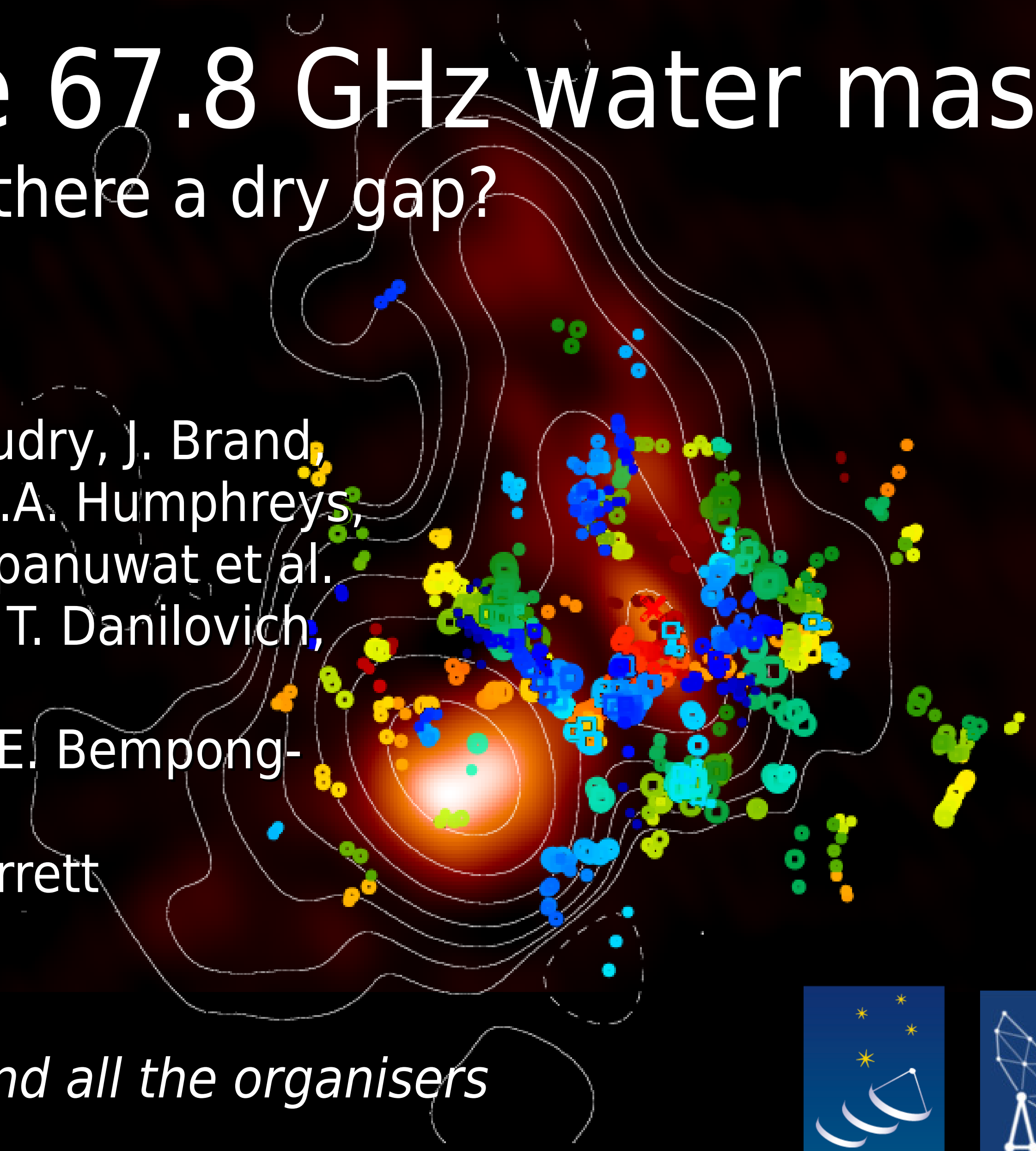
Looking for the 67.8 GHz water maser

Is there a dry gap?

Anita Richards
with many others including:
Masers/VY CMa: Y. Asaki, A. Baudry, J. Brand, S. Etoka, M.D. Gray, F. Herpin, E.A. Humphreys, R. Humphreys, E.E. Lekht, B. Pimpanuwat et al.
ATOMIUM: L. Decin, C. Gottlieb, T. Danilovich, K-.T. Wong et al.
HL Tau : J. Greaves, K. Hesterly, E. Bempong-Manful, S. Facchini et al.
SETI L. Mason, M.A. Garrett

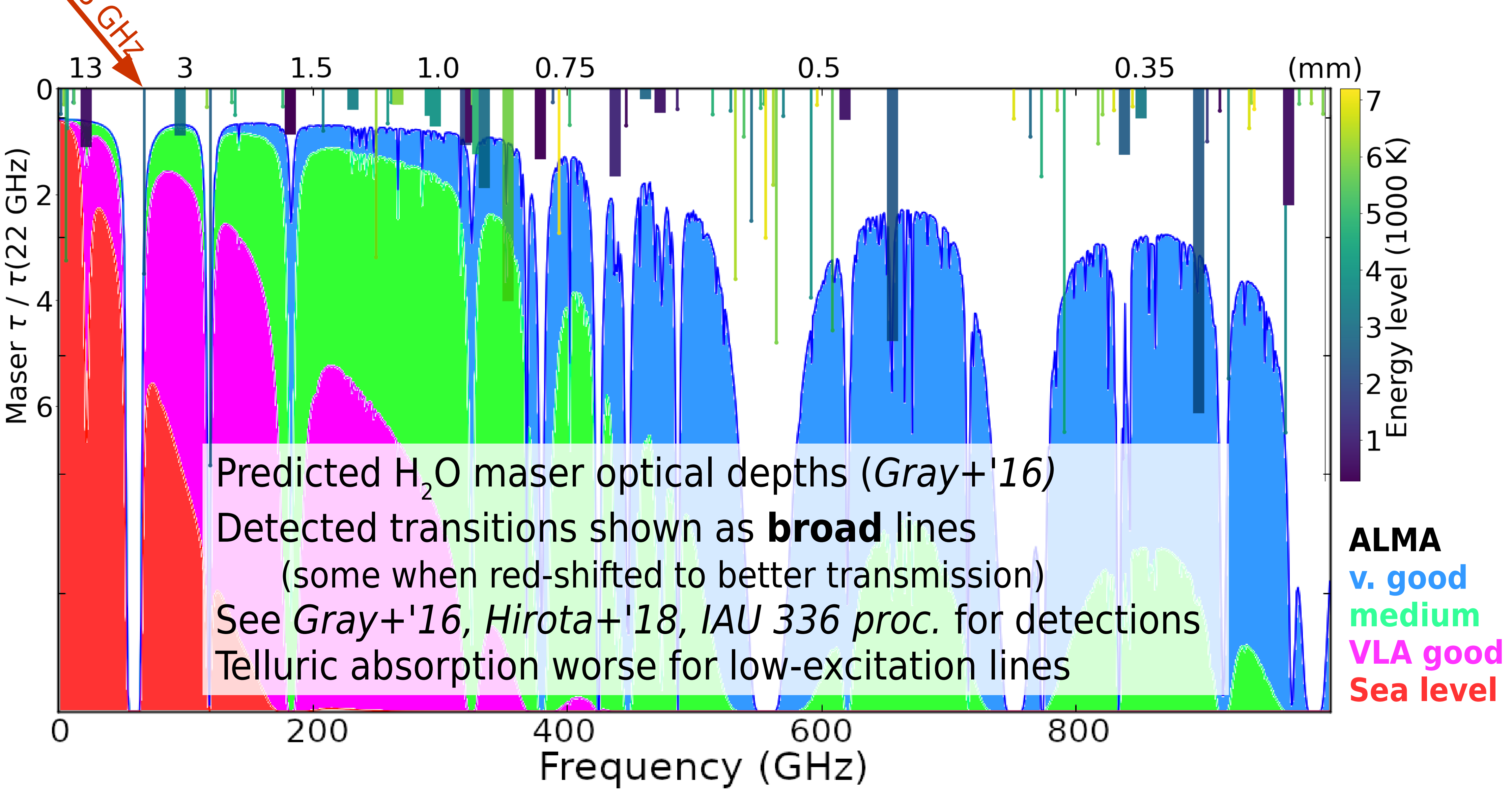


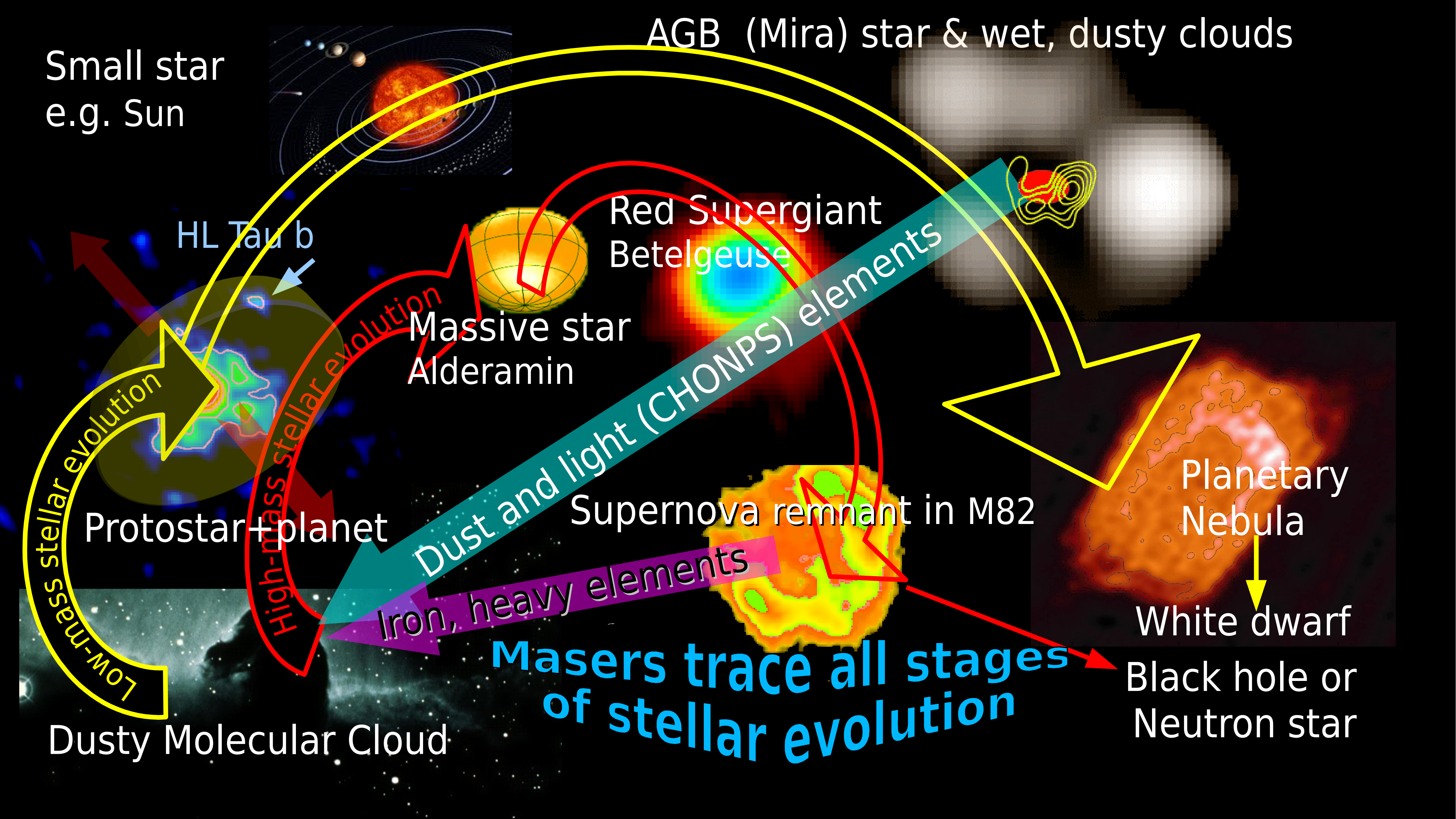
e-MERLIN
The University of Manchester Jodrell Bank Observatory
MANCHESTER 1824
IVOA
EUROPEAN VLBI NETWORK

and Thank You to Kazi and all the organisers

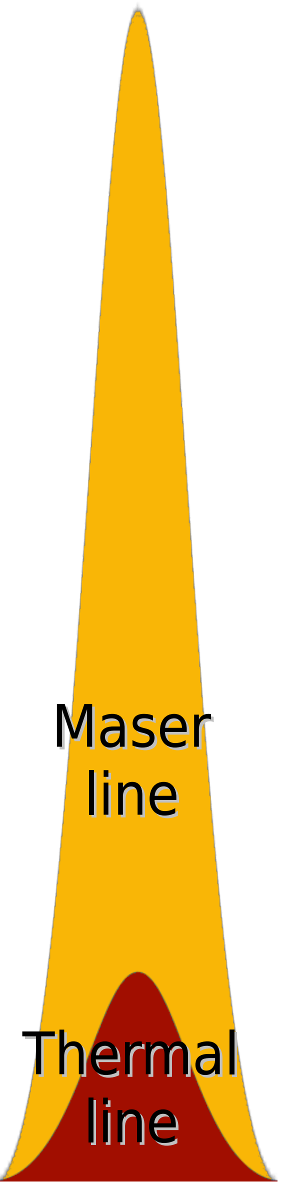
ALMA
ATOMIUM

Water maser lines

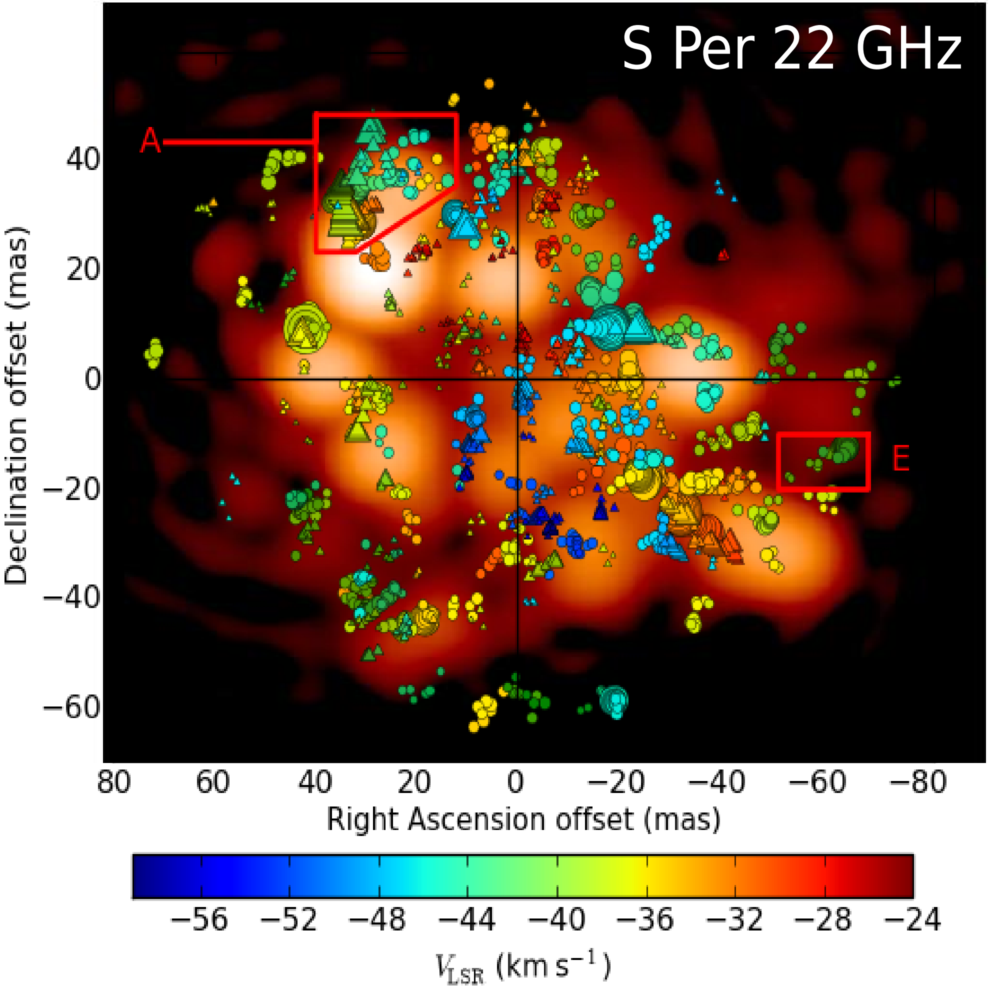



AGB (Mira) star & wet, dusty clouds
Small star
e.g. Sun
Red Supergiant
Betelgeuse
HL Tau b
Massive star
Alderamin
High-mass stellar evolution
Low-mass stellar evolution
Dust and light (CHONPS) elements
Planetary
Nebula
White dwarf
Protostar+planet
Supernova remnant in M82
Iron, heavy elements
Masers trace all stages
of stellar evolution
Black hole or
Neutron star
Dusty Molecular Cloud

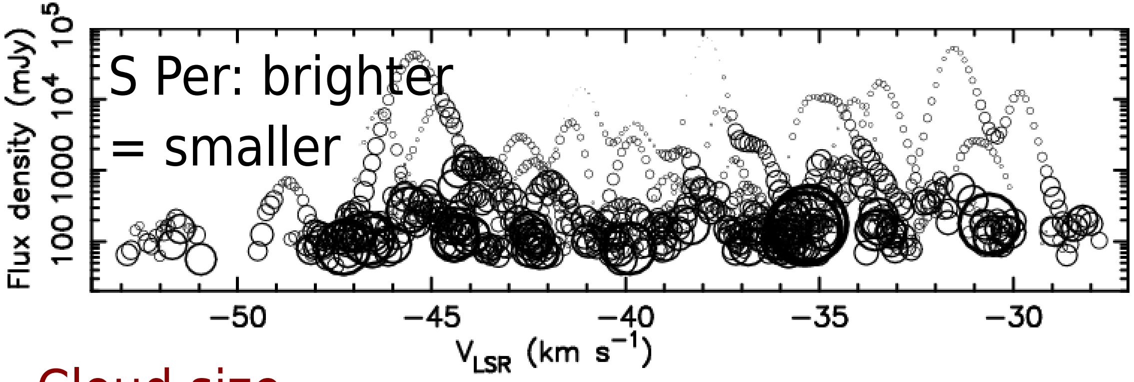
Measuring masers

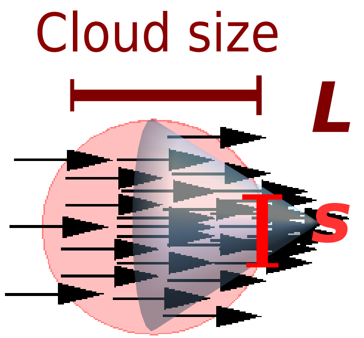


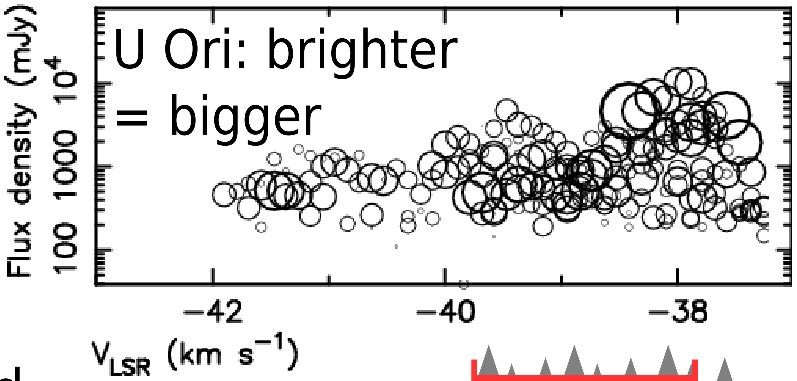
- Exponential amplification
  - Greater along longer paths
- **Line** narrowing
  - Re-broadens if saturated
- Maser spots mostly 2D Gaussians
- Fit beamed components with accuracy $\theta_b/(S/N)$
  - Sub-mas precision per ~0.2 km/s in few tens mas beam
  - Position-velocity gradient over many channels gives physical (unbeamed) size of emitting region



Maser properties reveal wind disturbances

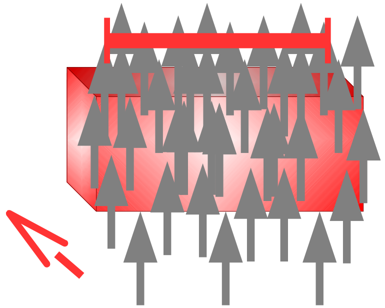


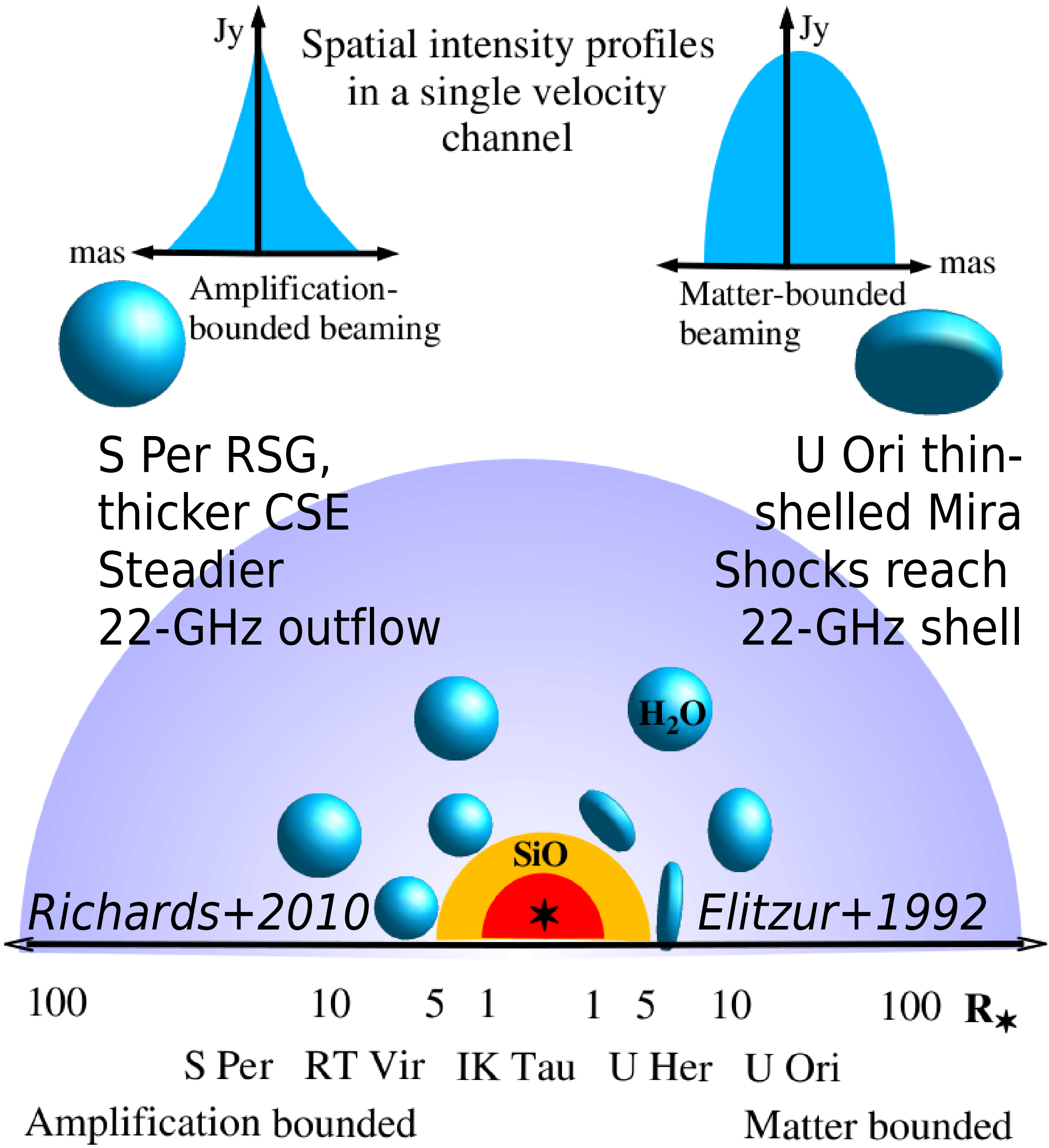




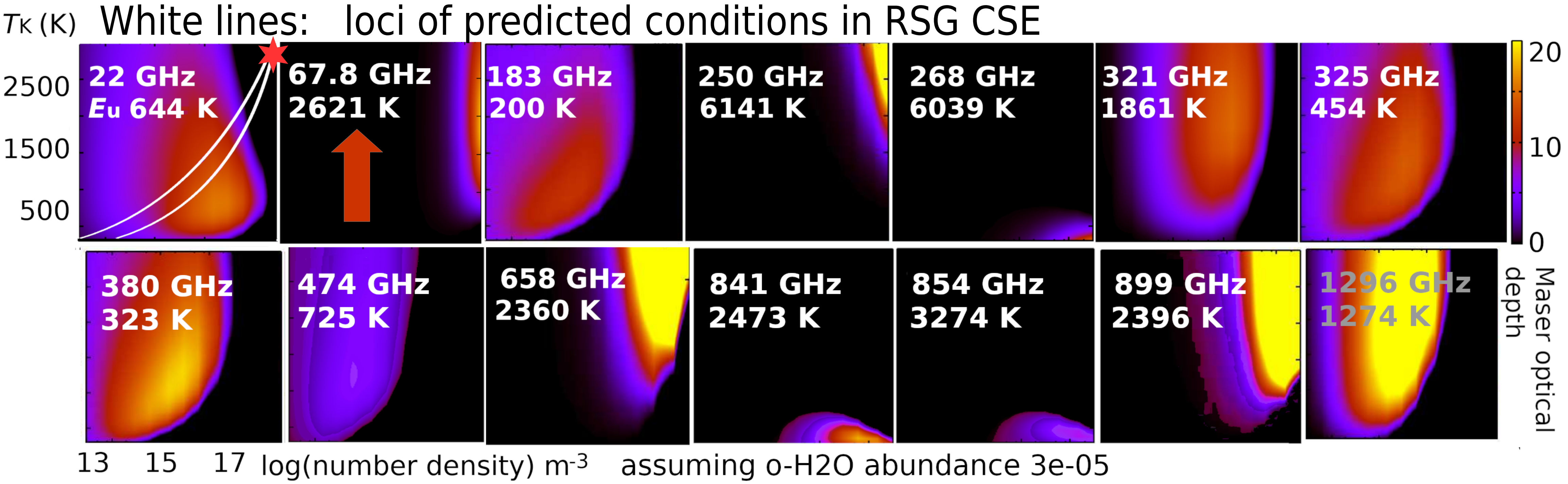
Spherical cloud:
spot size $s \ll L$

Shocked slab: $s \sim L$





Water maser energies 200 – >6000 K

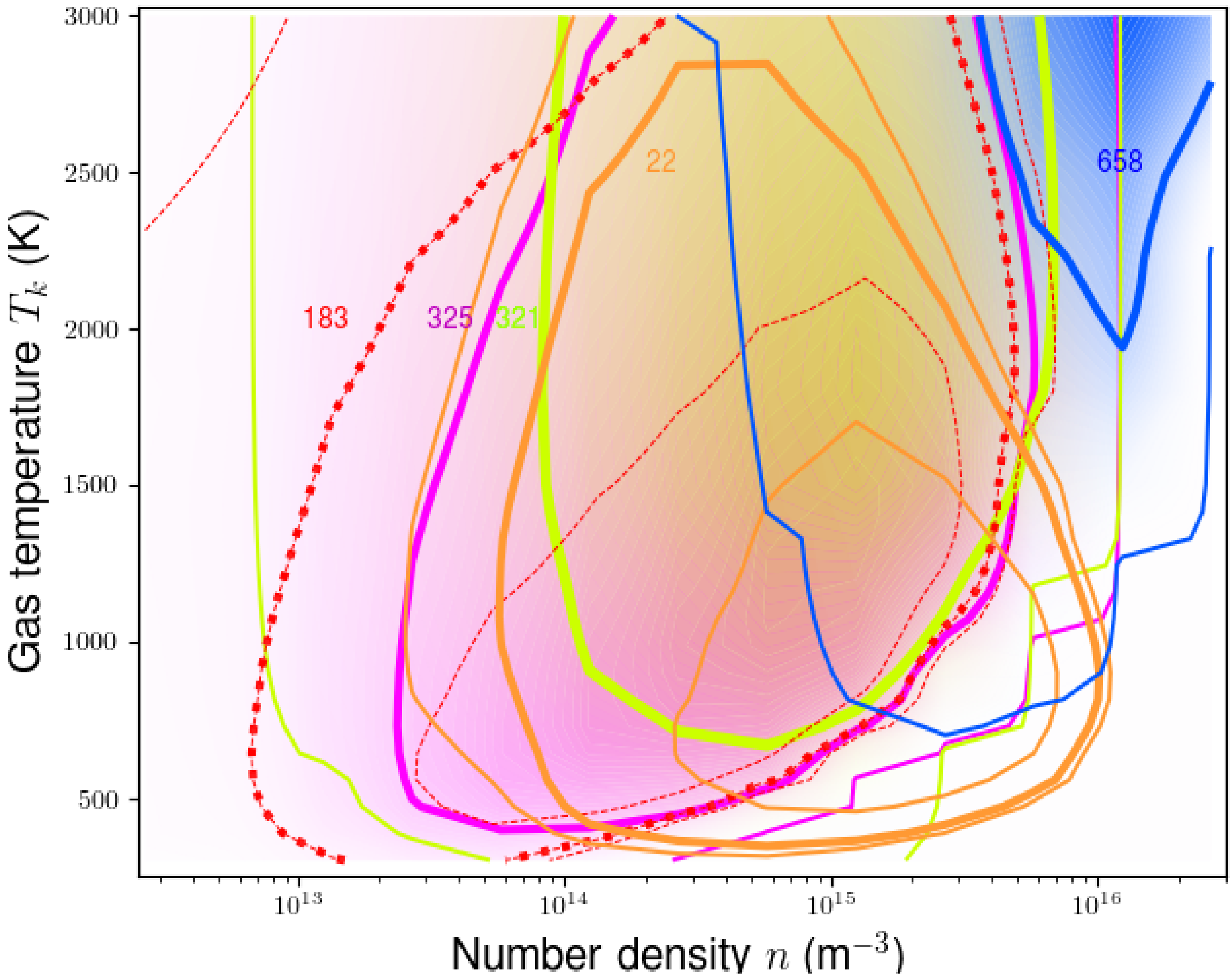


T_{dust} 50 K (268 GHz 1025 K) (models *Gray+ 2016*). All among detections **except 67 GHz**

Detections: *Cheung+1969; Waters+1980; Baudry+2022; Menten++; Hirota+2023; Neufeld+2017*)

- > 100 water masers predicted up to 2 THz (~half in ALMA bands)
  - Over half of those (plus extras!) detected but only ~dozen mapped

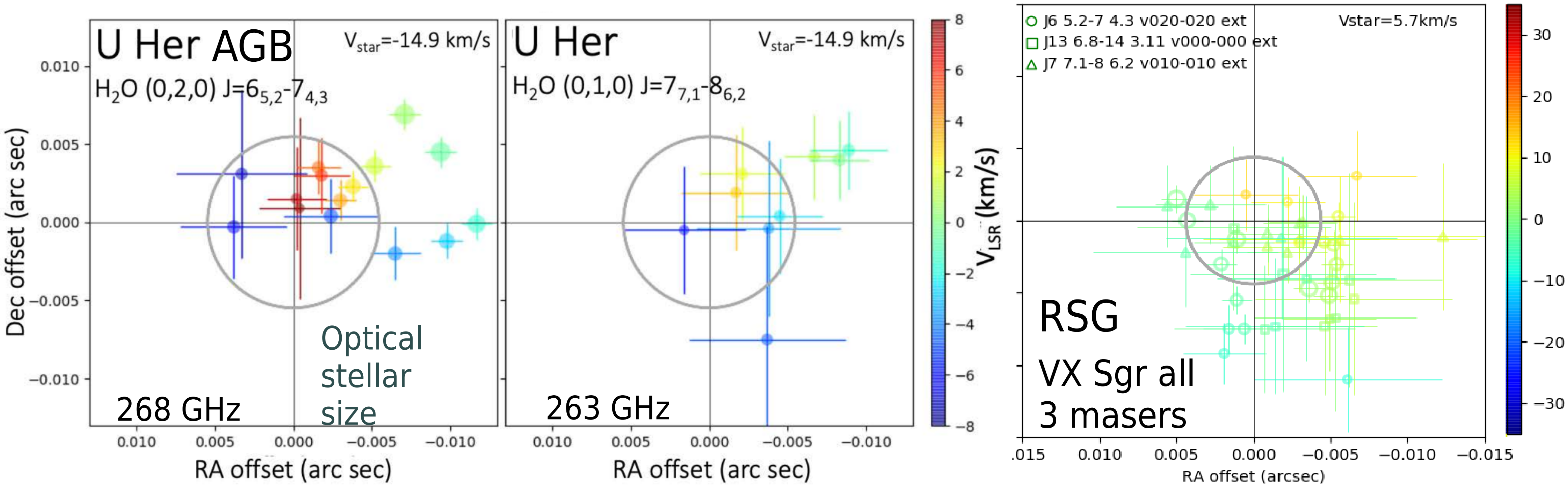
Infer physical conditions from maser model



- 658, 321, 325 GHz deeper shade = stronger maser τ
- 658, 321, 325, 22, 183 GHz **contour** at 50% max τ
- Lowest contour at crude estimate of sensitivity limit
- Identify overlapping or solitary line clumps
  - Deduce required number density n and gas T_k

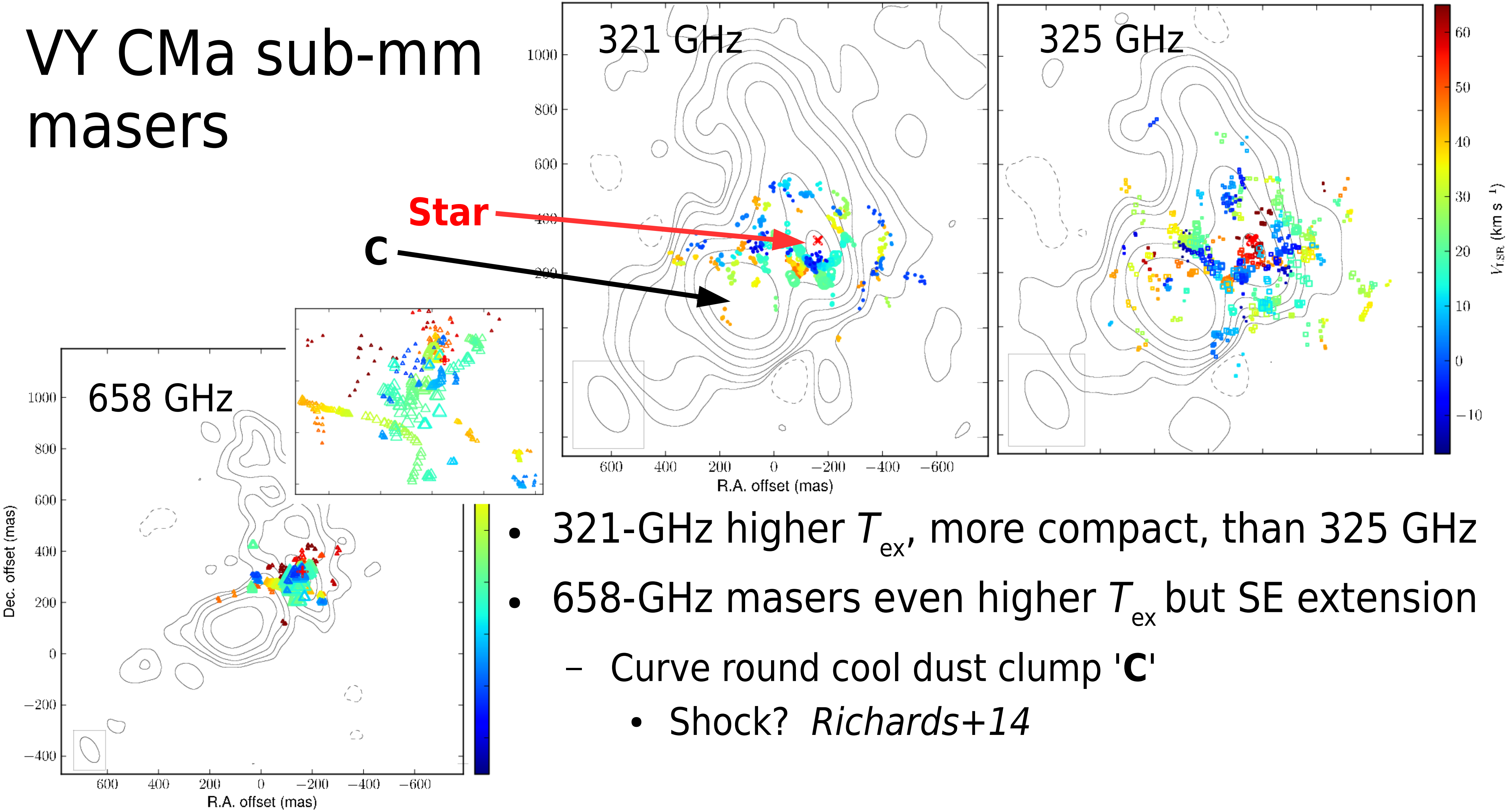
Water masers at 260, 263, 268 GHz

- ATOMIUM many new water thermal/maser detections *Baudry+2023*



- High T_{ex} , inner few R_*
  - Infall, outflow, some absorption.
- Original models don't predict 260, 268 GHz at high T_k

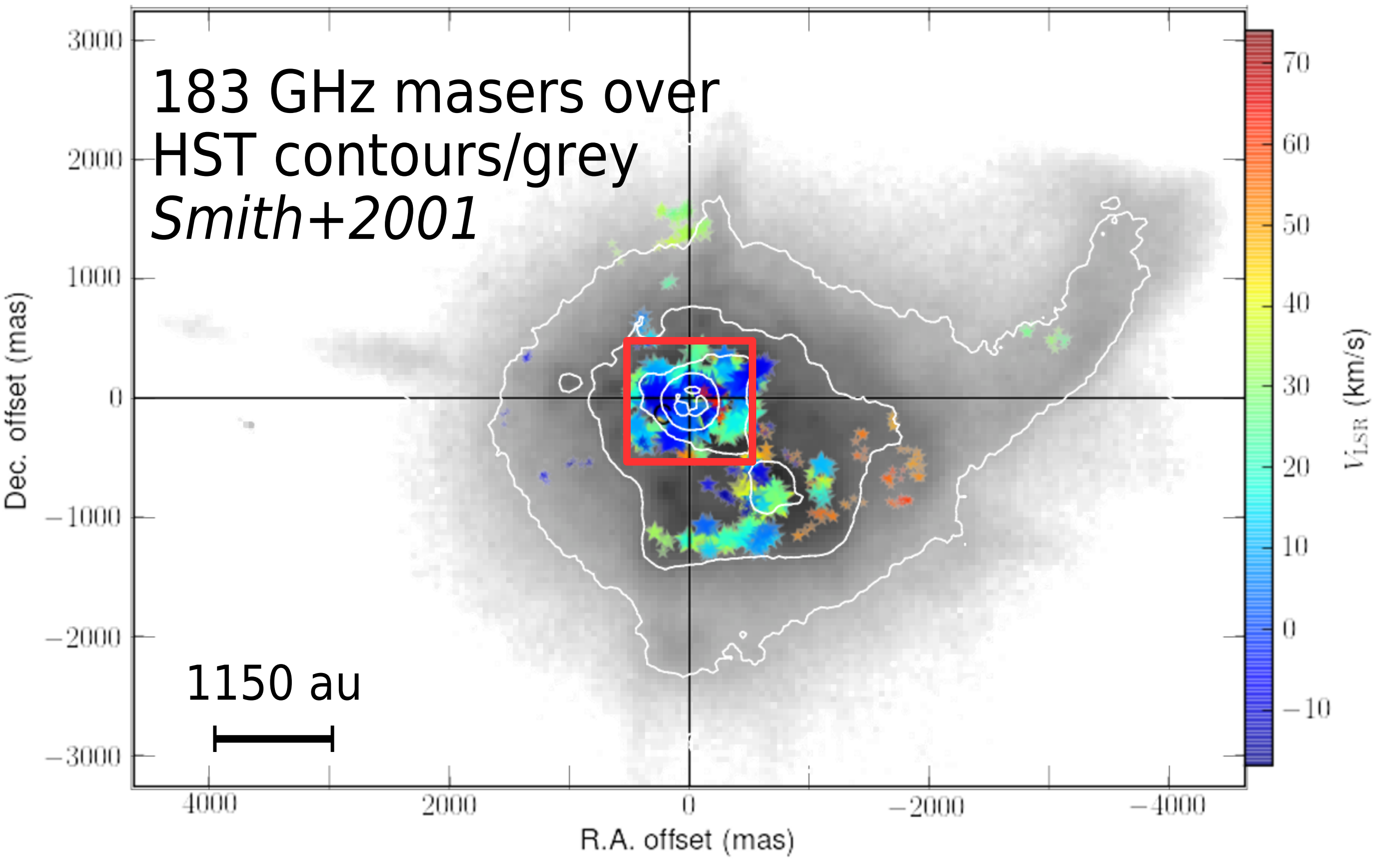
VY CMa sub-mm masers

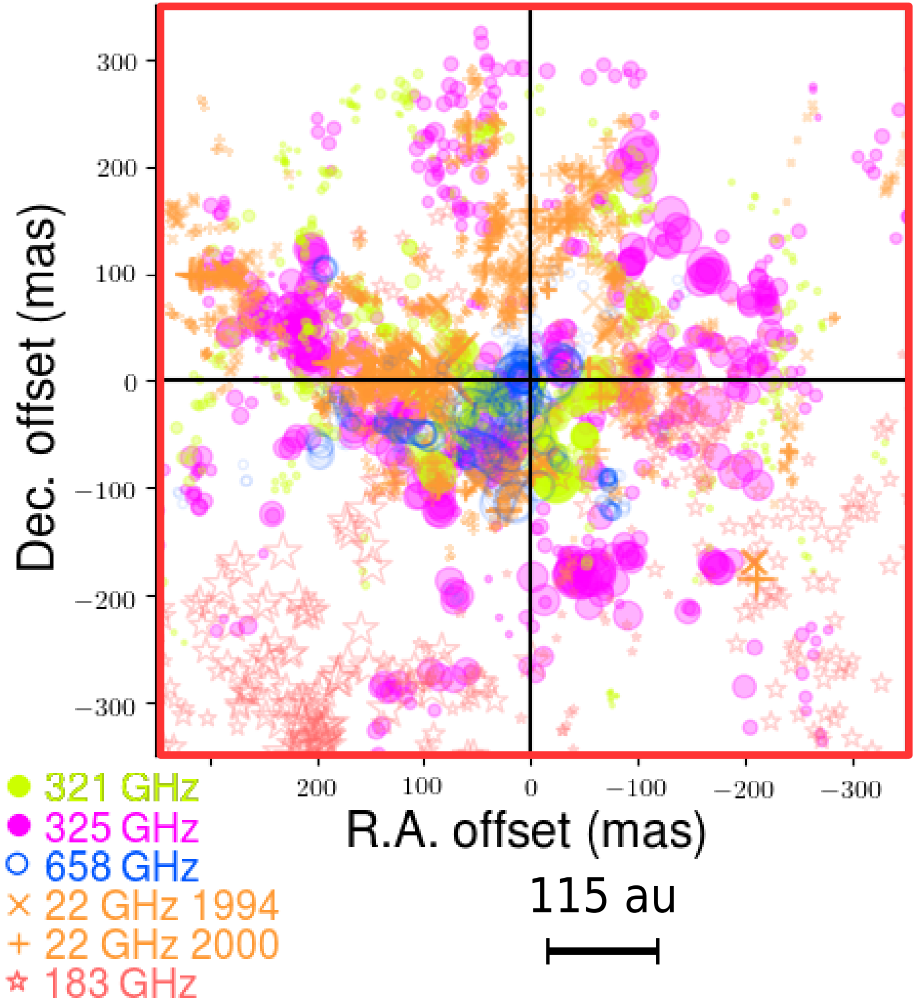


- 321-GHz higher T_{ex}, more compact, than 325 GHz
- 658-GHz masers even higher T_{ex} but SE extension
  - Curve round cool dust clump '**C**'
    - Shock? *Richards+14*

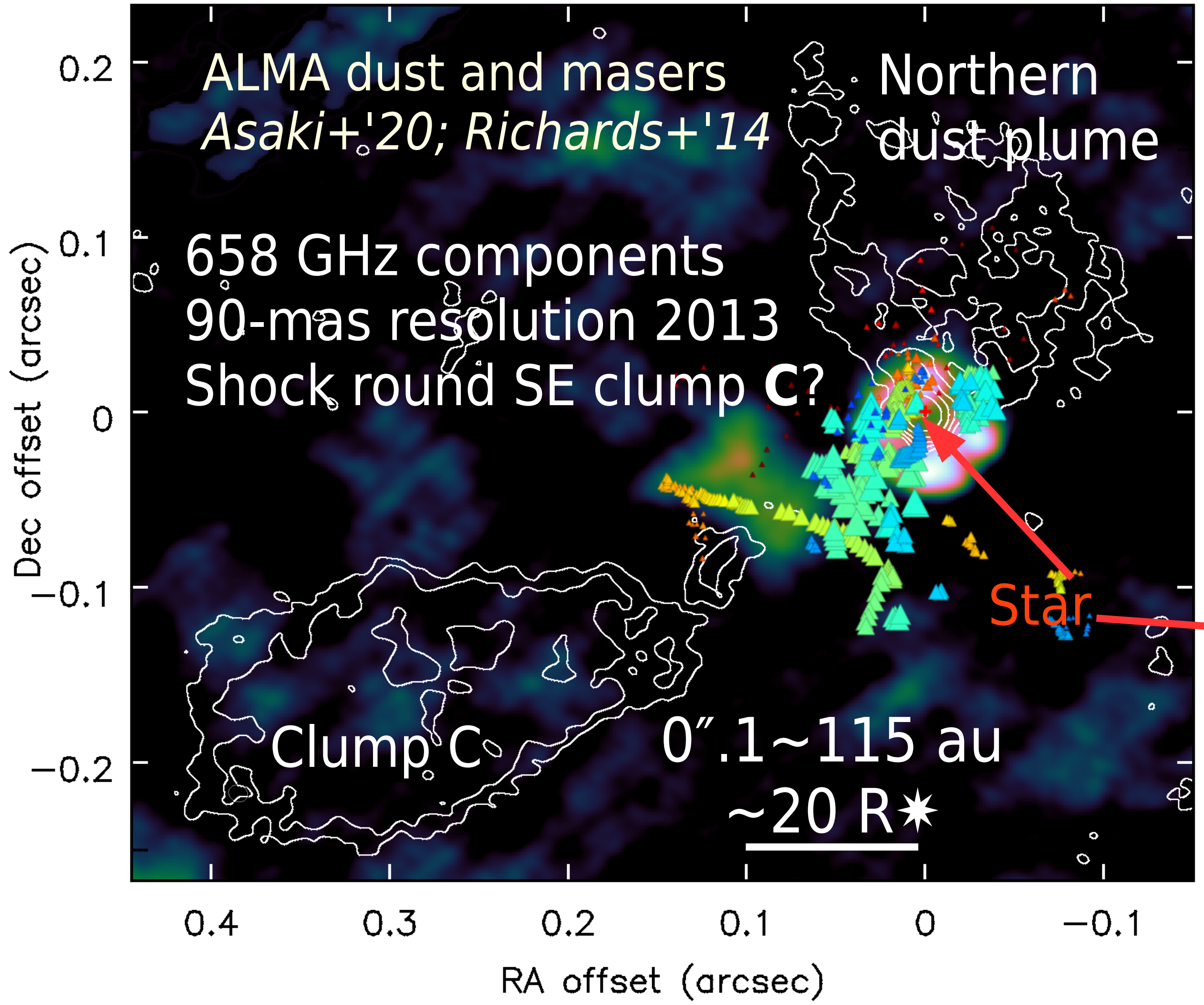
VY CMa multi-λ water masers

- 183 GHz masers (*Vlemmings+2017*) (cool T_{ex}) very extended as predicted
  - Distribution similar to HST dust-scattered light (as are OH)

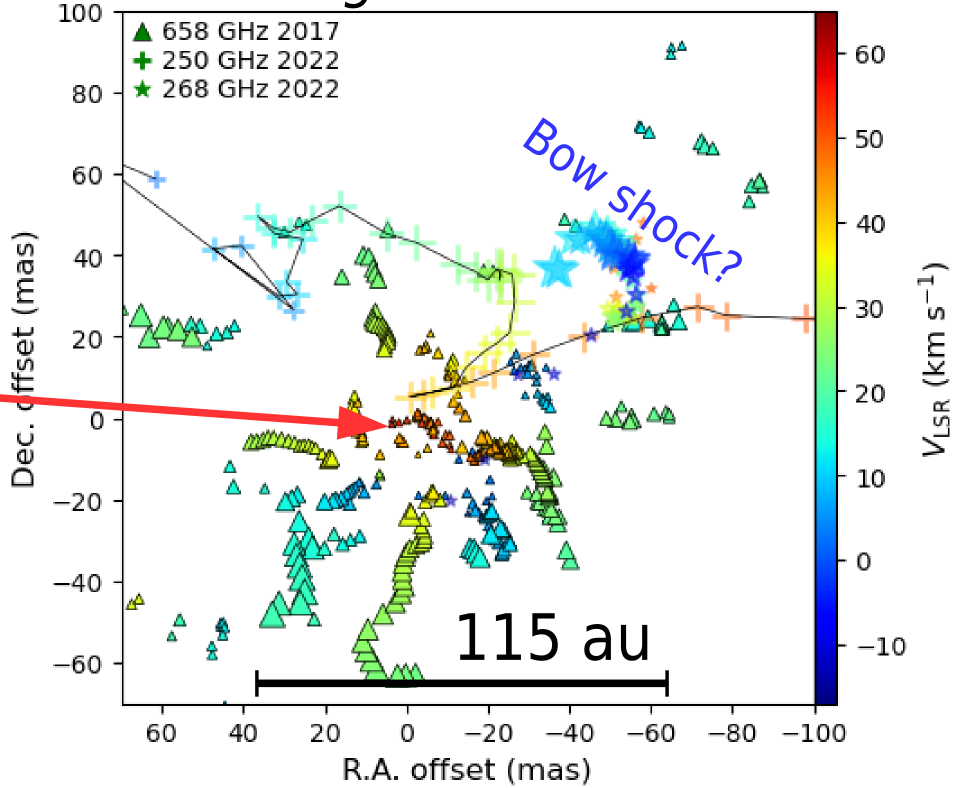




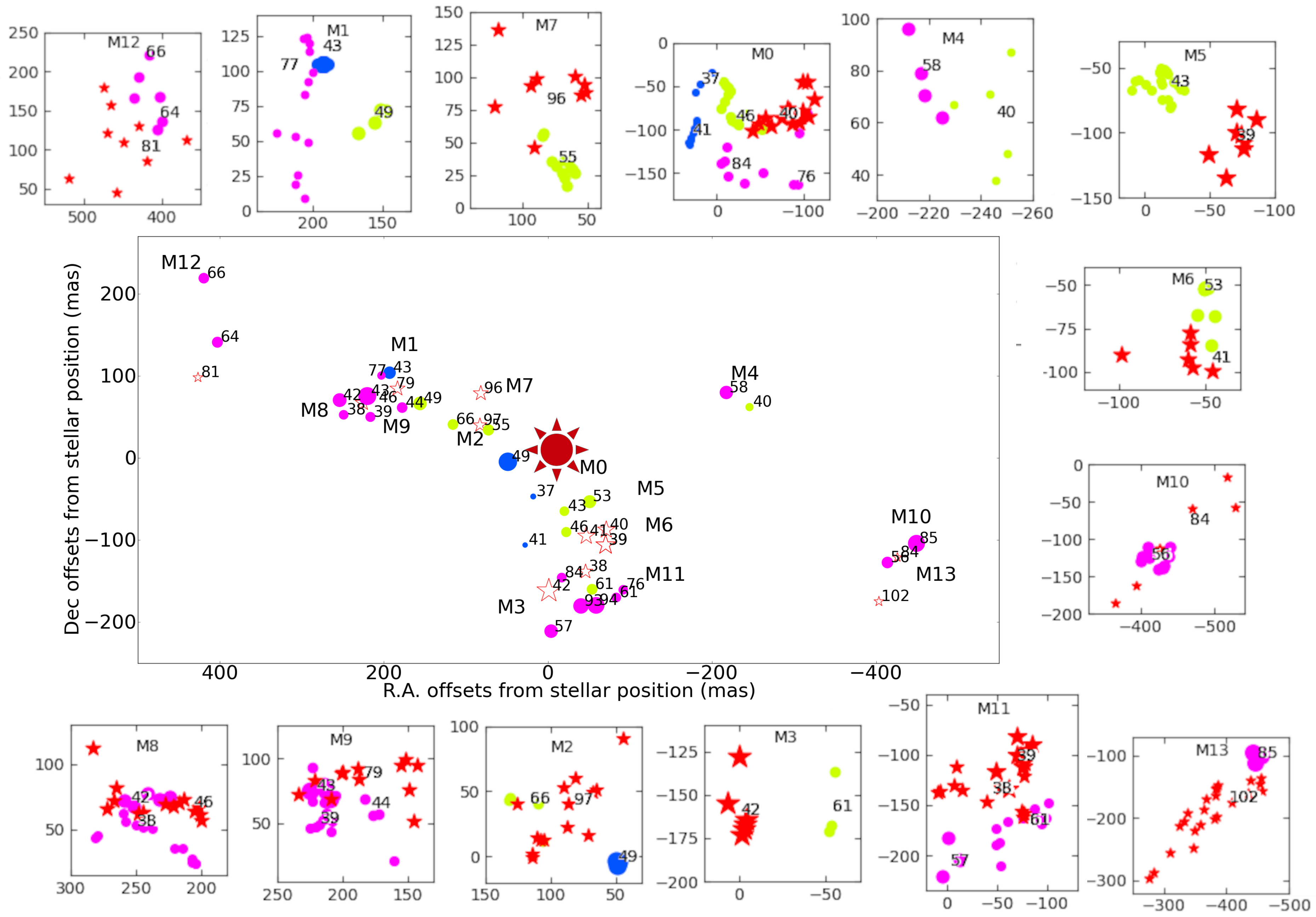
H_2O masers trace VY CMa pulsations & ejecta



- RSG discrete ejecta *Humphreys+24*
- 268 GHz confined to NW arc
  - ~60 au (~11 R_*) from star
  - Shock? *Singh+'23*



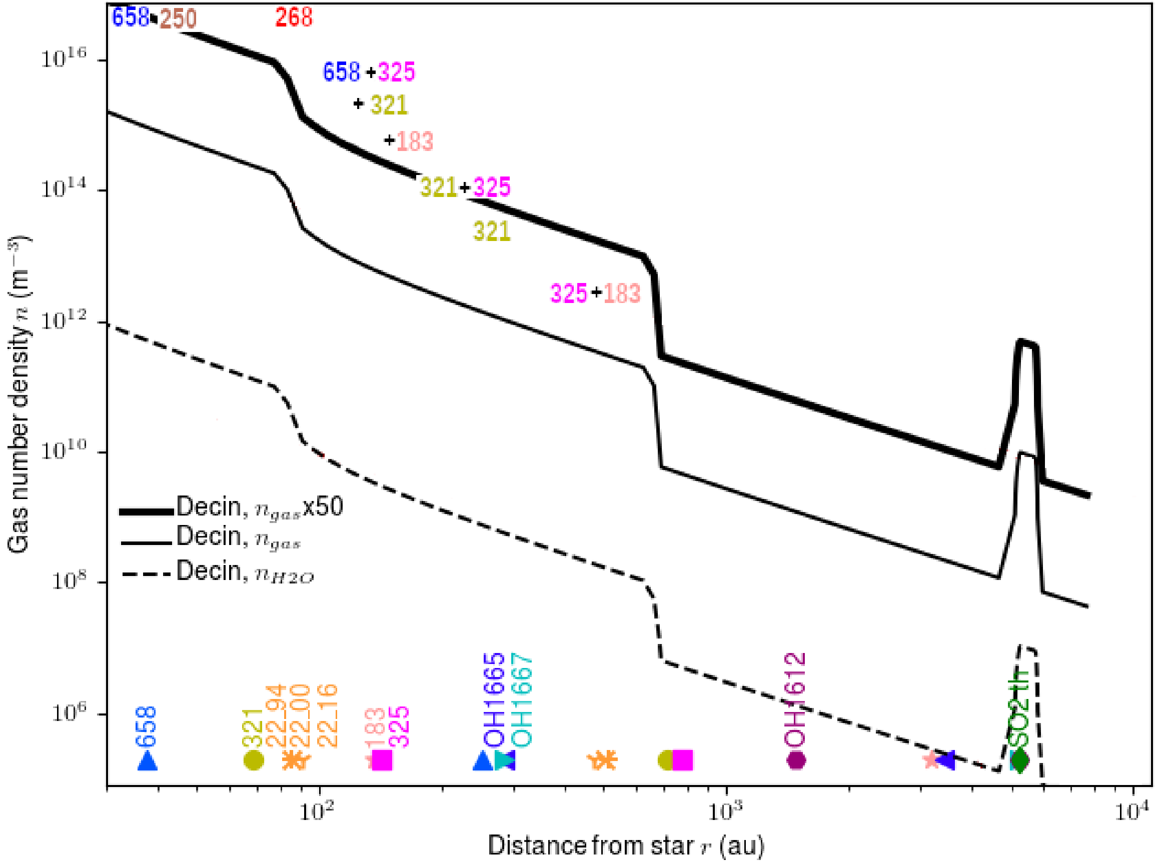
Clump overlap



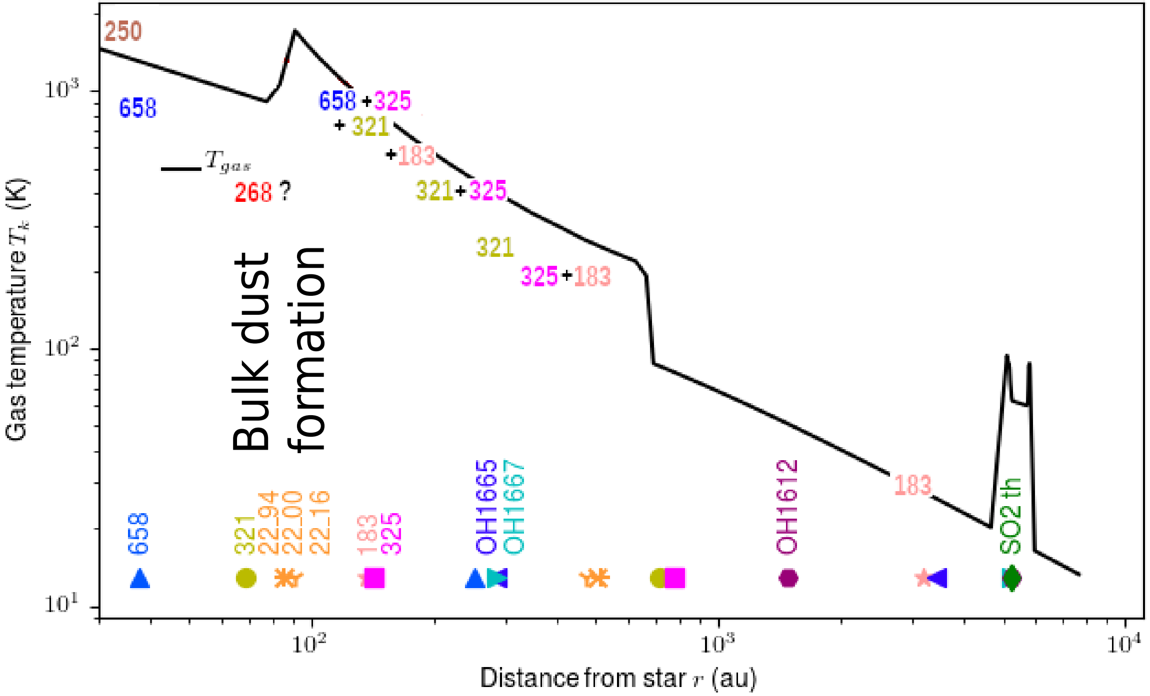
- Coincidence within clump extents
- Constrain conditions on few-au scales
- Work in progress!

VY CMa CSE model

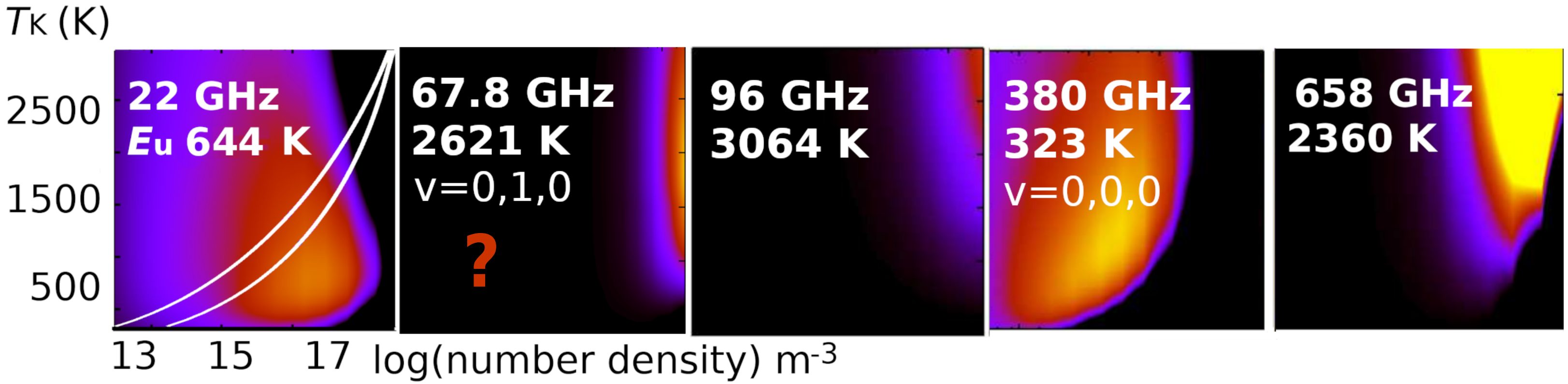
- *Gray+2016* maser conditions broad agreement with *Decin+2006* model
  - Must be ~50x overdense clumps (*Richards+'99,'12*)
  - Models for shocks and flares (*Gray+'21,'22,'23*)

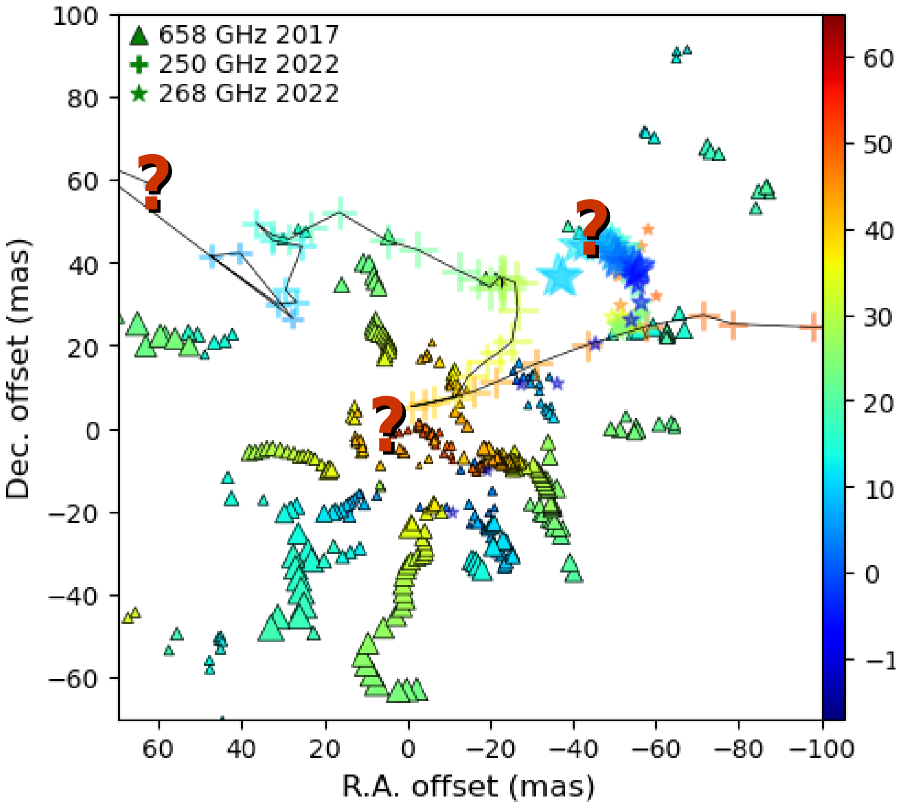


- 268 GHz unexpected at high T_k
- Confined to one shocked? region

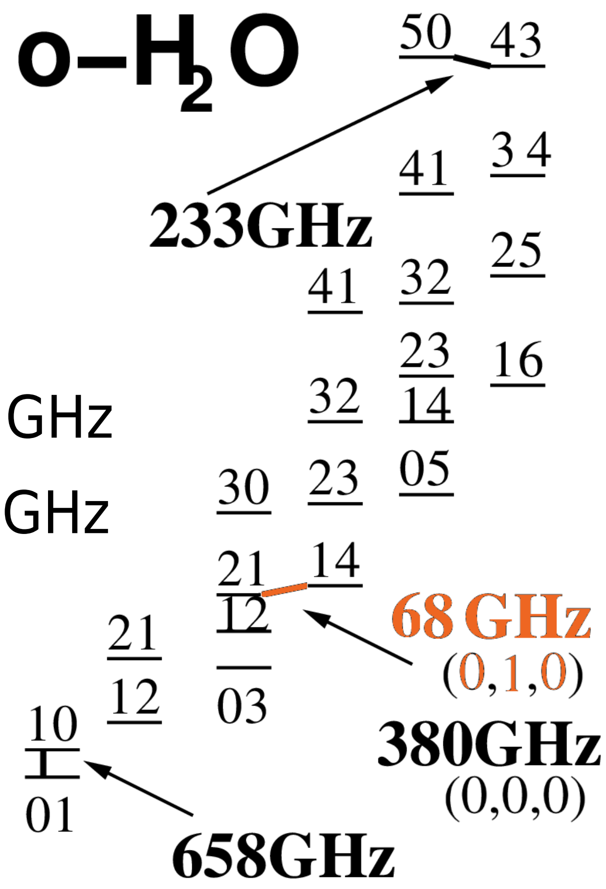


68 GHz masers: warm, dense environments





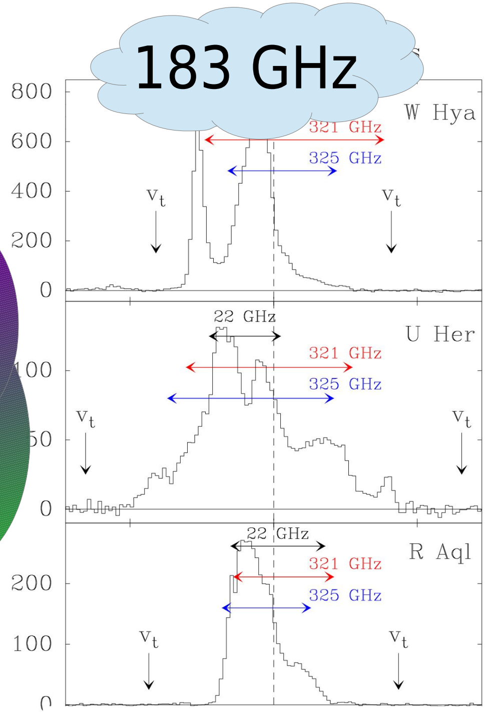
- Close to star like 658, 268 GHz in AGB?
  - Infall & outflow
- Quasi-thermal: 250 GHz
- Ejecta shocks: 658, 268 GHz
- Similar conditions to 96 GHz
  - *Menten+'89*, ~4 Jy
  - (*Nesterenok'15* predict 68 GHz much stronger!)



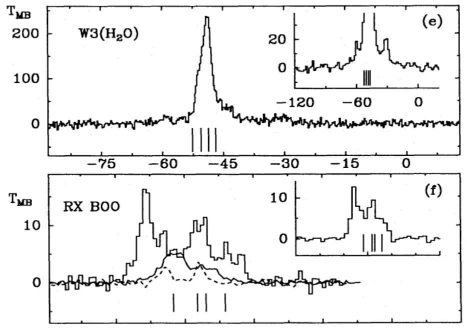
67.8 GHz detectability

- 0.5 km/s channels
  - 2-min sensitivity (good conditions)
    - ~1.2 Jy per antenna (both polarisations)
    - ~4-Jy peak needed for line self-cal
  - All antennas, 30 min, ~10 mJy
    - 50 mJy at 60 mas resolution, T_b ≥3700 K
      - Maser spots compact, higher T_b from fitting components
- Brightest stellar continuum around 68 GHz ~50 mJy?
  - Detectable but too weak to self-cal
  - 1-min sensitivity per antenna in 1 GHz ~20 mJy per pol
- Choose targets close to suitable phase calibrators!

67 GHz telluric absorption mostly O
High & dry less help
:-(



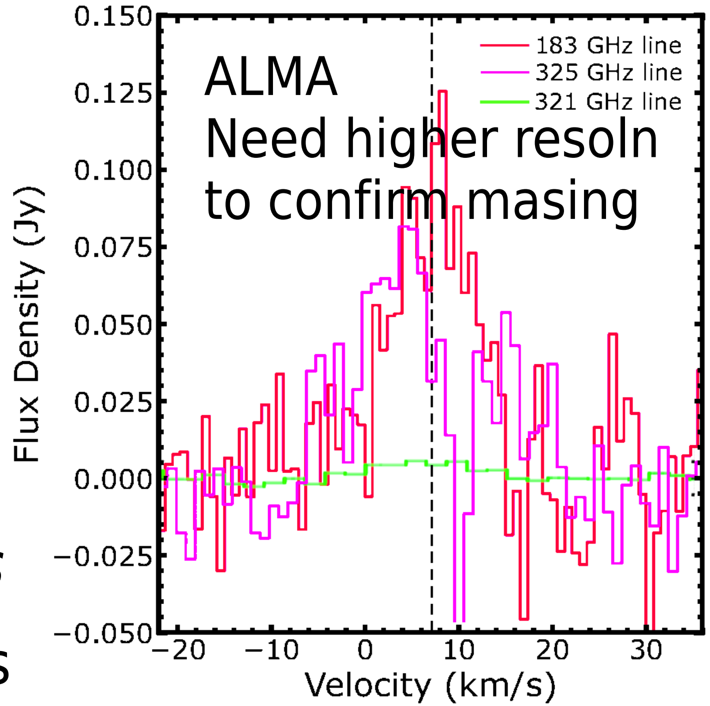
Humphreys+2017
APEX

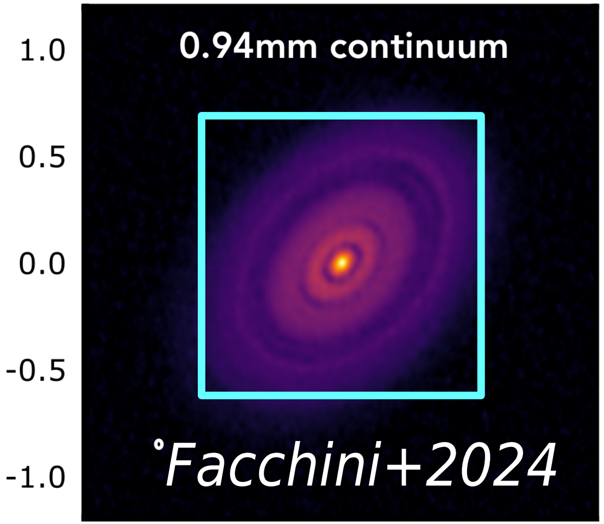


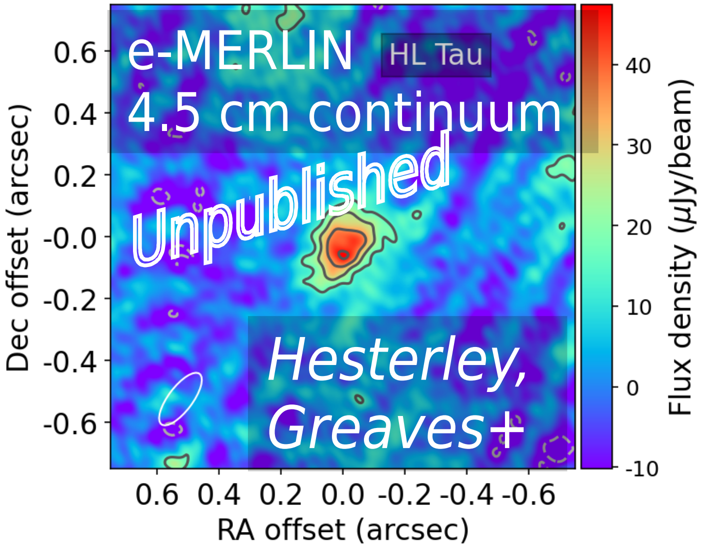
Cernicharo+1990
IRAM

Water in protoplanetary discs

- HL Tau H_2O column density 10^{18} cm^{-2} within 17 au
  - High optical depth at few au/in mid plane
  - 67.8 GHz line could penetrate cool, dense mid plane
- PEBBLeS e-MERLIN *Greaves*
  - ~80 hr on each of 10 fields
  - 6.5 GHz: sensitive to ~1–10 cm pebbles
  - Compare ALMA archive data; Discs@VLA *Chandler*+ VanDam *Tychoniec*+, fit disc masses
  - Solids few 100 M⊕ (within Jupiter – Uranus orbits)

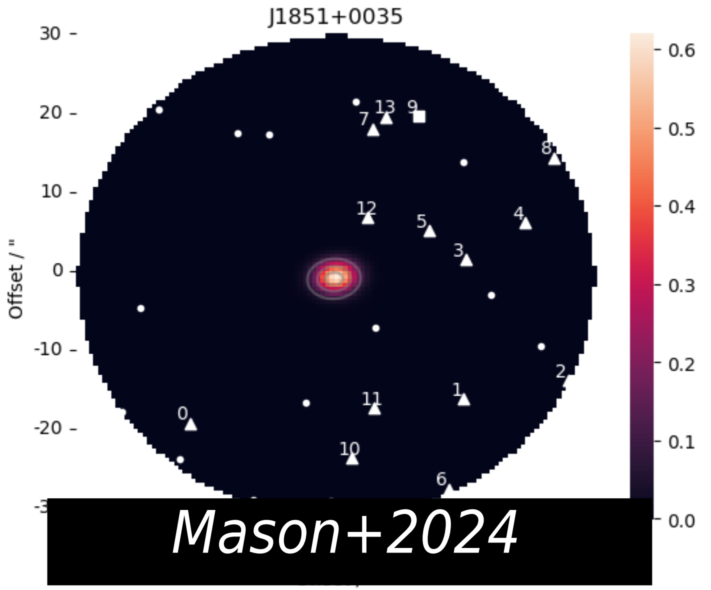




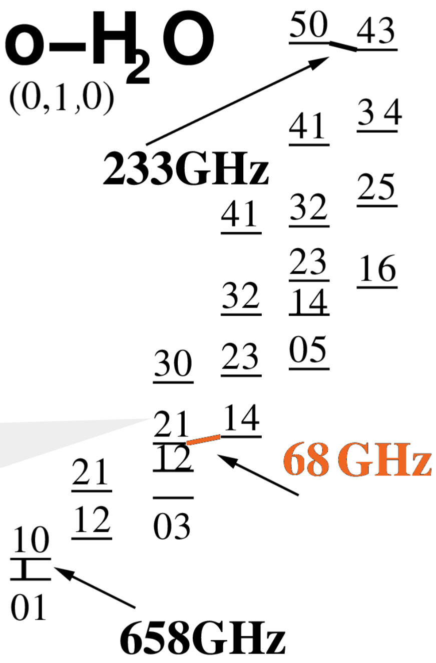


SETI serendipitous surveys

- Traditionally SETI searches 1 – 10 GHz
  - Survey large stellar populations for narrow-band transmissions e.g. radar
  - Lower ν = easier tech, wider fields
  - Higher ν = higher resolution
- Collision avoidance?
  - Used in 76–81 GHz car radar



- Search for narrow-band (35 kHz) signals using B3 ALMA archive calibrator data.
- Look in direction of Galactic stars within the ALMA FoV
- Planning more: JCMT/EAO, Breakthrough Listen
  - Develop techniques useful for ALMA WSU searches




Courtesy of Hirshhorn Museum, SI

Excited overpopulation? You are welcome, a-Masing!

Summary

- Dozens of water masers from 22 GHz to THz sample many decades of temperature, number density, velocity gradients...
- 67.8 GHz line could provide tighter constraints on local density/temperature/abundance in wind-launching zone of evolved stars
  - An order of magnitude higher resolution than thermal lines
  - Feed into chemical and dust formation/wind driving models
    - Non-detection > improved maser models! (e.g. relationship w. 380 GHz)
- 67.8 GHz maser excited in dense but cool conditions
  - Mid-plane of proto-planetary discs?
- Band 2 great potential for SETI

Further reading:
Gray 2012; +2016; Baudry+2023
Nesterenok 2015 etc.
WaterUniverse on Zenodo