On the origin of C_4H and CH_3OH in protostars

A study of the physics and chemistry of embedded protostars

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in collaboration with:

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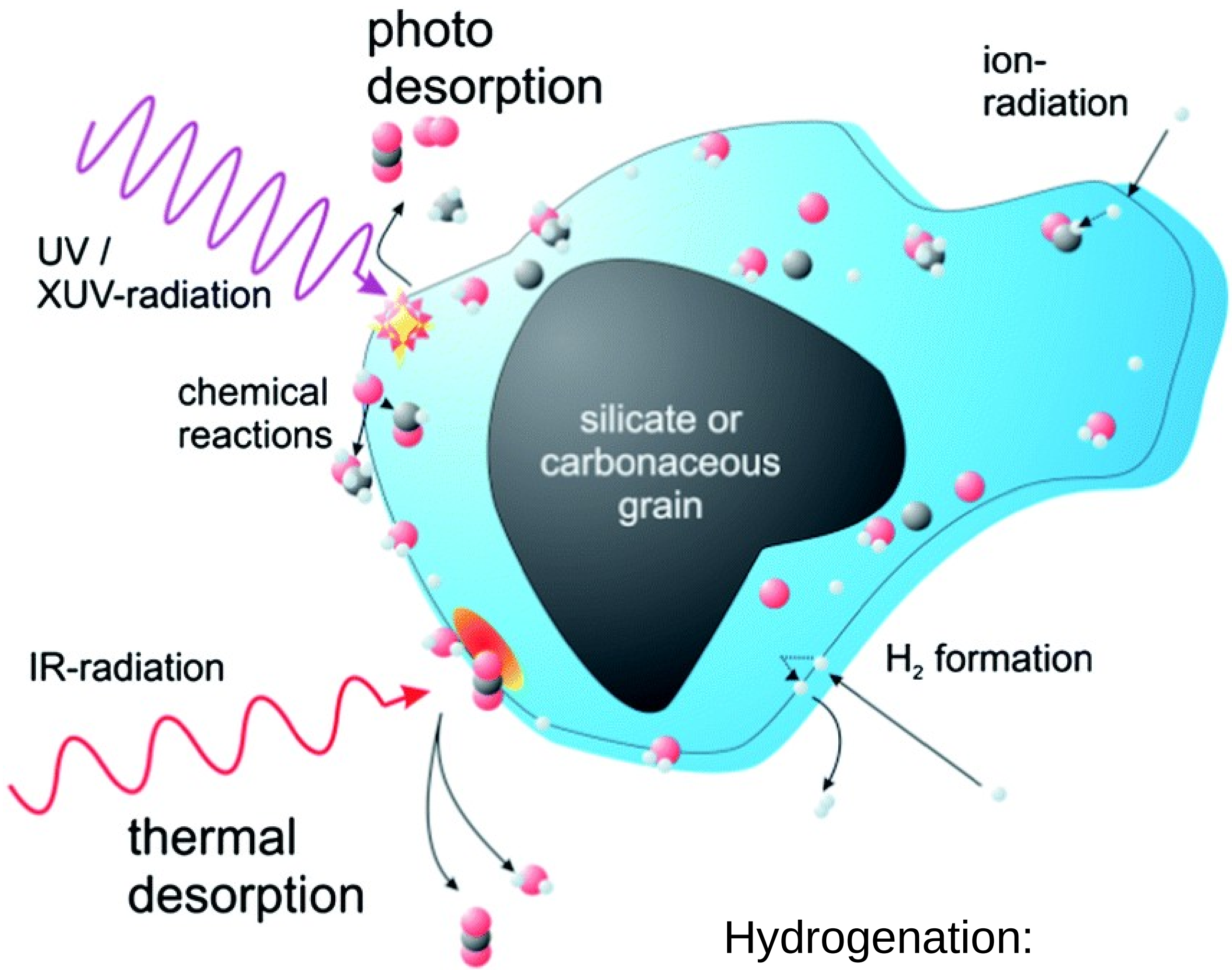
Outline

- Warm carbon-chain chemistry
- Line surveys of CrA and Ophiuchus
- C_4H and CH_3OH single-dish observations
- Future plans

Grain-surface chemistry



Hydrogenation:

C → CH → CH_2 → CH_3 → CH_4 (hydrides!)

CO → ... → H_2CO → ... → CH_3OH

One grain in every 100 m^3 at $n(H_2) = 10^4$ cm^{-3}

Credit: Siemer et al. (2014), FaDi

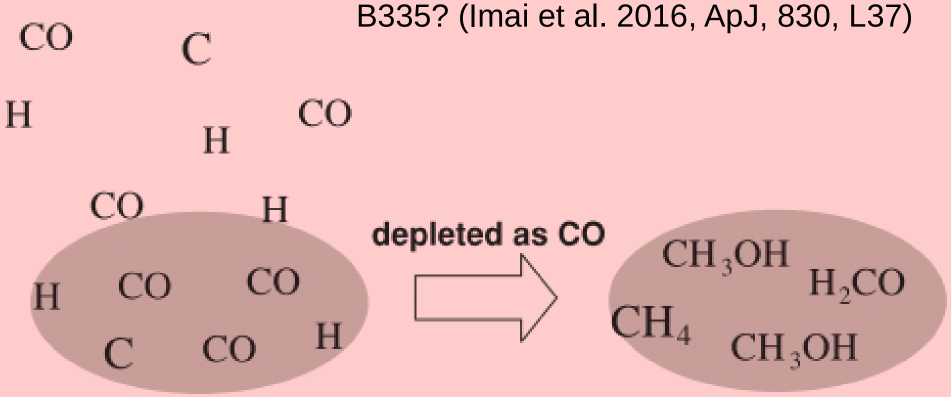
Complex molecules in low-mass Class 0 protostars: *Hot corino* vs. Warm Carbon Chain Chemistry sources

***Hot corino* sources**

- Complex organic molecules (CH_3OCH_3, $HCOOCH_3$, ...)
- Long pre-stellar phase:

  C → CO before freezeout
- T_{ex} ~ 100 K (COMs: high T_{evap})
- ≥ 4 known sources:

  IRAS 16293-2422 (Ophiuchus)
  NGC 1333 IRAS2A (Perseus)
  NGC 1333 IRAS4A (Perseus)
  NGC 1333 IRAS4B (Perseus)
  B335? (Imai et al. 2016, ApJ, 830, L37)

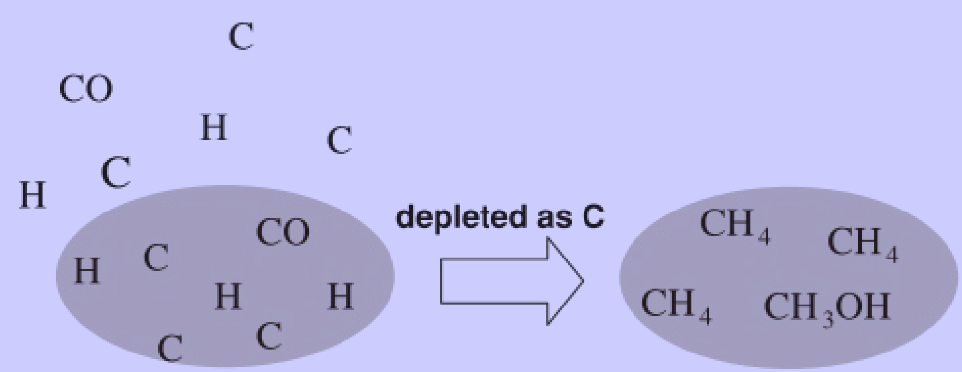


WCCC sources

- Long carbon chain species (C_4H, HC_5N, C_6H^-, ...)
- Short pre-stellar phase:

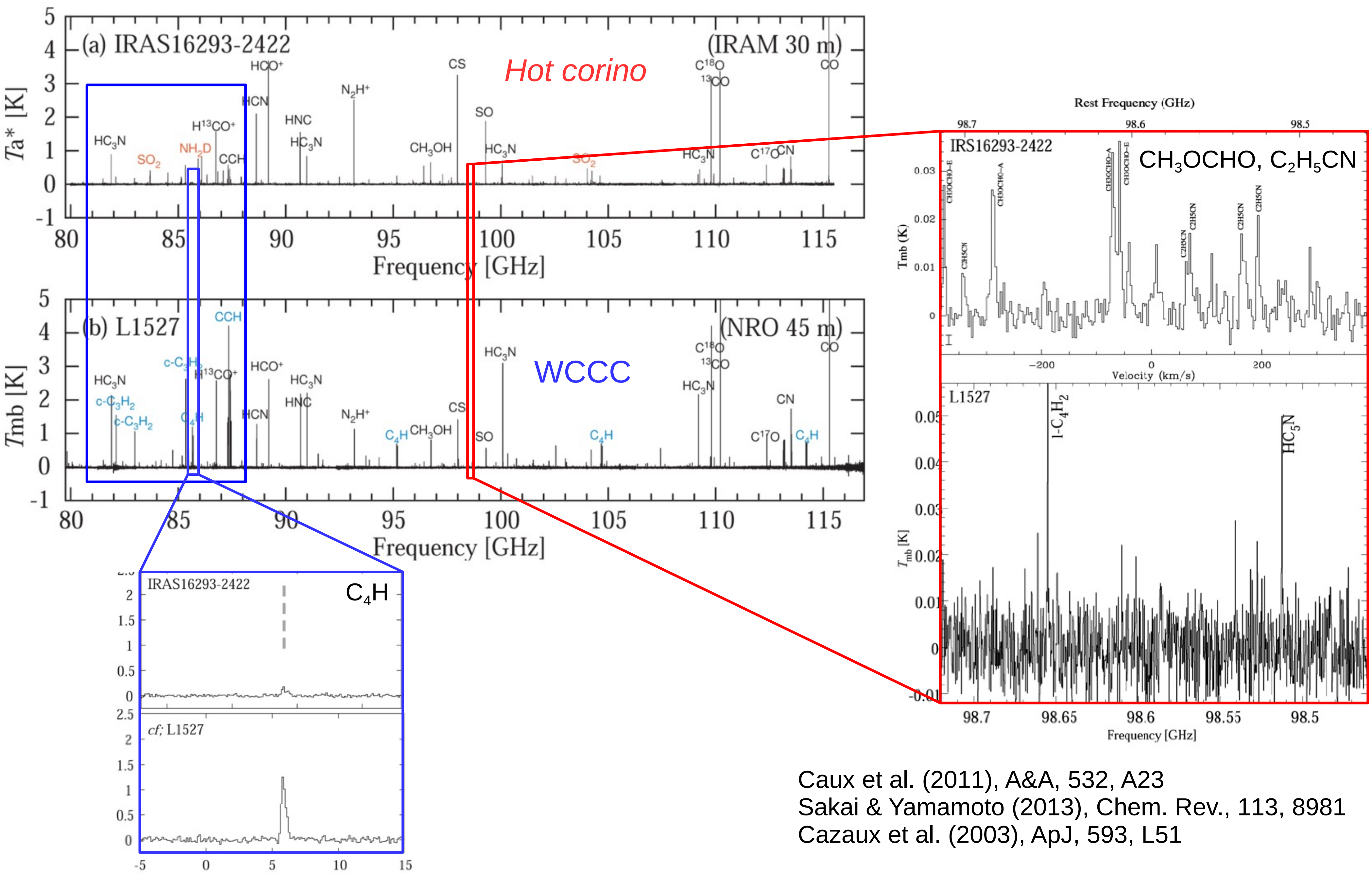
  C freezes out as atoms
- T_{ex} ~ 30 K (CH_4: low T_{evap})
- ≥ 2 known sources:

  L1527 IRAS 04368+2557 (Taurus)
  IRAS 15398-3357 (Lupus)



Sakai et al. (2009), ApJ, 697,769; Sakai & Yamamoto (2013), Chem. Rev., 113, 8981

Comparing *hot corino* and WCCC spectra

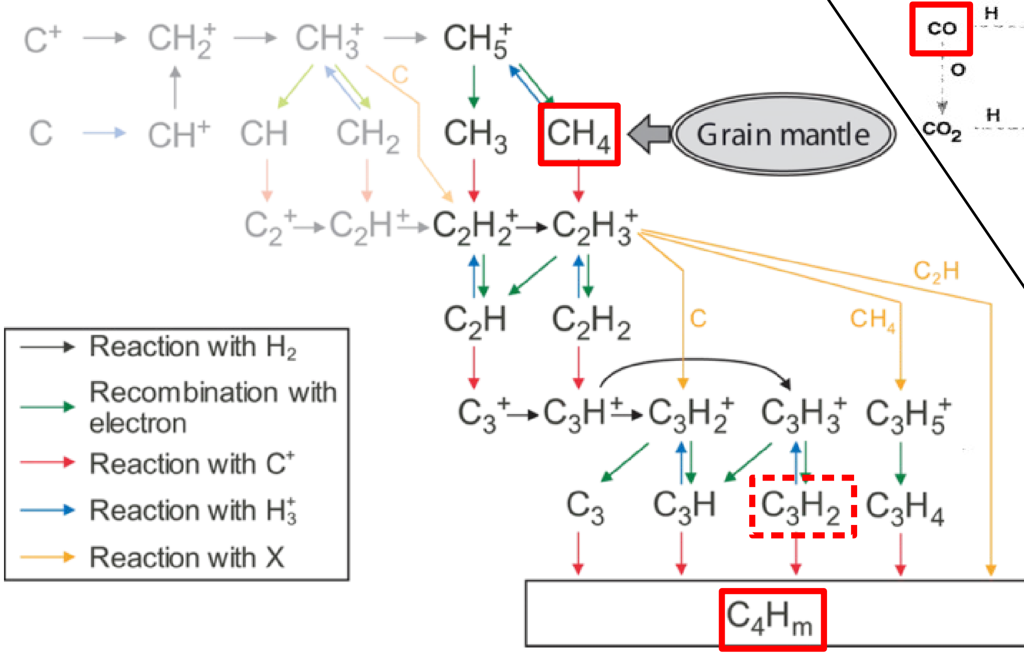


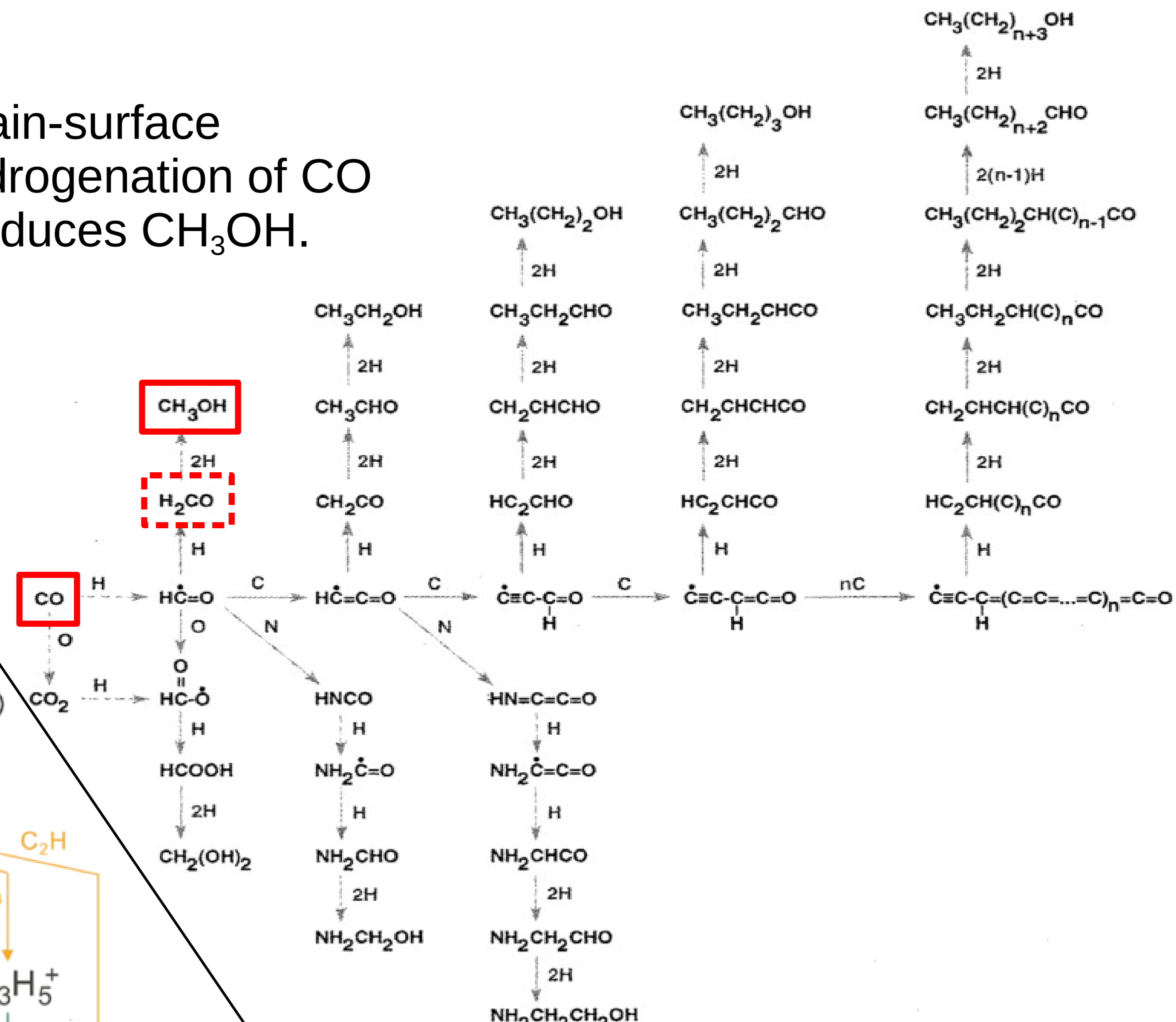
Caux et al. (2011), A&A, 532, A23
Sakai & Yamamoto (2013), Chem. Rev., 113, 8981
Cazaux et al. (2003), ApJ, 593, L51

Formation of complex organic molecules (COMs)

Gas-phase reactions of CH_4 produced on grain mantles form carbon chains such as C_4H.

Grain-surface hydrogenation of CO produces CH_3OH.





Charnley (2001), CNR, 139
see also Öberg et al. (2009), A&A, 504, 891

Sakai & Yamamoto (2013) Chem. Rev. 113, 8981

(Some COMs might also be formed in gas phase)

Line survey in R CrA IRS7B shows different T_{rot}

COMs, O- and S-bearing species: 23–40 K

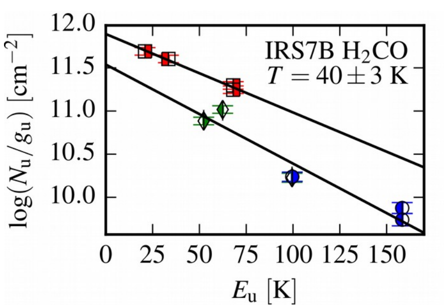
- H_2CO 40 K
- CH_3OH 28 K
- H_2CS 23 K
- SO 29 K
- SO_2 38 K
- CS 24 K

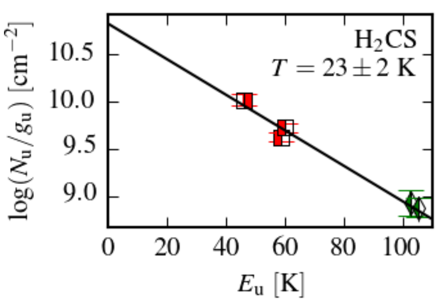
WCCC and CN-species: 10–17 K

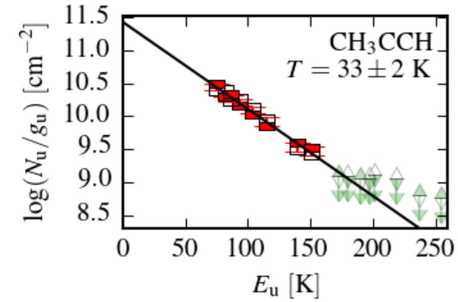
- CN 10 K
- DCN 11 K
- HC_3N 16 K
- C_2H 17 K
- *c*-C_3H_2 17 K

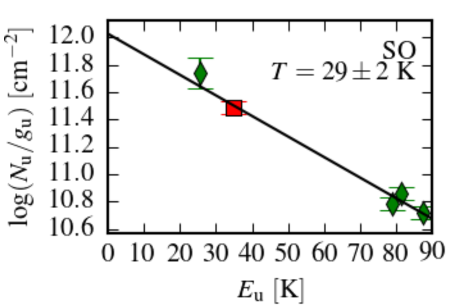
Exception:

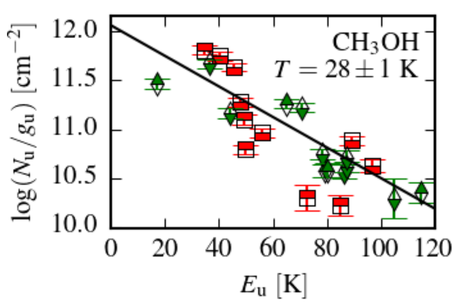
- CH_3CCH 33 K

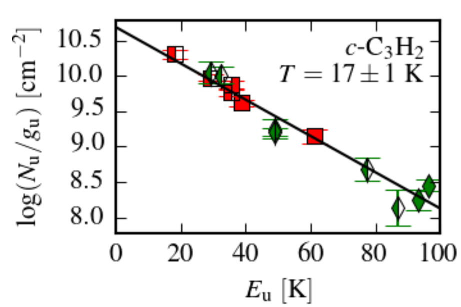


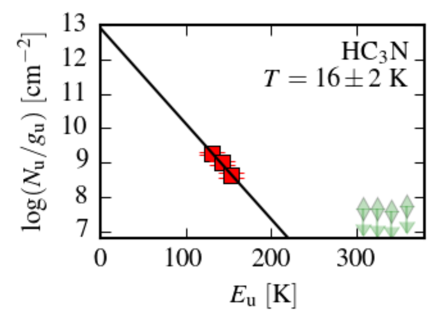










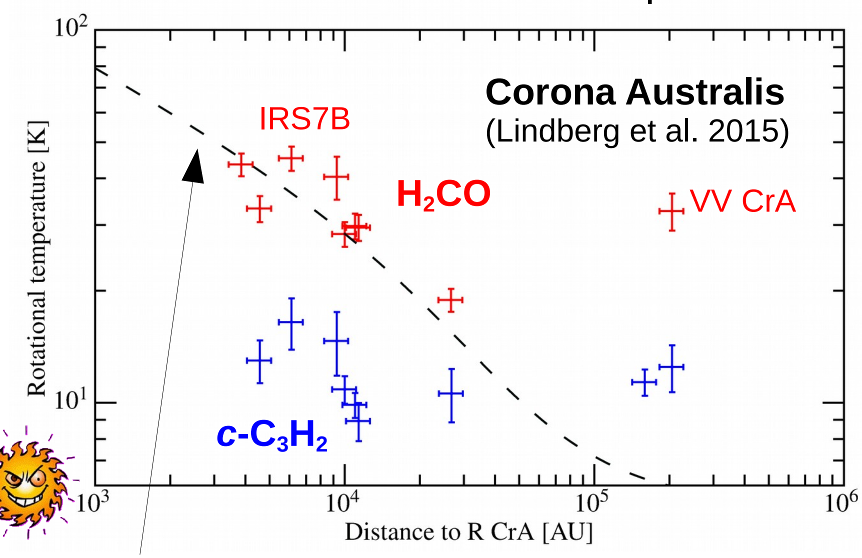


APEX 1.3 mm; ASTE 0.8 mm; APEX 0.8 mm

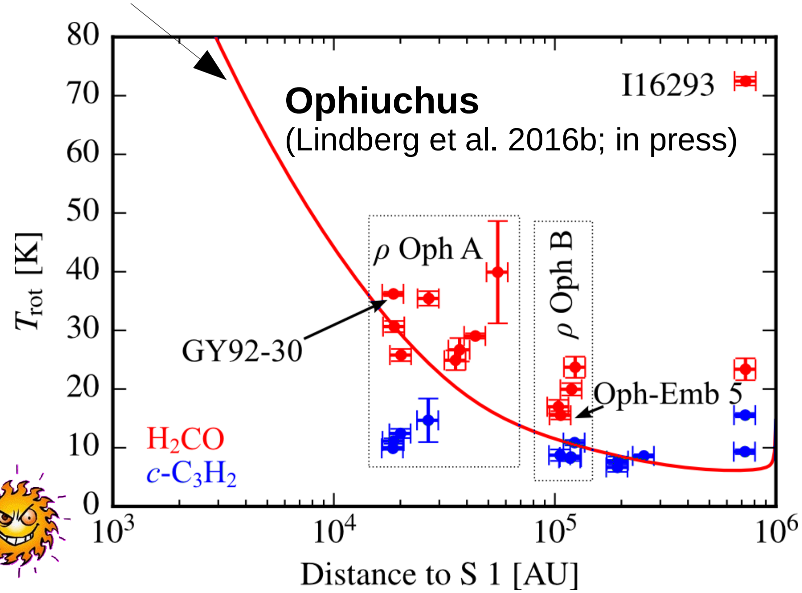
Lindberg et al. (2015), A&A, 584, A28

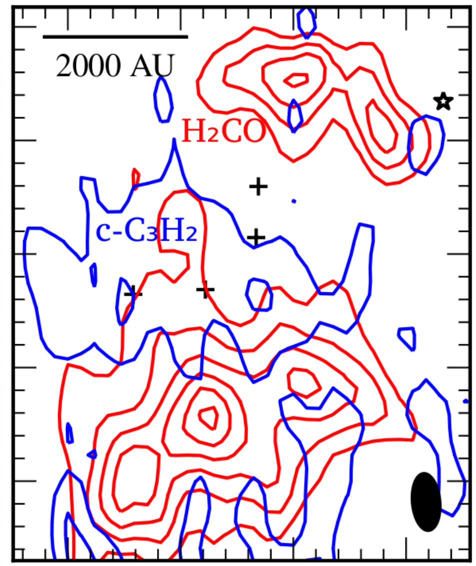
Other signs of COM/WCCC differentiation

APEX single-dish $T(H_2CO)$ and $T(c\text{-}C_3H_2)$ measurements towards embedded protostars:



Spherical (1-D) *Transphere* models of external heating

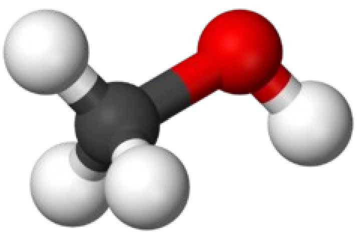




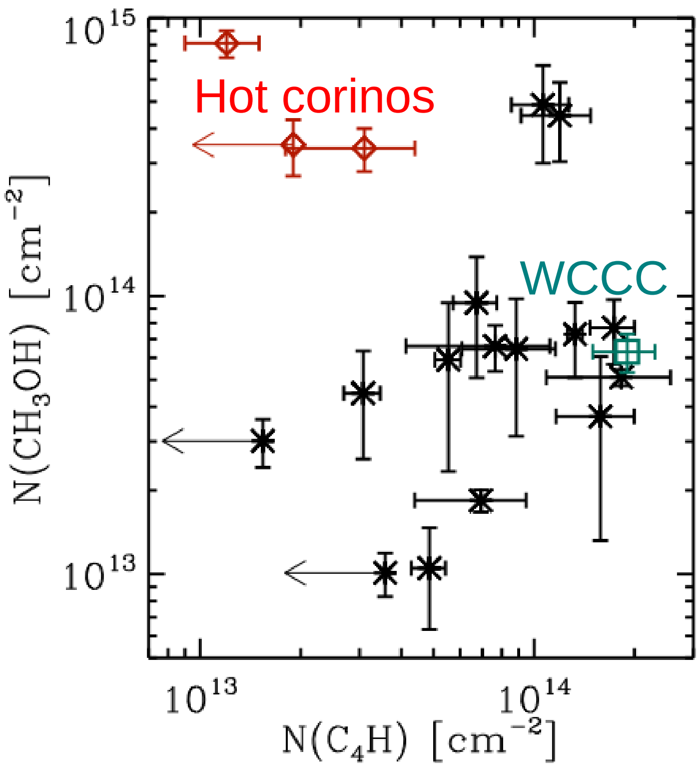
SMA map around IRS7B
Resolution: 6"x3" (800x400 AU)
(Lindberg & Jørgensen 2012)

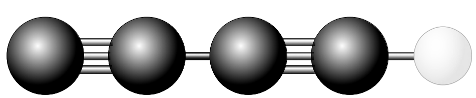
Upcoming ALMA Cycle 4 (with ACA and TP array) to map two protostars in Ophiuchus with different level of external irradiation. Resolution: 1.6" (200 AU)

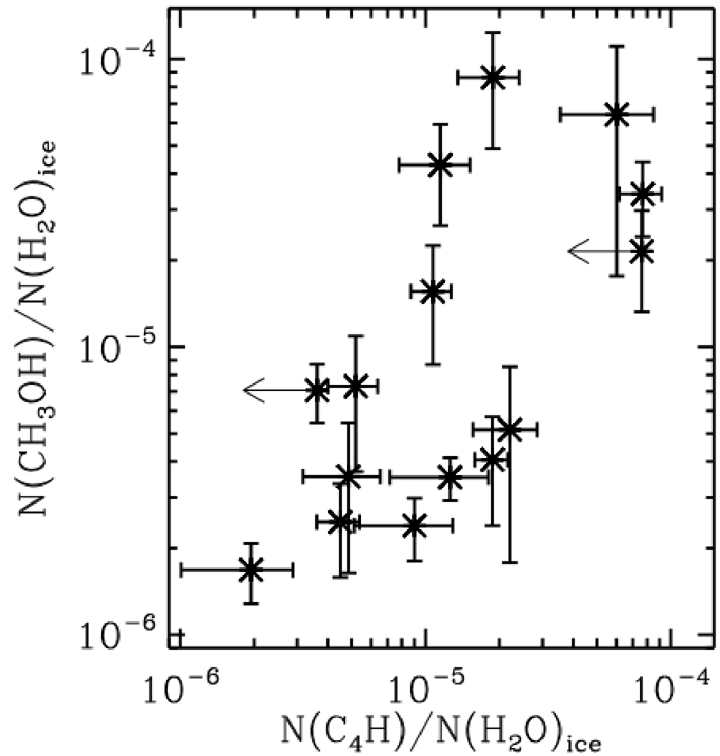
Proposed correlation between C_4H and CH_3OH in protostellar envelopes



Normalised by $N(H_2O)_{ice}$ from *Spitzer*:

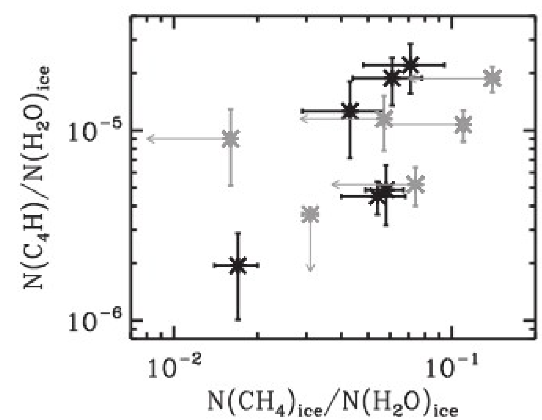






Spearman's rank correlation:
$\rho = 0.74$, $r = 0.003$

No significant correlation
even when excluding hot corinos



Graninger et al. (2016), ApJL, 819, 140

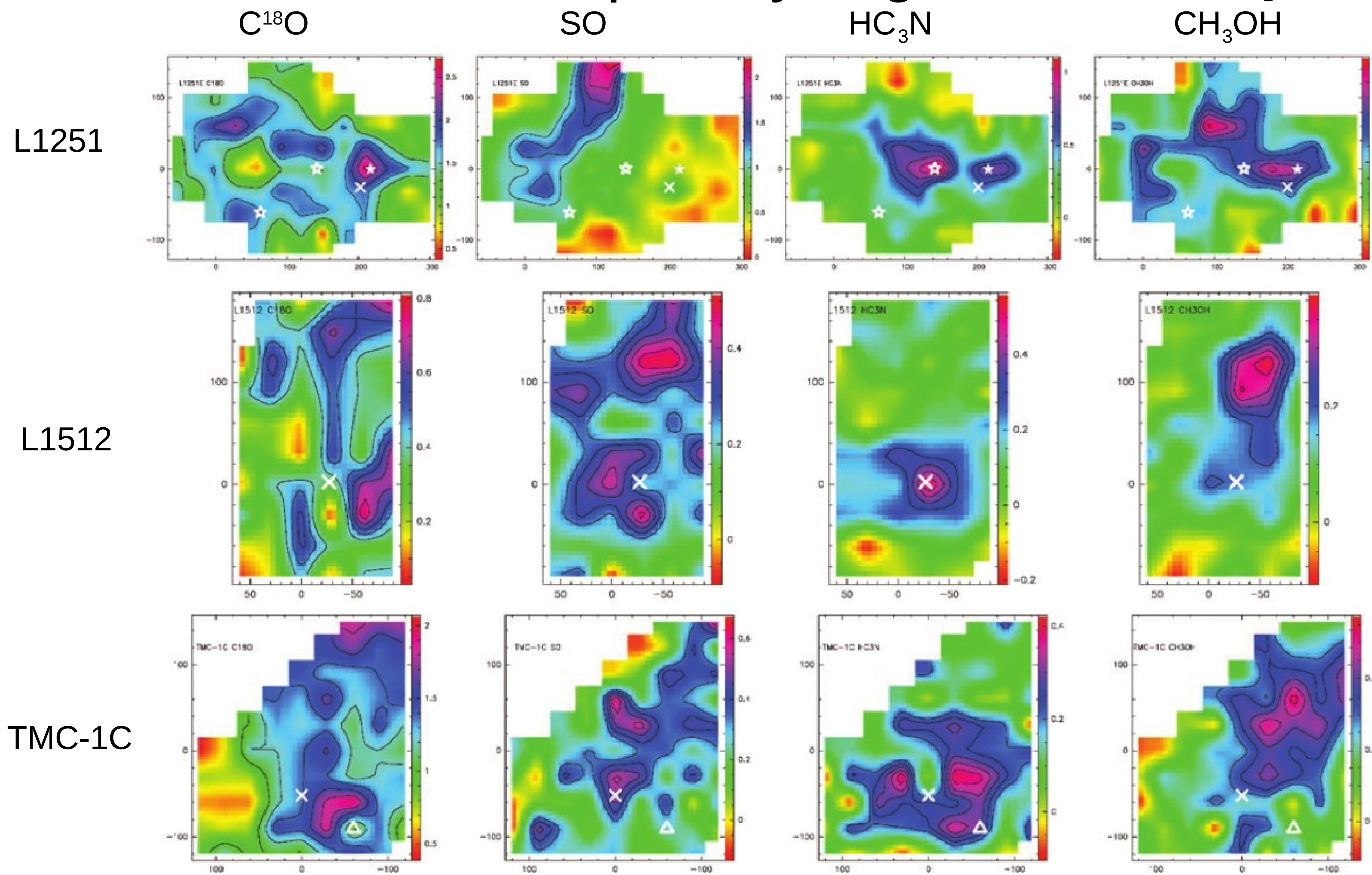
Proposed correlation between C_4H and CH_3OH in protostellar envelopes

- **Why?** CH_3OH forms on grains; C_4H forms from CH_4, which forms on grains.
- **What does it mean?** Carbon chains and COMs are not mutually exclusive.
- **Where?** Correlation as long as CH_3OH comes from non-thermal evaporation – hot corinos show no correlation.
- Suggests that CH_4 ($\rightarrow$ C_4H) and CH_3OH evaporate simultaneously.

Why is this C_4H-CH_3OH correlation unexpected?

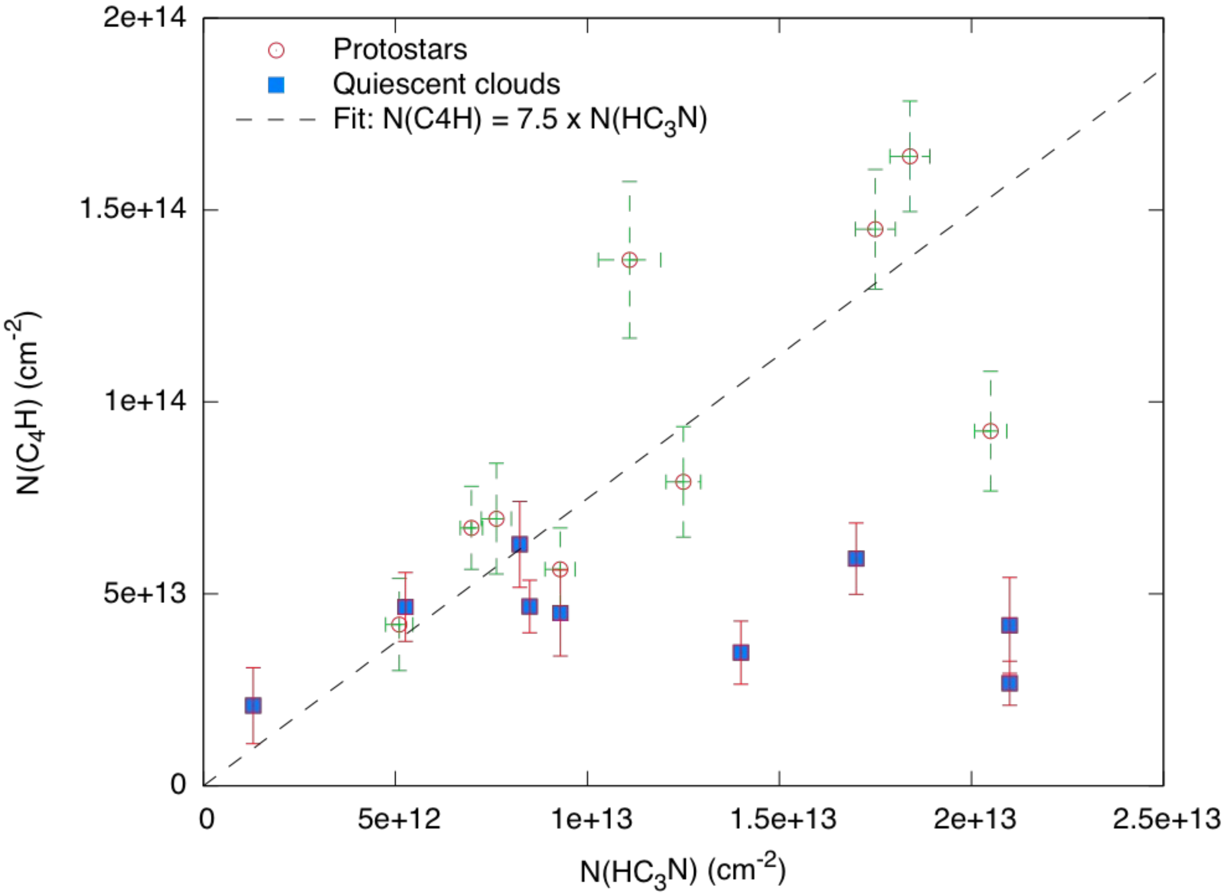
- Unknown non-thermal evaporation mechanism for CH_3OH;
  UV photodesorption not significant (Bertin et al. 2016).
- Would mean that CH_4 and CH_3OH evaporates at similar conditions despite different T_{evap} (~30 K vs. >70 K) and binding energies (1090 K vs. 5530 K).
- COMs and carbon chains often not spatially co-existent (see next slide).

Carbon chains not spatially aligned with CH_3OH



Buckle et al. (2006), FaDi, 133, 63

Are C_4H and HC_3N correlated?

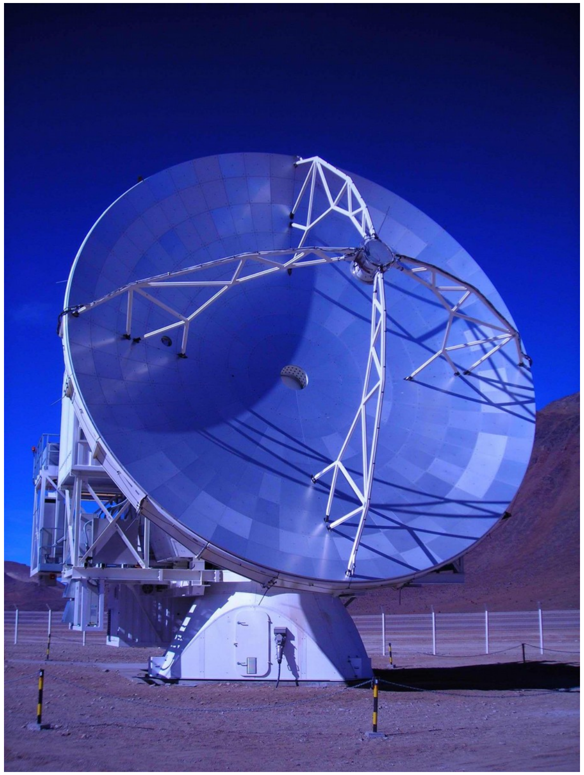


HC_3N typically forms from C_2H_2 + CN
Dark clouds: C_4H forms from atomic C
Protostars: C depleted, CH_4 required to form C_4H

MOPRA survey; Cordiner et al. (in prep.)

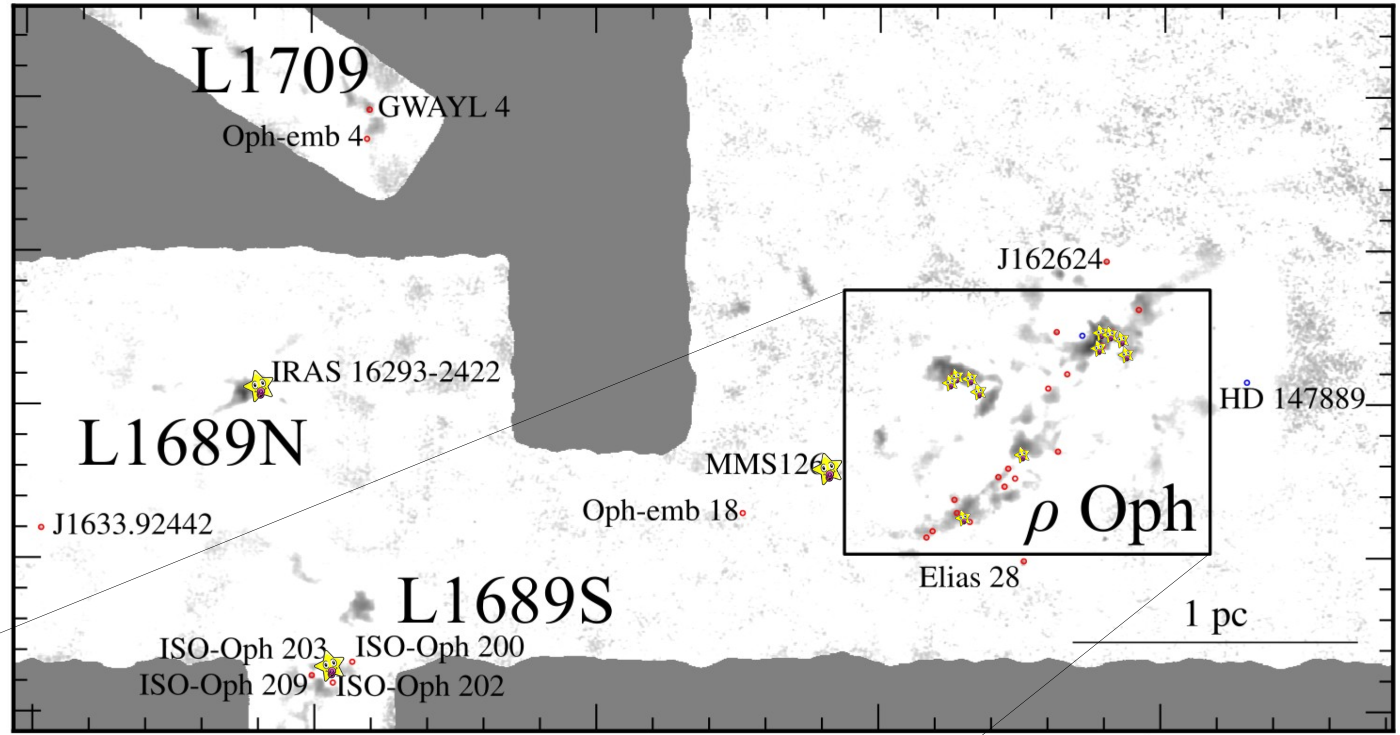
Survey of C_4H in 16 sources in Ophiuchus and Corona Australis

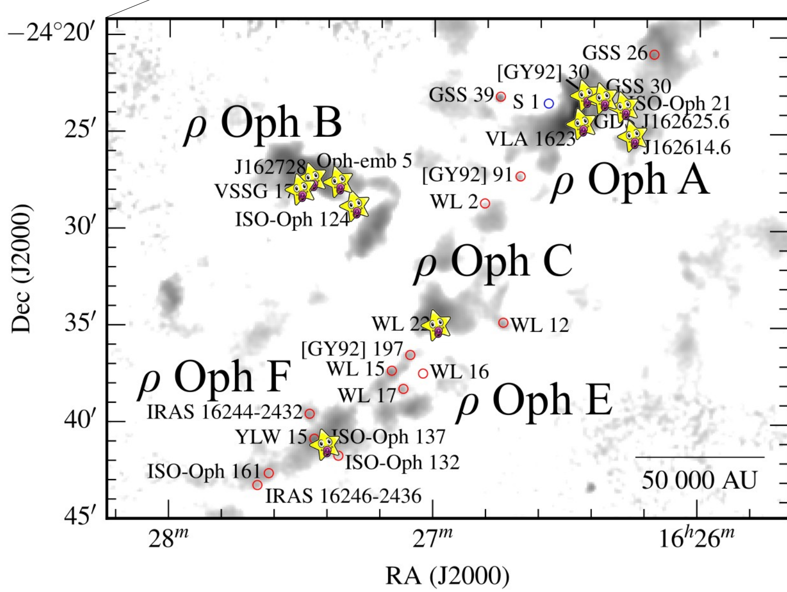
C_4H observations at 85 GHz with the Arizona Radio Observatory 12 m telescope in May 2016



CH_3OH observations at 218 GHz with the APEX 12 m telescope 2014-2015

Source sample (16 sources)



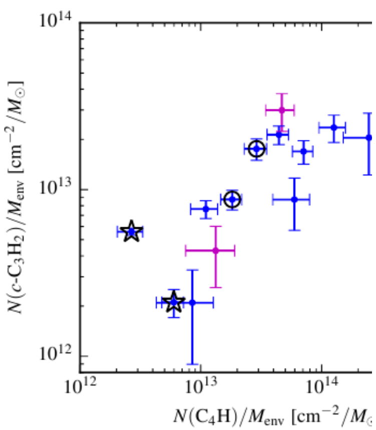


+ 2 additional in CrA

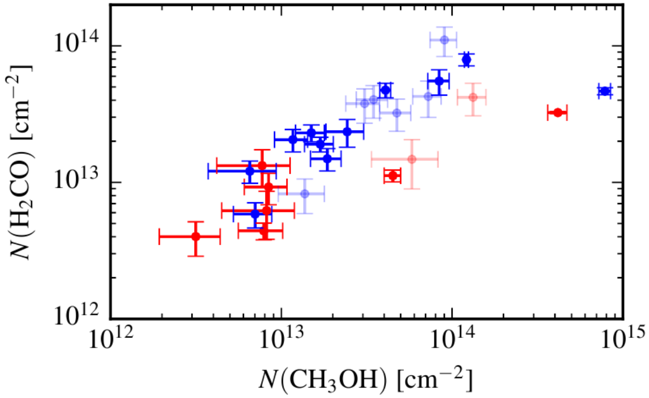
In addition 15 sources from Graninger et al. (2016) and another 9 sources from the literature.

Assumptions (caveats)

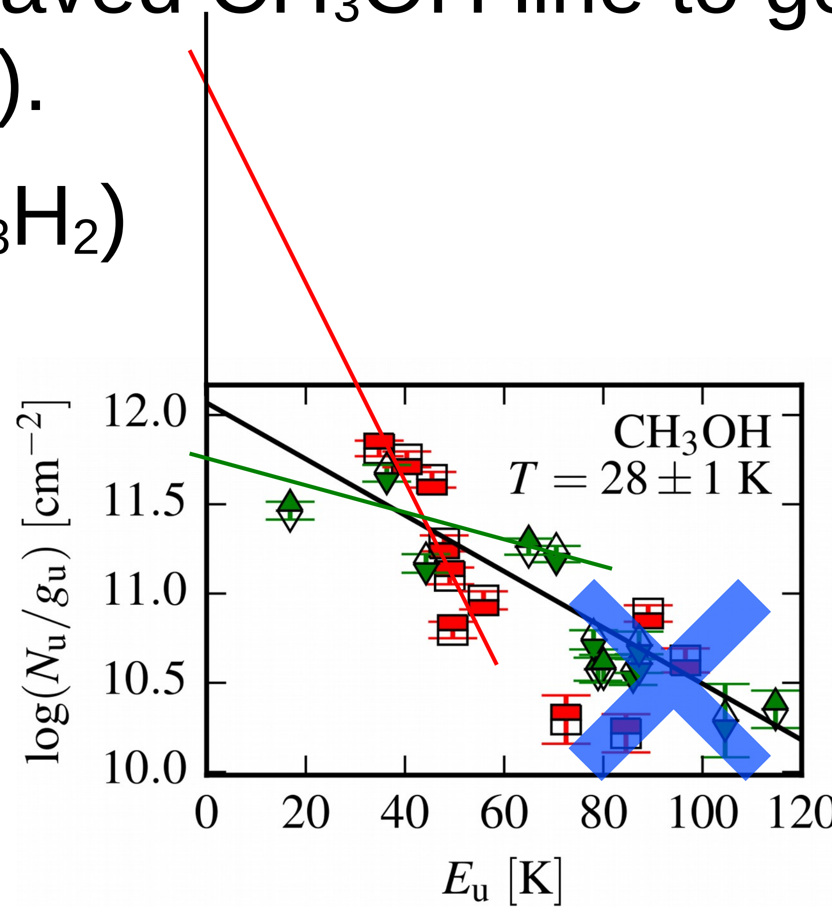
- CH_3OH often non-LTE (subthermally excited).
- Use $T(H_2CO)$ and well-behaved CH_3OH line to get a good value for $N(CH_3OH)$.
- We get $N(C_4H)$ from $T(c\text{-}C_3H_2)$ in the same way.



Lindberg et al. (2016a;ApJL, 833, L14)

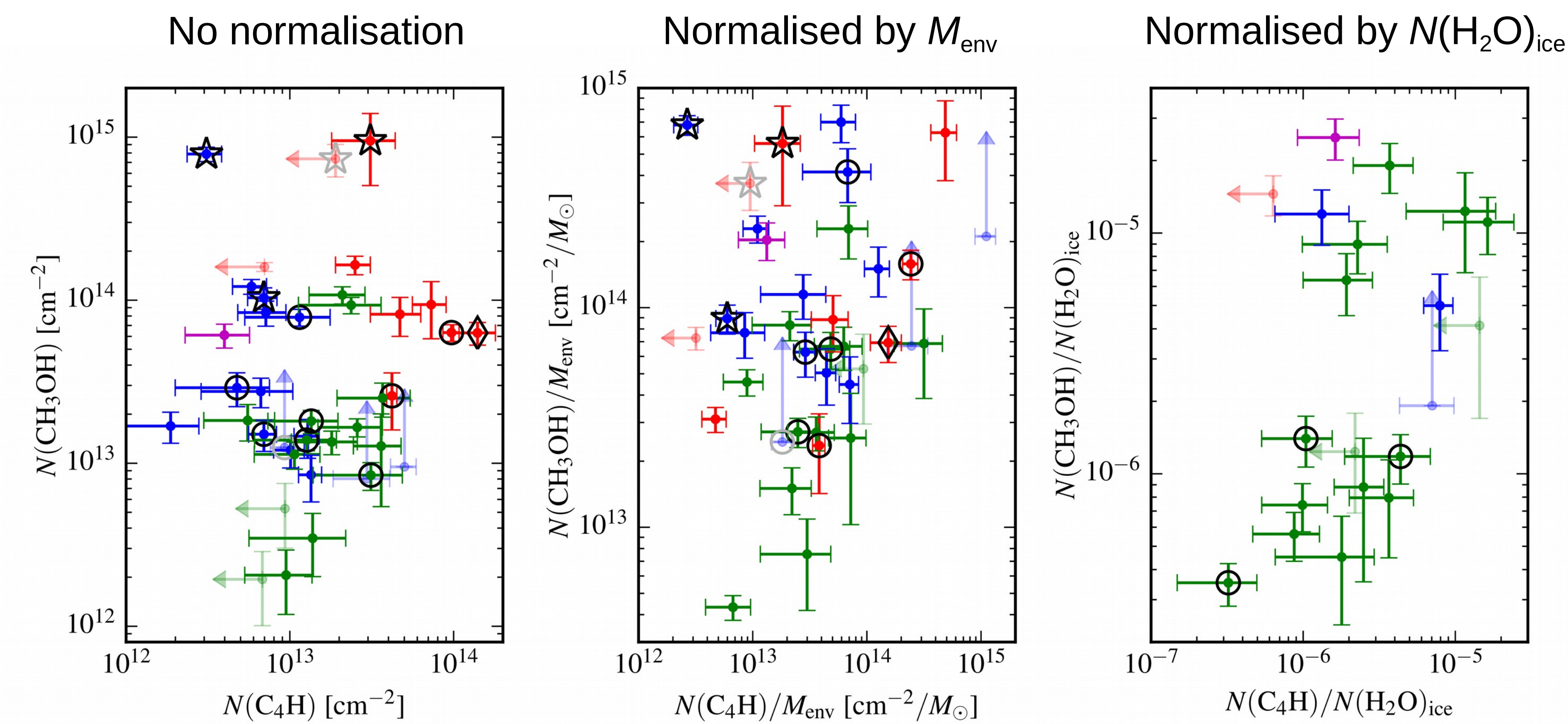


Lindberg et al. (2016b; in press)



R CrA IRS7B APEX ASTE (Lindberg et al. 2015)

Results from our C_4H/CH_3OH survey



☆ Hot corino

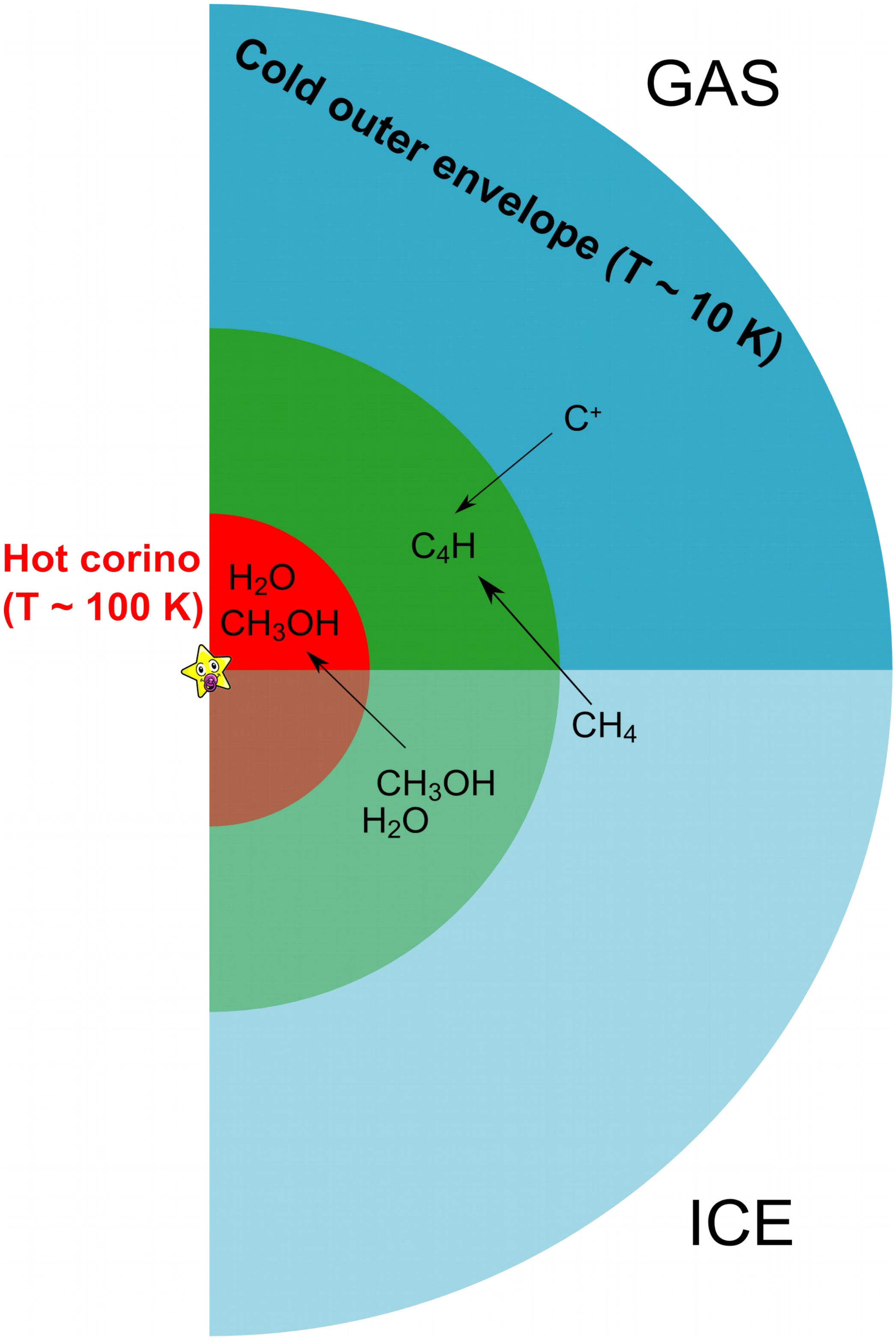
◇ WCCC source

○ Other Class 0 source

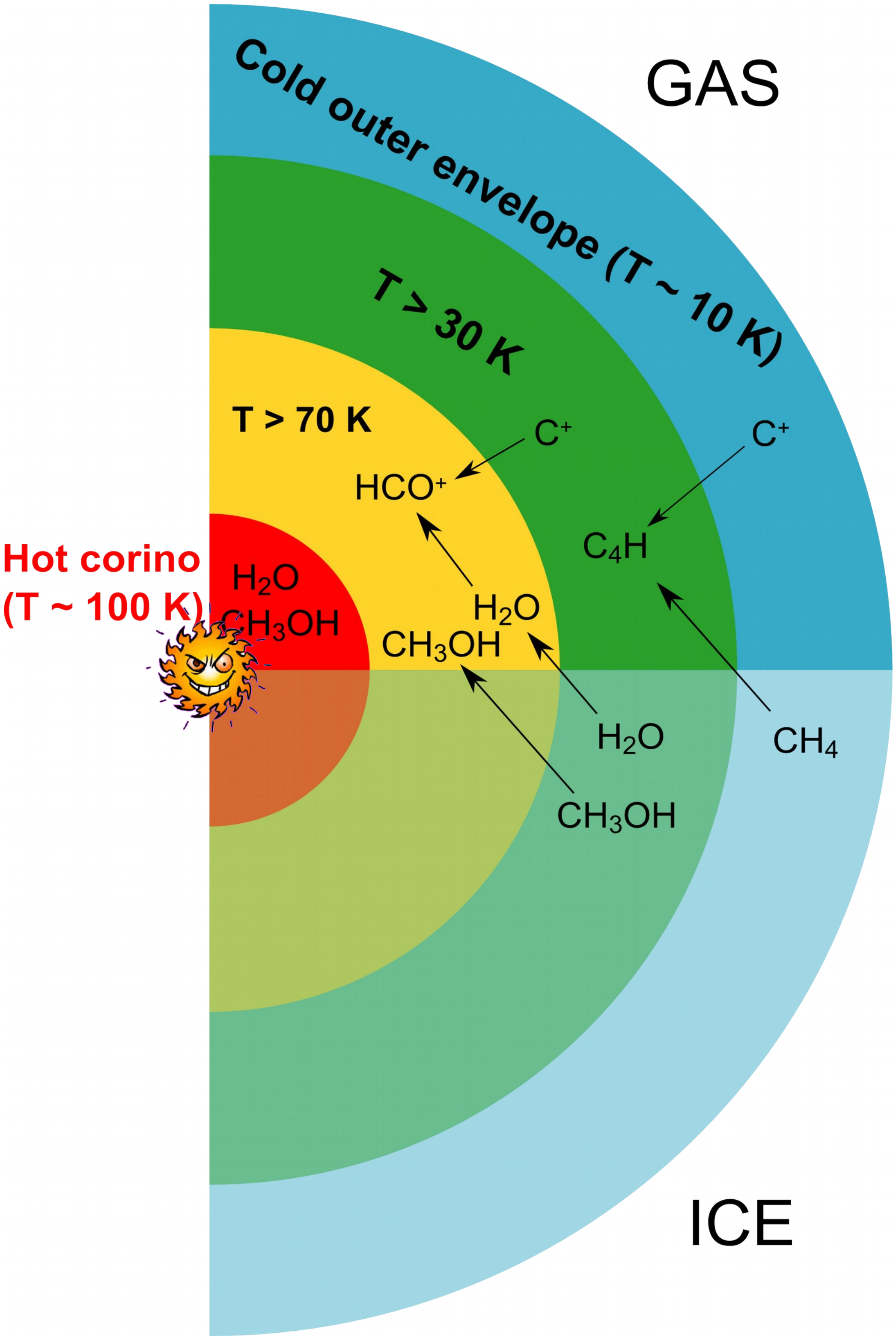
Graninger et al. (2016)
Our data (Oph)
Our data (CrA)
Other literature data

No significant correlation, will get worse with more $N(H_2O)_{ice}$ data.

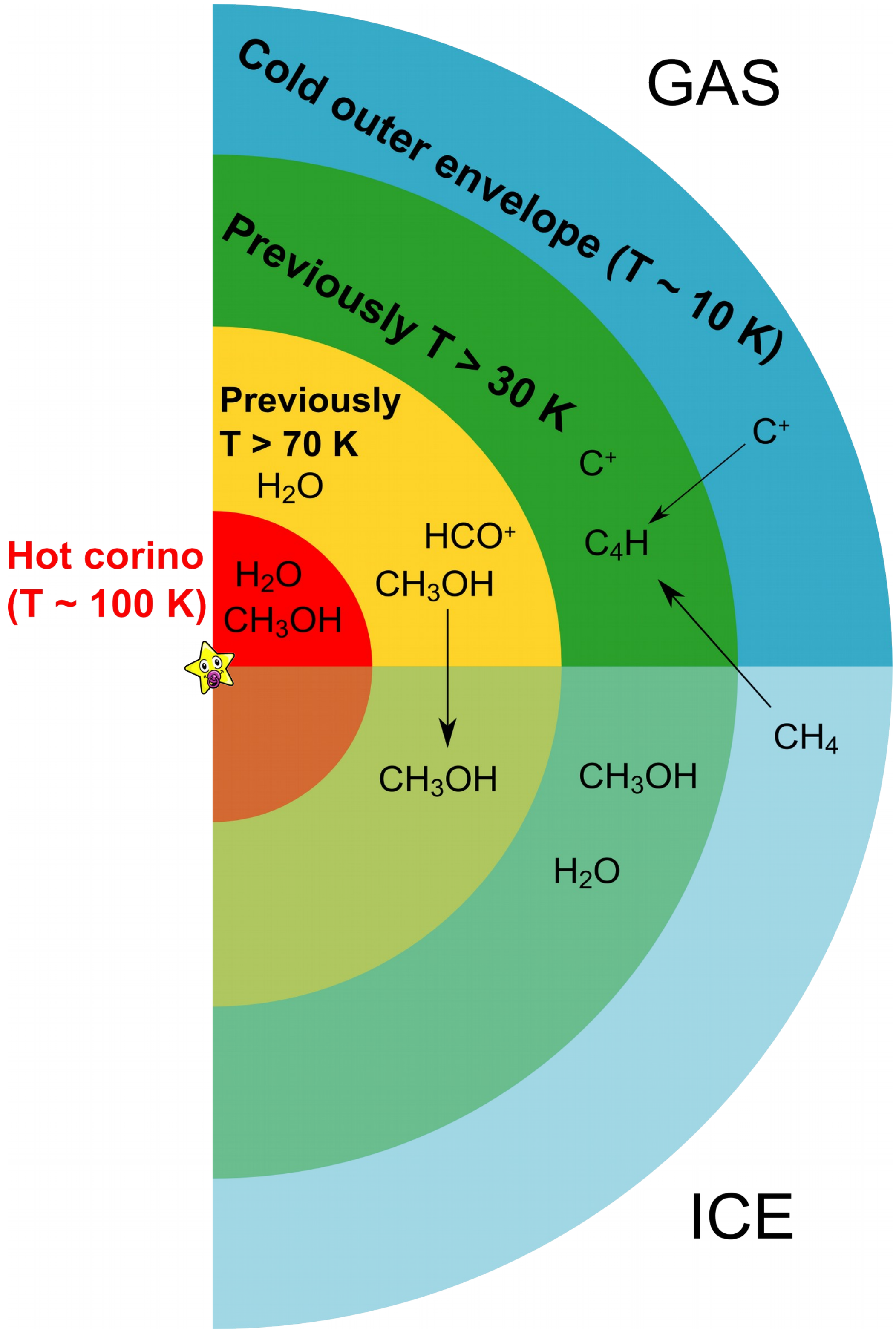
Lindberg et al. (2016a; ApJL, 833, L14)



- C_4H predominant at larger scales, where CH_4 has evaporated and reacted with C^+.
- High-*T* CH_3OH in hot inner envelope.



- C_4H predominant at larger scales, where CH_4 has evaporated and reacted with C^+.
- High-*T* CH_3OH in hot inner envelope.
- Accretion bursts release CH_3OH at larger scales.
- C_4H formation suppressed in inner envelope since C^+ is destroyed by H_2O (Sakai & Yamamoto 2013).

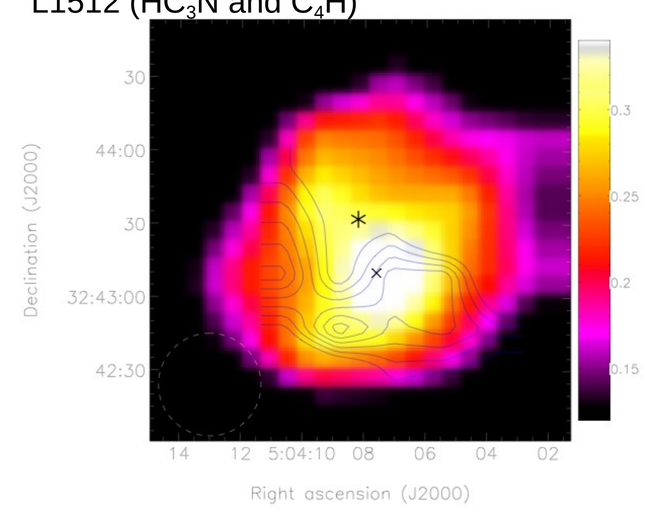


- C_4H predominant at larger scales, where CH_4 has evaporated and reacted with C^+.
- High-*T* CH_3OH in hot inner envelope.
- Accretion bursts release CH_3OH at larger scales.
- C_4H formation suppressed in inner envelope since C^+ is destroyed by H_2O (Sakai & Yamamoto 2013).
- Low-*T* CH_3OH likely a tracer of previously hot gas (e.g. by accretion bursts).

Other surveys (future work)

- MOPRA/OSO multi-line (C_4H, HC_3N, and CH_3OH, HCO^+, HCN, N_2H^+, ...) 3 mm survey of >100 low-mass sources across luminosities (0.03-11L_{sun}) and evolutionary stages (pre-stellar to Class I).
- Targeted follow-up on C_4H, HC_3N, and CH_3OH in 30 most promising sources using Nobeyama 45 m scheduled in March 2017.

L1512 (HC_3N and C_4H)



Cordiner et al. (2012), ApJ, 744, 131

Conclusions

- With a sample of 29 sources (not counting the lower/upper limits), we observe **no correlation or anti-correlation between C_4H and CH_3OH** in embedded protostars.
- Further observations needed to understand the importance of dust mantle chemistry: **Nobeyama 45 m observations** to expand search for C_4H, HC_3N, and CH_3OH to 30 additional northern sources in different environments and stages of evolution is upcoming.
- High-resoultion (e.g. NOEMA, ALMA) mapping of more sources in WCCC species like C_4H in many different sources is crucial but time-consuming.