Planet Formation in Dense Star Clusters

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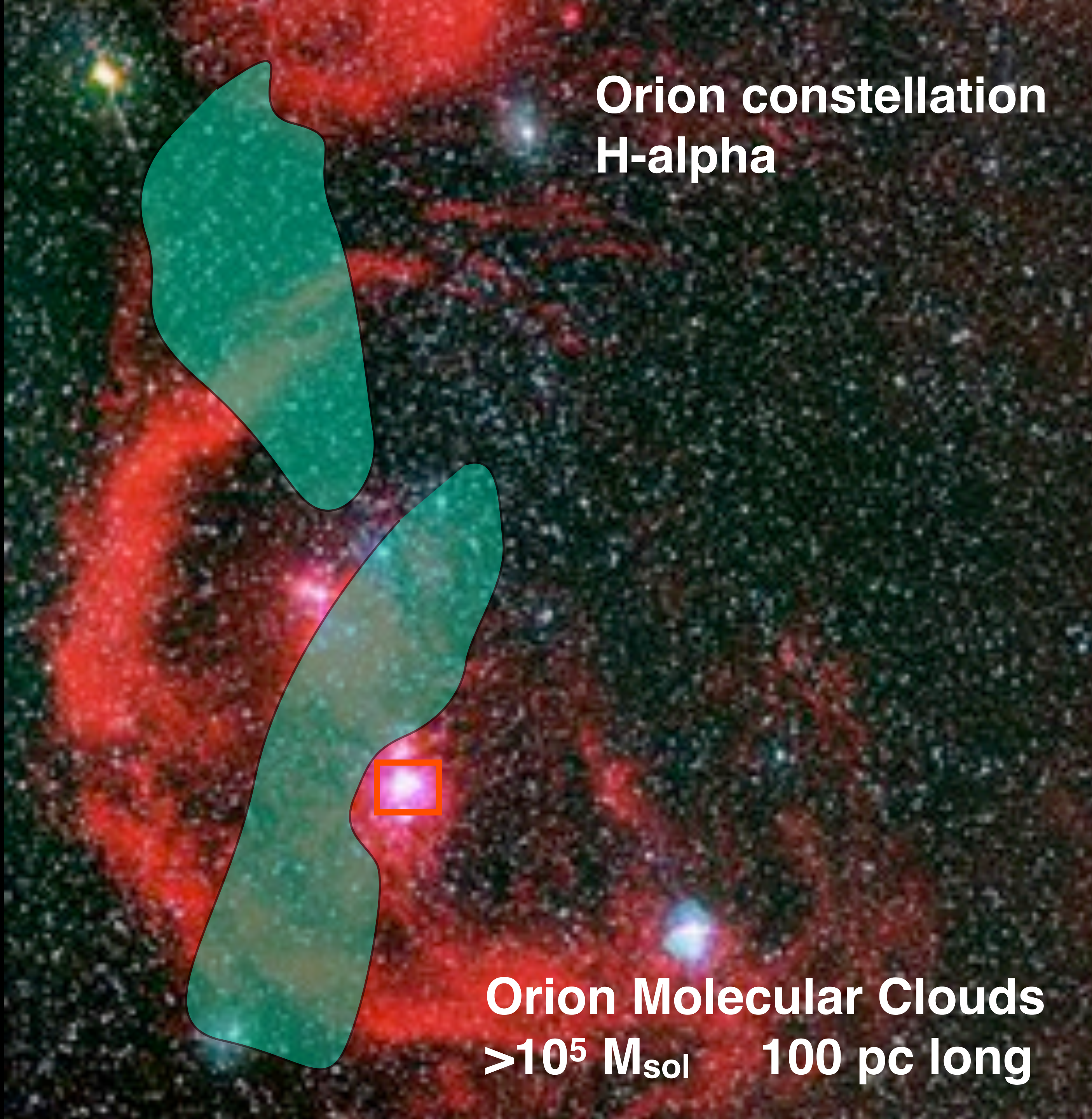
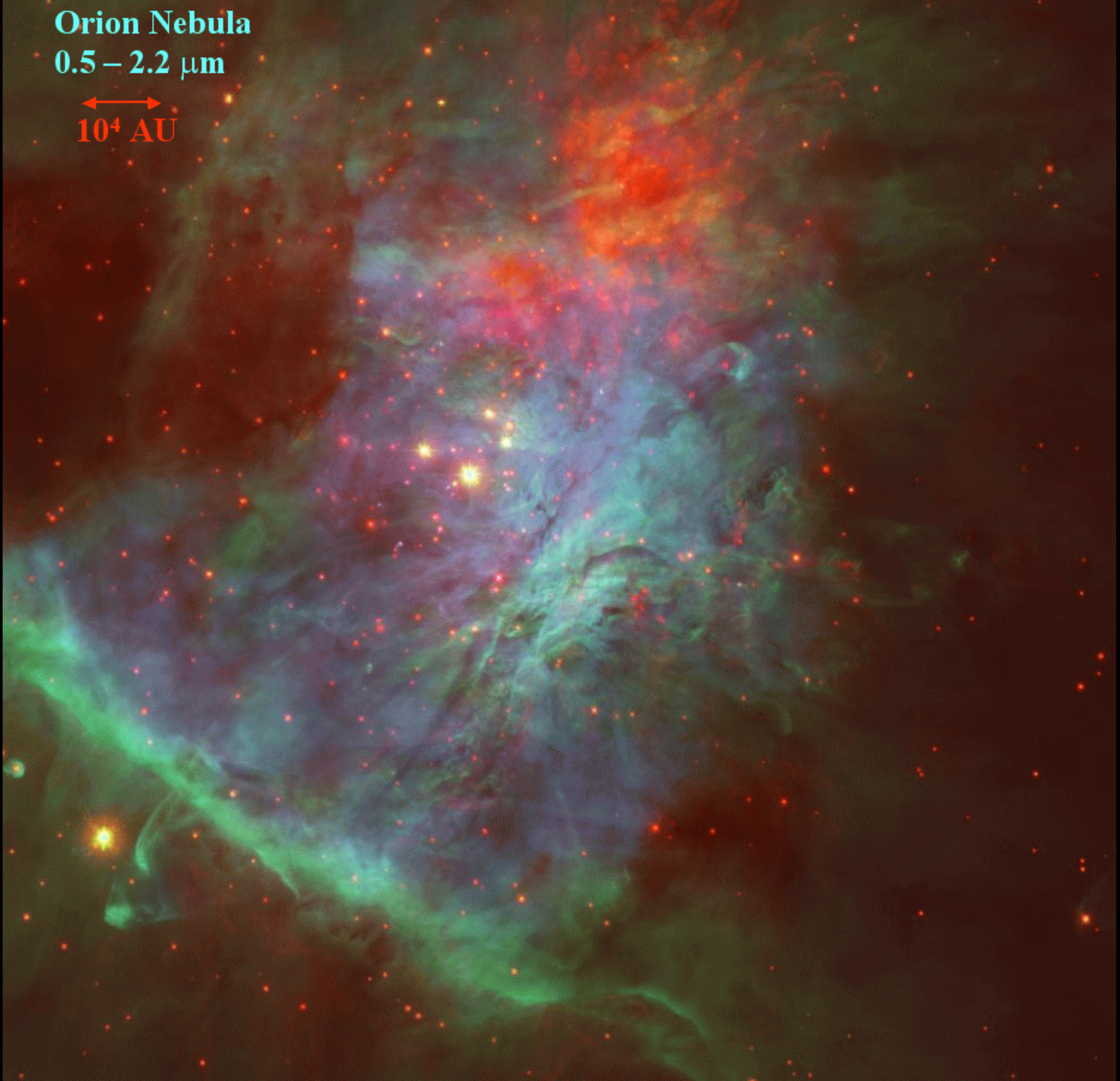
Nickolas Moeckel (Cambridge)

SwRI / Boulder
December 18, 2009


Orion Constellation
(visible light)

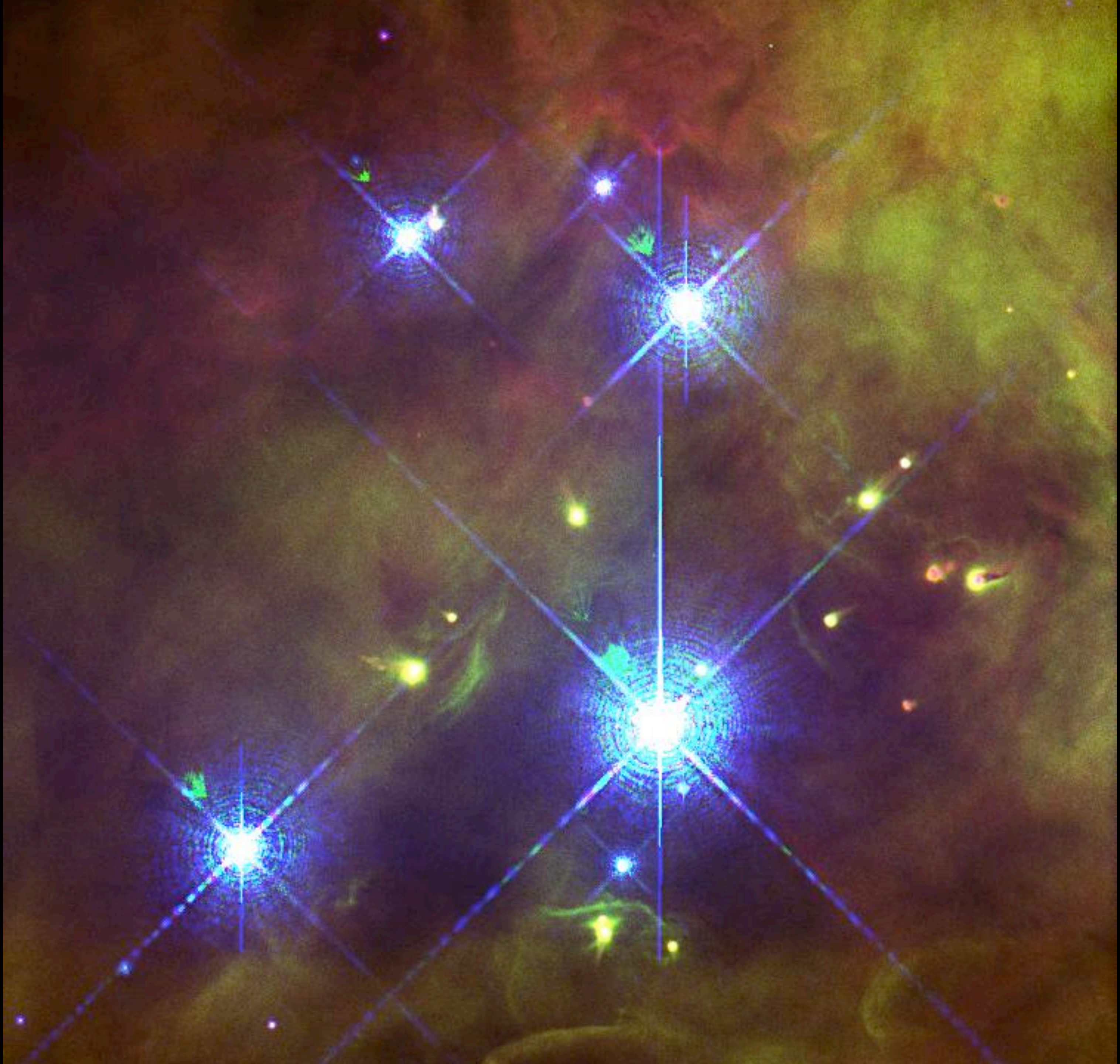

Orion constellation
H-alpha


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

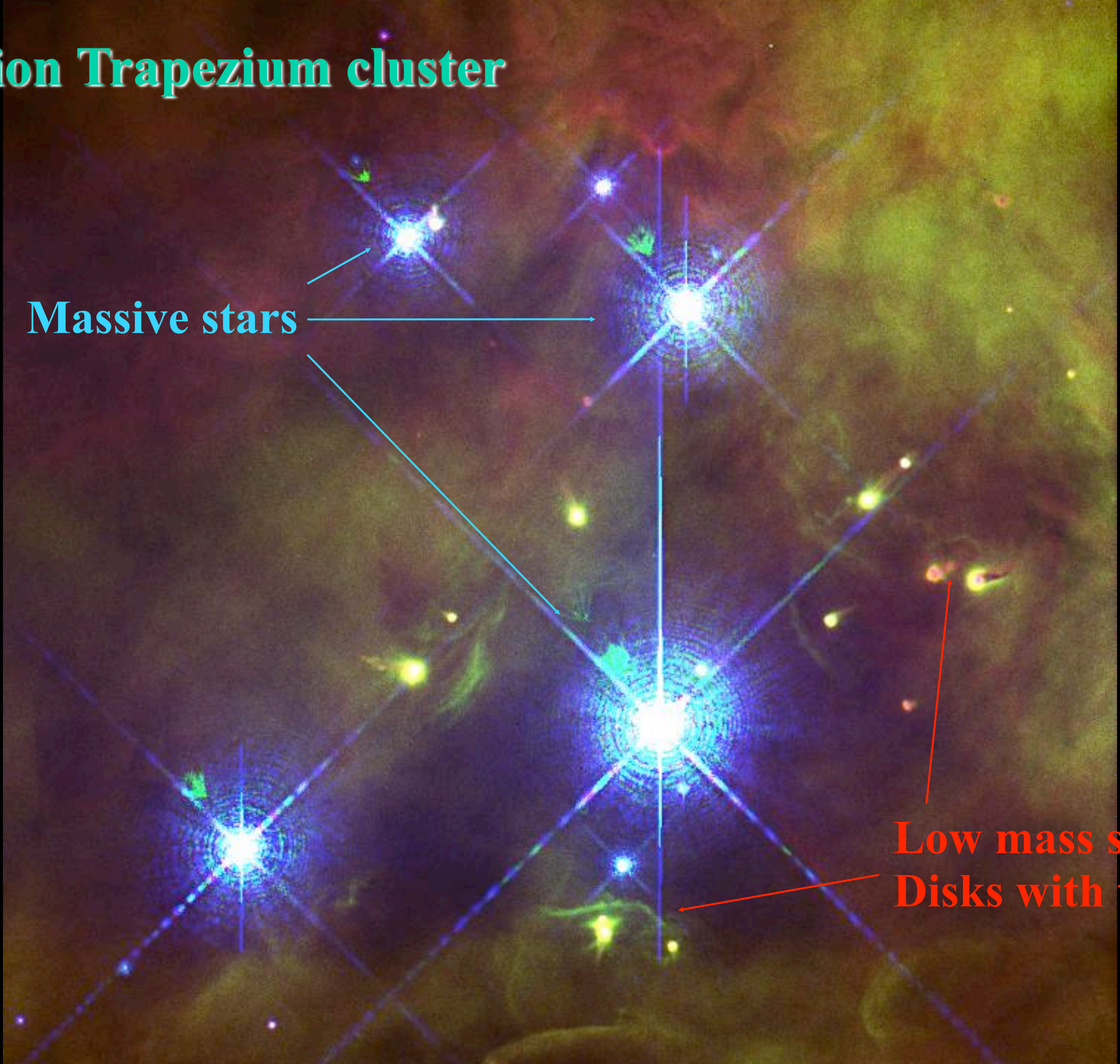

Orion Nebula
0.5 – 2.2 μm
10⁴ AU

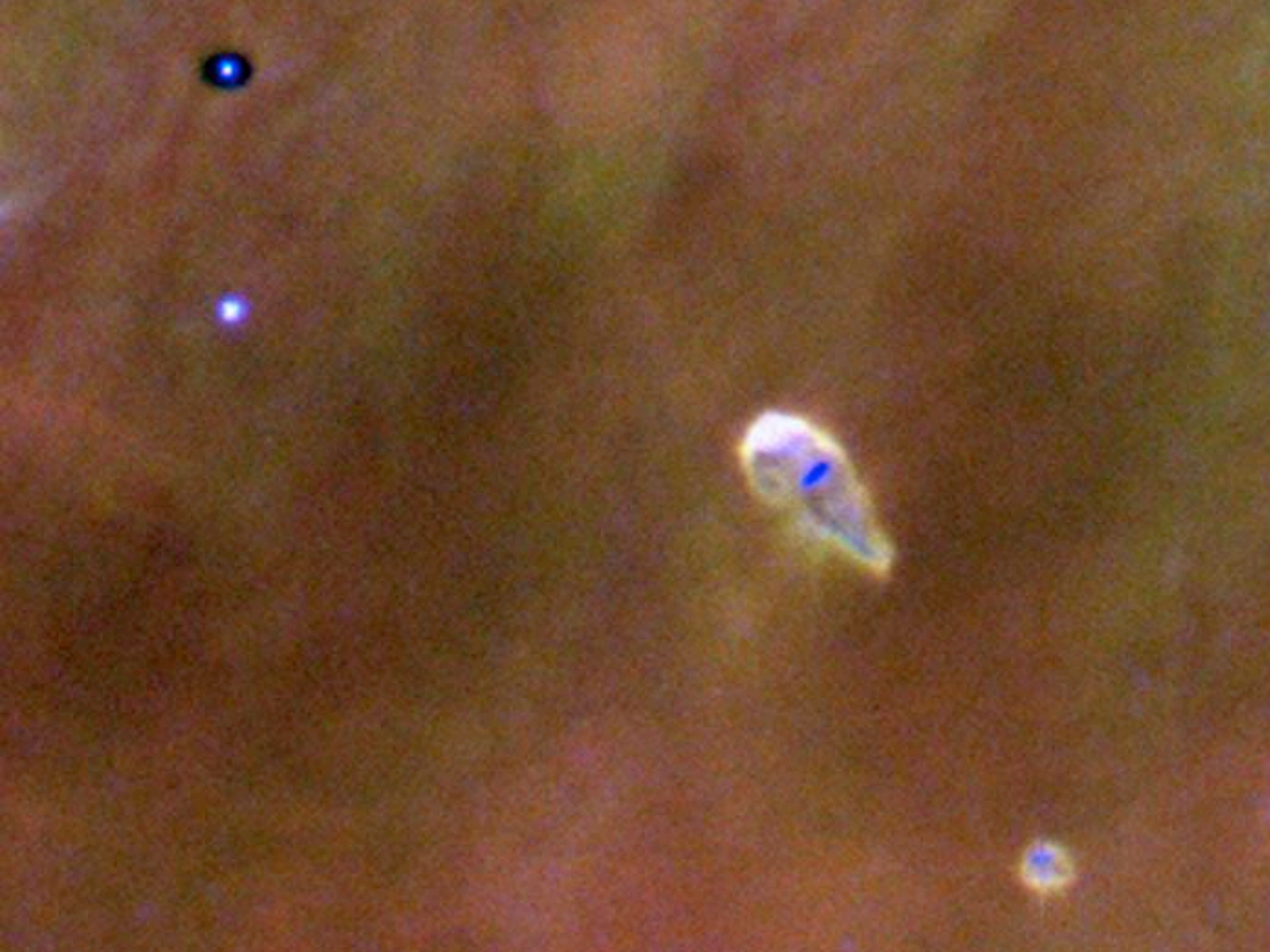
Orion Star Forming Region

- 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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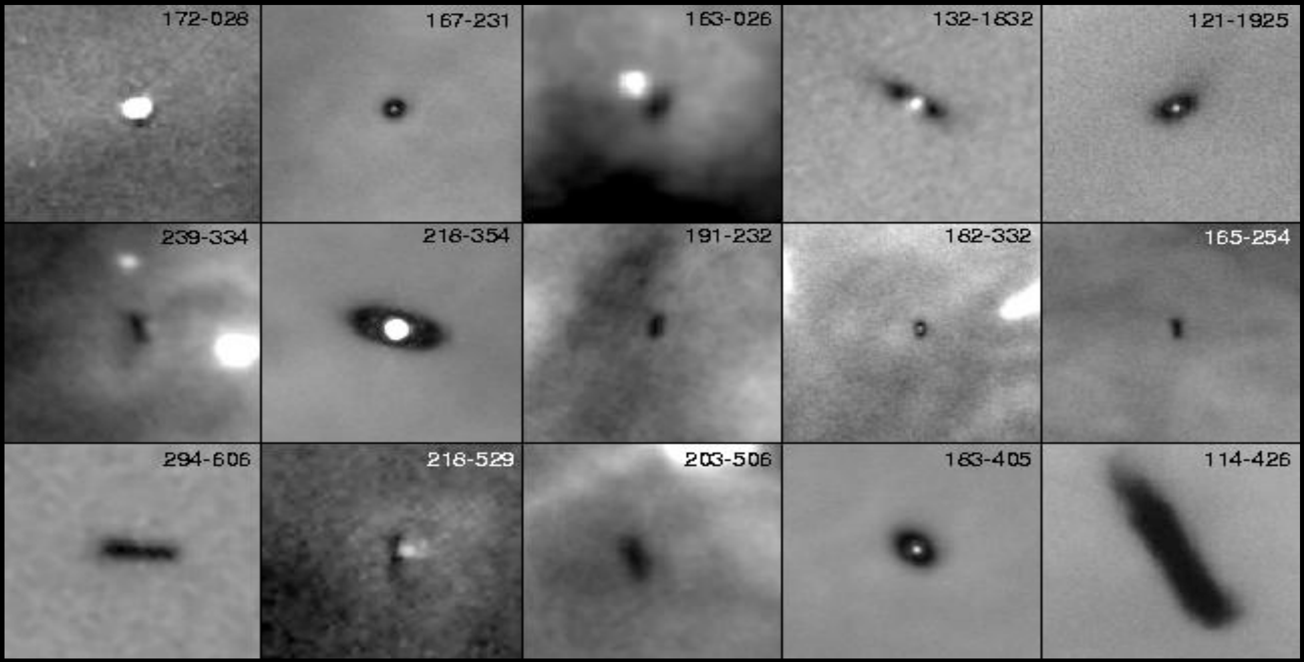
2000s view:

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

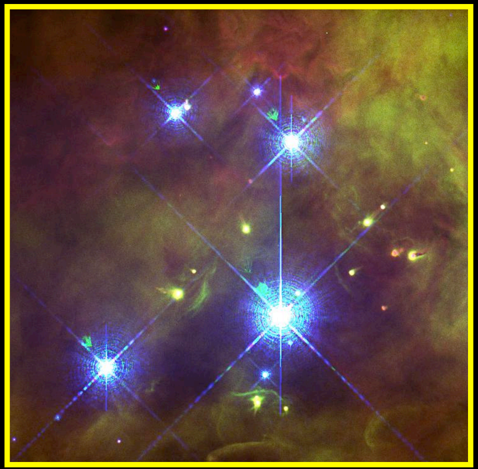
These stars are too distant and young to directly search for planets… but we want to study the environment and processes to understand the planets which would be produced in these dense clusters -- and therefore throughout the galaxy.

Regions of Star Formation

	Large Dense Clusters: Orion
# of stars	10^3 - 10^4 10^4 stars in last 10 Myr (Orion)
OB stars	Yes
Distance	450 pc (Orion)
Fraction of stars that form here	70-90%
Distance between stars	5000 AU
Dispersal lifetime	Few Myr
% of stars with disks	> 80%

Orion: Hot, Dense, Massive

Most stars form in large clusters.



Regions of Star Formation

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

Orion: Hot, Dense, Massive

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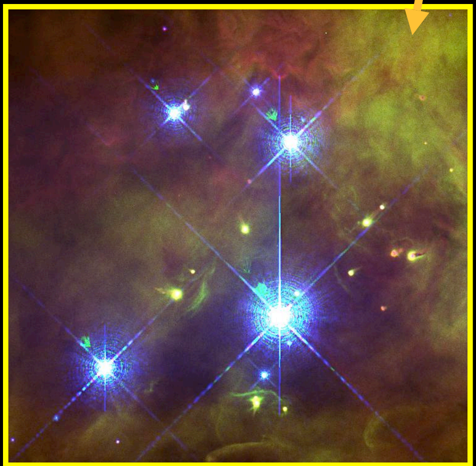

Taurus: Dark, Small, Cold

Most planet formation models study small clusters.

Where did our Sun form?

- We don’t know! The Sun is an isolated star today.
- 90% of stars formed in clusters
- But just 1% remain in clusters now.
- Stellar motions can be back-integrated for 100 Myr, but not 10 Gyr.

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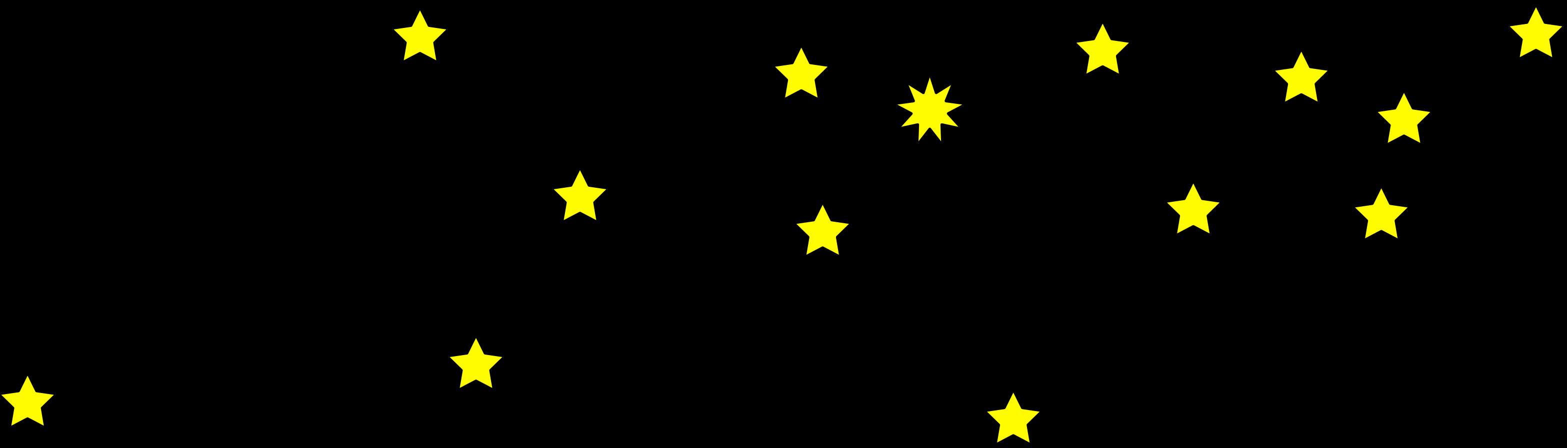

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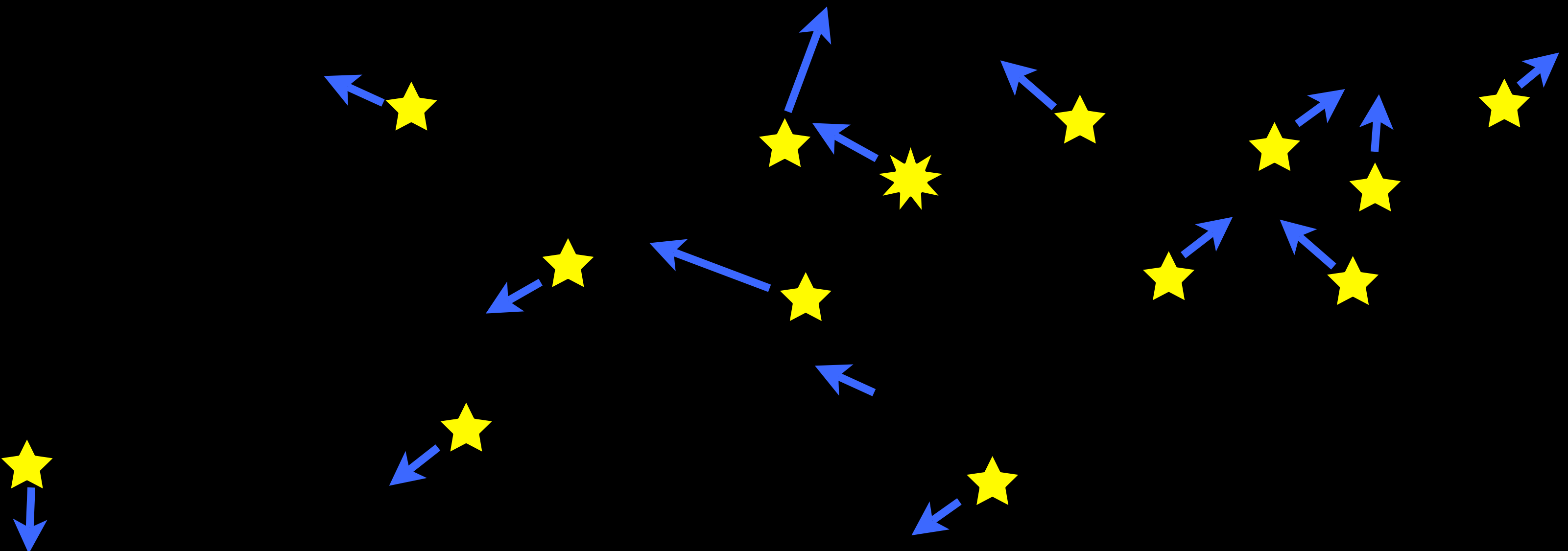

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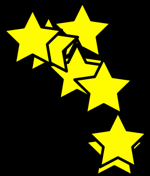

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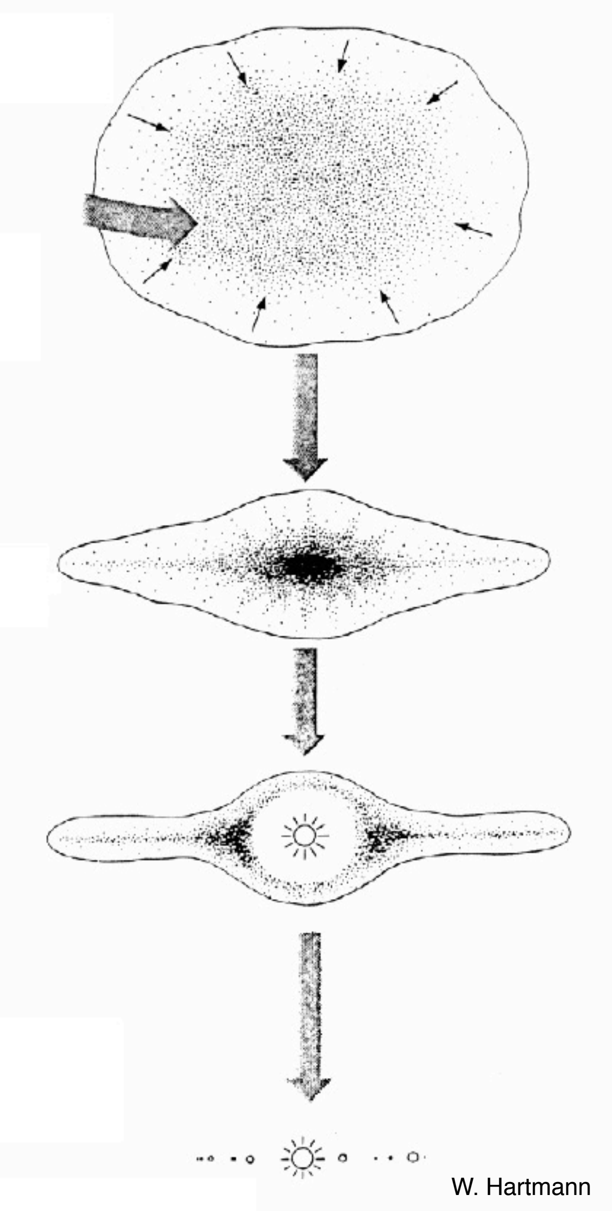
Planet Formation - Classical Model

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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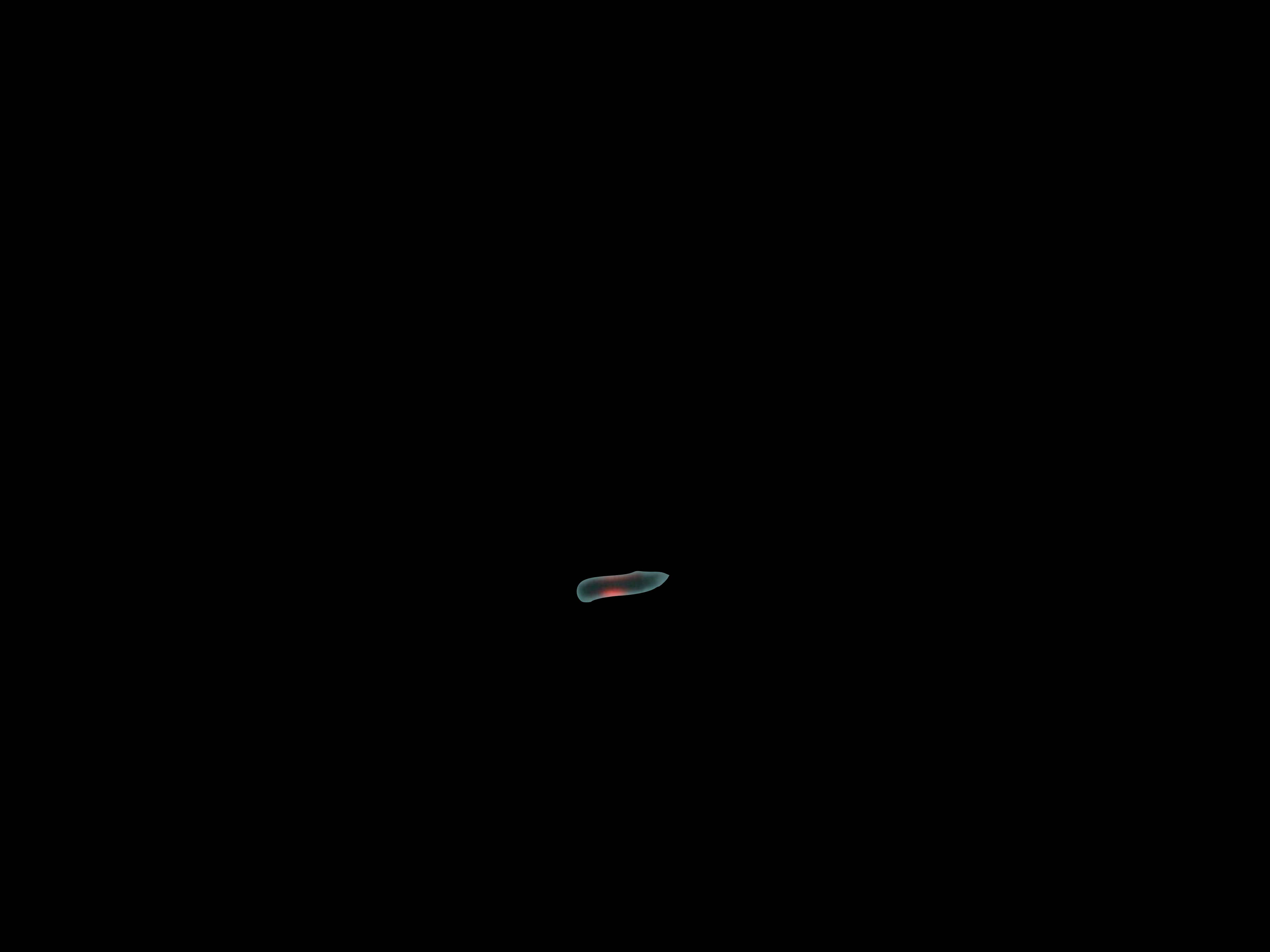
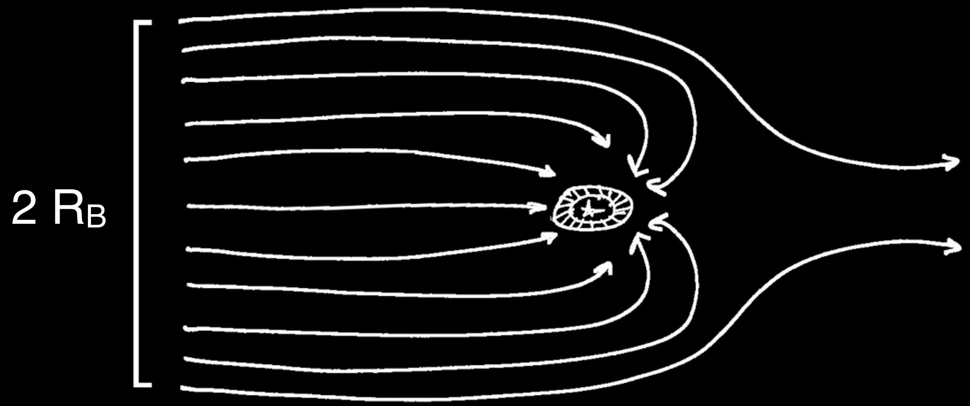


Bondi-Hoyle Accretion



- 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}

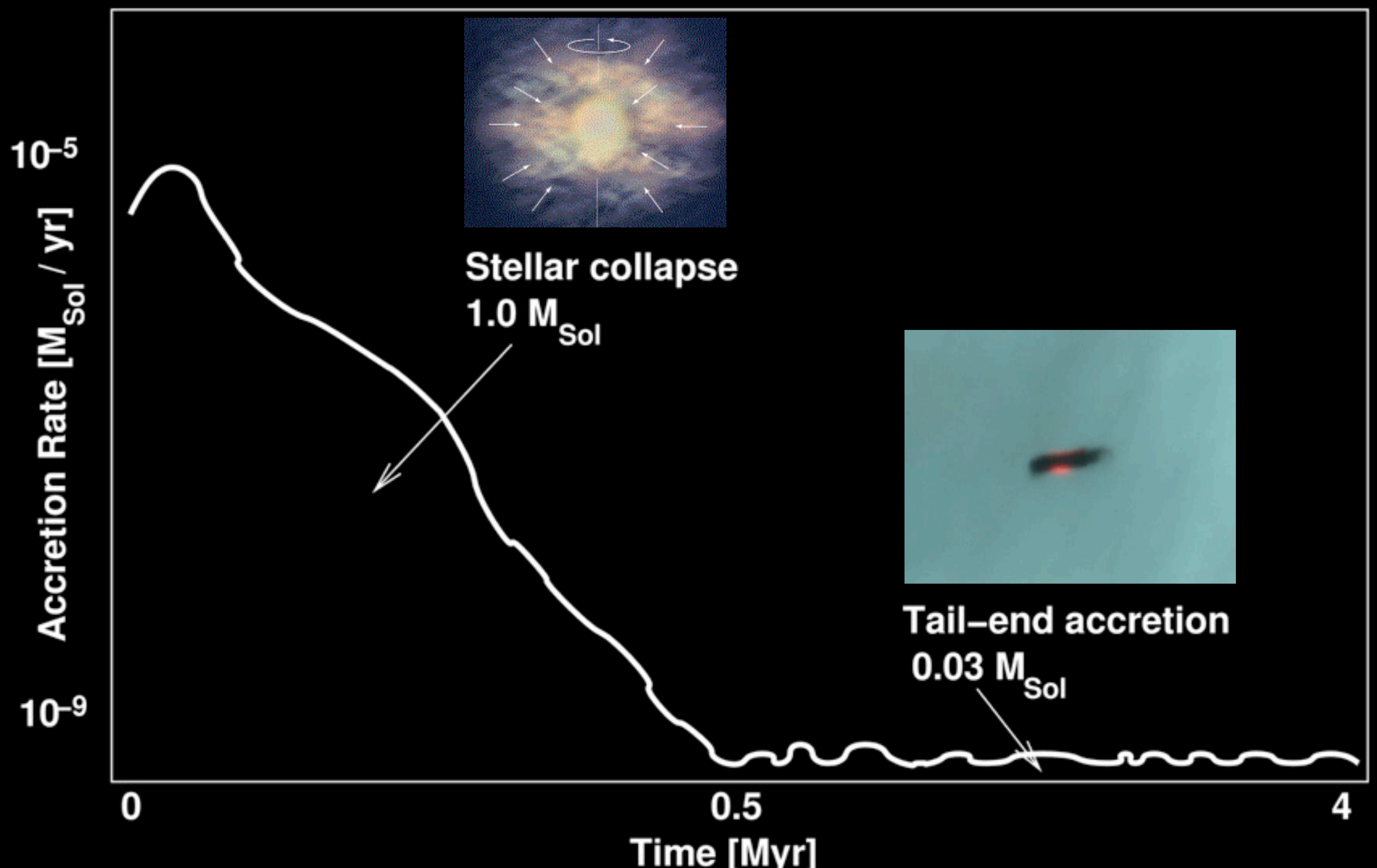
$$R_\mathrm{B} = \frac{2\,G\,M}{(v^2 + c_s^2)}$$

Accretion radius ~ 1000 AU

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

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 $M_{\odot}$
- Kroupa IMF
- R_0 = 0.5 pc

Gas:

- M_{gas} = 500 $M_{\odot}$
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- Disperses with timescale 2 Myr

Throop & Bally 2008

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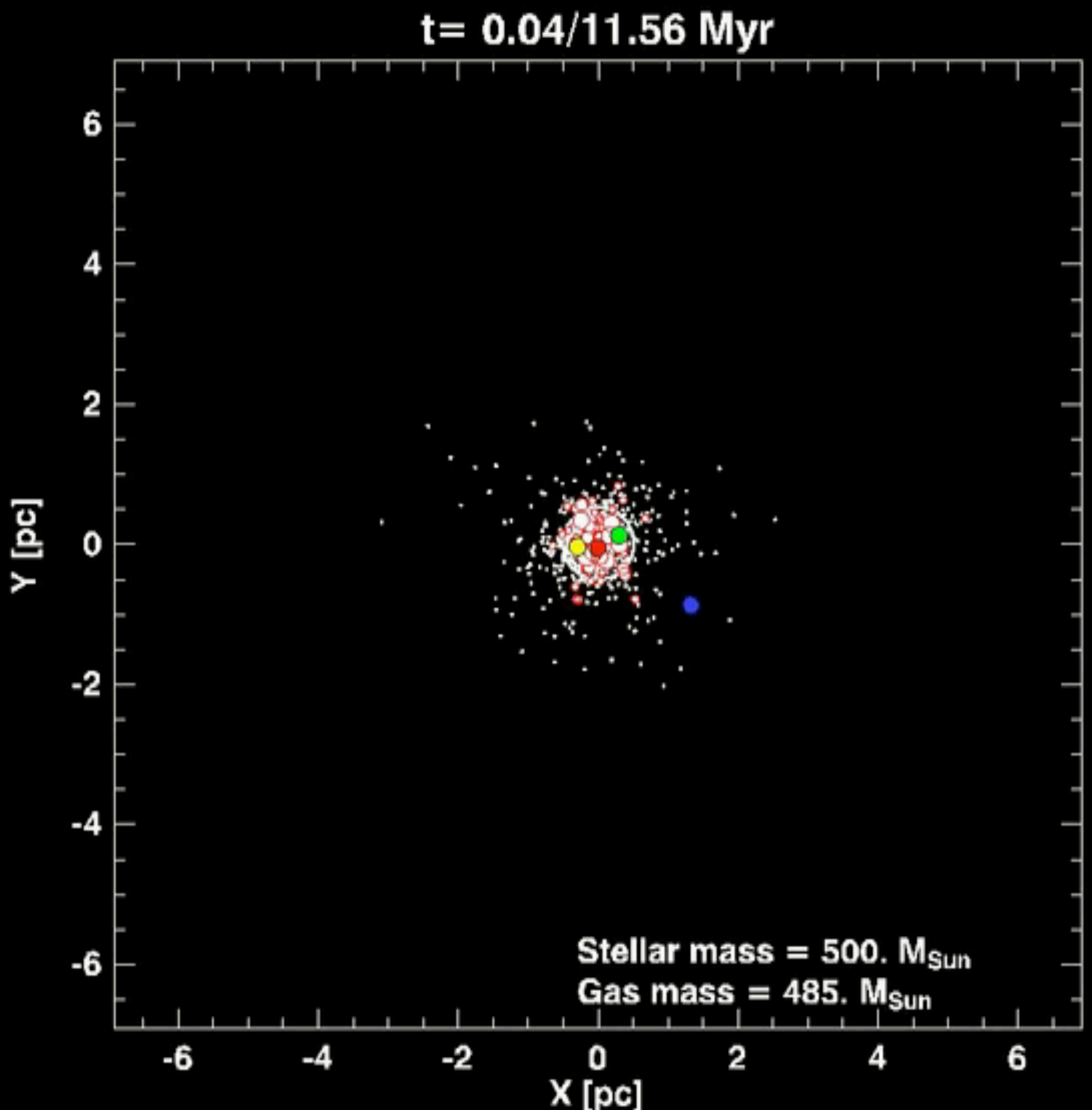

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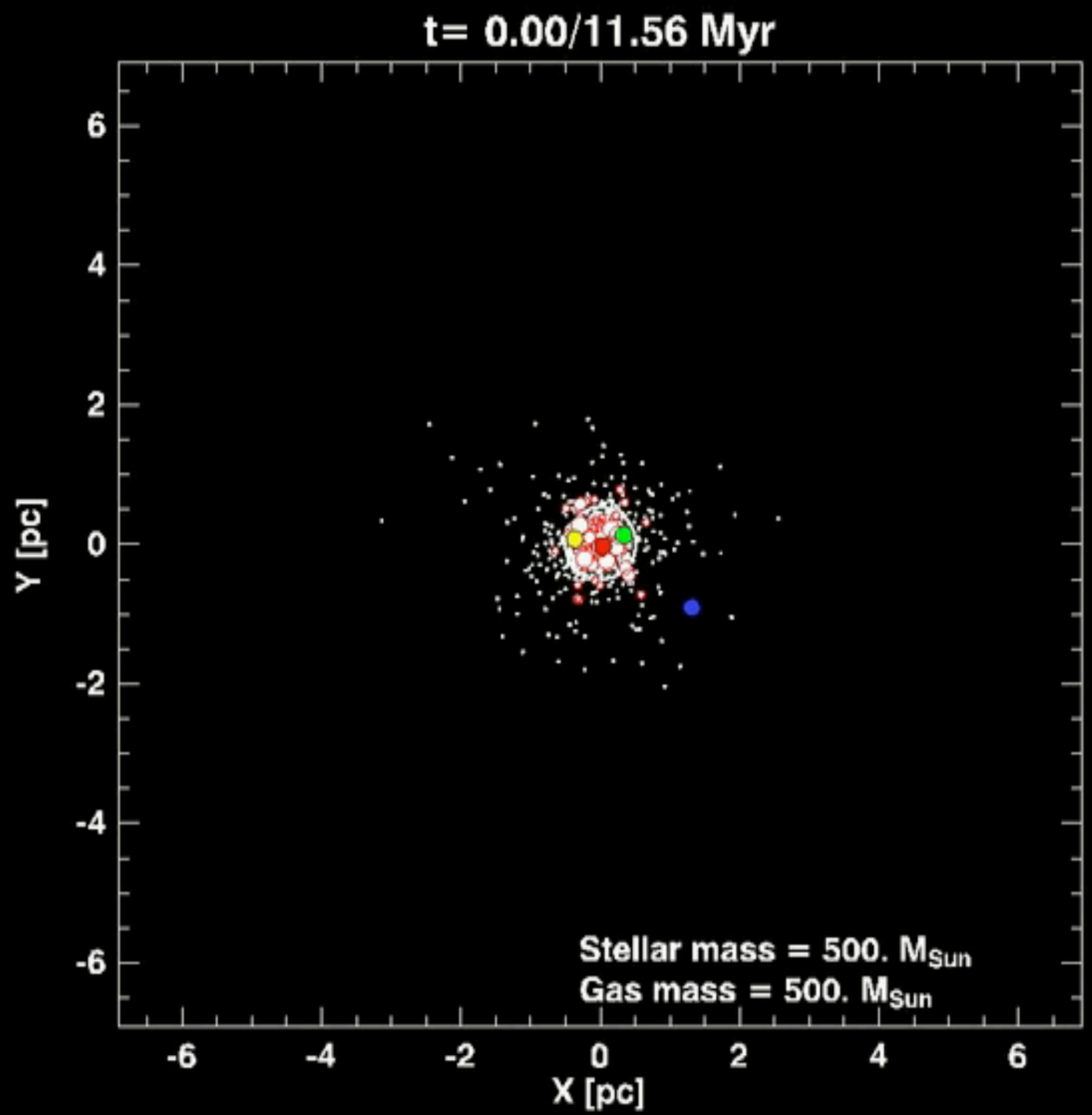
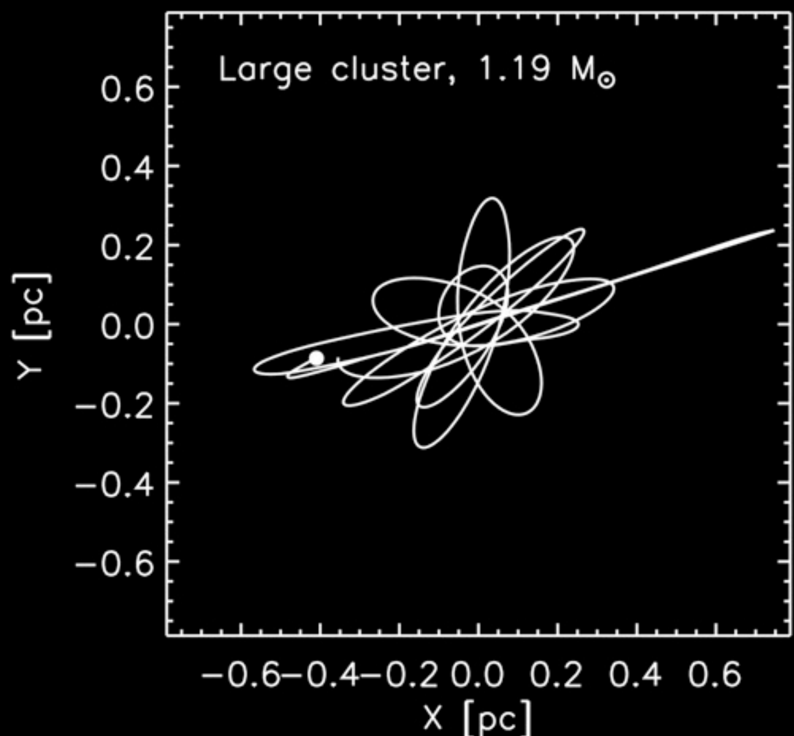
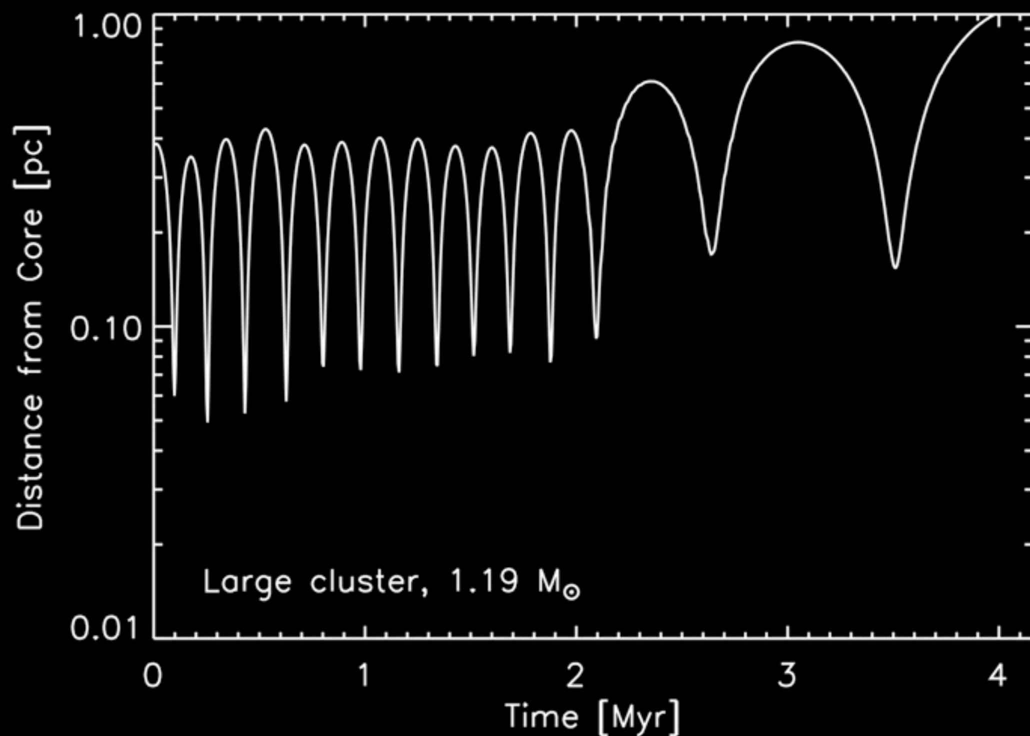


Throop & Bally 2008

BH Accretion: History of individual star





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

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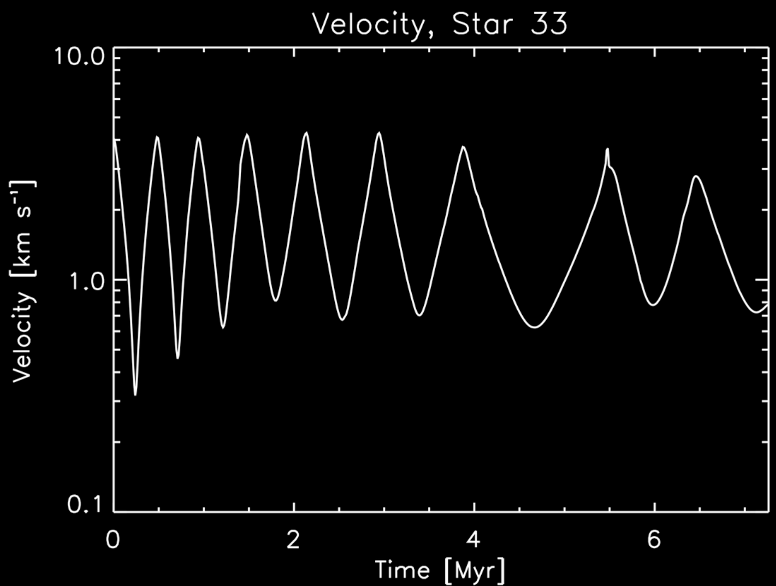
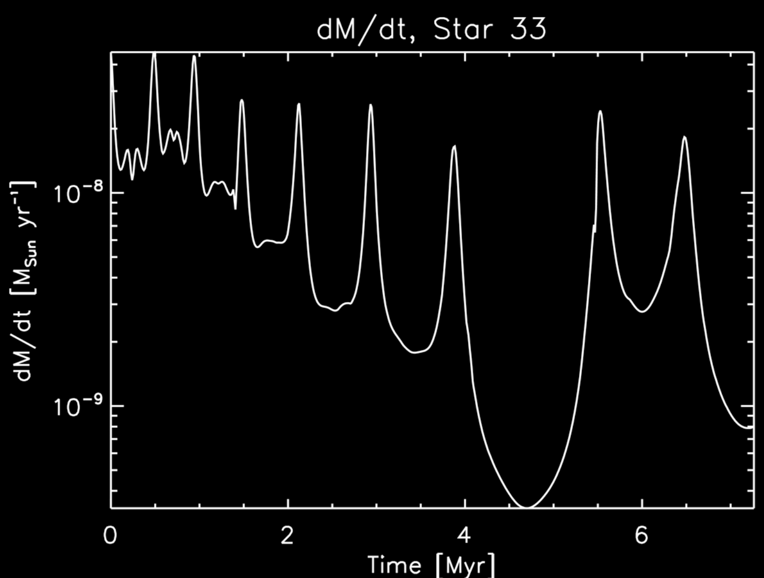
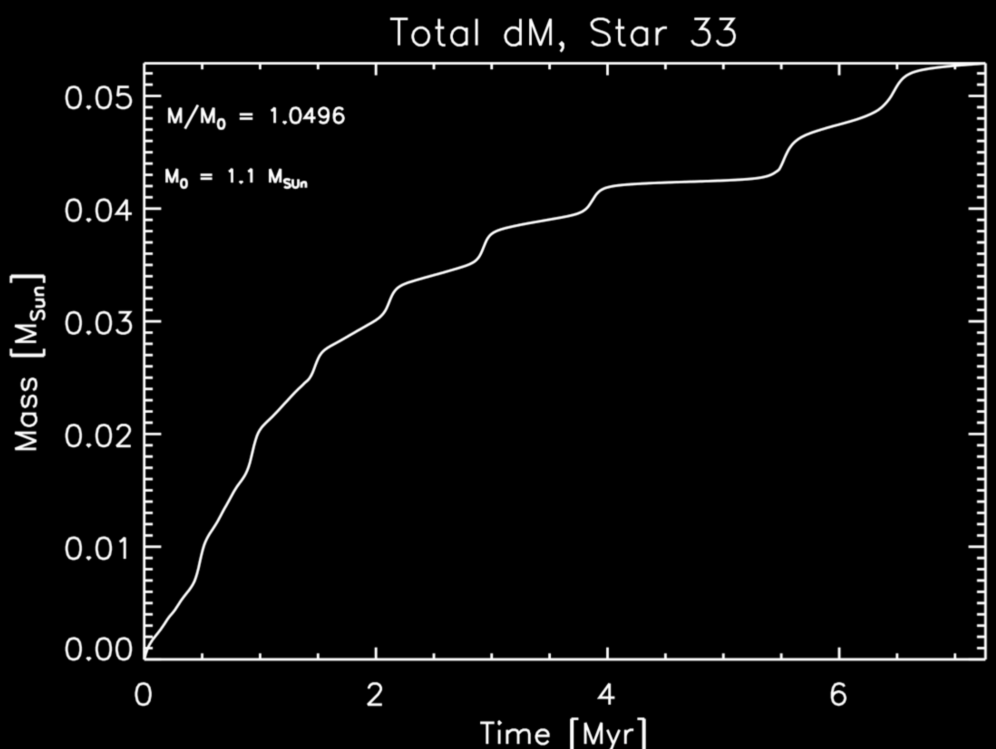




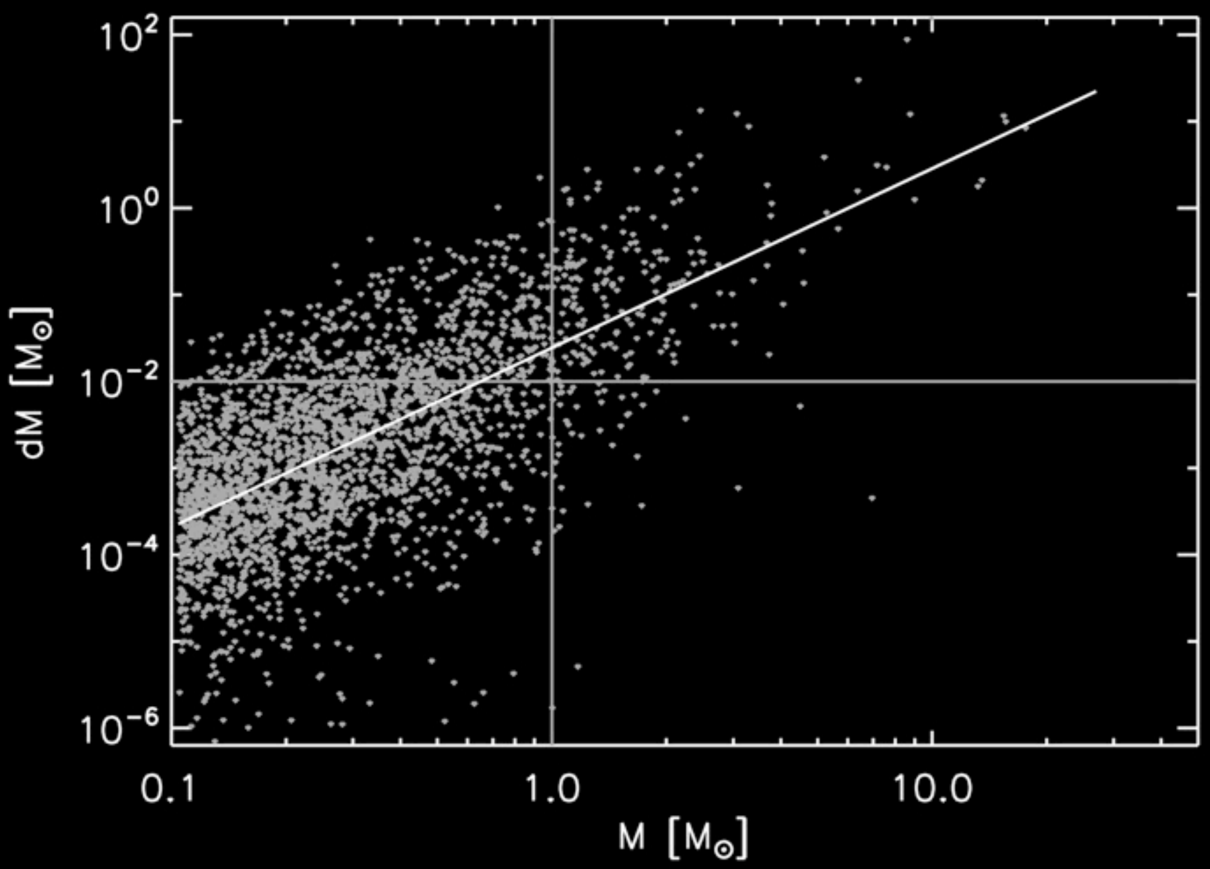


Star+disk accretes 5% of own mass in 5 Myr.

Accretion is episodic

- Highest at core: High velocity but high density

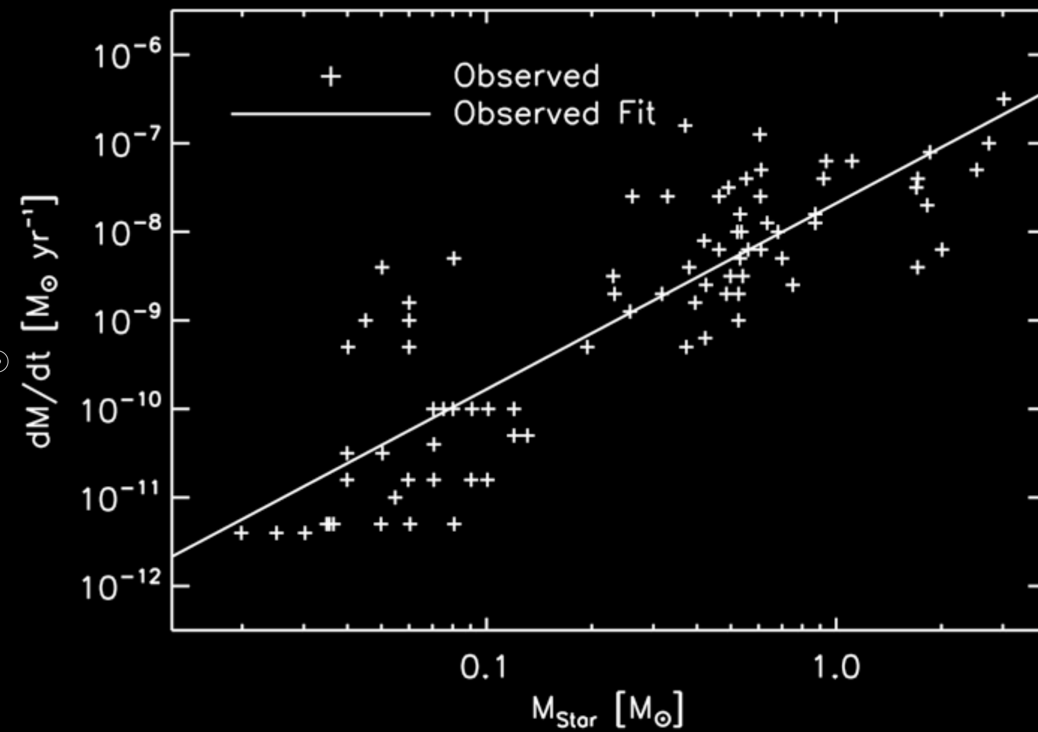
Results of N-Body sims



- 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 is seen onto hundreds young stars in molecular clouds.
- Varies with stellar mass: $dM/dt \sim M^2$
- Accretion is $\sim 0.01\ M_\odot\ Myr^{-1}$ for $1 M_\odot$
- Source of the accretion is unknown!



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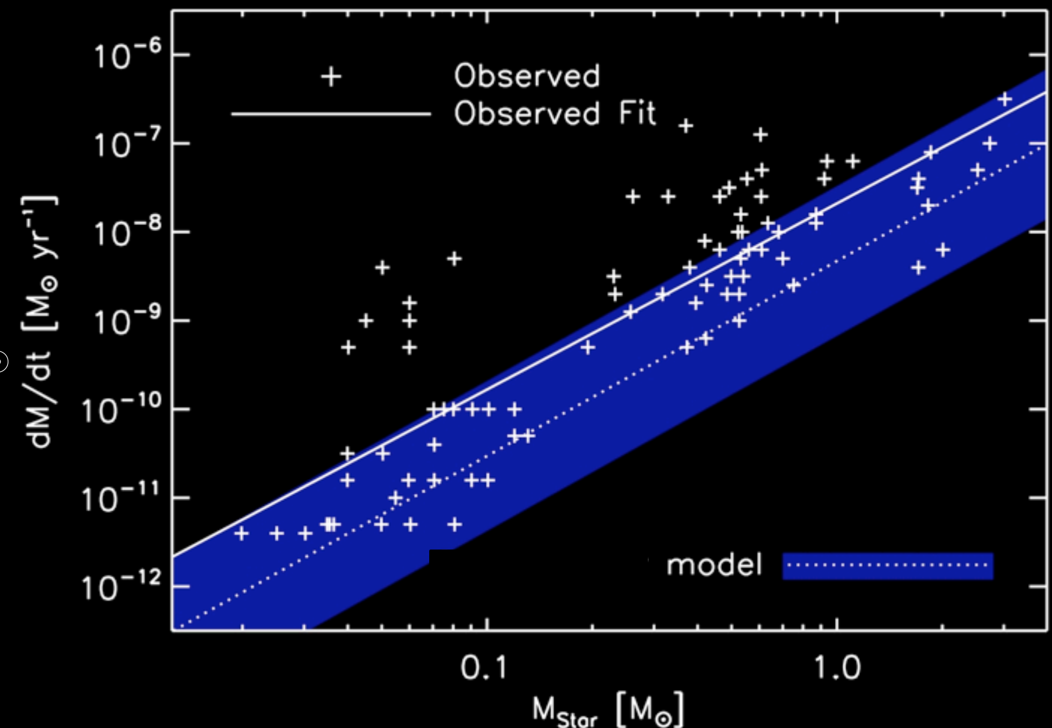

We propose: accretion **onto young stars** may be due to ISM accretion **onto their disks**

Throop & Bally 2008

Consequences of Tail-End Accretion

- Disks may accrete many 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*

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

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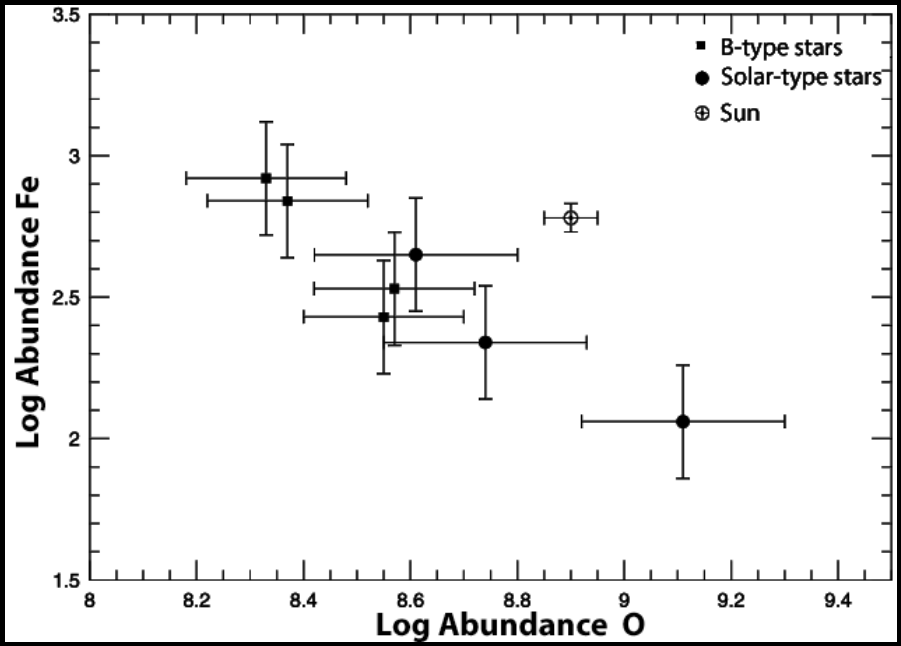
ABSTRACT

Throop & Bally 2008, *AJ*

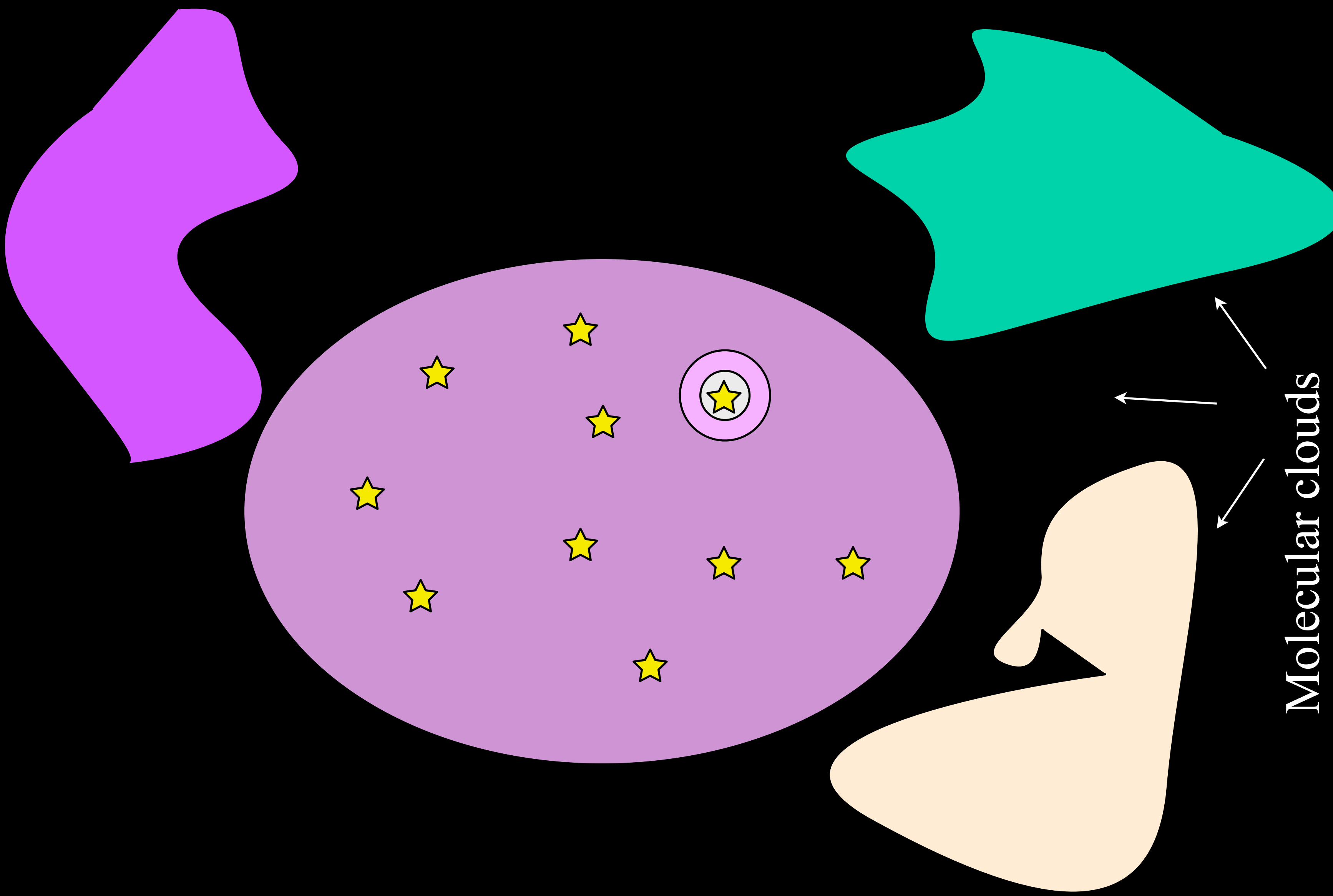
Accretion of 'polluted' ISM

- Stars of same age/position/type in Orion show metallicities that vary by up to 10x in Fe, O, Si, C
- 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



Cunha et al 2000

Late accretion may cause the composition of a stars and their disks to be different! There may be no 'Solar Nebula Composition.' Even in our Solar System, there is a lot of variation : isotope ratios.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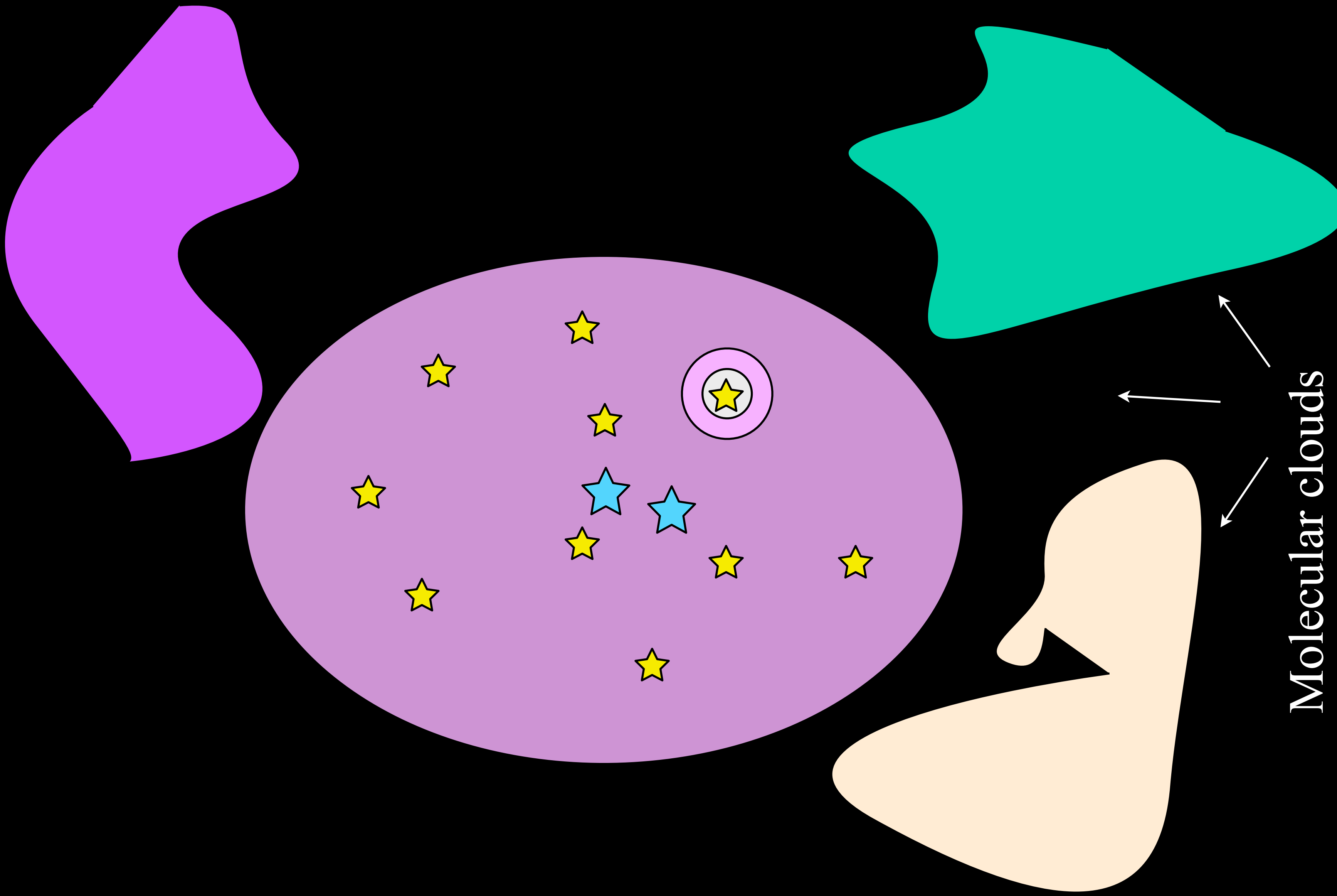
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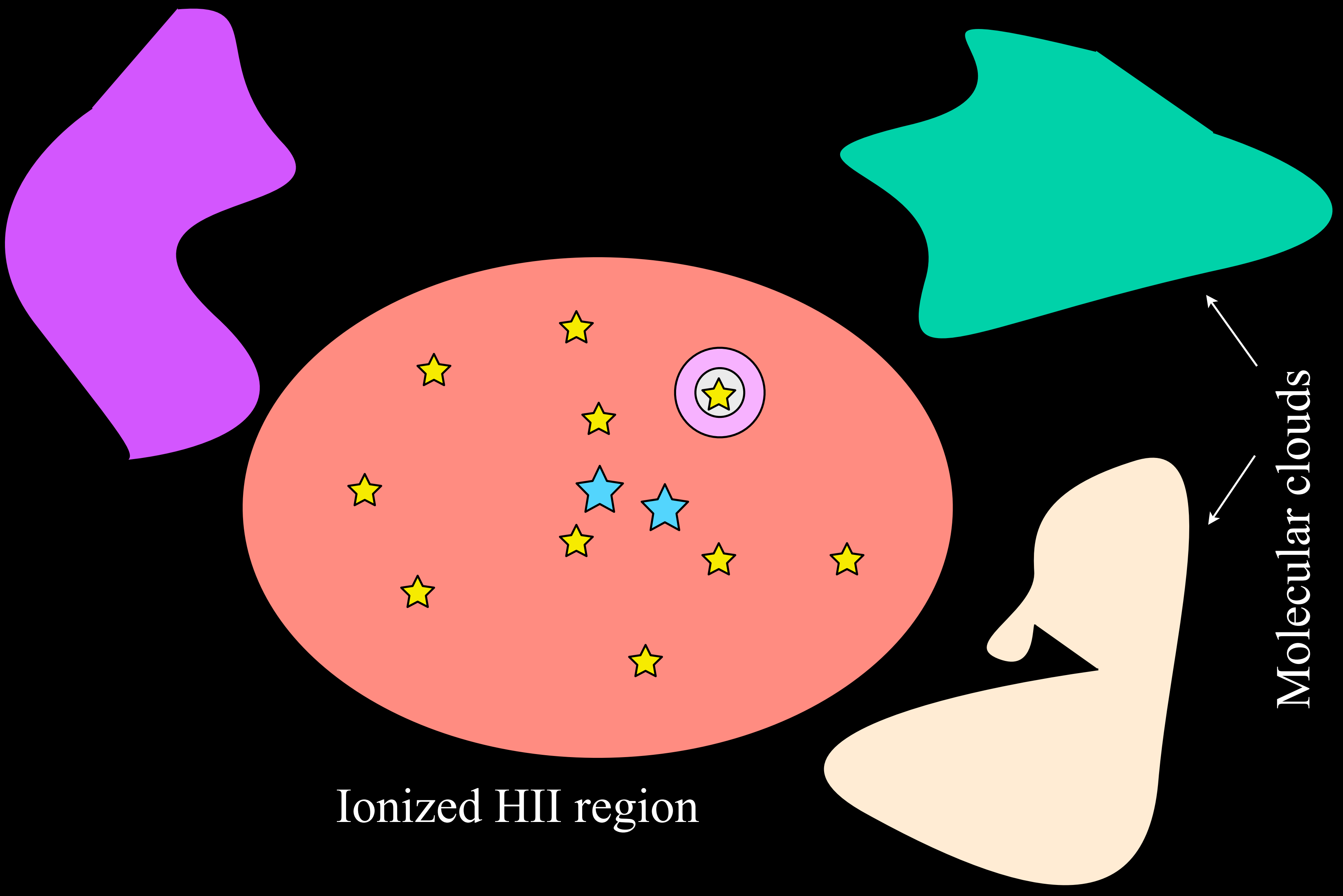
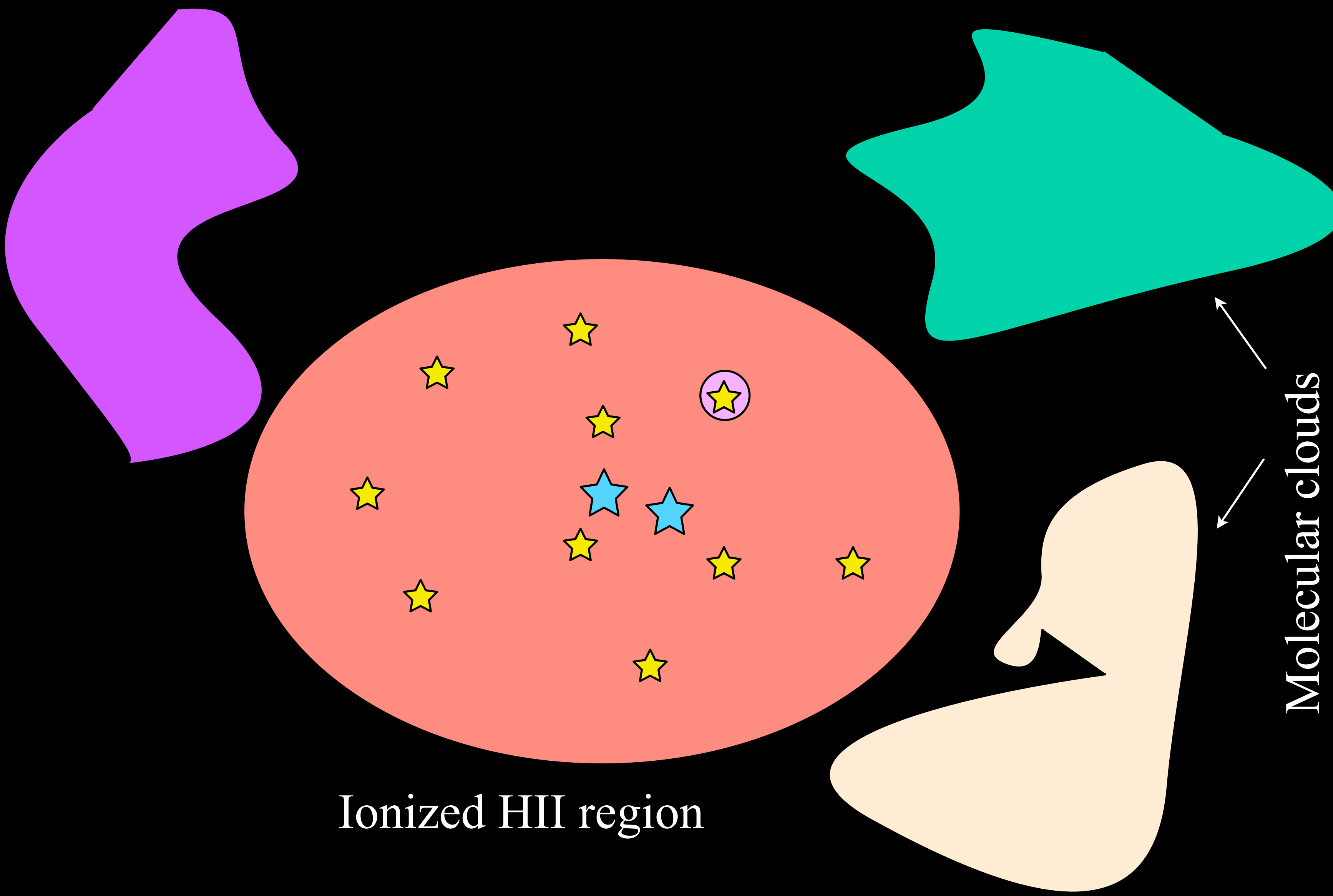


Molecular clouds
Ionized HII region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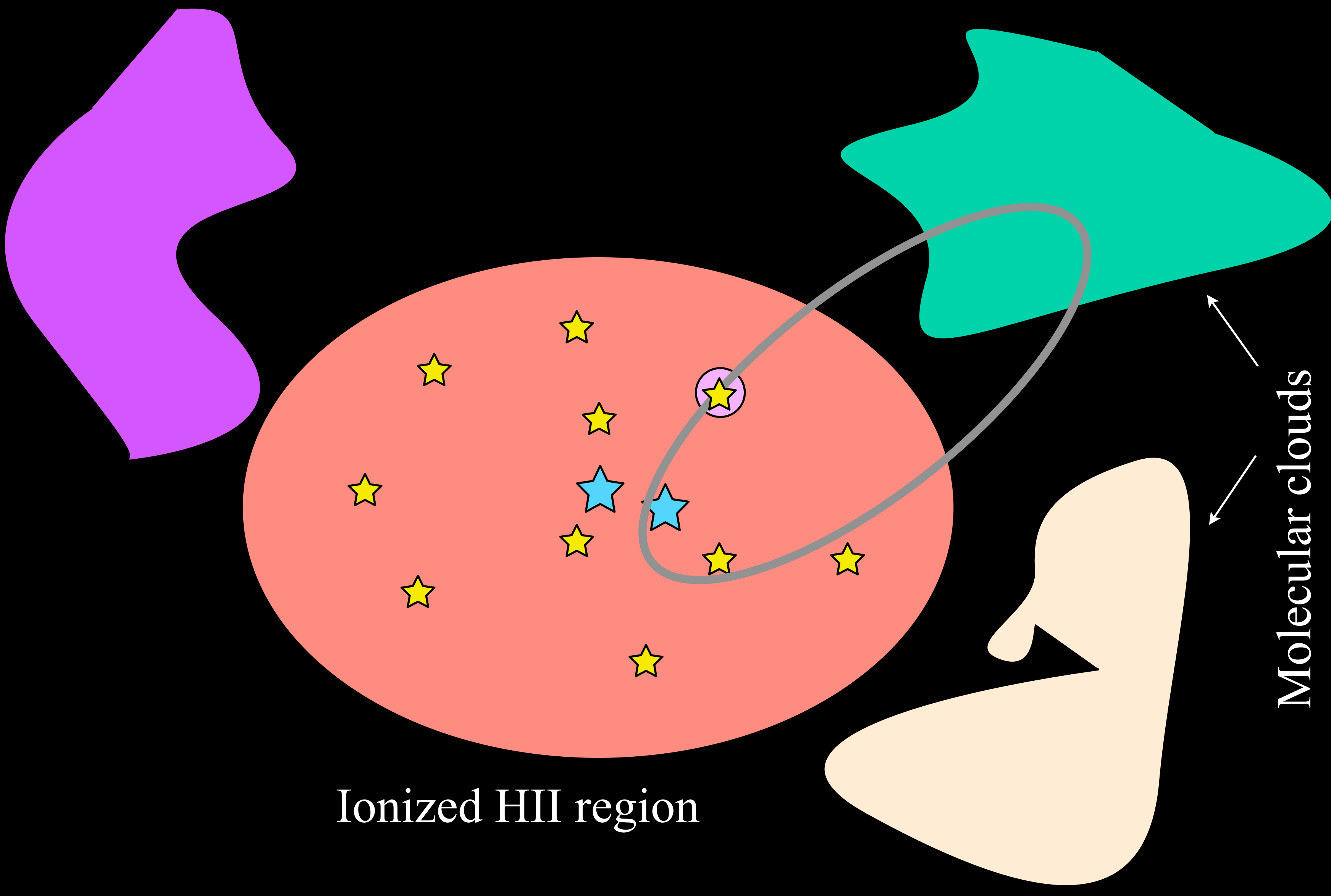
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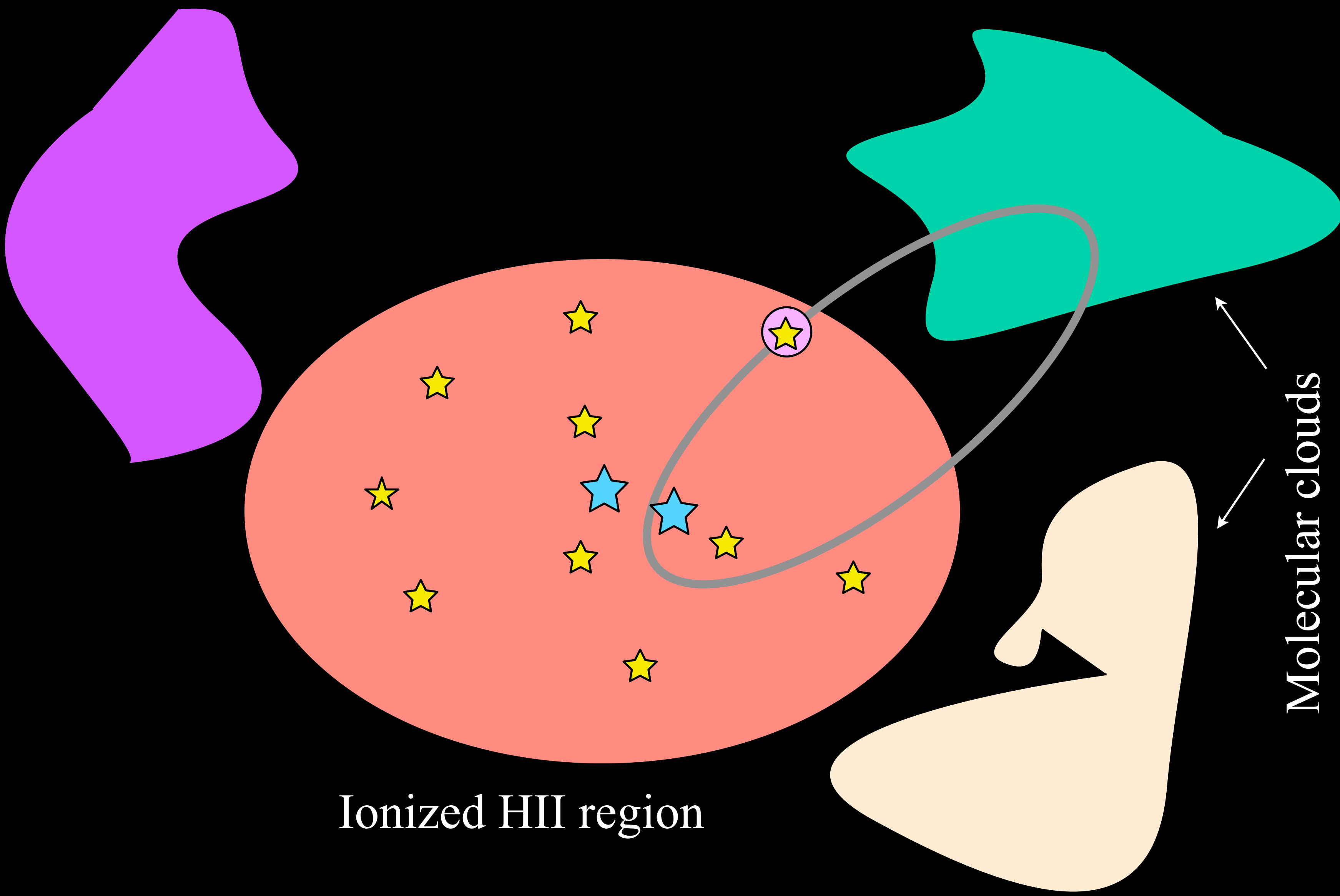
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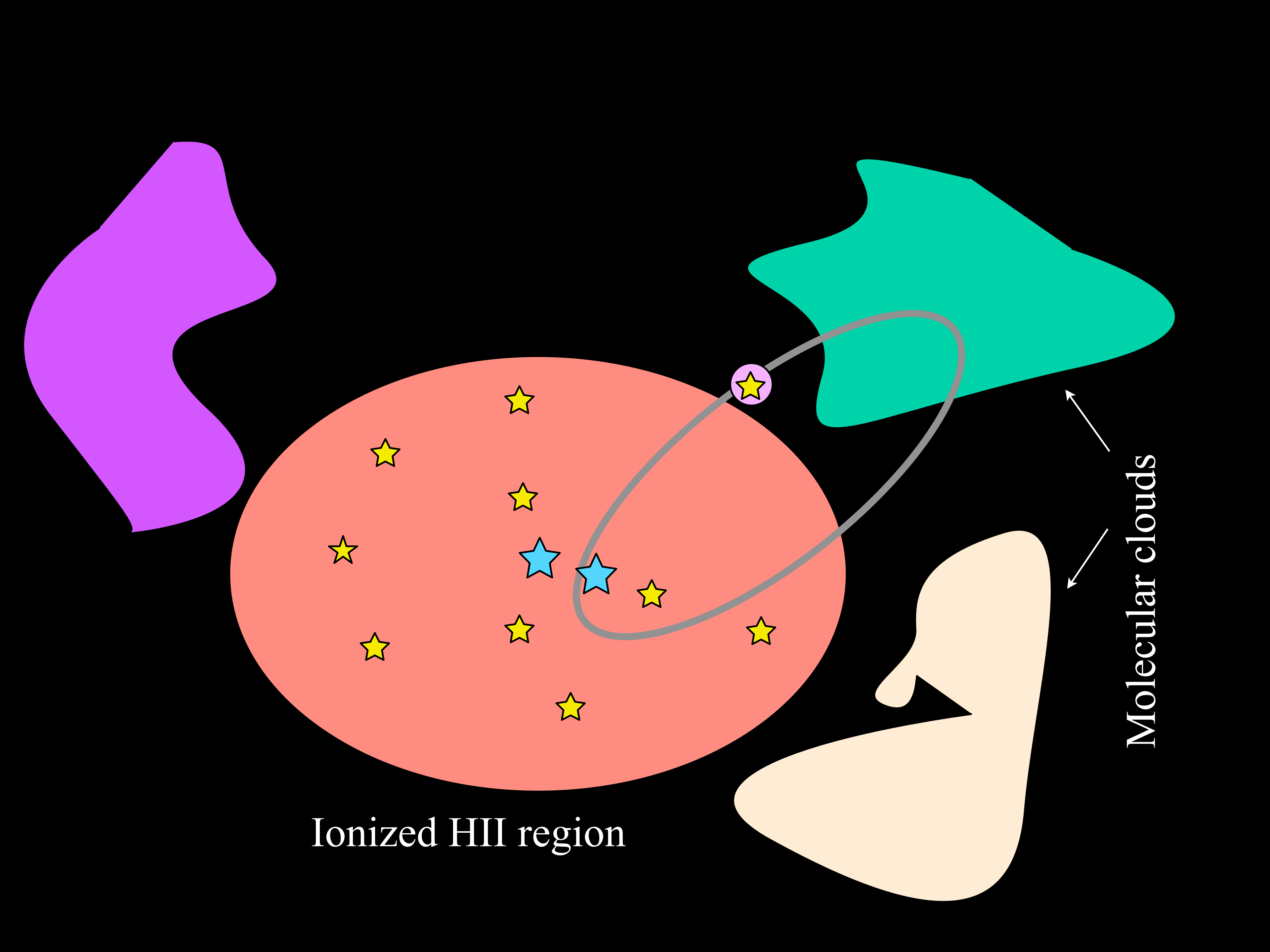
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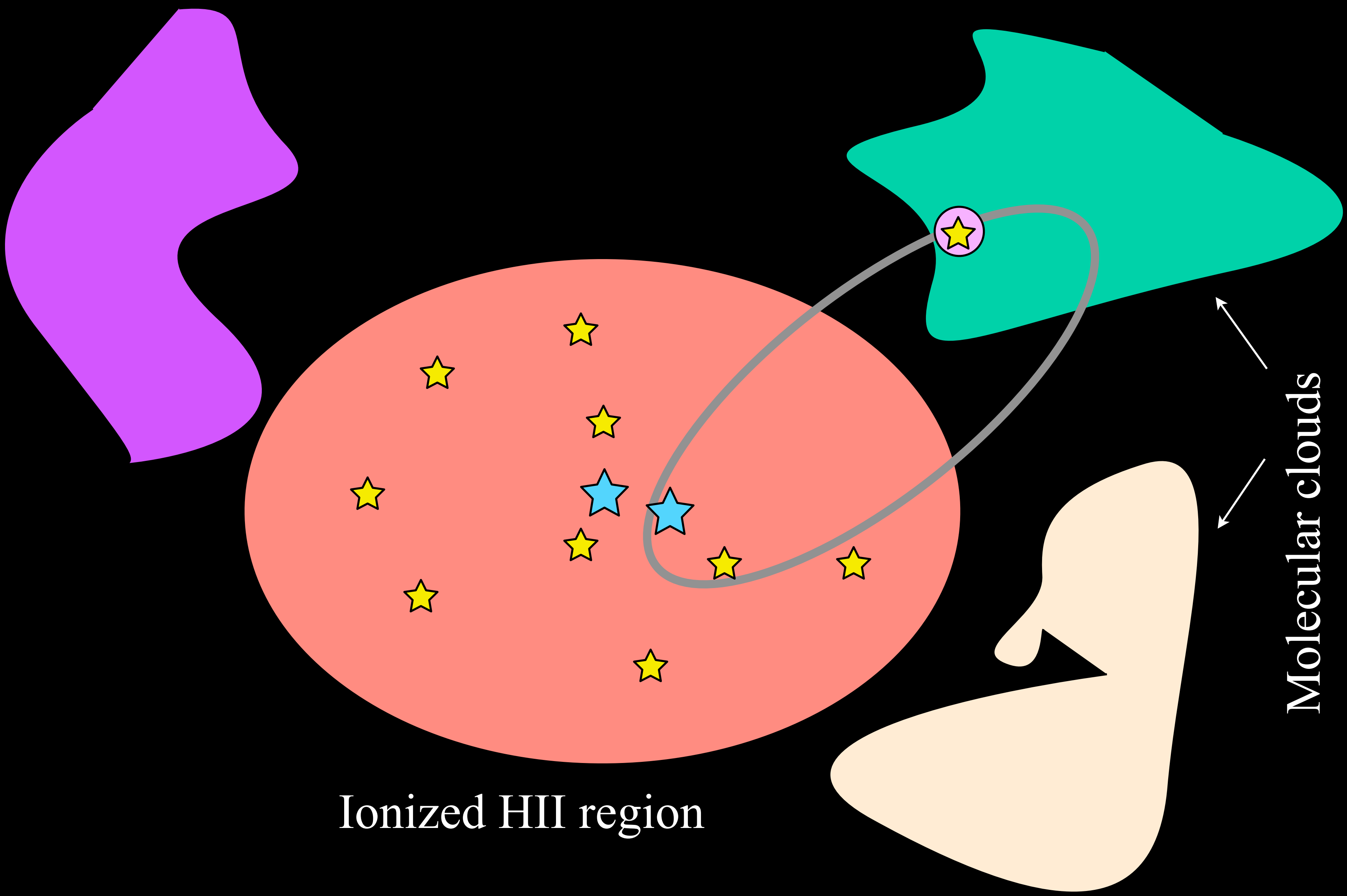
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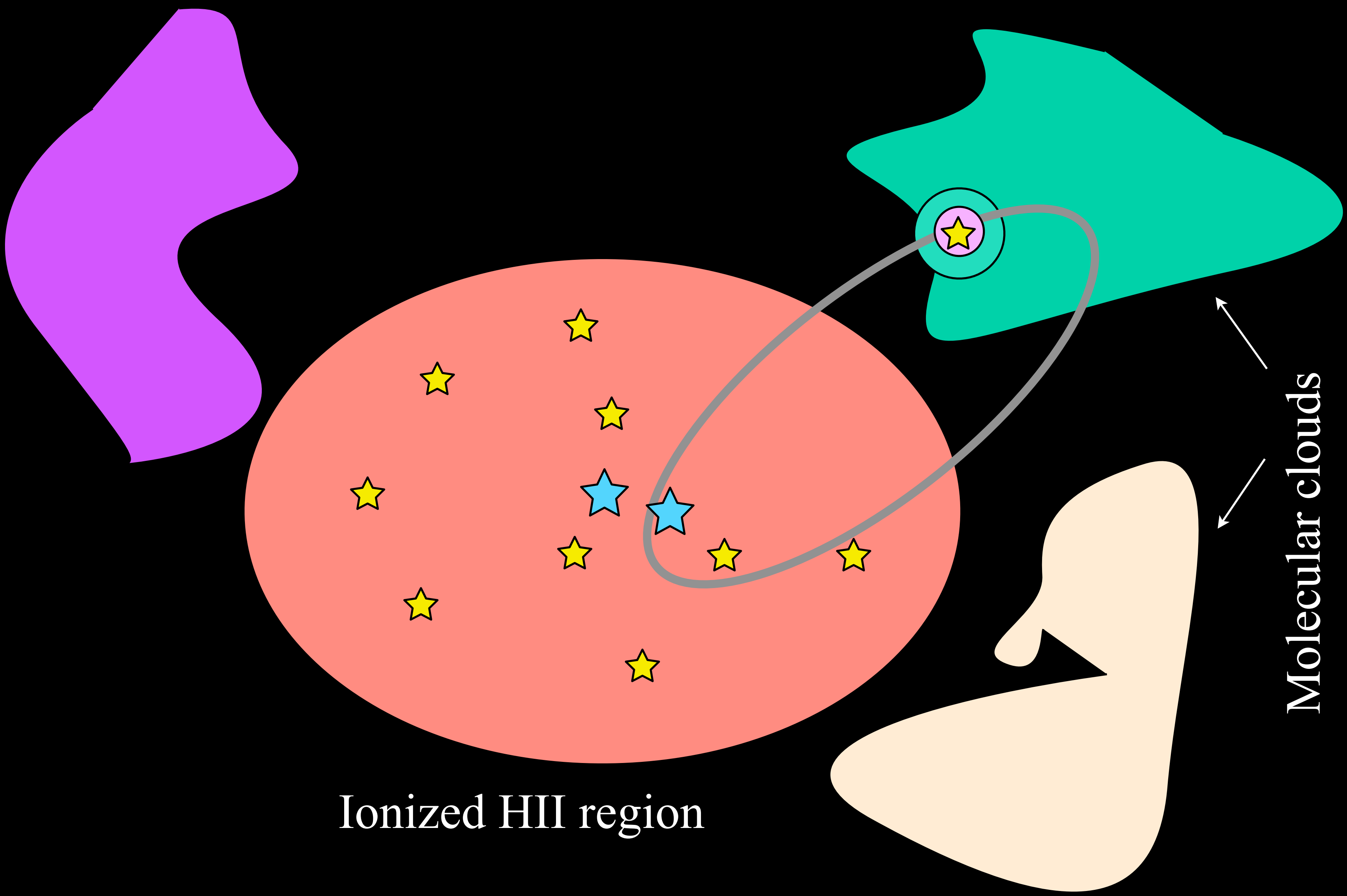
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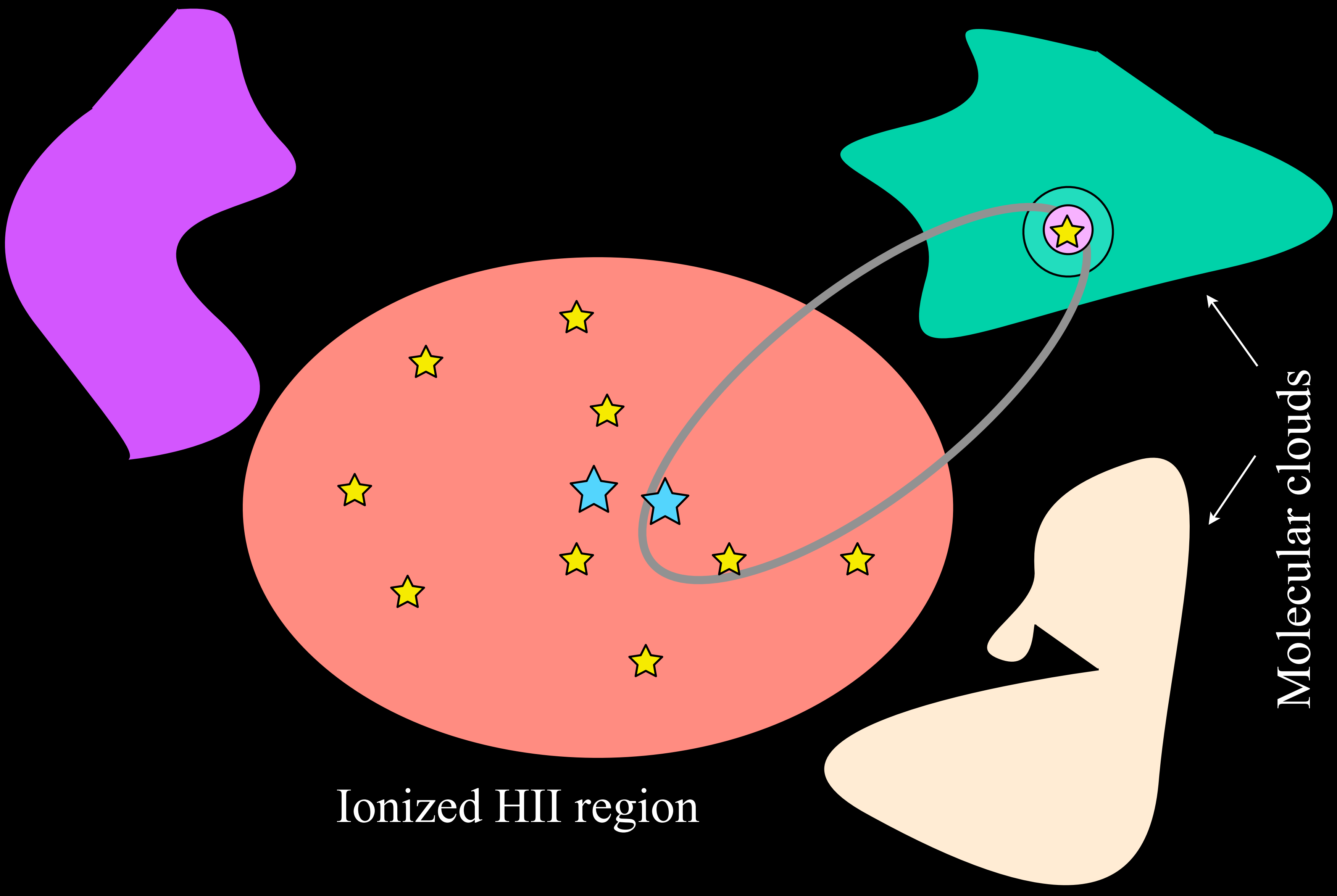
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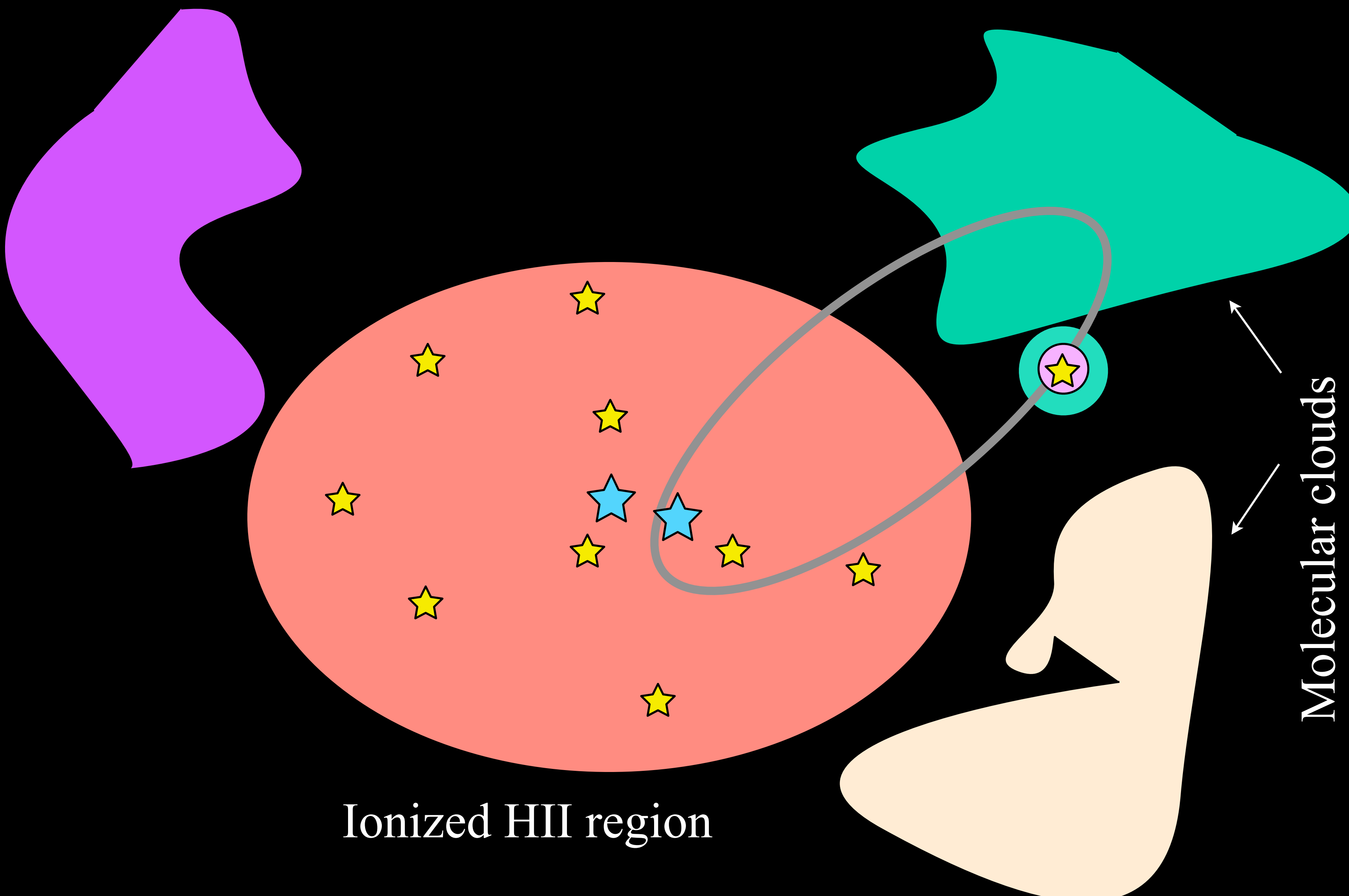
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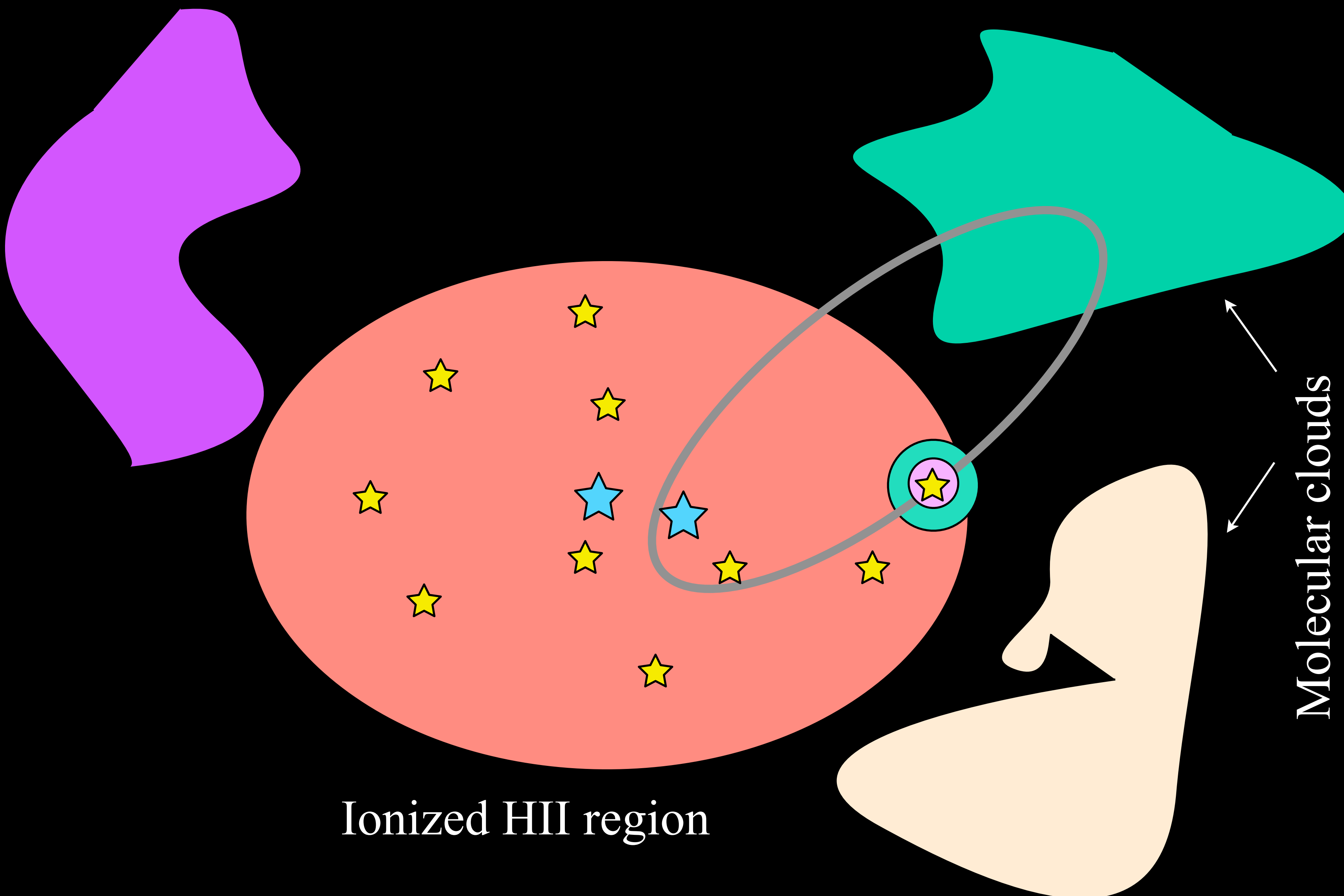

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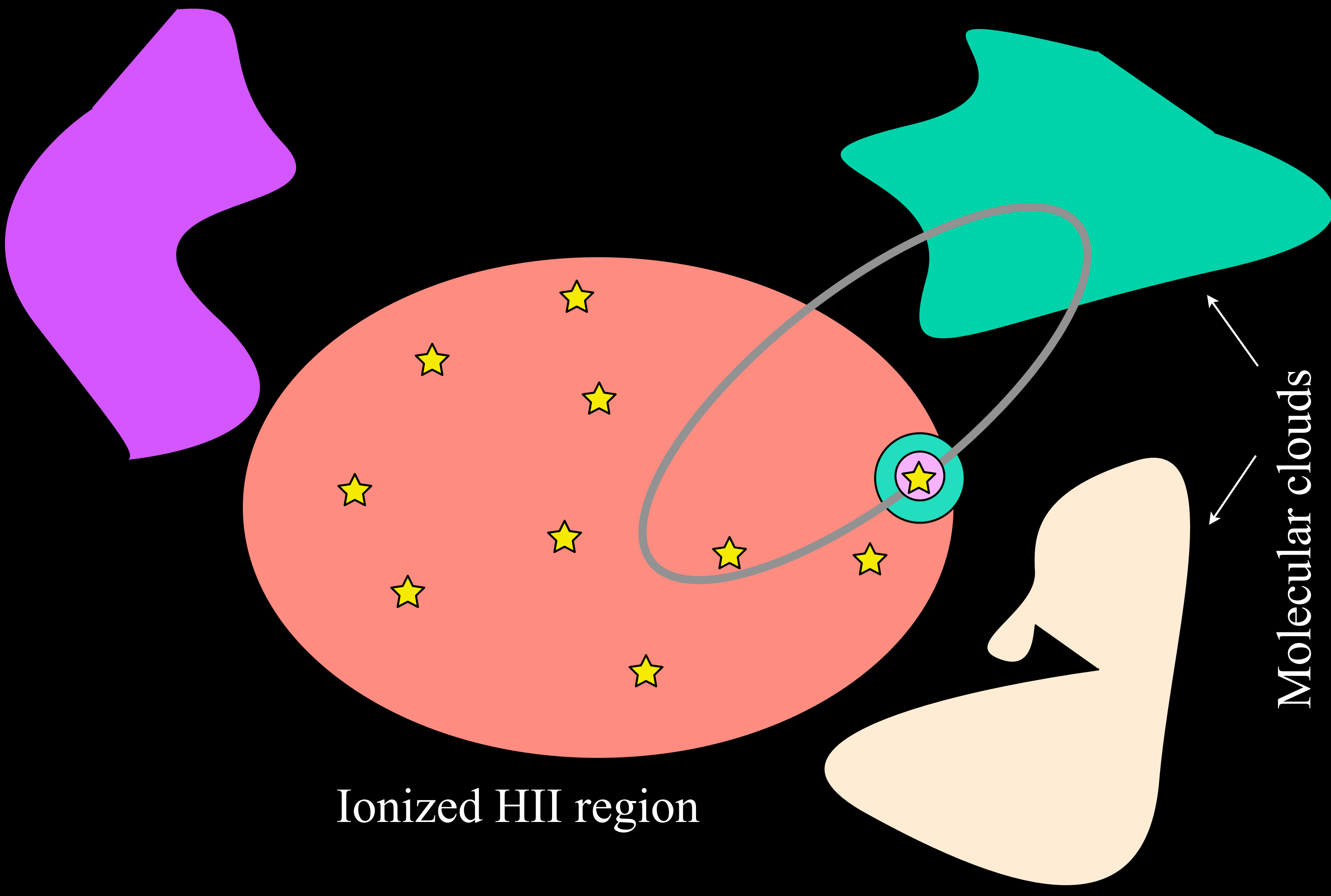
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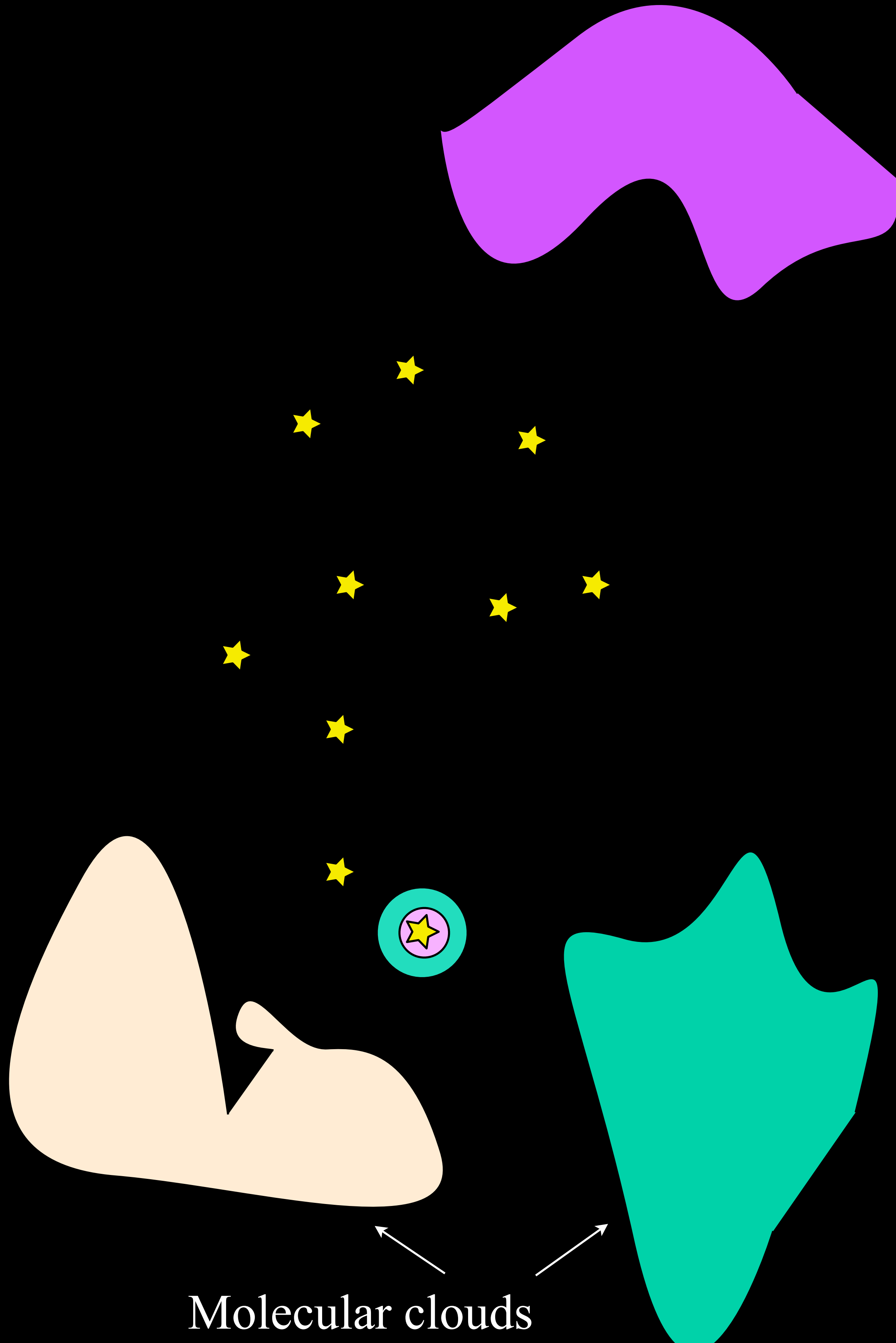
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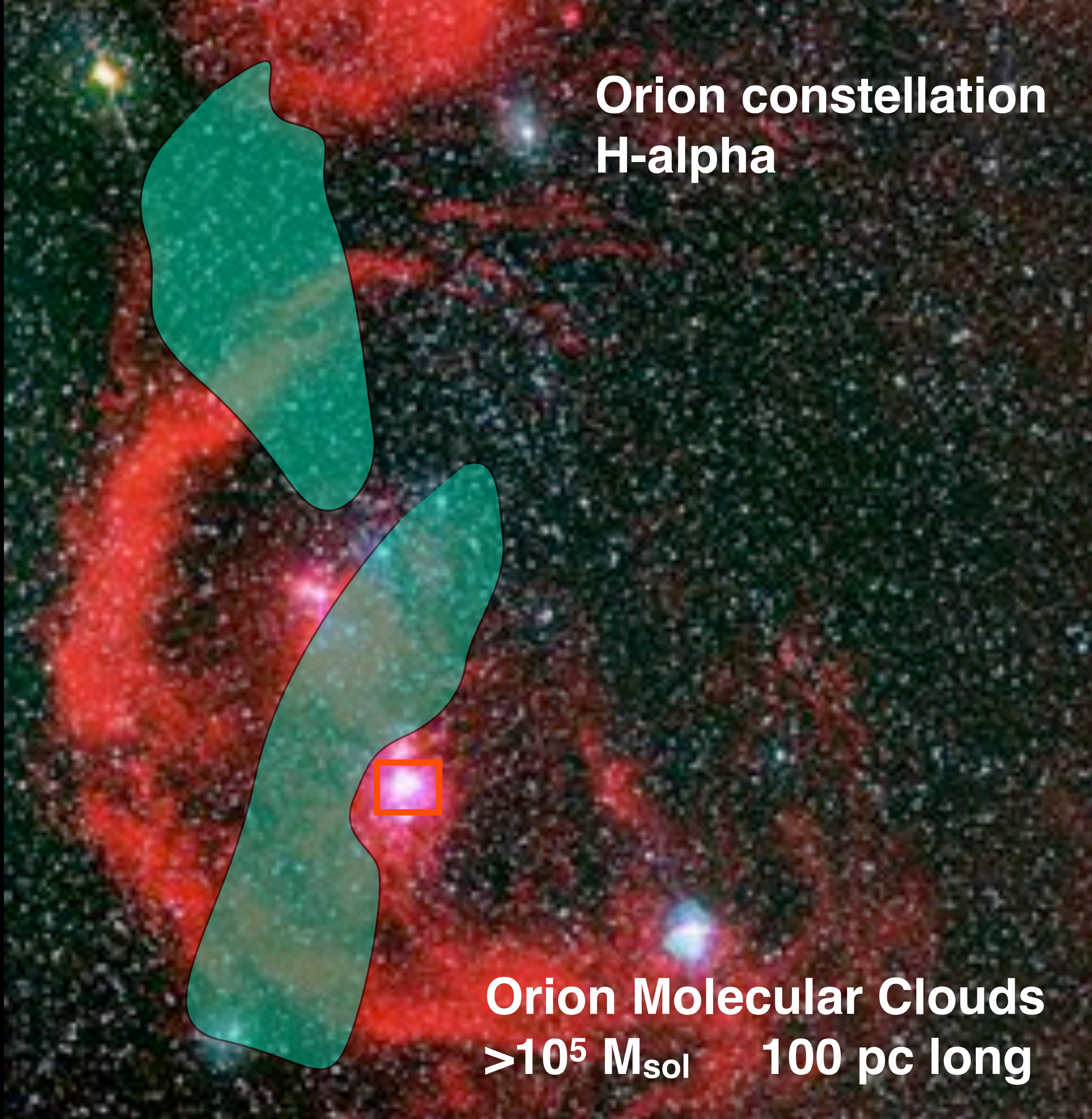
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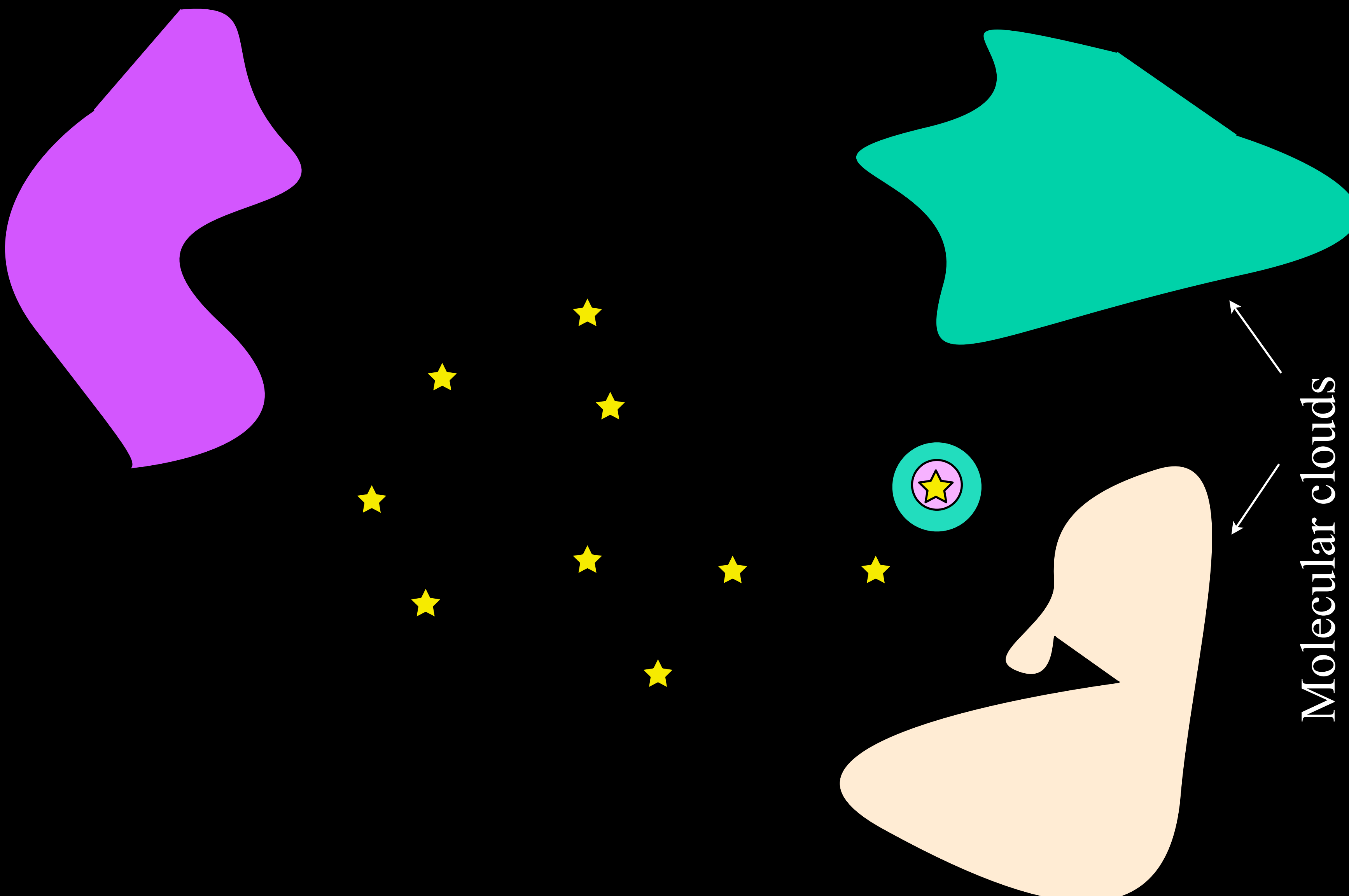
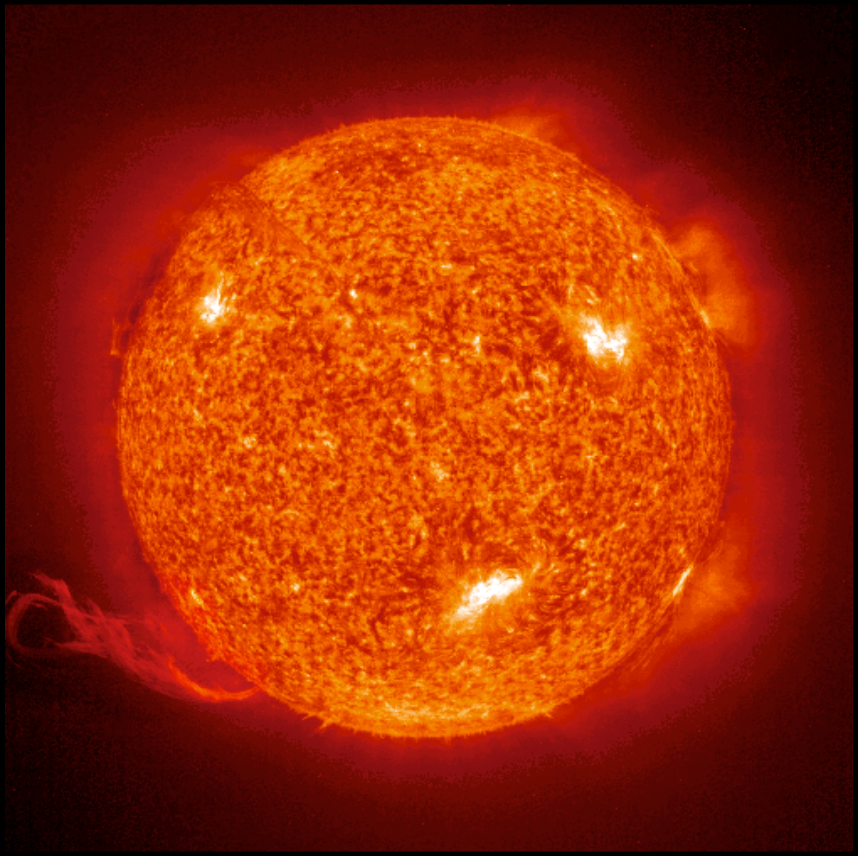

Molecular clouds

Jupiter vs. the Sun



If the Sun and Jupiter both formed from the same cloud, why are they made of such different stuff?

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.

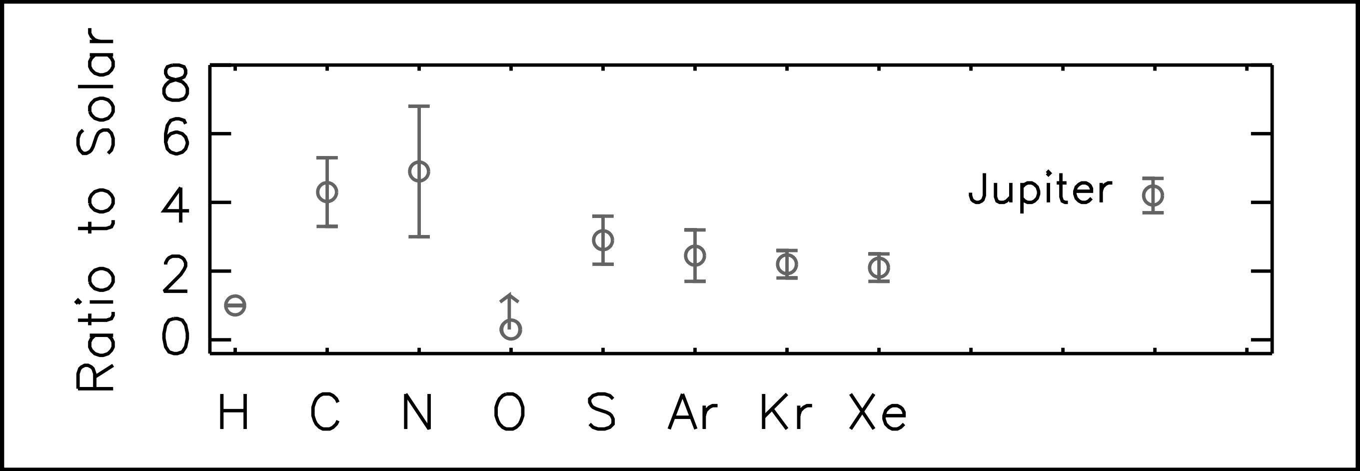
3. 'Pollution' from massive stars is accreted onto Jupiter.

    Accretion from ISM -> Solar Nebula Disk -> Jupiter

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

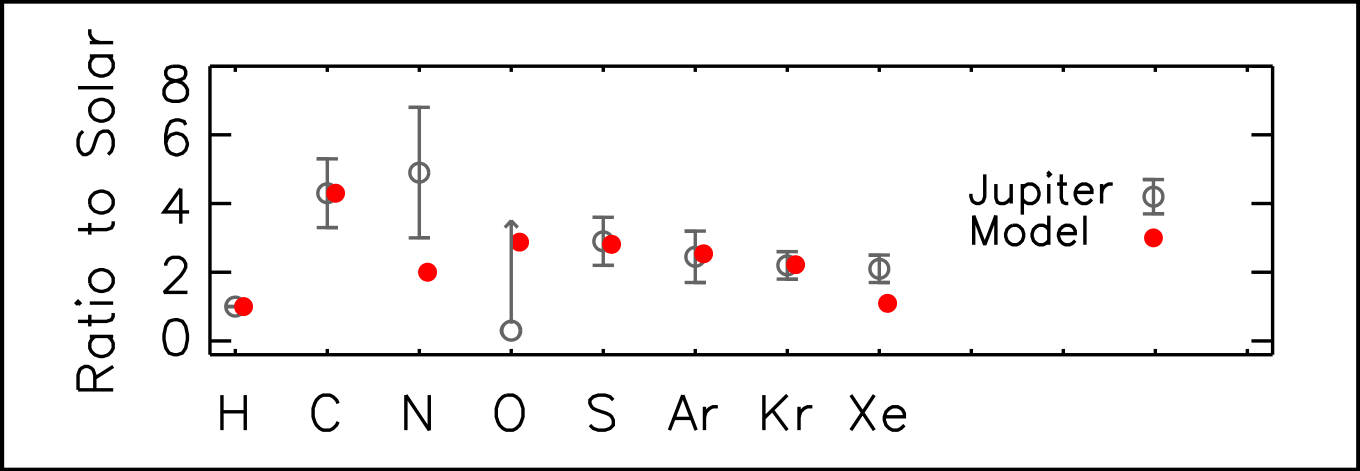
Throop & Bally 2009 (Icarus, submitted)

Observed Jupiter Composition



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

Jupiter 'Polluted Accretion' model



- Data: Galileo Probe
- Model: Accretion from ISM
  - 87% Solar nebula material
  - 9% Stellar winds from 20 $M_\odot$ star (provides C, N)
  - 4% SN from 25 $M_\odot$ 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 with the right chemistry!

Jupiter 'Polluted Accretion' model

- 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:

"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..."

- Heterogeneity between Jupiter and Sun is a natural extension to that already observed in meteorites (but much bigger).

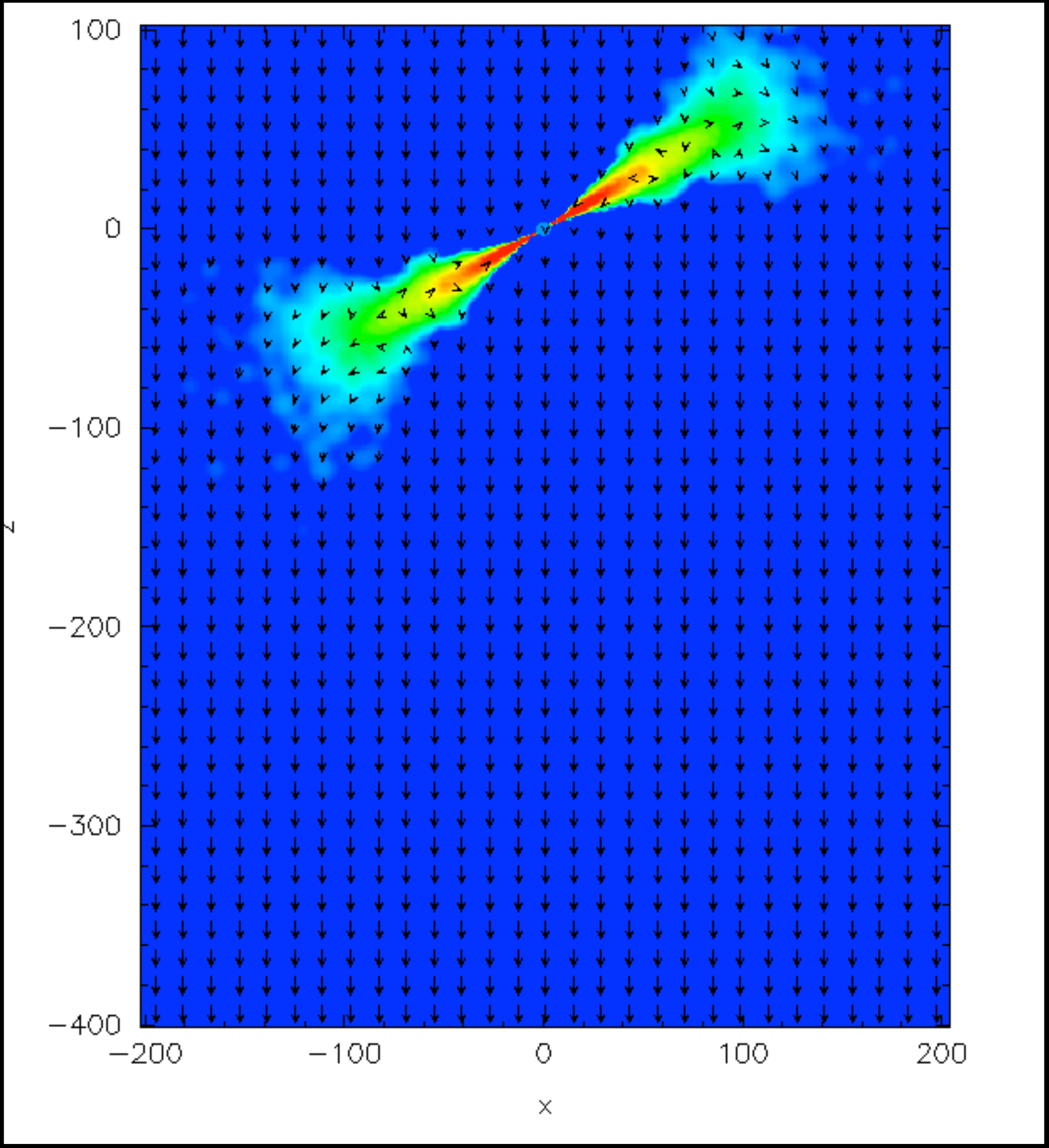
Throop & Bally 2009

SPH Sims: BH Acc onto 100 AU disk

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

Moeckel & Throop
2009 (AJ)

SPH Sims: BH Acc onto 100 AU disk

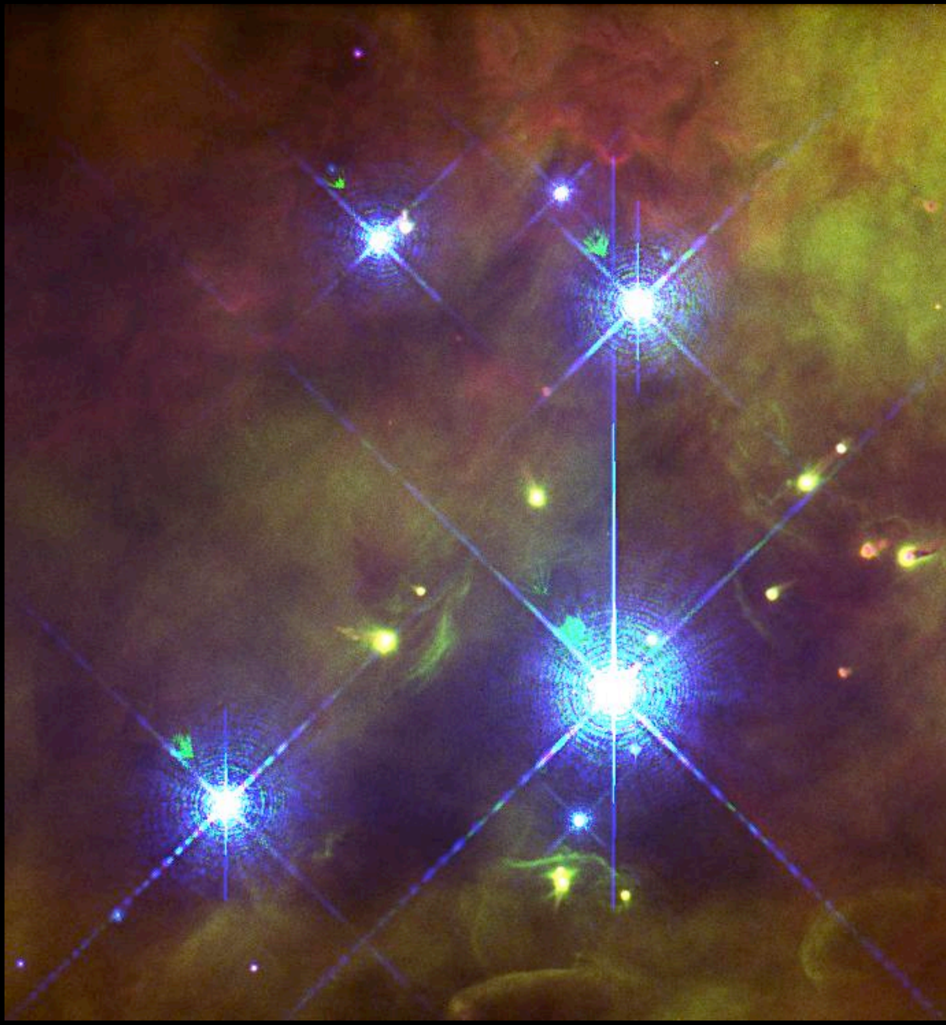


10,000 years
0.01 solar masses
v ~ 1 km/sec

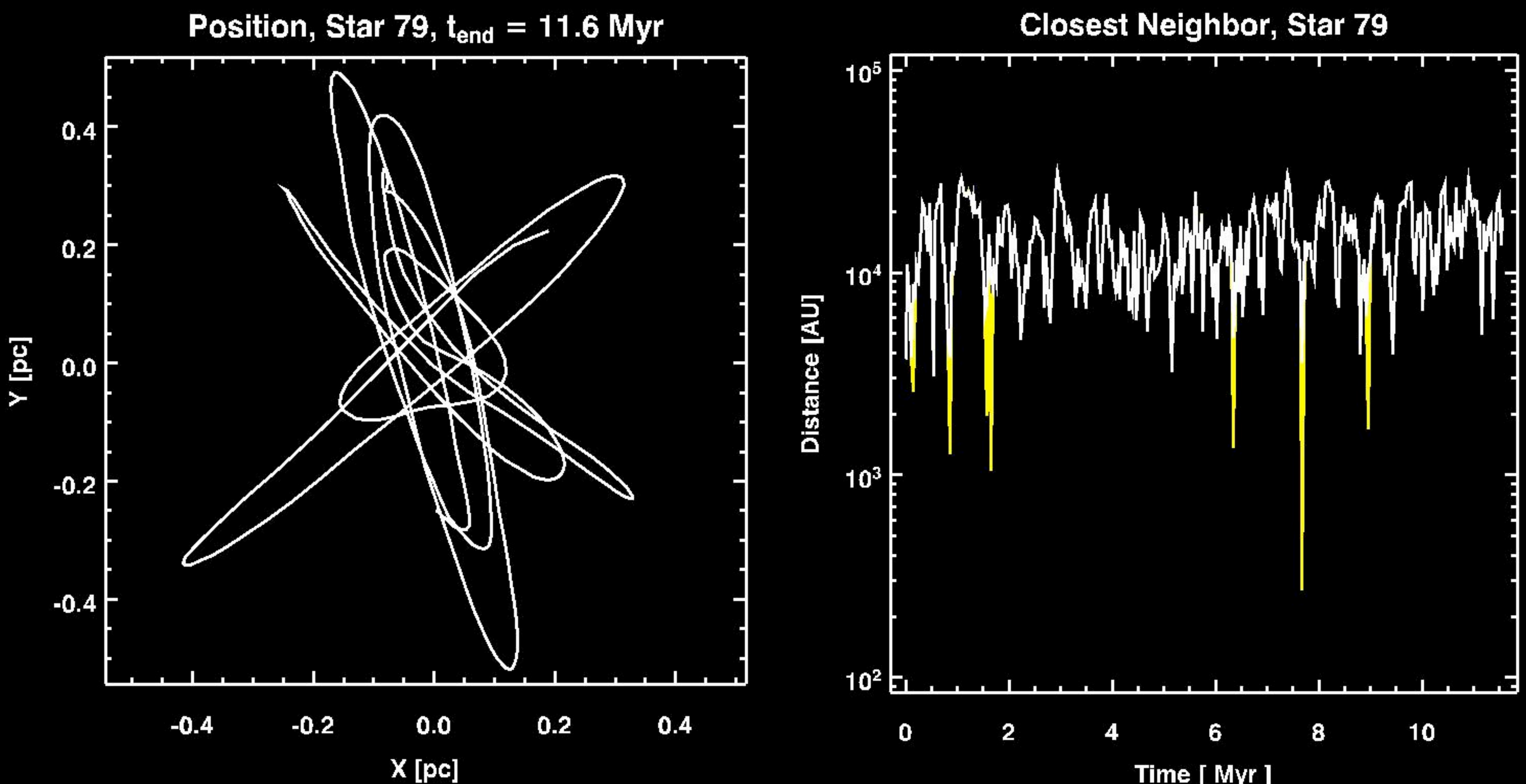
Moeckel & Throop 2009 (AJ)

Close Stellar Encounters

- 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?

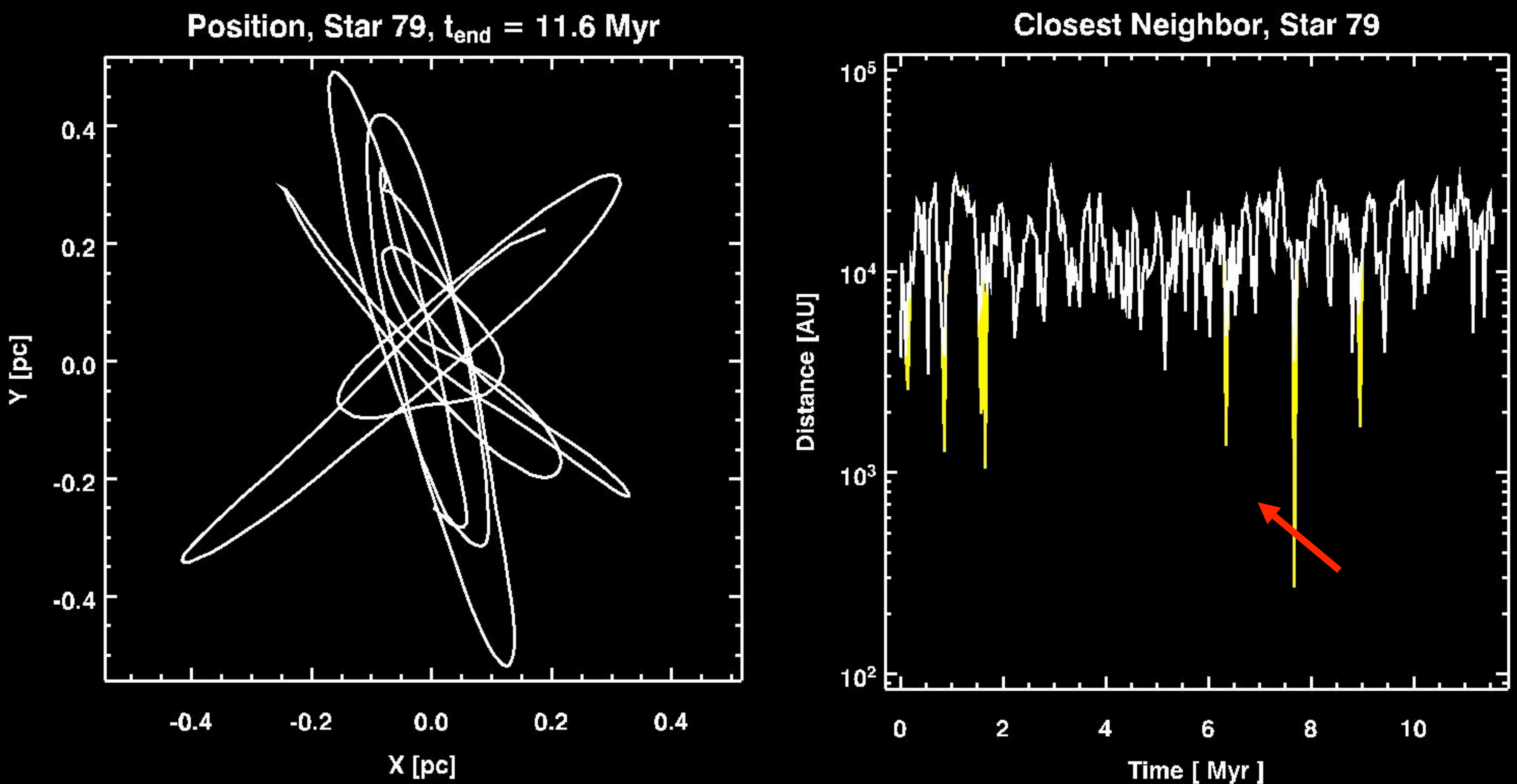


Close Approach History - Typical 1 M☉ Star



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

Close Approach History - Typical 1 $M_\odot$ Star



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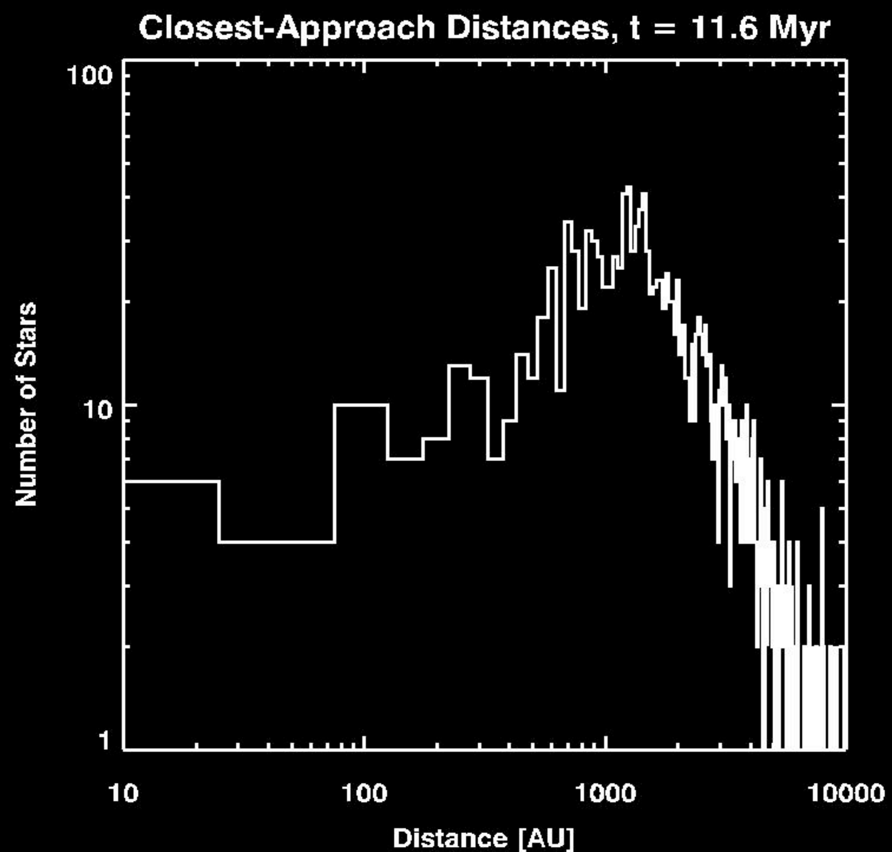
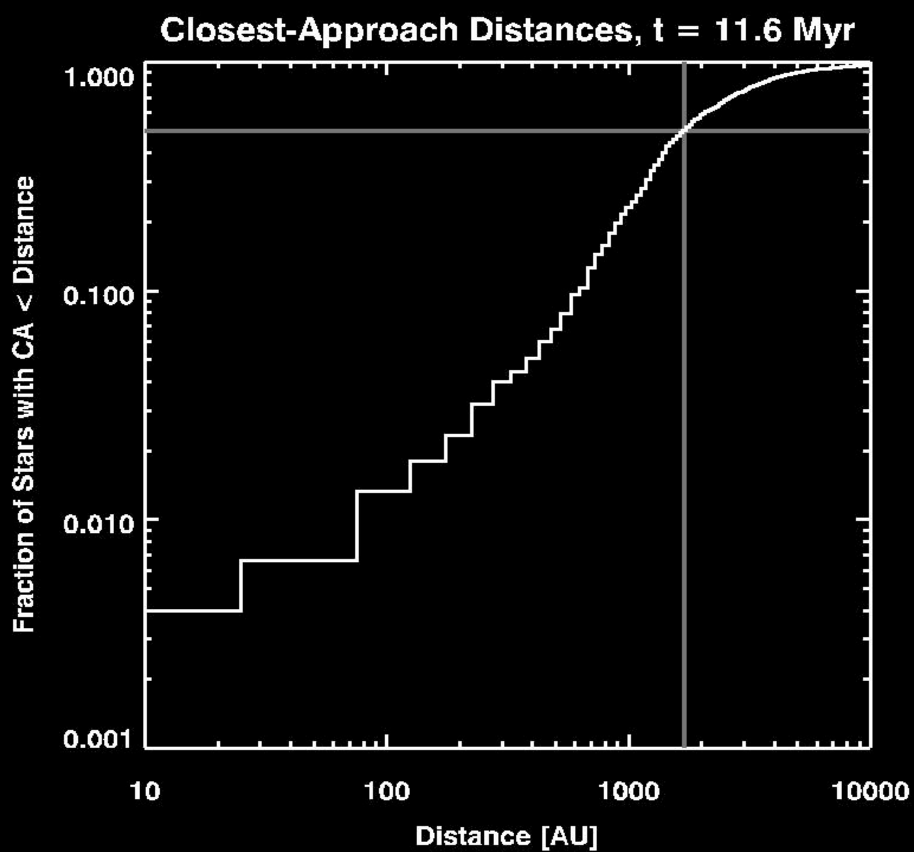
Throop & Bally 2008; also Adams et al 2006

Close Approaches - Entire Cluster





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  - Only 1% of disks are truncated to 30 AU, inhibiting planet formation

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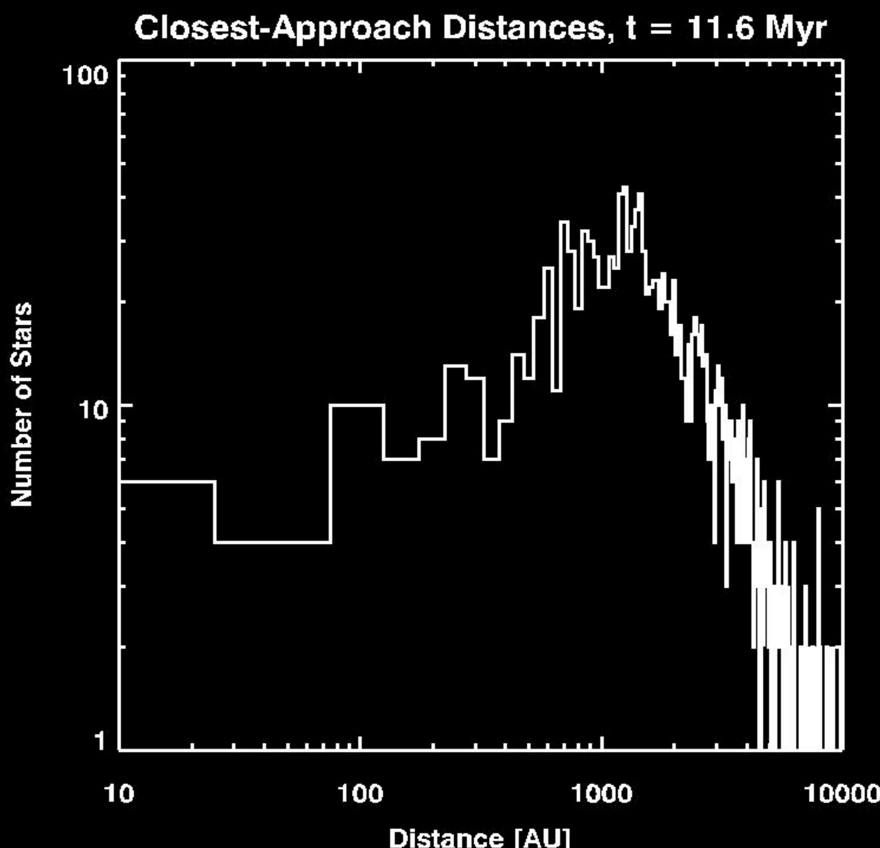

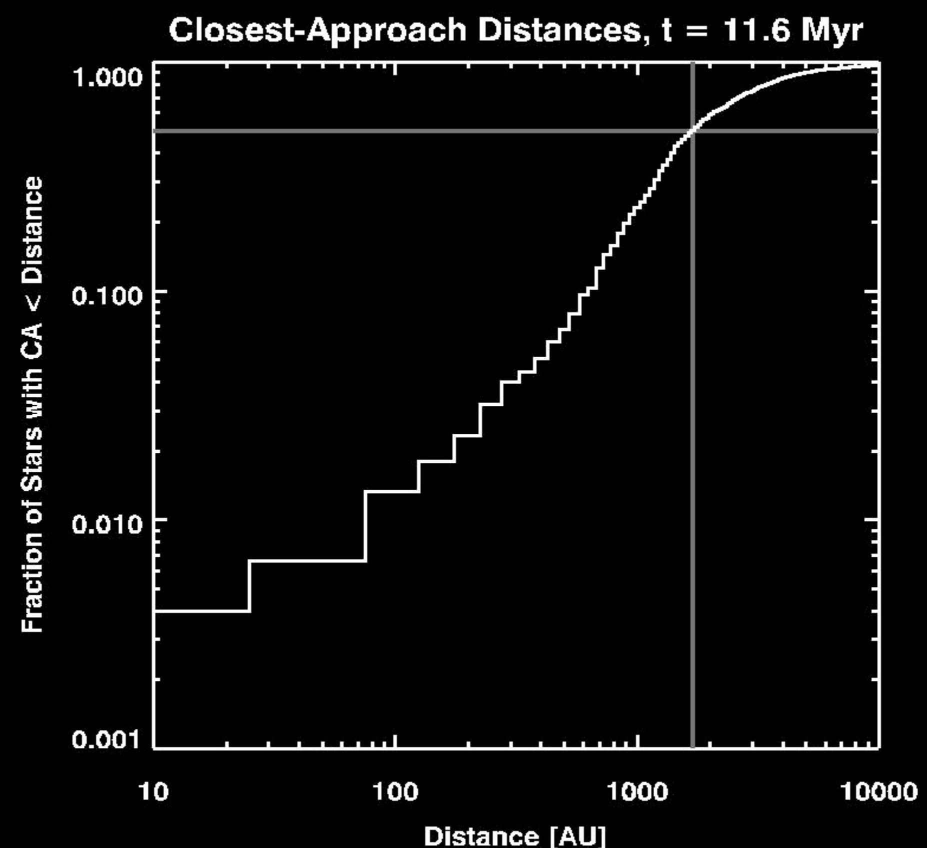

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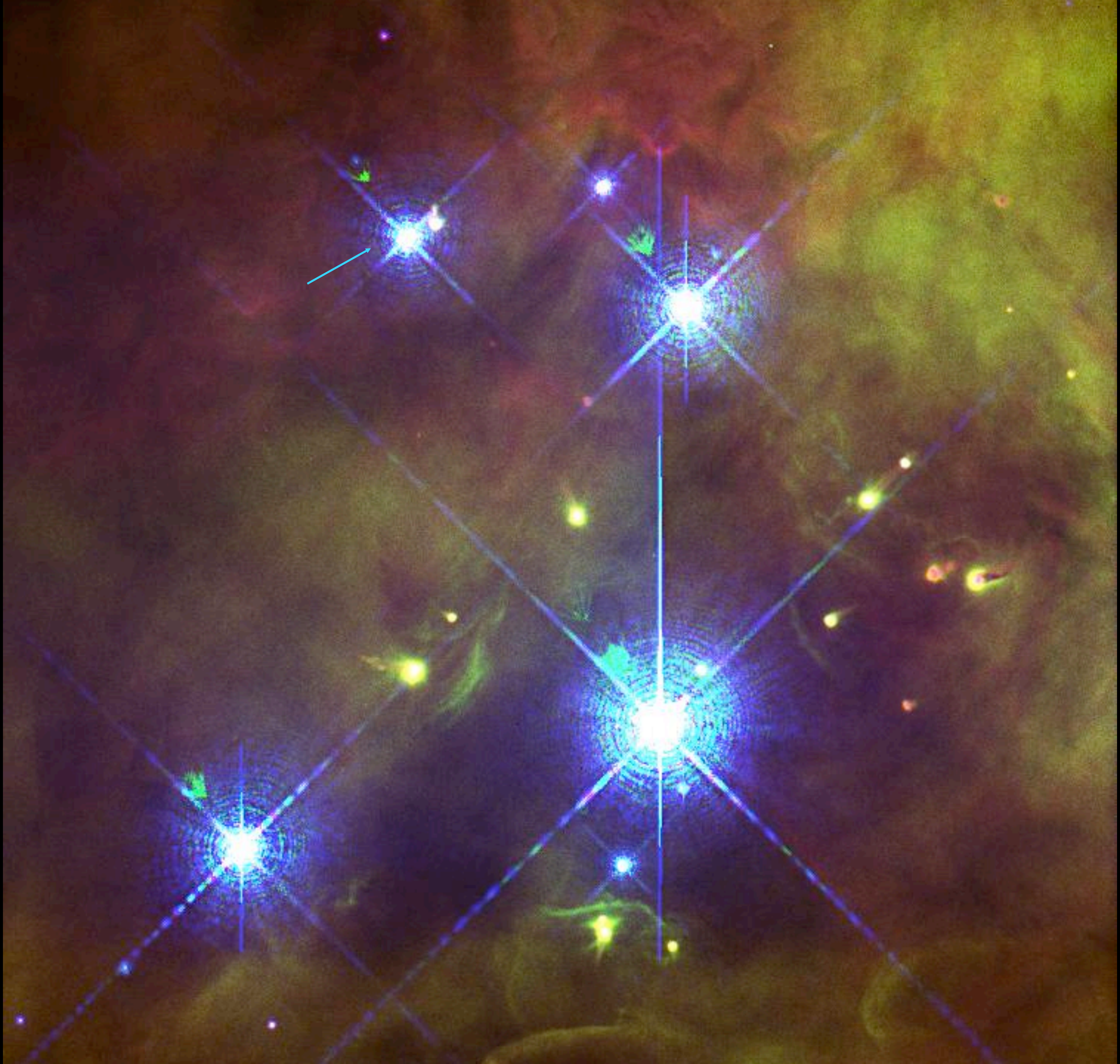


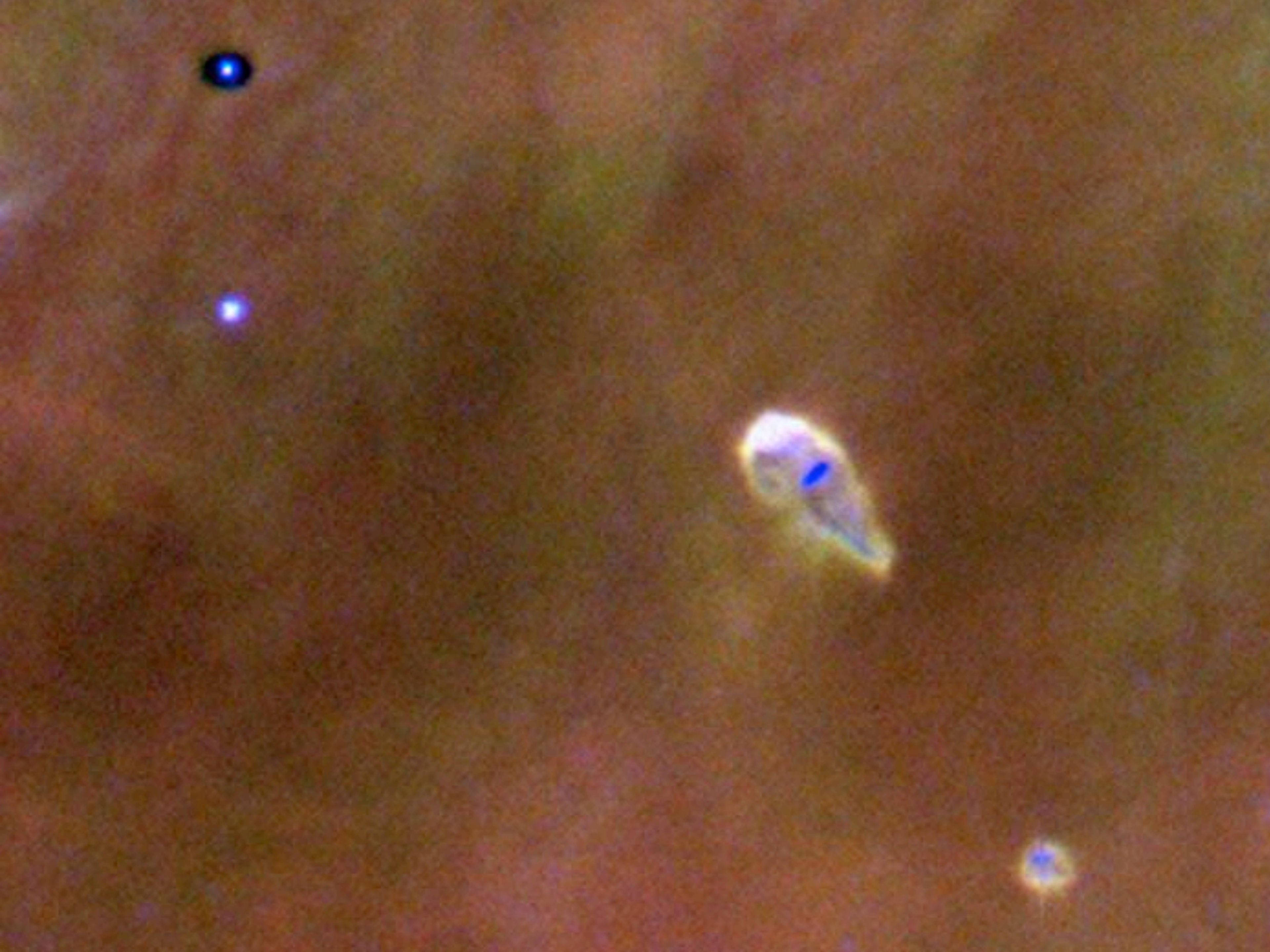
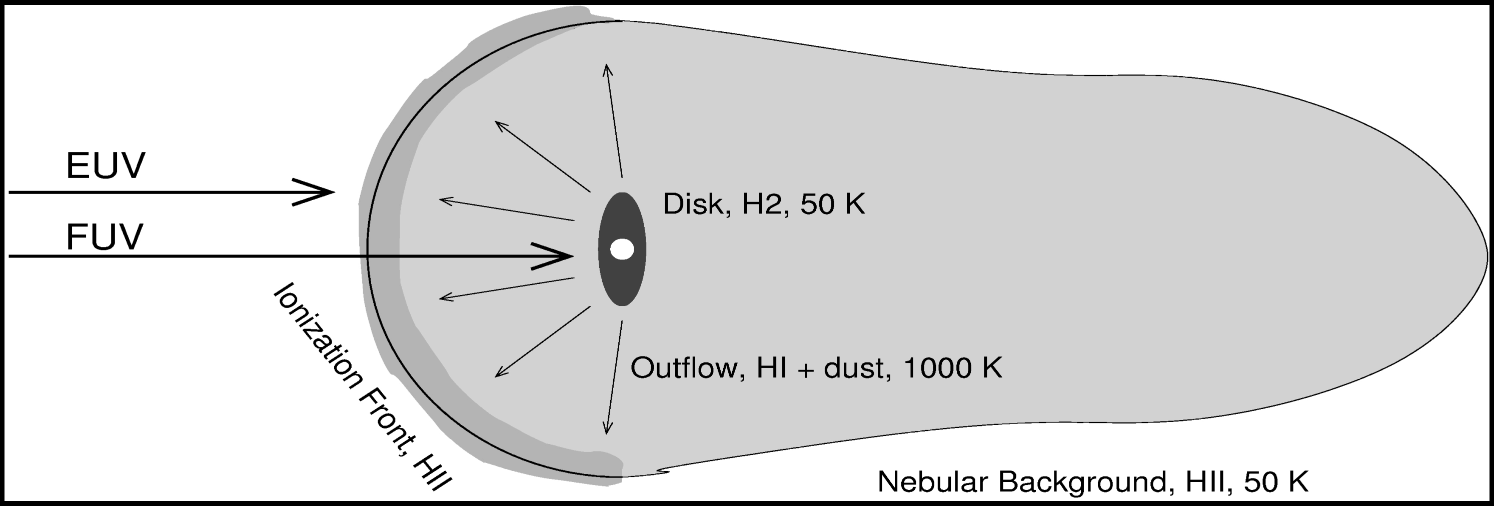


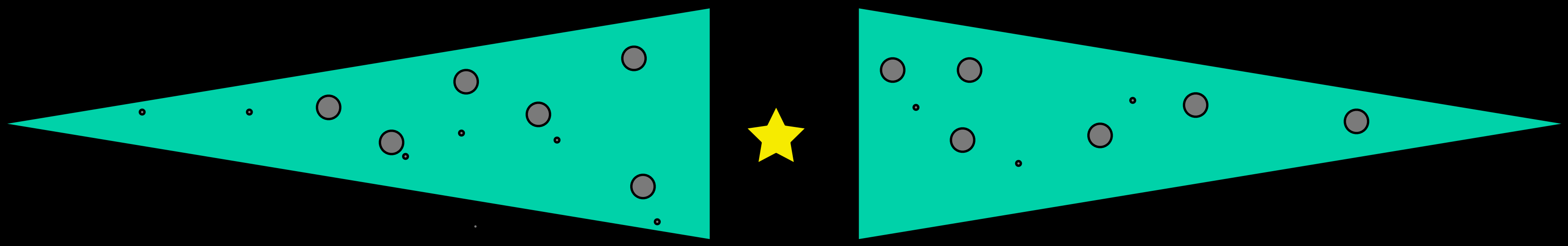
Photo-Evaporation in Orion

- 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!

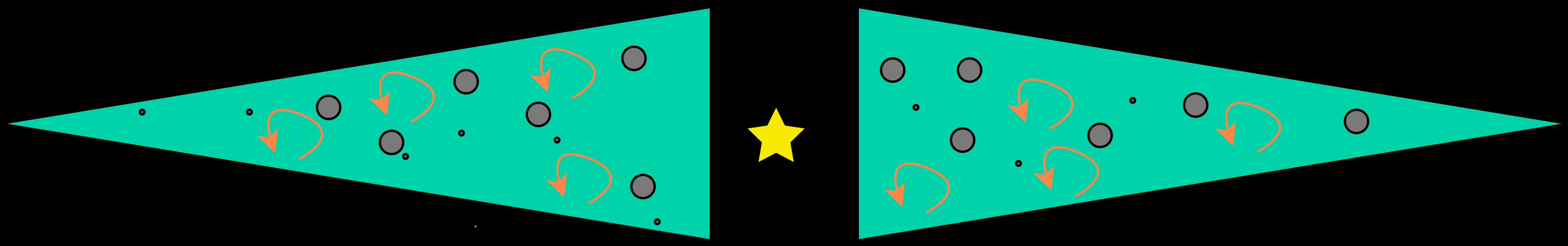


Triggered Planet Formation?

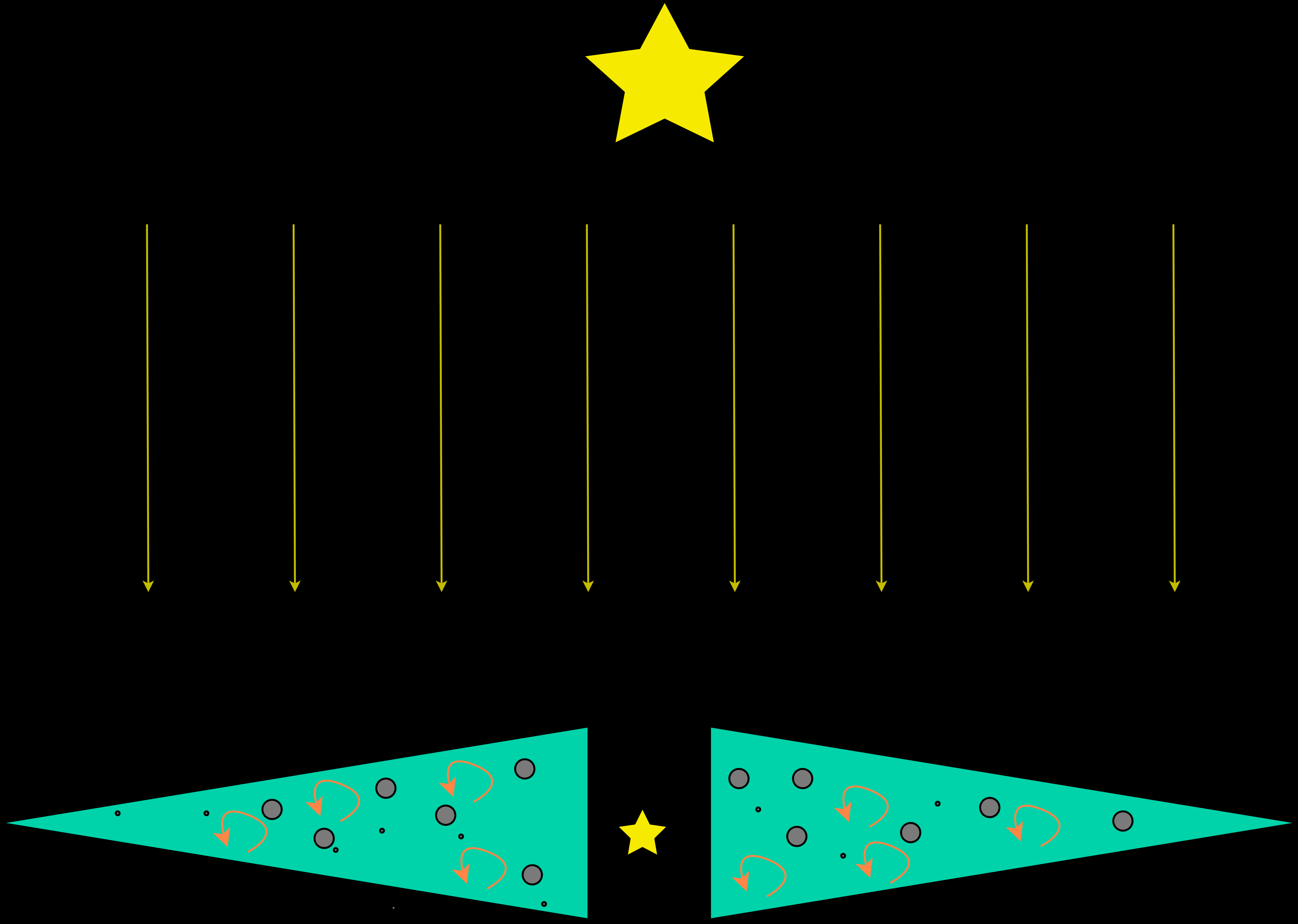
Triggered Planet Formation?



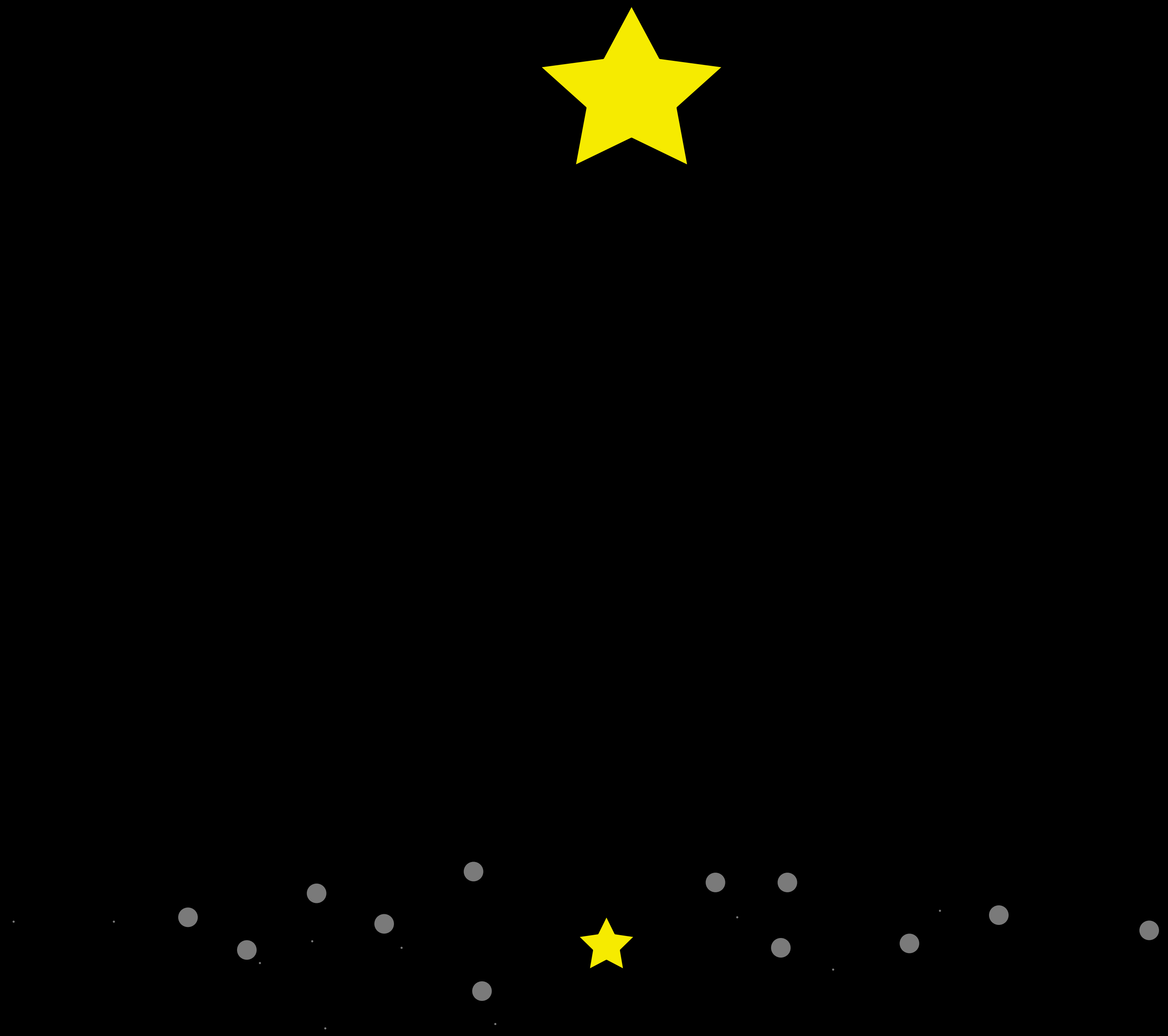
Triggered Planet Formation?



Triggered Planet Formation?



Triggered Planet Formation?



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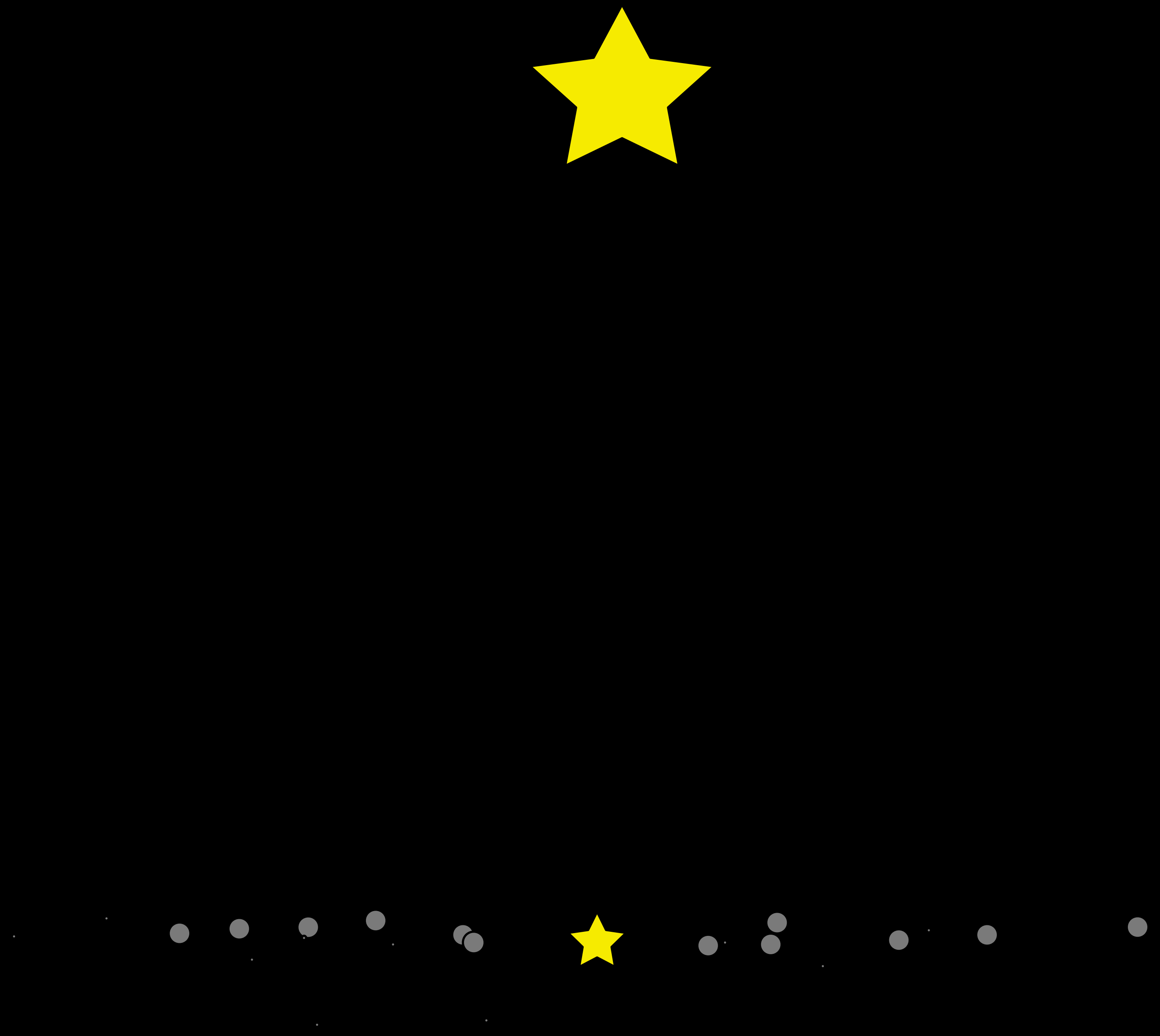

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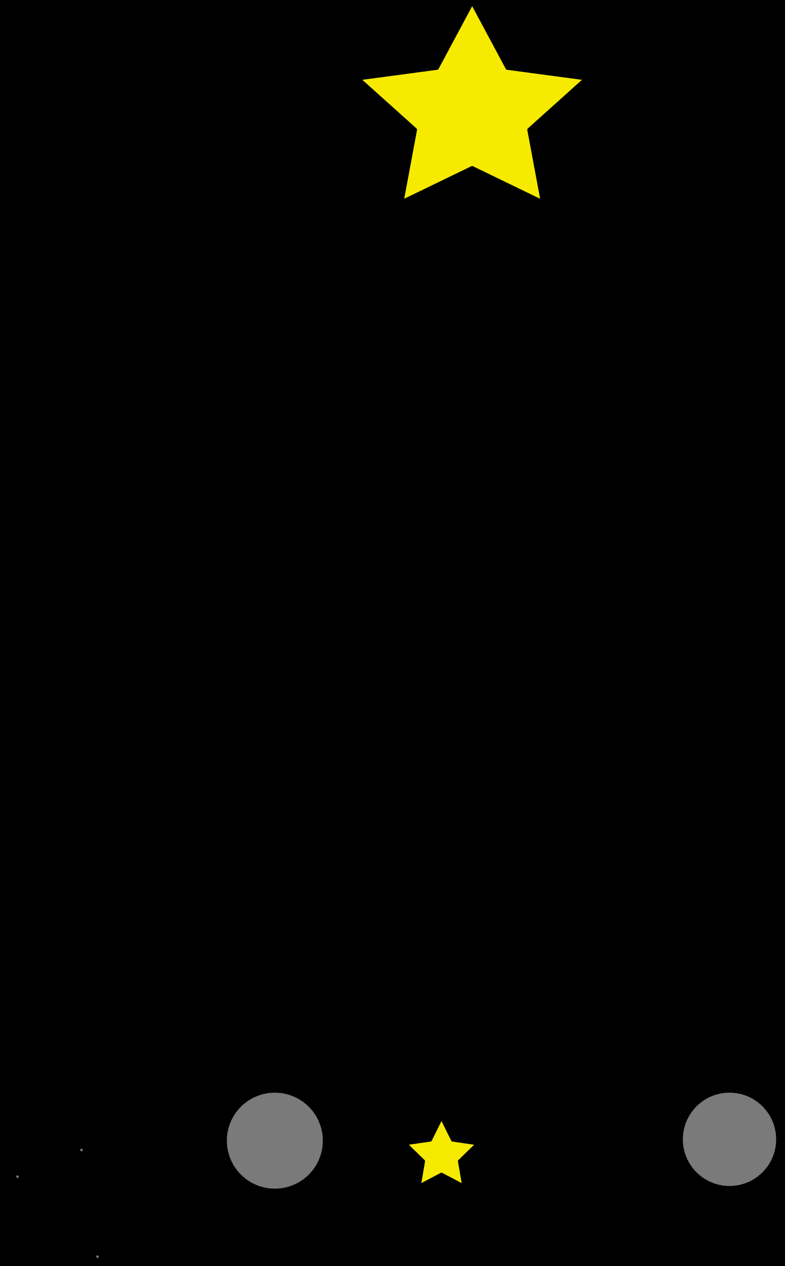
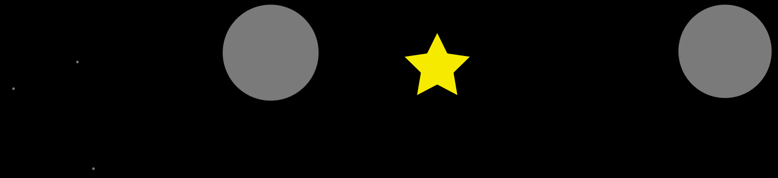


Triggered Planet Formation?

Photo-evaporation removes gas and allows gravitational instability to form planetesimals.

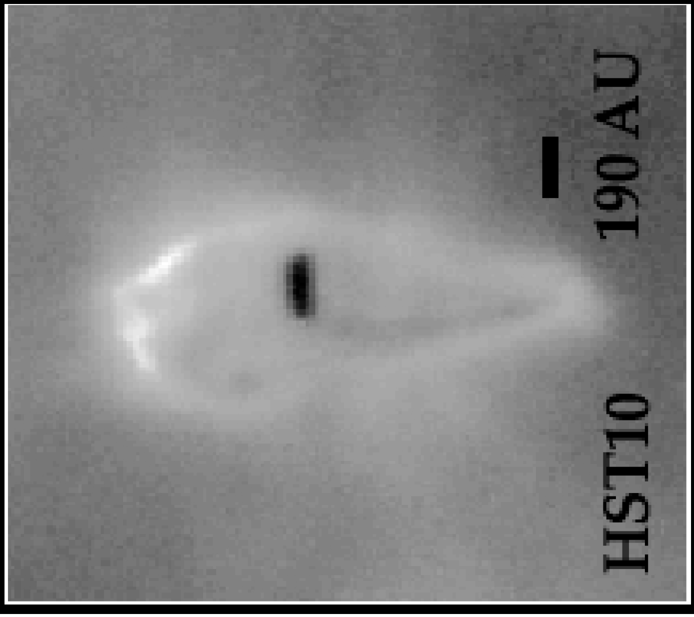


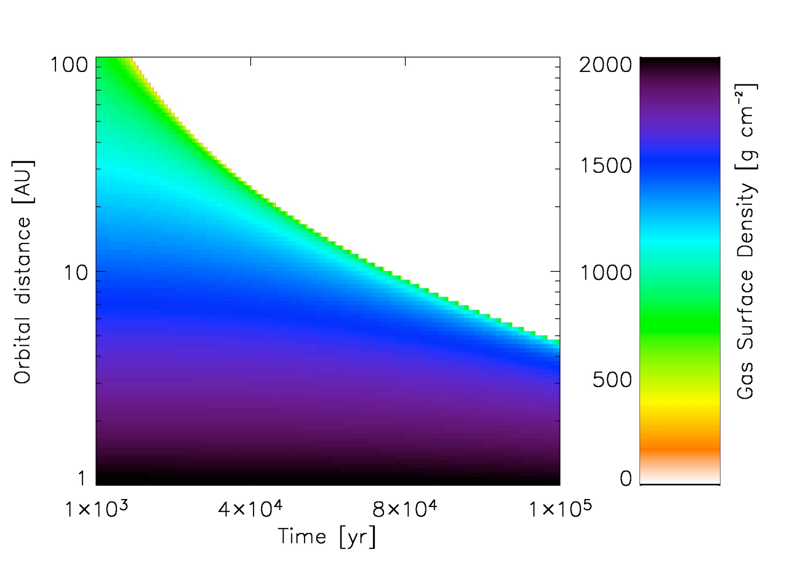
Throop & Bally 2005

Effects of Photo-Evaporation on Planet Formation

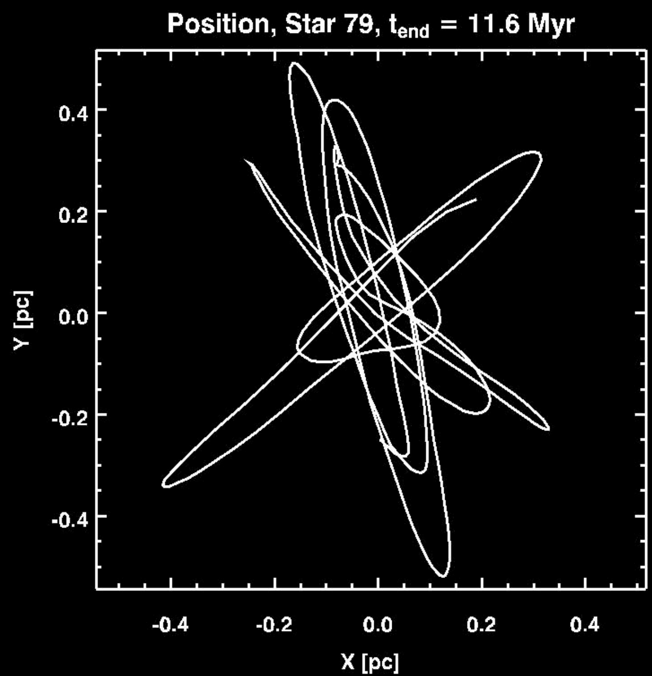
Solar System-like disks are removed in 1-10 Myr. Effects on...

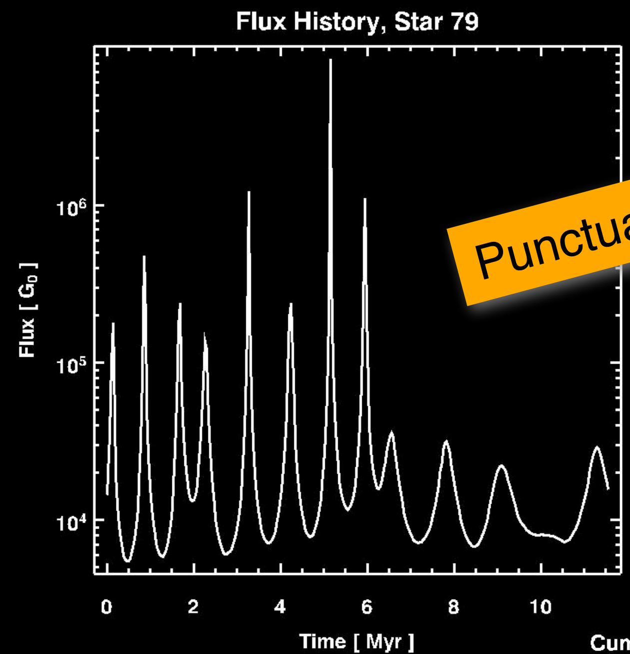
- **Kuiper Belt (> 40 AU)**: UV removes volatiles and small grains. Kuiper belts and Oort clouds **may be rare! Or, they may be formed easily and quickly** thru triggering.
- **Giant Planets (5-40 AU)**: Gas is rapidly removed from disk: If you want to build Jupiters in Orion, do it quickly! (e.g., Boss models).
- **Terrestrial Planets (1-5 AU)**: Safe against photo-evaporation since it's hard to remove gas from 1 AU.





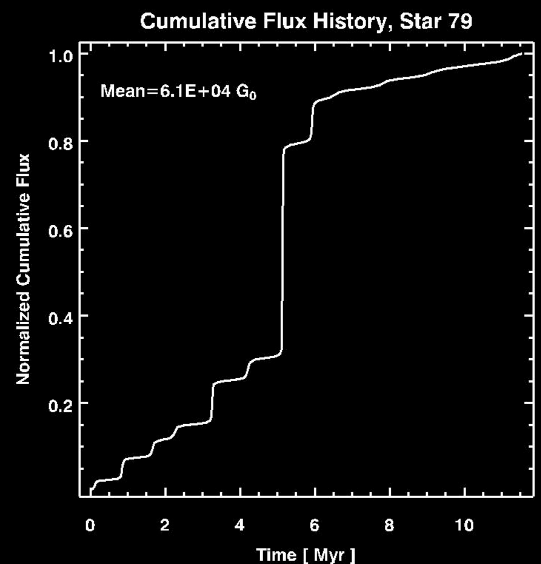
Flux Received onto a Disk vs. Time





Punctuated equilibrium

- Flux received by disk varies by 1000x as it moves through the cluster : **Freeze-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.’
- Photo-evap models assume steady UV flux. But if UV is not steady, then other processes (viscous, grain growth) can dominate at different times and dramatically change the disk.



Throop, in prep

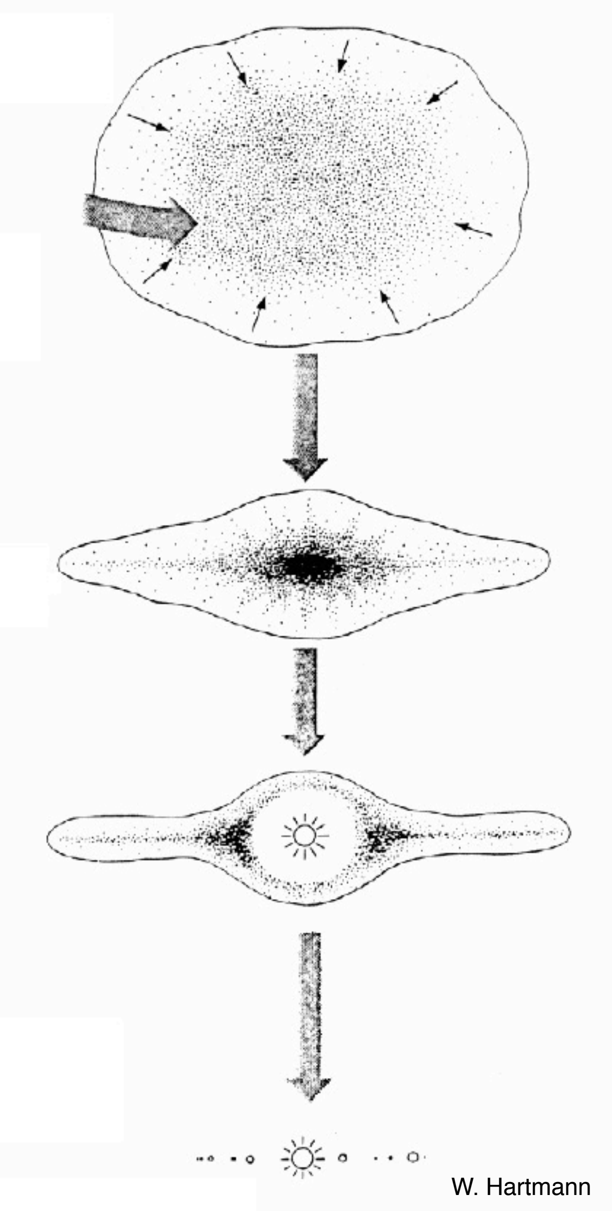
Planet Formation - Classical Model

Cloud core collapses due to self-gravity
10,000 AU, 1 $M_\odot$

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



PLANET FORMATION - ~~CLASSICAL~~ MODIFIED CLASSICAL MODEL

Cloud is heterogeneous and polluted

Cloud core collapses due to self-gravity

10,000 AU, 1 $M_\odot$

Cloud inherits 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

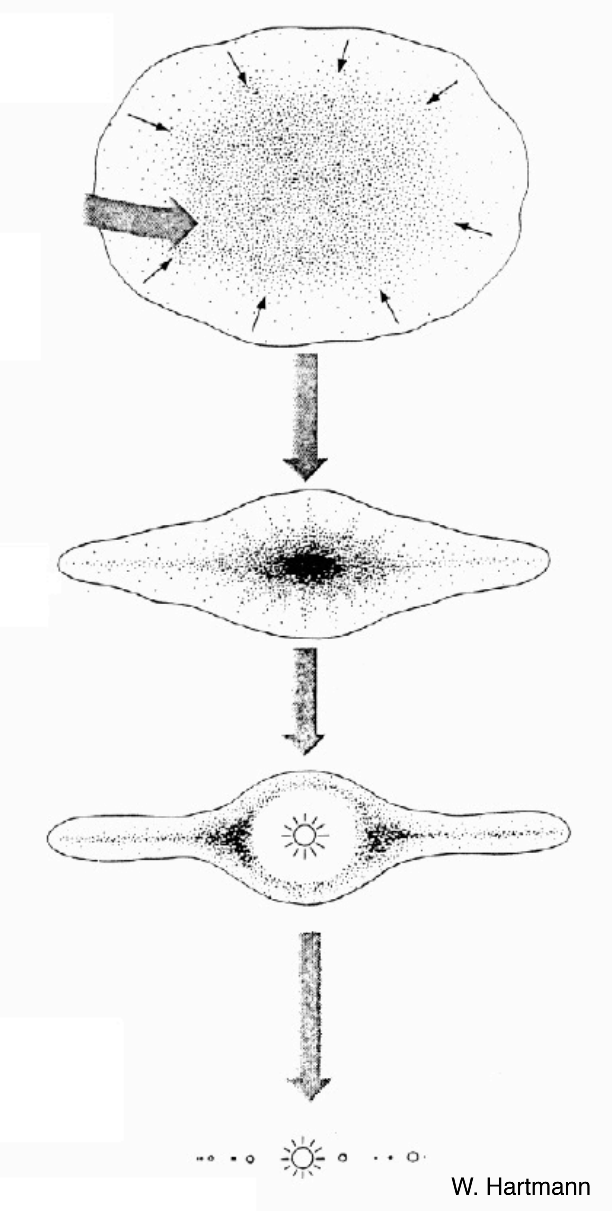
Jovian planets accrete gas

(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



Randomness as a factor in Disk Evolution

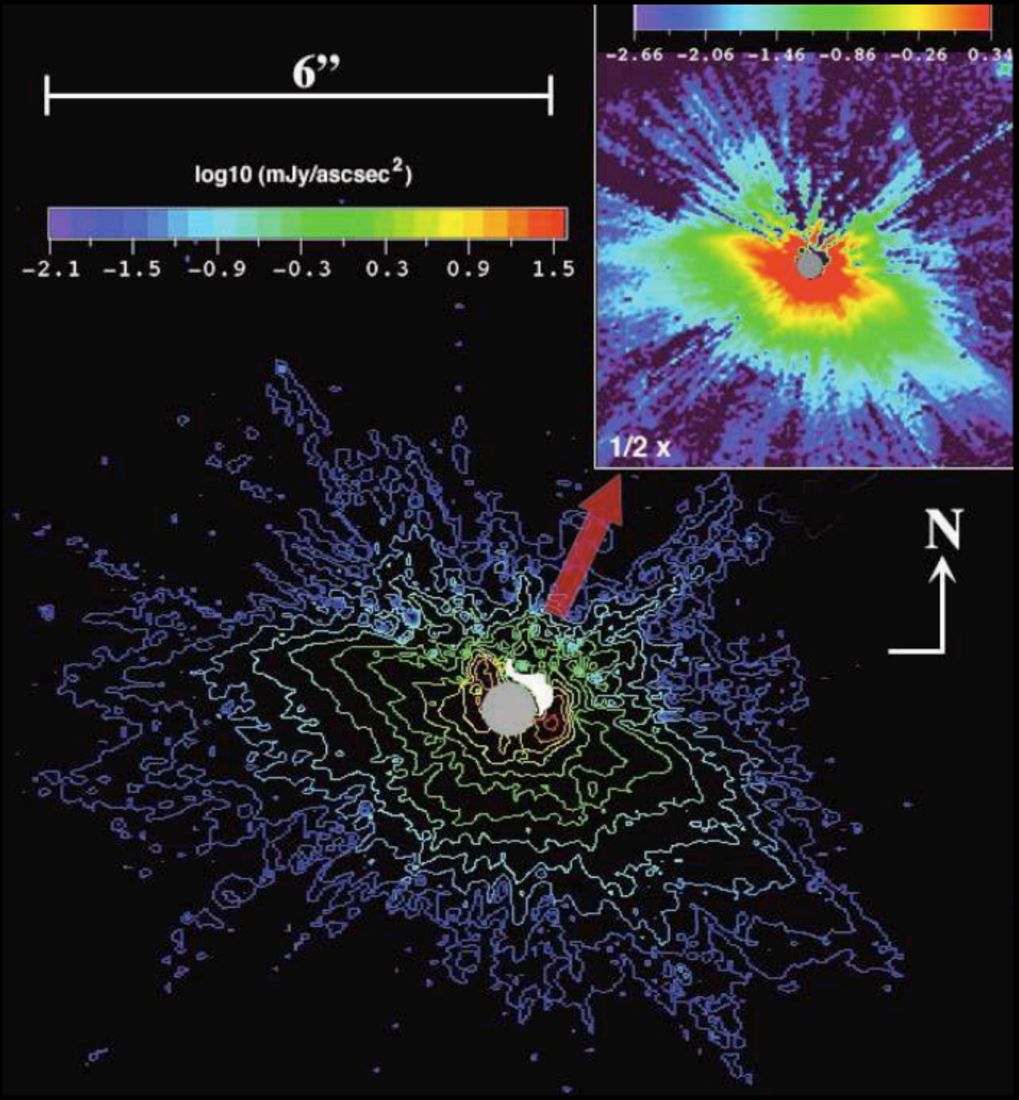
- Disk outcome depends not just on its ingredients, but on its individual history.
- If we try to predict what will form around individual stars or disks, we're doomed to fail!
- Disk systems are individuals, they interact with their environment, and random events and timing matter:
  - How much stuff was photo-evaporated by UV?
  - How hot was the disk, and how viscous, and how did its surface density evolve?
  - How strong, when, and how many times did UV hit it?
  - What SN events occurred? How did they contaminate the disk?
  - What molecular clouds did disk pass through? What material was accreted? Onto inner disk, or outer?
  - Do planetesimals form before, or after, photo-evaporation starts?
- There is no 'typical' disk, and no 'typical' planetary system, even if starting from the same initial disk structure and ingredients.


The
End

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



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.

Photo-evaporation is a major hazard to planet formation…

… but all hope is not yet lost!

Photo-Evaporation Triggered Instability

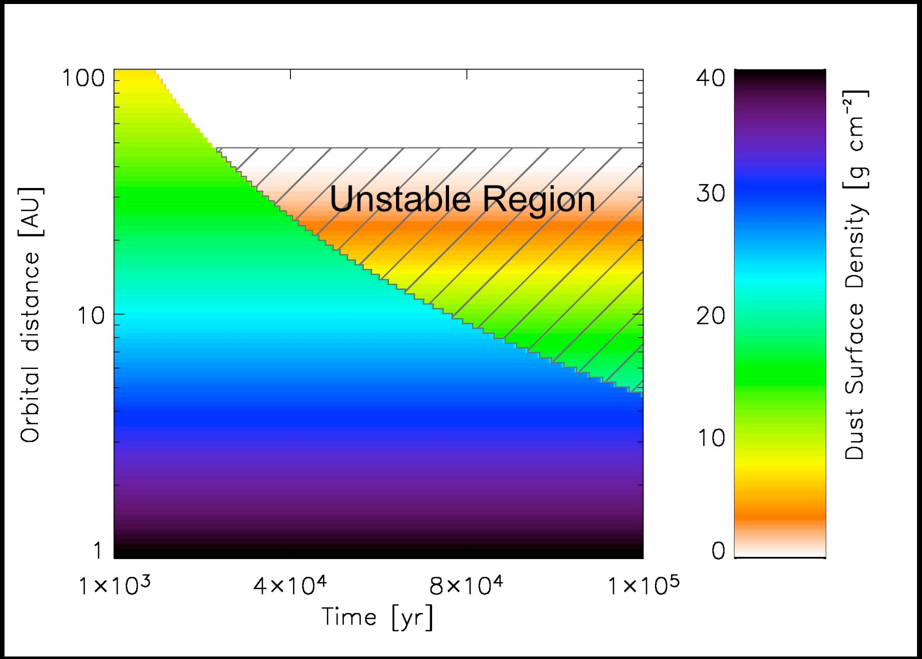
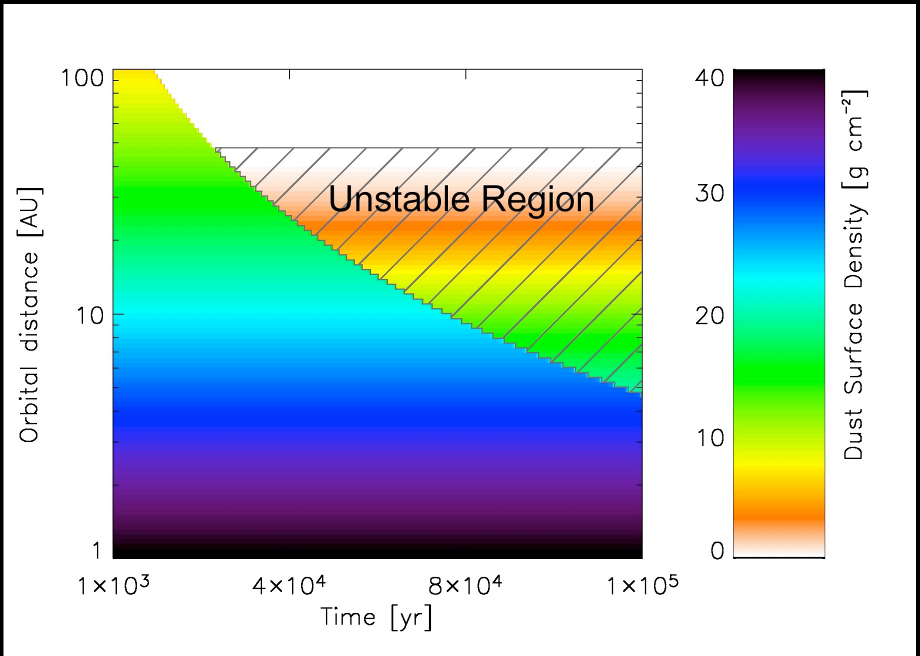


Photo-Evaporation Triggered Instability

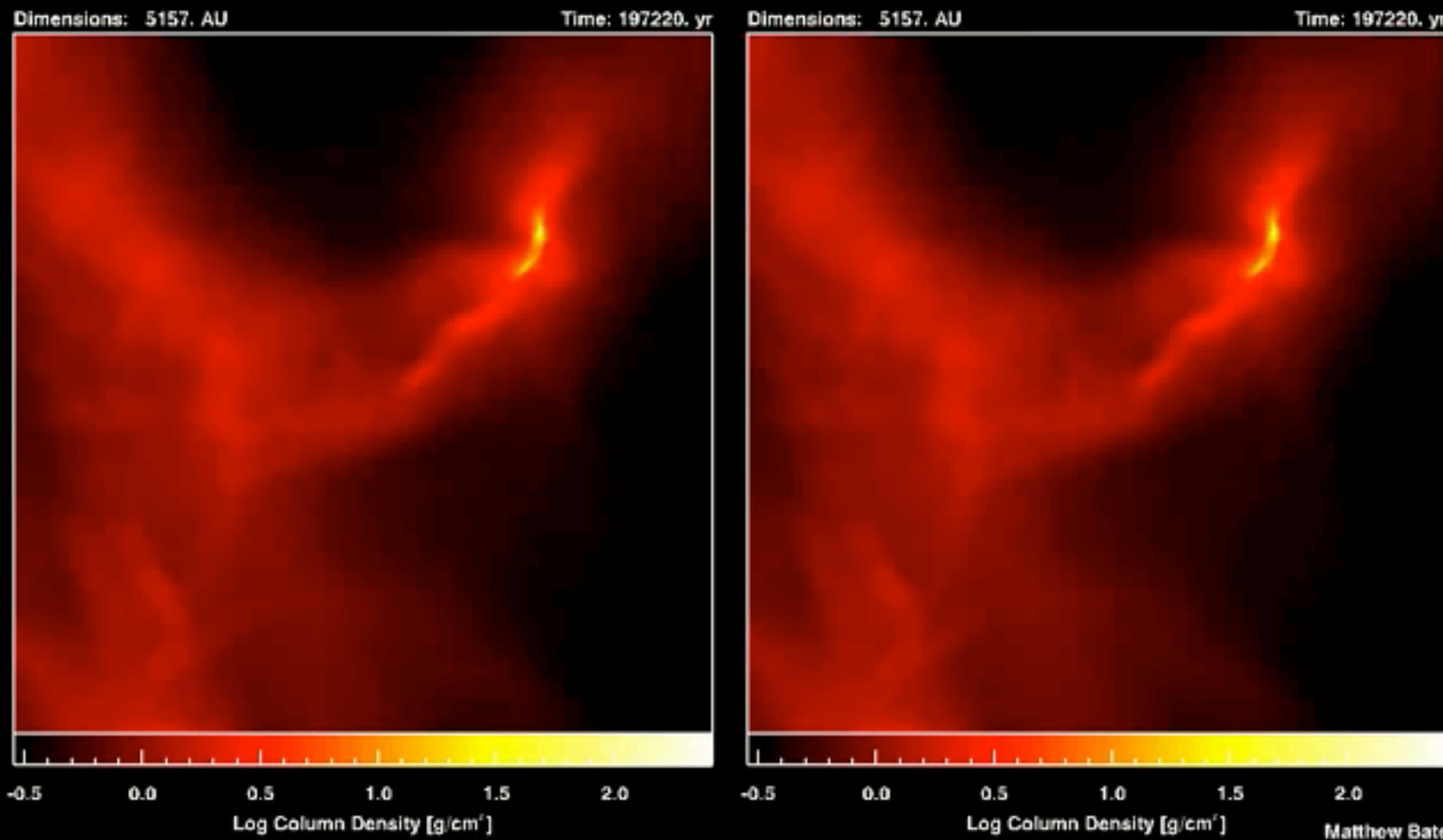
- But: Sometimes photo-evaporation **may also make planet formation easier**, by removing gas and leaving dust which can collapse gravitationally.
- Gravitational instability can occur if sufficiently low gas:dust ratio (Youdin & Shu 2004)

  $\Sigma_g / \Sigma_d < 10$

  (*i.e.*, we need to remove 90% of the gas)
- Photoevaporation removes gas and leaves the dust: exactly what we want!



Throop & Bally 2005


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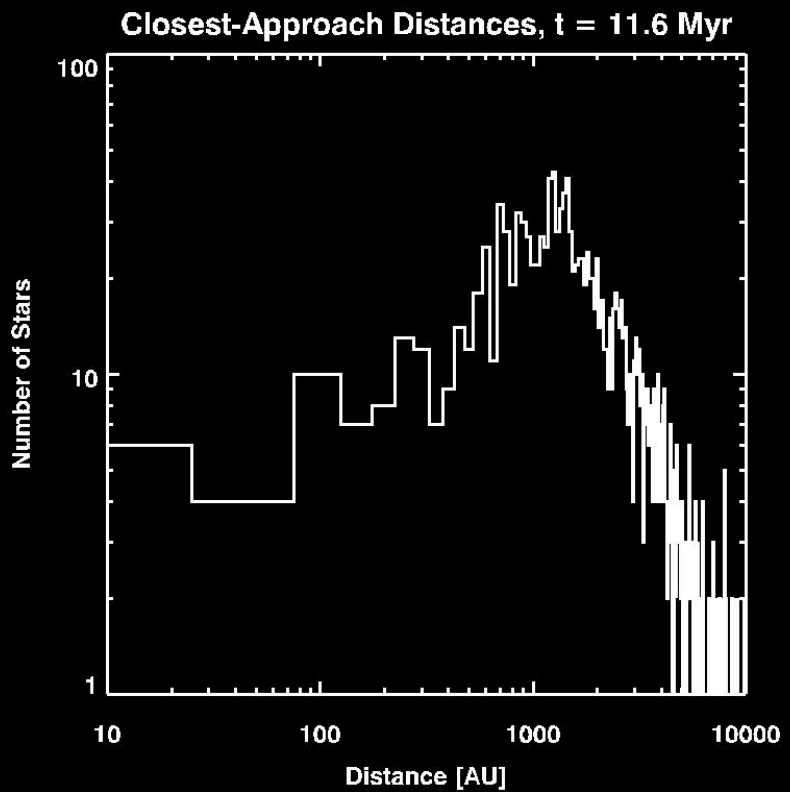
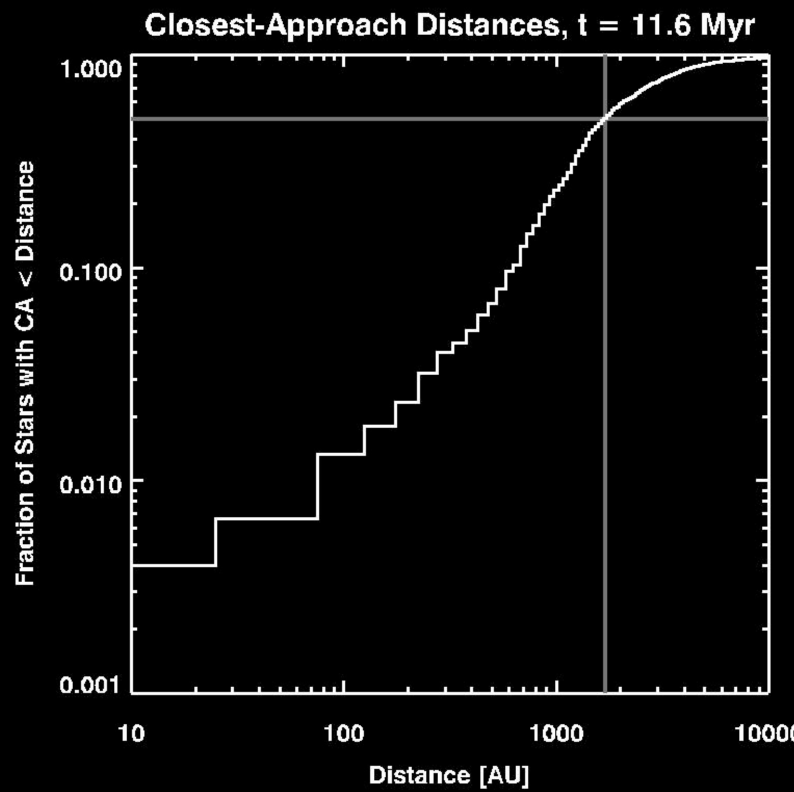
1.5
2.0
Log Column Density [g/cm²]
Matthew Bate

Close Approaches - Entire Cluster





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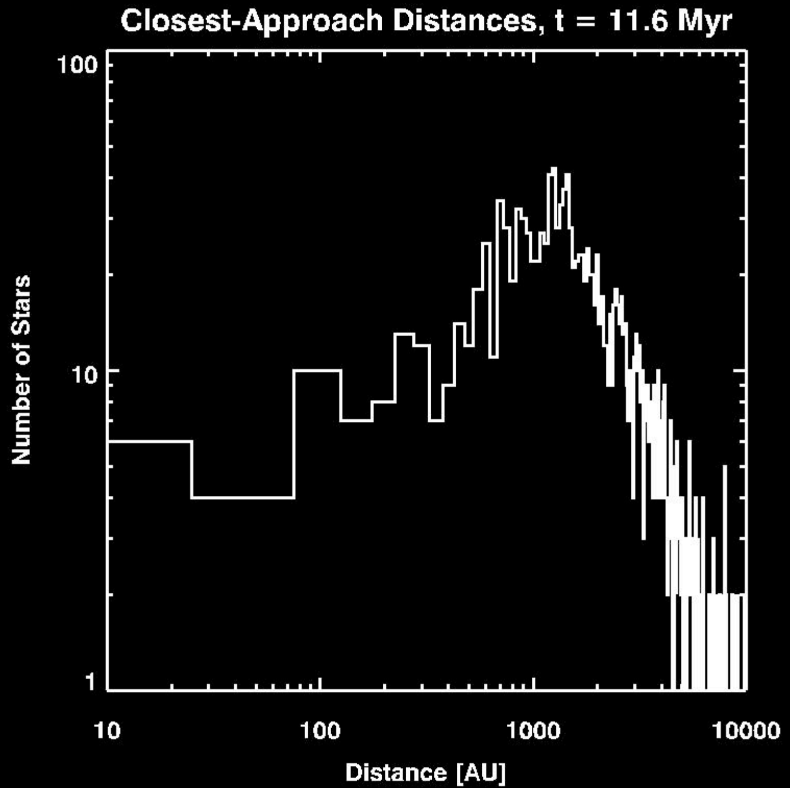

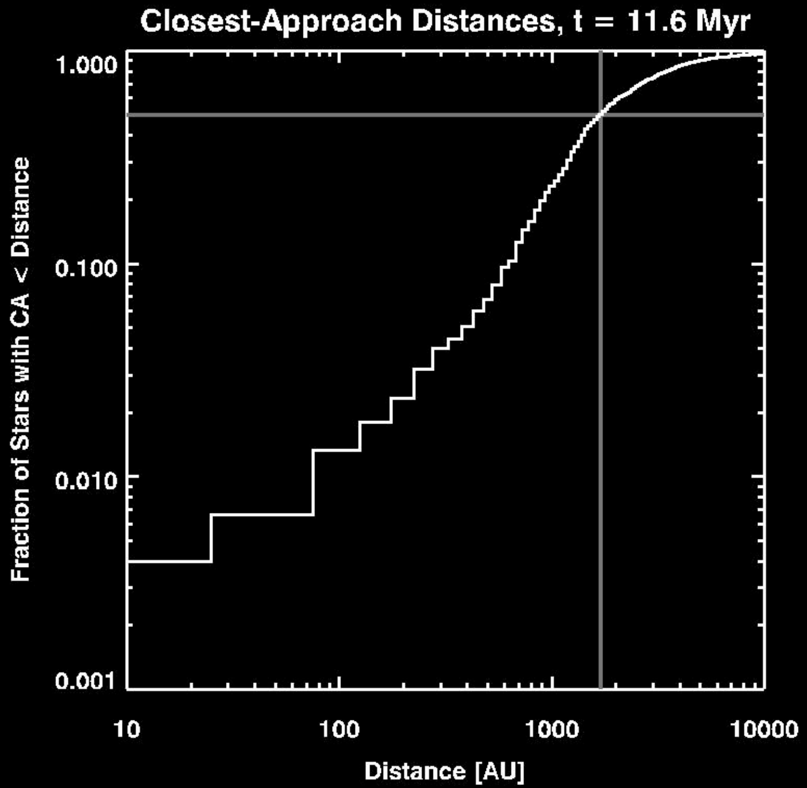

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Throop & Bally; also Adams et al 2006

A Crazy idea for forming Jupiters?

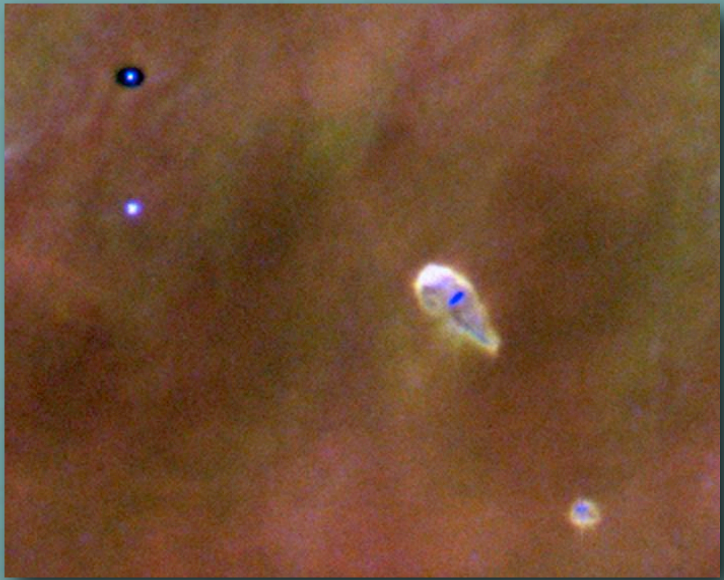
1. Star and disk forms in a young cluster
2. Jupiter's rocky core forms slowly
3. Disk gas is photo-evaporated before Jupiter can form
4. Disk gas is rejuvenated by passage through molecular cloud
5. Jupiter forms its atmosphere from new disk

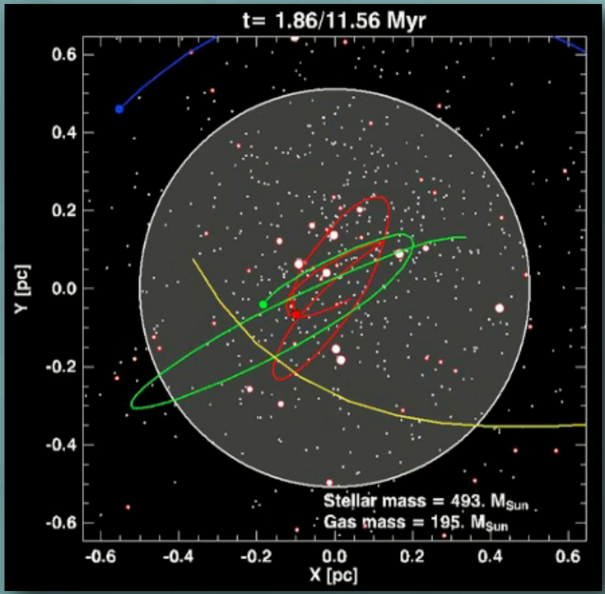
A solution to the ^{60}Fe problem?

- ^{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




t= 1.86/11.56 Myr
0.6
0.4
0.2
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-0.2
-0.4
-0.6
Y [pc]
-0.6
-0.4
-0.2
0.0
0.2
0.4
0.6
X [pc]
Stellar mass = 493. M_{Sun}
Gas mass = 195. M_{Sun}