Compton Lecture #6: A Galactic Bubble Bath, and Other Considerations

- Welcome!
- On the back table:
  - Lecture notes for today's lecture
  - Extra copies of last week's are on the back table
  - Sign-up sheets
    - please fill one out only if you're not already on the Compton Lectures mailing list or need to change your address
  - Luncheon Sign-up sheets
    - for lunch following the final lecture on Dec 13

Stars: Their Life and Afterlife

A Galactic Bubble Bath, and Other Considerations

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68^{th} Series, Compton Lecture #6

November 15, 2008

Outline

- Supernova Remnants and Star Formation
- Star Clusters, OB Associations, and Stellar Winds
- Superbubbles

Key Points to Take Away

- Supernovae can trigger star formation
  - One of several mechanisms
  - Our solar system may be an example
- Stars tend to form clustered
  - Young clusters with massive stars: OB associations
- Winds from massive stars carry a lot of energy
  - Carve out bubbles around stars, enrich ISM in metals, possibly accelerate CRs
- SNRs and winds from cluster can merge to form Superbubbles: large, hot, low-density regions surrounded by a shell of swept-up ISM
  - Many CRs accelerated inside superbubbles?

Supernova Remnants and Star Formation

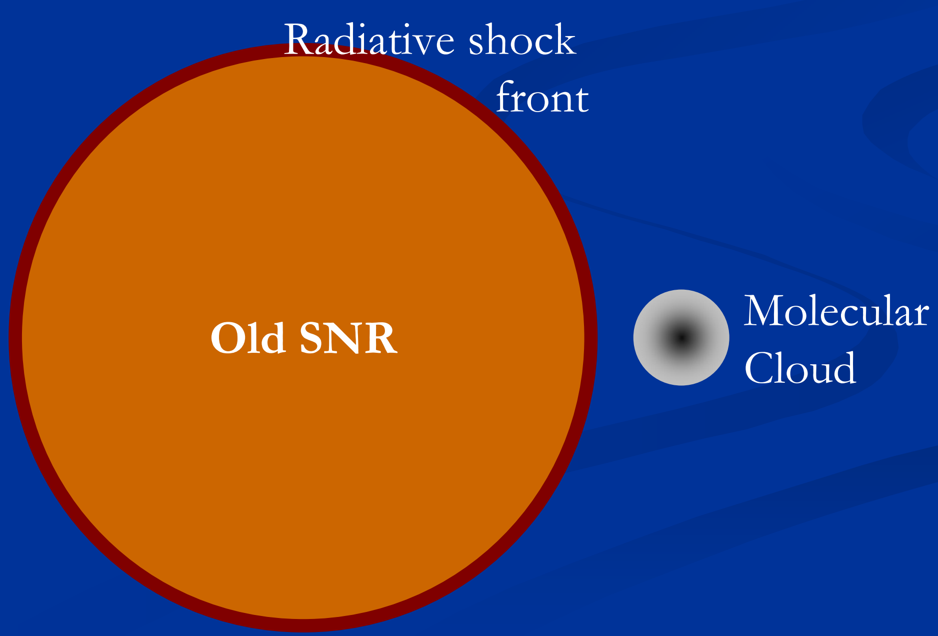
Supernovae: Triggering Cloud Collapse

- Stars form when overdense regions inside molecular clouds collapse.
  - How does density get high enough to cause collapse?
- Can happen a variety of ways
  - passage of galaxy's spiral arms
  - collisions between clouds
  - interactions with nearby galaxies
  - pressure from stellar winds, supernovae

- Lots of ongoing research!
  - How does each mechanism operate?
  - Which mechanisms are most important?
  - Do they produce different populations of stars?
    - mass distributions, …

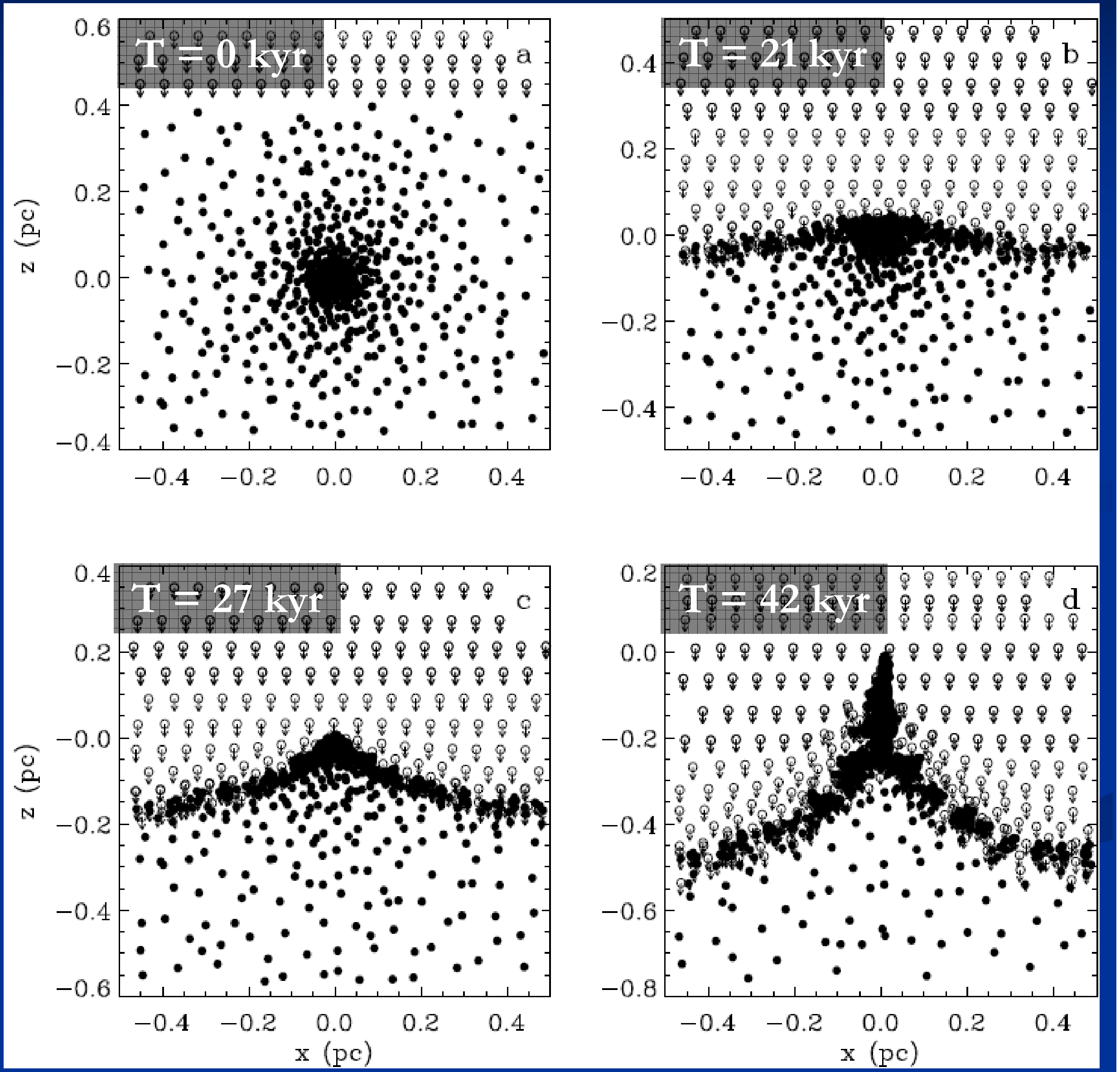
Supernova – Induced Star Formation

- Requires slow, radiative shock front
  - Old SNR (opposite of CR acceleration)
  - Slow: 10's km/s → shocked material stays cool enough to radiate efficiently
  - Faster shocks tear cloud apart
  - Simulations ⇒ works under right circumstances
- Perhaps our solar system formed as a result of a supernova?



Simulated SN-Induced Cloud Collapse

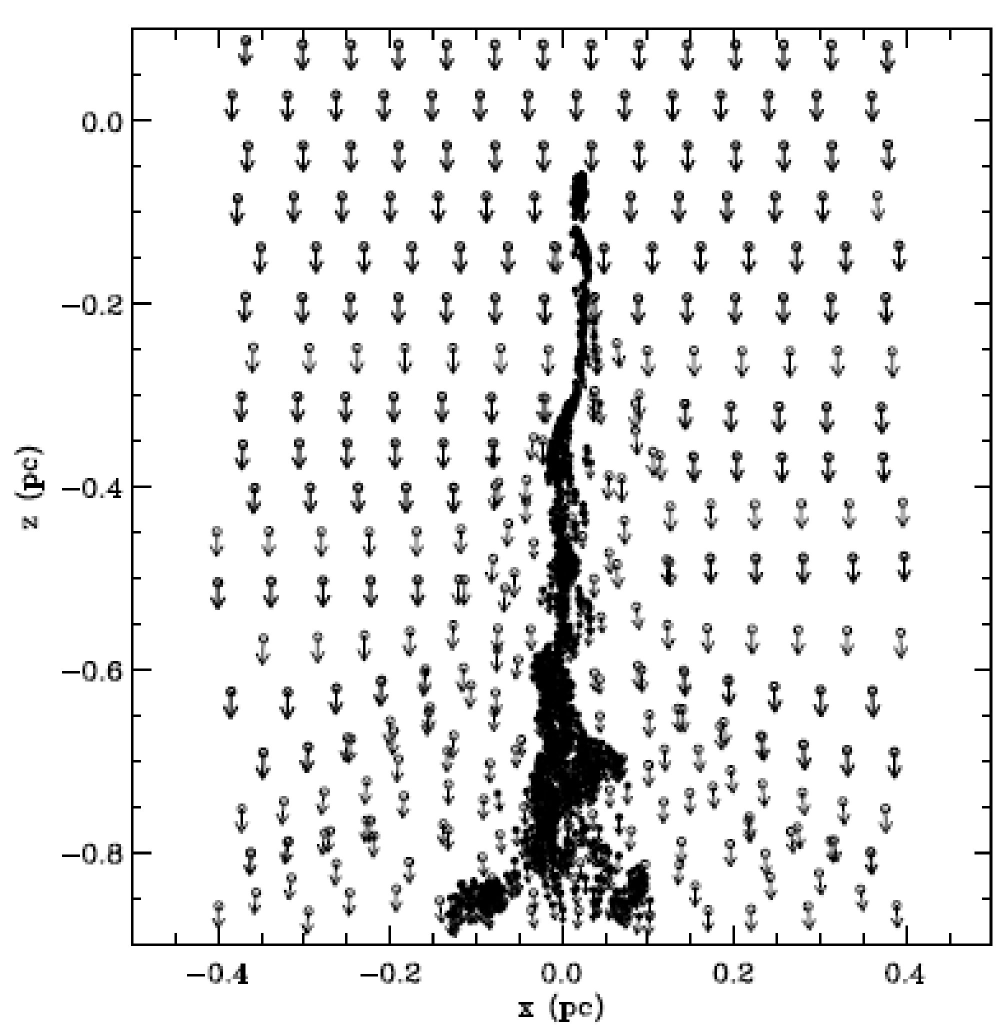
- 3-d numerical simulation.
- Start: Cloud temp 10 K, shock speed 25 km/s.
- 21 kyr: shock transmitted into cloud, cloud flattened.
- 27-42 kyr: cloud edges erode, core forms filament.
  - If shock too fast, erosion would tear cloud apart
  - In this case, self-gravity begins to collapse densest part of filament



From Vanhala & Cameron 1998

Simulated SN-Induced Cloud Collapse

- 70 kyr: head of filament is collapsing.
  - success!
  - most of filament will relax, expand over time.
  - shock front continues to “collect and collapse” matter, may eventually fragment and form some additional collapsing cores.



From Vanhala & Cameron 1998

Examples – Our Solar System?

- Allende meteorite
  - Fell in Mexico in 1969
  - Contains evidence of ^{26}Al and other rare radioactive isotopes that were present as it formed.
  - Suggests a supernova occurred near solar system before/during its formation.
  - Chance of random coincidence in time/space is small.

Credit: H. Raab

Examples – Canis Major R1

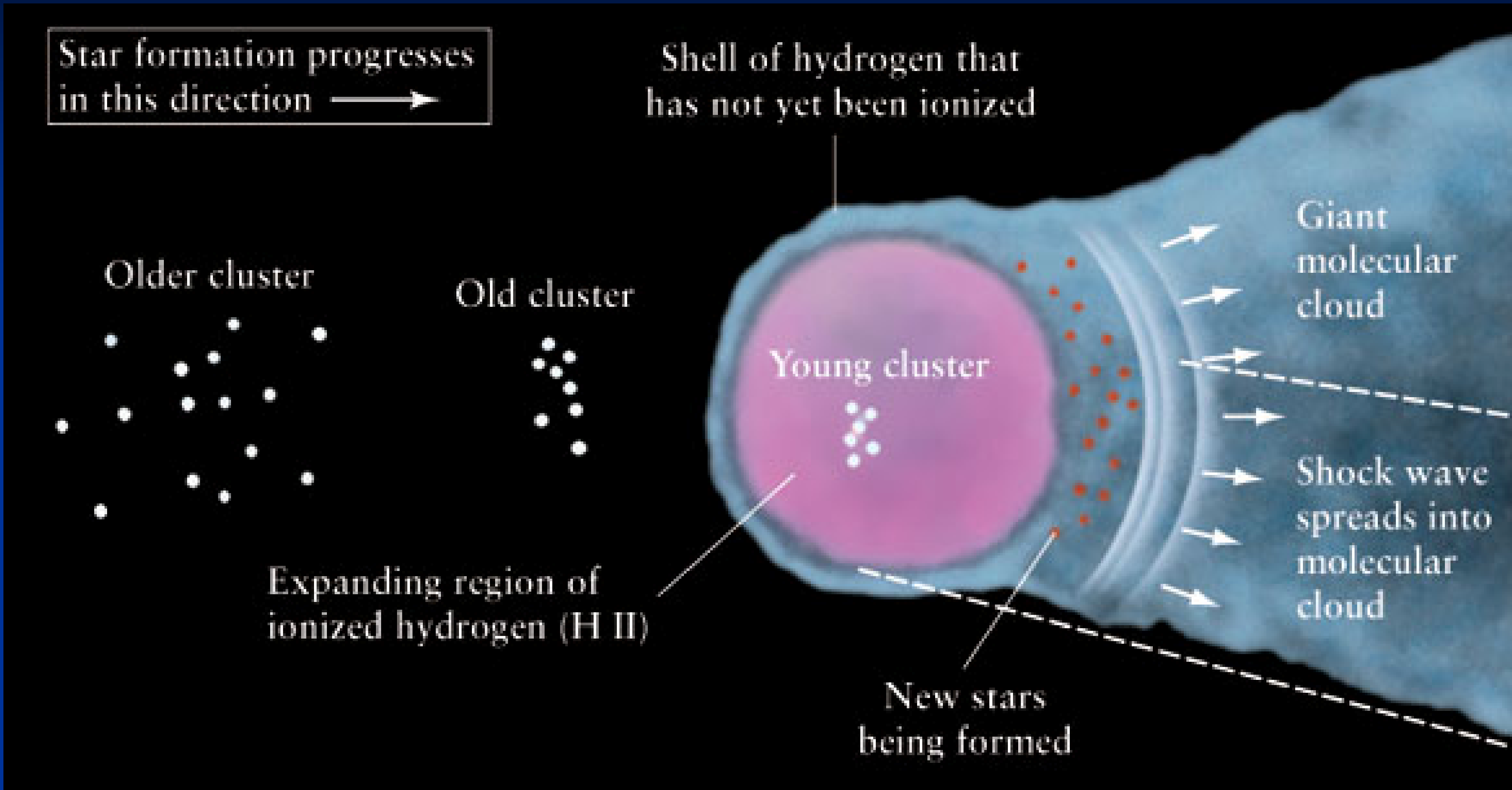
- Arc of active star formation, ~100 light year long and ~3700 light years away.
- Stars and gas expanding away from common point.
- Old (~ 1 Myr) SNR responsible for star formation?
  - Runaway star also observed near projected SN location.
  - Consistent picture, hard to prove.

Star Clusters, OB Associations, and Stellar Winds

Most stars form in Giant Molecular Clouds

- Naturally formed clustered together
  - 10's, 100's, 1000's of stars – range of masses
  - Small fraction of stars are "massive" > 8 $M_\odot$
- Typically not gravitationally bound to one another
  - Have small, random velocities: few km/s → dispersion
  - Drift apart over 10's of millions of years
- OB Associations: clusters of ~ 10 – 100+ "O" and "B" type stars (massive, hot stars) plus smaller stars
  - form in same cloud at roughly same time
  - span region of 10's – 100's light years

Sequential Star Formation in GMCs



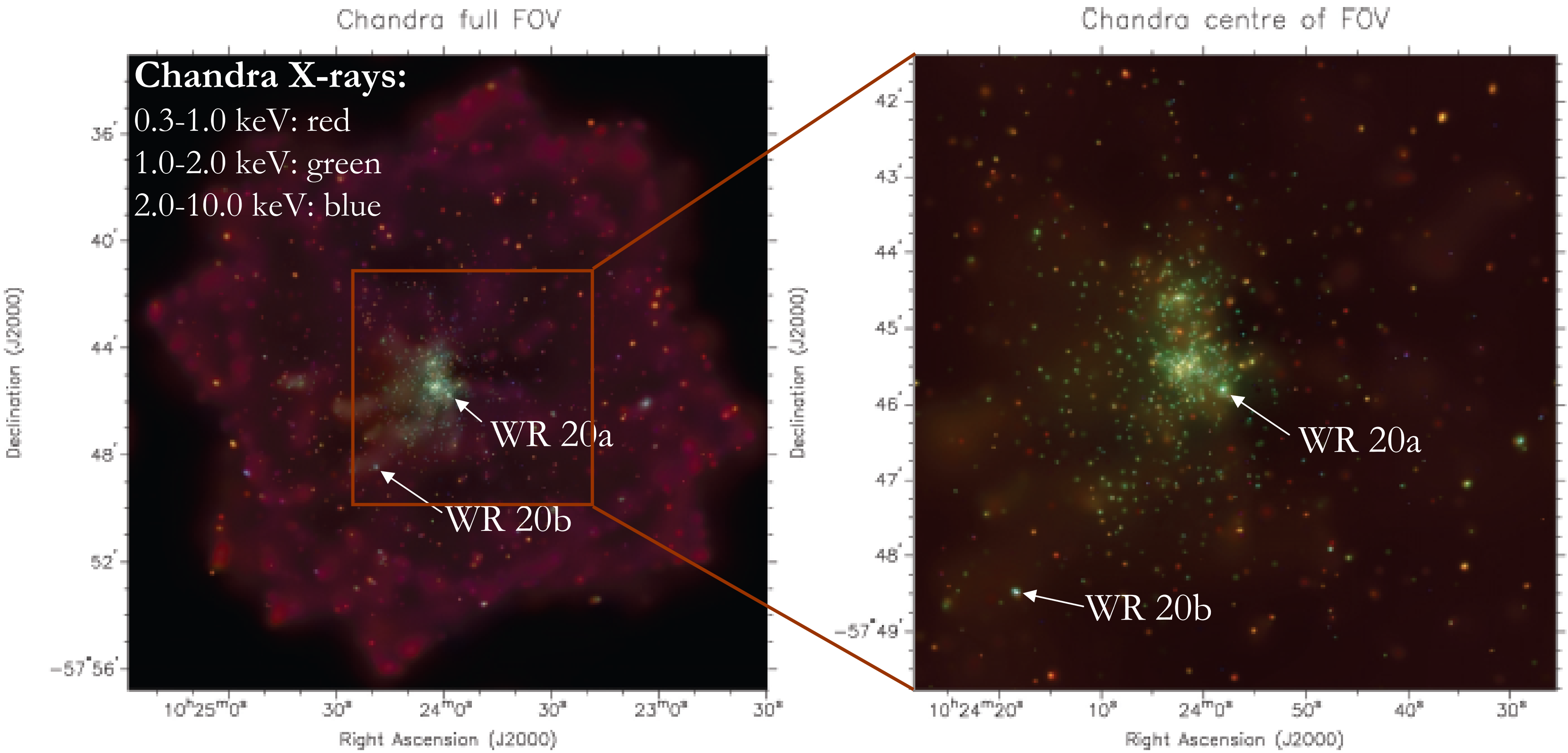
- The SNR that might've started the Canis Major R1 star formation may have been following this pattern.

Stellar Winds from Massive Stars

- Massive stars are hot and bright
  - "O" stars: 30,000 – 50,000 K
  - "B" stars: 11,000 – 30,000 K
  - Luminosity: $10^2 – 10^4\ L_\odot$
  - Lots of UV radiation
- UV radiation drives stellar winds
  - Create bubbles light-years across
  - Carry off potentially large fraction of stellar mass ($10^{-6} – 10^{-4}\ M_\odot$/yr)
  - Enrich ISM in metals: oxygen, nitrogen, …
  - Accelerate cosmic rays

Carina Nebula: shaped by stellar winds, mass ejection, ionizing radiation

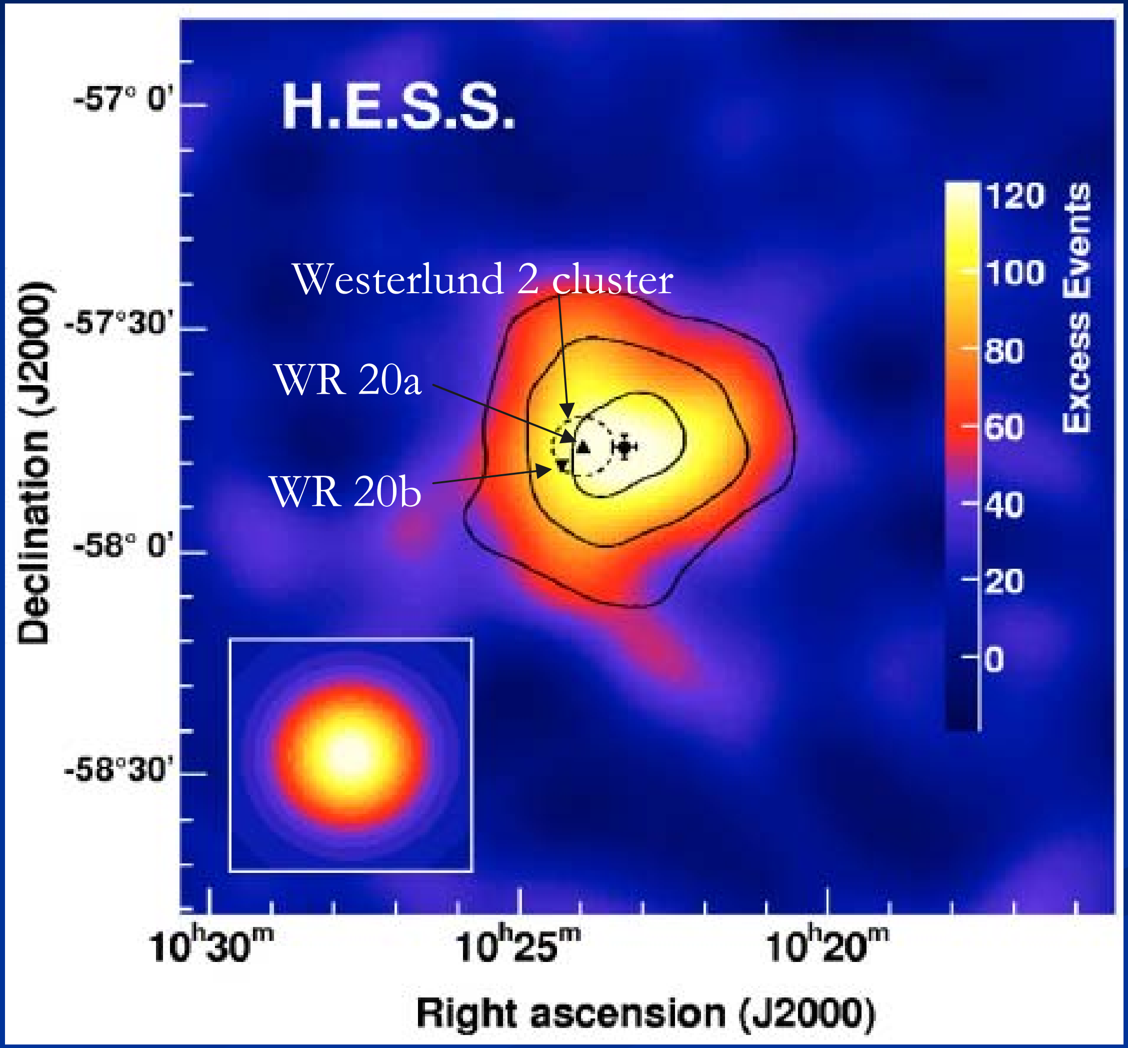
OB Association: Westerlund 2



- Massive star cluster in the giant HII region RCW 49: ~ 26,000 light years away, ~ 1-2 Myr old
- Chandra: > 100 X-ray sources in cluster region
- Spitzer: IR ⇒ ongoing star formation in RCW 49
- WR 20a is a binary with ~ 3.5-day period, both stars ~ 80-85 $M_{\odot}$ - most massive known binary!

TeV Gamma Rays from Westerlund 2

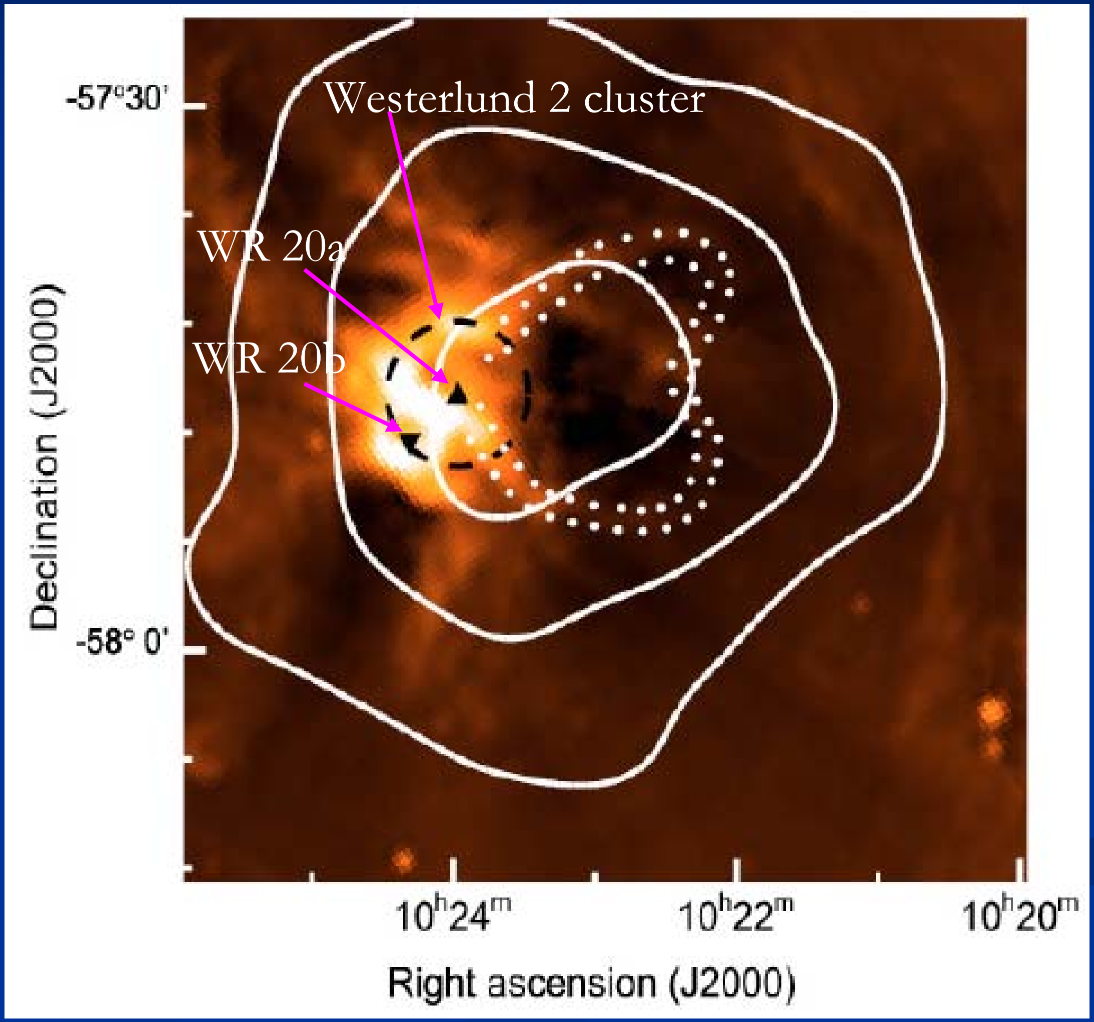
- In 2007, HESS reported TeV gamma-ray emission from the Westerlund 2 star cluster
  - First observation in TeV!
- Emission is extended (~0.18º) and not centered on WR 20a or cluster
- So it's not simply
  - colliding winds of WR 20a binary system
  - collective winds of the Westerlund 2 cluster



Gamma Rays Associated with Massive Stars

- Radio image of the region
- Deficit of emission to right of cluster
  - Low-density cavity

- Model for emission:
  - CRs accelerated in walls of cavity, diffuse through entire region
  - CRs interact with ambient matter to produce pions → gamma rays



Superbubbles

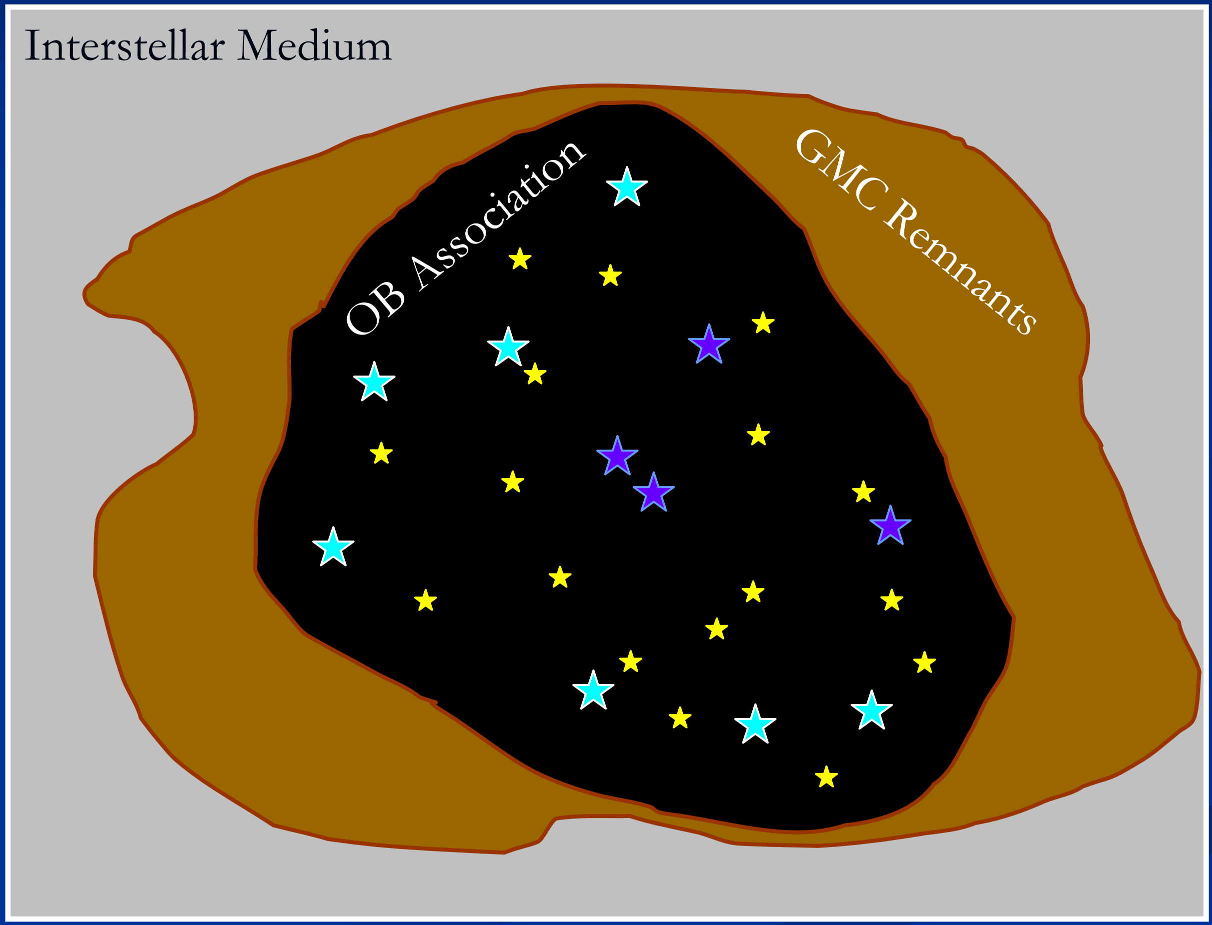
Superbubble Formation

- Most (~ 85%) supernovae are core collapse
- Most massive stars form in OB associations
  - Proximity means SNRs can collide
  - Even stellar winds can collide

- So… what happens when the massive stars in an OB association start exploding?

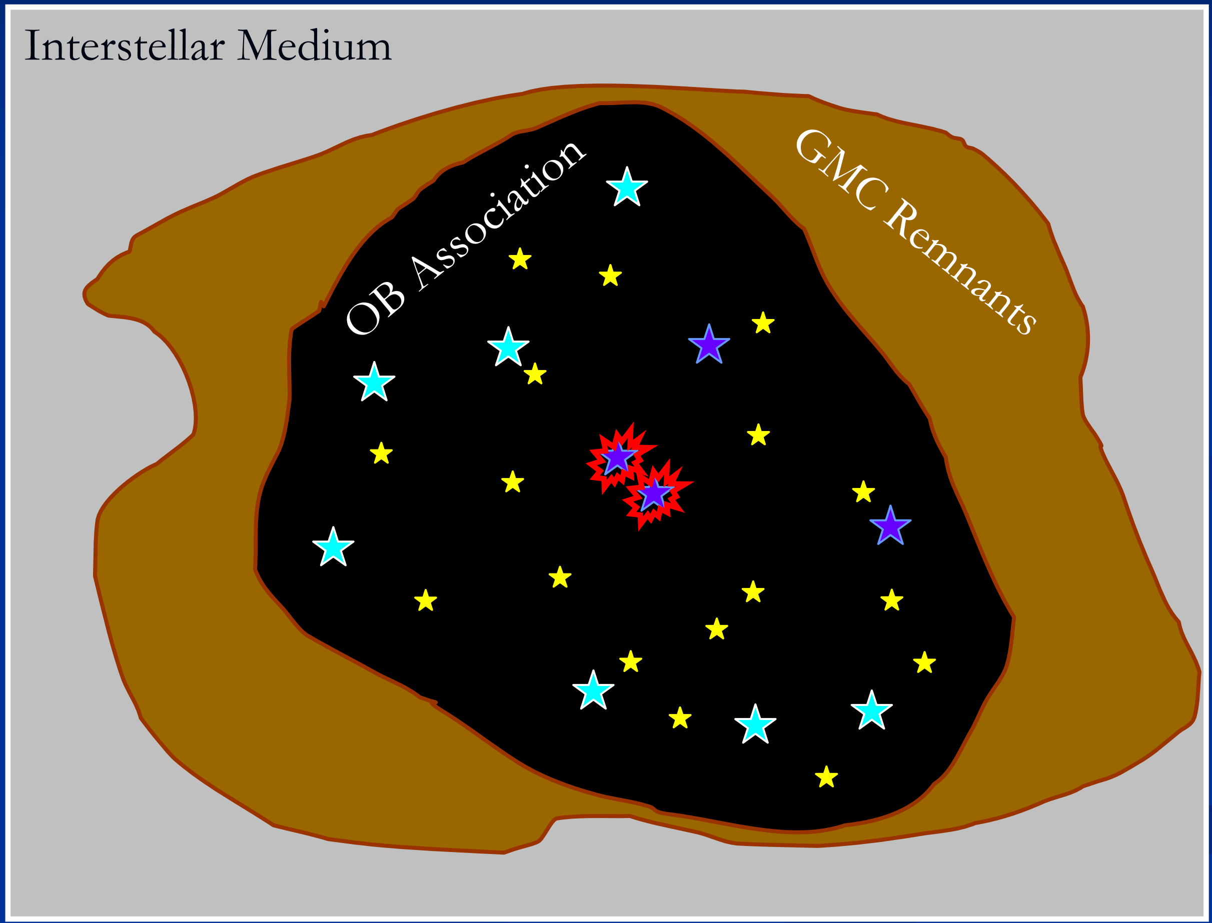
Making of a Superbubble

- Start with an OB association formed from a molecular cloud
  - ~10-100 massive stars
  - Many lighter stars, protostars, globules…
- From the beginning, winds from massive stars inject energy into cluster medium



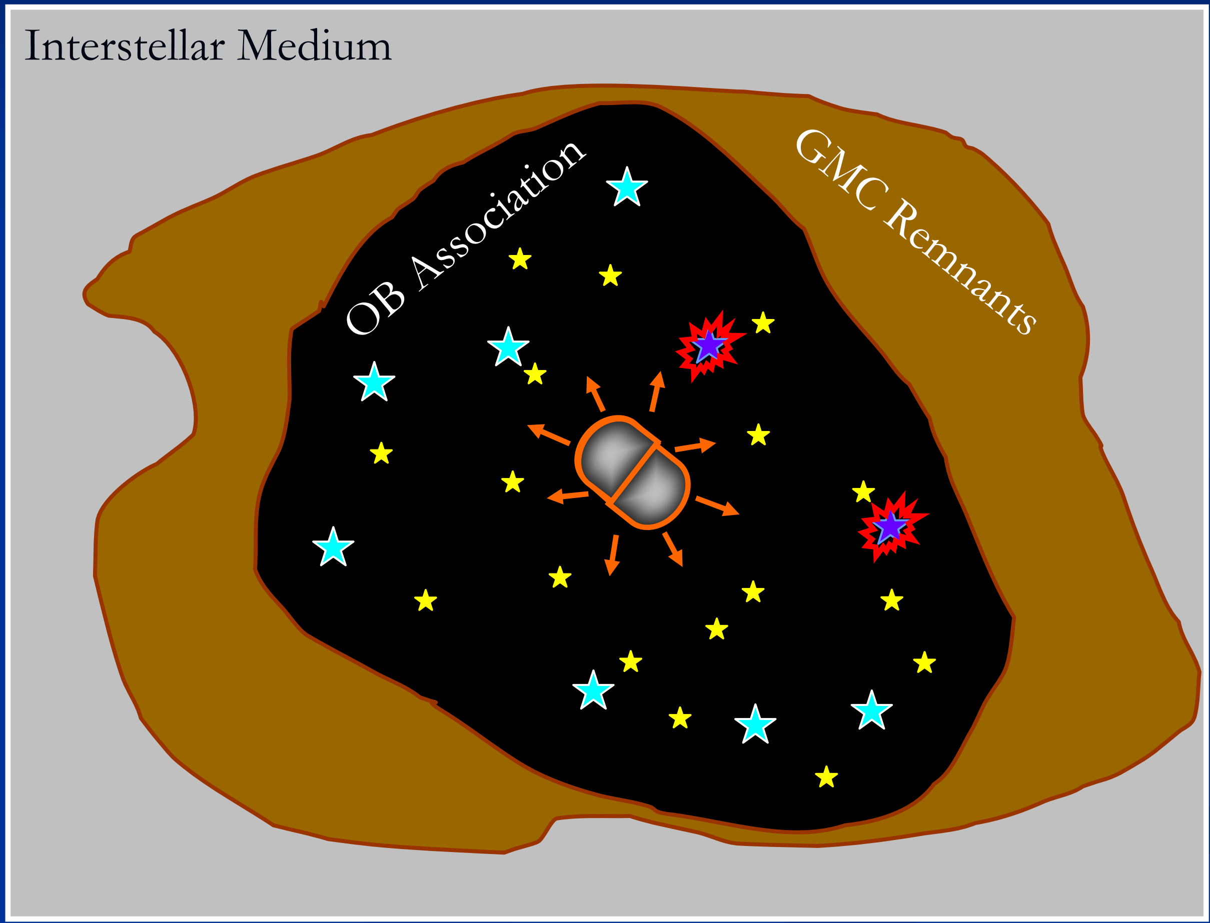
Fast forward a few million years:

- The most massive stars go supernova first

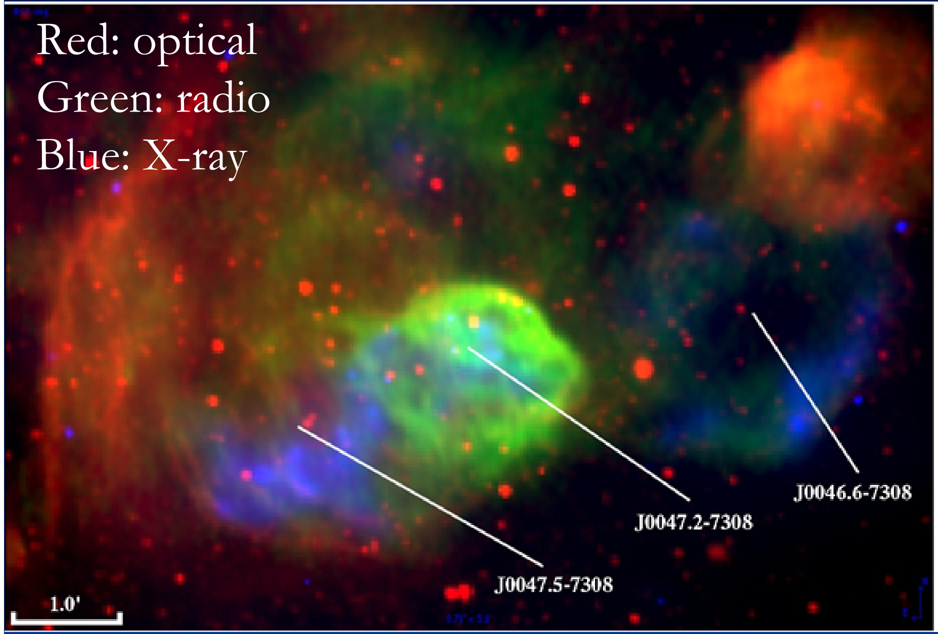


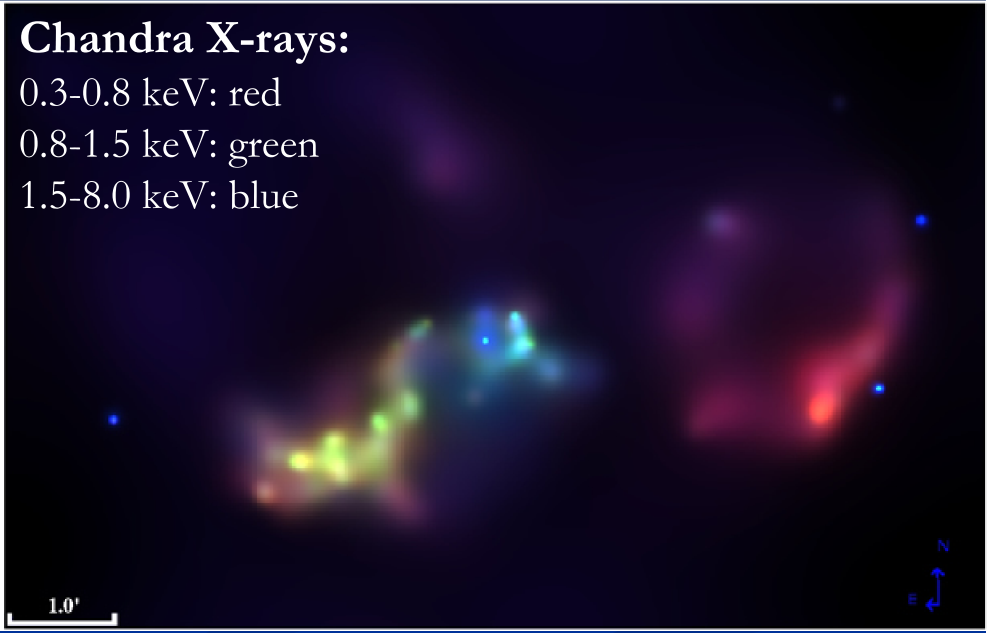
More time passes…

- As the SNRs expand, they eventually begin to merge
- Meanwhile, additional supernovae go off



Yes, this really happens: N 19 HII region

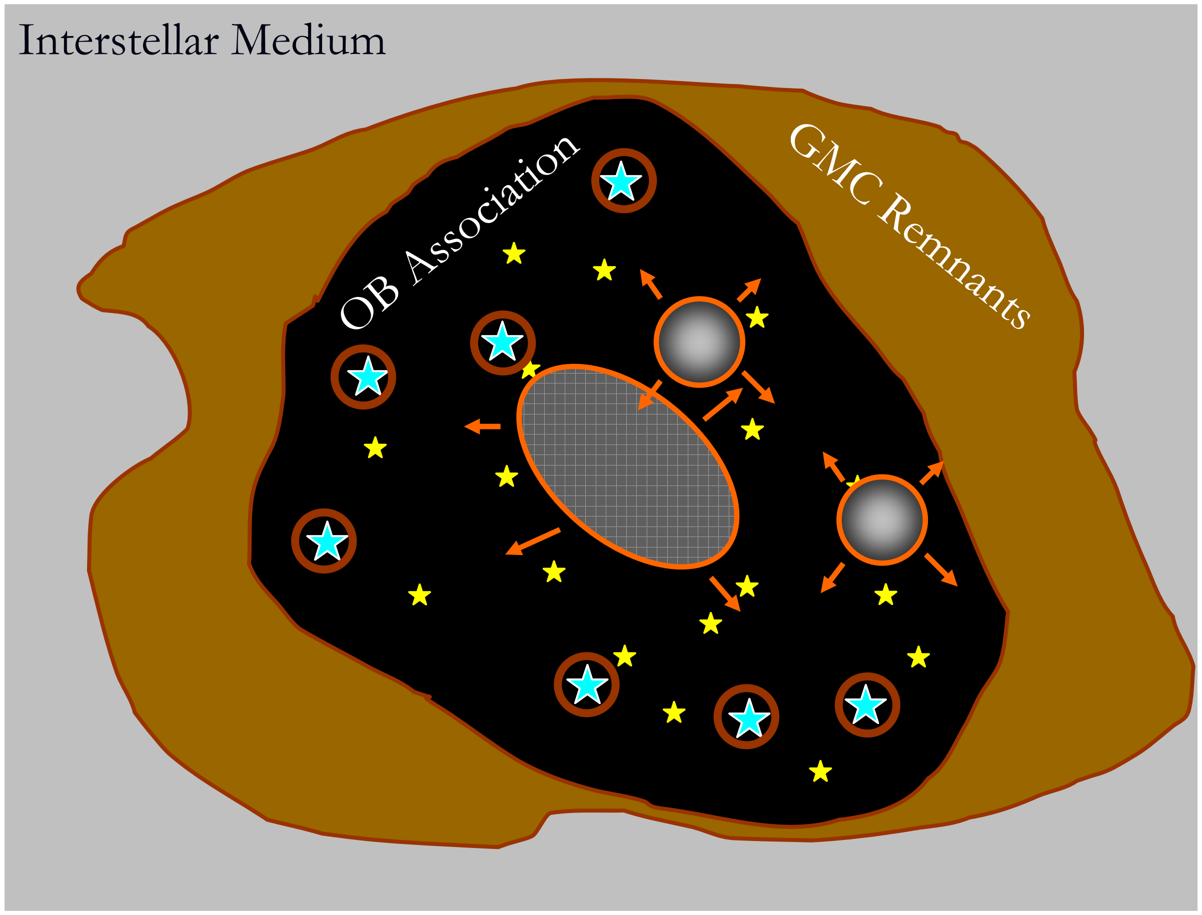




- Superbubble forming in SMC
  - 3 SNR shells observed, 2 overlapping
  - ~20+ additional massive stars nearby
  - Likely to form a superbubble in next few 100 kyrs or so

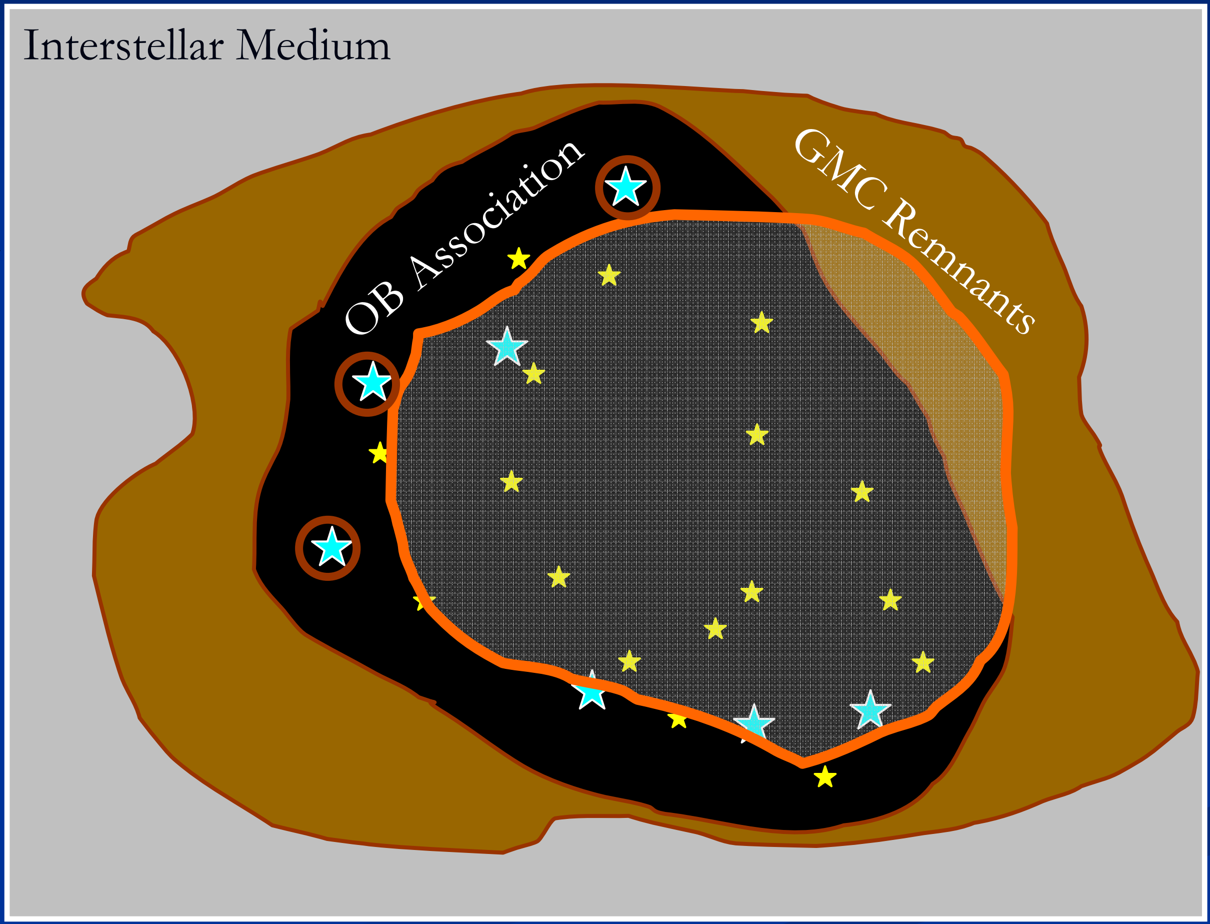
More time passes…

- SNRs continue to expand, merge
- Wind-blown bubbles form around remaining massive stars



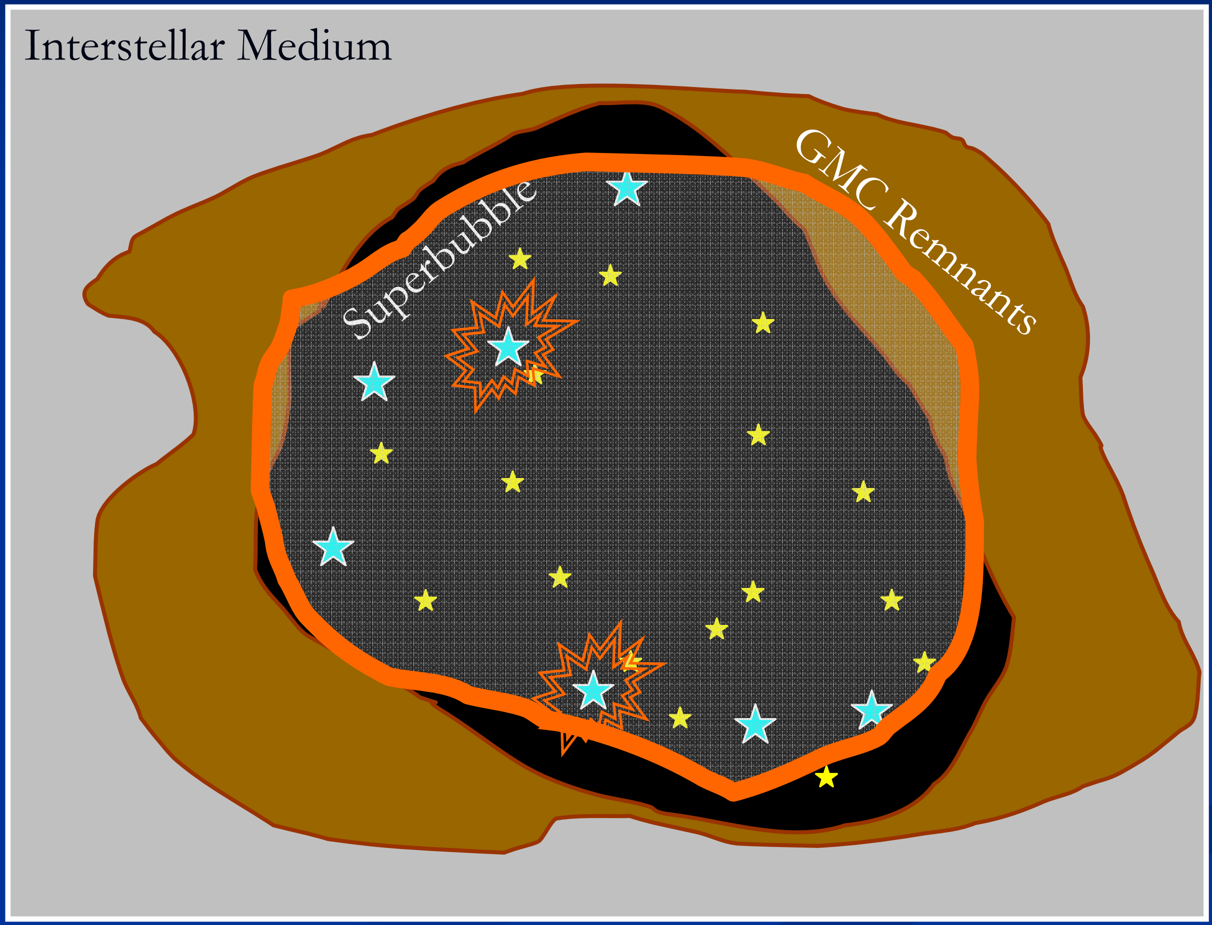
Individual bubbles merge, expand as one

- SNRs and wind-blown bubbles merge, forming Superbubble
  - Hot (10^6 K), low-density (0.01-$0.001/cm^3$) interior
  - Surrounded by shell of swept-up ISM
- $\gtrsim$ 5 SNe required to form a superbubble
- Superbubble expands similarly to a SNR but with cumulative power of many SNRs (and winds).



Mature superbubble

- Additional massive stars, now fully inside the bubble, explode
- Energy powers superbubble expansion to 100's – 1000's light years
  - Much larger than OB association
- 100 SN ⇒ 10^{53} erg

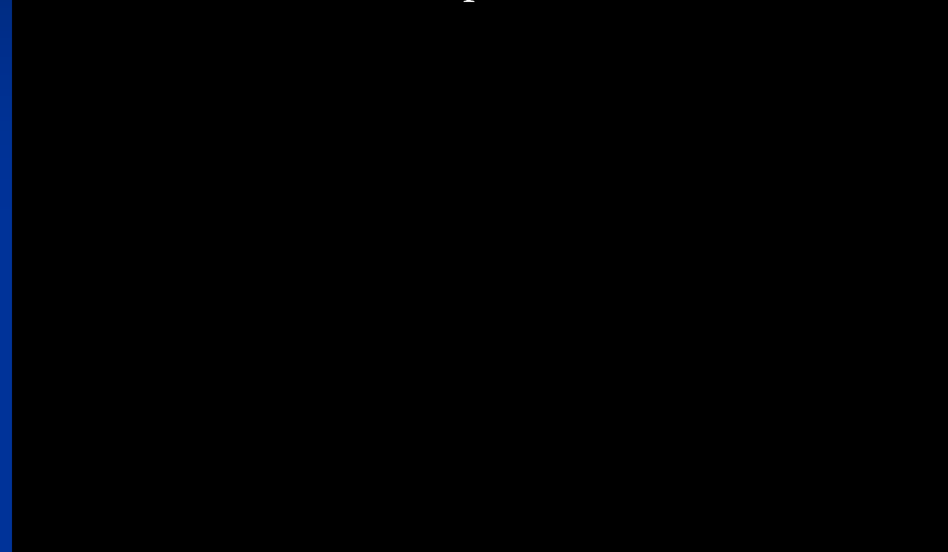


N44 Superbubble in the LMC

SNR evolution in superbubbles

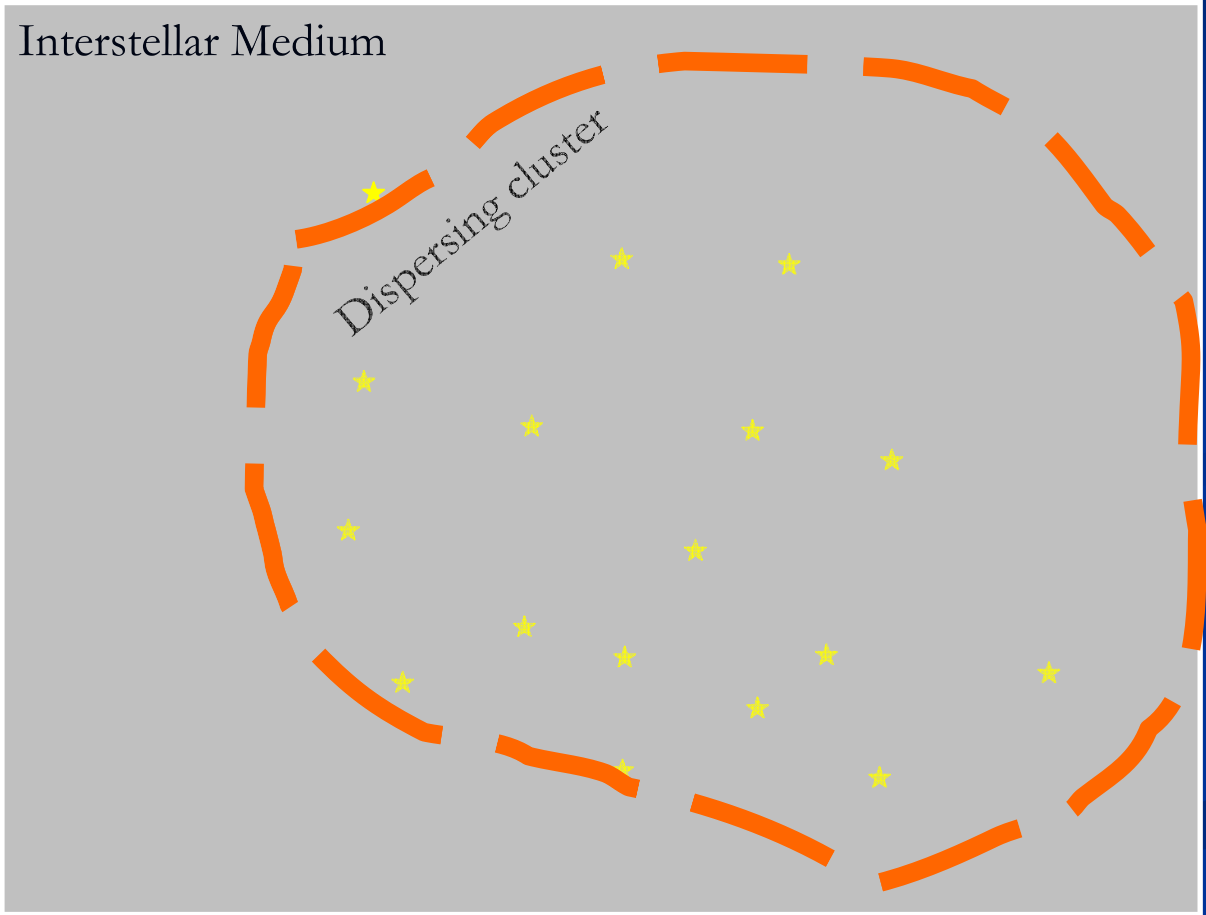
- Low ambient density
  - Free-expansion phase lasts much longer
  - Very little radio emission
- High sound speed
  - SNR goes from Sedov phase directly to subsonic dispersal
  - Skips radiative phase
  - All energy from SNR feeds bubble!

“Typical” radio view of SNR in a superbubble



Mature superbubble

- Superbubble begins to dissipate once no massive stars remain to inject additional power: ~40+ Myr after formation
- Lighter stars continue evolving, dispersing
- Cluster drifts apart, loses identity



Cosmic Rays in Superbubbles

- ~ 75% of supernovae occur inside of superbubbles: any impact on CR acceleration?
  - Higher efficiency
    - Faster shocks ⇒ bigger energy increase per cycle
    - X-ray-hot medium ⇒ more particles entering acceleration process
    - Reacceleration off multiple SNRs
  - Higher maximum energy (possibly)
  - Altered composition
    - Can explain excess of ^{22}Ne in CRs compared to ISM
  - Break out of disk into galactic halo
    - CRs escape disk, rise up, and rain back onto galactic disk isotropically

Cosmic Rays in Superbubbles

- Observations of CRs / SNRs difficult!
  - Interior density too low
    - For SNRs to produce radio shells
    - For CRs to produce pions → TeV gamma rays
  - Interior produces large thermal X-ray flux
- Gamma rays from shell?
  - Milky Way superbubbles are big on sky
  - Best bet may be LMC, SMC

Summary

- Supernovae can trigger star formation
  - One of several mechanisms
  - Our solar system may be an example
- Stars tend to form clustered
  - Young clusters with massive stars: OB associations
- Winds from massive stars carry a lot of energy
  - Carve out bubbles around stars, enrich ISM in metals, possibly accelerate CRs
- SNRs and winds from cluster can merge to form Superbubbles: large, hot, low-density regions surrounded by a shell of swept-up ISM
  - Many CRs accelerated inside superbubbles?

- Next week: Back to the center
  - Neutron stars, pulsars, and pulsar wind nebulae