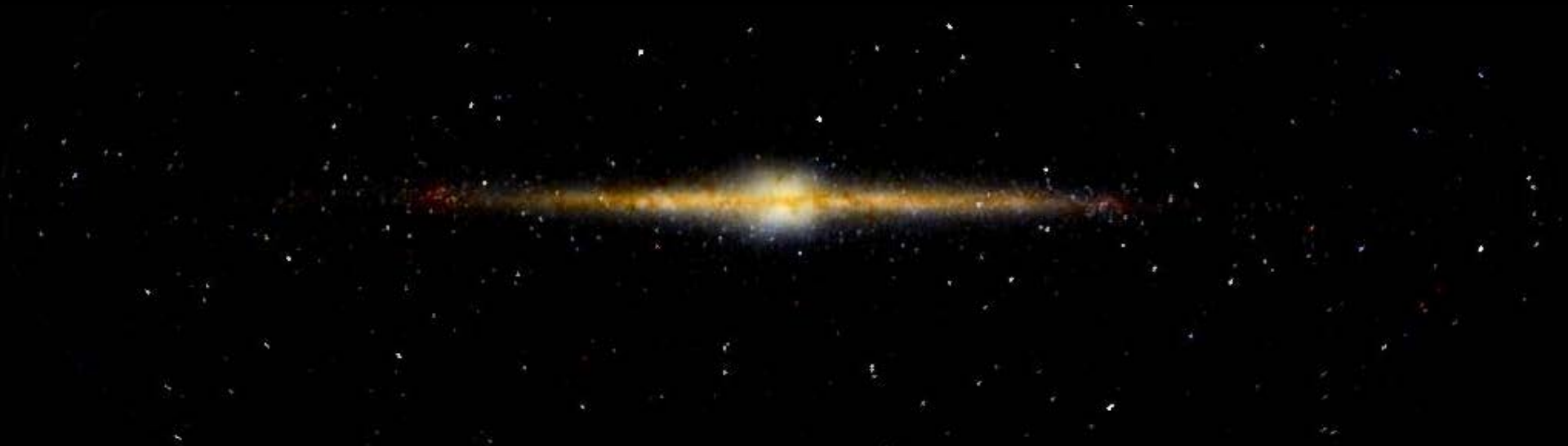


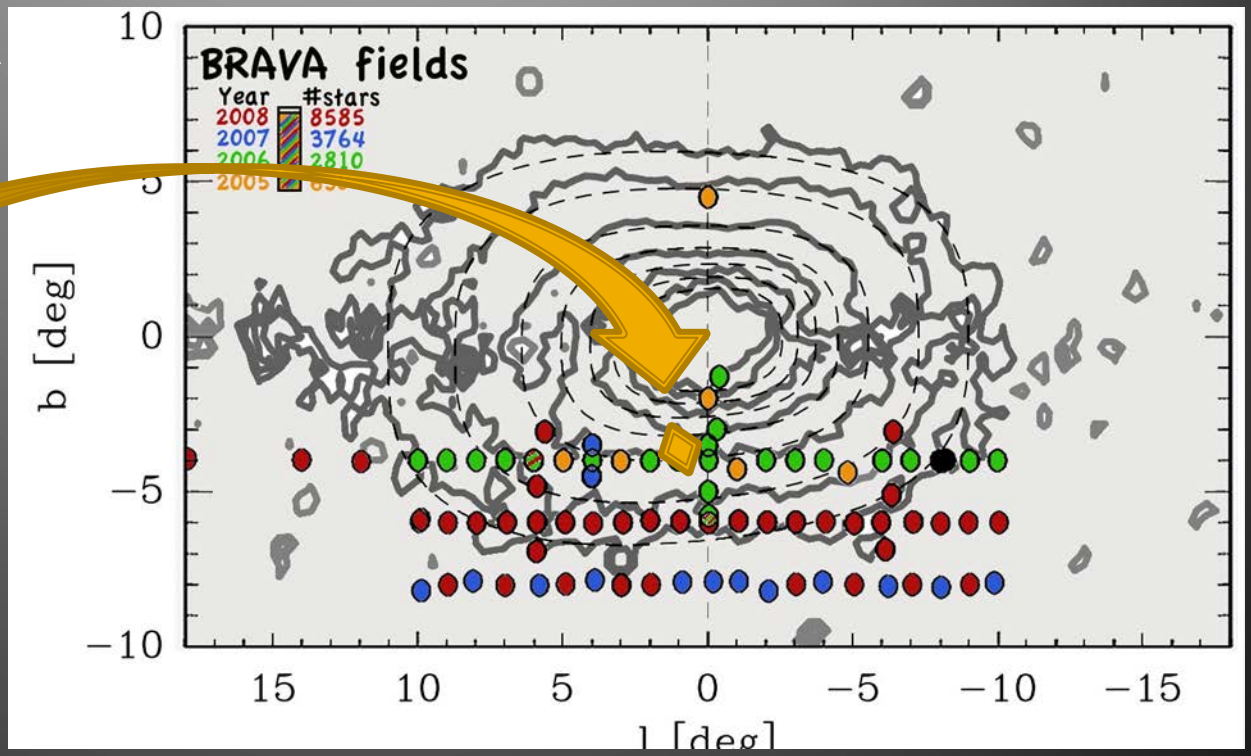
Loránt Sjouwerman, NRAO
The BAaDE collaboration

Thousands of Stellar SiO Masers in the Galaxy: The Bulge Asymmetries and Dynamic Evolution (BAaDE) survey

National Radio Astronomy Observatory
Enabling forefront research into the Universe at radio wavelengths

Optical surveys of the Bulge

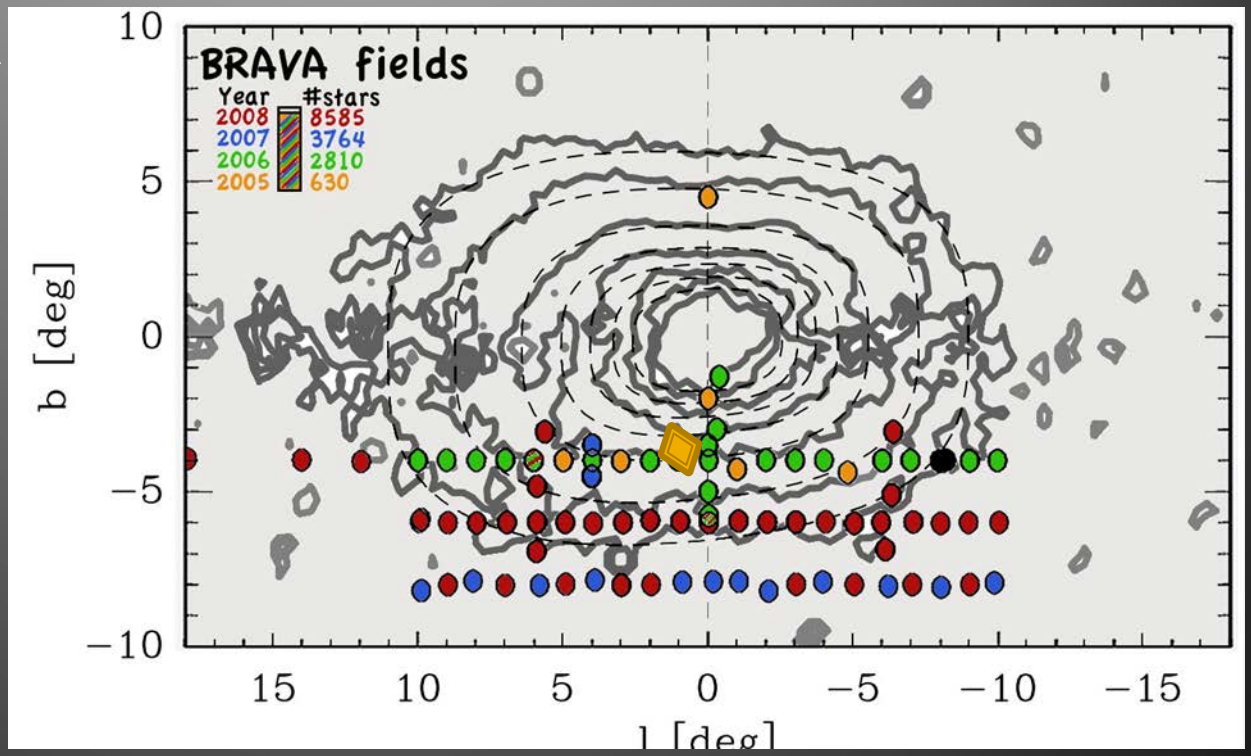
- e.g. BRAVA
- (OGLE)
- (APOGEE)
- (ARGOS)
- Baade's Window



- Cannot penetrate in Plane/Bulge region

Optical surveys of the Bulge

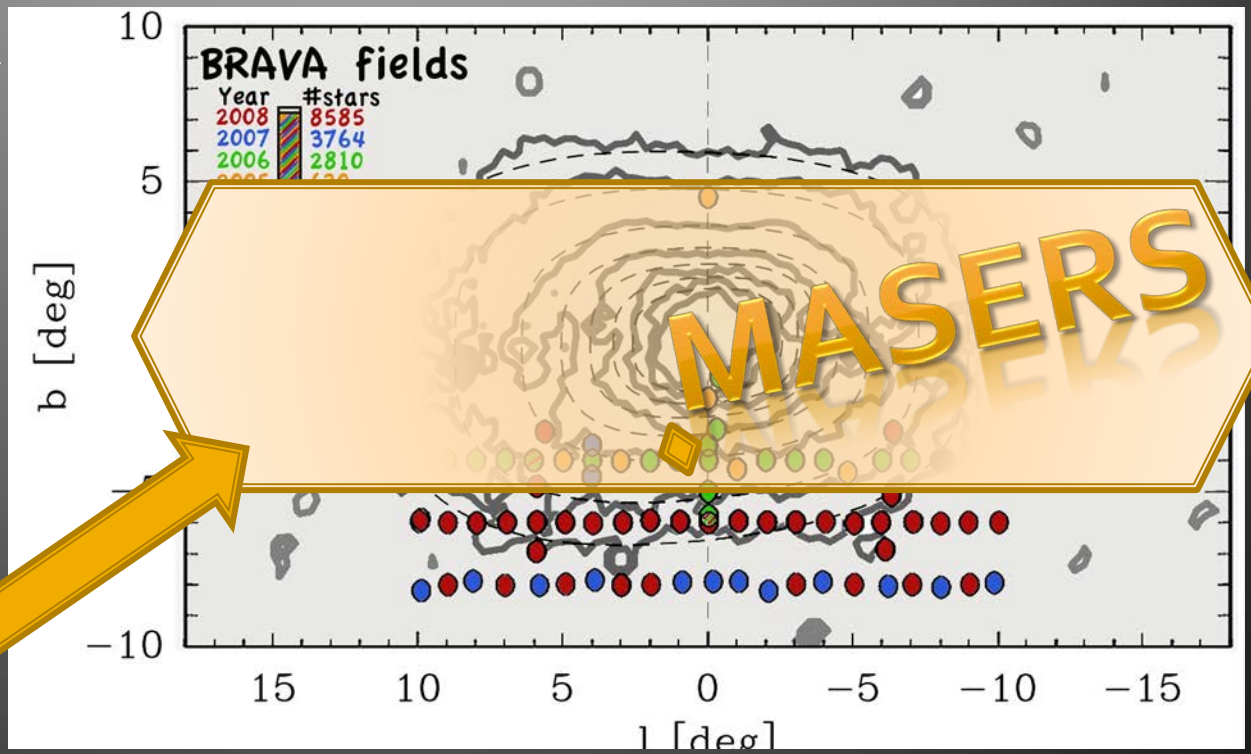
- e.g. BRAVA



- Baade's Window
- BAaDE's Window
- Can't penetrate in Plane/Bulge region

Optical surveys of the Bulge

- e.g. BRAVA



- Baade's Window
- BAaDE's Window
- Can't penetrate in Plane/Bulge region

BAaDE

The BAaDE project:

Aim:

- *Significantly* improve models of the dynamics and structure of the inner Galaxy
- By probing into regions not reachable with optical surveys in the Galactic Bulge/Plane
- Using stellar masers as ***radio*** detected point-masses
- Complimentary to e.g.GAIA and BeSSeL

The BAaDE project:

- Survey of evolved stars for maser emission:
  - Past: about 4,000 AGB stars with OH masers (1612 MHz)
  - BAaDE: survey up to ~34,000 AGB/RGB stars for SiO masers using both VLA and ALMA (~20,000 at 43 & 86 GHz)
- Galaxy modeling using line-of-sight velocities
- VLBI astrometry for characterizing orbit in a small subsample of the sources

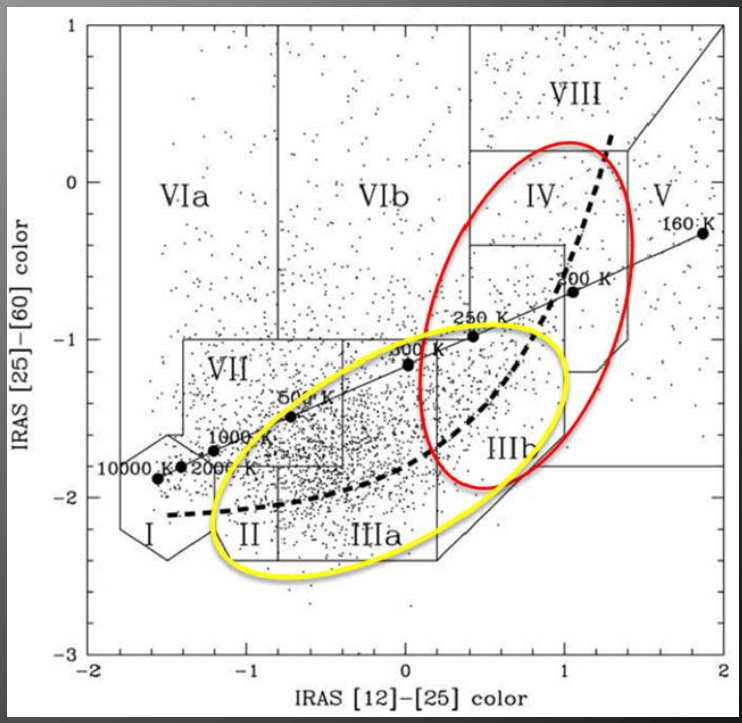
BAaDE spin-offs and by-products

- IR characteristics for about 34,000 evolved stars
- IR/SiO correlation for about 20,000 stars
- SiO line ratios and possibly luminosity functions
- Line images for stars, continuum maps of the area
- SiO maser detection rate as function of longitude
- All above also for Carbon stars
- Complement optical data (statistics/GAIA, P.43)
- New 43/86 GHz calibrators in the bulge/plane
  - Both for connected element (VLA/ALMA) and VLBI

Infrared source selection

Detecting SiO masers in stars

- SiO masers are found
  - Not so much in OH/IR stars
    - e.g. Nyman et al.; Lindqvist et al.
  - In lower mass-loss objects
  - Thinner circumstellar shells
  - IRAS color-color diagram:
    - In the not too red sources
  - Both AGB and RGB stars
    - But not in Carbon-rich stars

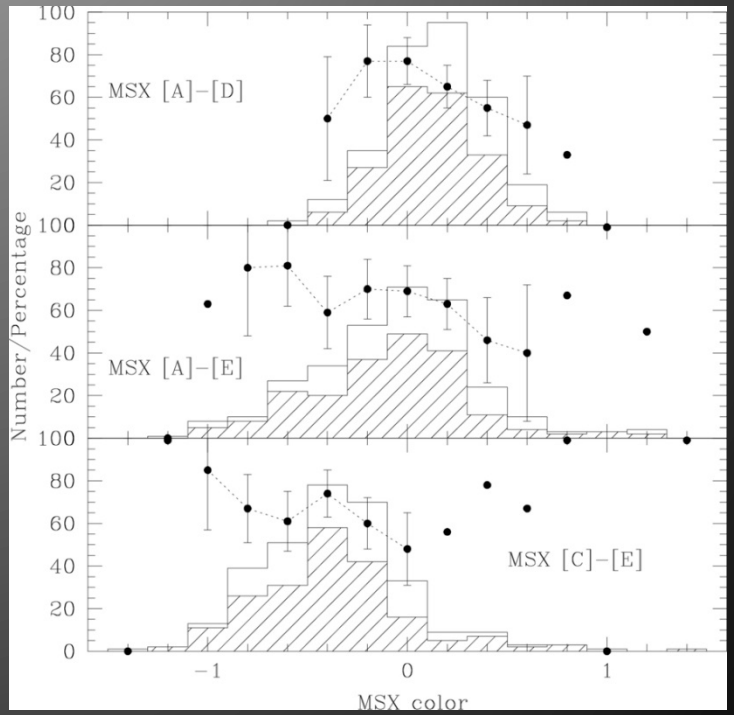


Van der Veen & Habing

- In Bulge: not by using the IRAS data..

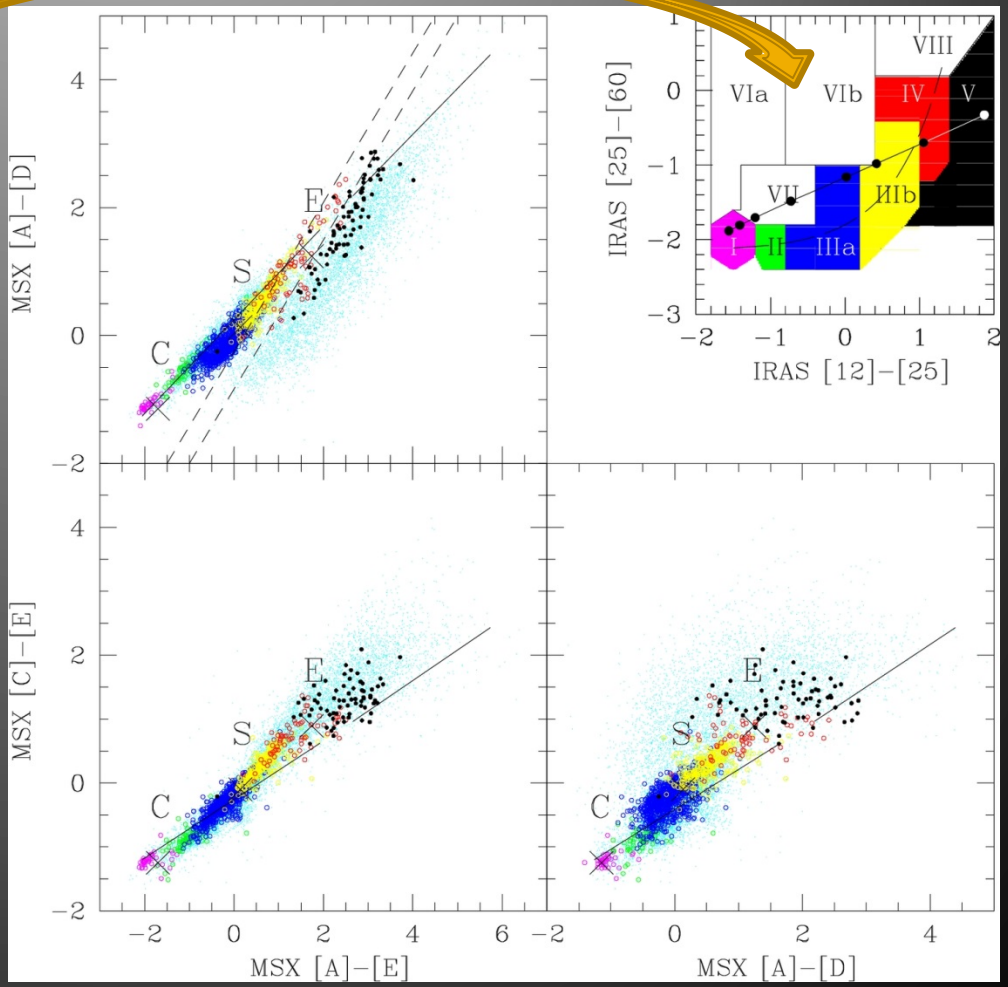
SiO masers in MSX sources

- Make equivalent IRAS color-color diagrams
  - MSX (1996)
  - 440,000 objects in the Plane!
  - 8, 12, 15 and 24 μm (no ~60 μm)
- MSX color selection
  - 50-90% SiO masers
    - Sjouwerman et al.
  - Convert IRAS to MSX regions



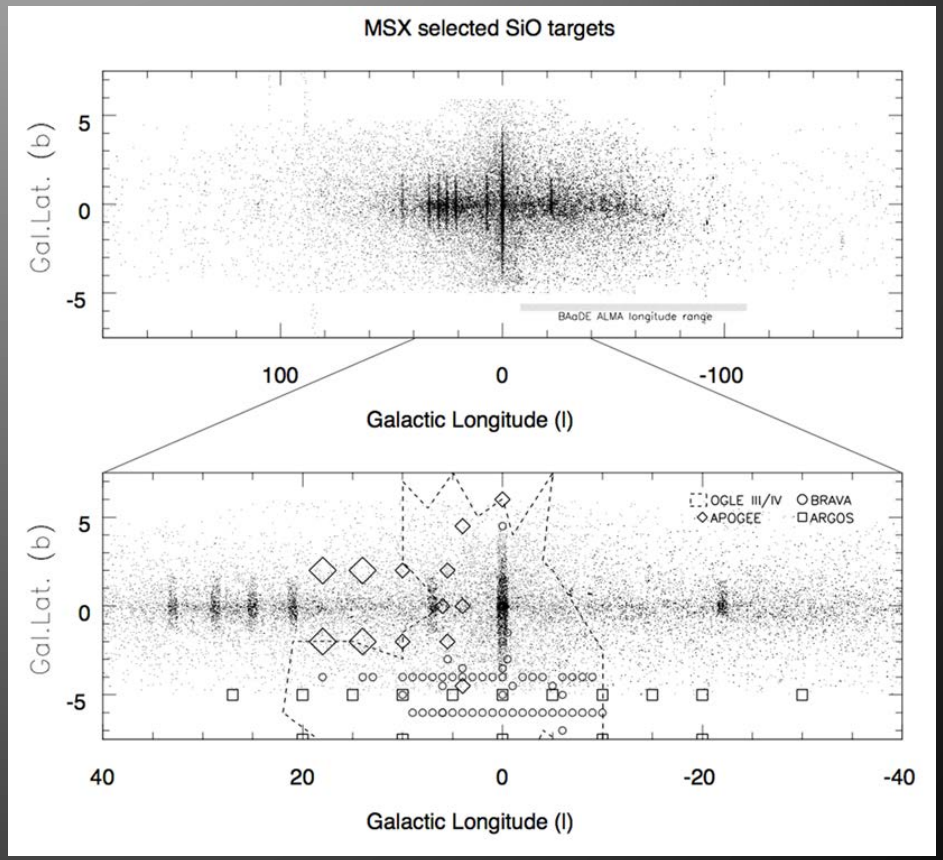
MSX color-color diagrams

- IRAS c-c legend
- CSE sequence
  Circumstellar envelope
  - i.e. shell thickness
- 3 distinct iiia/blue color selections to select sources with SiO masers
- No de-selection of Carbon-rich stars
  (have no SiO masers)



MSX target selection

- In the plane, $|b| < 5^{\circ}$, samples the Galactic plane where optical surveys do not reach and where dynamics are most revealing
  - Concentrated in Bulge
- ~34,000 targets
  - ~19,000 VLA: 43 GHz
  - ~14,000 ALMA: 86 GHz



Radio observation strategy

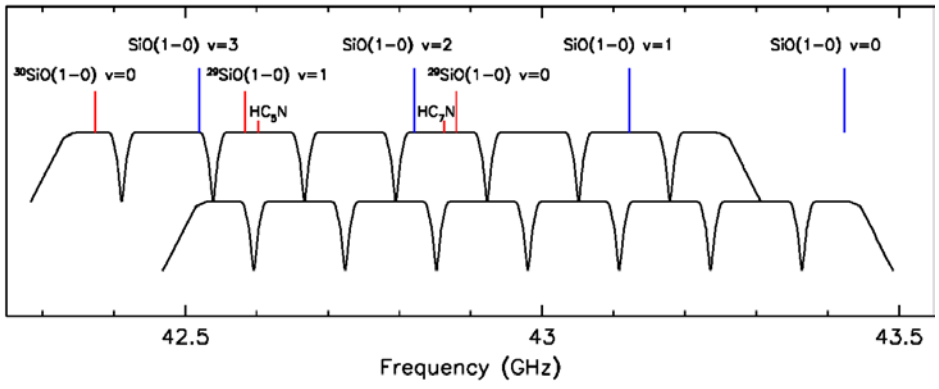
Observational strategy

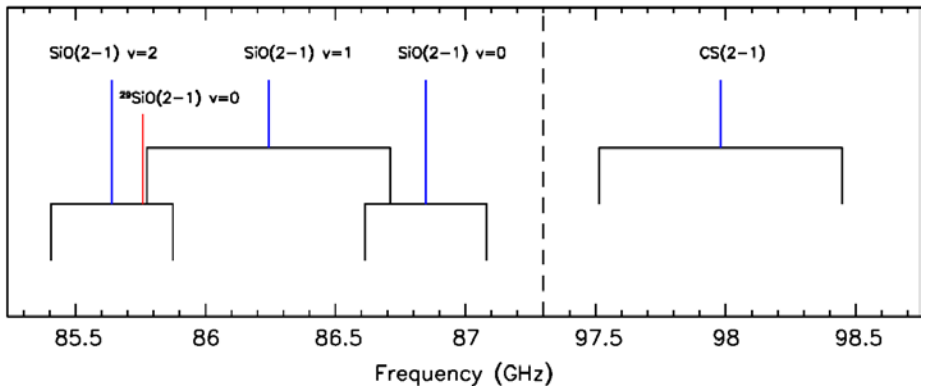
- Bright enough for follow-up VLBI
  - 15 mJy/bm/ch rms, 100 mJy/bm/ch maser peaks
  - Less than one minute per source! (ALMA or VLA, 1 km/s)
- Maximize detection rate
  - Cover multiple lines, including potential Carbon
  - Multiple transitions yield more accurate velocity
- Minimize overhead (mostly for VLA)
  - Fast-switching without fast-switching!

    (is almost the same as phase-referencing)

Observational setup

- Multiple maser lines, also lines for Carbon-rich stars



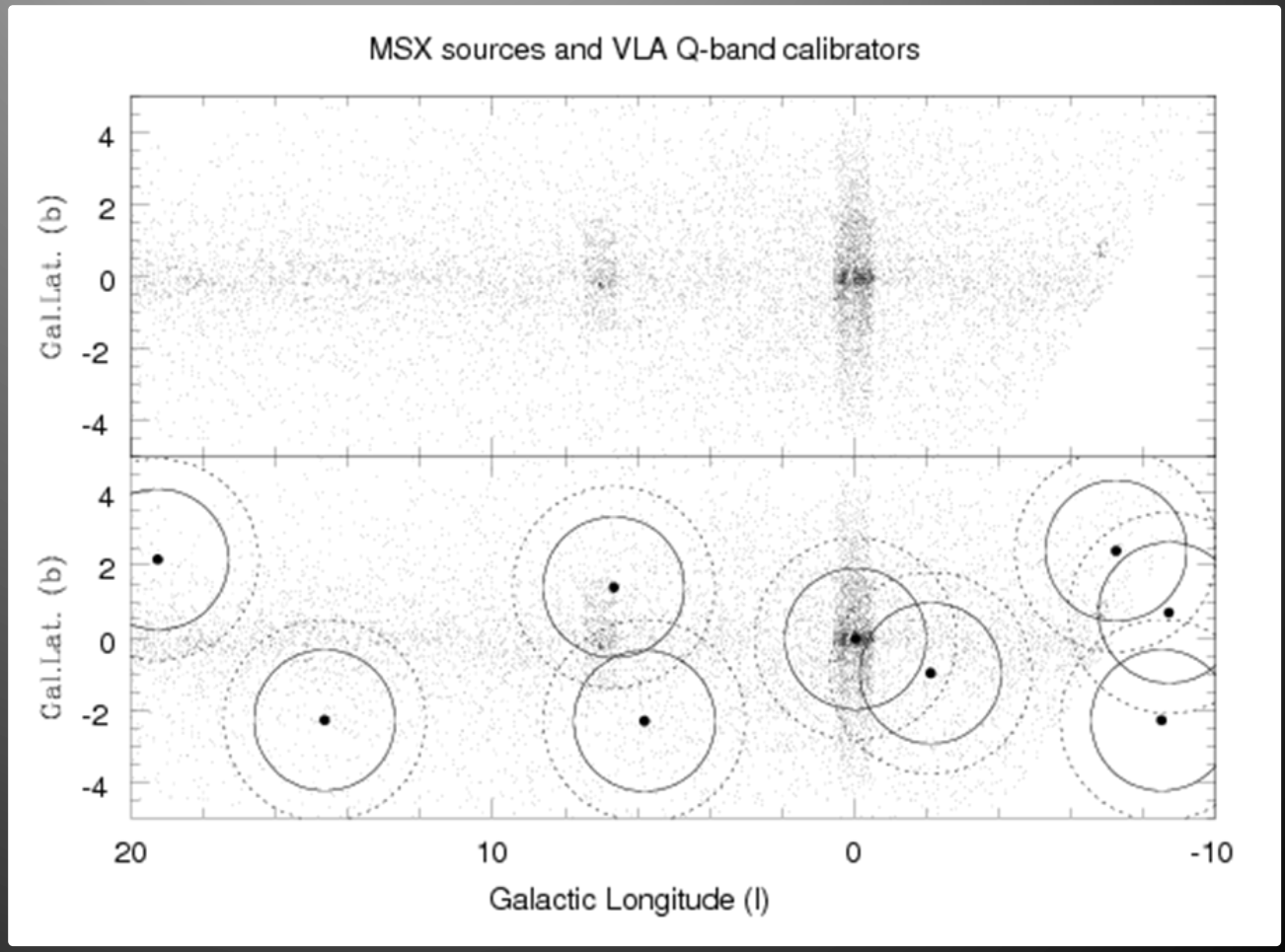


VLA - 43 GHz ALMA - 86 GHz

most sources display more than one line: very reliable velocities

Target and calibrator distribution

Inadequate number and distribution of VLA 43 GHz calibrators to calibrate all targets traditionally

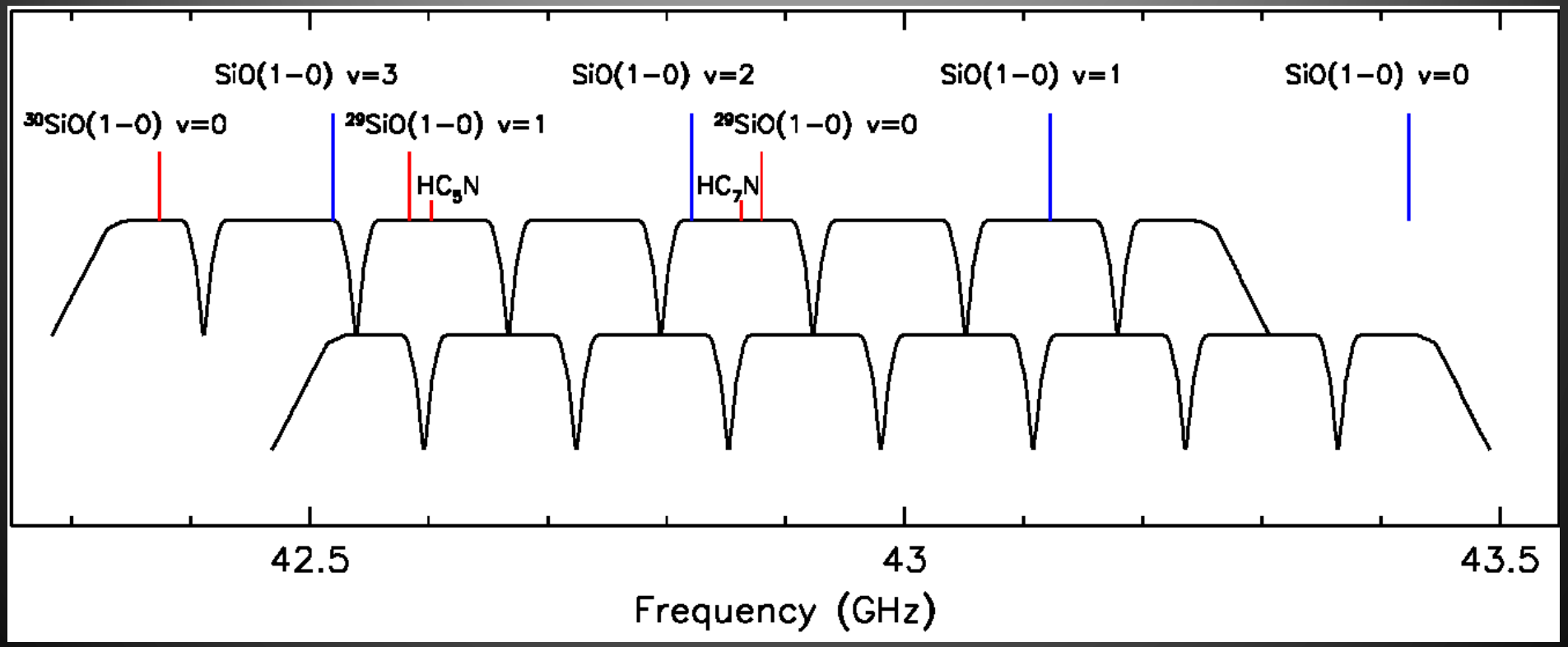


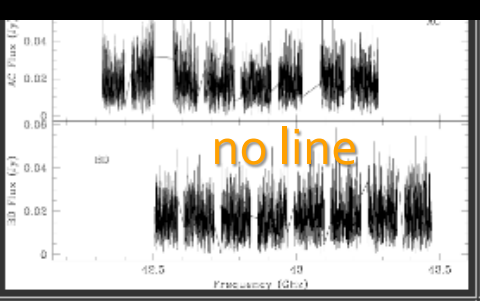
BAaDE calibration

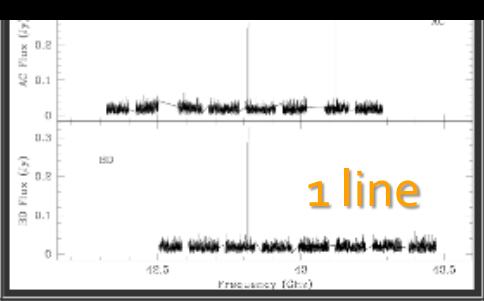
- Recall high SiO maser detection rate (>50%)
- Observe many clustered sources within coherence time
  - Slew few seconds, on source almost for full scan duration
  - High detection rate: every other few can be self-calibrated!
- Use bright masers to find/calibrate weaker ones
  - Repeat to build an increasingly complete SN table (4 or 5 times)
  - Use more than one line (if anticipated line is not detected)
- Instead of 350 target observing hours becoming well over 750 hours with fast-switching, we applied for 410 VLA hours
  - ALMA observations scheduled differently

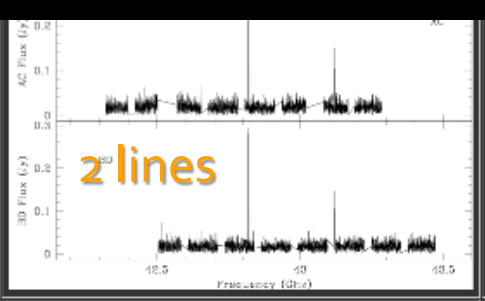
First data results

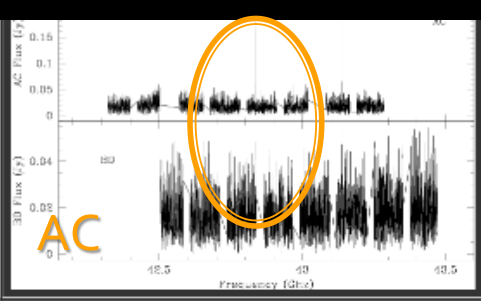
VLA setup (reminder)











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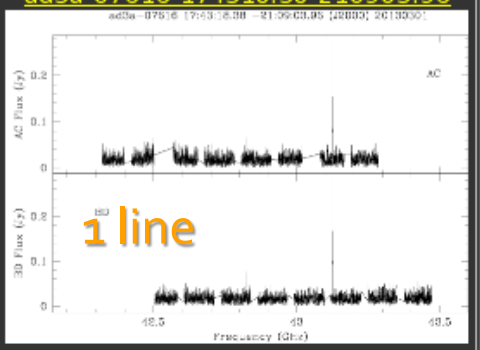

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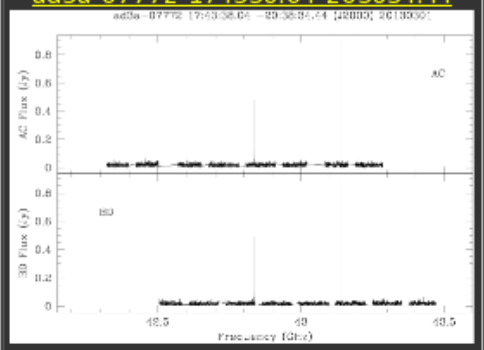

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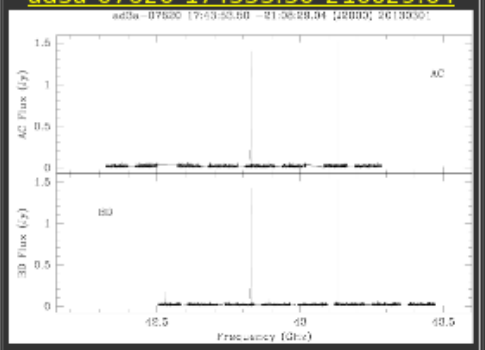

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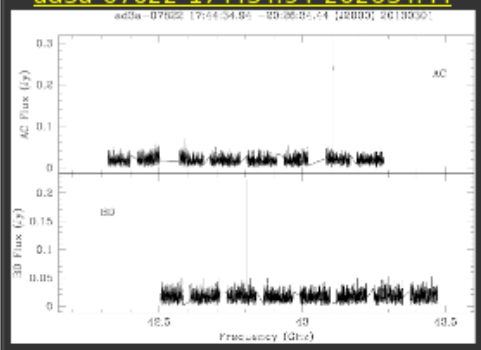

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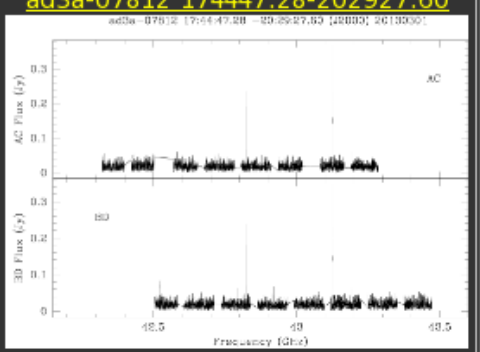

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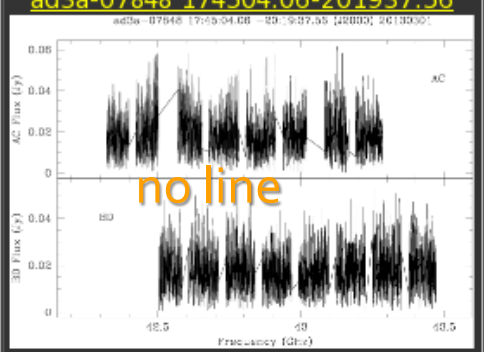

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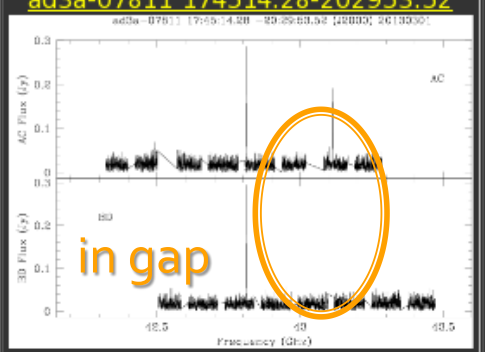

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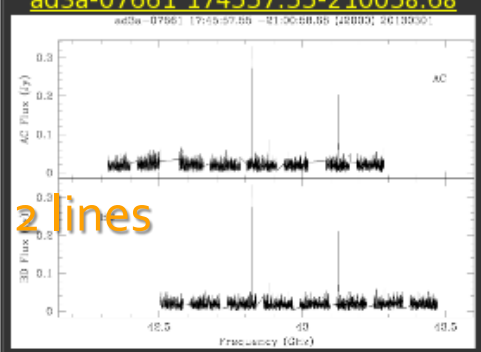

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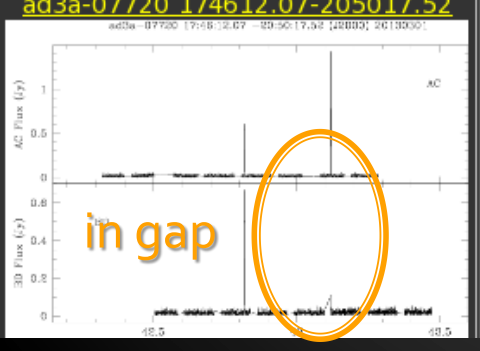

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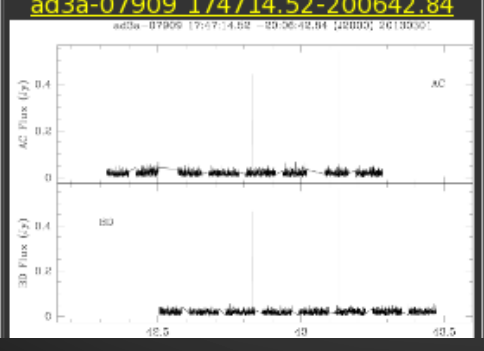

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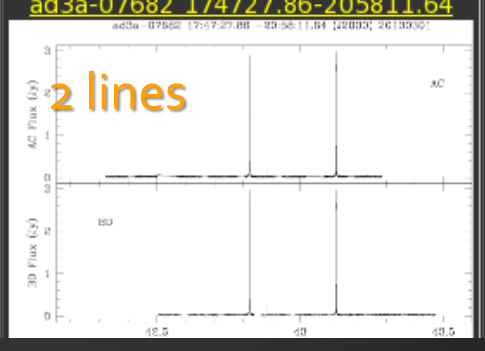

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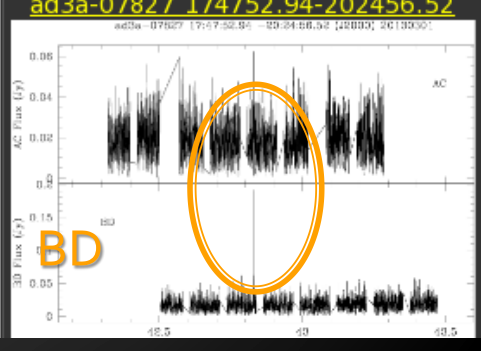
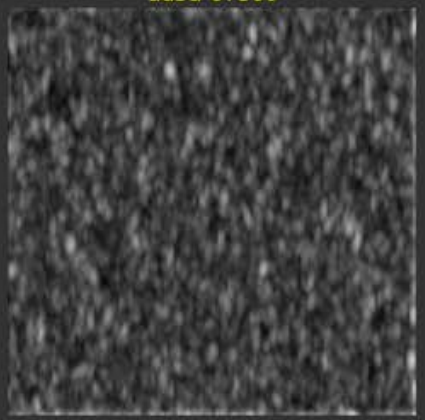
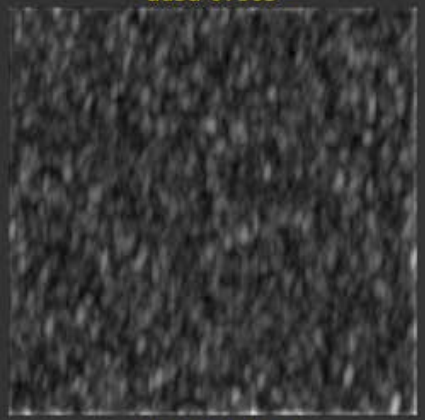
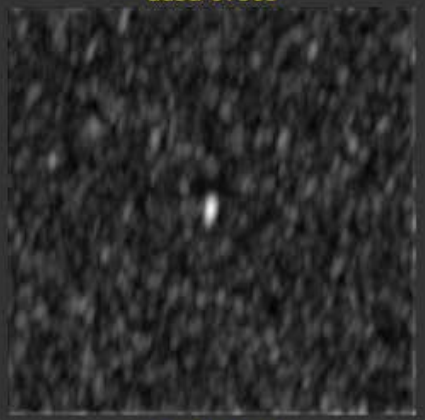
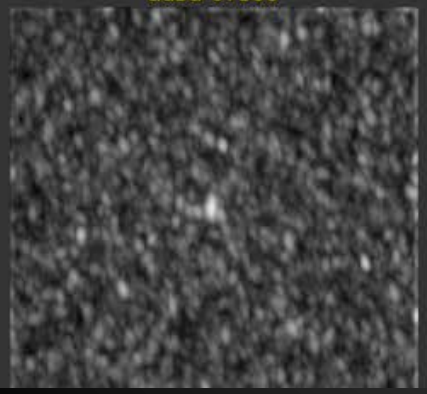
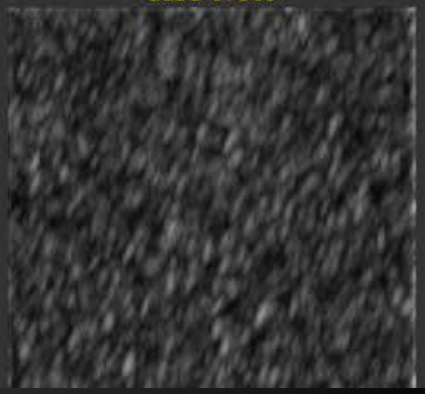
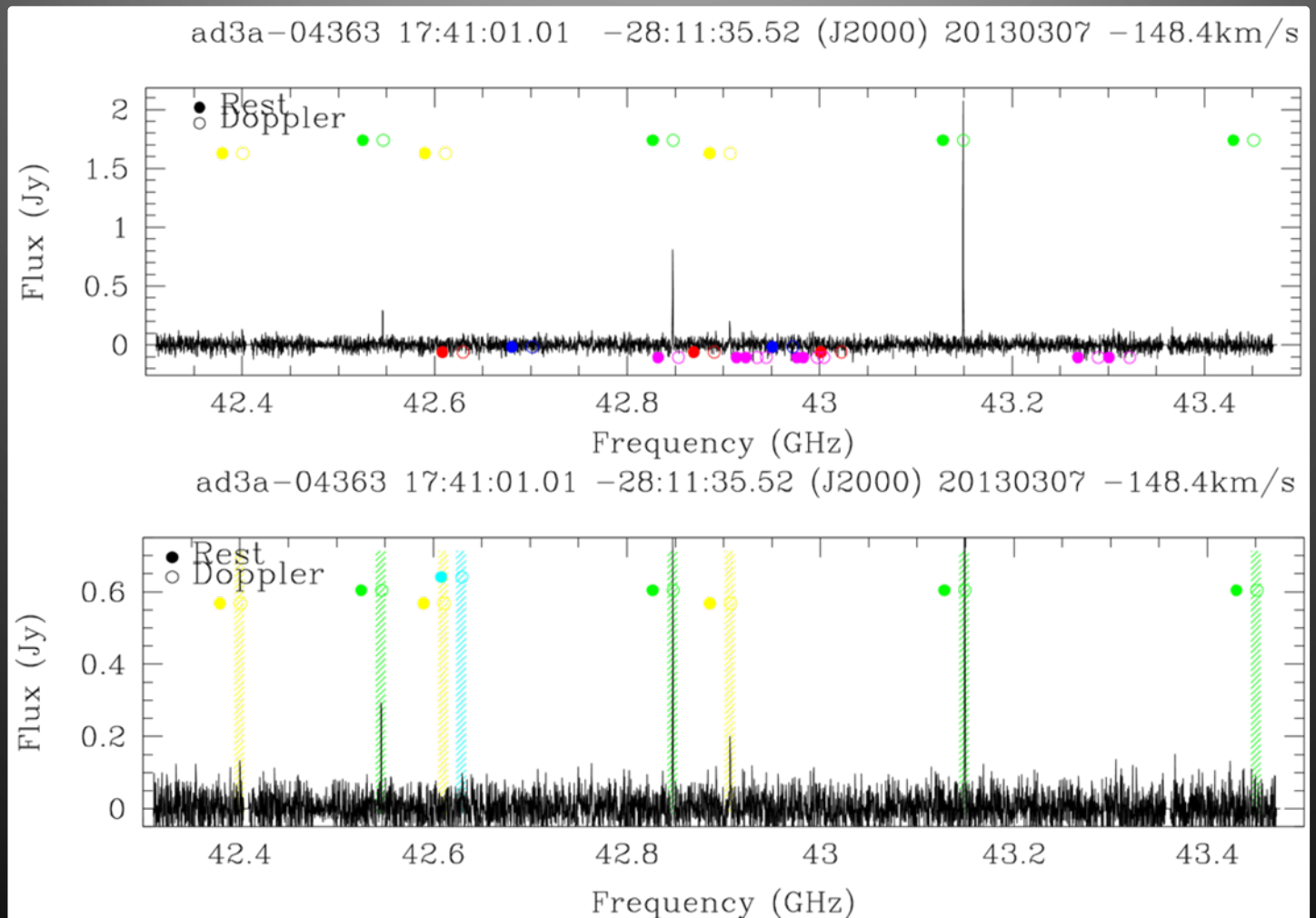


Latest update: 10 Feb 2014 [17:42 MST]

SiO J=1-0 v=1 (rest 43.12209 GHz)	SiO J=1-0 v=1 (rest 43.12209 GHz)	SiO J=1-0 v=1 (rest 43.12209 GHz)	SiO J=1-0 v=1 (rest 43.12209 GHz)
ad3a-07557 	ad3a-07558 	ad3a-07559 	ad3a-07560 
ad3a-07561 	ad3a-07562 	ad3a-07563 	ad3a-07565 
ad3a-07566 	ad3a-07567 	ad3a-07568 	ad3a-07569 

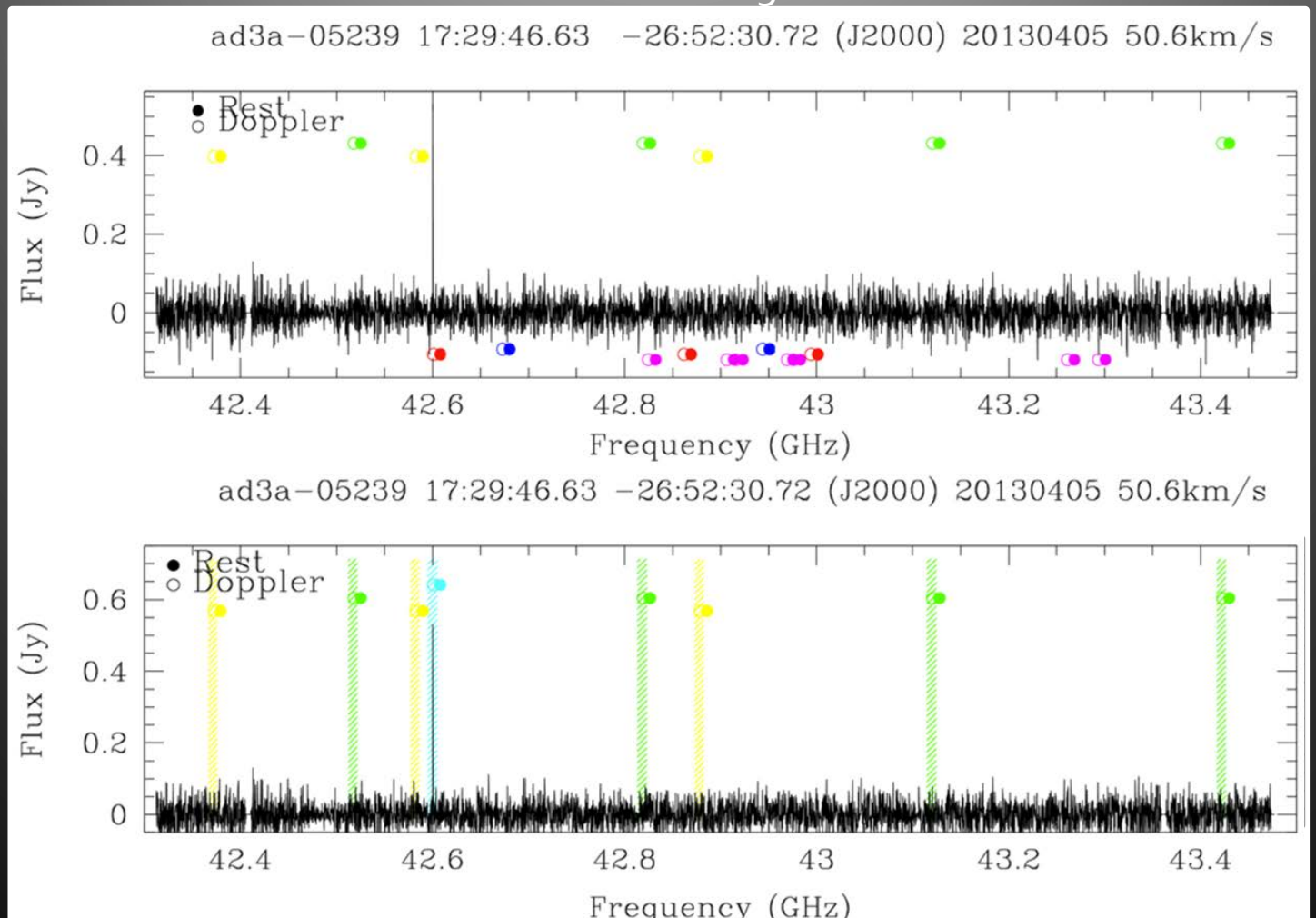
VLA data results

- Typical at 43 GHz: v=1 and/or v=2; rate about 70%



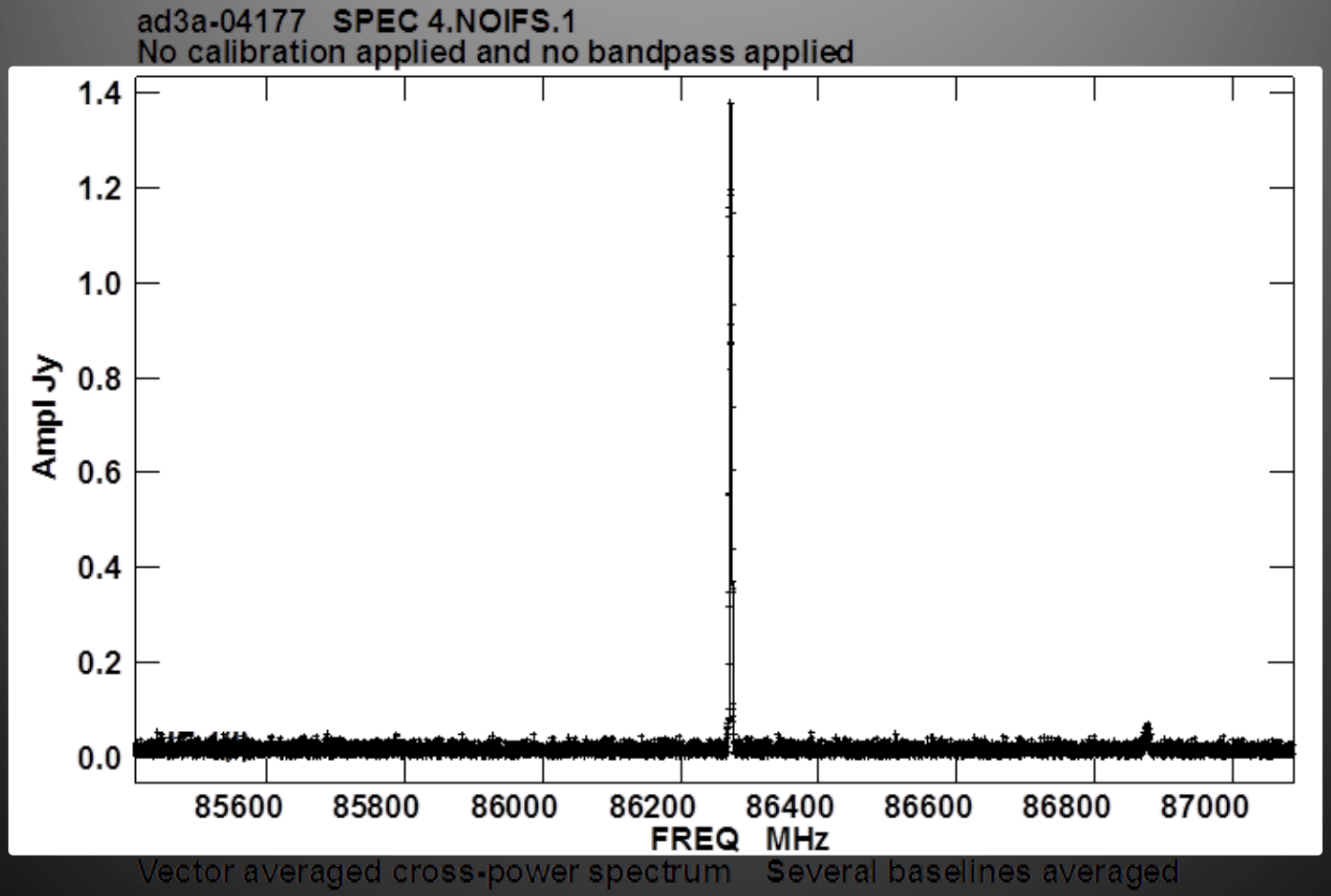
VLA data results

- Carbon-rich detection of HC_5N, near ^{29}SiO (v=1)



Typical ALMA pilot data results

- Typical at 86 GHz: v=1 (and v=0); rate about 70%



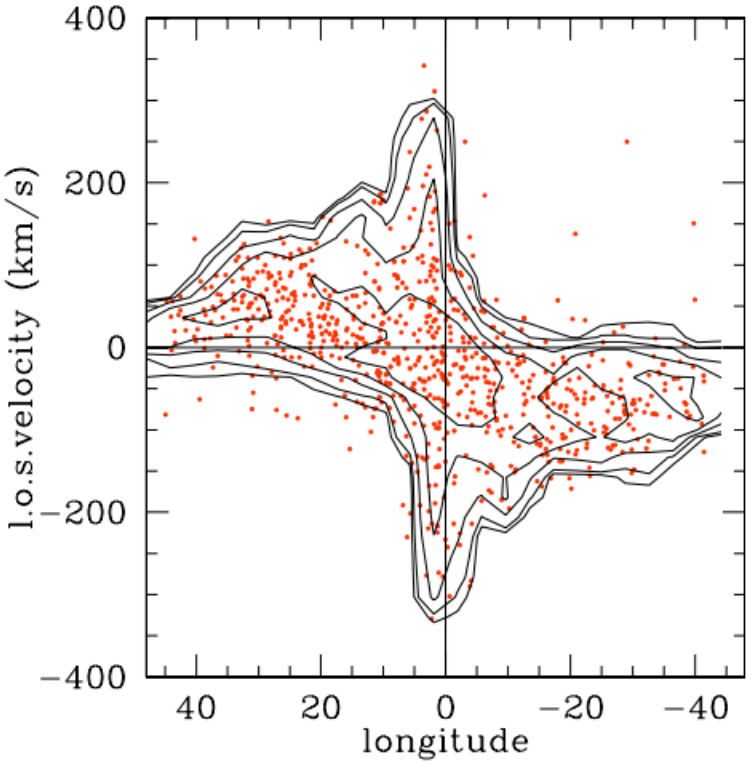
Current status of SiO maser survey

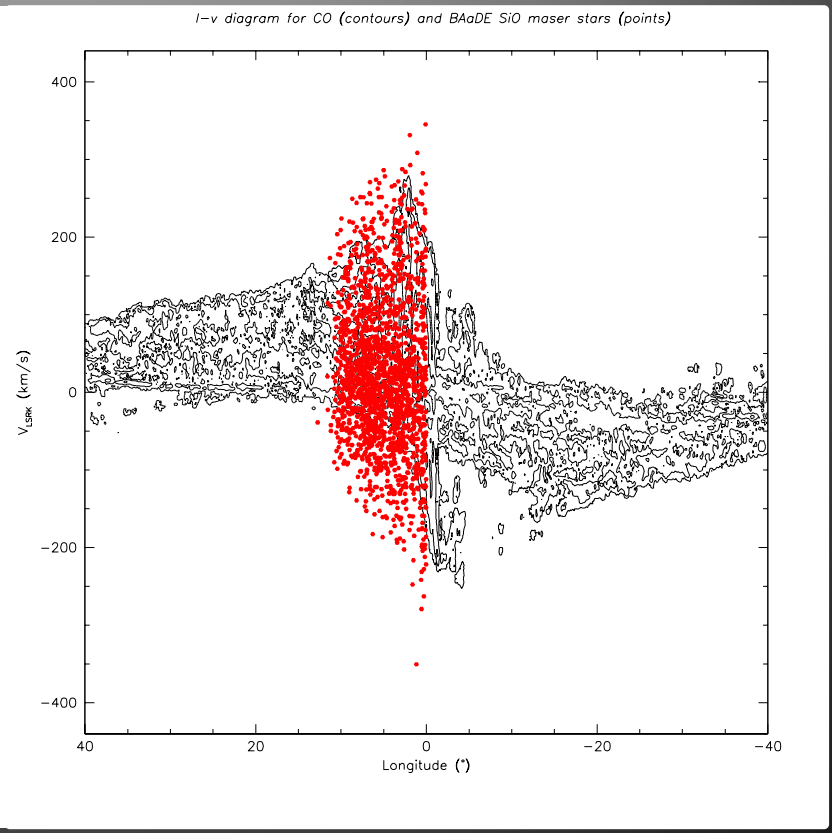
- ALMA
  - Pilots of 200+1200 stars observed and reduced
  - Cy 5 schedules for 2400 more stars created
- VLA
  - 3600 stars in Bulge analyzed
  - 3500 stars, all in outer Plane reduced
  - Remaining (13,000 in greater Bulge) all observed
- VLBI
  - Current pilots & calibrator searches with EVN/VERA/VLBA

Longitude-velocity diagram

OH maser density

SiO maser density





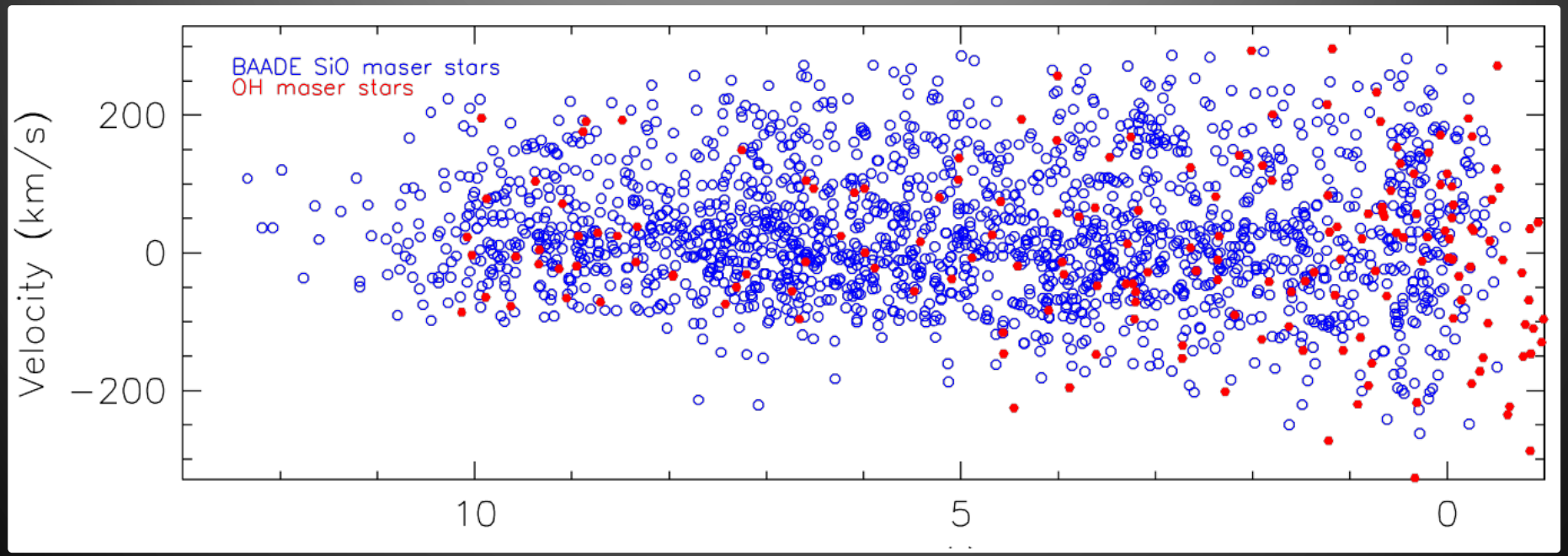
OH/IR star summary from Habing

CO contour map from Dame et al.

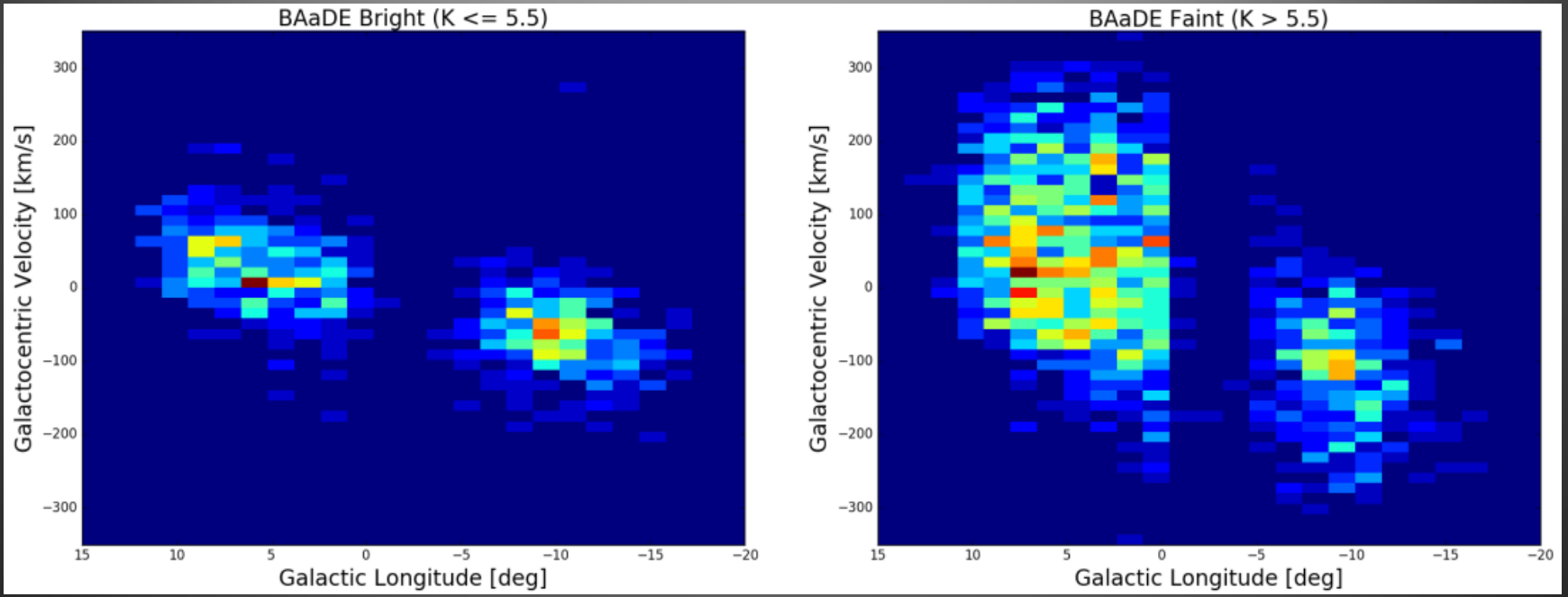
Longitude-velocity diagram

OH maser density

SiO maser density



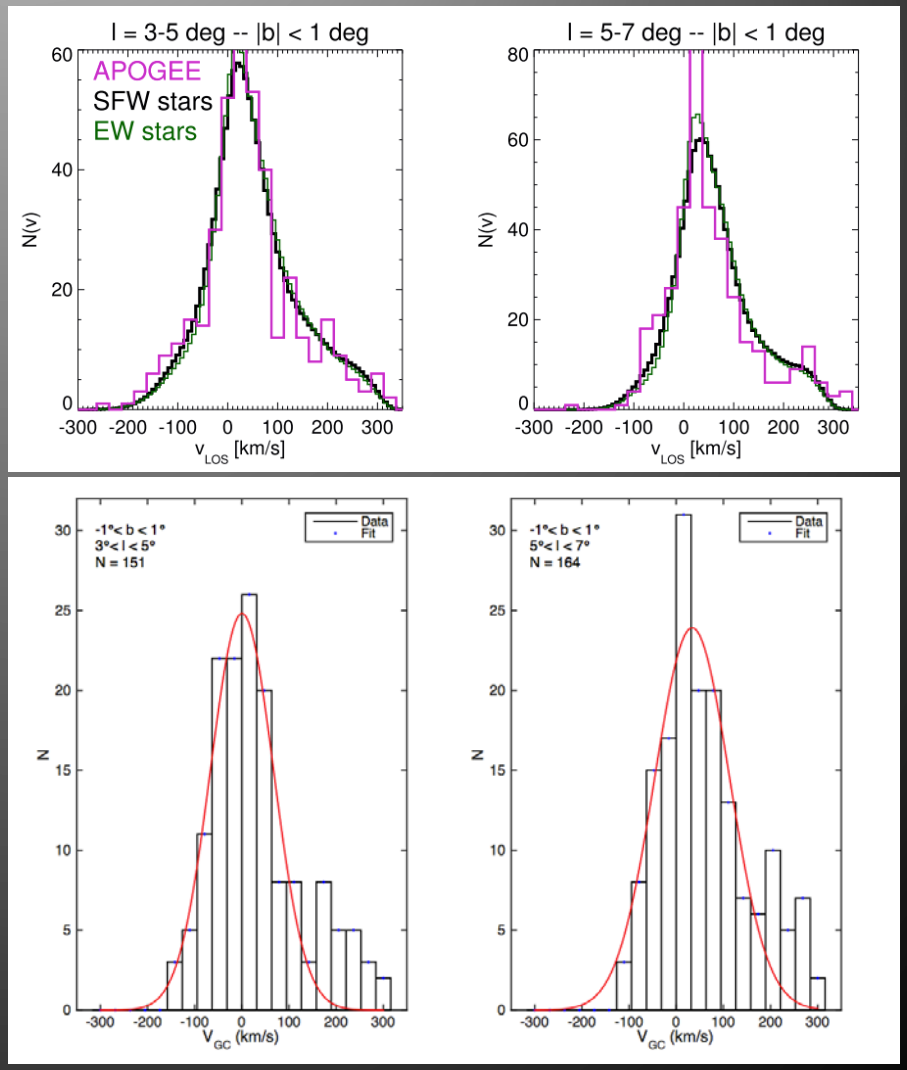
VLA 43 GHz versus ALMA 86 GHz



- Population studies, foreground stars (Adam Trapp)
- Transition and Malmquist bias (Michael Stroh, P.45)
  - Near side brighter 43, far with weaker 86?

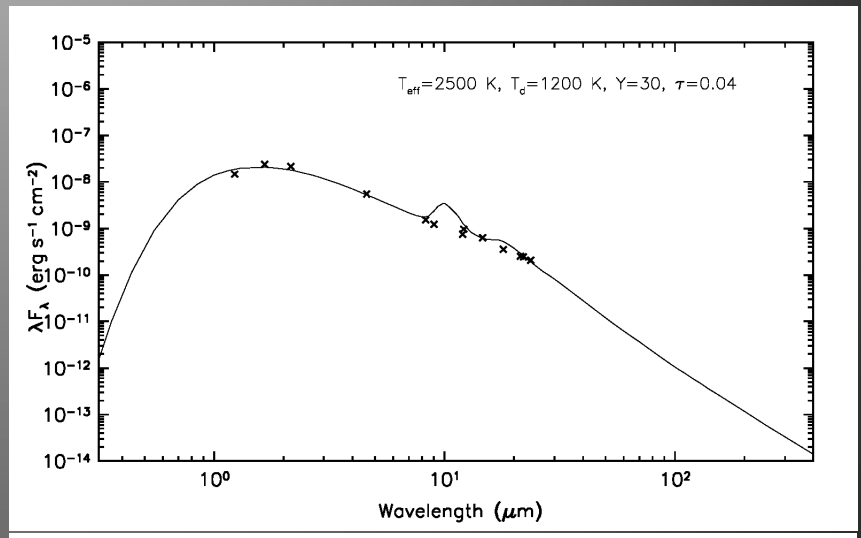
Example first modeling results

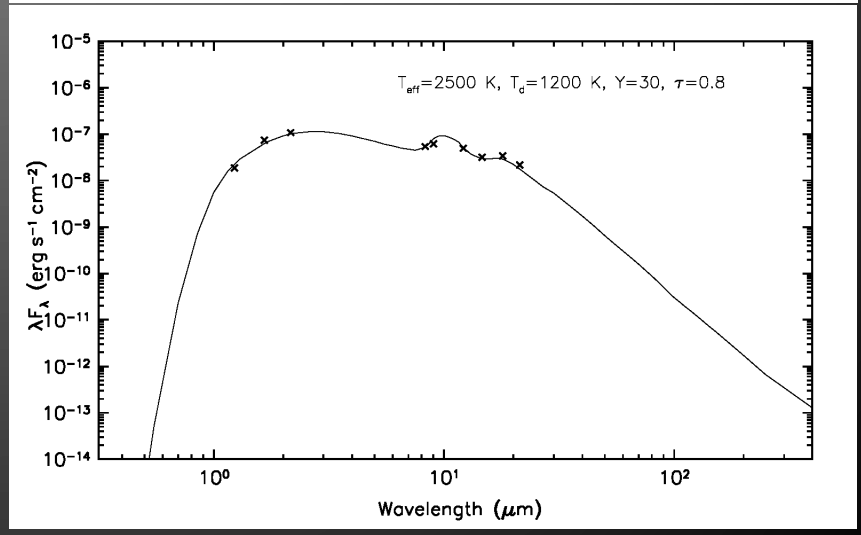
- Possible excess density feature at +200 km/s in APOGEE data
  - Aumer & Schönrich
- Dynamically cool population captured by the Bar?
- Small numbers in SiO maser suggestive in support of excess
- Much more to be done
  - Note: -200 km/s counterpart possibly seen in ALMA data



Circumstellar envelopes

- Every target IR selected
- MSX color "slope" range in SED
  - Different envelopes/shells
- Additional data from 2MASS, WISE, IRAS, etc
- Modeling and binning:
  - Stellar properties,reddening
  - Detected/non-detected, C!
  - Statistical distance estimate using template SEDs





Epilogue

We are collecting:

- IR catalog data/SEDs for 34,000 stars
  - May be used for crude distance determination
- SiO maser l-o-s velocities for ~20,000 stars
  - Some velocities from Carbon-rich stars instead
- Spectral line information at 43 or 86 GHz
  - Some interesting sources, e.g., isotope lines
- Follow-up some individual stars

  - infrared spectroscopy: metallicity

  - astrometry: accurate distance and proper motion
- VLBI "work in progress" ..

Summary

- BAaDE project:
  - Large SiO maser survey in IR color selected evolved stars with VLA (43 GHz) & ALMA (86 GHz)
  - Thousands of line-of-sight velocities in the Bulge
    - ALMA and VLA efficient instruments
  - VLBI follow-up for parallaxes and 3-D orbits

  Dynamics and Evolution of the Galactic Bulge
- "only just begun" …
  - SiO/IR catalog, line ratio's, new calibrators

The BAaDE collaboration

- Co-PI's:
  - Loránt Sjouwerman (NRAO) & Ylva Pihlström (UNM)
- Co-I's:
  - Mark Claussen (NRAO)
  - Mike Rich & Mark Morris (UCLA)
- Students:
  - Isaiah Santistevan, Cameron Trapp, Patrick Latimer & Chris Gallagher (UNM undergrads)
  - Michael Stroh (P.45), Megan Lewis & Eddie Hilburn (UNM)
  - Adam Trapp (UCLA)
  - Luis Henry Quiroga Nuñez (P.43) (JIVE/Leiden)
- Van Langevelde (JIVE), Habing (Leiden), Shen (UCLA), ..

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