Planet Formation in Orion

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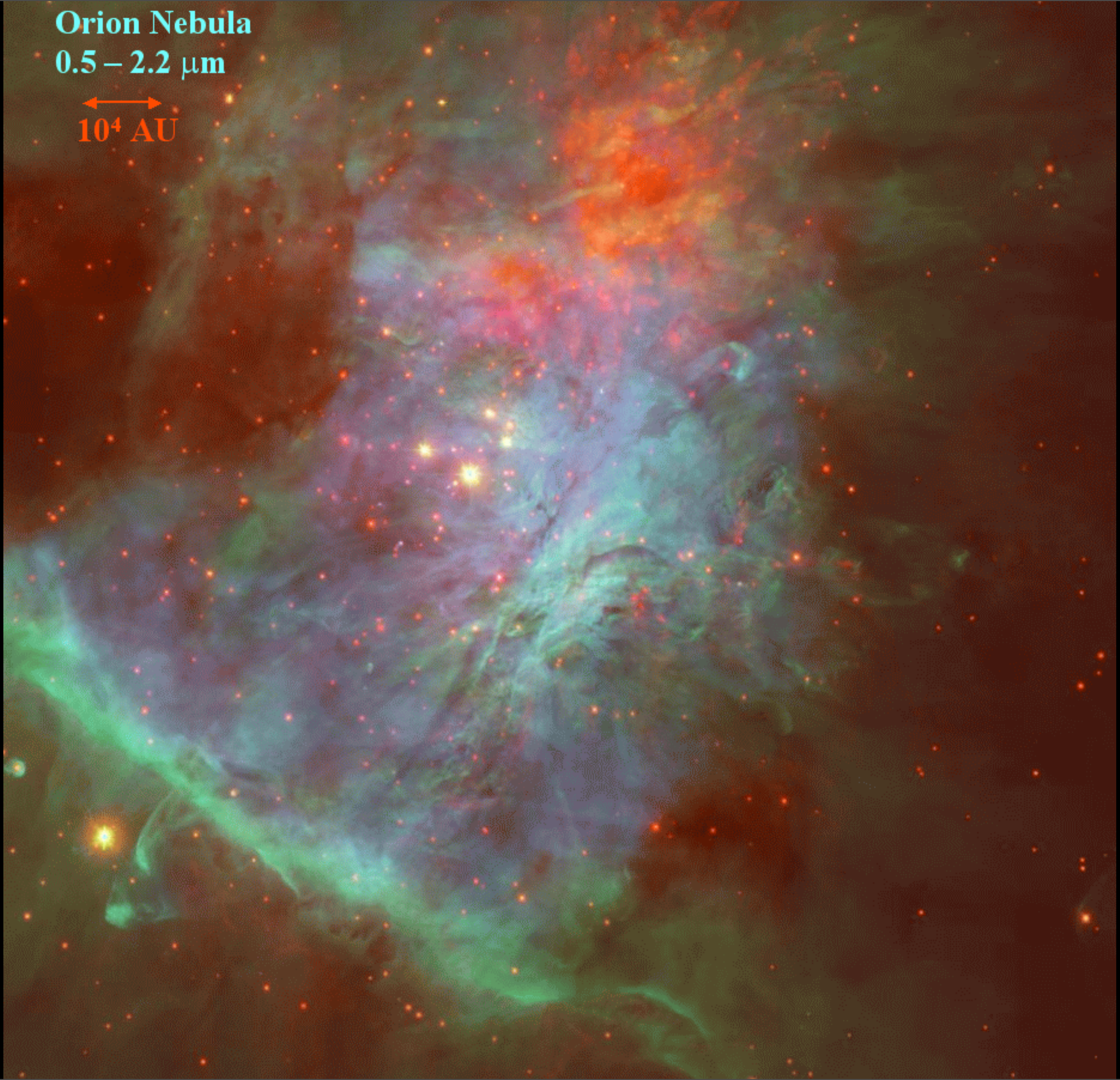
Orion Constellation
(visible light)

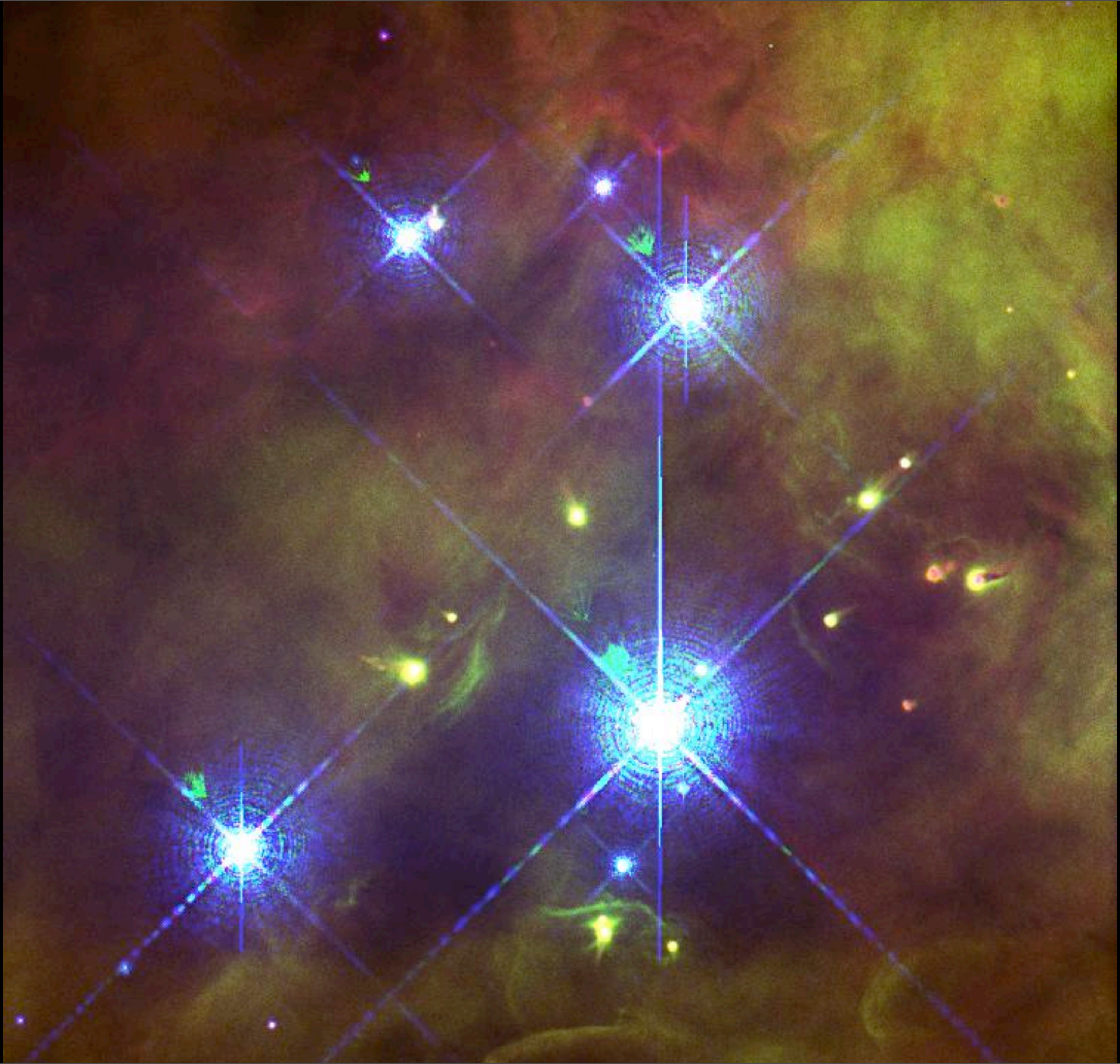

Orion constellation
(infrared light)


Orion Nebula
0.5 – 2.2 μm
10⁴ AU

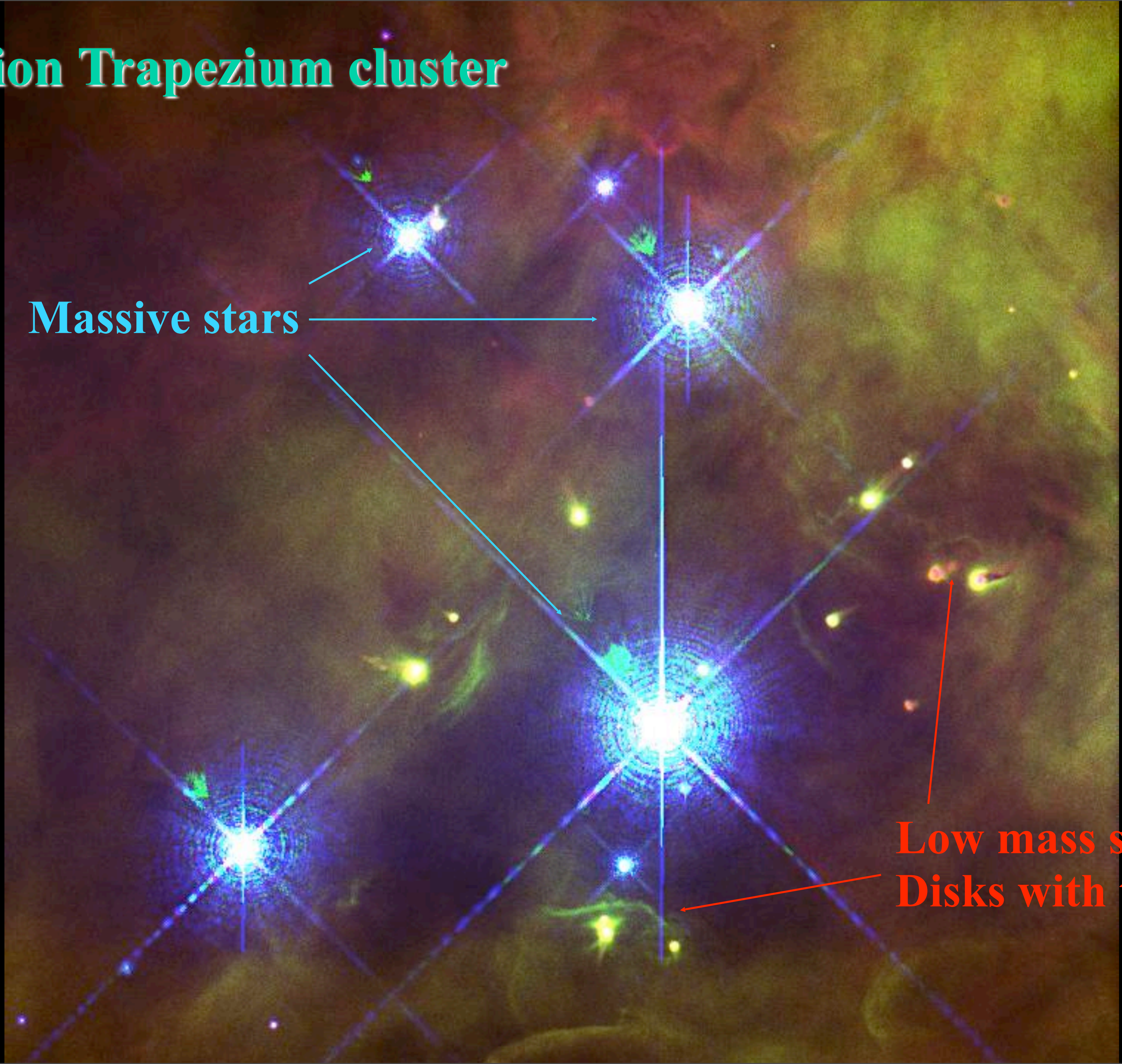
Orion Star Forming Region

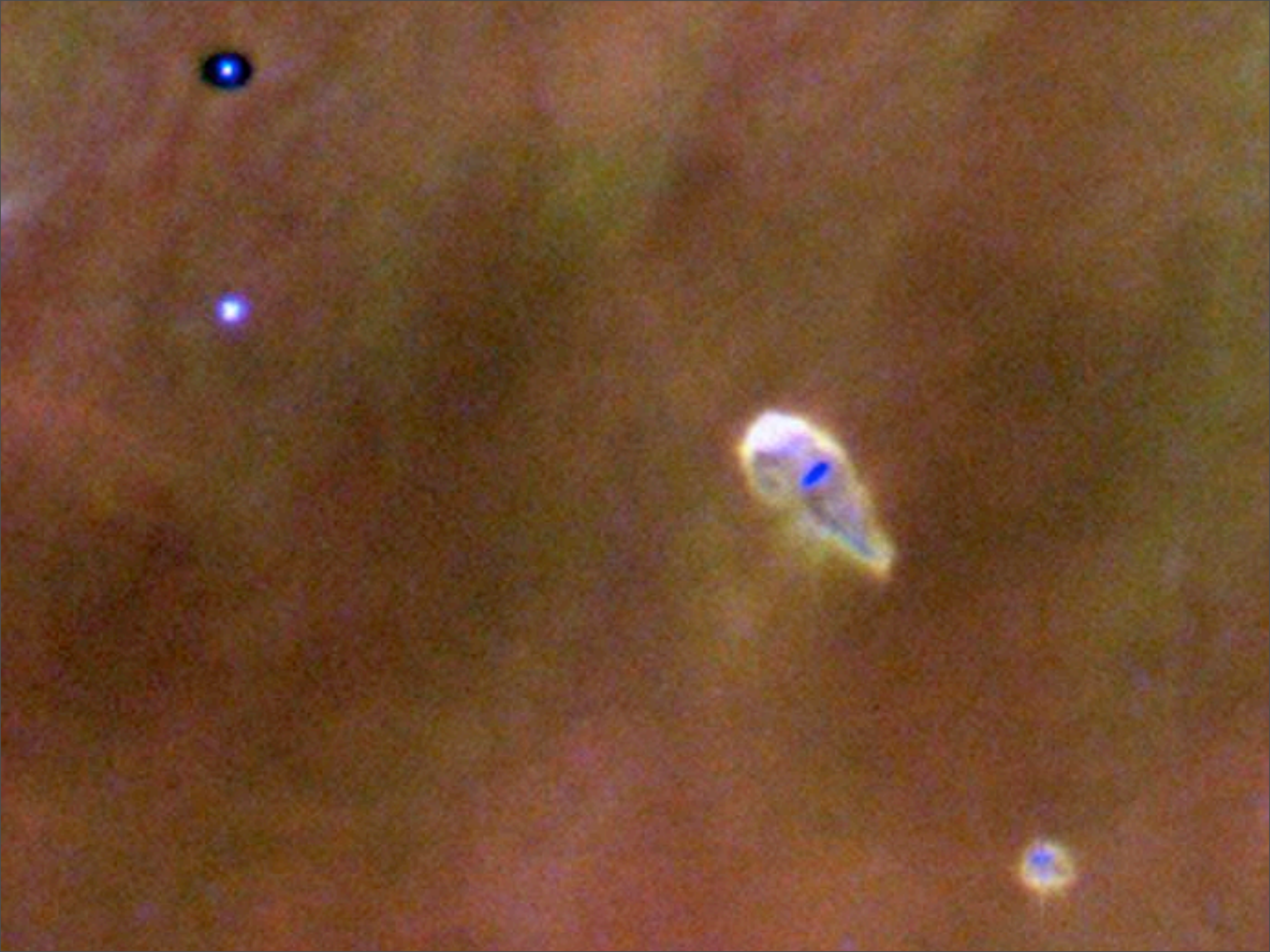
- Closest bright star-forming region to Earth
- Distance ~ 1500 ly
- Age ~ 10 Myr
- Radius ~ few ly
- Mean separation ~ 10^4 AU
- 20,000 young stars
- 10^5 solar luminosities from 4 OB stars

- HST resolution of Orion ~ 20 AU



Orion Trapezium cluster

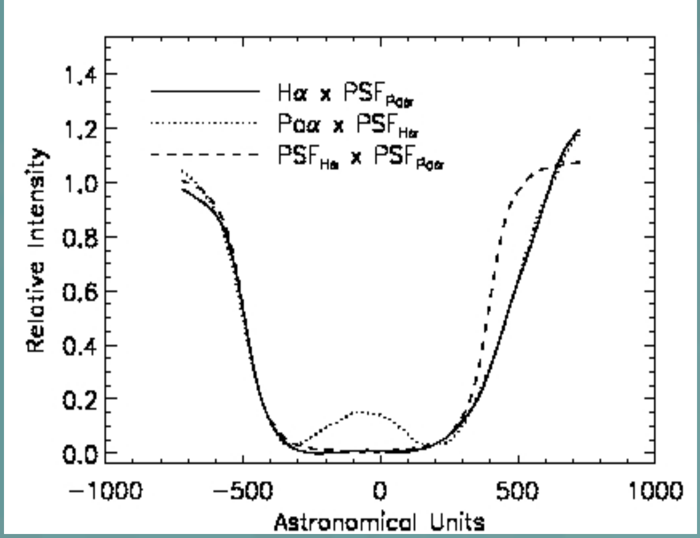


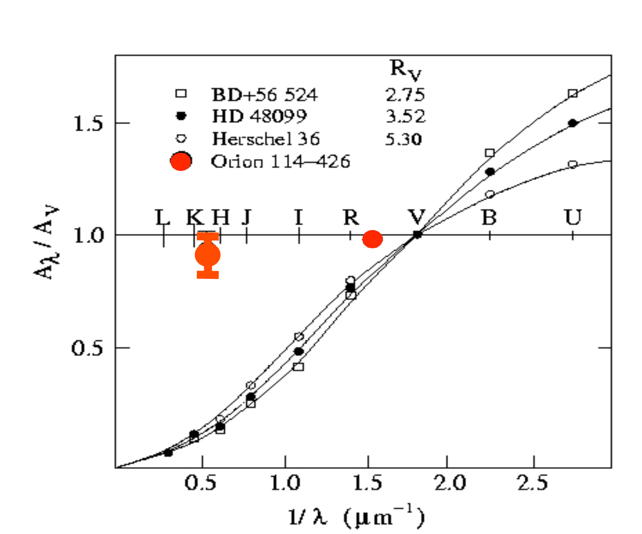



HST 16
200 AU disk diameter
0.3 ly to O star
HST 10
Disk at center
HST 17

Grain Growth in Young Disks

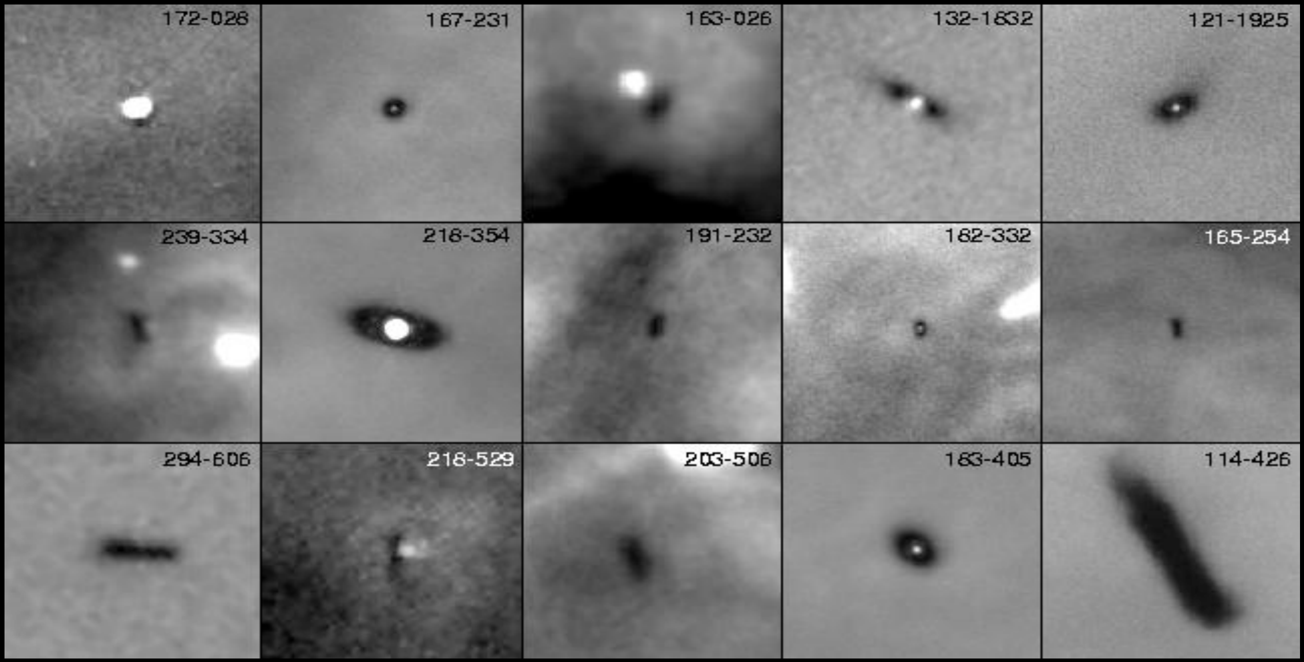
- Largest Orion disk: 114-426, D ~ 1200 AU
- Dust grains in disk are grey, and do not redden light as they extinct it
- Dust grains have grown to a few microns or greater in < 1 Myr





Throop et al 2001

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.

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..."

R. P. Feynman, *Lectures on Physics*

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2007 view:

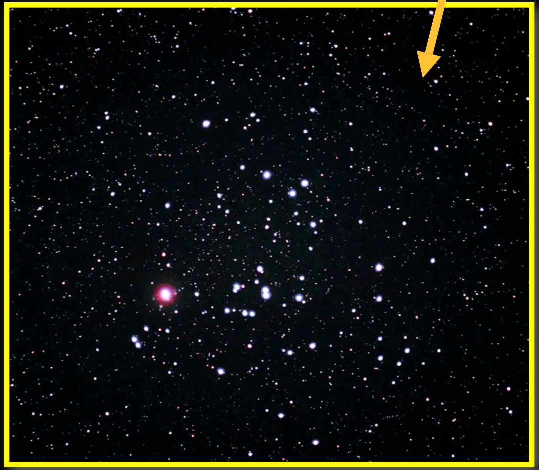
Infrared detectors have allowed us to directly see thousands of star forming -- nearly everywhere that we see an IR source. 1000+ young stars in Orion alone.

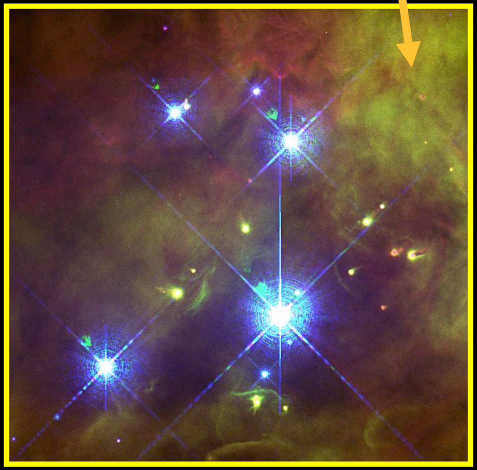
Whether we've ever seen a **planet** form or not is the current question!

Star Cluster Formation → Star Formation → Planet Formation

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)	





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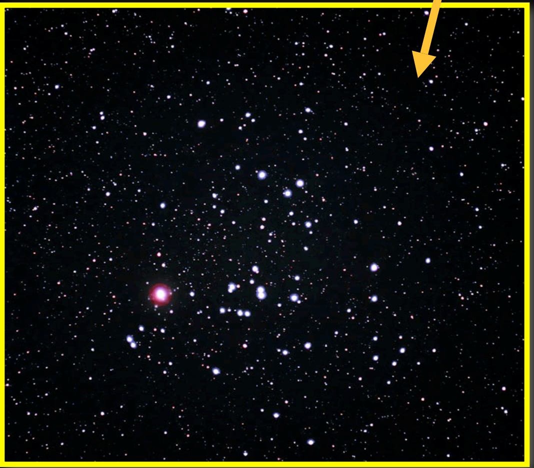
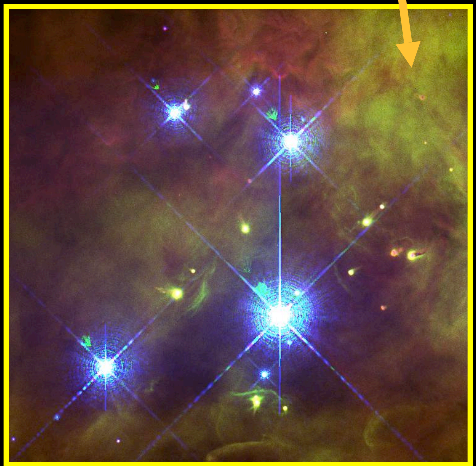


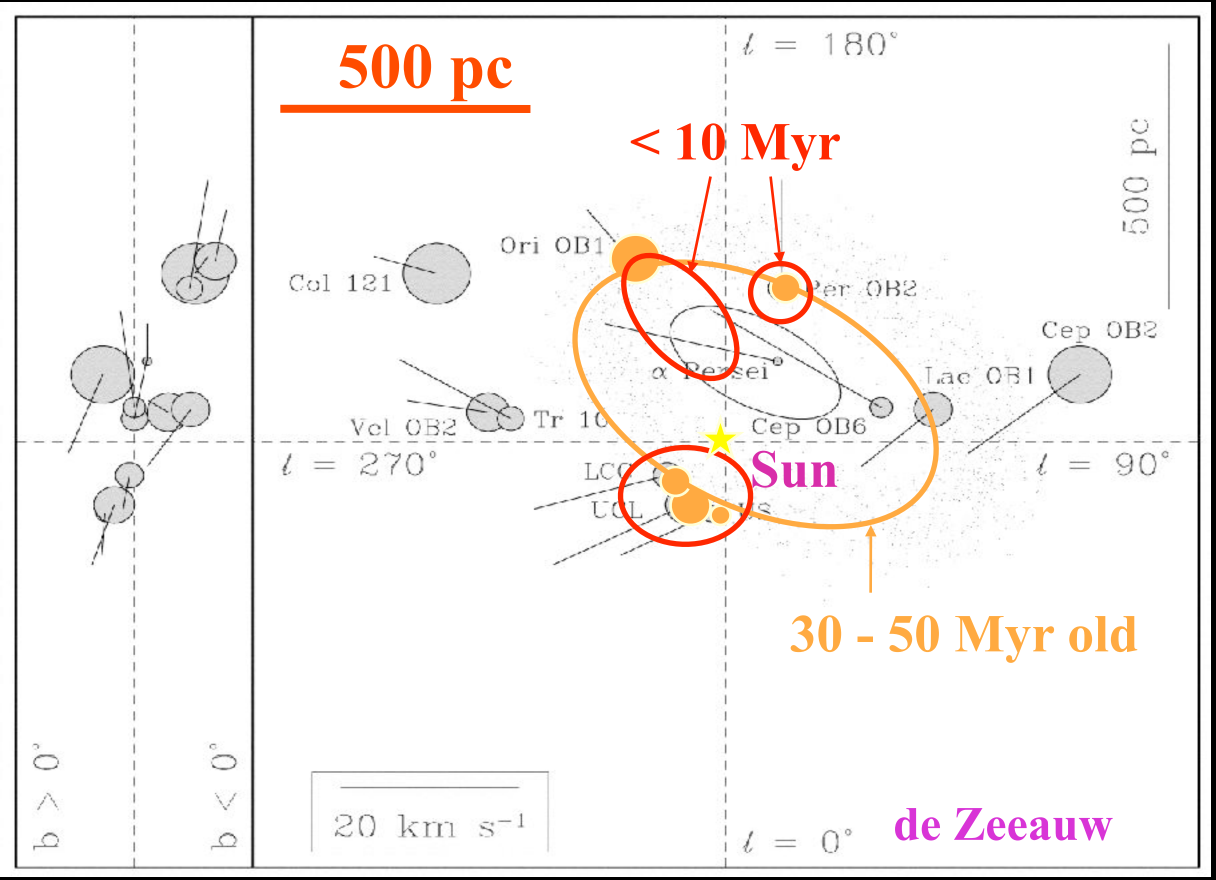


Majority of stars today form in dense but rare clusters like Orion!

Where did our Sun form?

- Only 1% of fields stars are in clusters today...
- But we see that 90%+ of stars form in clusters.
- Stellar motions can be back-integrated for 100 Myr, but not 10 Gyr.

- Birth environment of the Sun is unknown, but isotopic evidence (^{60}Fe) suggests Sun was born near supernova.



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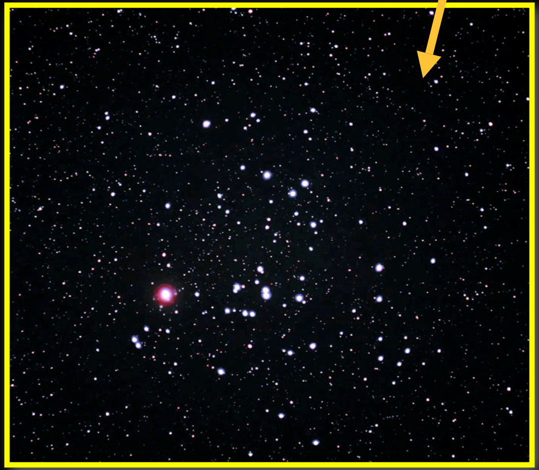

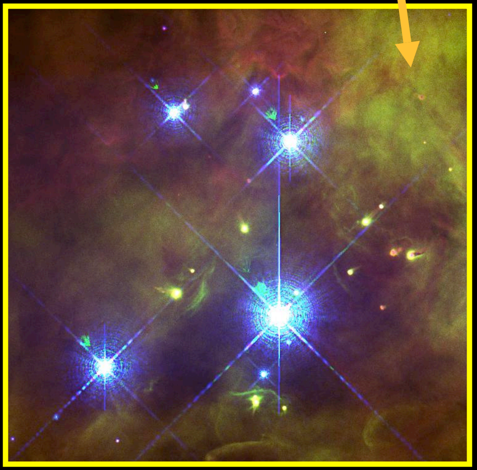

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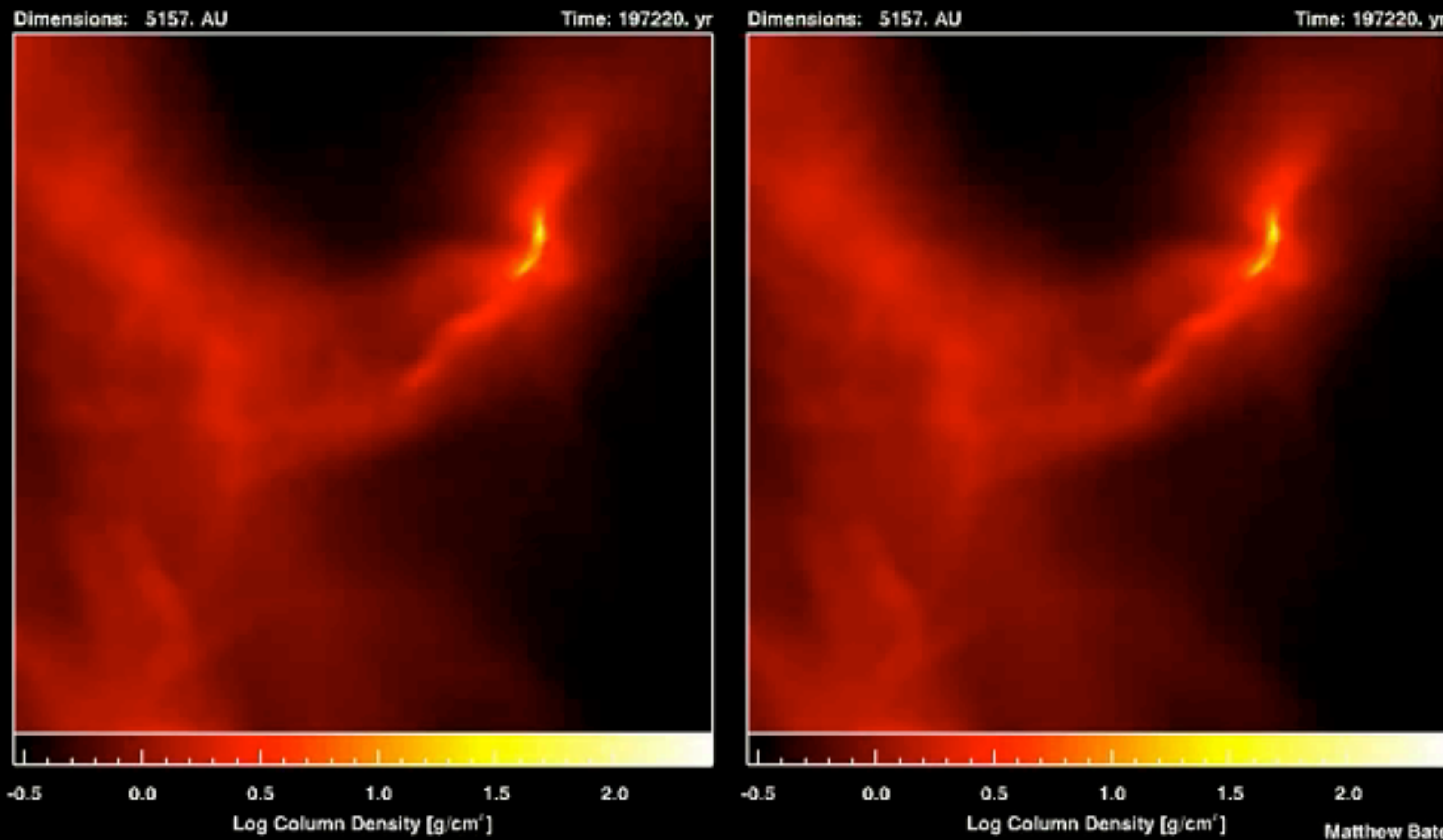
Dimensions: 5157. AU
Time: 197220. yr
-0.5
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1.5
2.0
Log Column Density [g/cm²]
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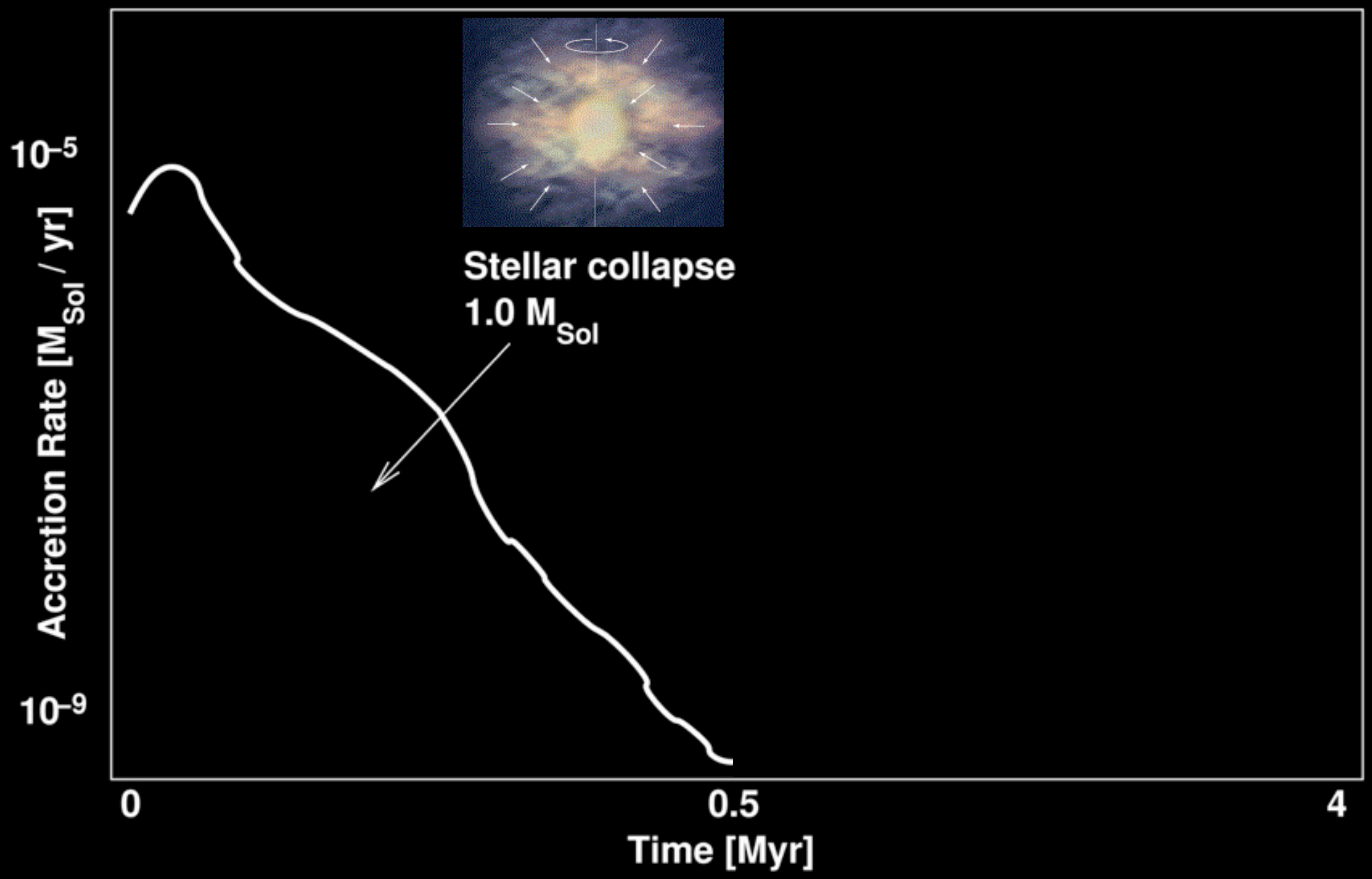
Matthew Bate

Timescale of Star Formation



How does Cluster Environment affect Disk

- Interaction with cluster gas
  - 70-90% of cluster gas is not used in star formation
  - Bondi-Hoyle accretion onto stars
- Photoevaporation from external, massive stars
  - 10^5 L_{sun} from O stars at cluster core
  - UV flux ~ 10^4 - 10^6 G_0 (G_0 = UV flux at Sun)
  - Truncates disks on Myr timescales
- Close stellar encounters
  - 2,000 stars in 0.5 pc^3
  - Mean stellar separations ~ 10,000 AU
- UV, X ray chemistry
  - Total UV dose is thousands of ionizing photons per (dust) molecule, in first 10 Myr.

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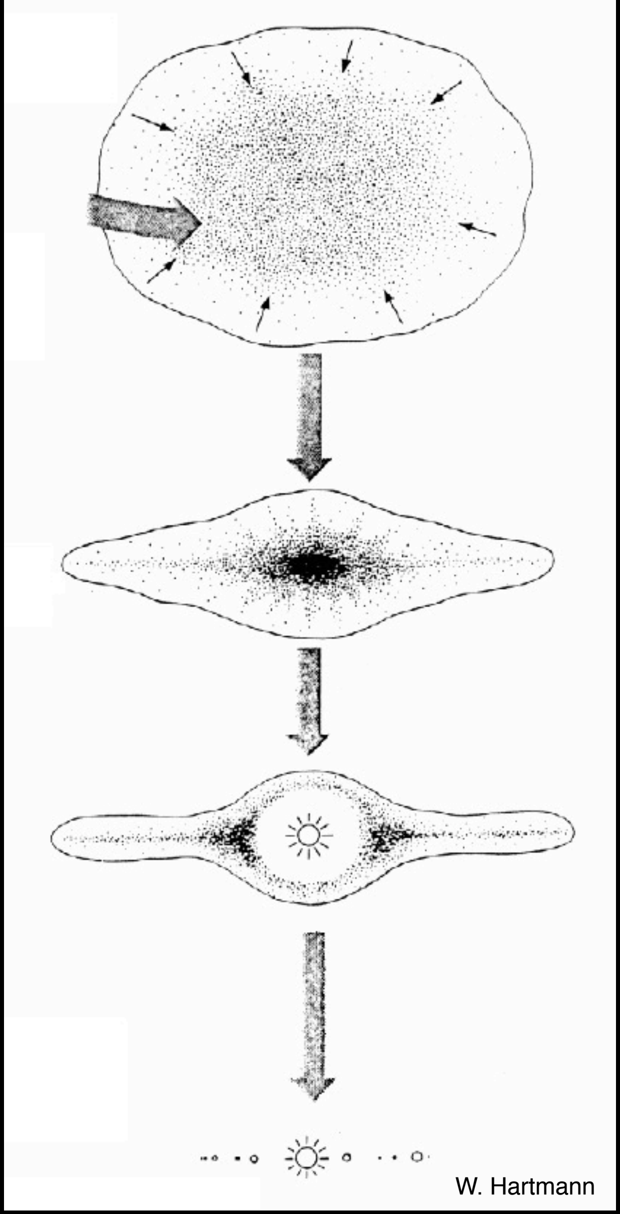
Planet Formation - Classical Model

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

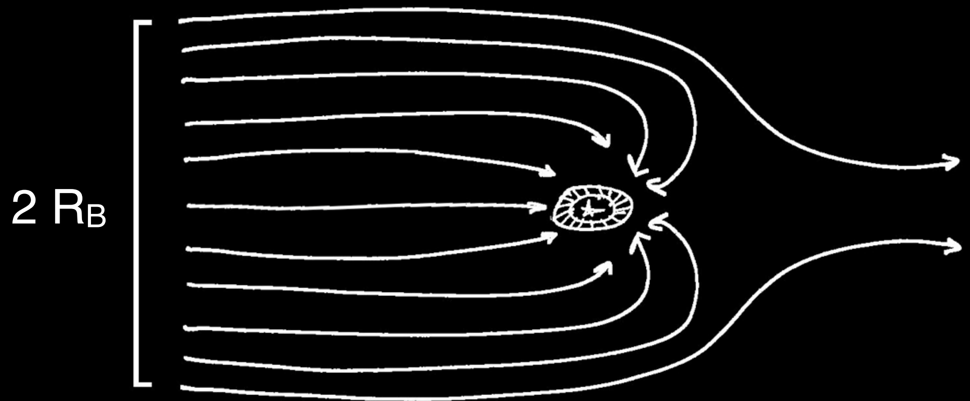
Disk flattens; grains settle to midplane
Planet cores grow

Terrestrial planets form
Jovian planets accrete gas

Disk disperses
SS formed after ~ 5-10 Myr



Bondi-Hoyle Accretion



- Accretion onto a moving point source
- Accretion rate is higher for lower velocities
- Cool molecular H_2 from cluster ISM accretes onto disks
- Accretion flow is onto disks, not stars.
- BH accretion from ISM onto young stars has not been considered by existing models of star or disk formation!

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

Accretion radius ~ 1000 AU

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

Accretion rate

N-Body Dense-Cluster Simulations

NBODY6 code (Aarseth 2003)

Stars:

- N=1000
- M_{star} = 500 M_{sun}
- Kroupa IMF
- R_0 = 0.5 pc
- O6 star fixed at center

Gas:

- M_{gas} = 500 M_{sun}
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Throop & Bally 2007

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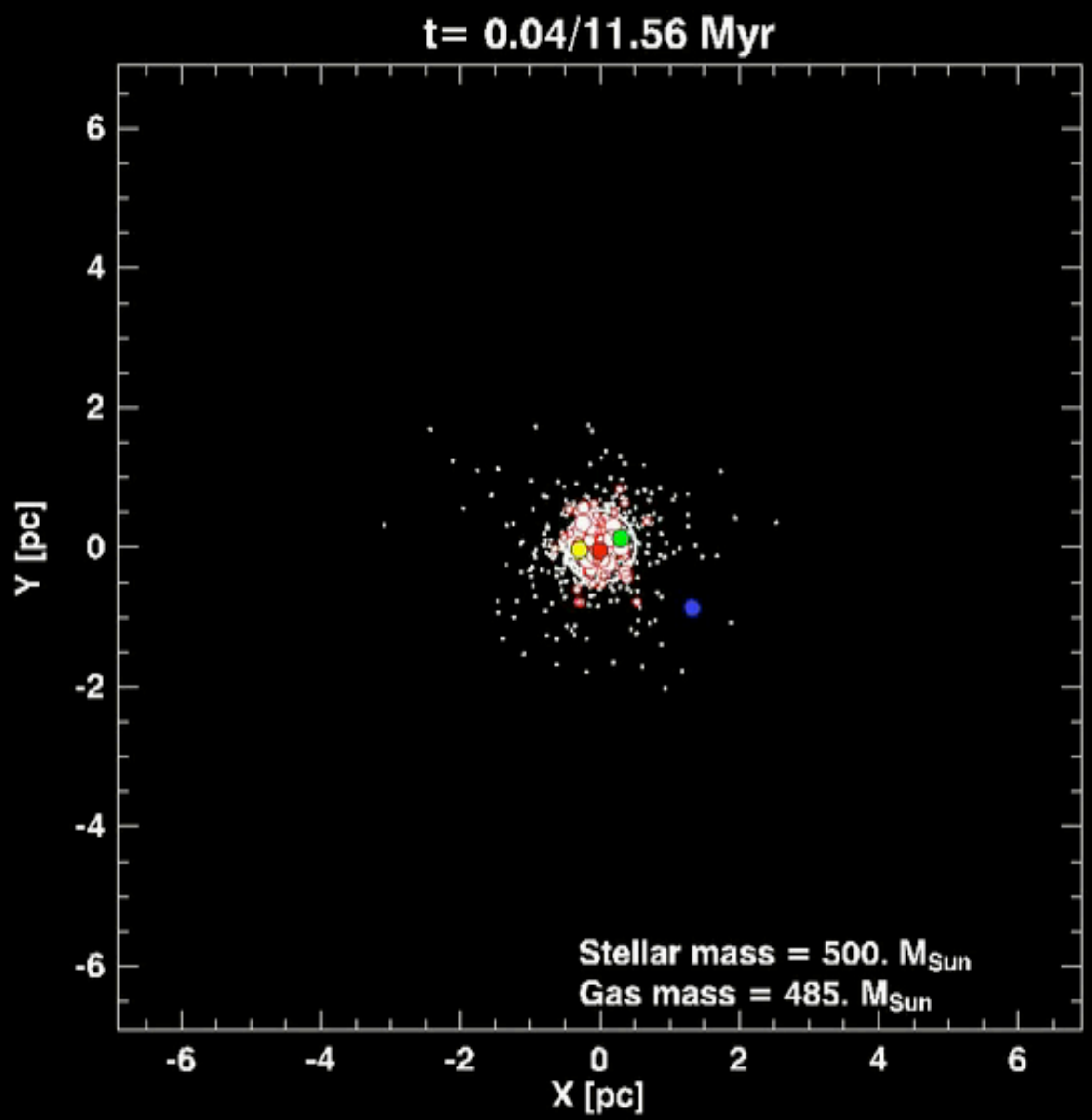

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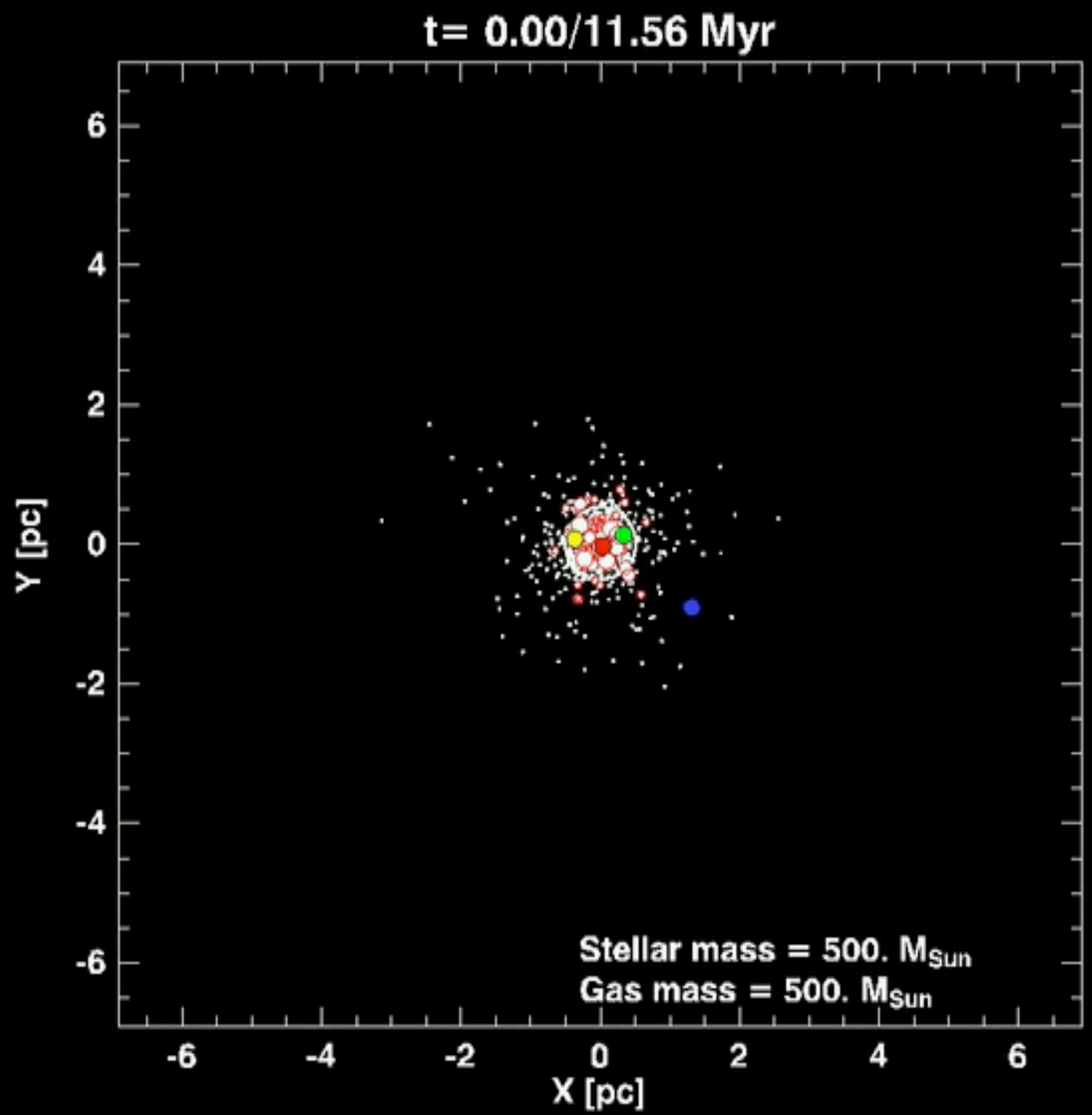

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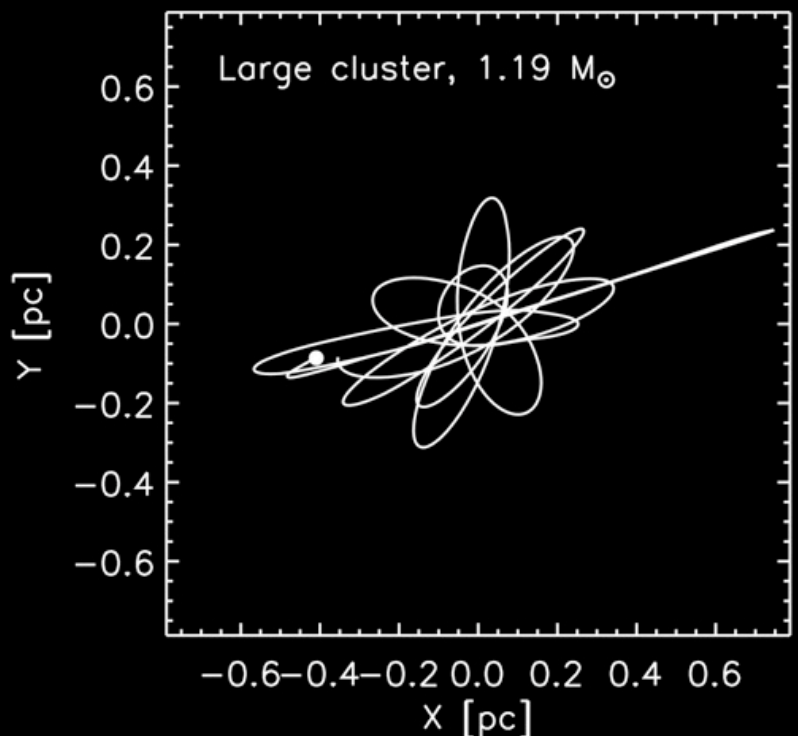
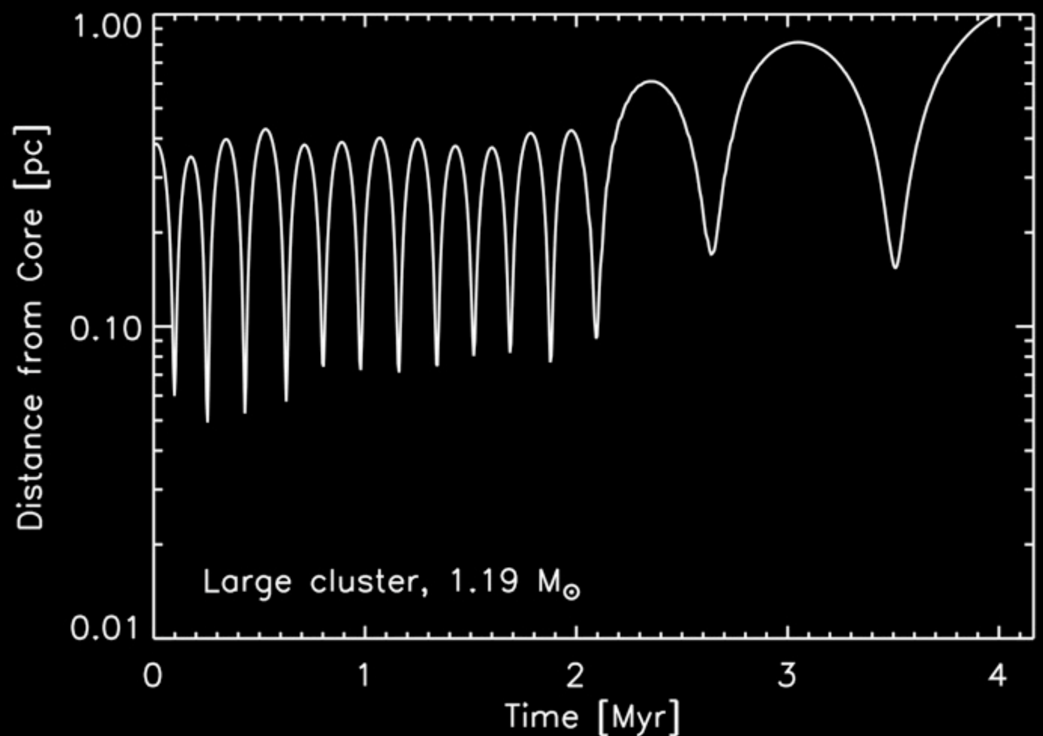
BH Accretion: History of individual star





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

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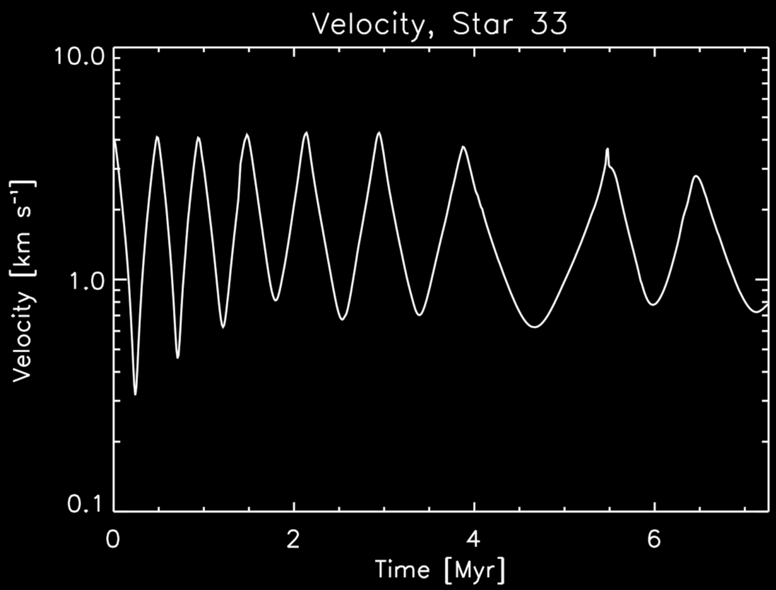
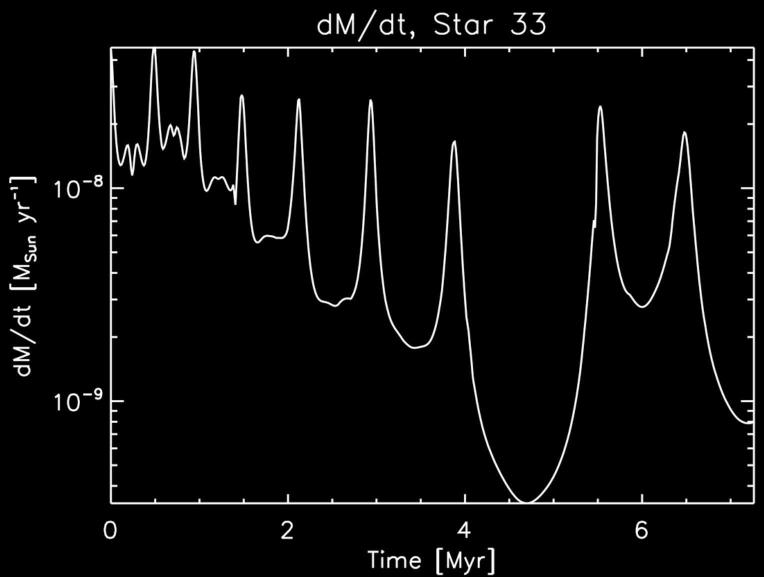
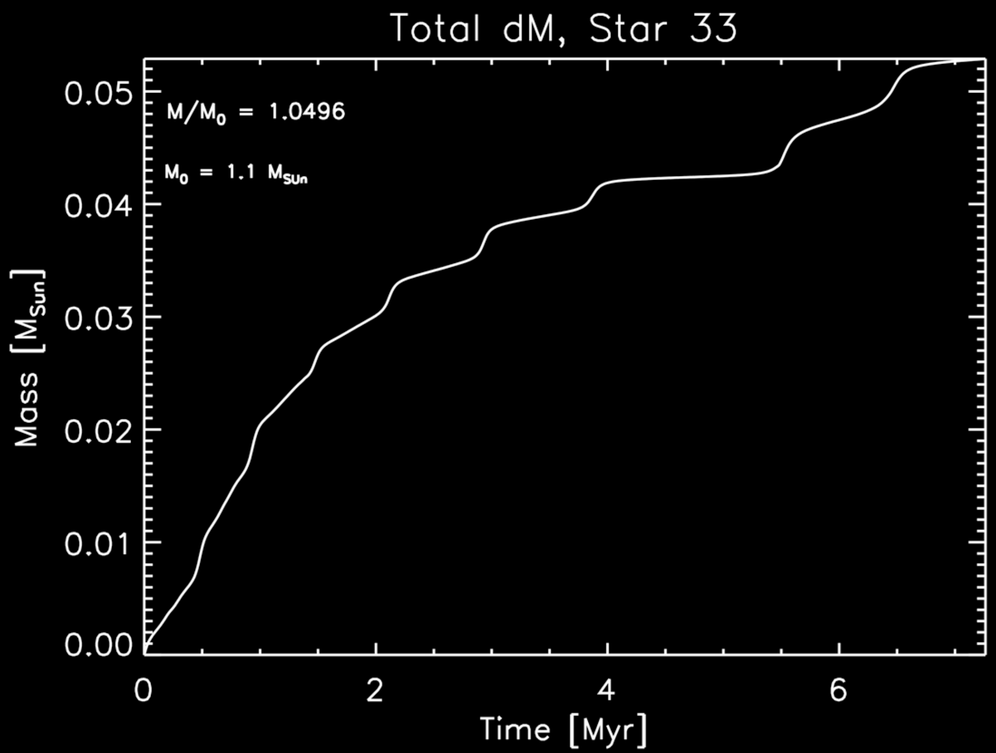


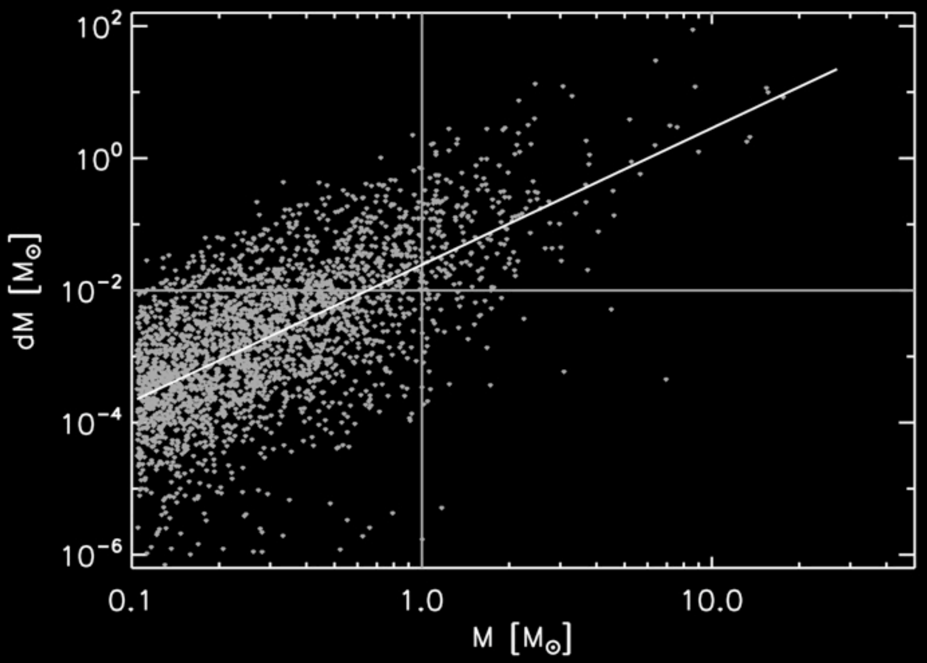




- Star+disk accretes 5% of own mass in 5 Myr.
- Accretion is episodic
  - Highest at core: High velocity but high density

Observations of accretion in young stars

- Accretion rates scales as dM ~ M^2
- Accretion is ~ 0.01 $M_\odot$ Myr^{-1} (i.e., one disk mass per Myr)
- Accretion rate is indep. of cluster size: small N -> small n, v
- This M^2 relationship is *observed* in many, many young disks (e.g., Natta et al 2006, Muzerolle 2003, etc.)
- There is no accepted physical explanation for this relationship.
  - BH explains magnitude, exponent, and scatter of observations.



Ensemble of accretion rates for 3000 stars in our N-body simulations, one point per star.

Simulation runs for 5 Myr.

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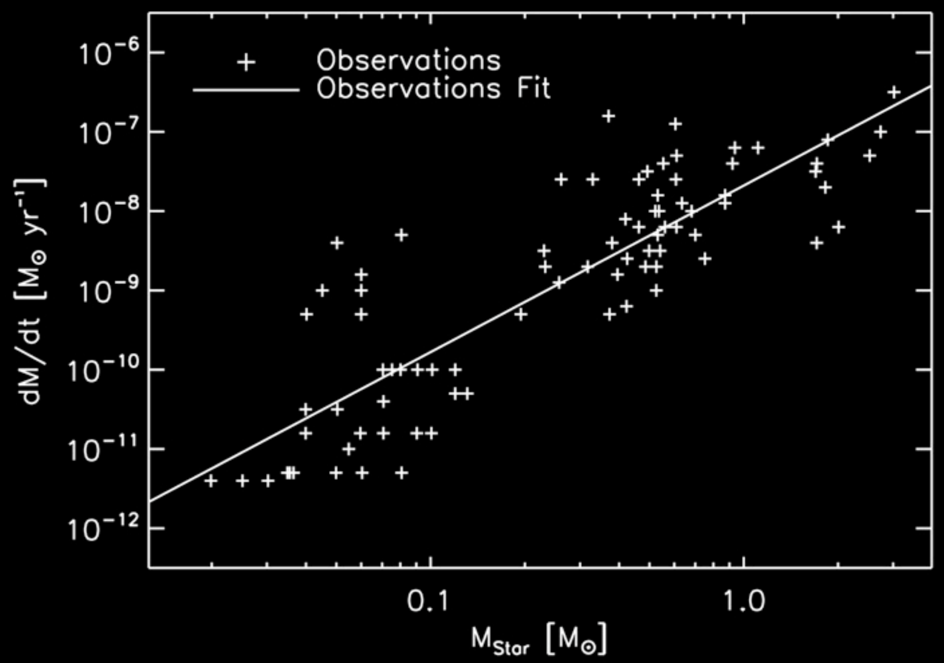

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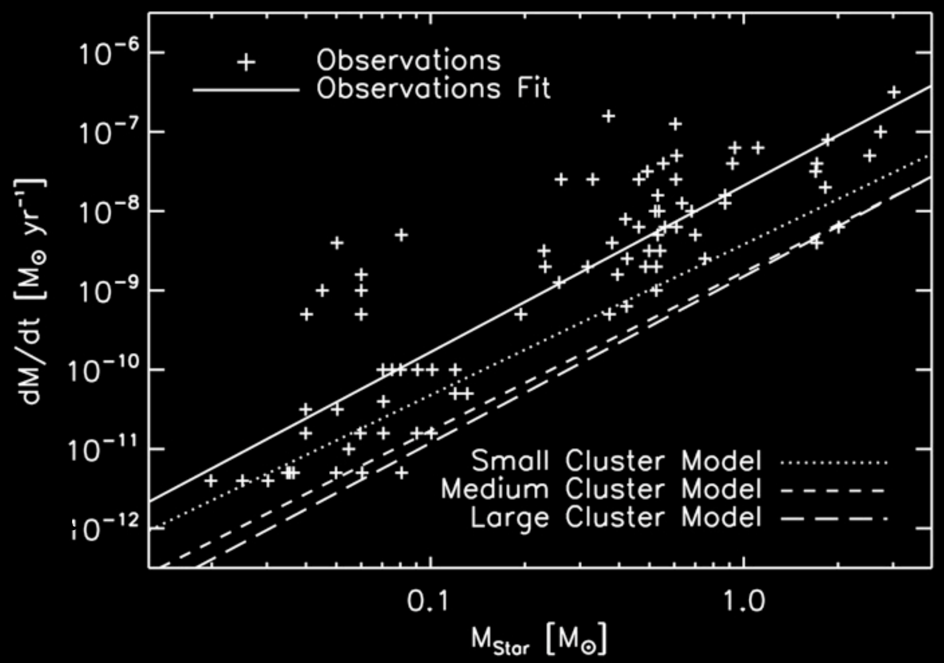

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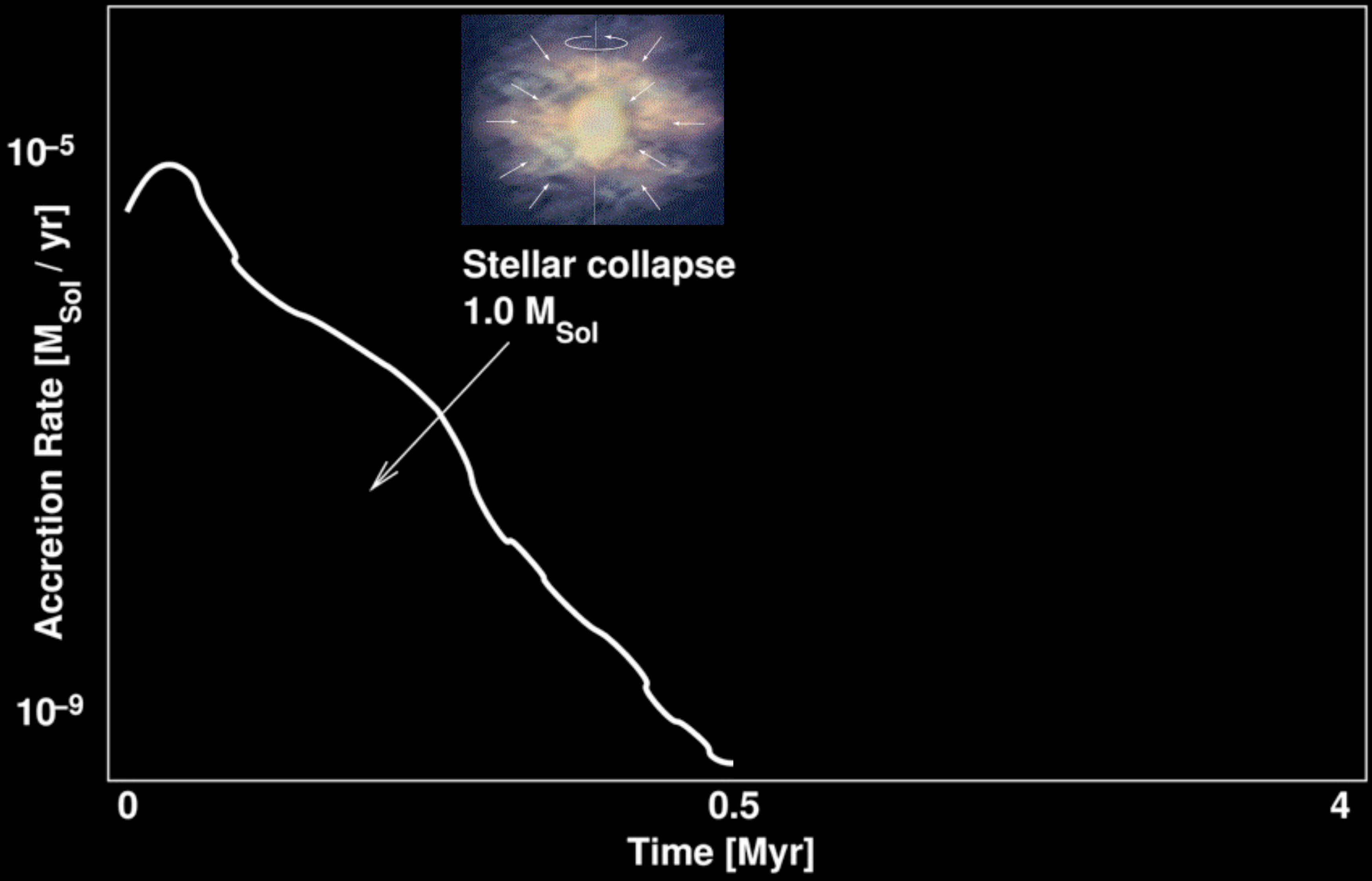
Timescale of Star Formation



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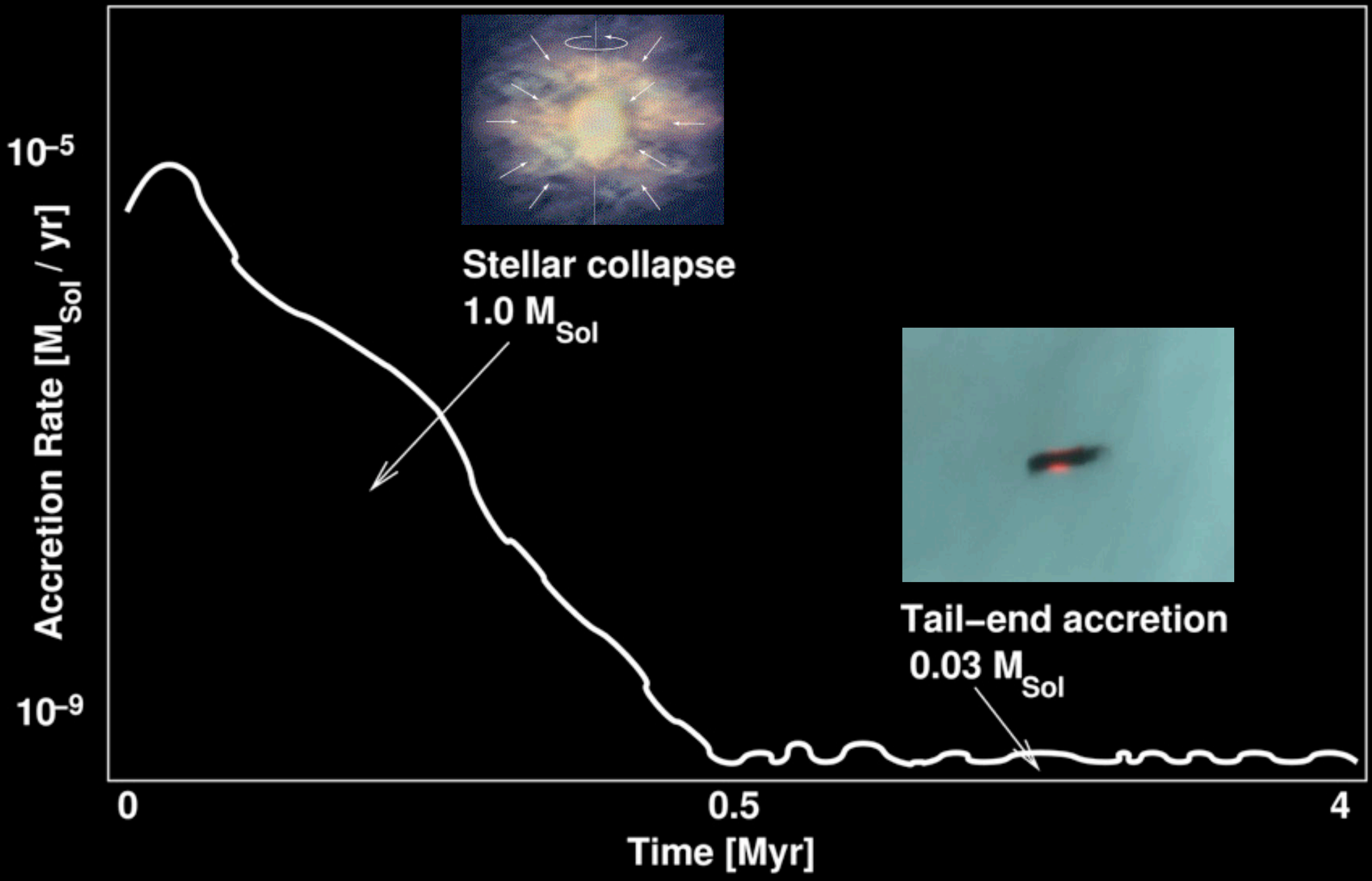


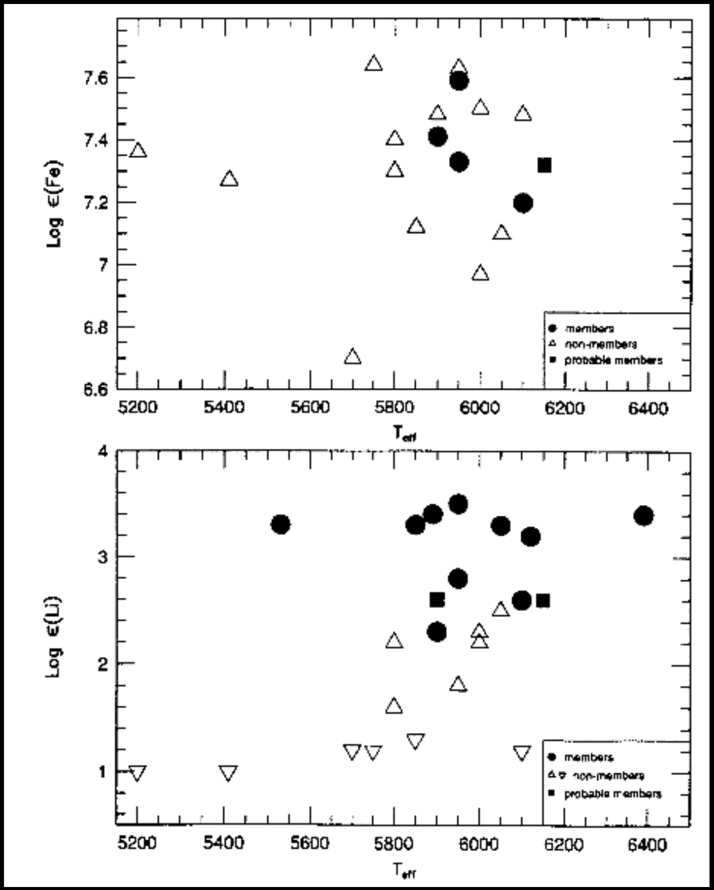
Effect of 'Tail-End Accretion' on Disk

- Typical $1M_{Sun}$ star-disk system accretes 5% of its mass
  - Mass increase is inconsequential for the star

    … but is of huge importance to the disk!
- $R_{BH} \sim 1000$ AU; $R_{disk} \sim 100$ AU; $R_{star} \sim 0.01$ AU
  - Most mass probably impacts disk, not star
- Where does the mass end up?
- Where does the angular momentum end up?

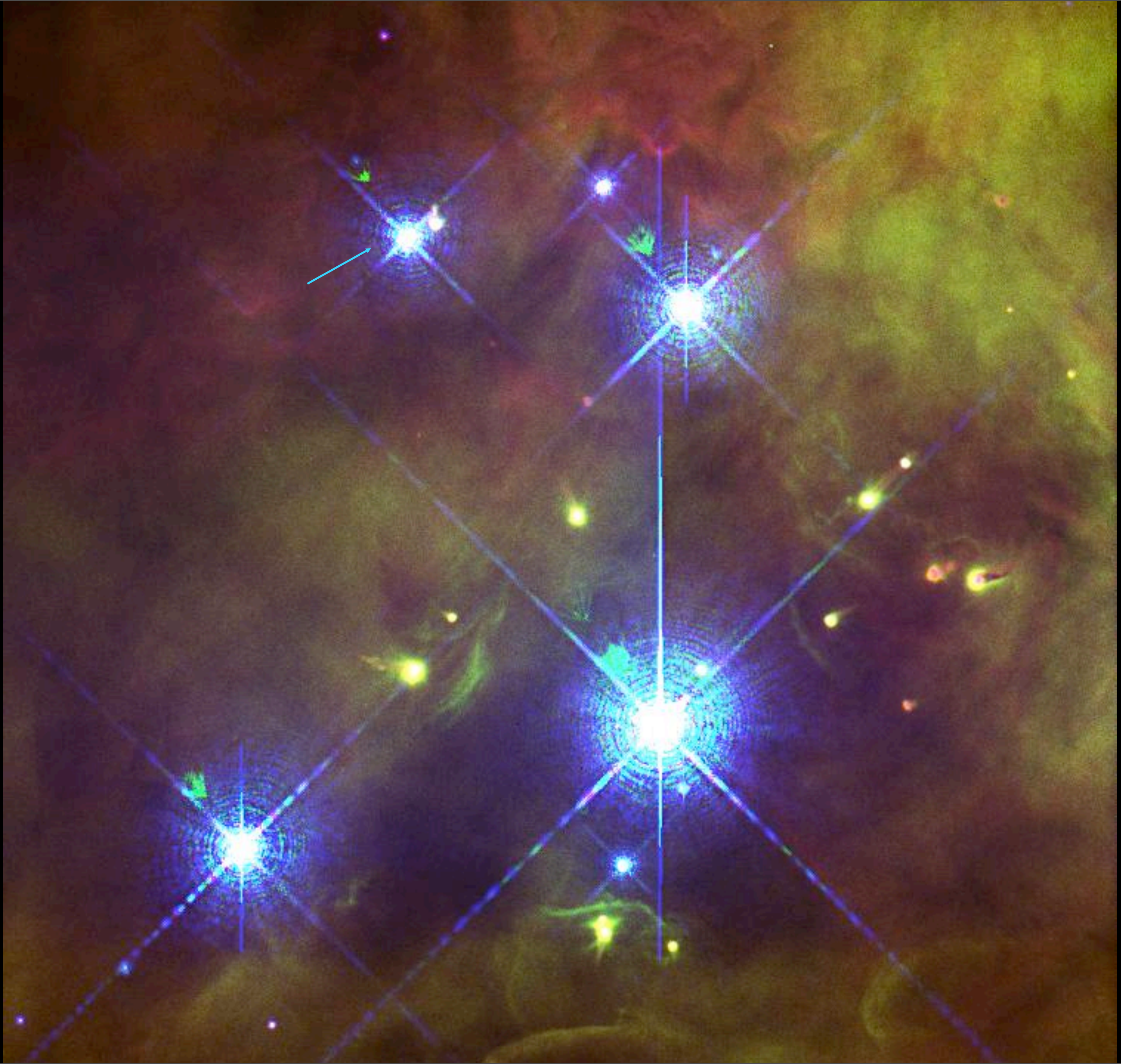
Consequences of BH accretion

- Late accretion of metallic 'veneers' could cause variation in stellar metallicity in single cluster (e.g., Cunha et al 1998, Orion)
  - BH accretion address this problem: multiple reservoirs of material from different regions of parent cloud
  - Parent cloud contaminated by SN ejecta and/or gas:dust variations



Evidence for BH Accretion on our young Solar System?

- Heterogeneity of Solar System
  - Some evidence suggests suggests that SS was not made from one homogeneous cloud core.
    - Unexplained differences in isotopes exist between Sun, Earth, Mars, meteorites
      - Cl isotopes (Sharp 2007)
      - O isotopes (Clayton 1973)
    - Unsolved 3:1 metallicity difference between Sun, Jupiter atmosphere?
      - Chemical condensation & processing have difficulty explaining Jupiter's composition
    - SN evidence (60Fe) already shows that SS cloud was not all the same!
- Ongoing BH accretion to disk changes timing of formation of Solar System
  - Long-lived availability of gas to form Jupiter
  - Total mass delivered to disk may exceed its original mass
  - Episodic gas in disk may aid in 'parking' hot Jupiters



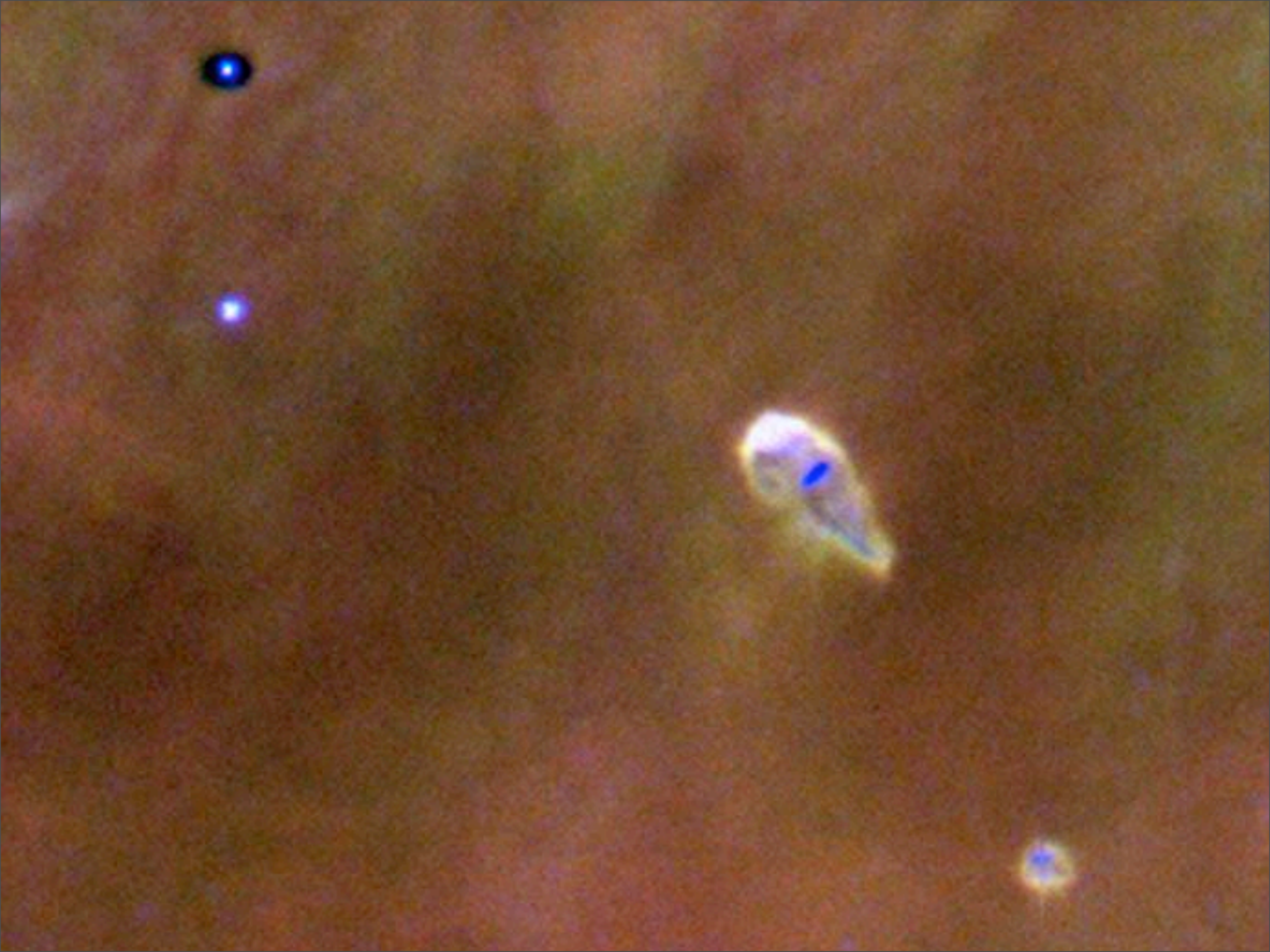


Photo-Evaporation in Orion

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

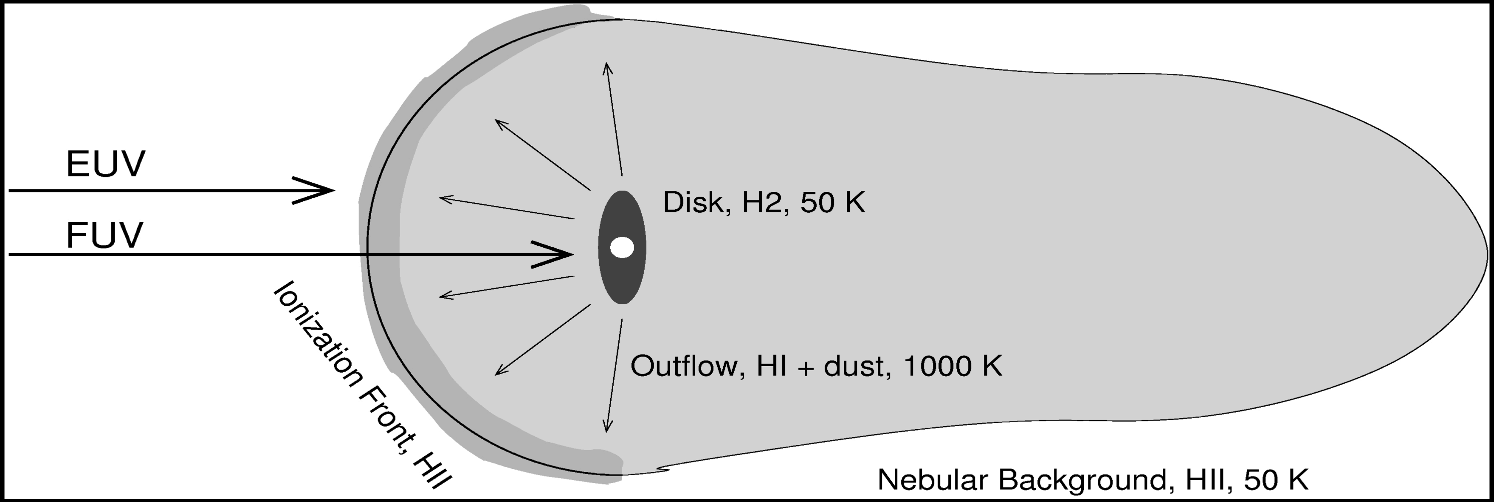
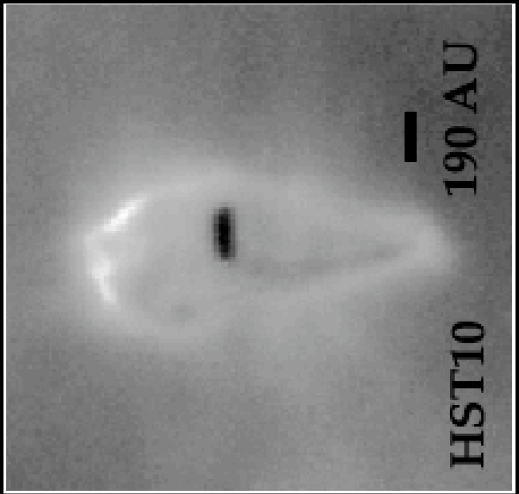


Photo-Evaporation and young Solar Systems

- UV flux from O stars heats and removes H and small dust grains from disks.
- Mass loss rates remove disk in < 1-10 Myr.
- MMSN disks surrounding most Orion stars can be truncated to a few AU in Myr.
  - Dust in disks can be retained: sharp outer edge with large grains
- **Giant Planets**: Gas is rapidly removed from disk at 5 AU: If you want to build Jupiters in Orion, do it quickly !
- **Kuiper Belt**: UV removes volatiles and small grains, and rapidly sputters surface.
- **Terrestrial Planets**: Safe from photo-evap due to deeper potential well at 1 AU.



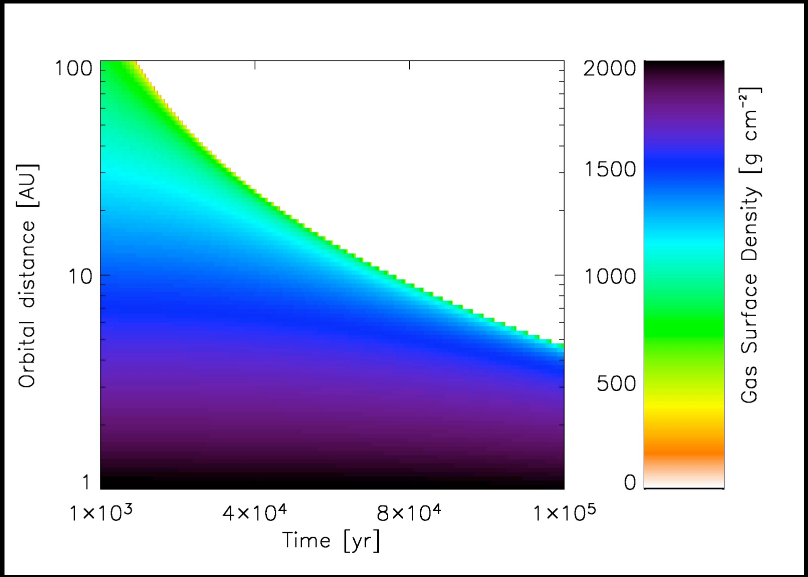


Photo-evaporation is a major hazard to planet formation…

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… but all hope is not yet lost!

Photo-Evaporation Triggered Instability

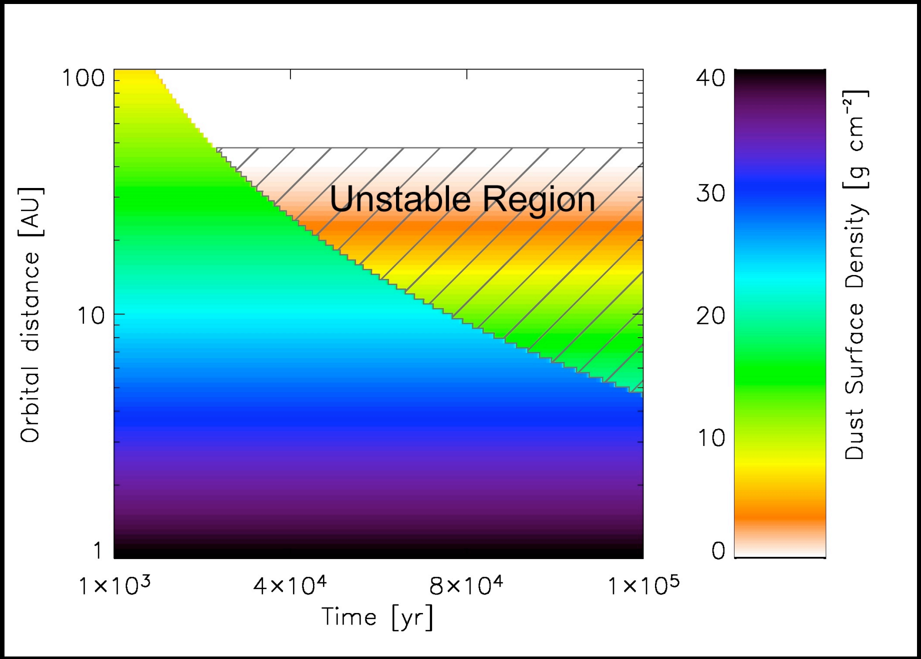
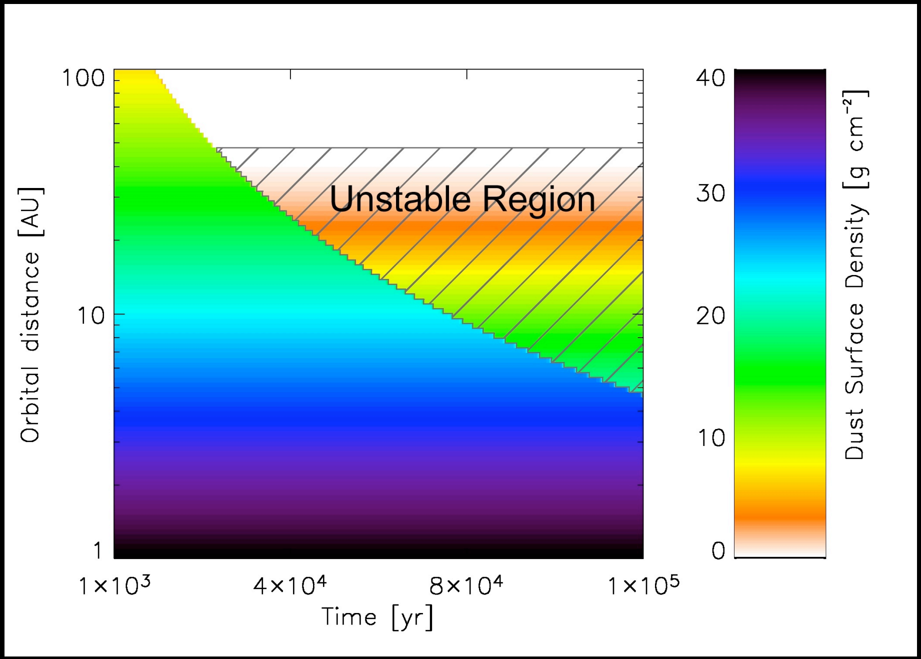


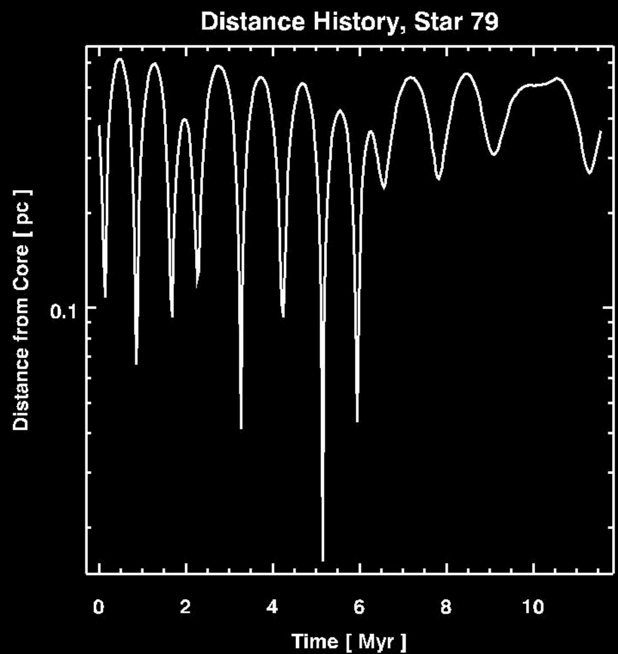
Photo-Evaporation Triggered Instability

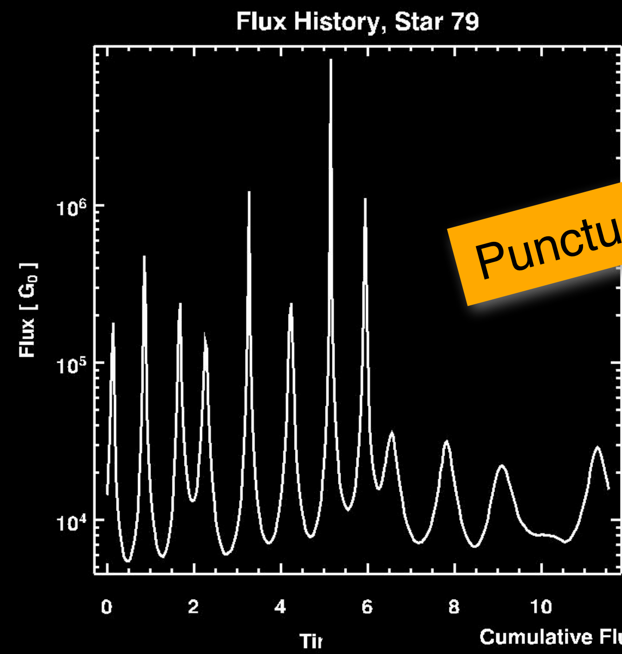
- Gravitational collapse of dust in disk can occur if sufficiently low gas:dust ratio:
  - Need to remove 90% of the gas, and **then** gravity can pull dust grains together.
- PE removes gas and leaves most dust
  - Grain growth and settling promote this further
- Dust disk collapse provides a rapid path to planetesimal formation, without requiring particle sticking.



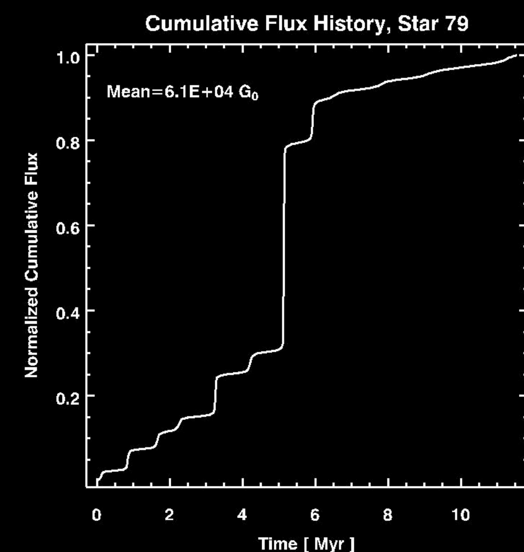
Throop & Bally 2005

Flux History, Typical 1 M_{sun} Star





Punctuated equilibrium

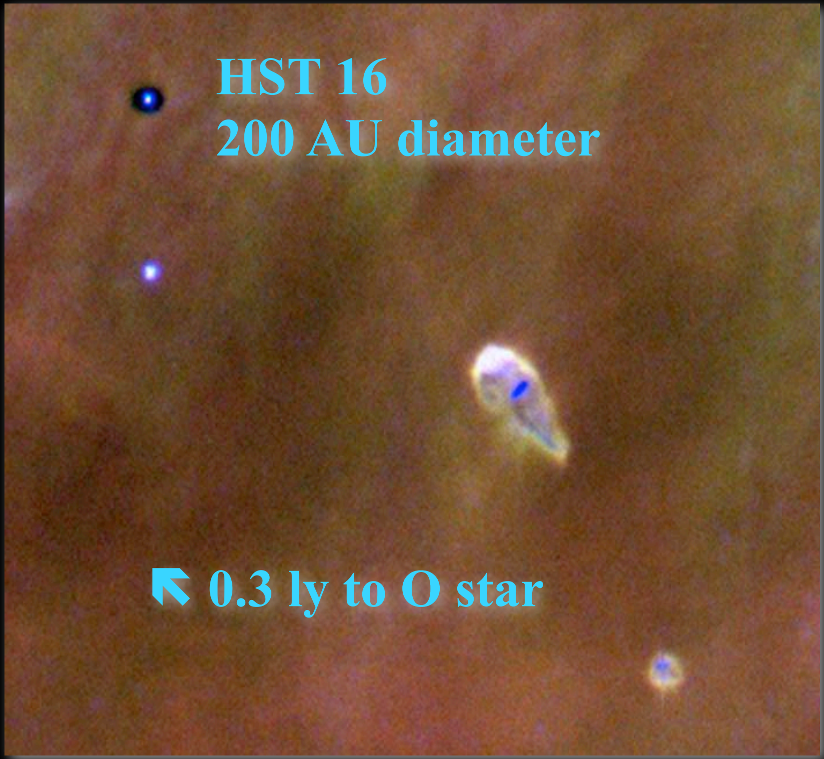


- Flux received by disk varies by 1000x as it moves through the GMC : ‘Broil-Freeze-Broil’
- Peak flux approaches 10^7 G_0.
- Most of the flux is deposited during brief but intense close encounters with core.
- There is no ‘typical UV flux.’
- Disk evolution models assume steady UV flux. But if PE is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

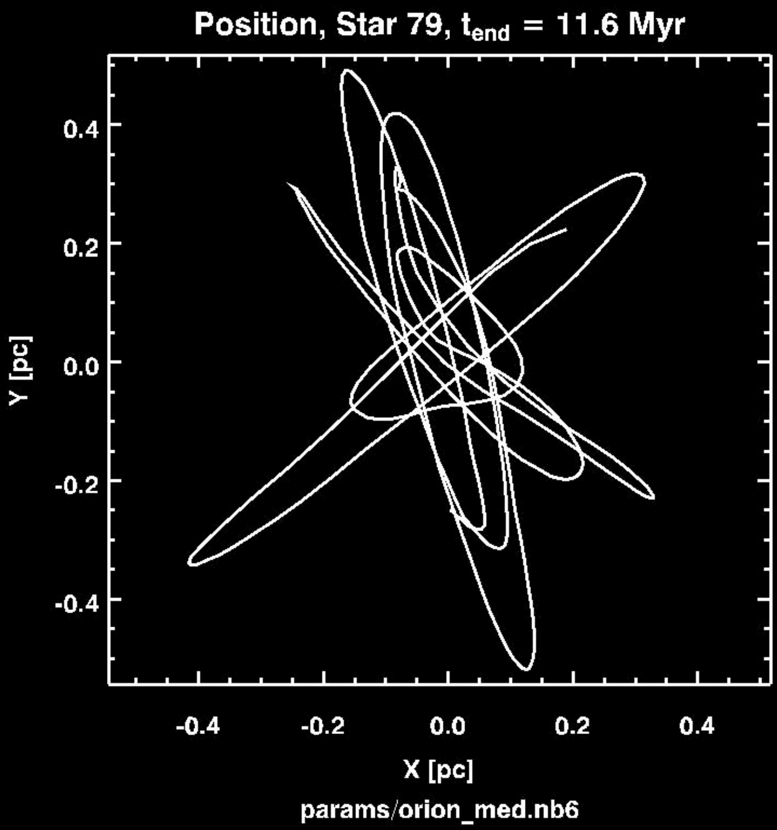
Throop & Bally, in prep

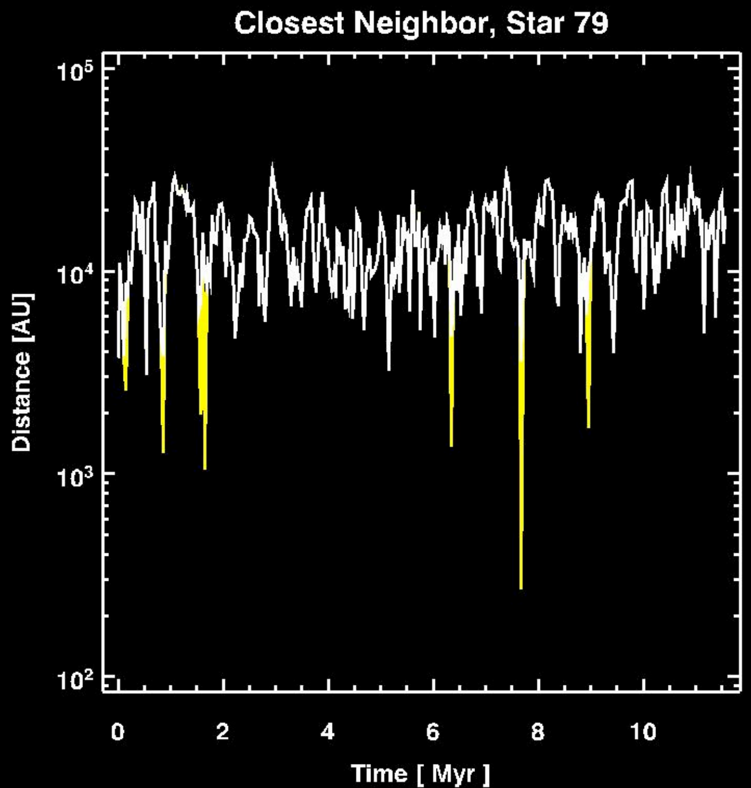
Close Approaches

- 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

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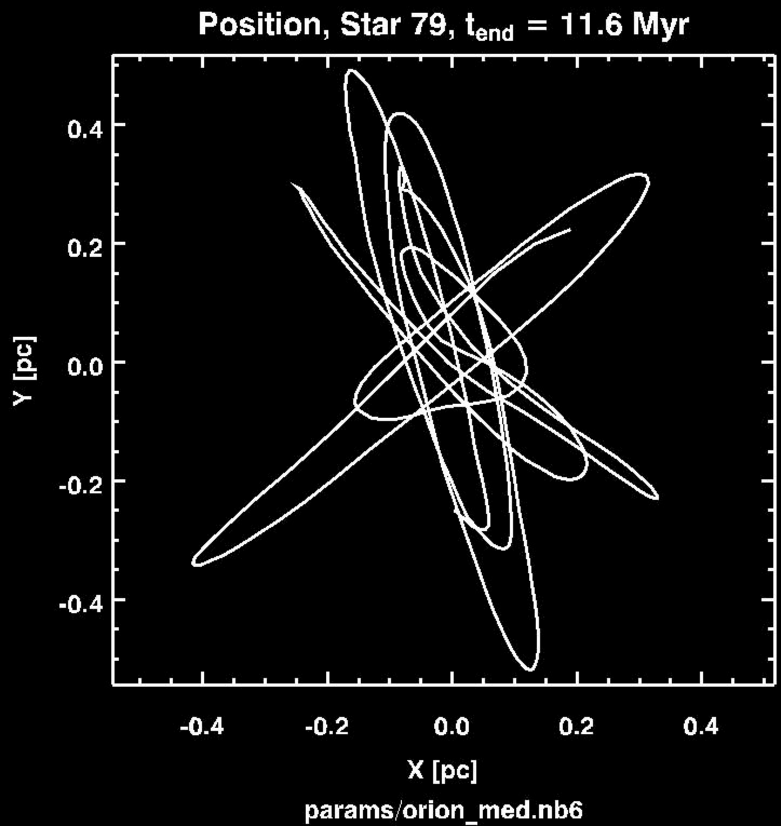

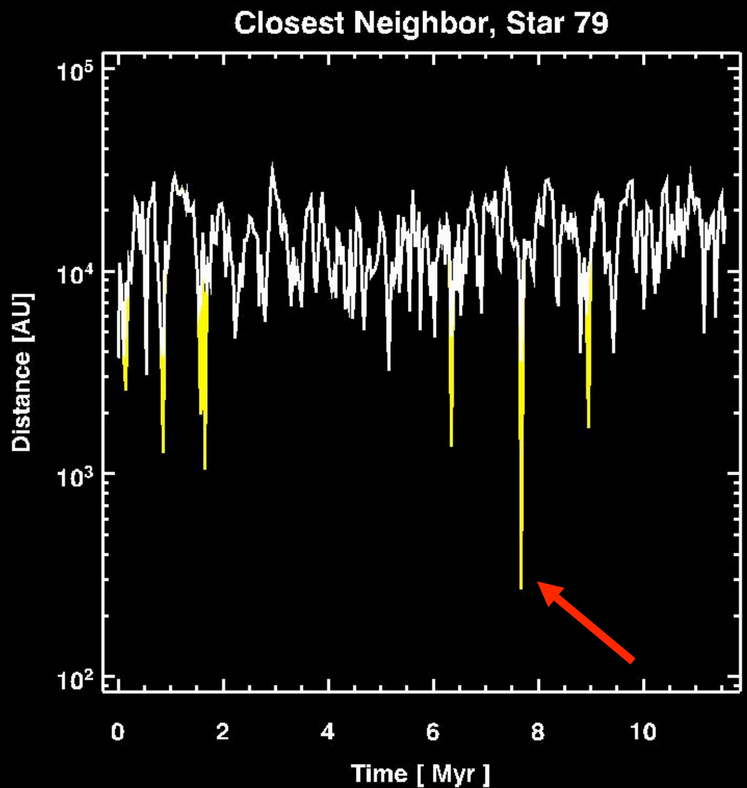

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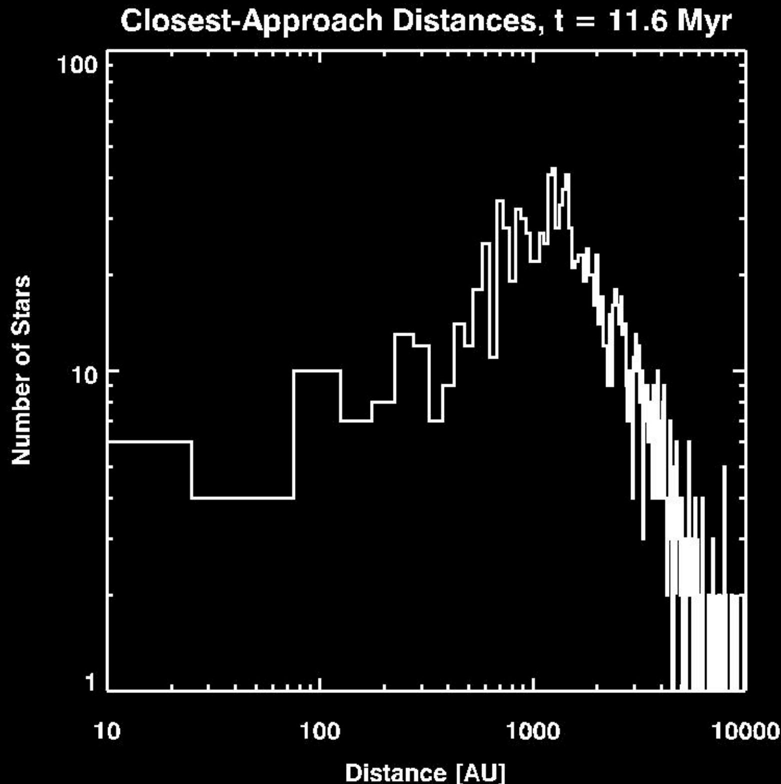
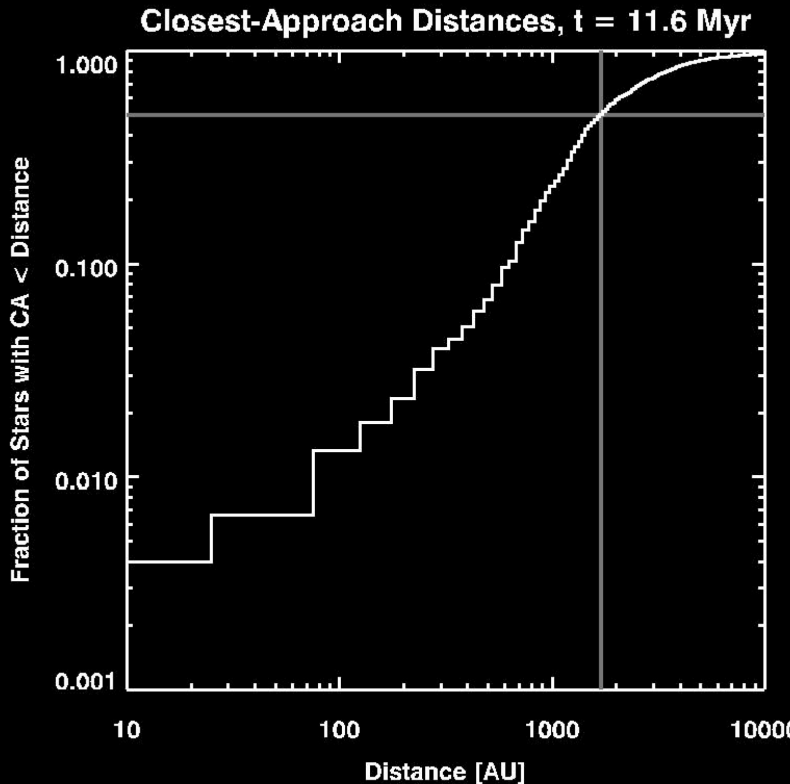
Close Approaches - Entire Cluster





- 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

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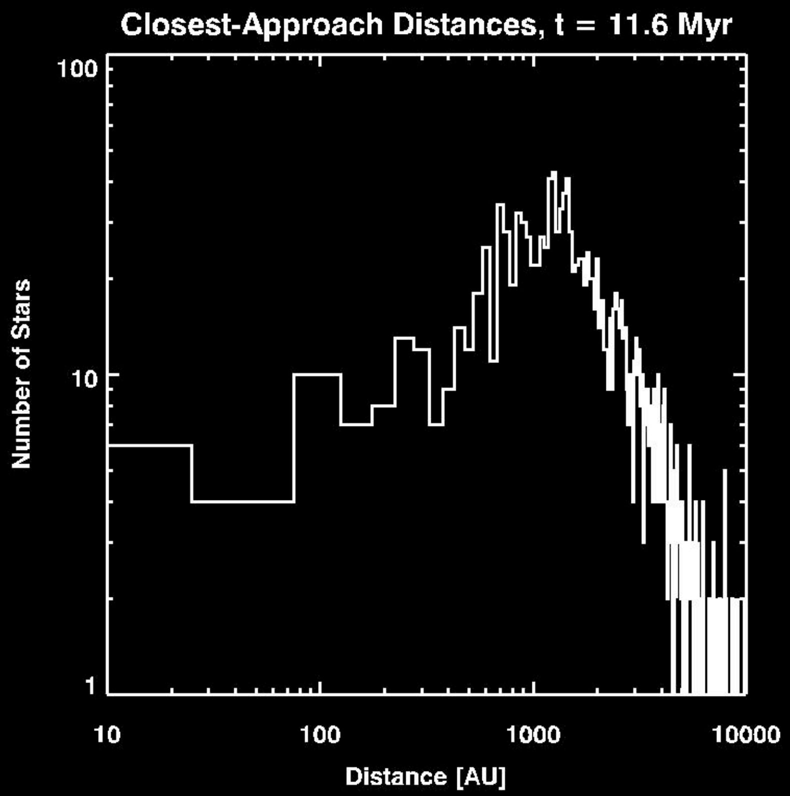

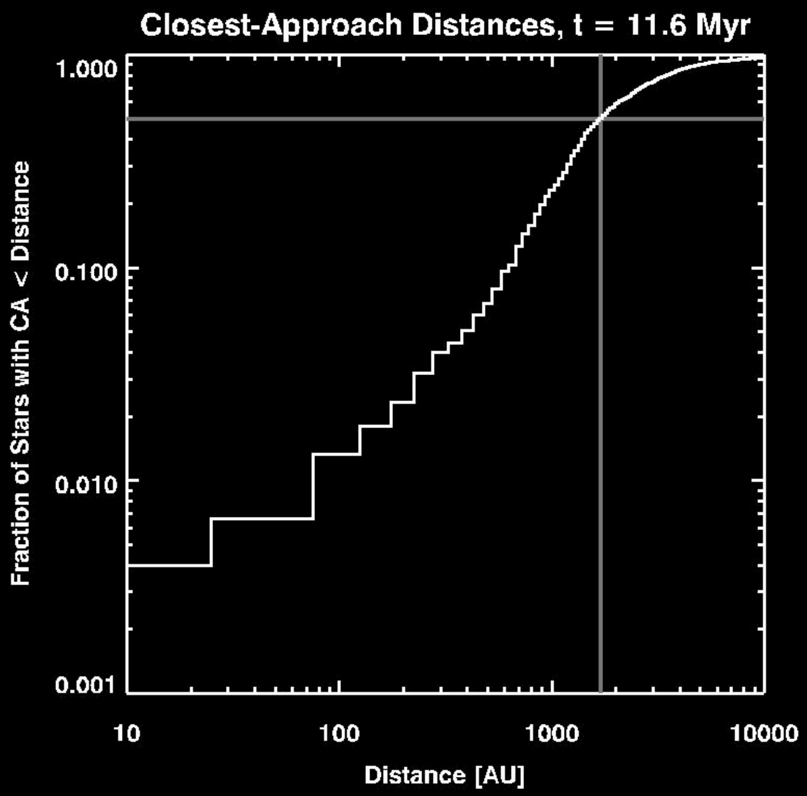

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Throop & Bally; also Adams et al 2006

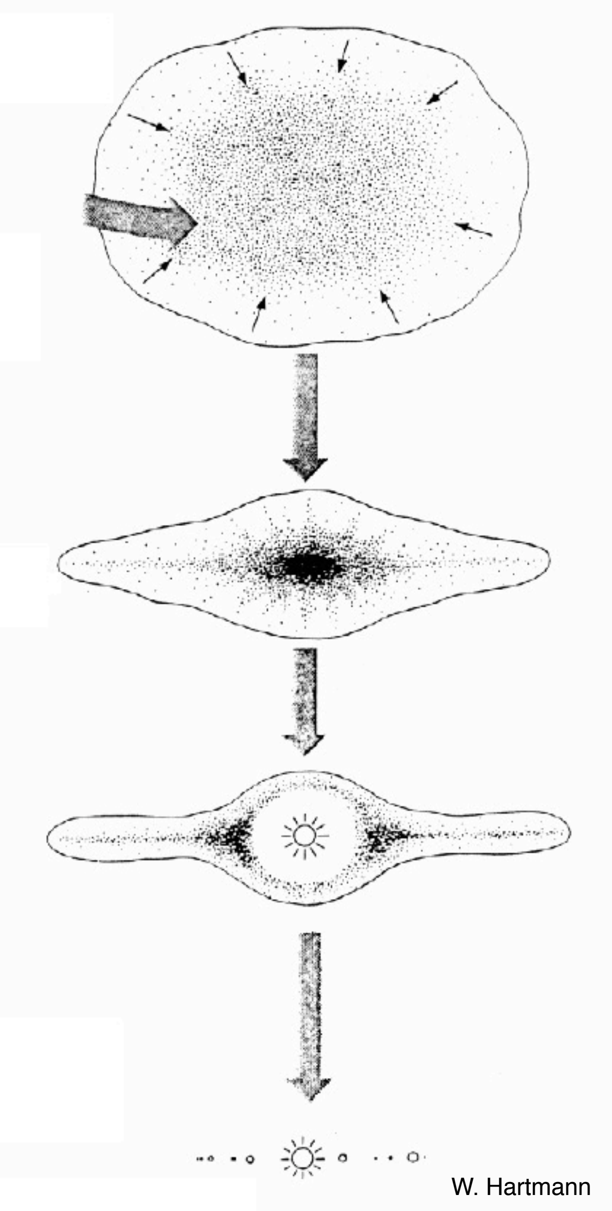
Planet Formation - Classical Model

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

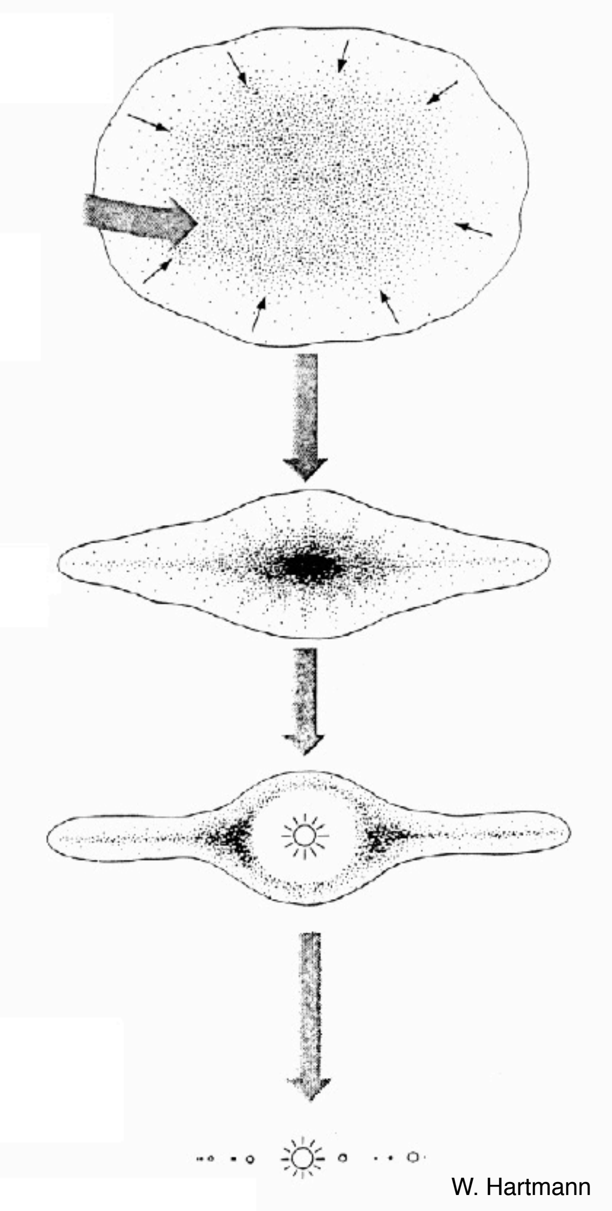
Disk disperses
SS formed after ~ 5-10 Myr



MODIFIED
Planet Formation - Classical Model

Cloud is heterogeneous and polluted
Cloud core collapses due to self-gravity
10,000 AU, 1 Msol
Cloud competes with other clouds

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
SS formed 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
  - Compositional difference between Jupiter, Sun
  - Isotopic anomalies in Solar System
  - **We need numerical simulations of accretion to understand where mass and angular momentum are deposited!**

- PE can rapidly destroy disks
  - Hard to make Jovian planets

- PE can also trigger rapid planetesimal formation
  - Easy to make planetary cores


The
End

What do we know?

- Large fraction of stars forming today are near OB associations, not in open clusters
- PE can rapidly destroy disks
  - Hard to make Jovian planets
- PE can also trigger rapid planetesimal formation
  - Easy to make planetary cores
- Close encounters are unimportant

Where do we go?

- Need better understanding of effect of time-variable PE on disk evolution
- Need better understanding of role of gravitational instabilities: how frequent is it?
- UV, X-ray chemistry in dense clusters unexplored

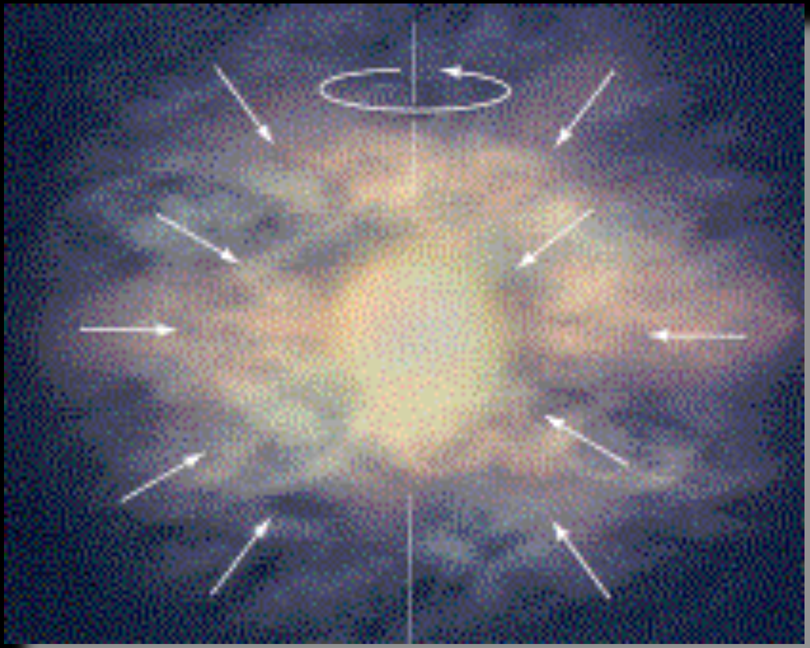
Conclusions

- Consequences of planet formation in dense star cluster:
  - UV: 10^3x time-variability: ‘broil, then freeze’
    - 90% of flux deposited during 10% of the time
    - Photo-evaporation can sometimes speed planetesimal formation
  - Close encounters: not important
    - Typical interstellar C/A distance of 1000 AU in 5 Myr
  - Post-formation BH accretion
    - Typical accretion rates 10-8 msun/yr
    - Typical disk may process its own mass in several Myr.
      - SS formation models have not included this.
      - Only minimal modeling of accretion process onto star-disk has been done.

Orion Nebula

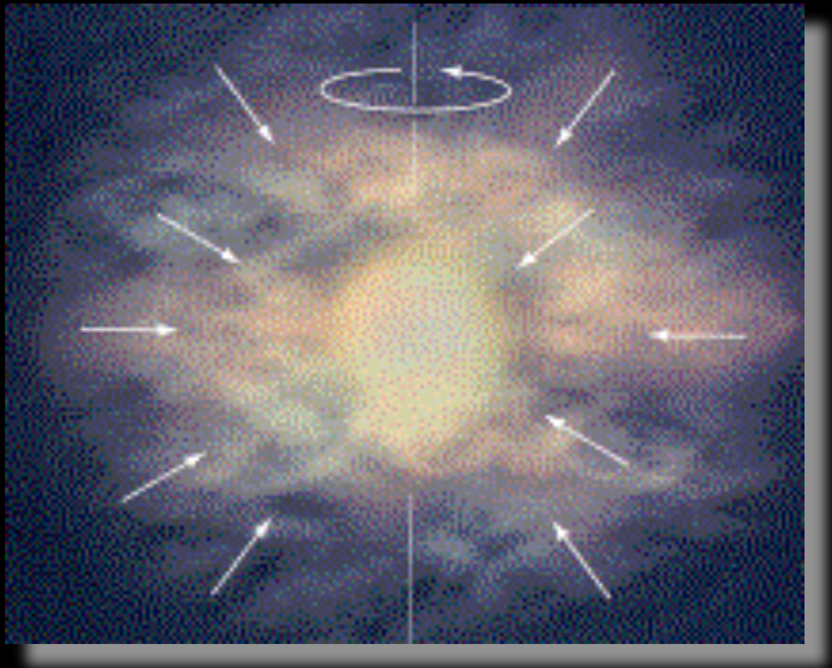
HST Cycle 4

Where Do Most Stars Form?



Where Do Most Stars Form?

- Mass range of molecular clouds: few $M_\odot$ – 10^6 $M_\odot$
- Mass spectrum of molecular clouds: $dn/dM \sim M^{-1.6}$



Where Do Most Stars Form?

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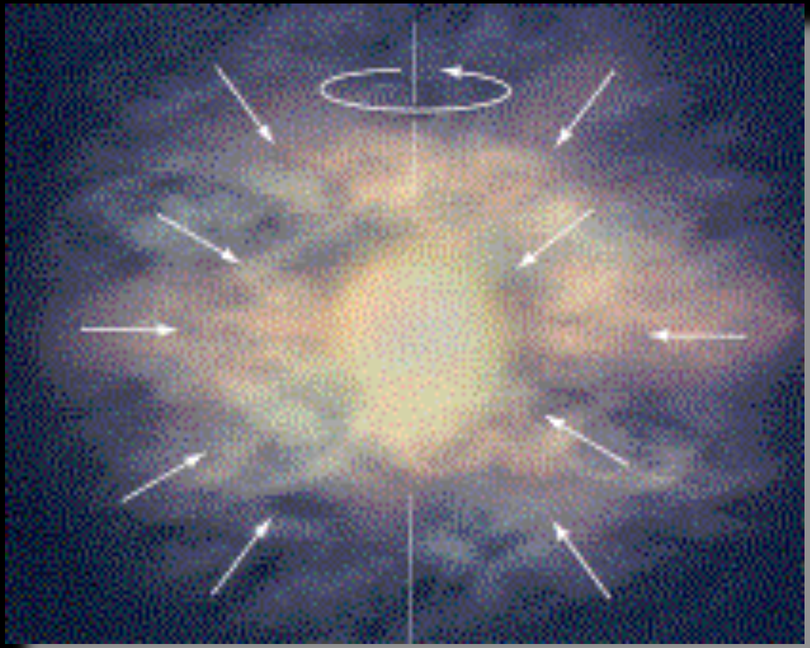
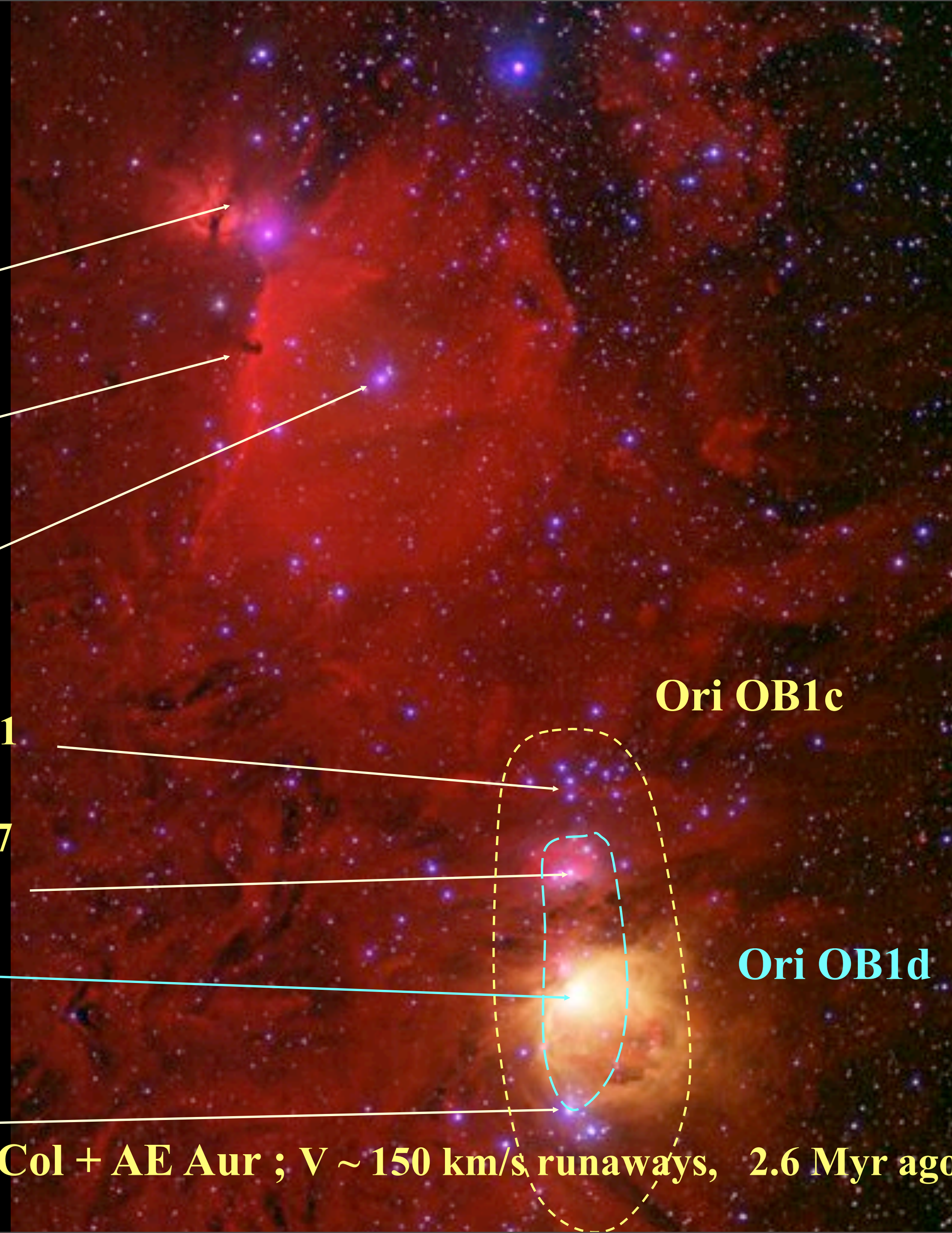
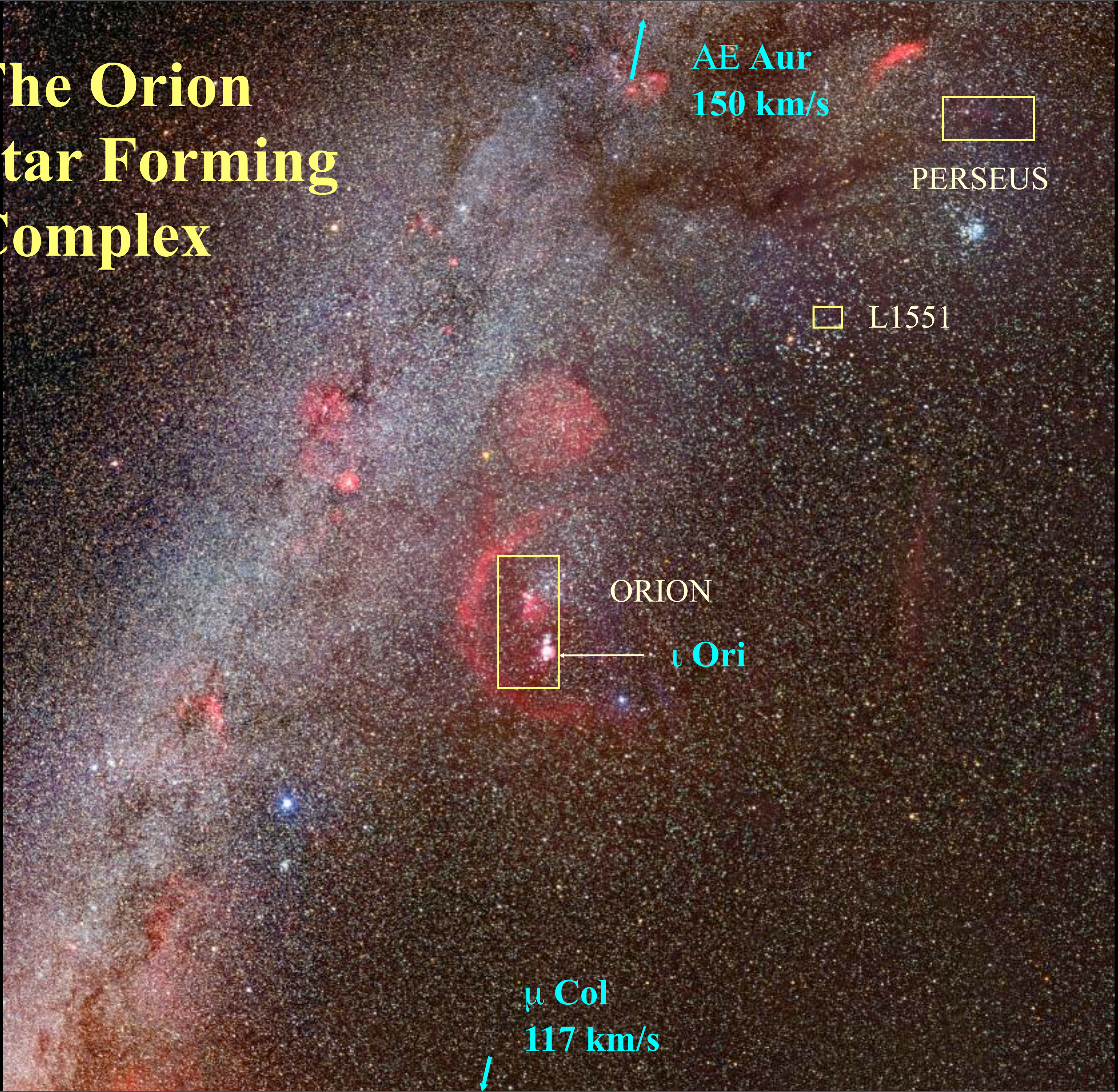
➔ Most of the mass is in the largest GMCs



Orion below the Belt:



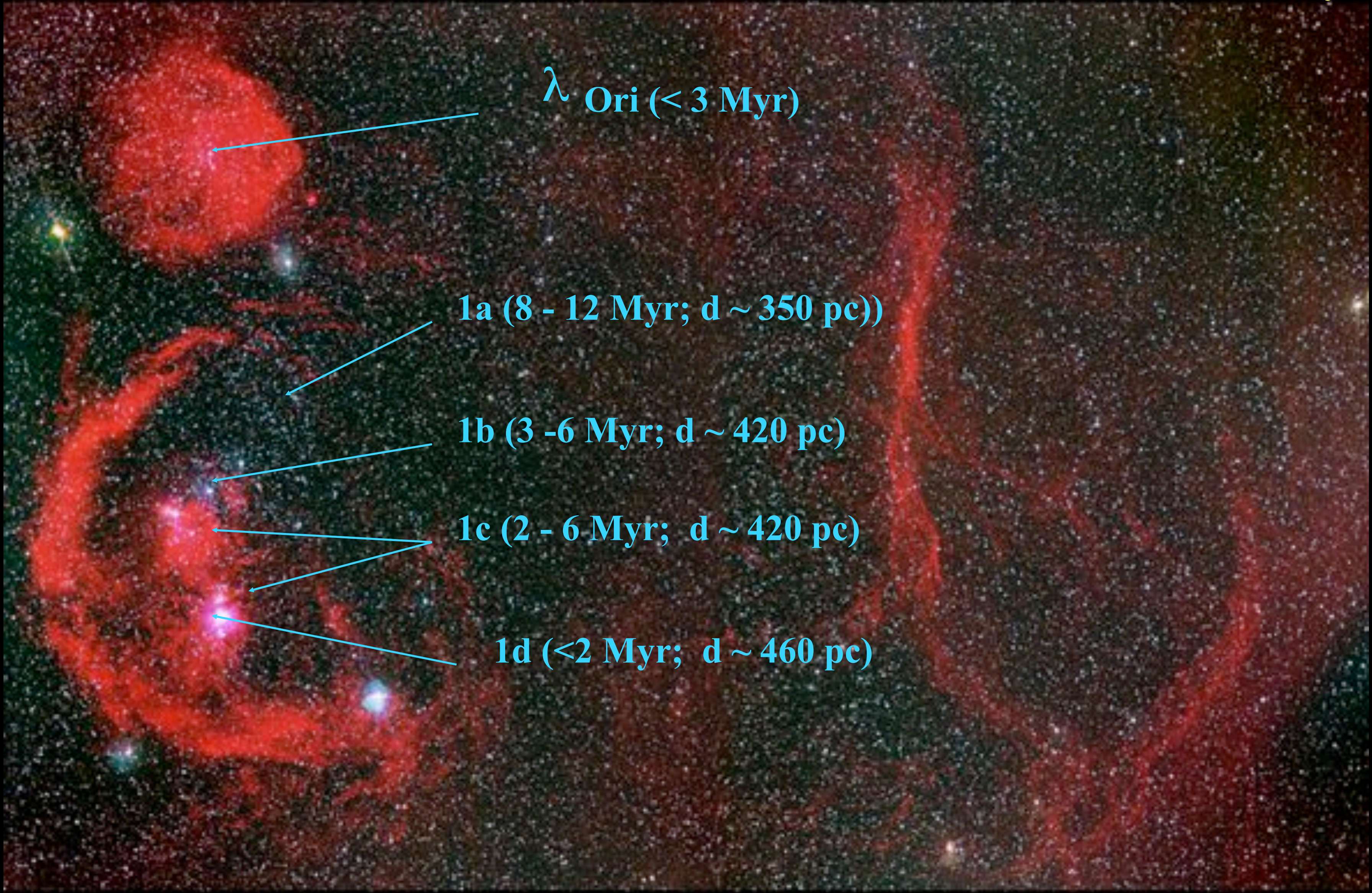
The Orion Star Forming Complex



Wei-Hao Wang

The Orion/Eridanus Bubble (Hα): d=180 to 500pc; l > 300 pc

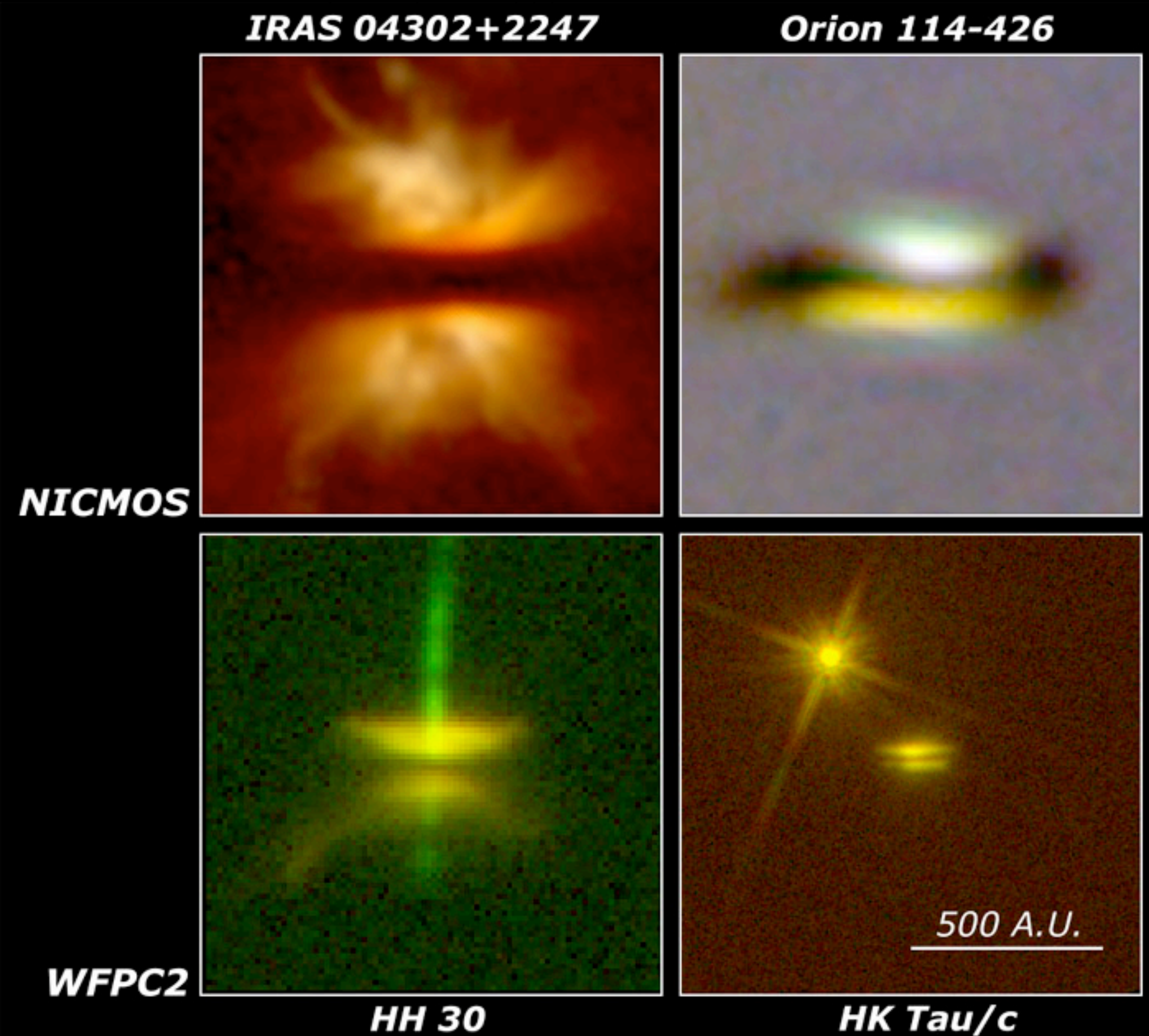
Orion OB1 Association: ~40 > 8 M stars: ~20 SN in 10 Myr



Barnards's Loop

Eridanus Loop

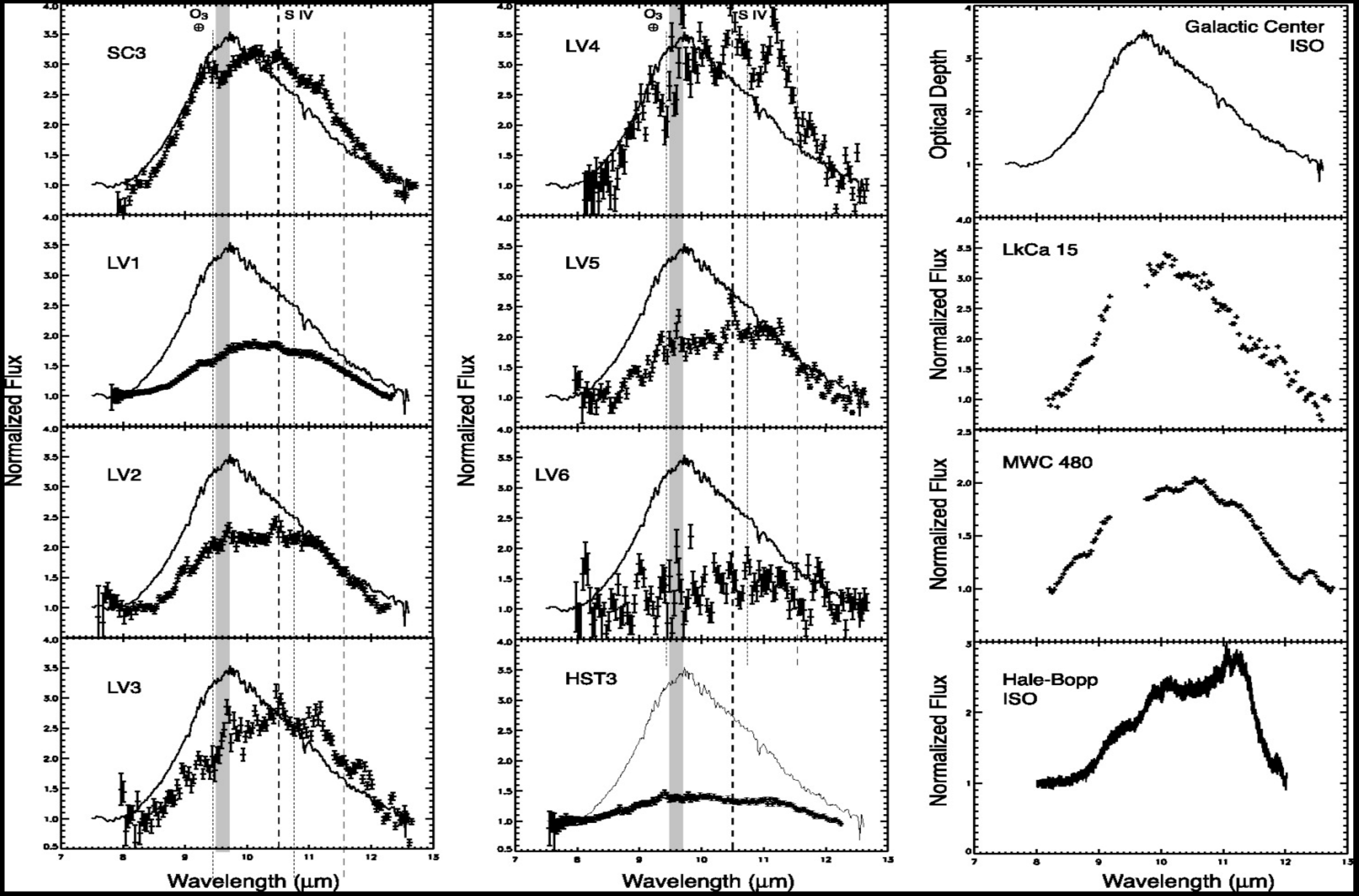
Taurus disks & jets: Stapelfeldt et al.

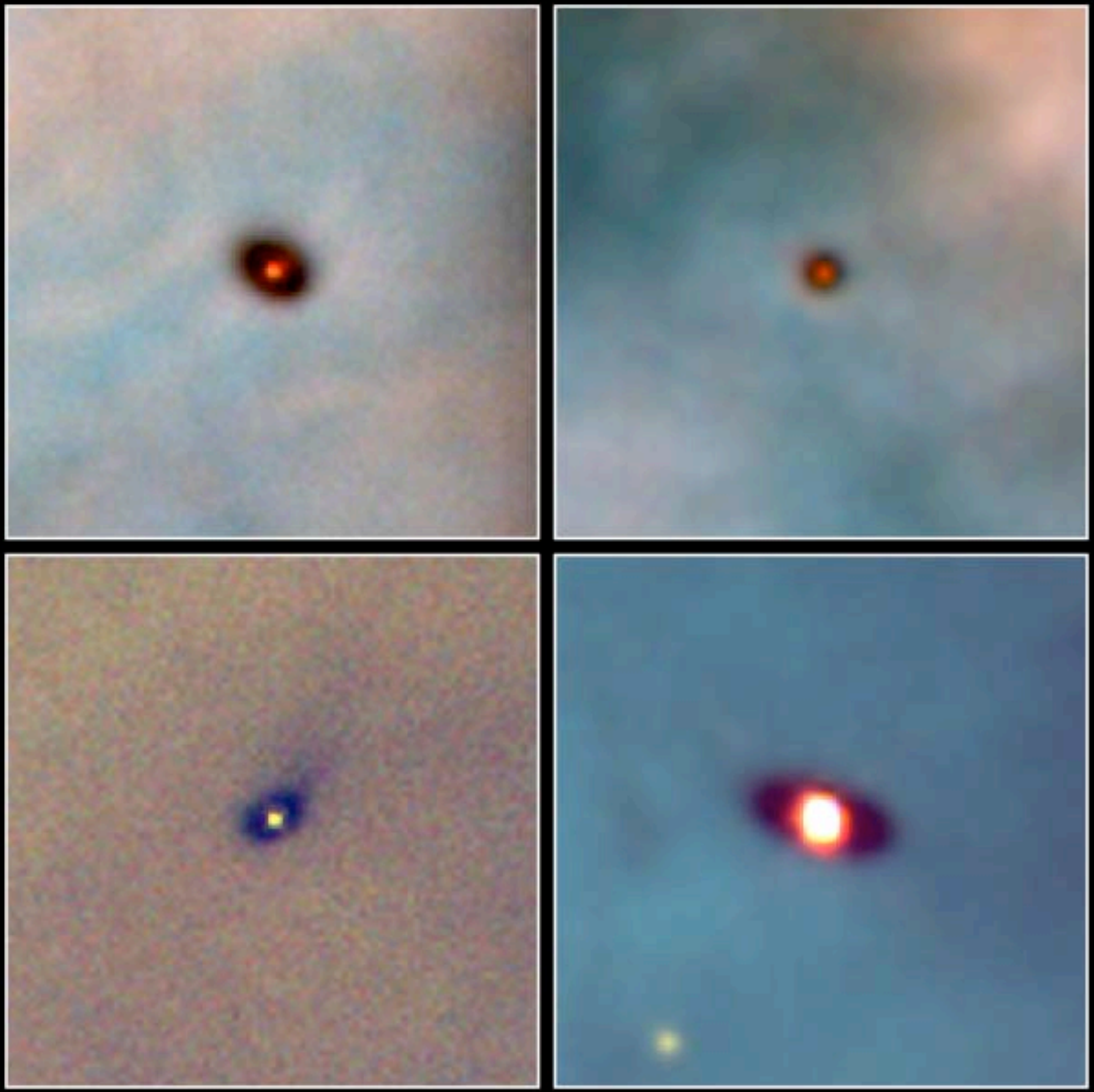


NGC 3603: 50 massive stars + 10^4 low mass stars

VLT + adaptive optics: 1.2, 1.6, 2.2 μm)

Growing grains: Si 10 μm feature (Shuping et al. 2006)

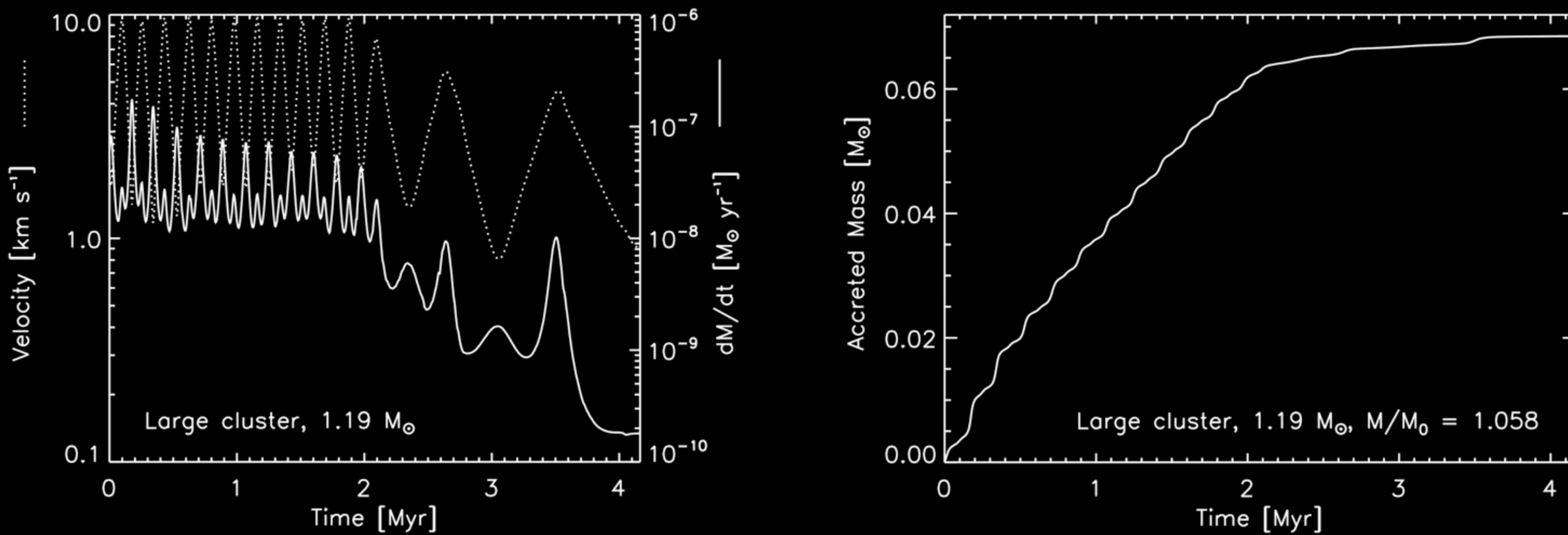




Protoplanetary Disks
Orion Nebula

HST • WFPC2

PRC95-45b • ST ScI OPO • November 20, 1995
M. J. McCaughrean (MPIA), C. R. O'Dell (Rice University), NASA

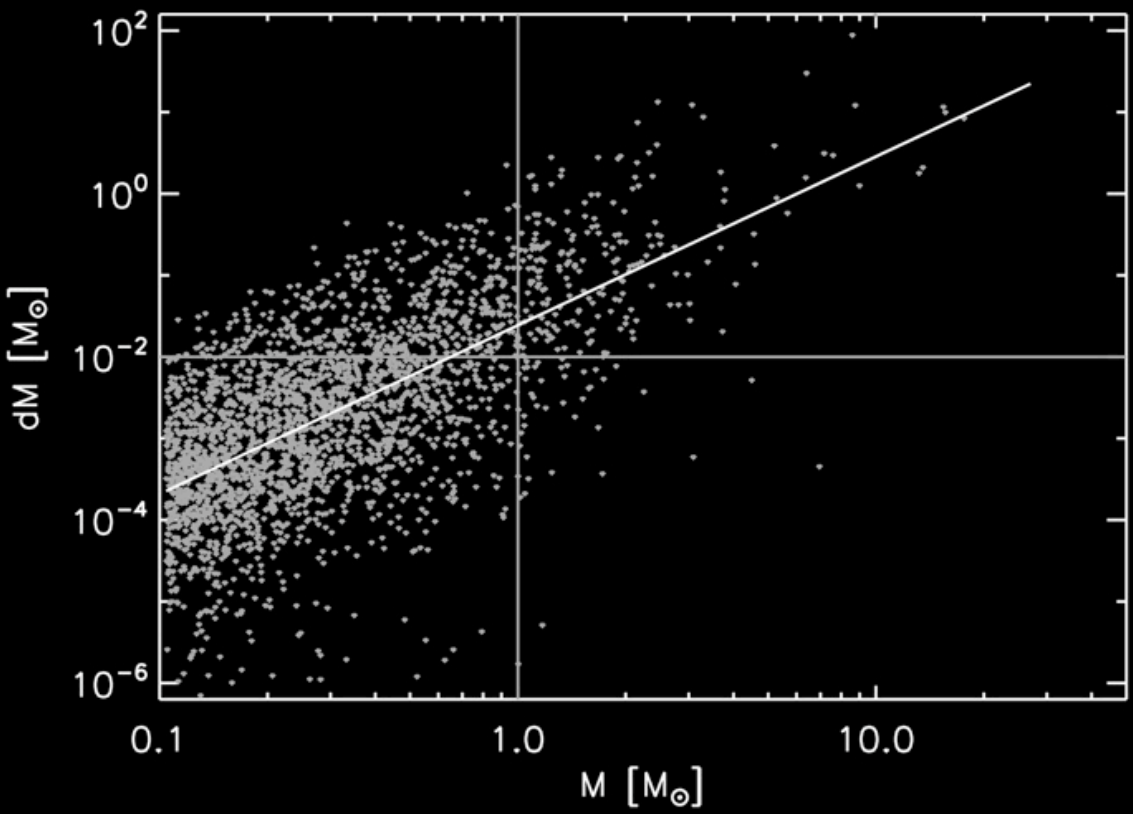


10.0
1.0
0.1
10^-6
10^-7
10^-8
10^-9
10^-10
Velocity [km s^-1]
dM/dt [M⊙ yr^-1]
Large cluster, 1.19 M⊙
0
1
2
3
4
Time [Myr]
0.06
0.04
0.02
0.00
Accreted Mass [M⊙]
Large cluster, 1.19 M⊙, M/M0 = 1.058
Time [Myr]

Case II: Star Formation in Dense Clusters

- N=10^3-10^4+ stars, made from the collapse of a giant cloud
- Low-mass stars near massive O & B stars ('OB associations')
- Region is bright and dense.
  - *Bright* - 10^5x brighter in UV than region near Sun today!
    - UV radiation **photo-evaporates disks**, removing them from stars
    - UV radiation **photolyzes ices** into complex molecules
  - *Dense* - 5000 AU separation between stars!
    - Close encounters between stars can **strip disks**.
    - Gas in cloud can continue to accrete onto star after formation
- Dense clusters are infrequent and distant… but they are huge!
- Observational surveys find that most stars (~90%) form in these dense clusters, not small clusters like Taurus.
- Orion is the best-studied example

N-Body Results



Ensemble of accretion rates for 3000 stars in our N-body simulations, one point per star.

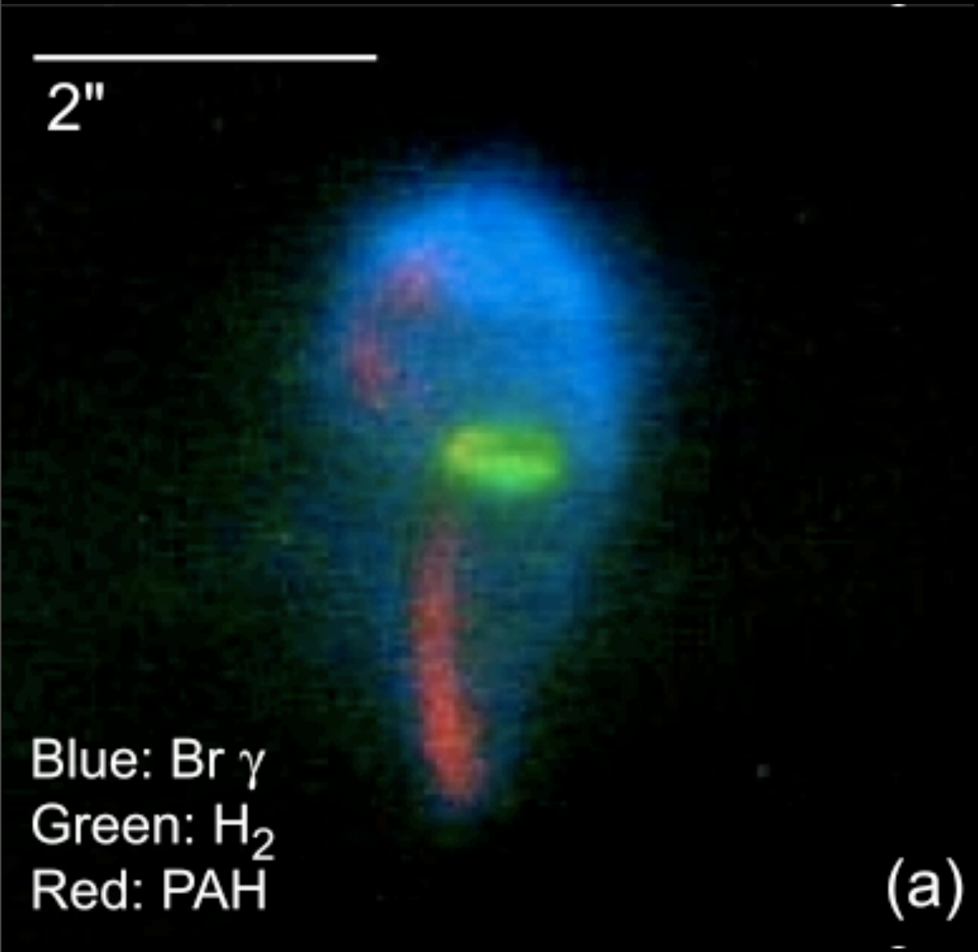
Simulation runs for 5 Myr.

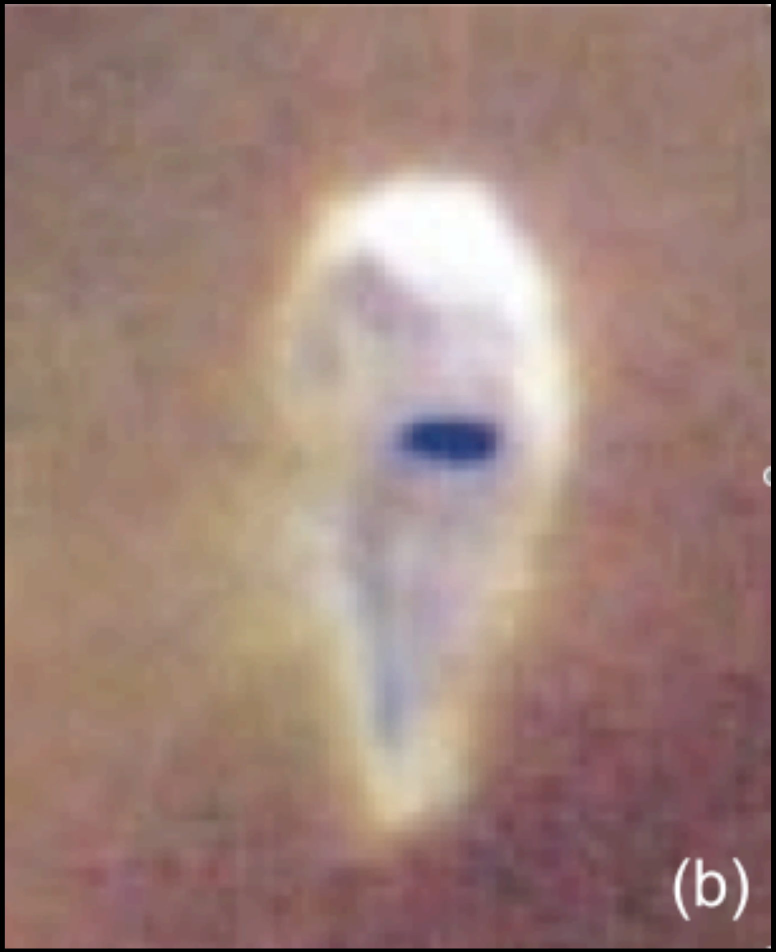
- Accretion rate scales dM ~ M_*^2
- Accretion is ~ 0.01 $M_\odot$ Myr^{-1} (i.e., one disk mass per Myr)

Throop & Bally 2007

Keck AO IR

HST H-alpha





2.12 μm H2

0.63 μm [OI]

=> Soft UV photo-heating of disk surface

(Kassis et al. 2007)