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Methanol (CH_3OH) masers & absorption features in massive star formation regions

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Outline

1 **Background for methanol masers**

2 **3mm methanol maser survey toward ATLASGAL clumps**

3 **Methanol absorption**
(107 GHz absorption toward the CMB**;**
Redshifted methanol absorption trace infall)

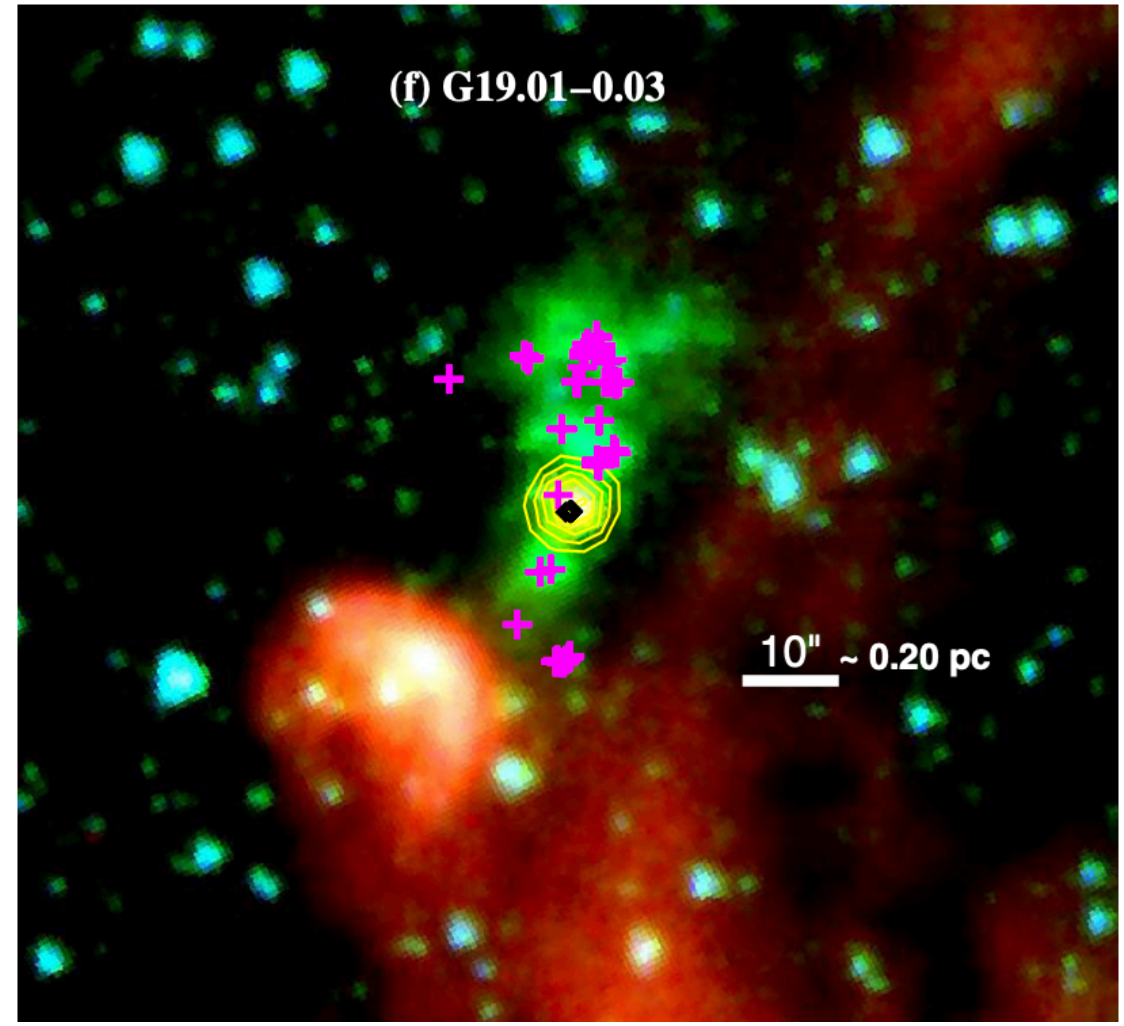
1.1 Classification of CH_3OH masers (associated objects + pumping mechanism)

Class I CH_3OH masers: (~650)
Scattered around YSOs (up to 1 pc)
Collisional pumping
astrophysical shocks

Transitions: 9.9, 25.0, 25.5, 25.9, 26.8, 27.4, 36.2, 44.1, 84.5, 95.2, 104.3, 146.6 GHz …
(e.g., Chen et al. 2011, 2012, 2013, Voronkov et al. 2006, 2014, Yang et al. 2017a)

Class II CH_3OH masers: (~1000)
Located in the nearest vicinity of YSOs
Radiative pumping
ONLY in high-mass SFRs

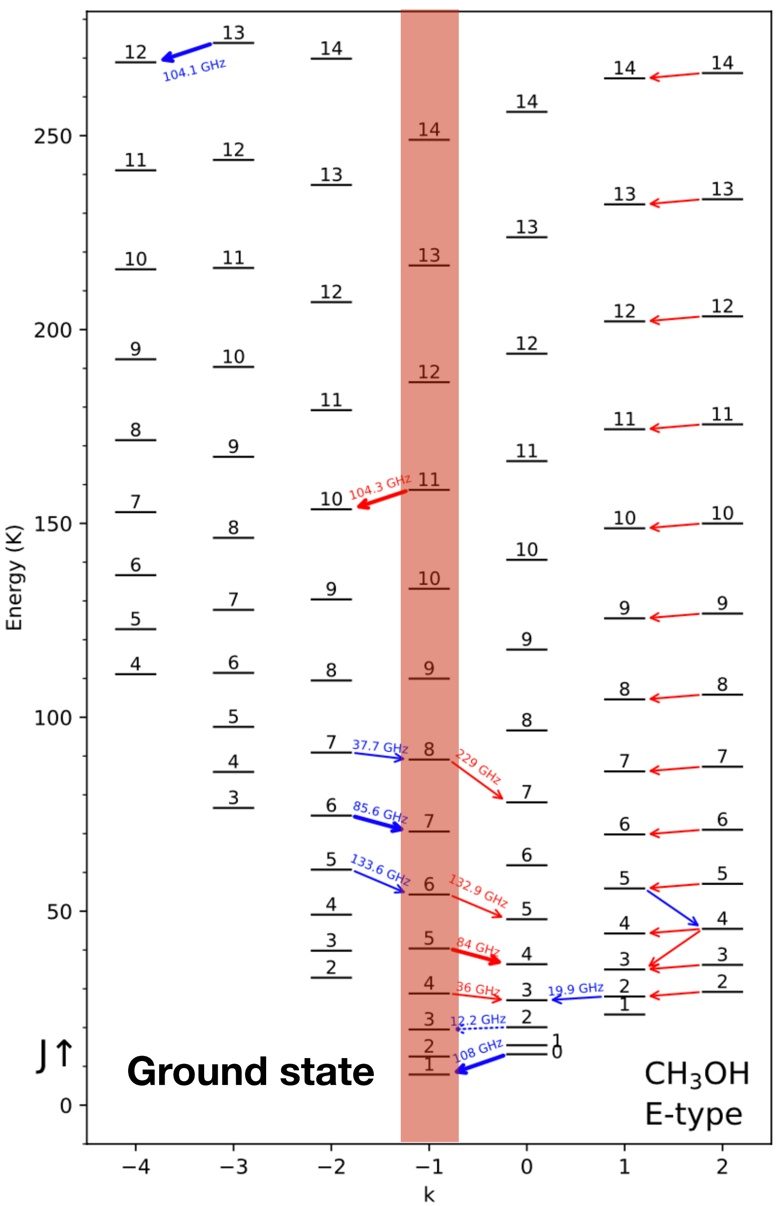
Transitions: 6.7, 12.2, 20.0, 23.1, 29.0, 37.7, 38.3, 38.5, 86.6, 86.9, 107.0, 108.8 GHz …
(e.g., Menten et al. 1991, Caswell et al. 1995, Yang et al. 2017b, 2019)

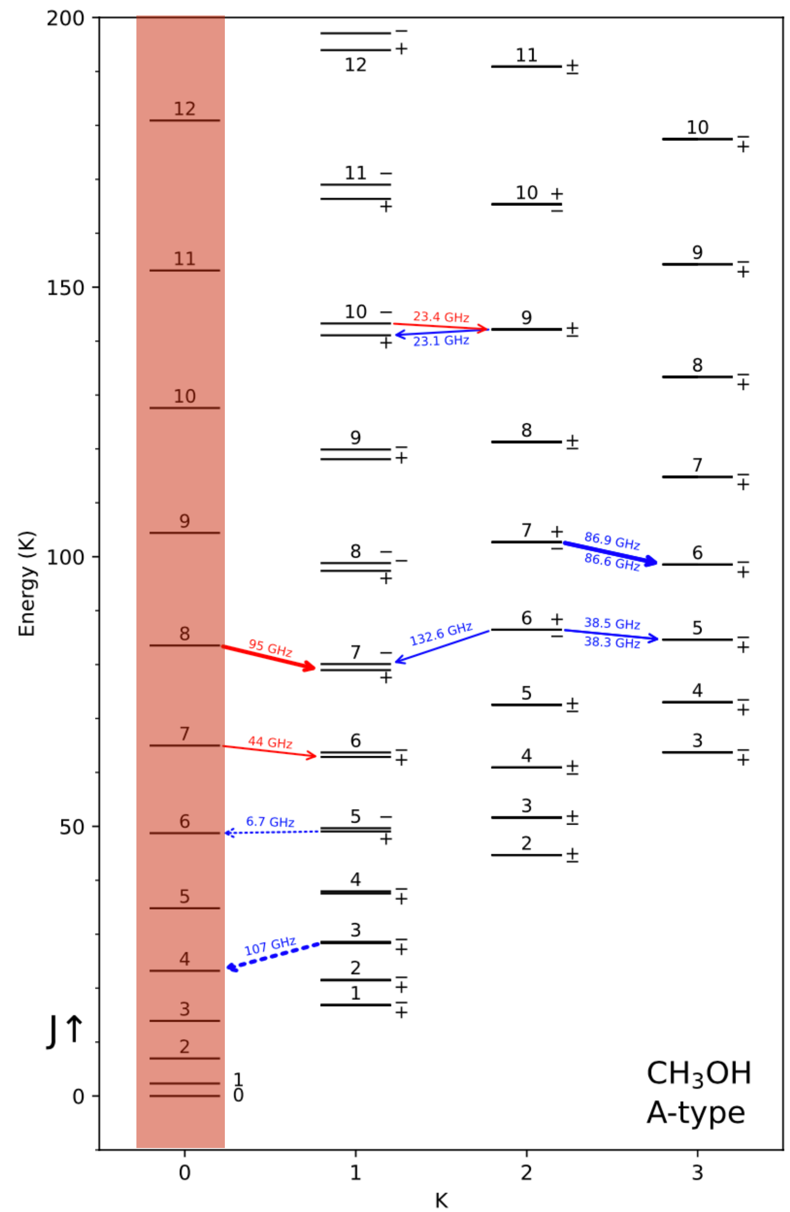


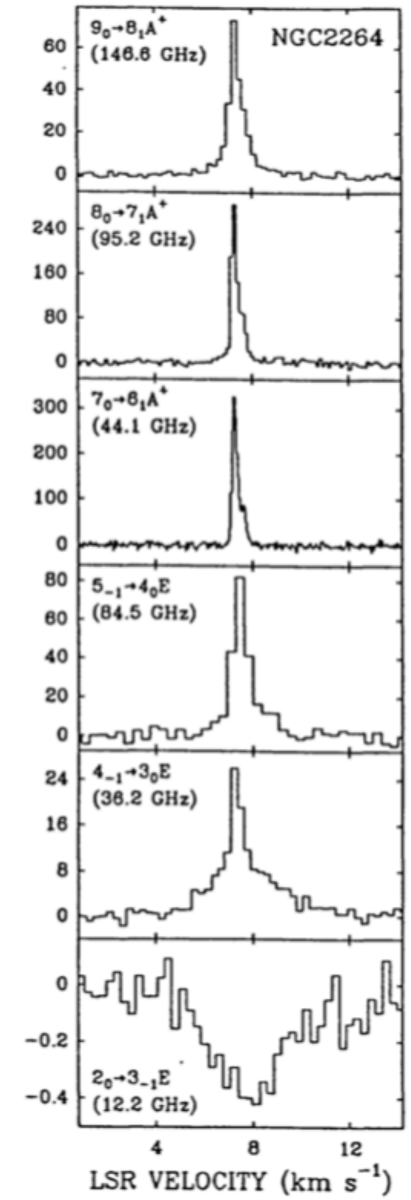
GLIMPSE IRAC 8.0 4.5 3.6 μm
24 μm contour
◆ 6.7 GHz class II maser
+ 44 GHz class I maser

Cyganowski+(2009)

1.2 Class I CH_3OH maser pumping mechanism







Menten(1991)

Collisional rates and selection rules —> $\Delta k = 0$, a dependence upon ΔJ as $1/\Delta J$ (Lees+1974)

When collisional excitation dominates:

E- type CH_3OH: k = -1 over-populated relative to k = 0 or -2

Maser action in the $J_{-1} \rightarrow (J-1)_0$ E lines (36, 84 GHz..), $J_{-1} \rightarrow (J-1)_{-2}$ E lines (104.3 GHz), **$T_{ex} < 0$**

Anti-inversion (i.e. enhanced absorption) at $2_0 \rightarrow 3_{-1}$ E (12.2 GHz), **$0 < T_{ex} < T_{CMB}$**

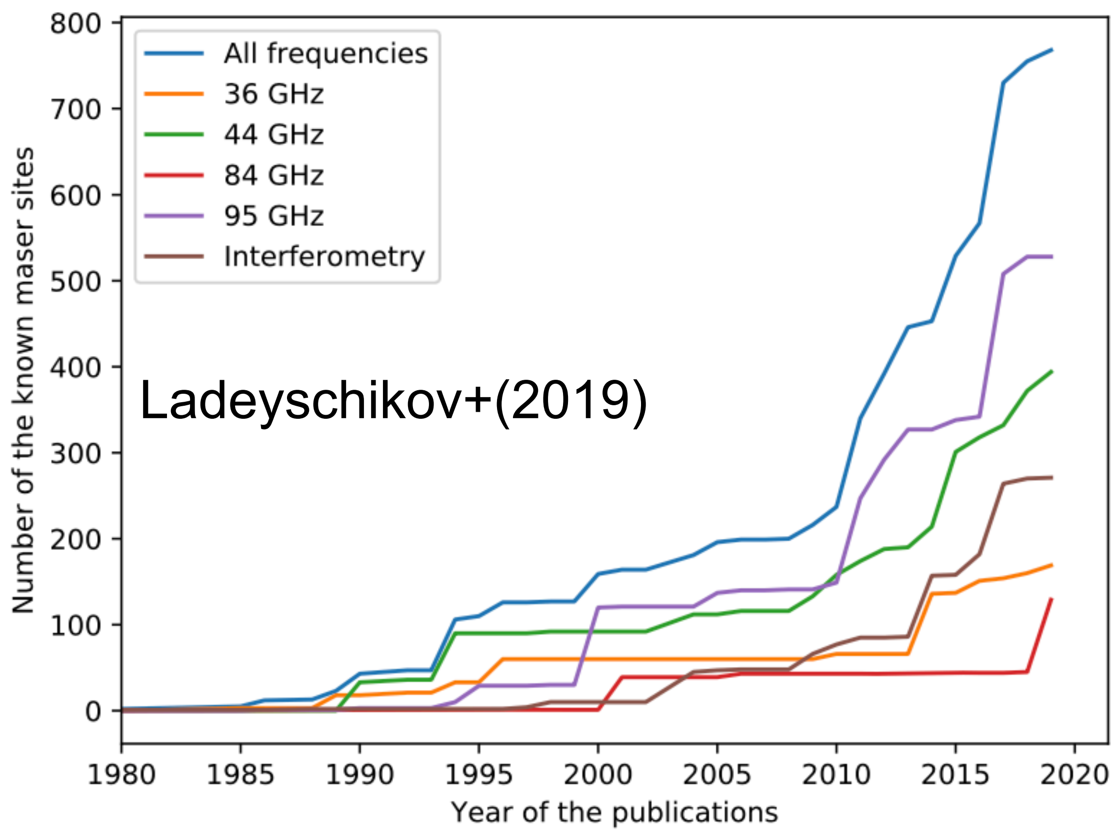
A- type CH_3OH: K = 0 over-populated relative to K = 1

Maser action in the $J_0 \rightarrow (J-1)_1$ A+ lines (44, 95 GHz..)

Anti-inversion at $5_1 \rightarrow 6_0$ A+ (6.7 GHz) and $3_1 \rightarrow 4_0$ A+ (107 GHz)

1.2 Nine CH_3OH maser transitions at 3 mm (84-116 GHz)

- **Wide spread class I masers at 84, 95 GHz**
  84 GHz 129 known (e.g., Breen+2019)
  95 GHz 534 known (e.g., Chen+2011, 2012, 2013, Yang+2017)



- **Rare class I maser at 104.3 GHz**
  5 known
  104.3 GHz mopra survey: a detection rate of 2/69 ~3% (Voronkov 2007)

- **Rare class II masers at 85.6, 85.6, 86.9, 104.1, 107 and 108 GHz.**

  107 GHz
  25/175 known 6.7 GHz masers;
  5 sources show absorption
  (Val'tts+1995,1999, Caswell+2000, Minier+2002)

  85.6, 86.6, 86.9 GHz masers
  4,4,3 known, observing targets < 150
  (e.g. Cragg+2001, Ellingsen+2003)

  104.1 and 108 GHz maser
  ONLY found in G345.01+1.79
  (Val'tts+1998, Ellingsen+2012)

1.3 Motivations

1. **Study these so far fewer detected and less studied masers**
   Large/Complete survey → new maser sources
   Rare maser species → unusual excitation conditions, tracing a short stage

2. **Why we need multiple transitions for one source?**
   Line ratios usually gives stronger constraints on physical conditions than one single line

3. **Study the statistical relationships between class I masers and shocks**
   84, and 95 GHz masers in a large sample survey
   \+ shock tracer (such as SiO)

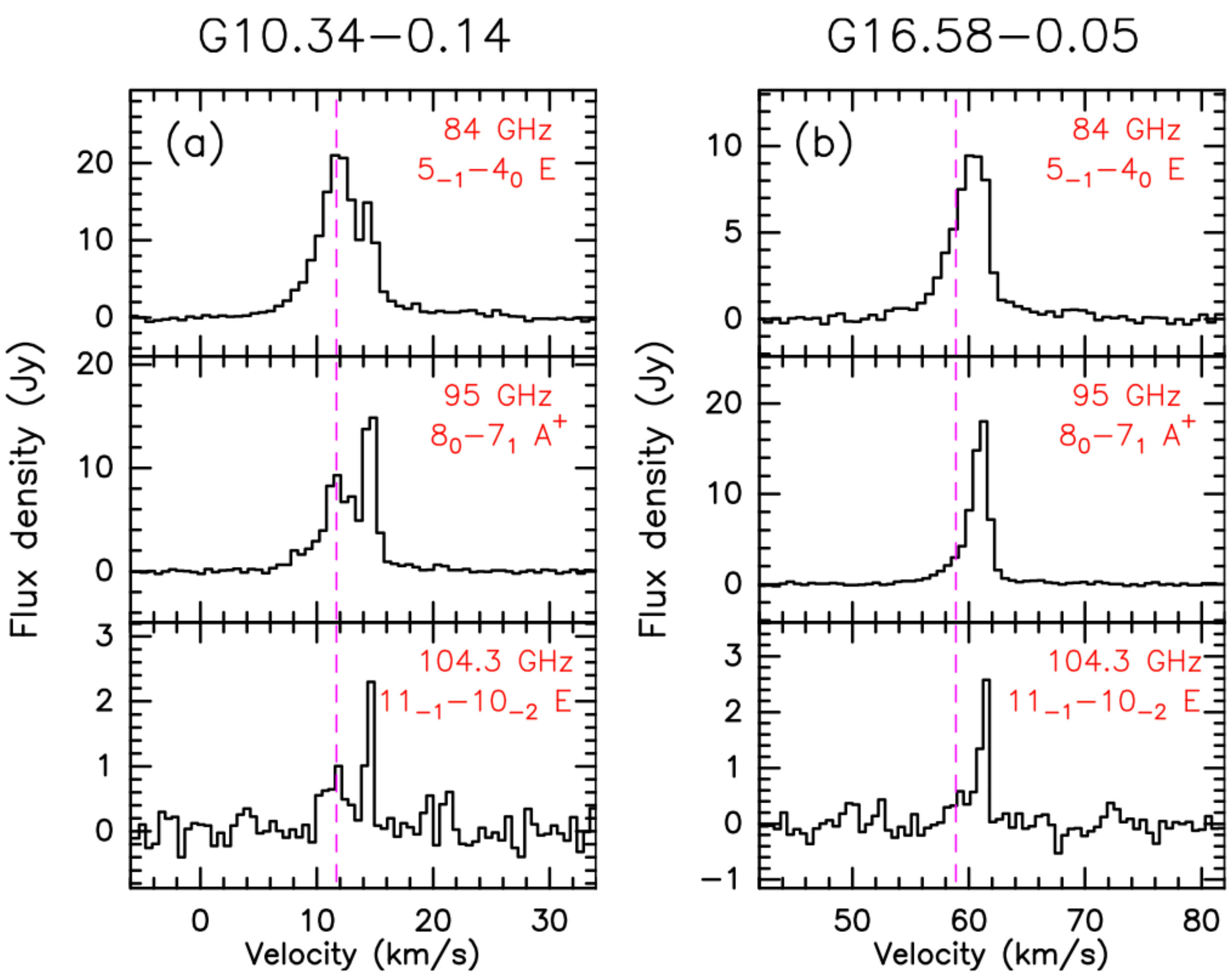
2.1 Targeted sample: massive ATLASGAL clumps

- **A**PEX **T**elescope **L**arge **A**rea **S**urvey of the **Gal**axy
  an unbiased 870-μm sub-millimetre continuum survey (300° < l < 60°, |b| < 1.5°)
- A large inventory of dense molecular clumps (~10 000 clumps; e.g. Csengeri+2014)
- Full evolutionary stages (from starless to evolved HII regions, e.g. Urquhart+2022)

- IRAM observations at 3mm (84 —116 GHz) toward **408 ATLASGAL clumps** (6° < l < 60°)
  The brightest ATLASGAL clumps with 1) infrared bright; 2) embedded massive (proto)stars; 3) 8 μm dark + 24 μm bright; 4) 8 and 24 μm dark → cover full evolutionary stages
- Observing dates: 2010.05 — 2012.10
- Beam size: 29 — 23 arcsec, Vres ~ 0.8 — 0.6 km/s, typical 1σ ~ 0.2 Jy
- SiO (Csengeri+2016)
- **The largest survey to search for 84, 85.5, 86.6, 86.9, 104.1, 104.3, 107 and 108 GHz masers**

2.2 Overview of CH_3OH maser detections

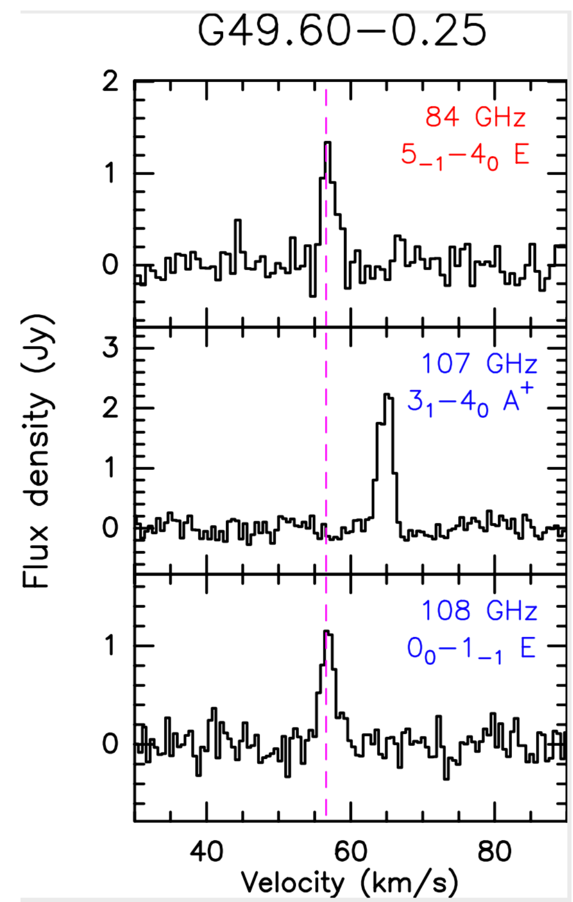
- **Class I CH_3OH masers:**
  54 (50 new) @84 GHz
  100 (29 new) @95 GHz
  4 (4 new) @104.3 GHz; Known: 5 → 9

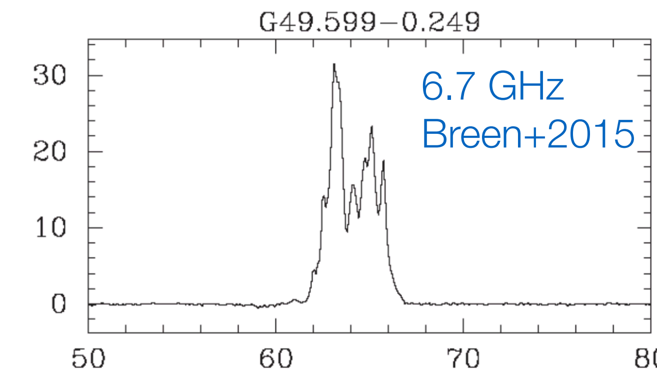


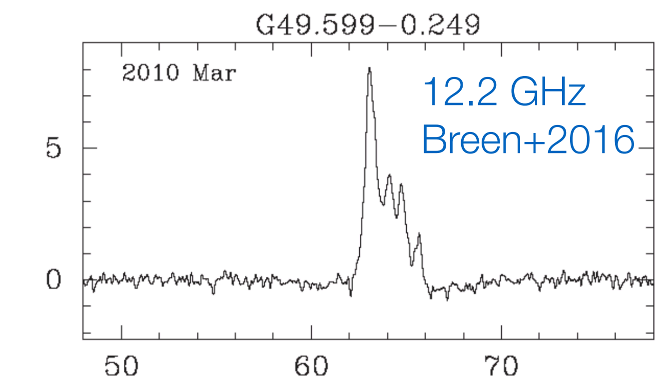
class I maser velocity alignments

[Yang+ 2023, A&A, 675, A112]

- **Class II CH_3OH masers:**
  11 (8 new) @107 GHz; Known: 25 → 33
  No sources show maser emission at 85.5, 86.6, 86.9, 104.1 and 108 GHz



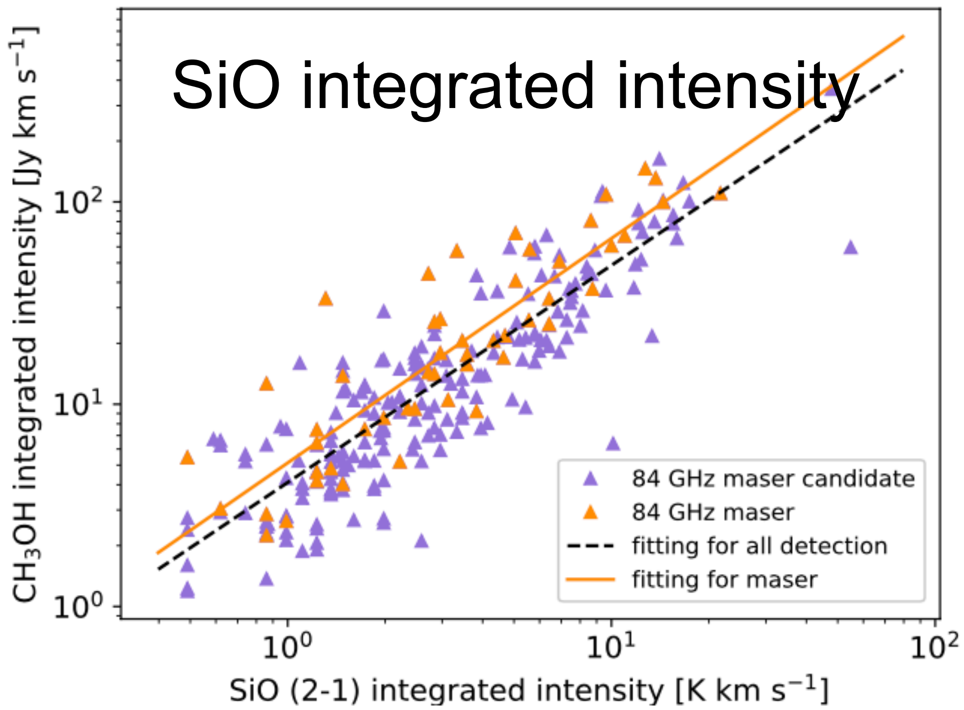


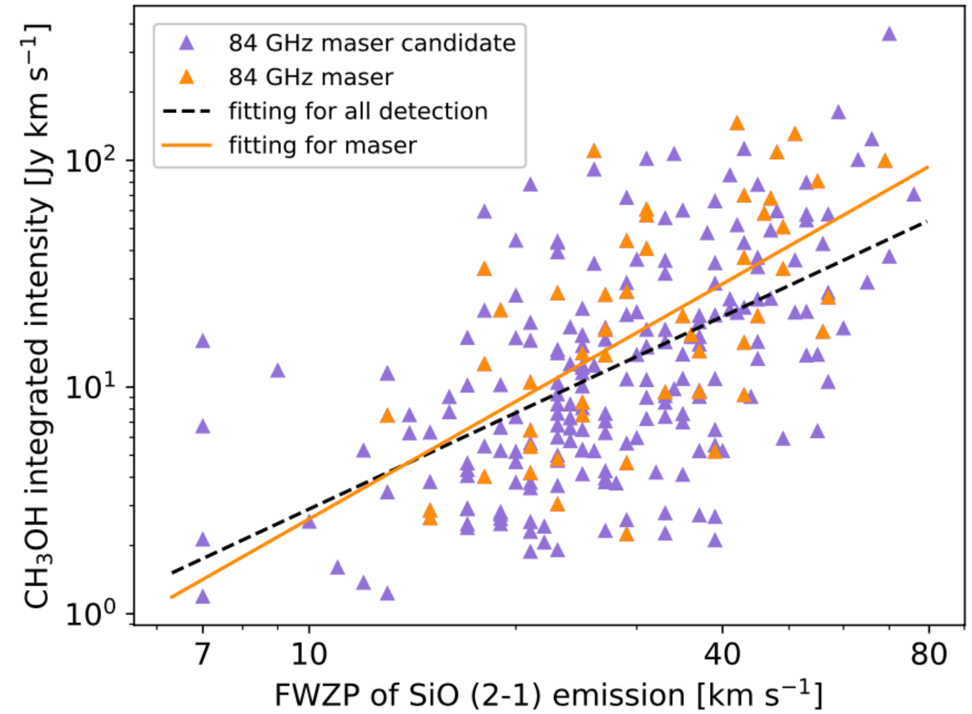


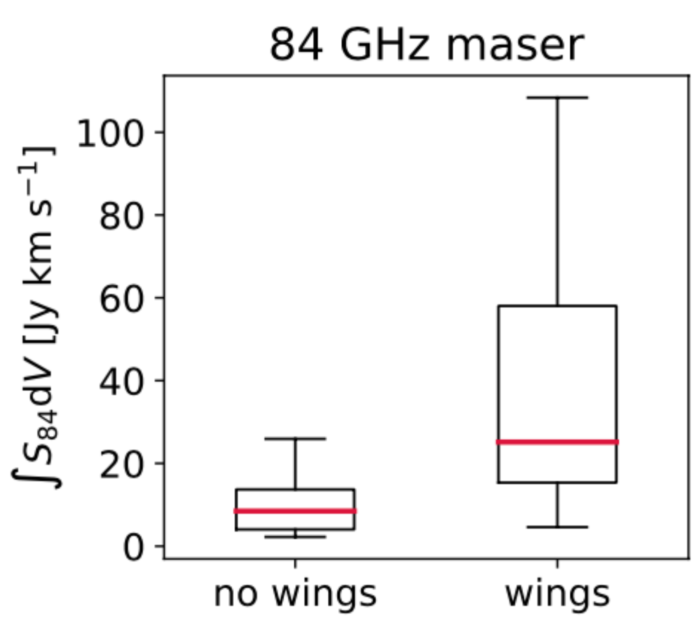
107 GHz maser velocity aligns with the strongest 6.7 +12.2 GHz

[Yang+ in prep.]

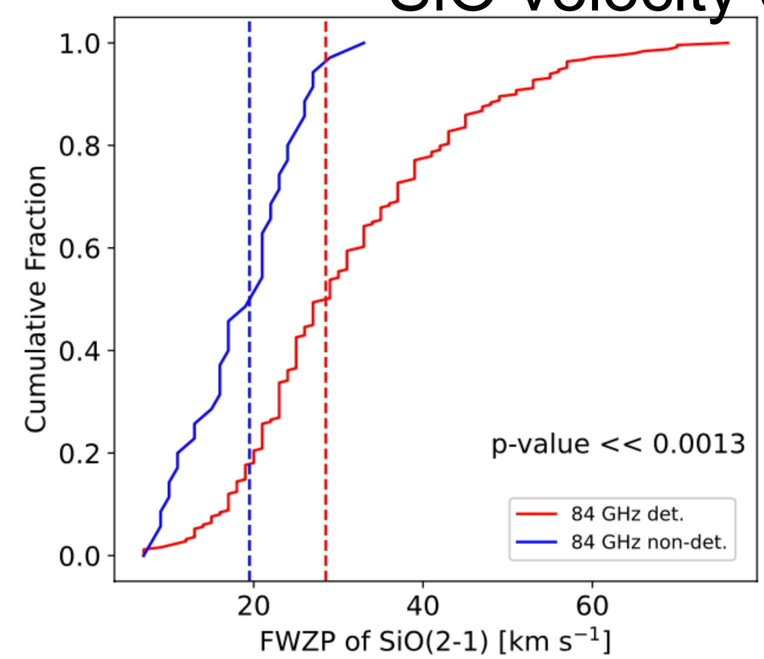
2.3 The properties of class I masers are regulated by shock properties traced by SiO





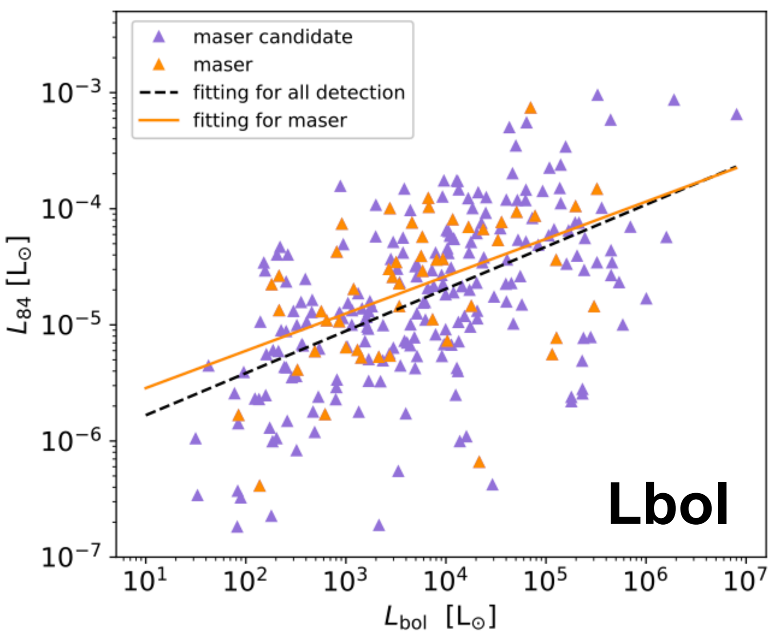


SiO velocity coverage

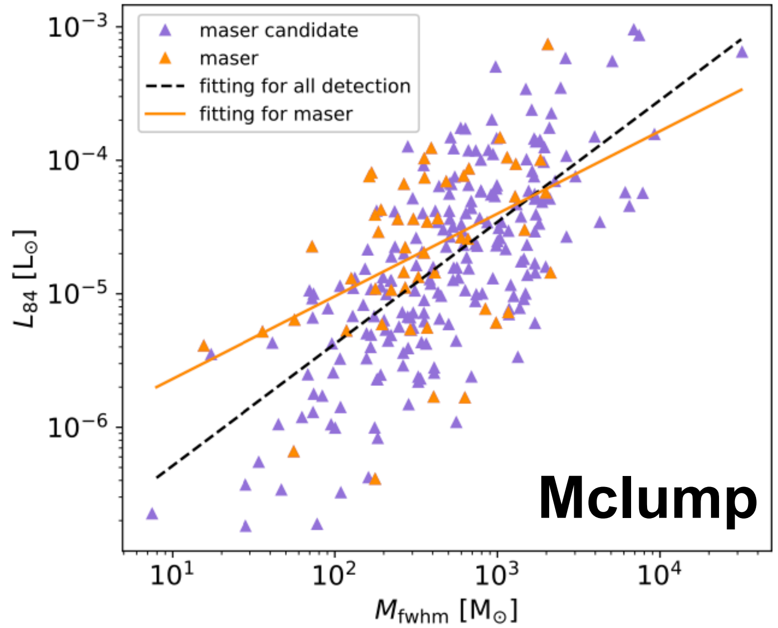


Stronger maser with SiO wings

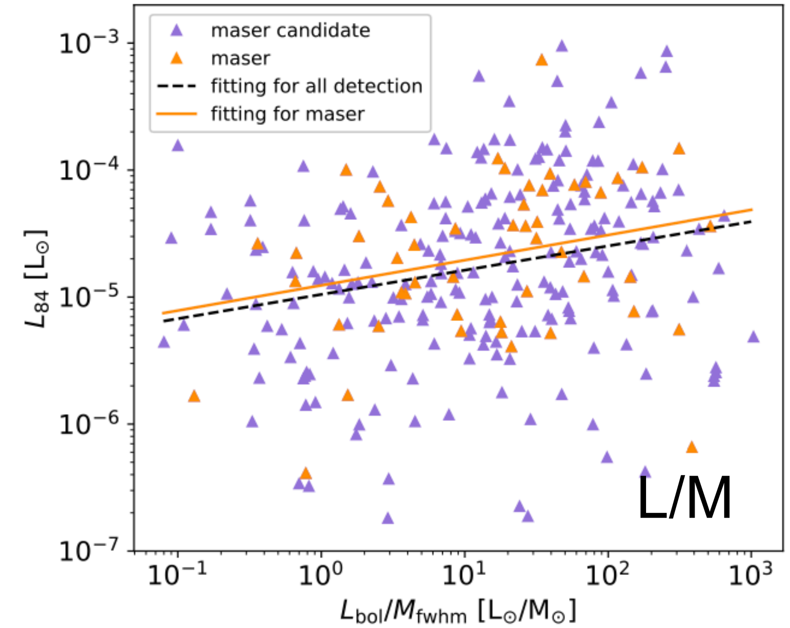
2.3 ATLASGAL clumps properties: correlations



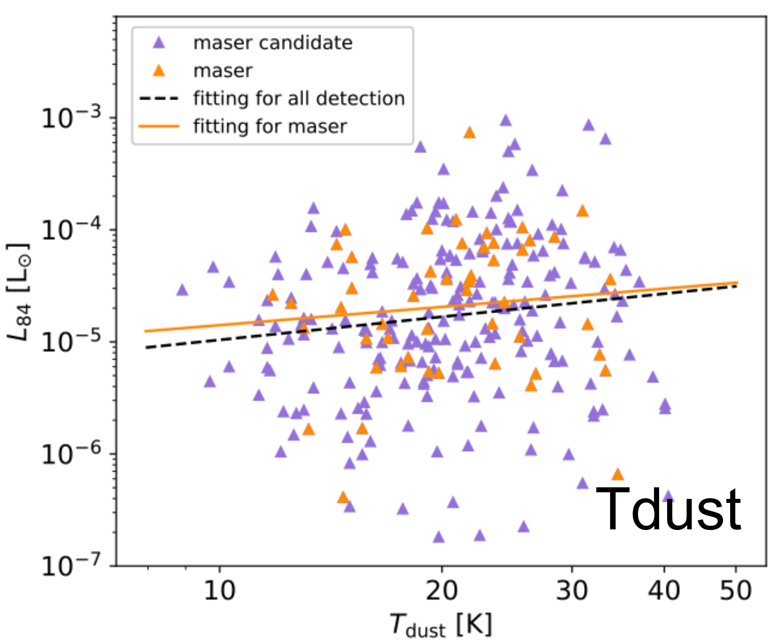
(a)



(b)



(c)



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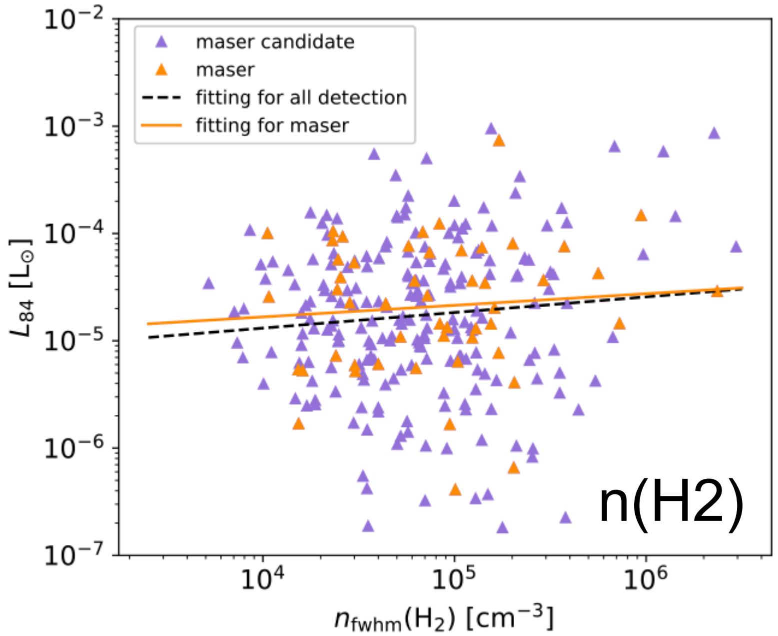

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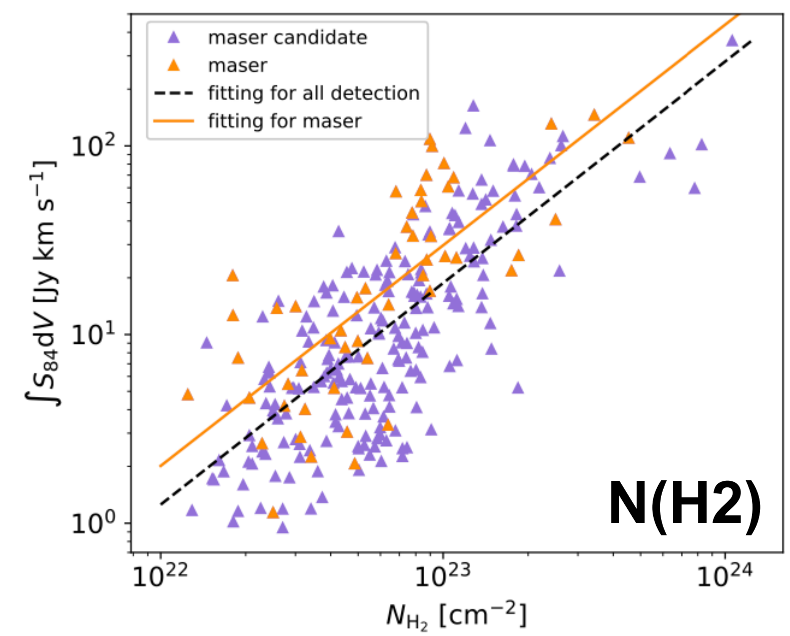
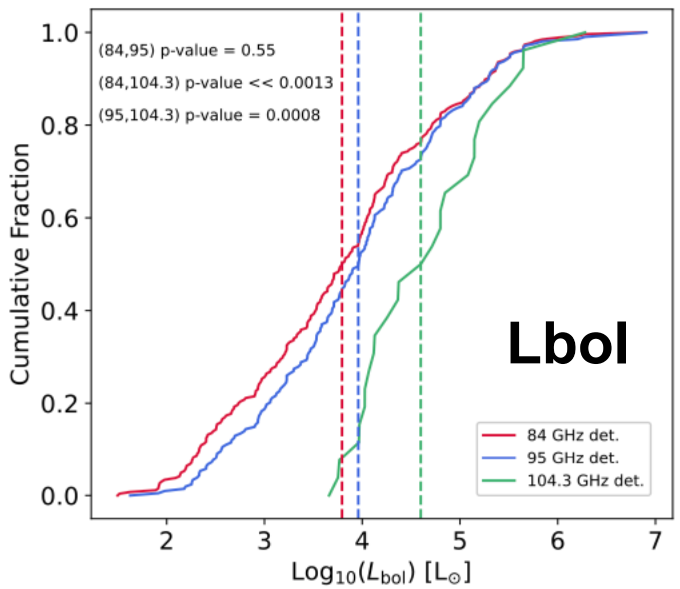


(f)

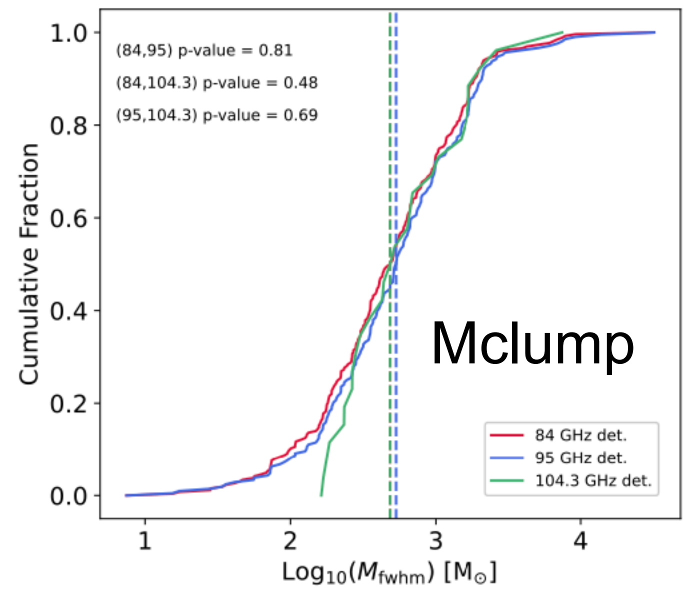
Positive correlations: Lbol, Mclump, N(H2)

No statistically correlation: L/M, Tdust, n(H2)

2.3 ATLASGAL clumps properties: comparisons



(a)



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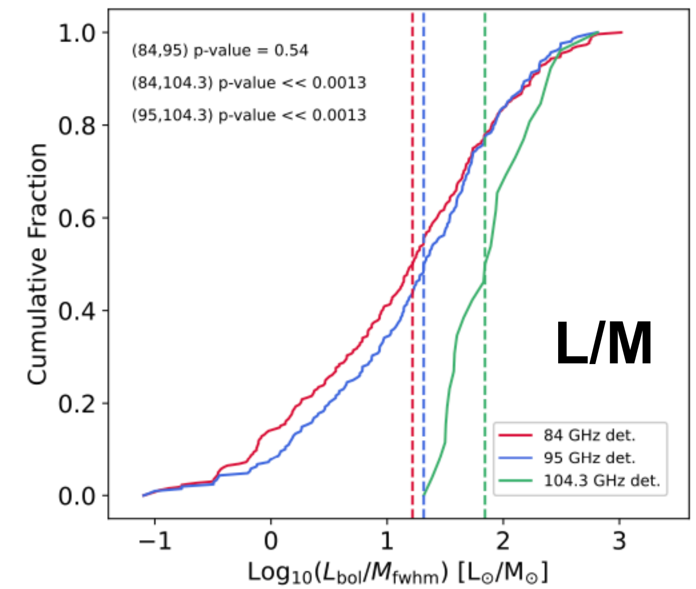

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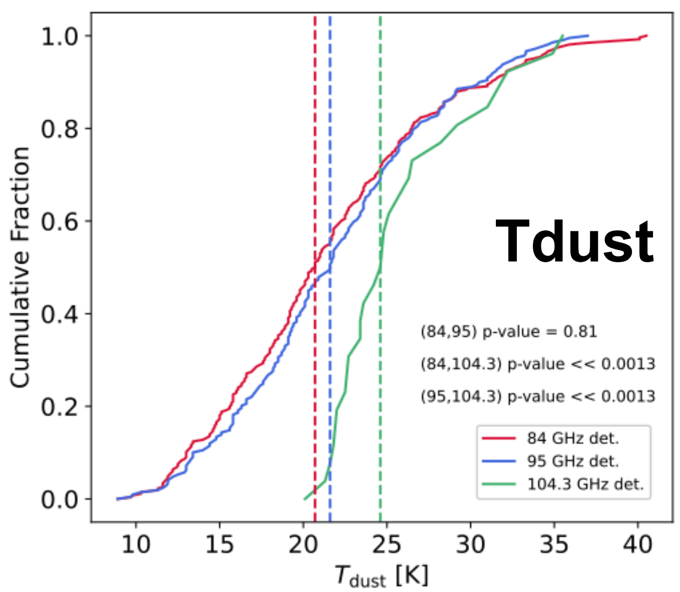

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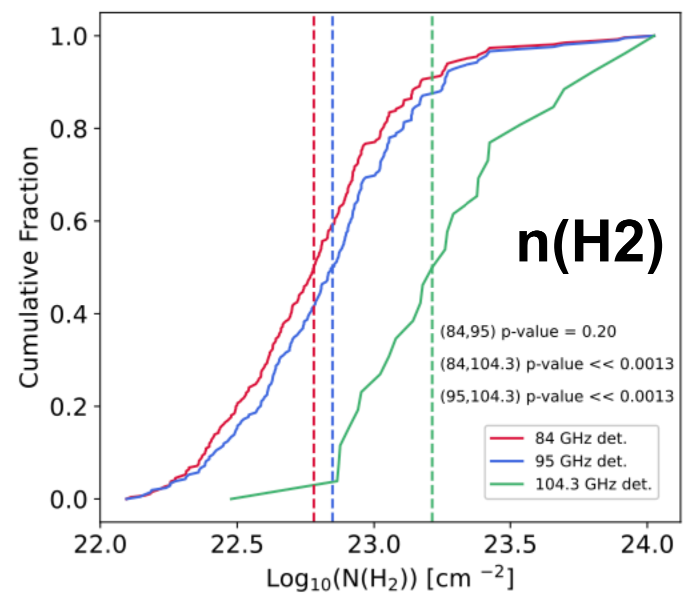

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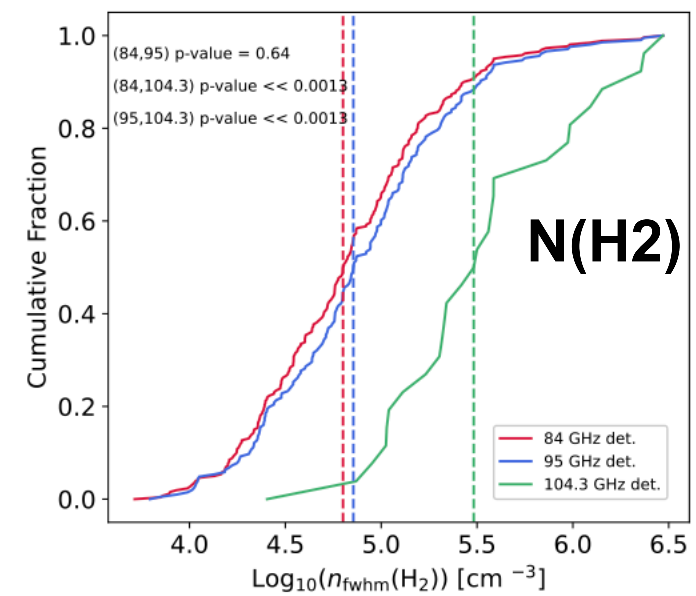
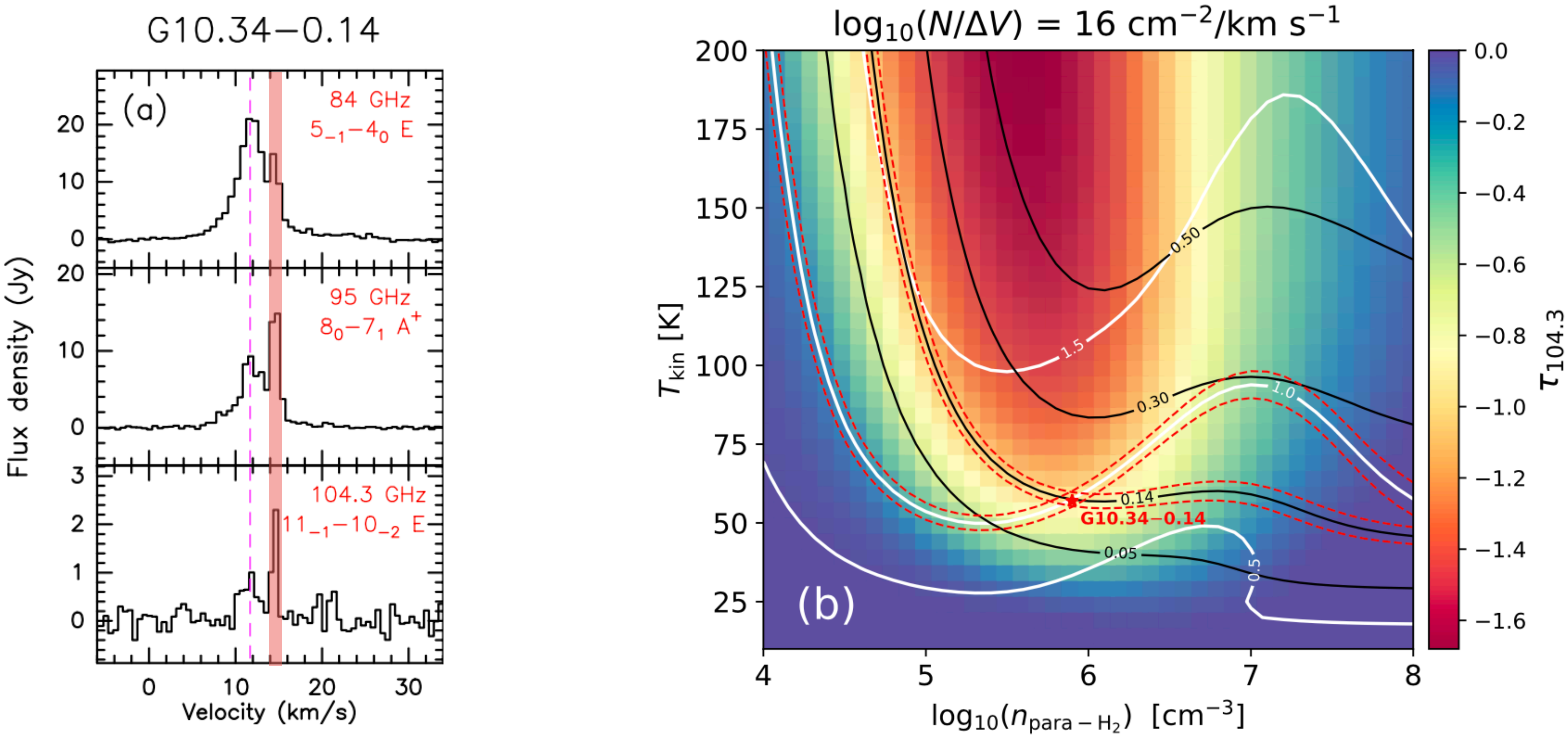


(f)

Clumps with 104.3 GHz masers generally show **brighter Lbol**, **warmer Tdust**, **larger L/M ratios,** and **denser environments**.

2.4 Co-spatial line ratios better constrain conditions



Black contour: $T_{R104.3}/T_{R84}$
White contour: T_{R95}/T_{R84}

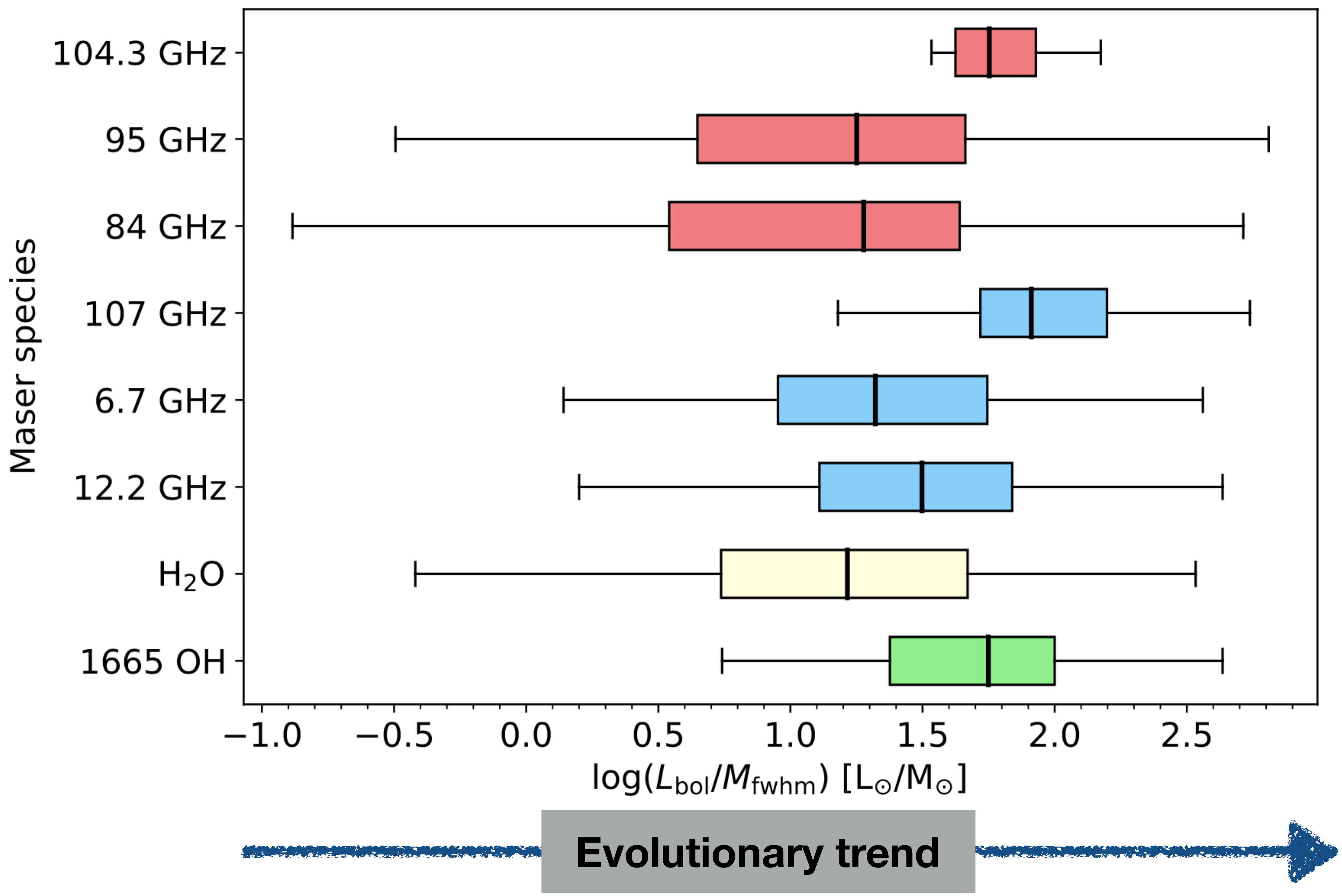
- myRadex (a RADEX analog; Du 2022)

- Maser feature at 15 km/s in G10.34-0.14

→ T_{kin} = 57±3 K

n(para-H_2) = 7.9(±2.5)×10^5 cm^{-3}

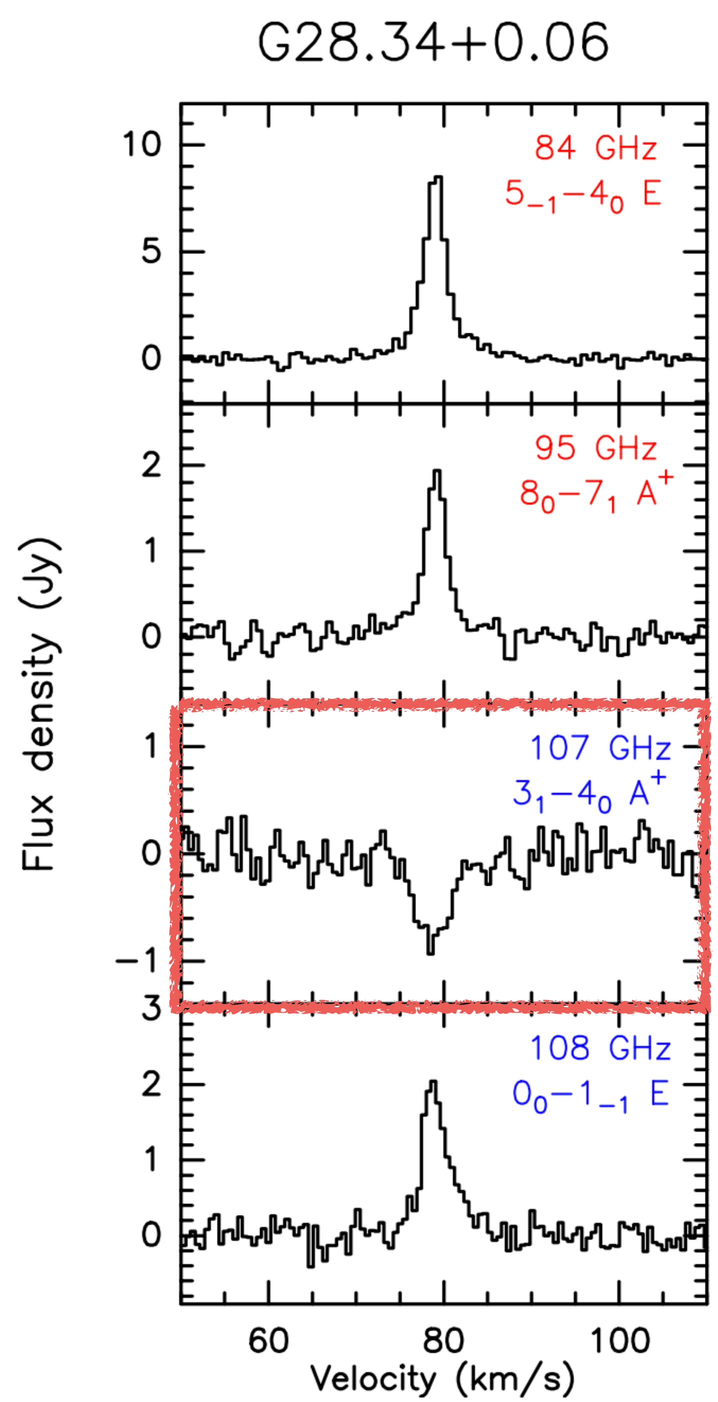
2.5 The evolutionary stage of masers



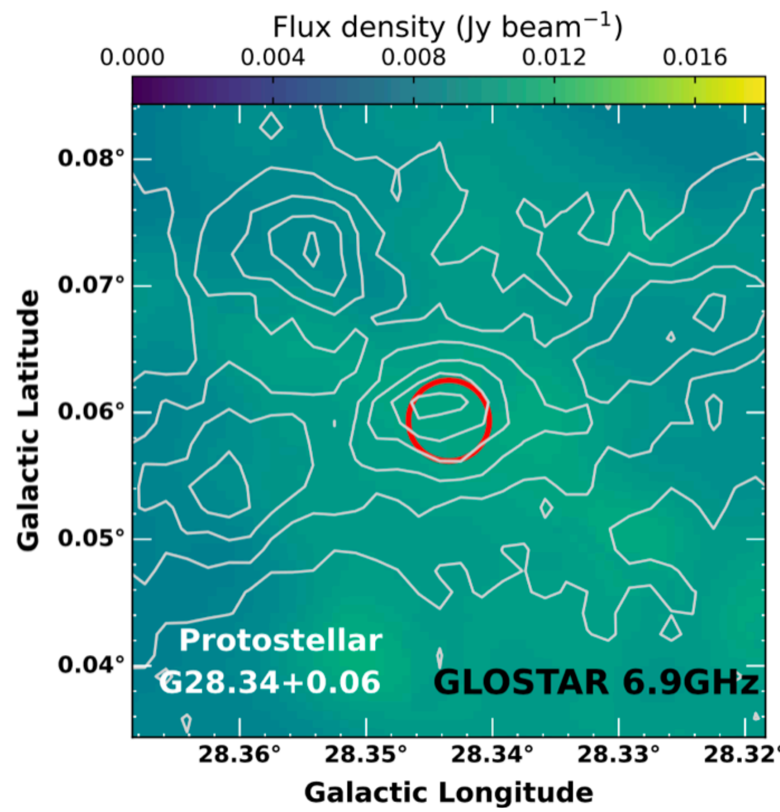
[Yang+2024, IAU, 380, 266]

3.1 107 GHz methanol absorption

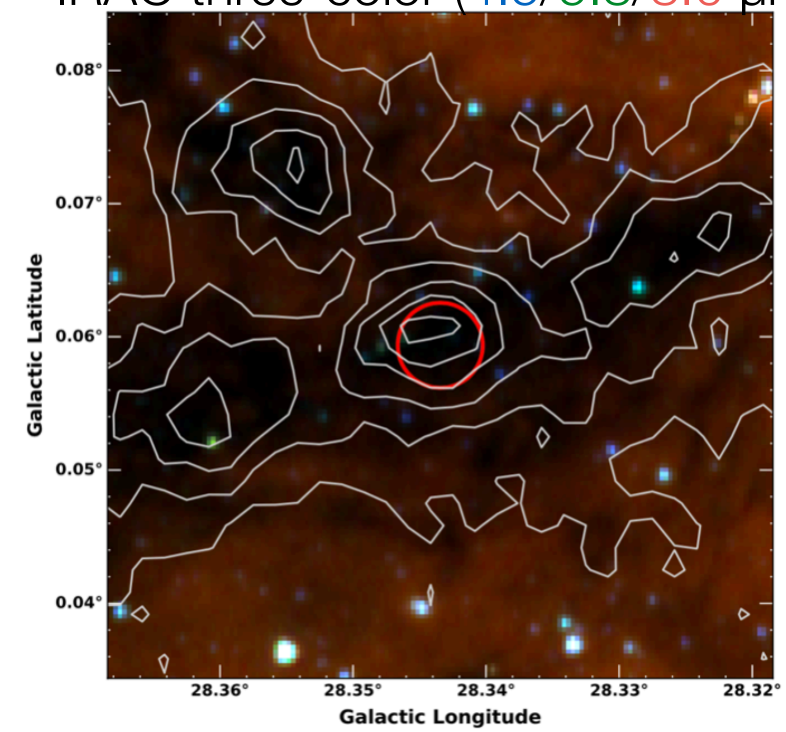
19 newly detected absorption features → 24 known 107 GHz absorption



protostellar



IRAC three-color (4.5/5.8/8.0 μm) map



$$T_L = (J_\nu(T_{ex}) - J_\nu(T_c) - J_\nu(T_{bg}))(1 - e^{-\tau_\nu}) < 0 \qquad J_\nu(T) = \frac{h\nu/k}{e^{h\nu/kT} - 1}$$

Analysis on dust and free-free emission

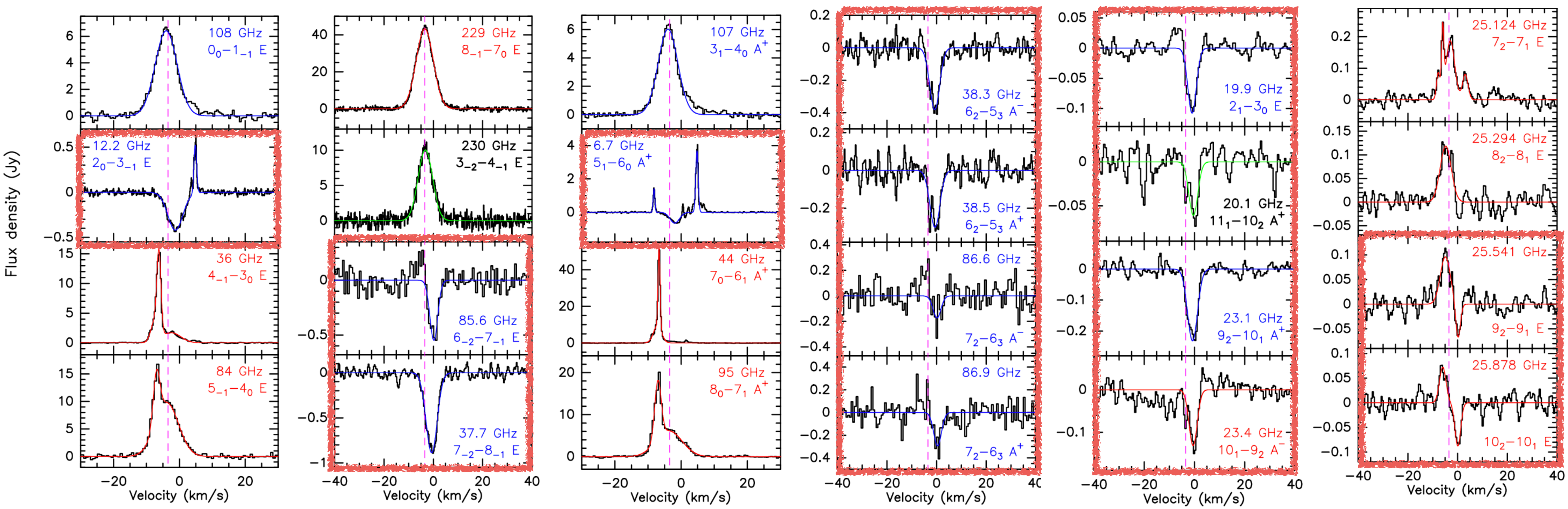
→ $T_c << T_{bg}$

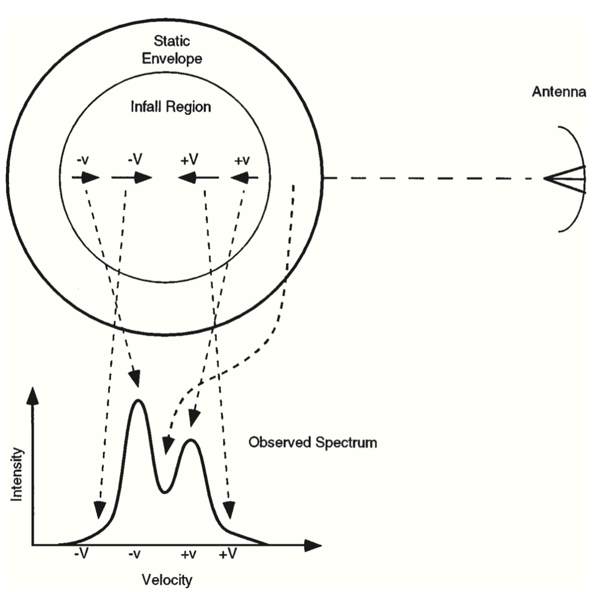
→ 107 GHz CH_3OH absorption toward CMB, $T_{ex} < T_{bg}$

anti-inversion

[Yang+ in prep.]

3.2 Redshifted CH_3OH absorptions trace infall motions in AGAL010.624−00.384 (W31C)





Bright continuum background (f-f) + over-cooling
→ enhance the absorption lines' detectability

14 methanol lines show redshifted absorption features
→ trace infall motions within HMSFRs hosting bright HII regions

[Yang+ 2022, A&A, 658, A192]

Summary

- **Highlighted detections**

4 (4 new) rare class I masers at 104.3 GHz (known 5 → 9)
11 (8 new) rare class II masers at 107 GHz (known 25 → 33)
19 new sources with 107 GHz absorption features → anti-inversion

Redshifted methanol absorption trace infall motions in AGAL010.624−00.384 (W31C)

- Rare masers appear to trace a short and evolved stage

- The properties of class I CH_3OH masers are regulated by SiO traced shocks

- Physical conditions can be better constrained in regions with multiple class I CH_3OH masers

Thanks for your attention!

Homepage: https://wjyang7.github.io