High Resolution 3D Radiative Transfer Modeling and Virial Analysis of Starless Cores

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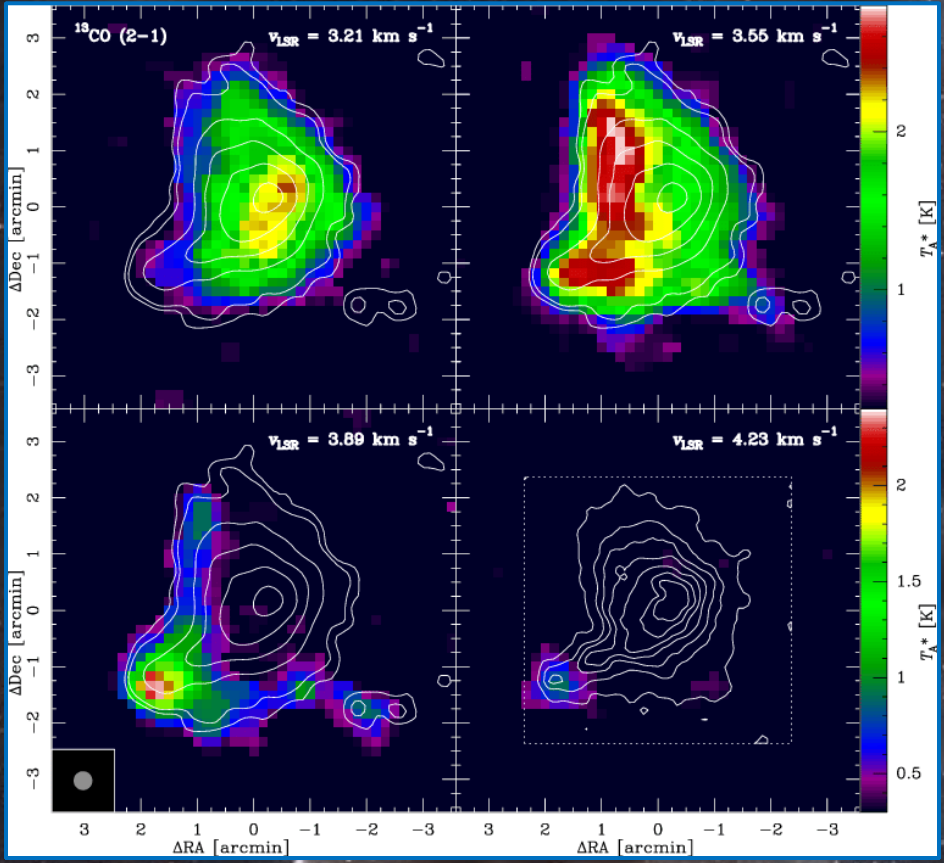
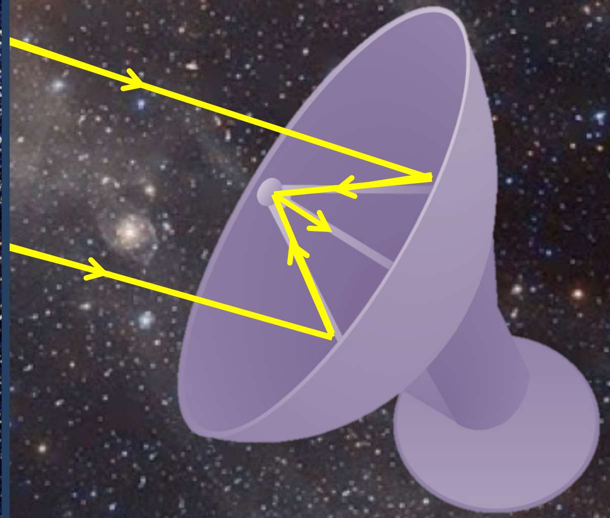
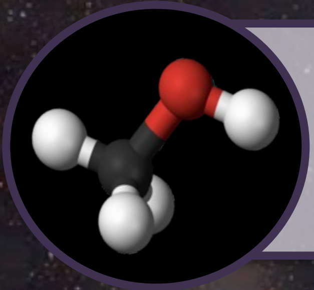
Low-Mass (M ≤ a few $M_\odot$) Star Formation



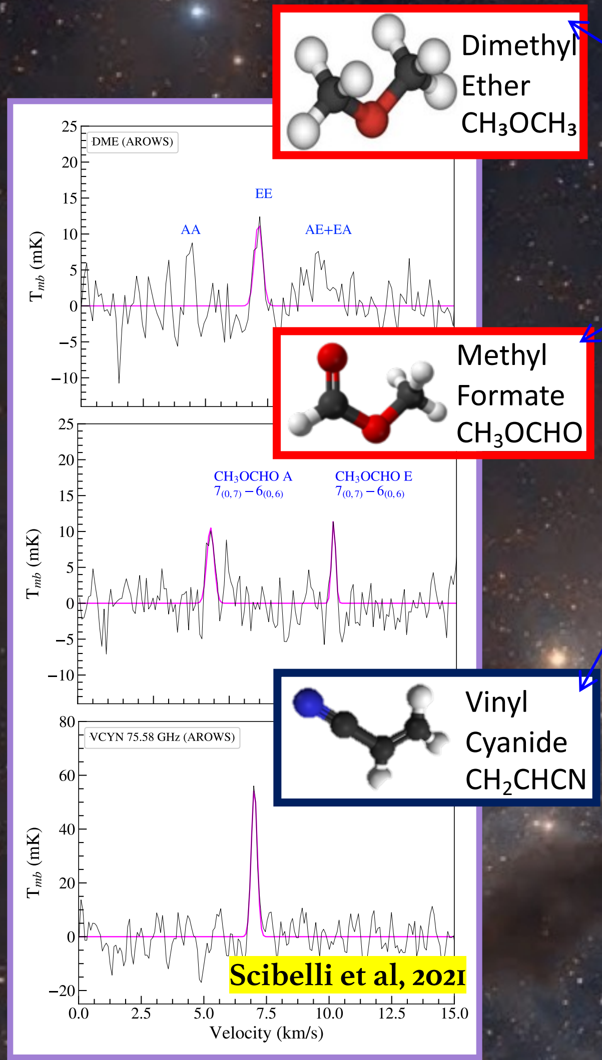
Nielbock et al. 2012

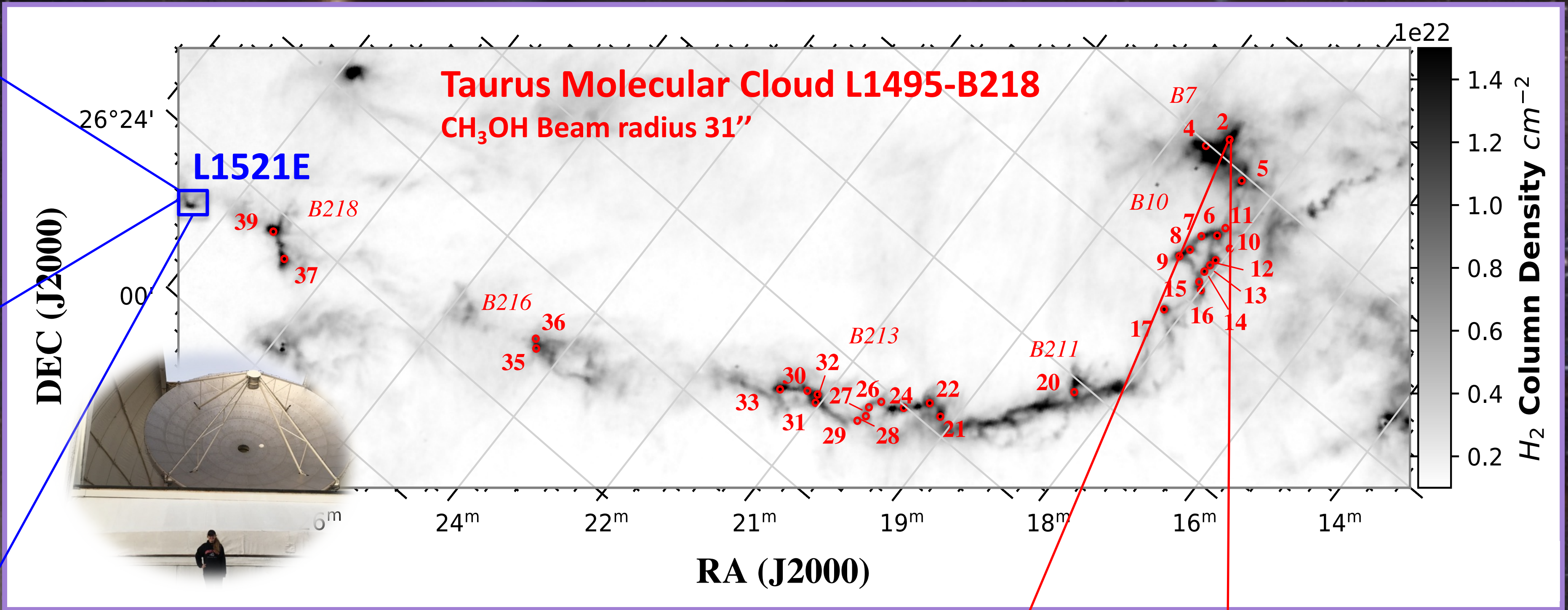
Birthplace of low-mass stars
(M ≤ a few $M_\odot$)
Dense (10^4 - 10^5 cm^{-3}) & cold (≤ 10K)





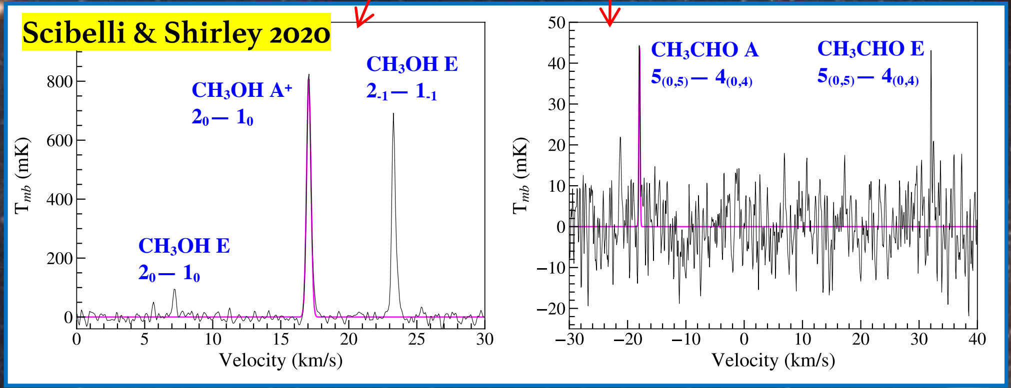
Complex Chemistry in Starless Cores



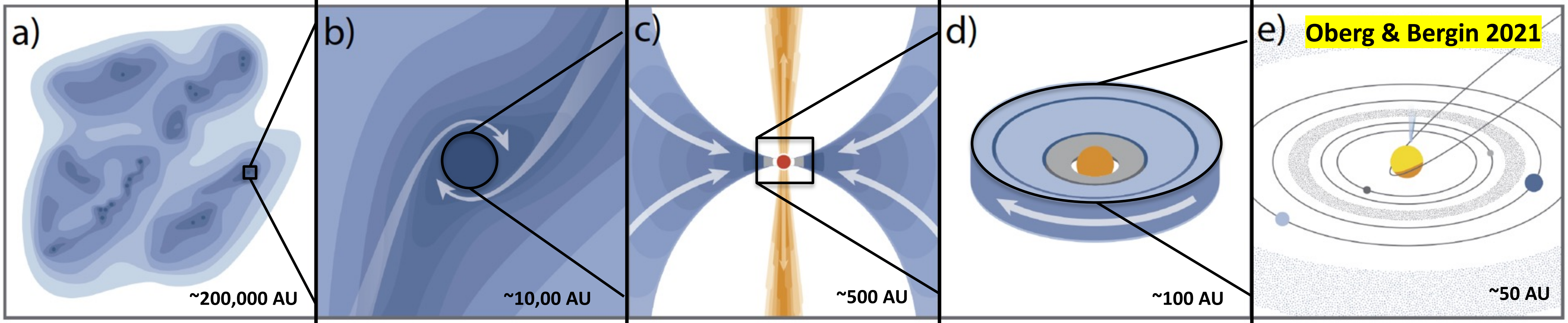


Observations with the Arizona Radio Observatory (ARO) 12m show COMs are prevalent in 31 more 'typical' starless and prestellar cores – **methanol (CH_3OH) found in 100% & acetaldehyde (CH_3CHO) found in 70%!** →

← PLUS even higher complexity found in young, starless core L1521E!



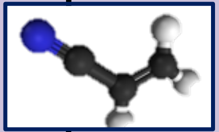
Low-Mass ($M \leq$ a few $M_{\odot}$) Star Formation



a) Dense starless cores embedded in larger filaments

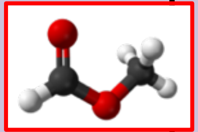
t_{ad} ~ 5 million yrs.

Acetaldehyde (CH3CHO), etc.
Vastel et al. 2014
Vinyl Cyanide (CH2CHCN)
Jimenez-Sera et al. 2021



b) Dense (10^5 cm^{-3}) & cold (10K) prestellar cores collapse due to gravity and pressure

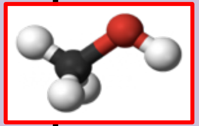
t_{iso} ~ .2 million yrs.



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

~1 million yrs.

Glycolaldehyde (CH2OHCHO),
Methyl Formate (CH3OCHO), etc.
Jørgensen et al. 2012, 2016



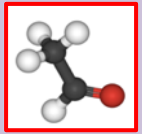
d) Pre-main sequence star left with a circumstellar disk

1-10 million yrs.

Methanol (CH3OH)
Walsh et al. 2016, 2017
Dimethyl Ether (CH3OCH3)
Brunken et al. 2022

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

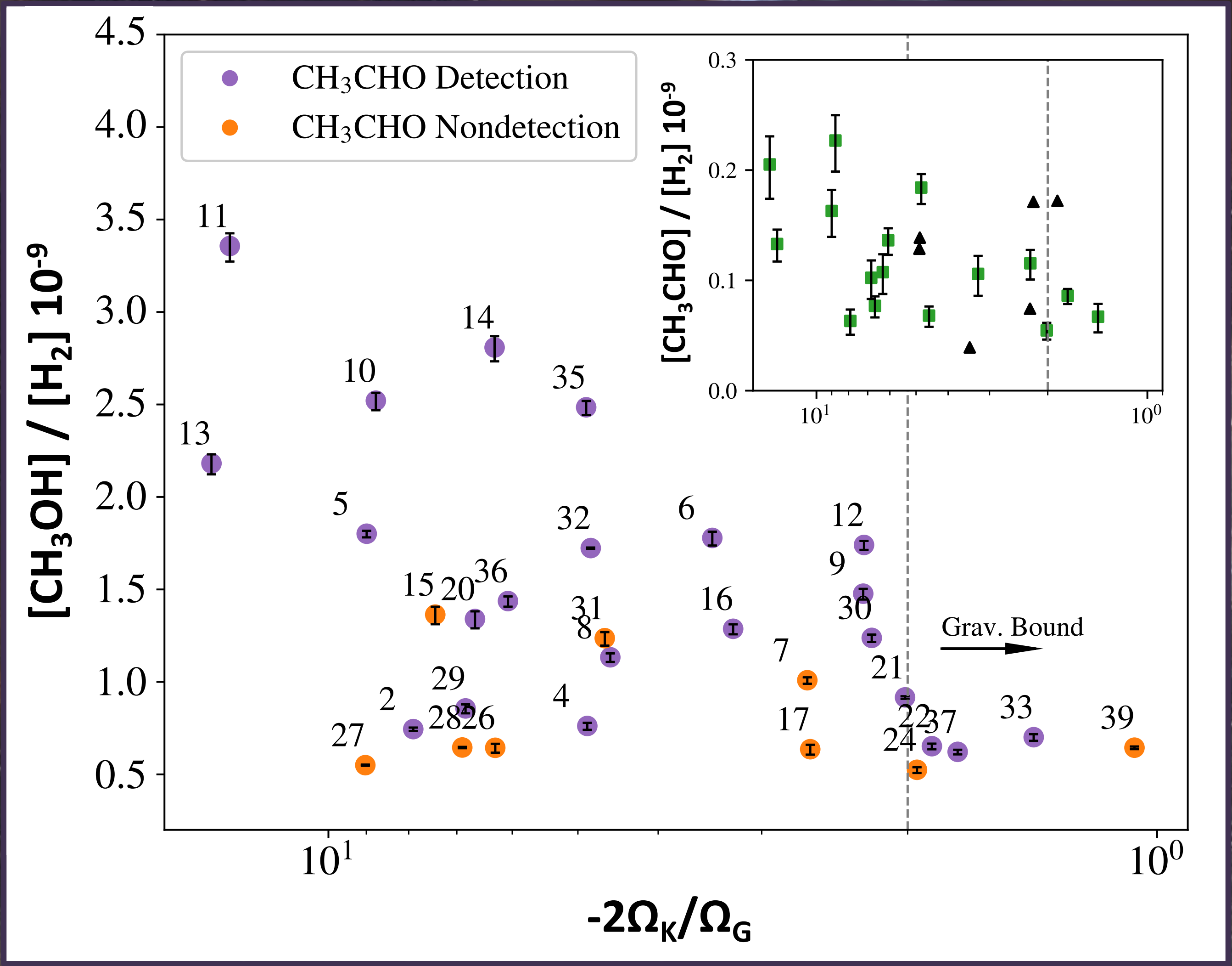
10-50 million yrs.



(CH2OH)2, CH3CHO,
NH2CHO, C2H5OH
Biver 2019

How do solar-type stars evolve?
What kind of "chemical inheritance" gets passed on from preceding evolutionary stages?

Virial Analysis



Scibelli & Shirley 2020

Will the COM-rich starless cores go on to form stars?

Kinetic Energy Term

NH3 Observations

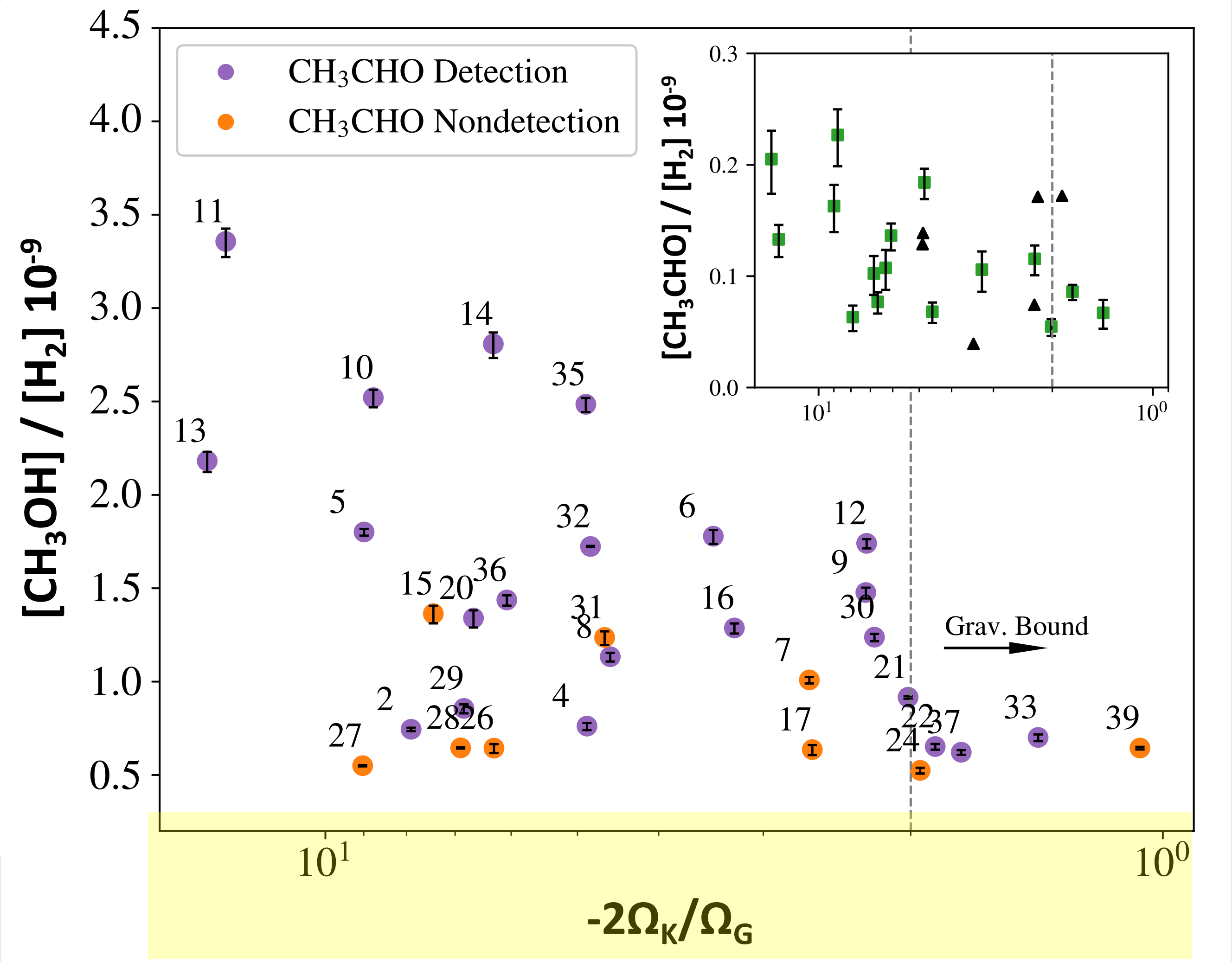
$$\Omega_K = \Omega_{K_{\text{bulk}}} + \frac{3}{2}\int \sigma_{\text{tot}}(x,y)^2 \Sigma_c \, dx dy$$

Gravitational Energy Term

Dust (H_2) Observations

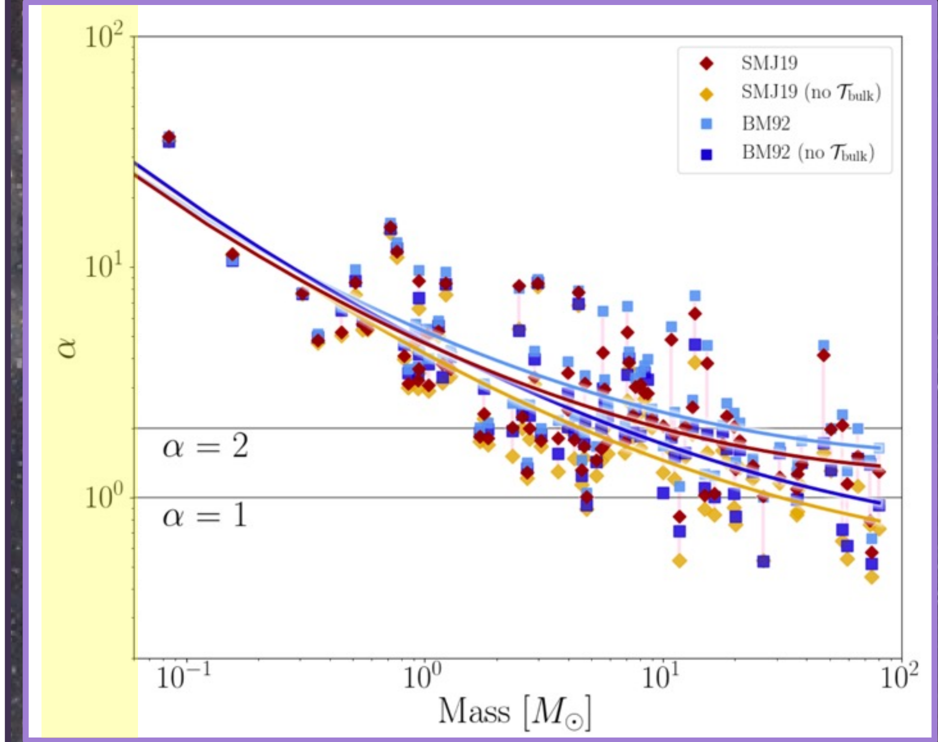
$$\Omega_G = -a\frac{3GM(R_c)^2}{5R_c}$$

Virial Analysis



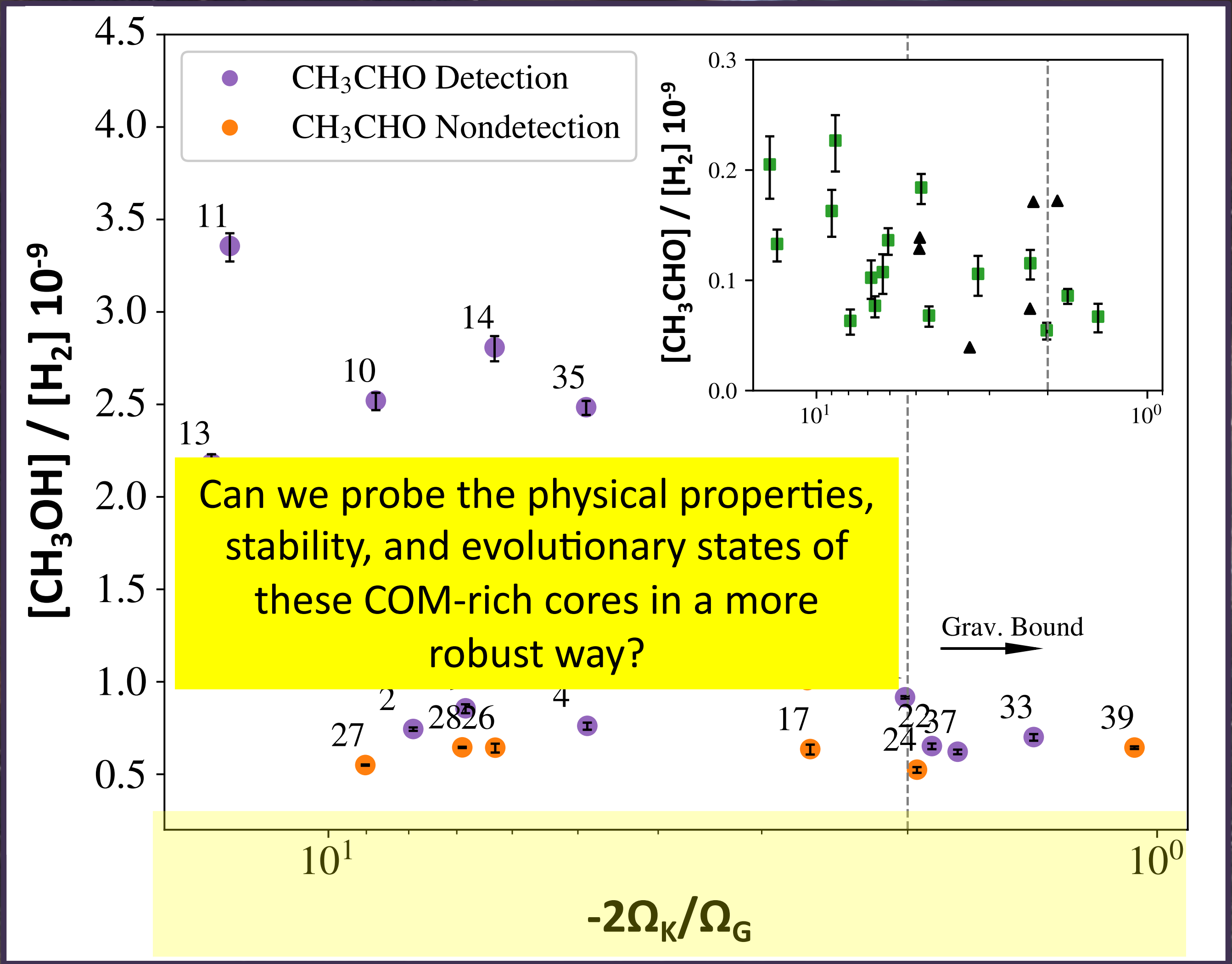
Scibelli & Shirley 2020

Systematic error, such as insufficient removal of foreground and background material, can lead to different virial parameters and trends



Singh et al. 2021

Virial Analysis



Scibelli & Shirley 2020

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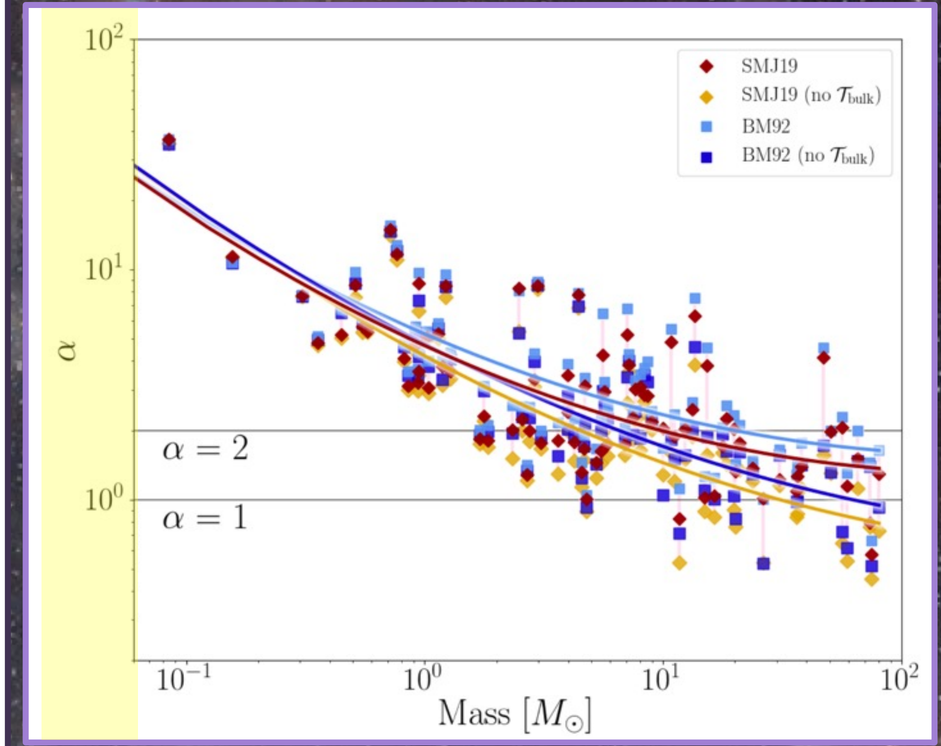
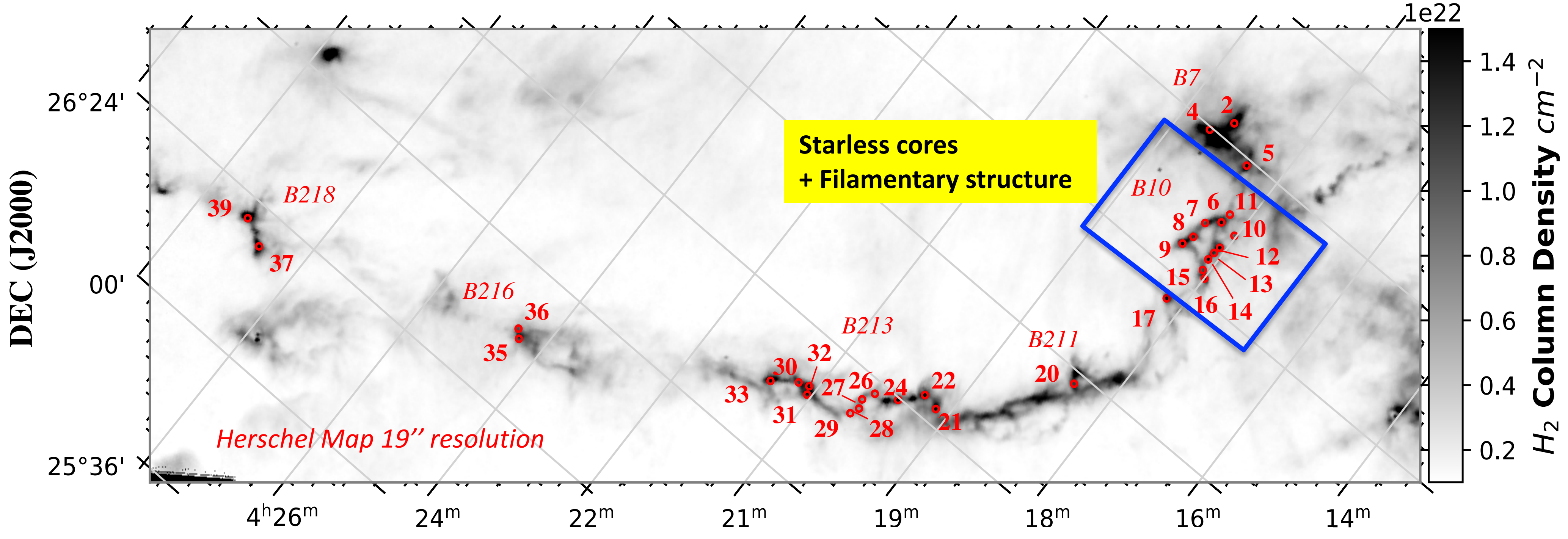


Singh et al. 2021

High Resolution Continuum Study of the B10 region of the Taurus Molecular Cloud



H_2 map: Palmeirim et al. 2013, Marsh et al. 2016

We decided to focus on the B10 region of Taurus, as it is considered a 'less-evolved' region due to lack of protostellar activity and thus not as affected by external radiation from surrounding star formation

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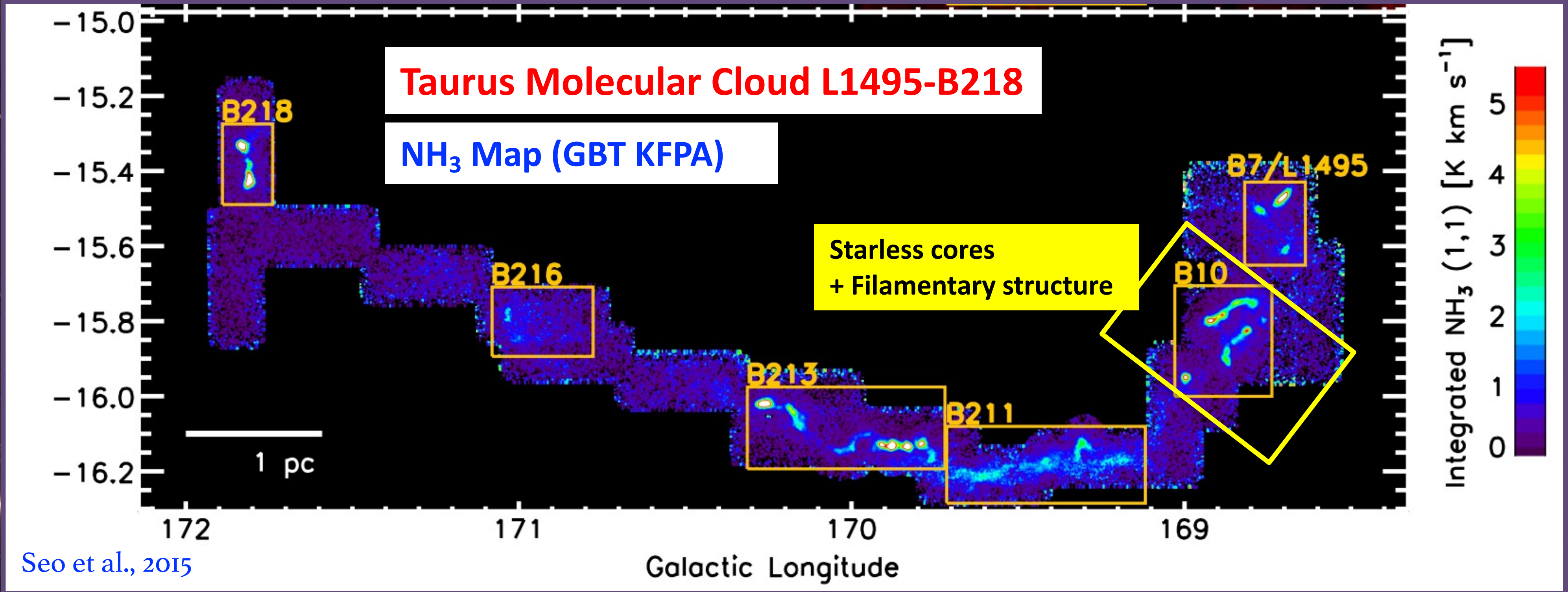

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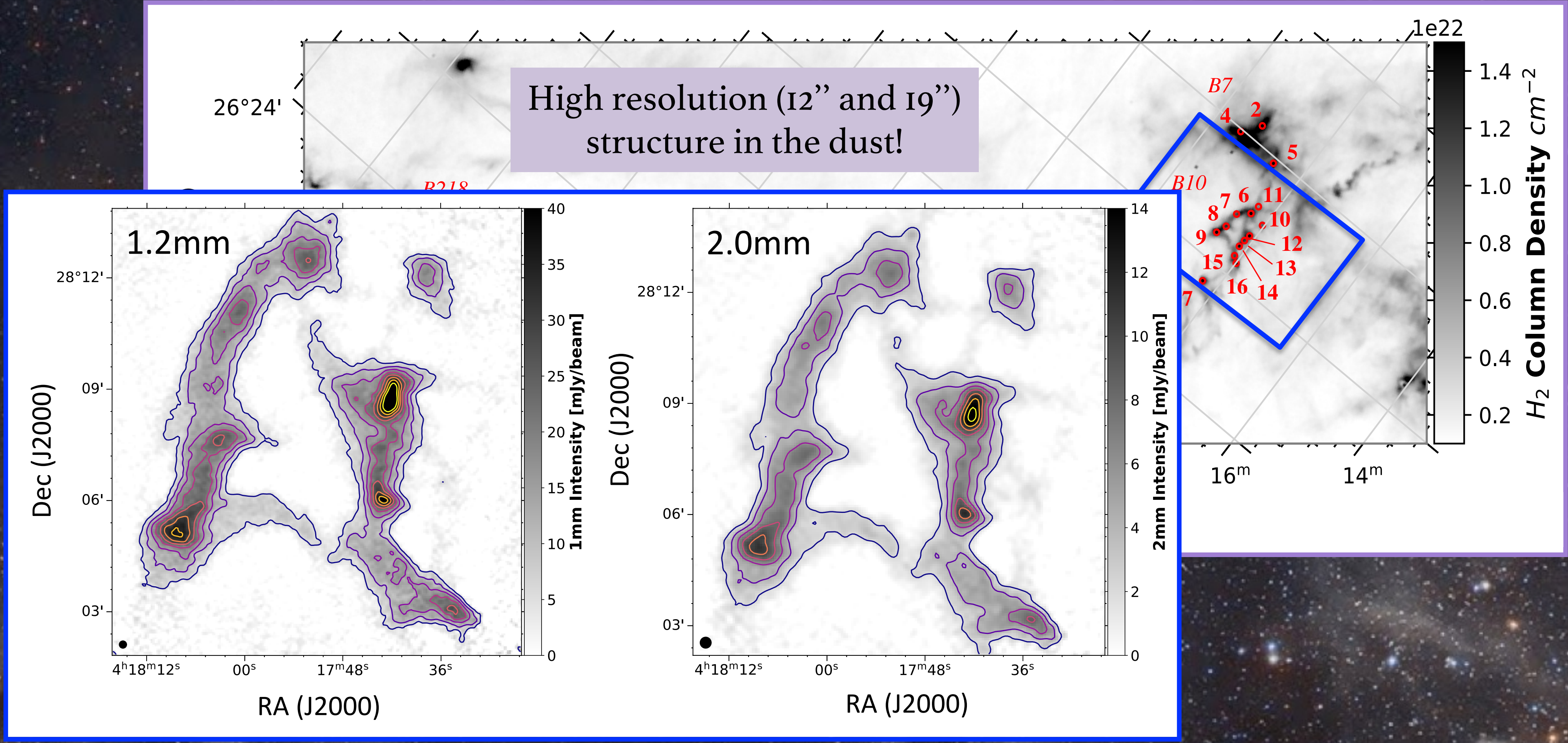
High Resolution 3D Radiative Transfer Modeling of the B10 region in Taurus

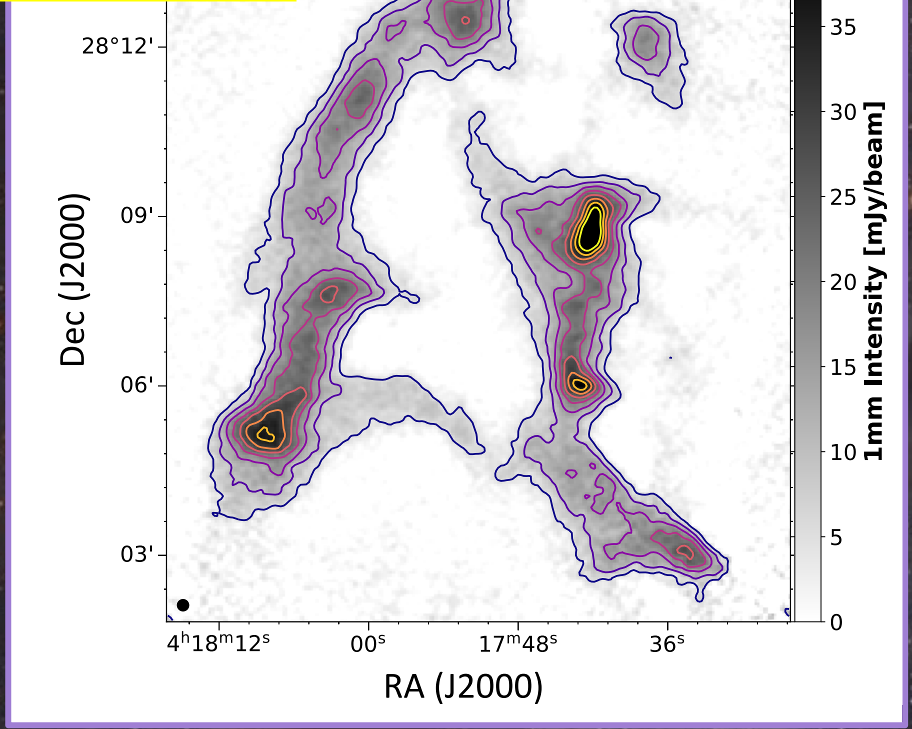
Maps from observations I obtained with the NIKA 2 Instrument on the IRAM 30m in Spain

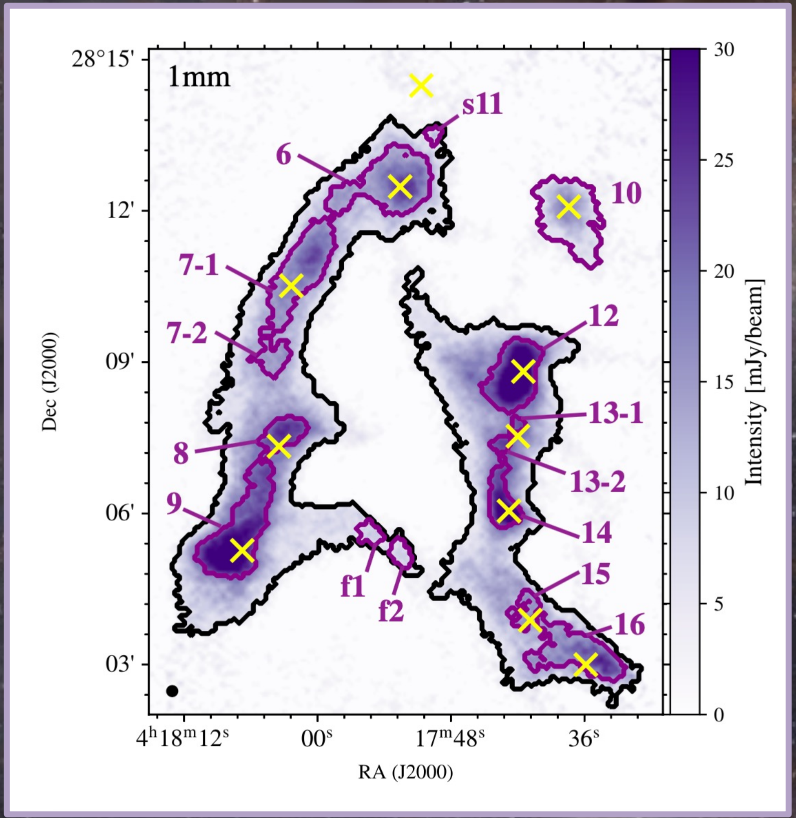


Scibelli et al., 2023, *in review*

High Resolution Continuum Study of the B10 region of the Taurus Molecular Cloud

IRAM 30m NIKA2 Dust Data



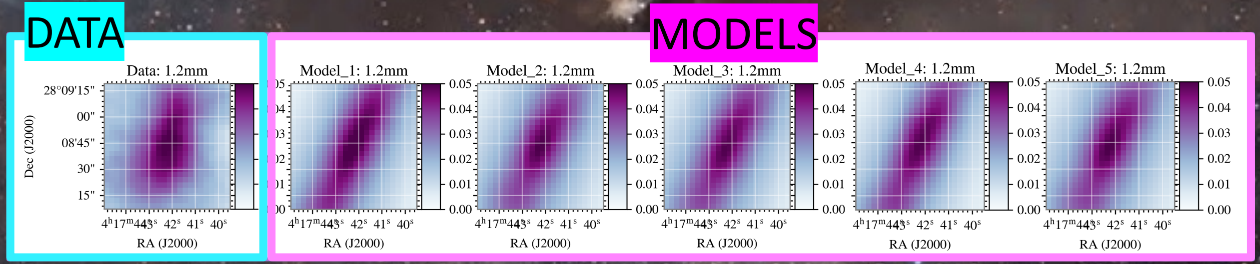


Dendrogram analysis of 1.2 mm emission found **14 starless cores**

Scibelli et al., 2023, *in review*

High Resolution Continuum Study of the B10 region of the Taurus Molecular Cloud

Radiative Transfer Dust Modeling
RADMC-3D (Dullemond 2019, version 0.41)
Modified *pandora* Framework for processing
(see *Schmiedeke et al. 2016*)



Input:

1) Set source + telescope parameters (i.e., location on sky and beam size).

2) Global parameters like cell size, number of cells, number of photons, etc.

2) Grids of physical parameters

Radmc-3d:

Adaptive Mesh Grid Generation, Dust Temperature Calculation, Creation of Dust Continuum Maps

Outputs:

*SEDs, emission maps, column density maps, and dust temperature maps (as .fits files)

*we have corresponding Herschel data at 160, 250, 350, and 500 micron (in addition to the NIKA2 1mm and 2mm data)

Diagnostics:

Best fit SED peaks, best fit 1D normalized radial profiles & sectored radial profiles (from χ^2 analysis)

Scibelli et al., 2023, *in review*

High Resolution Continuum Study of the B10 region of the Taurus Molecular Cloud

1,040,000 models run

Density parameters defined by Plummer-like Profile,

$$n(r) = \frac{n_0}{(1 + |\boldsymbol{r}|^2)^{\frac{\eta}{2}}}$$

$$|\boldsymbol{r}| = \sqrt{(\frac{r_x}{r_{0,x}})^2 + (\frac{r_y}{r_{0,y}})^2 + (\frac{r_z}{r_{0,z}})^2}$$

n_0 (cm^{-3})	[1.0e4, 5.0e4, 1.0e5, 2.0e5, 3.0e5, 4.0e5, 5.0e5, 6.0e5 7.0e5, 8.0e5, 9.0e5, 1.0e6, 2.0e6]
η	[1.5, 2.0, 2.5, 3.0, 3.5, 4.0, 4.5, 5.0, 5.5]
r_x (AU)	[1620, 1890, 2160, 2430, 2700, 2970, 1890, 2160, 2430, 2700, 2970, 3240, 3510, 3780, 4050, 4320, 4590, 4860, 5130, 5400, 5670, 5940, 6210, 6480, 6750]
r_y (AU)	[1620, 1890, 2160, 2430, 2700, 2970, 1890, 2160, 2430, 2700, 2970, 3240, 3510, 3780, 4050, 4320, 4590, 4860, 5130, 5400, 5670, 5940, 6210, 6480, 6750]
s_{isrf}	0.3, 0.6, 1.0, 2.0, 3.0
O&H94	0, 1, 10, 11

Scibelli et al., 2023, *in review*

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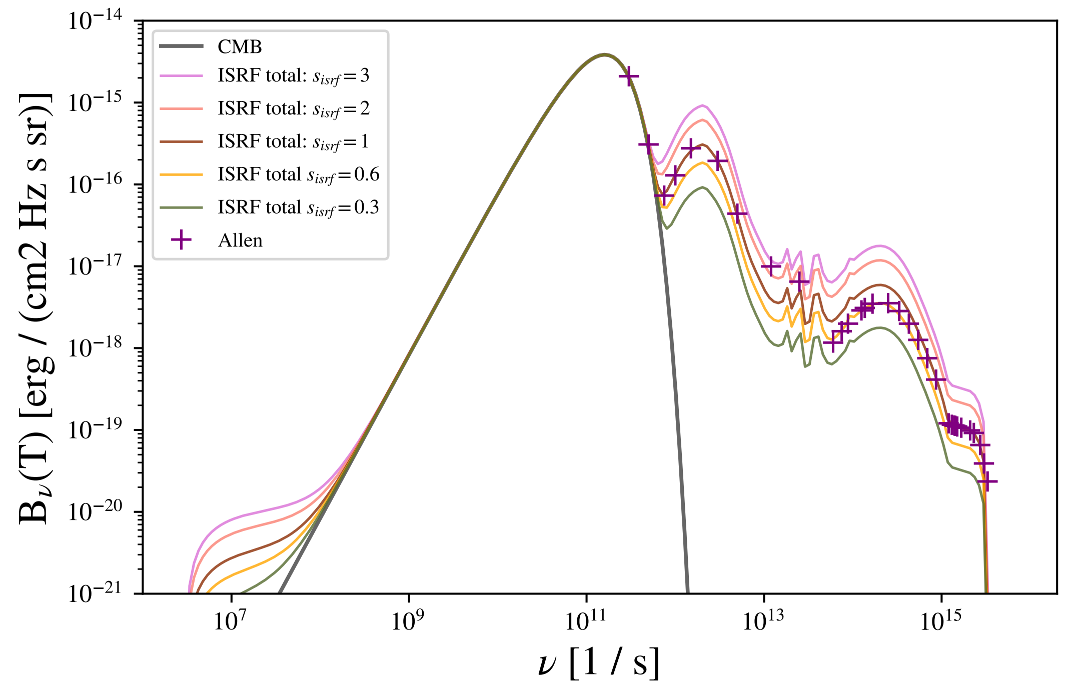

Interstellar radiation field scaled from Draine & Li (2007)

1,040,000 models run

n_0 (cm^{-3})	[1.0e4, 5.0e4, 1.0e5, 2.0e5, 3.0e5, 4.0e5, 5.0e5, 6.0e5 7.0e5, 8.0e5, 9.0e5, 1.0e6, 2.0e6]
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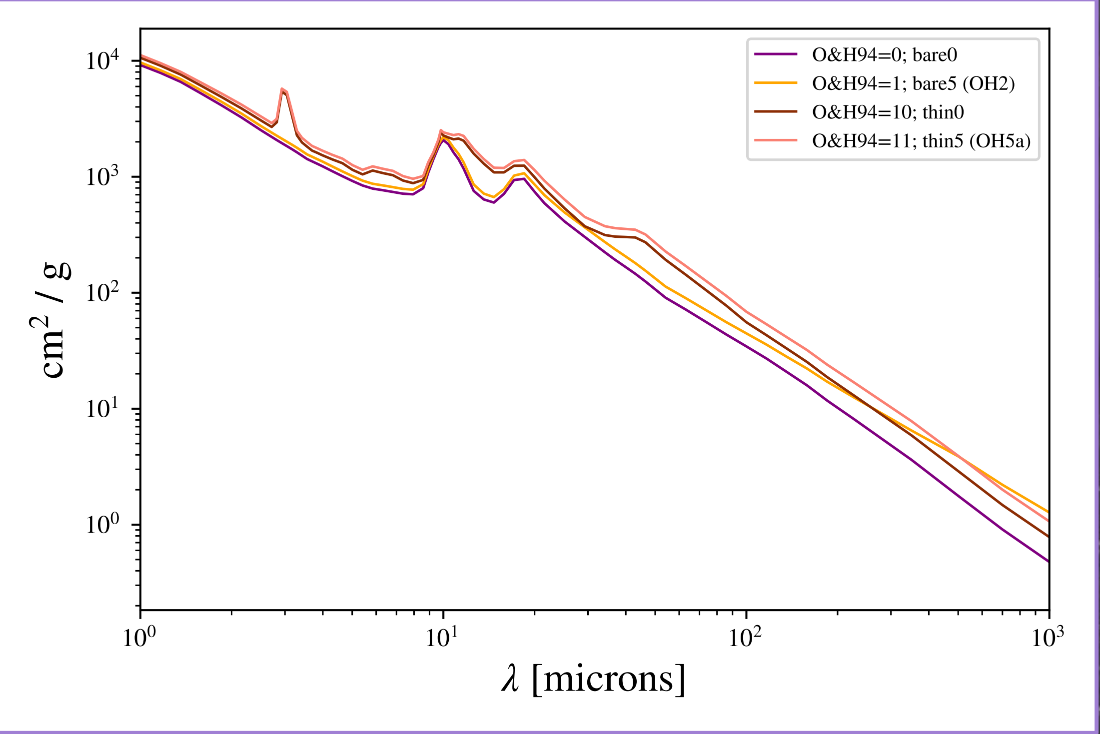

Opacity from Ossenkopf & Henning (1994) assuming either no initial gas density or a gas density of 10^5 cm^{-3}, with bare or thin ice mantles

1,040,000 models run

n_0 (cm^{-3})	[1.0e4, 5.0e4, 1.0e5, 2.0e5, 3.0e5, 4.0e5, 5.0e5, 6.0e5 7.0e5, 8.0e5, 9.0e5, 1.0e6, 2.0e6]
η	[1.5, 2.0, 2.5, 3.0, 3.5, 4.0, 4.5, 5.0, 5.5]
r_x (AU)	[1620, 1890, 2160, 2430, 2700, 2970, 1890, 2160, 2430, 2700, 2970, 3240, 3510, 3780, 4050, 4320, 4590, 4860, 5130, 5400, 5670, 5940, 6210, 6480, 6750]
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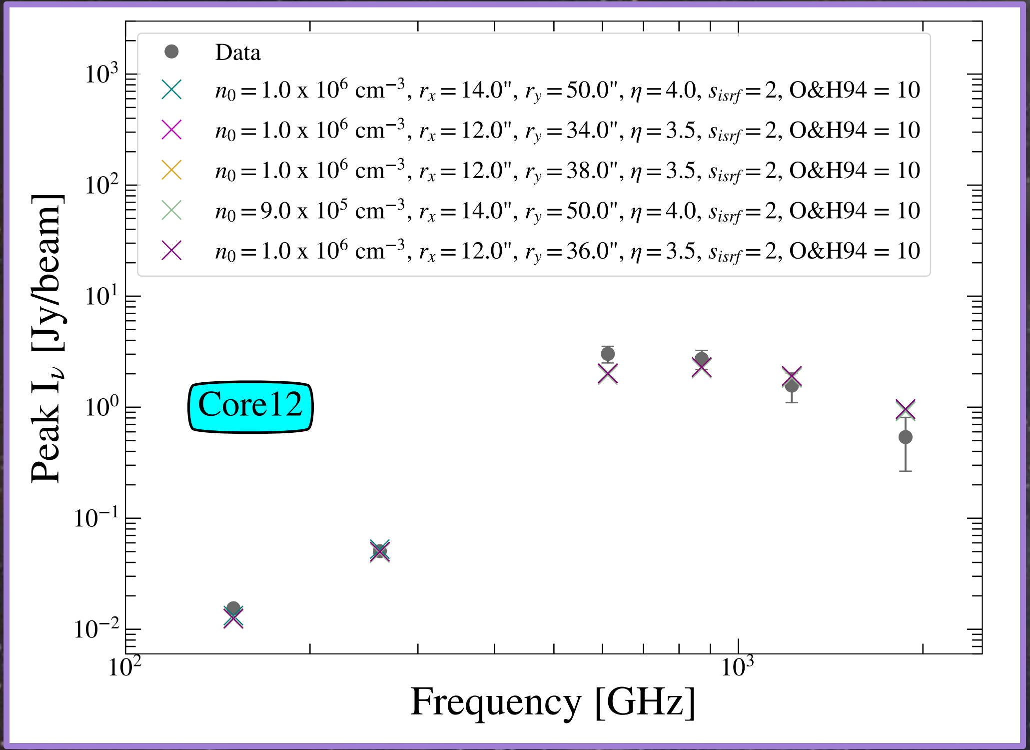
Scibelli et al., 2023, *in review*

High Resolution Continuum Study of the B10 region of the Taurus Molecular Cloud

Diagnostics:

1) Models need to fit within 1**σ** of 1.2mm and 250micron peak emission
2) Modeled normalized radial profile χ^2 cutoff ensures 2D structure accounted for



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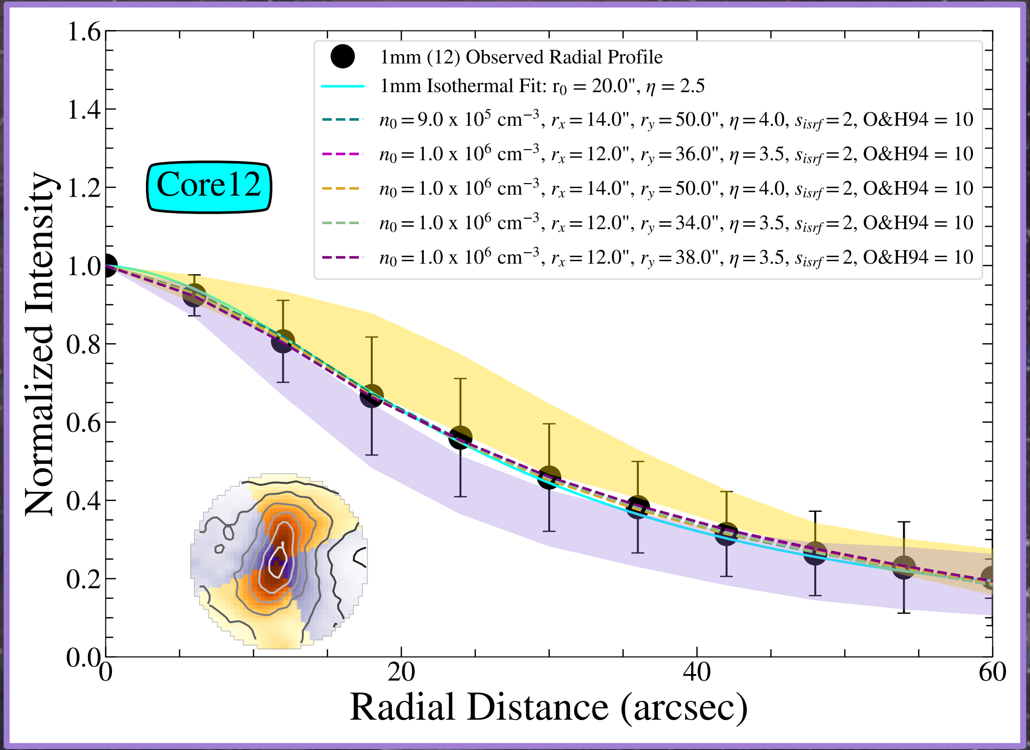
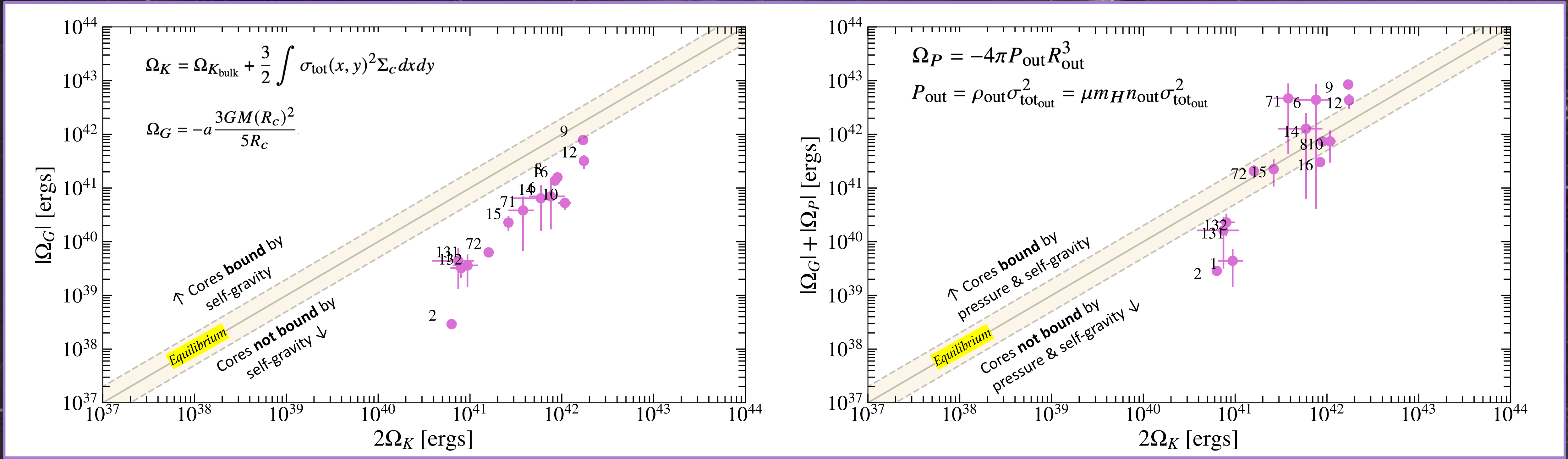


Scibelli et al., 2023, *in review*

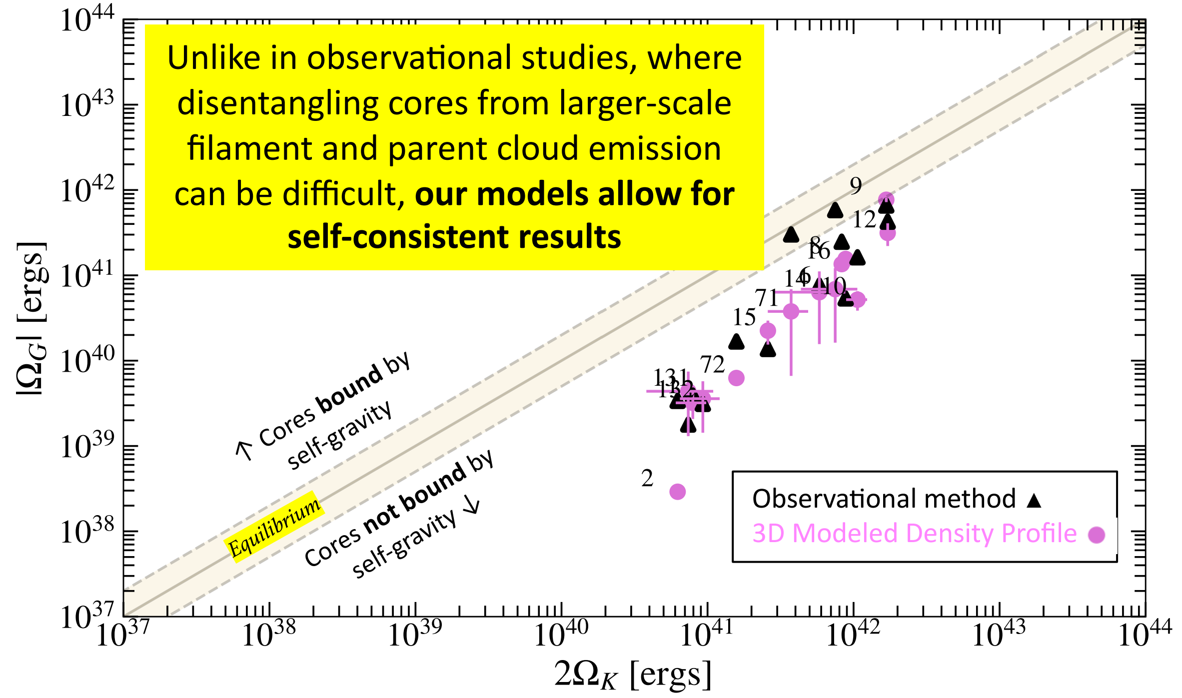
High Resolution 3D Radiative Transfer Modeling of the B10 region in Taurus

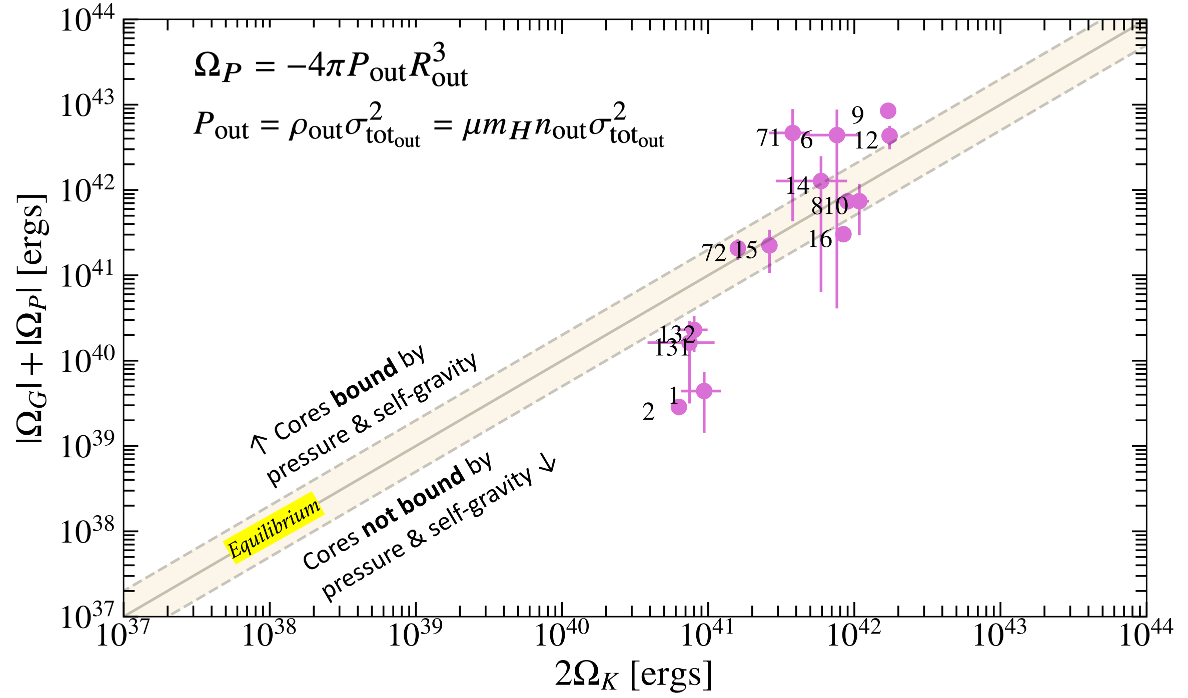


Virial parameters calculated directly from *3D density models* and observed NH_3 for velocity and temperature information. Most (64%) of the cores are either in virial equilibrium or bound by external pressure and self gravity.

Scibelli et al., 2023, *in review*

High Resolution 3D Radiative Transfer Modeling of the B10 region in Taurus





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Scibelli et al., 2023, *in review*

High Resolution 3D Radiative Transfer Modeling of the B10 region in Taurus

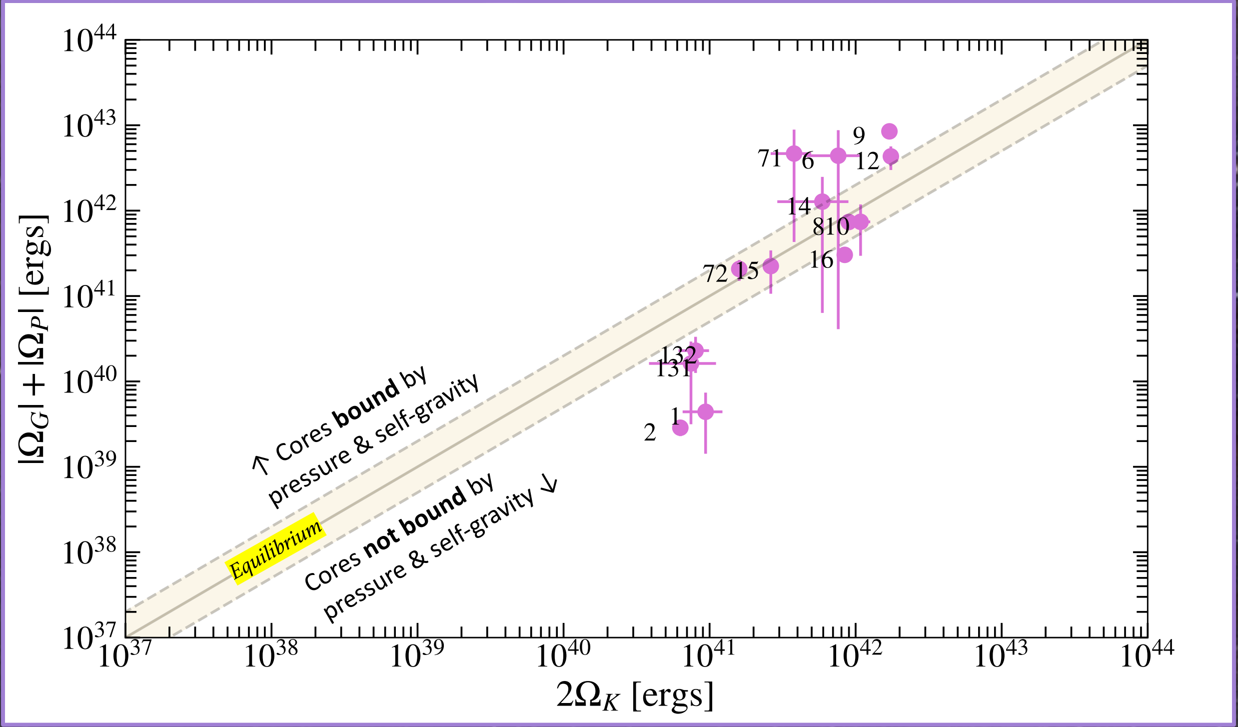
Only a small effective magnetic field difference of ~ **15μG** would be needed to push the bounded cores (6, 7-1, 9, 12 and 14) back to equilibrium.

$$\Omega_B = \frac{(B^2 - B_0^2)R^3}{6},$$

$$\Delta B_{\text{eff}} = \sqrt{(B^2 - B_0^2)},$$

Equilibrium when,

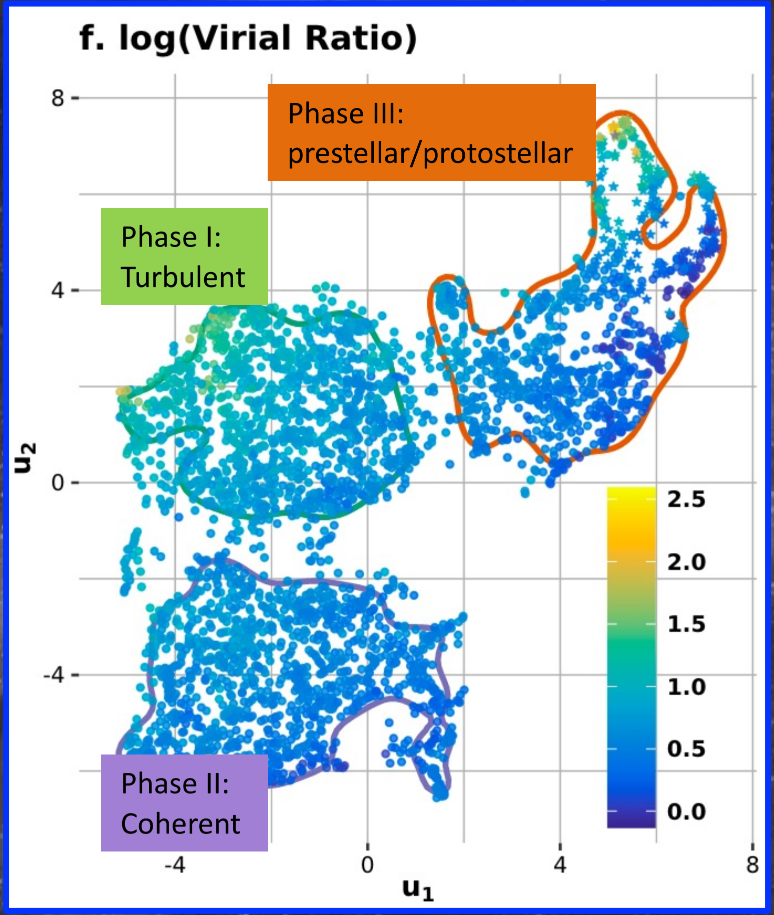
$$-(\Omega_G + \Omega_P) = 2\Omega_K + \Omega_B$$

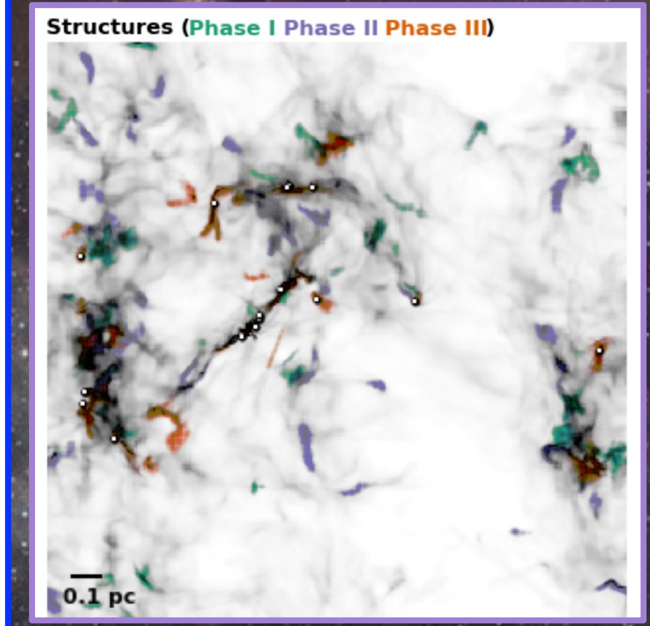


Scibelli et al., 2023, *in review*

High Resolution 3D Radiative Transfer Modeling of the B10 region in Taurus

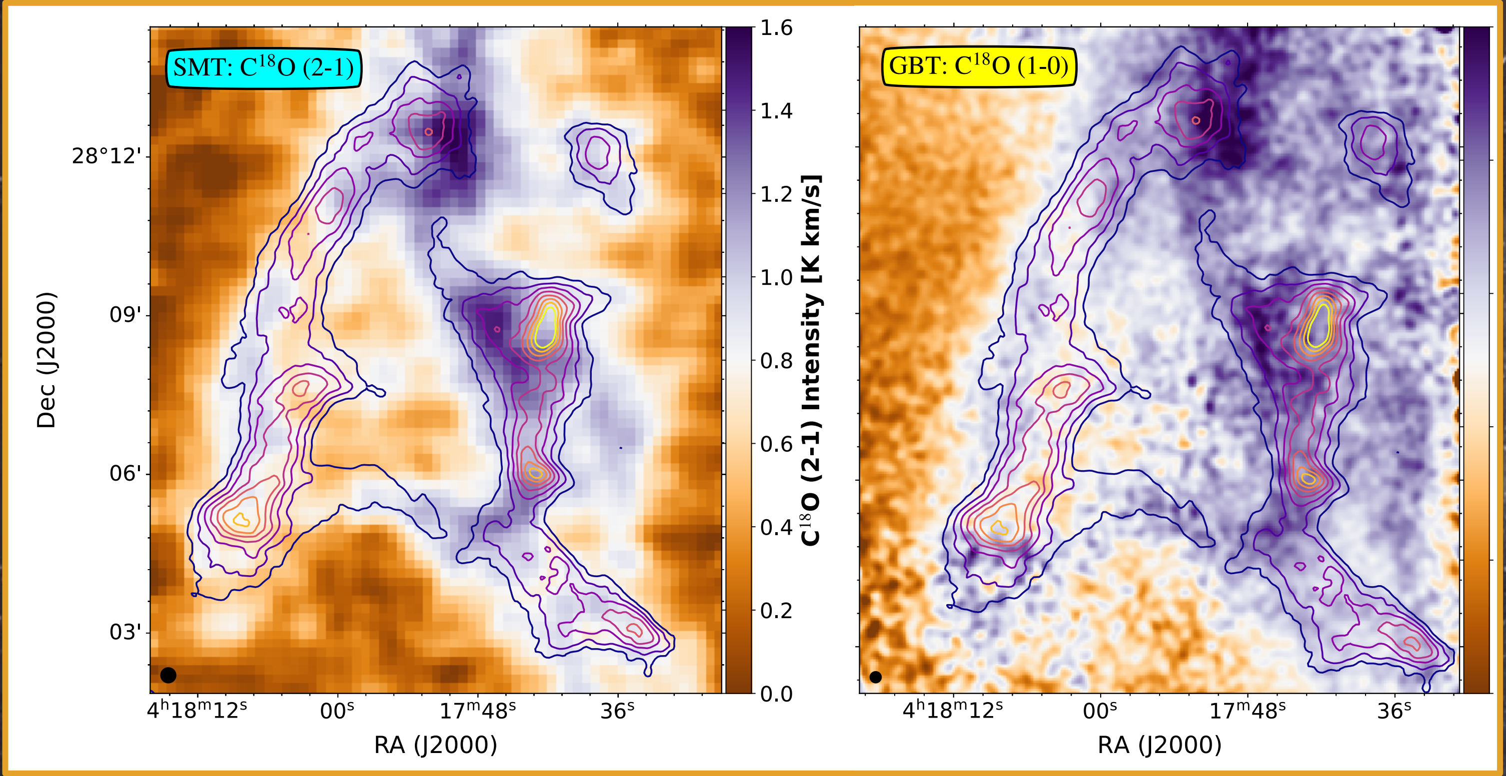
Recent magnetohydrodynamic simulation work, that has categorized cores based on coherence, also warn readers that one **should not rely on kinetic and gravitationally energy alone to predict if a core will go on to form a star**





Offner et al., 2022

High Resolution Continuum Study of the B10 region of the Taurus Molecular Cloud



Scibelli et al., *in prep*

GBT 100m

I am currently working on a CO depletion analysis at core scales using $C^{18}O$ mapping results from ARGUS on the GBT

In conjunction with our tight constraints on the physical properties of the B10 cores, measurements of the cores' depletion fractions (f_d 's) can tell us about the dynamical evolution of the cores through comparisons of chemical evolution timescales to free-fall timescales

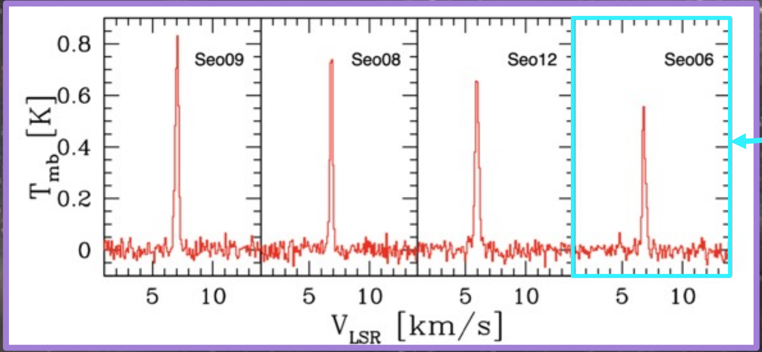
High Resolution Continuum Study of the B10 region of the Taurus Molecular Cloud

Robust physical models allow for additional chemical studies!

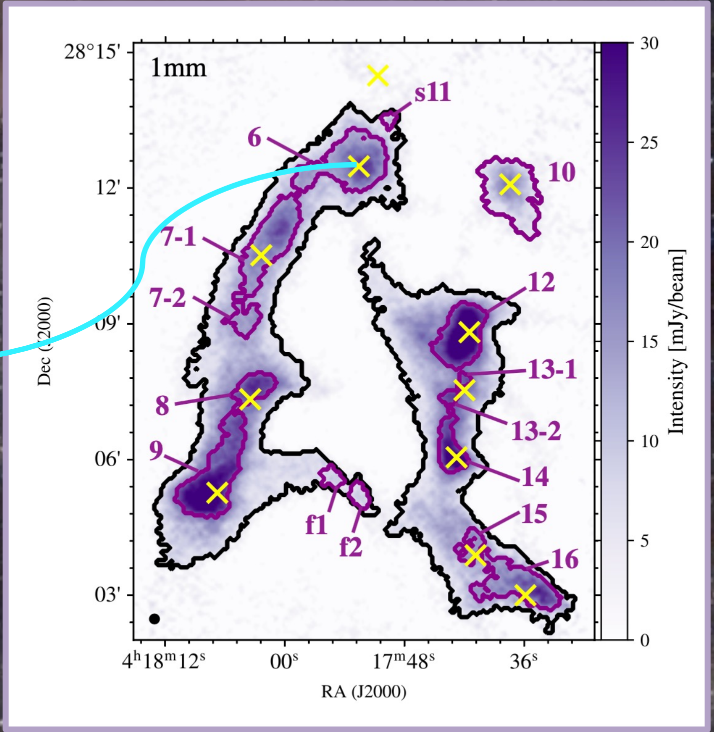
Hanga Andras-Letanovszky's undergraduate thesis project!

Mapping of HDCO to study deuteration chemistry!

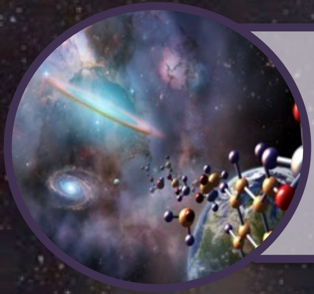
ARO 12m



Check out poster #5 !



Scibelli et al., 2023, *in review*



Summary & Important Takeaways

- I've carried out 3D radiative transfer modeling, utilizing high resolution dust observations, for the starless cores in the B10 region of the Taurus Molecular Cloud (Scibelli et al., 2023, *in review*)
    - The study allowed for a unique virial analysis that found that the majority of the B10 cores (9 out of 14) are either in virial equilibrium or are bound by external pressure self-gravity.
    - To better understand the dynamical timescales of these cores, an analysis of the CO-depletion fraction is underway (Scibelli et al., *in prep*)
- Acetaldehyde, dimethyl ether, methyl formate, and vinyl cyanide have been detected in the **chemically young** Taurus core, L1521E, supporting the idea that some complex molecules are seeded early in the star formation process

  Scibelli et al., 2021 →
- We have observed methanol in 100% of the 31 Taurus L1495/B218 cores targeted and acetaldehyde in 70%!
  There is a prevalence of complex molecules in starless and prestellar cores!

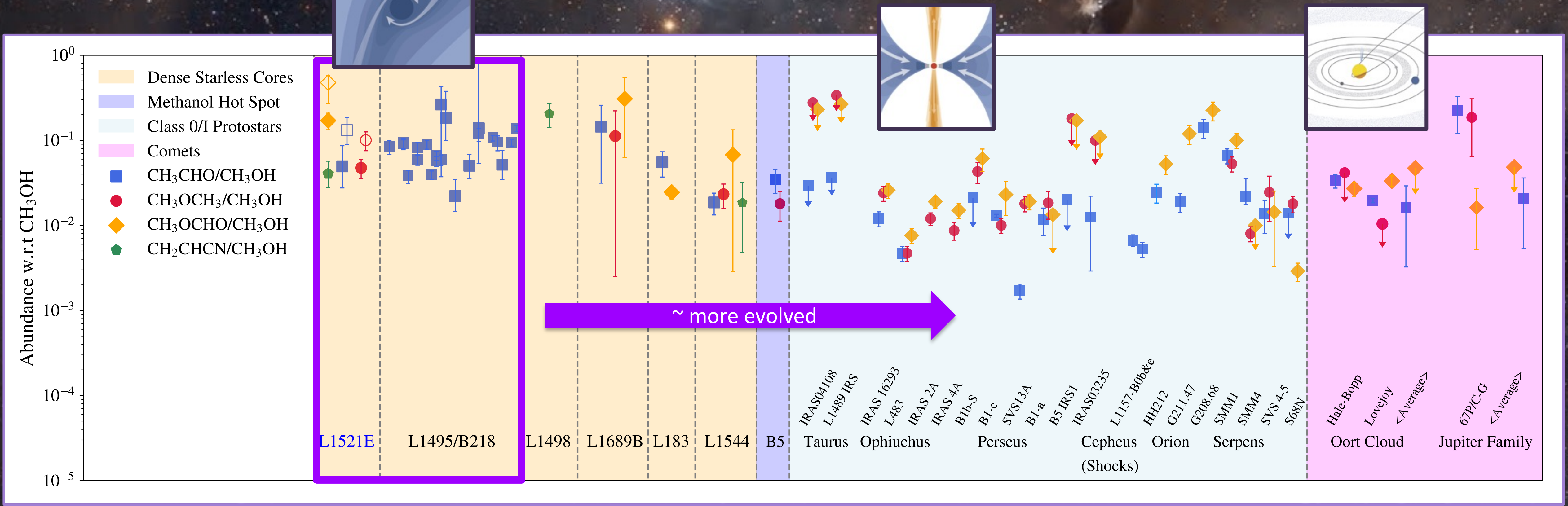
  Scibelli & Shirley 2020 →

Happy to answer questions! Email: sscibelli@arizona.edu


EXTRA SLIDES

COM Abundance vs. Evolutionary Stage

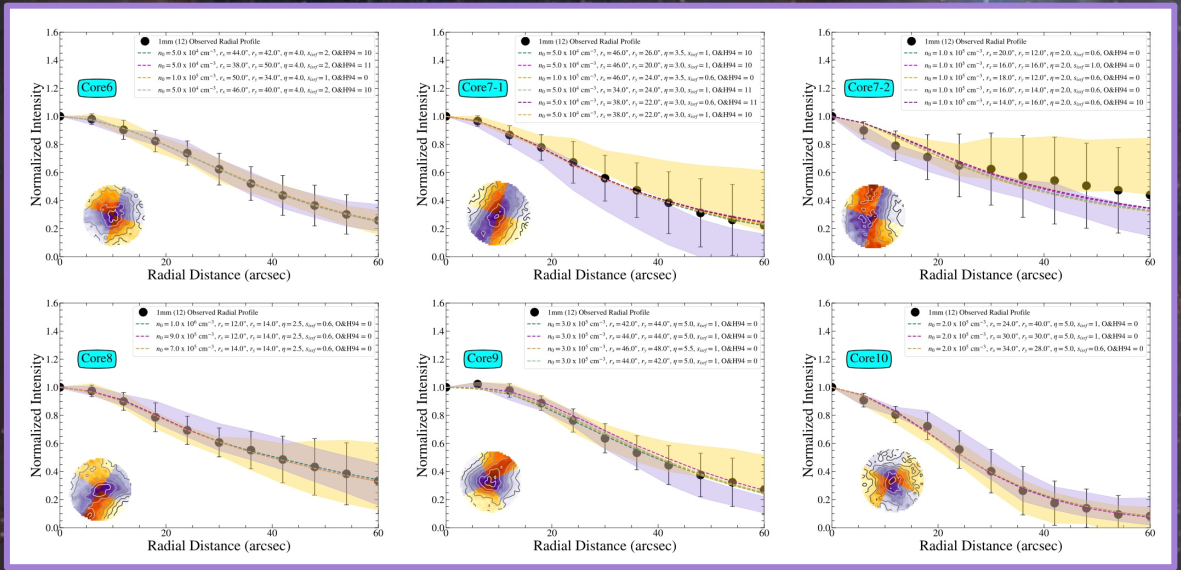
I've significantly increased the sample size of prestellar cores with COM detections!
AND I see possible chemical evolution between different stages of star formation!

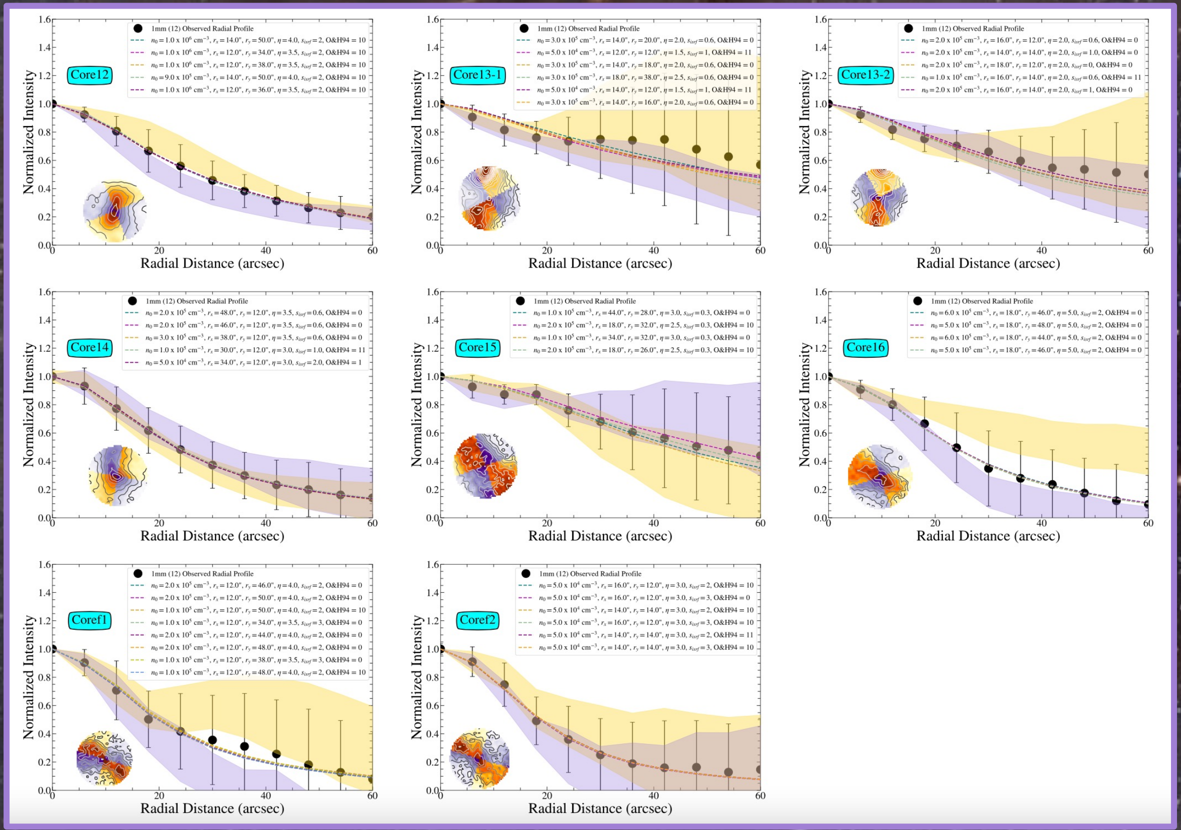


[L1495] Scibelli & Shirley 2020, [L1498] Jimí enez-Serra et al. 2021, [L183] Lattanzi etal. 2020, [L1544] Jimenez-Serra et al. 2016, [L1689B] Bacmann et al. 2012, [B5] Taquet et al. 2017, [B1-c, B1-bs and S68N] van Gelder et al. 2020, [IRAS2A, IRAS4A] Taquet et al. 2015, López-Sepulcre et al. 2017; [IRAS 16293-2422] Jaber et al. 2014, Jørgensen et al. 2018, [SVS313A] Bianchi et al. 2019, [IRAS03245, B1-a, B5, IRS 1, SVS 4-5, IRAS 04108, L1489 IRAS], Graninger et al. 2016, Bergner et al. 2017, [SMM1, SMM4], Lee et al. 2019, Hsu et al. 2020 [HH212, G211.47, G208.68], Öberg et al. 2011, Taquet et al. 2015, [L483] Jacobsen et al. 2019, [L1157-Boe L1157-Bob] Codella et al. 2020, [B335] Imai et al. 2016. , [Hale-Bop and Lovejoy] Biver & Bockeĺ ee-Morvan 2019, [67P/ChuryumovGerasimenko(67/C-G)] Schuhmann et al. 2019 & Rubin et al. 2019

Adapted from Scibelli et al., 2021

High Resolution Continuum Study of the B10 region of the Taurus Molecular Cloud

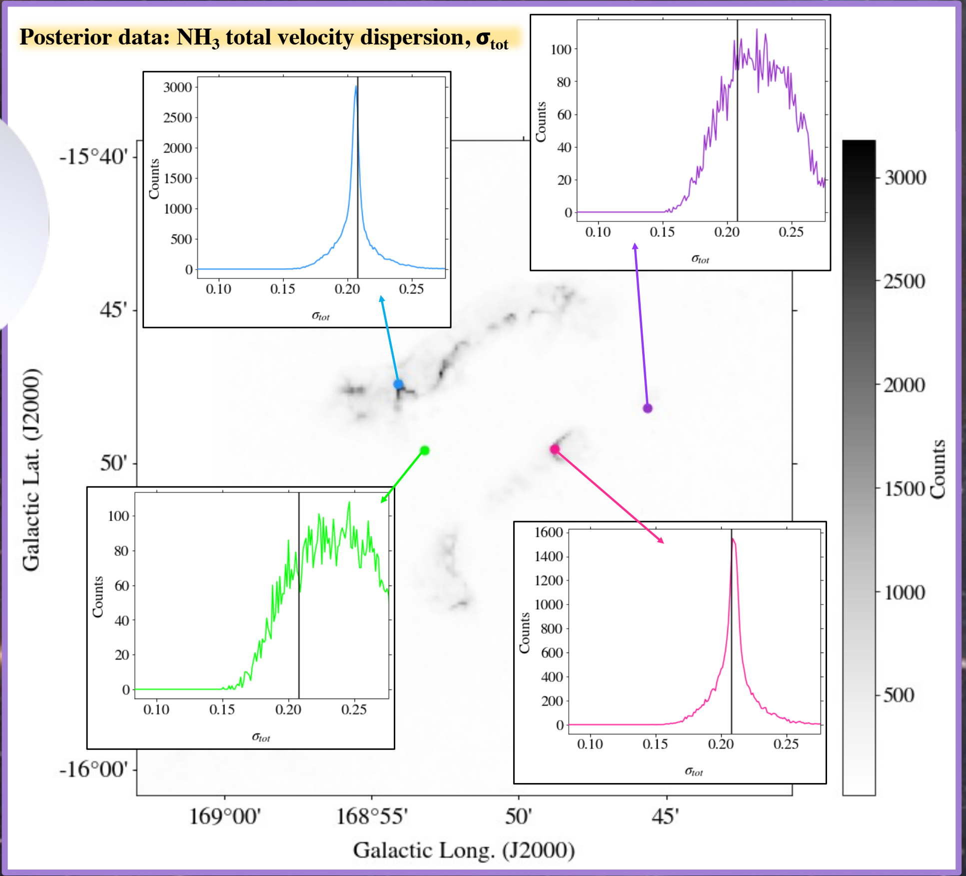


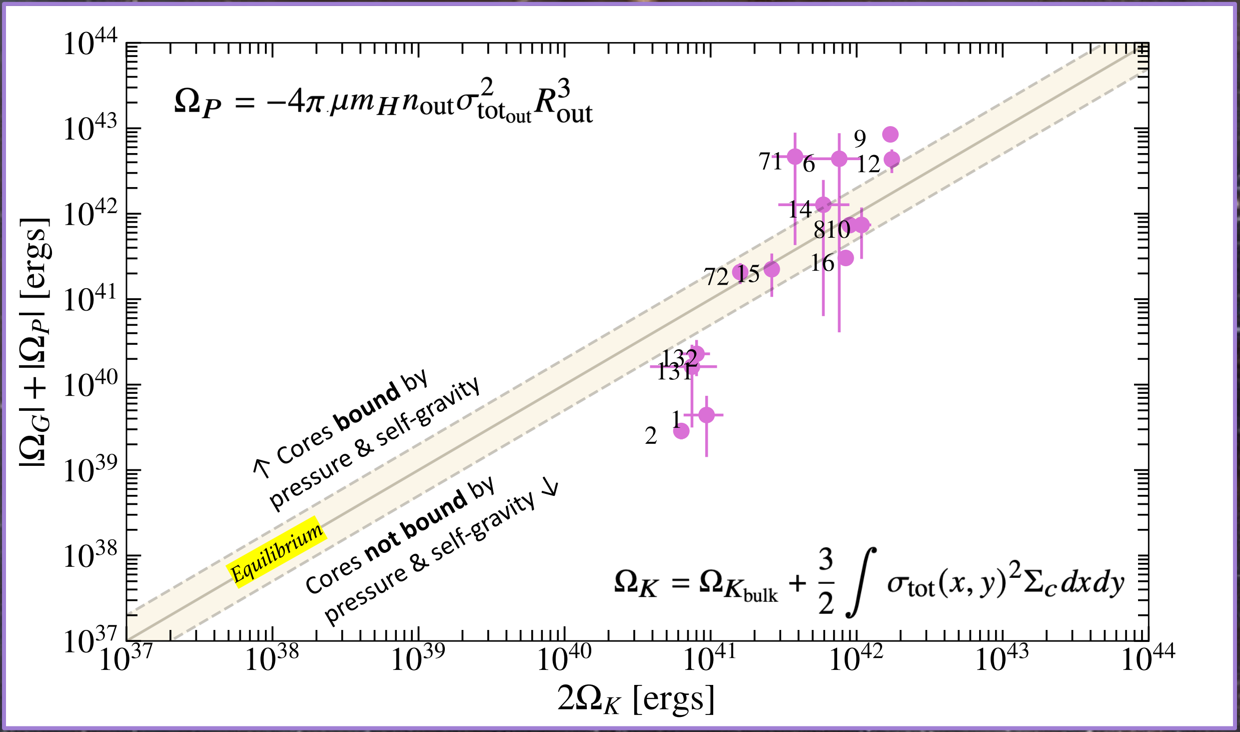


Best-fit models were found for all 14 cores

Scibelli et al., 2023, *in review*

High Resolution Continuum Study of the B10 region of the Taurus Molecular Cloud





Total velocity dispersion from NH_3 for the Ω_K and Ω_P terms calculated via **NestFit** software; a Bayesian framework for fitting spectral line data (Svoboda in prep.)

Scibelli et al., 2023, *in review*

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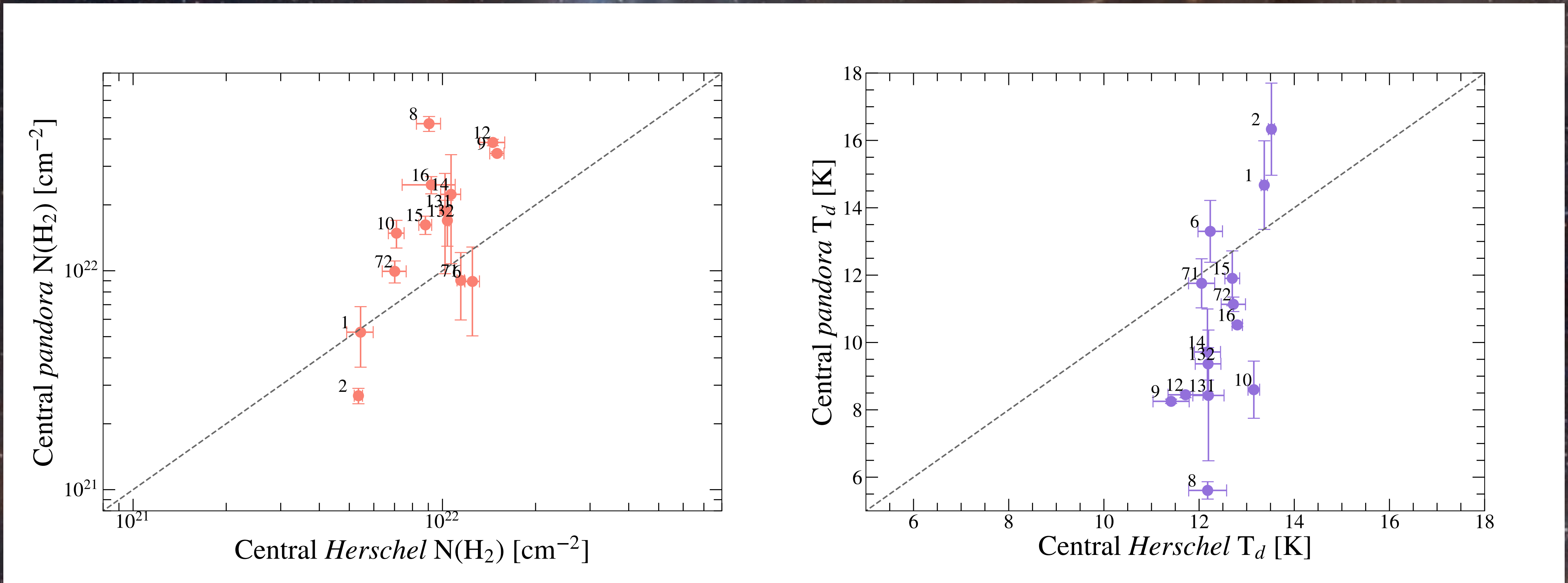

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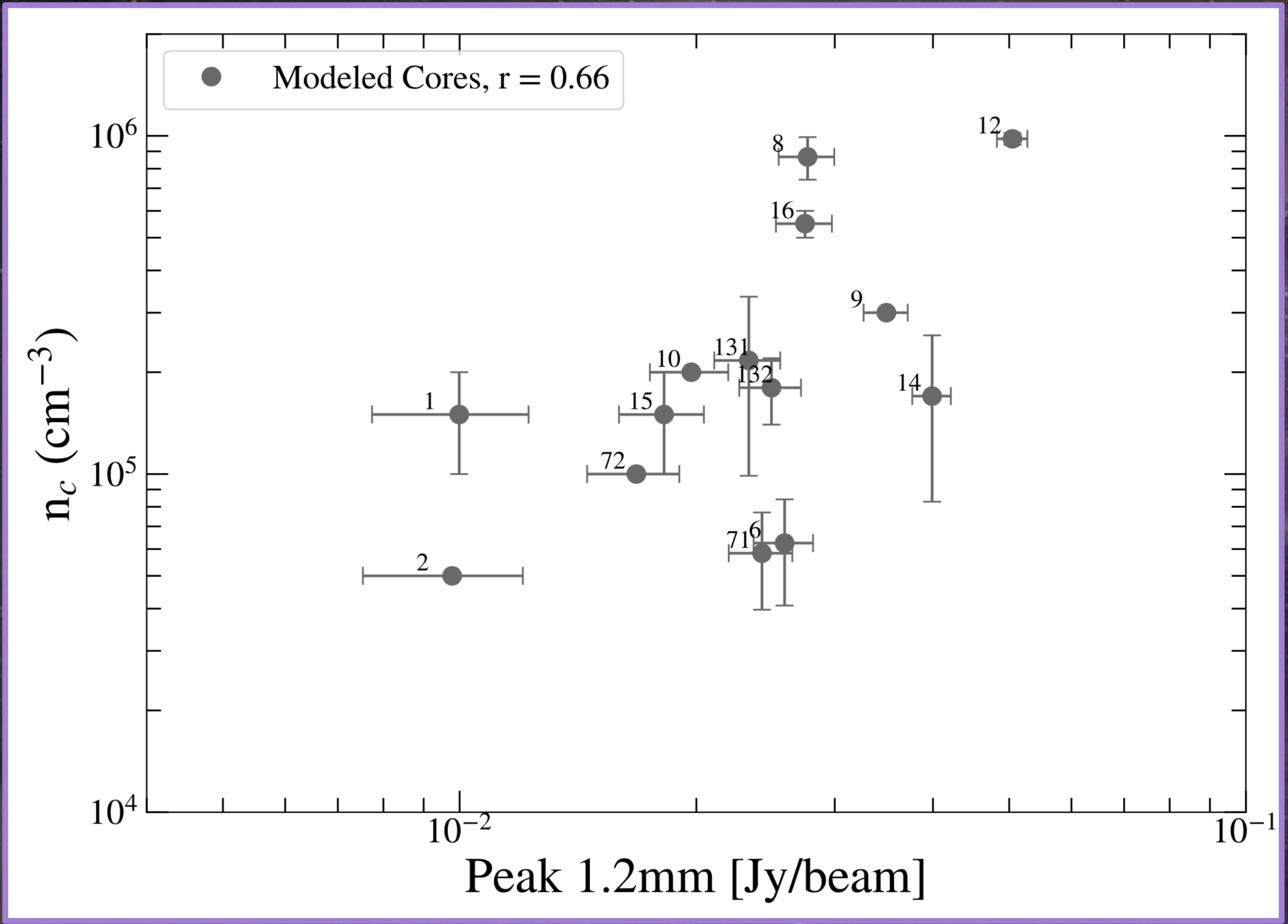

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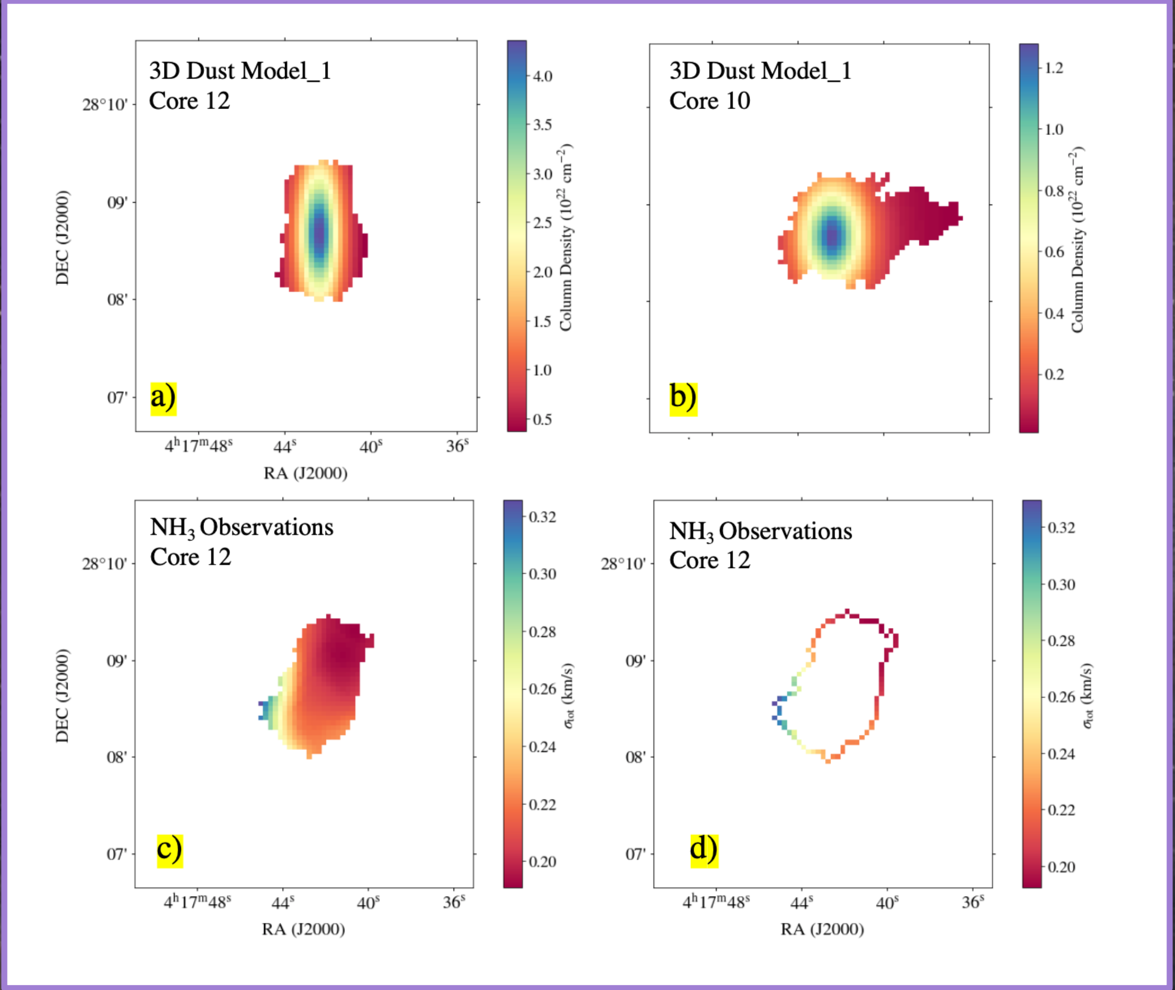

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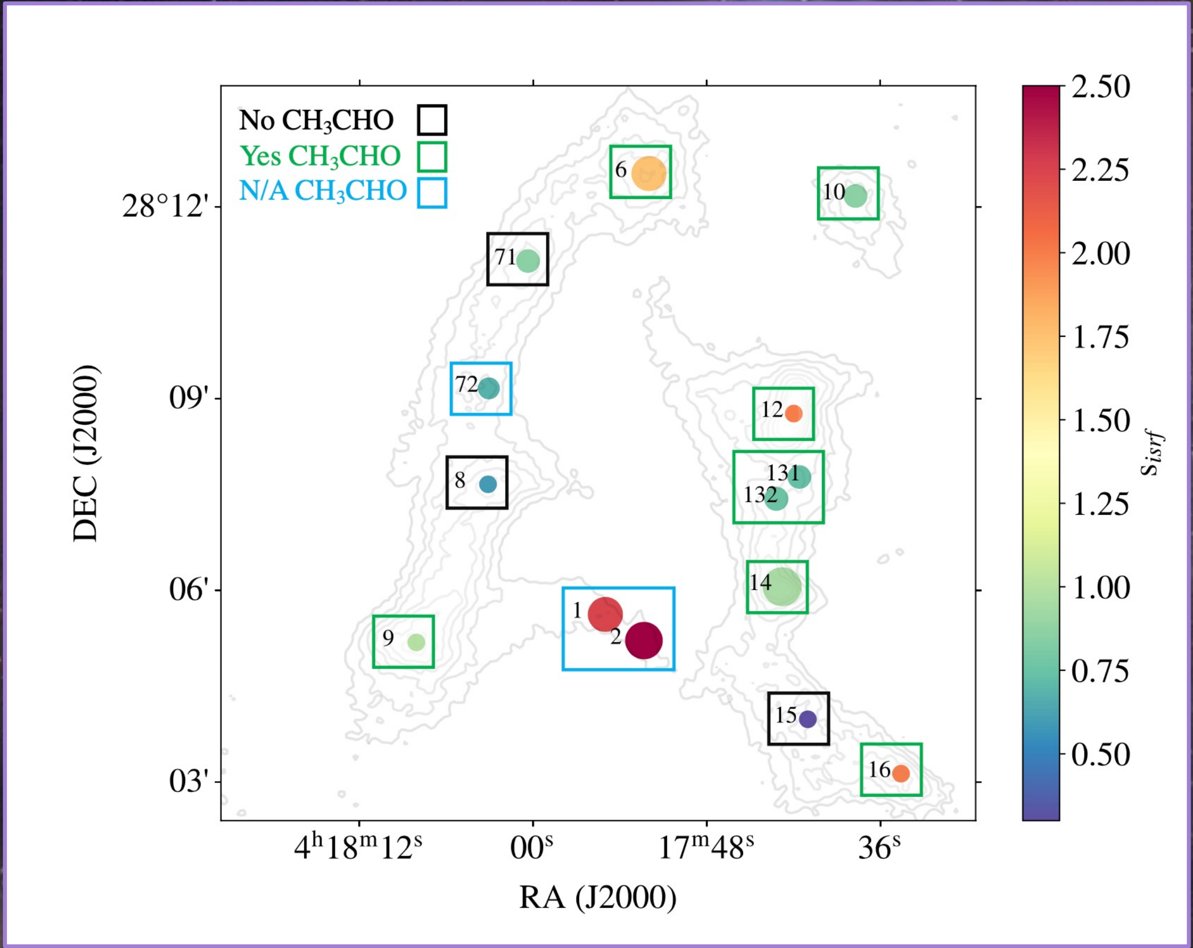

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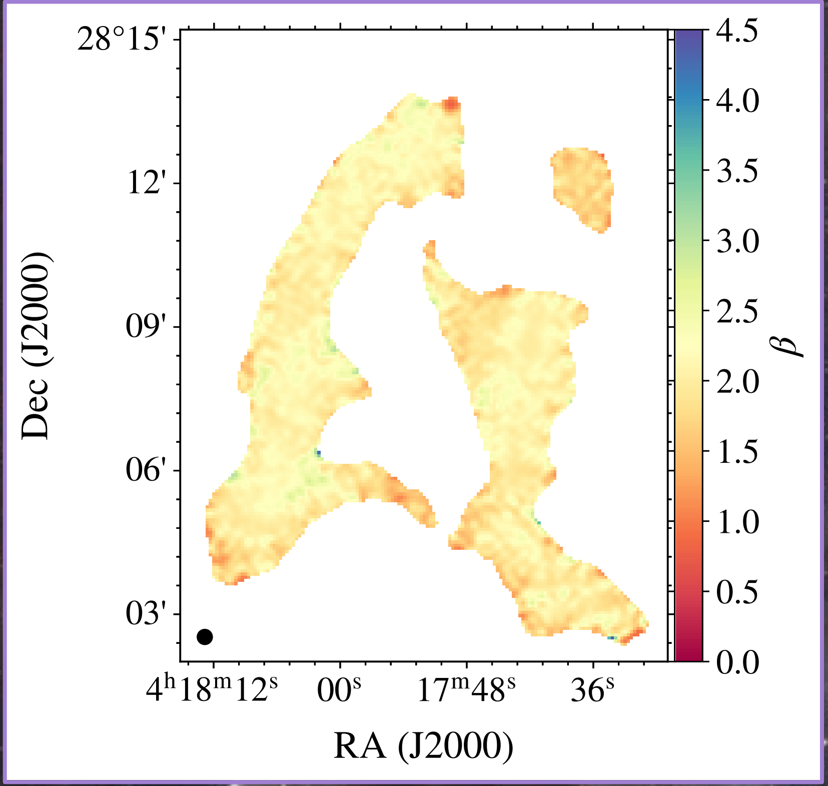

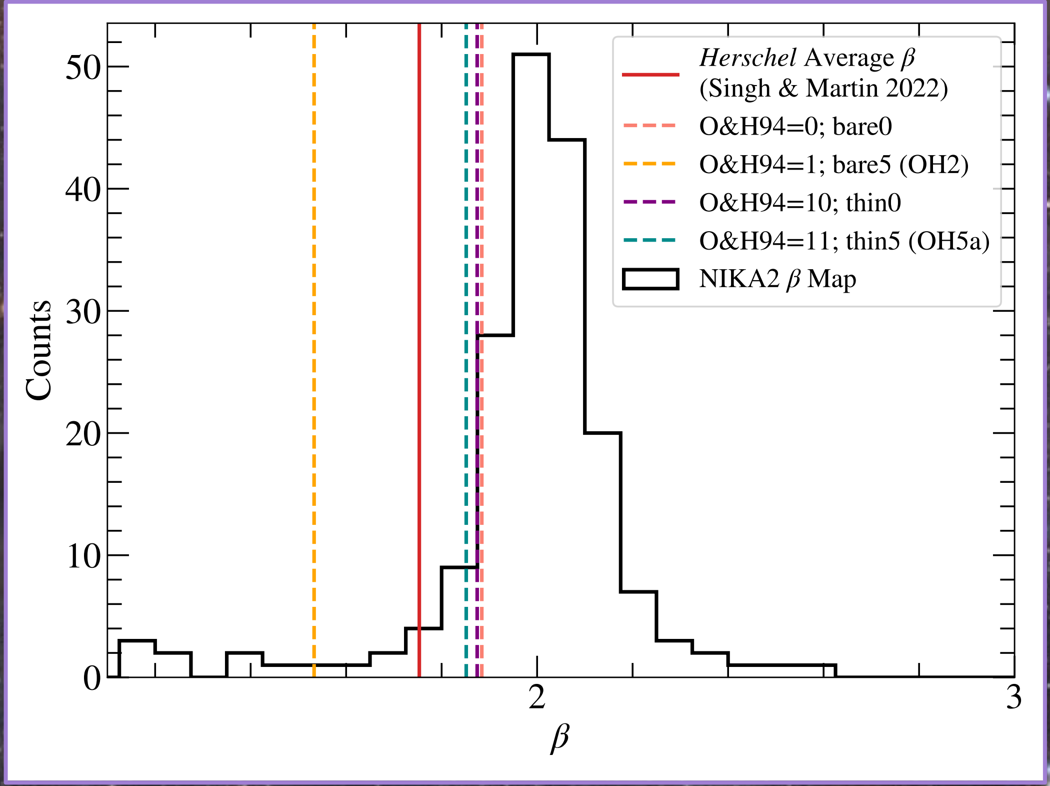

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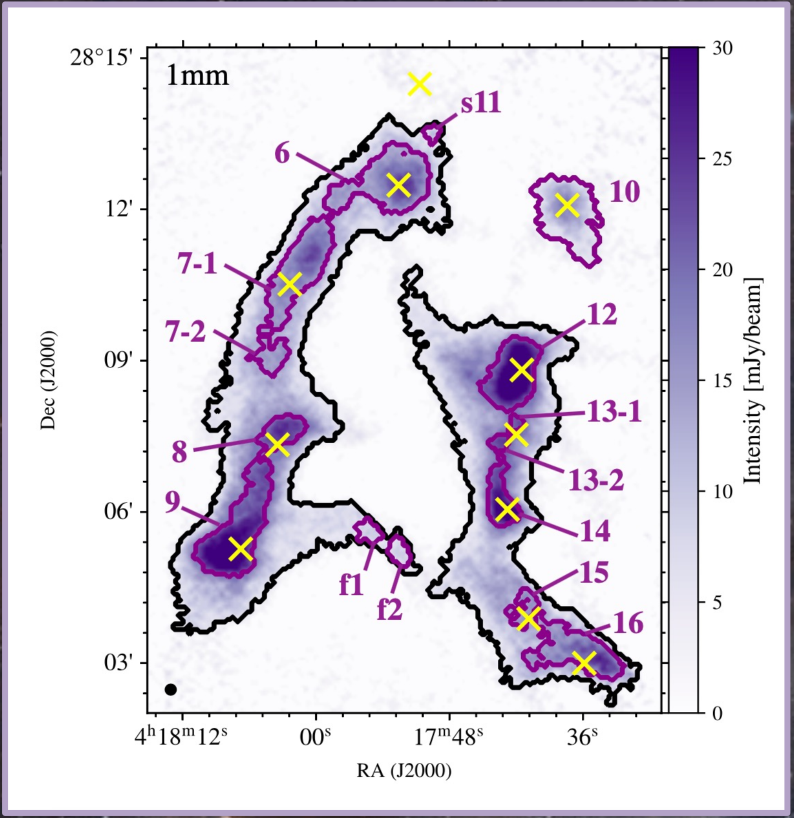
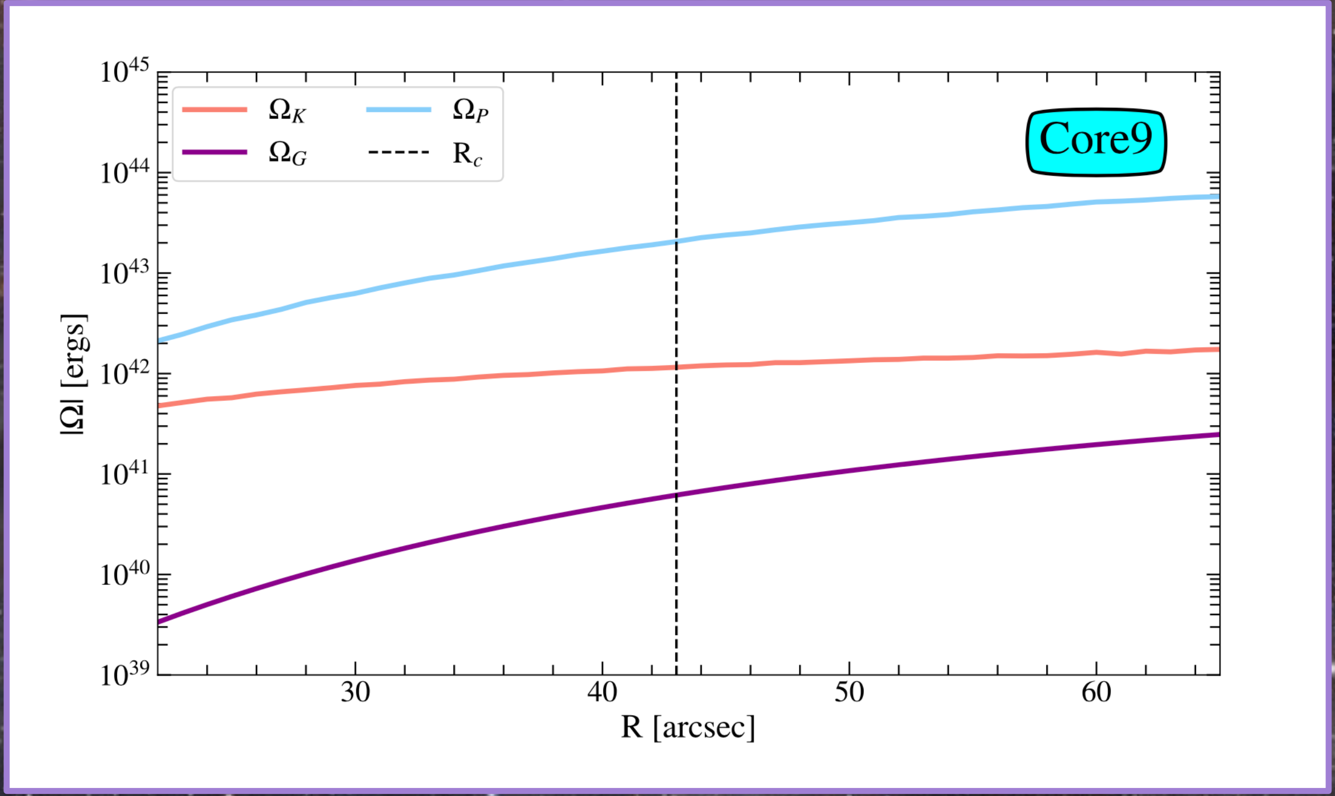


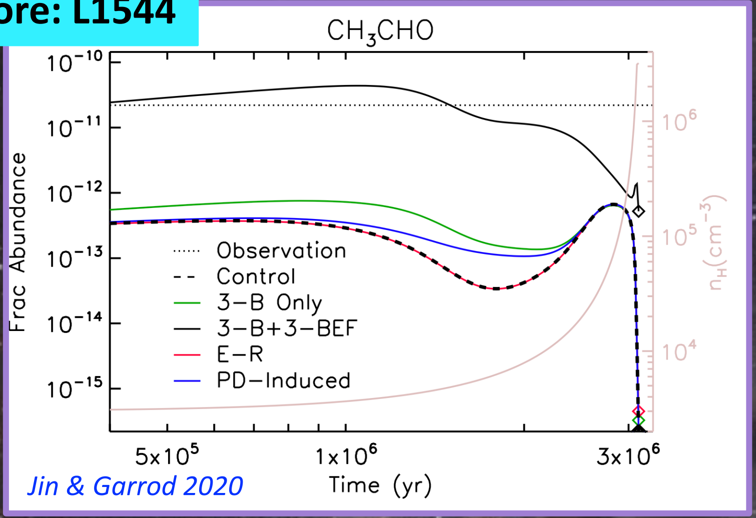


Scibelli et al., 2023, *in review*

High Resolution Continuum Study of the B10 region of the Taurus Molecular Cloud

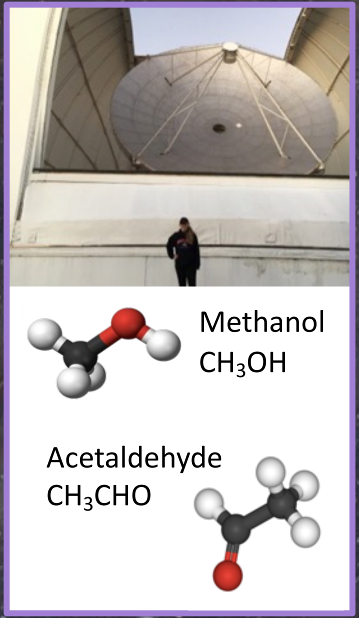
Physical parameter constraints, such as dust temperature and volume density radial profiles, will help us create future chemical models for cores that had COMs detections from Scibelli & Shirley 2020

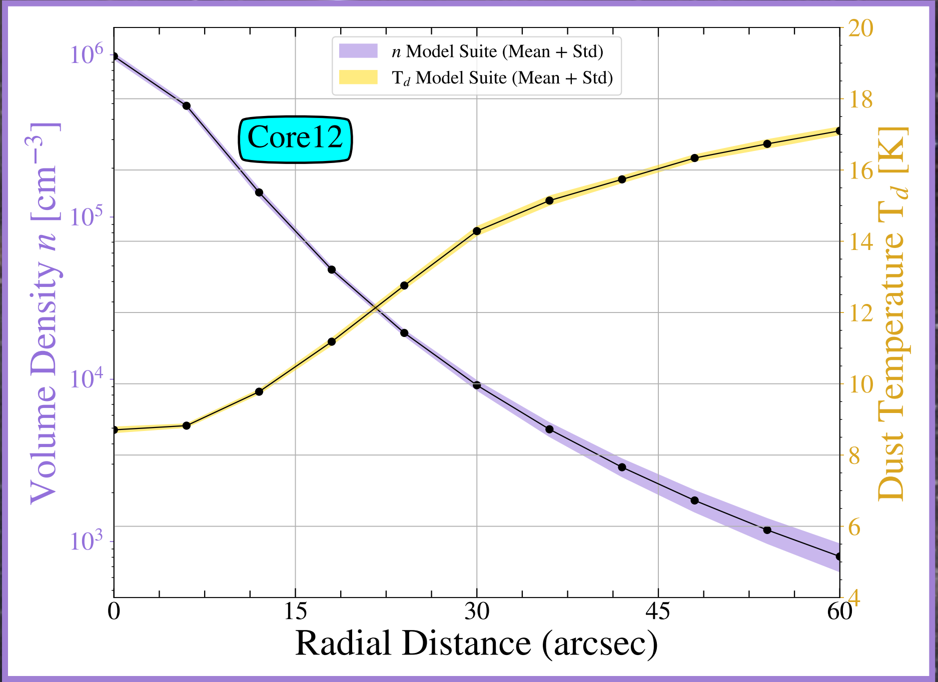
Core: L1544



Jin & Garrod 2020

Can abundances be reproduced with chemical models?





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