Stellar Masers as Probes of the Galaxy

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Masers as probes of the Galaxy

Single epoch: Positions and velocity

Multiple epochs: Proper motion and parallax distances

Probes of structure and dynamics

- Using CH_3OH and H_2O masers in star forming regions
  - Example: BeSSel
- Using SiO and OH masers in evolved stars
  - OH and SiO: Deguchi et al; Habing et al; Sevenster et al.; Messineo et al., Sjouwerman et al.; Fujii et al.
  - SiO: BAaDE

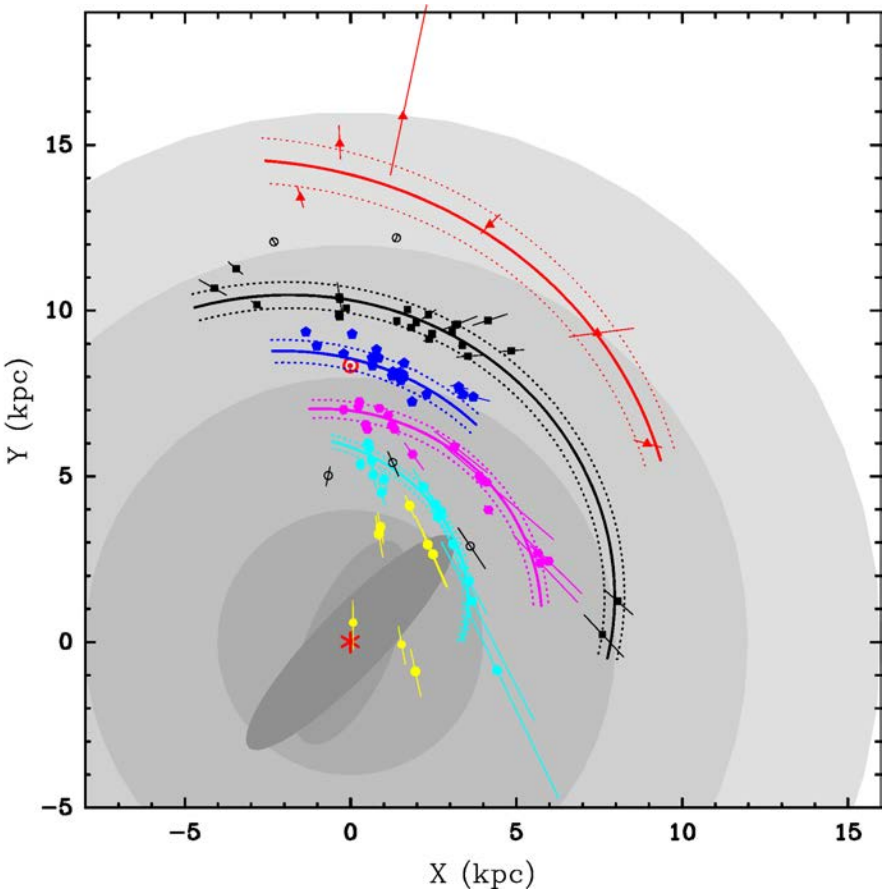
Probes of the stellar environment (in the Galaxy)

- Circumstellar envelopes for SiO and OH
- Metallicity effects as a function of position in Galaxy

Bar and Spiral Structure Legacy Survey

BeSSeL, using CH_3OH and H_2O

- Structure of the Galaxy, by determining positions of spiral arms
- Parameters like rotation speed and distance to GC derived



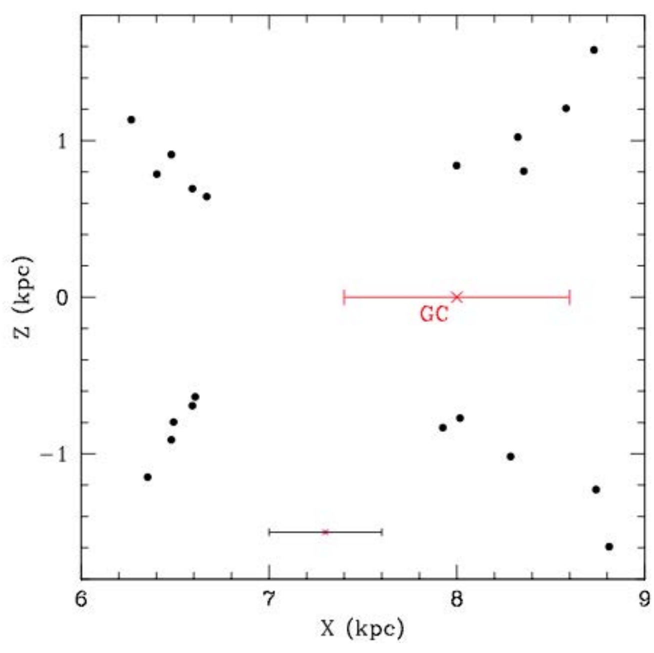
Reid et al. 2014

Galactic dynamics: bar/bulge

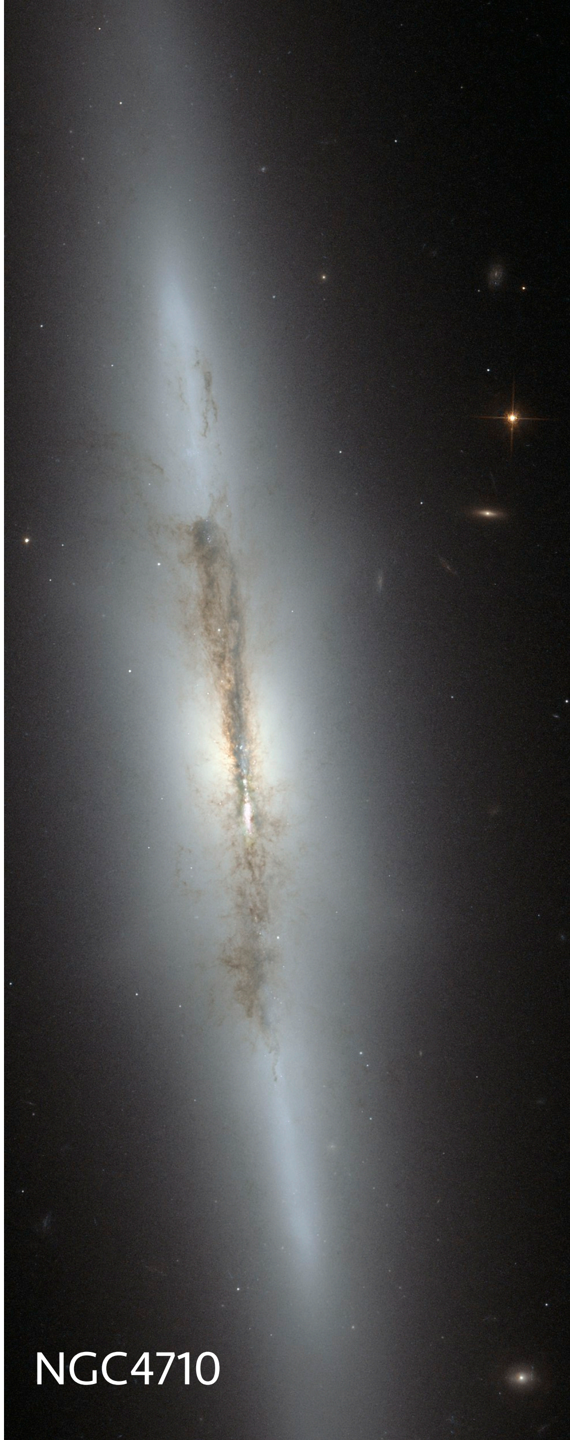
Details about structure, age, chemical composition, kinematics

- Evolution: Classical Bulge or “buckling”?
- Cylindrical rotation (triaxial or boxy shapes, Howard et al. 2008; Rich et al. 2007)

Want information of stellar orbits!



McWilliam & Zoccali 2010



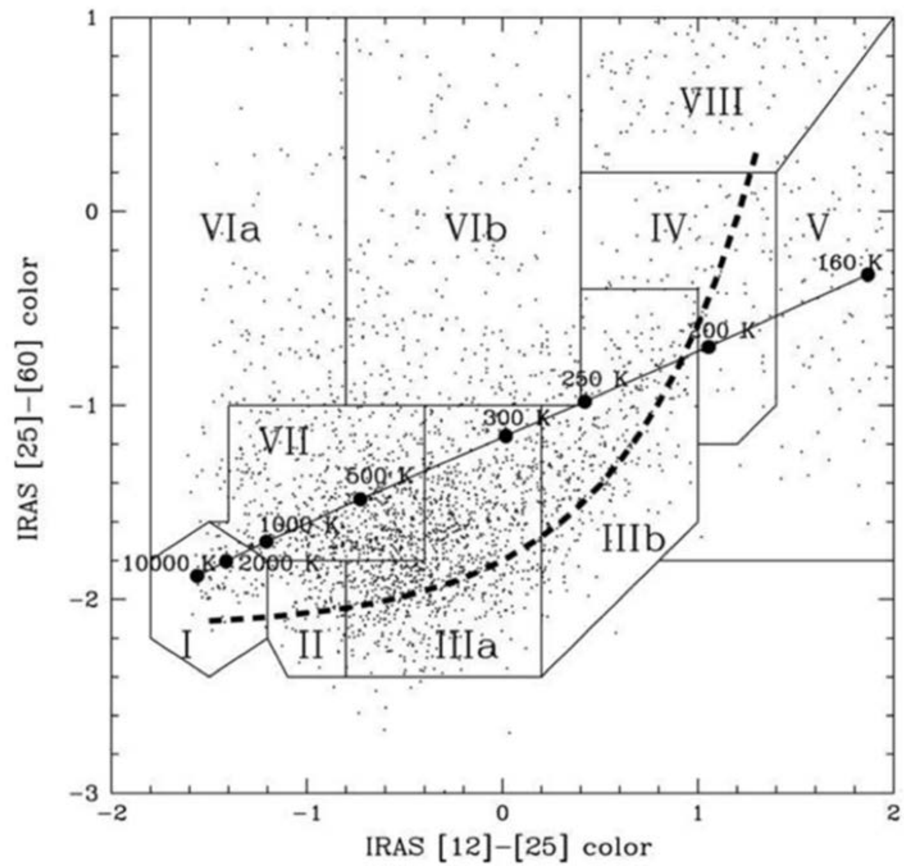
IRAS and evolved stars

Low mass, evolved stars good potential probes.

- InfraRed Astronomical Satellite
  - 1983, all-sky survey
  - 12, 25, 60 and 100 μm
  - 300,000 sources

- Color-color diagram
  - Rough SED shape
  - Circumstellar material
  - Predict stellar masers

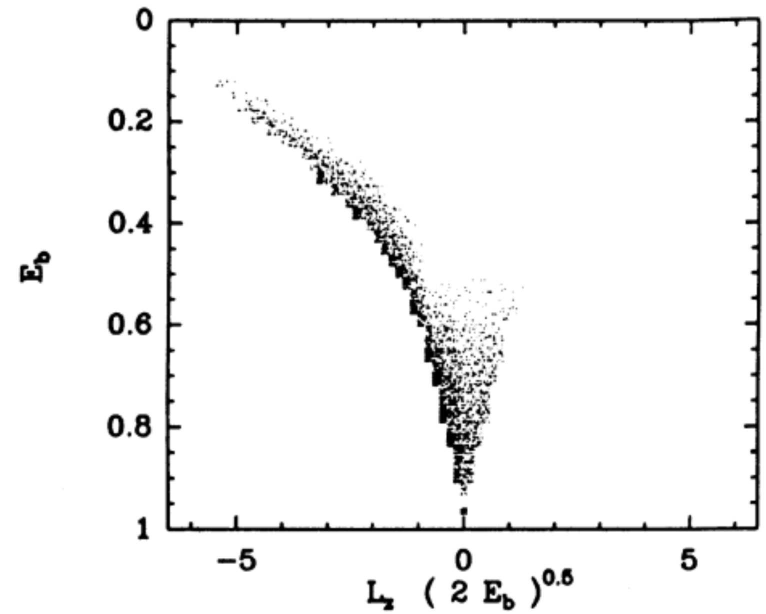
- About 1 arcmin beam
  - Confused in Gal. Plane



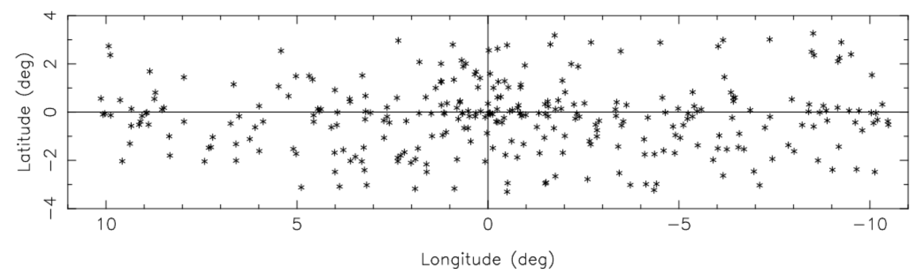
Van der Veen & Habing 1988

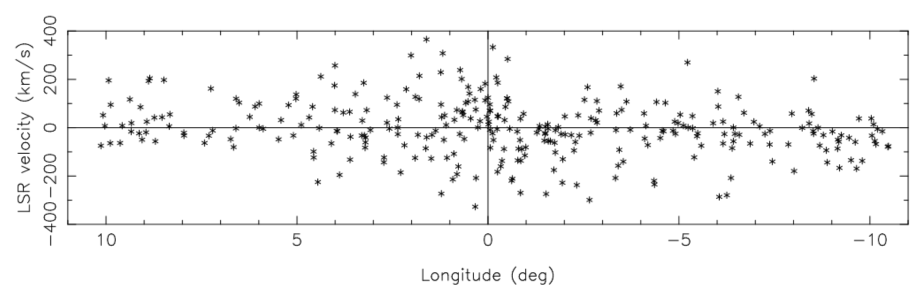
Galactic 1612 MHz OH masers

- Targeted surveys using IRAS colors
  - Obtain line-of-sight velocity
  - Dynamical models of Galaxy (e.g., Te Lintel-Hekkert et al. 1991)



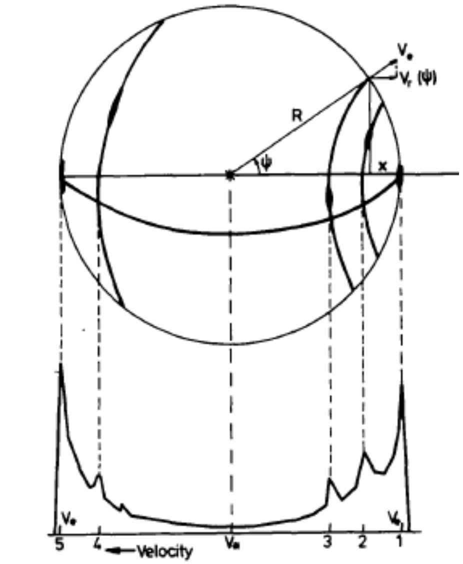
- Blind surveys in Plane & GC
  - Much higher maser density
  - Few IRAS detections/colors (e.g. Lindqvist et al. 1992; Sevenster et al. 1997ab, 2000)

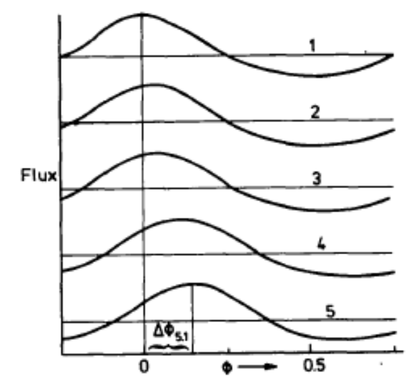


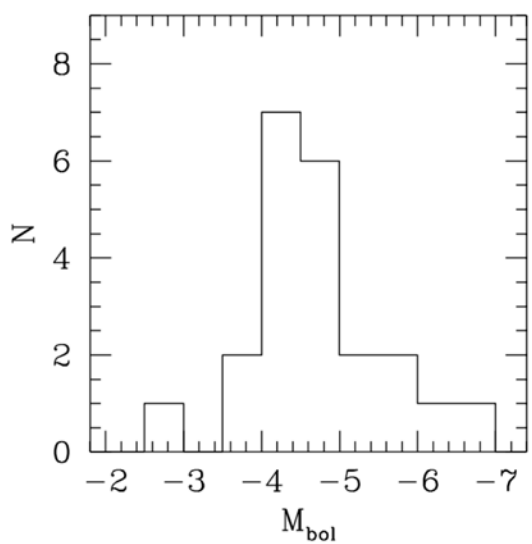


<u>Individual follow-up observations</u>

- Stellar and circumstellar environment properties
  - e.g., Olofsson et al.
- (phase-lag) distances & proper motions
  - e.g. Herman et al. 1985; Van Langevelde et al.
- Bolometric luminosities
  - e.g. Blommaert et al. 1998







Specific dynamics/kinematics

Different populations

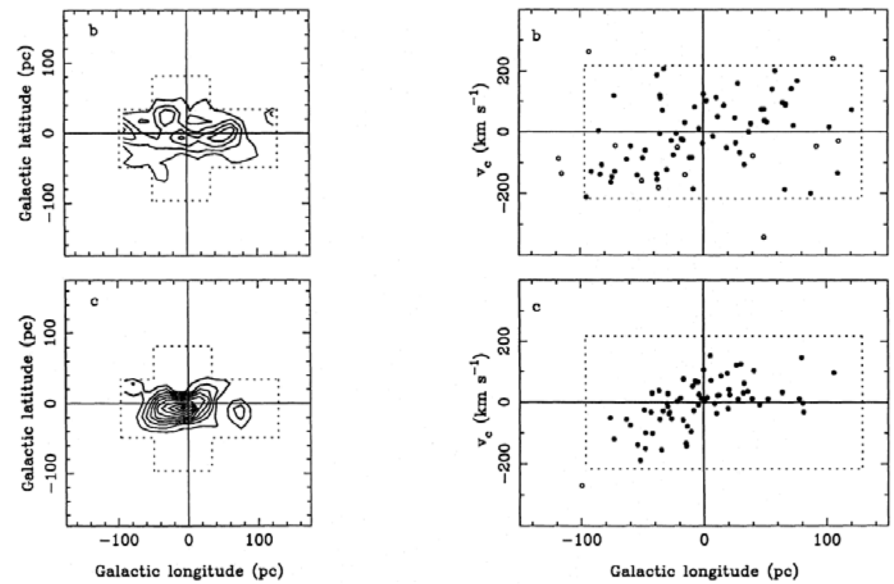
- Galactic rotation versus other types of orbits
- Bulge modeling

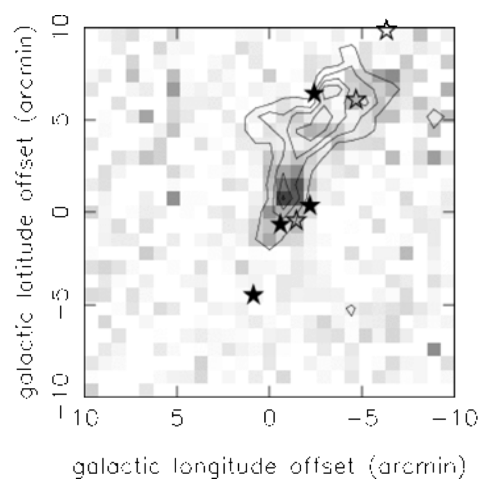
High velocity stars

- Individual encounters
- Elongated orbits
- Captured system

~4,000 OH masers in total in the MW, insufficient sample

(Vauterin & Dejonghe)





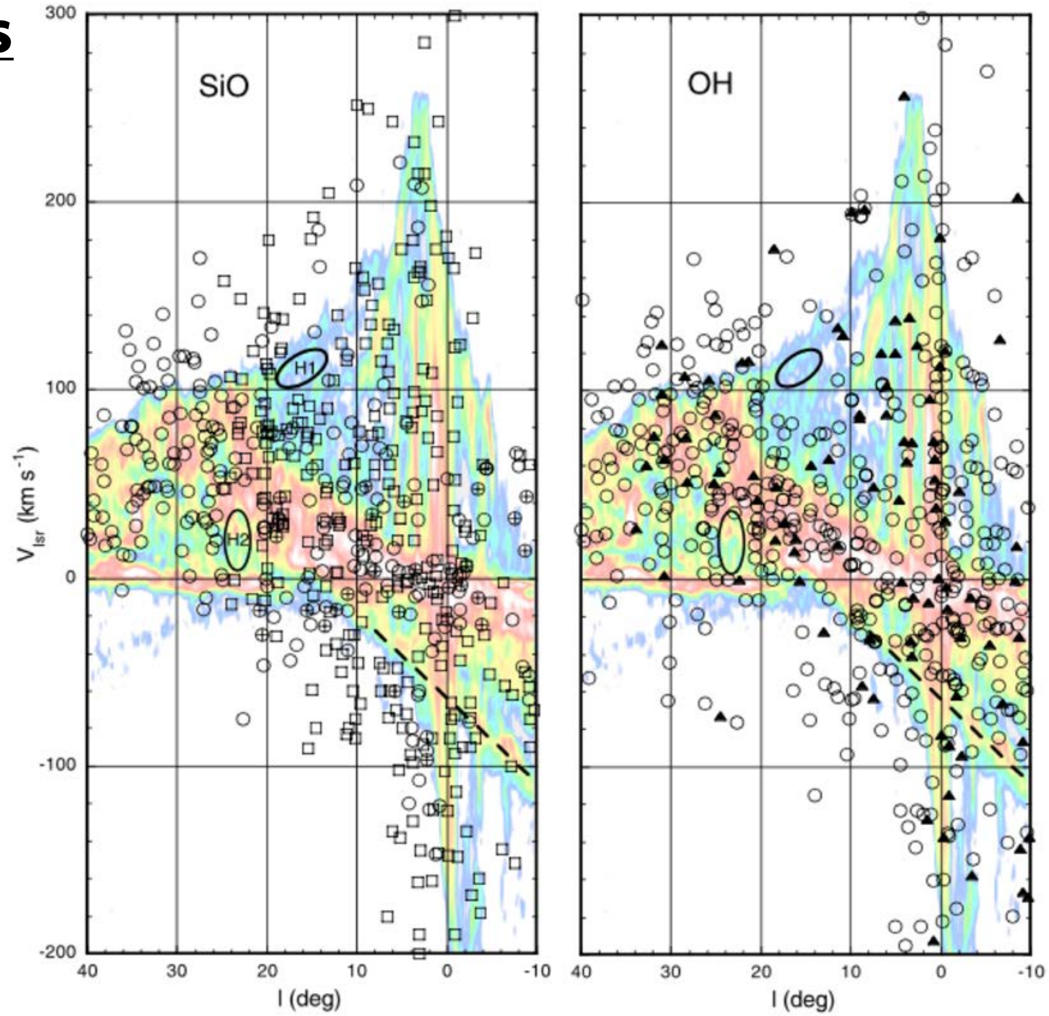
Lindqvist et al. 1992;
Sjouwerman et al. 1999)

43 GHz SiO maser surveys

SiO has the benefit of occurring in stars with lower mass-loss rates

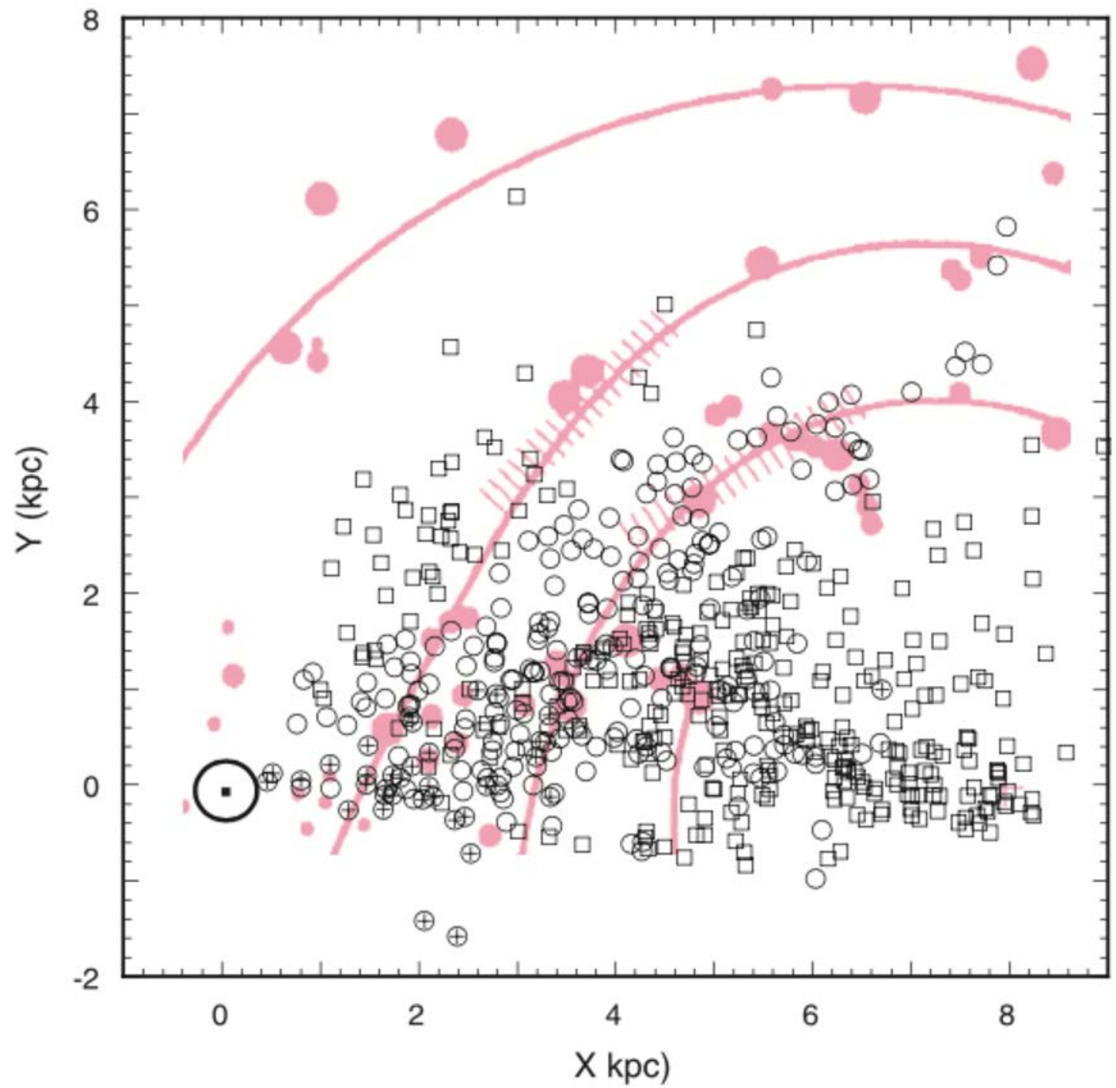
- Deguchi et al., Messineo et al., Benson et al., Izumiura et al. , Fujii et al.

- Here comparison with CO(1-0) from Dame et al. 2001



Deguchi et al., 2004

- Using Galaxy rotation curves to position the maser stars
- In total around 4,000 SiO maser stars in the literature, most toward the Bulge region

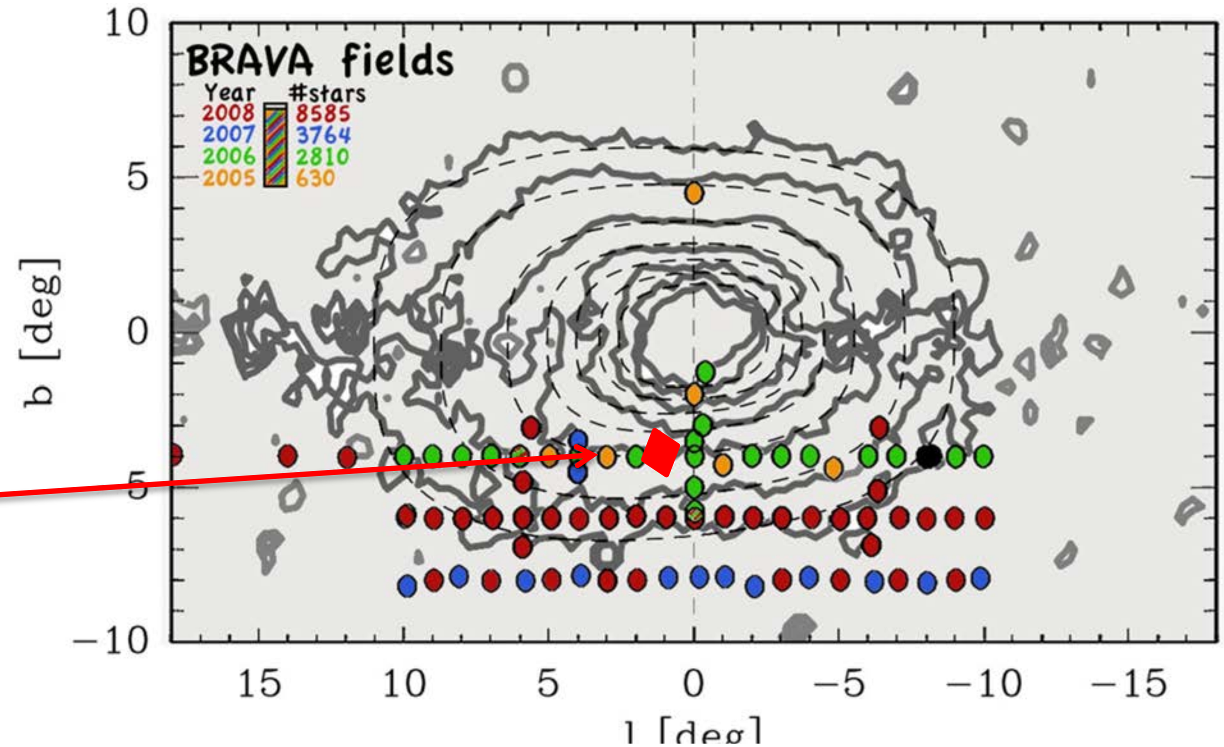


Deguchi et al., 2004

Optical/near-infrared surveys of the bulge

For example:

- *BRAVA*
- OGLE
- APOGEE
- ARGOS
- GIBS



Baade's Window

Cannot penetrate the Bulge and Plane region

Rich et al. 2007;
Kunder et al. 2012

Optical/near-infrared surveys of the bulge

For example:

- *BRAVA*
- OGLE
- APOGEE
- ARGOS
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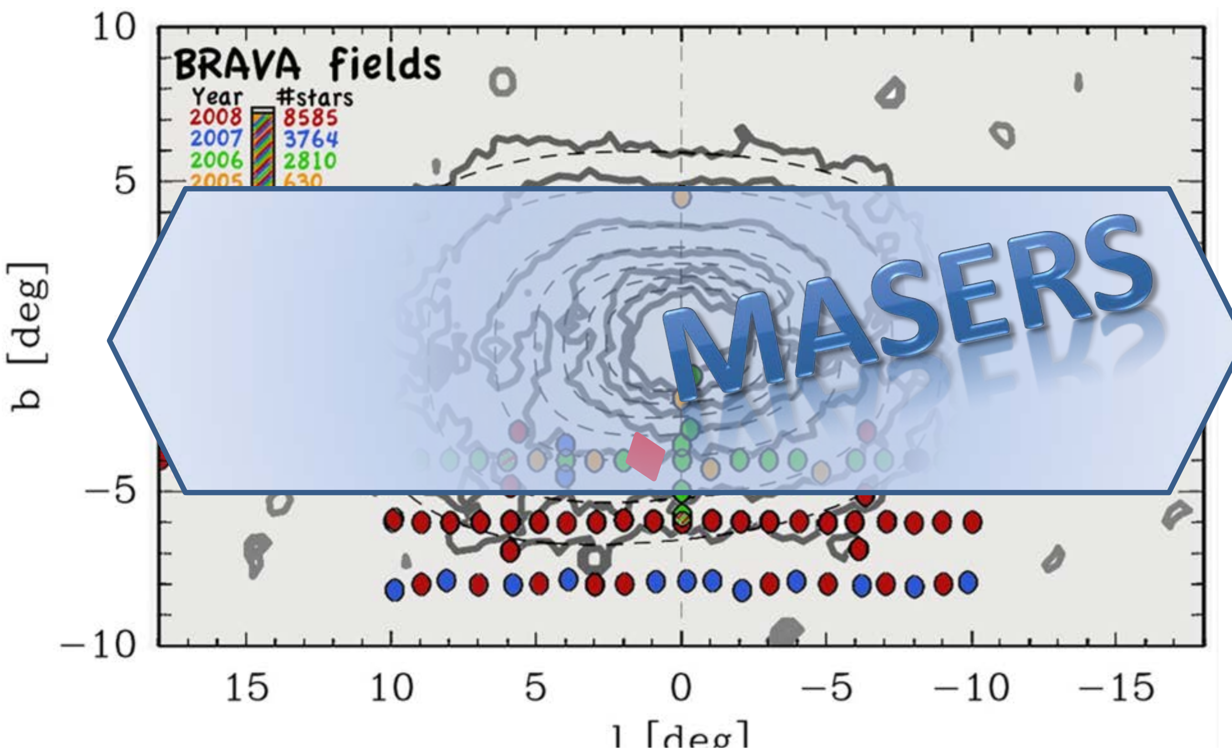
Extended version

BAaDE's Window



Can~~not~~ penetrate the Bulge and Plane region

Rich et al. 2007;
Kunder et al. 2012

The BAaDE project:

Bulge Asymmetries and Dynamical Evolution

Aim:

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

The BAaDE project:

- Survey of evolved stars for maser emission:
  - Survey ~28,000 AGB/RGB stars for SiO masers using both VLA and ALMA (at 43 & 86 GHz)

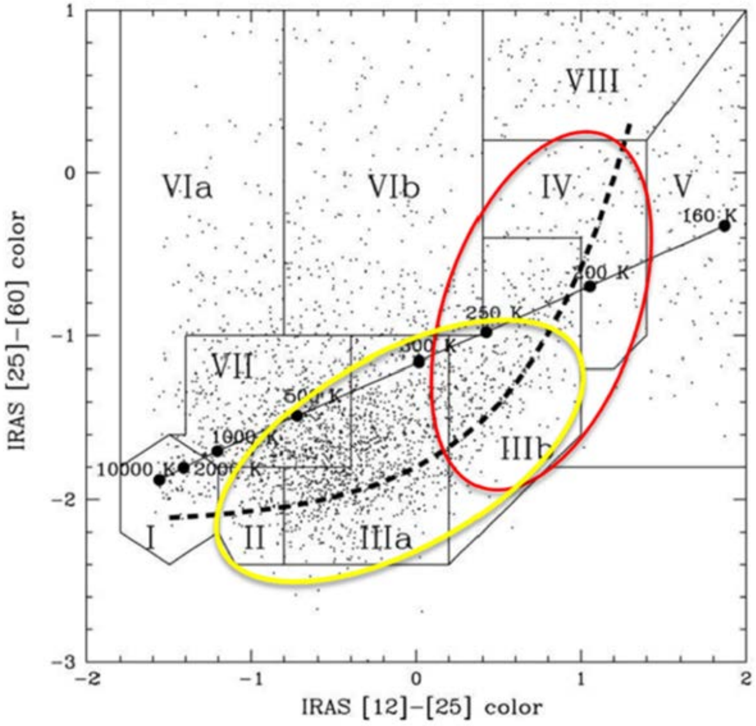
- Galaxy modeling using line-of-sight velocities

- VLBI astrometry for characterizing orbits in a small subsample of the sources
  - Complement optical data (statistics/Gaia, Next talk by L.H. Quiroga Nunez)

Detecting SiO masers in stars: IRAS

- SiO masers are found
  - In both AGB and RGB stars
  - In lower mass-loss objects
  - Thinner circumstellar shells
  - IRAS color-color diagram:
    - In sources not too red
    - Not in OH/IR stars
    - Not in Carbon-rich stars

- In Bulge: not by using the IRAS data.



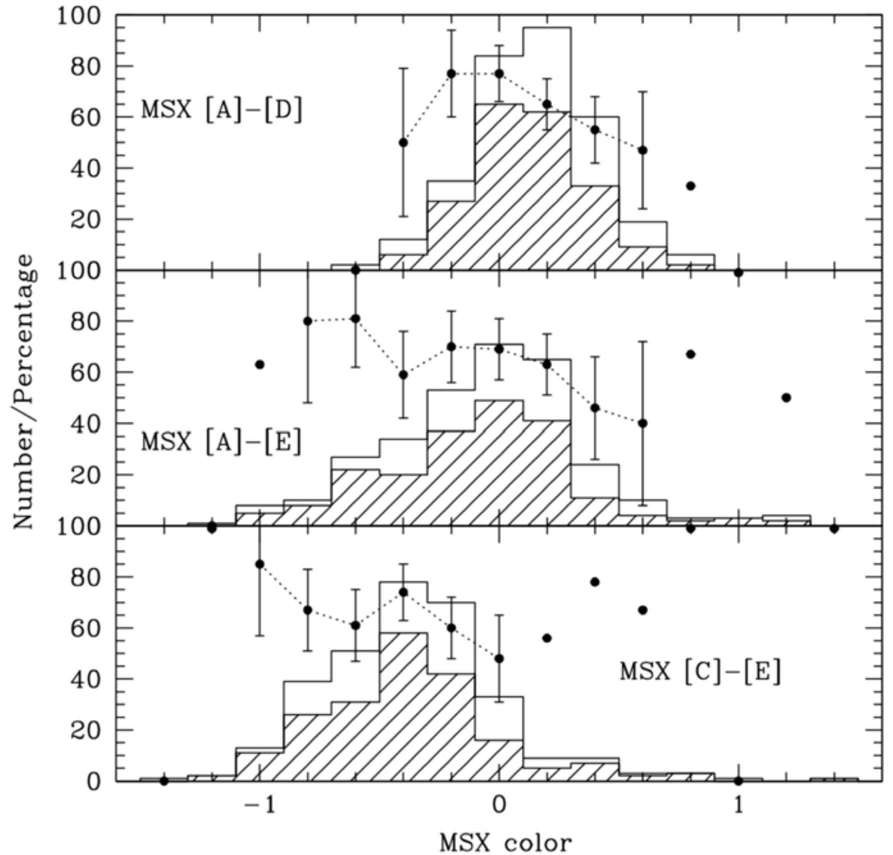
Van der Veen & Habing 1988

SiO masers in MSX sources

Midcourse Space eXperiment (MSX, 1996)

- Make equivalent IRAS color-color diagrams
  - 440,000 objects in the Plane
  - 8, 12, 15 and 24 μm (no ~60 μm)

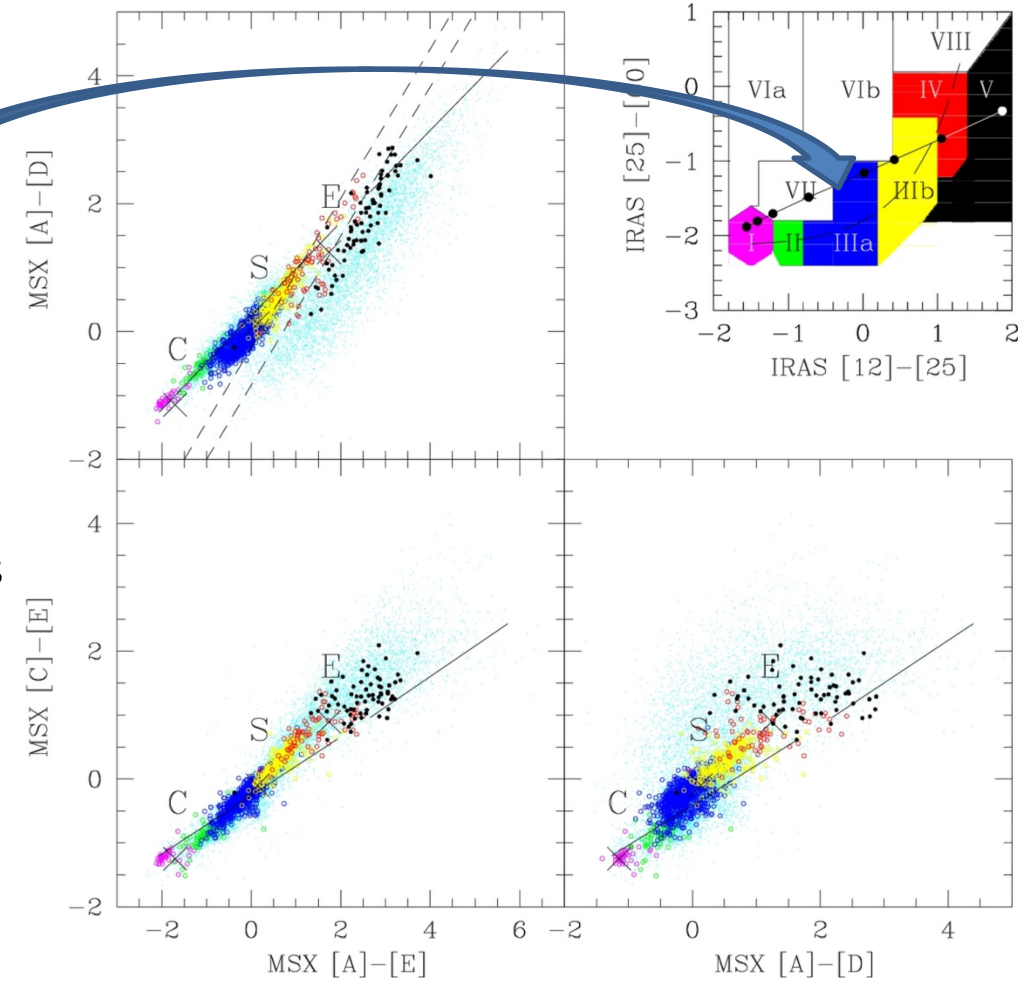
- MSX color selection
  - 50-90% SiO masers (Sjouwerman et al. 2009)
  - Convert IRAS to MSX regions



Sjouwerman et al. 2009

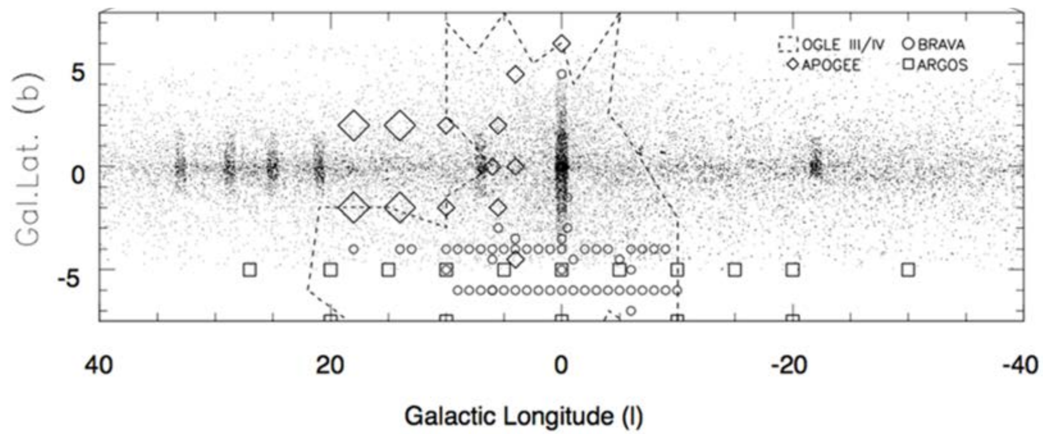
MSX color-color diagrams

- 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

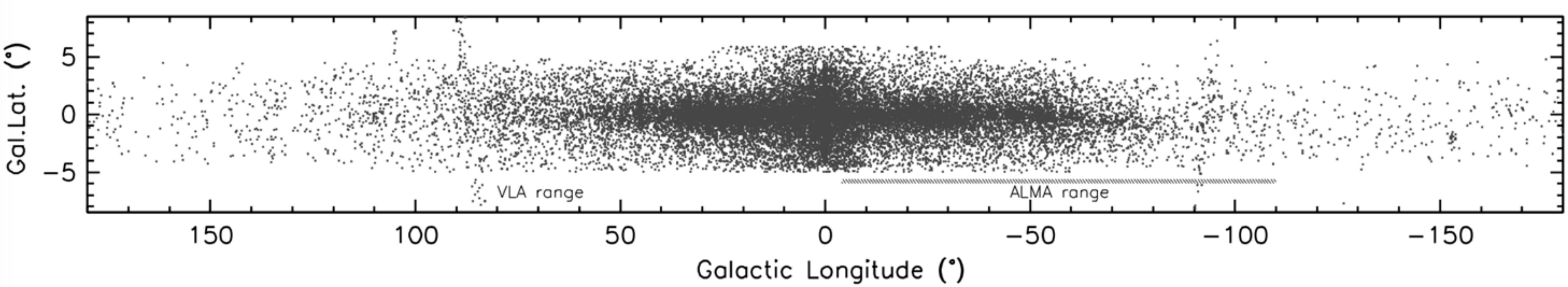


MSX target selection

- In the plane, $|b| < 5^o$, samples the Galactic plane where optical surveys do not reach and where dynamics are most revealing
  - Concentrated in Bulge



- ~28,000 targets
  - ~19,000 VLA: 43 GHz
  - ~9,000 ALMA: 86 GHz



Observational strategy

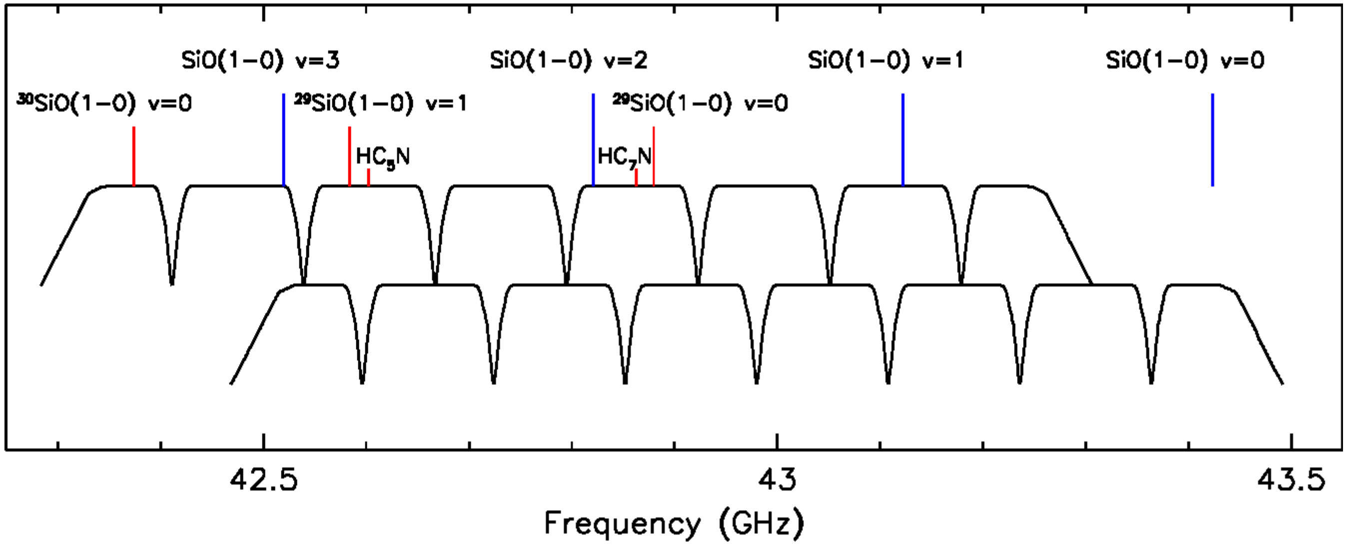
- Bright enough for follow-up VLBI
  - 15 mJy/bm/ch rms, 100 mJy/bm/ch maser peaks
  - Less than one minute per source (ALMA or VLA, 1.7 km/s)

- Maximize detection rate
  - Cover multiple lines, including potential Carbon
  - Multiple transitions yield more accurate velocity

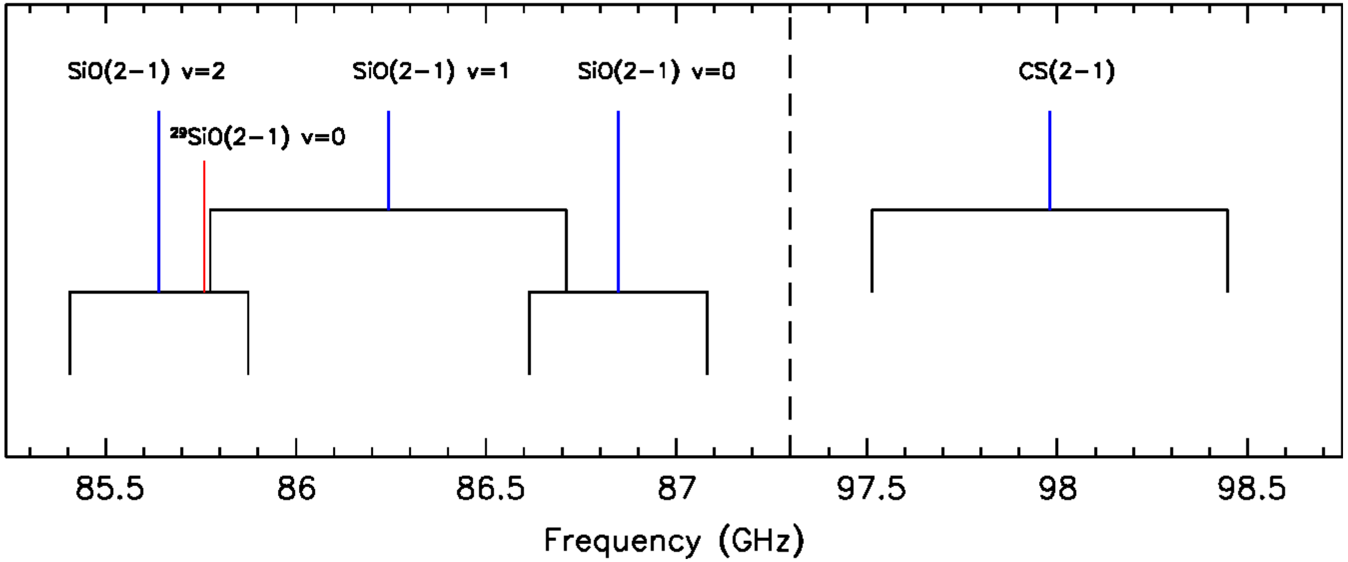
- Minimize overhead (mostly for VLA)
  - Fast-switching without fast-switching!
    (almost the same as phase-referencing, although utilizing masers)
  - Instead of >750 fast-switching hours, applied for 410 VLA hours
  - ALMA observations scheduled differently

Observational setup

Multiple maser lines, also lines for Carbon-rich stars



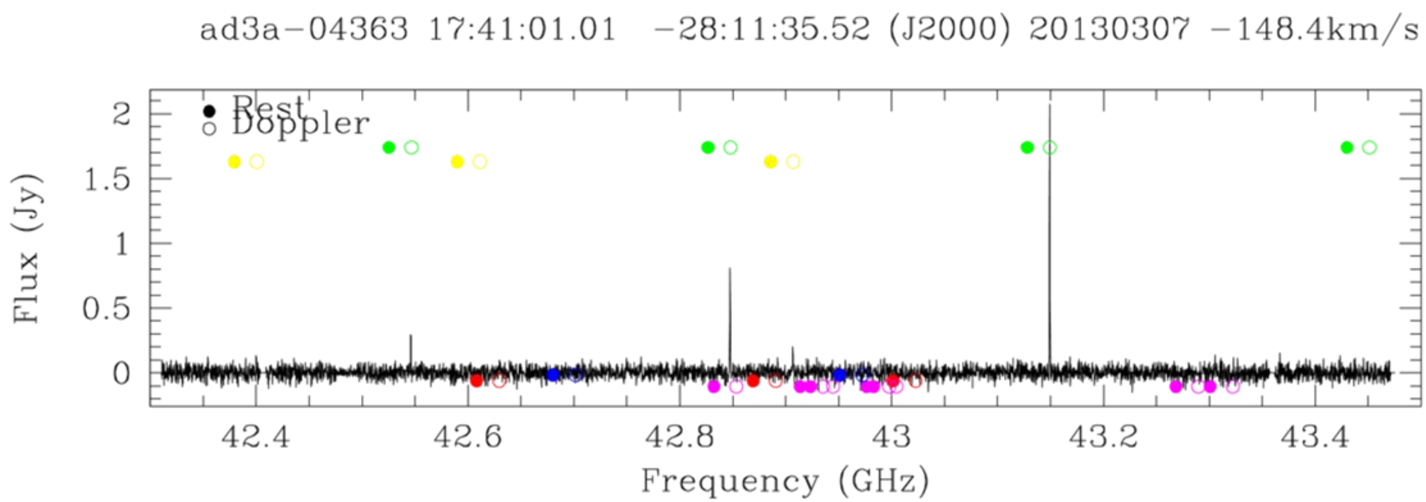
VLA 43 GHz

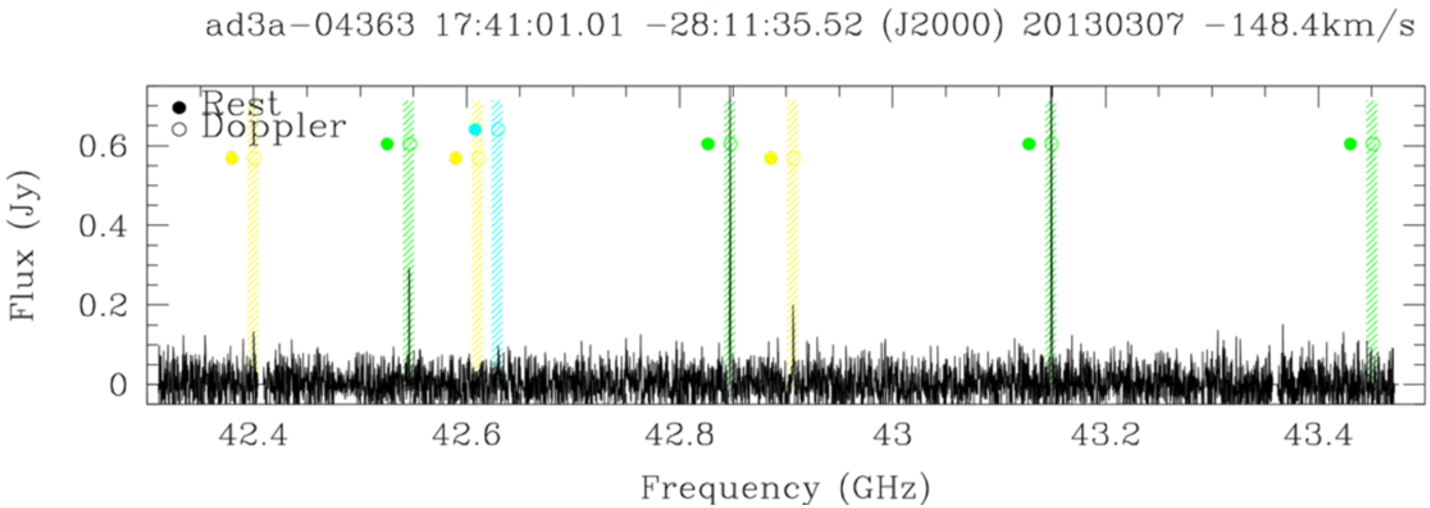


ALMA 86 GHz

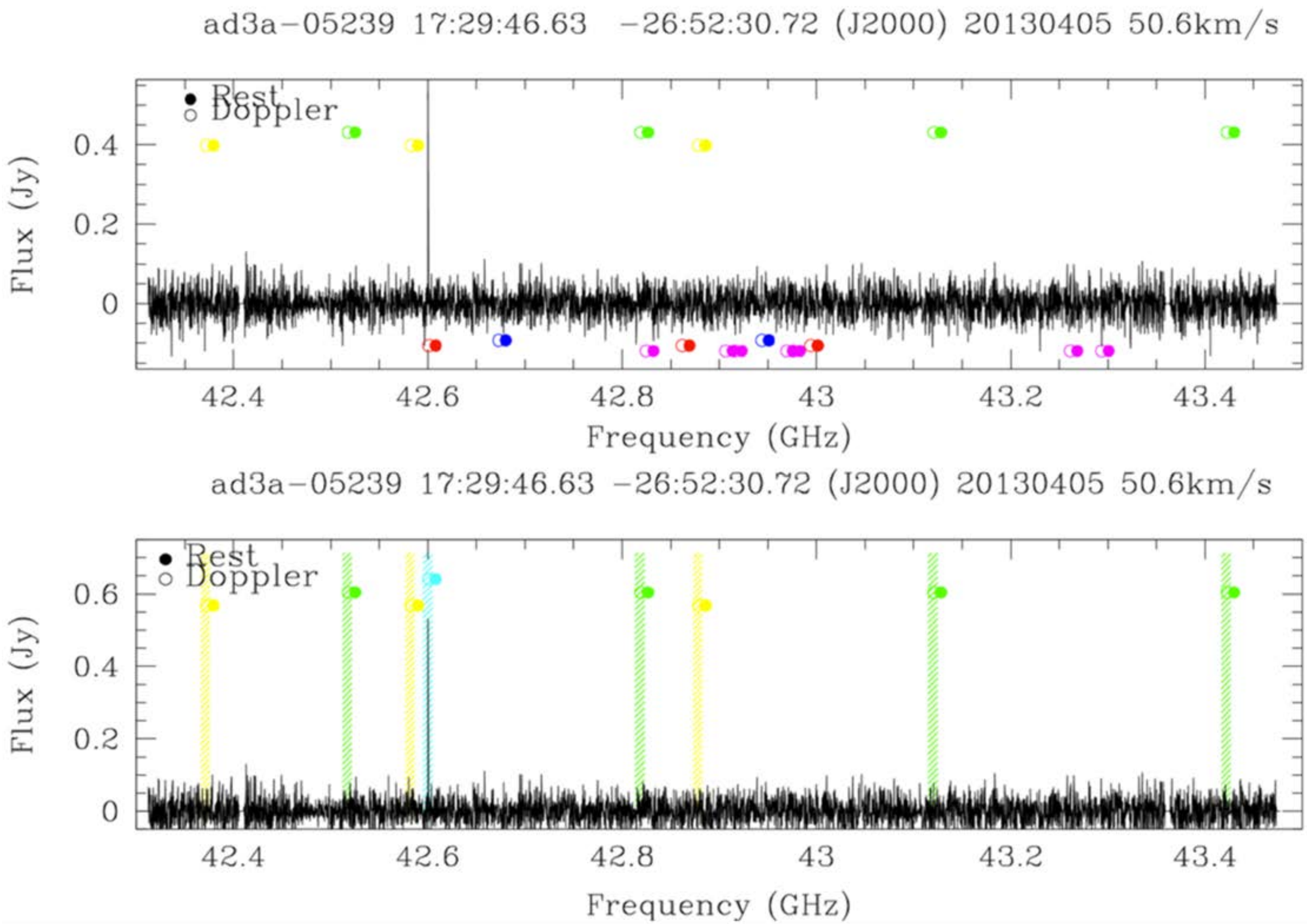
VLA data results

- Typical at 43 GHz: v=1 and/or v=2; rate about 60-70%

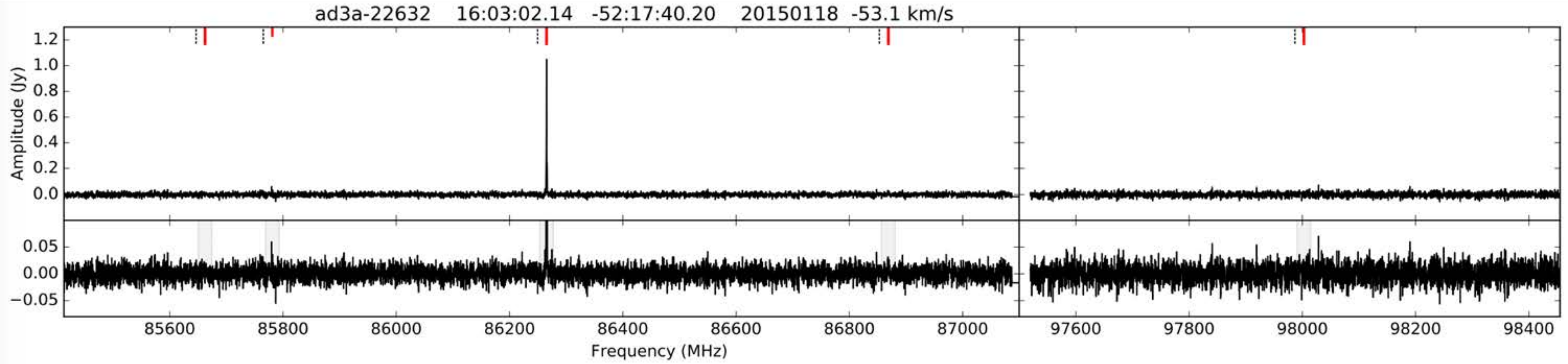


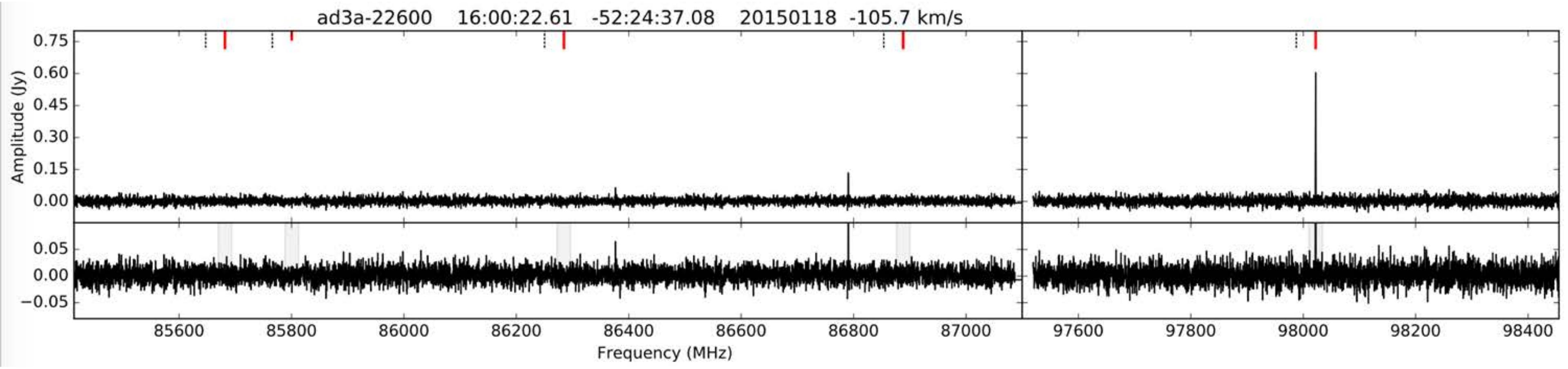


Carbon-rich detection of HC_5N, near ^{29}SiO (v=1)

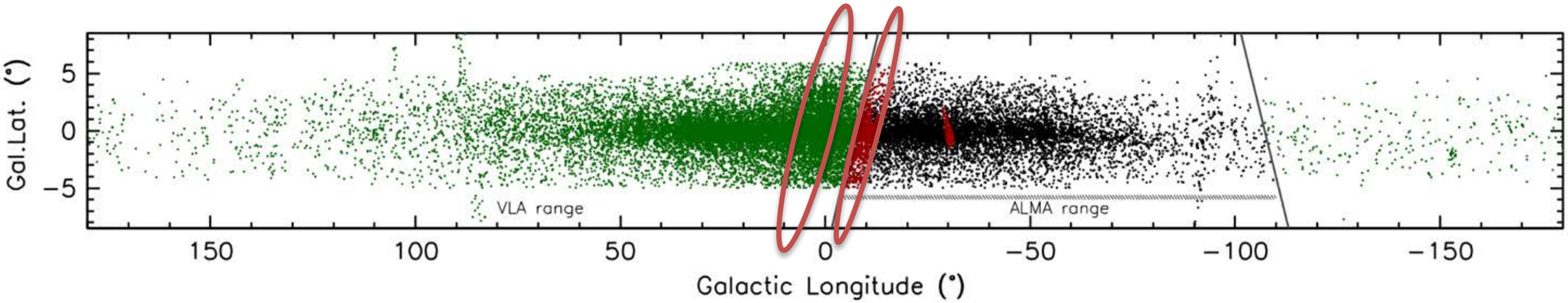


Typical ALMA results





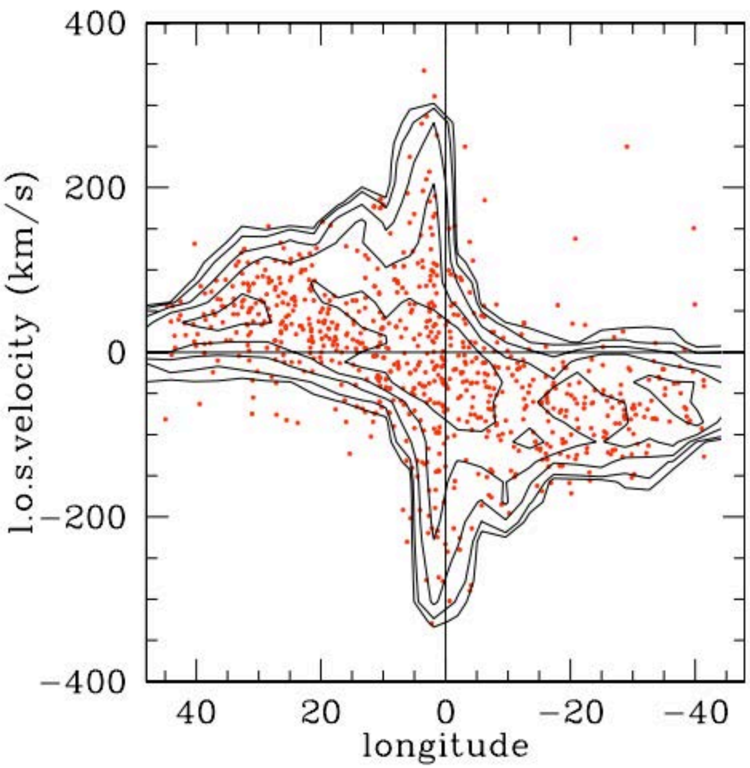
Current status of survey



- ALMA
  - Pilots of 200+1200 stars observed and reduced
  - Cy 5 schedules for 2300 more stars created
- VLA
  - 3600 stars in Bulge analyzed
  - 3500 stars, all in outer Plane reduced
  - Remaining (12,000 in greater Bulge) all observed, reduction started this week.
- VLBI
  - Current pilots & calibrator searches with EVN/VERA/VLBA

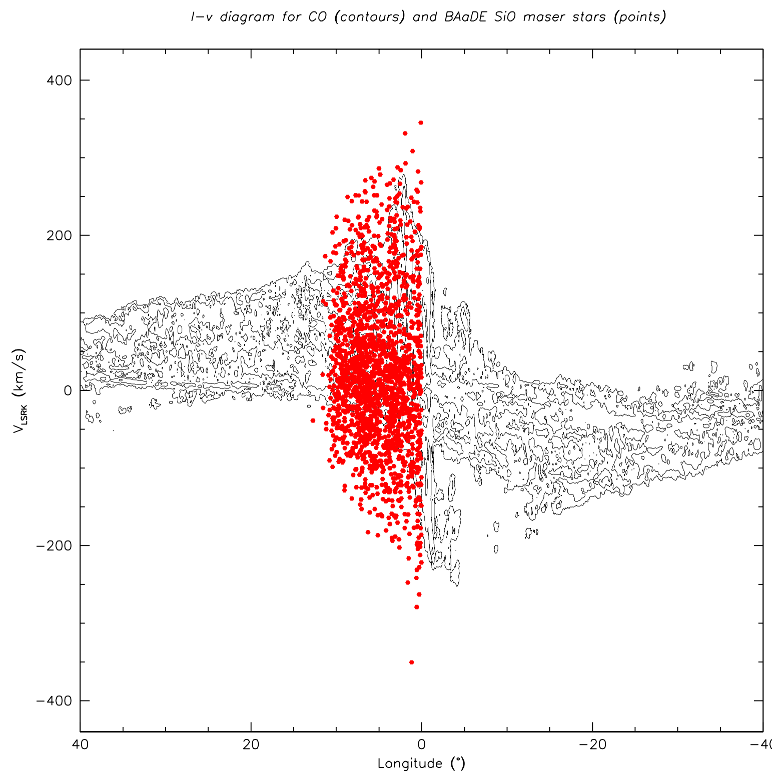
Longitude-velocity diagram

OH maser density



OH/IR star summary from Habing

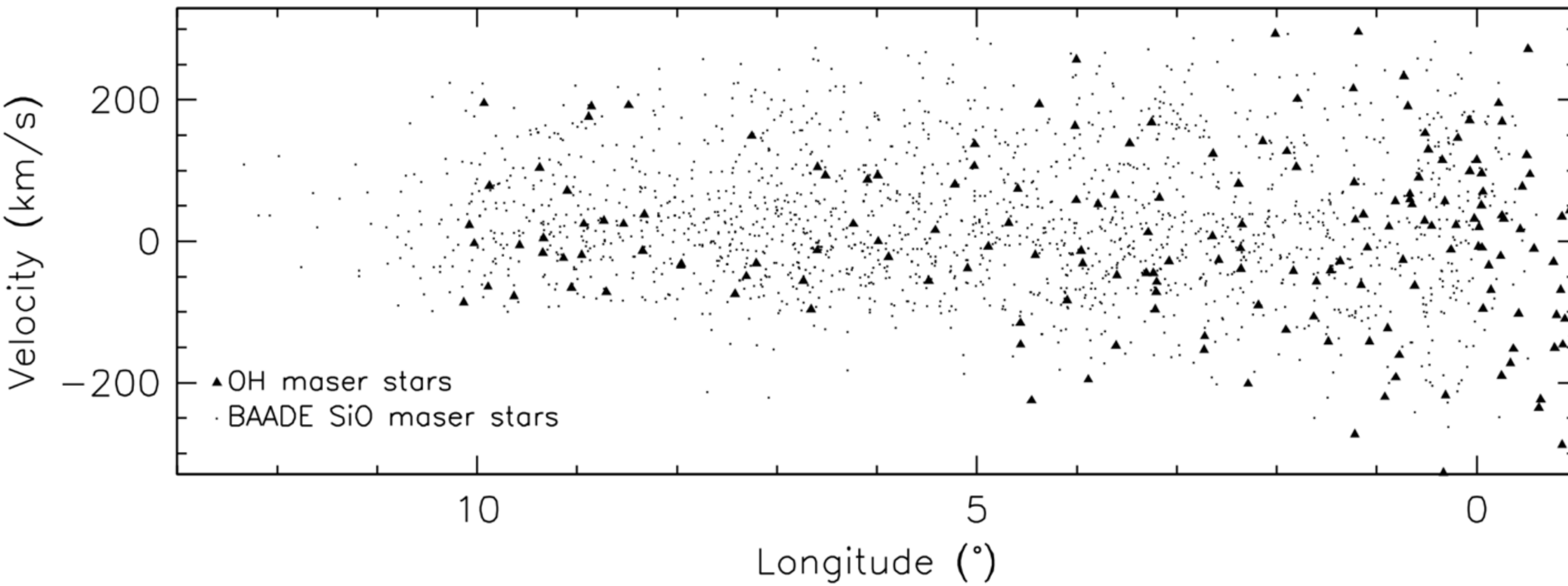
BAaDE SiO maser density



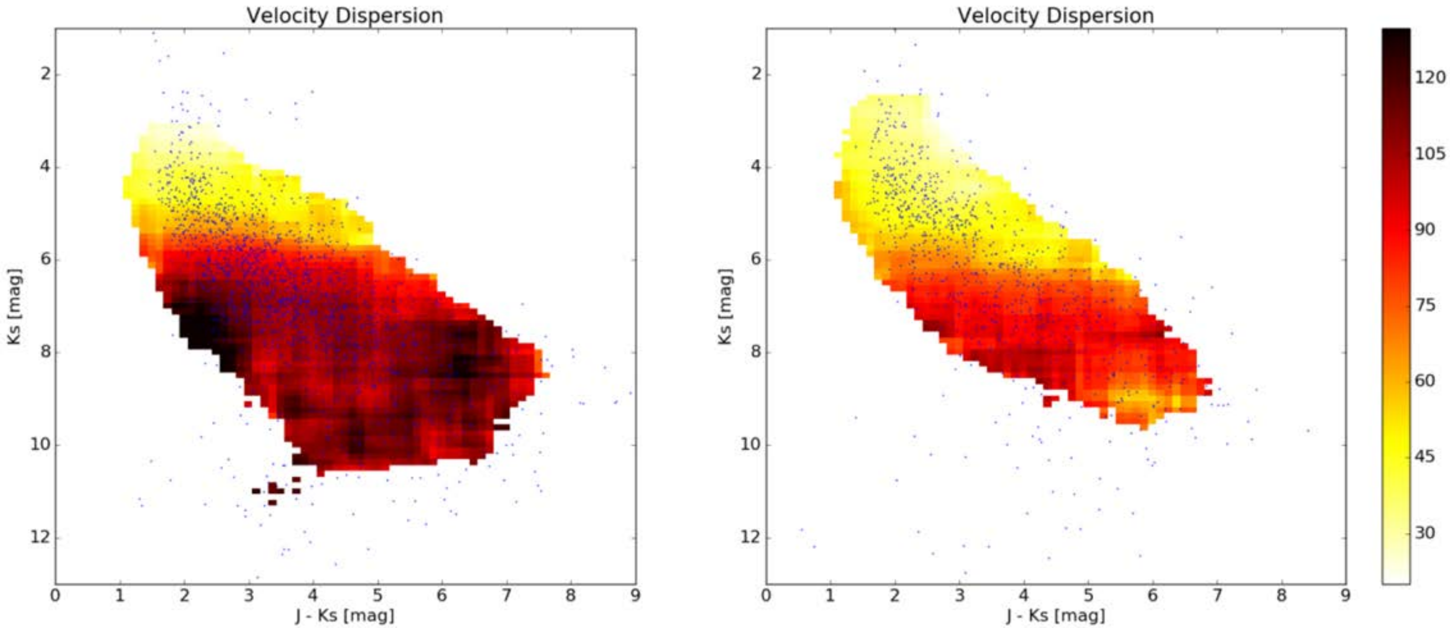
CO contour map from Dame et al.

Longitude-velocity diagram

OH maser density (triangles) versus BAaDE SiO masers (dots)

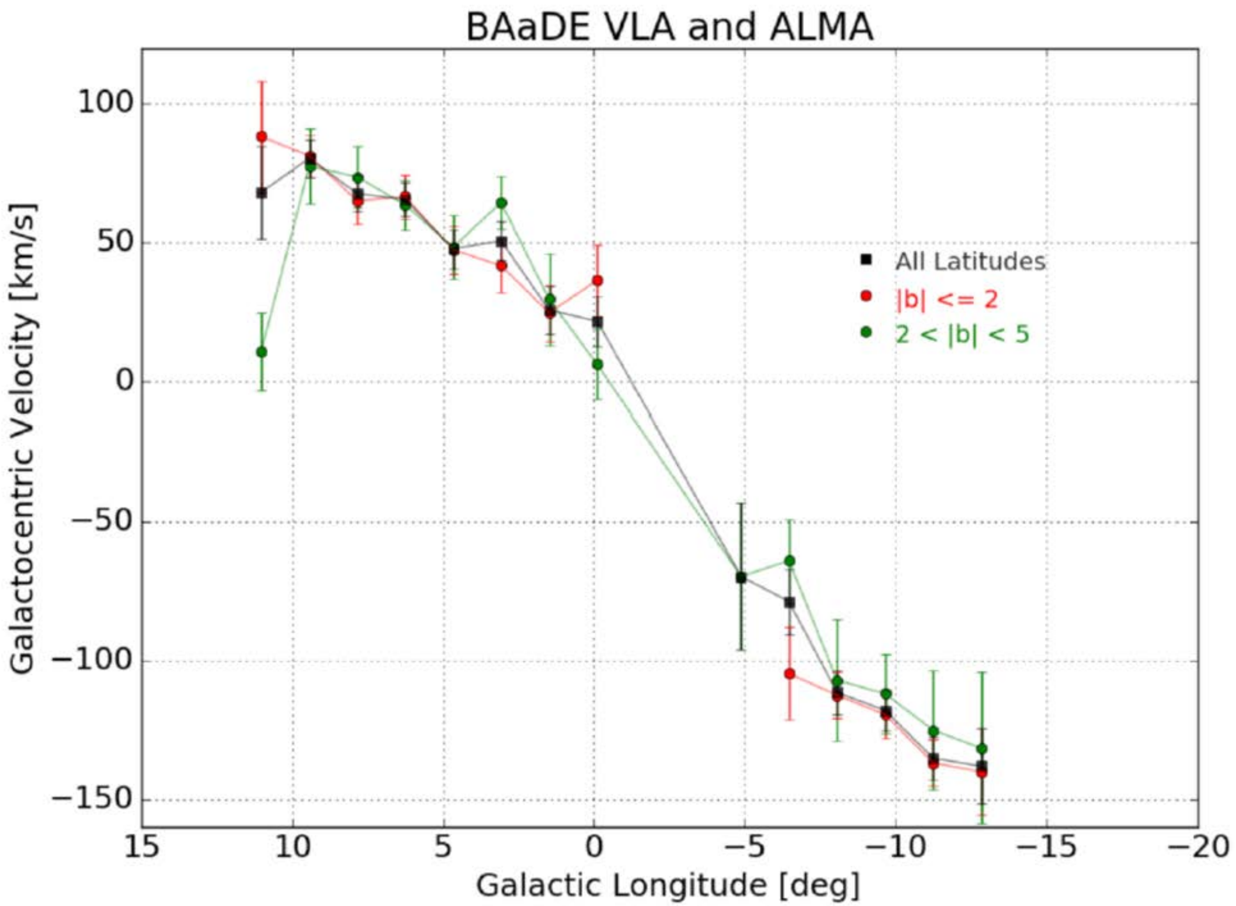


Initial results: population studies



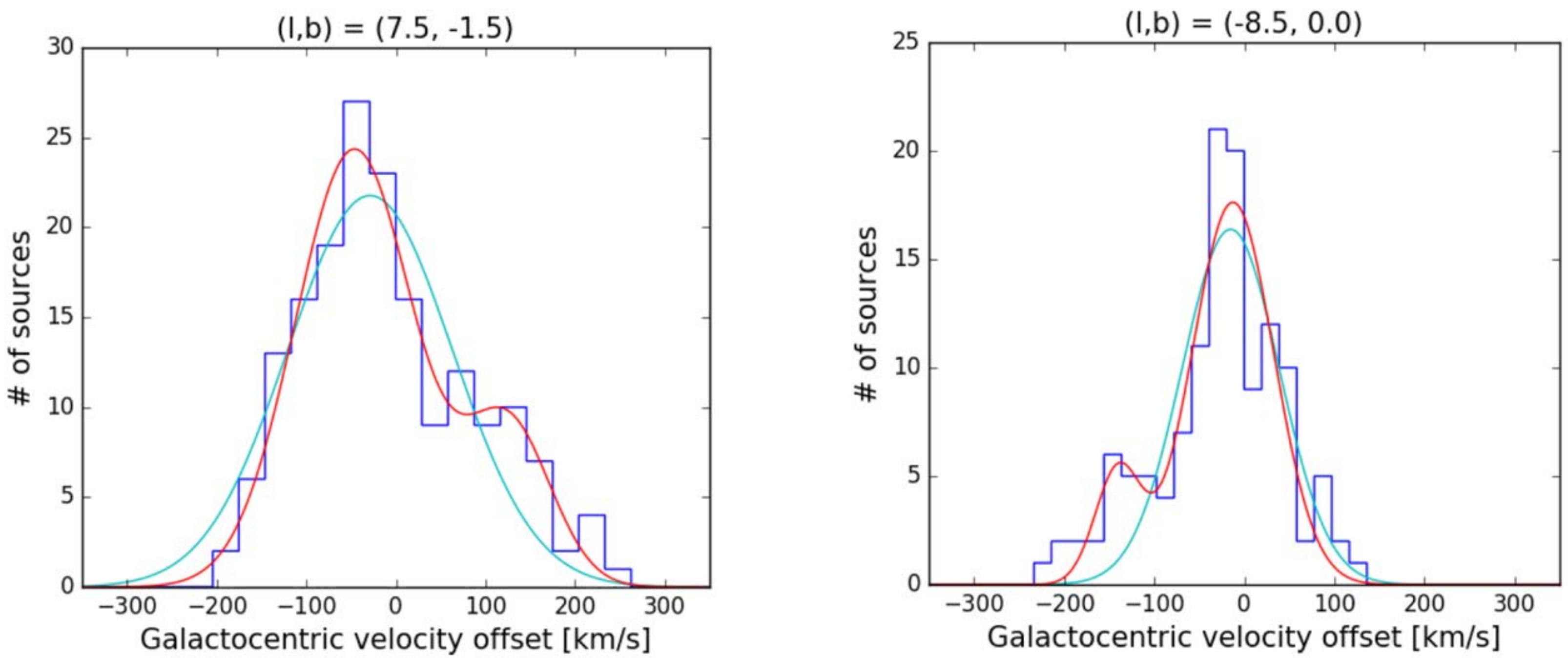
- Foreground vs bulge population based on velocity dispersion (Trapp et al., in prep)

Initial results: cylindrical rotation



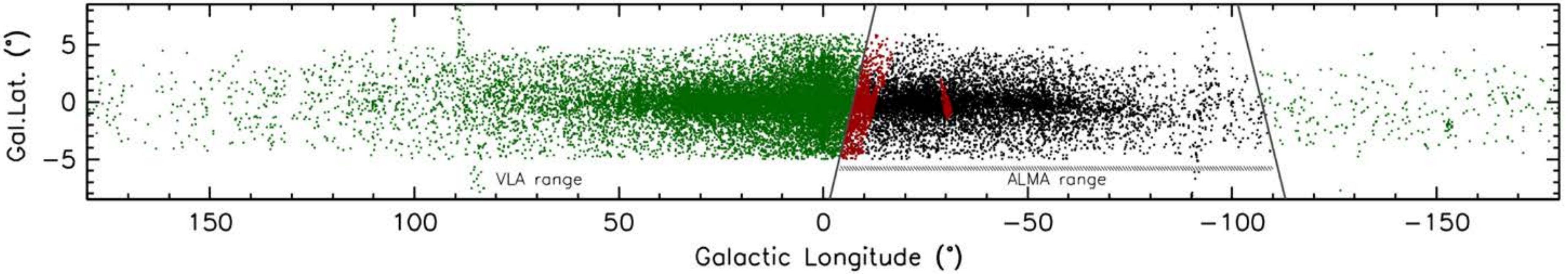
- Rotation curve similar at different latitudes

Initial results: additional kinematical population?

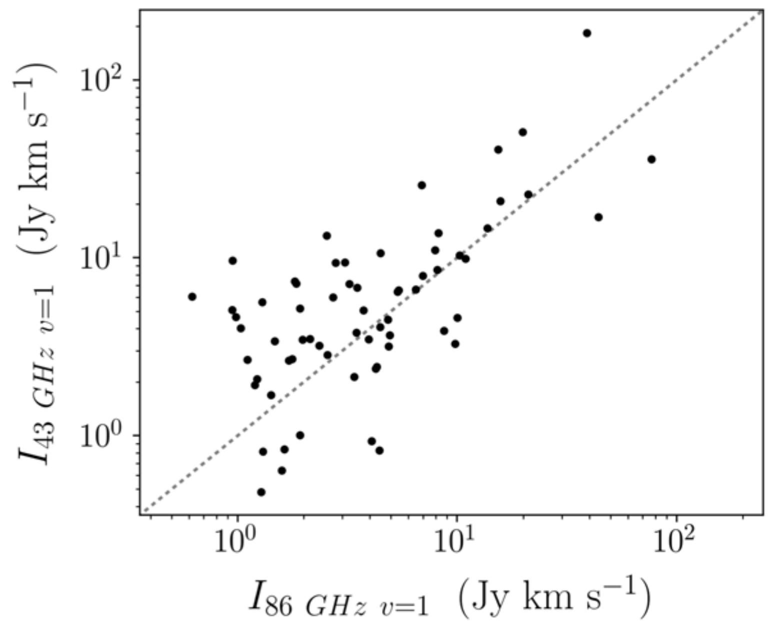


- This possible excess density feature hinted at previously at +200 km/s in APOGEE data (Aumer & Schönrich 2011)
- Separate kinematical population or combined effect from bar+foreground disk?
- Habing 2016: In fact an effect from the expected set of stellar orbits in the bar potential

Transition and Malmquist bias



- Is 43 GHz and 86 GHz SiO co-occurring?
- Is the 86 GHz on average brighter than the 43 GHz v=1 transitions?
- Near-simultaneous observations using ATCA implies 43 GHz v=1 may be brighter, although a very large scatter (Stroh et al., in prep)



<u>BAaDE spin-offs and by-products</u>

Huge data base of stars harboring SiO masers!

- Statistics of SiO maser line ratios (including isotopologues), thermal transitions
  - Typical pumping conditions

- SiO maser detection rate as function of longitude/population
  - Metallicity effects
  - Age population effects (younger disk stars vs older bulge stars)

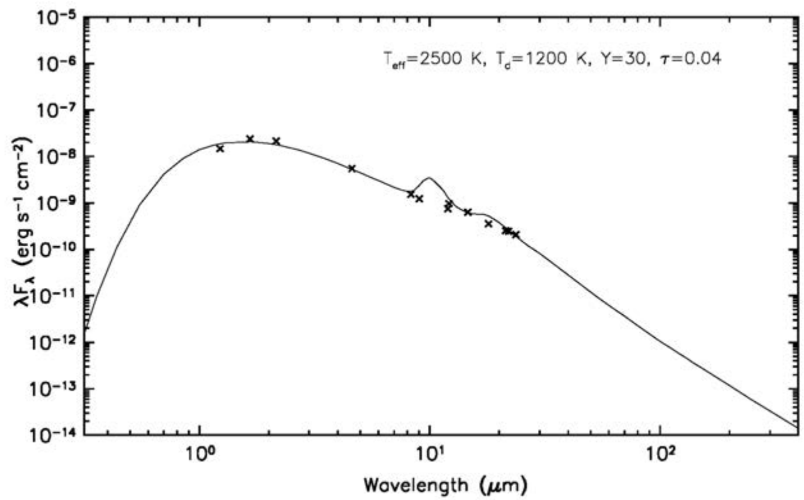
- Luminosity functions

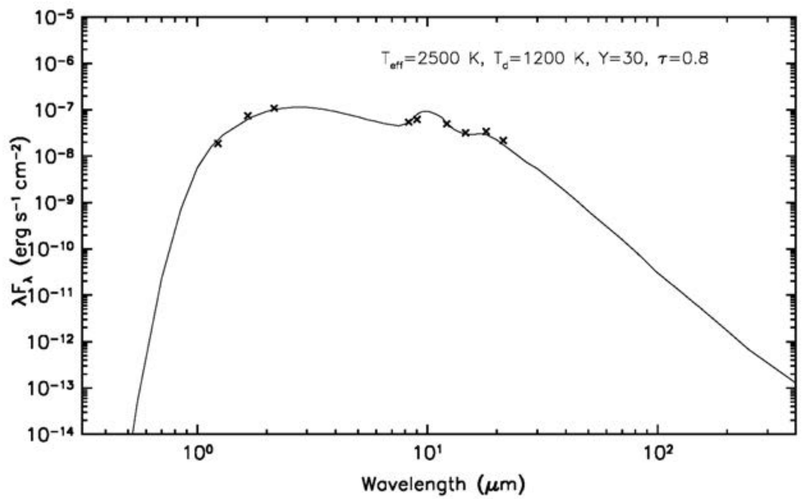
- IR characteristics for 28,000 evolved stars
  - Correlate with the SiO detections (color, underlying SED properties)
  - Improved IRAS CC diagram with information about shell

…and most of the above for Carbon-detections

Circumstellar envelopes

- Every target IR selected from MSX
  - Additional data from 2MASS, WISE, GLIMPSE, Herschel, etc.
- MSX color "slope" range in SED
  - Different envelopes/shells
- Modeling and binning:
  - Range of stellar/CSE properties (function of color?)
  - F_{bol} => rough distance estimates
  - Statistical using template SEDs
  - De-reddening effects
  - Detected/non-detected, carbon!





Follow up

Individual stars

- infrared spectroscopy: metallicity
- astrometry: accurate distance and proper motion

SEDs/magnitudes/velocities may be used for rough (statistical) distance estimates

- May be possible to derive parallaxes for a subset using VLBI
- Test and calibrate the statistical estimates
- Complement optical data (Gaia)

Additional spin-off:

- New 43/86 GHz calibrators in the bulge/plane
- Both for connected element (VLA/ALMA) and VLBI

Summary

- Stellar masers effective probes of the Galactic structure and dynamics

- New surveys capable of greatly increasing the number

- BAaDE project: Huge database for dynamics but also
  - SiO and Carbon line statistics (long/lat, color)
  - Information about the CSE: optical depths, variability
  - VLBI follow-up for parallaxes and 3-D orbits
  - Preparing SiO/IR catalog, including vel/pos/line ratios etc.

- Need ngVLA + VLBA for large scale astrometry of these targets

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, Megan Lewis & Eddie Hilburn (UNM)
  - Adam Trapp (UCLA)
  - Luis Henry Quiroga Nuñez (JIVE/Leiden)
- van Langevelde (JIVE), Habing (Leiden), Shen (UCLA), ..

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