Masers
making the most of high resolution

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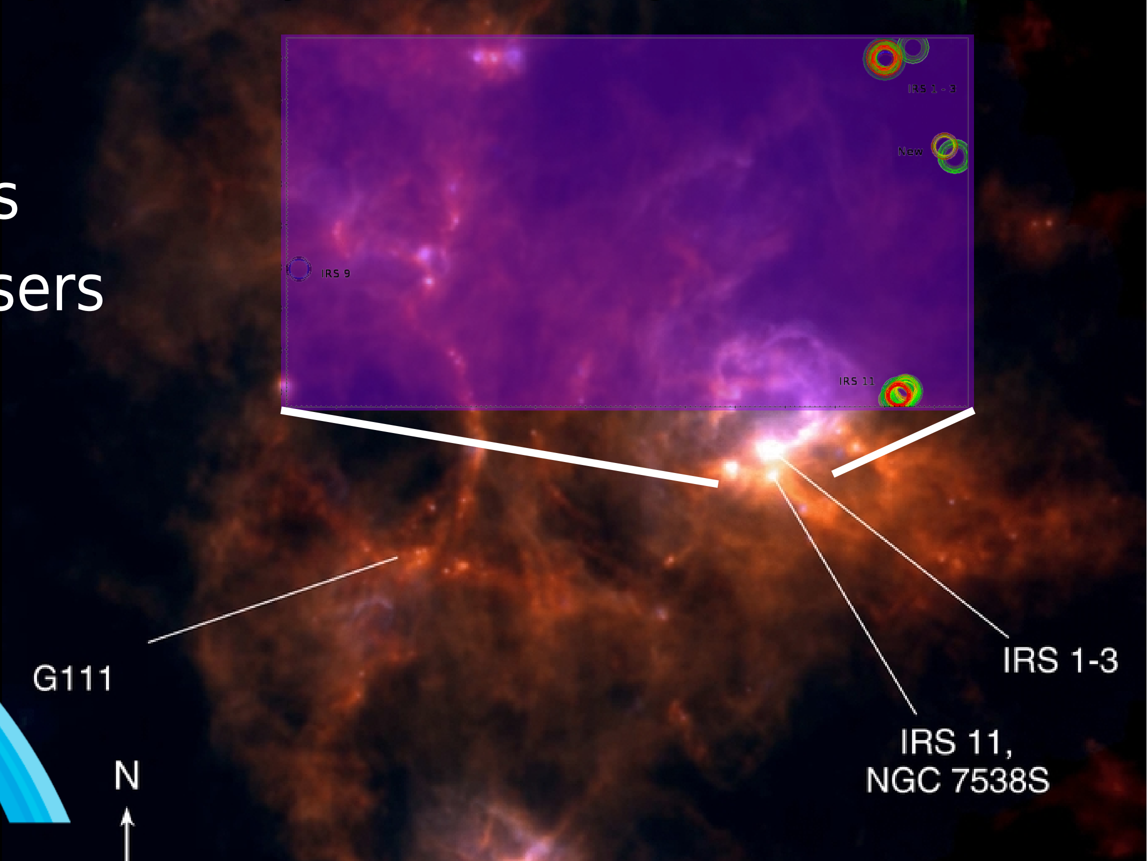
thanks to Kityanee Asanok, Alain Baudry, Leen Decin, Dieter Engels, Sandra Etoka, Malcolm Gray, Fabrice Herpin, Liz Humphreys, Marcello Leal-Ferreira et al., plus Rob Beswick, Eddie Blackhurst, Jimmy Cullen, John Edgeley, Gary Fuller, Paul Harrison, Xavier Moldon, Tom Muxlow, Nick Wrigley and everyone else who got K-band going!

- What's a maser?
- e-MERLIN early results
- K-band and water masers



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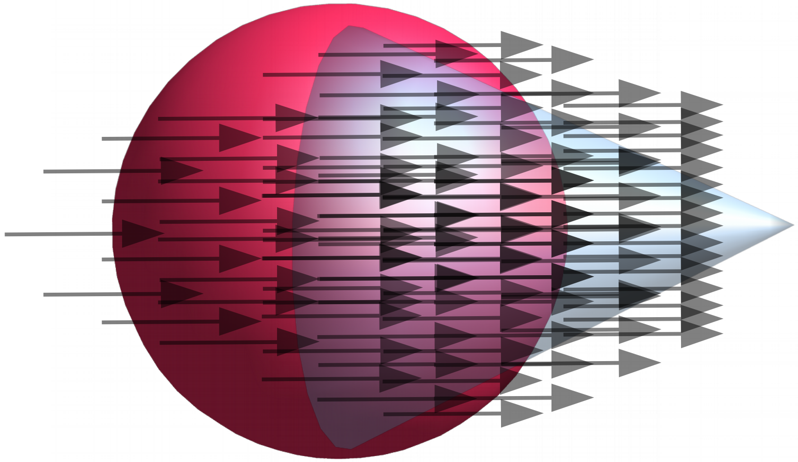
ALMA Regional Centre || UK

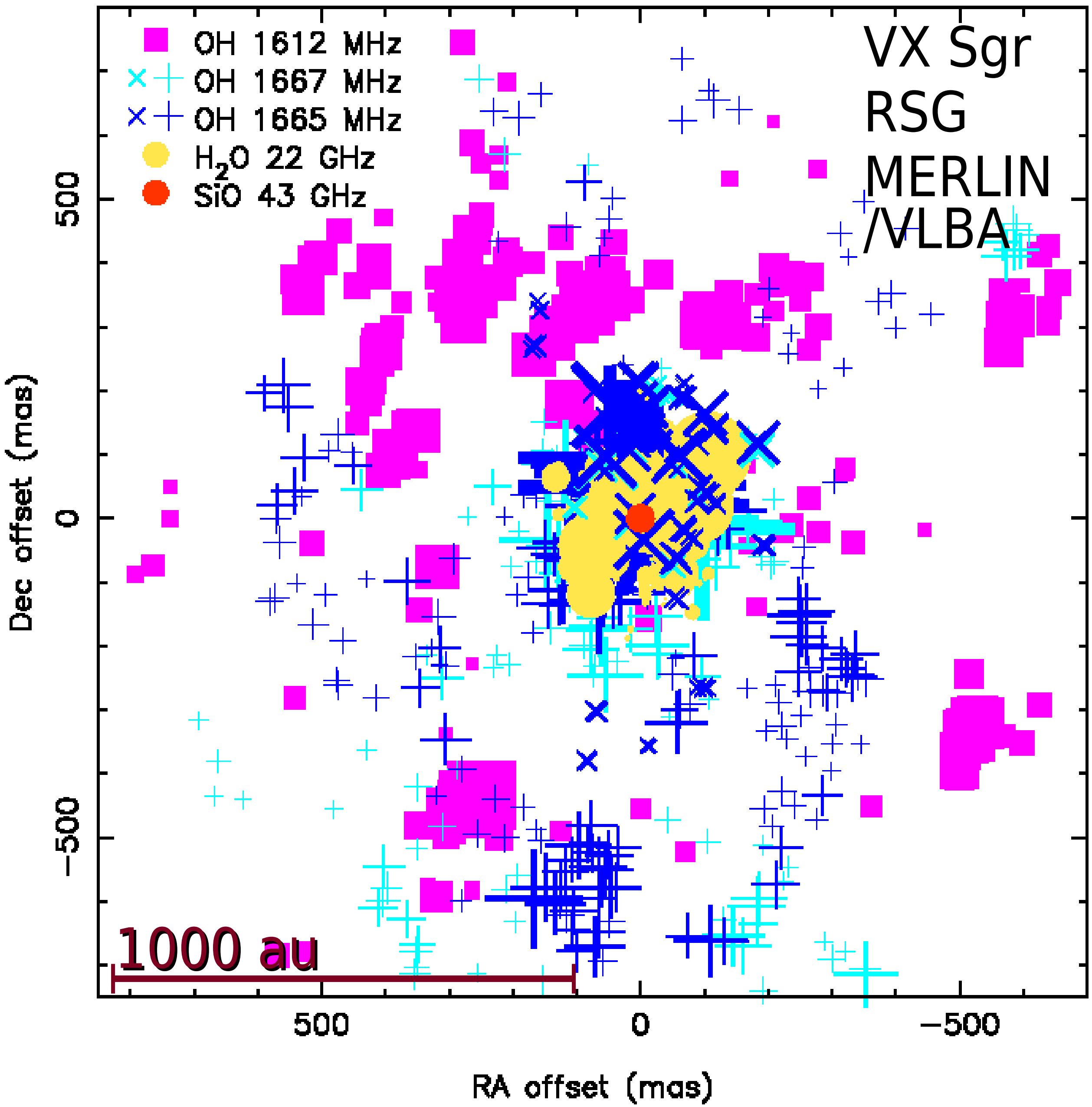
What's a maser?



- Maser emission
  - Naturally-occuring radio analogue of laser
  - Excess of molecules in a higher energy state
    - Collisional, IR etc. pumping
  - One radio photon of the right λ for the state enters a cloud
  - Stimulated emission produces 2, 4, 8, 16...
  - Cloud brightness can be amplified x millions
  - Appears very compact, measure very accurately

  - Emission wavelength precisely known
  - Deviations due to Doppler effect
  - Measure speed of gas towards or away from telescope

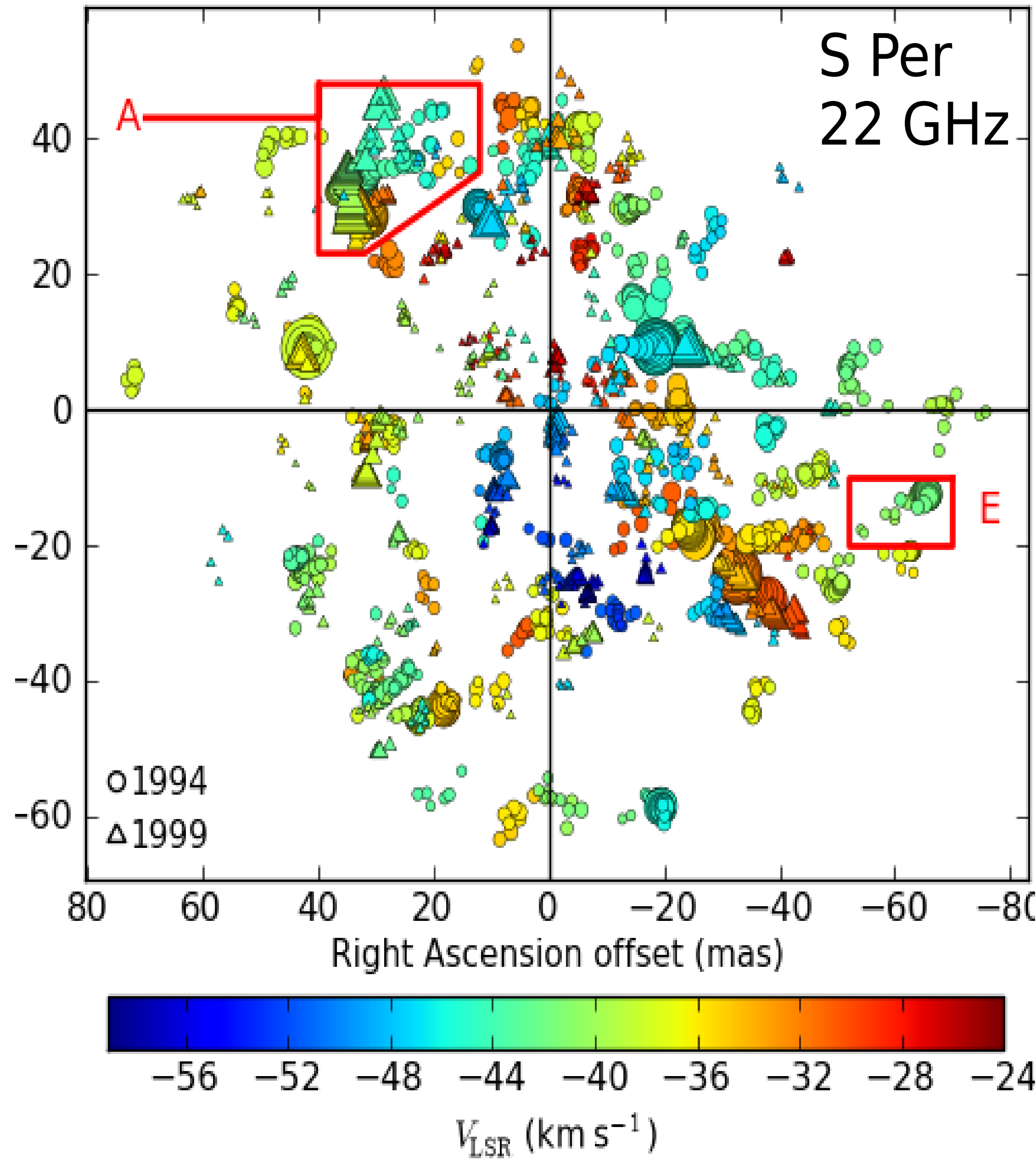
Maser location depends (partly) on E_U



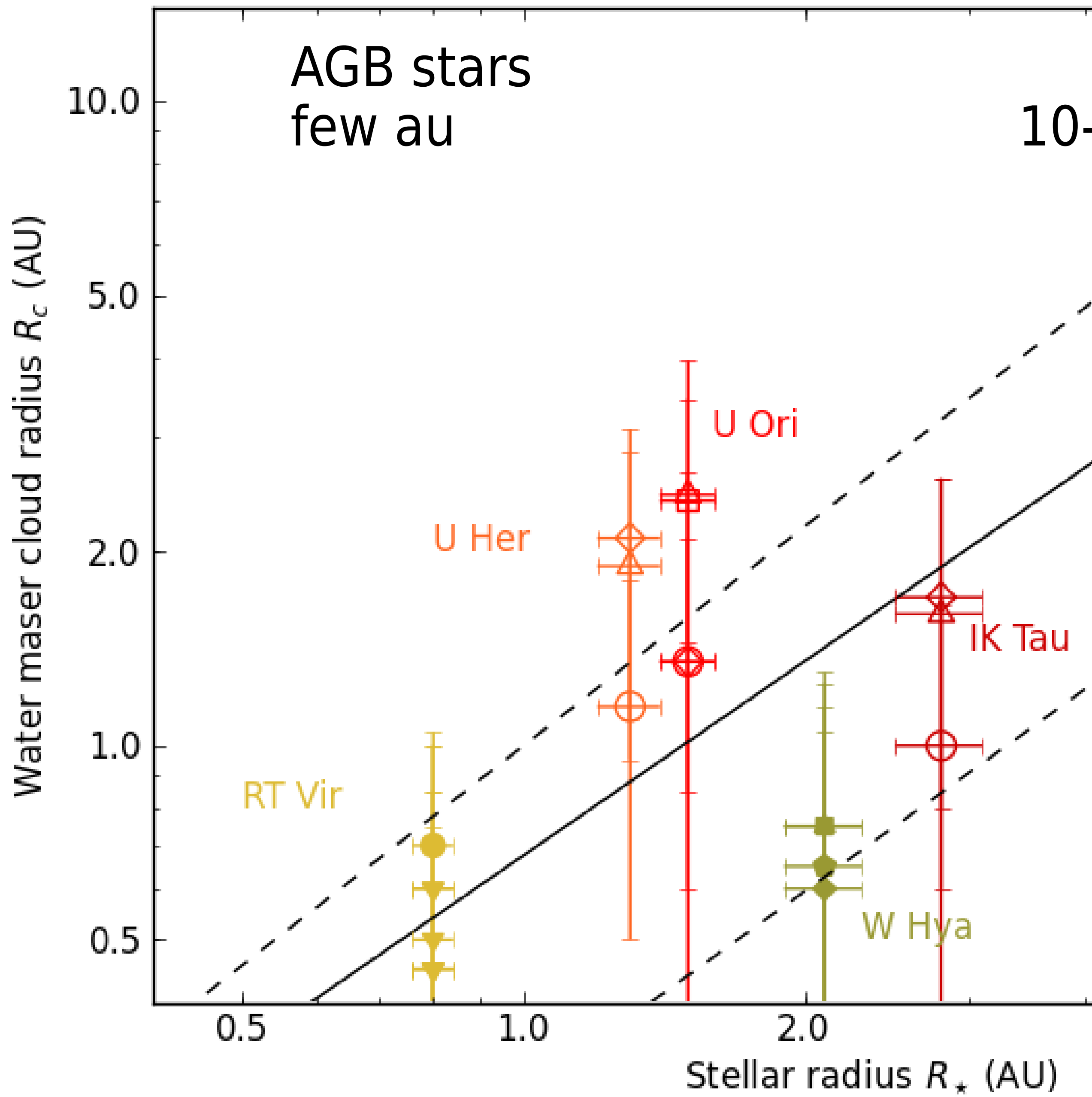
- SiO 43, 86 GHz
  - E_U >1800 K
  - < 4 $R_\star$
- H_2O 22GHz
  - E_U ~650 K
  - 5-30 $R_\star$
- OH 1612 MHz
  - E_U tens K
    - >50 $R_\star$
- OH mainlines (1665-1667 MHz)
  - E_U < 500 K
  - Intermediate locations

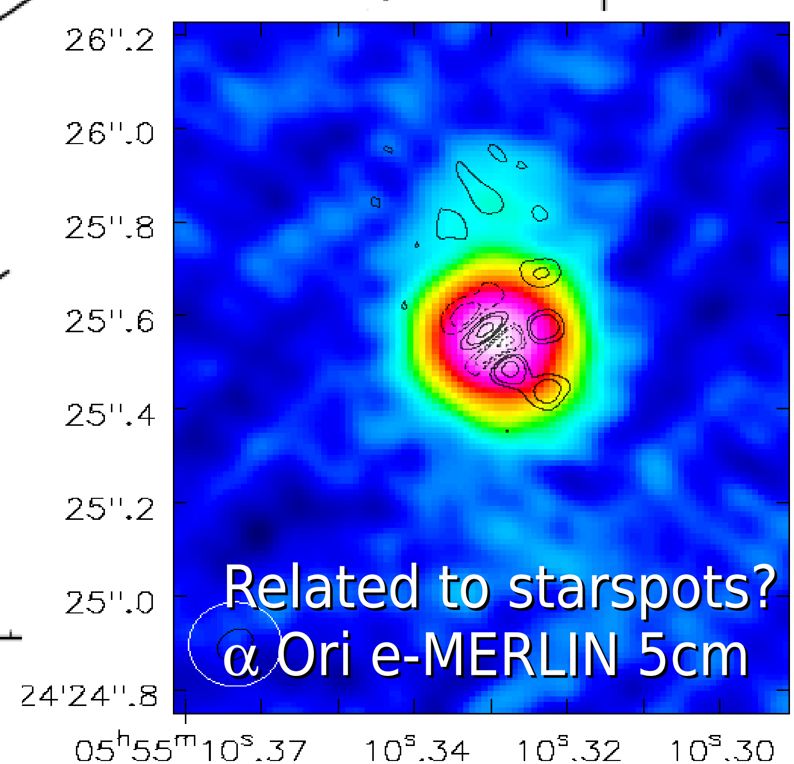
Cloud measurements

- Fit 2-D Gaussian
  - Pos. error beamsize/(S/N)
- Component beamed size *s*
  - 1-2 km s^{-1} series
    - Gaussian spectra
      - $\Delta V_c \gtrsim \Delta V_{th}$
- Beamed size typically 0.1-10 mas
- Series = discrete clouds
    - R_{cAGB} 1 - 2 AU
    - R_{cRSG} 10-15 AU
- Beaming angle $\sim(0.5s/R_c)^2$



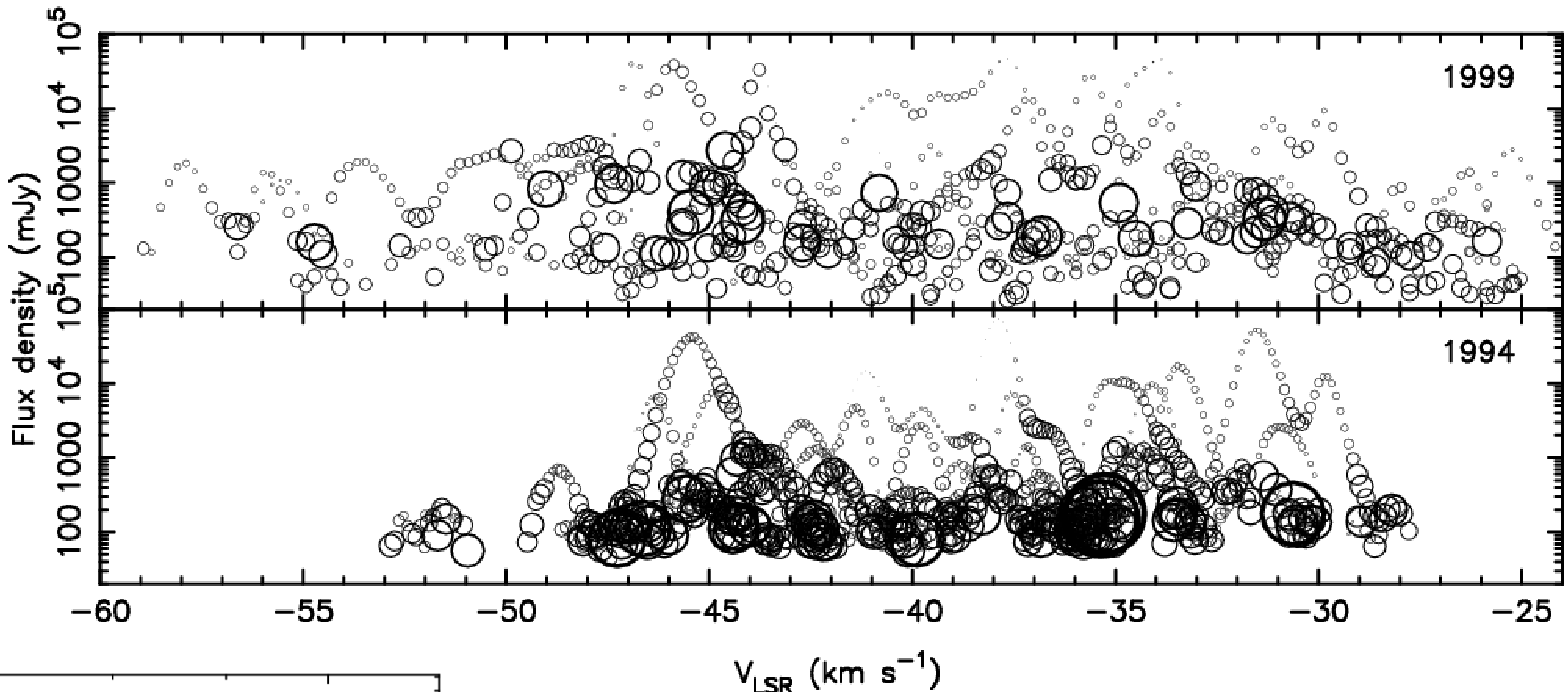
Cloud size depends on star size

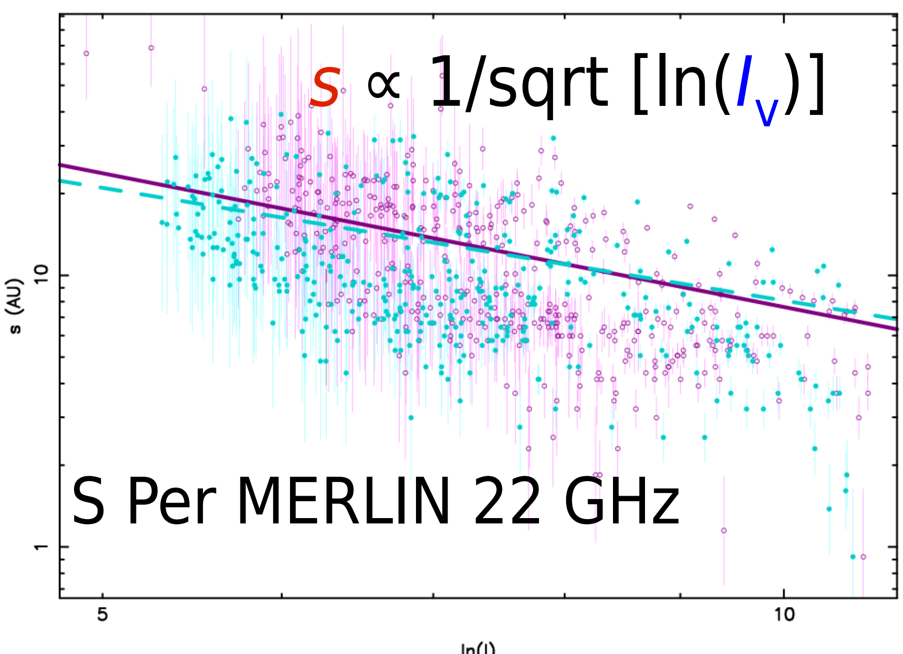




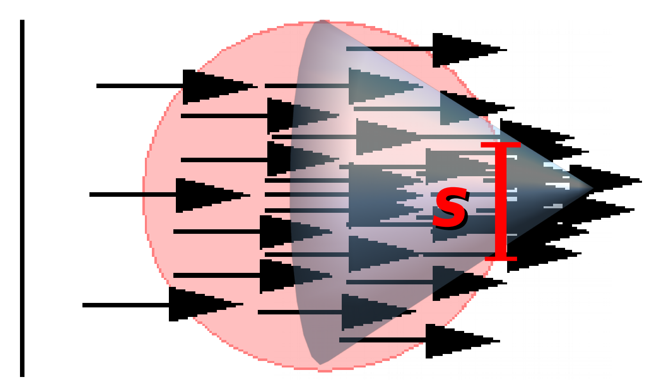
Shrinking of brighter water masers

- Component size s
- Intensity I_ν
- Brighter spots are smaller



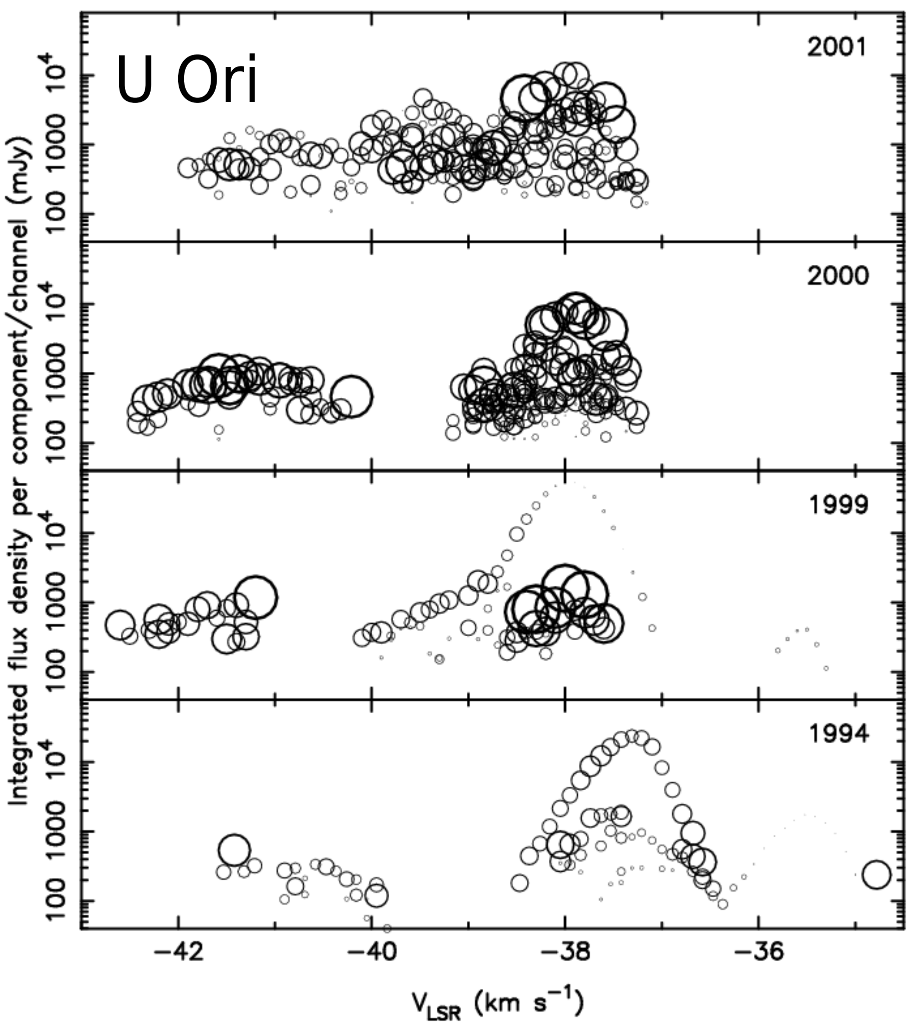


- “Amplification-bounded” beaming from ~spherical clouds

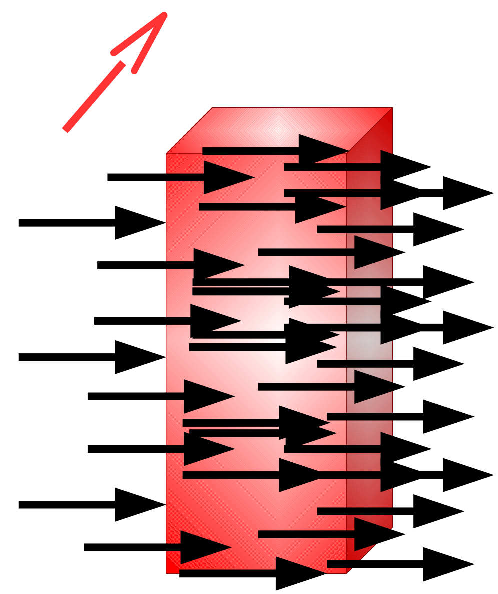


But *sometimes* brighter=bigger

- Spectral peak components swell

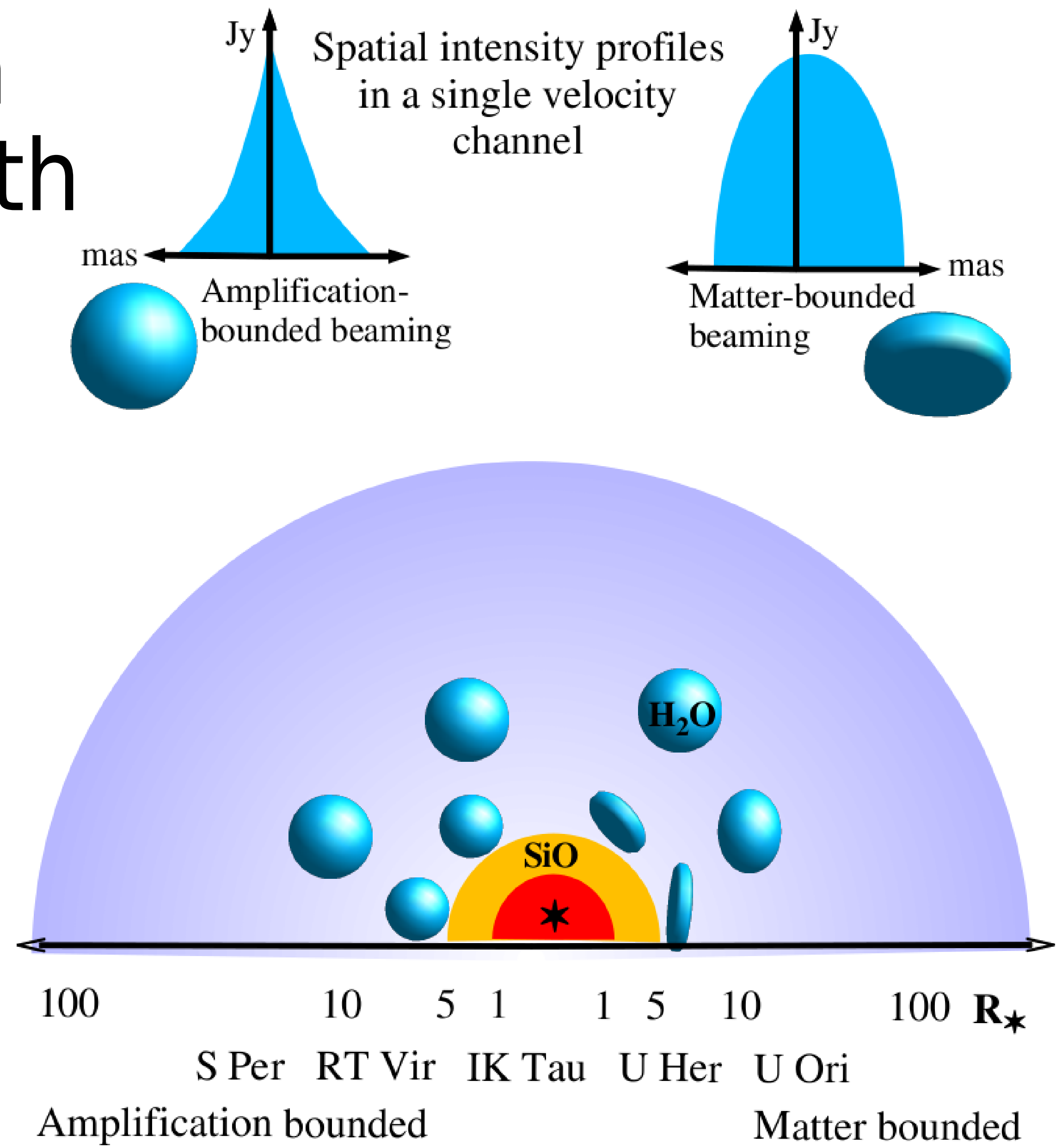


- Shock 'into page'
  - Maser propagates perpendicular to shock
    - Pump photons escape orthogonally
    - Entire surface emission is amplified
    - “Matter bounded” beaming
    - Apparent size ~ actual size



Masers distinguish shocks from smooth outflows

- VLA can't resolve clouds
- VLBI resolves out 20-90% of emission
- Only (e-)MERLIN can fully detect *and* resolve all emission from Galactic 22-GHz water masers
- e-MERLIN+EVN prospect for methanol, hydroxyl



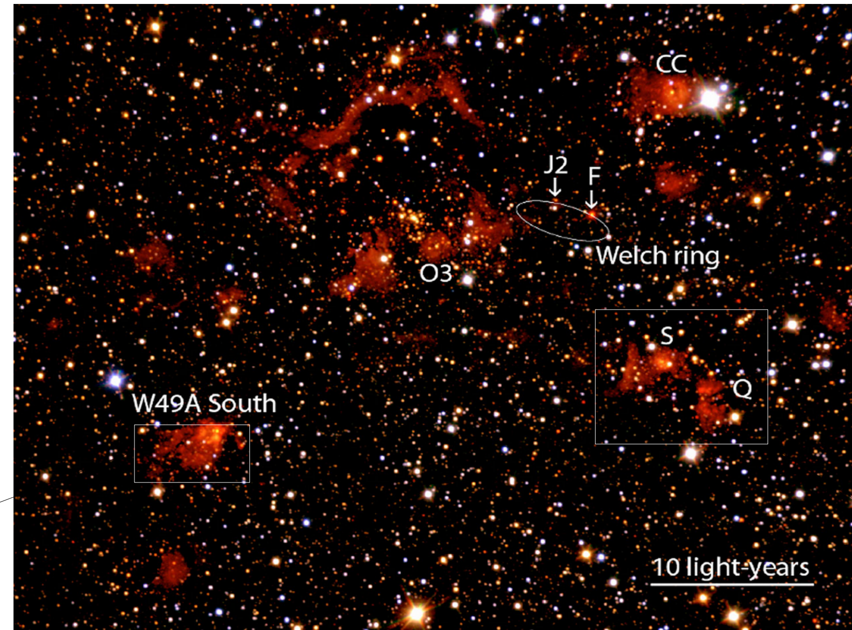
Richards Elitzur & Yates 2011
Elitzur Hollenbach & McKee 1992

e-MERLIN first masers: W49

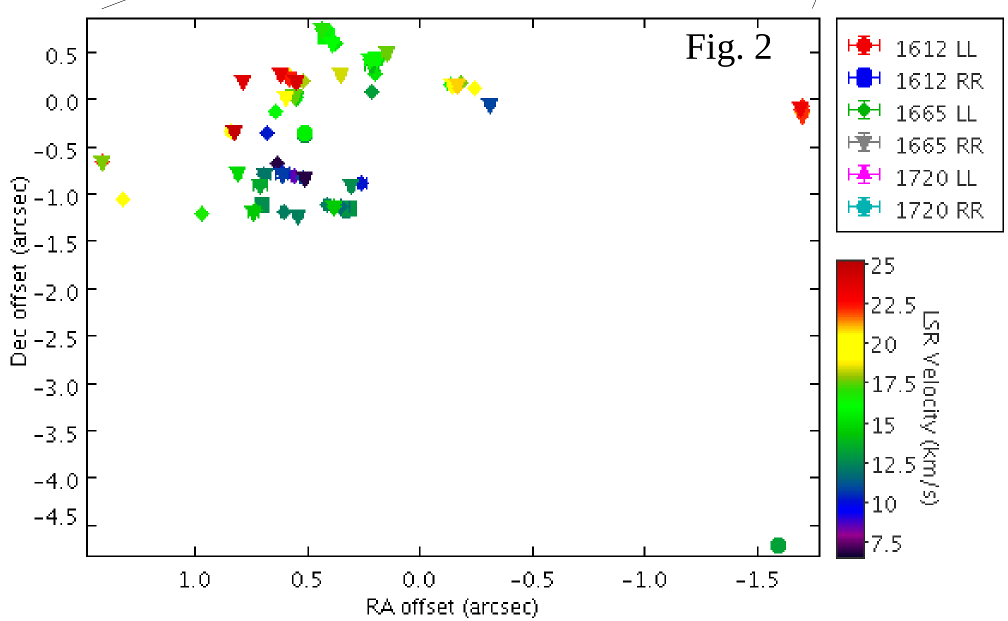
- OH traces discs and outflows in massive SFR
  - New maser site
  - Velocity gradients suggest discs

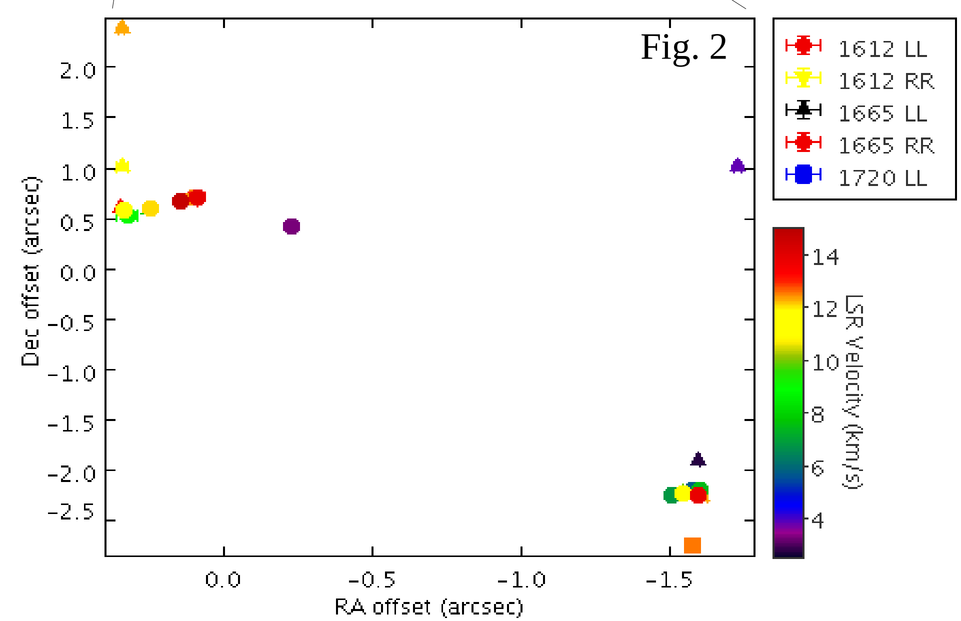
e-MERLIN 1612,1665/7, 1720 GHz

Asanok, Etoka et al.



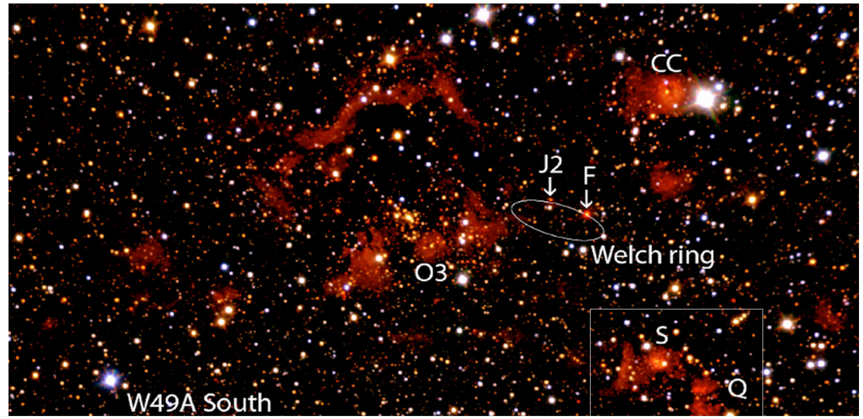
http://www.eso.org/public/archives/images/screen/eso0322a.jpg

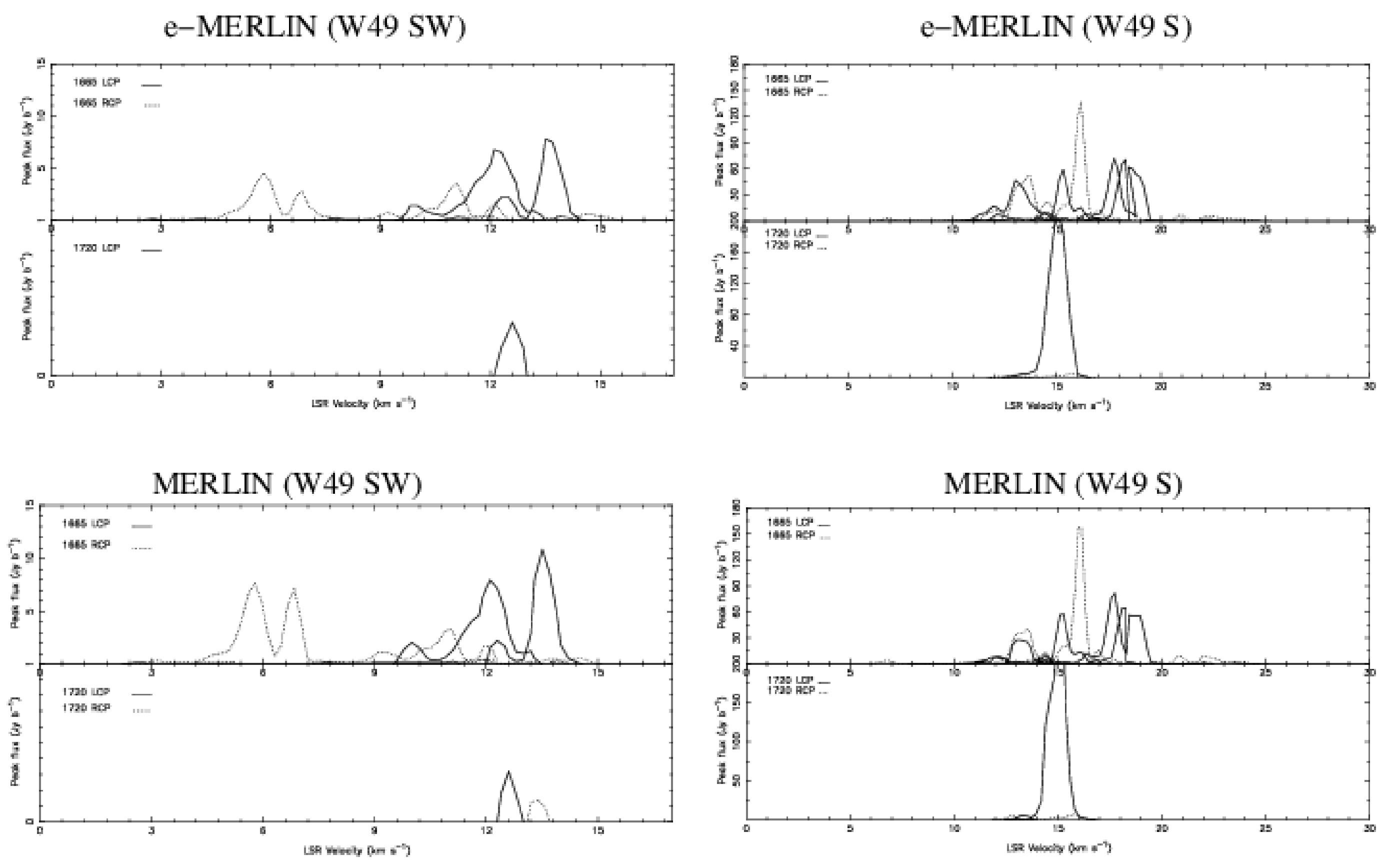


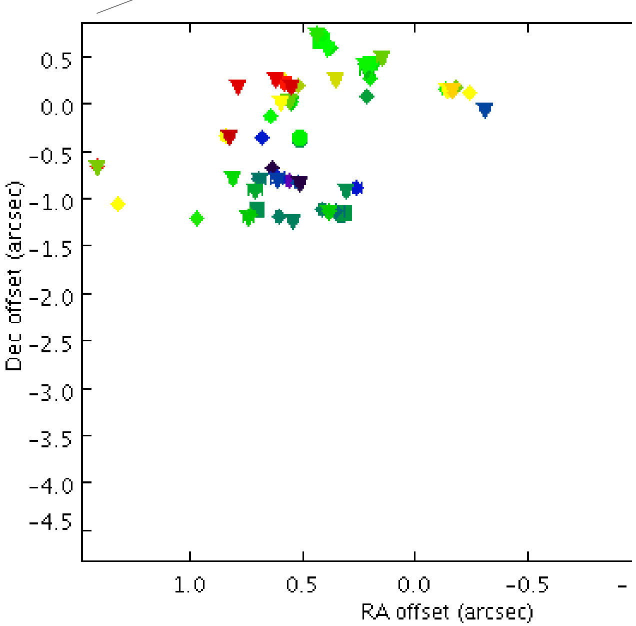


e-MERLIN first masers: W49

- Zeeman splitting for magnetic field measurements





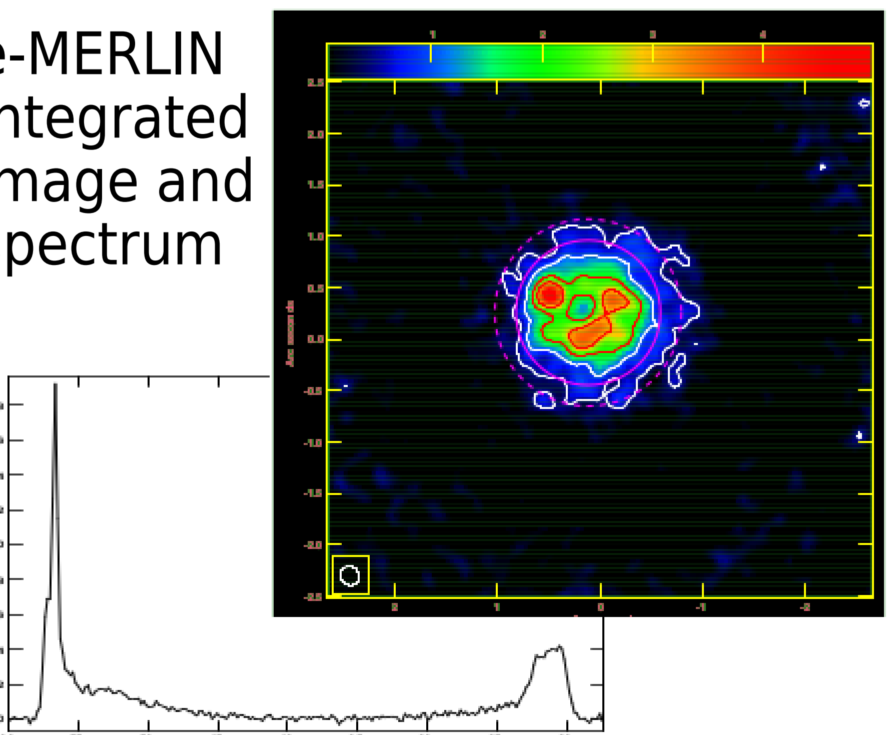


RA offset (arcsec)

OH phase-lag distances

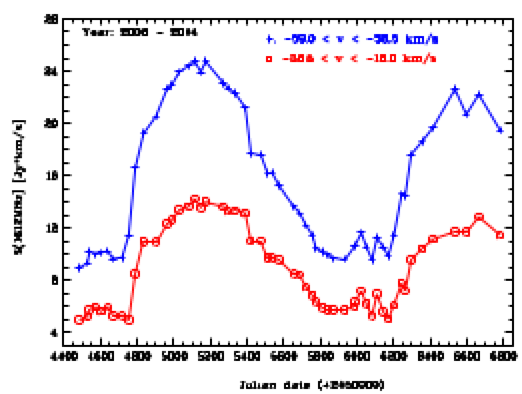
- OH 1612-MHz maser radiatively pumped
  - Varies with stellar pulsations.
    - Red- (back) lags blue-shifted front of shell
- Time delay v. angular size gives distance
  - Need high resolution to model aspherical shells

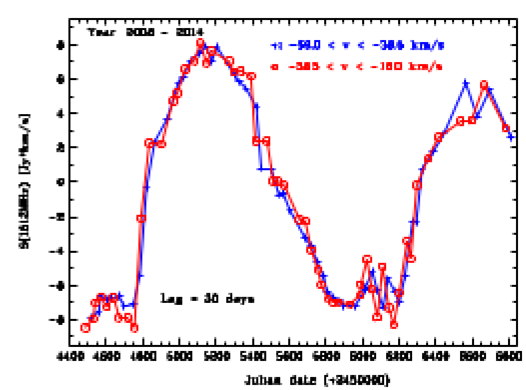
e-MERLIN integrated image and spectrum



- OH 83.4-0.9
  - 3.3 (0.6) kpc

  Etoka et al. 2014



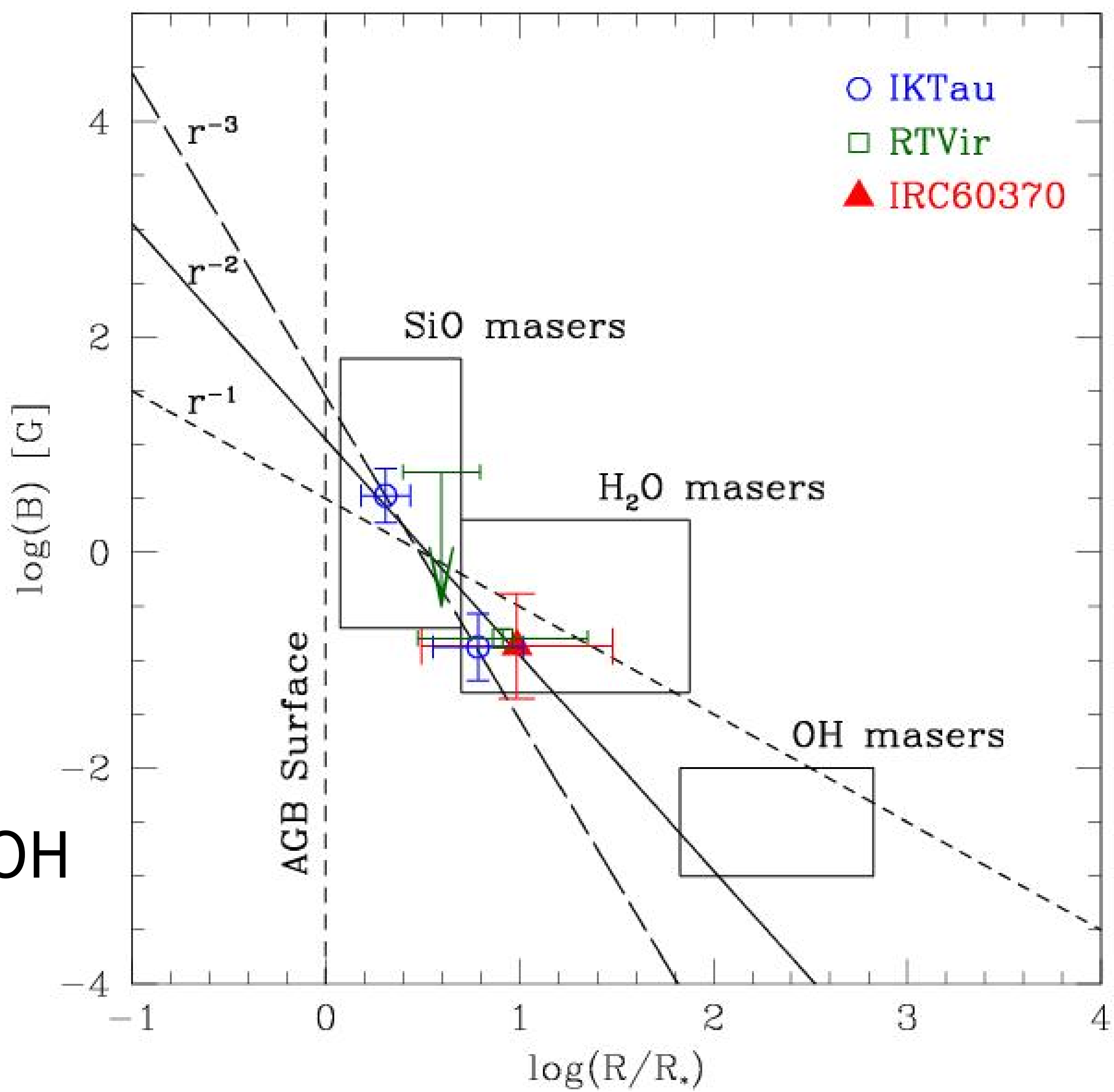


Nancay light curves and phase lag

Evolved star magnetic fields

- What allows magnetic fields around non-rotating stars ?
  - Form provides clues
    - *r*$^{-1}$ toroidal
    - *r*$^{-2}$ Solar-type
    - *r*$^{-3}$ poloidal
- Only 1 or 2 RSG measured in all 3 species
- e-MERLIN project to measure fainter AGB OH Zeeman splitting

  Leal-Ferreira et al.

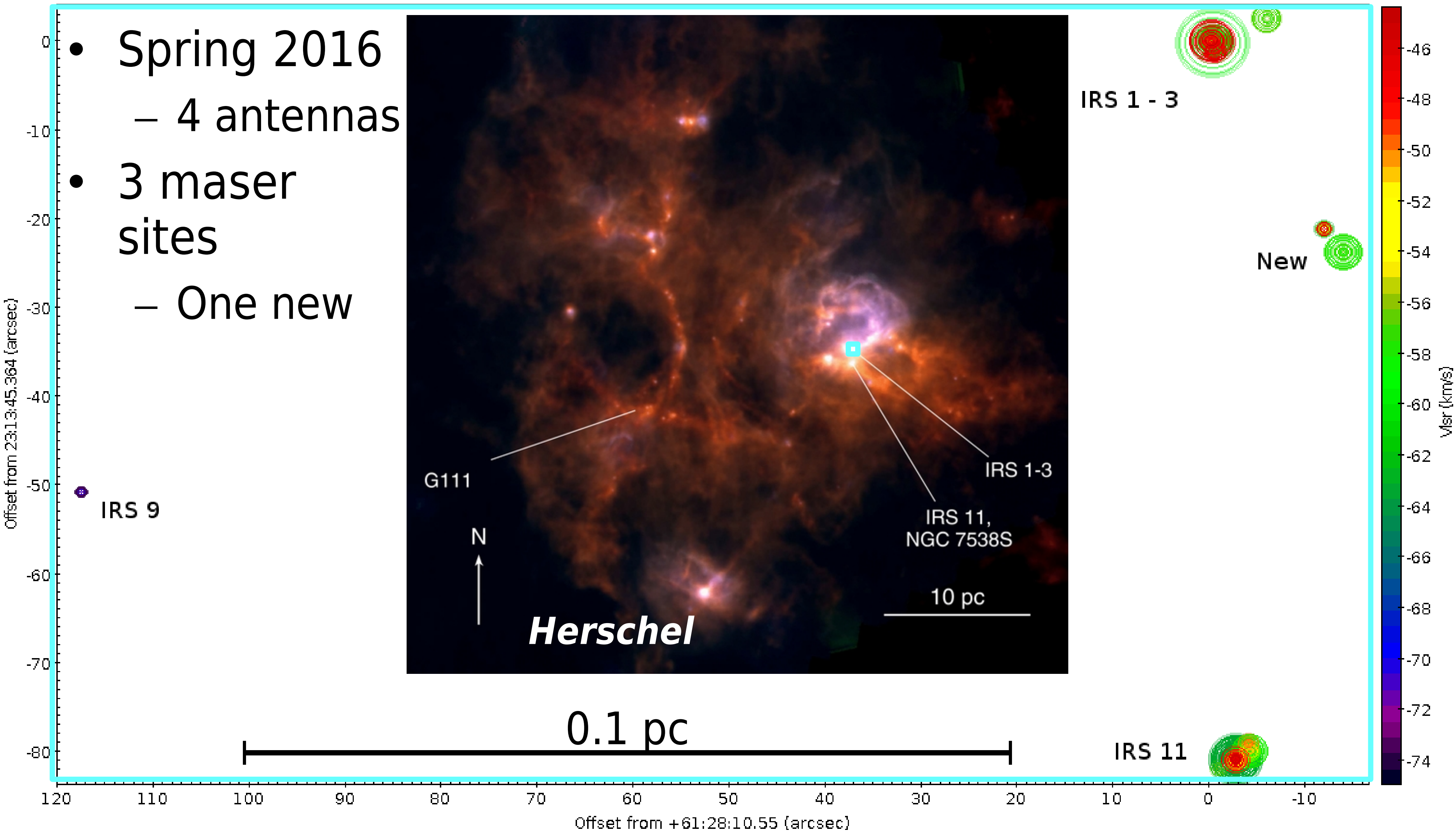


K-band (around λ 1.3 cm)

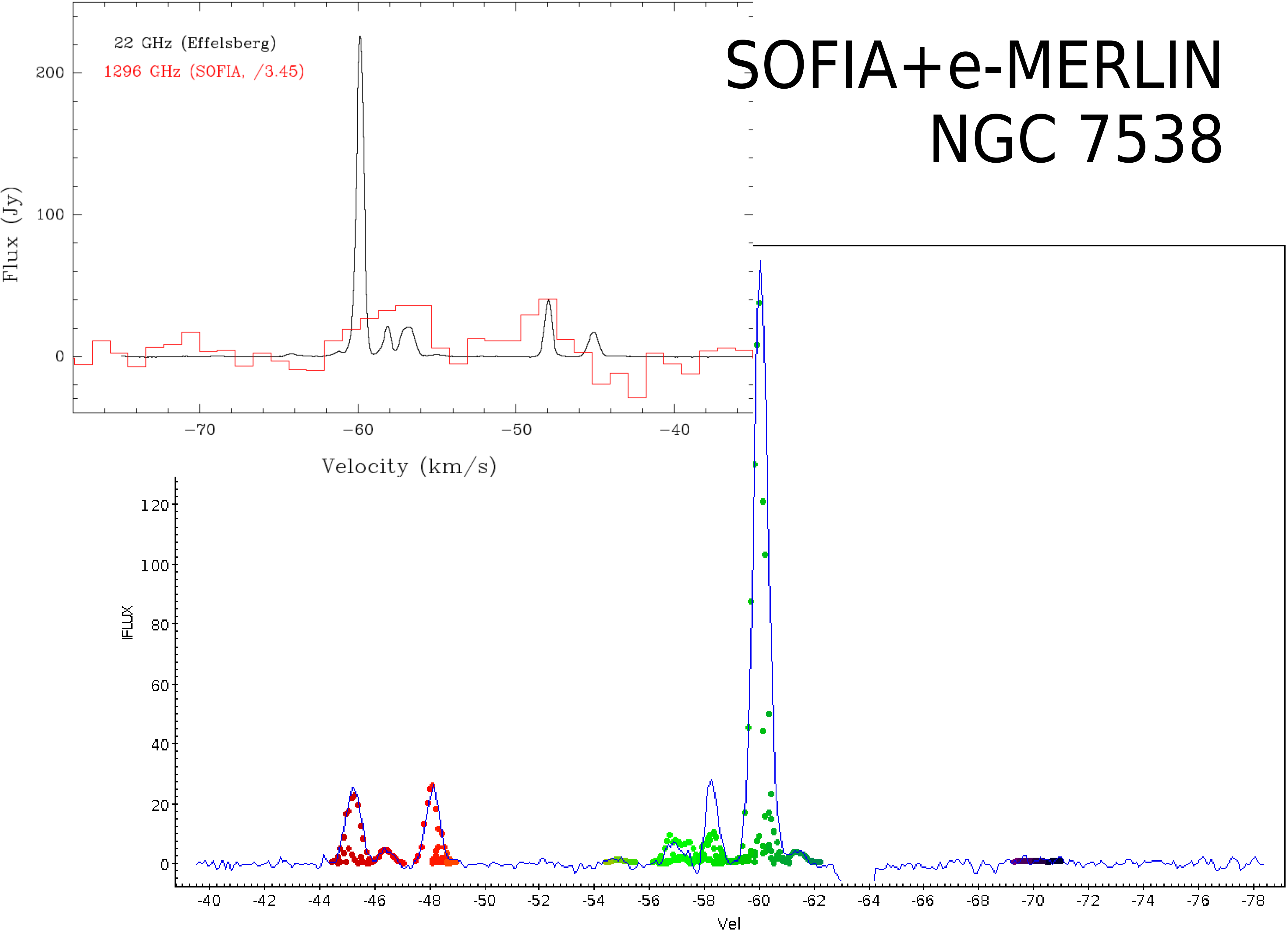
- 20-24 GHz (see Simon's talk)
  - Observe in dry, cold weather ~Oct - Jun (best at nights)
- 2016-2017 all 5 telescopes with suitable surfaces
  - Mark2, Pickmere, Darnhall, Knockin, Cambridge
- 10-20+ mas resolution depending on Dec.
- 15 - 30+ μJy 12-hr $1\sigma_{rms}$ on-source sensitivity
  - 2 GHz continuum b/w, depends on Declination
  - 10-20+ mJy $1\sigma_{rms}$ for 0.1 km/s spectral resolution
- Field of view ~2 arcmin
  - Use e-MERLIN simulator for extended sources
    - Available around deadlines/on request
- Tests precision of pointing, delay etc.!
  - But almost no RFI 😁

K-band first light: NGC 7538

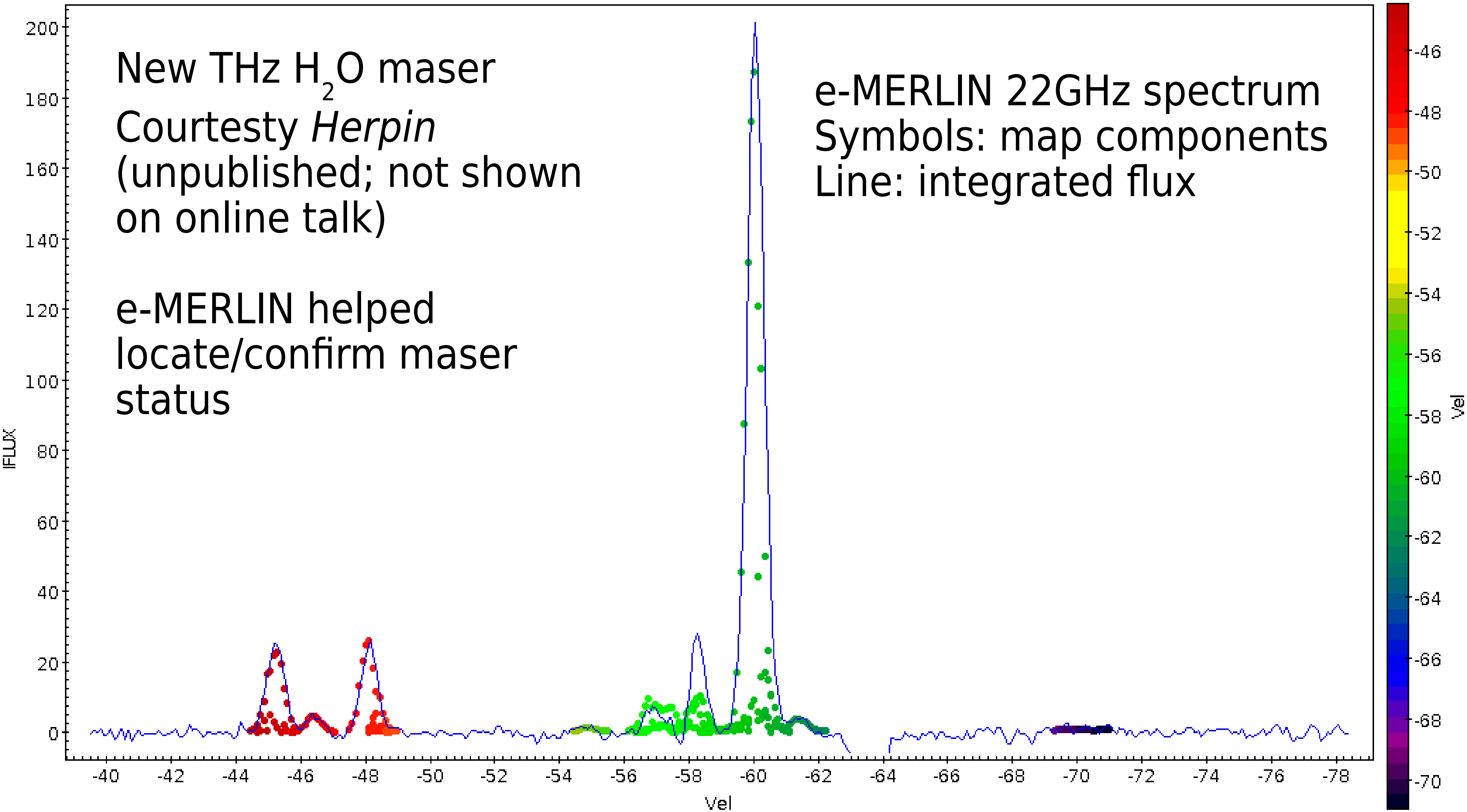
- High-mass star-forming region
- Spring 2016
  - 4 antennas
- 3 maser sites
  - One new



SOFIA+e-MERLIN
NGC 7538

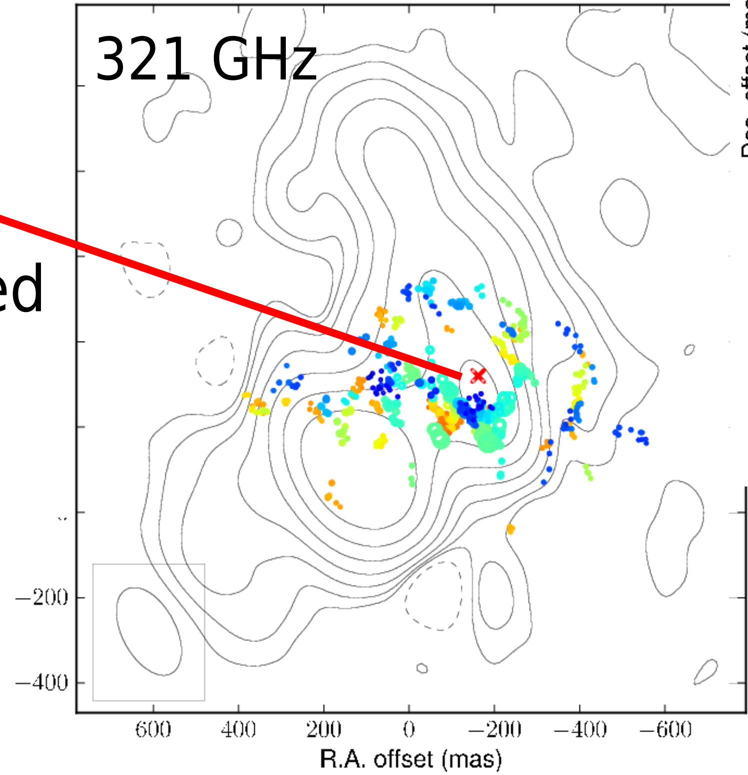


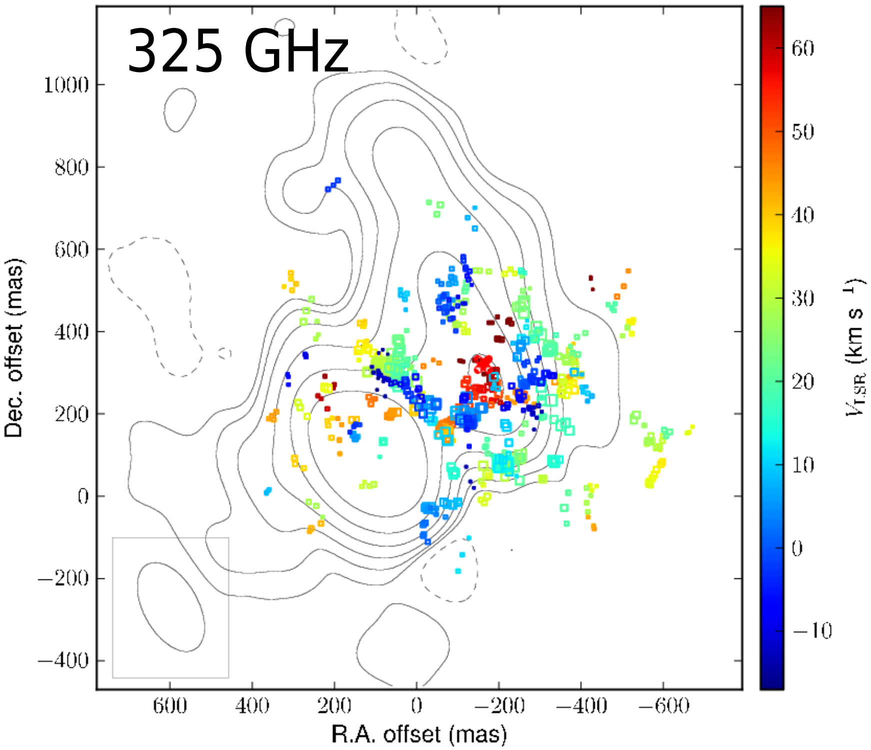
SOFIA IRS1 maser



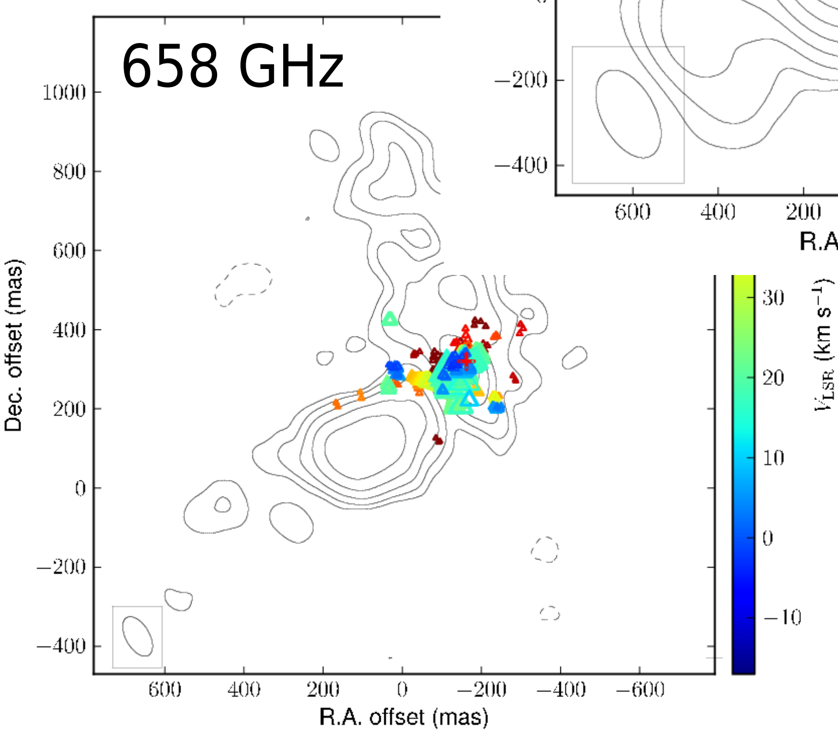
ALMA resolves sub-mm H_2O masers

- Expansion centre star **VY CMa**
  - Surrounded by dust





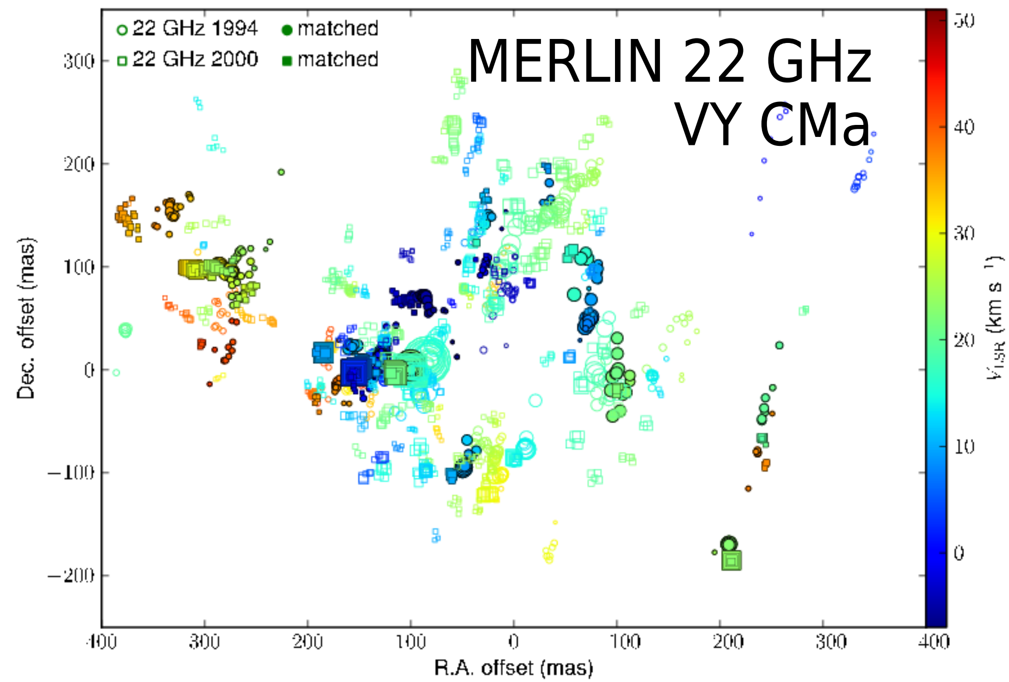
- 325-GHz most extended, as predicted
  - Moderate acceleration

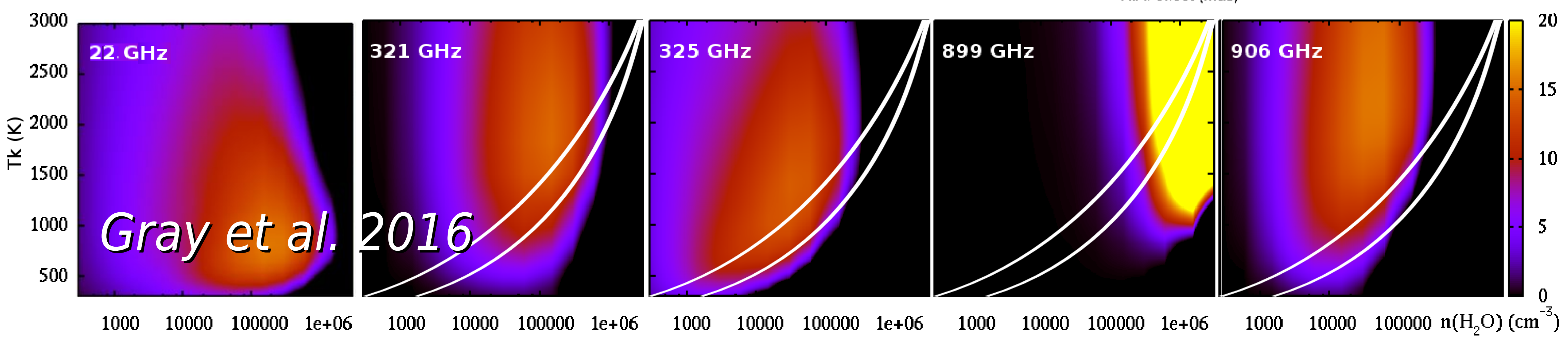


- 321-GHz similar distrib. to 22 GHz
  - Strong acceleration
- 658-GHz starts at few $R_\star$, inside dust formation radius – OK
  - Extends to tens $R_\star$!

Multi-ν reconstruction of physical conditions on au scales

- 100s predicted H_2O maser lines, 10s detected spectrally
  - Multi-line observations constrain temperature, number density, H_2O abundance, radiation field, velocity gradient



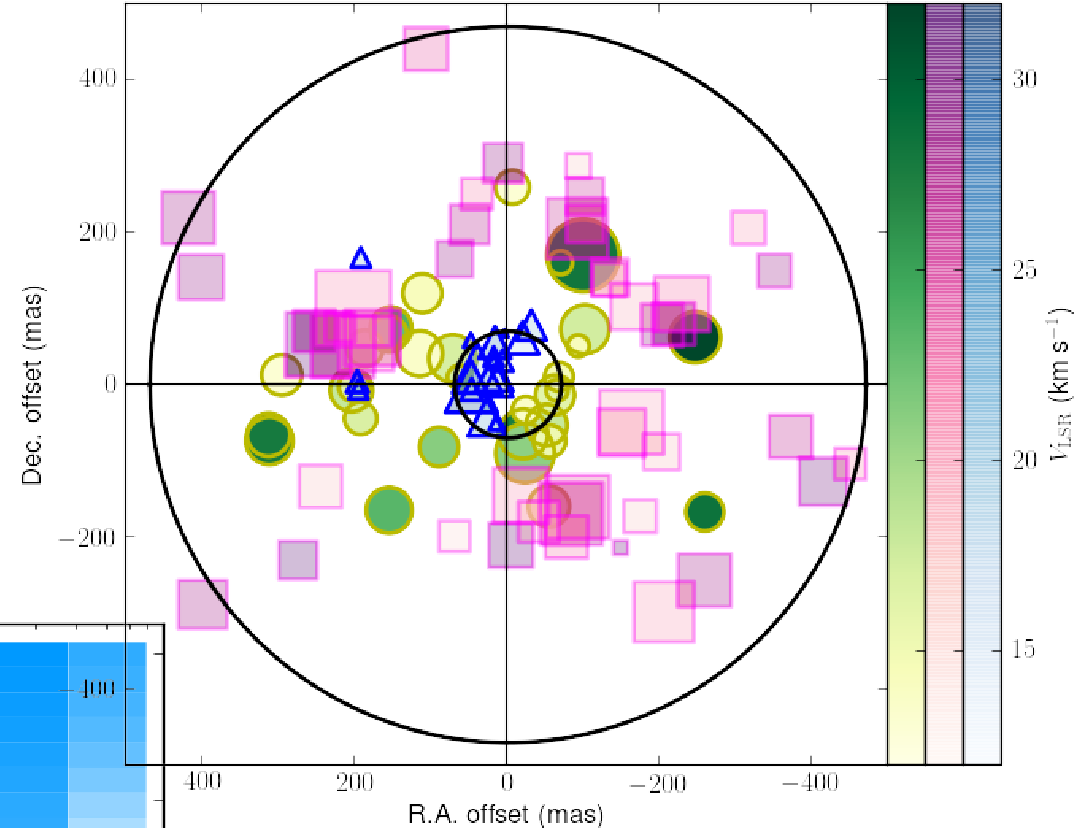


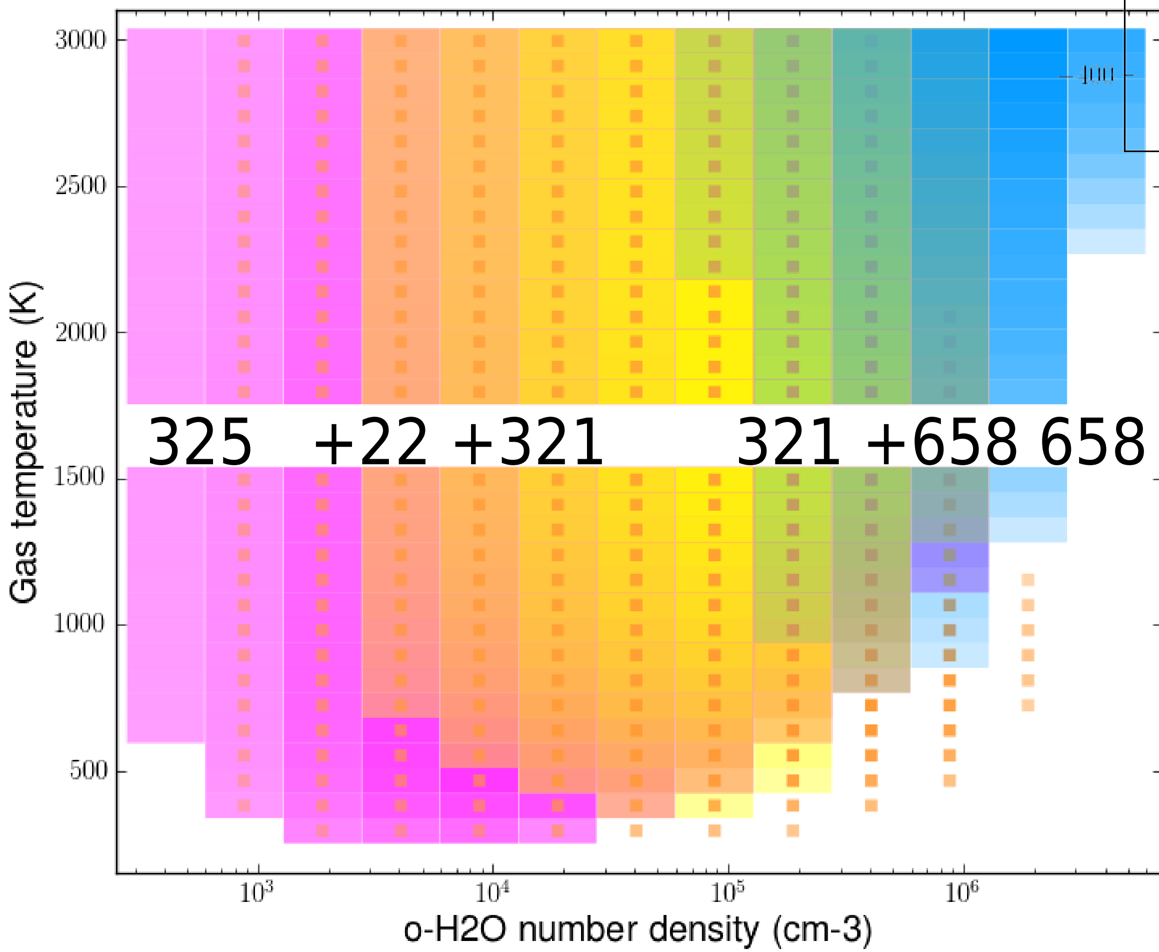
Gray et al. 2016

Constraining *n*, *T*

- VY CMa observed masers
  - within $V_\star$ ±5 km/s

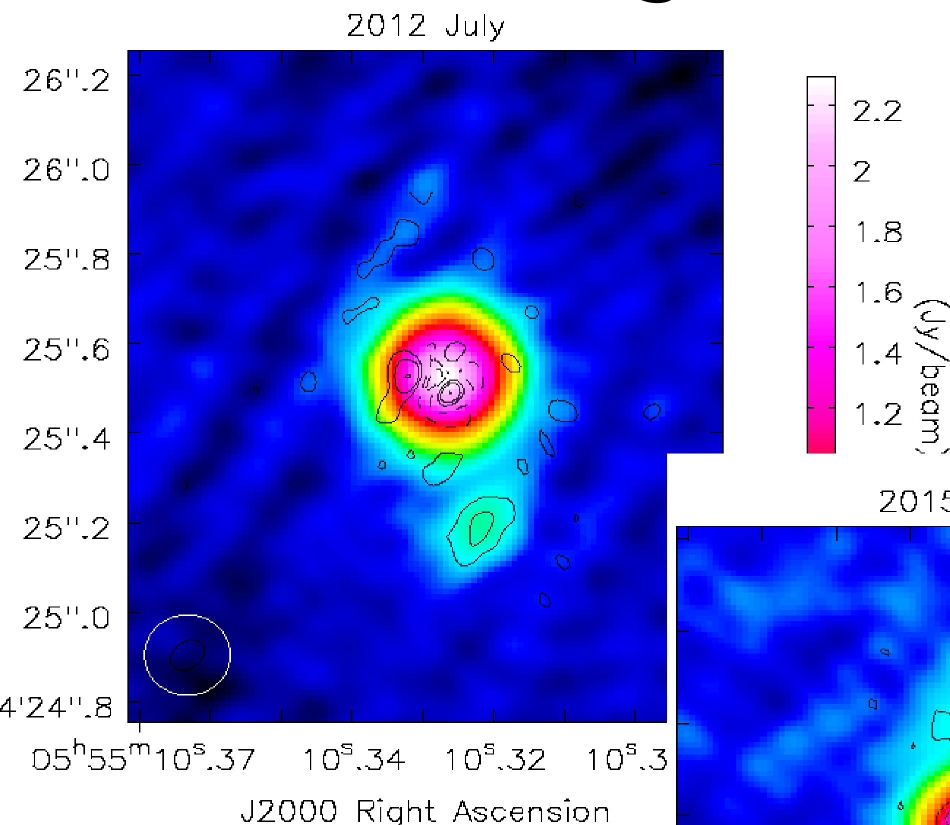
325 321 658 22 GHz



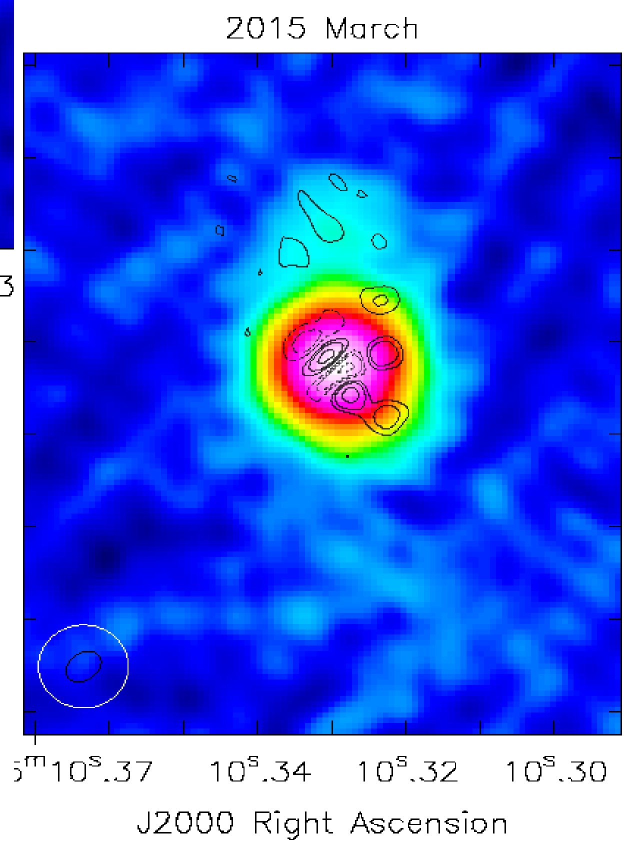


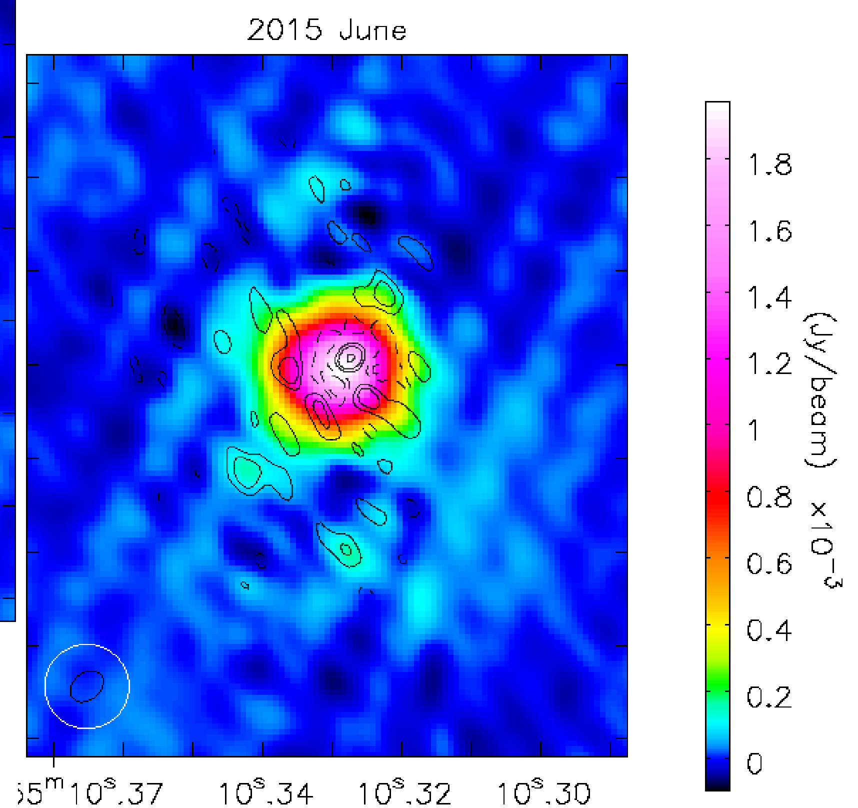
- Inferences from combinations/sole H_2O masers
  - e.g. 325-GHz only implies n<3 10^7 cm^{-3}
  - 658-GHz at n<10^9 cm^{-3} implies high T
- More lines: constrain more parameters

Betelguese 5-cm continuum



- 3 epochs 2012-2015
  - Correct Cm axis offset!
- 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?

Overview

- Accessible maser lines include:
  - Multiple OH lines around 1.6, 4.8, 6.0 GHz
    - 1.6, 6.0 strong Zeeman splitting
  - Formaldehyde around 4.8 GHz
  - Methanol 6.7 GHz; multiple lines around 23 GHz
  - Water 22 GHz
- Multiple masers give physical conditions as well as kinematics at au/sub-kpc scales (Galactic/extra-gal)
- Extra-galactic lines
  - Most of the above as masers or thermal absorption
    - HI and recombination lines
    - Absorption from CN, ammonia, maybe CCS, ???
- We need to understand individal objects to interpret surveys!

Wish list

- High-mass stars - young or old - in Galactic plane
  - Good North-South coverage: Goonhilly, AVN... *incl. 22 GHz*
- High sensitivity at 10-100 mas resolution, 0.1 km/s
  - Total b/w tens - few thousand km/s
- SKA for Galactic-type masers
  - Great survey potential e.g. low luminosity masers tracing shocks in SFR *Etoka et al.* SKA OH masers case
  - AGB outflow velocity v. metallicity in Local Group
- SKA OH megamaser Zeeman splitting (100+ km b'lines)
  - 100-pc scale magnetic fields at *z* 0-0.2 (SKA 1); -2 (2)
  - Need 2x correlation? (but small FoV)
    - 1 km/s, low spatial resolution for Zeeman splitting
    - Decompose spectral components using 200-mas resolution, broad channels