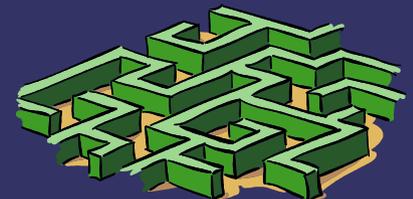


# *The formation of Sol*

Justin Spengel

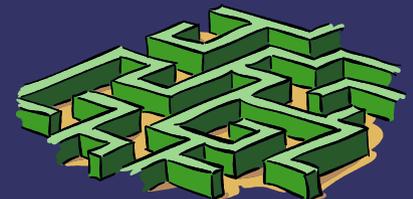
The formation of low mass stars in the presence of developed massive stars.



## *It makes a difference*

Until recently, there was relative isolation between studies of the history of our system, and of the creation of stars. Recent advances in each have allowed us to bridge that gap.

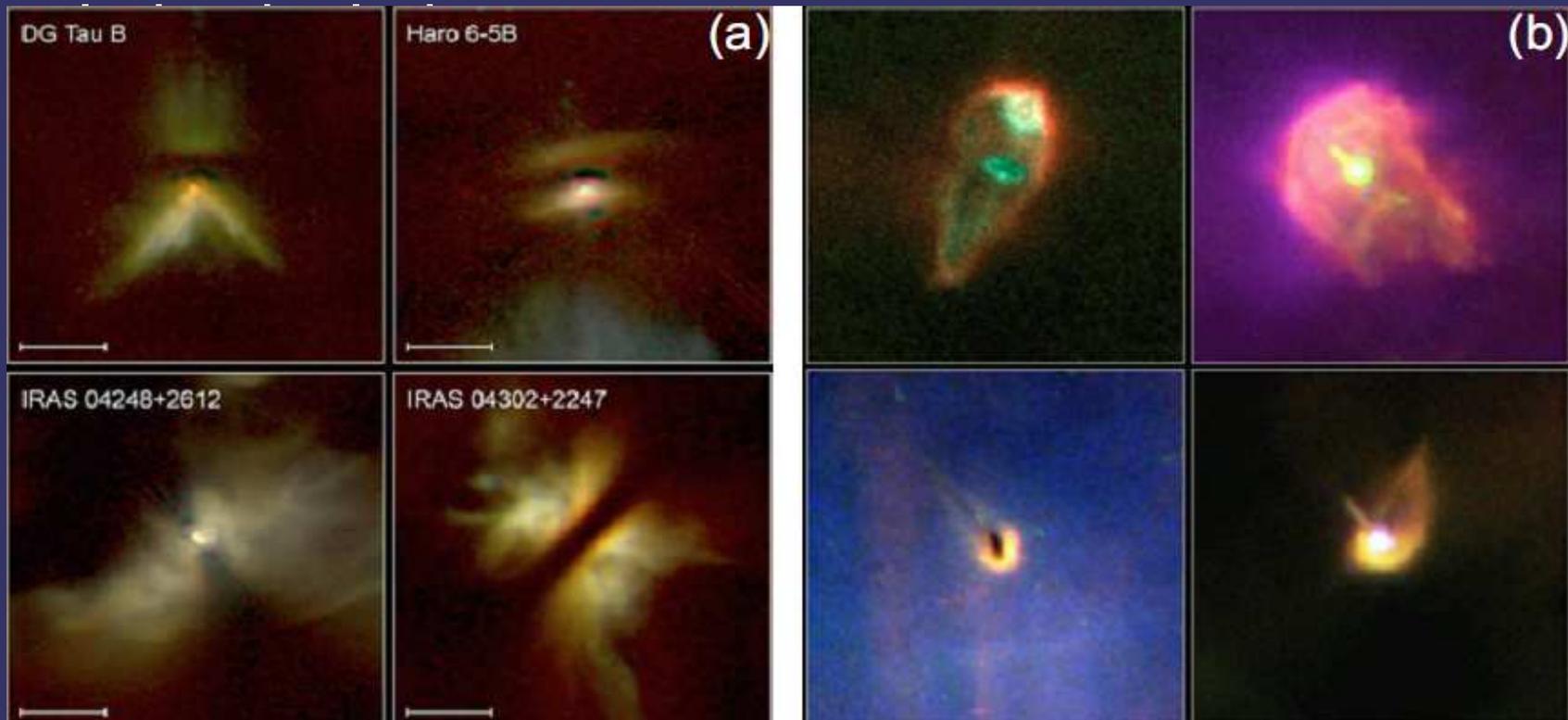
The presence of live  $^{60}\text{Fe}$  in the early system tells us that *we* formed near a massive star. So what does this mean?



# *HST image of the forming discs*

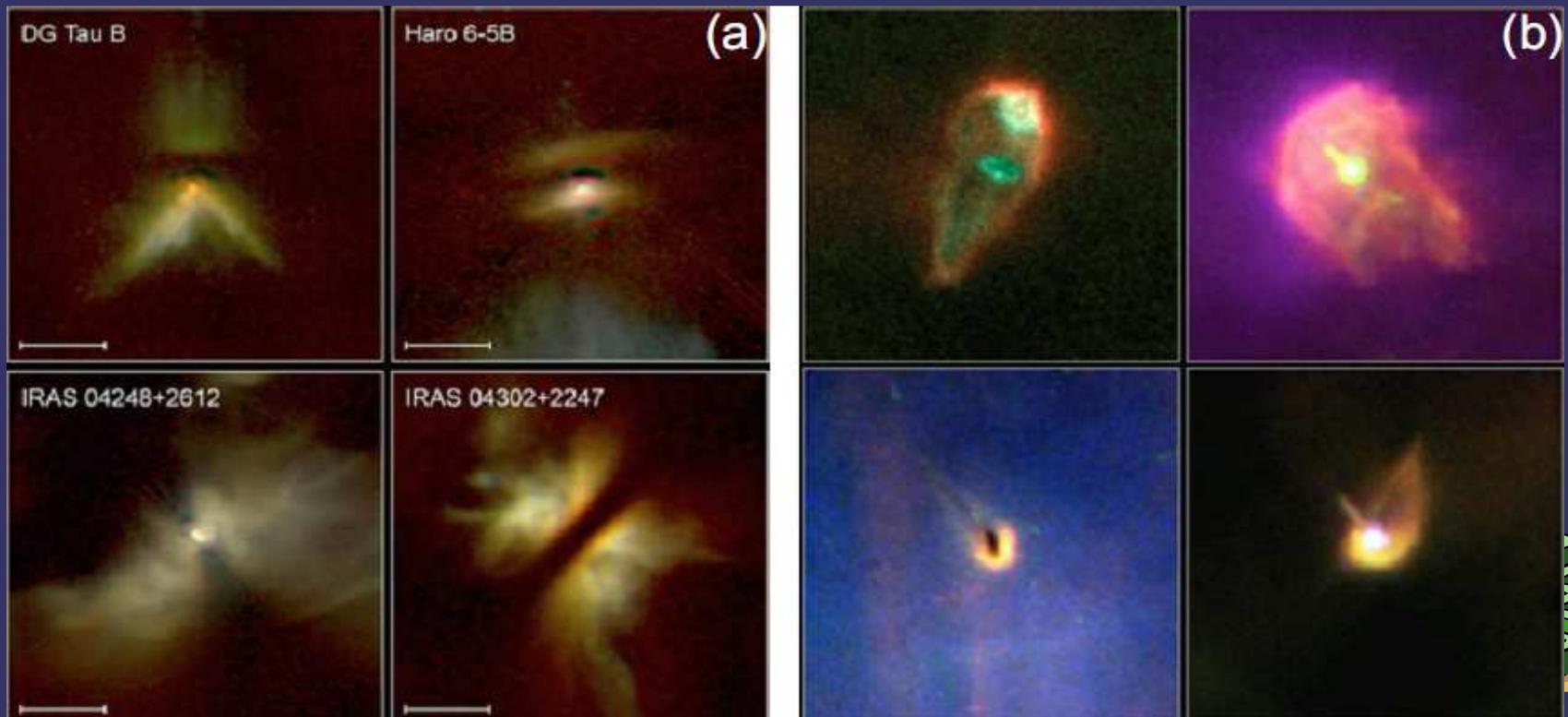
a) four young stellar objects in the cold and dark Taurus-Auriga molecular cloud, in

b) four stellar objects in the hot, ionized interior of the Orion Nebula, dense with luminous,



# *More Radiation*

In (b), it is easily visible that the protoplanetary discs are relatively sparse, having been photoevaporated by the intense UV radiation from their massive neighbors.



# *Meteorites: Cosmic Lumbar Puncture*

Meteorites give us a snapshot of the proto-planetary disc.

- Chemical

- Physical

- Thermodynamic

- Time constraints

- Short Lived Radionuclides

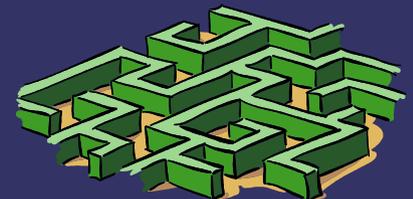
26 Al, 60 Fe, 36Cl, 41Ca, 53Mn,

etc.



# *Trajectory of Decay*

Radioactive isotopes act like clocks. With longlived radionuclides, like  $^{238}\text{U}$ , we can measure the amount of the parent nuclide and the amount of the daughter isotope and calculate the time since the daughter isotope began to accumulate. This method has given us the age of the solar system, the age of the Earth, and more. SLRs are more precise but are more temperamental.



# *Using SLRs (not the camera)*

SLRs have similar lifecycles that place them more closely in line with Star creation, but they are also more difficult to account for.

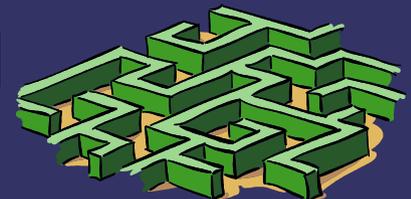
The object in question must have been recently homogenized.

melting followed by crystallization

evaporation followed by condensation

A chemical fractionation must occur.

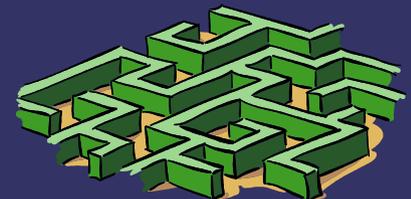
The objects must have remained undisturbed  
i.e. remelted, heated to diffusion, dissolved.



## *How it applies to us*

SLRs may have formed by spallation reactions in the protoplanetary disc from cosmic rays and solar flares, or made in nearby stars and injected. 'Which' is the key question.

$^{60}\text{Fe}$  in our early system can only fit into our models if the sun were near a massive neighbor that went supernova.



# *Small Star Formation*

Up until now, we mainly studied isolated star creation in regions like the Taurus Auriga molecular cloud. Since it is so close, we can gather a lot of data on otherwise unobservable phenomena, and provide bases for theoretical speculation, but the isolation is not necessarily typical of low mass star formation. In fact, most low mass class G stars form near massive stars.



# Taurus Auriga is a particularly odd specimen

More Binary Stars than would be expected

Fewer Brown Dwarfs

The initial mass function peaks at a higher mass ( $\sim 0.8M_{\text{Sun}}$ ) than is expected.

Deficient for masses  $> 1M_{\text{Sun}}$

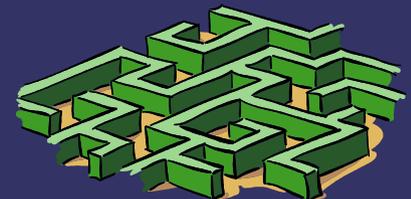
So our conclusions based on this data might not apply more generally.

Lada & Lada found 70-90% of young stars within 2 kpc formed in rich embedded clusters.

$\sim 75\%$  are in clusters with live massives ( $> 8M$ )

Others likely contained massives previously

This now disputes previous theories.



# *We were wrong?*

Adams & Myers reached the precise opposite conclusion- that small isolated groups dominate low-mass star formation

The fatal flaw

They underestimate the birth rate drastically

The cause

The Adams & Myers calculation discounted quickly dispersing clusters.

<10% of cluster survive  $10^7$  years

<4% survive  $10^8$  years

Since they disperse quickly, they were not included in the catalog used by Adams & Myers



# *And this applies?*

Most low mass stars formed near massives but did we?

According to Adams & Laughlin (2001), the likelihood is  
~0.85%

But this is subject to the same criticisms as the Adams & Myers paper.

This time they OVERestimated the likelihood of disruption from others stars, because of their assumption of the lifespan of all included clusters.

## SLRs again

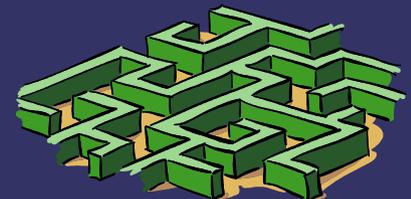
26 Al was present in our young Solar System

Perhaps from nearby Supernova

Or by spallation involving Solar cosmic rays

Self-contained (no outside source for radioisotopes)

Accounts for live  $^{10}\text{Be}$  (only from spallation)



# *So bet on Spallation...*

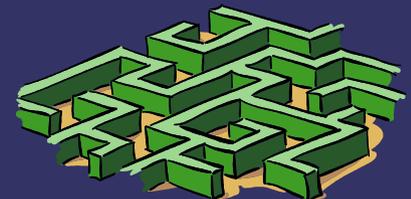
In 2003, Tachibana & Huss reported live  $^{60}\text{Fe}$  in our early system.

$^{60}\text{Fe}$  has 1.5 Myr half life, but does NOT form in spallation

Only in supernovae

Other spallation-unfriendly include  $^{182}\text{Hf}$  &  $^{107}\text{Pd}$

Meteoritic studies also show  $^{36}\text{Cl}$  in the outer system



# *Explaining 60 Fe*

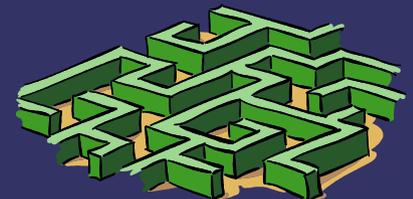
Explaining 60 Fe has proven difficult

Busso, Gallino, & Wasserburg suggested Asymptotic Giant Branch stars are the source (2003)

Unlikely- not usually found in relation to low mass stars.

Kastner & Myers (1994) set  $P(e) < 3 \times 10^{-6}$

Massive stars *are* correlated with low mass star formation, and their supernovae produce necessary materials.



# *So do they work?*

Their supernovae produce  $^{60}\text{Fe}$  (and other SLRs)

Their lifespan and occurrence places them in proximity to young low mass stars (3-30Myr)

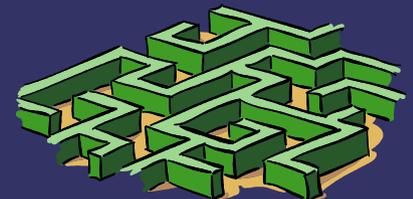
Supernova rate is somewhat constant throughout 'nova season' (TV reference, someone laugh plz)

With only 5 massives, the median gap between Supernova exposures is 3Myr

In Scorpious-Centaurus OB, ~95% of low-mass stars formed in last 8-12Myr.

So ~20 supernovae in that period

Assuming constant, that's every 0.5 Myr



# *Sounds good, we're done right?*

There is still one element a Supernova cannot produce-  
the one that recommended spallation in the past.  $^{10}\text{Be}$   
Spallation might *still* contribute (we're not limited to only  
one event)

but there is a recent theory...

Desch, Connolly, & Srinivasan (2004) found the amount  
of  $^{10}\text{Be}$  present could be sourced by purely galactic  
cosmic rays, negating the necessity of spallation in  
the model.

We can safely say  $^{60}\text{Fe}$  implies Sol's creation in a rich  
cluster near at least one massive

Certainly more than  $^{10}\text{Be}$  implies spallation!



# Massive stars and their environments

Very luminous ( $>10^5 L_{\text{sun}}$ )

Extreme EUV/FUV

Surrounding interior gas is , tenuous, ionized and hot ( $10^4\text{K}$ )

Transparent to UV (lets it out)

Gas at ionization front is dense like cloud, but hot like interior

Causes photoevaporative flow into interior, and a shock into molecular cloud (higher pressure)

Eagle Nebula, M16, from Palomar Observatory, blister H II region.

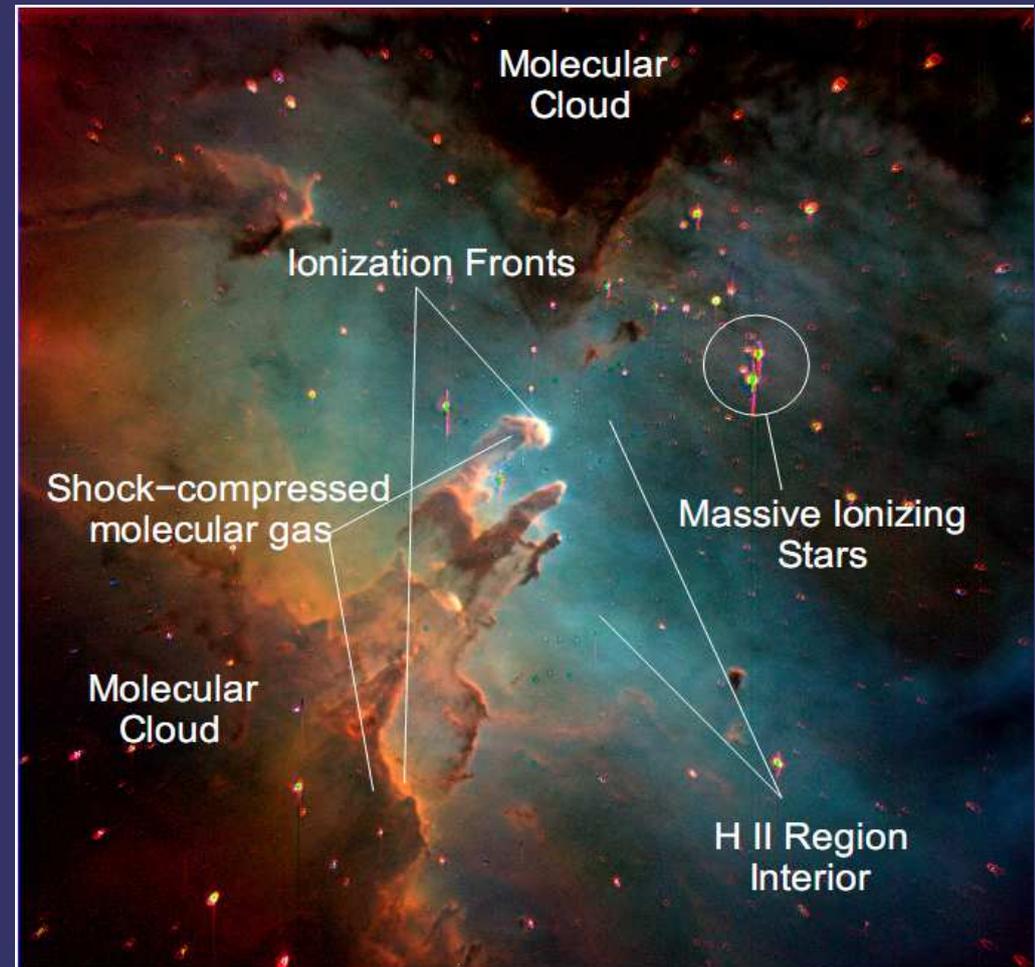


Figure 2. The structure of a blister H II region. This is a ground-based image of the Eagle Nebula, M16, obtained with the 1.5-m telescope at Palomar Observatory.

# *Other massive's effects (post form)*

Source of intense stellar winds

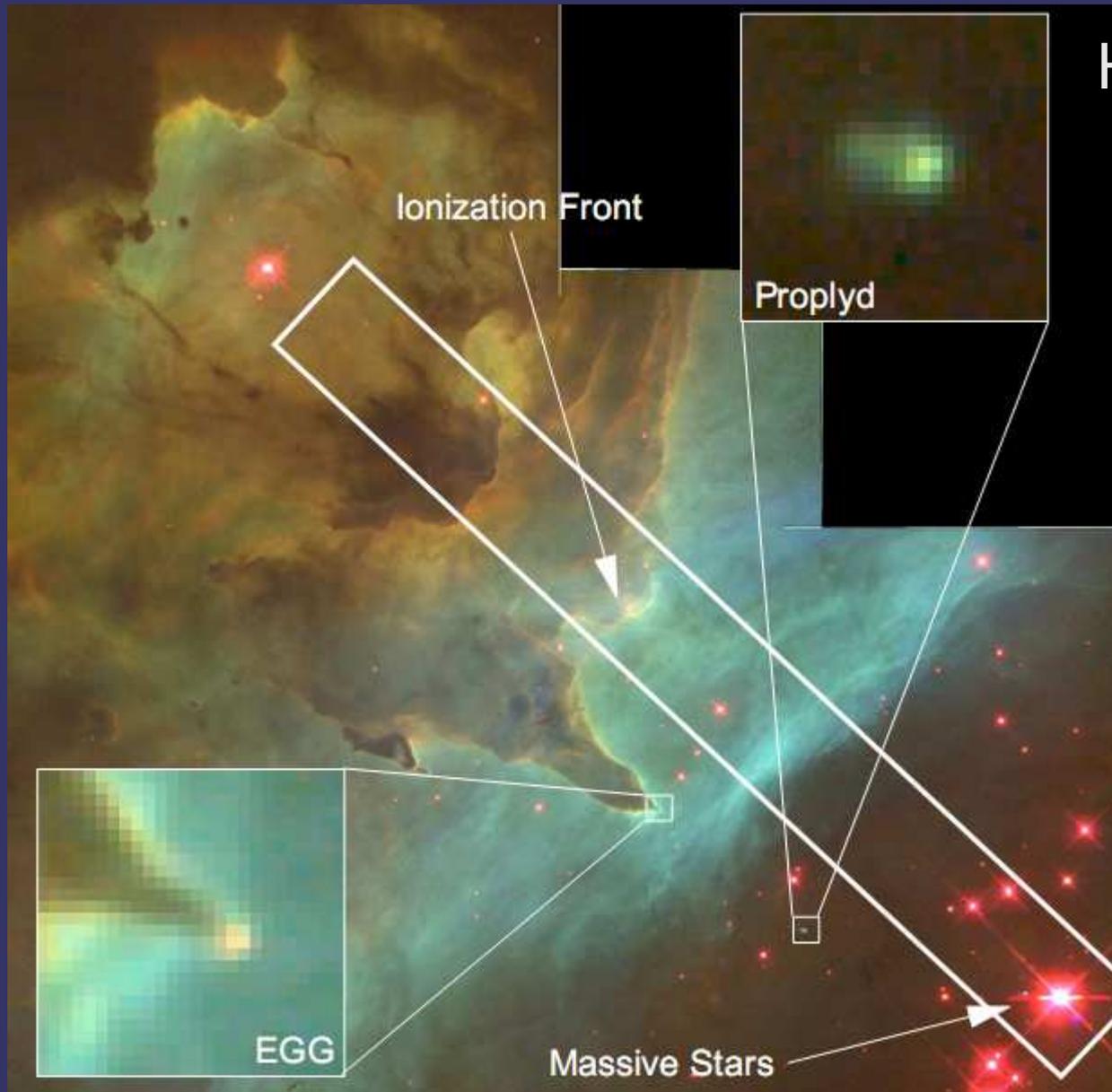
Supernova

Injects energy, momentum, and fresh nuclei into the region.

Quickly influences and controls its environment, including the low-mass star formation.



# *The evolution of low mass stars*



HST image of G353.2+0.9  
H II region in NGC 6357



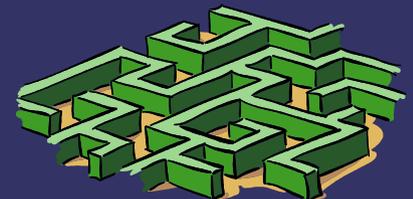
# *Where they start*

They do not form in interior region.

We know this

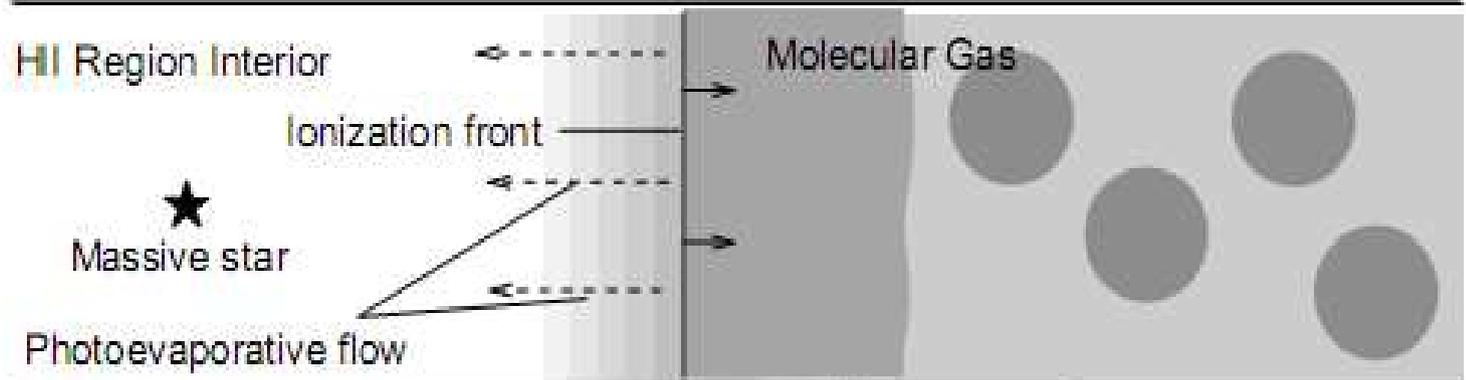
They formed in the dense molecular gas that once enveloped the region and were uncovered by the ionization front.

During this time, they go through a distinct sequence of events.

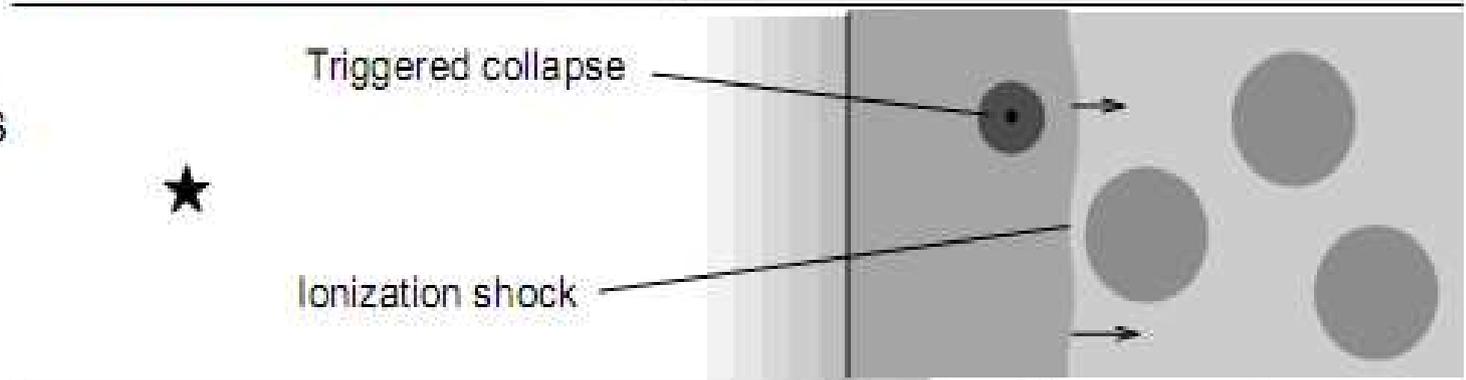


# Star Formation (in H II regions)

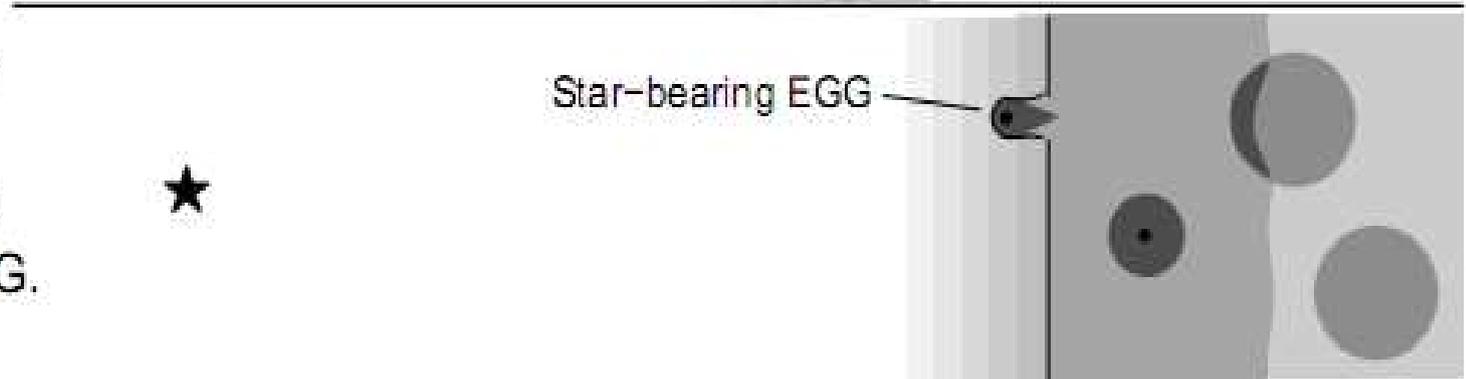
(1) Radiation from a massive star drives an ionization front into surrounding molecular gas.



(2) The ionization front (plus winds and previous SNe) drive a shock, triggering collapse of molecular cores.



(3) ~100,000 years after triggered collapse, the ionization front overruns the core, forming an EGG.



# Star Formation in H II cont'd

(4) EGGs evaporate in ~10,000 years, exposing the disk. The evaporating disk is a proplyd.



Proplyd



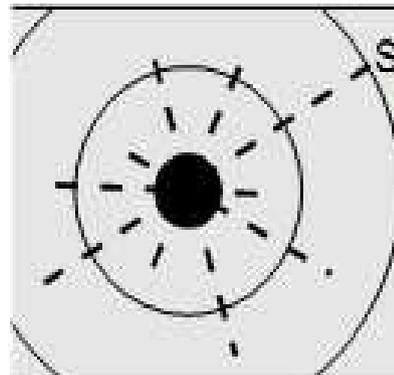
(5) In ~10,000 years, disks erode to ~50 AU. Disk evaporation ends, leaving a protostar and bare protoplanetary disk.



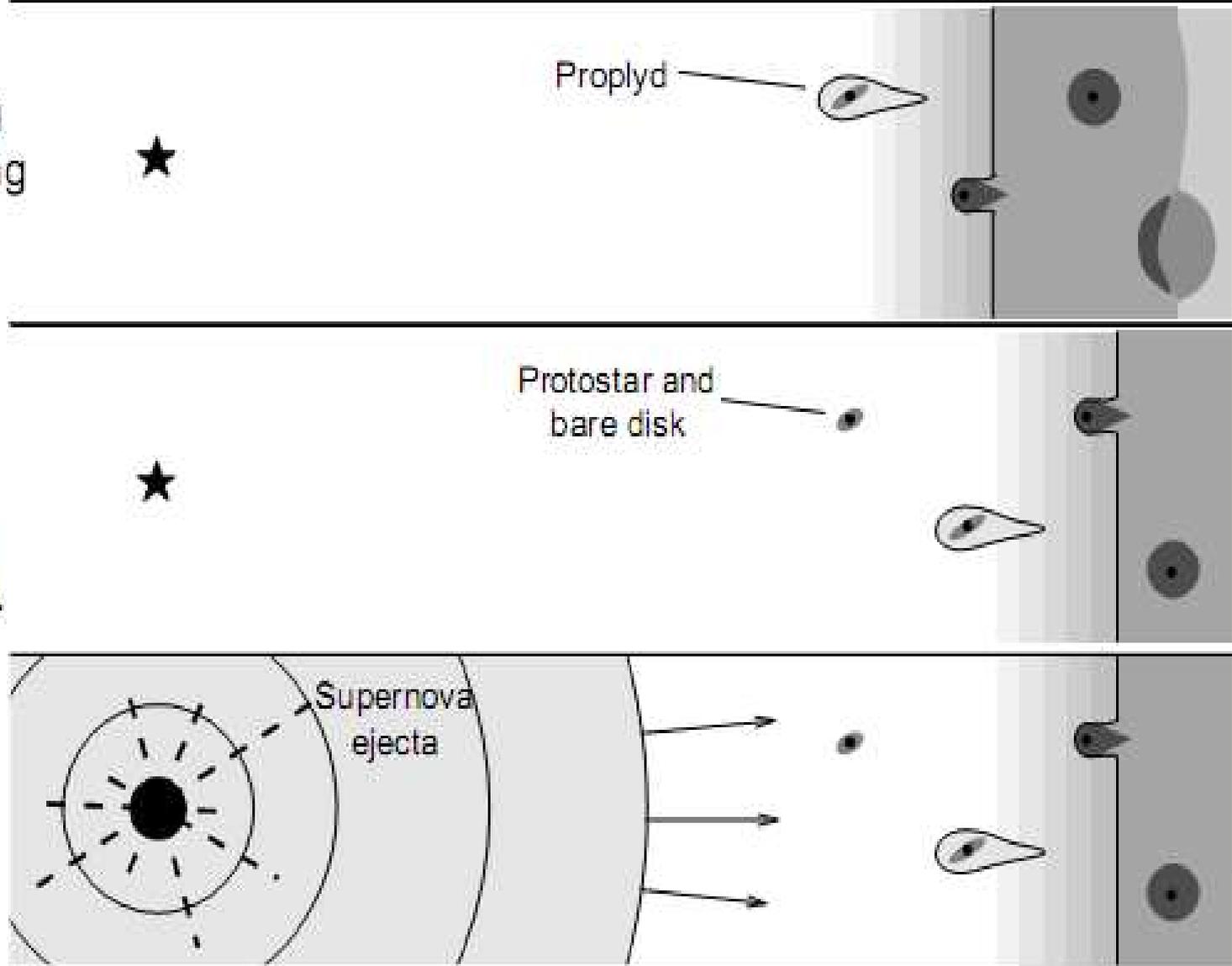
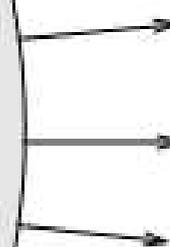
Protostar and bare disk



(6) The massive star goes supernova, injecting newly synthesized elements into surrounding disks.



Supernova ejecta



# How Supernovae deposit material

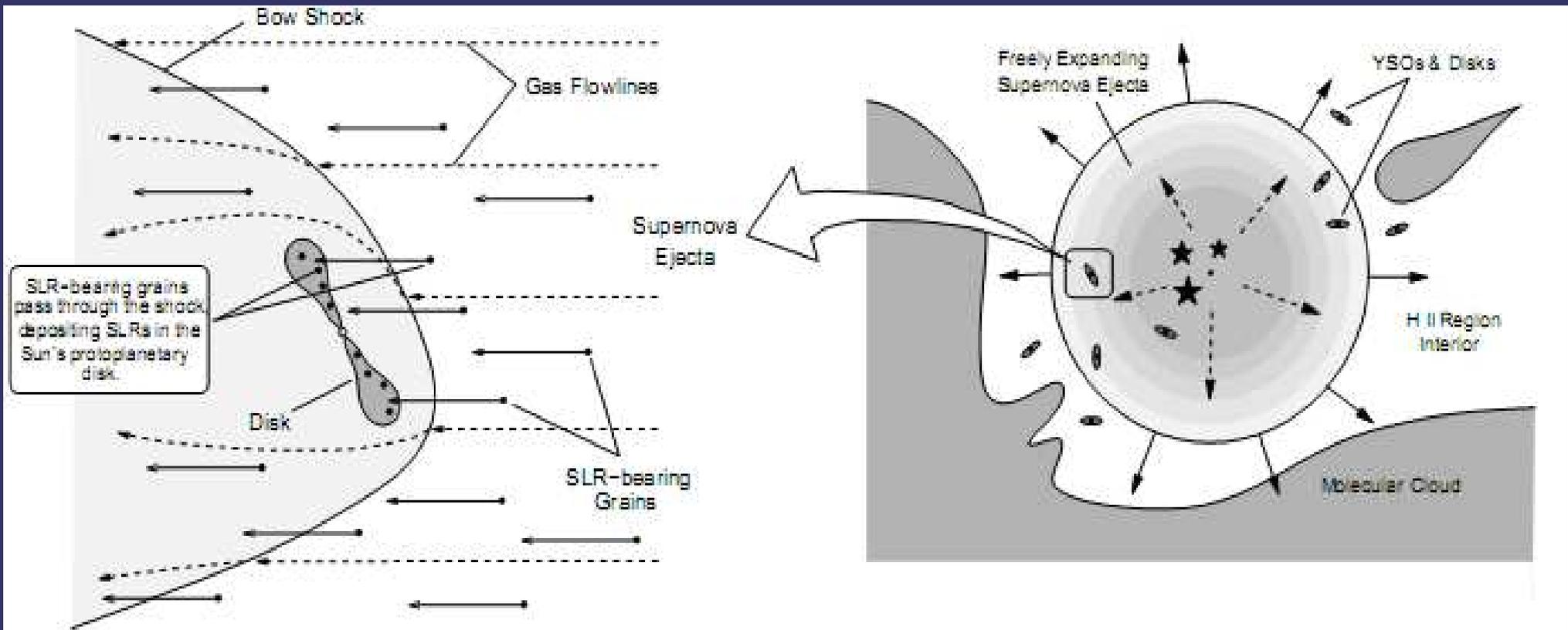
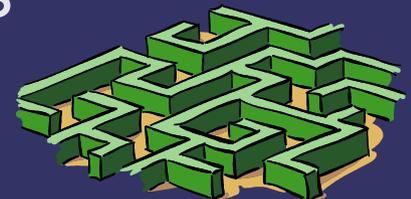


Figure 7. Illustration of the "aerogel" model for injection of SLRs from Ouellette, Desch, & Hester (this volume).

NOTE: Not necessarily the only source of SLRs  
Also, most clusters disburse in similar time frames as Massives go Supernova.



# *What triggers an actual star*

We assume there's a trigger because of the quantity of young stars in the H II region.

If low-mass star formation takes place independently of the effect of massive stars, then it should have no relation to the compressed gas.

We would see formations out in the extended regions around H II's, and in gas unaffected by H II expansion

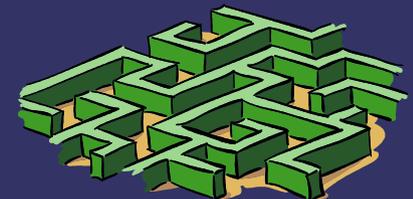
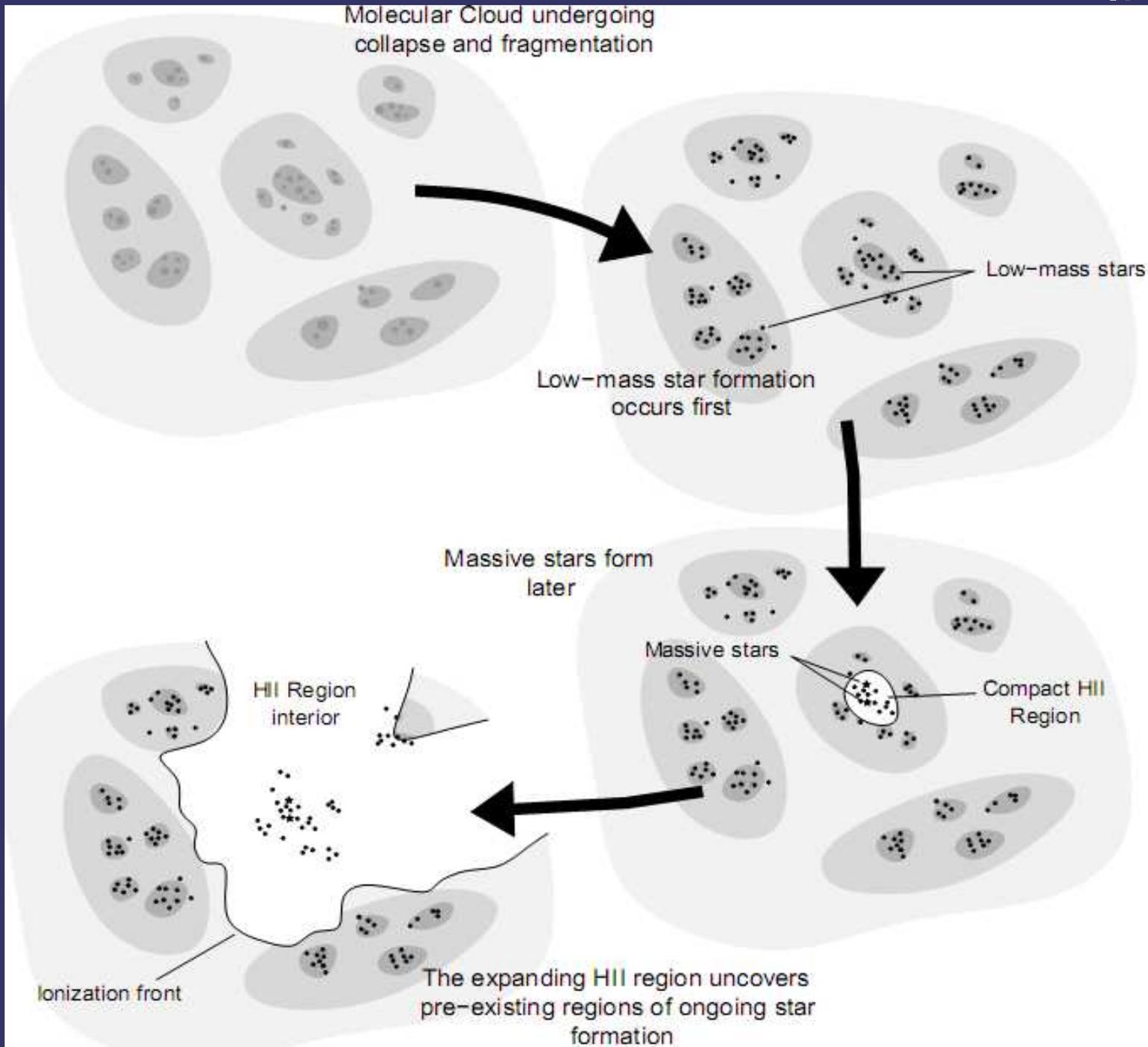
This would also imply that a significant number of low mass stars should be older than the nearby massive

Obviously, some star formation is triggered by

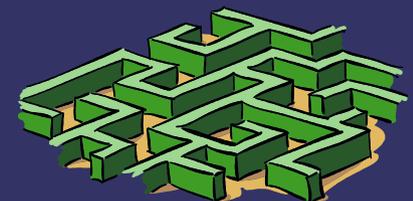
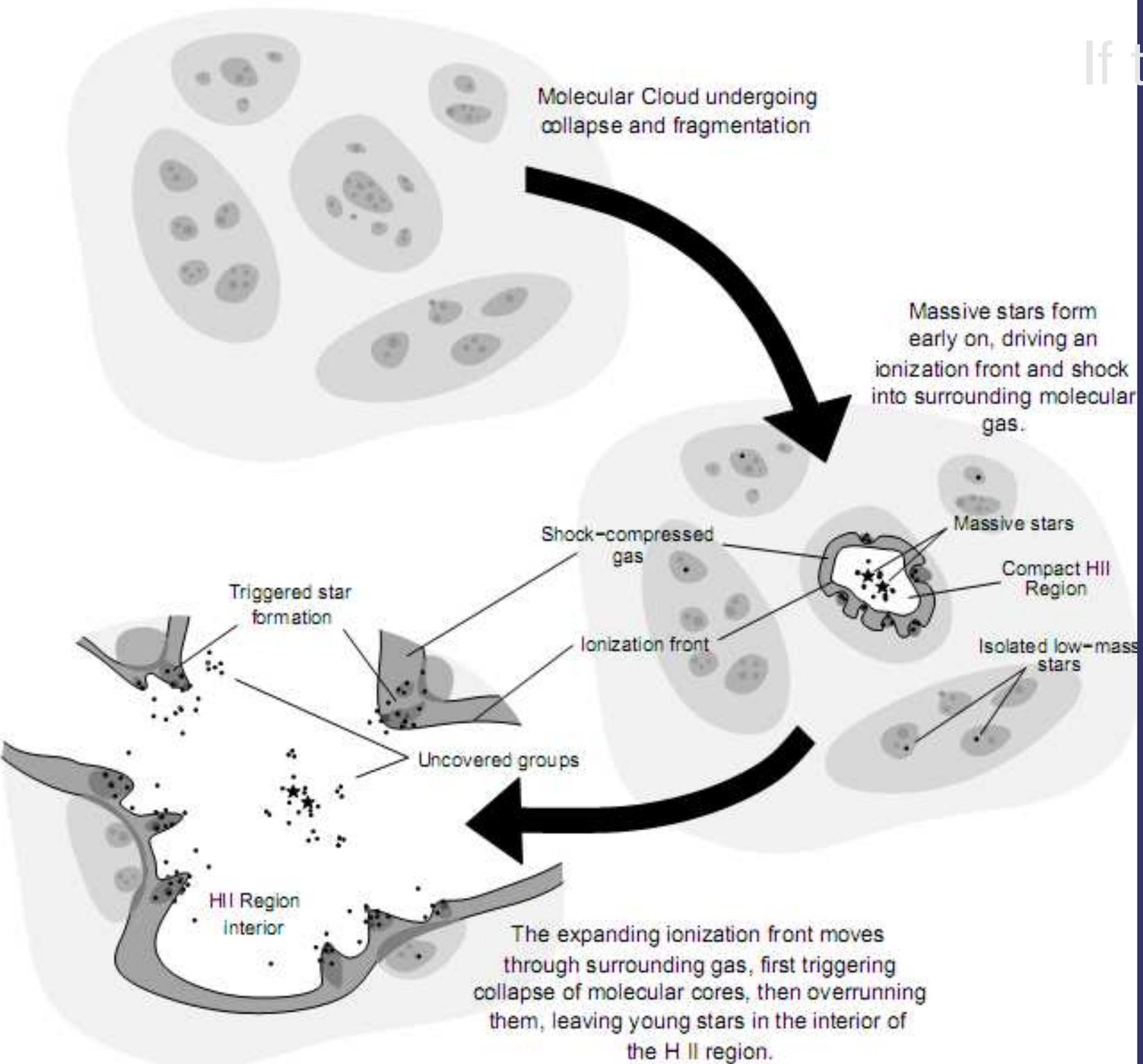
massive stars, but other formations are not.



If the formations are independent.



If they are mostly triggered by massive



# ***NOT Supernova Triggered Formation***

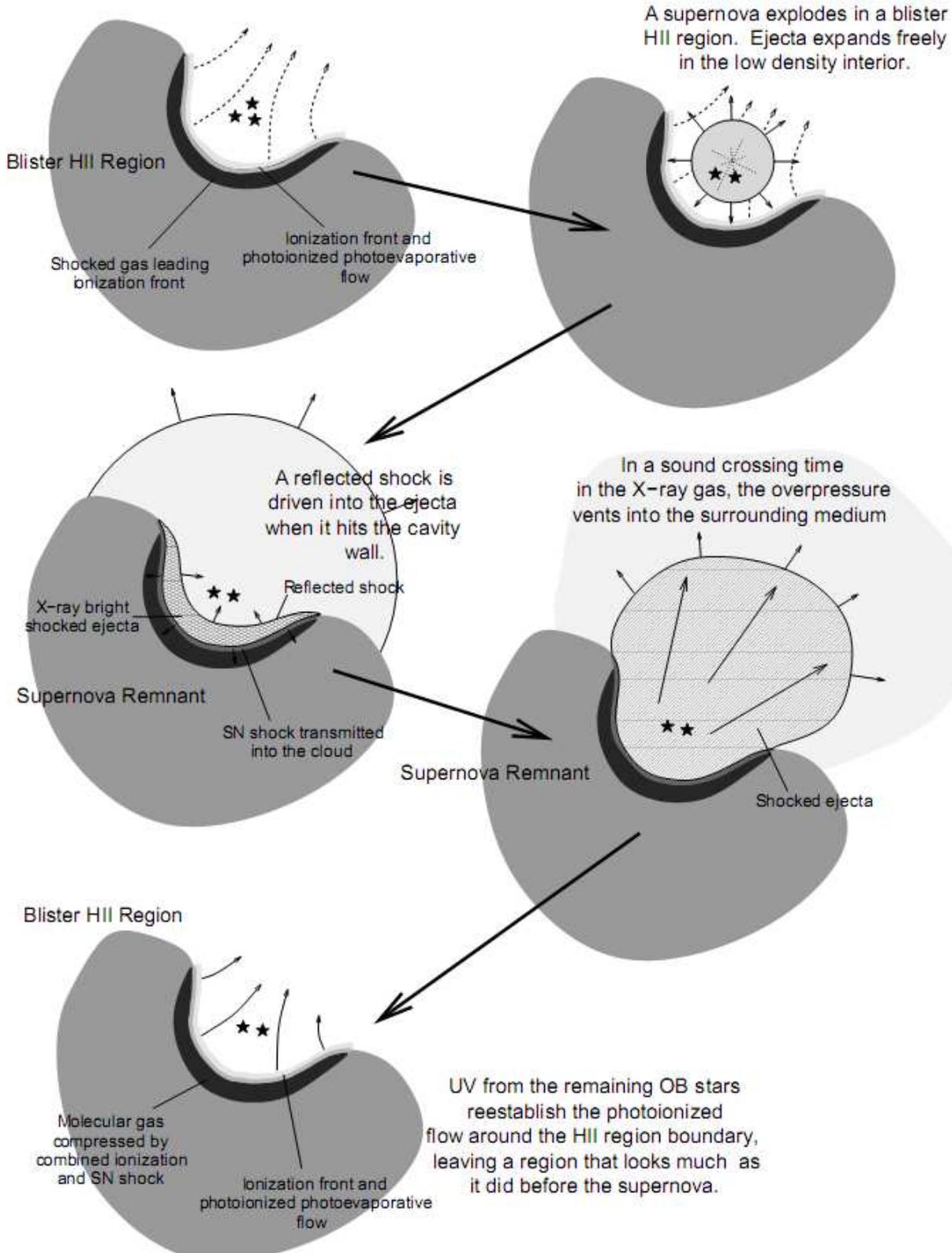
That infers the direct creation of the formation by the sudden burst of energy of the supernova explosion.

The process discussed here affects the environment in which the stars are produced

The supernova is not the dominant energy source

Even during the supernova, the energy will likely not dominate the other effects.





How the supernova effects the H II region.

Nor is our hypothesis alike the meteorite context.

Although it is *possible* for a single supernova to both collapse a star and inject SLR, the environment is highly unlikely.



# *Conclusions*

Most low mass star form near massives

It is NOT similar to the process observed in near isolated regions

Research needs to shift focus from the Taurus-Auriga and like regions and onto massive stars

EUV and FUV from nearby massives is stronger than from the star itself, explains Clayton's observed abundances of 16/17/18 O via Young & Lyons findings (2003)

Explains the Kuiper Belt and relatively small masses of Uranus and Neptune. (disc truncation)

The model scales to potentially apply to giant H II regions in other galaxies (like 30 Doradus)



# *Conclusions cont'd*

SLRs apply to much more than 'timestamping'

Calcium-Aluminum-rich inclusions require consistent abundance of  $^{26}\text{Al}/^{27}\text{Al}$  at formation, but the most primitive contain no  $^{26}\text{Al}$

The simplest answer is an injection of fresh material shortly after formation, which fits perfectly with our new model  $^{26}\text{Al}$  decay sourced energy contributing to planetesimal differentiation- which in turn sourced Earth's water.

