Planet Formation in Dense Star Clusters

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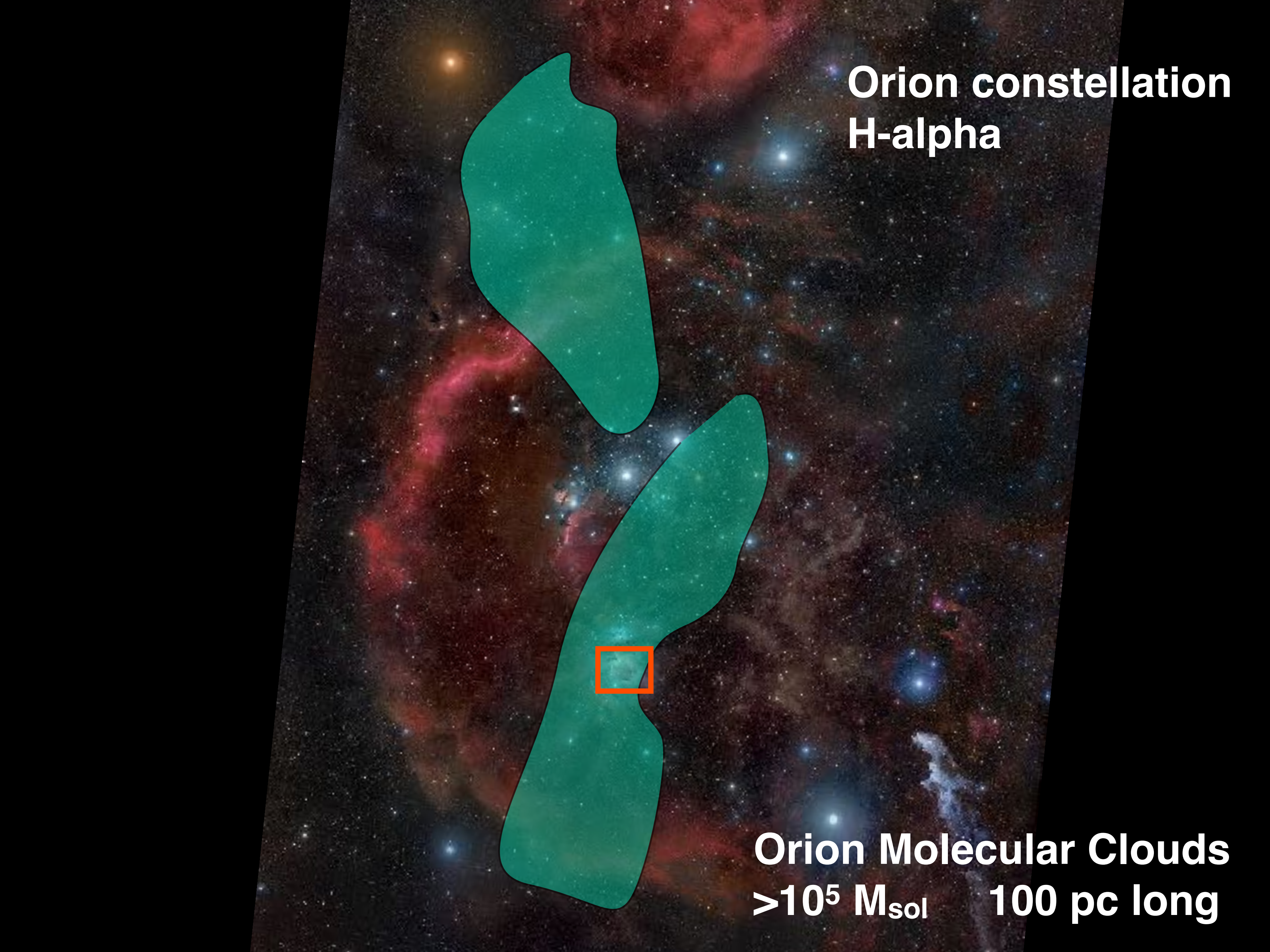
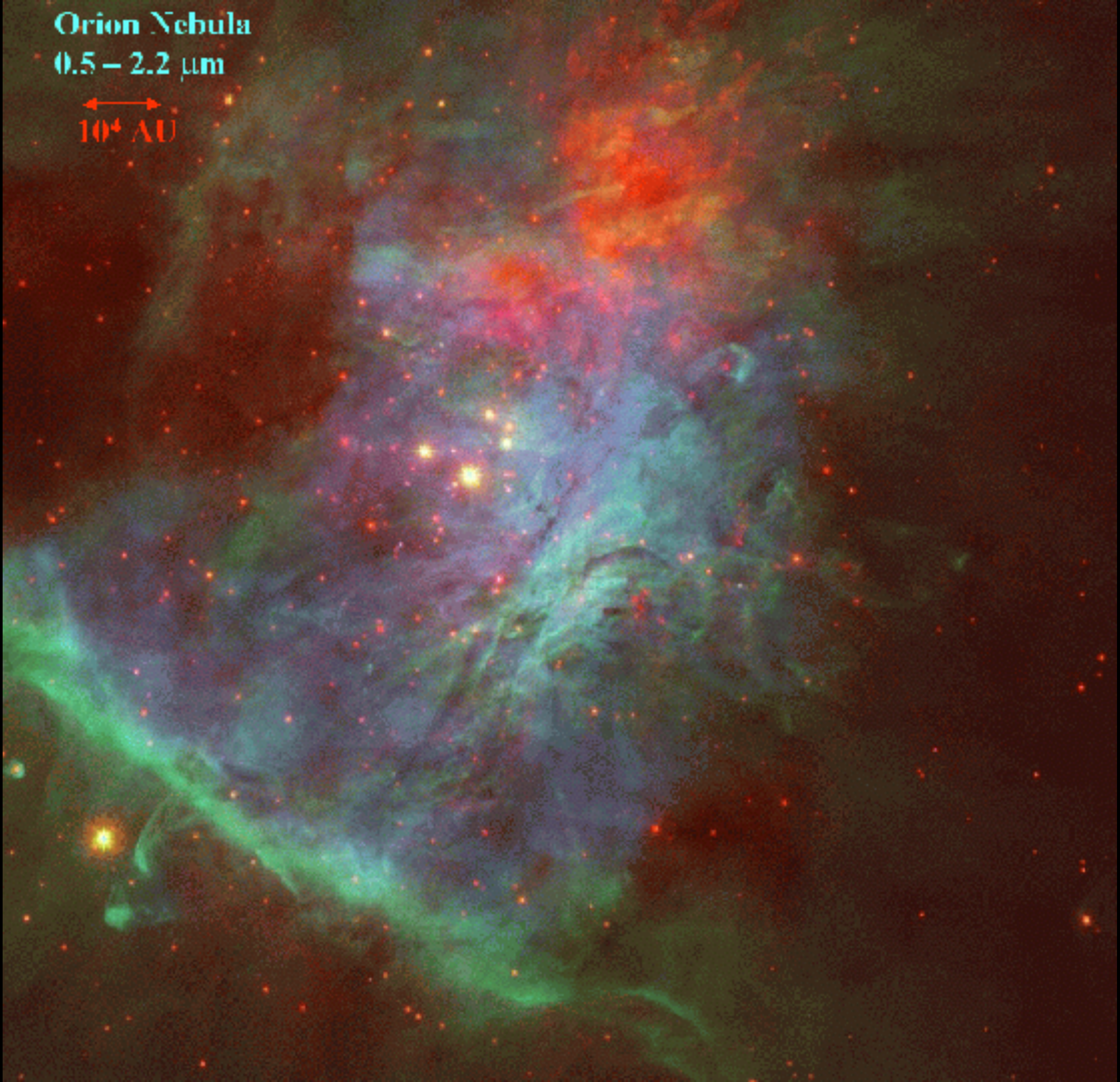
Orion Constellation
(visible light)


Orion constellation
H-alpha

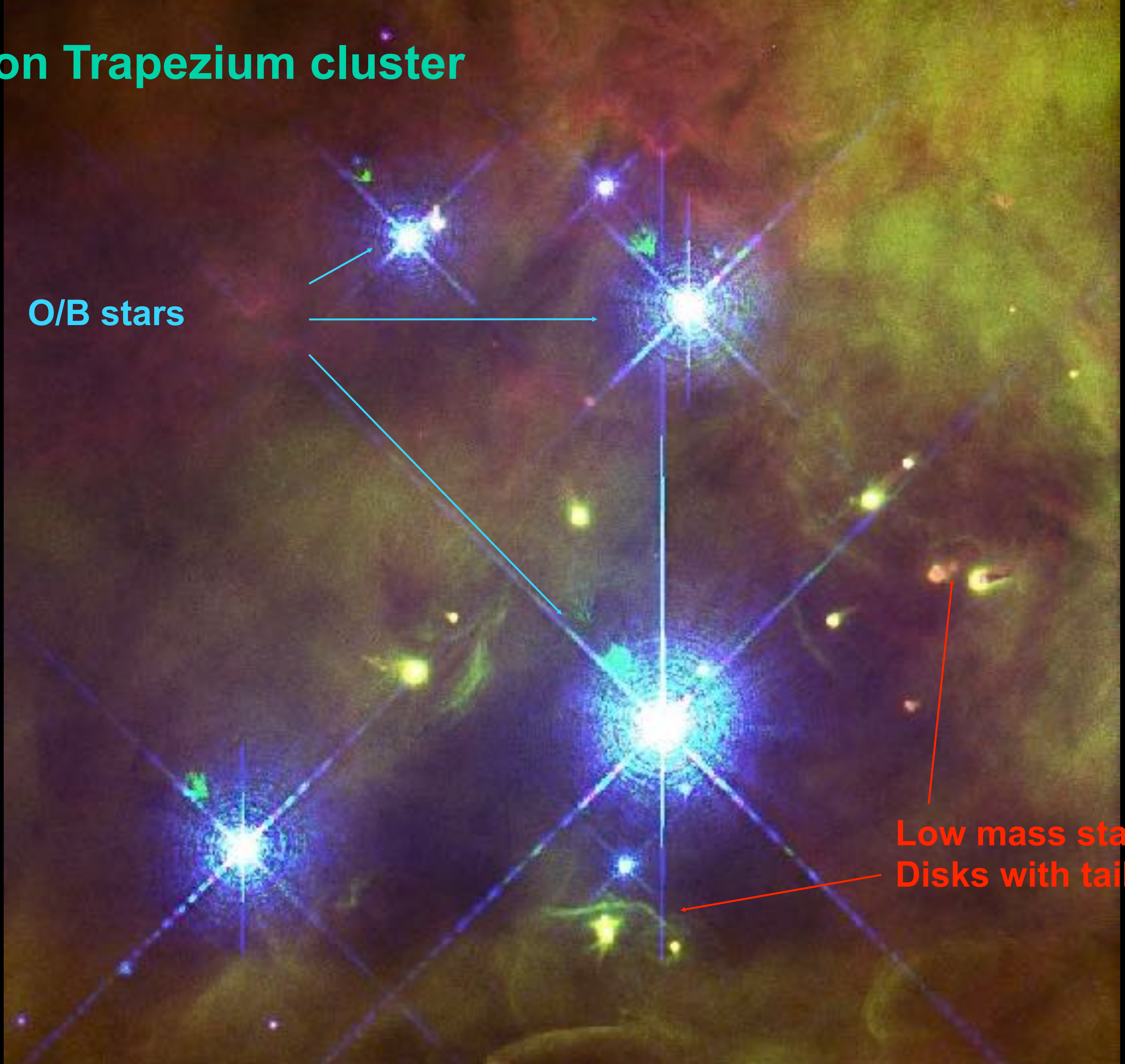

Orion constellation
H-alpha
Orion Molecular Clouds
>10^5 M_{sol} 100 pc long

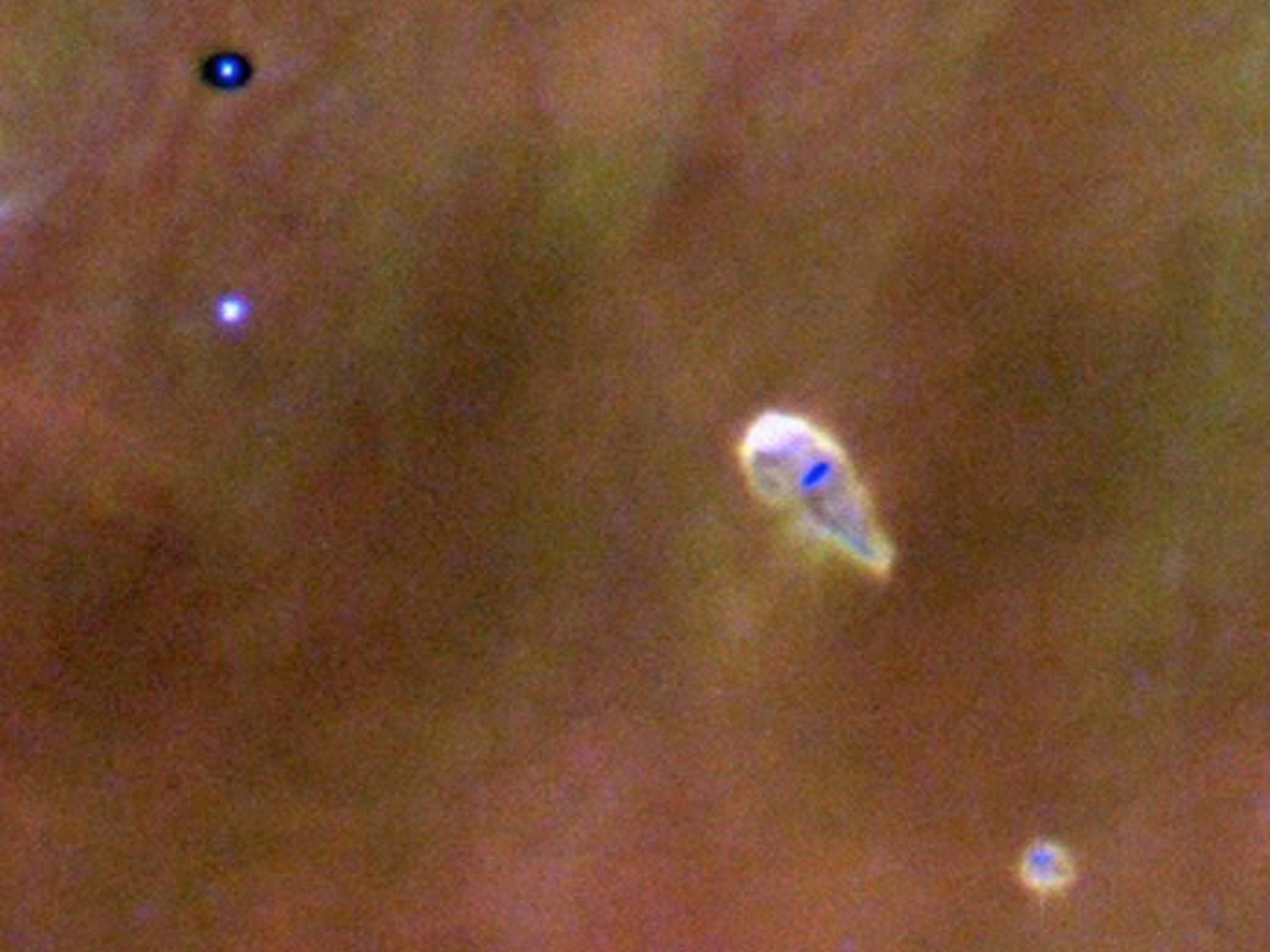

Orion Nebula
0.5 – 2.2 μm
10^4 AU

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*

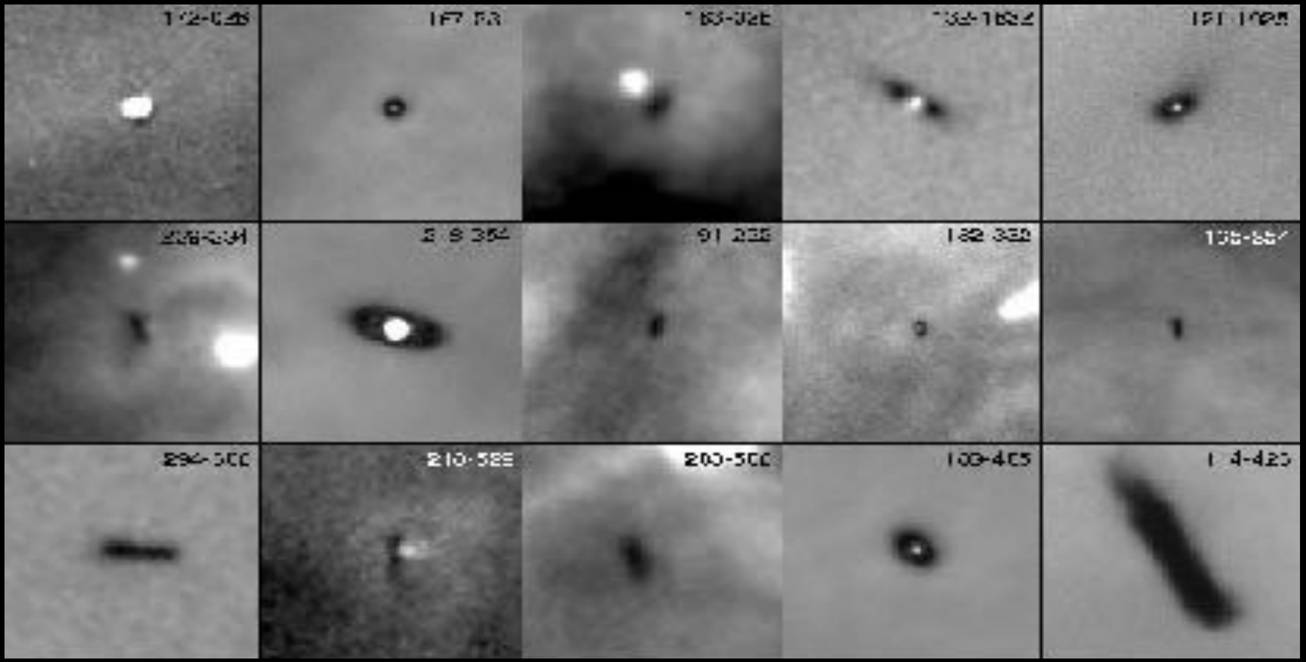
2000s view:

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

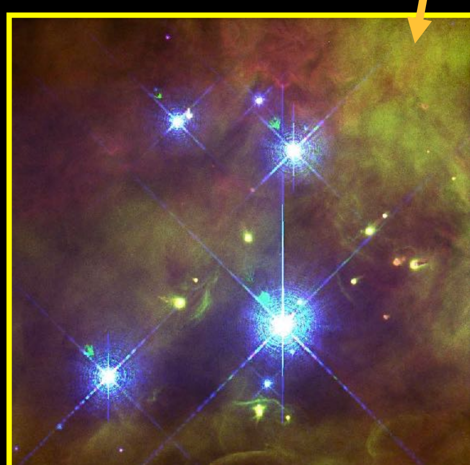
These stars are too distant and young to directly search for planets… but we want to study the environment and processes to understand the planets which would be produced in these dense clusters -- and therefore throughout the galaxy.

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.



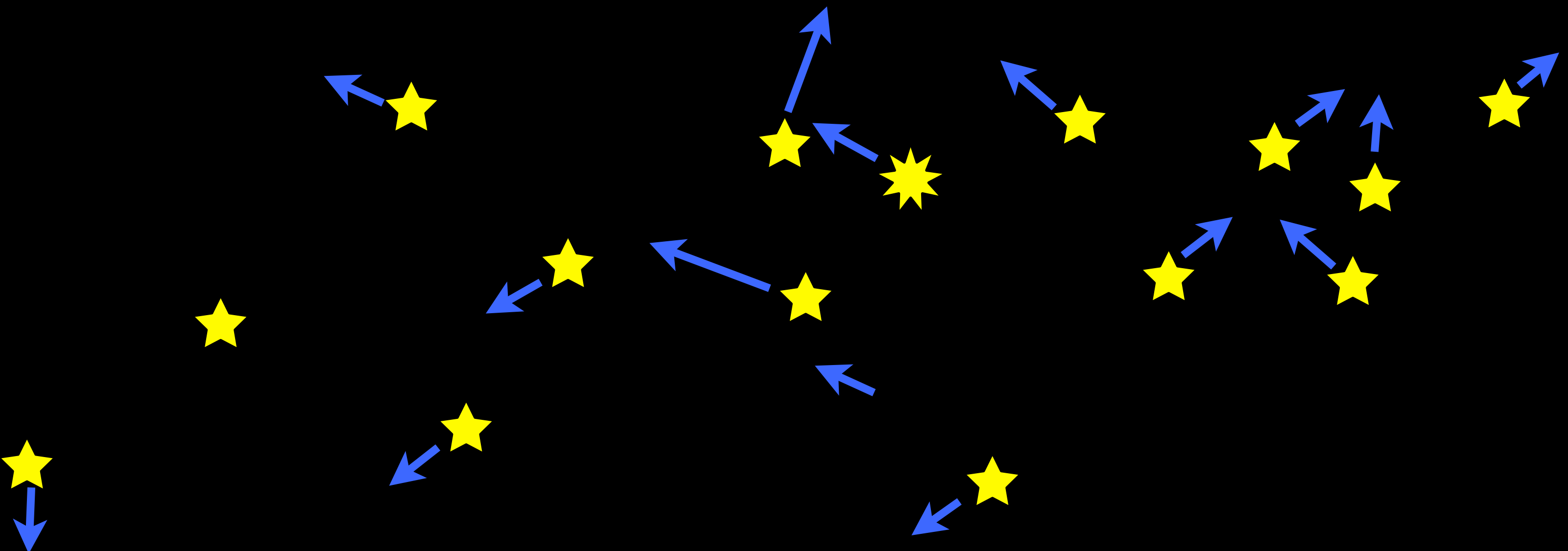
Taurus: Dark, Small, Cold

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.

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



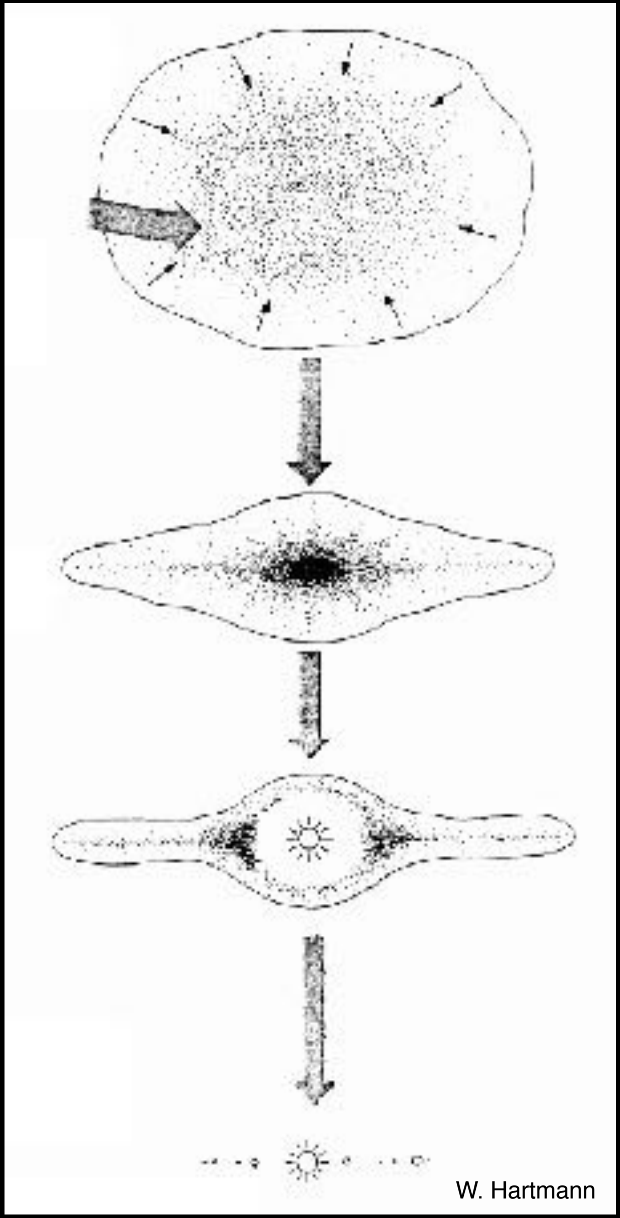
Planet Formation - Classical Model

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



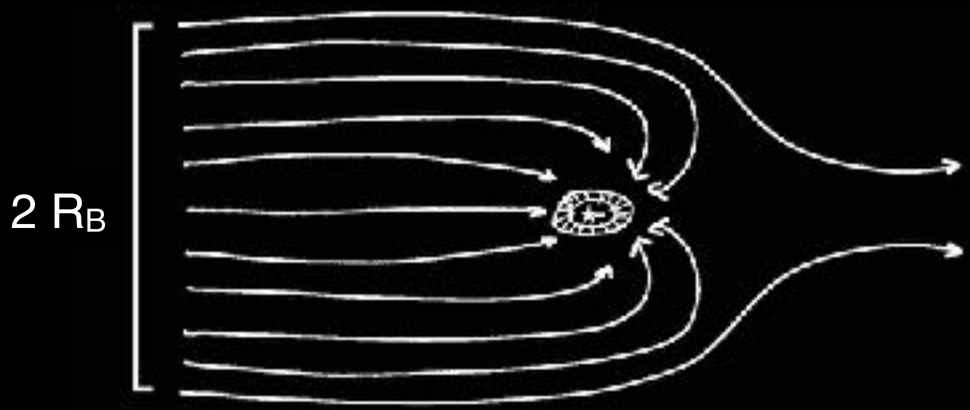
How does Cluster Environment affect Disk Evolution?

Work we have done involves ...

- UV photo-evaporation from massive stars
- Interaction with cluster gas
- Close stellar encounters
- Organics and UV photolysis from massive stars

Throop 2000; Bally et al 2005; Throop & Bally 2005; Throop & Bally 2008; Moeckel & Throop 2009; Throop & Bally 2010; Pichardo et al 2010; Throop 2011.

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 'Minimum Mass Solar Nebula' = 0.01 M_{Sol}

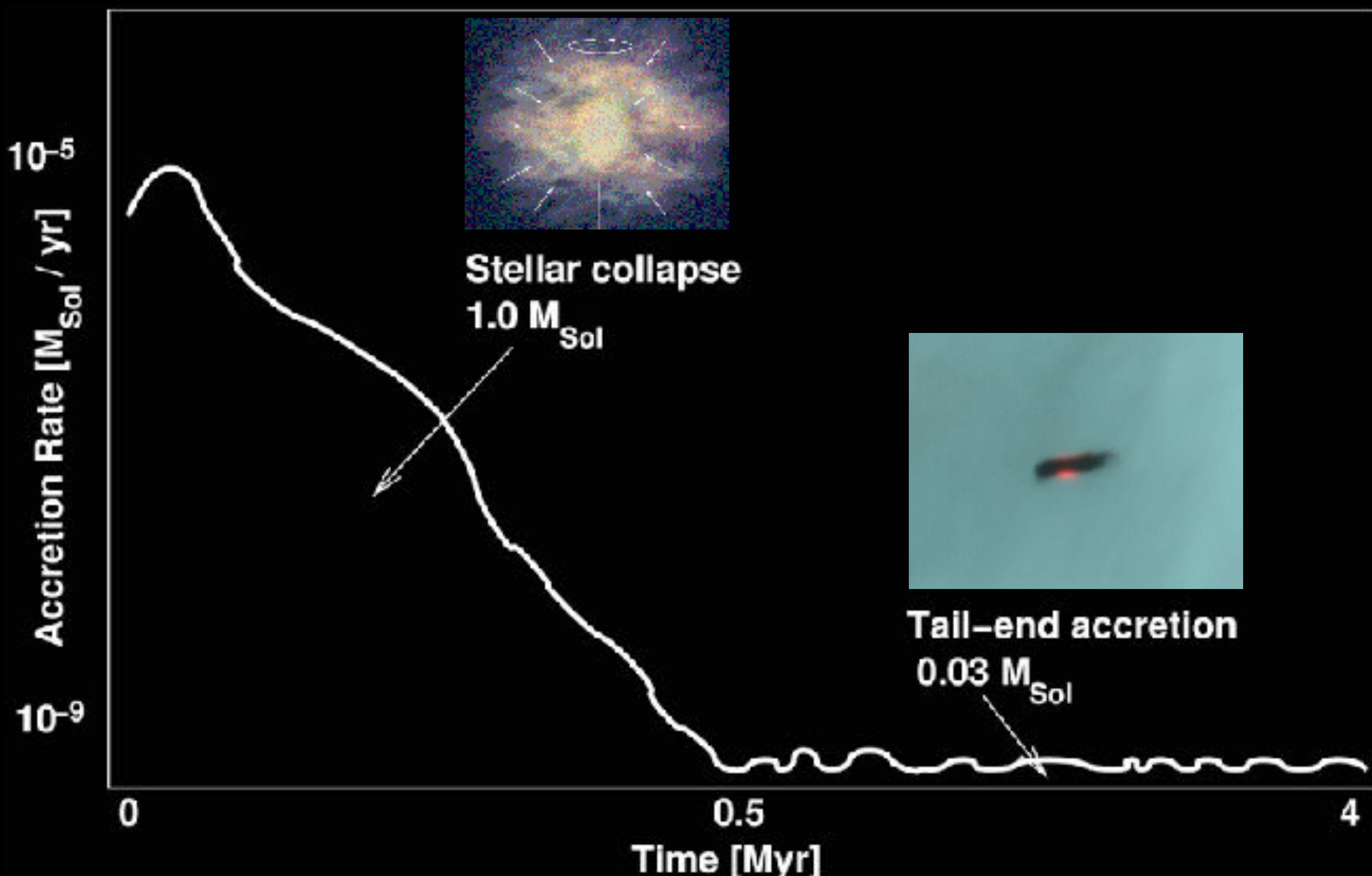
$$R_B = \frac{2\,G\,M}{(v^2 + c_s^2)}$$

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

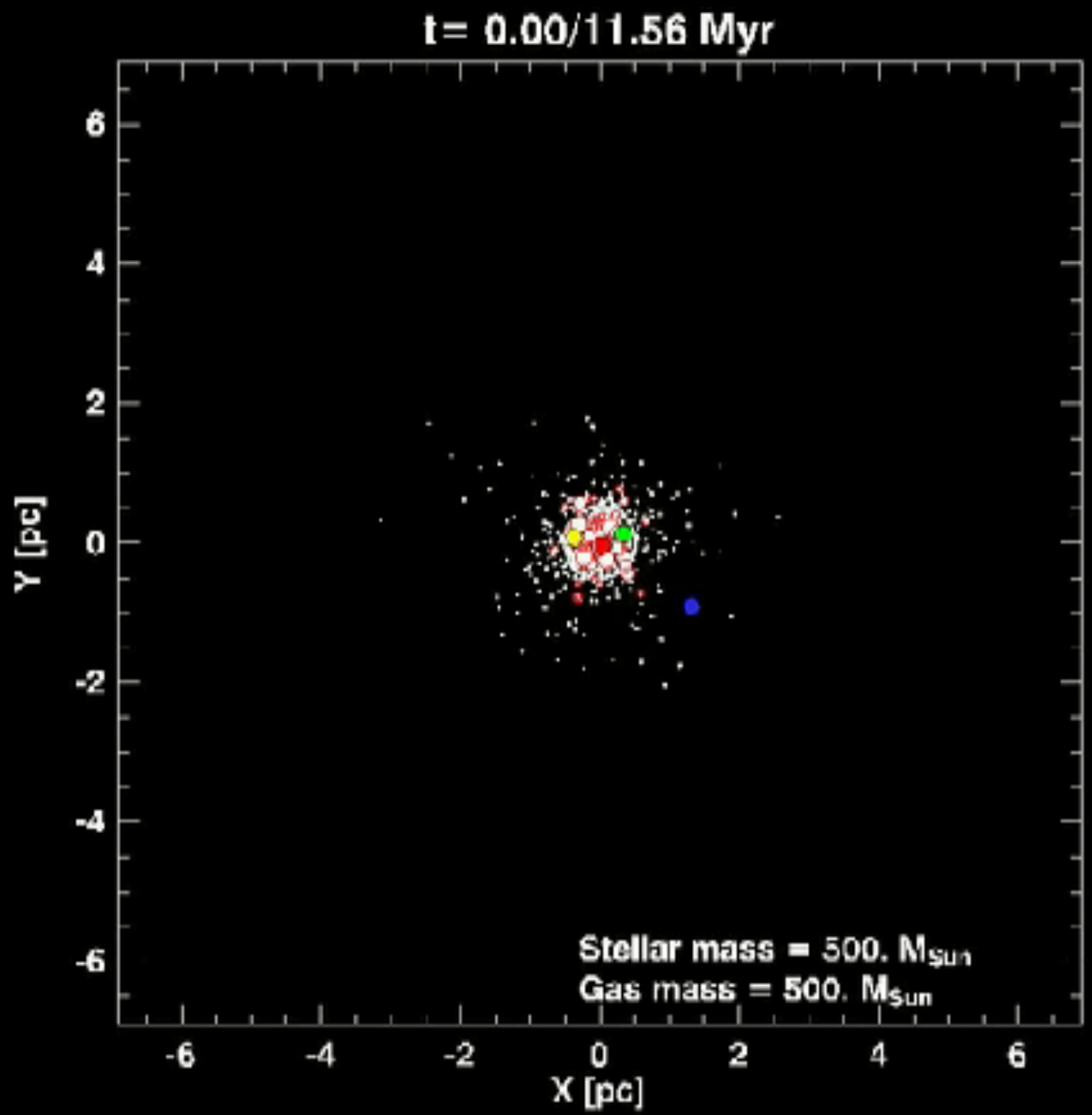
NBODY6 code (Aarseth 2003)

Stars:

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

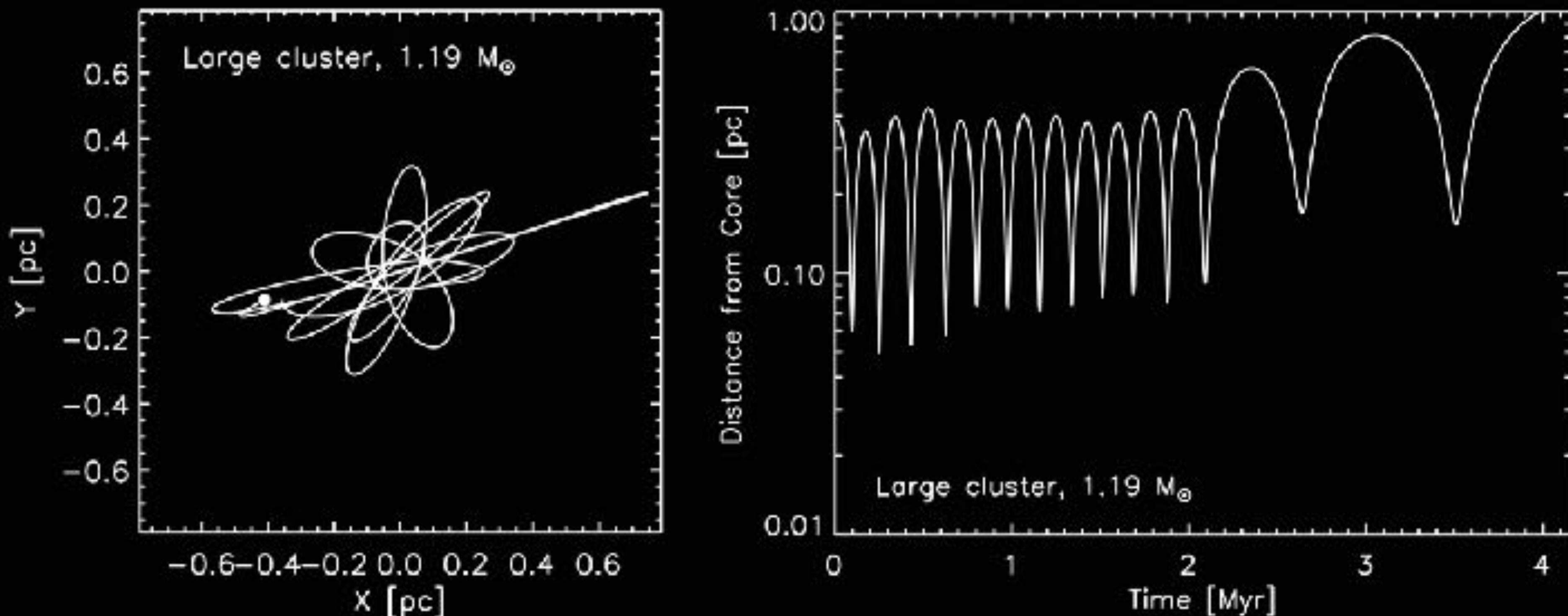
Gas:

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



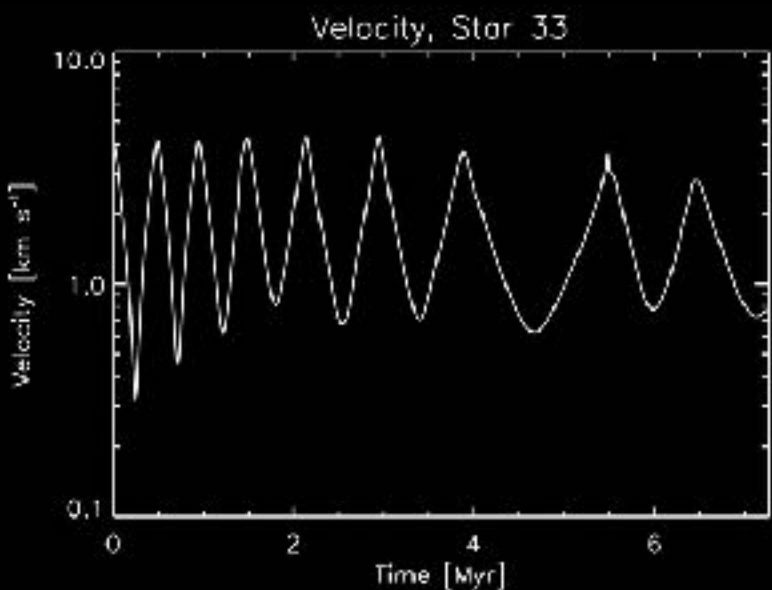
Throop & Bally 2008

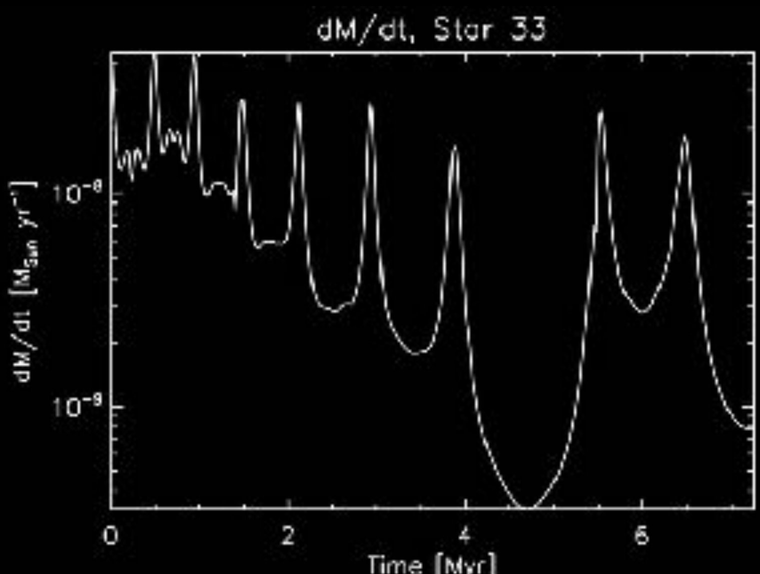
BH Accretion: History of individual star

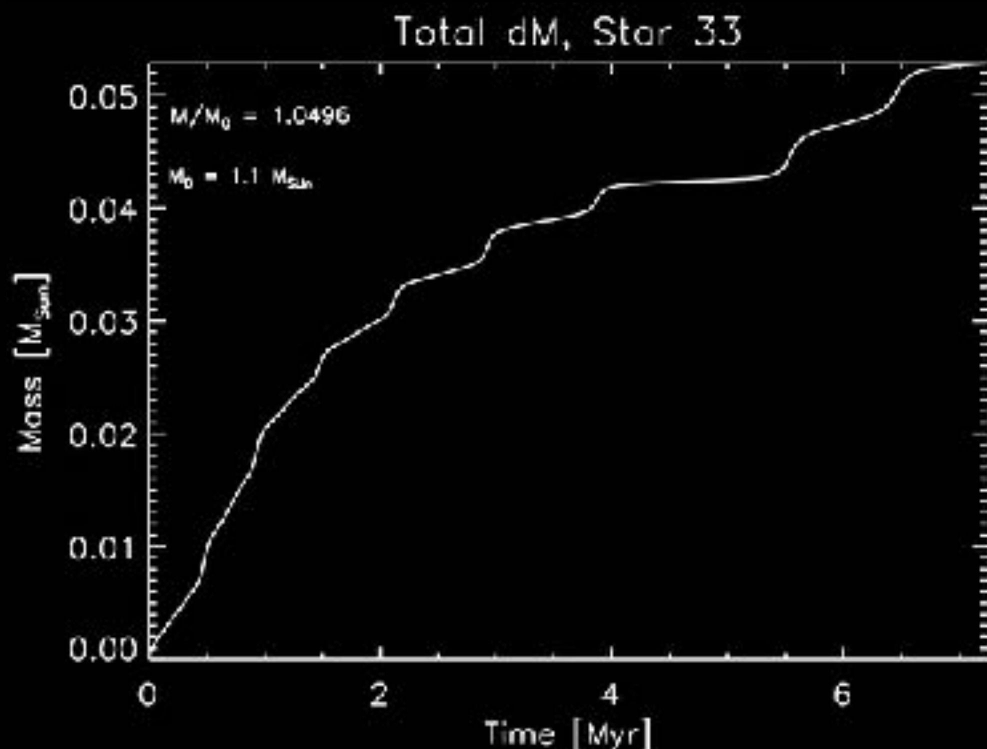


Following trajectory of one star of 3000 from N-body simulation...

BH Accretion: History of individual star





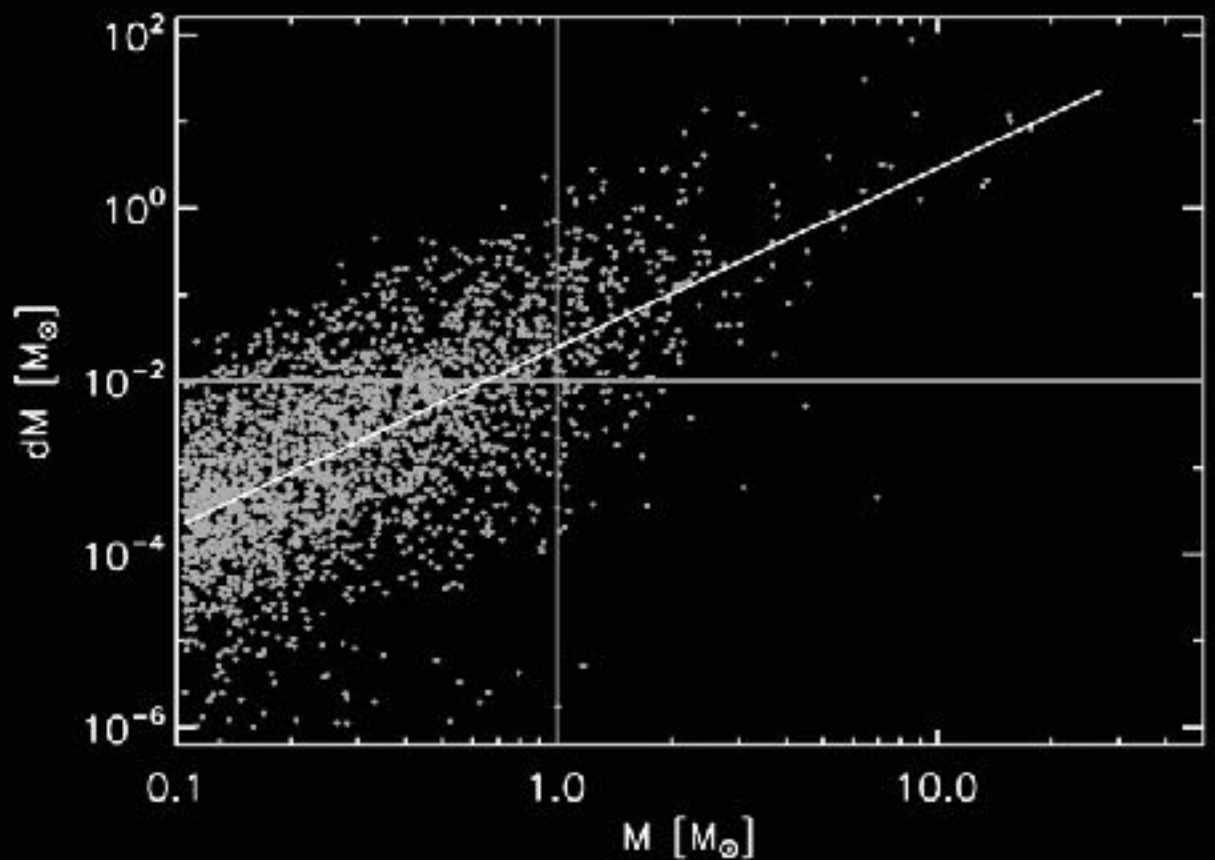


Star+disk accretes 5% of own mass in 5 Myr.

Accretion is episodic

- Highest at core: High velocity but high density

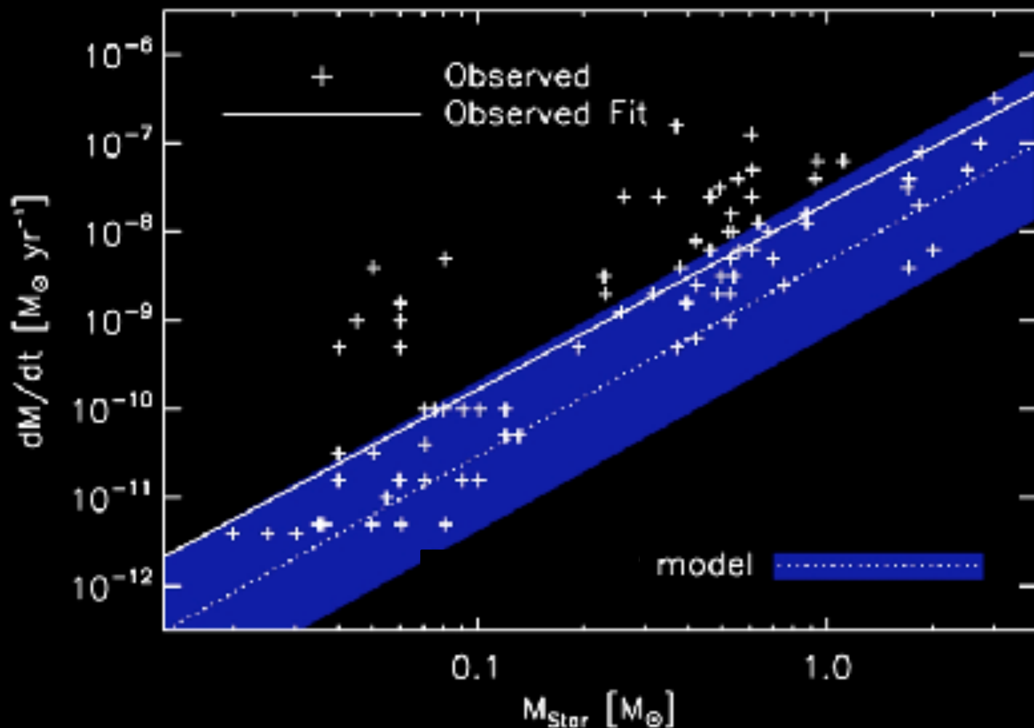
Results of N-Body sims



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



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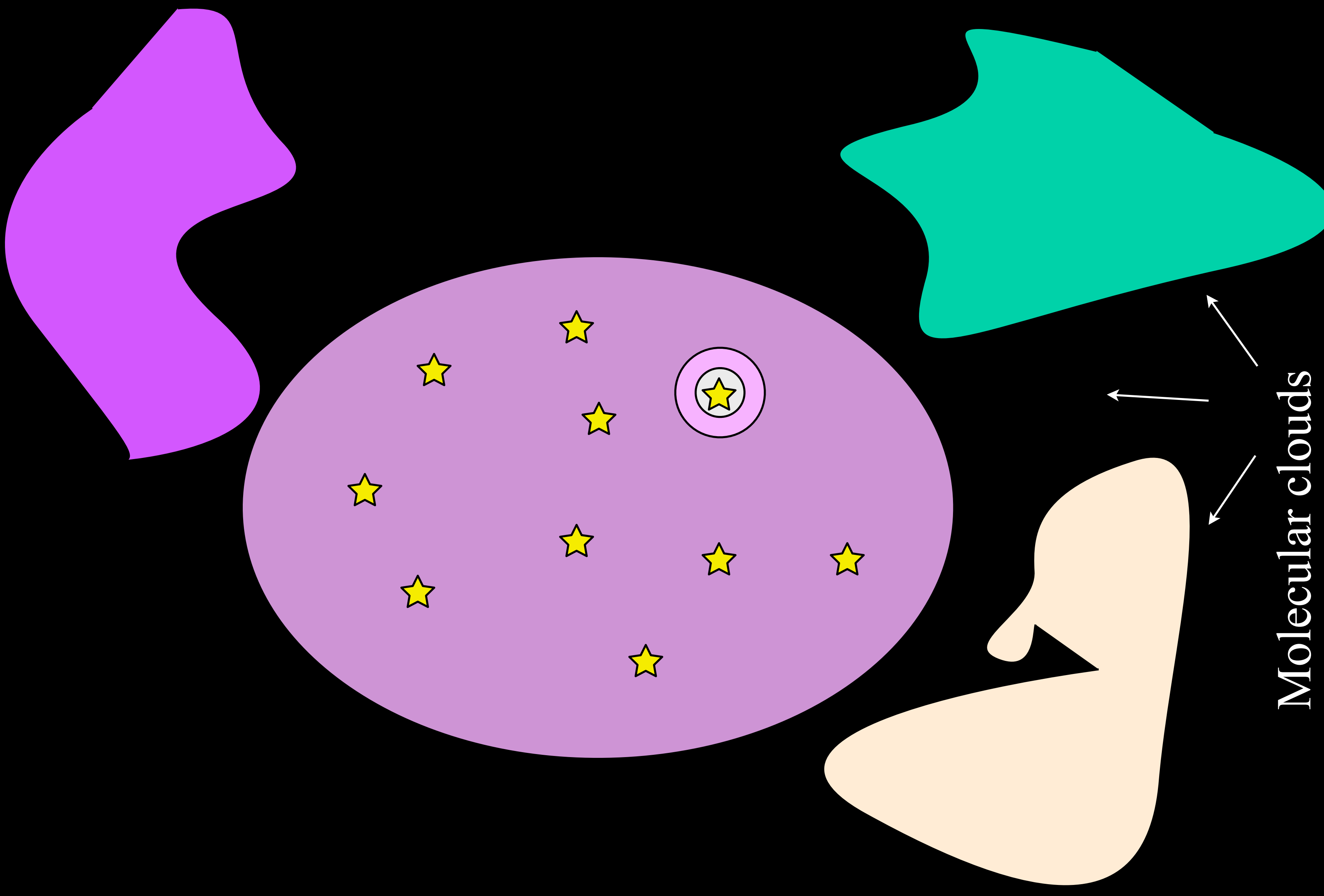
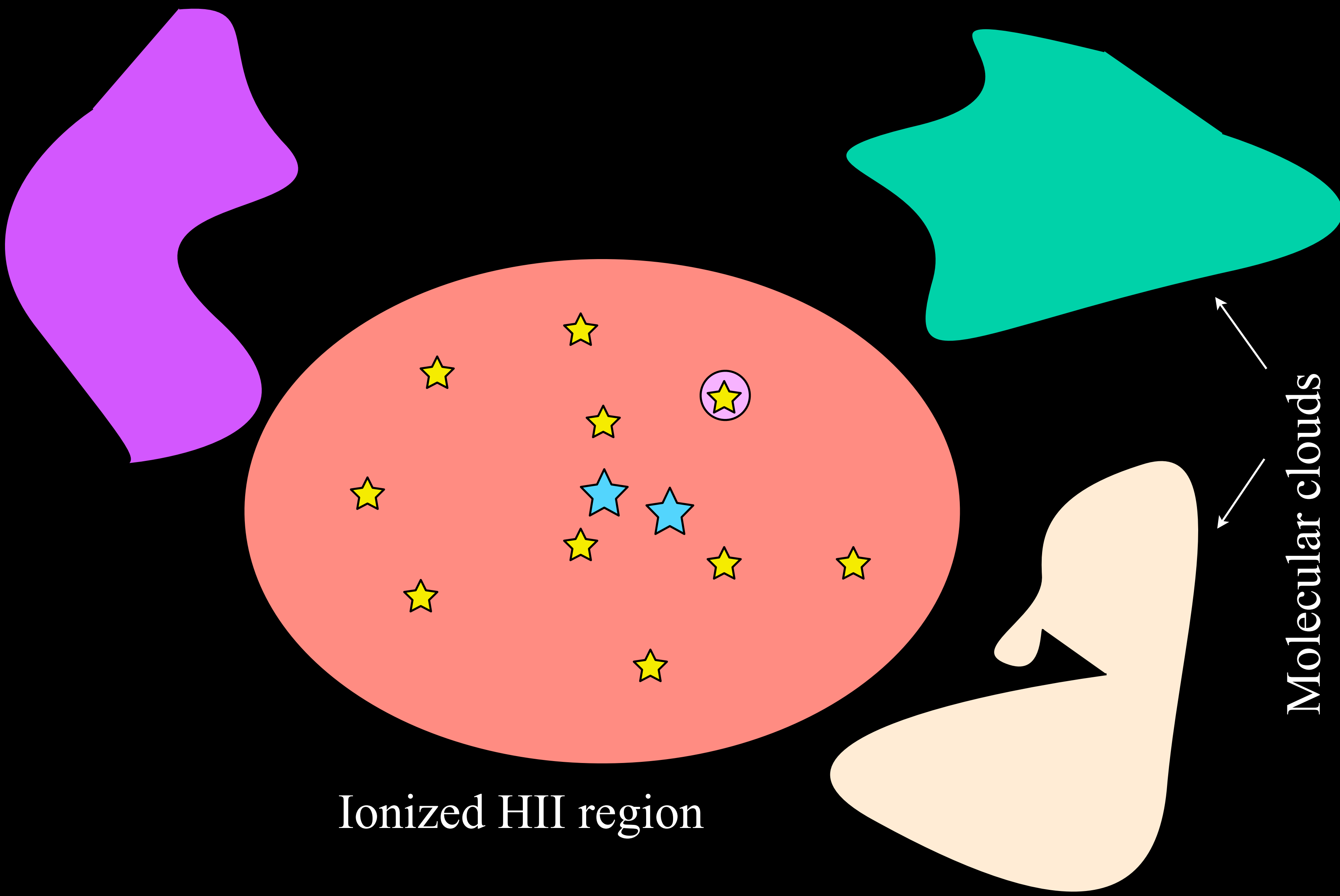
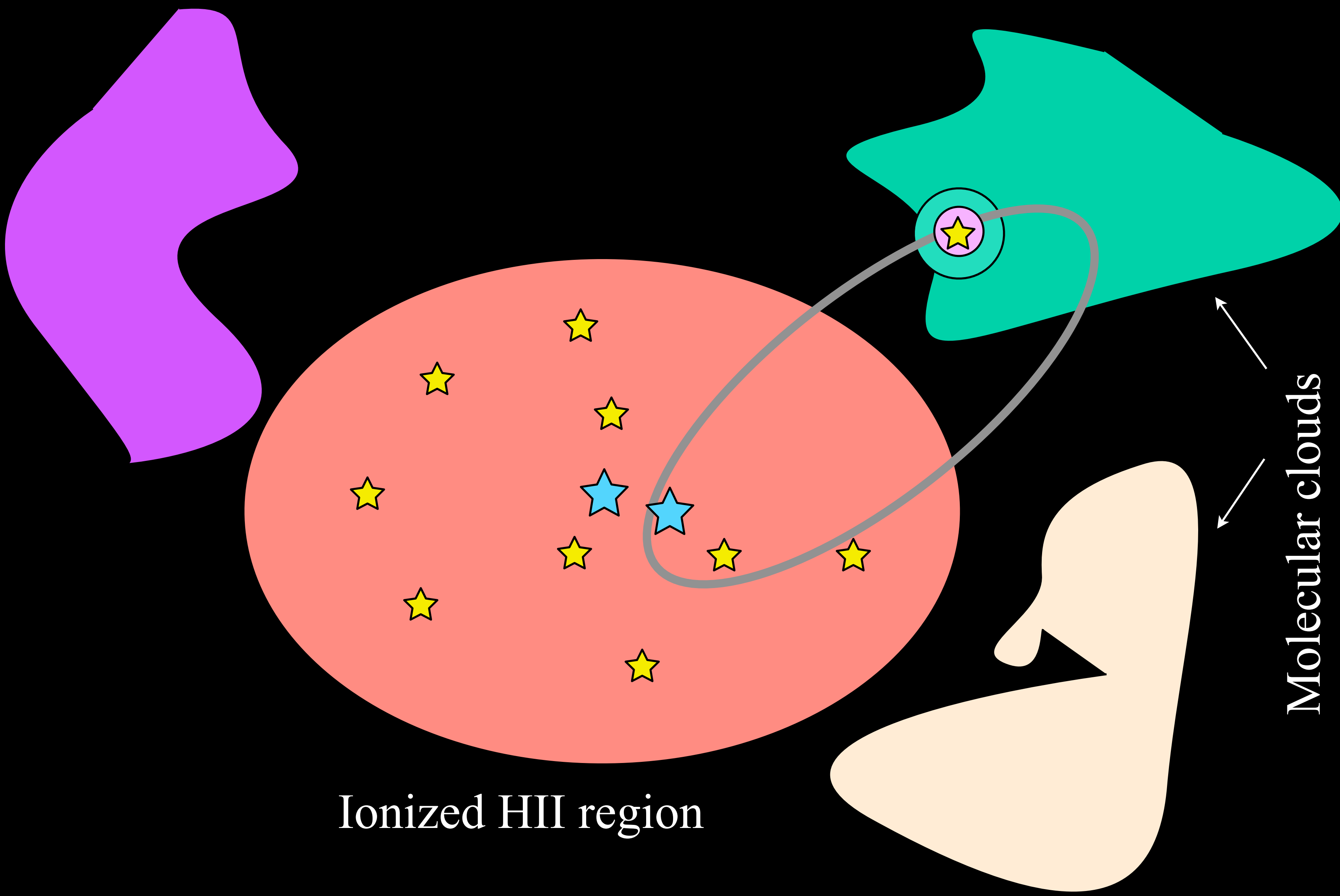

Molecular clouds


Molecular clouds
Ionized HII region



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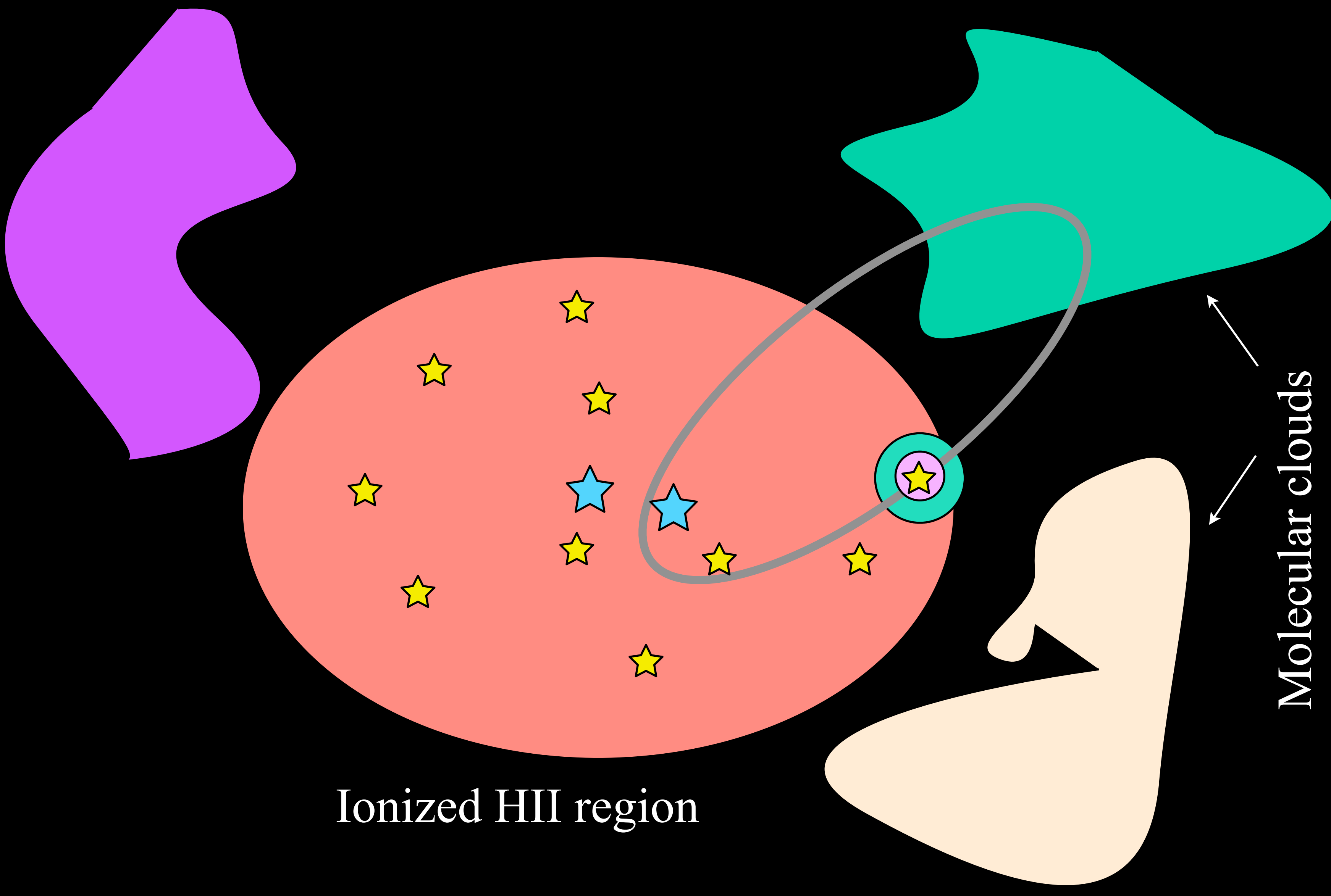
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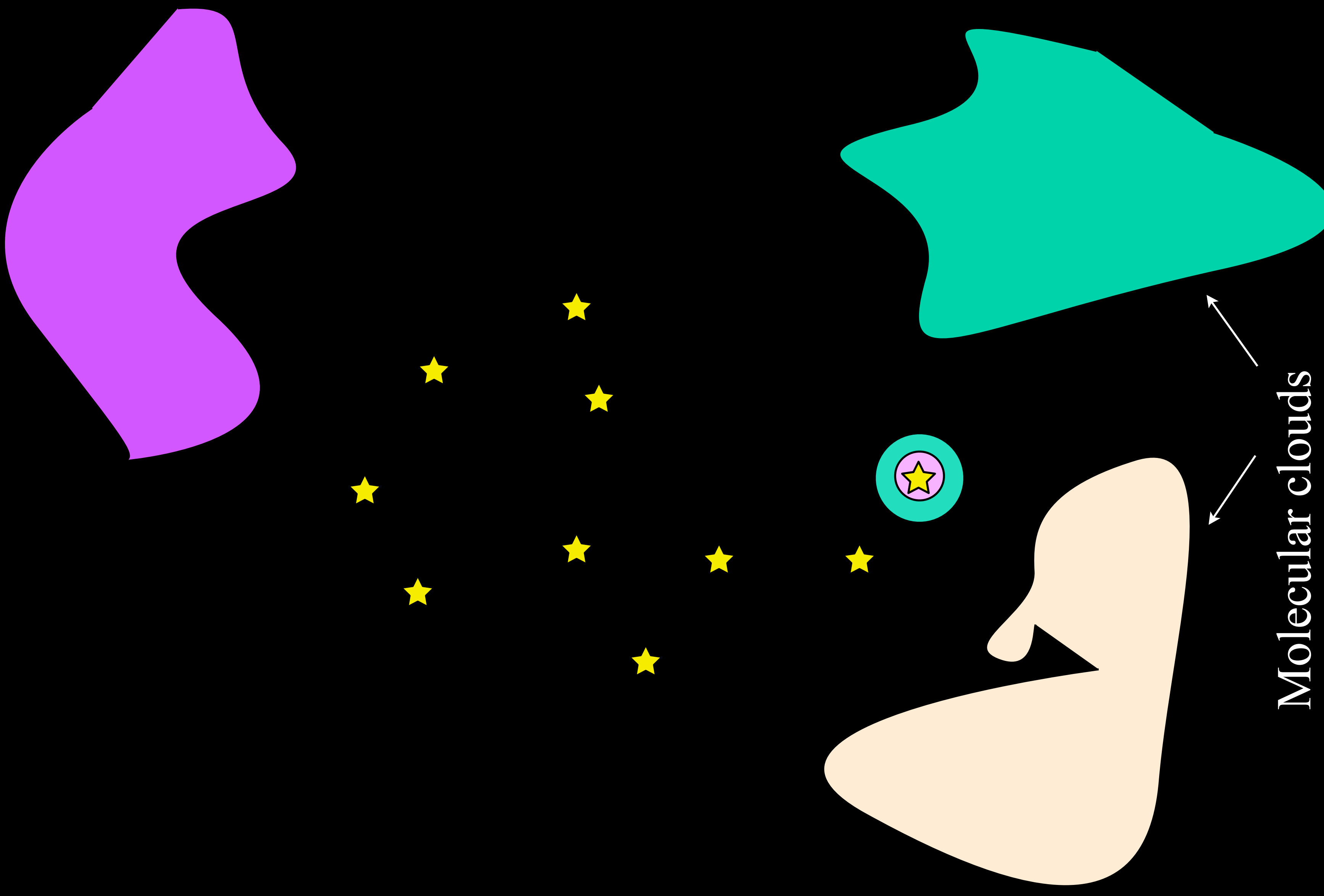
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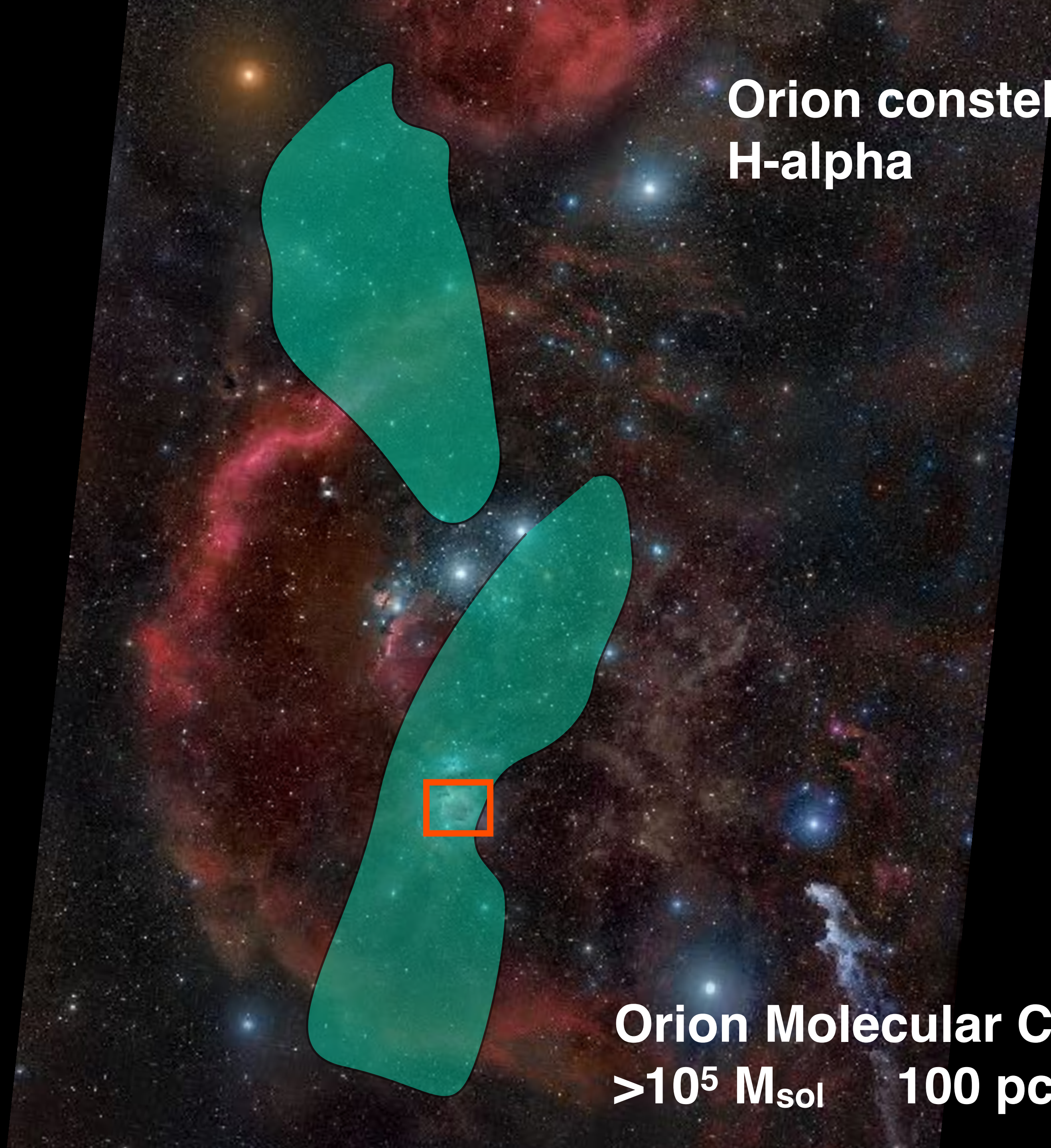
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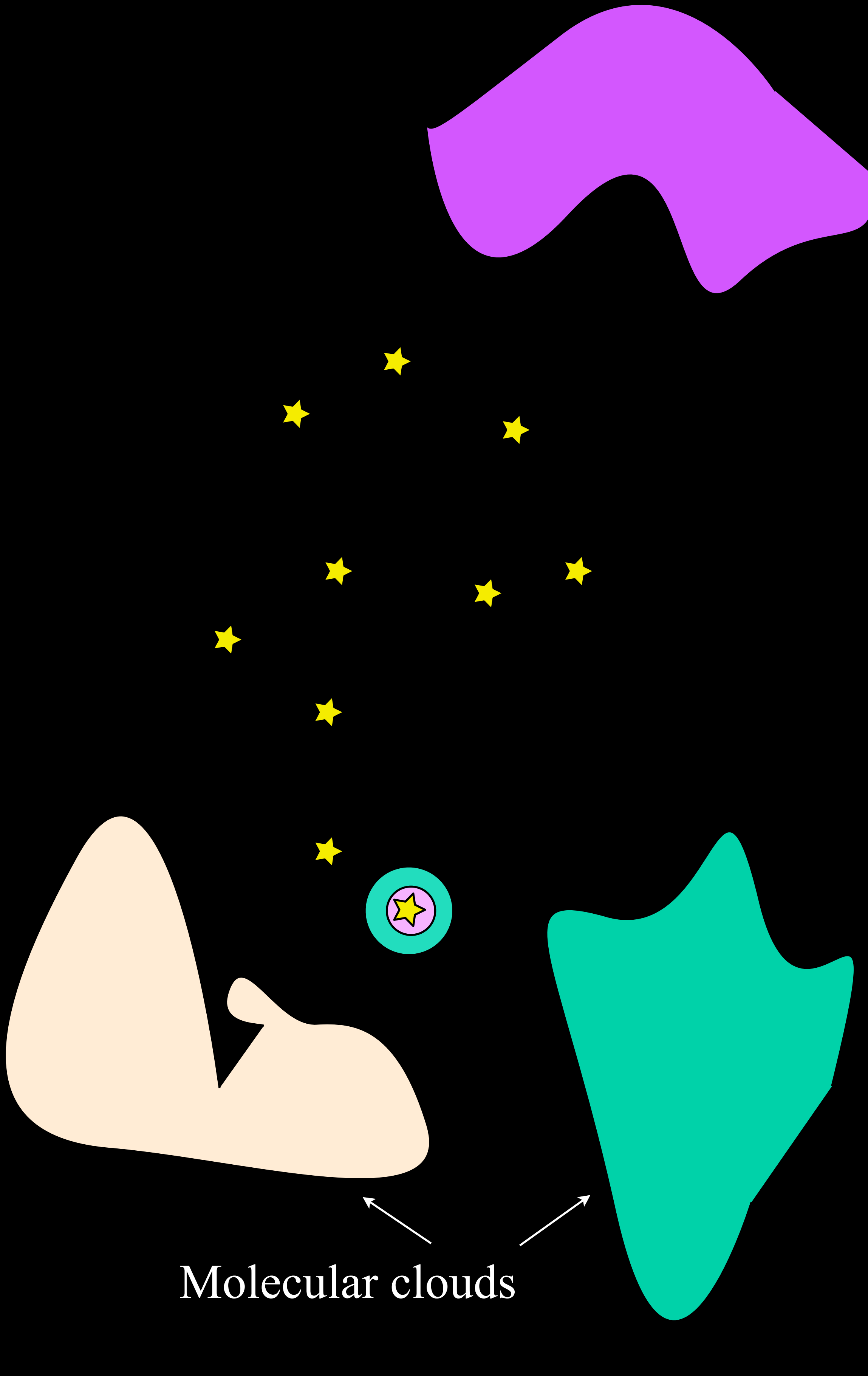
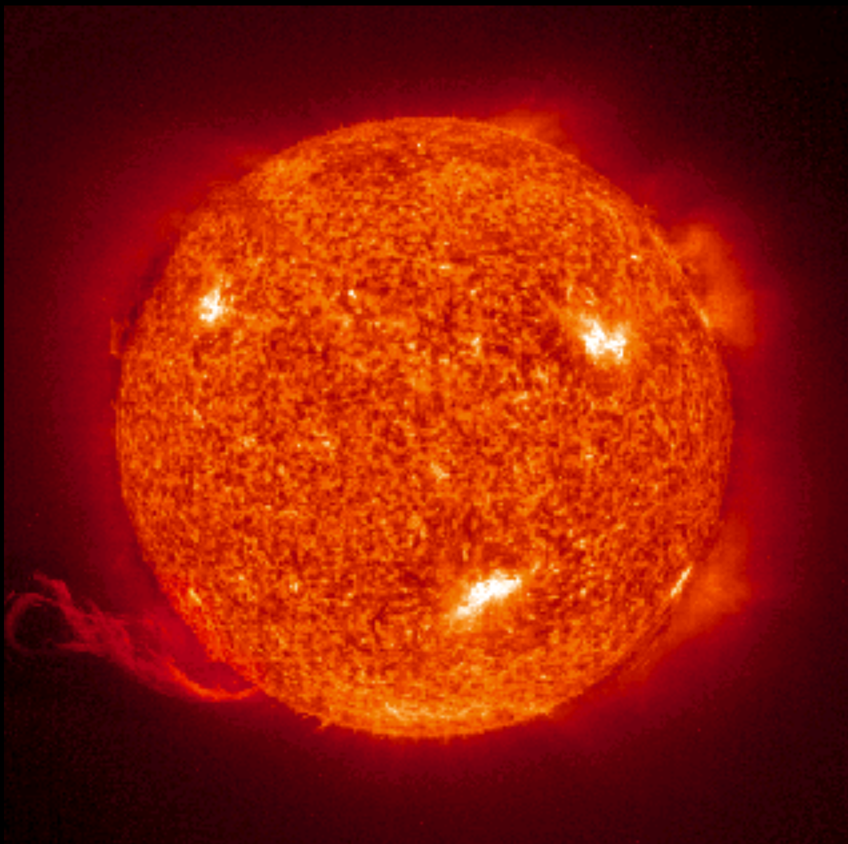

Molecular clouds

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 to ~20 bars
- Found Jupiter atmosphere to be 2-6x higher in metals vs. Sun, when normalized to H.
  - C, S, Ar, Kr, Xe
  - All these are stable and long-lived: enrichment was a complete surprise!
  - v_{esc} = 45 km/sec
- GPMS likely passed through 'dry spot' on Jupiter.
- Several explanations proposed:
  - Noble gases may be enhanced by freeze-out onto ices. But requires extremely cold disk < 30K (Guillot, Hersant, Lunine).
  - Jupiter may be H-depleted, and S could be a better reference (Lodders 2004).

Jupiter 'Polluted Accretion' model

We propose a crazy idea for Jupiter's composition:

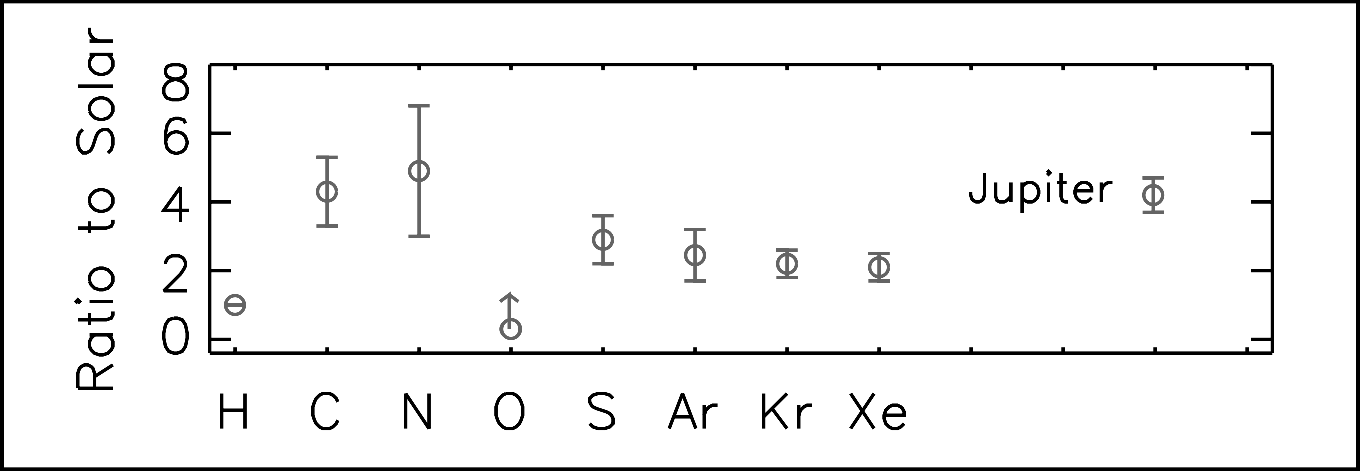
1. Solar System forms in a large star cluster.

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

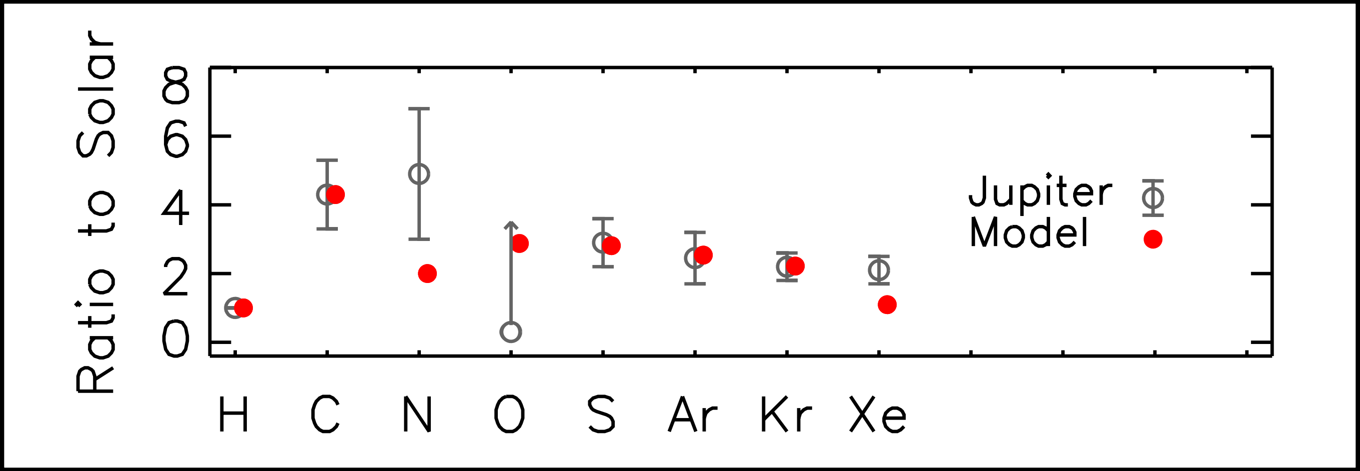
Throop & Bally 2010 (Icarus)

Observed Jupiter Composition



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

Jupiter 'Polluted Accretion' model

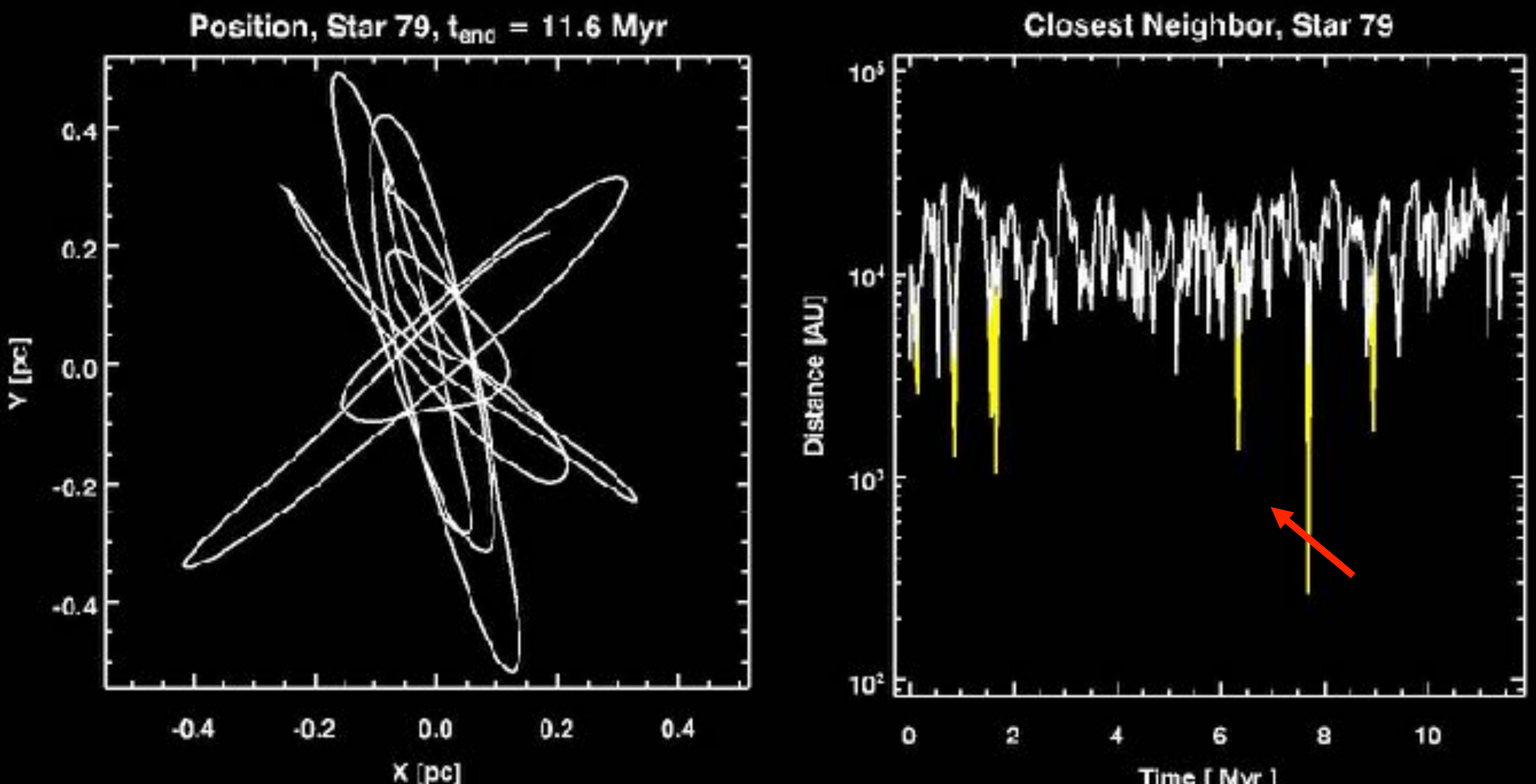


- Data: Galileo Probe
- Model: Accretion from ISM
  - 87% Solar nebula material
  - 9% Stellar winds from 20 $M_\odot$ star (provides C, N)
  - 4% SN from 25 $M_\odot$ star (provides S, Ar, Kr, Xe)
  - Requires total of ~0.13 M_J of accretion to explain Jupiter's current metallicity.
  - Bondi-Hoyle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

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 $M_\odot$ Star

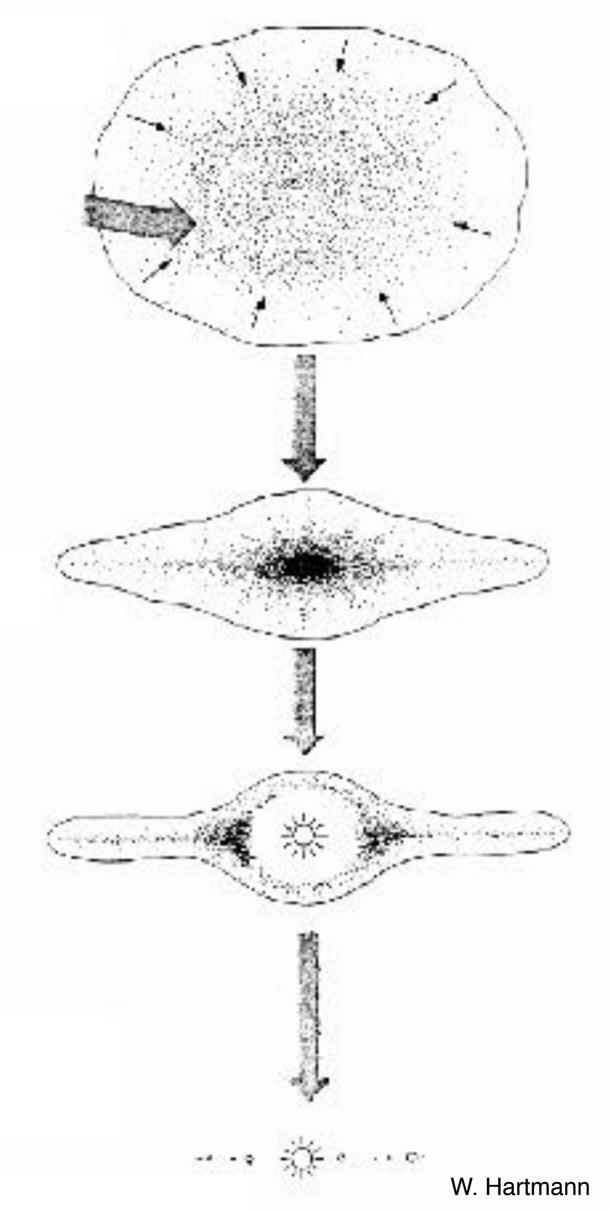


- Star has 5 close approaches at < 2000 AU.
- Closest encounter is 300 AU at 8 Myr
  - Too late to do any damage

Planet Formation - ~~Classical~~ Modified 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


W. Hartmann