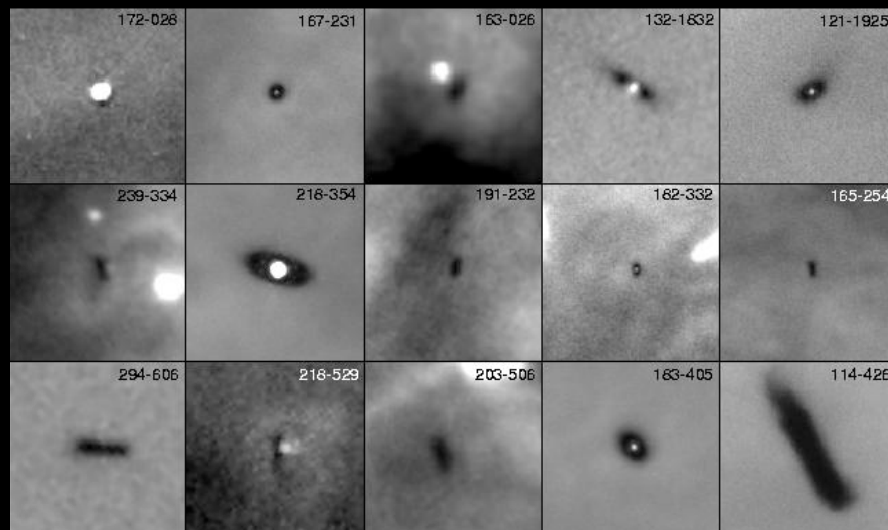
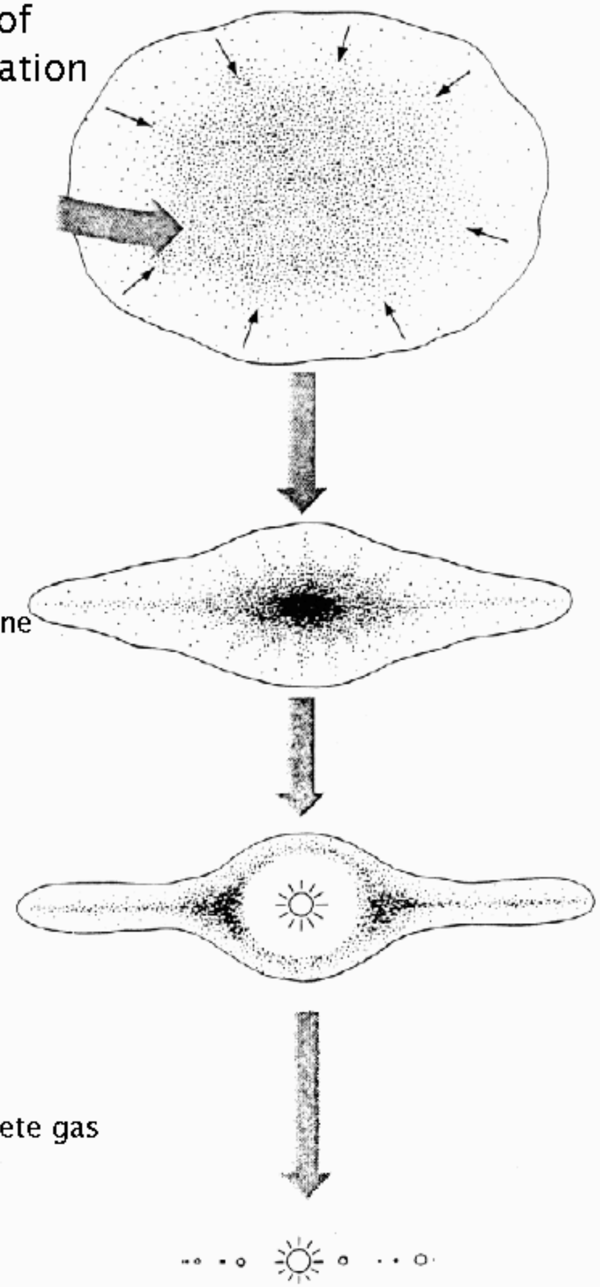
The Orion Nebula and Formation of Planets in Dense Star Clusters



Henry Throop
Department of Space Studies
Southwest Research Institute (SwRI)
Boulder, Colorado

Little Thompson Observatory -- May 19, 2006

Traditional model of Solar System Formation



Slowly rotating cloud

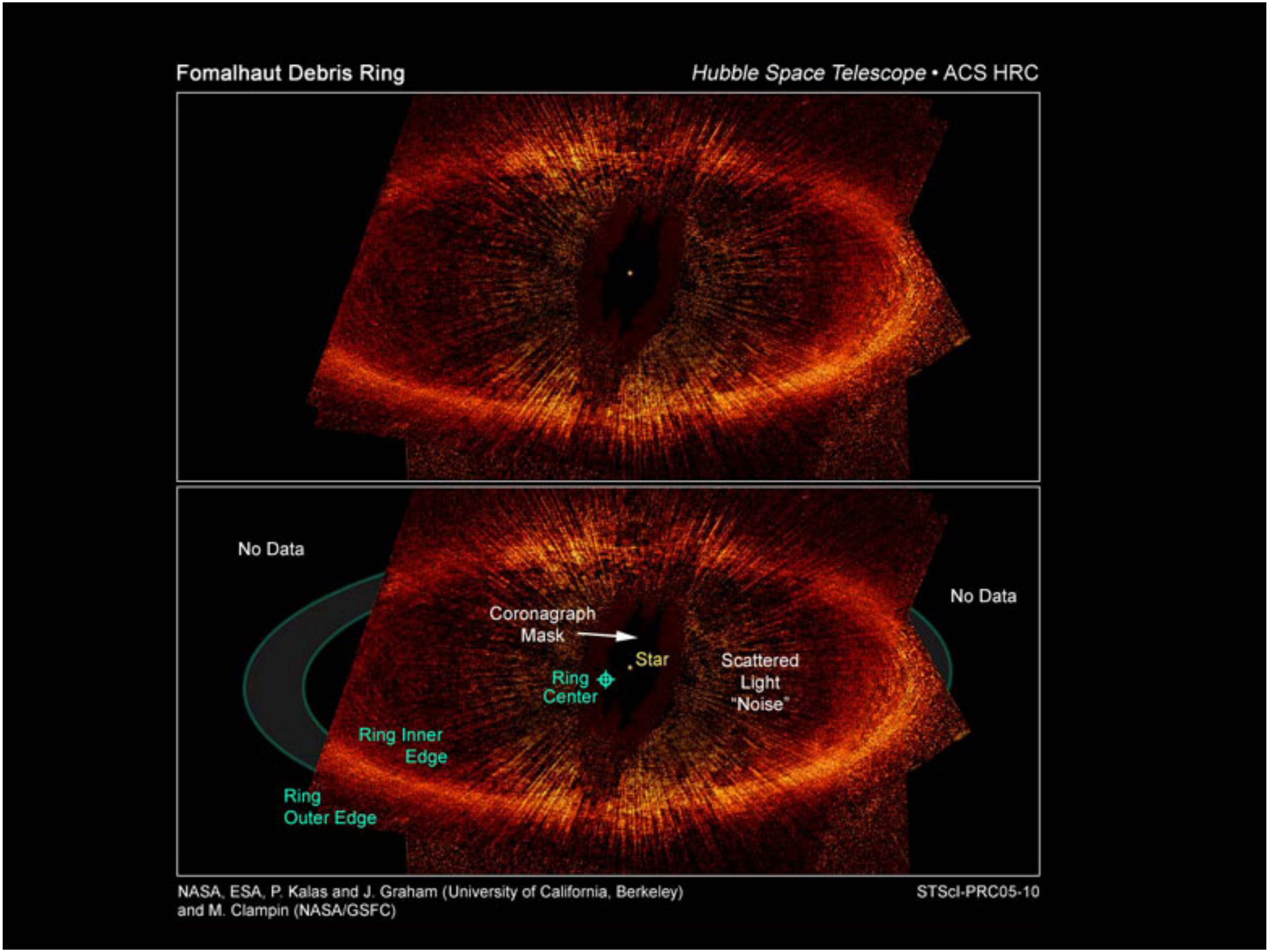
Cloud collapses

Dust settles to midplane

Dust grains grow

Planets form and accrete gas

Solar System is formed after ~ 10 Myr

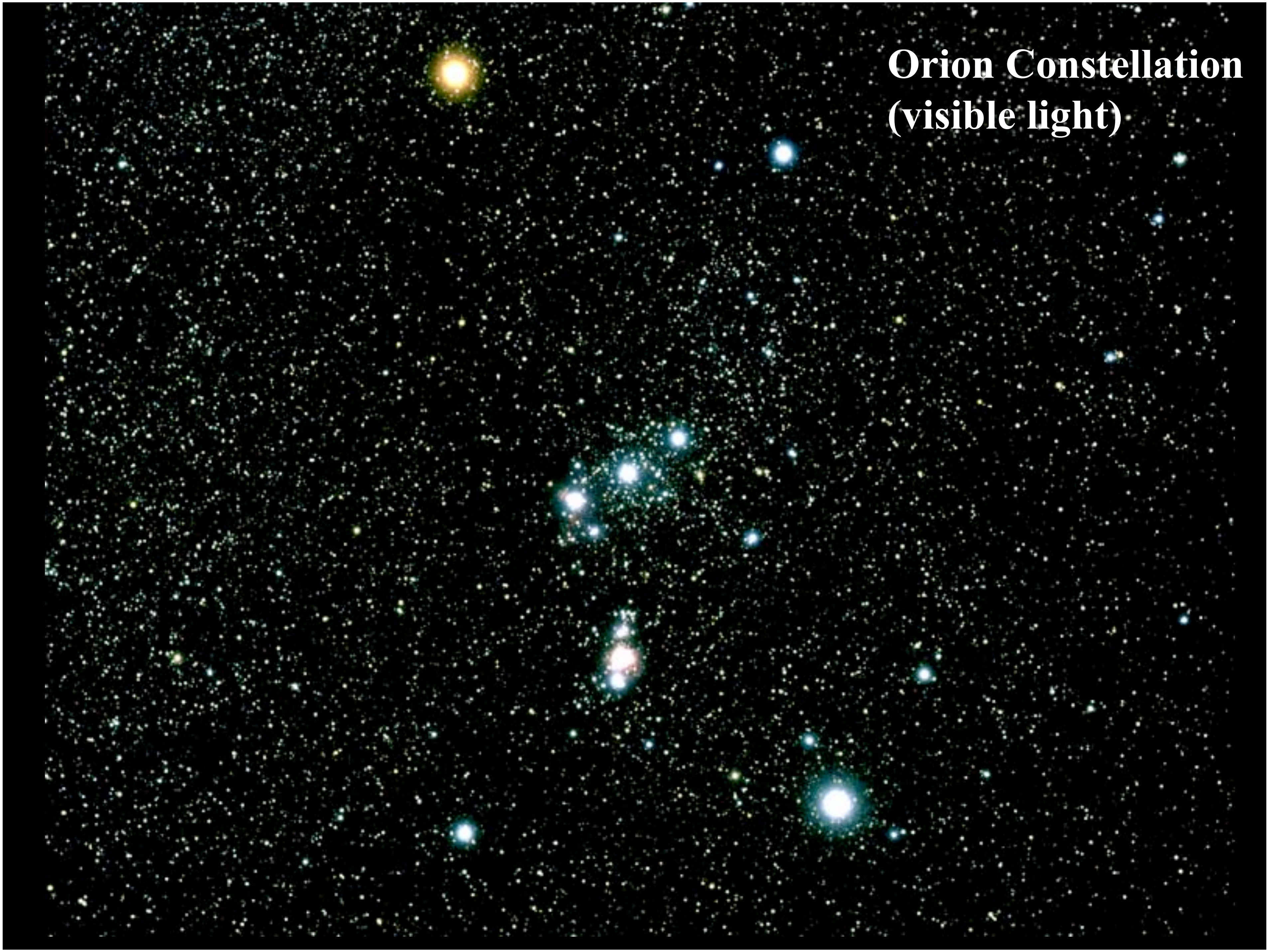

Fomalhaut Debris Ring
Hubble Space Telescope • ACS HRC
No Data
No Data
Coronagraph Mask
Star
Ring Center
Scattered Light "Noise"
Ring Inner Edge
Ring Outer Edge
NASA, ESA, P. Kalas and J. Graham (University of California, Berkeley) and M. Clampin (NASA/GSFC)
STScI-PRC05-10

Case I: Star Formation in Open Clusters

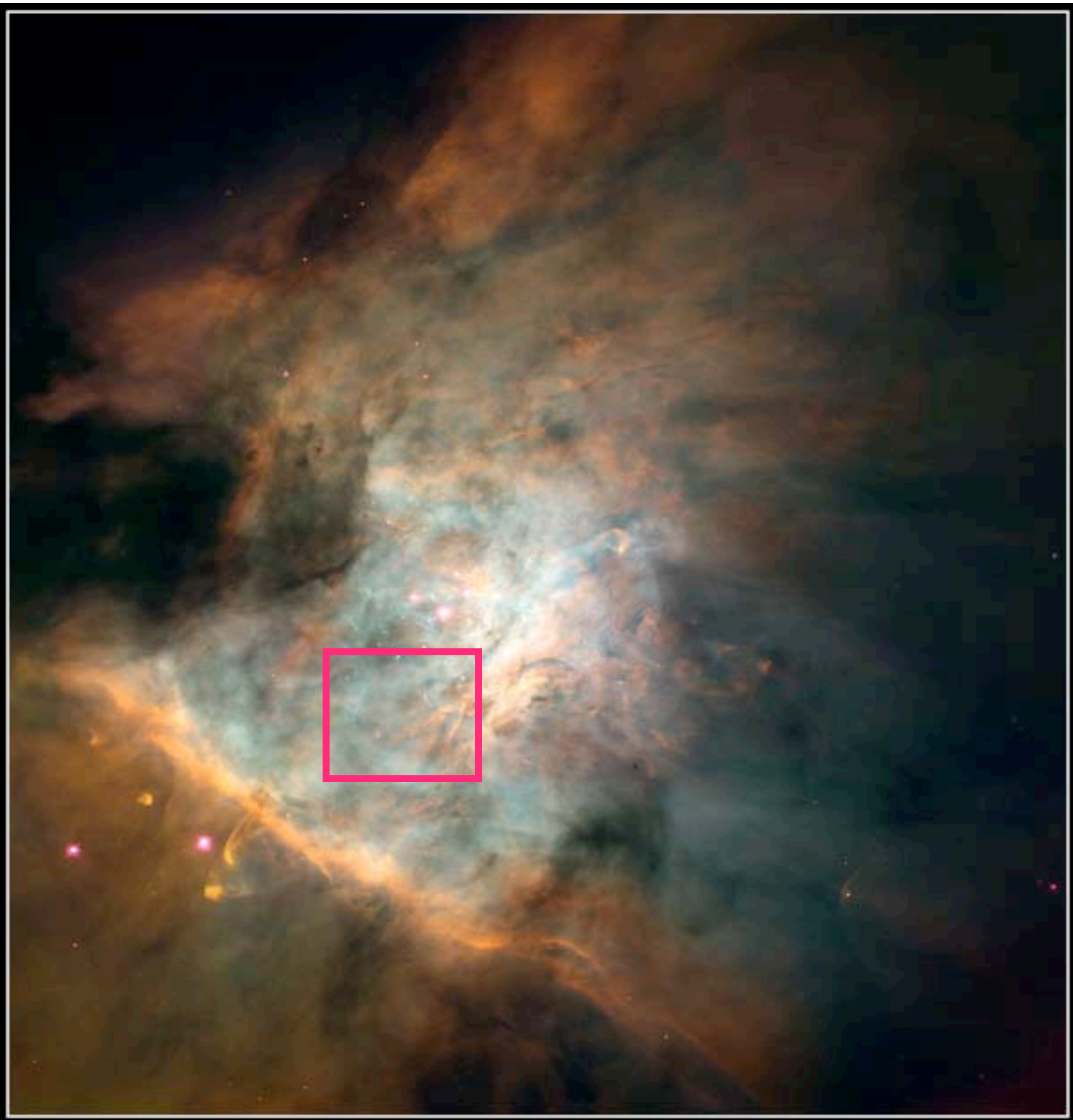
Small clouds: e.g., Taurus

- 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

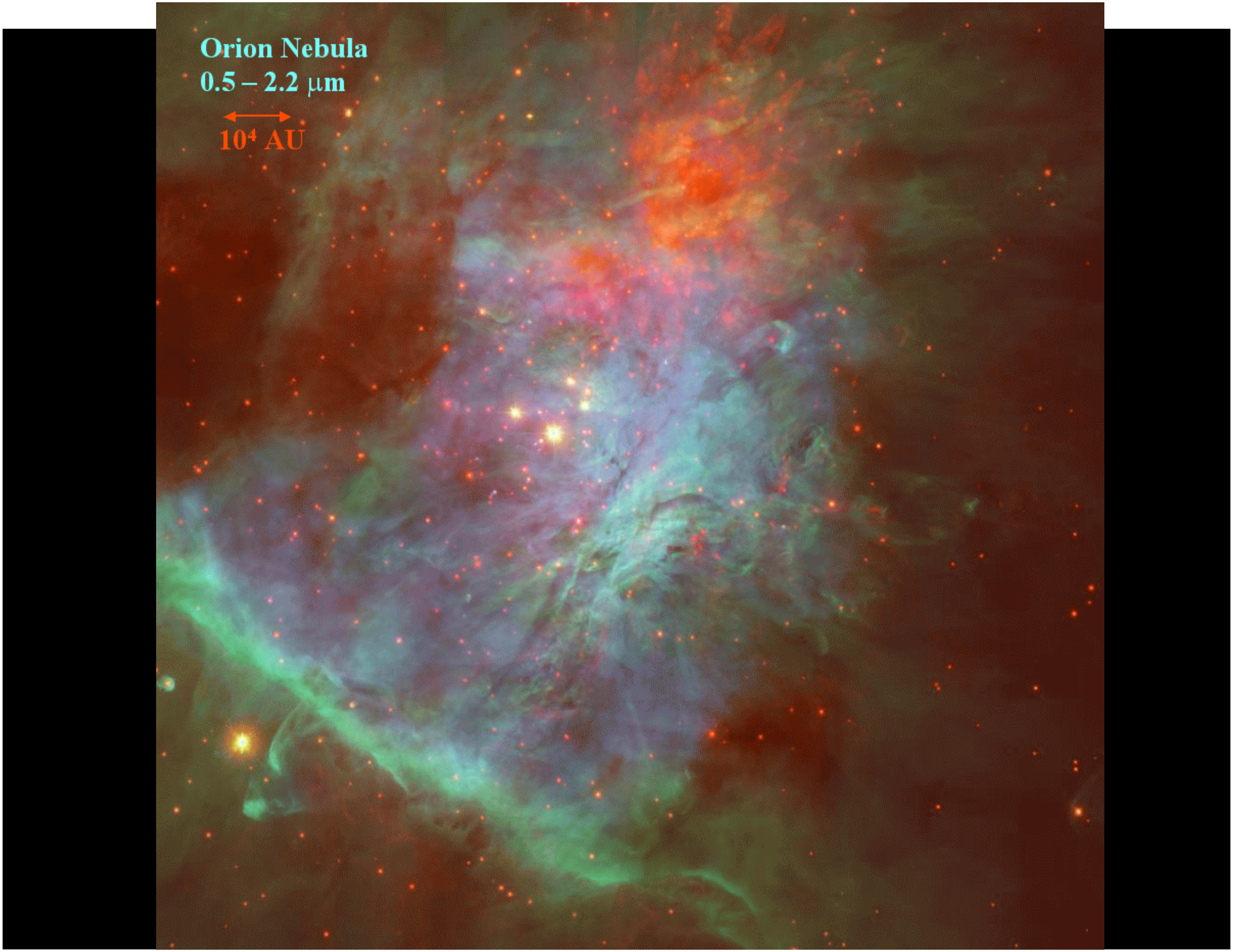

Orion Constellation
(visible light)

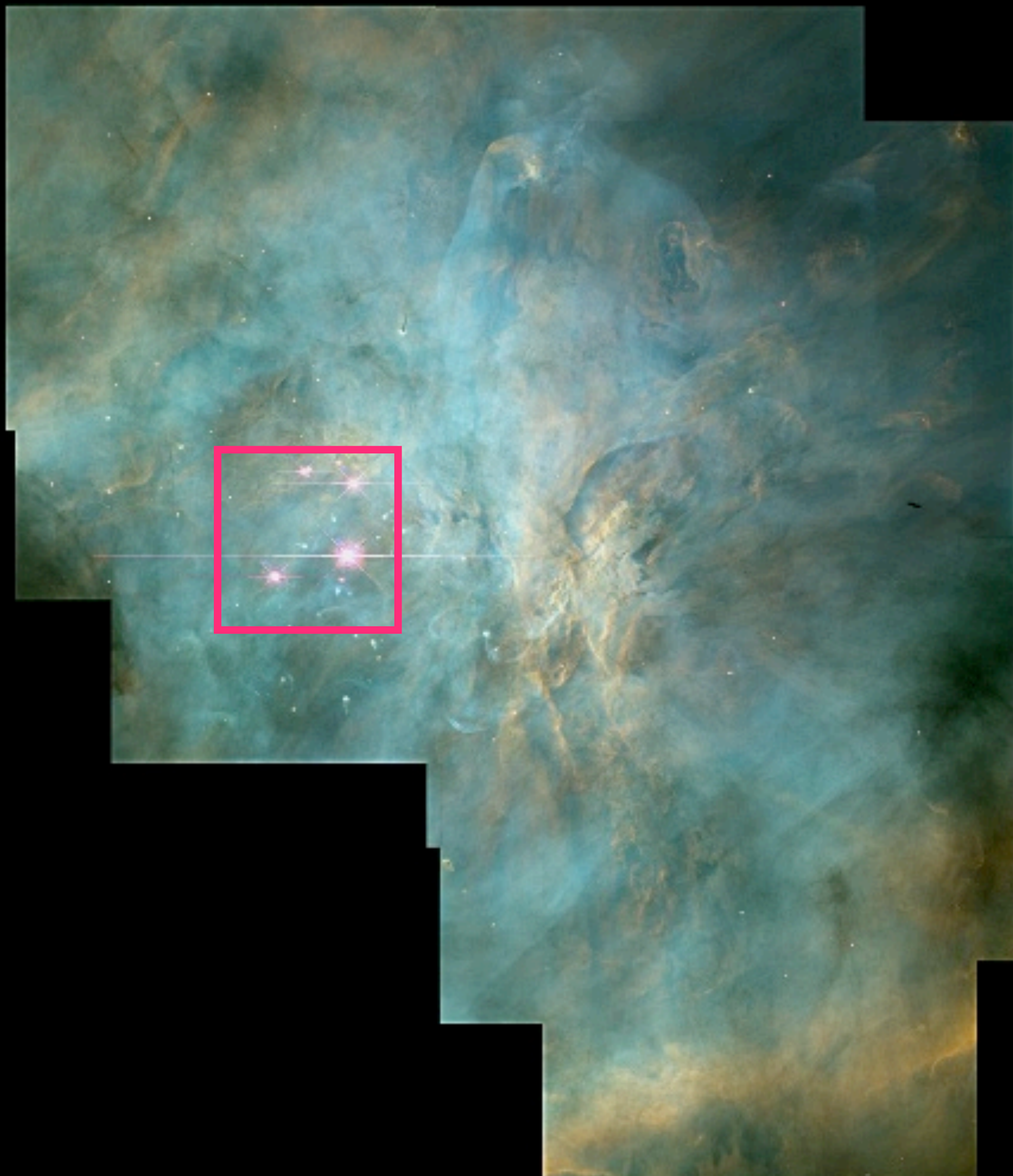

Orion constellation
(infrared light)



Orion Nebula Mosaic HST • WFPC2

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

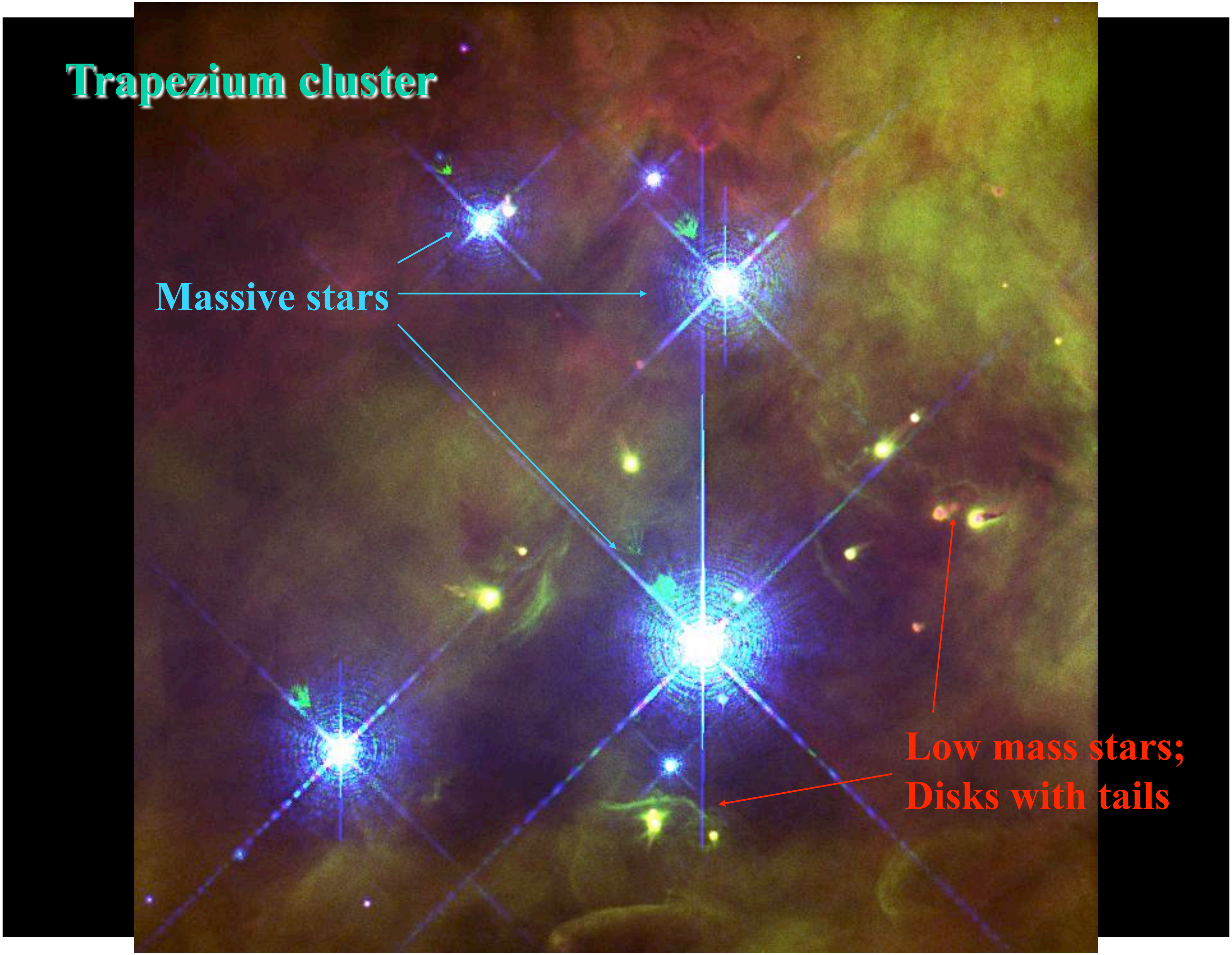

Orion Nebula
0.5 – 2.2 μm
10⁴ AU



Orion

- 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

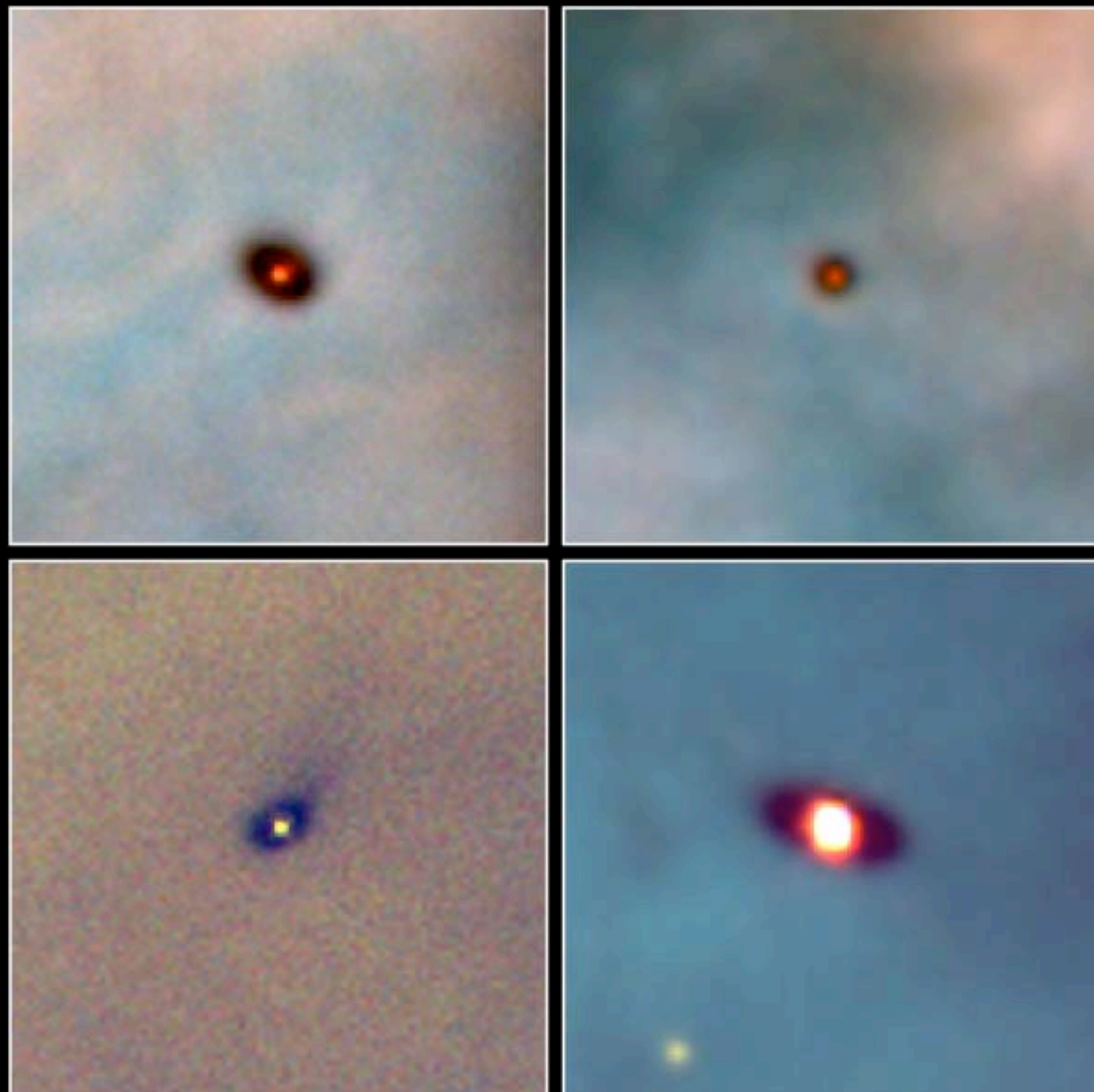
- HST resolution of Orion ~ 20 AU



Trapezium cluster
Massive stars
Low mass stars;
Disks with tails

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

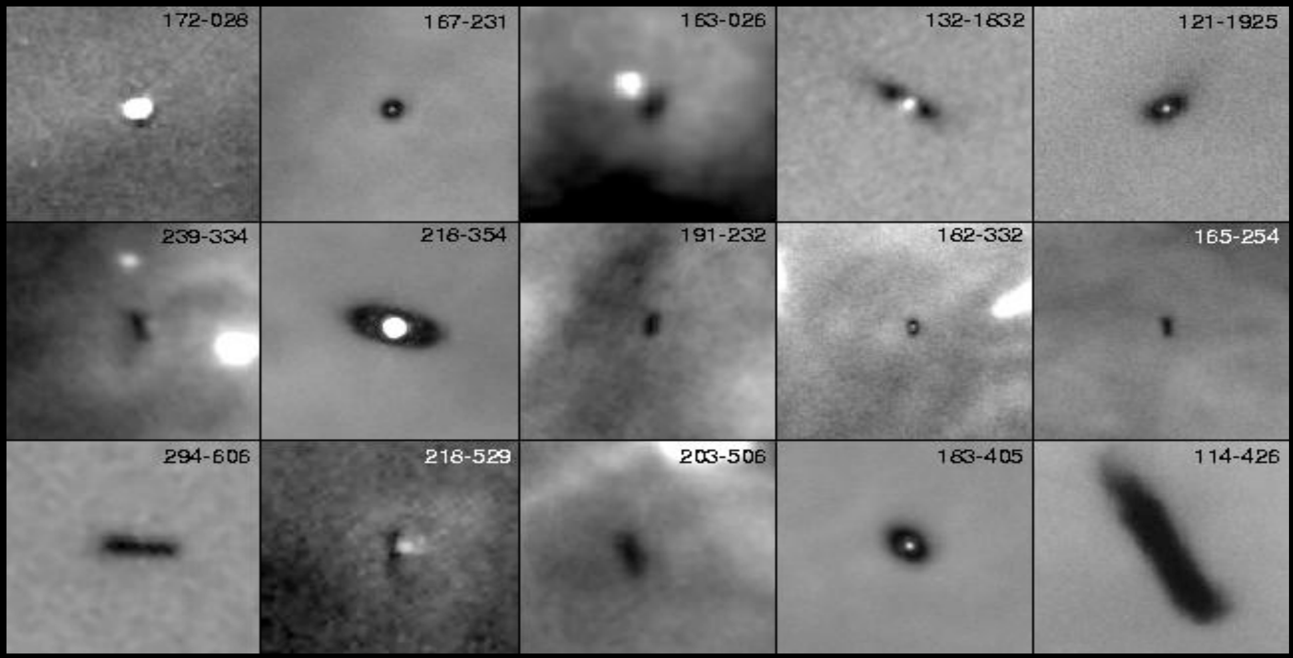


Protoplanetary Disks
Orion Nebula

HST • WFPC2

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

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.

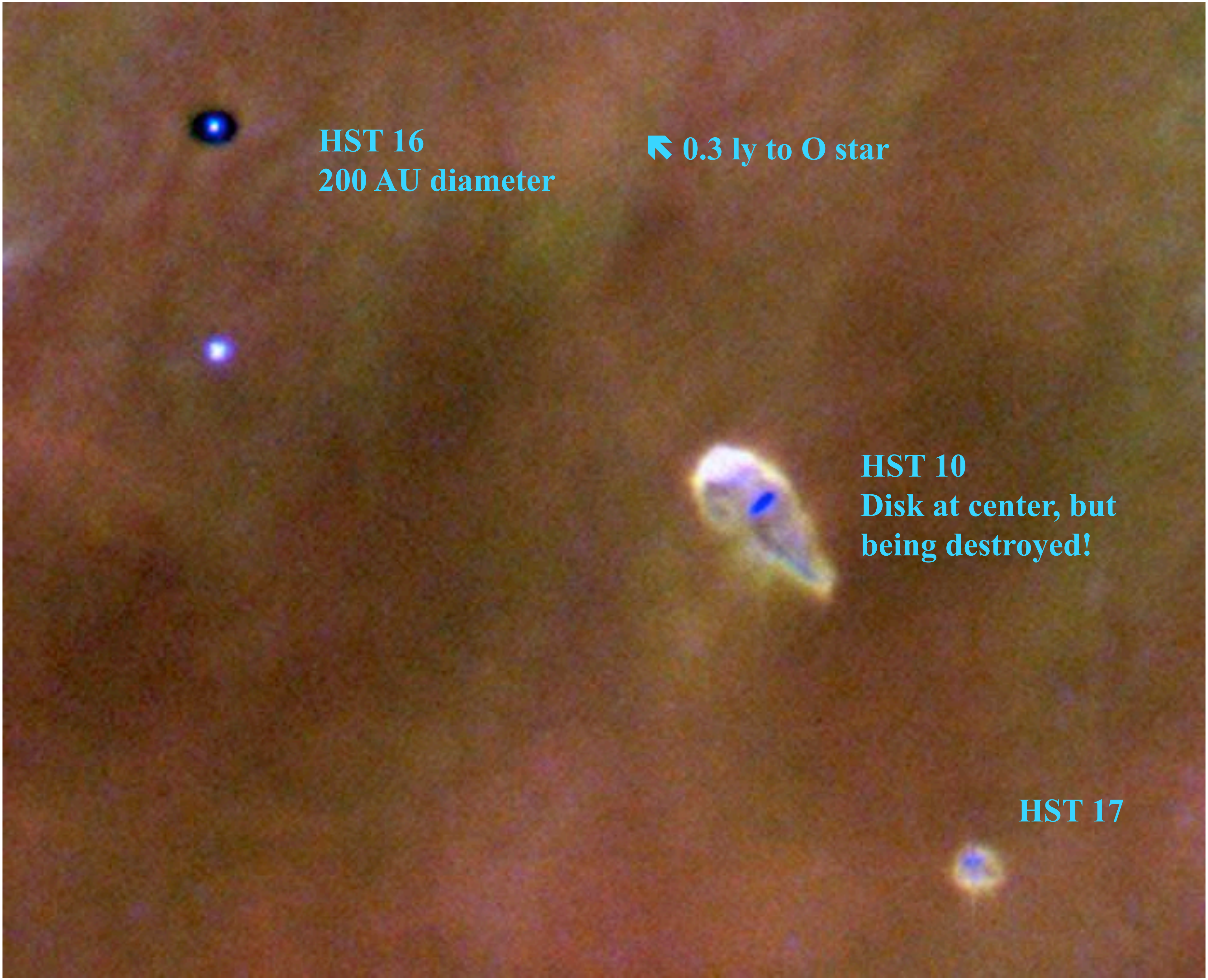
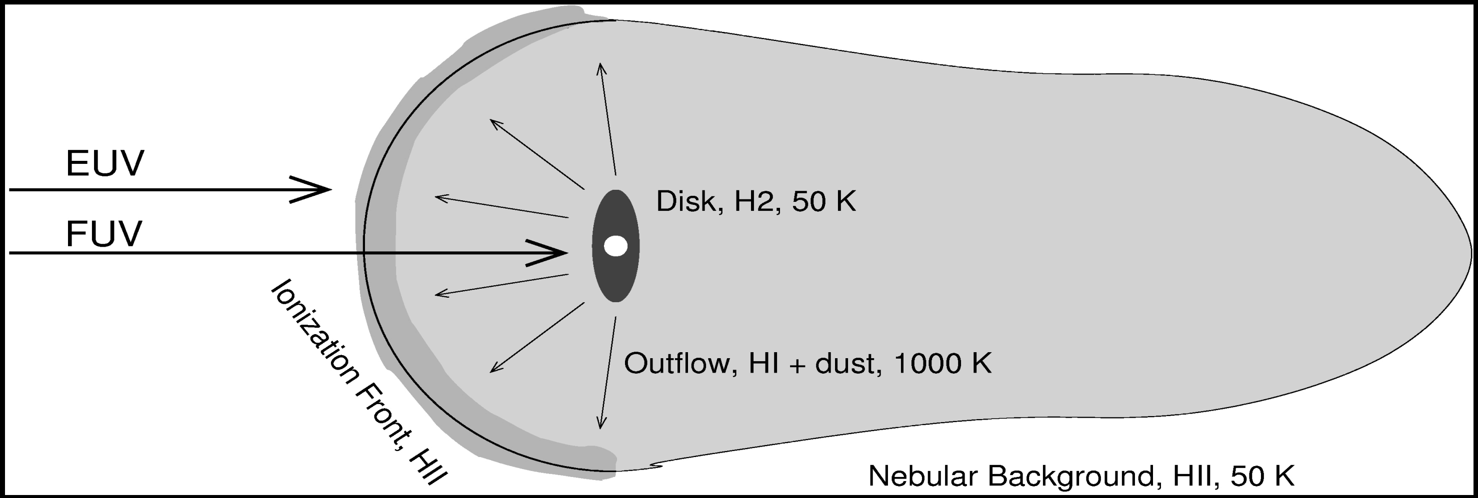

HST 16
200 AU diameter
0.3 ly to O star
HST 10
Disk at center, but
being destroyed!
HST 17

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!

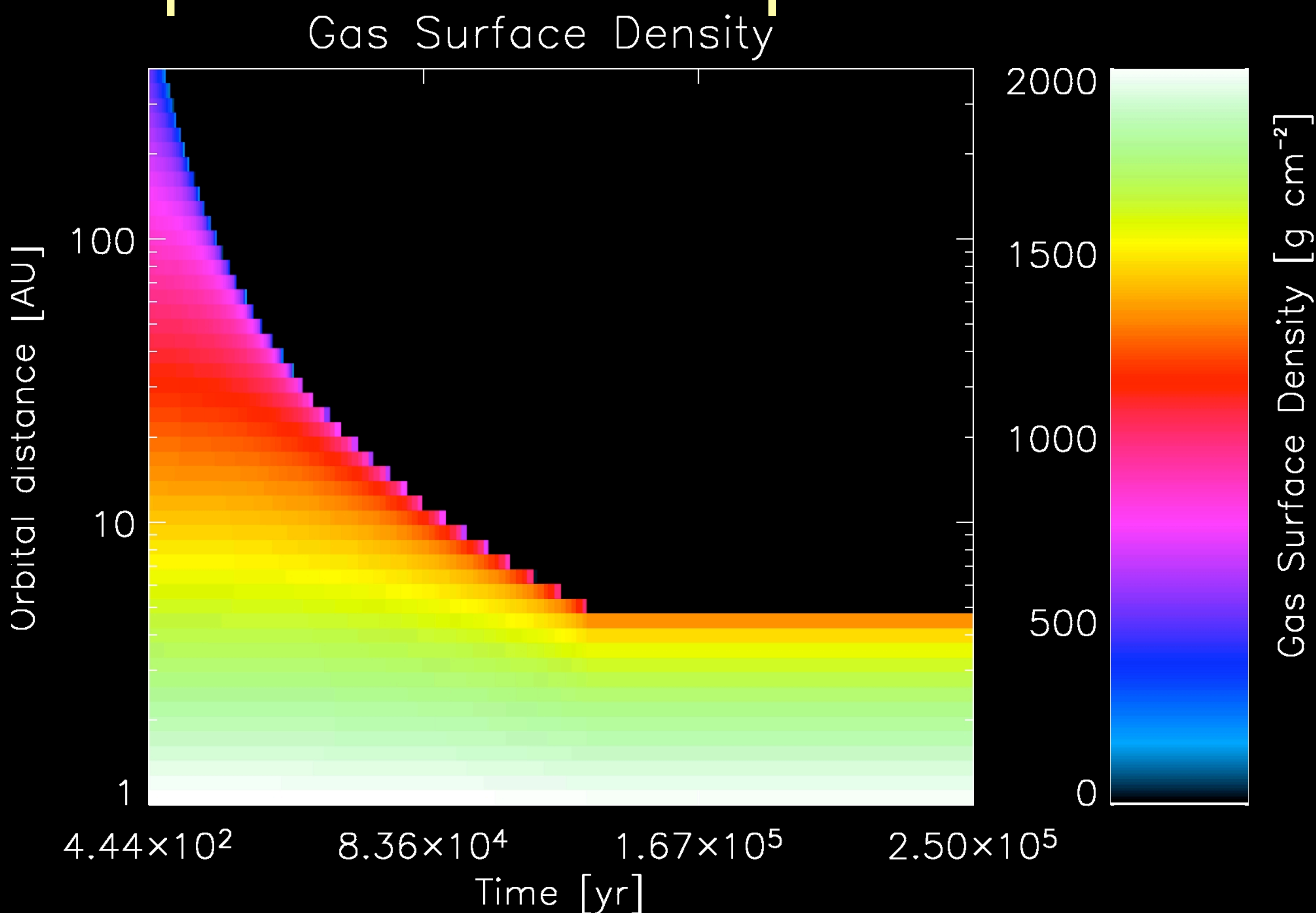
We can't see planets in Orion. But, by modeling the interaction between the disk and UV flux, we can make predictions about how the disk is lost, and how this affects planet formation.



Model of Photoevaporation

- Numerical code which tracks gas, ice, dust around solar-mass star.
- Processes:
  - Grain growth
  - 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.*

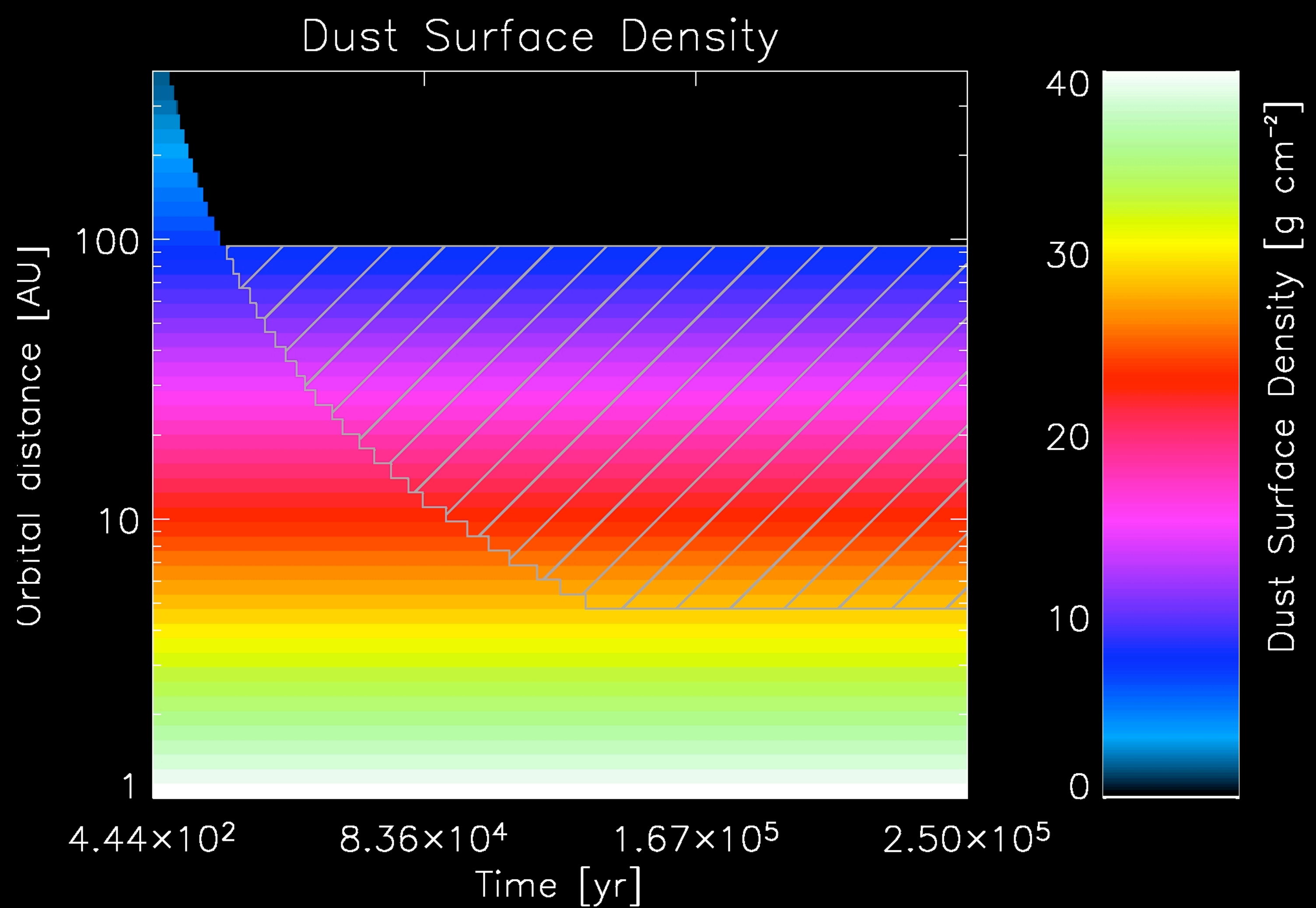
Output of Photoevaporation Models



Disk is removed in < 1 Myr

Jupiter takes ~ 10 Myr to form

-> Gas planets like Jupiter could not form in these systems!

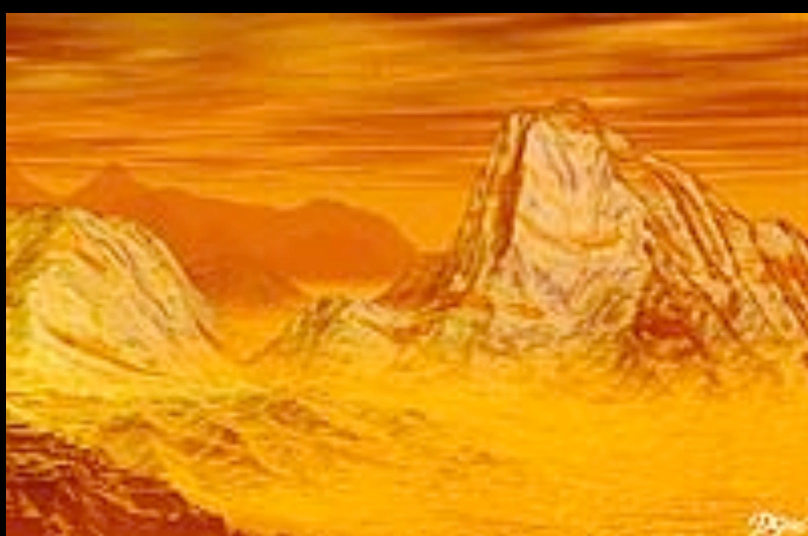


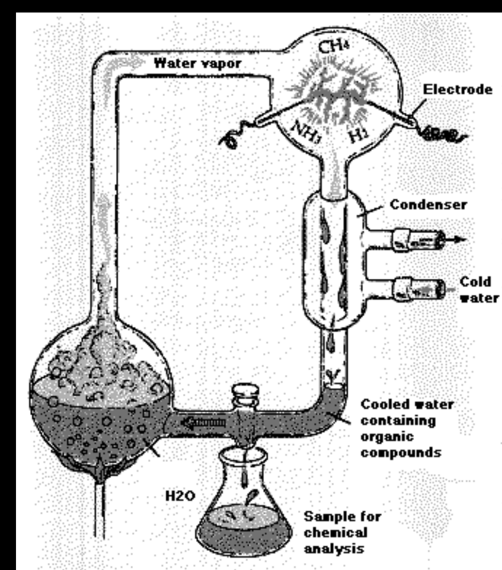
Dust is removed from the disk, but only at the outer edges

-> **Formation of terrestrial planets is possible!**

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

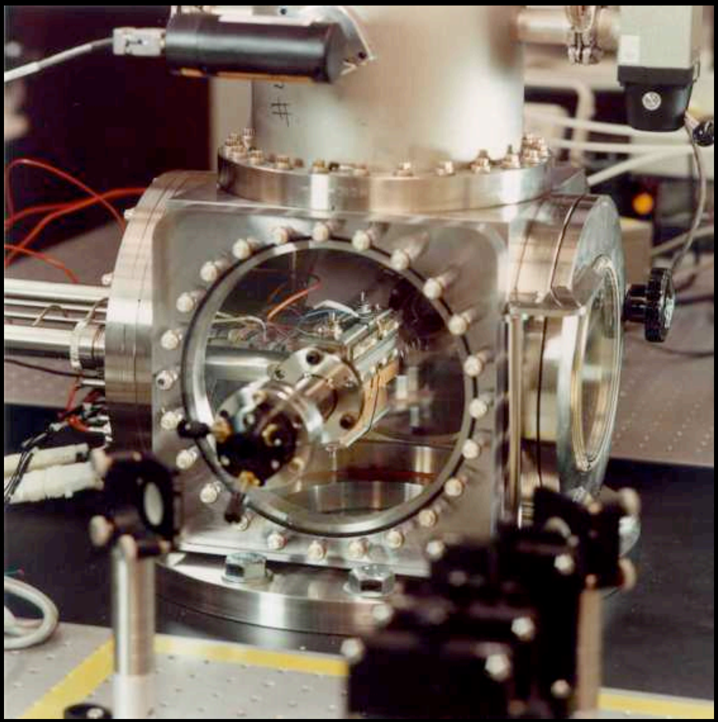
- Standard model for formation of organic molecules on Earth uses warm, wet, liquid chemistry and lightning (e.g., Miller-Urey experiment).
- Comets are 30%+ organics by mass - much of this complex organics
- Murchison meteorite had 70+ different amino acids on surface (~5% aminos + carbon polymers by mass). Did asteroid *really* have oceans + lightning, or were organics made a different way?



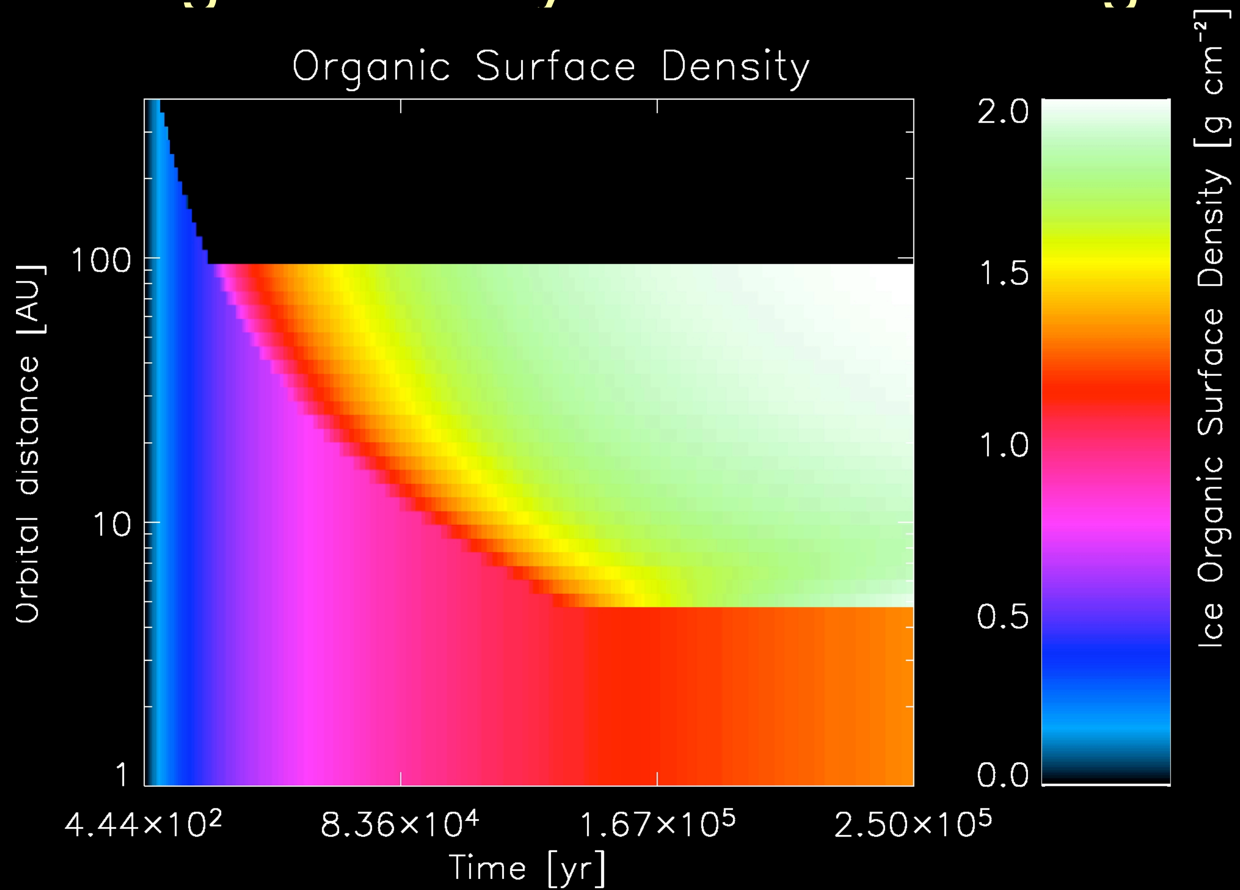


UV Formation of Organic Molecules

- Lab work at NASA Ames: UV flux into frozen ices can create complex organic molecules from simple ones.
  - 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



UV light from bight stars in Orion turns simple ices into organic molecules.

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

Question: Does UV **destroy** these organics in addition to **creating** them?
A: We don't know, yet…

Where Did Our Solar System Form?

- Statistically, most stars formed near O stars -- although this says nothing about our Sun.
- We are not in a giant cluster now -- but could we have been, 5 billion years ago?
  - Any cluster would have dispersed long ago -- they are short-lived.
  - Hard to track back motions of the stars for 5 Byr.
- Can chemistry of the solar system give us any clues?
  - Chemical isotopes found in young meteorites (e.g., ^{26}Al) require a strong neutron source at their formation. No known natural object besides a supernova from massive stars can provide this neutron source.
  - Conclusion: Solar System probably formed near a supernova.

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!

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
- Gas giant planets may be able to form, if they form rapidly
- Photo-evaporation may encourage the formation of high-metallicity planetary systems (e.g., gas giants with high-mass cores)

Circumstellar Disks and Pluto

- We have found literally **thousands** of young circumstellar disks. Disks are easier to detect than planets, and more plentiful.

- From Alpha Centauri, the easiest way to see our solar system directly (at least when young) is not by looking for planets, but by looking for its Kuiper Belt (i.e., Pluto) and Oort Cloud!

- The disks surrounding other stars relate directly most directly to Pluto, more than any other planet.

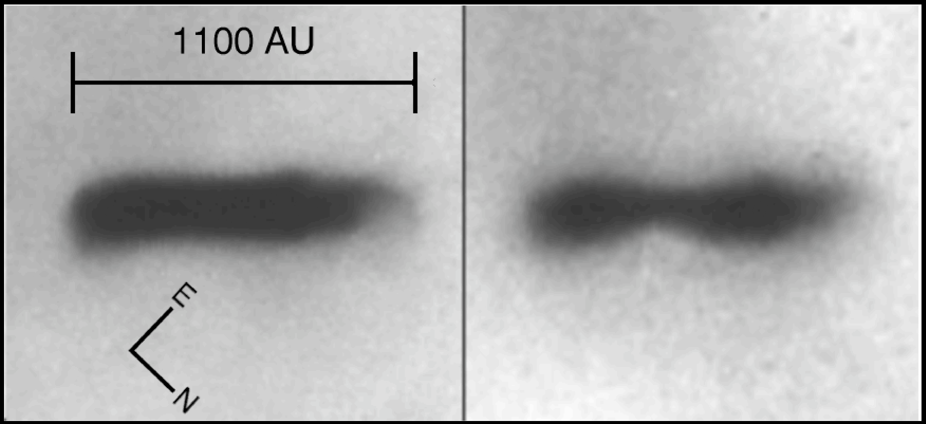
- Pluto is:
  - Cold (35K)
  - Old (4.5 Gyr surface; little erosion on surface beyond impacts)
  - Distant (40+ AU)

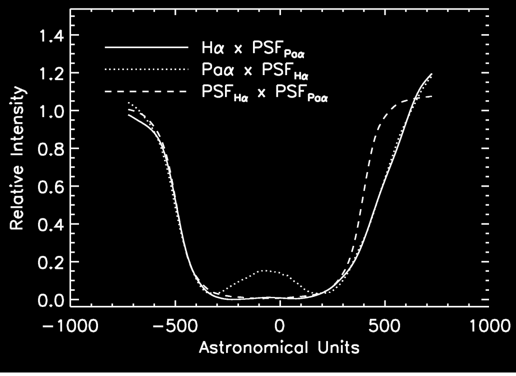
… And we're going there!

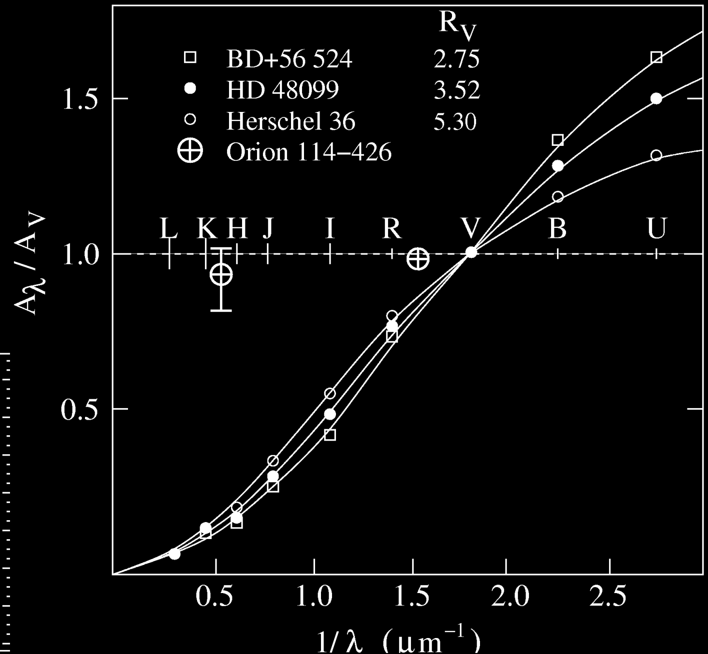
July 14, 2015: First visit to the circumstellar disk surrounding our own Solar System, when New Horizons reaches Pluto…

Observations of Grain Growth

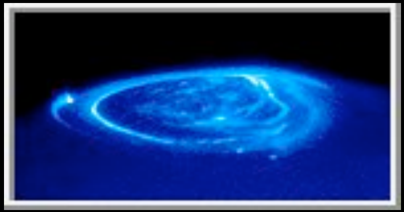
- Grain size can be probed by measuring the disk's wavelength-dependent extinction
- Low optical depth dust usually causes reddening, but here it is grey: indicates grains have grown to > few µm.
- This dust is unlike any other astrophysical dust ever observed.

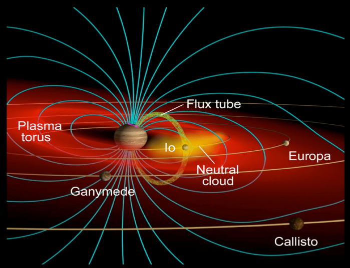


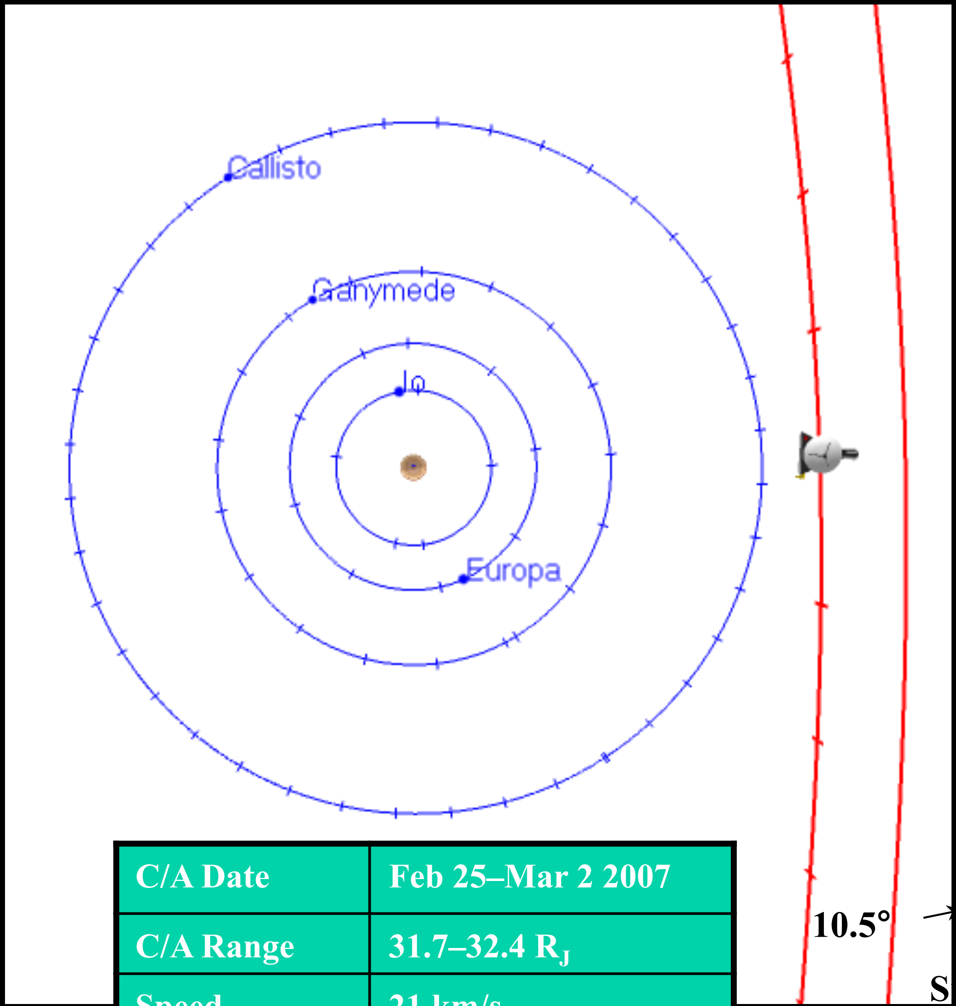




Throop et al 2001







C/A Date	Feb 25–Mar 2 2007
C/A Range	31.7–32.4 R_J
Speed	21 km/s

Proposed Timeline for Planetary Systems Formed in Dense Clusters

0 yr: Low-mass star with disk forms

10^4 yr: Grains grow and settle

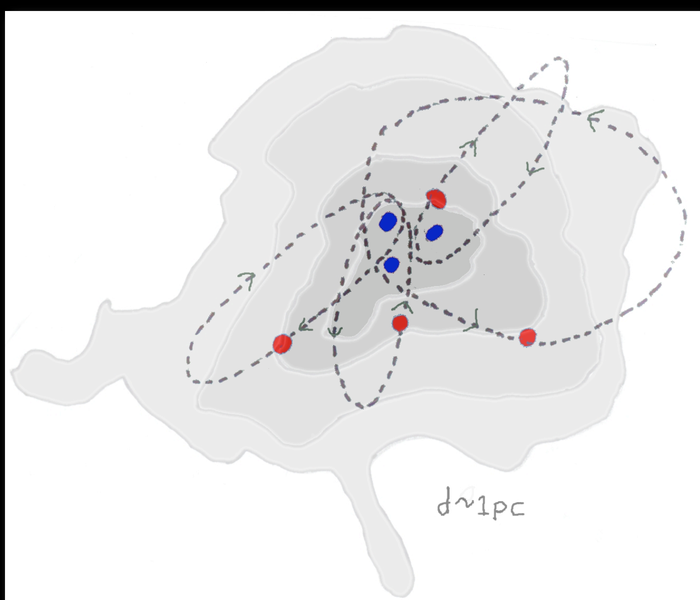
10^5 yr: Any gas giants form quickly by GI, before gas is lost

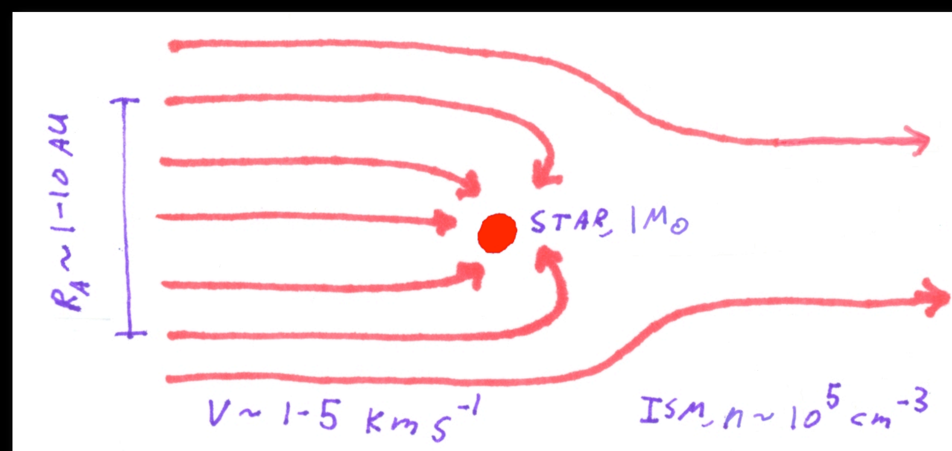
10^5 yr: O stars turn on

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

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

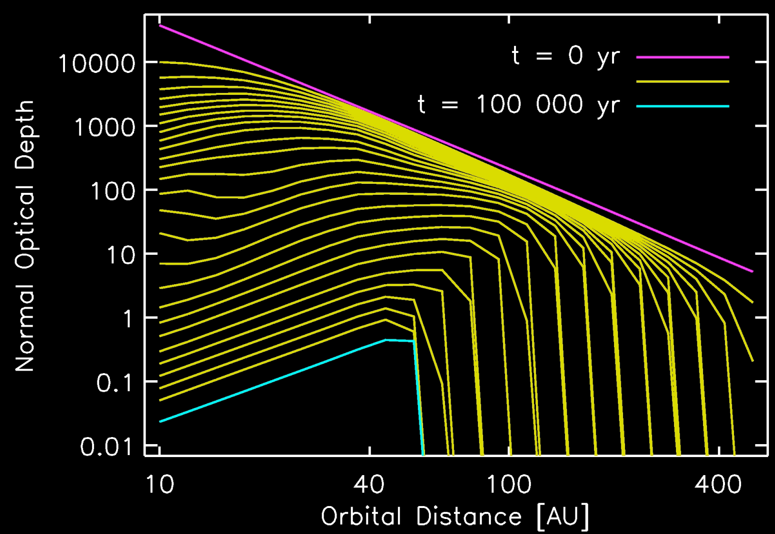


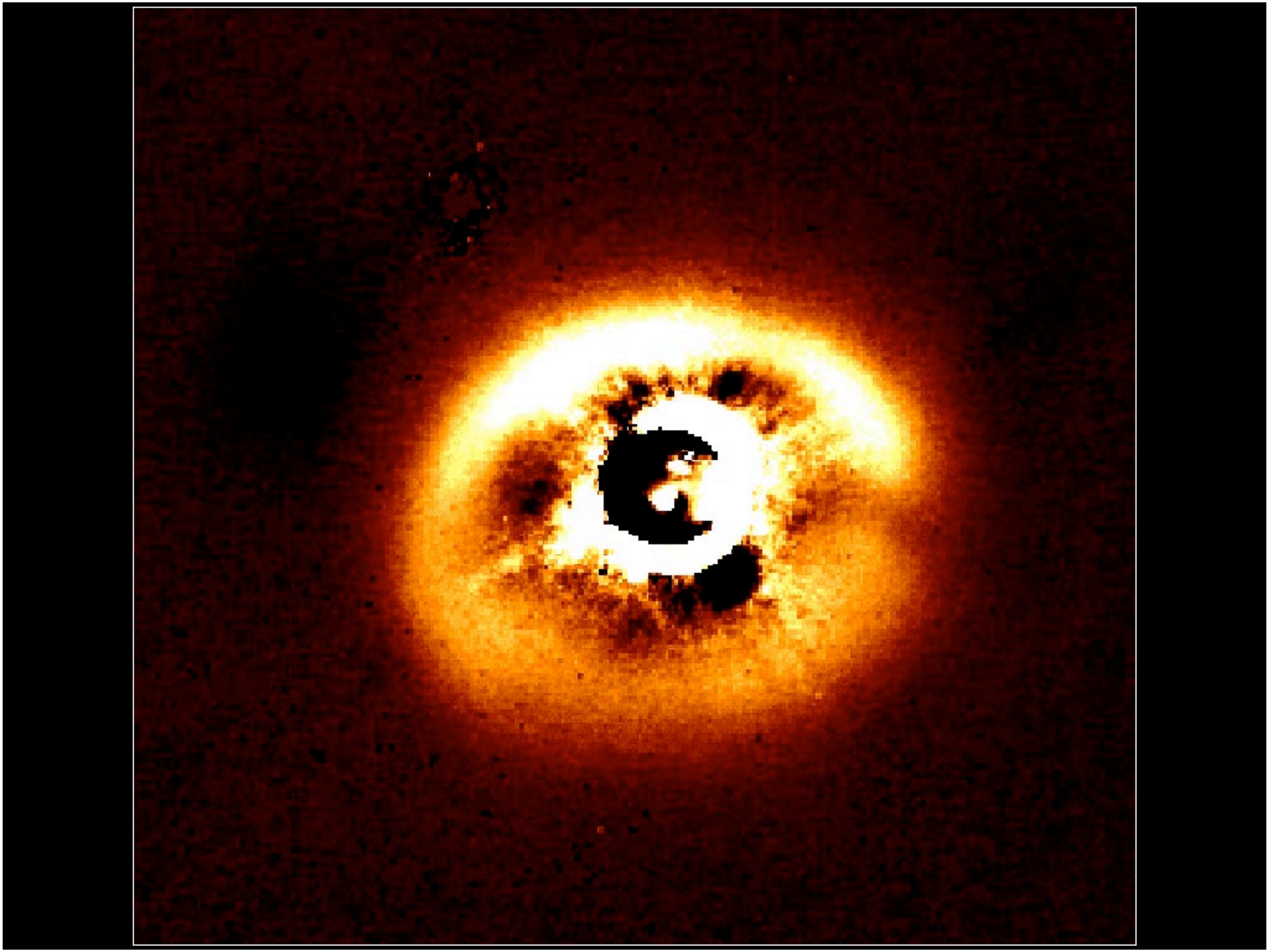


Moeckel, Throop, Bally (2005)

Grain Growth and Photo-Evaporation

- Grains grow fastest at inner edge
- Grains are most easily lost at 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!)





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.


© Akira Fujii/DMI

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.

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

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.

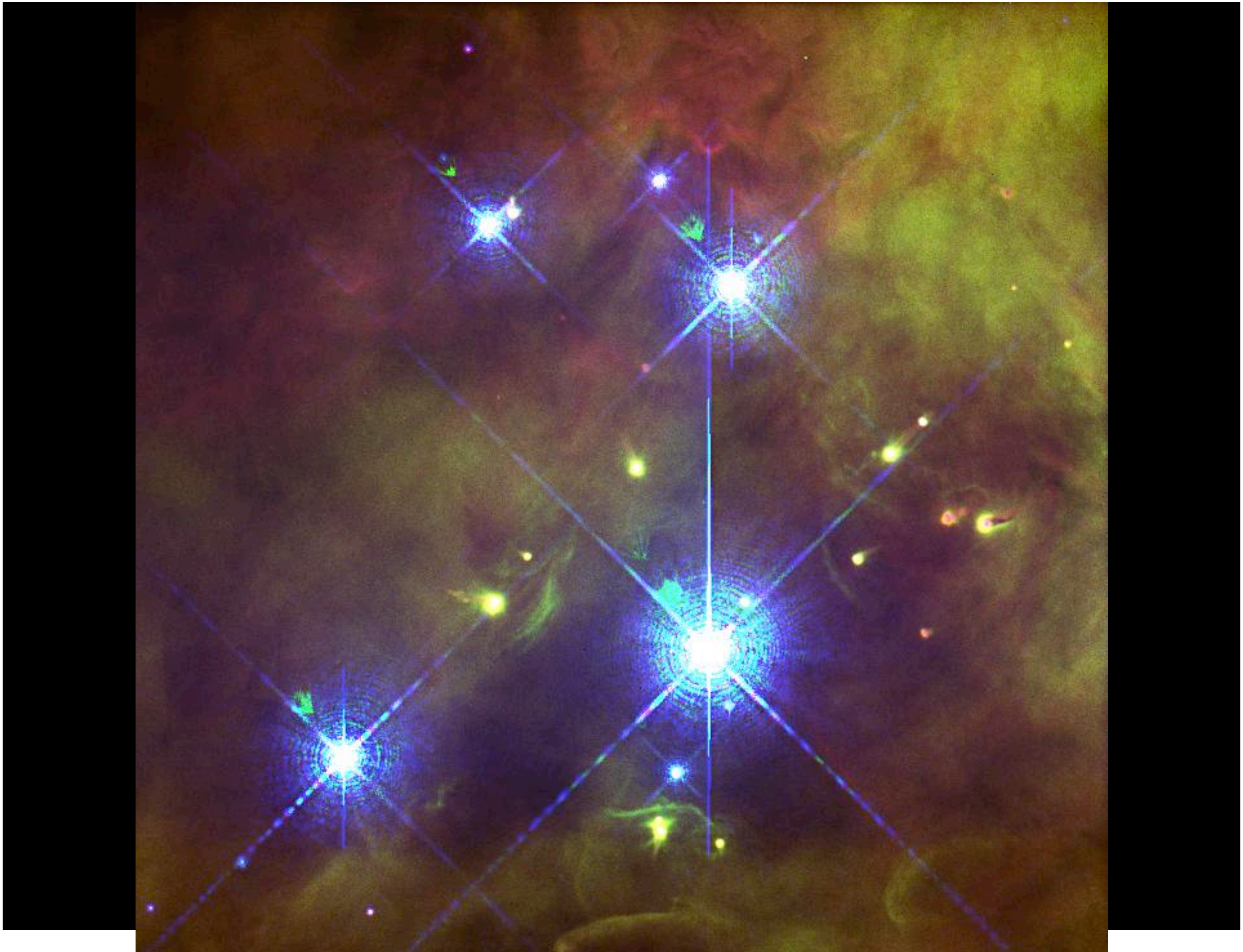
The Environment of Planet Formation

GG Tau

Ultra-high-sensitivity HDTV I.I. color camera (NHK)
Exp. 9 sec. (9 frames coadded) January 16, 1999

Subaru Telescope, National Astronomical Observatory of Japan

Dense Clusters vs. Field Stars



Dense Clusters

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

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)

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

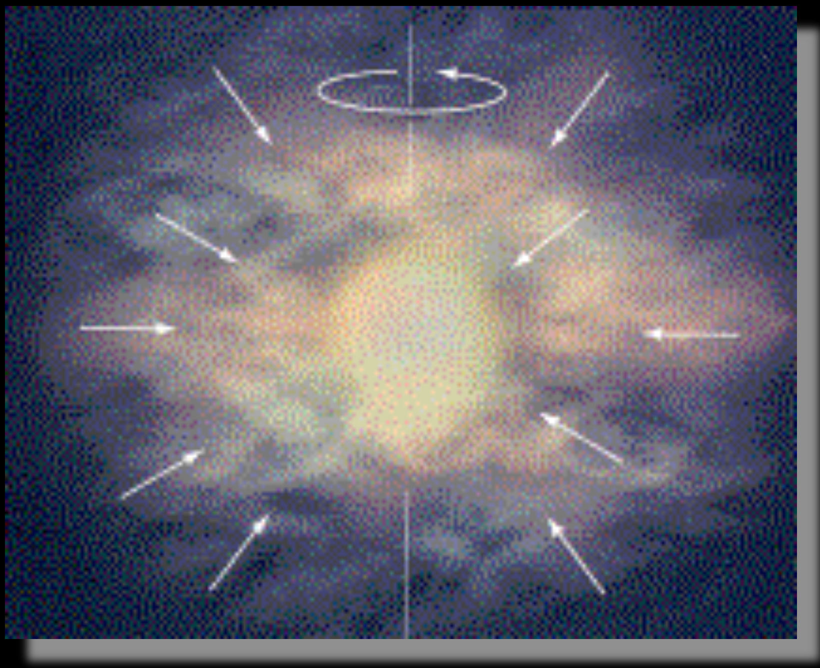
Close Encounters

Is Planet Formation in these Environments Hazardous… or Not?

The End

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)



Life Cycle of Giant Molecular Clouds (GMCs)

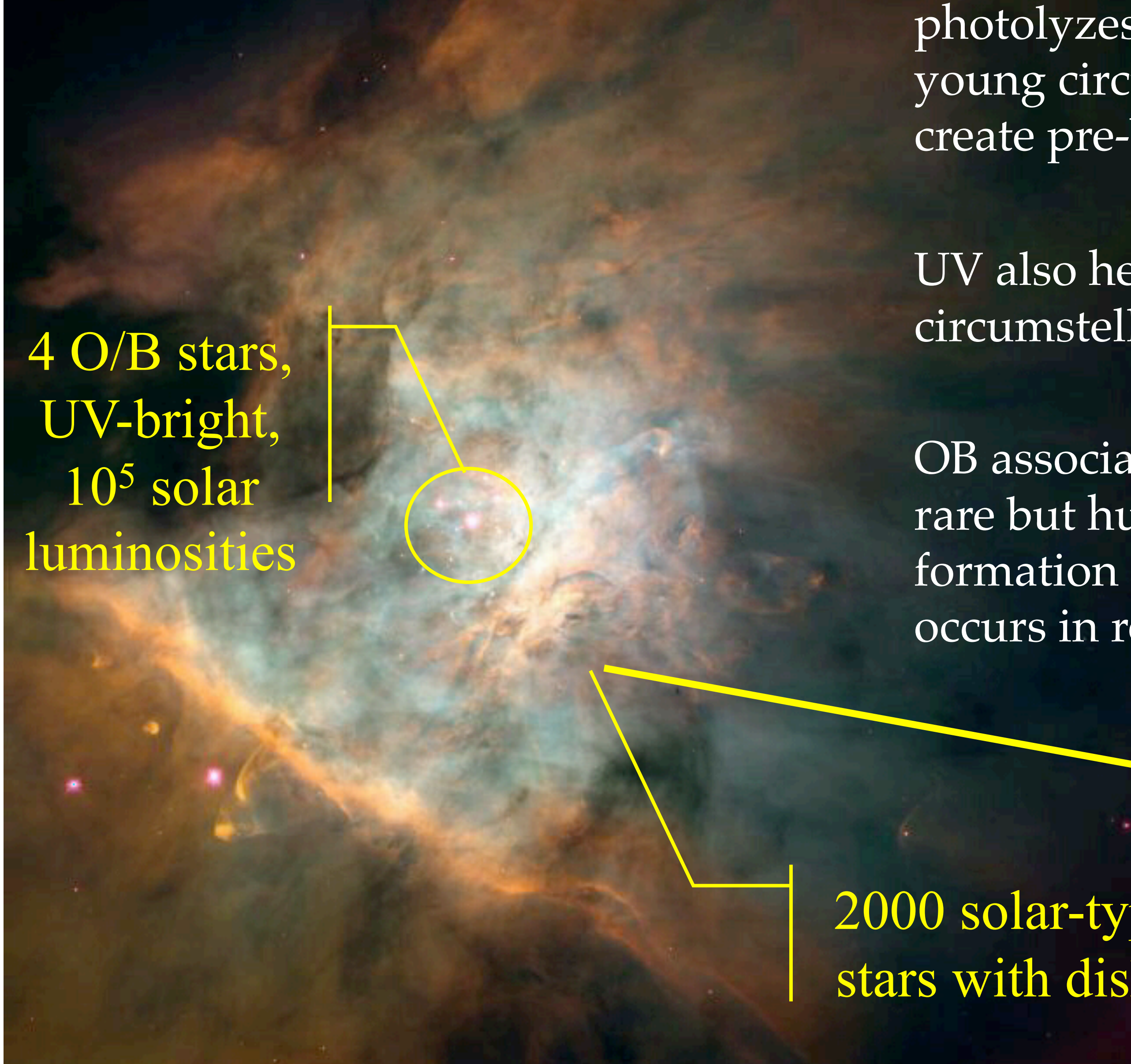
- Star formation is inefficient: 90% of gas remains not in stars, but in nebula
- After O and B stars die (few Myr), gas is dispersed. Nebula is gravitationally unbound, and stars are ejected as field stars.
- Most field stars today were formed in GMCs.
  - Orbital paths cannot be traced backward for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

Additional Slides


0.5 – 2.2 μm
10^4 AU

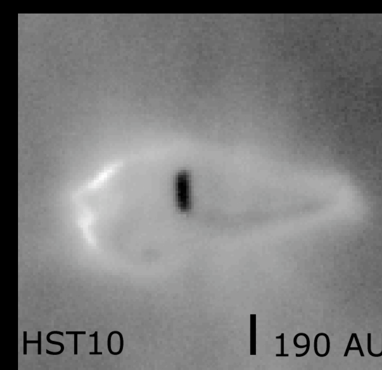
Orion Nebula

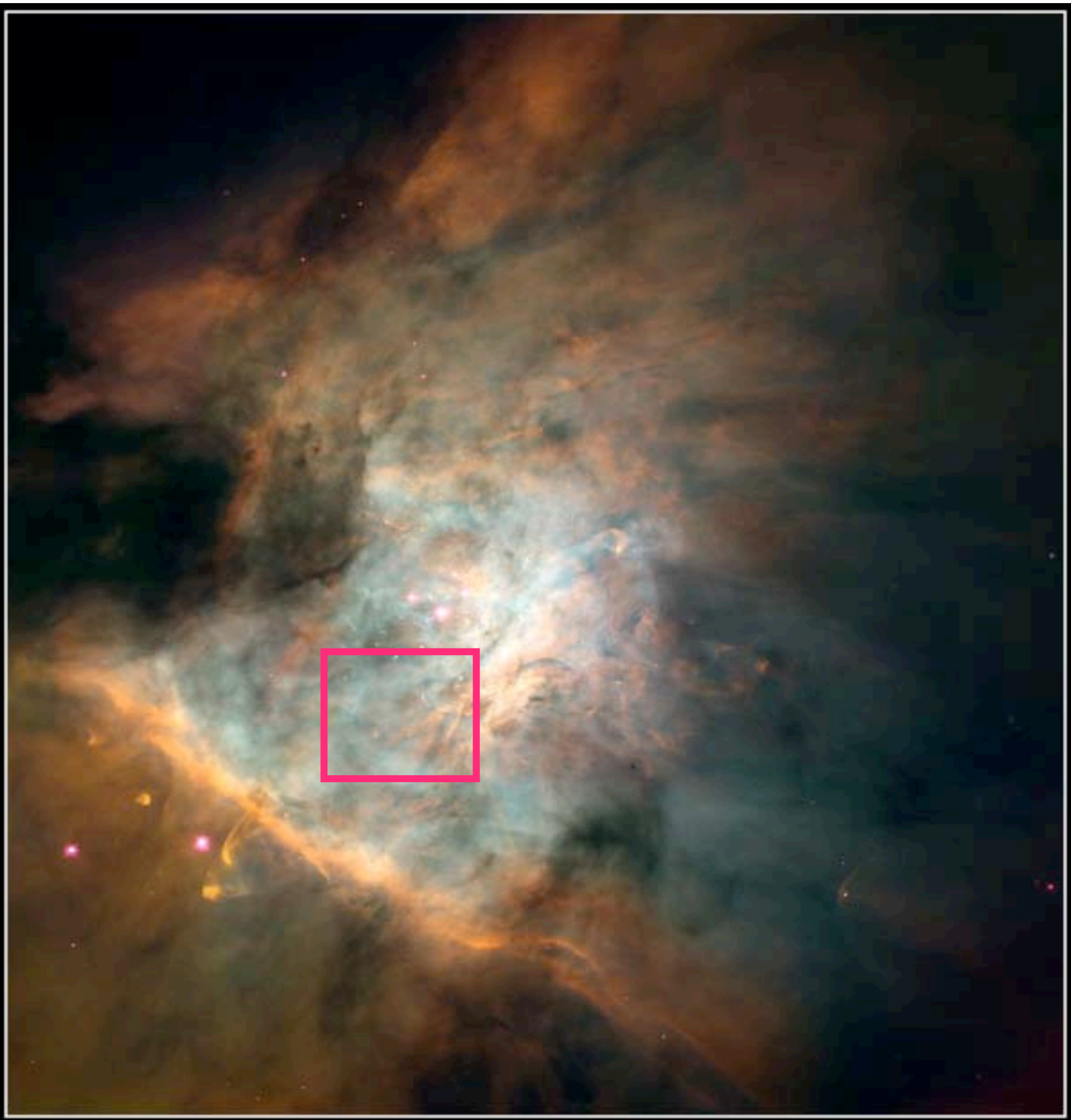


UV light from massive O/B stars photolyzes ices in nebula and young circumstellar disks to create pre-biotic organics.

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

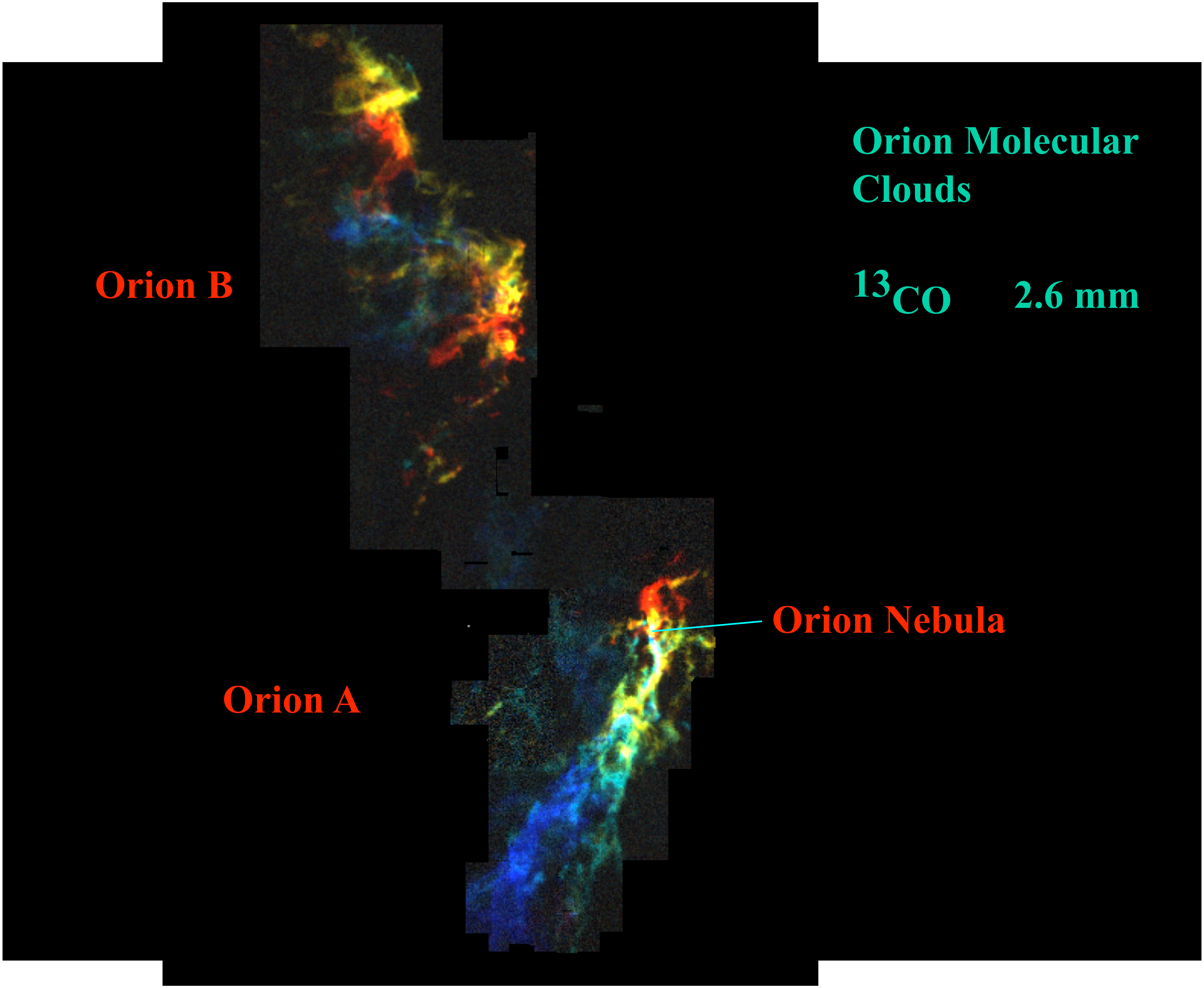
Henry Throop / Southwest Research Institute, Boulder

throop@boulder.swri.edu

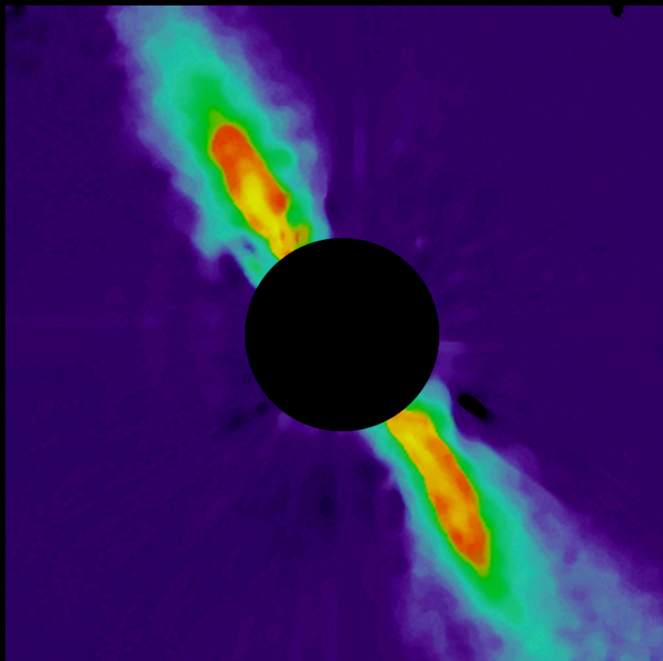
John Bally / University of Colorado, Boulder

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.

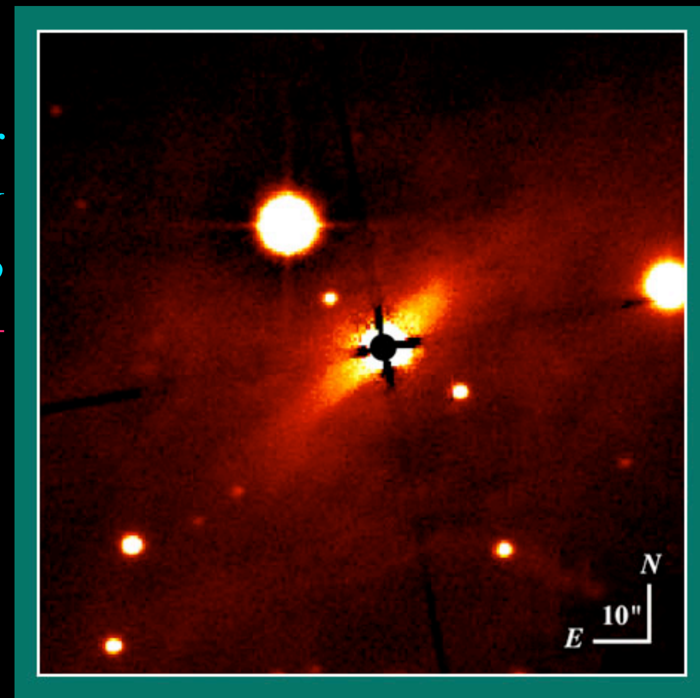

Orion Molecular
Clouds
^{13}CO 2.6 mm
Orion B
Orion Nebula
Orion A

Dust disks are common in the universe!

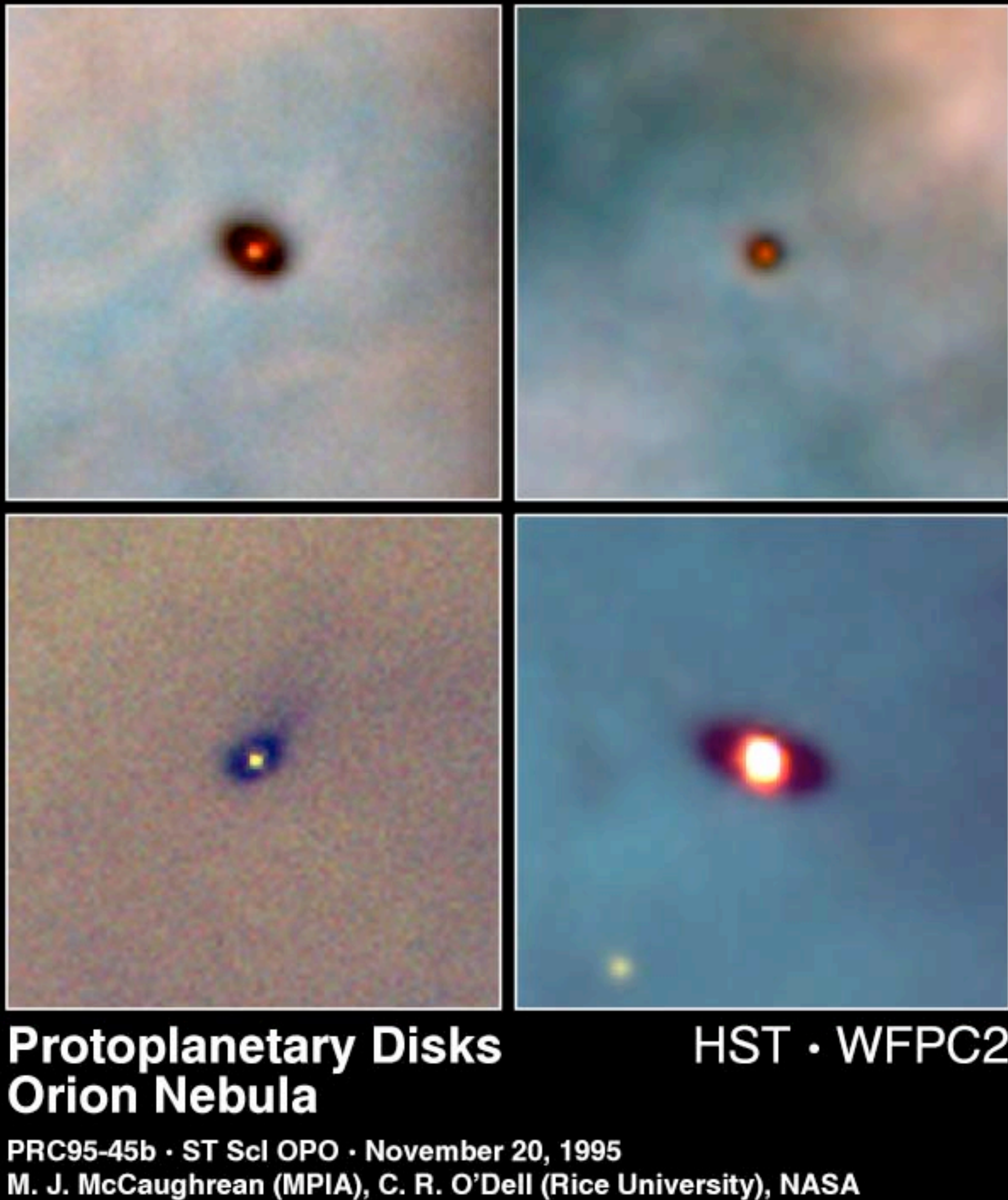


Beta Pictoris
1000 AU
Old - 1 Byr?

BD +31 643
Orbits binary star
500 AU
10 Myr?



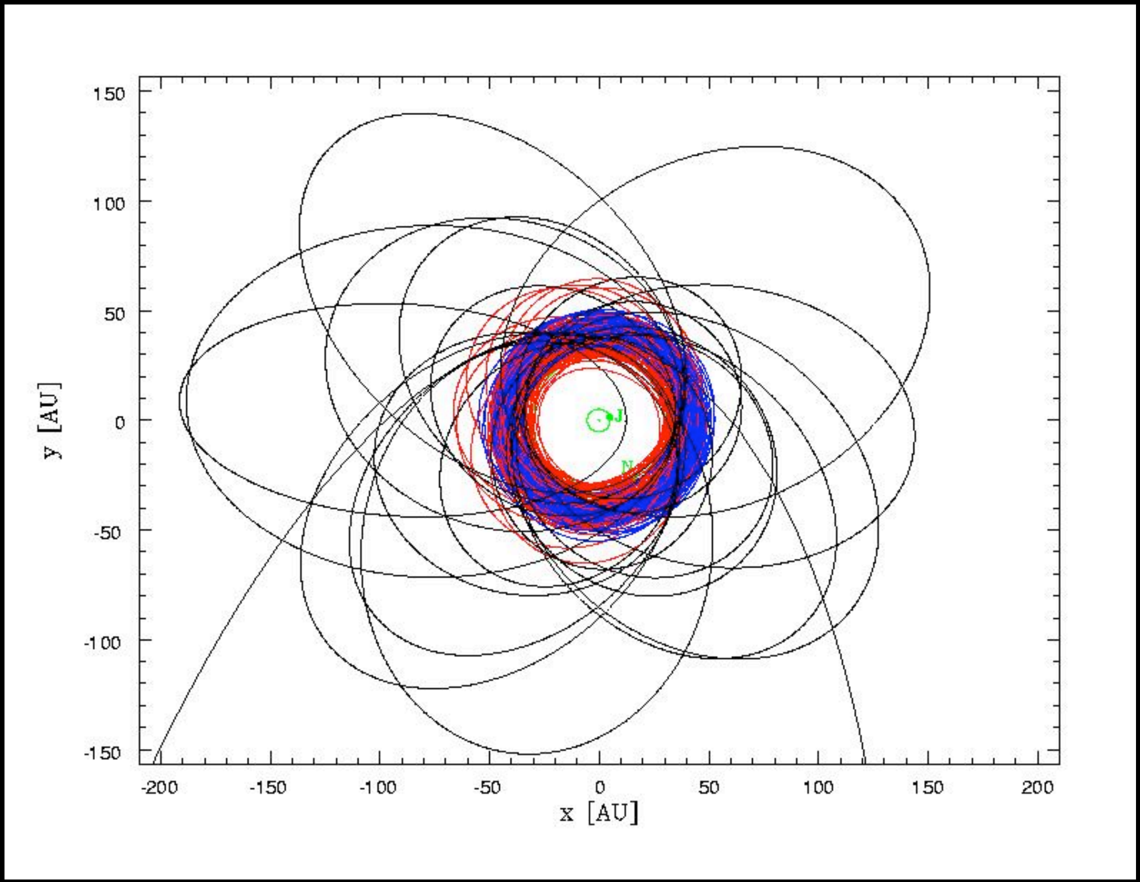
Zodiacal dust
Surrounds Sun
2-2000 AU?
5 Byr



Orion Disks

- Size scales 50-1000 AU
- Dozens of disks
- We see them by their dust
- Disks are in silhouette,
  lit from behind
- Central stars usually visible
- Young - age ~ 1 M yr
- No planets - yet?

Structure of our Solar System



0-3 AU: Terrestrial planets (rocky)

5-40 AU: Jovian planets (gas giants)

40-200 AU: Kuiper Belt, Pluto (icy)

-200,000 AU? : Oort cloud (icy)

Plot shows orbits of known Kuiper Belt Objects ('planets' beyond Pluto)