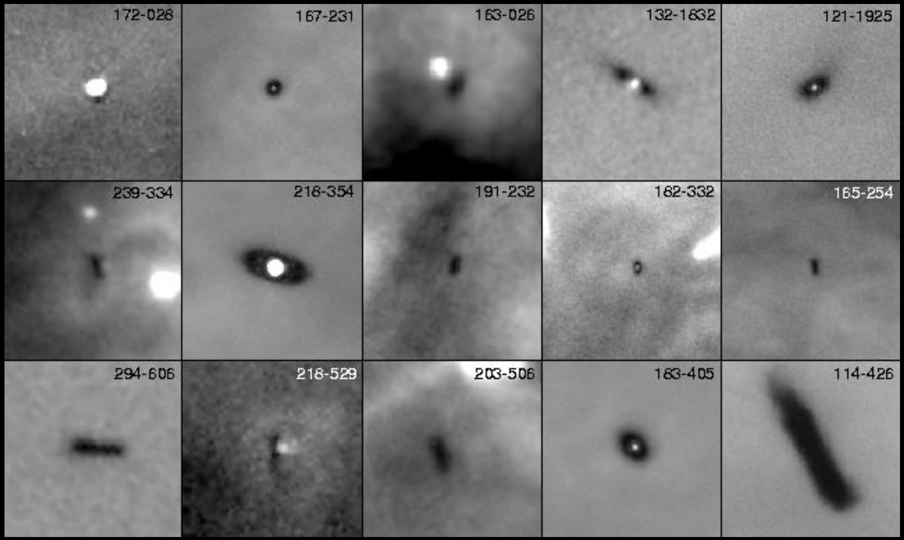
# Formation of Planets in Dense Star Clusters

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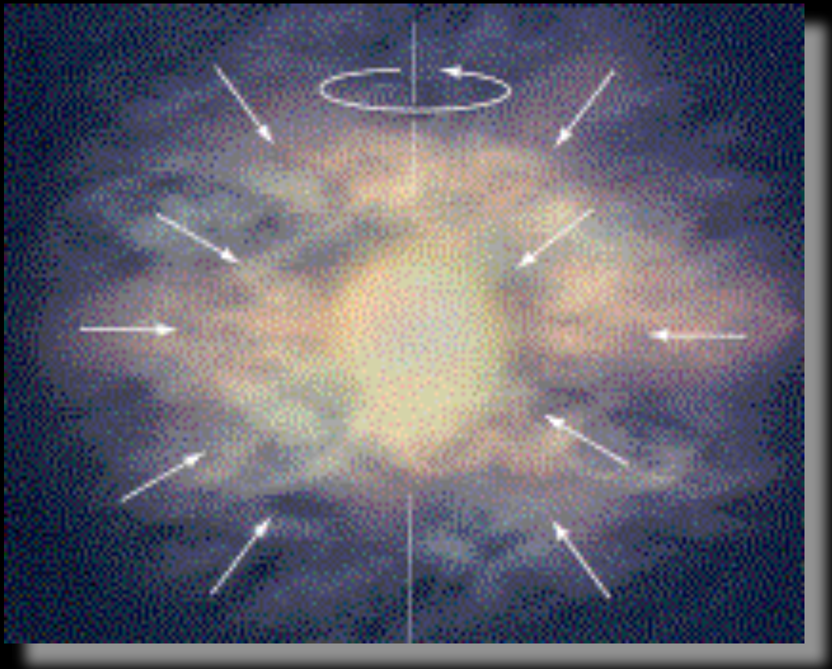
NMSU September 23, 2005

# Where Do Most Stars Form?

- Stars form by the collapse of molecular clouds (few $M_{\odot}$ – $10^6$ $M_{\odot}$)
- Mass spectrum $dn/dM \sim M^{-1.6}$
- ➔ Most of the mass is in the largest clouds (GMCs = Giant Molecular Clouds)



# Case I: Star Formation in Open Clusters

Small clouds: e.g., Taurus

- N=10-500 stars
- Low-mass stars
- Stars do not interact
  - Low stellar density
  - Long crossing times
- Dark, cool, calm
- Close, common, and easy to observe
  - d ~ 150 pc

Taurus: Radius ~ few pc

# Case II: Star Formation in Dense Clusters

- $N=10^3$-$10^4$+ stars, made from the collapse of a GMC
- Low-mass stars near massive O & B stars (OB associations)
- Region is bright and dense.
  - *Bright* - $10^5$x bright 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
    - Distance ~ 450 pc, diameter ~ few pc, N ~ 10,000+ stars in last 10 Myr

# Life Cycle of Giant Molecular Clouds (GMCs)

- Star formation is inefficient: 90% of gas remains not in stars, but in nebula
- After O and B stars die (few Myr), gas is dispersed. Nebula is gravitationally unbound, and stars are ejected as field stars.
- Most field stars today were formed in GMCs.
  - Orbital paths cannot be traced backward for 5 Gya to recreate a progenitor GMC!

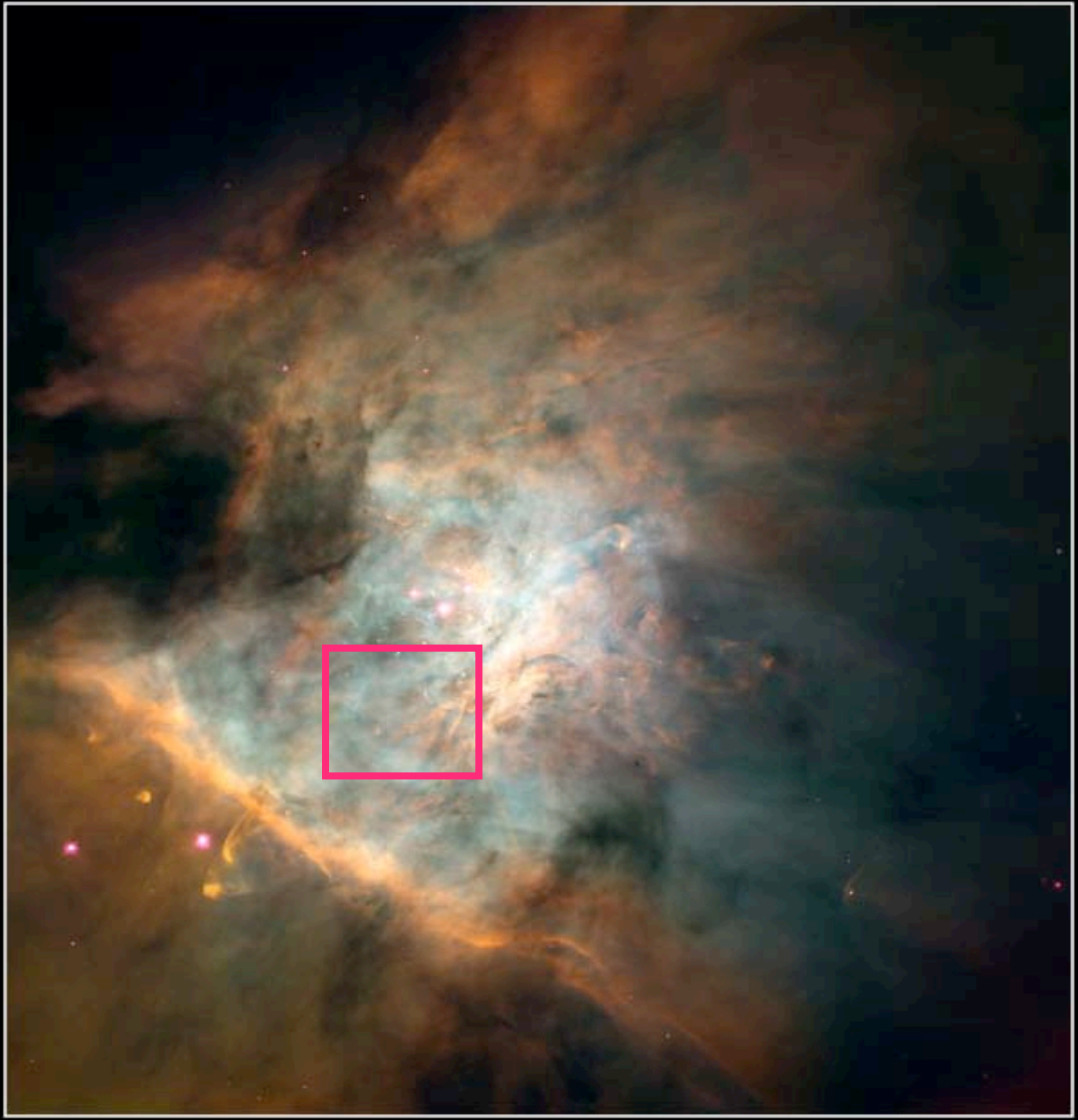
Our Sun could have been formed in a GMC but there is no way to determine this from its current position!

# Where Did Our Solar System Form?

- Isotopes found in young meteorites ($^{26}Al$, $^{60}Fe$) and comets (SiO) requires a strong neutron source at their formation. No known natural object besides a supernova from massive stars can provide this neutron source.

- Statistically, most stars formed near O stars

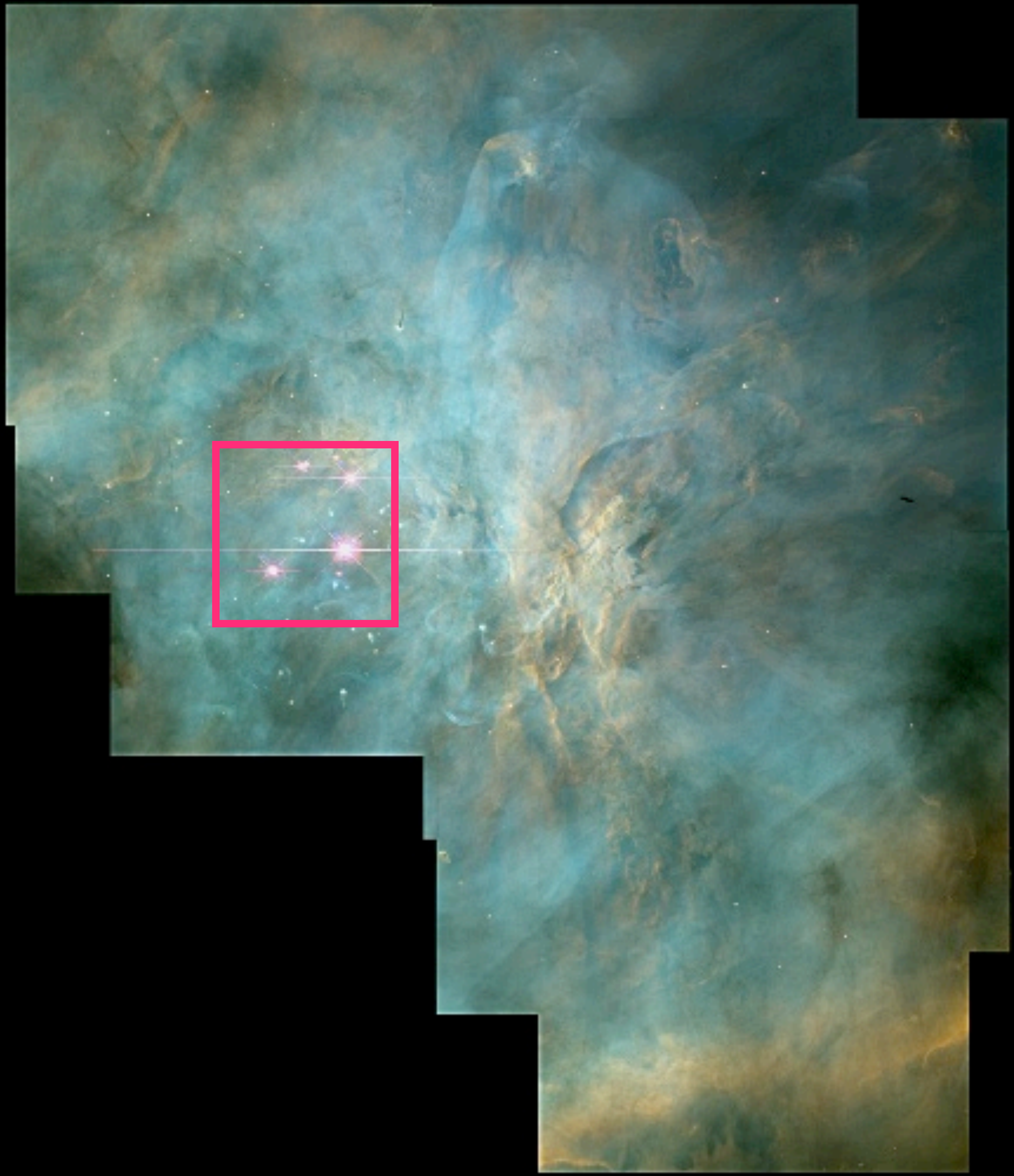
Almost all models for formation of planetary systems assume an isolated environment. This assumption is not necessarily true for our Solar System -- and is almost certainly not true for the vast majority of planetary systems!



**Orion Nebula Mosaic** HST • WFPC2

PRC95-45a • ST ScI OPO • November 20, 1995
C. R. O'Dell and S. K. Wong (Rice University), NASA


0.5 – 2.2 μm
10^4 AU

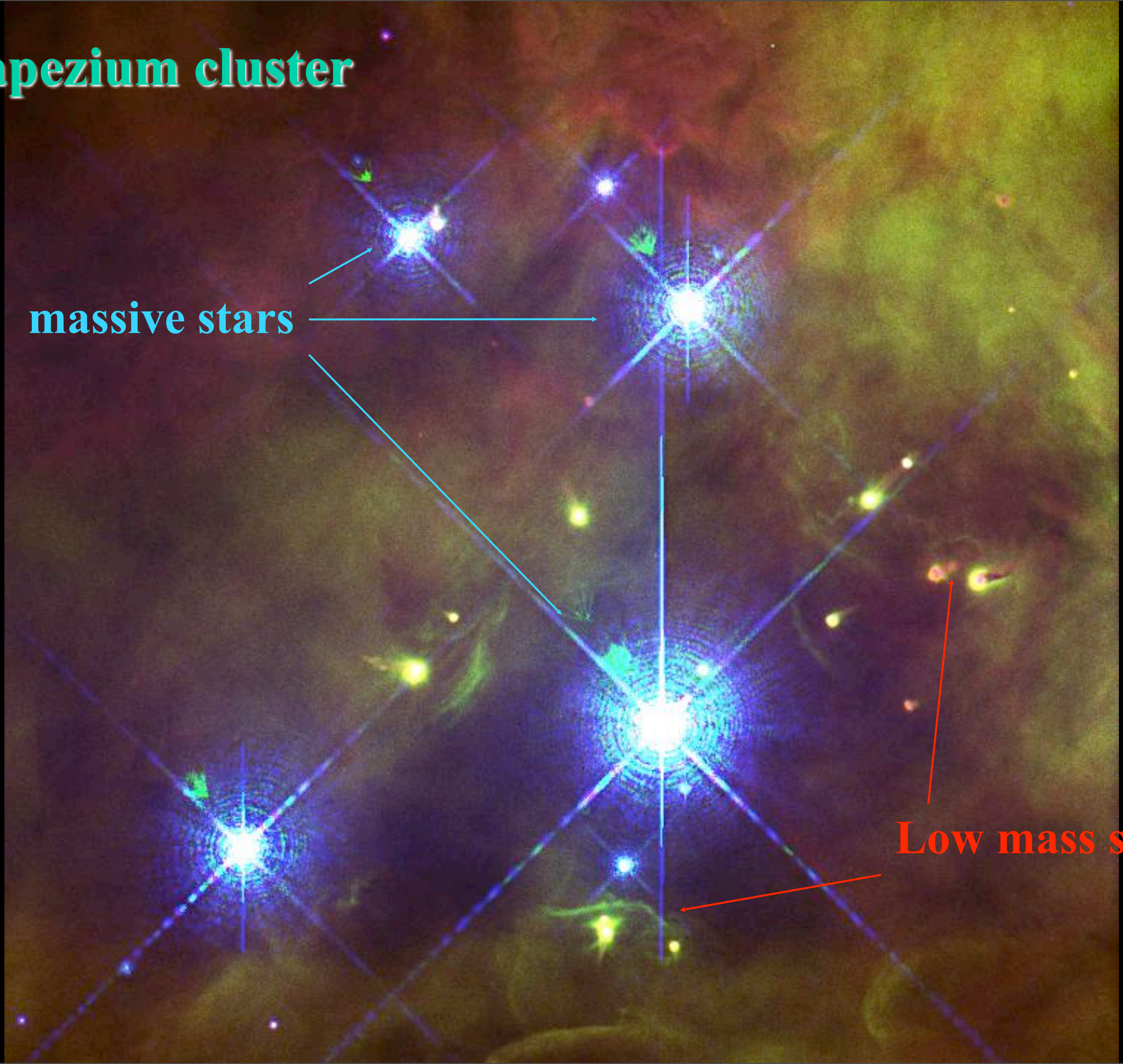


# Orion Molecular Cloud

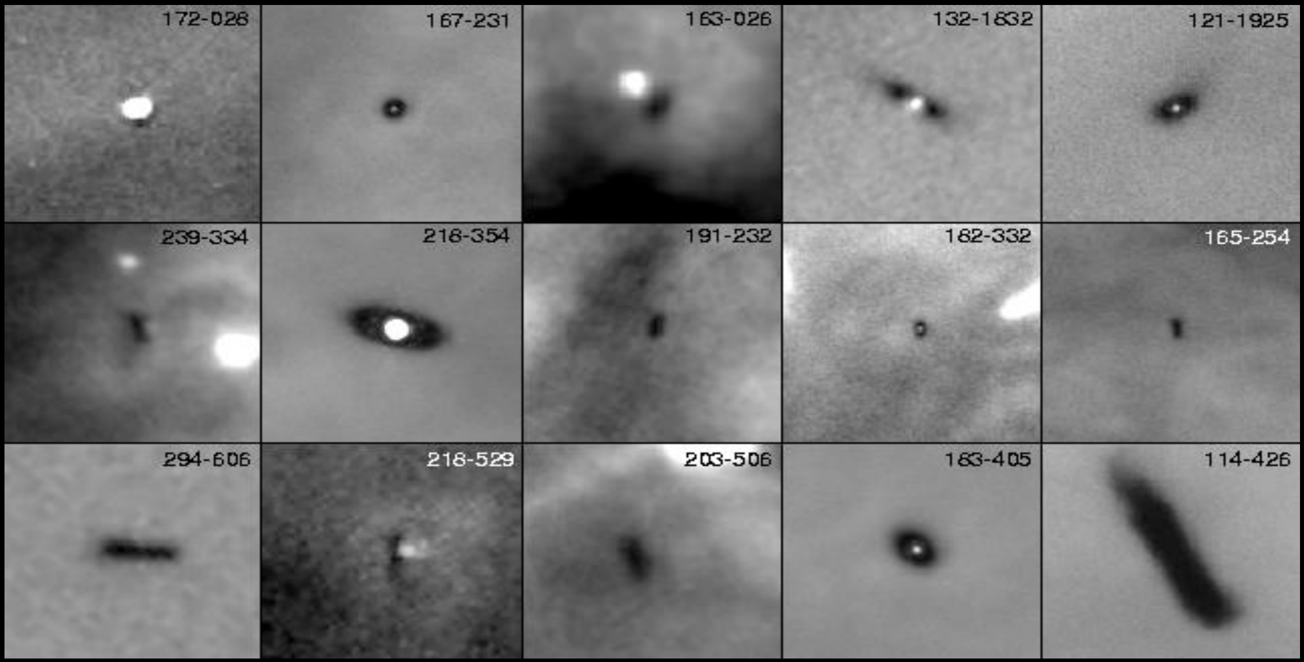
- Closest bright star-forming region to Earth
- Distance ~ 1500 ly
- Age ~ 10 Myr
- Radius ~ few ly
- Mean separation ~ $10^4$ AU
- 20,000 young stars
- $10^5$ solar luminosities from 4 OB stars

- HST resolution of Orion ~ 20 AU

# Trapezium cluster

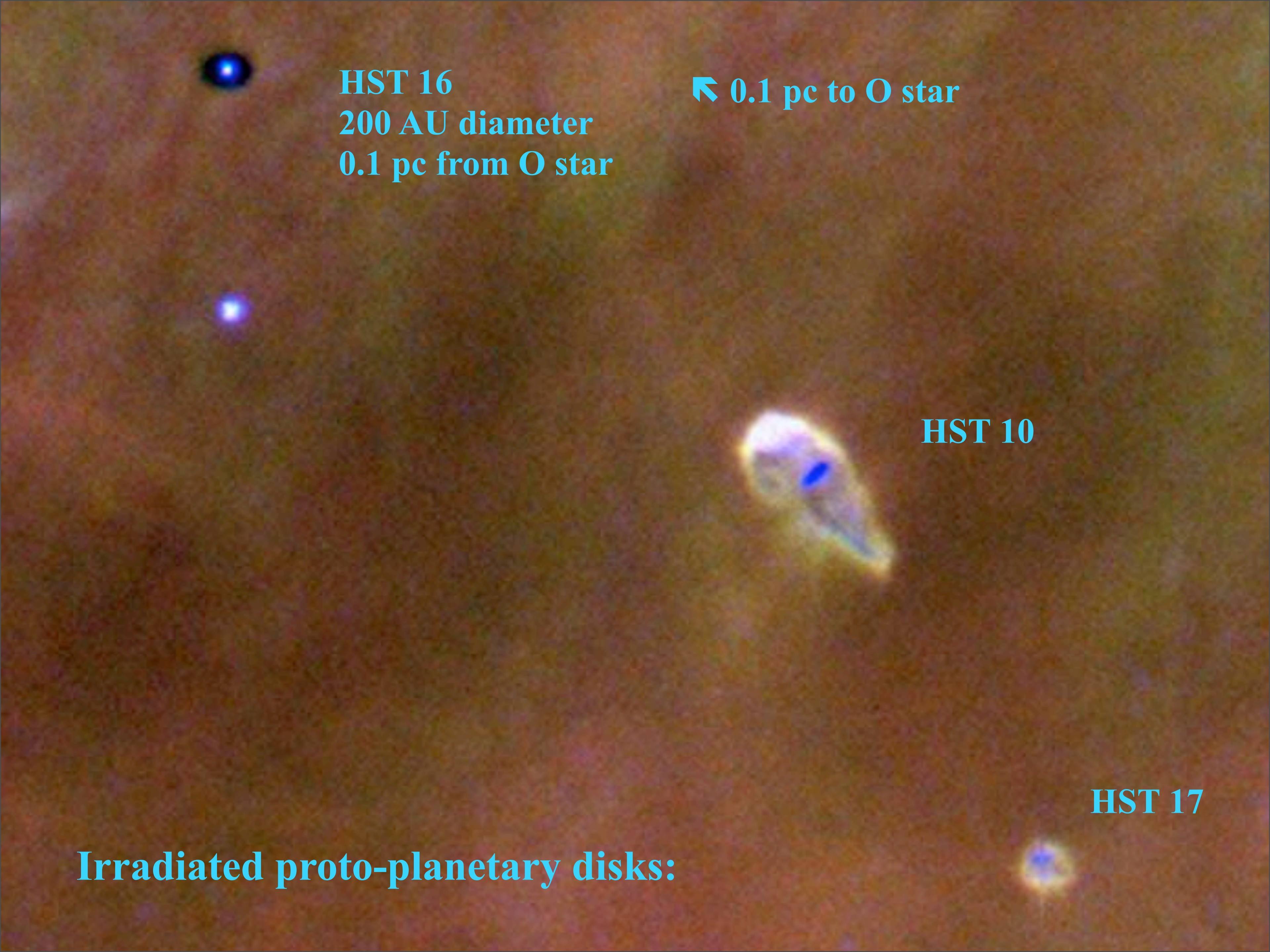


# Circumstellar Disks In Orion




- 100+ disks directly observed, diameters 100-1200 AU
- 80%+ of stars in Orion show evidence for having disks
- Most are being currently photo-evaporated

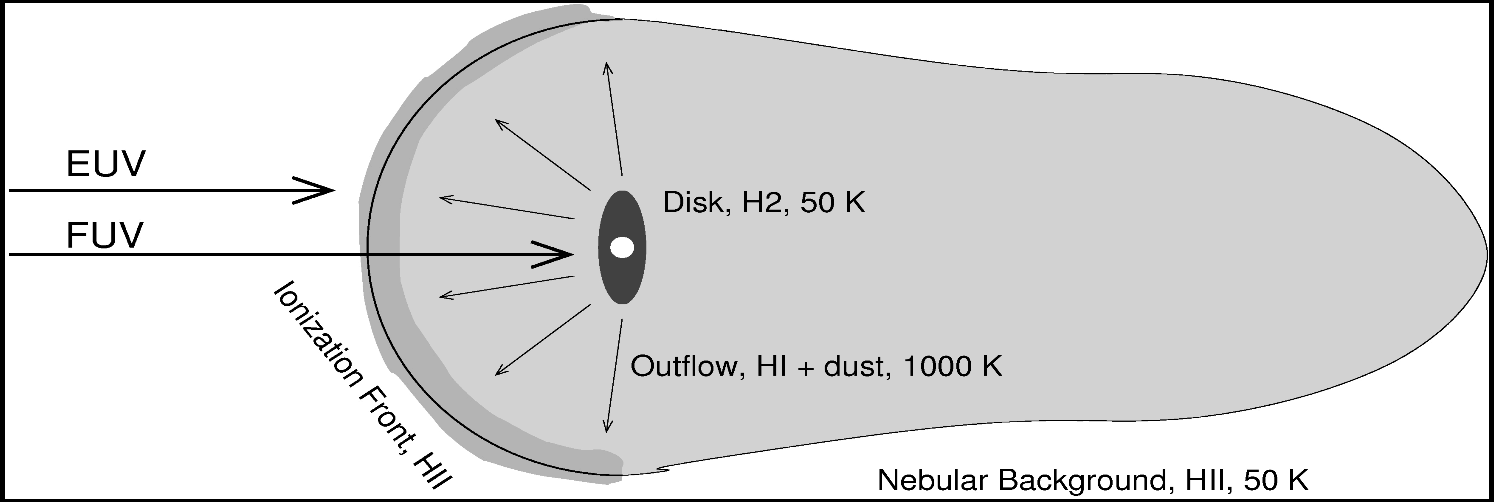
*These stars are too distant and young to directly search for planets… but we want to study the environment and processes to understand the planets which would be produced in these dense clusters -- and therefore throughout the*


HST 16
200 AU diameter
0.1 pc from O star
0.1 pc to O star
HST 10
HST 17
Irradiated proto-planetary disks:

# Photo-Evaporation in Orion

- Disks surrounding solar-type stars are heated by external O/B stars
- Gas heats to 1000K and exceeds escape velocity from star

External UV flux can remove disks in $10^5$ - $10^6$ yr. This is much faster than the $10^8$ yr timescale for giant planet formation!

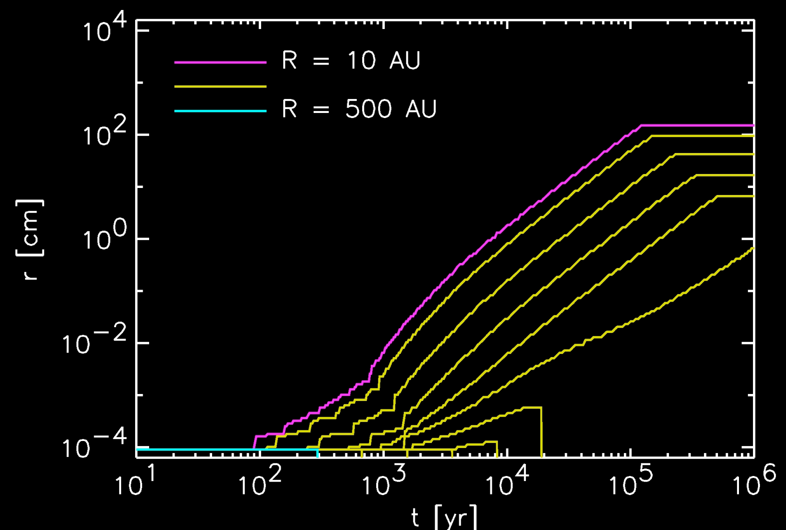


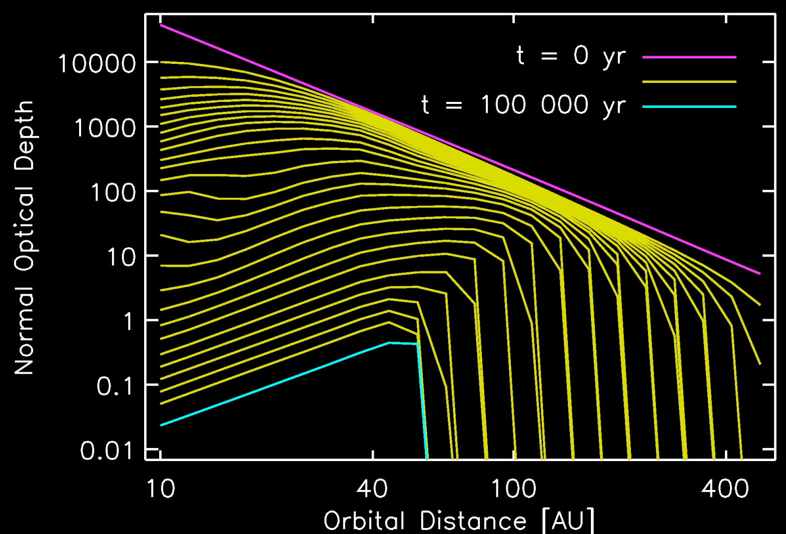
# Model of Photoevaporation

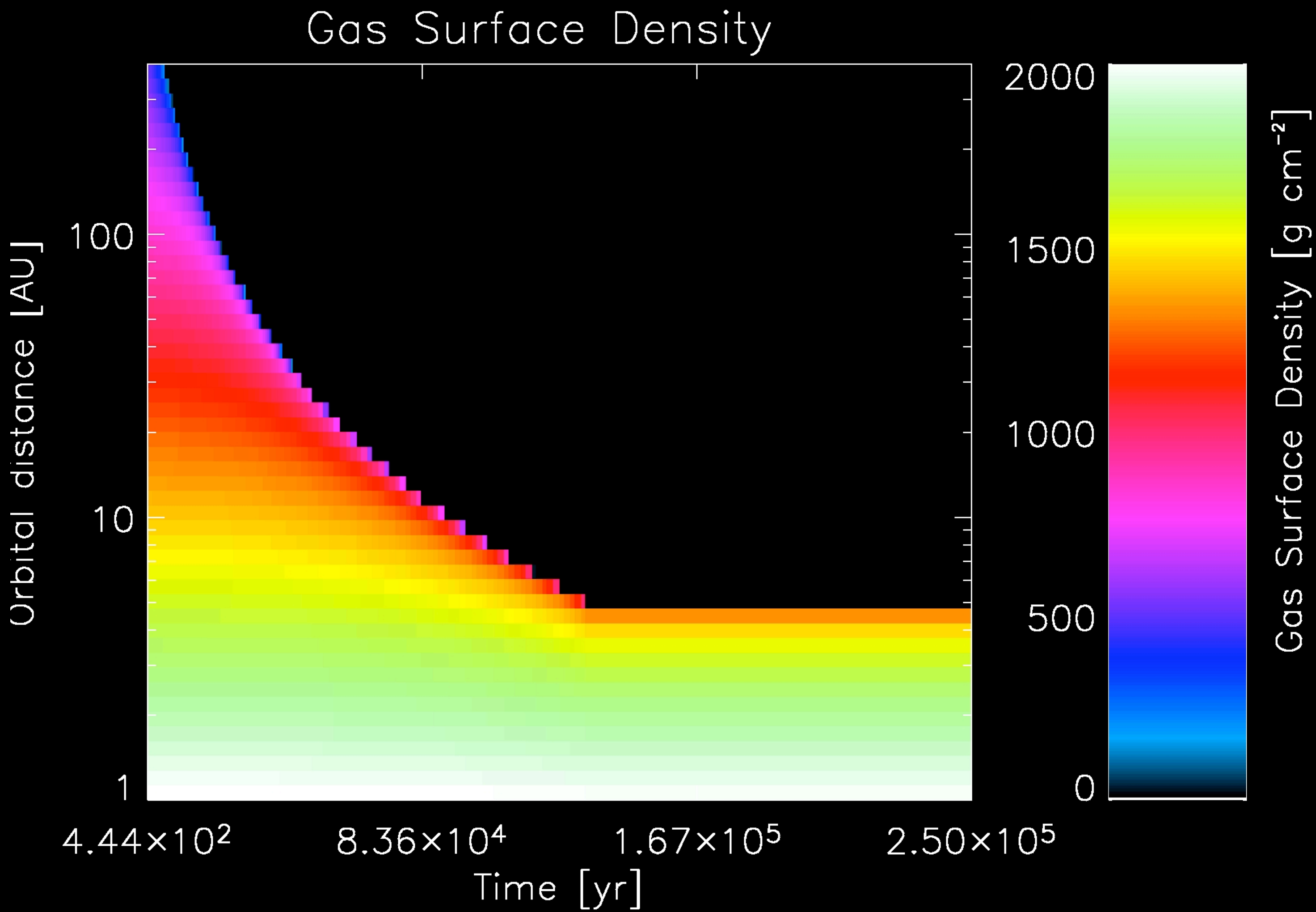
- Numerical 2D code which tracks gas, ice, dust around solar-mass star.
- Processes:
  - Grain growth (microns-cm)
  - Vertical settling
  - Photo-evaporation
  - Dust gravitational instability
- Photo-evaporation heats gas and removes from top down and outside in
  - Gas is preferentially removed
  - Dust in midplane is shielded and retained
- *Our model is the first to examine dust and gas separately during photo-evaporation, and is the first to incorporate GI into photo-evaporation calculations.*

# Grain Growth and Photo-Evaporation

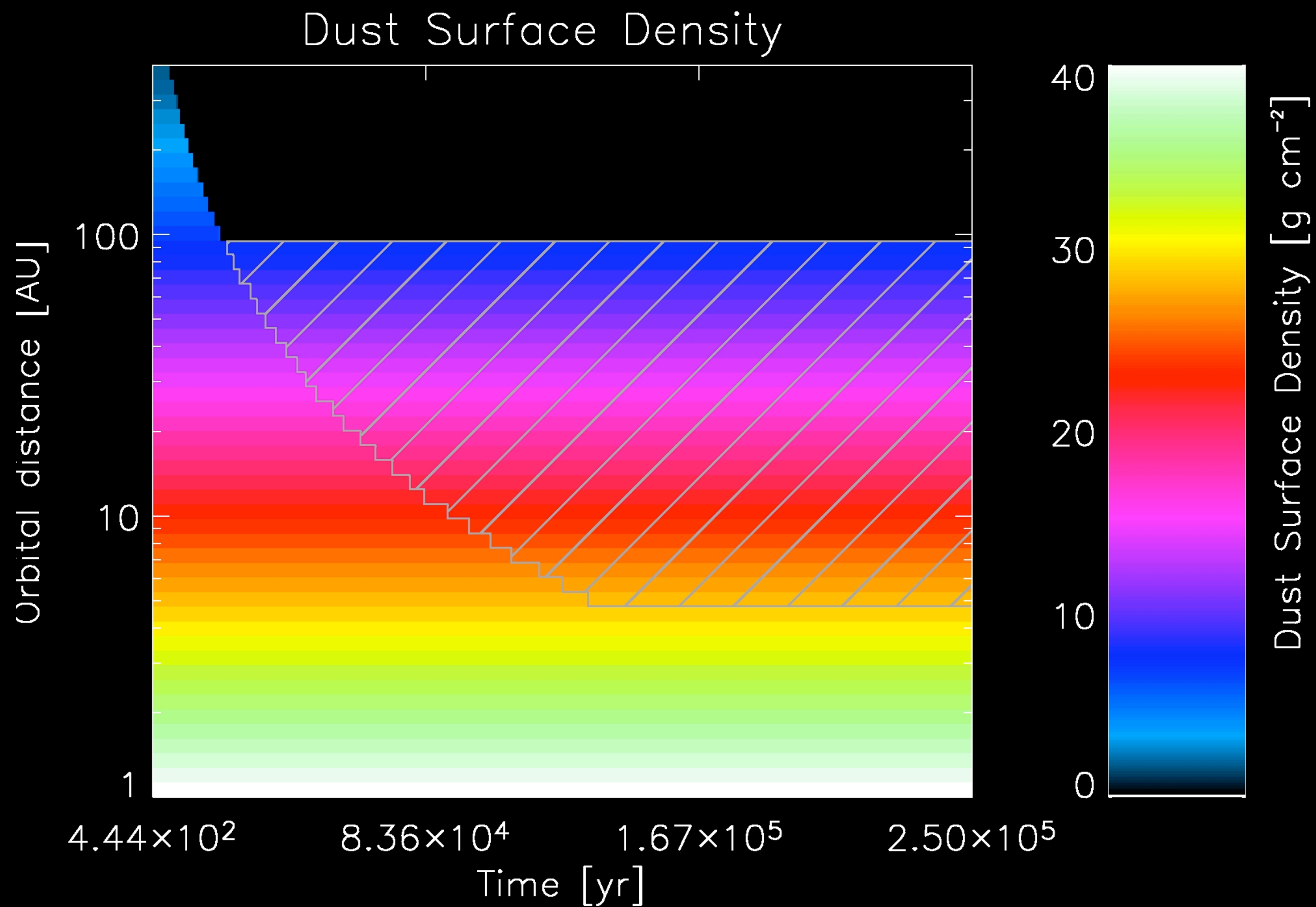
- Grains grow fastest at inner edge
- Grains are most easily lost as outer edge
  - Small grains
  - Easier to entrain in outflow
- Predicts a sharp outer edge at 5-100 AU
- Ingredients for giant planets and KBO’s removed
- Terrestrial planets not affected (fast growth at 1 AU!)





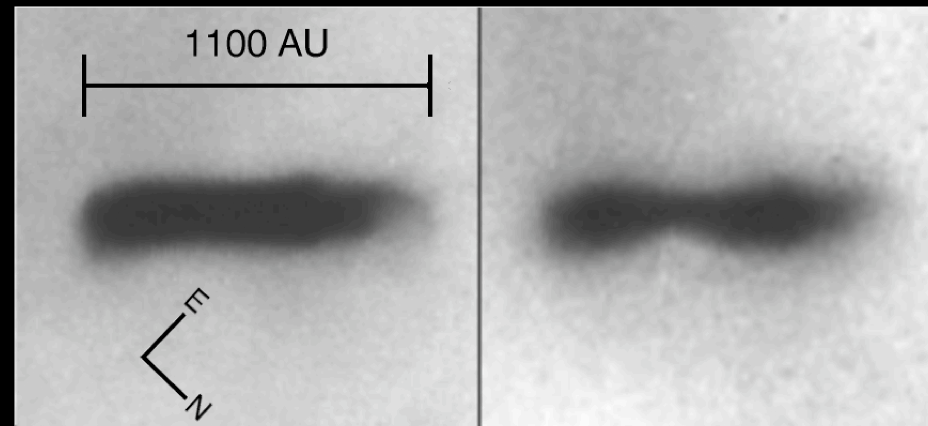

UV radiation heats and removes gas from the disk. After $10^5$ years, the gas outward of 5 AU is entirely removed. **Gas giant planets cannot be formed, unless they form rapidly (e.g., gravitational instability of A. Boss).** Once formed, planets themselves are safe against photo-evaporation.

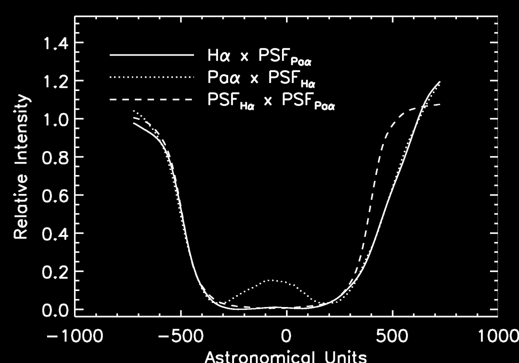


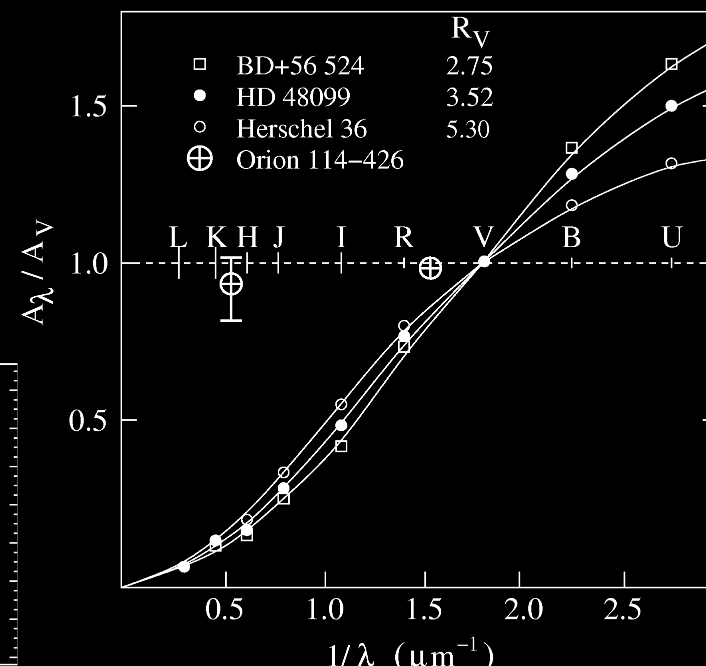

Dust is removed from the disk. Grains inward of 20 AU have grown large enough to be retained. **Formation of terrestrial planets is possible.**

# Tangent: Observations of Grain Growth

- Grain size can be probed by measuring the disk's wavelength-dependent extinction
- Low optical depth dust usually causes reddening, but here it is grey: indicates grains have grown to > few μm.
- This dust is unlike any other astrophysical dust ever observed.
- Our model predicts large grains at sharp outer edge -- precisely what is observed.




Throop et al 2001

# Photo-Evaporation and Gravitational Instability

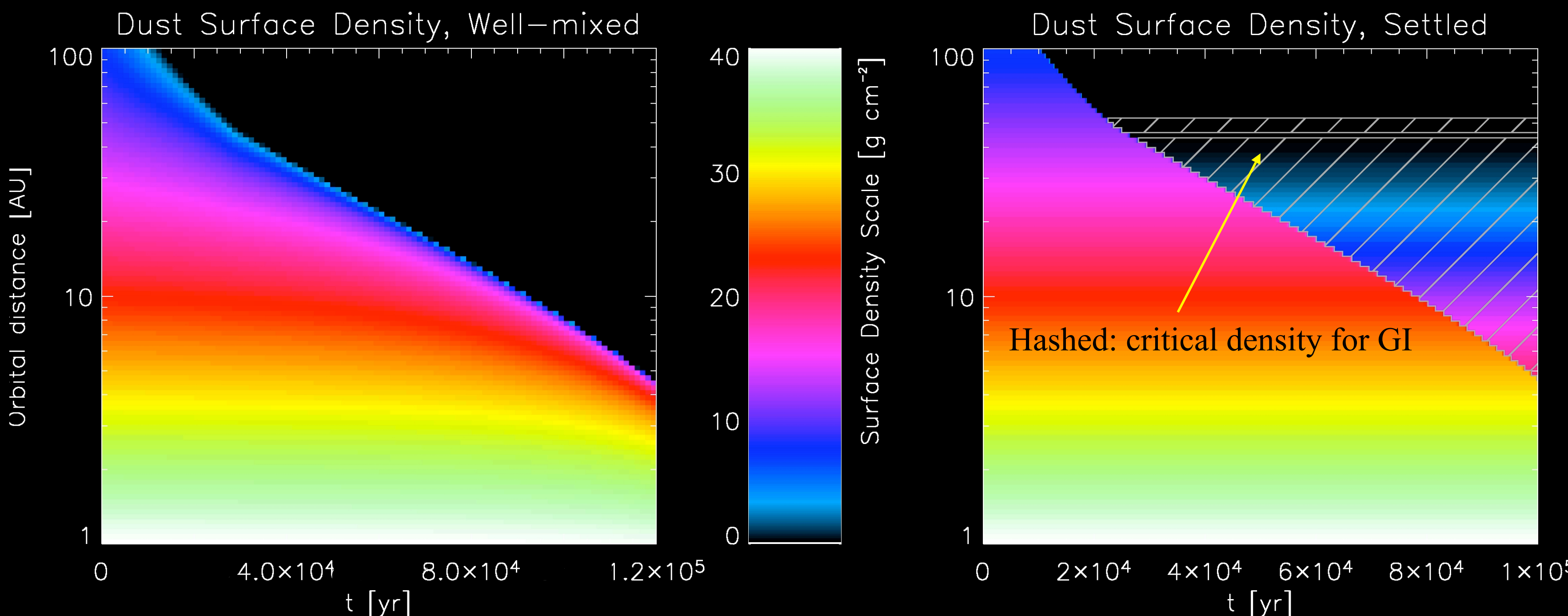
- Problem: Planetary formation models explain grain growth on small sizes (microns) and large (km) but intermediate region is challenging. We do not know how grains really grow -- but we know that they do!

- Our previous model assumes that grain just 'stick' -- a common assumption but hard to justify.

- Grains could grow by gravitational instability -- but gas turbulence usually inhibits this from being effective.

- Can photo-evaporation (PE) preferentially remove the gas, and allow dust to form via gravitational instability (GI)? We add dust GI to our model to address this.
  - Dust disk collapses if dust:gas surface density ratio is increased by 10x from initial (Youdin & Shu 2002)

# Effect of Sedimentation on PE



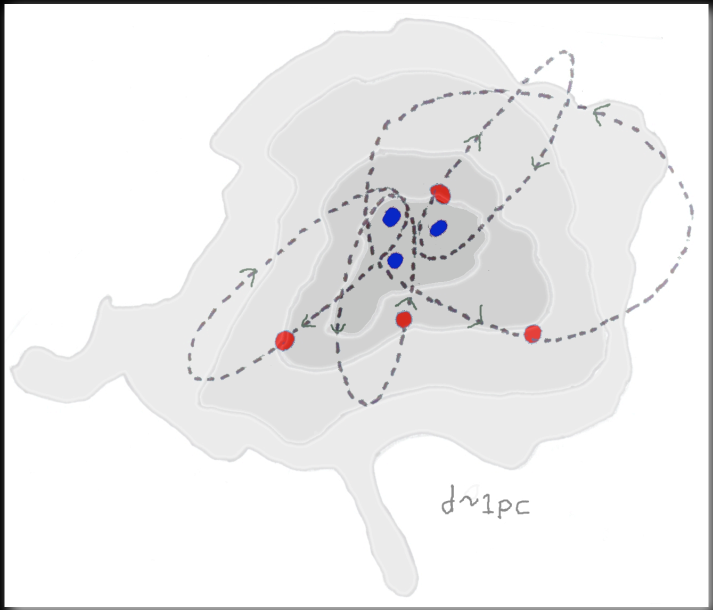

- Case I: Dust and gas well-mixed (no settling); 0.02 $M_{sol}$
- Model result: Disk is evaporated inward to 2 AU after $10^5$ yr

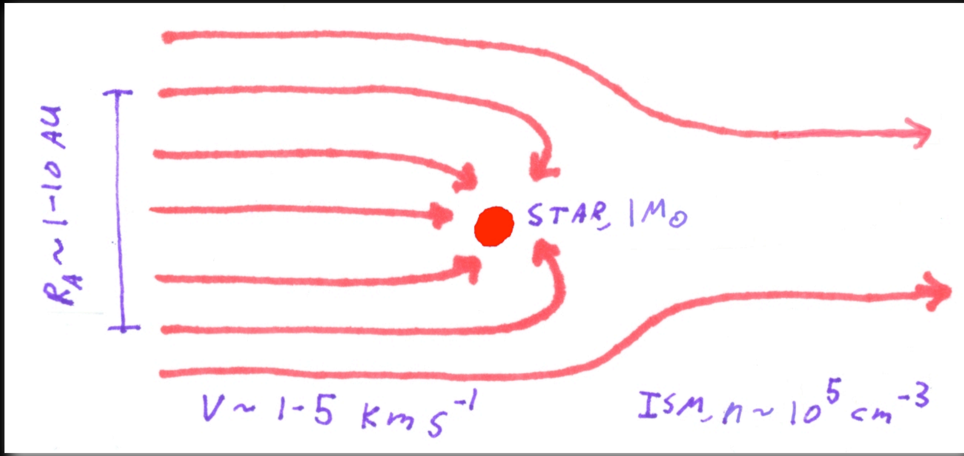
- Case II: Dust grows and settles to midplane
- Model result: Disk is evaporated inward, but leaves significant amount of dust at midplane (40 Earth masses outside 2 AU)
- Dust has sufficient surface density to collapse via GI

Throop & Bally 2005

# Accretion of Nebular Gas

- After star has formed, gas in GMC may still be swept up by disk and stars.
- Accretion rate ~ $10^{-6}$ $M_{sol}$/yr
- Accreted material may fall onto star and/or disk
- This process acts in the opposite direction to photo-evaporation! Could it rejuvenate' disk after it is lost?
- We are currently doing simulations of this process




Moeckel, Throop, Bally (2005)

# Proposed Timeline for Planetary Systems Formed in Dense Clusters

0 yr: Low-mass star with disk forms

$10^4$ yr: Grains grow and settle

$10^5$ yr: Any gas giants form quickly by GI, before gas is lost

$10^5$ yr: O stars turn on

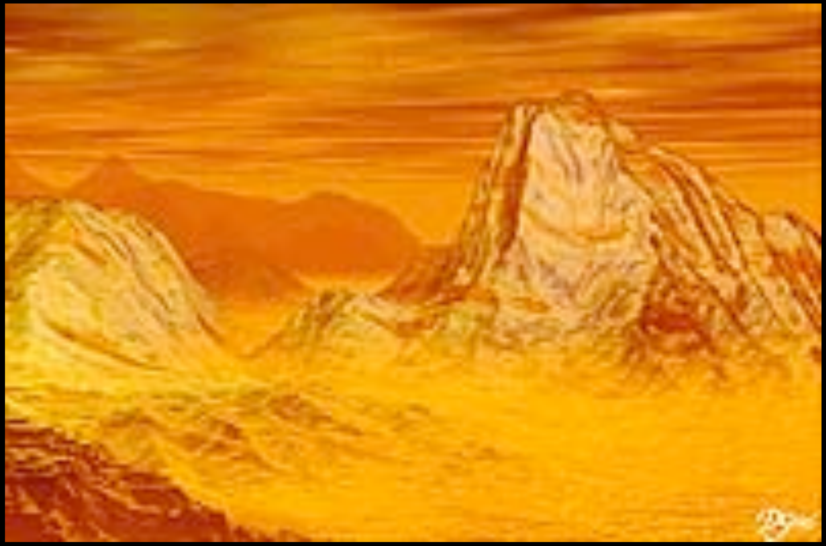
$10^6$ yr: Gas disk is lost, allowing planetesimals and terrestrial planets to form from disk

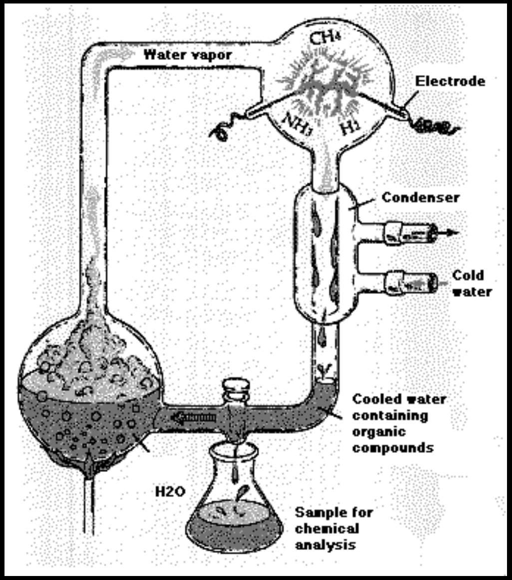
# Can A Dense Cluster Explain the Origin of Solar System's Organic Molecules?

- Standard model for formation of organic molecules on Earth uses warm, wet, liquid chemistry and lightning (e.g., Miller-Urey experiment).

- Comets are 30%+ organics by mass - much of this complex organics

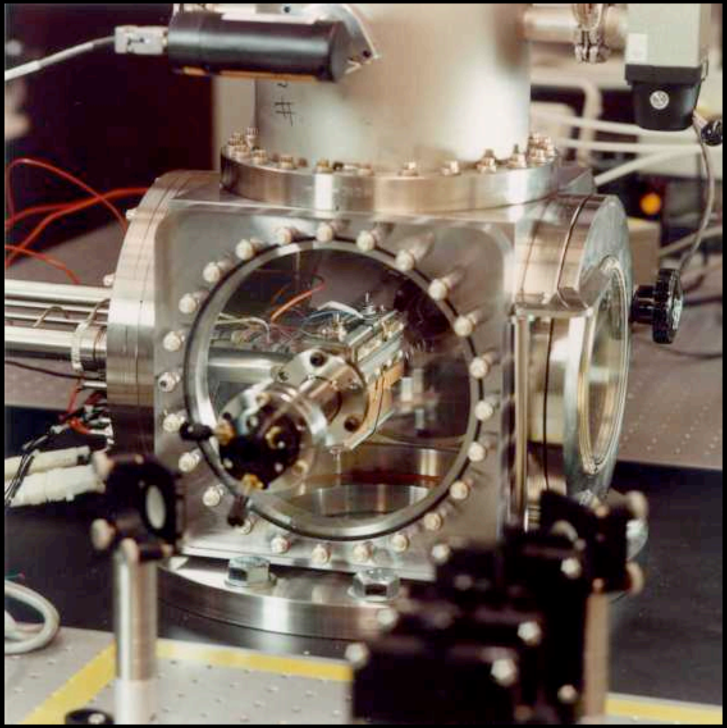
- Murchison meteorite had 70+ different amino acids on surface (~5% aminos + carbon polymers by mass). Did asteroid *really* have oceans + lightning, or were organics made a different way?



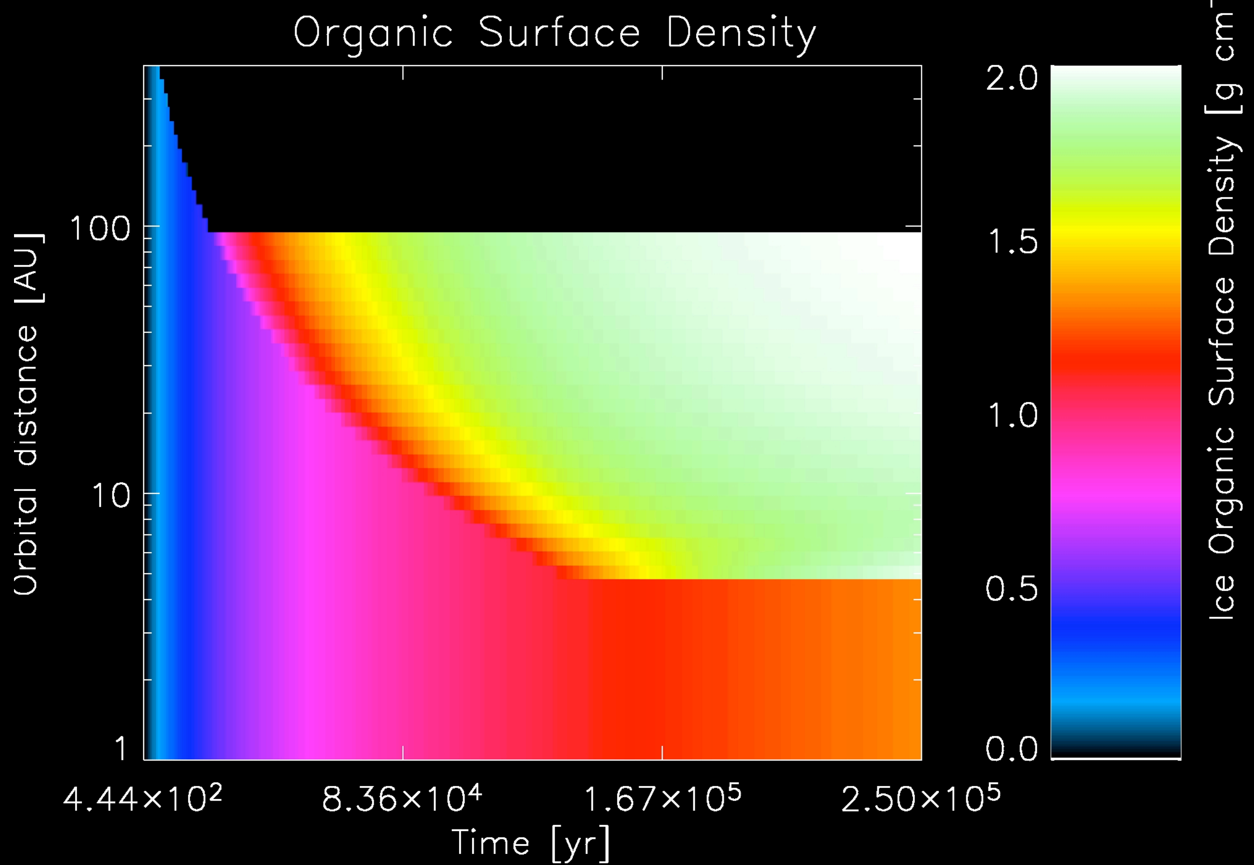


# UV Formation of Organic Molecules

- Lab work at NASA Ames: UV flux into frozen ices can create complex organic molecules from simple ones. (M. Bernstein, L. Allamandola)
  - $CO$, $HCN$, $NH_3$, $H_2O$ + UV ➔ Amino acids (cytosine, lysine), DNA bases, sugars, etc.
  - Solid phase, 10 K
  - Conversion efficiency ~ $10^{-3}$ organics per photon
  - This process can happen in ISM, young disks, etc -- before planets form!



# Modeling of Photolysis of Ices → Organics




Organic production is fastest at outer edge, where gas is lost and exposes small grains to UV

UV flux is sufficient to create Solar System's entire inventory of organic molecules in < $10^6$ yr.

This is a previously unrecognized mechanism, and $10^7$x faster than UV photolysis from Sun's UV.

But, it may be that volatiles are lost before they can be photolyzed -- we do not know!

Throop et al 2004

# Summary: Planetary Formation in Dense Clusters

- Dense clusters provide a number of *hazards to planet formation*…
  - Photo-evaporation removes disks on rapid timescales, before planets can form
  - Close encounters can strip disks / planets
- But, dense clusters may also *help planet formation!*
  - Gas removal can trigger planetesimal formation
  - Gas can be accreted from long-lived GMC nebula cloud
  - Organic molecules can be created in large quantities

- Did Solar System form near an OB association?
  - Isotopic data indicate it was quite likely
  - Modeling indicates it is hard: *Giant planets, KBOs must be formed rapidly, or rarely*
  - Statistics indicate it is likely, but this is statistics of N=1

# Implications for Extrasolar Planets

- Our goal is to constrain the number and characteristic of planets which form throughout the galaxy.
- Planets *may* be common in the galaxy -- but photo-evaporation is *definitely* common.
- Terrestrial planets can form in OB associations -- perhaps sped by dust GI
- Gas giant planets may be able to form, if they form rapidly (e.g., gas GI)
- Photo-evaporation may encourage the formation of high-metallicity planetary systems (e.g., gas giants with high-mass cores)

# Star Formation and Photo-Evaporation (PE)

- The majority of low-mass stars in the galaxy form near OB associations, not in dark clouds (ie, Orion is the model, not Taurus)
- PE by FUV and EUV photons removes disks from outside edge inward, on $10^6$ yr timescales.
- PE is caused by external O and B stars – not the central star.
- In Orion, typical low-mass star age is $10^6$ yr, but O star age is $10^4$ yr – disks have had a quiescent period before PE begins.

# Implications

- Coagulation models of grain growth have difficulty in the cm-km regime.  This model allows for that stage.

- Model addresses how giant planets could be common, in spite of fact that majority of low-mass stars form near OB associations, and thus may rapidly lose their disks

- Solar System's entire organic molecule inventory can be explained without requiring warm, liquid chemistry

# Caveats

- Our model assumes a single species and conversion efficiency.  Organic chemistry is much more complex than this!
- We model only the production of organics, not their loss by UV photolysis
- Photo-sputtering (which we do not consider) will convert some ices into gas which may be subsequently lost.
- Grain growth rates play an important role, but are poorly understood.  If  grains grow rapidly into km-scale bodies, only limited surface area for photochemistry sites is available.

# Conclusions

- There is sufficient flux in the UV to account for the creation of the Solar System's current organic content.
- The total UV dose received during the first $10^6$ yr exceeds $10^4$ photons/molecule.
- Our model predicts a greater conversion of inorganic ices to organic molecules in the outer solar system relative to the inner.
- The amount of UV photolysis experienced depends on the grain growth rate: slower grain growth allows more exposed surface area and thus greater UV production.

# The Environment of Planet Formation

# Dense Clusters vs. Field Stars

# Dense Clusters

# Orion Cluster

- 20,000 young stars in last 10 Myr
- Several dozen O stars (Myr lifetimes)
- Current population is much less: clusters are not bound and dissolve rapidly
- Most stars seen as *field stars* today were formed in clusters

# Where did Our Solar System Form?

- We have a kuiper Belt, ices
- 26Al isotopes
- CO fractionation
- Most stars form in clusters

# Triggered Formation of Planetesimals

# Ongoing Accretion

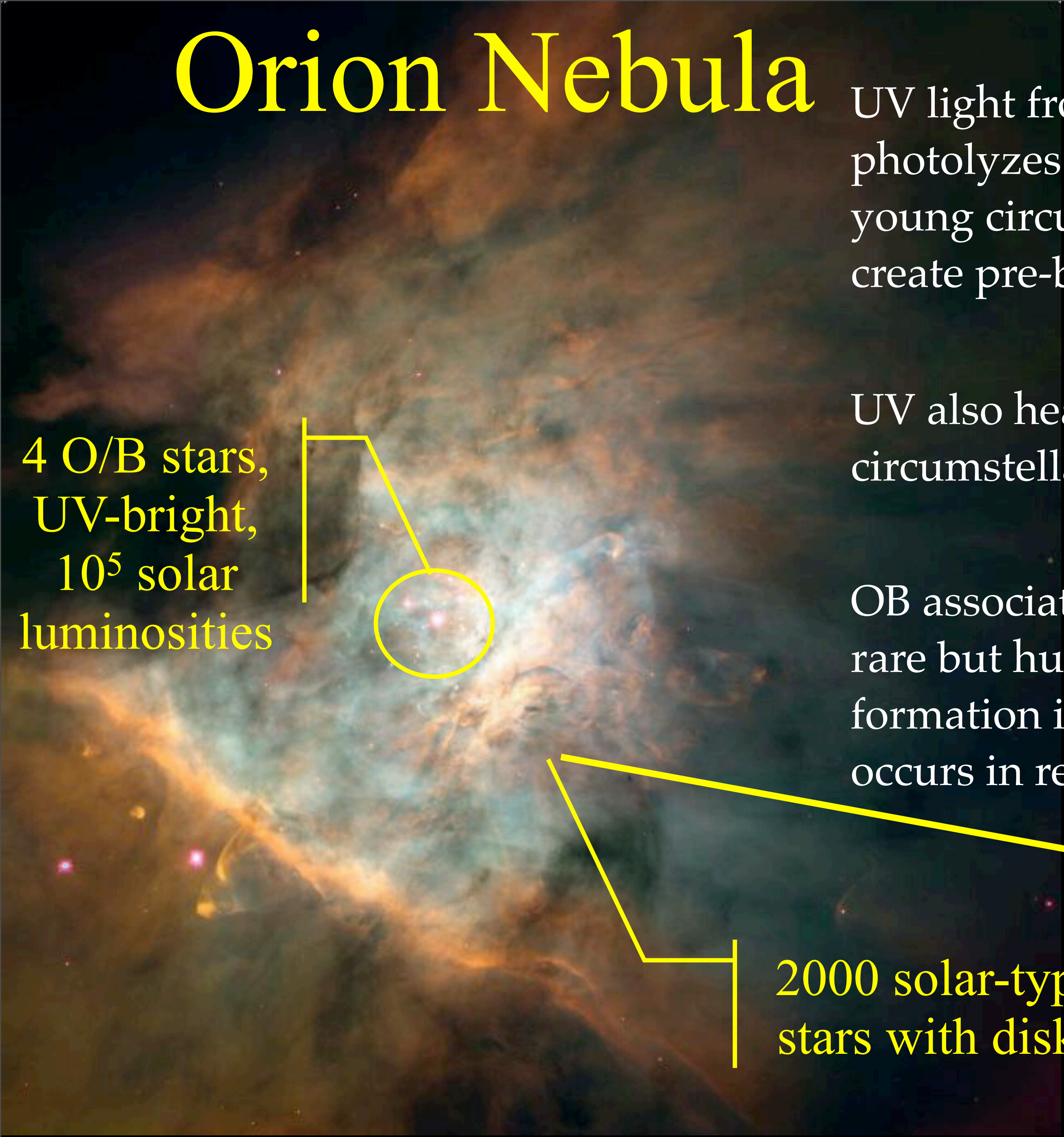
# Close Encounters

# Is Planet Formation in these Environments Hazardous… or Not?

The End

# Additional Slides

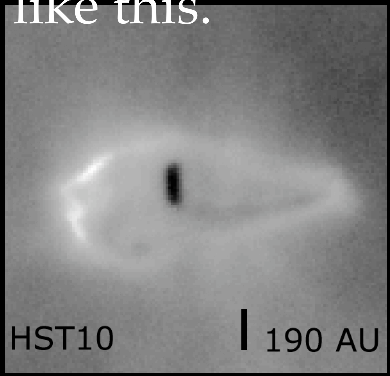
# Orion Nebula

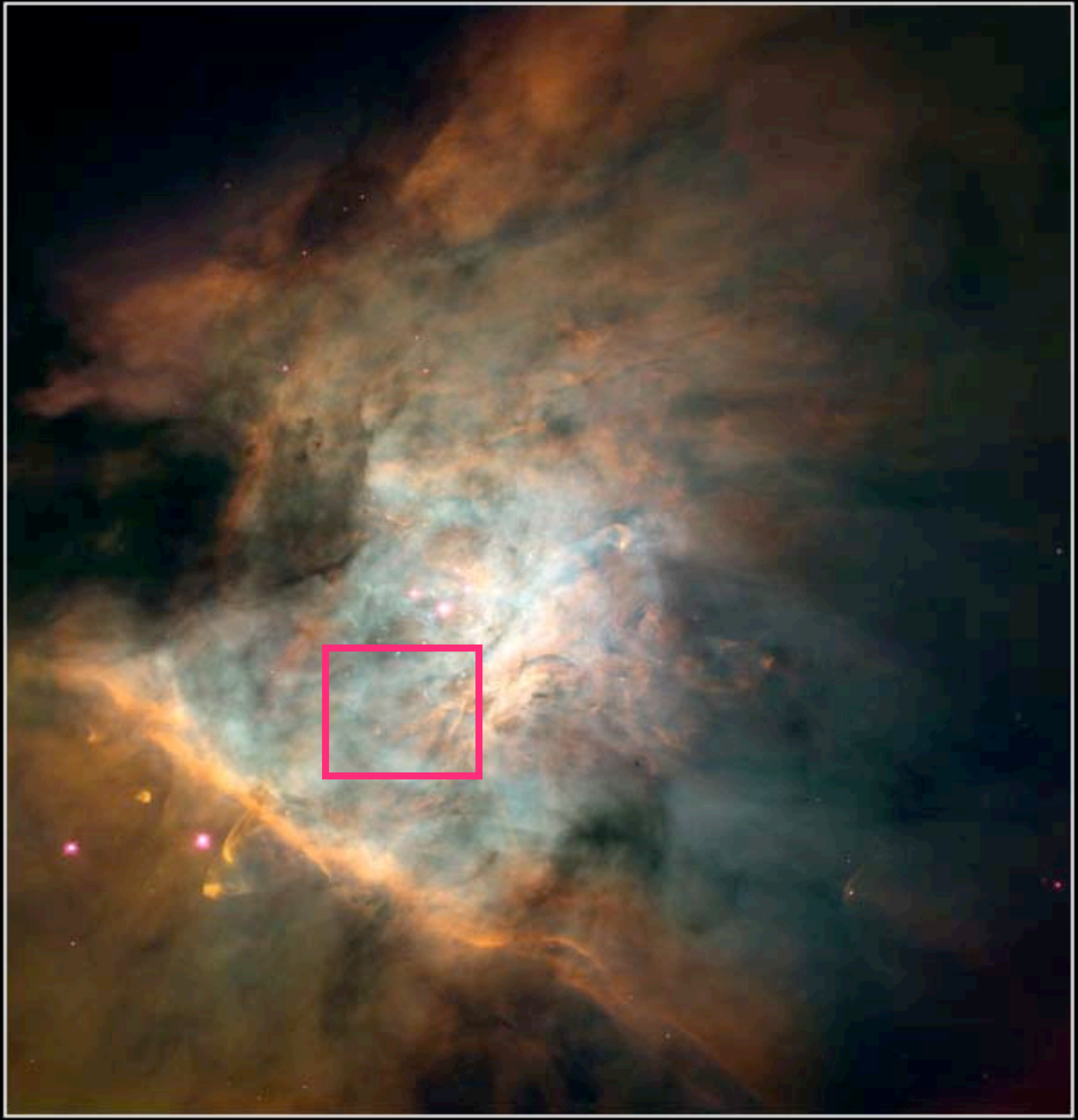



UV light from massive O/B stars photolyzes ices in nebula and young circumstellar disks to create pre-biotic organics.

UV also heats and destroys circumstellar disks.

OB associations like Orion are rare but huge – majority of star formation in the galaxy probably occurs in regions like this.





**Orion Nebula Mosaic** HST • WFPC2

PRC95-45a • ST ScI OPO • November 20, 1995
C. R. O'Dell and S. K. Wong (Rice University), NASA

# Creation of Pre-Biotic Organic Molecules in Young Circumstellar Disks

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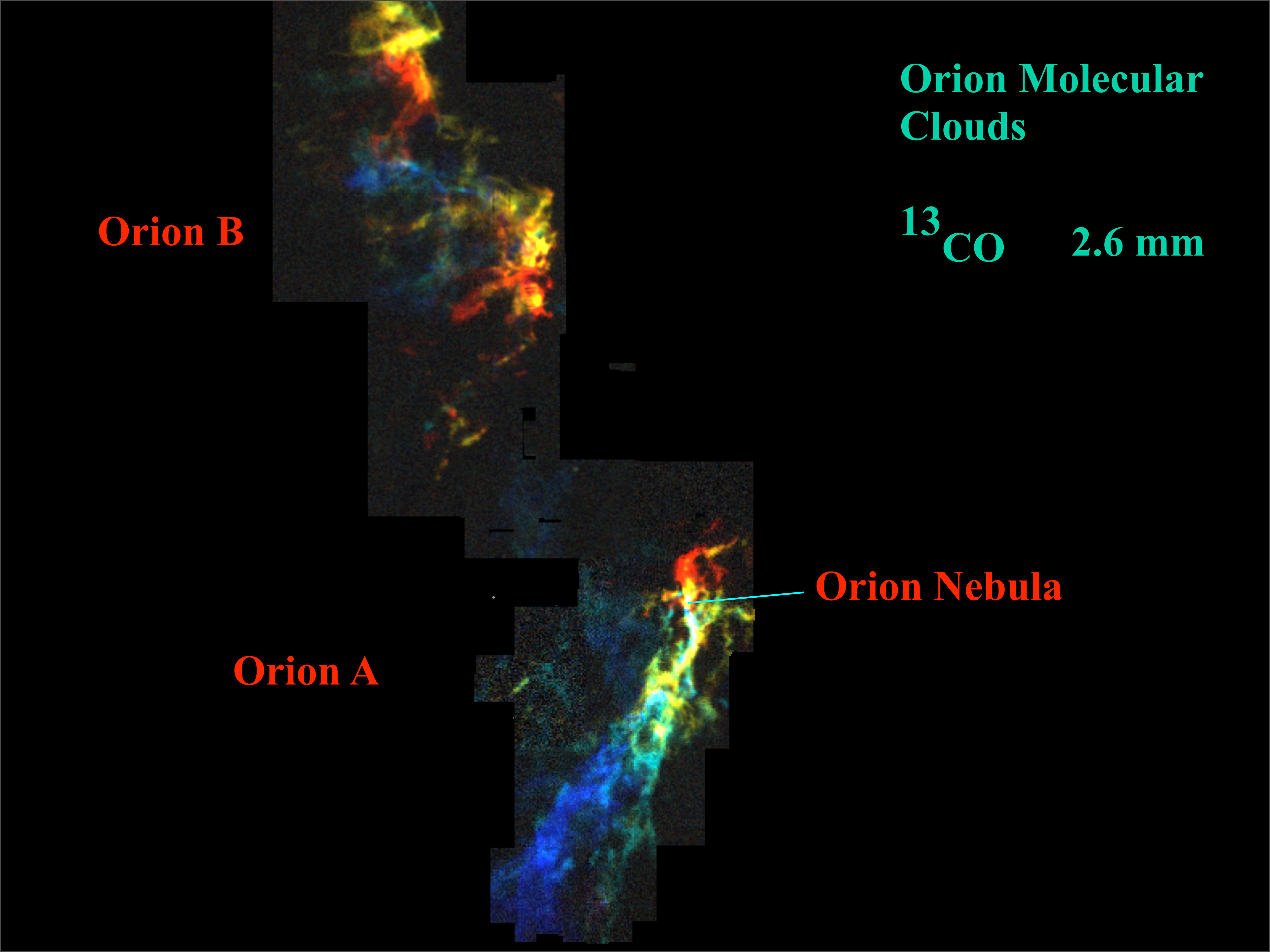
TAKE-AWAY MESSAGE

Models for the early Solar System assume that UV processing of volatiles played virtually no role in the formation of organic molecules. However, if the Sun formed in a dense OB association such as Orion, ionizing UV flux from nearby massive stars would be increased by $10^7$ times, providing sufficient flux to create a plethora of simple and complex organic molecules needed for life.



Orion Molecular Clouds
$^{13}CO$ 2.6 mm
Orion B
Orion Nebula
Orion A