Feedback from high-mass star-forming regions

Peter Schilke

(University of Cologne)

ALMAGAL team including **John Bally**

Background image credit: G. Stroud

DFG

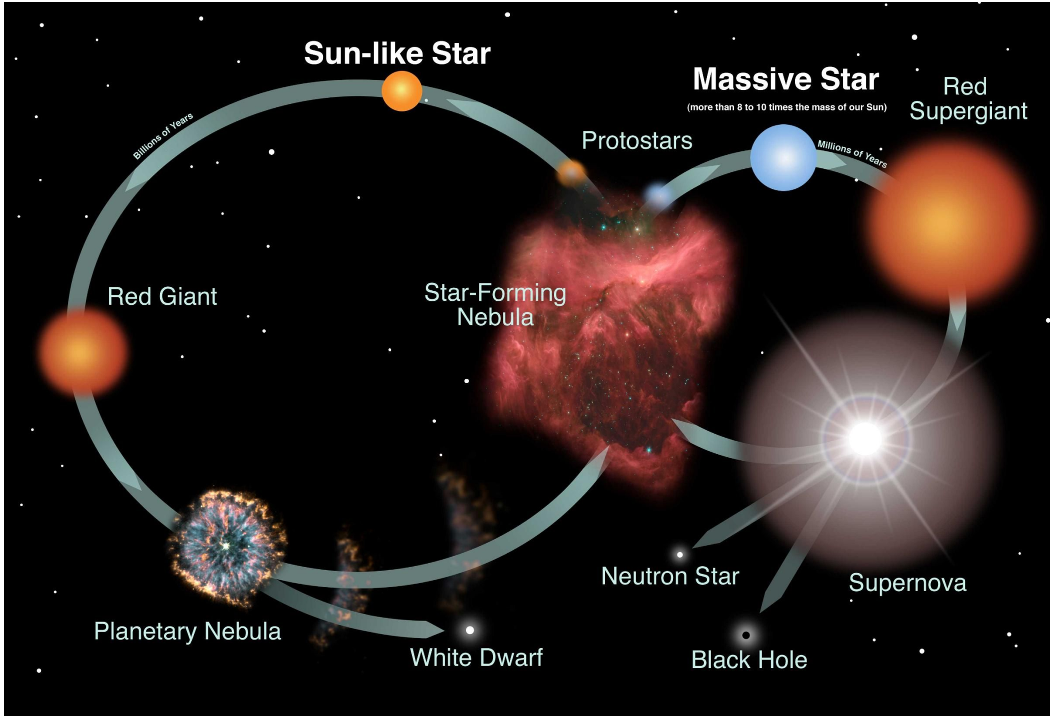
Bundesministerium für Bildung und Forschung

UNIVERSITY OF COLOGNE

ph1 Universität zu Köln

Feedback

- Thermal: IR radiation
- Ionizing: UV radiation
- Mechanical: shocks (outflows and winds, eventually supernova)
- Matter: injection of heavy elements (winds, supernova)
- Cosmic Rays: SNR



Credit: NASA and the Night Sky Network.

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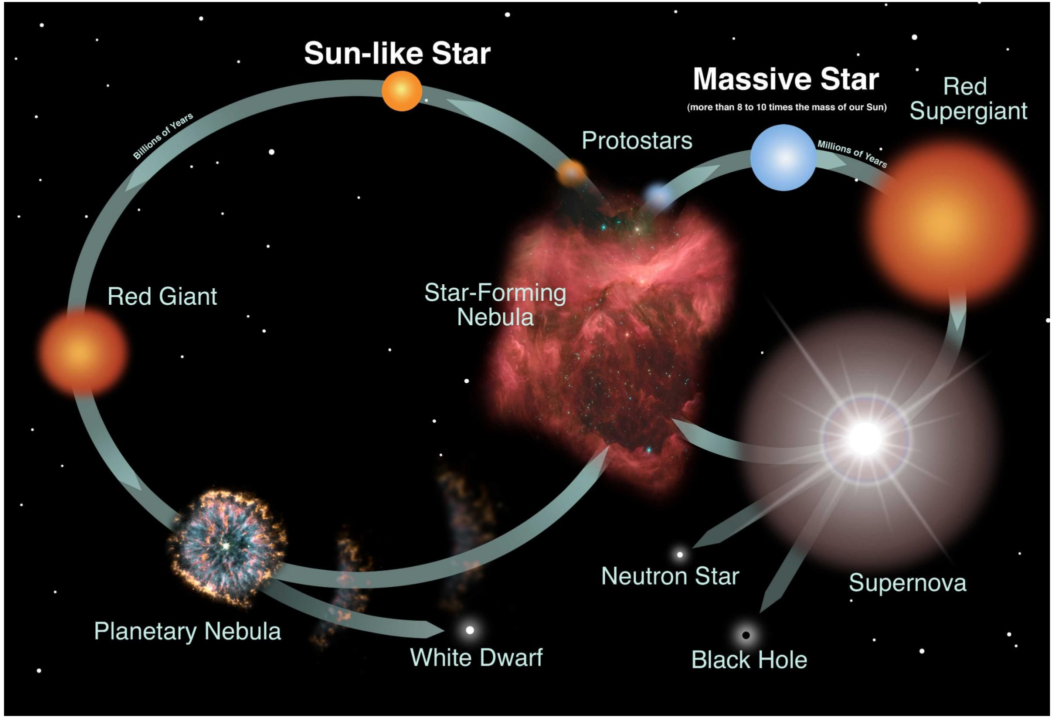

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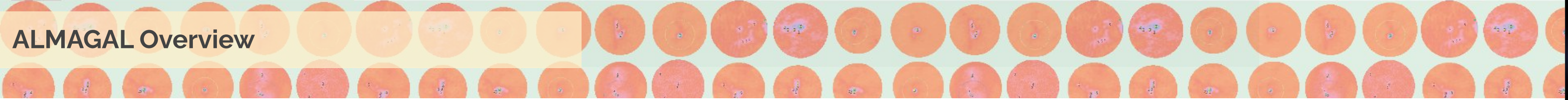


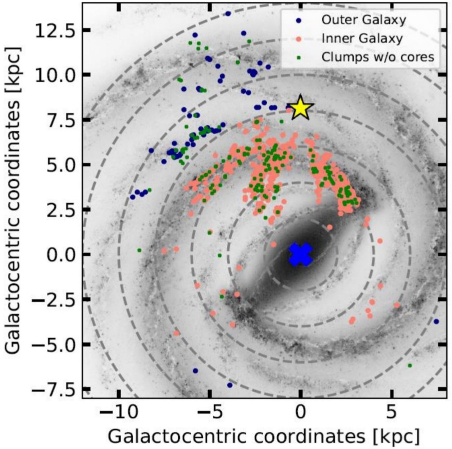
The ALMAGAL Survey: a statistical study

Cycle 7 ALMA Large Program
PIs: Sergio Molinari (I), Peter Schilke (D), Cara Battersby (US), Paul Ho (Tw)

The ALMAGAL Survey

- 1017 high-mass star forming clumps
- Luminosity-to-mass ratio from 0.05-500 $L_\odot/M_\odot$
- 3 configurations of ALMA in band 6 (1mm)
- Spatial resolution of ~1000 AU
- Continuum sensitivity of 0.1 mJy (0.3 $M_\odot$)
- 10,000 spectral channels at 1.5, 0.3 km/s resolution

Graphics: B. Jones



Science goals

Fragmentation, chemistry, cluster evolution history, intra-clump core dynamics, core-clump feedback, outflows, disks, …

Large sample size: 1013 unique sources

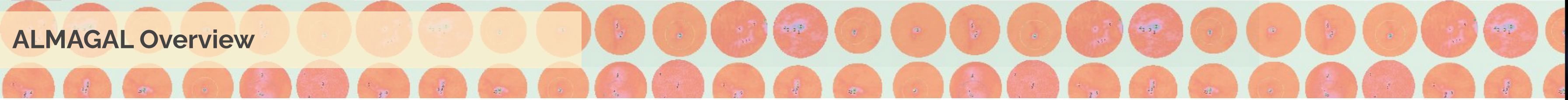
Complete within the selection criteria (> 500 $M_\odot$, < 7 kpc, < 0° dec, outside CMZ)

But single pointings – may lose outer cluster members

Technical working group lead:
Álvaro Sánchez-Monge

Joint deconvolution of all configurations
3 years
12M CPU hours @ JSC
450 TB FITS products

ALMAGAL Survey Overview: Sergio Molinari et al. (2025)
ALMAGAL Technical Paper: Álvaro Sánchez-Monge et al. (2025)



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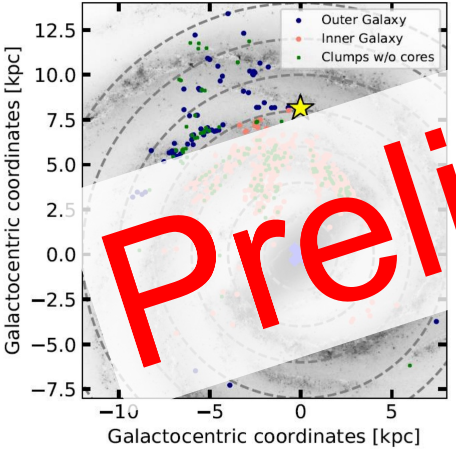

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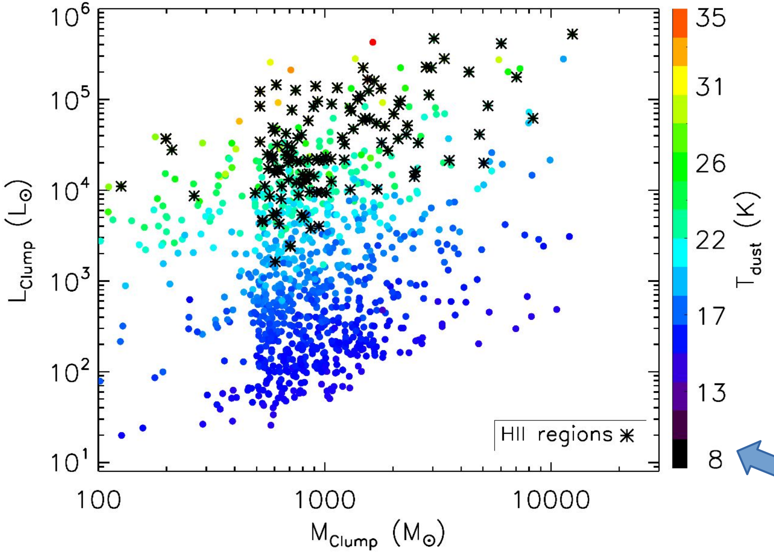
A&A, 696, A149 (2025)
https://doi.org/10.1051/0004-6361/202452702

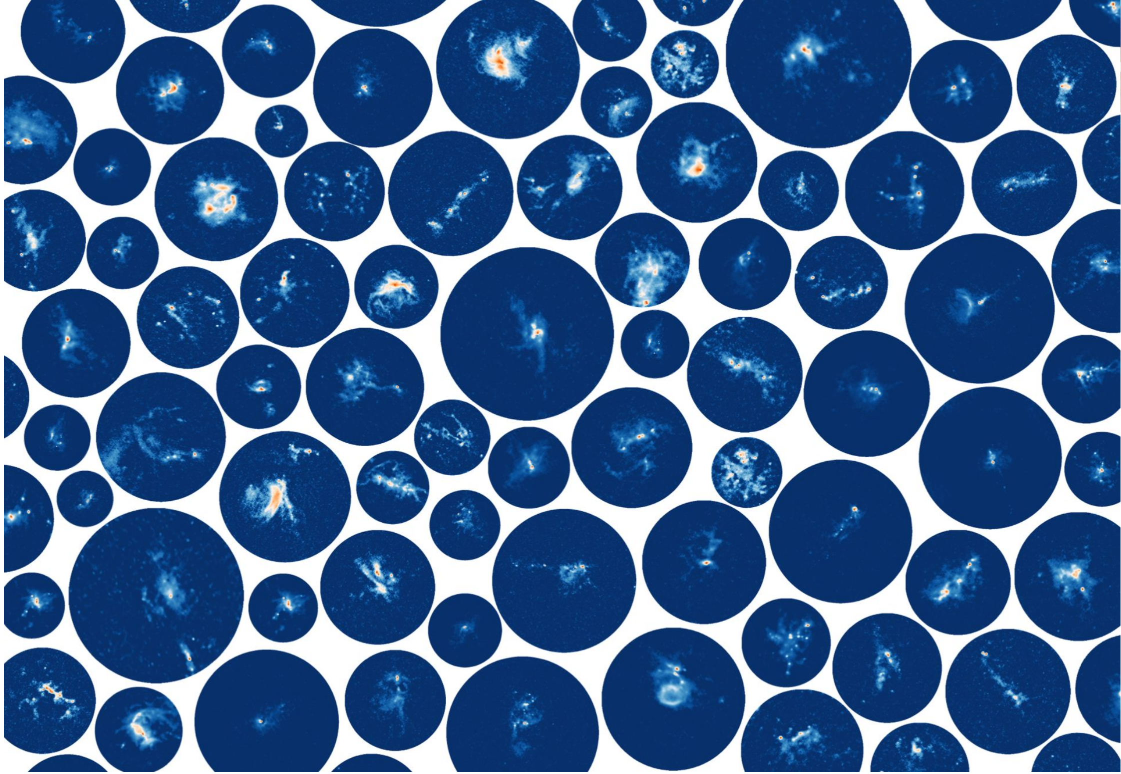
Astronomy & Astrophysics

ALMAGAL

I. The ALMA evolutionary study of high-mass protocluster formation in the Galaxy: Presentation of the survey and early results

S. Molinari[1,★], P. Schilke[2], C. Battersby[3], P. T. P. Ho[4], Á. Sánchez-Monge[5,6], A. Traficante[1], B. Jones[2], M. T. Beltrán[19], H. Beuther[7], G. A. Fuller[9,2], Q. Zhang[13], R. S. Klessen[10,11,13,14], S. Walch[2,12], Y.-W. Tang[4], M. Benedettini[1], D. Elia[1], A. Coletta[1,47], C. Mininni[1], E. Schisano[1], A. Avison[8], C. Y. Law[19], A. Nucara[1,16], J. D. Soler[1], G. Stroud[9], J. Wallace[3], M. R. A. Wells[7], A. Ahmadi[17], C. L. Brogan[15], T. R. Hunter[15], S.-Y. Liu[4], S. Pezzuto[1], Y.-N. Su[4], B. Zimmermann[2], T. Zhang[2], F. Wyrowski[18], F. De Angelis[1], S. Liu[1], S. D. Clarke[4], F. Fontani[19,20,21], P. D. Klaassen[22], P. Koch[4], K. G. Johnston[23], U. Lebreuilly[25], T. Liu[26], S. L. Lumsden[24], T. Moeller[2], L. Moscadelli[19], R. Kuiper[28], D. Lis[30], N. Peretto[32], S. Pfalzner[29], A. J. Rigby[24], P. Sanhueza[31,33], K. L. J. Rygl[27], F. van der Tak[35,36], H. Zinnecker[37], F. Amaral[2], J. Bally[38], L. Bronfman[44], R. Cesaroni[19], K. Goh[2], M. G. Hoare[24], P. Hatchfield[30], P. Hennebelle[25], T. Henning[7], K.-T. Kim[40,41], W.-J. Kim[2], L. Maud[42], M. Merello[44,45], F. Nakamura[33], R. Plume[43], S.-L. Qin[46], B. Svoboda[34], L. Testi[39], V. S. Veena[2,18], and D. Walker[9]

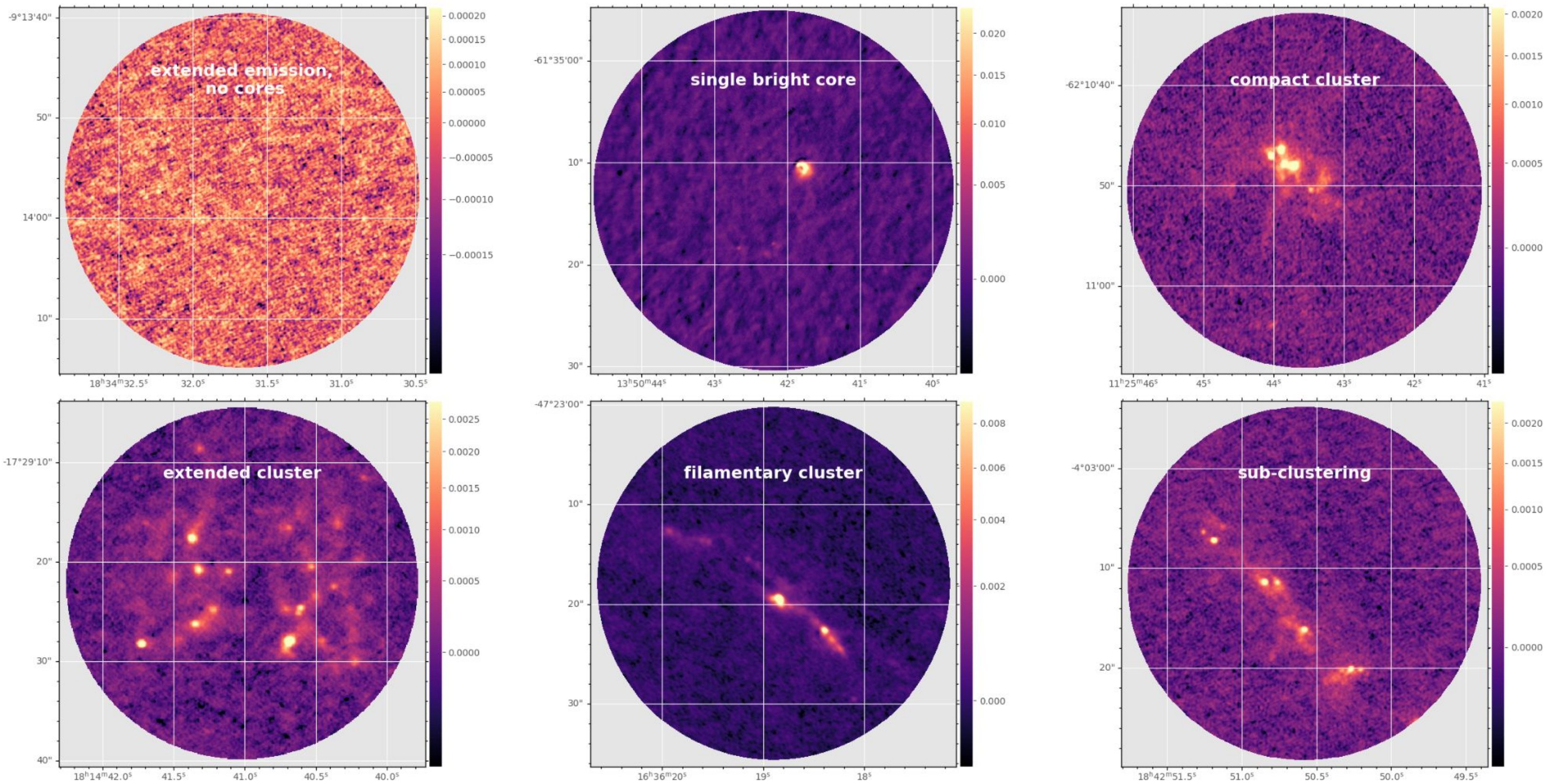




Large diversity of morphologies (image credit Chiara Mininni)

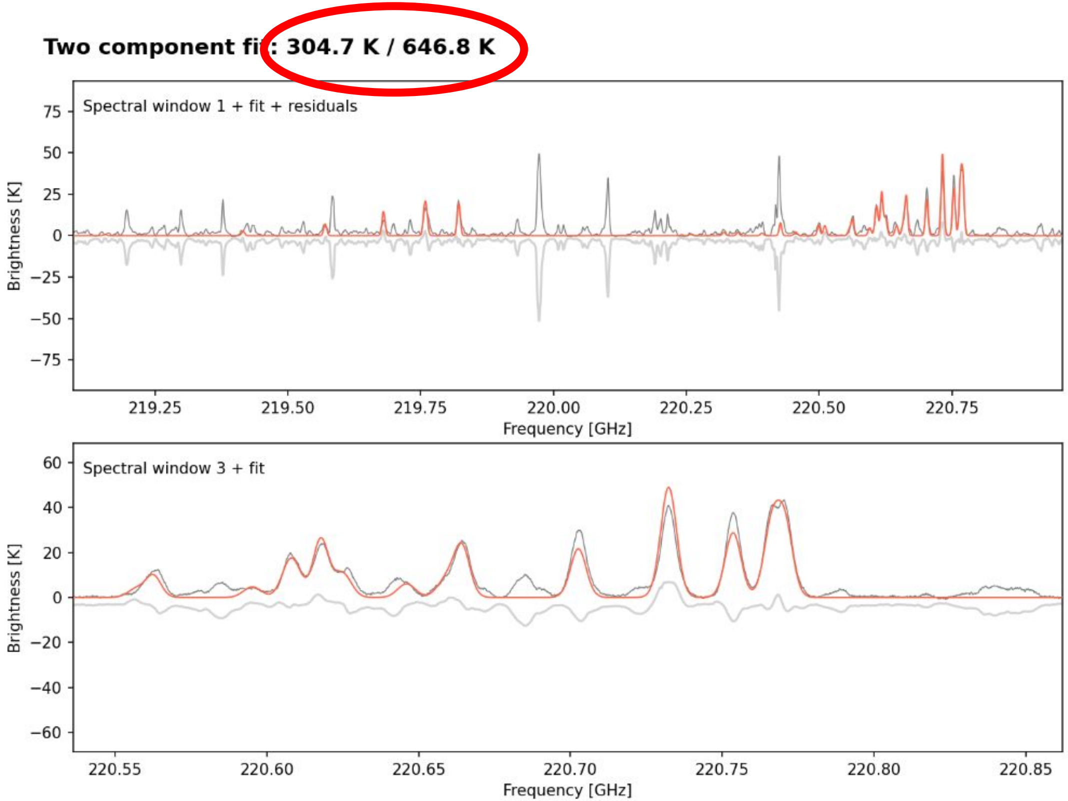
Large sample (1013 unique sources), but still spread over a large L/M space, which means part of the parameter space are still poorly sampled.

ALMAGAL: Morphological Examples



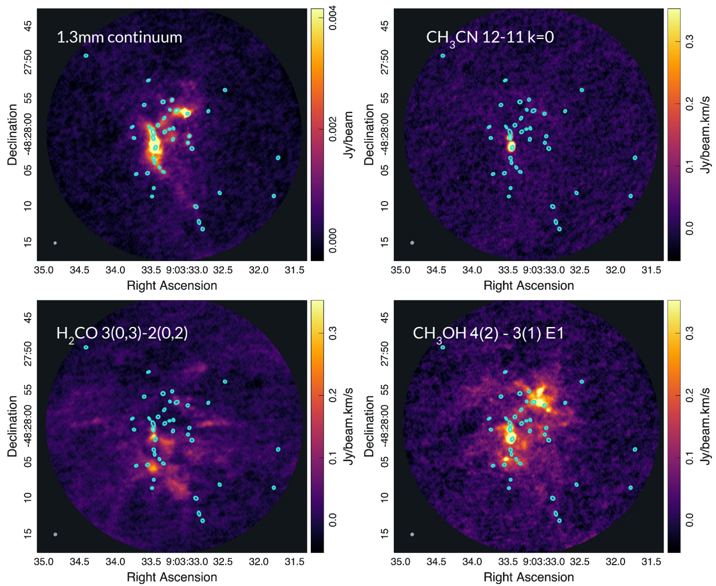
Thermal feedback on core scales

Beth Jones (UoC)



Maps of temperature tracers

For cores, we use CH_3CN



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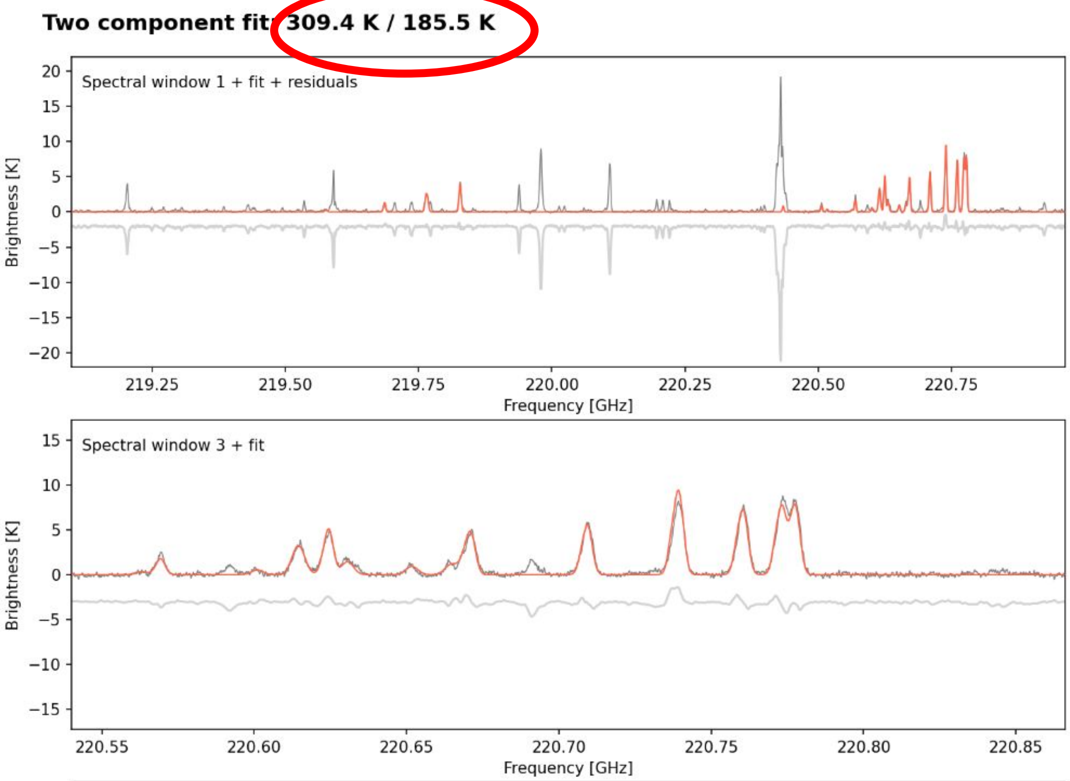

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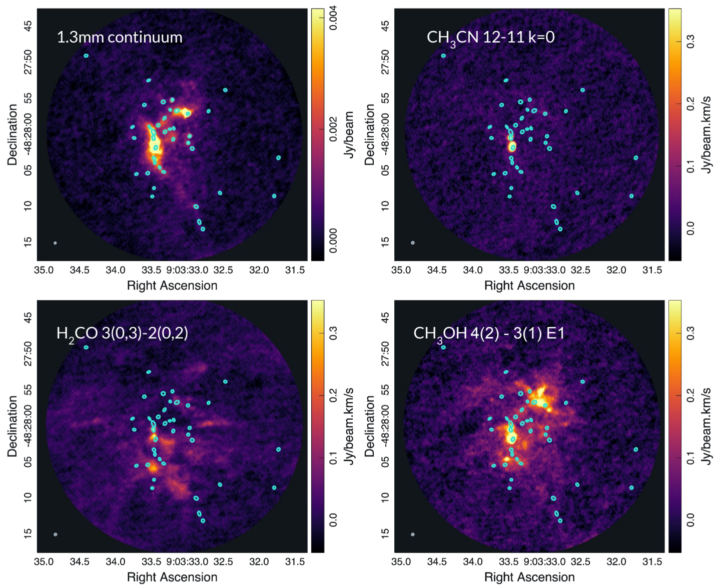
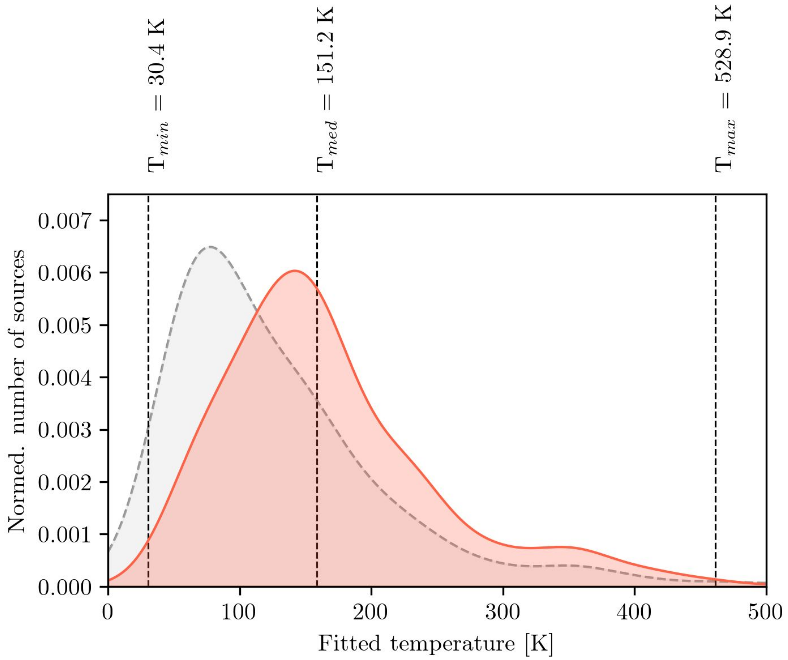


Temperature distribution of cores: single component fits for >15-sigma sources



Threshold on S/N set to exclude low signal to noise sources with large temperature uncertainties - limits provided for these sources

Fitted temperature KDE shown for high-reliability sources (S/N>15, 457, red) and whole sample (1375, grey)

For full ALMAGAL sample: 1375 cores detected in CH_3CN above a S/N of 5

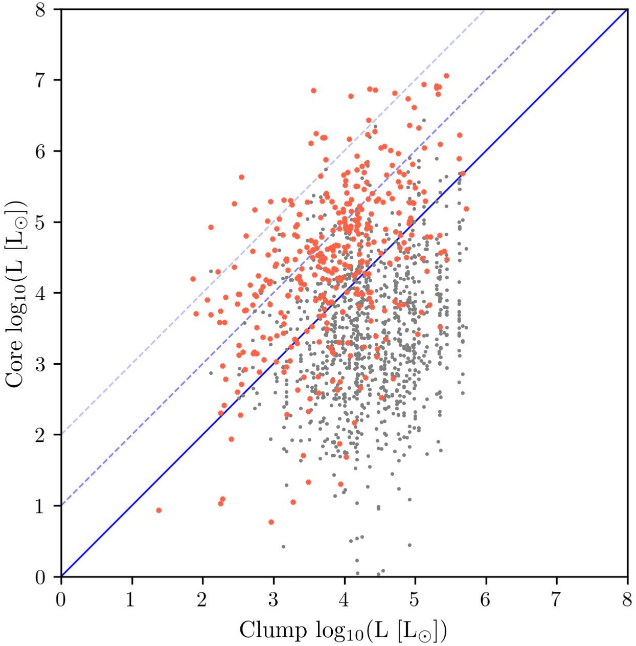
Limits are provided for low signal-to-noise sources only

Single component fits, core-averaged spectra

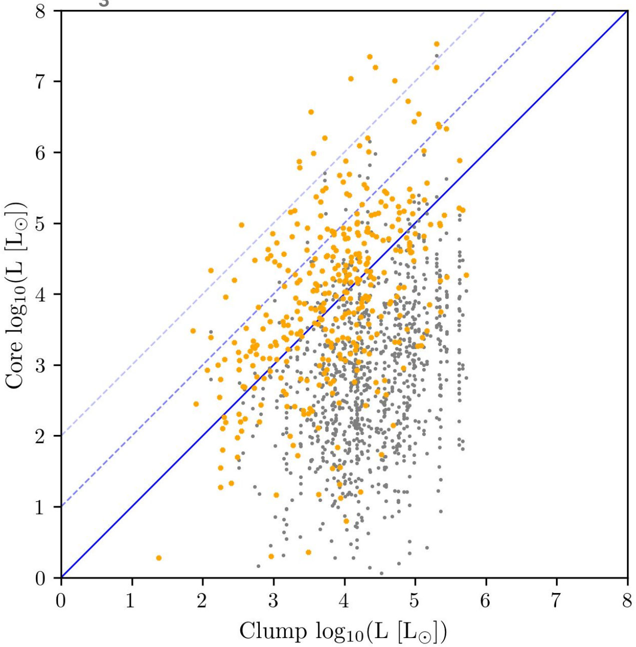
Final catalogue includes advanced fitting for complex line structures

Stefan-Boltzmann core luminosities as a function of clump luminosity

Continuum-derived source size



CH_3CN fit-derived source size



$$L = 4\pi r^2 \sigma_{\mathrm{SB}} T^4$$

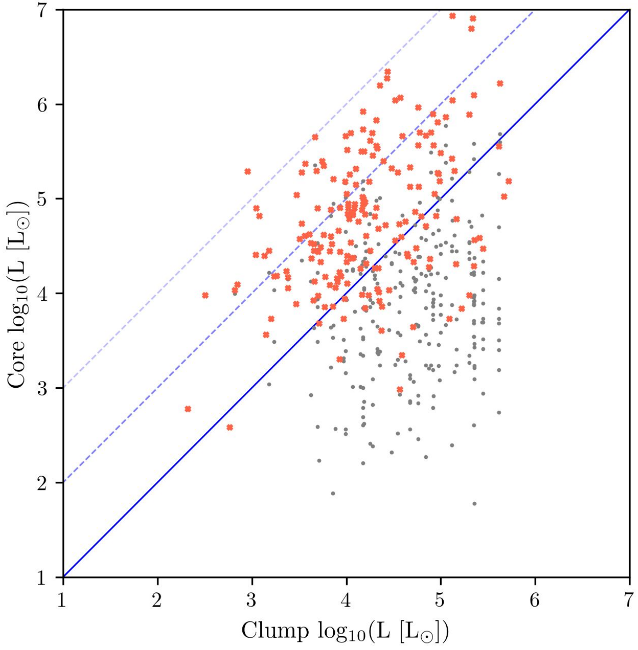
Houston, we got a problem!

Blue lines at 1x, 10x, 100x clump luminosity

Coloured sources mark the highest luminosity source per field

Luminosities: as a function of clump luminosity

Continuum-derived source size



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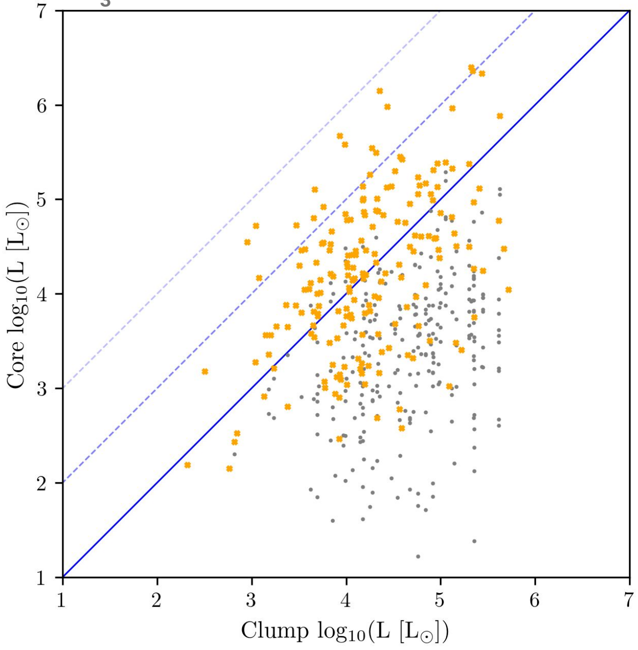

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Houston, we still got a problem!

Blue lines at 1x, 10x, 100x clump luminosity

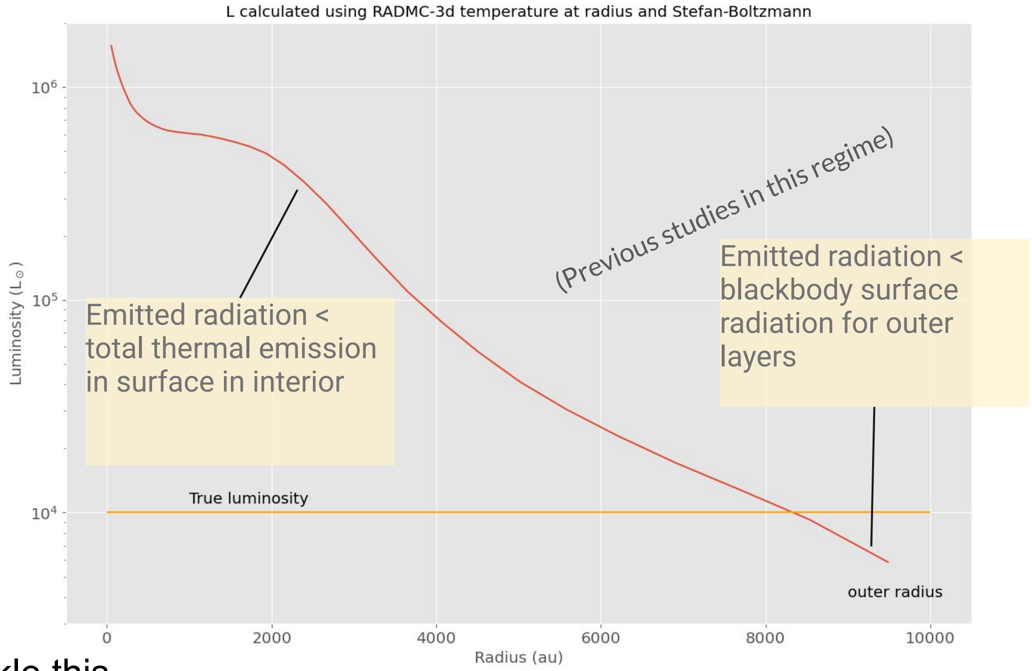
Coloured sources mark the highest luminosity source per field

Only sources with S/N > 15 CH_3CN detection are shown

The core luminosity problem: no high spatial resolution dust temperatures available

Line observations determine the temperature at a radius **within** a core – Stefan-Boltzmann is **not** applicable there

$$L = 4\pi r^2 \sigma_{\mathrm{SB}} T^4$$



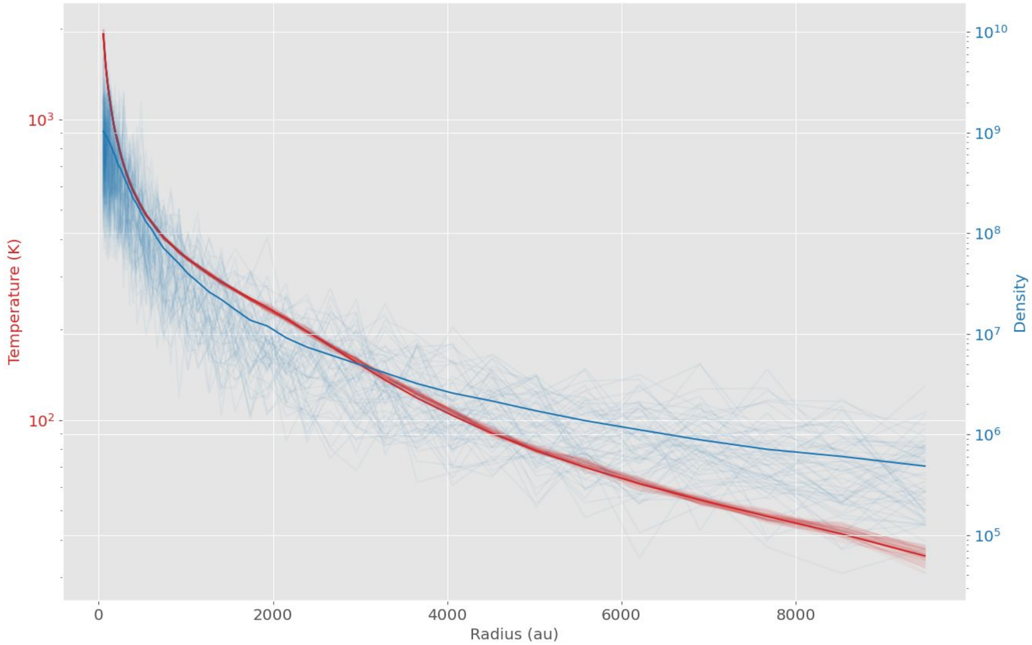
Poster by **Tatiana Rodriguez** for one way to tackle this

Self-consistent radiative transfer models @ JSC

Training set of full physical models suitable for science application
RADMC-3D models + density asymmetry, abundance variation
Accompanying ML development
Upgrade neural network for better generalisation + posterior distributions with SBI (Simulation Based Inference)
Immediate application: ALMAGAL source structure recovery
Obtain radial and density profiles for population for comparison to existing simulations (Zimmermann et al. subm)

With supplementary line coverage

Full tomography of structure with wideband coverage
Relative abundance profiles
Colder, younger cores

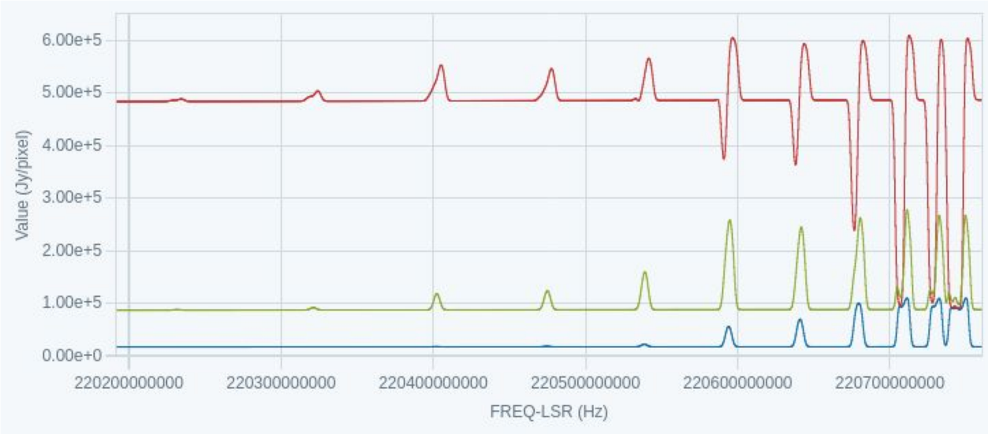


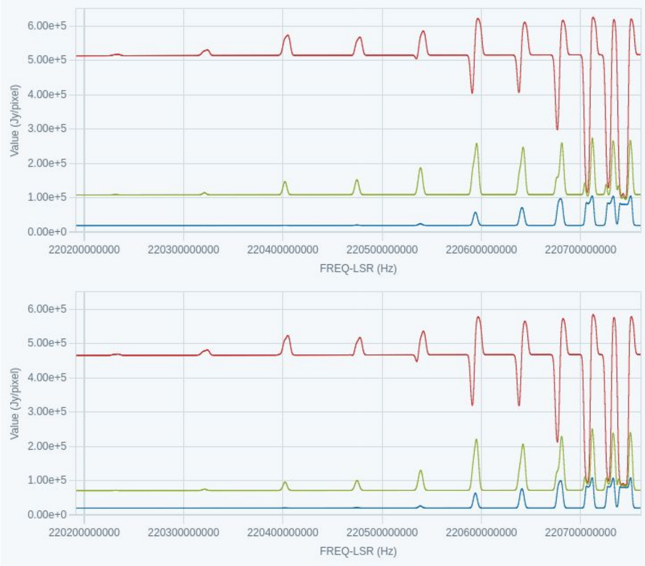
Beth Jones (UoC), Stefan Kesselheim (JSC)
UoC master theses: Judith Beck, Timon Danowski, Tobias Solymosi

3D modelling: the spectral fingerprints of substructure

Typical linewidths of 5 km/s but opacity effects and velocity gradients **cause continuous complex spectral substructure**

Simulated structured sources





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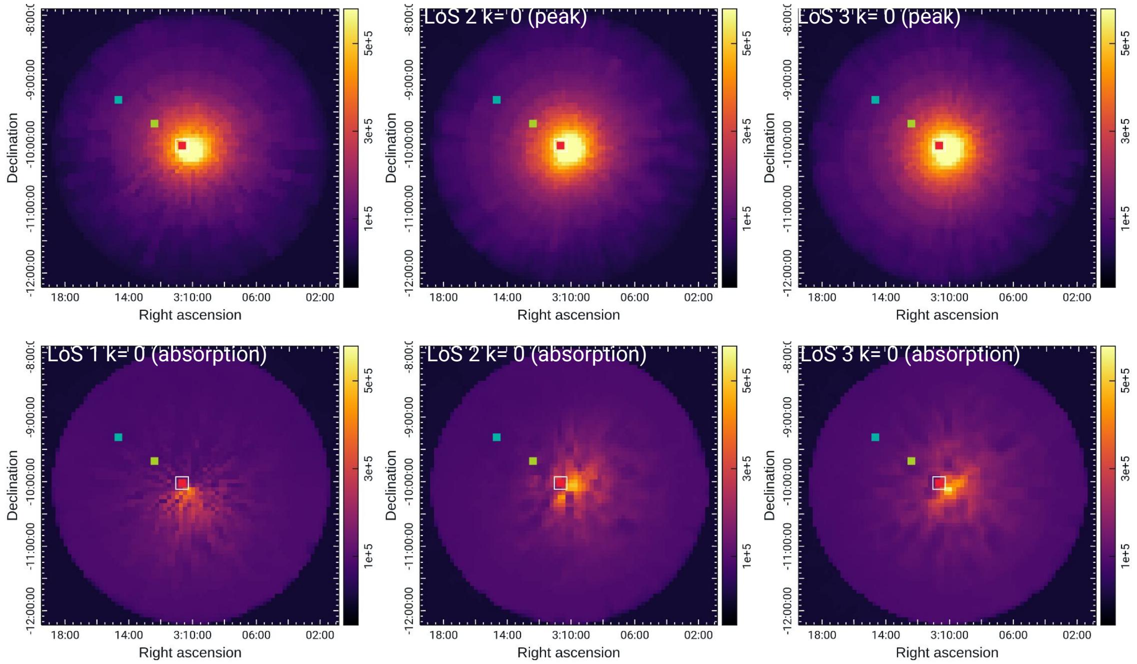
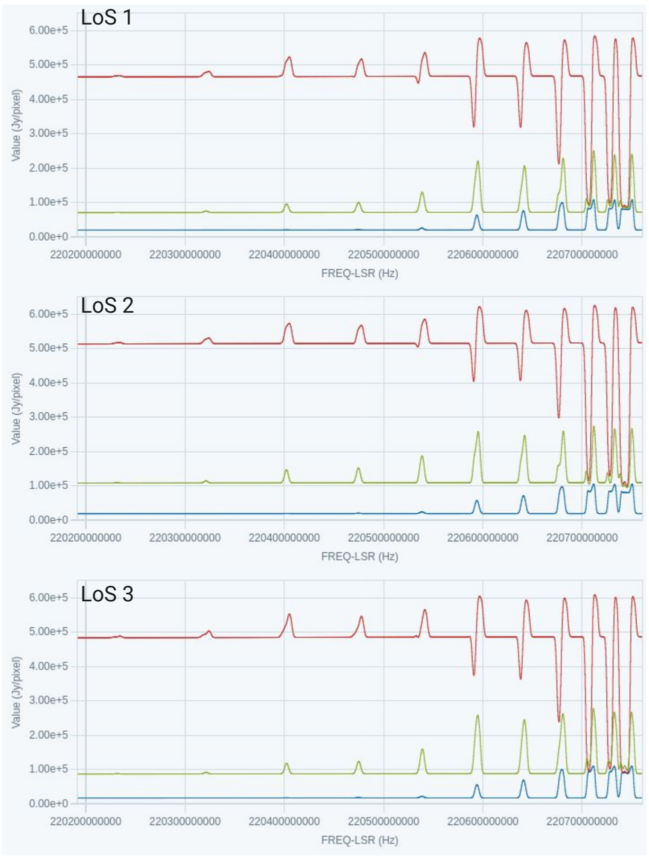
Self-consistent radiative transfer models





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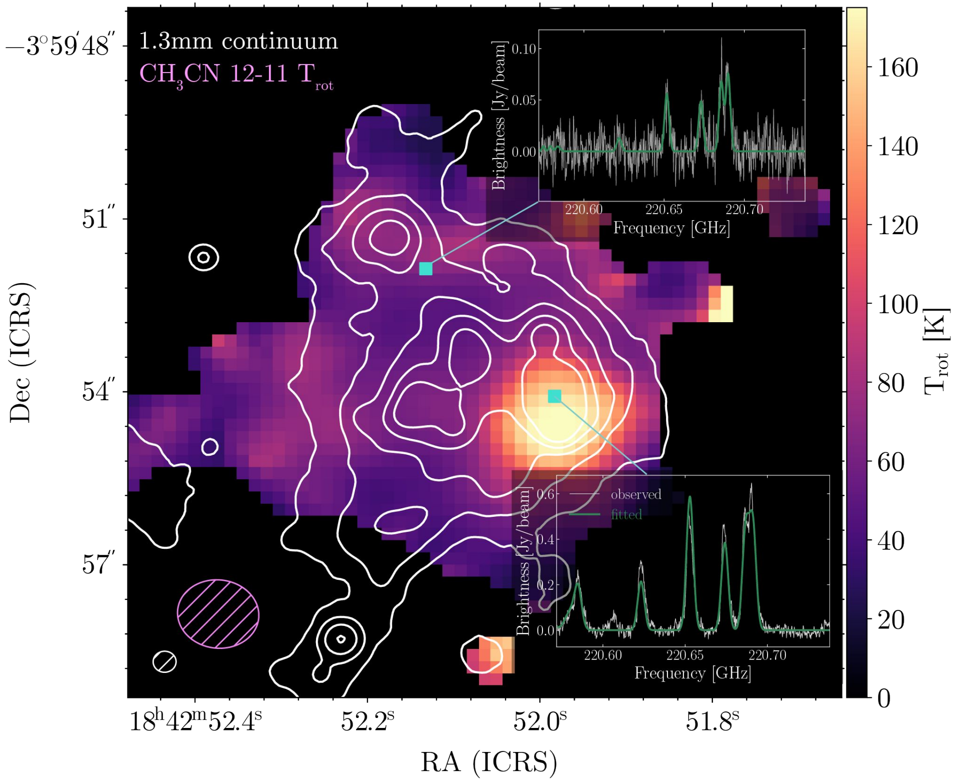
Temperature maps

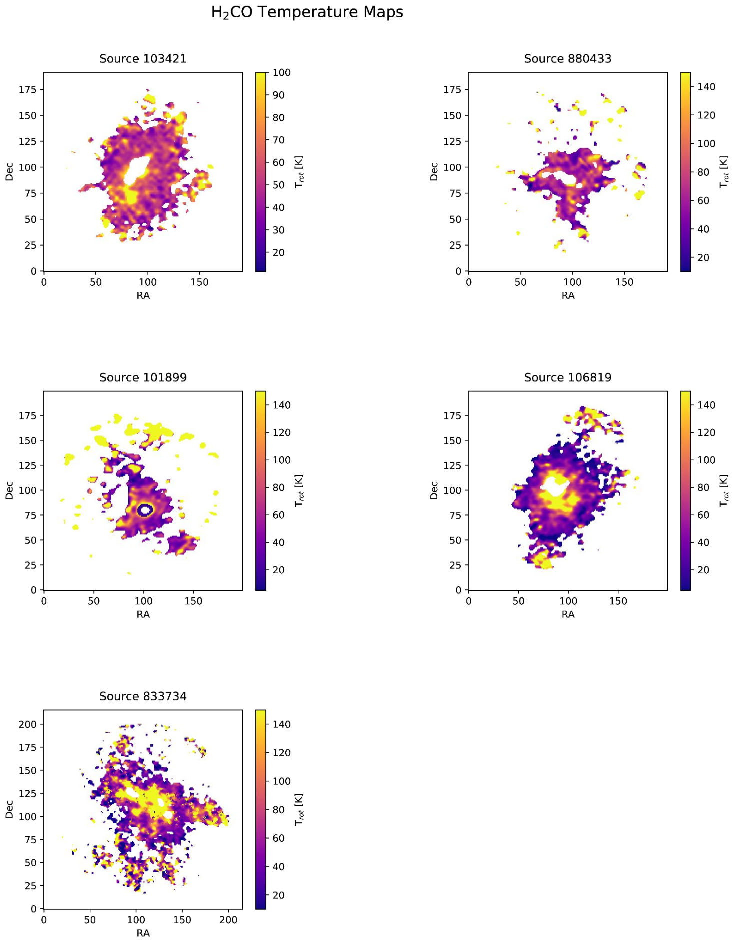
Gives line temperature estimate as function of radius
Possible to implement in realistic runtime

Low resolution required for signal-to-noise per pixel
Still relies on single LoS component fits (not true 3D for profiles)
Unusual to have very widespread emission in multiple CH_3CN transitions



Beth Jones (UoC)

Thermal Feedback on clump scales



Heating from the emerging stars by either IR radiation or shocks can modify the fragmentation processes/the mass flow

Gas temperatures from H_2CO

Caveats:

- $T_{gas} > T_{dust}$ for shock heating
- Available lines have T_{upper} < 70 K
  ➪ not very sensitive to very hot gas
- H_2CO can suffer from missing flux, which can falsify the temperatures

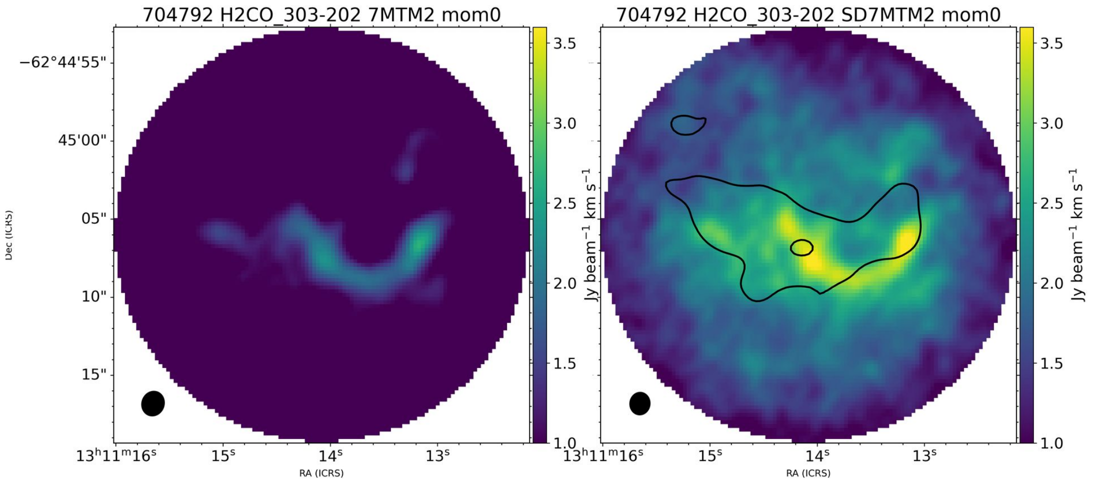
Beth Jones
UoC master thesis: Nayab Gohar

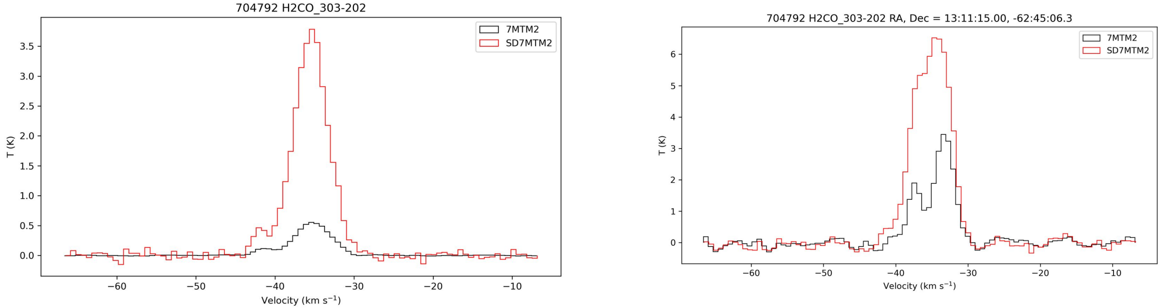
Extended emission

Missing flux solution - combining with single pointing by APEX!

ALMA only

ALMA+APEX





Even with added ACA, we still have considerable missing flux

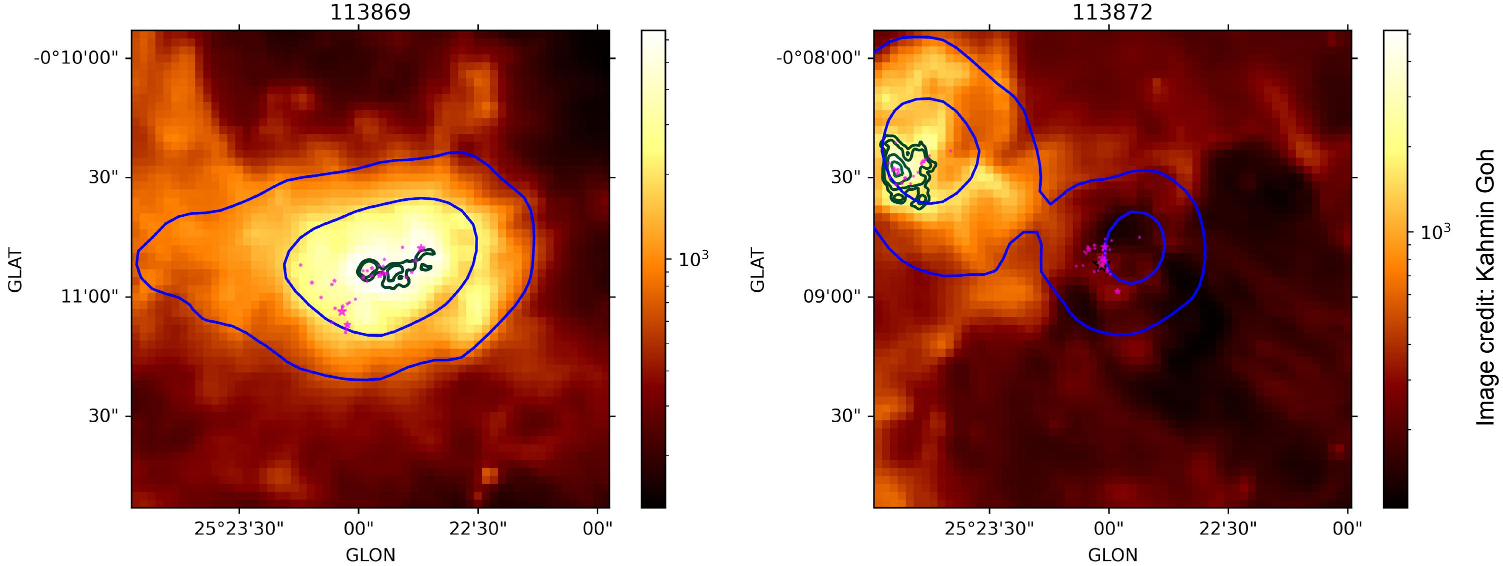
Combining with single pointing APEX spectra can recover most of the missing flux

Mandatory for studies using these data

- Infall
- Temperature determinations
- Chemical studies

UoC PhD thesis Han-Tsung Lee

Ionizing feedback and IR environment



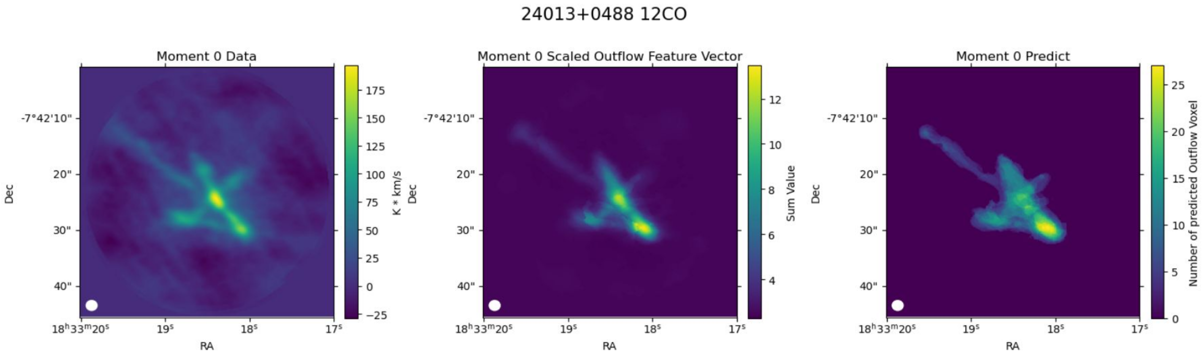
External ecosystem: GLIMPSE 8 μm (color), ATLASGAL (blue contours), CORNISH HII regions (green contours), ALMAGAL cores (pink stars)

How does it affect the properties? Are some cores already so evolved that they are not longer visible in ALMAGAL, but in the IR?

Connection to larger scale mass reservoir: are the clumps isolated, or do they also still accrete? Follow the flow!

Outflows

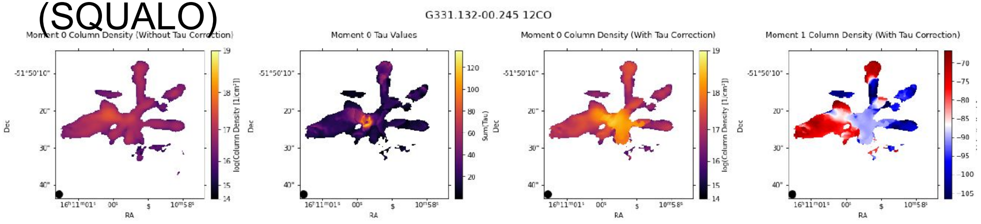
- Not feasible manually: ML
- Here: support vector machine (SVM) based on local properties (intensity, line width, gradients (DoG)), **not** on morphology trained on synthetic data

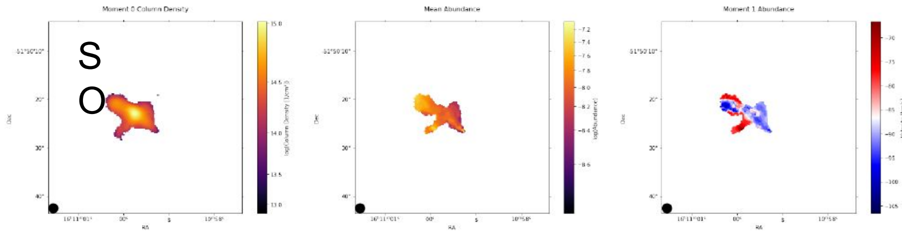


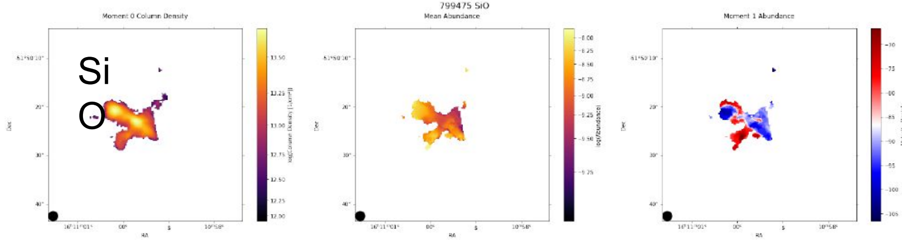
SQUALO project
Traficante et al 2023

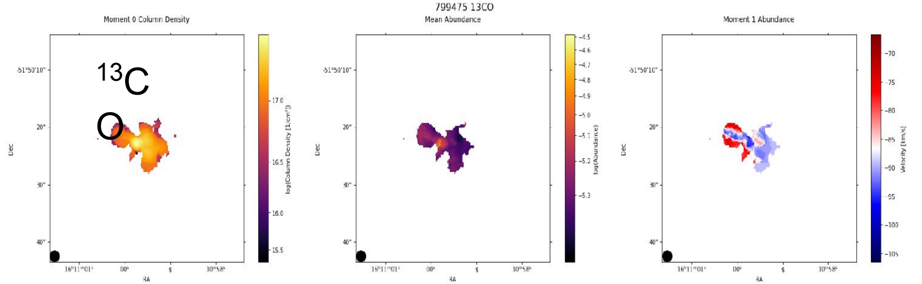
UoC Master Thesis Marcel Günther

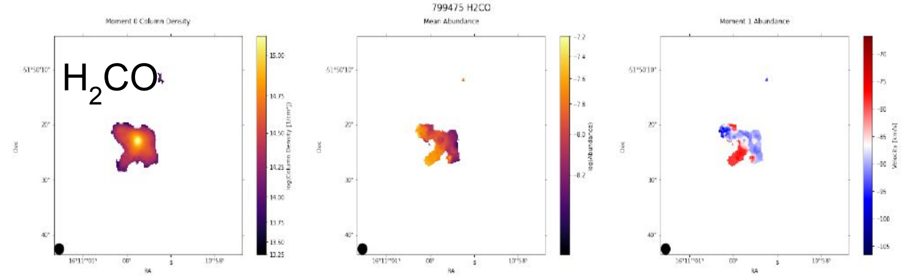
Reference ^{12}CO (SQUALO)

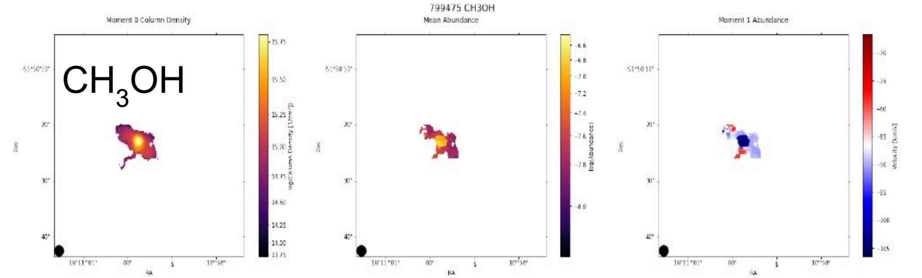








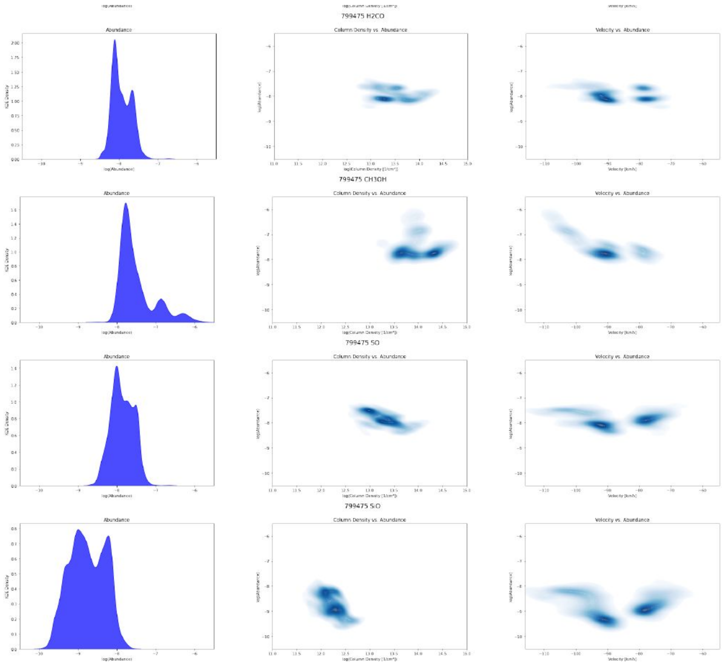


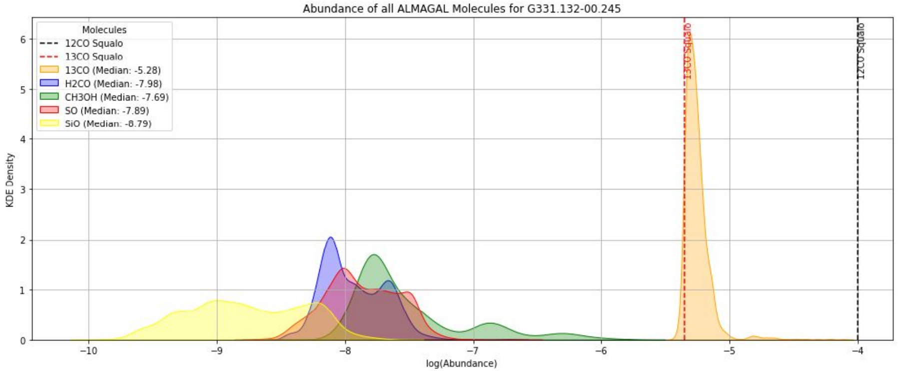


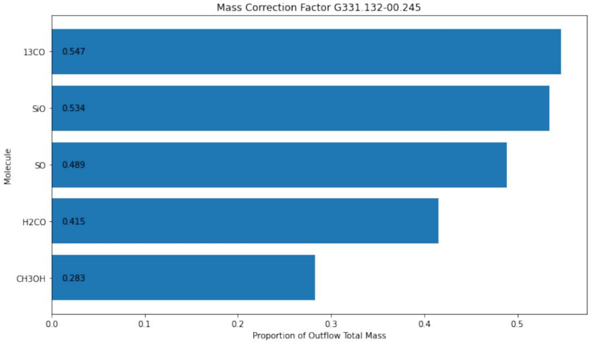
Not all species trace the same gas – so far, no short spacings

UoC Master Thesis Marcel Günther

Outflows: Results





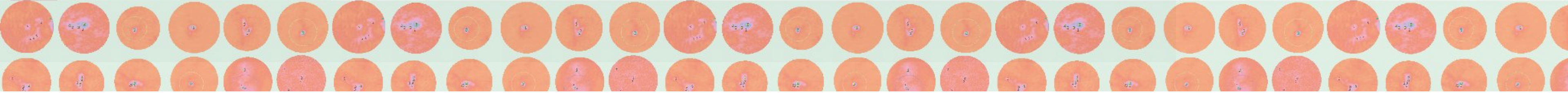


In some species we find a decreasing abundance with H_2 column density, corresponding to a butterfly pattern in velocity. This could be due to either

- increased production rate with shock velocity,
- the molecule existing only in a shell independent of total column density

At any rate, the abundances show a wide spread

To be used with caution – no short spacings

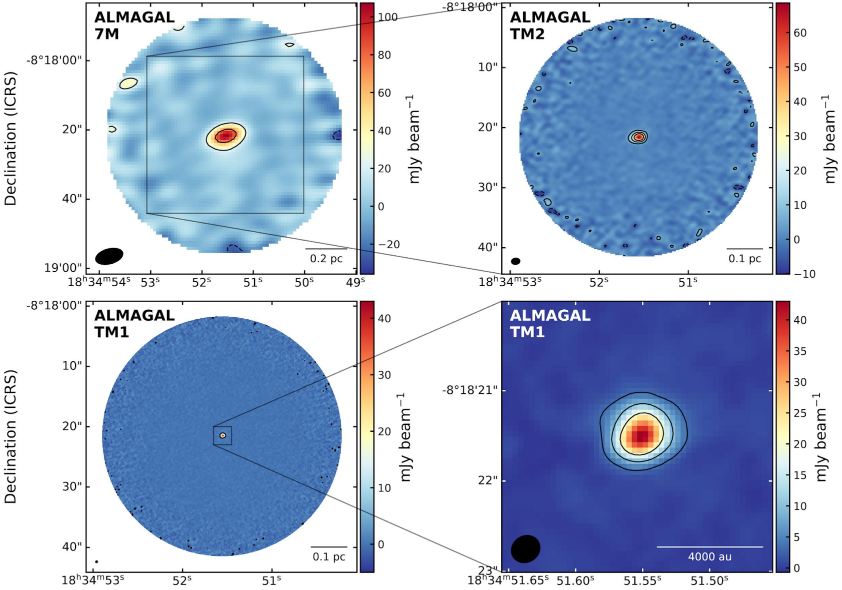


Outlook – lots left to do

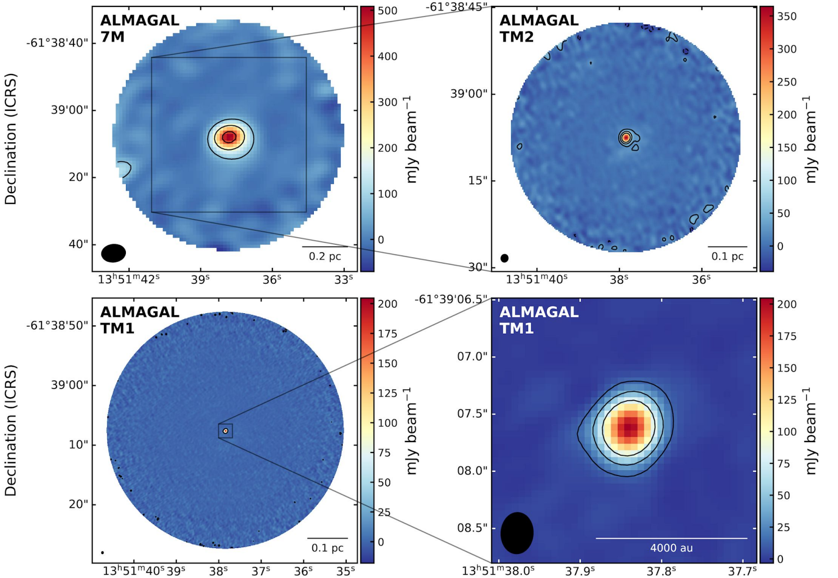
- Determine core temperature structure
- Find outflows and filaments on data including short spacings
  - Temperature structure
  - Characterize their velocity fields
  - Determine chemical properties
- Characterize environment and see if any of the properties correlate
- Zoom in – high-mass disks

Sneak preview – disks (Aida Ahmadi)

Target: G023.6566-00.1273



Target: G310.0135+00.3892



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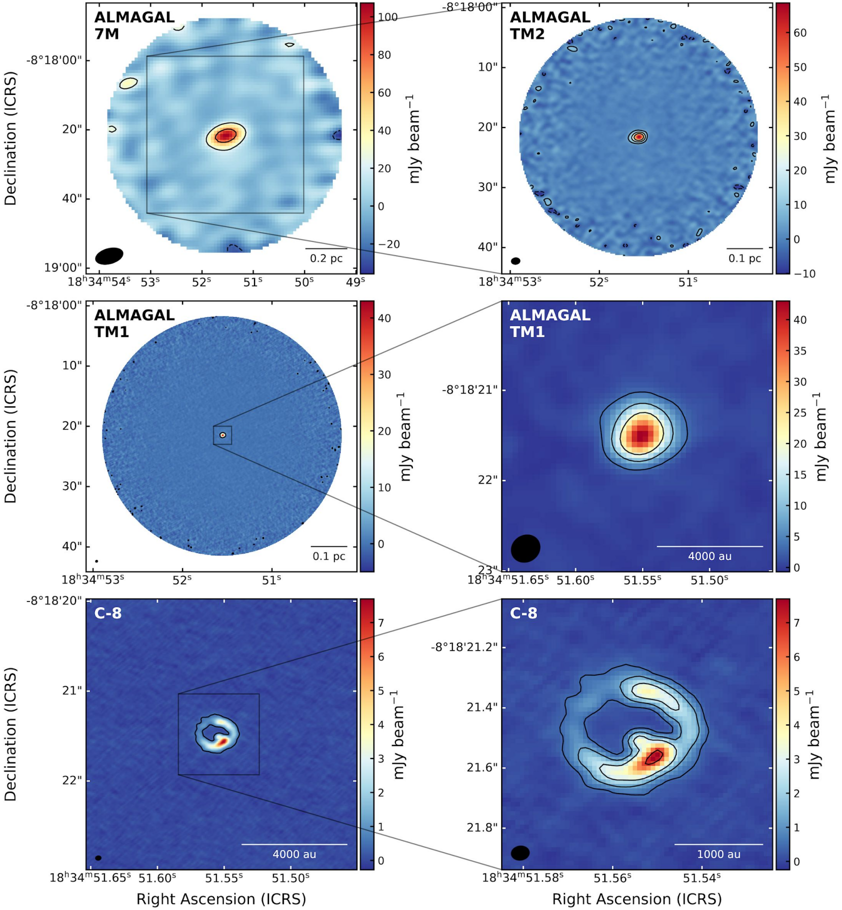

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