Making a splash:

22-GHz water masers and mass loss from stars

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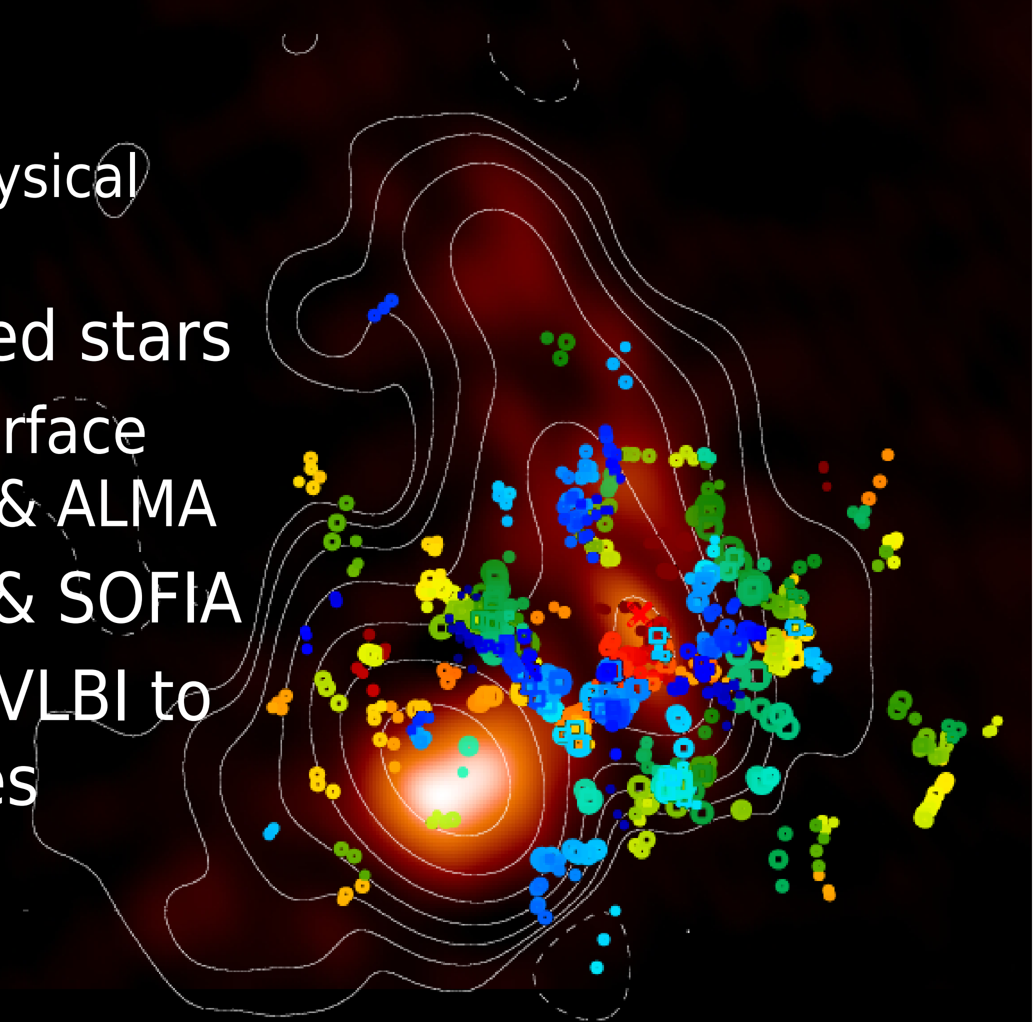
Malcolm Gray, Sandra Etoka, Liz Humphreys, Wouter Vlemmings, many more

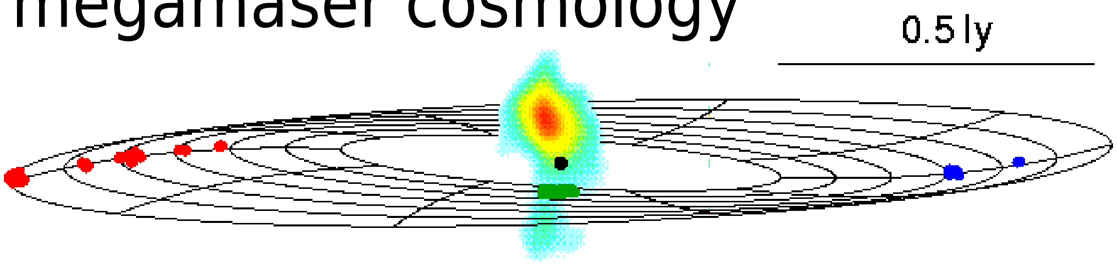
- Water masers:
  - Astrophysics, physics, physical conditions
- Mass loss from evolved stars
  - Resolving the stellar surface and clouds - e-MERLIN & ALMA
- SFR NGC 4258 - e-M & SOFIA
- Optimising e-MERLIN/VLBI to go with multi-λ studies



EUROPEAN ARC
ALMA Regional Centre || UK

Where and why water masers

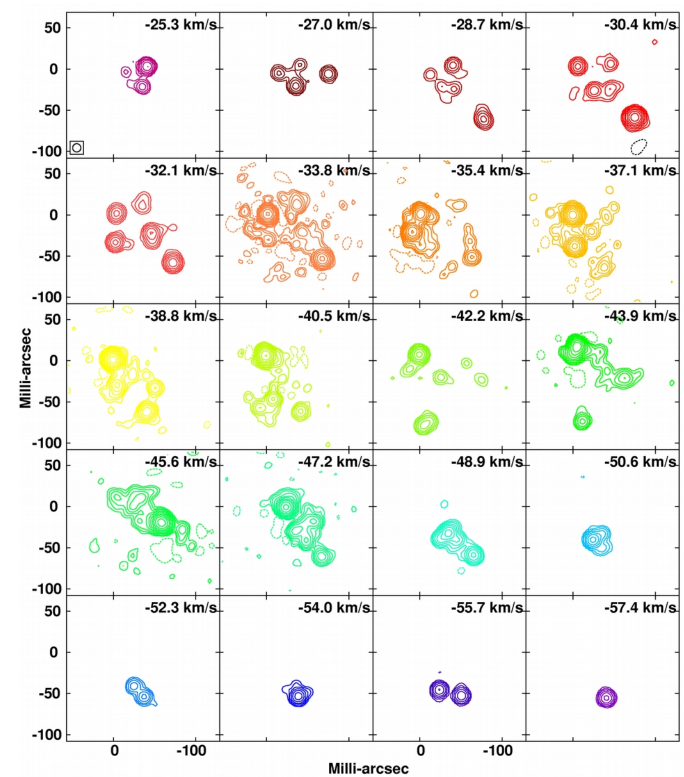
- H_2O masers from any warm molecular gas
  - From Saturn's rings to megamaser cosmology
  - 22 GHz to THz

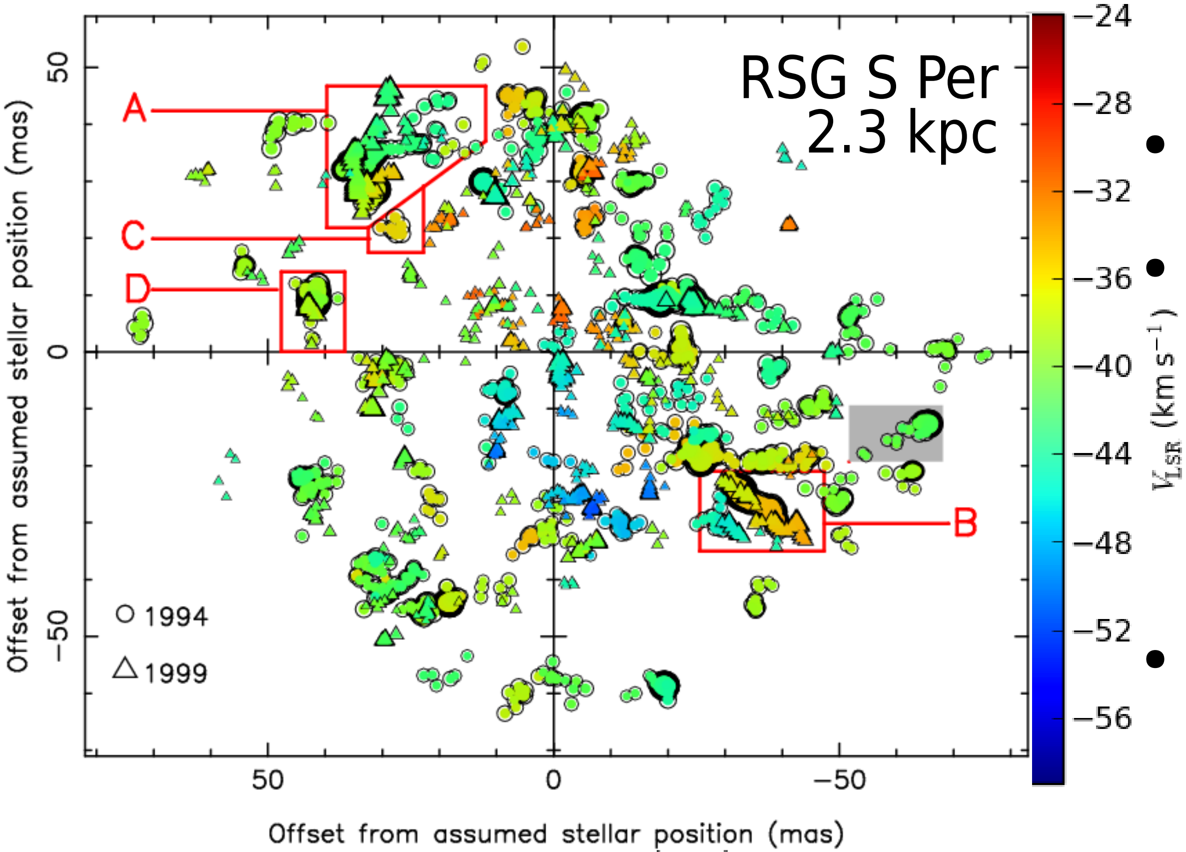


- H_2O plentiful
  - (Re-)forms rapidly in stellar winds, after shocks etc.
- Conditions for population inversion at 22 GHz
  - T_k few 100 K to ~2000 K (but T_{dust} range cooler)
  - Number density n 10^{16} to $\leq 10^{9}$ m^{-3} (depends on f_{H2O})
  - Velocity coherence - enhanced by modest gradient
    - Shocks, warm winds, discs...
- Small but well-modelled Zeeman splitting

Water maser scales

- 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 $\Omega = s^2/L^2$
    - Maser physics
    - Accurate T_b
- $\theta_B \lesssim$ 5-10 mas resolve out
  - Distant proper motions

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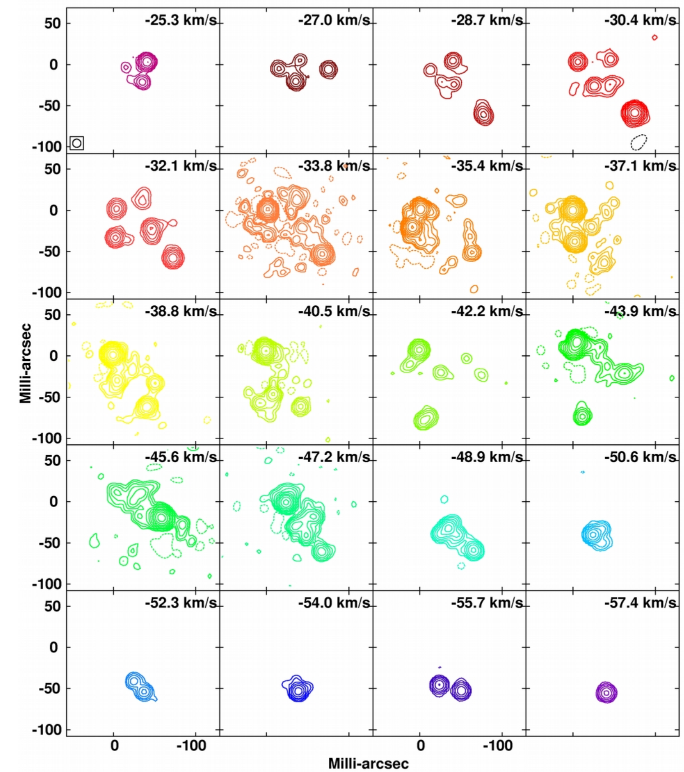
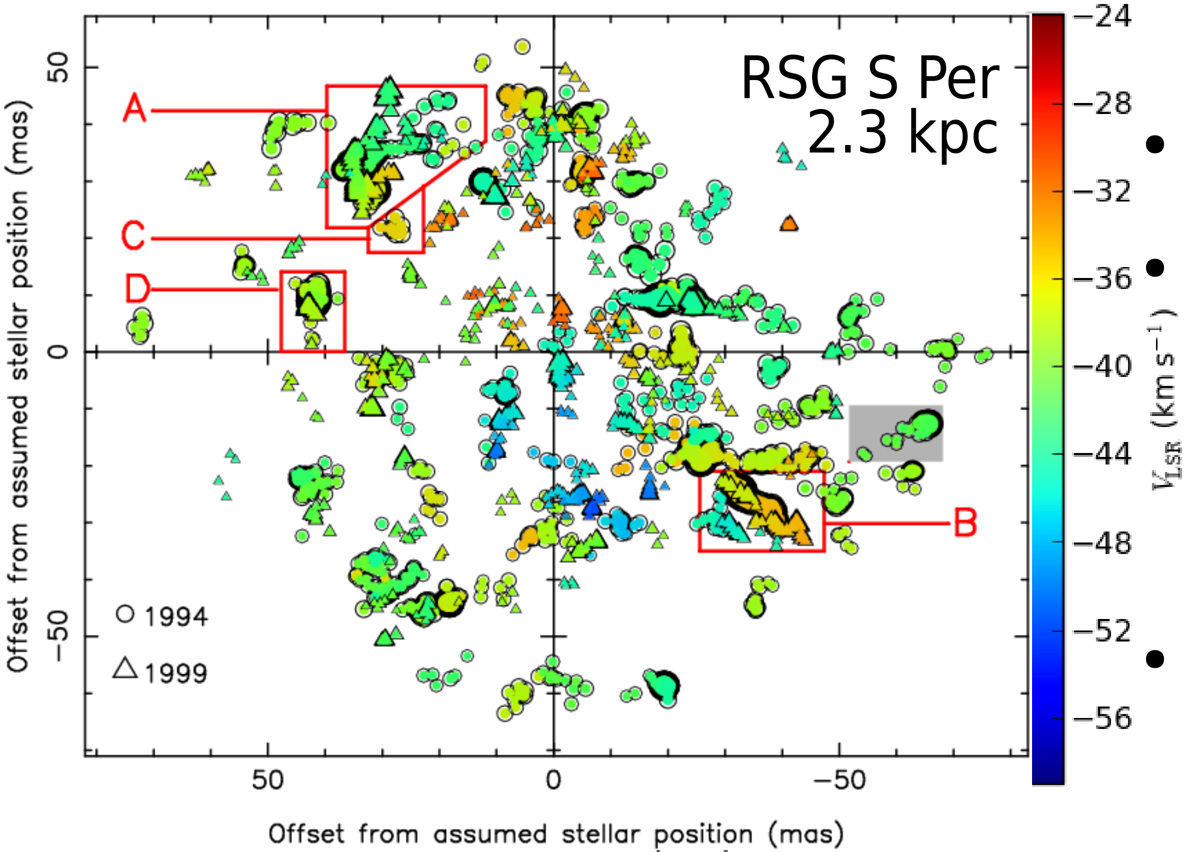
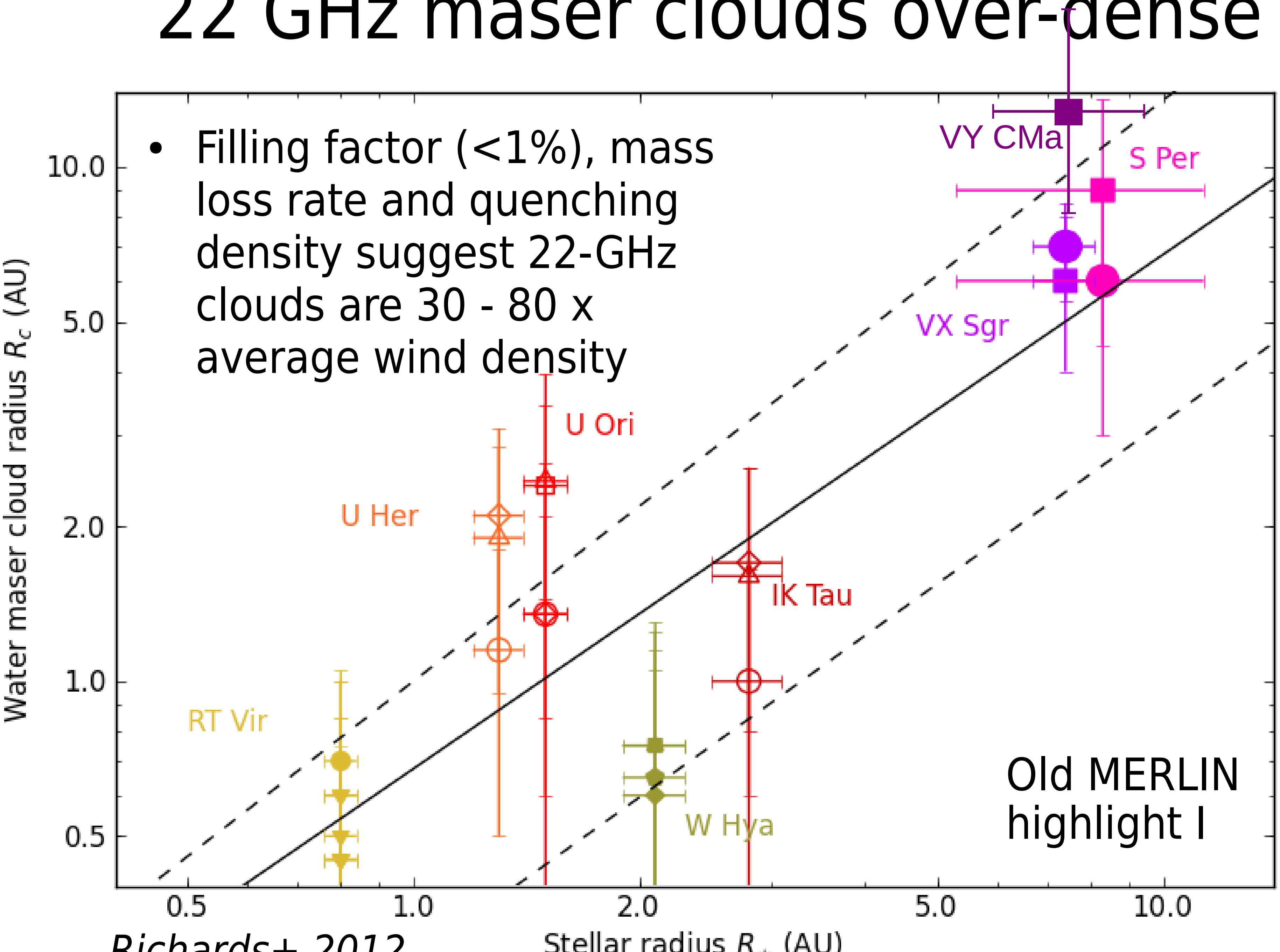




- θ_B<(few)100 mas **ALMA SV** **VLA**
- $\theta_B \lesssim$ 25 mas **ALMA LB, e-MERLIN**
  - Beaming
    - Maser physics
    - Accurate T_b
- $\theta_B \lesssim$ 5-10 mas **VLBI alone**
  - Distant proper motions

22 GHz maser clouds over-dense

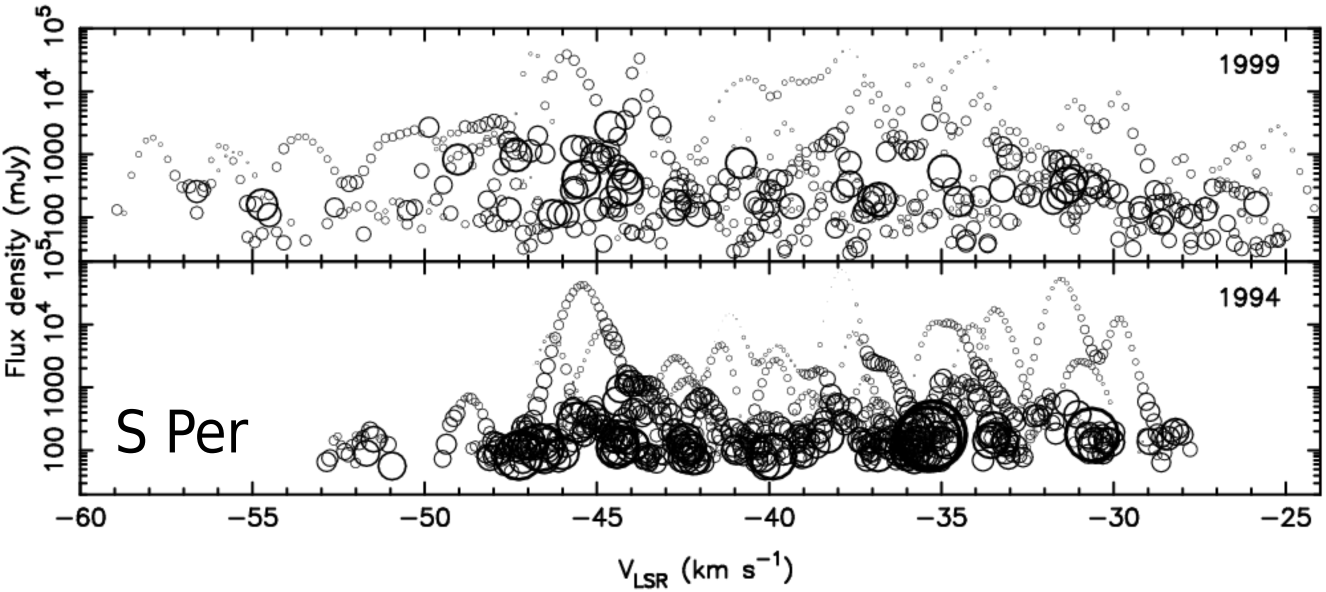


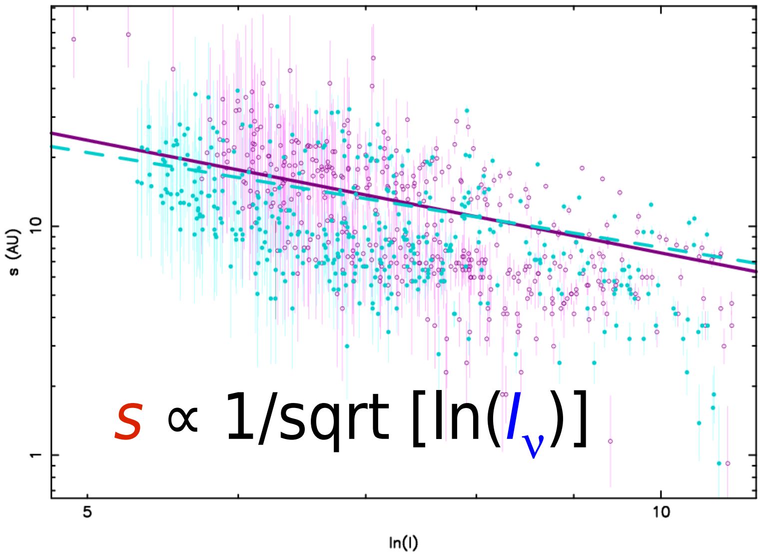
- Filling factor (<1%), mass loss rate and quenching density suggest 22-GHz clouds are 30 - 80 x average wind density

Old MERLIN highlight I

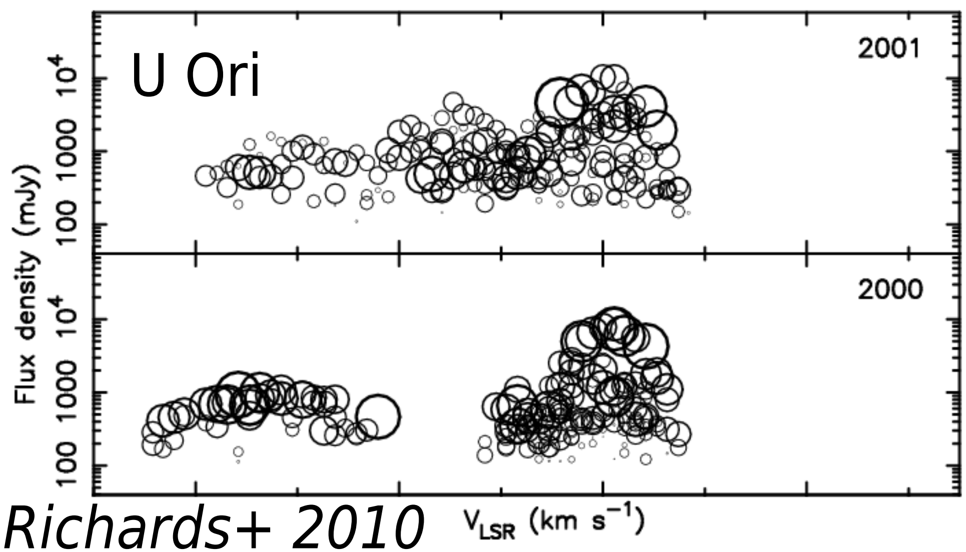
Richards+ 2012

Clouds: symmetric or shock-distorted?

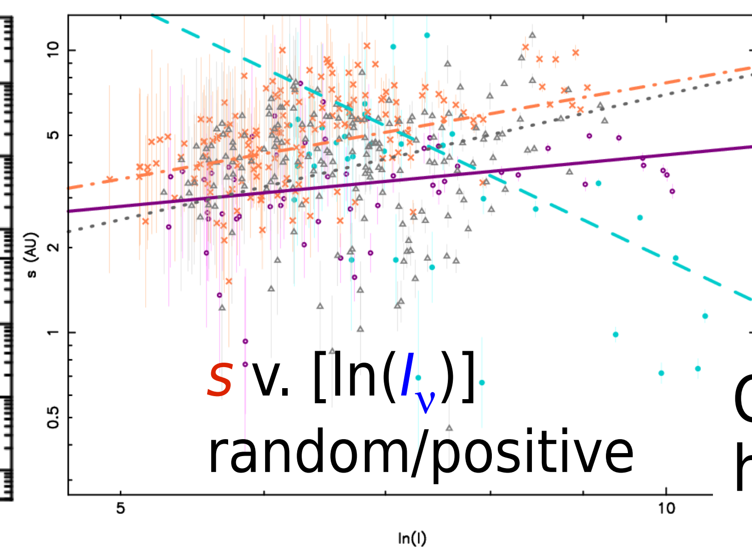




- S Per: brighter I_ν - smaller beamed size s - ~spherical cloud?
- U Ori: some brighter spots are larger - shocked slab?



Richards+ 2010



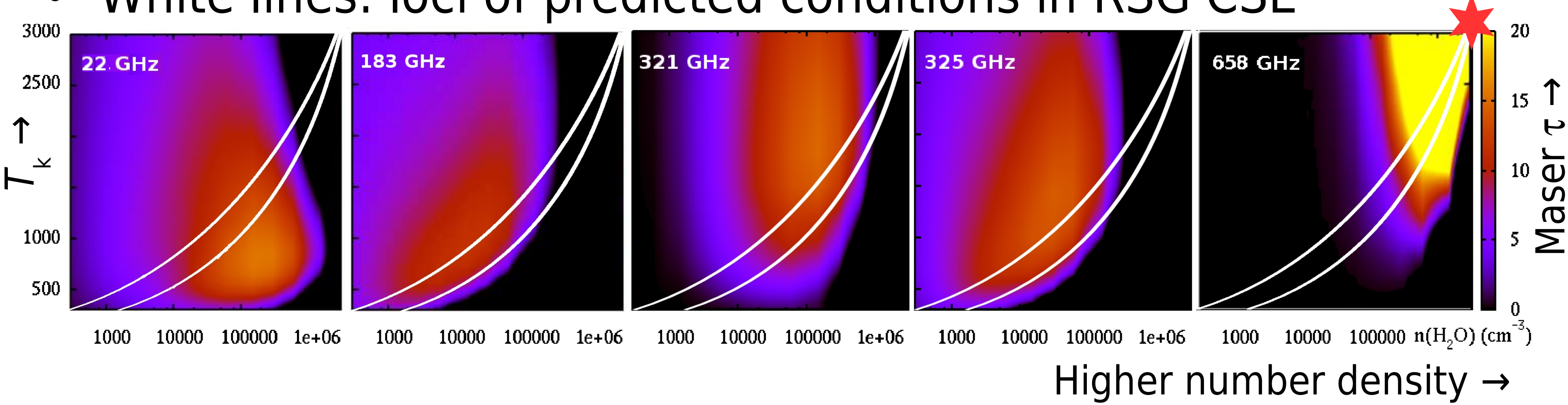
Old MERLIN highlight II

Water maser model (Gray et al. 2016)

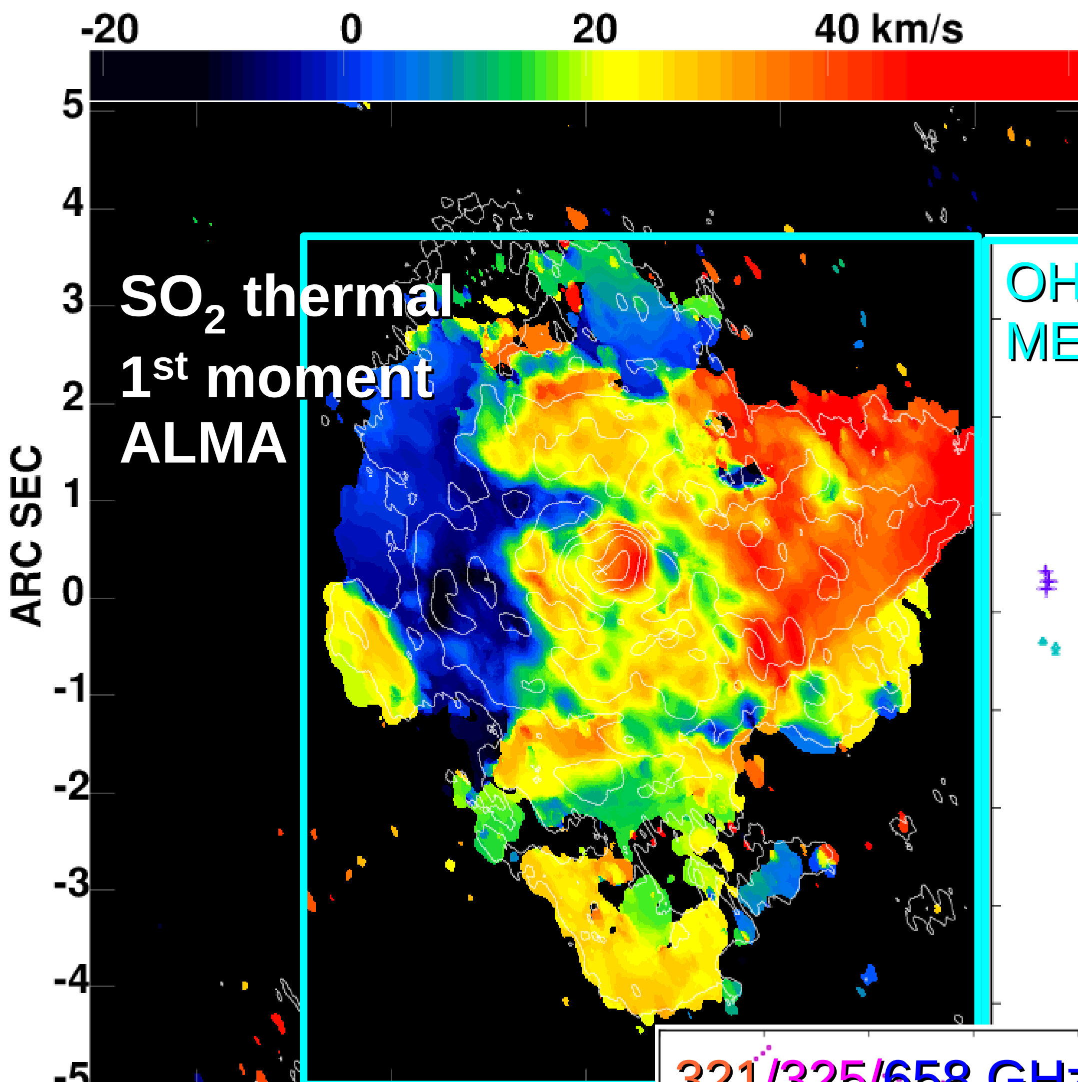
- Collisional and radiative pumping, vibrational ground and excited states, ortho and para H_2O, $\nu \leq 1.91$ THz
  - Dozens of lines in ALMA and SOFIA bands
  - Wide range physical conditions
- Apply to evolved star wind using e-MERLIN, ALMA SV data

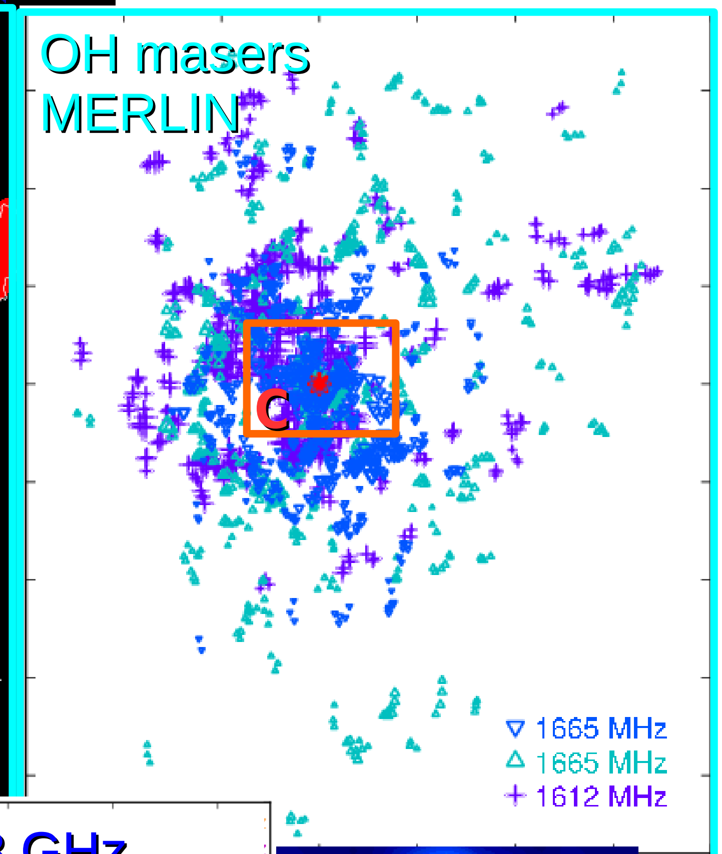
Line GHz	22	183	321	325	658
Eu K	521	200	1861	454	2360

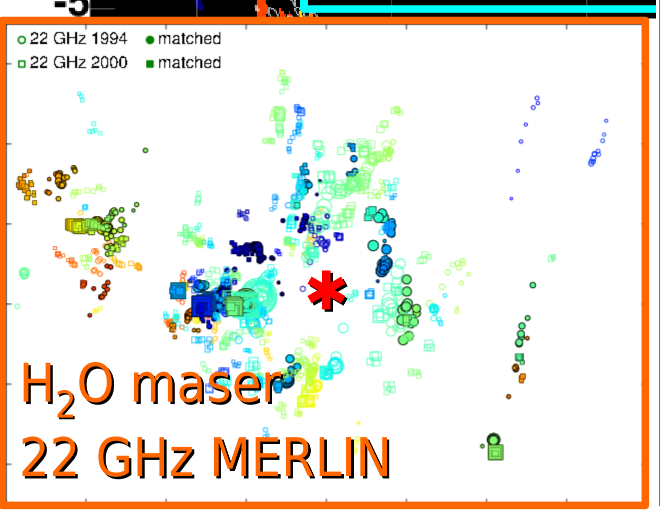
- White lines: loci of predicted conditions in RSG CSE

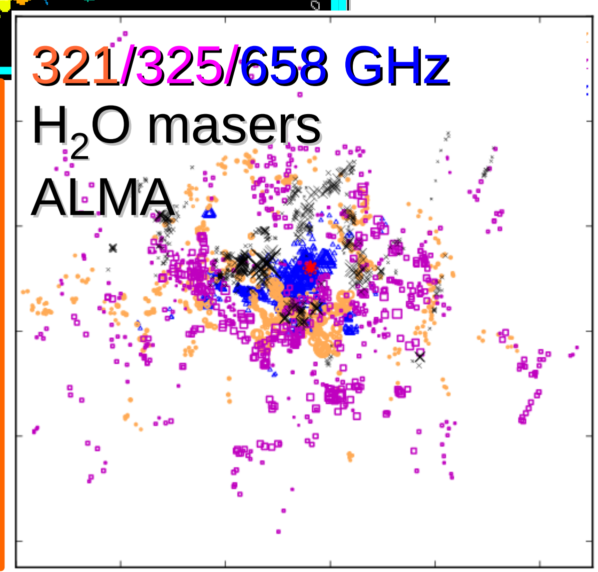


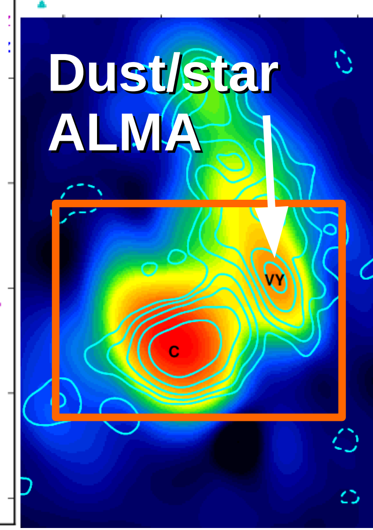
VYCMa







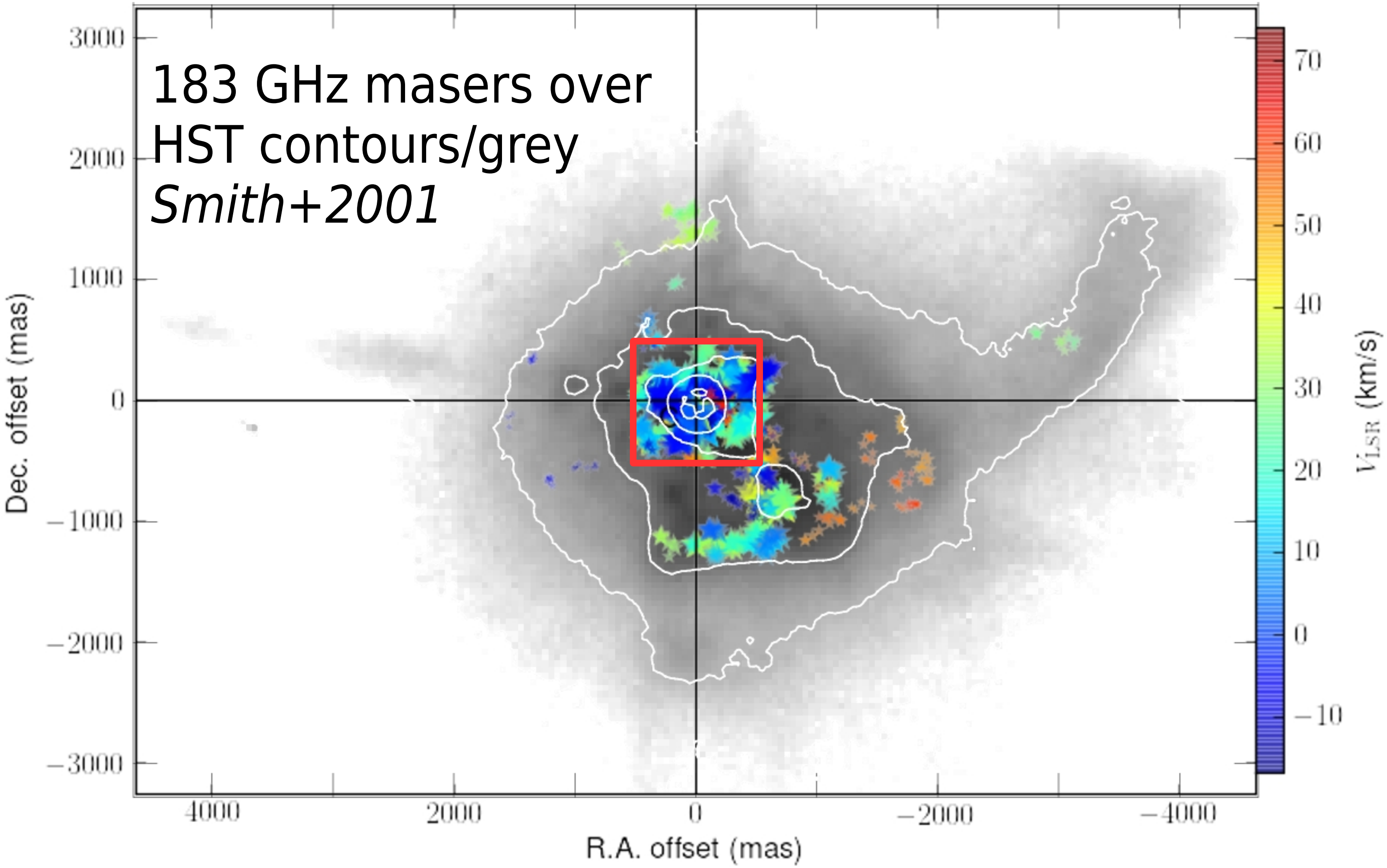




- RSG 1.2 kpc
  Choi+08; Zhang+12
- $R_\star$ 5.7 mas
  Wittkowski+12
- VY centre of outflow
  - 22-GHz 3D radial accel.
- No axis of symmetry
- Different velocity offsets on different scales

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

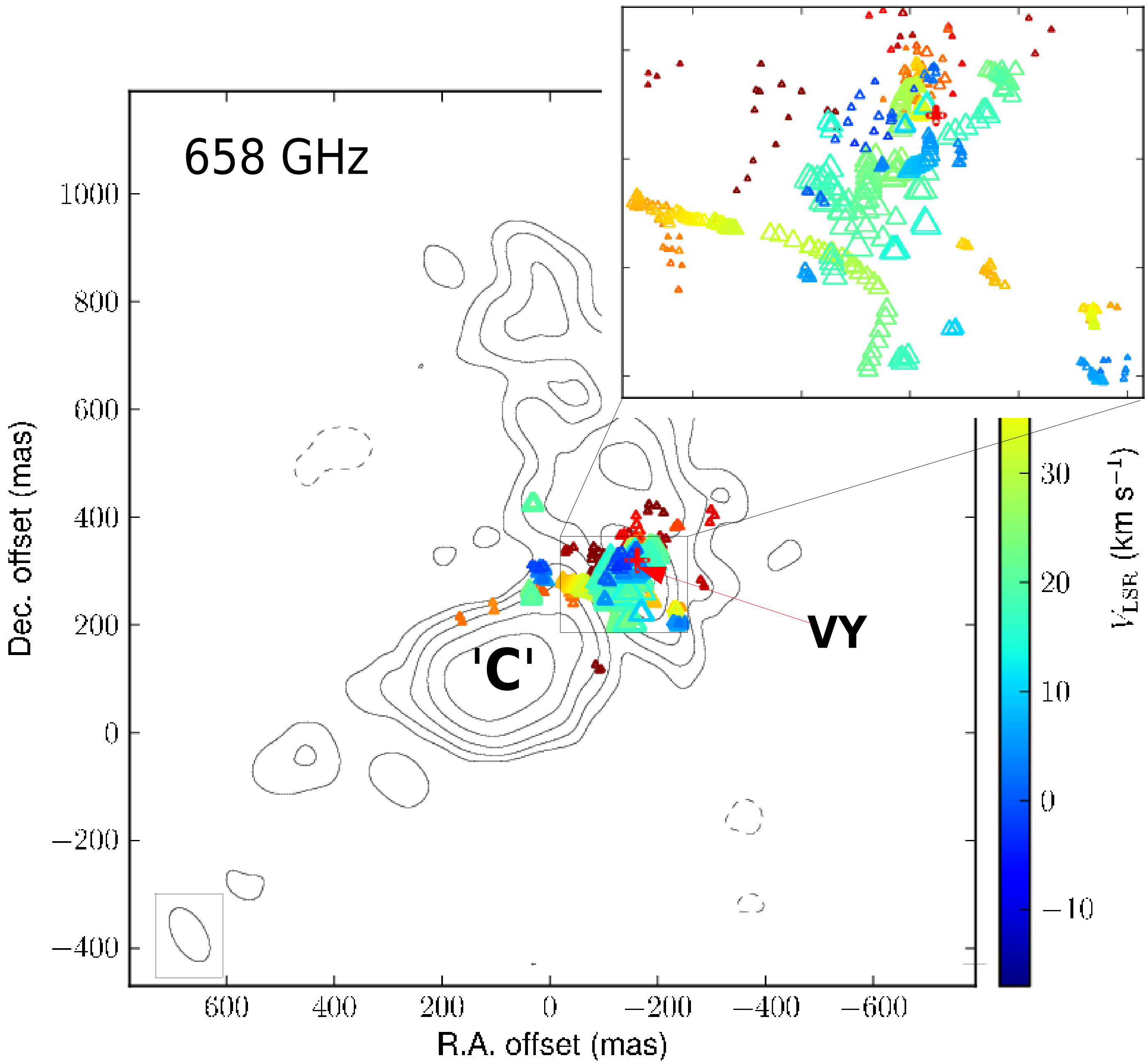


(an aside)

- Does VY CMa fling out clumps almost ballistically?

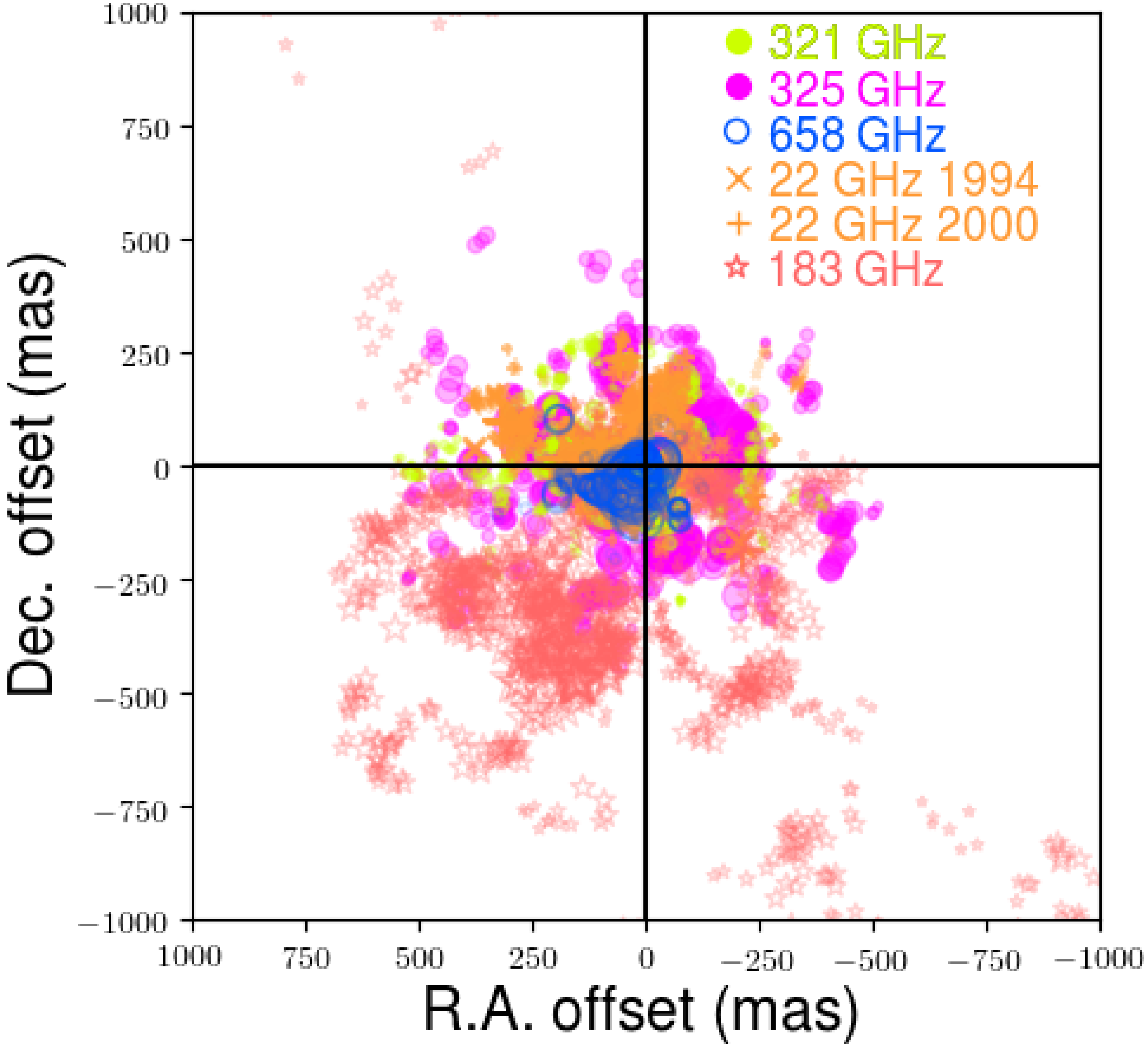
R Humphreys et al 2007

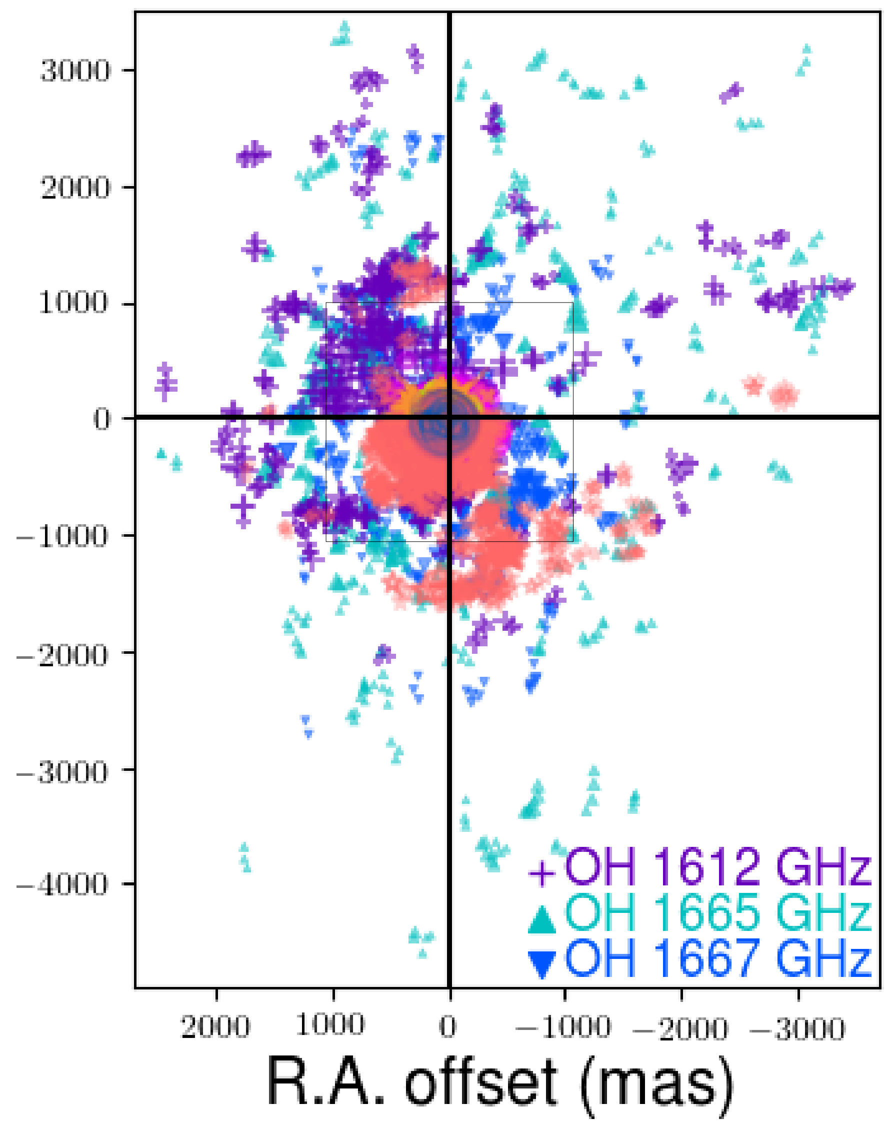
658 GHz mostly compact but ...



- 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

Water and OH masers



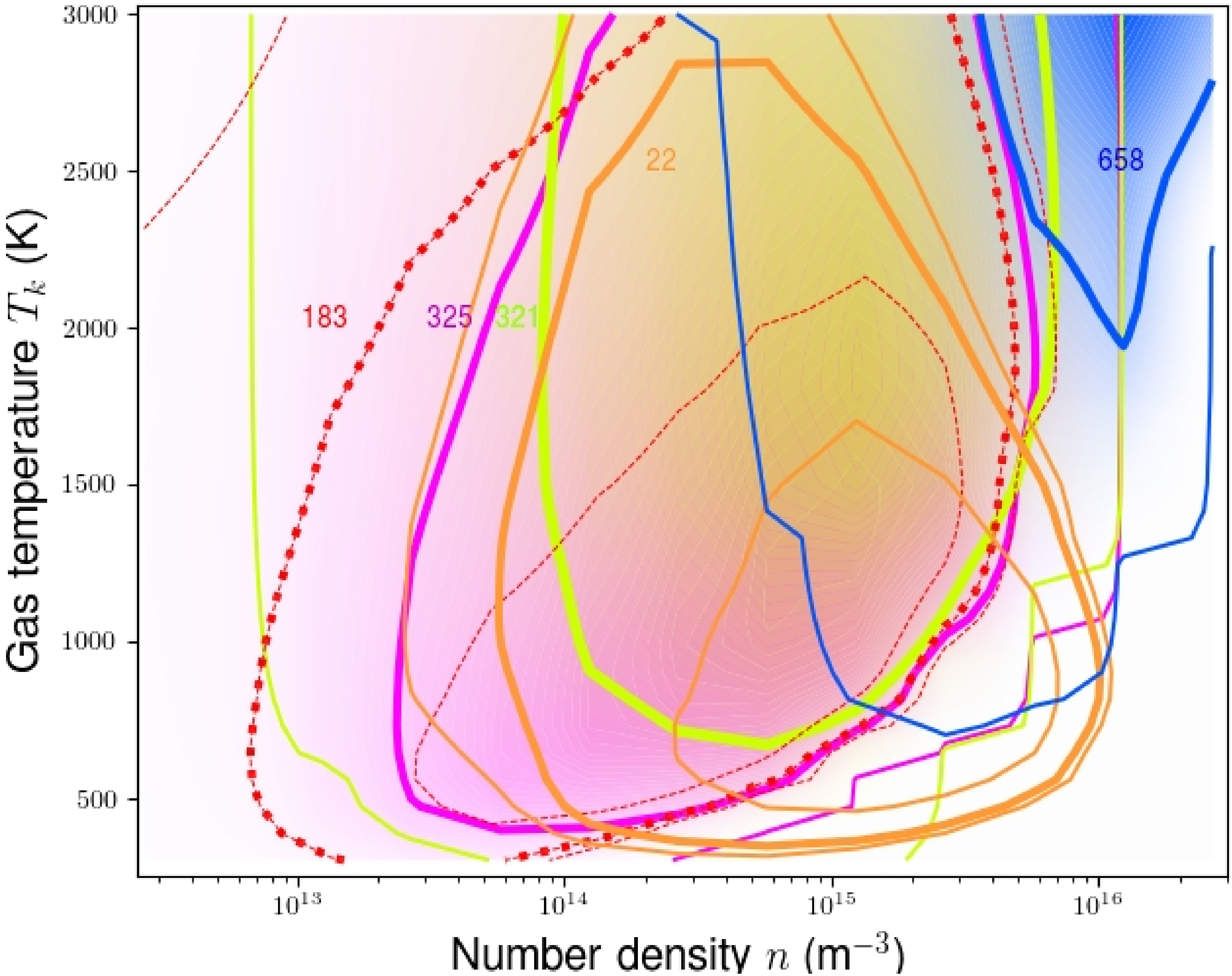


- 321, 325, 658 GHz obs 2013
- 183 GHz obs 2016
- OH obs 1993

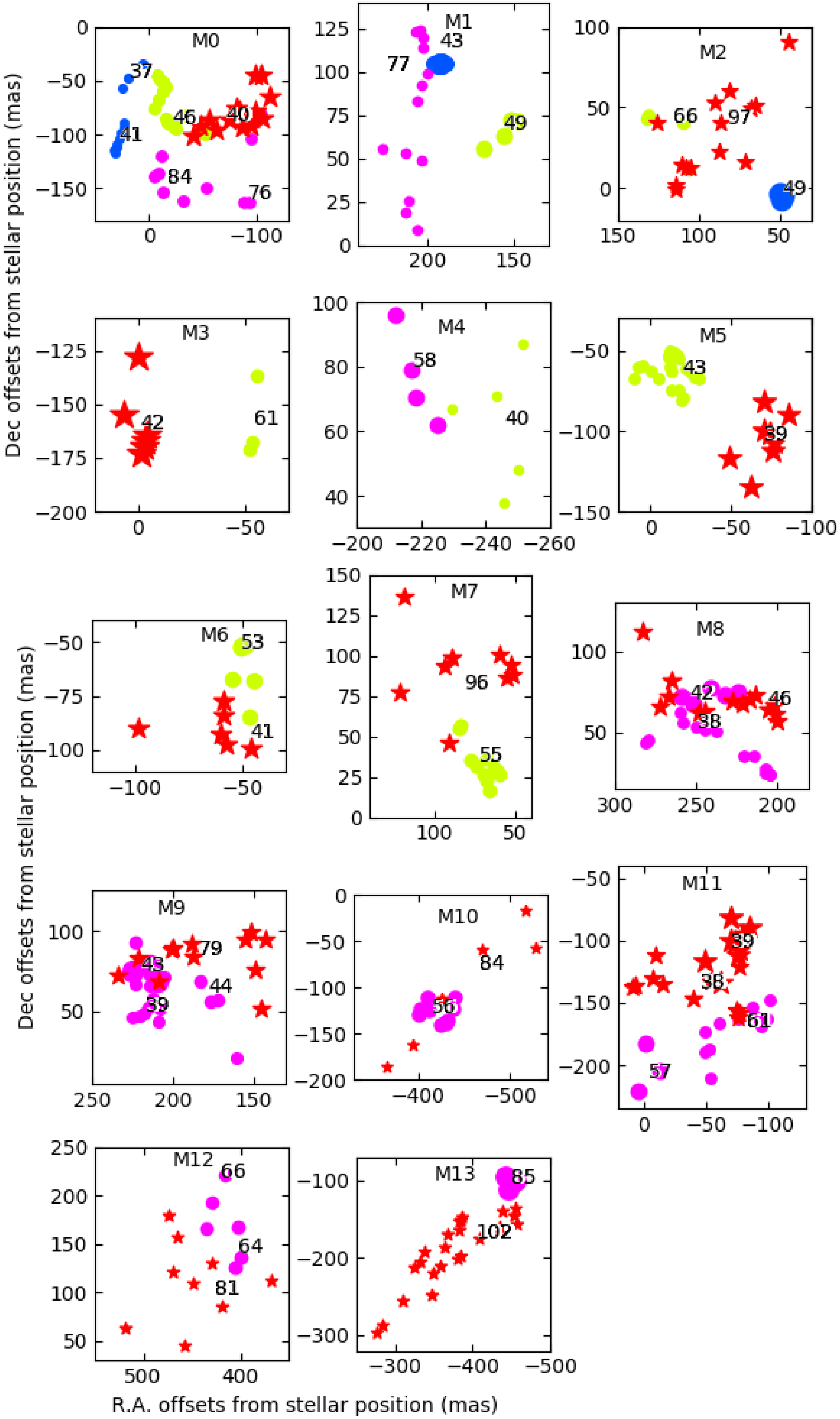
Maser modelling of VY CMa

- 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/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*)



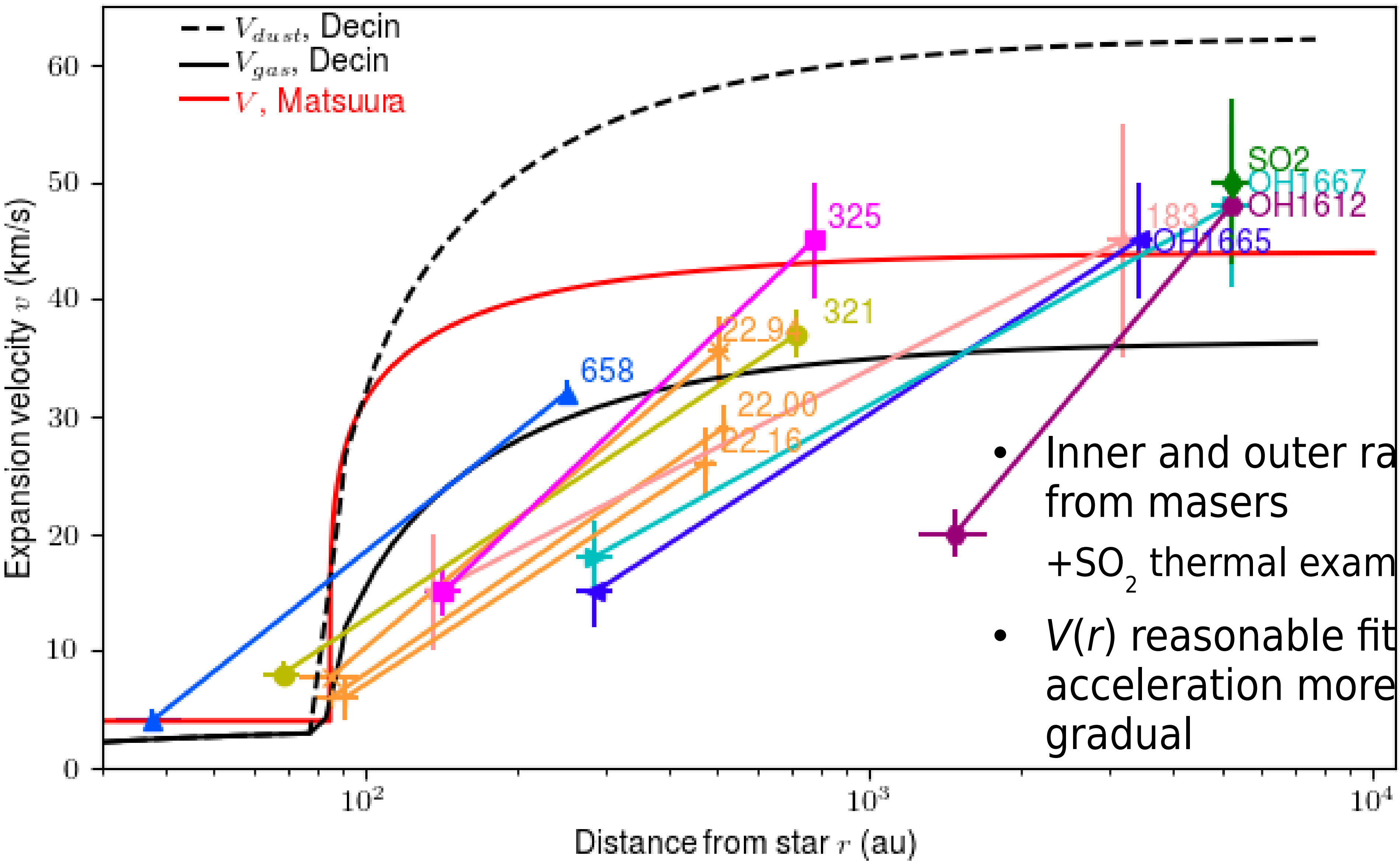
- 658, 321, 325 GHz deeper shade = stronger maser τ
- Also for 22, 183 GHz **contour** at 50% max τ
- Lowest contour at crude estimate of sensitivity limit



Surprisingly few line overlaps

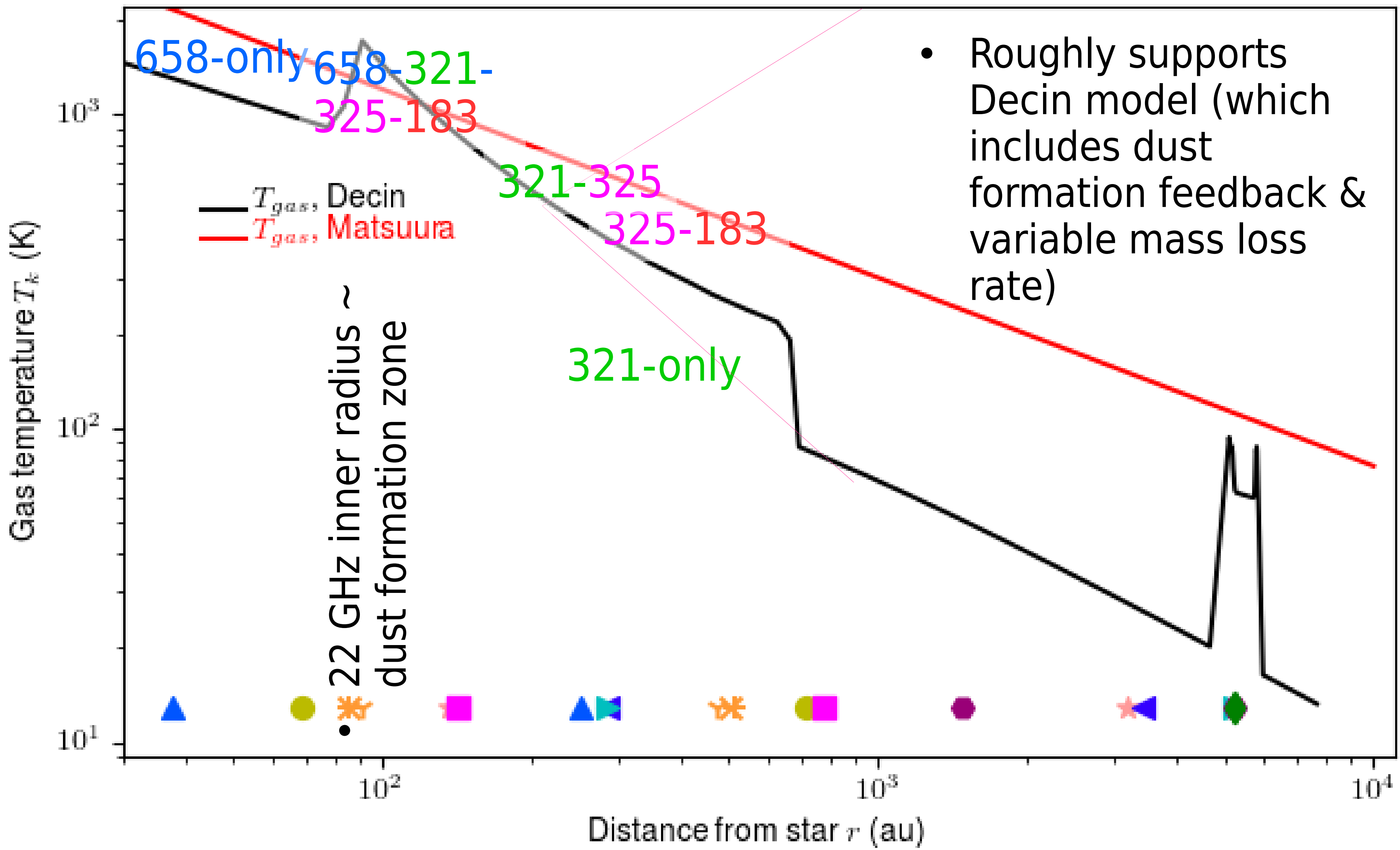
- ~70 - 170 features per line
- 13 regions of line overlap or close association
  - Probably more if 22 GHz contemporaneous included
- Size of symbol proportional to estimated feature peak τ
  - Too crudely estimated - apparent highest τ have small ang size
    - Probably from clouds elongated along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

Comparison with shell models



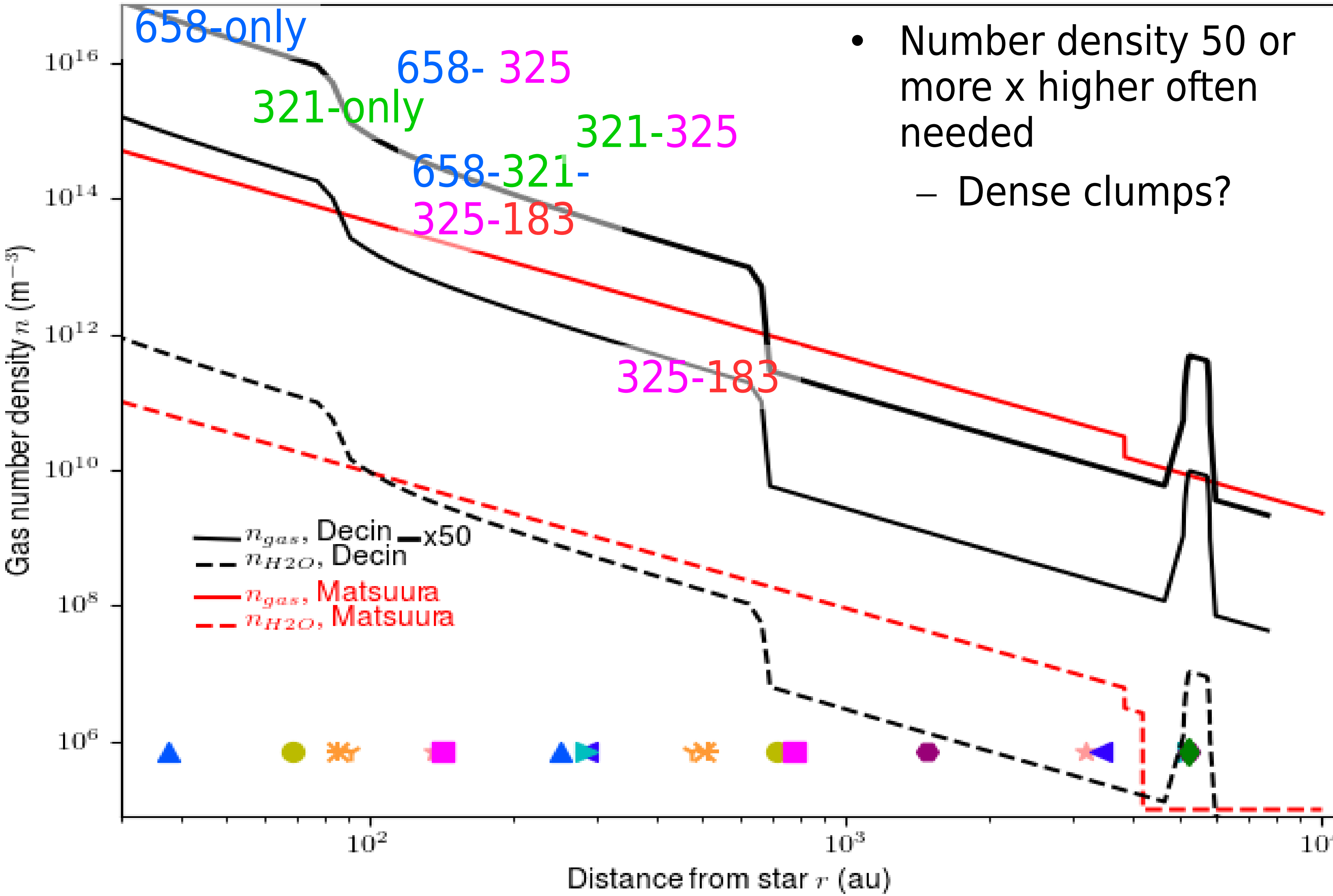
- Inner and outer radii from masers
  +SO_2 thermal example
- $V(r)$ reasonable fit but acceleration more gradual

Temperature constraints



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

Number density constraints

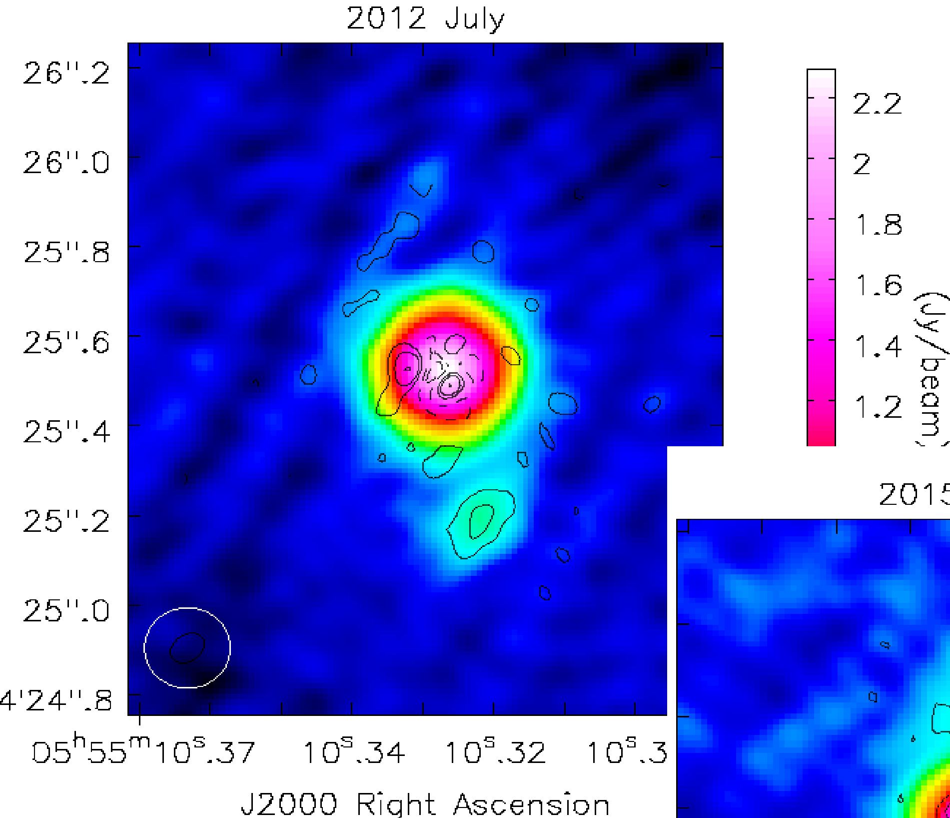


- Number density 50 or more x higher often needed
  - Dense clumps?

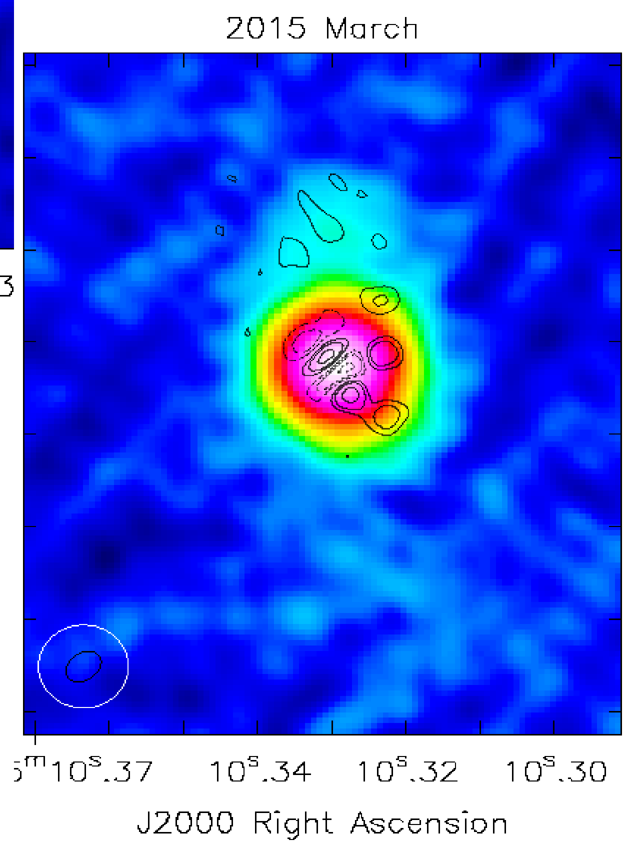
Mass loss from stars

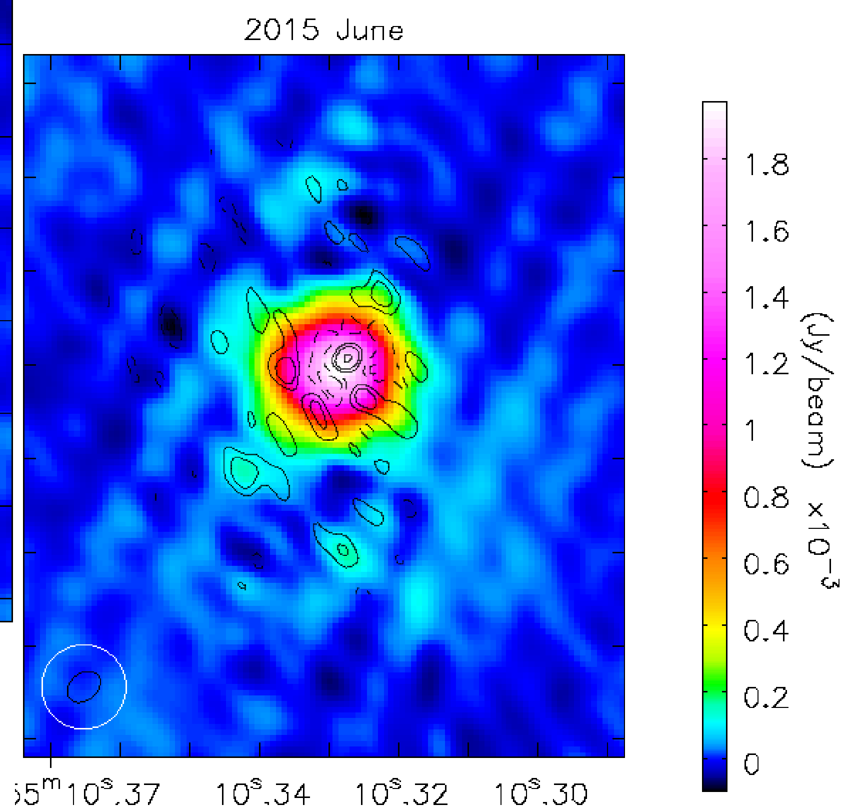
- H_2O masers trace evolution of different conditions in clumps and surrounding wind
  - Shielding and survival into ISM
  - Large-scale asymmetry - equatorial density contrast
  - Changes across dust formation zone
  - Wind driving in hot regions before much dust forms
    - Pulsation, scattering off nascent grains?
- Aligning data sets for different transitions
  - Really helps to detect star
- Mass ejection from stellar surface
  - Clump scales consistent with ~10% starspots
    - Convective heating/cooling? Magnetic field?

Betelguese 5-cm continuum



- 3 epochs 2012-2015
- Stellar disc resolved with 180-mas beam
  - $R_{\star}$ ~100 mas/ 20au
    - T_b ~2300 K

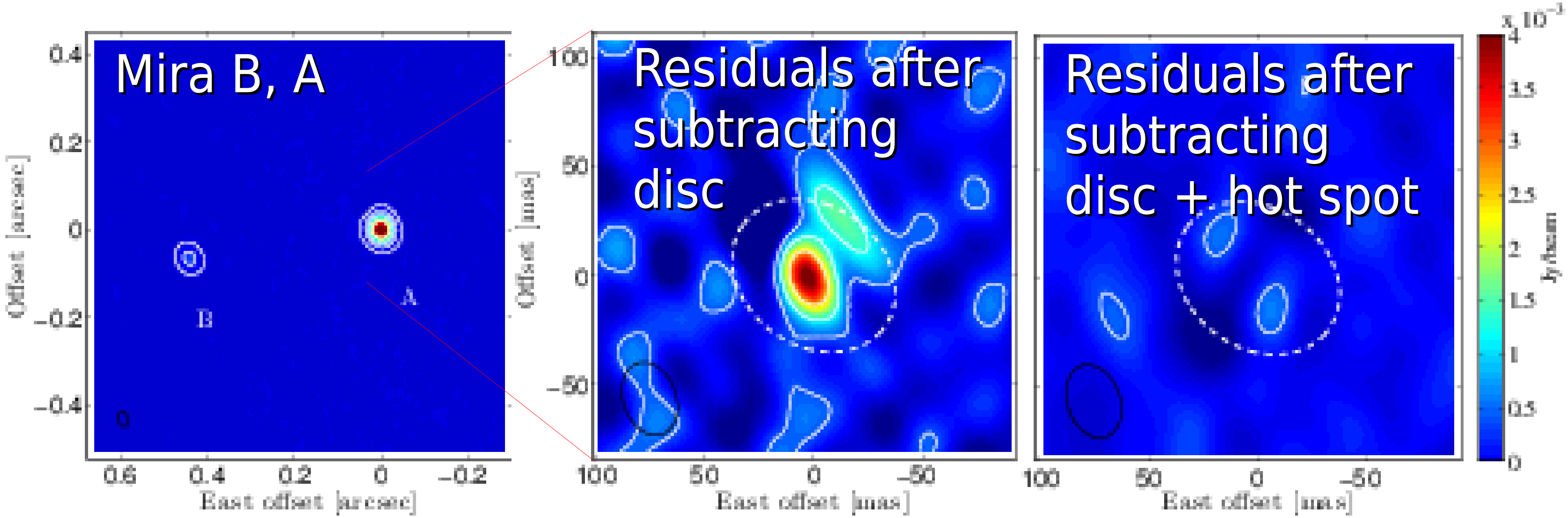




- Subtract ~70-mas Gaussian
  - 7 residuals >6σ
  - Up to ±~10% flux density
  - Convection cell link?

Mira starspot

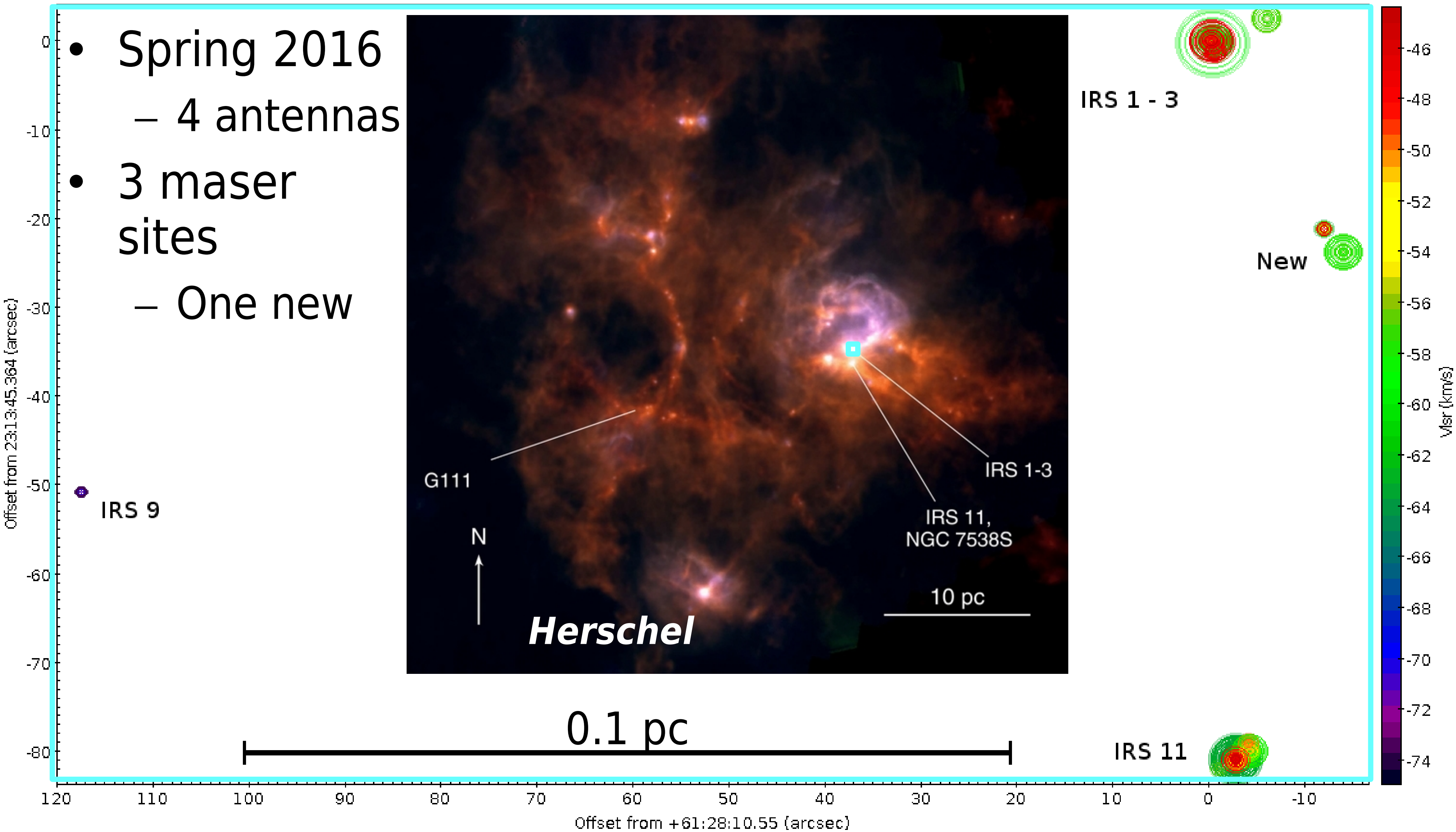
- ALMA 230 GHz, 30-mas resolution (*Vlemmings+'15*)
  - Mira A disc $R_\star$ ~2 au, T_b 2500 K, with 10^4 K hotspot



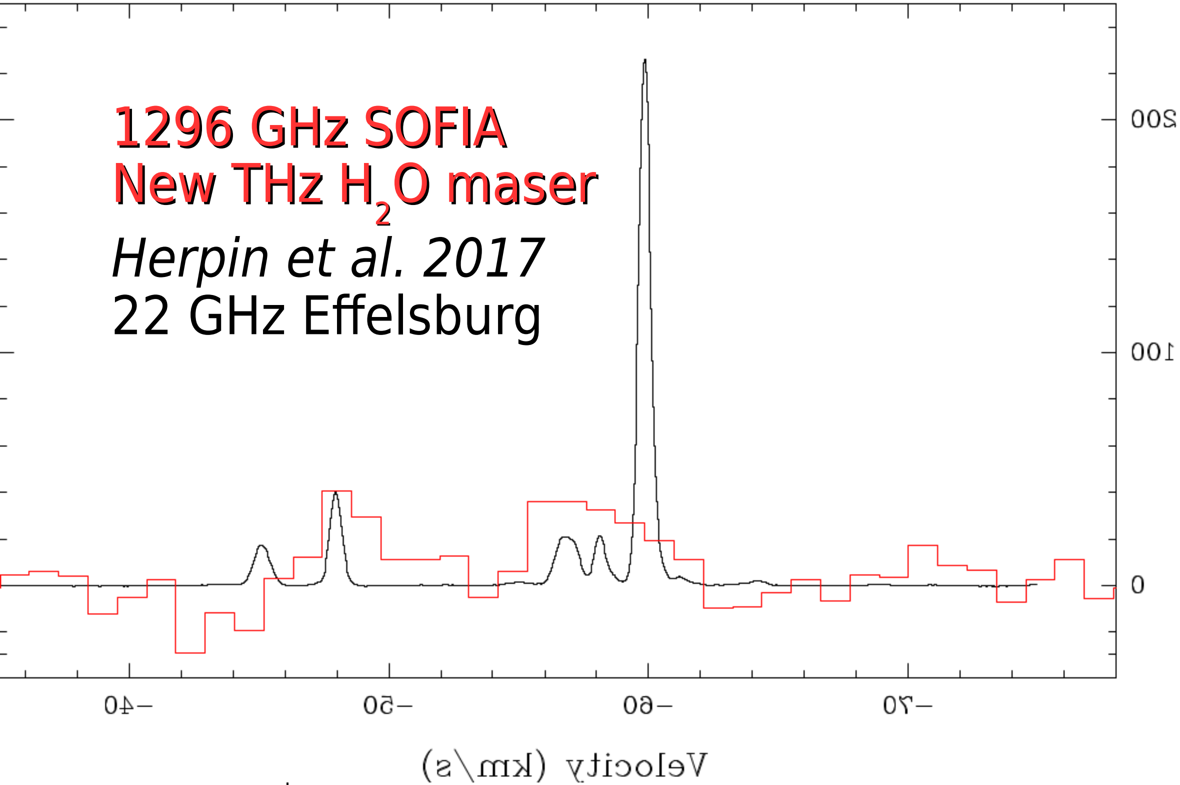
- Mira few mJy at 22 GHz
  - Weak water masers, never imaged,
    - Few Jy, probably within ~100 mas of star, ideal for e-MERLIN

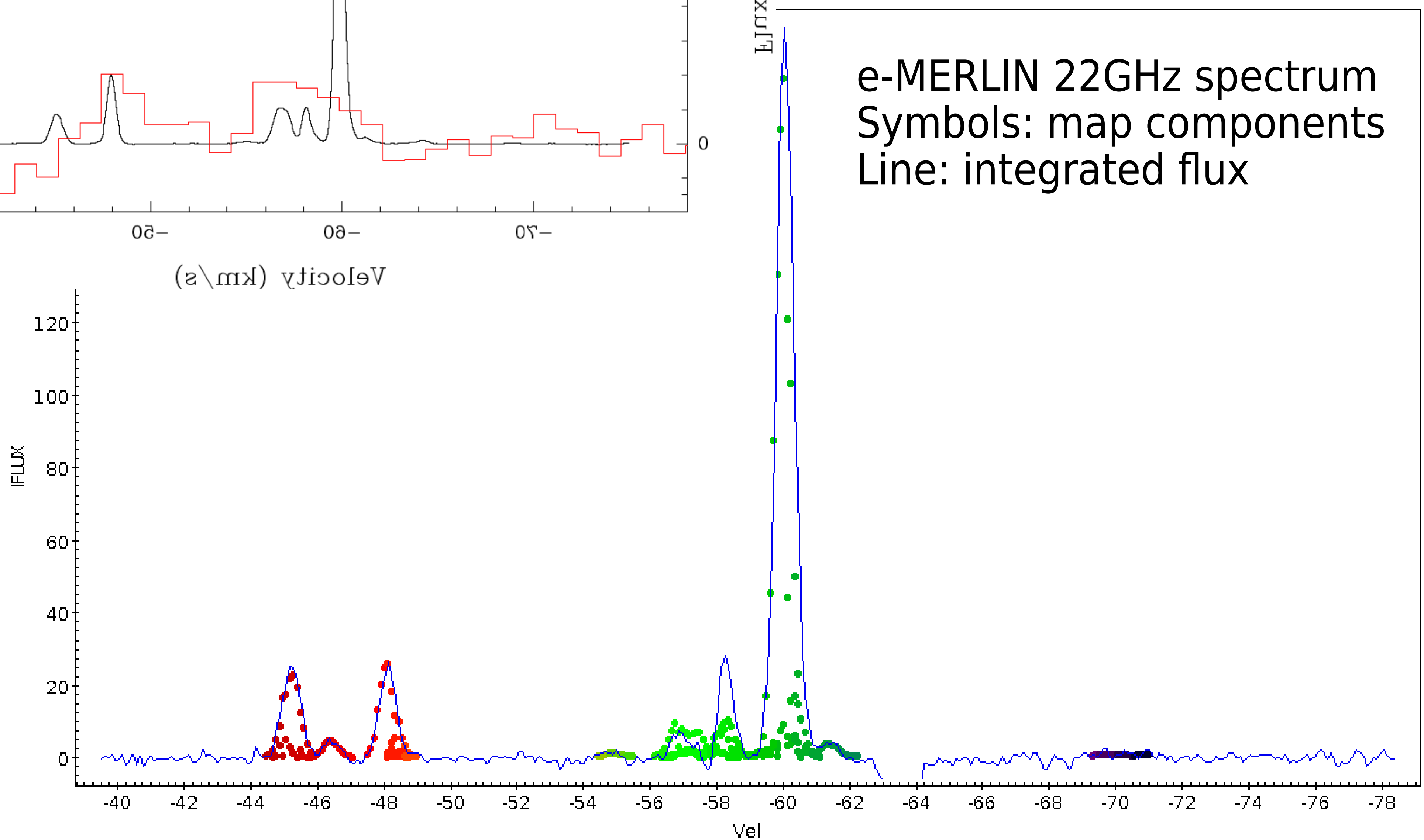
e-MERLIN K-band first light: NGC 7538

- High-mass star-forming region
- Spring 2016
  - 4 antennas
- 3 maser sites
  - One new

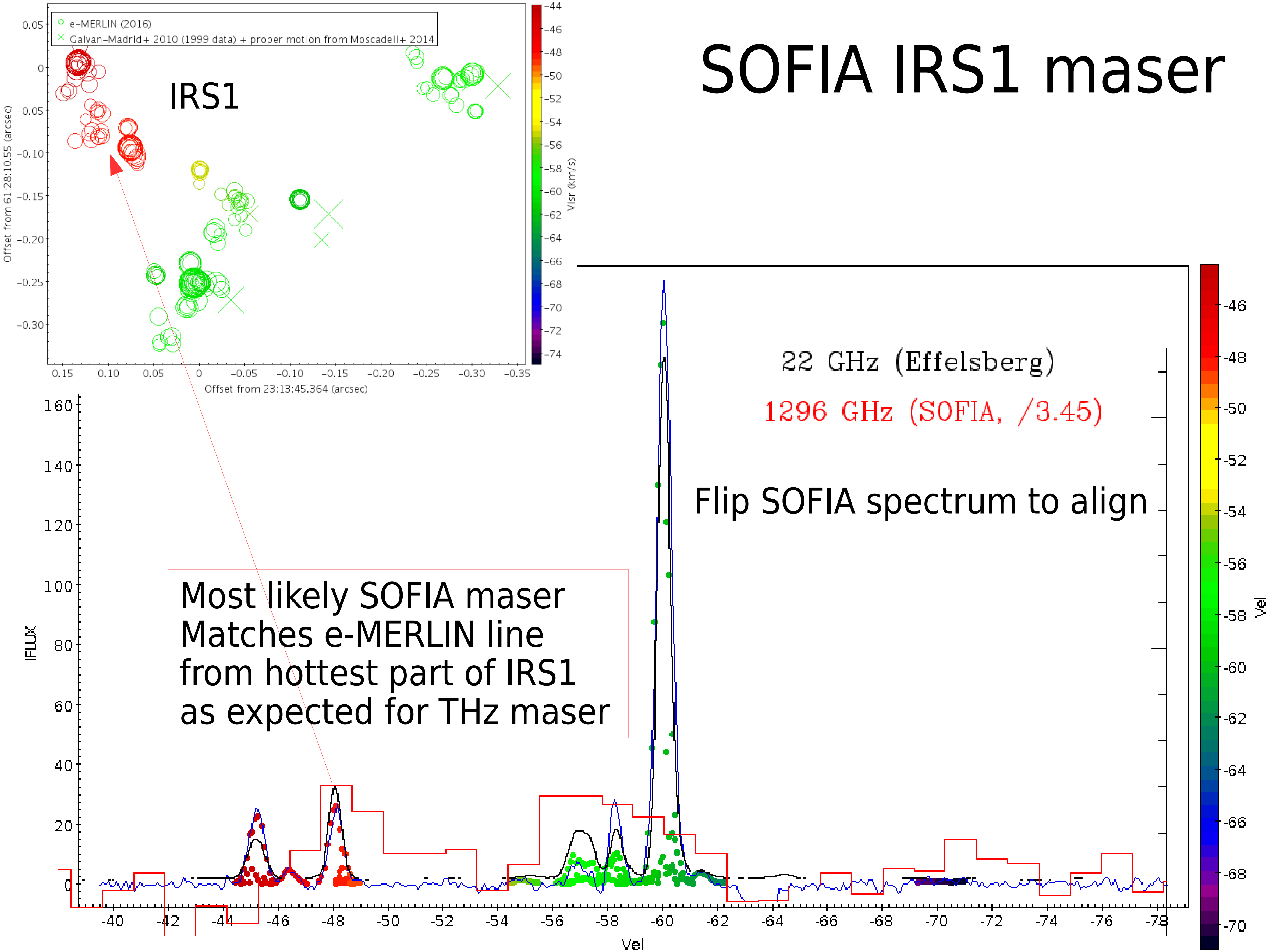


SOFIA+e-MERLIN NGC 7538





SOFIA IRS1 maser



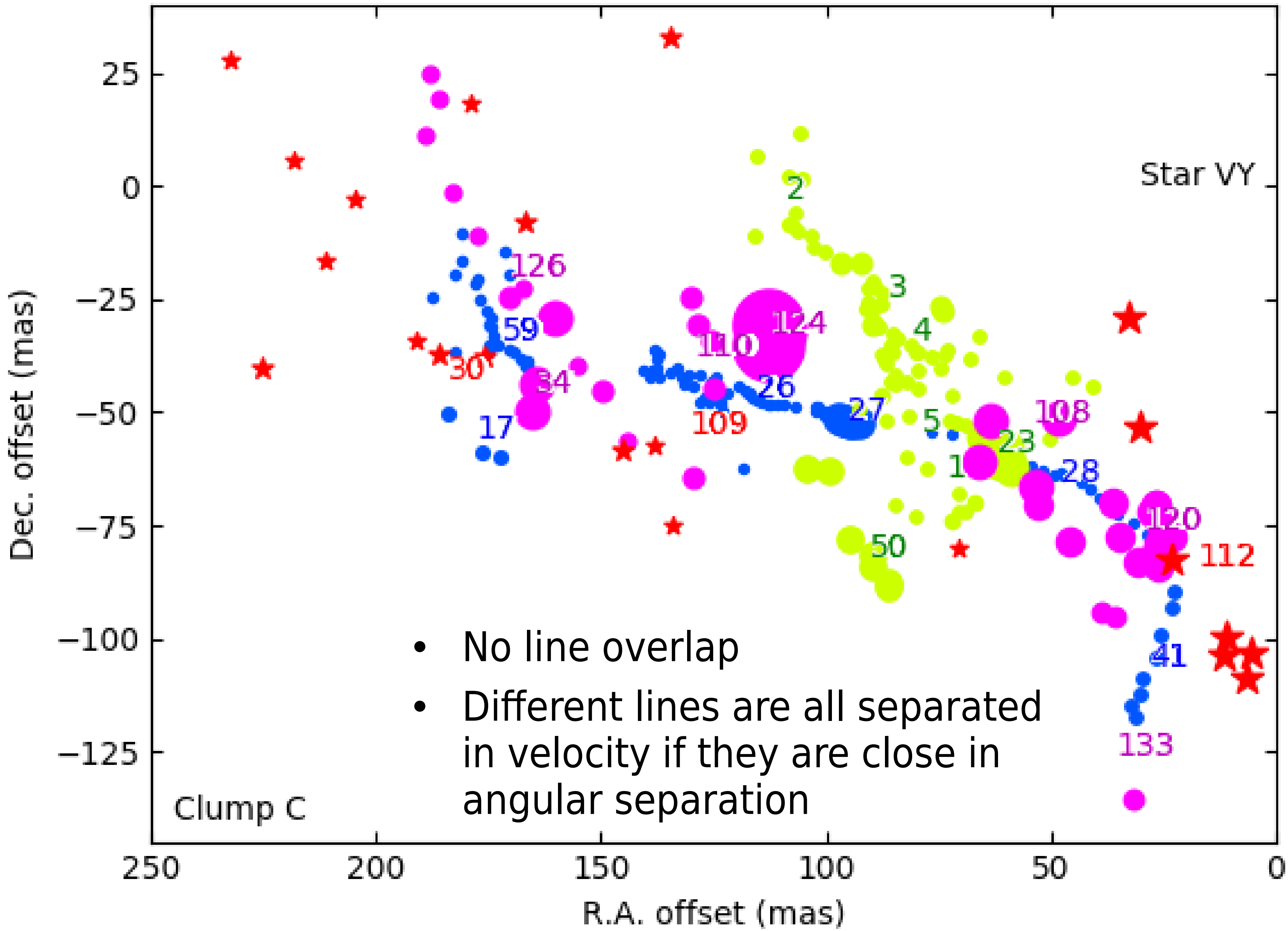
Summary/wish list for K-band I

- Multiple maser transitions map wide range of physical conditions on 10x finer scale than thermal lines.
- 5-50 mas resolution ideal (e-MERLIN, ALMA LB)
  - Recover all the flux from extrasolar sources
  - Extract information on au scales (Galactic)
    - Regions in ~homogenous radiative contact
- e-MERLIN integrated into EVN
  - Full potential for proper motions *and* maser physics
    - Maser beaming models provide 3D structure of clumps
      - Aspect ratio (spherical, cylindrical, slab…) needed for τ
  - H_2O Zeeman splitting slight but well-understood
    - Obscured by blending
      - Need 0.1 km/s, few mas resolution, high sensitivity

Summary/wish list for K-band II

- Velocity spans ≲(3000) 200 km/s (extra-)Galactic
  - e-MERLIN correlator capabilities
- Where's the star? Typically 0.5-1 mJy, 10-50 mas
  - Detectable with 0.5 - 2 GHz b/w
    - Also more phase refs available
- Galactic plane sources, overlap with ALMA
  - Defford replacement, Goonhilly....
- Severe gain-elevation effects; >10^3 Jy masers common
  - Commision observational T_{sys} measurements
- Multi-λ interferomery sporadic
  - Single dish monitoring to aid inter-epoch interpolation

Shocks round clump C?



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