

Star formation in an "extreme" environment

*A molecular line survey of a warm core
and the medium around it
in G0.253+0.016 (The Brick)*

Image by Adam Ginsburg
blue points: NIRCam F182M
green points: NIRCam F212N
red points: NIRCam F410M
magenta extended: ACES CS J=2-1
blue extended: ACES HC3N
red extended: ACES HNC
green extended: ACES SiO J=2-1
cyan extended: ACES SO J=3-2

Alyssa Bulatek (she/her)

Committee: Adam Ginsburg, Desika Narayanan,
Jaehan Bae, and Siyao Xu (UF Physics)

Monday, March 9, 2026
PhD Defense

Outline

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Star formation in the Milky Way's Galactic Center

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How do we observe star formation?

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The Brick Line Survey

- Survey setup and process

- Results and implications

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A methanol dasar in The Brick

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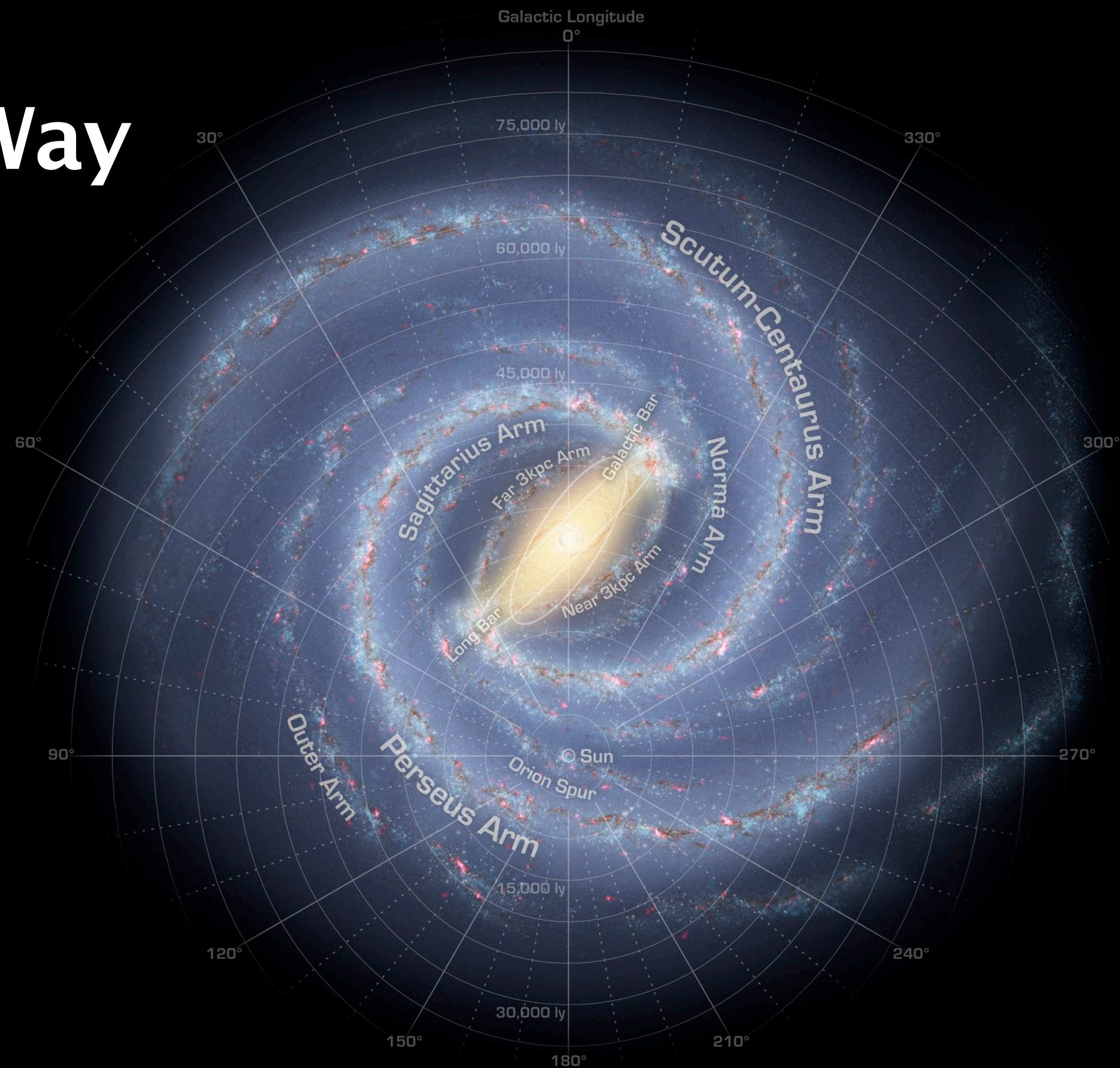
- Survey setup and process

- Results and implications

A methanol dasar in The Brick

Remaining open questions

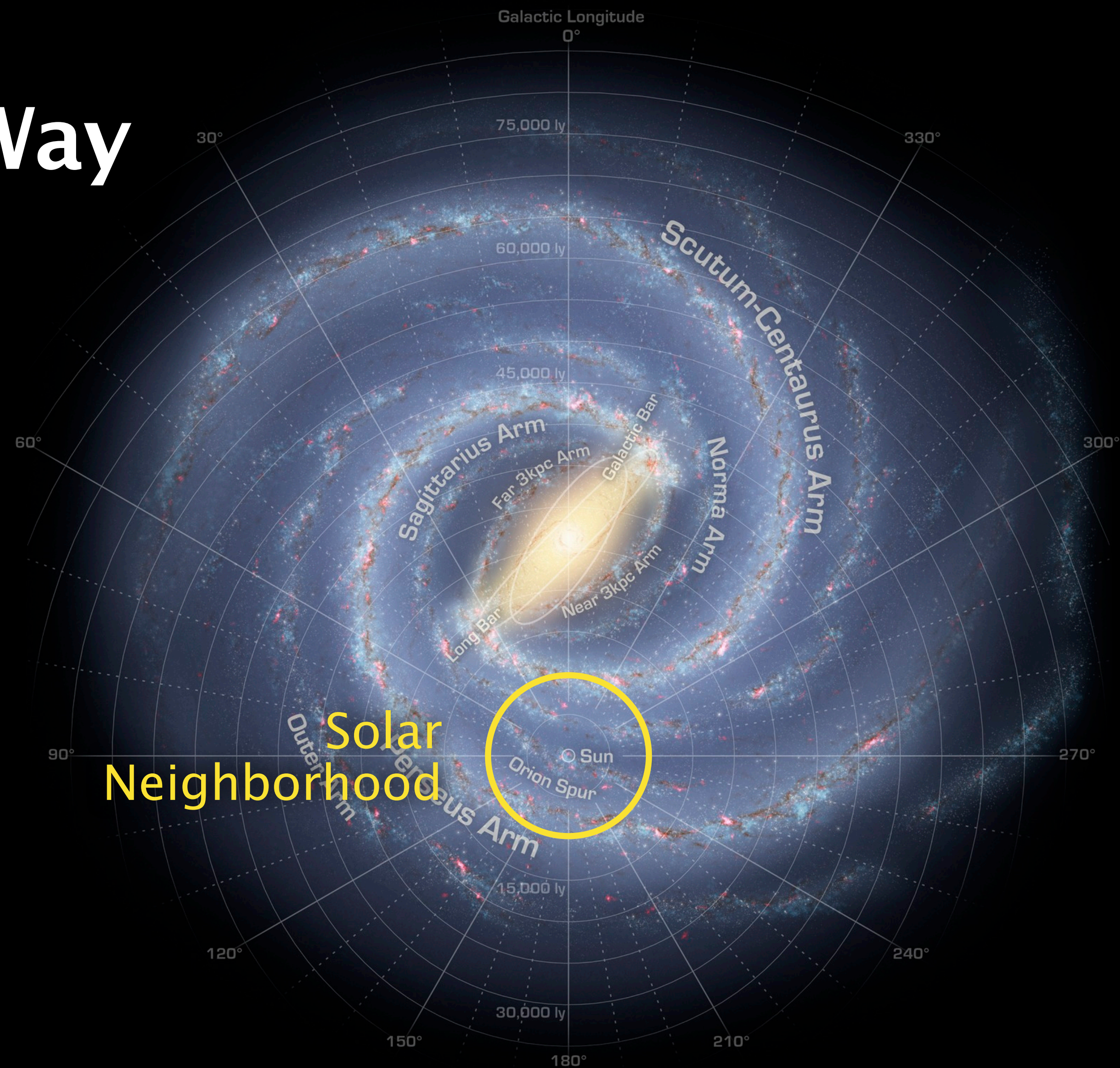
The Milky Way



Annotated Roadmap to the Milky Way

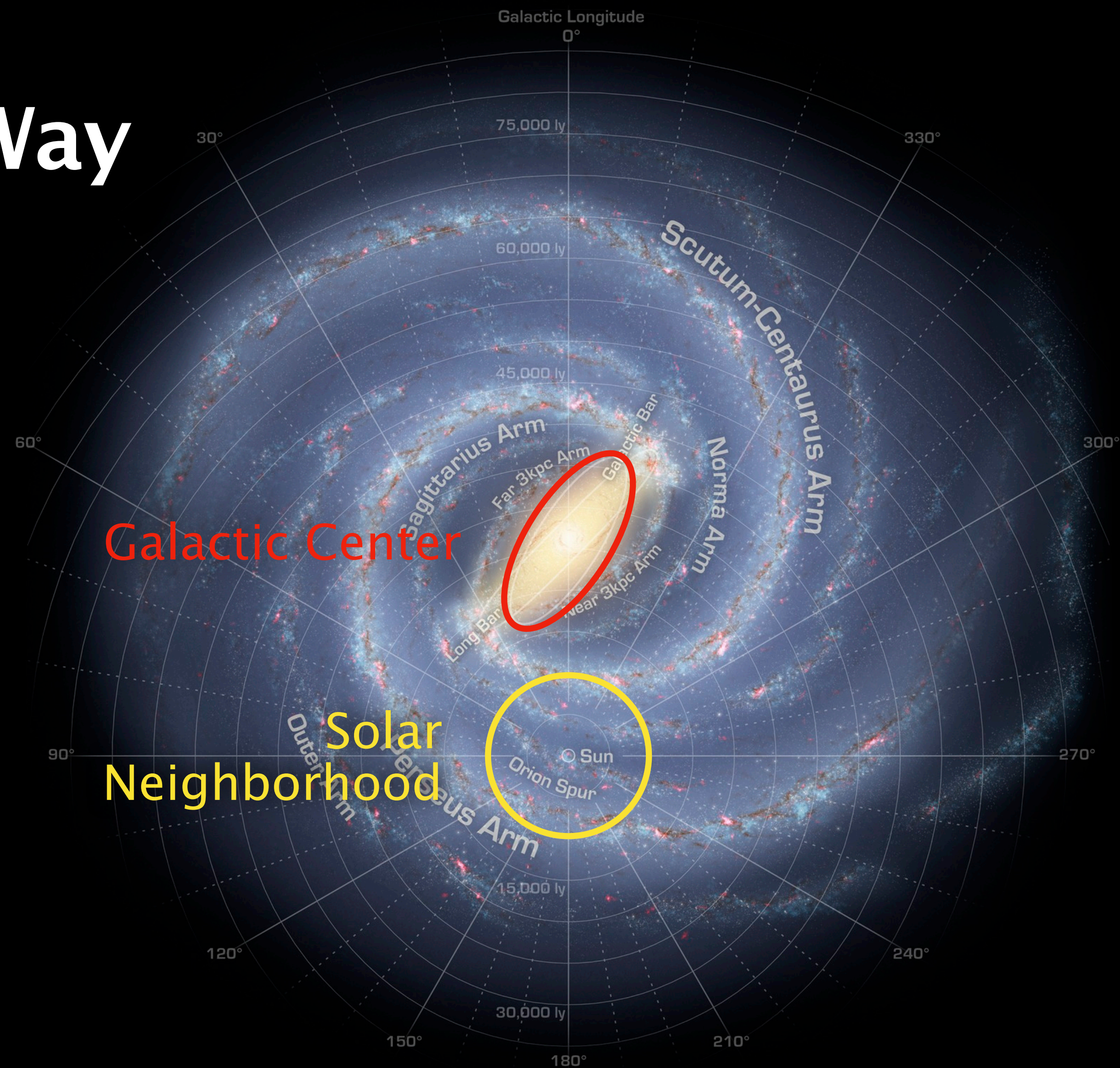
[artist's concept]

The Milky Way



Annotated Roadmap to the Milky Way
(artist's concept)

The Milky Way



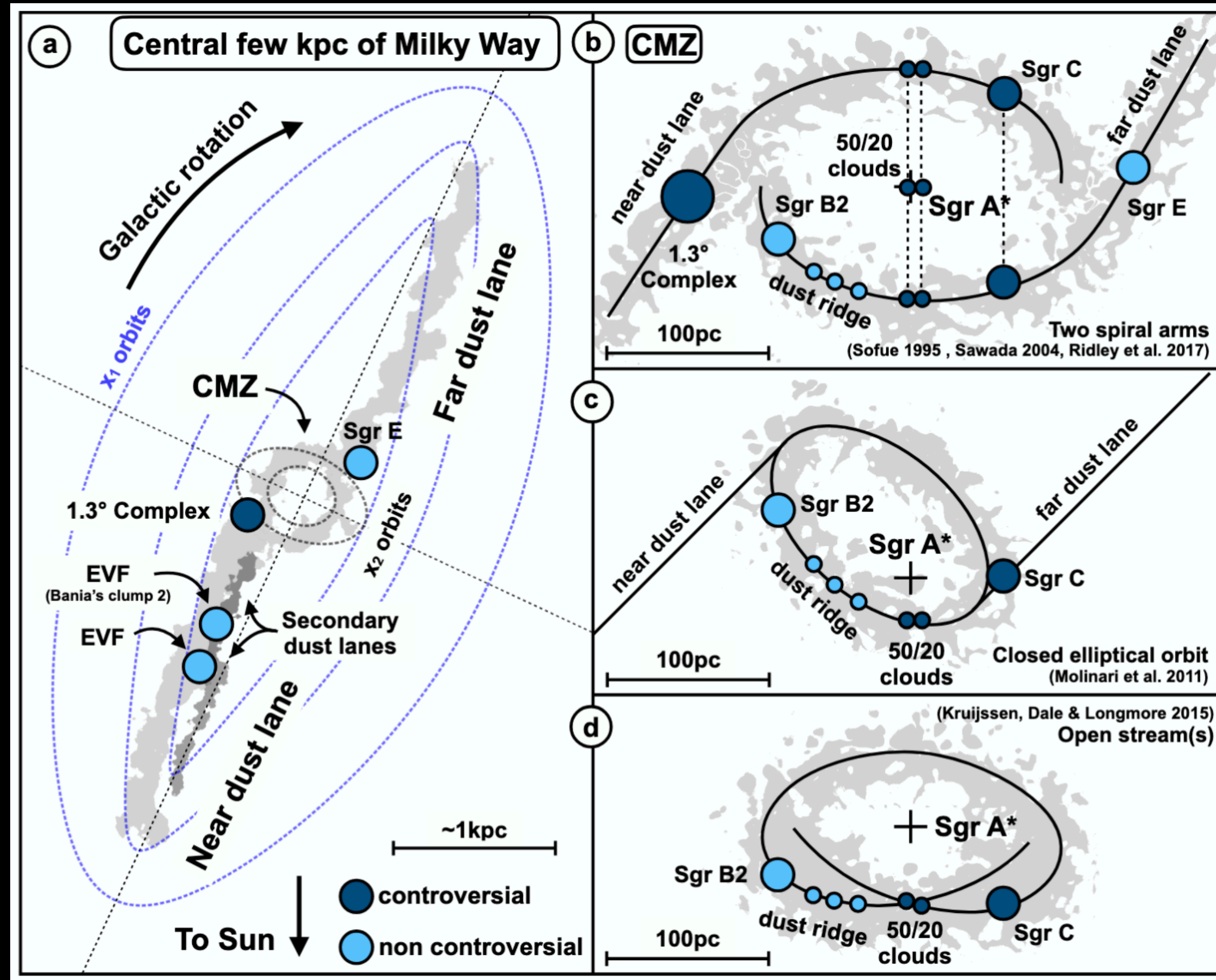
Galactic Center

Solar Neighborhood

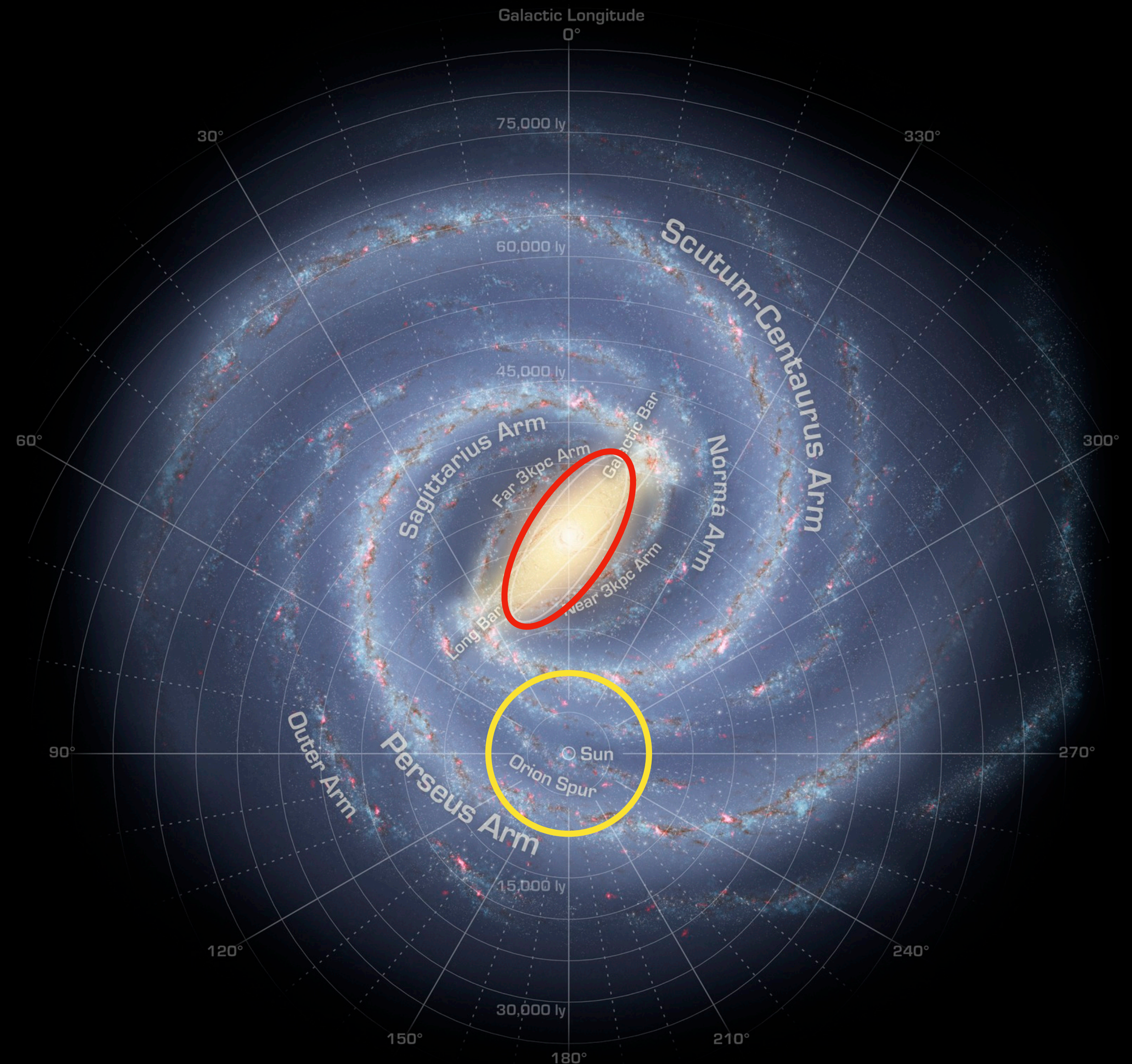
Annotated Roadmap to the Milky Way

[artist's concept]

The Milky Way



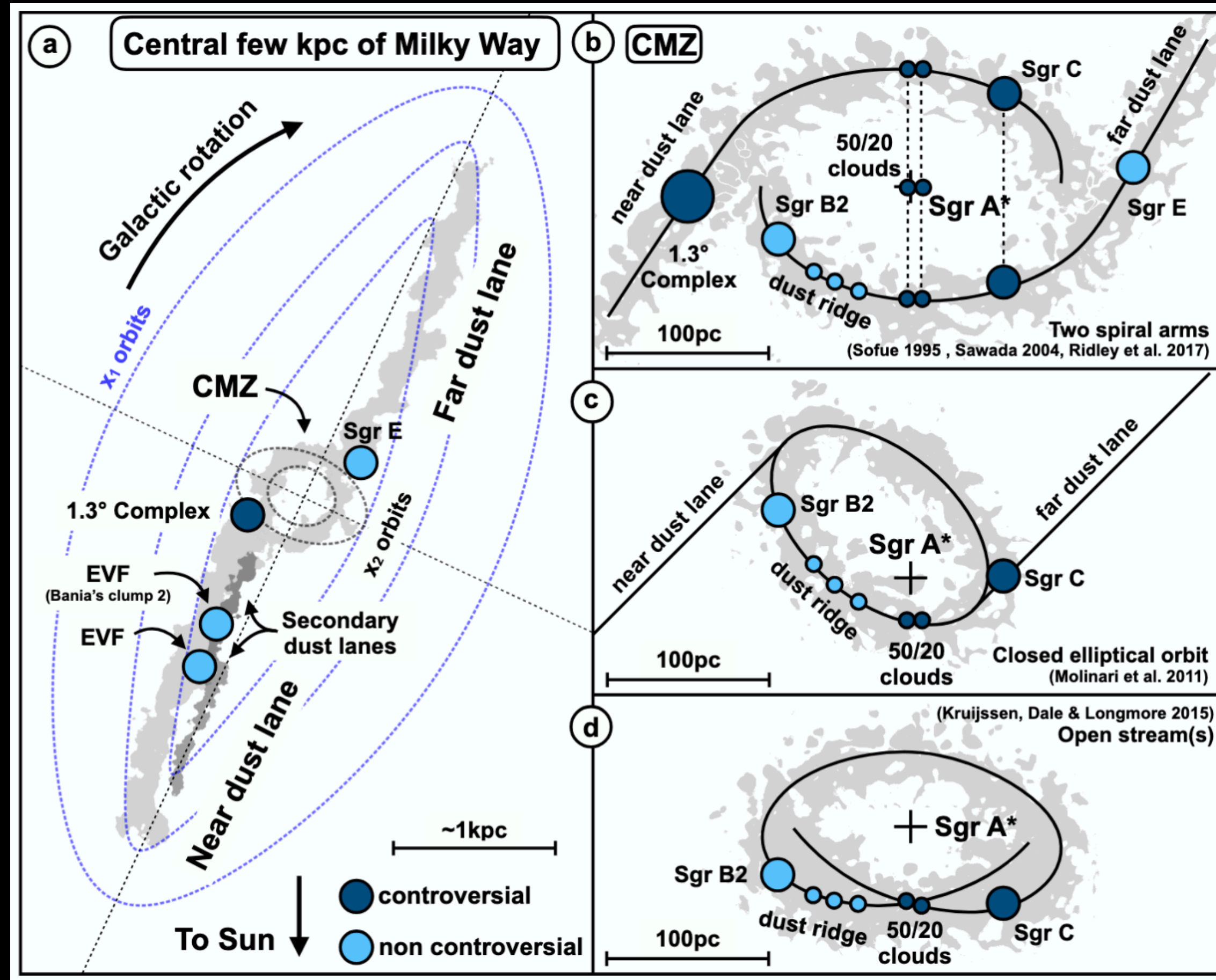
Henshaw+2023



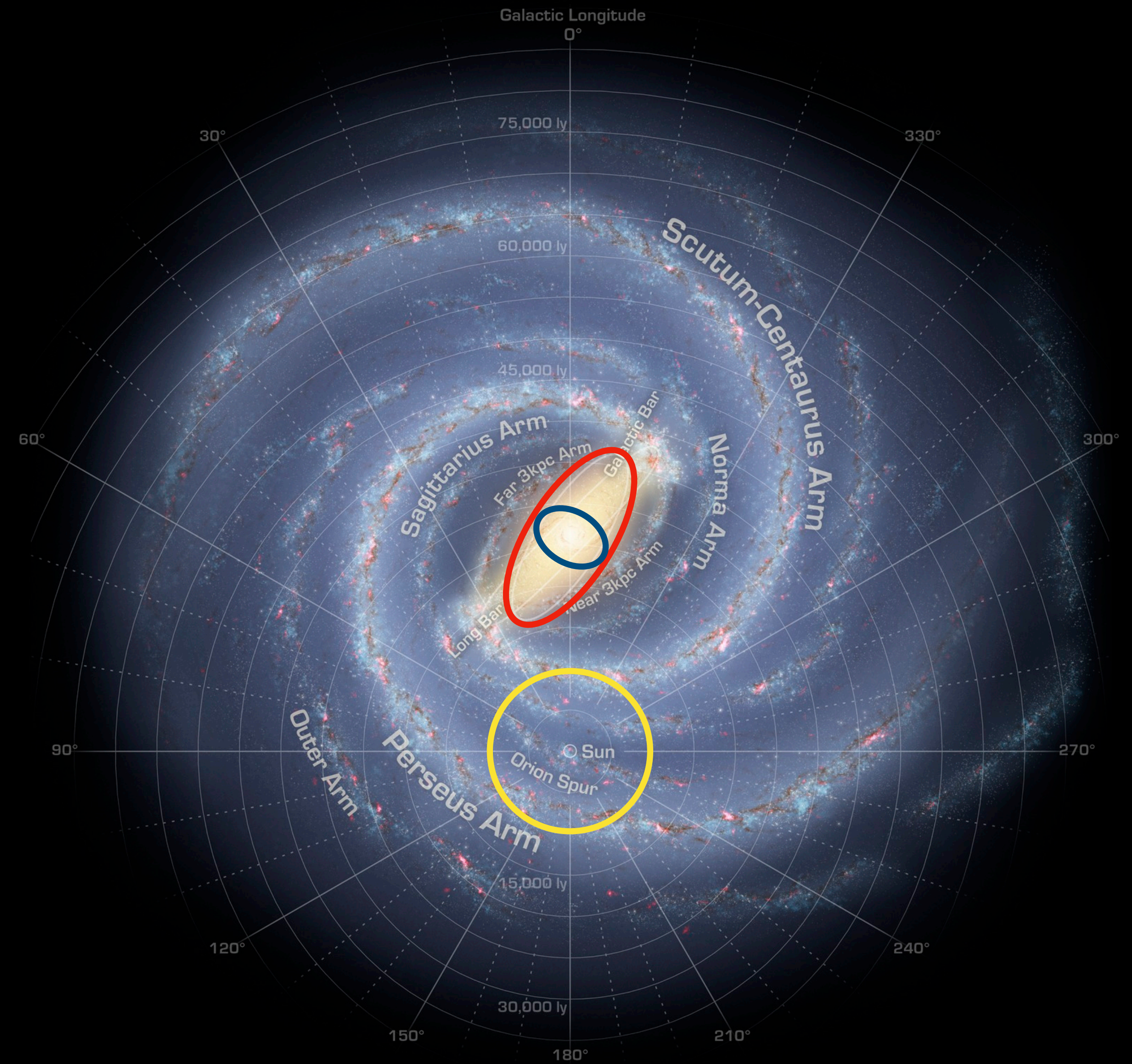
Annotated Roadmap to the Milky Way

[artist's concept]

The Milky Way



Henshaw+2023



Annotated Roadmap to the Milky Way

[artist's concept]

The Milky Way's Galactic Center



The Milky Way's Central Molecular Zone (CMZ)

Molecular material within $R_{gal} \approx 300 pc$

SO, SiO, HNC, HC₃N, CO



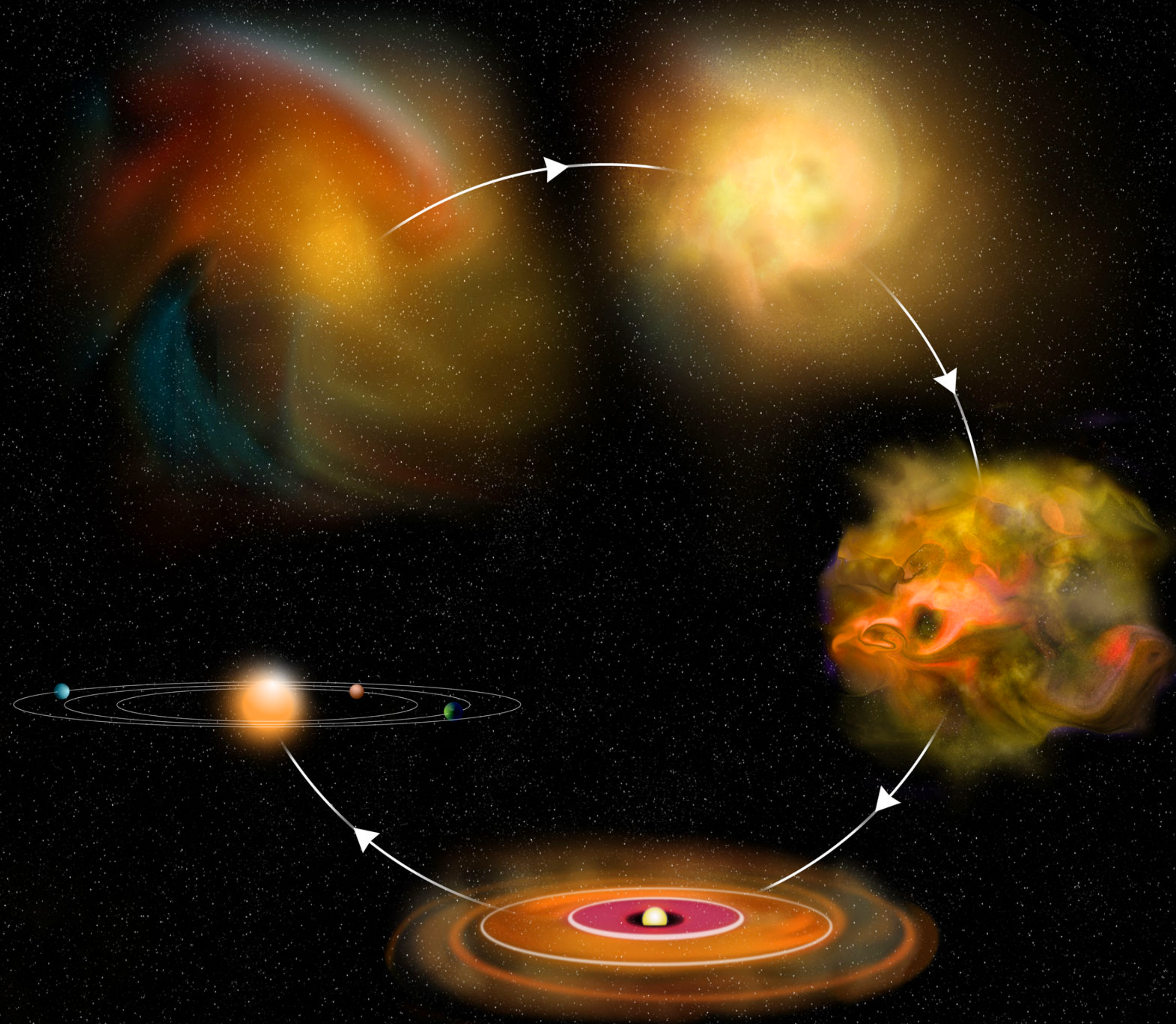
Physical Quantity	CMZ	Solar Neighbourhood	Extragalactic CMZs	$z \sim 2$
Distance [kpc] ^(a)	8.2	0.1 - 0.5	3500 - 20000	$\sim 10^6$ ($z \sim 2$)
SFR [$M_{\odot}\text{yr}^{-1}$] ^(b)	0.07 (0.012-0.14)	0.002	0.001-0.08	1-100
Σ_{gas} [$\log_{10}(M_{\odot}\text{pc}^{-2})$] ^(c)	3.1 (2.8-3.2)	1.5	0.6-3	1.5-3.5
Σ_{SFR} [$\log_{10}(M_{\odot}\text{yr}^{-1}\text{kpc}^{-2})$] ^(d)	0.3 (-0.4-0.6)	-2.5	-3-0	-1.5-1.5
Σ_{*} [$\log_{10}(M_{\odot}\text{pc}^{-2})$] ^(e)	3.9	1.5	3.4-3.9	1-4
t_{dep} [Gyr] ^(f)	0.5 (0.4-1.5)	1	0.3-2.6	0.2-1
t_{dyn} [Myr] ^(g)	5	220	4-40	?
B [μG] ^(h)	10-1000	1-100	?	?
Metallicity, Z ⁽ⁱ⁾	2	1	~ 2	0.2-0.6
CRIR [$\log_{10}(\text{s}^{-1})$] ^(j)	-15 to -13	-17 to -15	?	?
Linewidth, $\sigma(10\text{pc})$ [km s^{-1}] ^(l)	12	3	10	20-70
Linewidth scaling, b ^(m)	0.7	0.5	?	?
IMF slope, α ⁽ⁿ⁾	≤ 2.35	2.35	?	?
DGMF, $f(n > 10^4)$ ^(o)	0.95	0.03	?	?
T_{gas} [K] ^(p)	50-100	10-30	50-250	?
T_{dust} [K] ^(q)	20-50	10-30	30-45	?
$P_{\text{ext}}/k_{\text{B}}$ [K cm^{-3}] ^(r)	$\gtrsim 10^7$	$\gtrsim 10^5$	10^6 - 10^8	?

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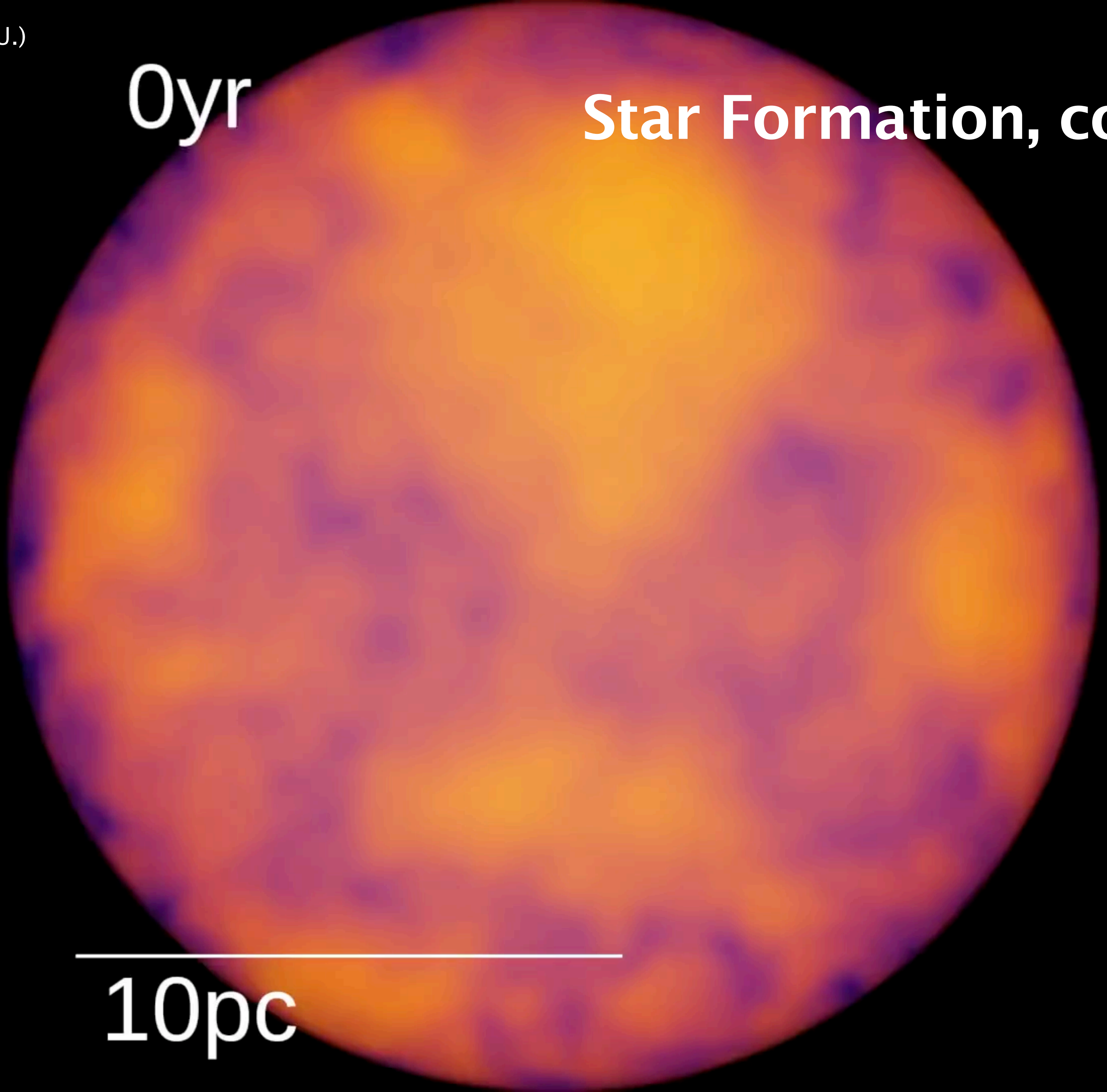
Star Formation, simplified



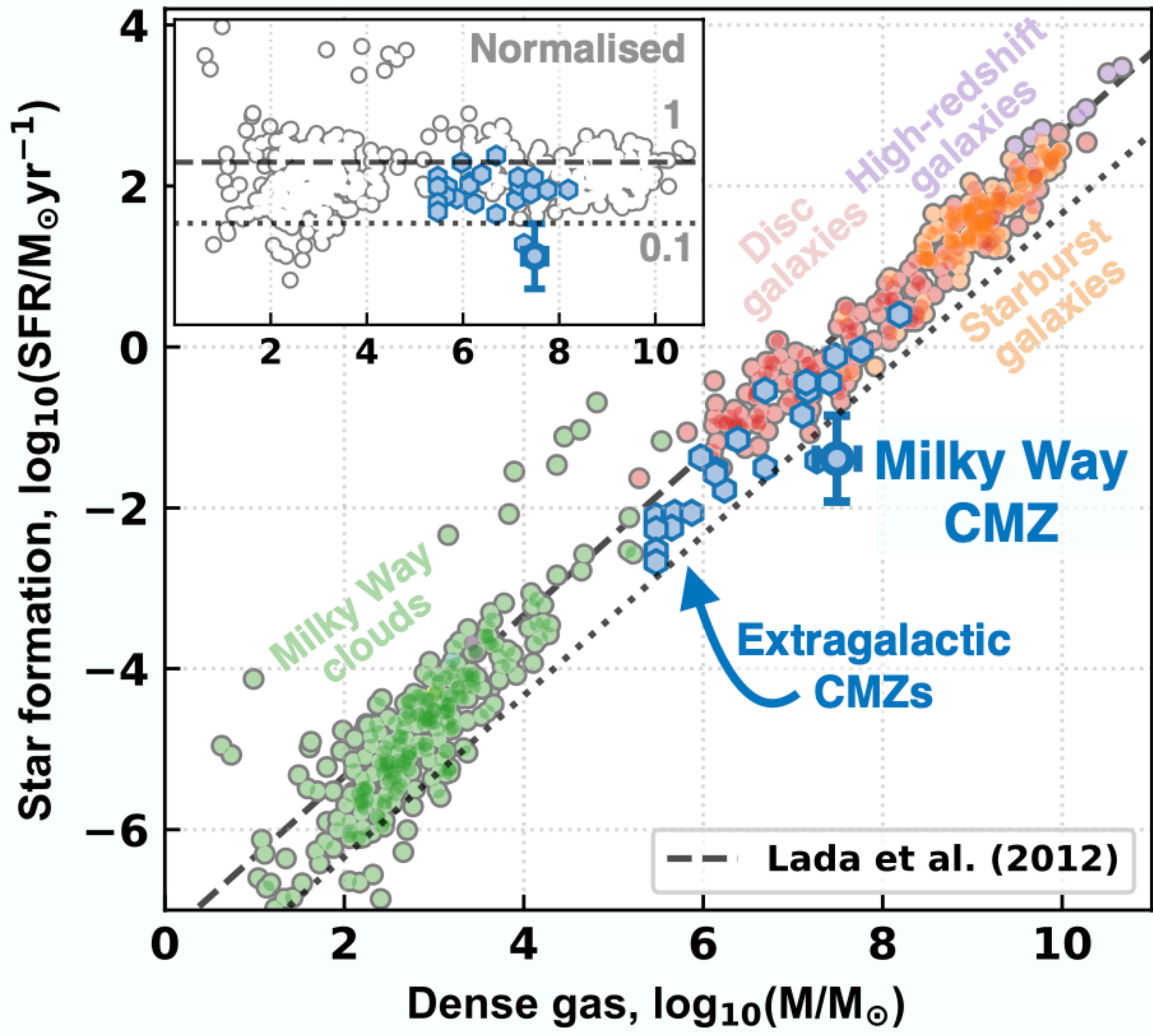
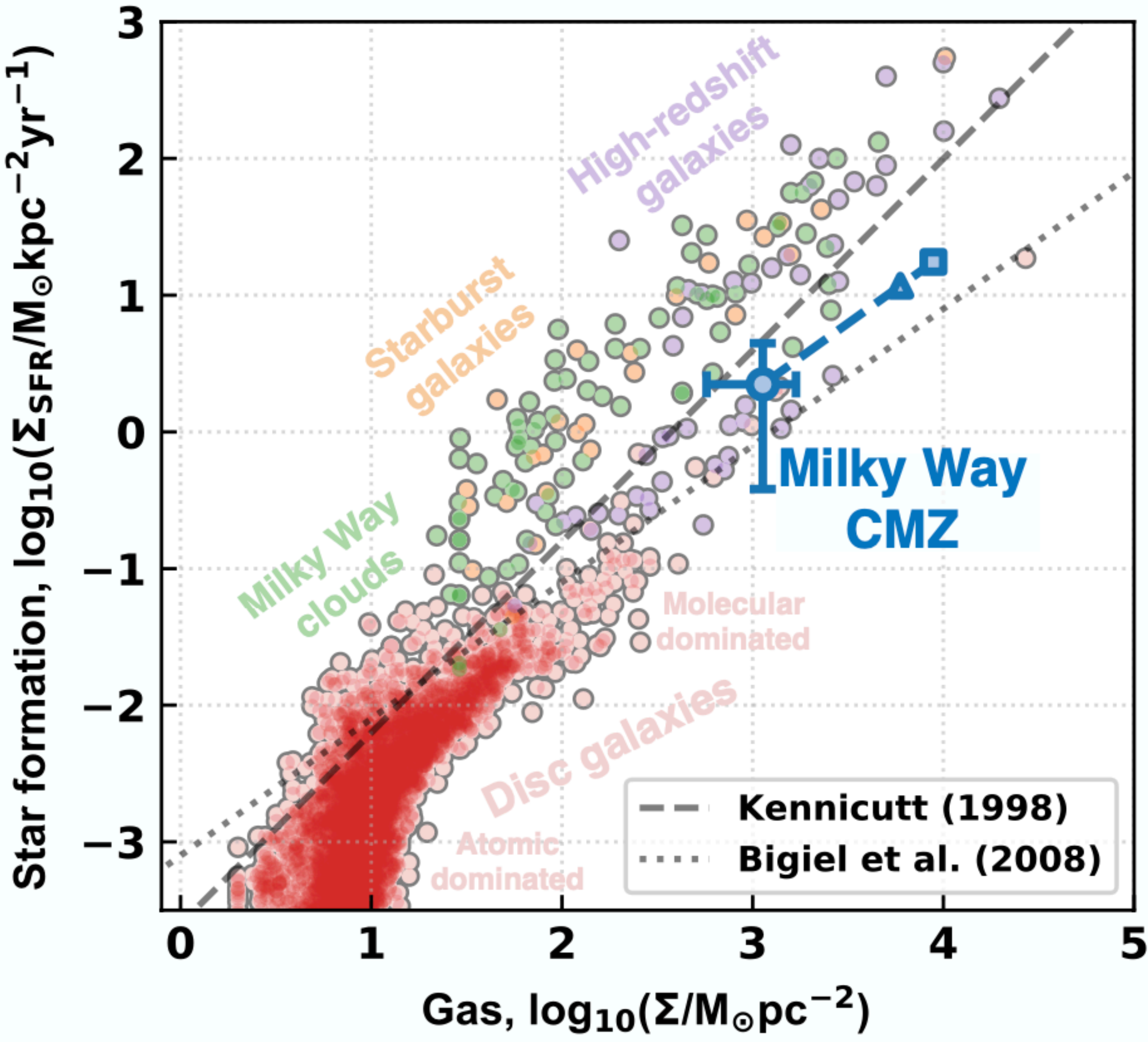
Star Formation, complicated

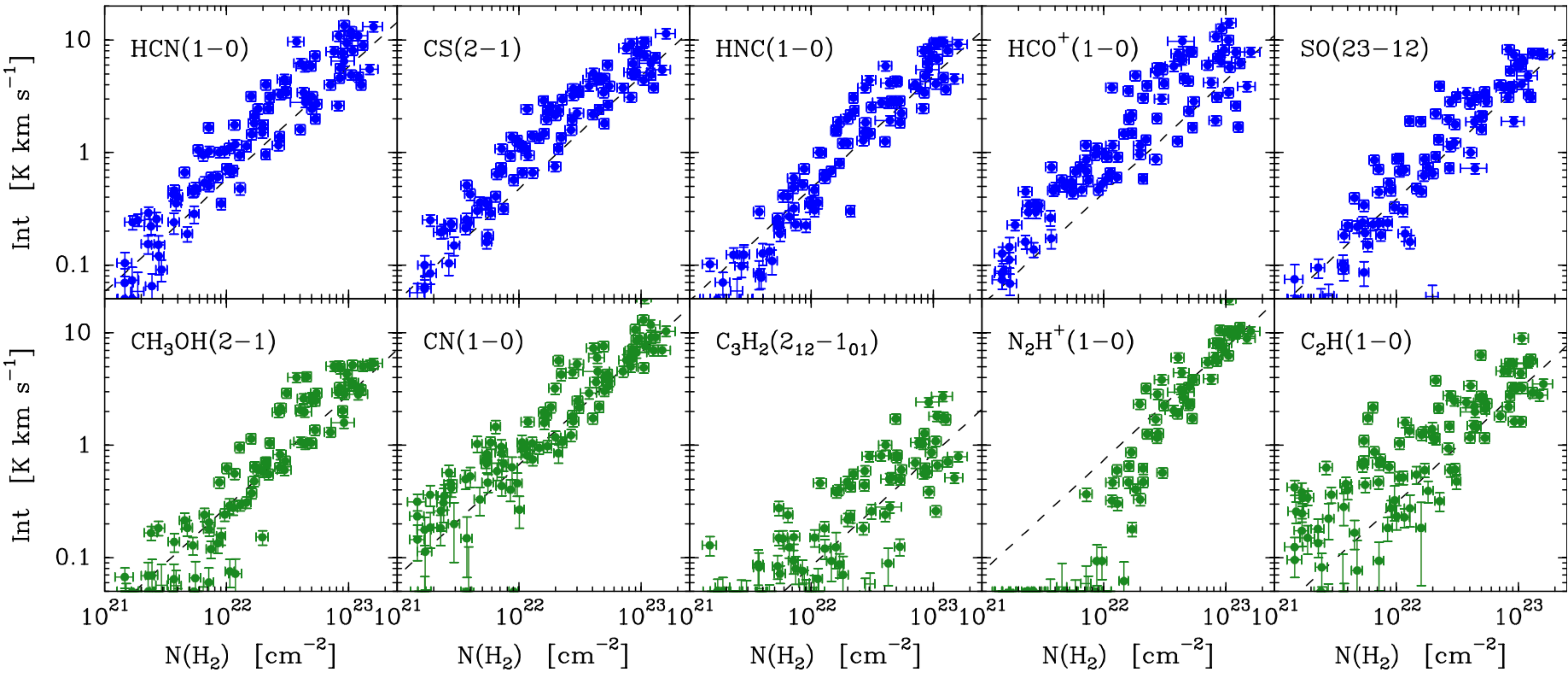
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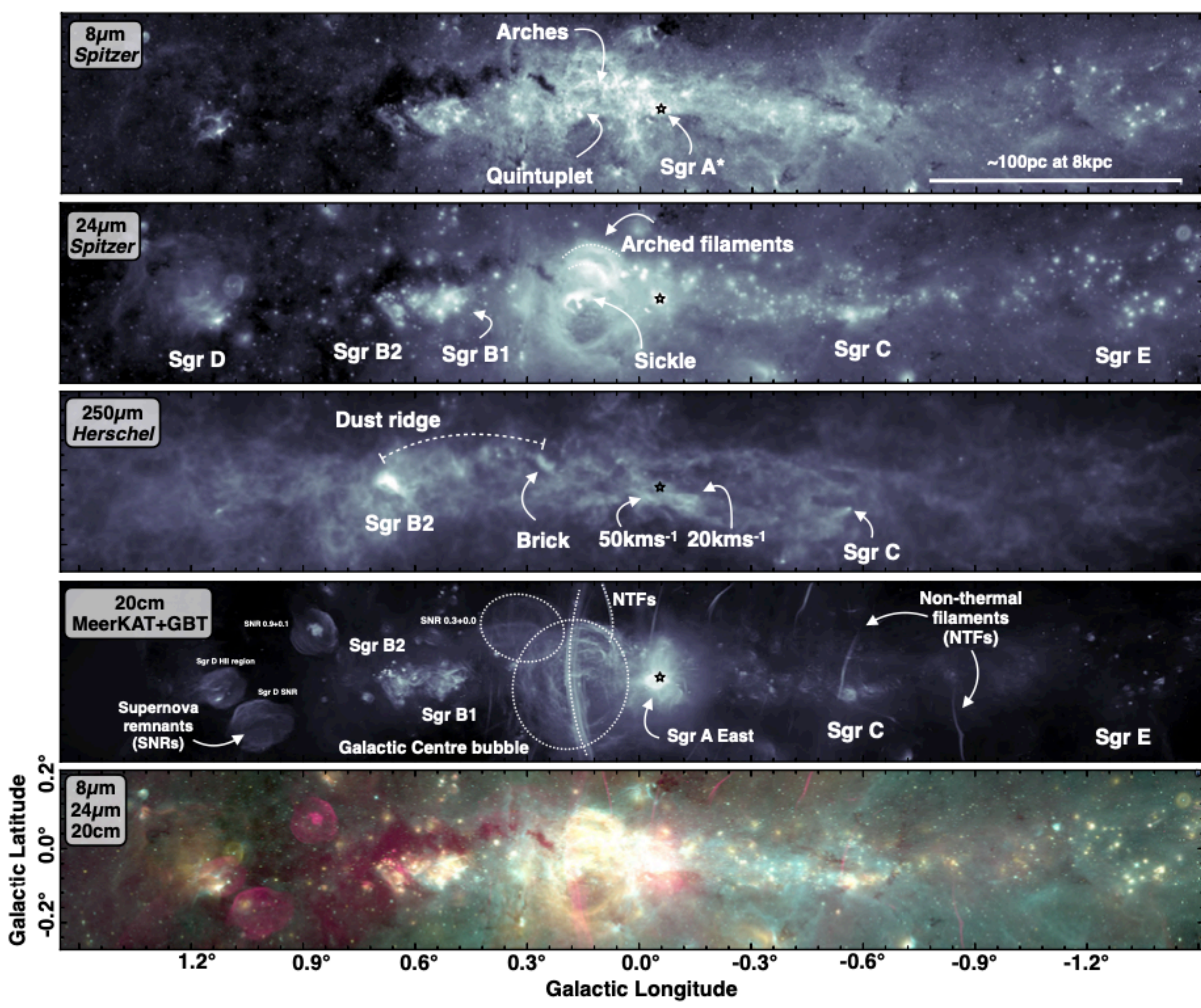
Star Formation, complicated

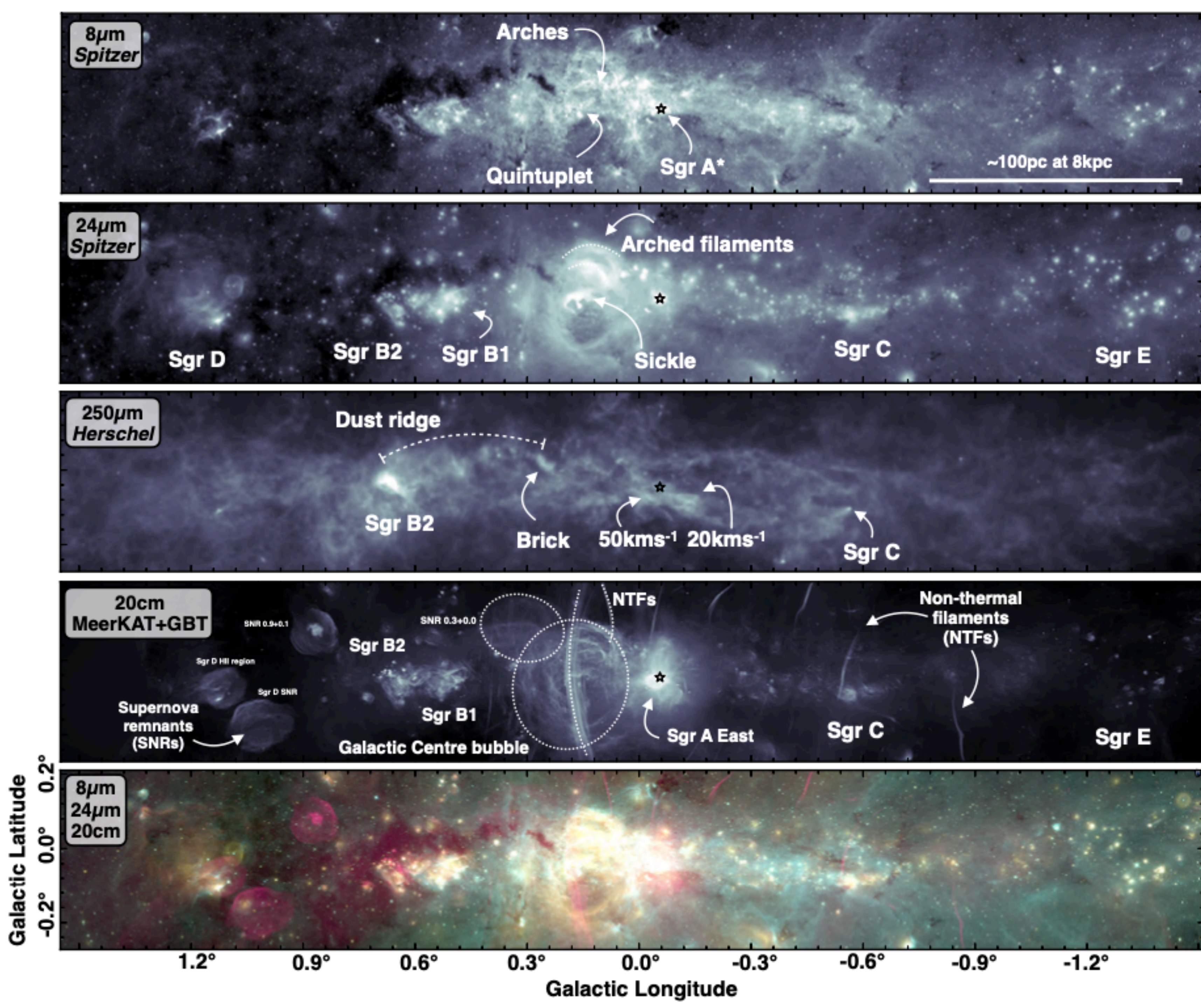


10pc









STAGE 2 The Brick

Ability
 100,000 M_{\odot}
 2 – 3 pc

resistance
 weakness
 retreat

©2014 Pokémon
 MRSKADRA42

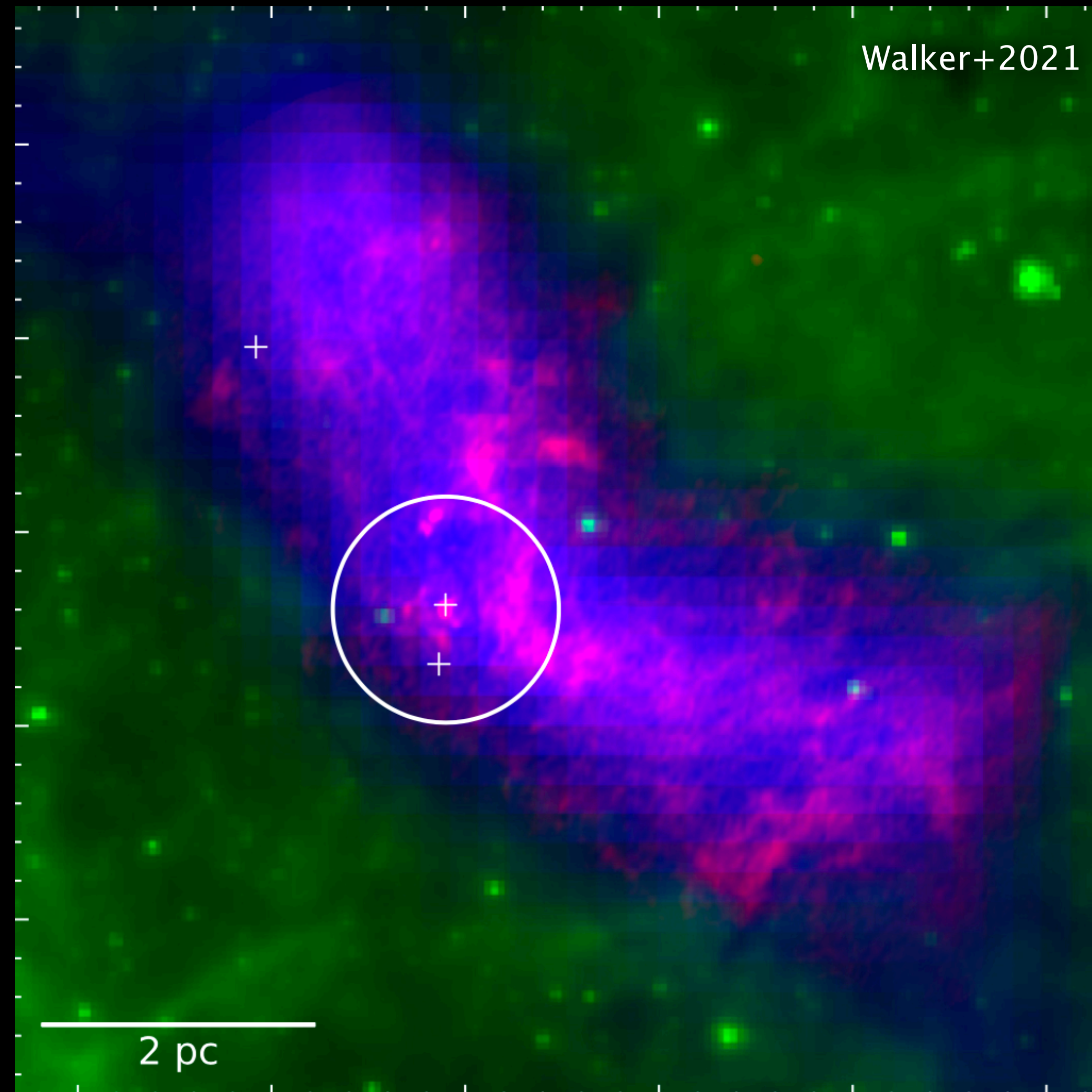
The (low-res) Brick

ALMA 3mm dust
continuum
(Rathborne+2014)

Spitzer/GLIMPSE
8 μ m emission
(Churchwell+2009)

Herschel/HiGal dust
column density
(Battersby+2011,
Molinari+2016)

+ water masers
(Lu+2019)



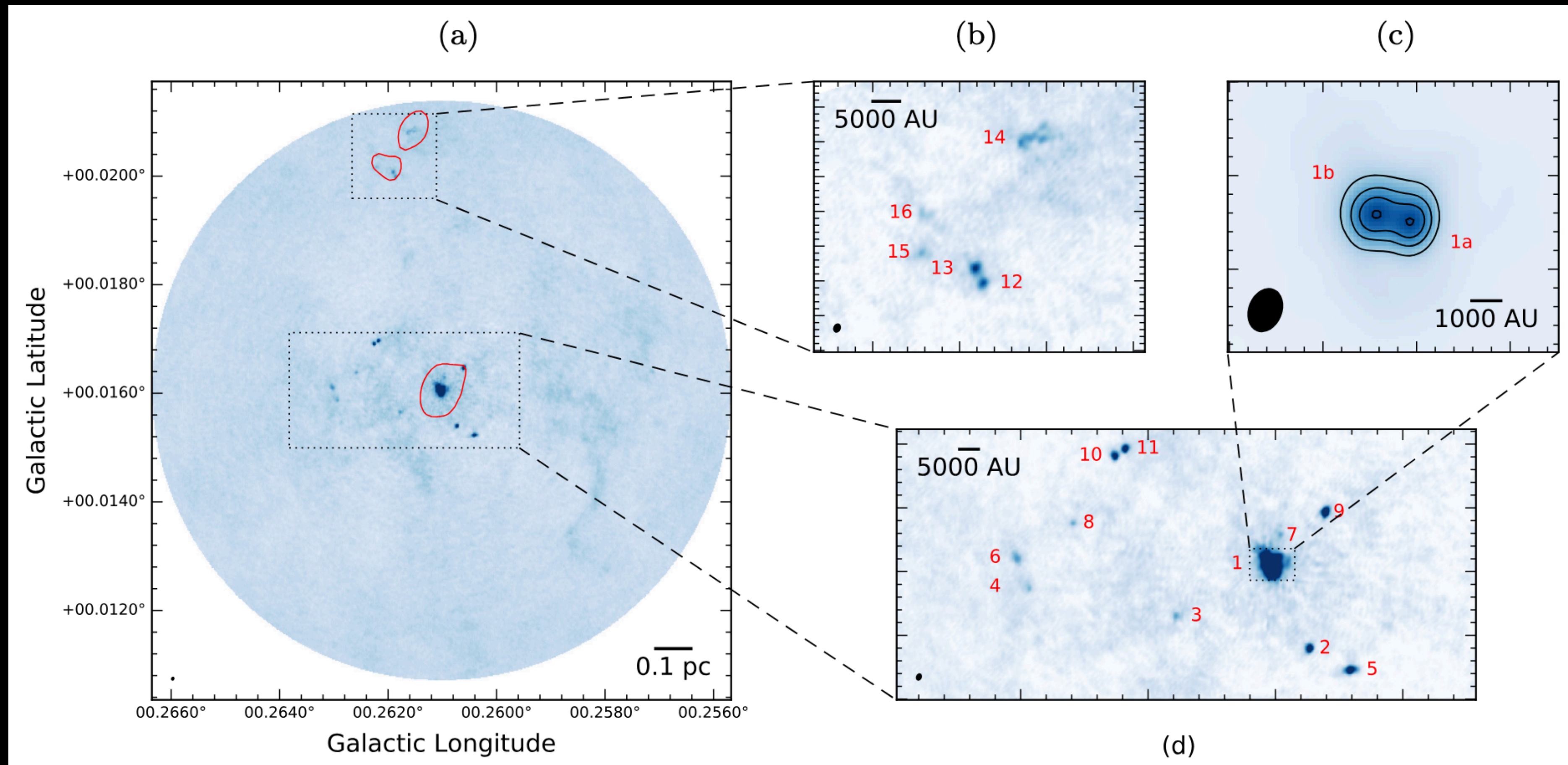
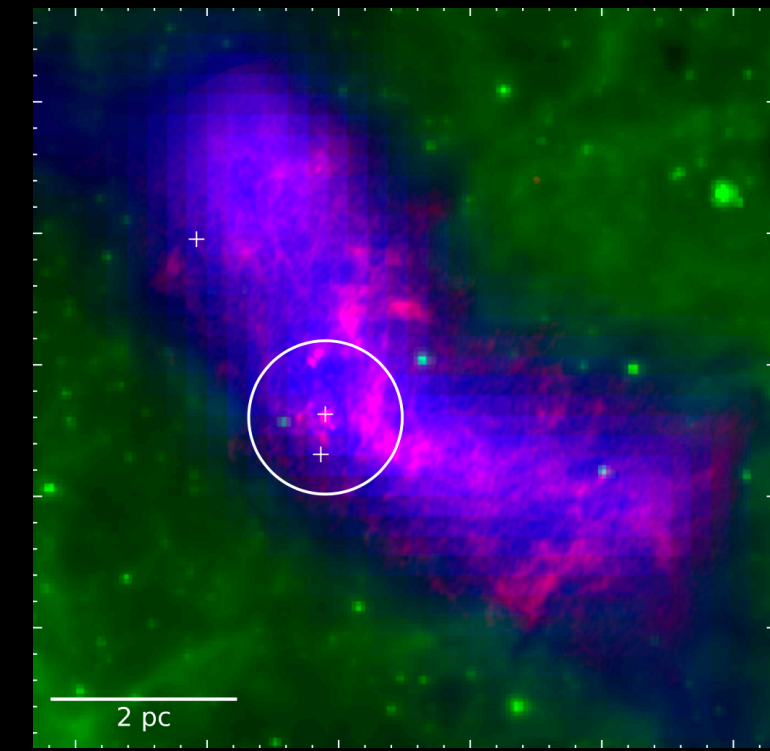
The (high-res) Brick

Walker+2021

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Walker+2021

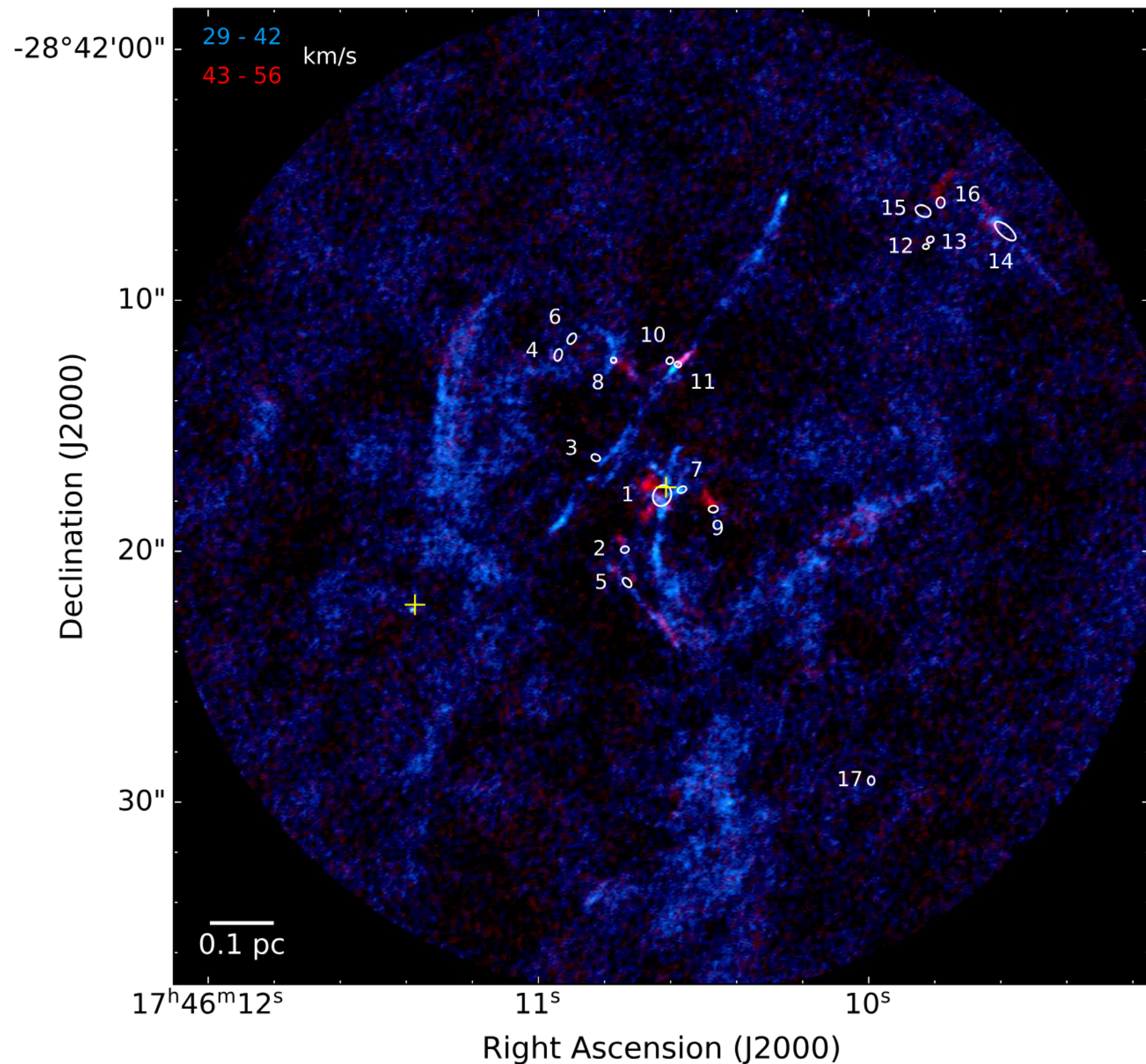
- 1.3mm dust continuum



The (high-res) Brick

Walker+2021

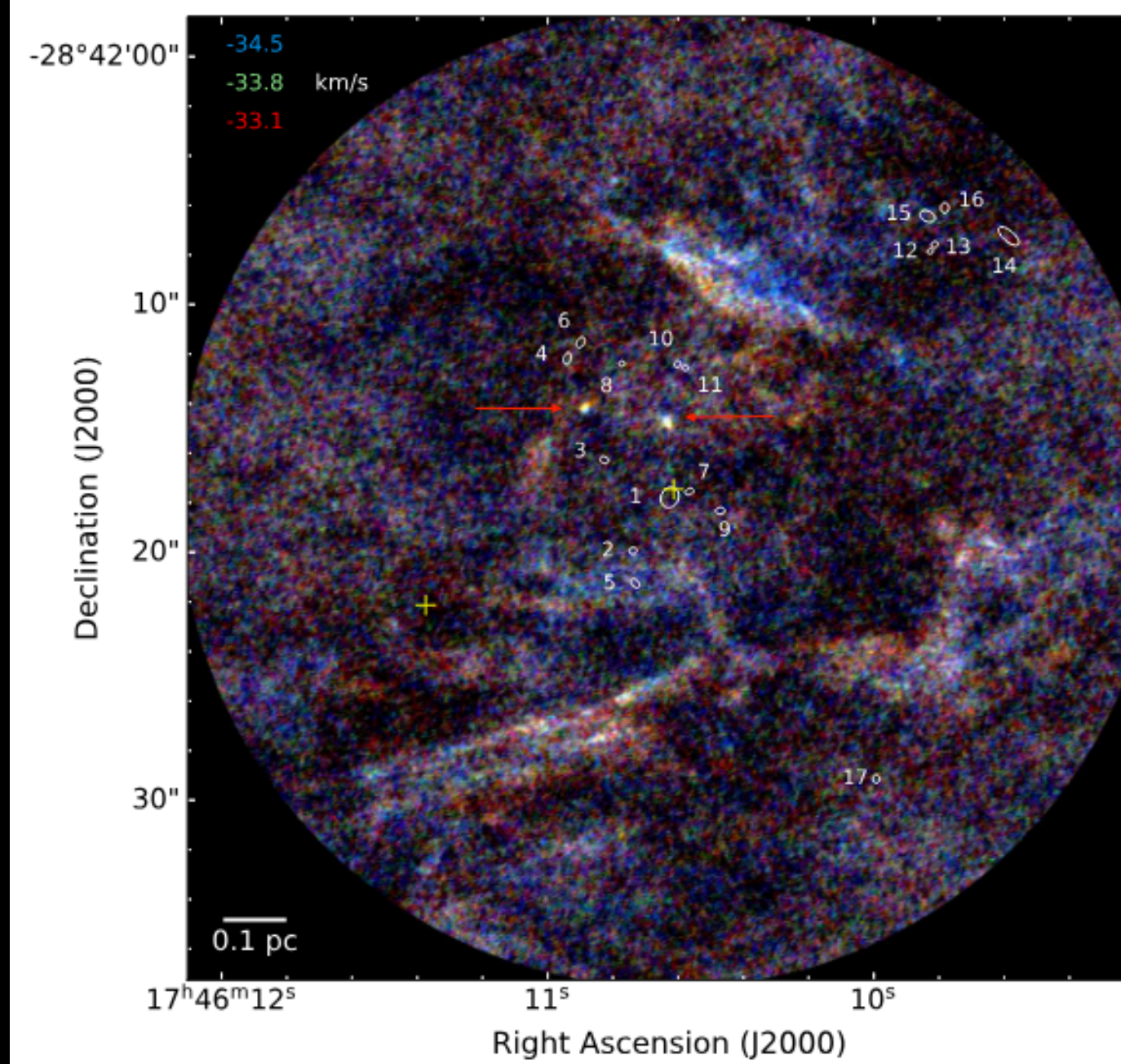
- 1.3mm dust continuum
- SiO outflows (blueshifted, redshifted)



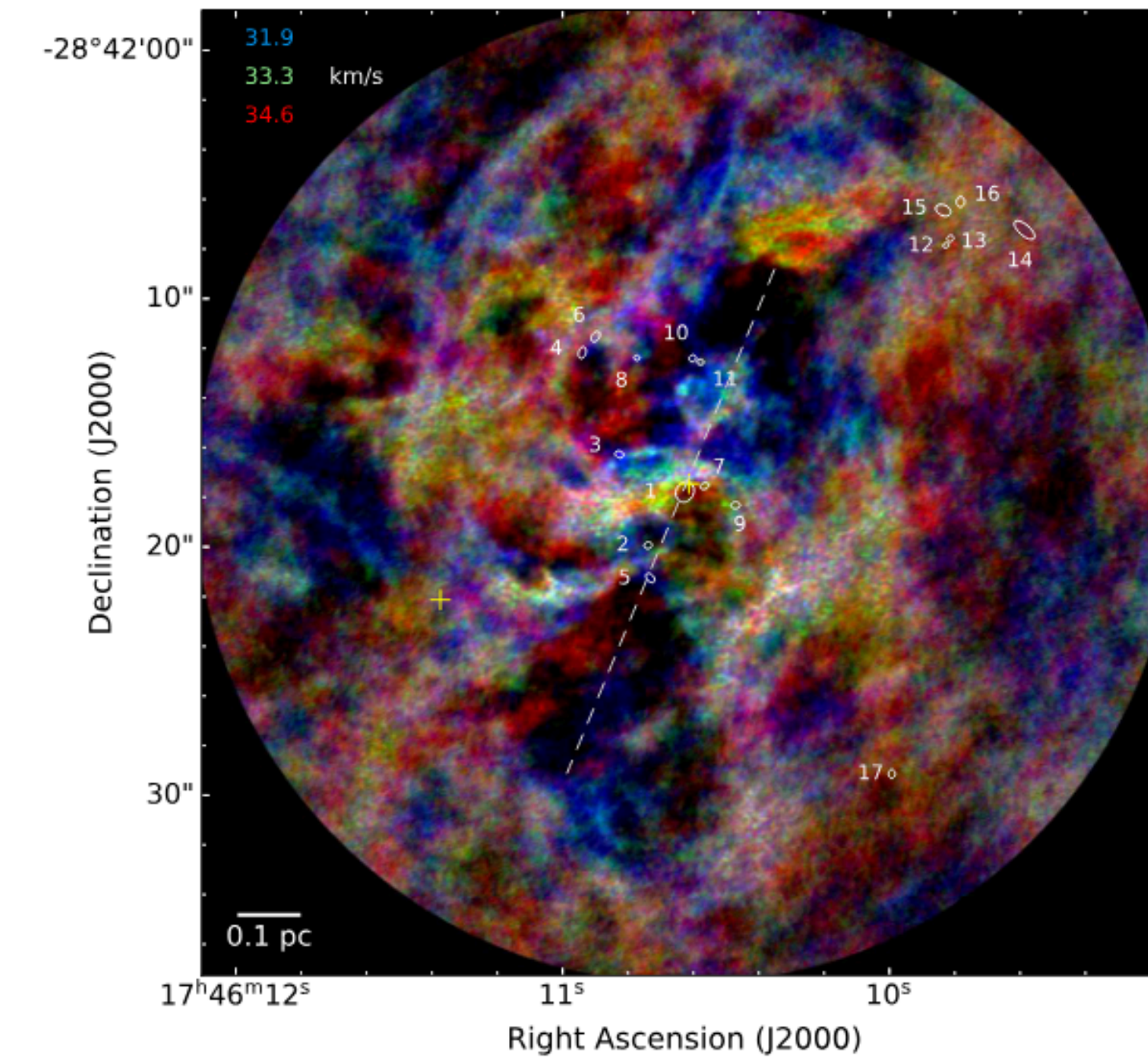
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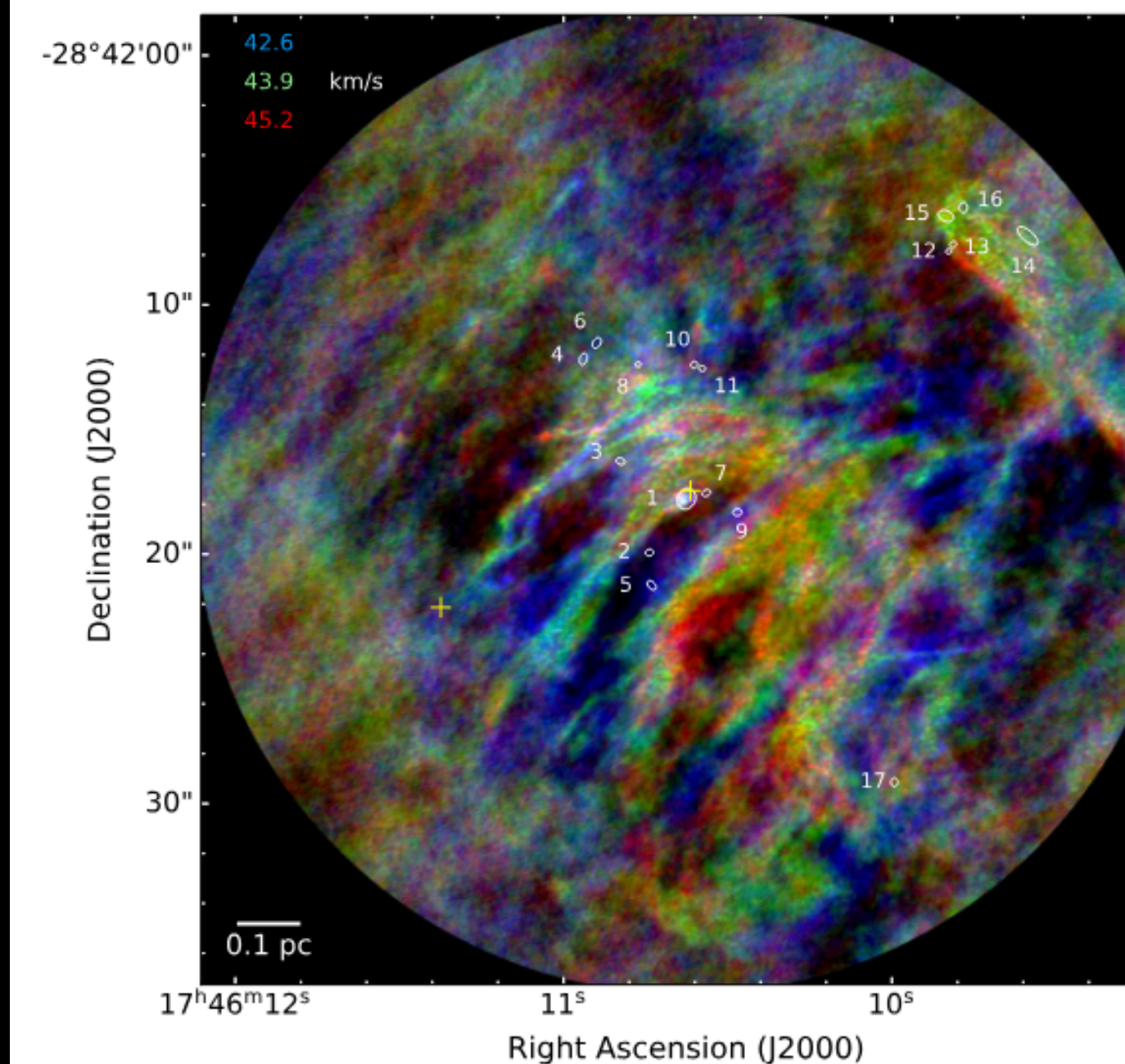
- 1.3mm dust continuum
- SiO outflows (blueshifted, redshifted)
- ^{13}CO emission, complicated velocity structure, outflows?



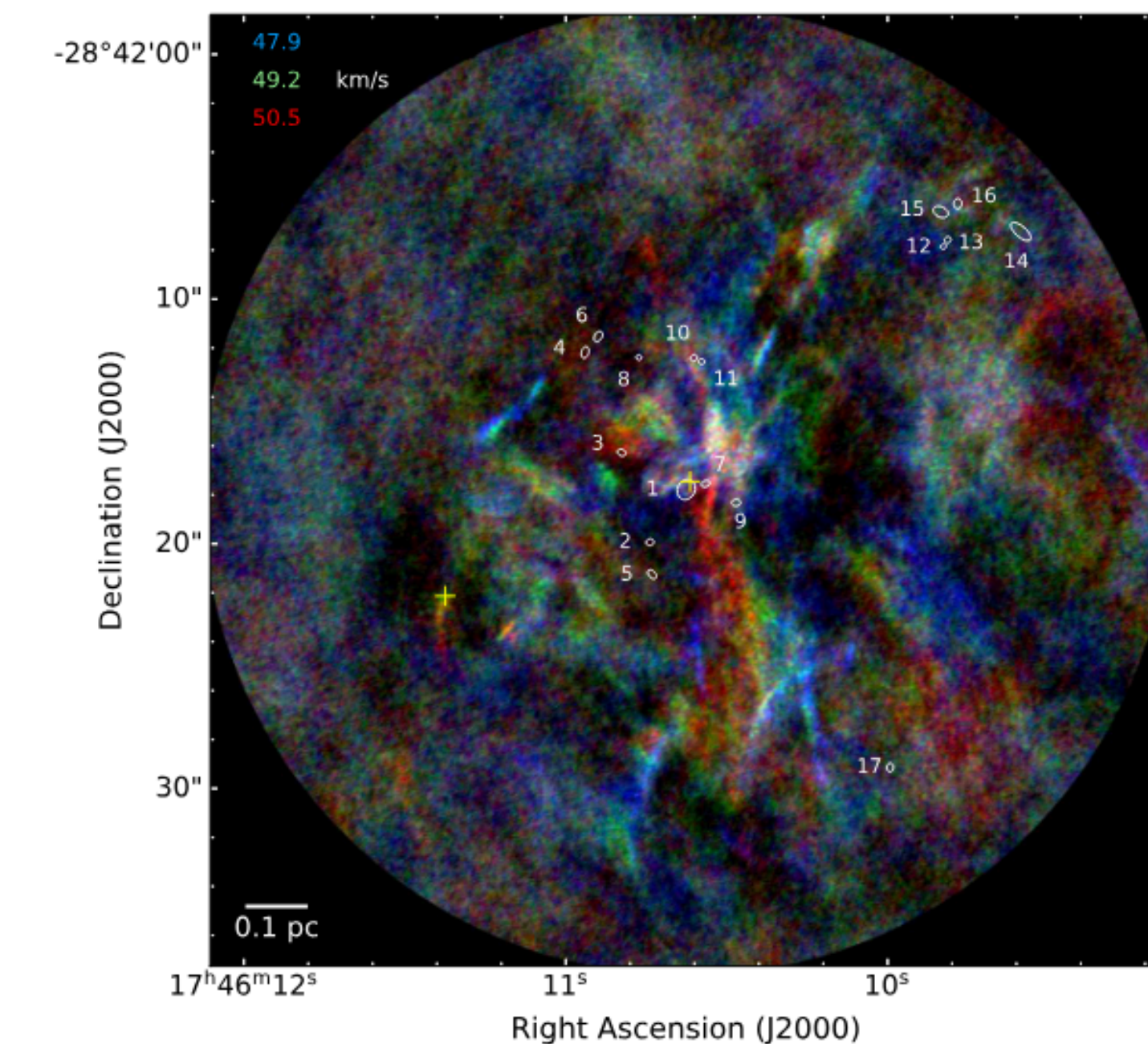
(a)



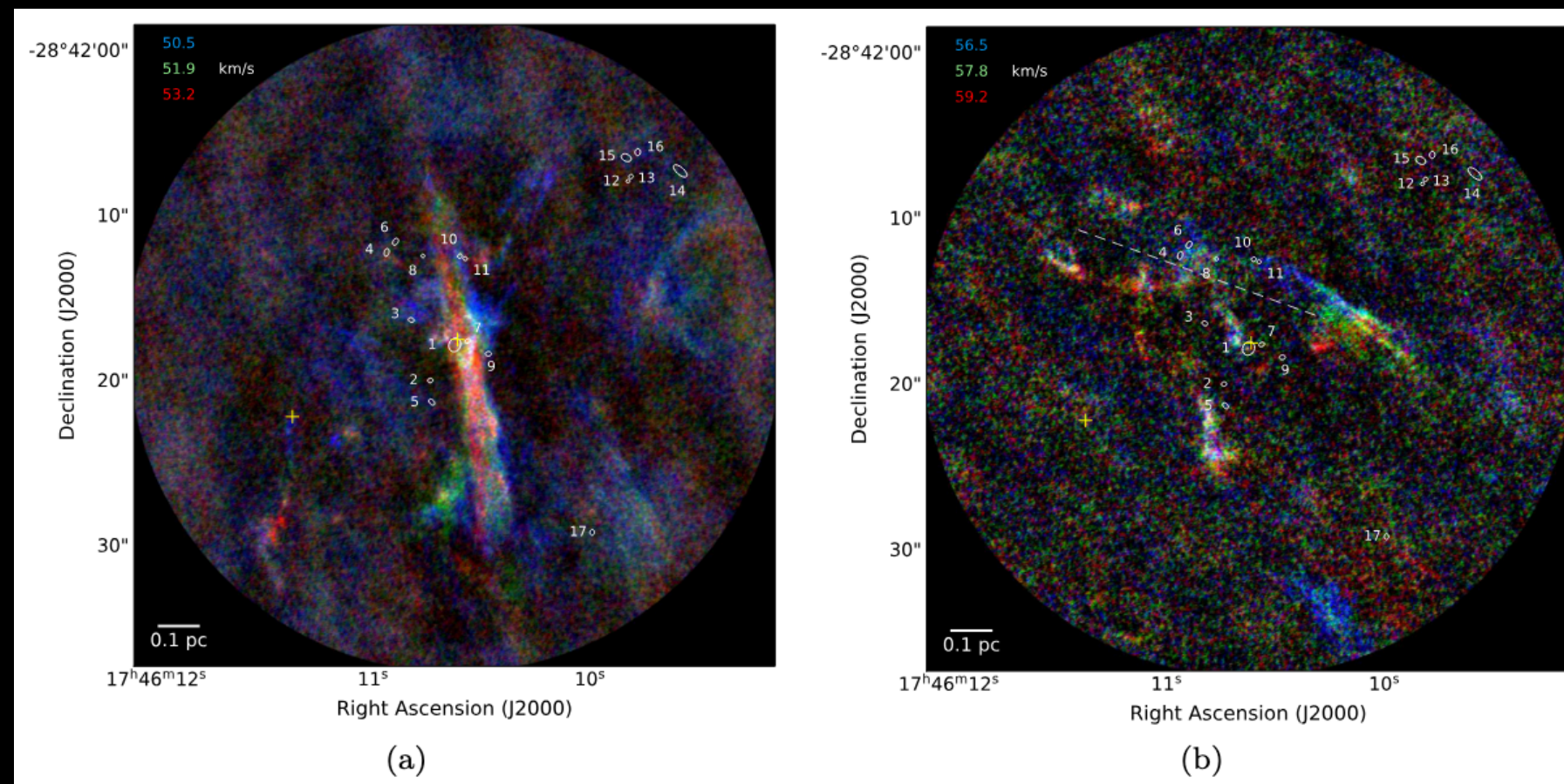
(b)



(c)



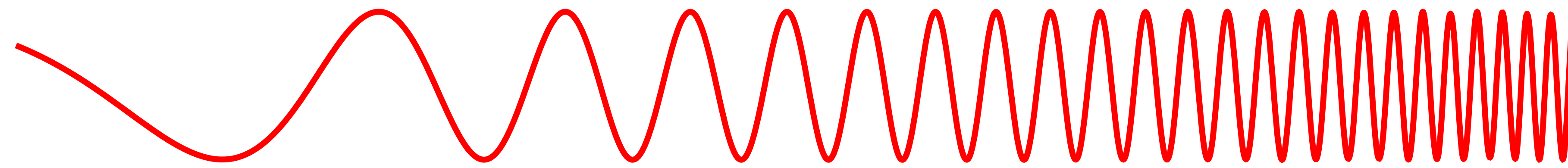
(d)



(a)

(b)

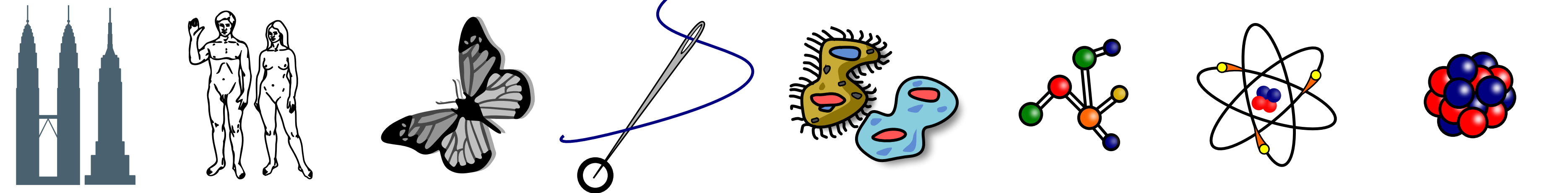
Penetrates Earth's Atmosphere?



Radiation Type
Wavelength (m)

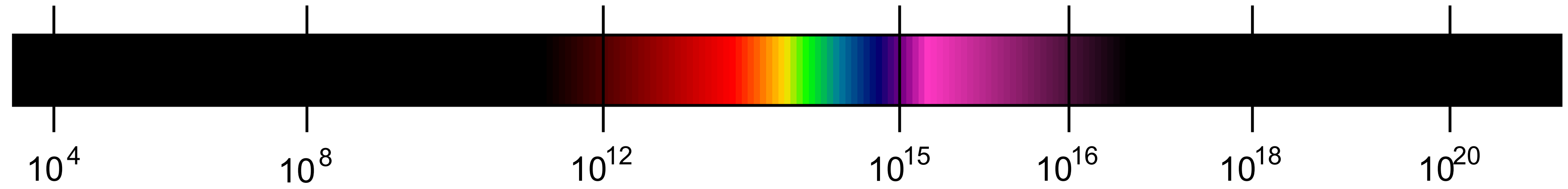
Radio 10^3	Microwave 10^{-2}	Infrared 10^{-5}	Visible 0.5×10^{-6}	Ultraviolet 10^{-8}	X-ray 10^{-10}	Gamma ray 10^{-12}
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Approximate Scale of Wavelength

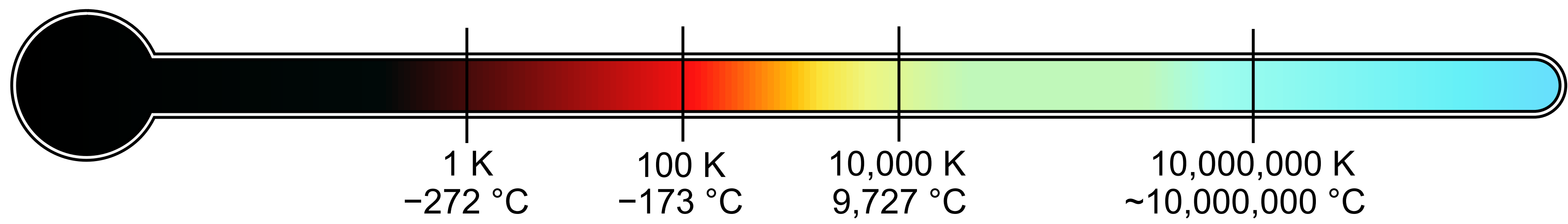


Buildings	Humans	Butterflies	Needle Point	Protozoans	Molecules	Atoms	Atomic Nuclei
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Frequency (Hz)



Temperature of objects at which this radiation is the most intense wavelength emitted





The Atacama Large Millimeter/submillimeter Array

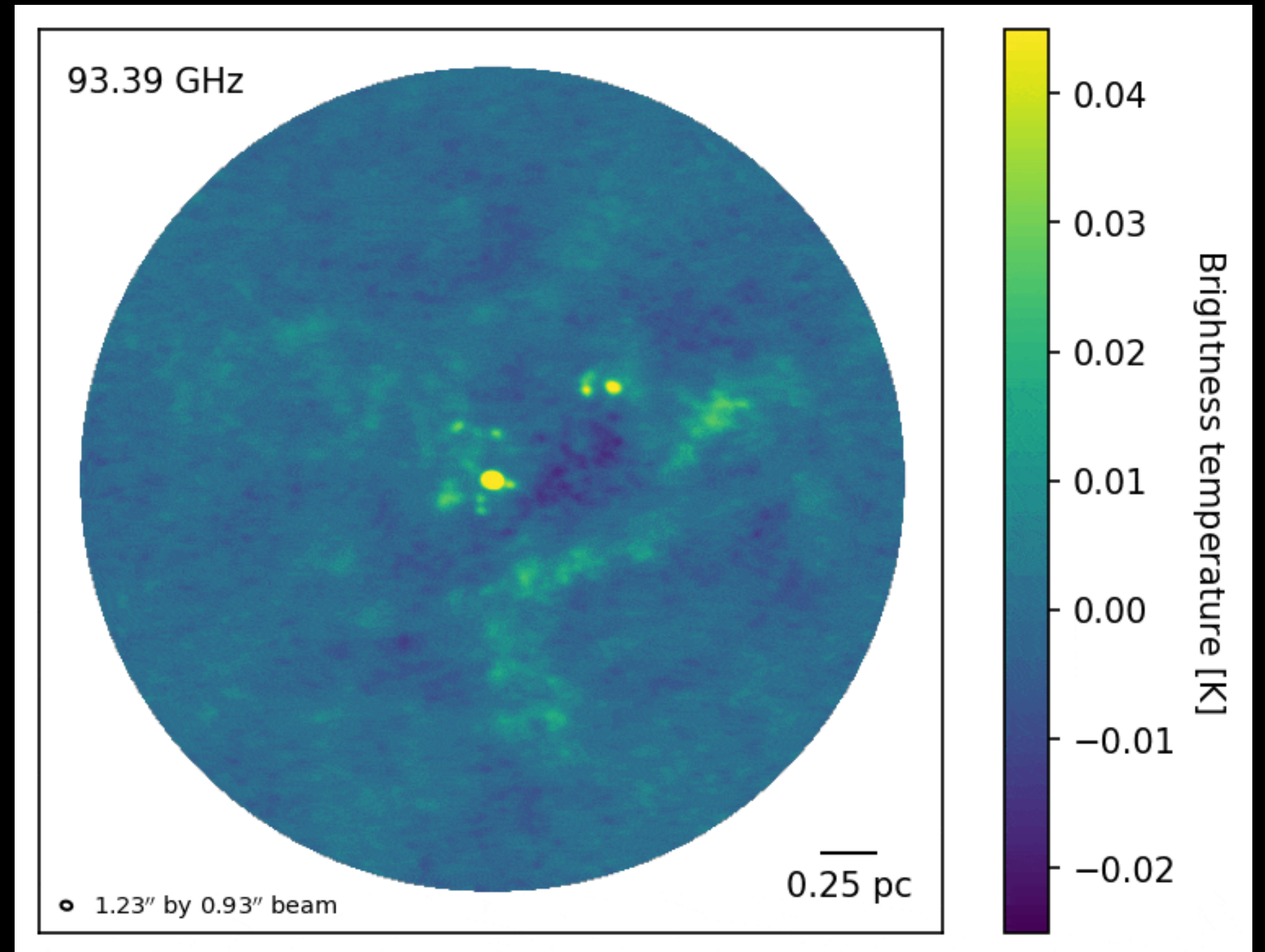


The Atacama Large Millimeter/submillimeter Array



The Atacama Large Millimeter/submillimeter Array

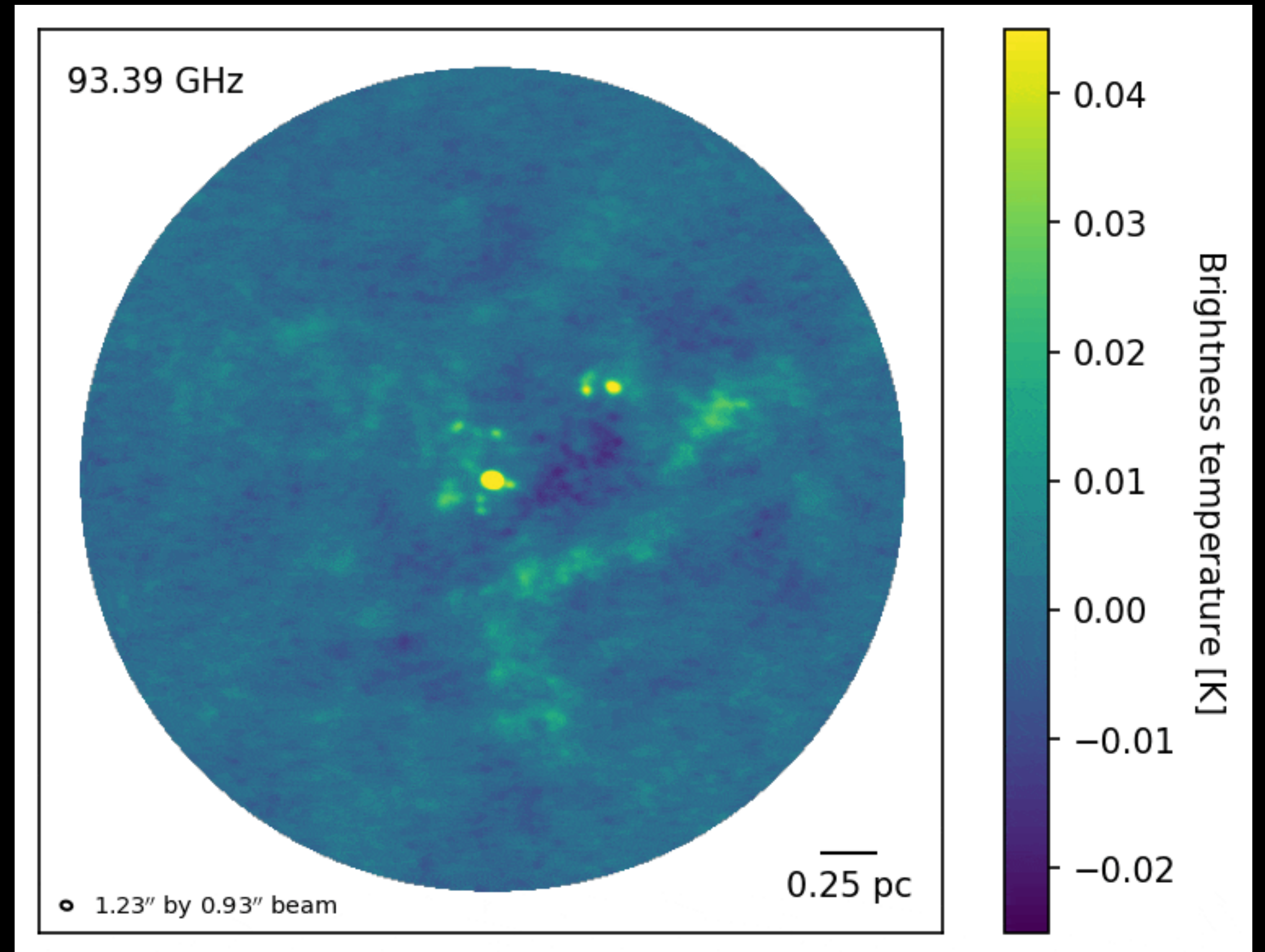
The Brick Line Survey (BLS) with ALMA



The BLS covers ALMA Bands 3, ~4, and the upper half of 6 (= 90 total GHz of coverage)

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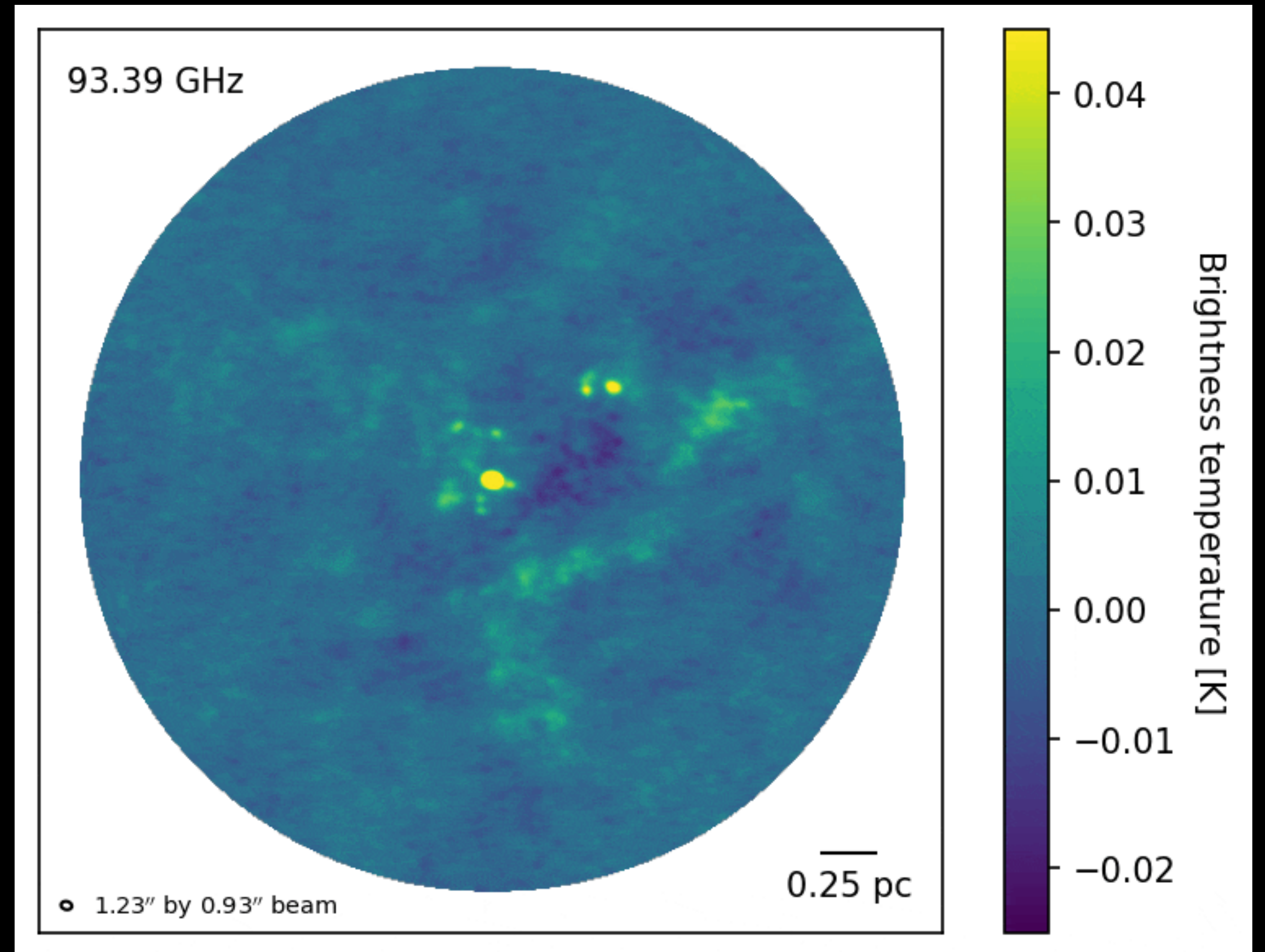
- Goal is to find clear and unique molecular tracers for different physical processes present in The Brick, differentiating SF-related ones (cores, outflows) from those unassociated with SF (shocks, diffuse gas)



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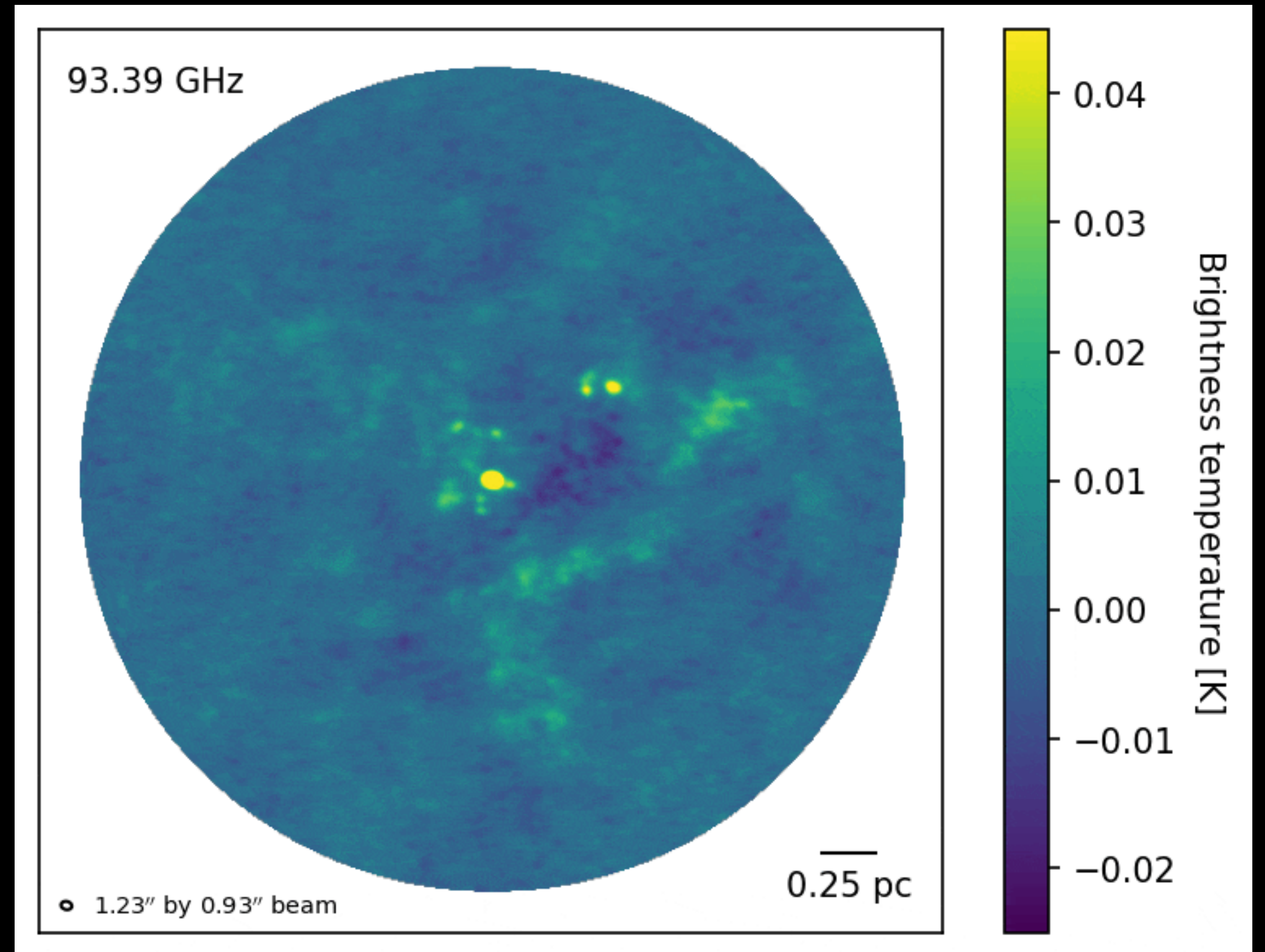
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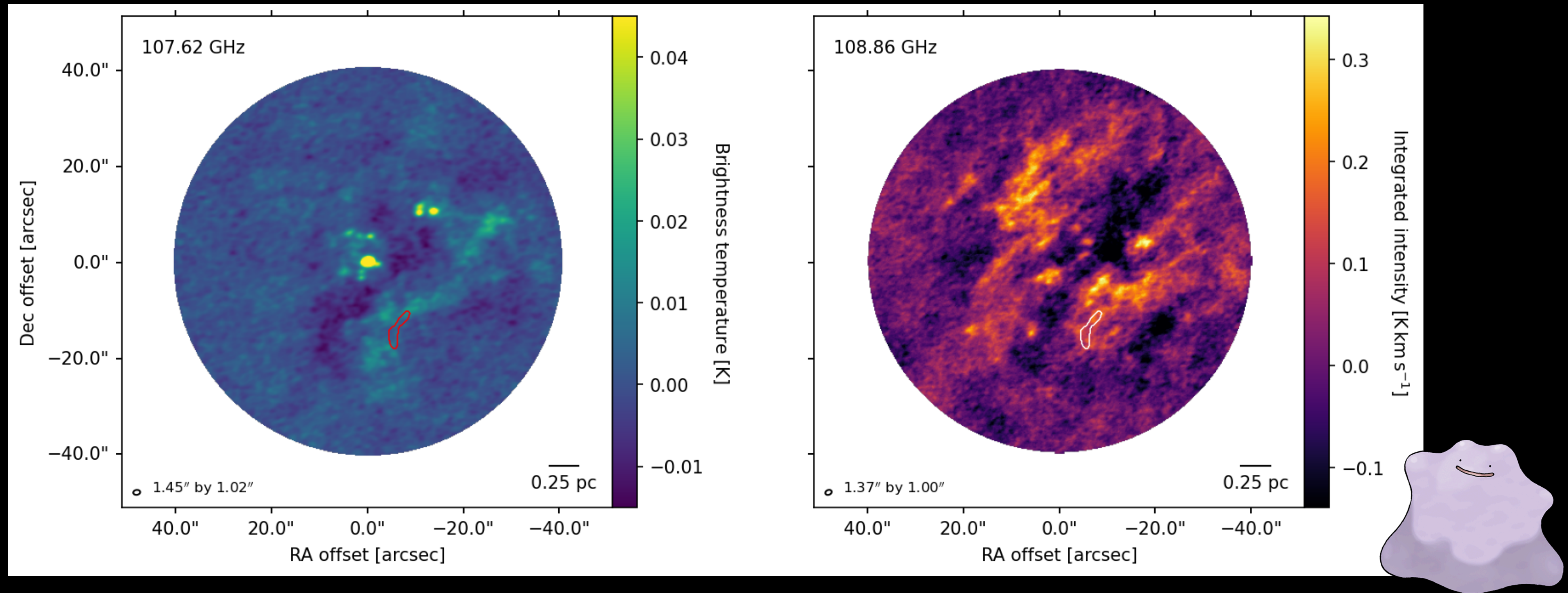
- Goal is to find clear and unique molecular tracers for different physical processes present in The Brick, differentiating SF-related ones (cores, outflows) from those unassociated with SF (shocks, diffuse gas)
- "New" tracers can be used to interpret existing, smaller-bandwidth surveys of the CMZ or extragalactic CMZs



The BLS covers ALMA Bands 3, ~4, and the upper half of 6 (= 90 total GHz of coverage)

The Brick Line Survey (BLS) with ALMA

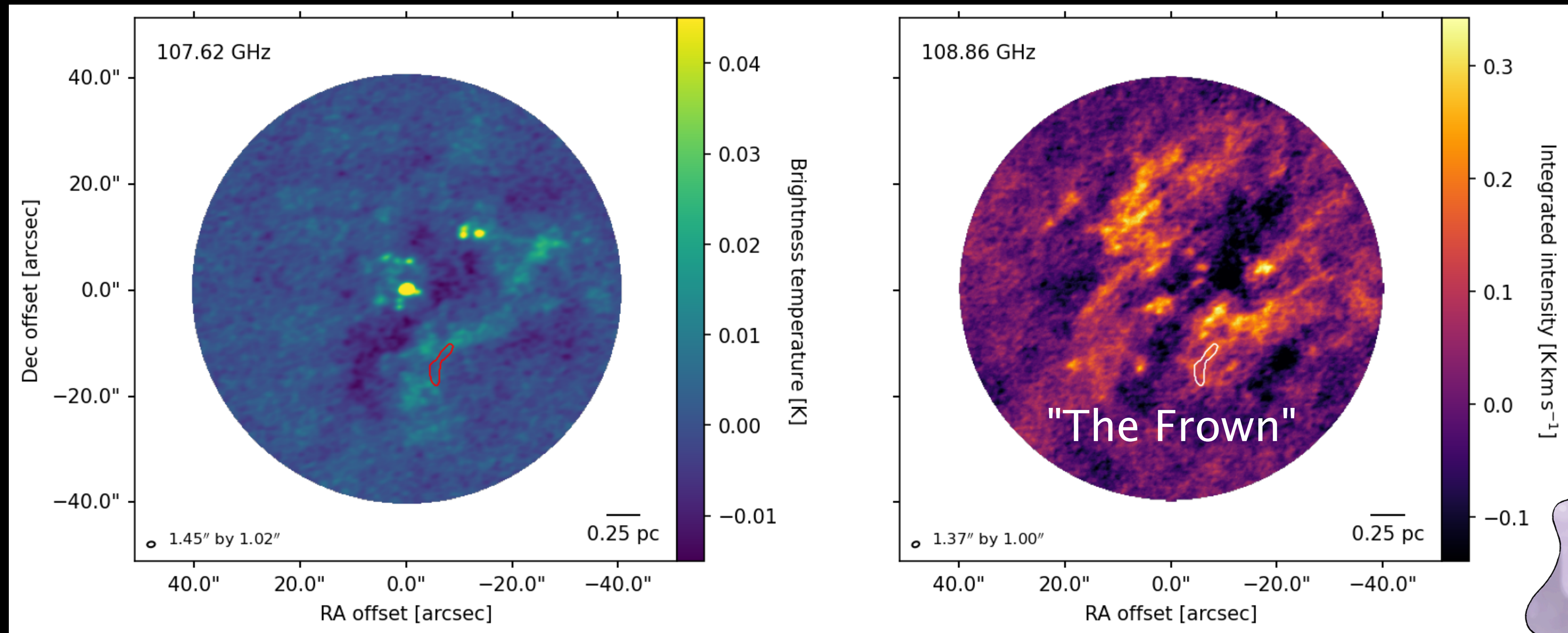
- First step: compare a protostellar core with more diffuse gas around it



Left: part of Band 3 continuum, right: nearby CH₃OH/methanol line emission (108.86 GHz)

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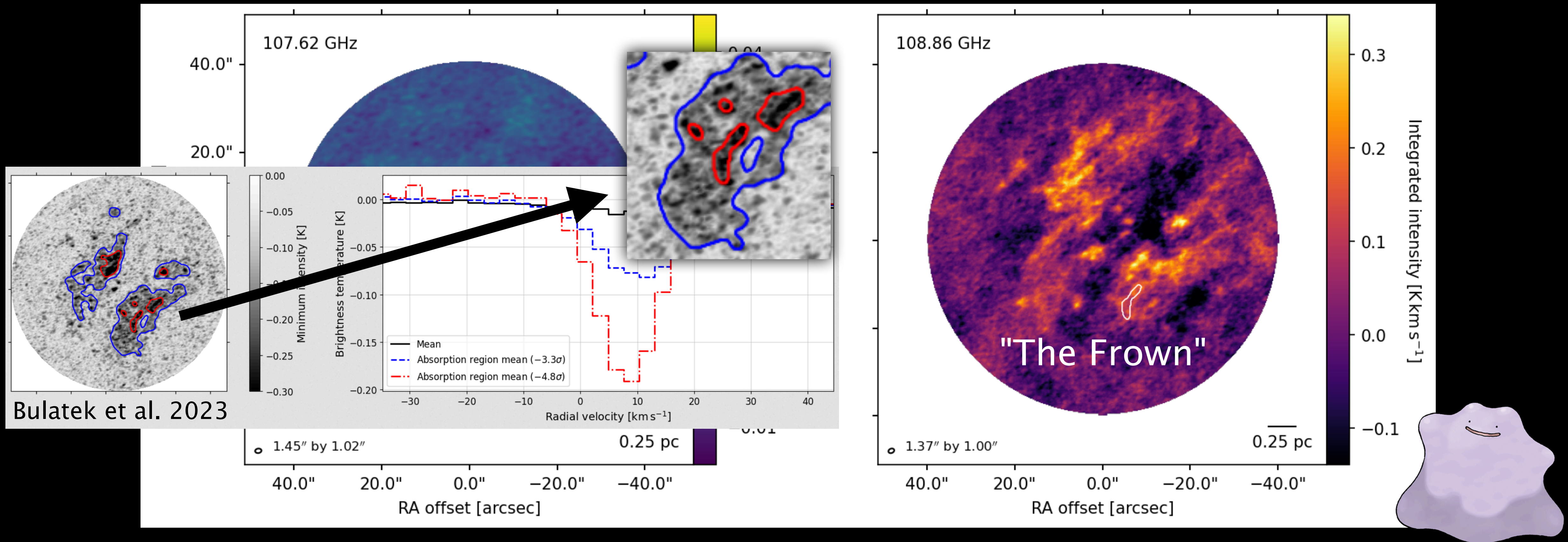
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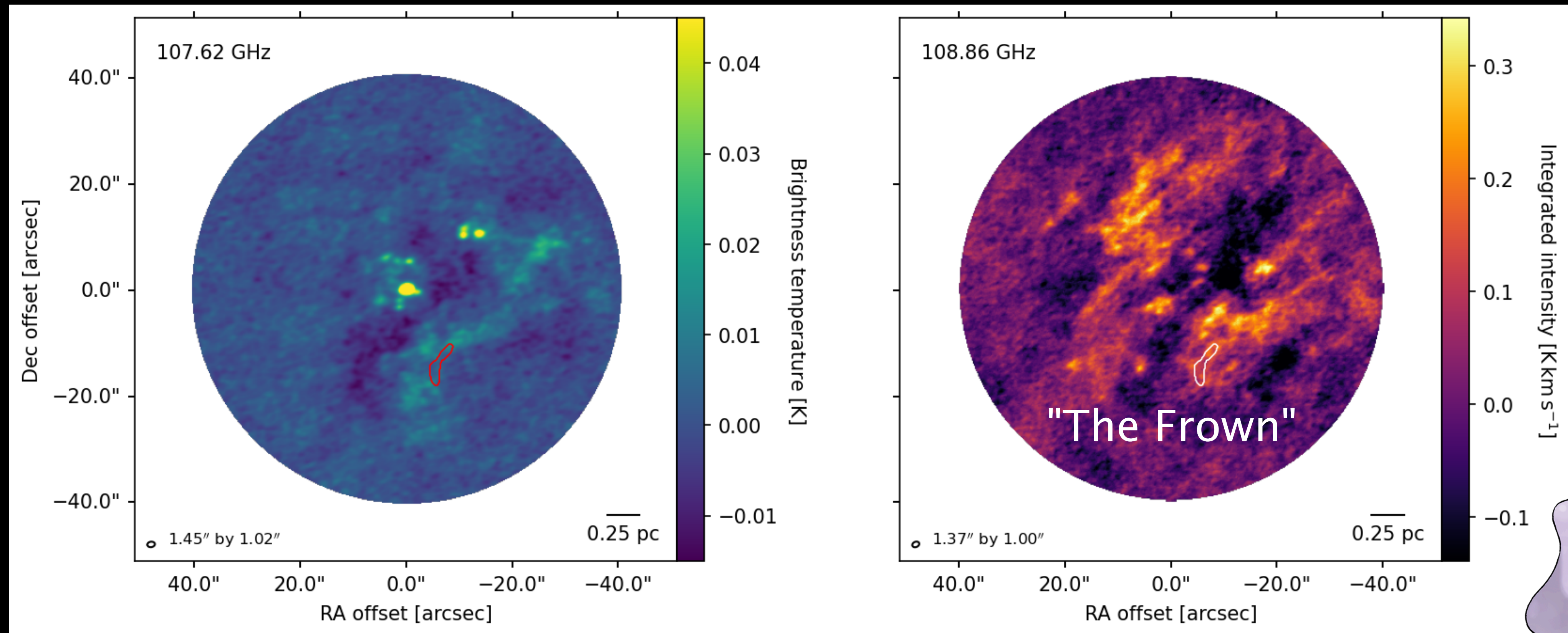
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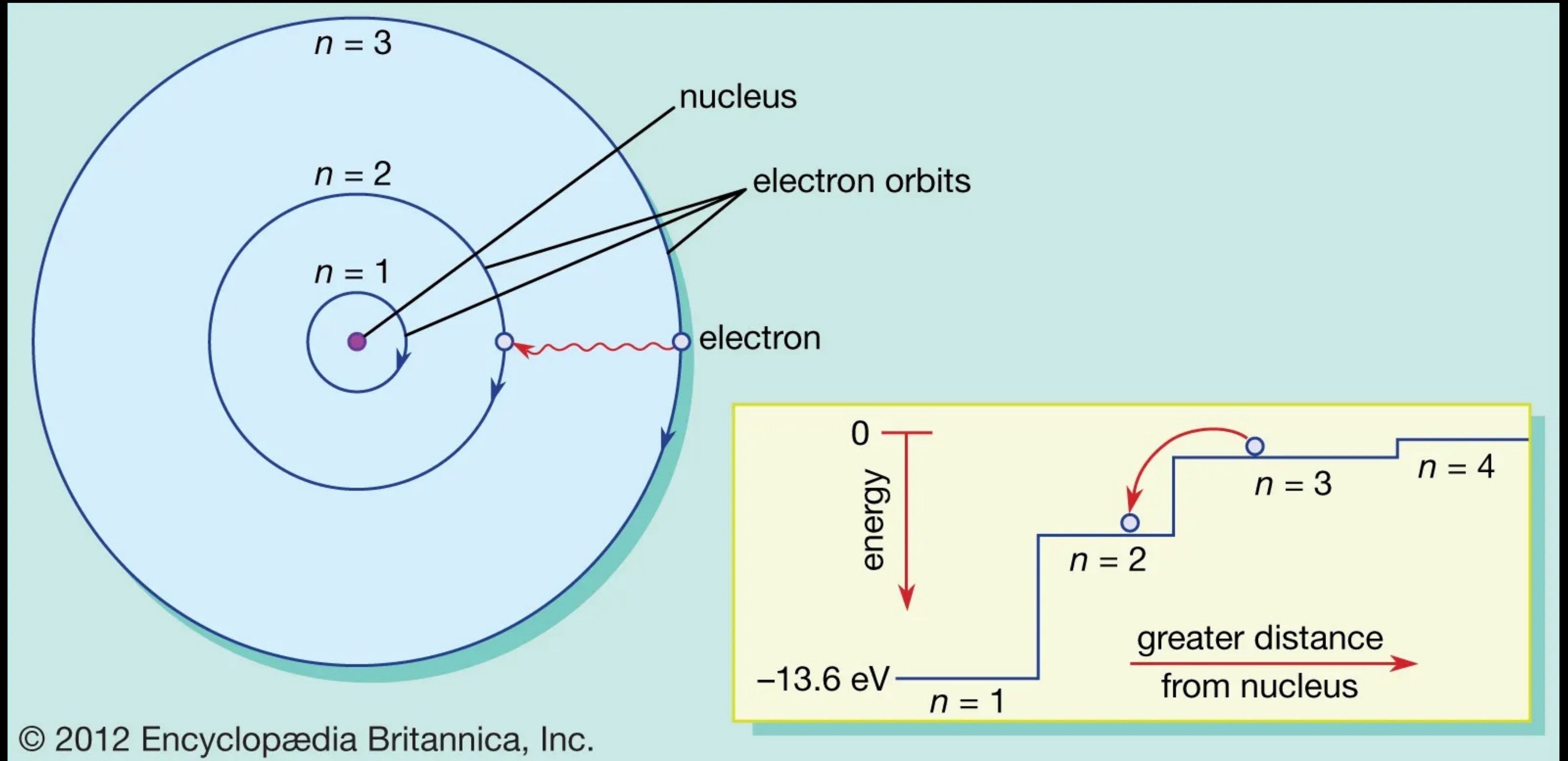
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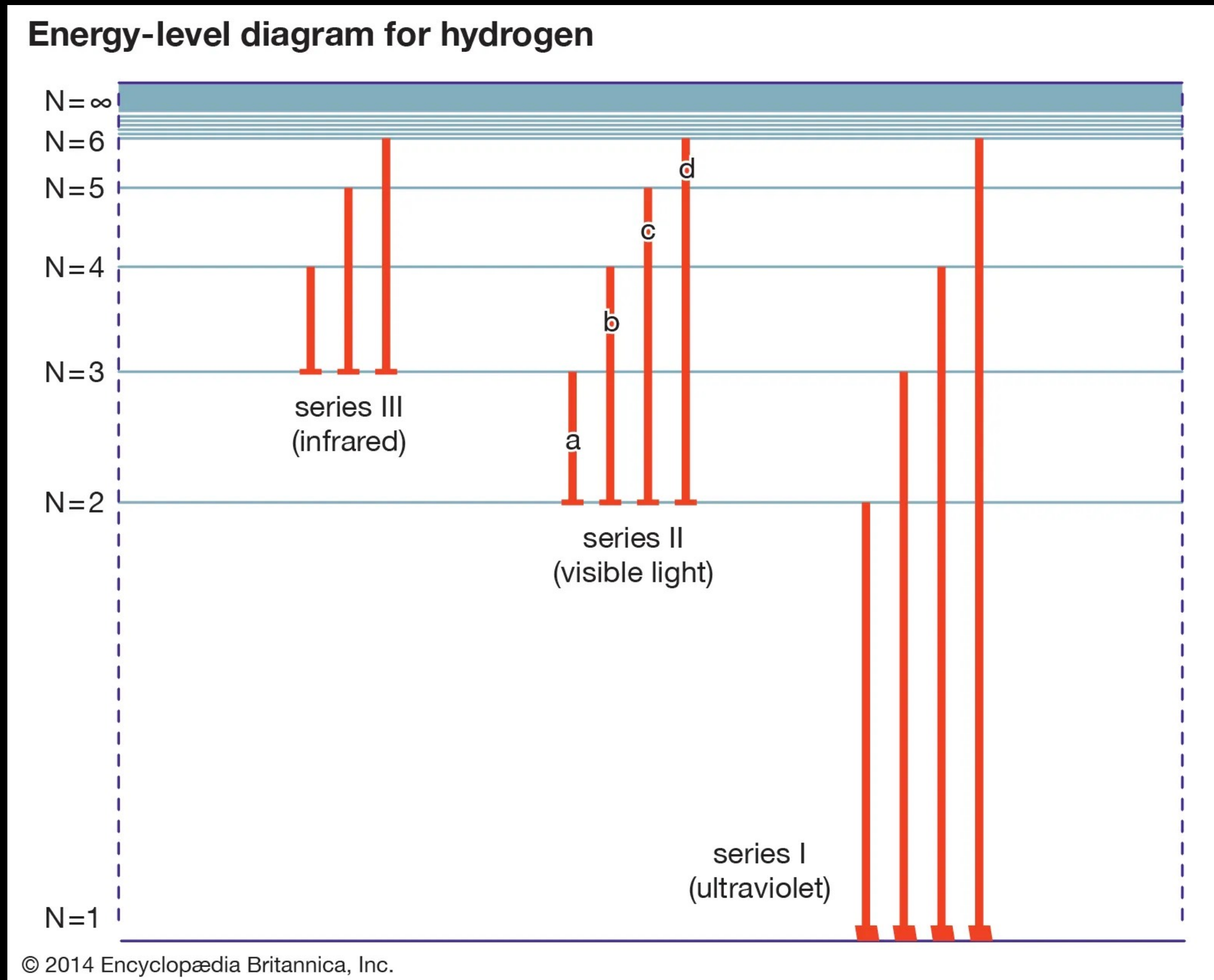
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Energy Levels, simplified

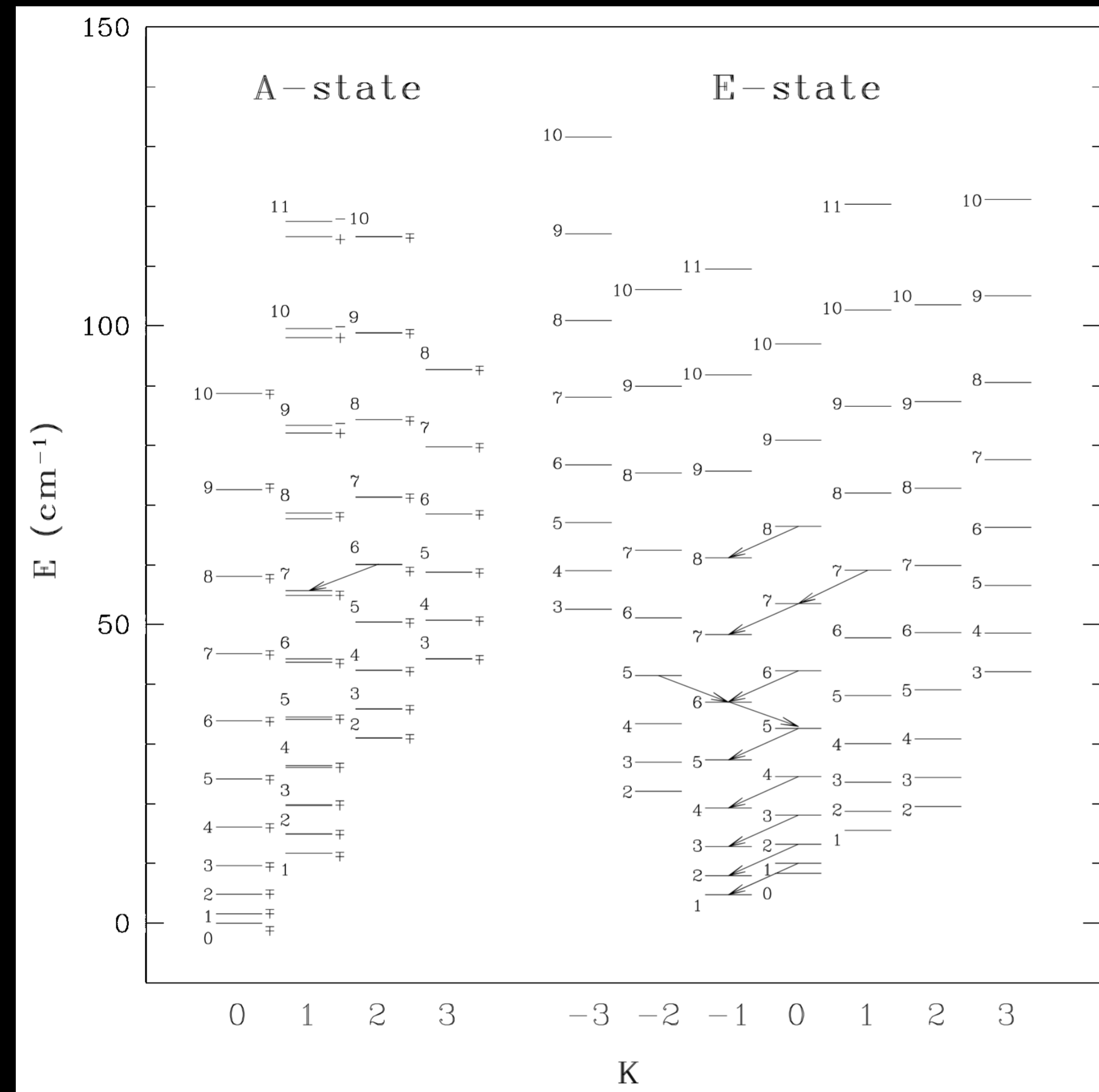
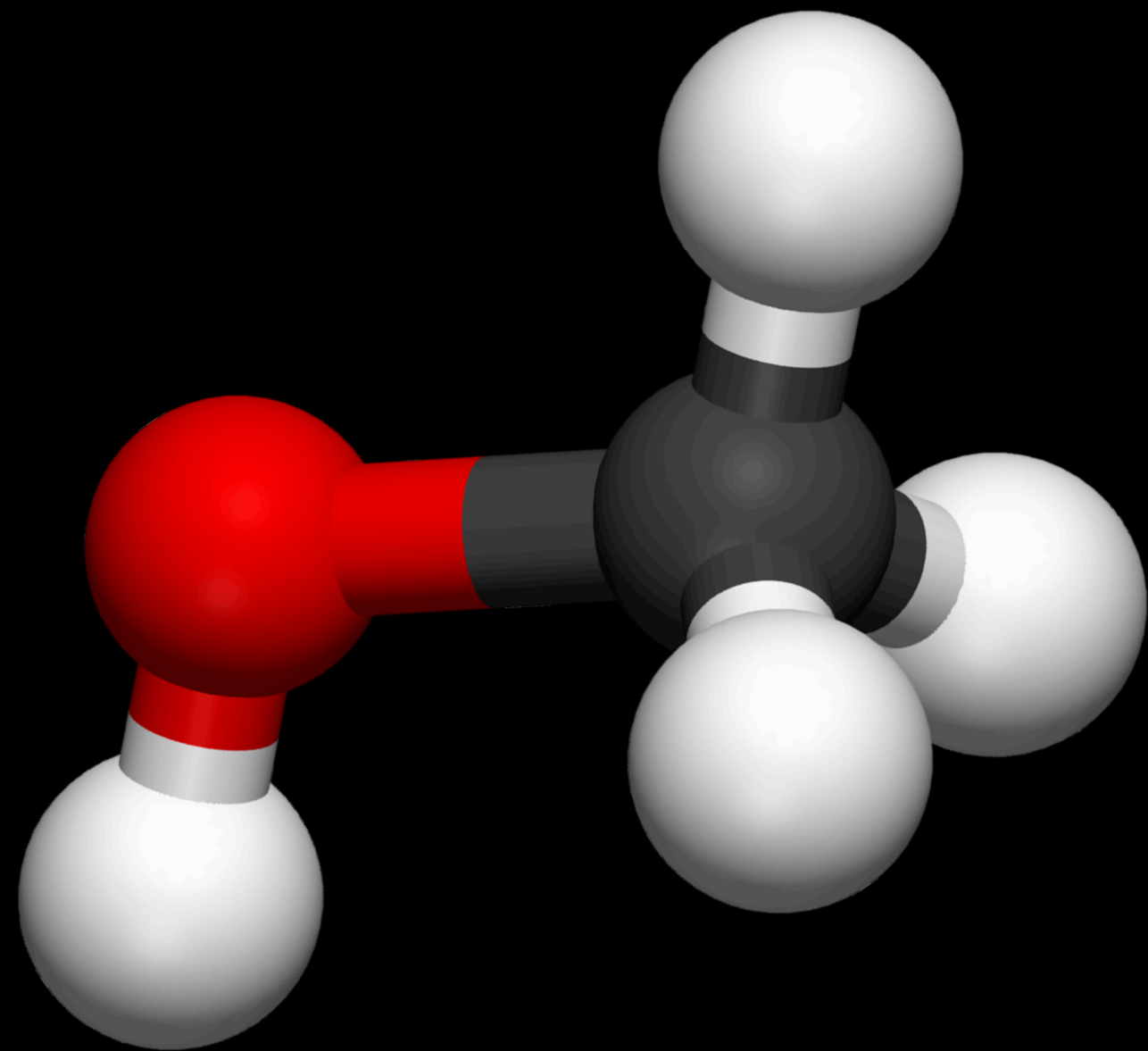


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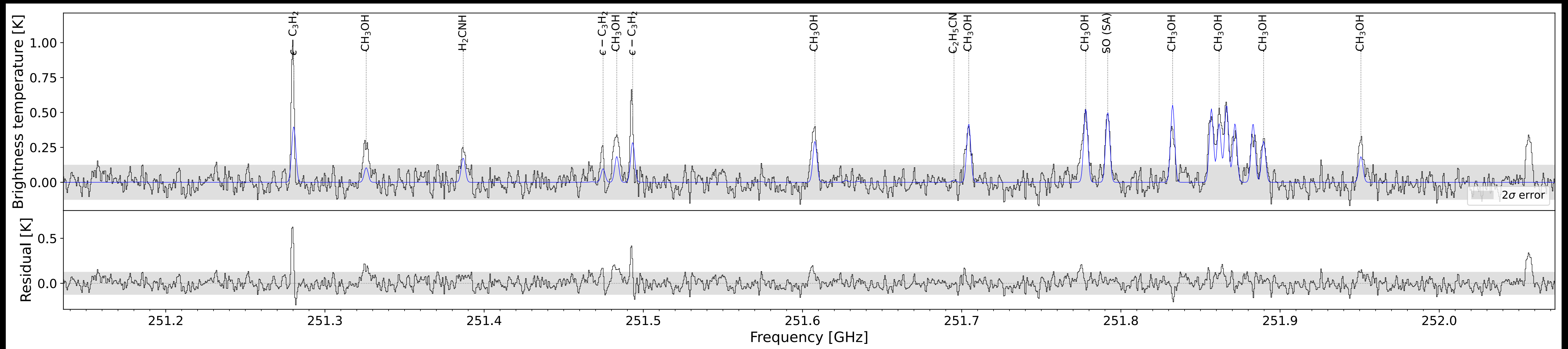


Energy Levels... complicated

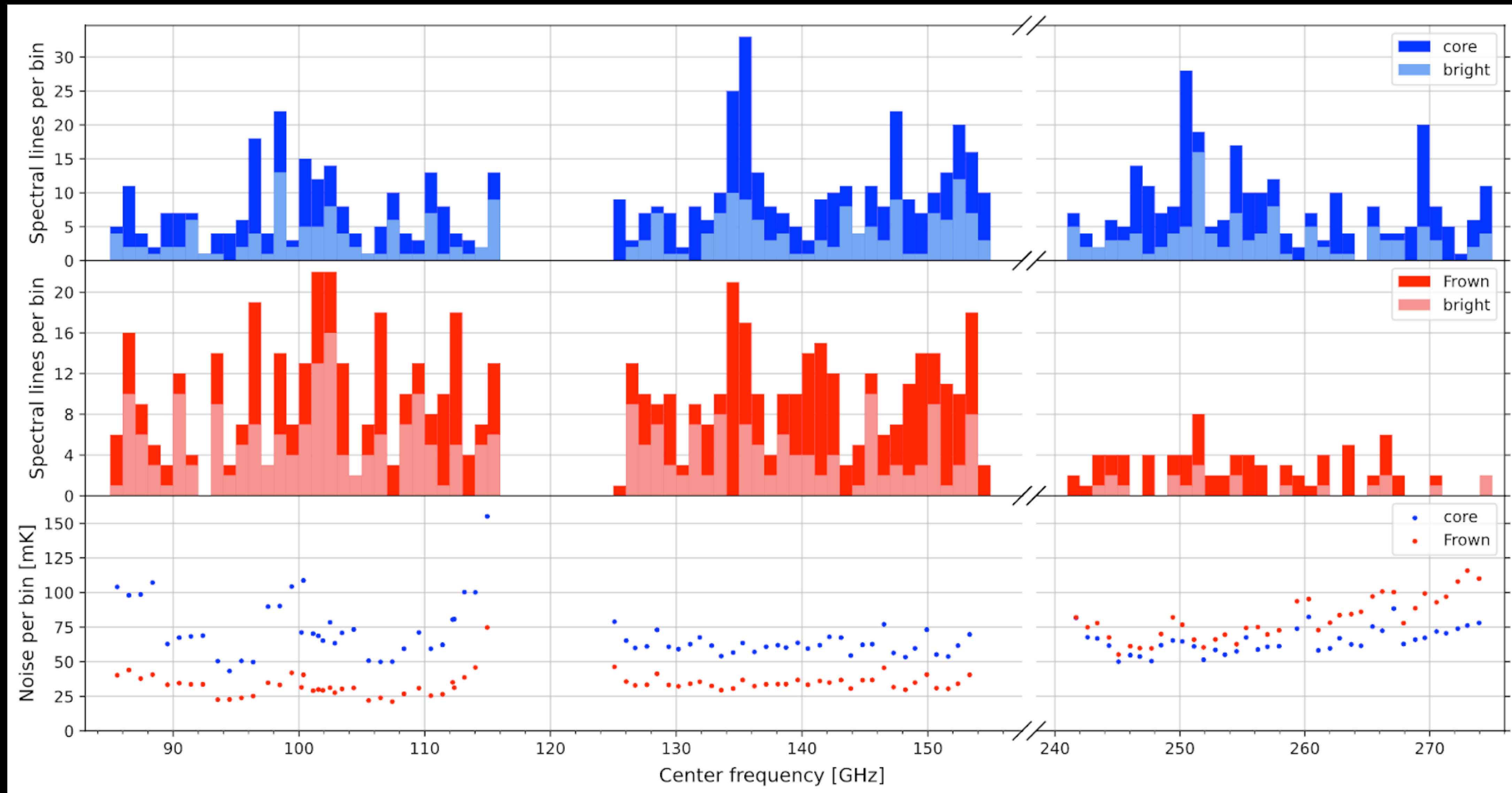


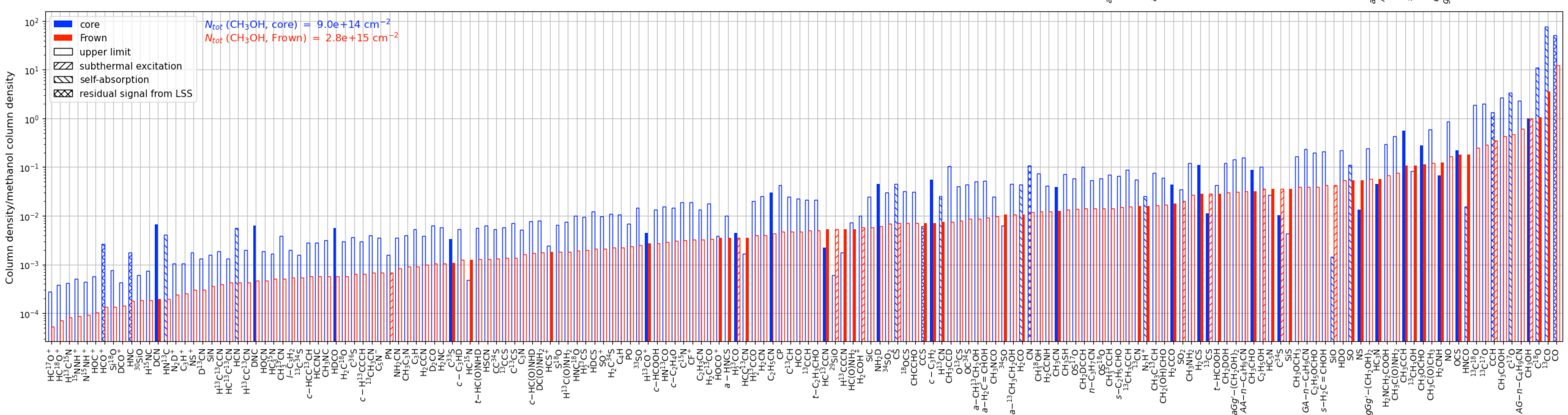
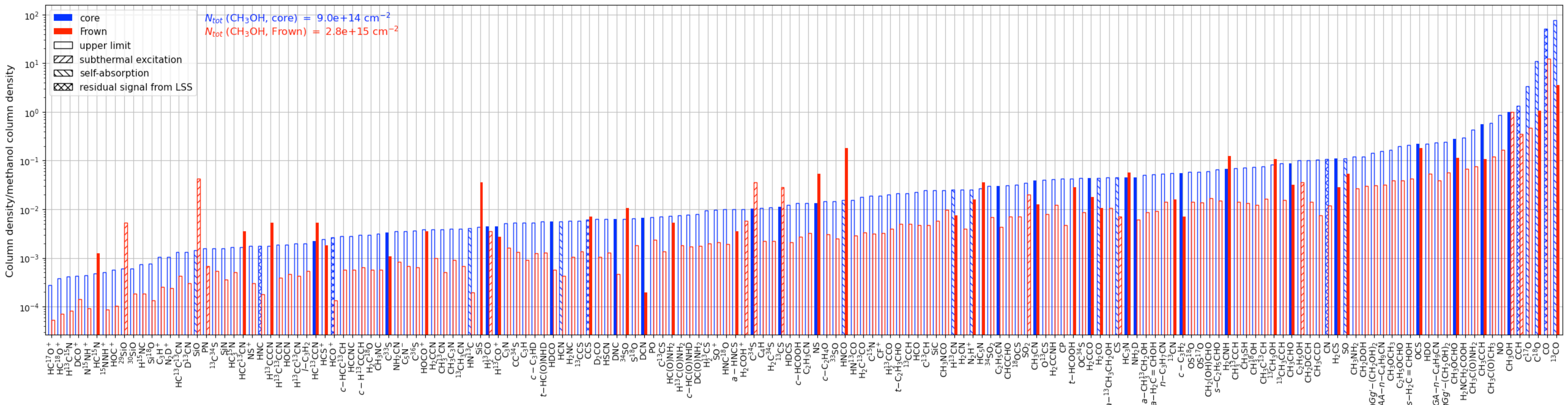
Slysh+1999

Energy Levels... complicated

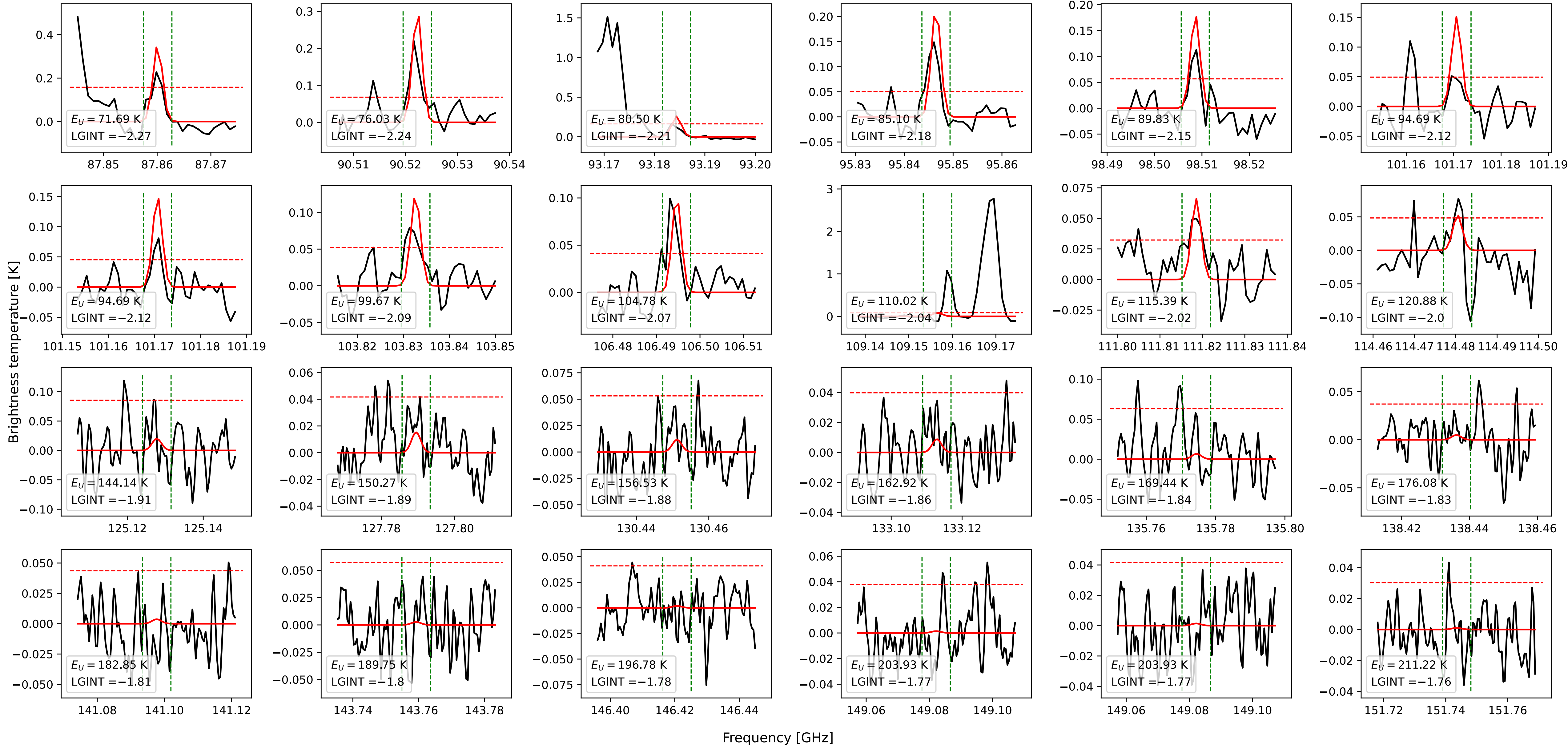


The Brick Line Survey: Line Density





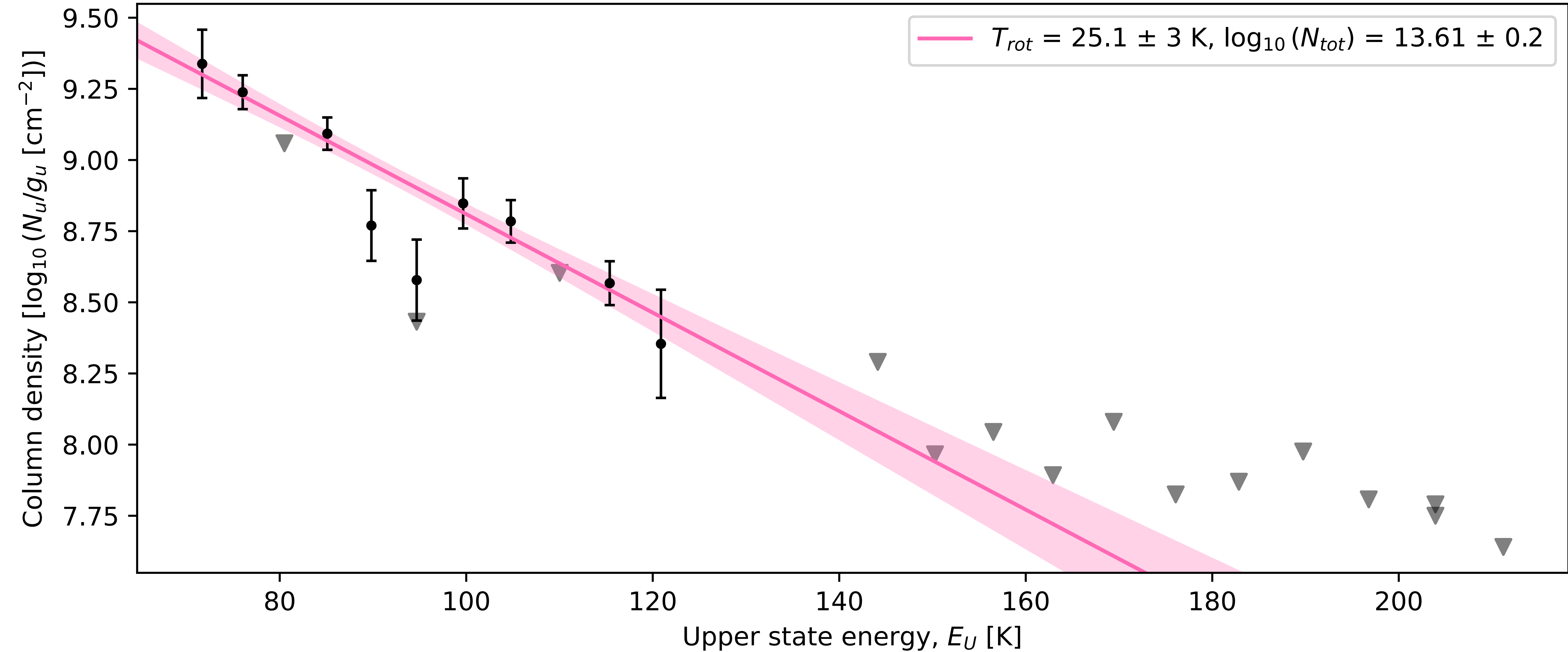
HC₅N, frown, $T_{rot} = 20.0$ K, $N_{tot} = 1e+14$ cm⁻², $v_{cen} = 12.0$ km s⁻¹, $v_{disp} = 3.0$ km s⁻¹



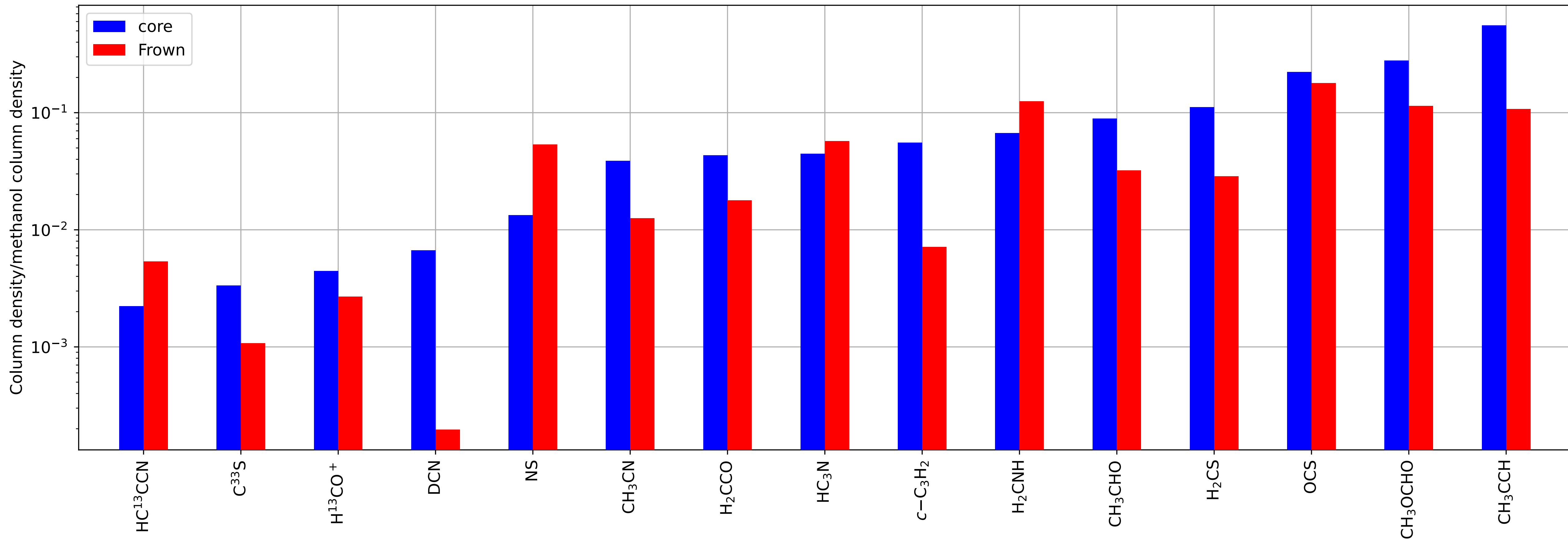
Rotational Diagrams

Mangum and Shirley (2015)

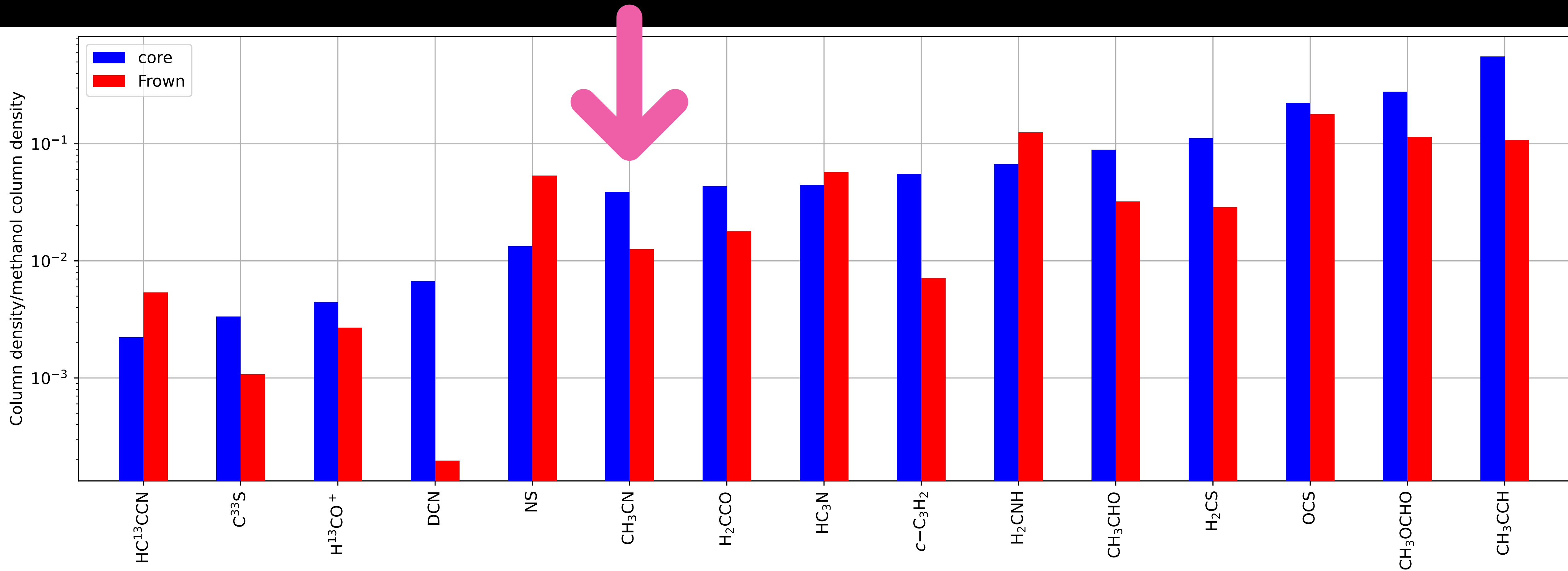
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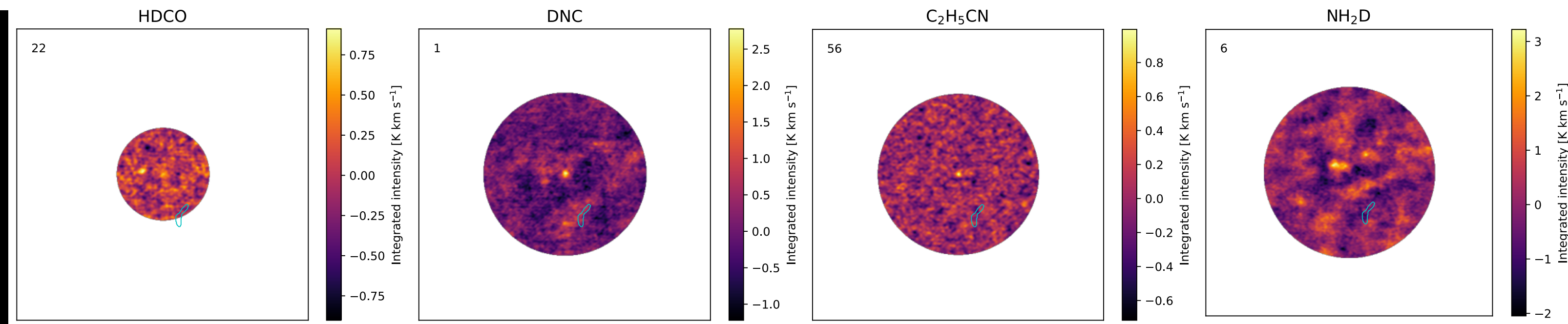
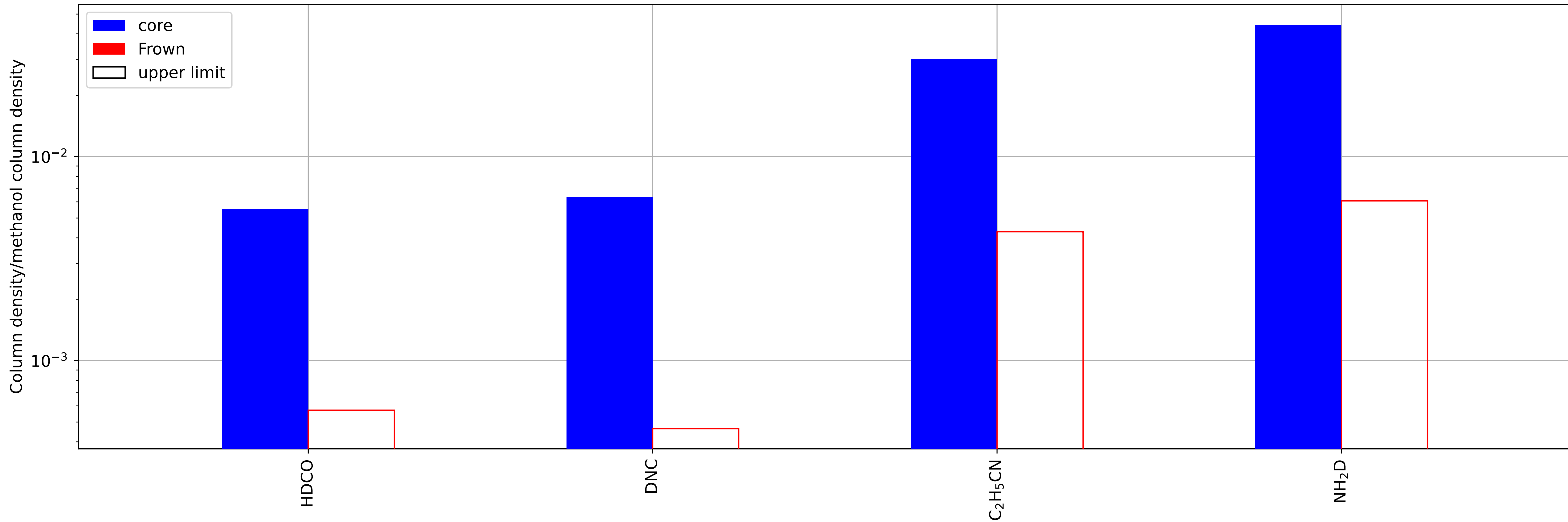
Molecules Clearly Detected in Core and Frown



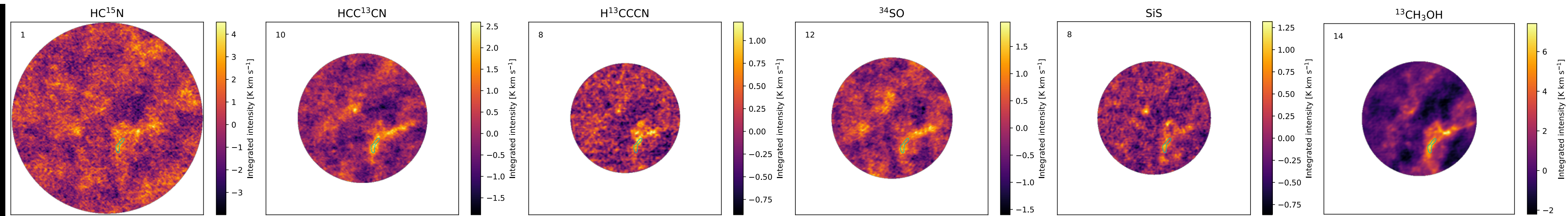
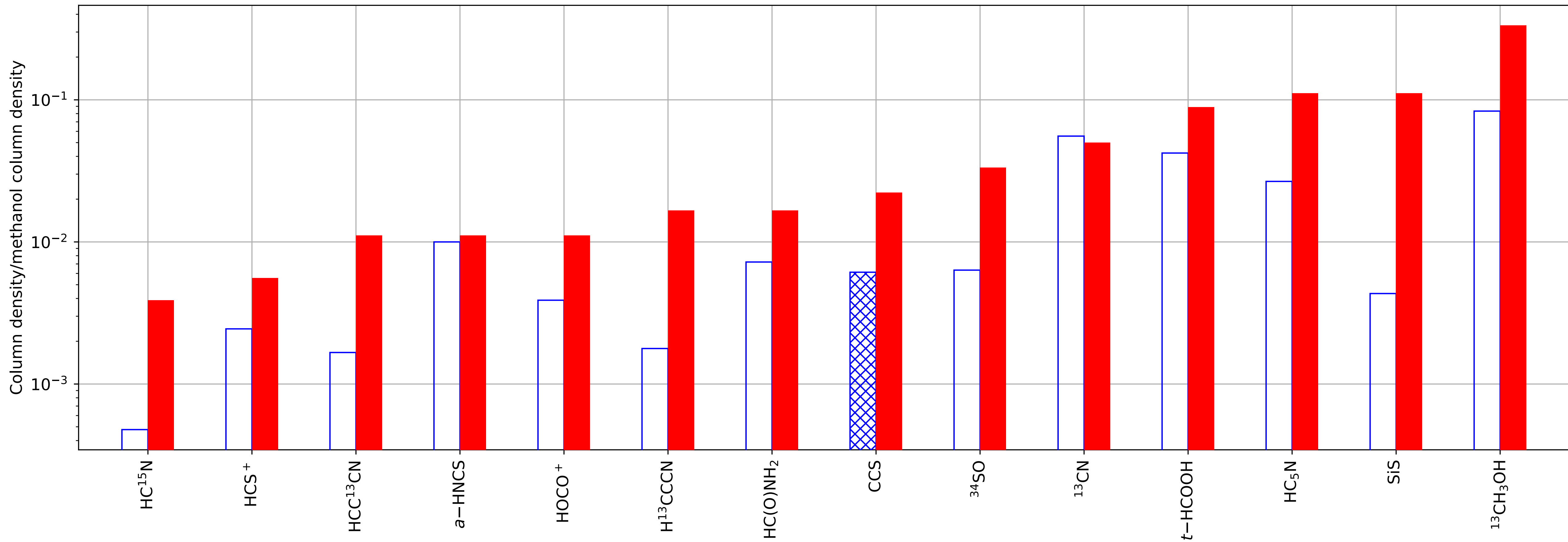
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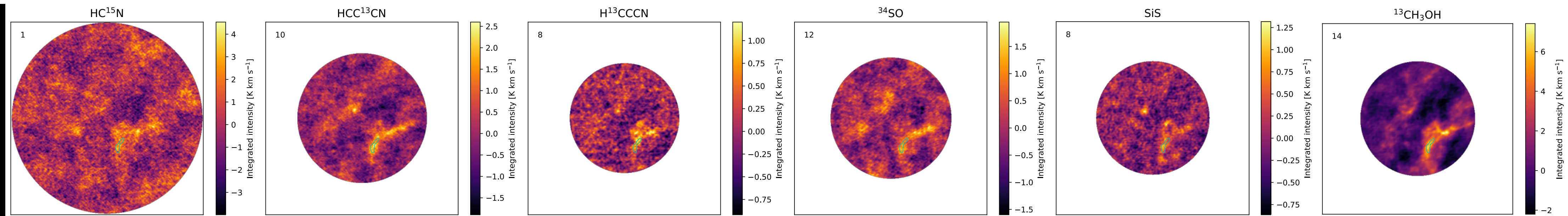
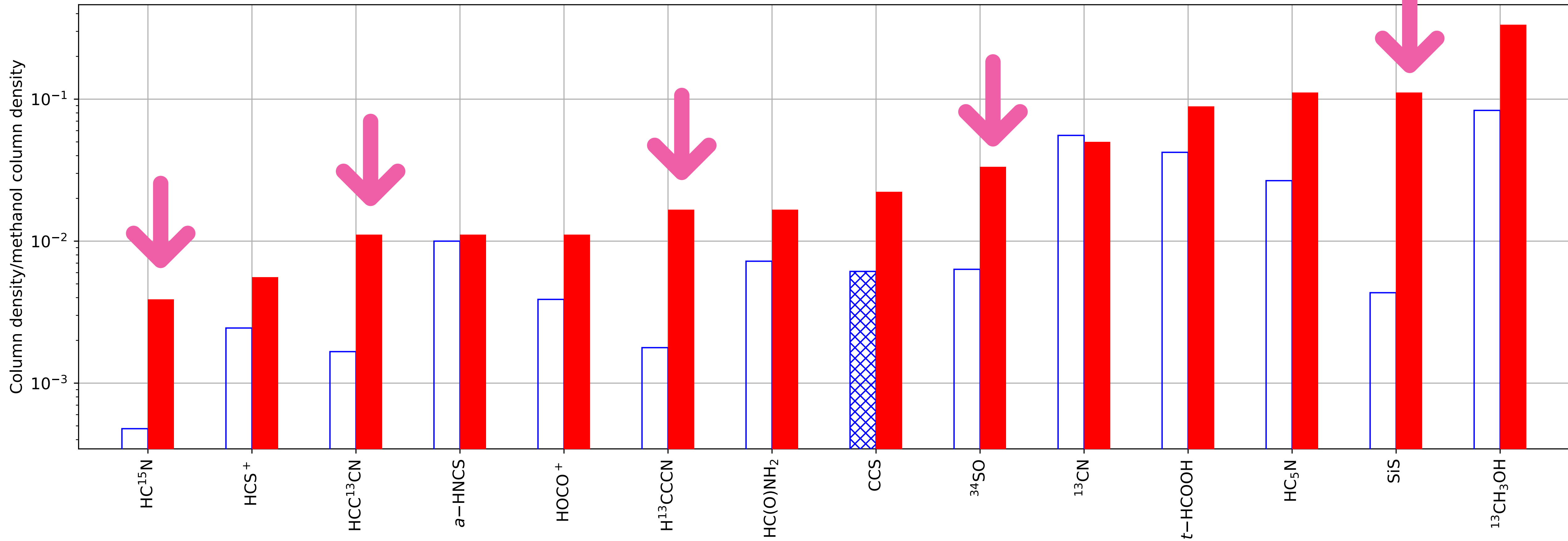
Molecules Unique to the Core



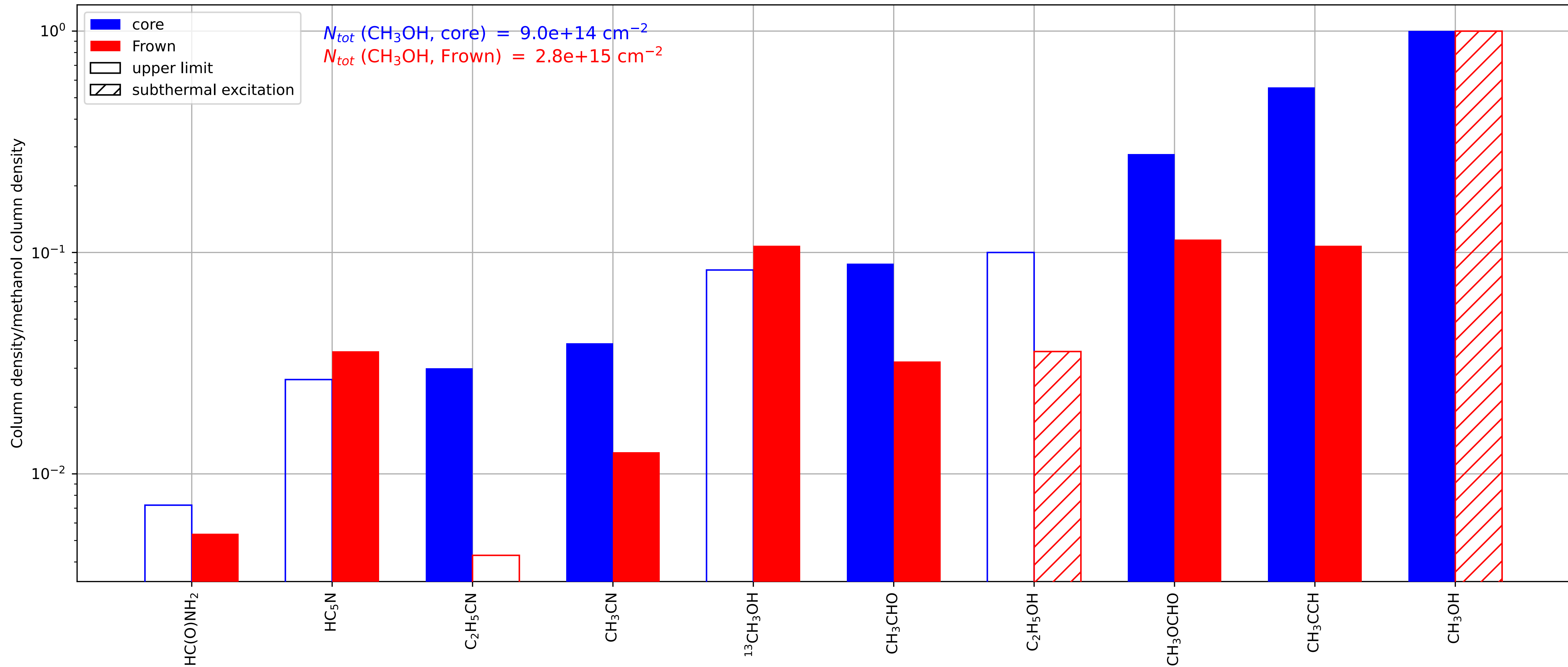
Molecules Unique to the Frown



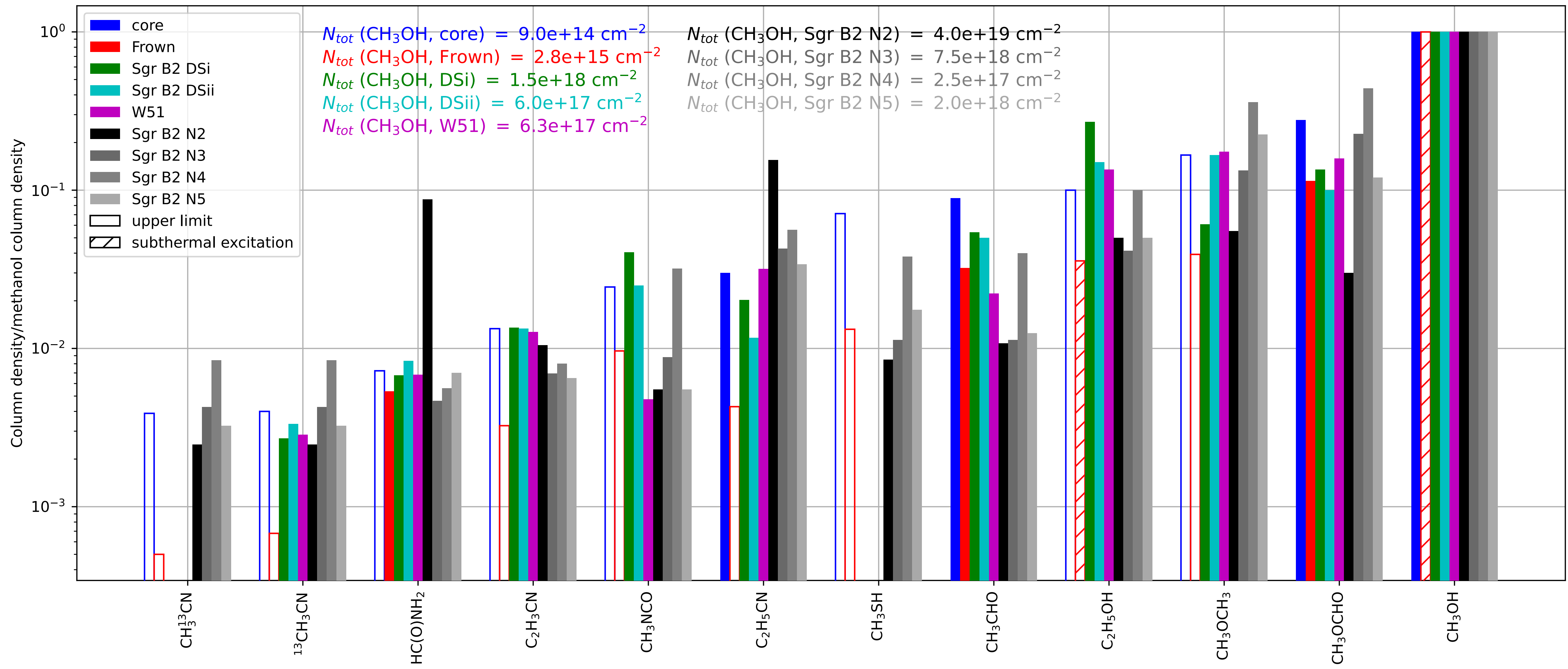
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COMparing to Other Star-Forming Environments



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Chemistry: Isotopic and Elemental Ratios

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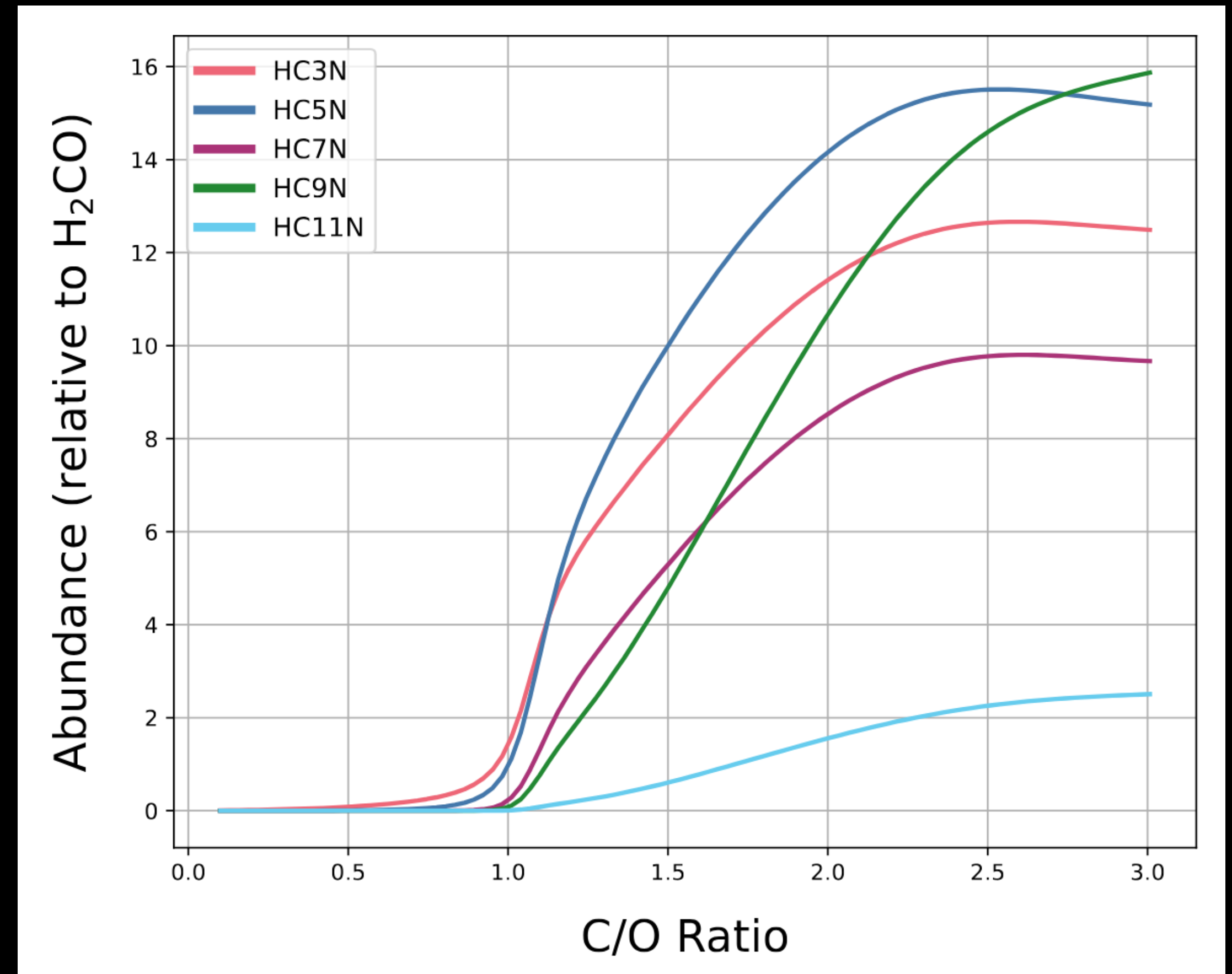
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 - Maybe The Brick has a lower ^{34}S abundance than other CMZ clouds, but maybe not

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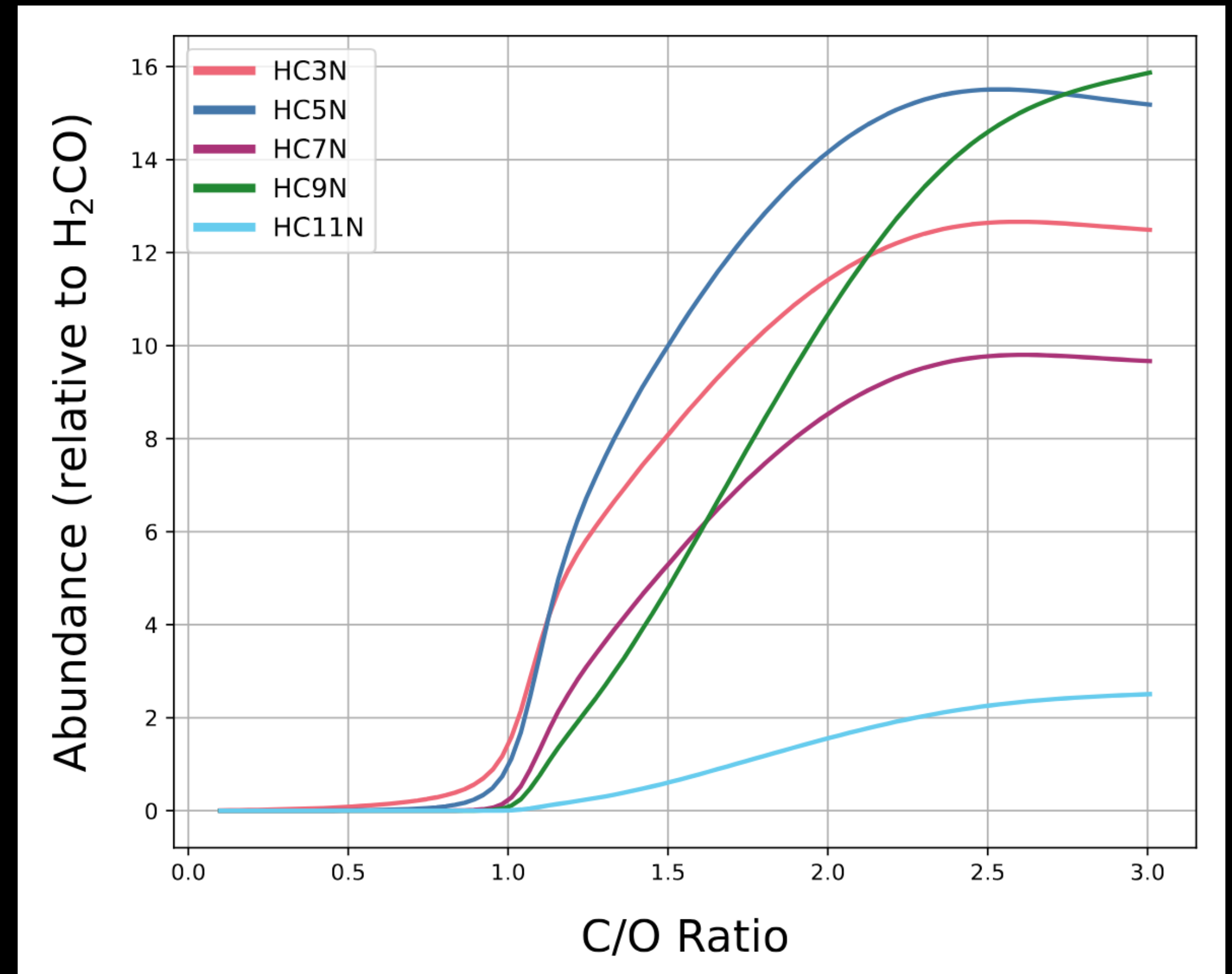
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Byrne+2026

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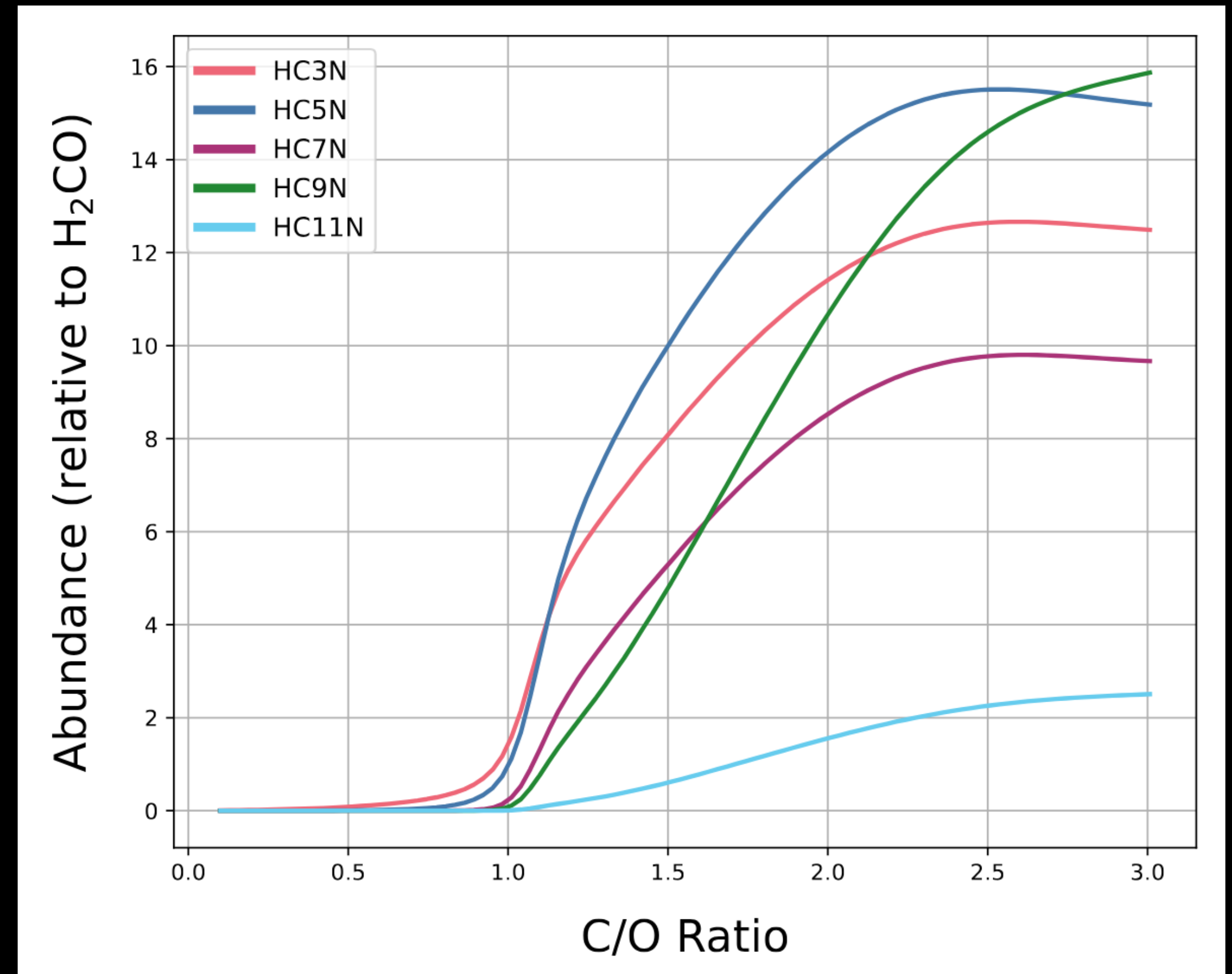
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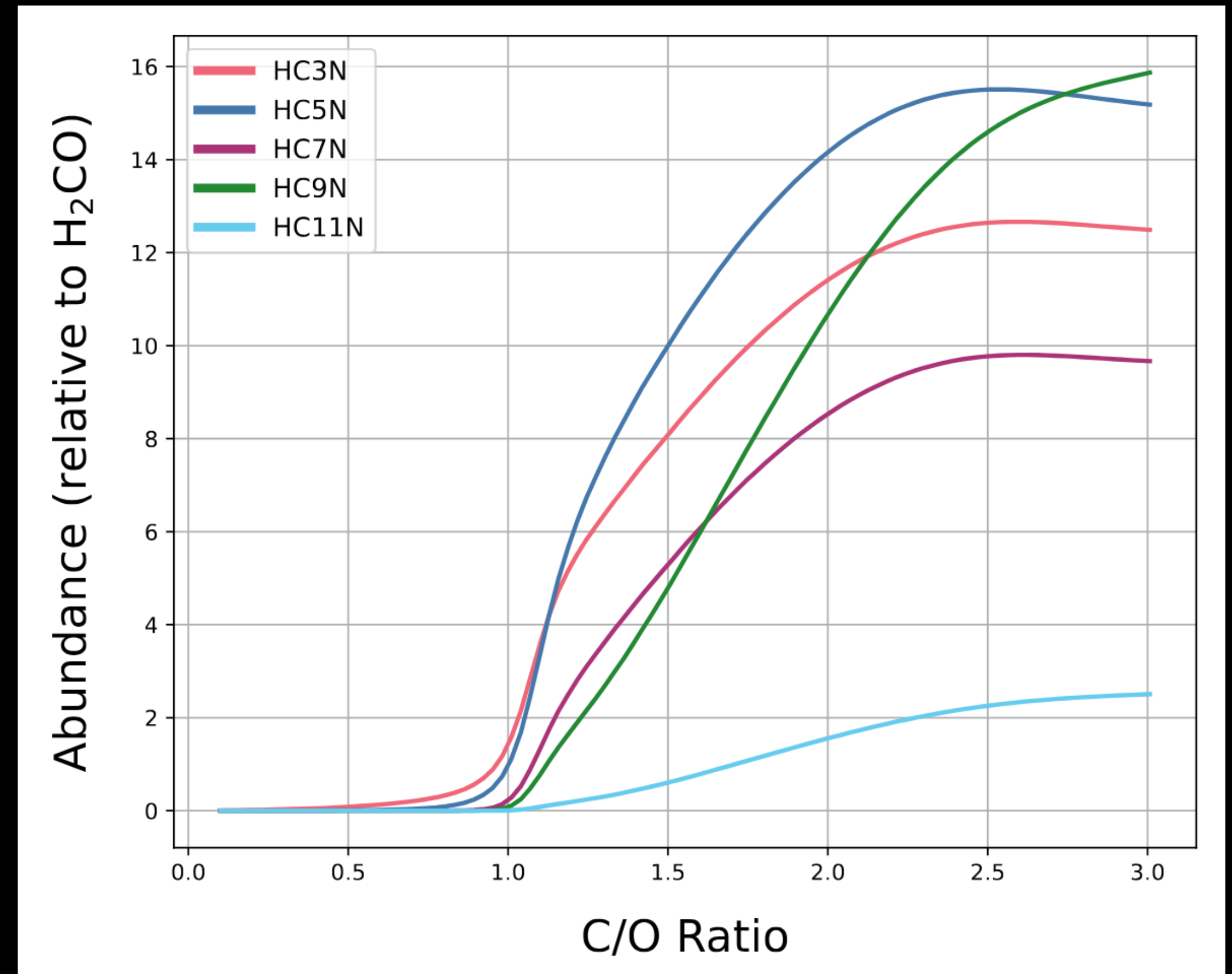
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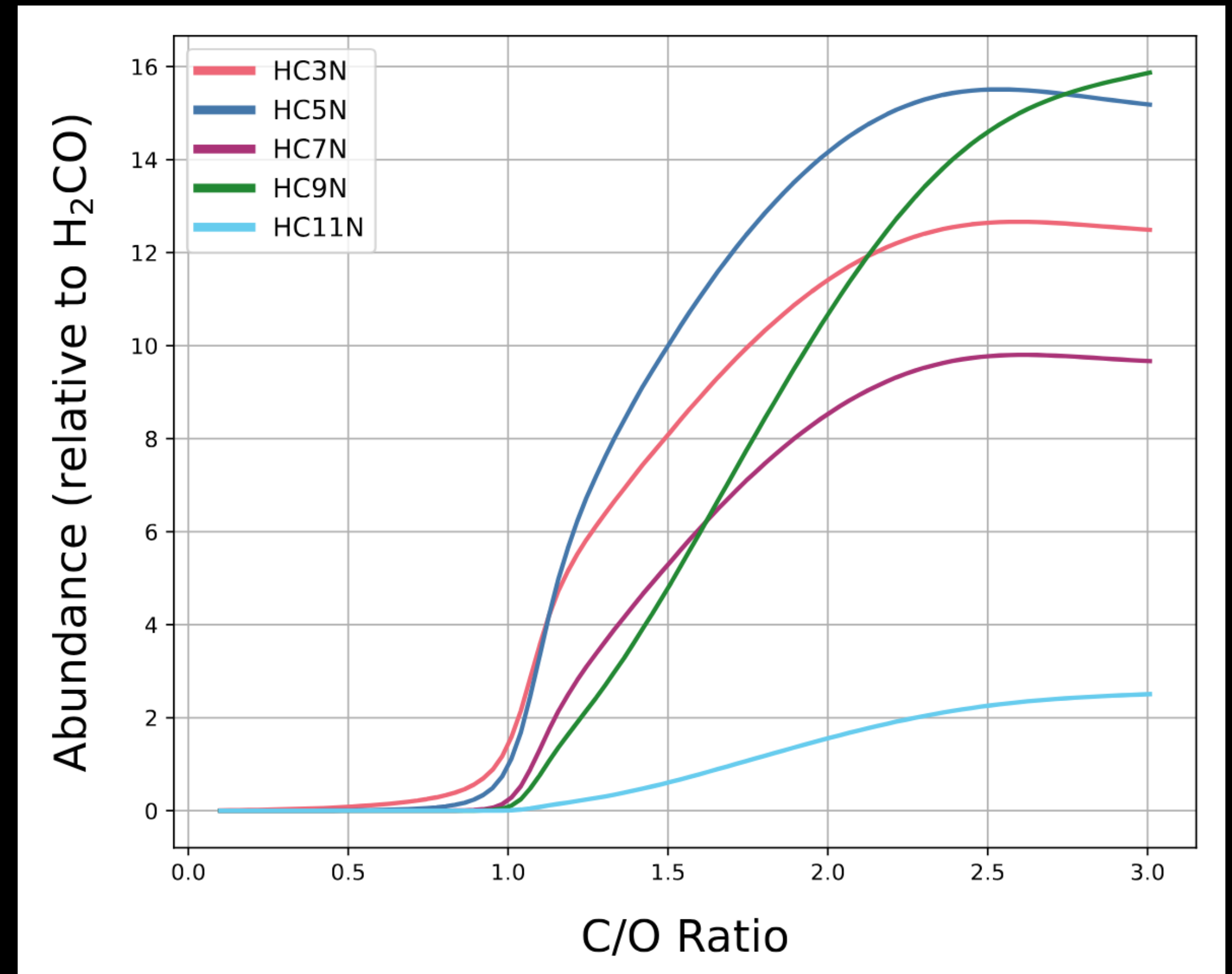
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 - An HC₃N/H₂CO ratio of 4.6 corresponds to a C/O ratio of ~1.2, an HC₅N/H₂CO ratio of 1.1 corresponds to a C/O ratio of ~1.0 (within 1σ of each other)



Byrne+2026

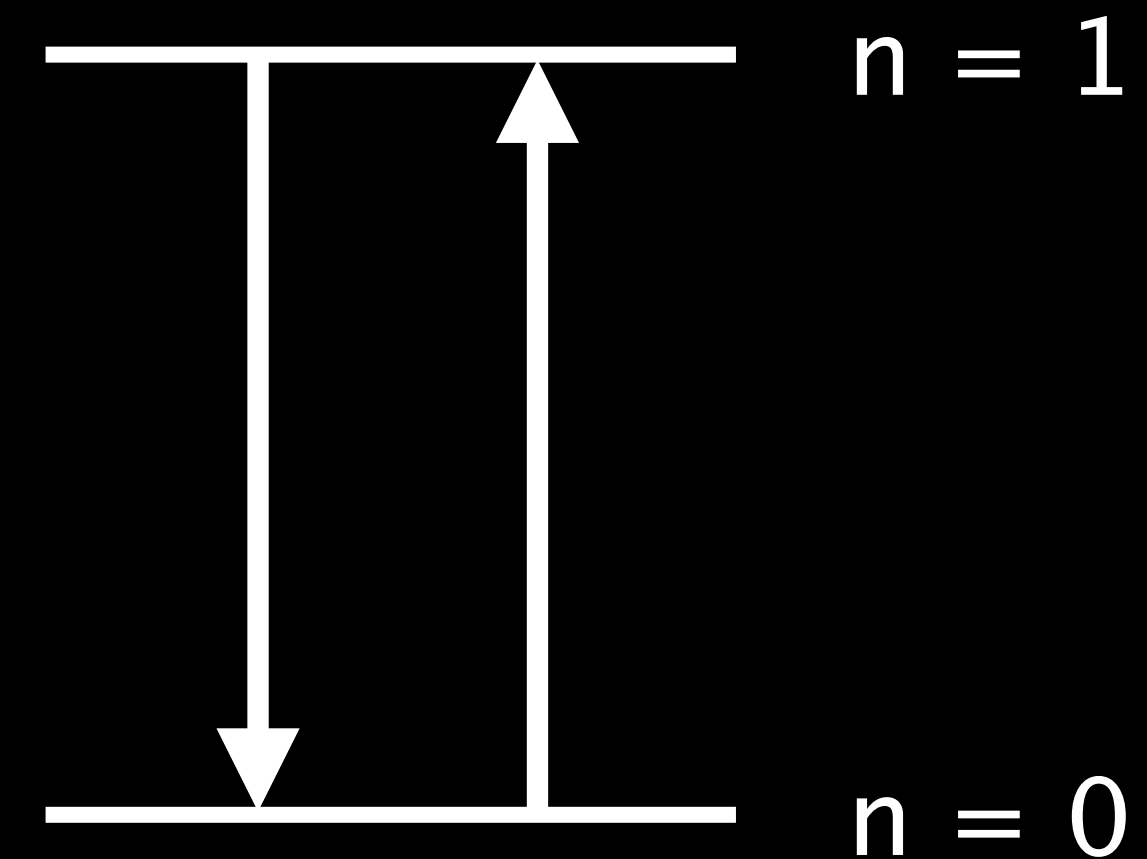
Methanol Dasar in The Brick

Bulatek et al. 2023

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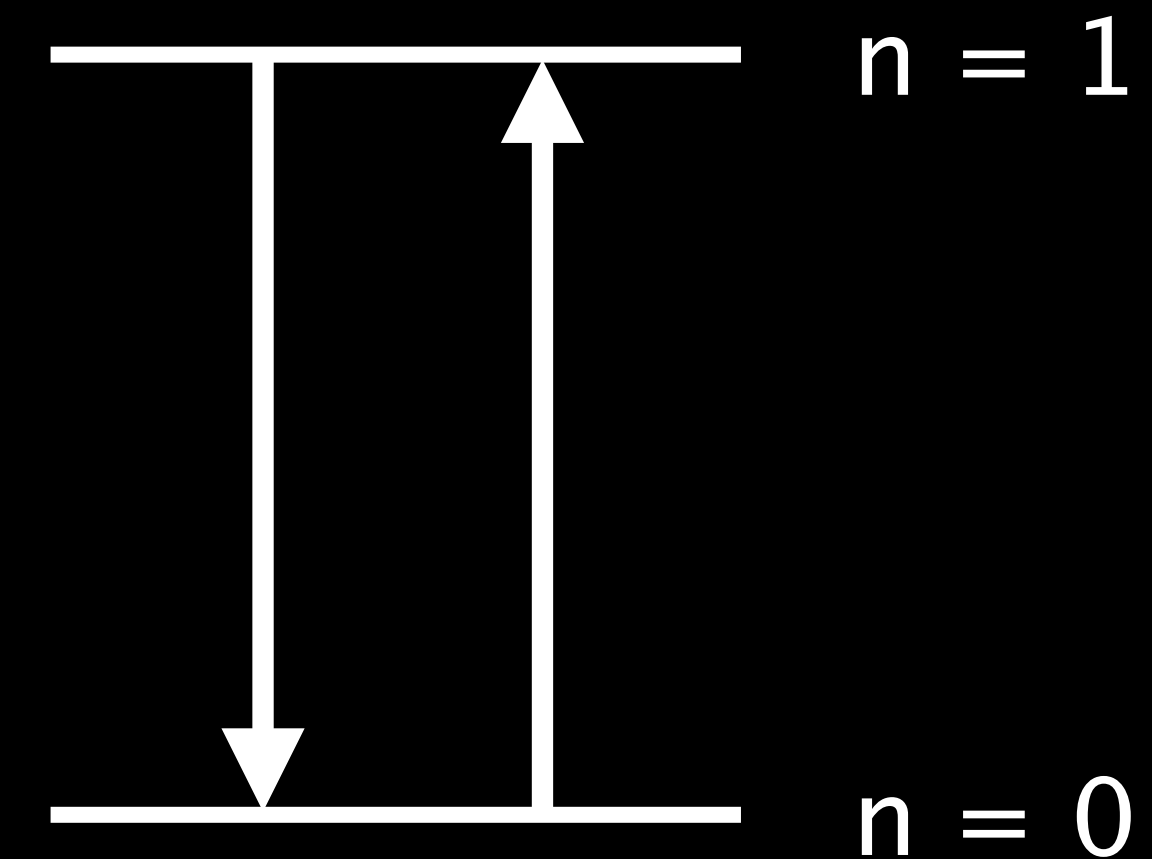
- **MASER = Microwave Amplification by Stimulated Emission of Radiation**
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- **DASAR = Dark "Amplification" by "Stimulated" Absorption of Radiation**
 - Pump drives molecules into lower energy state, that then absorb photons

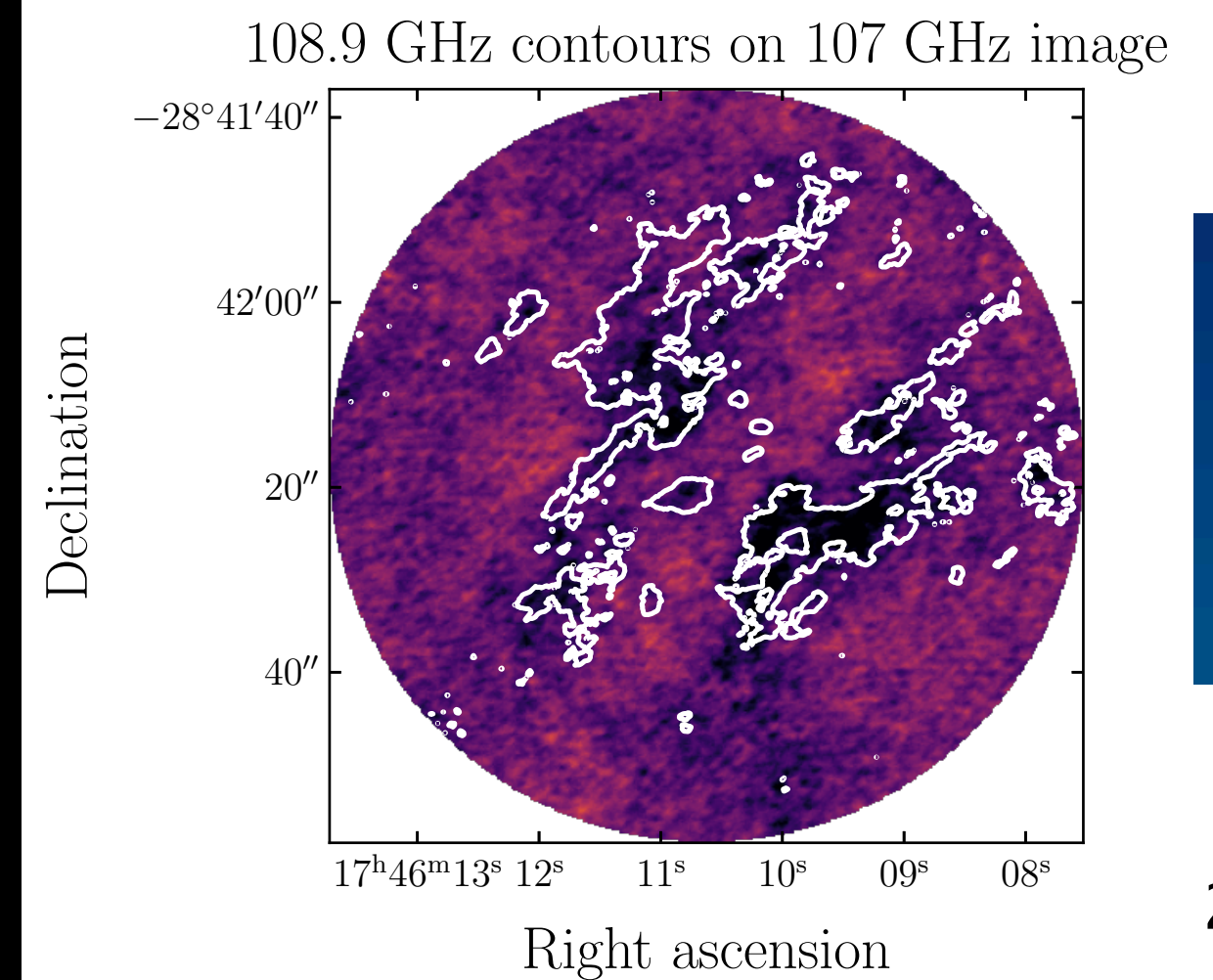
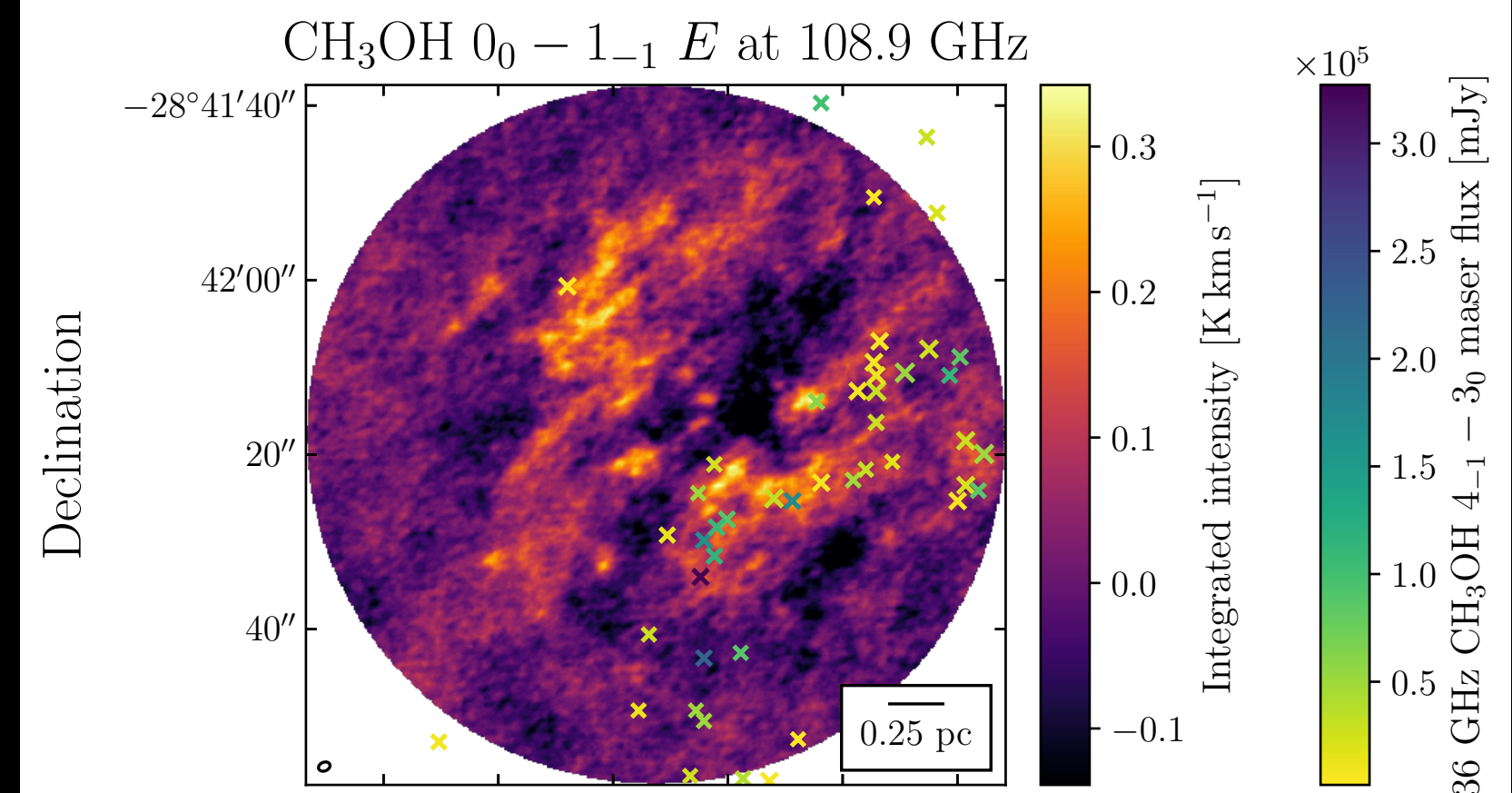
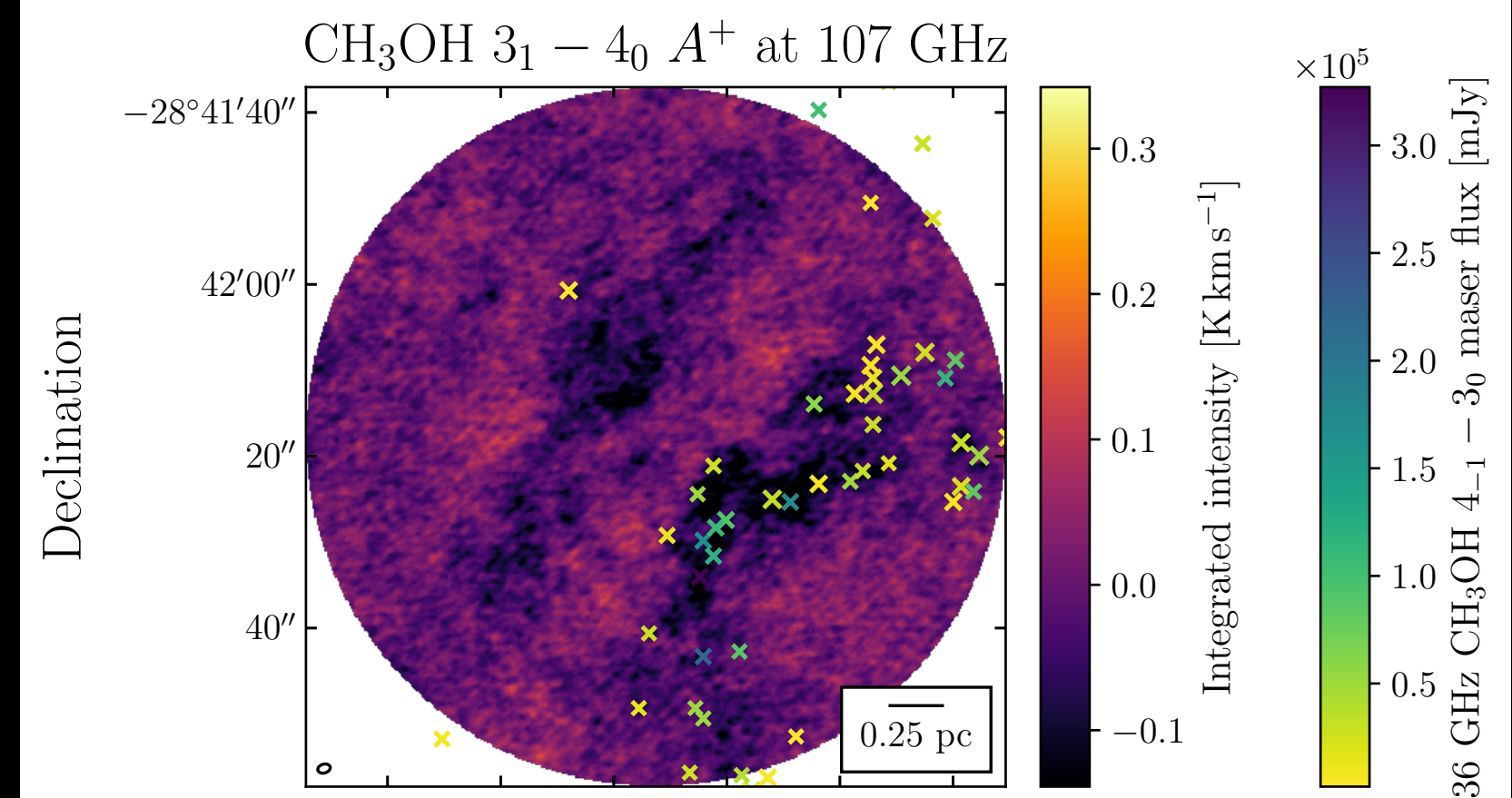
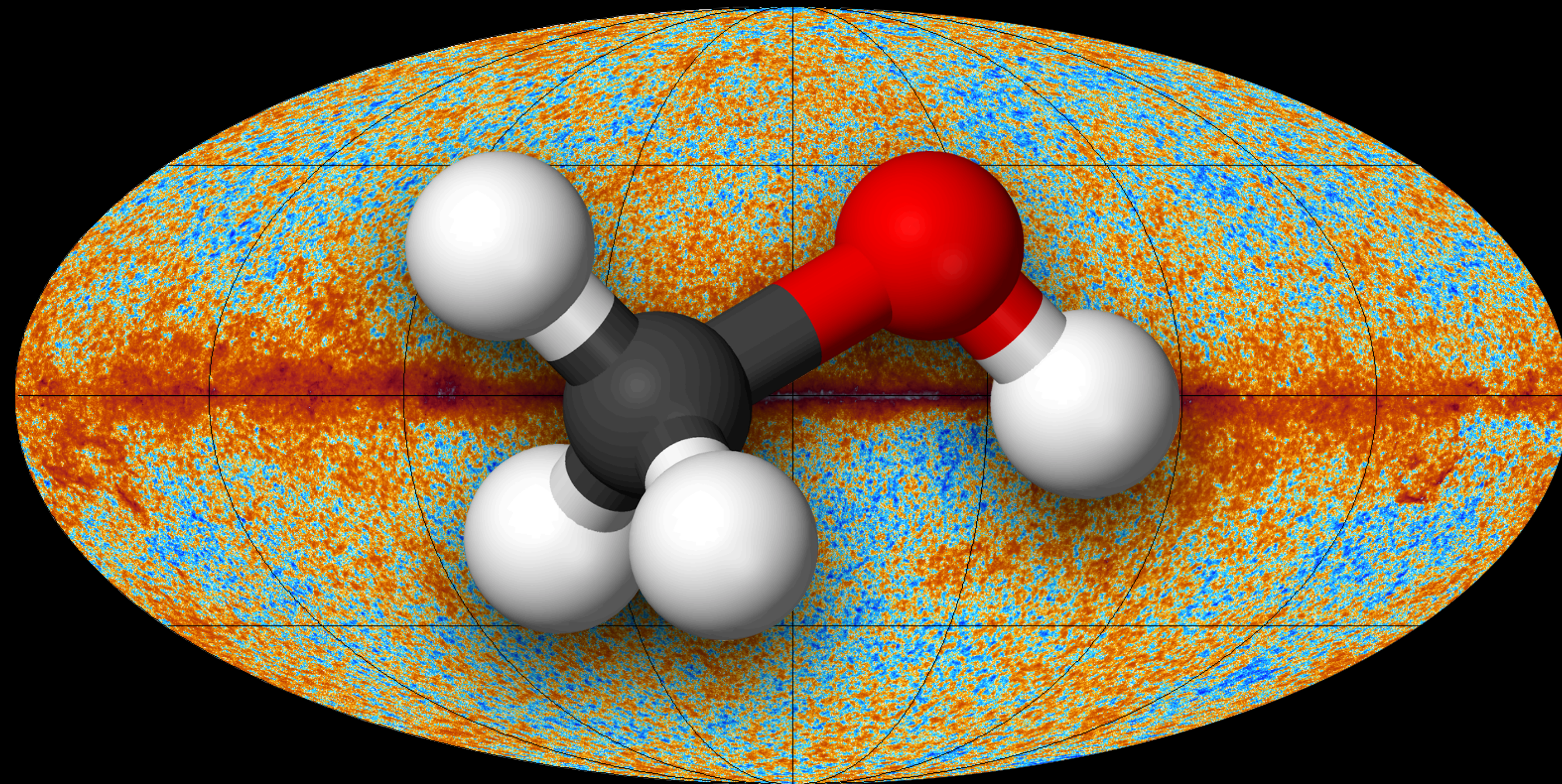


$$\frac{N_u g_l}{N_l g_u} = \exp\left(\frac{-\Delta E}{k_B T_{ex}}\right)$$

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Bulatek et al. 2023

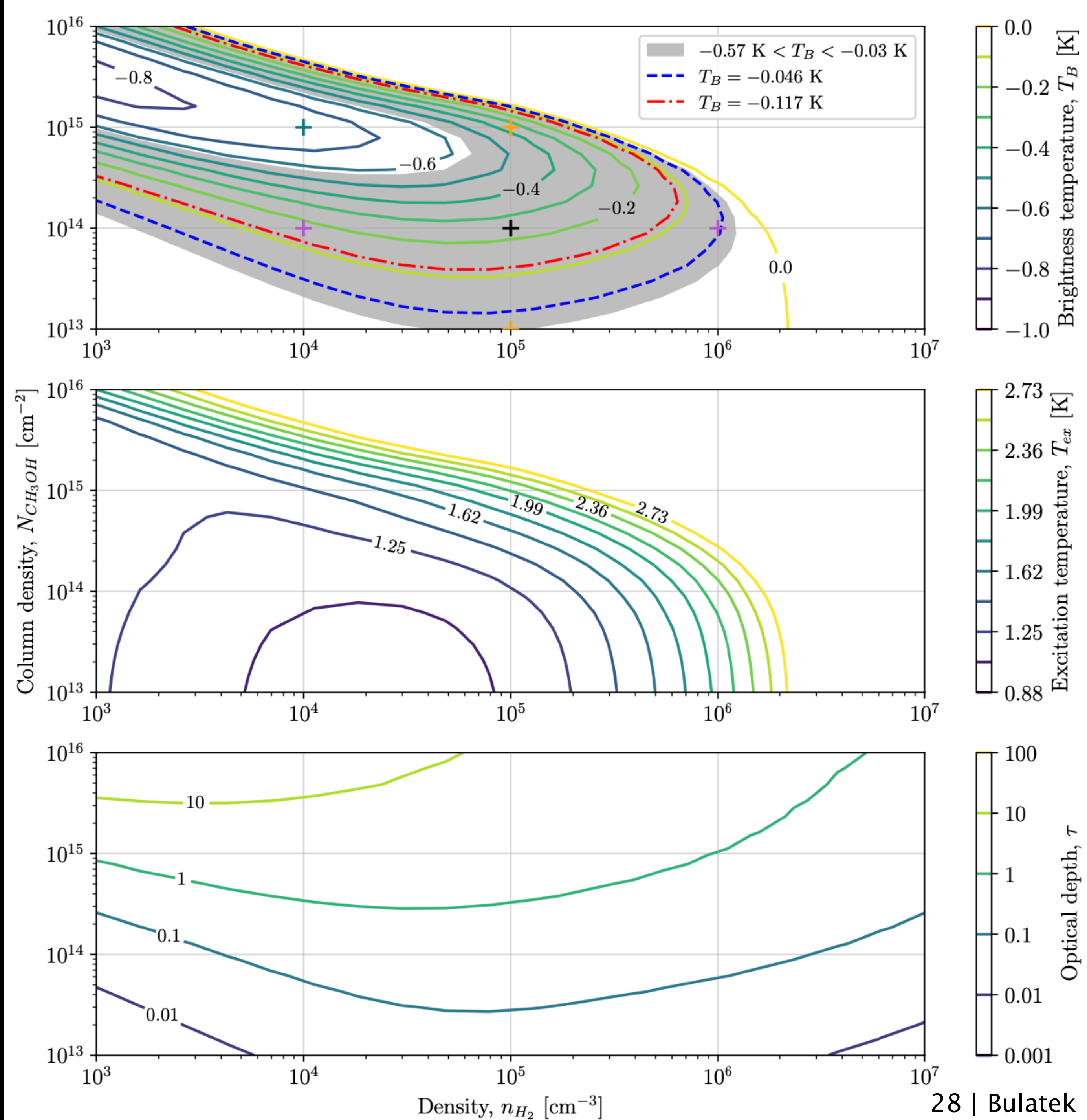
- If the pump gets T_{ex} cold enough, the molecule could even absorb the CMB!



Methanol Dasar in The Brick

Bulatek et al. 2023

- Modeled dasing volume density, column density, and temperature using RADEX
- Evaluated the use of this line for detecting/measuring dasing regions in high-redshift galaxies
 - Preference for edge-on spirals
- The ngVLA will be able to observe this line (and others) in starburst galaxies up to at least $z = 5$



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- Which lines trace what physical processes in the Galactic Center?