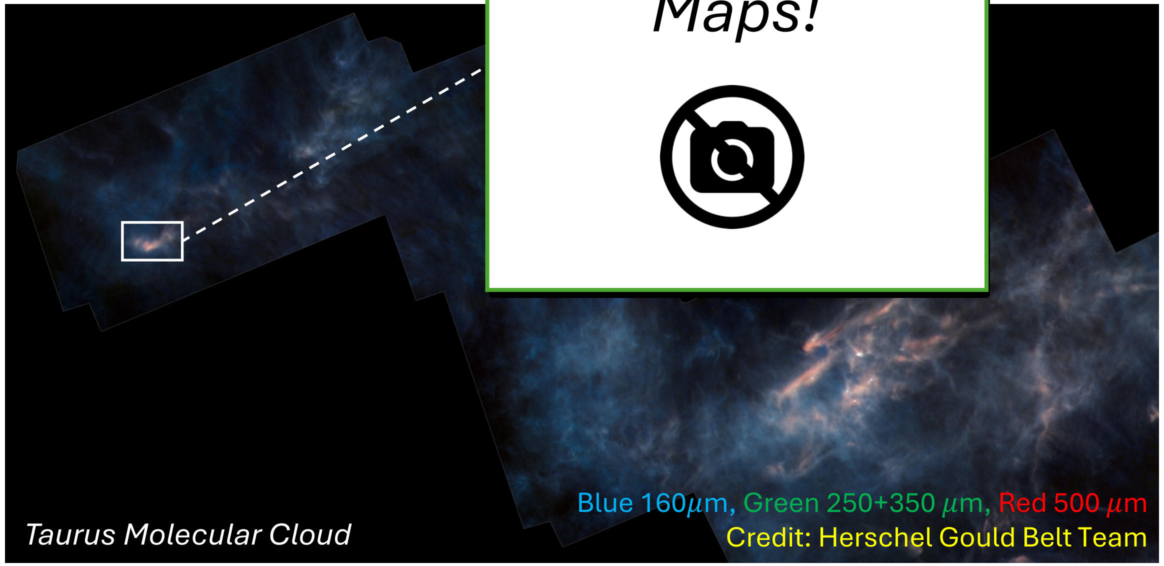
Novel mapping of complex molecules toward low-mass stellar nurseries with ALMA

Preliminary Maps!



Samantha Scibelli, PhD

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National Radio Astronomy Observatory (NRAO)
Charlottesville, Virginia, USA

ALMA Band 2 Workshop
February 24-26, 2026
Contact: sscibell@nrao.edu

A Molecular Universe

Known Interstellar Molecules

Created with **ASTROMOL** v2021.9.1
bmcguir2.github.io/astromol
McGuire 2022 *ApJS* 259, 30

2 Atoms

CH, CN, CH^+, OH, CO, H_2, SiO, CS, SO, SiS, NS, C_2, NO, HCl, NaCl, AlCl, KCl, AlF, PN, SiC, CP, NH, SiN, SO^+, CO^+, HF, N_2, CF^+, PO, O_2, AlO, CN^-, OH^+, SH^+, HCl^+, SH, TiO, ArH^+, NS^+, HeH^+, VO, PO^+, SiP, FeC

3 Atoms

H_2O, HCO^+, HCN, OCS, HNC, H_2S, N_2H^+, C_2H, SO_2, HCO, HNO, HCS^+, HOC^+, SiC_2, C_2S, C_3, CO_2, CH_2, C_2O, MgNC, NH_2, NaCN, N_2O, MgCN, H_3^+, SiCN, AlNC, SiNC, HCP, CCP, AlOH, H_2O^+, H_2Cl^+, KCN, FeCN, HO_2, TiO_2, CCN, SiCSi, S_2H, HCS, HSC, NCO, CaNC, NCS, MgC_2, HSO, CaC_2

4 Atoms

NH_3, H_2CO, HNCO, H_2CS, C_2H_2, C_3N, HNCS, $HOCO^+$, C_3O, *l*-C_3H, $HCNH^+$, H_3O^+, C_3S, *c*-C_3H, HC_2N, H_2CN, SiC_3, CH_3, C_3N^-, PH_3, HCNO, HOCN, HSCN, HOOH, *l*-C_3H^+, HMgNC, HCCO, CNCN, HONO, MgCCH, HCCS, HNCN, H_2NC, $HCCS^+$, CH_3^+, HCNS, $HOCS^+$, HNSO

5 Atoms

HC_3N, HCOOH, CH_2NH, NH_2CN, H_2CCO, C_4H, SiH_4, *c*-C_3H_2, CH_2CN, C_5, SiC_4, H_2CCC, CH_4, HCCNC, HNCCC, H_2COH^+, C_4H^-, CNCHO, HNCNH, CH_3O, NH_3D^+, H_2NCO^+, $NCCNH^+$, CH_3Cl, MgC_3N, HC_3O^+, NH_2OH, HC_3S^+, H_2CCS, C_4S, CHOSH, HCSCN, HC_3O, NaCCCN, MgC_3N^+, $C_2H_3^+$, NCCHS

6 Atoms

CH_3OH, CH_3CN, NH_2CHO, CH_3SH, C_2H_4, C_5H, CH_3NC, HC_2CHO, H_2C_4, C_5S, HC_3NH^+, C_5N, HC_4H, HC_4N, *c*-H_2C_3O, CH_2CNH, C_5N^-, HNCHCN, SiH_3CN, MgC_4H, CH_3CO^+, H_2CCCS, CH_2CCH, HCSCCH, C_5O, $HCCNCH^+$, C_5H^+, *c*-C_5H, HC_4S, HMgCCCN, MgC_4H^+, $H_2C_3H^+$, HOCOOH, H_2C_3N, H_2CNCN

7 Atoms

CH_3CHO, CH_3CCH, CH_3NH_2, CH_2CHCN, HC_5N, C_6H, *c*-C_2H_4O, CH_2CHOH, C_6H^-, CH_3NCO, HC_5O, $HOCH_2CN$, HC_4NC, HC_3HNH, *c*-C_3HCCH, MgC_5N, CH_2C_3N, *l*-H_2C_5, NC_4NH^+, MgC_5N^+

8 Atoms

$HCOOCH_3$, CH_3C_3N, C_7H, CH_3COOH, H_2C_6, CH_2OHCHO, HC_6H, CH_2CHCHO, CH_2CCHCN, NH_2CH_2CN, CH_3CHNH, CH_3SiH_3, NH_2CONH_2, $HCCCH_2CN$, CH_2CHCCH, MgC_6H, $C_2H_3NH_2$, HOCHCHOH, HCCCHCCC, C_7N^-, CH_3CHCO, MgC_6H^+

9 Atoms

CH_3OCH_3, CH_3CH_2OH, CH_3CH_2CN, HC_7N, CH_3C_4H, C_8H, CH_3CONH_2, C_8H^-, CH_2CHCH_3, CH_3CH_2SH, HC_7O, CH_3NHCHO, $H_2CCCHCCH$, HCCCHCHCN, H_2CCHC_3N

10 Atoms

CH_3COCH_3, $HOCH_2CH_2OH$, CH_3CH_2CHO, CH_3C_5N, CH_3CHCH_2O, CH_3OCH_2OH, H_2CCCHC_3N, C_6H_4, C_2H_5NCO, HC_7NH^+, $CH_3CHCHCN$, CH_2CCH_3CN, CH_2CHCH_2CN, NH_2COCH_2OH, CH_3CH_2CCH

11 Atoms

HC_9N, CH_3C_6H, C_2H_5OCHO, CH_3COOCH_3, CH_3COCH_2OH, C_5H_6, $NH_2CH_2CH_2OH$, CH_2CCHC_4H, $C_{10}H^-$, C_4H_5CN

12 Atoms

C_6H_6, *n*-C_3H_7CN, *i*-C_3H_7CN, $C_2H_5OCH_3$, 1-C_5H_5CN, 2-C_5H_5CN, *n*-$CH_3CH_2CH_2OH$, *i*-$CH_3CH_2CH_2OH$, *i*-C_4H_8

13+ Atoms

C_6H_5CN, $HC_{11}N$, 1-C_5H_5CCH, 2-C_5H_5CCH, *c*-$C_5H_4CCH_2$, $CH_3OCH_2CH_2OH$, *c*-C_6H_5CCH, 1-$C_{10}H_7CN$, 2-$C_{10}H_7CN$, C_9H_8, 2-C_9H_7CN, C_{60}, C_{60}^+, C_{70}

~340 (Feb 2026; CDMS)

~~307~~ Molecules

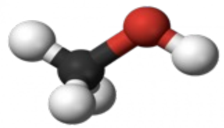
Last Updated: 31 Dec 2024

McGuire 2022

Interstellar
"Complex" Organic Molecules
"COMs" or "iCOMs"

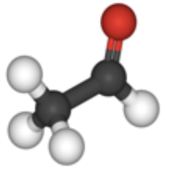
- Contains at least 6 or more atoms
- Contains at least one carbon atom

Herbst & van Dishoeck 2009; Ceccarelli et al. 2017

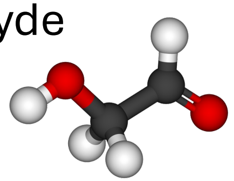


Methanol
CH_3OH

Acetaldehyde
CH_3CHO



Glycolaldehyde
CH_2OHCHO



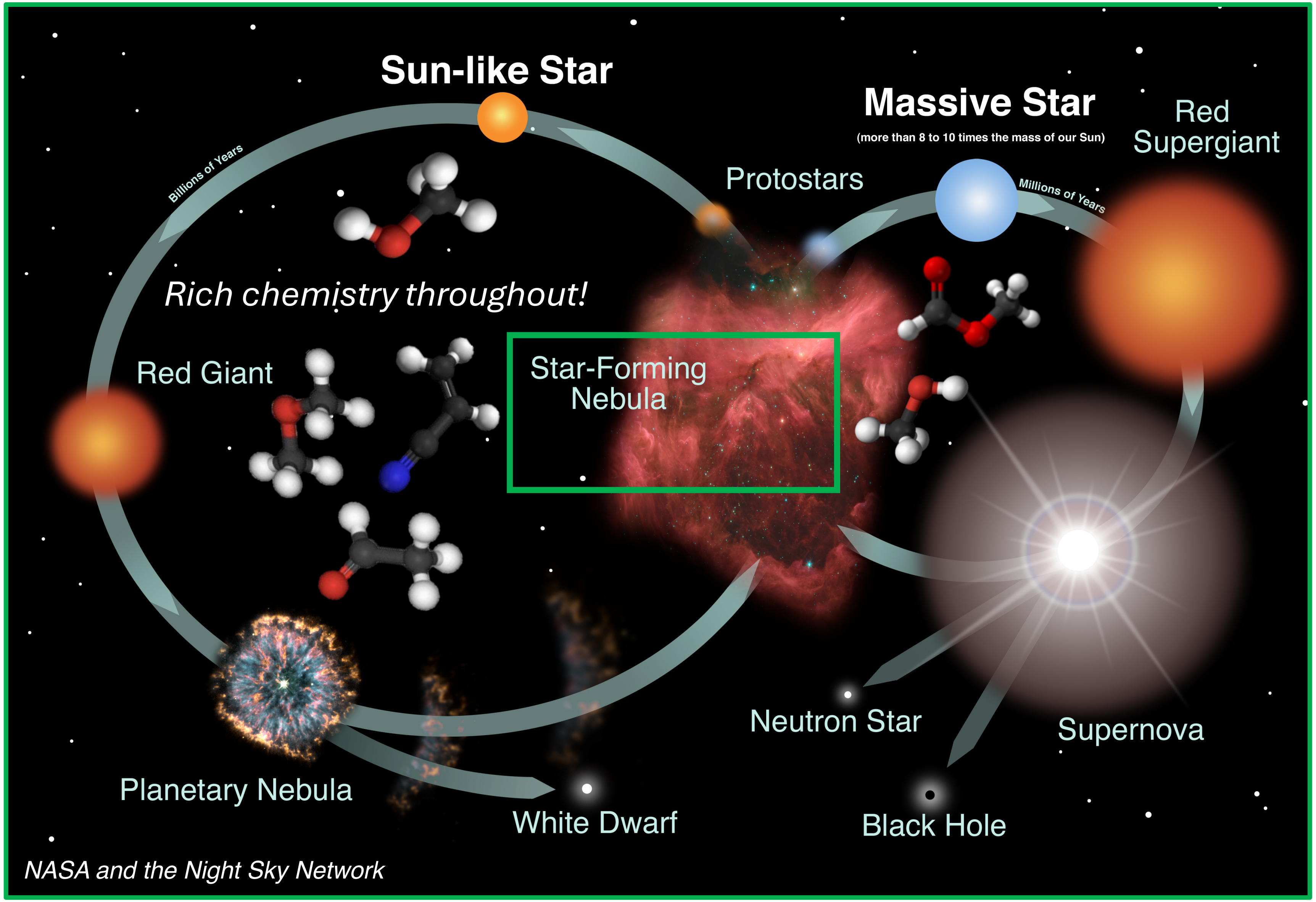
Of interest to **astrochemists** and **astrobiologists**, COMs are the precursor molecules of **prebiotic chemistry**!

Samantha Scibelli

Molecular Life Cycle

There is a **rich** **complex chemistry** throughout the **interstellar medium (ISM),** from the beginning to the end stages of both **low-mass and high-mass star formation**

The natal **molecular cloud environment** where stars begin their life-cycle sets constraints on ***initial conditions***



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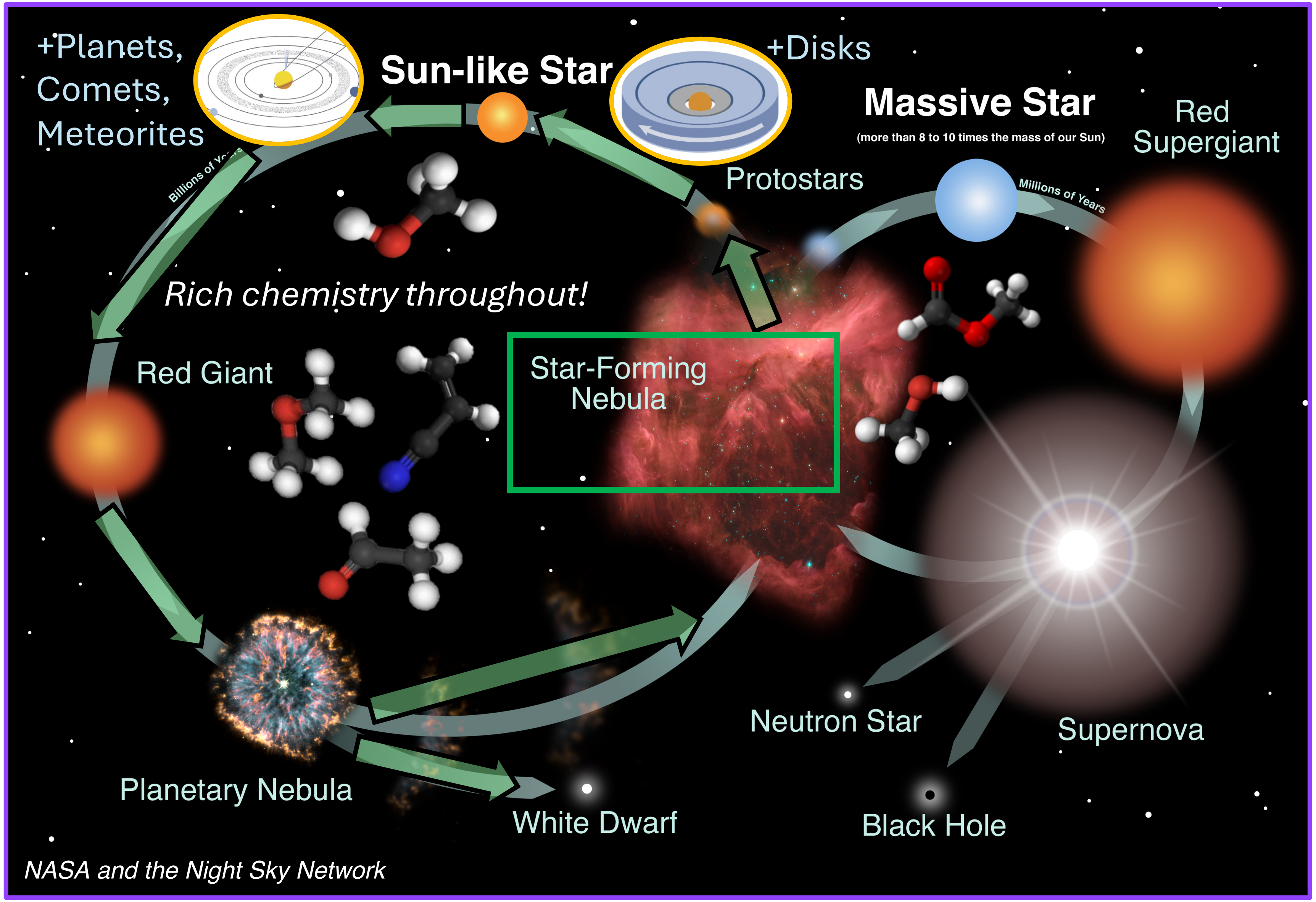
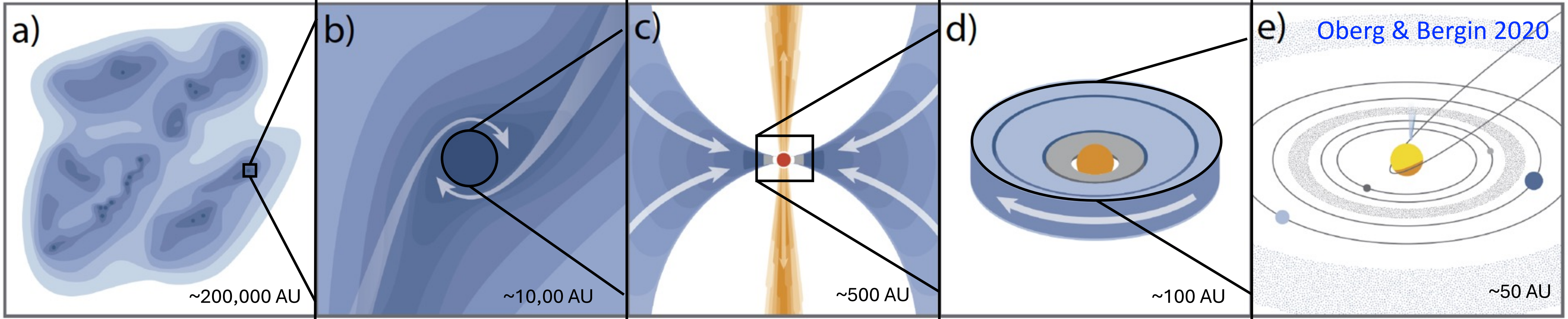


Samantha Scibelli

COMs in Low-mass ($M \lesssim$ a few $M_\odot$) Star and Planet Formation



Dense starless cores embedded in larger filaments

t_{ad} ~ 5 million yrs.

Dense (10^5 cm^{-3}) & cold (10K) prestellar cores that will dynamically collapse

t_{ff} ~ .2 million yrs.

Protostar forms. Accretion of remnant cloud material. Outflows present.

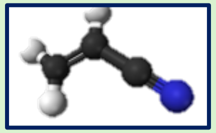
~1 million yrs.

Pre-main sequence star left with a circumstellar disk

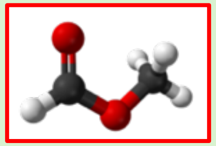
1-10 million yrs.

Rocky and icy planets continue to grow into mature planetary system

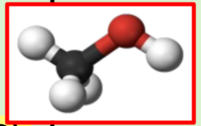
10-50 million yrs.



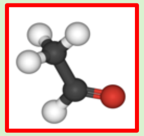
Acetaldehyde (CH_3CHO), etc.
Vastel et al. 2014, Scibelli & Shirley 2020
Vinyl Cyanide (CH_2CHCN)
Jimenez-Serra et al. 2016, 2021



Glycolaldehyde (CH_2OHCHO), Methyl Formate (CH_3OCHO), etc.
Jørgensen et al. 2012, 2016



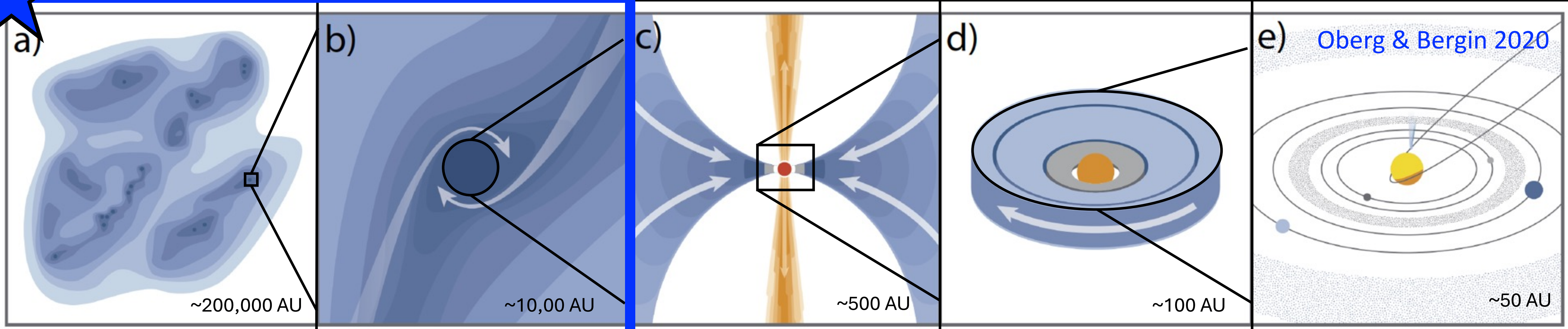
Methanol (CH_3OH)
Walsh et al. 2016, 2017
Dimethyl Ether (CH_3OCH_3)
Brunken et al. 2022



$(CH_2OH)_2$, CH_3CHO, NH_2CHO, C_2H_5OH
Biver 2019

Samantha Scibelli

COMs in Low-mass (M ≲ a few $M_\odot$) Star and Planet Formation



a) Dense starless cores embedded in larger filaments

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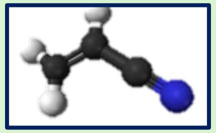

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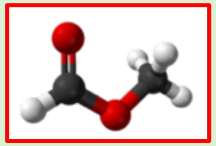

c) Protostar forms. Accretion of remnant cloud material. Outflows present.

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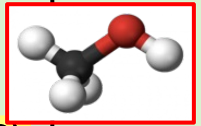

d) Pre-main sequence star left with a circumstellar disk

1-10 million yrs.

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Brunken et al. 2022

e) Rocky and icy planets continue to grow into mature planetary system

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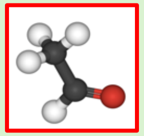


$(CH_2OH)_2$, CH_3CHO,
NH_2CHO, C_2H_5OH
Biver 2019

Evidence for a "chemical inheritance" that get passed on from preceding evolutionary stages

Samantha Scibelli

Starless Core B68

Visible light Image

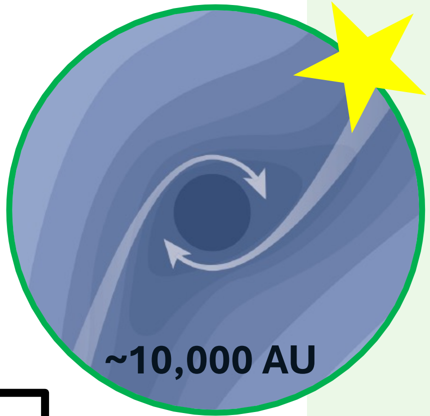
Birthplace of low-mass stars
(M ≤ a few $M_\odot$)
Dense (10^4 - 10^5 cm^{-3}) & cold (≤ 10K)

10K = - 441.67° F!
Low temp. at poles of Mars −243 °F

Starless cores and dynamically evolved and collapsing prestellar cores are at one of the earliest phases of star formation – observations can give us better constraints on initial conditions!

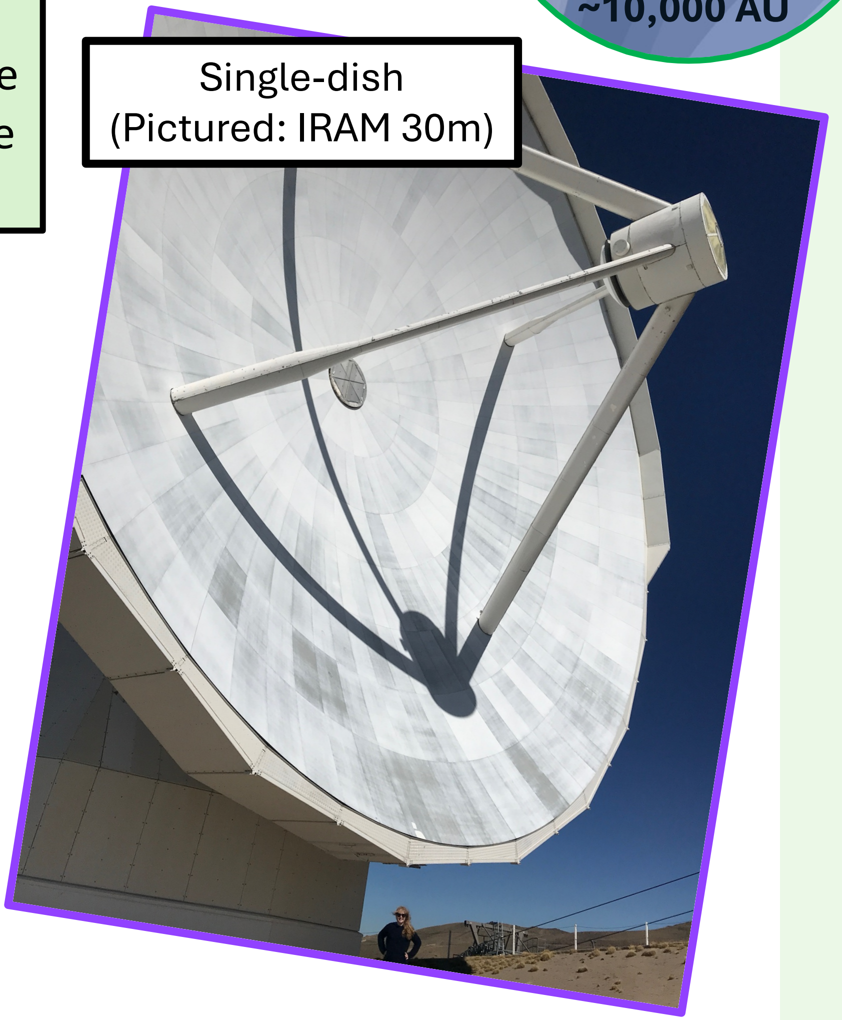
Samantha Scibelli

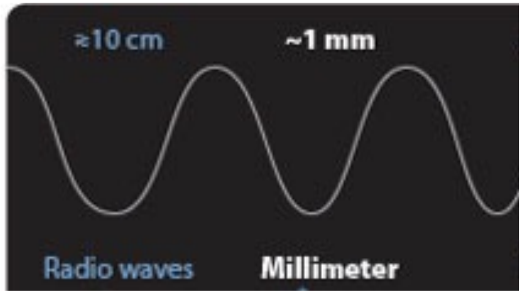
Radio Telescopes Probe Cold Gas and Dust



Radio telescopes let us see objects we can't see in visible light - the dust and gas inside dense starless cores!

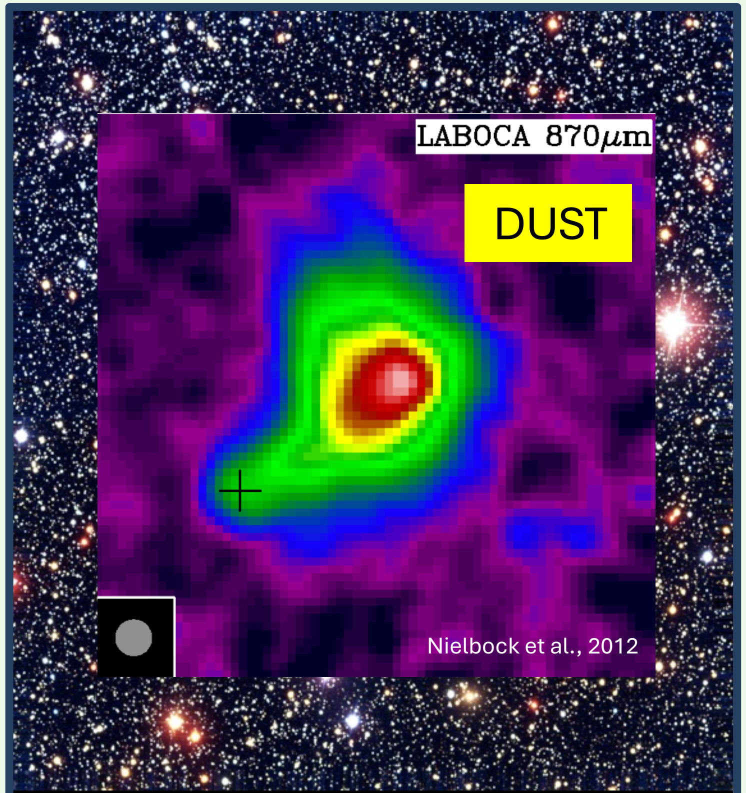
Single-dish
(Pictured: IRAM 30m)





Starless Core B68

Radio light Image



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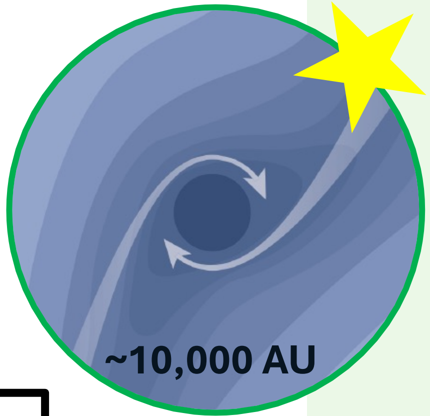

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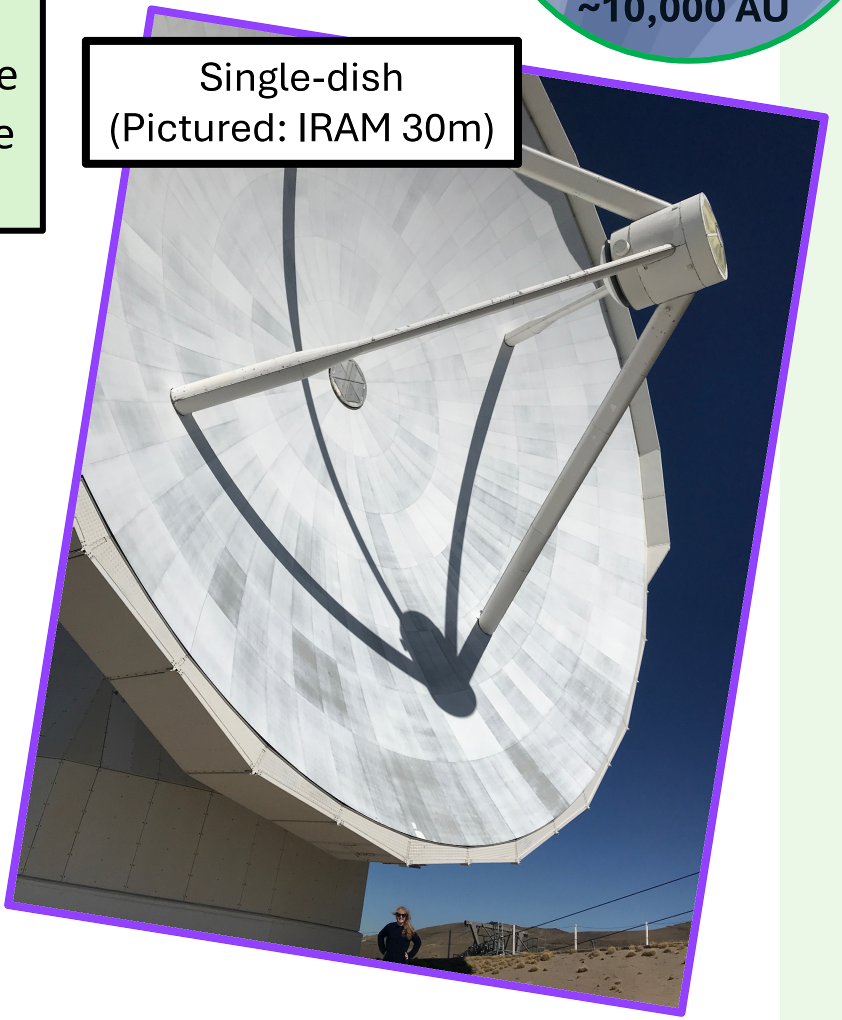

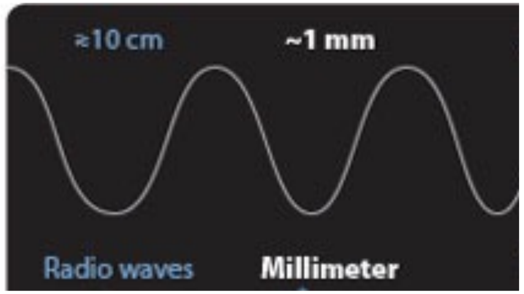

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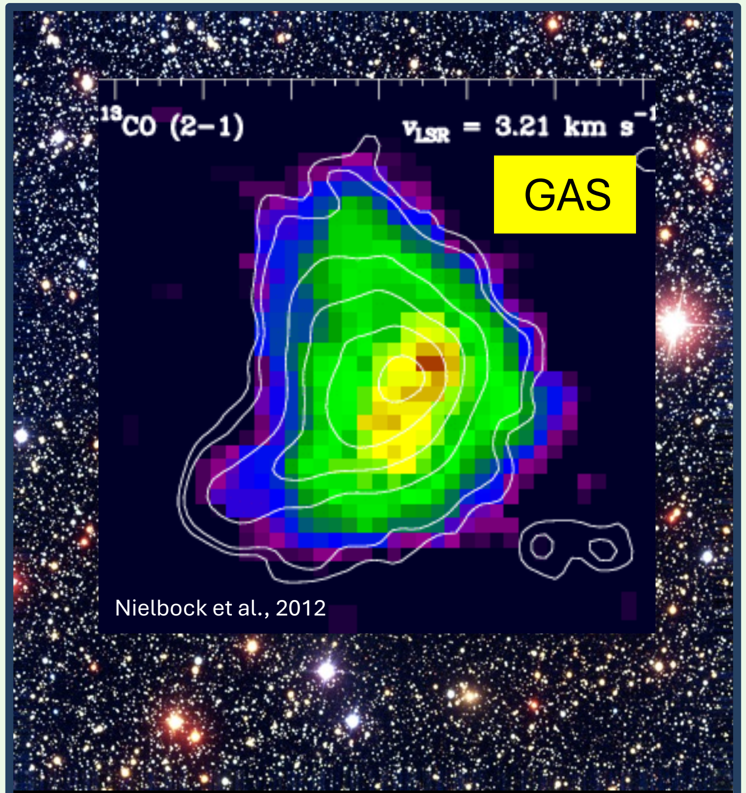
Radio light Image



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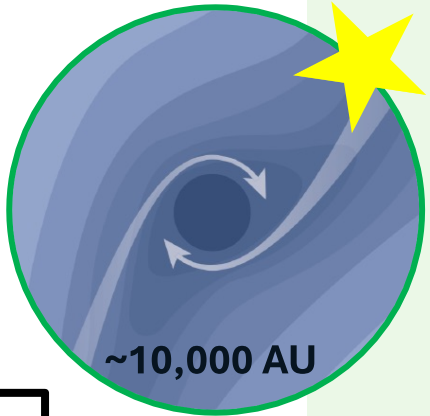

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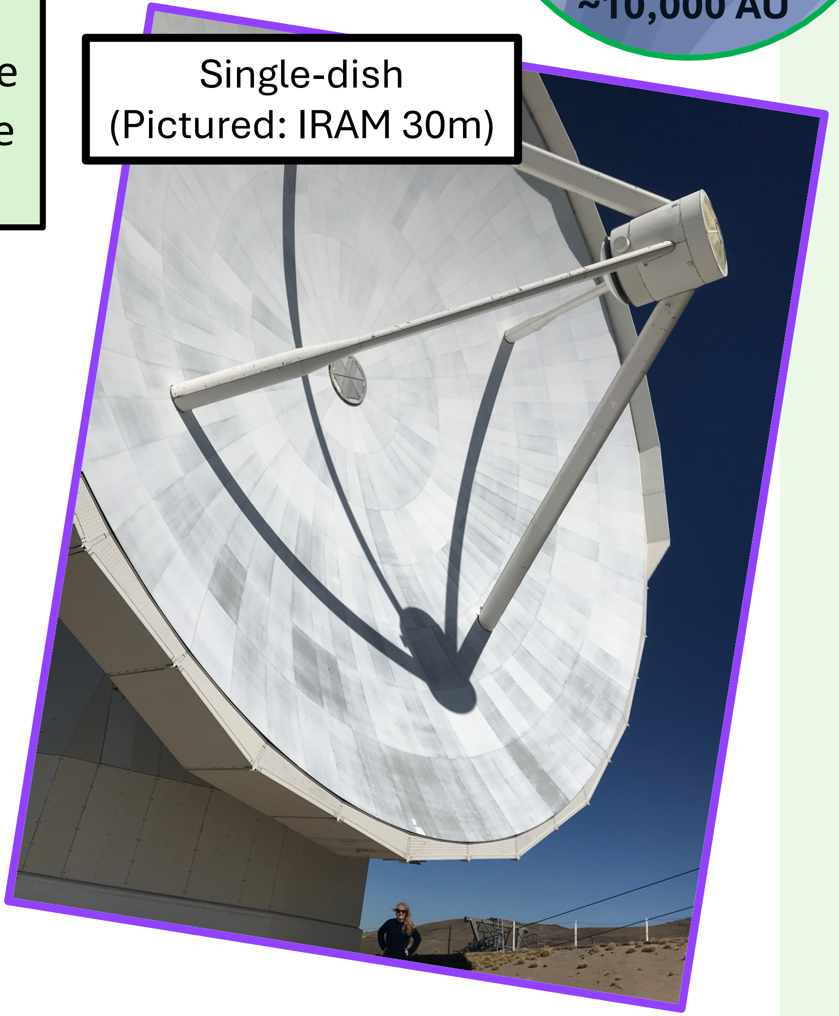

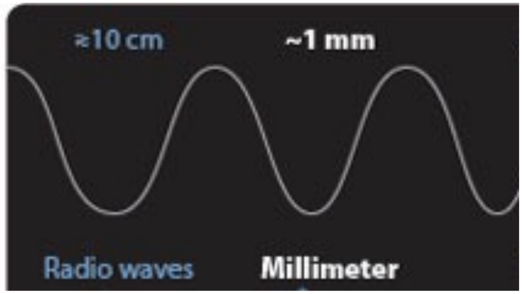

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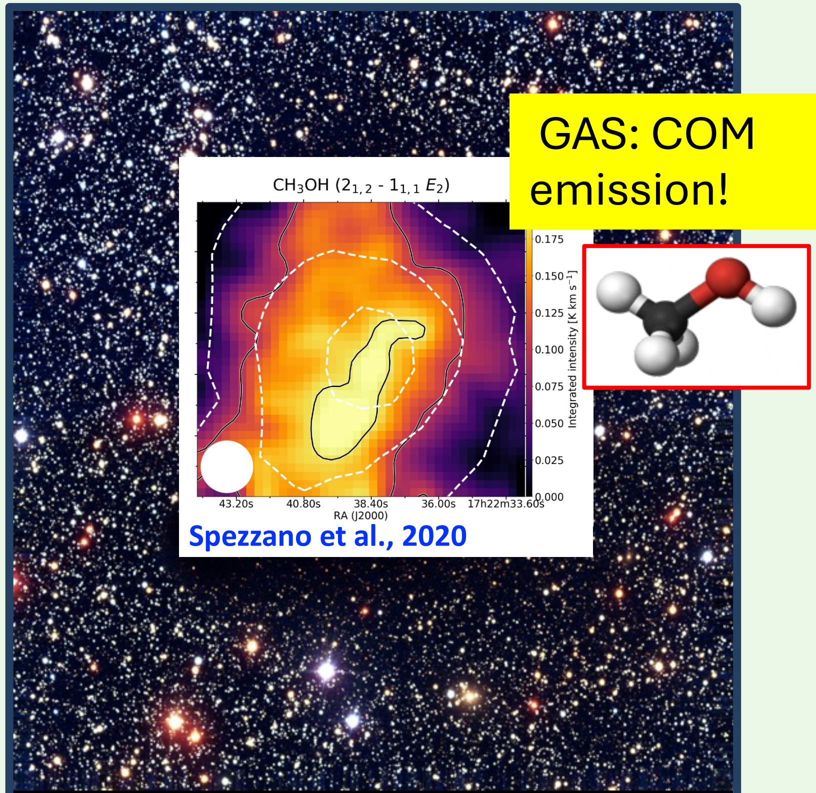

Spezzano et al., 2020

GAS: COM emission!

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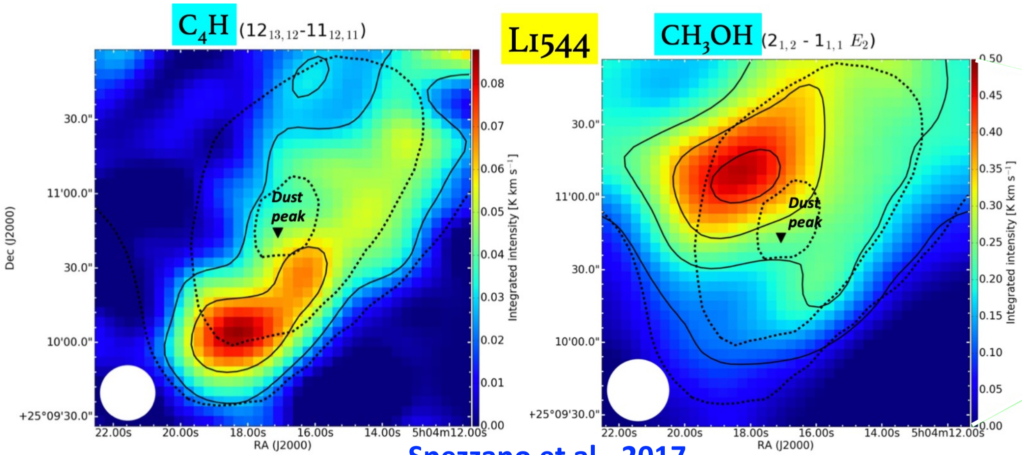
Importance of Understanding the Spatial Distribution of COMs in Starless and Prestellar Cores

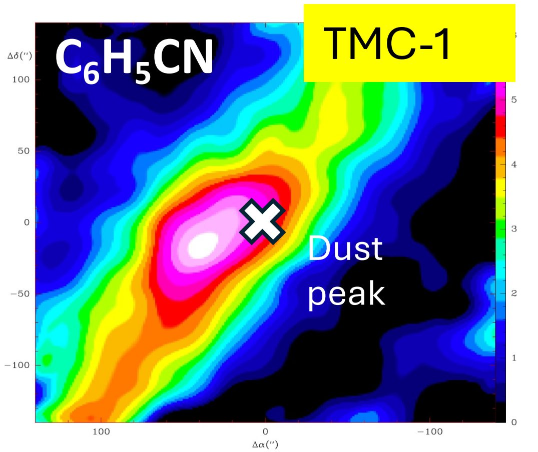
There has been some effort to map simpler COMs (mostly CH_3OH) in dense cores with **single-dish radio telescopes**, which show:

- **Chemical differentiation**, i.e., differences in spatial distribution, column densities, and temperatures between species, *caused by environmental effects or local physics, such as the UV radiation field*
- COMs **trace filaments**, at low A_V, as well as dense cores – *need to understand the spatial extent beyond global average probed by single-pointing!*

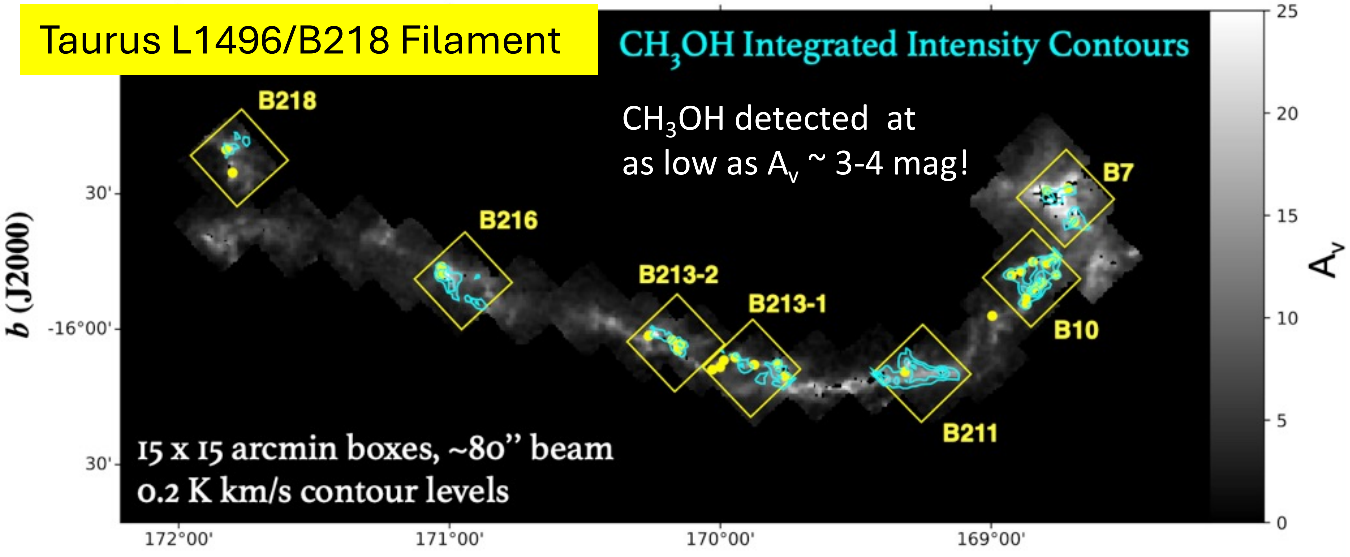
(Bizzocchi et al. 2014; Soma et al. 2015; Spezzano et al., 2016, 2017, 2020, Nagy et al., 2019, Scibelli & Shirley 2020, Punanova et al., 2022, 2025; Cernicharo et al., 2023)



Spezzano et al., 2017



Cernicharo et al., 2023

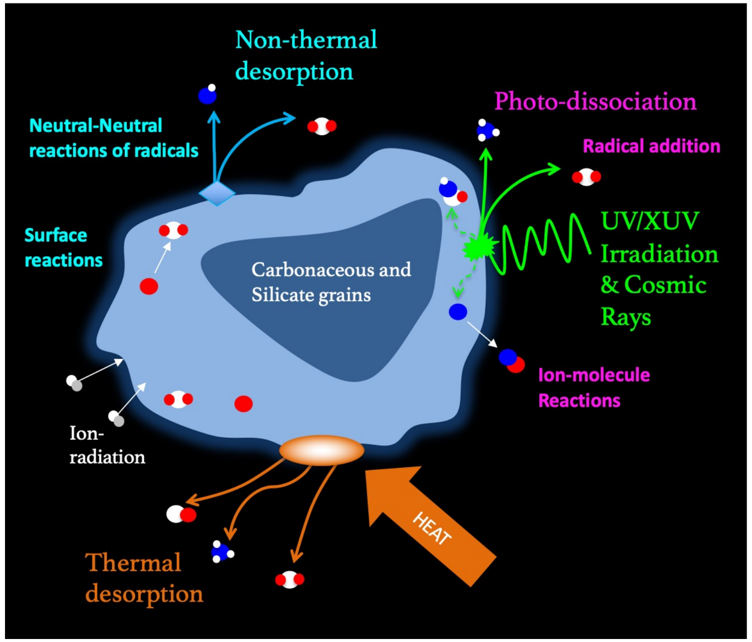


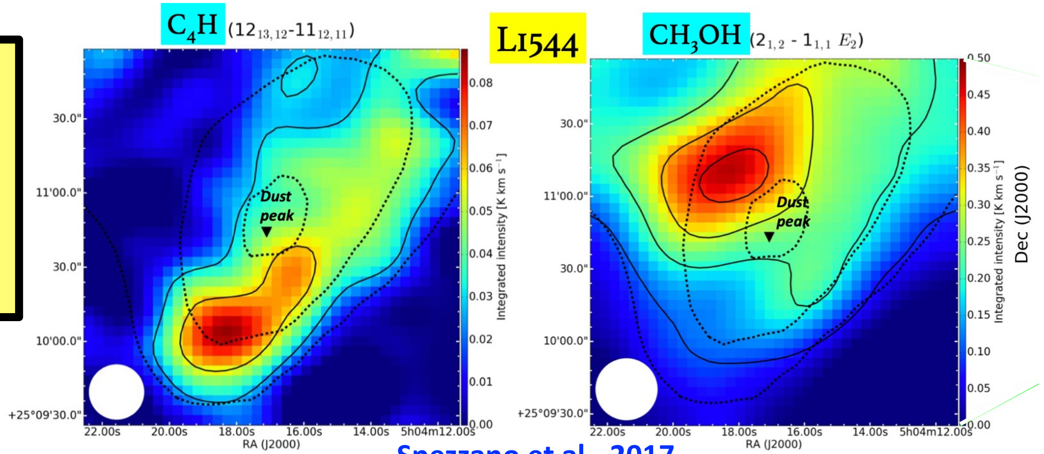
Scibelli & Shirley 2020

Extinction Map: Schmalzl et al. 2010

Importance of Understanding the Spatial Distribution of COMs in Starless and Prestellar Cores

Major question to answer: How do COMs form *efficiently* in colder (10 K) regions, with no internal heating source and shielding from UV radiation?





Spezzano et al., 2017

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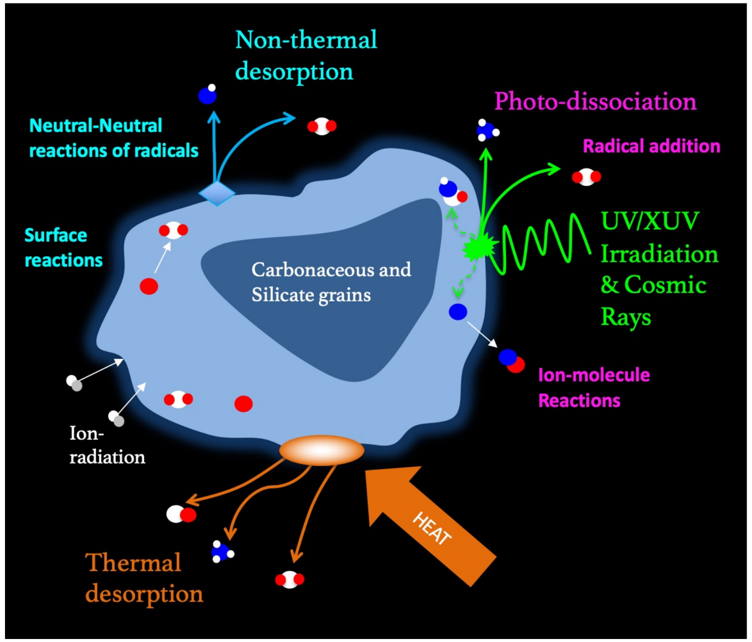
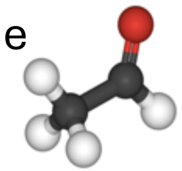


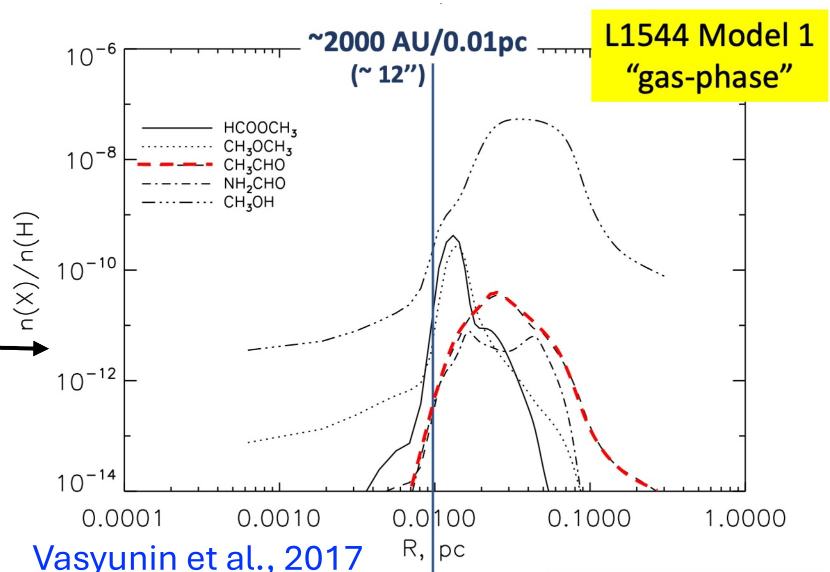
Acetaldehyde
CH_3CHO



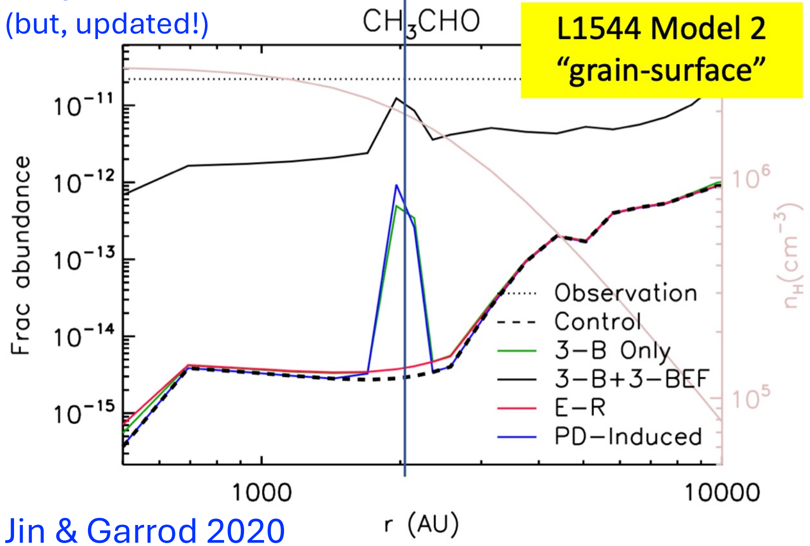
Chemical models predict abundances of COMs, which we can constrain with our observations

Different models, with different initial condition, predict differences in the **radial abundances** of COMs →

Need sensitive maps of higher complexity species at 'high resolution'!



Vasyunin et al., 2017
(but, updated!)



Jin & Garrod 2020

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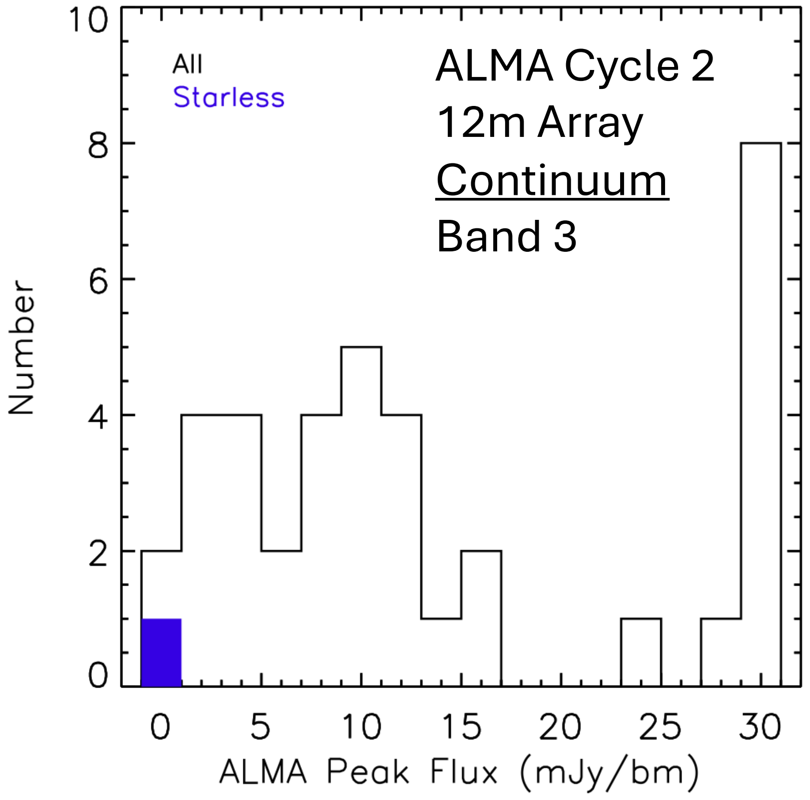
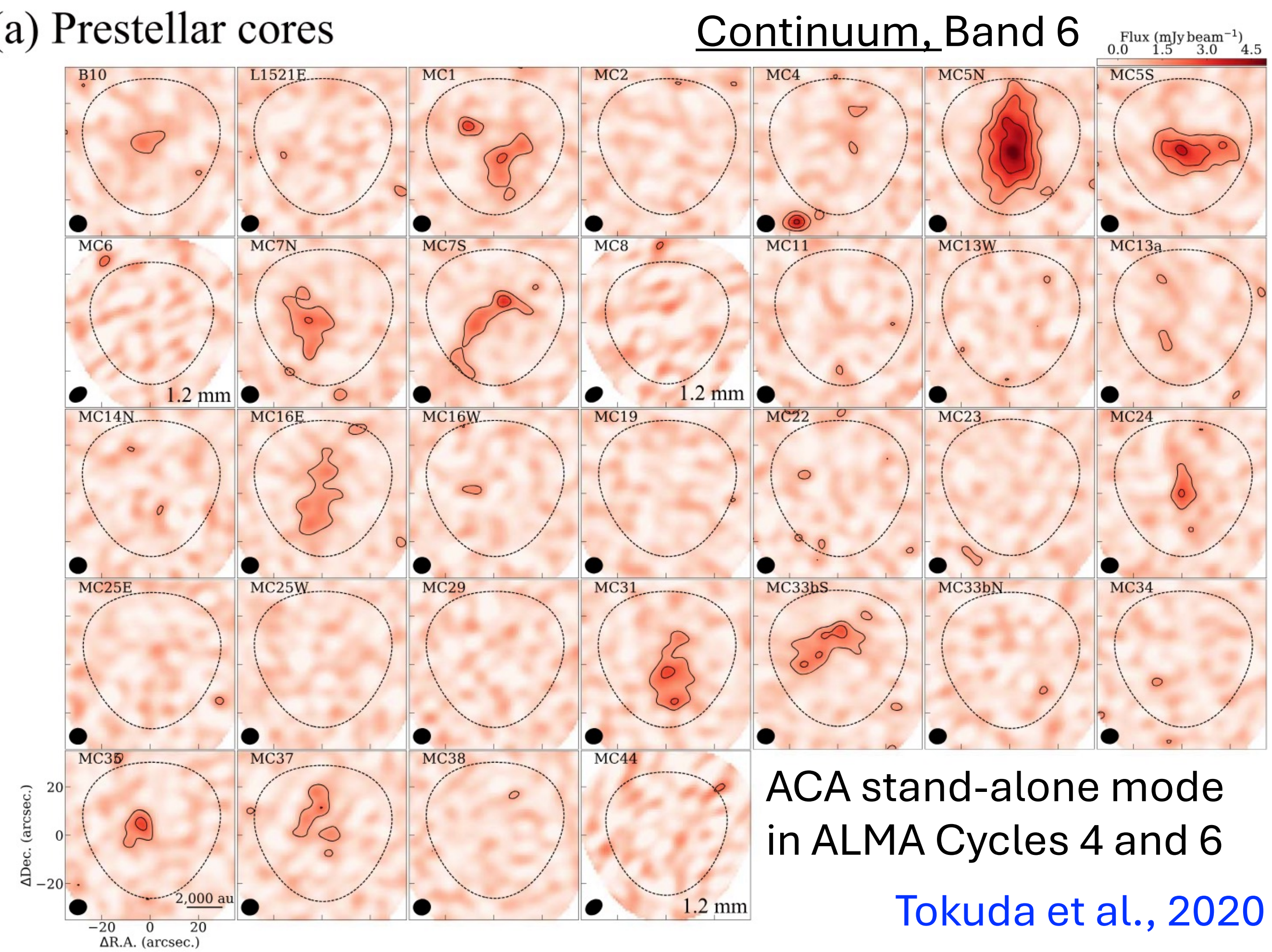
Historically, Mapping of Starless and Prestellar Cores with ALMA has been a *Challenge*!

60 starless and protostellar cores observed in Ophiuchus, 38 detections and only ***~1 starless core resolved****!*



Kirk et al., 2017

32 prestellar sources, confirmed emission in ***12***



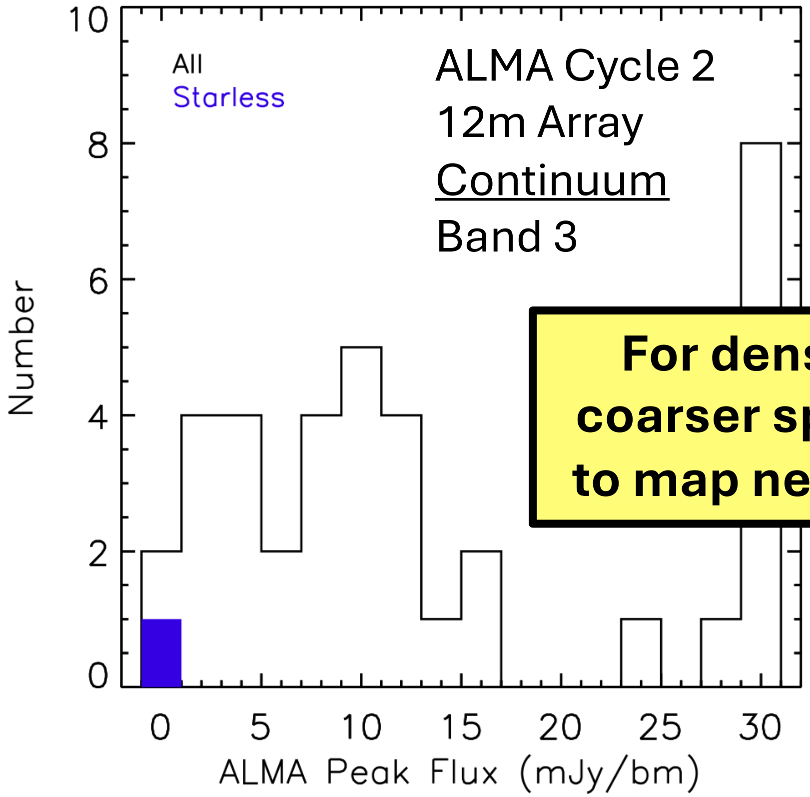
ACA stand-alone mode in ALMA Cycles 4 and 6

Tokuda et al., 2020

Samantha Scibelli

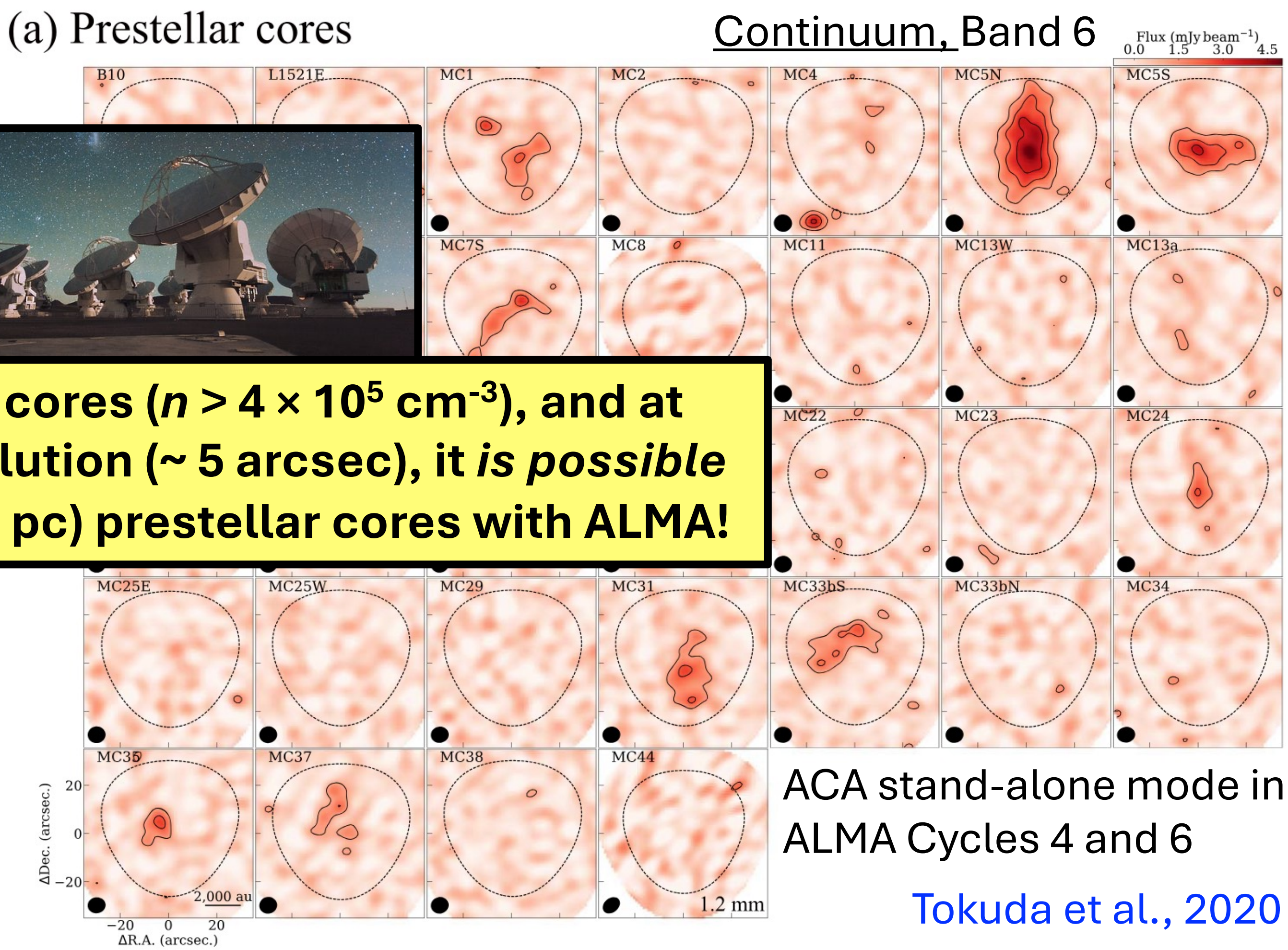
Historically, Mapping of Starless and Prestellar Cores with ALMA has been a *Challenge*!

60 starless and protostellar cores observed in Ophiuchus, 38 detections and only ***~1 starless core resolved****!*



Kirk et al., 2017

32 prestellar sources, confirmed emission in ***12***



For dense enough cores ($n > 4 \times 10^5$ cm^{-3}), and at coarser spatial resolution (~ 5 arcsec), it *is possible* to map nearby (<200 pc) prestellar cores with ALMA!

ACA stand-alone mode in ALMA Cycles 4 and 6

Tokuda et al., 2020

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ALMA Band 1: Lower frequencies probe 'bright' COM emission

Three separate **ALMA Band 1 (~30-50 GHz) Cycle 11 and 12 programs** map (for the first time!) large (>6 atom) COMs, as well as other precursor prebiotic species, in prestellar cores across different nearby molecular cloud environments

Reminder: previous attempts to map larger (>6 atoms) COMs towards *prestellar* cores was **not possible** in the past due to:

1. The total time it would take with single dish telescopes
2. ALMA's decreased sensitivity for extended emission at higher frequencies

Ophiuchus Core: IRAS 16293E

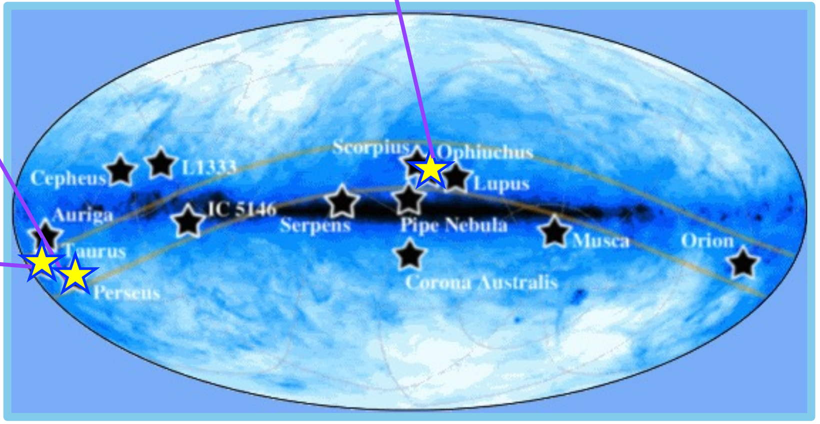
PI: Scibelli
Based on single-dish observations in: Scibelli et al., 2025b

Perseus Core: 326

PI: Scibelli
Based on single-dish observations in: Scibelli et al., 2024, Scibelli et al., 2025a

Taurus Core: L1544

PI: Scibelli
Based on single-dish observations w/ GLUCOSE Large Legacy Program (Scibelli et al., in prep.)



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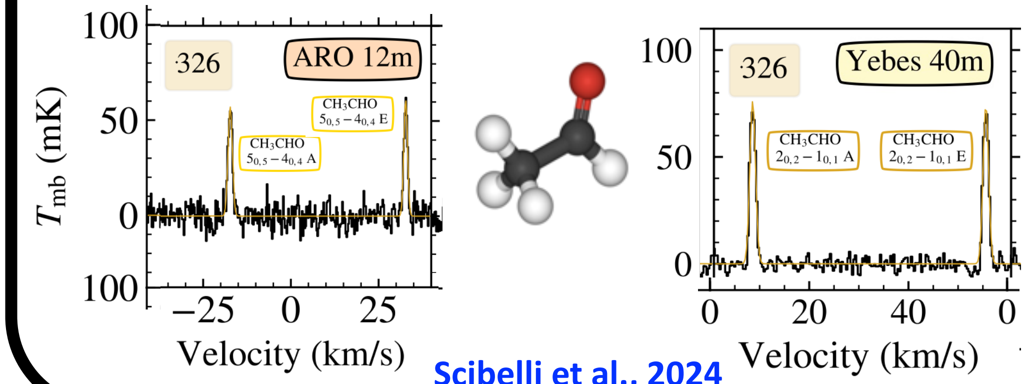
Single Dish, single-pointing observations:

Band 3 (95 GHz) **Band 1 (38 GHz)**



Scibelli et al., 2024

Ophiuchus Core: IRAS 16293E

PI: Scibelli
Based on single-dish observations in: Scibelli et al., 2025b

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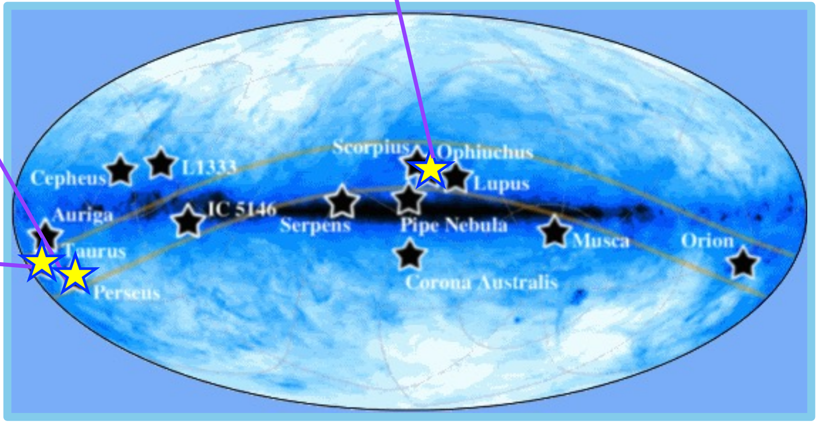

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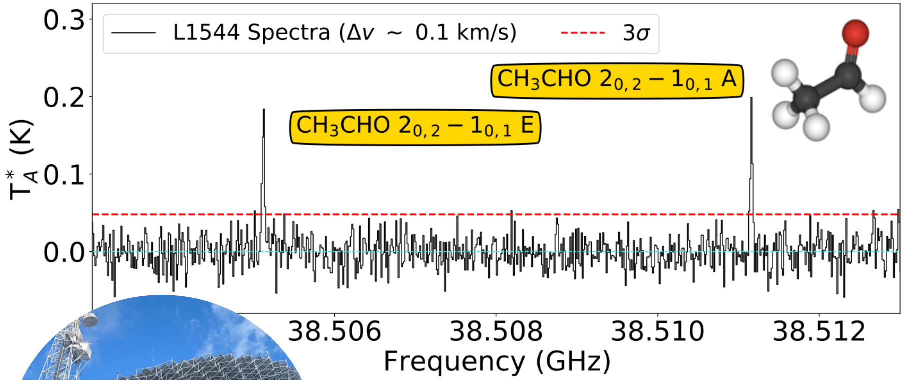

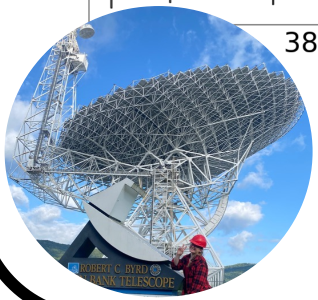

Band 1, w/ GBT (GLUCOSE Large Program)

Taurus Core: L1544

PI: Scibelli
Based on single-dish observations w/ GLUCOSE Large Legacy Program (Scibelli et al., in prep.)

Perseus Core: 326

PI: Scibelli
Based on single-dish observations in: Scibelli et al., 2024, Scibelli et al., 2025a

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PI: Scibelli
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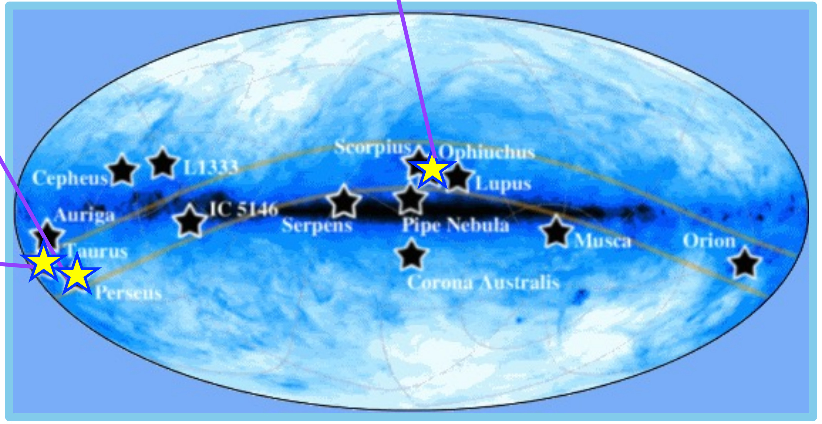

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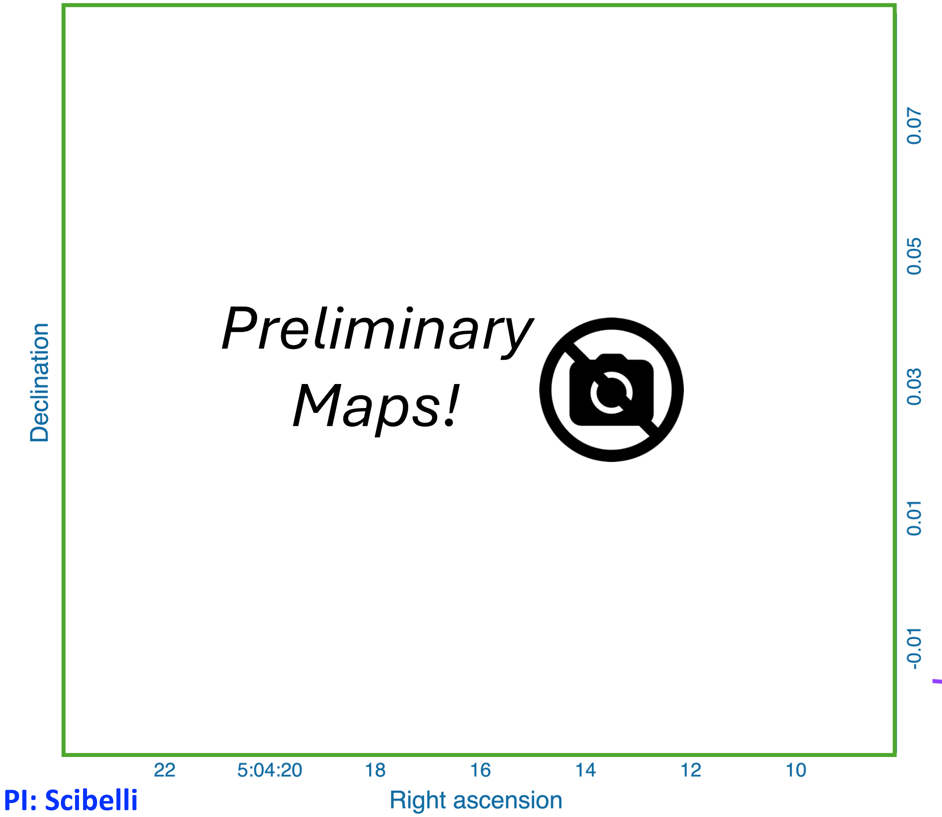
ALMA Band 1: Lower frequencies probe 'bright' COM emission



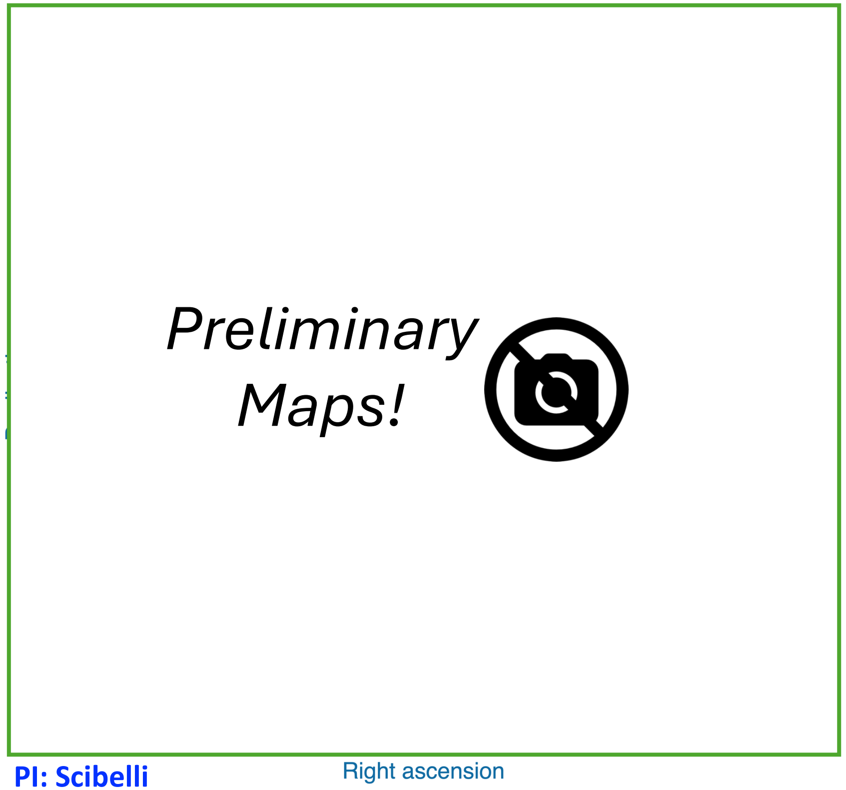
PI: Scibelli

Data collection and reduction is still in progress!

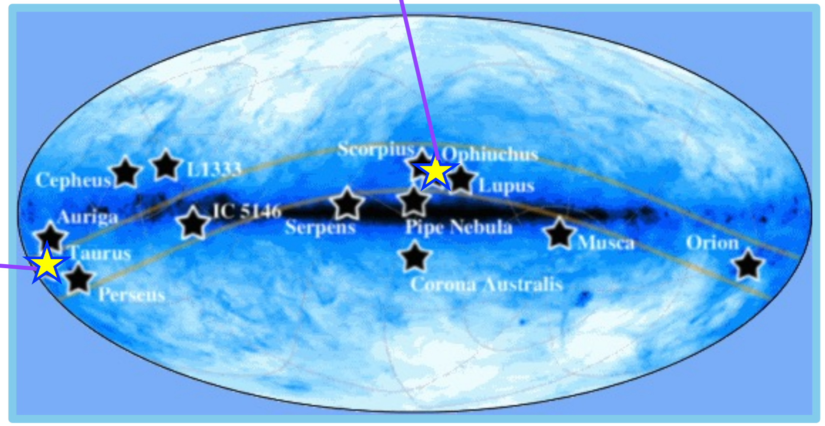
'Bonus' bright emission of 'smaller' species not a part of the main science goal, but within our frequency windows!

Trace infall? Accretion? Streamers? Outflow?

WORK IN PROGRESS



PI: Scibelli



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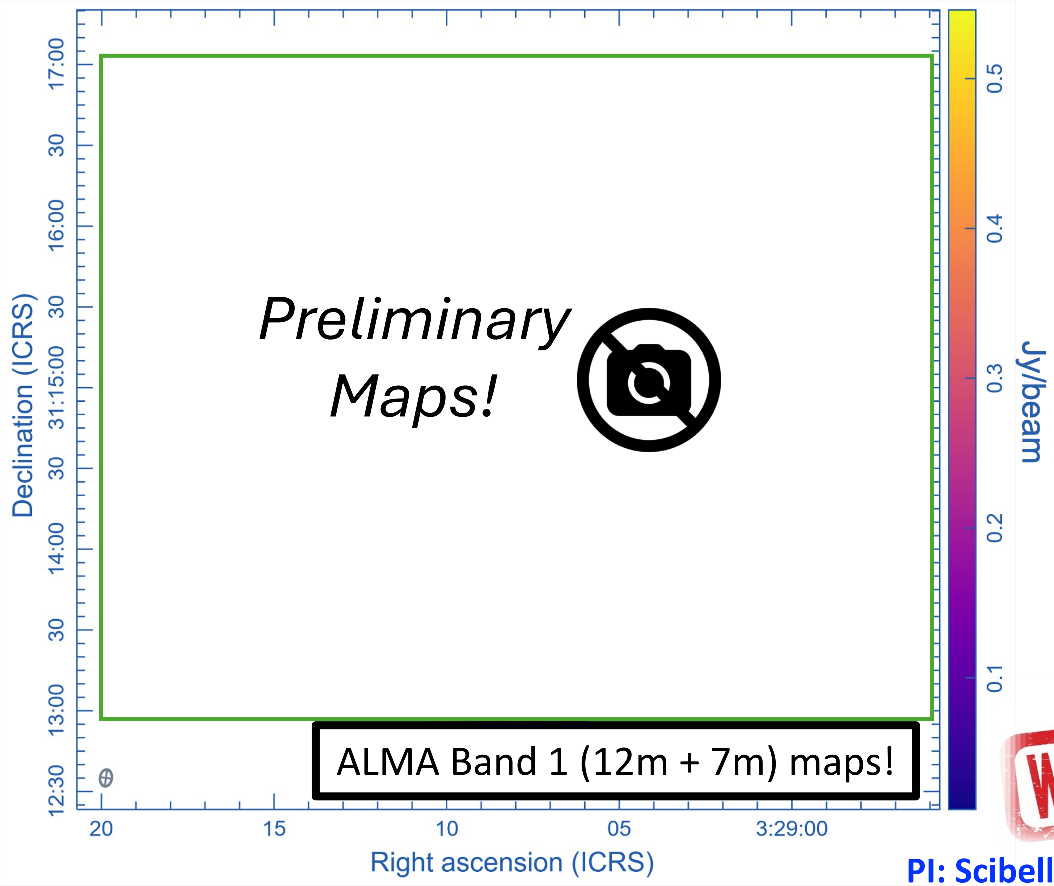
ALMA Band 1: Lower frequencies probe 'bright' COM emission

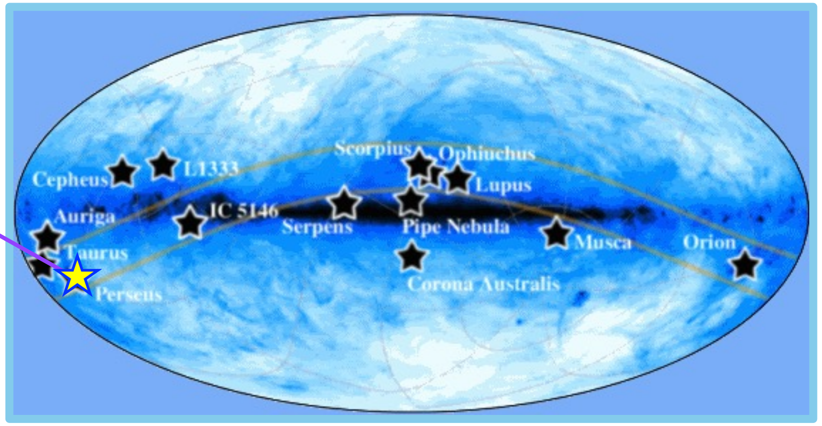
Current Student Project!

ALMA SOS 2025 Bachelors Student
Nate Morin (Echols Scholar, UVa)
In collab. w/ Prof. Rob Garrod (UVa)

Goal: Understand the **shocks and/or shock history** in the region, which **correlates with phosphorus chemistry** (follow-up from first detection of PO, PN and PO^+ from **Scibelli et al., 2025a**)



WORK IN PROGRESS



PI: Scibelli
Morin, Scibelli, Garrod et al., *in prep*

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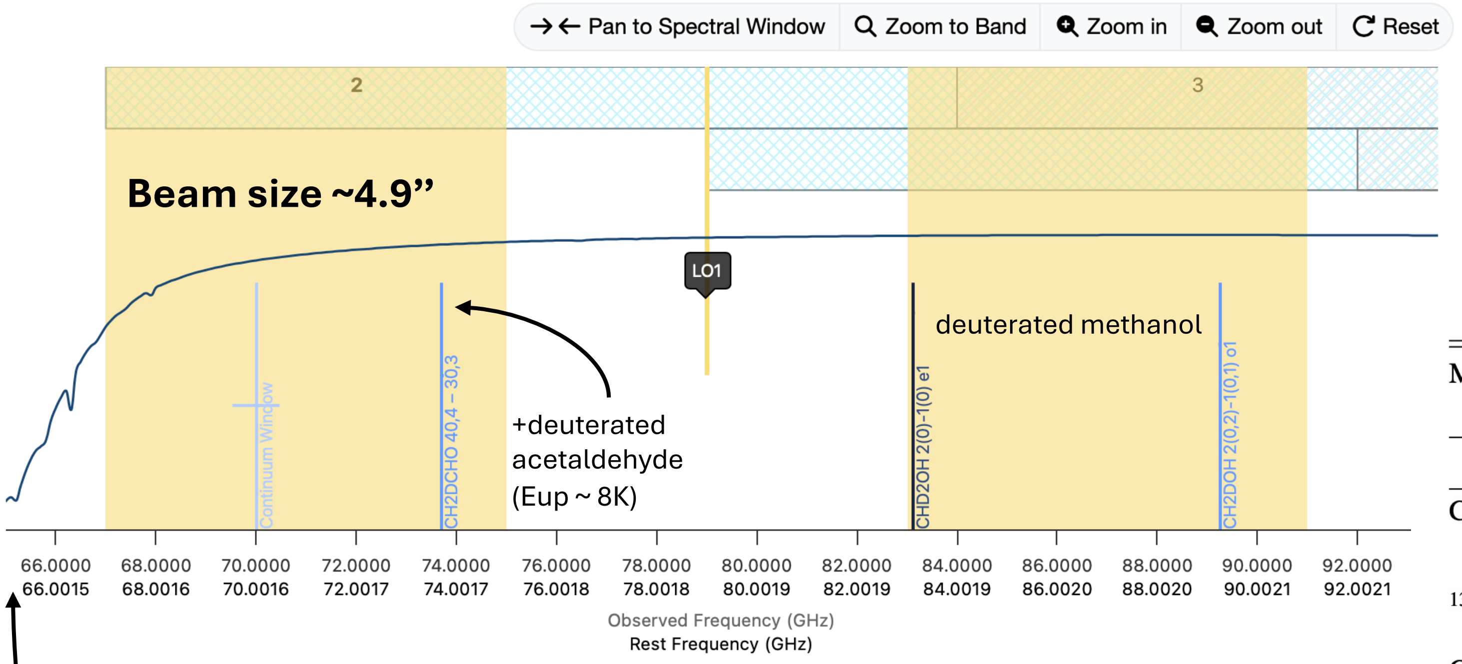
Future ALMA Band 2: Reach ‘bright’ deuterated COMs!

NOTE: it is critical for us galactic astronomers to have ACA and TP, please!



Example spectral setup from new OT!

PI: Scibelli

Molecule	Transition	Frequency (GHz)	E_u (K)	A_{ul} (s^{-1})	g_u	T_{mb} (mK)
			ARO 12 m			
CH_3OH	$2_{-1,2}-1_{-1,1}$ E	96.739358(2)	12.5	2.6E-06	20	1011.9
	$2_{0,2}-1_{0,1}$ A^+	96.741371(2)	6.7	3.4E-06	20	1223.7
	$2_{0,2}-1_{0,1}$ E	96.744545(2)	20.1	3.4E-06	20	206.7
$^{13}CH_3OH$	$2_{-1,2}-1_{-1,1}$ E	94.40516(5)	12.4	2.3E-06	5	19.7
	$2_{0,2}-1_{0,1}$ A	94.407129(4)	6.7	3.1E-06	5	30.6
CH_2DOH	$1_{1,0}-1_{0,1}$ e_0	85.29690(10)	6.2	4.5E-06	3	40.8
	$2_{1,1}-2_{0,2}$ e_0	86.66886(10)	10.6	4.6E-06	5	56.0
	$2_{1,2}-1_{1,1}$ e_0	88.07312(10)	10.4	1.4E-06	5	15.6
	$2_{0,2}-1_{0,1}$ e_0	89.40791(16)	6.4	2.0E-06	5	64.0
CHD_2OH	$2_{1,2}-1_{1,2}$ e_0	82.16582(10)	9.1	1.6E-06	5	16.7
	$2_{0,1}-1_{0,1}$ e_0	83.28963(10)	6.0	2.2E-06	5	24.8

Samantha Scibelli

Scibelli et al., 2025b

Summary and Important Takeaways

Thank you for your attention!

- **Low-mass (M < a few Msun), cold (10 K) starless and prestellar cores** are ideal places to trace complex chemistry (i.e., COMs), since their presence can tell us about the **initial chemical conditions of stars and planets like our own Sun and Solar System**

- **While large surveys (>60 cores)** with the ARO 12m and Yebes 40m single-dish telescopes toward a few local (< 400 pc) molecular clouds reveal COMs are widespread and likely inherited to the next stages of star and planet formation **(Scibelli & Shirley 2020, Scibelli et al., 2021, 2024, 2025a,b)**, we still *need sensitive maps* to constrain: **1) the spatial extent of COM emission in the larger-scale filaments, 2) local environmental factors (e.g., UV radiation), and 3) chemical models**

- **ALMA Band 1 and 2 pave the way for this!** At lower frequencies (< 80 GHz) there are many 'bright' COMs (& D-COMs!) at more favorable 12m beam sizes (~5'') that can map this emission, as evidence by my three ALMA Band 1 programs toward L1544, Pers326 and IRAS 16293E

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