Planet Formation in Dense Star Clusters

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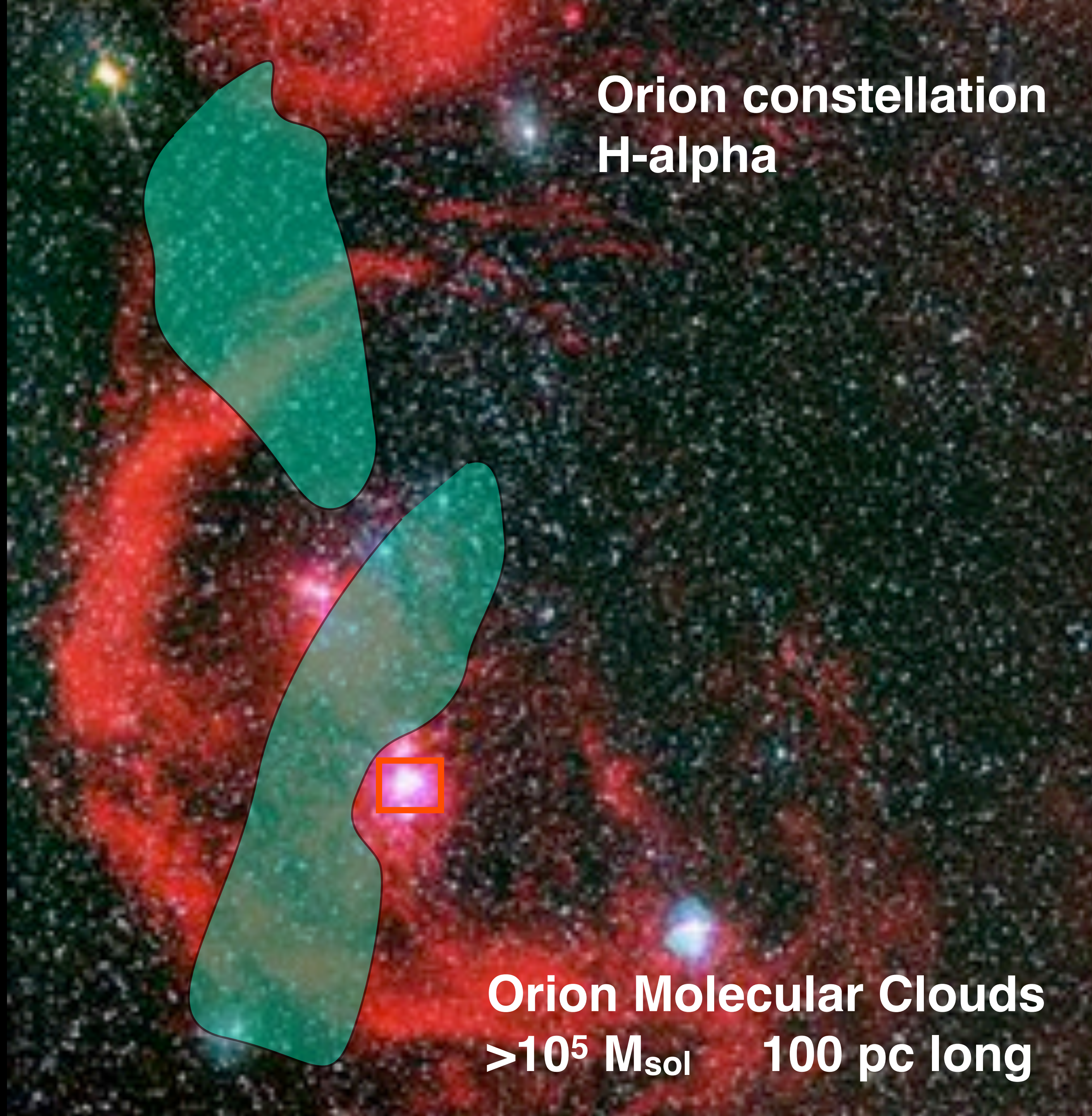
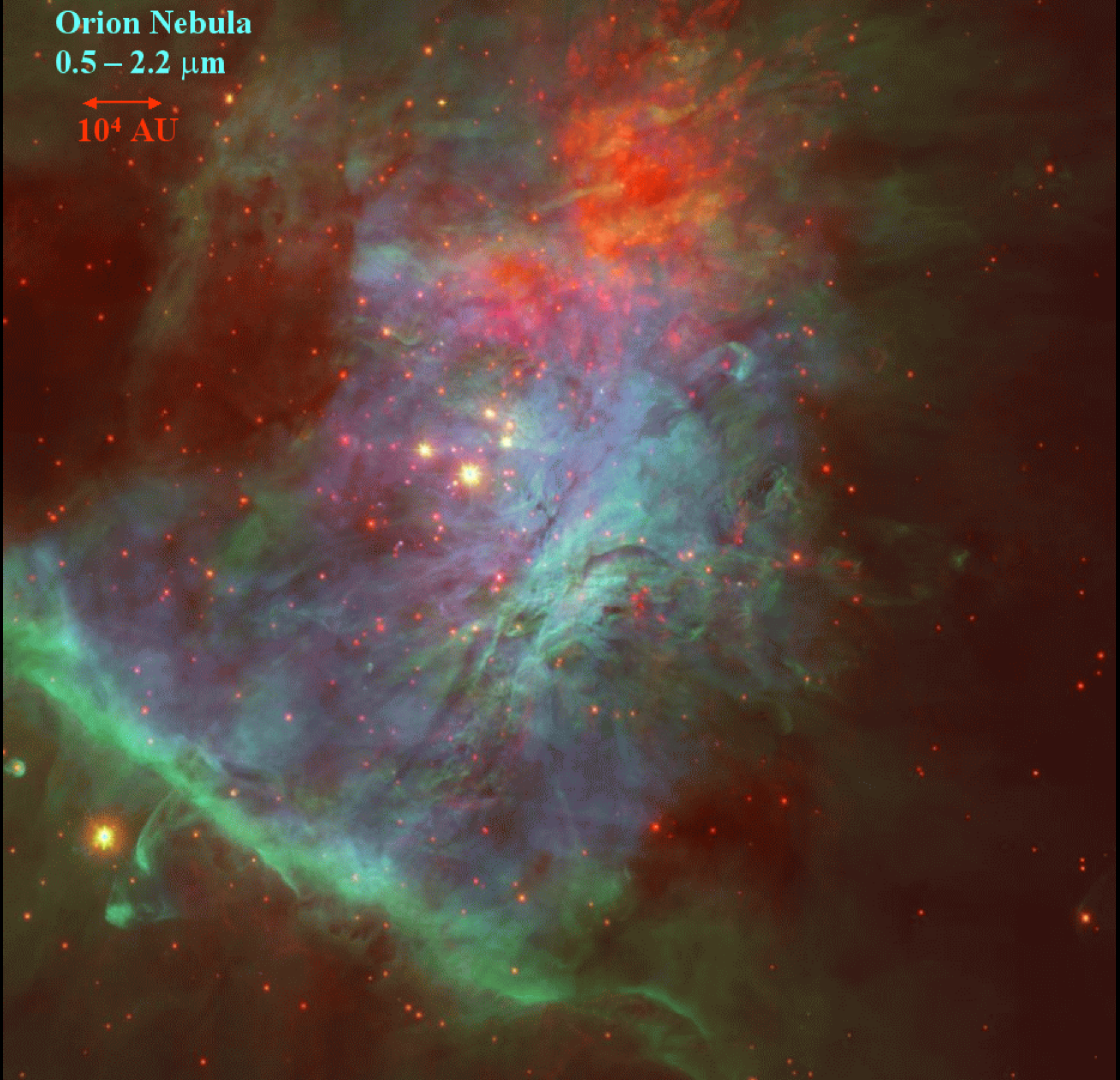
Orion Constellation
(visible light)


Orion constellation
H-alpha

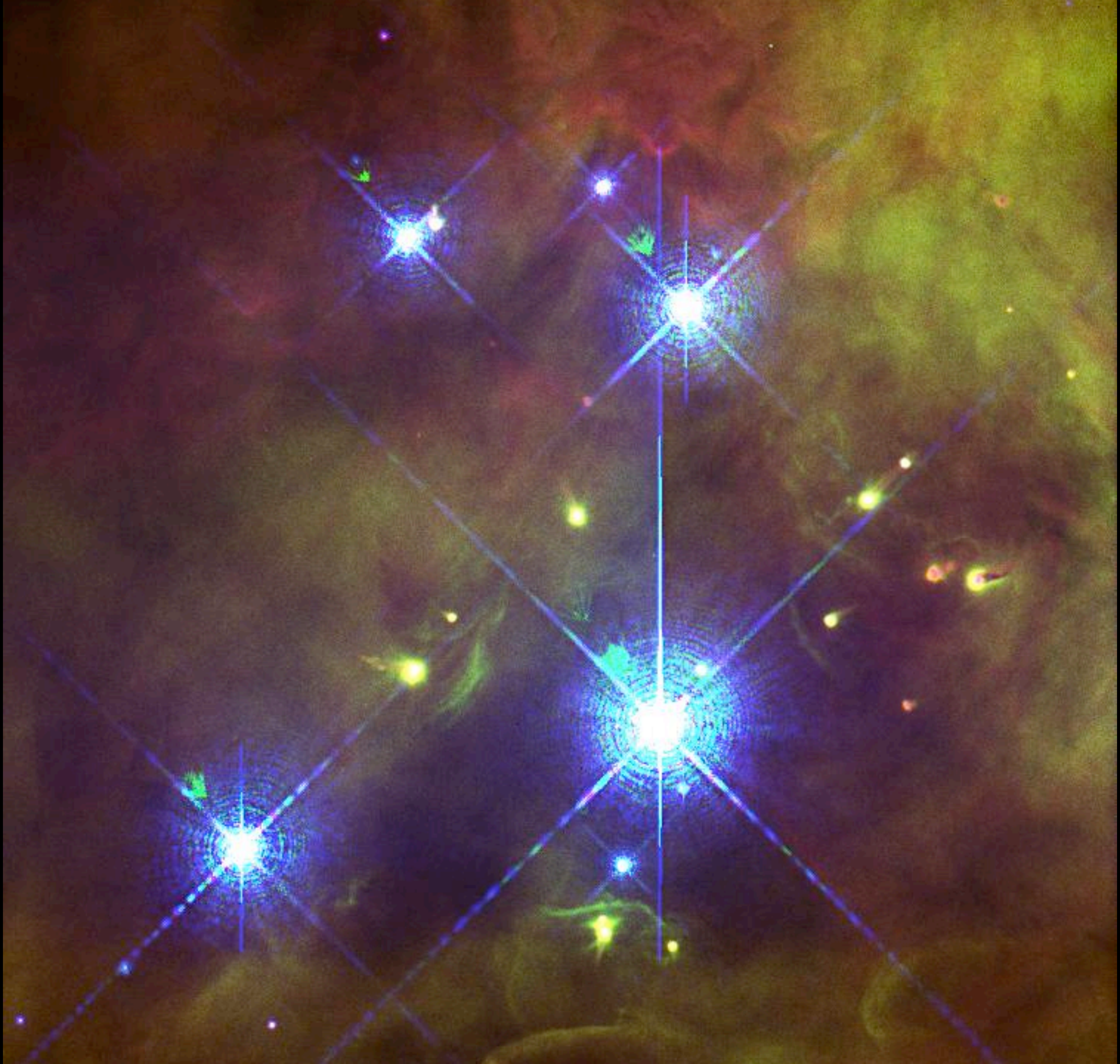


Orion constellation
H-alpha
Orion Molecular Clouds
>10⁵ Msol   100 pc long

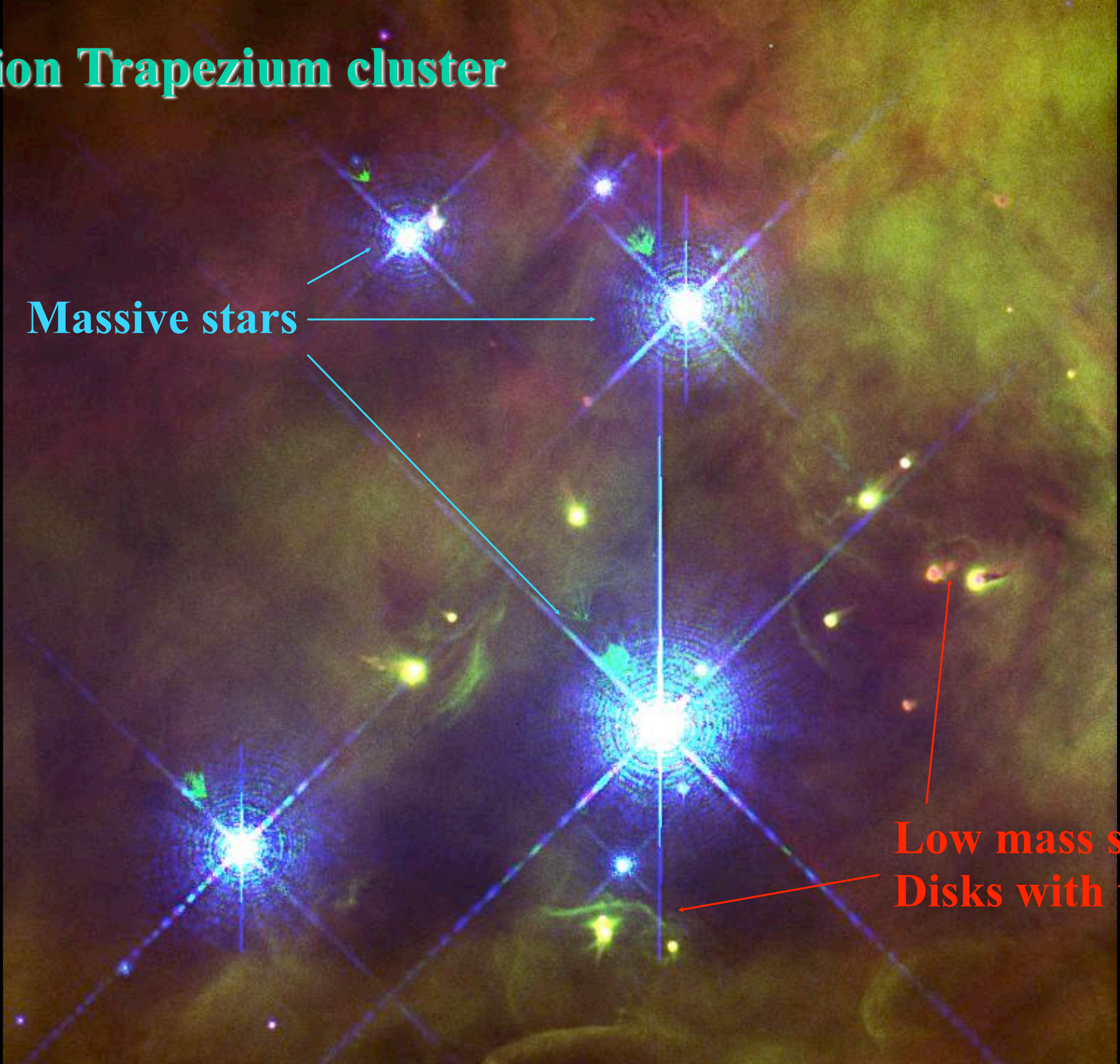

Orion Nebula
0.5 – 2.2 μm
10⁴ AU

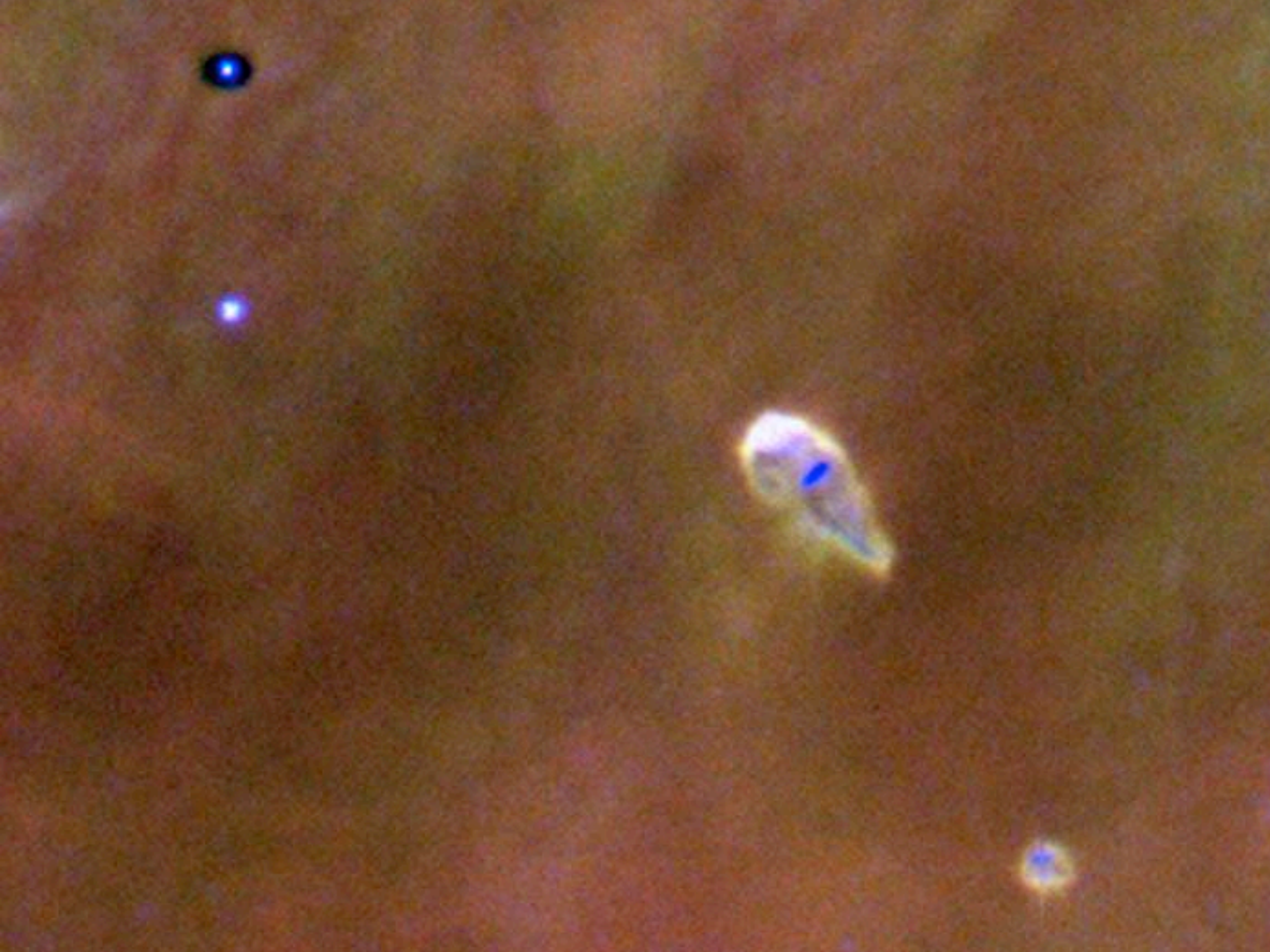
Orion Star Forming Region

- Closest bright star-forming region to Earth
- Distance ~ 1500 ly
- Age ~ 10 Myr
- Radius ~ few ly
- Mean separation ~ 10^4 AU



Orion Trapezium cluster





Largest Orion disk: 114-426, diameter 1200 AU

Star Formation

1961 view:

"Whether we've ever seen a star form or not is still debated. The next slide is the one piece of evidence that suggests that we have. Here's a picture taken in 1947 of a region of gas, with some stars in it. And here's, only two years later, we see two new bright spots. The idea is that what happened is that gravity has..."

Richard Feynman, *Lectures on Physics*

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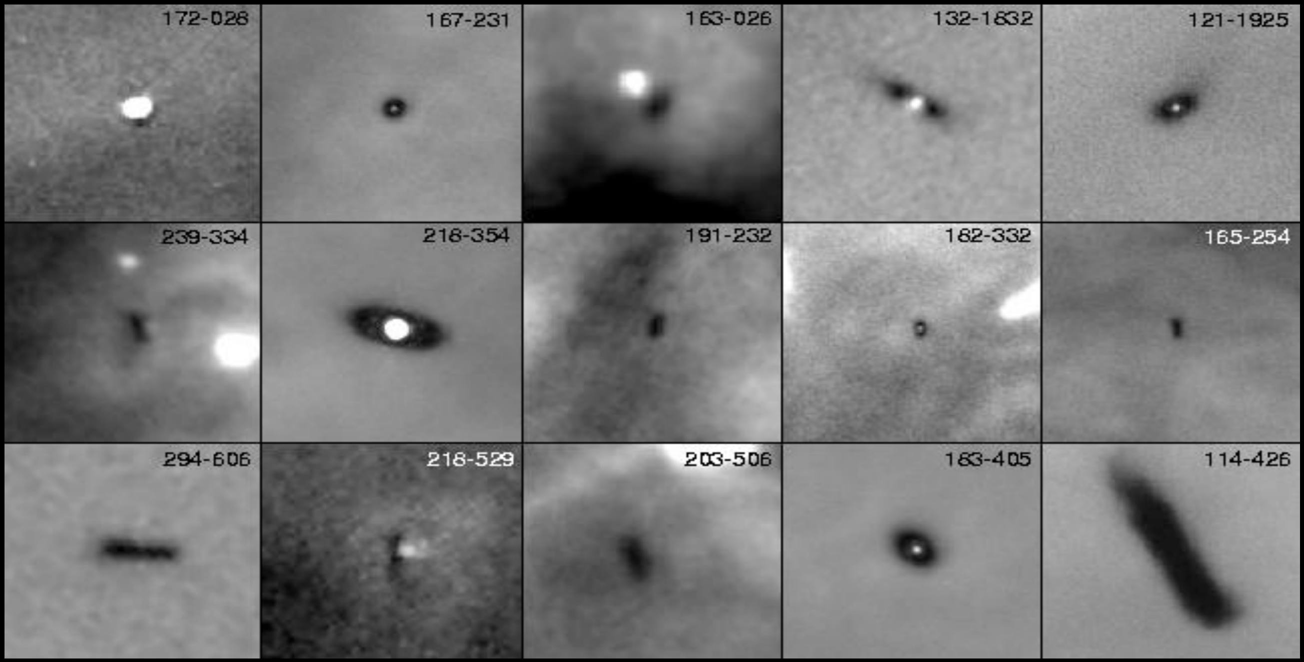
2000s view:

Infrared detectors have allowed us to directly see thousands of star forming -- nearly everywhere that we see an IR source. 1000+ young stars in Orion alone.

Whether we've ever seen a **planet** form or not is the current question!

Star Cluster Formation → Star Formation → Planet Formation

Circumstellar Disks In Orion



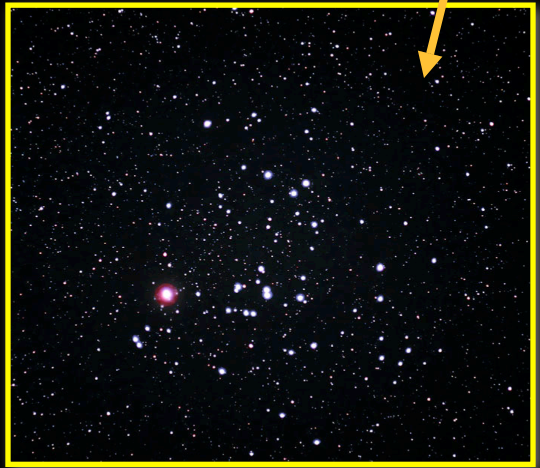
- 100+ disks directly observed, diameters 100-1200 AU
- 80%+ of stars in Orion show evidence for having disks

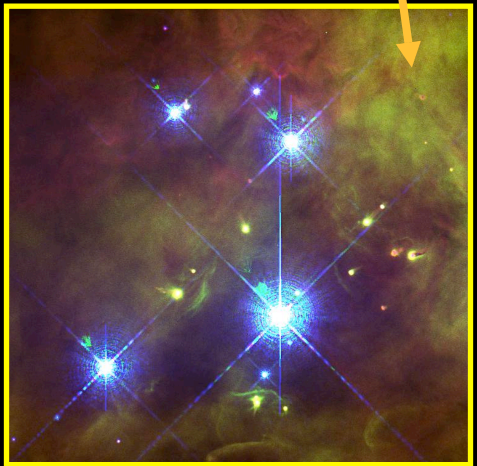
These stars are too distant and young to directly search for planets… but we want to study the environment and processes to understand the planets which would be produced in these dense clusters -- and therefore throughout the galaxy.

Regions of Star Formation

	Small Sparse Clusters	Large Dense Clusters
# of stars	10 - 100	10^3 - 10^4 10^4 stars in last 10 Myr (Orion)
OB stars	No	Yes
Distance	140 pc (Taurus)	450 pc (Orion)
Fraction of local stars which form here	10-30%	70-90% (Lada and Lada 2003)
Distance between stars	20,000 AU	5000 AU
Dispersal lifetime	Few Myr	
% of stars with disks	>80% (Smith et al 2005)	

Taurus: Dark, Small, Cold





Orion: Hot, Dense, Massive

** Most stars form in Orion-like regions!

Where did our Sun form?

- We have no idea!
- Only 1% of fields stars are in clusters today, but clusters only survive for 10 Myr.
- 90%+ of stars **form** in clusters.

- ^{60}Fe isotopes suggest Sun was born in a large cluster, few pc away from a supernova

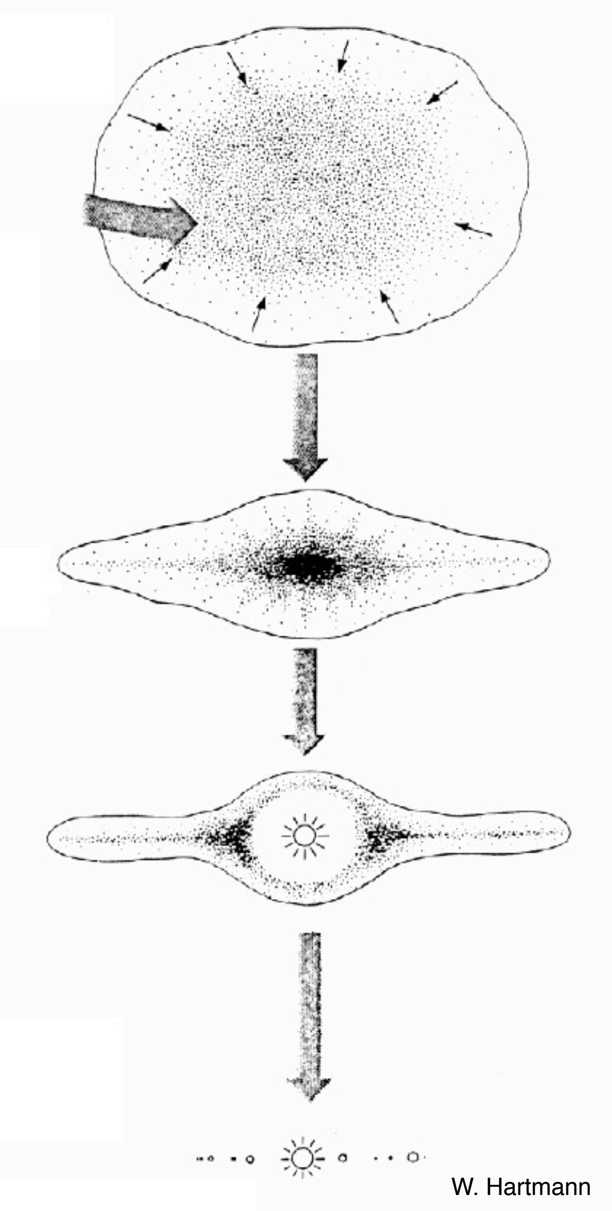
Planet Formation - Classical Model

Cloud core collapses due to self-gravity
  10,000 AU, 1 M_{sol}

Disk flattens; grains settle to midplane
Planet cores grow
  Disk Mass: 'Minimum Mass Solar Nebula'
    MMSN = 0.01 M_{sol}
  Star Mass: ~ 1 M_{sol}

Terrestrial planets form
Jovian planets accrete gas

Disk disperses
Solar System complete after ~ 5-10 Myr



How does Cluster Environment affect Disk Evolution?

- Interaction with cluster gas
- UV photoevaporation from massive stars
- Close stellar encounters
- UV, X ray chemistry

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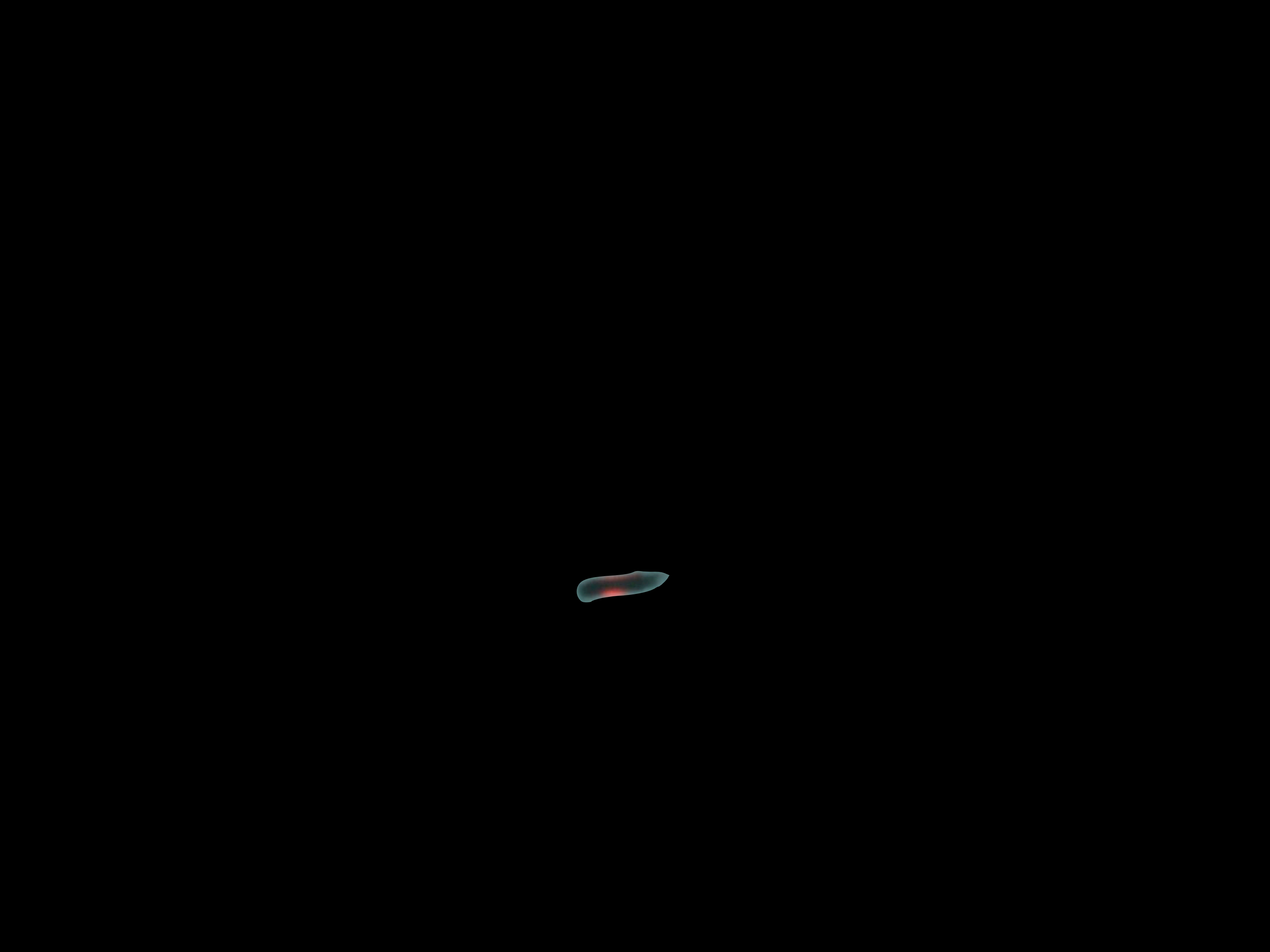
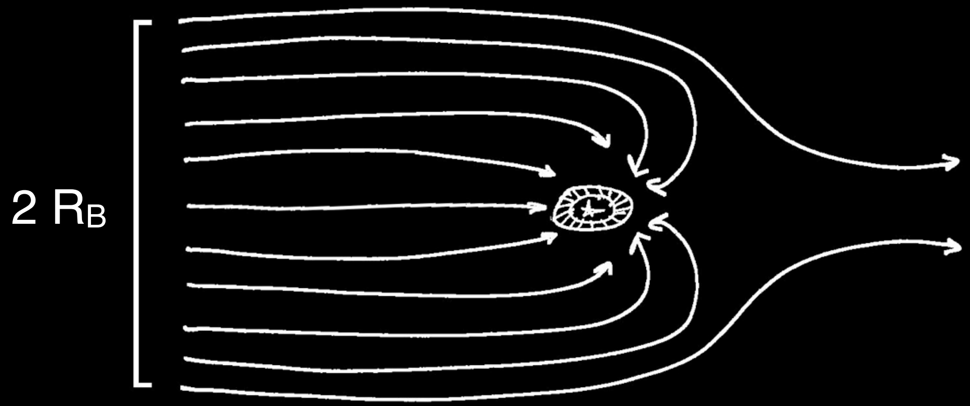


Bondi-Hoyle Accretion



- Cool molecular H_2 from cluster ISM accretes onto disks
- Accretion flow is **onto disk**, not star.
- Accretion is robust against stellar winds, radiation pressure, turbulence.
- This accretion is not considered by existing Solar System formation models!

1 MMSN = 1 'Mimimum Mass Solar Nebula' = 0.01 M_{Sol}

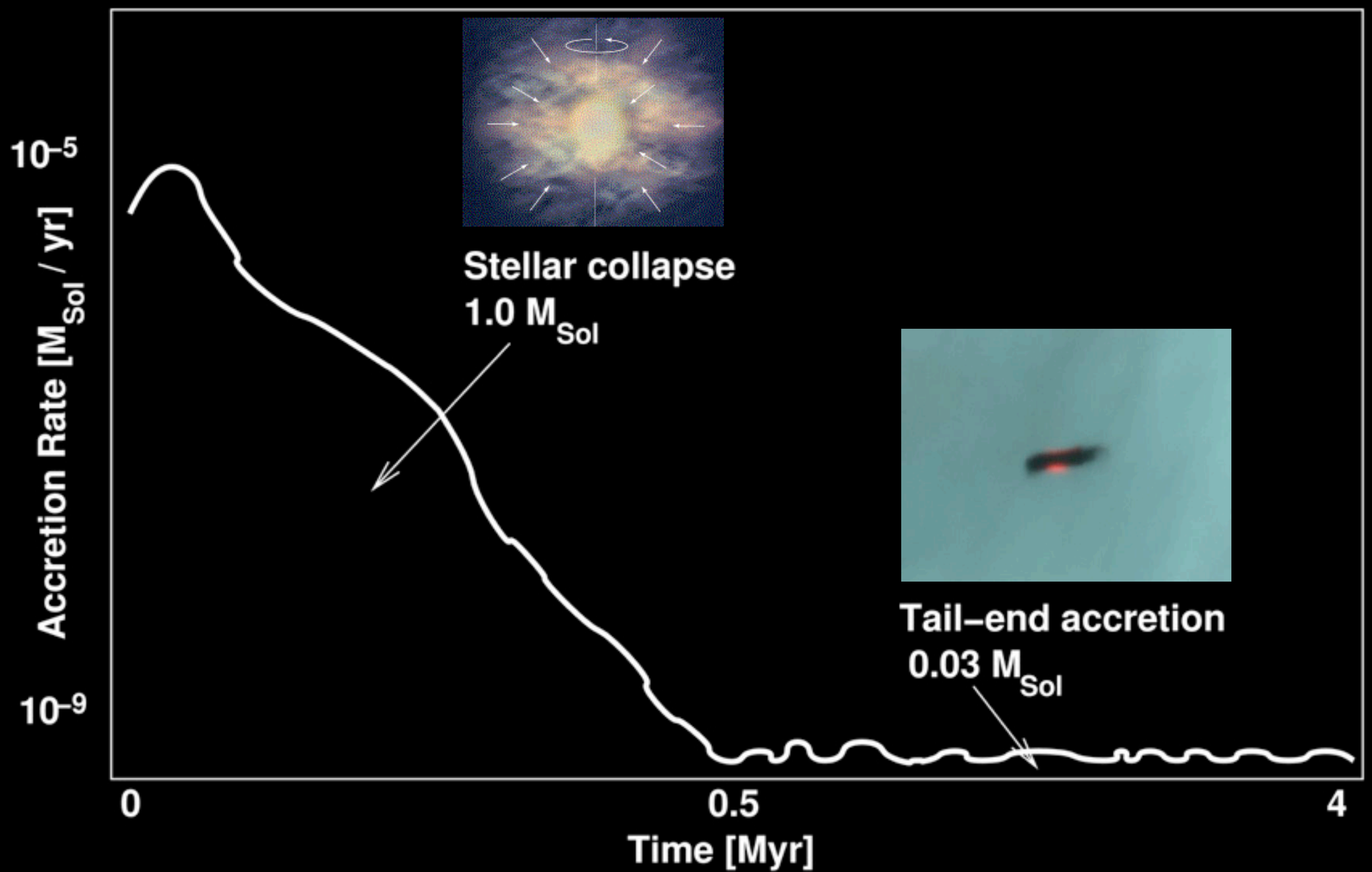
$$R_B = \frac{2\,G\,M}{(v^2 + c_s^2)}$$

Accretion radius ~ 1000 AU

$$\dot{M}_B = \frac{4\pi\,G^2 M^2}{(v^2 + c_s^2)^{3/2}}\; n\, m_h$$

Accretion rate ~ 1 MMSN / Myr

Timescale of Star Formation



Gas Accretion + N-Body Cluster Simulations

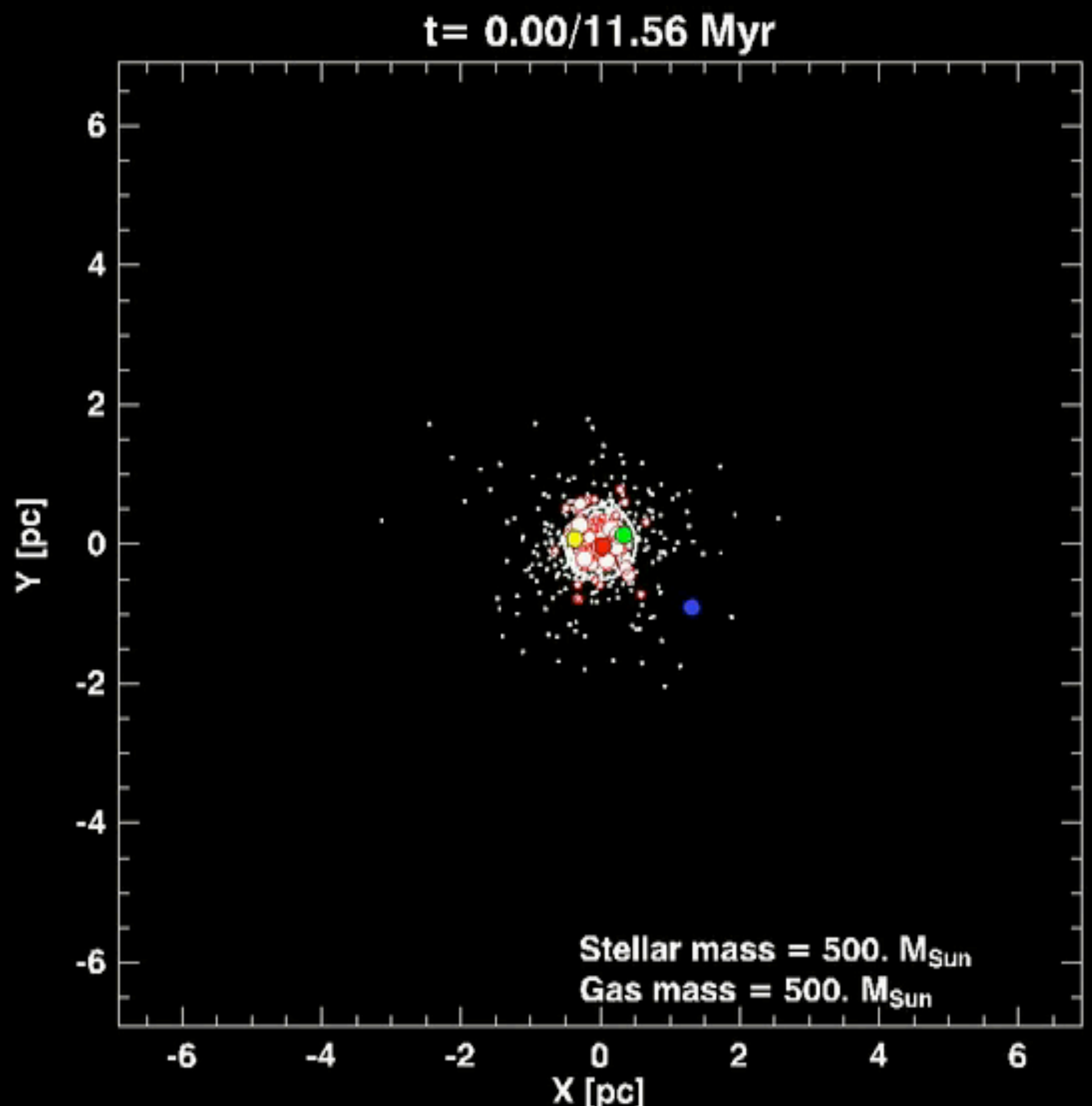
NBODY6 code (Aarseth 2003)

Stars:

- N=1000
- M_{star} = 500 M_{sun}
- Kroupa IMF
- R_0 = 0.5 pc

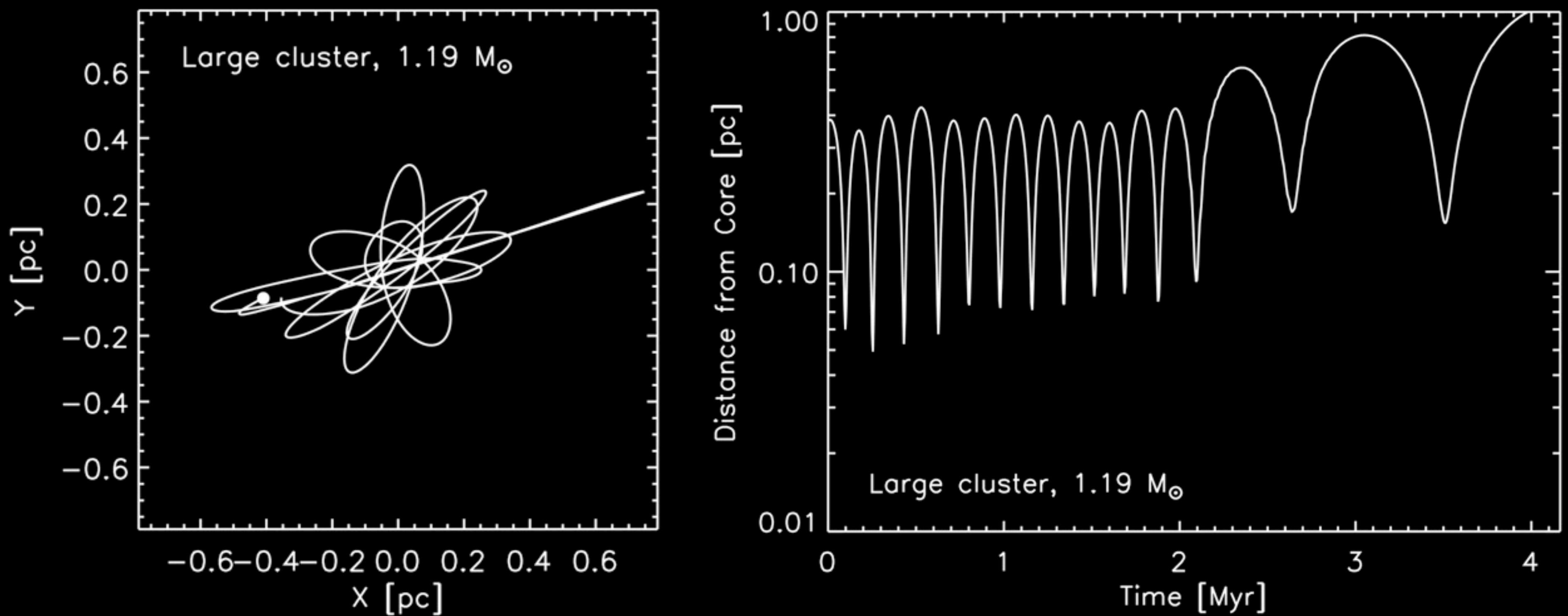
Gas:

- M_{gas} = 500 M_{sun}
- R_0 = 0.5 pc
- Disperses with timescale 2 Myr



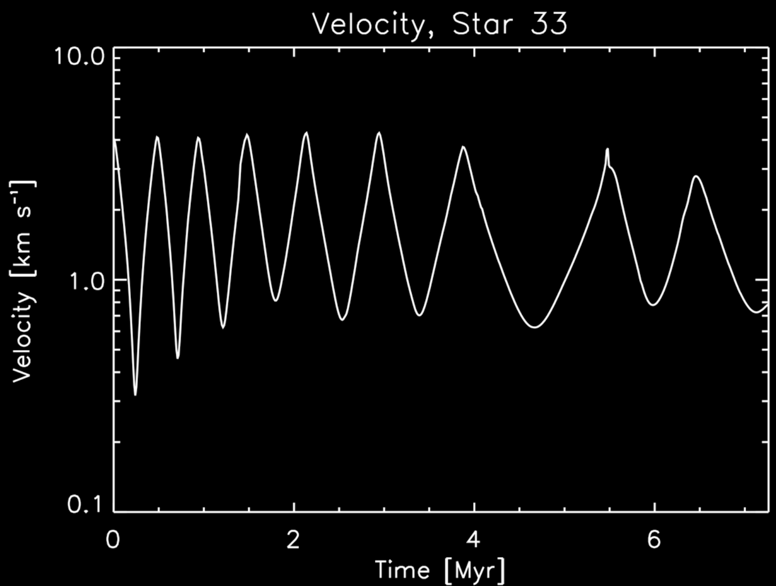
Throop & Bally 2008

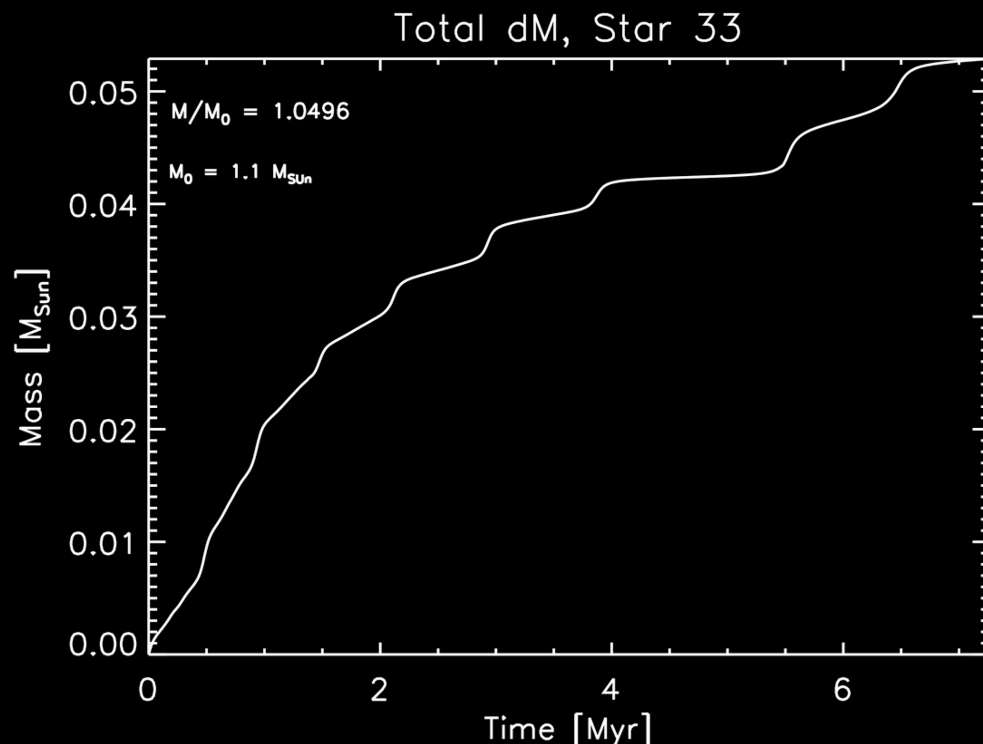
BH Accretion: History of individual star

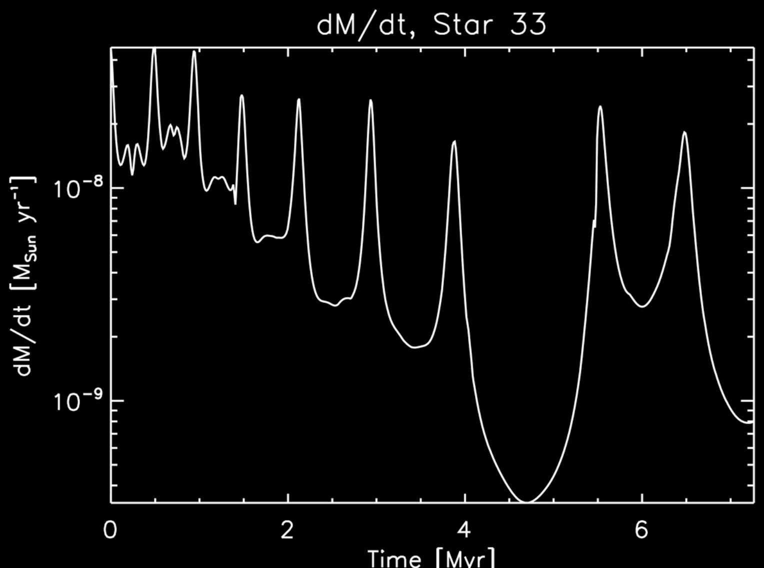


Following trajectory of one star of 3000 from N-body simulation...

BH Accretion: History of individual star





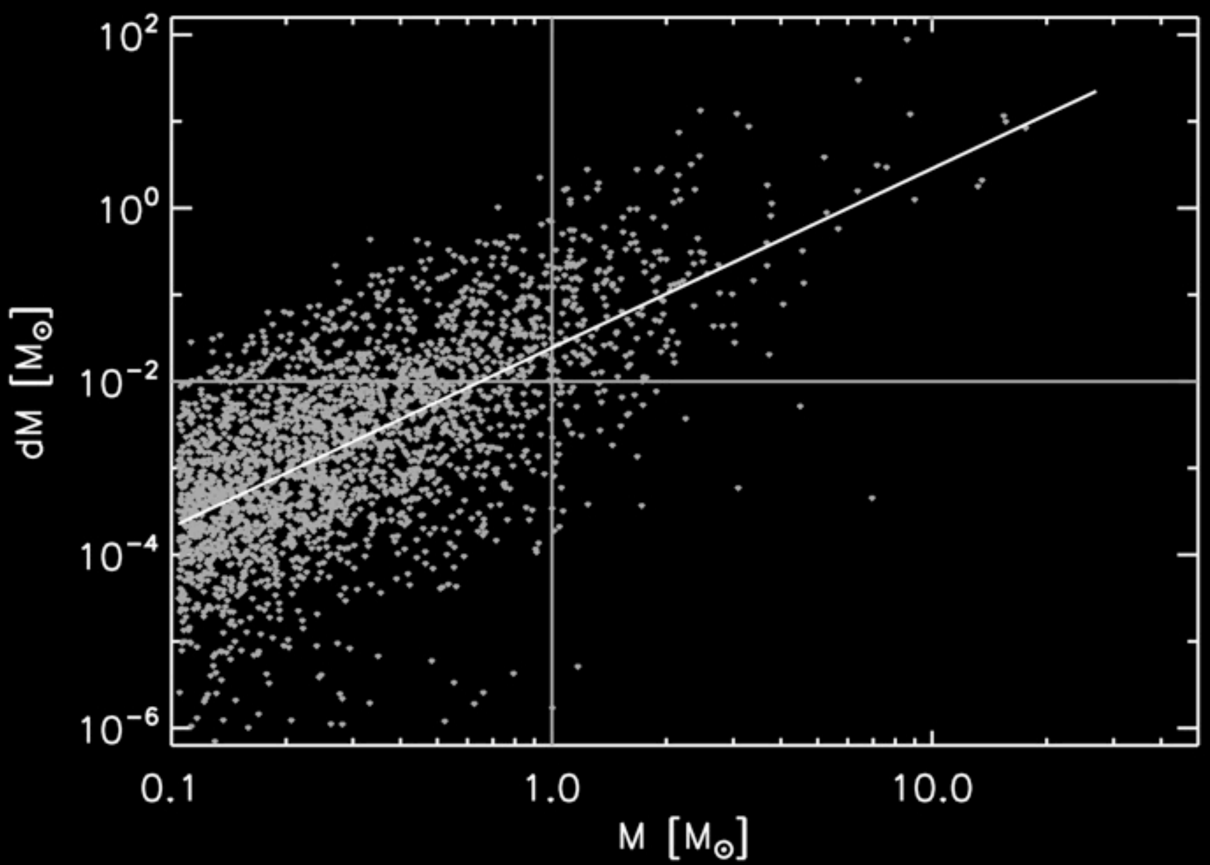


Star+disk accretes 5% of own mass in 5 Myr.

Accretion is episodic

- Highest at core: High velocity but high density

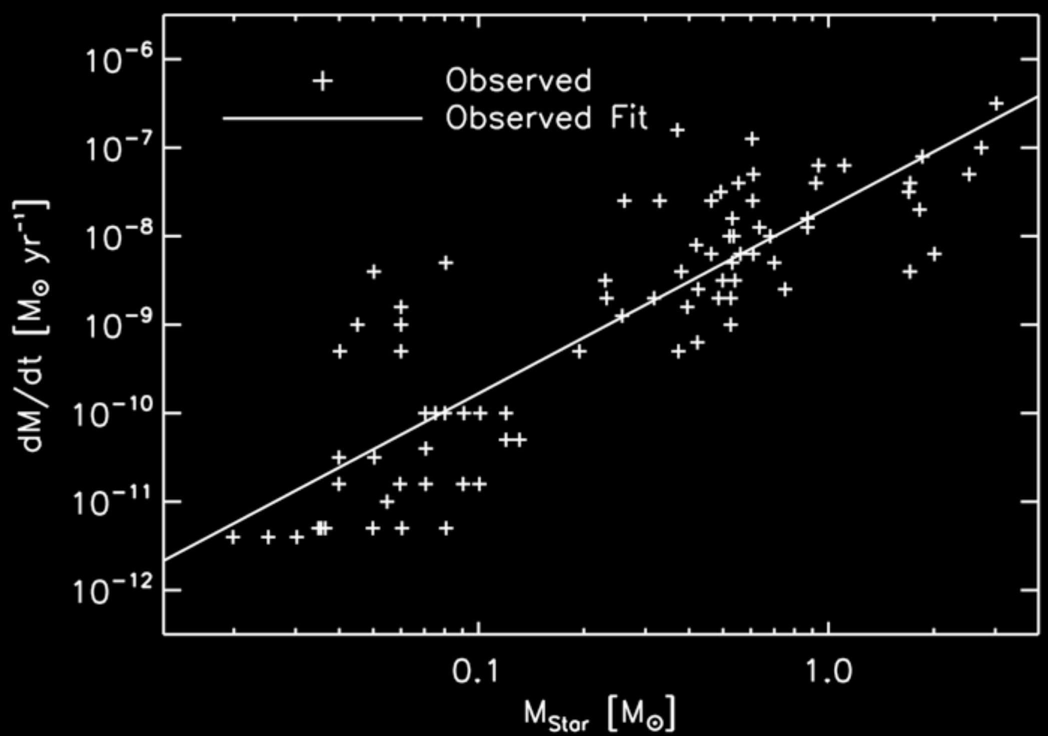
Results of N-Body sims



- Typical mass accreted by disks surrounding Solar-mass stars is 1 MMSN per Myr
- Accretion occurs for several Myr, until cluster disperses or cloud is ionized

Observations of accretion in young stars

- Accretion observed onto hundreds young stars in molecular clouds varies with stellar mass: $dM/dt \sim M^2$
  - Natta et al 2006, Muzerolle et al 2005, etc
- Accretion is $\sim 0.01\ M_\odot\ \mathrm{Myr}^{-1}$
- There is no accepted physical explanation for this relationship.



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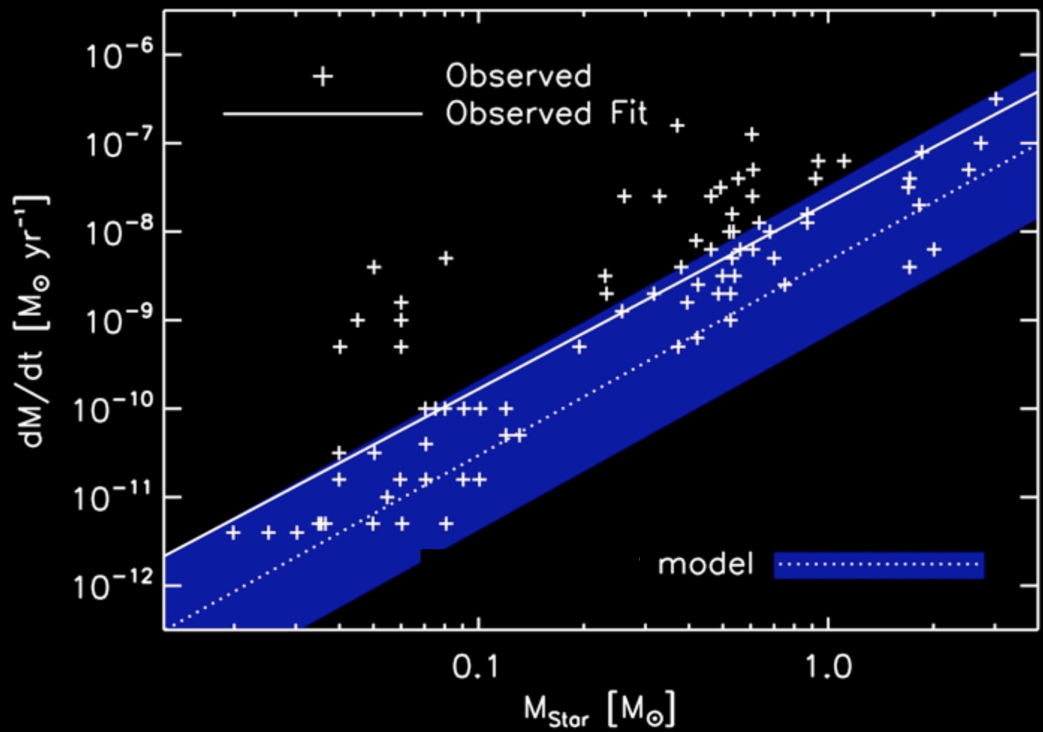
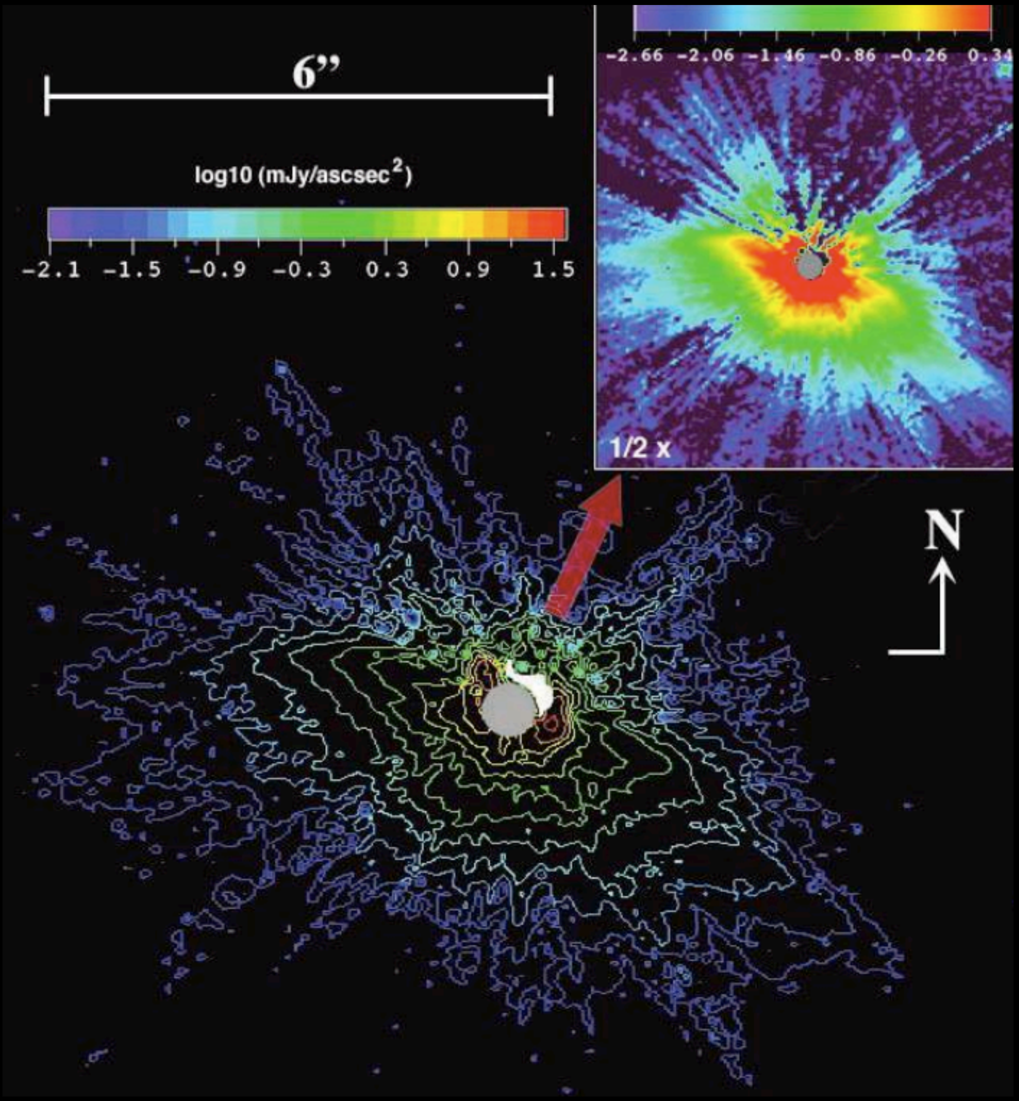


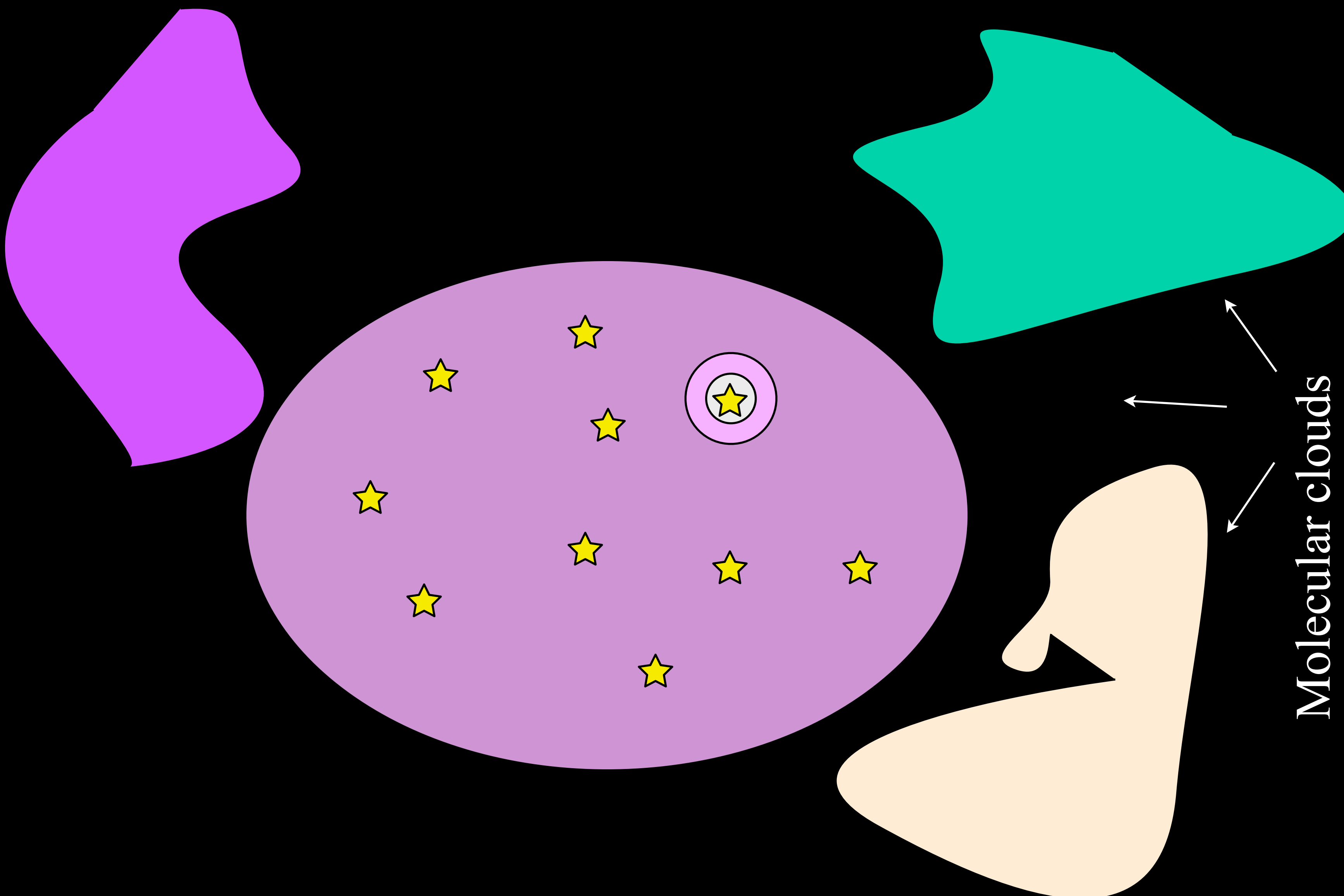
Accretion **onto young stars** may be due to ISM accretion **onto their disks**

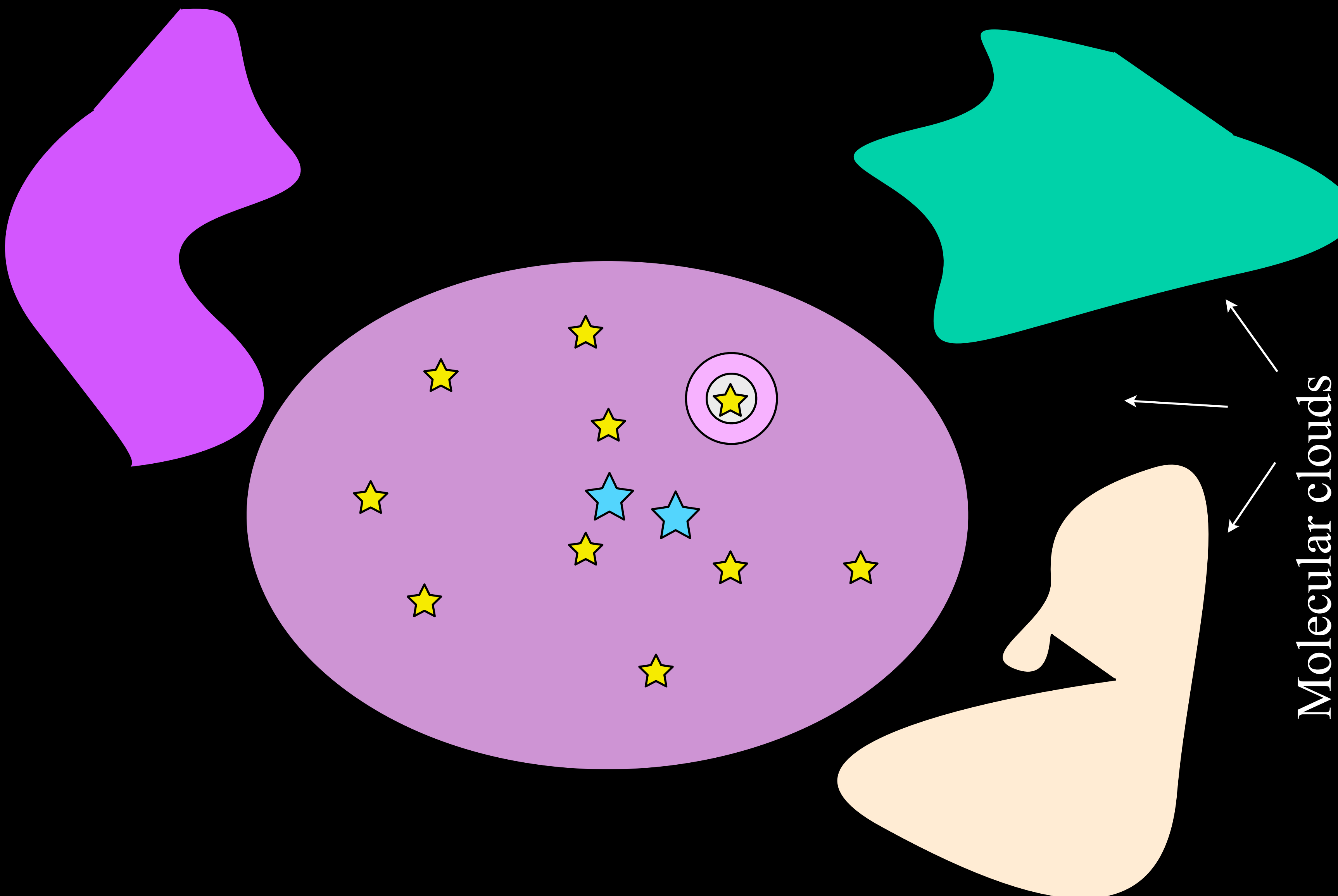


Possible BH accretion in ‘The Moth’, HD 61005
(Hines et al 2007)

Disk is swept back due to ram pressure, n ~ 100 cm^{-2}, 35 pc.

Evidence of ISM-disk interaction.


Molecular clouds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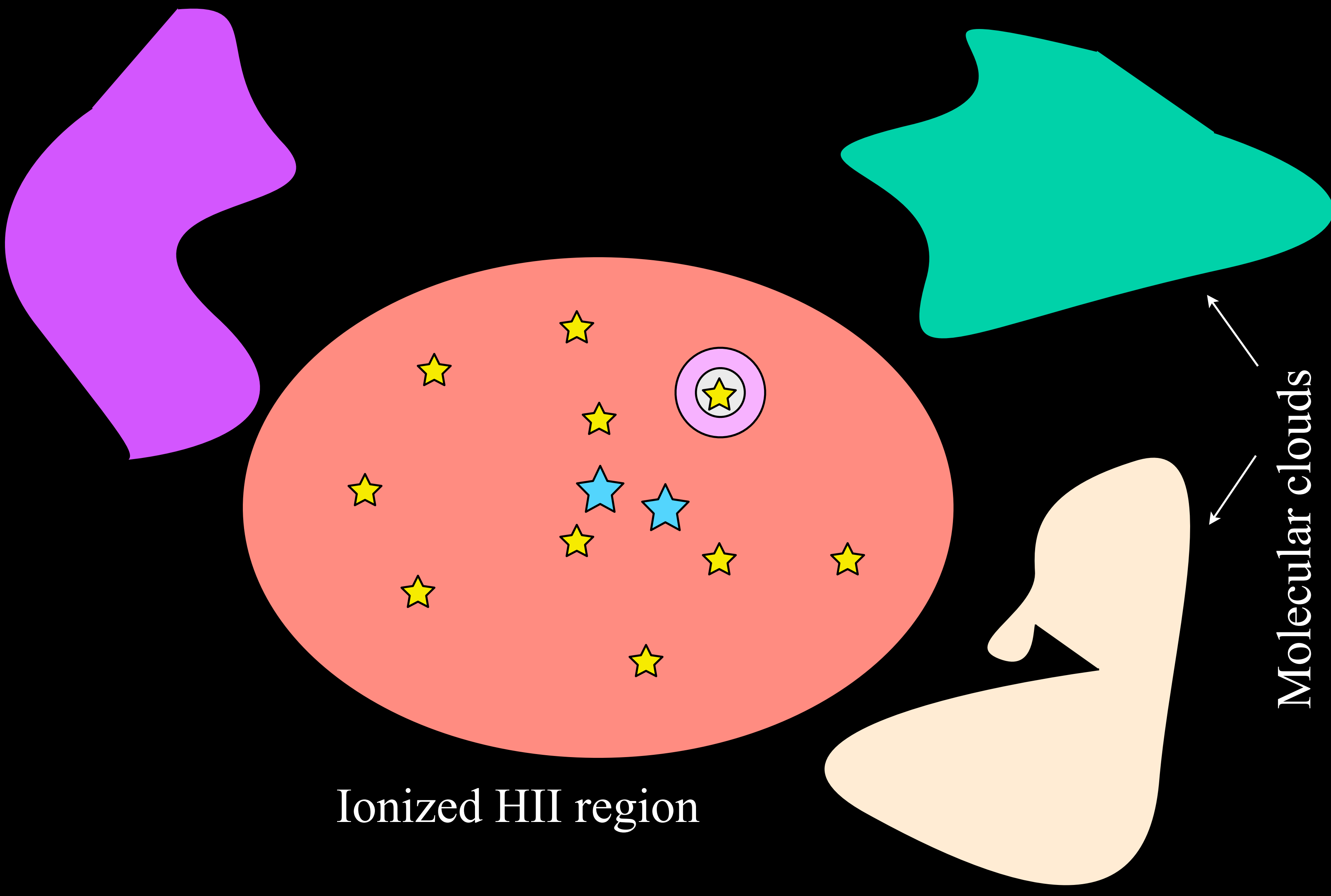
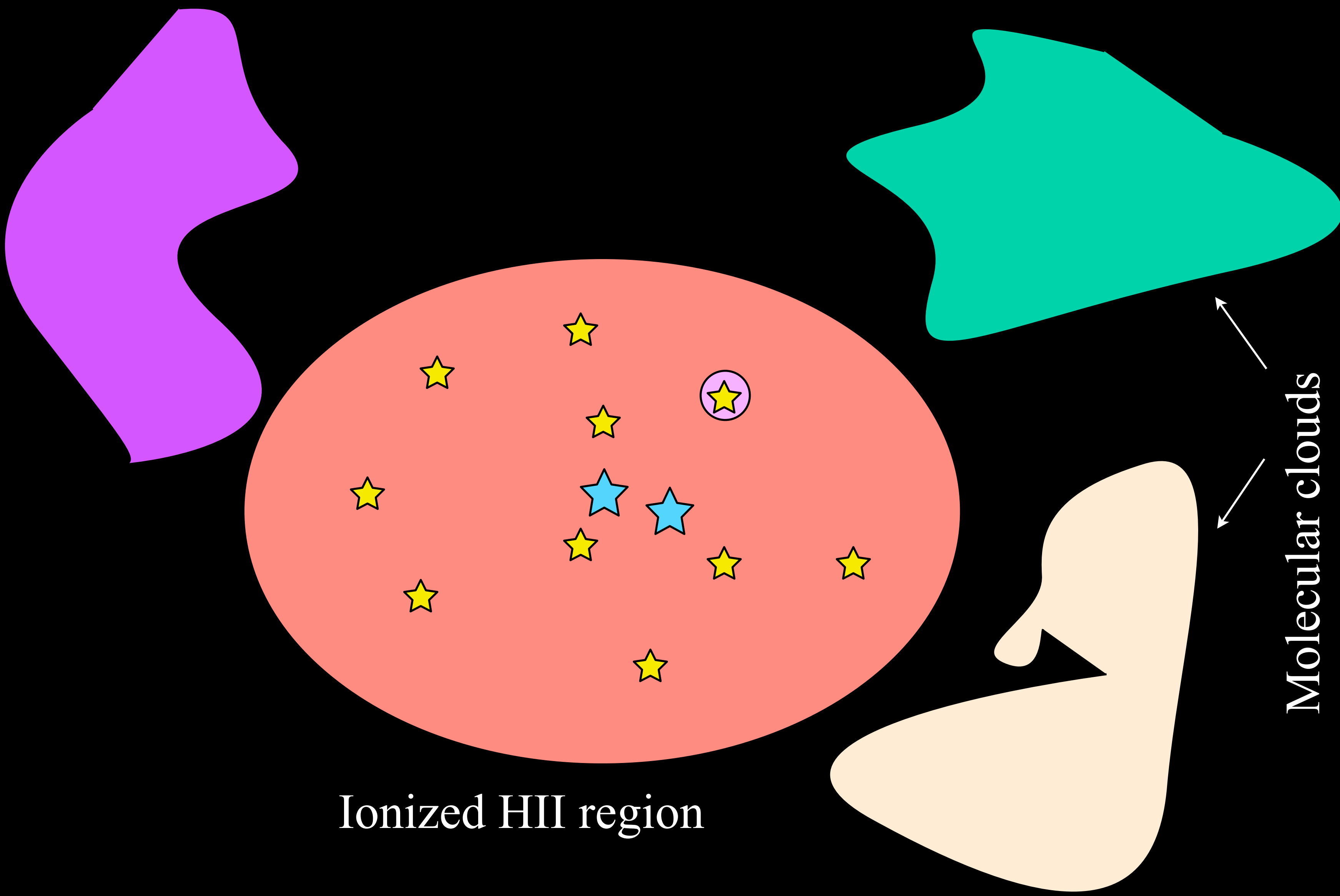

Molecular clouds
Ionized HII region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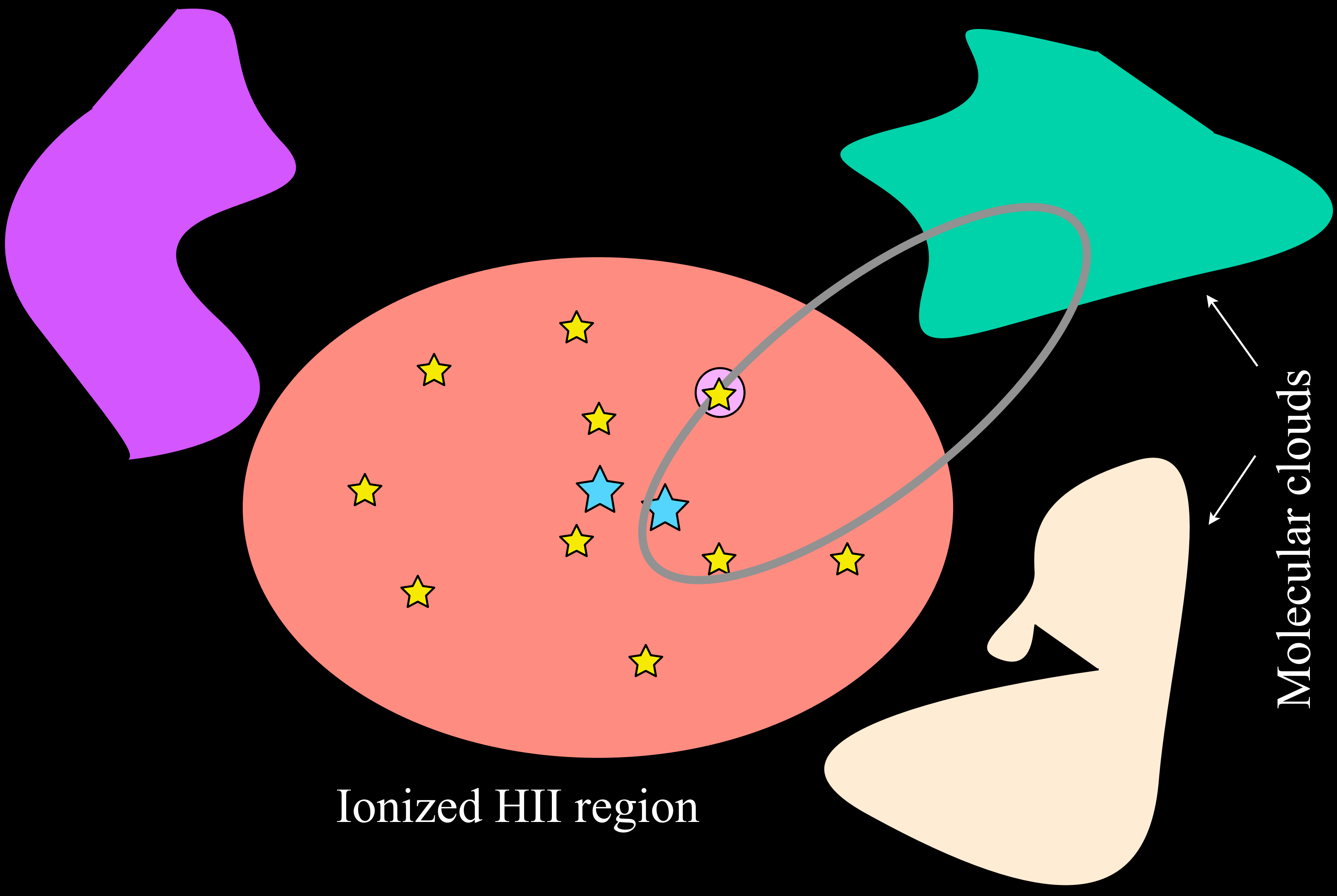
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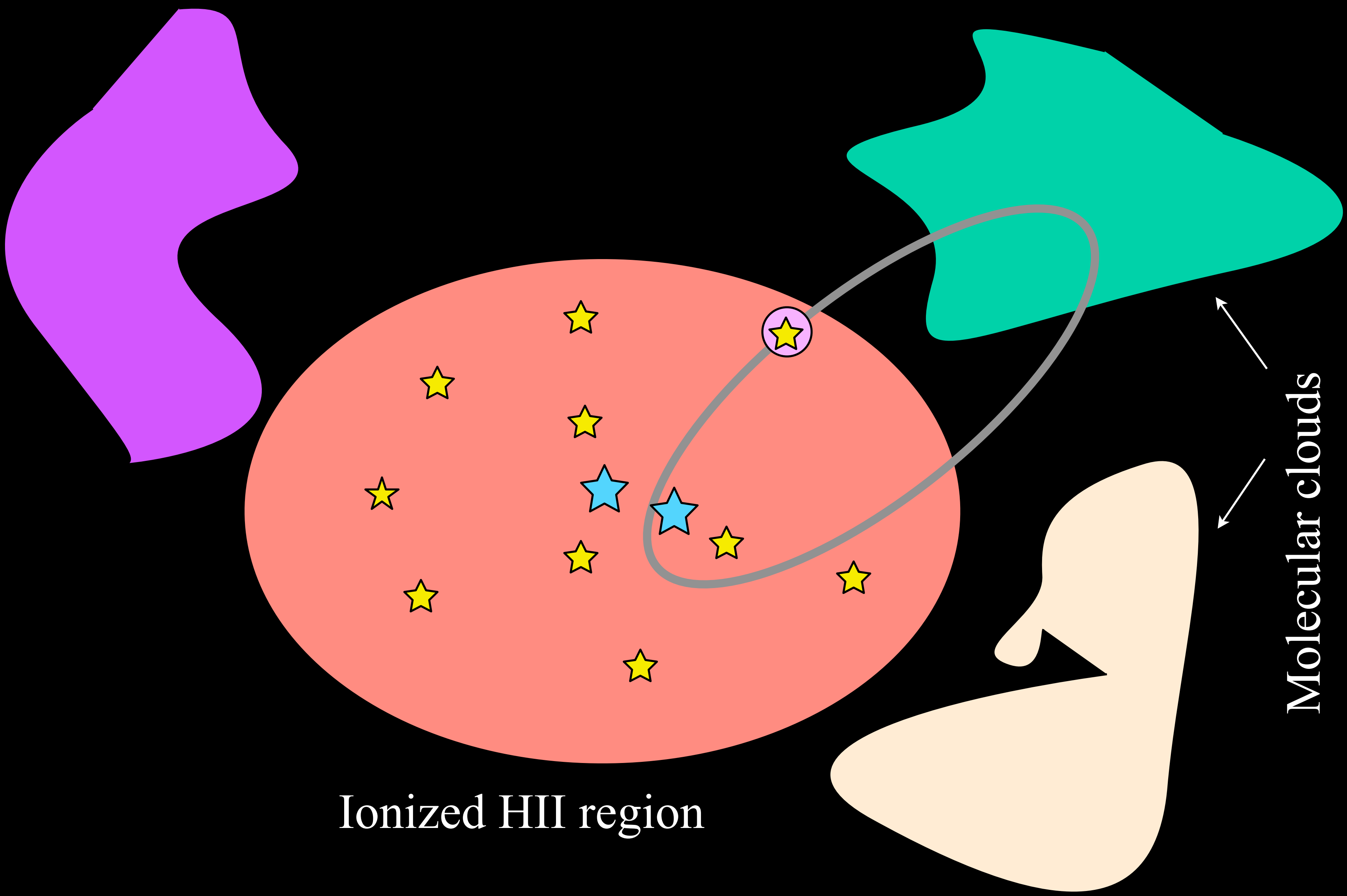

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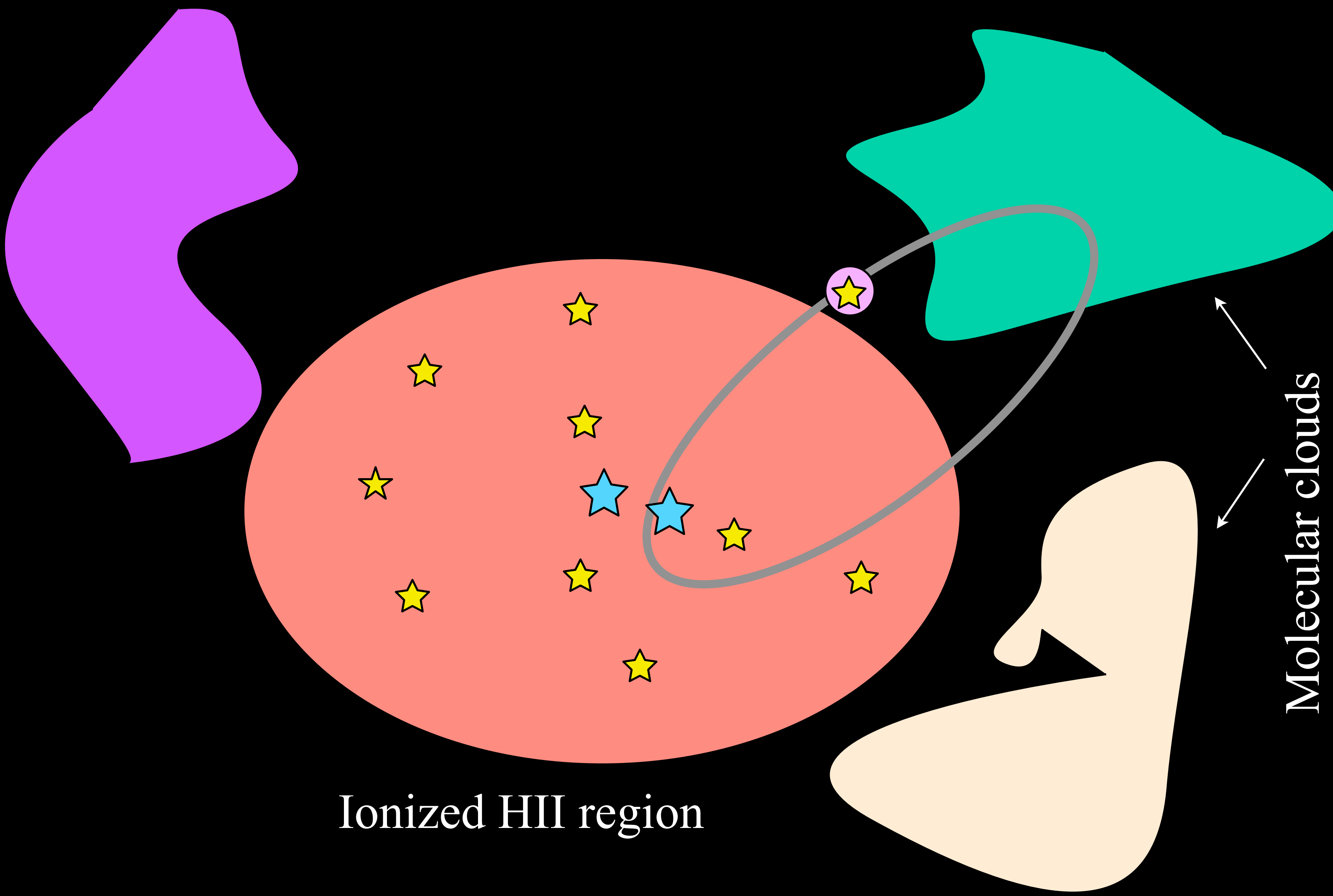
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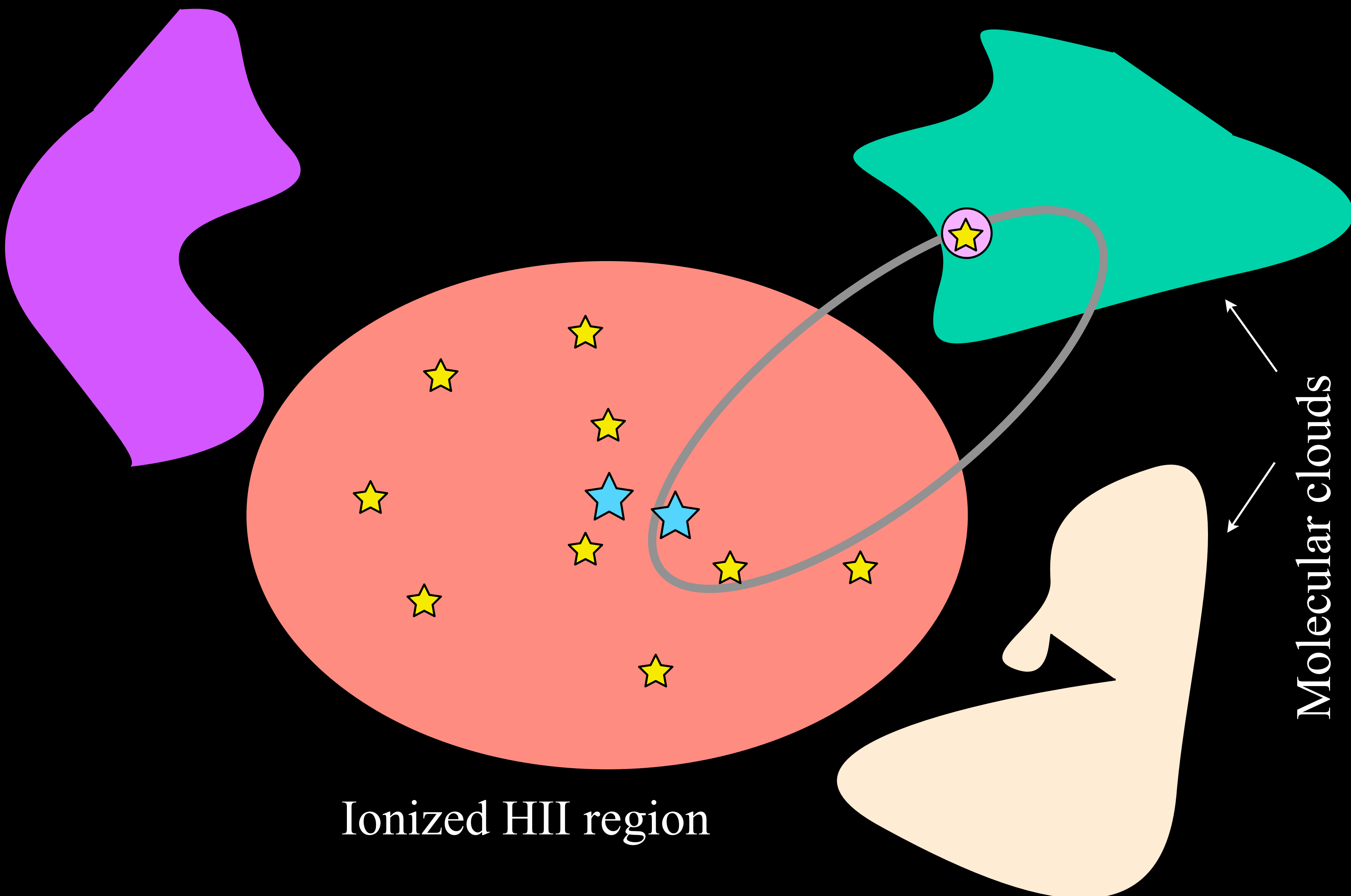
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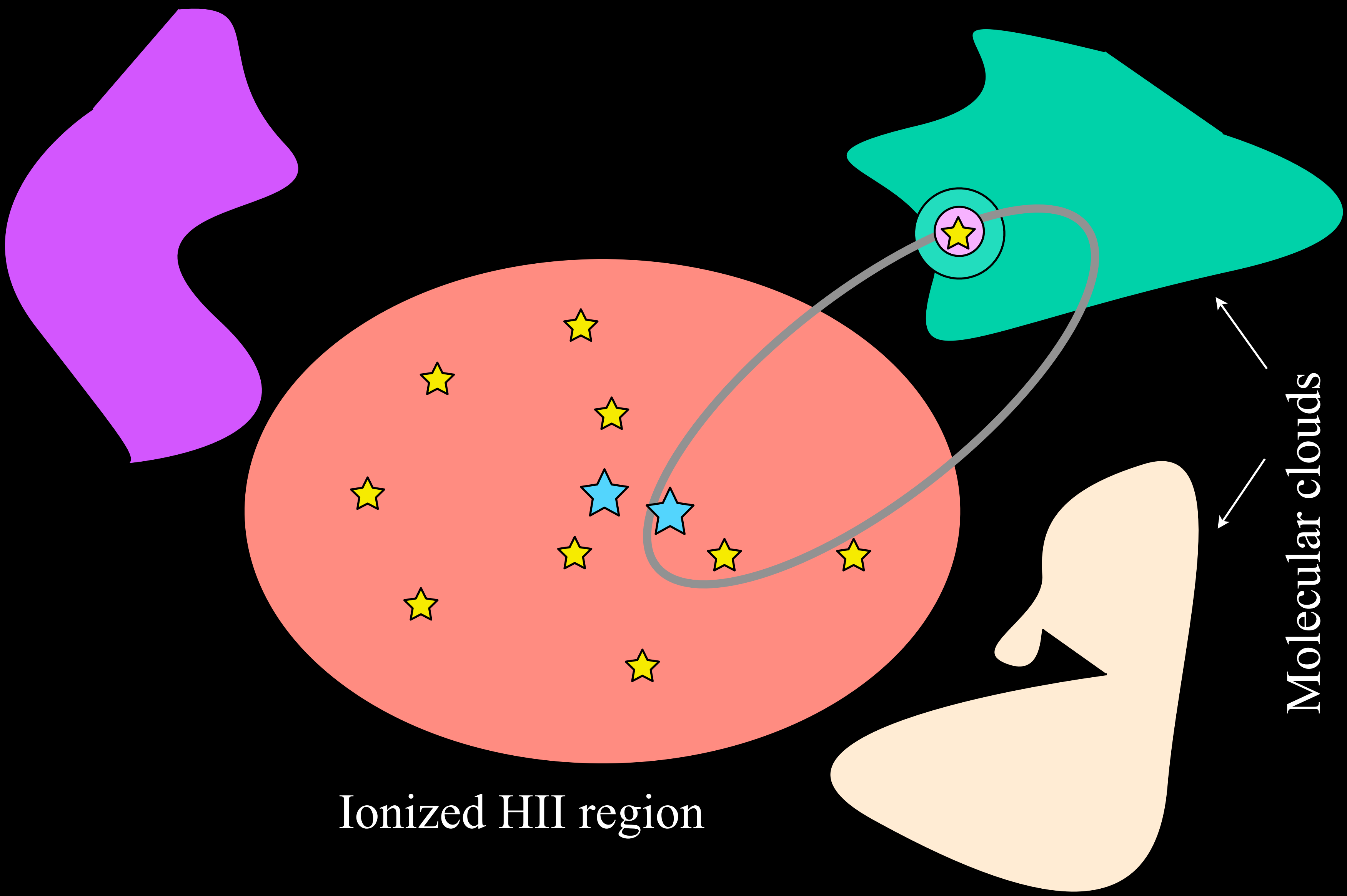
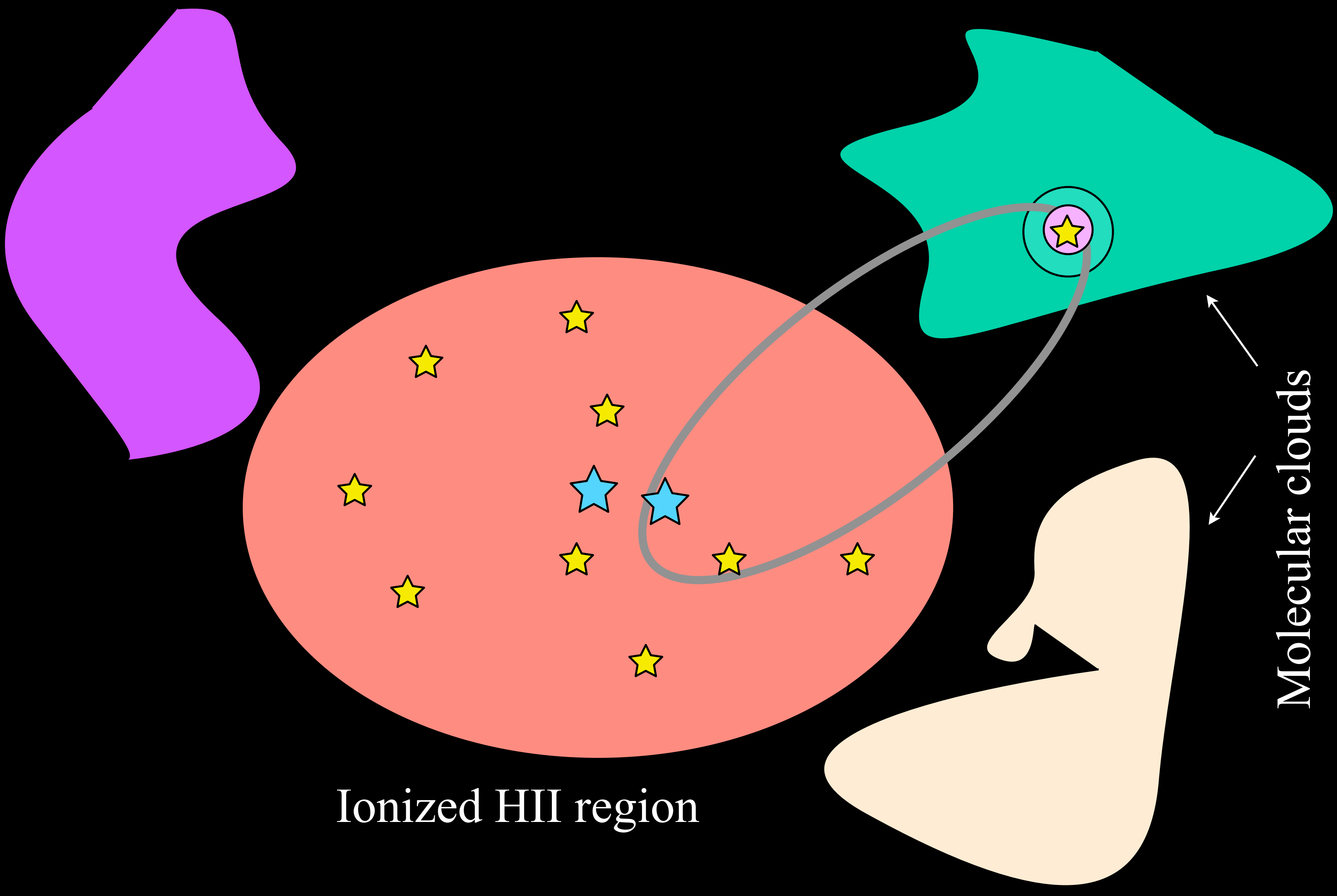

Ionized HII region
Molecular clouds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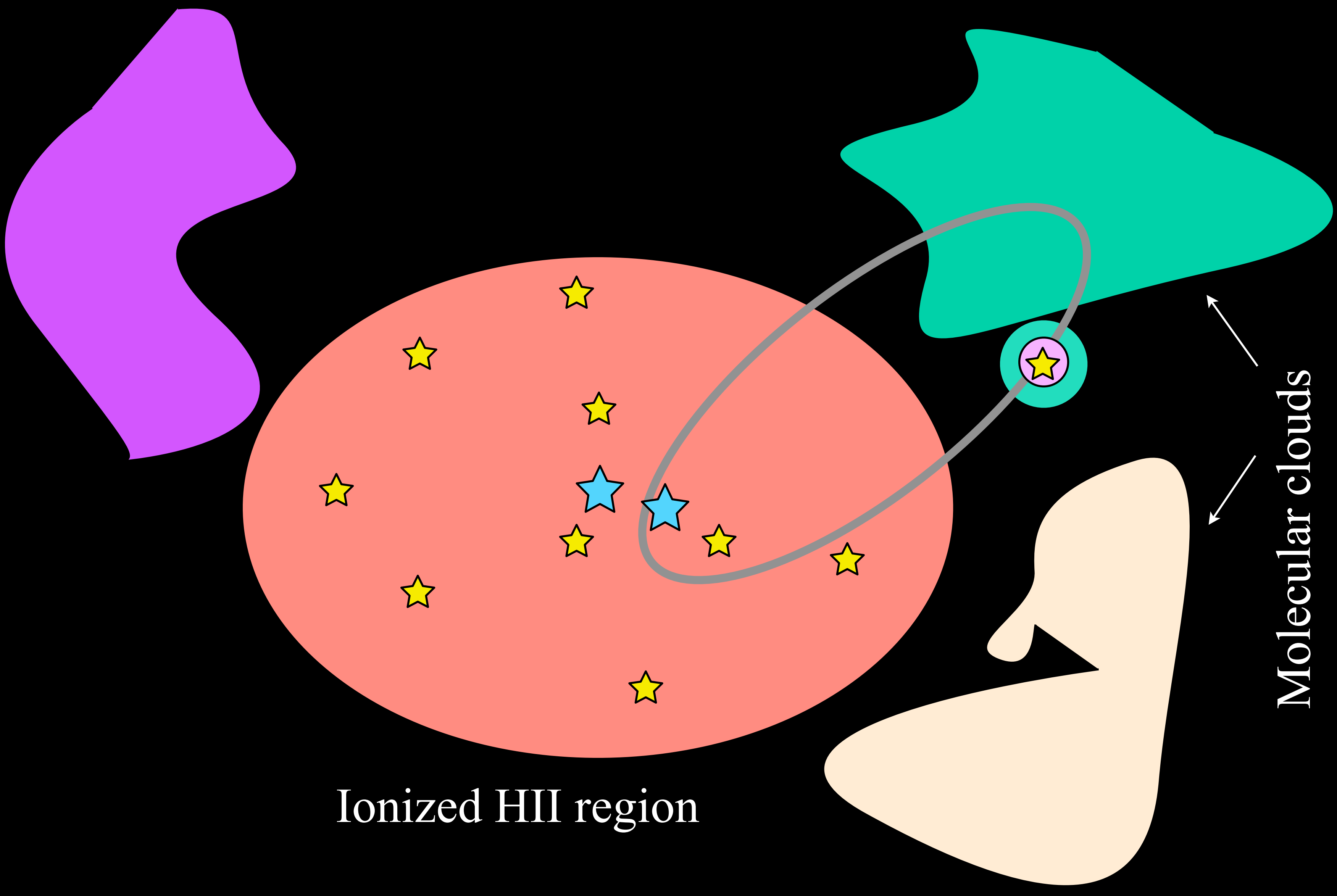
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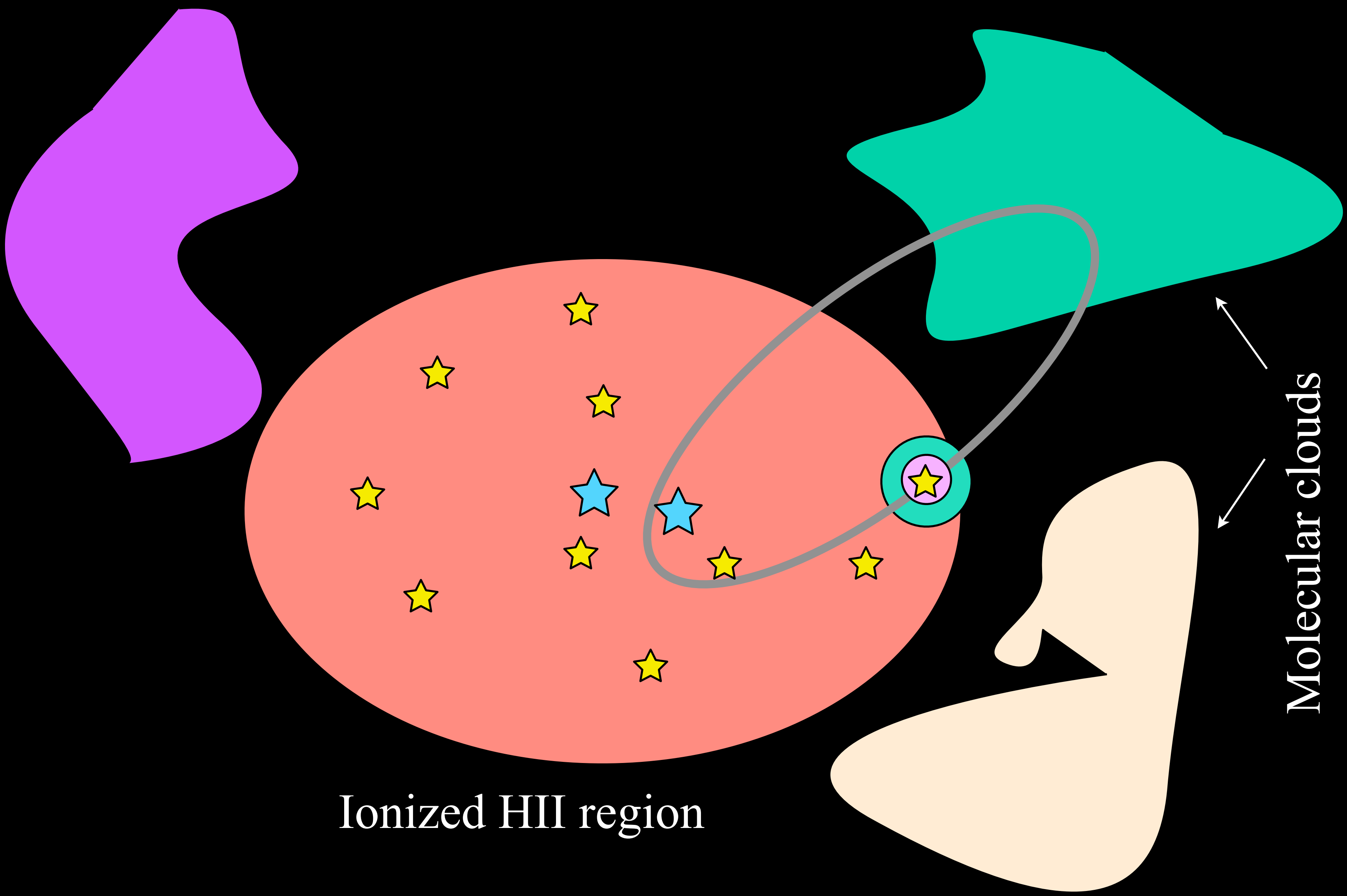
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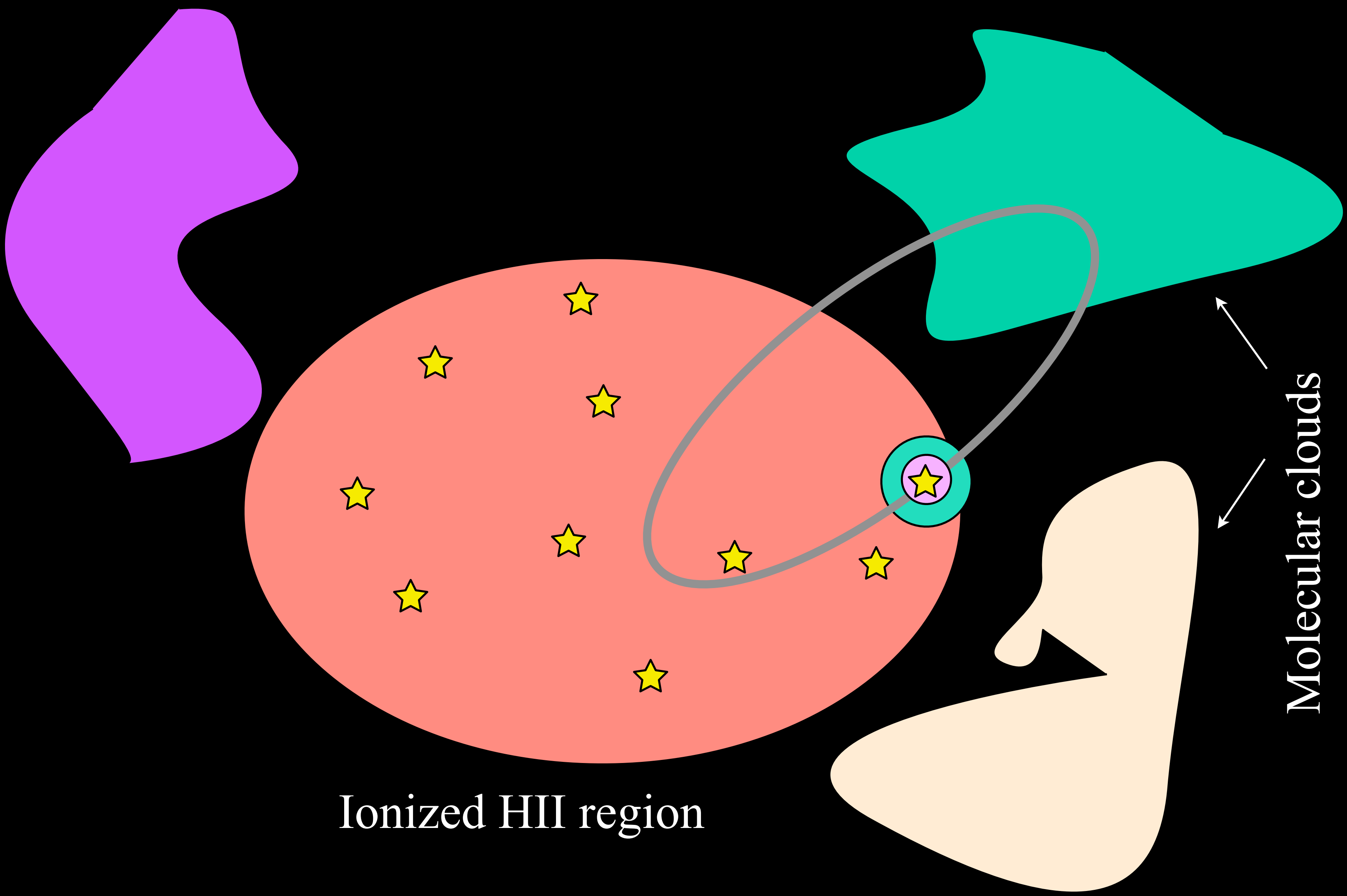
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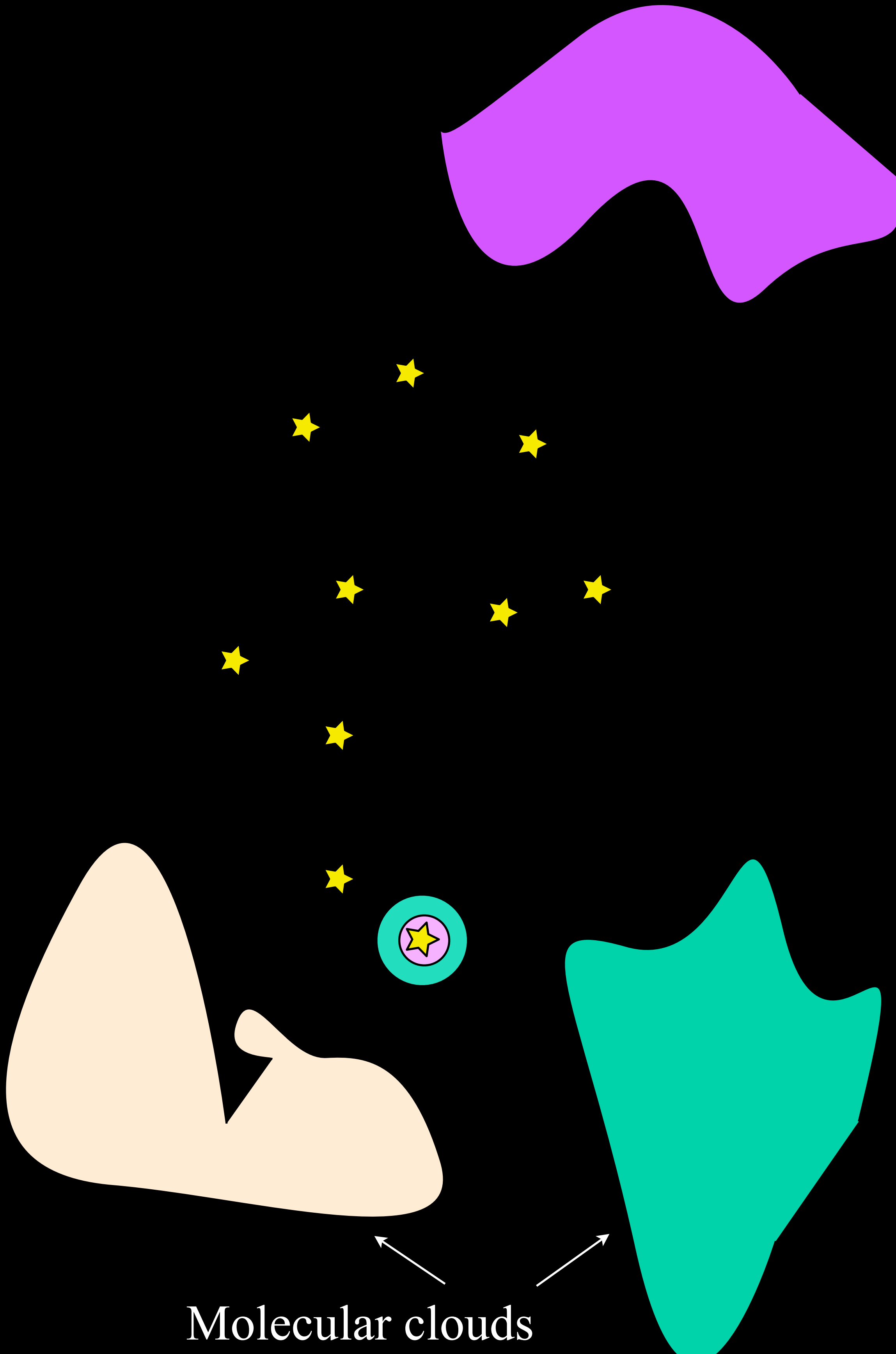
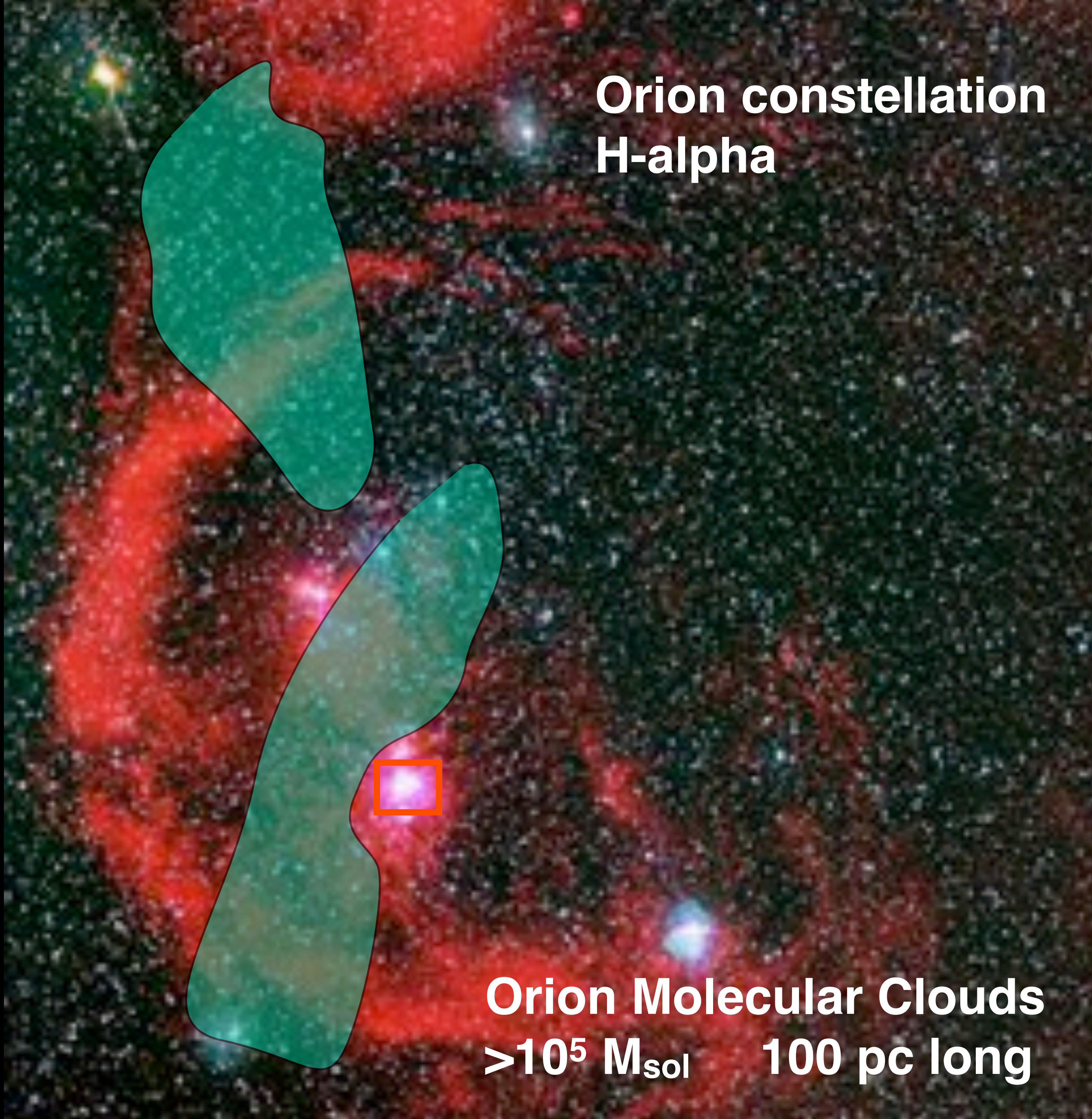
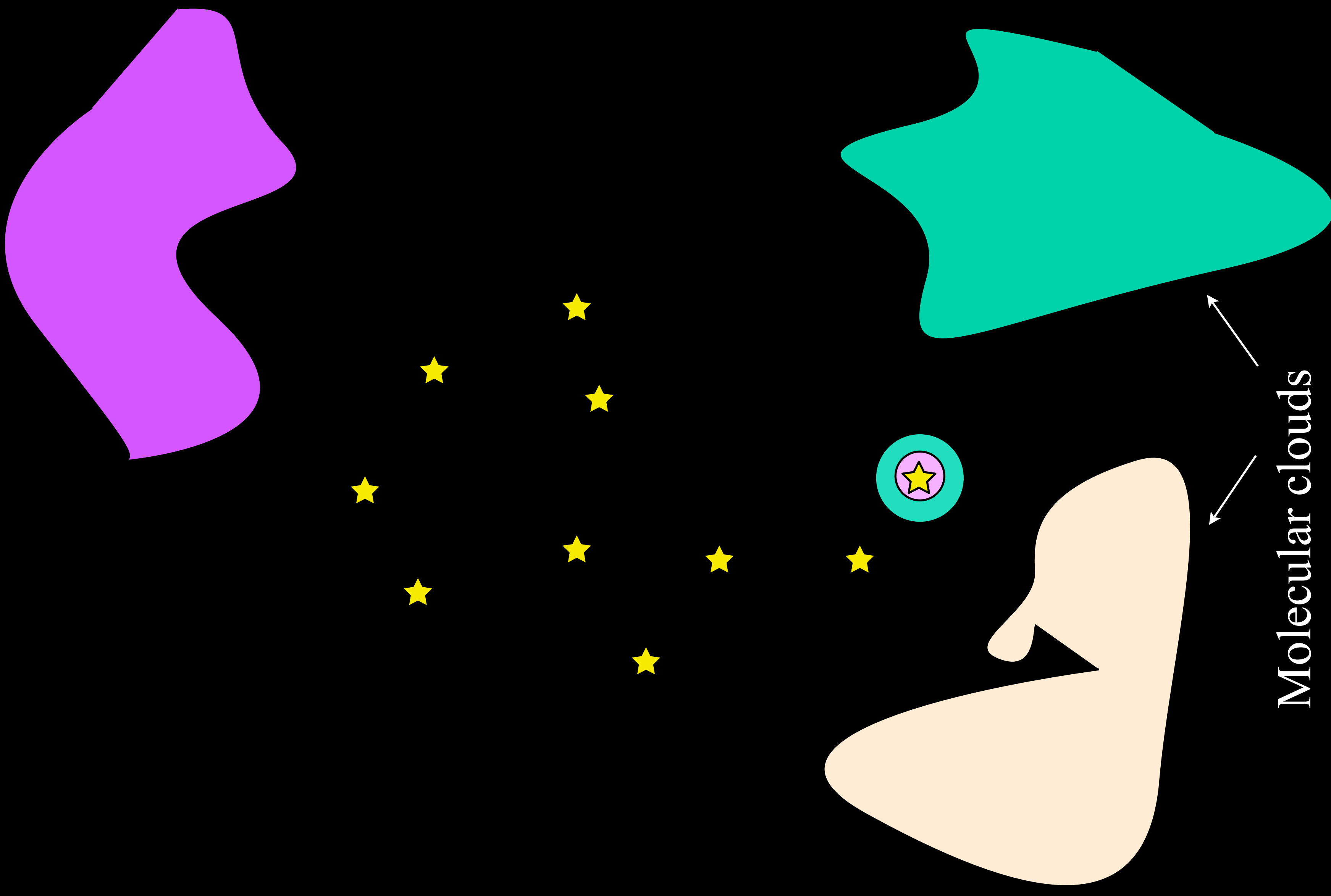
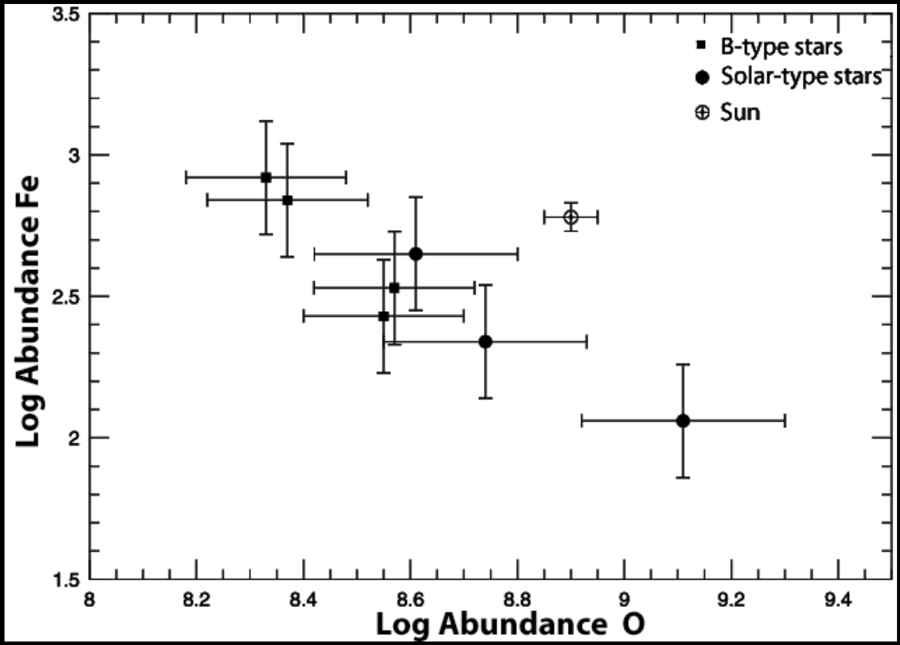

Molecular clouds


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


Molecular clouds

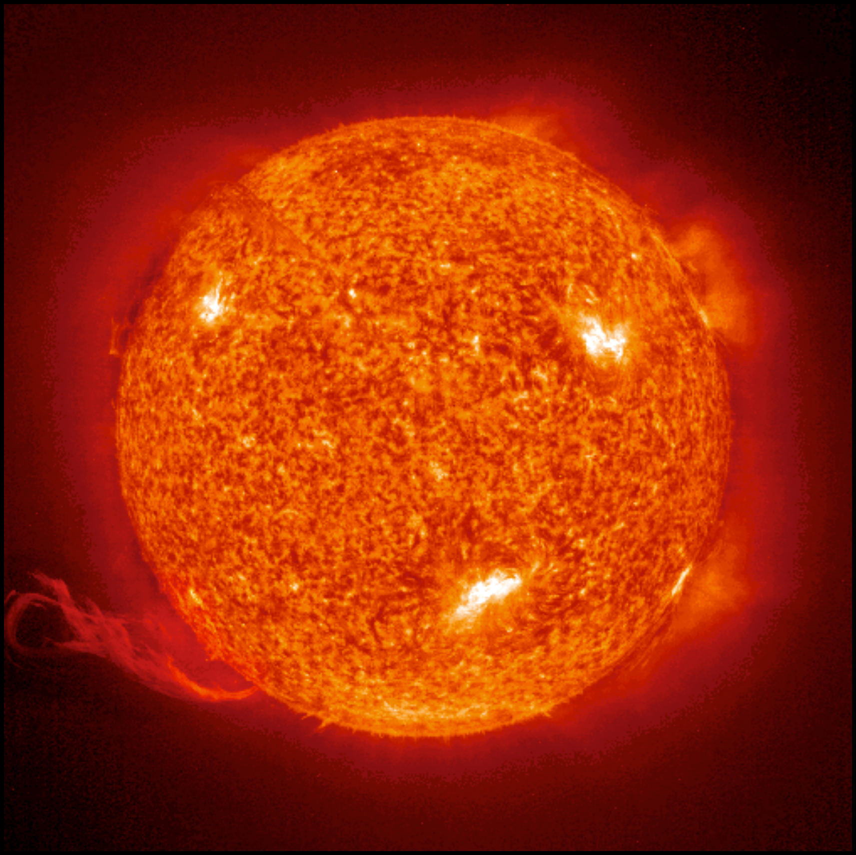
Accretion of 'polluted' ISM

- Stars of same age/position/ type in Orion show metallicities that vary by up to 10x in Fe, O, Si, C (Cunha et al 2000)
- Could stars have accreted metallic 'veneers' by passing through nearby molecular clouds, contaminated with supernova ejecta?
- 20 M_{Sol} SN produces 4 M_{Sol} O



Late accretion may cause the composition of a star, its disk, and its planets to all be different! There may be no 'Solar Nebula Composition.'

Jupiter vs. the Sun



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

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

We propose a crazy idea for Jupiter's composition:

1. Solar System forms in a large star cluster.

2. Massive stars pollute ISM with heavy elements.

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

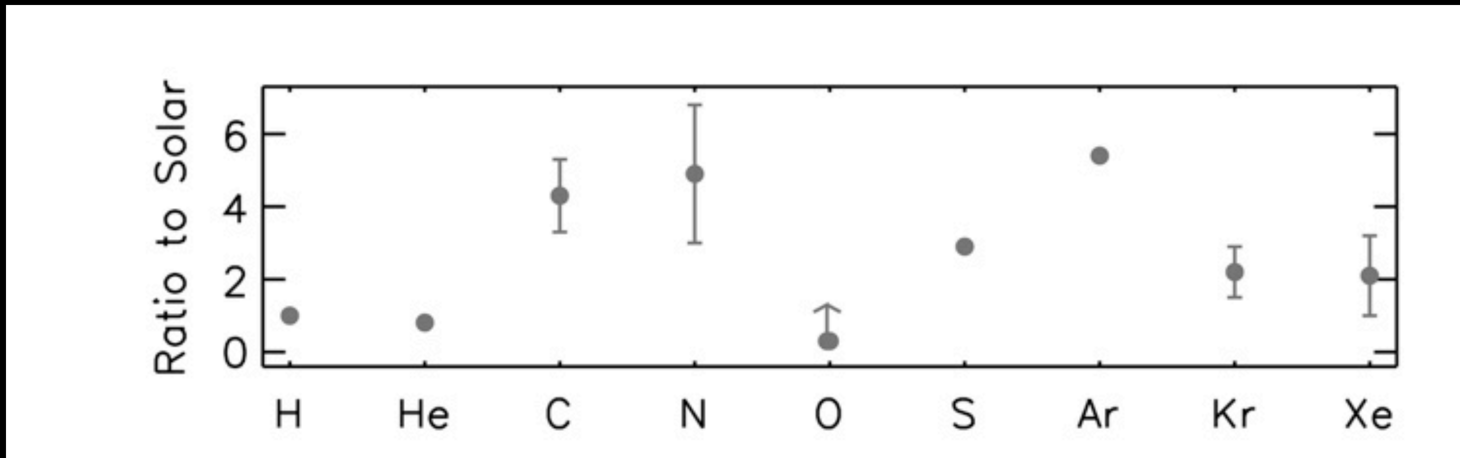
3. 'Pollution' from massive stars is accreted onto Jupiter.

   Accretion from ISM -> Solar Nebula Disk -> Jupiter

   Sun's metallicity is not affected, only Jupiter's

Throop 2009 (submitted to Icarus)

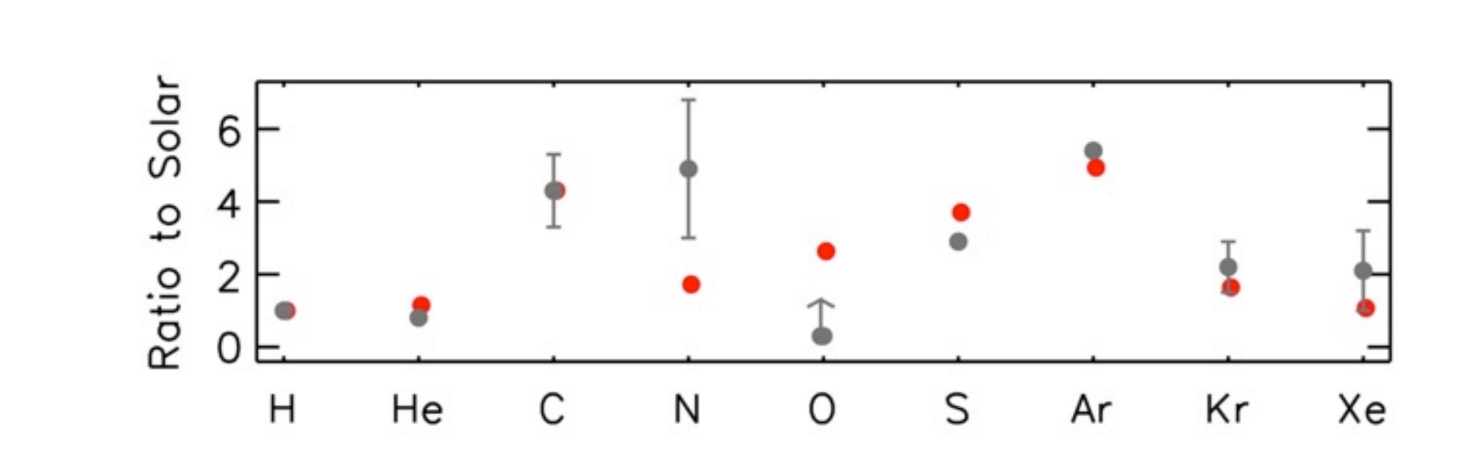
Observed Jupiter Composition



Can Jupiter’s measured enhancement be explained by accretion of heavy elements from the ISM?

Throop 2008 (in prep)

Jupiter 'Polluted Accretion' model



- Data: Galileo Probe
- Model: Accretion from ISM
  - 87% Solar nebula material
  - 9% Stellar winds from 20 Msol star (provides C, N)
  - 4% SN from 25 Msol star (provides S, Ar, Kr, Xe)
  - Requires total of ~0.13 M_J of accretion to explain Jupiter's current metallicity.
  - Bondi-Hoyle accretion supplies 10 M_J of accretion per Myr -- plenty of mass, and at the right abundances!

Throop 2009 (submitted)

Consequences of Tail-End Accretion

- Disks may accrete may times their own mass in a few Myr.
- Disks may still be accreting gas at >5 Myr, after planetesimals form, and maybe after giant planet cores form.
- Disk may be ‘rejuvenated’ after being partially lost
- Final composition of disk may be different than star
  - There may be no ‘Solar Nebula Composition’
  - Isotopes may not be diagnostic of solar vs. extrasolar material

Throop & Bally 2008, *AJ*


‘Tail-end’ Bondi-Hoyle Accretion in Young Star Clusters: Implications for Disks, Planets, and Stars

Submitted to AJ, 7-Nov-2007
Revised, 29-Feb-2008

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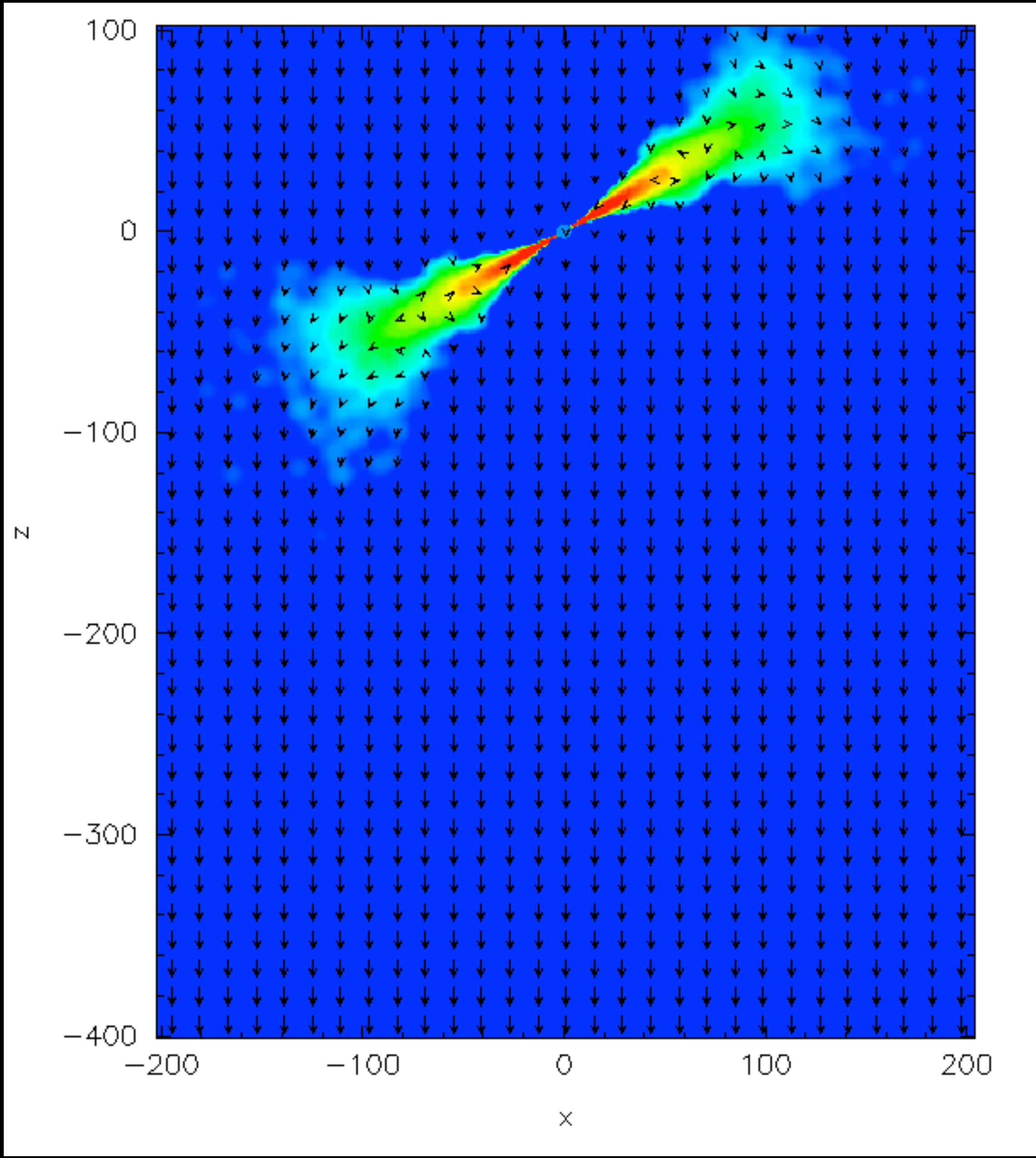
ABSTRACT

SPH Sims: BH Acc onto 100 AU disk

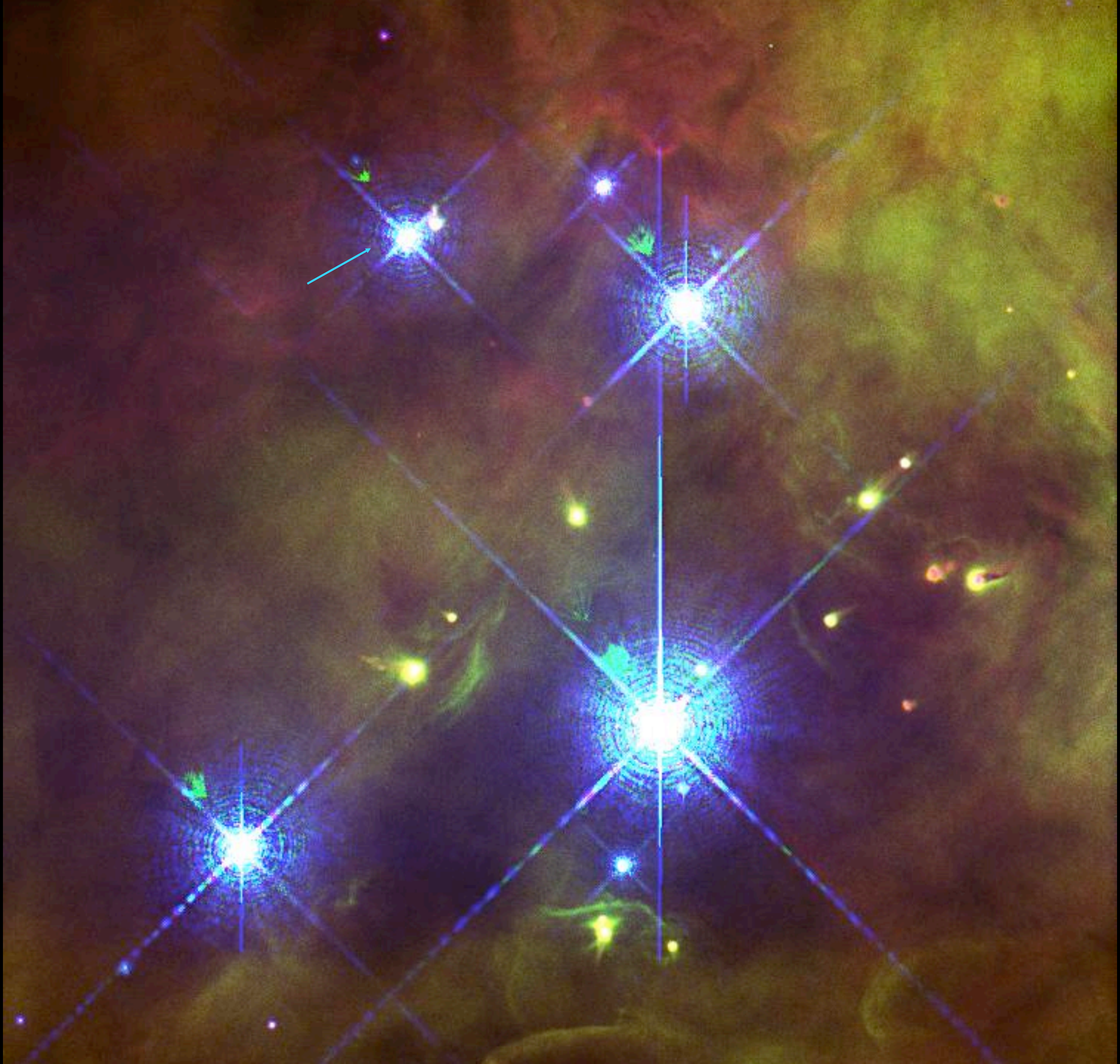


10,000 years
0.01 solar masses
v ~ 1 km/sec

Moeckel & Throop 2009 (AJ)

How does Cluster Environment affect Disk

- Interaction with cluster gas
- UV photoevaporation from massive stars ★
- Close stellar encounters
- UV, X ray chemistry



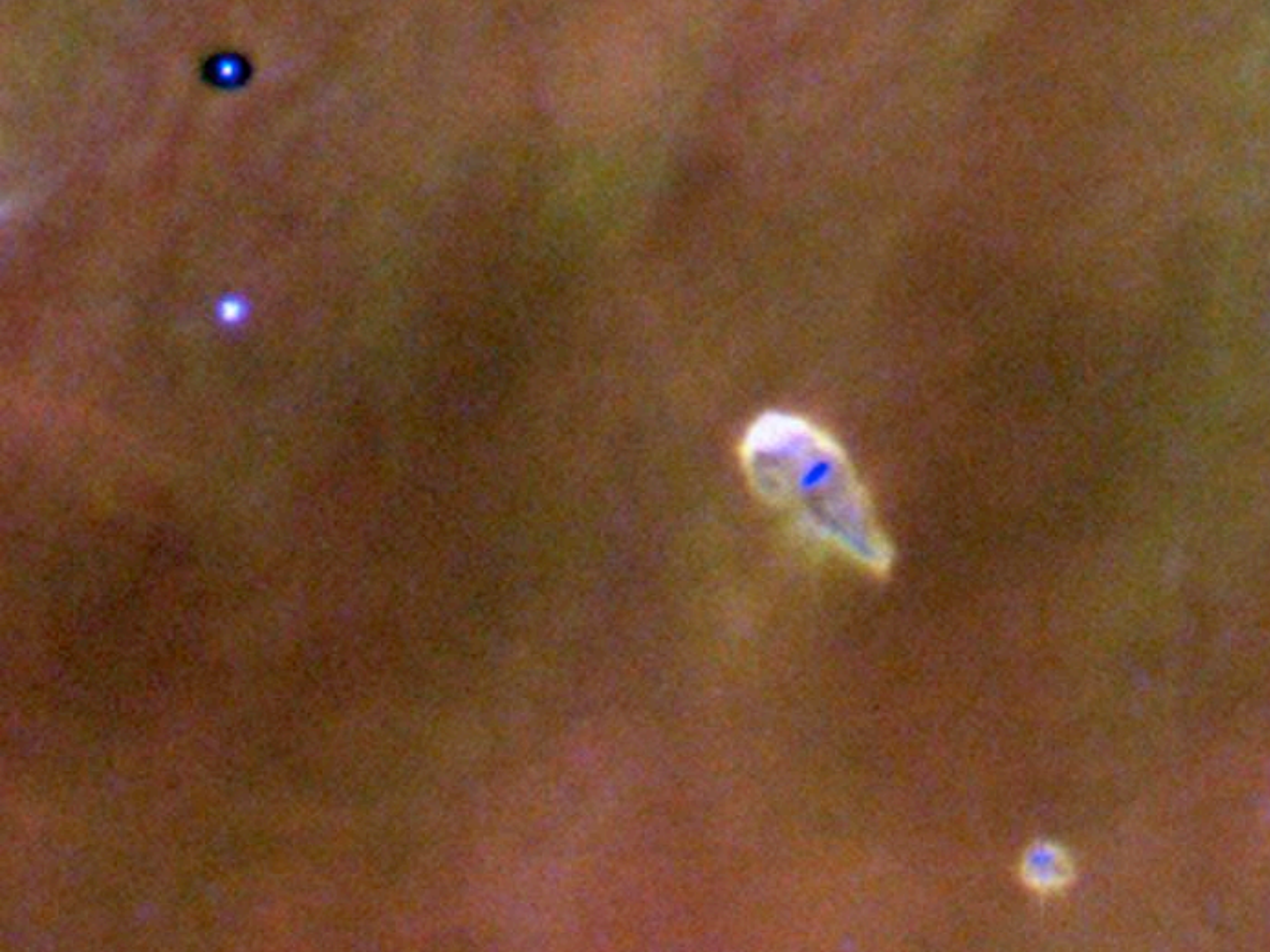


Photo-Evaporation in Orion

- Disks surrounding solar-type stars are heated by UV-bright stars.
- Gas is heated and removed from disk on 1-10 Myr timescales.
- If disk is removed quickly, we can't form planets!

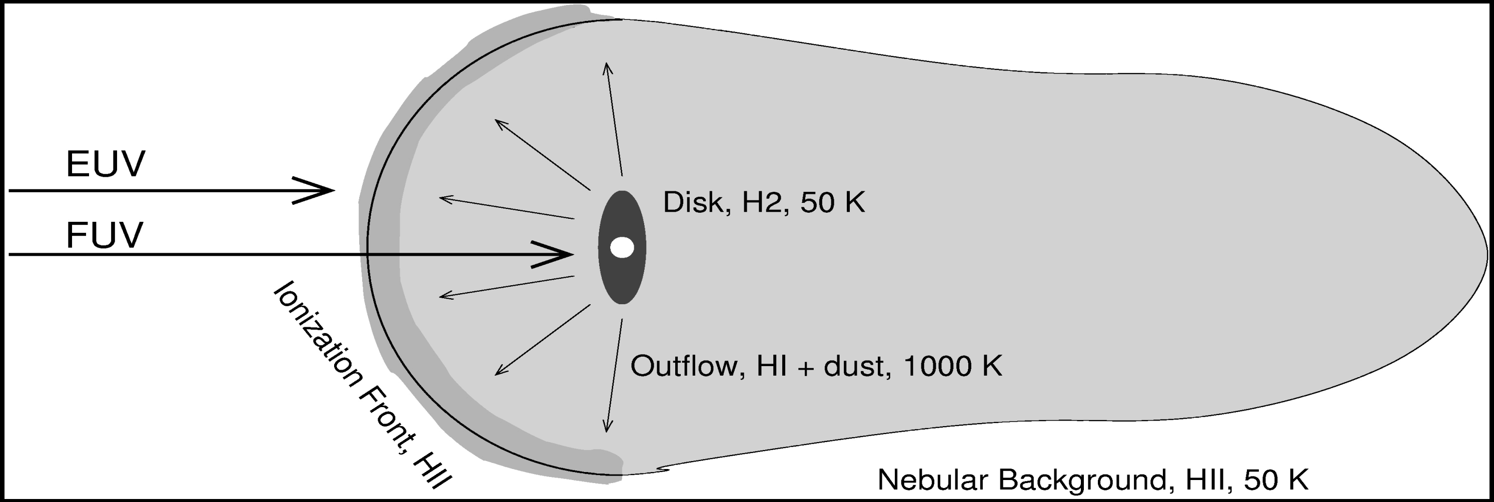


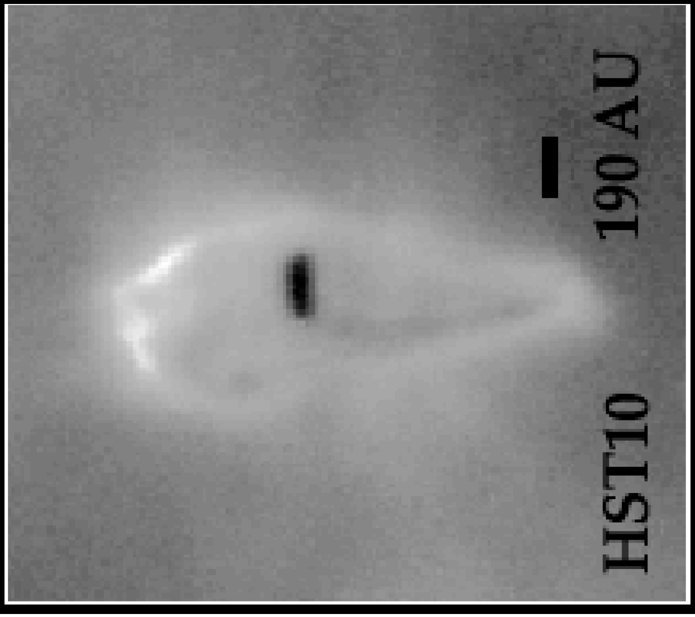
Photo-Evaporation and young Solar Systems

- Disks surrounding most Orion stars can be truncated to a few AU in 1-10 Myr.
  - Dust in disks can be retained: sharp outer edge with large grains (Throop et al 2001)

- **Kuiper Belt (> 40 AU)**: UV removes volatiles and small grains. Kuiper belts and Oort clouds may be rare!

- **Giant Planets (5-40 AU)**: Gas is rapidly removed from disk: If you want to build Jupiters in Orion, do it quickly! (e.g., Boss models)

- **Terrestrial Planets (1-5 AU)**: Safe from photo-evaporation due to deeper potential well at 1 AU.



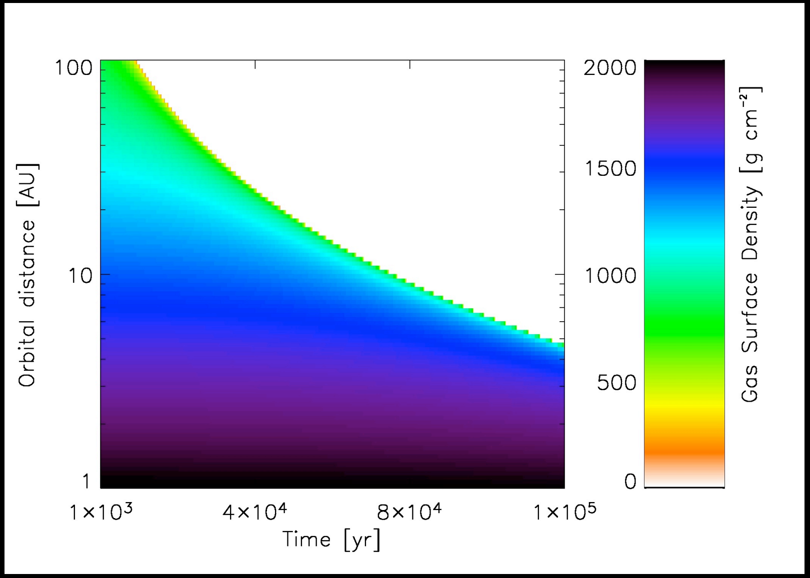


Photo-evaporation is a major hazard to planet formation…

… but all hope is not yet lost!

Photo-Evaporation Triggered Instability

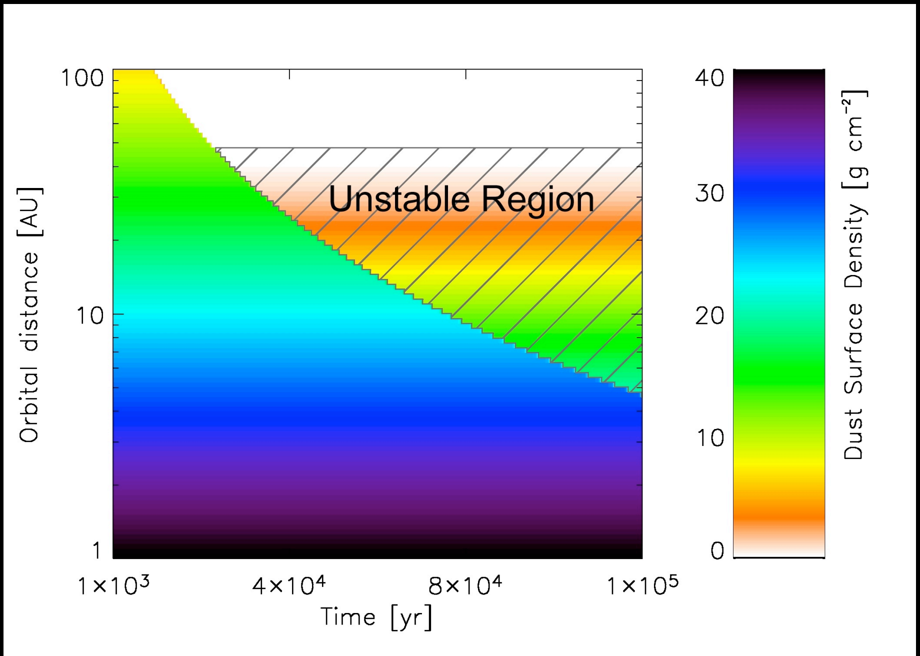
- But: Sometimes photo-evaporation **may also make planet formation easier**, by removing gas and leaving dust which can collapse gravitationally.

- Gravitational instability can occur if sufficiently low gas:dust ratio (Youdin & Shu 2004)

  $$\Sigma_g / \Sigma_d < 10$$

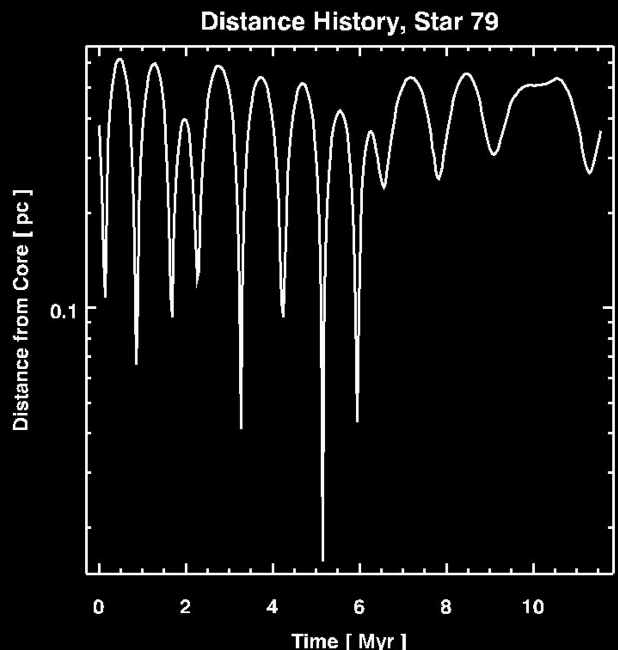
  (*i.e.*, we need to remove 90% of the gas)

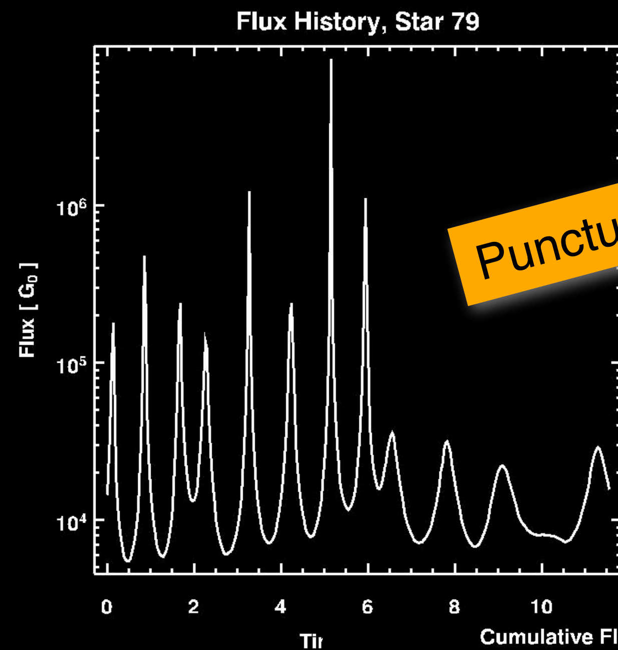
- Photoevaporation removes gas and leaves the dust: exactly what we want!



Throop & Bally 2005

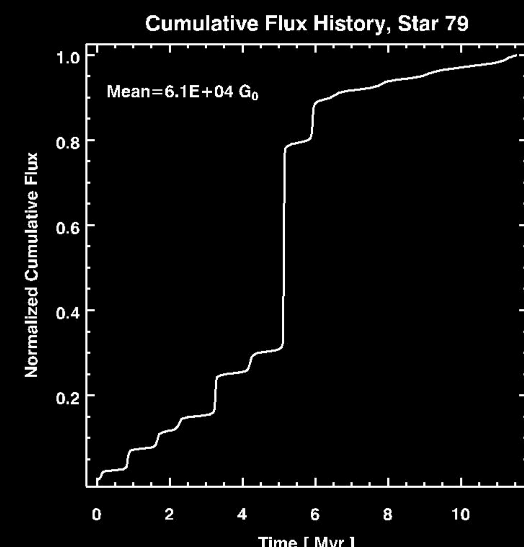
Flux History, Typical 1 M_{sun} Star





Punctuated equilibrium

- Flux received by disk varies by 1000x as it moves through the GMC : ‘Broil-Freeze-Broil’
- Peak flux approaches 10^7 G_0.
- Most of the flux is deposited during brief but intense close encounters with core.
- There is no ‘typical UV flux.’
- Disk evolution models assume steady UV flux. But if PE is not steady, then other processes (viscous, grain growth) dominate and may dramatically change the disk.



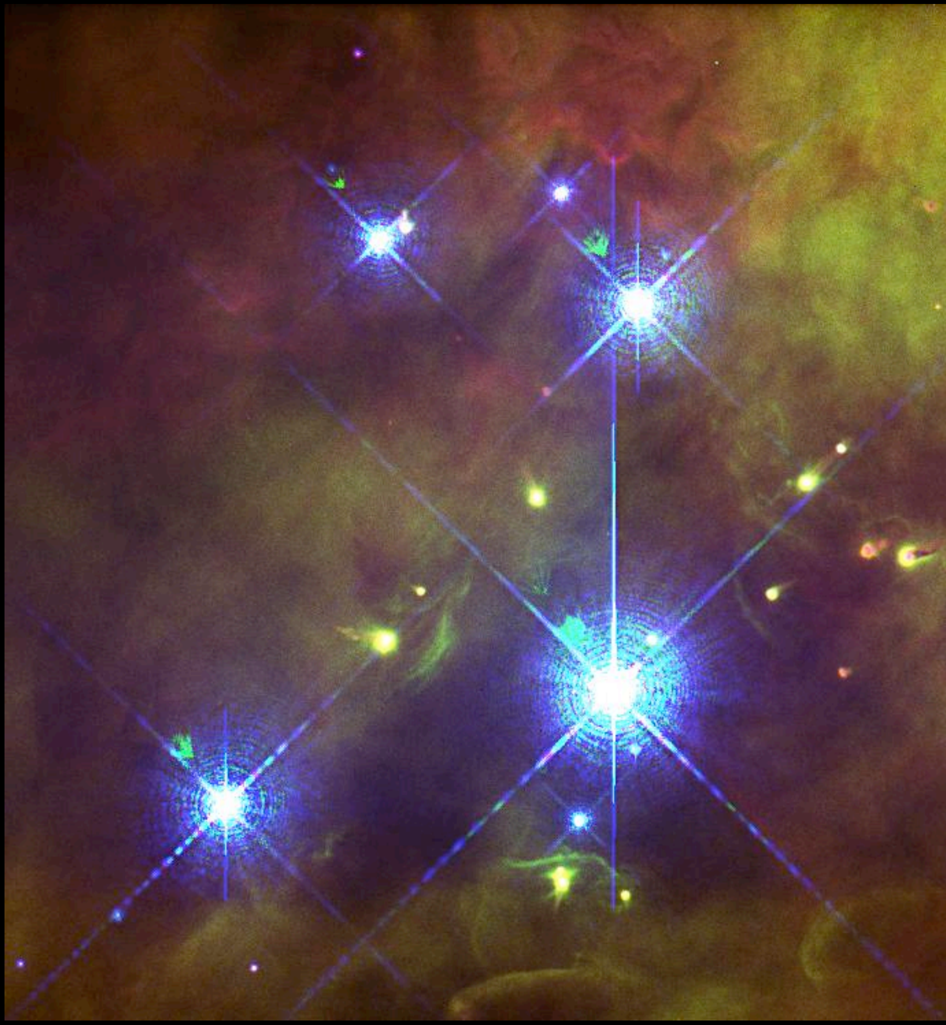
Throop & Bally, in prep

How does Cluster Environment affect Disk

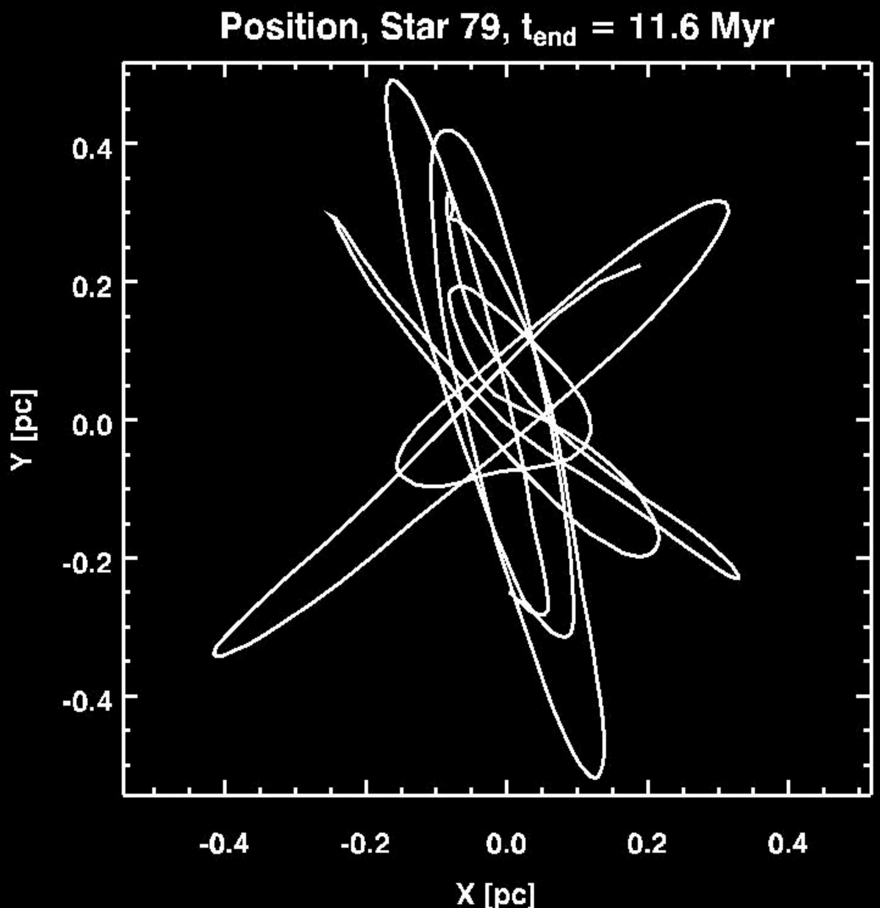
- Interaction with cluster gas
- UV photoevaporation from massive stars
- Close stellar encounters ★
- UV, X ray chemistry

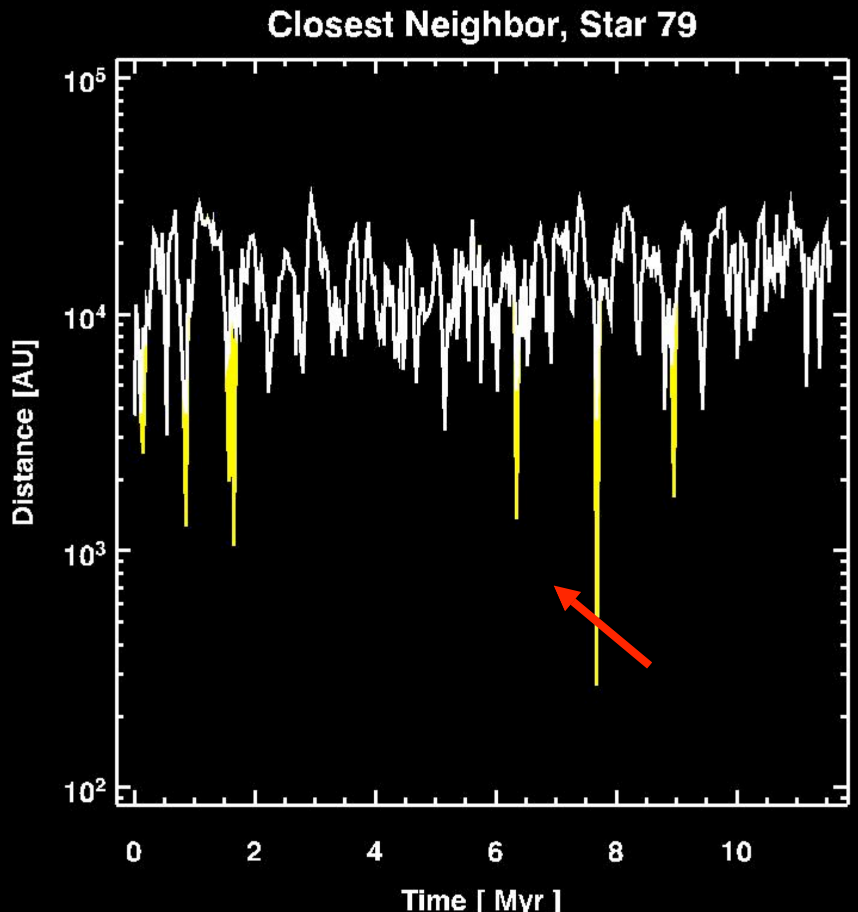
Close Approaches

- Typical distances today ~ 10,000 AU
- C/A strips disks to 1/3 the closest-approach distances (Hall et al 1996)
- Question: What is the minimum C/A distance a disk encounters as it moves through the cluster for several Myr?



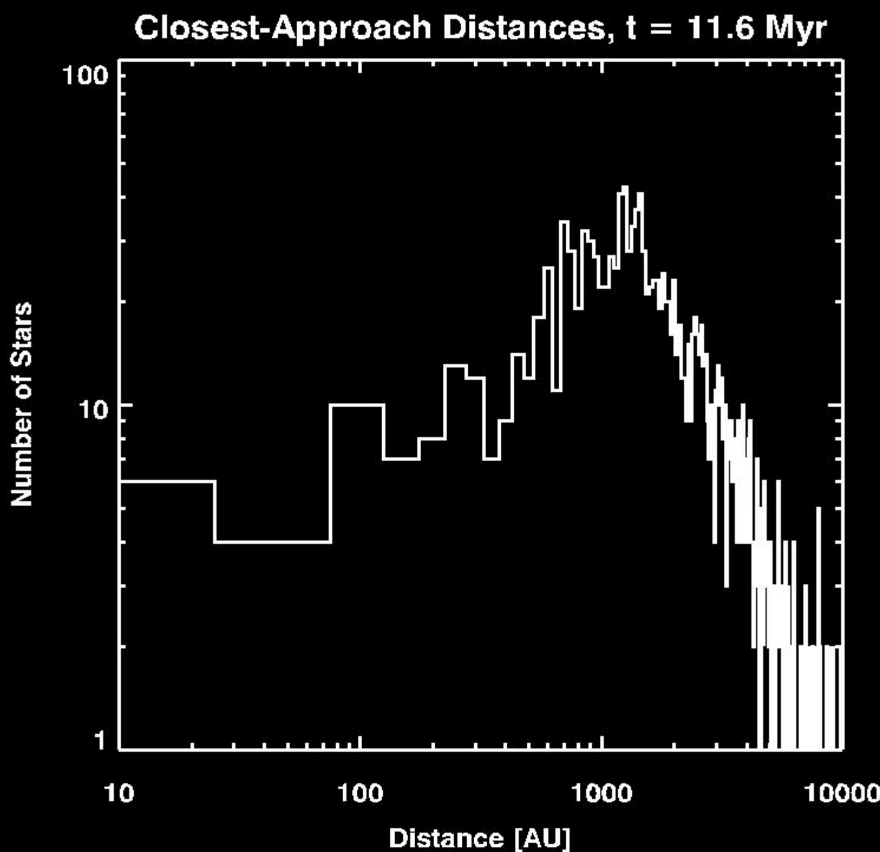
Close Approach History - Typical 1 M_{sun} Star

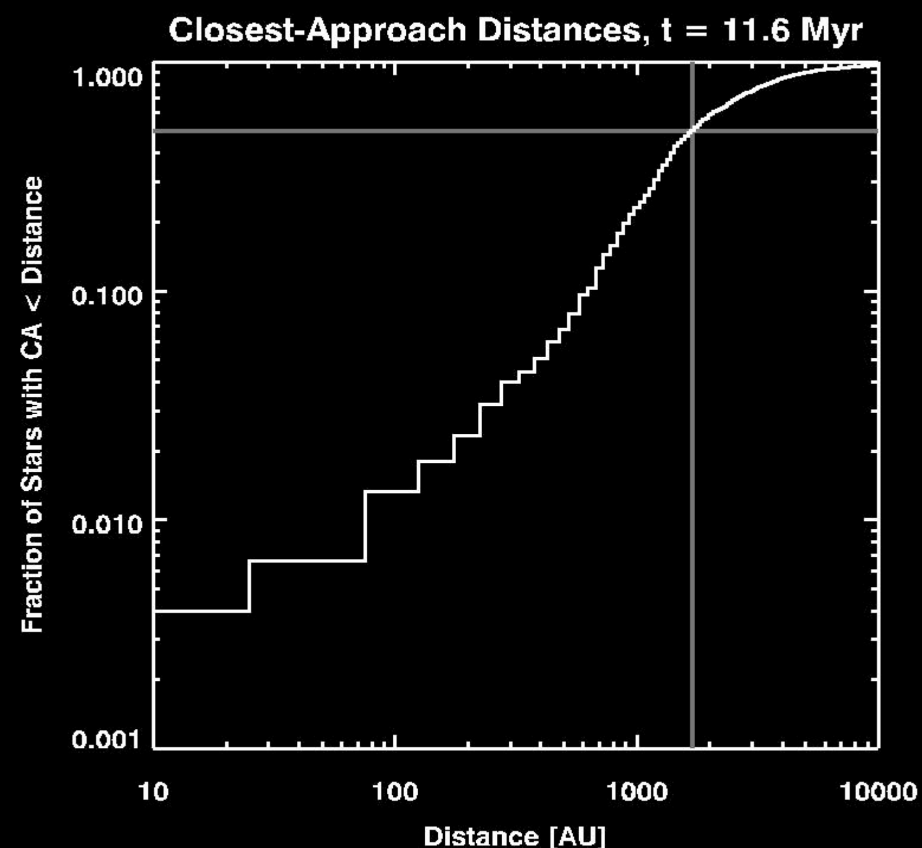




- Star has 5 close approaches at < 2000 AU.
- Closest encounter is 300 AU at 8 Myr
  - Too late to do any damage

Close Approaches - Entire Cluster





- Typical minimum C/A distance is 1100 AU in 10 Myr
- Significant disk truncation in dense clusters is rare!
  - Only 1% of disks are truncated to 30 AU, inhibiting planet formation

Throop & Bally 2008; also Adams et al 2006

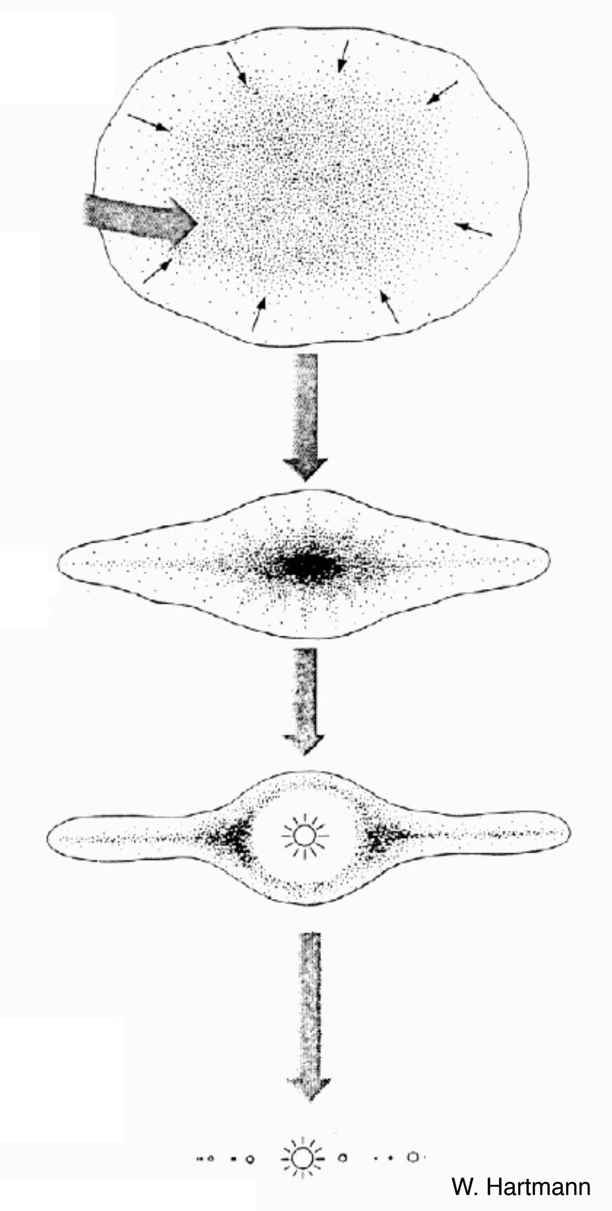
Planet Formation - Classical Model

Cloud core collapses due to self-gravity
10,000 AU, 1 Msol

Disk flattens; grains settle to midplane
Planet cores grow

Terrestrial planets form
Jovian planets accrete gas

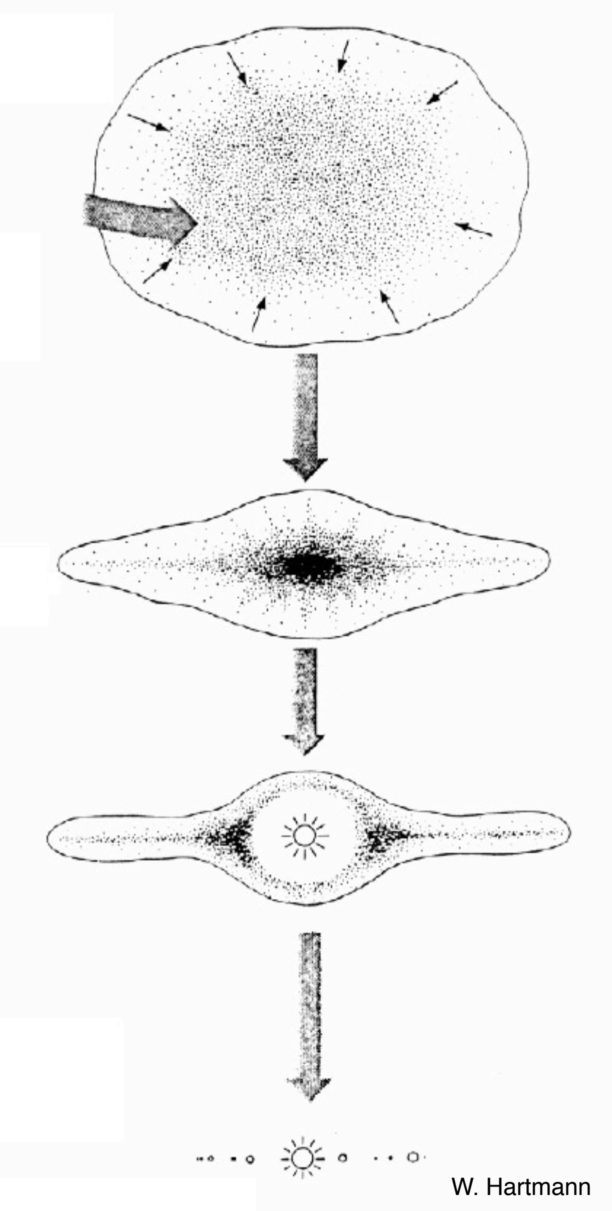
Disk disperses
Solar System complete after ~ 5-10 Myr



MODIFIED
Planet Formation - Classical Model

Cloud is heterogeneous and polluted
Cloud core collapses due to self-gravity
10,000 AU, 1 Msol
Cloud composition from nearby SN

Disk flattens; grains settle to midplane
Planet cores grow
Disk is photo-evaporated by UV stars
Disk is injected with ^{60}Fe from nearby SNs
Terrestrial planets form
Jovian planets accrete gas
(Disk is stripped due to close approaches)
Disk accretes gas from environment
Disk disperses and is photo-evaporated
Solar System complete after ~ 5-10 Myr

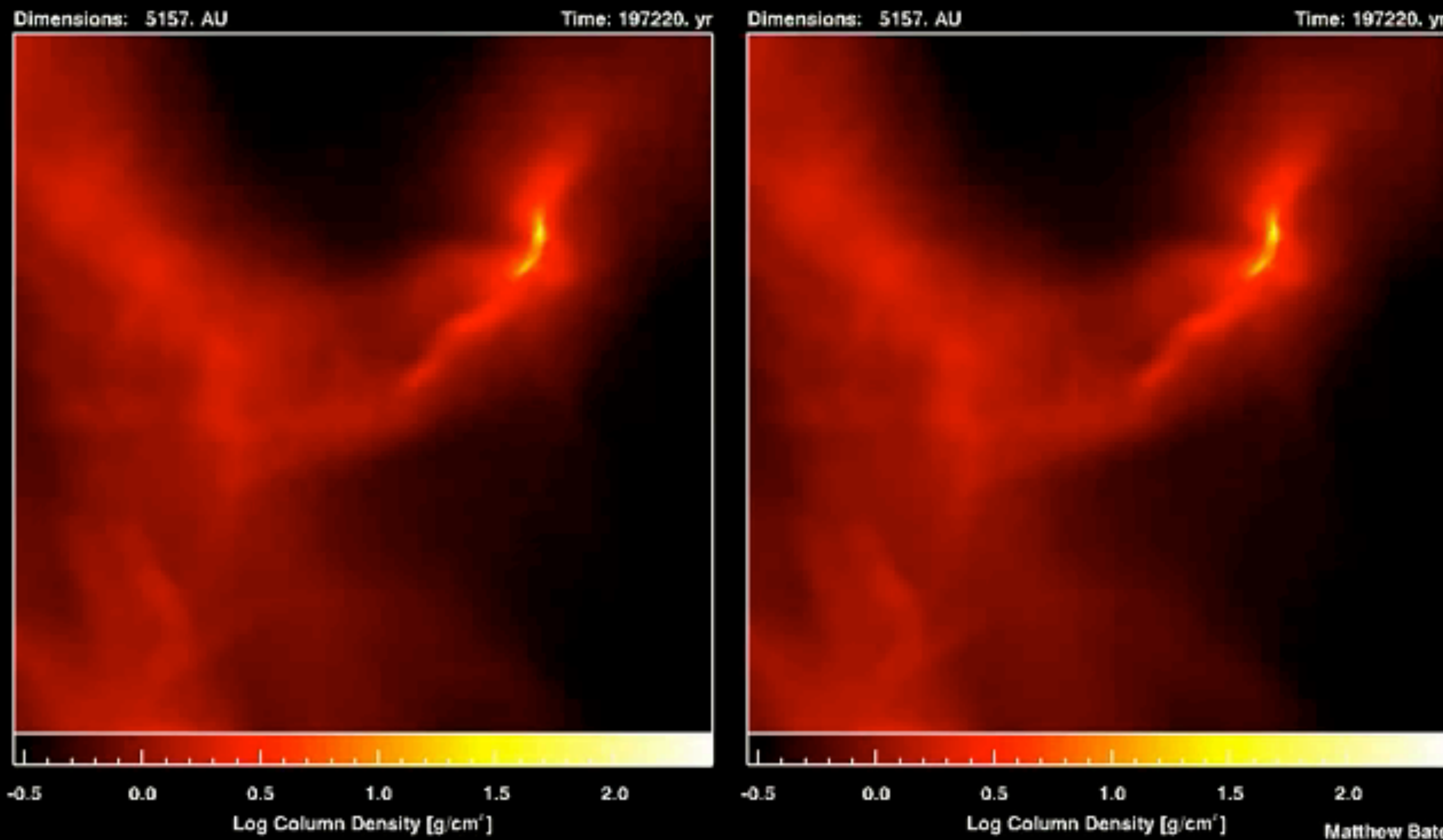


Star Clusters and Planetary Systems

Recent observations of star formation and star clusters gives insight into previously-ignored processes in planet formation.

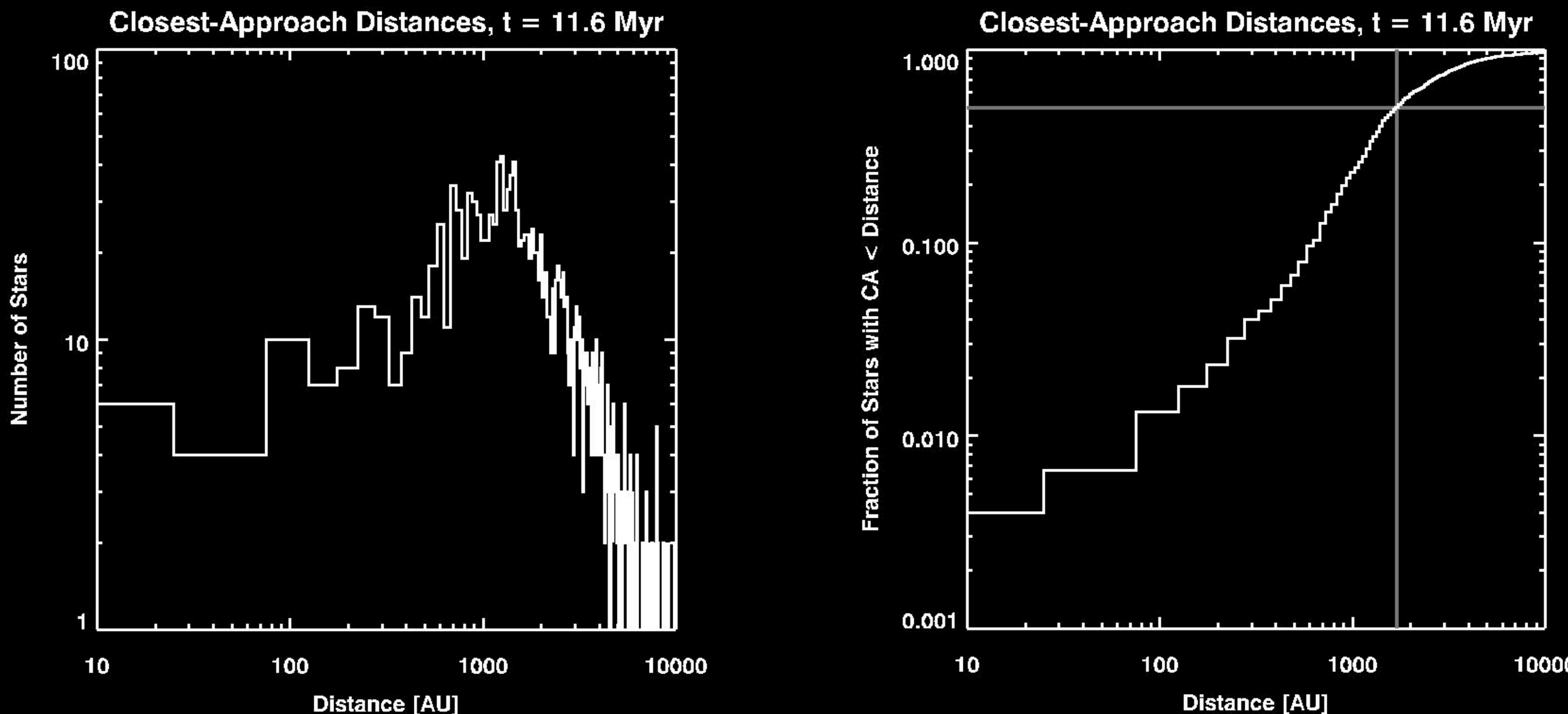
- 'Tail-end' accretion from cluster onto disks complicates existing SS formation models, but may explain...
  - Observations of accretion in young disks
  - Compositional heterogeneties in cluster stars
  - Isotopic anomalies in Solar System
  - Compositional difference between Jupiter, Sun
  - We need numerical simulations of accretion to understand how mass and angular momentum are deposited from ISM -> disks.
- Photoevaporation can rapidly destroy disks
  - Hard to make Jovian planets
- Photoevaporation can also trigger rapid planetesimal formation
  - Easy to make planetary cores
- Close encounters are unimportant


The
End



Dimensions: 5157. AU
Time: 197220. yr
-0.5
0.0
0.5
1.0
1.5
2.0
Log Column Density [g/cm²]
Dimensions: 5157. AU
Time: 197220. yr
-0.5
0.0
0.5
1.0
1.5
2.0
Log Column Density [g/cm²]
Matthew Bate

Close Approaches - Entire Cluster



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Throop & Bally; also Adams et al 2006

A Crazy idea for forming Jupiters?

1. Star and disk forms in a young cluster
2. Jupiter's rocky core forms slowly
3. Disk gas is photo-evaporated before Jupiter can form
4. Disk gas is rejuvenated by passage through molecular cloud
5. Jupiter forms its atmosphere from new disk

A solution to the ^{60}Fe problem?

- ^{60}Fe is created in supernovae -> Solar System formed in large cluster
- But, in order to directly implant ^{60}Fe into disk we need:
  - Solar System formed in an OB association
  - Solar System was close to an O star, d < 0.2 pc
  - But not too close!
  - And this happened at just the right time, as SN explodes
- Odds of this happening: < 1% (Gounelle + Meibom 2008)

We propose instead:

1. Sun forms in molecular cloud
2. O star forms ~ 10 pc away and explodes
3. SN ejecta mixes with ISM, distributes ^{60}Fe
4. Solar System disk accretes ^{60}Fe from ISM