The formation of Sol

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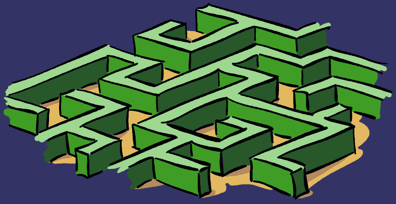
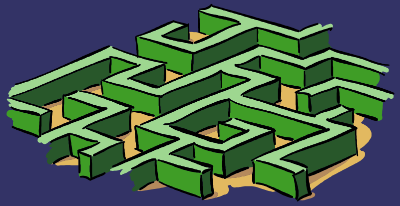
The formation of low mass stars in the presence of developed massive stars.



It makes a difference

Until recently, theres 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.

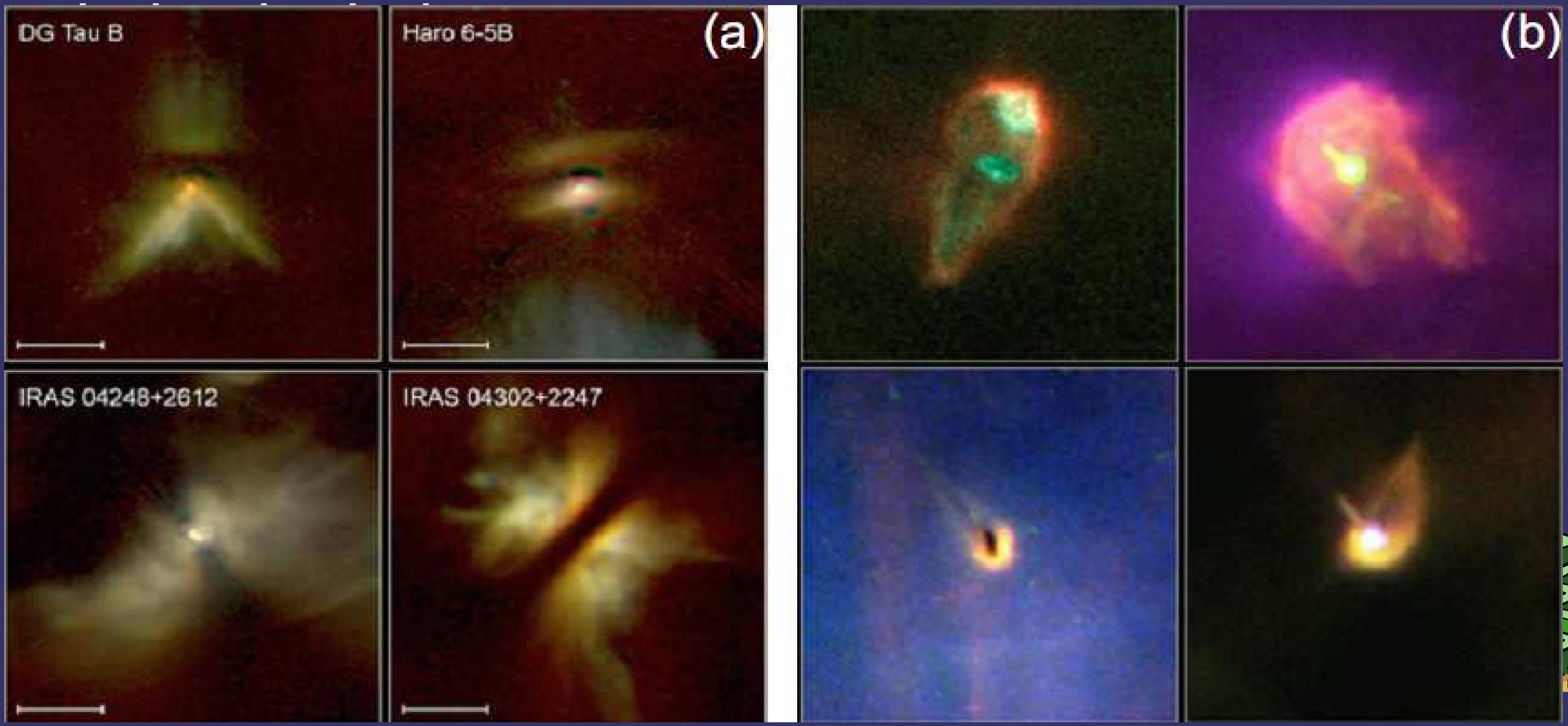
The presence of live 60-Fe in the early system tells us that *we* formed near a massive star. So what does this mean?



HST image of the forming discs

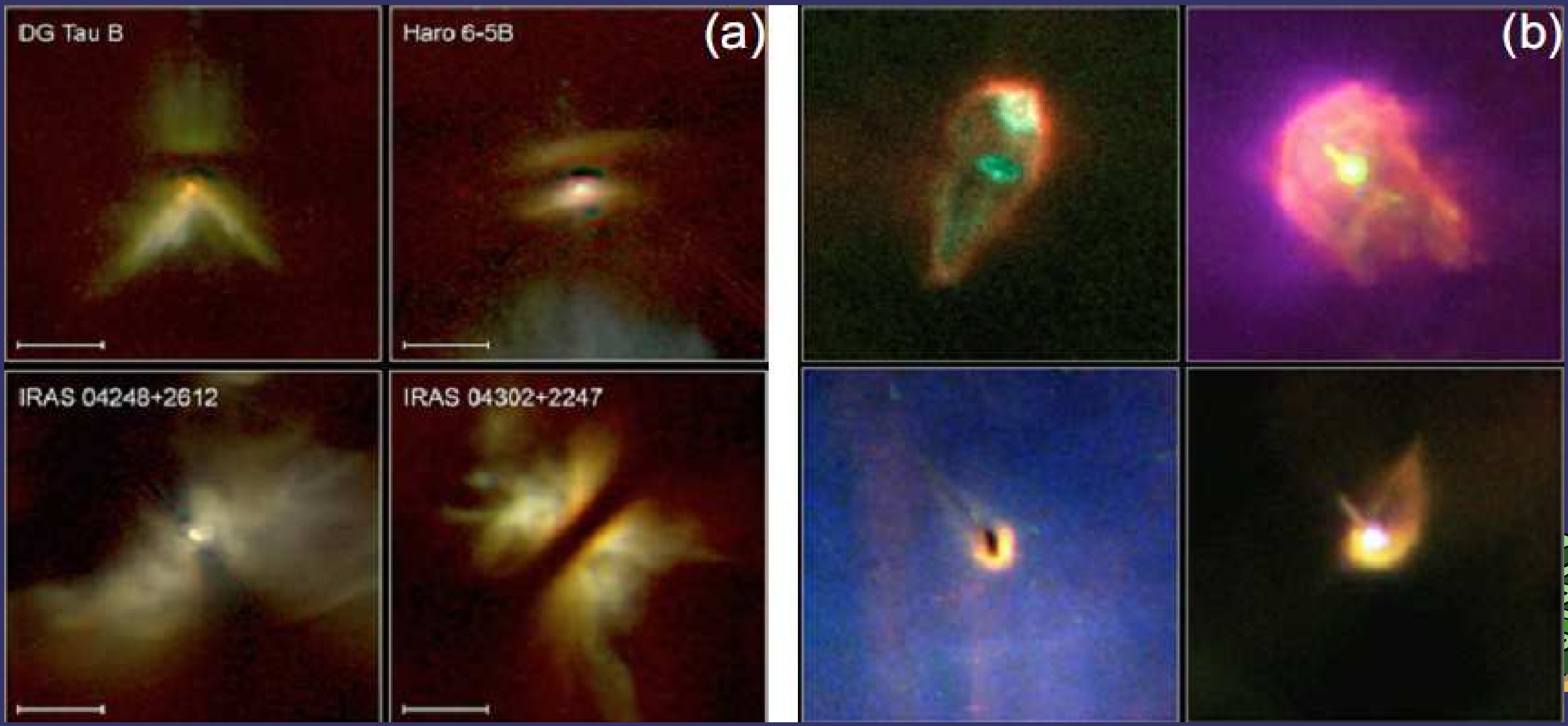
a) four young stellar objects in the cold and dark Taurus-Auriga molecular cloud, in

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



More Radiation

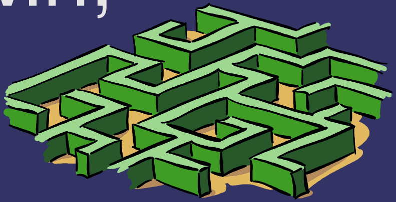
In (b), it easily visible that the protoplanetary discs are relatively sparse, having been photoevaporated by the intense UV radiation from their massive neighbors.



Meteorites: Cosmic Lumbar Puncture

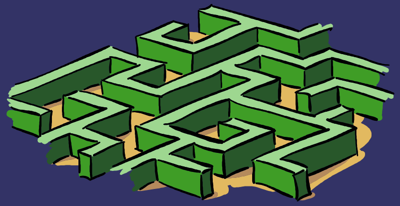
Meteorites give us a snapshot of the proto-planetary disc.

- -Chemical
- -Physical
- -Thermodynamic
- -Time constraints
- -Short Lived Radionuclides
  - 26 Al, 60 Fe, 36Cl, 41Ca, 53Mn, etc.



Trajectory of Decay

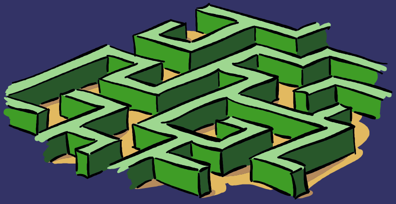
Radioactive isotopes act like clocks. With longlived radionuclides, like 238U, we can measure the amount of the parent nuclide and the amount of the daughter isotope and calculate the time since the daughter isotope began to accumulate. This method has given us the age of the solar system, the age of 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.

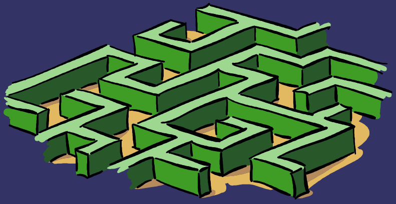
- The object in question must have been recently homogenized.
  - melting followed by crystallization
  - evaporation followed by condensation
- A chemical fractionation must occur.
- The objects must have remained undisturbed
  - i.e. remelted, heated to diffusion, dissolved.



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 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.

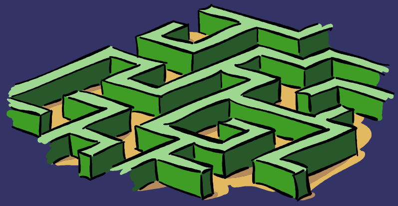
Taurus Auriga is a particularly odd specimen

- More Binary Stars than would be expected
- Fewer Brown Dwarfs
- The initial mass function peaks at a higher mass (~$0.8M_{Sun}$) than is expected.
- Deficient for masses >$1M_{Sun}$

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.
- ~75% are in clusters with live massives (>8M)
- Others likely contained massives previously

This now disputes previous theories.

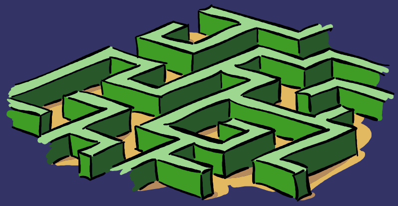


We were wrong?

- 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?

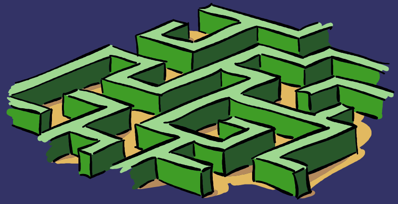
- Most low mass stars formed near massives but did we?
  - According to Adams & Laughlin (2001), the likelihood is ~0.85%
    - But this is subject to the same criticisms as the Adams & Myers paper.
    - This time they OVERestimated the likelihood of disruption from others stars, because of their assumption 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 Be (only from spallation)



So bet on Spallation...

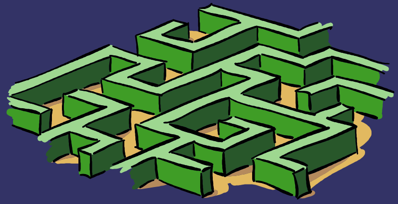
In 2003,Tachibana & Huss reported live 60 Fe in our early system.

- 60 Fe has 1.5Myr half life, but does NOT form in spallation
  - Only in supernovae
- Other spallation-unfriendlies include 182 Hf & 107 Pd
- Meteoritic studies also show 36 Cl in the outer system



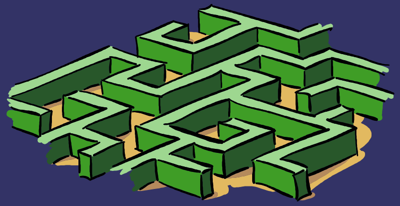
Explaining 60 Fe

- 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)<3x10^-6
  - Massive stars *are* correlated with low mass star formation, and their supernovae produce necessary materials.



So do they work?

- Their supernovae produce 60 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 'no-va 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, thats 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. 10Be

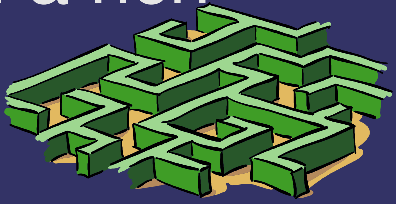
Spallation might *still* contribute (we're not limited to only one event)

but there is a recent theory...

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

We can safely say 60 Fe implies Sol's creation in a rich cluster near at least one massive

Certainly more than 10 Be implies spallation!



Massive stars and their environments

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

Extreme EUV/FUV

Surrounding interior gas is , tenuous, ionized and hot (10^4K)

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 Plaomar Observatory, blister H II region.

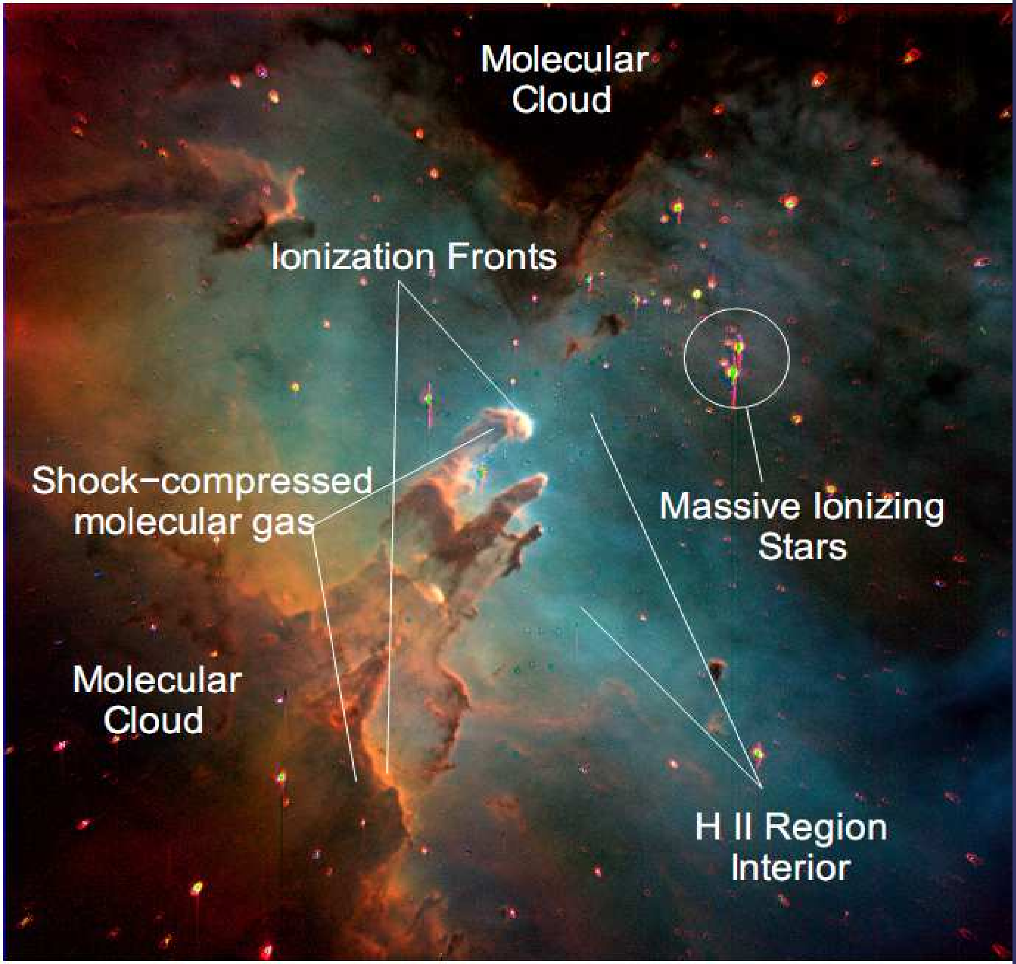
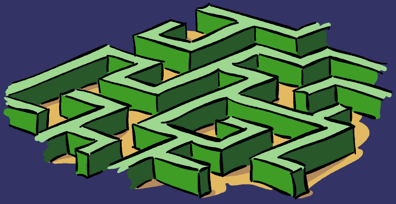


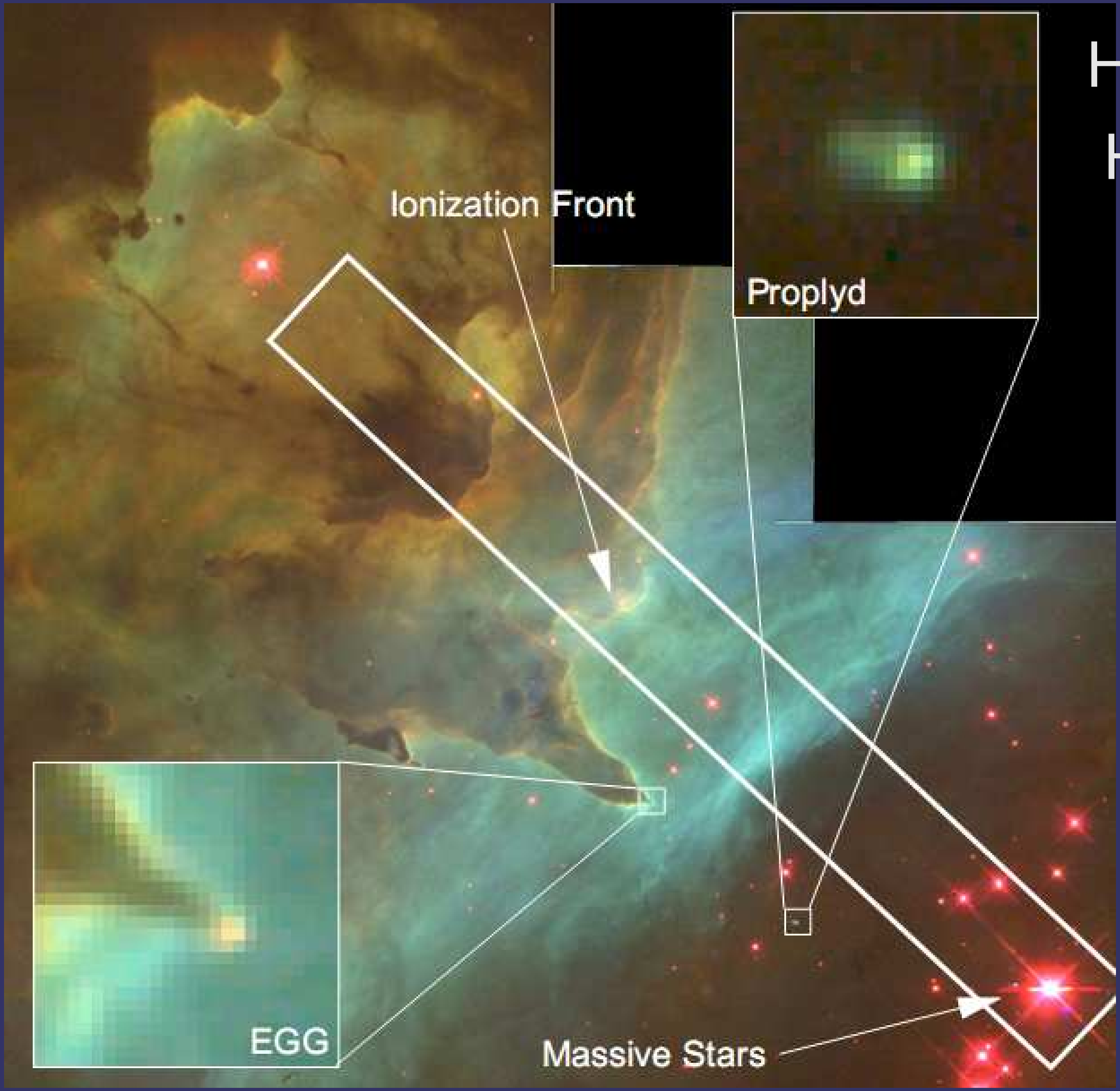
Figure 2. The structure of a blister H II region. This is a ground-based image of the Eagle Nebula, M16, obtained with the 1.5-m telescope at Palomar Observatory.

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

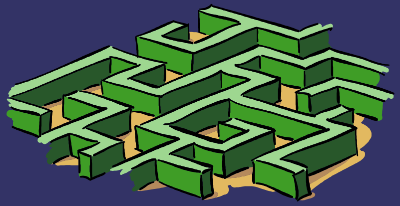
Where they start

They do not form in interior region.

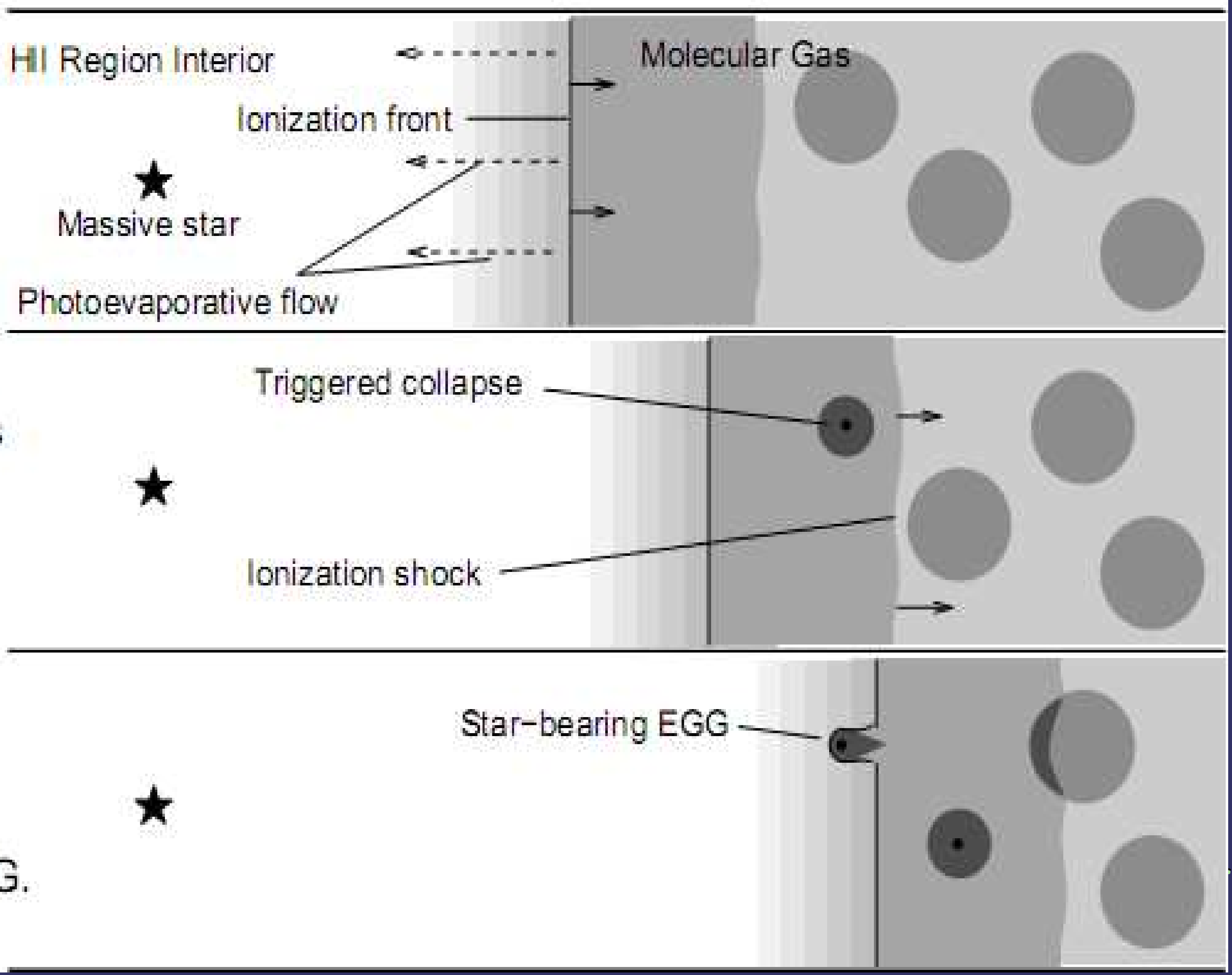
- We know this

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)

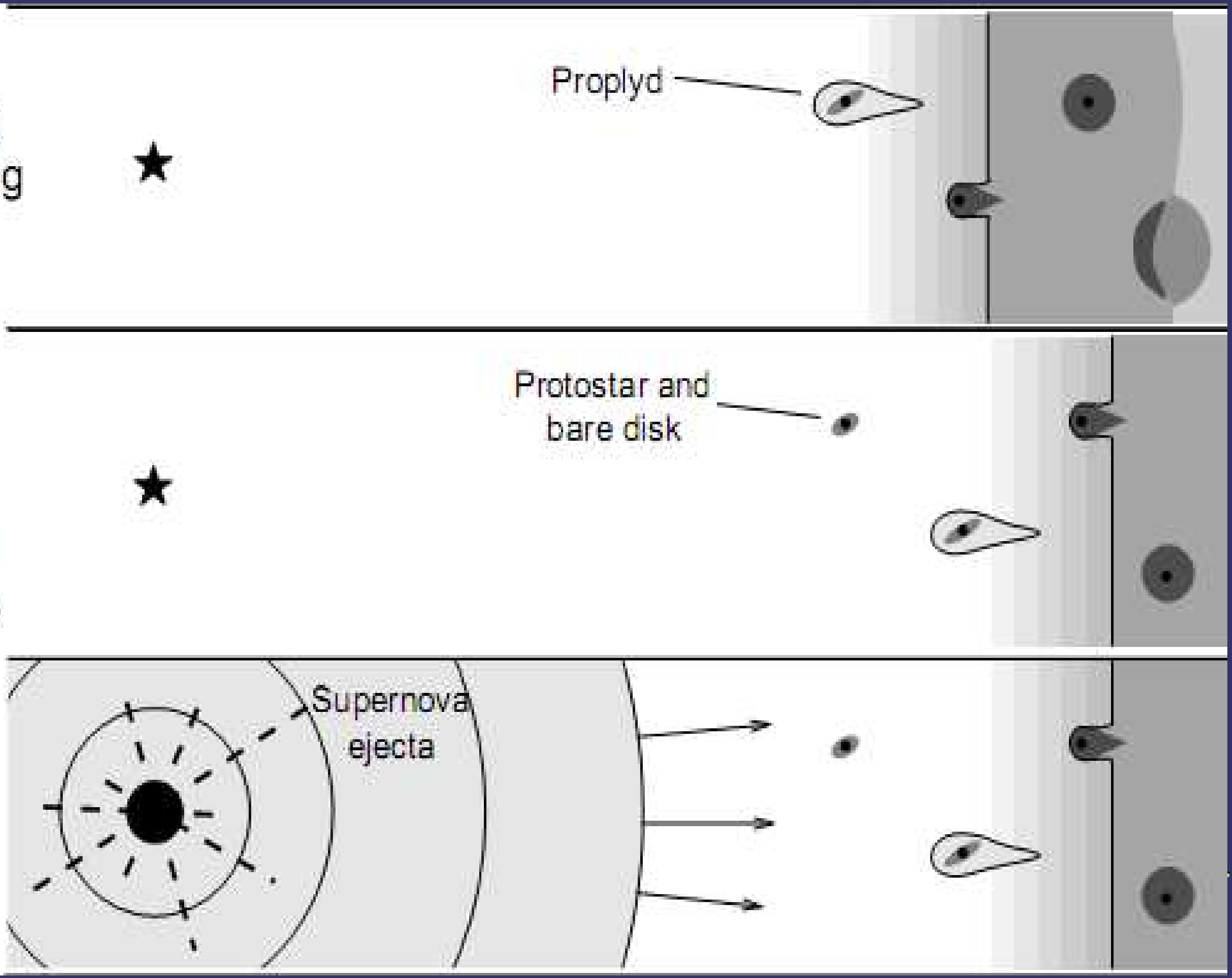


(1) Radiation from a massive star drives an ionization front into surrounding molecular gas.

(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.

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

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

How Supernovae deposit material

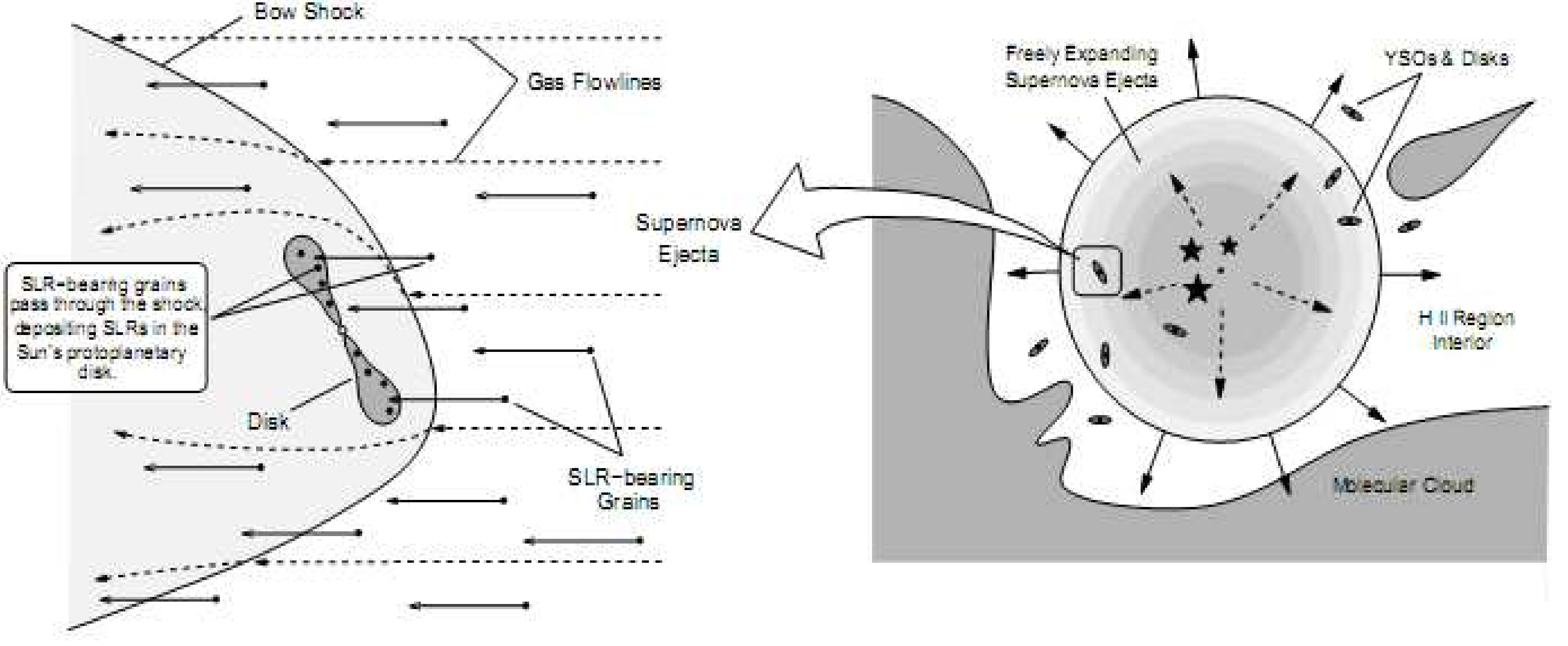
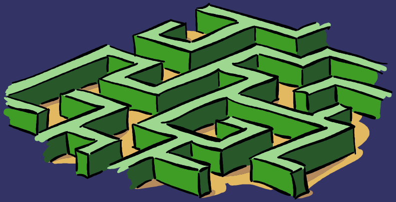


Figure 7. Illustration of the "aerogel" model for injection of SLRs from Ouellette, Desch, & Hester (this volume).

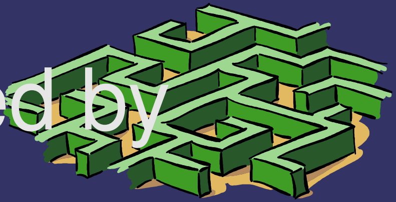
NOTE:Not necessarily the only source of SLRs

Also, most clusters disburse in similar time frames as Massives go Supernova.

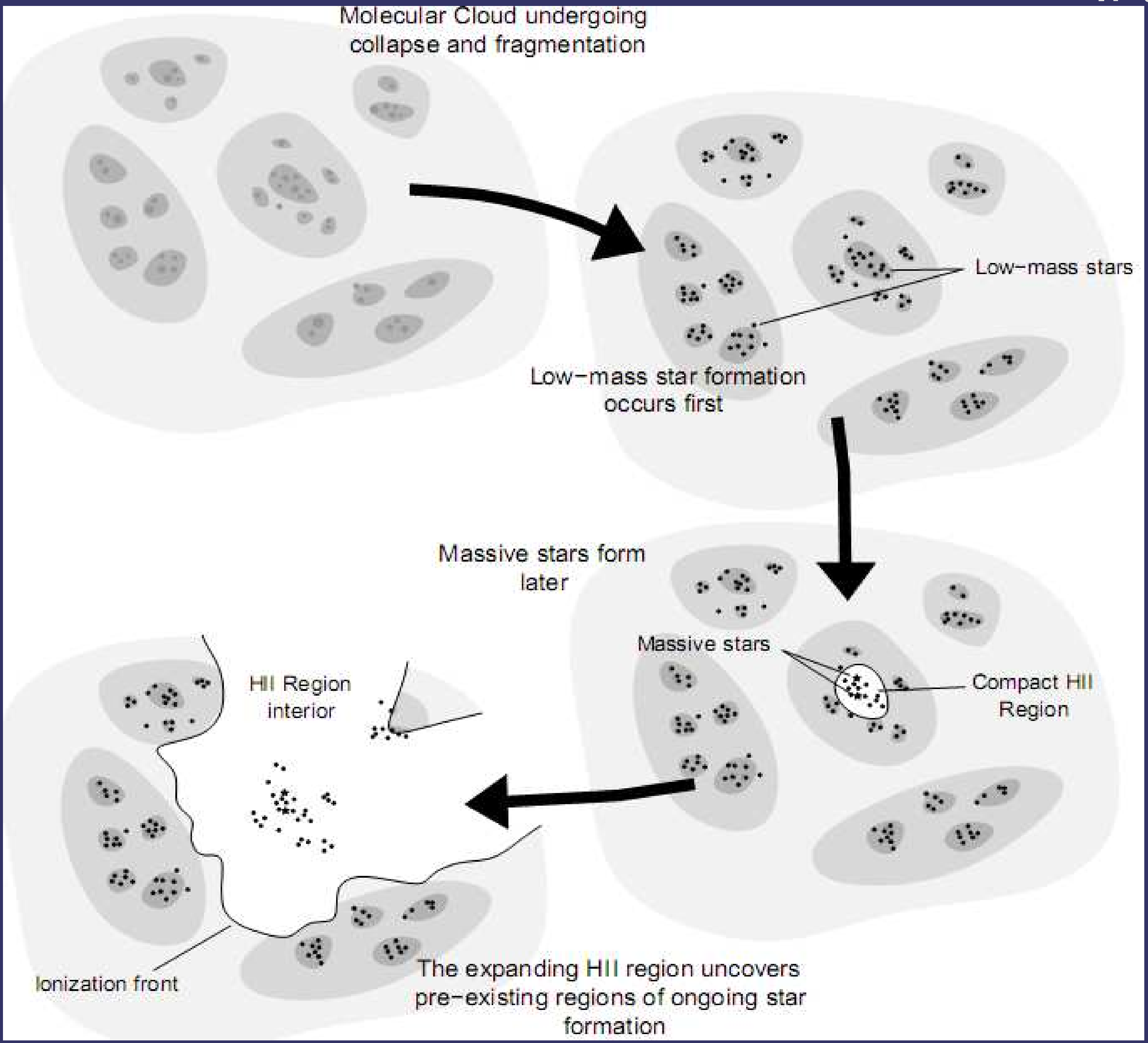


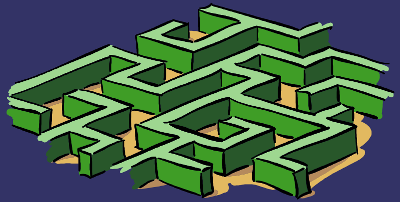
What triggers an actual star

- We assume theres 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 massives, 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 massives, but other formations are not.

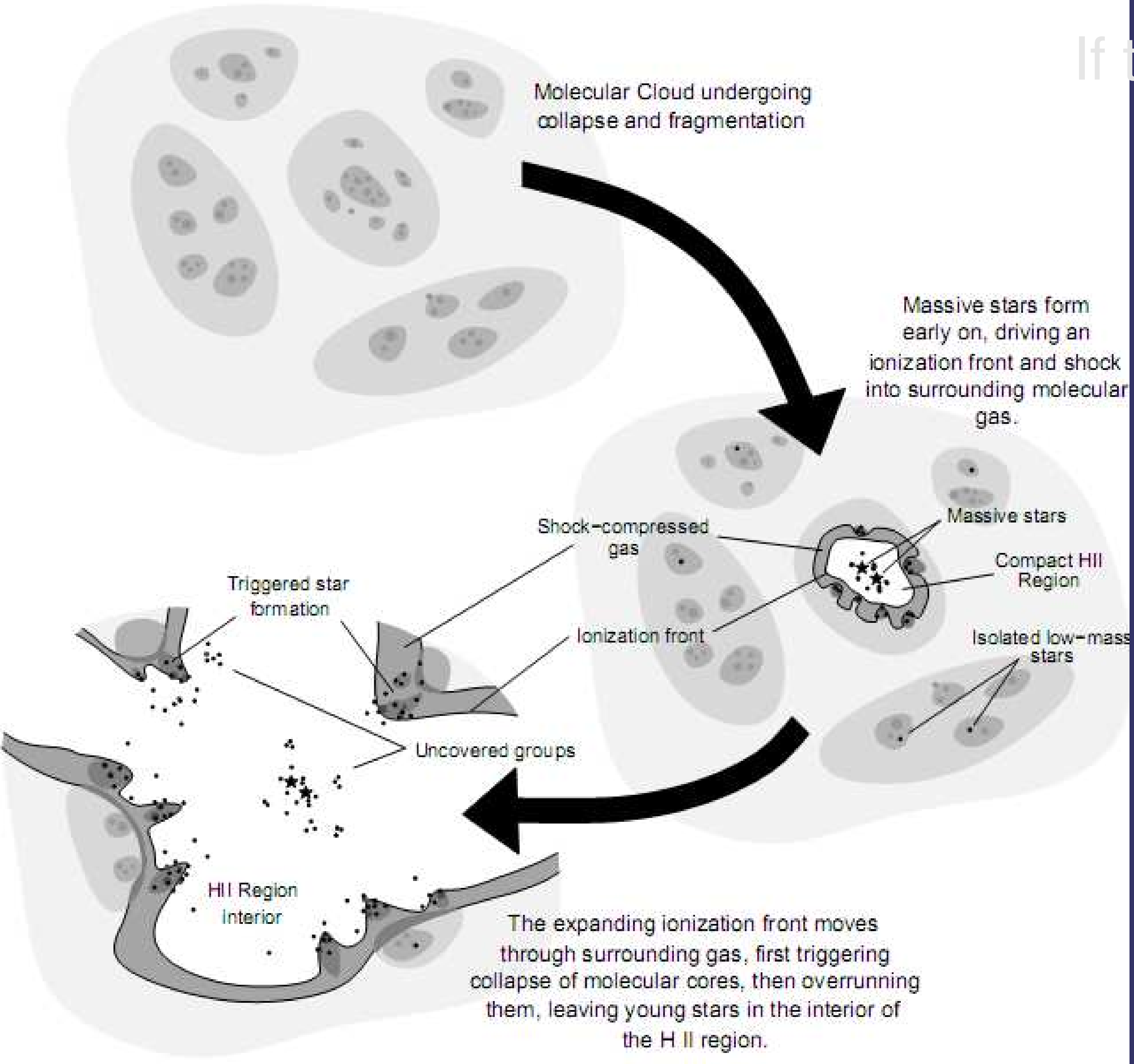


If the formations are independent.





If they are mostly triggered by massives



Molecular Cloud undergoing collapse and fragmentation

Massive stars form early on, driving an ionization front and shock into surrounding molecular gas.

Massive stars

Compact HII Region

Isolated low-mass stars

Shock-compressed gas

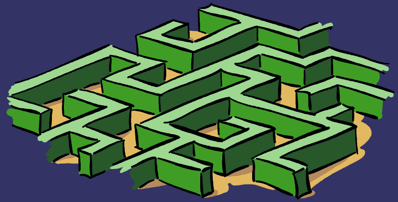
Ionization front

Triggered star formation

Uncovered groups

HII Region Interior

The expanding ionization front moves through surrounding gas, first triggering collapse of molecular cores, then overrunning them, leaving young stars in the interior of the H II region.

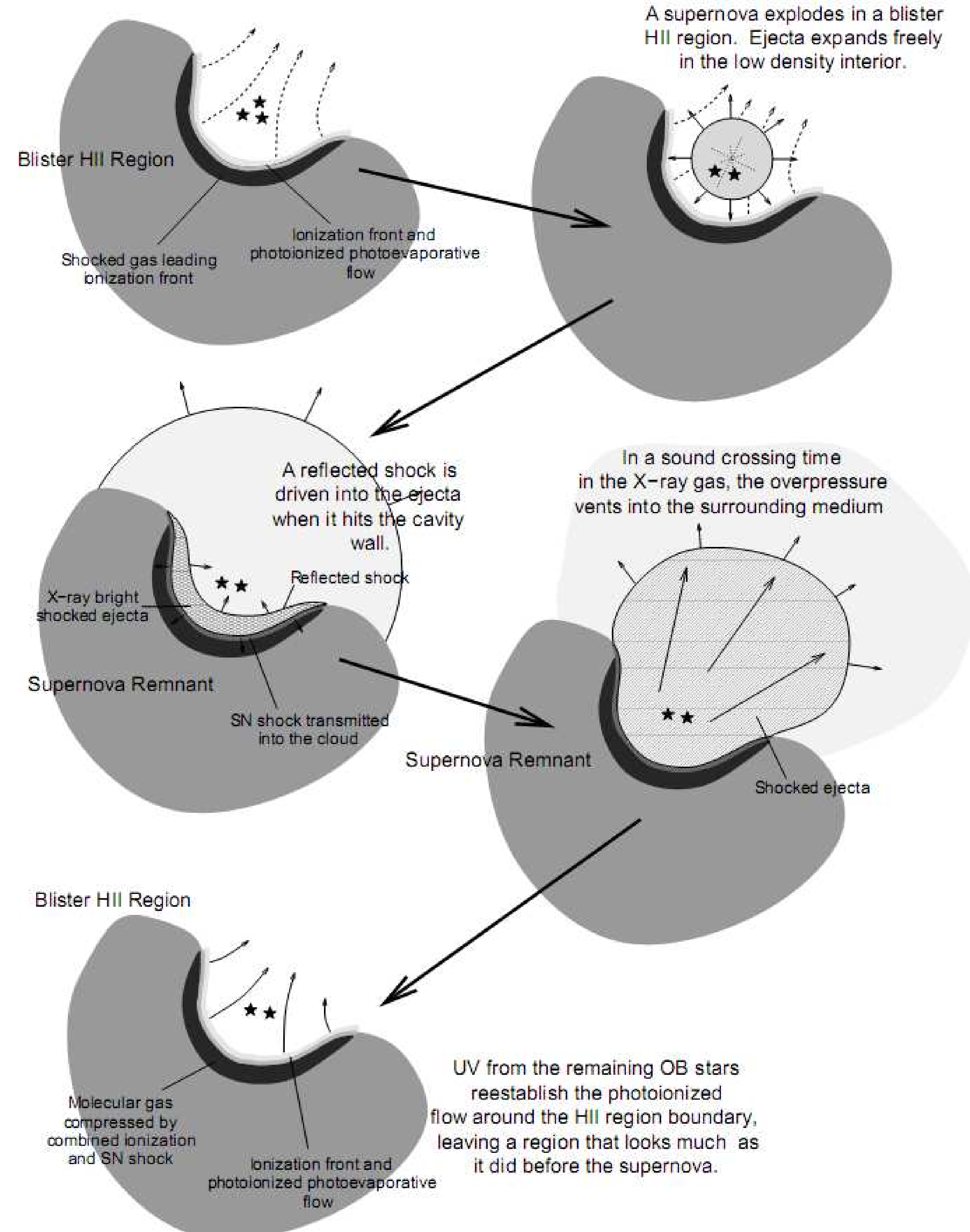


NOT Supernova Triggered Formation

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 then from the star itself, explains Clayton's observed abundancies 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 consistant abundance of 26Al/27Al at formation, but the most primitive contain no 26Al
  - The simplest answer is an injection of fresh material shortly after formation, which fits perfectly with our new model
  - 26Al decay sourced energy contributing to planetesimal differentiation- which in turn sourced Earth's water.