Type II Supernovae

- Iron has the highest binding energy of any nucleus
  Bethe-von Weisäcker mass formula:
  Energy = Bulk + Bulk Symmetry + Surface + Surface Symmetry + Coulomb
  Symmetry energy comes from having unequal numbers of neutrons and protons

$$E_{A,Z} = A\left(-16+30\left(\frac{N-Z}{A}\right)^2\right)+A^{2/3}\left(18-45\left(\frac{N-Z}{A}\right)^2\right)+0.75\frac{Z^2}{A^{1/3}}\ \mathrm{MeV}$$

The optimum mass and charge for a nucleus happen when

$$\left.\frac{\partial E_{A,Z}}{\partial A}\right|_Z = 0, \qquad \left.\frac{\partial E_{Z,A}}{\partial Z}\right|_A = 0$$

$$\left.\frac{\partial E_{A,Z}}{\partial A}\right|_{Z/A} = 0, \qquad \left.\frac{\partial E_{Z,A}}{\partial (Z/A)}\right|_A = 0$$

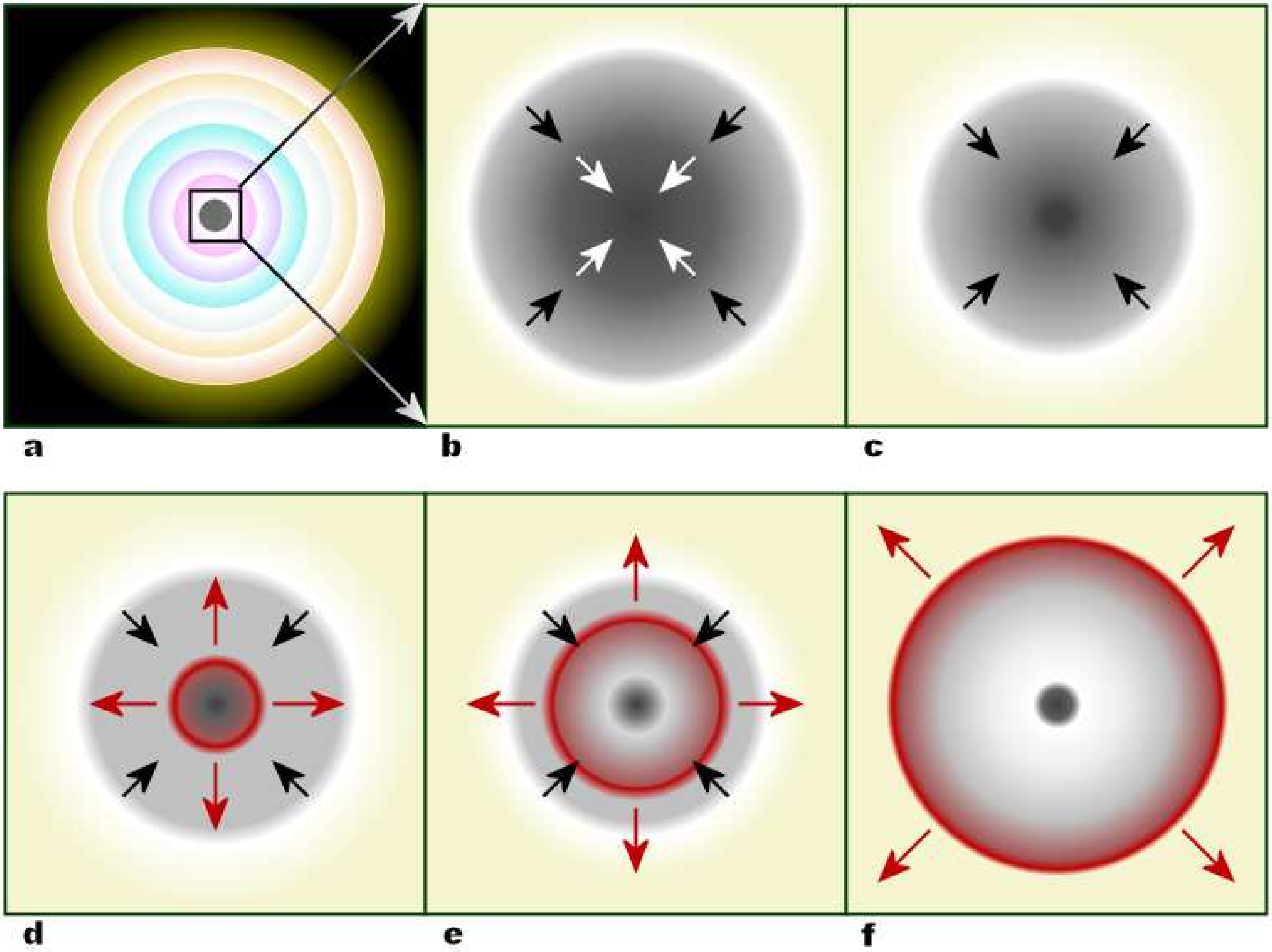
- $$A_{opt} = \left(18-45\left(\frac{N-Z}{A}\right)^2\right)\Bigg/\left(1.5\frac{Z^2}{A^2}\right), \qquad \left(\frac{Z}{A}\right)_{opt} = \left[2+\frac{.75}{2(30A^{1/3}-45)}\right]^{-1}$$

$$A_{opt} \simeq 60, \qquad Z_{opt} \simeq 26$$

Collapse

- In a massive star, the core which has matter burned into iron nuclei has a maximum size determined by the Chandrasekhar limit, about 1.4 $M_\odot$.
- As the silicon shell surrounding the iron core continues to burn, the iron core mass slowly increases.
- When the core exceeds the Chandrasekhar mass, it has to collapse.
- The collapsing core separates into a sonically cohesive inner core and a supersonic outer core.
- The collapsing core continues to collapse until the density inside nuclei is reached, when nuclear repulsive forces abruptly halt the collapse.
- The abrupt halt creates a pressure shock wave at the inner core's outer boundary. The shock slows down or reverses the collapse of the overlying infalling matter.
- This shock by itself does not seem capable of exploding the star and ejecting matter into space.
- The inner core plus additional matter falling onto it creates a new neutron star, called a protoneutron star. A protoneutron star differs from a neutron star in having many more protons and electrons as well as being much hotter.
- During collapse, some protons are converted to neutrons. These beta reactions produce neutrinos.

$$p + e^- \rightarrow n + \nu_e$$


a
b
c
d
e
f

Neutrinos

- Neutrinos interact very weakly with matter. Their cross section is about $10^{-44}(E_\nu/\mathrm{MeV})^2$ cm^2.
- They travel an average distance $d = 1/(n\sigma)$ between collisions with nucleons, where n is the number density of nucleons $n = N_0\rho$.
- When the distance d is comparable to the stellar radius R, the neutrinos can no longer escape the star and become temporarily trapped within it. This happens when the density is about 10^{11-12} g/cm^3, about 1000 times less than the final neutron star density.
- The law of mass action then results in an equilibrium (called beta equilibrium) that prevents more proton conversion.

$$p + e^- \leftrightharpoons n + \nu_e$$

- Gravitational collapse converts gravitational potential energy into internal and thermal energy in the protoneutron star.

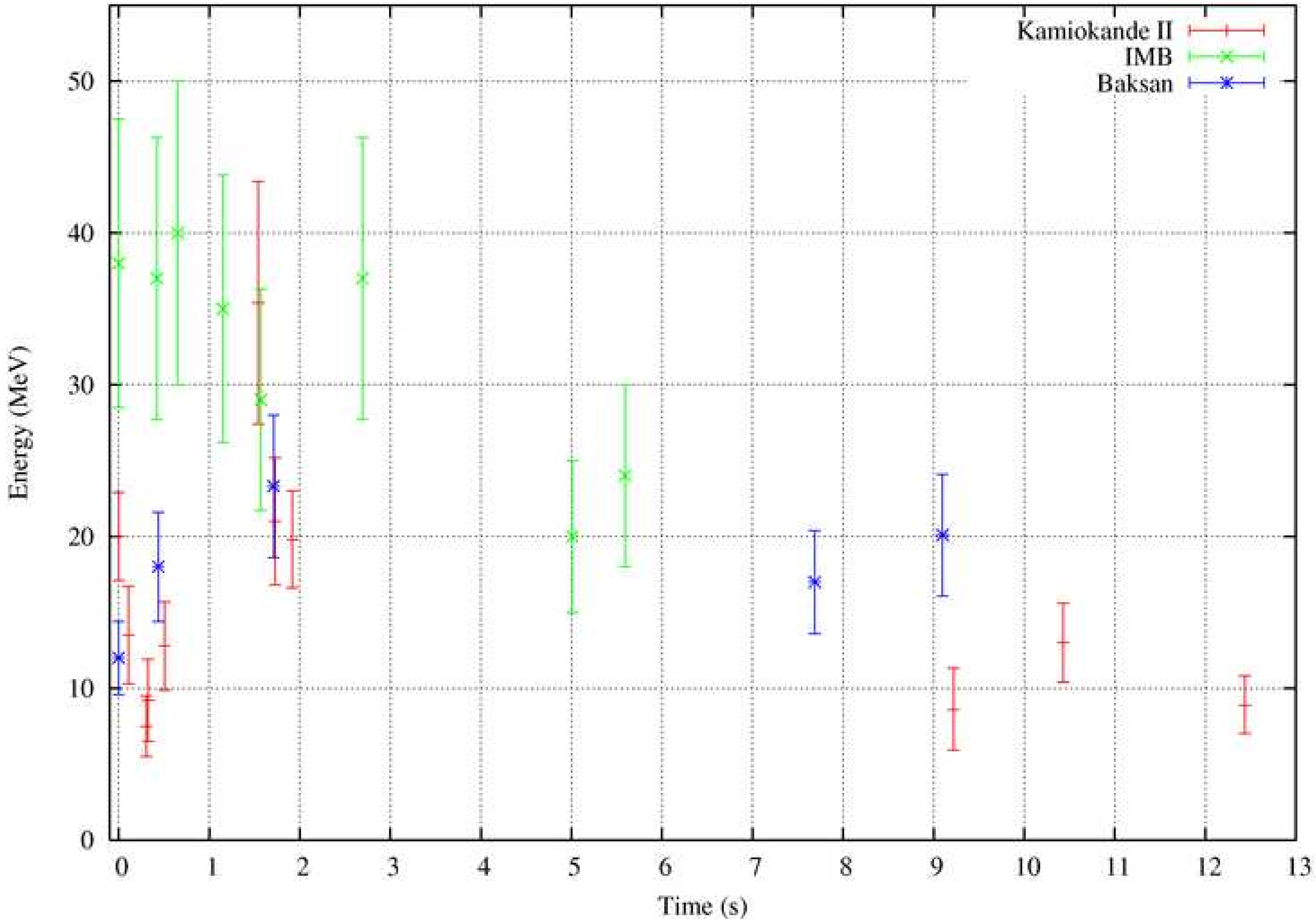
$$\frac{3GM^2}{5R} \simeq 3 \times 10^{53}\ \mathrm{ergs}$$

- This energy is the same as the Sun’s power output over 2500 Gyr.

Explosion

- The luminosity at peak of a Type II supernova is about 10^{43} erg/s.
- It is brightest for about a month and therefore radiates about 10^{49} erg.
- The outer several solar masses of the star are ejected at velocities up to 1% the speed of light.
- The kinetic energy of the ejected mass is about 10^{51} erg.
  $(1/2)M_\odot c^2 = (1/2)2 \cdot 10^{33} * (3 \cdot 10^{10})^2 = 9 \cdot 10^{53}$ erg.
- Where does the rest of the energy go? Neutrino emission.
- Neutrinos flowing through the outer material can transfer just enough energy to eject them. Less than 1% of their energy needs to be used in this way.
- The emission of neutrinos was detected from SN 1987A by the Kamiokande and the IMB detectors.
- The trapping of neutrinos was confirmed because the timescale over which the neutrino burst appeared was about 10 seconds and the average detected neutrino energy was about 20 MeV.
- The neutrinos in the core's center is about 300 MeV; the energy is degraded because of energy losses as the neutrinos diffuse from the center to the surface. This diffusion takes time

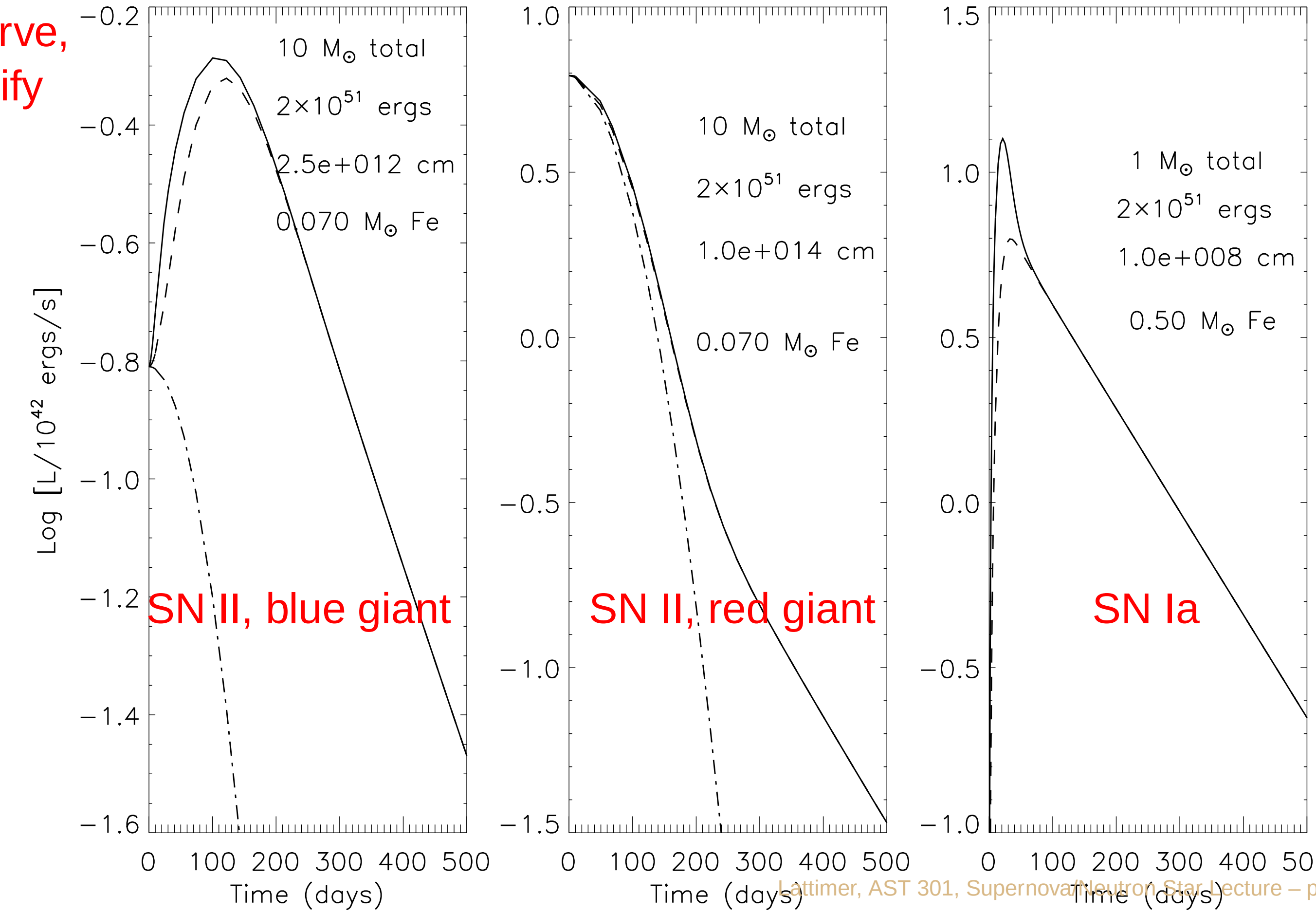
$$\tau = \frac{3R^2}{cd} \simeq 10 \frac{\rho}{10^{15}\ \mathrm{g\ cm^{-3}}}\ \mathrm{s}$$


Kamiokande II
IMB
Baksan
Energy (MeV)
0
10
20
30
40
50
Time (s)
0
1
2
3
4
5
6
7
8
9
10
11
12
13

Neutrino Detection

- Neutrino detectors had total detector water masses of about $M_d = 1$ kt = 10^9 g.
- Only the protons in water could detect neutrinos. The number of protons in the detectors is $N_p = 2(N_o/18)M_d\rho_{water} = (2/3) \cdot 10^{32}$.
- The energy release from a $1.4M_\odot$ neutron star should be about $E_{SN} = (3/5)(GM^2/R) = 3 \cdot 10^{53}$ erg.
- If the average energy of detected neutrinos is E_ν, measured in MeV, the total number of radiated neutrinos is $E_{SN}/(E_\nu/1.6 \cdot 10^{-6}) = (2/E_\nu) \cdot 10^{59}$.
- Only anti-electron neutrinos were observed. Because the neutrinos thermalized due to diffusion, equal numbers of all neutrino types were radiated. The number of anti-electron neutrions is then $N_{\bar\nu} = (3/E_\nu) \cdot 10^{58}$.
- The cross section of the neutrinos with protons is $\sigma \sim 4 \cdot 10^{-44} E_\nu^2$.
- The number of detected neutrinos is $N_d = N_p \sigma N_{\bar\nu}/(4\pi D^2)$ where $D = 50$ kpc = $1.5 \cdot 10^{23}$ cm. This is about $N_d = 0.3E_\nu$.
- The average observed energy was about $E_\nu = 20$ MeV, suggesting of order 6 neutrinos should be observed.
- The duration of the event, about 10 s, is consistent with an average escaping energy of 20 MeV.

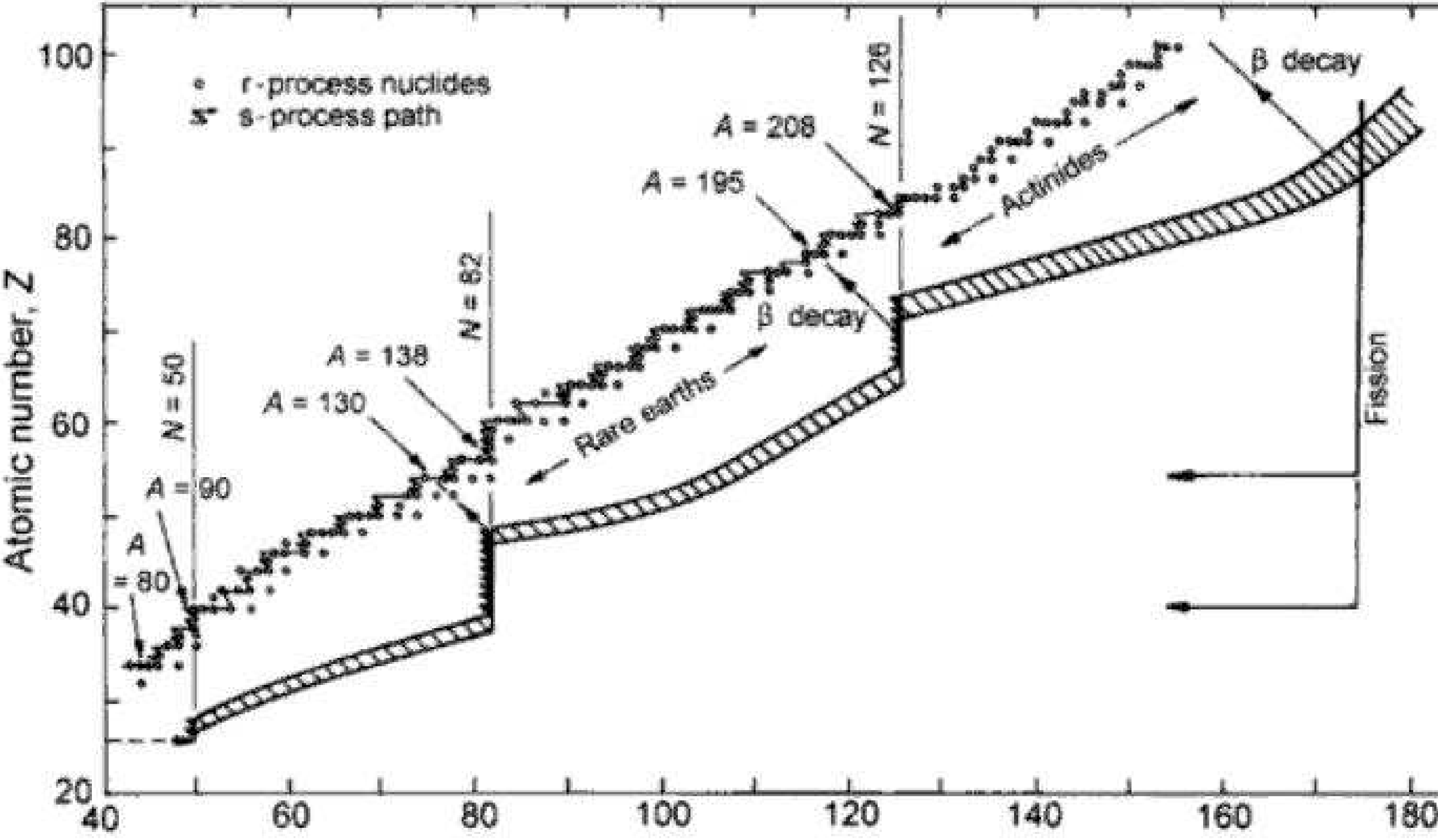
- Although neutrinos carry energy into the outer matter, simulations indicate this is insufficient to eject these layers except in the smallest stars.
- Auxiliary energy from rotation, magnetic field compression, or acoustic vibrations have all been suggested to augment neutrino energies.
- As for Type Ia supernovae, the complete mechanism is uncertain, and the progenitors are not clearly identified.
- From the light curve, it is easy to identify the amount of radioactive ^{56}Ni that is ejected.



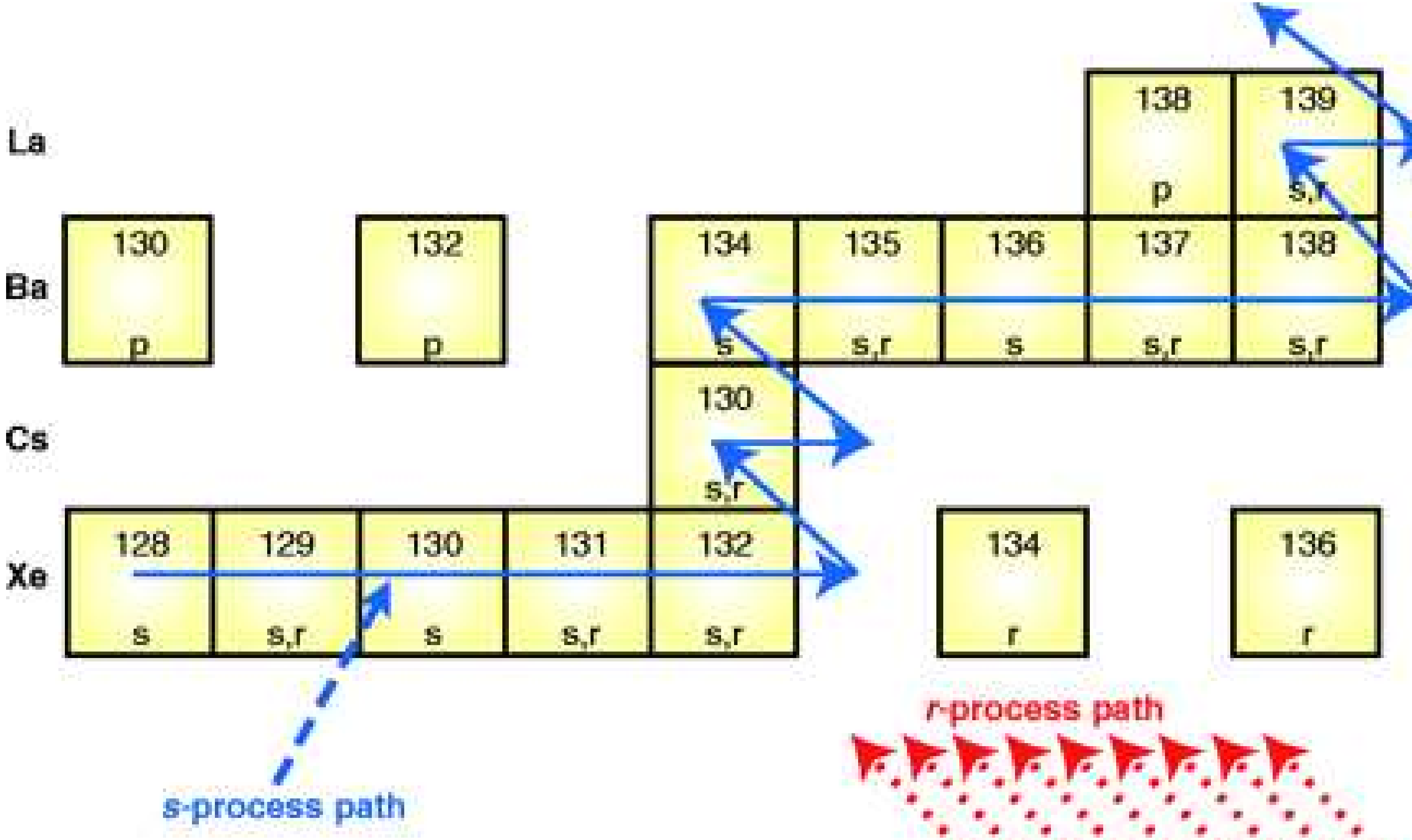
Nucleosynthesis Of The Heavy Elements

- Three basic processes can be identified by which heavy nuclei can be built by the continuous addition of protons or neutrons:
    - p-process (proton)
    - s-process (slow neutron)
    - r-process (rapid neutron)
- Capture of protons on light nuclei tend to produce only proton-rich nuclei.
- Capture of neutrons on light nuclei produce neutron-rich nuclei, but which nuclei are produced depends upon the rate at which neutrons are added, compared to typical beta-decay timescales.
- Beta decay: $n \longrightarrow p + e^- + \bar{\nu}_e$
- Slow capture path is in and produces nuclei near the valley of beta stability.
- Rapid capture initially produces very neutron-rich radioactive nuclei that eventually beta-decay towards the valley of beta stability.
- Neutron magic numbers (50,82,126) impede flows to larger N; they form waiting points where beta decays increase Z.
- Some nuclei can be built by more than one process.

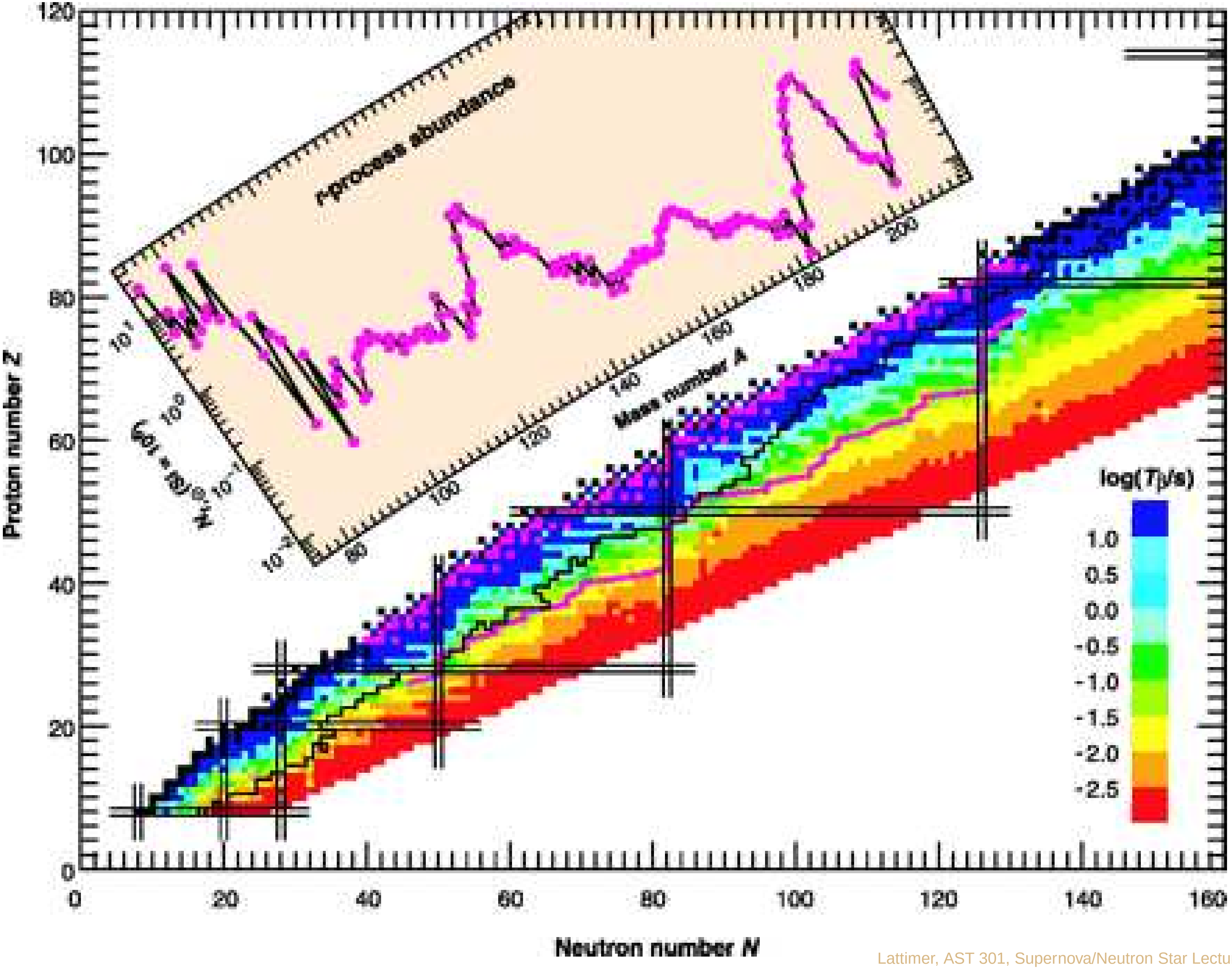
Chart Of The Nuclides



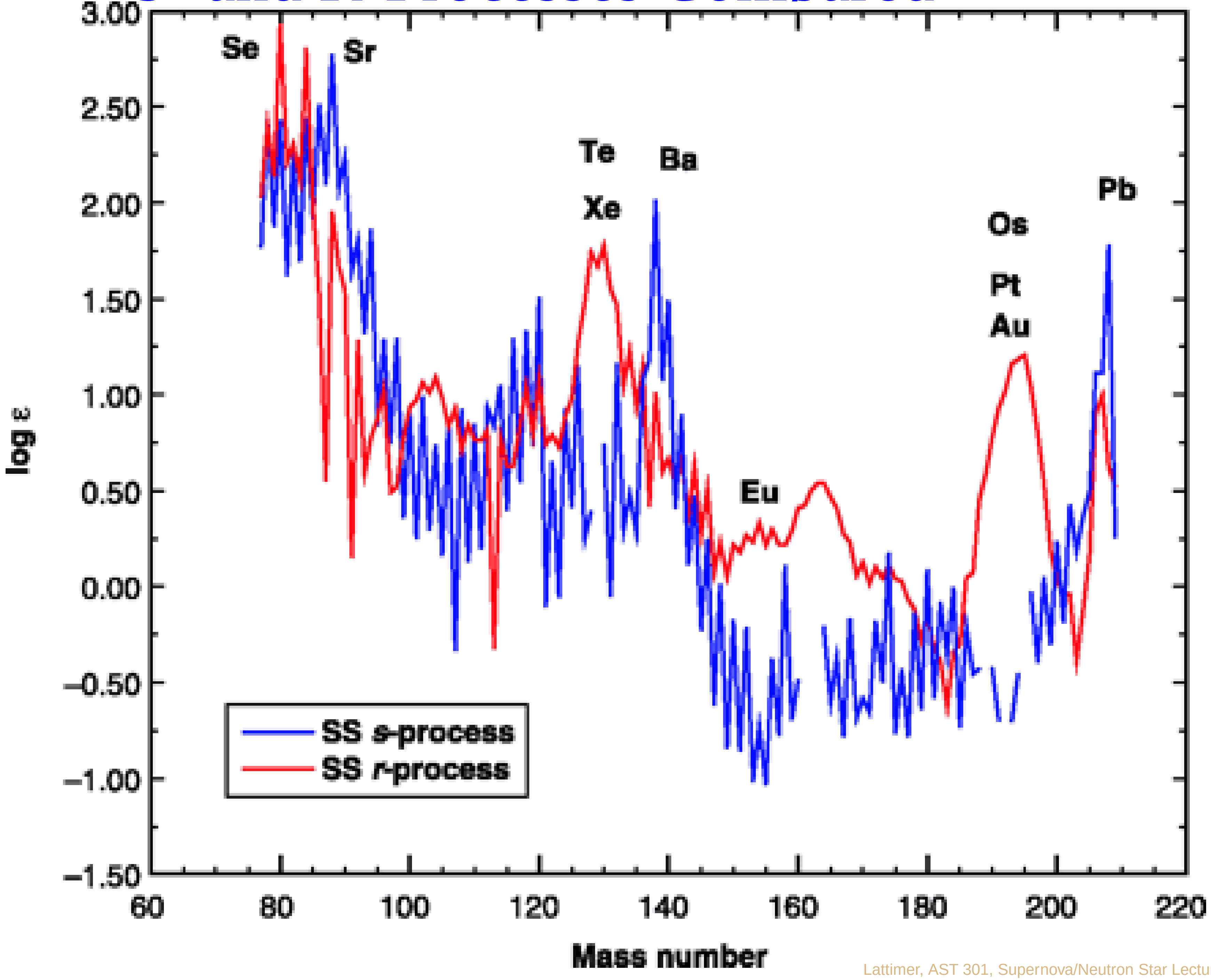
Nuclide Chart Portion



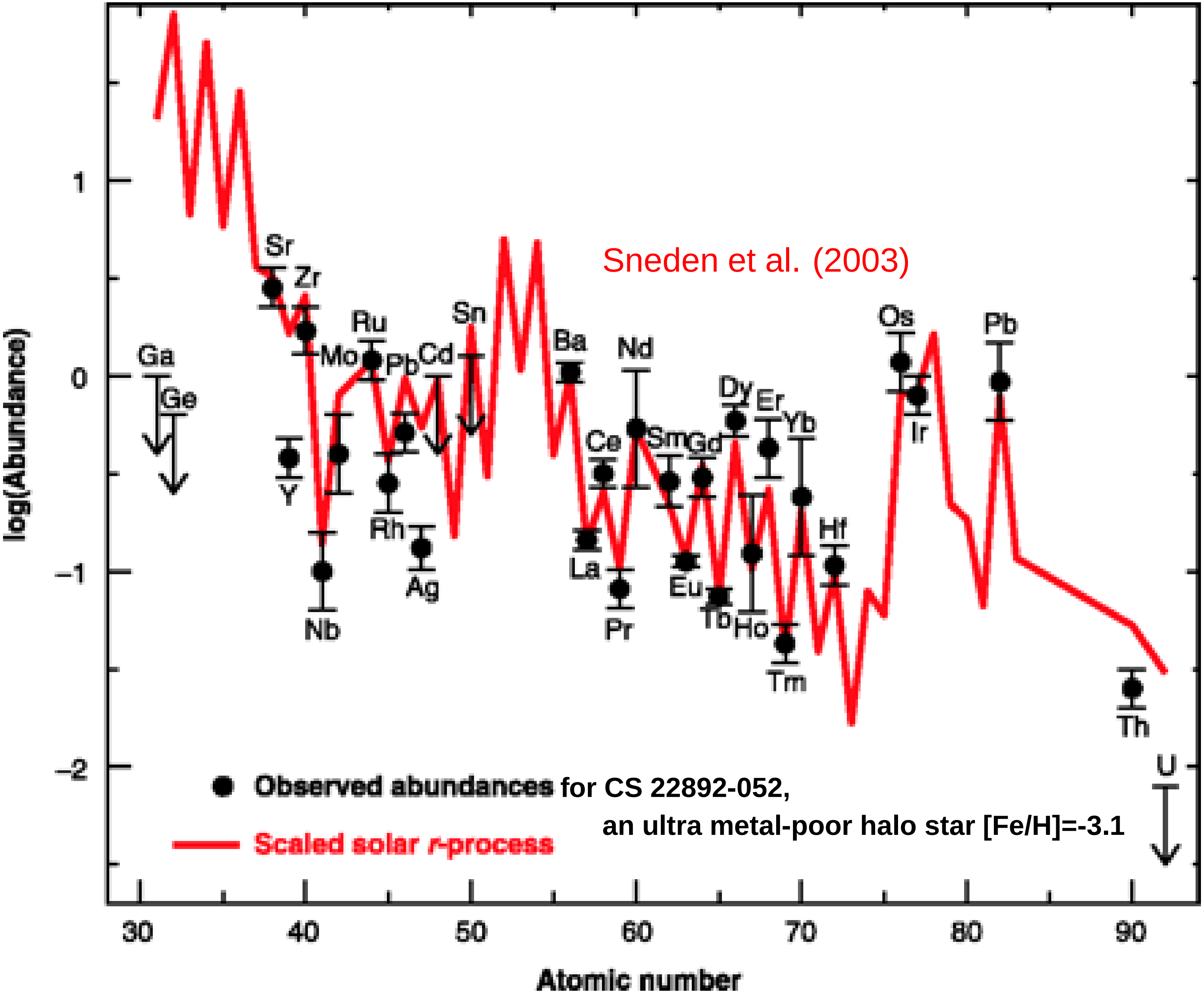
Beta Decay Rates



S- and R-Processes Compared



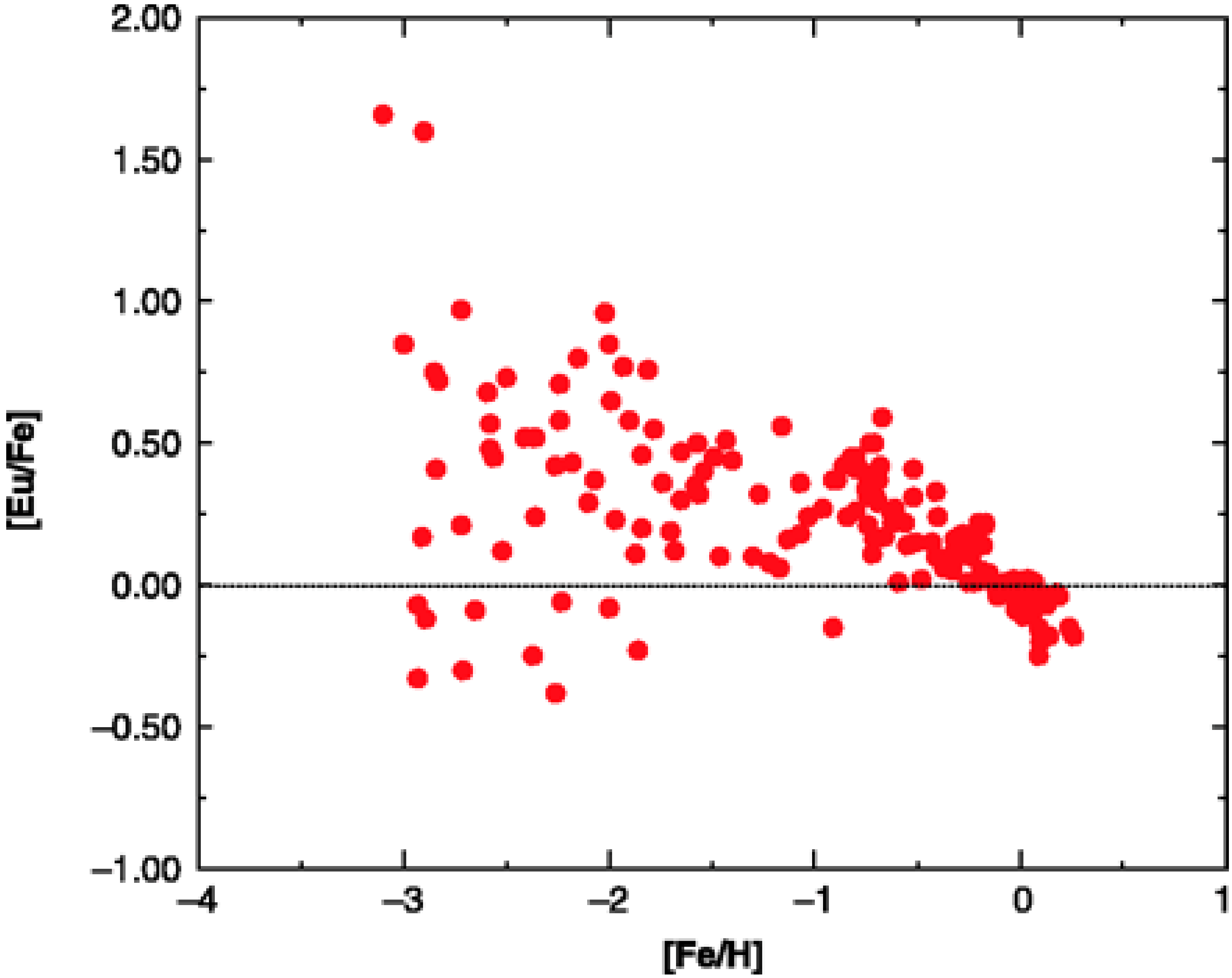
R-Process In An Old Star



Sneden et al. (2003)

for CS 22892-052, an ultra metal-poor halo star [Fe/H]=-3.1

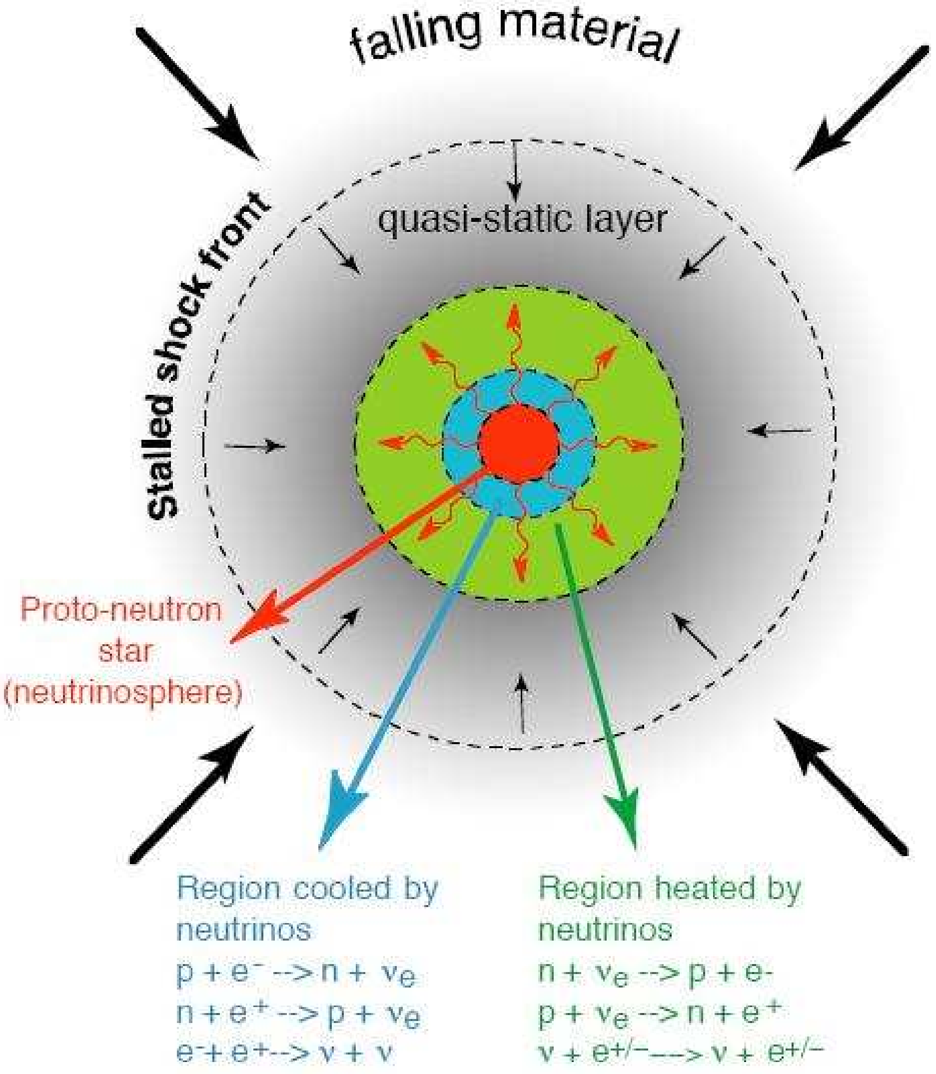
The R-Process Through The Ages



Proposed Astrophysical Sites

- Traditional (and favorite) source is SN II.
  - Neutrino-driven wind following gravitational collapse of a massive star and formation of proto-neutron star.
  - Develops into a $(\gamma, n) - (n, \gamma)$ equilibrium.
  - Advantages: Higher frequency requires small yield (10^{-5} M$_\odot$ per event), naturally early onset in cosmic history.
  - Problems: Requires high n/p, *i.e.* extremely large s or small Y_e, and long duration.
- Non-standard model is decompressing neutron star matter.
  - Tidal disruption of a neutron star merging with a neutron star or black hole in a compact binary whose orbit is decaying because of gravitational radiation.
  - Develops into a competition between (n, γ) and $\beta-$decay reactions.
  - Advantages: Naturally high n/p, relatively robust in terms of initial conditions.
  - Problems: Rarity requires relatively large yield (0.01 M$_\odot$ per event), early onset in galactic history requires short orbital decay timescales.

The favorite r-process site: the ν-driven wind in SNII



Goriely 2005

Decompression of hot material

n,p at $T_9 \approx 10$ $\rho \sim 10^6 \mathrm{g/cm}^3$

↓ NSE

^{4}He recombination

↓ $\alpha\alpha n$-^{9}Be(α,n)

^{12}C bottleneck

↓ (α,γ) & (α,n)

$60 \leq A \leq 100$ seed

↓ (n,γ) & (γ,n) + β-decays

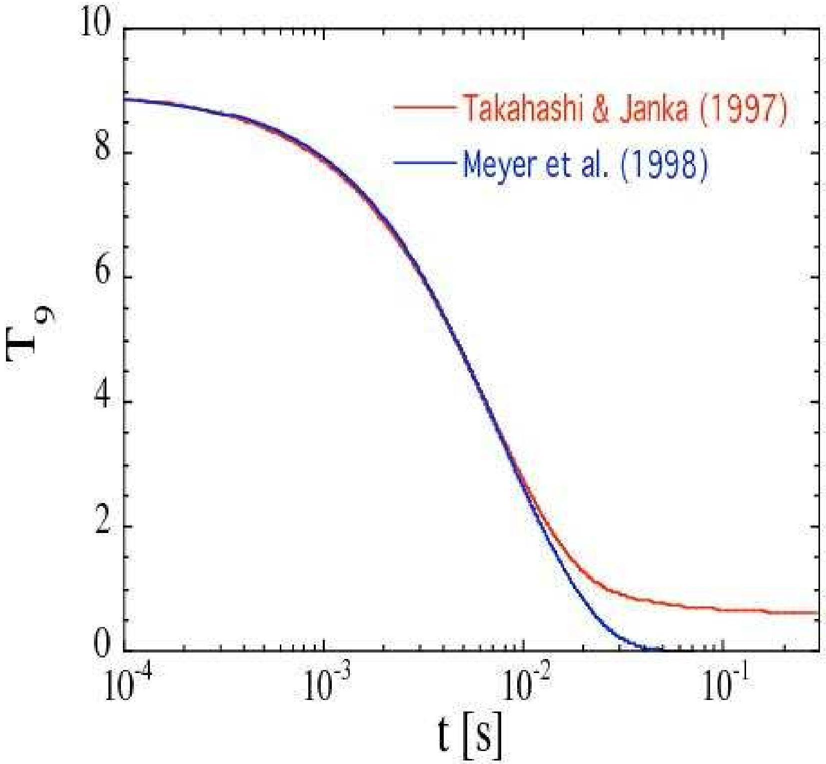
r-process

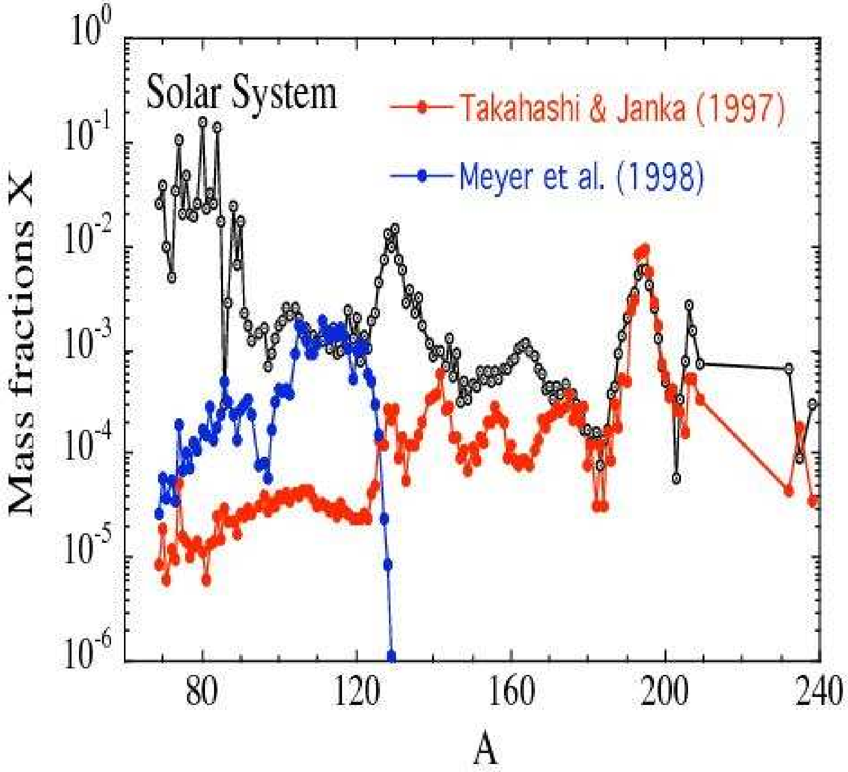
if Y_n/Y_{seed} large enough !!

Artificially large S, small Y_e, τ_{ex}

Sensitivity to supernova conditions

In both calculations, initial $s = 200$, $Y_e = 0.48$. Neither calculation matches observations.





Additionally, it is difficult to keep n/p high enough. Kinetic equilibrium:

$$\nu_e + n \rightarrow p + e^- \qquad \bar{\nu}_e + p \rightarrow n + e^+$$

$$\frac{n}{p} = \frac{\lambda_{\bar{\nu}_e}}{\lambda_{\nu_e}} \simeq \frac{L_{\bar{\nu}_e} T_{\bar{\nu}_e}(1 - \Delta/2T_{\bar{\nu}_e})}{L_{\nu_e} T_{\nu_e}(1 + \Delta/2T_{\nu_e})}, \qquad \Delta = (m_n - m_p)c^2 = 1.293 \text{ MeV}$$

$$T_{\nu_e} = T_{\bar{\nu}_e} = 3 \text{ MeV}, \qquad L_{\nu_e} = L_{\bar{\nu}_e} \Longrightarrow \frac{n}{p} \simeq \frac{5.7}{7.3} \simeq 0.78$$

Gravitational Radiation

A gravitational wave is a fluctuation in the curvature of spacetime which propagates as a wave. Gravitational radiation is the energy transported by these waves. Gravitational radiation can be produced by sources with time-varying quadropole moments, such as

- Binary star systems
- Rapidly rotating non-axisymmetric stars, such as a neutron star with a “mountain”
- Oscillating asymmetric stars, such as $g-$modes of neutron stars
- Collapsing and exploding stars to the extent the are not spherically symmetric
- The Big Bang

Gravitational radiation has not been directly detected, yet it has been indirectly shown to exist by the decay of binary neutron star orbits. Some properties of gravitational waves are

- Amplitudes of at most 10^{-20}
- Frequencies in the range $10^{-7} - 10^{11}$ Hz
- Velocity of c
- Waves are polarized

Example: Binary Star With Circular Orbit

To a good approximation, components of binaries will follow decaying Keplerian orbits.
Orbital frequency:

$$\Omega = \left(\frac{G(M_1+M_2)}{a^3}\right)^{1/2} = \frac{2\pi}{P}$$

Power radiated:

$$L = -\frac{dE}{dt} = \frac{32G^4}{\pi c^5}\frac{M_1^2 M_2^2 (M_1+M_2)}{a^5} \approx 2^7 \frac{M_1}{M_2}\left(\frac{v}{c}\right)^5 \frac{E_{kin,1}}{P}$$

Wave amplitudes (for observes at distances $r > c/\Omega$):

$$h_+ = -\frac{1}{r}\frac{G^2}{c^4}\frac{2M_1M_2}{a}(1+\cos^2\theta)\cos[2\Omega(t-r)-2\phi]$$
$$h_\times = -\frac{1}{r}\frac{G^2}{c^4}\frac{4M_1M_2}{a}\cos\theta\sin[2\Omega(t-r)-2\phi]$$

An observer in the orbital plane has $\theta = \pi/2$ and $h_\times = 0$.
The observed frequency of gravitational waves is $\nu = \Omega/\pi$.
The intensity of gravitational waves decreases as $1/r$.

Consider two 1.4 $\mathrm{M}_\odot$ neutron stars in a binary with separation of $\mathrm{R}_\odot$ observed from a distance of 1 kpc:

$P \simeq 7000$ s, $\quad \nu \simeq 2.9 \cdot 10^{-4}$ Hz
$L \simeq 6.5 \cdot 10^{32}$ erg/s $\simeq 0.17$ $\mathrm{L}_\odot$
$|h| \simeq 2 \cdot 10^{-22}, \quad |hr| \simeq 0.6$

Decay of Binary Orbits

For a binary with arbitrary eccentricity, the binary period decays due to gravitational radiation emission as

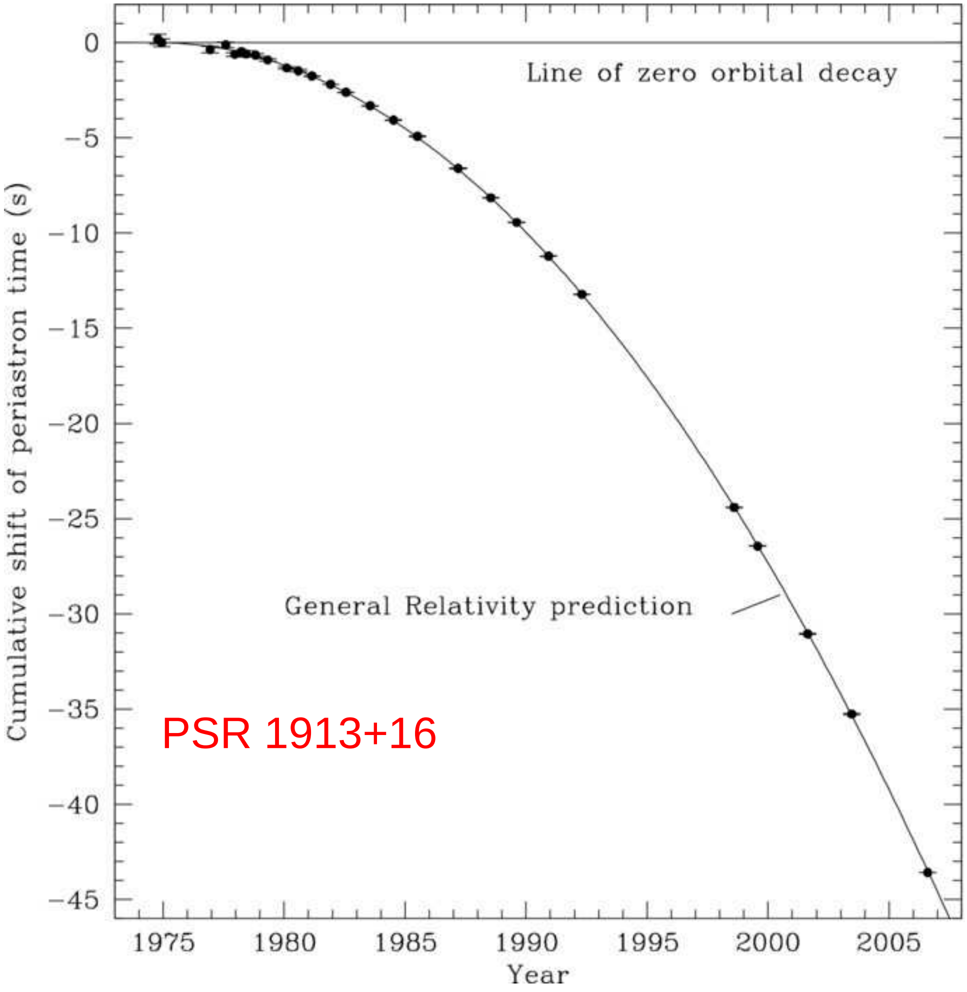
$$\dot{P} = \frac{-192\pi}{5}\left(\frac{2\pi P_\odot}{P}\right)^{5/3}\frac{M_1}{\mathrm{M}_\odot}\frac{M_2}{\mathrm{M}_\odot}\left(\frac{M_1+M_2}{\mathrm{M}_\odot}\right)^{1/3} f(e)$$

$$\equiv -AP^{-5/3}.$$

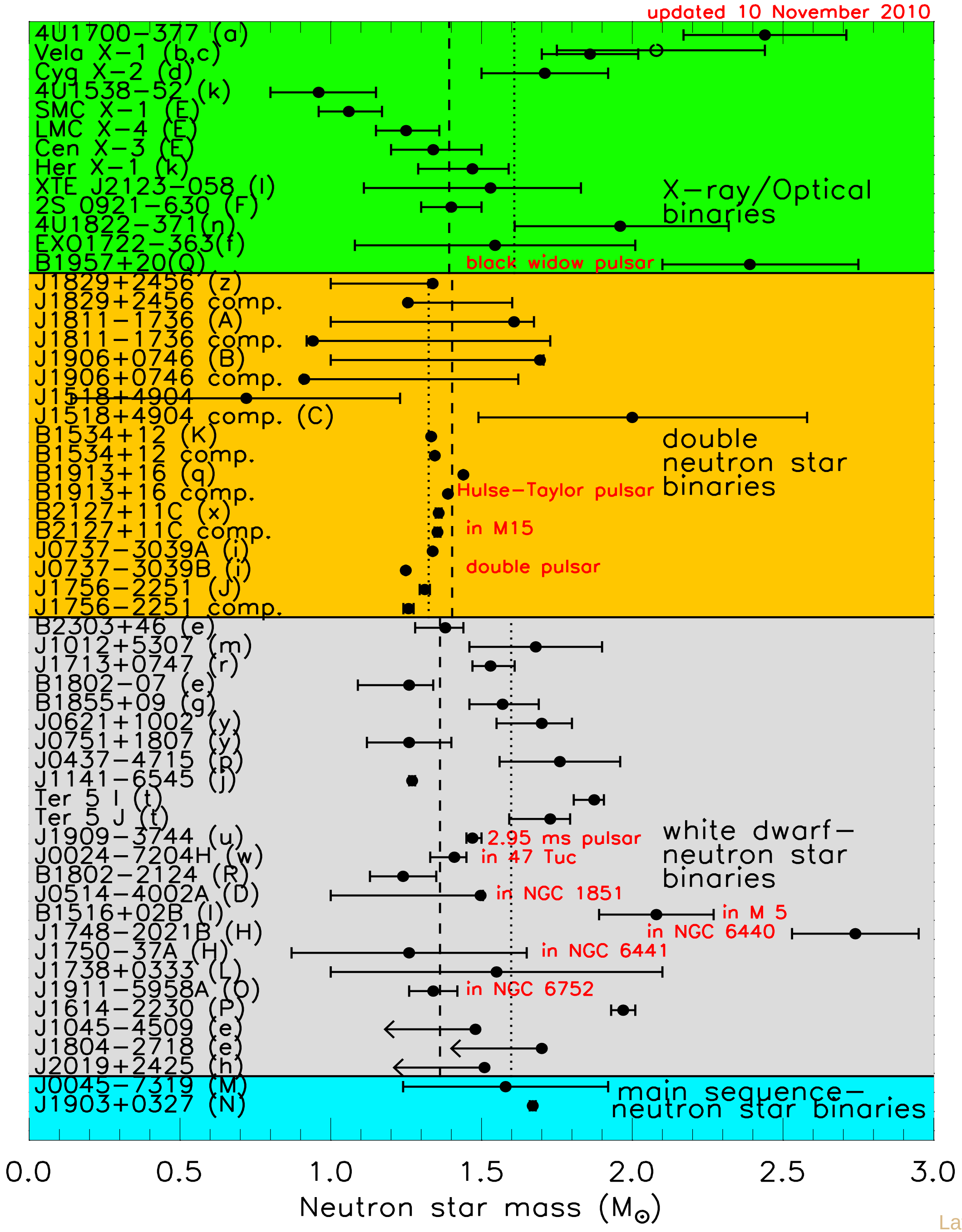
$P_\odot \equiv G\mathrm{M}_\odot/c^3 = 4.9255 \cdot 10^{-6}$ s.

$f(e) \equiv \left(1 + \frac{73}{24}e^2 + \frac{37}{96}e^4\right)\left(1-e^2\right)^{-7/2}$

For a circular orbit, $e = 0$.
Time to coalescence is
$t_c = \int_P^0 dP/\dot{P} = 3P^{8/3}/(8A)$.
For our previous example,
$A = 4.6 \cdot 10^{-6}$ s$^{5/3}$
so $t_c = 3.9 \cdot 10^{15}$ s $= 122$ Myr.
For an eccentricity of $e = 0.5$,
this timescale is reduced by
about a factor of 5.



Mergers involving Neutron Stars Must Occur



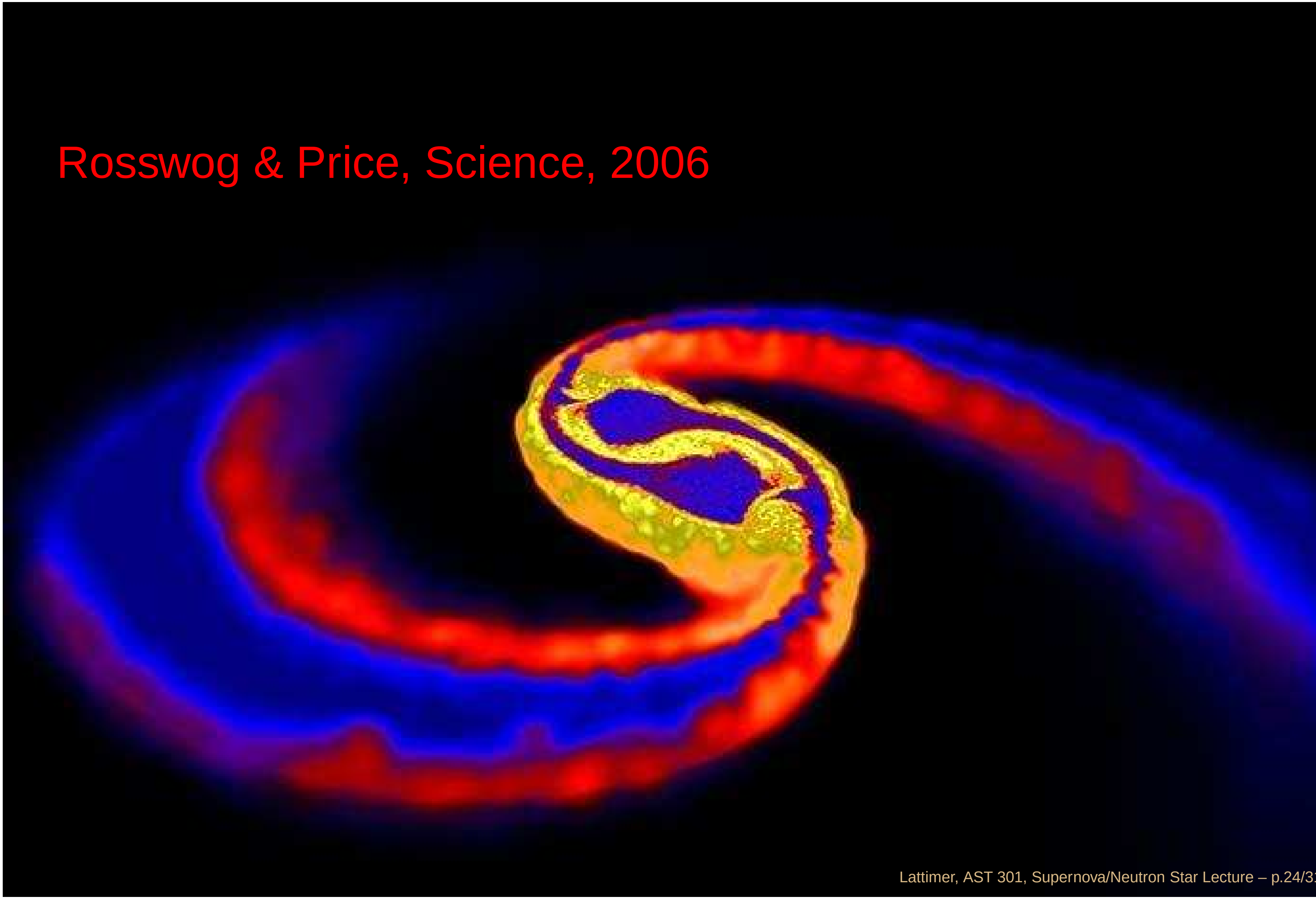
Comparison of Binary Pulsars

References	**PSR 0707-3039** **a, b, c**	**PSR 1913+16** **d**	**PSR 1534+12** **e, f**
a/c **(s)**	**2.93**	**6.38**	**7.62**
P **(h)**	**2.45**	**7.75**	**10.1**
e	**0.088**	**0.617**	**0.274**
M_A **($M_\odot$)**	1.337 ± 0.005	1.4414 ± 0.0002	1.333 ± 0.001
M_B **($M_\odot$)**	1.250 ± 0.005	1.3867 ± 0.0002	1.345 ± 0.001
T_{GW} **(M yr)**	**85**	**245**	**2250**
i	$87.9 \pm 0.6^\circ$	47.2°	77.2°

a: Lyne et al. (2004); b: Solution 1, Jenet & Ransom (2004); c: Coles et al. (2004)
d: Weisberg & Taylor (2002, 2004); e: Stairs et al. (2002, 2004); f: Bogdanov et al. (2002)

- **The shortest orbital period binaries have non-zero eccentricities.**
- **Mean pulsar velocities (300-400 km/s) imply neutron stars receive large kicks at birth.**
- **Kicks enhance supernova survival probability and shrink post-supernova orbital separations if directed opposite to supernova's motion.**

Neutron Star Merger



Rosswog & Price, Science, 2006

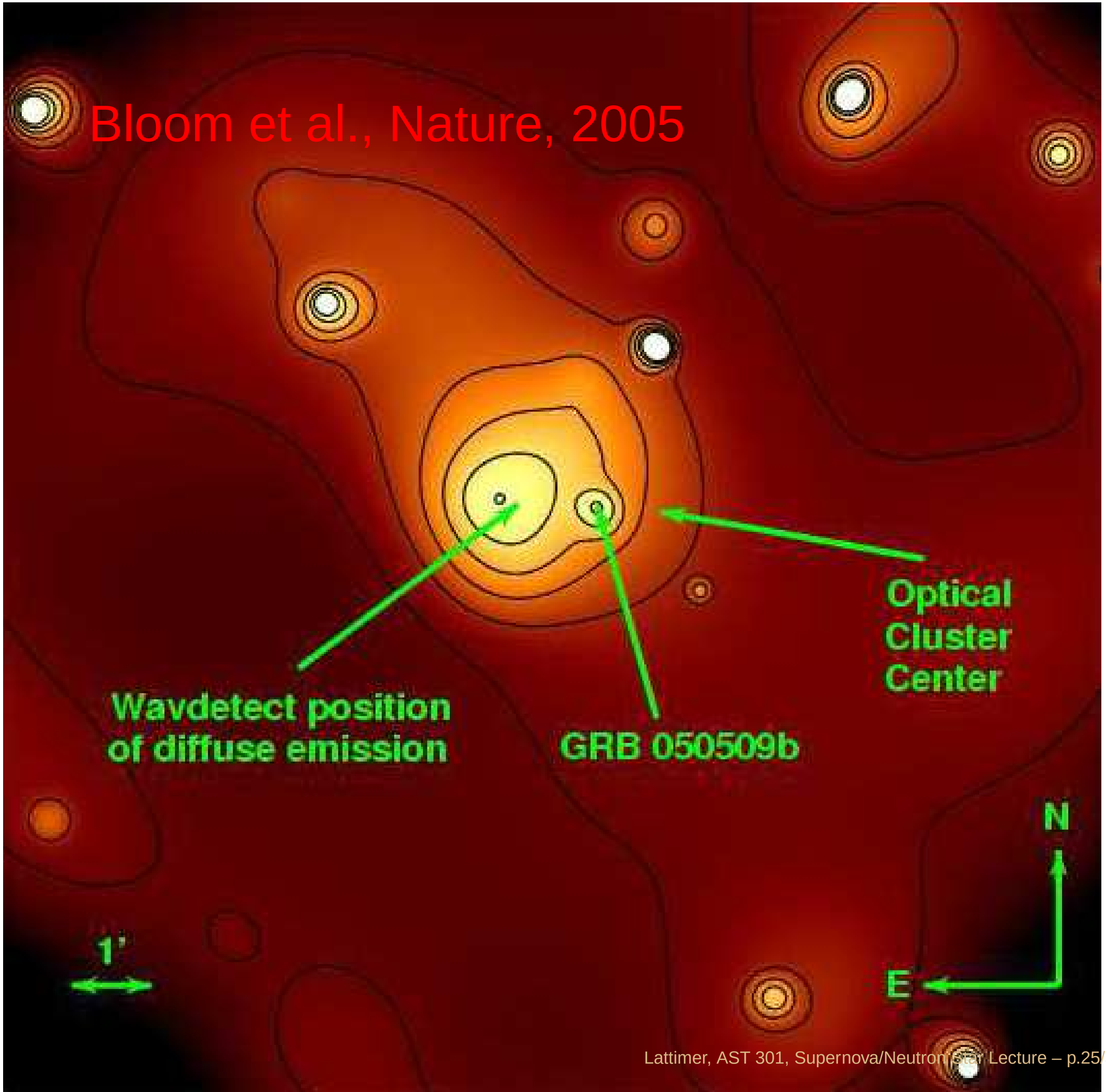
Short Gamma Ray Burst

Short duration

No afterglow

Occurs in elliptical galaxy

No coincident supernova



Bloom et al., Nature, 2005

Lethal Effects of Nearby Supernovae

1. Optical and UV light
2. X-rays from explosion
3. X-rays from supernova remnant
4. Gamma rays
5. Neutrinos
6. Cosmic rays

Lethality of High-Energy Radiation

Exposure and absorption of high-energy radiation is measured in

- gray = 1 joule per kilogram = 10^4 erg/g
- rad = 0.01 gray = 100 erg/g
- rem = 1 rad $\times Q$
  Q is a quality factor which accounts for various factors, such as protection by clothing, body orientation, internal body organs and structures. It is generally $0.1 \leq Q \leq 1$. We will assume $Q = 1$.

Short-Term Radiation Effects

Dosage (REM)	Effects
0 – 25	Nothing detectable
25 – 100	Temporary and slight decrease is white blood cell count
100 – 200	Nausea, vomiting, longer-term decrease in white cell count
200 – 300	Vomiting, diarrhea, appetite loss, listlessness
300 – 600	Above plus hemorrhaging and eventual death in some cases
above 600	Eventual death in nearly all cases

Long-term safe limit is 5 rem/yr (US Nuclear Regulatory Commision)

Calculating Doses

Assume a human in space, unshielded by Earth's atmosphere.
The cross-sectional area of a human is about

$$\text{height} \ \times \ \text{width} = 150 \text{ cm } \ \times 40 \text{ cm } \ = 6000 \text{ cm}^2$$

The average body mass is about 50 kg (110 lbs) = 50,000 g.

$$\text{Dose} \ = \text{SN flux} \ \times \ \frac{\text{area}}{\text{mass}} \times Q \text{ rem/s.}$$

. The flux of radiation from a supernova is (units are erg/cm^2/s)

$$\text{Flux} \ = L/(4\pi D^2)$$

where L is the luminosity in X-rays and gamma-rays and D is the distance. If D is in pc, a supernova of luminosity $L = 10^{42}$ erg/s at distance D will generate a flux at Earth

$$\text{Flux} \ = \frac{10^{42}}{4\pi(3.1 \times 10^{18} D)^2} = \frac{8280}{D^2} \text{ erg/cm}^2\text{/s.}$$

The dose is

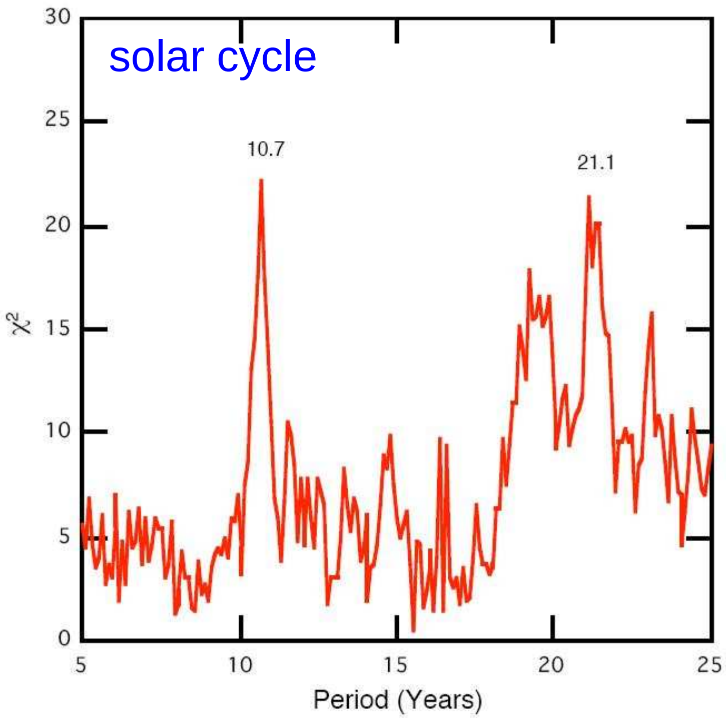
$$\text{Dose} \ = \frac{8280}{D^2} \times \frac{6000}{50,000} Q = \frac{994}{D^2} \text{ rem/s.}$$

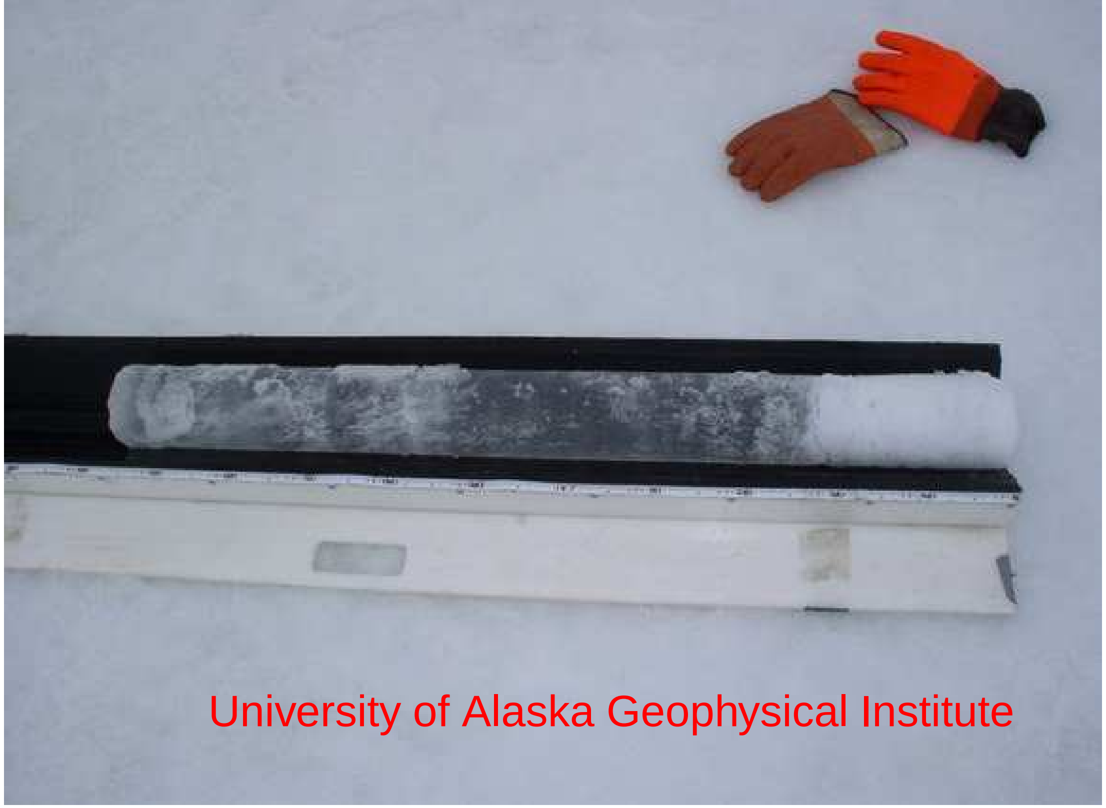
A lethal dose is accumulated in 0.6 s from a SN at $D = 1$ pc. If the flux persists for a month, a lethal dose is received from a SN up to 2.1 kpc away.

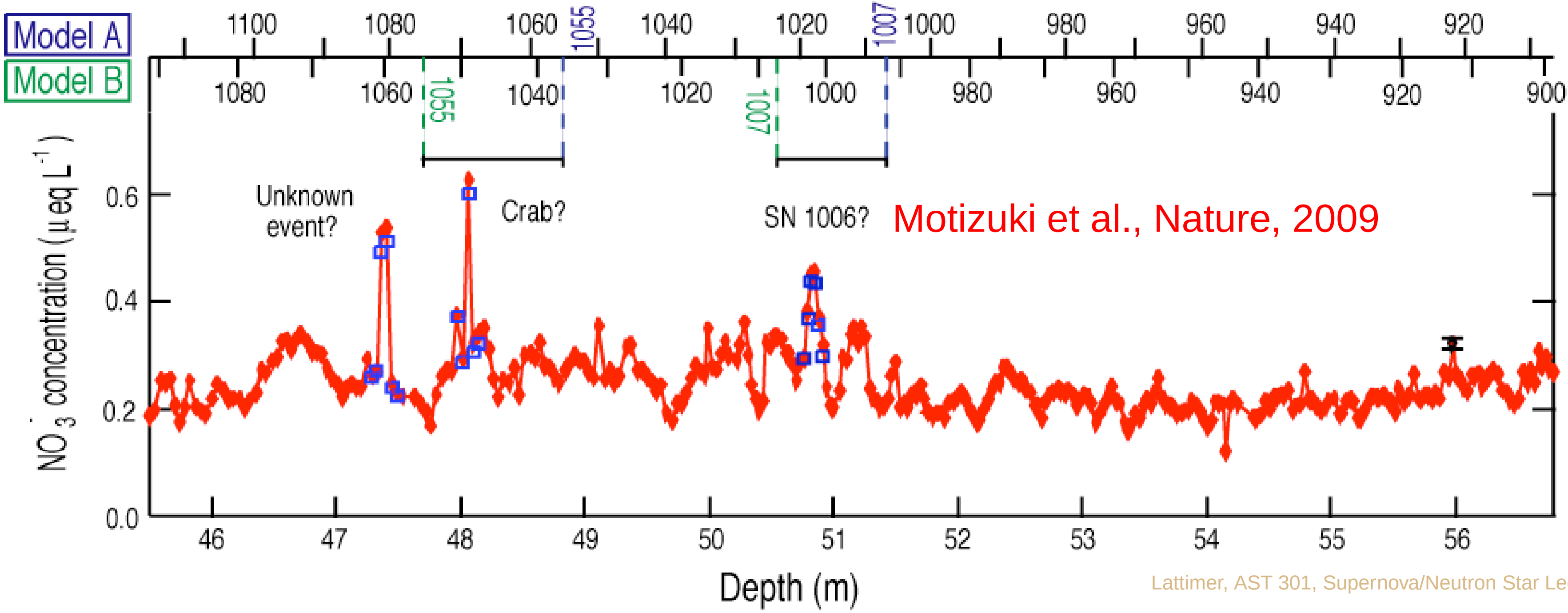
Effects on the Planet

- Type Ia supernova are potentially more deadly because of their greater total X-ray energy.
- Gamma-rays can induce reactions in which N_2 and O_3 are converted into nitrogen oxides, depleting the ozone layer which increases surface exposure to solar and cosmic radiation.
- Nitrates have been found in ice cores coinciding with SN 1006, SN 1054 (Crab), and a SN 1060-1080 or X-ray burster. (The 11-year solar cycle and volcanic eruptions are also detected from 1000-1100.)
  - Radiation is particularly harmful to phytoplankton and reef communities, although some water shielding is available.
  - Estimates set an ozone-destroying SN II at closer than 8 pc, based on SN 1987A, an underluminous SN II.
  - Rates of SN within 10 pc in solar neighborhood vary from 0.05 - 10 per billion years, mostly occuring when Sun is passing through disc (10 million out of 200 million years). Sun is now entering the galactic disc.
  - For $D < 200$ pc, time between events is estimated to be about 100,000 yrs.
  - Nearby SN include Vela (800 lt yr, 12,000 yrs ago), Geminga (550 lt yr, 300,000 yrs ago), RX J0852.0-4622 (660 ly yr, 900 yrs ago).
  - There is abundant evidence from short-lived radioactive isotopes that nearby supernovae have occurred, both prior to the solar system's formation (^{26}Al), as well as more recently (^{60}Fe).

Ice Core Samples and SN




University of Alaska Geophysical Institute



Motizuki et al., Nature, 2009

Fe^{60} and Supernovae Near the Sun

- Evidence exists that ^{60}Ni/^{58}Ni ratios in primitive meteorites are lower than samples from Earth, Mars and the chondrite parent bodies.
- The implication is that the oldest solar system planetismals formed in the absence of ^{60}Fe, halflife 1.5 million years.
- Younger objects had live ^{60}Fe which must have been injected a million or so years after solar system formation, when ^{26}Al was already homogeneously distributed.
- This decoupling of live ^{26}Al and ^{60}Fe tells us about the environment where the Sun formed: in a dense stellar cluster with numerous massive stars.
- There is other evidence for a SN 2.8 million years ago a few tens of parsecs distant from dust enriched in ^{60}Ni found in dust on the ocean floor 15,750 feet below sea level in the Pacific Ocean.
- A shift in the African climate toward more arid conditions, resulting in deforestation, occurred about the same time and may have forced hominids to climb down from trees and walk upright.