

Sulphur-bearing species trace ongoing star formation in the Central Molecular Zone of NGC 253

Mathilde Bouvier

Leiden Observatory, Leiden University

bouvier@strw.leidenuniv.nl

Collaborators:

S. Viti, E. Behrens, J. Butterworth, K.-Y. Huang, J. G. Mangum,, N. Harada, S. Martín, V. M. Rivilla, S. Muller, K. Sakamoto, K. Tanaka, K. Nakanishi, L. Colzi, M. D. Gorski, C. Henkel, P. K. Humire, D. S. Meier, P. P. van der Werf, and Y. T. Yan

*Bouvier et al. 2024, A&A, 689, A64
Bouvier et al. in prep.*

NGC 253 and its Central Molecular Zone (CMZ)

Prototypical starburst galaxy

$D \sim 3.5 \pm 0.2$ Mpc *Rekola+ 2005*

Inclination: 76° *McCormick+ 2013*

Starburst-driven large-scale molecular outflow e.g. e.g. *McCarthy et al. 1987; Bolatto et al. 2013, Walter et al. 2017, Krieger et al. 2019*



Image credit: NAOJ: Subaru, NASA & ESA: Hubble, ESO: VLT & Danish 1.5-m;

Images: NAOJ, NASA, ESO
Processing: R. García & R. Côté



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MOPPEX

Colloque PCMi 2024 - 31/10/2024

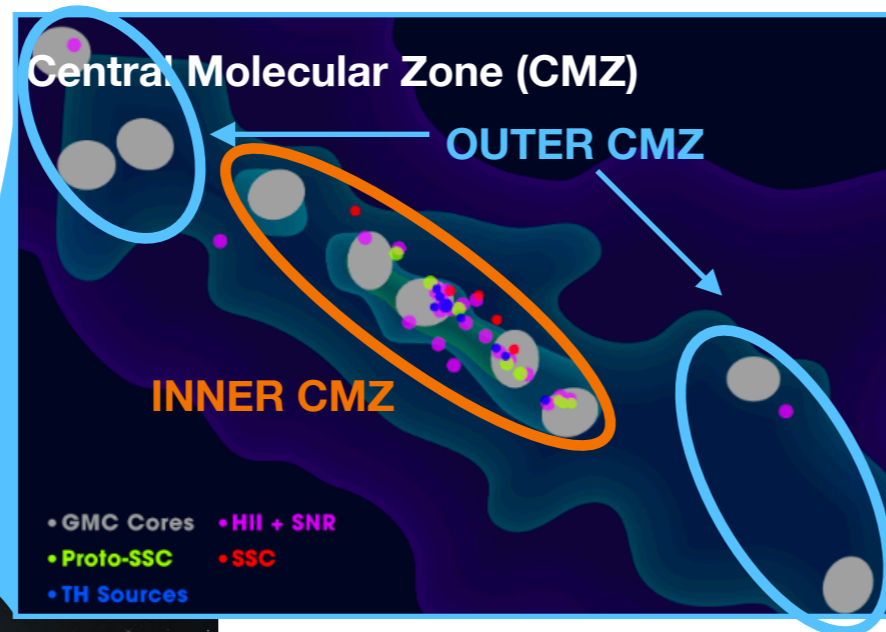
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Central Molecular Zone (CMZ):

- 300×100 pc *Sakamoto et al. 2011*
- Intense SFR of $\sim 2 M_\odot/\text{yr}$ in central kpc (50% of global SF activity), hence defined as **nuclear starburst** *Leroy+2015, Bendo+2015*
- 10 well-studied Giant Molecular Clouds (GMCs) *Leroy+2015*

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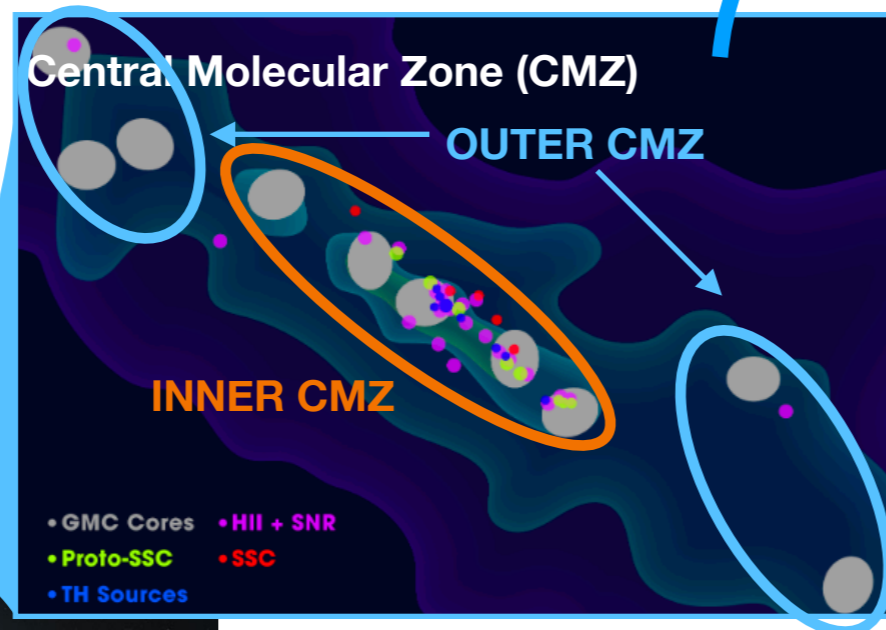
First unbiased molecular survey towards a nearby (starburst) galaxy: **ALCHEMI**

ALMA Comprehensive High-resolution Extragalactic Molecular Inventory

Co-PI.s: S. Martín, N. Harada and J. Mangum

ALMA Band 3 to 7: ~ 84.2 to 373.2 GHz
Spatial resolution: **1.6''** (~ 28 pc);
LAS of $15''$ (~ 255 pc);
Spectral resolution: **10 km/s**

15 published ALCHEMI papers so far



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Sulphur-bearing species in starburst galaxies



IC 342

Credit: Ed Henry

Hot-core like regions (e.g H₂S)?

e.g. Minh+2007; Sato+2022

Shocks (CS, H₂S, OCS, SO₂)?

e.g. Martin+2003, 2005, Meier+2015; Sato+2022

PDRs (CS, C³⁴S)?

e.g. Meier & Turner 2005, Martín+2009

NGC 3256

Credit: ESA/Hubble, NASA



NGC 253

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Limitations by low angular resolution (single-dish) or poor number of transitions

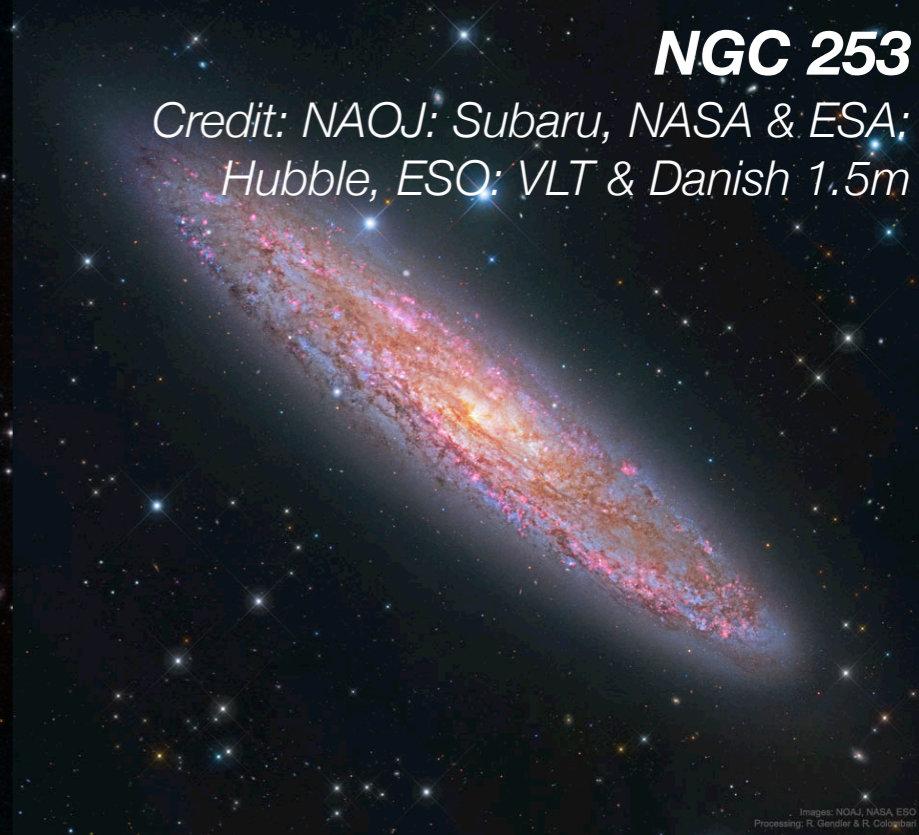
NGC 3256

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NGC 253

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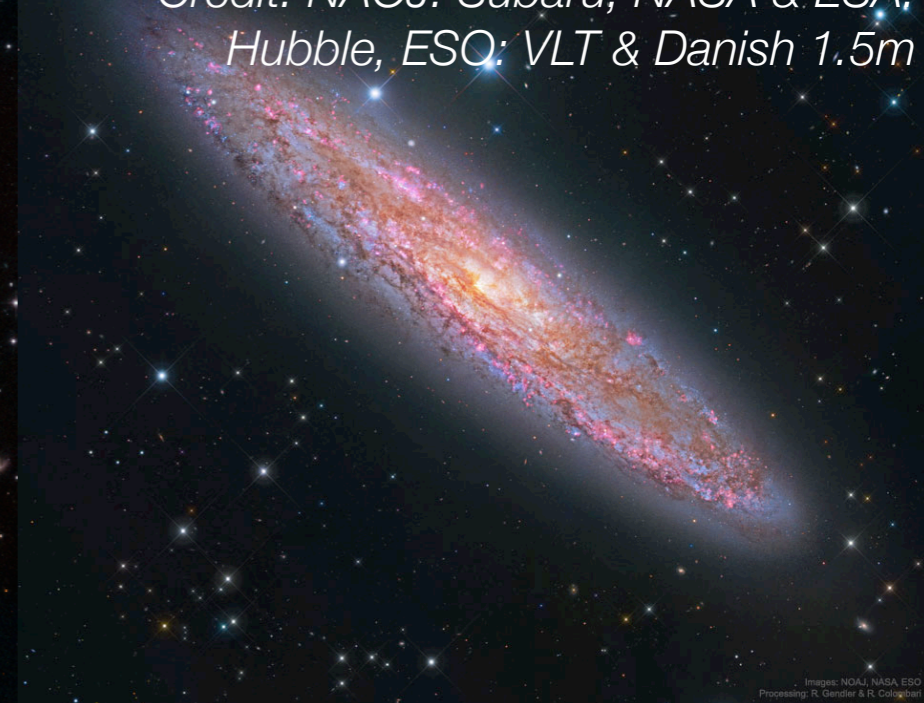
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ALCHEMI provides both high angular resolution and high number of transitions!

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Shocks (CS, H₂S, OCS, SO₂)?

+2022

Goal: Complete investigation of most common S-bearing species towards a starburst nucleus: CS, H₂S, OCS, SO, SO₂, H₂CS, and CCS

What do they trace?

NGC 253

J, NASA & ESA:
& Danish 1.5m

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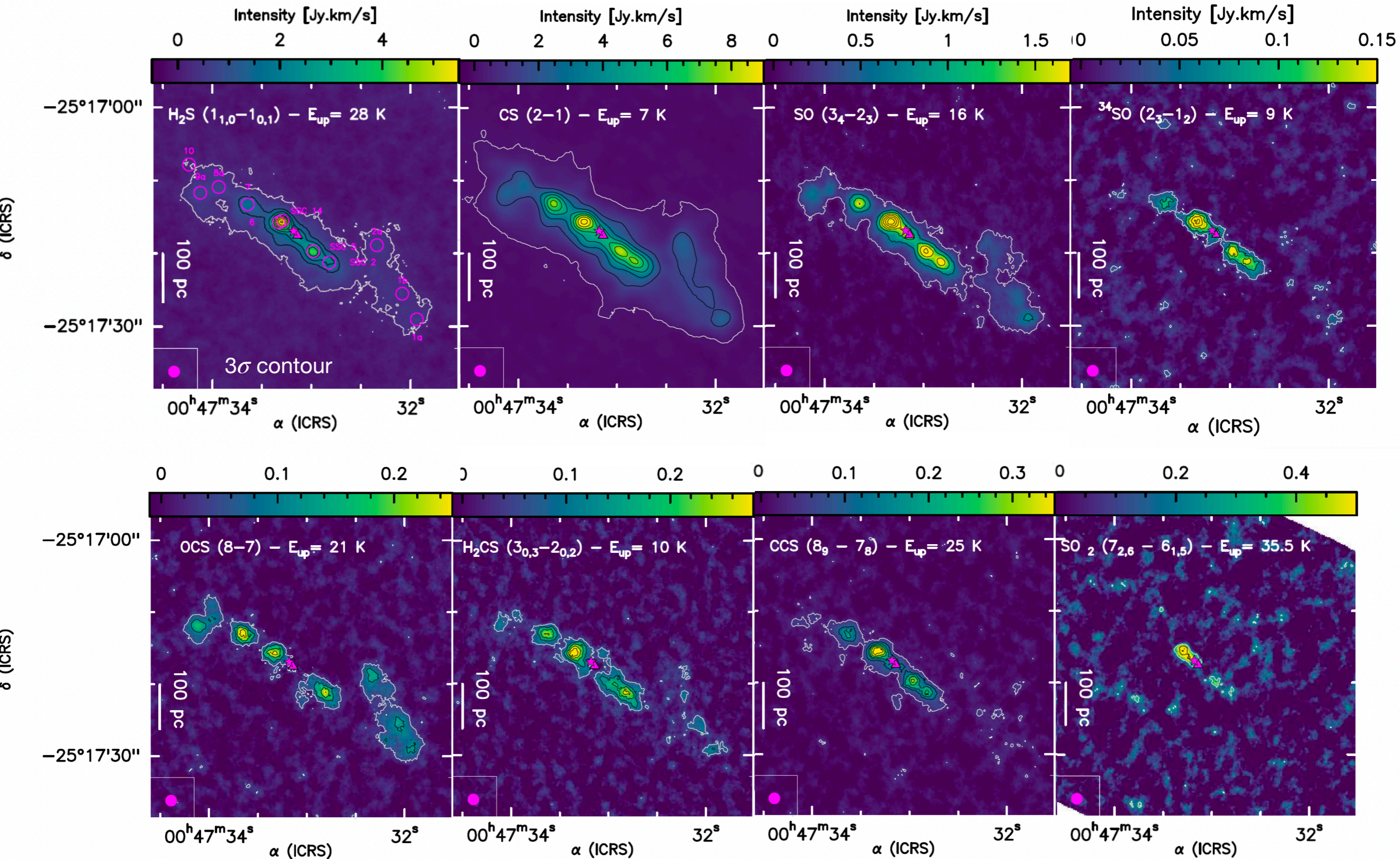
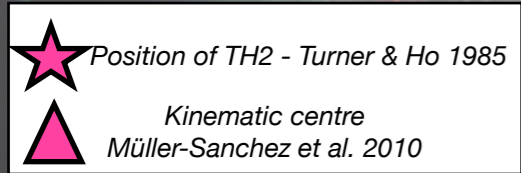


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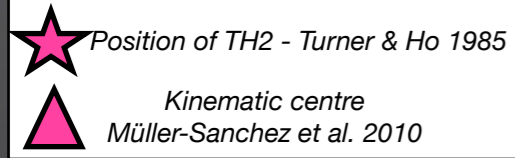
Colloque PCMi 2024 - 31/10/2024

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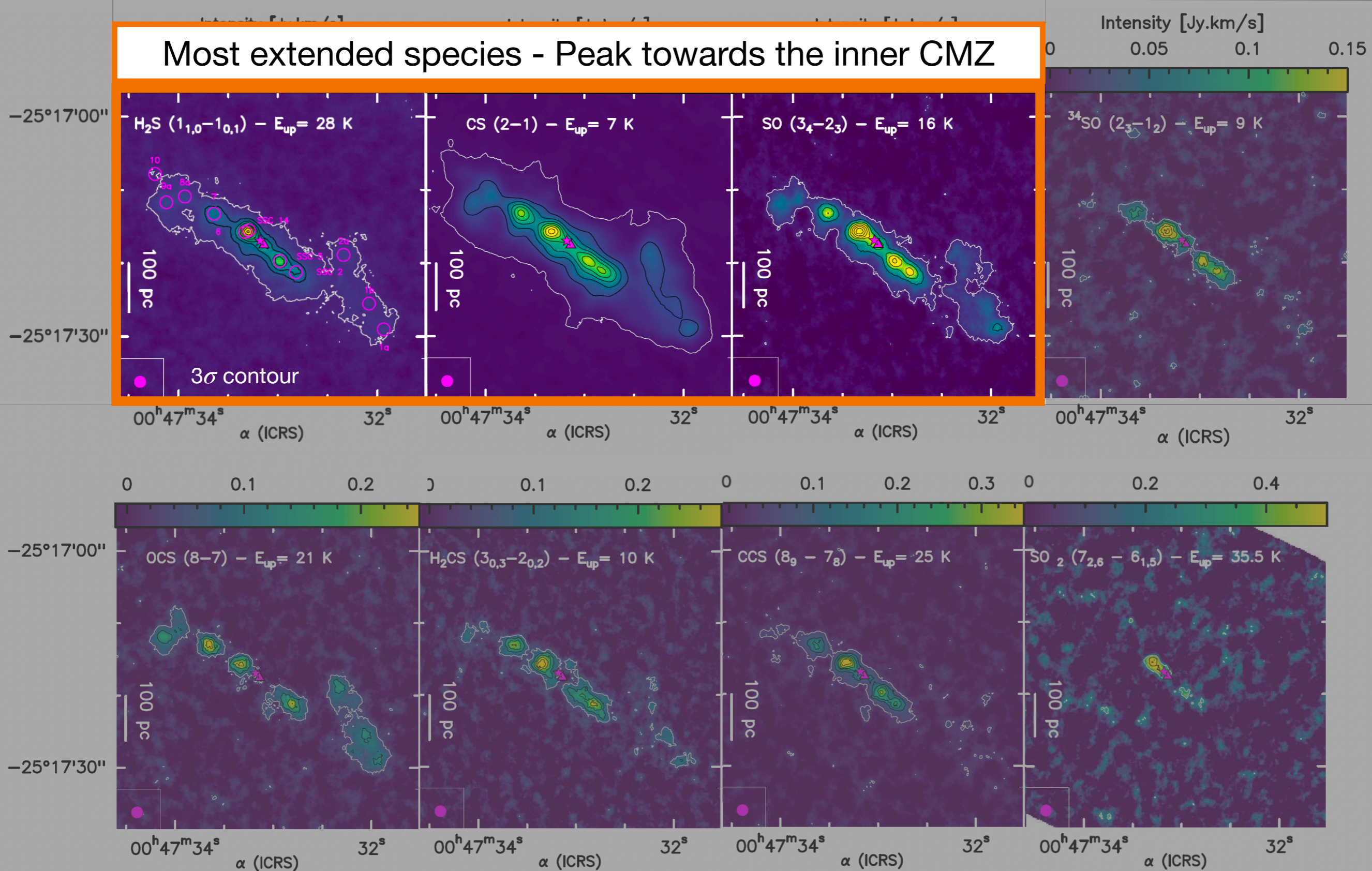
Emission distribution



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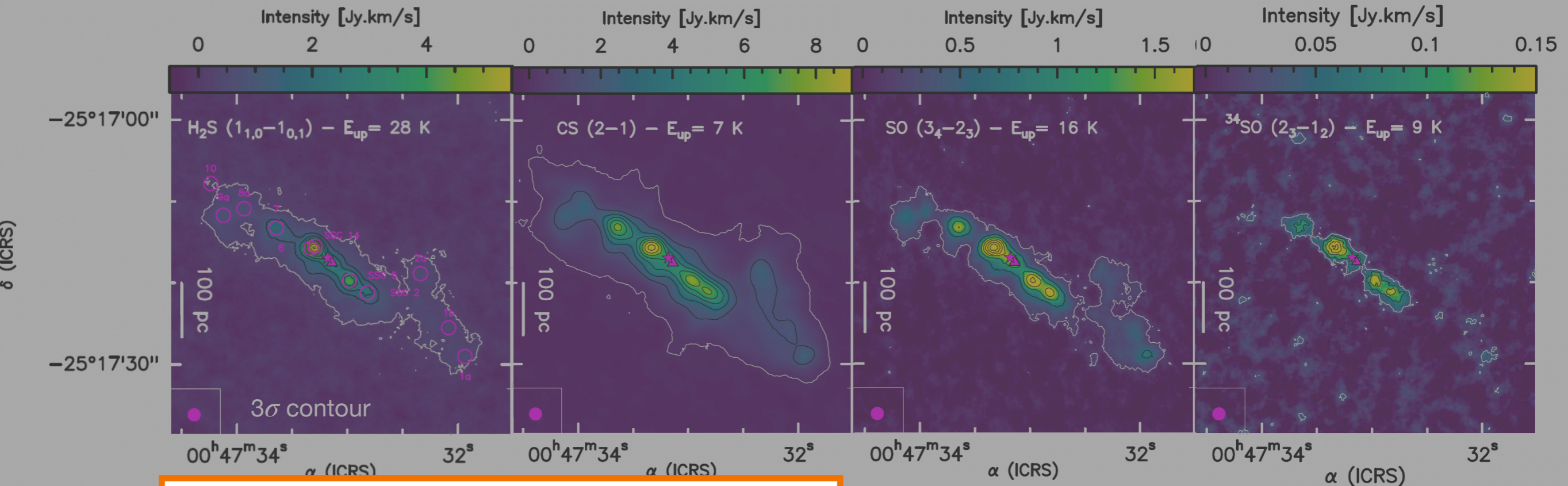


Most extended species - Peak towards the inner CMZ

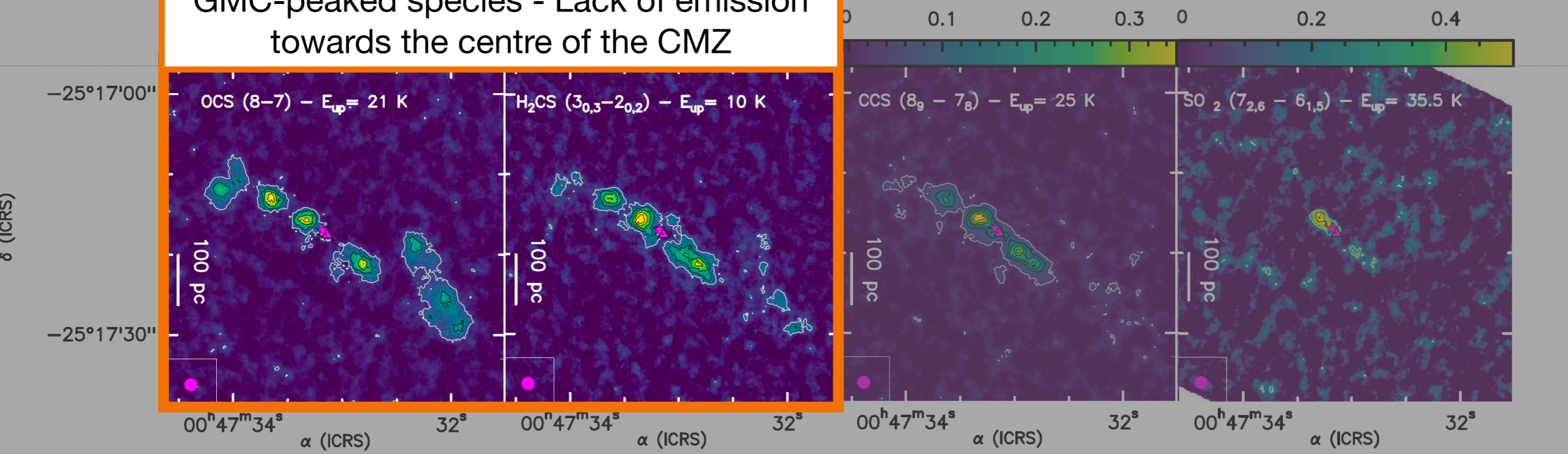


Emission distribution

★ Position of TH2 - Turner & Ho 1985
▲ Kinematic centre
Müller-Sanchez et al. 2010

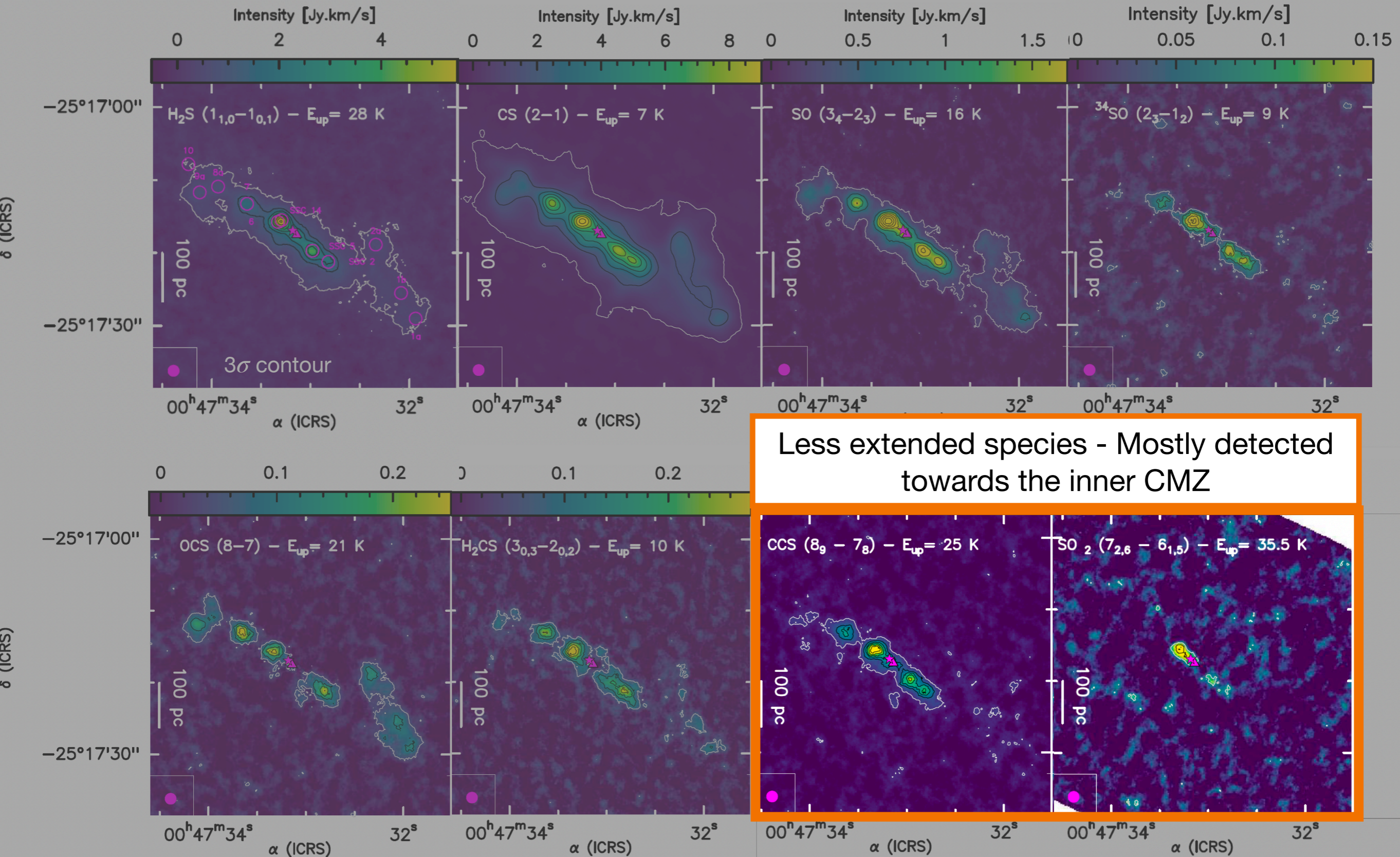


GMC-peaked species - Lack of emission towards the centre of the CMZ



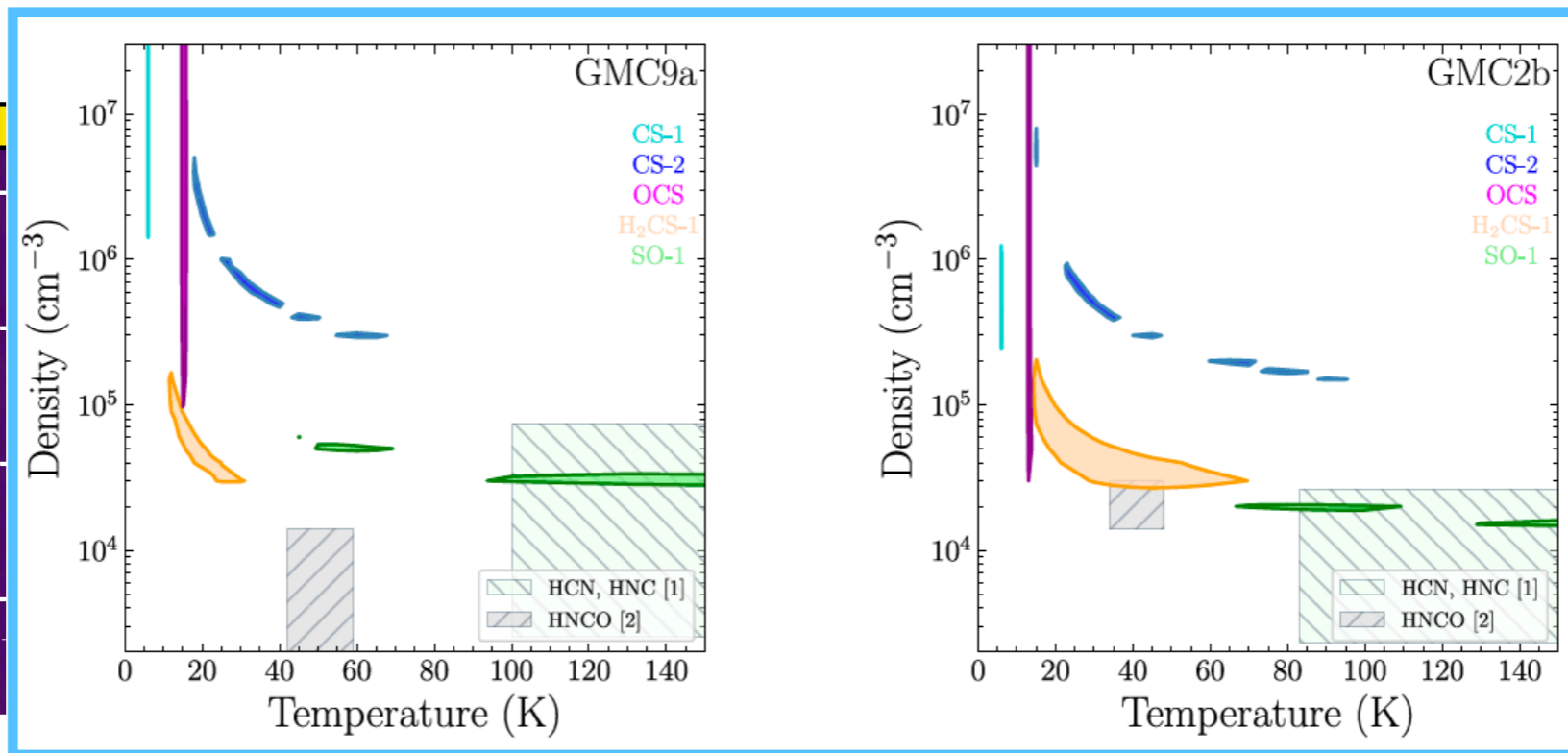
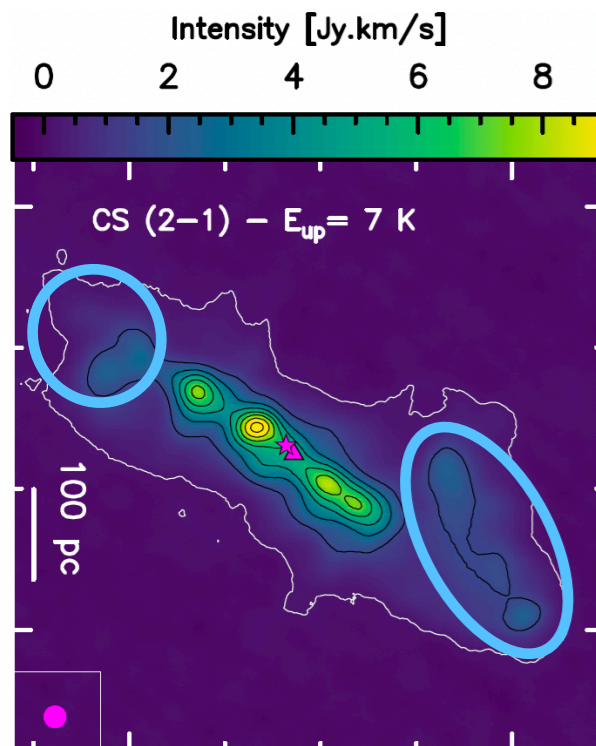
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Less extended species - Mostly detected towards the inner CMZ

Physical parameters & comparison with other tracers



- Outer CMZ:**
- CS and SO: higher T_g
 - CS: densest lower limit ($n_g \geq 10^5 \text{ cm}^{-3}$)
 - Good correlation of SO with HNC, HNC

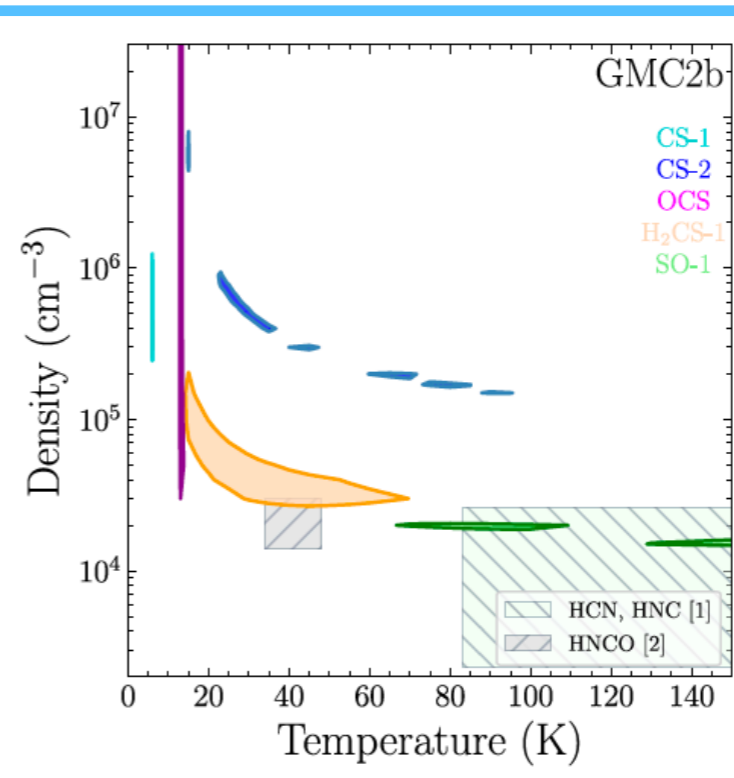
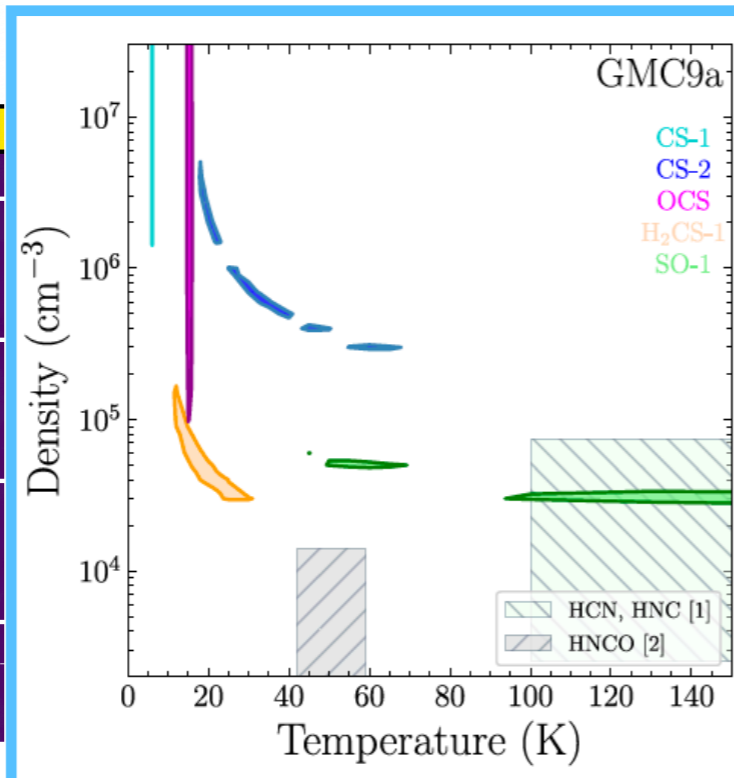
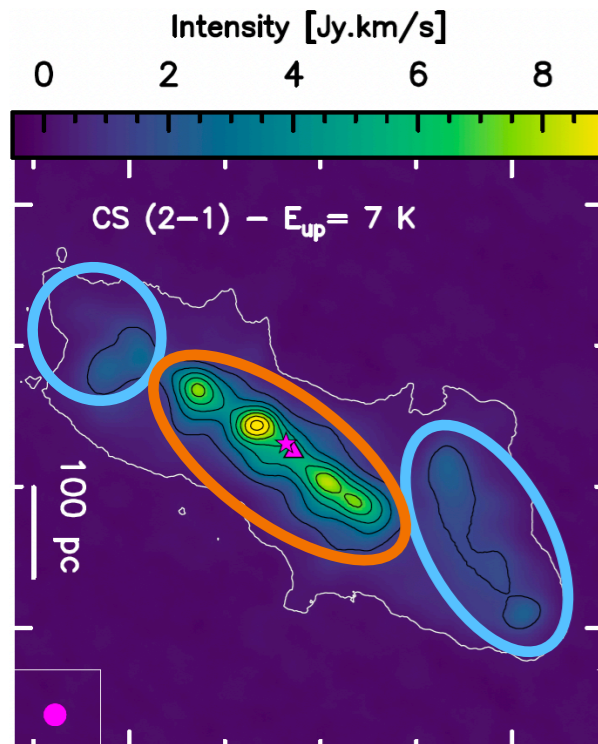
LVG code: GRELVG
 Ceccarelli et al. 2003

Previous ALCHEMI studies:

HNCO: shock (low-velocity) tracer
 Huang et al. 2023

CCH, HCN/HNC and SO/H₃O⁺: sensitive to CRs, GMC tracers
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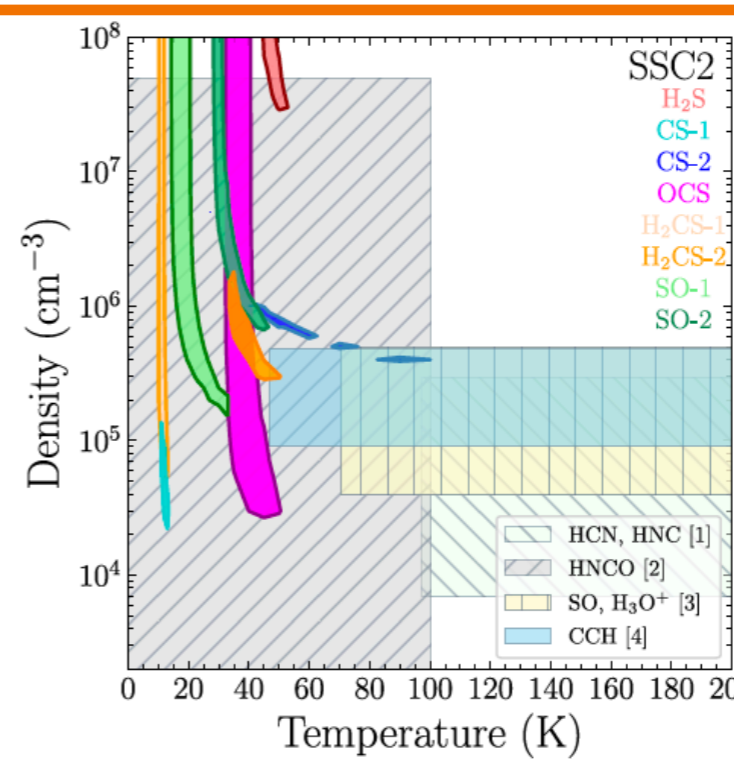
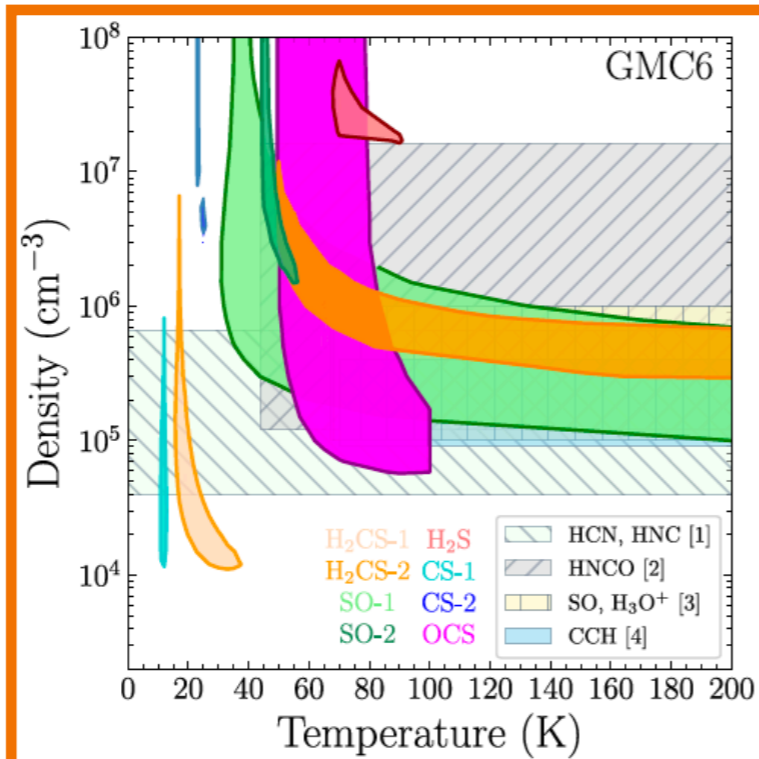
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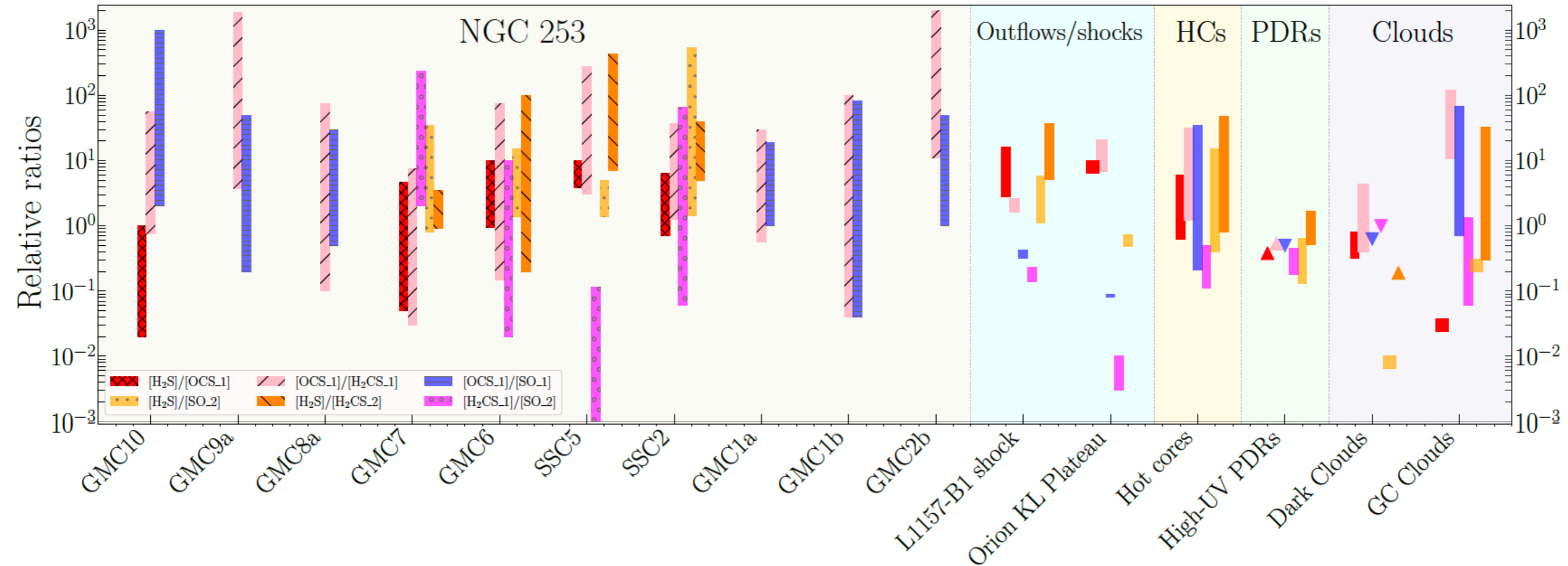
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- Inner CMZ:**
- Two gas component/species
 - H₂S: densest gas ($n_g \geq 2 \cdot 10^6 \text{ cm}^{-3}$)
 - Differences/regions: SSC2 cooler (most $T_g < 60 \text{ K}$)
 - OCS, H₂S, SO (high Eu)~HNCO in all regions

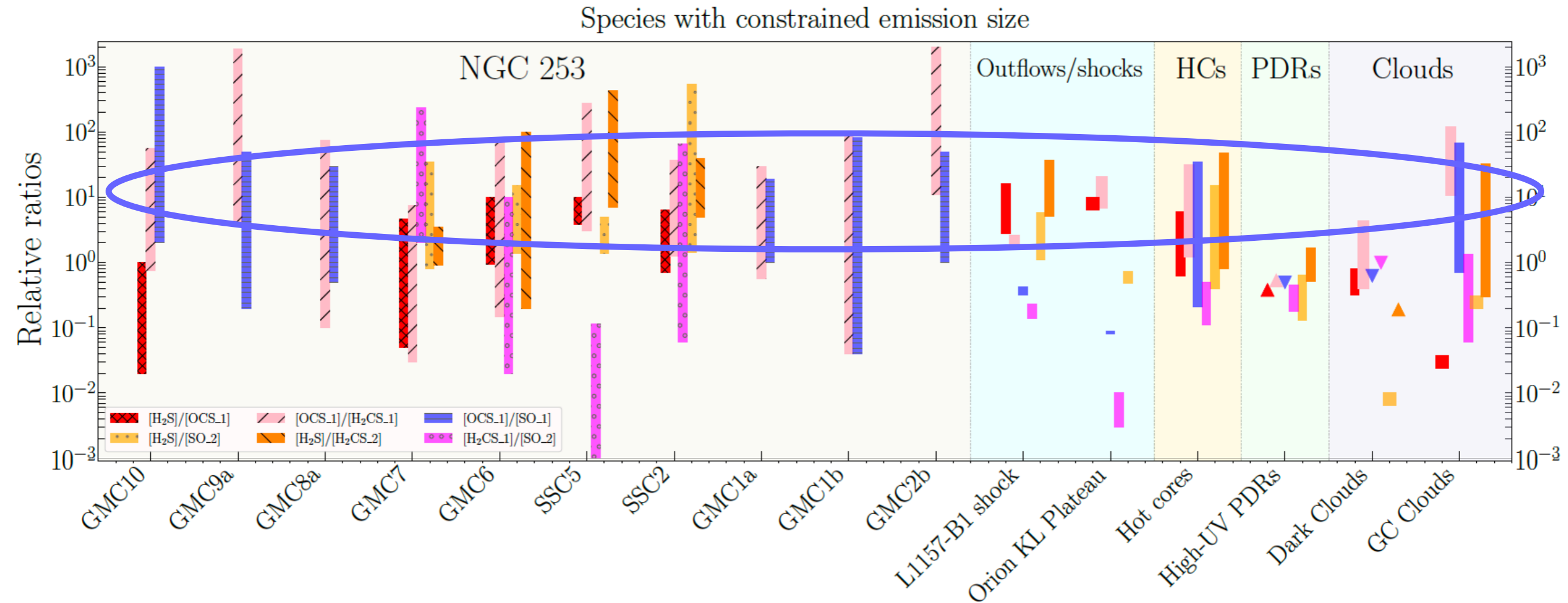
Comparison with Galactic environments

Species with constrained emission size



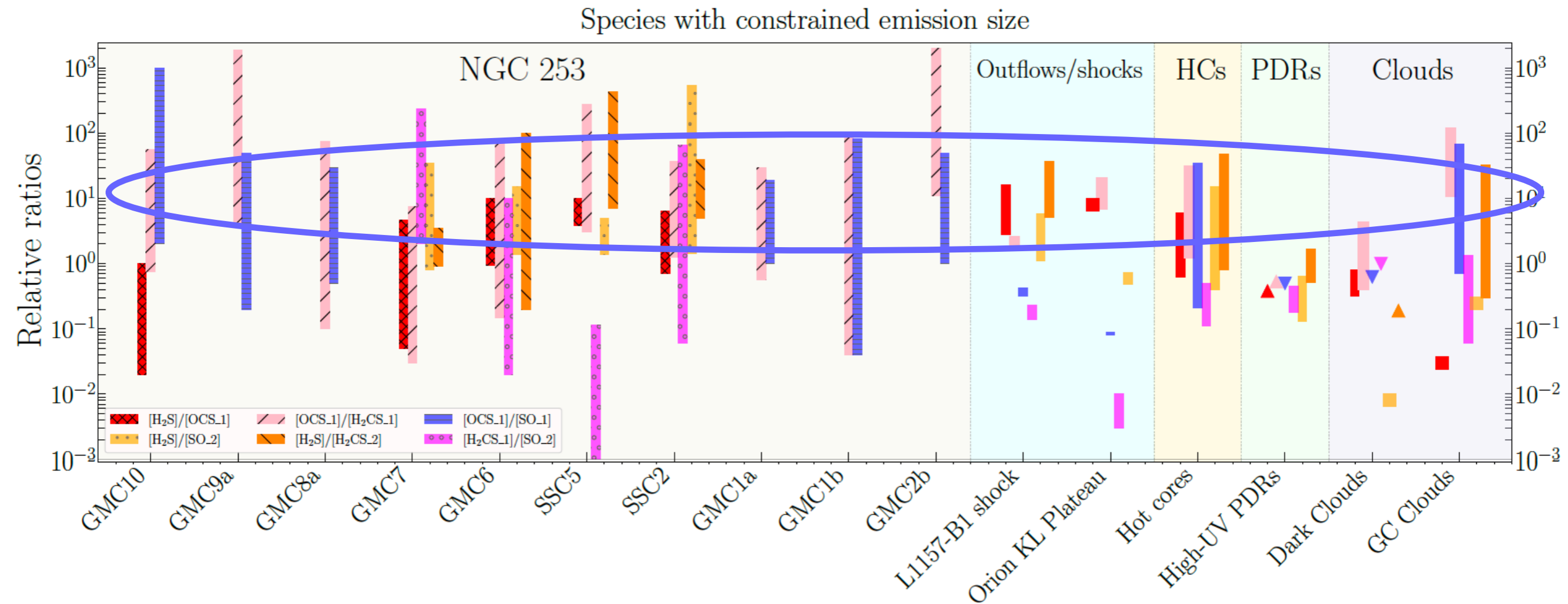
Some abundance ratios are similar to what is found in various galactic SFR environments

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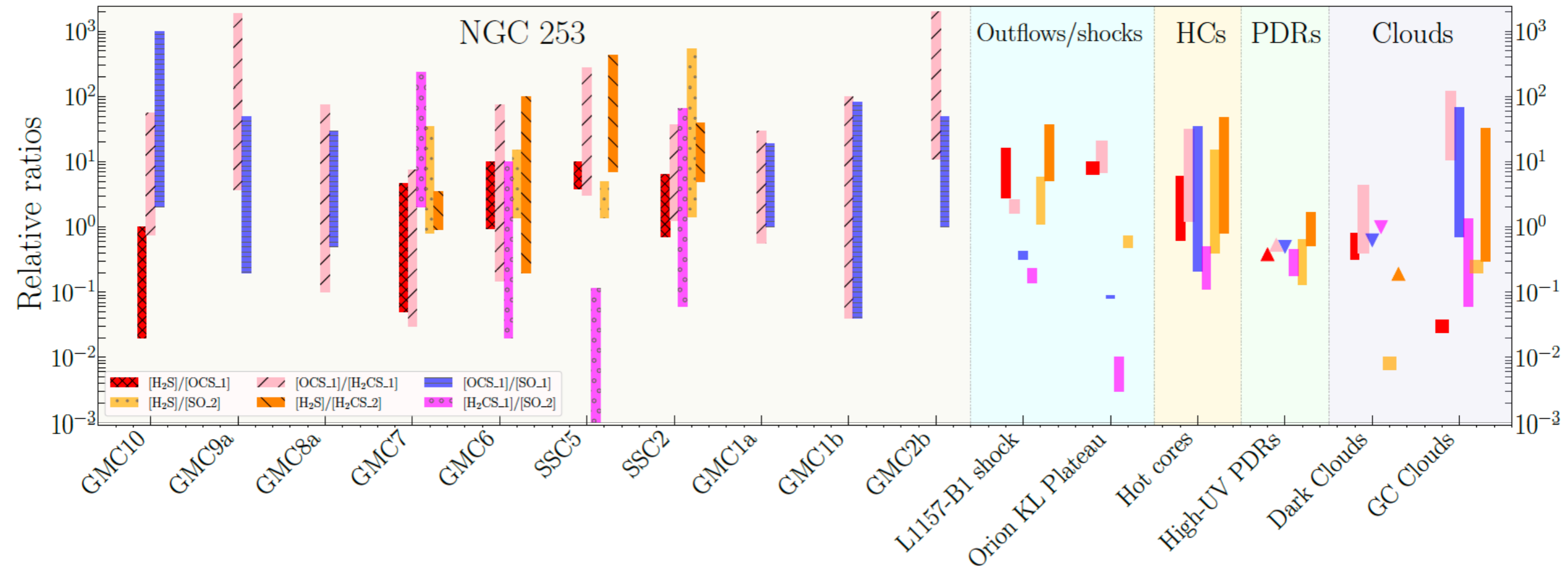


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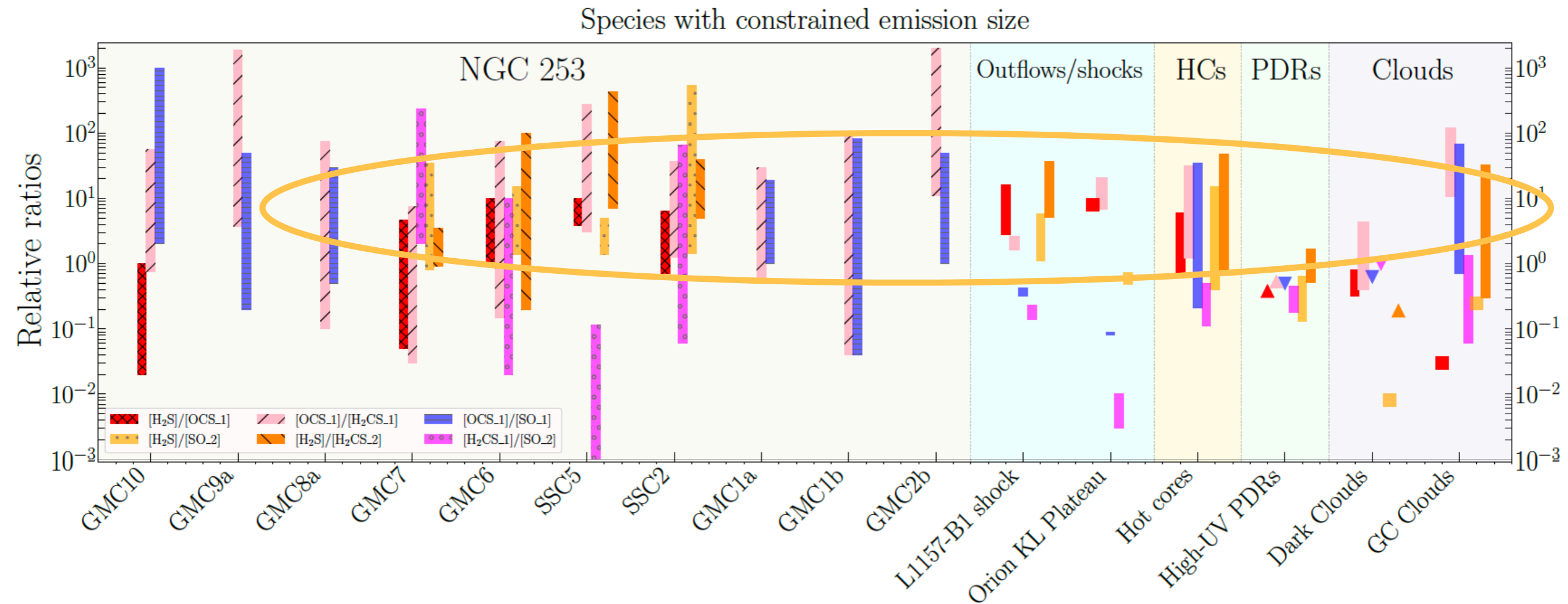
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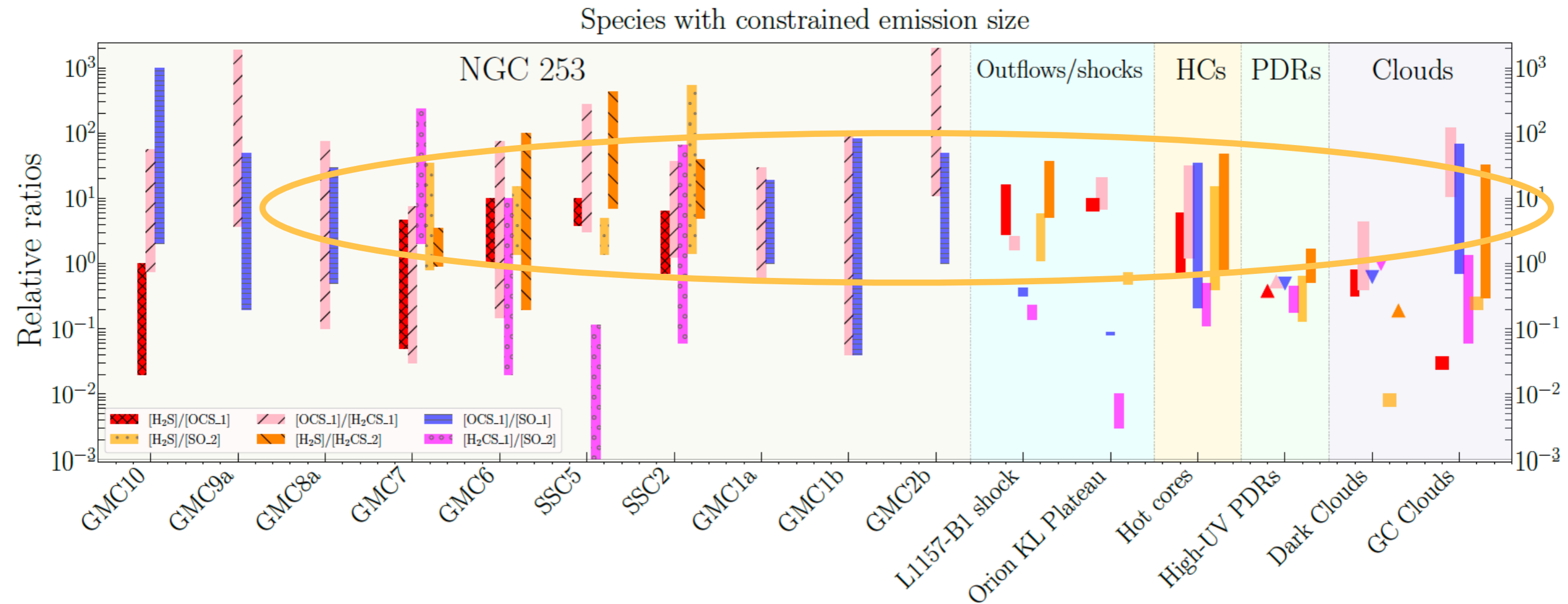
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The ratio OCS/SO (low Eu) resembles that of hot cores (HCs) and Galactic centre (GC) clouds

The ratio H₂S/SO (high Eu) resembles that of outflows/shocks and HCs

Some abundance ratios are similar to what is found in various galactic SFR environments

S-bearing species trace shocks due to ongoing star-formation

Bouvier et al. 2024, A&A, 689, A64

Scheme NOT to scale!

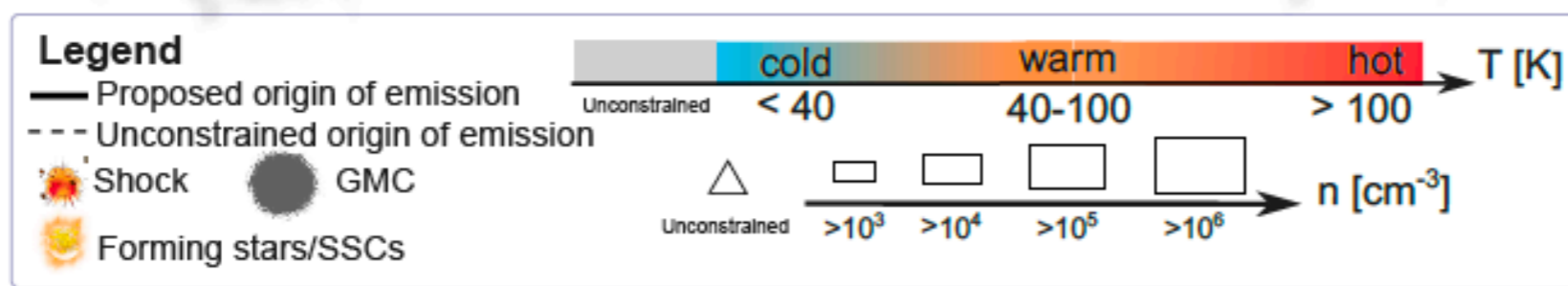
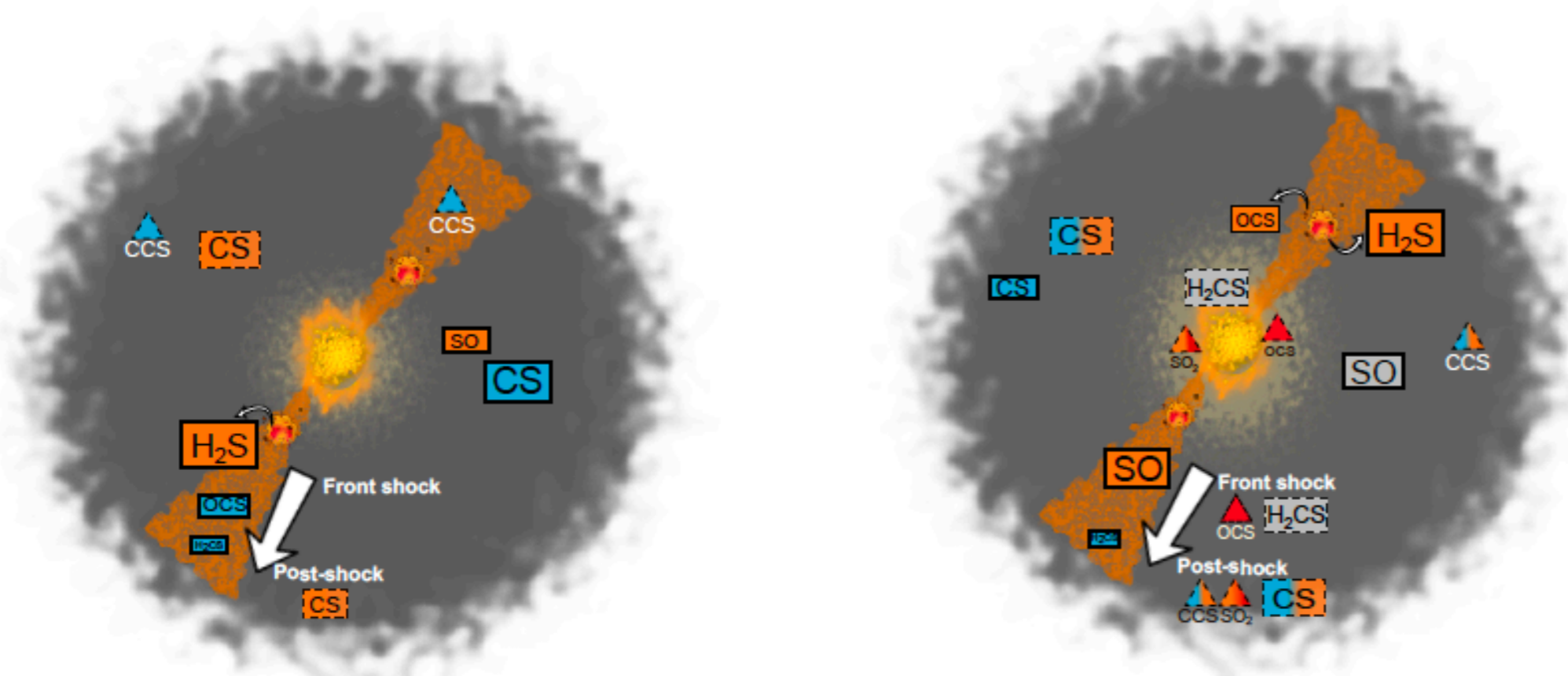
Origin of emission of S-bearing species towards the CMZ of NGC 253

OUTER CMZ

(older shocks: $t > 10^5$ yr)

INNER CMZ

(younger & stronger shocks: $t < 10^4$ yr)



Shock age from H₂CO & SiO (Huang et al. 2023)

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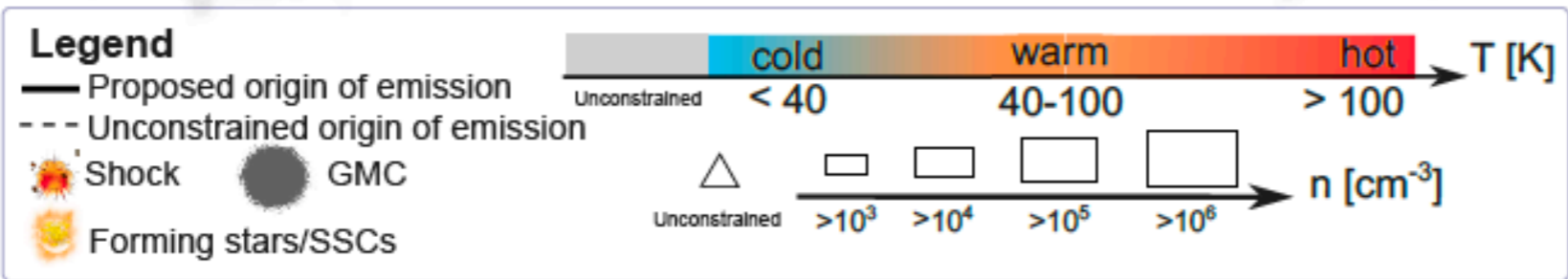
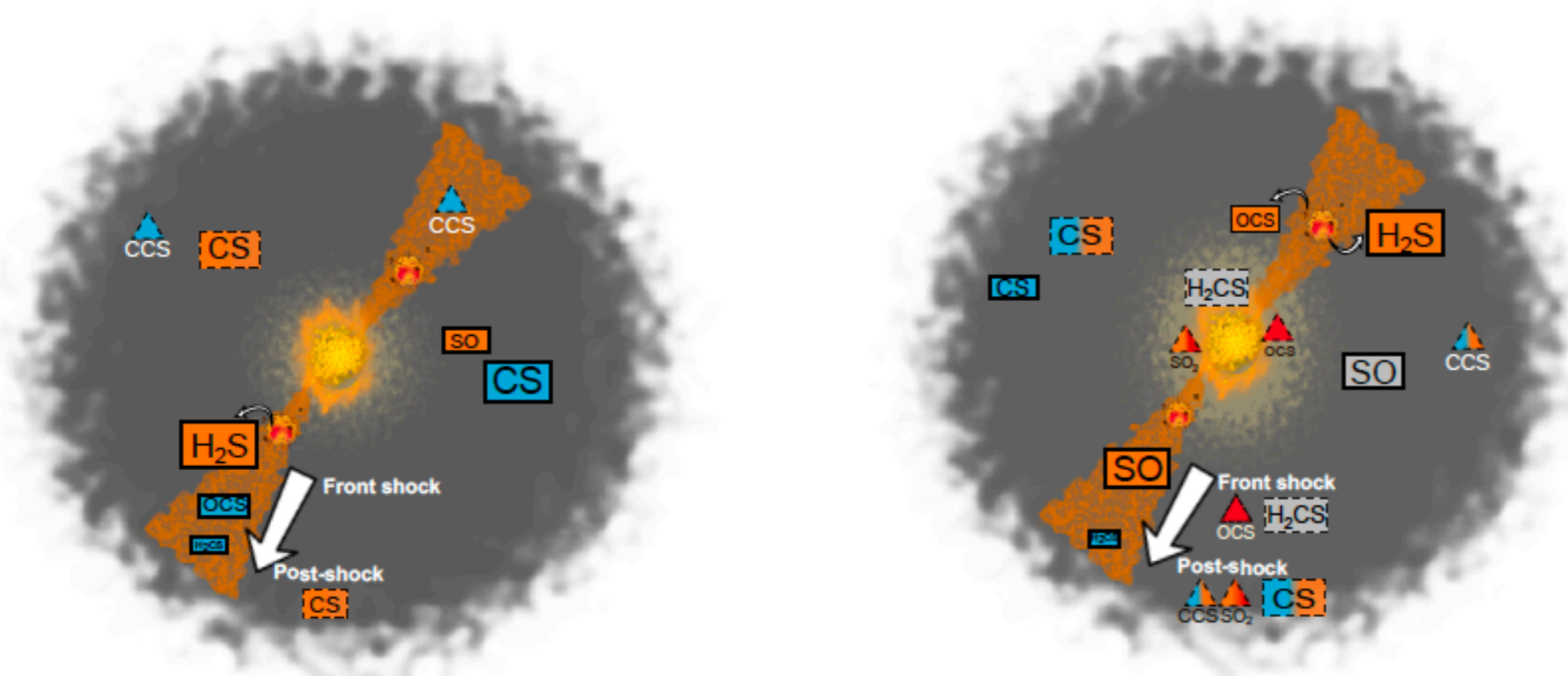
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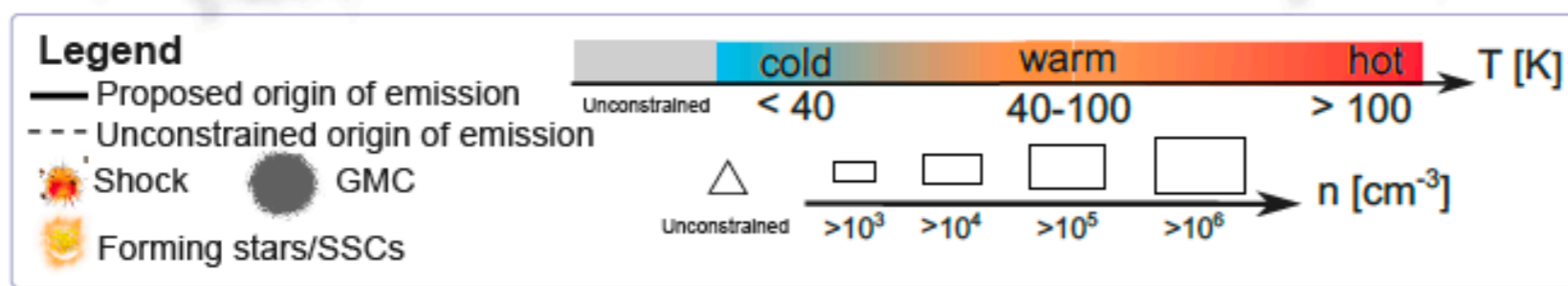
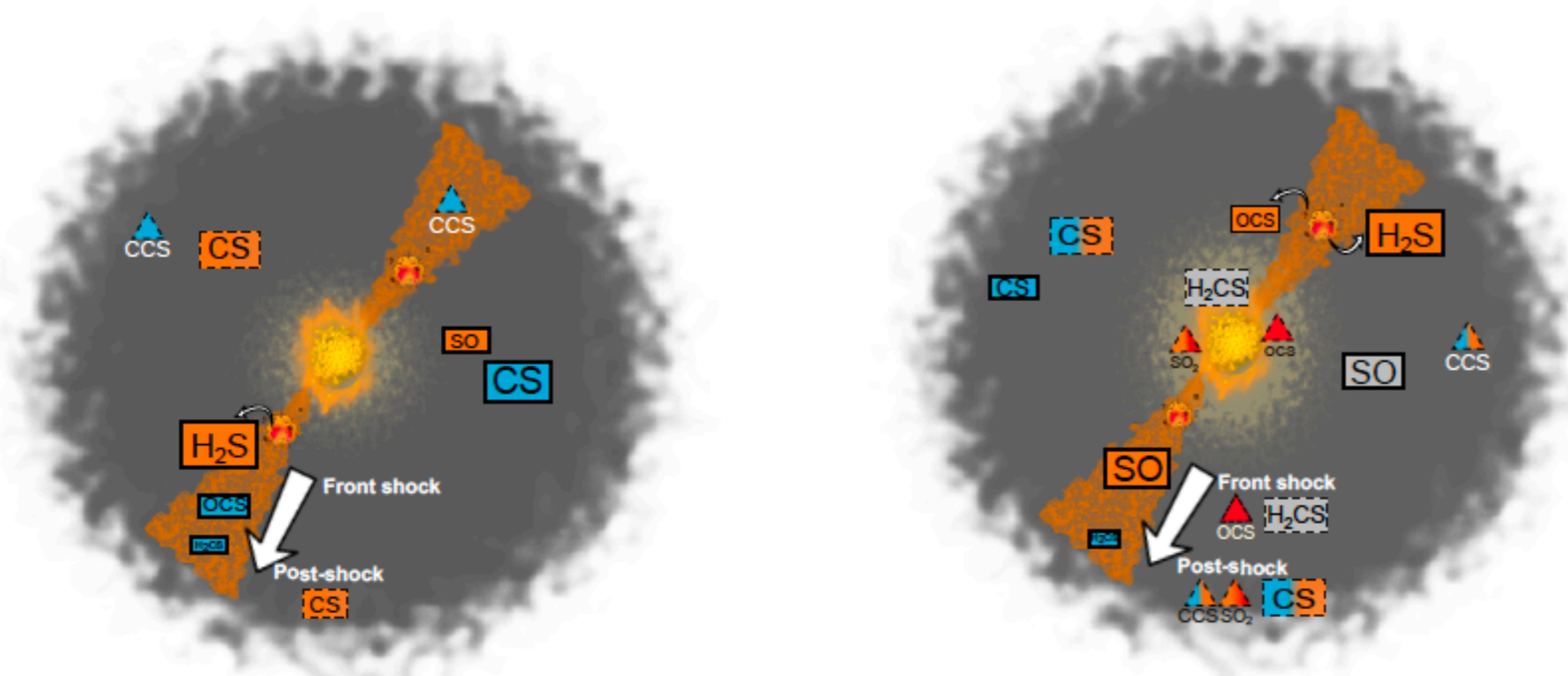
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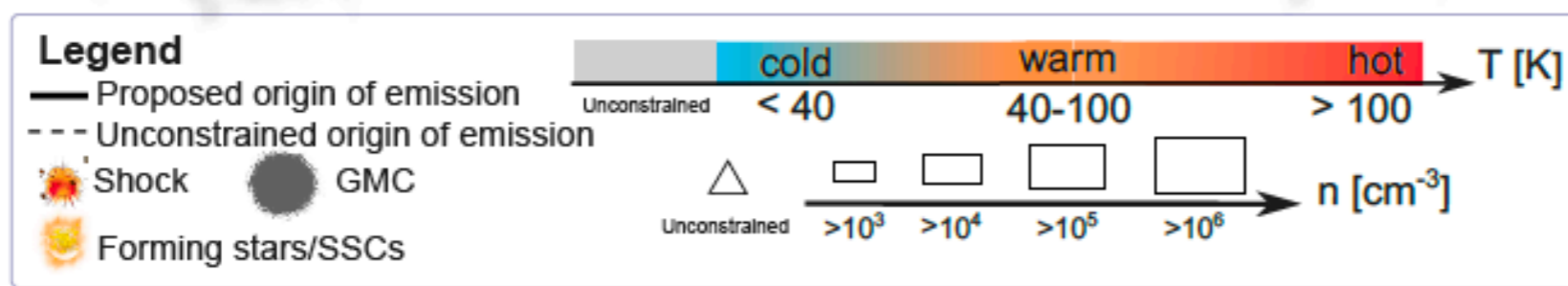
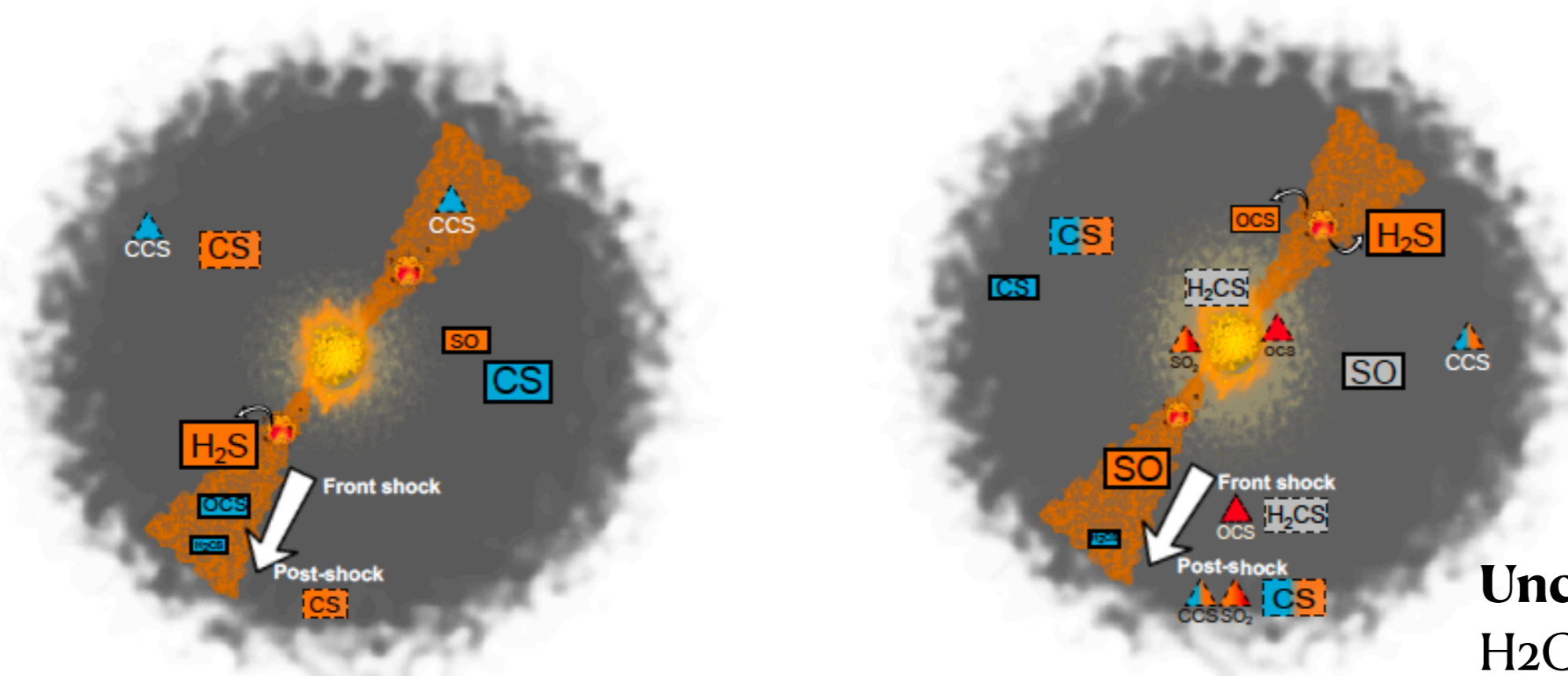
GMC tracers:

CS (low-Eu),
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Unconstrained origins:

H₂CS and OCS (high Eu),
SO₂: shock or "hot core"?

CS (high-Eu) and CCS:
shock or GMC?



Shock age from H₂CO & SiO (Huang et al. 2023)

Comparing observation with chemical modelling

UCLCHEM: Time-dependent gas-grain chemical model

3-phase model: gas, surface and bulk

Main collaborators: K. Dutkowska & S. Viti

Models tested: hot core (pre-warmup + hot core) and C-shock (shock + post-shock)



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Hot core

Final Temp (K): 50 to 550 by steps of 50

Initial density (cm^{-3}): $10^5 - 10^8$

Shock

Velocity (km.s^{-1}): 5 to 30 by steps of 5

Initial density (cm^{-3}): $10^4 - 10^6$

B_0 (μG): 10, 100, 1000

CRIR NGC 253: $\geq 10^{-14} \text{s}^{-1}$

Measured gas Temp: $\leq 300 \text{ K}$

Other parameters:

$\zeta_{cr} (\times \zeta_0) = 10, 100, \mathbf{1000}, \mathbf{10000}$

Rad. Field ($\times G_0$): 100, 1000

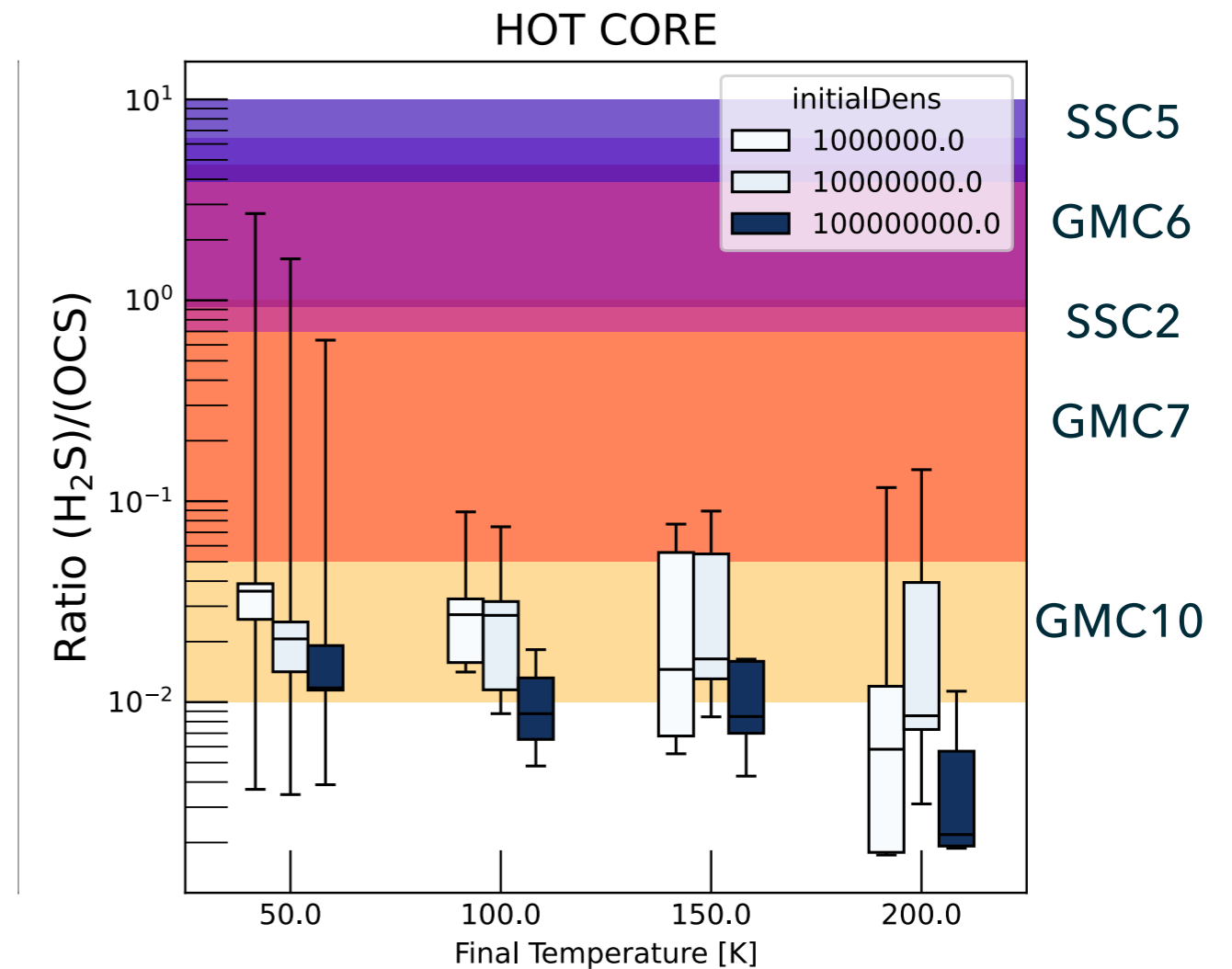
Initial Temperature (K): 15, 20, 25, 30, 35

Comparing observation with chemical modelling

A few examples: H₂S/OCS

Observed ratio H₂S/OCS₁: 0.01-10
 Observation conclusion: shock tracers

Observation constrains:
 Results only $n \geq 10^6 \text{ cm}^{-3}$; $T \leq 200 \text{ K}$



Ratio reproduced mostly
 for GMC10 and 7
 Never for SSC5

Comparing observation with chemical modelling

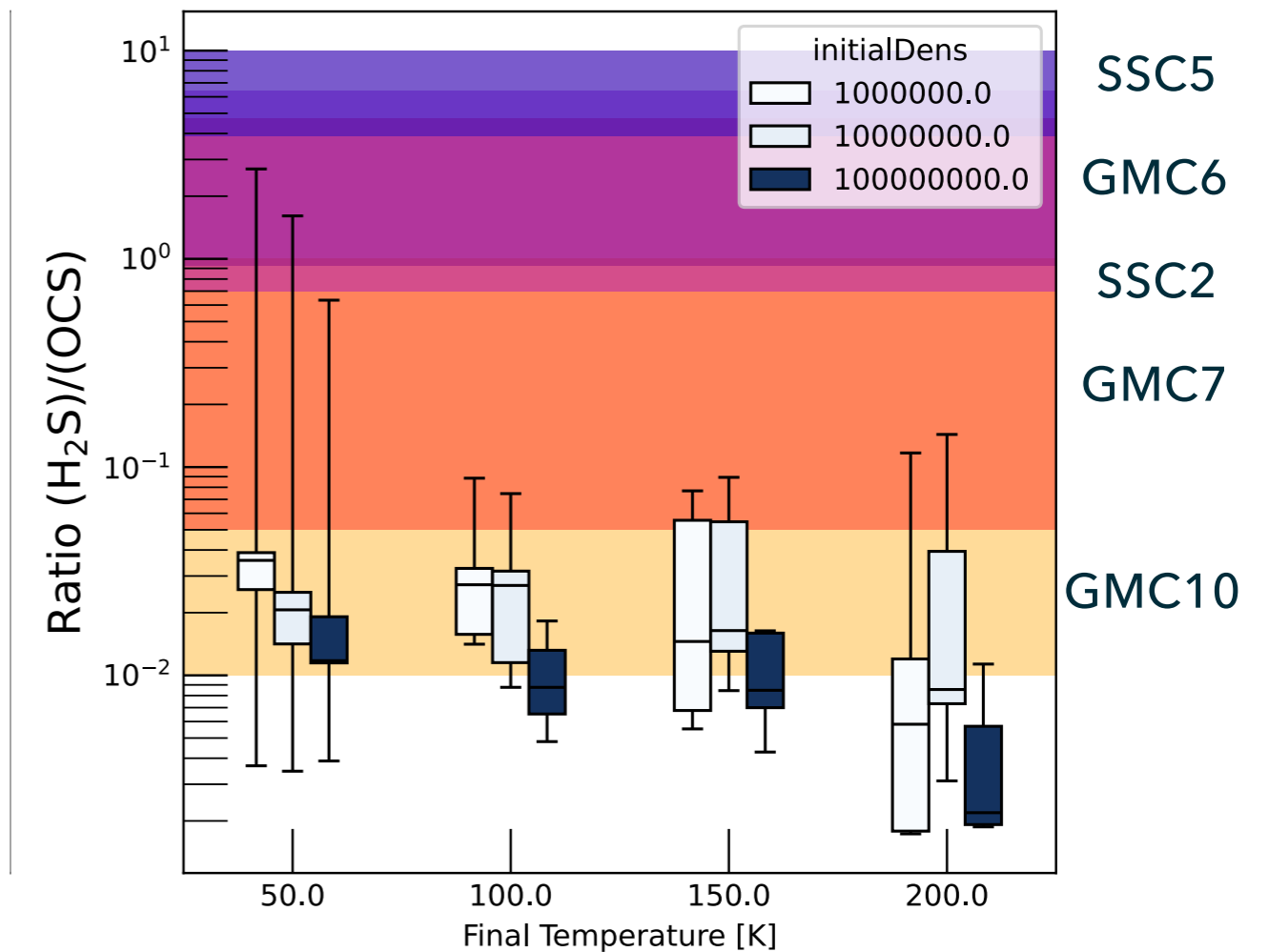
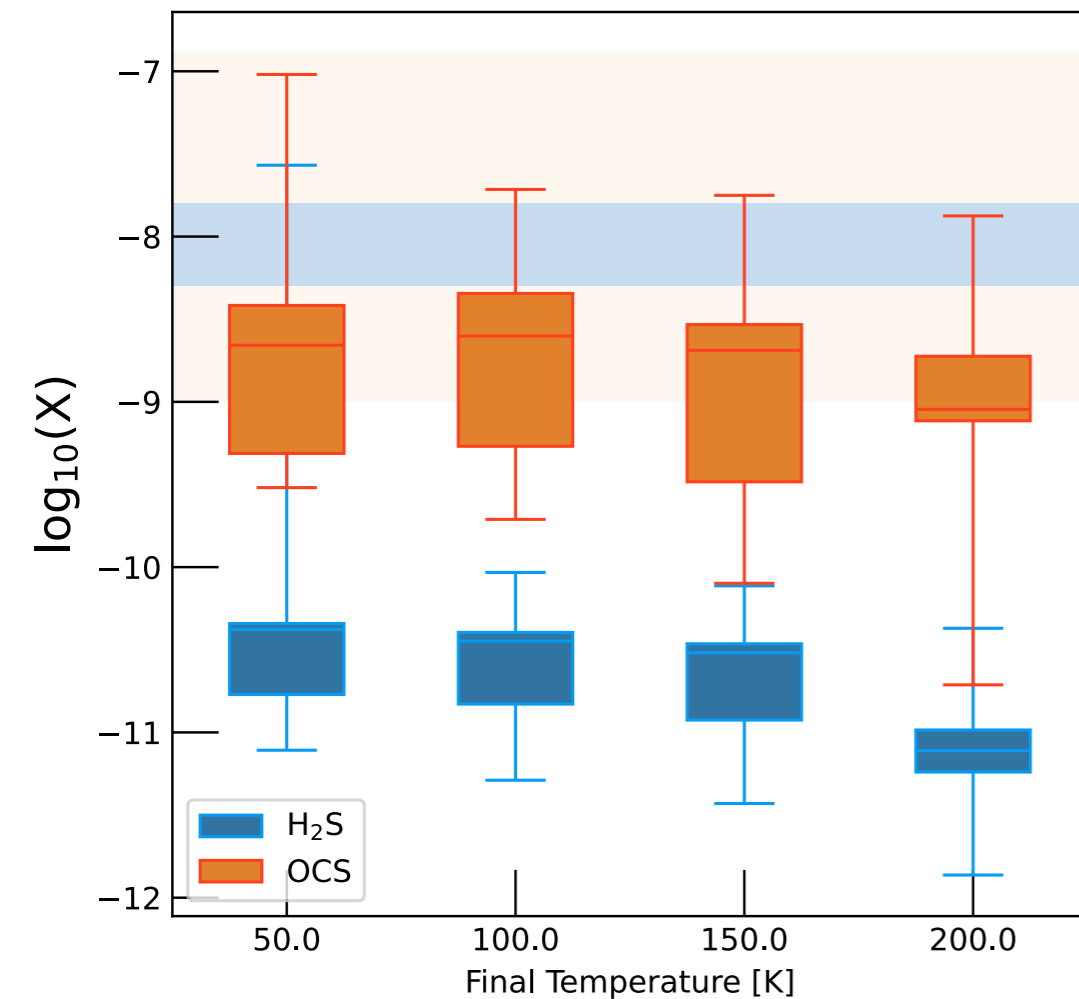
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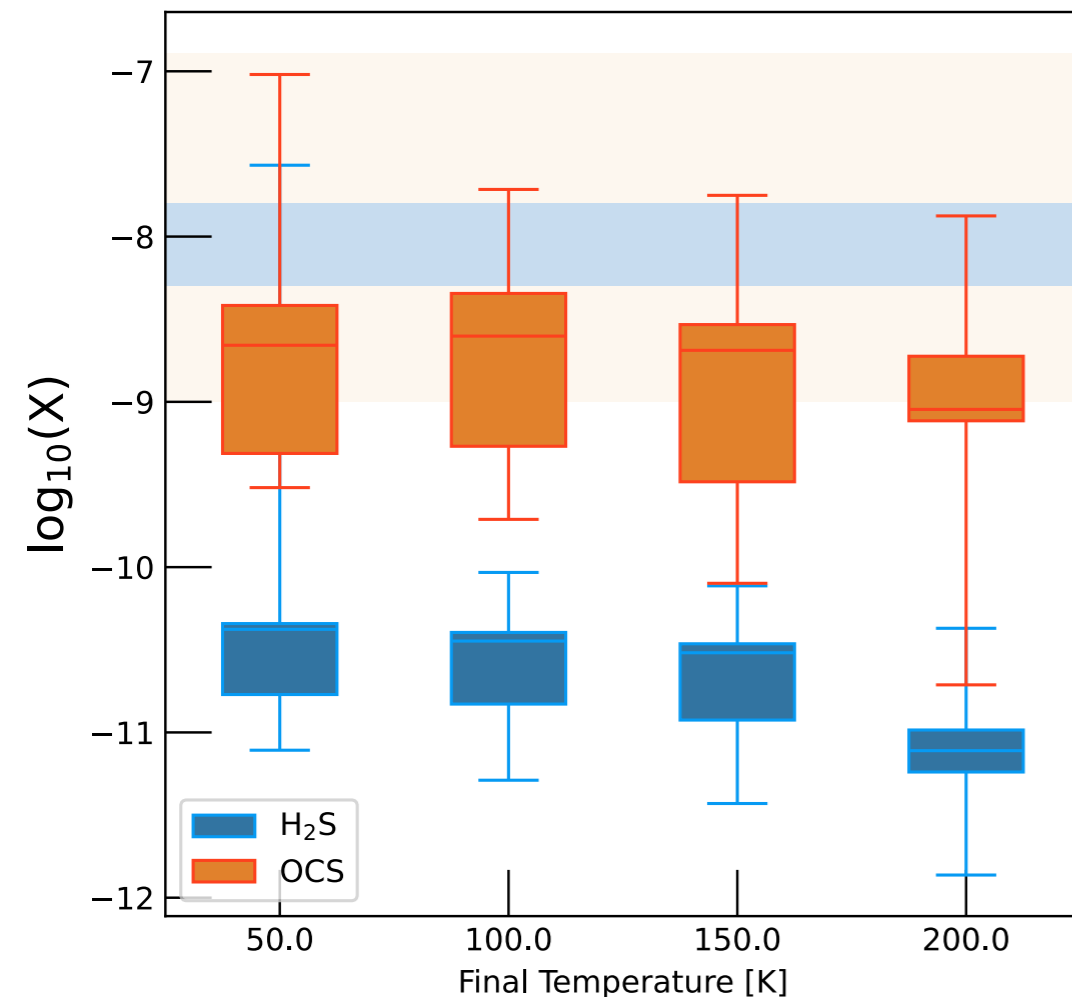
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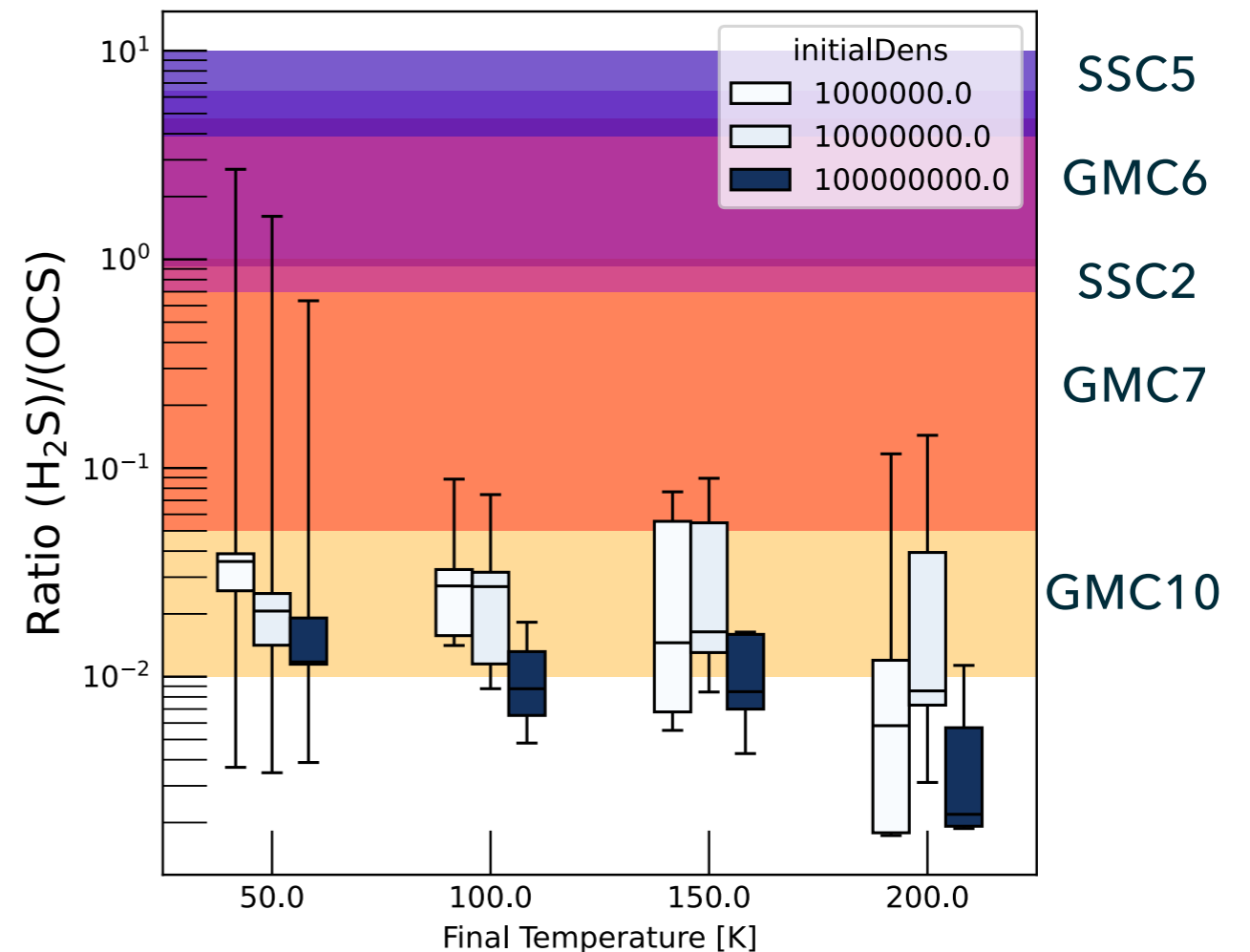
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Hot core model not suitable

HOT CORE



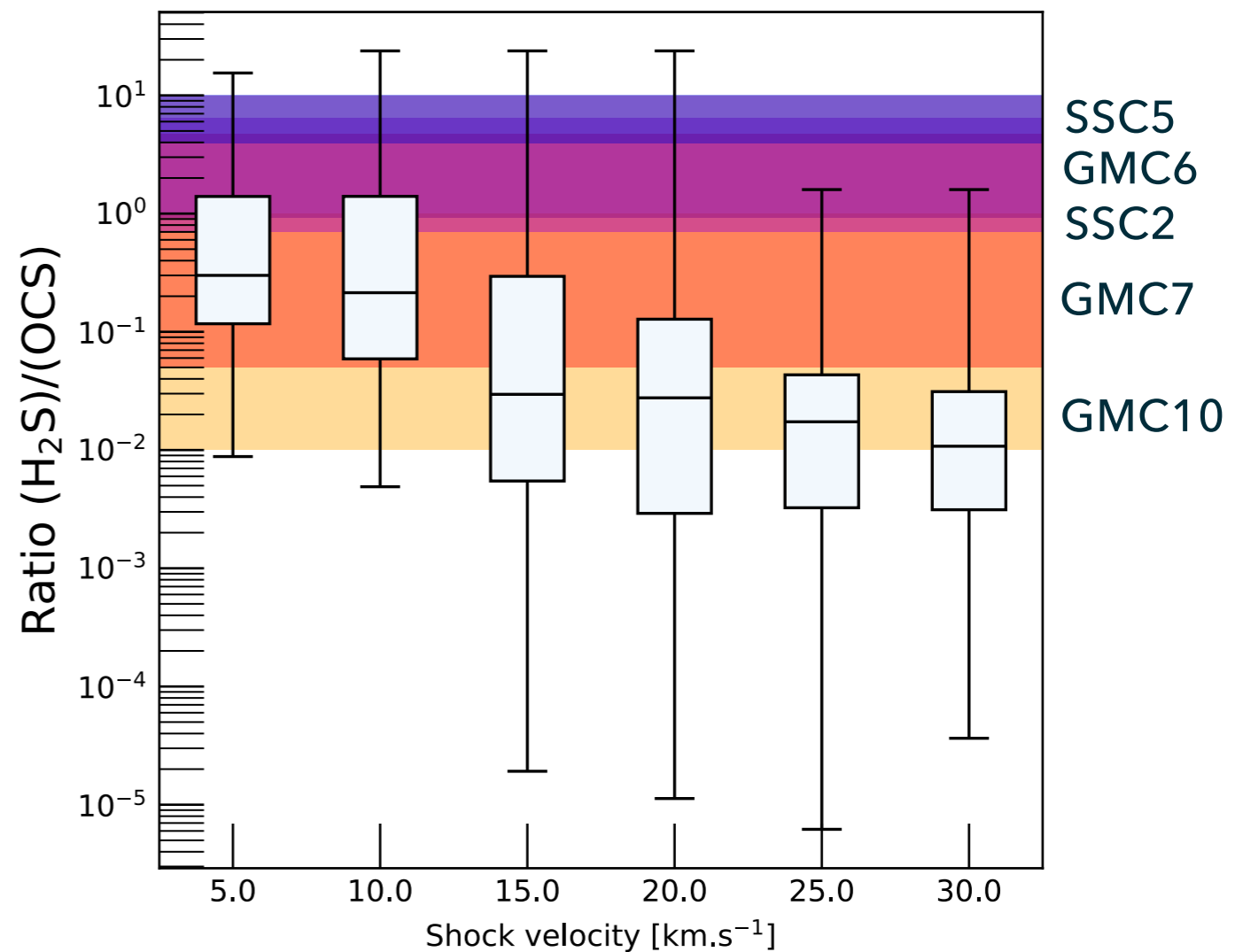
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A few examples: H₂S/OCS

Observed ratio H₂S/OCS (low-J): 0.01-10
Observation conclusion: shock tracers

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SHOCK



Ratio reproduced in all regions for $v \leq 20 \text{ km/s}$

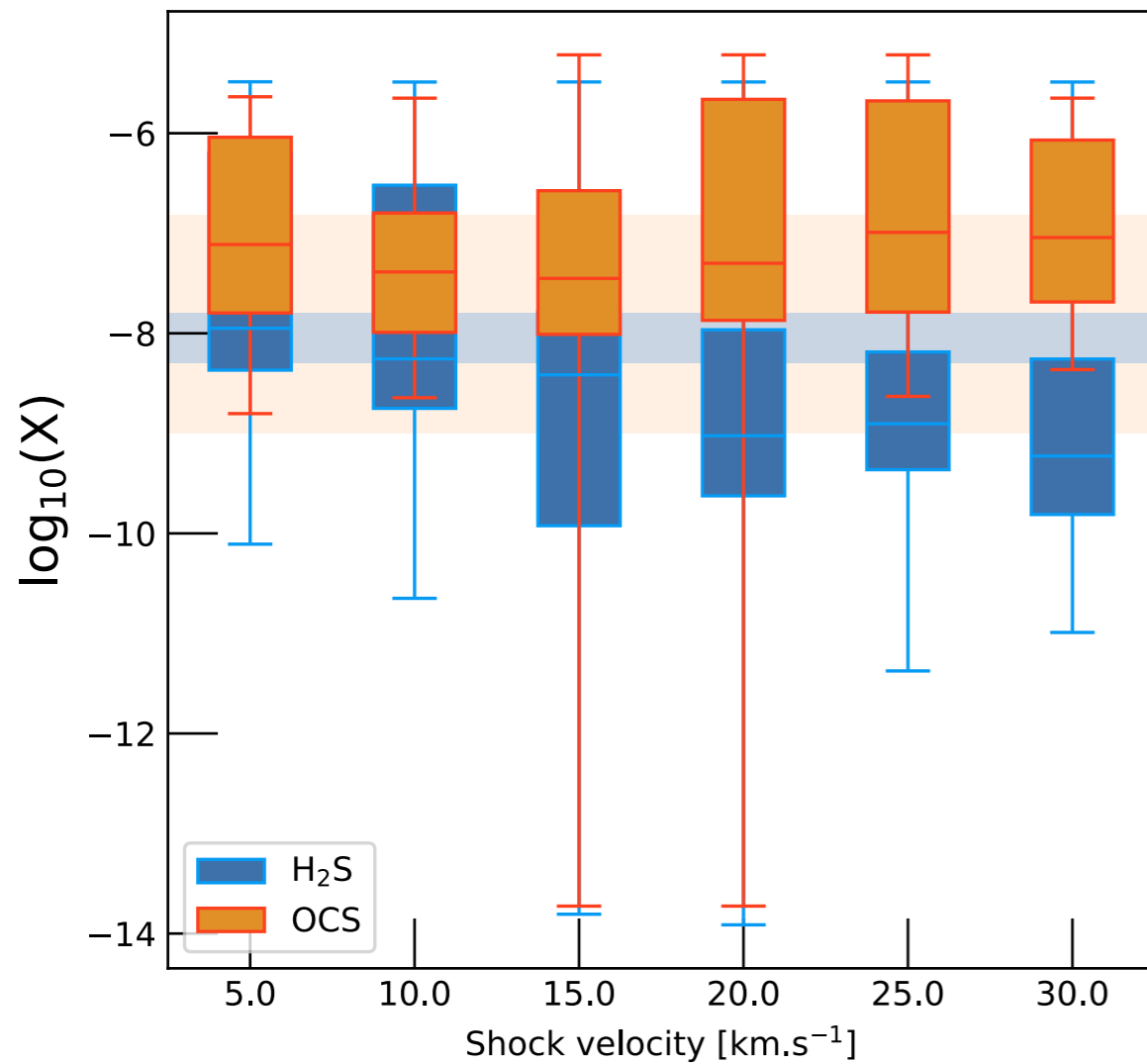
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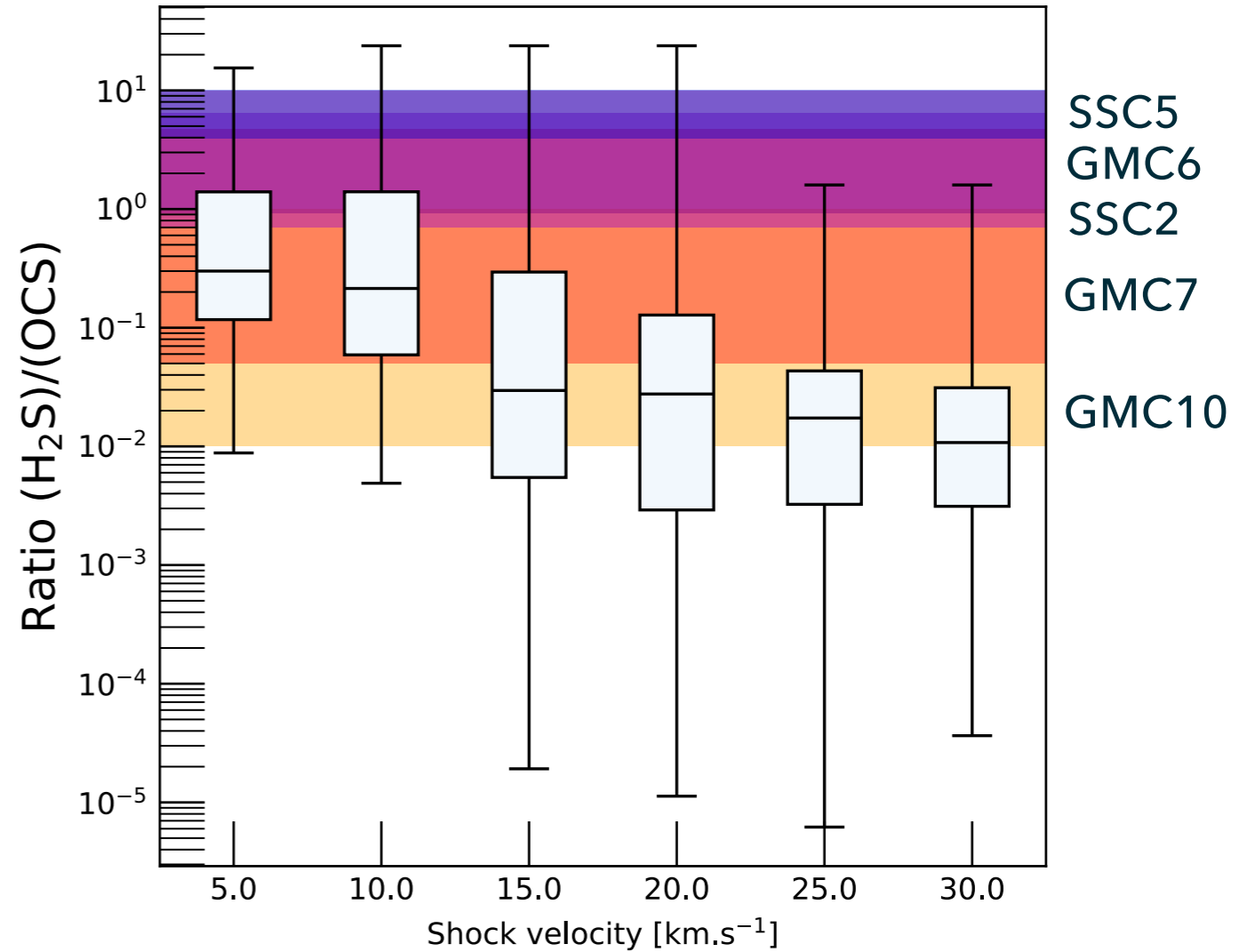
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Abundances reproduced



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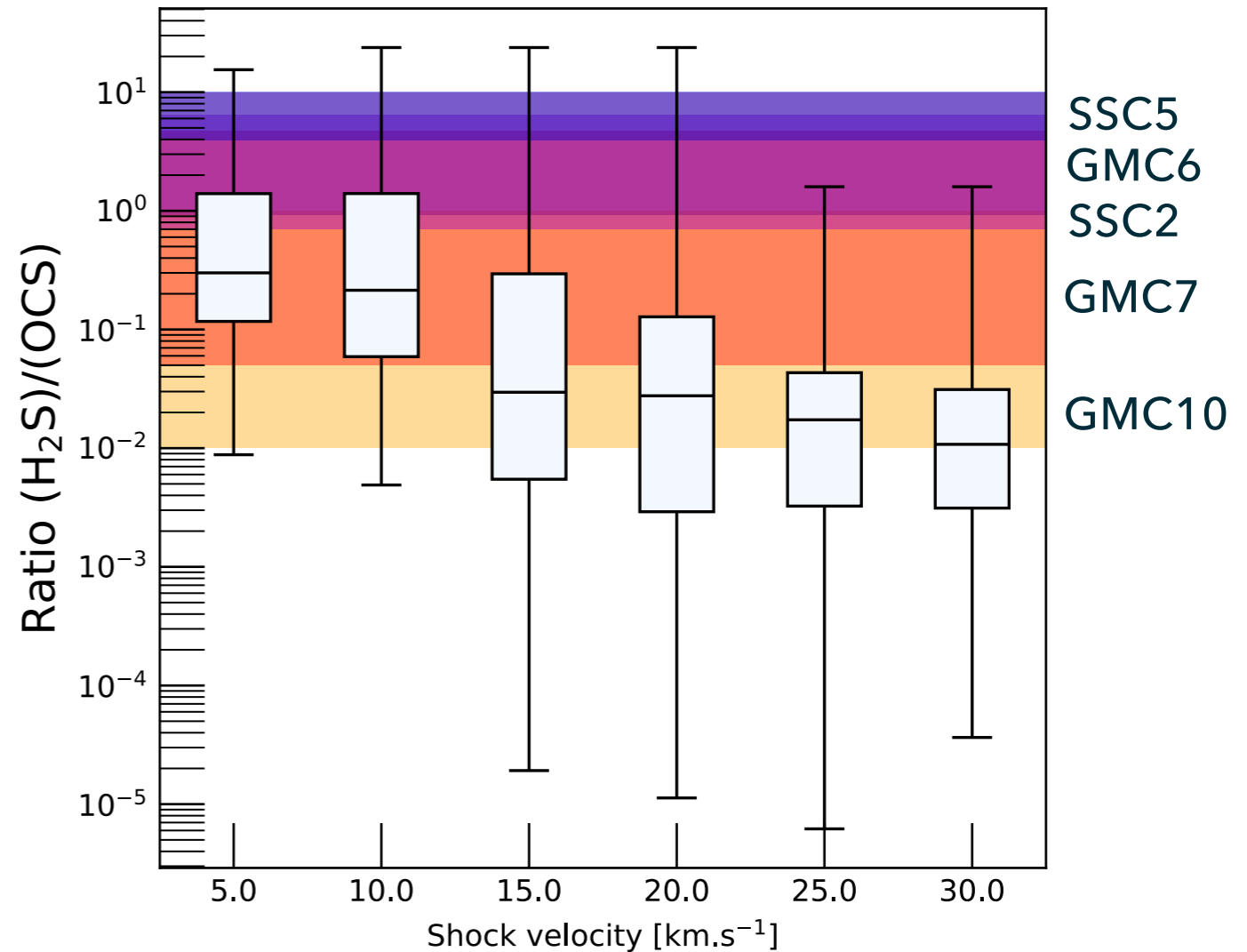
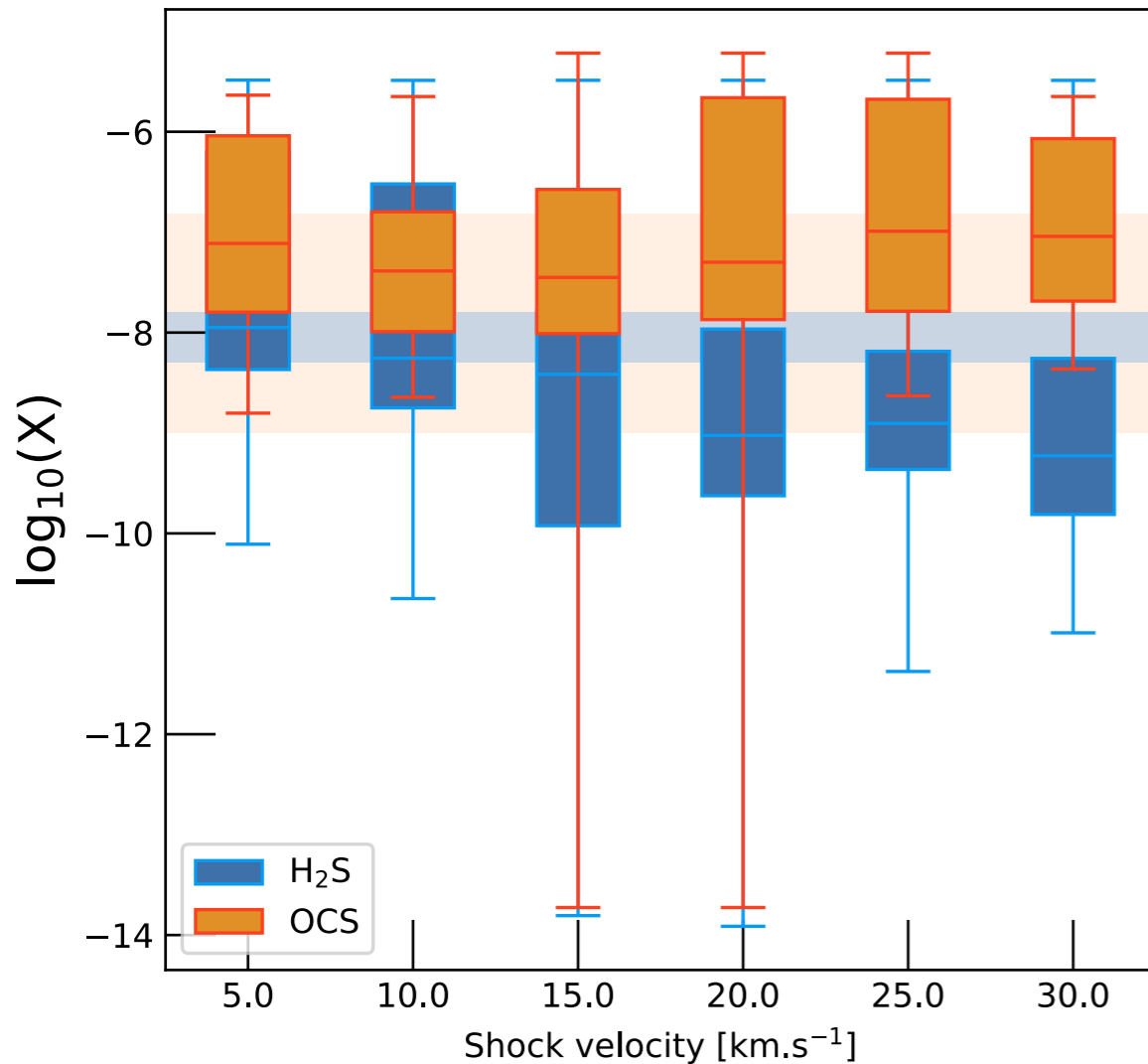
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Abundances reproduced

Shock scenario favoured ($v_s \leq 20 \text{ km/s}$)

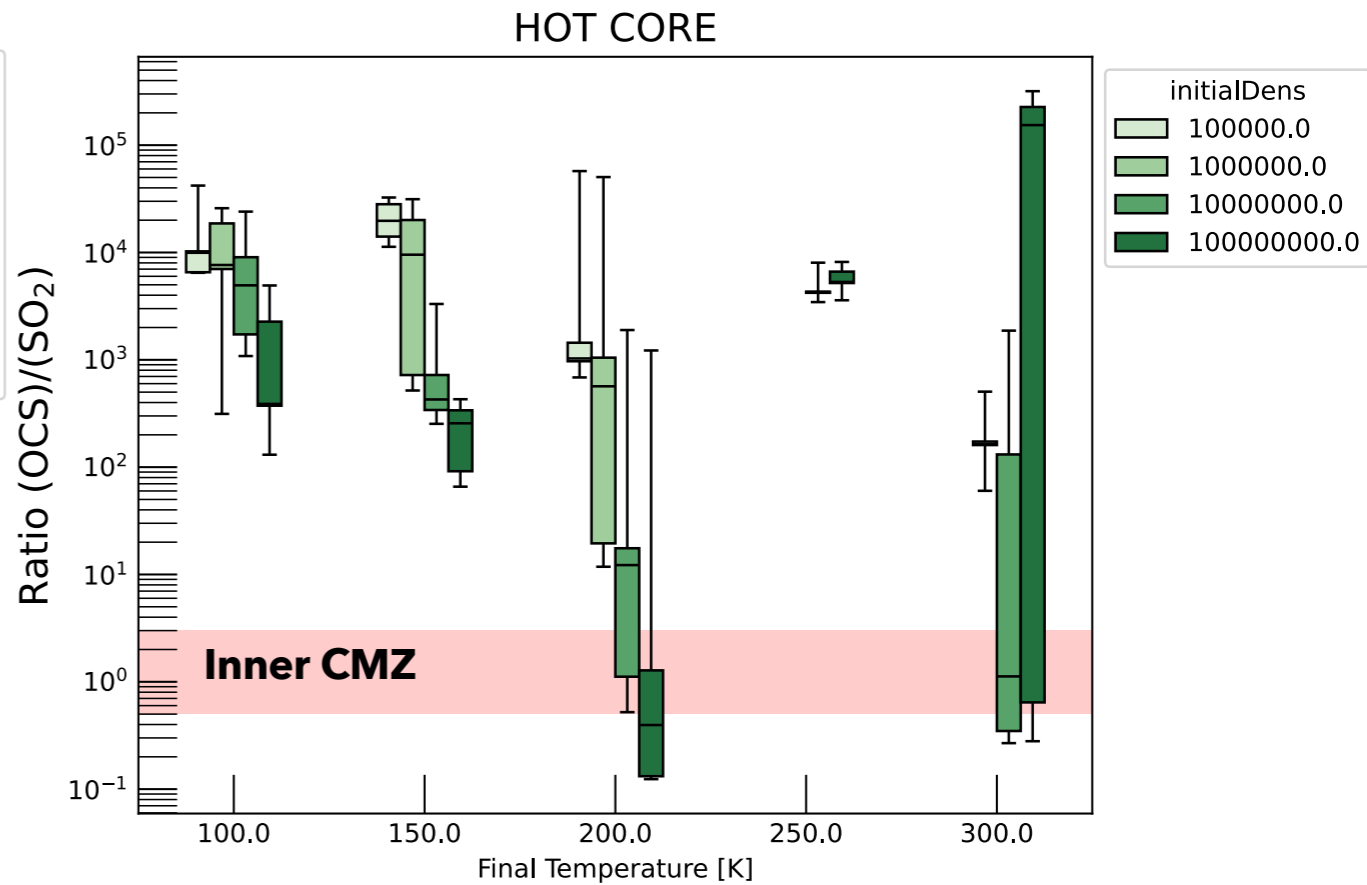
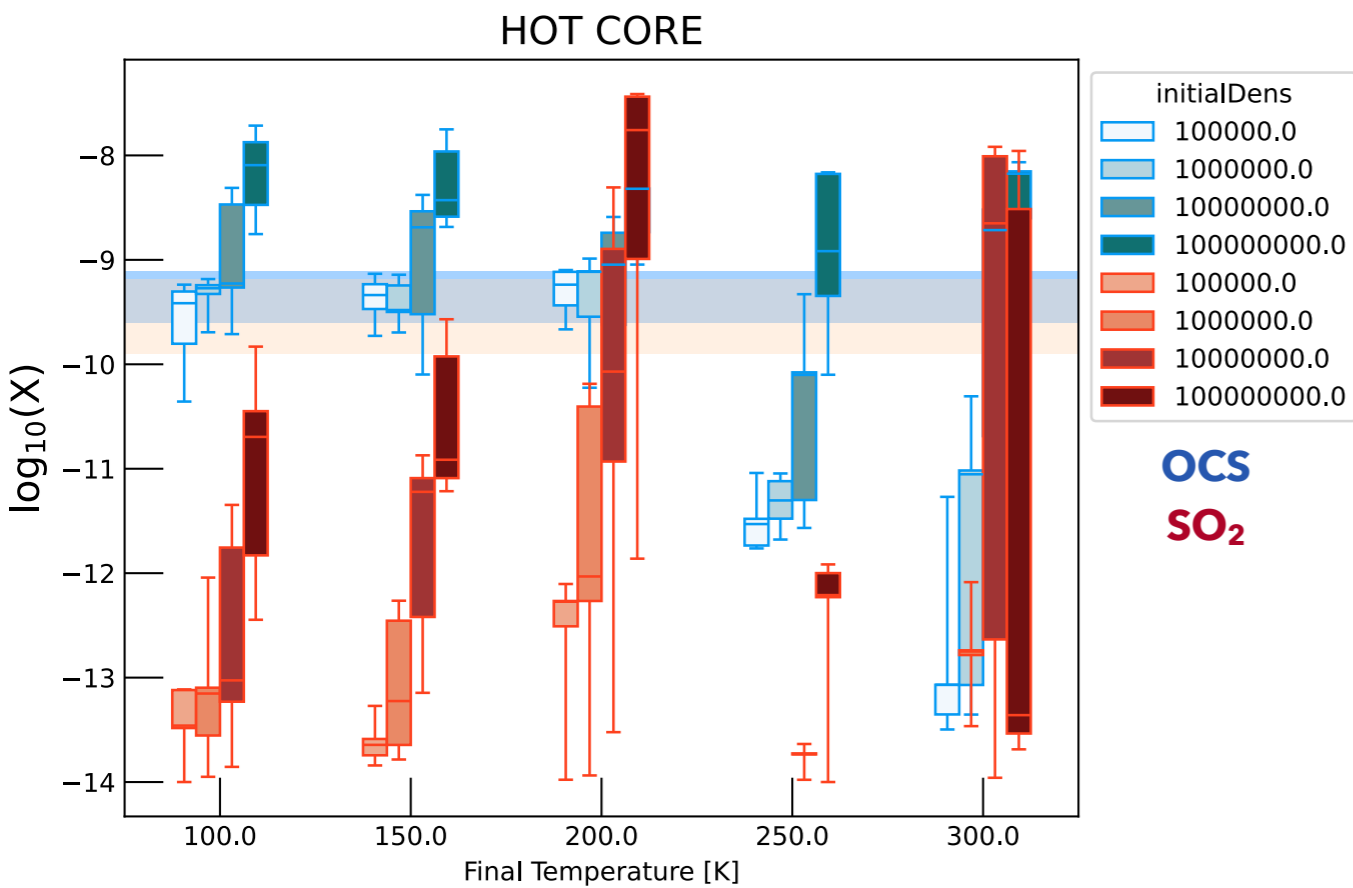
Ratio reproduced in all regions for $v \leq 20 \text{ km/s}$

Comparing observation with chemical modelling

A few examples: OCS(high-J)/SO₂

Observed ratio OCS (high-J)/SO₂: 0.5-3
 Observation conclusion: shock or hot core

Observation constrains:
 Results for T ≤ 300 K



SO₂ abundances only reproduced
 for $n \geq 10^8 \text{ cm}^{-3}$ for all T or for
 T=200 & 300K with $n \geq 10^7 \text{ cm}^{-3}$

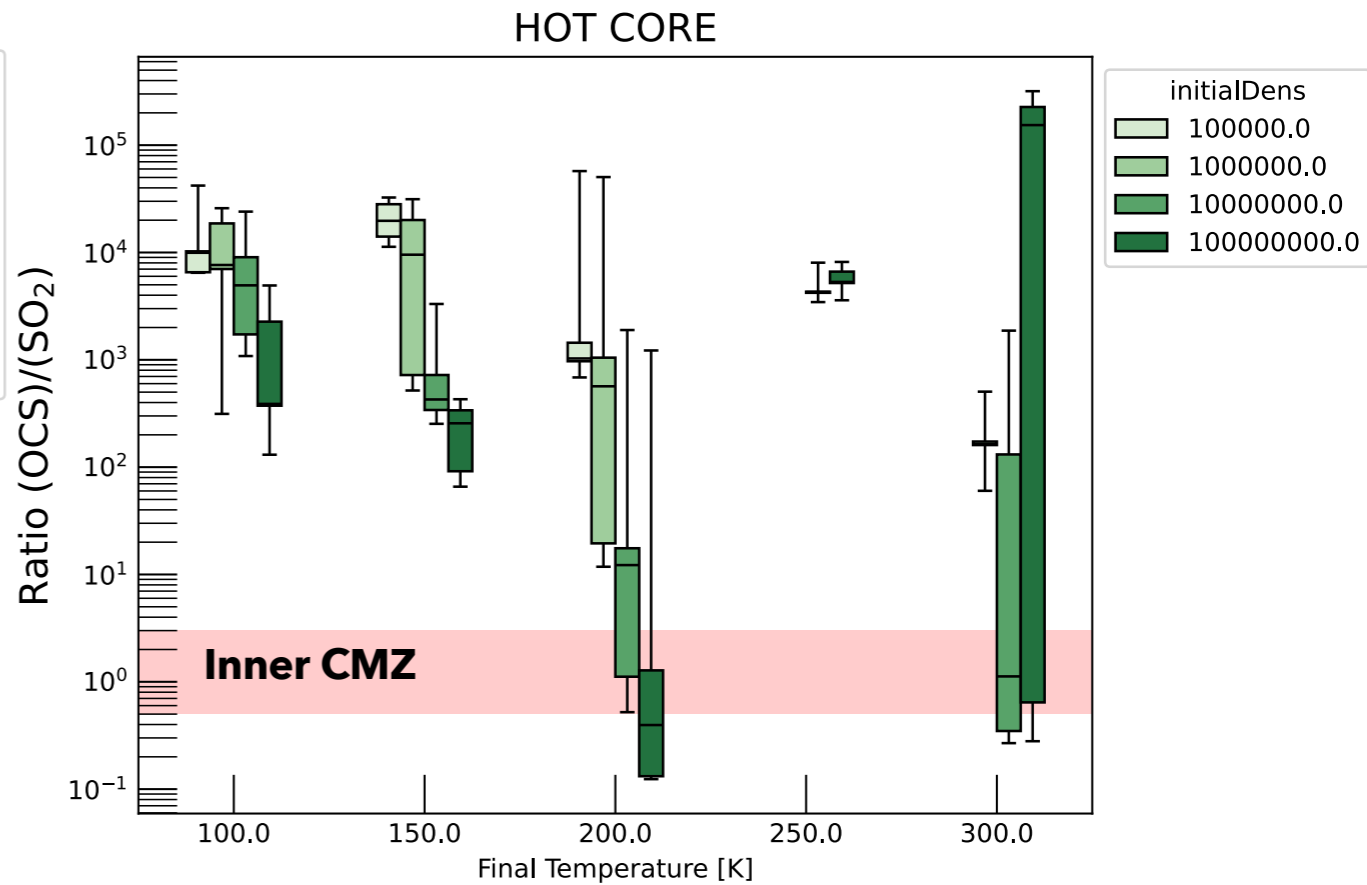
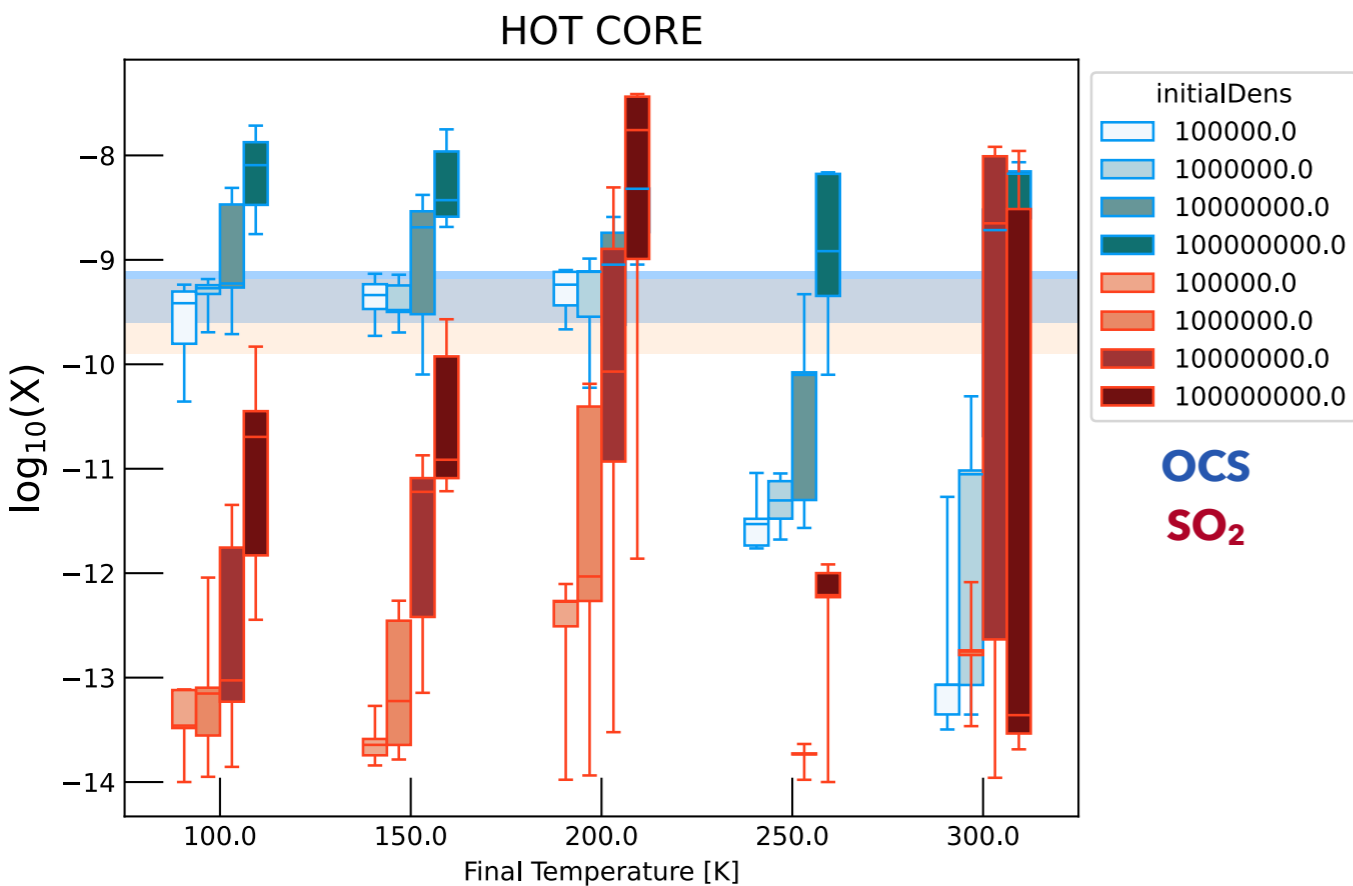
Ratio reproduced at T=200 K and
 300 K for $n \geq 10^7 \text{ cm}^{-3}$

Comparing observation with chemical modelling

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SO₂ abundances only reproduced for $n \geq 10^8 \text{ cm}^{-3}$ for all T or for T=200 & 300K with $n \geq 10^7 \text{ cm}^{-3}$

Hot core scenario suitable at T=200K & 300 K for $n \geq 10^7 \text{ cm}^{-3}$

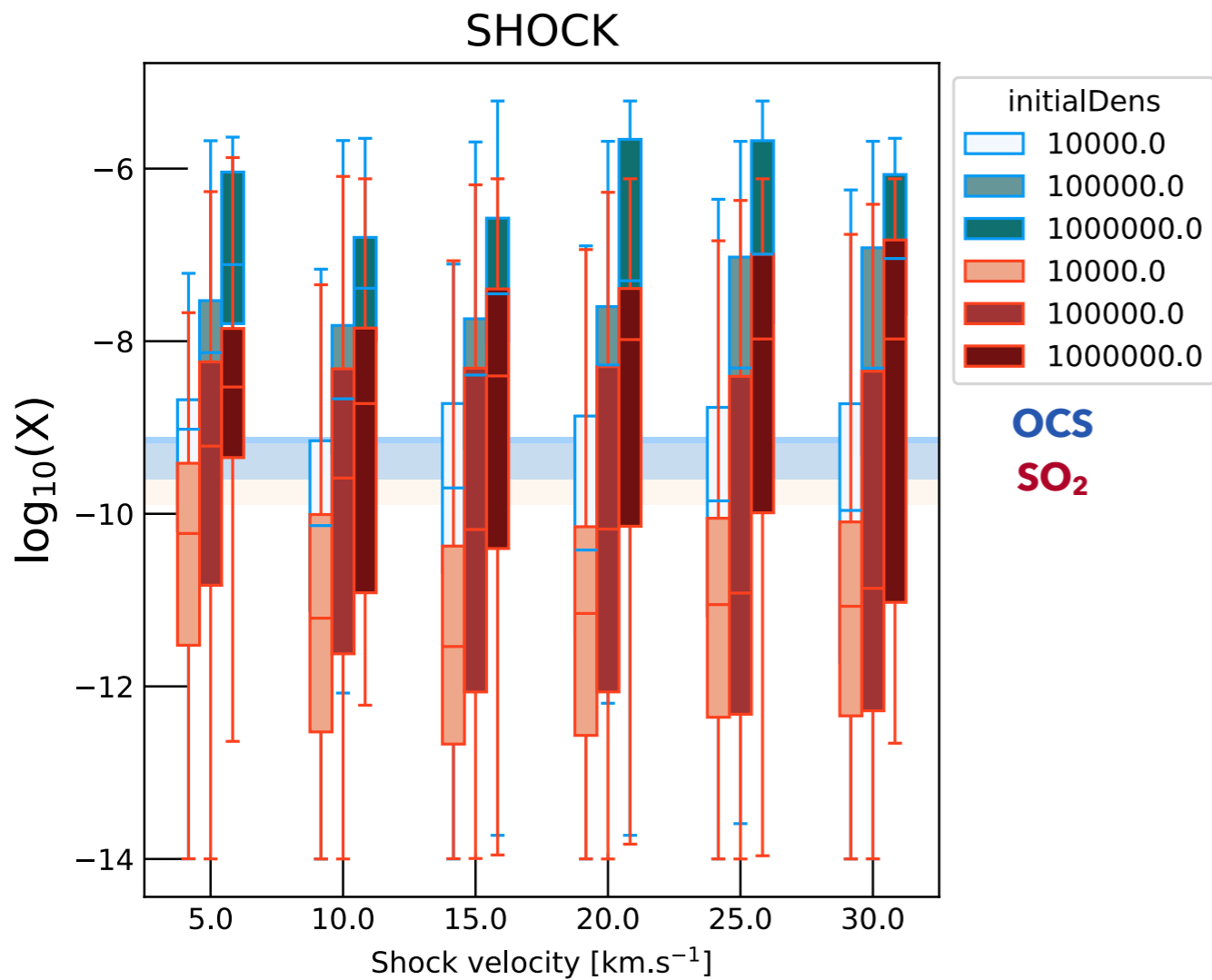
Ratio reproduced at T=200 K and 300 K for $n \geq 10^7 \text{ cm}^{-3}$

Comparing observation with chemical modelling

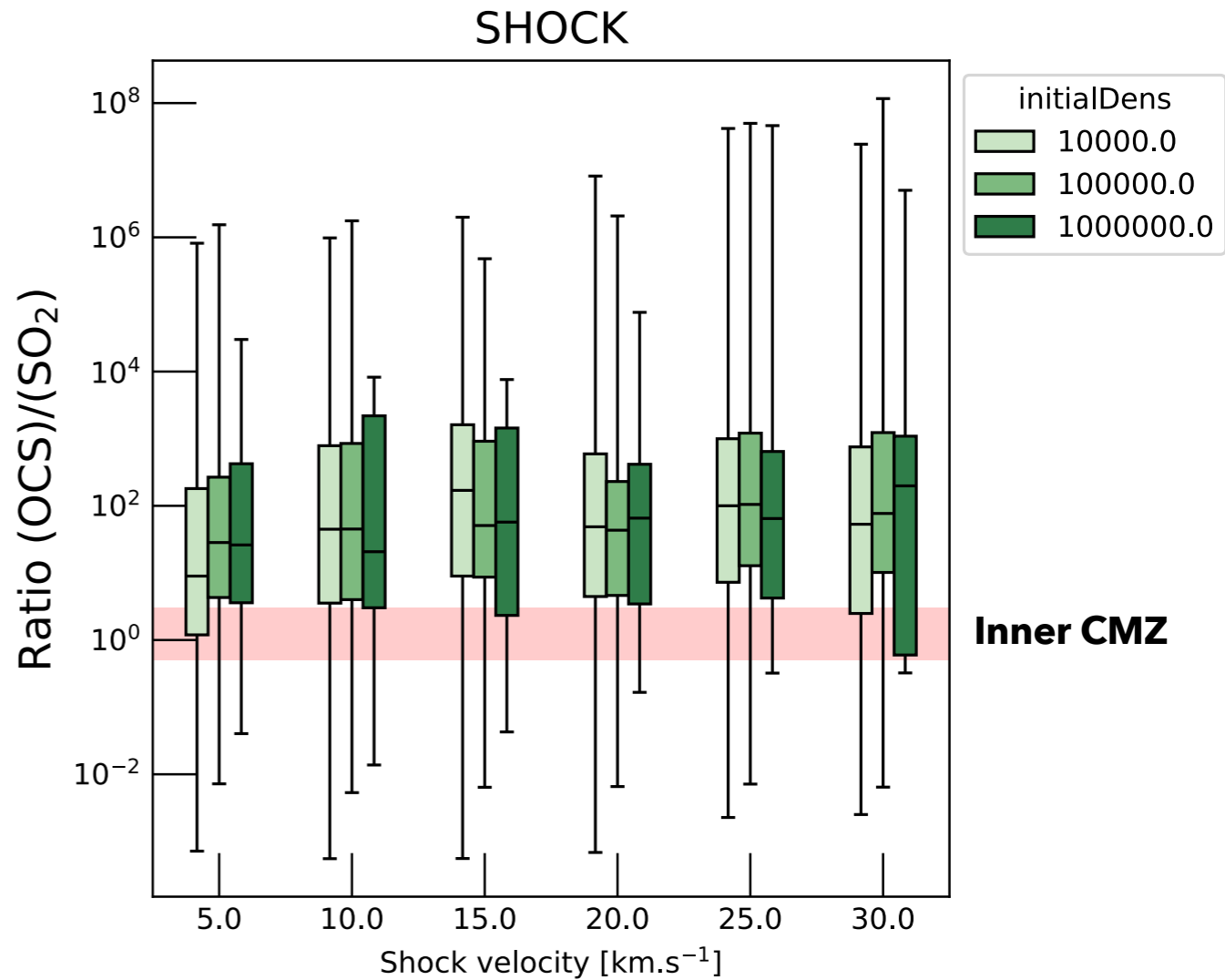
A few examples: OCS(high-J)/SO₂

Observed ratio OCS (high-J)/SO₂: 0.5-3
 Observation conclusion: shock or hot core

Observation constrains:
 Results for T ≤ 300 K



Both SO₂ and OCS abundances are reproduced, for all models



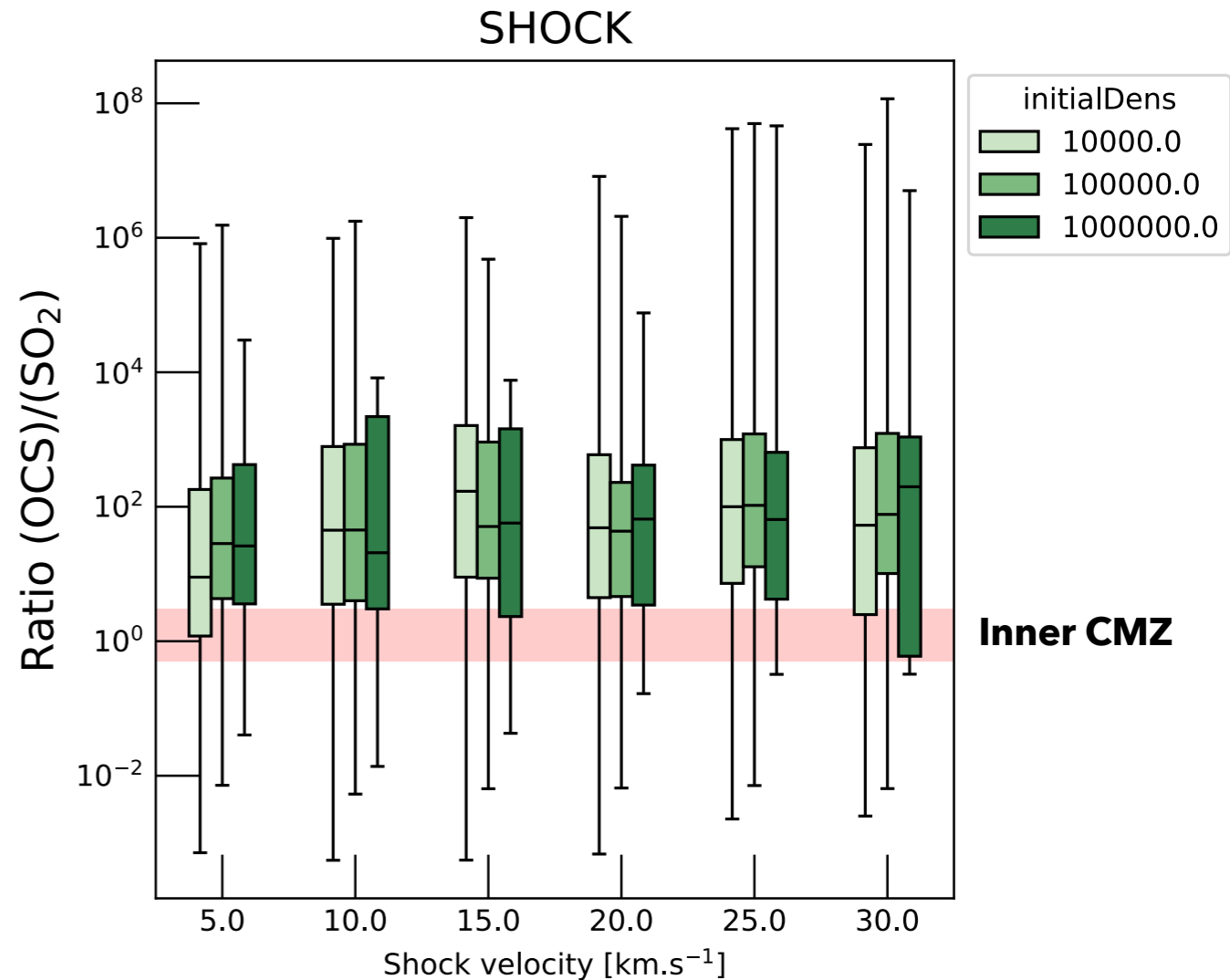
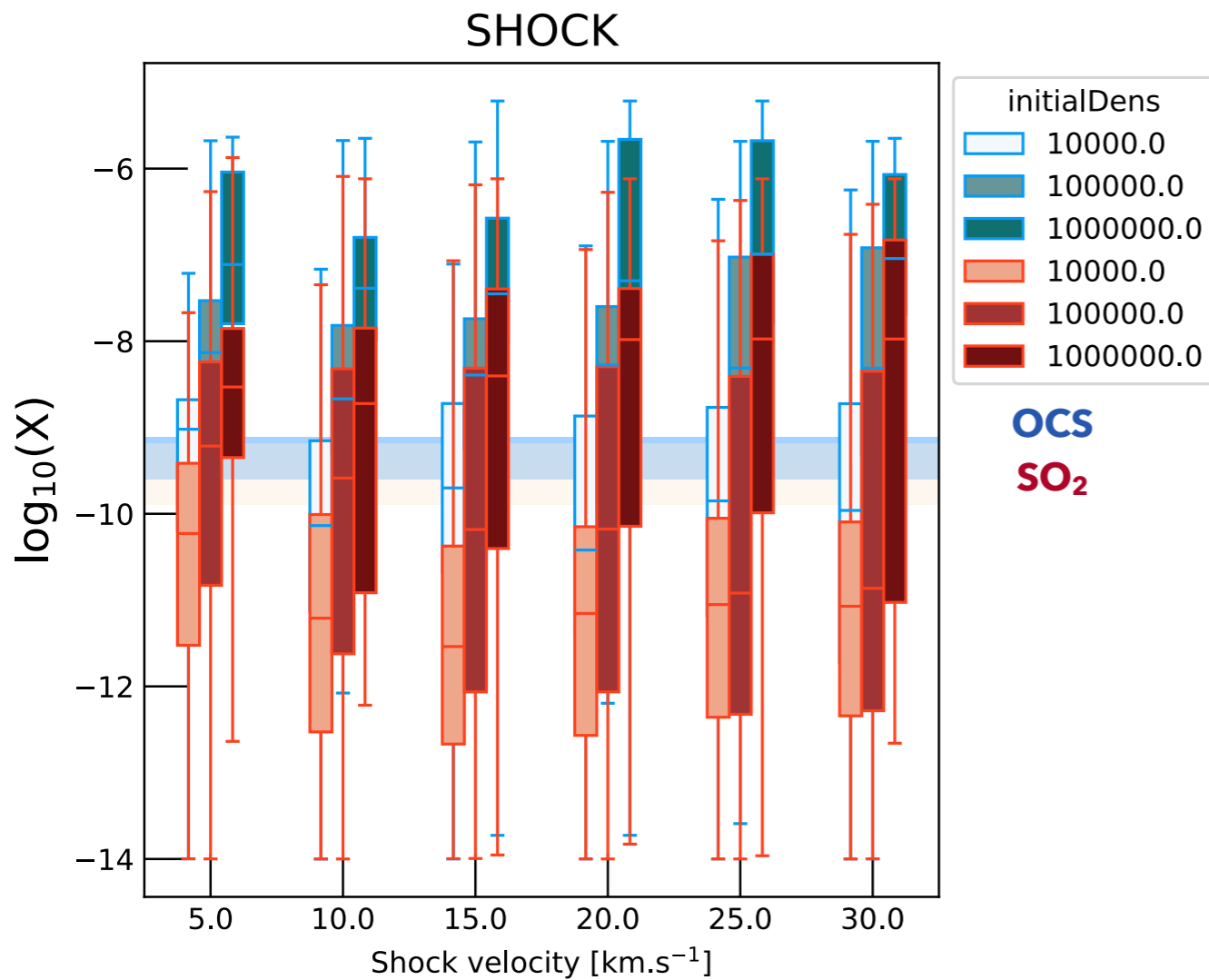
Statistically, ratio always reproduced

Comparing observation with chemical modelling

A few examples: OCS(high-J)/SO₂

Observed ratio OCS (high-J)/SO₂: 0.5-3
 Observation conclusion: shock or hot core

Observation constrains:
 Results for T ≤ 300 K



Both SO₂ and OCS abundances are reproduced, for all models

The shock scenario is also suitable

Statistically, ratio always reproduced

Next step: Improving the grid



Run a grid more specific to the CMZ of NGC 253

Next step: Improving the grid



Run a grid more specific to the CMZ of NGC 253

Current grid:

Stage II: $10M_{\odot}$ \rightarrow change to $60M_{\odot}$ (Max possible) since SF more intense towards NGC 253
No sulphur depletion \rightarrow factor of 10 (minimum depletion factor in galactic SFRs)

Next step: Improving the grid



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Current grid:

Stage II: $10M_{\odot}$ \rightarrow change to $60M_{\odot}$ (Max possible) since SF more intense towards NGC 253
No sulphur depletion \rightarrow factor of 10 (minimum depletion factor in galactic SFRs)

Hot core

Final Temp (K): **50 to 300, steps of 50**

Initial density (cm^{-3}): $10^5 - 10^8$

Shock

Both C- and J-type

Velocity (km.s^{-1}): **5, 15, 30, 45**

Initial density (cm^{-3}): $10^4 - 10^6$

B_0 (μG): **values from literature**

($B_0 \geq 100 \mu G$; *Yoast-Hull+2013; Konishi et al. 2022*)

Other parameters:

$\zeta_{cr} (\times \zeta_0) = 1000, 10000$

Rad. Field ($\times G_0$): **100**

Initial Temperature (K): **15, 30**

Next step: Improving the grid



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Current grid:

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Stay tuned!

Next step: Improving the grid



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Rad. Field ($\times G_0$): **100**

Initial Temperature (K): **15, 30**

Stay tuned!

Thanks for your attention



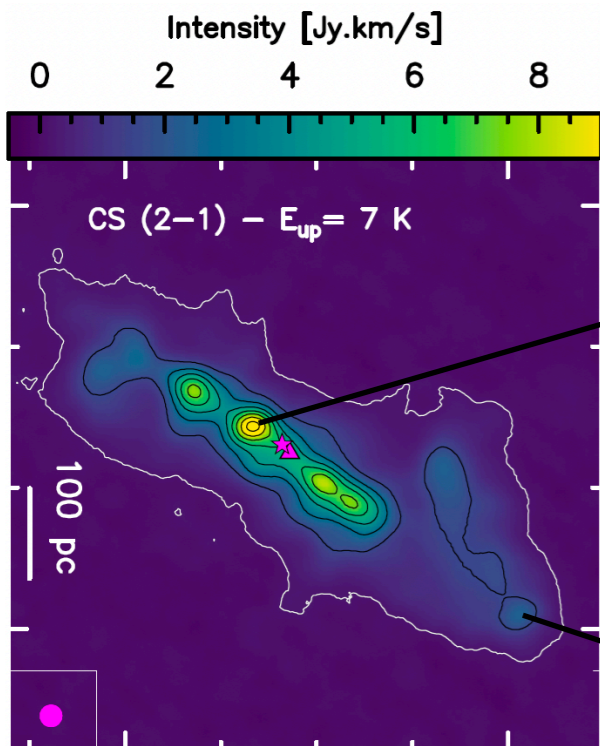
Back-up slides

Physical parameters

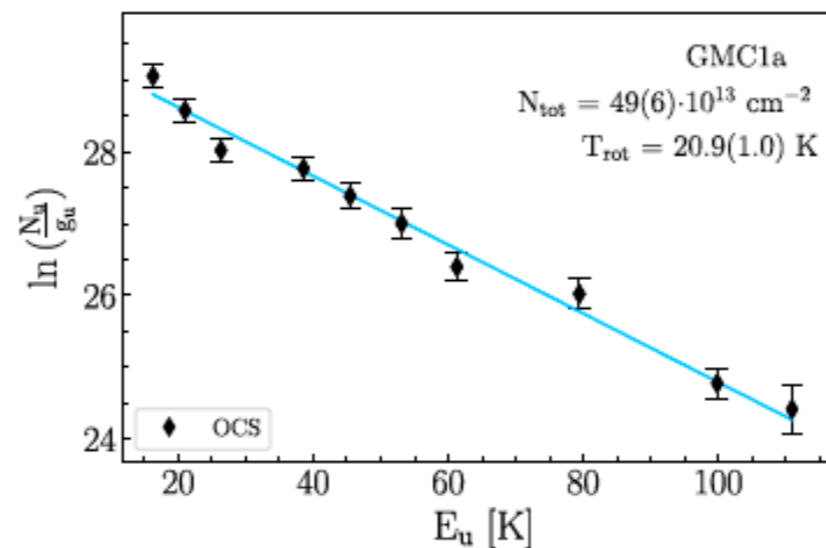
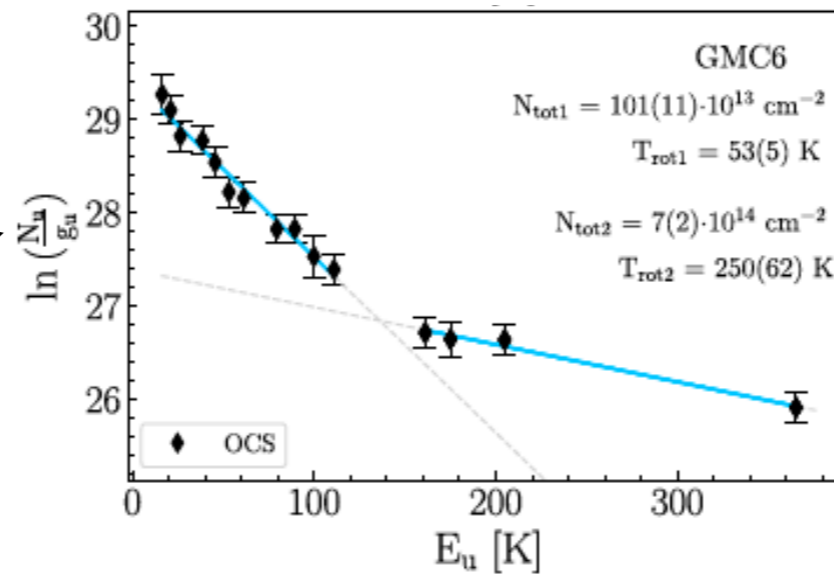
Step 1: Rotation diagrams

Step 2: Non-LTE Large Velocity Gradient (LVG) analysis using GRELVG (Ceccarelli+2003)

Except for CCS, SO₂ and OCS (for J>13)



Example: OCS



Second gas component in the inner CMZ for most species

Consistent with shift in velocity peak/FWHM between low-J and higher J lines

Comparing observation with chemical modelling



Holdship et al. 2017

In house open-source gas-grain chemical code: UCLCHEM

Main collaborators: K. Dutkowska & S. Viti

Models tested: hot core (pre-warmup + hot core) and C-shock (shock +postshock)

Comparing observation with chemical modelling

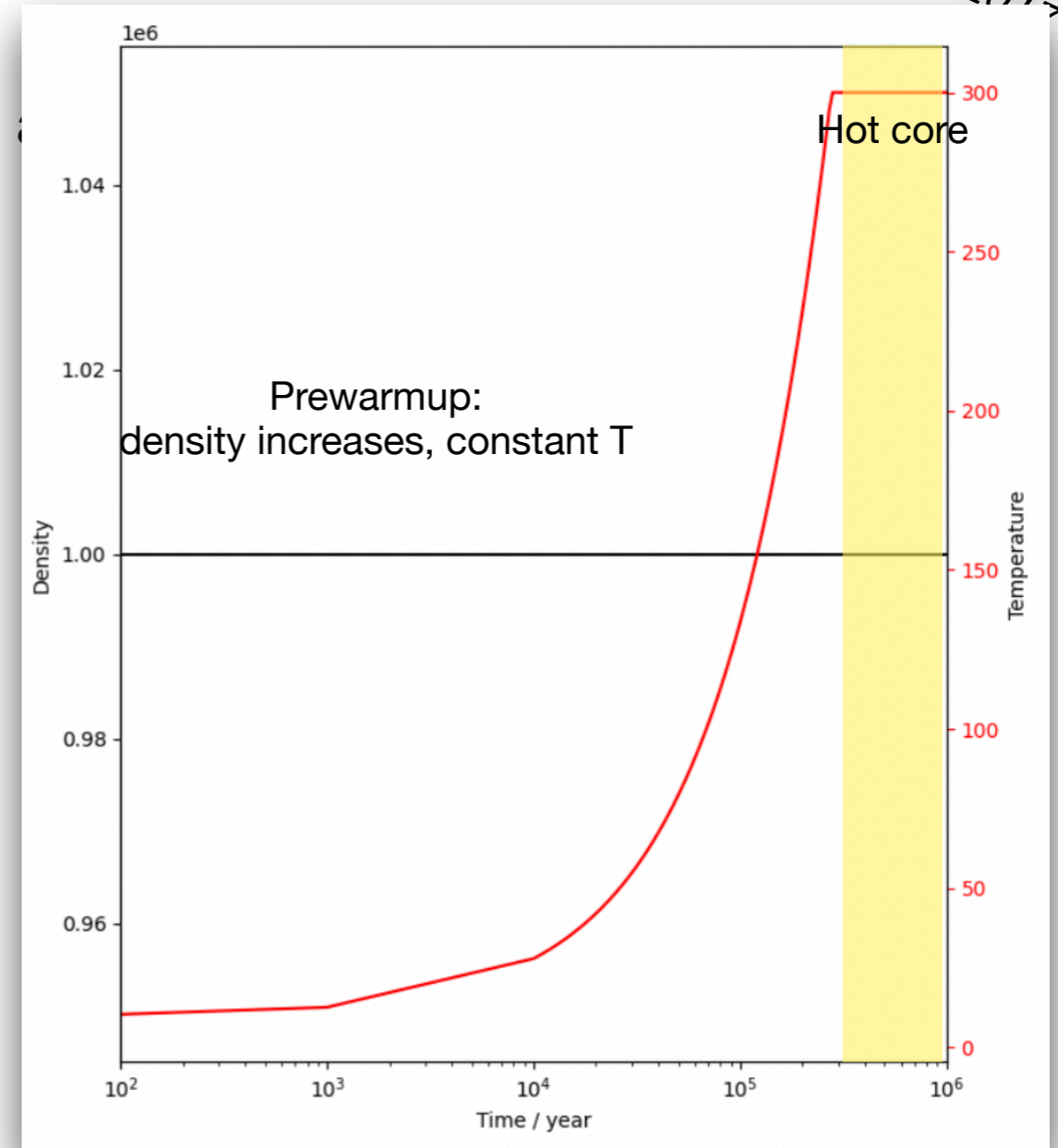


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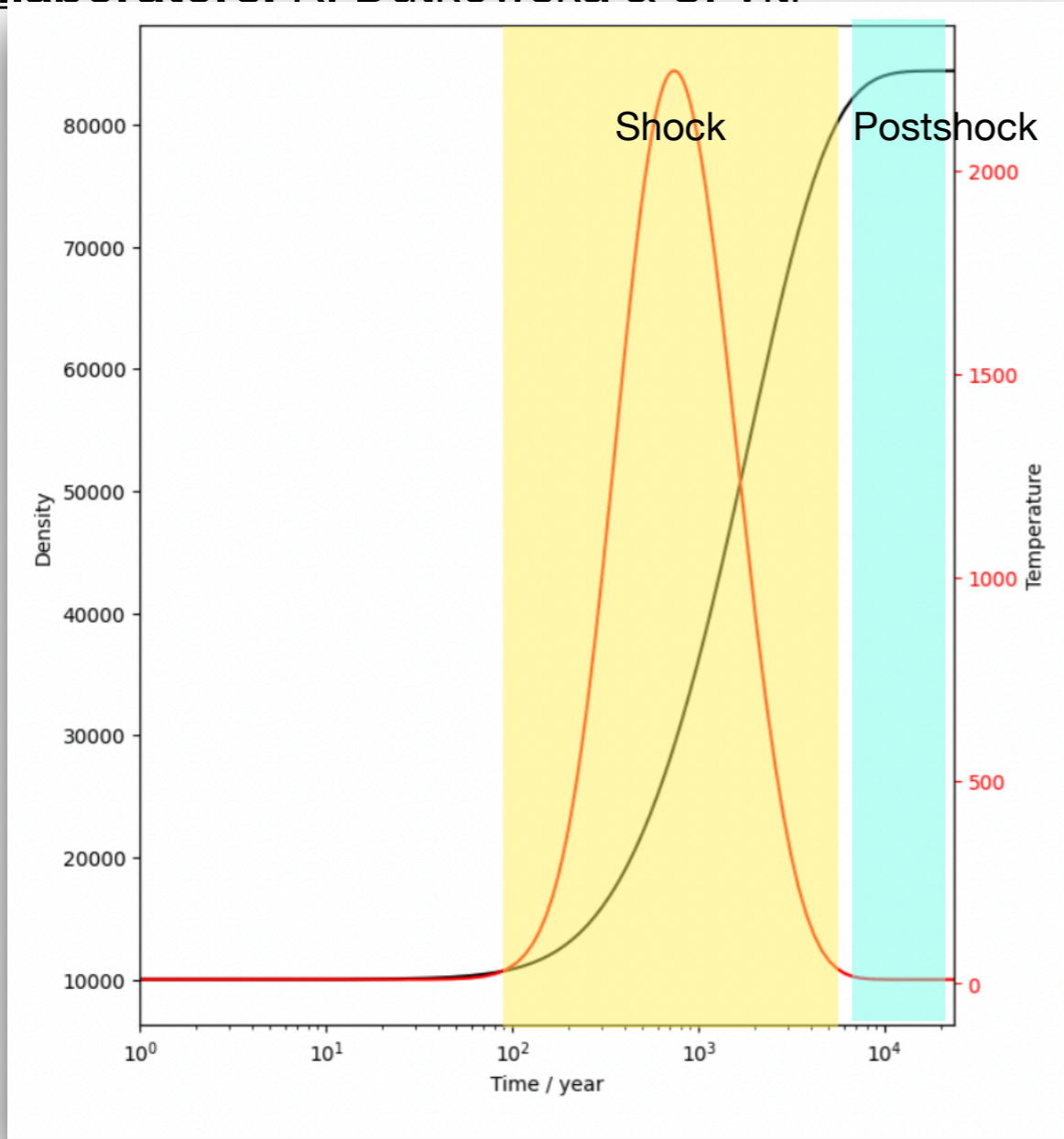


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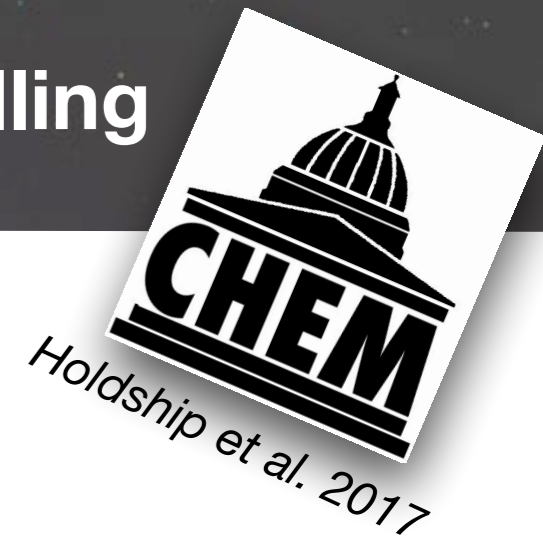
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Main collaborators: K. Dutkowska & S. Viti

Models tested: hot core (pre-warmup + hot core) and C-shock (shock + postshock)

Hot core

Final Temp (K): **50., 100., 150., 200., 250., 300., 350., 400., 450., 500., 550.**

Initial density (cm^{-3}): $10^5 - 10^8$

Shock

Velocity (km.s^{-1}): 5, 10, 15, 20, 25, 30

Initial density (cm^{-3}): $10^4 - 10^6$

B0 (μG): 10, 100, 1000

CR NGC 253: $\geq 10^{-14} \text{s}^{-1}$

Measured gas Temp: $\leq 300 \text{ K}$

Other parameters:

$\zeta_{cr} (\times \zeta_0) = 10, 100, \mathbf{1000}, \mathbf{10000}$

Rad. Field ($\times G_0$): 100, 1000

Initial Temperature (K): 15, 20, 25, 30, 35