Mass loss from evolved stars
super-detailed observations

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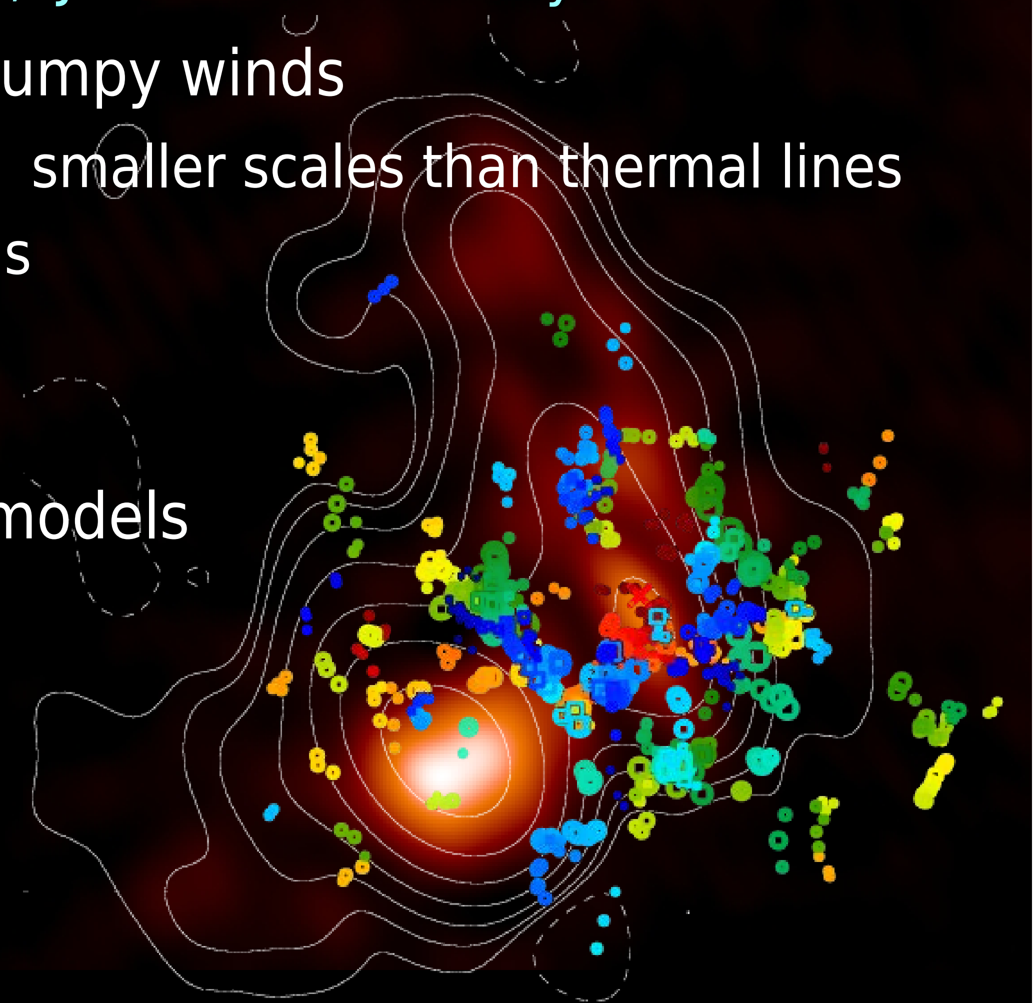
A. Baudry, L. Decin, M.D. Gray, E.M.L. Humphreys, I. Marti-Vidal, A. Sobolev, W. Vlemmings, J.A. Yates and many more

- Maser imaging resolves clumpy winds
  - Physical conditions on much smaller scales than thermal lines
  - ALMA, e-MERLIN observations
    - VY CMa
- Maser models *Gray+'16*
- Compare results with 1D models
  - *Herschel*-based



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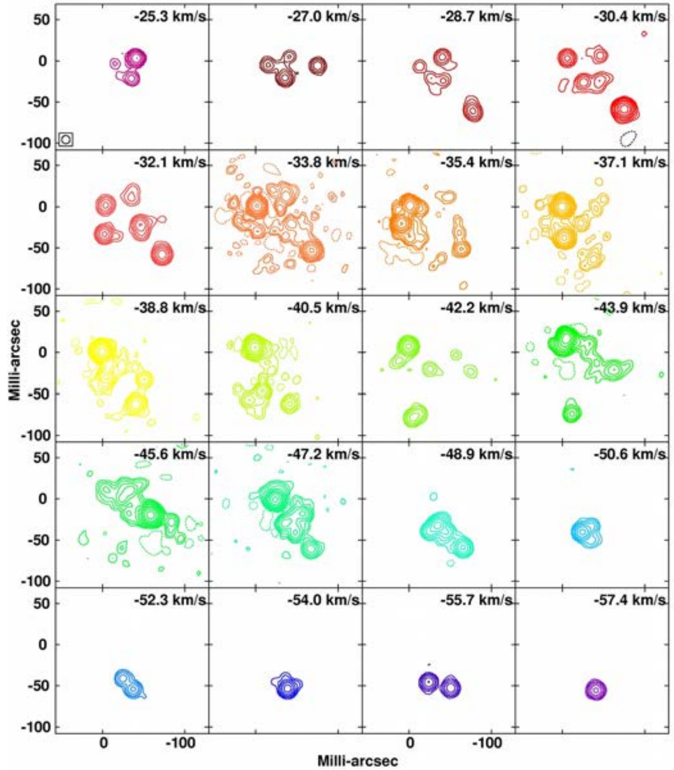
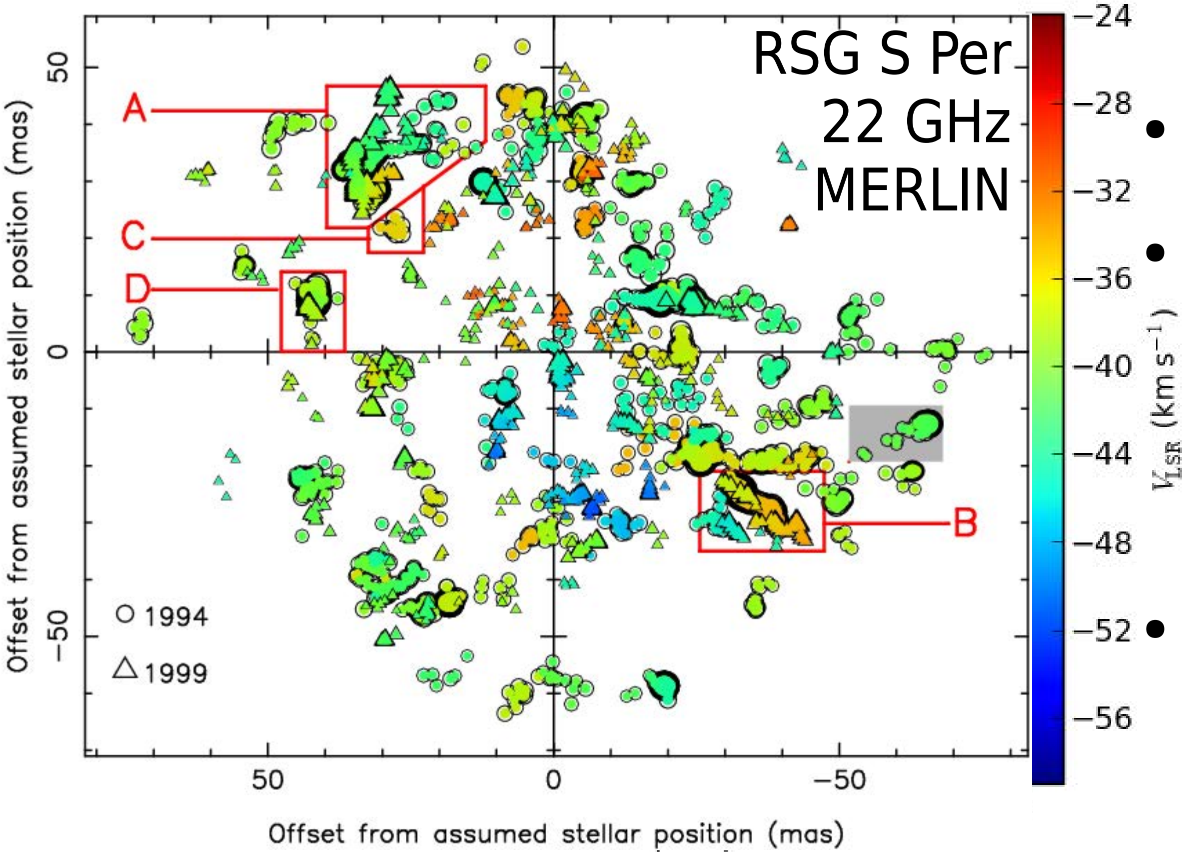
Mass loss problems for O-rich cool stars

- How is mass lost from the stellar surface?
  - Pulsation, convection, magnetic effects
    - Clumpy right from the start?
- How does O-rich dust form? Al oxide nucleation?
    - (e.g. *Hoefner, Bladh, Gobrecht, Wittkowski, Decin*)
  - Grains within few R_* must be transparent to survive
    - Driven by scattering out to cooler, growth zone?
  - Radiation pressure on dust drives wind at >~5 R_*
- Consider conditions in clumps, not just average
  - Uneven dust formation - uneven acceleration?
    - Do dust properties evolve at >~5 R_* ?
  - Do clumps survive/shield dust into ISM?

Resolving H_2O masers

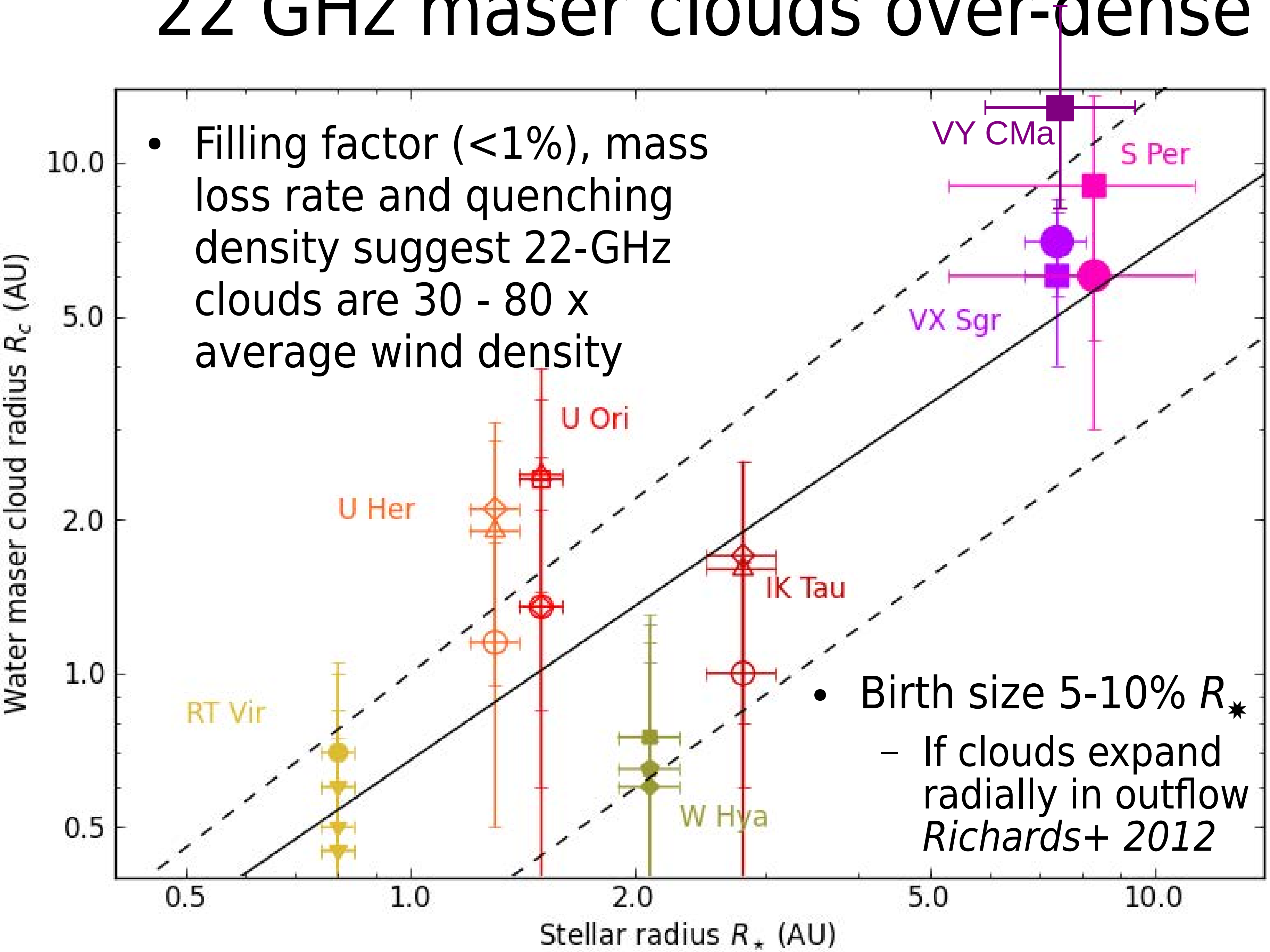
- Each channel: beamed **components:**
- Fit 2-D Gaussian, FWHM *s* (0.01-10 mas)
  - Uncertainty $\sigma_{pos} \propto$ (beamsize)/(S/N)
- Series make **features** (e.g. **A - D**):
  - Gives 'true' **cloud** size *L* (2-100 mas)





- θ_B<(few)100 mas resolve *L*
- $\theta_B \lesssim$ 25 mas also resolve *s*
  - Beaming angle $\Omega = s^2/L^2$
    - Shock v. quiescent clouds
    - Accurate T_b
- $\theta_B \lesssim$ 5 mas resolve out?
  - *If* shortest spacing $\lesssim$80 mas (1.5 Mλ)

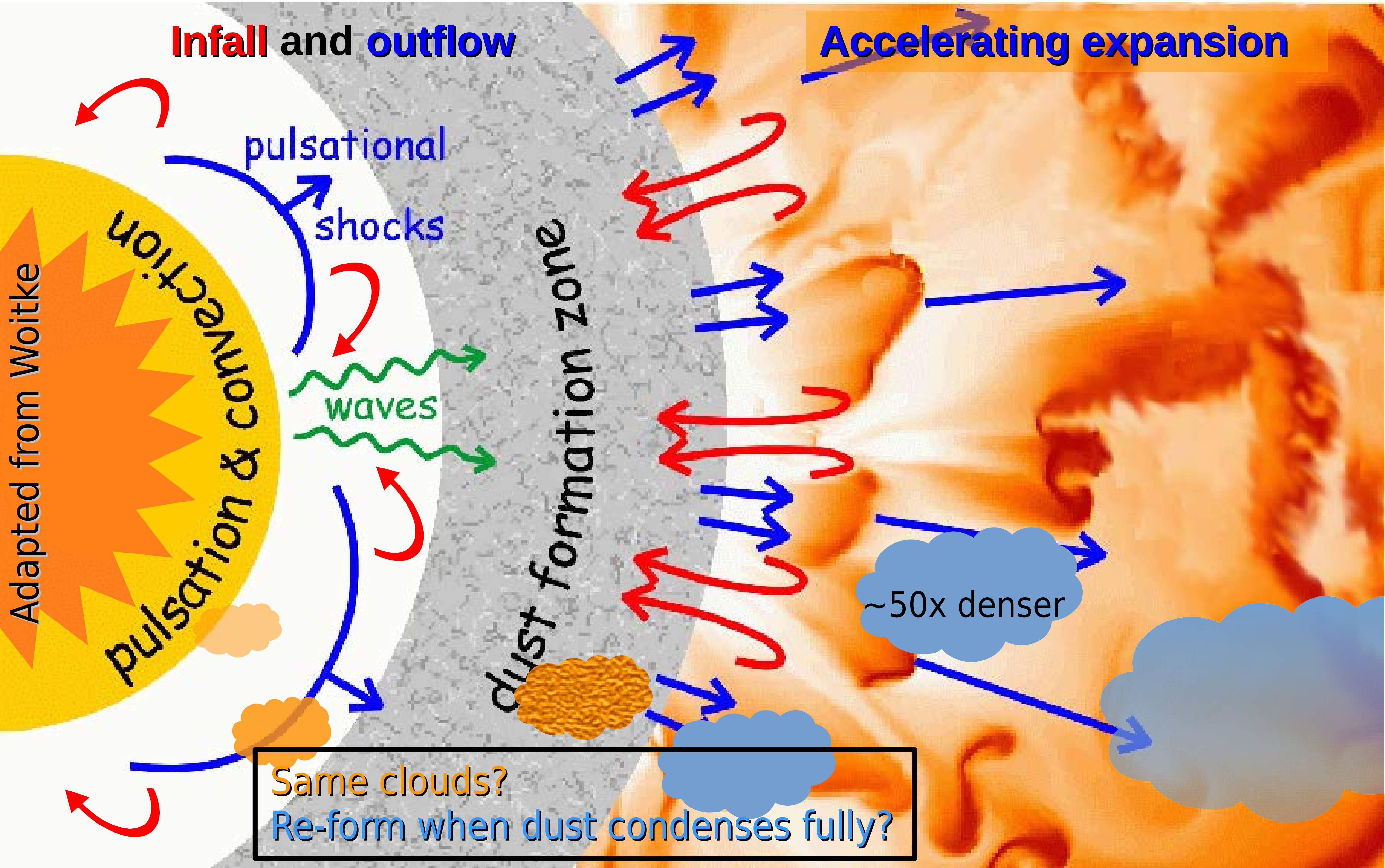
22 GHz maser clouds over-dense



- Filling factor (<1%), mass loss rate and quenching density suggest 22-GHz clouds are 30 - 80 x average wind density

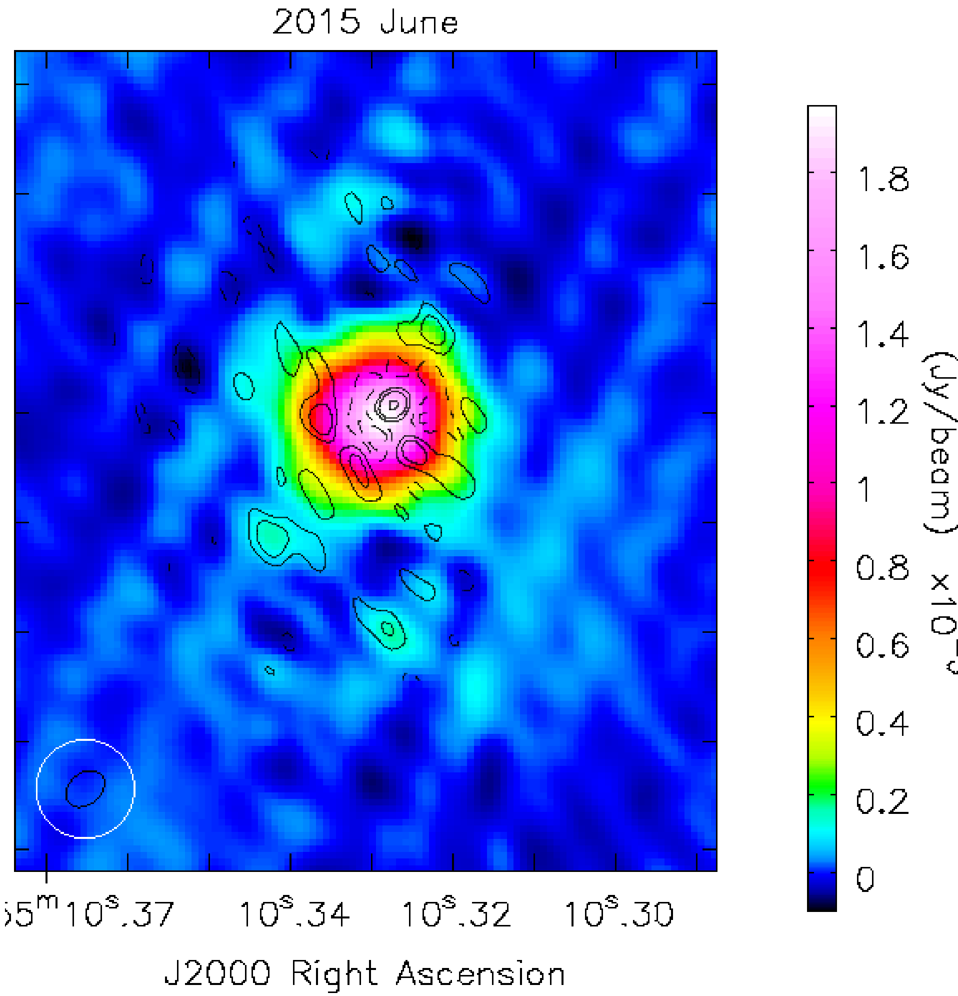
- Birth size 5-10% $R_\star$
  - If clouds expand radially in outflow *Richards+ 2012*

Zones around the star



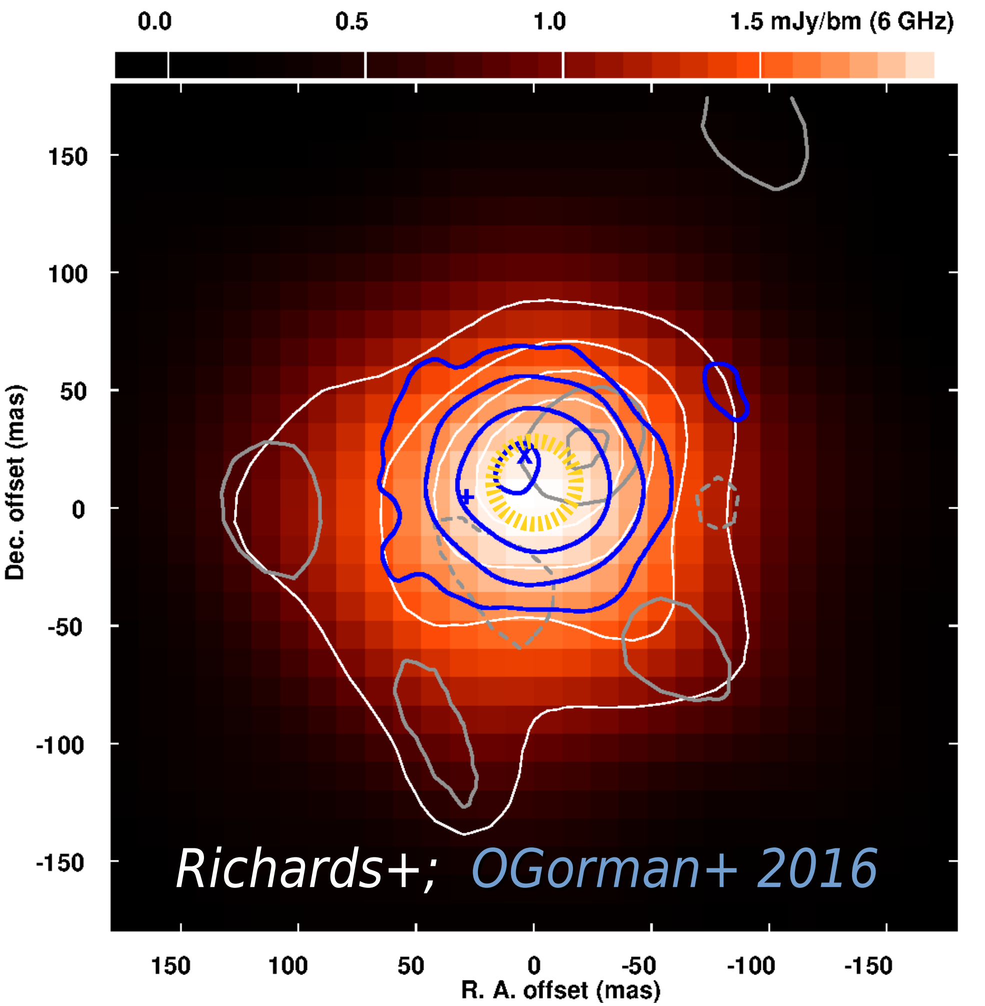
Starspots

- Background e-MERLIN 5cm low-resolution 2015 Jun
- Contours: 5cm hot/cold spots
  - ~10% contrast, size
    - *Chiavassa* convective cells?
- 3 epochs - different spots
  - Changes in few months-yrs
    - Radiative effects needed?
  - Zoom in....

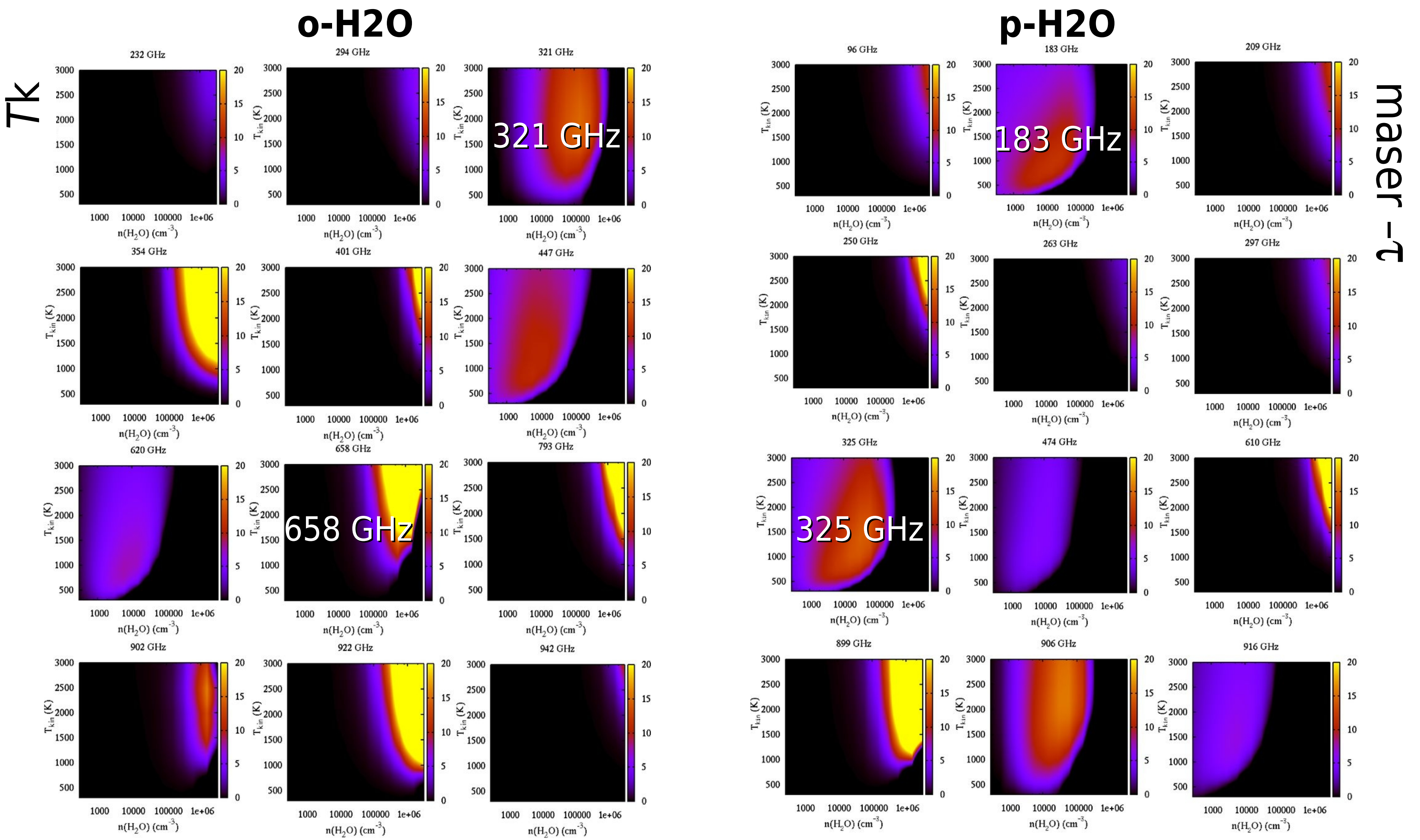


Starspots

- Background e-MERLIN 5cm low-resolution 2015 Jun
- White: 5cm 180-mas beam
- Grey: 5cm hot/cold spots
- Blue: 0.089cm ALMA
  - ~50% contrast + x
- Yellow ring: photosphere
- ALMA - e-MERLIN hotspots no obvious correlation
  - Depth difference 1.3-4.5 $R_\star$
- *Any day now: ALMA absorption Doppler imaging, Kervella et al. 2017*



Maser (negative) optical depths for some of the ~50 lines of H_2O visible to ALMA as functions of kinetic temperature & o-H_2O number density

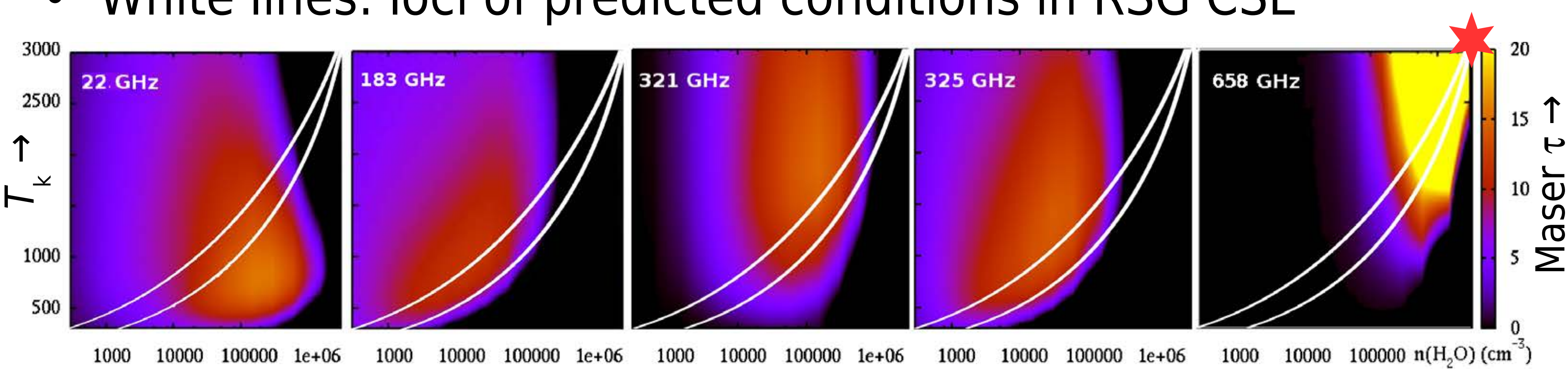


M. D. Gray et al. MNRAS 2016

ALMA sci. verification (sub-)mm masers

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

- Model predictions for maser optical depth/brightness:
  - 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

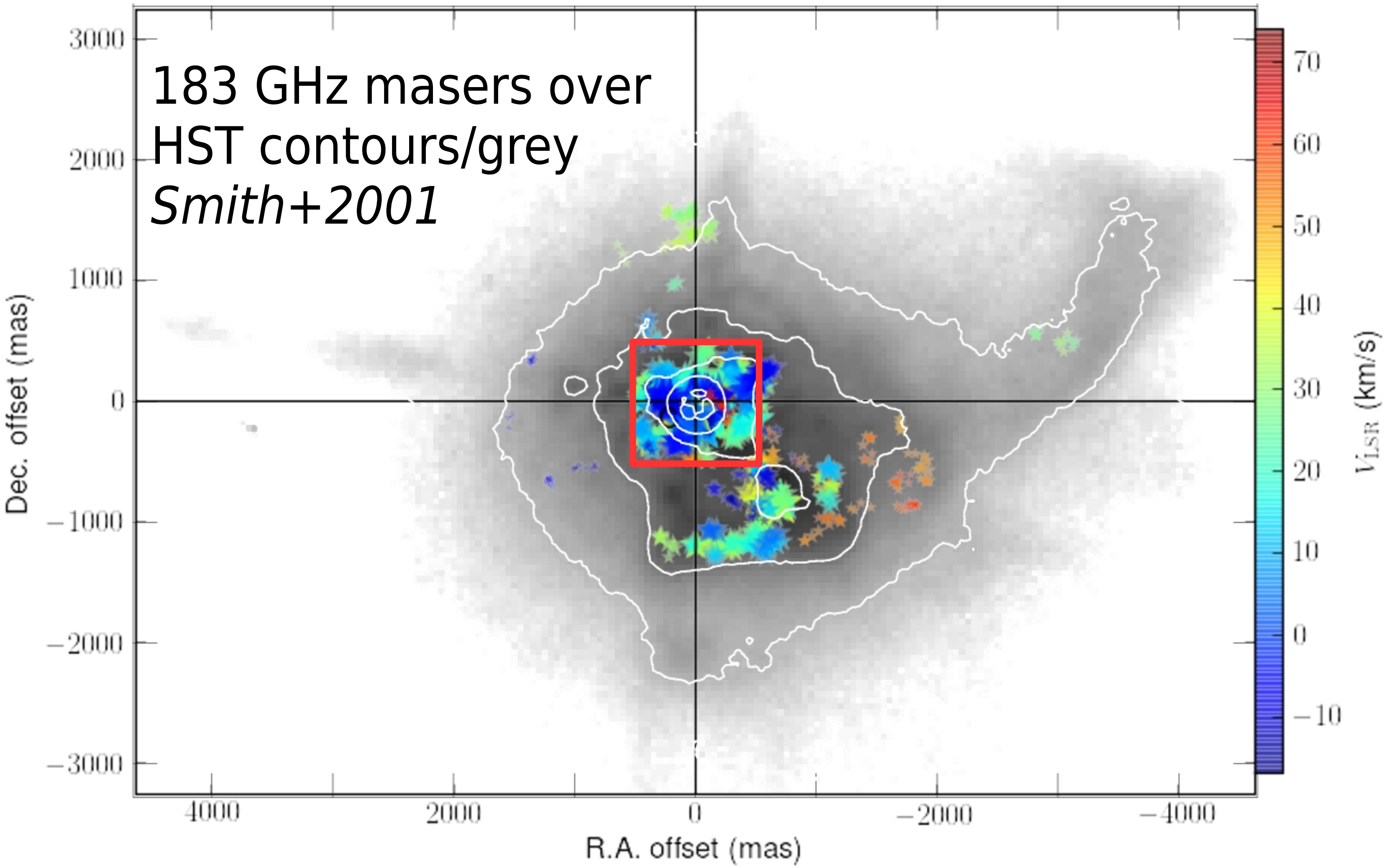


Gray et al. 2016

Higher number density →

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

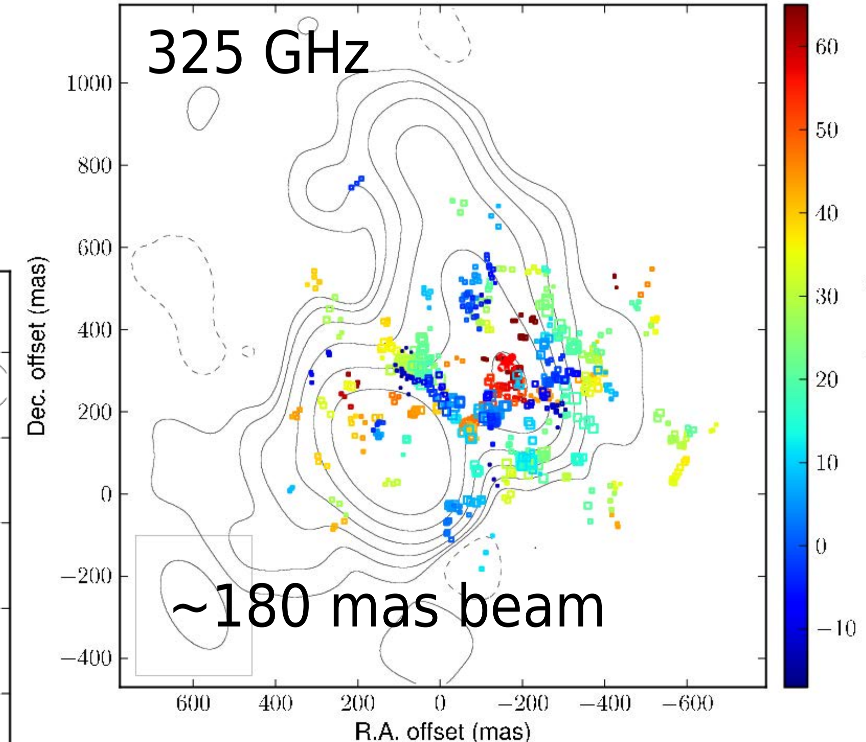


(an aside)

- Does VY CMa fling out clumps almost ballistically?

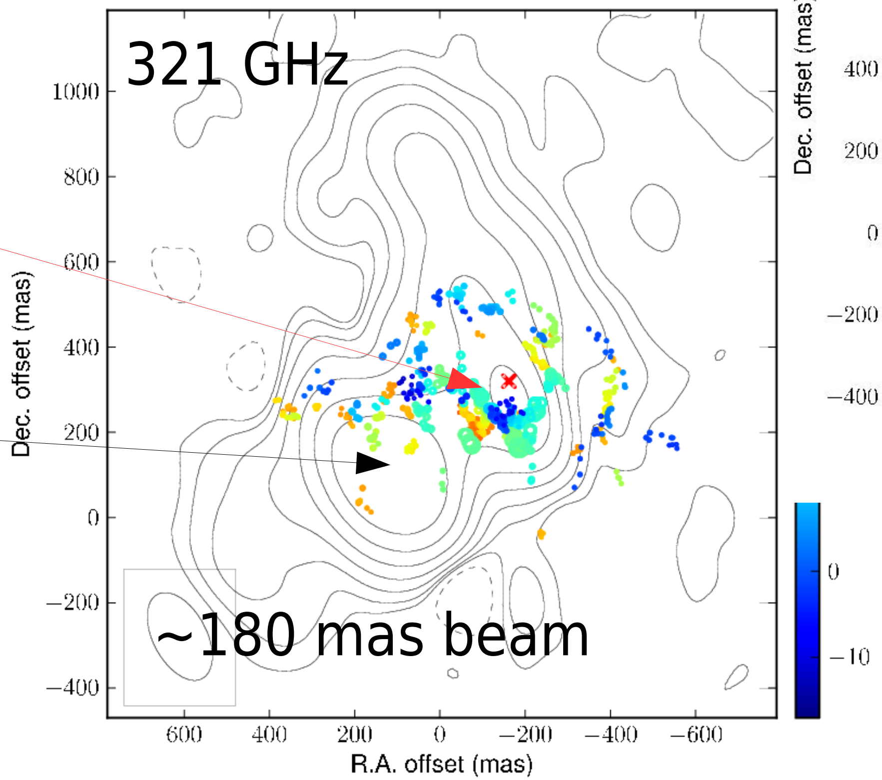
R Humphreys et al 2007

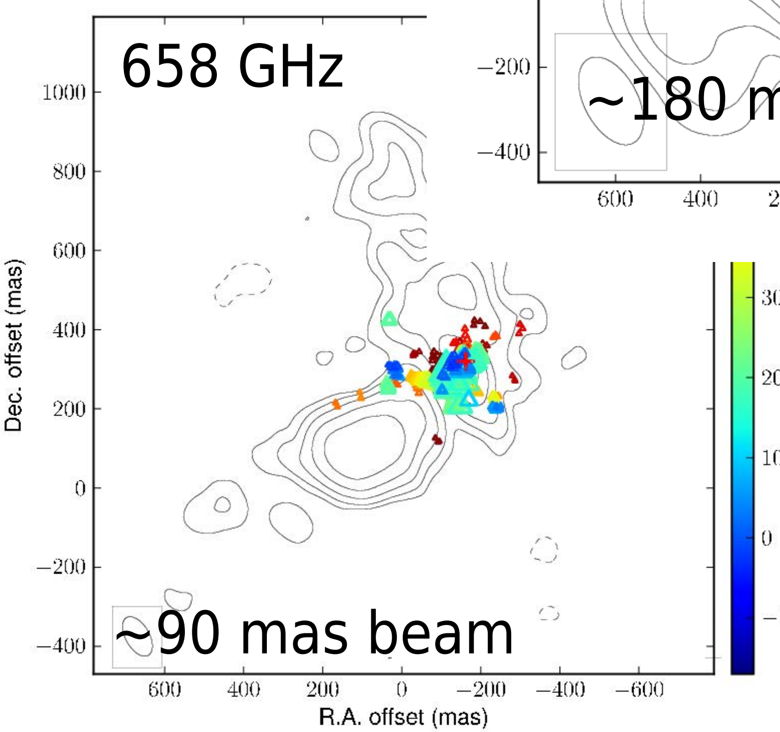
VY CMa sub-mm H_2O masers



Star, **VY**

C

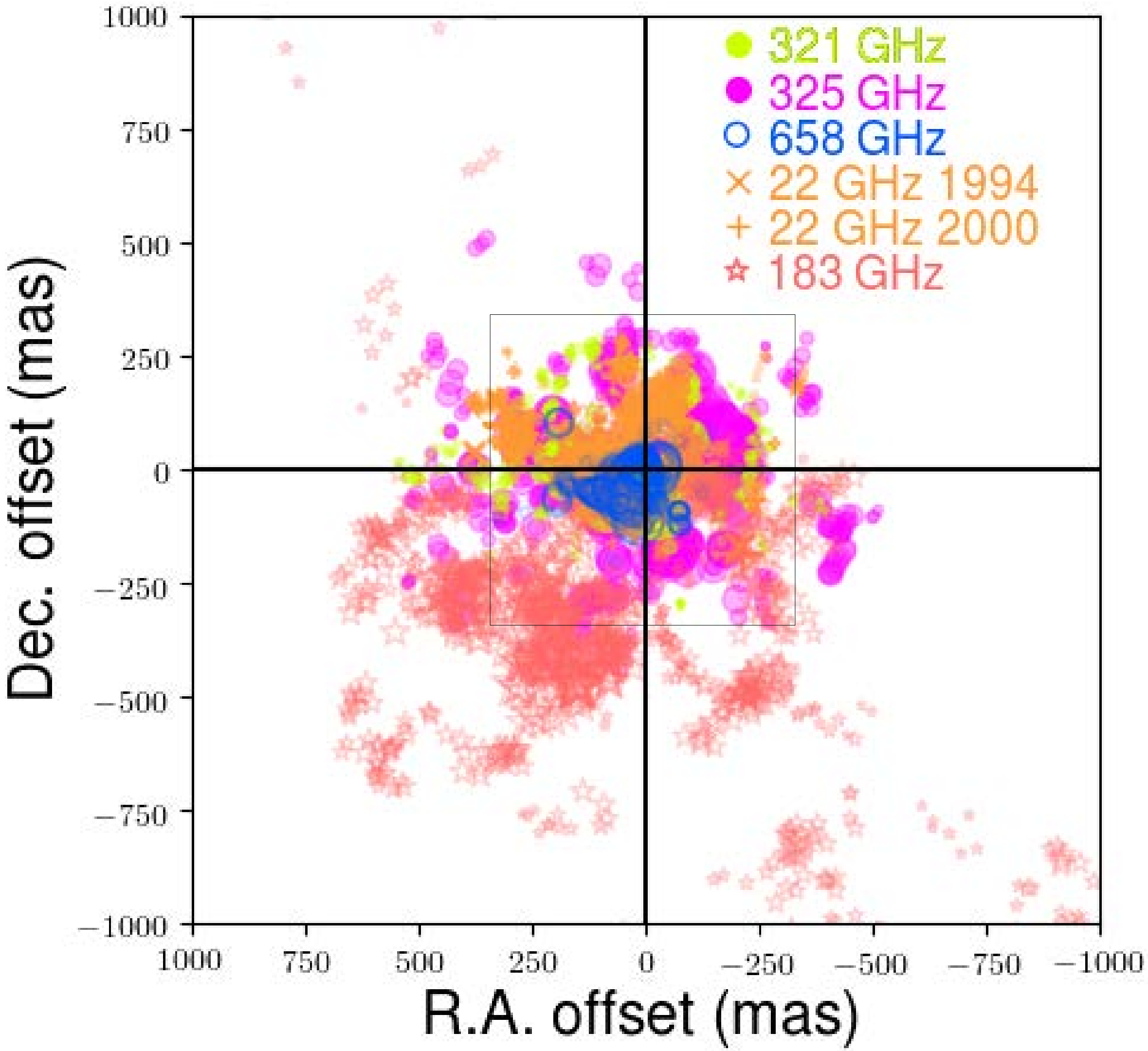




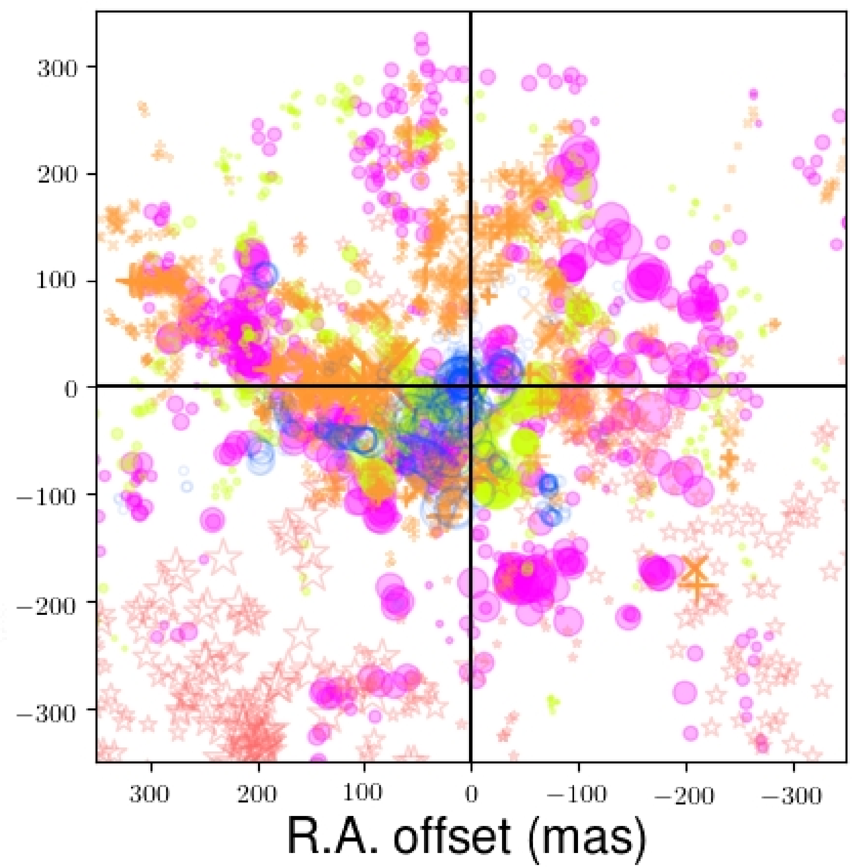
- 658-GHz surprisingly extended round cold clump **C**
  - Shock?
    - *OGorman+15*

- Masers centre on **VY**
  - 325 GHz furthest
  - 658 GHz closest
  - 321 GHz between
    - Clearest strong acceleration
    - *Richards+14*

Zoom in on 5 transitions

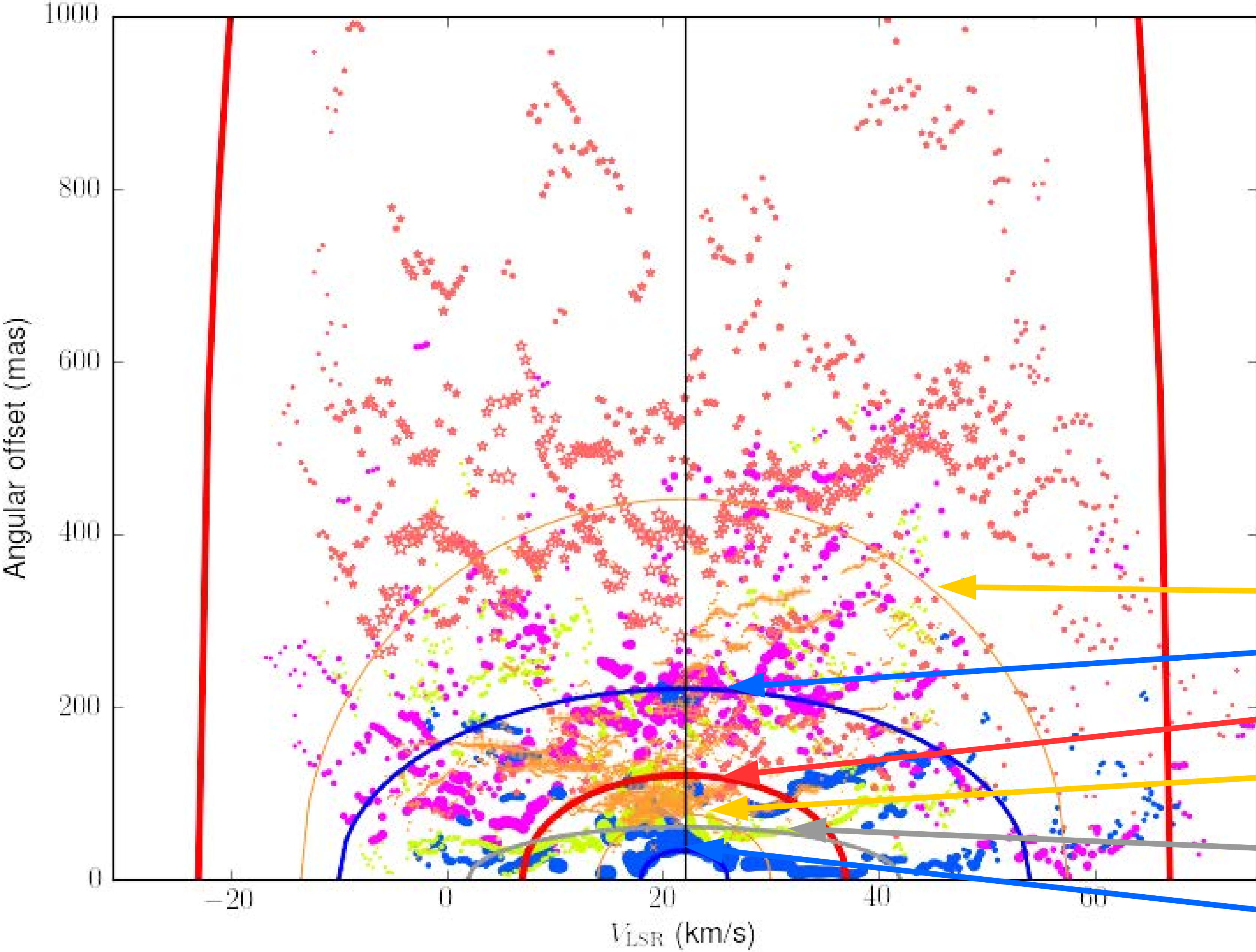


- H_2O components
- Size ∝ √flux density
- VY at (0, 0)



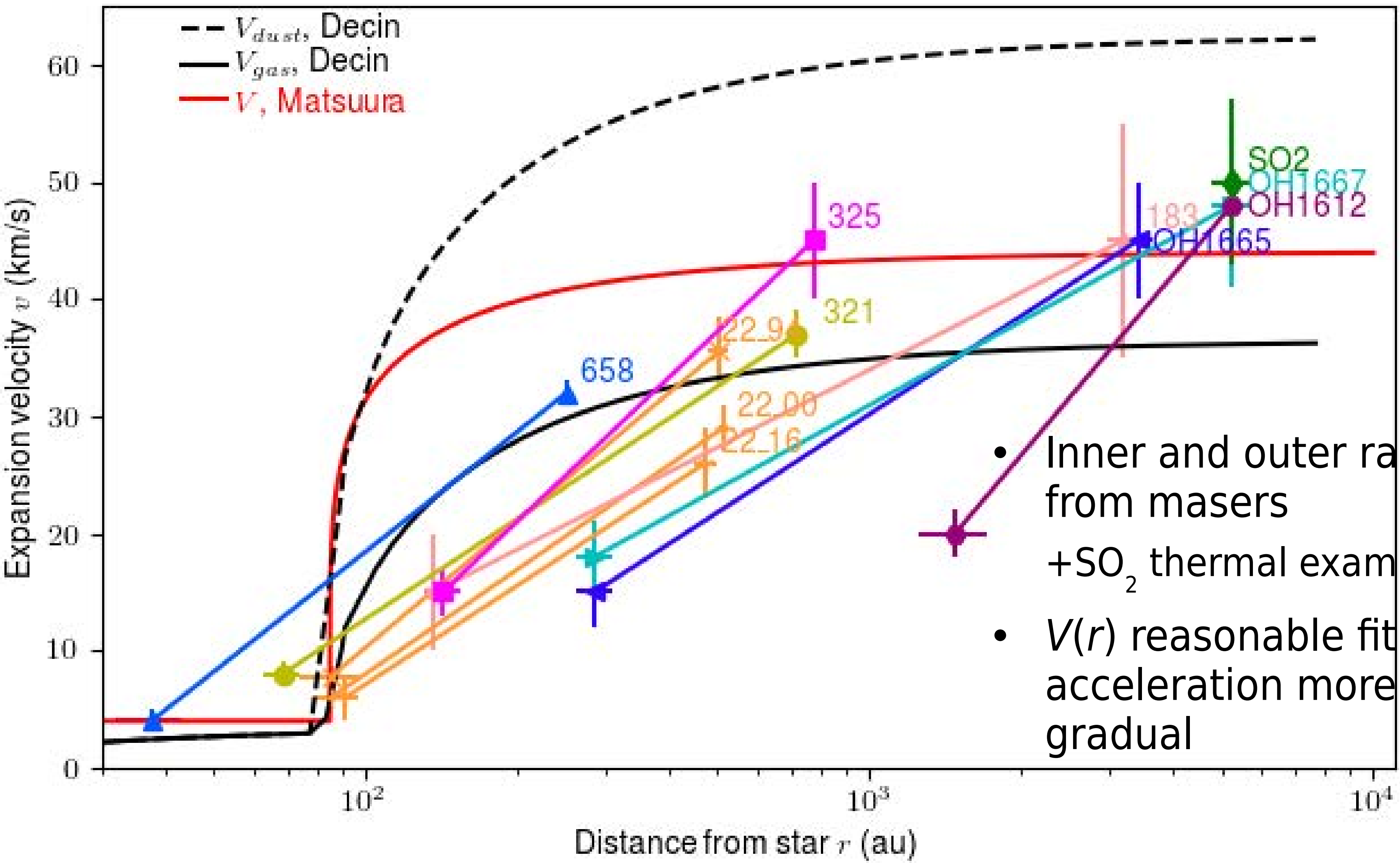
- 321, 325, 658 GHz obs 2013
- 183 GHz obs 2016

Angular separation-velocity



- Well-defined inner shell limits

Gradual acceleration



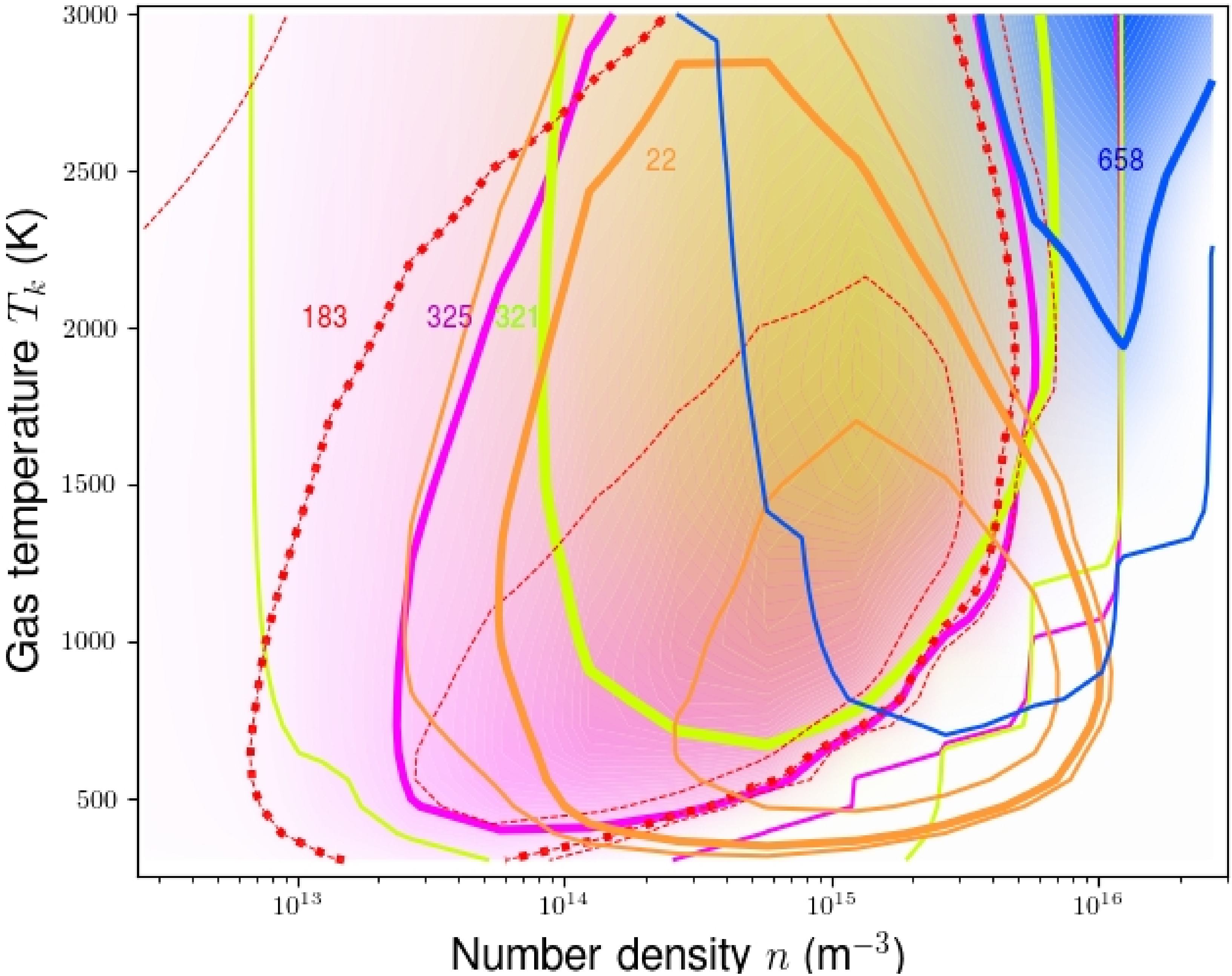
- Inner and outer radii from masers

  +SO_2 thermal example
- *V*(*r*) reasonable fit but acceleration more gradual

Maser modelling of VY CMa

- Asymmetry - hard to use velocity as 3rd axis for VY CMa
- Hope that within inner ~1/4 ($V_{\ast}$ ±12 km/s), emission within ~2 km/s is spatially close
- Cloud sizes ~10-100 au (183 GHz biggest)
  - Proper motions few mas/yr
  - Small between ALMA 2013 and 2016 obs
    - 22 GHz not phase referenced, star not yet detected
      - 2016 GHz tests taken with 3 e-MERLIN antennas
- Use Gray model to infer number density n, temp T_k for combinations/exclusions of different ALMA lines
- Compare Decin & Matsuura predictions for locations

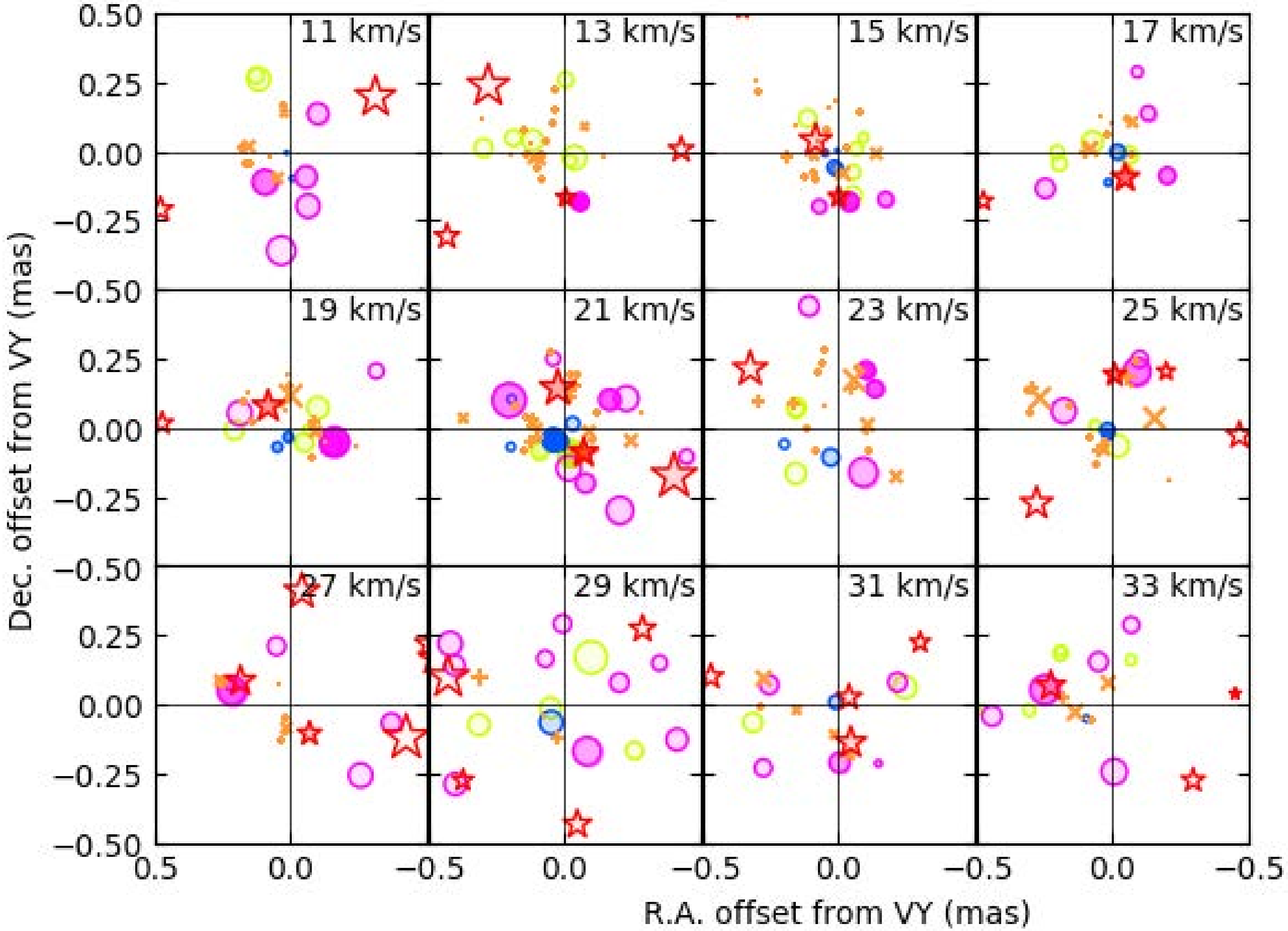
VY CMa maser model (*Gray*)



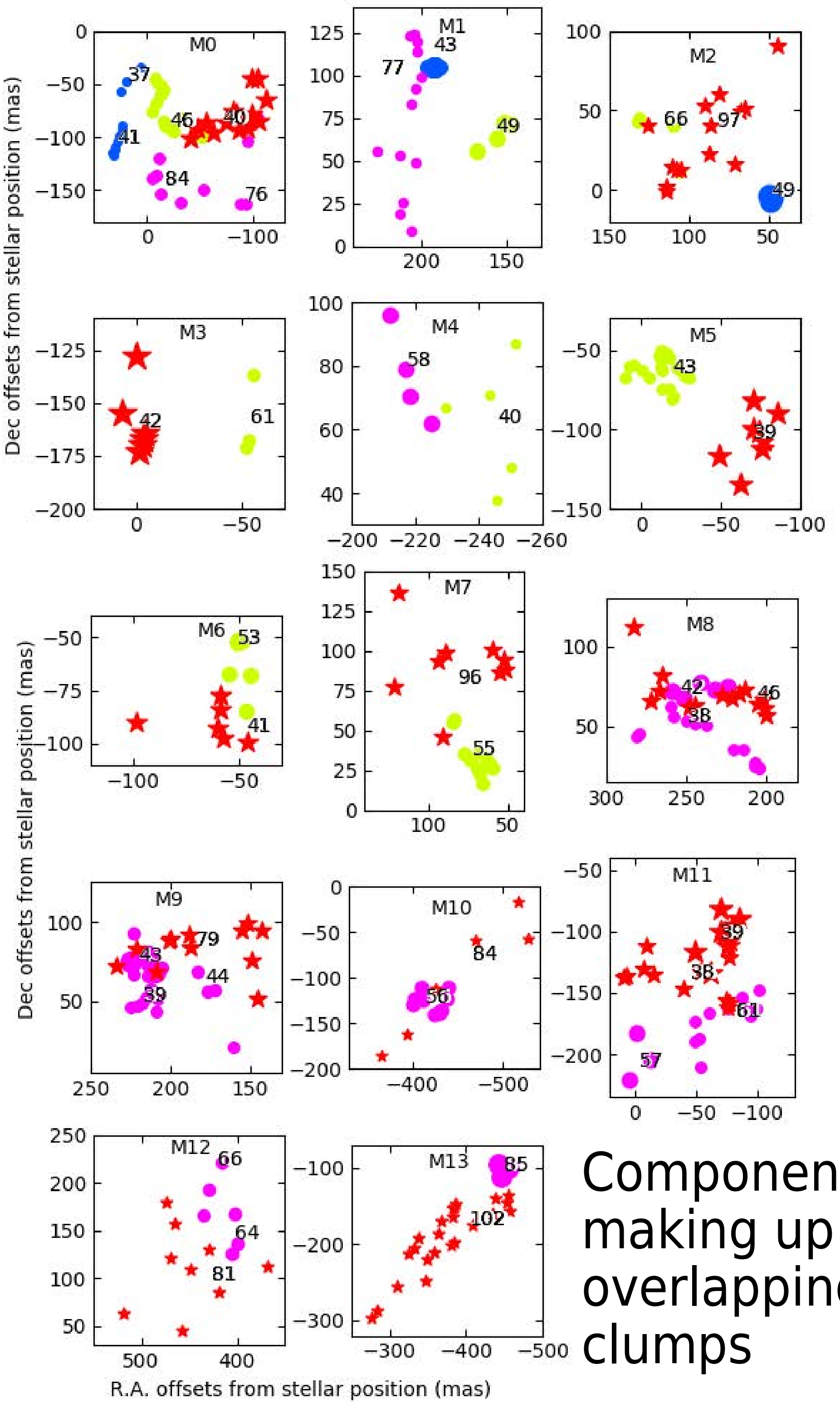
- 658, 321, 325 GHz deeper shade = stronger maser τ
- Also for 22, 183 GHz **contour** at 50% max τ
- Lowest contour at crude estimate of sensitivity limit

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



Components making up overlapping clumps

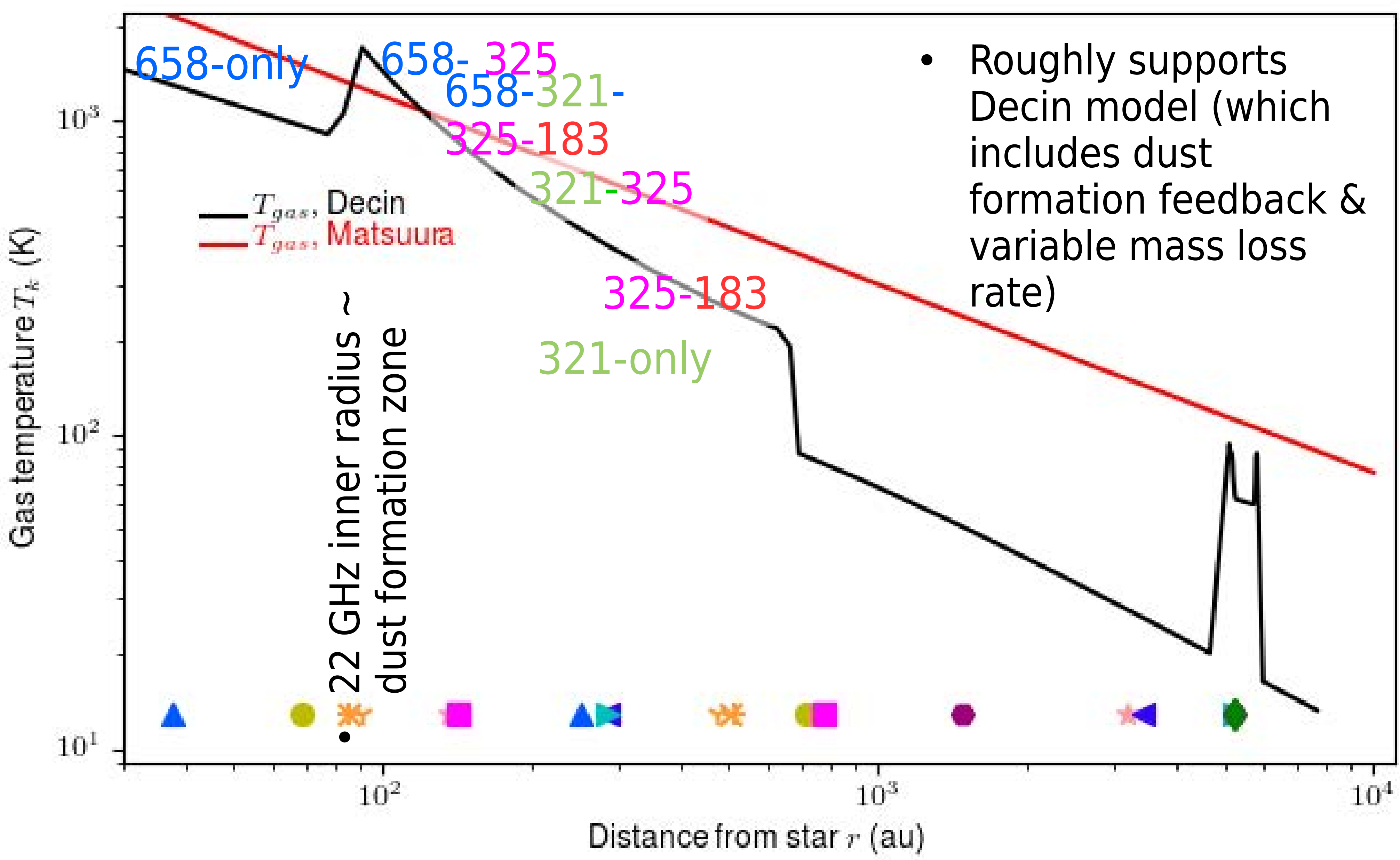
Surprisingly few line overlaps

- ~70 - 170 features per line
- 14 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 angular size
      - Probably from clouds elongated along line of sight
    - Saturation, shocks ignorred

Analysis (rough)

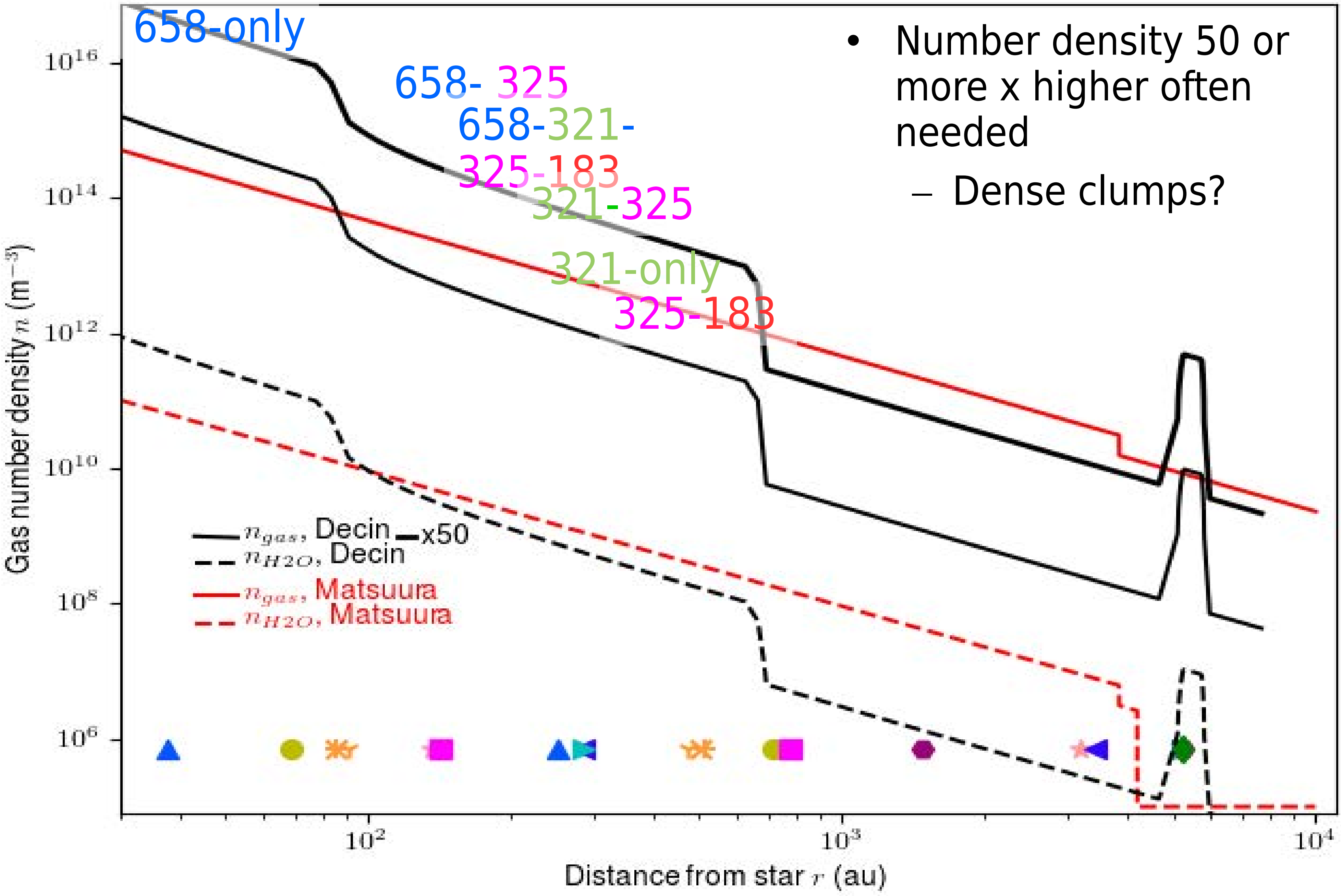
- **M1** 658-325 GHz copropagate? 321 GHz near
  - T_k ~1000 K; n [6-10]x10^{15} m^{-3} (high end if no 22 GHz)
- **M0** all 4 ALMA lines may overlap
  - $T_k \gtrsim$1000 K; n <5x10^{15} m^{-3}
- **M2** similar but no 325 GHz; **M3,5,6,7** 321-183 GHz
  - 183 without 325 in 321 region not covered by 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** $\gtrsim$ 500 mas from star
  - $T_k \lesssim$ 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?

Temperature constraints



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

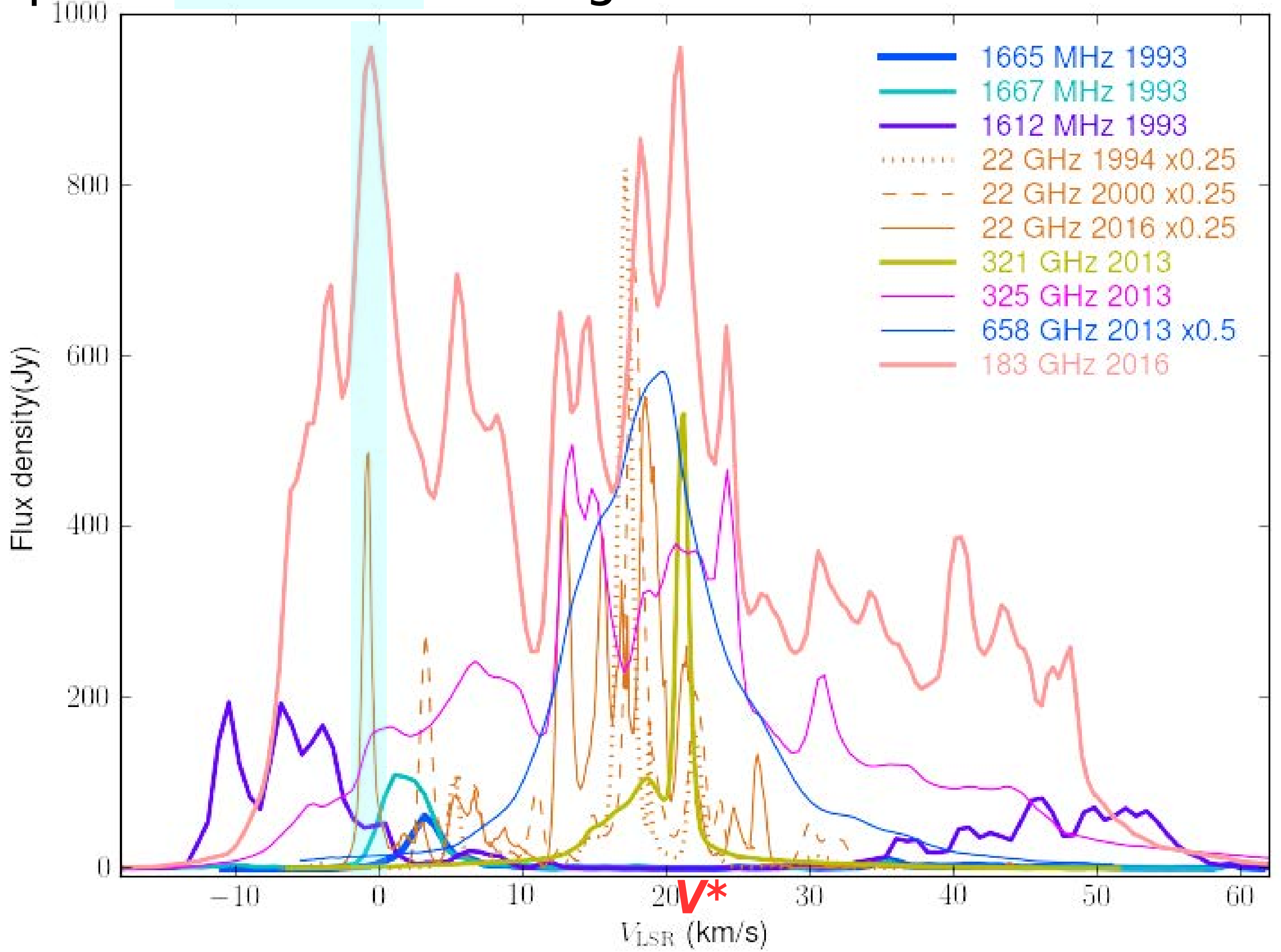
Number density constraints



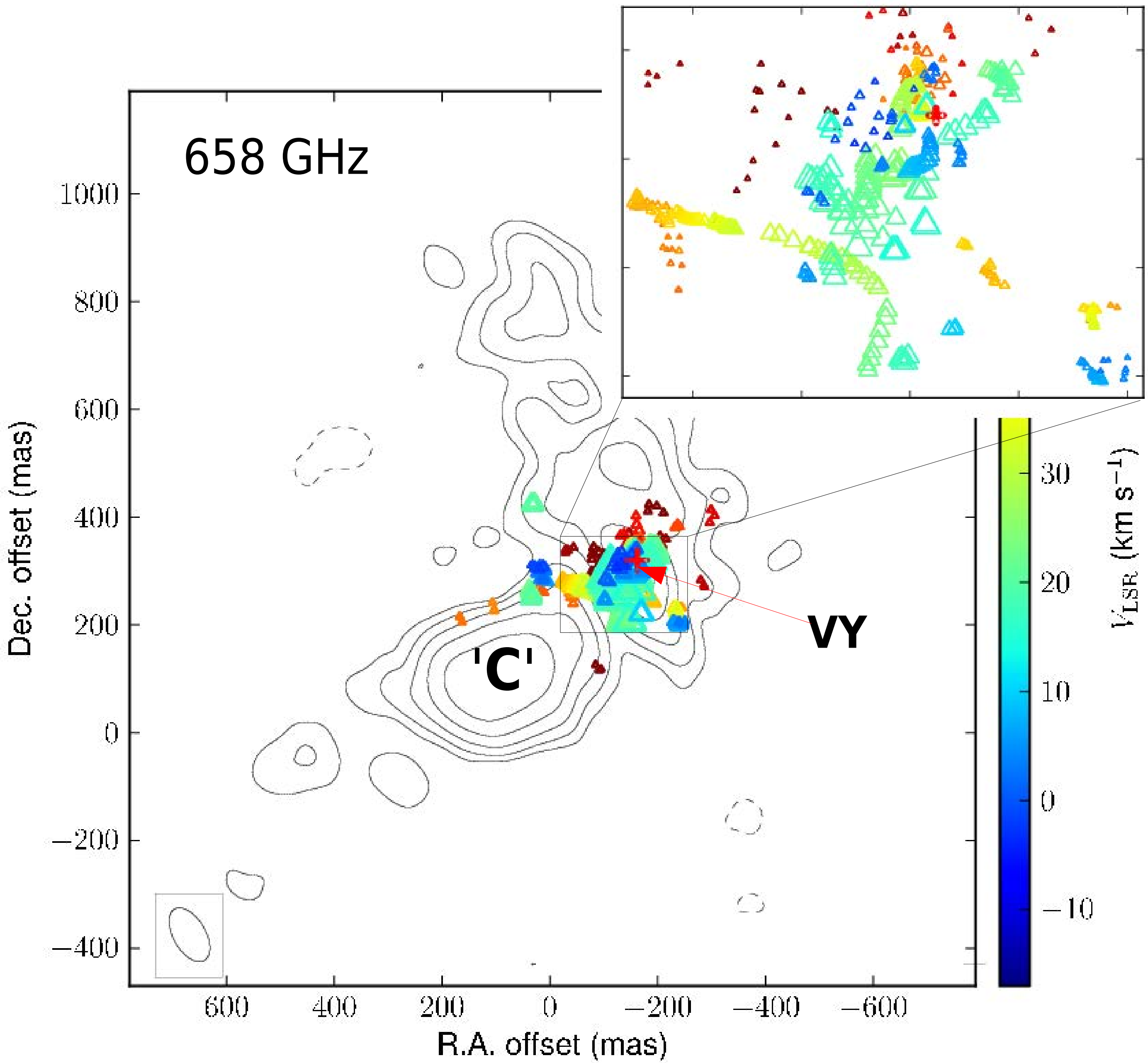
- Number density 50 or more x higher often needed
  - Dense clumps?

183 & 22 GHz blue-shifted flare?

- VY CMa **V*** 22 km/s, 22-GHz peak ~18 km/s for decades
- 2016 183-GHz peak ~-1 km/s as bright as close to V*
- 2016 22 GHz similar: ~-1 km/s ~90% of central peak
- 2013 KVN 22 GHz ~-1 km/s ~30% of central peak
- 1994, 2000 weak 22 GHz ~-1 km/s



Clump '**C**' shock?

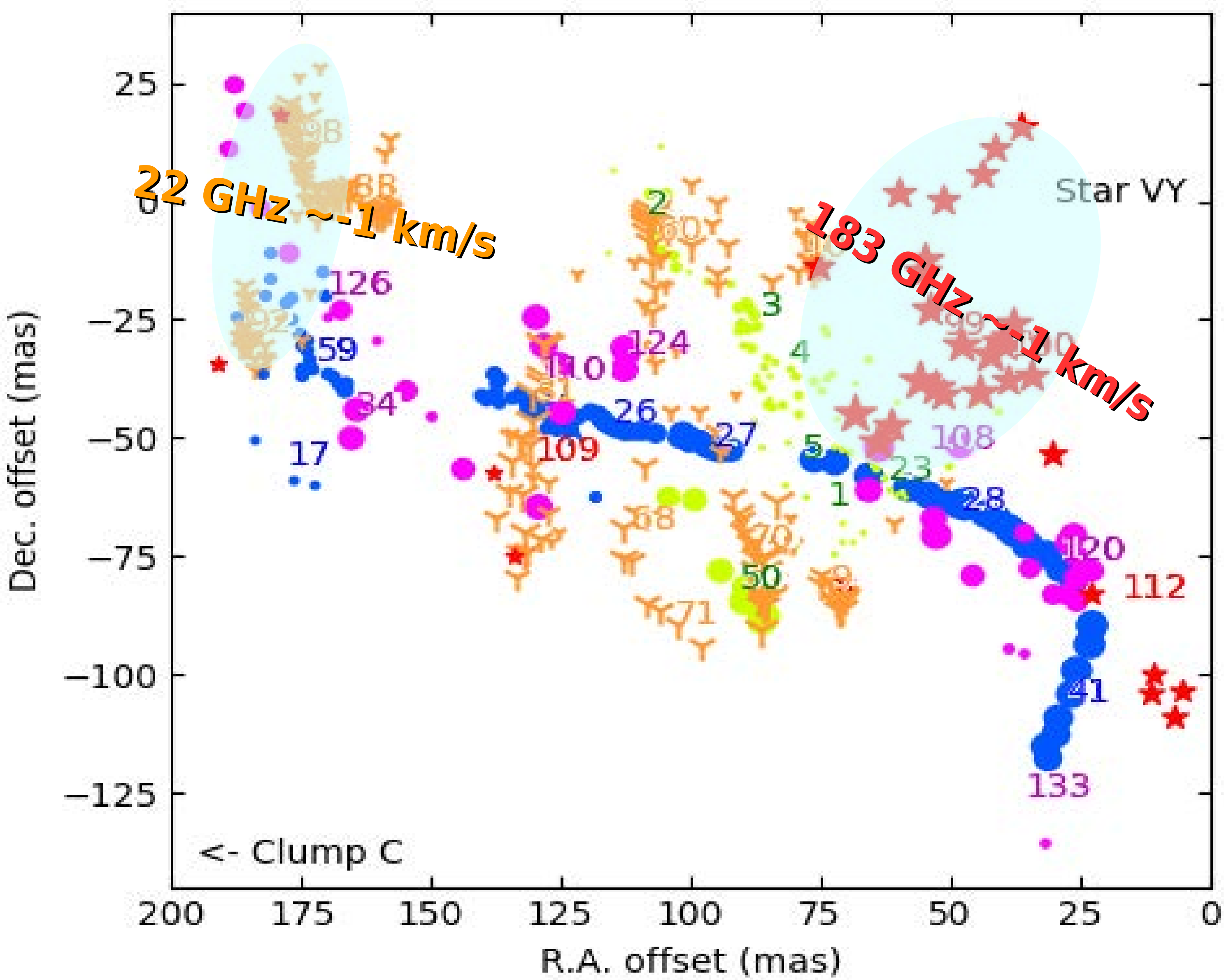


- Continuum contours
- 658-GHz masers appear to curve round '**C**'
  - Wind collides with cold, dense clump?
    - *OGorman+14*
- All masers, many lines avoid '**C**'
  - Only seen at velocities very different from $V_{\star}$ in that direction

Shocks round clump C?

- 2016: 183 and 22 GHz flares around -1 km/s
- 2013 (KVN): 22 GHz flare starts?
- Both lie between **VY** & Clump **C**
- Probably not co-spatial
  - 22 GHz aligned only by centre of expansion

NB faint &/or extreme velocity emission not shown



Work in progress

- Current model: T_d 50 K; $f_{[H2O]}$ 3×10^{-5}
  - Try higher T_d; $f_{[H2O]}$ 2×10^{-4} (Matsuura)? 1.1×10^{-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
- Model τ based on average angular cloud size per line
  - But can't assume VY CMa clouds spherical
    - 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!