Star Formation in Action

Tracing Kinematics and Complex Chemistry of Embedded Protostars with ALMA

Yao-Lun Yang (楊燿綸)

RIKEN (JSPS Postdoctoral Fellow)

➠ University of Virginia (VICO Origins Fellow)

APEC Seminar, Kavli IPMU

December 19, 2019

Collaborators

- Neal Evans
- Aaron Smith
- Jeong-Eun Lee
- Joel Green
- Jes Jørgensen
- John Tobin
- Susan Terebey
- Hannah Calcutt
- Tyler Bourke
- Nami Sakai
- Yichen Zhang
- Ziwei Zhang
- PEACHES Team

10 arcmin

BHR 71 (credit: The DECam Plane Survey)

Star Formation in Action

at z=4.5×10^{-8}

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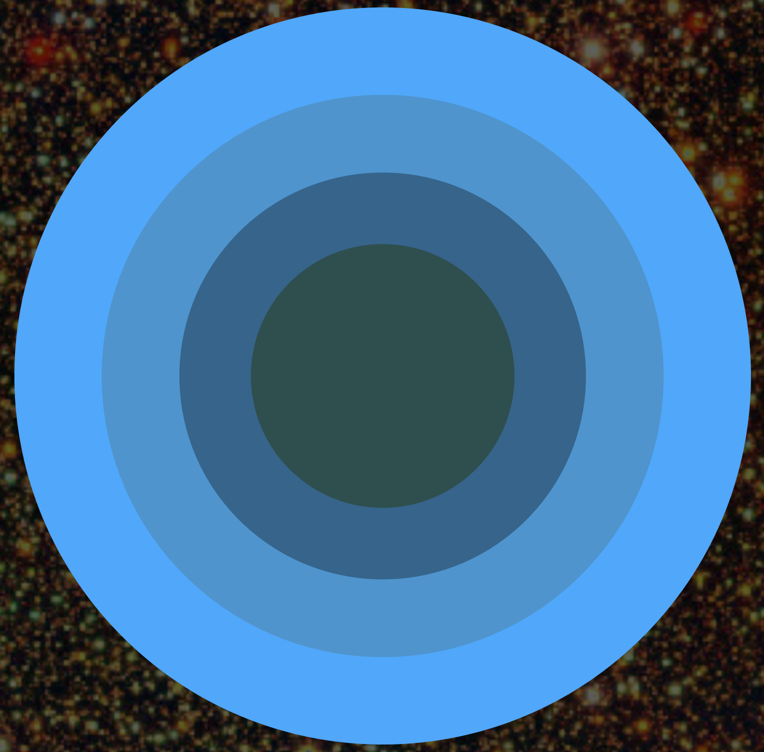
How do protostars form and grow?



Dense cores

- Gravitational collapse
- Turbulence
- Magnetic fields
- Heating and cooling
- (fragmentation)

10 arcmin

RIKEN | Yao-Lun Yang

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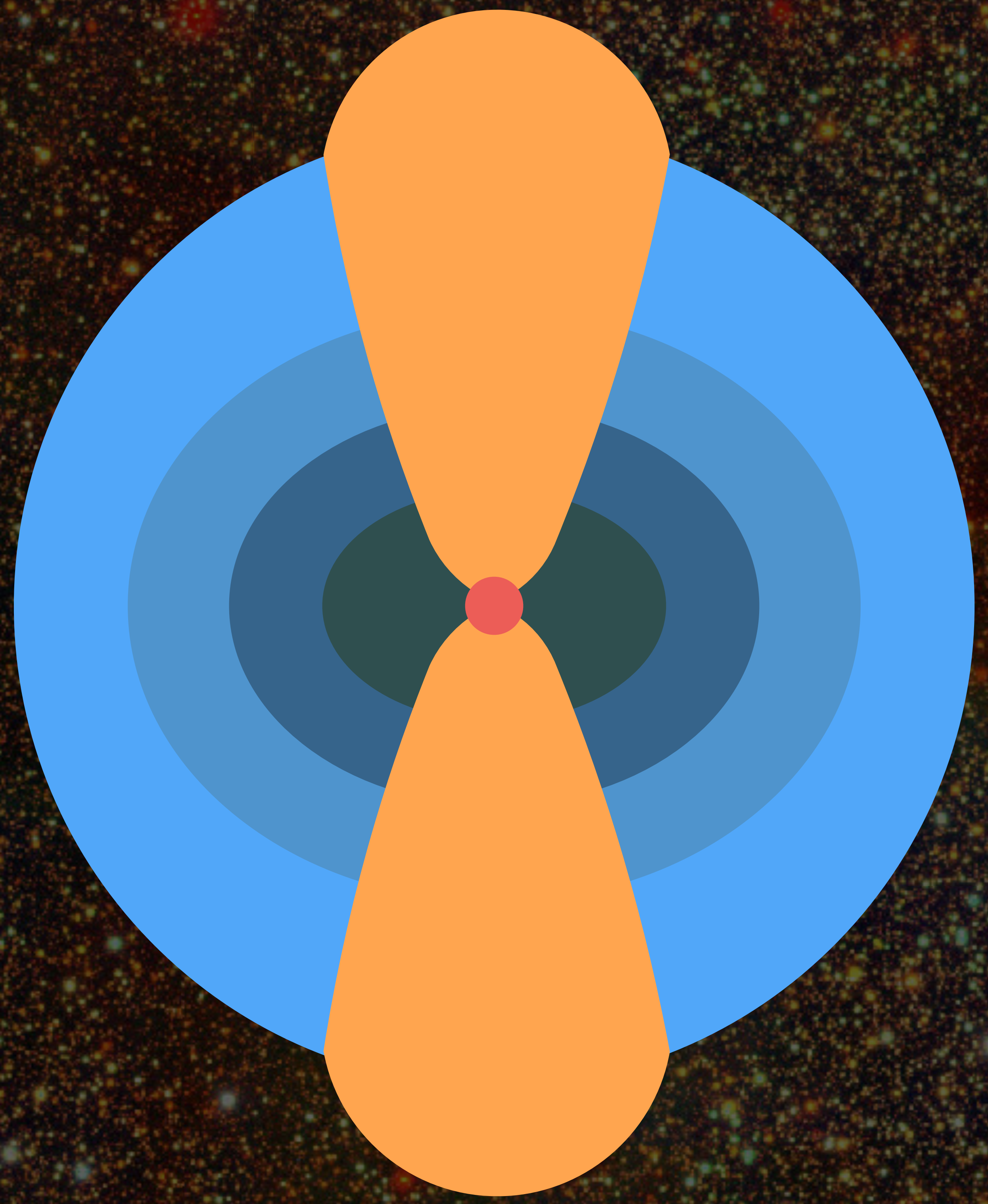

Collapsing protostellar envelopes

- Gravitational collapse
- Rotation
- Outflows
- Disks
- Chemistry

10 arcmin

BHR 71 (credit: The DECam Plane Survey)

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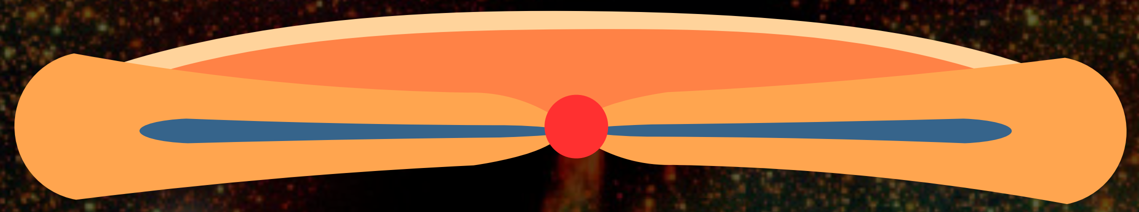

- Gravitational collapse
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↓

Protostar + disk

10 arcmin

RIKEN | Yao-Lun Yang

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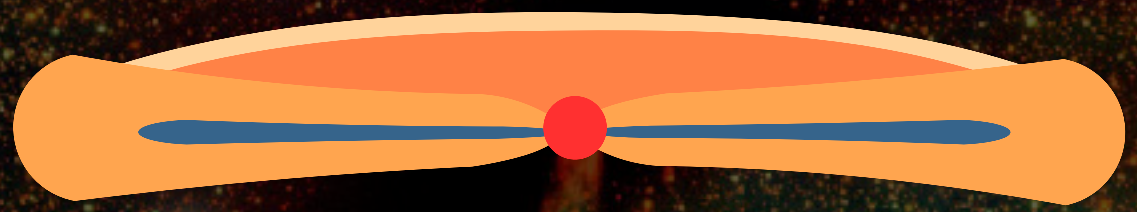

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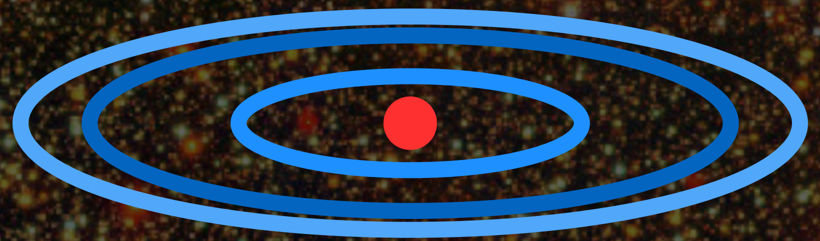

Planetary systems

10 arcmin

RIKEN | Yao-Lun Yang

BHR 71 (credit: The DECam Plane Survey)

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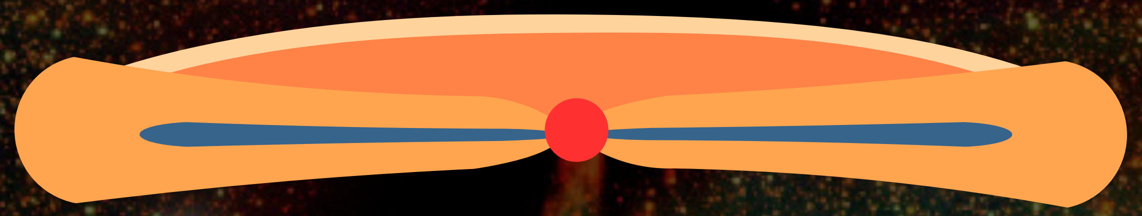

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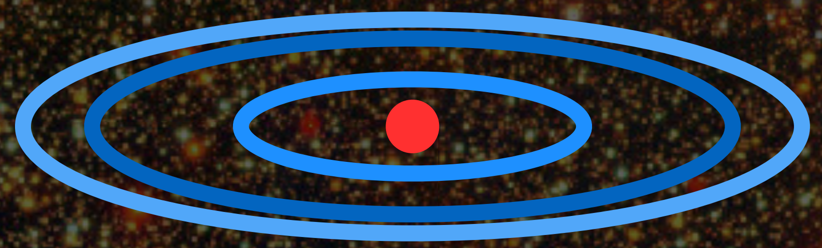
Protostar + disk



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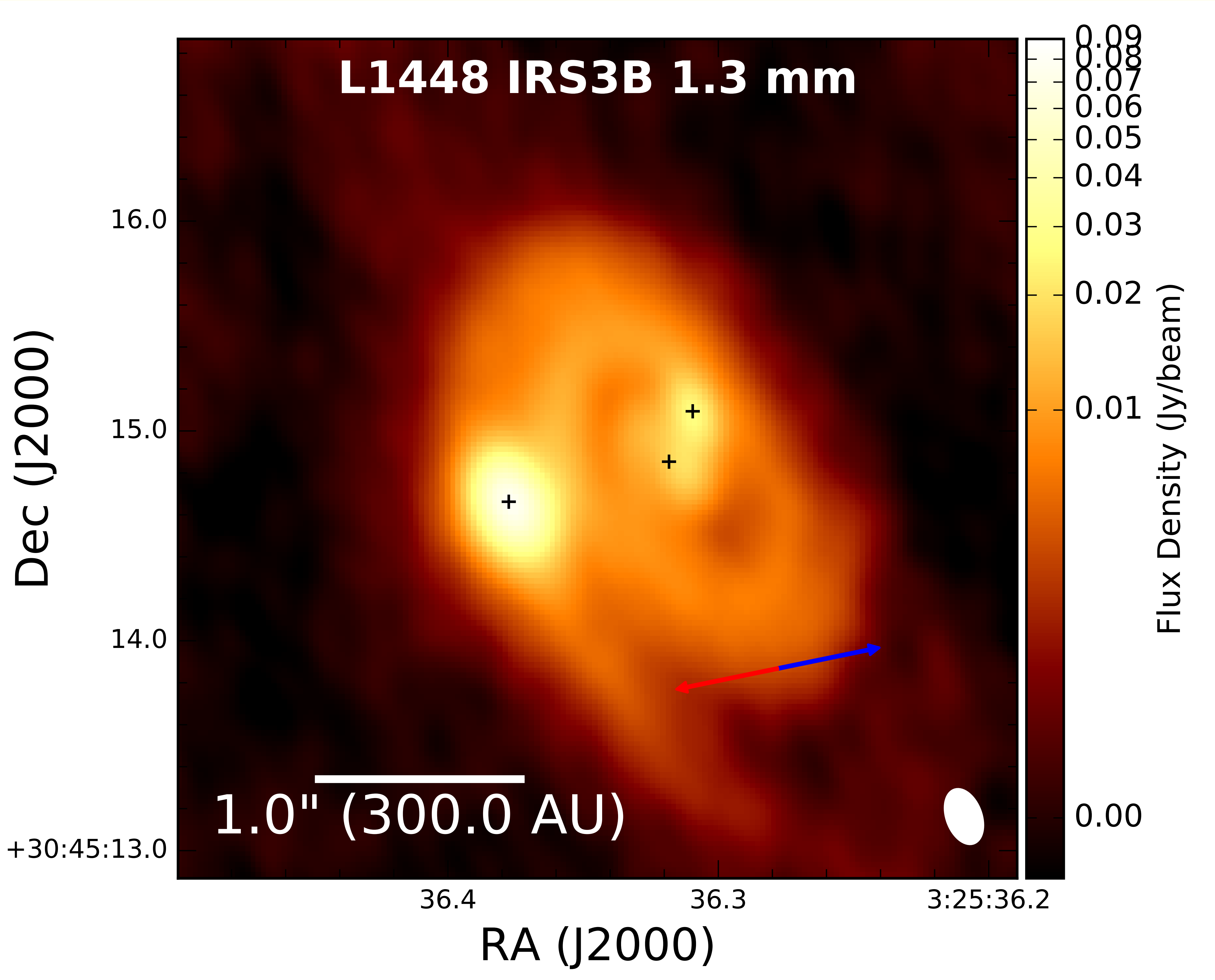
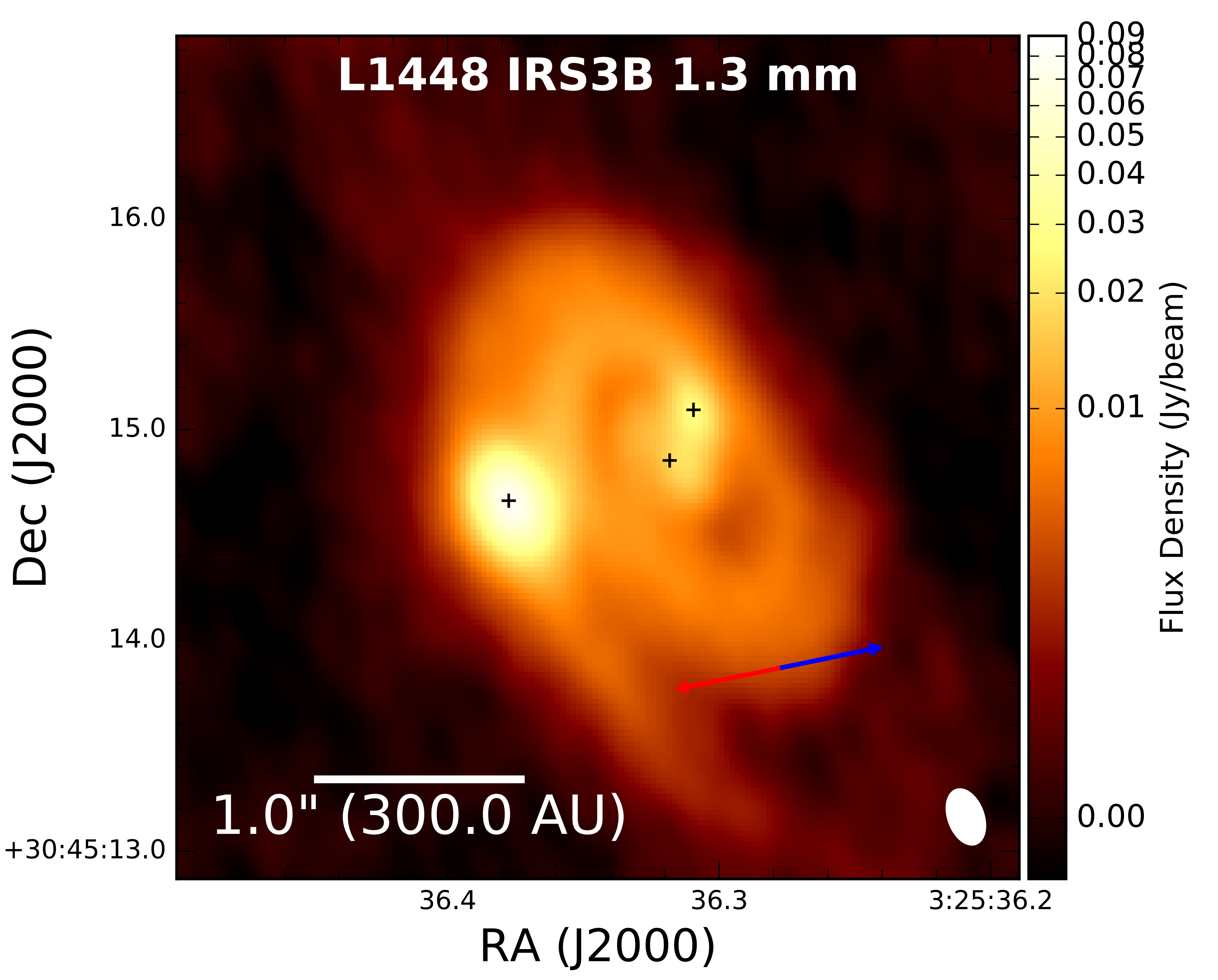
The origins of close binary systems

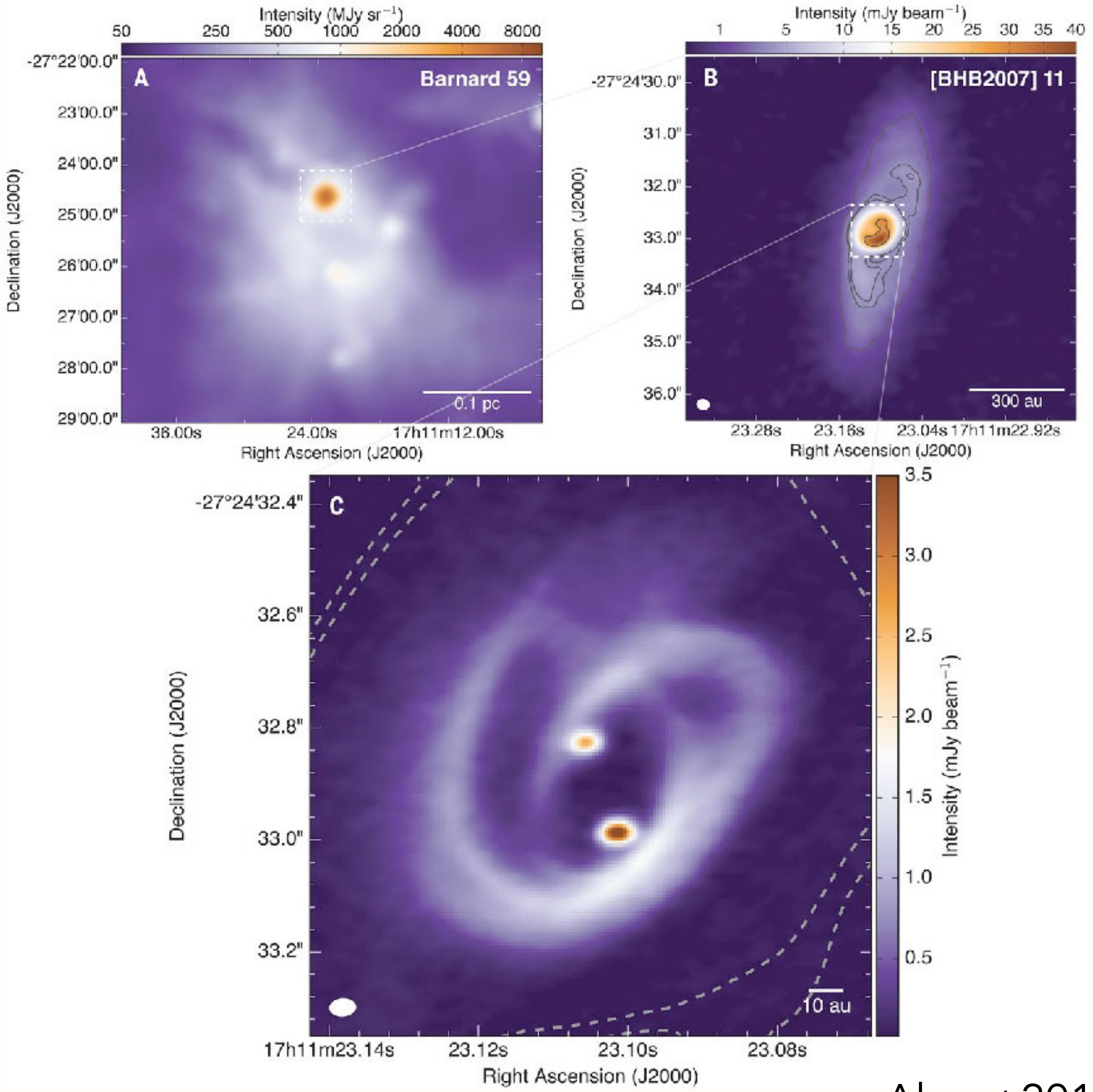


Tobin+2018

The origins of close binary systems

BHB 07-11





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Alves+2019

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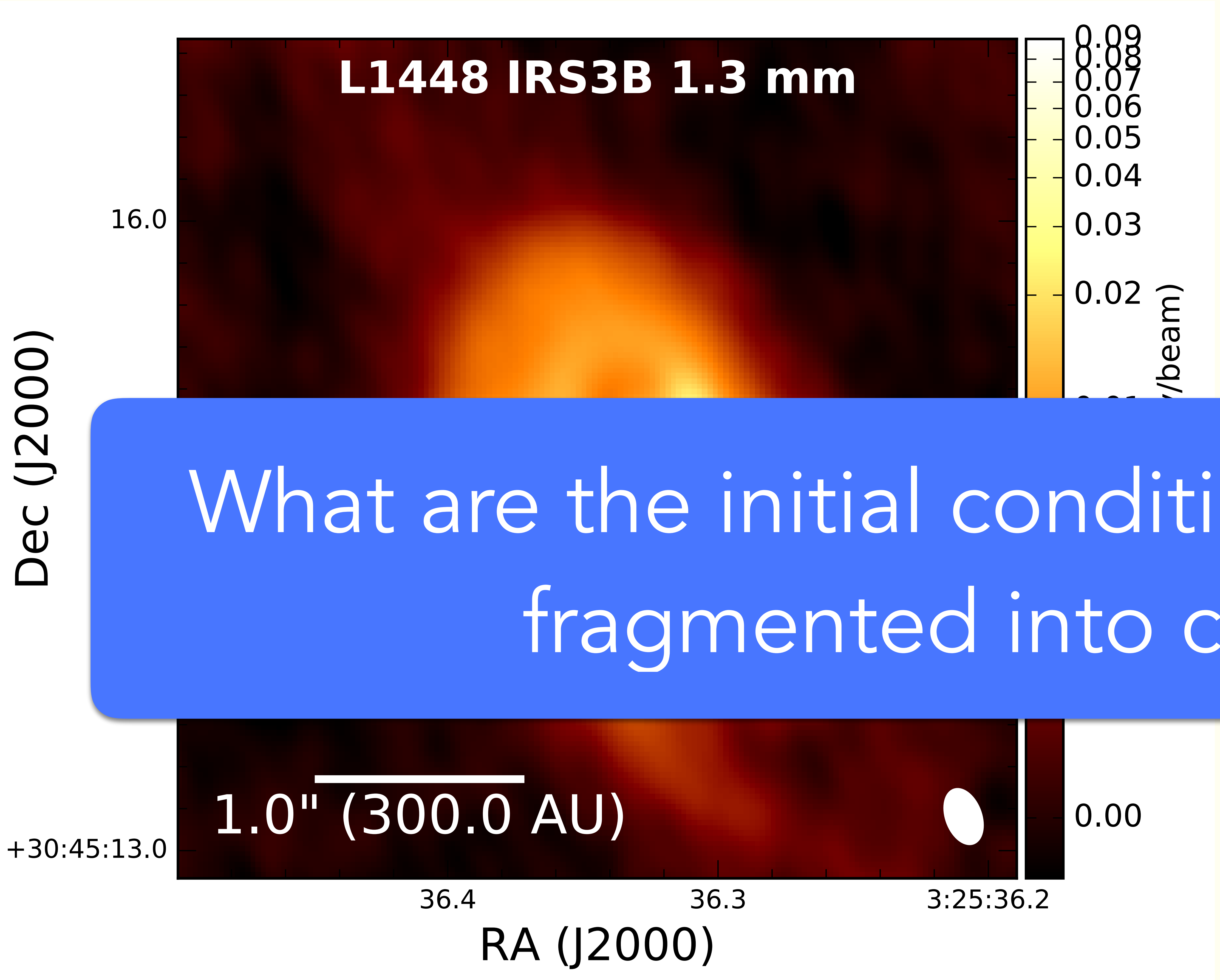

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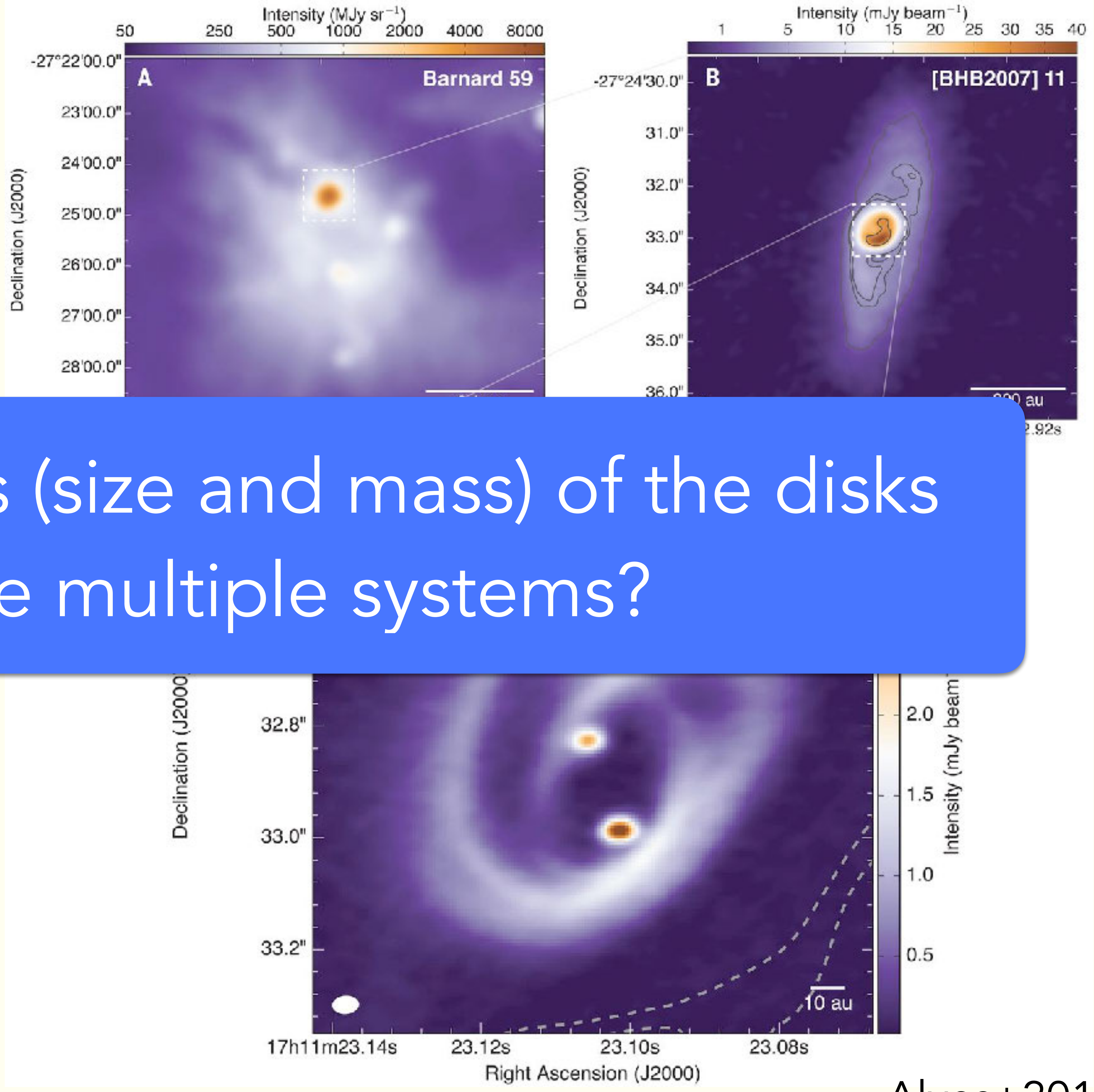
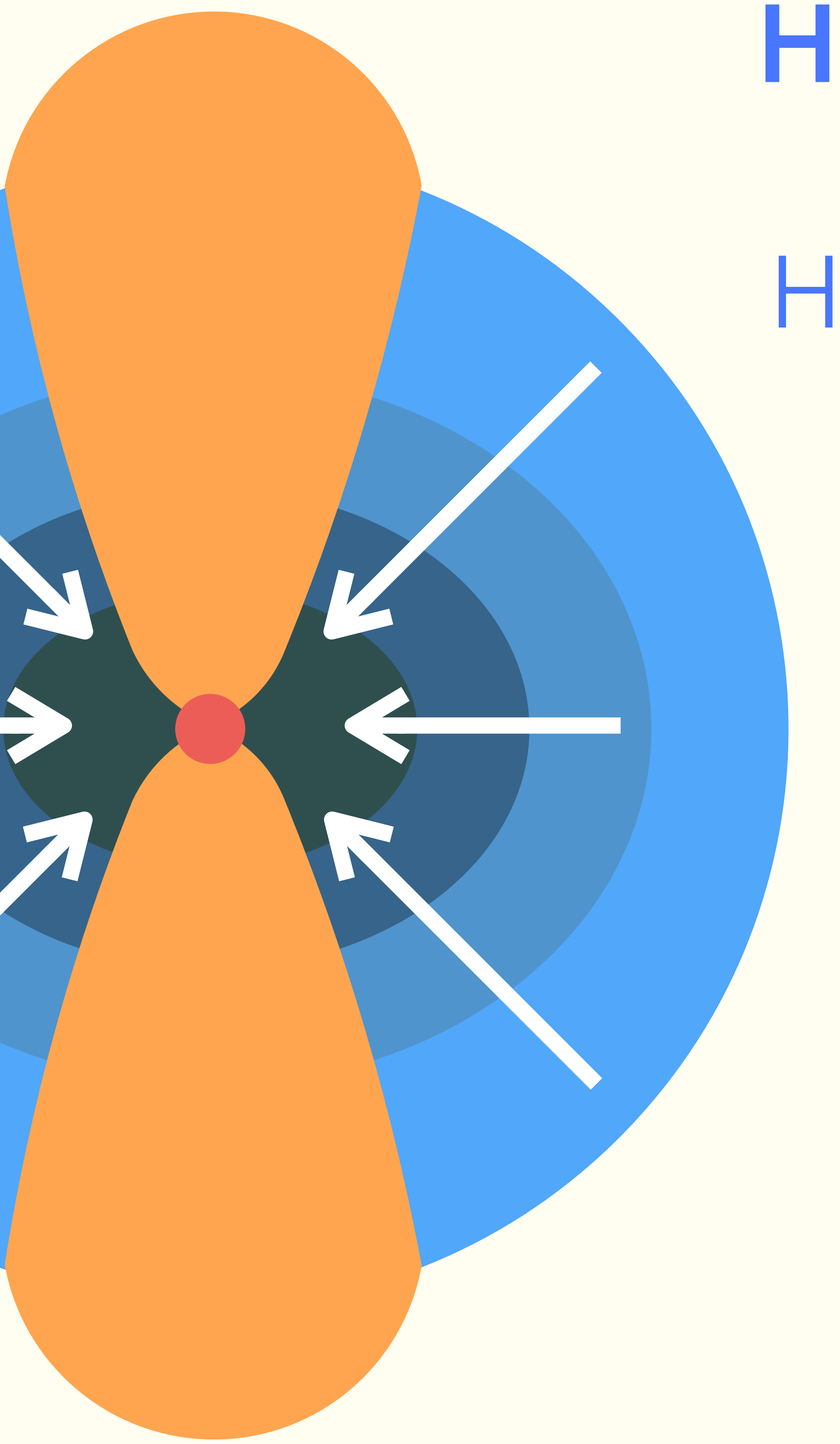


Alves+2019

What are the initial conditions (size and mass) of the disks fragmented into close multiple systems?



How do protostars grow?

How does infall occur and evolve at the youngest protostars?

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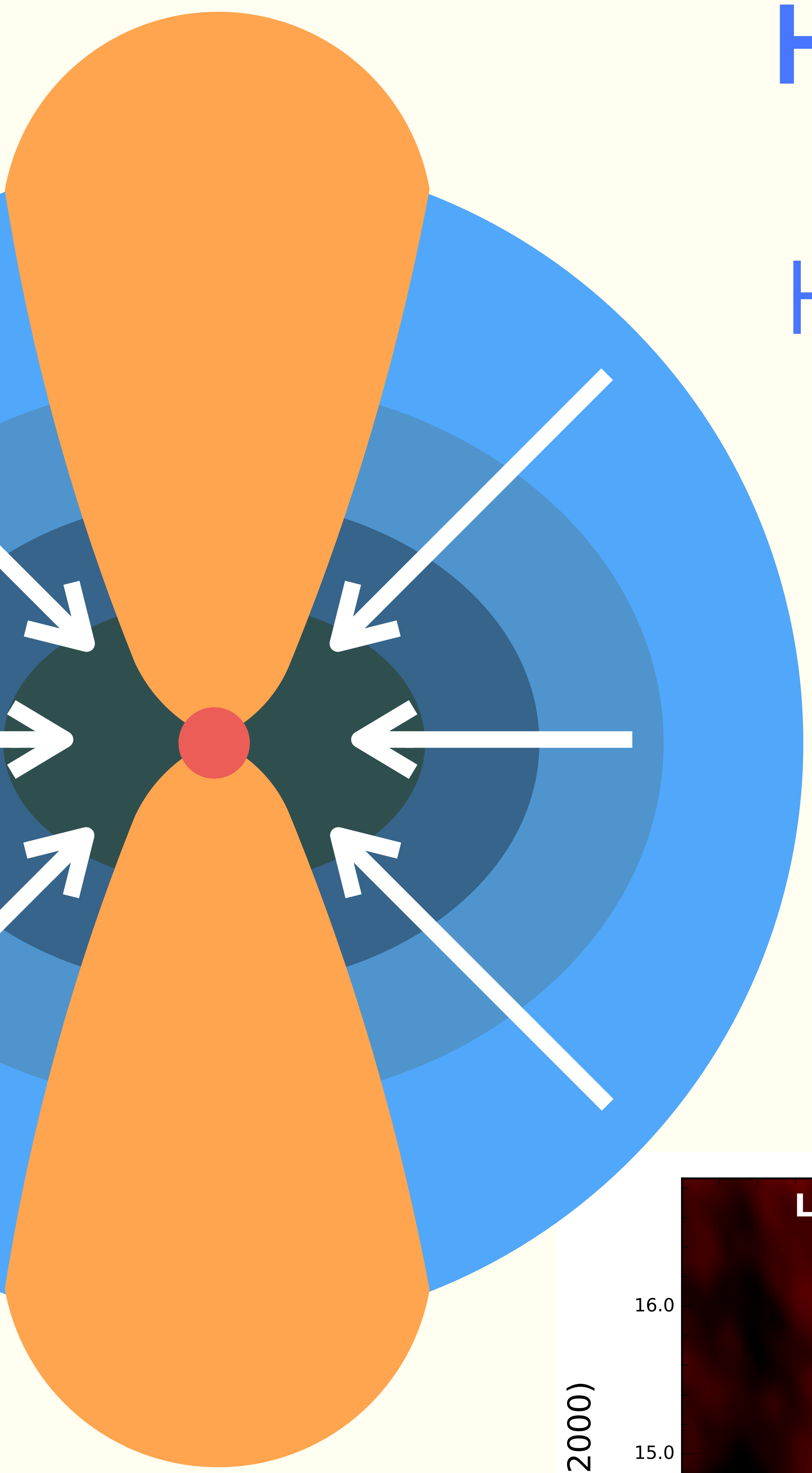

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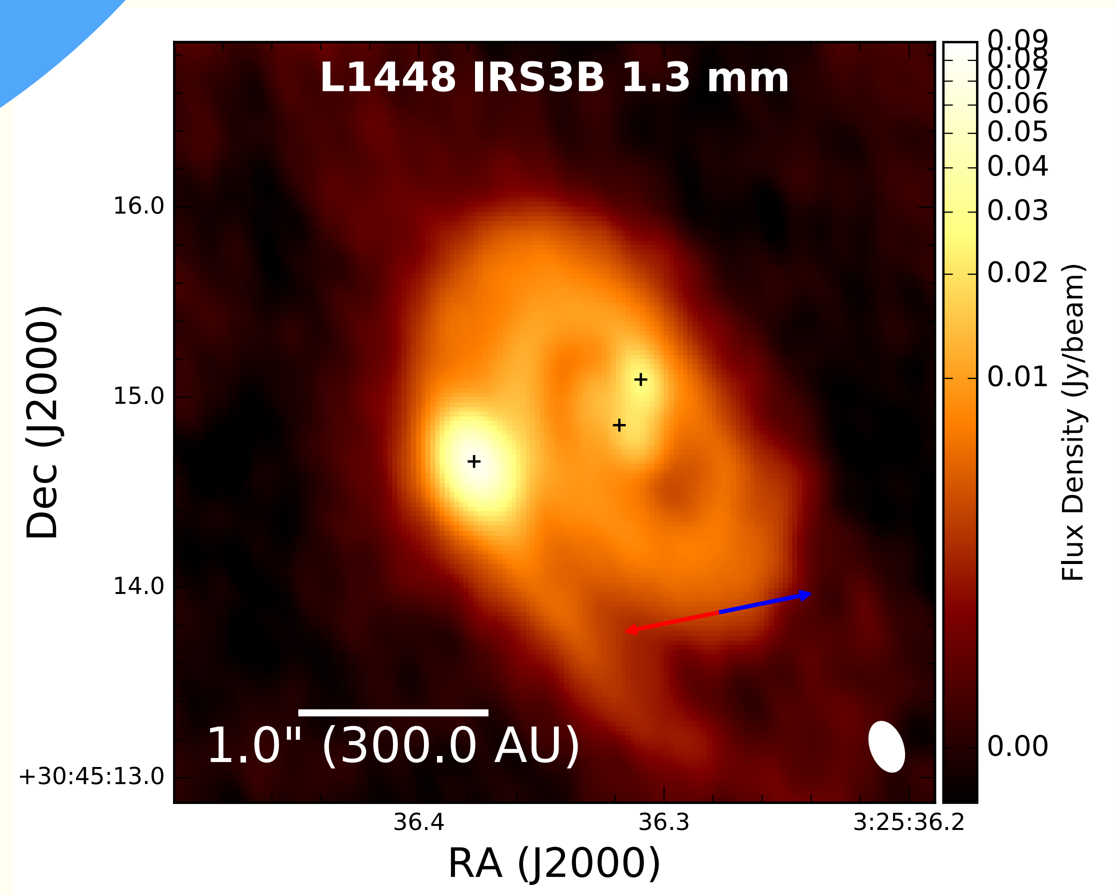
- Transport mass onto disks and protostars



Tobin+2018b

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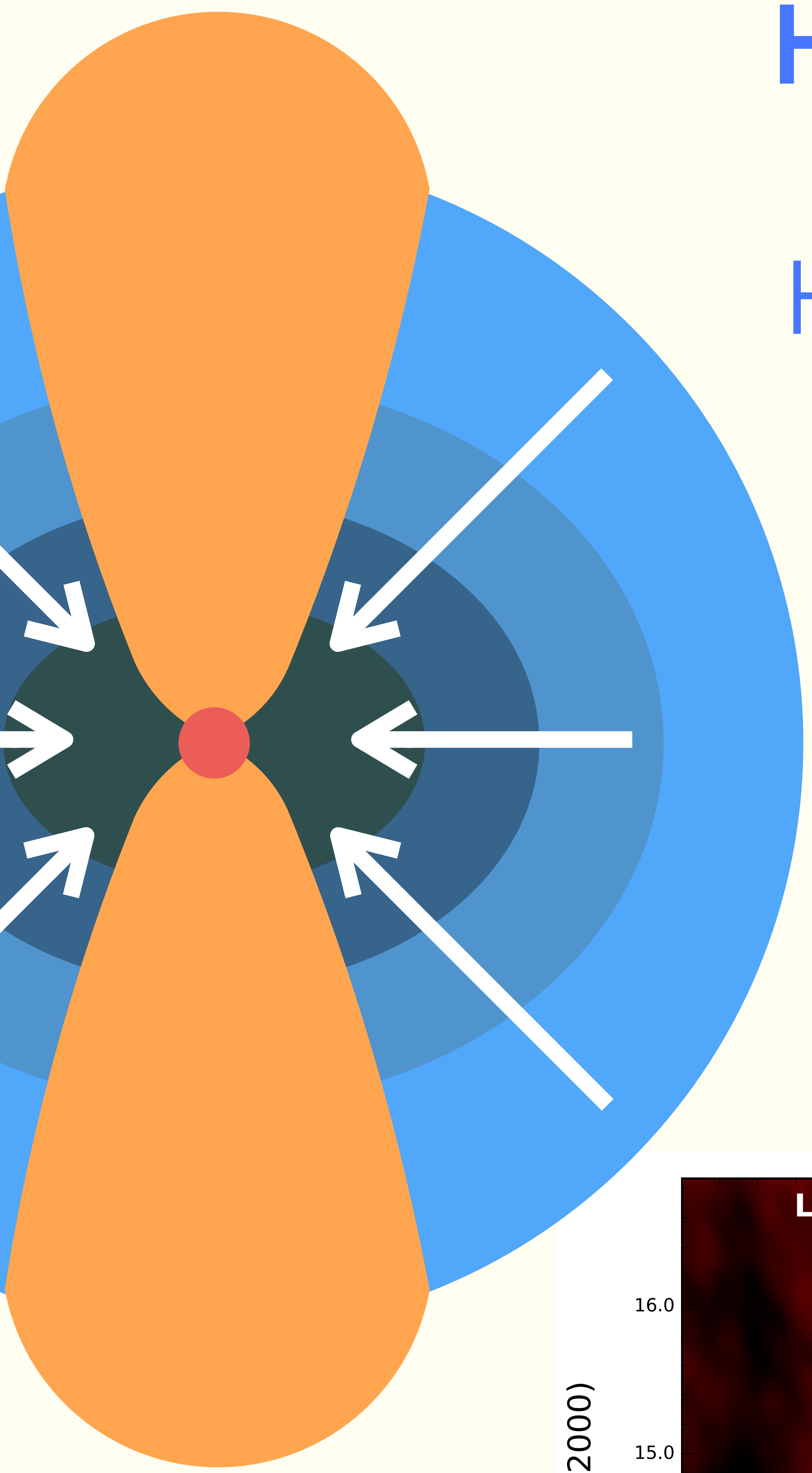
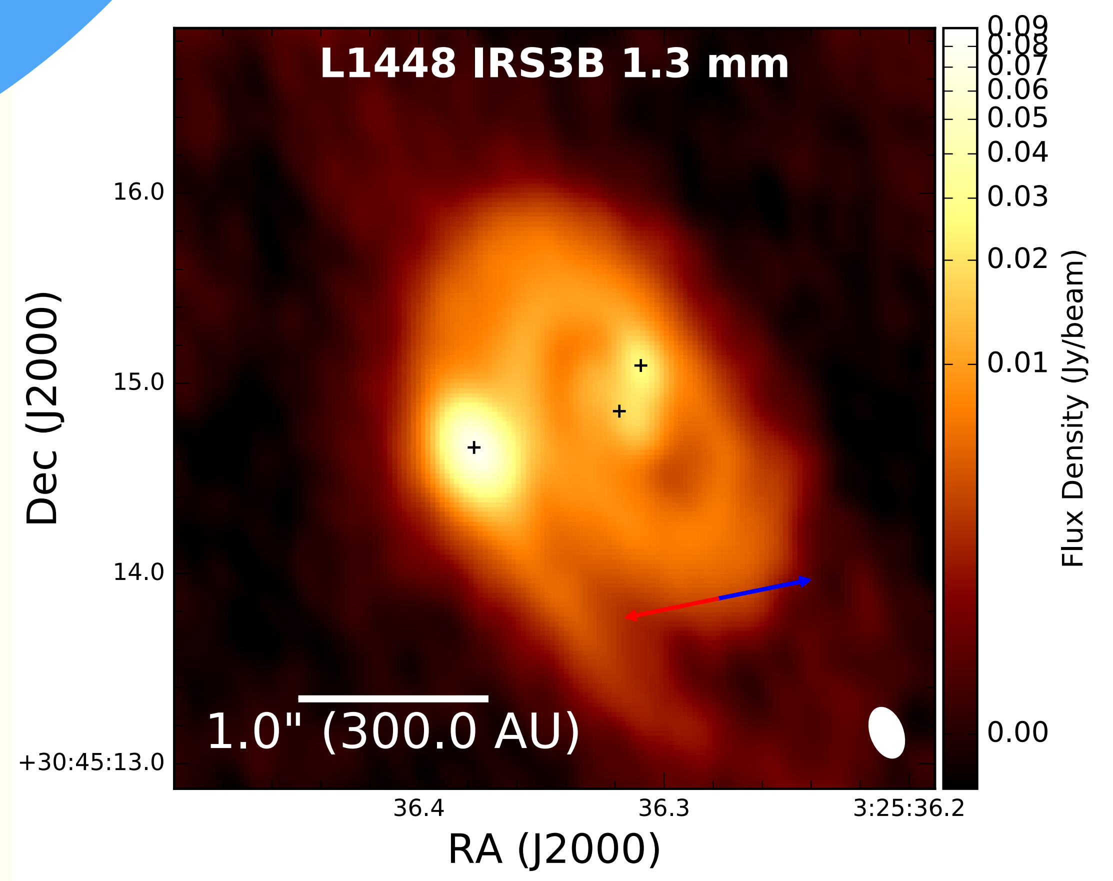


How does infall occur and evolve at the youngest protostars?

- Transport mass onto disks and protostars
- Regulate the thermal history of gas, thus the chemistry of protostellar system (envelopes & disks)



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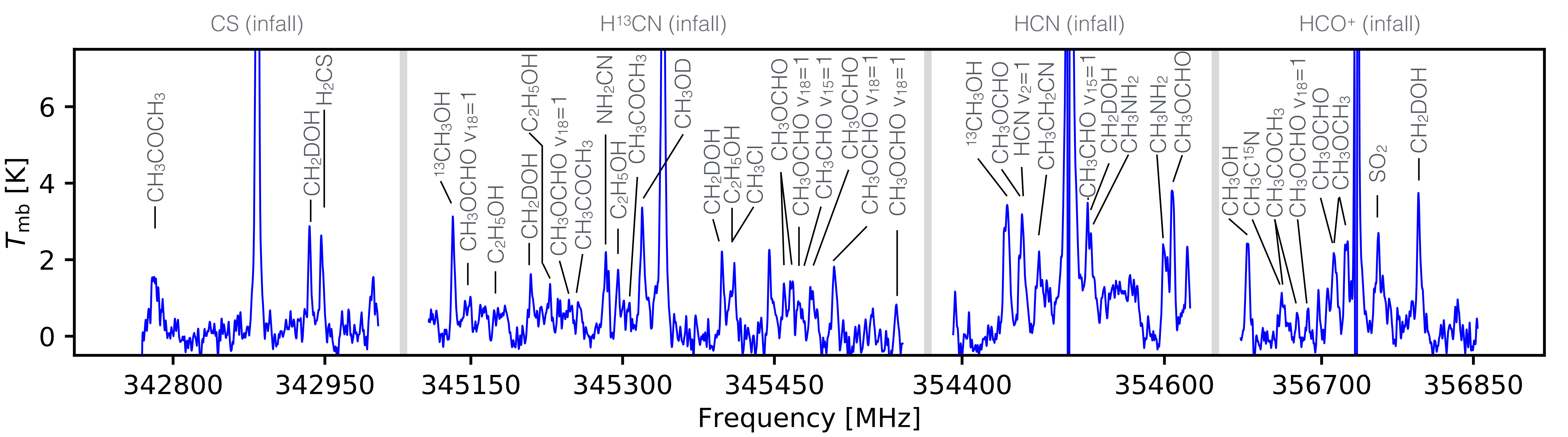
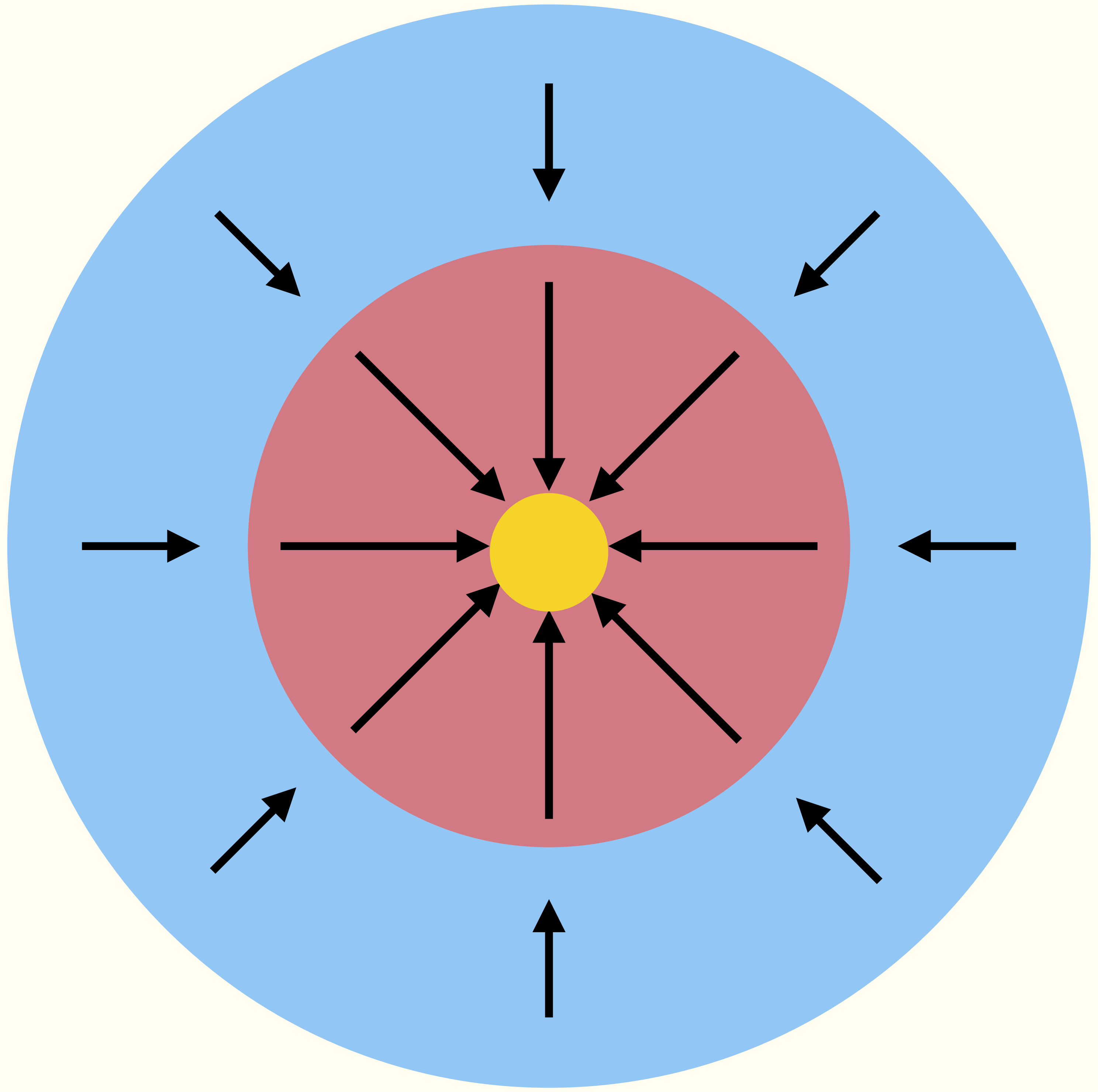
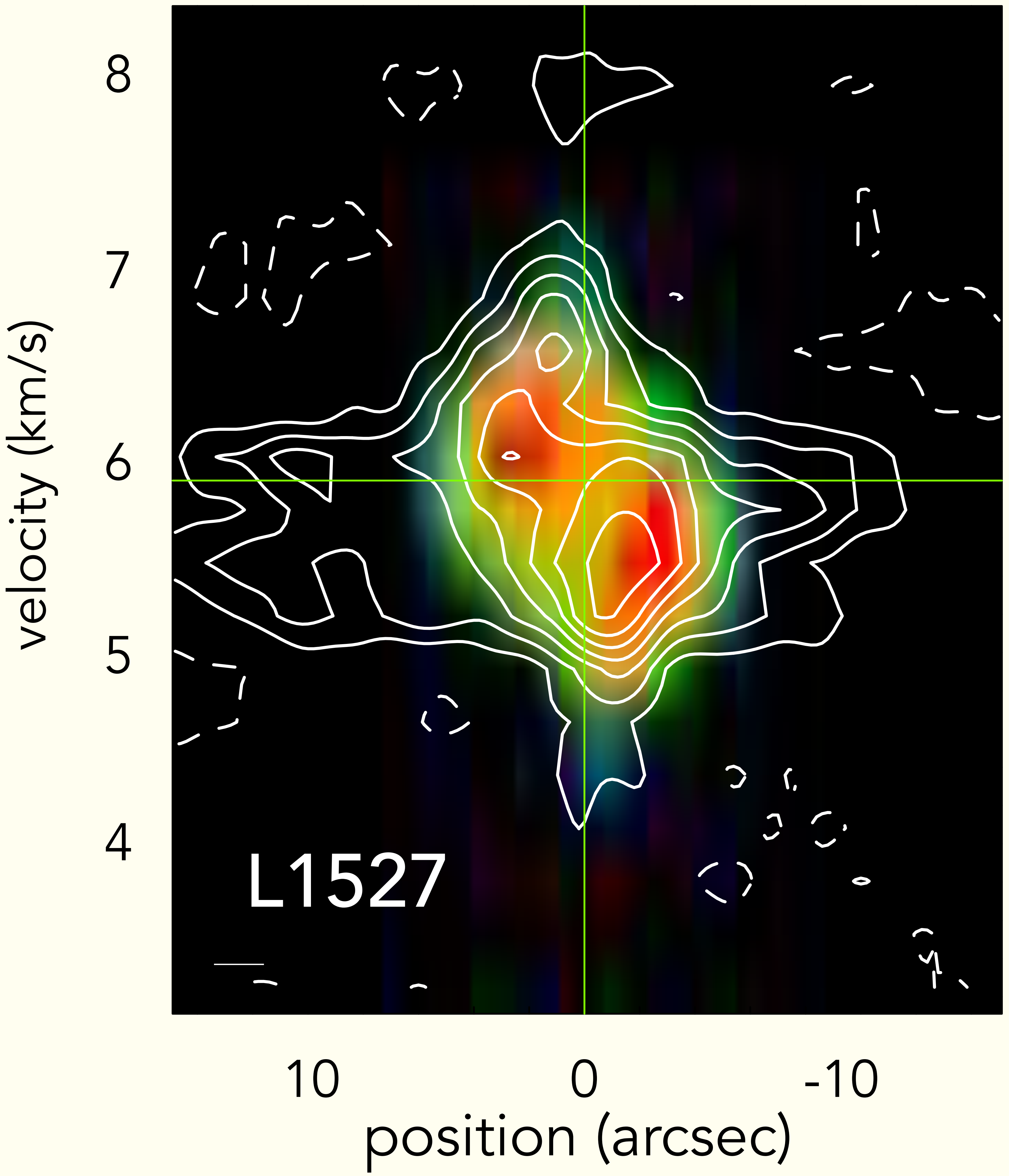


Yang+2019 subm.

The “smoking gun” evidence of the collapsing envelope





Yen+2015

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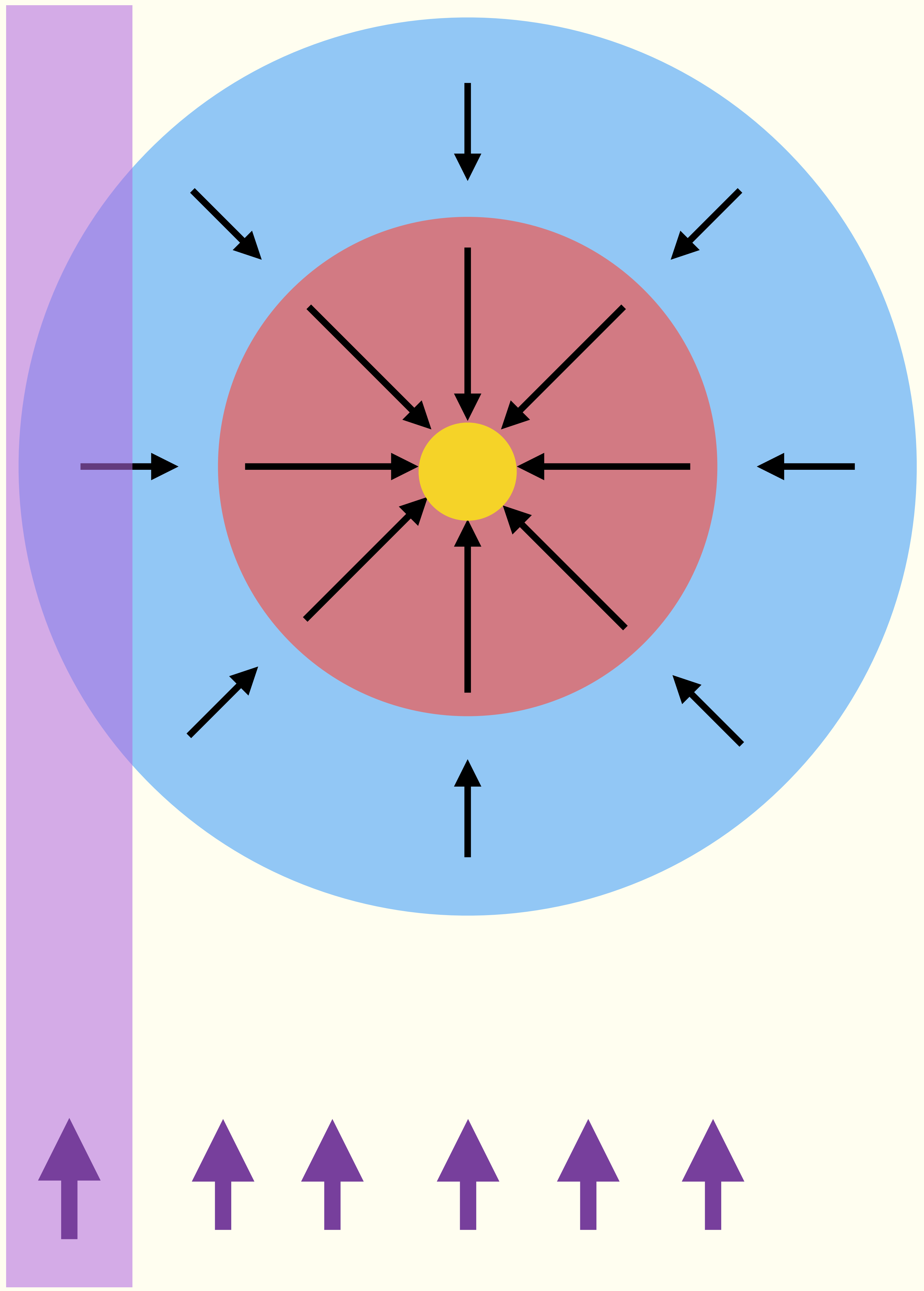

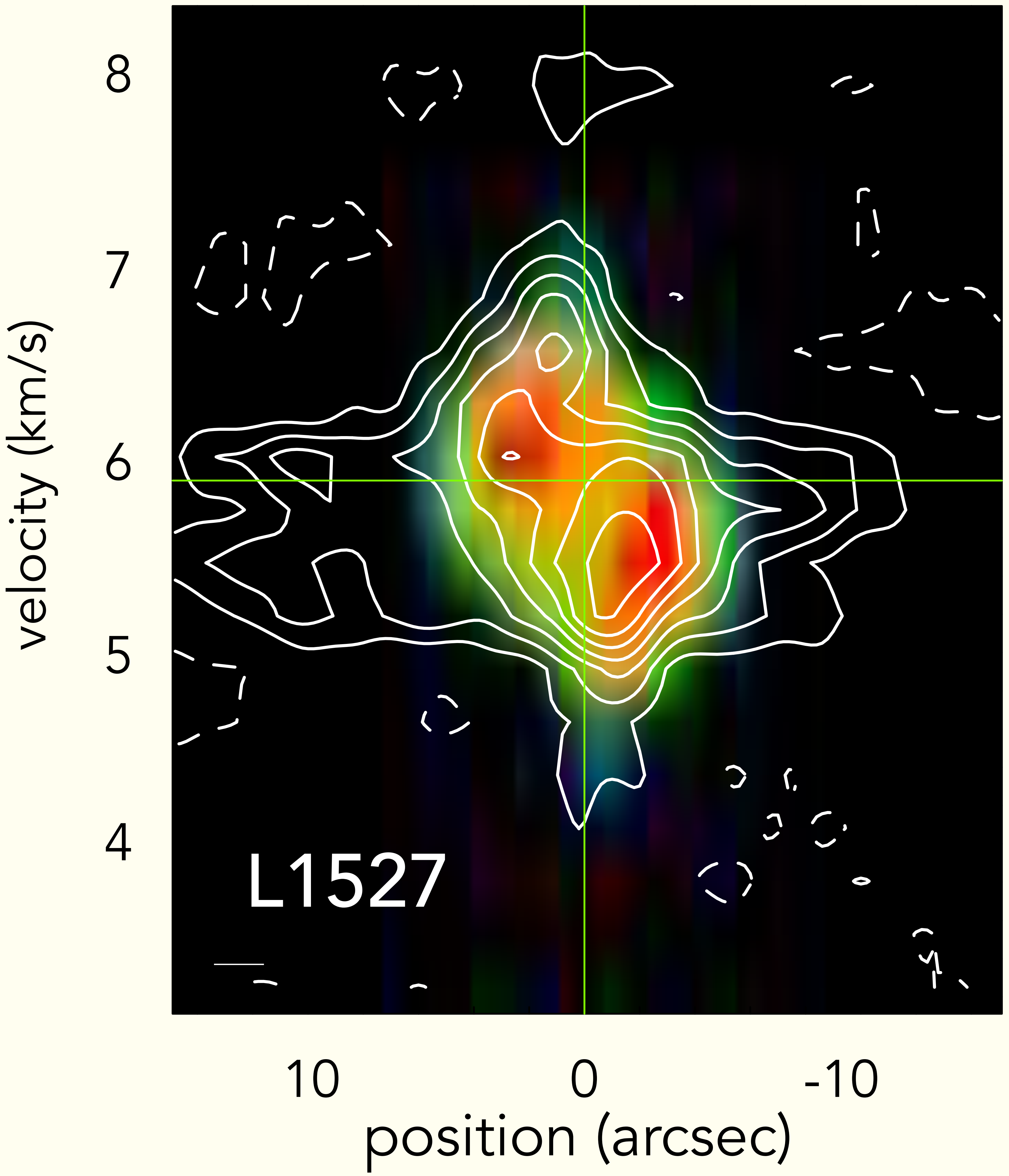

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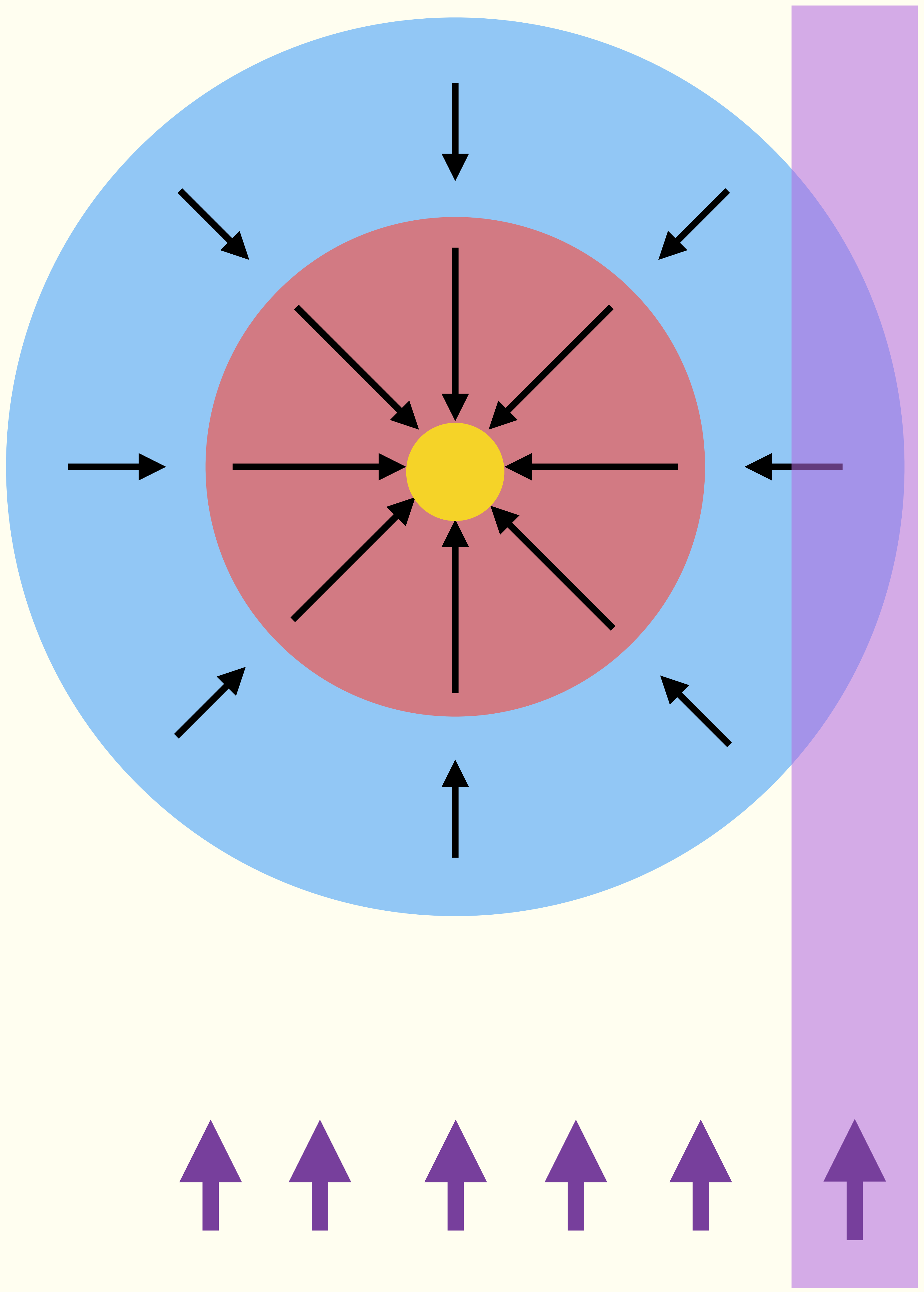

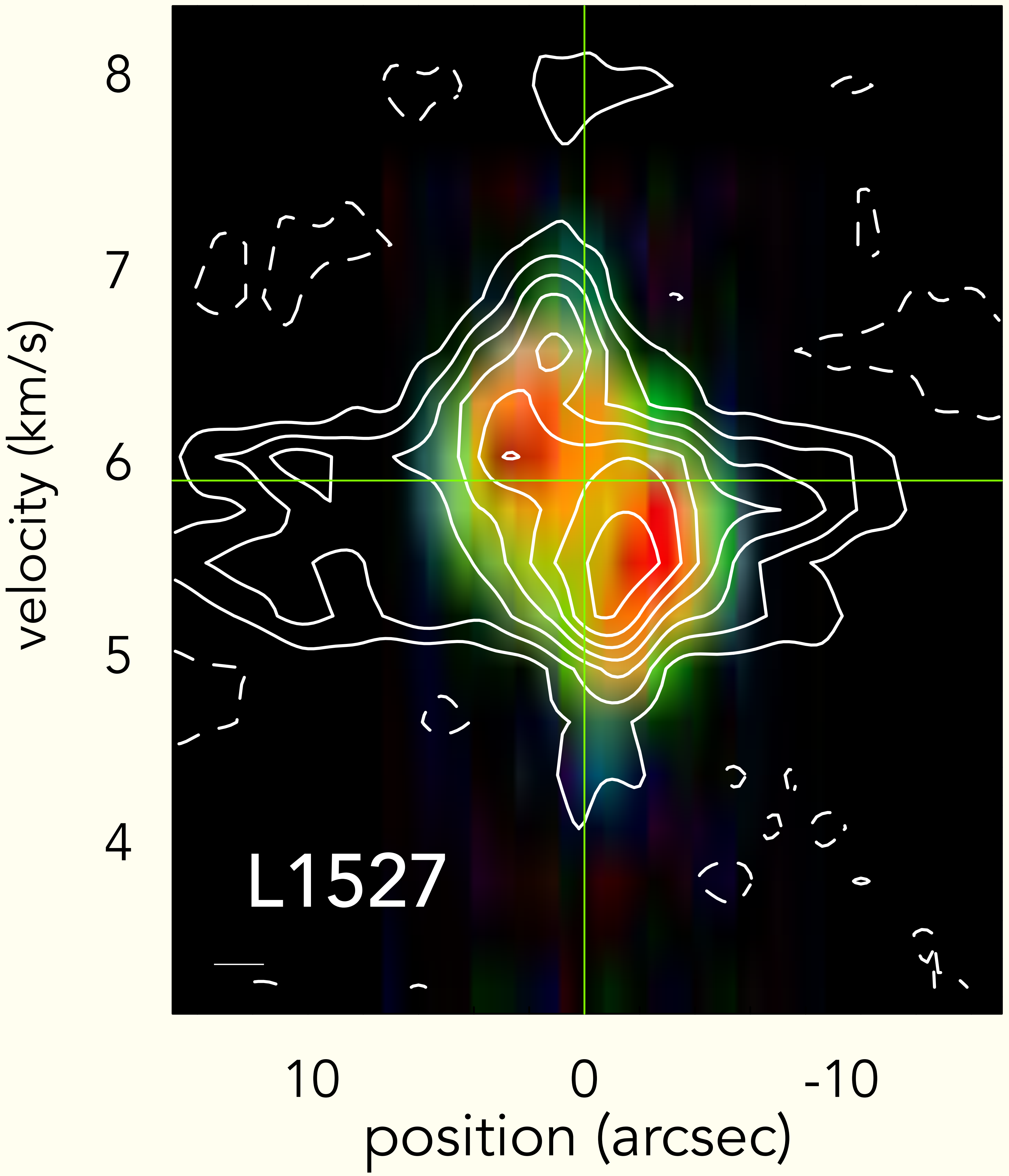

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The “smoking gun” evidence of the collapsing envelope

Red-shifted absorption against continuum from optically-thick lines

(Snell & Loren, 1977; Leung & Brown, 1977; Zhou+1993; Choi+1999; Di Francesco+2001)

- How does infall start, evolve, and be taken over by rotation?
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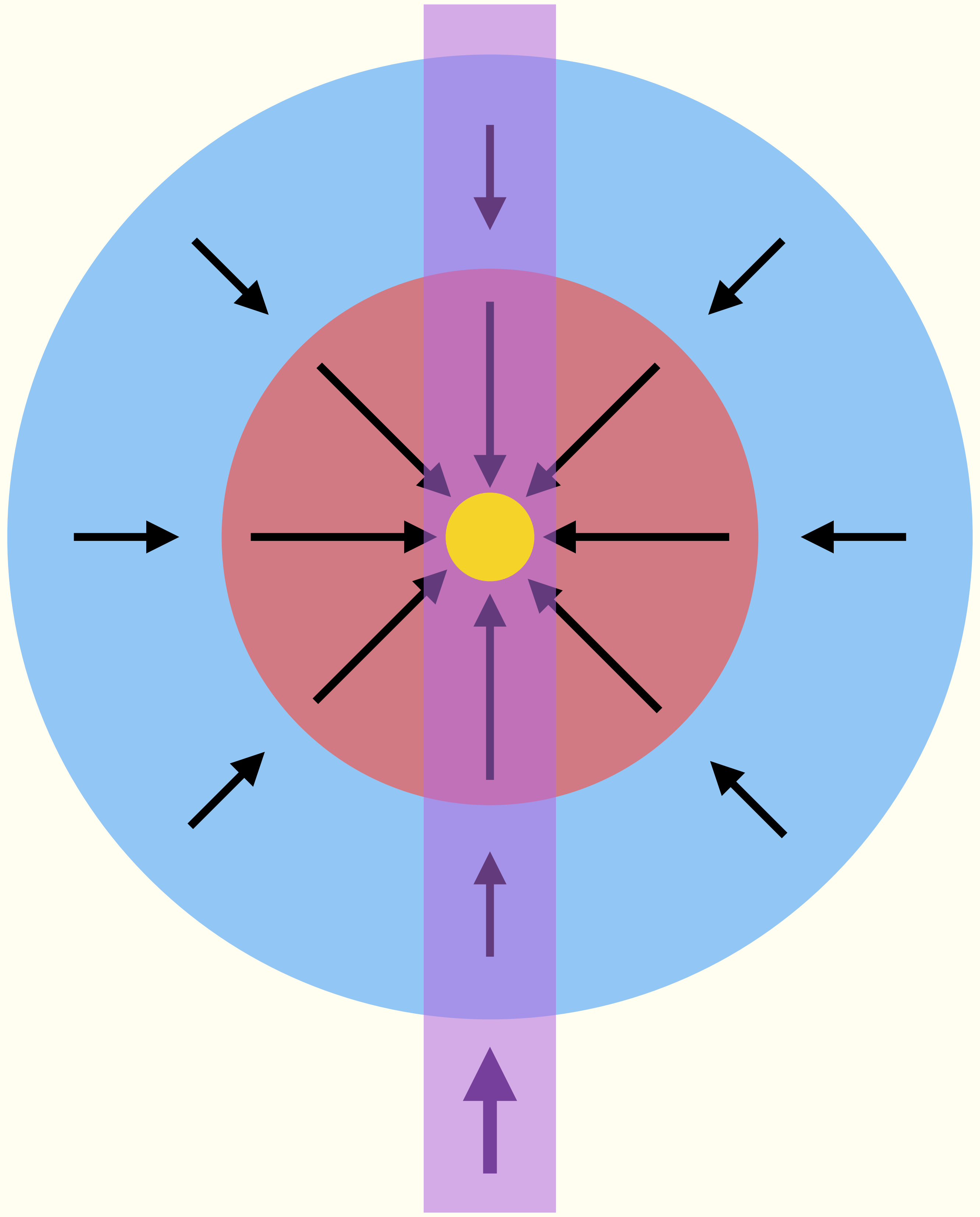

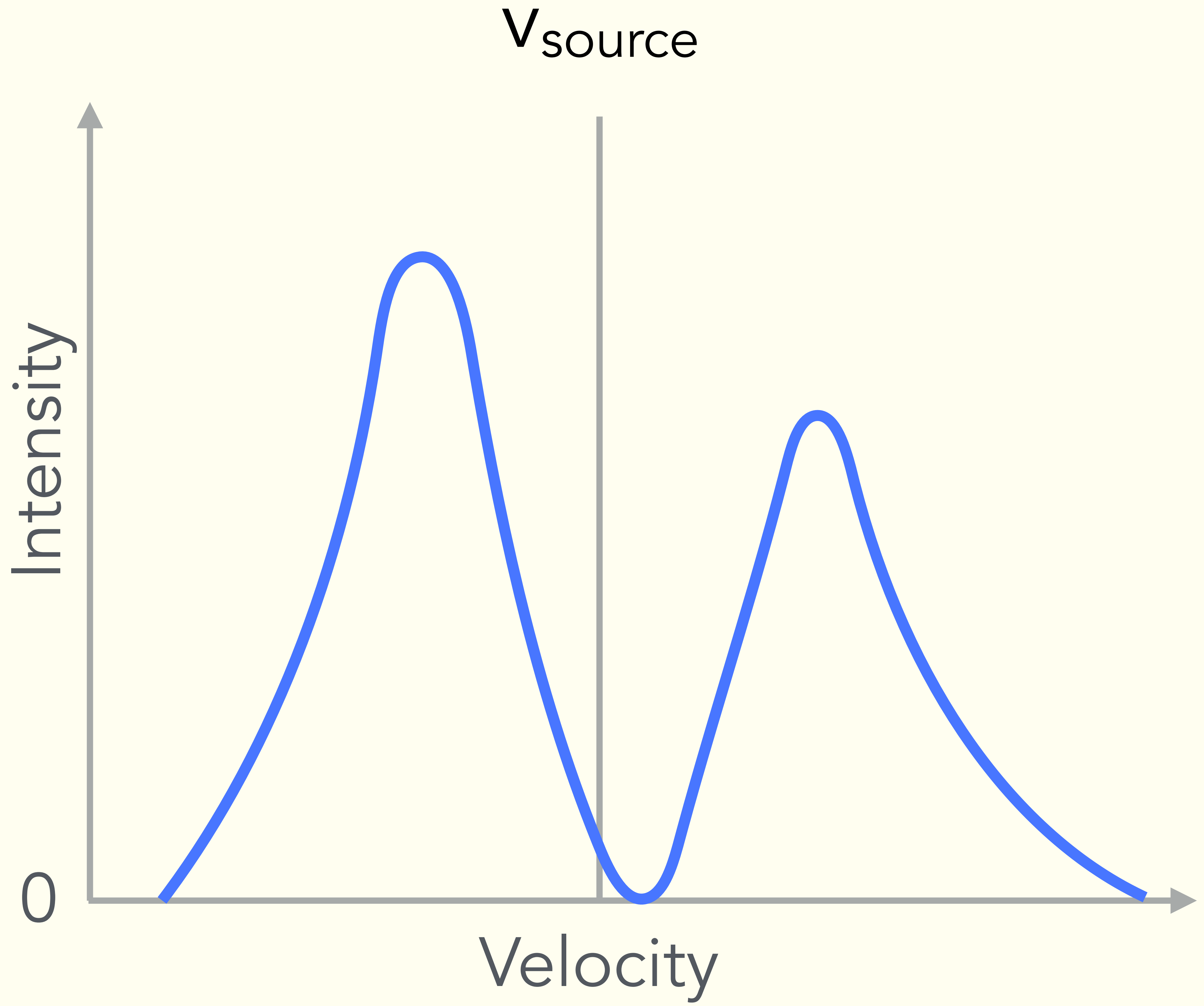

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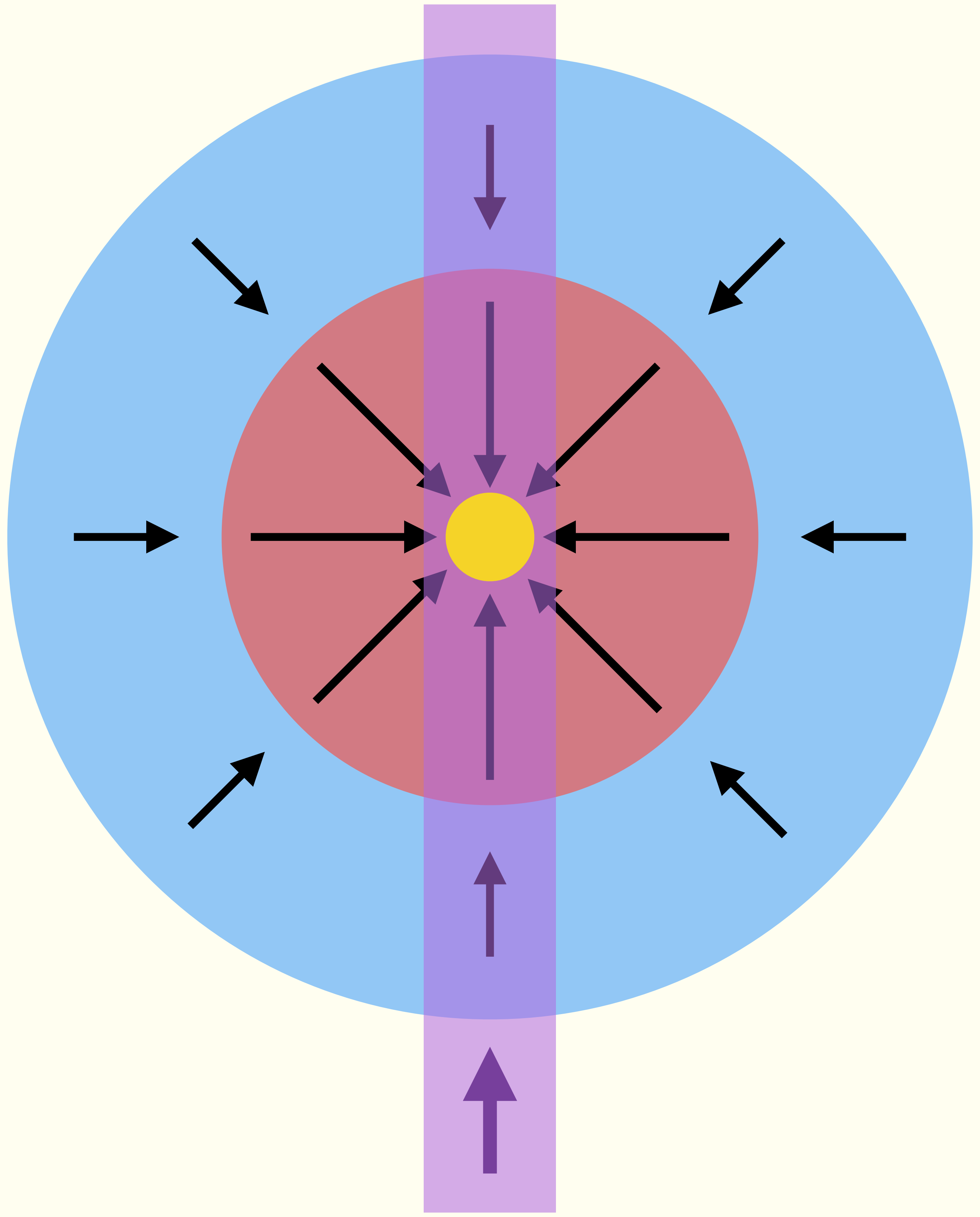

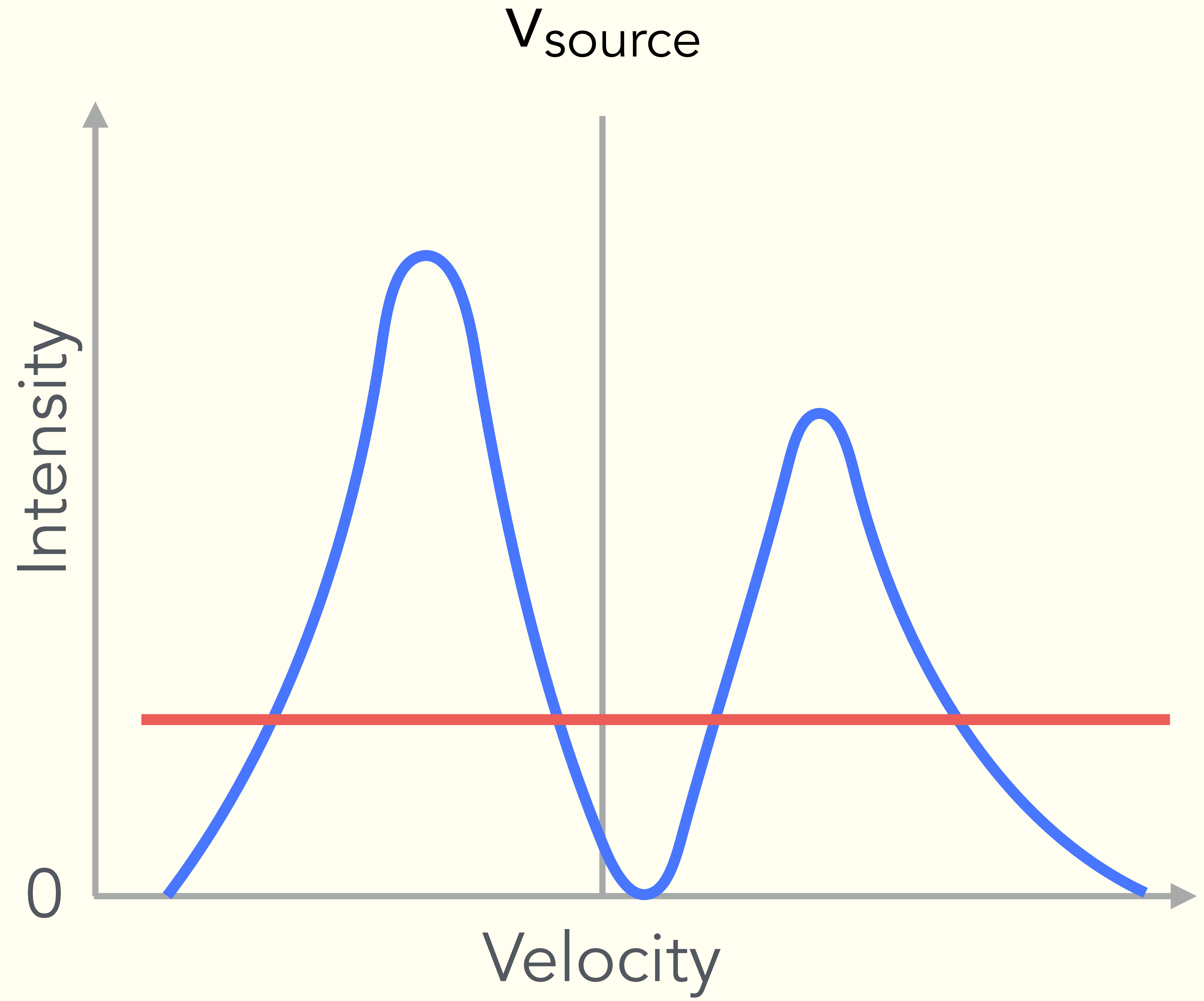

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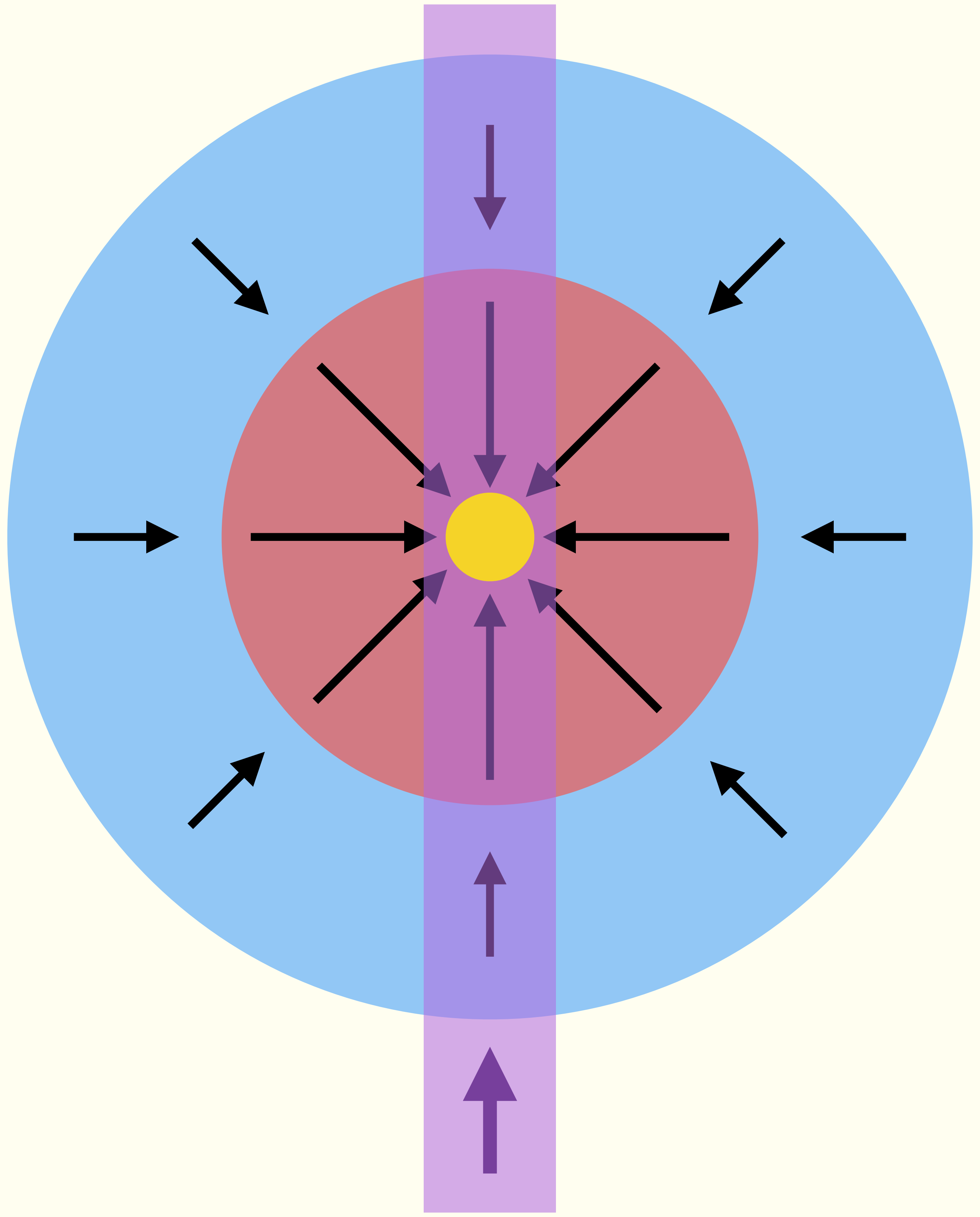

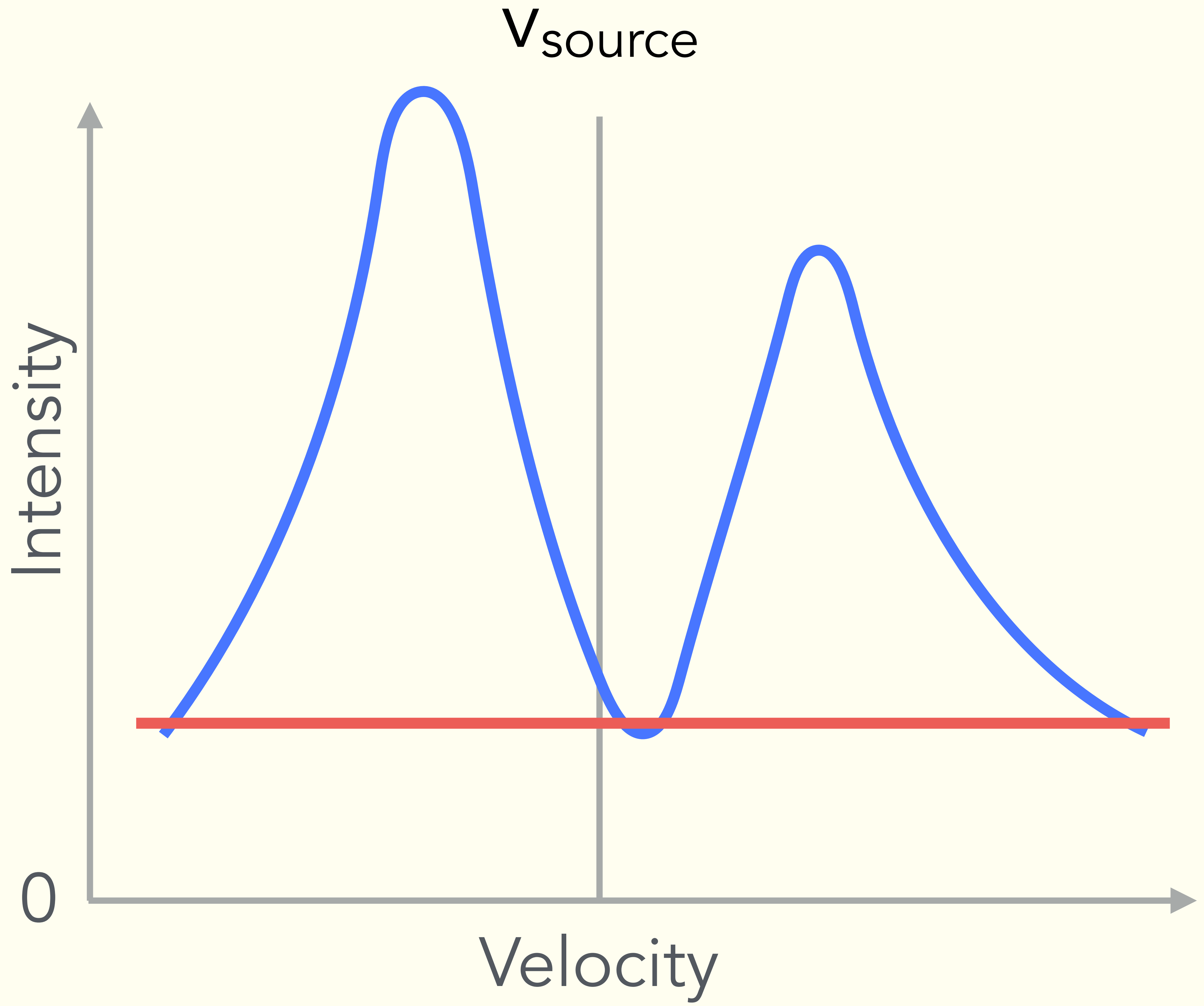

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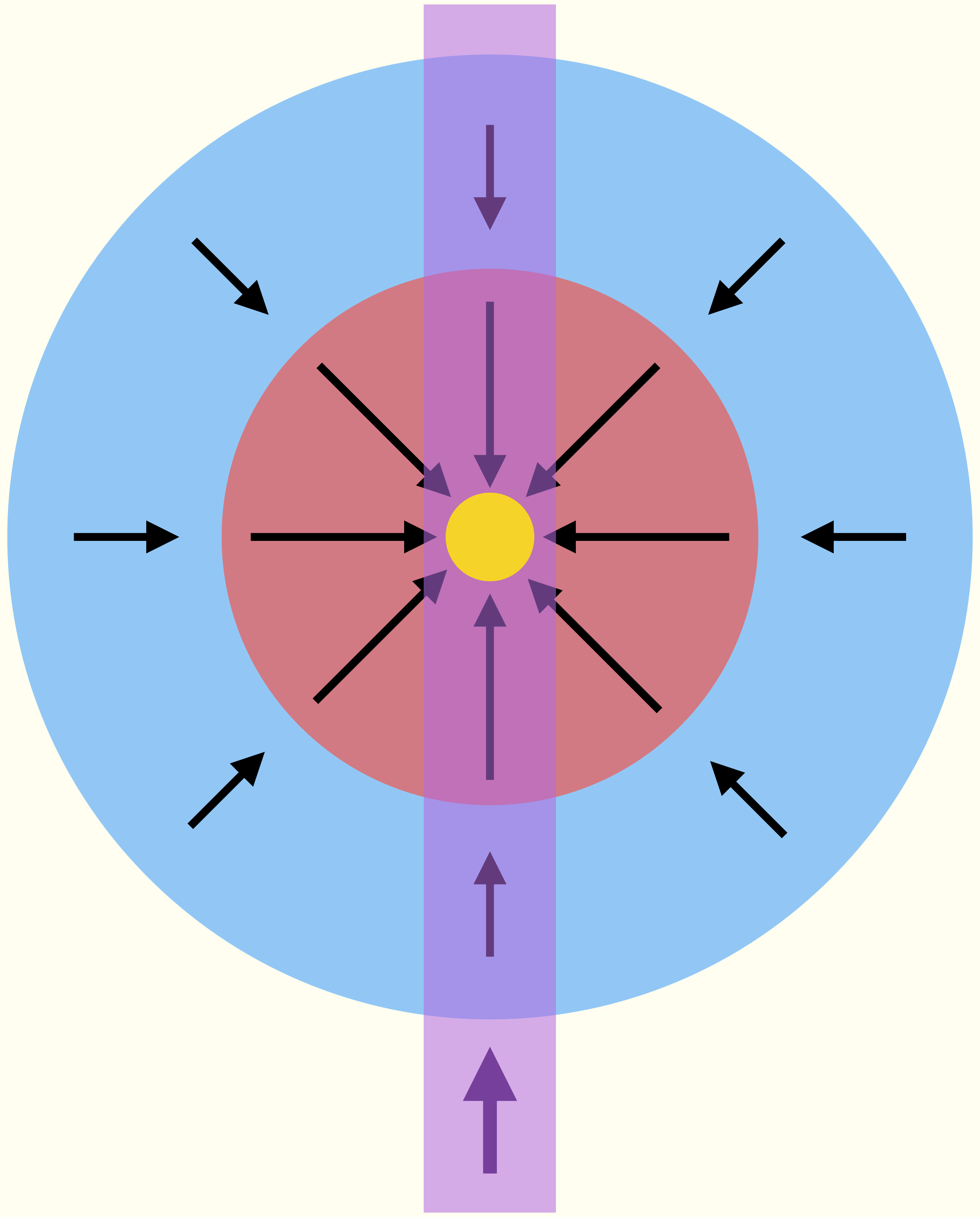

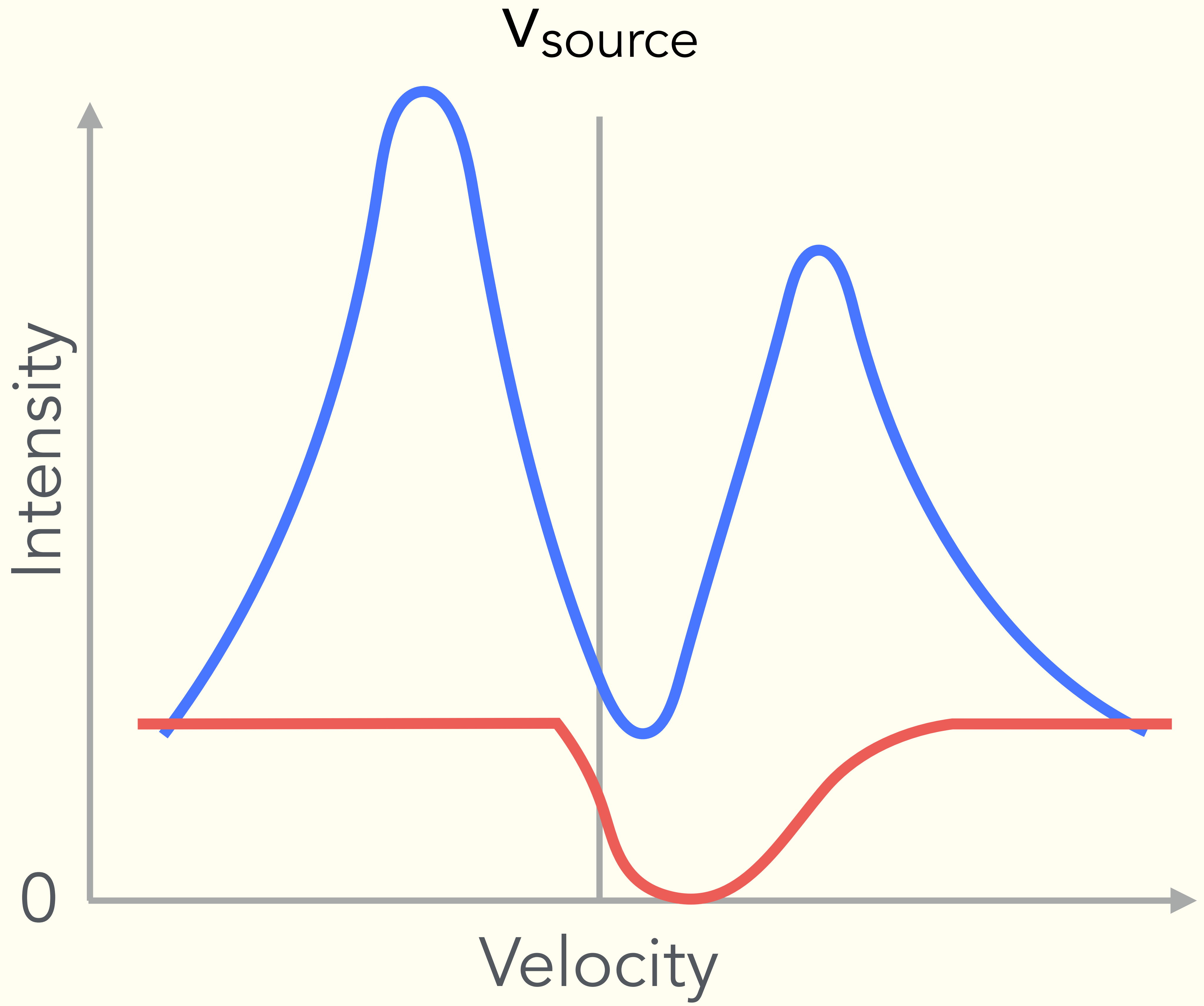

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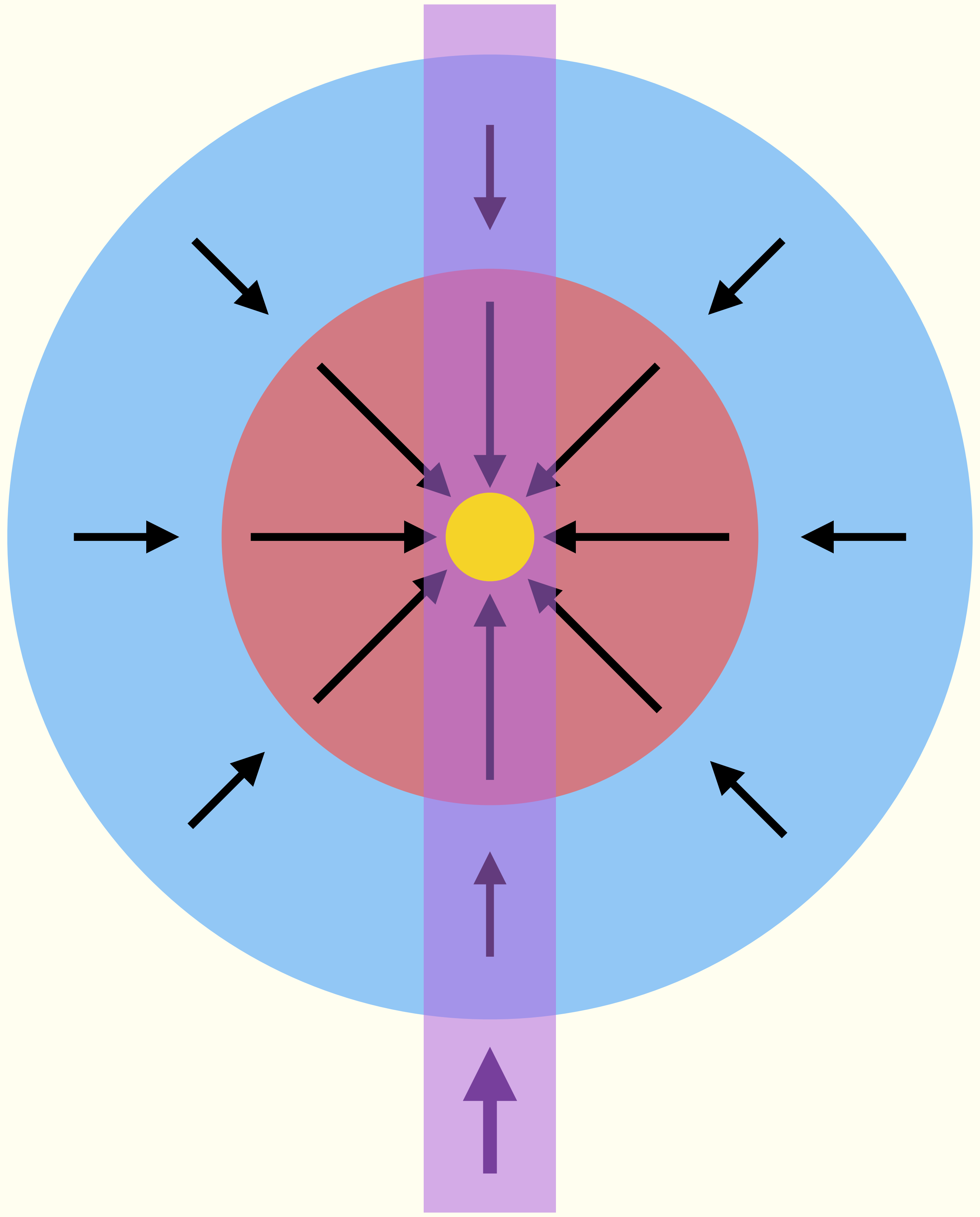
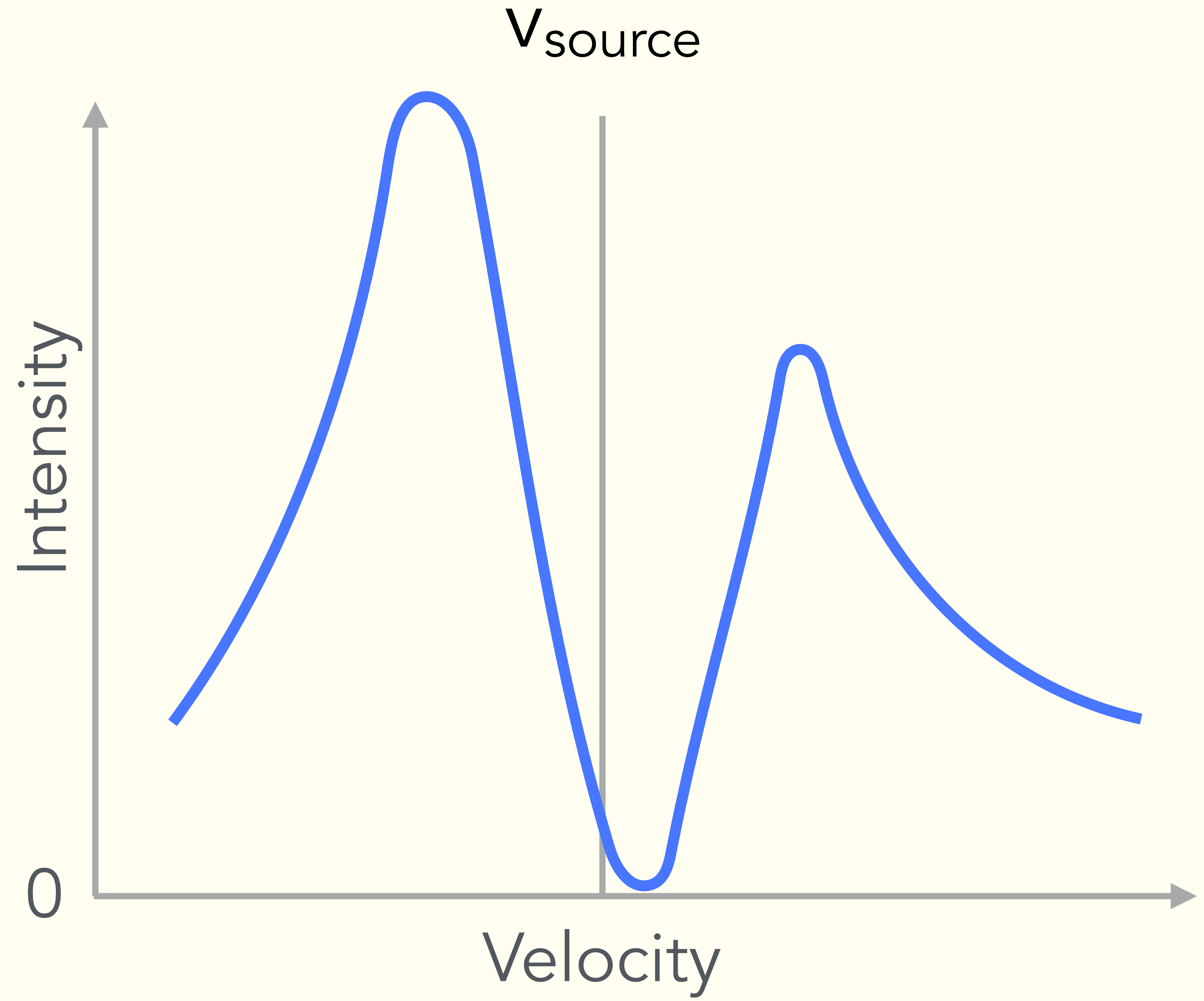
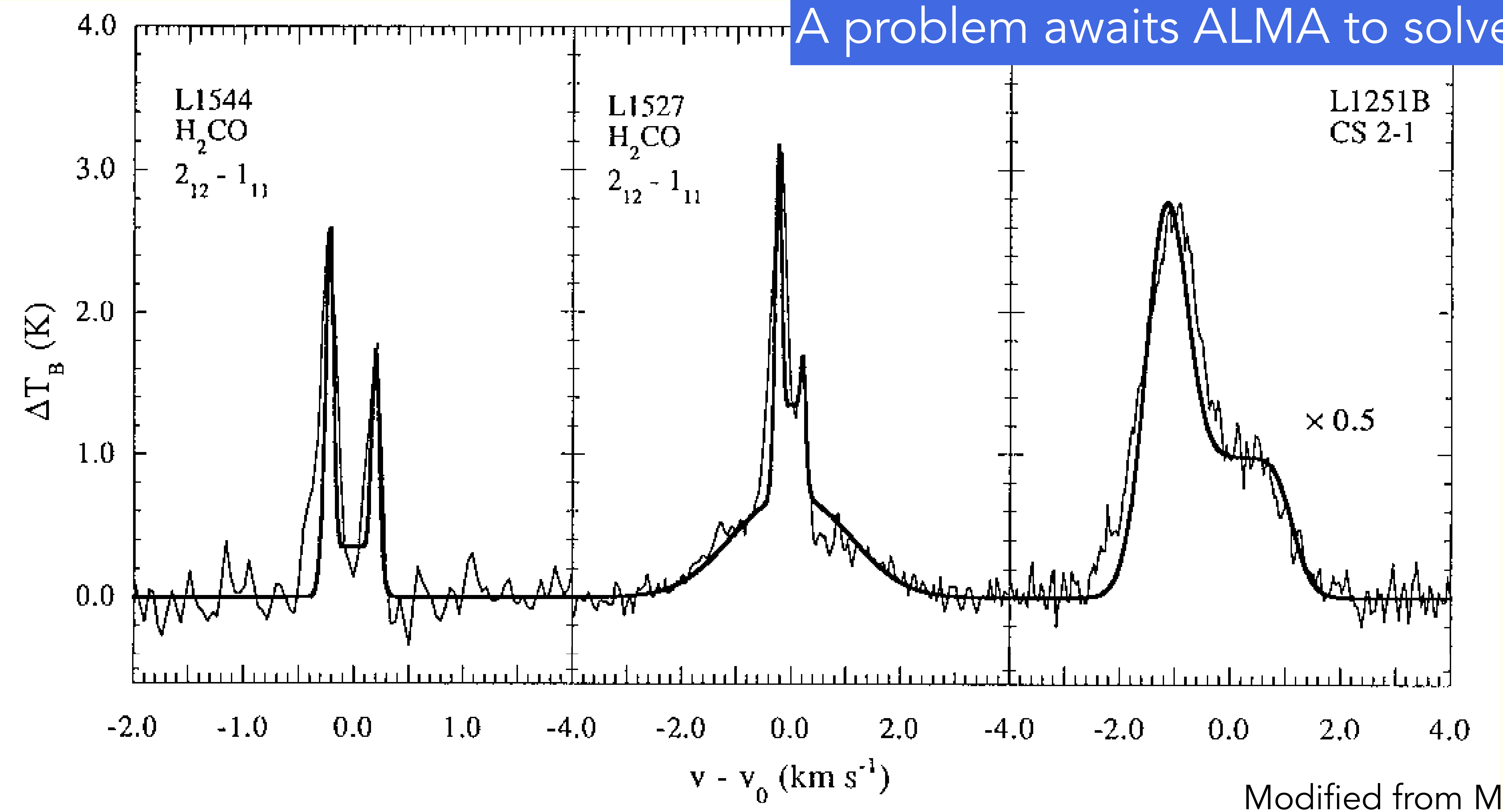




Irrelevant kinematics may contaminate the infall signatures

A problem awaits ALMA to solve

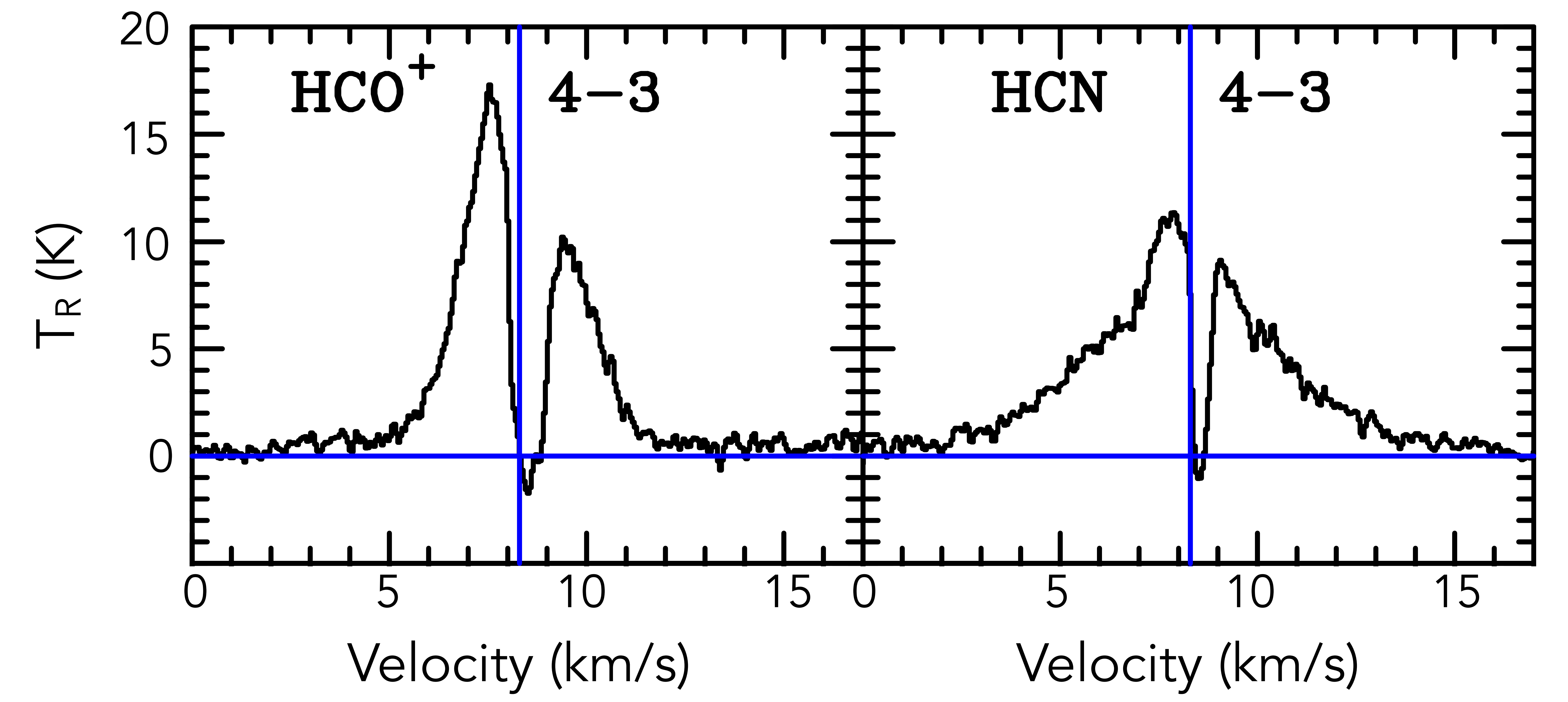


Modified from Myers+1996

The “smoking gun” evidence of the collapsing envelope

- The pencil beam of ALMA can detect the compact continuum to detect the absorption against the continuum, **placing the infalling gas in front of the protostar** (IRAS 16293-2422B: Pineda+2012; L1527: Ohashi+2014; HH212: Lee+2014; B335: Evans+2015; see also Friesen+2018 for a tentative case).

B335 Continuum-subtracted spectra



Evans+2015

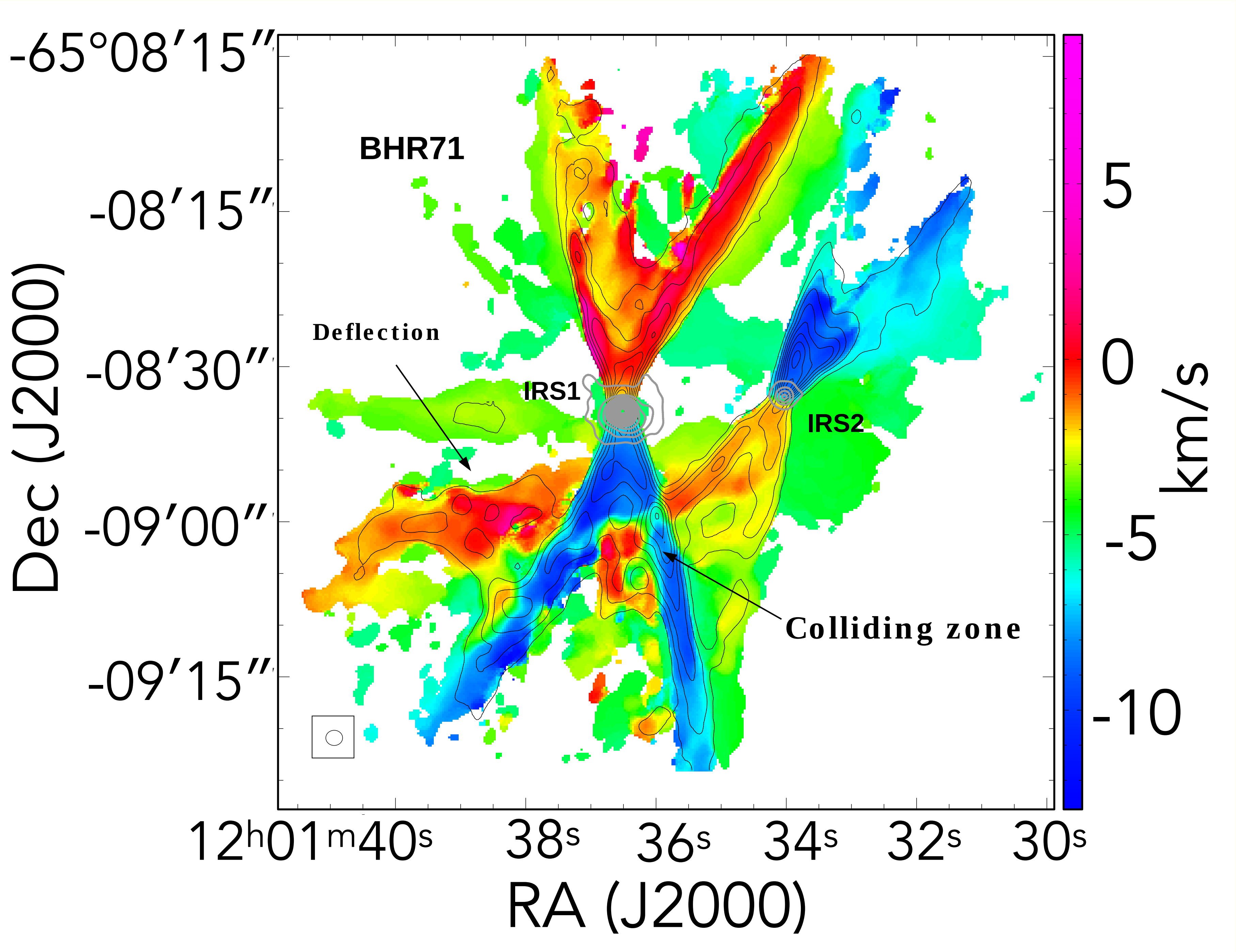
Measure the infall: A case study with BHR 71

BHR 71: an isolated embedded protostar with high luminosity (13.5 $L_\odot$)

→ deeper absorption, thus stronger infall signatures

Optical (VLT)

Infrared (*Spitzer*)



Millimeter (ALMA, ^{12}CO 2-1)

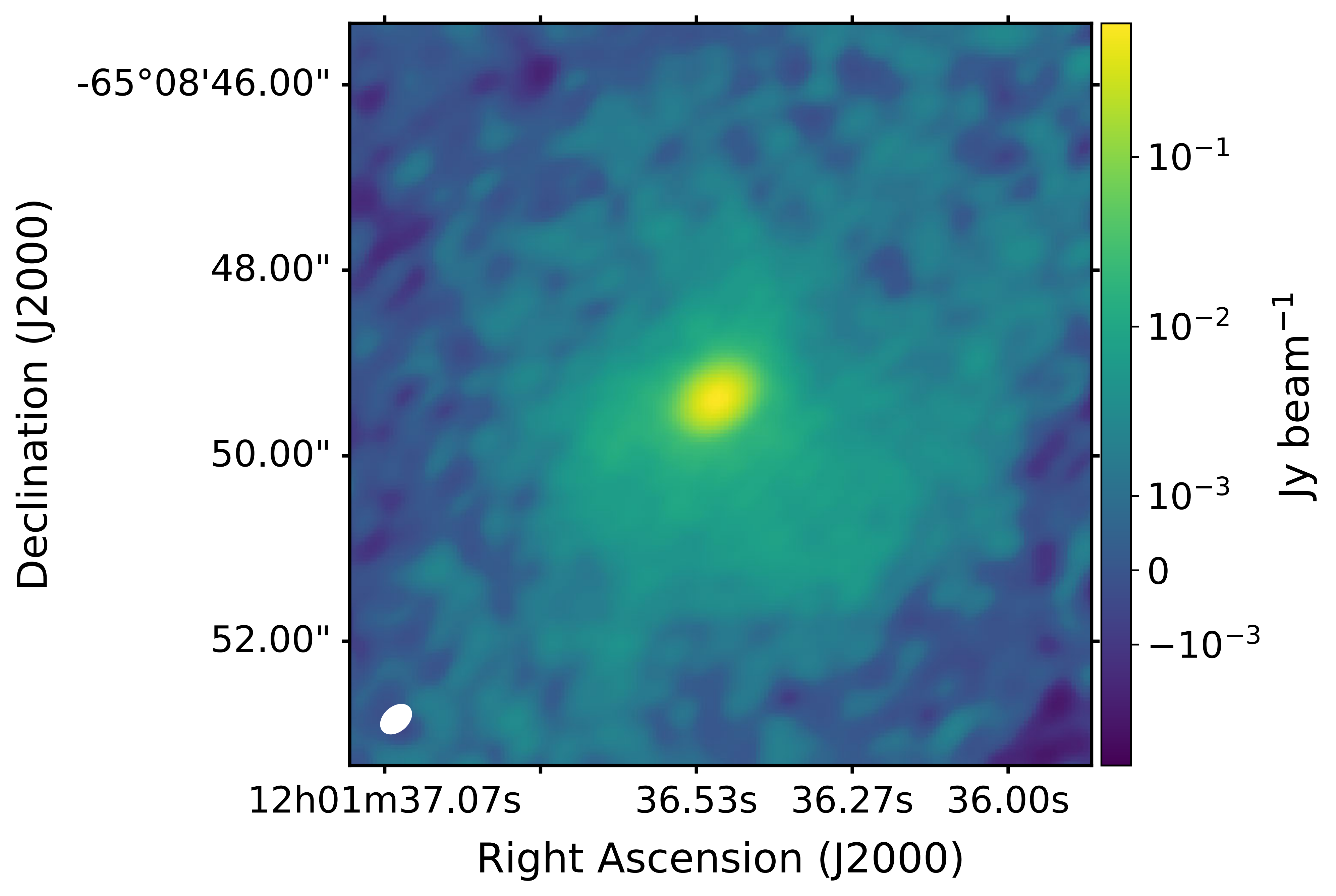
Bourke+1997

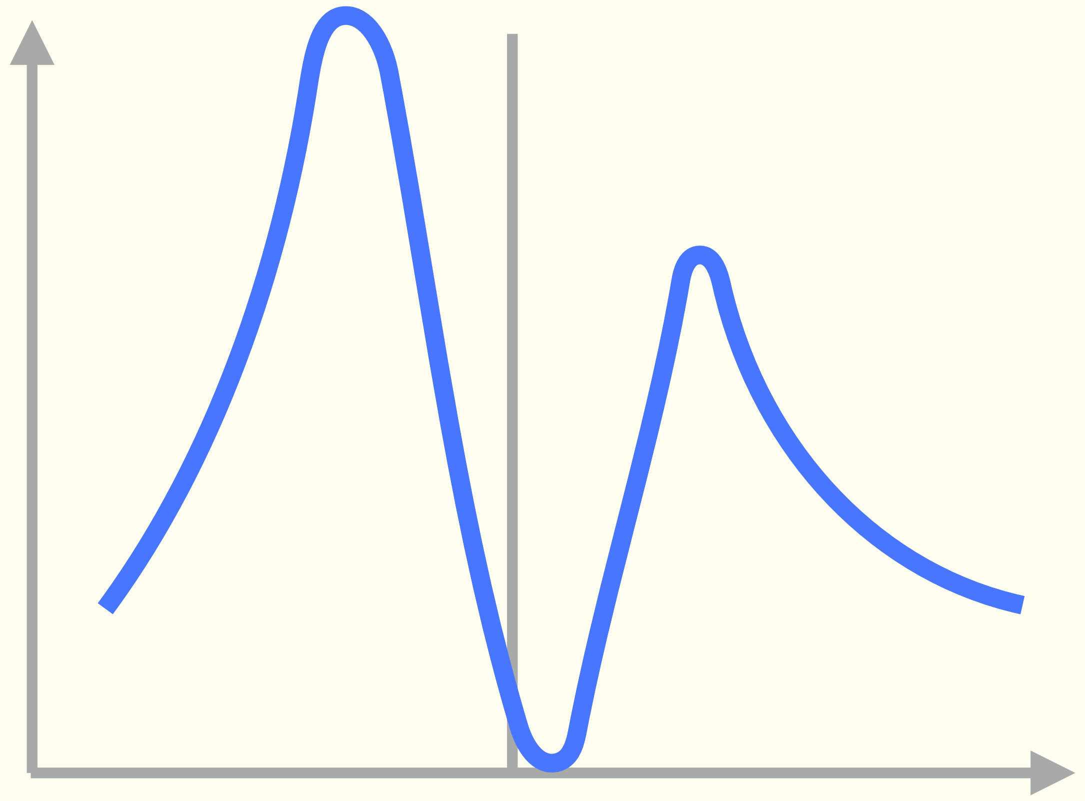
see also Praise+2006, Chen+2008, and Tobin+2019

Zapata+2018

Unambiguous signatures of infall toward BHR 71 with ALMA

ALMA Cycle 4 (PI: Y.-L. Yang)





Yang+2019 subm.

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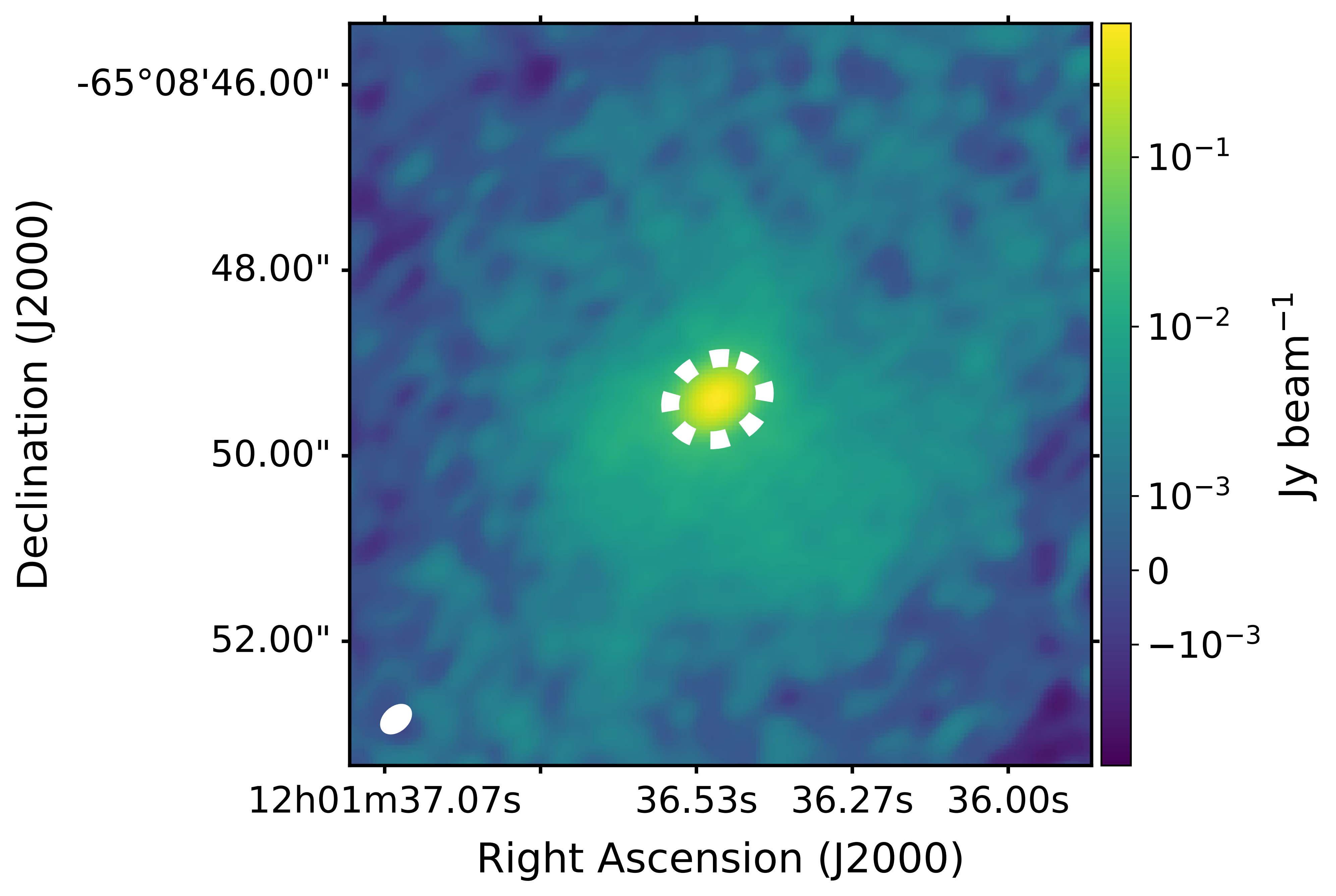

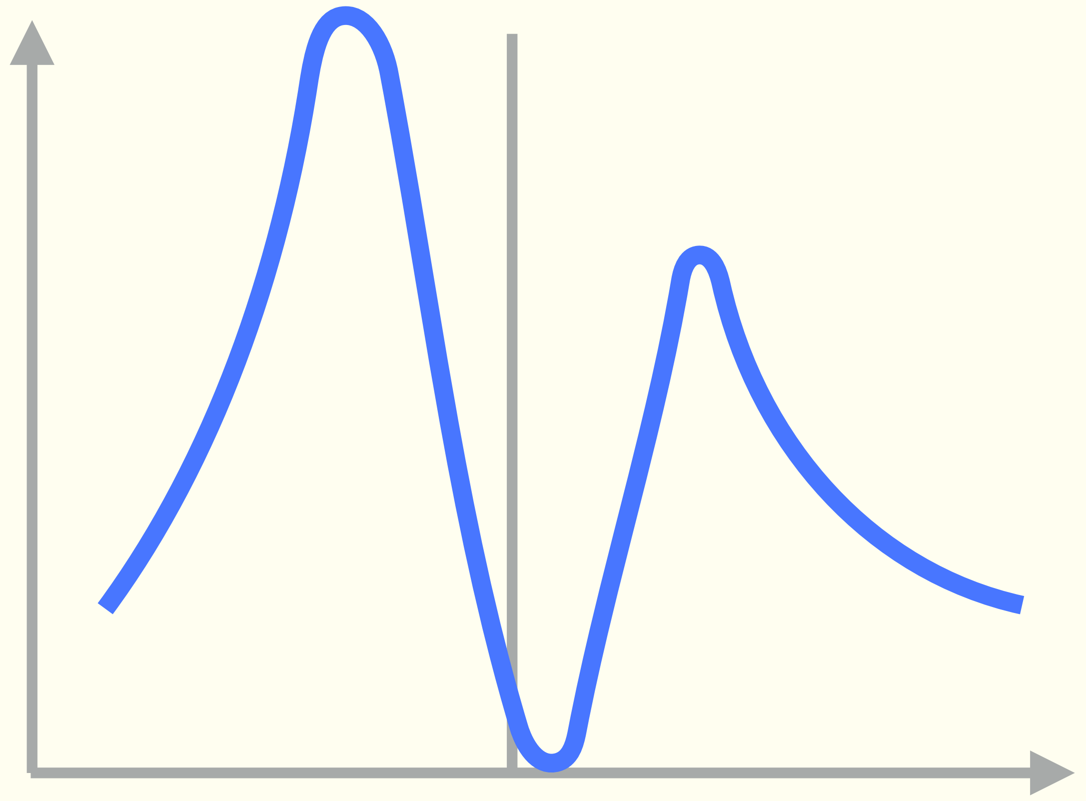

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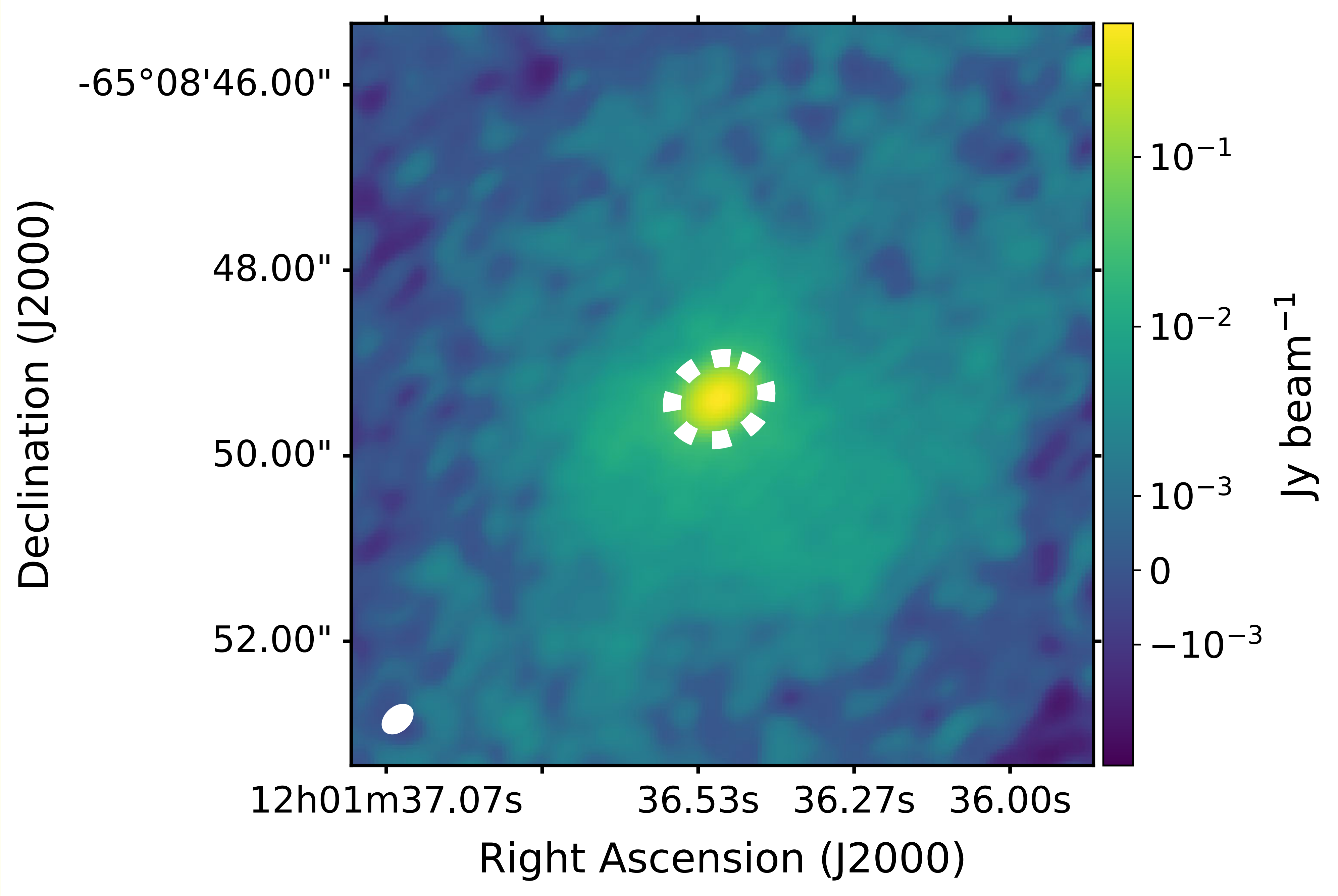
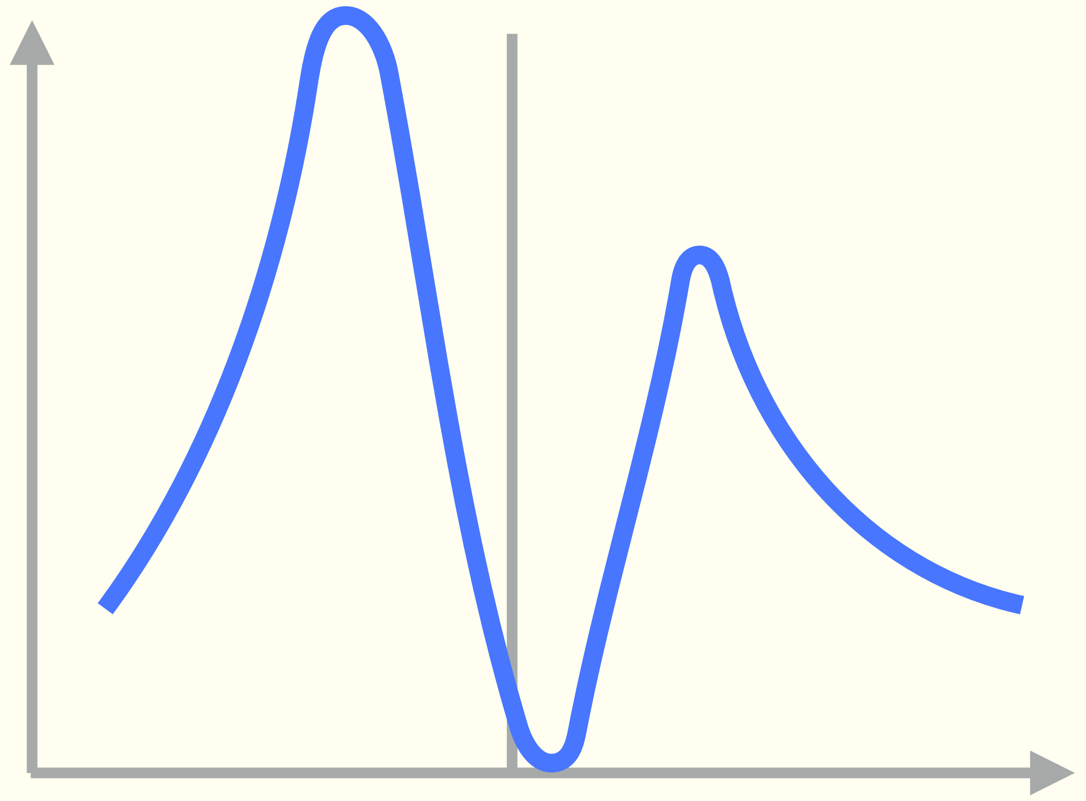
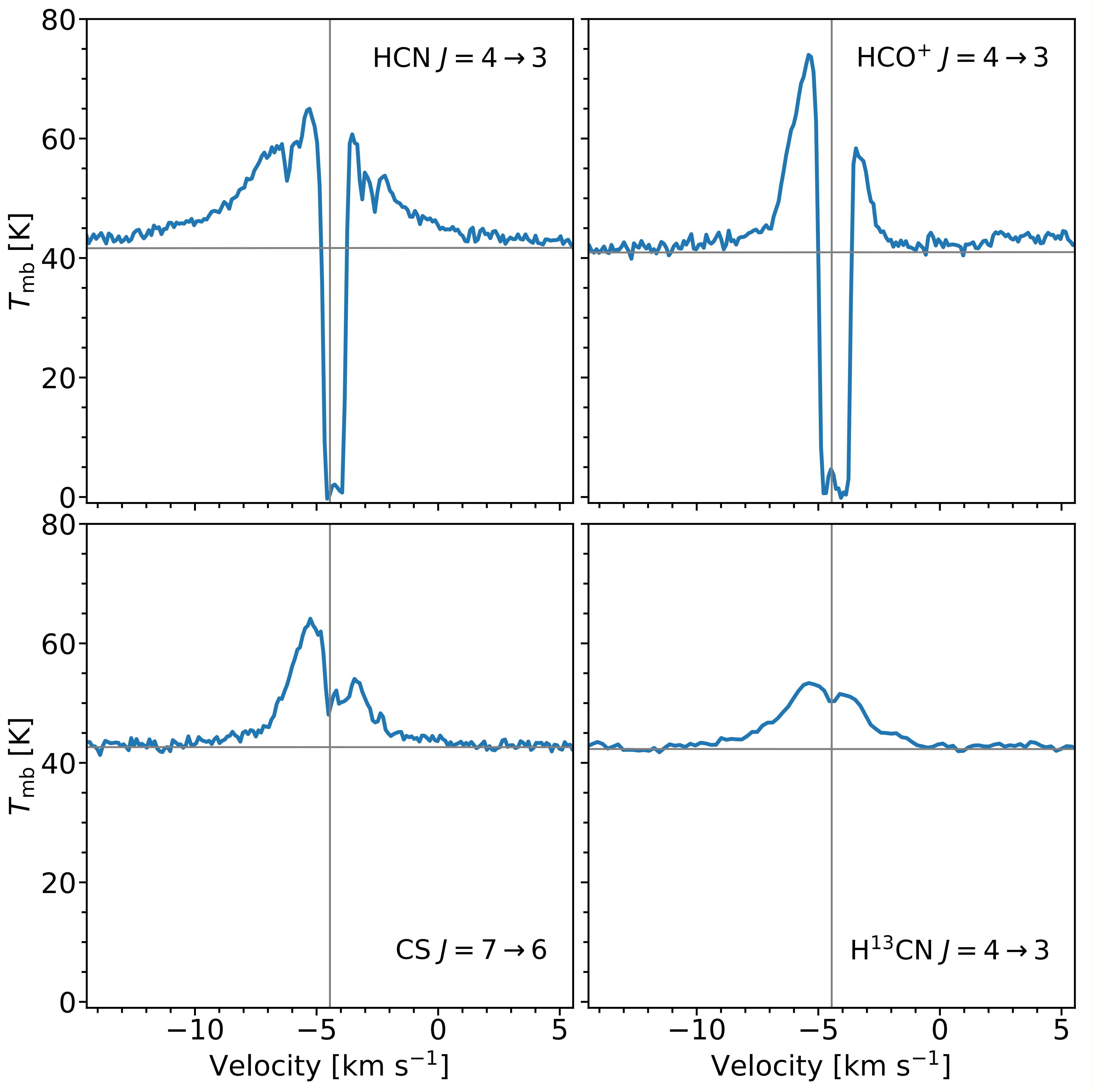
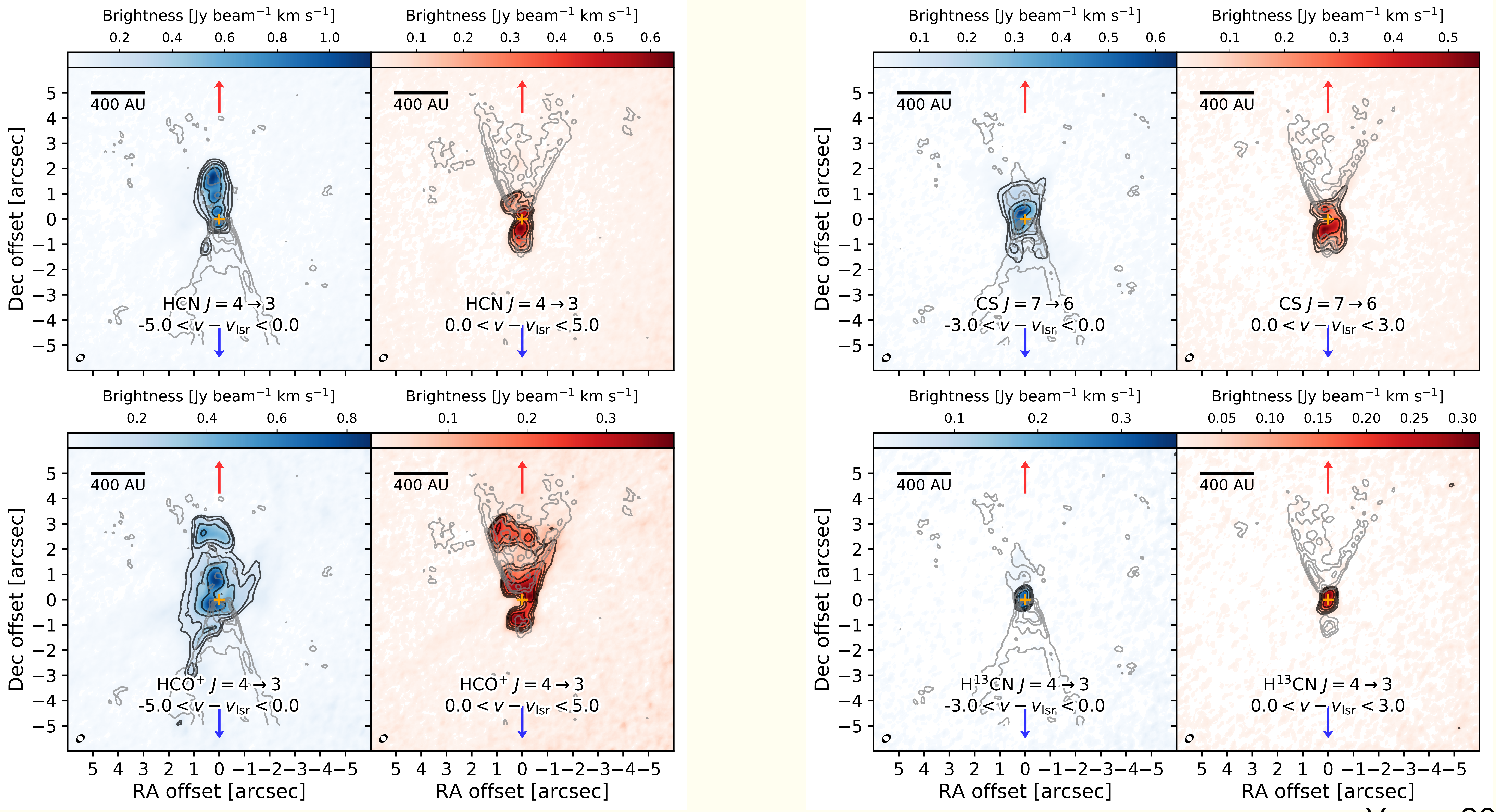






Yang+2019 subm.

Molecular lines trace outflows at off-center positions



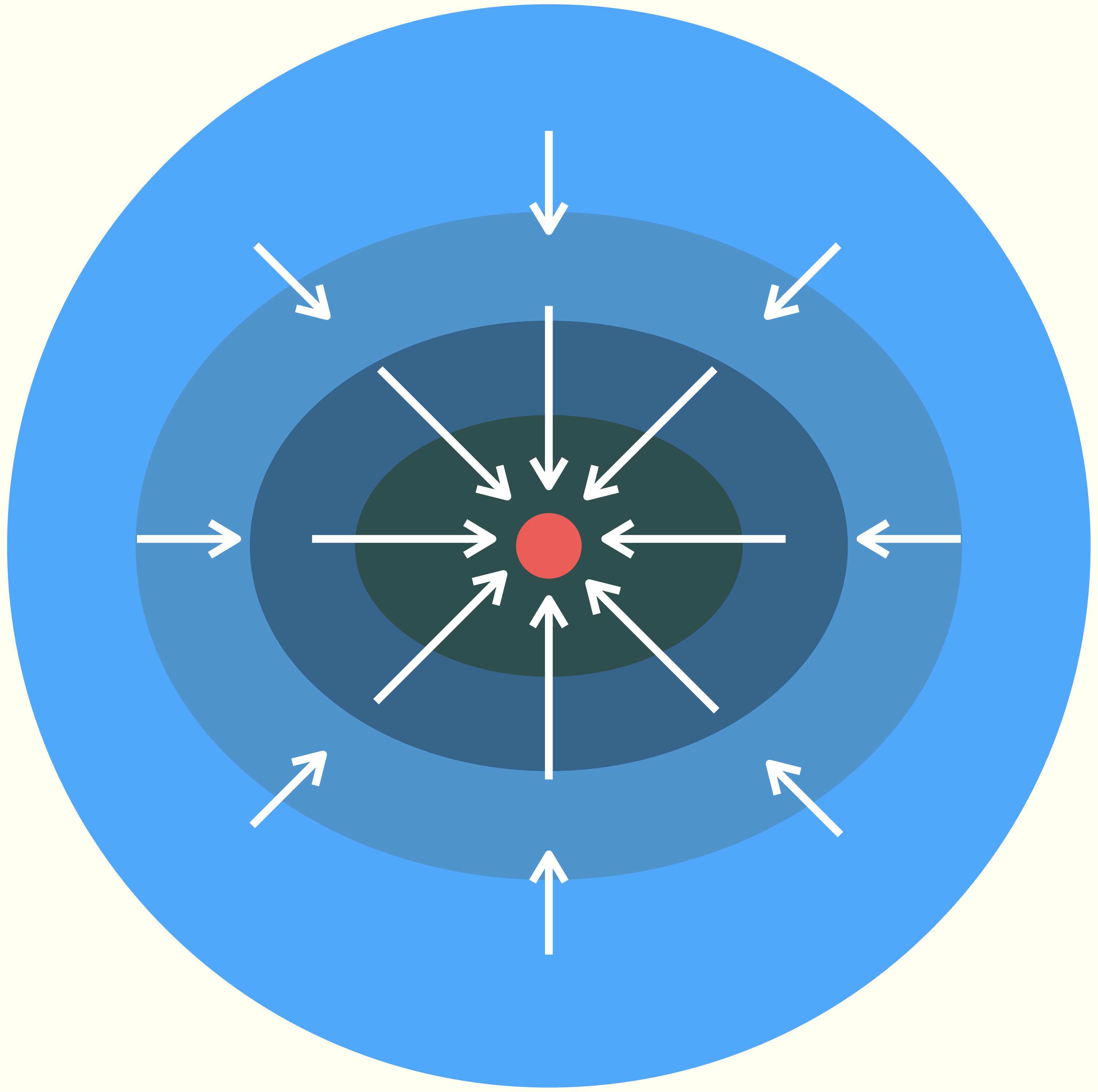
Yang+2019 subm.

A centrally peaked dense cores should undergo gravitational collapse

The gravitational collapse drives the dynamical evolution, while other processes may regulate the course of collapse. Thus, we start from testing simple models of gravitational collapse against robust observations of the kinematics.

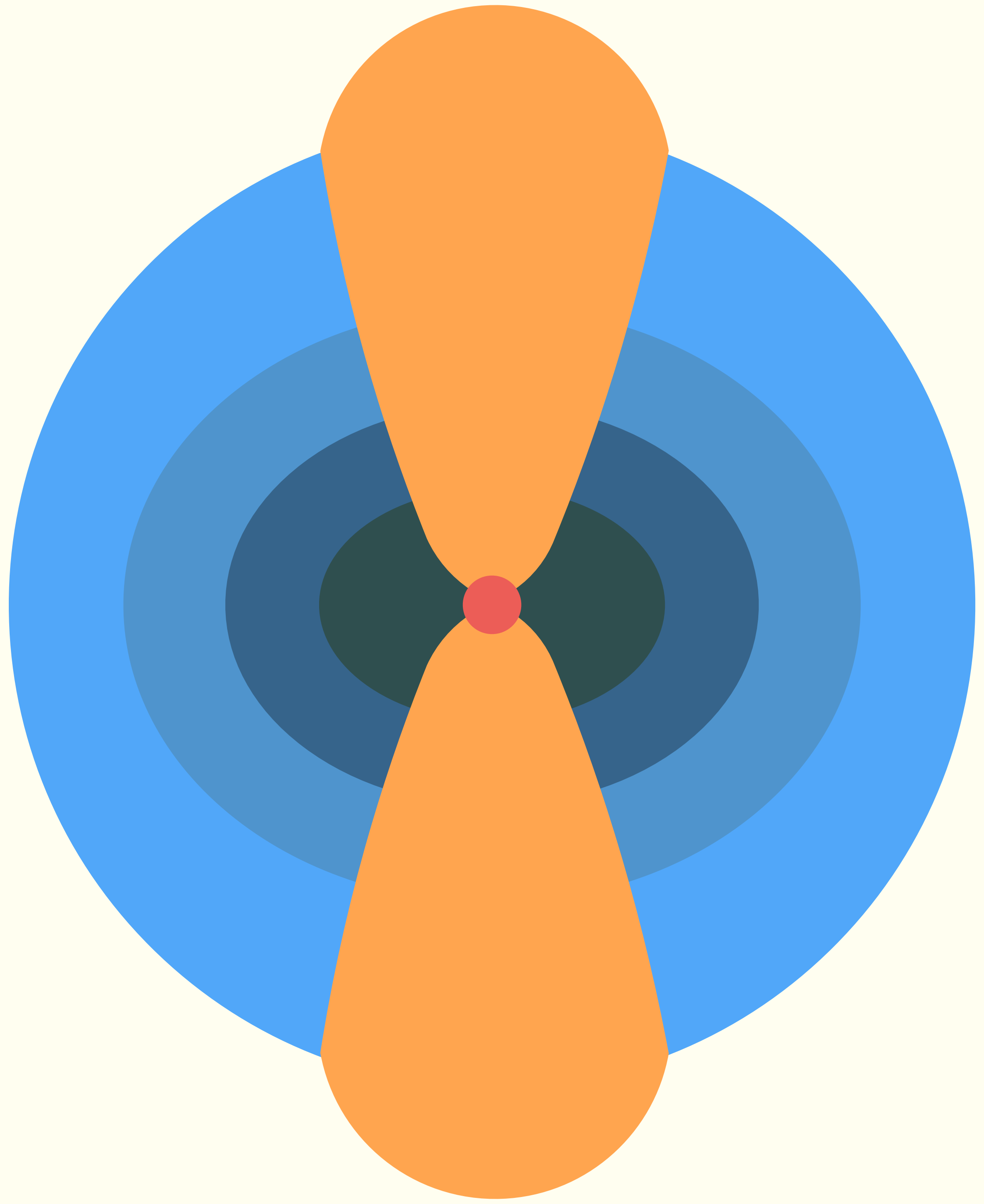
The outcome of infall determines the initial conditions of disk and planet formation.

- The formation of close binary systems
- The chemistry of disks and planets



Model the kinematics with a 3D radiative transfer pipeline

slowly rotating infalling envelope
Terebey, Shu, & Cassen (1984)



Structures of the envelope and outflows

Herschel continuum SED and *Spitzer* images

Gas kinematics

Molecular line profiles observed by ALMA

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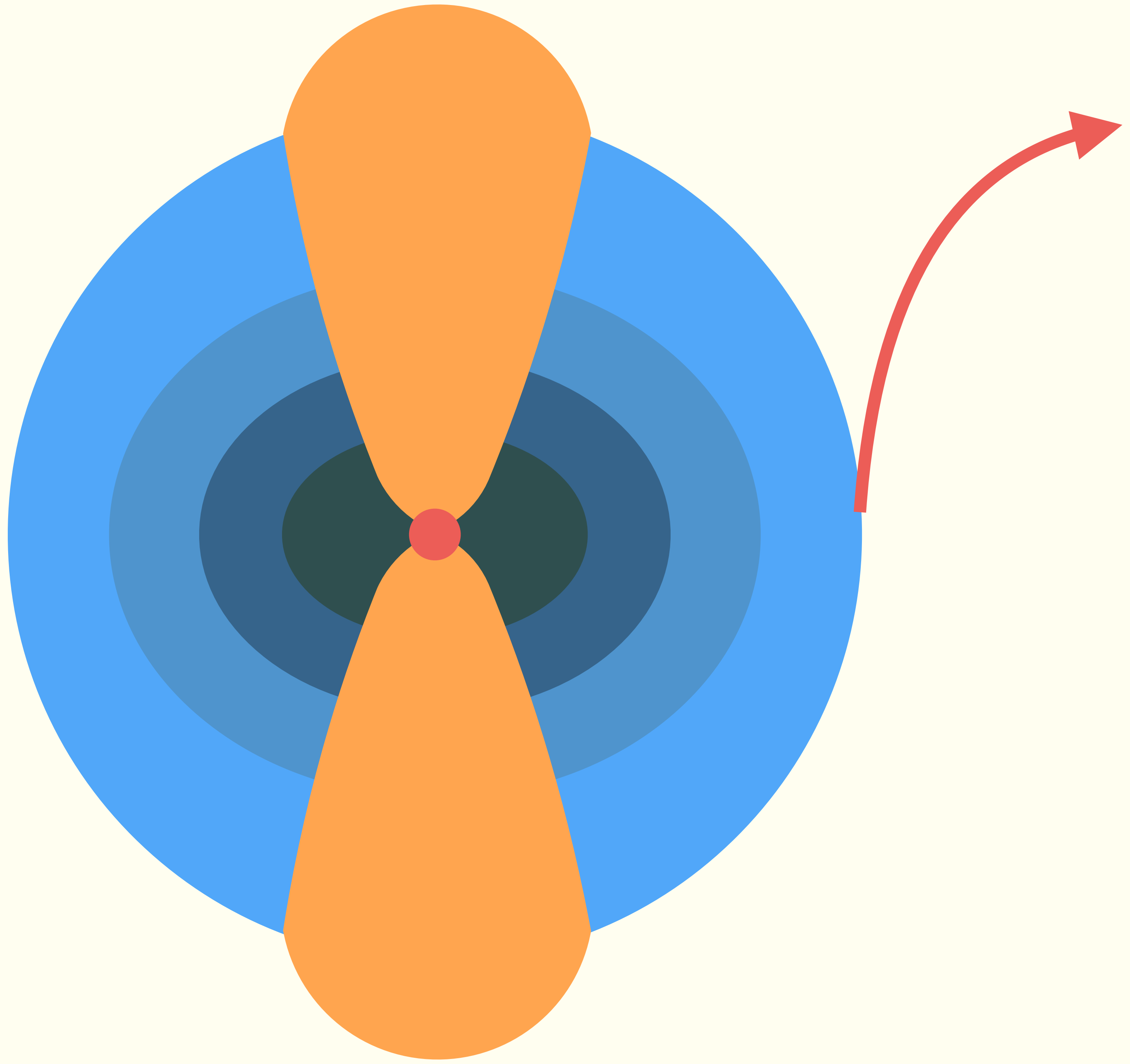

`Hyperion` (Robitaille 2012)
continuum radiative transfer

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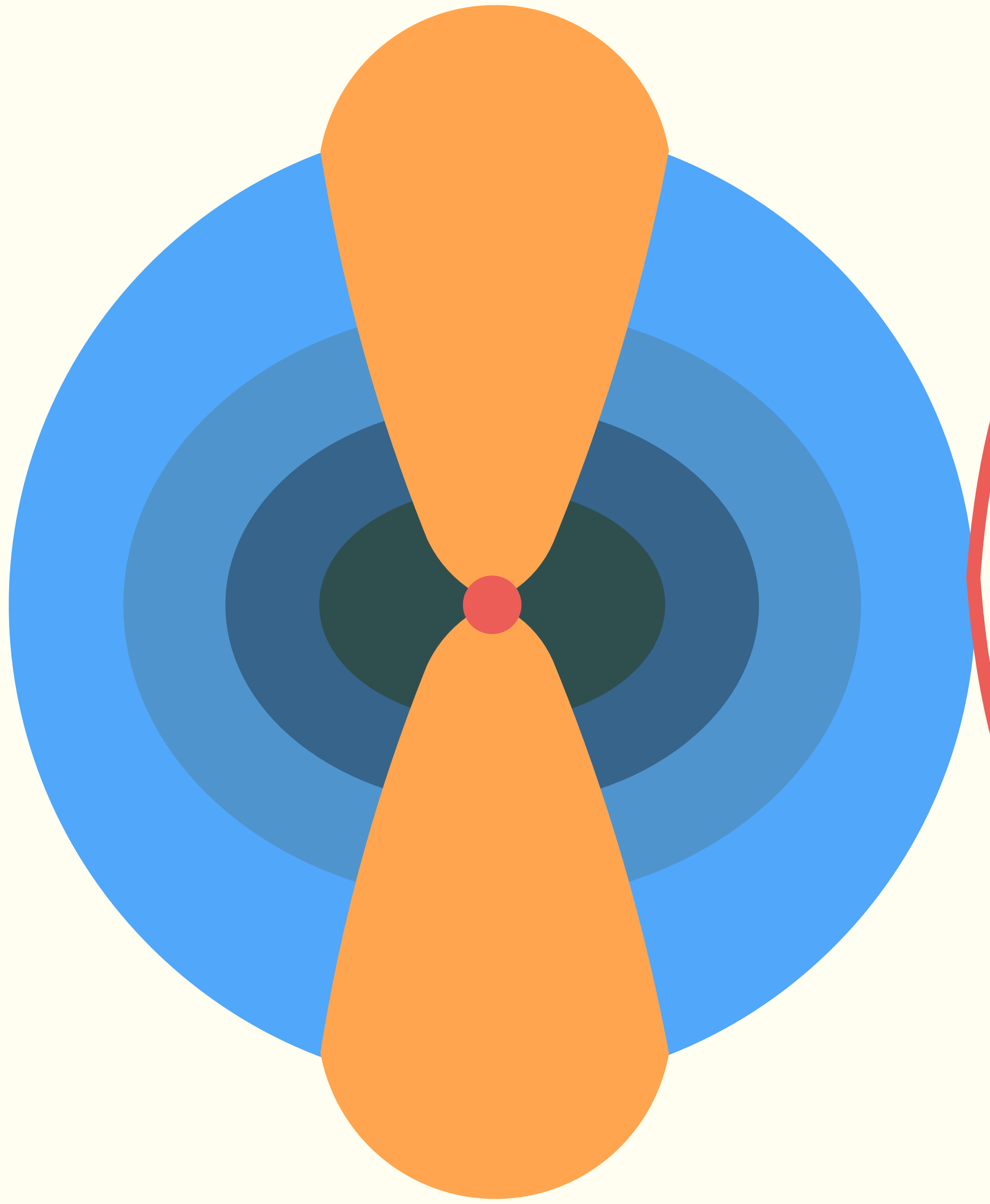


`Hyperion` (Robitaille 2012)
continuum radiative transfer

Structures of the envelope and outflows

Herschel continuum SED and *Spitzer* images

temperature
initial envelope age
inclination

`LIME` (Brinch & Hogerheijde 2010)
line radiative transfer + `CASA`

Gas kinematics

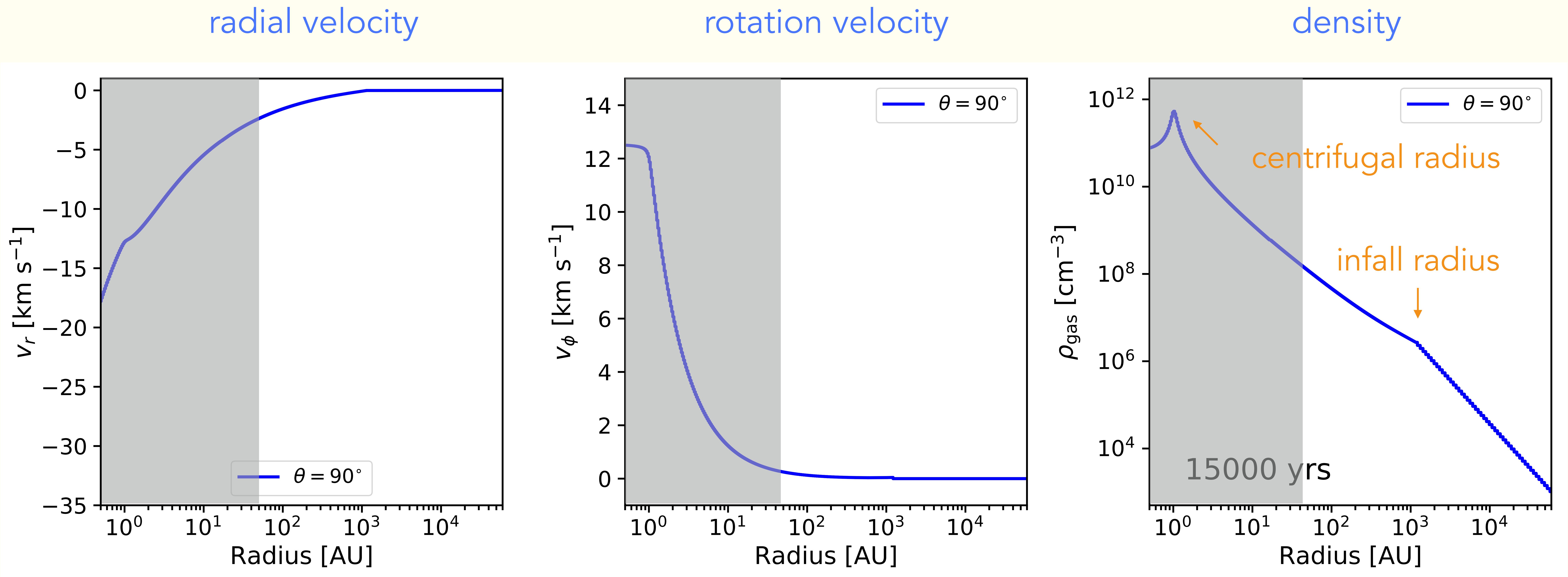
Molecular line profiles observed by ALMA

Customized ray-tracing package (`LIME-Additional Intensity Decoder`) for including the absorption of the continuum (adopted from Smith+2015 for Lyα emission)

The TSC slowly rotating infalling envelope

Terebey, Shu, & Cassen (1984, TSC)

v_θ included but not shown here



along the midplane of the envelope

(disk dynamics are not properly considered)

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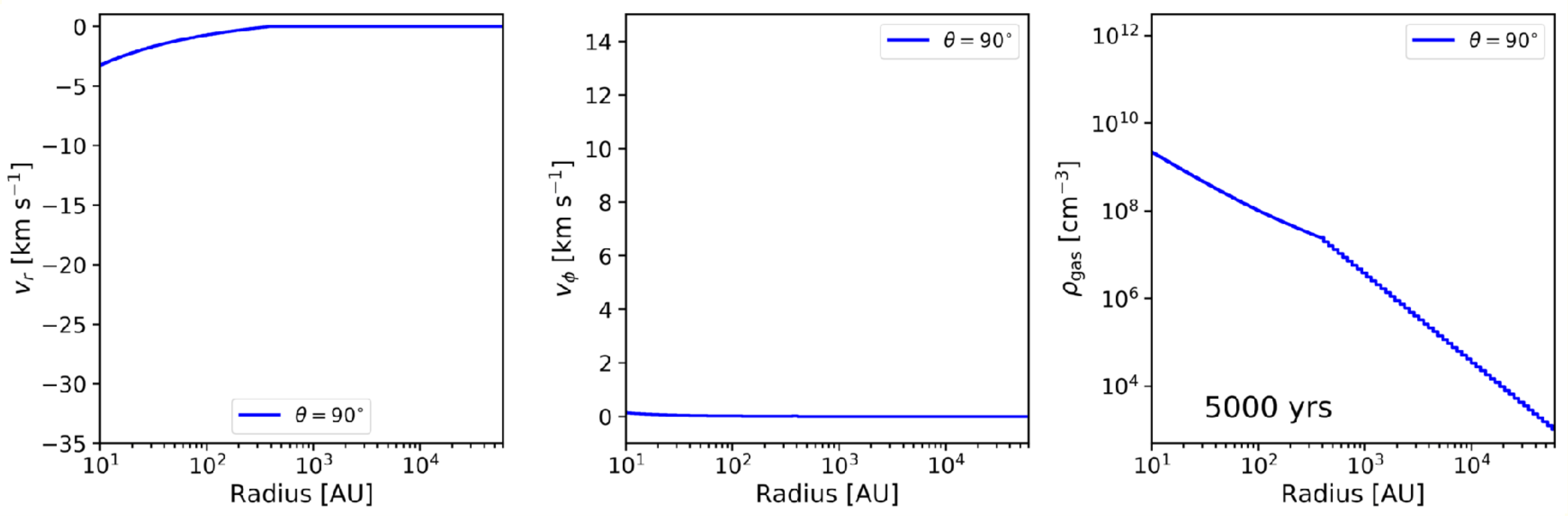
radial velocity

rotation velocity

density



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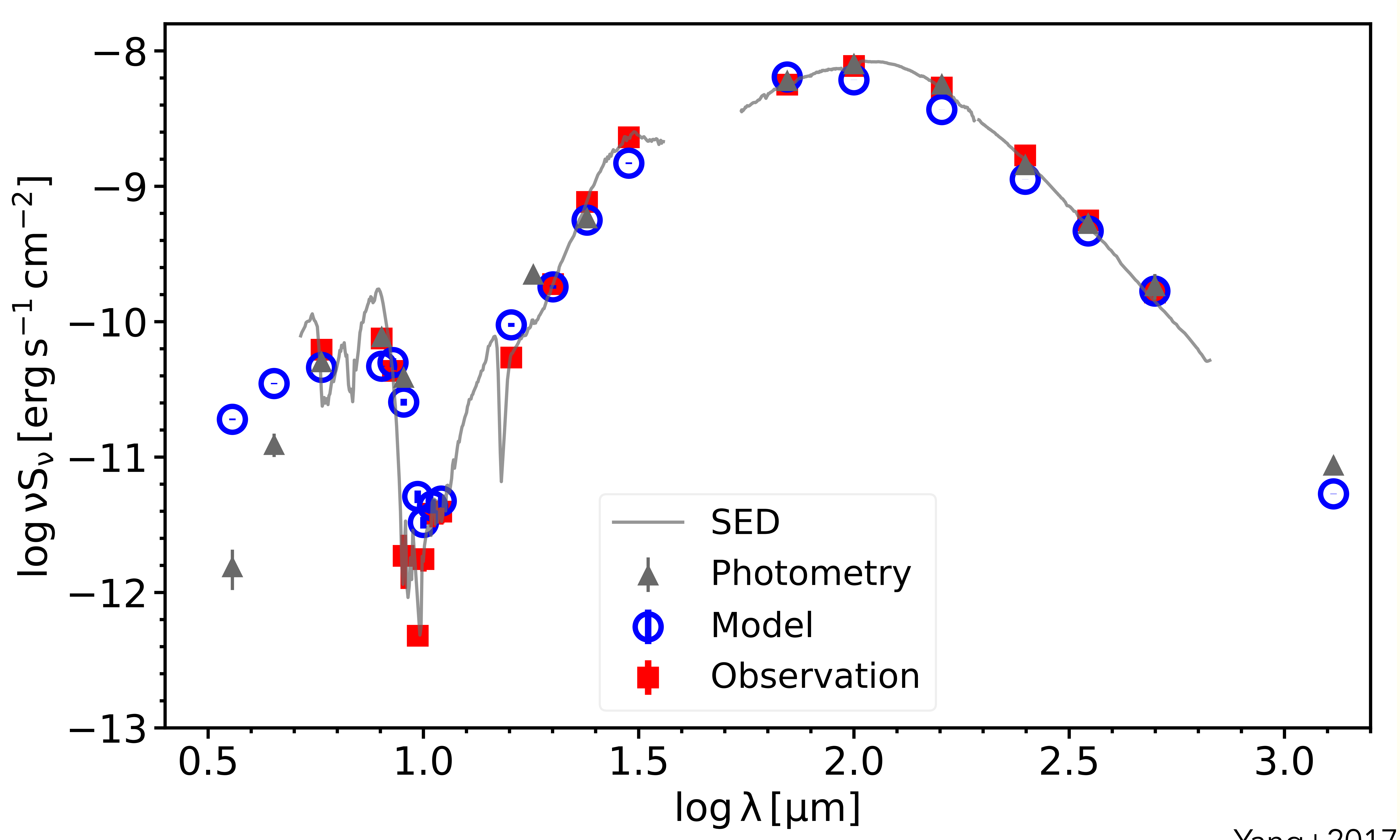
Slowly rotating infalling envelope fits the SED

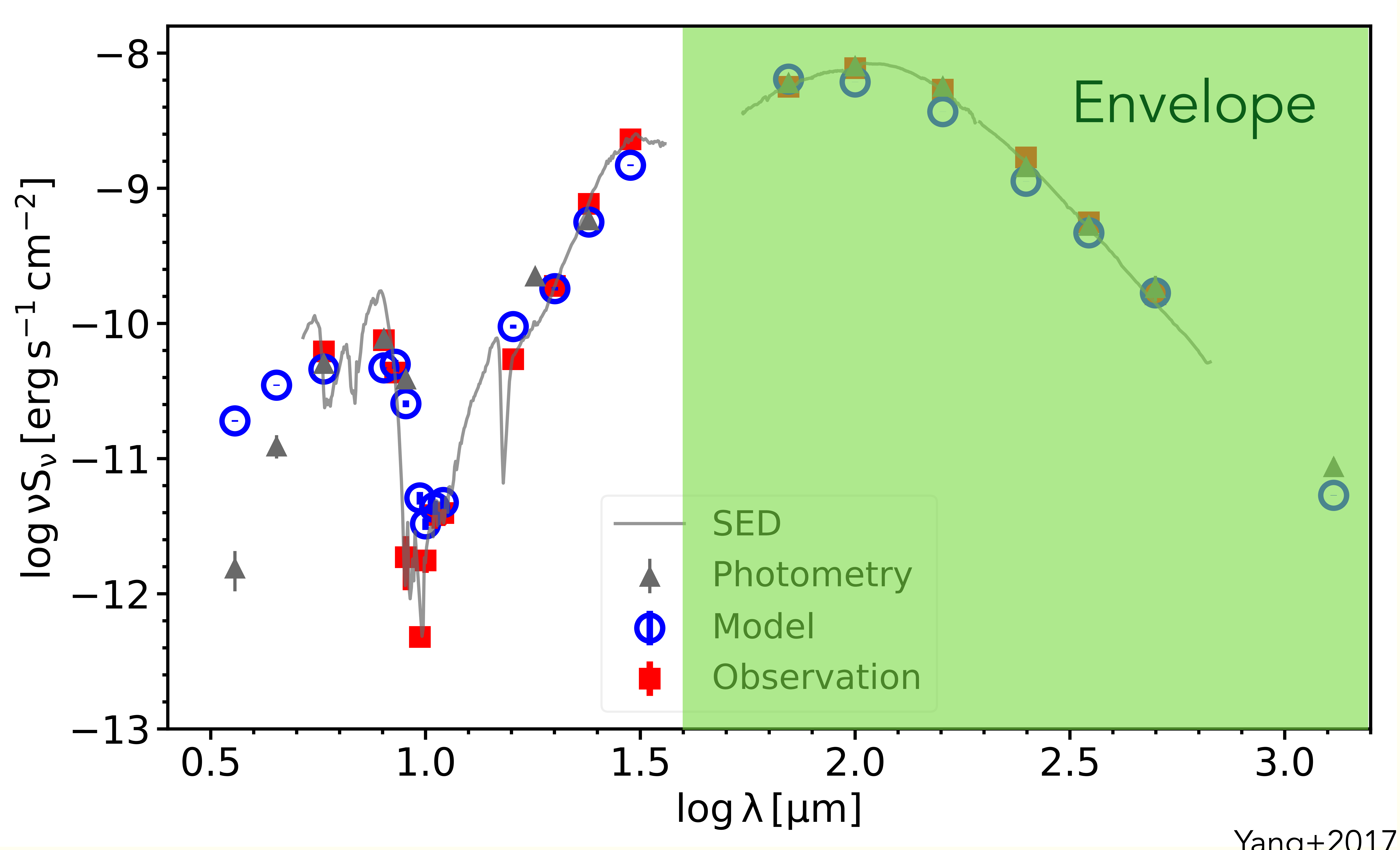
Age ➠ Inclination ➠ **SED**



Yang+2017

Slowly rotating infalling envelope fits the SED

Age ➠ Inclination ➠ **SED**



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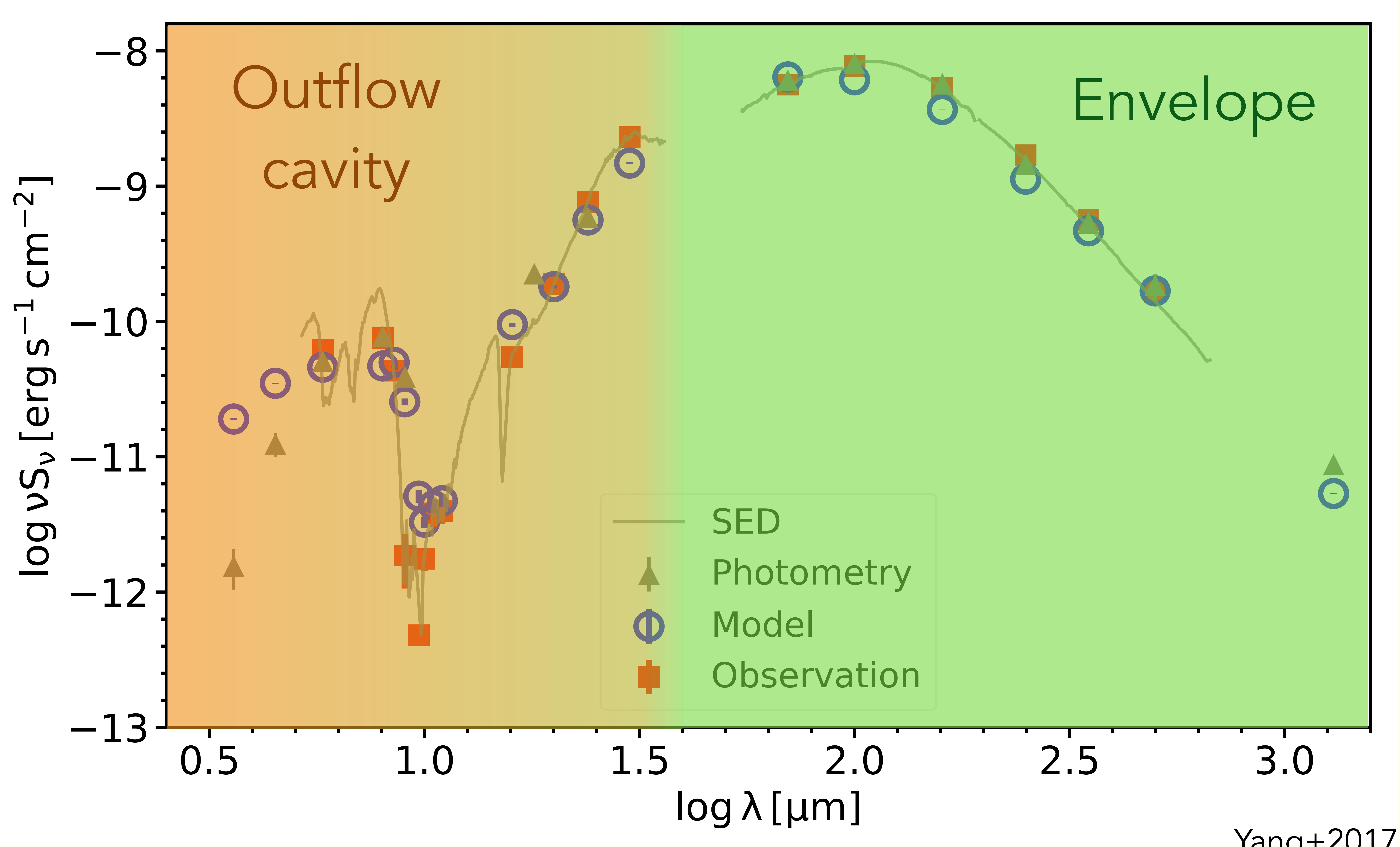

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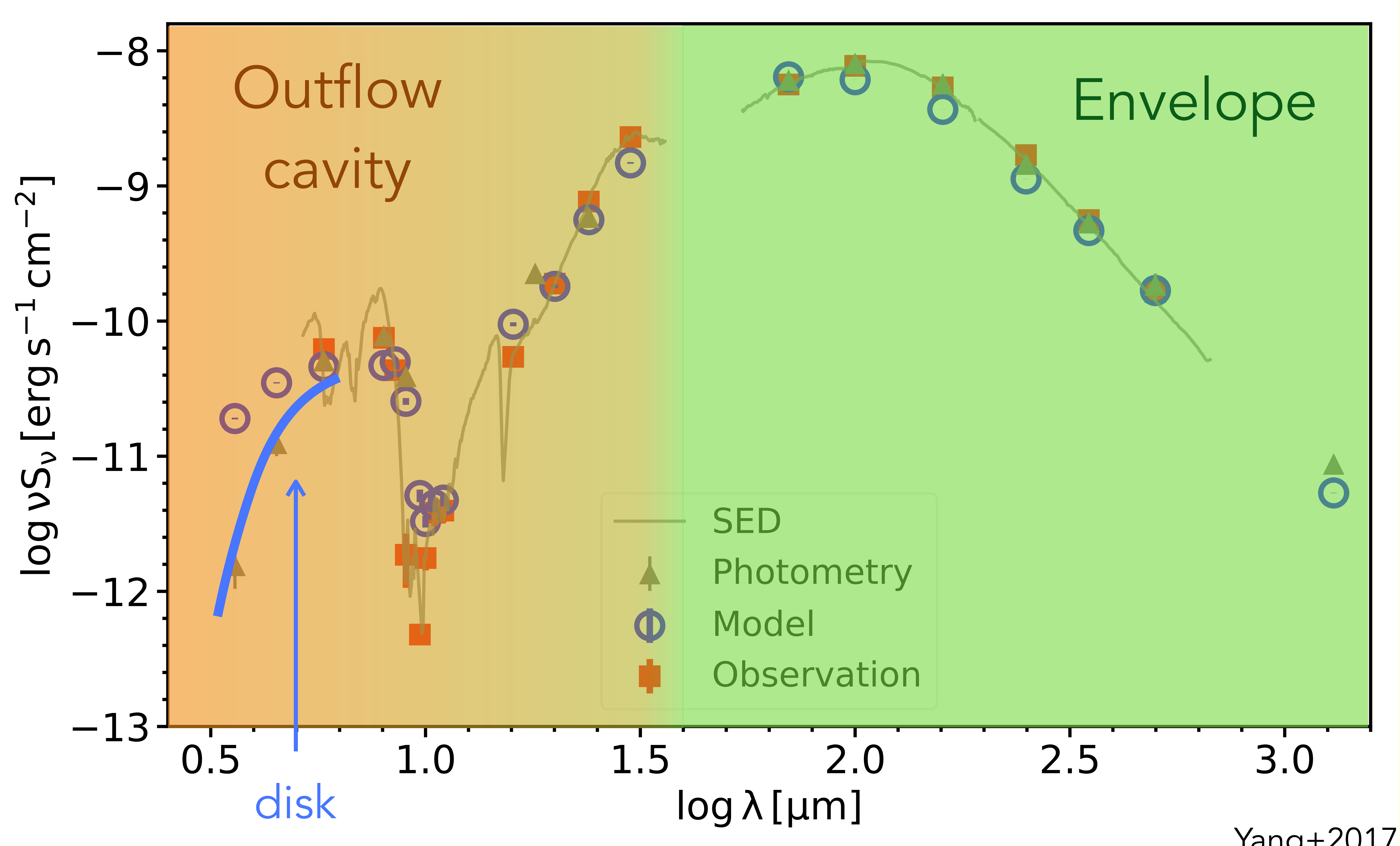
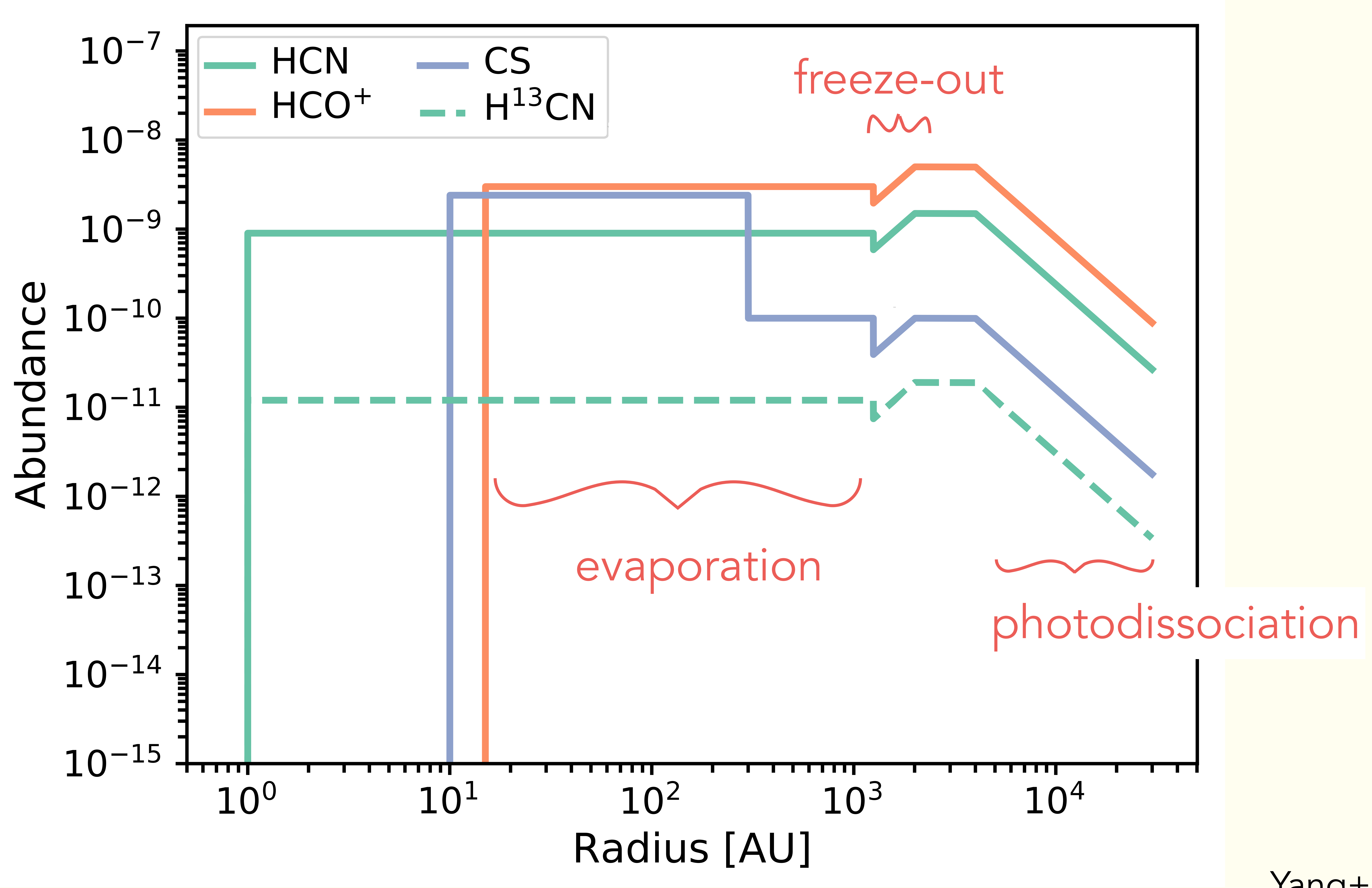


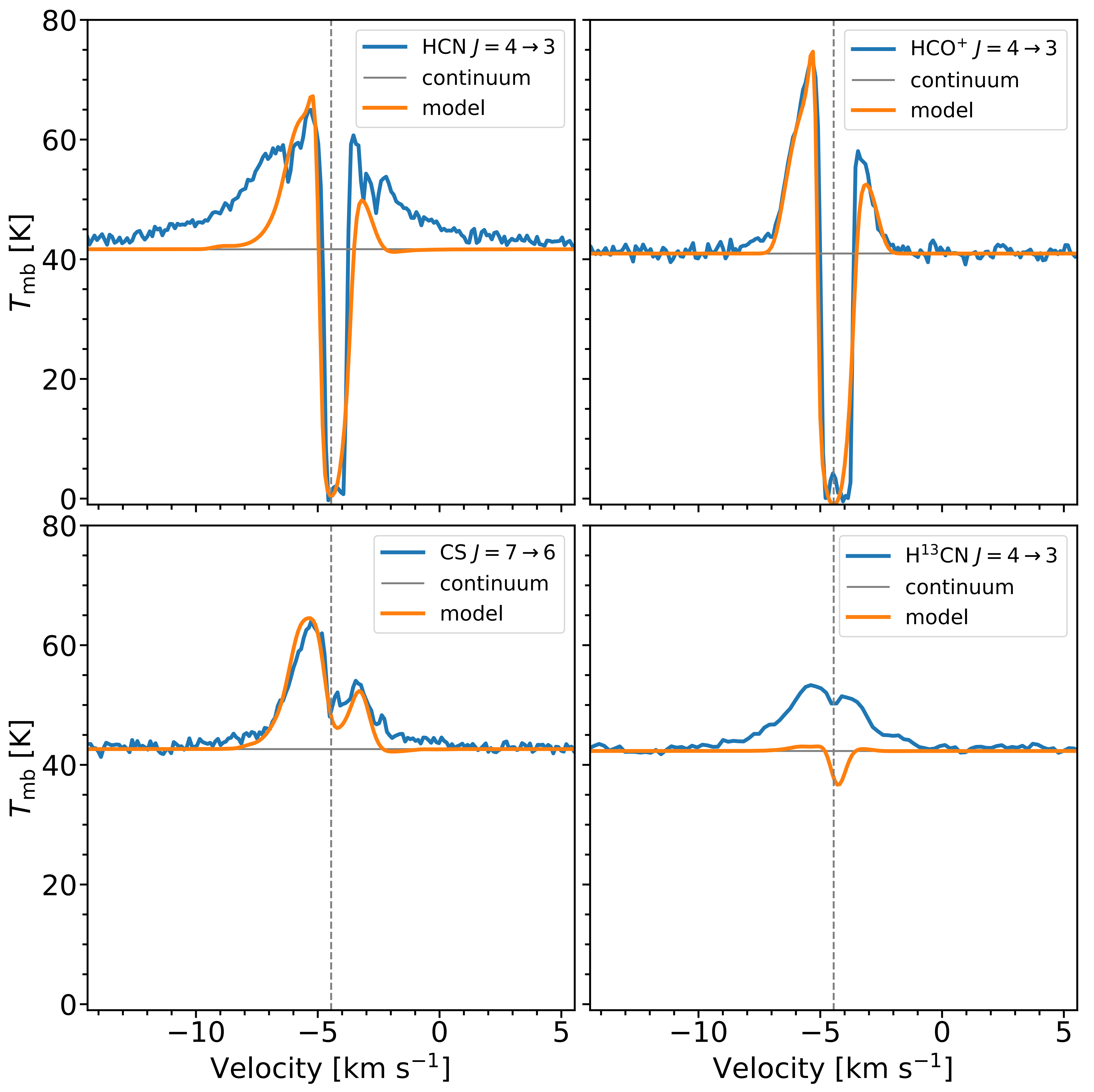
Yang+2017

A parameterized treatment of chemical abundance



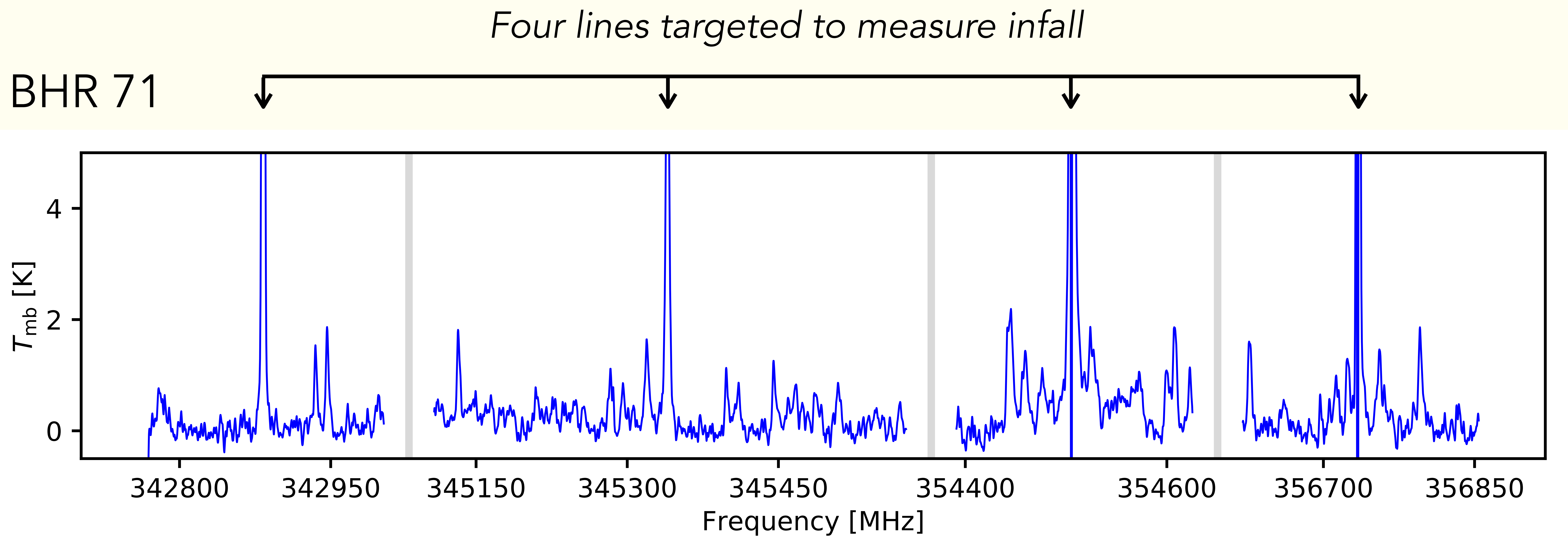
Yang+2019 subm.

A simple TSC envelope reproduces (most of) the ALMA observations



Yang+2019 subm.

A serendipitous discovery of complex organic molecules (COMs)

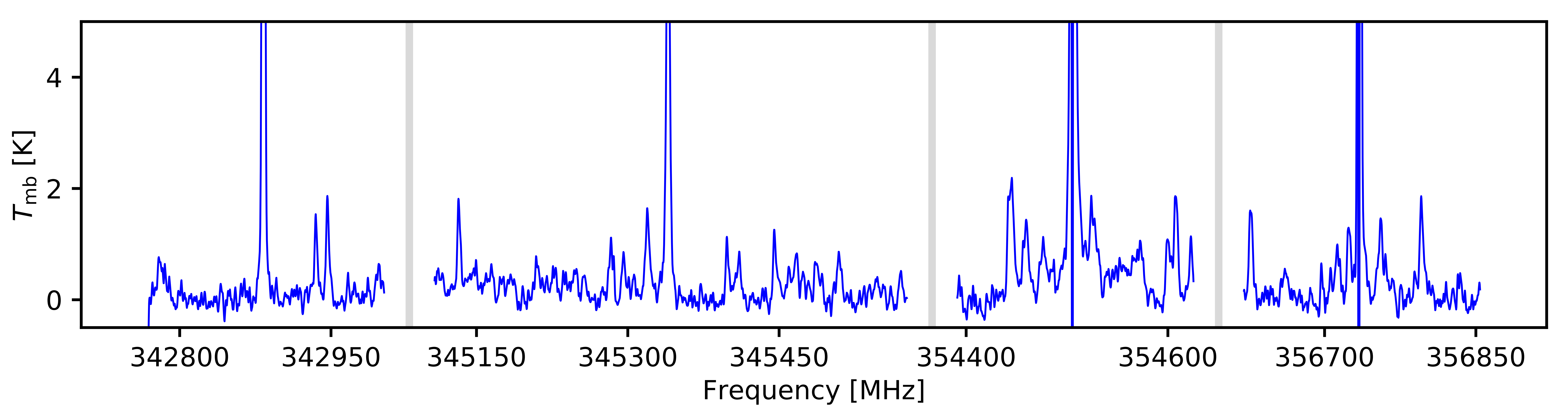


Yang+2019 subm.

A serendipitous discovery of complex organic molecules (COMs)

Four lines targeted to measure infall

BHR 71



What are those emission lines?

Yang+2019 subm.

A serendipitous discovery of complex organic molecules (COMs)

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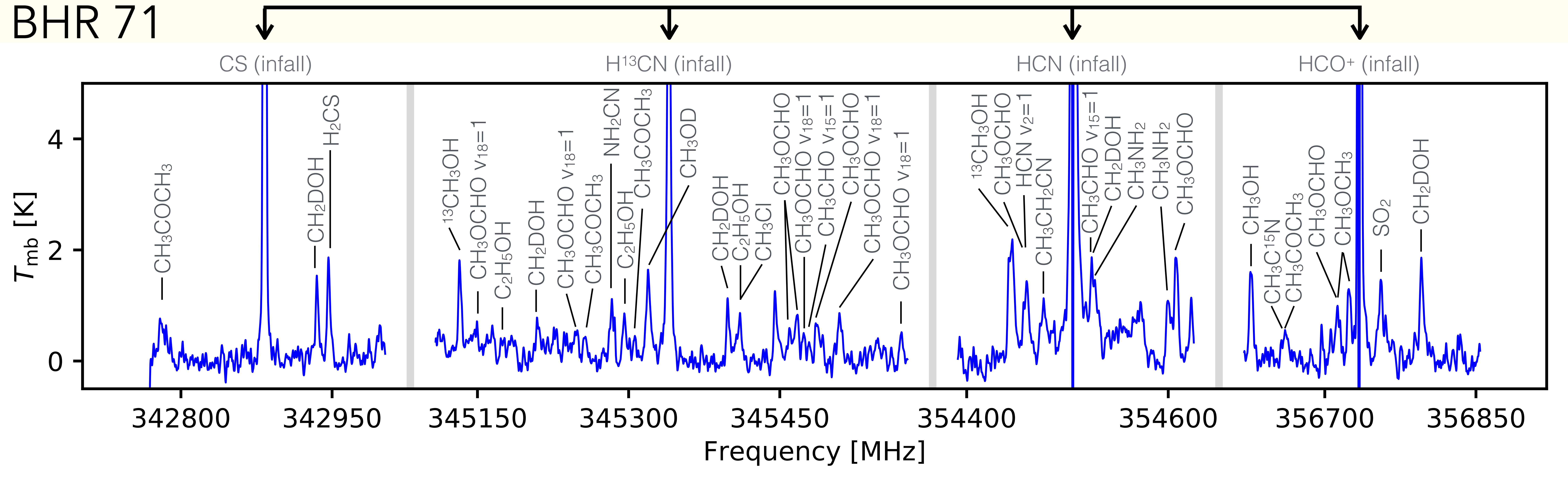
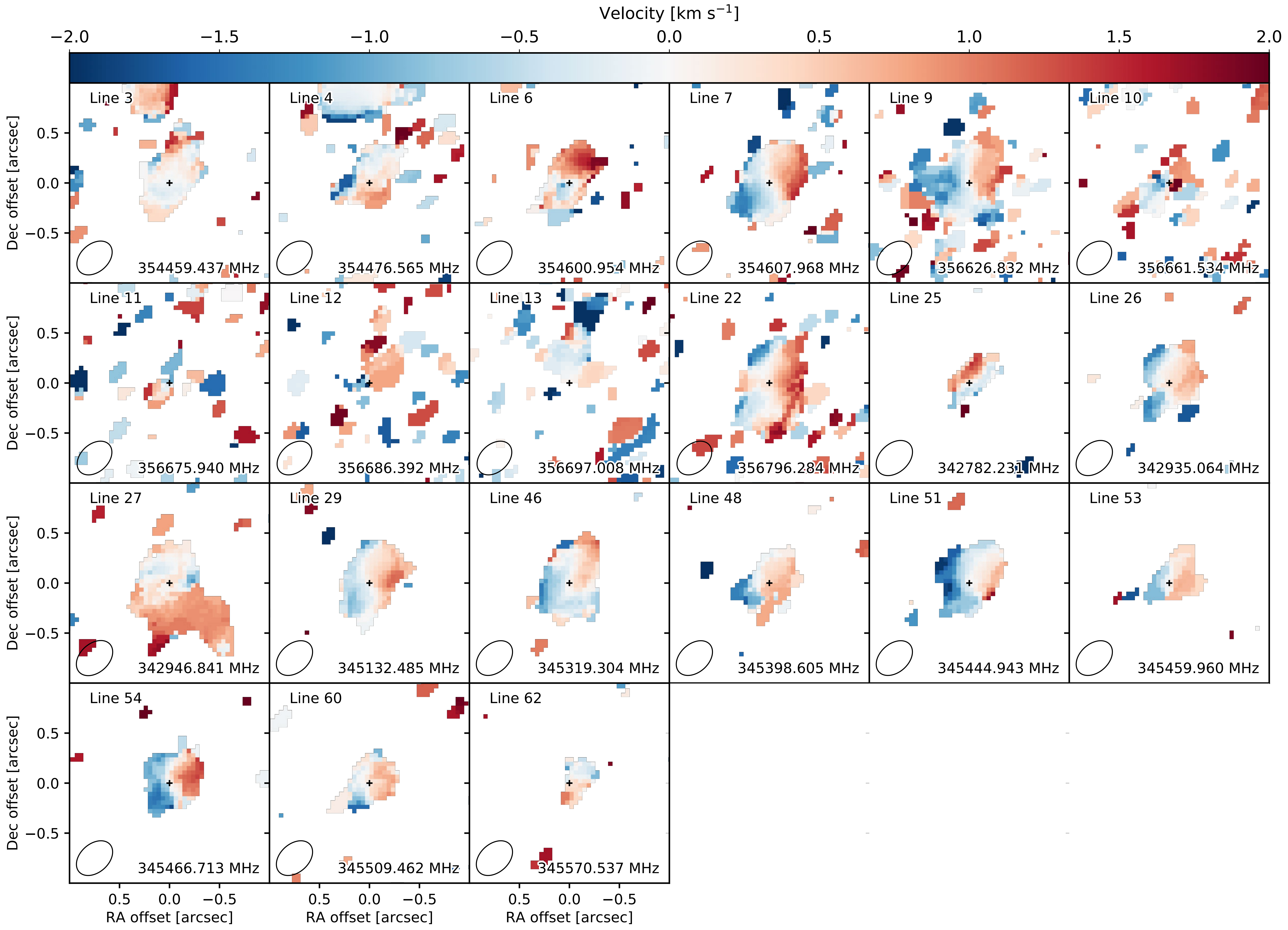


Identified 8 species of COMs + many tentatively identified

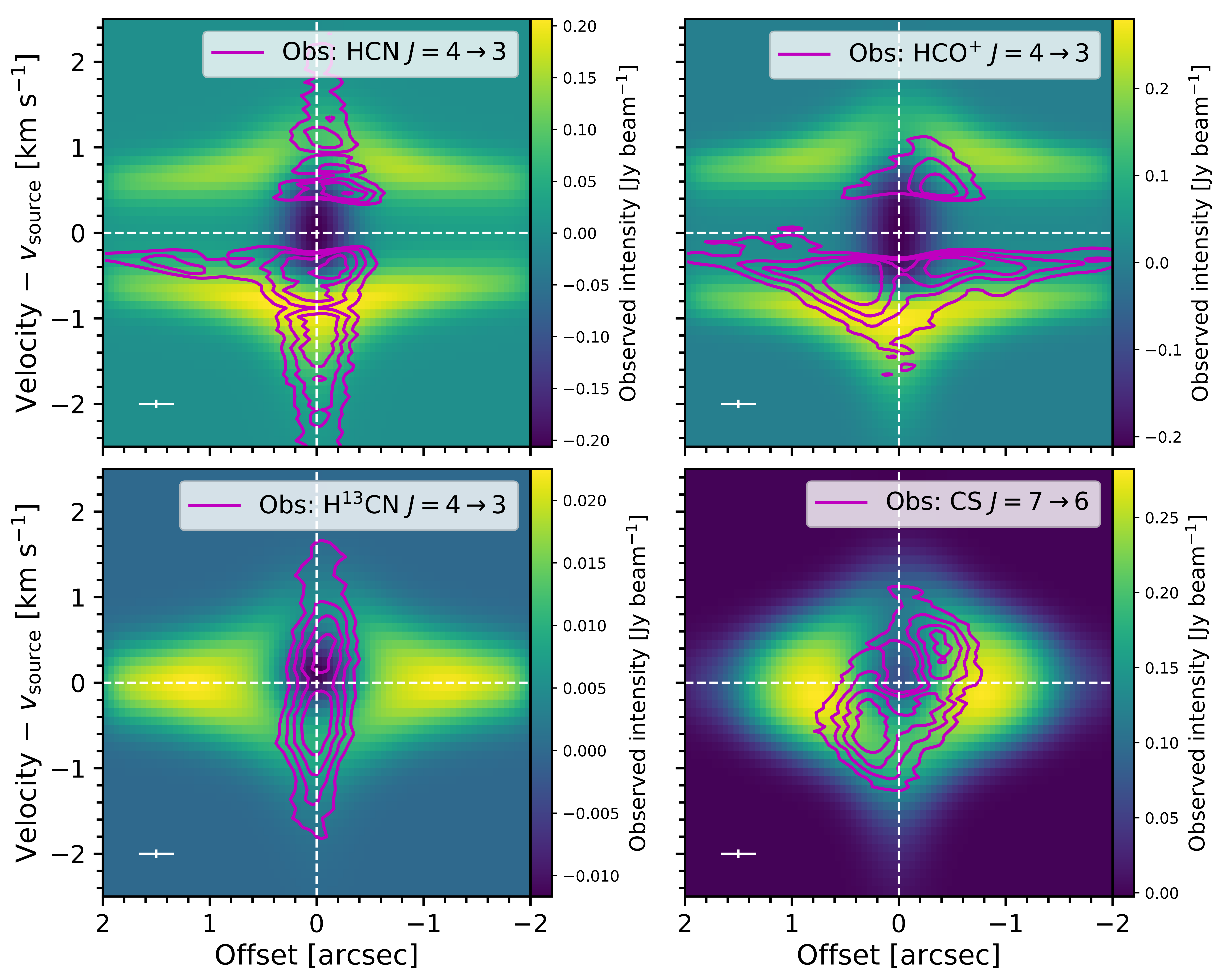
Yang+2019 subm.

The rotation kinematics traced by COMs



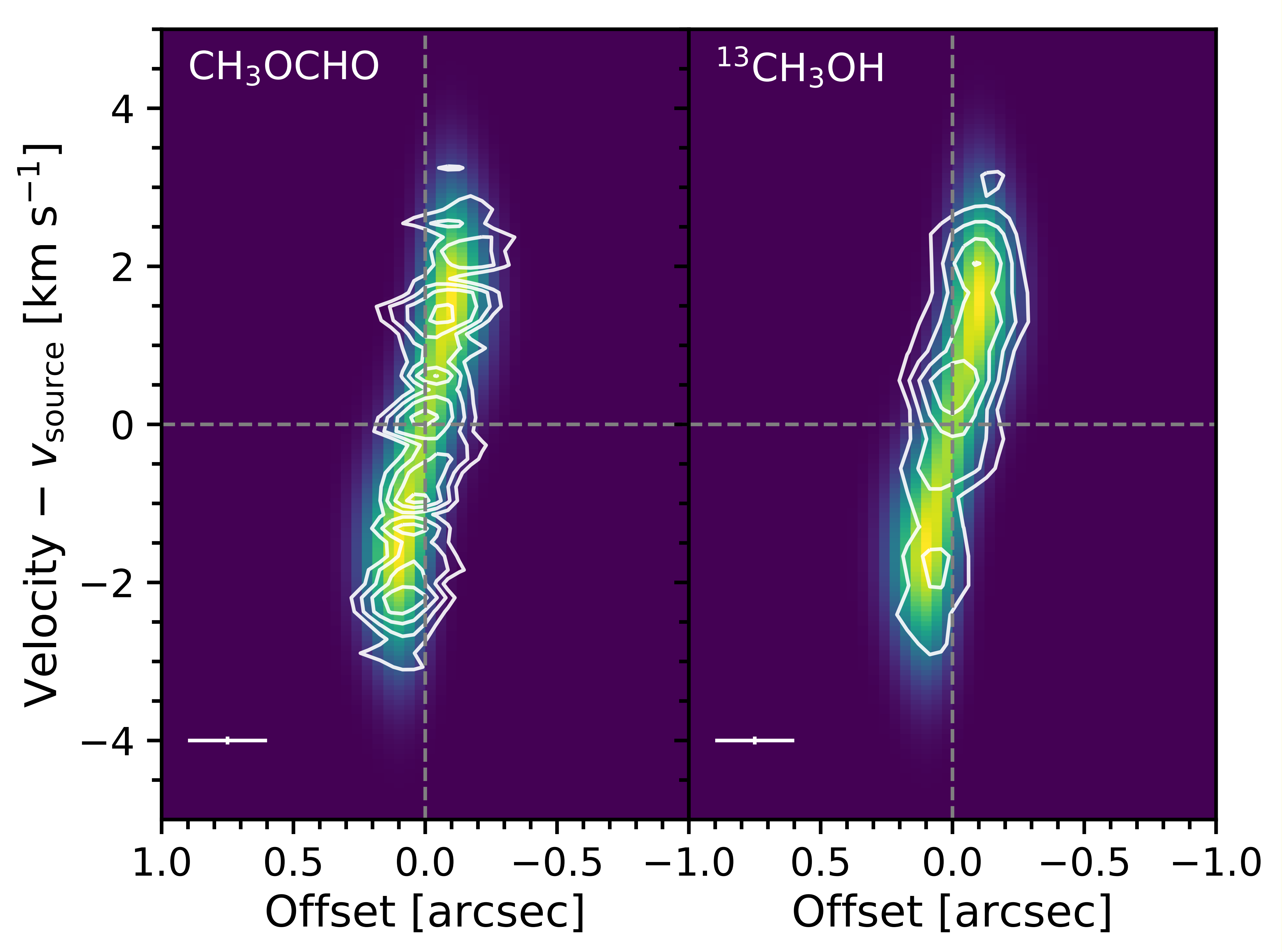
Yang+2019 subm.

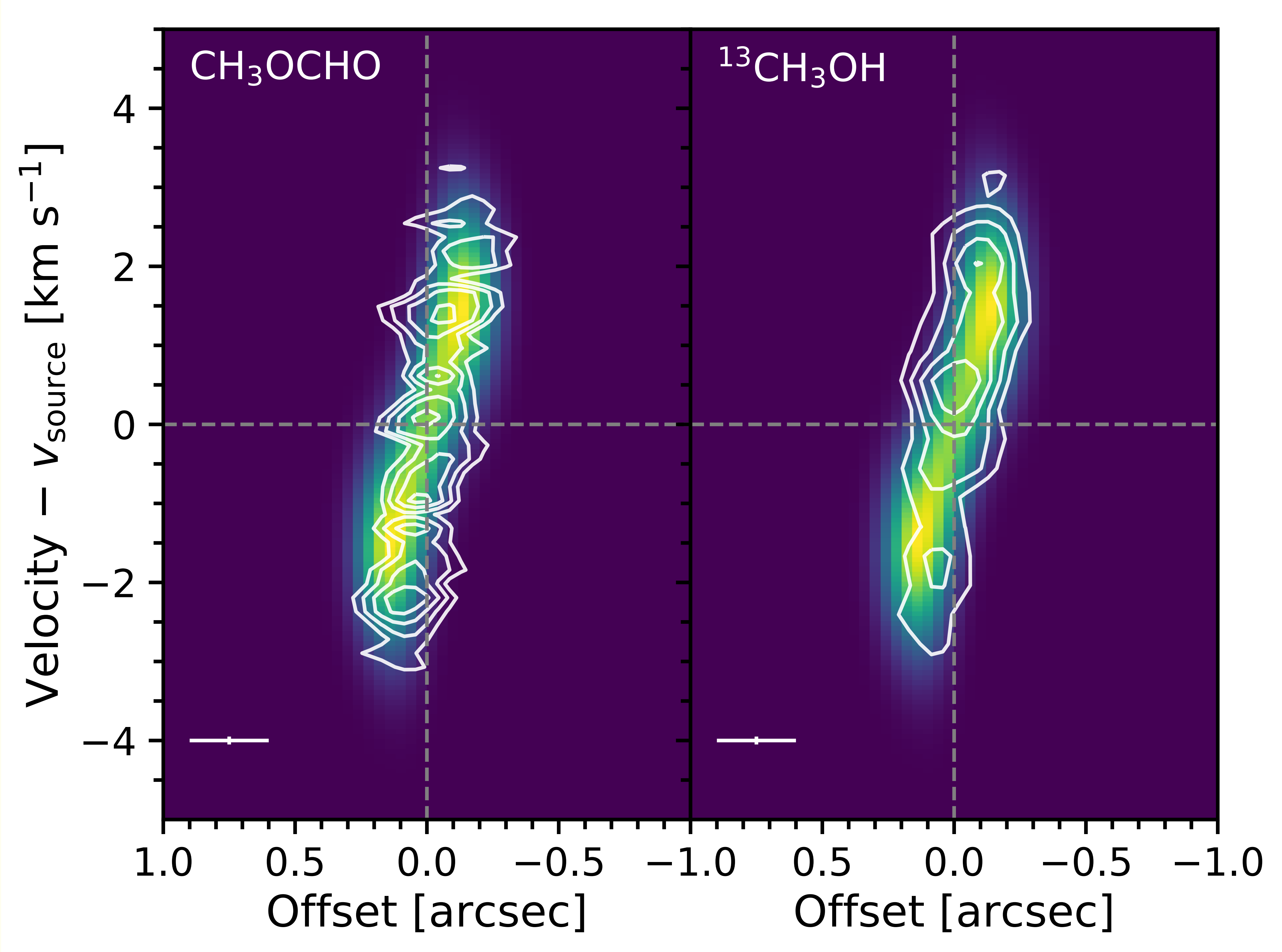
A higher rotation at the inner region



Yang+2019 subm.

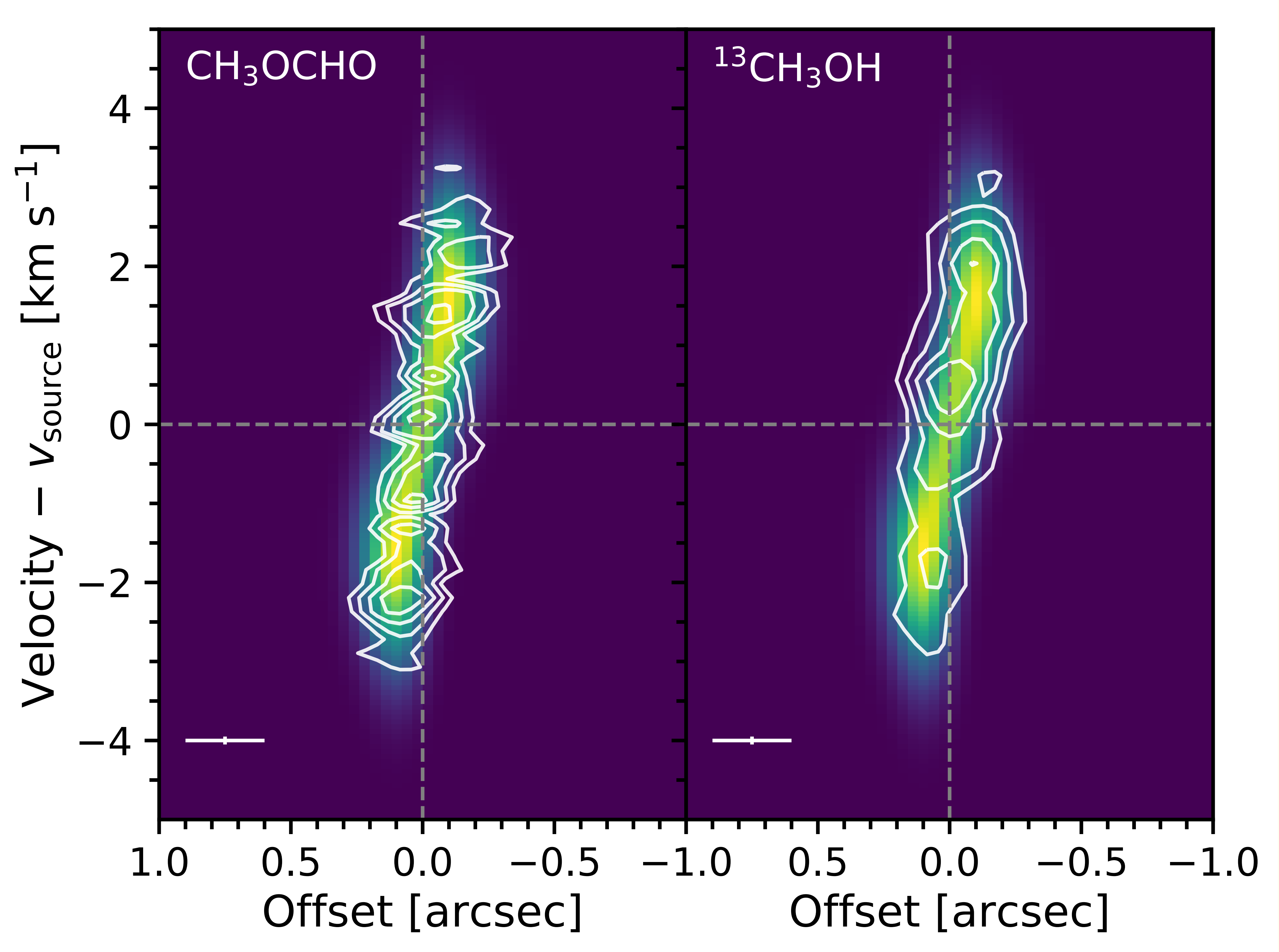
The Kinematics traced by the COMs emission: a disk?



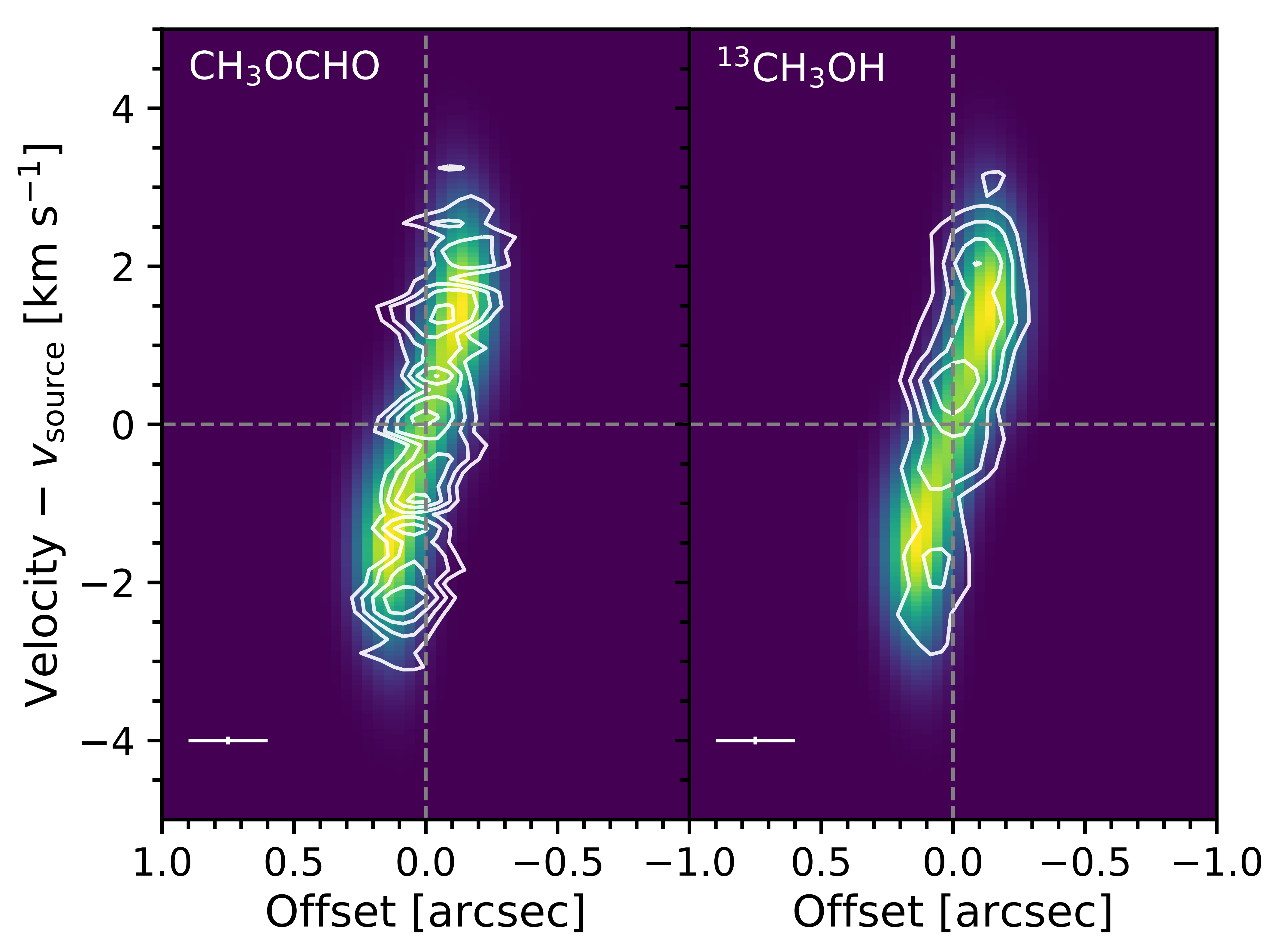


The Kinematics traced by the COMs emission: a disk?

power-law brightness

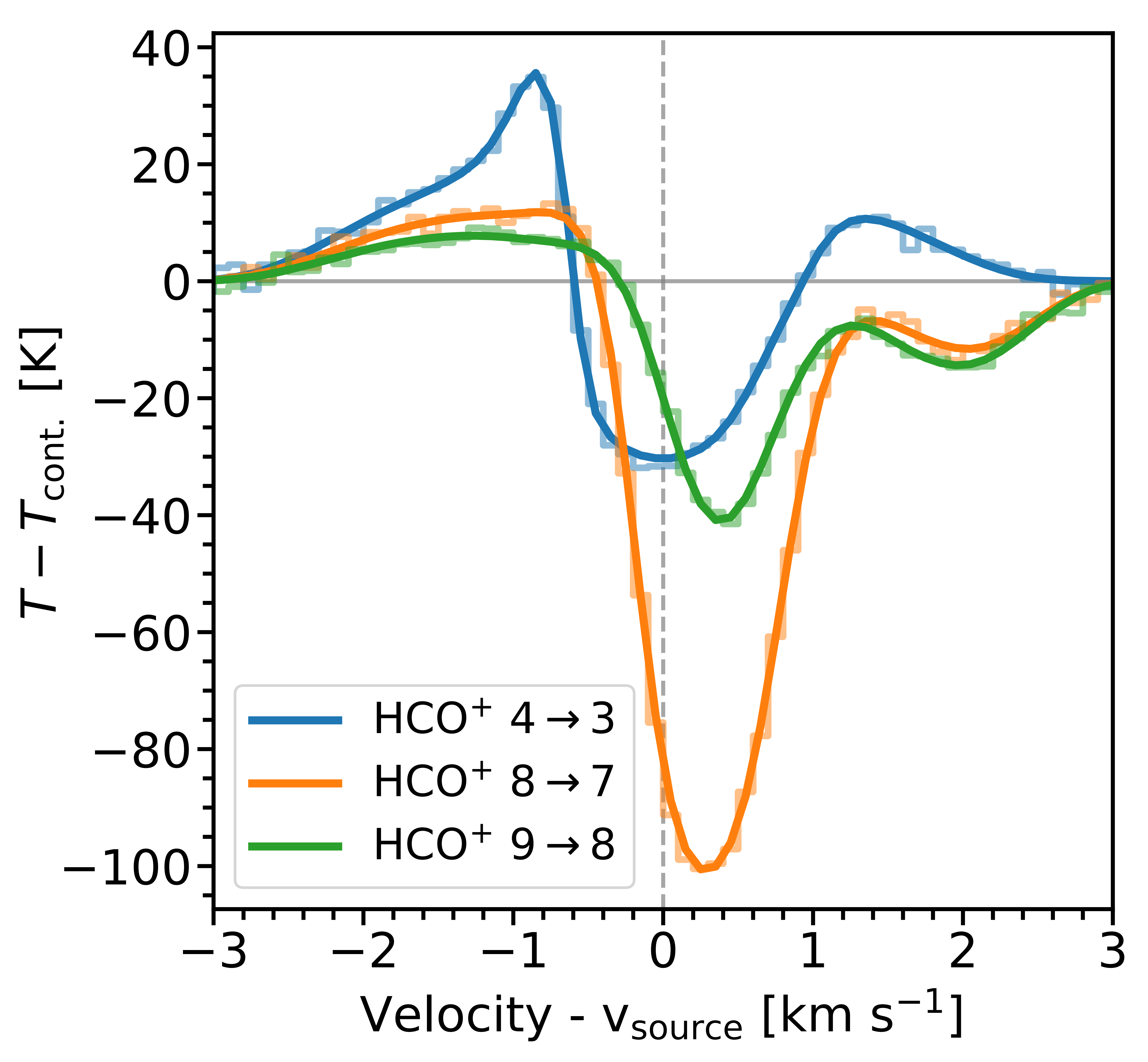


uniform brightness



Toward empirical measurements of kinematics as function of radius

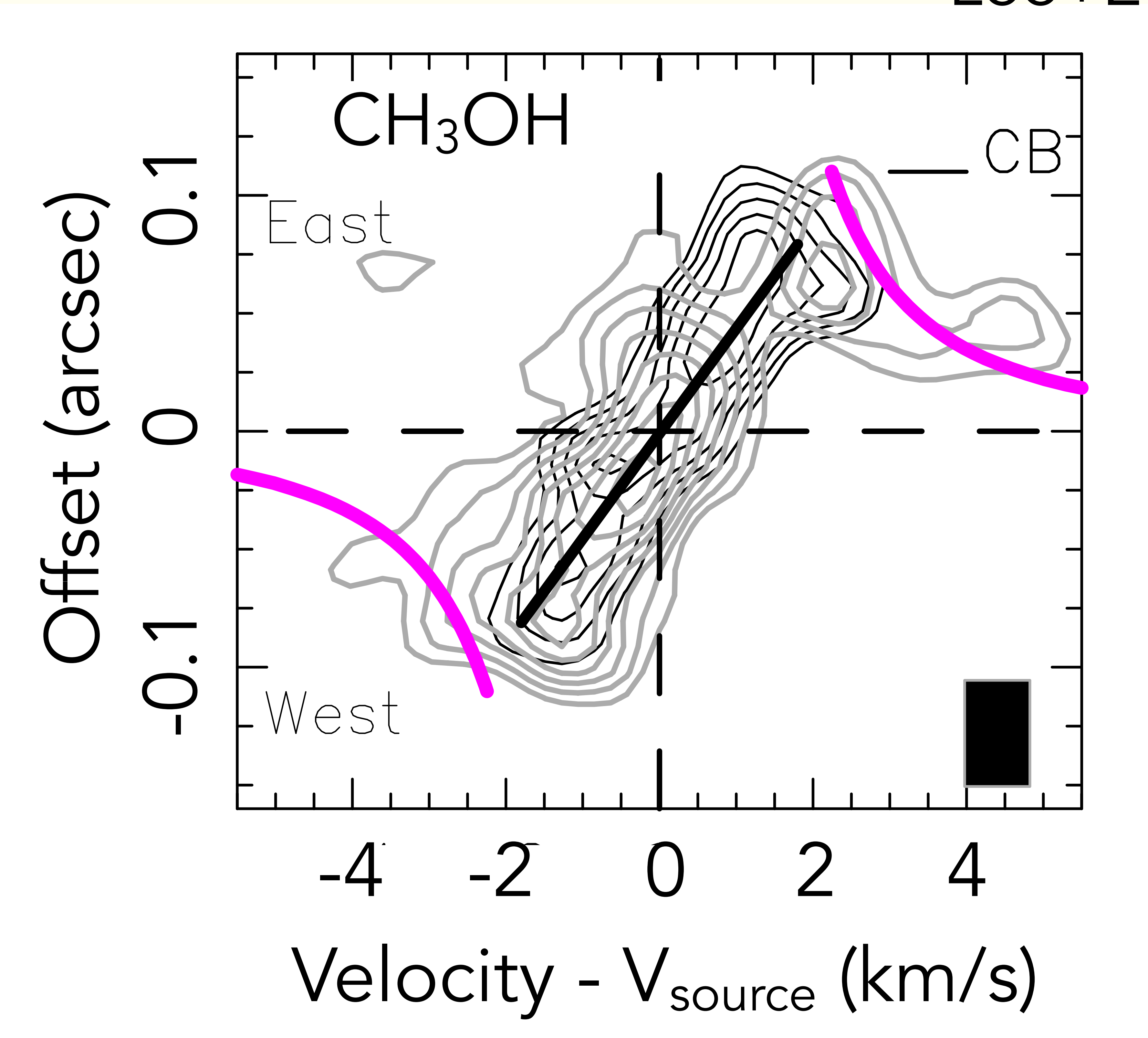
Empirical measurements of infall with multiple transitions of the same molecule



+

Kinematics at the disk-forming region traced by COMs

Lee+2017

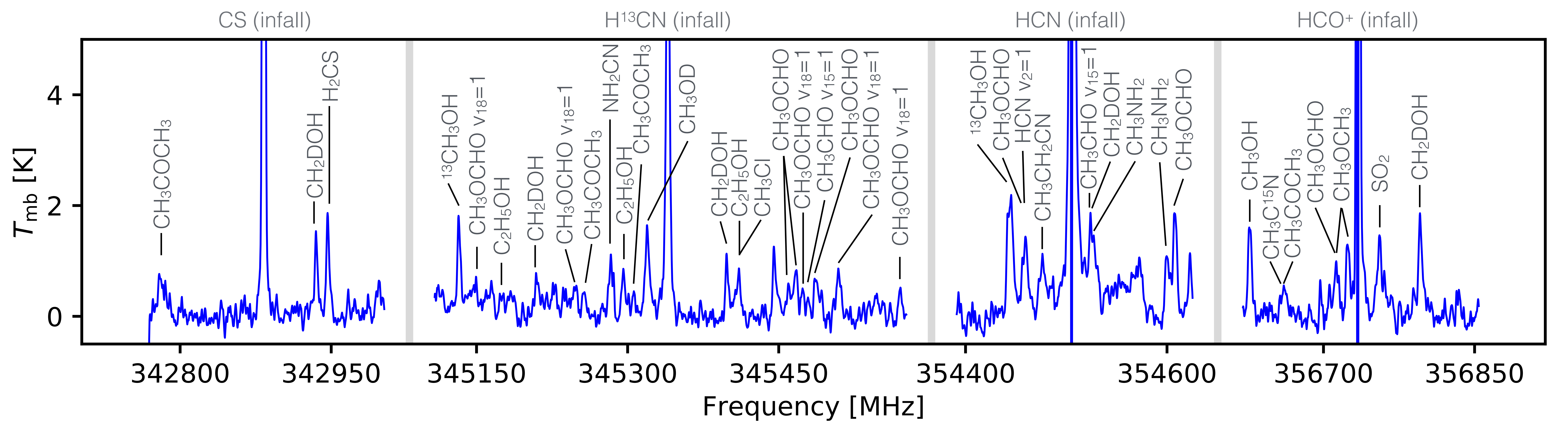


Direct comparison between simulations and observations with synthetic observations

We are approved for Cycle 7!

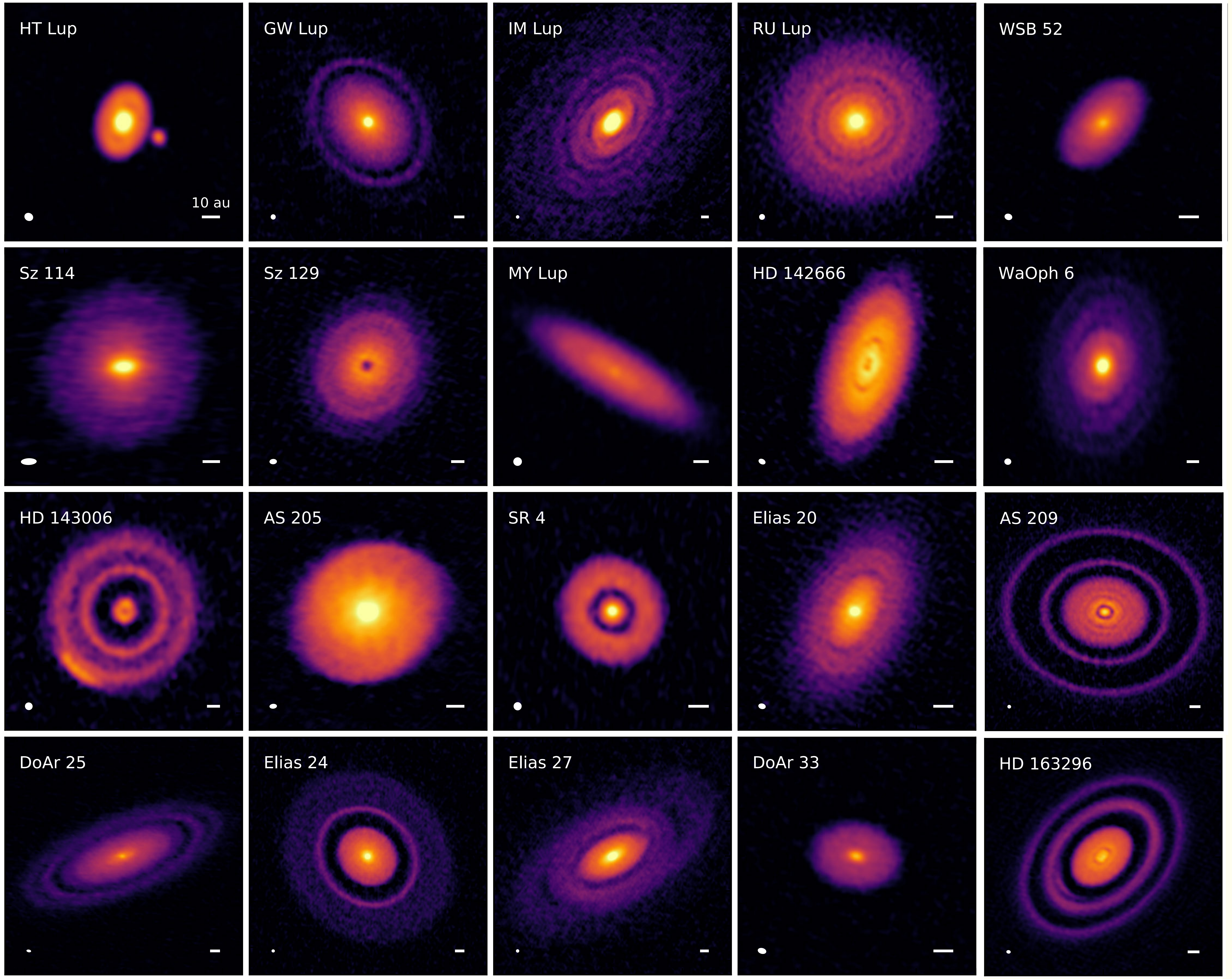
Are COMs common for embedded protostars?

BHR 71



Yang+2019 subm.

Diverse planets born from a complex environment

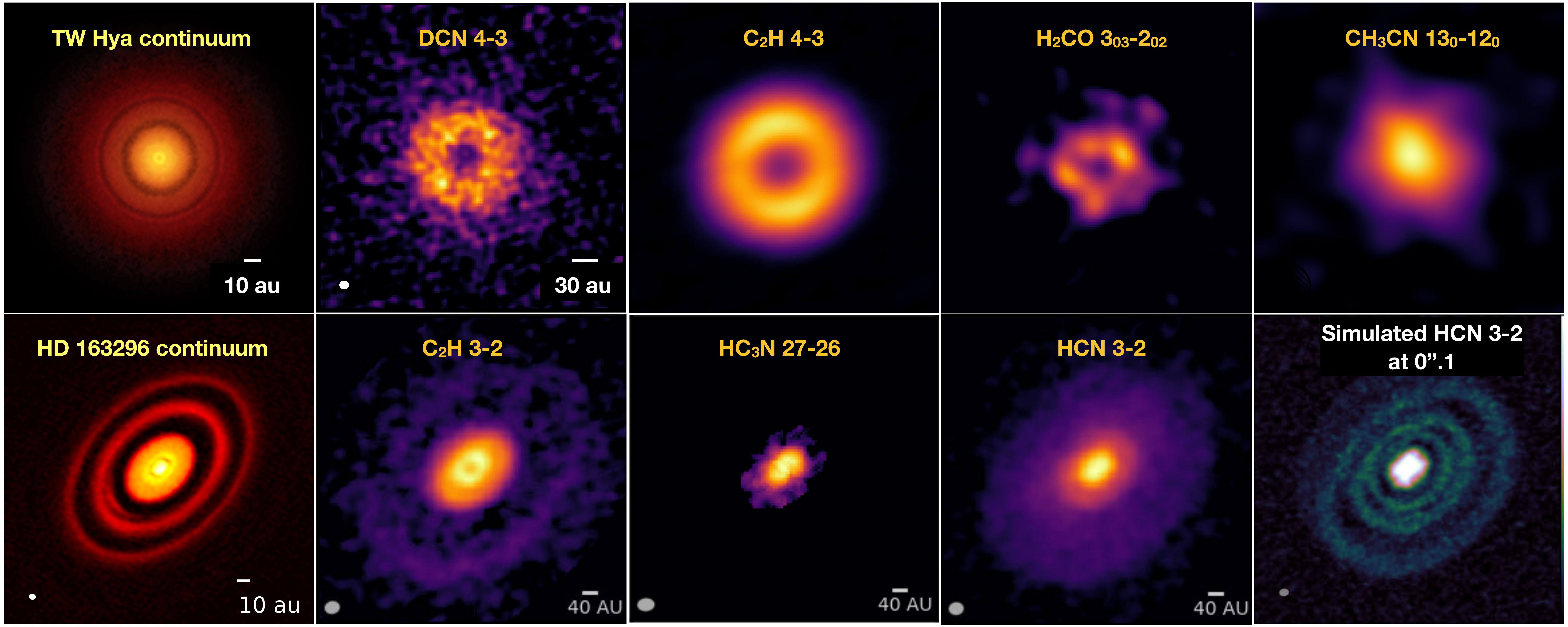


Andrews+2018 (DSHARP)

Diverse planets born from a complex environment

What processes lead to these complex environments?

What are the initial conditions of protoplanetary disks and the star-forming cores that gave birth to those disks?



Öberg+2019 (astro2020 white paper)

Complex molecules at protostellar cores

What are complex molecules and where do they come from?

In Herbst & van Dishoeck (ARA&A, 2009)

"We arbitrarily refer to species with **six** atoms or more as complex"

"100% of the detected species with **six** or more atoms are organic." (carbon-bearing)

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Complex molecules (organic):

Saturated - richer in hydrogen (limited to single chemical bonds)

e.g. CH_3OH (methanol), CH_3OCH_3 (dimethyl ether), C_2H_5OH (ethanol)

Unsaturated - fewer in hydrogen

e.g. C_n, C_nH, HC_nN (cyanopolyynes)

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Long carbon-chain molecules - fewer in hydrogen

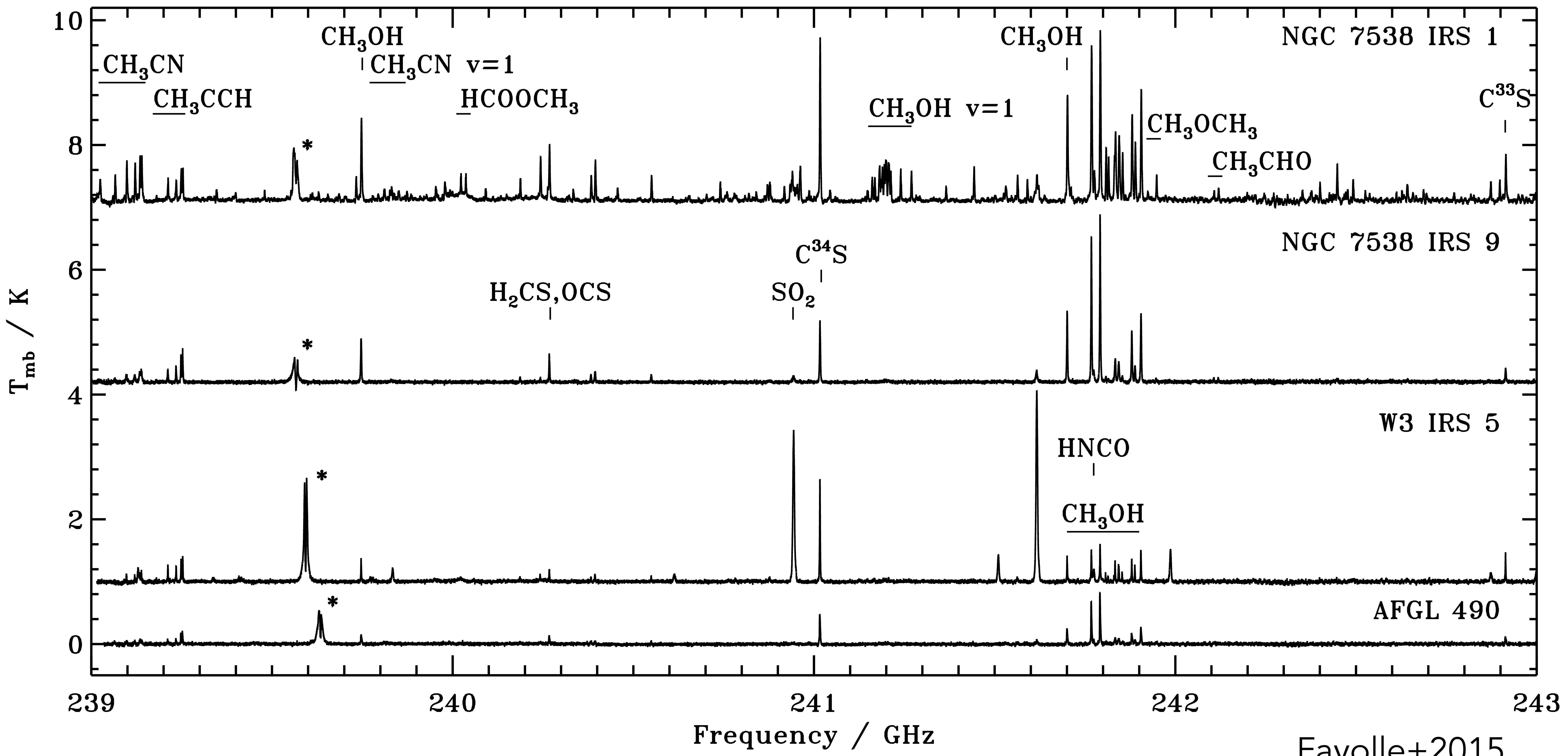
e.g. C_n, C_nH, HC_nN (cyanopolyynes)

"Most common terrestrial organic molecules tend to be saturated or near-saturated."

Complex organic molecules (COMs): high-mass sources

Massive young stellar objects (hot cores)

also Sgr B2(N), (M) (e.g.Belloche+2013)



Fayolle+2015

Complex organic molecules (COMs) at low-mass sources

Hot Corinos

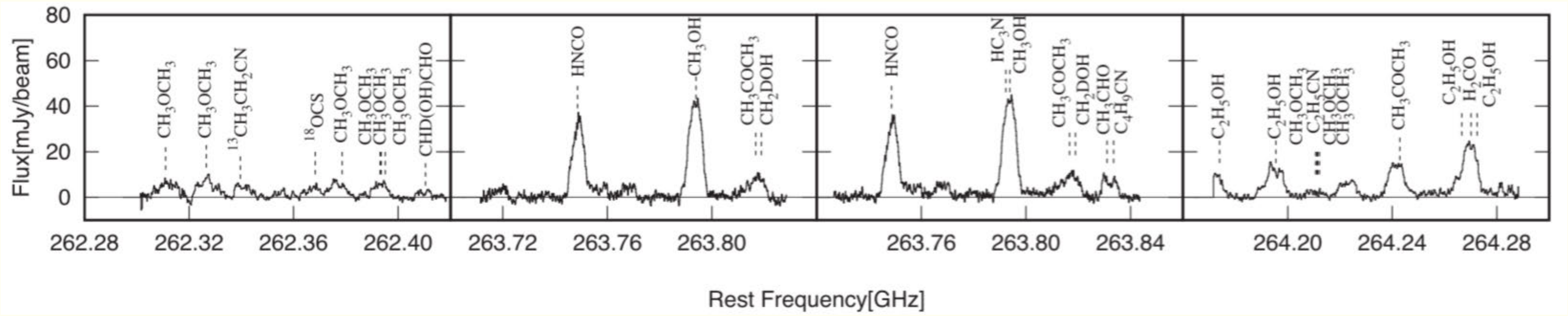
aka. small hot cores

(Ceccarelli 2004)

- rich in saturated complex molecules
- similar chemical abundances as hot cores, but the ratios of some molecules are distinctively different

IRAS 16293-2422 (e.g. van Dishoeck+1995, Jørgensen+2016, The PILS survey), B335 (Imai+2016, Evans+ in prep.), L483 (Oya+2017, Jacobsen+2018), BHR 71 (Yang+2019 subm.), and surveys like Bergner+2017 and Higuchi+2018

B335 (Imai+2019)



Warm carbon-chain chemistry sources

- Rich in unsaturated complex molecules
- In some cases (e.g. L483, Oya+2017), found outside of the continuum source coexisted with COMs

(e.g. Sakai+2008, 2009, Oya+2017, Law+2018)

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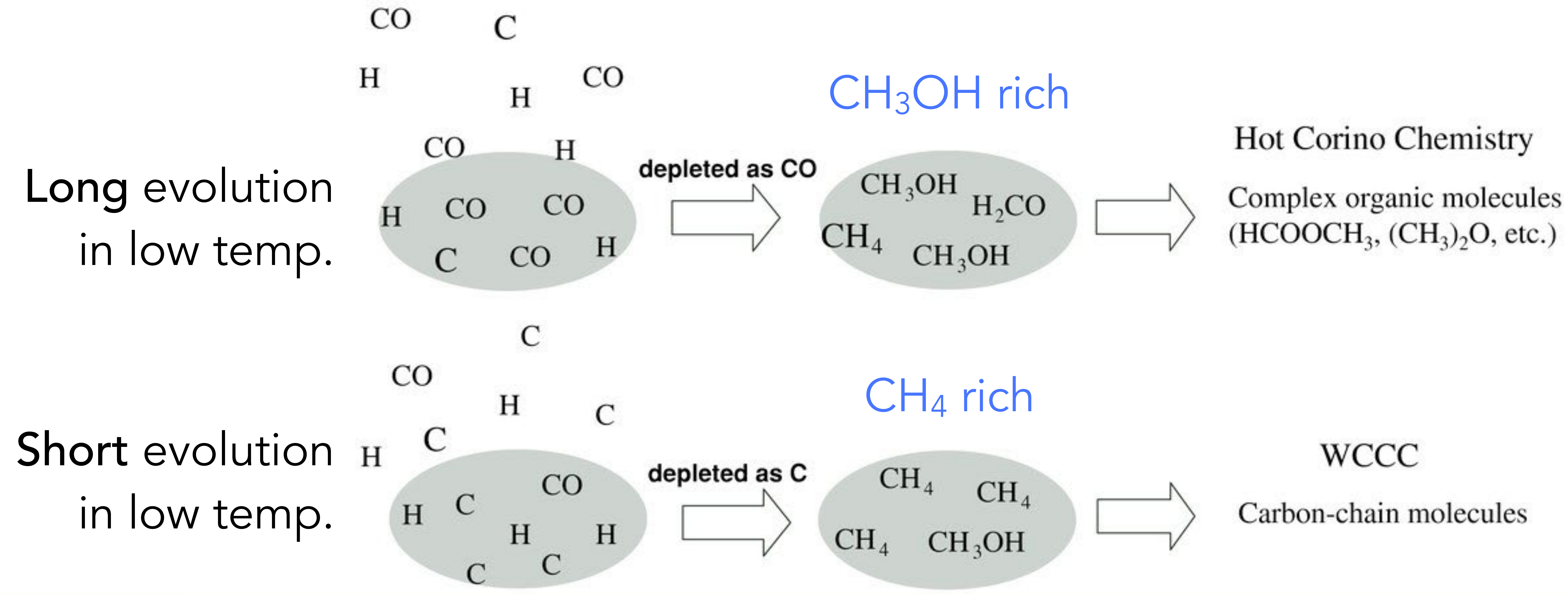

Sakai+2009a

Are COMs & long carbon-chain molecules mutually exclusive?

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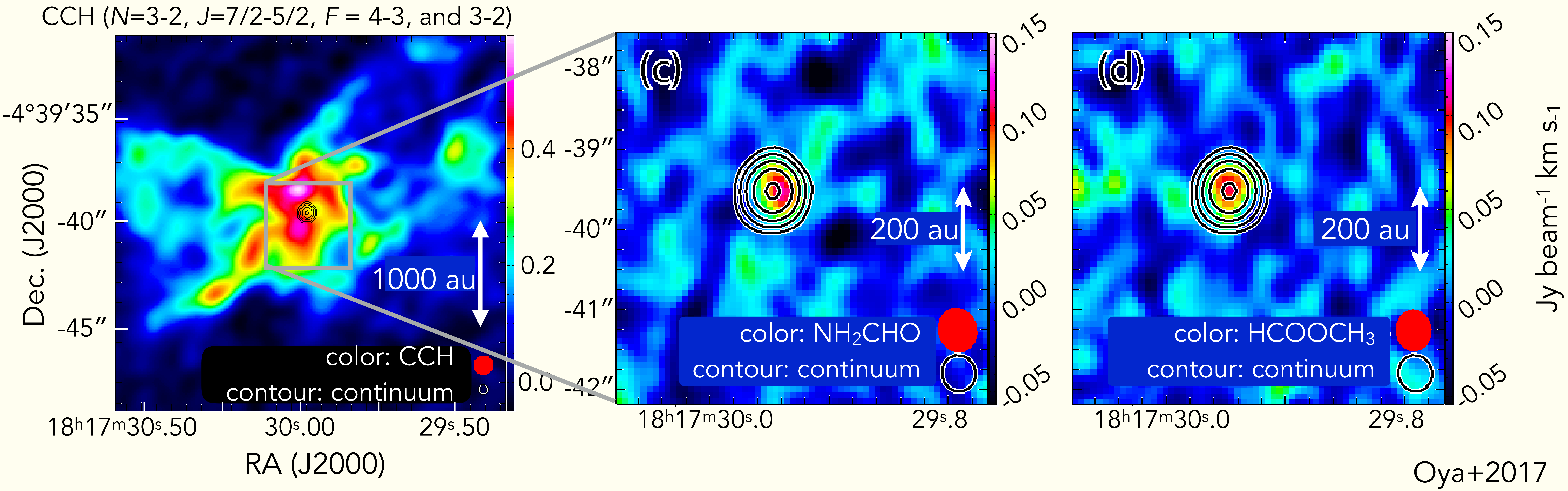
L483 - a source with long carbon-chain molecules harboring a hot corino



Oya+2017

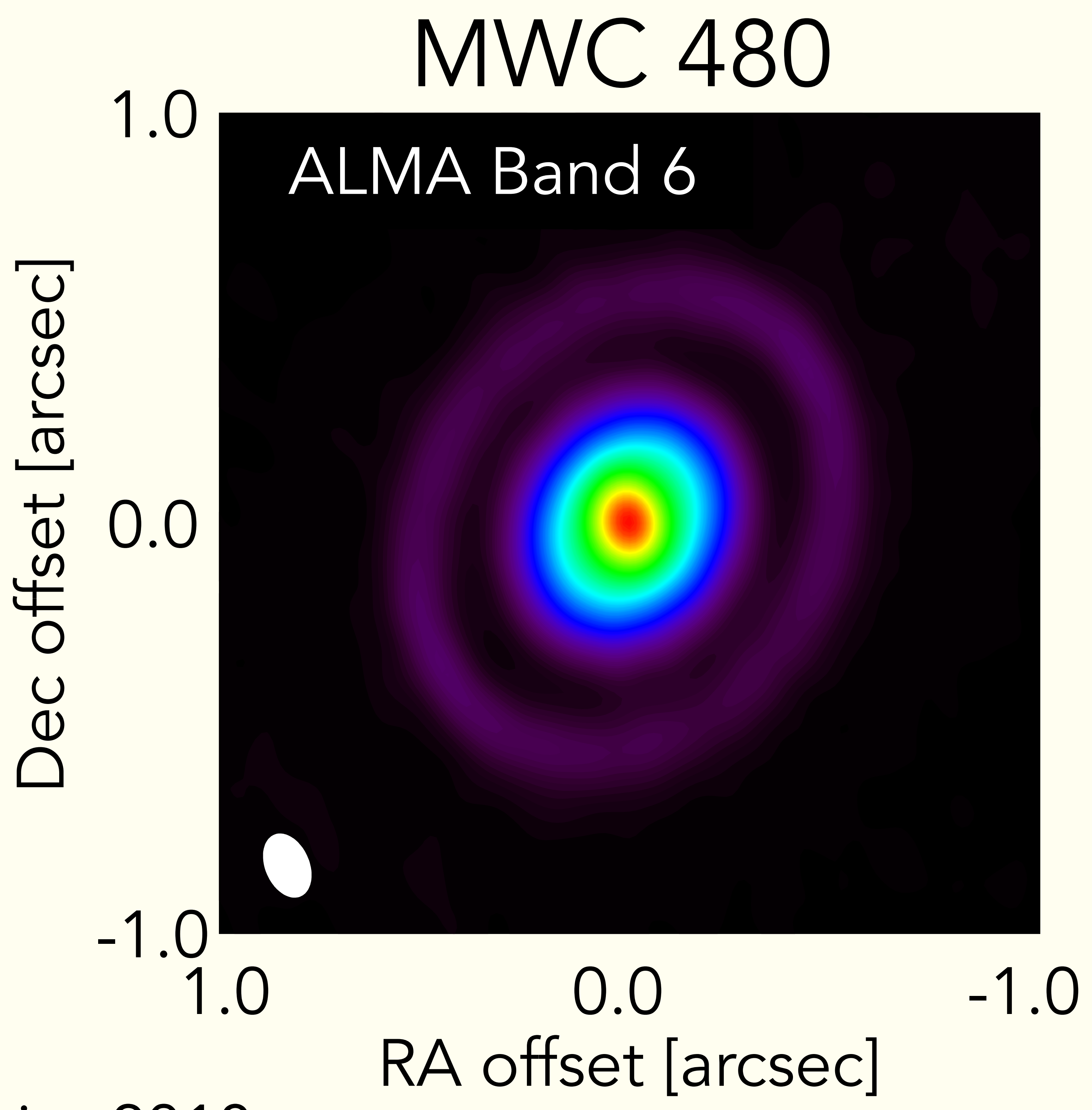
carbon-chain

COMs

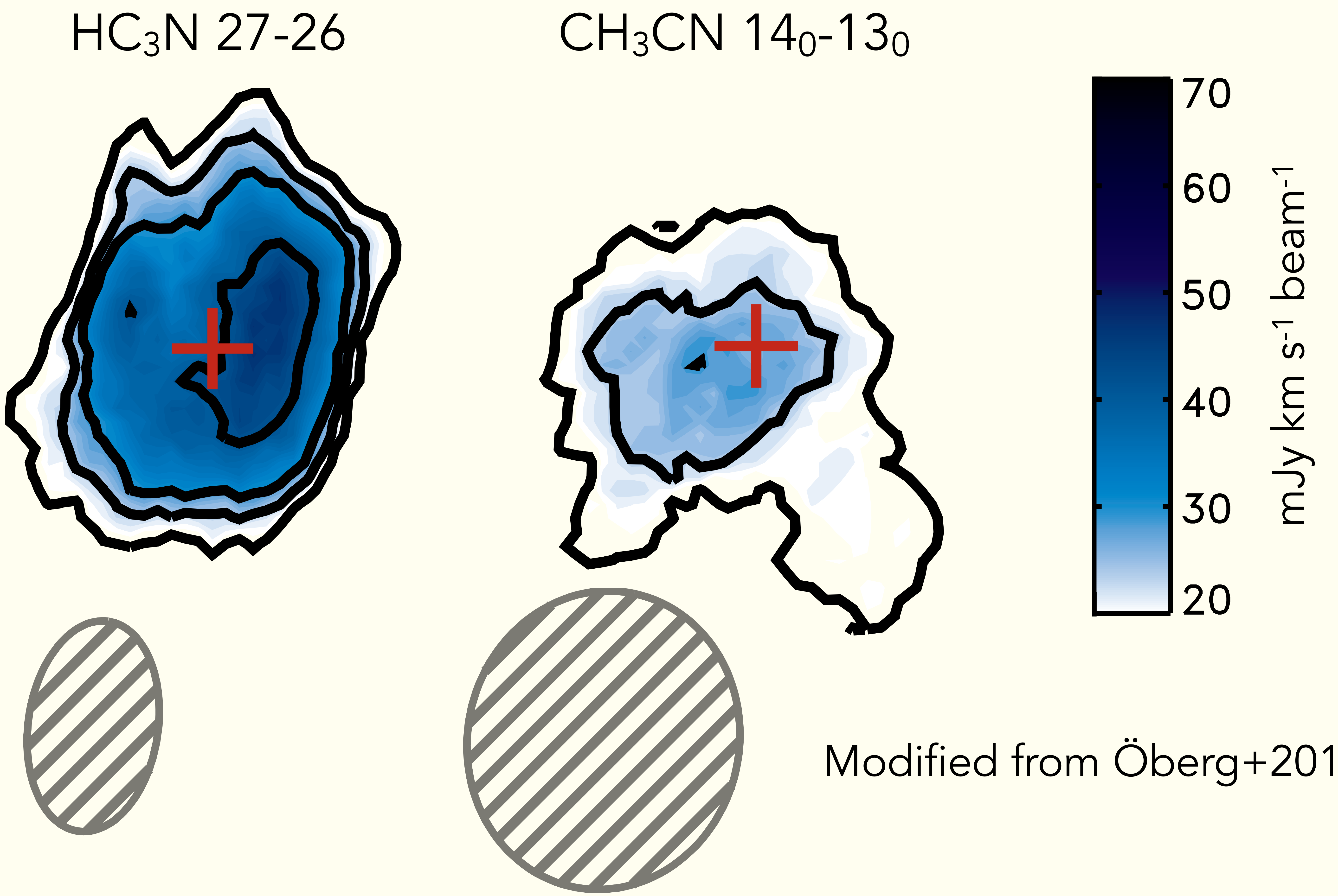
Key questions to answer

What is the future of COMs detected at the protostellar phase?

- How does the chemical evolution continue to protoplanetary disks and planetary systems?

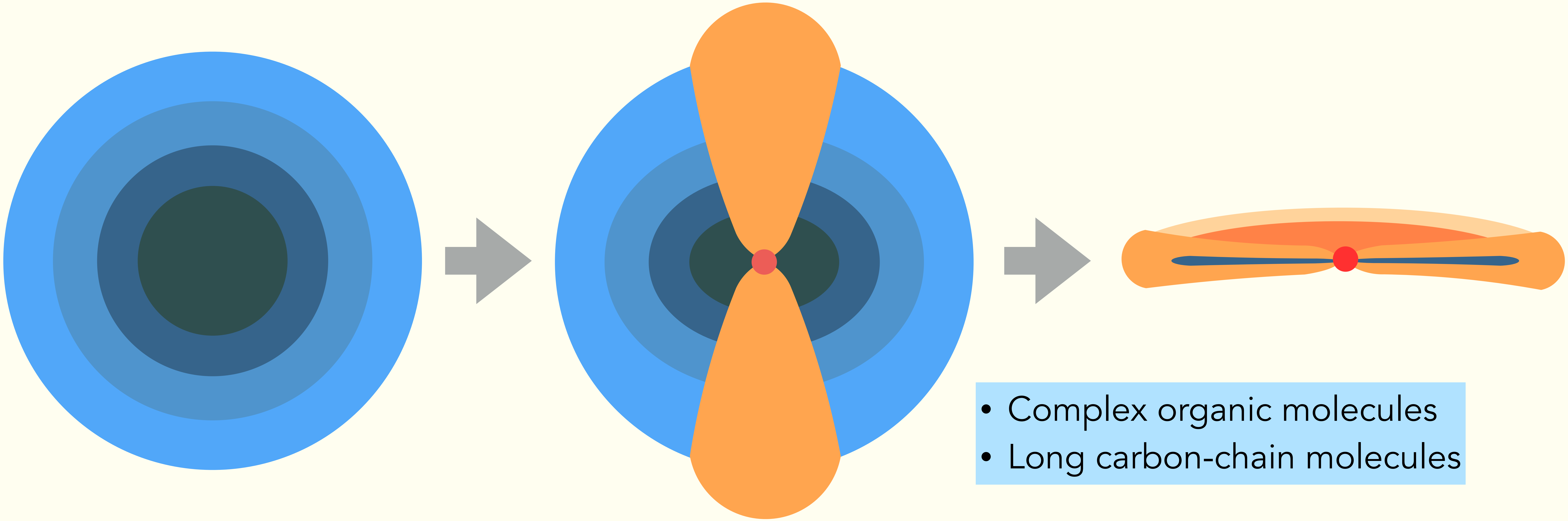


Liu+2018



Modified from Öberg+2015

The origins of chemical differences from stages to stages

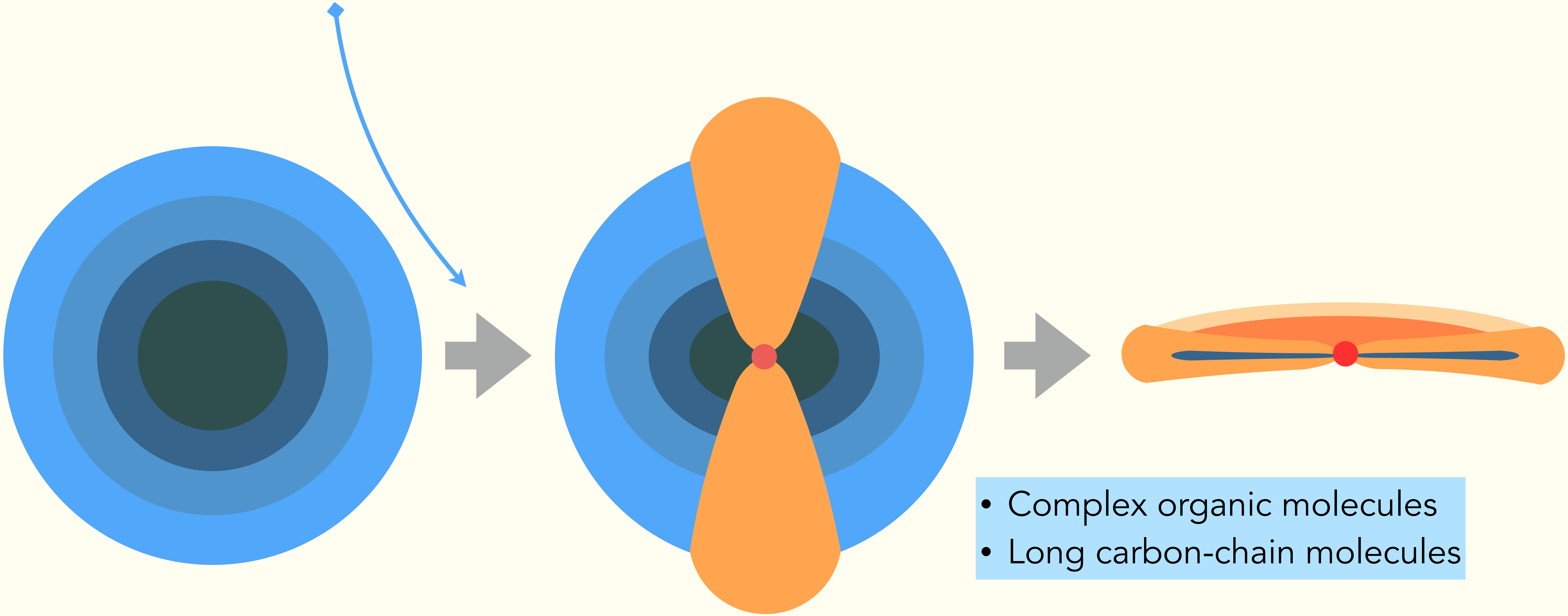


- Complex organic molecules
- Long carbon-chain molecules

RIKEN | Yao-Lun Yang

The origins of chemical differences from stages to stages

Does the chemical diversity at protostellar phase indicate different formation history?



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The origins of chemical differences from stages to stages

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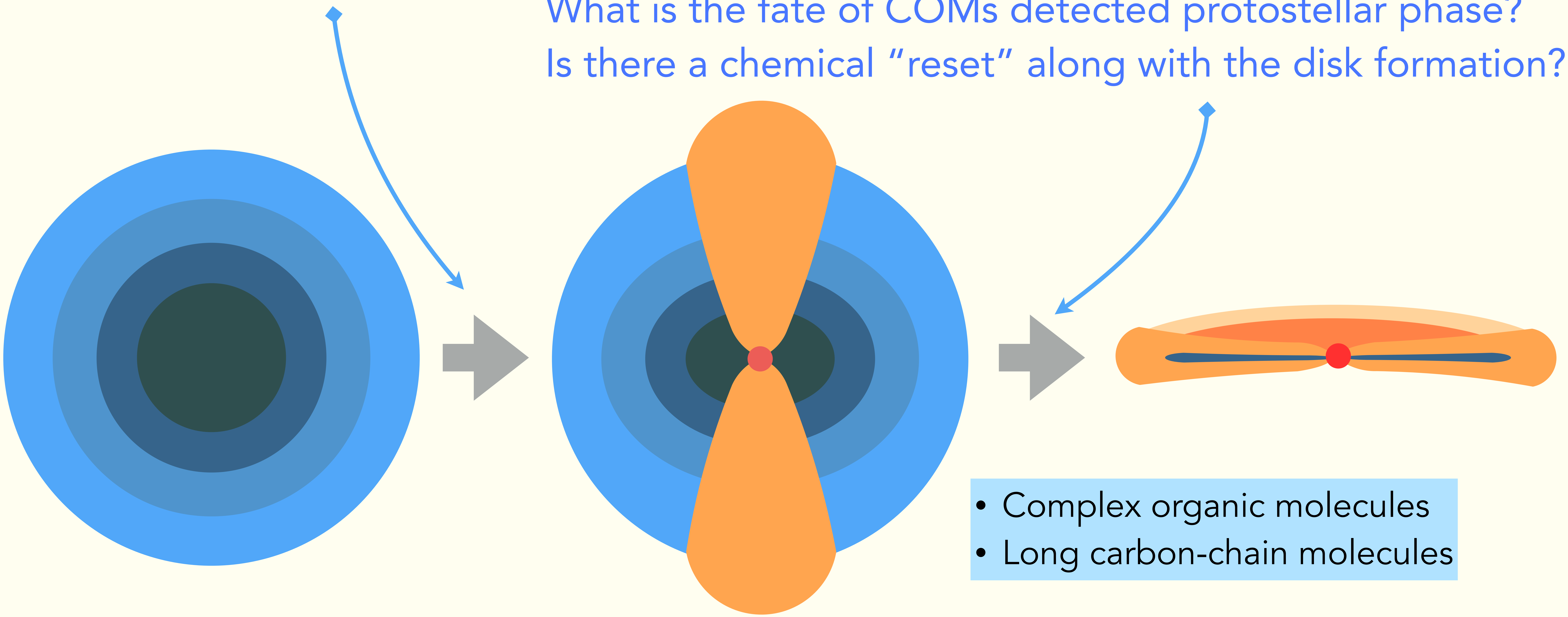
What is the fate of COMs detected protostellar phase?
Is there a chemical “reset” along with the disk formation?



- Complex organic molecules
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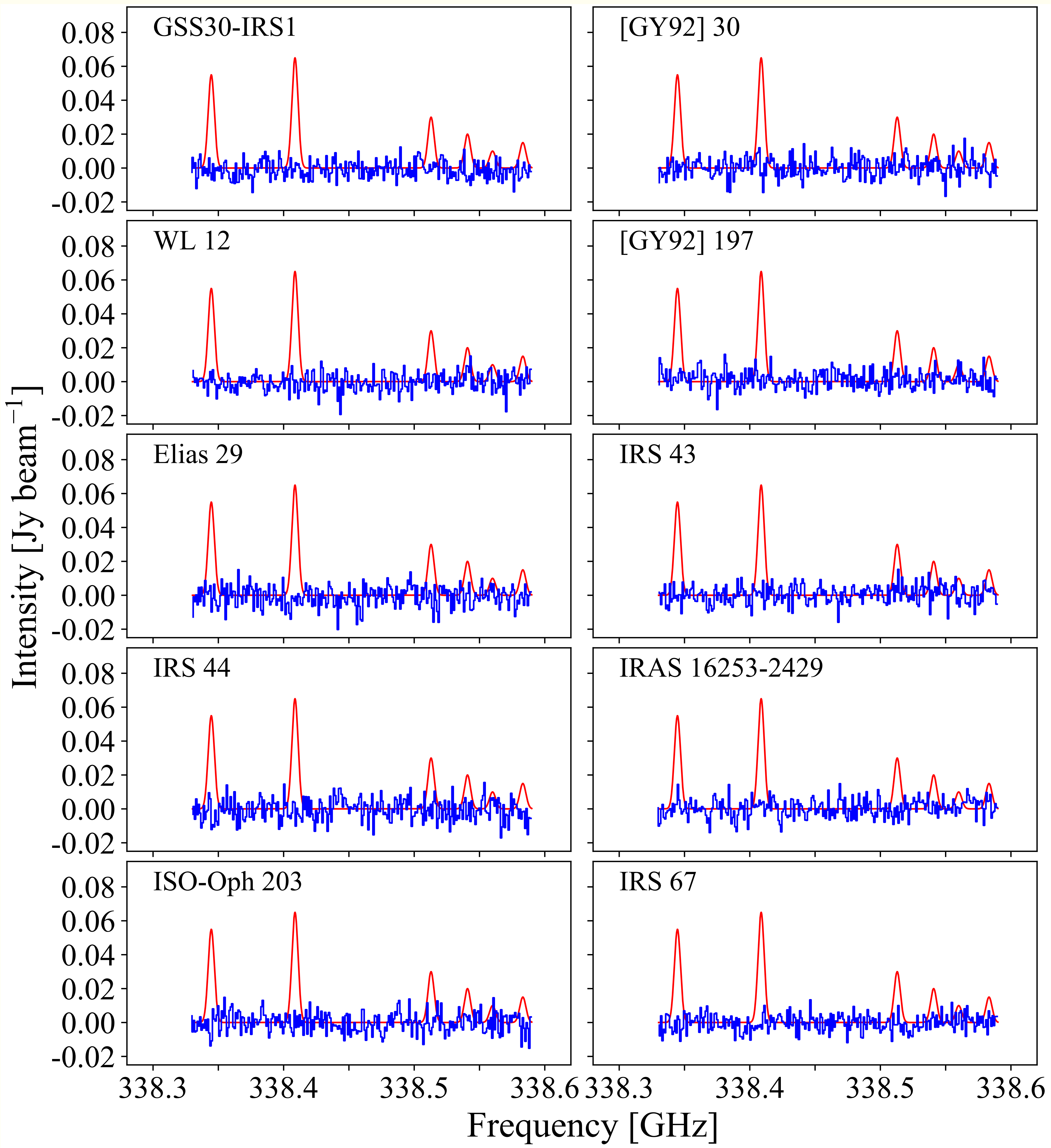
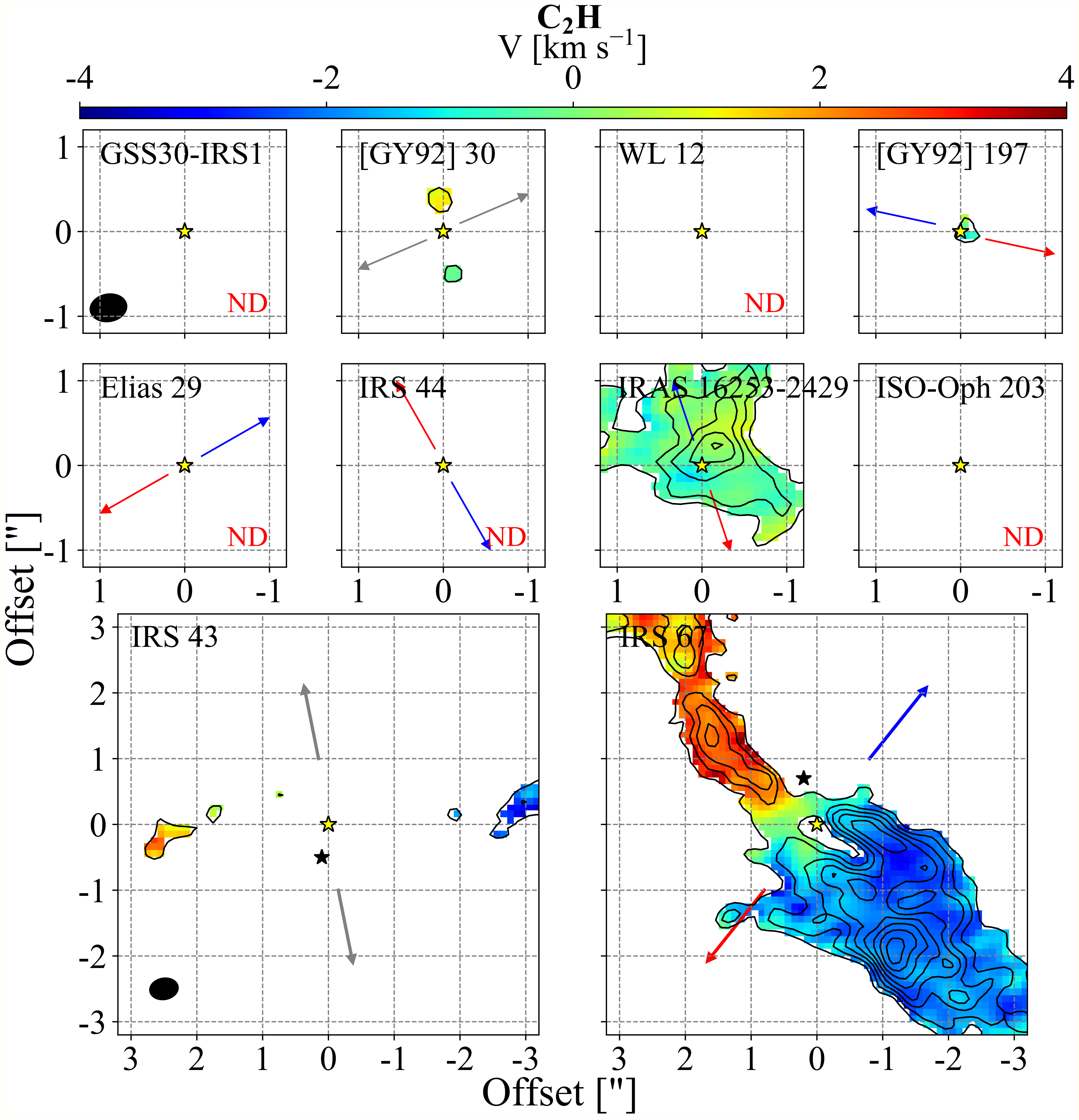
Ophiuchus Class I protostars show no methanol emission





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Artur de la Villarmois+2019

What is the origin of the chemical diversity at early protostellar phase?

- We simply observed protostars at different stages in their evolution?

  Is there a continuous distribution from long carbon-chain molecules to COMs or a bimodal distribution?

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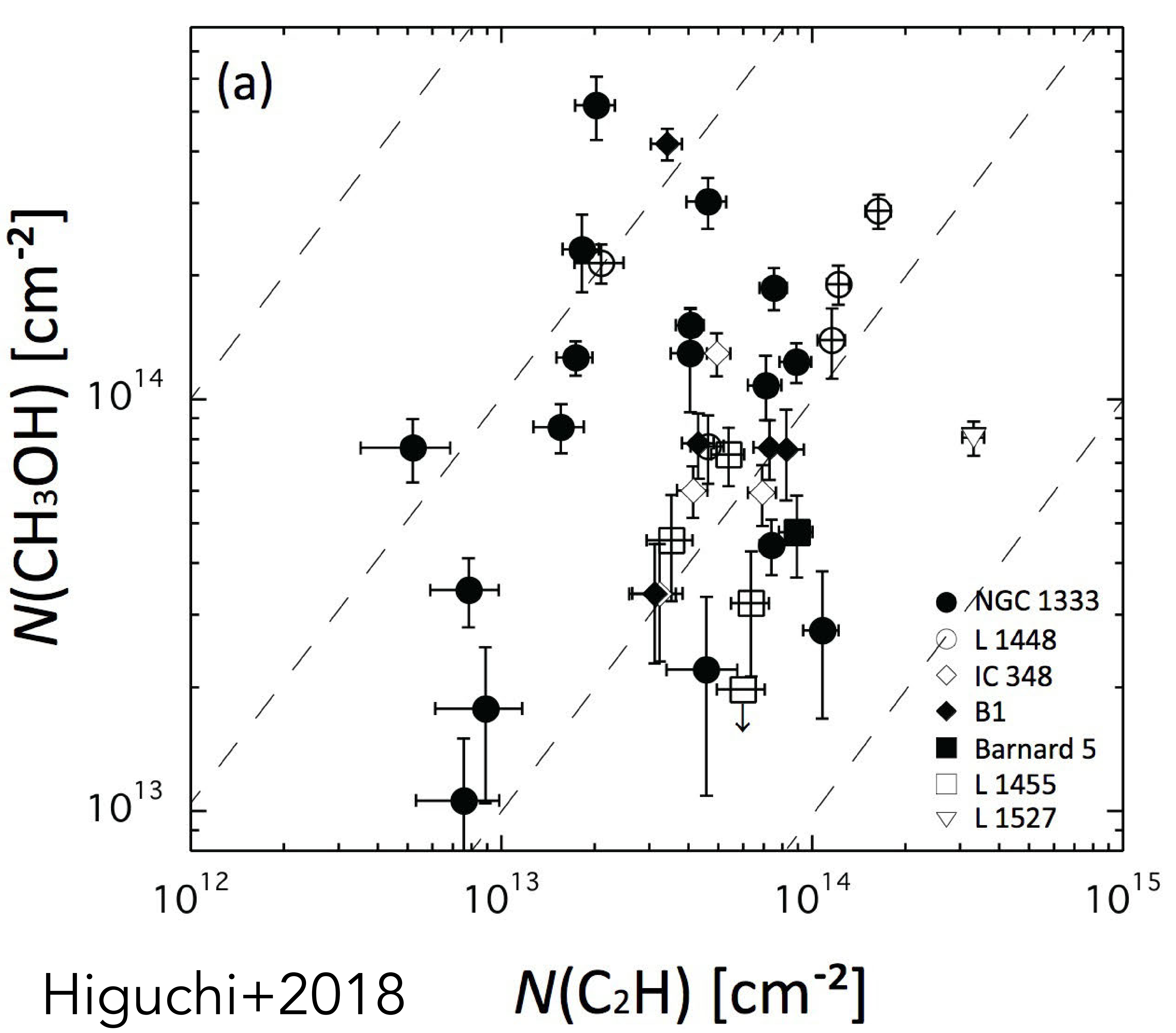

Higuchi+2018

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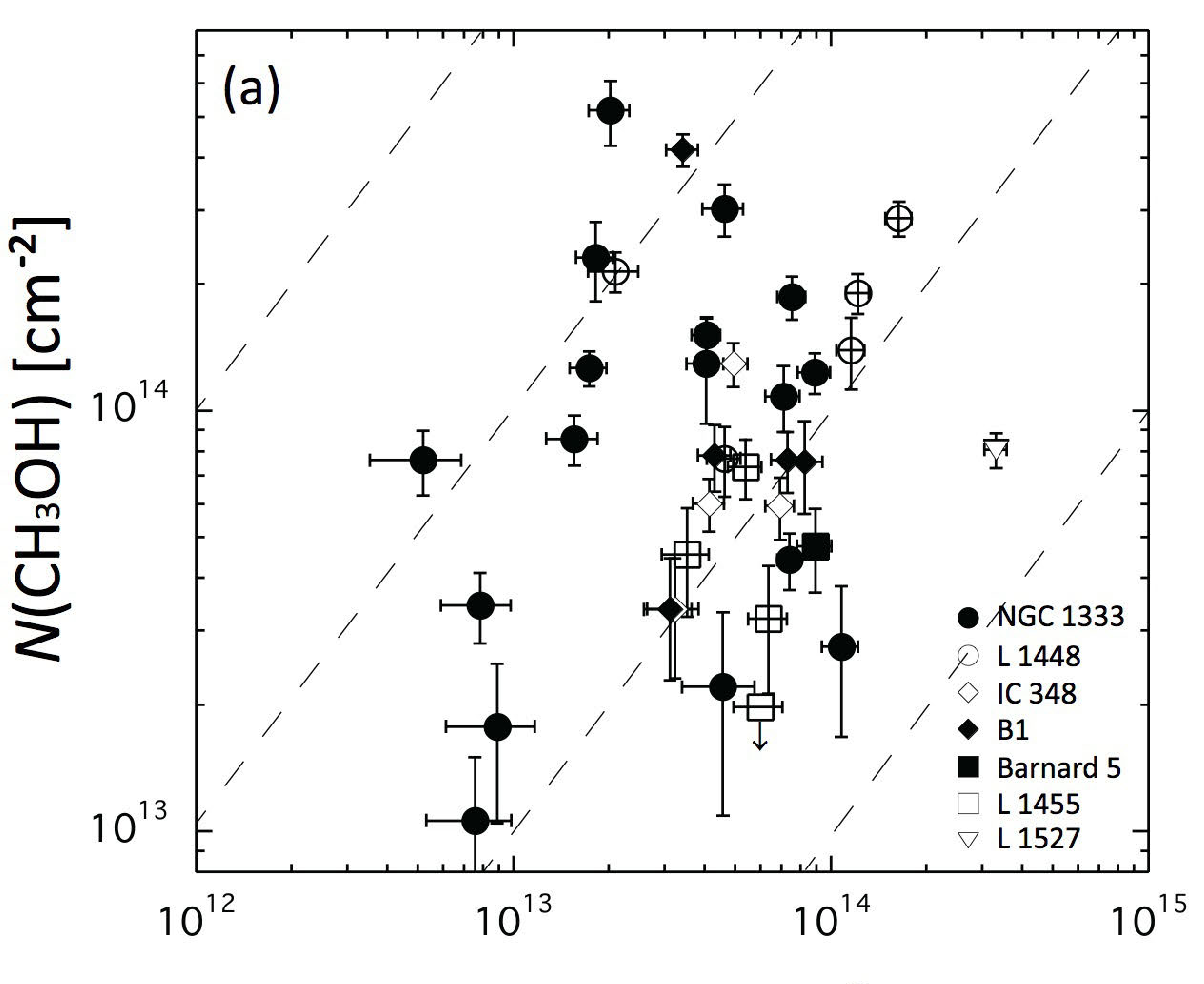

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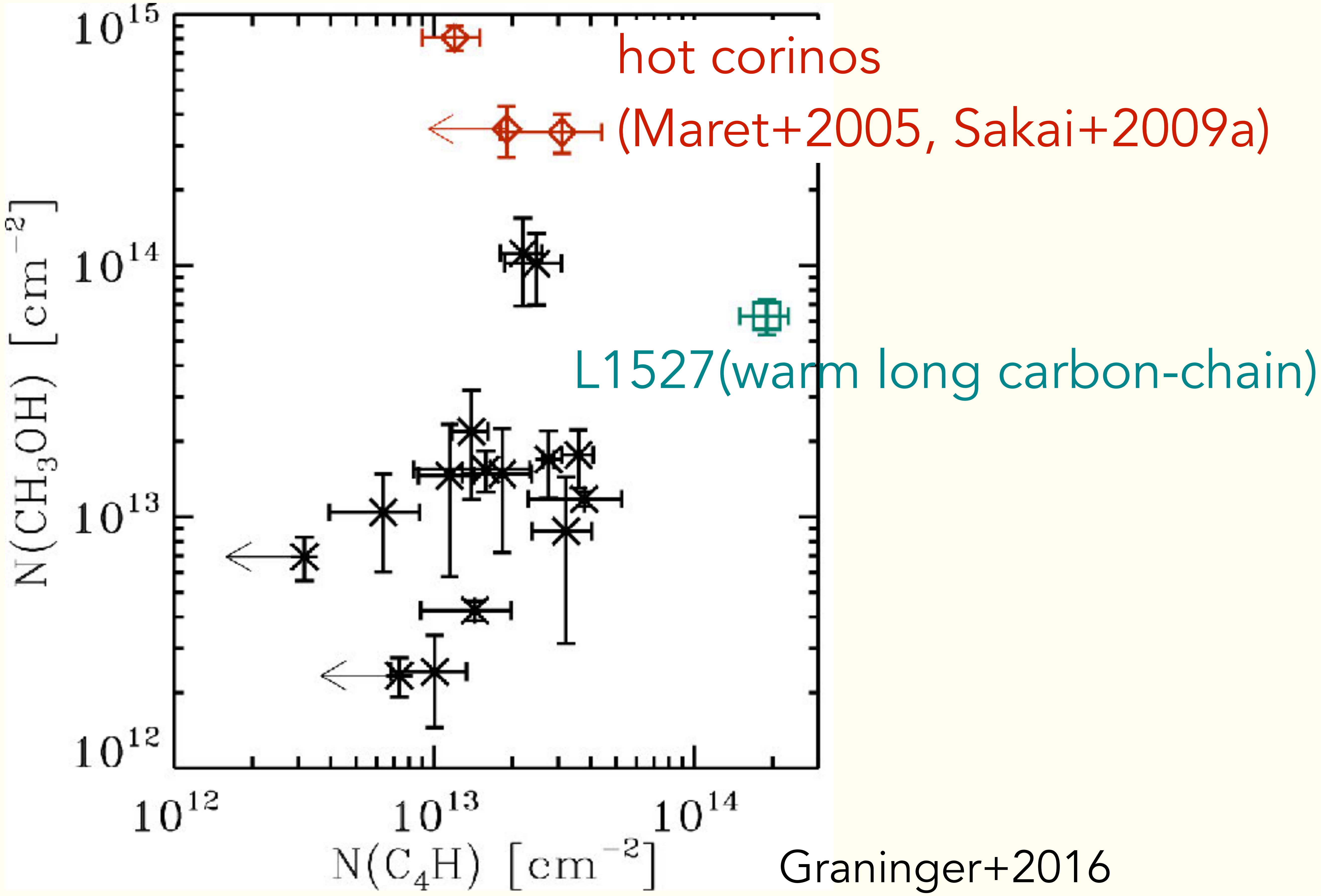

Graninger+2016

PEACHES: Perseus ALMAChemistry Survey (PI: N. Sakai)

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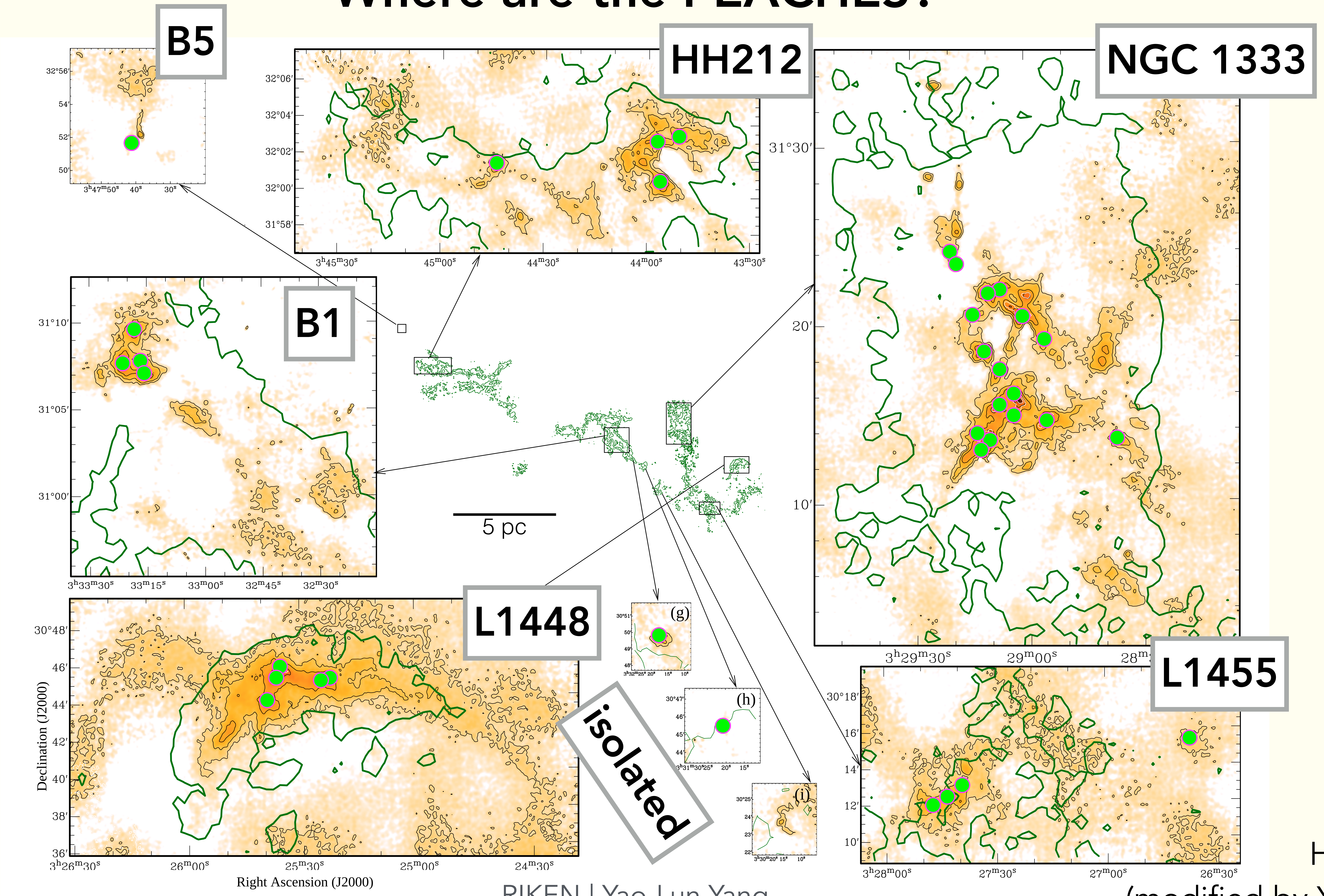
- ALMA Band 6 observations target CS, $H^{13}CN$, SO, SO_2, CCH, CH_3OH, CH_3OCHO, SiO, and more
- A typical beam size of 0.4″-0.6″ with a line sensitivity of ~6 mJy/beam

Where are the PEACHES?



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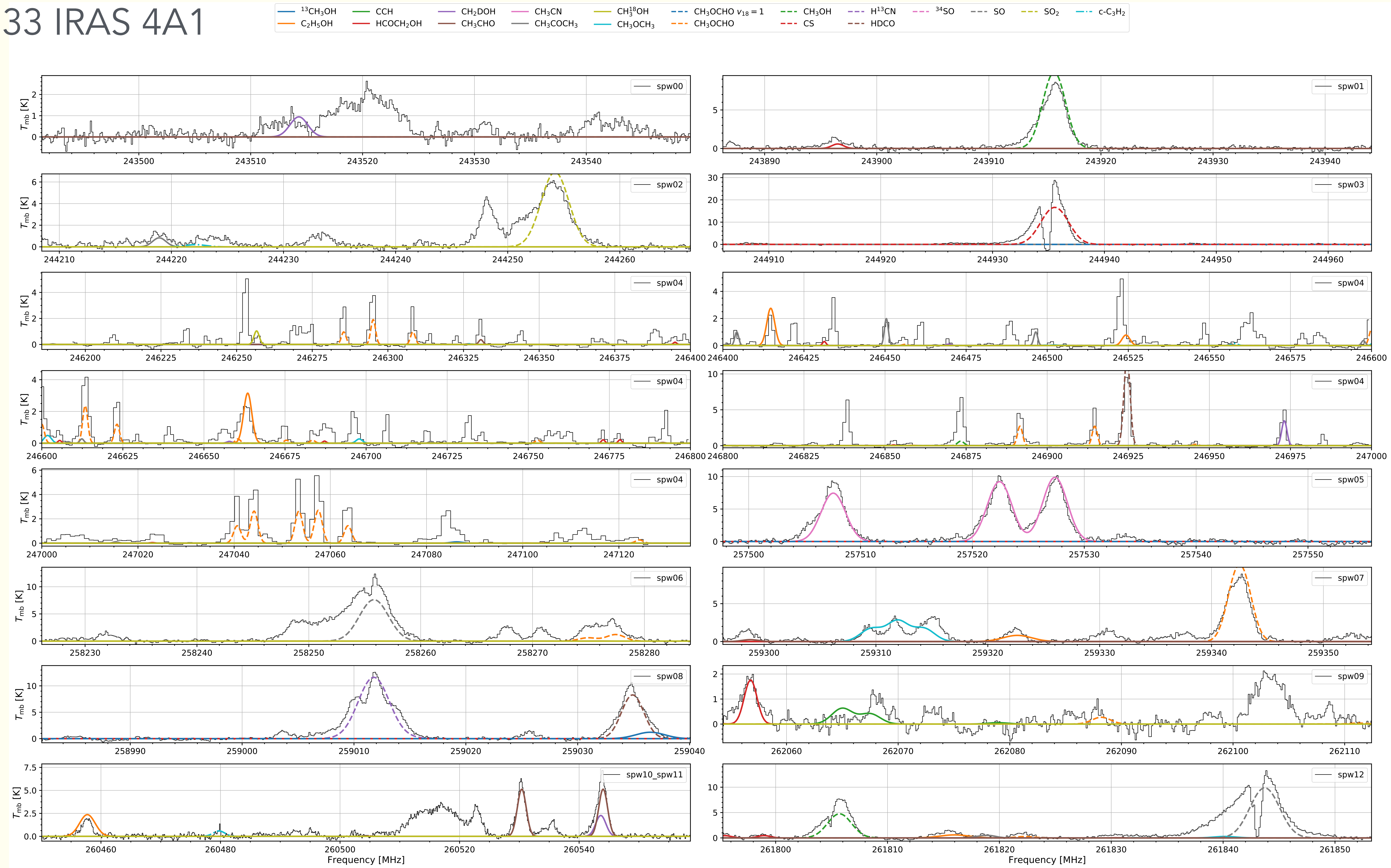
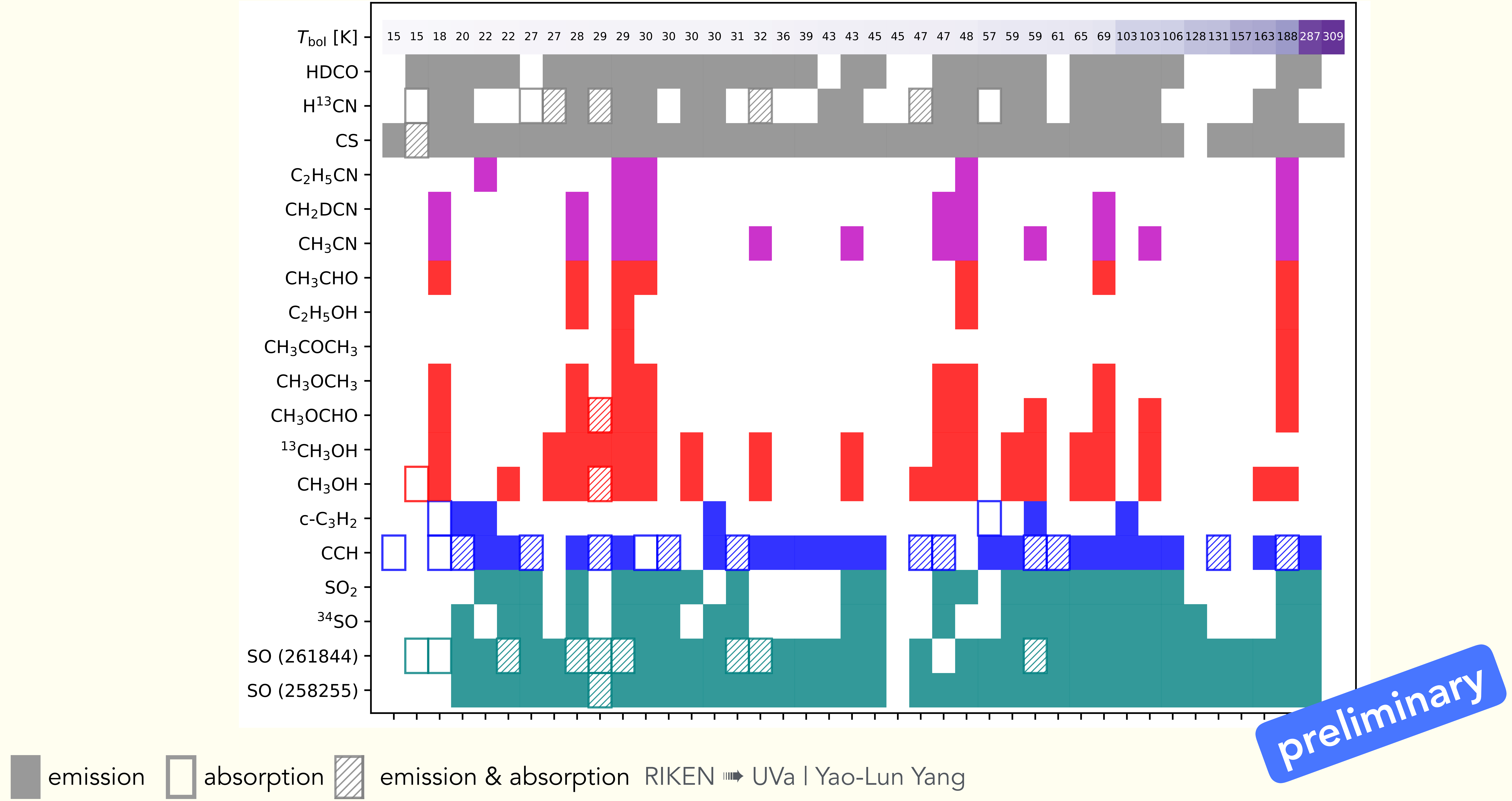
Hatchell+2005
(modified by Yichen Zhang)

The survey is quite rewarding

NGC 1333 IRAS 4A1



Detection statistics vs. evolutionary indicators (T_{bol})



RIKEN ➠ UVa | Yao-Lun Yang

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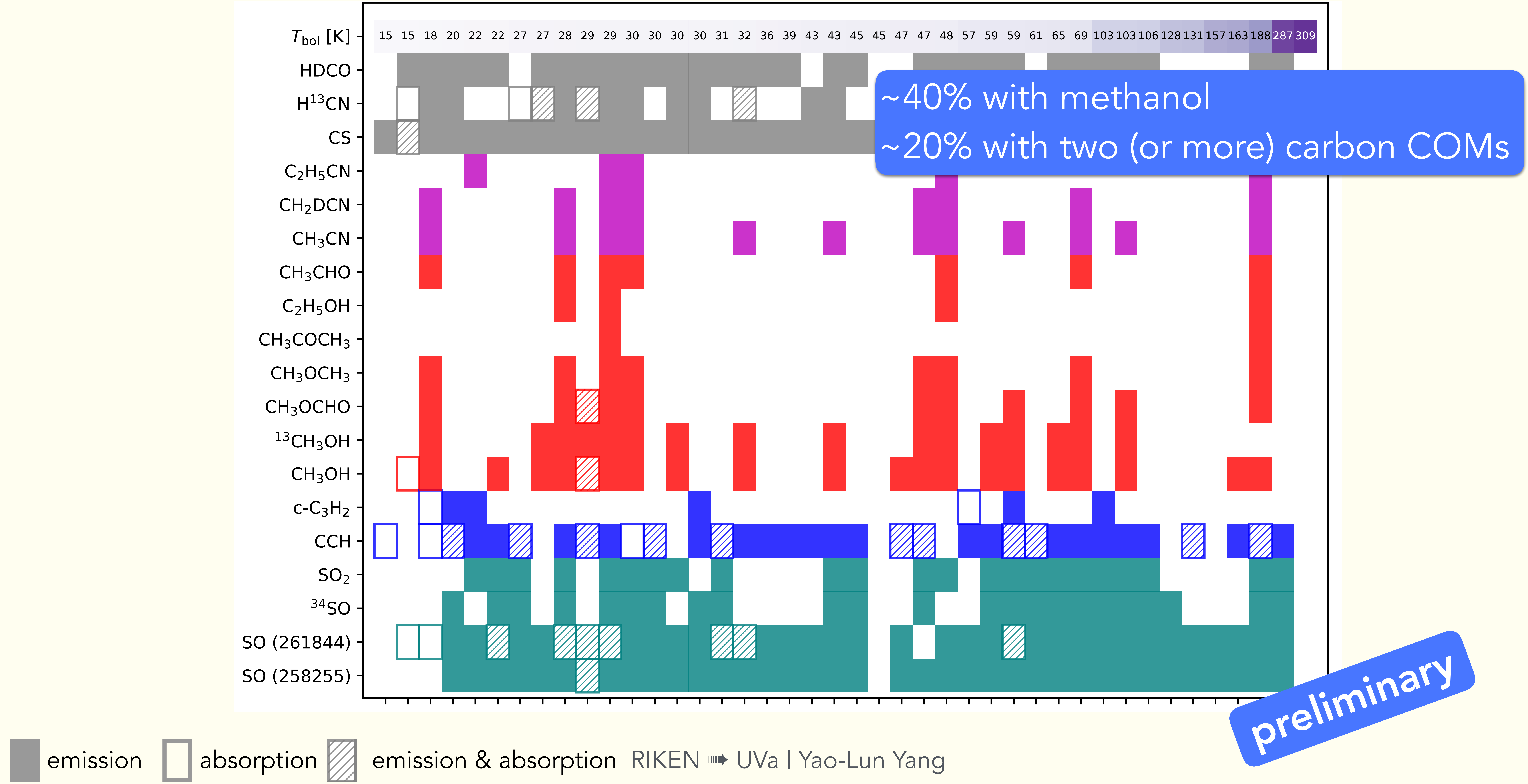
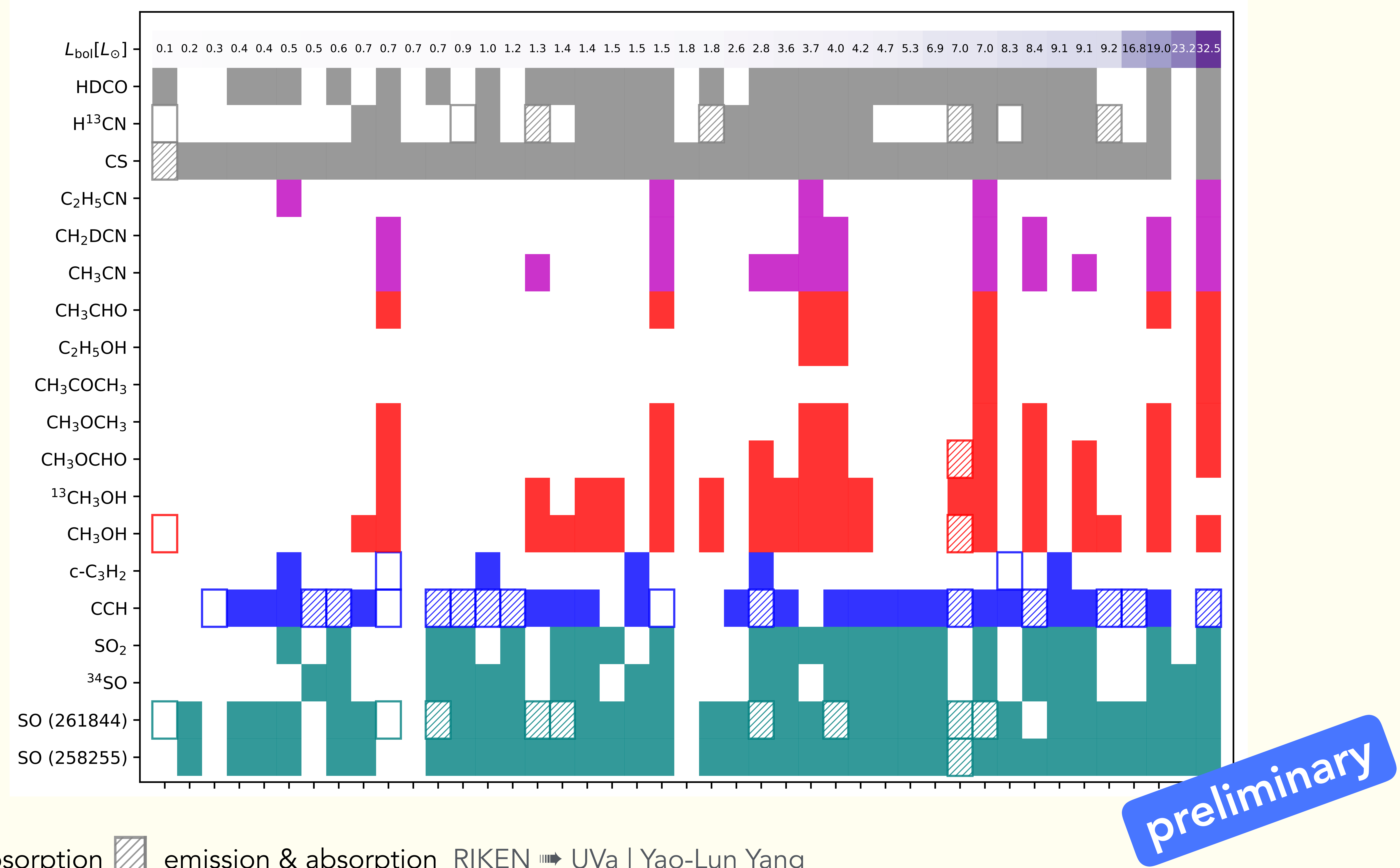


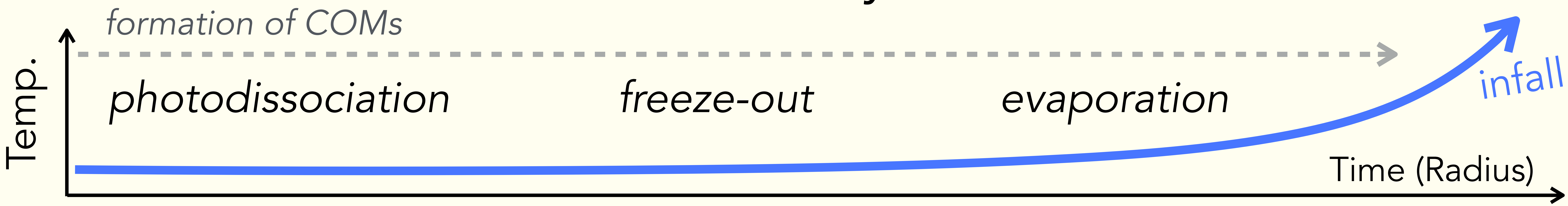
RIKEN ➠ UVa | Yao-Lun Yang

Detection statistics vs. evolutionary indicators (L_{bol})



emission absorption emission & absorption RIKEN ➠ UVa | Yao-Lun Yang

Summary



- The TSC envelope reproduces the infall signature toward BHR 71, also hinting a disk.
- Chemical abundance is a major uncertainty for synthetic observation
- BHR 71 is a hot corino, where the emission of COMs probes the kinematics at the disk-forming region.

- Among the PEACHES sample, ~40% sources show methanol and ~20 % sources have COMs with more than two carbons.
- Protostars show apparently chemical diversity, even for binary sources. However, the nature of the diversity requires further analyses.