Fire it up

Using accretion outbursts to study the chemistry of protoplanetary disks

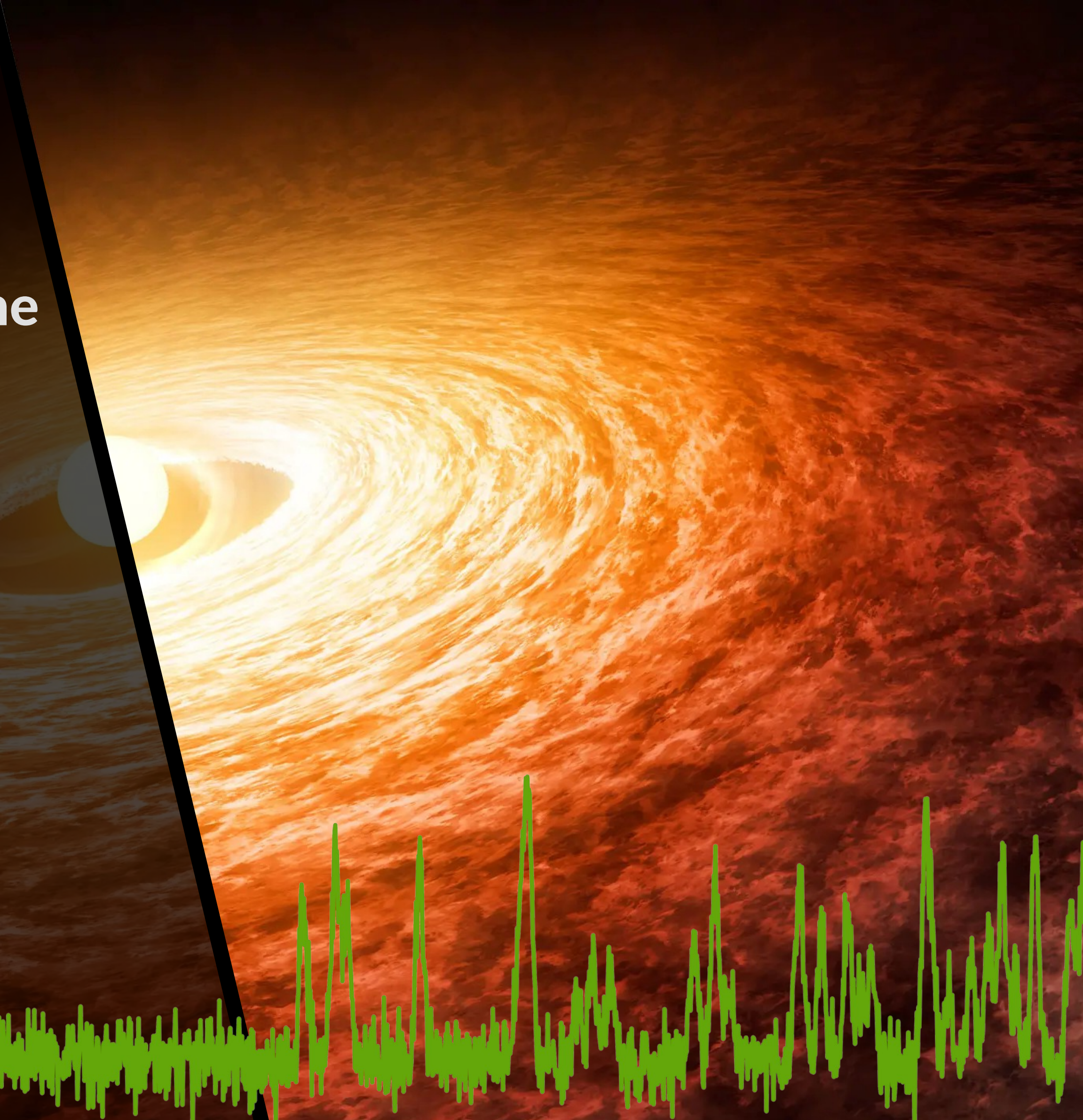
Fernando Cruz Sáenz de Miera

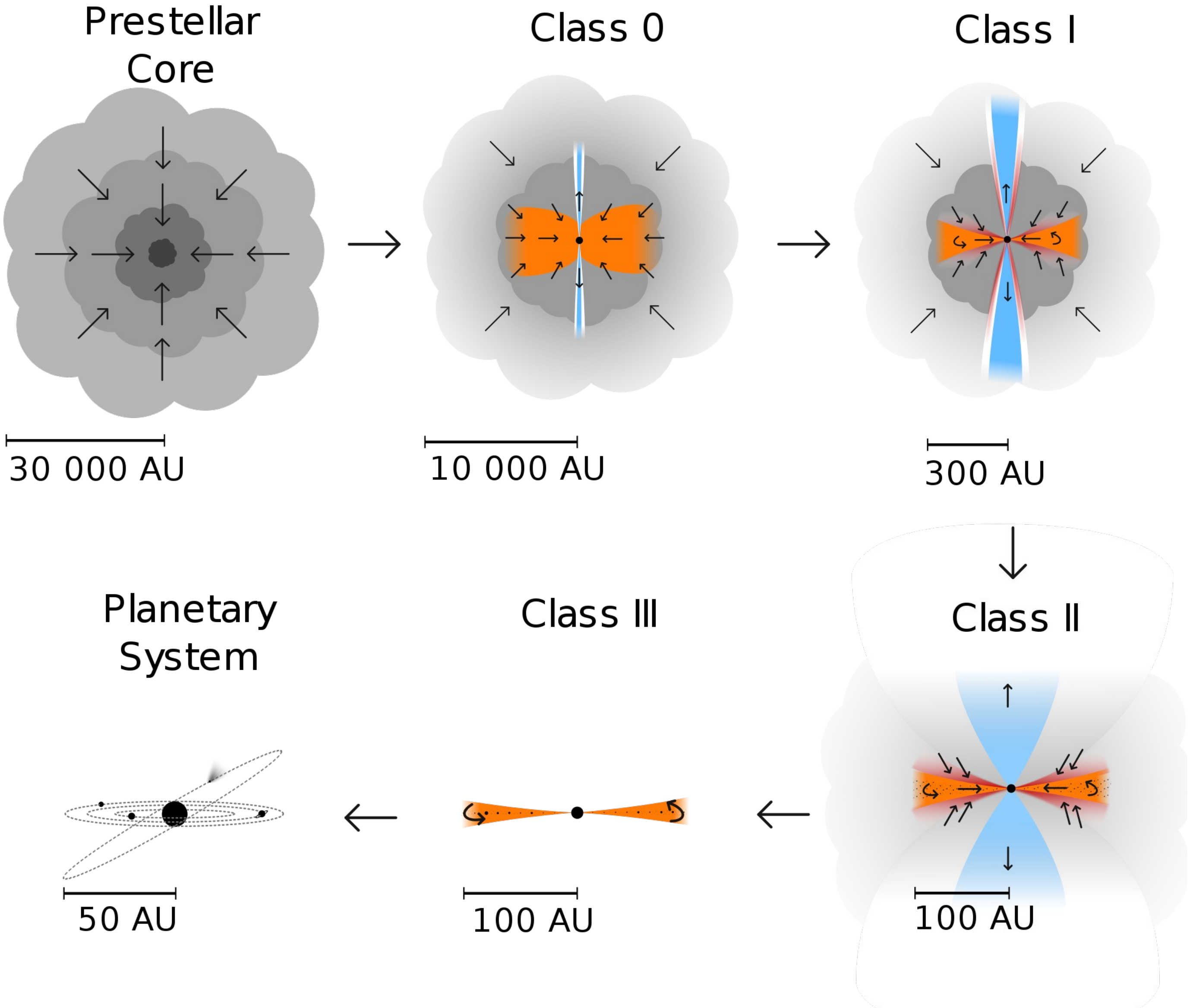
Collaborators:
Audrey Coutens, Ágnes Kóspál, Péter Ábrahám,
Anne Dutrey, Stéphane Guilloteau, Antoine Espagnet

European Research Council
Established by the European Commission

Chemtrip
The CHEMical TRail In Protostars: From the deeply embedded phase to the planet-forming disk

irap




Prestellar Core
30 000 AU
Class 0
10 000 AU
Class I
300 AU
Class II
100 AU
Class III
100 AU
Planetary System
50 AU

- Accretion is not smoothly decreasing but **episodic**

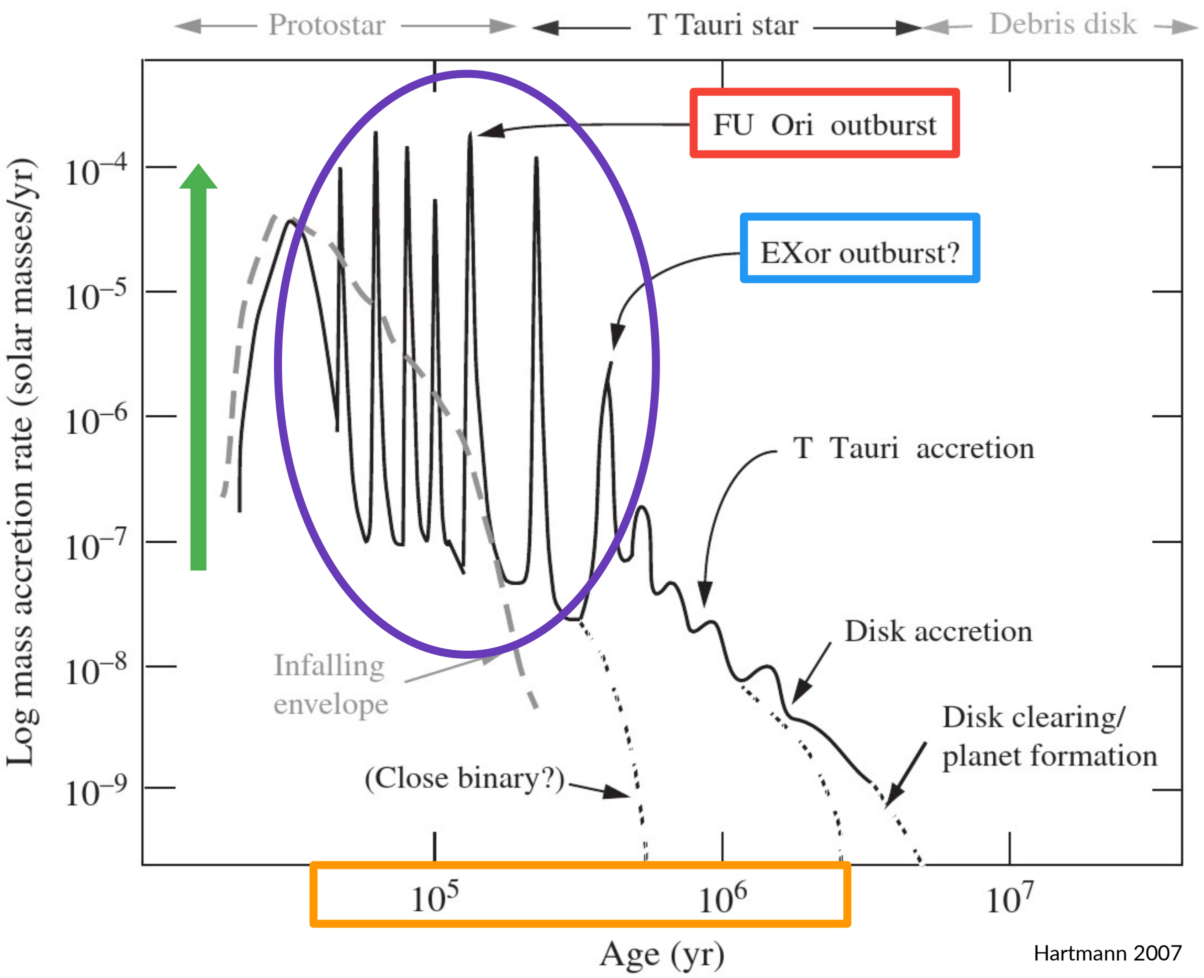
- Mass accretion rate increases
  - **10^{-8} up to 10^{-4} $M_\odot$ year^{-1}**

- Increase in L_{bol}
  - $L_{bol} = L_{star} + L_{acc} + L_{disk} + L_{env}$

- Mostly occur in **Class I or II** YSOs

- Typically detected as a brightening in optical/NIR photometry
  - Between 1 and 4 mag

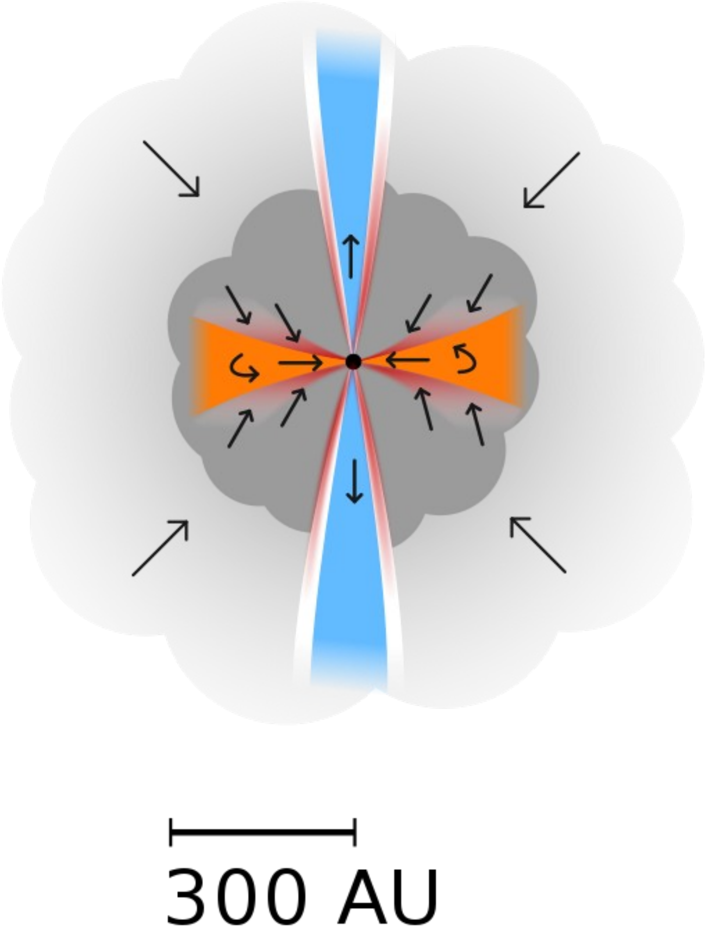
- Divided into two main sub-categories
  - **FUors** & **EXors**



Hartmann 2007

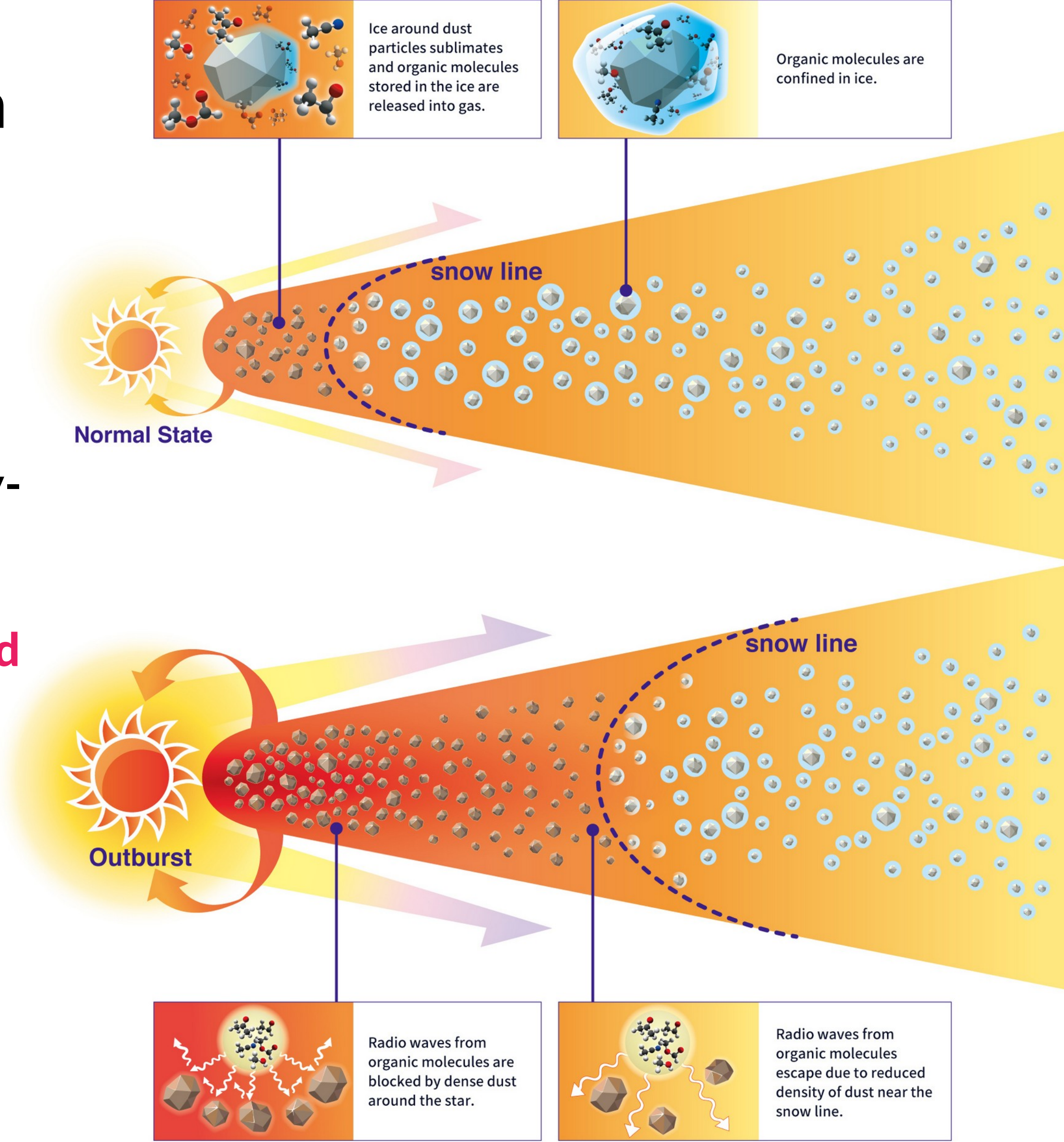
- <200 outbursting YSOs
  (Contreras-Peña, in prep.)
- Prevalence is unknown
  (Fischer+2019; Contreras-Peña+2019)

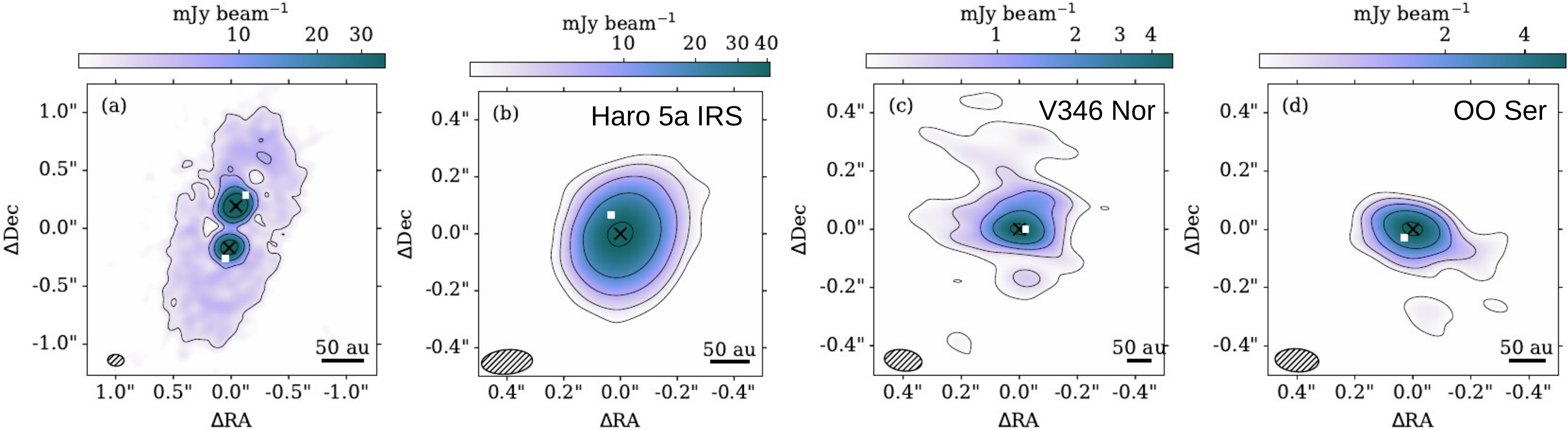
- Have a significant impact on
  - Total mass of the star
    (Fischer+2019; Cruz-Sáenz de Miera+2023b)
  - Envelope depletion (Fehér+2017)
  - Jets and outflows
    (Whelan+2010; Cruz-Sáenz de Miera+2023a)
  - Disk structure (Mosoni+2013)
  - Disk temperatures
    - Planet formation
    - Mineralogical evolution (Ábrahám+2009)
    - **Chemical evolution**



What role do outbursts have on the chemistry?

- Planets inherit chemical composition from disk.
- **Hot corinos are the hot, compact, chemically-rich (COMs) inner regions of Class 0 YSOs.**
- As the YSOs cool down, **molecules freeze and are harder to detect.**
- **Outbursts can sublimate them and make them detectable.**
- **But do outbursts affect the chemical evolution?**





L1551 IRS 5

Cruz-Sáenz de Miera (2025, A&A, 696, A18)

Three FUor-like targets + 1 “peculiar”

ALMA Band 6

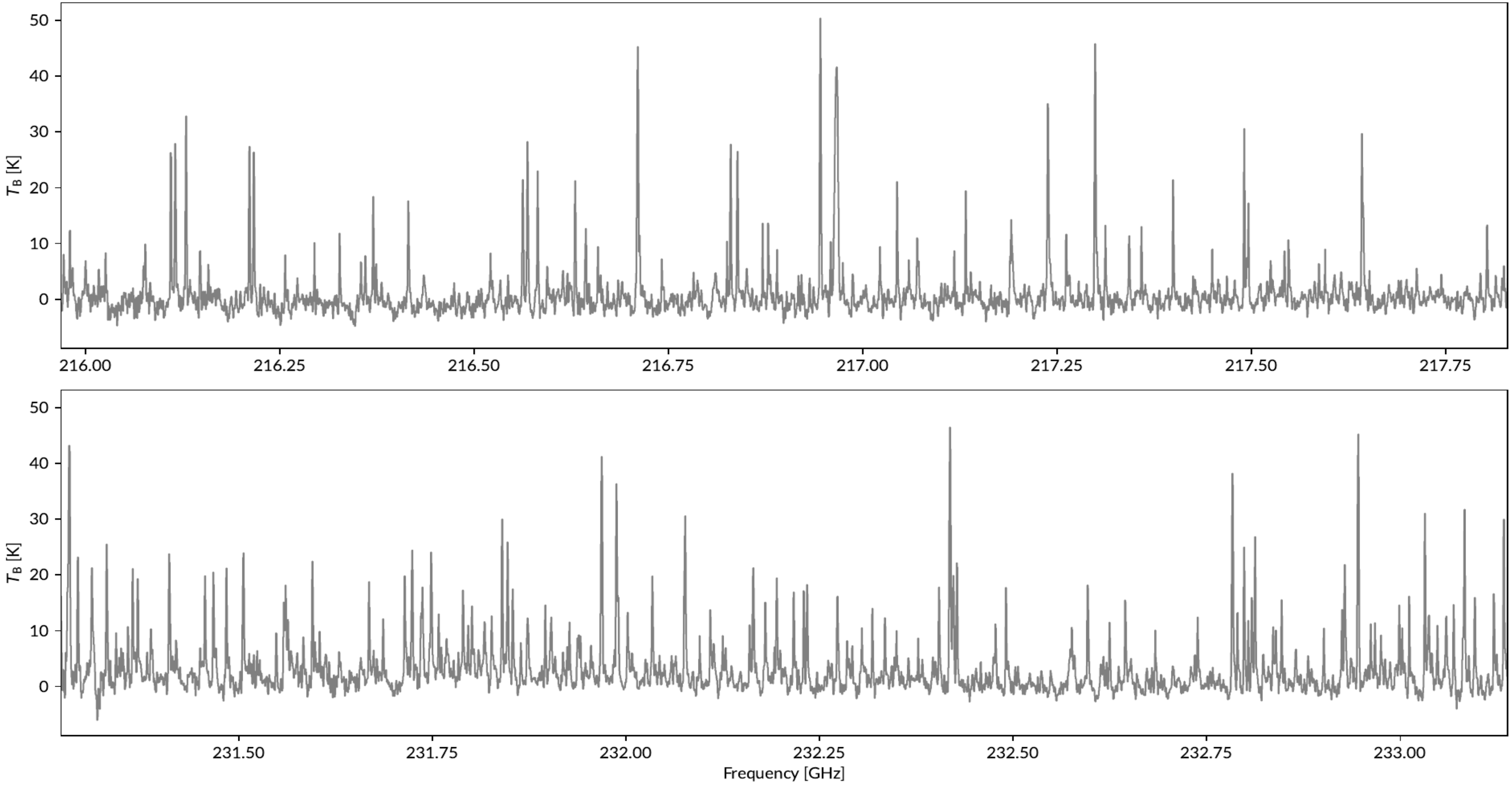
“Continuum” spws (0.977 MHz)

Two ALMA conf. + ACA

“Close” distances (140 - 700 pc)

36 ≤ Lbol ≤ 160 L⊙

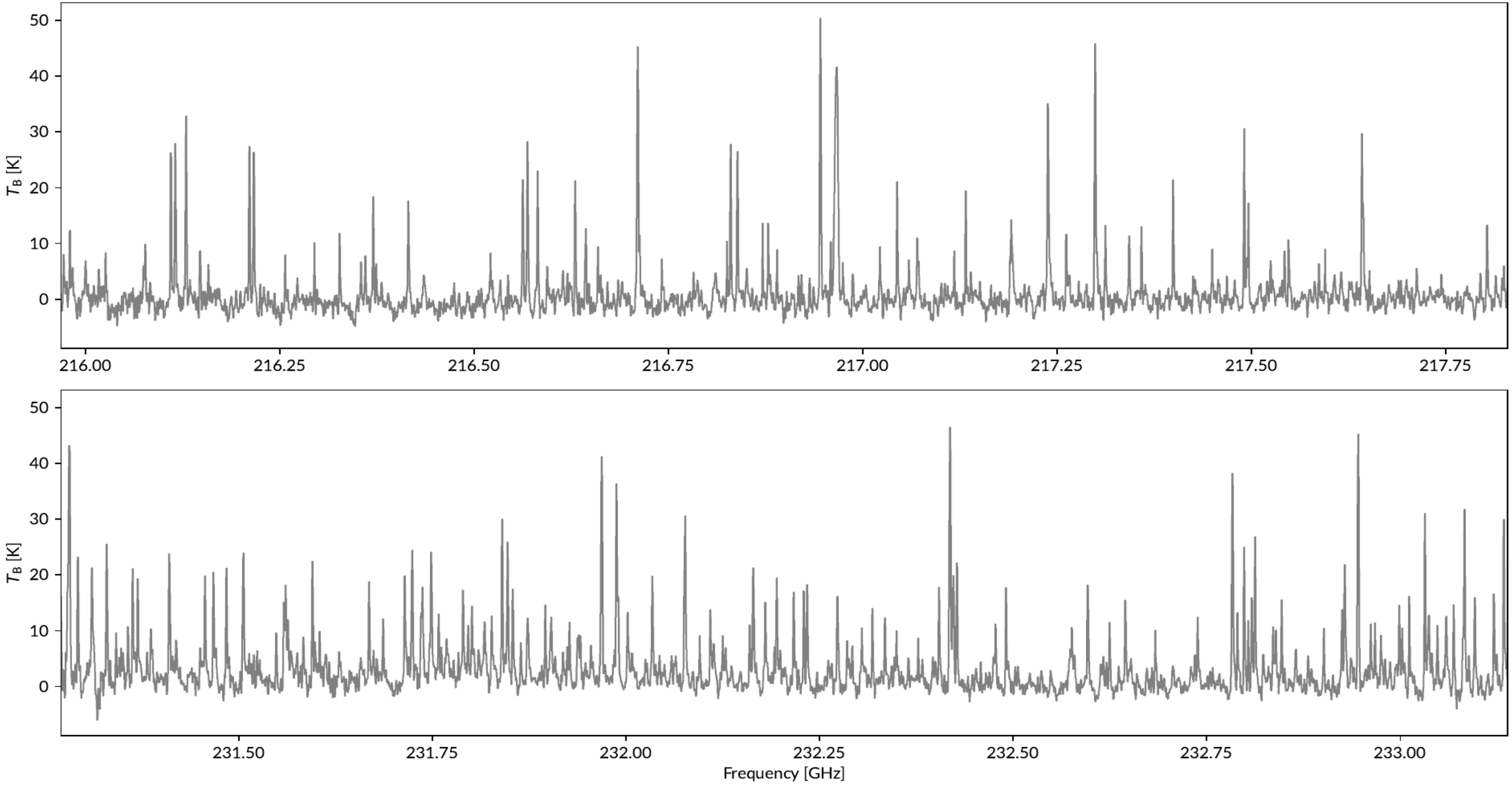
Spectra of L1551 IRS 5



Used CASSIS to identify species in all the spectra

↑tool developed at IRAP for spectral analysis

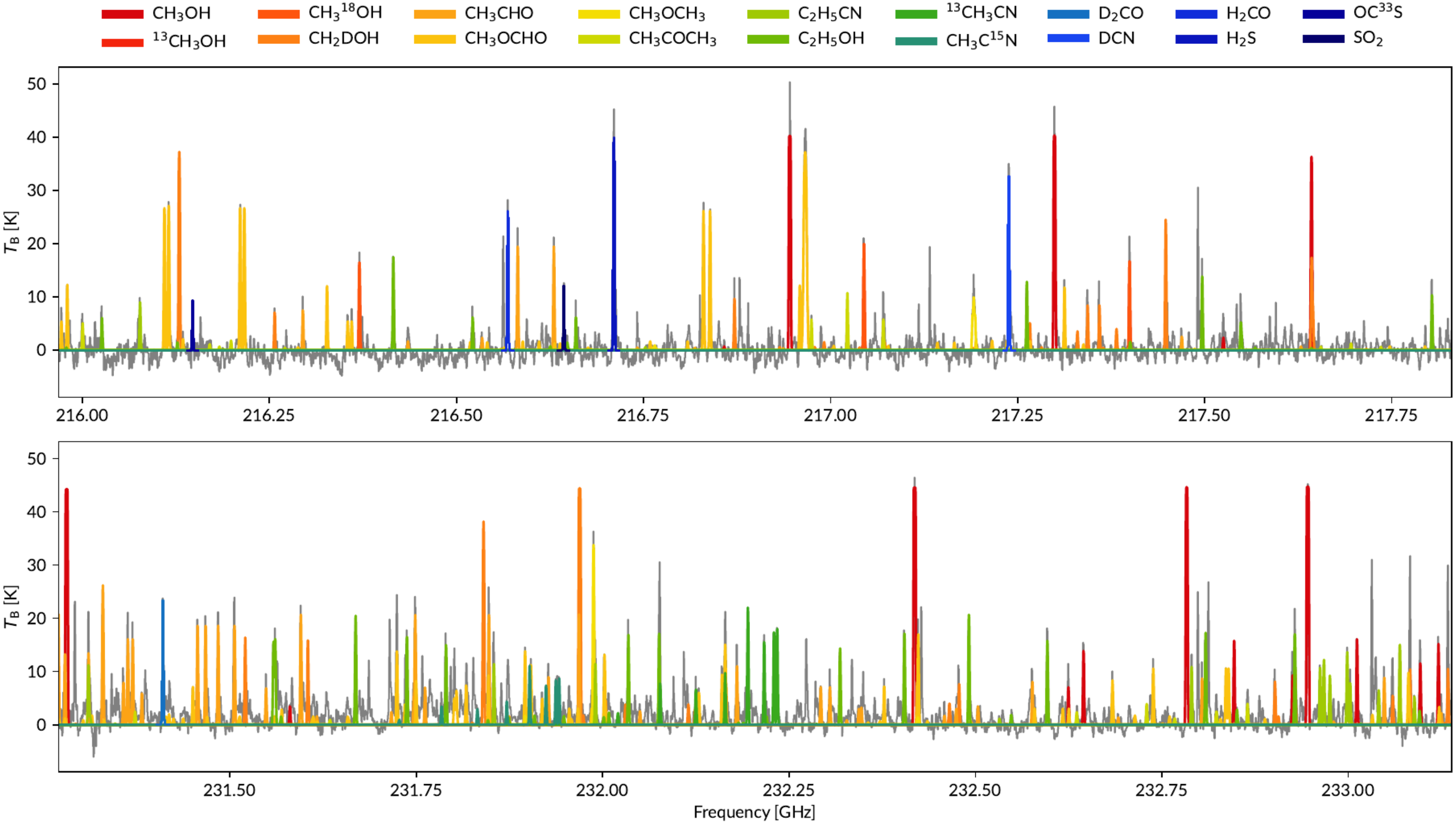
Spectra of L1551 IRS 5



Used CASSIS to identify species in all the spectra

↑tool developed at IRAP for spectral analysis

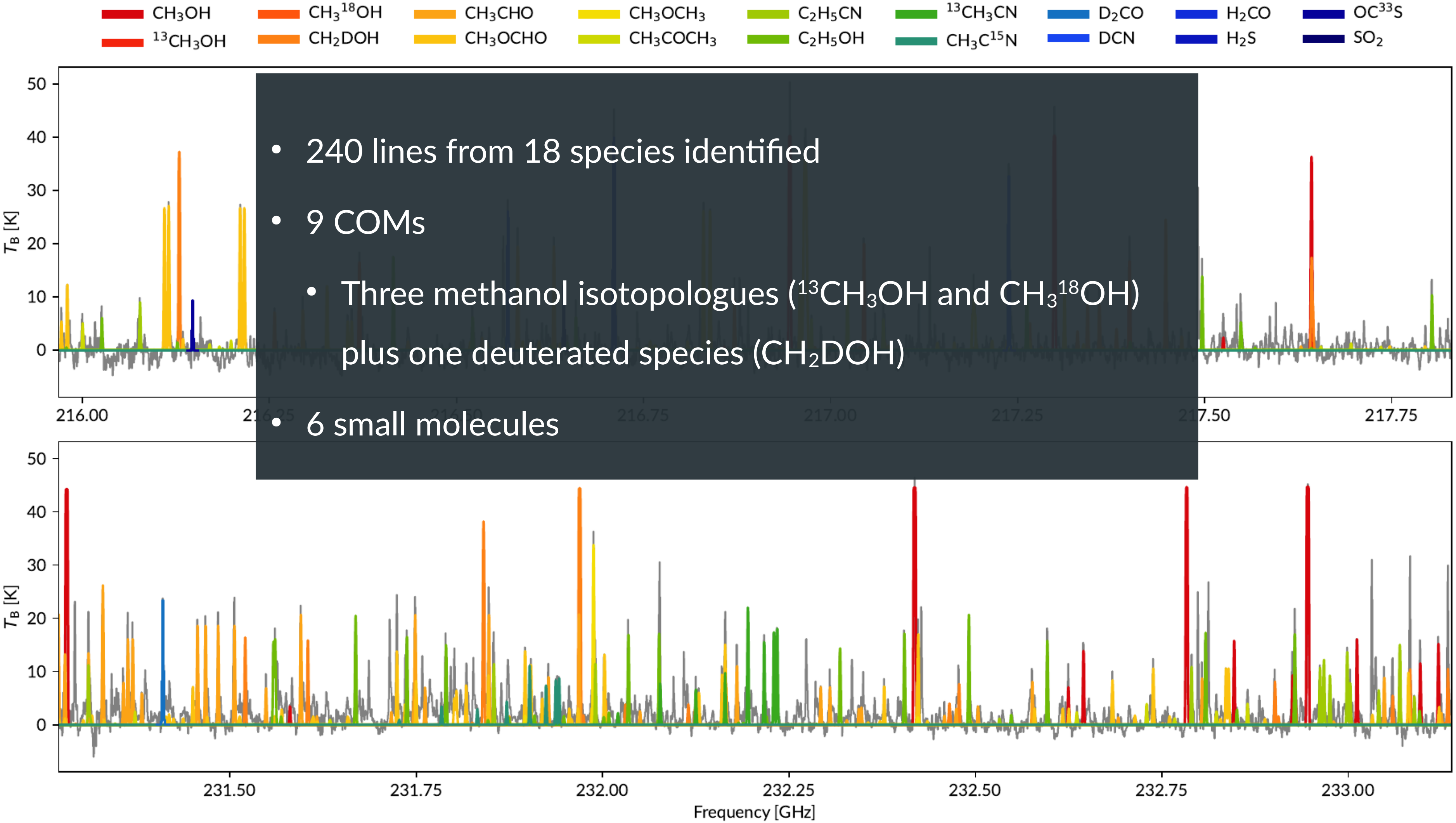
Spectra of L1551 IRS 5



Used CASSIS to identify species in all the spectra

↑tool developed at IRAP for spectral analysis

Spectra of L1551 IRS 5

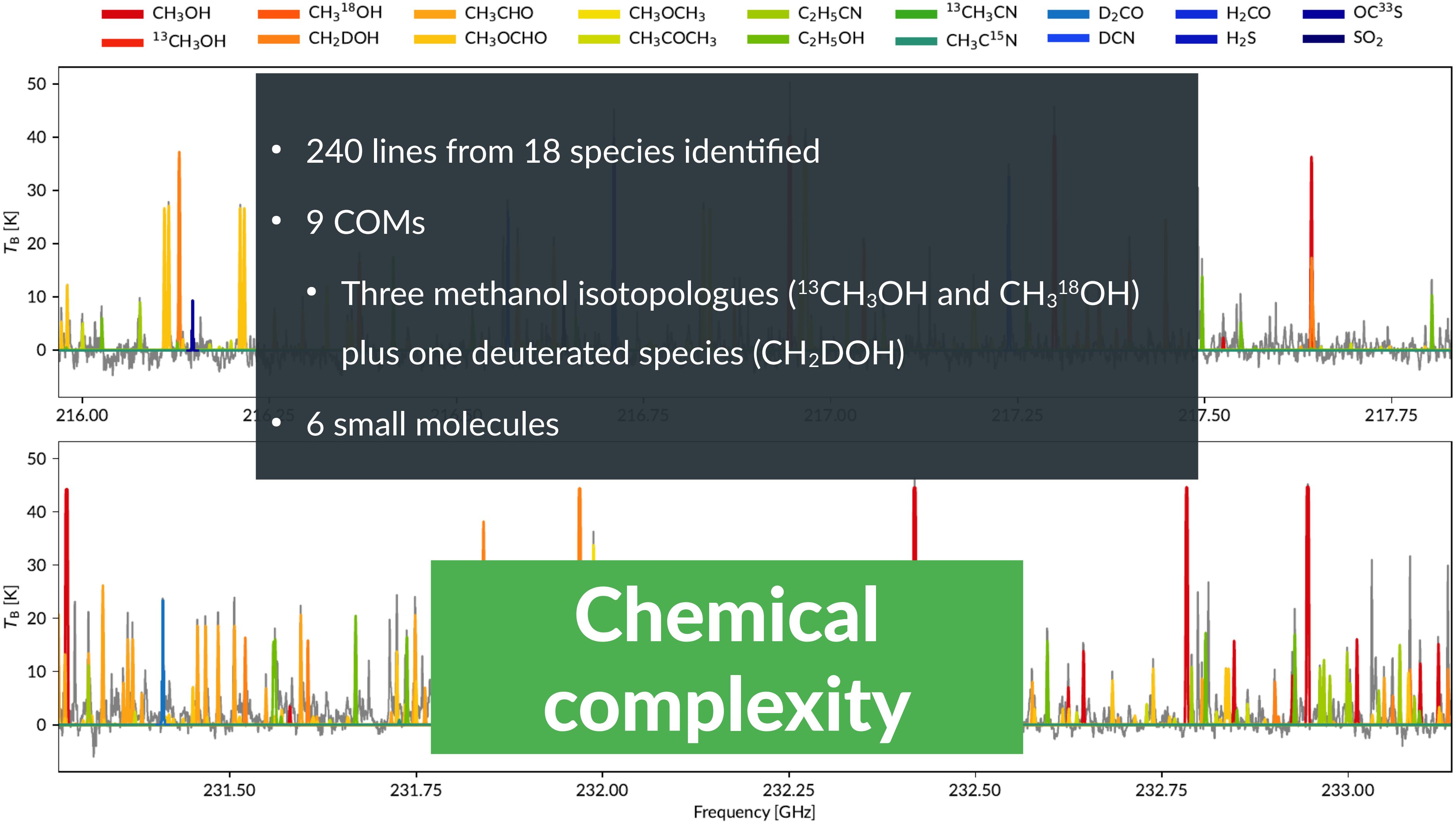


- 240 lines from 18 species identified
- 9 COMs
  - Three methanol isotopologues ($^{13}CH_3OH$ and $CH_3{}^{18}OH$) plus one deuterated species (CH_2DOH)
- 6 small molecules

Used CASSIS to identify species in all the spectra

↑tool developed at IRAP for spectral analysis

Spectra of L1551 IRS 5



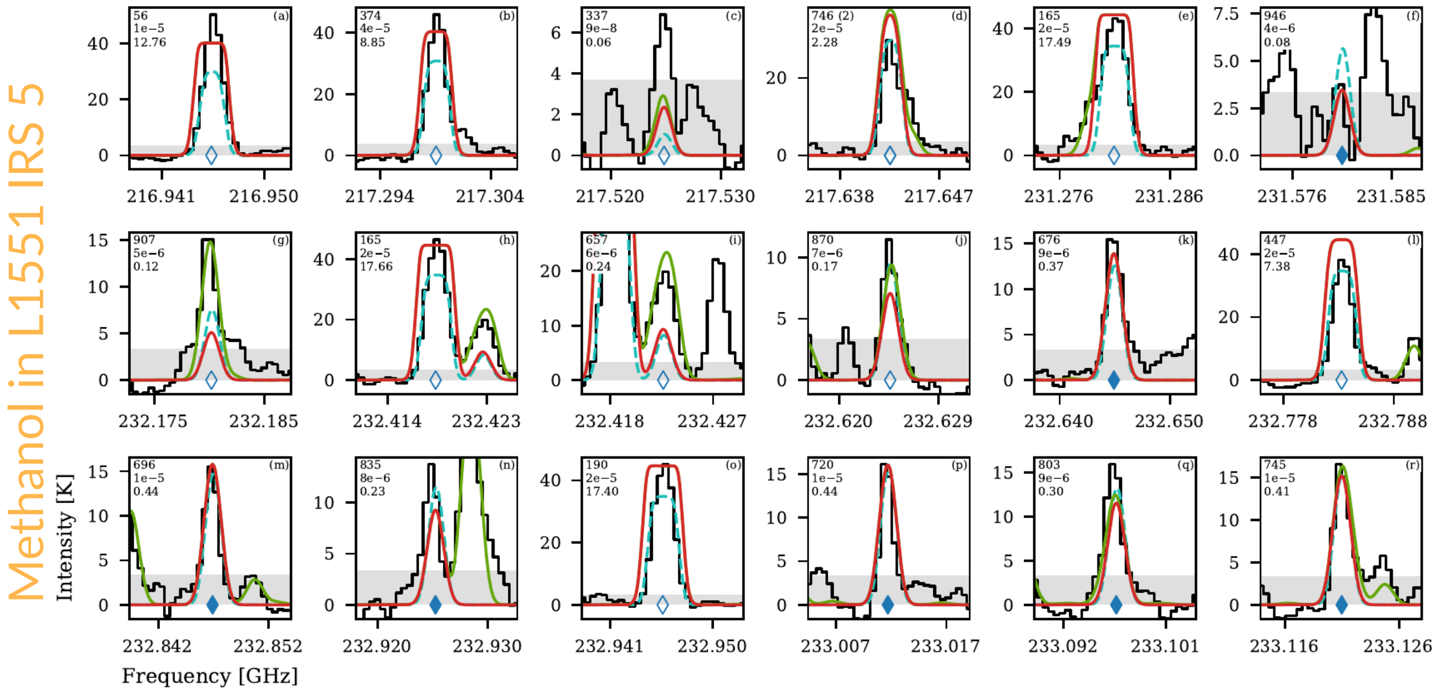
- 240 lines from 18 species identified
- 9 COMs
  - Three methanol isotopologues ($^{13}CH_3OH$ and $CH_3{}^{18}OH$) plus one deuterated species (CH_2DOH)
- 6 small molecules

Chemical complexity

Used CASSIS to fit LTE models on the line profiles

↑tool developed at IRAP for spectral analysis

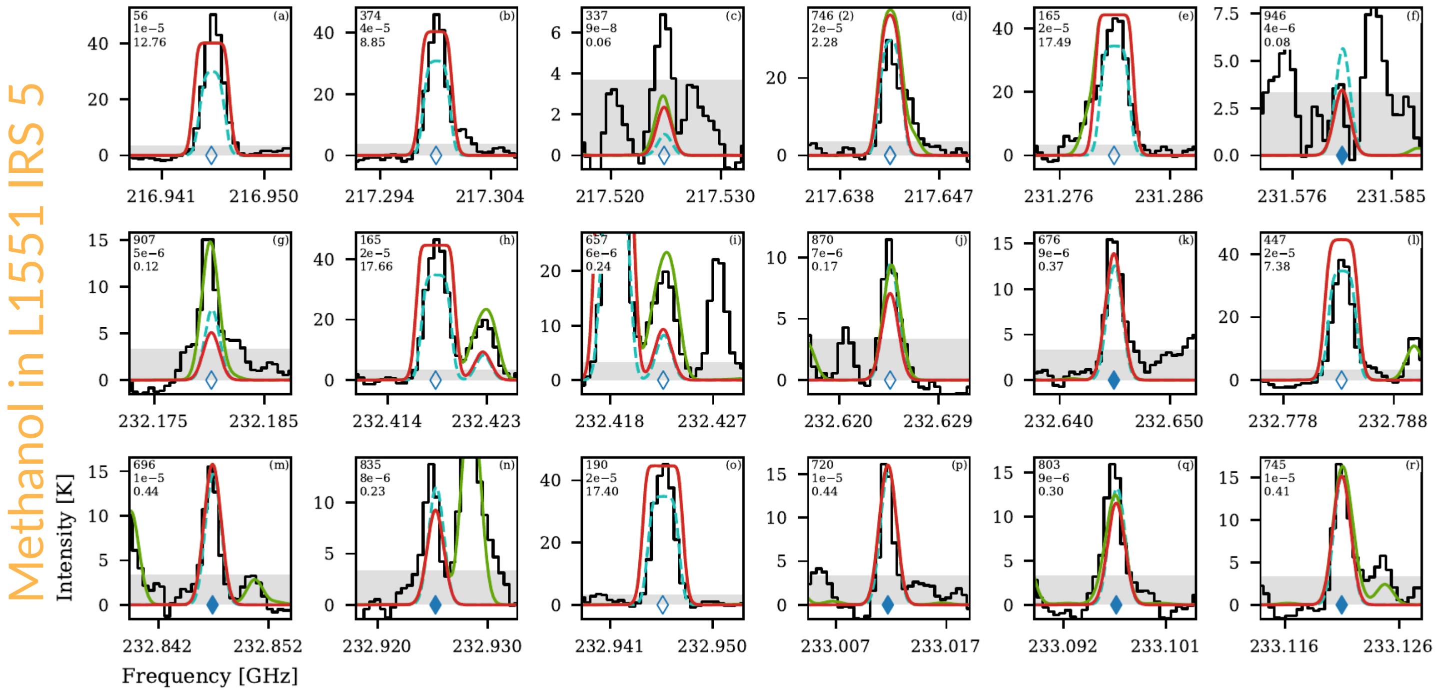
Obtained source size, FWHM, v_{LSR}, column density, excitational temperature for each species in each target



Used CASSIS to fit LTE models on the line profiles

↑tool developed at IRAP for spectral analysis

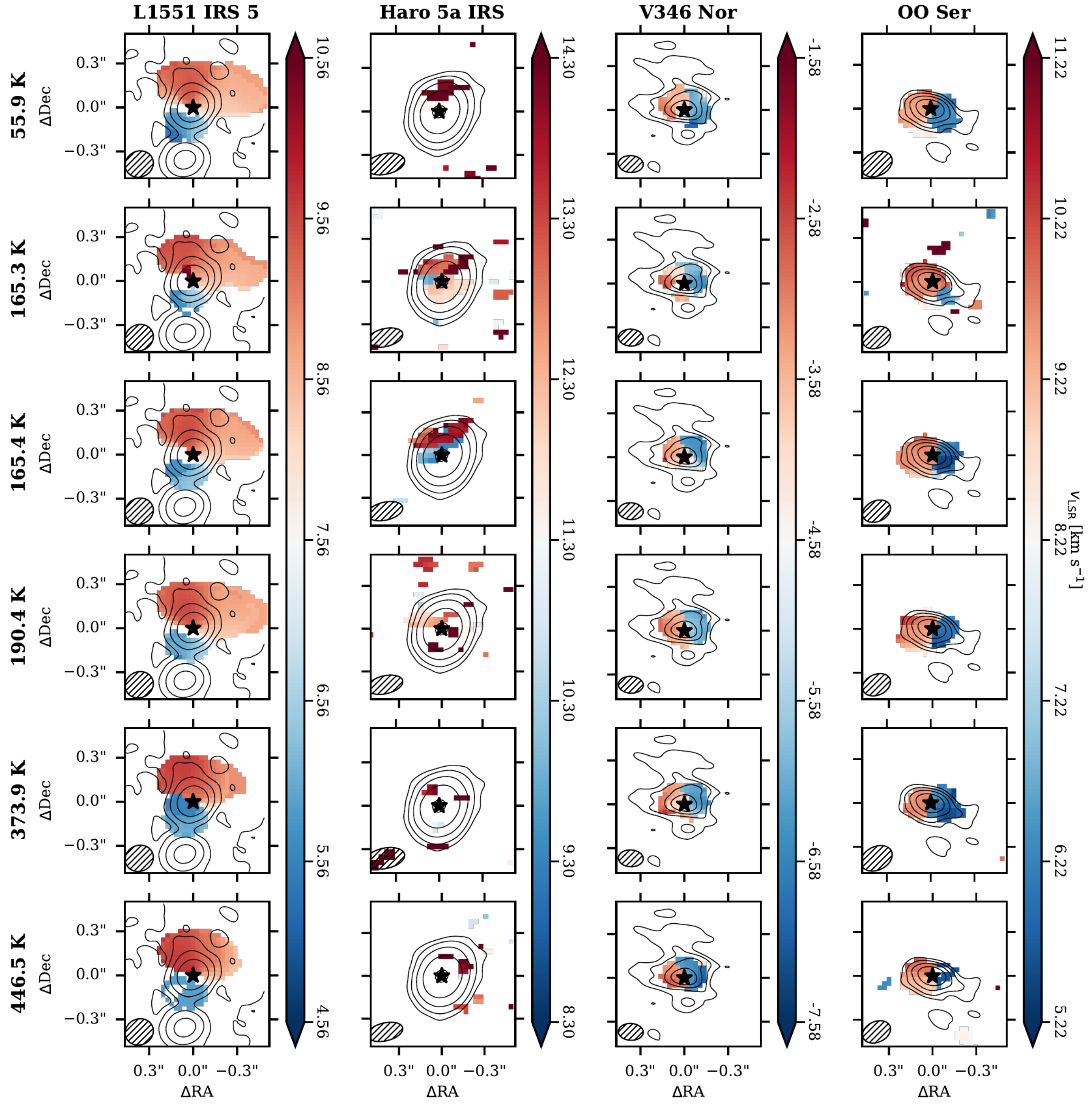
Obtained source size, FWHM, v_{LSR}, column density, excitational temperature for each species in each target



COMs have T_{ex} > 100 K

Spatial distribution of Methanol and other COMs

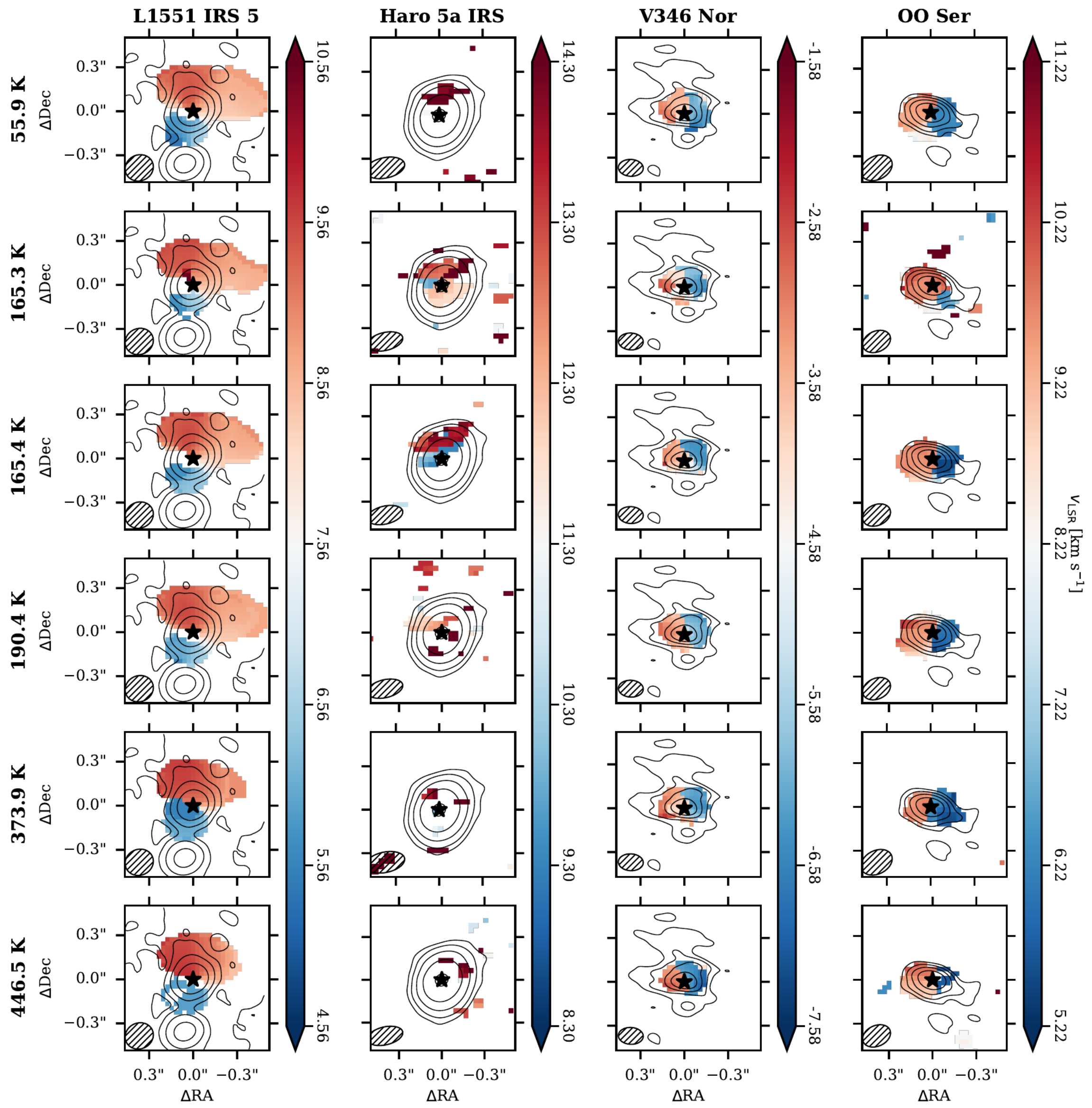
Moment maps of COMs indicate the extension of the warm chemically rich region.

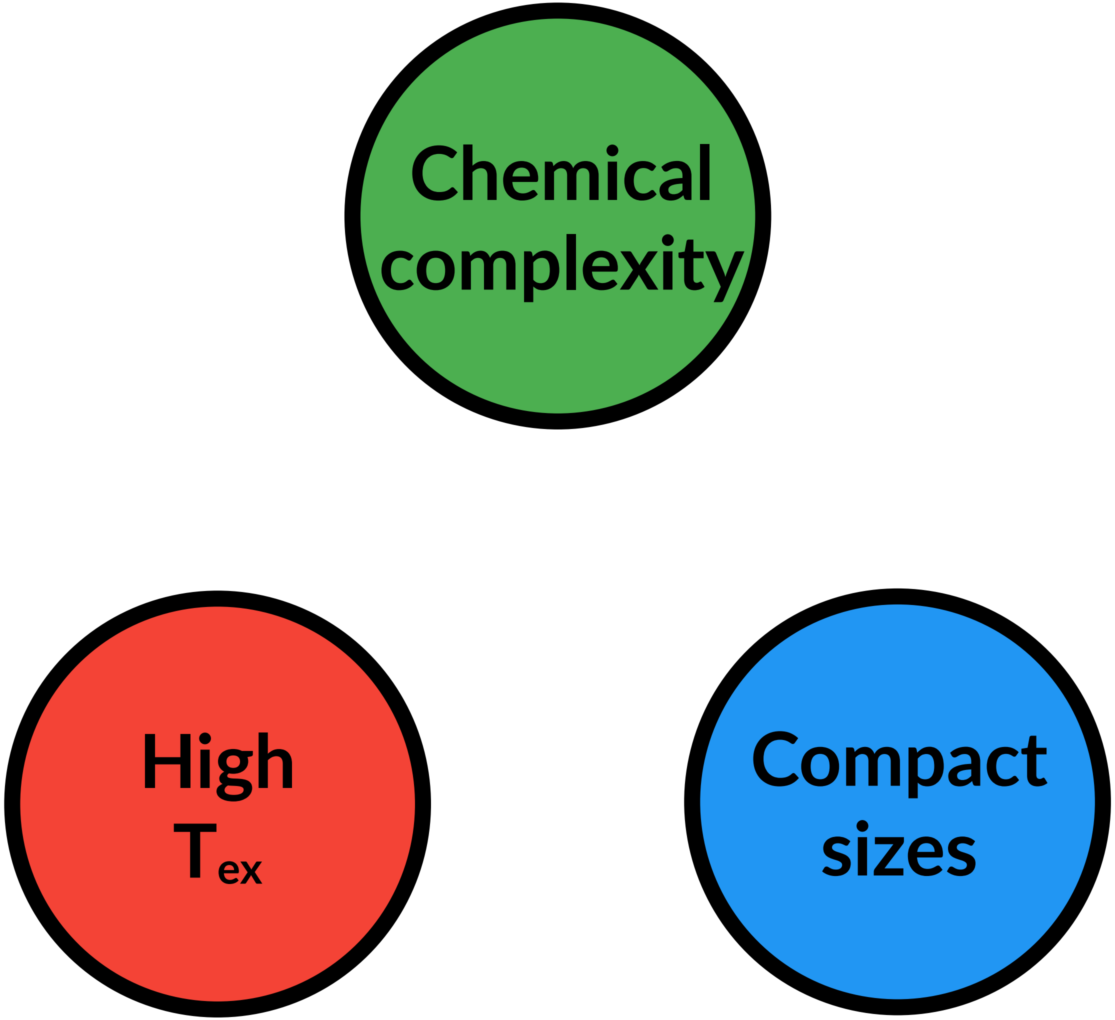


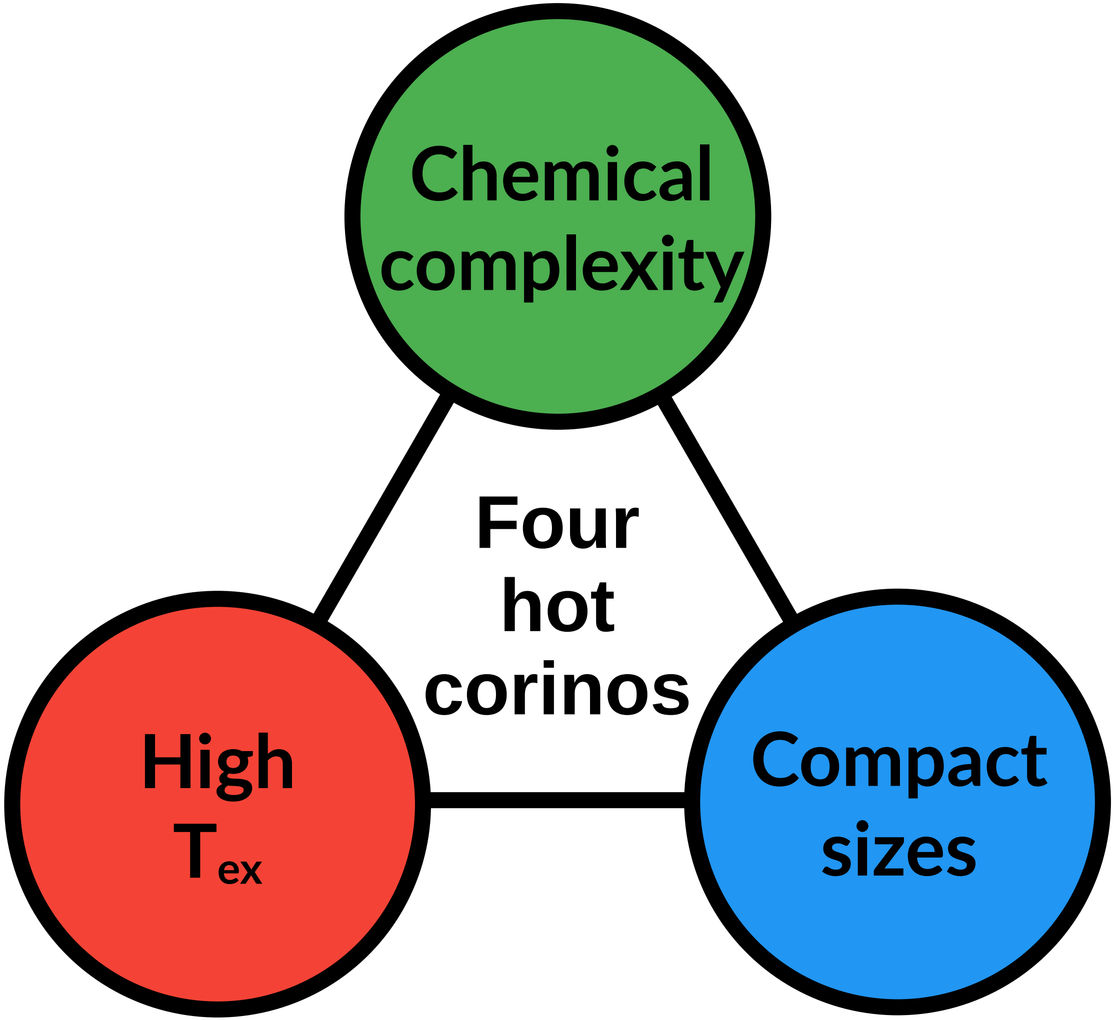
Spatial distribution of Methanol and other COMs

Moment maps of COMs indicate the extension of the warm chemically rich region.

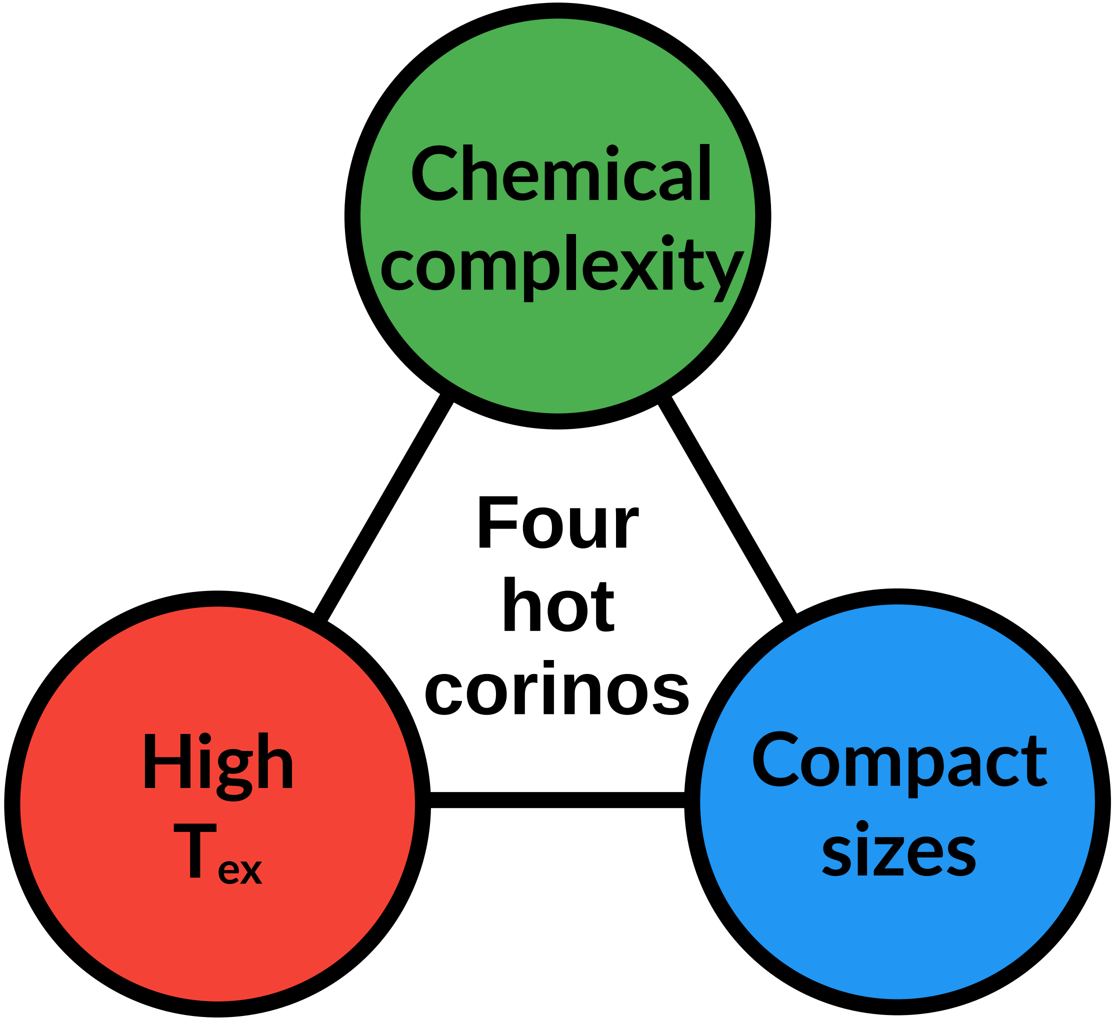
Compact $r \lesssim 70$au




Chemical complexity
High T_{ex}
Compact sizes

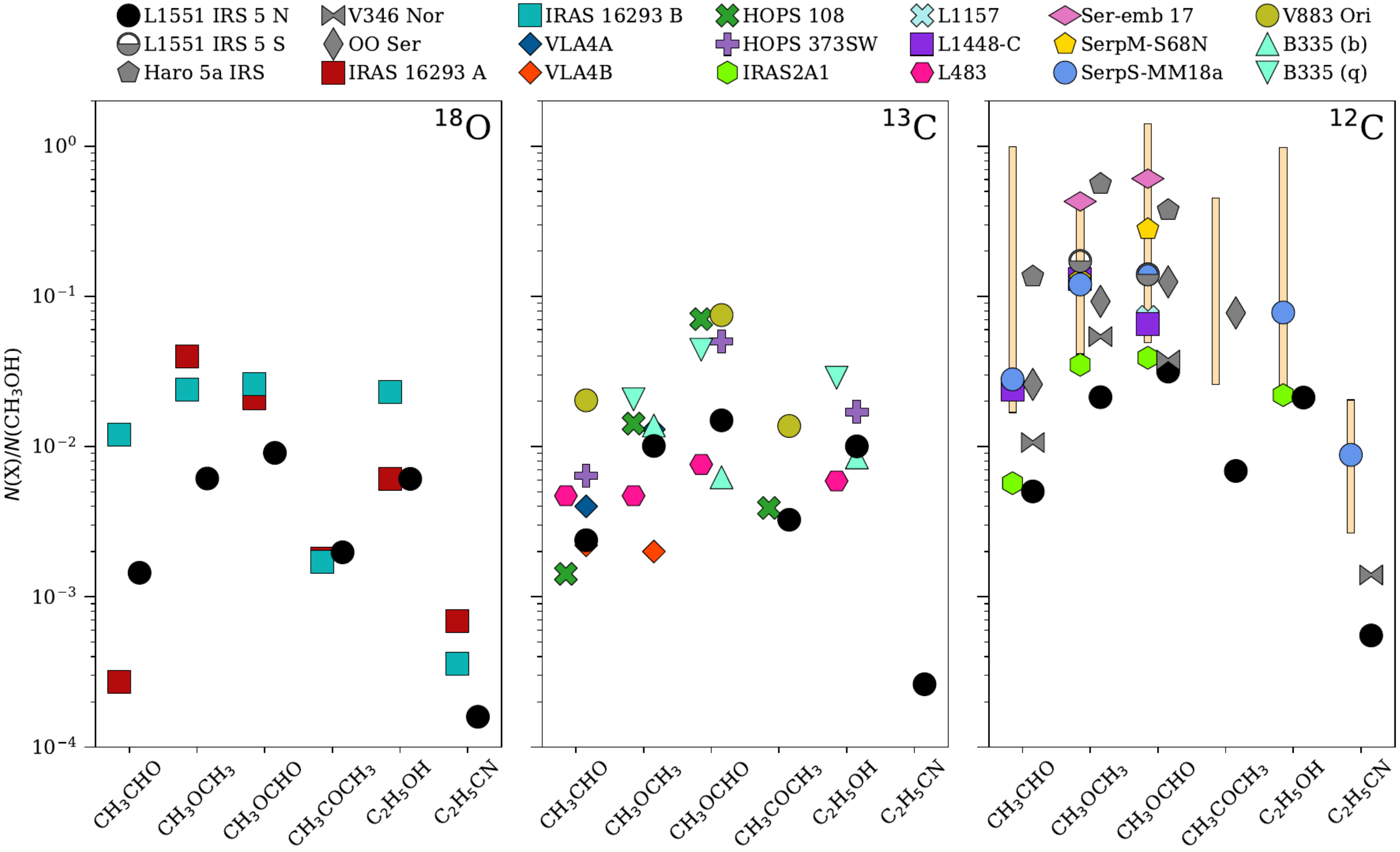


Chemical complexity
Four hot corinos
High T_{ex}
Compact sizes



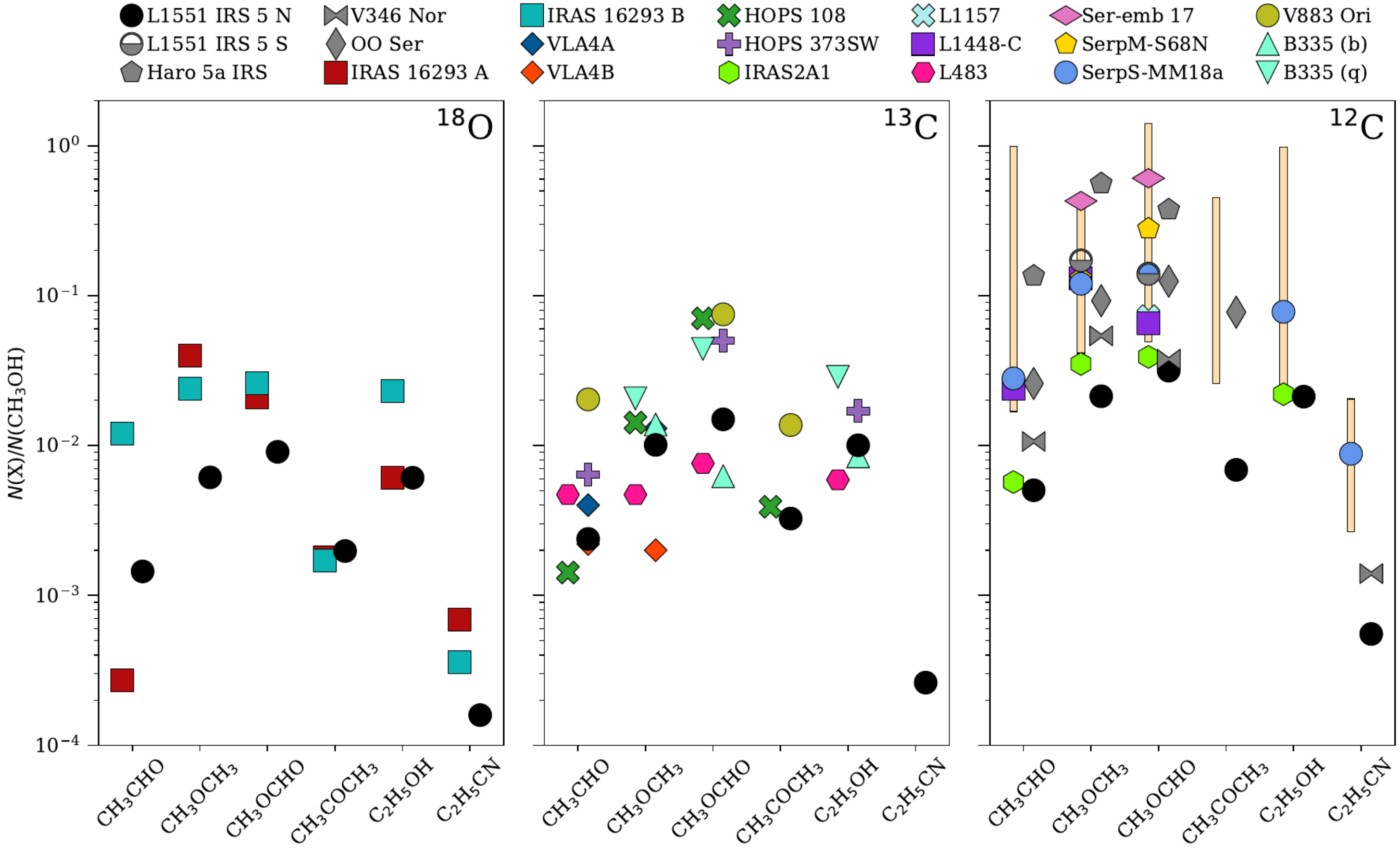
...so how do the abundances in these FUor-likes compare with those in other hot corinos?

How do these FUors compare with other "quiescent" Class 0/I sources?



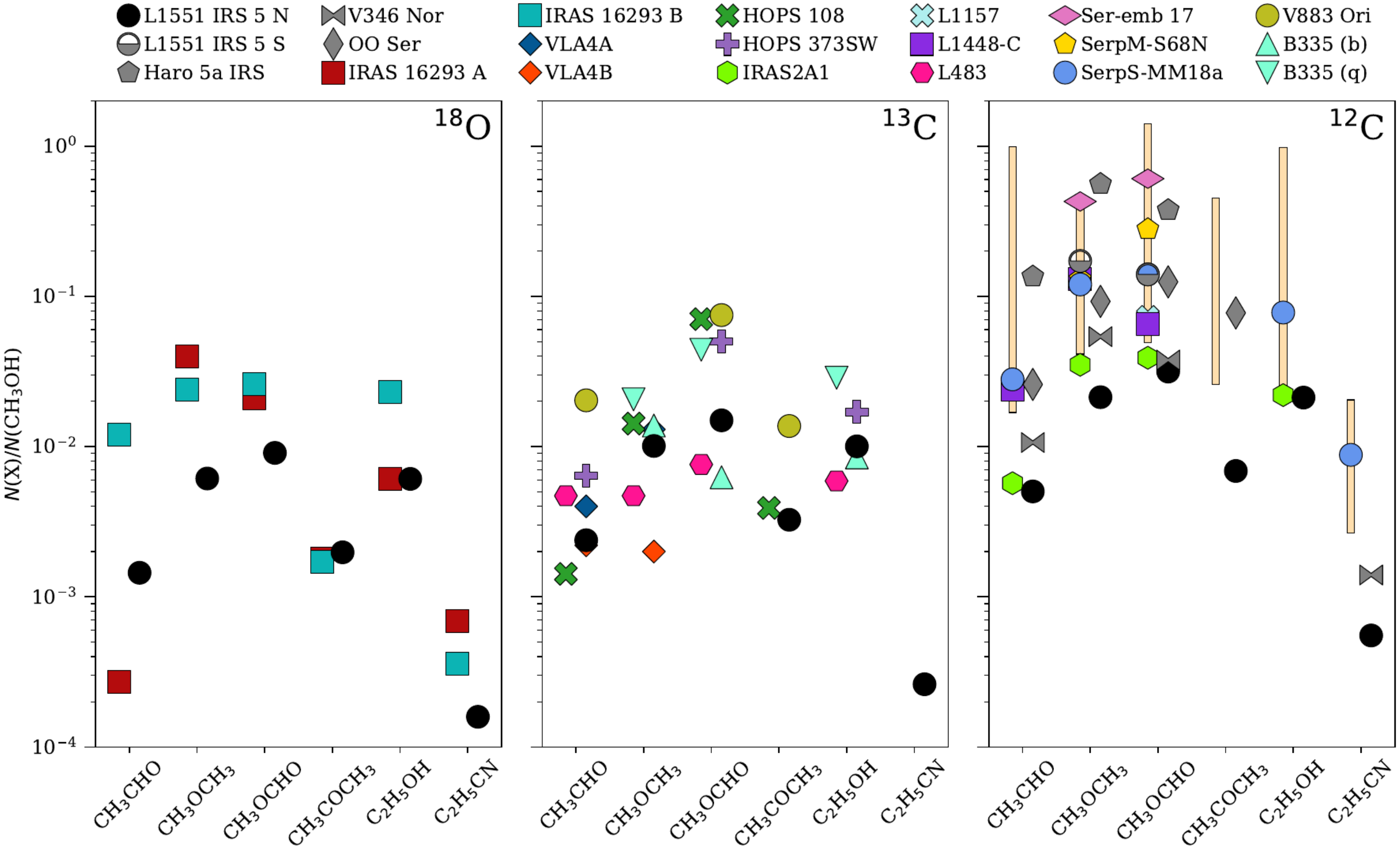
How do these FUors compare with other "quiescent" Class 0/I sources?

- Lines of CH_3OH are optically thick so $^{13}CH_3OH$ or $CH_3{}^{18}OH$ are better



How do these FUors compare with other "quiescent" Class 0/I sources?

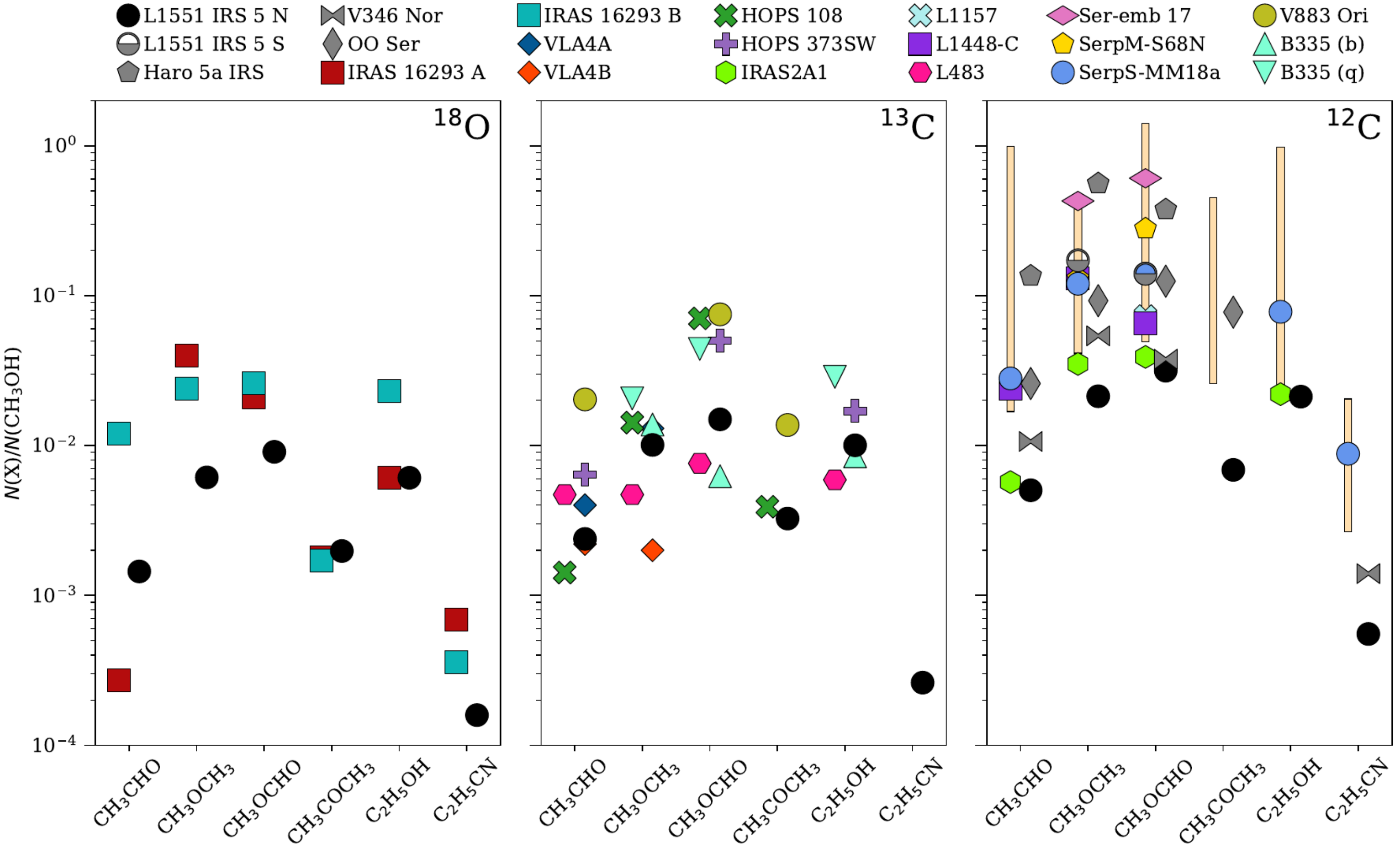
- Lines of CH_3OH are optically thick so $^{13}CH_3OH$ or $CH_3{}^{18}OH$ are better
- Other COMs might also be dominated by optically thick lines



How do these FUors compare with other "quiescent" Class 0/I sources?

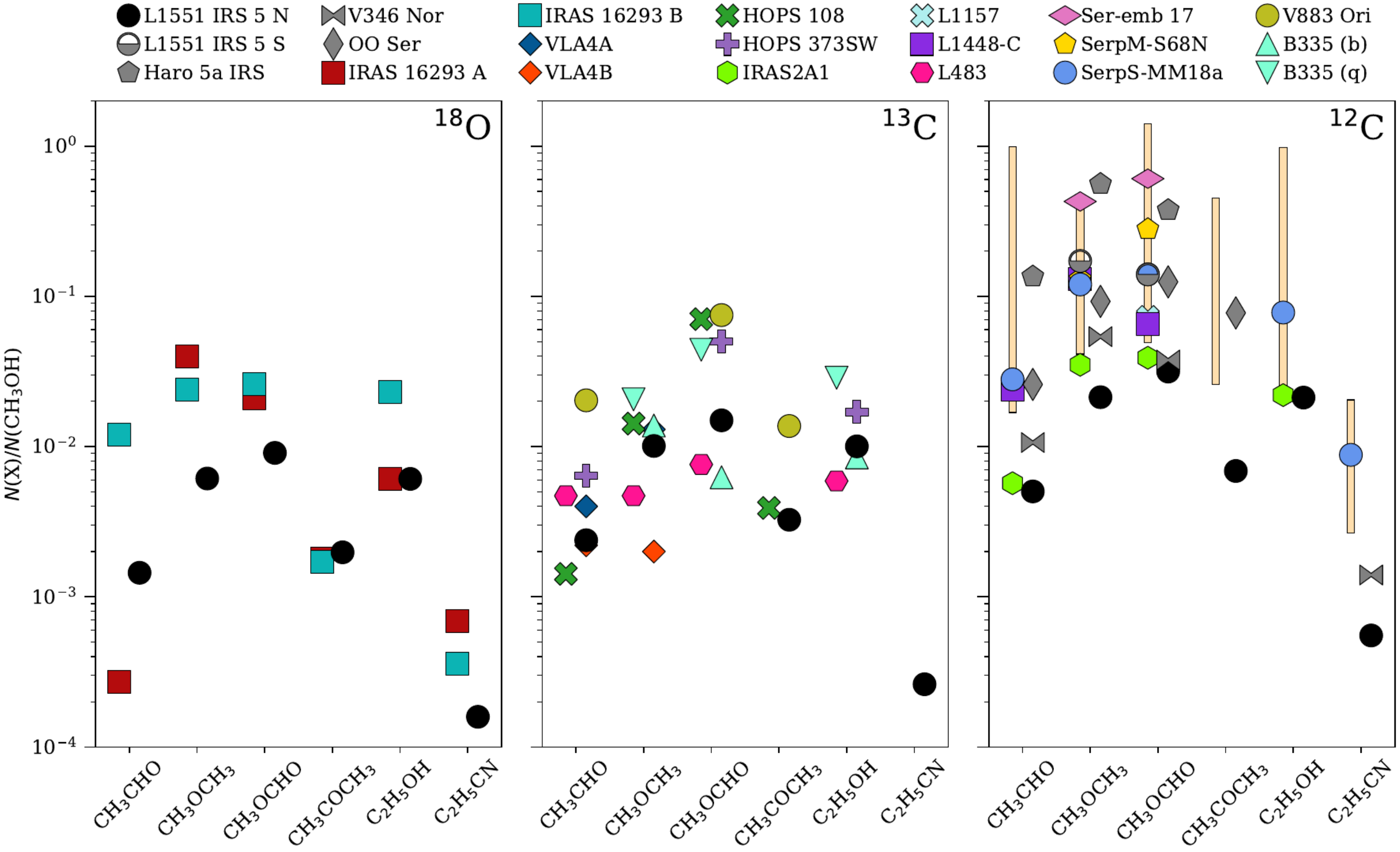
- Lines of CH_3OH are optically thick so $^{13}CH_3OH$ or $CH_3{}^{18}OH$ are better
- Other COMs might also be dominated by optically thick lines

- Different surroundings and age



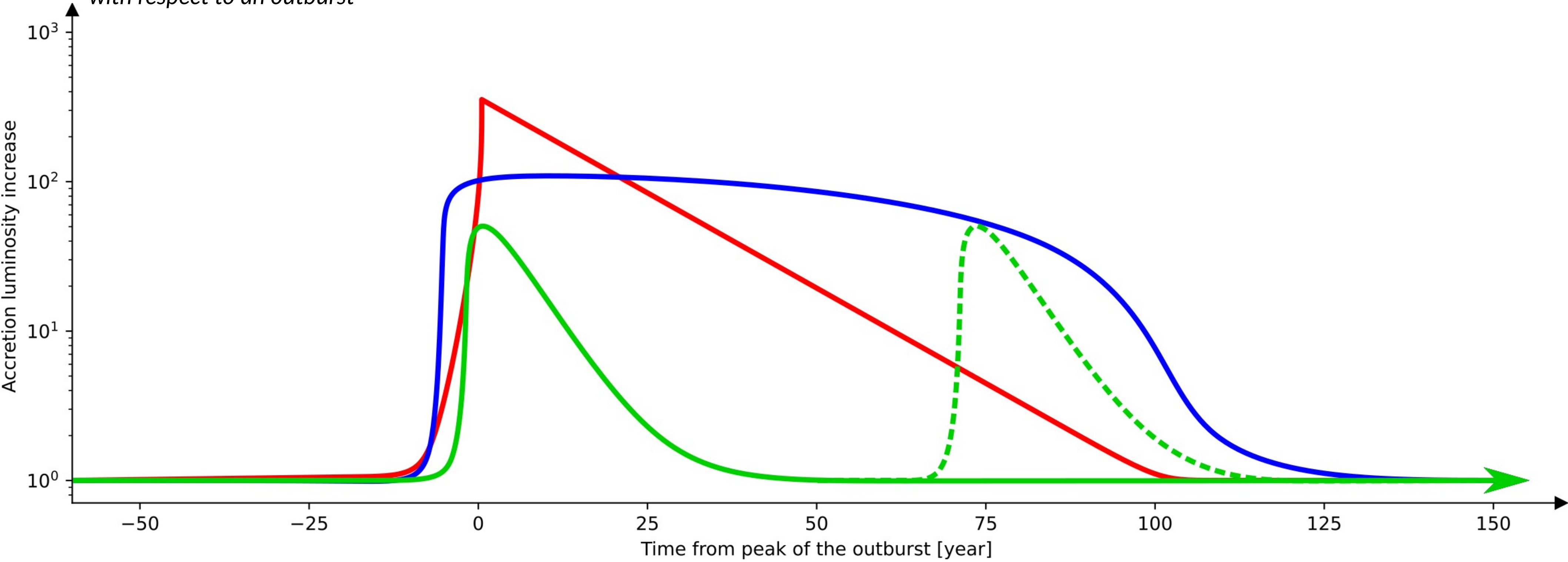
How do these FUors compare with other "quiescent" Class 0/I sources?

- Lines of CH_3OH are optically thick so $^{13}CH_3OH$ or $CH_3{}^{18}OH$ are better
- Other COMs might also be dominated by optically thick lines
- Different surroundings and age
- Unknown accretion histories



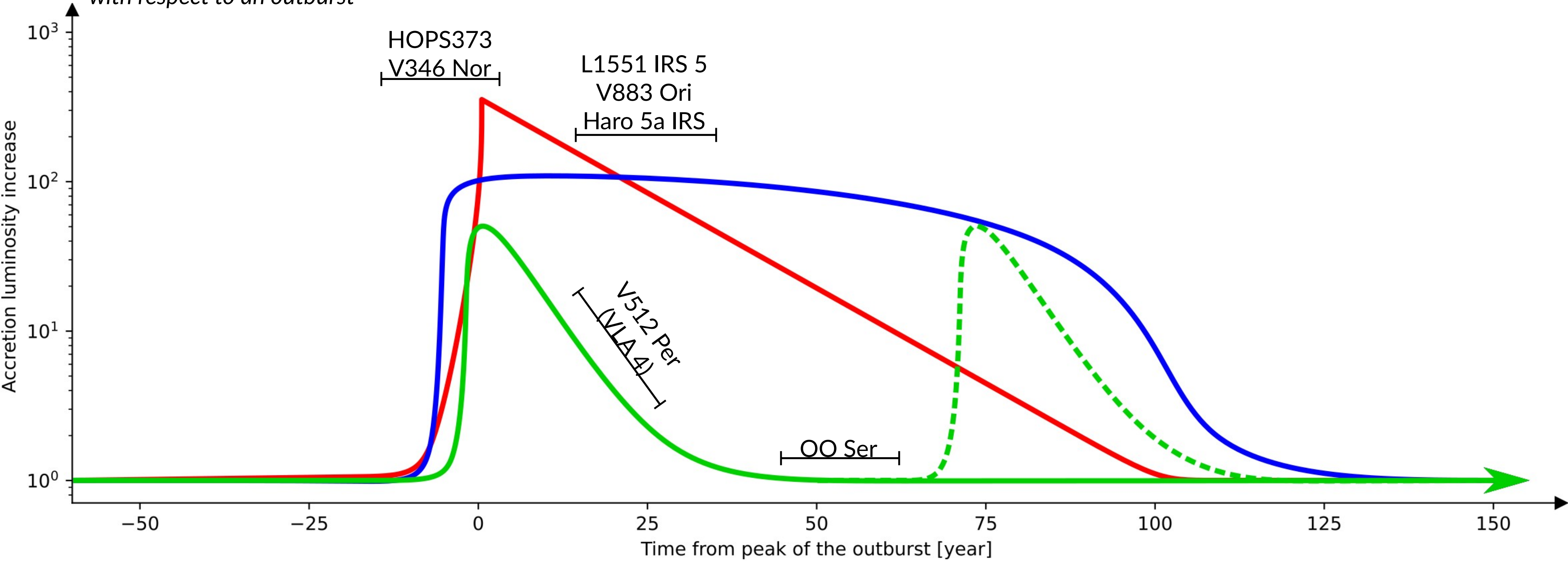
When you observe the FUor is key when wanting to put one chemical snapshot into context.

Each target is at a different point with respect to an outburst



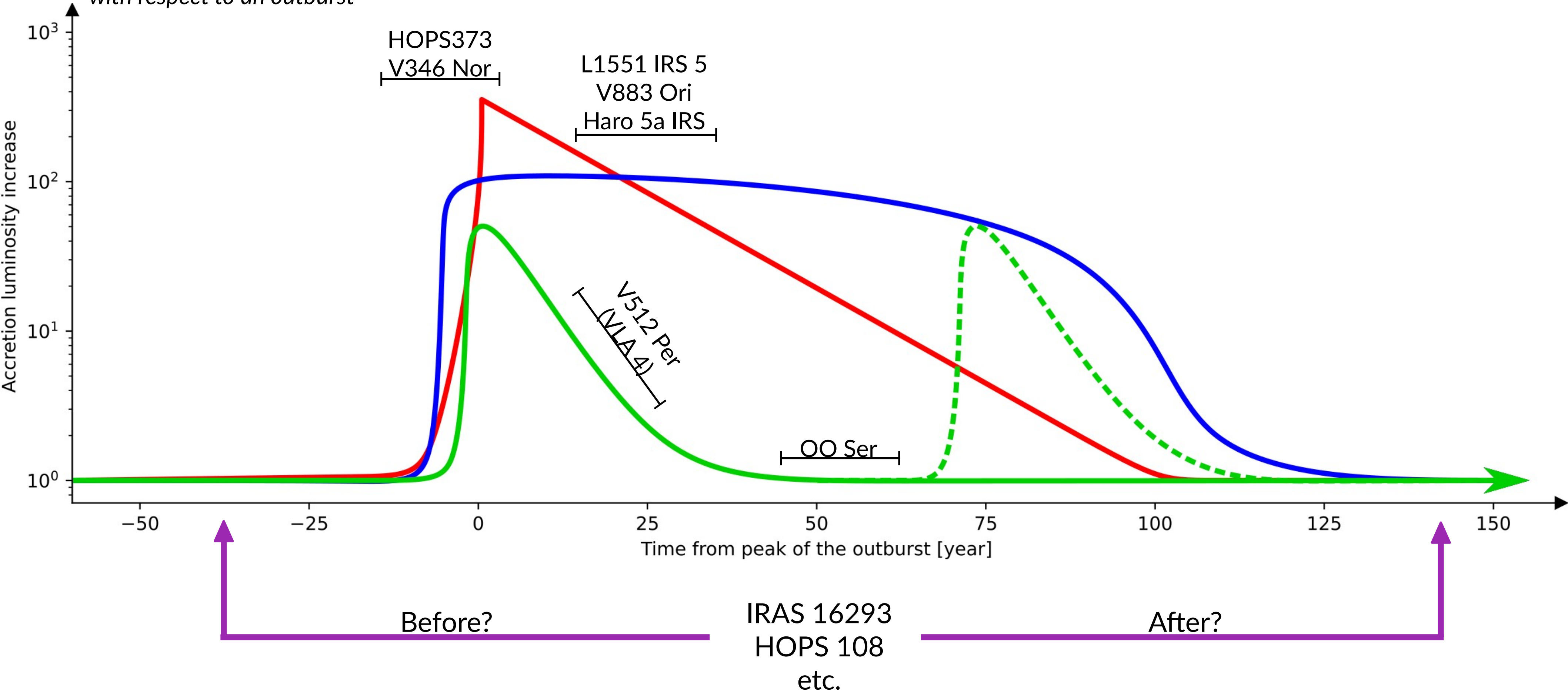
When you observe the FUor is key when wanting to put one chemical snapshot into context.

Each target is at a different point with respect to an outburst



When you observe the FUor is key when wanting to put one chemical snapshot into context.

Each target is at a different point with respect to an outburst

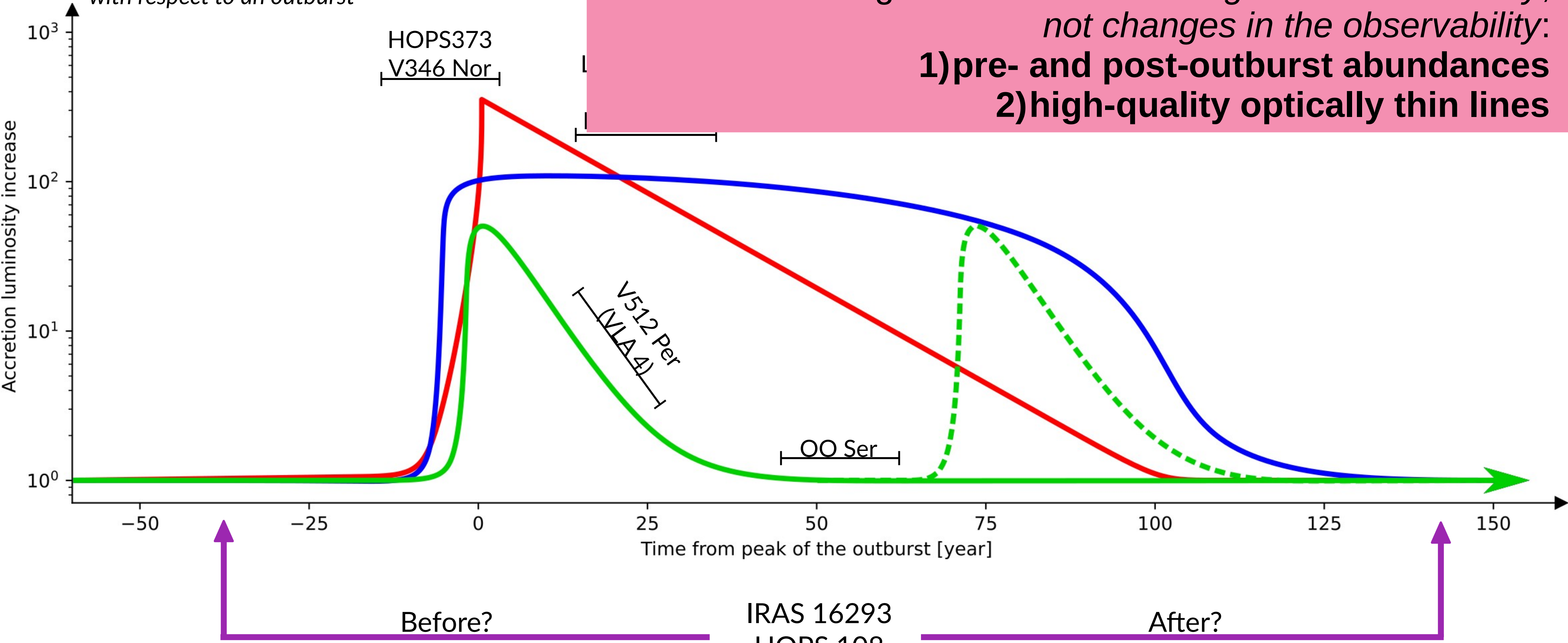


When you observe the FUor is key when wanting to put one chemical snapshot into context.

We need two things to find out the *changes in the chemistry*, *not changes in the observability*:

1) **pre- and post-outburst abundances**
2) **high-quality optically thin lines**

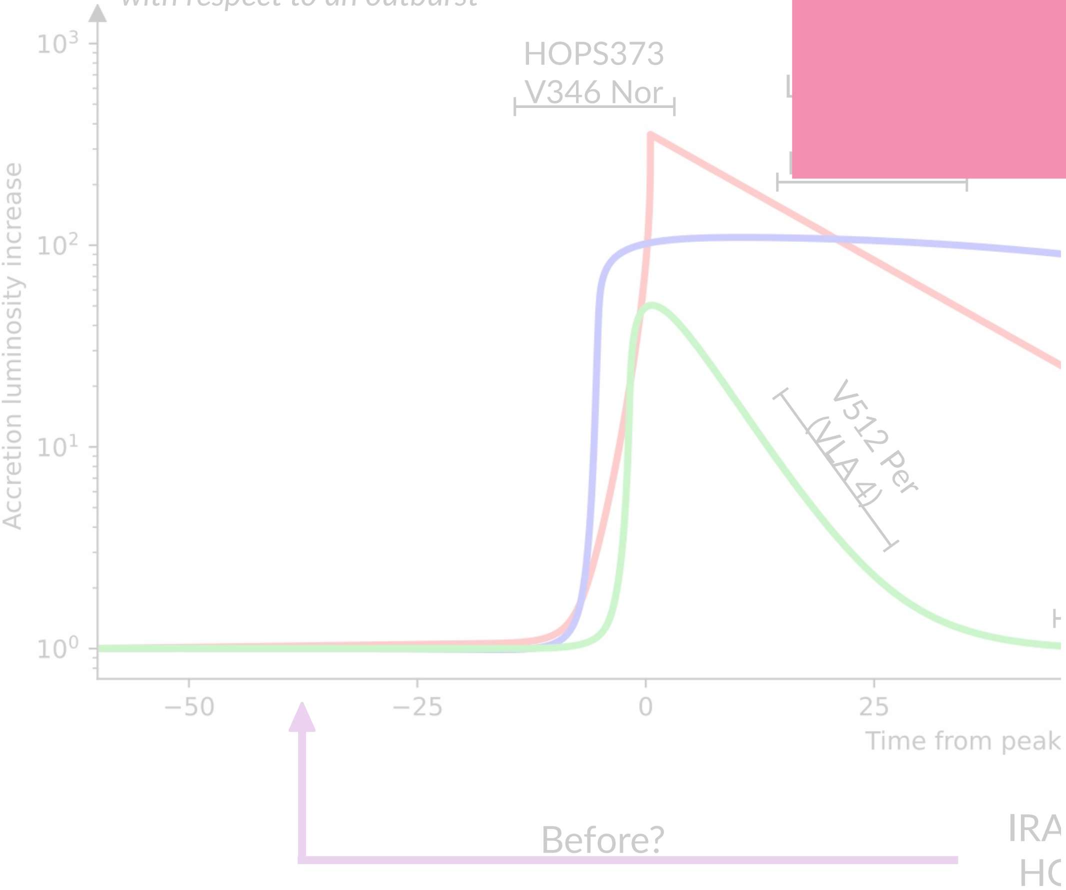
Each target is at a different point with respect to an outburst



IRAS 16293
HOPS 108
etc.

When you observe the FUor is key when wanting to put one chemical snapshot into context.

Each target is at a different point with respect to an outburst

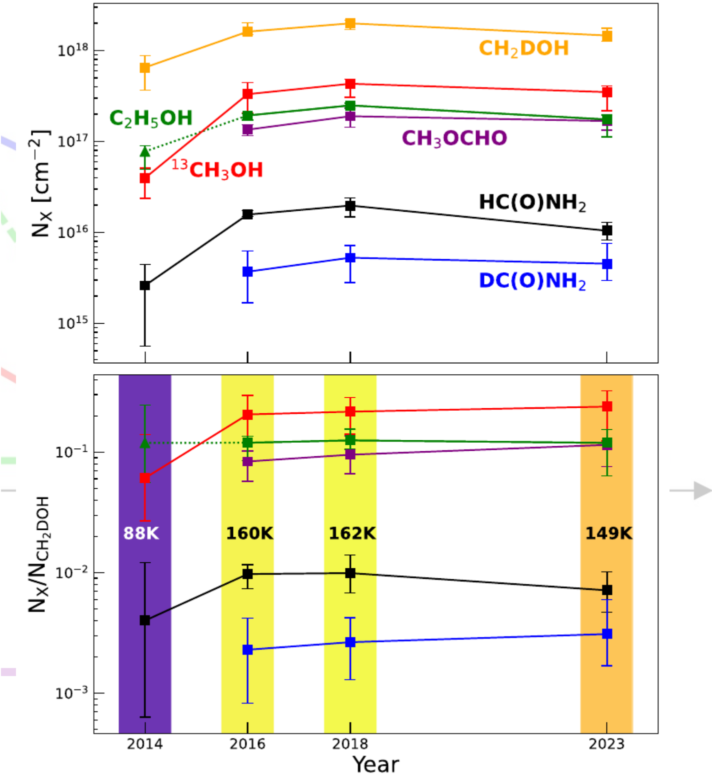


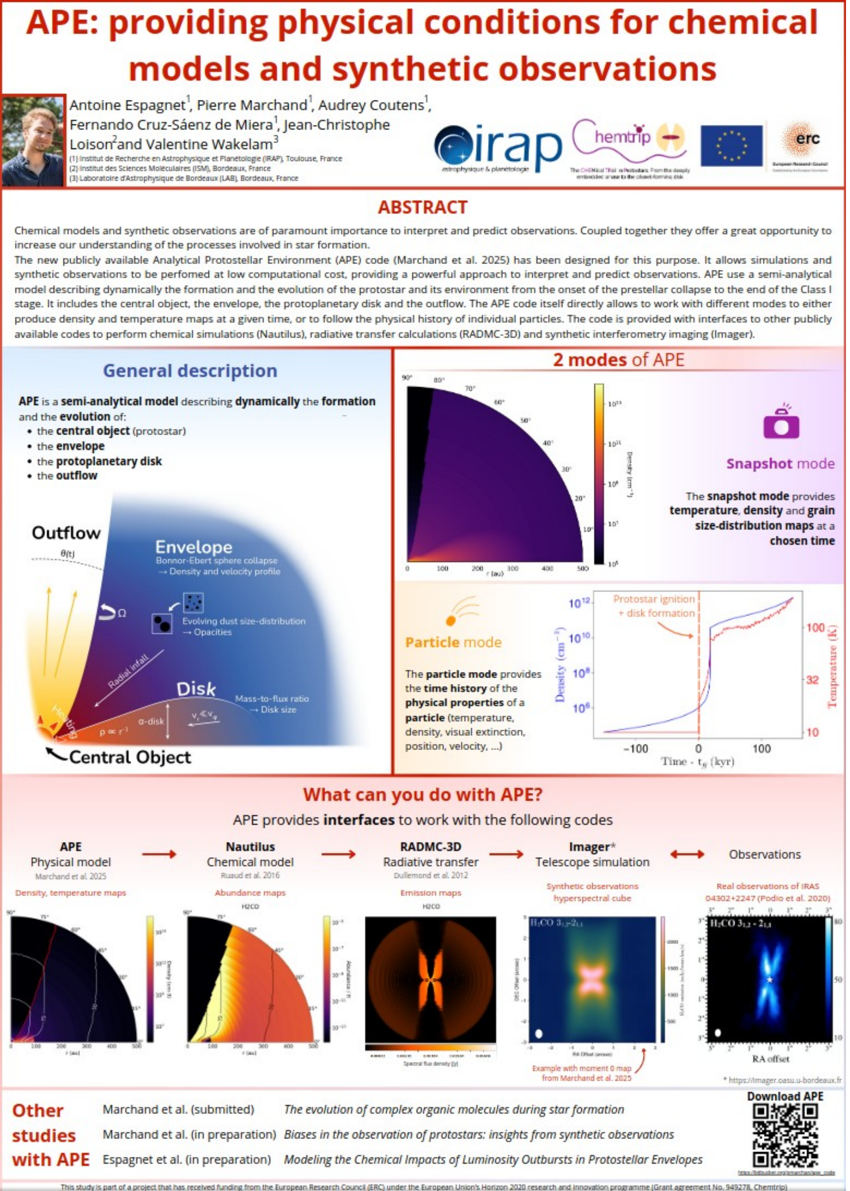
We need two things to find out the *changes in the chemistry*, *not changes in the observability*:

1) **pre- and post-outburst abundances**
2) **high-quality optically thin lines**

Like the case of B335.

Lee+2025 measured pre-, in-, and post-outburst abundances of a few COMs.

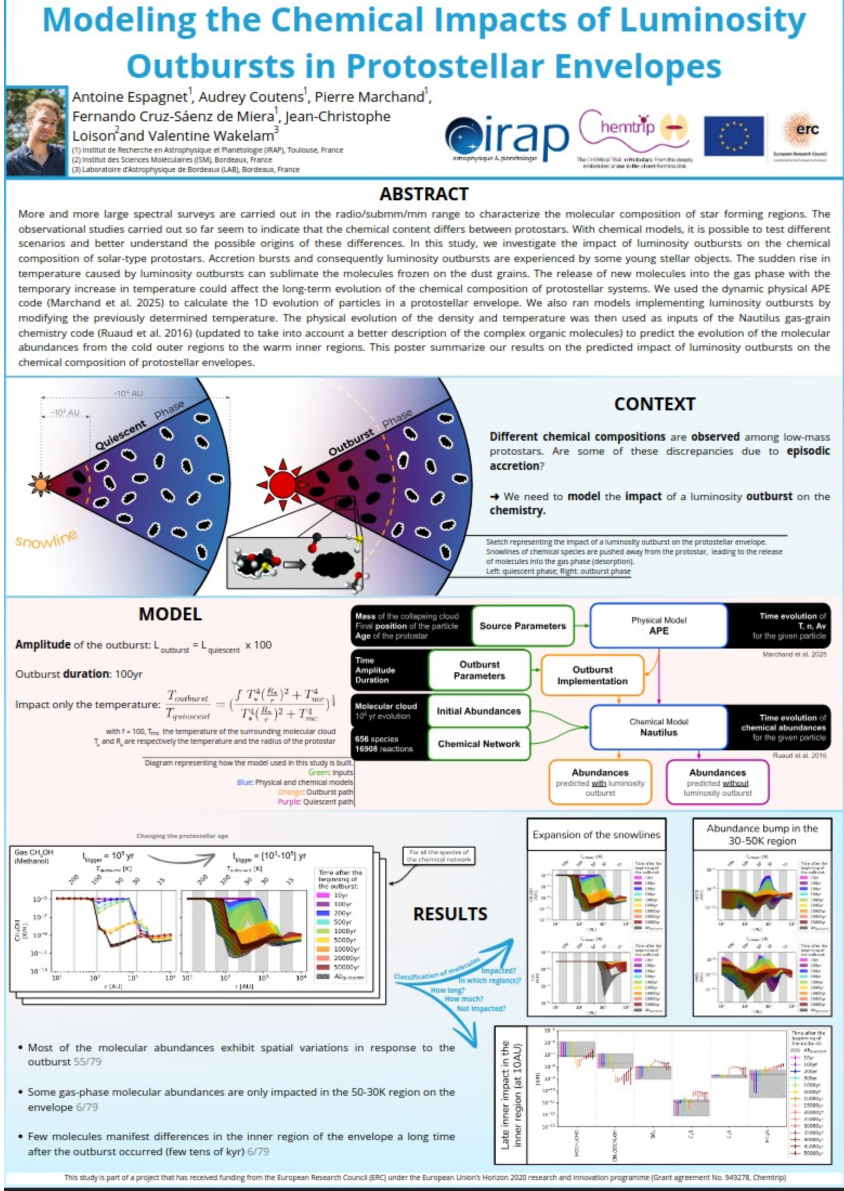




Alternatively, we can let the computers do the work.

(Marchand et al. 2025a, submitted, in prep)
(Espagnet et al., in prep)

(e.g., Taquet+2016, Rab+2017, Molyarova+2018, Zwicky+2024)



We need a systematic study of more protostars to put chemical evolution into context. Including different ages, histories and surroundings.

Complex Organic Molecules in Protostars from ALMA Spectral Surveys

ALMA Large Program

125 hours of telescope time (all obtained!)

We are observing 11 young protostars.

Different environments, different ages.

Some in outburst and some not.

PI/Co-PIs: Jes Jorgensen, Audrey Coutens, Maria Drozdovskaya, Jeong-Eun Lee, Adelete Plunkett

We need a systematic study of more protostars to put chemical evolution into context. Including different ages, histories and surroundings.

Complex Organic Molecules in Protostars from ALMA Spectral Surveys

ALMA Large Program

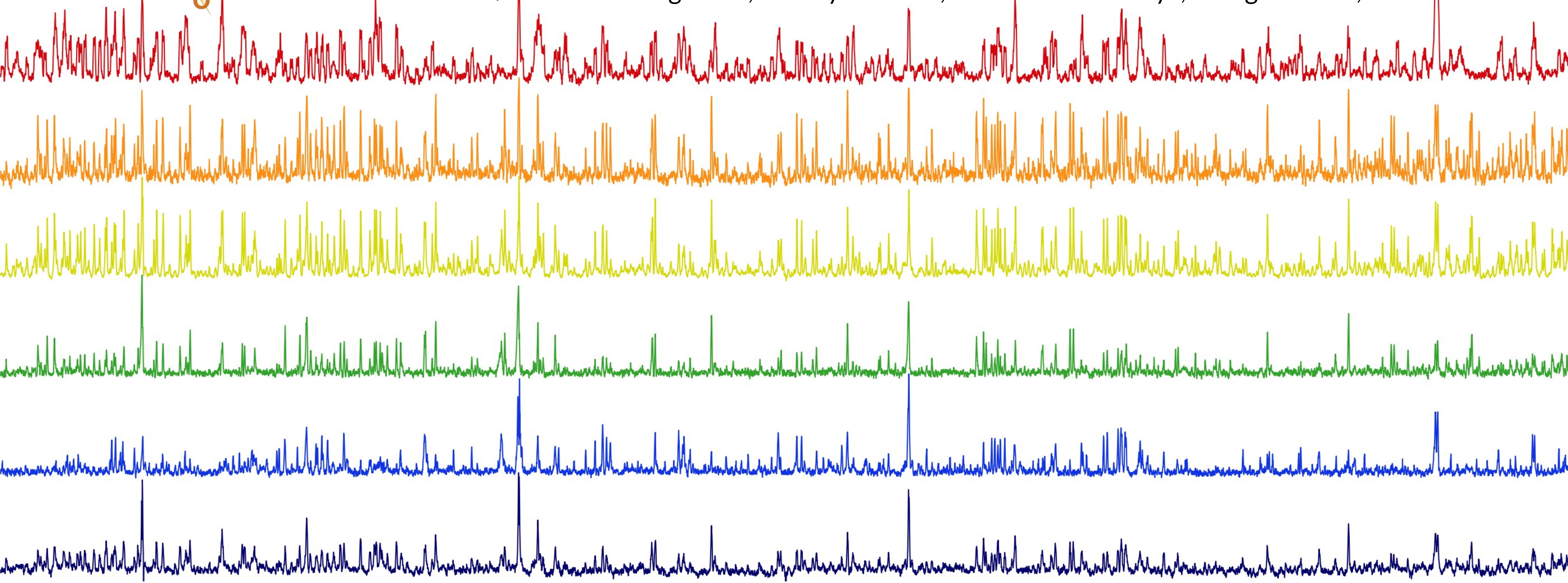
125 hours of telescope time (all obtained!)

We are observing 11 young protostars.

Different environments, different ages.

Some in outburst and some not.

PI/Co-PIs: Jes Jorgensen, Audrey Coutens, Maria Drozdovskaya, Jeong-Eun Lee, Adelete Plunkett



Takeaway messages

1) Accretion outbursts cause significant changes in their systems.

2) Accretion outbursts affect the morphology, temperatures and chemistry of the disks.

3) Complex organic molecules in FUors suggest these YSOs have hot corinos (hot, compact and chemically rich inner regions).

4) Little to no difference in column density ratios between hot corinos in quiescence and outburst. Unclear whether a change occurred.

5) Comparison limited due to lack of information about sources and of multi-epoch measurements.

6) More computational and observational work is needed.