Mass Loss from Cool Stars

prospects with ALMA and other radio interferometers

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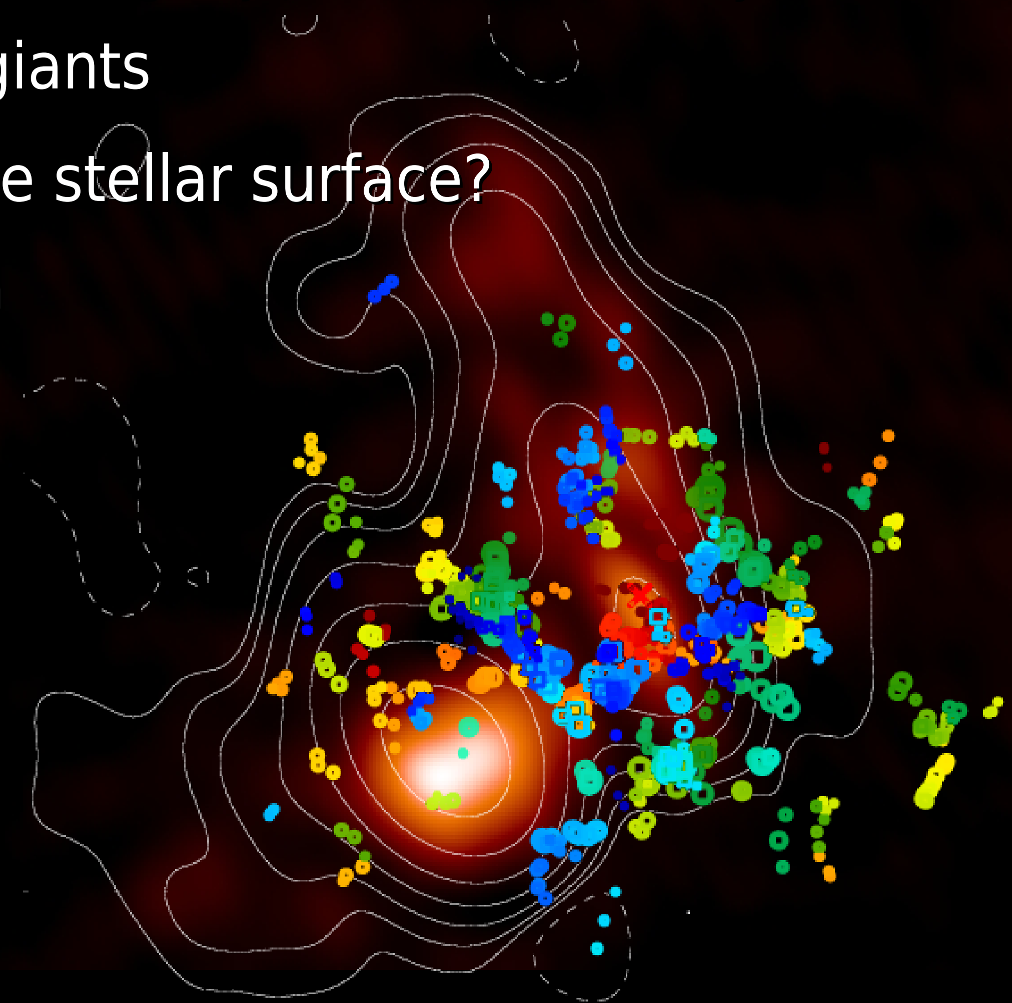
A. Baudry, L. Decin, S. Etoka, M.D. Gray, E.M.L. Humphreys, P. Kervella, E. O'Gorman, A. Sobolev, W. Vlemmings, J.A. Yates and many more

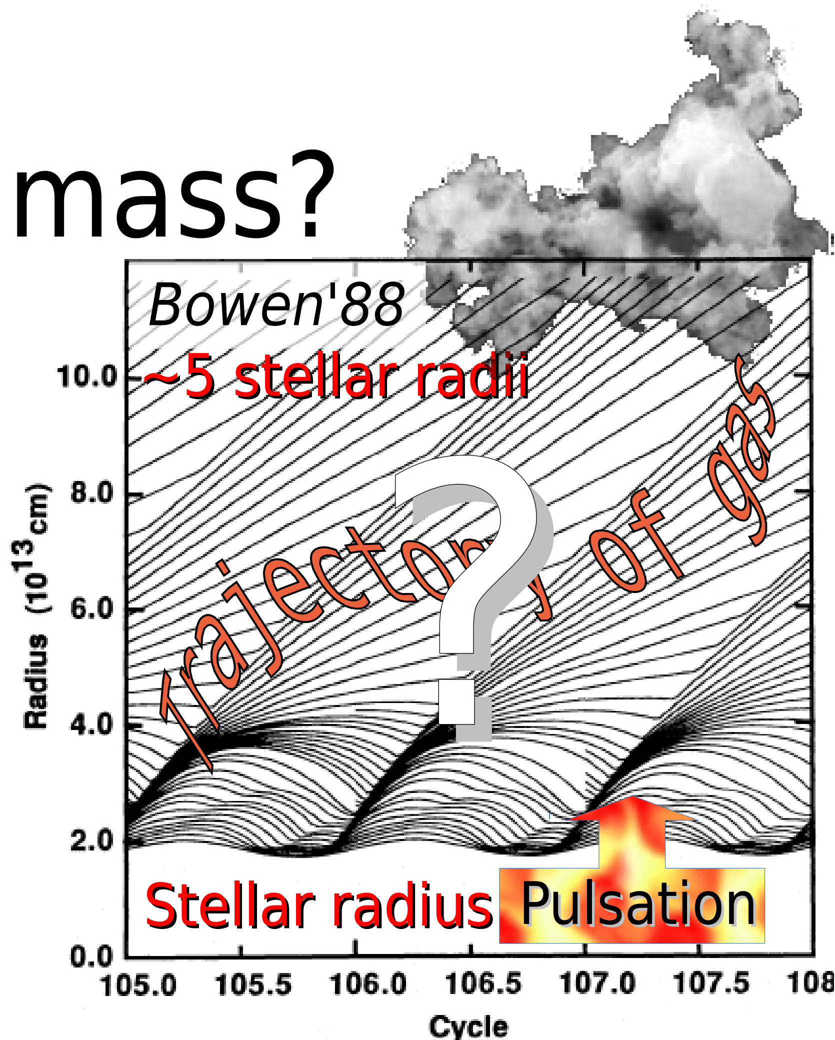
- AGB stars and Red Supergiants
- How does matter leave the stellar surface?
  - Pulsation, spots, convection
    - Mapping the layers
  - What's going on 2-5 R_*?
- Driving the wind
  - Dust formation



EUROPEAN ARC
ALMA Regional Centre || UK

How does star lose mass?

- Pulsation levitates photosphere
  - Parcels of gas move out more than they fall back
    - But pulsations damped before wind reaches V_{esc}
- Radiation pressure on dust?
  - Opaque O-rich dust destroyed close to star (*Woitke+'06*)
  - Large grains (*Norris+'12*)? Scattering (*Hofner+'12*)?



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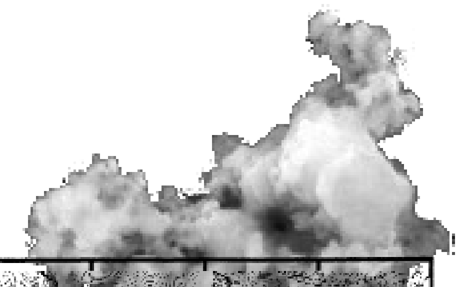

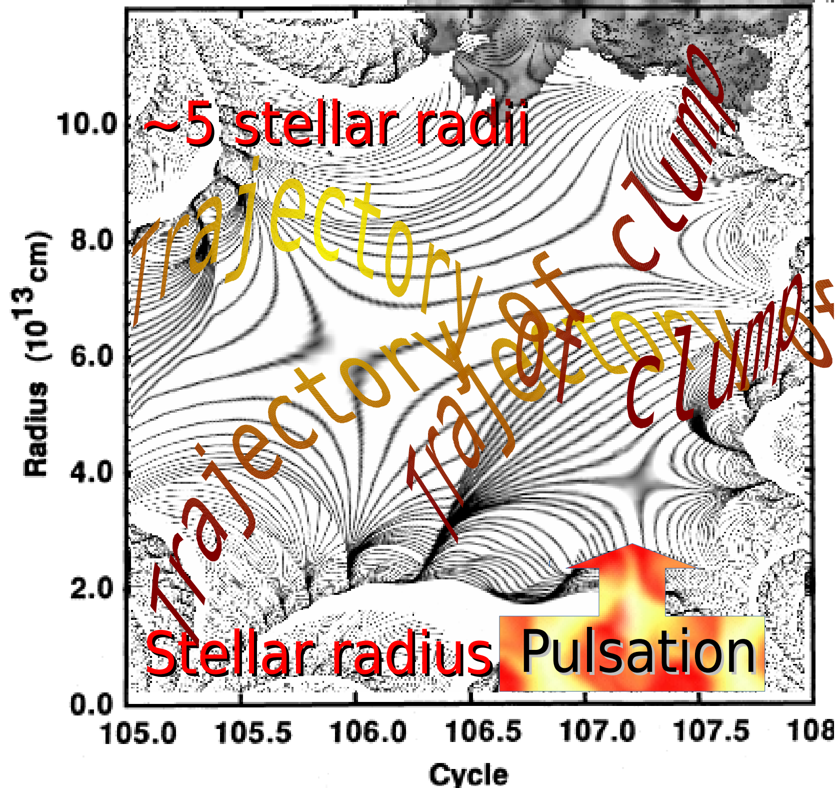

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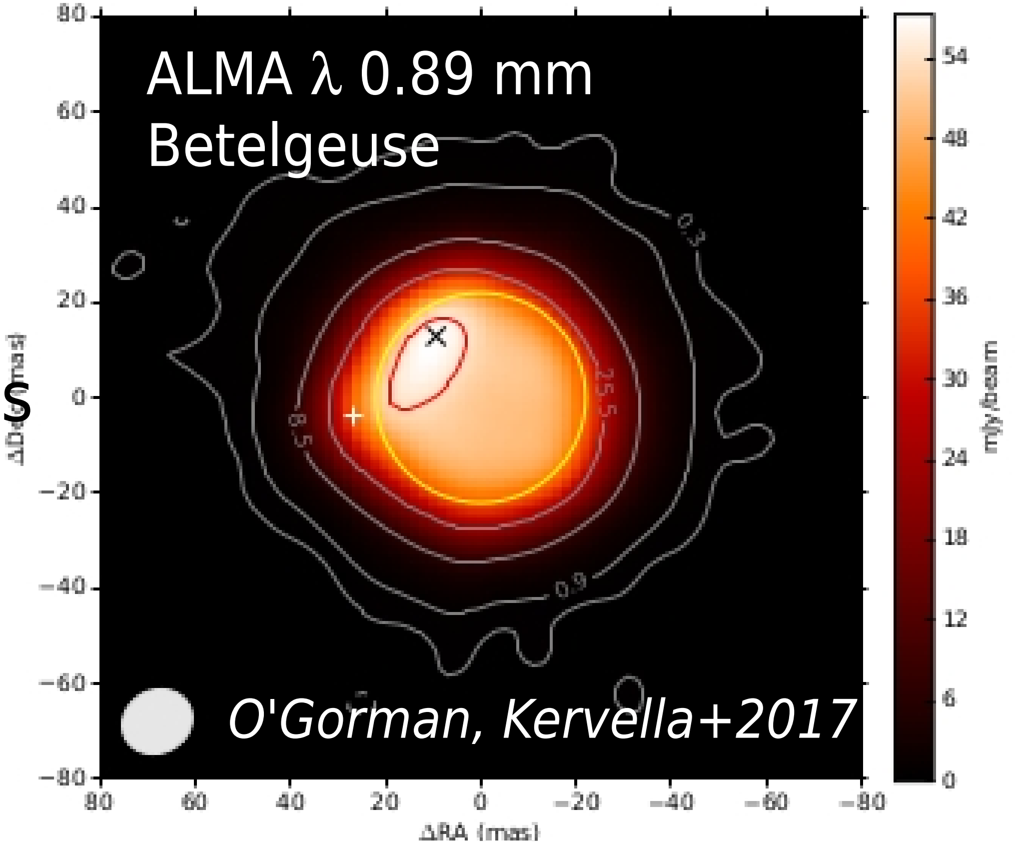
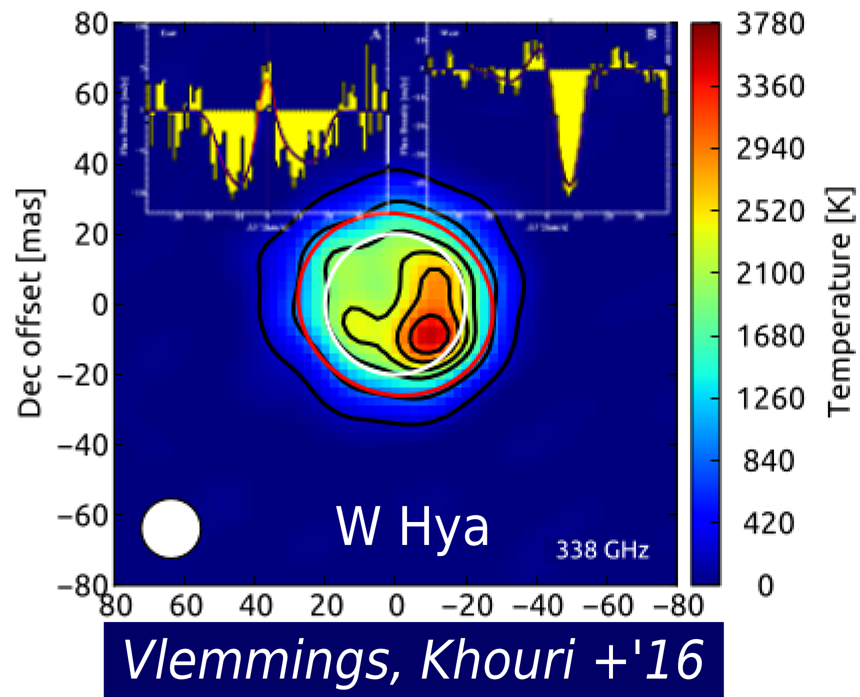
- Local ejections?
  - Heating - expansion? Cooling - dust enhancement?
    - Interaction between convection and pulsation
  - Chromosphere, magnetic fields?
- *Evidence for all these presented earlier in this meeting*

Imaging star spots

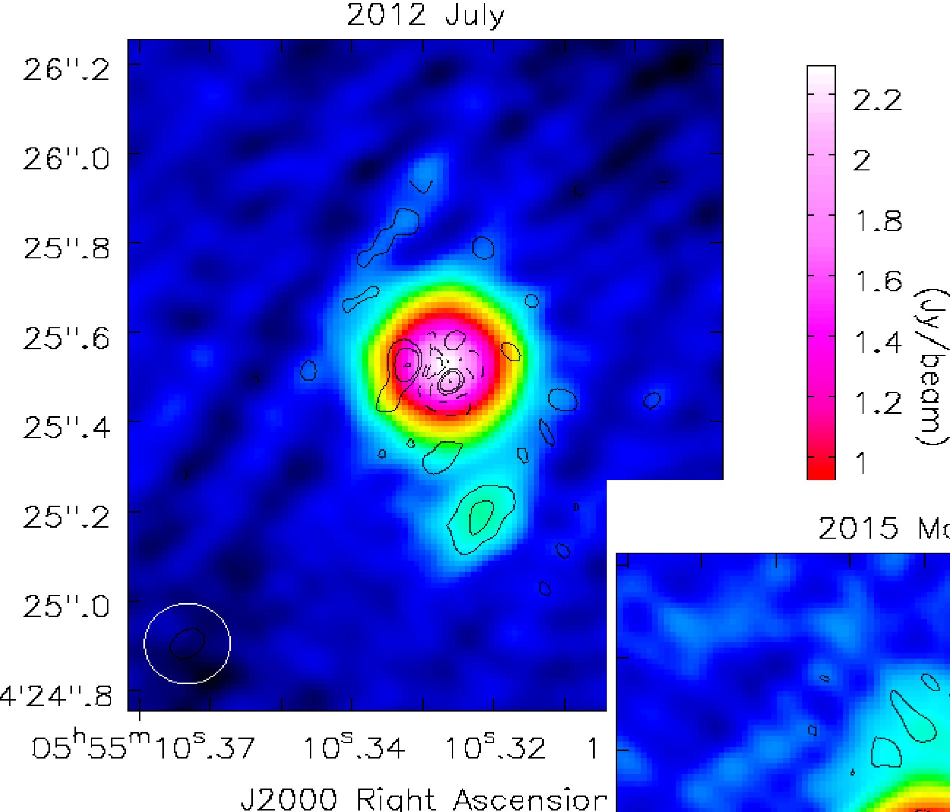
- Many maps show a few spots across optical/IR/mm discs
  - Aggregates of small spots?
- Cycle 8? ALMA best resolution
  - 935 GHz, 16km
  - 5.5 mas beam
    - 8 beams across 44 mas photosphere
    - 3σ ~100 K in a few hr
- ALMA super-resolution using absorption velocity gradient against hot-spots ?
  - As shown for VLTI, *Ohnaka*

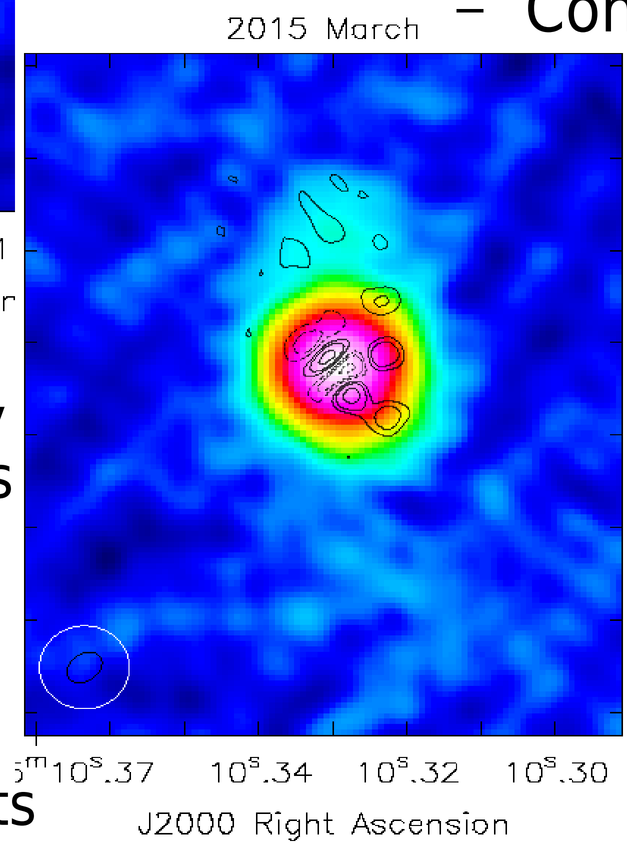


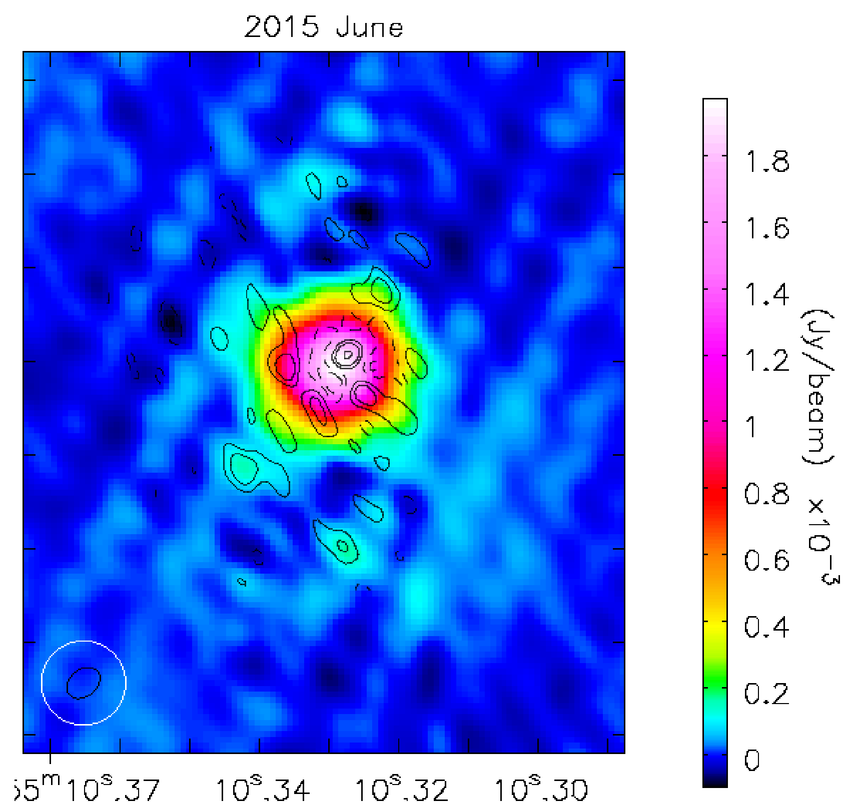


Betelgeuse λ 5cm hot/cold spots

- e-MERLIN, 3 yr & 3 m apart
- 180-mas resolution disc (colour)
  - Radius ~100 mas, 4.5 $R_{photosphere}$
    - Subtract Gaussian from 70-mas resolution image
  - Contours: ~7 residuals >6σ



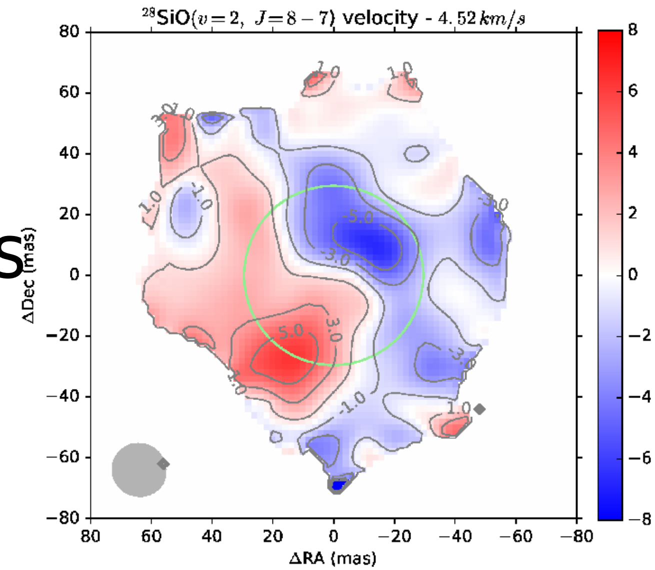




- Up to ±~10% avg. flux density
  - Location errors ≳(10, 15) mas
  - Unresolved
    - Maybe clustered smaller components

Betelgeuse rotation

- 18-mas resolution SiO v=2 J=8-7
  - Absorption against stellar continuum
- V_{eq} sin i ~5.5 km/s at 29.5 mas radius
  - Compared with UV lines shows solid-body rotation to 2 $R_{\star}$ (optical photosphere)
- N. pole of axis at position angle ~48°
  - Similar to Dupree axis orientation



Velocity wrt $V_{\star}$
Kervella+2017

- 5cm hot/cold spot positions change tens mas / 3 months
  - >~~100 km/s~~? - so not rotation/bulk sideways motion

Timescales (*Harper & Linsky 99*)

Radius (φ_* = 56 mas)	**1.5 R_***	**2.0 R_***	**4.0 R_***
Hydrogen Density (10^9 cm^{-3})	8	3	0.4
Electron temperature (K)	3805	3447	2072
Time-scales (days) for;			
C II recombination to C I	5	13	67
Wind crossing of density scale-height	2000	2000	2900
Sound crossing of density scale-height	270	500	1700
CO formation		~40	
Sound crossing of radio emission region	600	840	2200
Free-fall across radio emission region	180	280	800

- Uses old Betelgeuse R_* but should scale OK
- $n_e \sim 3.8 \times 10^{-4}\, n_H$

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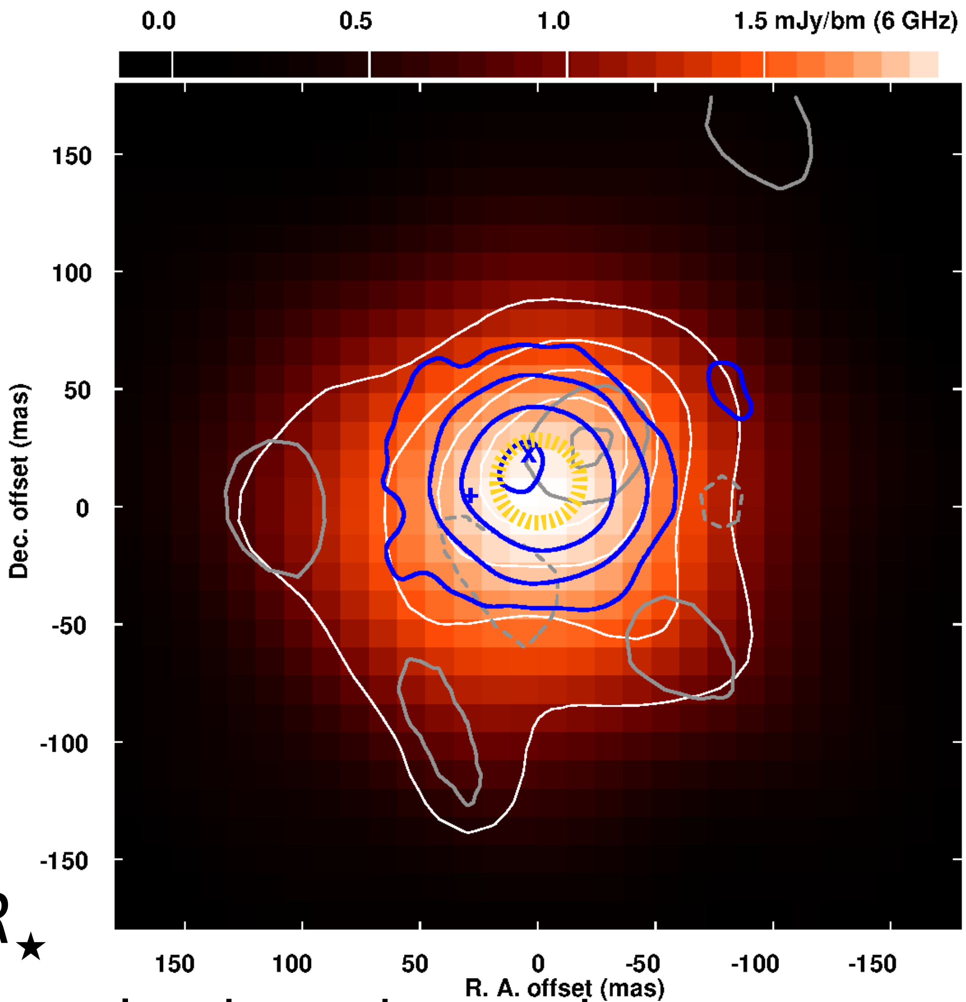
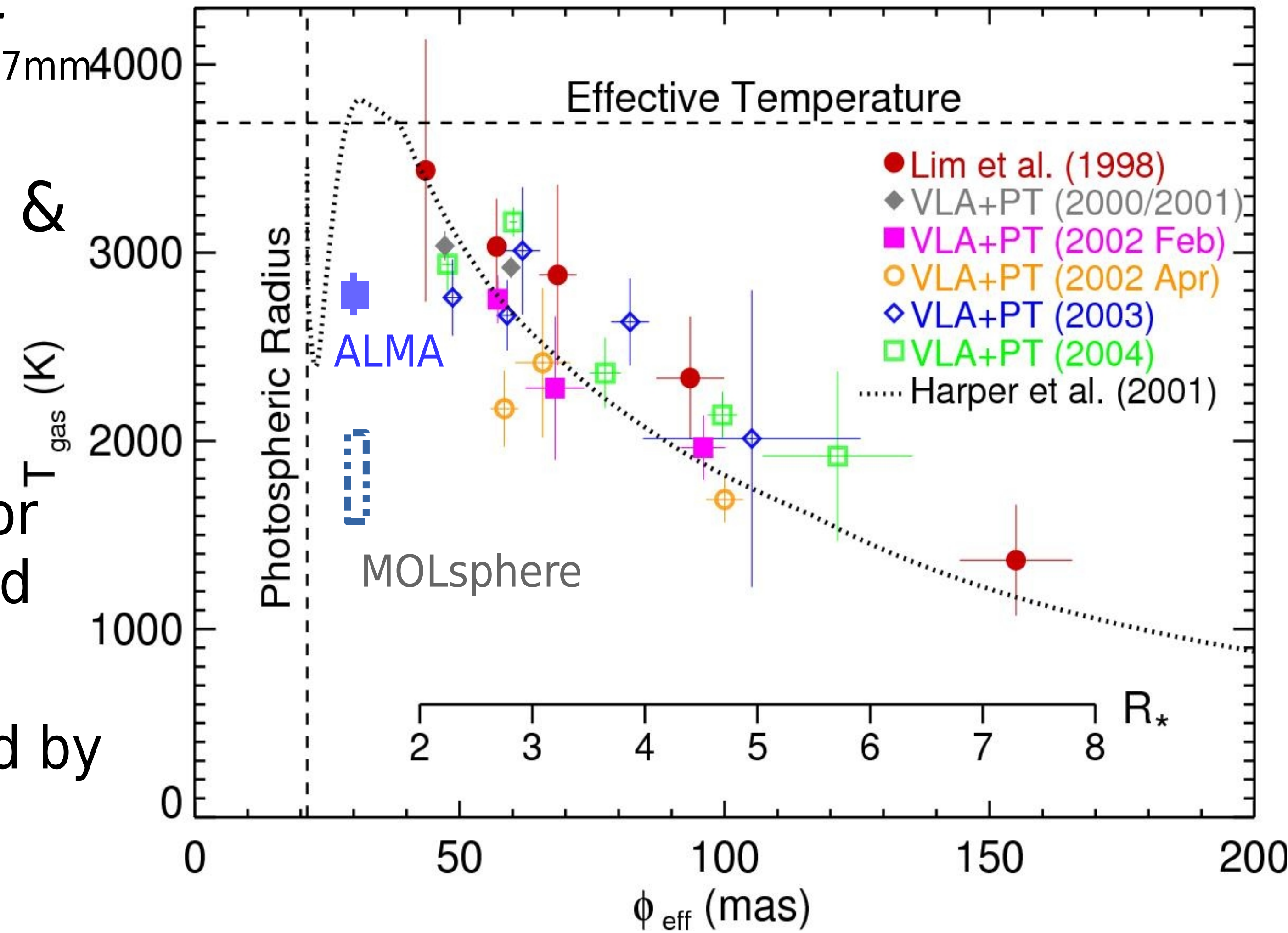
Compare 0.89 mm - 5 cm λ

- Background e-MERLIN 5cm low-resolution 2015 Jun
- White: 5cm 60-mas beam
- Grey: 5cm hot/cold spots
- Blue: 0.089cm ALMA + x
  - Spectral index α~1.7
    - α~1.3 at cm wavelengths
- Yellow ring: photosphere
  - Alignment by eye
- No hotspot correlation
  - Depth difference 1.3- 4.5 $R_\star$
    - ~1.8 $R_\star$ end of convection, pulsations damped



Constraining the inner few $R_\star$

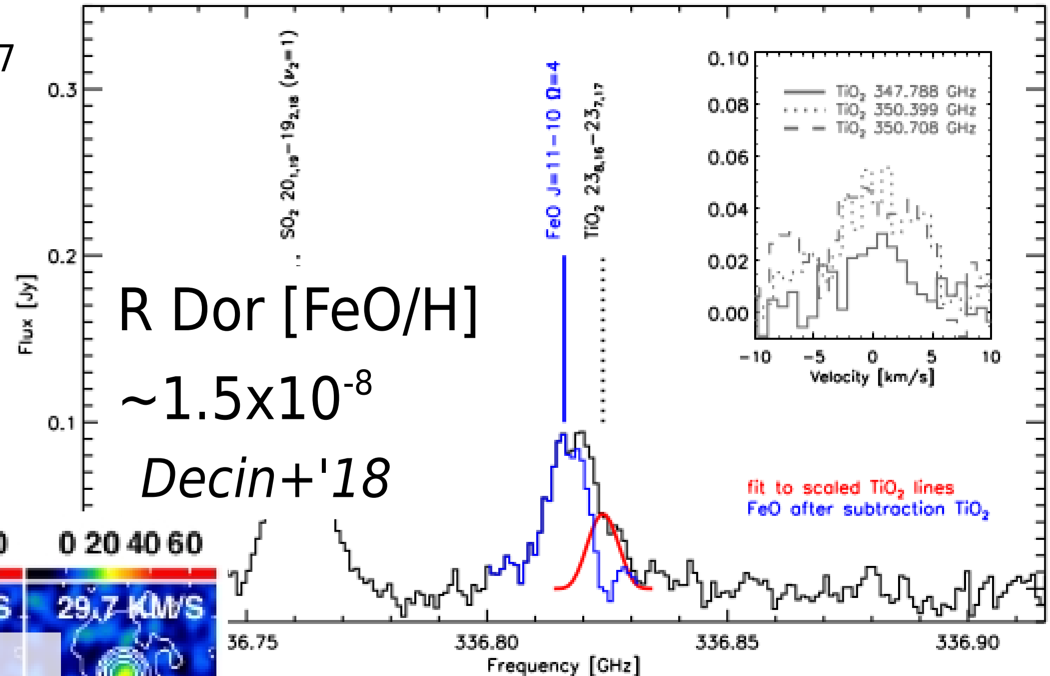
- ALMA 0.89mm continuum ~1.3 $R_\star$ - MOLsphere region
- Temperature <T_{7mm}
- Measures free electron density & temperature
  - Mix of cool MOLsphere & chromosphere-or shock-influenced peak?
  - Hotspots heated by convection in presence of magnetic field?



O'Gorman et al. '15, '17

ALMA investigations of dust precursors

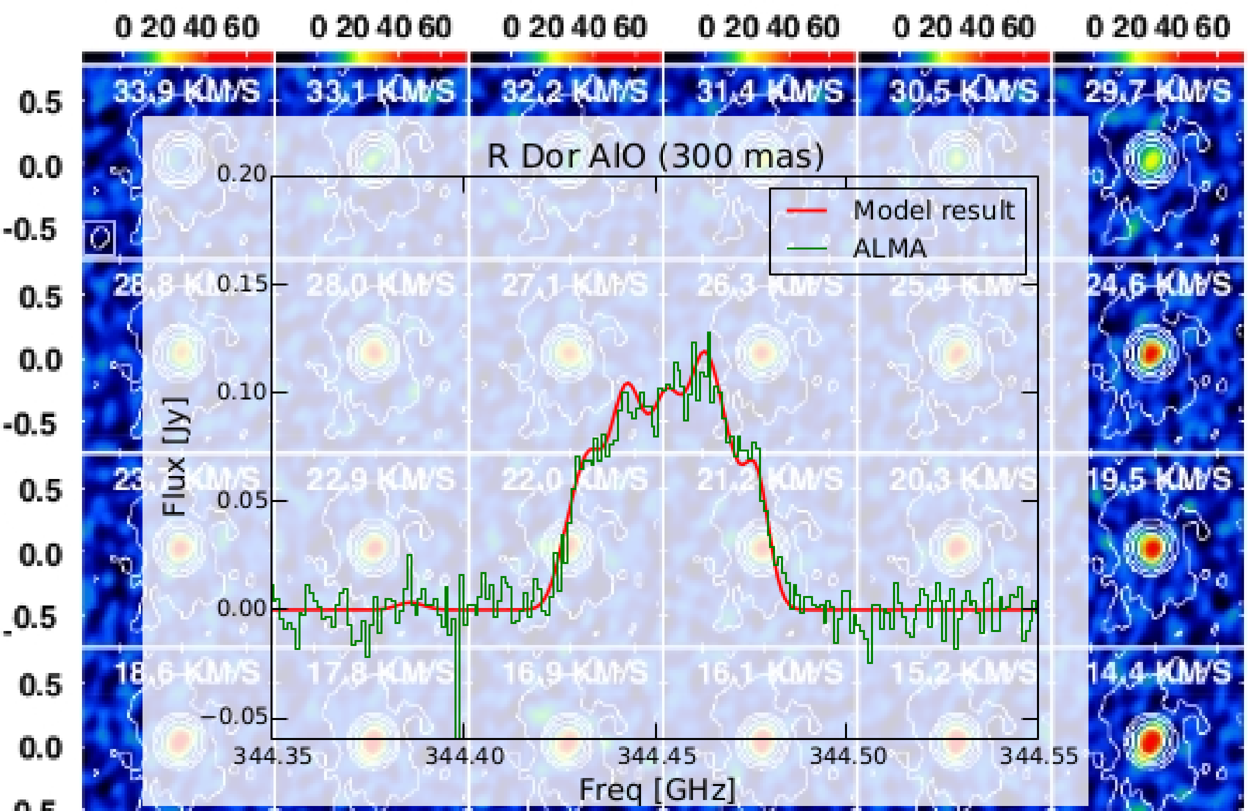
- R Dor , IK Tau [AlX/H] <1.1×10^{-7}
  - X=O, OH, Cl
  - Extend beyond R_{dust}
  - Enough likely to have condensed into $(Al_2O_3)_n$ to explain 11 μm feature

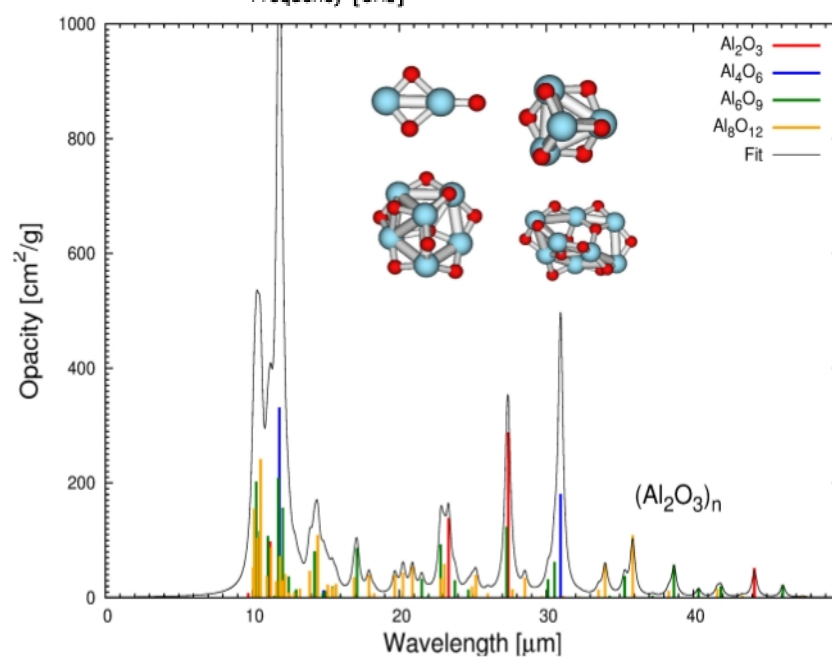


R Dor [FeO/H]

~1.5×10^{-8}

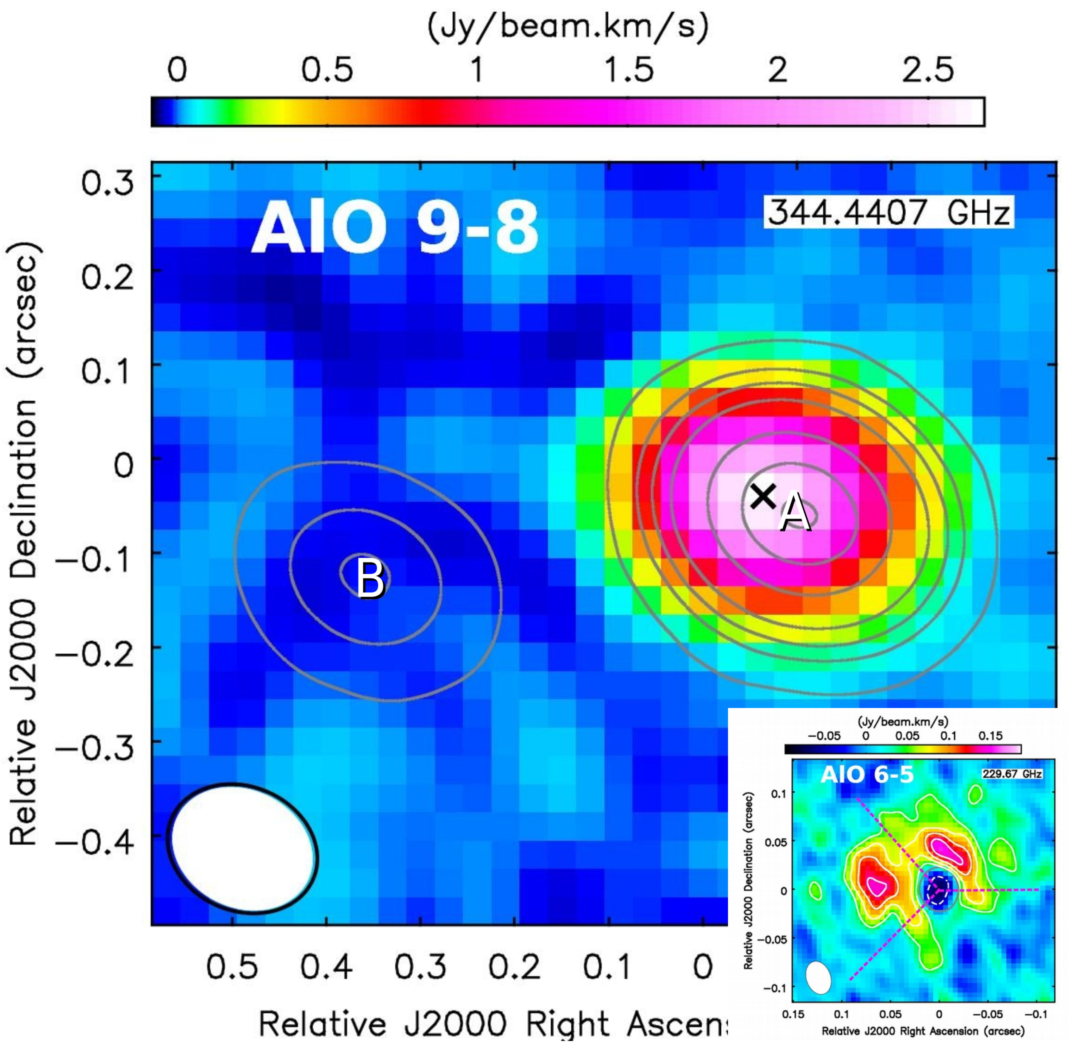
Decin+'18





AlO around Mira

- Likeliest dust nucleator (refractory, Al abundance > Ti)

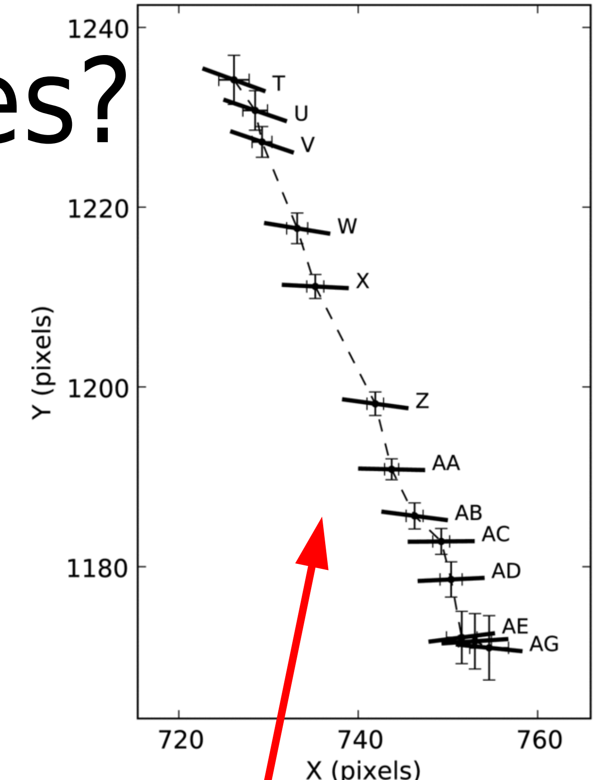


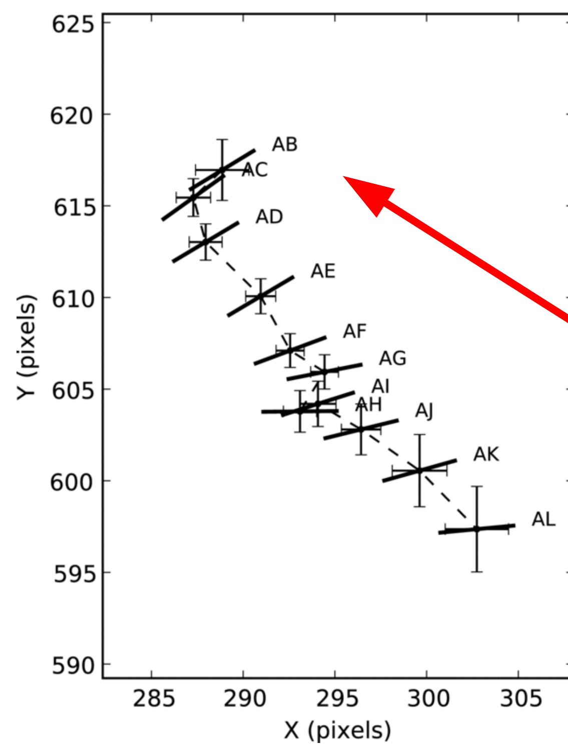
Kaminski, Wong + 2016

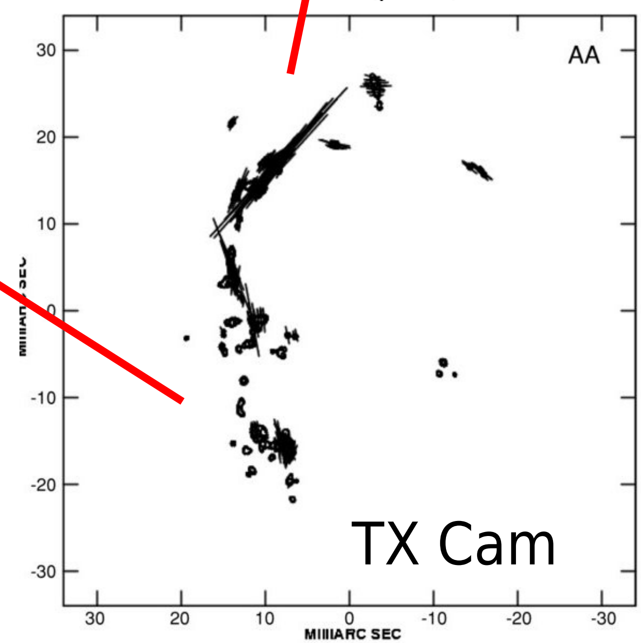
- 30-mas resolution clumps
  - Absorption, infall & outflow
- AlO predicted to be destroyed & reform 1-3 $R_\star$
  - Need <20-mas beam
    - Also proper motion?
- Complicated variability v. ϕ
  - Short spacings to ensure scales up to ~200-mas
  - Multiple transitions, species
    - Estimate depletion → dust

SiO clumps follow field lines?

- TX Cam proper motions not consistently radial (*Kemball+11*)
  - Non-ballistic?
  - Polarization vectors <u>*B*</u> follow direction of motion
  - Are masers tracing matter accelerated along field lines?
    - Or dragging the field in masing clumps? (*Hartquist+96*)

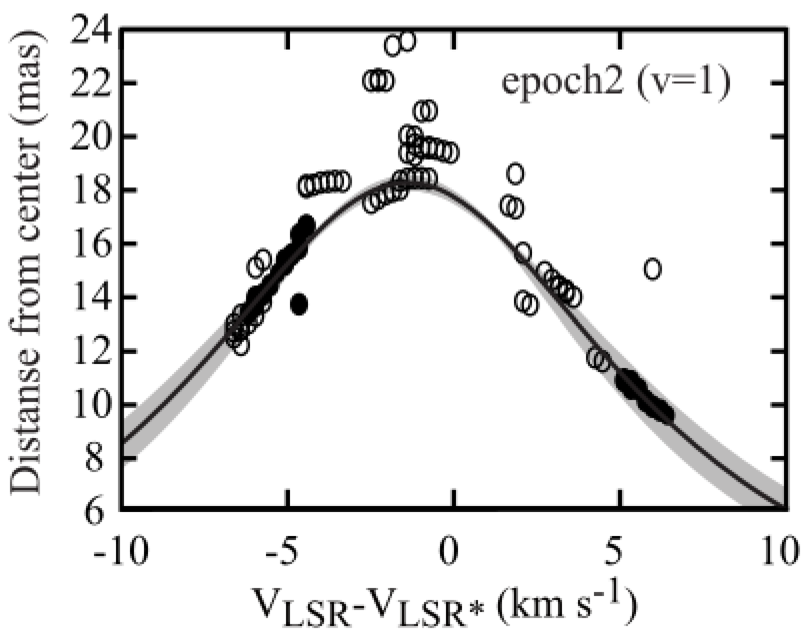


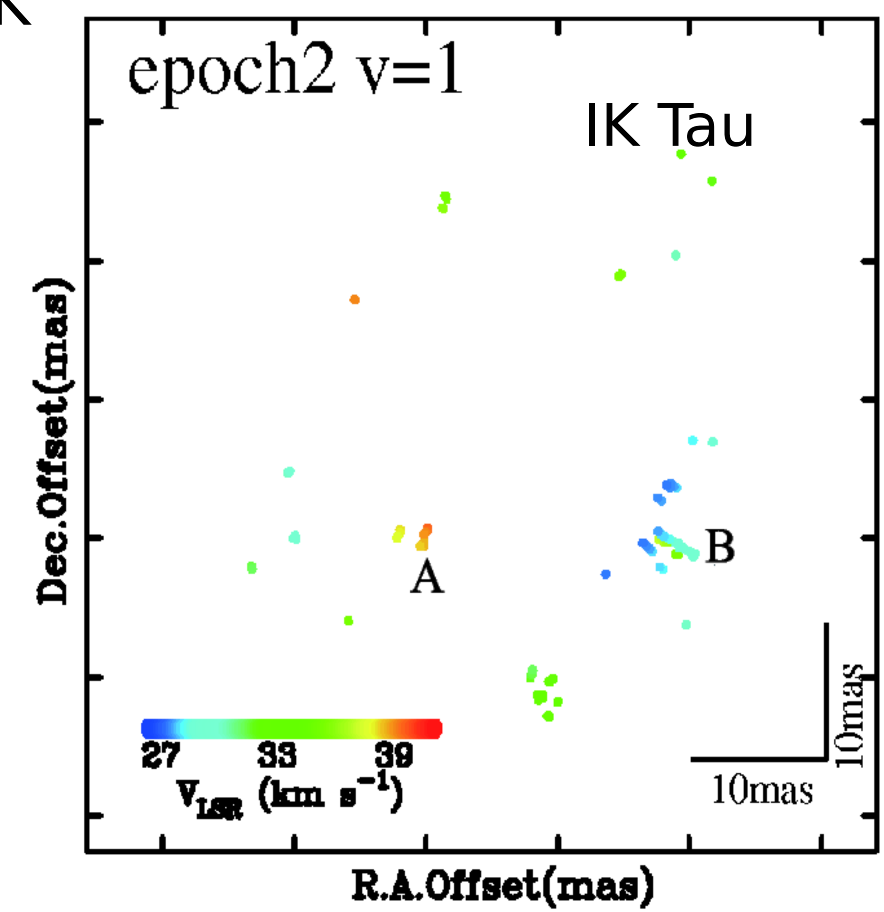




Or ballistic proper motions?

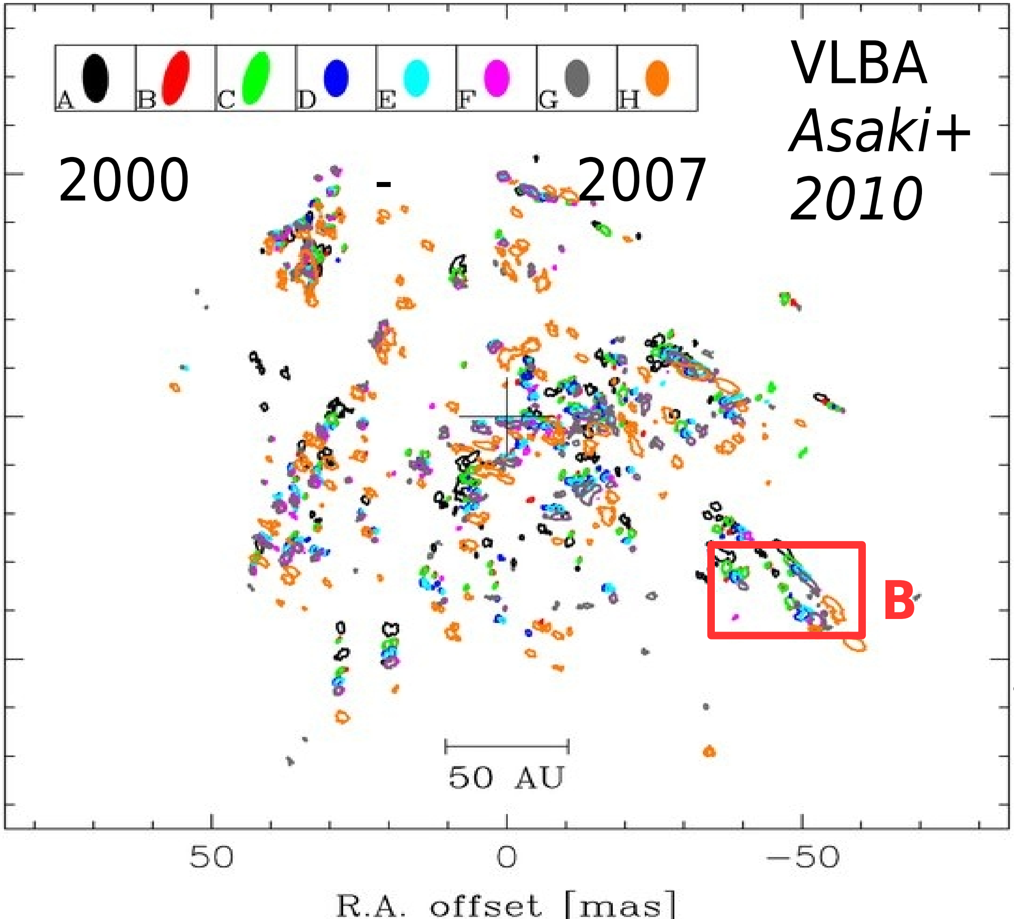
- IK Tau SiO shell asymmetries vary between epochs
  - Not rotation (VERA multi-epoch, *Matsumoto+08*)
  - Spoke-like SiO masers seen around several stars
  - Ballistic trajectories fitted to IK Tau radial streamers
    - Including deceleration due to star's gravity

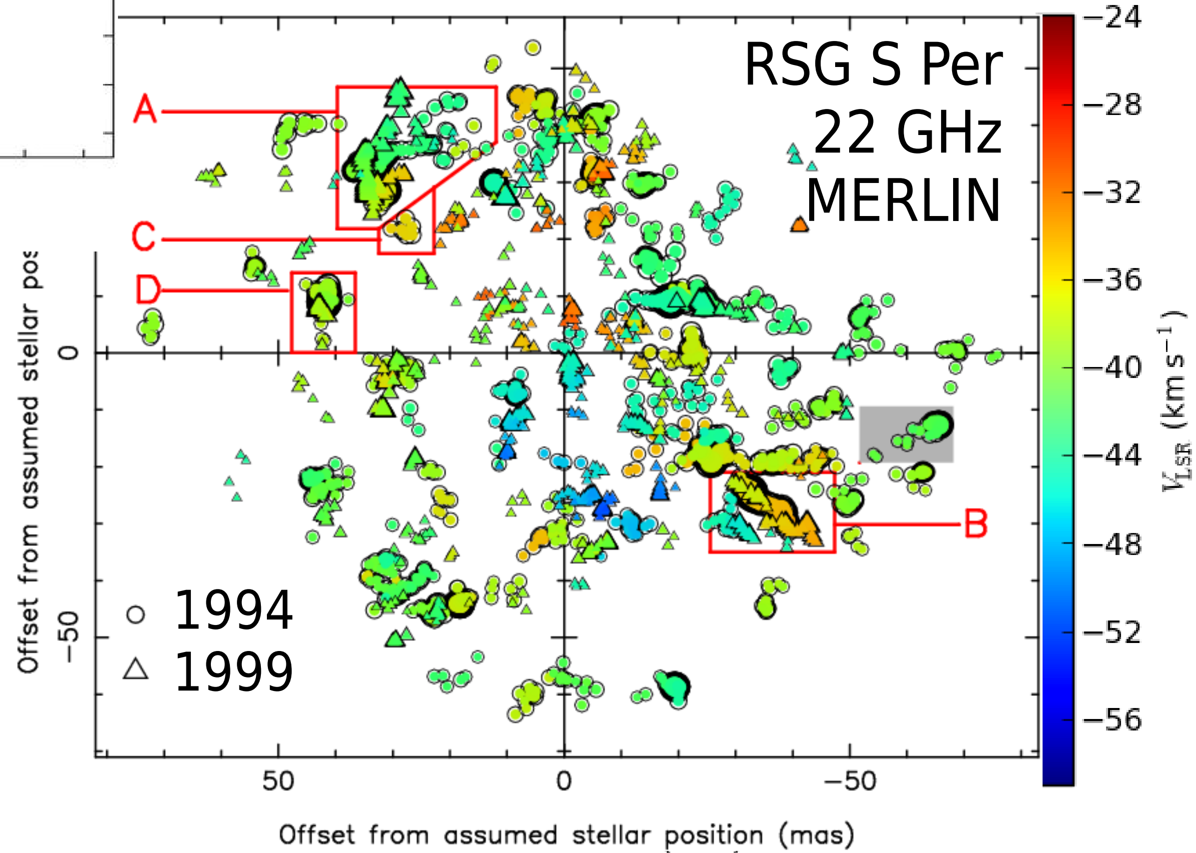




Larger-scale streamers

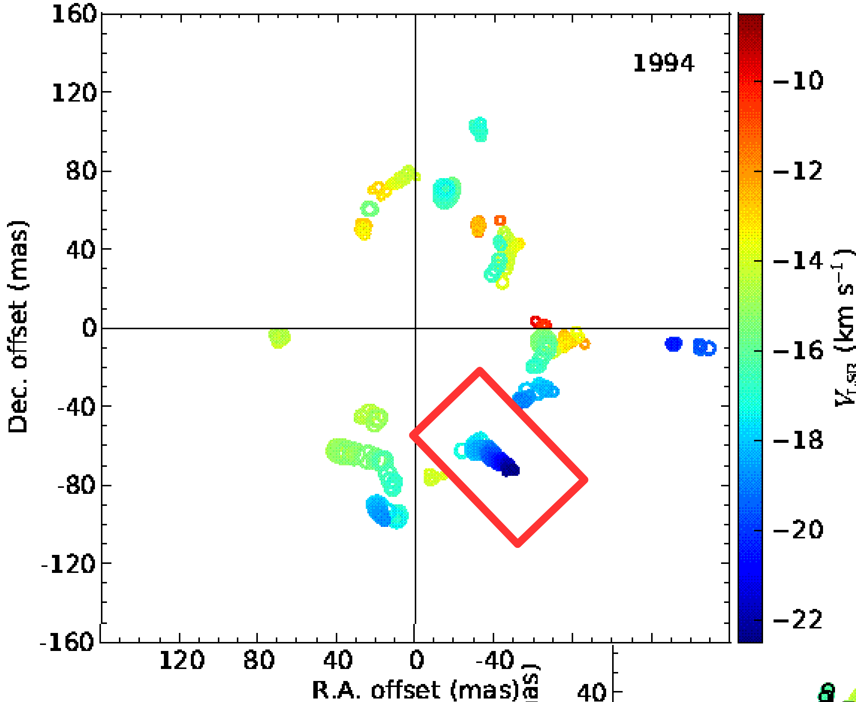
- Seen, but rarely

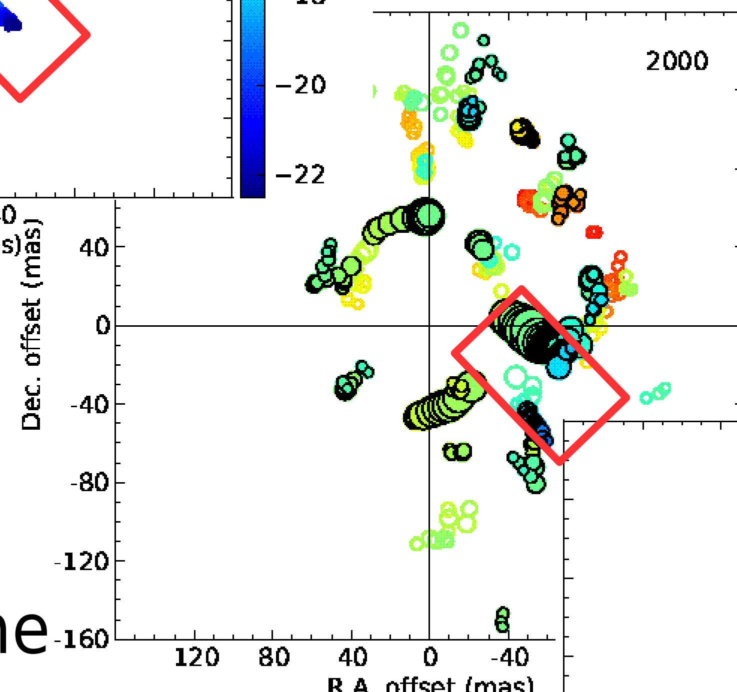


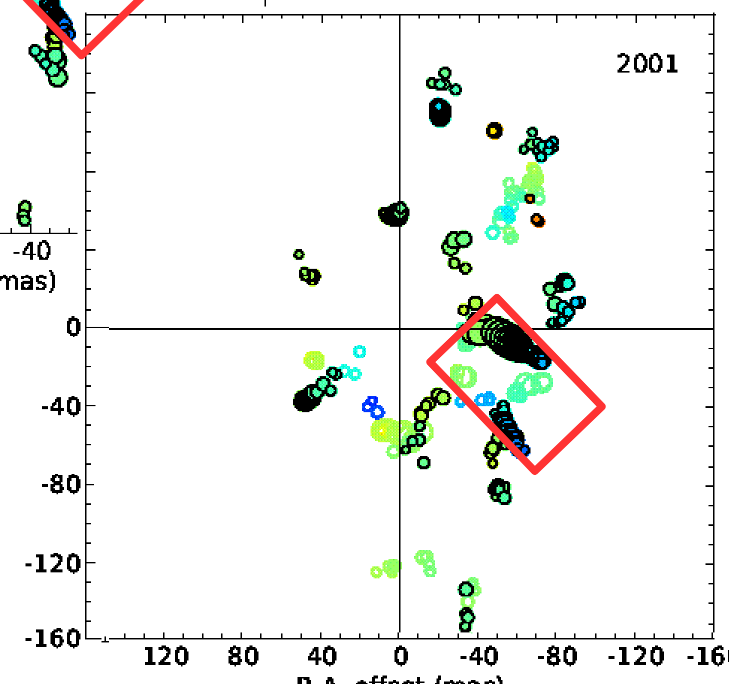


- Many RSG 22-GHz clumps persist > 5 yr
- Most patterns randomly-oriented
- A few of the longest-lived are radial e.g. B

Larger-scale streamers





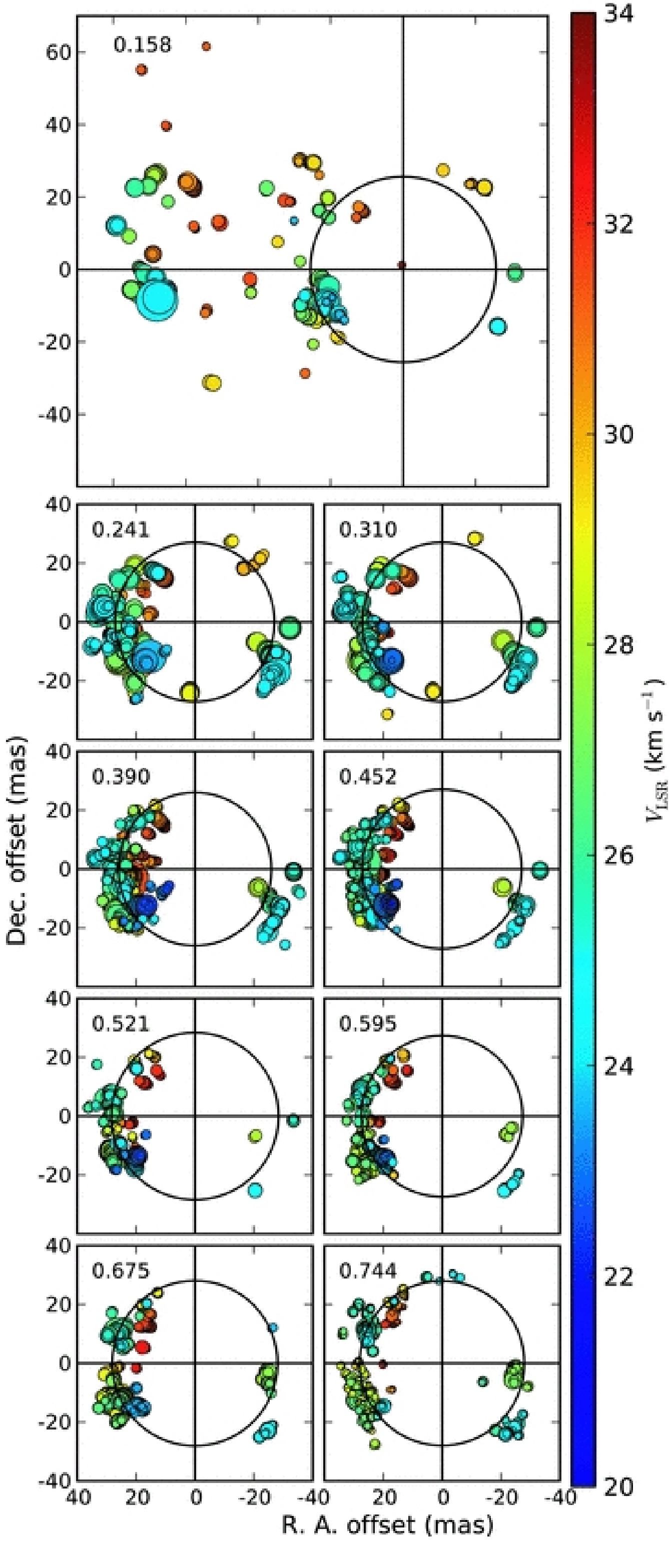


AGB U Her

22 GHz MERLIN

- AGB 22-GHz clumps smaller, 1-2 yr lifetime
- Most patterns randomly-oriented or tangential
- U Her radial streamers in persistent direction if not exact same clump

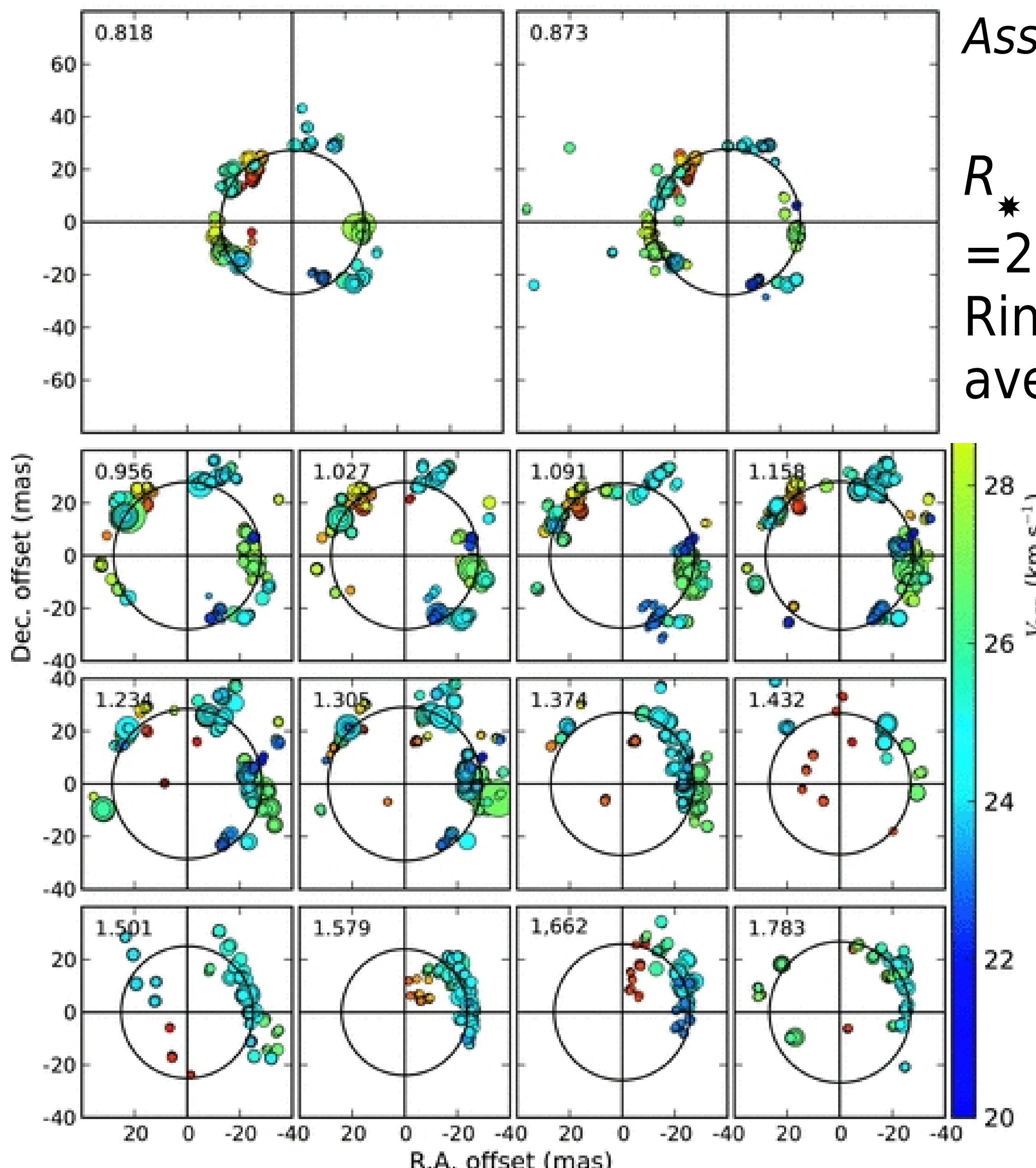
R Cas SiO ϕ 0.1 - 1.8



Assaf+ 2010

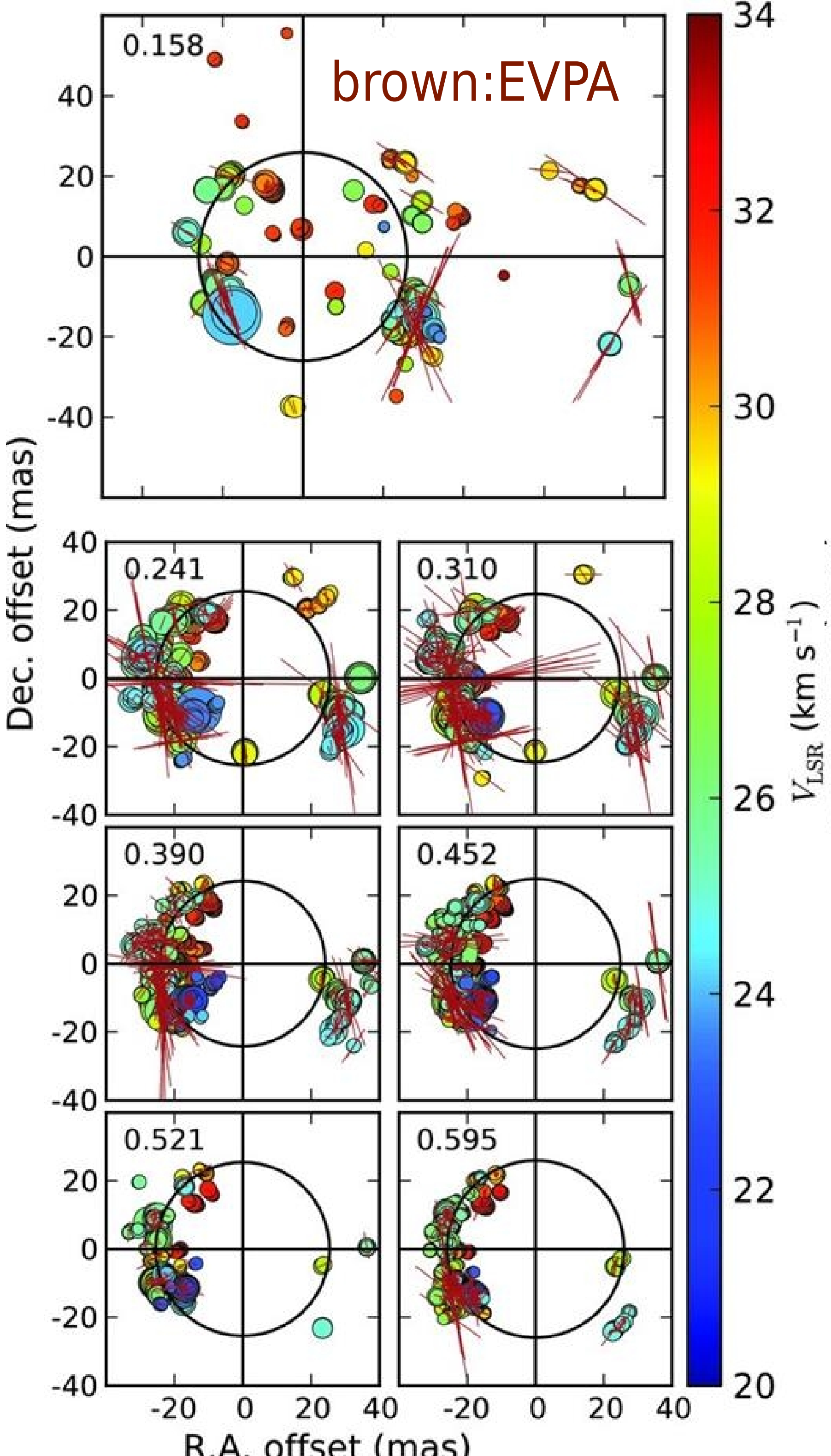
R_* 12.6 mas =2.2 au

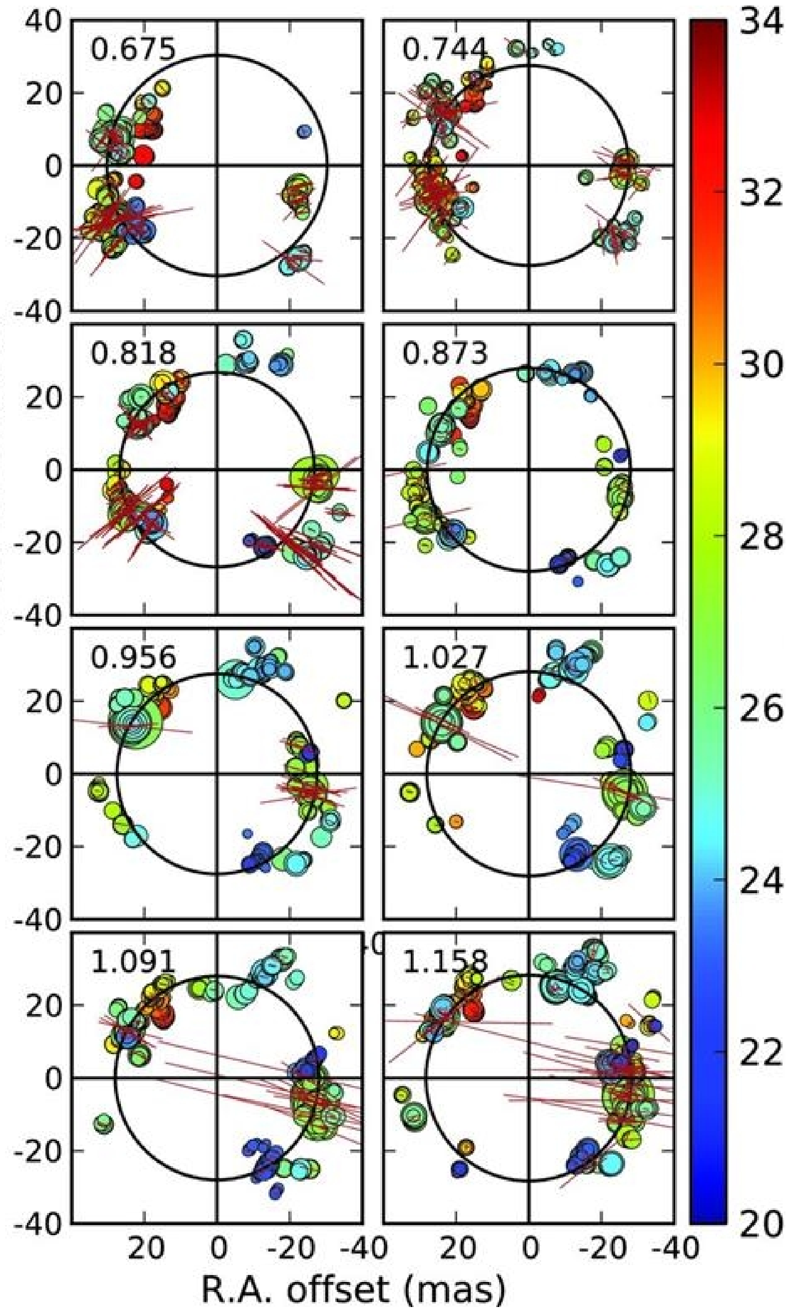
Ring= average R_{maser}



V_{exp} < 10 km/s mostly < 7 km/s

R Cas polarization





23 epochs
VLBA
43 GHz
Assaf+ 2013

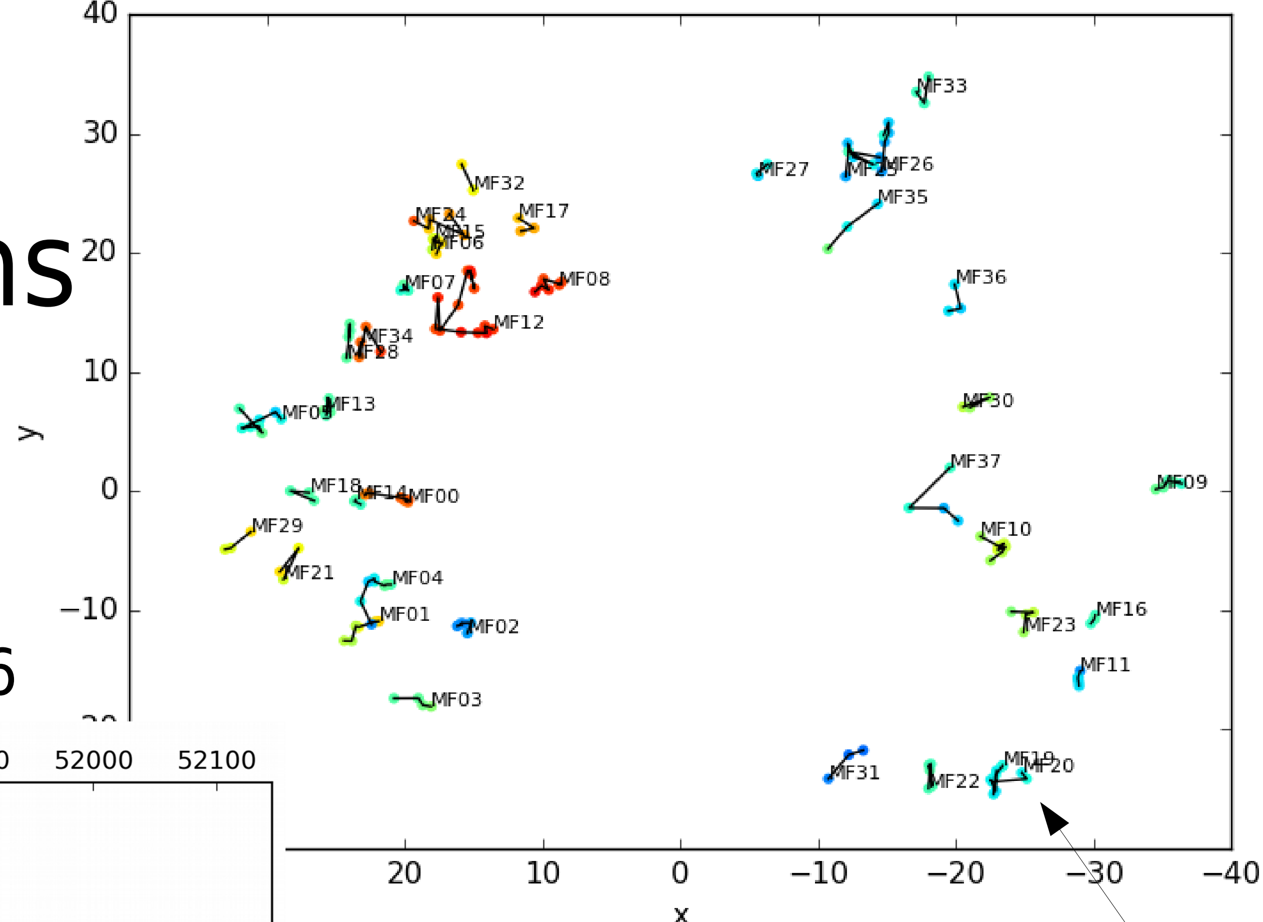
Magnetic energy density ~ thermal & kinetic energy densities

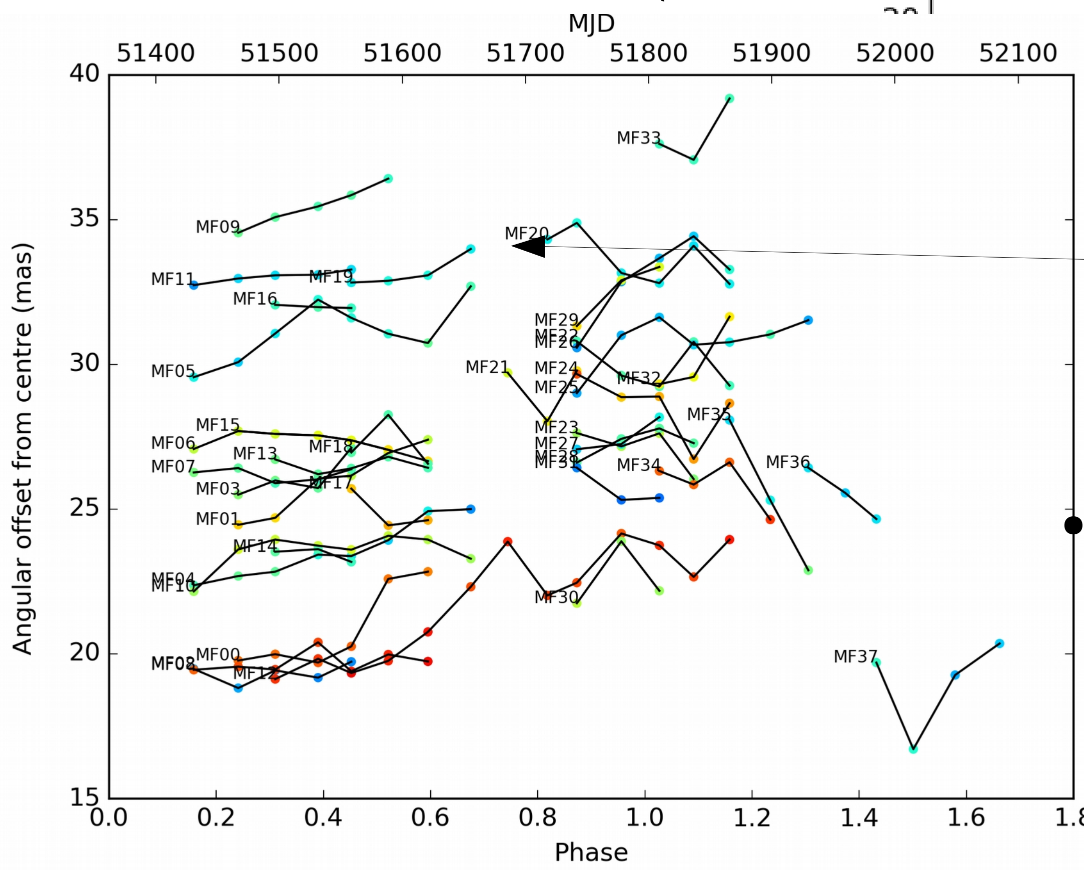
Mean linear pol 10-60%

Few >100%
Smaller-scale pol. structure than tot. I

R Cas proper motions

- 38 series of features matched ≥3 epochs
  - 20% of all features
  - All masers fade $\phi>0.6$

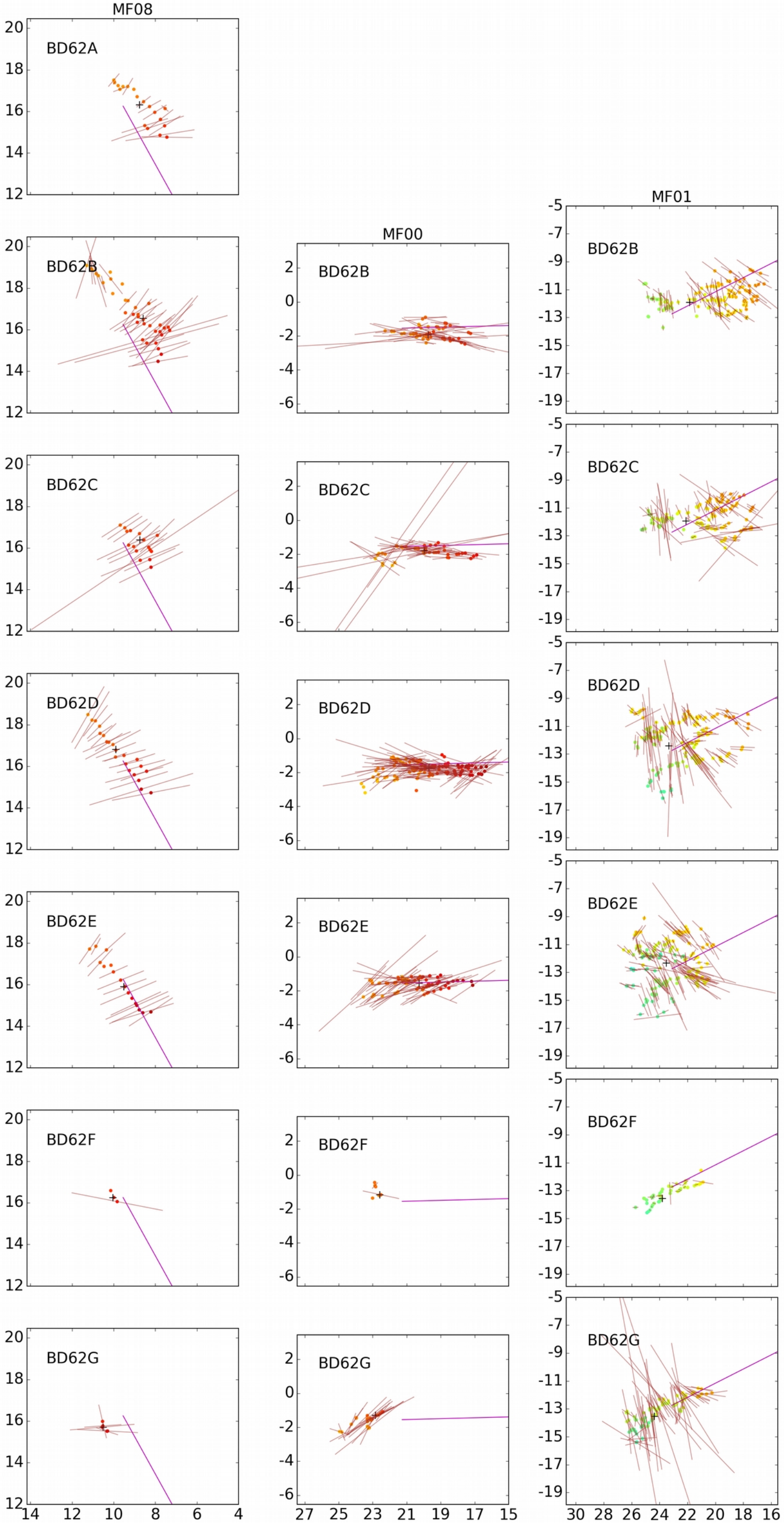




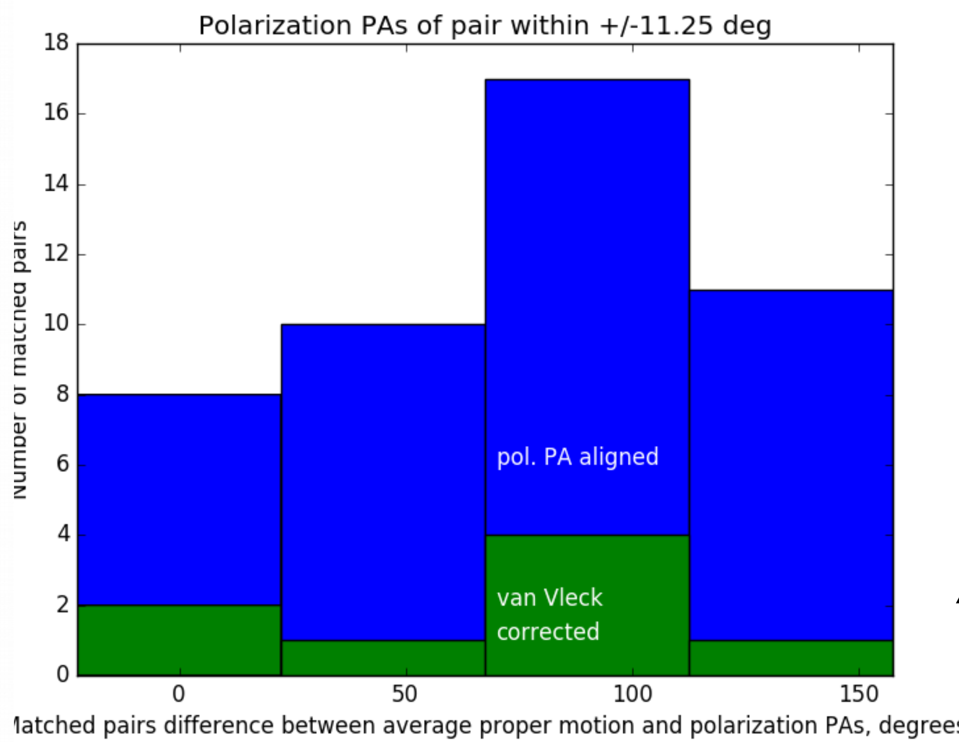
- At least 1 series re-appears
- Average expansion consistent with R_{shell} evolution

- Net V_{exp} 0.4 km/s
  - 67 yr to cross shell
  - Implies $\dot{M}$ ~$4\text{x}10^{-7}$ M⊙ /yr
    - (*Gray, Ireland n* models)

Polarization alignment?



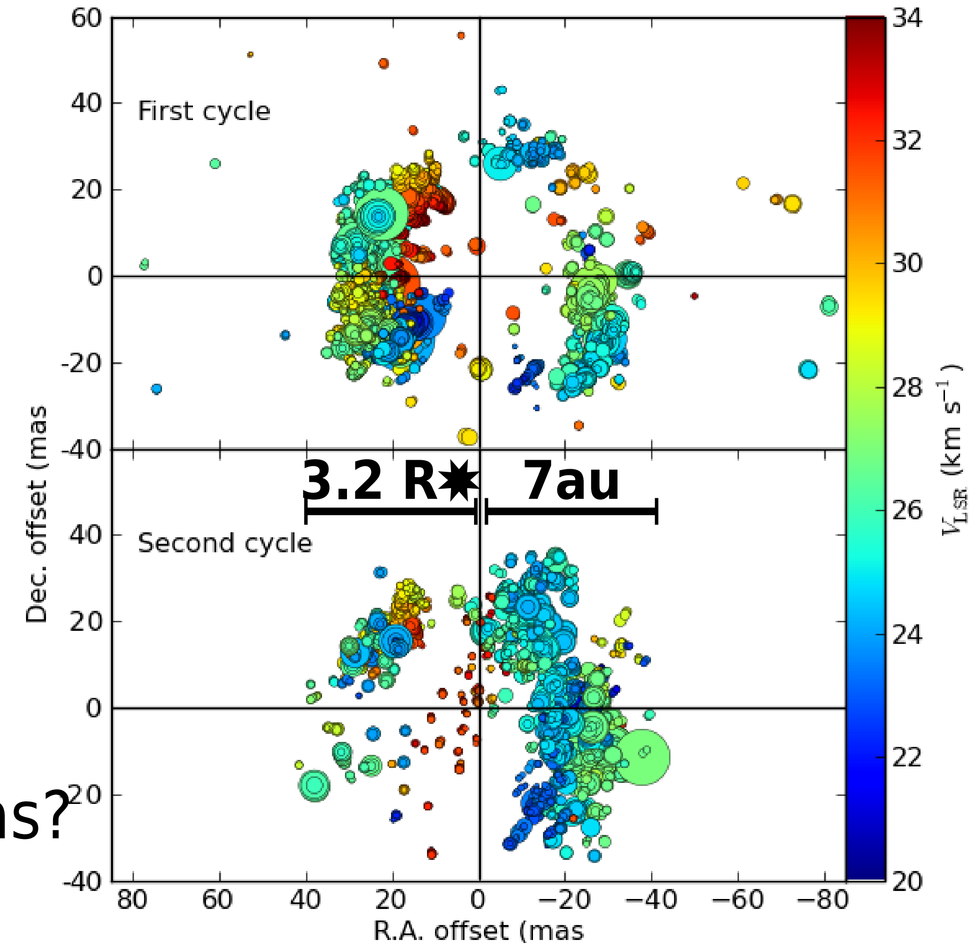
- 17 pairs of features have EVPA approx. orthgonal to proper motions
    - Assume *B* perpendicular to EVPA
  - Most popular (2σ) alignment but:
    - Only 10 pairs have radial motion
    - Most motions far more complex



Assaf 2018 (submitted)

What forces act on SiO at 2-5 $R_{\star}$?

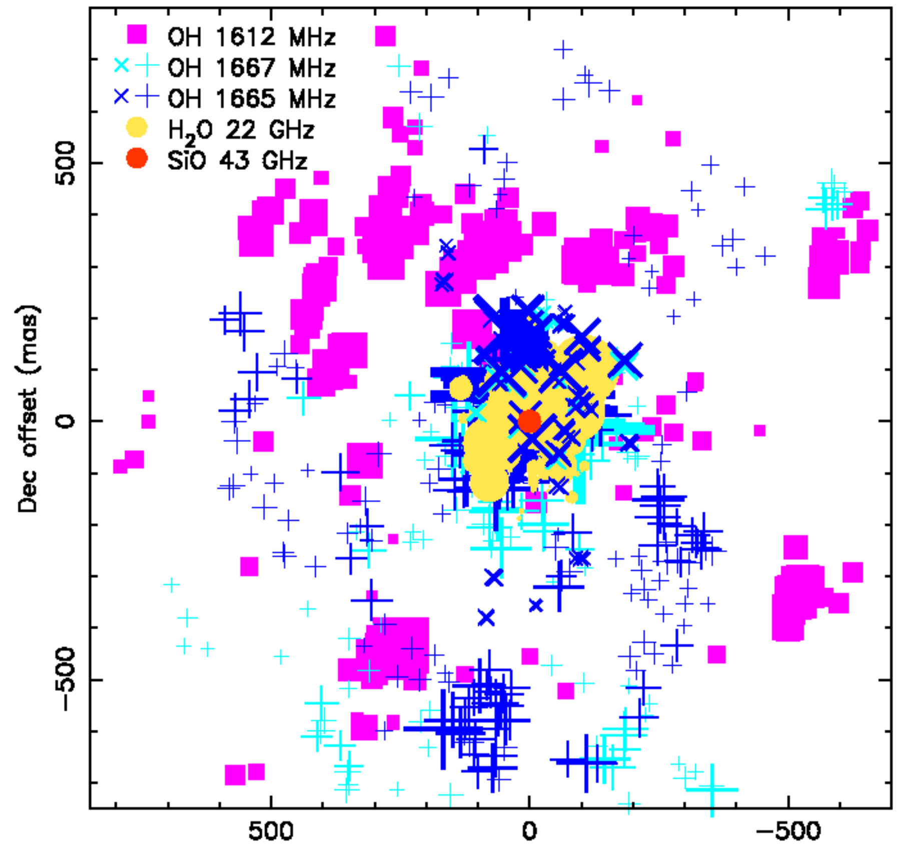
- Heating⇨expansion⇨convection
  - Fails once τ_{NIR} <1
    - But + pulsation = waves
- Flow mostly not along B lines?
  - (or data too messy...)
- Scattering by heat-resistant grains?
- Magnetic buoyancy?
  - Obs. evidence for small-scale field complexity; *Lopez Ariste* model

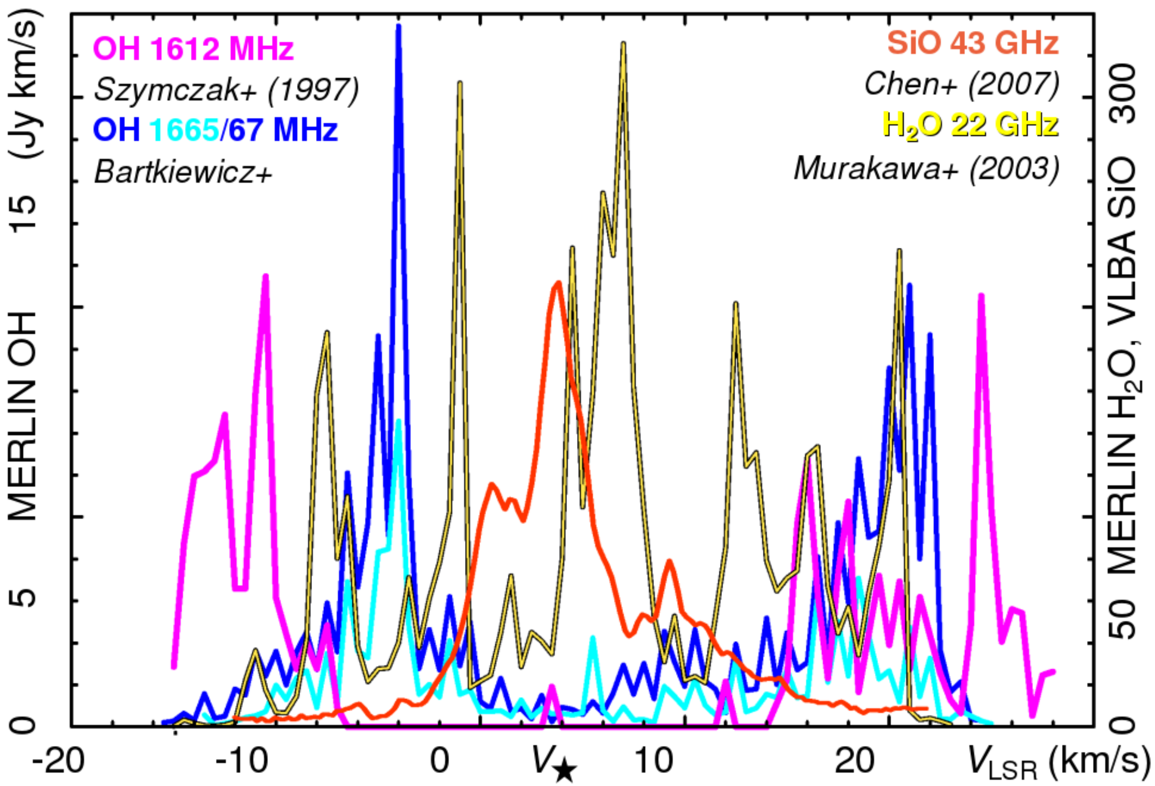


Temperature Density Entropy ~streamlines opt. intensity

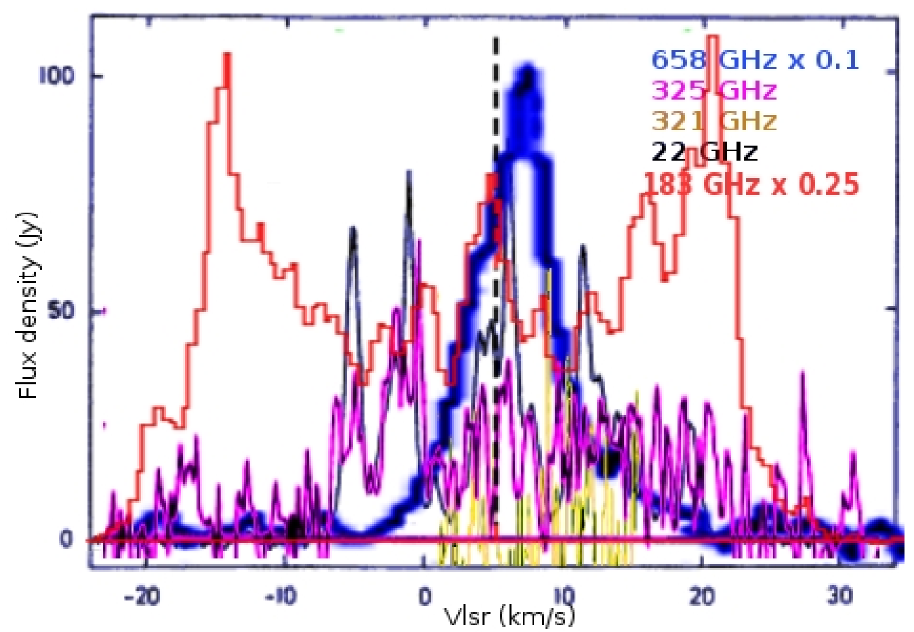
Masers trace clumpy outflow

- 'Well-behaved' VX Sgr
- Lower T_{ex} - further out - faster
  - Some overlap/inhomogeneities





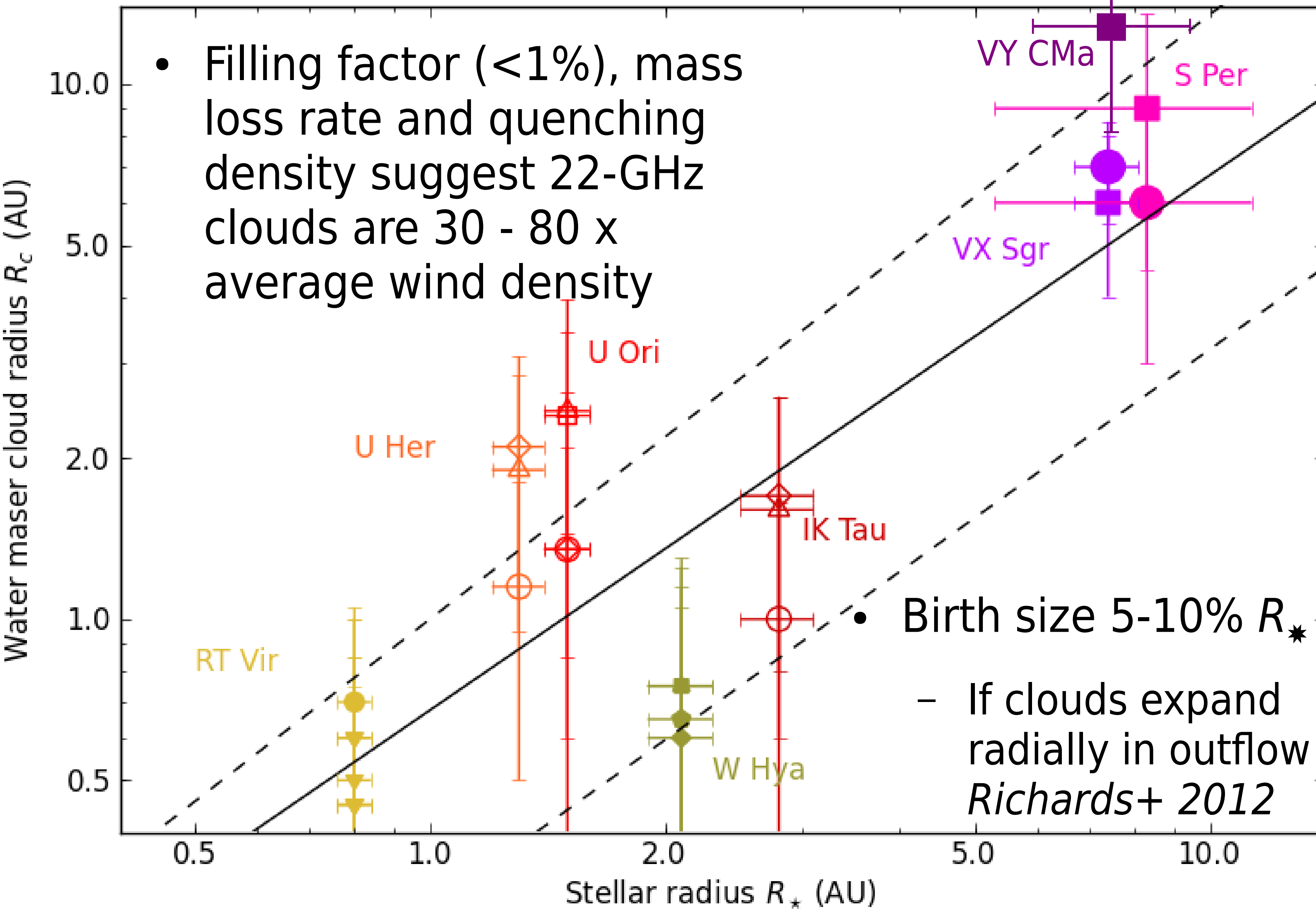
cm λ spectra



(sub-)mm λ H2O spectra

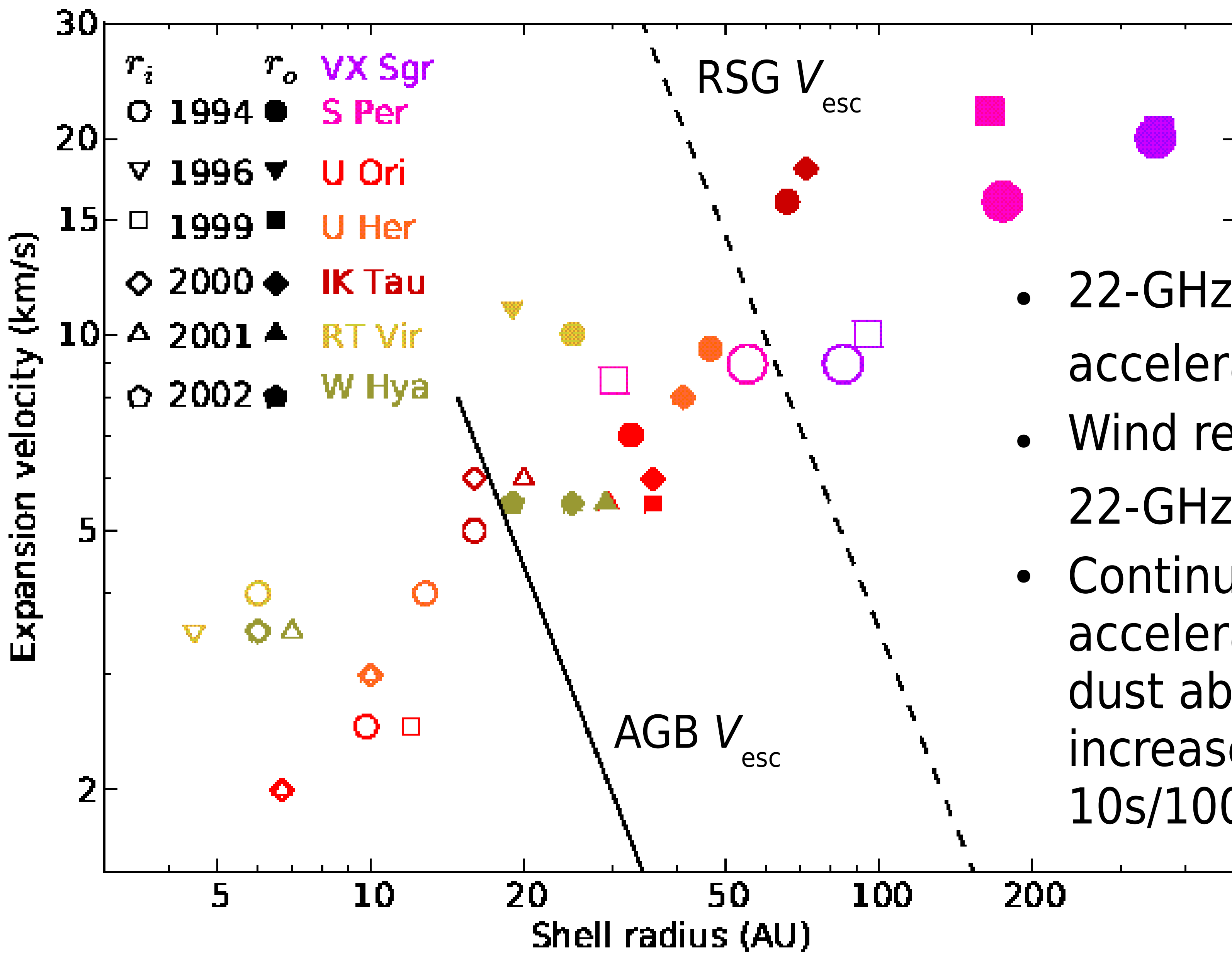
22 GHz maser clouds over-dense

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



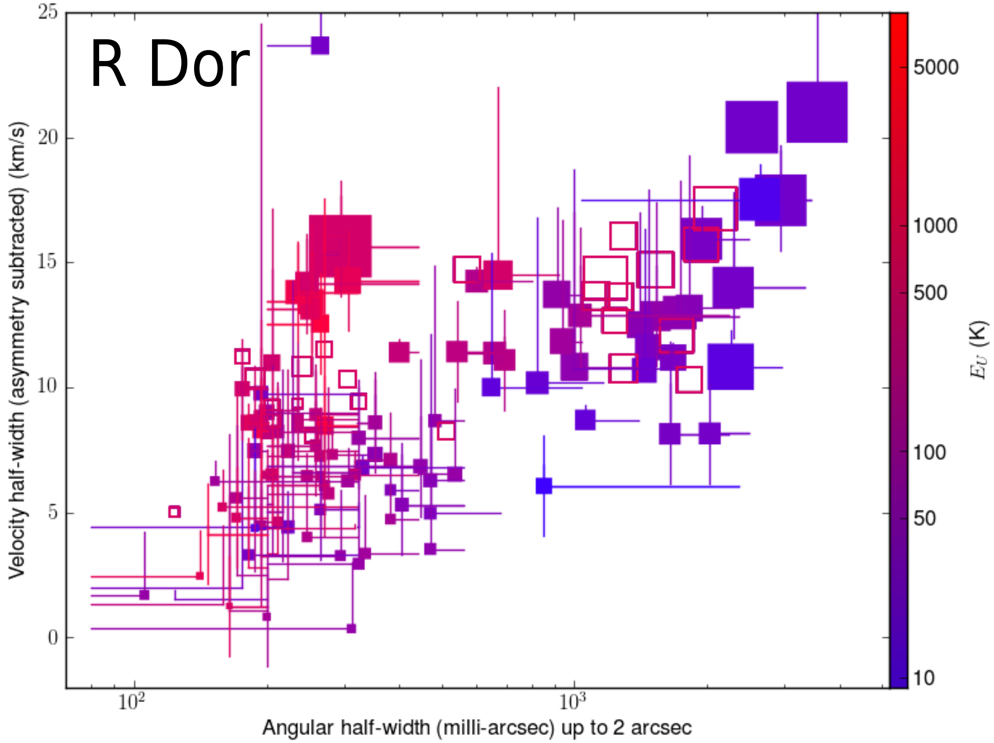
- Birth size 5-10% $R_\star$
  - If clouds expand radially in outflow *Richards+ 2012*

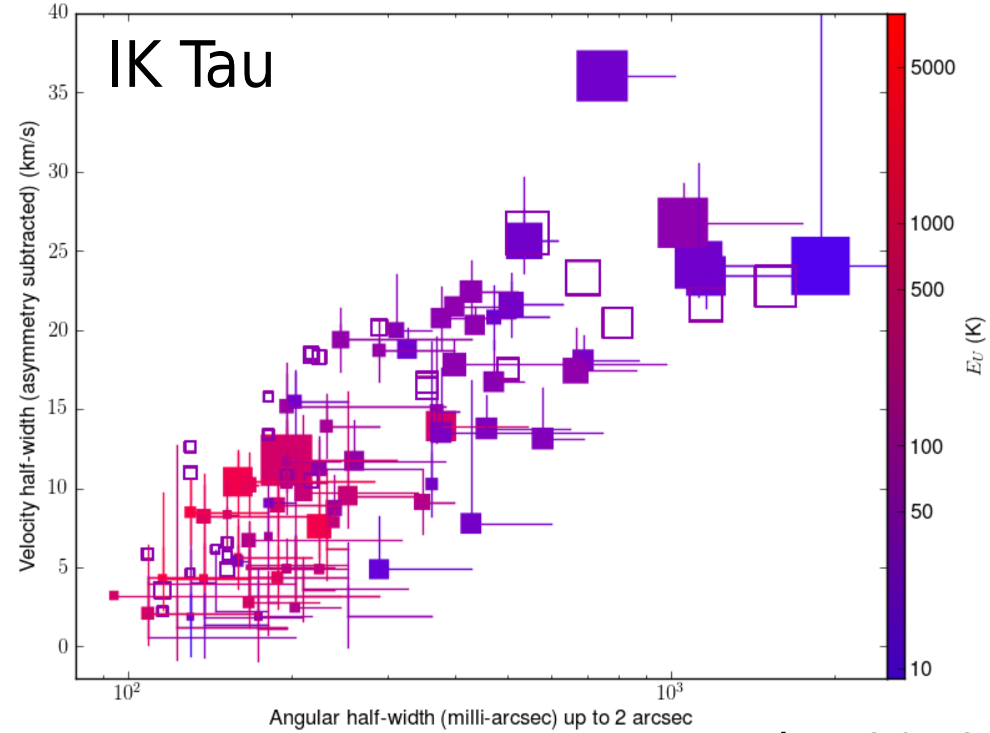
Escape velocity @10-15 R_*



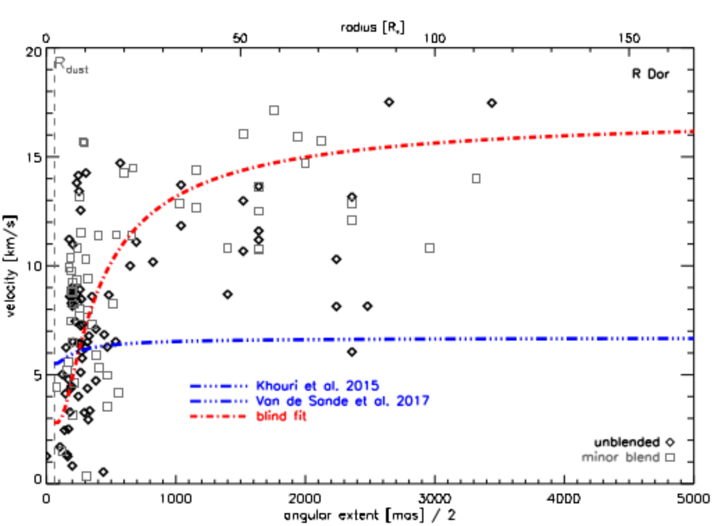
- 22-GHz H_2O maser acceleration zone
- Wind reaches V_{esc} in 22-GHz shell
- Continued acceleration implies dust absorptivity increases to 10s/100s R_*

ALMA sensitivity: high thermal V_{max}



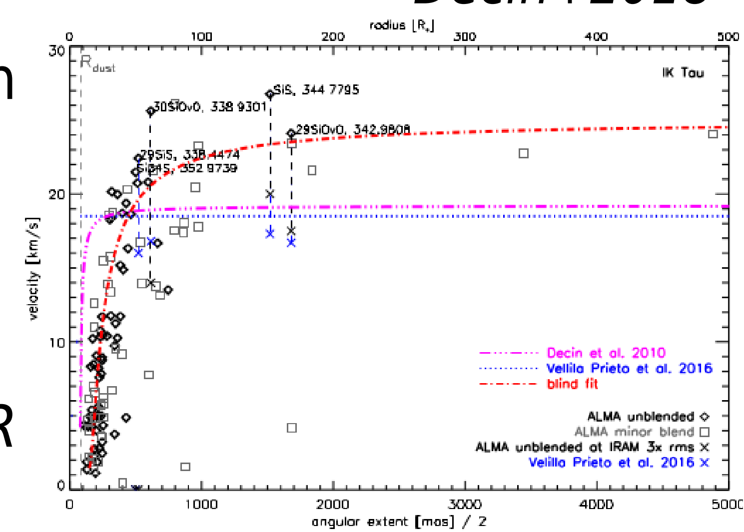


Decin+2018



Some fast high-E_U lines in pulsation/shocked region near $R_{photosphere}$

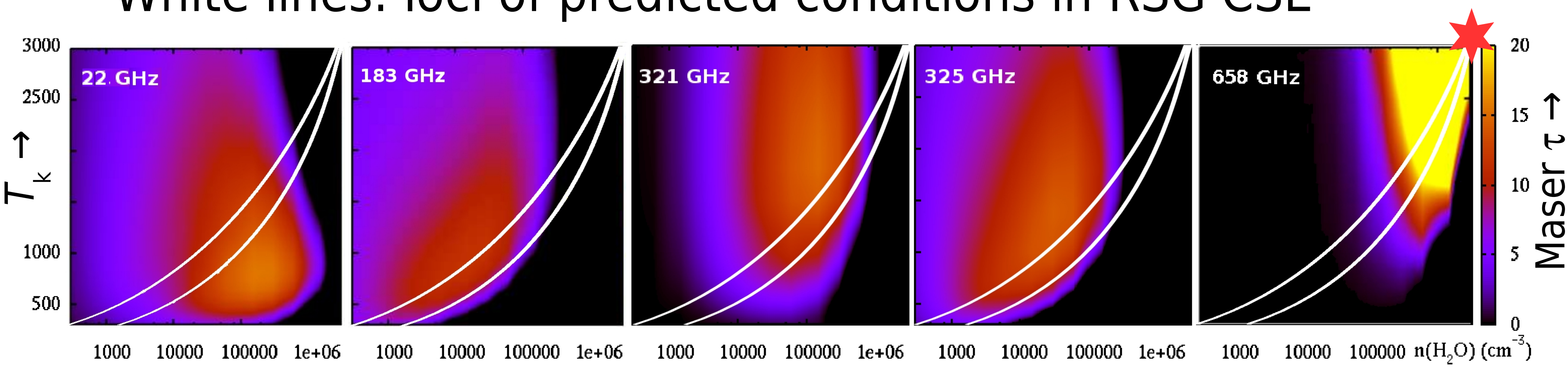
Most high-Vexp lines low E_U in cool regions, large R



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

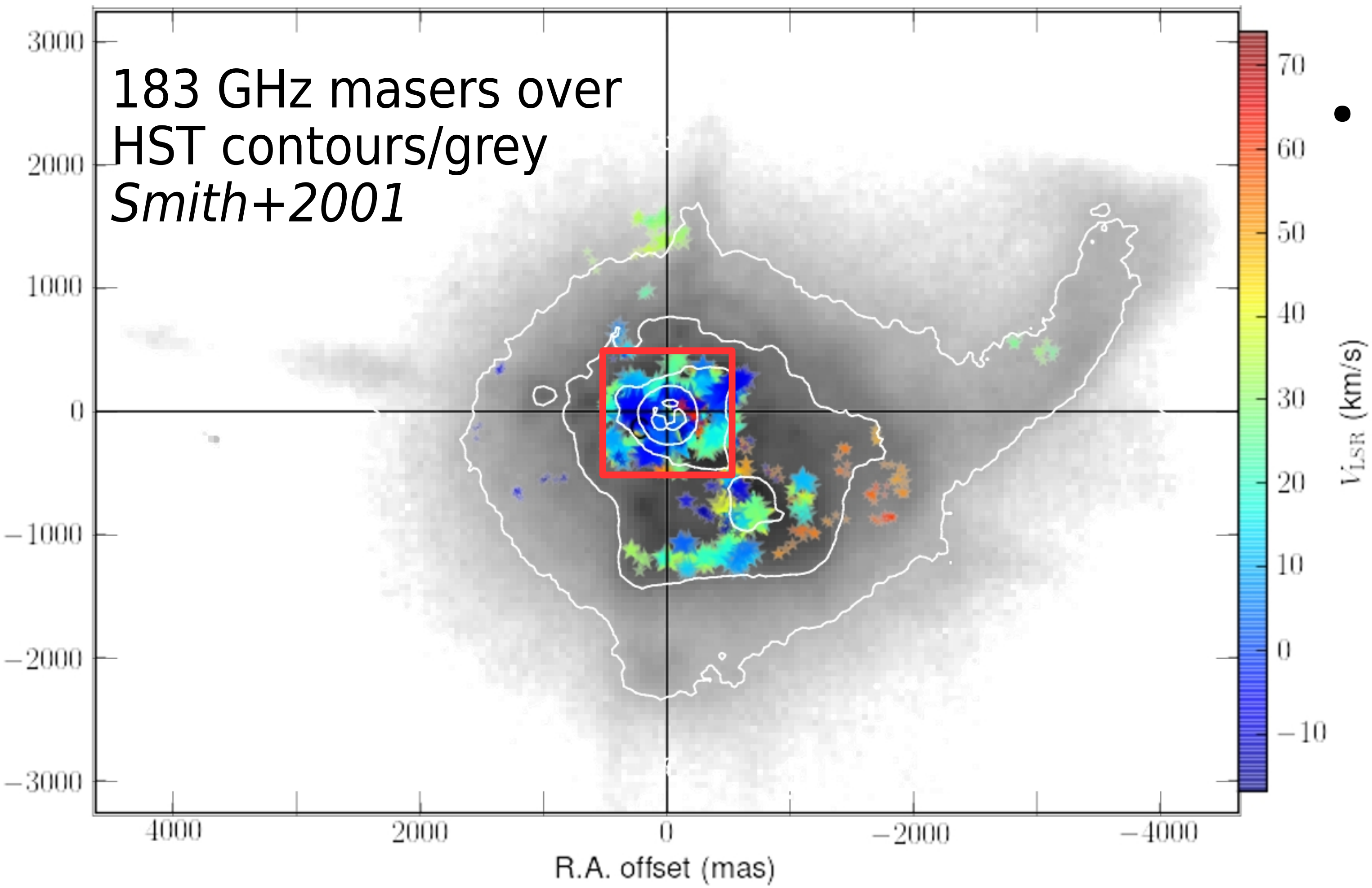


Gray et al. 2016

Higher number density →

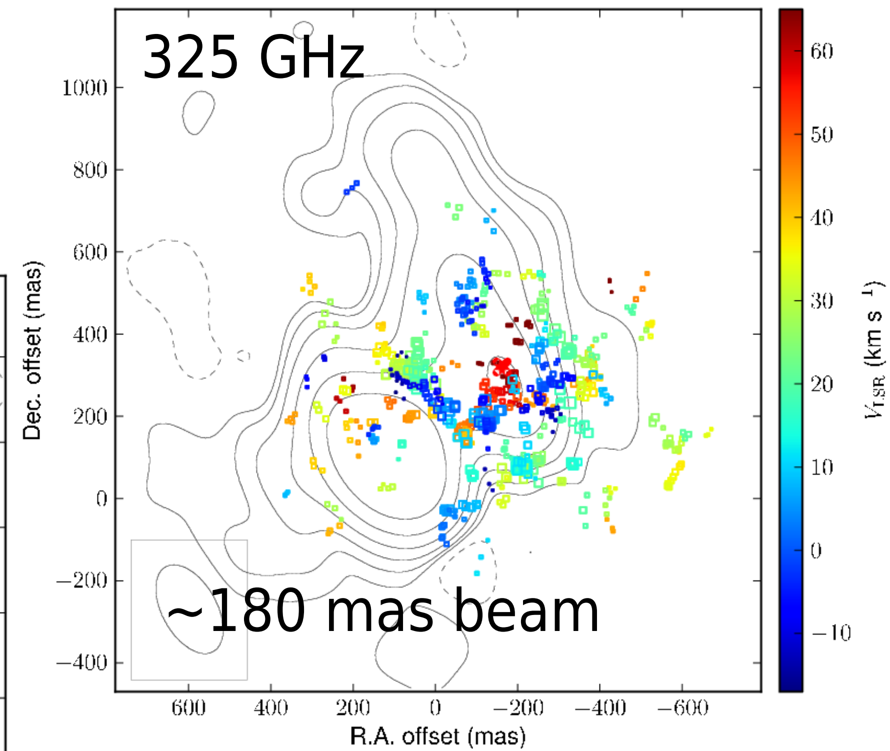
ALMA SV VY CMa multi-λ water masers

- 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



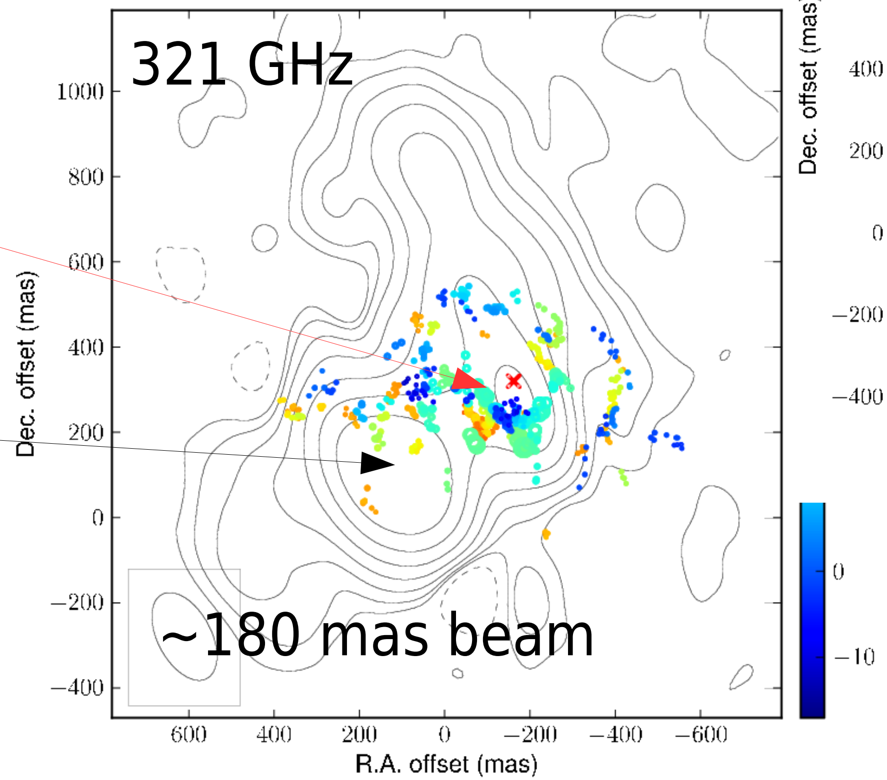
- HST proper motions of clumps (scattered lines)
  - Does VY CMa fling out clumps ballistically?
    - *R Humphreys et al 2007*

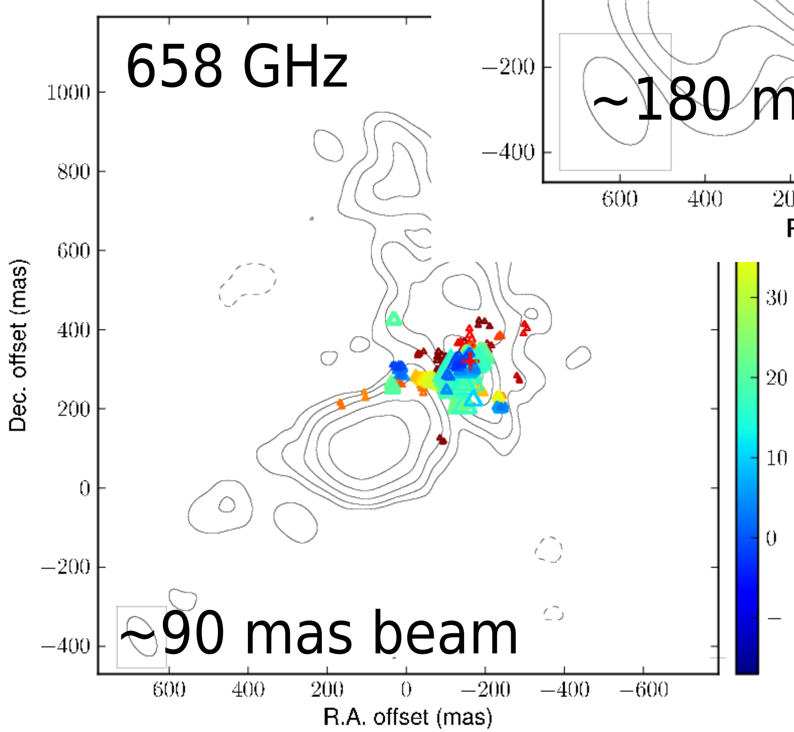
VY CMa sub-mm H_2O masers



Star, **VY**

C

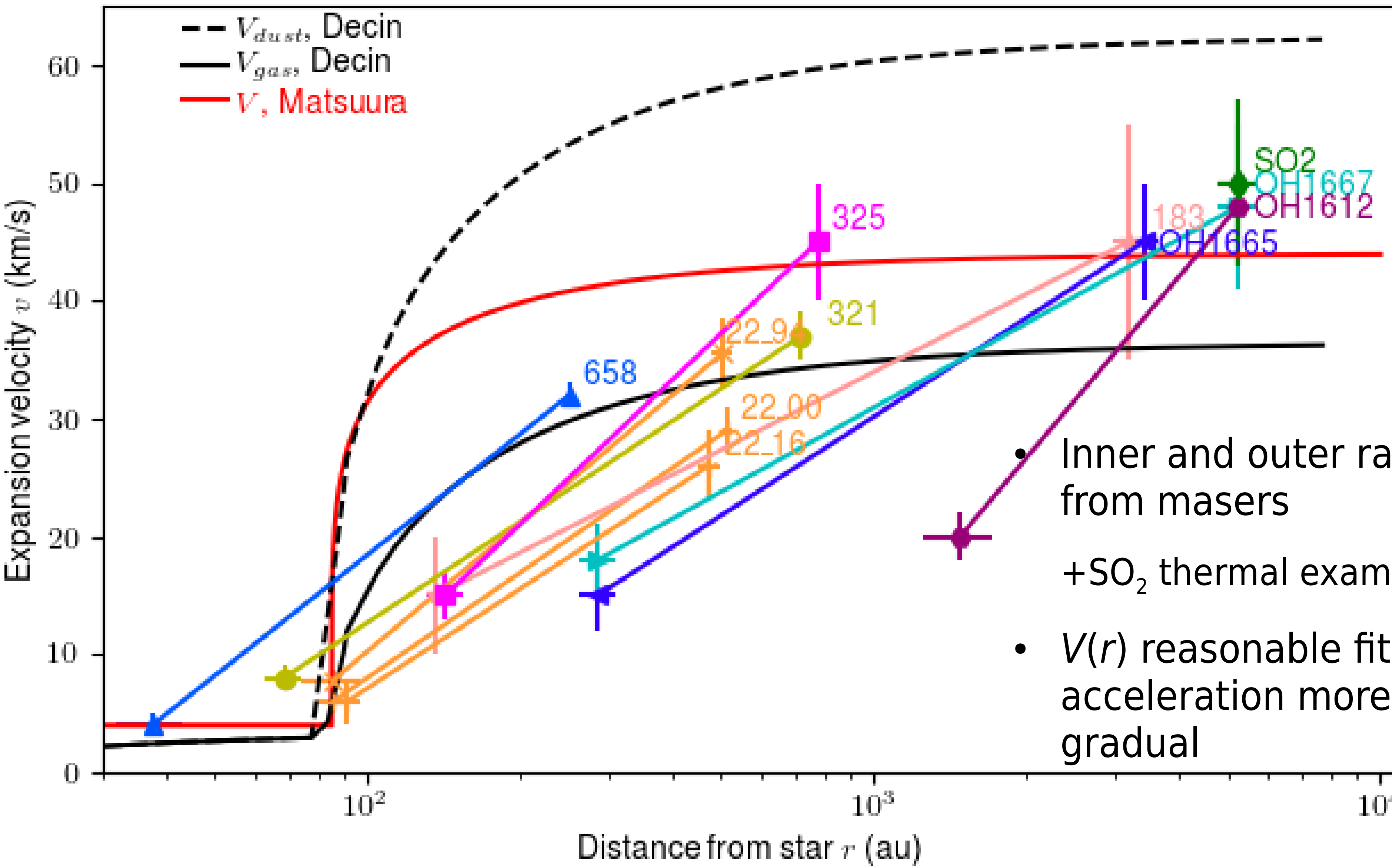




- 658-GHz surprisingly extended round cold clump **C**
  - Shock?
    - *OGorman+15*

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

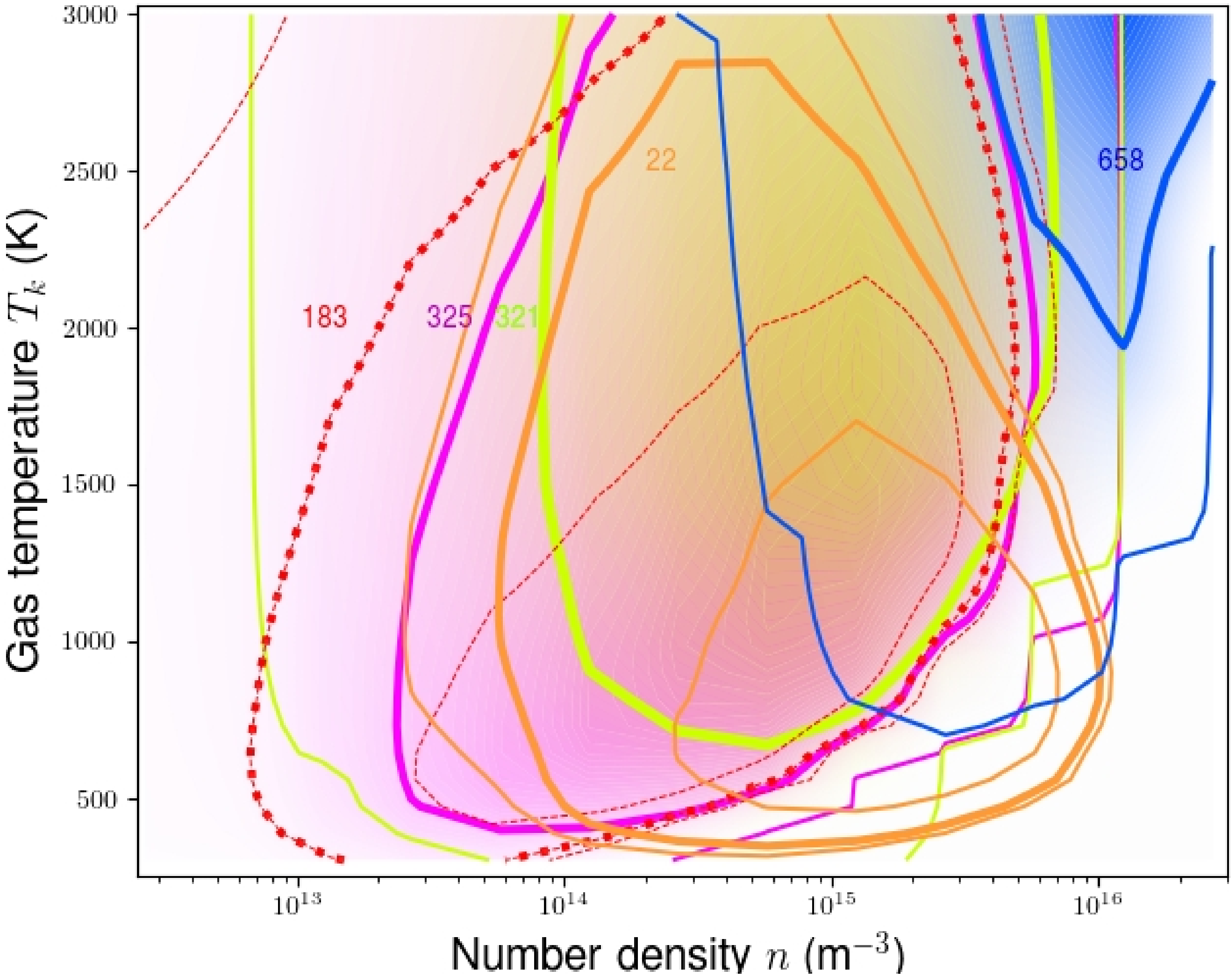
Gradual acceleration



- Inner and outer radii from masers

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

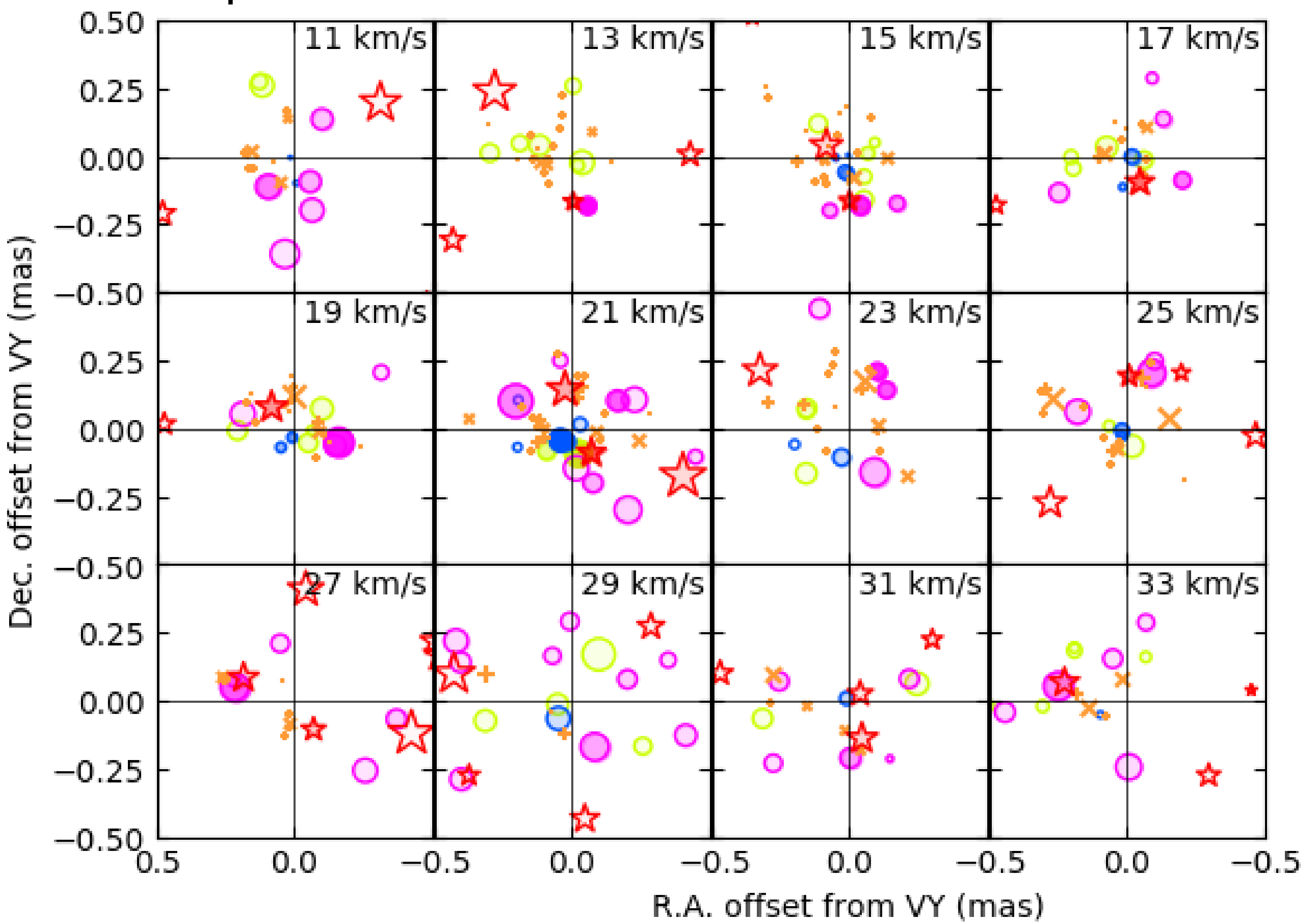
VY CMa maser model (*Gray*)



- 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

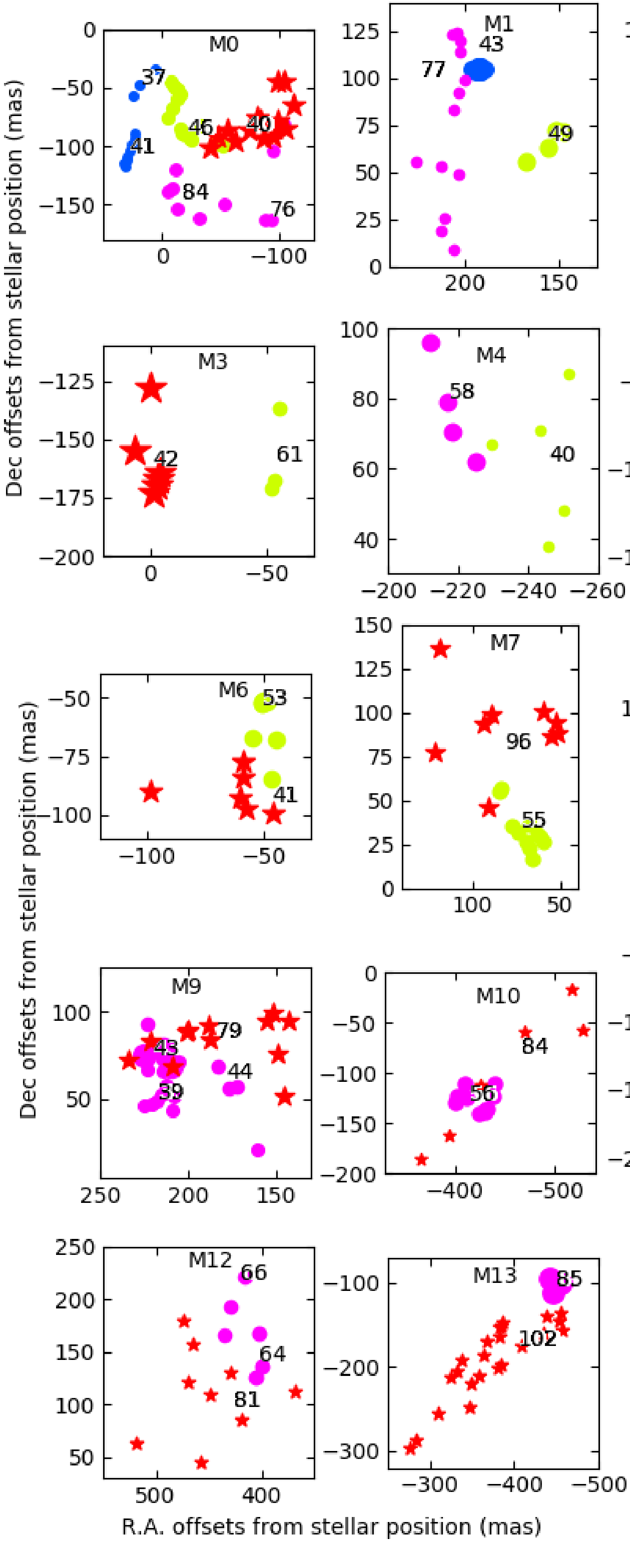
Maser cloud overlap

- Features within 500 mas of VY CMa, $V_{\star}$ ±12 km/s
- Compare *Decin+'06, Matsuura+'13* 1D models



- '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

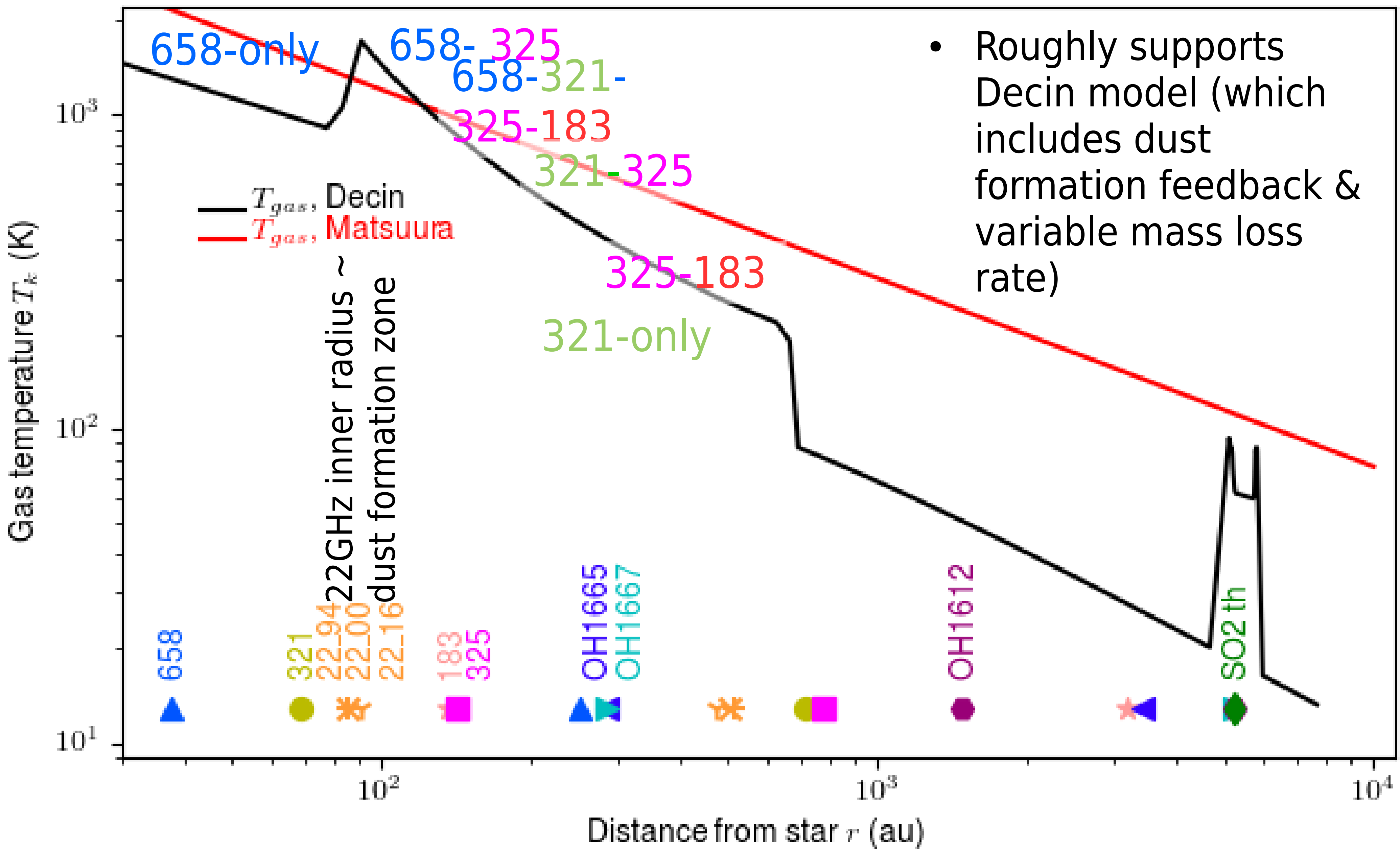
Surprisingly few line overlaps



Components making up overlapping clumps

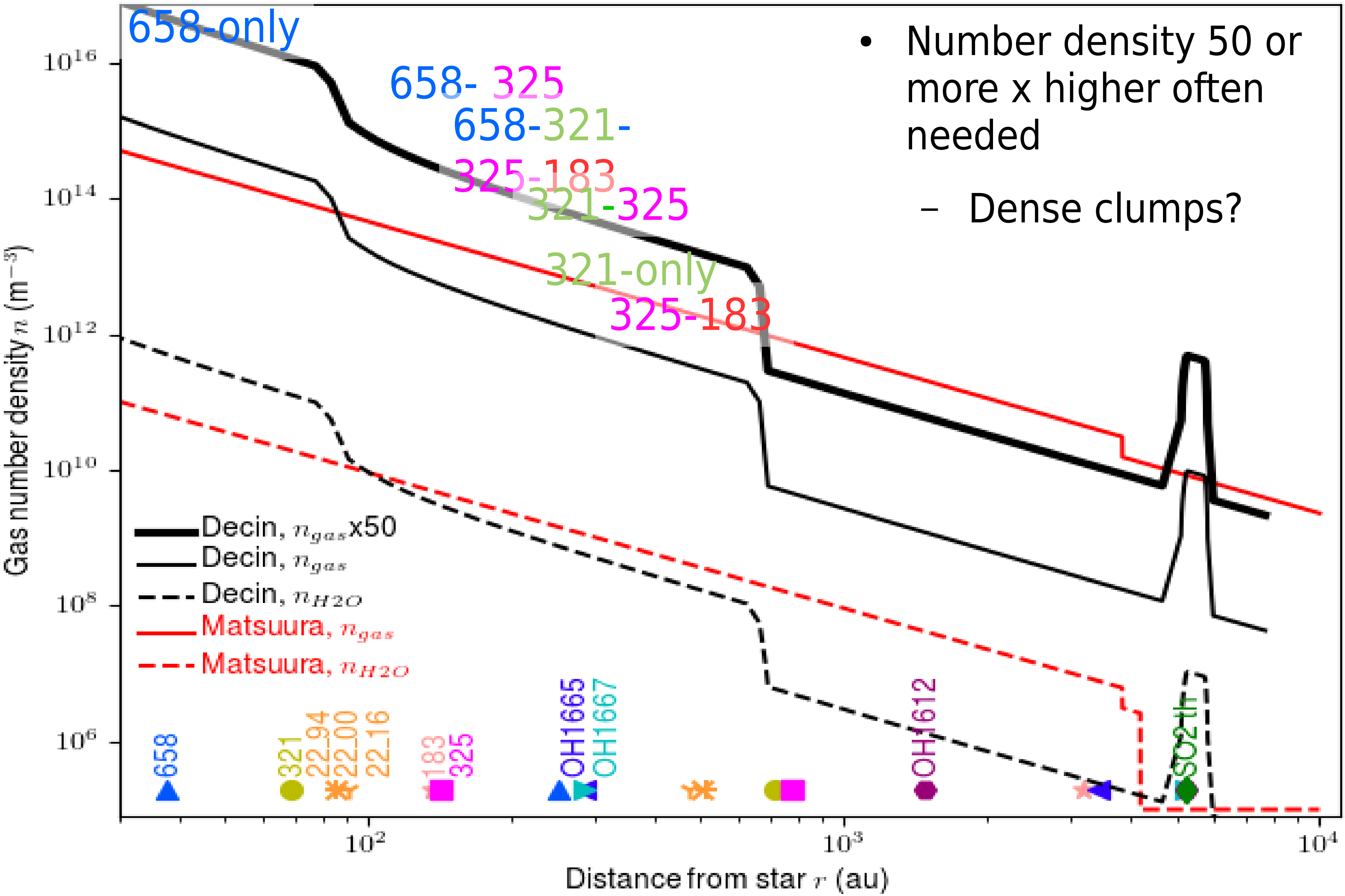
- ~70 - 170 features per line
- 14 regions of line overlap or close association
  - Probably more if 22 GHz contemporaneous included
- Size of symbol proportional to estimated feature peak τ
  - Too crudely estimated:
    - Apparent highest τ have small angular size
      - Probably from clouds elongated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

Temperature constraints



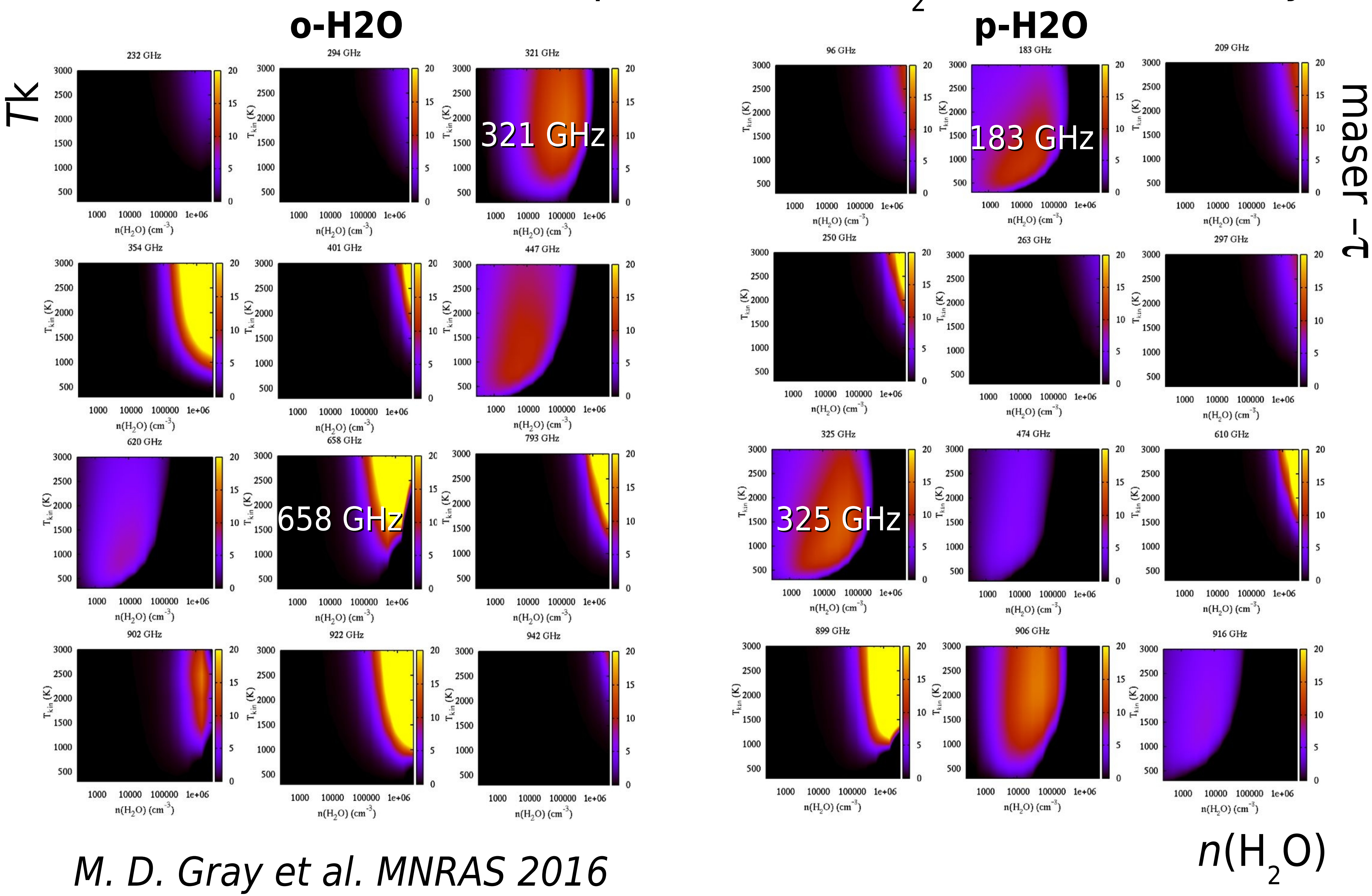
- Roughly supports Decin model (which includes dust formation feedback & variable mass loss rate)

Number density constraints



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

Maser optical depths for some of ~50 H_2O lines in bands 3–10 as functions of kinetic temperature & o-H_2O number density



M. D. Gray et al. MNRAS 2016

DEATHSTAR

alma investigation of cool giants

PI: S. Ramstedt, Uppsala university

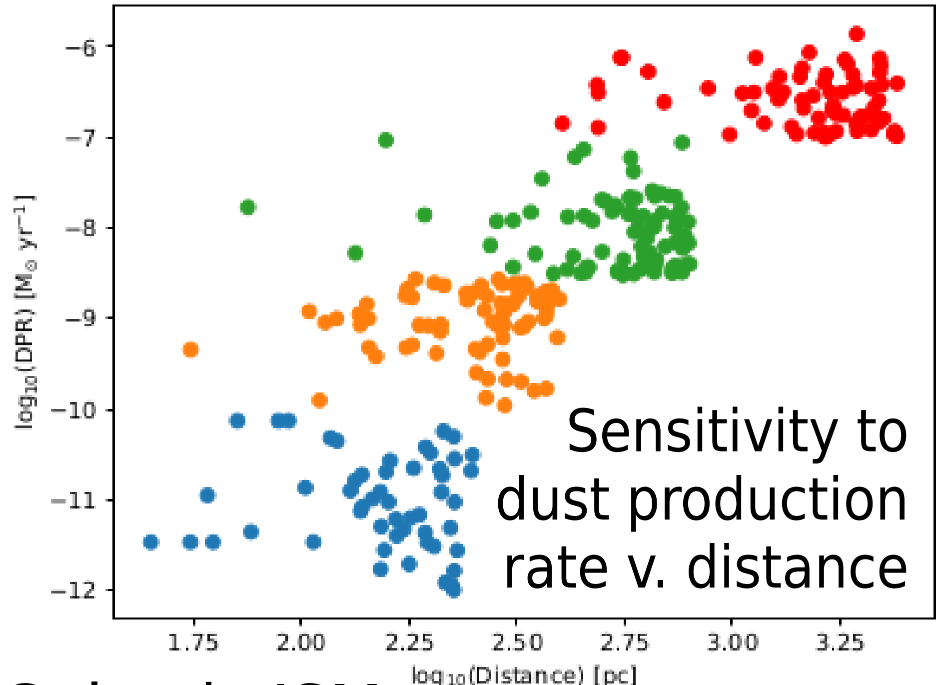
DEATHSTAR is a project to map the winds around nearby (< 500 pc) AGB stars and improve the accuracy of previously published models of the wind properties of the Galactic AGB stars (*Schöier et al. 2001* for carbon stars; *Gonzalez-Delgado 2003* for M-type stars; *Ramstedt et al. 2009* for S-type stars).

Currently close to 50 AGB have already been observed using band 6 and 7 at ALMA. Around 20 different molecular emission lines are detected within the wide bandwidth covered by the observations.

For more information see www.astro.uu.se/deathstar and *Ramstedt et al. 2018* (soon to be submitted)

Nearby **E**volved **S**tars **S**urvey

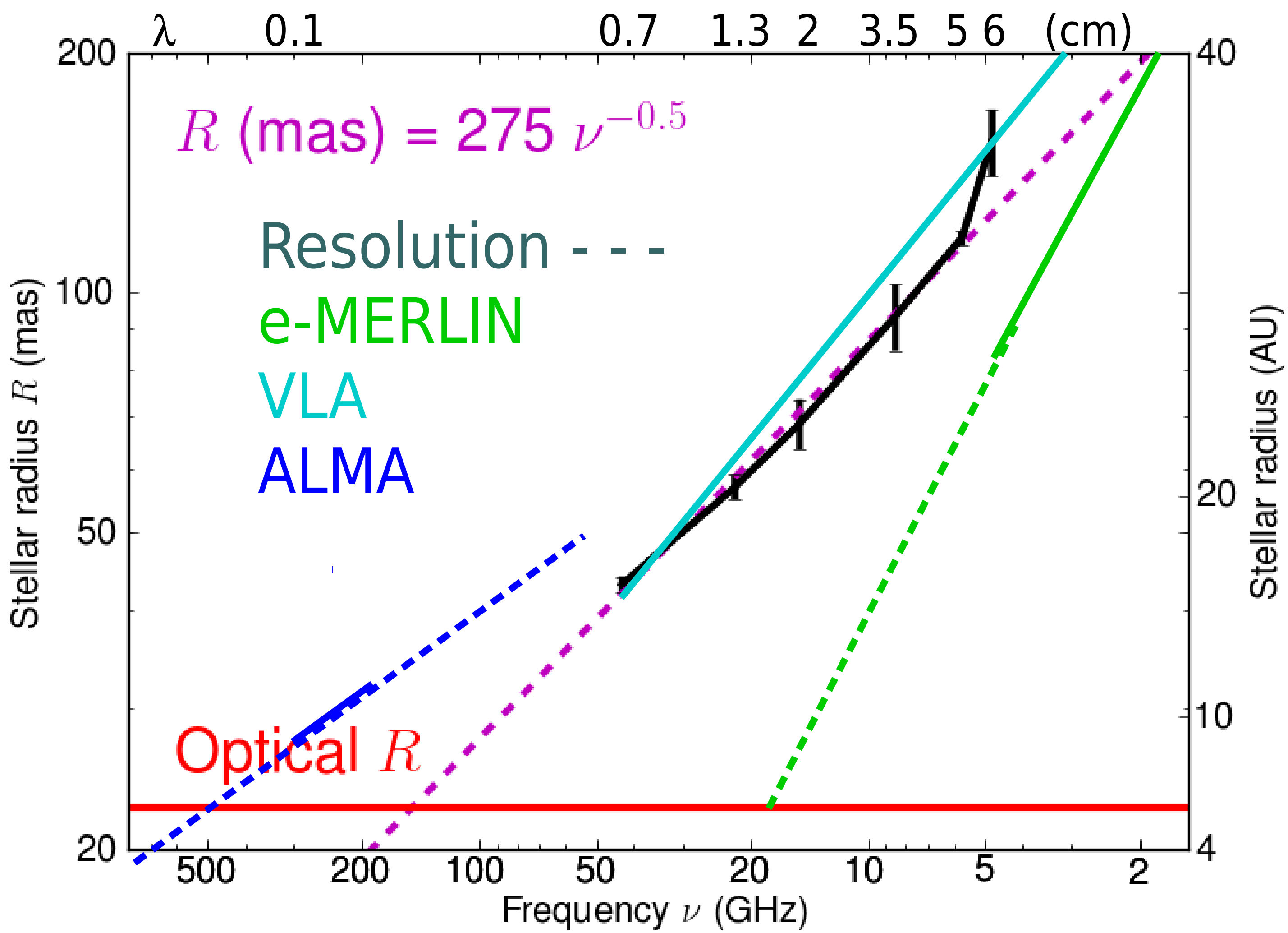
- Volume-limited JCMT survey
    - Approved Large Program
  - ~300 stars, large range $\dot{M}$
  - CO and dust continuum
- Constrain:
  - Total gas+dust returned to Galactic ISM
  - Dust to gas ratios
  - Physics of mass loss
  - Mass loss history
  - $^{13}CO/^{12}CO$
- Large-scale complement to stellar surface studies



NESS: Lead Peter Scicluna
team from China, Taiwan, South Korea, Japan, Canada, UK
http://www.eaobservatory.org/jcmt/science/large-programs/ness/

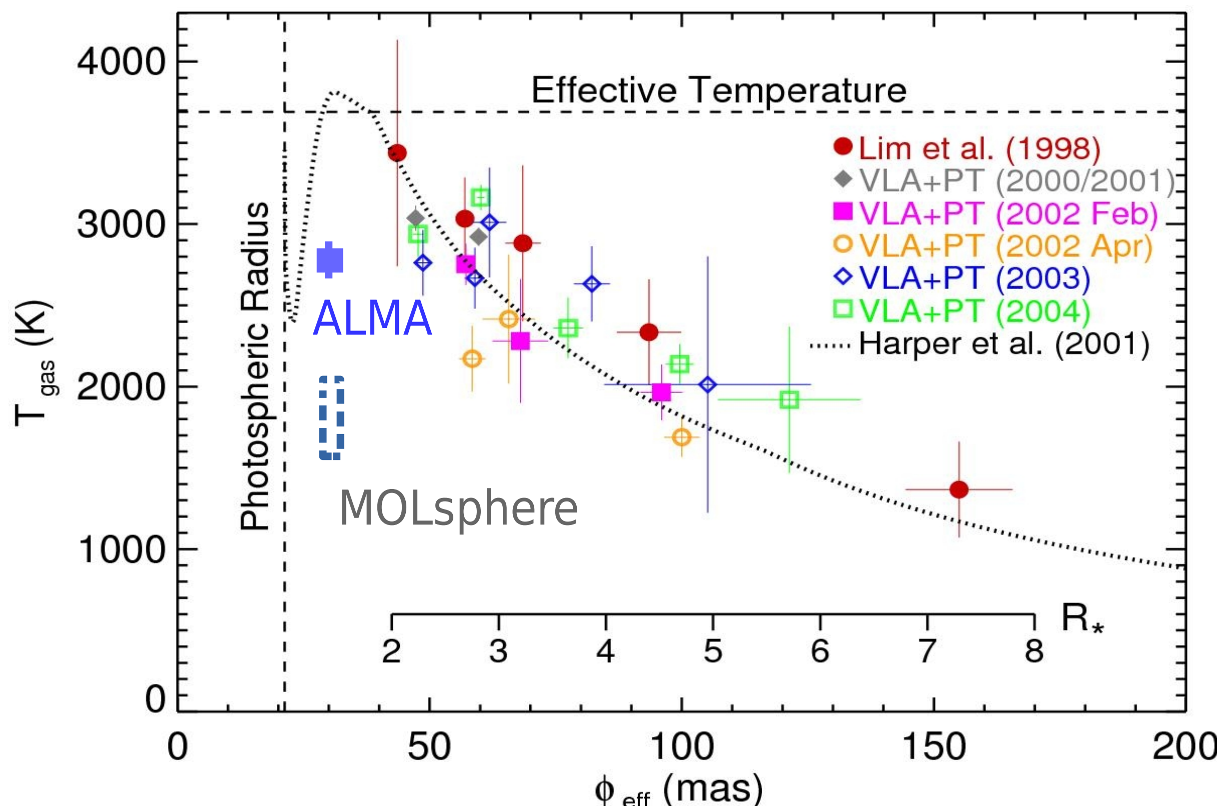
Betelgeuse continuum monitoring

- Observe from sub-mm to cm at sub-R_* resolution
- ~weekly for 1 or a few months at increasing λ
- Probe 1.5-6 R_*
  - Variability/ motions like SiO in this region round later stars?
- Per epoch multi-λ obs.
  - Spectral indices
- Test energy transport mechanisms



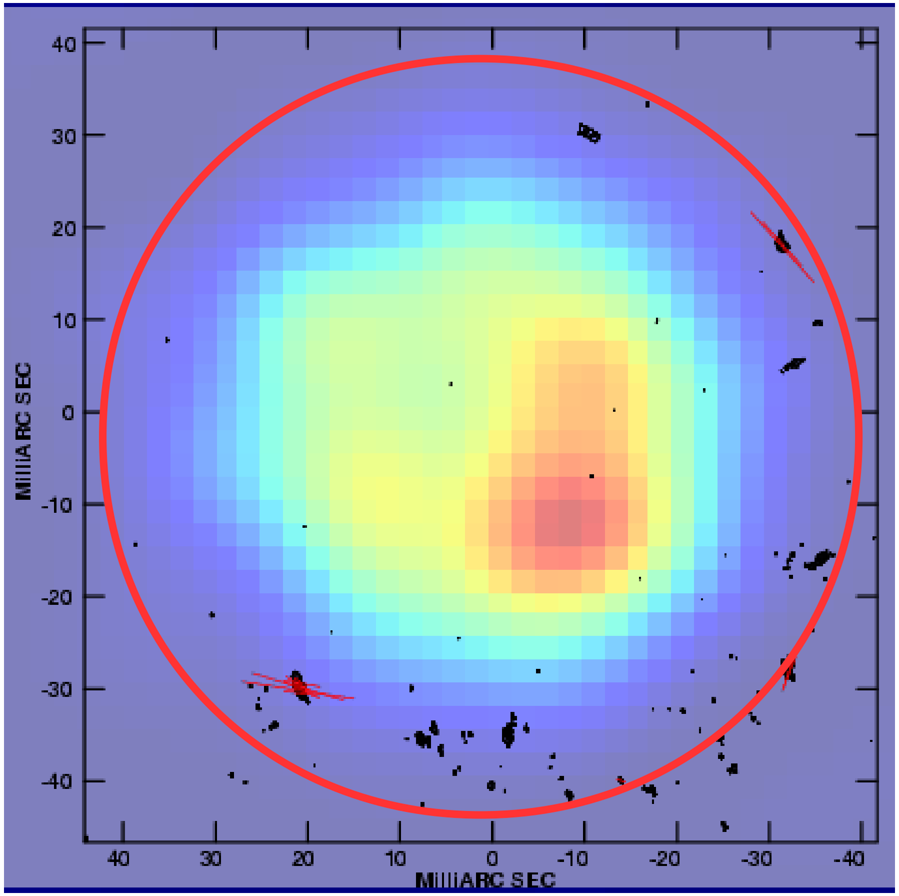
Transport across radio photosphere

- **Inside ~2 *R*$_*$** strong convection and pulsation
  - W Hya (etc.) CO v=1 velocities ±20 km/s
  - AGB SiO masers 2 to ≥ 5 *R*$_*$, *V*$_{exp}$ < 10 km/s
    - Shock damping ~1.8 *R*$_*$ (*O'Gorman; Harper; Reid&Menten*)
  - What is (non-linear) *R*$_*$ dependence on λ between 0.4 - 7 mm?
  - Image ALMA star+lines
    - In all bands



Transport across radio photosphere

- **2~5+ *R*$_*$** radio photosphere
  - λ 1 - 6+ cm
- Compare VLBA/KVN monitoring of SiO masers
  - VLA/e-MERLIN stellar continuum
    - ? 6 GHz size ?
  - Optical/IR interferometry &/or ALMA dust formation?
    - As done with SiO masers + VLTI in S Ori
      - *Wittkowski et al. 2007*



W Hya
Color *Vlemmings et al.* 338 GHz
Reid & Menten 22 GHz disc
Contours *Cotton et al.* 43 GHz SiO masers

>5 R_*: the acceleration zone

- Starspots lead to wind plumes, streamers, clumps?
  - Locally-concentrated mass loss
    - Just a few maser/dust clumps formed per stellar period?
      - Correlated with large-scale star spots
        - Masers fade, re-appear further out with similar structure
          - Masing beaming fluctuates (months-yrs), clumps survive
    - Dusty clumps accelerated more than less dense surroundings?
- Multi-λ (sub-)mm H_2O masers would give physical conditions 10x finer scale than thermal lines
  - Do 658 GHz/SiO maser clumps evolve into 22/321/325 GHz ?
    - Can any instrument resolve few-au dust clumps at $\gg 5\ R_*$?
- Also: hunting low-mass close compansions; polarization....

ALMA 16 km baselines and more

- c. 50 predicted H_2O maser transitions in ALMA bands
  - $T_b \gtrsim$ few 10^4 K (representative ν, good & bad transmission)
    - Detectable at 10-20 mas resolution in 30-60 min
      - Resolve all maser emission, model physical conditions

1st octile	0.1 km/s	current specs		Resolution/2		Resolution/3	
Freq (GHz)	Time (h)	beam (mas)	5σ (K)	beam (mas)	5σ (K)	beam (mas)	5σ (K)
86	0.5	66.0	1,172	33.0	4,686	**22.0**	**10,544**
137	0.5	41.4	1,024	**20.7**	**4,095**	**13.8**	**9,213**
183	1.0	31.0	6,201	**15.5**	**24,803**	10.3	55,807
230	0.5	**24.7**	**911**	**12.3**	**3,643**	**8.2**	**8,197**
325	1.0	**17.5**	**7,079**	**8.7**	**28,315**	5.8	63,709
354	0.5	**16.0**	**1,288**	**8.0**	**5,153**	5.3	11,595
447	0.5	**12.7**	**9,018**	6.3	36,073	4.2	81,165
658	0.5	**8.6**	**13,226**	4.3	52,903	2.9	119,033
899	0.5	**6.3**	**24,724**	3.2	98,894	2.1	222,512
906	1.0	**6.3**	**29,804**	3.1	119,216	2.1	268,236

ALMA 16 km baselines and more

- c. 50 predicted H_2O maser transitions in ALMA bands
  - $T_b \gtrsim$ few 10^4 K (representative ν, good & bad transmission)
    - Detectable at 10-20 mas resolution in 30-60 min
      - Resolve all maser emission, model physical conditions
  - GMVA/EHT-type baselines for proper motions of peaks

1st octile	0.1 km/s	current specs		Resolution/2		Resolution/3		Resln/20 (3200 km)	
Freq (GHz)	Time (h)	beam (mas)	5σ (K)	beam (mas)	5σ (K)	beam (mas)	5σ (K)	beam (mas)	5σ (K)
86	0.5	66.0	1,172	33.0	4,686	**22.0**	**10,544**	**0.33**	**1.9E+8**
137	0.5	41.4	1,024	**20.7**	**4,095**	**13.8**	**9,213**	**0.21**	**1.6E+8**
183	1.0	31.0	6,201	**15.5**	**24,803**	10.3	55,807	**0.15**	**9.9E+8**
230	0.5	**24.7**	**911**	**12.3**	**3,643**	**8.2**	**8,197**	**0.12**	**1.5E+8**
325	1.0	**17.5**	**7,079**	**8.7**	**28,315**	5.8	63,709	**0.09**	**1.1E+9**
354	0.5	**16.0**	**1,288**	**8.0**	**5,153**	5.3	11,595	**0.08**	**2.1E+8**
447	0.5	**12.7**	**9,018**	6.3	36,073	4.2	81,165	**0.06**	**1.4E+9**
658	0.5	**8.6**	**13,226**	4.3	52,903	2.9	119,033	**0.04**	**2.1E+9**
899	0.5	**6.3**	**24,724**	3.2	98,894	2.1	222,512	**0.03**	**4.0E+9**
906	1.0	**6.3**	**29,804**	3.1	119,216	2.1	268,236	**0.03**	**4.8E+9**

Continuum

- Stellar/dust continuum extremely valuable, including:
  - Register masers
  - Self-calibration across the band in 20 sec solint
    - Sufficient S/N simultaneous with masers at same resoln

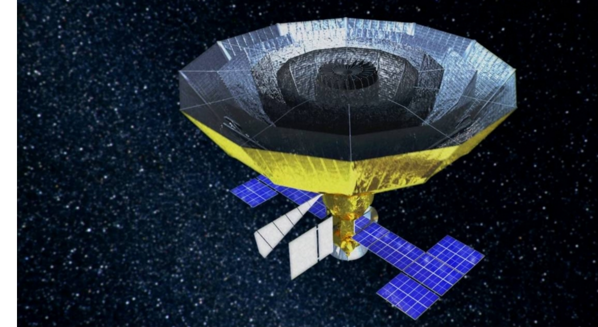
1st octile	3.5 GHz	current specs		Resolution/2		Resolution/3		Est Teff	S/N
Freq (GHz)	Time (h)	beam (mas)	5σ (K)	beam (mas)	5σ (K)	beam (mas)	5σ (K)	(K)	Continuum
86	0.5	66.0	3.4	33.0	13	**22.0**	**30**	*2,000*	331
137	0.5	41.4	3.7	**20.7**	**15**	**13.8**	**33**	*2,247*	337
183	1.0	31.0	25.9	**15.5**	**104**	10.3	233	*2,416*	117
230	0.5	**24.7**	**4.3**	**12.3**	**17**	**8.2**	**38**	*2,558*	333
325	1.0	**17.5**	**39.4**	**8.7**	**158**	5.8	355	*2,789*	88
354	0.5	**16.0**	**7.5**	**8.0**	**30**	5.3	67	*2,849*	476
447	0.5	**12.7**	**58.9**	6.3	235	4.2	530	*3,020*	257
658	0.5	**8.6**	**104.7**	4.3	419	2.9	943	*3,326*	159
899	0.5	**6.3**	**228.8**	3.2	915	2.1	2,060	*3,596*	79
906	1.0	**6.3**	**276.9**	3.1	1,108	2.1	2,493	*3,603*	65

cm-wave continuum

λ (cm)	Array	Resolution (mas)	LAS (mas)	Tb sensitivity (3σ, K)
0.7	VLA	45	1200	120
1.3	e-MERLIN (winter)	12-25	160	1000-2000
1.3	e-MERLIN+VLA	~50	2400	few 100
5	e-MERLIN	40-70	600	250-500
18	e-MERLIN	180	2200	300-600
18	e-MERLIN+EVN	50-70	2200	100s-1000+

- Sensitivity depends on elevation, e-MERLIN with or without Lovell, weighting of combined arrays...
  - e-MERLIN/VLBI ~12 hr on-source; VLA ~1 hr or less
- Maybe masers: SiO 0.7 cm, H_2O 1.3 cm, OH 18 cm
  - Often bright enough to self-cal especially SiO, H_2O

Dream on....



Sooner **Later**

- ALMA sub-mm λ on 16-km baselines
  - Self-calibrate on bright stars/masers; thermal absorption
    - Spectral line mm VLBI - masers
  - ALMA + 20-50+ km baselines high res. for mm λ
- SKA Phase 1: λ≥5 cm, low resolution, v. sensitive
  - SKA Phase 2 (+ Global/African VLBI Network) high-res
- EVN/VLBA/VLBI phase referencing (align maser epochs/star)
- e-MERLIN 2 GHz b/w : double sensivity
  - Correlate with Goonhilly, EVN, AVN ... superb resolution
  - 2-4 and 15 cm receivers: high resolution
- ngVLA / (SKA high?): ideal few mm - cm