Accretion of Jupiter's Atmosphere from a Supernova-Contaminated Molecular Cloud

Henry Throop

Department of Space Studies

Southwest Research Institute (SwRI)

Boulder, Colorado

John Bally

University of Colorado

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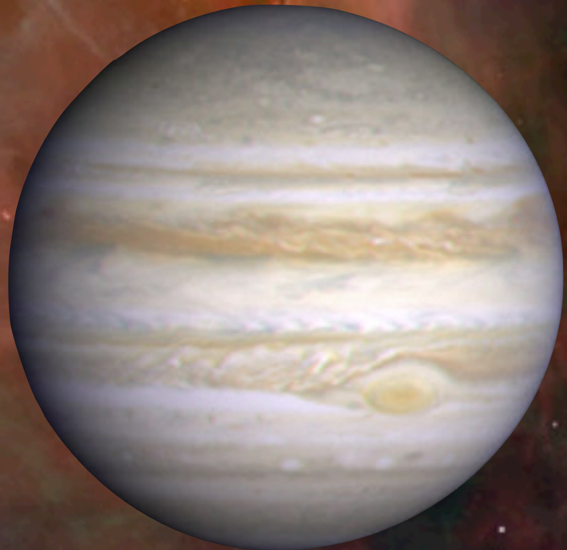
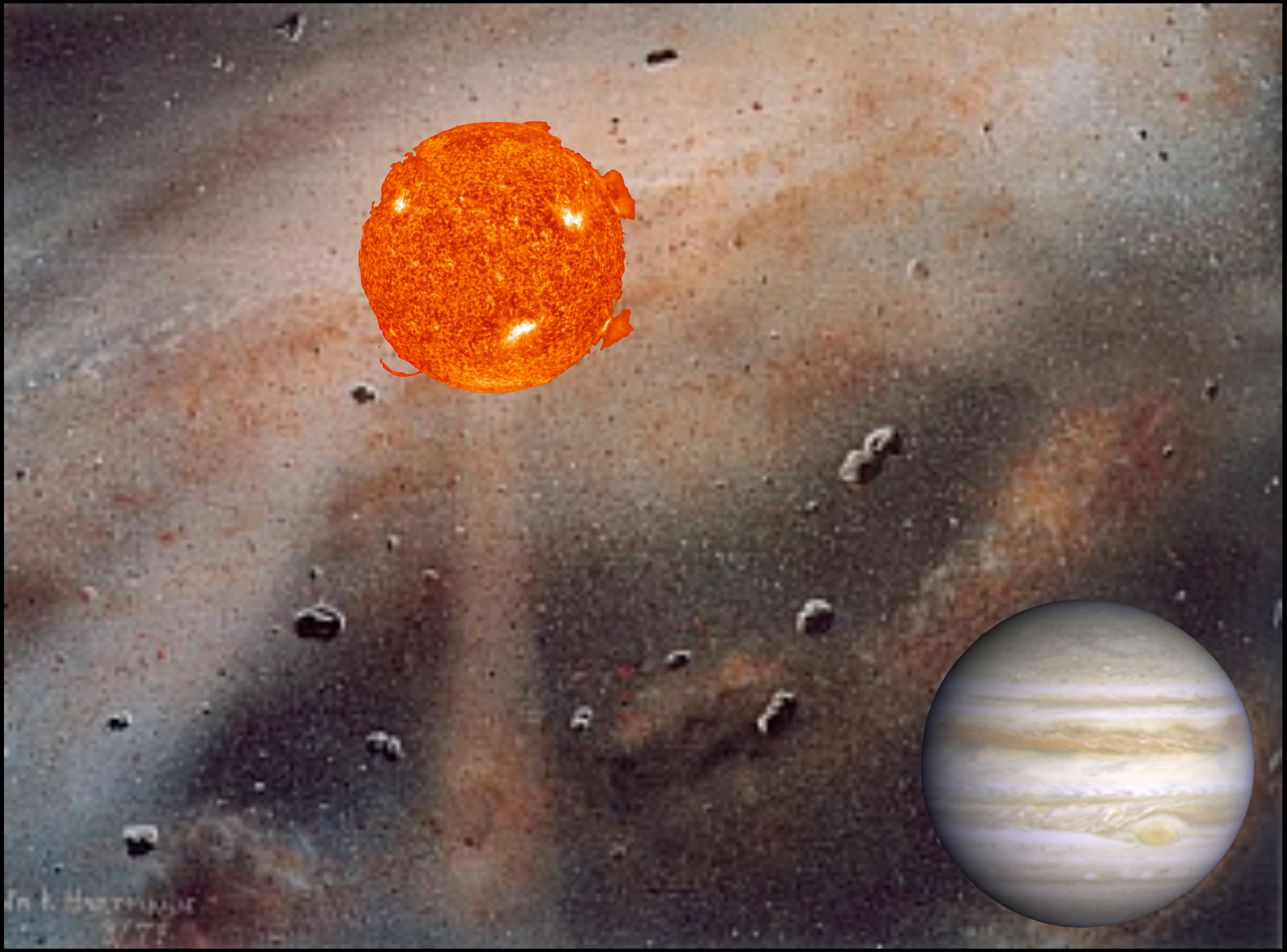
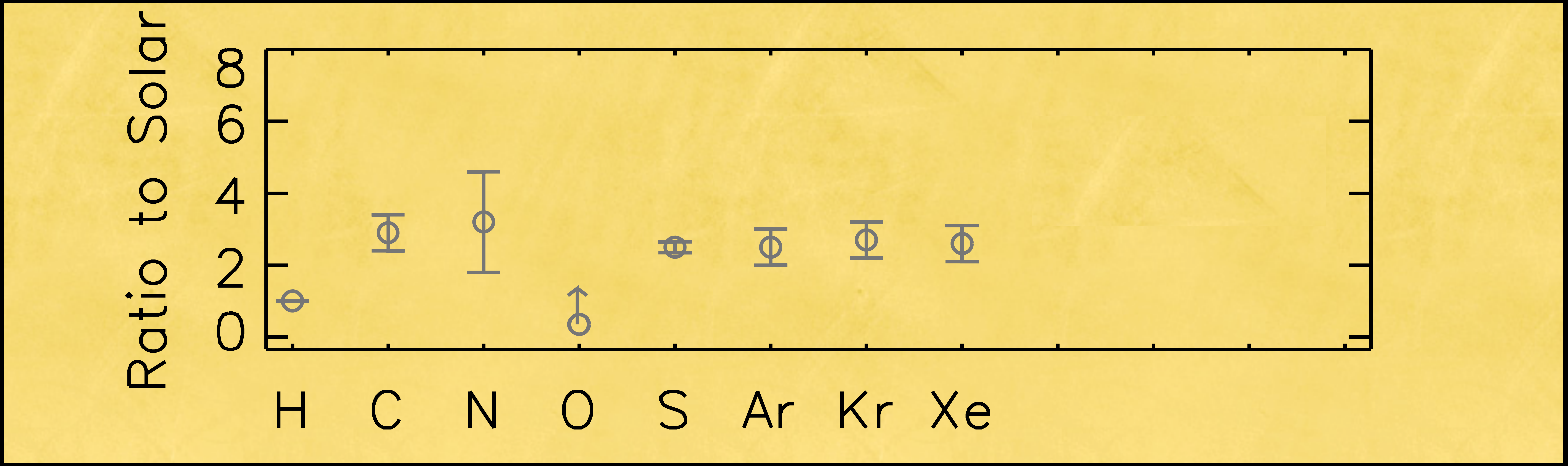




Jupiter:Solar abundances



Enriched by 3±1× (Anders & Grevesse 1989 Solar abundances)

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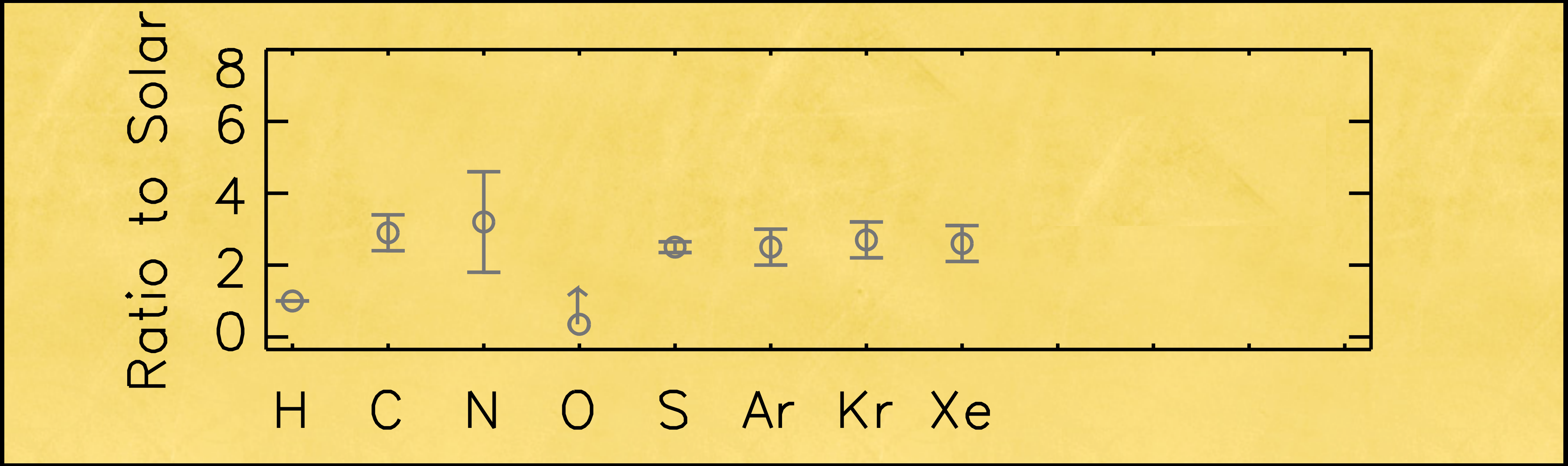

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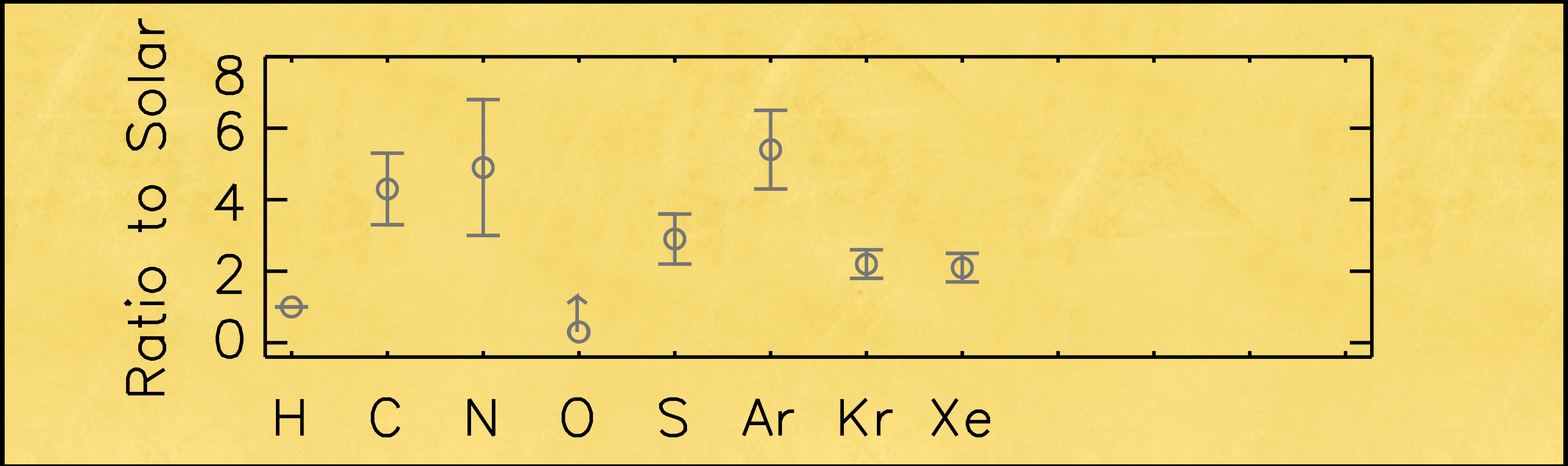


Enriched by 4±2× (Grevesse 2005 Solar abundances)

Jupiter Atmospheric Formation Models

- Existing models to enhance Jupiter's metals
  - Condense the species in extremely cold, 30K solar nebula
  - Then concentrate these
  - Then heat and release at Jupiter
    - Owen *et al*, Hersant *et al*, Guillot et al, Alibert *et al*

- Problem with these models:
  - 30K is a very cold disk!
    - ISM itself is 20-50K (e.g., Bally *et al* 1991)
  - Models generally predict similar enhancement factors for all species (~3×, *not* 2-6×).
  - For clathrate hydrates, condensation requires grains to stay tiny for many Myr.

Jupiter 'Polluted Accretion' model

We propose instead:

1. Solar System forms in a large star cluster.

   N > 1000 stars: consistent with ^{60}Fe.

2. Massive stars pollute ISM with heavy elements.

   SNs and massive stellar winds convert H ➔ C, N, S, etc.

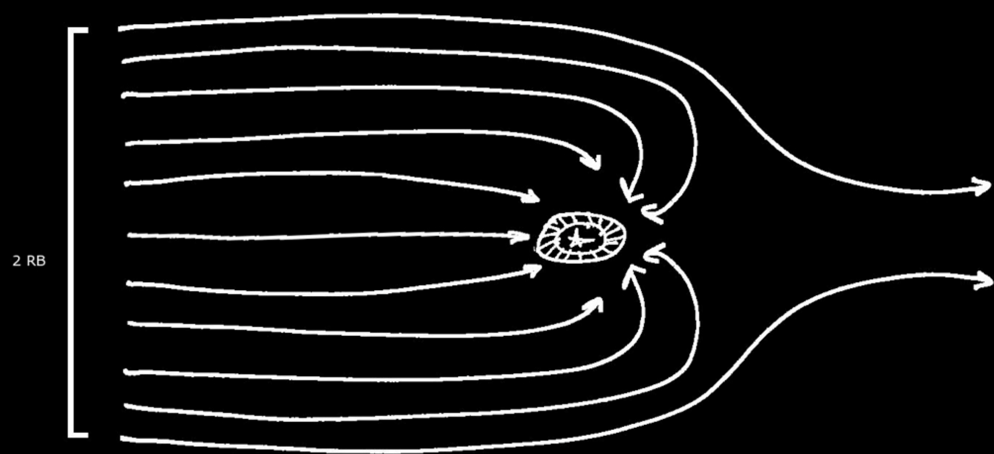
3. 'Pollution' from massive stars is accreted onto Jupiter.

   Accretion from ISM ➔ Solar Nebula Disk ➔ Jupiter (Throop & Bally 2008)

   Easier to enrich disk's metallicity than the Sun's

ISM → Disk Accretion

Accretion from ISM can change relative composition of Sun, Disk



- ISM can accrete onto the disk after disk formation.
- Accretion rate ~ 1 MMSN / Myr
- It is easier to accrete onto the disk than onto Sun
  ➔ The disk get polluted and the Sun does not!

- Throop & Bally 2008 (*AJ* 135)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"TAIL-END" BONDI–HOYLE ACCRETION IN YOUNG STAR CLUSTERS: IMPLICATIONS FOR DISKS, PLANETS, AND STARS

Henry B. Throop[1] and John Bally[2]
[1] Southwest Research Institute, Department of Space Studies, 1050 Walnut St, Ste 300, Boulder, CO 80302, USA; throop@boulder.swri.edu
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ABSTRACT

Young stars orbiting in the gravitational potential well of forming star clusters pass through the cluster's dense molecular gas and can experience Bondi–Hoyle accretion from reservoirs outside their individual protostellar cloud cores. Accretion can occur for several million years after the stars form, but before the cluster disperses. This accretion is predominantly onto the disk and not the star. N-body simulations of stars orbiting in three young model clusters containing 30, 300, and 3000 stars are presented. The simulations include the gravitational potential of the molecular gas which smoothly disperses over time. The clusters have a star-formation efficiency of 33% and a radius of 0.22 pc. We find that the disks surrounding solar-mass stars in the $N = 30$ cluster accretes $\sim 0.01\ M_\odot$ (1 minimum-mass solar nebula, MMSN) per Myr, with a 1σ width of 50 times due to variations in initial stellar positions and velocities within the cluster. The accretion rate scales as $M^{2.1\pm0.1}$ for stars of mass M. The accretion rate is ~5 times lower for the $N = 3000$ cluster, due to its higher stellar velocities and higher temperature. The Bondi–Hoyle accretion rates onto the disks are several times lower than accretion rates observed directly onto young stars (e.g., Muzerolle et al. 2005): these two accretion rates follow the same M^2 behavior and may be related. The accreted disk mass is large enough that it may have a substantial and unappreciated effect on disk structure and the formation of planetary systems. We discuss a variety of implications of this process, including its effect on metallicity differences between cluster stars, compositional differences between a star and its disk, the formation of terrestrial and gas-giant planets, and isotopic anomalies observed in our solar system.

Key words: ISM: kinematics and dynamics – planetary systems: formation – planetary systems: protoplanetary disks – solar system: formation – stars: formation

Online-only material: color figure

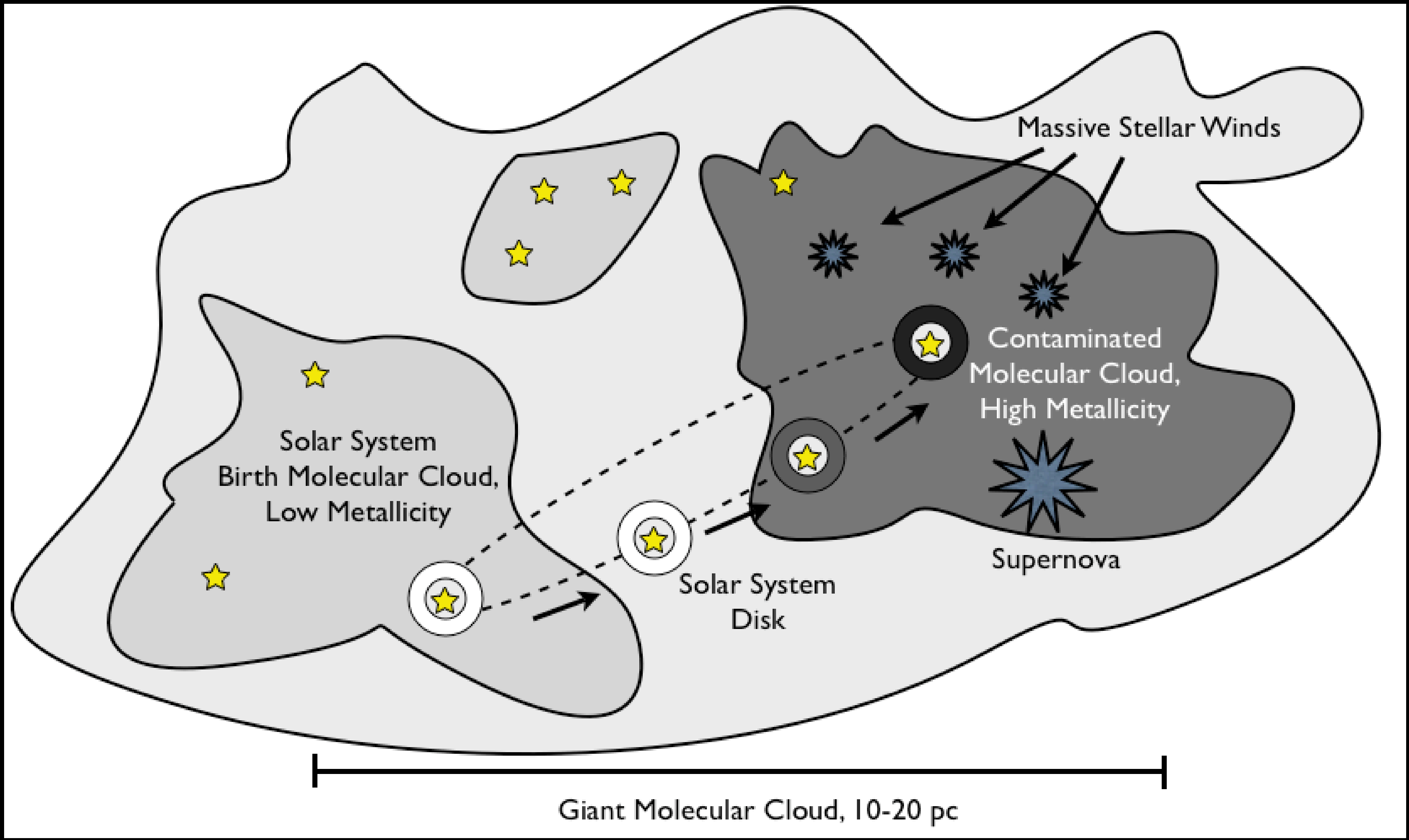
1. INTRODUCTION

Stars form from the collapse of dense cores in giant molecular clouds (GMCs). While some stars form in relative isolation or in small groups, the majority of stars in the solar neighborhood appear to be born in transient clusters containing hundreds or thousands of members (e.g., Adams et al. 2006; Lada & Lada 2003). Dense cores have masses ranging from under $1\ M_\odot$ to over $10^4\ M_\odot$ for the most massive cluster-forming environments. Self-gravity and efficient cooling by dust and molecular line radiation leads to collapse and fragmentation. The timescale for the birth of an isolated star can be estimated by considering the accretion rate onto a protostar from an isothermal sphere: $\tau_{acc} \sim M/\dot{M} \approx GM/c_s^3$, where M is the final stellar mass and c_s is the effective sound speed in the core. Assuming a $1\ M_\odot$ star in a cloud with $c_s = 0.35$ km s^{-1}, we find that $\tau_{acc} \approx 10^5$ yr. In contrast, the observed age spread of young stellar objects (YSOs) in clusters indicates that the formation timescale for an entire cluster is a few million years. Thus, only about 3–10% of the final population of YSOs in a cluster are expected to be in their main accretion phase (Class 0/Class I) at any time. Star formation then can be characterized by a hierarchy of at least three timescales: the 10^5 yr scale to form an individual star; the 10^6 yr to form a cluster; and the 10^7 yr timescale of an OB association. Planet formation operates on roughly comparable timescales: 10^5 yr to form meter- to kilometer-sized bodies; 10^6 yr to form planetesimals and cores (for the terrestrial and giant planets, respectively); and 10^7 yr to complete the planets (Lissauer & Stevenson 2007; Nagasawa et al. 2007; Lada & Lada 2003; Throop et al. 2001; Bally 2001; Weidenschilling 1997).

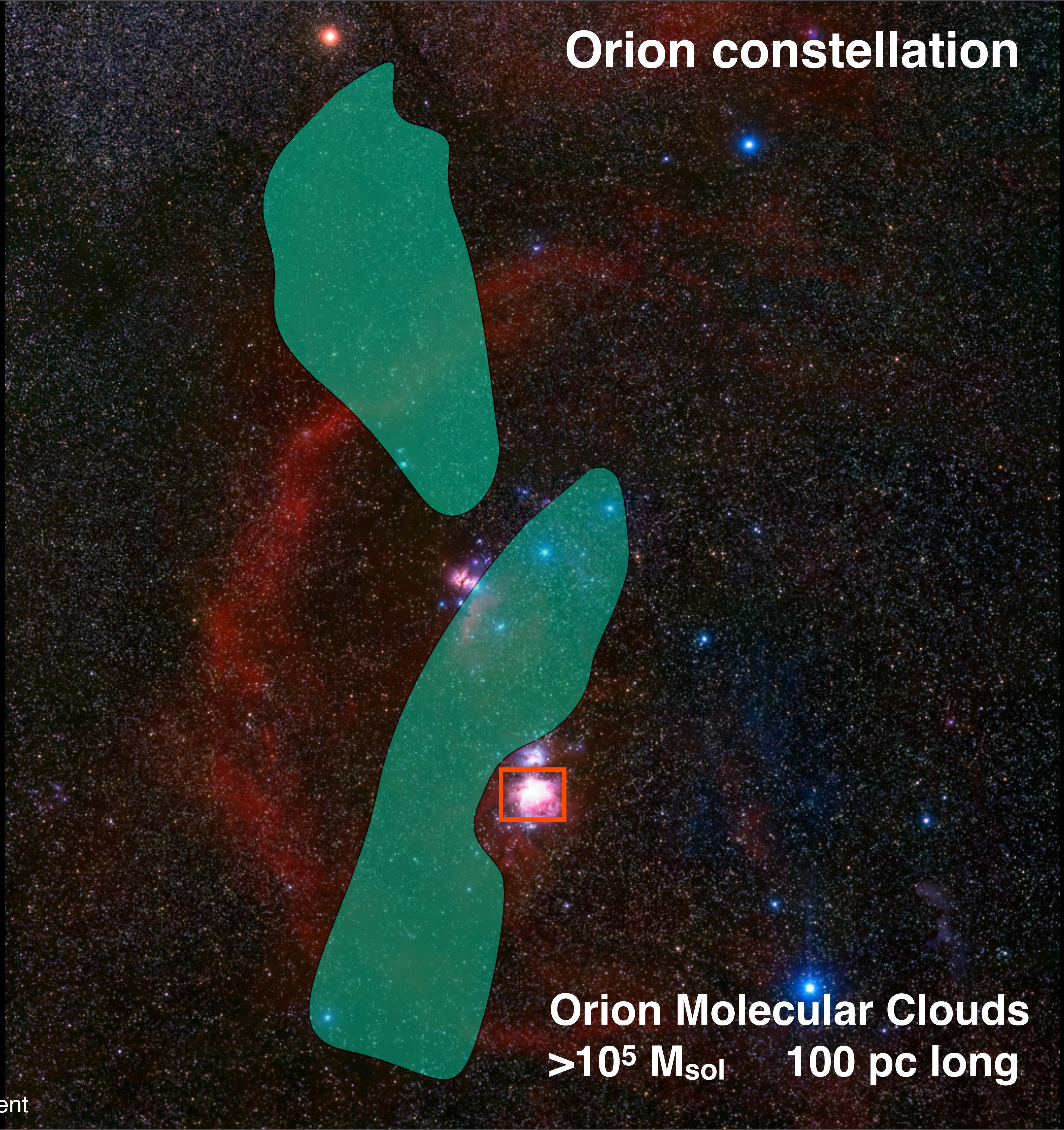
As the cluster gives birth to more stars, the oldest stars will evolve into Class II and III YSOs surrounded by protoplanetary disks. For at least a few million years, as these YSOs move through the cluster, they have a chance to accrete additional material from reservoirs of dense gas remaining in the region. Bondi–Hoyle (BH) accretion describes the rate at which material will be added to the star (Bondi 1952; Bondi & Hoyle 1944). The accretion rate is generally much less than that experienced by stars in the collapse and accretion phases of their formation: $10^{-8}\ M_\odot$ yr^{-1} versus $10^{-5}\ M_\odot$ yr^{-1} (Bate & Bonnell 2005). The total mass accreted is small compared to the star, but it can be large compared to the mass of the protoplanetary disk. Moreover, the disk intercepts material falling toward the star, so mass is deposited onto the disk and not the star. Thus, this "tail-end accretion" can have profound consequences for the evolution of very young planetary and pre-planetary systems. Because accretion scales as $\dot{M} \propto M^2$, it is likely to be most important for the larger members of a forming cluster that spend the longest time moving through dense gas.

Typical star-formation efficiency (SFE) in a cluster-forming cloud core is 10–30% (e.g., Jorgensen et al. 2007; Lada & Lada 2003). The majority of the gas is not consumed by stellar birth, but remains in the cloud for millions of years, even in the presence of ongoing star formation. For instance, dense molecular cores located as close as 0.1 pc to the ONC cluster core continue to produce stars; the OMC-1S core 90″ southwest of the Trapezium stars contains several dozen currently accreting protostars (Zapata et al. 2006). Likewise, the moderate mass cluster IC 348 in the Perseus Molecular cloud contains more than 400 young stars with an age spread of least 2.5–5 Myr (Muench et al. 2007),

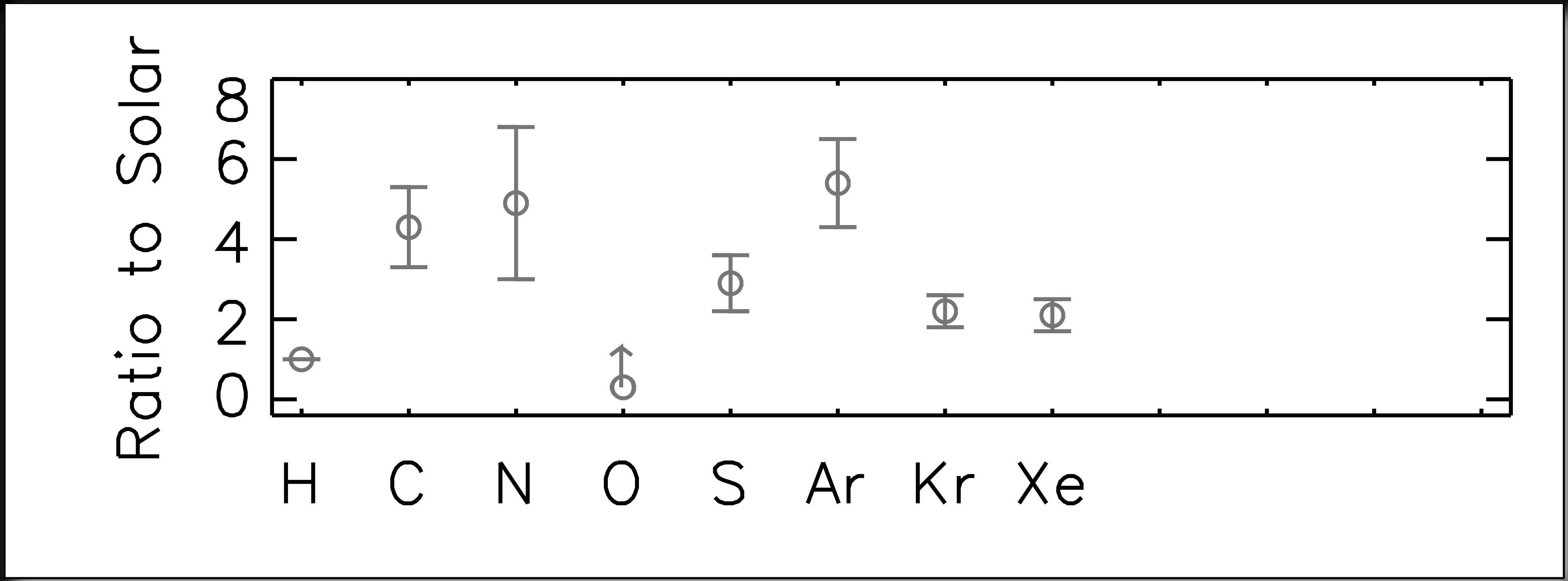
Jupiter 'Polluted Accretion' model



Stellar winds, SN are enriched 10-100× in metals.

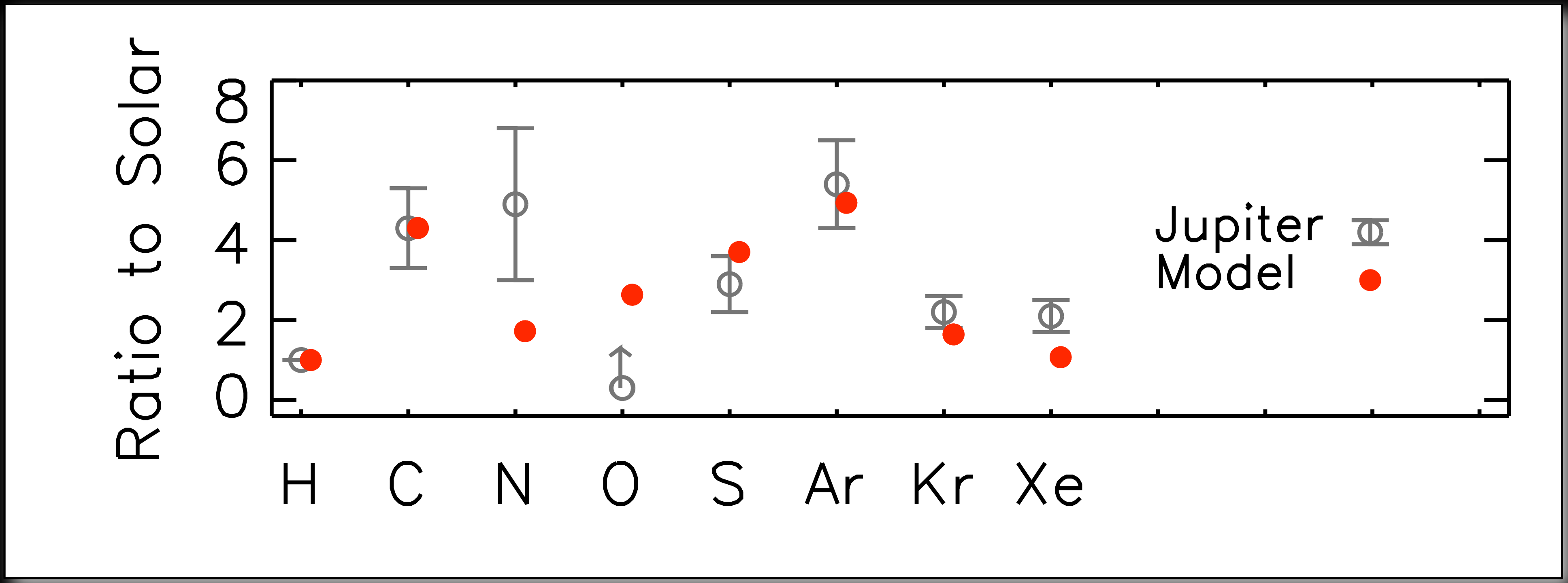

Orion constellation
Orion Molecular Clouds
$>10^5 M_{sol}$ 100 pc long

Jupiter Composition



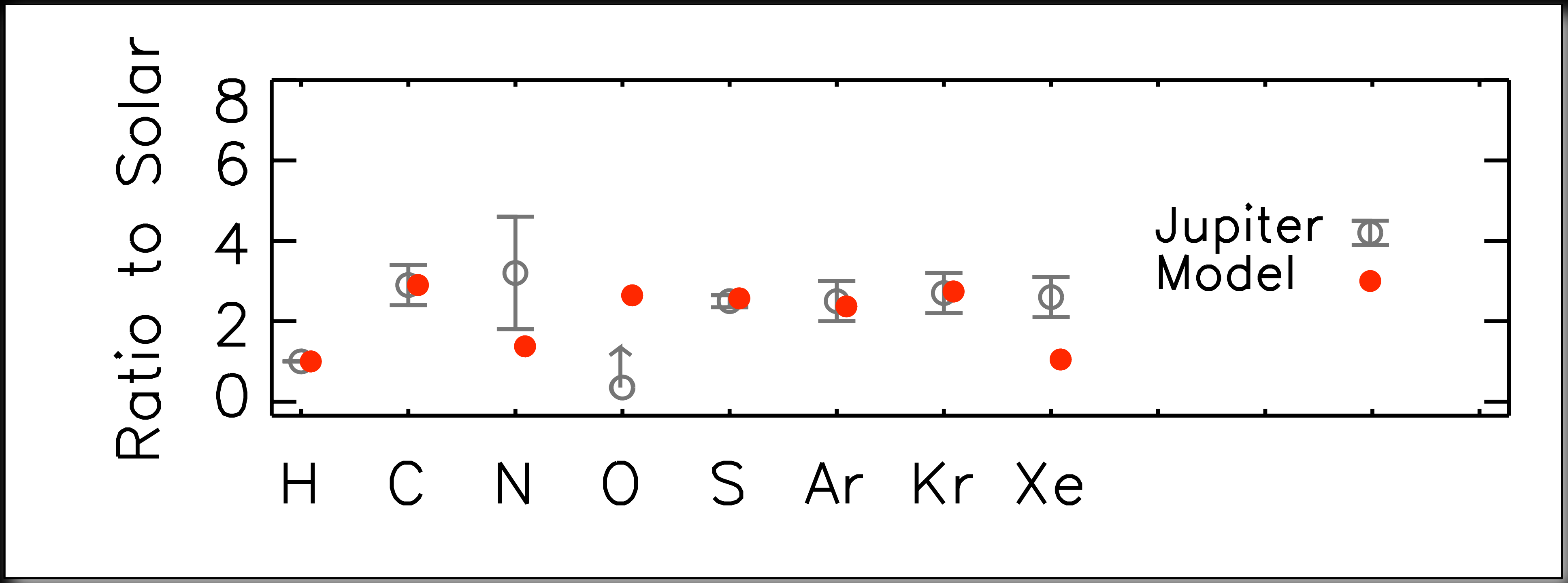
- Data: Galileo Probe

Jupiter Composition



- Data: Galileo Probe (Grevesse et al 2005 Solar abundances)
- Model: Accretion from ISM
  - 94% Solar nebula material
  - 4% Stellar winds from 40 $M_\odot$ star (provides C, N, O)
  - 1.5% SN from 25 $M_\odot$ star (provides S, Ar, Kr, Xe)
  - Requires ~0.06 M_J of accretion to explain Jupiter's enrichment
  - Stellar lifetimes of ~5-10 Myr, consistent with Jupiter formation times

Jupiter Composition



- Data: Galileo Probe (Anders & Grevesse 1989 Solar abundances)
- Model: Accretion from ISM

Jupiter 'Polluted Accretion' model

- The Solar System did not form as a closed, isolated system!

- Our model reflects current understandings of star formation
  - The ISM is readily polluted by stellar winds and SN ejecta
  - Stars have long orbits that take them through the ISM
  - Stars/disks can accrete material from the ISM (Throop & Bally 2008)

- Moreover, there is existing strong evidence for spatial / temporal variability of the proto-solar nebula
  - Isotopic heterogeneities in our Solar System (Cr, Mb, Ba, S, Ti, Zi):

> **Trinquier *et al* 2007:**
>
> "Preservation of the ^{54}Cr heterogeneity in space and time (several Myr) motivates us to speculate that **late stellar input(s) could have been significant contributions** to inner nebular Cr reservoirs..."

> **Dauphas *et al* 2002:**
>
> "'Mb isotope abundances were heterogeneously distributed in the Solar System's parental molecular cloud, and **the large-scale variations we observed were inherited from the interstellar environment where the Sun was born.**"

  - Late accretion of ^{60}Fe from SN source within ~ few pc in first few Myr
  - Metallicity differences within star clusters (Cunha, Smith)

Throop & Bally (submitted)

Throop - Jupite

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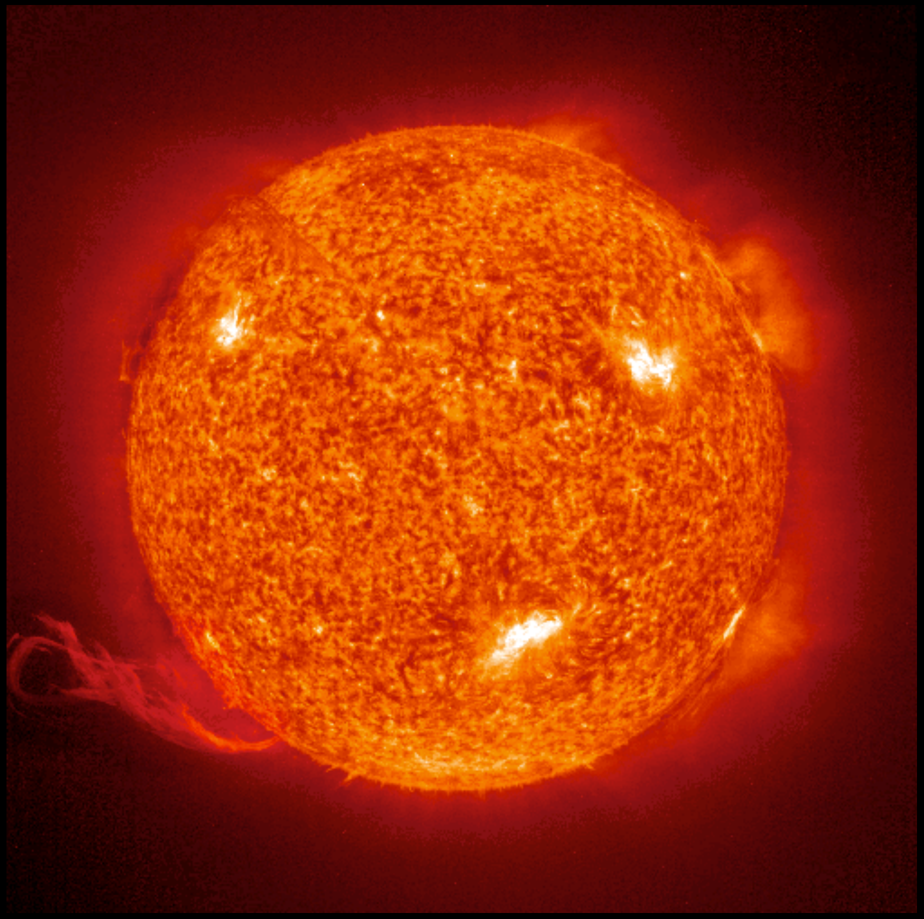

The Galileo Probe gave us a big problem:

Jupiter is enriched in heavy elements vs. the Sun.

- Enriched in C, N, S, Ar, Kr, Xe relative to H
- Original results: enriched by 3±1× (Anders & Grevesse 1989 Solar abundances)
- Newer results: enriched by 4±2× (Grevesse 2005 Solar abundances)

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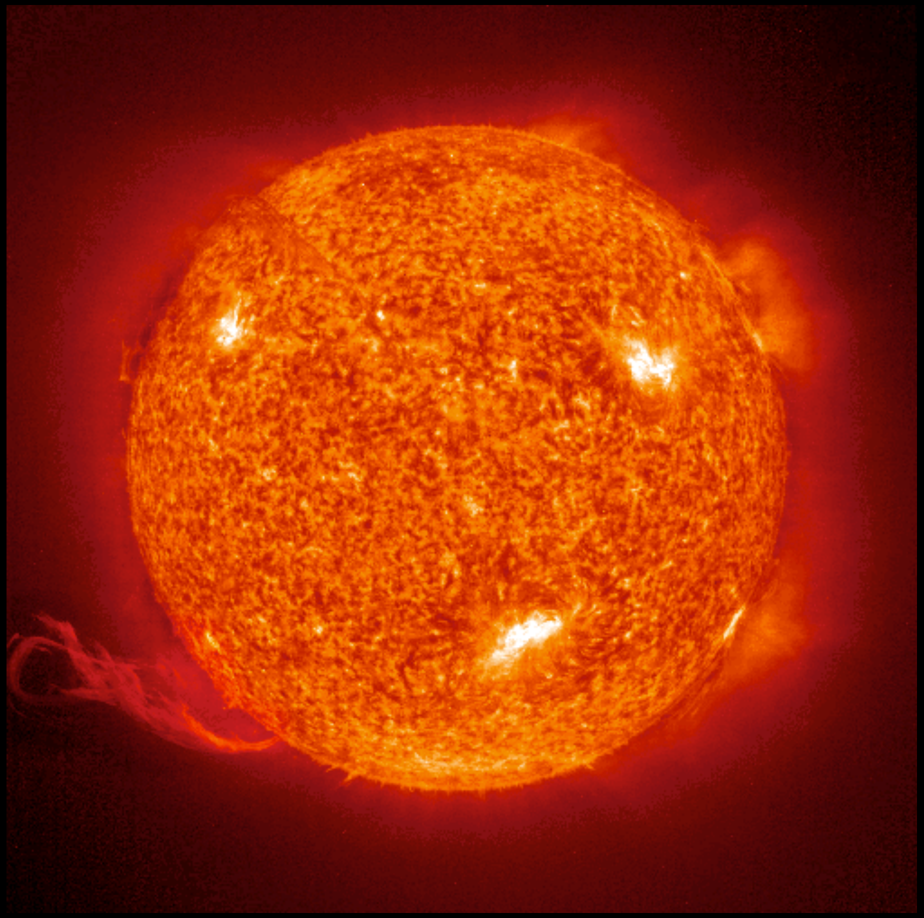

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Jupiter 'Polluted Accretion' model

Our model attempts to fit Jupiter's current composition with combination of:

1. Solar-composition material
2. Metal-enriched ejecta from massive stellar winds
3. Metal-enriched ejecta from supernovae

Ejecta from SNs stellar winds is enriched in all elements.

Jupiter vs. the Sun

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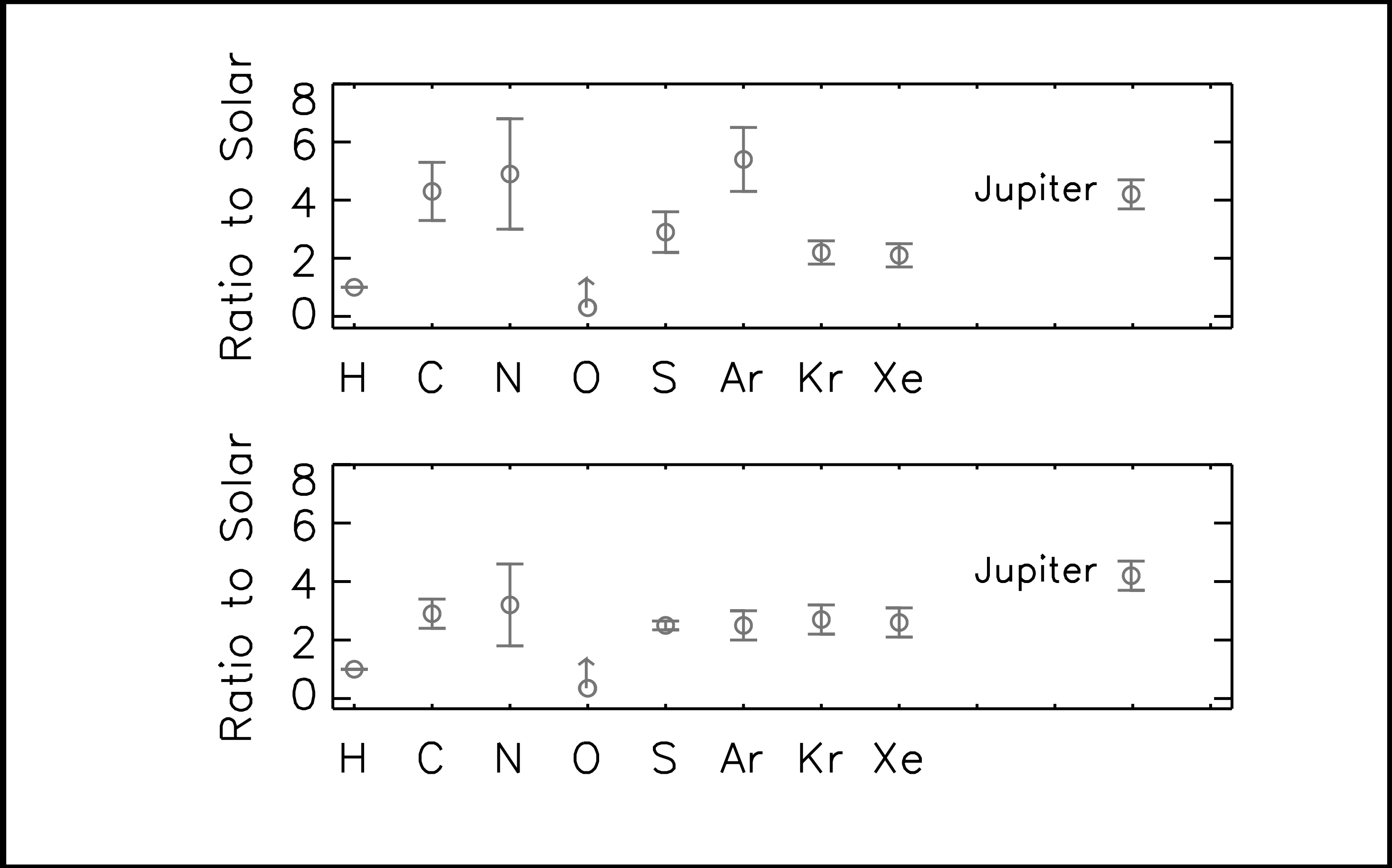
Ratio to Solar
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Ratio to Solar
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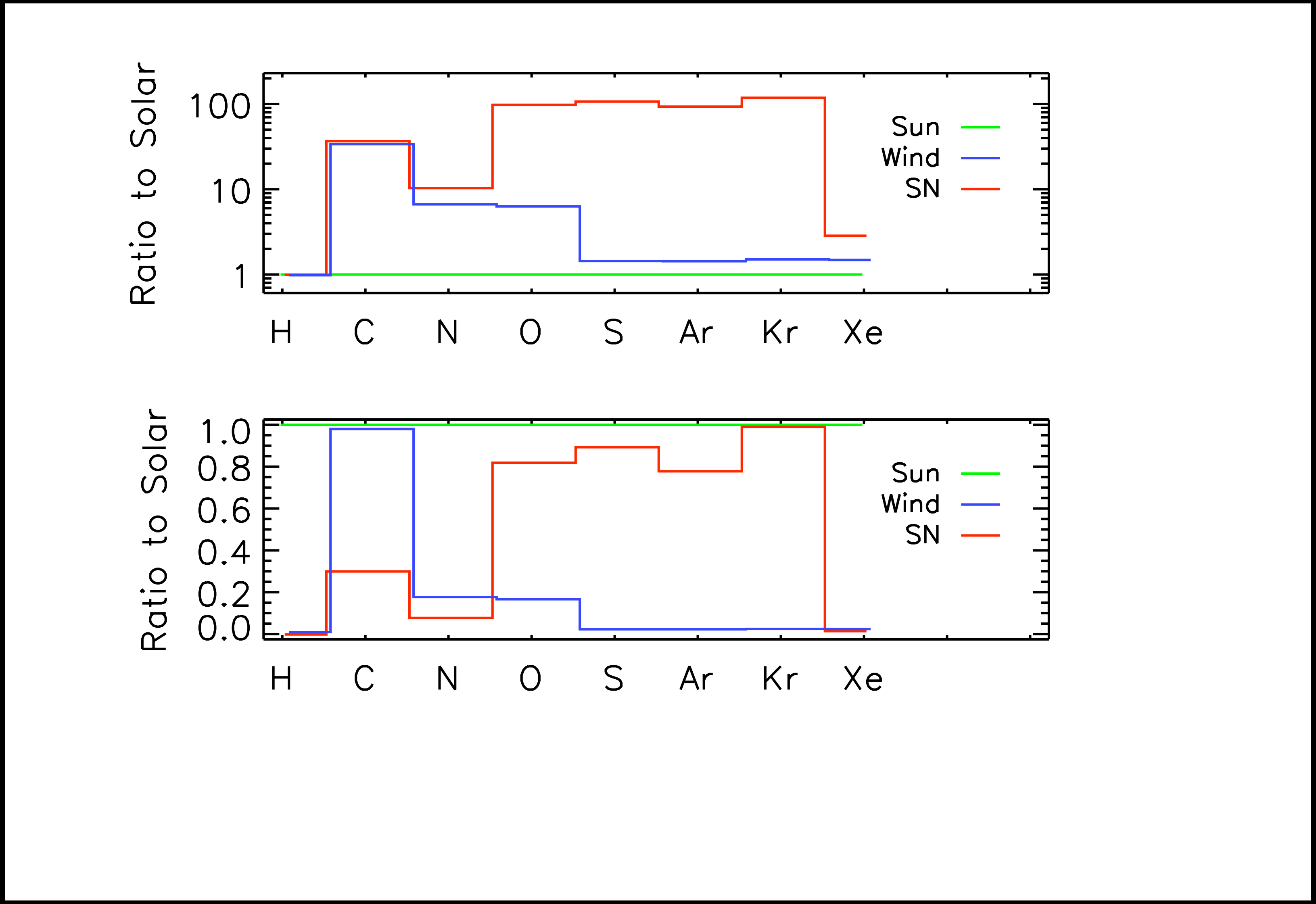
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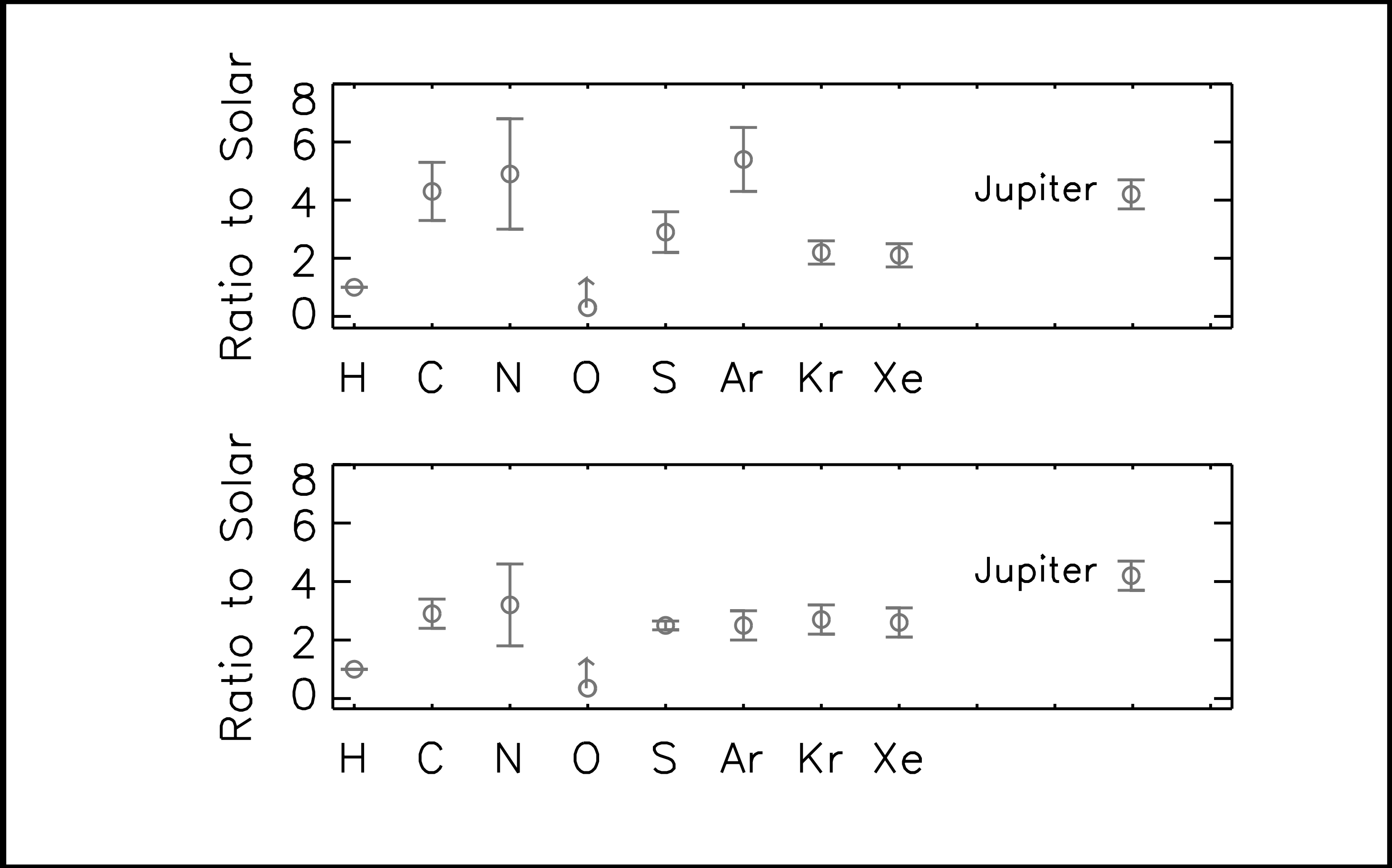
Ratio to Solar
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Ratio to Solar
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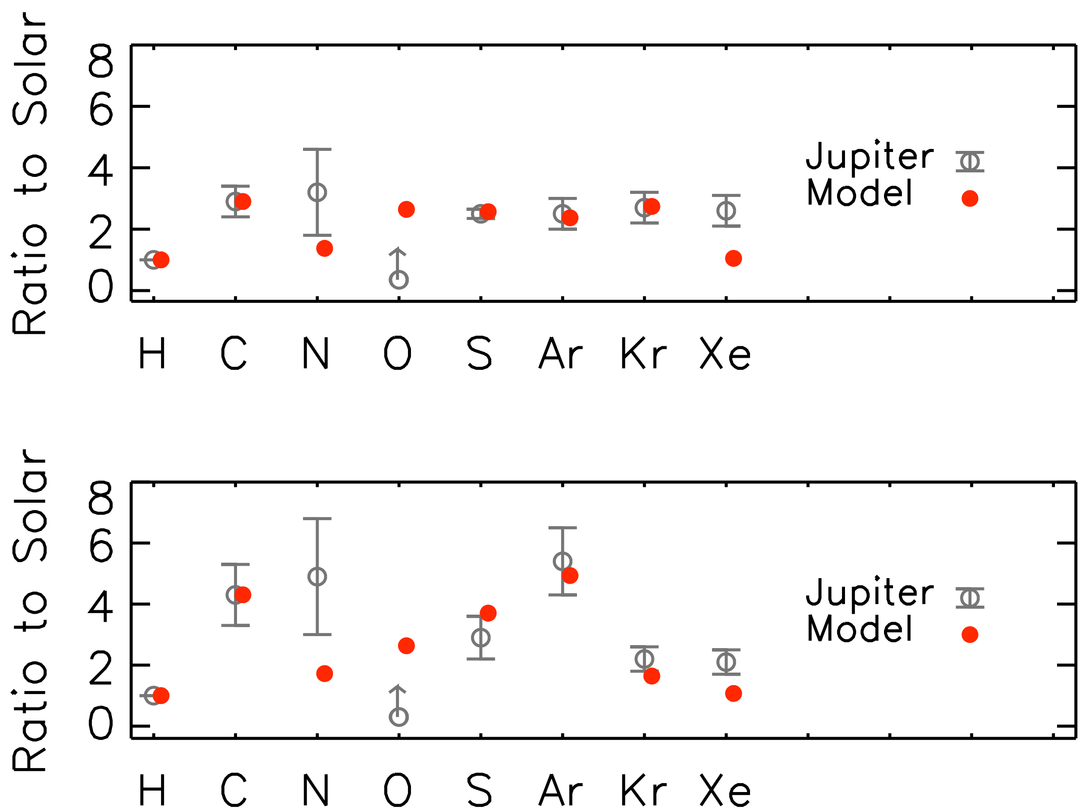

Ratio to Solar
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Ratio to Solar
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Jupiter
Model

Jupiter's Atmosphere

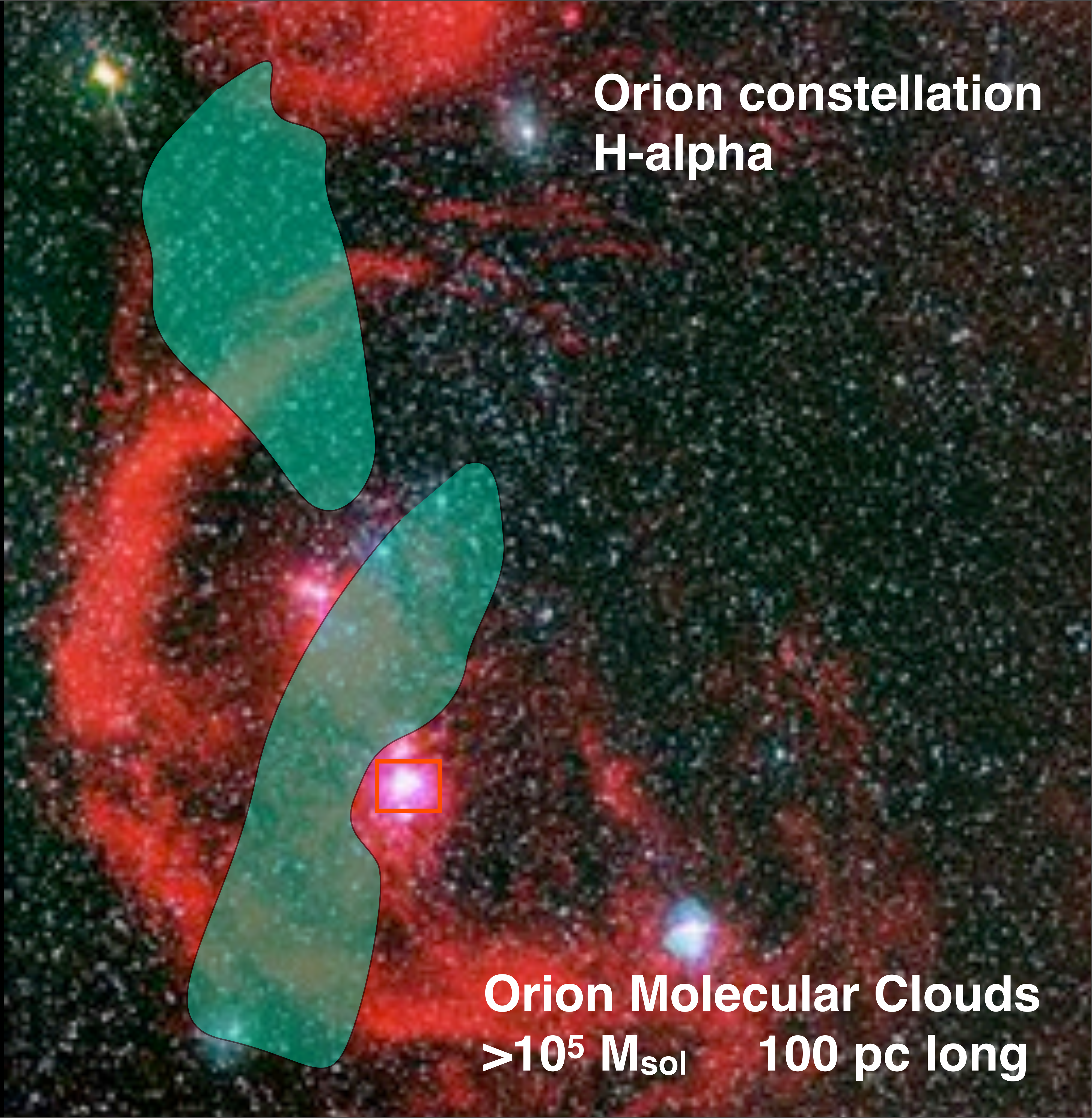
- Mass Spectrometer aboard Galileo Probe
- Measured atomic and molecular species to ~20 bars
- Found Jupiter atmosphere to be 2-6x higher in metals vs. Sun
  - C, S, Ar, Kr, Xe
  - All these are stable and long-lived: enrichment was a complete surprise!
  - v_{esc} = 45 km/sec

Jupiter 'Polluted Accretion' model

- **Conclusion**: Jupiter's enrichment can be matched if we allow for the Solar nebula's composition to have slight temporal and/or spatial variations.

- And we already know this happens!


Orion constellation
H-alpha


Orion constellation
H-alpha
Orion Molecular Clouds
$>10^5\ M_{sol}$ 100 pc long

Our 'Polluted Accretion' model for Jupiter

1. The Sun and its disk form in a cluster within a giant molecular cloud.
2. Other clusters in GMC form simultaneously.
3. Massive stars in nearby clusters pollute the ISM with metals.
4. Sun + disk pass through polluted region and accrete polluted ISM
5. Jupiter forms from this disk

Jupiter 'Polluted Accretion' model

- **Conclusion**: Jupiter's enrichment can be matched if we allow for the Solar nebula's composition to have temporal and/or spatial variations due to its stellar neighbors.
- Evidence for a heterogeneous nebula is not new!

Dauphas *et al* 2002:

"'Mb isotope abundances were heterogeneously distributed in the Solar System's parental molecular cloud, and **the large-scale variations we observed were inherited from the interstellar environment where the Sun was born**."

Ranen & Jacobsen 2006:

"There are resolvable differences between the Earth and carbonaceous chondrites that are most likely caused by **incomplete mixing of** r- and s-process nucleosynthetic **components in the early Solar System**."

Trinquier *et al* 2007:

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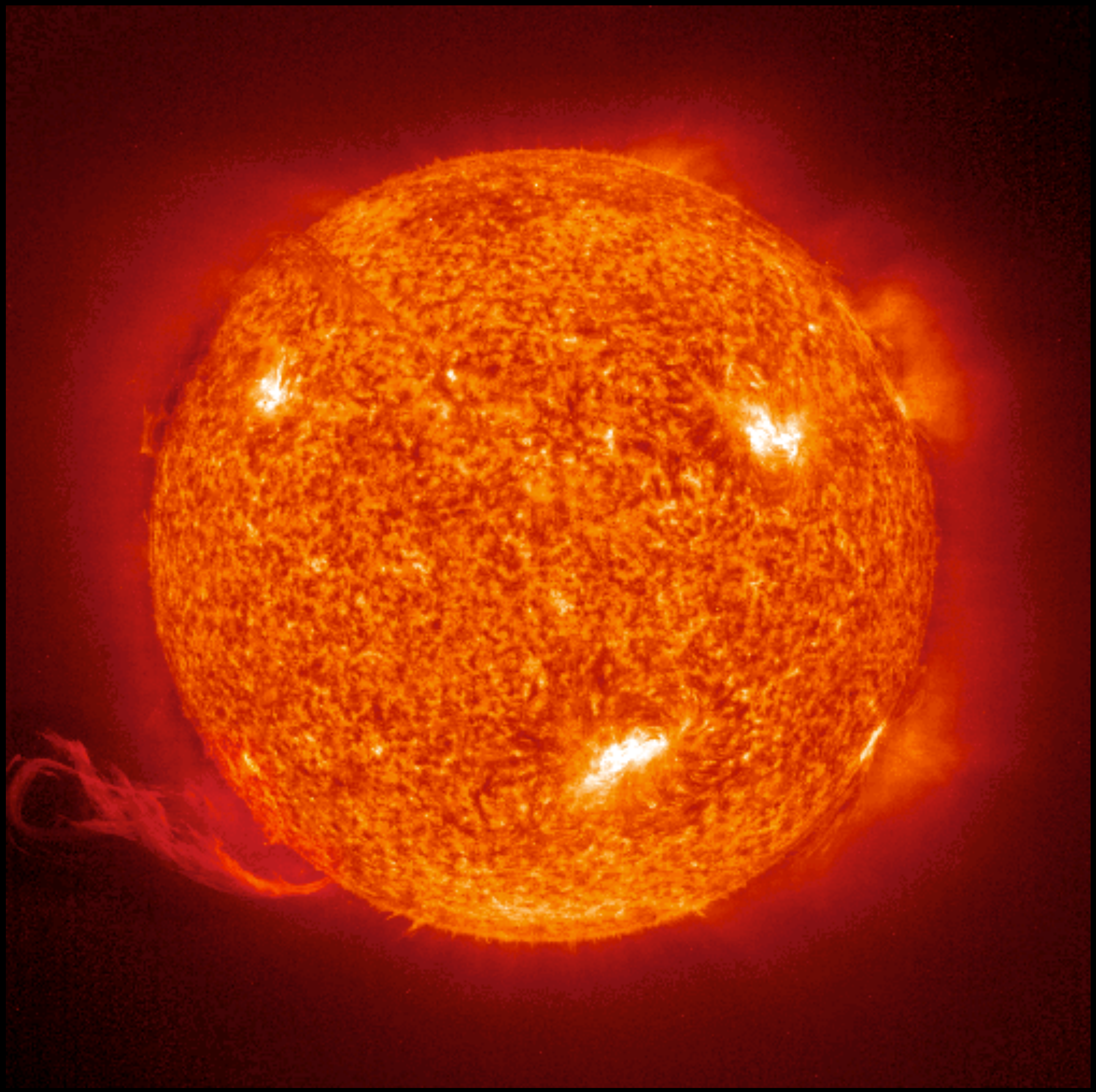
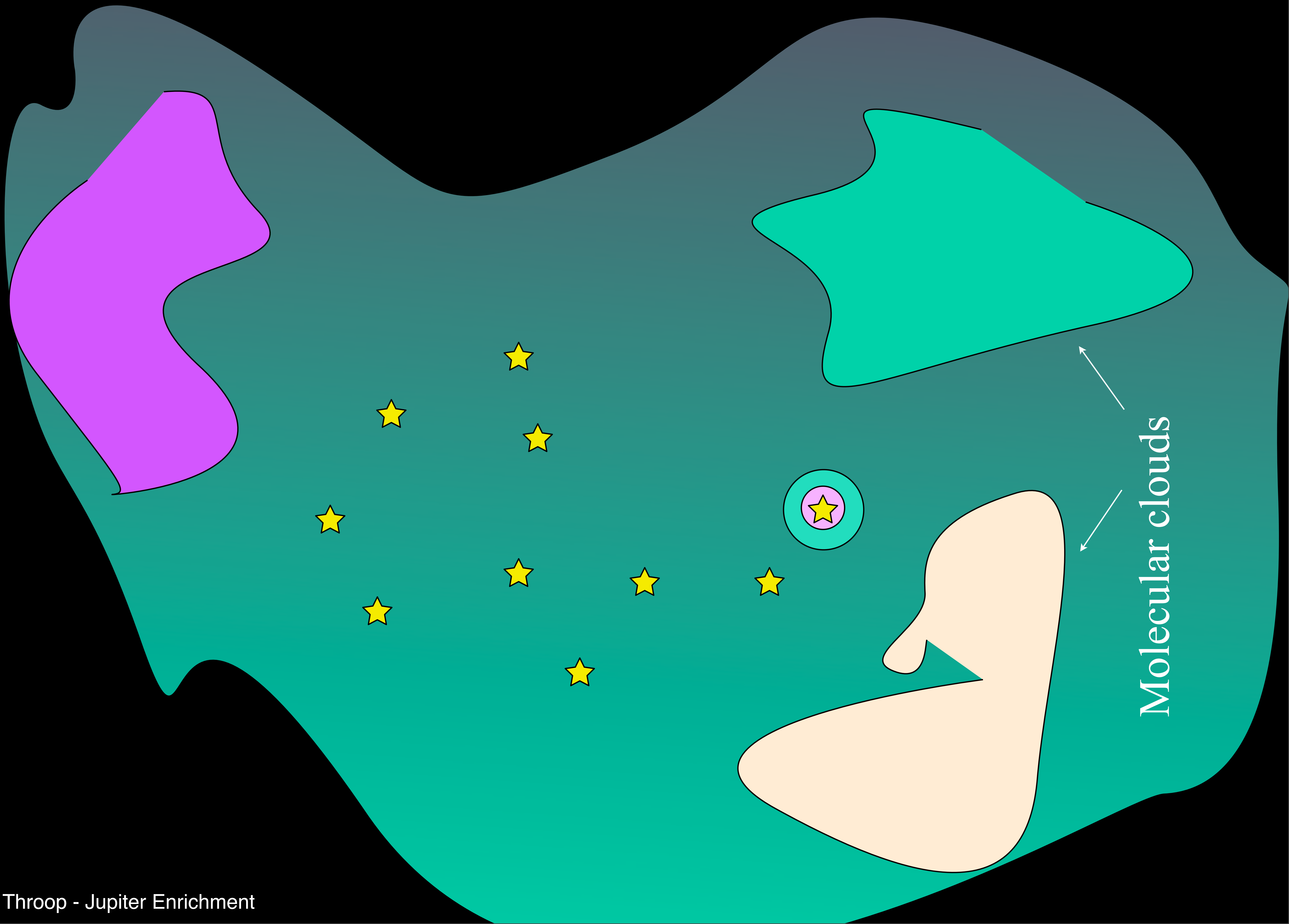
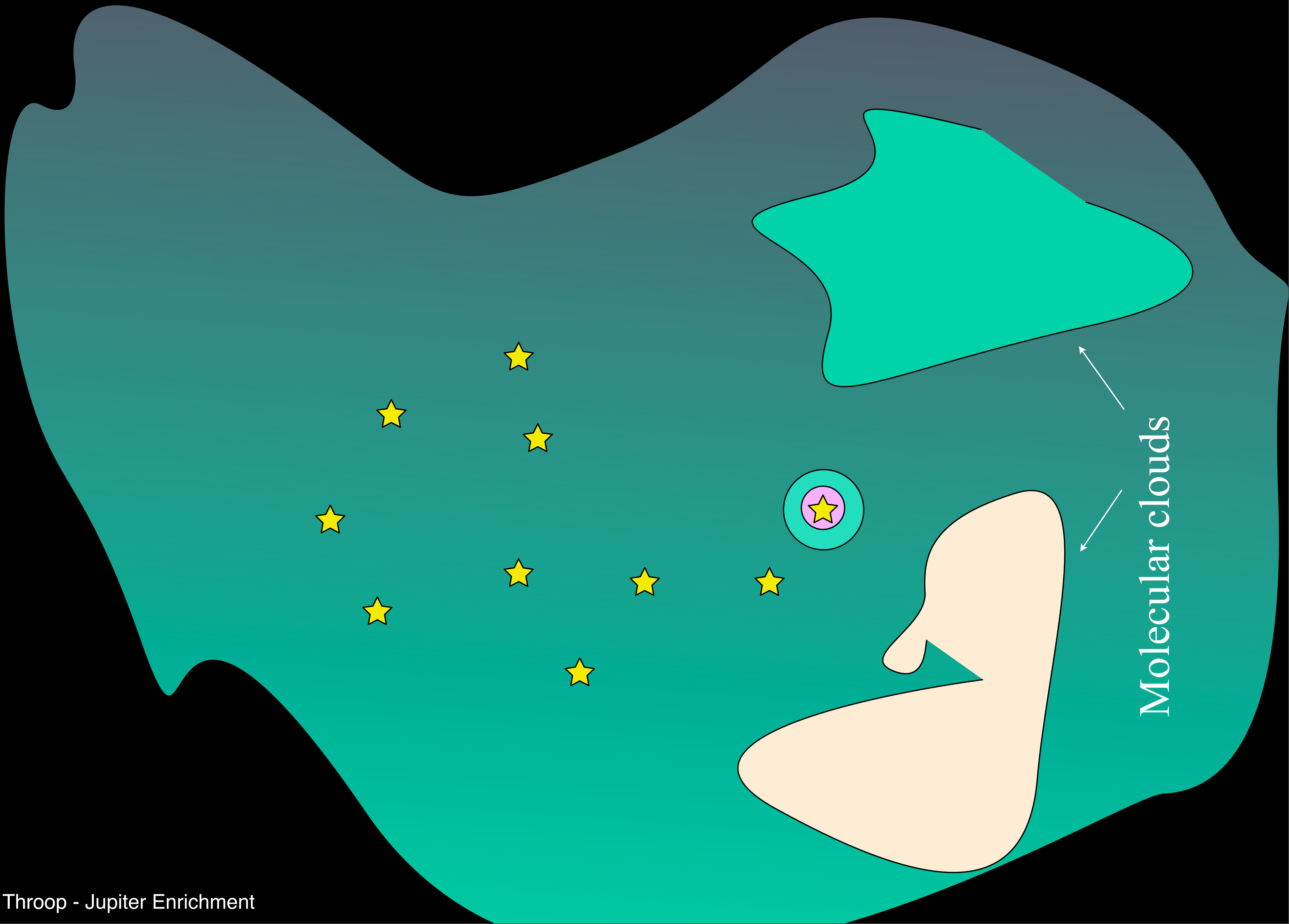
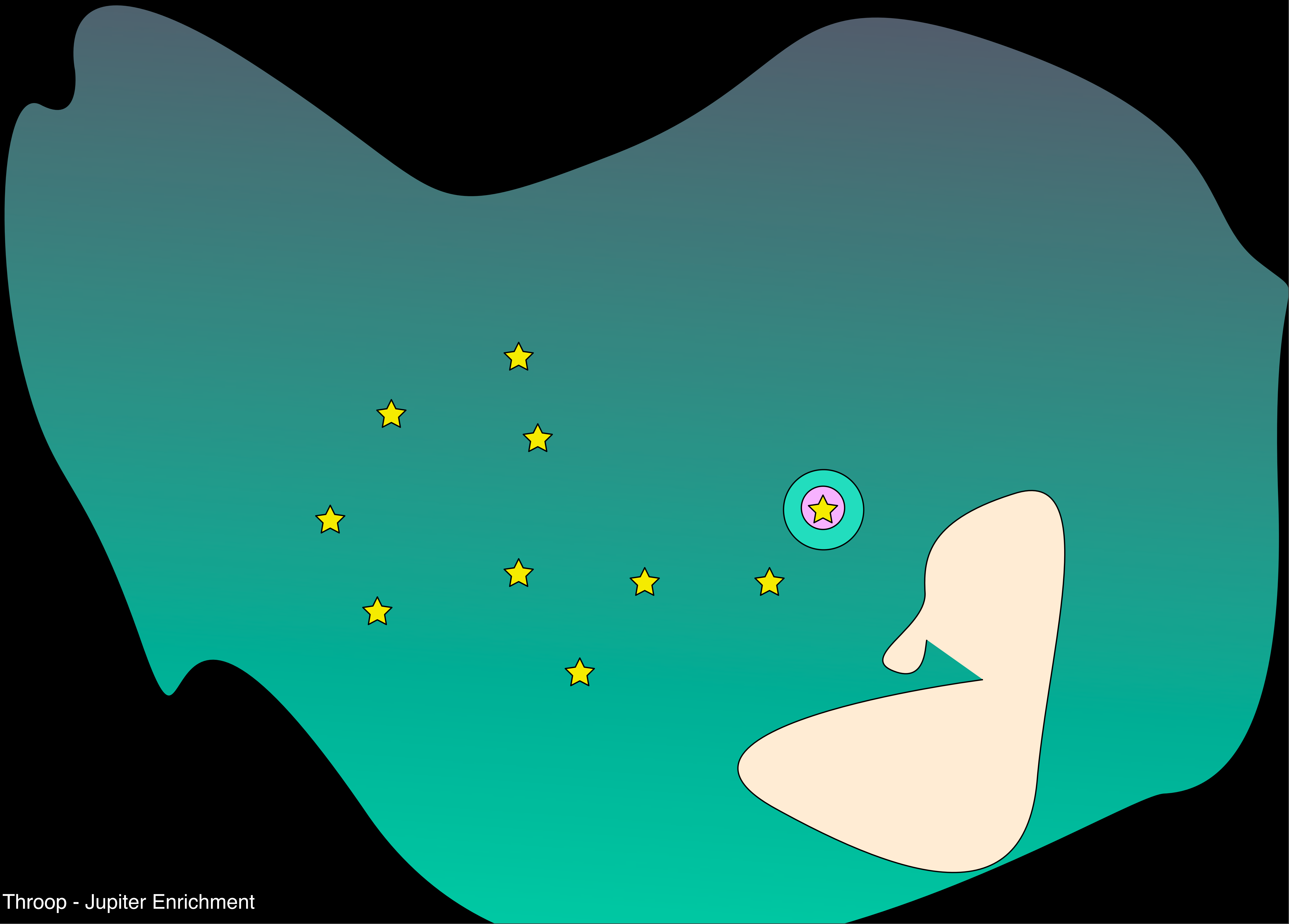


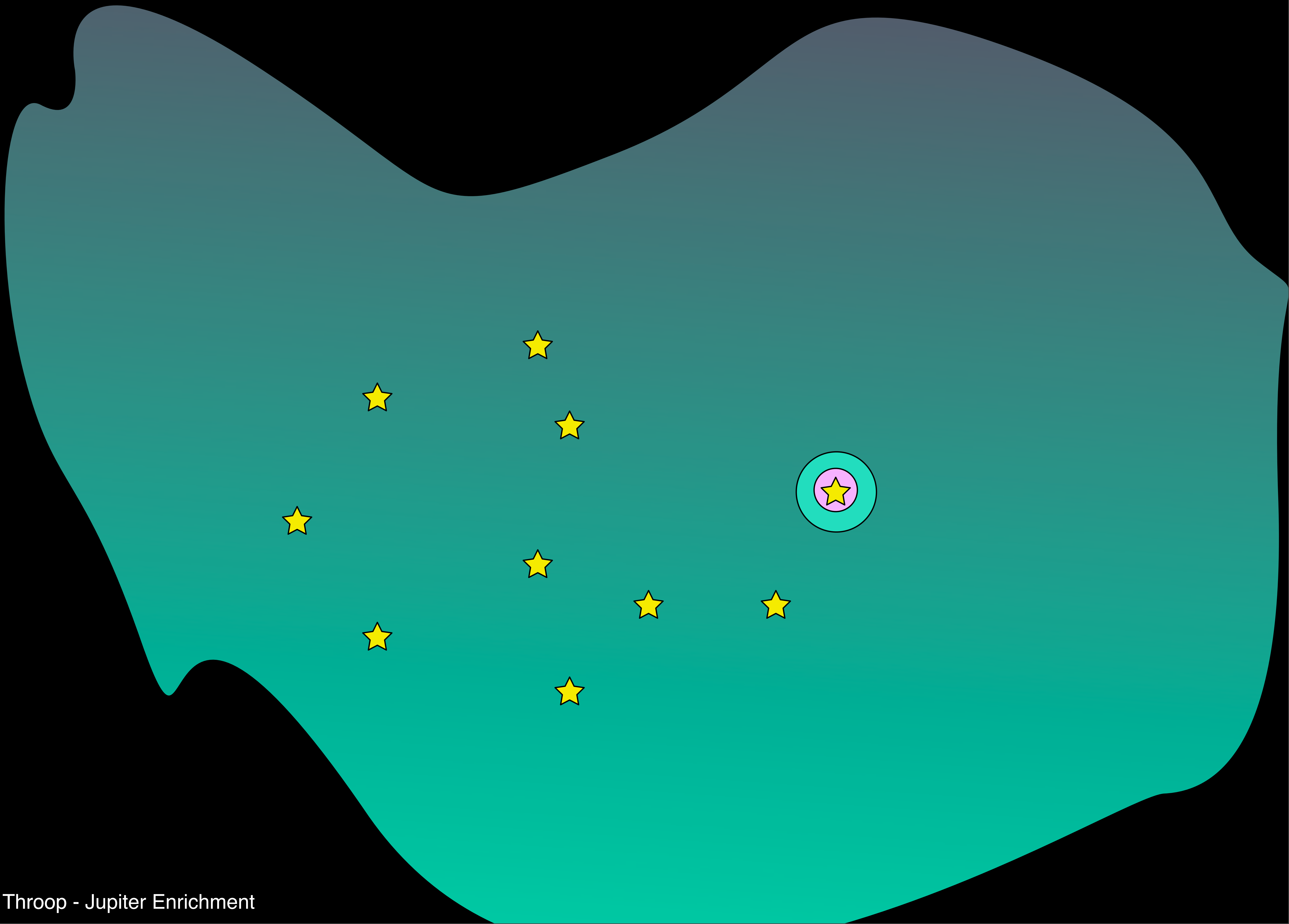
If the Sun and Jupiter both formed from the same cloud, why is their atmospheric composition so different?


Molecular clouds


Molecular clouds



Throop - Jupiter Enrichment



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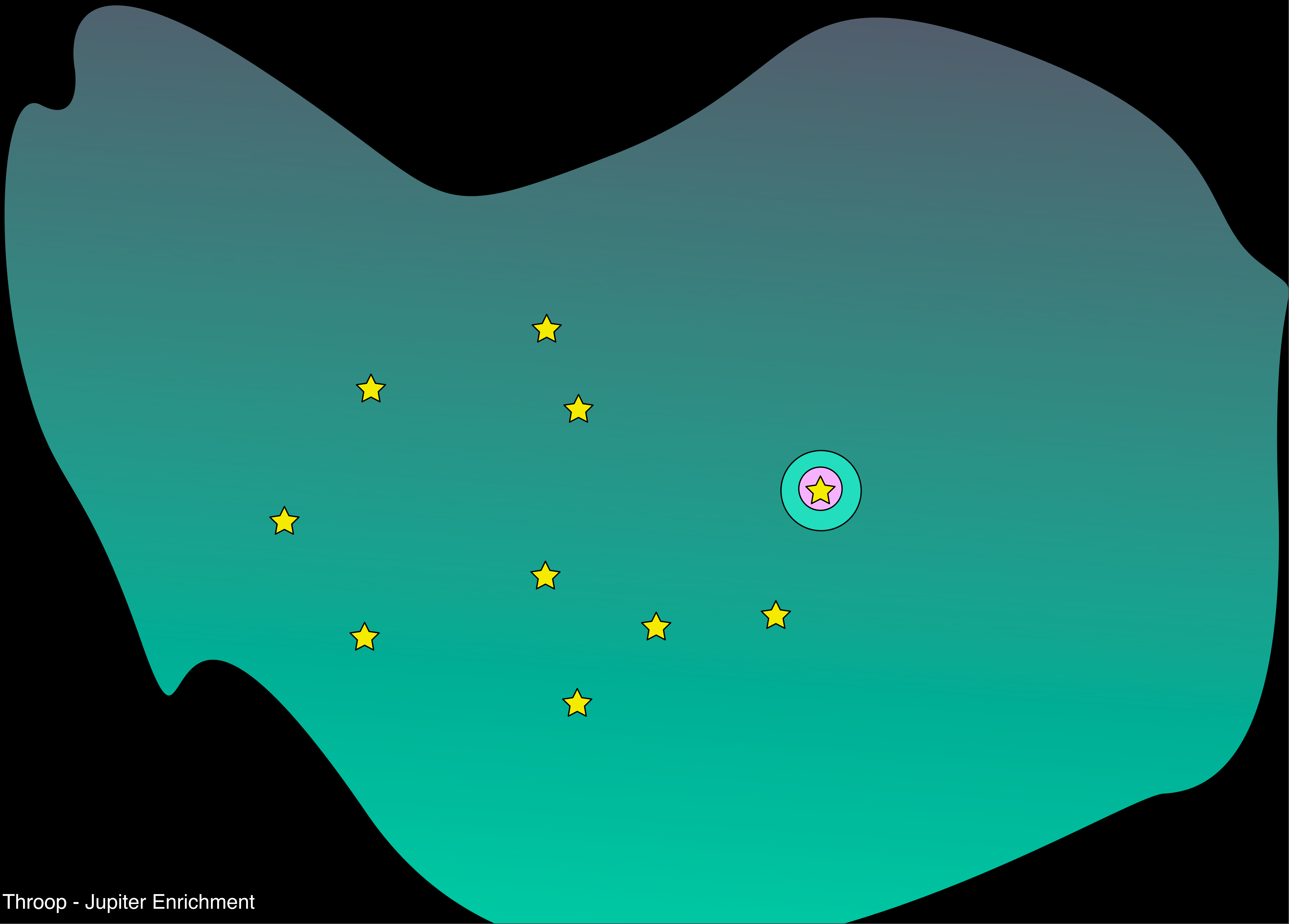
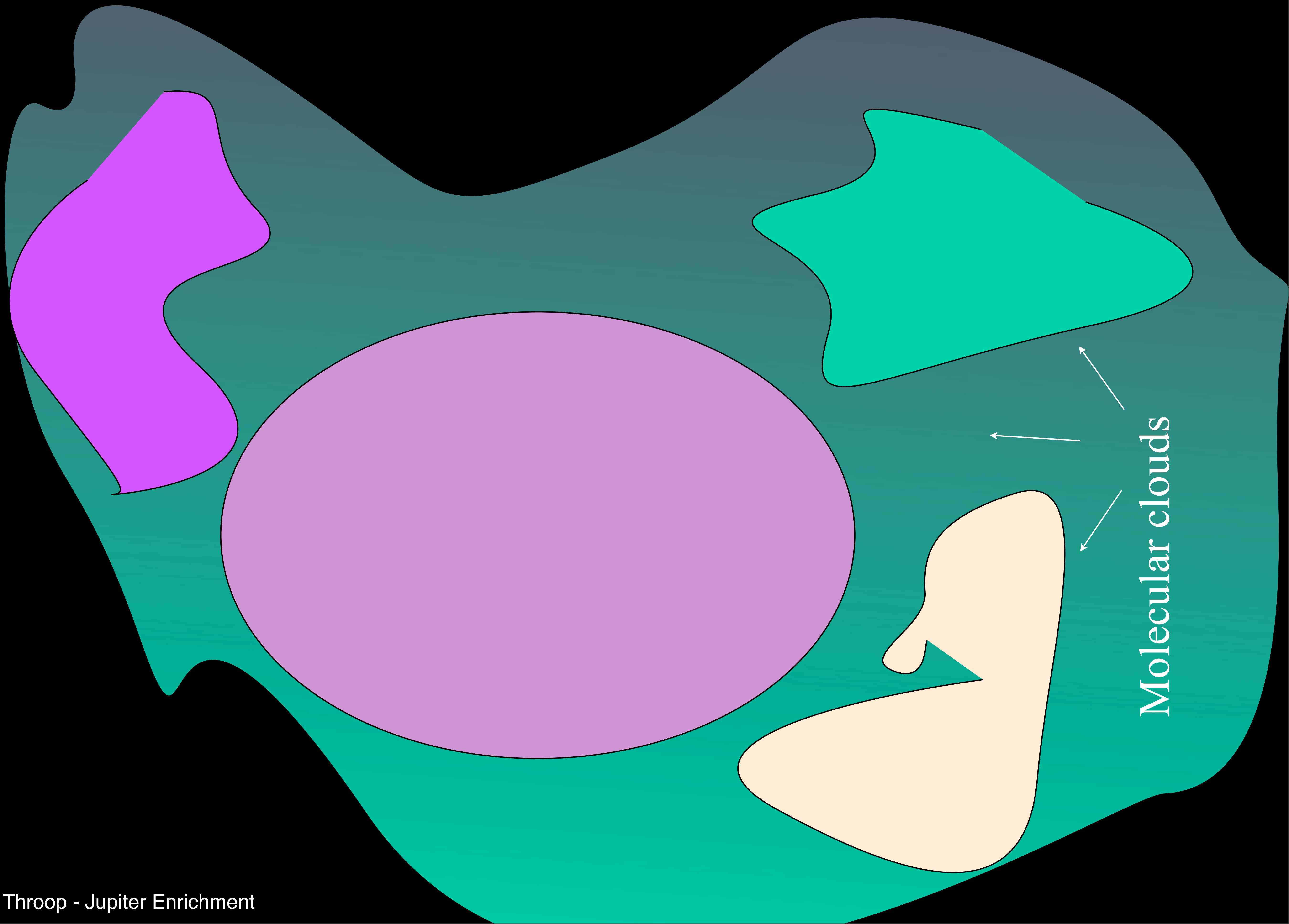
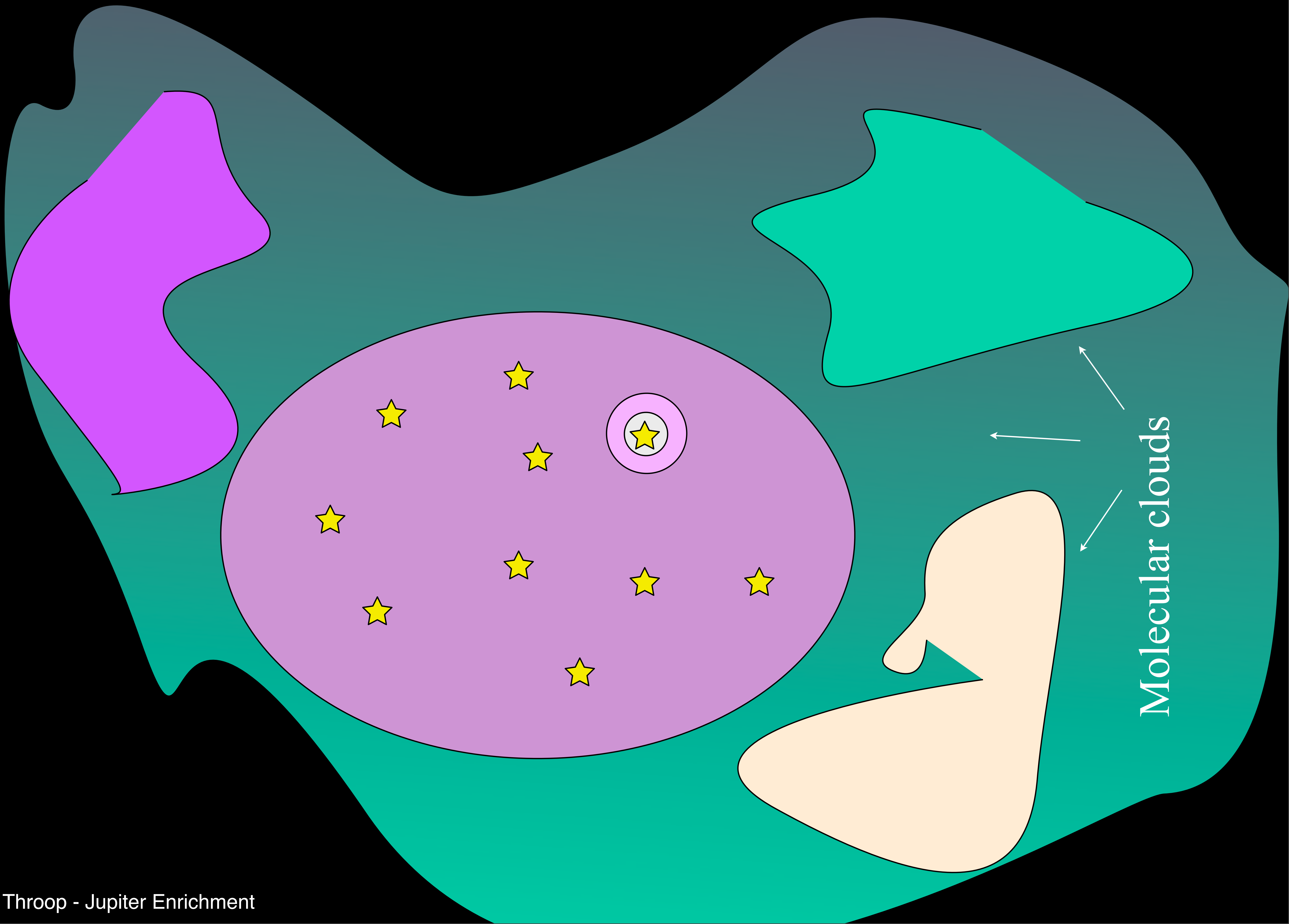
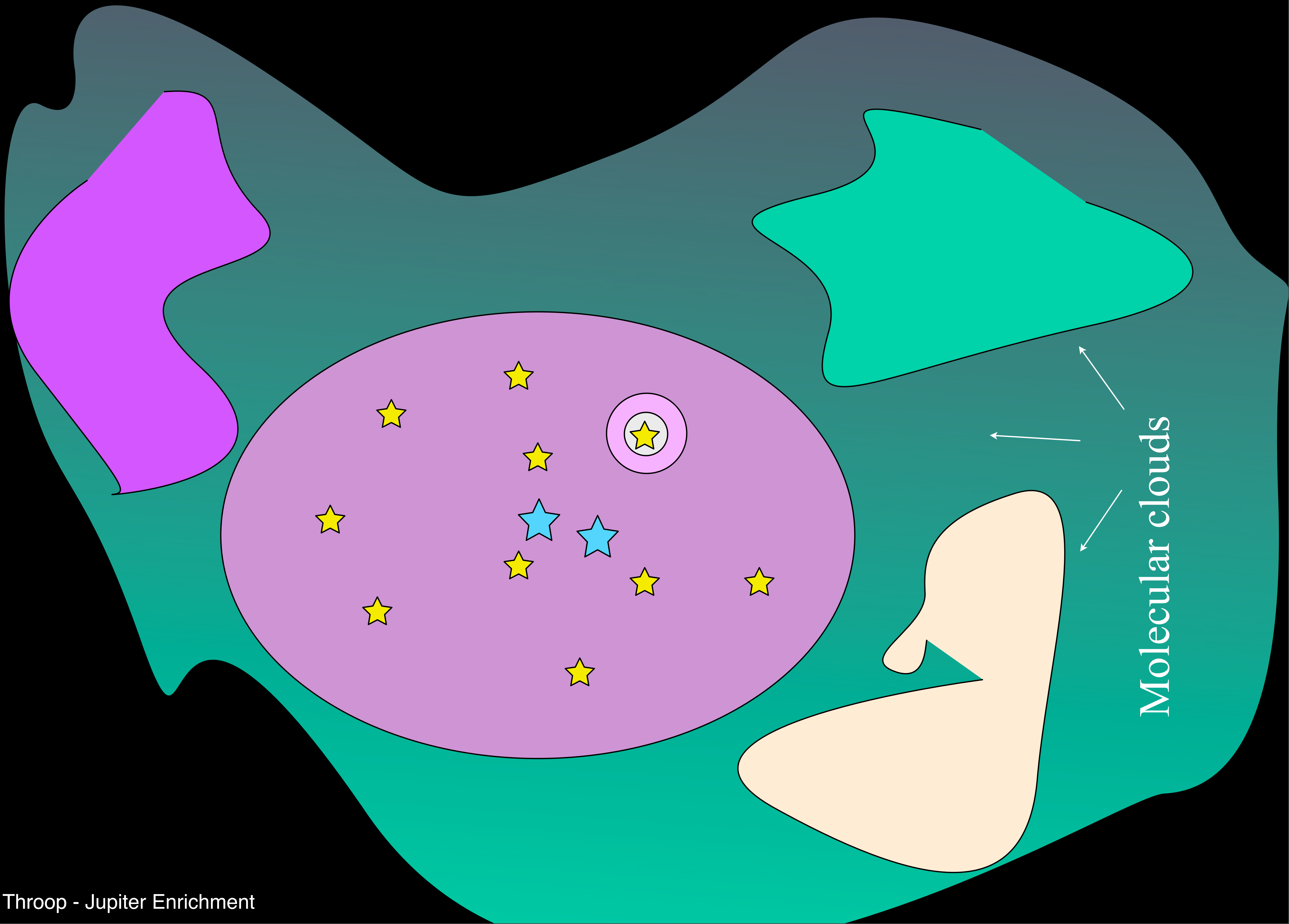


Throop - Jupiter Enrichment

Giant Molecular Cloud, 10-20 pc


Molecular clouds


Molecular clouds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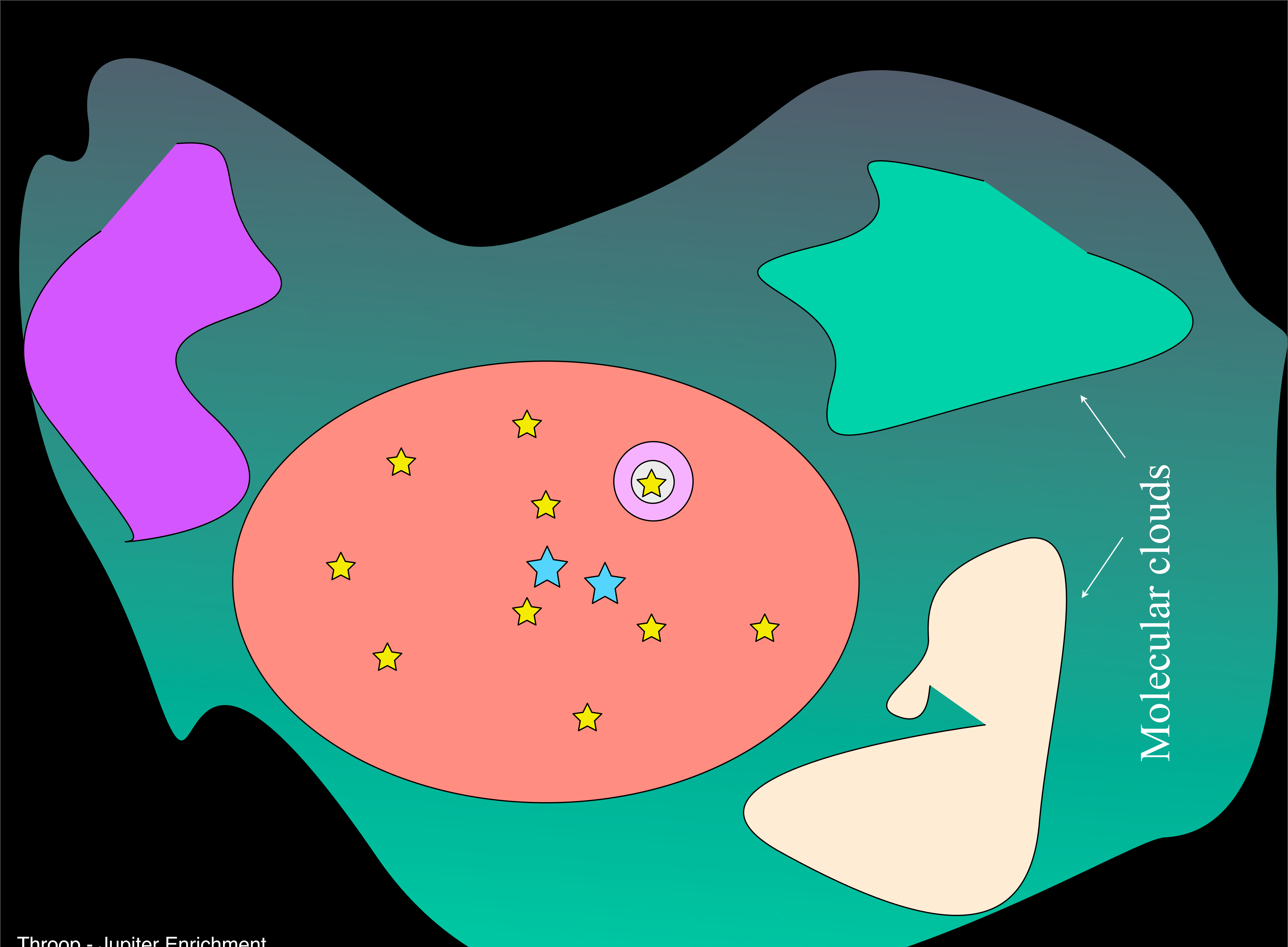

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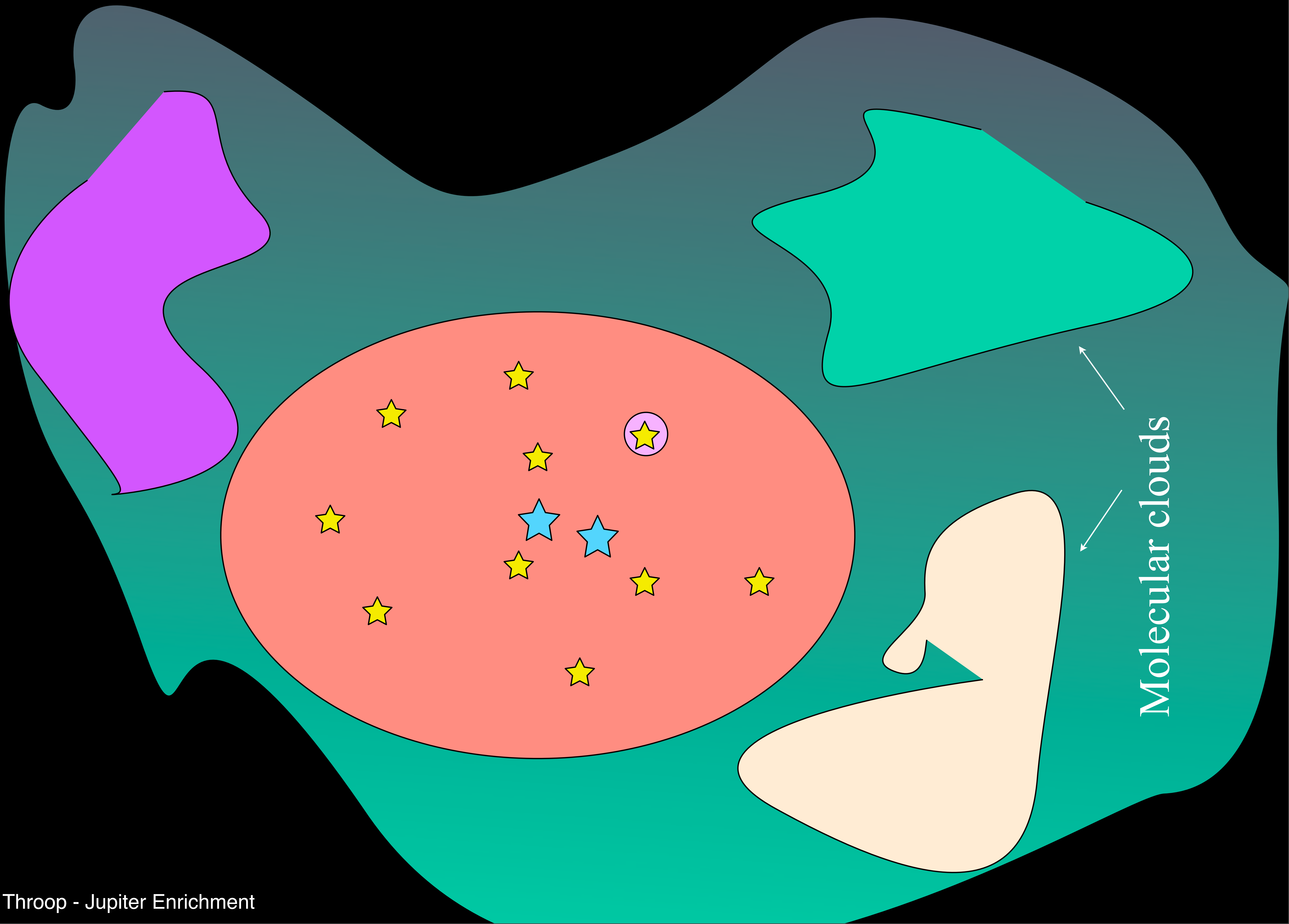
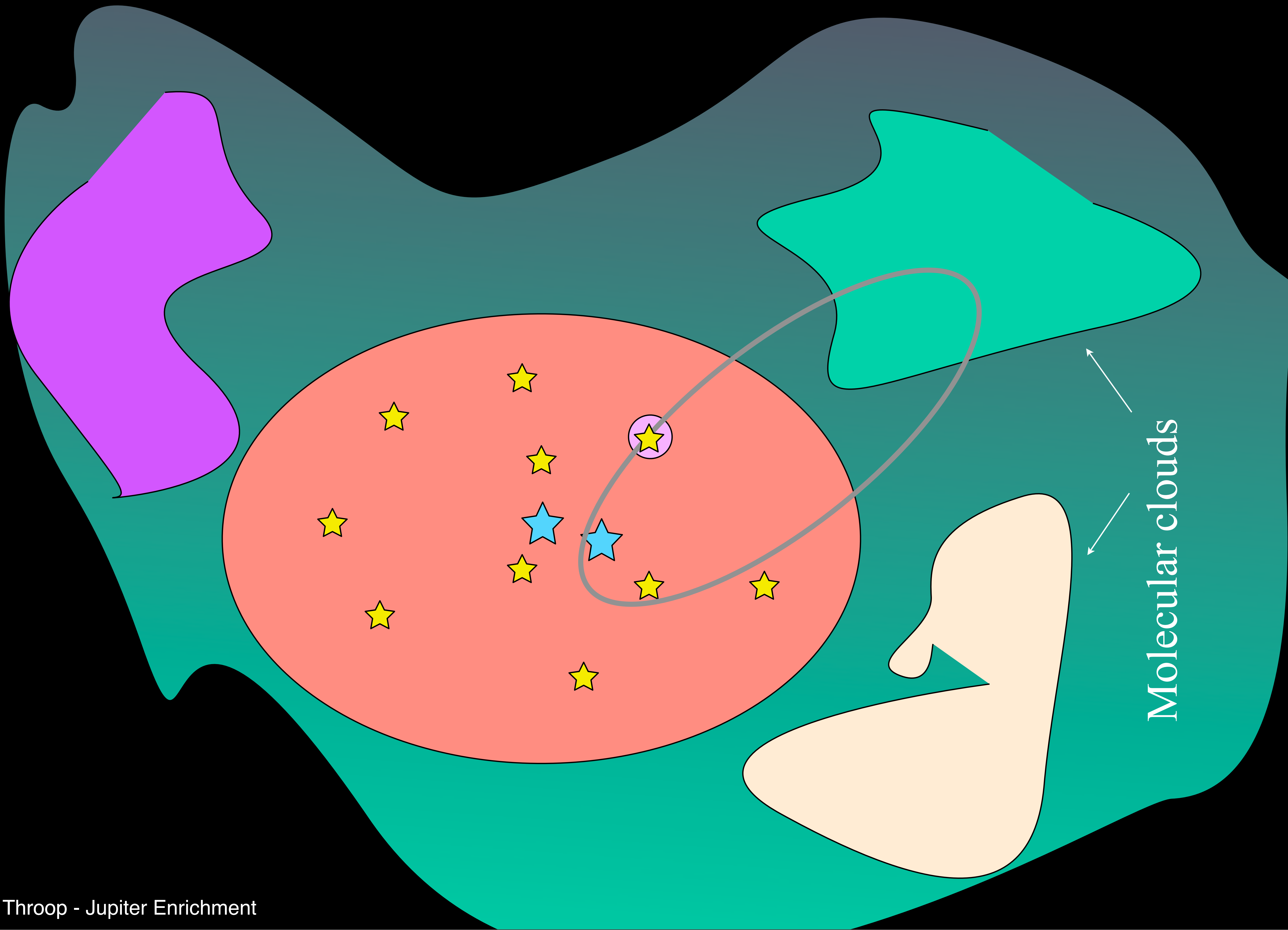
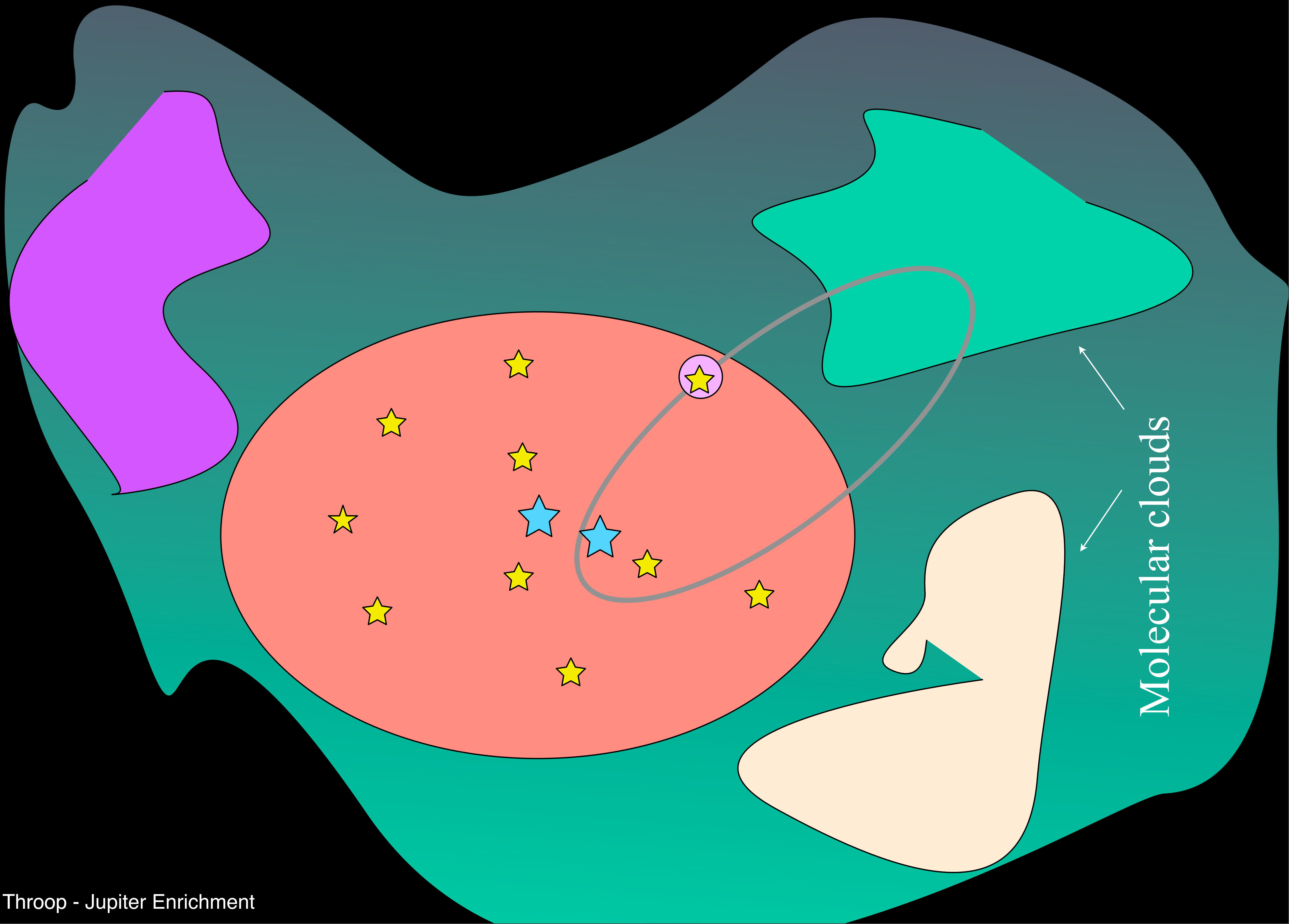
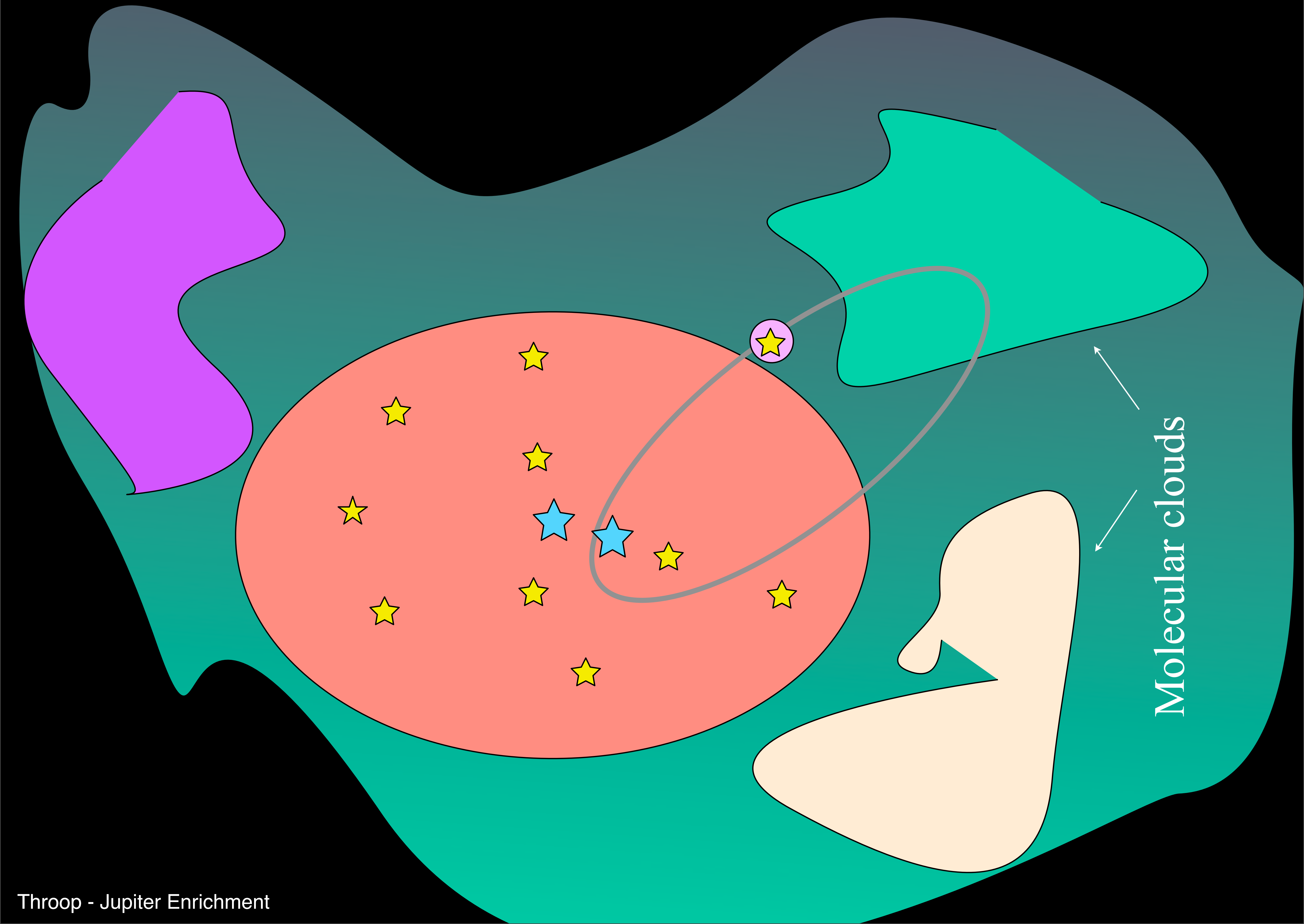

Molecular clouds


Molecular clouds


Molecular clouds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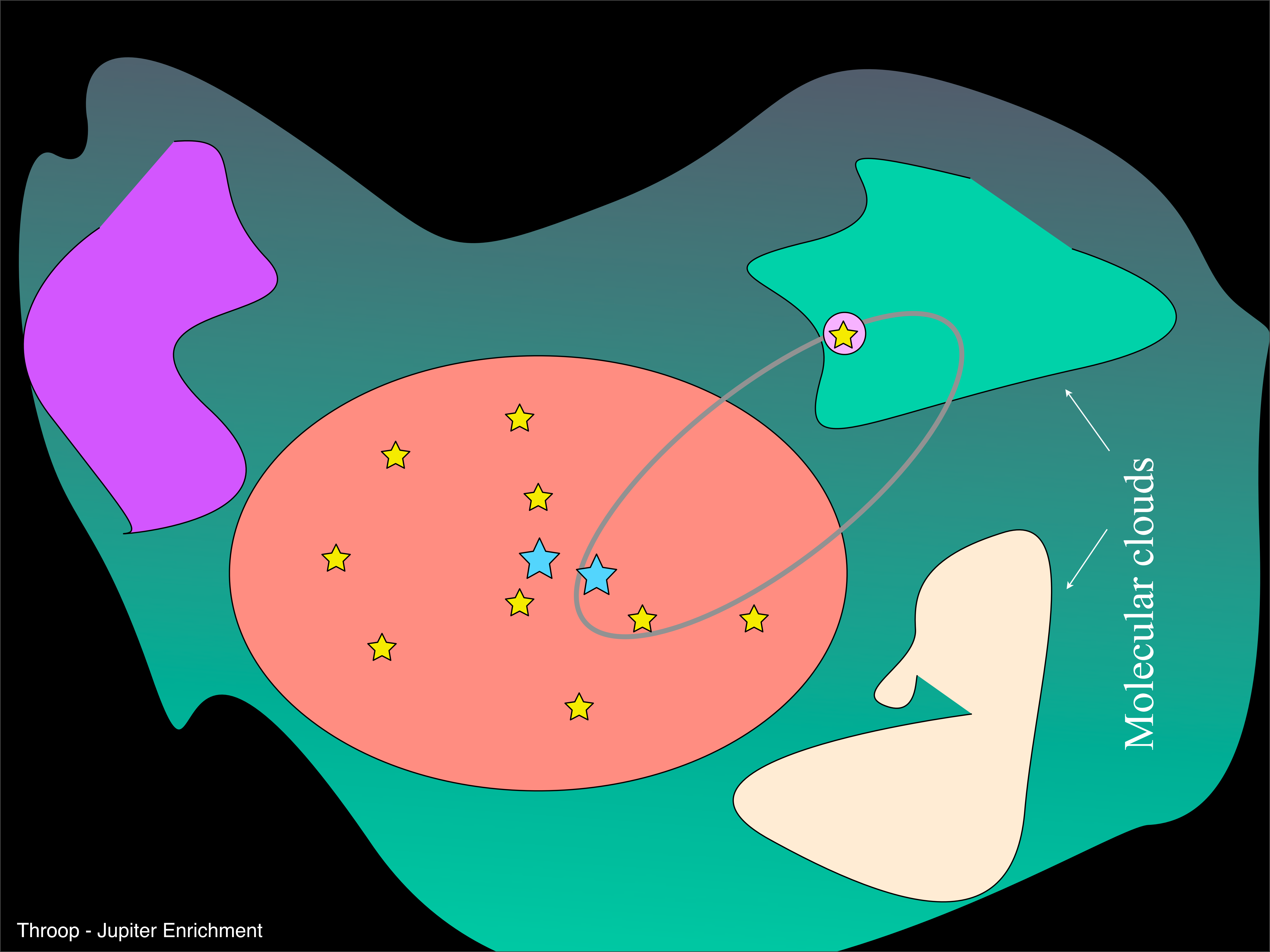

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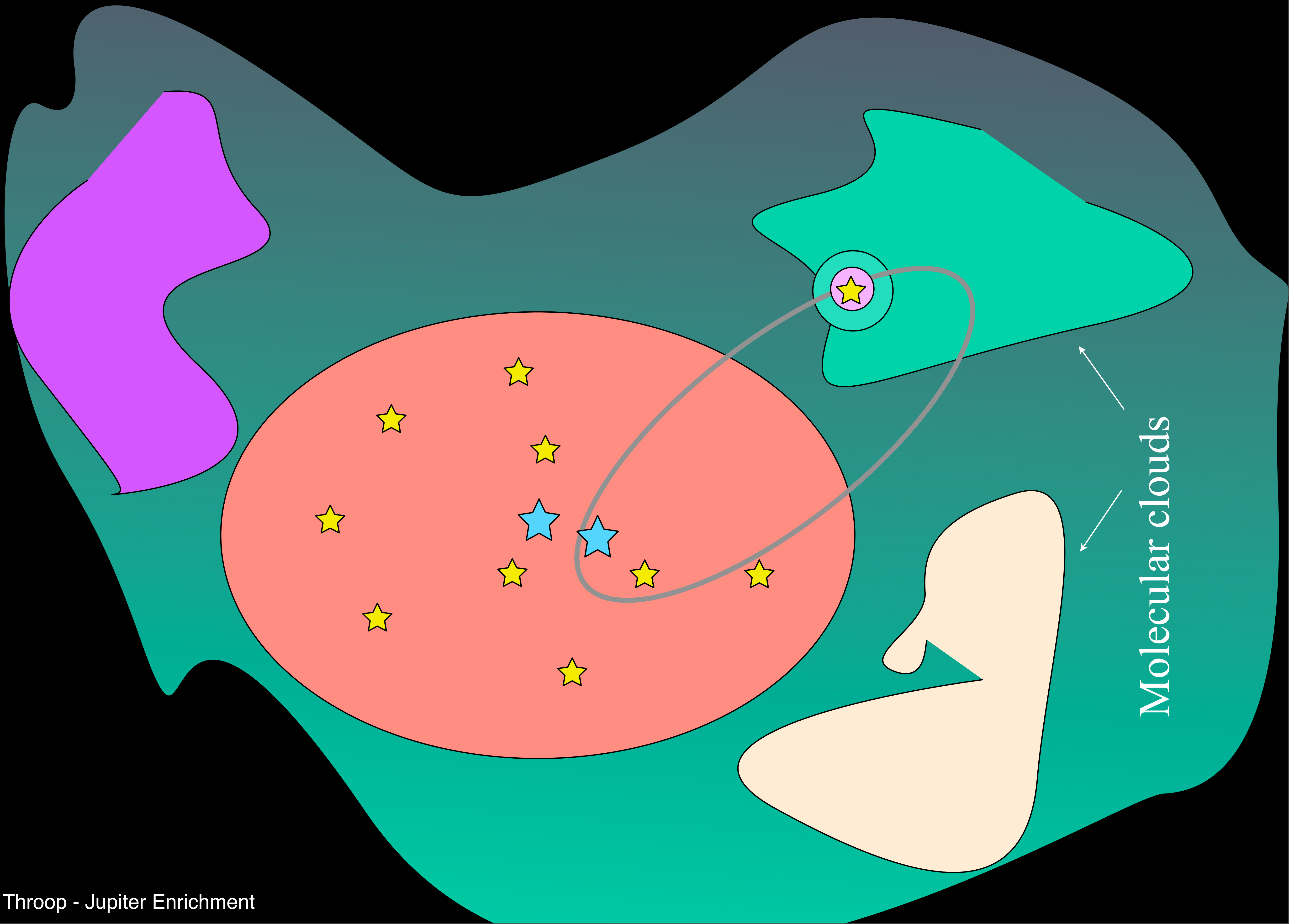

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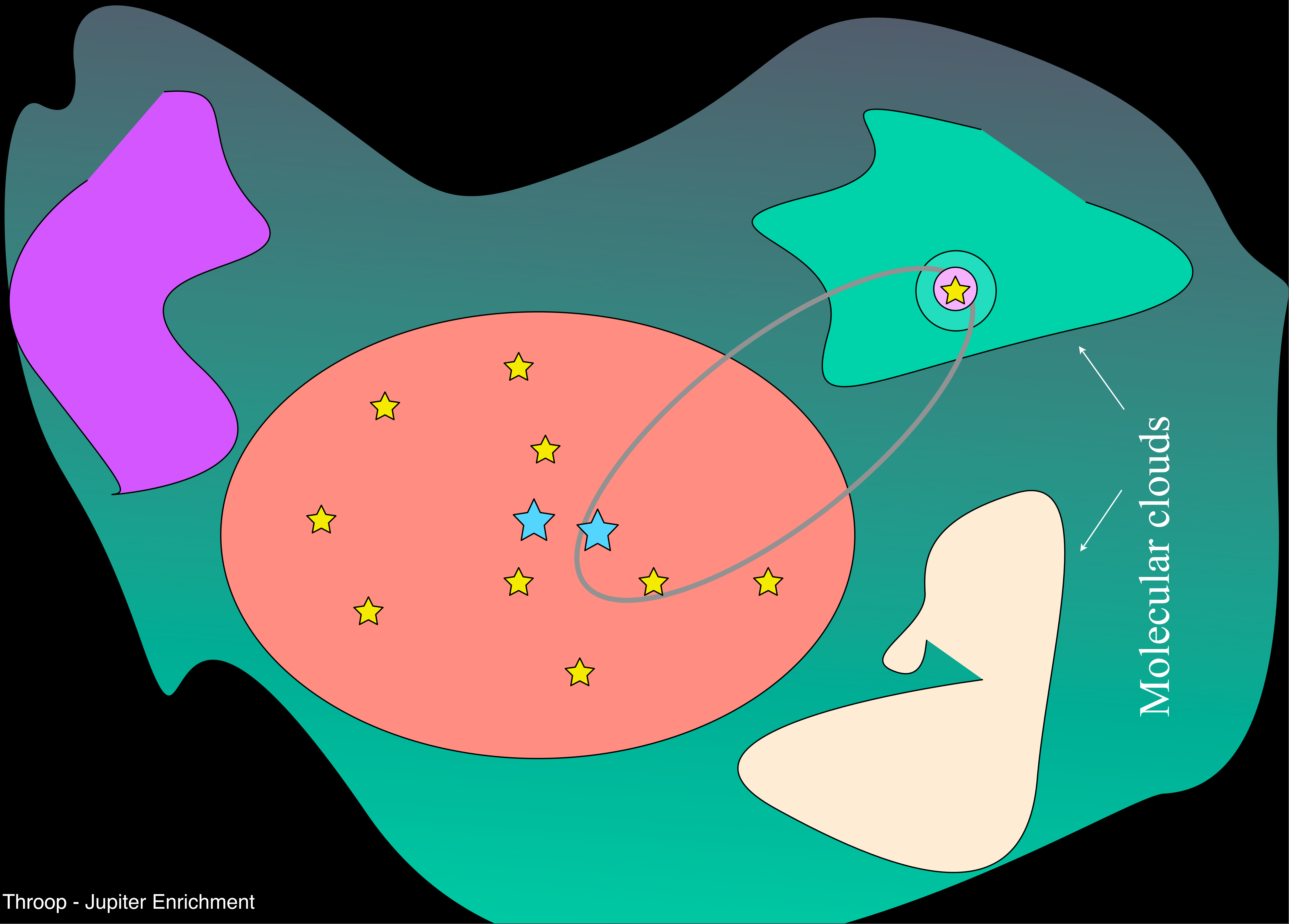

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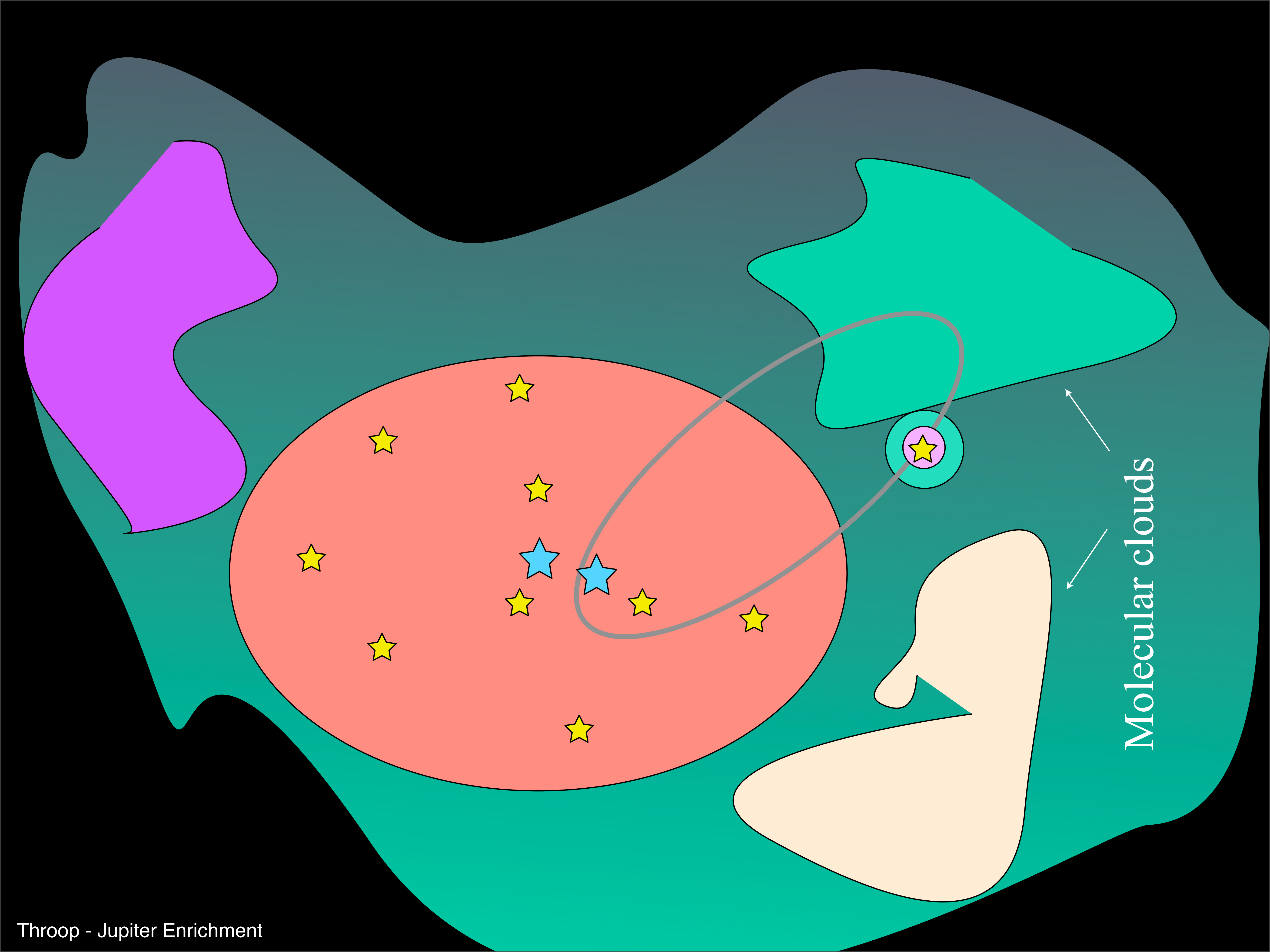
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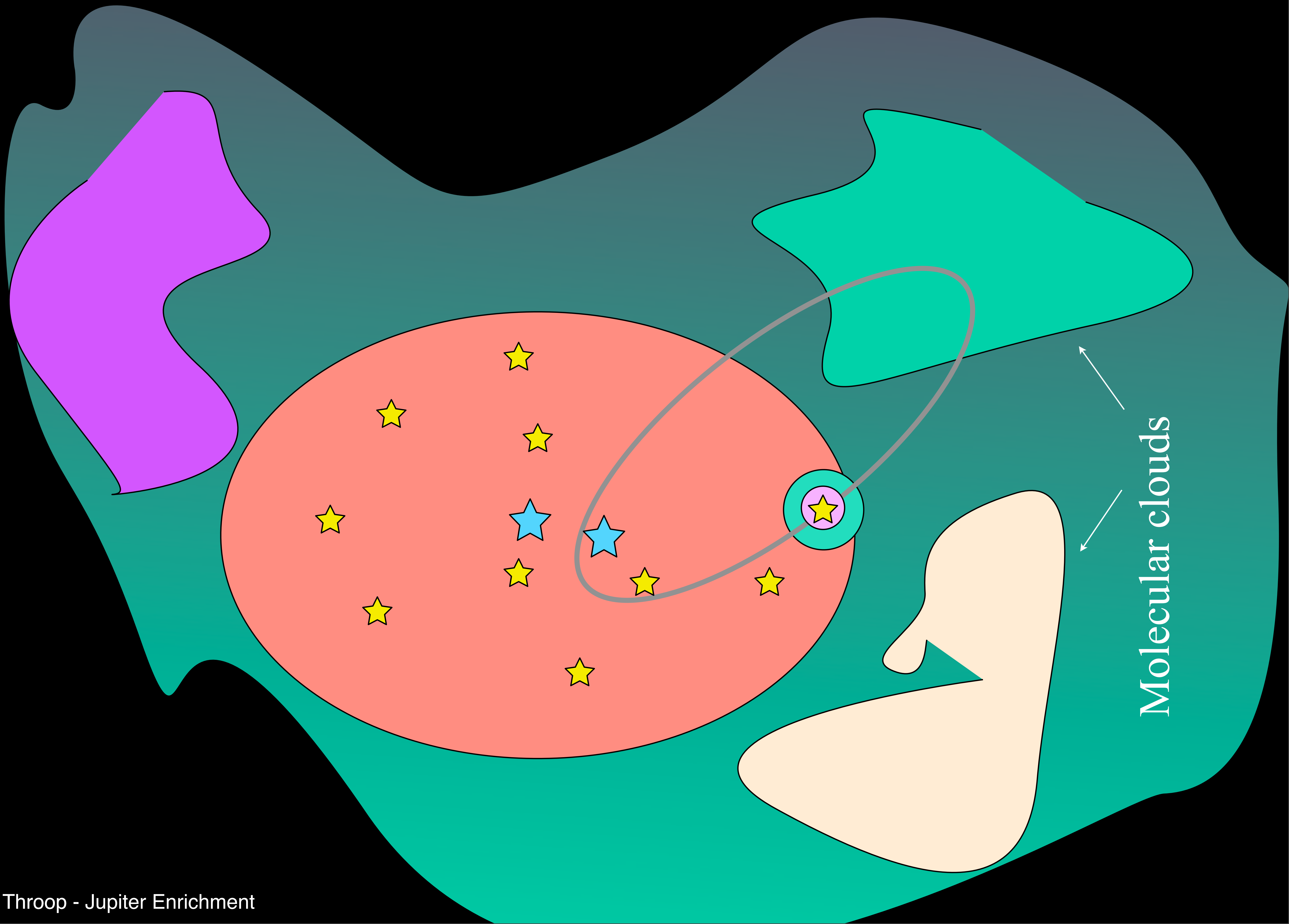

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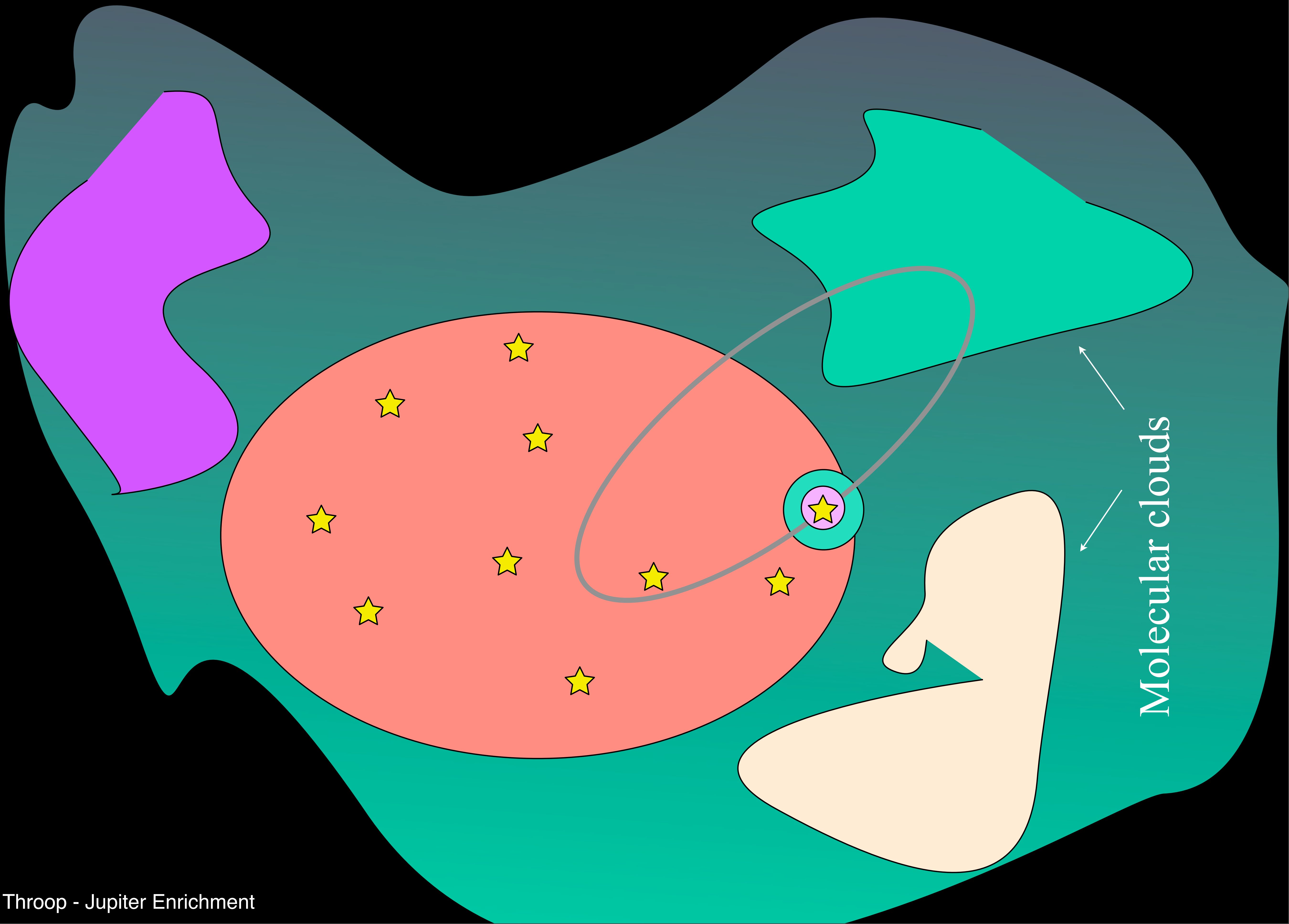
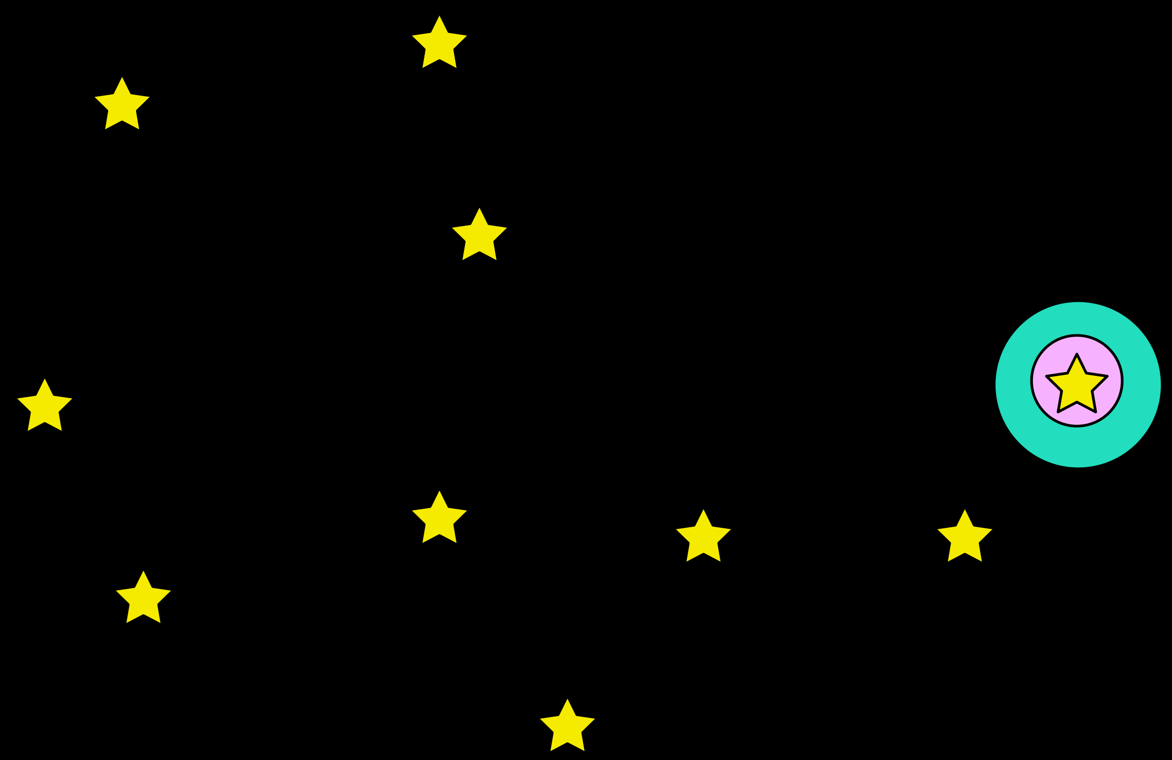

Molecular clouds



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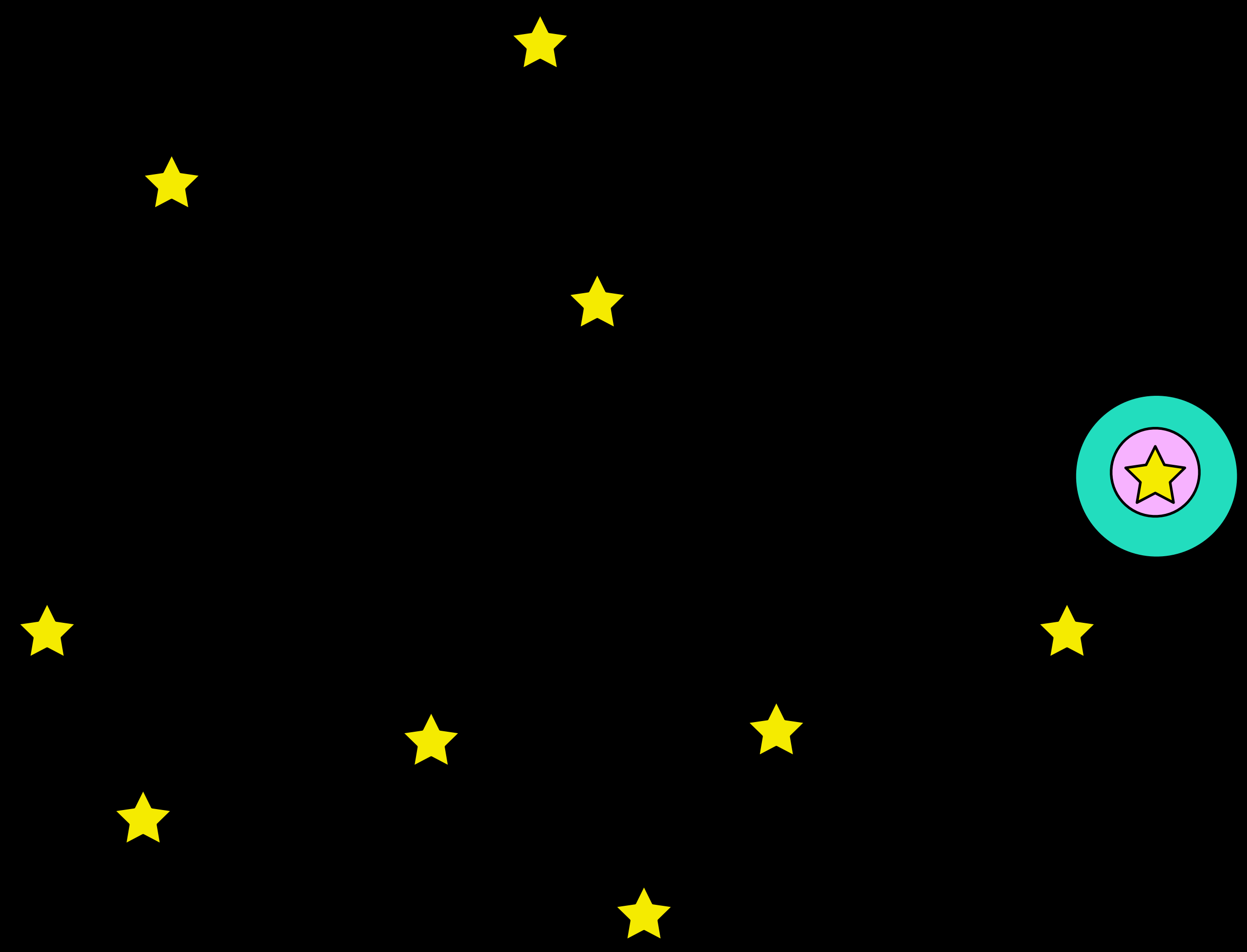

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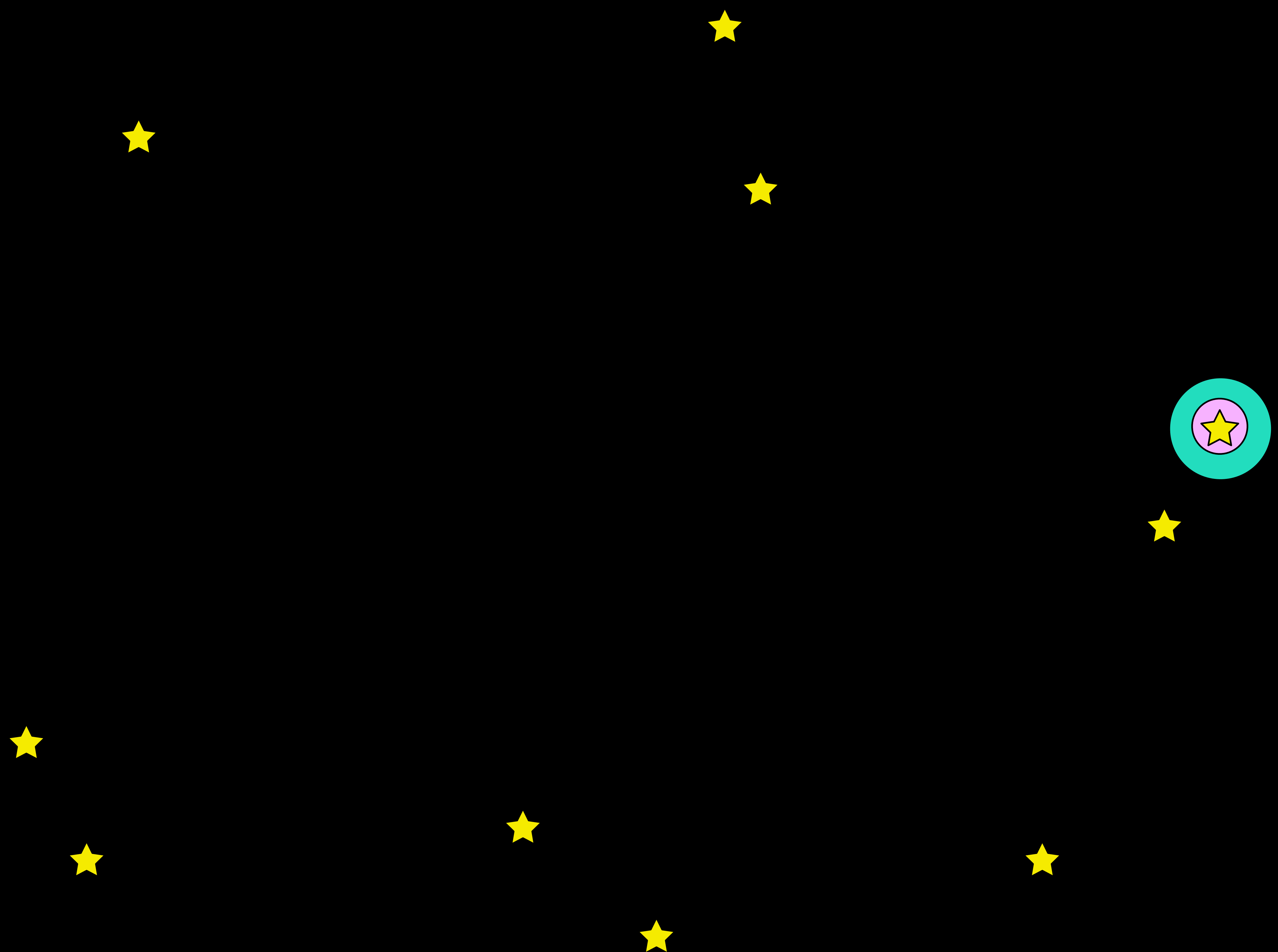

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