Where planets are formed: Protoplanetary disk evolution and planet formation in different Galactic environments

M. G. Guarcello – Harvard-Smithsonian Center for Astrophysics

Outline

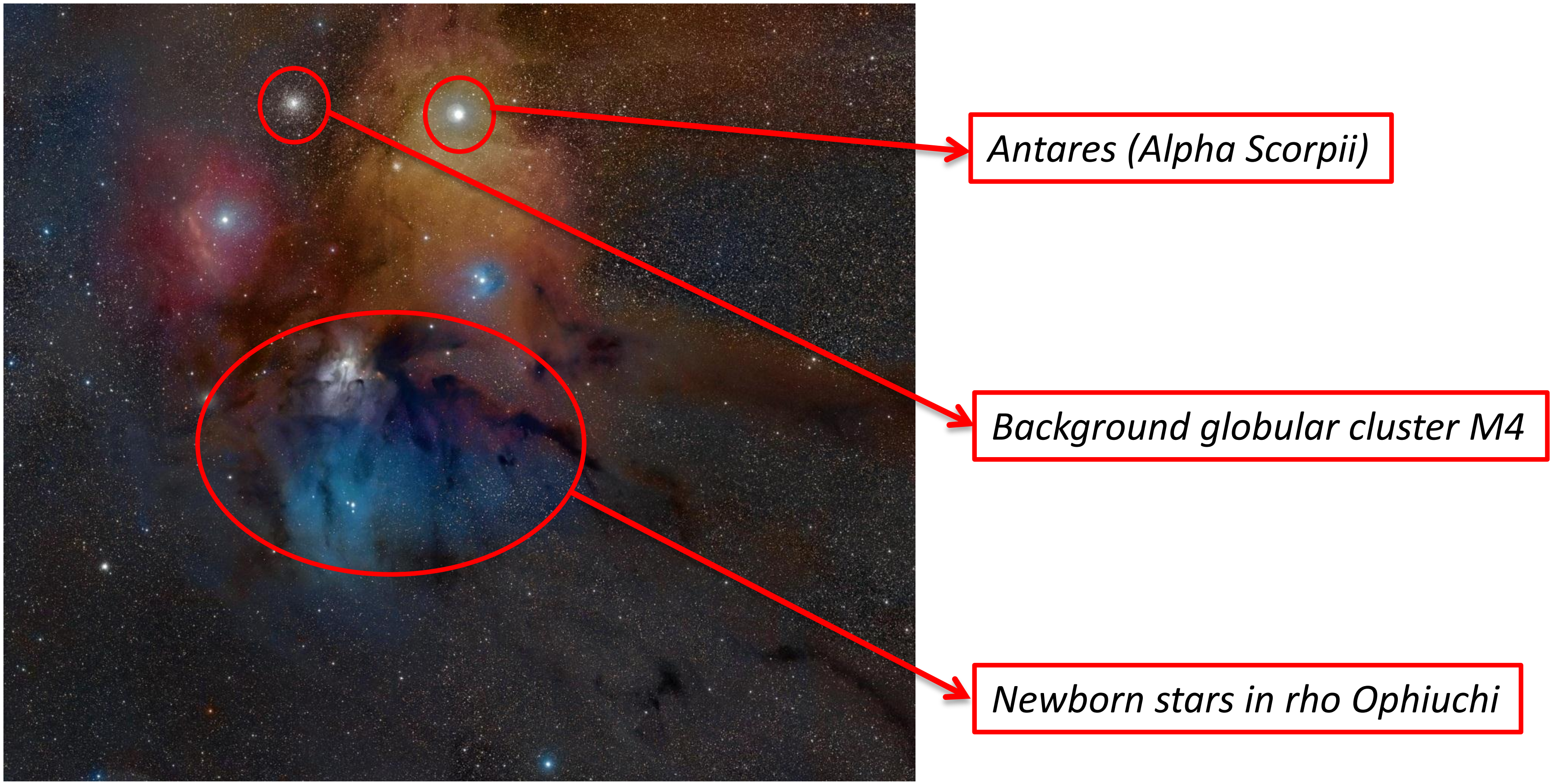
- Where stars and planets form?
- How the environment can affect planet formation?
- What is the most suitable environment for planet formation?
- What was the forming environment of the Solar System?

Where stars and planet form?

Where we observe star formation

90% of stars form in clusters embedded in collapsing molecular (mostly neutral hydrogen) cloud. ***(Lada & Lada 2003)***

E.G.: rho Ophiuchi (140 pc away)



Cluster's infant mortality

Why we don't observe almost all the stars in cluster?

Less than 10% of the embedded clusters survive longer than 10Myrs ***(Lada & Lada 2003)***

The large majority of stars spend the first 10Myrs of their life in a stellar cluster.

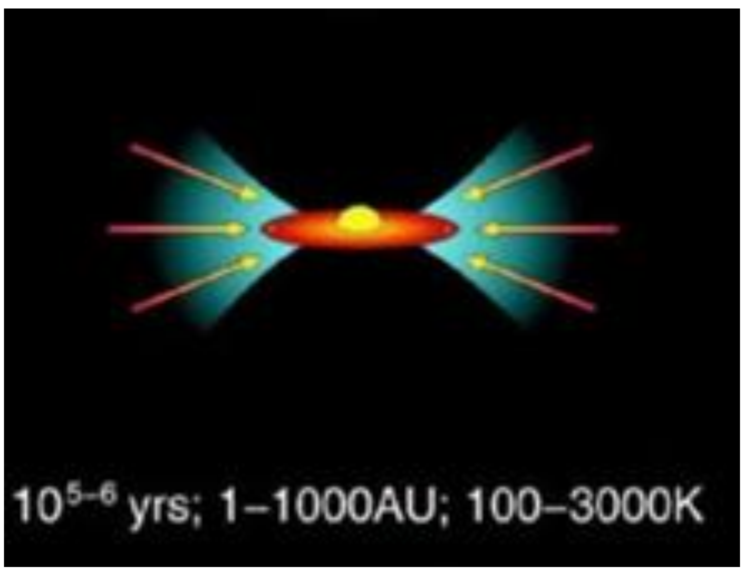
Optical image of the double open cluster NGC 869 and NGC 884. From Astronomical Picture of the Day

Pre-Main Sequence (PMS) Stars

Stars form from the gravitational collapse of gaseous dense cores. Once the star is formed, it starts its Pre-Main Sequence (PMS) phase

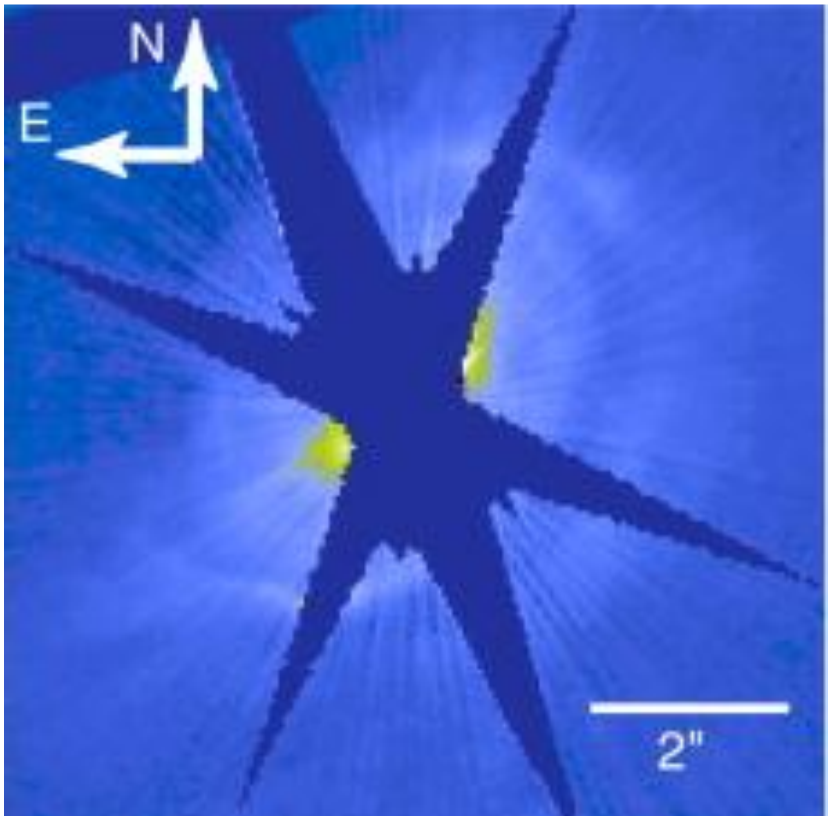
The PMS is a phase in stellar evolution where the newborn star contracts after the formation, increasing its temperature until the core initiates the nuclear reactions

PMS stars can be observed with a circumstellar disk:

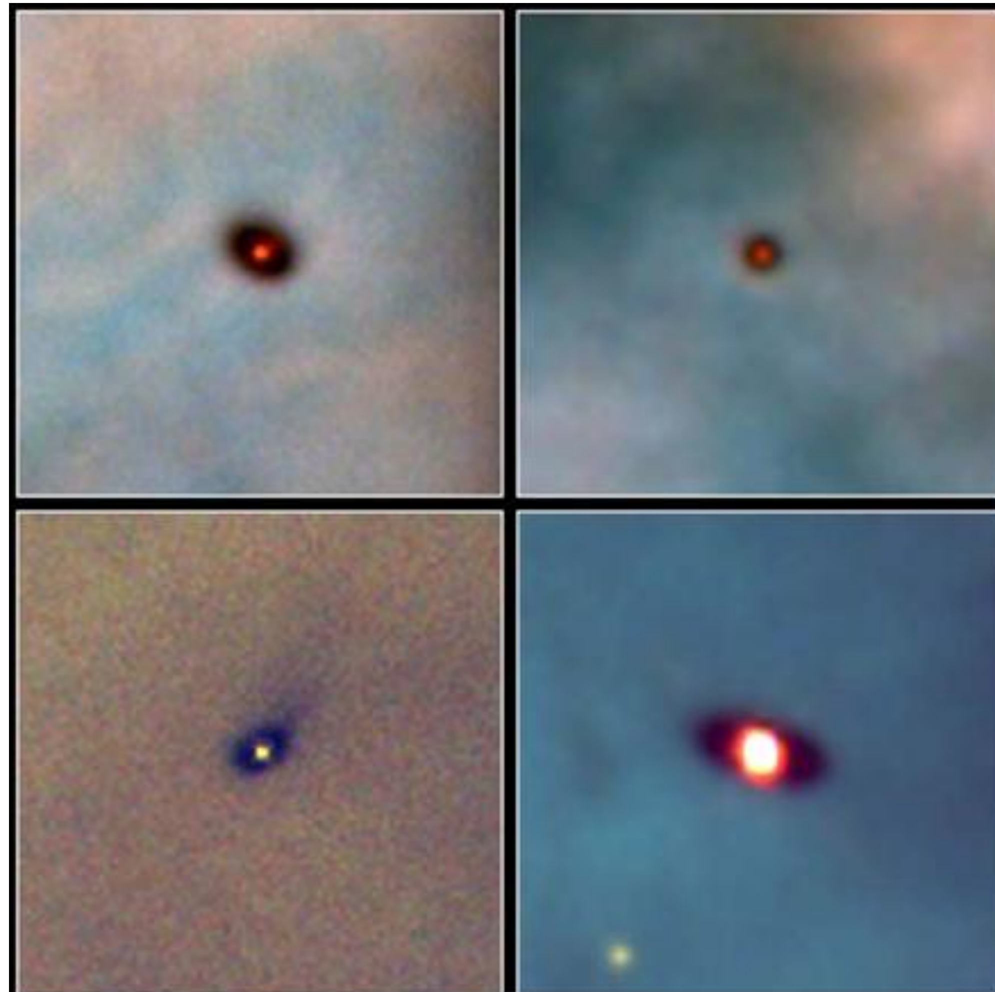


Circumstellar disks are the sites where planet form

Stars with disk

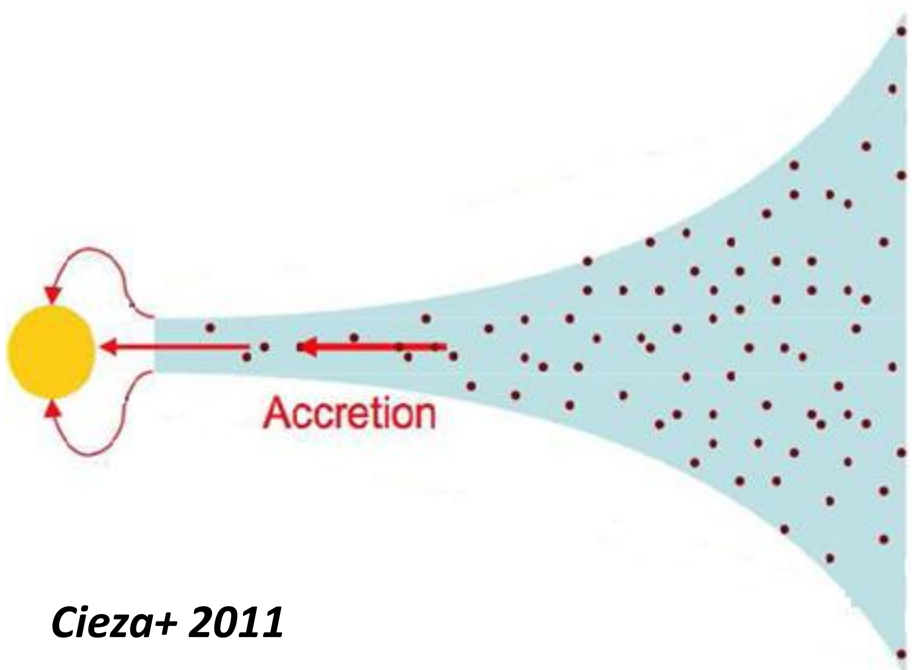


Circumstellar disk around HD100546
(103pc, HST/STIS, Grady+ 2001)



Stars with disk observed in Orion (410 pc)
with the HST/WFPC2 (O'Dell+ 1996)

Disks structure



Cieza+ 2011

Circumstellar disks contain both gas and dusts orbiting around the star.

Typical mass ratio: 100/1.

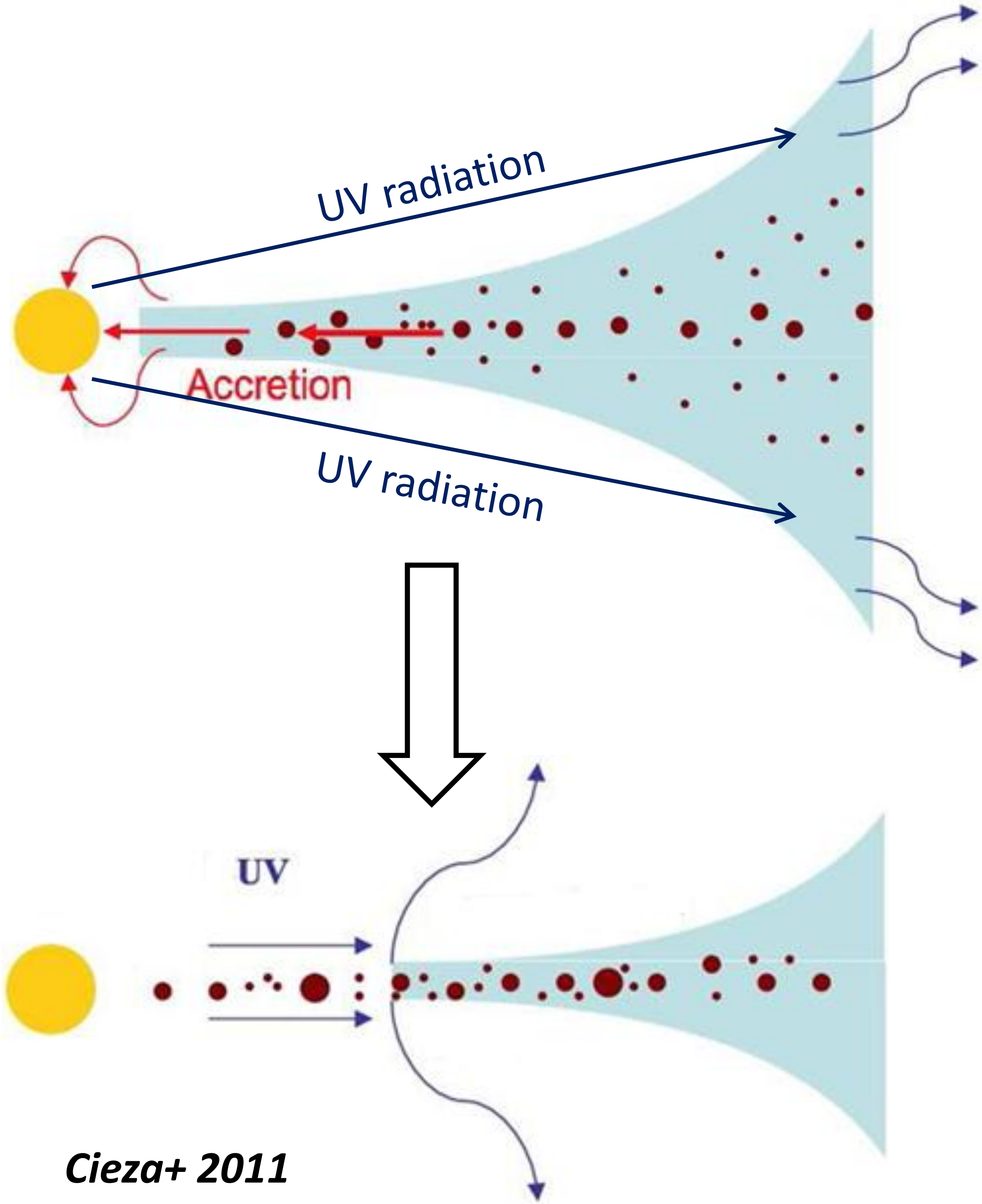
Typical dusts dimension: about μm.

Typical radius: few hundreds AU.

Typical mass: few $0.01M_{\odot}$.

Inner disk T~1000K, outer disk T few 10K.

Circumstellar disks evolution



Cieza+ 2011

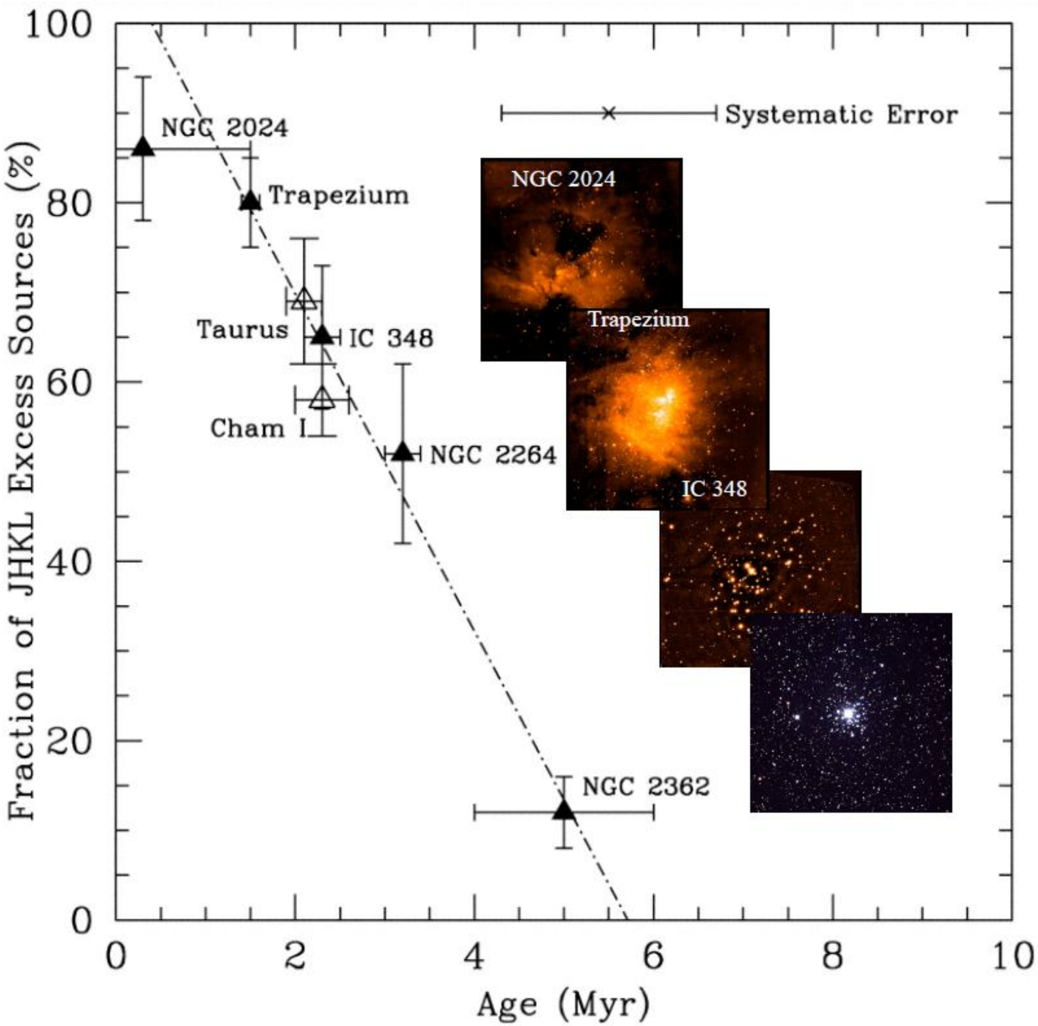
Gas is dispersed by accretion on the central star and heating by the UV radiation from the central star

Dusts settle in the midplane and coagulate in larger solid bodies

Debris disk

Once the gas is dissipated, eventually a disk of debris, planetesimals, and planets remains

Disks evolution timescale



Observed decline of the fraction of members with disks in star forming regions with increasing age ***(Haish+ 2001)***

Typical timescale for disks dissipation ~10 Myrs ***(Hernandez+ 2007)***

Typical timescale for giant planet formation ~10 Myrs ***(Lissauer & Stevenson 2007)***

Timescale for cluster dissipation is ~10Myrs → **disks and planets evolve while the hosting star is still associated to the parental cluster**

How the environment can affect planet formation?

Close encounters

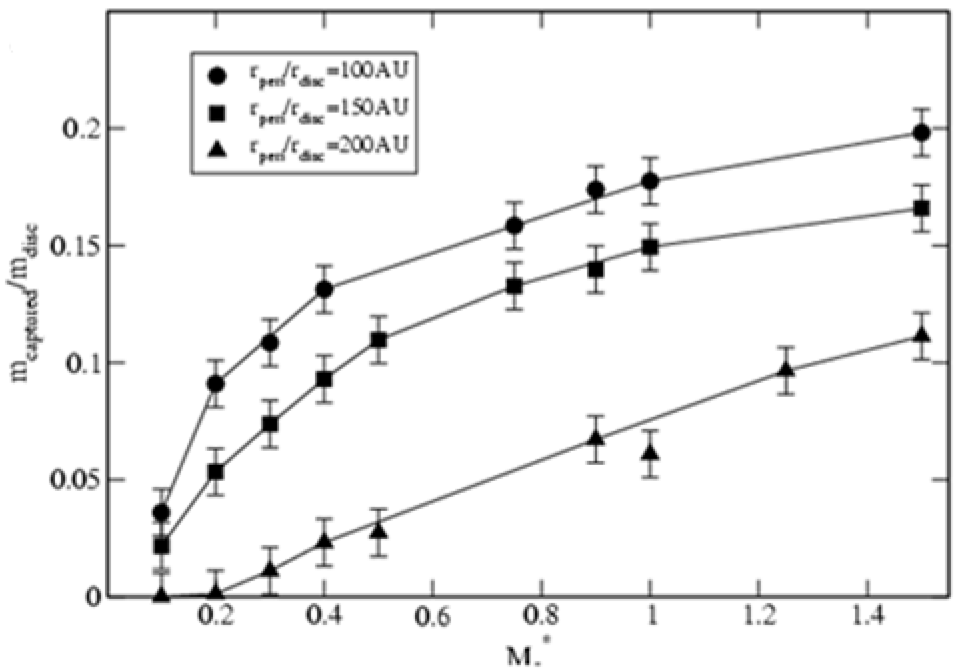
- During the dynamical evolution of clusters, stars orbit around the cluster center, and sometime they can get very close each other.

- A close encounter between a disk-bearing star and another star can have crucial consequences on the disk evolution, resulting in:

  - Significant mass loss from the disk, some of the mass lost can be captured by the second star, resulting in an exchange of material between the two stars; particularly important if one of the disks started to develop the basic elements for life (*lithopanspermia*, ***Adams+ 2005, Valtonen+ 2009, Belbruno+ 2012***)

  - Perturbation of the orbit of forming planets. A perturbed planet can be expelled by disk, resulting in the most extreme cases floating planets such those observed in nearby star-forming regions (i.e. Chamaleon I, σ Orionis, the Trapezium, ***Tamura+ 1998, Zapatero-Osorio+ 2000, Lucas & Roche 2000***)

Mass loss in close encounters



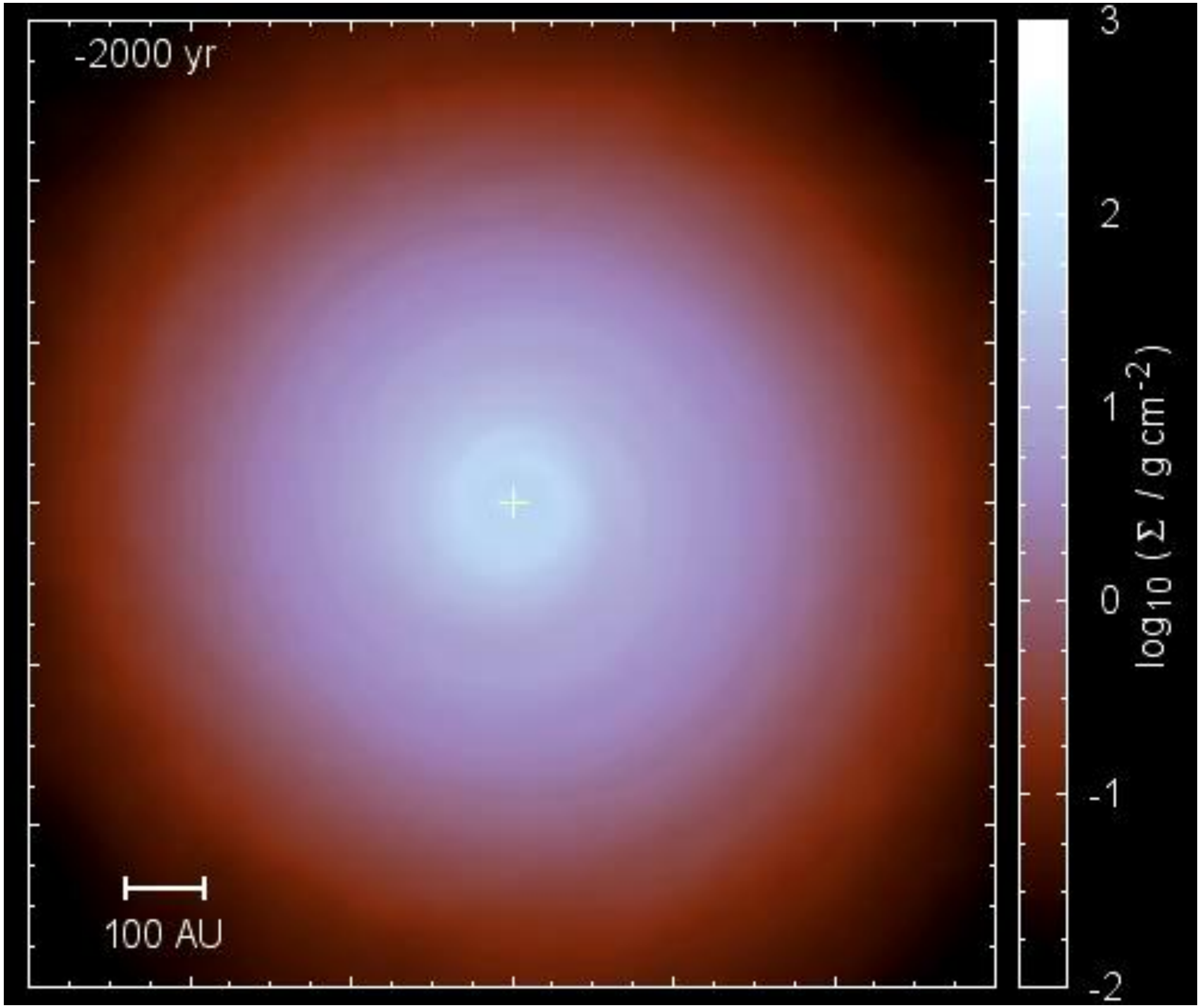
Pfalzner+ 2005

Fraction of mass lost from a disk orbiting a $1M_{\odot}$ star in coplanar, prograde close encounter

Similar results for inclination between orbits smaller than 45°

Several other configurations result in significant mass lost

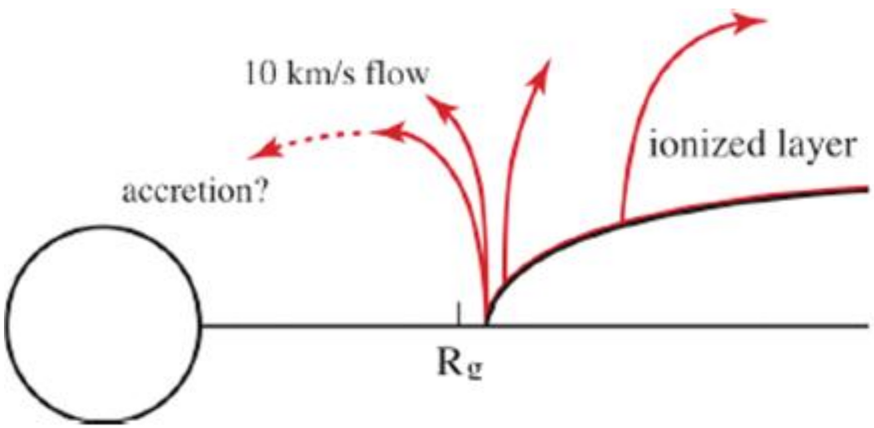
Simulation of a close encounter



Thies + 2010

Disks photoevaporation

- Occurs when UV photons irradiate the disk.
- UV photons ionize and dissociate gas atoms and molecules, heating the gas up to several thousands degrees.
- High thermal pressure drives heated gas to flow away from the disk:

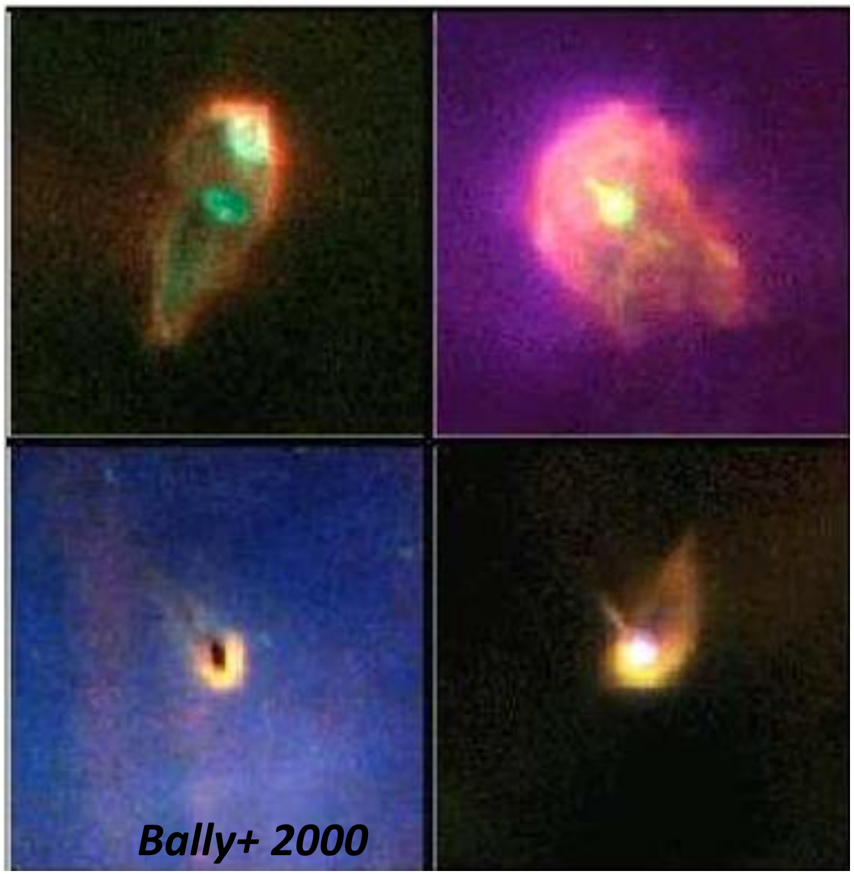


Crucial process in disk evolution when induced by the central star

Hollenbach et al. 1994

Externally induced photoevaporation (1)

Photoevaporation can be induced by external ionizing sources, mainly OB stars whose UV emission is order of magnitudes more intense than normal stars.

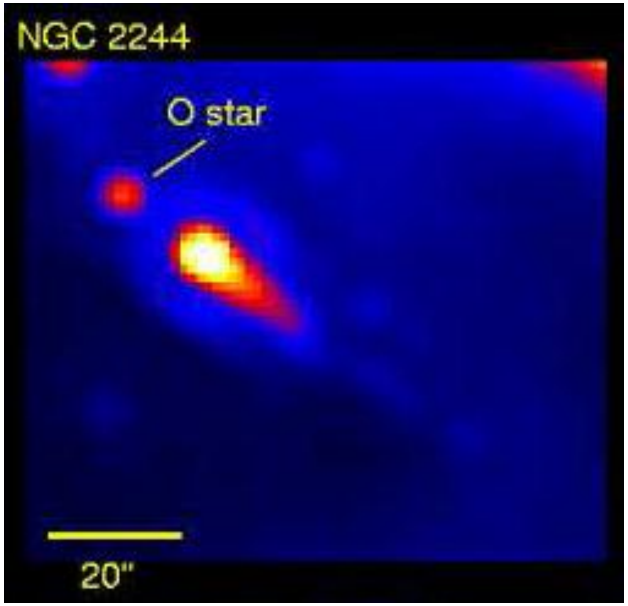


Photoevaporating disks observed in Orion by HST, embedded in the envelope formed by the evaporating gas. Distance of disks from ionizing source (an O star) is less than 0.1 pc.

Externally induced photoevaporation (2)

Externally induced photoevaporation affects directly the gas, but:

1. Small grains (~μm) are drained in the evaporating flow, as observed in evaporating disks with dust emission ***(Balog+ 2008)***



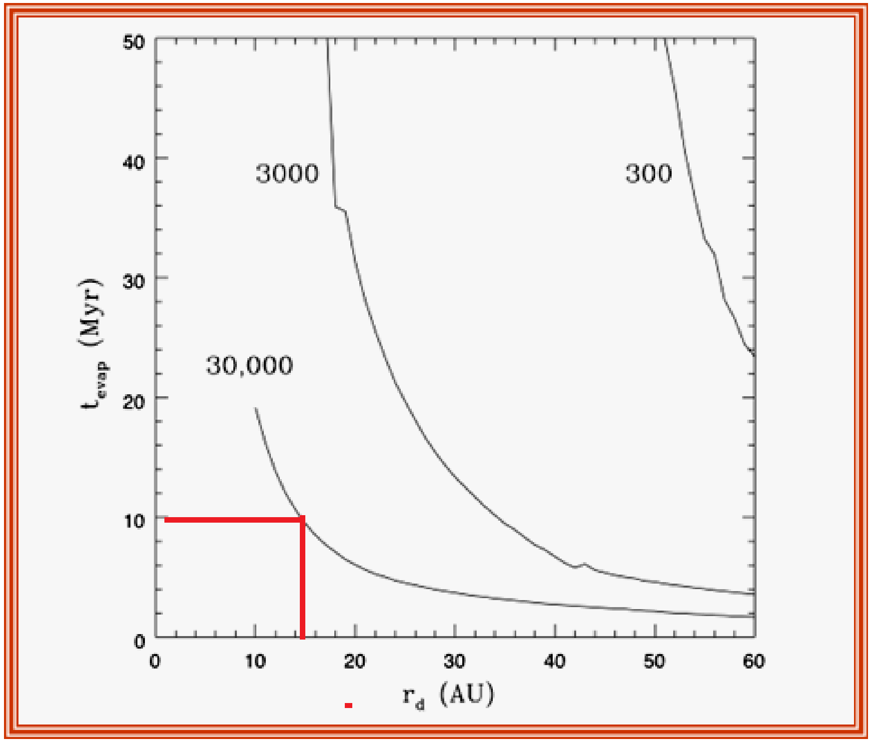
2. Solid bodies in a gas-depleted disk become gravitationally unstable → reduced gas to dust ratio can trigger planetesimal formation ***(Throop+ 2005)***

3. External UV radiation illuminating ice grains (i.e. H2O, CO2, NH3, etc..) can dissociate the molecules and synthesize complex organic molecules such as amino acids ***(Throop+ 2011)***

Externally induced photoevaporation (3)

Dissipation timescales for disks (M_{disk}=0.01$M_{\odot}$, M_{star}=1$M_{\odot}$) illuminated by FUV radiation of increasing intensity (in unit of G_0, the local interstellar UV field)

Adams+ 2004



To dissipate the disk down to 10 AU:

- UV: 3000×G_0 → $t_{diss} \geq$ 30Myrs
- UV: 30000×G_0 →t_{diss} ~ 10Myrs

photoevaporation induced by external UV fields thousands times more intense than G_0 has strong impact on the evolution of circumstellar disks, grain growth, planet formation and disks chemical evolution.

What is the most suitable environment for planet formation?

Small clusters (N=few tens or hundreds)

DSS2 image

prototype: the Taurus Molecular Cloud (140pc)

diameter about 25-35pc

density: 1-10 stars pc^{-3}

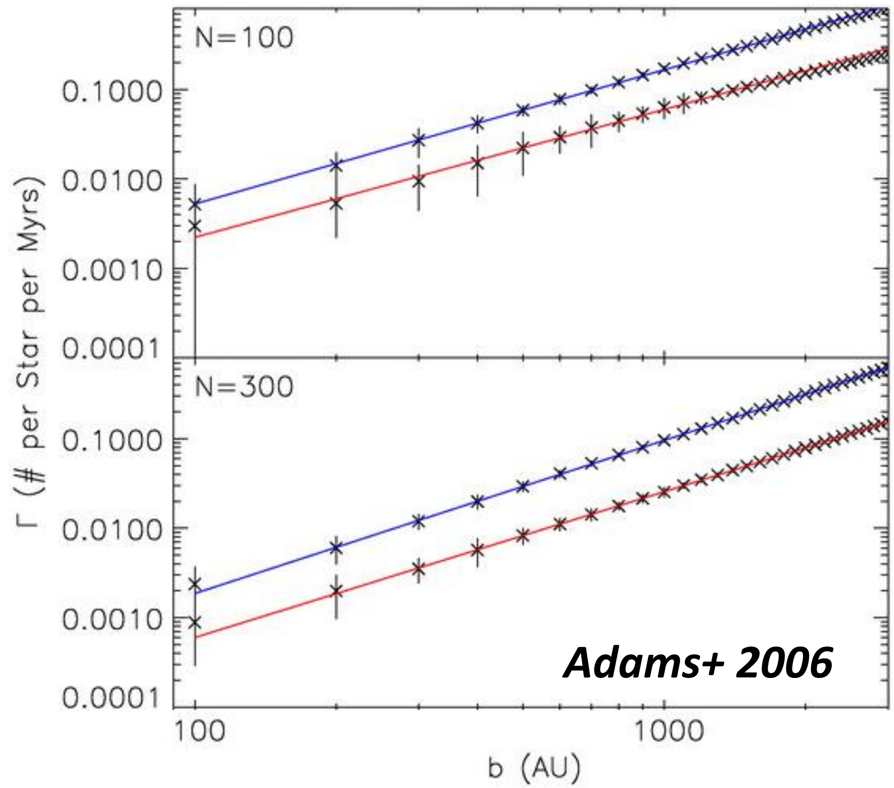
no O stars, few B stars

Kenyon+ 1994, Luhman+ 2000, Loinard+ 2005

Small clusters (N=few tens or hundreds)

Distribution of close encounters for small clusters (N encounter per Myr) at different b, for average kinetic energy of cluster members

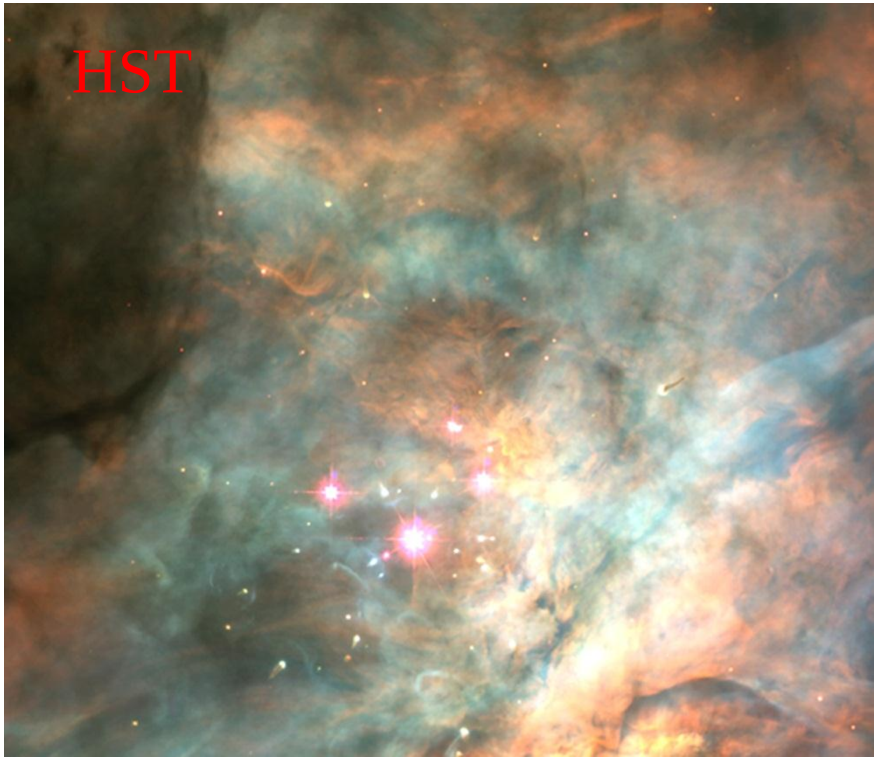
Frequency of close encounters too small to affect disk evolution

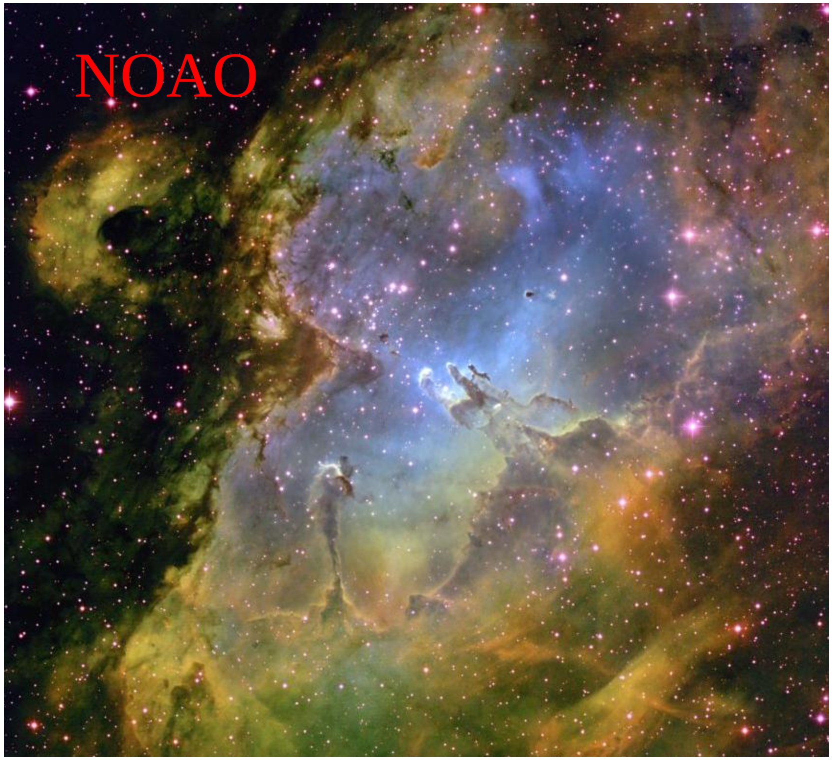


UV field ranging from G_0=1 to few hundreds, implying dissipation timescale > 50 Myrs, larger than typical timescales:

The environment in typical clusters in Solar Neighborhood does not affect disk evolution and planet formation

Large clusters (N>1000)





Trapezium in Orion:

Distance: 410 pc

Density: more than 2000 stars in ~1 pc^{-3} ***(Hillenbrand 1997)***

>10 OB stars

NGC6611 in M16:

Distance: 1750 pc

N: about 3000 members ***(Guarcello+ 2012)***

94 OB stars ***(Hillenbrand+ 1993)***

Close encounters in Trapezium

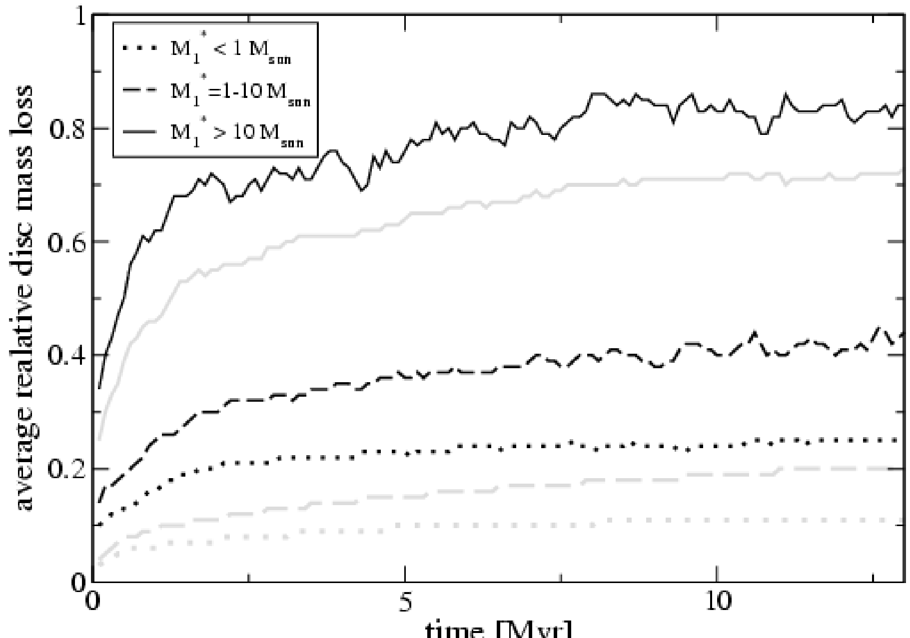
Stars in Trapezium-like clusters experience several encounters during cluster lifetime.

Simulations show significant mass-loss from disks after few Myrs

In 10Myrs, disks in high-mass stars lost about 80% of their initial mass, solar type stars about 30%

Larger mass lost for massive stars which populate the cluster center

For solar type stars, odds of encounters with b<90AU between 1%-10% ***(Adams 2010)***

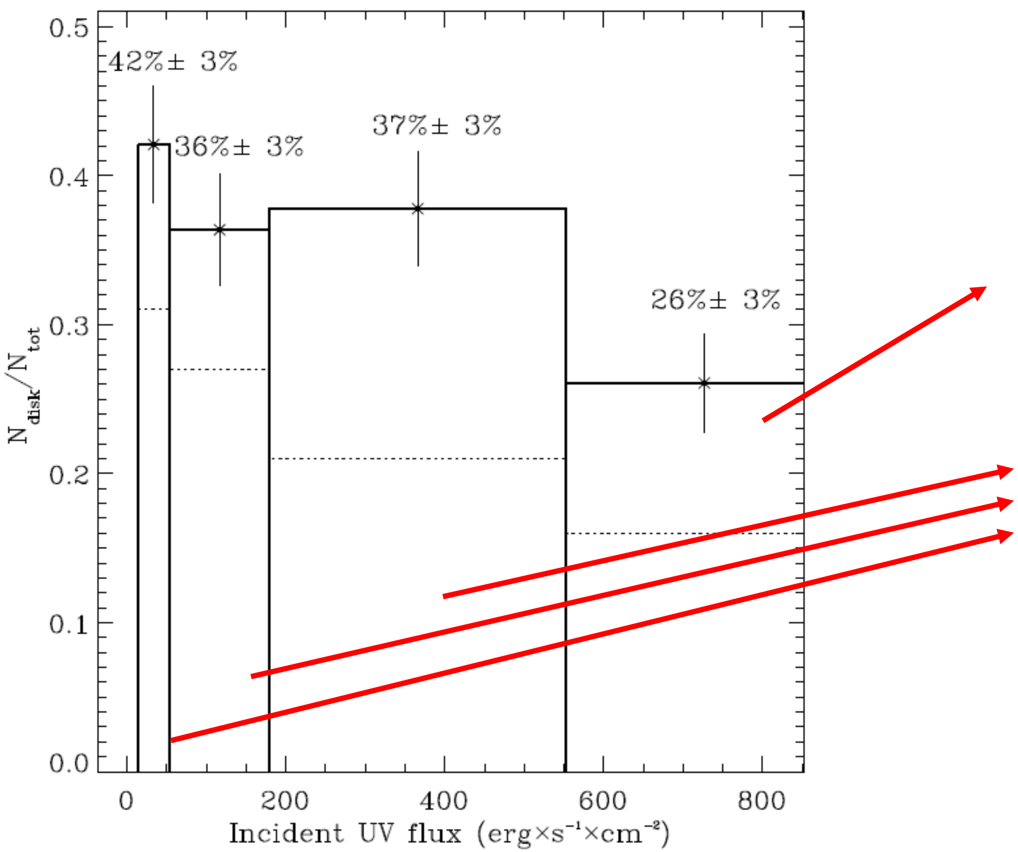


Fraction of mass lost from disks in stars with different masses, in a Trapezium-like (black) and Orion-like(grey) cluster ***(Pfalzner+ 2006)***

Photoevaporation in NGC6611

In NGC6611 the fraction of members with disk is observed to decline closer than 1 pc from O stars, i.e., at high values of incident UV flux ***(Guarcello+ 2012)***.

Also observed in NGC2244 ***(Balog+ 2007)*** and Trapezium ***(Bally+ 2000)***



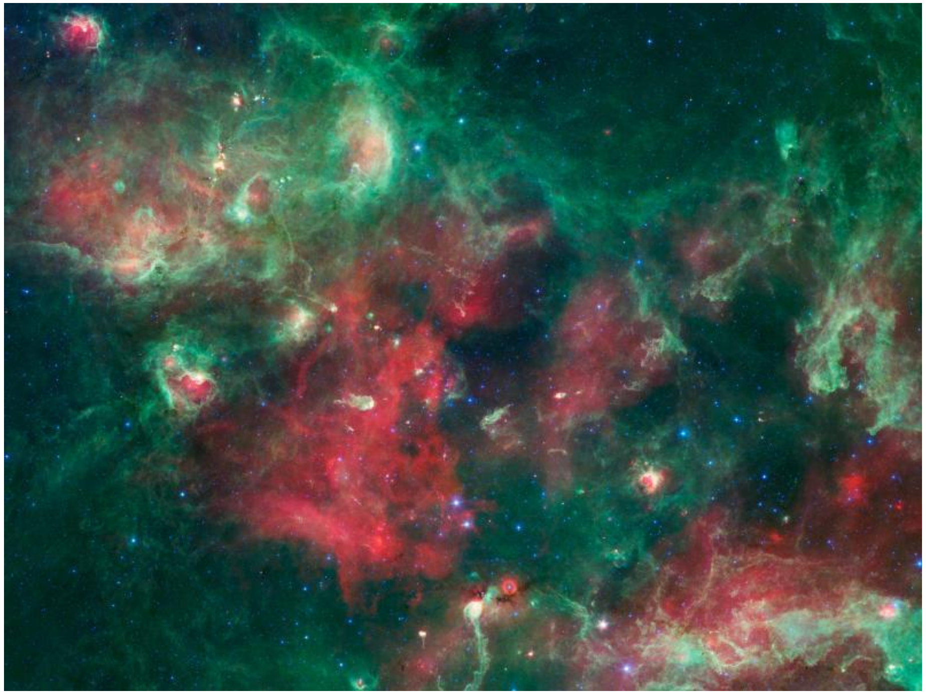
INDUCED PHOTOEVAPORATION (EUV regime)

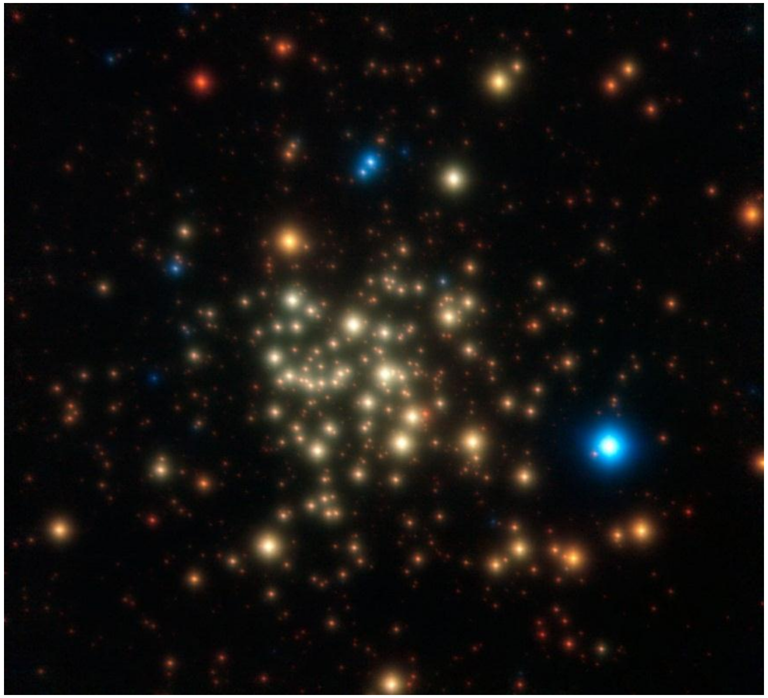
NO EVIDENCE FOR PHOTOEVAPORATION

Large clusters (N>1000)

- High stellar density in the core → frequent close encounters with significant mass lost from circumstellar disks
- Tens of OB stars → intense UV fields of $G_0=10^4-10^6$ in the cluster core, where disks experience externally induced photoevaporation
- The core of large clusters are hostile environments to disk evolution, and affect planet formation. More suitable conditions in the outer clusters

Very large clusters/associations (N>10000)





Cygnus-X complex (CygOB2):

Distance: 1450 pc.

Density: more than 10000 in 20pc×20pc area ***(Wright+ in prep***)

Thousands of OB stars, among which the most massive O stars

Arches cluster:

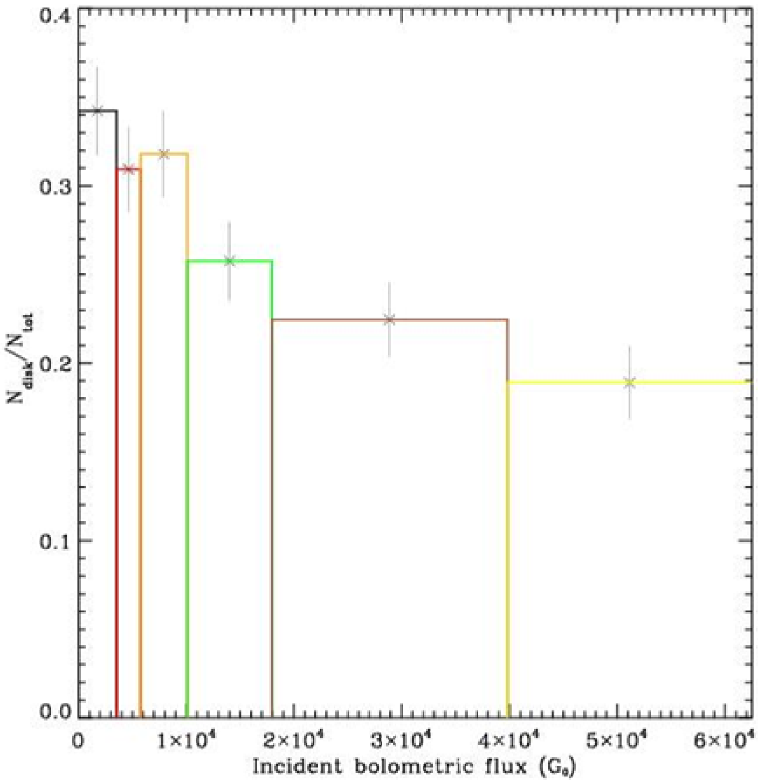
Distance: 8500 pc.

Density: 125 O stars in about 1pc

Very large clusters/associations (N>10000)

- Close encounters: simulations of the Arches cluster indicate that in 2.5 Myrs more than one third of disks are destroyed by gravitational interaction ***(Olczak+ 2012)***

- Photoevaporation: in CygOB2 (3-5Myrs) decrease of disk fraction observed in the whole cluster, not only in the core ***(Guarcello+ in prep)***



Very massive clusters, given their high stellar density and content of massive stars, are hostile environments for disks evolution and planets formation

What was the forming environment of the Solar System?

The Sun forming environment *(Adam 2012)*

Properties of the solar system that constrain the properties of Sun's forming environment:

- Orbits of planets: coplanar and with low eccentricities → require no close encounter with $b<90AU$ → $N<10^4$

- High eccentricity of Sedna's orbit and sharp end of Kuiper Belt → require at least one encounter with b=200-300 AU → $10^3 < N < 10^4$

- Presence of giant planets → no hostile environments

- Low gas content in the outer icy planets and the trans-Neptunian objects → UV flux > 2000 G_0 → $N > 1000$

The Sun forming environment

- The Solar System survived photoevaporation → UV flux < 10^4 G_0
- Short-lived radio nuclei with half-life < few Myrs (^{26}Al, ^{30}Fe) present in our Solar System → supernova enrichment of Solar Nebula → distance from supernova < 0.3 pc → N>1000
- The Solar System survived the supernova explosion → distance from the supernova > 0.1 pc

Solar System properties require the Sun formed in the outer region of an intermediate massive cluster, with few thousand members, necessary to provide the required number of close encounters. Then, it moved in the cluster core, being enriched by a supernova explosion and experiencing photoevaporation, but never too close to massive stars.

Conclusions

- Star mainly form in embedded cluster of moderate size (N<1000), but only 10% of these clusters survive longer than 10Myrs.

- Planet formation occurs in circumstellar disks orbiting around young stars.

- The first 10Myrs evolution are crucial for: Disk evolution, planet formation, environmental effects.

- Disk evolution and planet formation can be externally affected by close stellar encounters and externally induced photoevaporation.

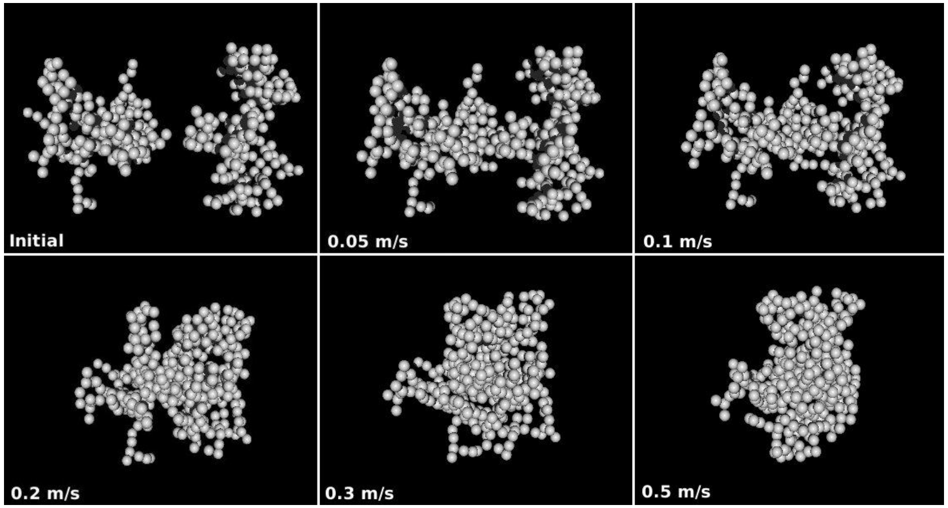
- Small clusters (N<1000) provide a safe environment where disk can evolve and planets can form.

Conclusions

- Massive clusters (N few thousands) are harsh environments in their core, while are relatively safe in the cluster outer region
- Extremely massive regions (N>10000) are large stellar nurseries, but provide a hostile environment for planet formation
- Given the characteristics of the Solar System, the Sun must be formed in the outer region of an intermediate cluster (N few thousand), moving later in the cluster core close to some O stars

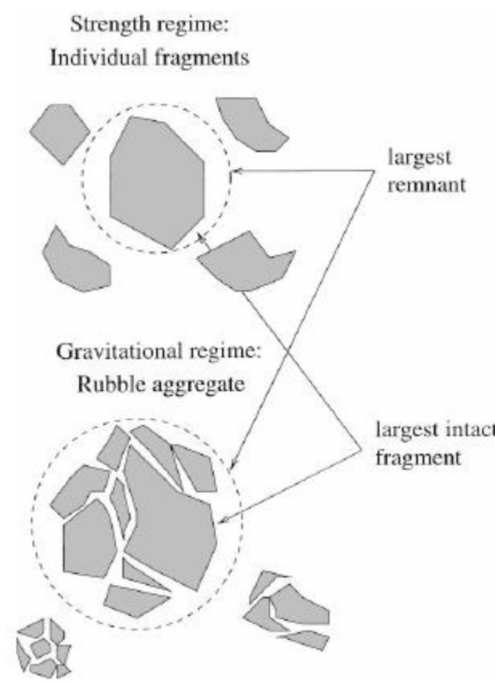
PLANET FORMATION MUST OCCUR AROUND THE LARGE MAJORITY OF STARS IN OUR GALAXY

Grains coagulation

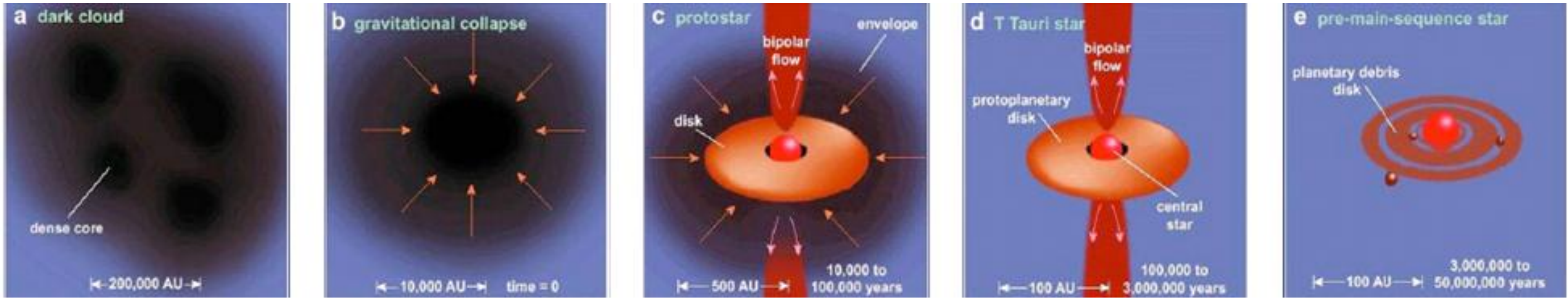


Aggregates up to few dm can be created by collision between grains and smaller aggregates, cohesion due to electric forces (i.e. van der Waals)

Formation of larger bodies should require gravitational interaction between fragments, but problem still open



YSOs Classification



Dark Cloud:

Molecular cloud fragmented in collapsing dense clumps

Class 0:

Protostellar core in gravitational collapse, central star and circumstellar disk in formation

Class I:

Star and disk embedded in collapsing envelope. Gas outflow and accretion

Class II:

Central star and accreting disk where planetesimals are growing. Bipolar outflow

Classe III:

Young star contracting toward the Main Sequence. Eventually a debris disk and/or planets