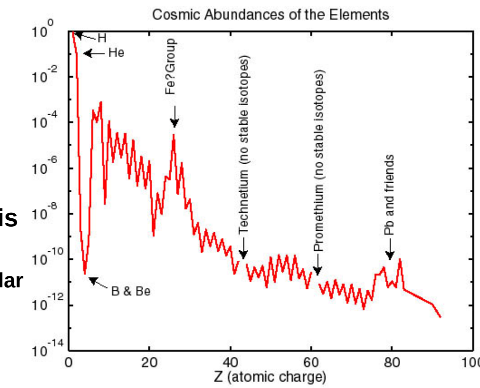
Cosmic abundances, nucleosynthesis and origin of the elements

- The cosmic abundance of the elements
  - general patterns
- Creating the universe
  - Primordial nucleosynthesis
- The birth, life and death of a star
  - Origins and fusion modes
  - The end results
  - Nucleosynthesis

Cosmic abundance of the elements

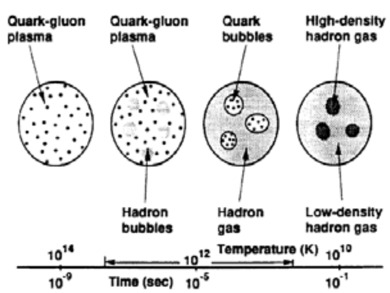
Why???

- Two answers:
  1. nuclear stability
  2. **nucleosynthesis**
     - **big bang**
     - **galactic and stellar evolution**



Let there be light...

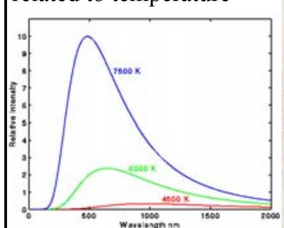
- The universe was created in a big bang about 14 x 10^9 years ago:
  - a hot, infinitely dense singular point
  - Initially expanded very rapidly
  - Protons & neutrons couldn't exist for the first minute or two
  - Inhomogeneities due to quantum fluctuations



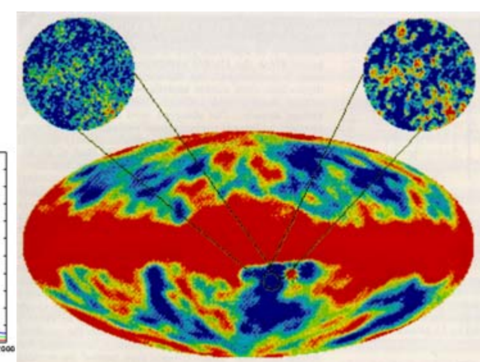
And there was light...

Cosmic microwave background: echo of the big bang

All bodies emit a "black body radiation spectrum" whose amplitude and maximum wavelength related to temperature



CMB is red-shifted to an incredibly low temperature i.e. ~ 4K



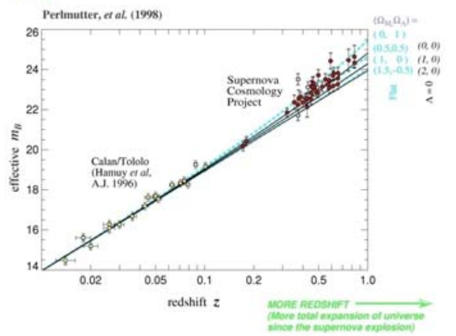
Patches caused by inflation of quantum fluctuations

And there was motion...

The Hubble Red Shift:
Objects further away are receding more rapidly (velocity proportional to distance) means the universe is expanding…

The HRS and CMB form 2 most convincing "proofs" of the Hot Big Bang

Luminosity of Standard Candles vs. Red (Doppler) Shift

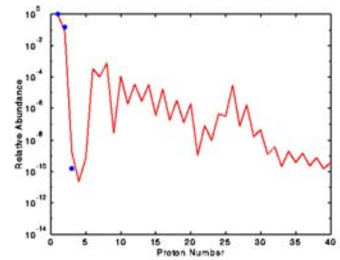


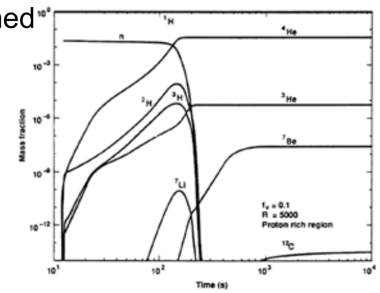
If slope decreases further out, expansion is decelerating, if slope increases outward, <u>expansion is accelerating</u>, and if neither, then universe is "flat"

And then matter...

- The universe was created in a big bang about ~14 x 10^9 years ago:
  - a hot, infinitely dense singular point
  - expanded very rapidly
  - light elements formed

So where did the rest come from?





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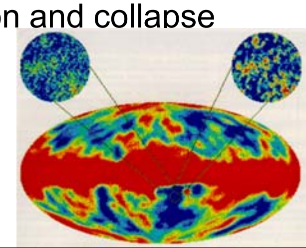
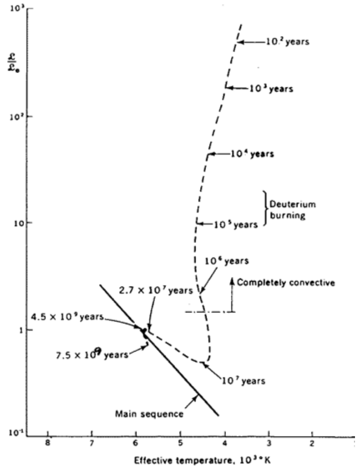
Stellar Birth

- Initial inhomogeneities or some compression of the otherwise homogeneous gas cloud
  - collision of clouds
  - or a shock wave
- gravitational self attraction and collapse
  - accelerates with time
  - collapse ==> heating



Stellar Evolution:

- Gravitational heating
- Early high luminosity
  - effective cooling
- Deuterium burning
  - D rapidly exhausted
- Further collapse
  - intense heating
  - opacity increases
- Density reaches fusion threshold...



The onset of fusion:

- If gas is hot enough
  - nuclei moving fast enough to overcome mutual repulsion due to like (positive) nuclear charges
- and if gas is dense enough
  - many collisions per unit time to allow reactions to proceed
- then nuclei can begin to hit each other and "stick together" with strong nuclear force

Fusion Energy

- The whole is less than the sum of the parts
  - 4 of ^{1}H weigh more than ^{4}He

$$ {}^1_1H + {}^1_1H \Rightarrow {}^2_1H + \beta^+ + \nu_e + \Delta E_1 $$

$$ {}^1_1H + {}^2_1H \Rightarrow {}^3_2He + \gamma + \Delta E_2 $$

$$ {}^3_2He + {}^3_2He \Rightarrow {}^4_2He + 2\,{}^1_1H + \Delta E_3 $$

  - mass is energy!!

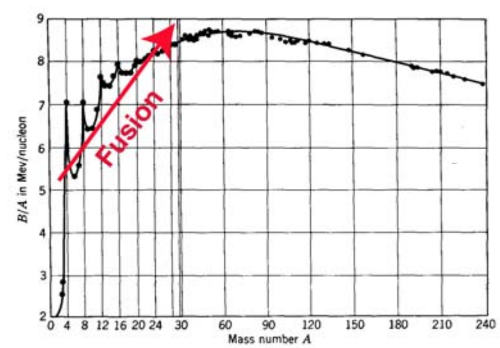
Mass ^{1}H = 1.0078 amu (x 4 = 4.0312 amu)

Mass ^{4}He = 4.0026 amu

(NB: the neutrino takes away 1/3 of the energy of the beta decay)

The onset of fusion:

- Moving up the binding energy curve…
- you gain energy by making bigger nuclei



Hydrogen "burning"

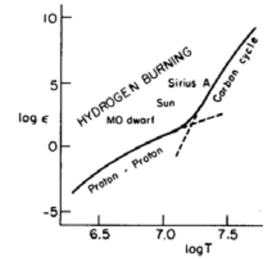
- The first/best viable energy source
- Rate ~ T^4
- lasts most of the star's life (n x 10^{8-9} y)*
- makes He from H
- eventually runs out…
  - the star begins to cool
  - … and starts to collapse further
  - … compression leads to additional heating

*Inversely related to stellar size: big candles burn faster

Fusion Energy

- Other ways to skin the cat, e.g., the CNO bi-cycle

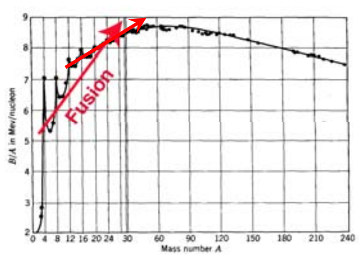
$$
\begin{aligned}
{}^{12}C + H &\Rightarrow {}^{13}N + \gamma \\
{}^{13}N &\Rightarrow {}^{13}C + e^{+} + \nu \\
{}^{13}C + H &\Rightarrow {}^{14}N + \gamma \\
{}^{14}N + H &\Rightarrow {}^{15}O + \gamma \\
{}^{15}O &\Rightarrow {}^{15}N + e^{+} + \nu \\
{}^{15}N + H &\Rightarrow {}^{12}C + {}^{4}He
\end{aligned}
$$



- Uses C,N, & O as catalysts, so don't need much
- Rate ~ T^{20}, so strong that there are sharp delineations between PP and CNO shells in star

Doing more of a good thing:

- Moving up the binding energy curve…
- combine He to make bigger nuclei
- actually difficult, because there's no stable "mass 8" nucleus



Burning He

- Requires higher temperatures to overcome bigger charge barriers (He is 2+) E ~ Z_1Z_2
- Requires higher pressures to increase collision rates (half-life of intermediary nucleus is 10^{-16} s)
  - takes place in stellar cores

$$ {}_{2}^{4}He + {}_{2}^{4}He \Rightarrow {}_{4}^{8}Be + \gamma \xrightarrow{10^{-16}s} 2\,{}_{2}^{4}He $$

$$ {}_{4}^{8}Be + {}_{2}^{4}He \Rightarrow {}_{6}^{12}C + \gamma $$

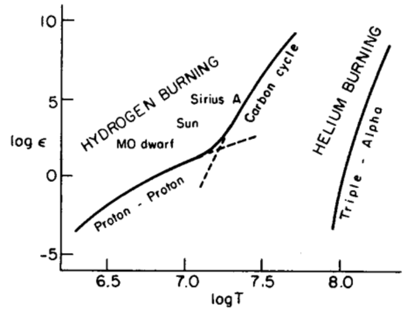
Burning He

- Requires higher temperatures
- Requires higher pressures
  - takes place in stellar cores
  - is very exothermic (high yield)
  - Very flammable*

This is called "Helium Flashing" and is mostly done by "white dwarves"

*Reaction rate is very sensitive to temperature and pressure: T^{30}

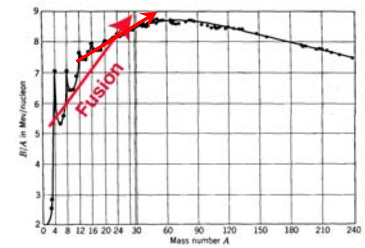
A star suddenly heats up due to the onset of He burning: expands, cools, and then extinguishes the He burning



He Burning: climbing the "alpha ladder"

- The next rung: $^{12}_{6}C + ^{4}_{2}He \Rightarrow ^{16}_{8}O + \gamma$
  - For stars with M > 1-5 M_S
- And so on:

$$^{12}_{6}C(\alpha,\gamma)^{16}_{8}O$$
$$^{16}_{8}O(\alpha,\gamma)^{20}_{10}Ne$$
$$^{20}_{10}Ne(\alpha,\gamma)^{24}_{12}Mg$$



A short-hand for the reactions

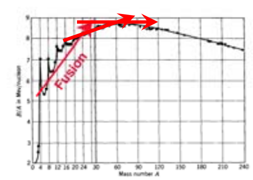
Only for more massive stars: Z_1Z_2 is much larger

Living in the balance: what makes the star "tick"

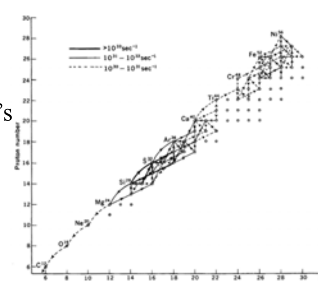
- The enemy:
  - relentless gravitational pull to implode
  - Lower efficiency (B.E. slope decreases) and higher cost (Z_1Z_2 increases)
  - heat loss due to:
    - electromagnetic radiation (light) into space
    - neutrino losses from beta-decay (p => n)
- The defense:
  - use strong nuclear force to fuel fusion
  - heat produced from fusion:
    - creates heat and pressure to balance gravity and prevent further collapse
    - further collapse raises temperature (energy to overcome coulomb barriers) and pressure (reaction rates)

The beginning of the end...

- Running out of steam (for M > 11 M_S)
  - higher temperatures/pressures needed to burn
    - higher charge barriers for higher Z
  - fewer gains for work done
    - lower slope on BE curve



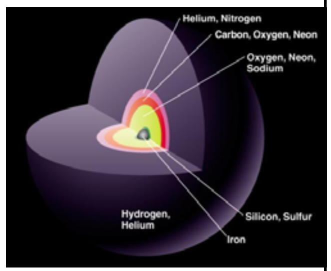
Rate of destruction by γ's balances rate of production i.e. equilibrium or "e-process"



Eventually the slope turns over (becomes negative) so the reaction becomes "endothermic", nuclei above maximum B.E. tend to fall apart

A highly evolved stellar profile

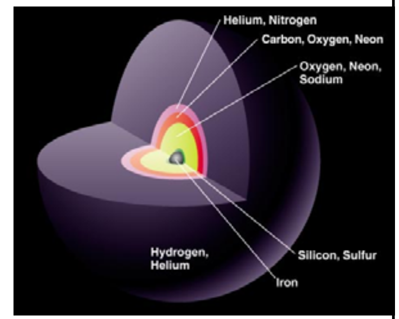
- (for M > 11 M_S)
- The star has an shell or onion-like character
  - with hotter shells near the core
  - cooler shells on the outside
  - H-burning on the outer shell
  - He, C, O, Si burning inward
  - Ultimate core is Fe-Ni
- It can't last:
  - lifetime is measured in hours…



- Further fusion is fundamentally fruitless
  - neutrino losses are relentless
- the star has nowhere to go...

Structure of an Evolved Massive Star

- inner core
  - turns endothermic above Fe-Ni maxium in B.E. curve
  - Collapses in milliseconds
    - relativistic speeds
  - compresses to nuclear density (10^{15}g cc^{-1})
  - becomes a giant nucleus
    - stopped from further collapse by fermionic degeneracy forces & coulomb repulsion…
  - beta decays!



Collapse & rebound produces mechanical shockwave that is too weak to blow outer shell of star off:
something else does it…

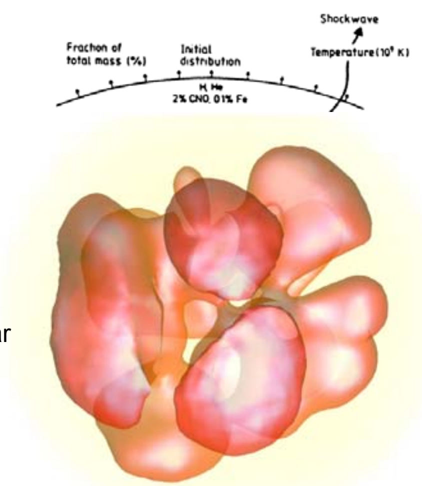
Bang!
You're dead

- Lifetime measured in seconds
- inner core
  - turns endothermic
  - collapses
  - compresses to nuclear density (10^{15}g cc^{-1})
  - becomes a giant nucleus
  - ~ all of p's beta-decay

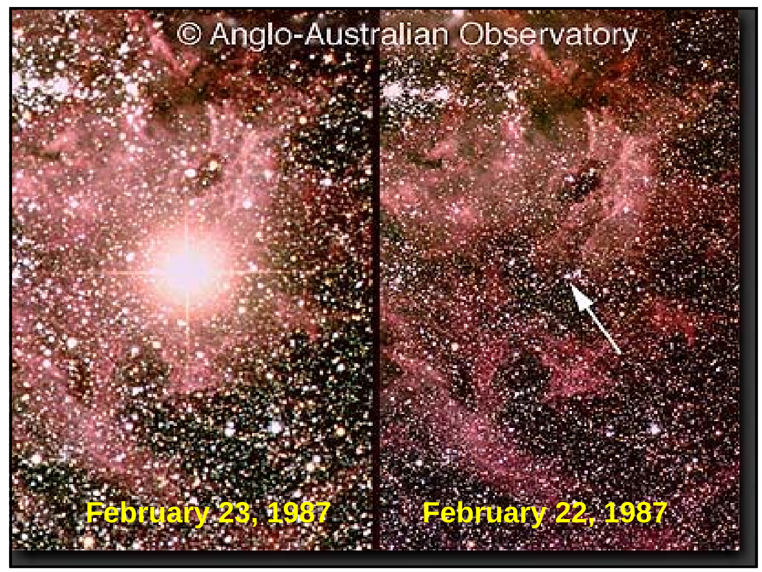
$p \rightarrow n + e^+ + \nu$

(N:Z ratio ~ 200:1)

n, p, e, γ plasma produces 6 kinds of neutrinos by pair production



Neutrino shock wave blows off the outer stellar shell

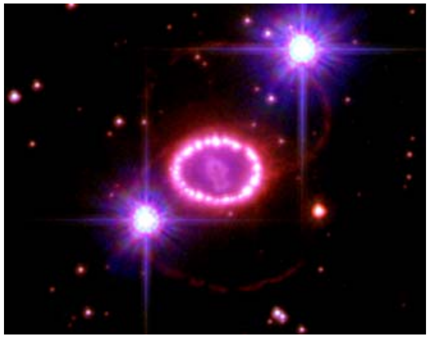


SN1987A

Core collapse produces neutrinos for two reasons:
(1) Promptly, by beta-decay (e^- capture by protons → neutrons)
(2) Delayed, by "pair production" to cool down*

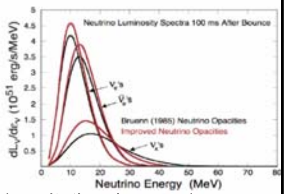
*the collapsed stellar core is initially a hot plasma containing n, p, γ (the last carries heat) but none can escape due to scattering off each other. The γ's can "dump energy" by pair production, which produces a particle and its antiparticle (to conserve charge and parity) traveling in opposite directions (to conserve momentum). But the only particle/antiparticles that can escape are neutrinos.

* "Delayed" *vs.* "Prompt" means a matter of seconds…



Gaseous shell ejected into surrounding space, lit up by subsequent x-ray emissions

Neutrinos from SN 1987A



- Energy output of supernova:
  - Core temperature ~ 200 x 10^9 K
  - Core collapse releases 10^{46}-10^{47} joules (gravitational energy)
  - <0.1% emerges as light
  - <1% is released as physical shock wave (expanding gas)
  - >99% is lost by neutrinos:
    - NS radius ~ 13 km, ν_x mfp ~ 5 m (they diffuse out of NS), T_{diff} ~ 10s
- On earth ~5 x 10^{10} neutrinos passed through each cm^2
  - 24 interaction events seen over a 13 second period* at 7:35 UTC Feb. 23rd, 3 hours prior to arrival of light**
- 51 kparsec (168,000 light-years) distance

*40% arrived in first second, 60% in remaining 12 seconds

**This is expected: neutrinos are released in two waves on core collapse, the light escapes once the shock wave reaches stellar surface

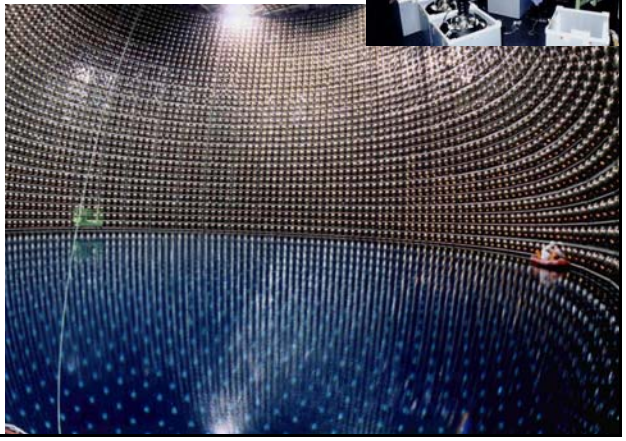
Neutrinos from SN 1987A

- How do you "detect" a neutrino?
  - Have a very large target
  - Eliminate "non-events"
  - Be very very patient
  - E.g., Super-Kamiokande
    - Cherenkov radiation* detector
    - 50,000 tons ultrapure water (40 m diam., 40 m high)
    - 1000 m underground

*photonic "sonic boom"

Neutrinos and Super-K

Cherenkov radiation* detector
50,000 tons ultrapure water
1000 m underground
11,000 22" PMTs inside
2,000 8" PMTs outside



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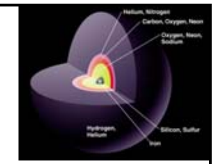
  - **Nucleosynthesis**

The final stages before nova



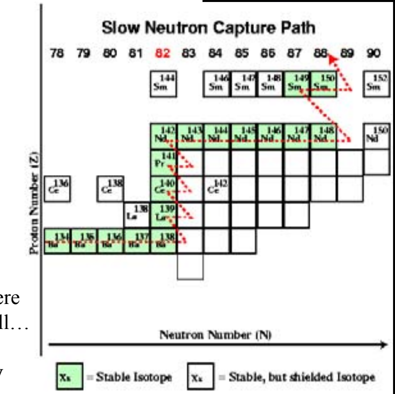
- Neutrons made during He and Si burning are boiled off during e-process fragmentation of Fe-type nuclei
  - called the "s-process"
  - Time-scales ~ 10^4 y

Neutron addition rate is slower than or comparable to β^- decay rates of unstable nuclei near the "valley of stability"

Nuclides follow the floor of the valley like a river

NB: only showing stable nuclei here, there are some long-lived radioisotopes as well…

Some isotopes not made this way



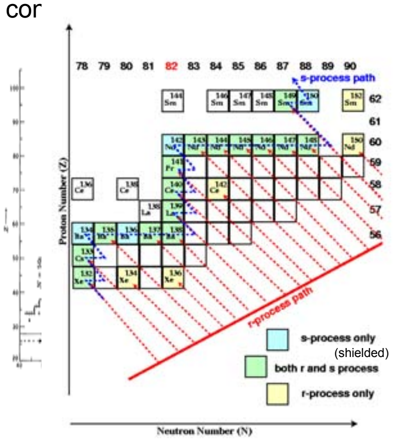
The final seconds of nova

- Neutrons boil off the collapsing core, streaming outward through the outer cor
  - called the "r-process"

Neutron addition rate is much faster than decay rates of unstable nuclei near the "valley of stability"
Nuclides continue to build on high-N side of the valley

A landslide of beta-decay nuclides fall down toward the central valley

The valley is flooded!



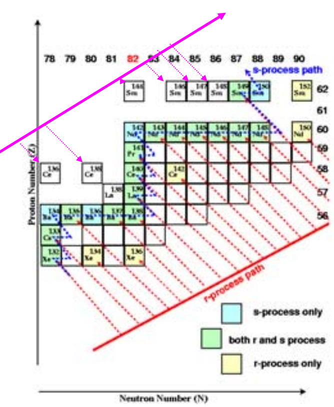
The final milliseconds of nova

- The outbound stream of neutrons entrains protons and other nuclei
  - Leads to p–capture reactions
  - called the "p-process"
  - Cascade down by β^+-decay

Drives nucleosynthesis up the proton-rich side of the valley, e.g., making ^{136}Ce and $^{144-148}$Sm isotopes

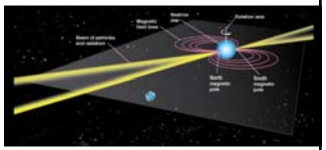
Relative abundances of s-, r-, and p- nuclei indicative of n & p fluxes and cross-sections

p-types are very rare…



What happens next?

- What's left behind depends on stellar mass
  - small initial mass → sputter to dwarfdom
  - medium mass → collapse
    to neutron star (pulsars)
    $1.4\ M_S^* < M < 3\ M_S$
    spin rate from $0.1\ s^{-1}$
    to $10{,}000\ s^{-1}$
  - major league → collapse to black hole
    $M > 3\ M_S$
    & @ galactic centers
- Gas and material ejected into large clouds expand to seed new star formation
  - At speeds approaching 10,000 km/s
  - shock wave compresses gases → new stars
  - second/third generation stars rework material

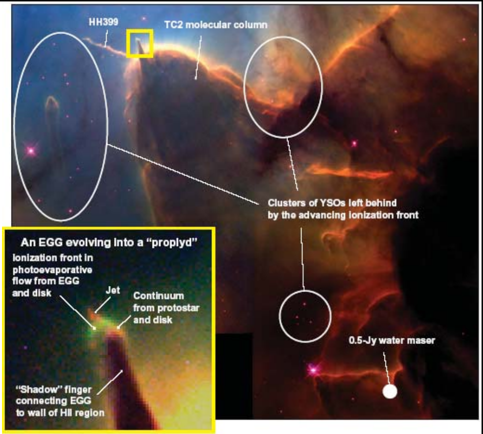


*the Chandrasekhar limit: below this electron degeneracy will prevent collapse and a white dwarf will form

A Stellar Nursery

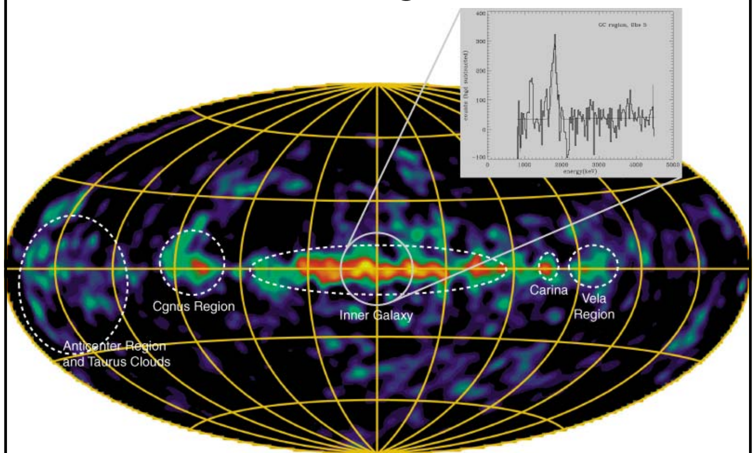
- Material from nearby supernovae rapidly mixed into clouds
- Intense UV from young/massive stars creates bubbles in nebulae
- Shockwave of growing bubbles cause gravitational collapse and star seeding
- UV stripping photo-evaporates collapsed material
- Late stage nucleosynthesis pelts baby stars with fresh material

Hester et al, 2004
Science 304, p1116



Planetary system nursery. Hubble Space Telescope wide-field camera observation of a field in the southern portion of the Trifid Nebula illustrating several of the observational consequences of the star-formation scenario discussed. The inset (an enlargement of the region indicated by the small yellow box) shows a YSO-bearing EGG seen as it is evolving into a "proplyd." Evidence for triggered star formation in the region includes the HH399 jet, which arises from an embedded source immediately interior to the ionization front, and the presence of a 0.5-Jy water maser. Clustering of YSOs, especially around the remains of a largely evaporated column in the upper left of the field, is evidence of pockets of triggered star formation that have been overrun by the ionization front.

And the beat goes on...

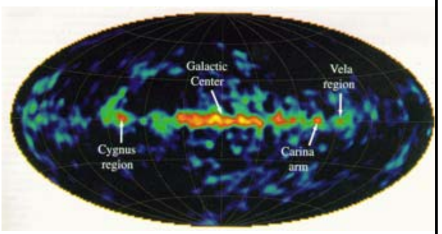


Sky map of ^{26}Al gamma-ray emissions

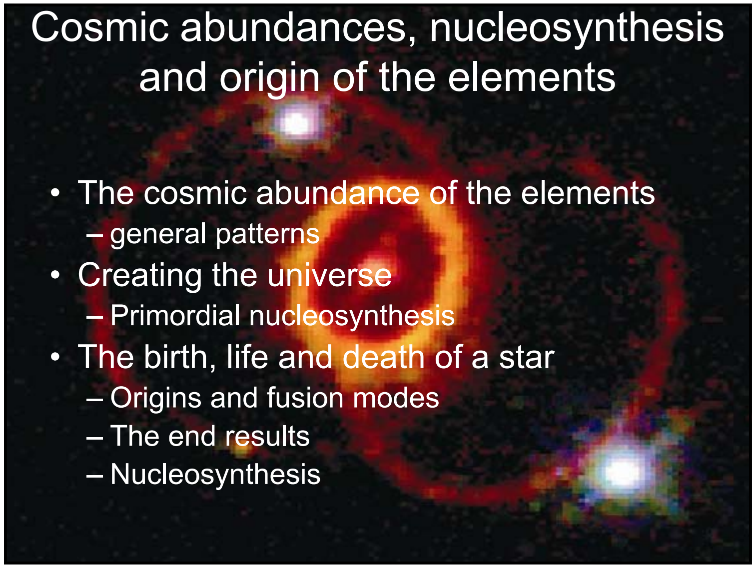
And the beat goes on...

^{26}Al has a half-life of only 730,000 years (short compared to the universe)

It must have been produced recently in nucleosynthetically active regions



Sky map of ^{26}Al gamma-ray emissions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