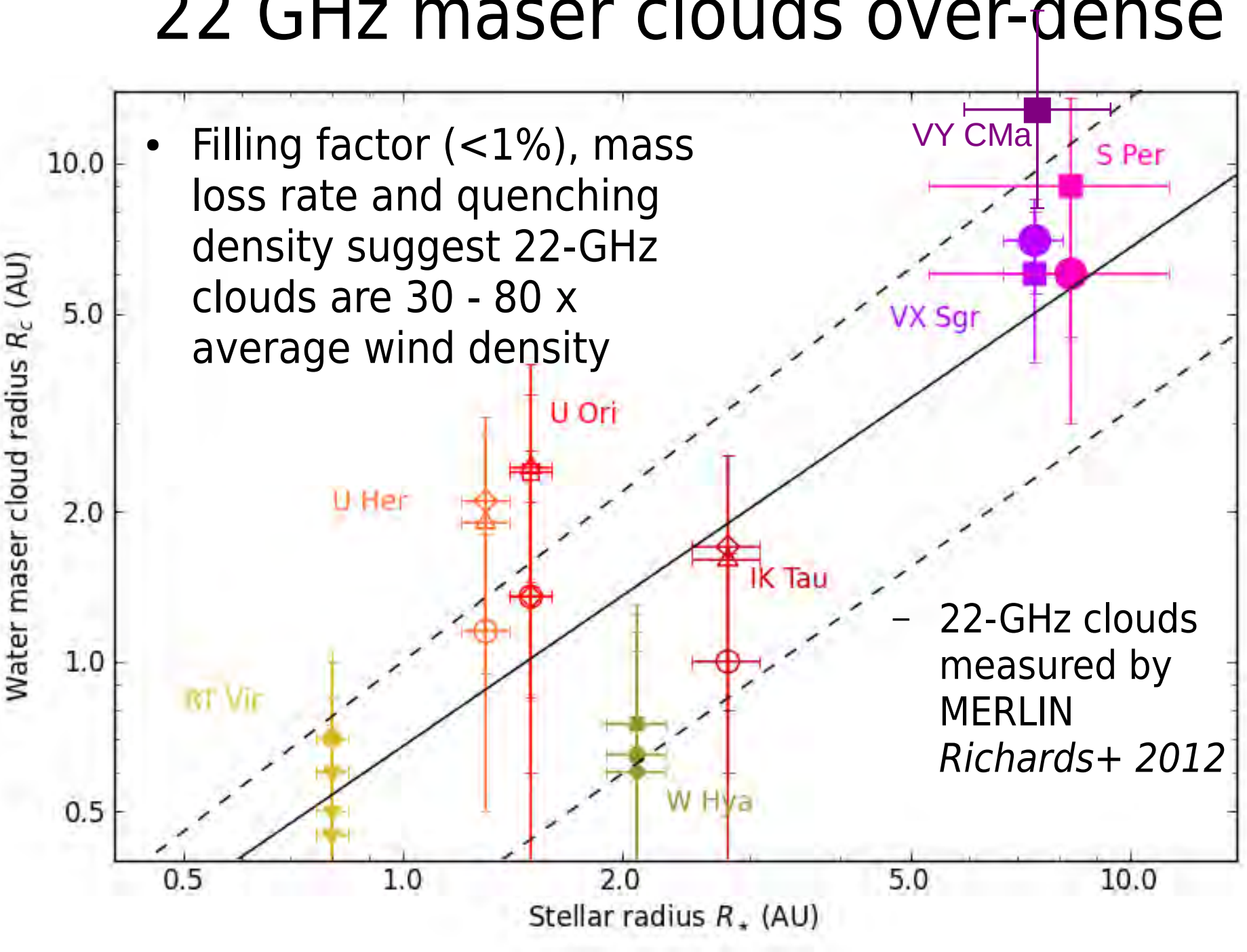


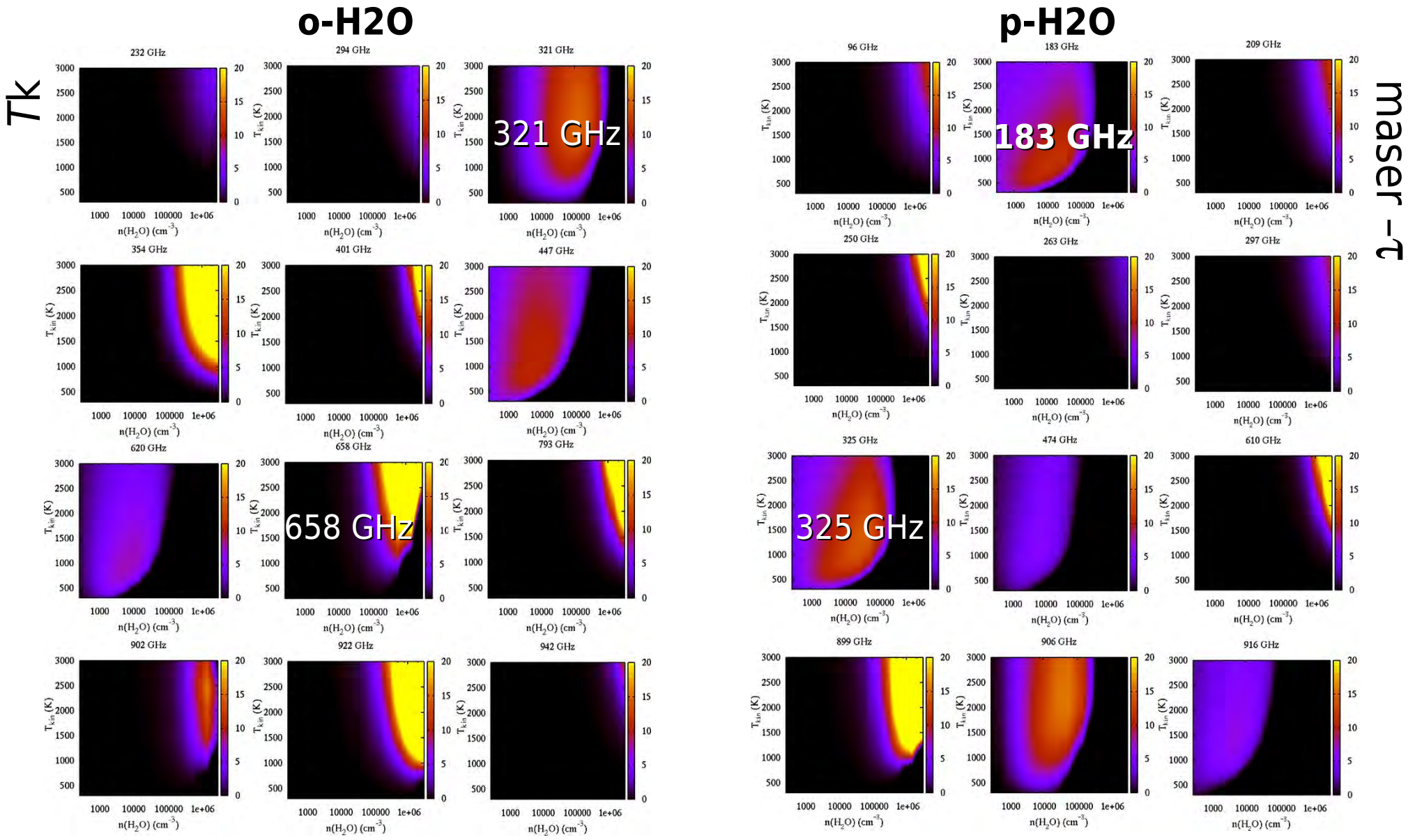


- θ_B<(few)100 mas **ALMA SV VLA**
- $\theta_B \lesssim$ 25 mas **ALMA LB, (e-)MERLIN** (high Dec)
  - Beaming a
    - Shocked slab v. quiescent clouds (*Richards+10*)
    - Accurate T_b
- $\theta_B \lesssim$ 5-10 mas **VLBI**
  - (limits depend on line *E*)

22 GHz maser clouds over-dense



Maser (negative) optical depths for lines of H_2O visible to ALMA in bands 3–10 as functions of kinetic temperature & o-H_2O number density

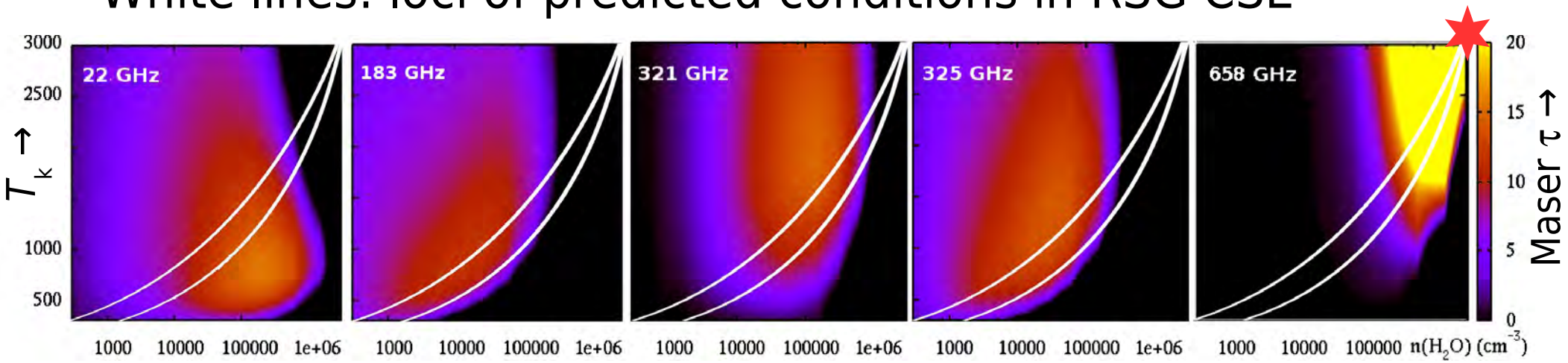


M. D. Gray et al. MNRAS 2016

Sub-millimetre masers

Line GHz	22	183	321	325	658
Eu K	521	200	1861	454	2360

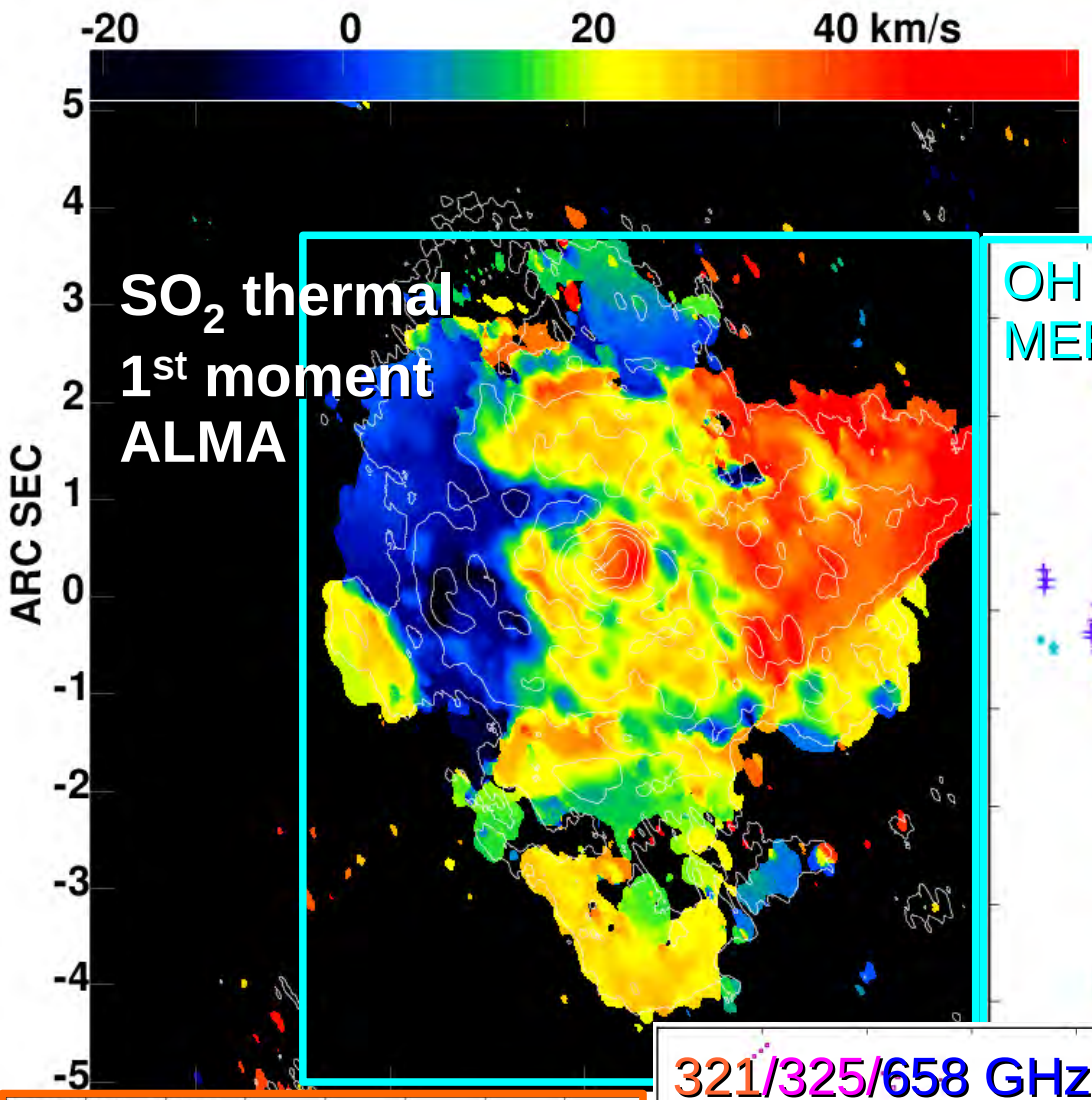
- Model predictions:
  - 183-GHz masers furthest from star
  - SiO and 658-GHz closest
  - 321 GHz crossing dust formation zone?
  - 22 and 325 GHz just outside?
    - All complicated by clumping
- White lines: loci of predicted conditions in RSG CSE



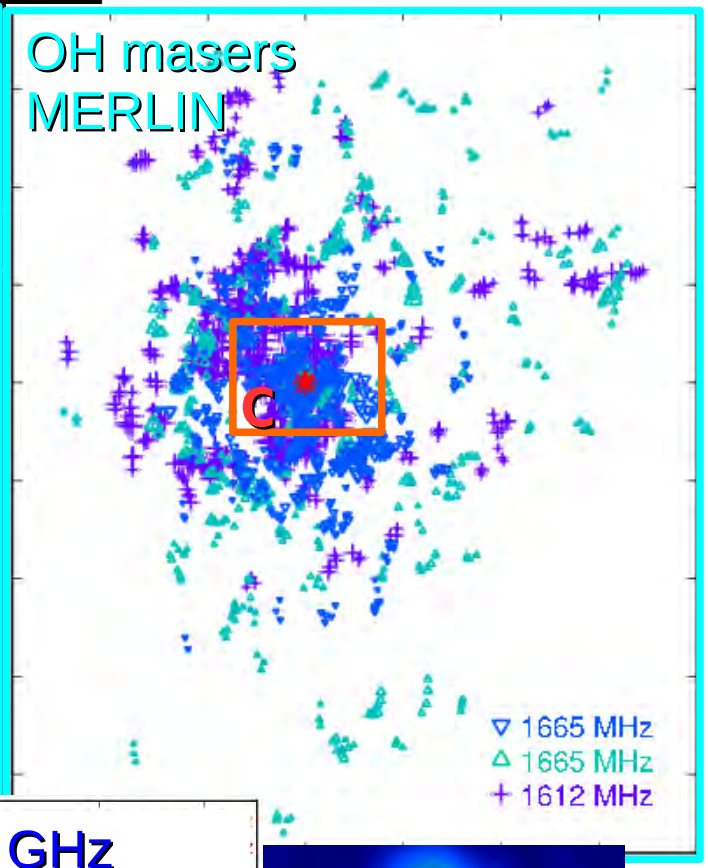
Gray et al. 2016

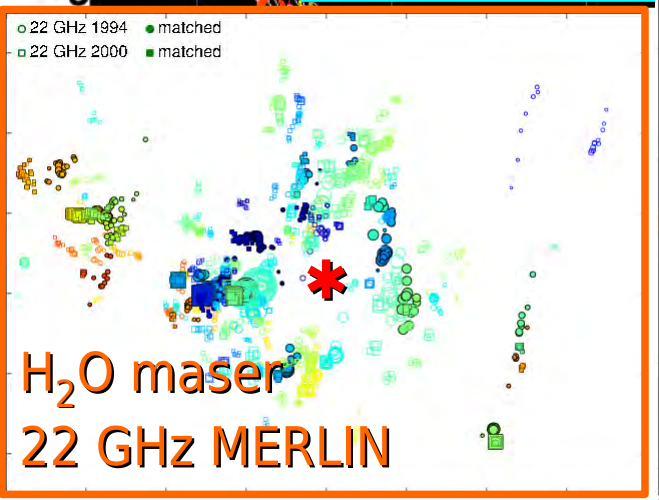
Higher number density →

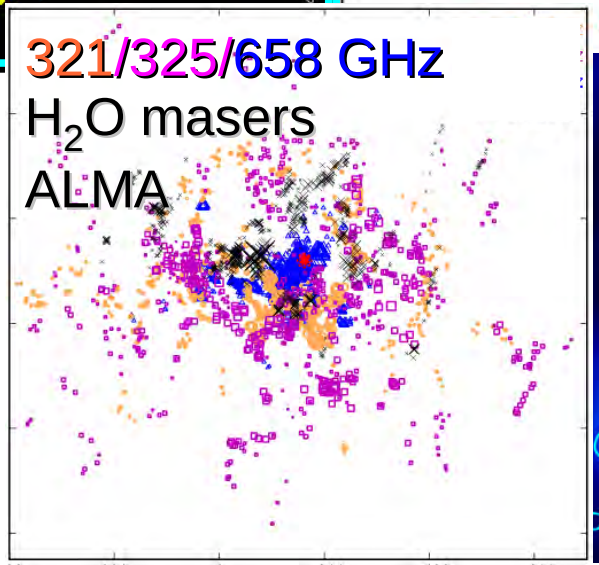
VYCMasperical

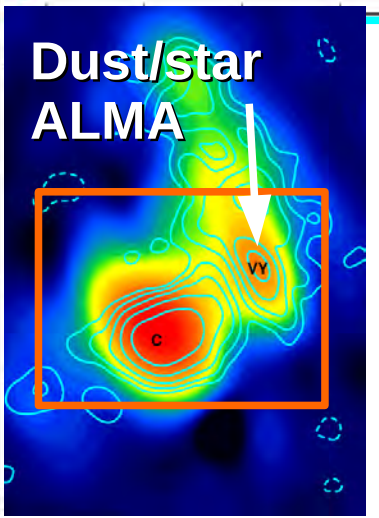


SO_2 thermal
1st moment
ALMA





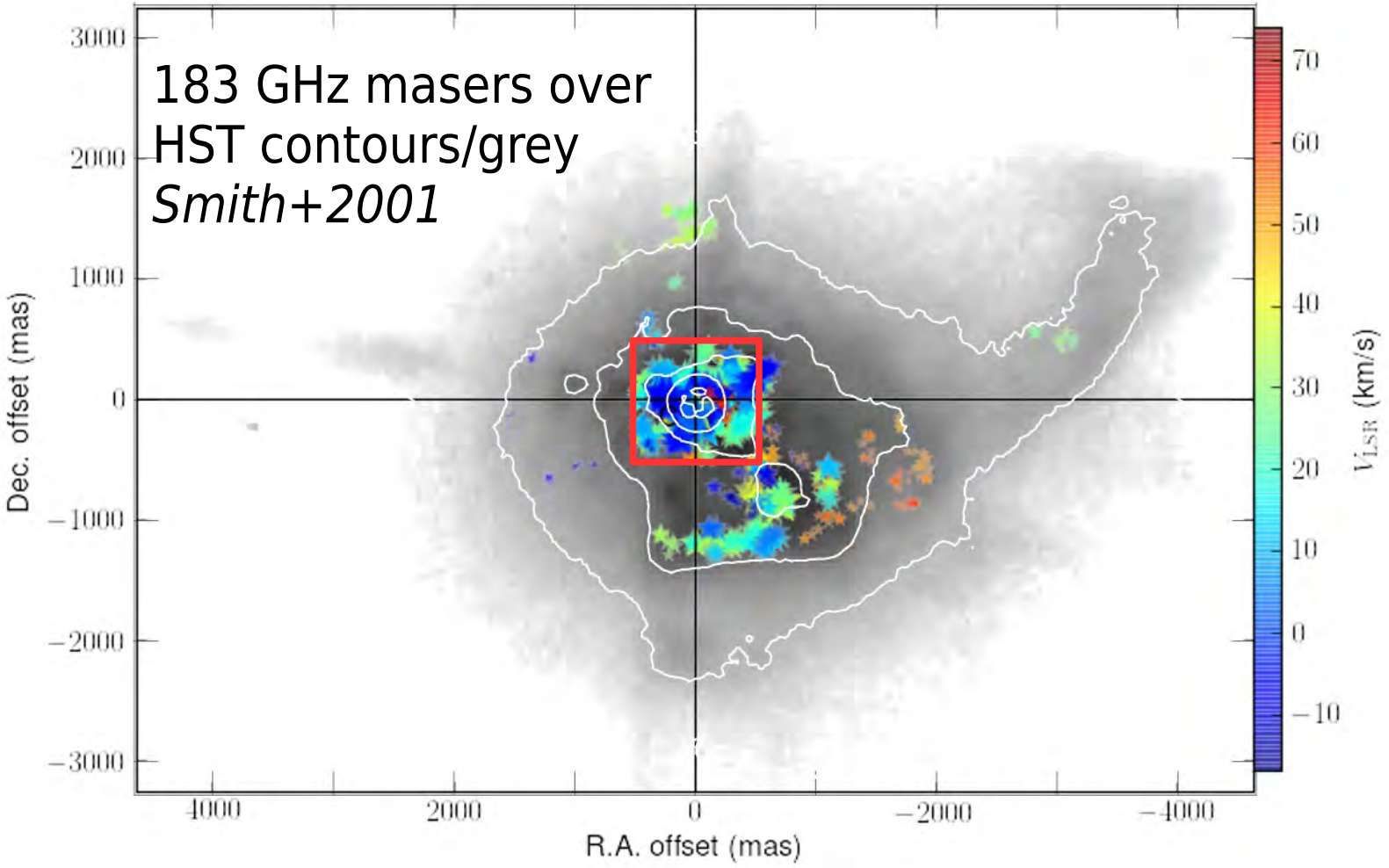




- RSG 1.2 kpc
  Choi+08; Zhang+12
- R_* 5.7 mas
  Wittkowski+12
- VY centre of outflow
  - 22-GHz 3D radial accel.
- No axis of symmetry
- Different velocity offsets on different scales

VY CMa multi-λ water masers

- 183 GHz masers very extended as predicted
  - Distribution similar to/within HST scattered light (as are OH)
    - Follows small, cool dust grains/extends to low densities

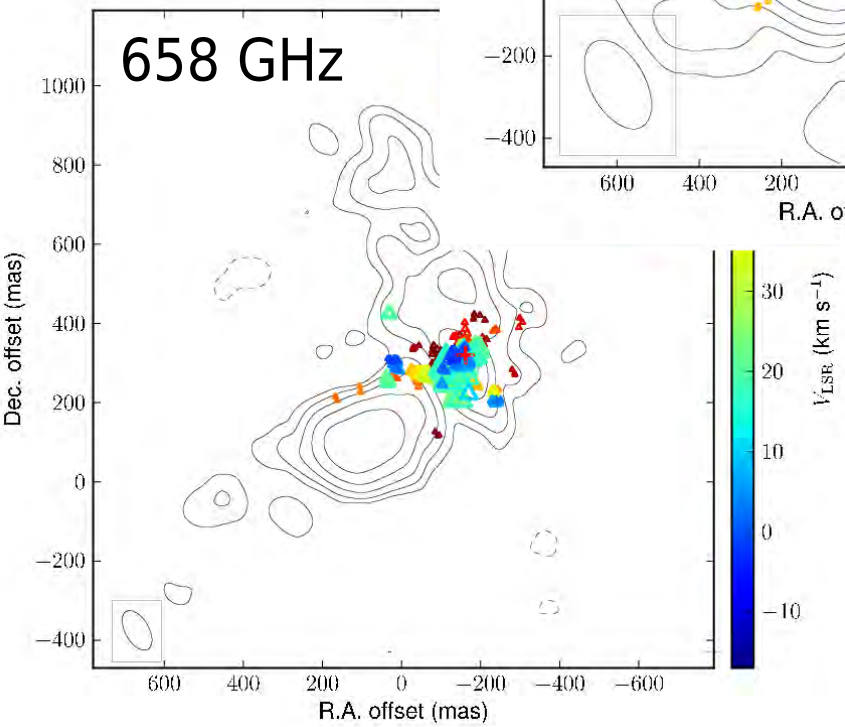


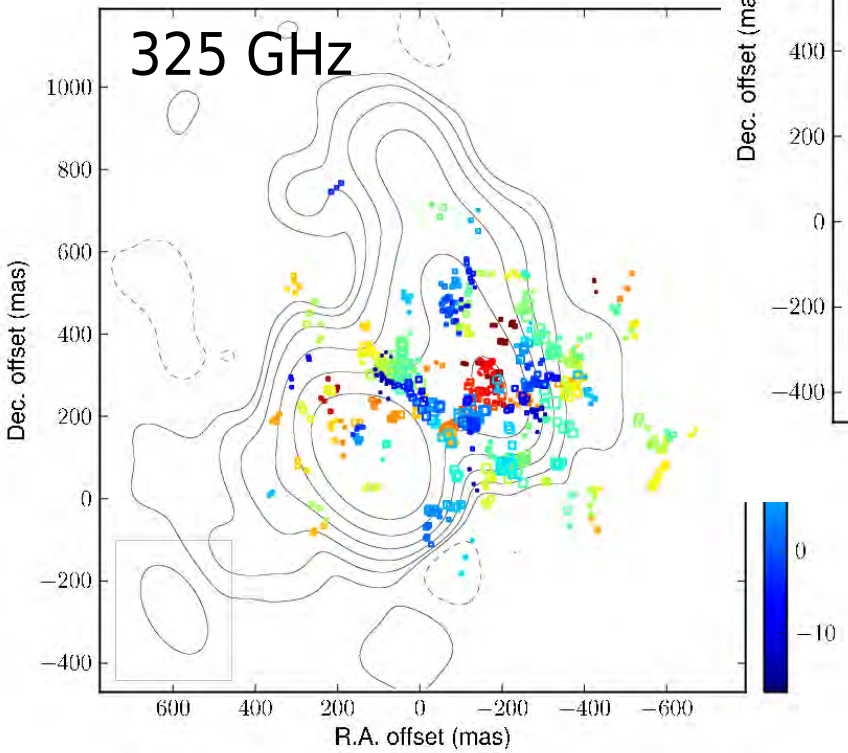
(an aside)

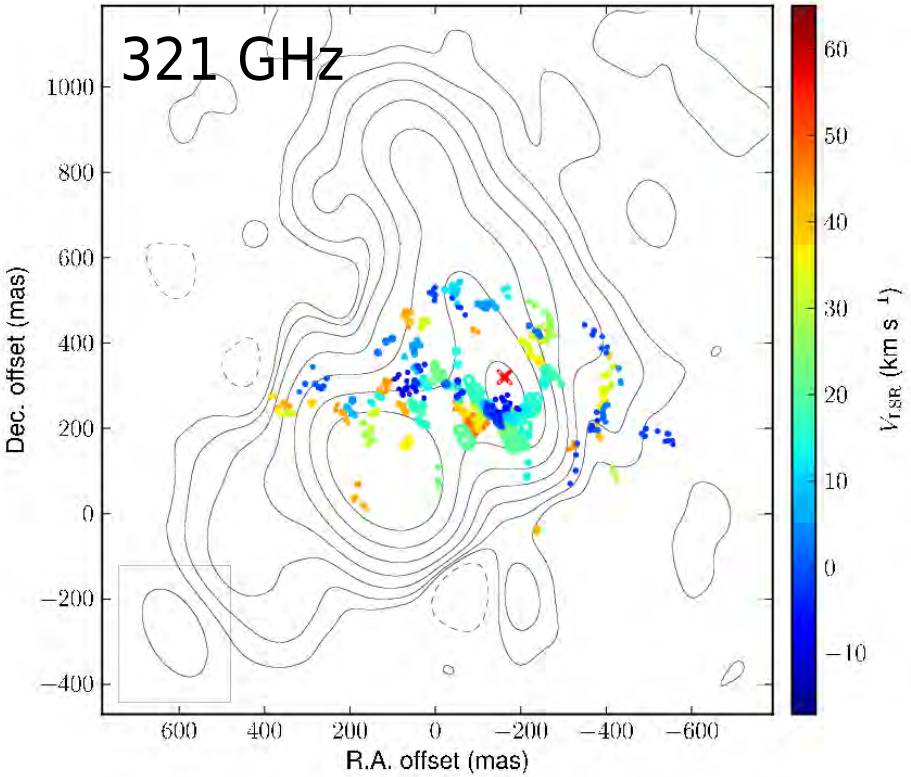
- Does VY CMa fling out clumps almost ballistically?

R Humphreys et al 2007

VY CMa sub-mm masers

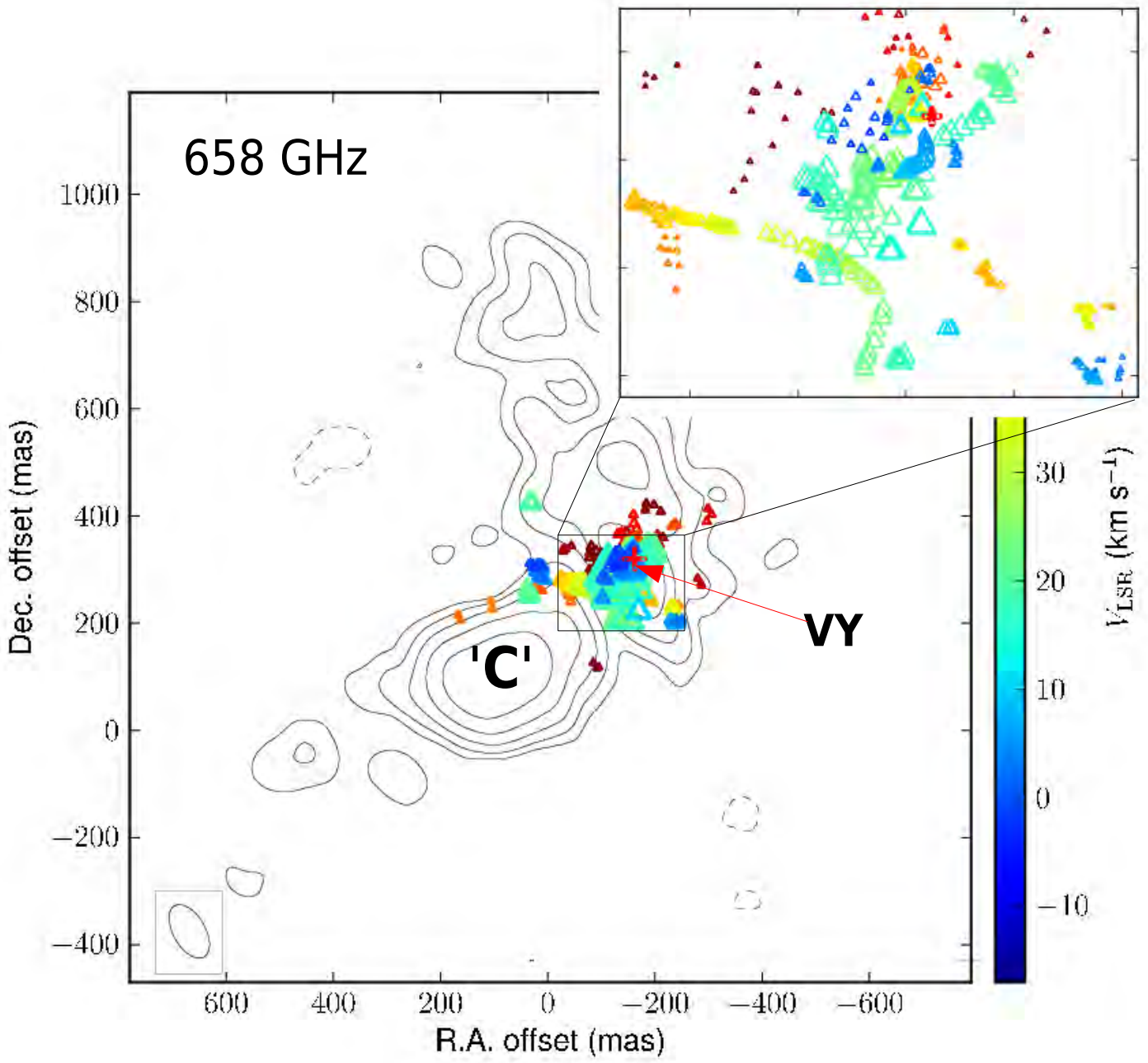






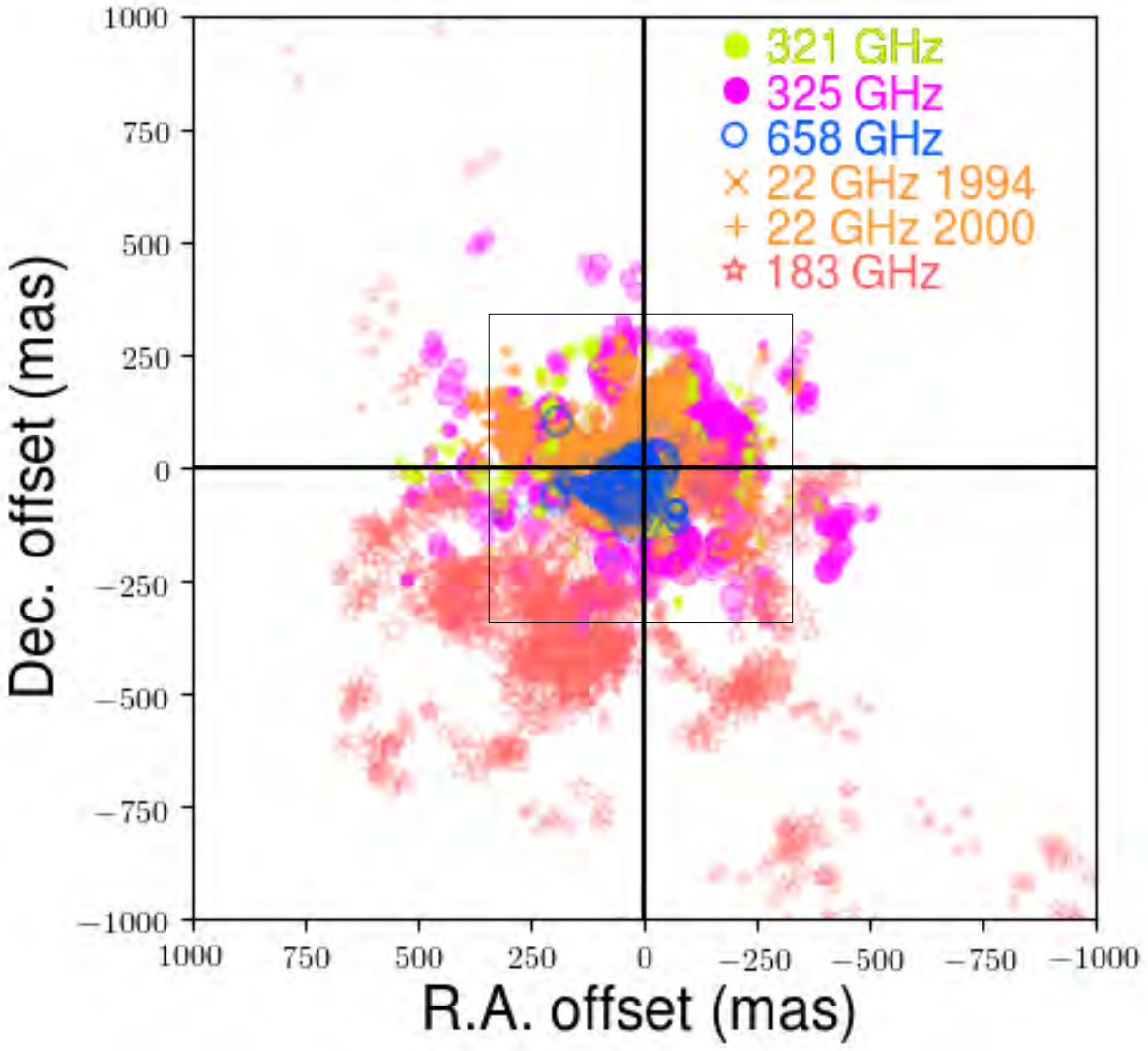
- Centre of expansion found by maximising separation from emission close to $V_\star$
- All three masers centred on 2nd peak
  - Direct detection of stellar position

Unusual environment?

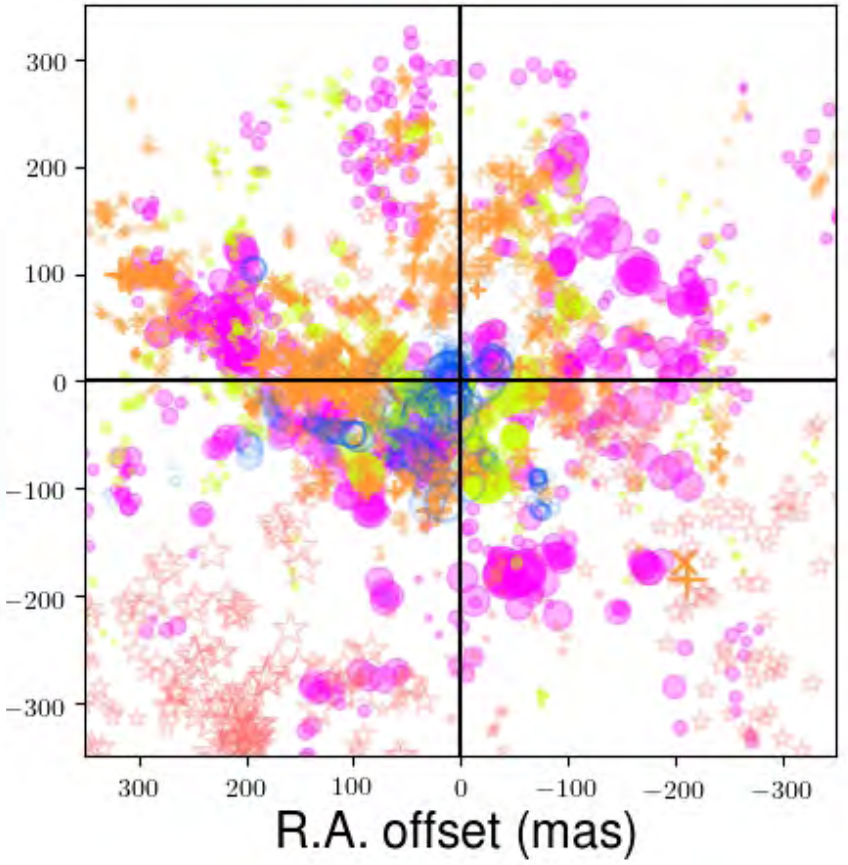


- Continuum contours
- 658-GHz masers appear to curve round '**C**'
  - Wind collides with cold, dense clump?
    - *OGorman+14*
- All masers, many lines avoid '**C**'
  - Only seen at velocities very different from V_* in that direction

Zoom in on 5 transitions

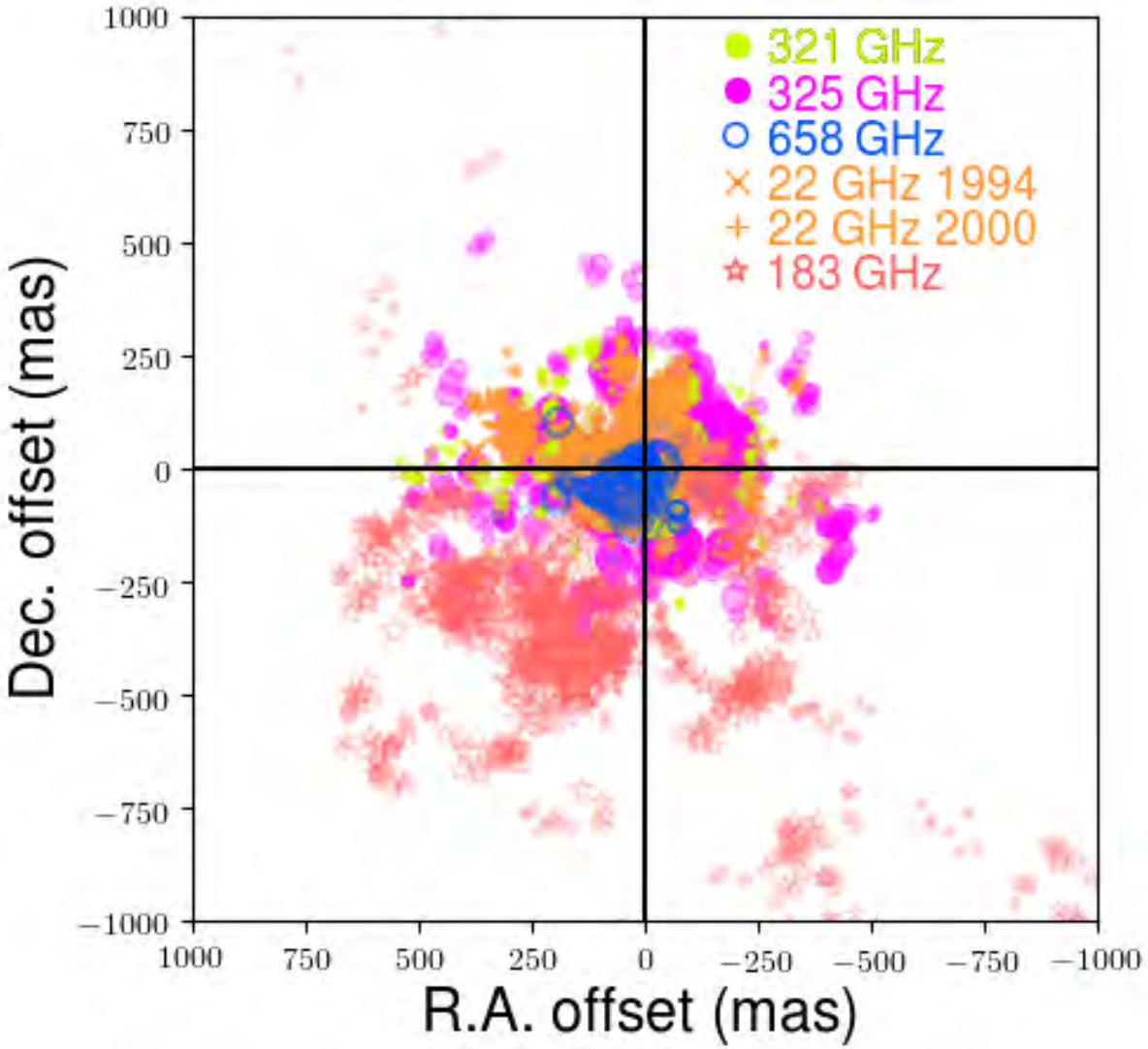


- H_2O components
- Size ∝ √flux density
- VY at (0, 0)



- 321, 325, 658 GHz obs 2013
- 183 GHz obs 2016

Zooming out...



- 321, 325, 658 GHz obs 2013
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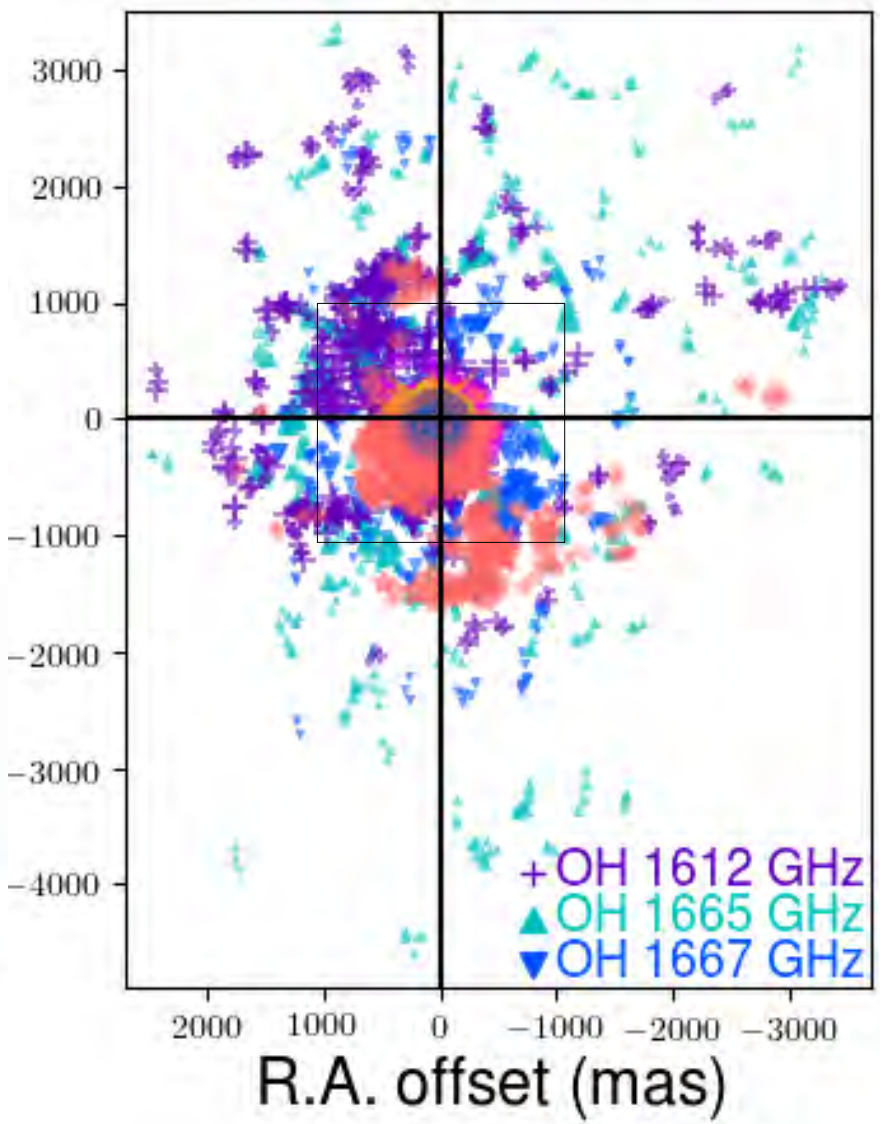
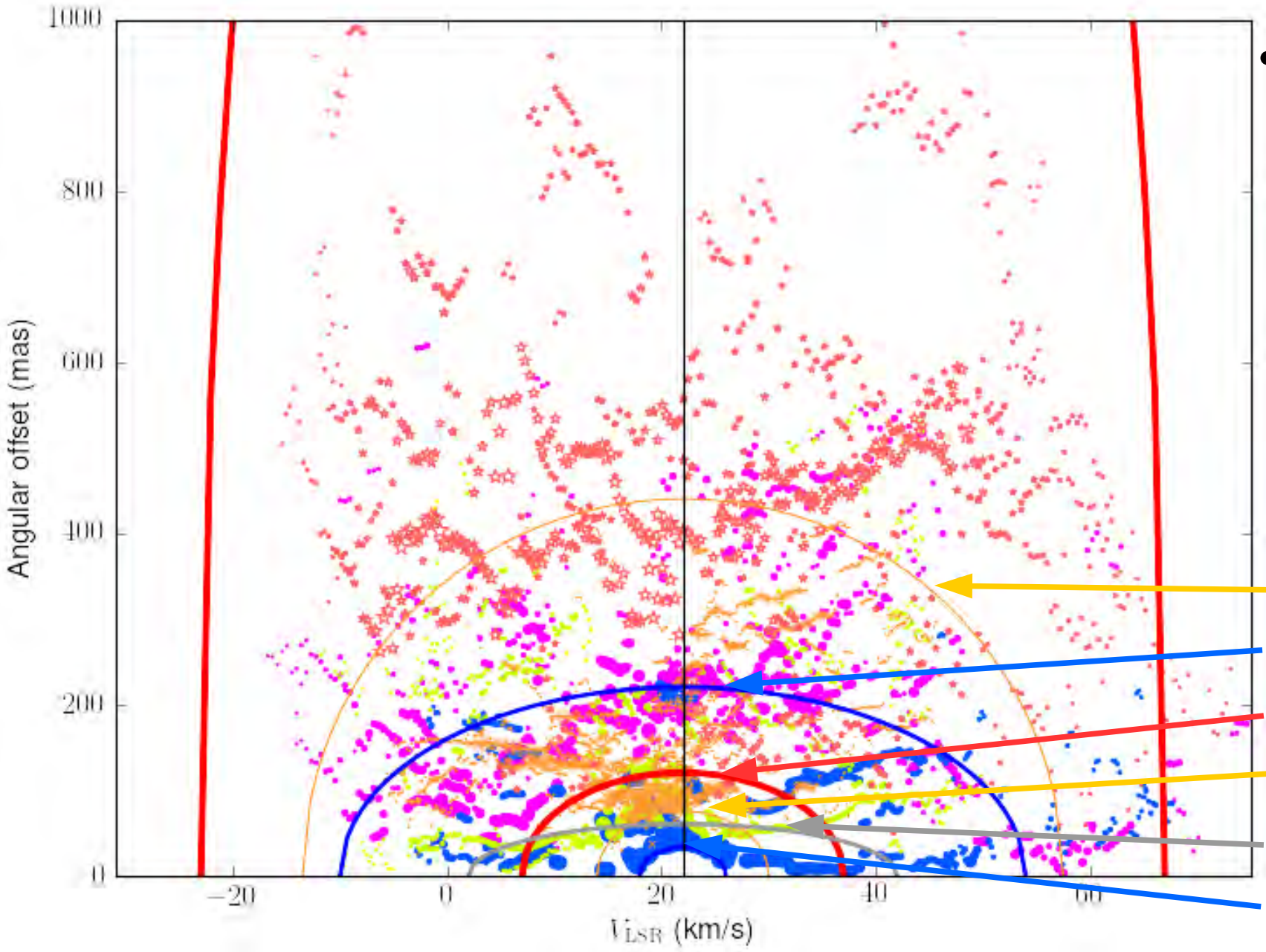


- OH obs 1993

Angular separation-velocity



- Well-defined inner shell limits

22 GHz outer

658 GHz outer

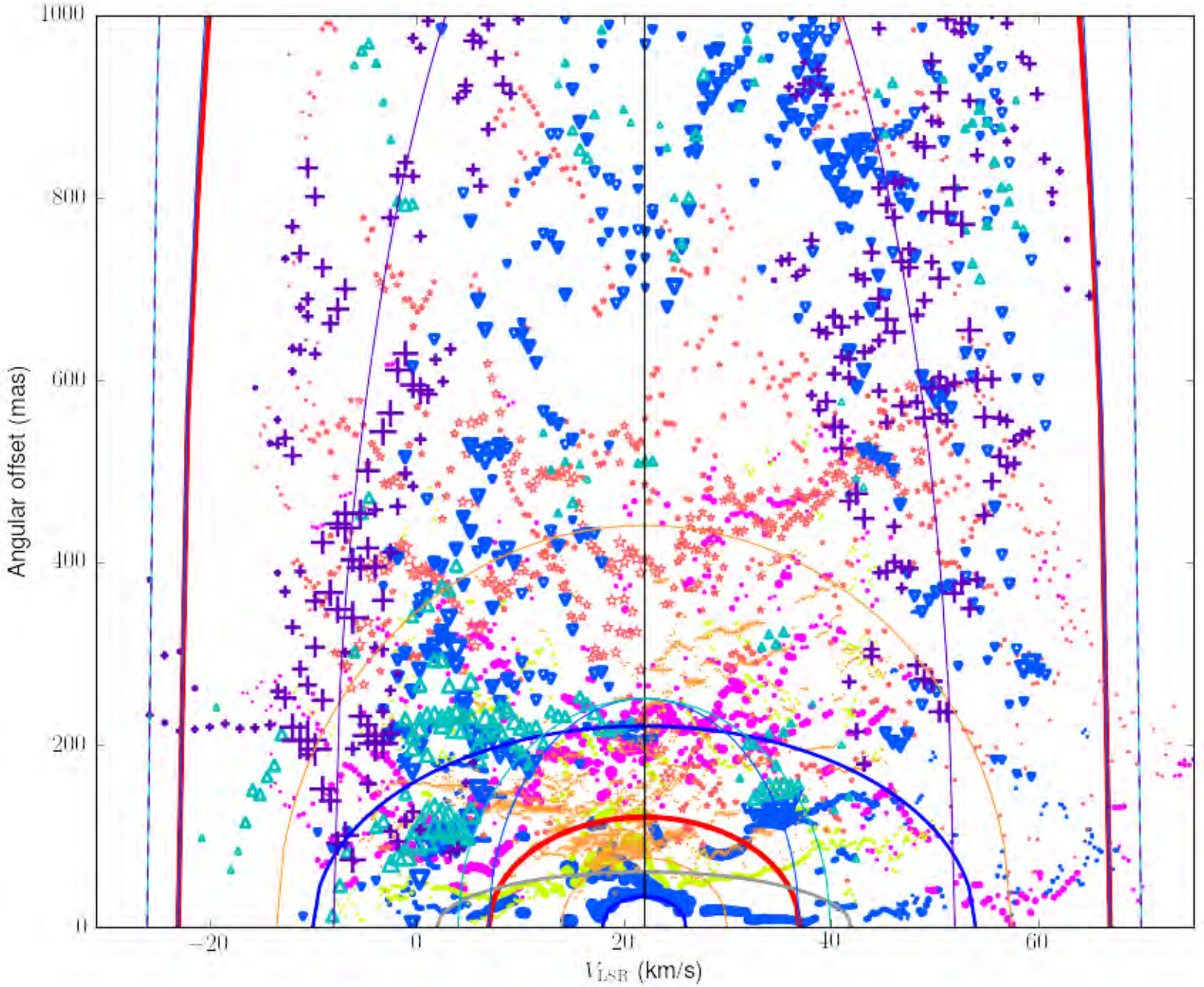
183 GHz inner

22 GHz inner

SiO outer

658 GHz inner

Mixed-up masers!

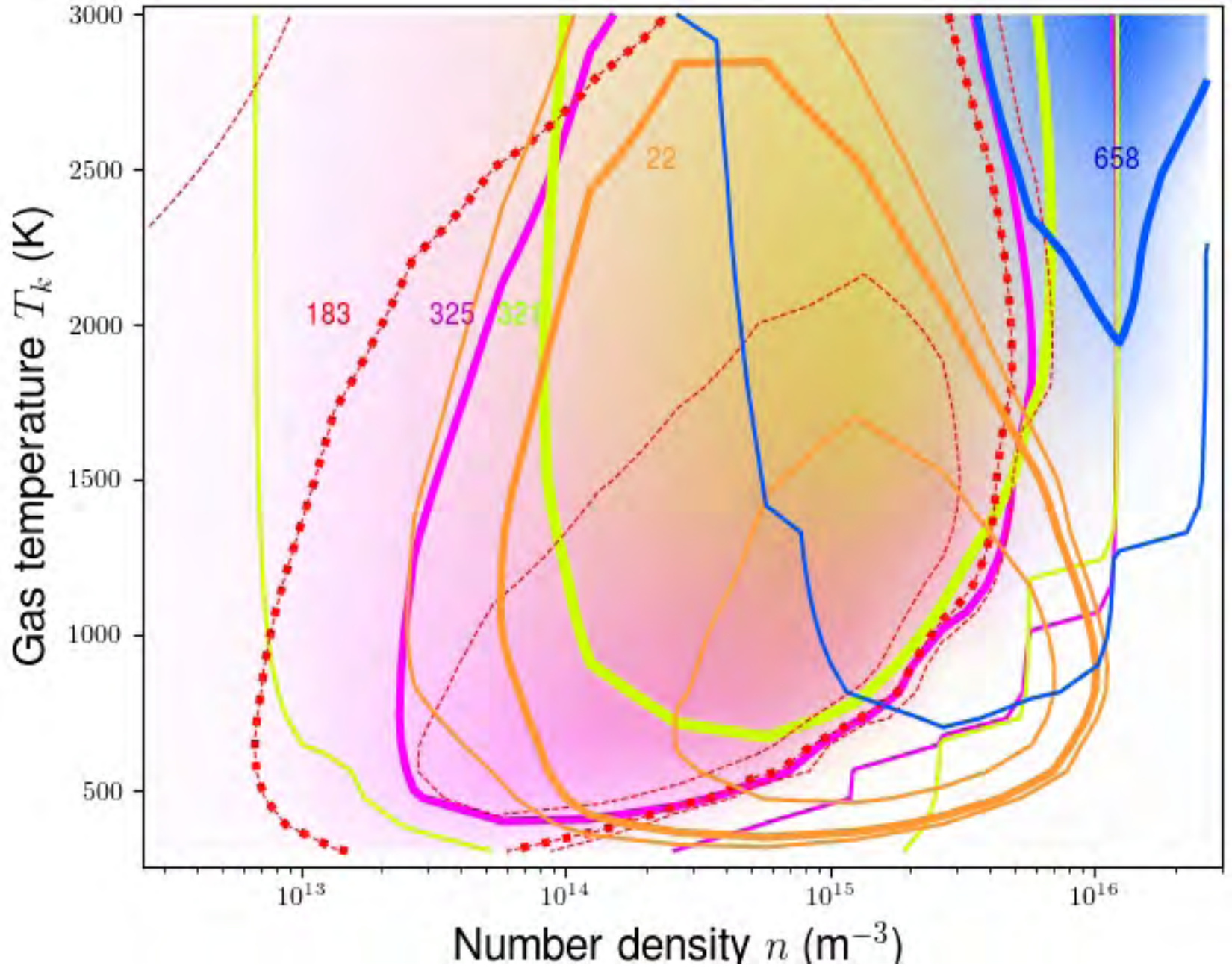


- 658 GHz extends outside SiO
- OH ▲▼ mainlines almost as far in!
- Some water clumps denser /hotter /shocks ?
- Large-scale asymmetry ?

Maser modelling of VY CMa

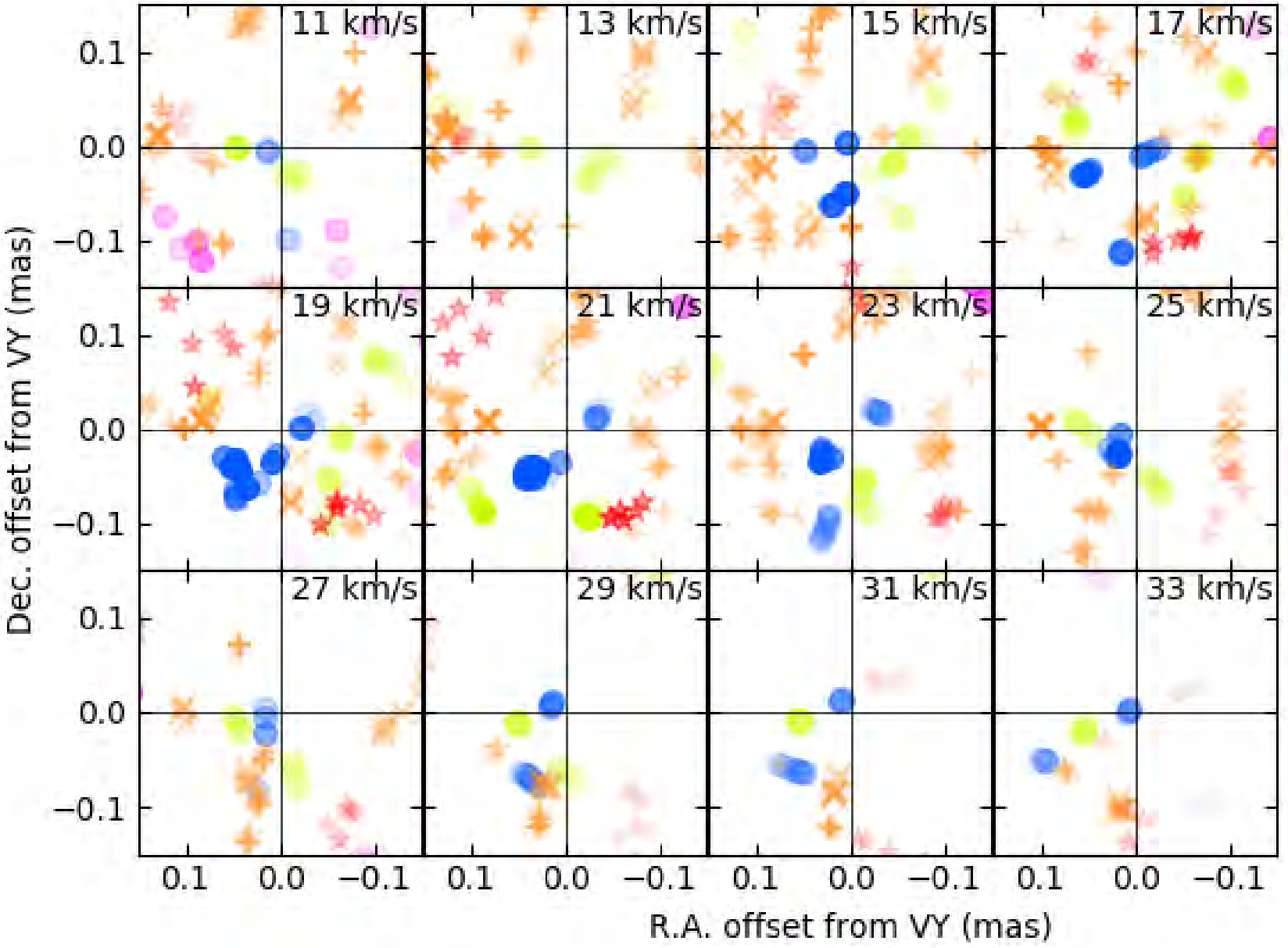
- Asymmetry - hard to use velocity as 3rd axis for VY CMa
- Hope that within inner ~1/4 ($V_\star$ ±12 km/s), emission within ~2 km/s/feature velocity span is spatially close
- Cloud sizes ~10-100 au (183 GHz biggest)
  - Proper motions few mas/yr
  - Small between ALMA 2013 and 2016 obs
    - Can only compare overall shape with 1994, 2000 22 GHz
      - 2016 GHz tests taken with 3 e-MERLIN antennas; confirm overall shape is stable but one surprise - not used here!
- Use Gray model to infer number density n, temp T_k for combinations/exclusions of different ALMA lines
- Compare Decin & Matsuura predictions for locations

VY CMa maser model (*Gray*)



- 658, 321, 325 GHz deeper shade = stronger maser τ
- Also for 22, 183 GHz **contour** at 50% max τ
- Lowest contour at crude estimate of sensitivity limit

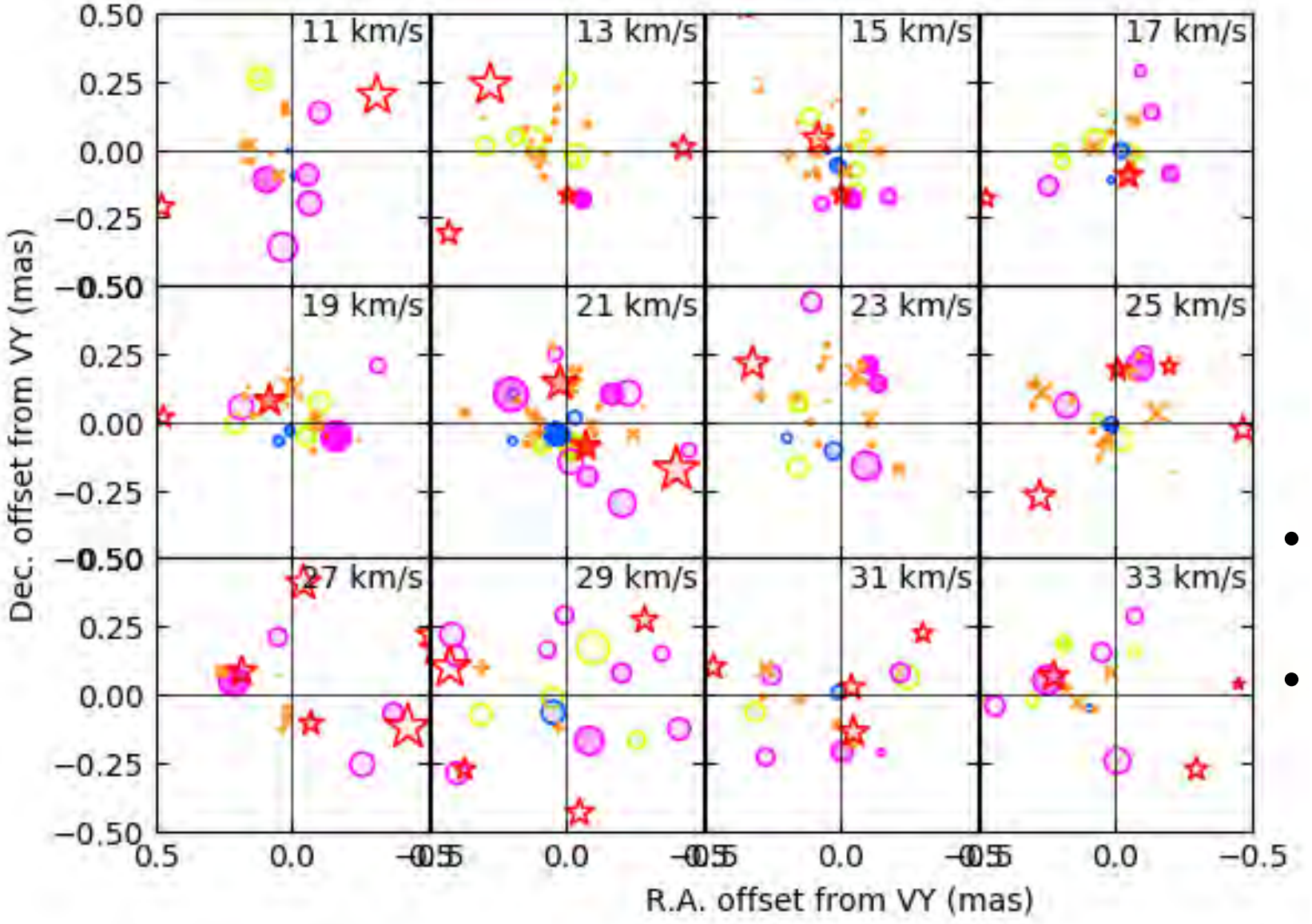
Observed maser relationships



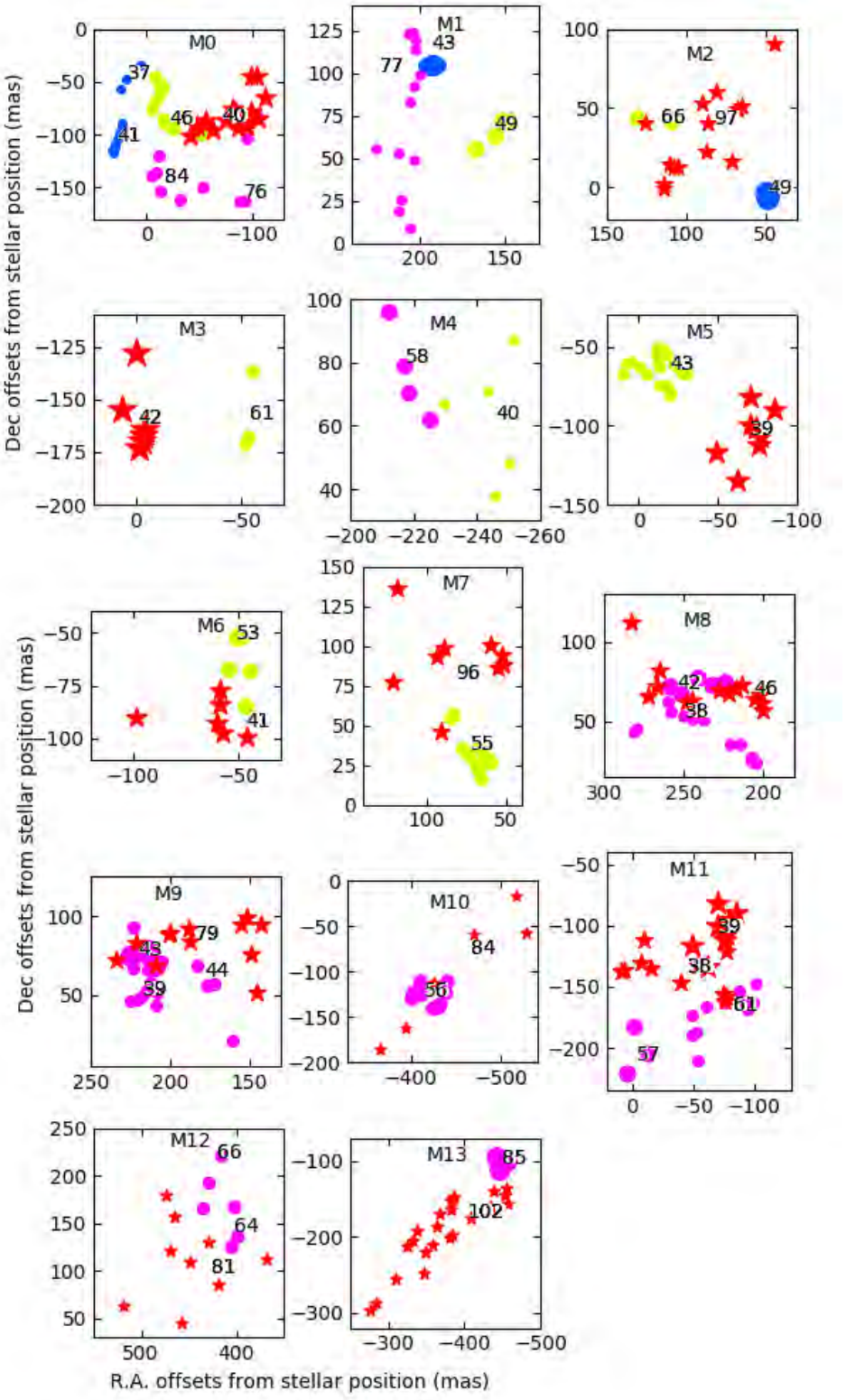
- 658, 321, 325, 22, 183 GHz components
- 2 km/s channels
- Within 150 mas of VY
- Deeper shade = higher flux density

Maser cloud overlap

- Features within 500 mas of VY CMa



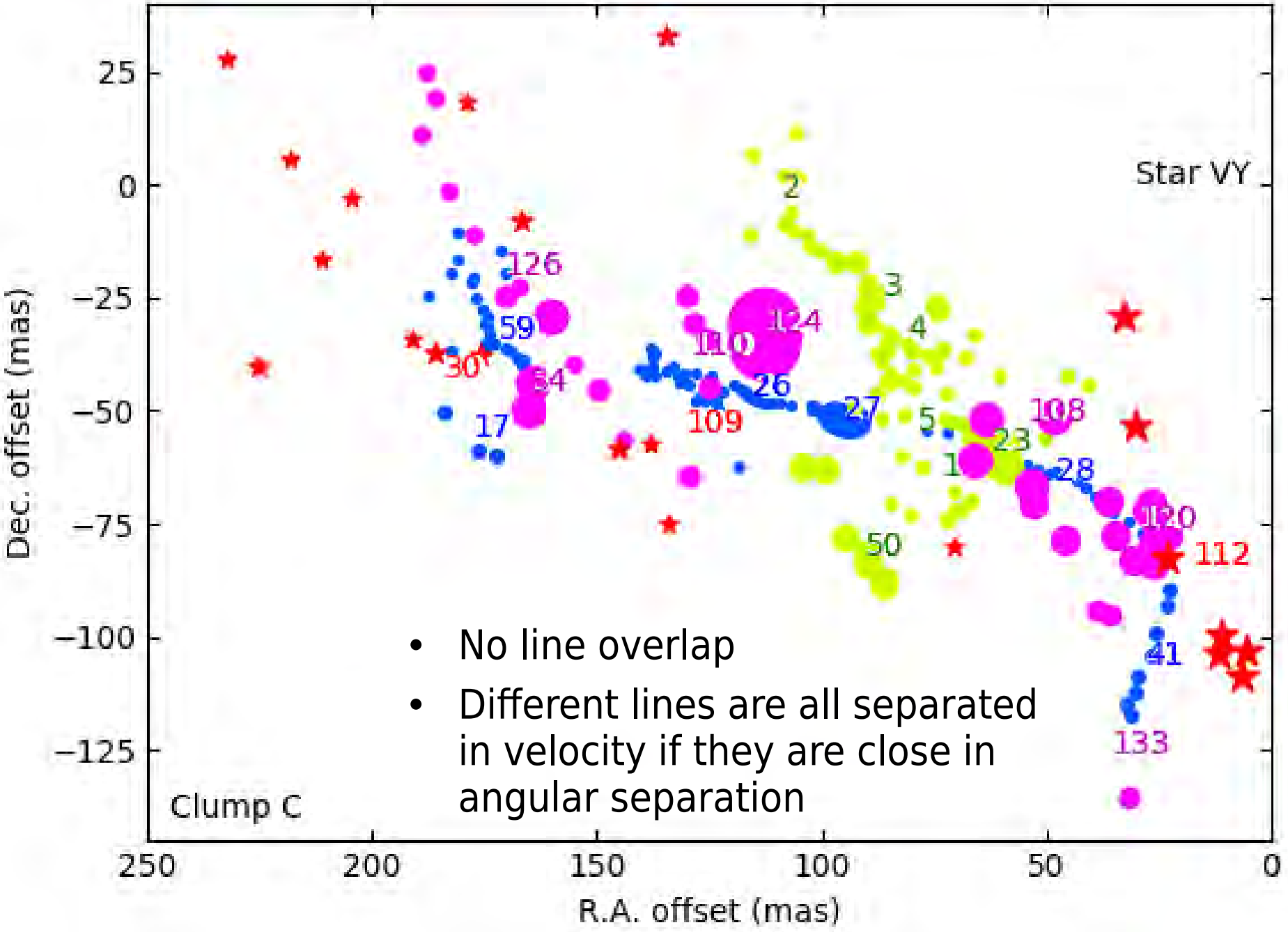
- 'Match' 2 transition features if within
  - Half max. V_{LSR} span
  - Half sum of angular size
    - i.e. touch
- Assumes spherical
- Series of matches may not all match individually



Surprisingly few line overlaps

- ~70 - 170 features per line
- 13 regions of line overlap or close association
  - Probably more if 22 GHz contemporaneous included
- Size of symbol proportional to estimated feature peak τ
  - Too crudely estimated - apparent highest τ have small ang size
    - Probably from clouds elongated along line of sight
    - Saturation, shocks ignorred

Shocks round clump C?

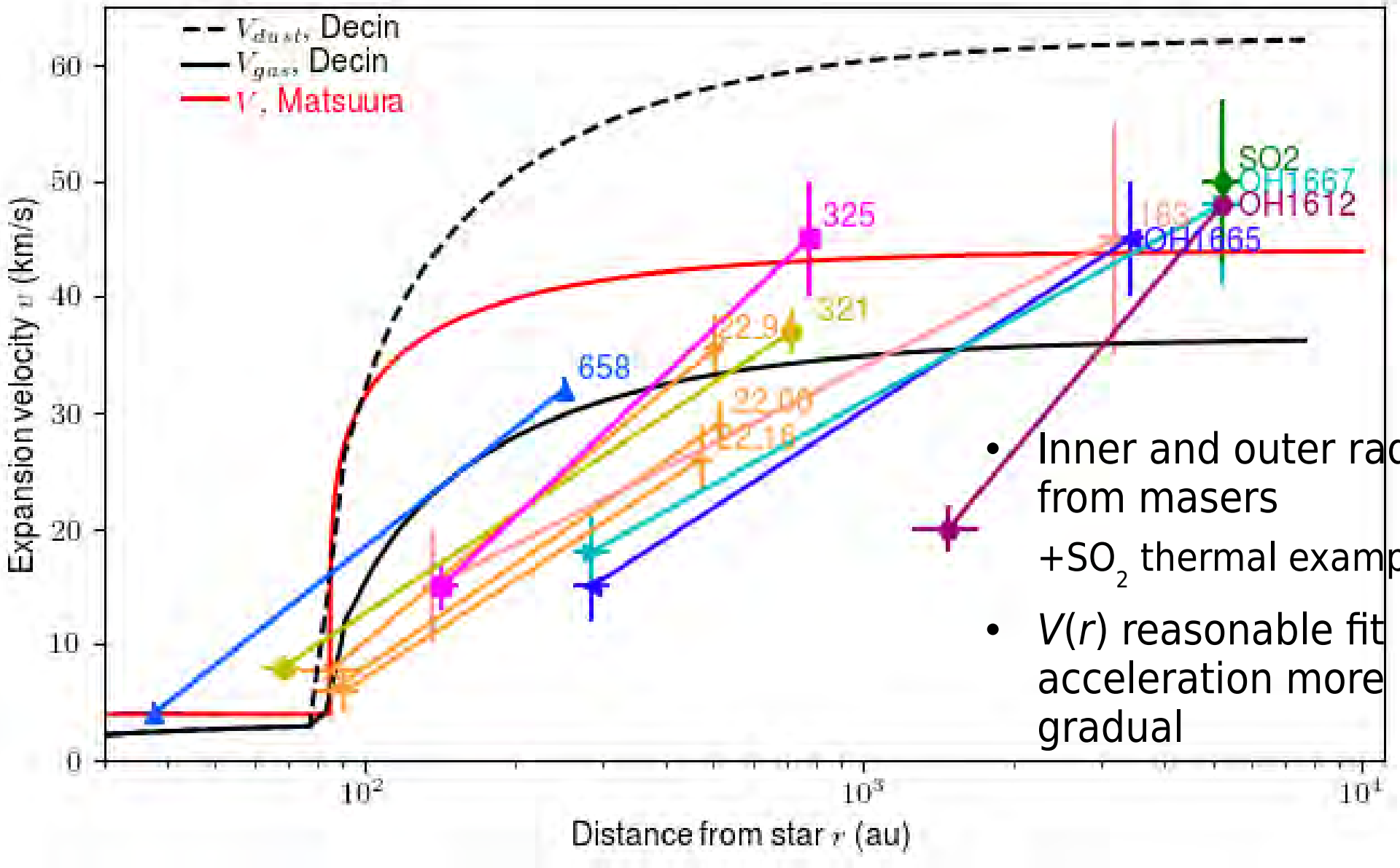


- No line overlap
- Different lines are all separated in velocity if they are close in angular separation

Analysis (rough)

- **M1** 658-325 GHz copropagate? 321 GHz near
  - T_k ~1000 K; n [6-10]x10^{15} m^{-3} (high end if no 22 GHz)
- **M0** all 4 ALMA lines may overlap
  - T_k ≳1000 K; n <5x10^{15} m^{-3}
- **M2** similar but no 325 GHz; **M3,5,6,7** 321-183 GHz
  - 183 without 325 in 321 region not covered by model!
- **M4** 321-325 GHz - T_k [500-750] K; n [0.9-2]x10^{15} m^{-3}
- **M8,9,11** 325-183 GHz within ~300 mas of star
- **M10, 12, 13** ≳ 500 mas from star
  - T_k ≲ 600 K if n > 10^{13} m^{-3} going to any T_k if n < 10^{12} m^{-3}
    - Some of these in inter-clump gas?

Comparison with shell models

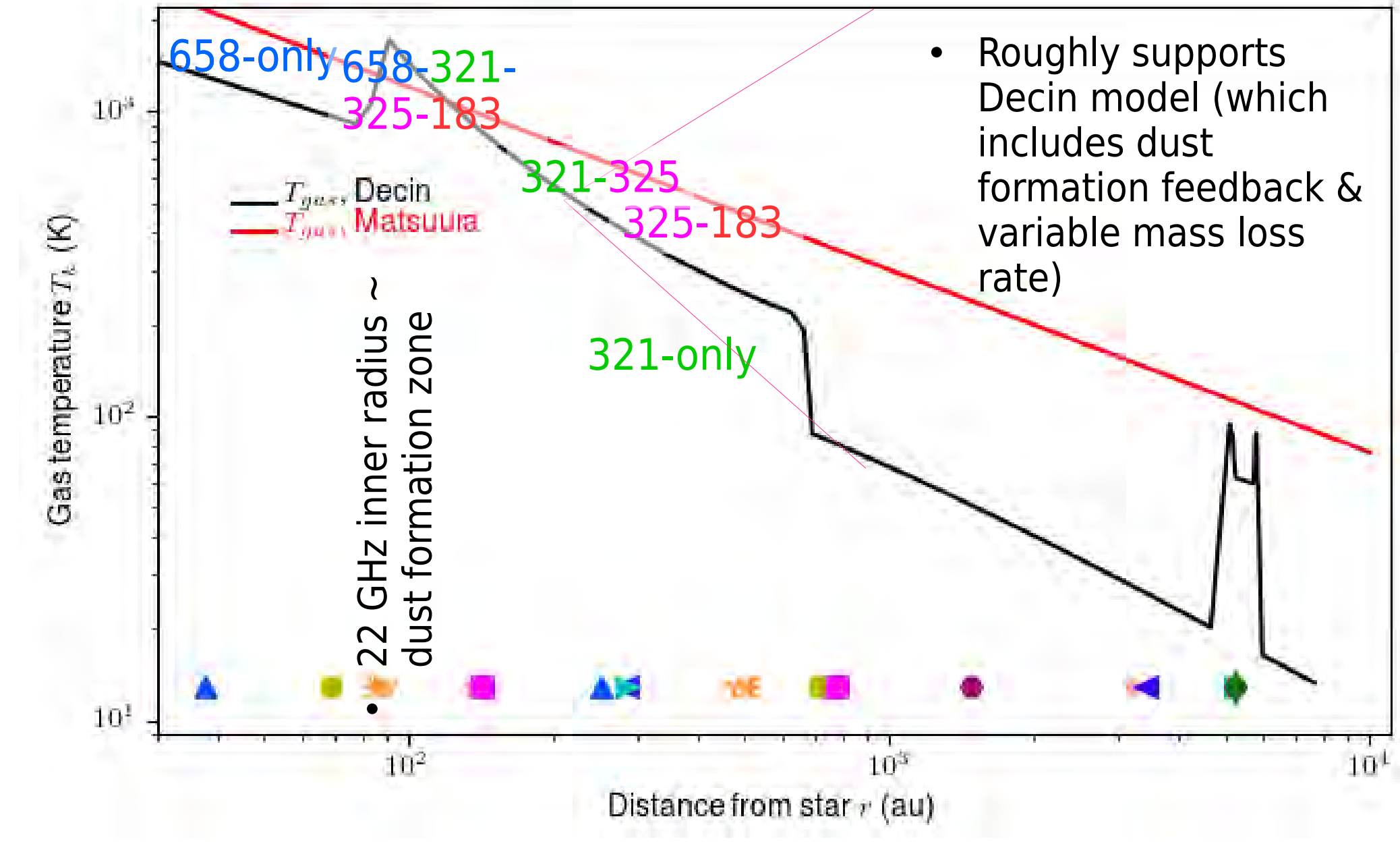


- Inner and outer radii from masers

  +SO_2 thermal example

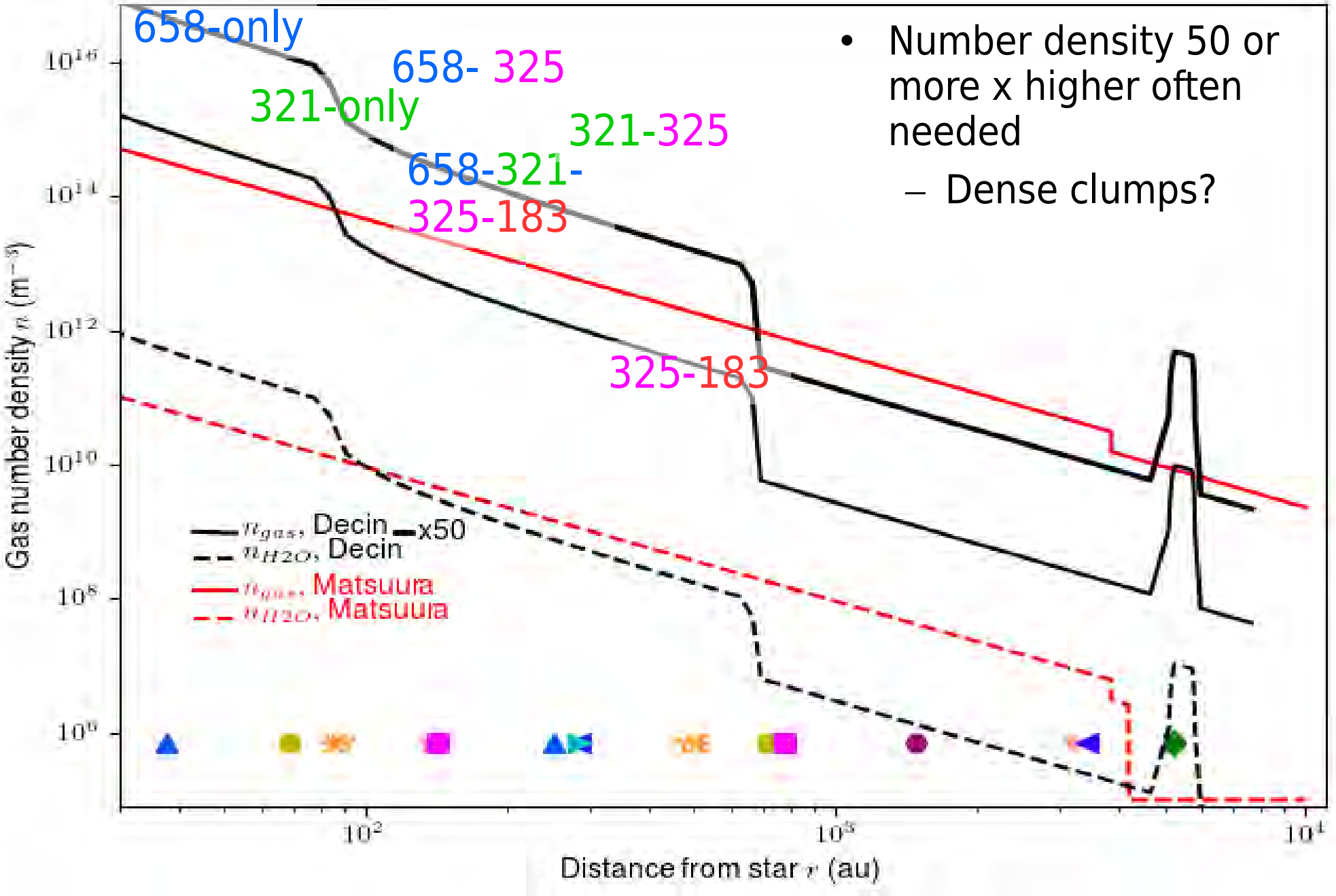
- $V(r)$ reasonable fit but acceleration more gradual

Temperature constraints



- Roughly supports Decin model (which includes dust formation feedback & variable mass loss rate)

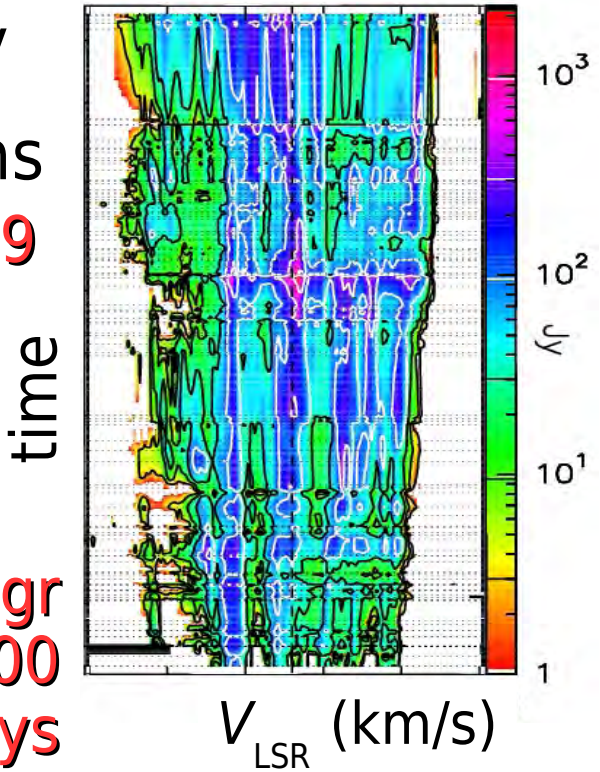
Number density constraints



- Number density 50 or more x higher often needed
  - Dense clumps?

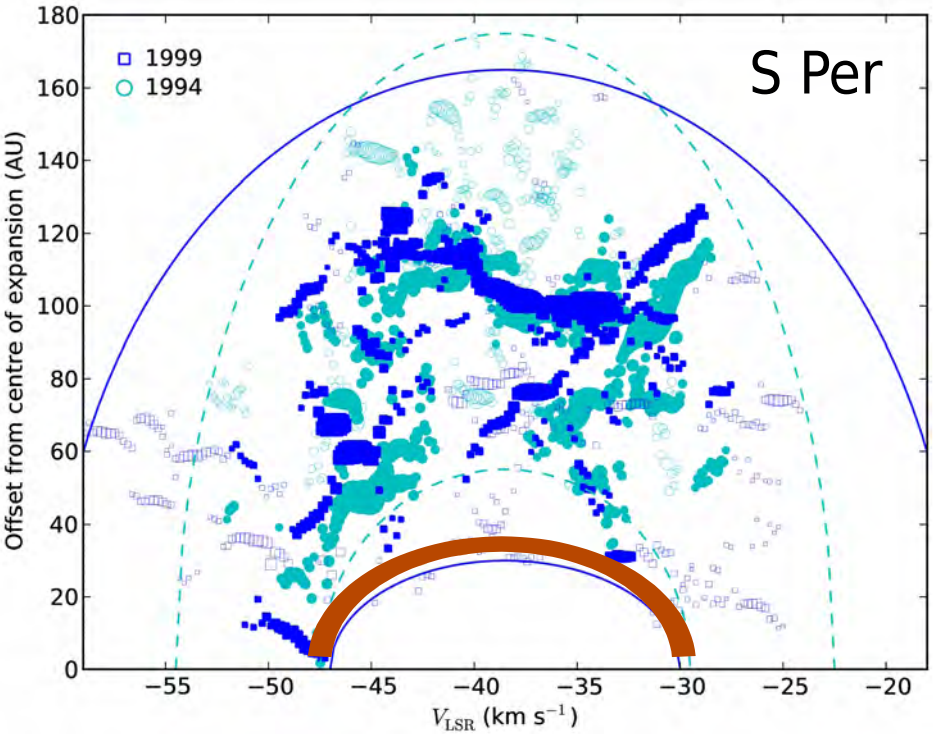
Work in progress

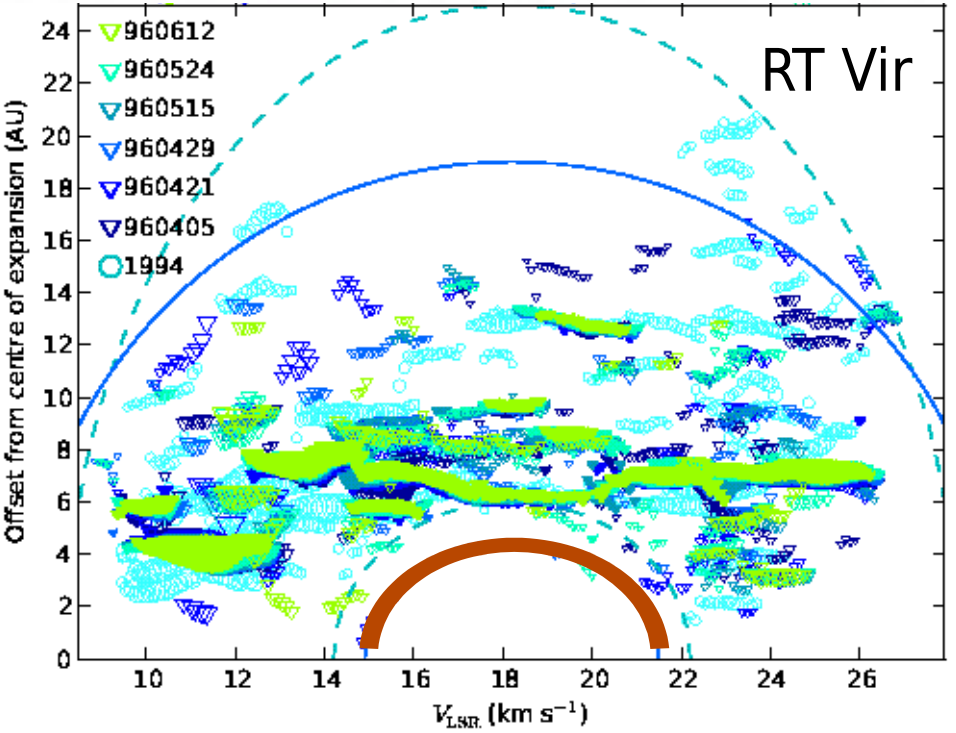
- Current model: realistic cloud sizes; T_d 50 K; $f_{[H2O]}$ $3x10^{-5}$
  - Try higher T_d; $f_{[H2O]}$ $2x10^{-4}$ (Matsuura)? $1.1x10^{-3}$ (Decin)?
    - Explain combinations like 658+321 without 325 GHz?
- Decin model reasonable if dense clumping allowed for
  - Slow acceleration: hope Hoefner/Bladh will model RSGs!
- Hard to observe all lines contemporaneously
  - Single-dish between interferometry epochs
    - Pushchino, Mc, Ef *Brand & Engels* poster 29
- Cloud geometry using maser beaming
  - High resolution to resolve components
- Observe a more reasonable star
  - Dear ALMA PC, please give us VX Sgr on long baselines!



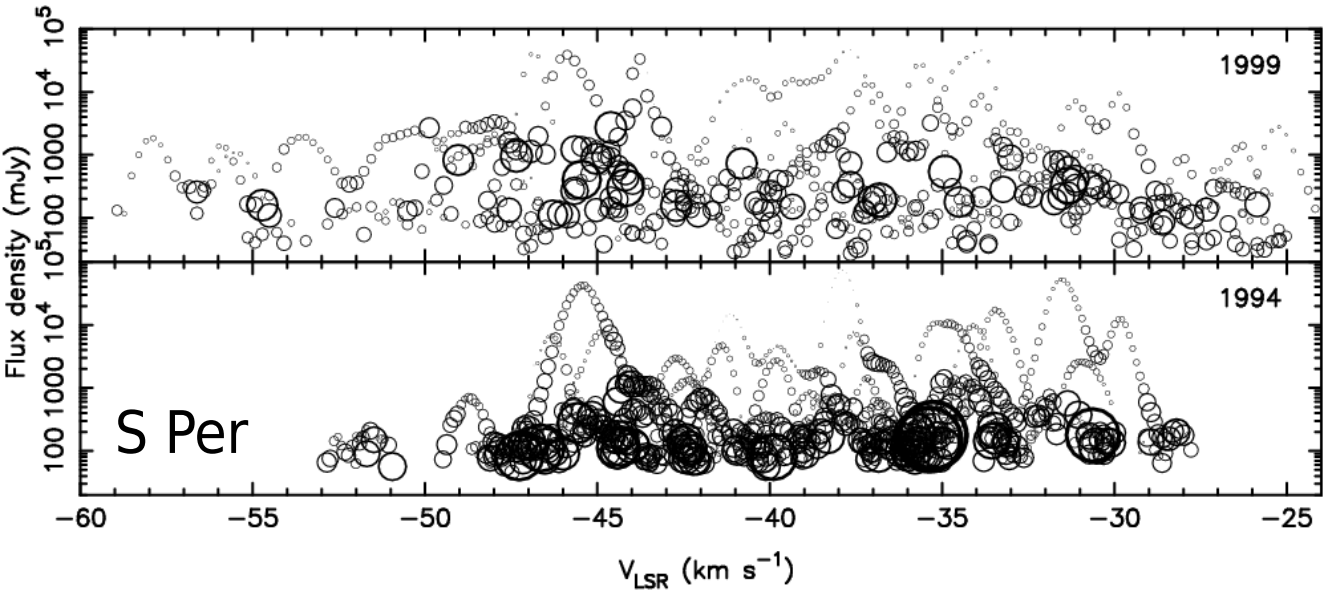
Cloud density

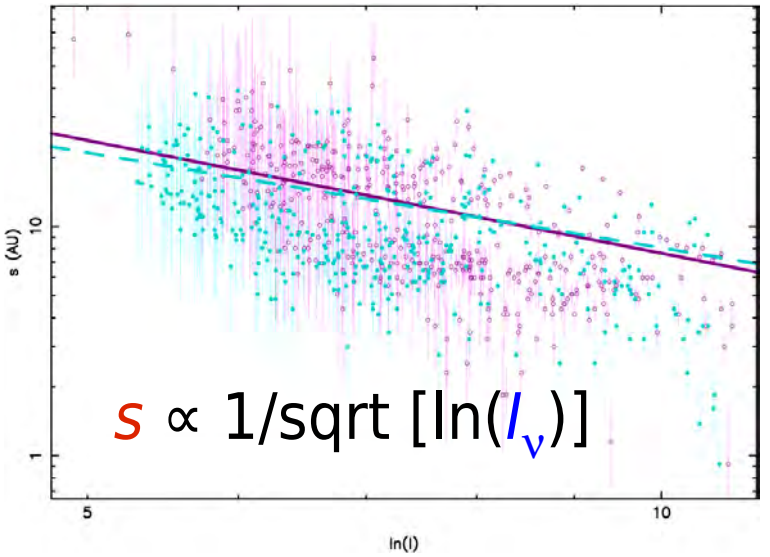
- 22 GHz **H_2O** masers start at r_i
  - 40–70 AU RSG, 5–15 AU AGB
  - Where collision rate < masing rate (*Cooke & Elitzur 85*)
    - Quenching density ~$5 \times 10^{15} m^{-3}$
- Clouds ≳45x average (e.g. CO) wind density
  - Filling factor ≲1%
  - Up to 90% mass loss concentrated in clouds
  - 2–6 clouds/stellar period





Beamed size – maser brightness





- S Per: brighter I_ν - smaller beamed size s - ~spherical cloud?
- U Ori: some brighter spots are larger - shocked slab?

