Water masers

High resolution probes of physical conditions

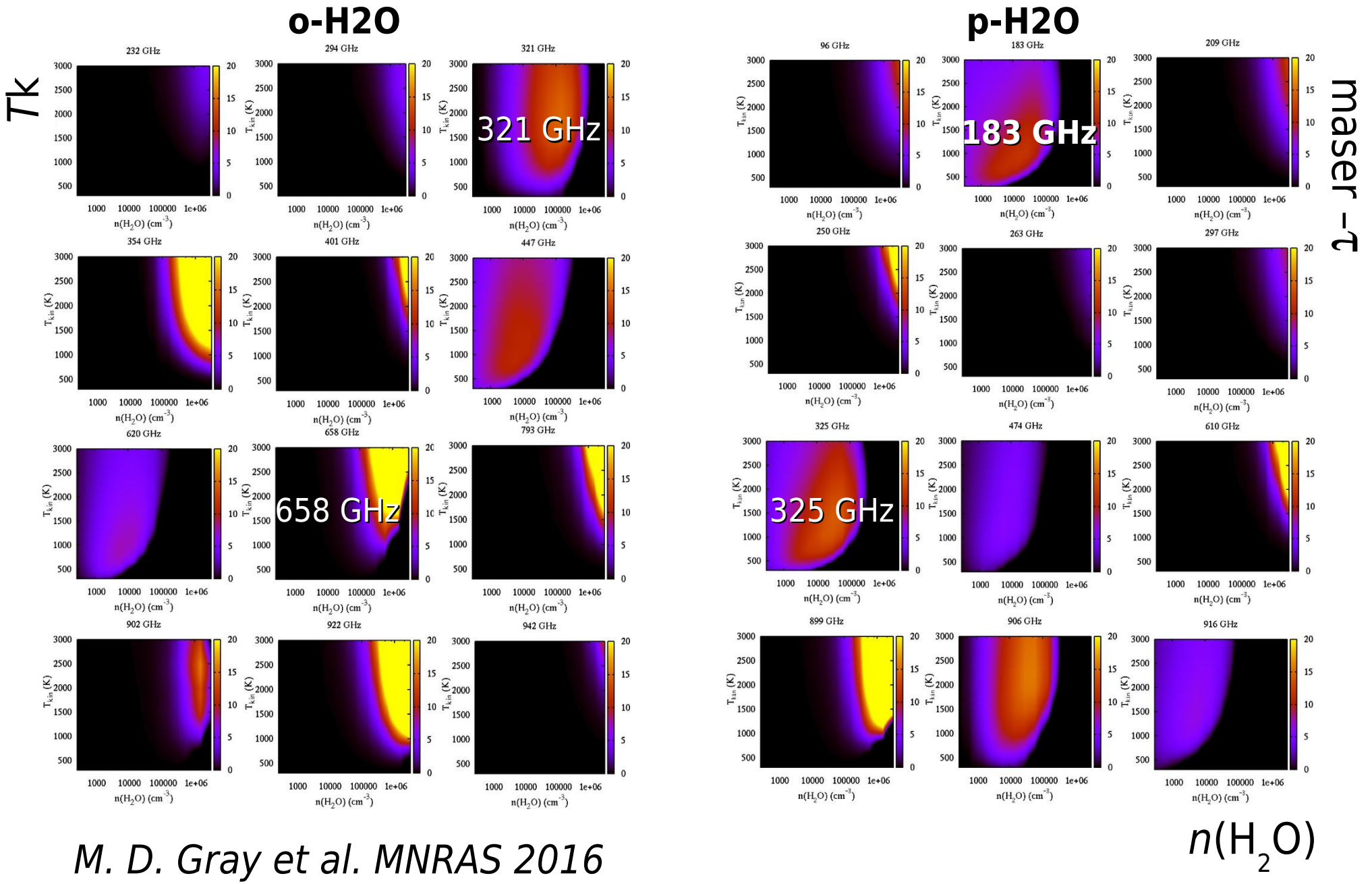
Anita Richards (Manchester) & thanks to Liz, Wouter, Ivan, Sebastien, Sabine, Daniel, Ana, Lydia and all the rest of the B5 team and the chocolate shops of Kungsbacka

Mass loss, wind driving, shaping of circumstellar envelopes around evolved stars
Clumpy winds, density inhomogeneities
Survival of dust and molecules in late stellar evolution
See *de Beck/Humphreys* introduction
***Vlemmings* magnetic fields**

Masers aren't just for kinematics, they are for physics

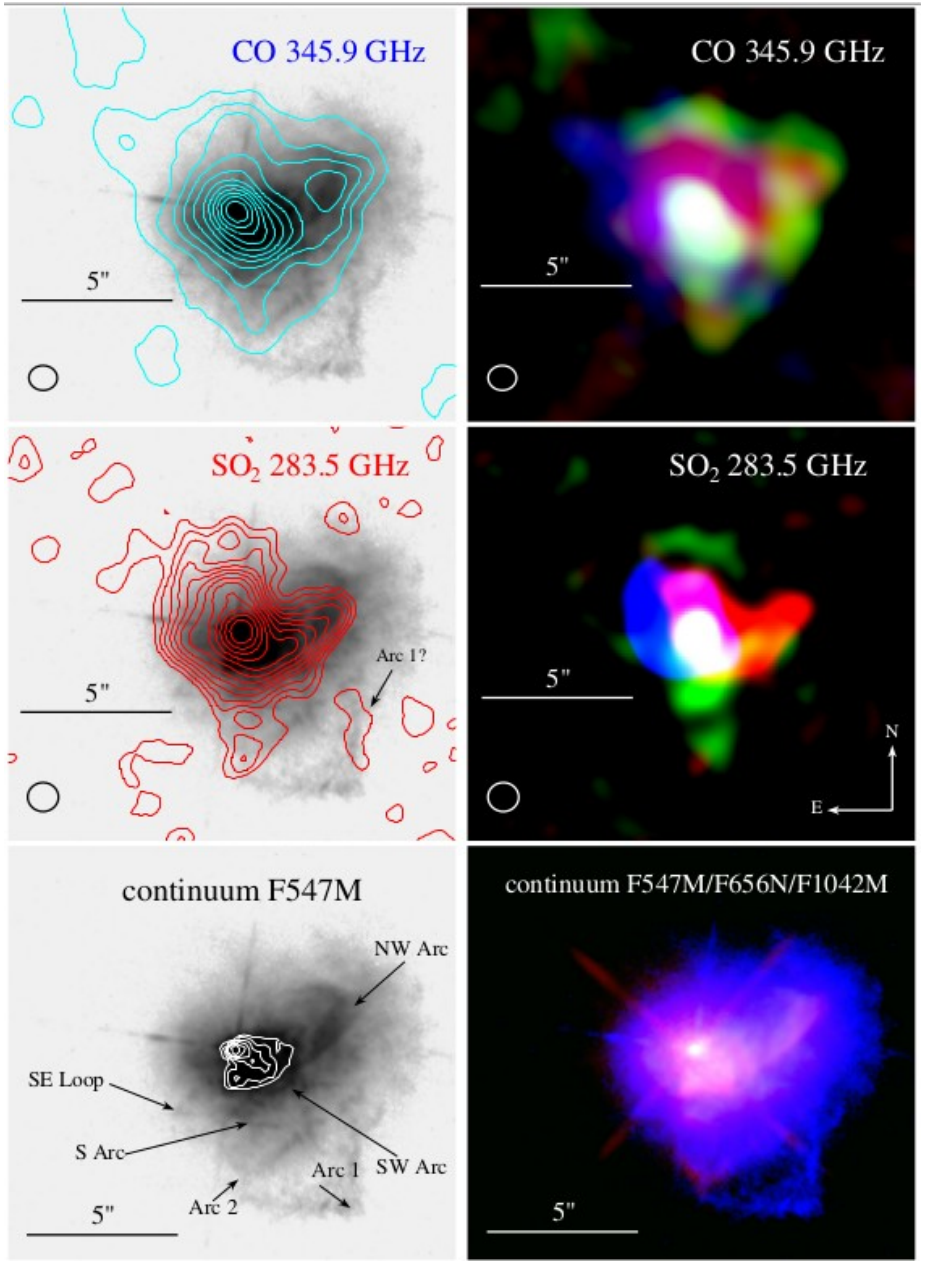
- Exponential amplification
  - Hard to reconstruct underlying environment from one line
- Multiple water transitions mase
  - Wide range of physical conditions for inversion
  - Water widespread in inner O-rich CSE – and elsewhere
- Gray et al. models for >50 lines accessible to ALMA
    - Also Yates, Sobolev, Humphreys, Nesterenok, Neufeld ...
  - Number density, Tk, Tdust/IR radiation field, vel. grad.
    - ortho:para 3:1
    - Some transitions radiatively pumped at high IR temp.
- Reconstruct physical conditions as well as kinematics

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



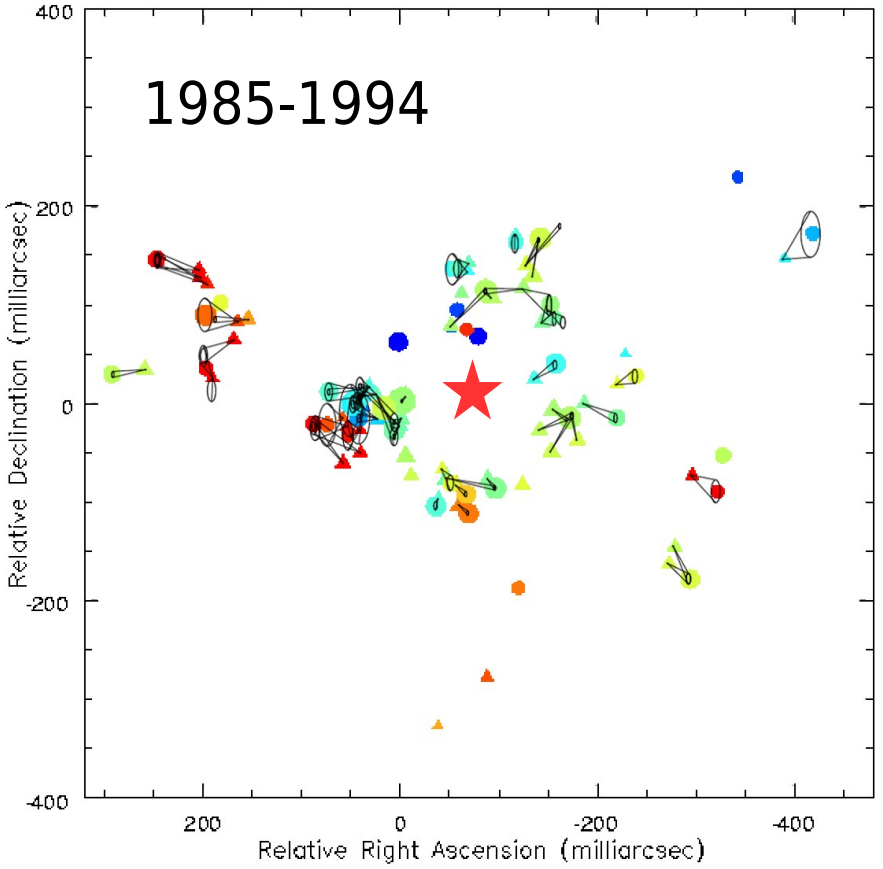
M. D. Gray et al. MNRAS 2016

VY CMa's CSE before ALMA

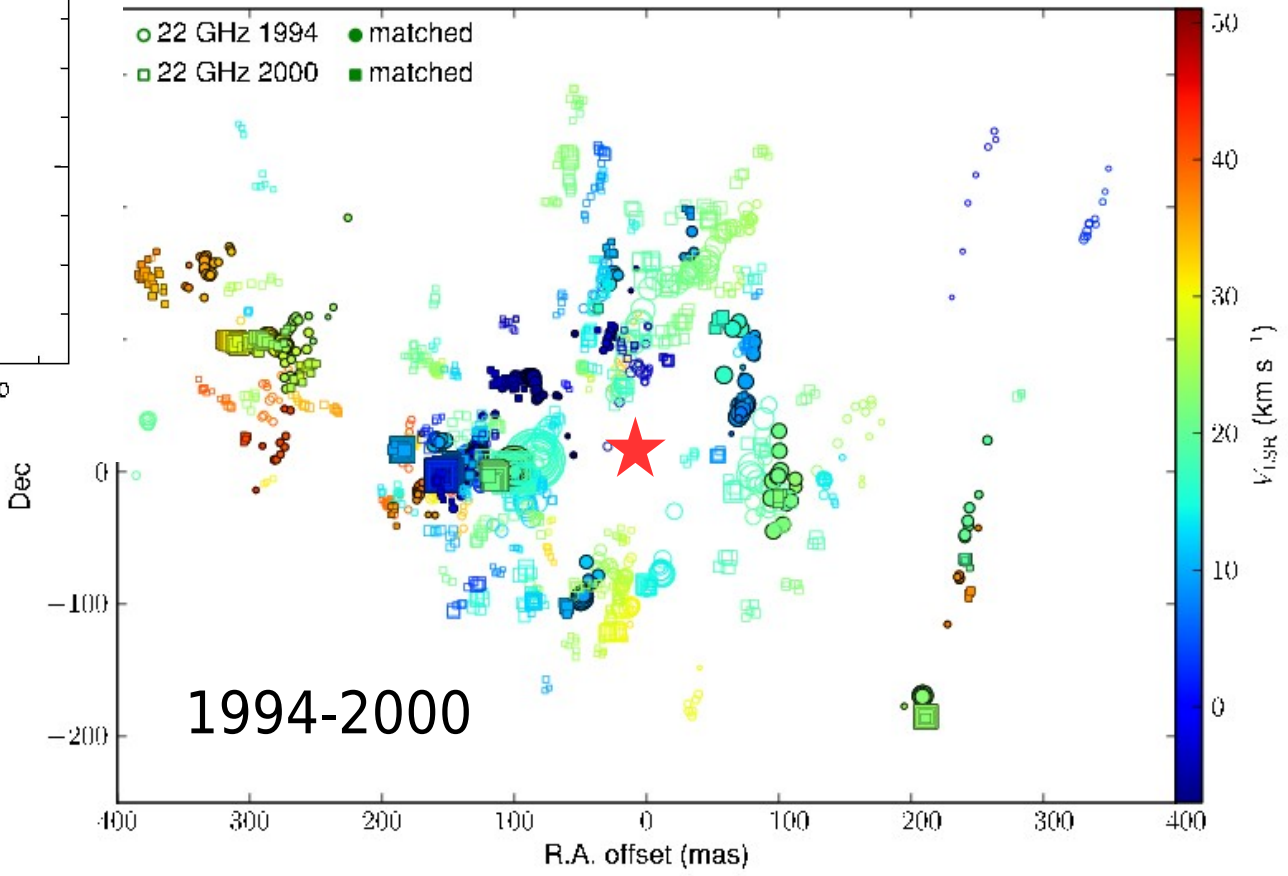


- *Kaminski et al. 2013* (SMA), *Shennoy, R. Humphreys* (HST)
  - ~5'' heart-shaped nebula
  - Mostly irregularly expanding
- Largest, longest-lived 22-GHz water maser features of any well-studied RSG
  - ~half features survived at least 9 yr from 1989 (*Bowers et al. 1993*, VLA) to 1994 (*Richards et al. 1998*, MERLIN)
  - Similar survival rate to 2000

VY CMa 22-GHz clouds

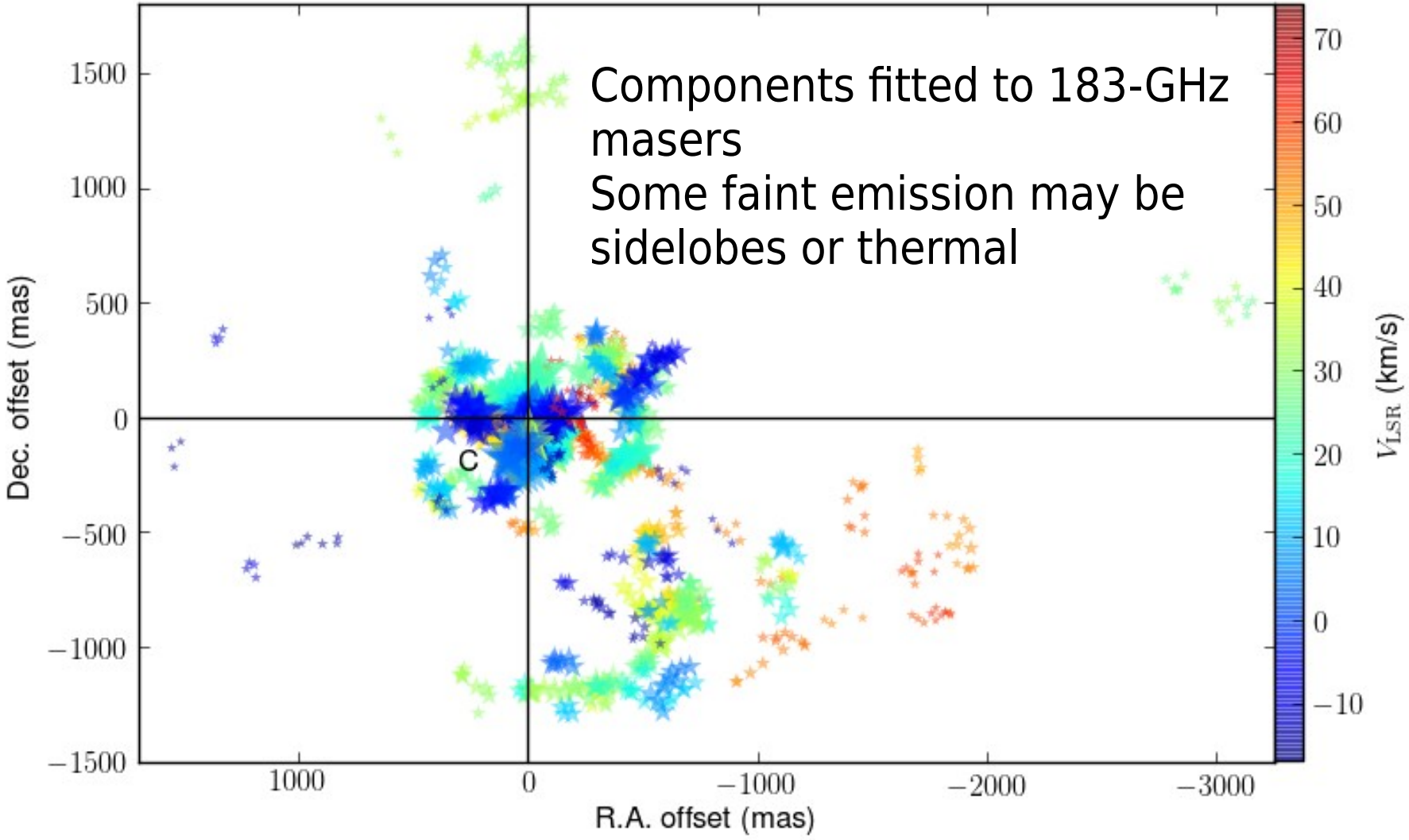


- Largest (~20-25au), longest-lived features of well-studied RSG
- Position of star ★ uncertain



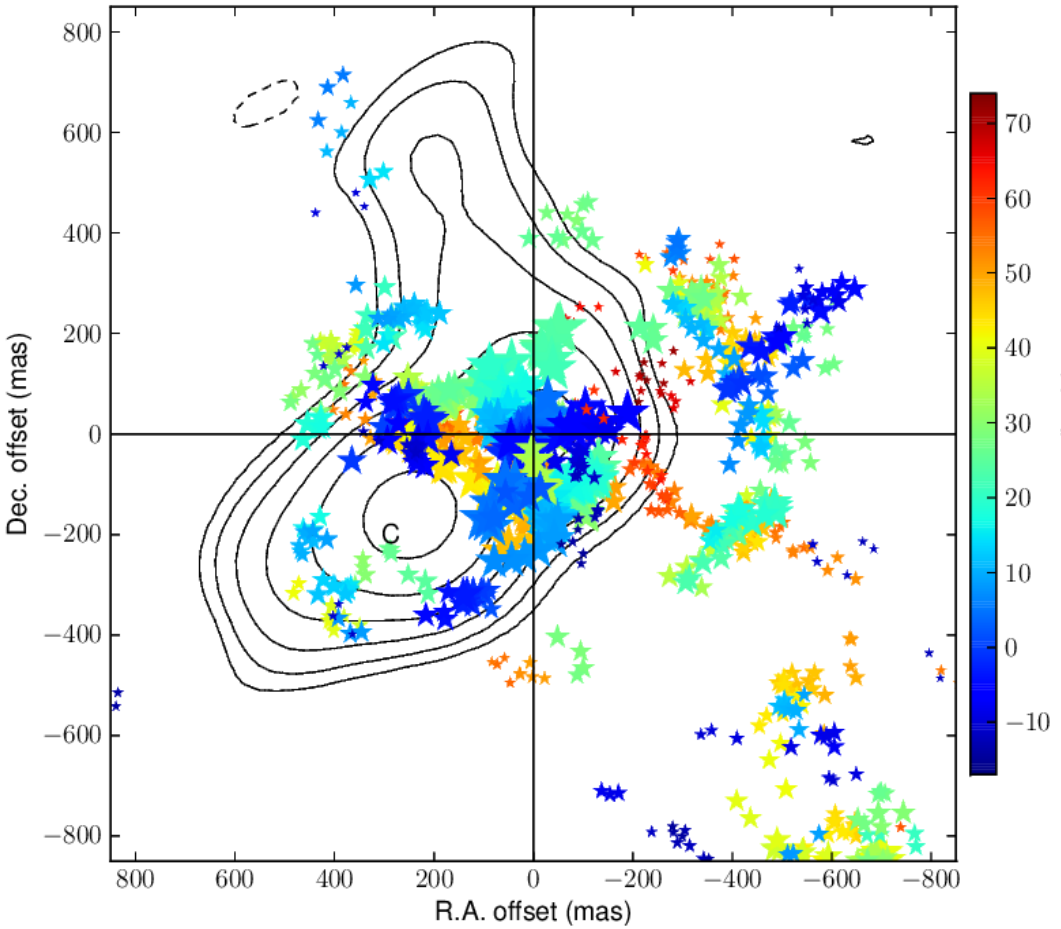
VY CMa ALMA SV

- 183-GHz see Liz's talk for observational details
- 321, 325, 658 GHz *Richards+'14, O'Gorman+14, De Beck+15, Decin+16*



All masers avoid clump C

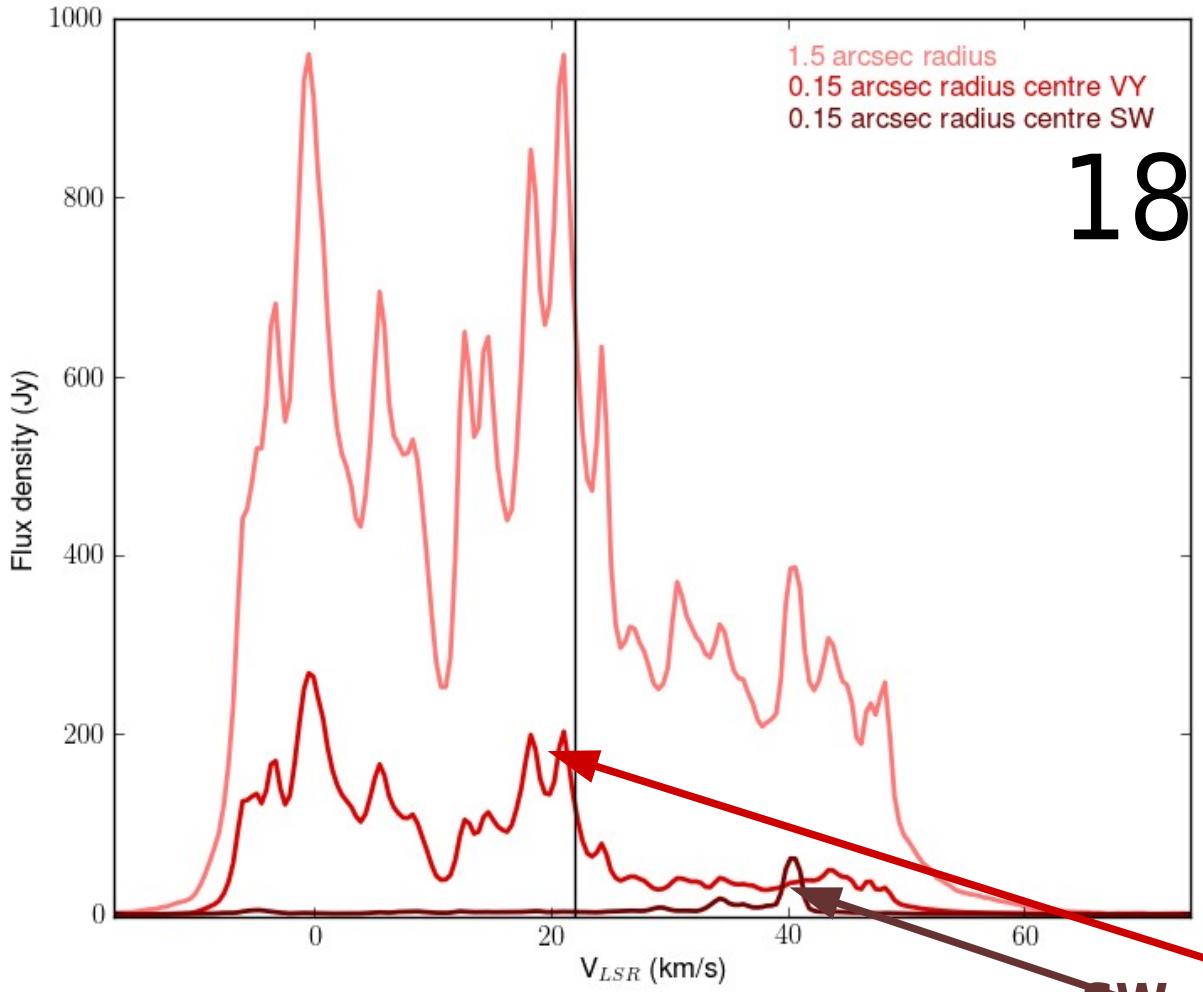
- Central 183-GHz masers overlying continuum contours

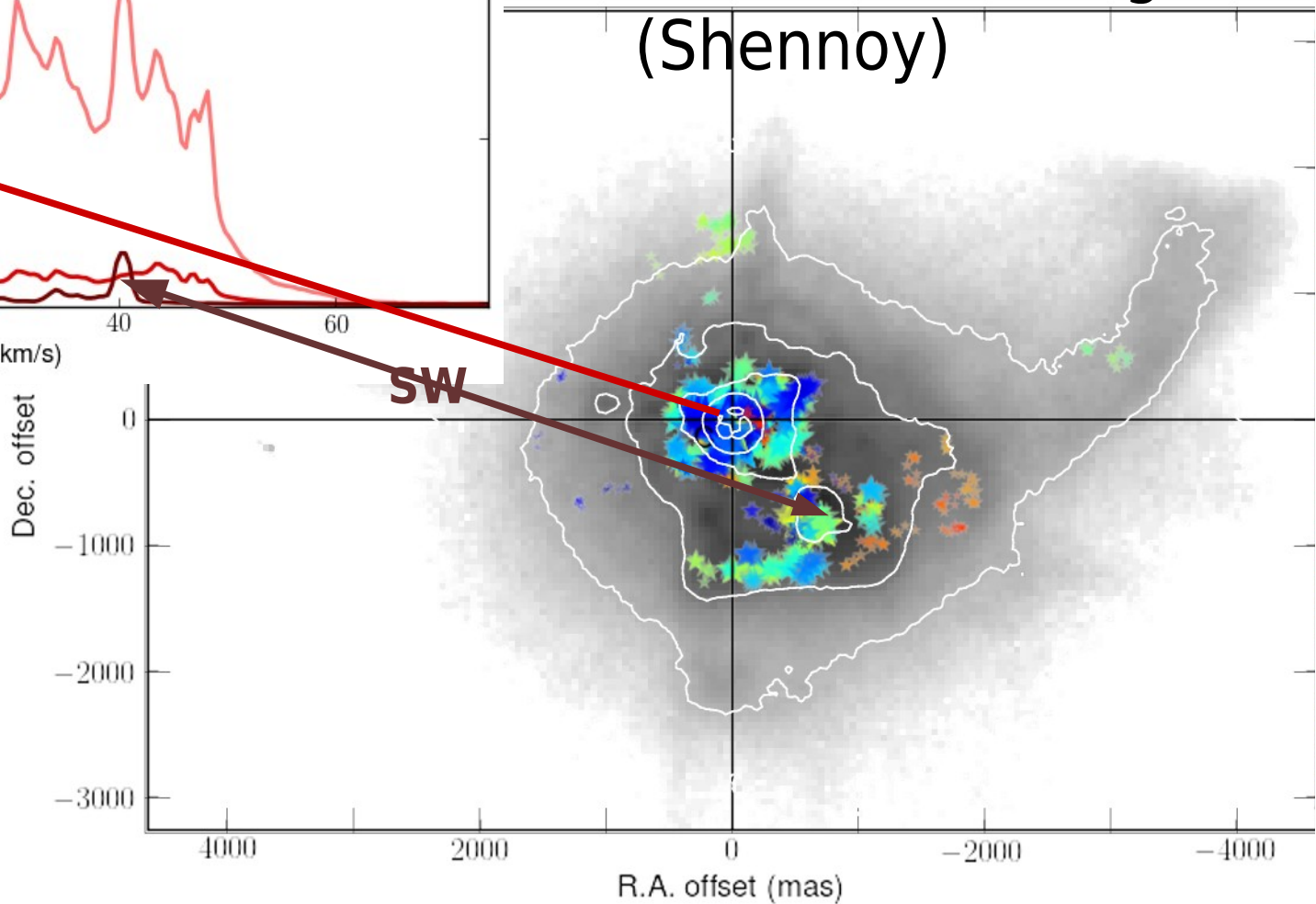


- Origin at stellar position VY
  - Brightest masers surround VY
- Clump C has strongest (sub-)mm continuum
  - No masers at all!
- Dust temperatures 970 K VY, <450 K C (*O'Gorman+14*)
- 183-GHz continuum consistent with VY, C sub-mm spectral indices (2.7, 1.9)

183 GHz extended

- Follow cold dust not detected by ALMA
- HST scattered light (Shennoy)





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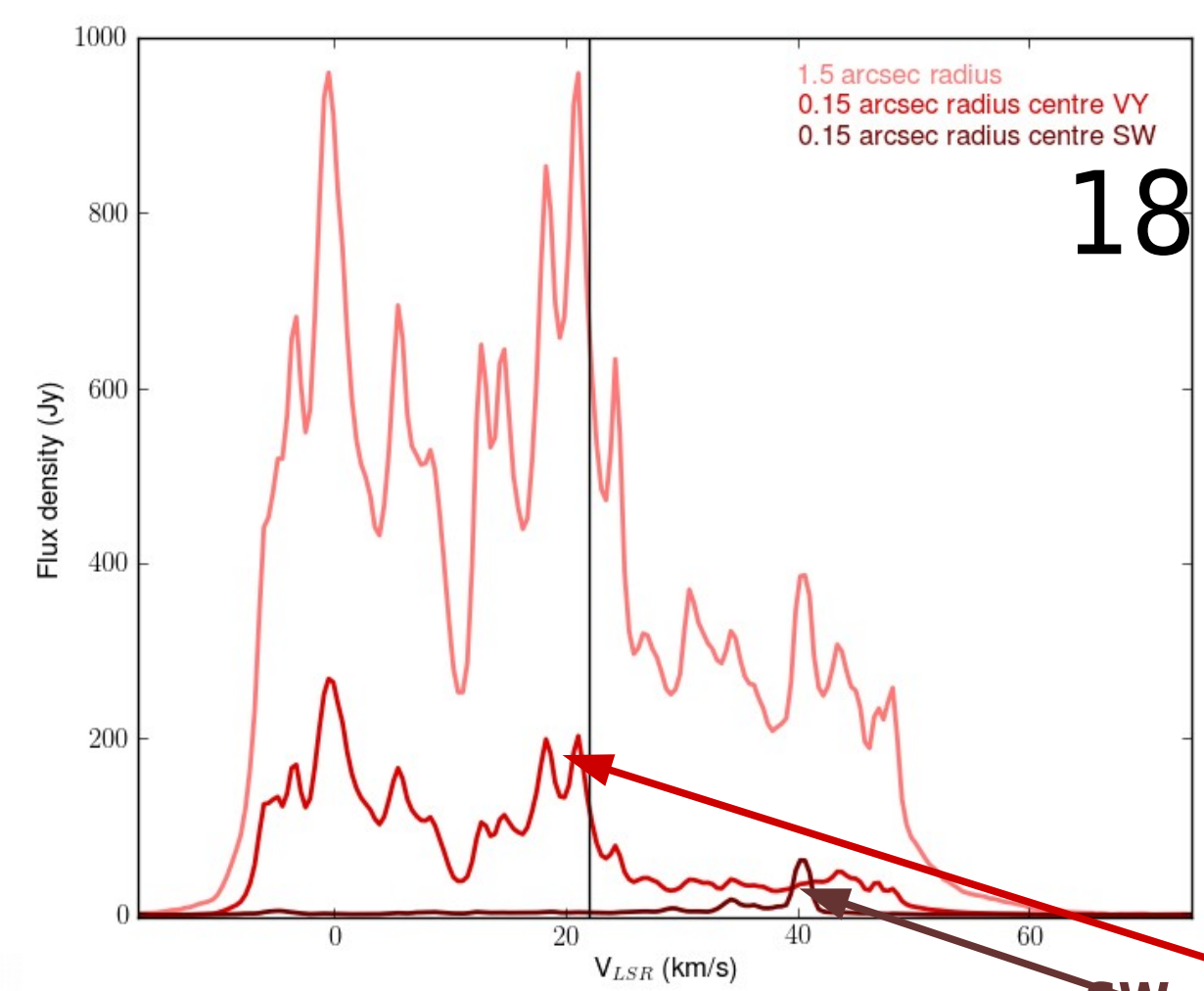
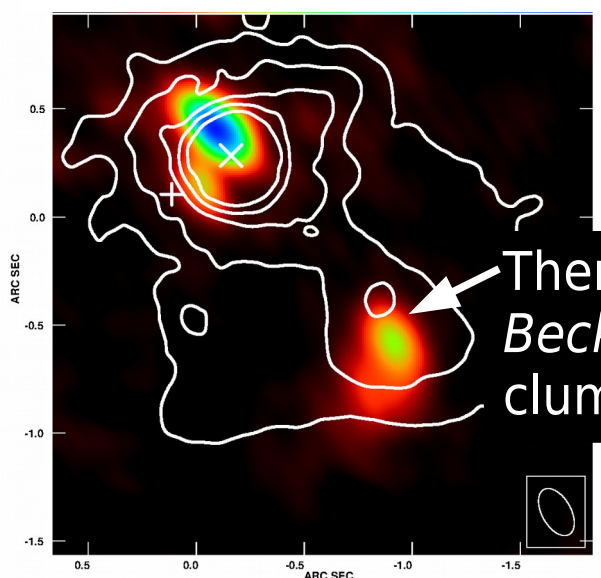


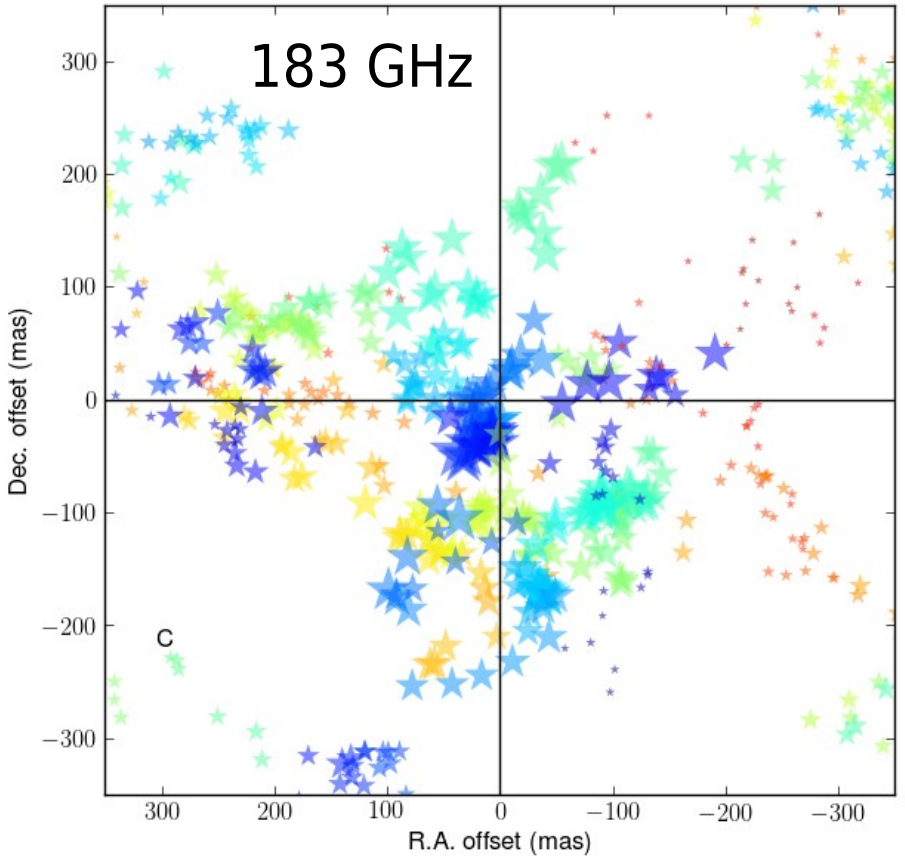


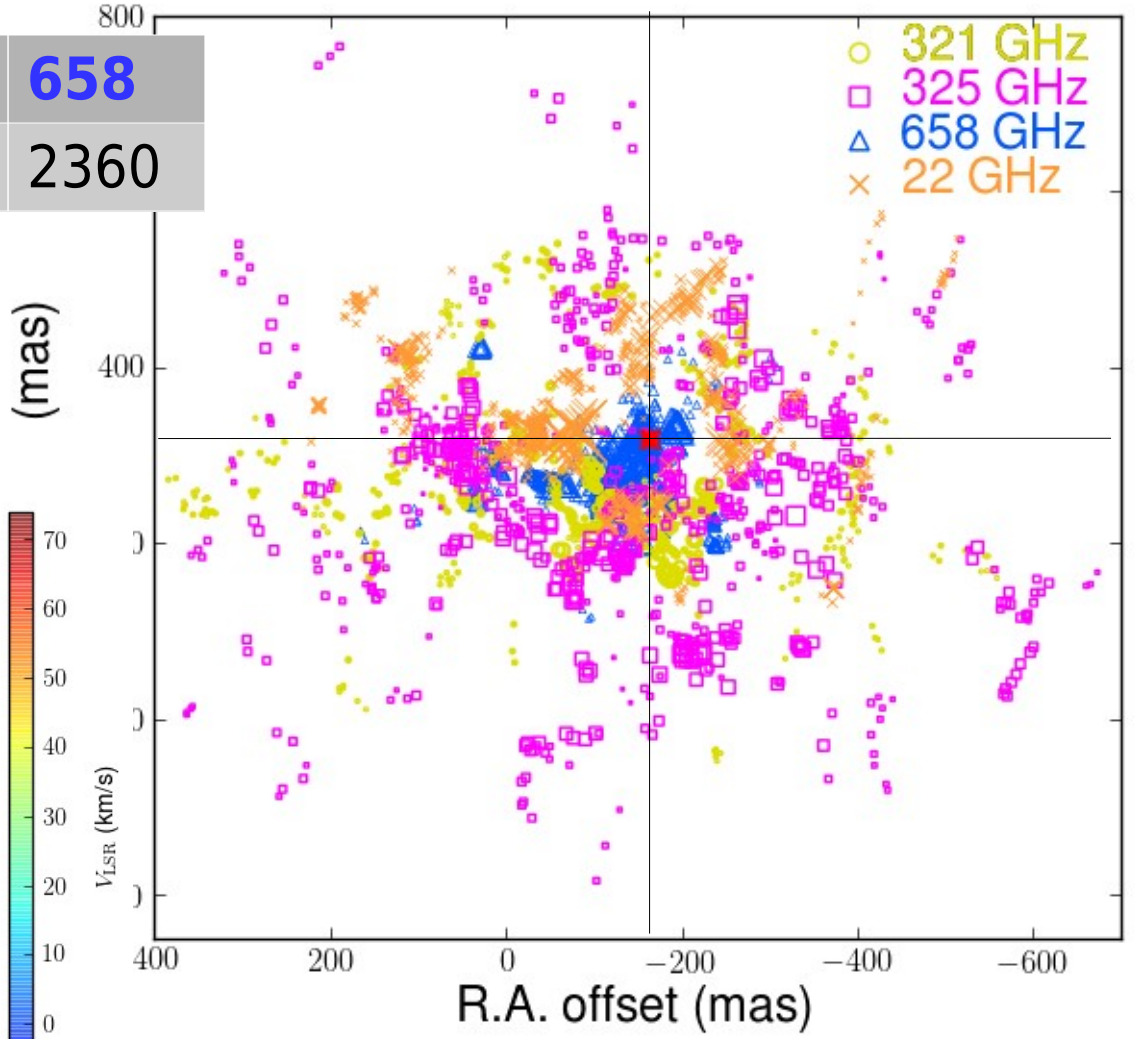
Thermal NaCl (*Decin*), TiO2 (*De Beck*) also associated with SW clump, but no other H2O masers

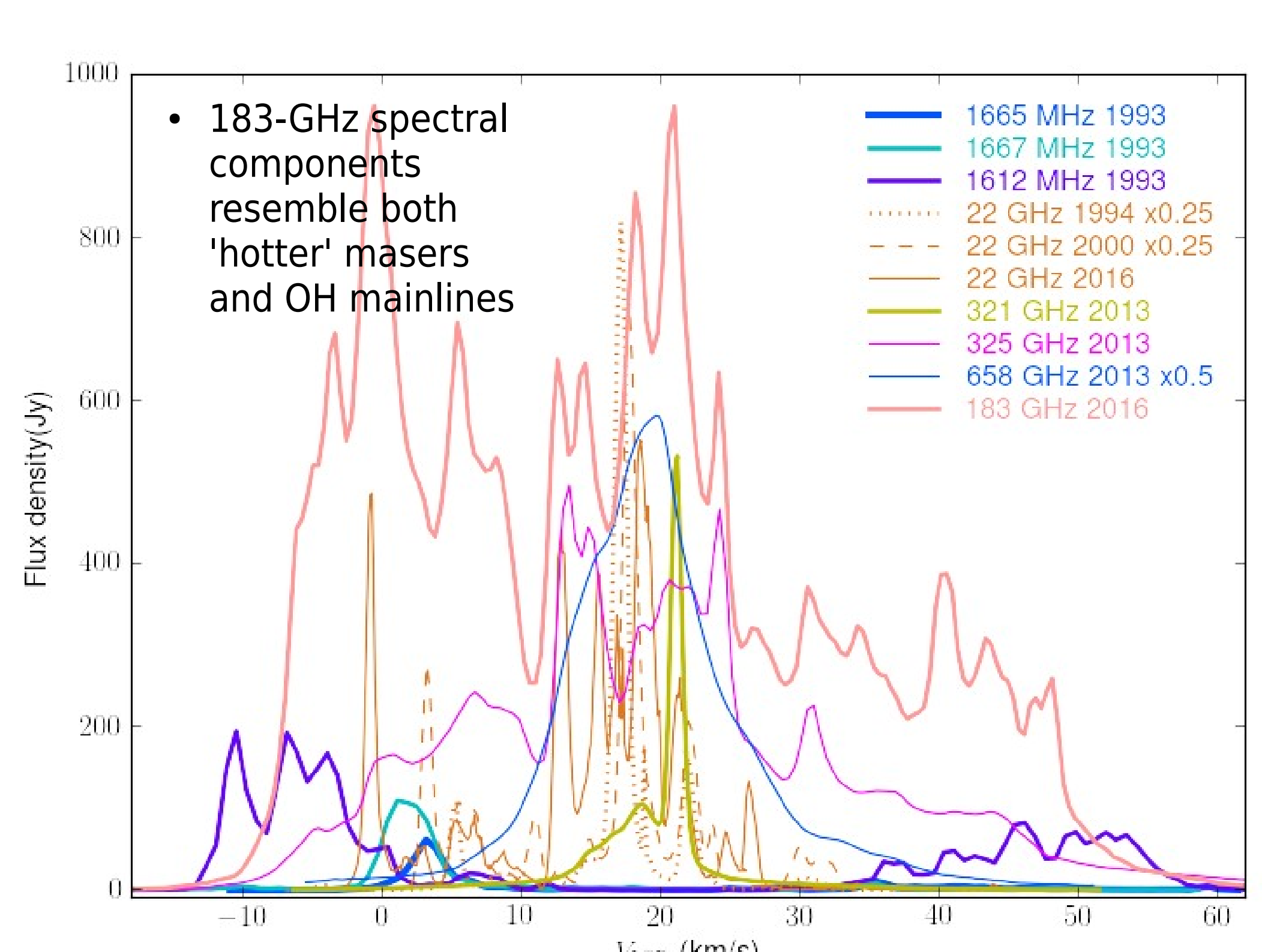
Water maser comparisons

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

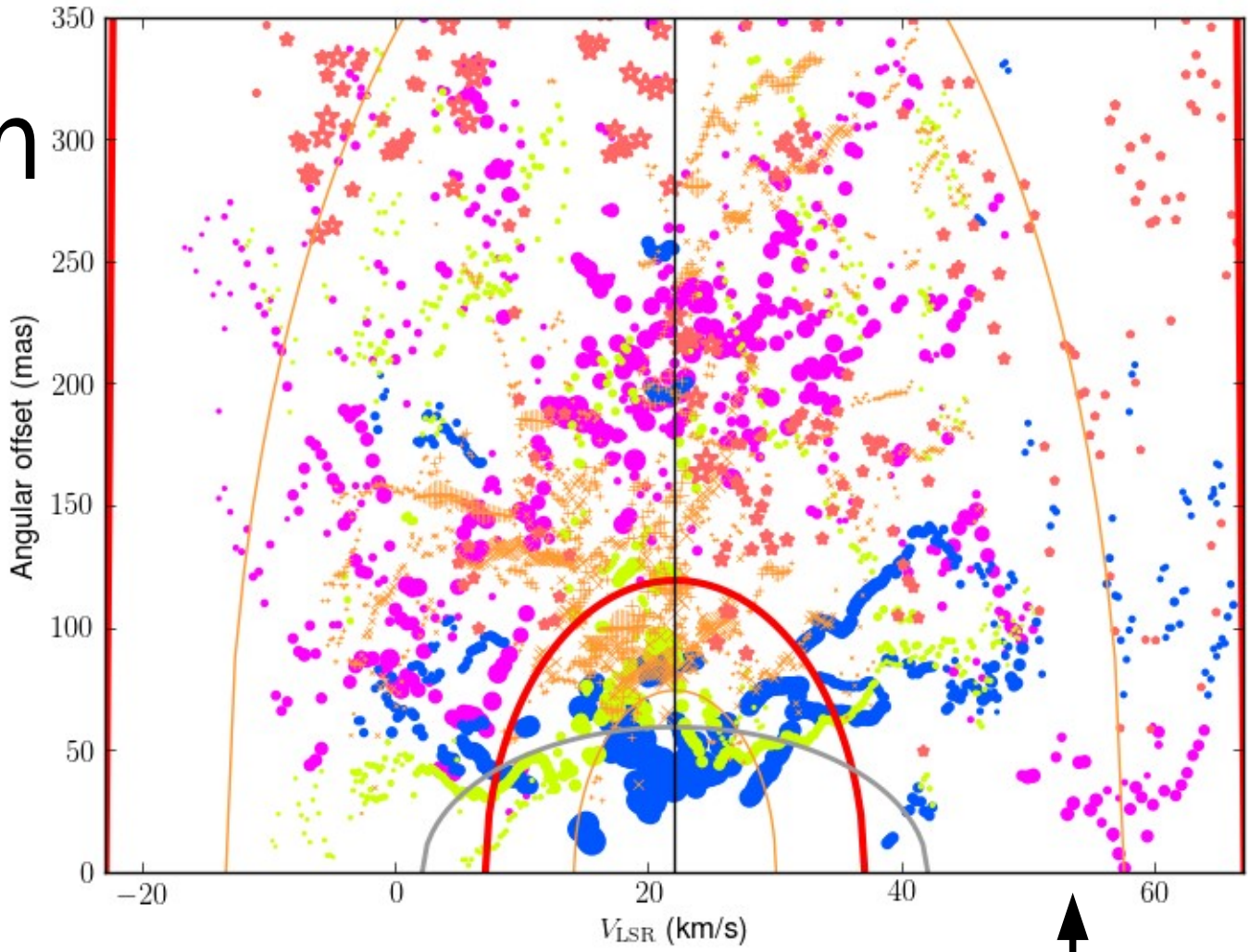
- Similar shell to 22, 321, 325 GHz in inner few 100 mas

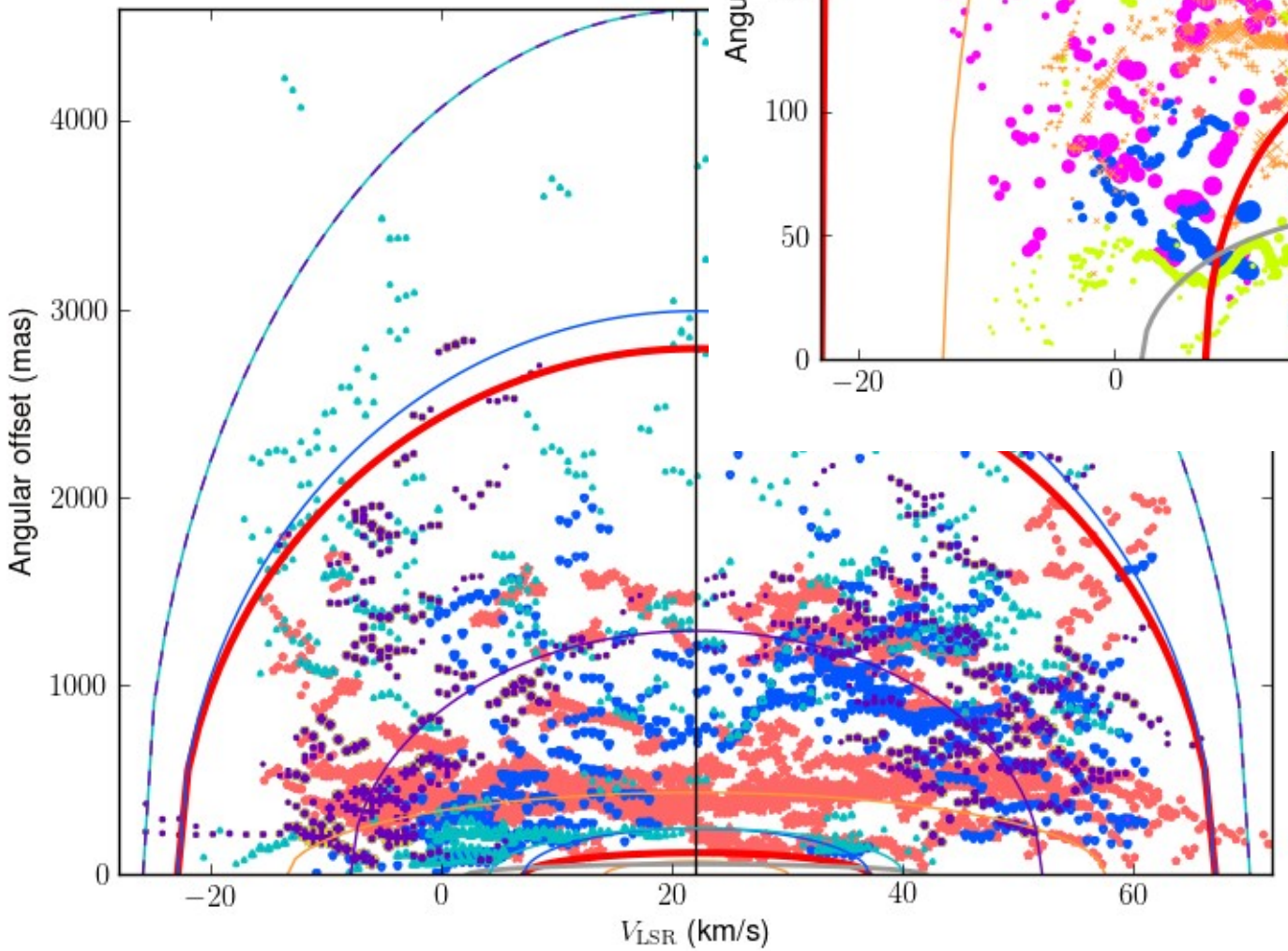





183-GHz spectral components resemble both 'hotter' masers and OH mainlines
1665 MHz 1993
1667 MHz 1993
1612 MHz 1993
22 GHz 1994 x0.25
22 GHz 2000 x0.25
22 GHz 2016
321 GHz 2013
325 GHz 2013
658 GHz 2013 x0.5
183 GHz 2016
Flux density(Jy)
1000
800
600
400
200
0
−10
0
10
20
30
40
50
60

Distance from star v. *V*expansion



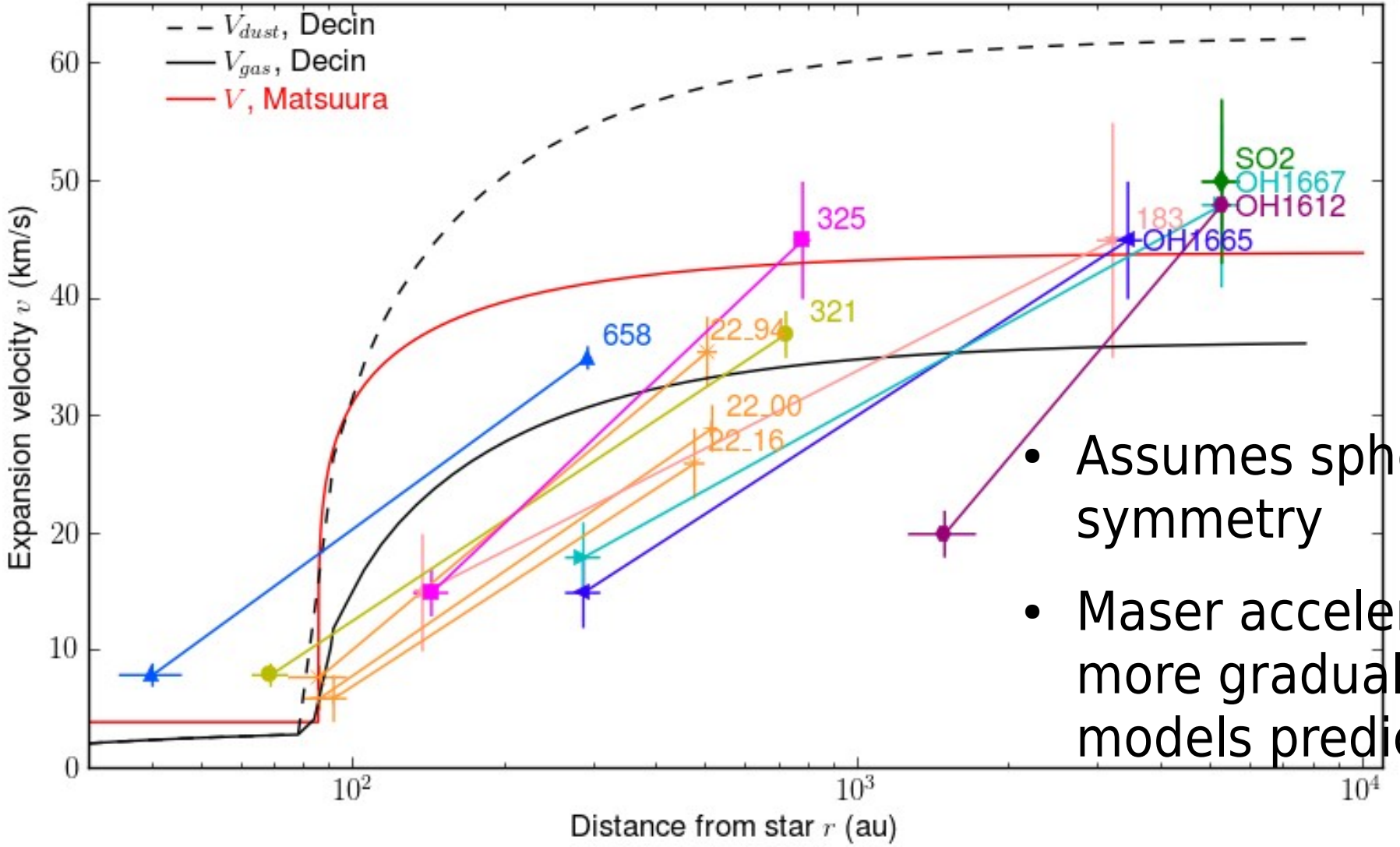


Zoom of water masers 183 GHz red

← OH masers + 183 GHz – uniquely extended among water masers

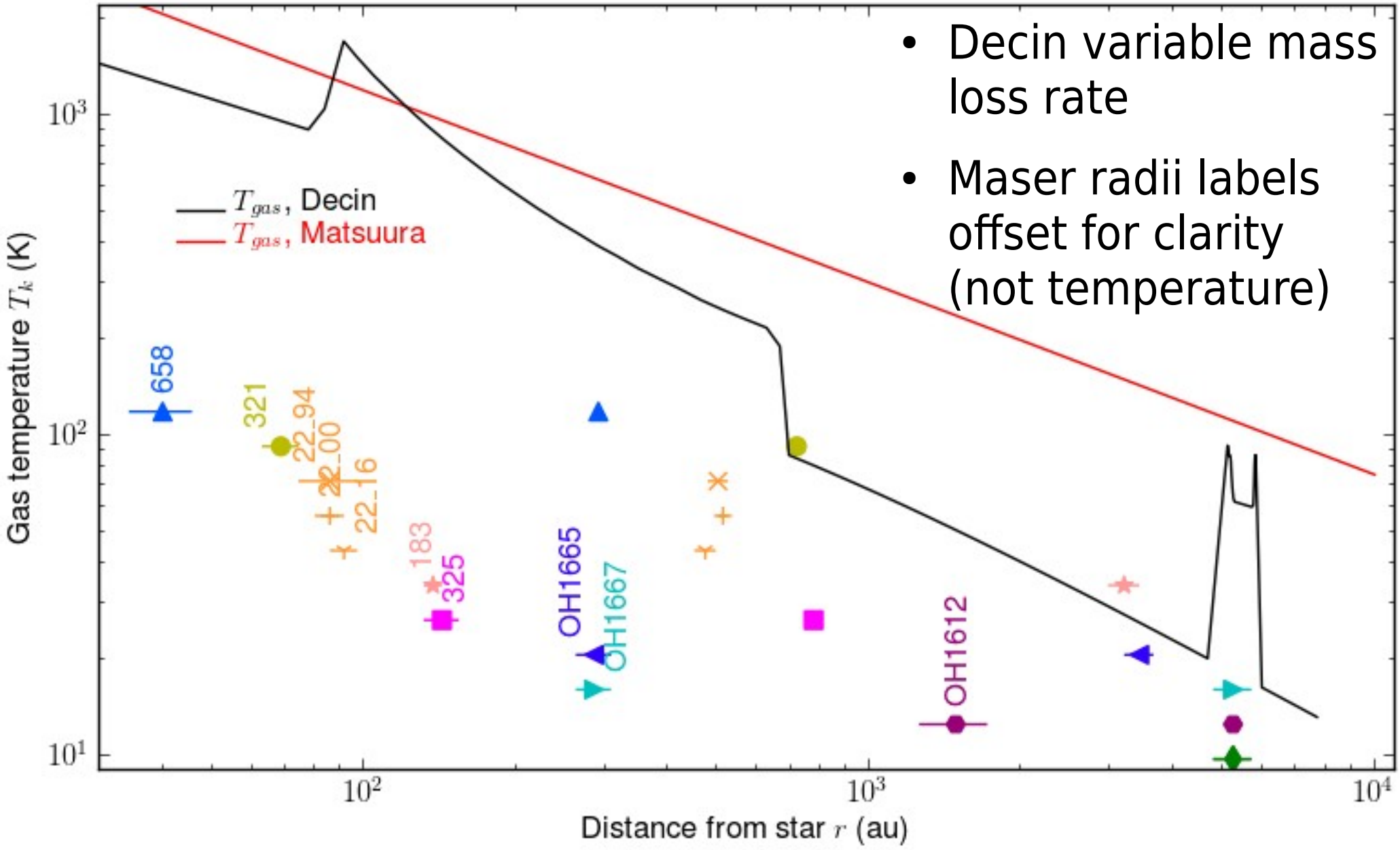
Comparison with thermal models

- Based on *Herschel* CO and other multi-transition single dish surveys *Decin+ 2006, Matsuura+ 2013*



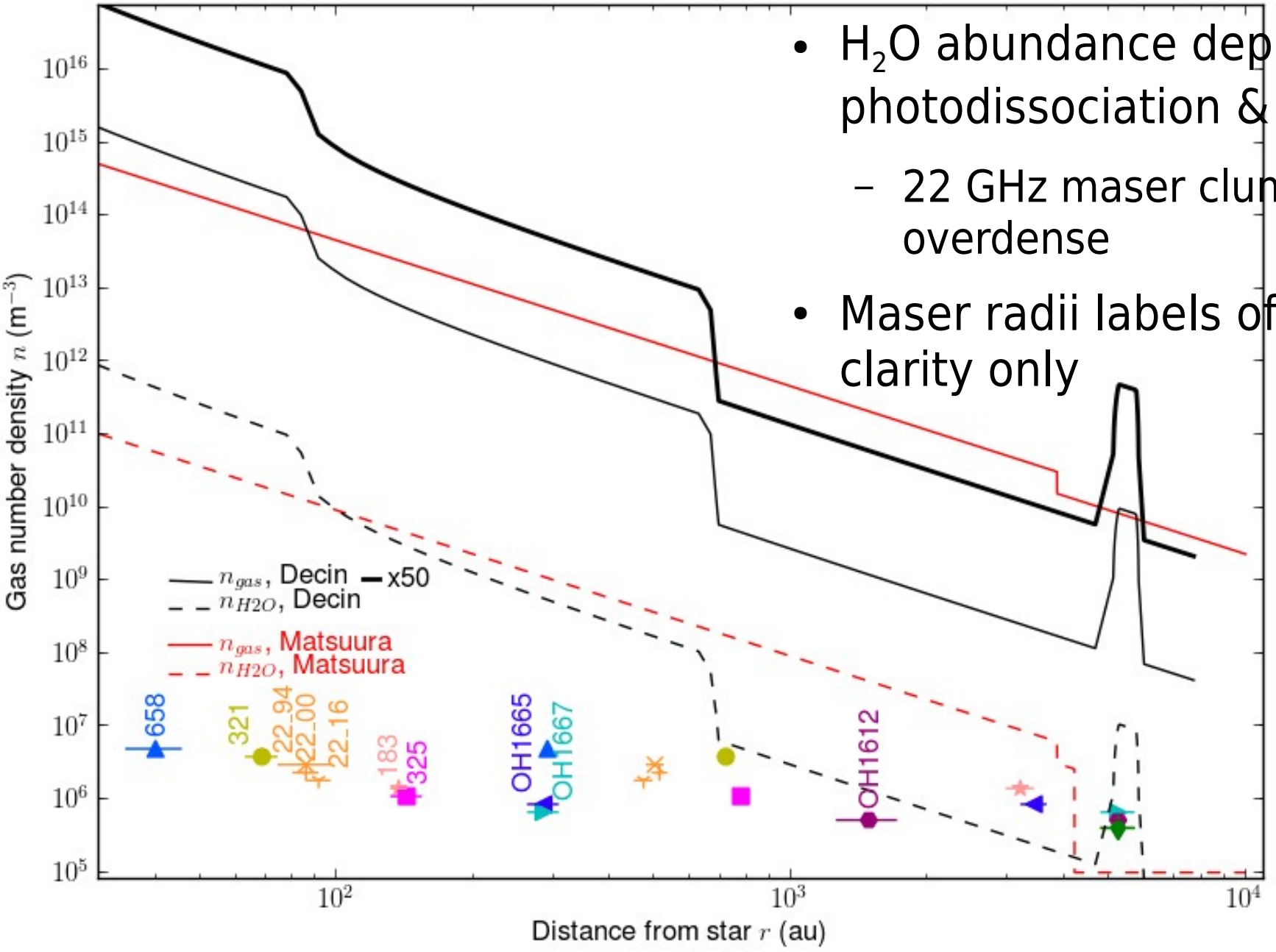
- Assumes spherical symmetry
- Maser acceleration is more gradual than models predict

Gas temperature v. radius



- Decin variable mass loss rate
- Maser radii labels offset for clarity (not temperature)

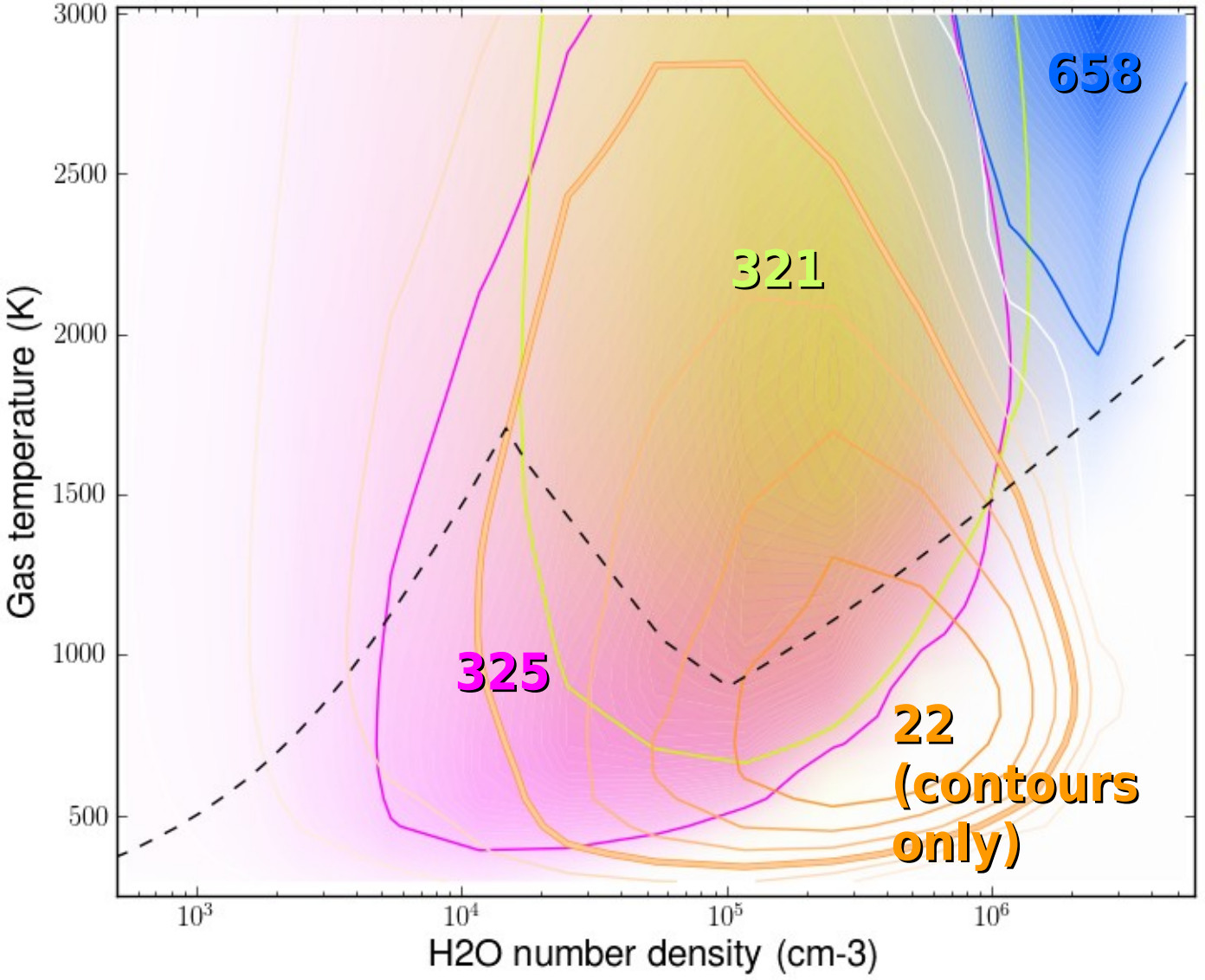
Number density v. radius



- H_2O abundance depleted by photodissociation & freezeout
  - 22 GHz maser clumps ~x50 overdense
- Maser radii labels offset for clarity only

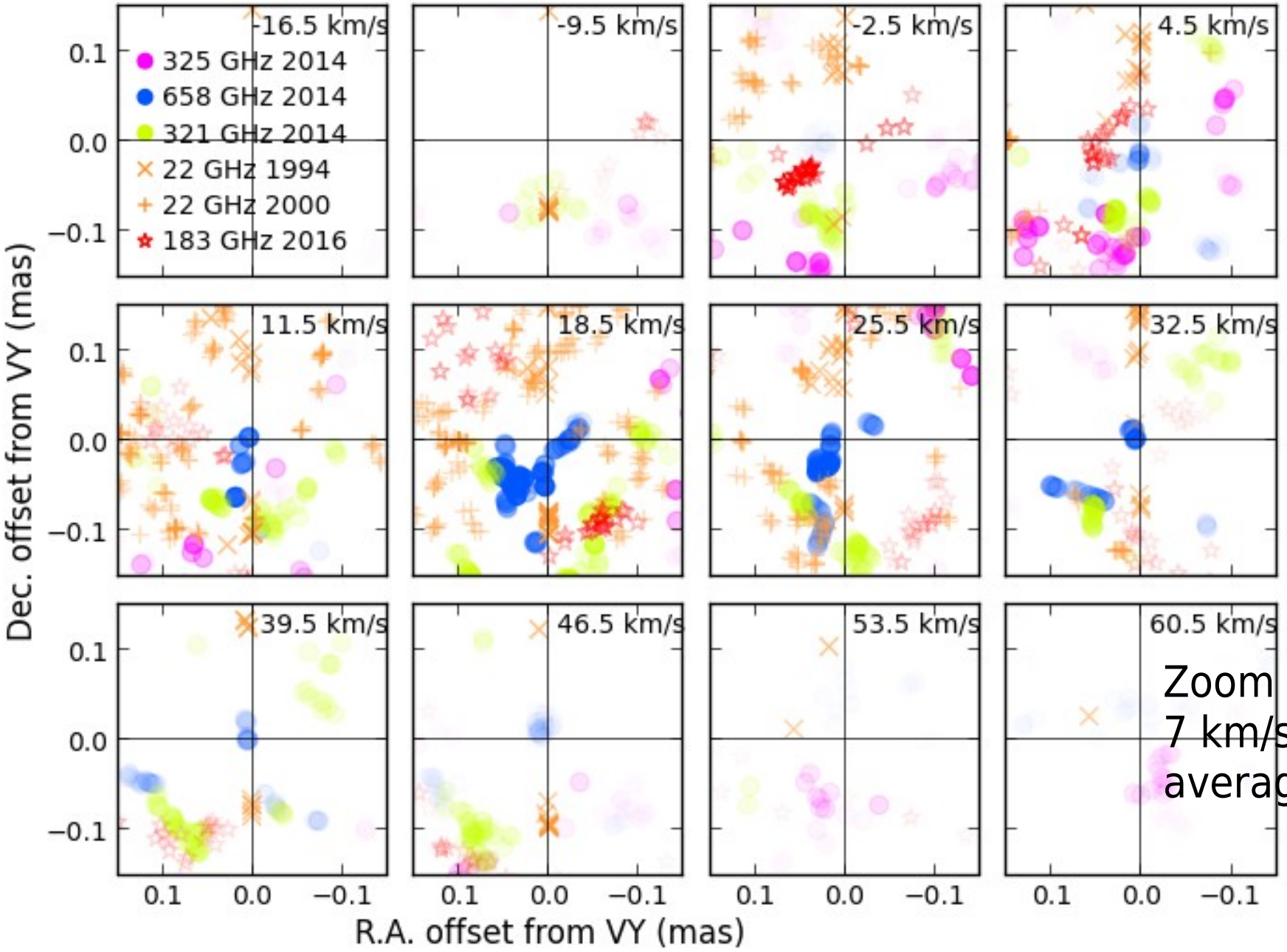
VY CMa maser model (*Gray*)

- Waiting for 183 GHz tailored to VY CMa



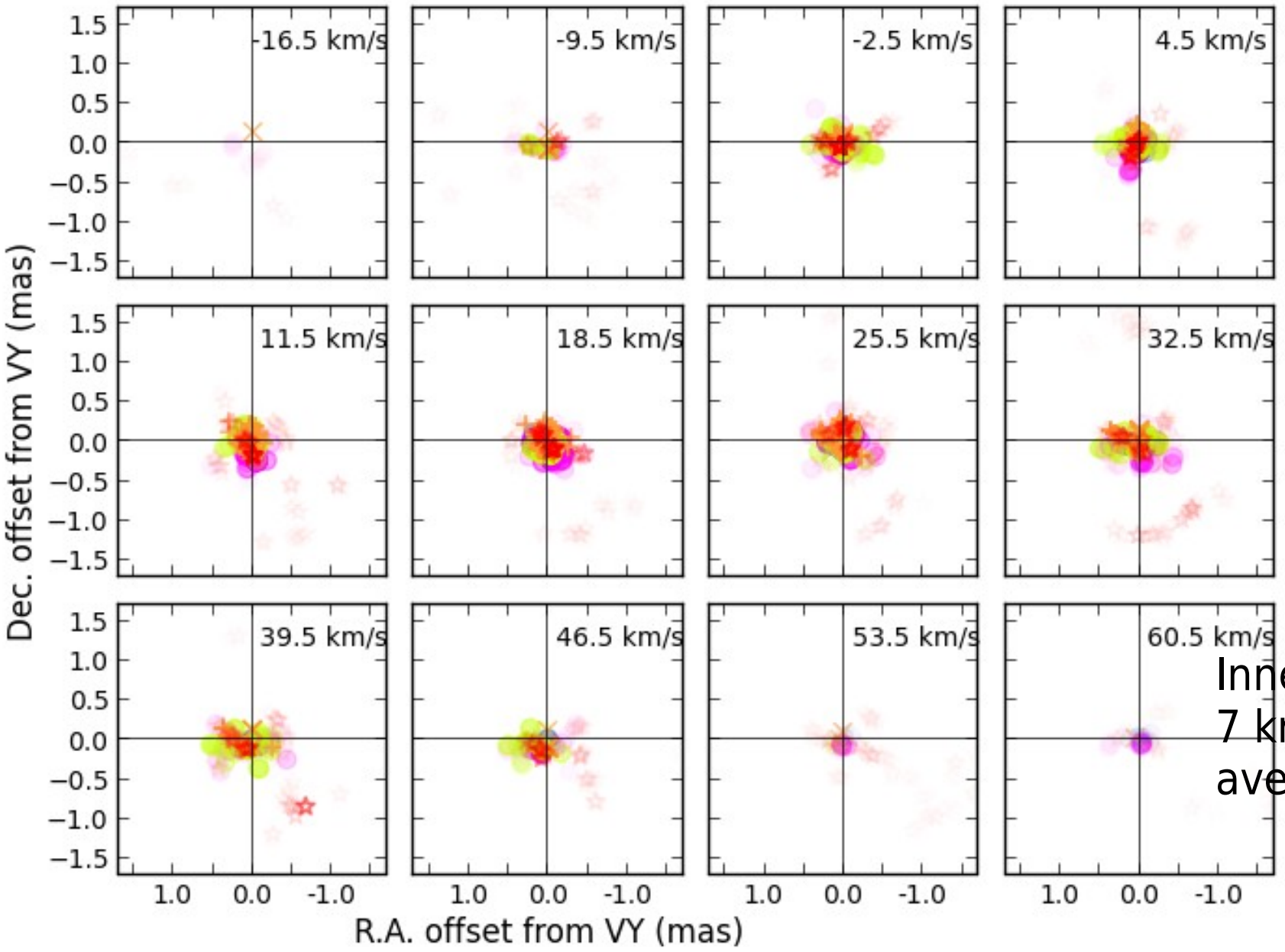
- Deeper shade = stronger maser inversion
- Contour at 50% maximum maser optical depth

Observed maser relationships



Zoom example
7 km/s channel
averages

Observed maser relationships



Inner 3 arcsec
7 km/s channel averages

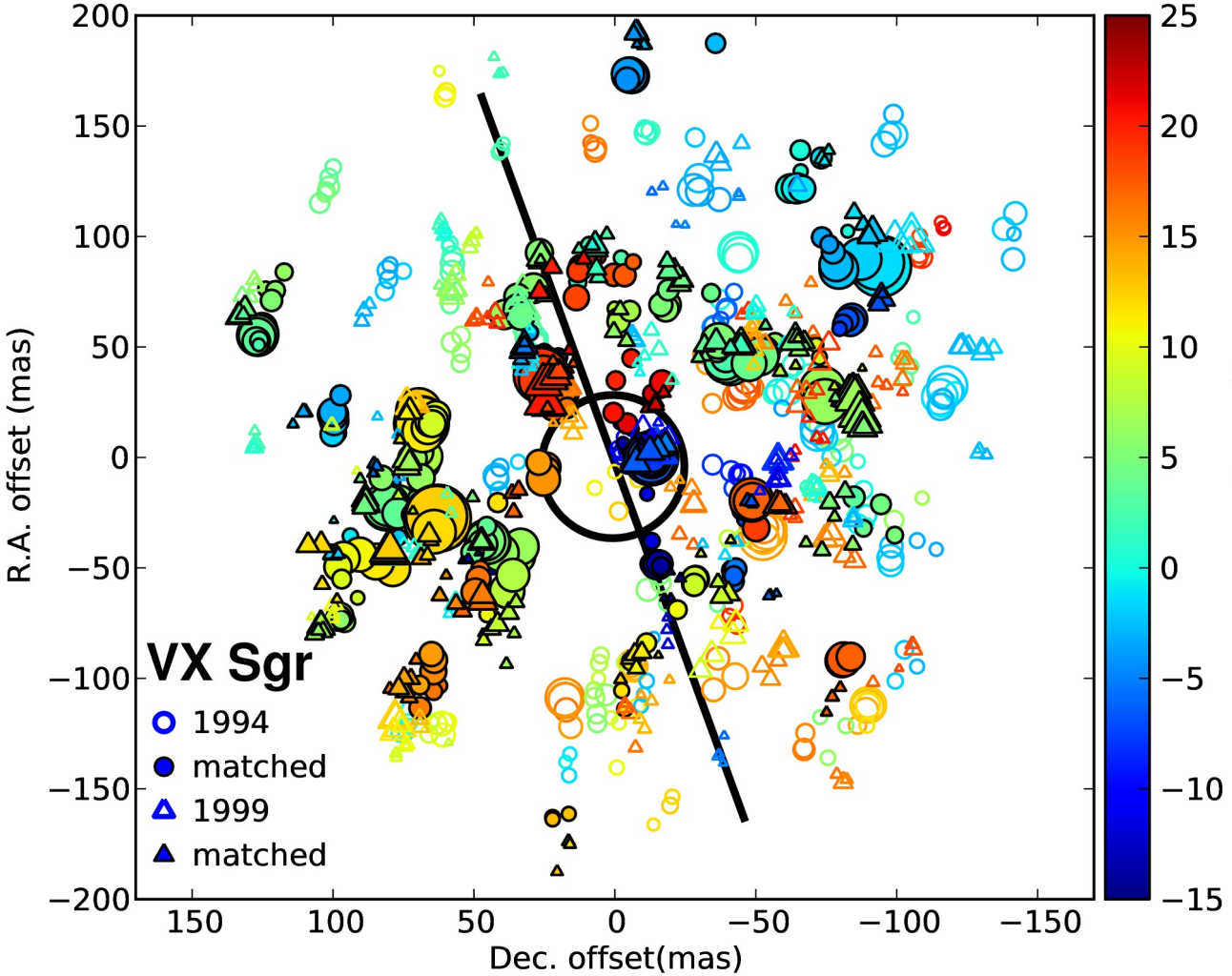
Ongoing work

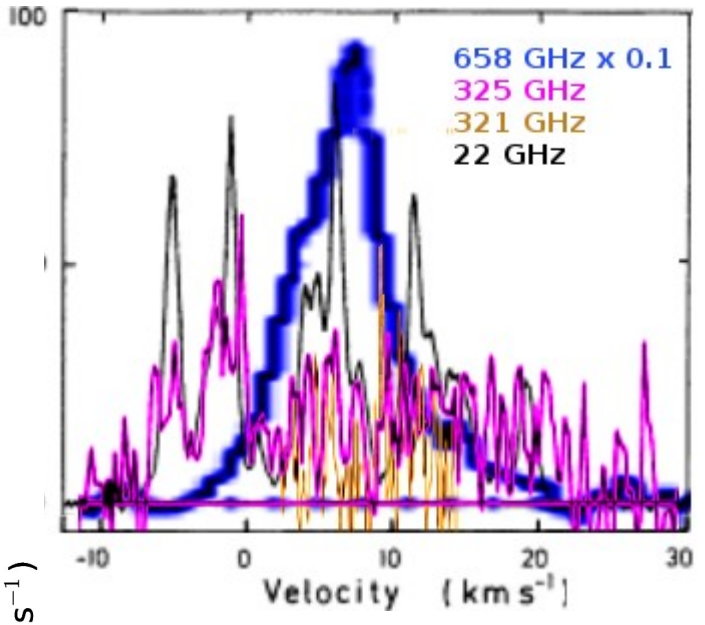
- Physical conditions in inner CSE
  - Clump v. surroundings – *T*, density contrasts
  - Larger scale/axisymmetric inhomogeneities
  - Shock tracers
- Much higher resolution than thermal lines
  - Resolve 5-50 au clumps
- VY CMa least symmetric
  - Hard to use velocity as 3rd axis
- VX Sgr? Almost symmetric at least outside r_{dust}
  - Benchmark water maser models

VX Sgr cm and sub-mm

- 22 GHz slight axisymmetry

  (Murakawa, Richards, Vlemmings)





- Sub-mm spectra *(Yates, Hunter)*
  - No water maps yet

Need for high resolution

- MERLIN 10-20 mas res^{n} detects all 22 GHz emission,
  - Resolves spots
    - Maser physics
    - Shock diagnostics
- Need ALMA high resolution
- Disentangle clouds
  - Co-propagation v. avoidance
    - Constrains *T*k, *T*dust, *n*, d*V*/d*r*, H_2O abundance...
- Central star 10s – 100s Jy in ALMA bands 3 – 10
  - Bright enough to self-calibrate
    - As are most water masers!
- ***Please give us long baselines at all bands!***