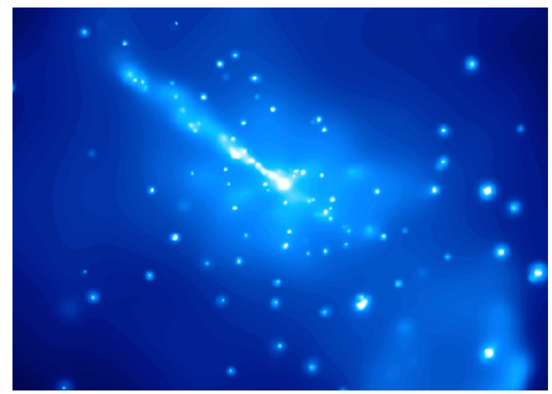
Neutrino astronomy and telescopes

Crab nebula



Cen A

Overview

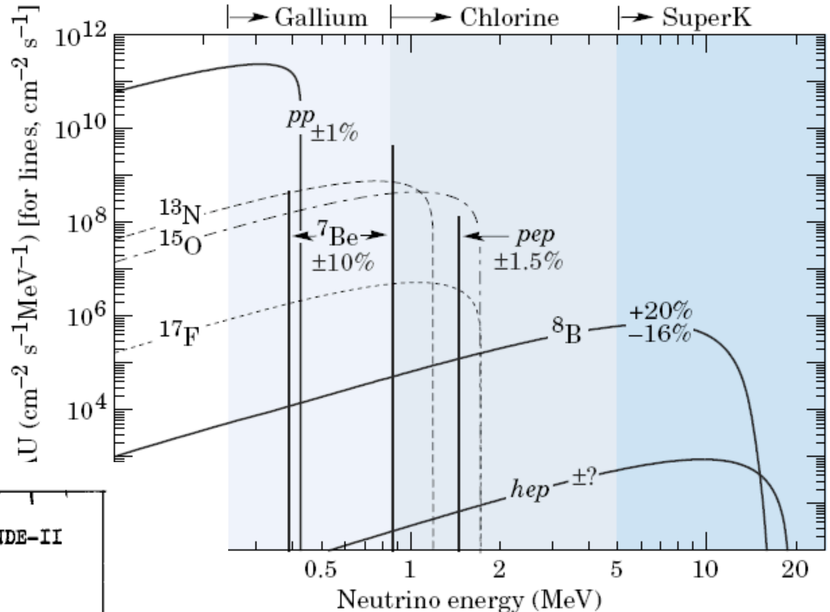
- Neutrinos and their properties (done)
- Neutrino astronomy and connections to Cosmic rays and gamma-astronomy
- Neutrino sources and neutrino production

  SN collapse and nutrino burst
- Neutrino telescopes and detection technique
- Search Methods
- Current experimental scenario

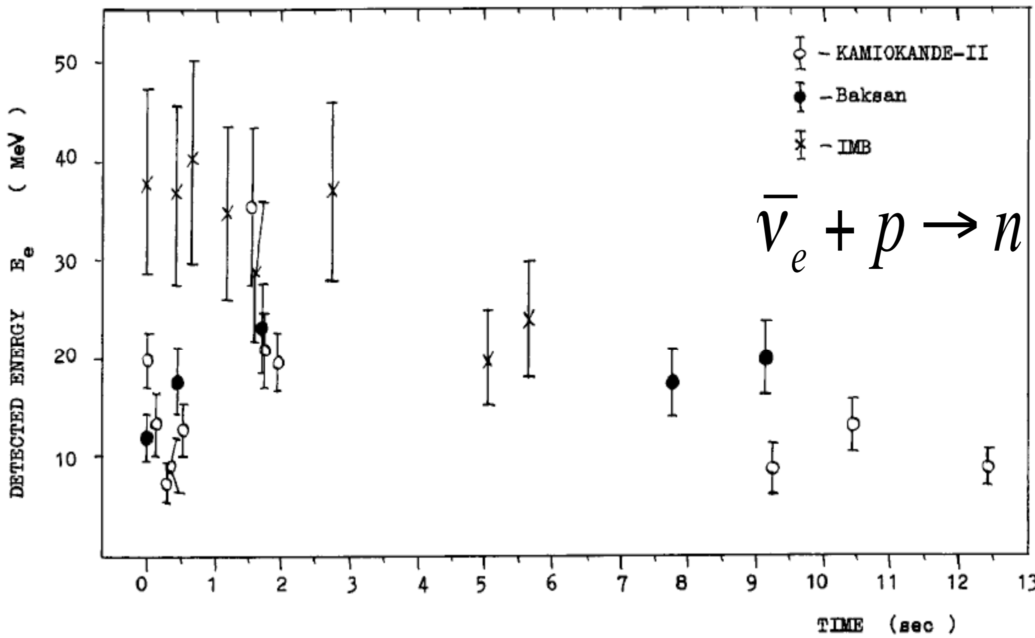
Astrophysical neutrinos: Sun and SN1987A

Combined effect of nuclear fusion reactions

$$4p \rightarrow {}^4\mathrm{He} + 2e^+ + 2\nu_e$$

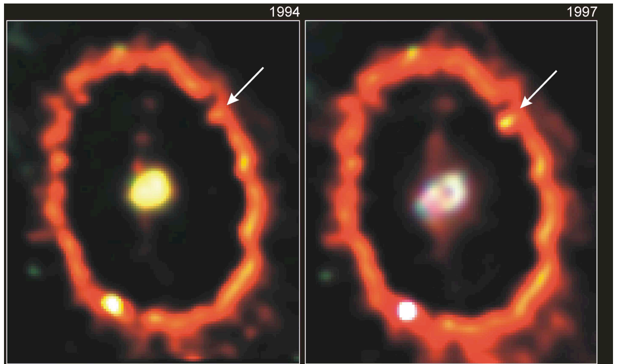


http://www.nu.to.infn.it/Supernova_Neutrinos/#7



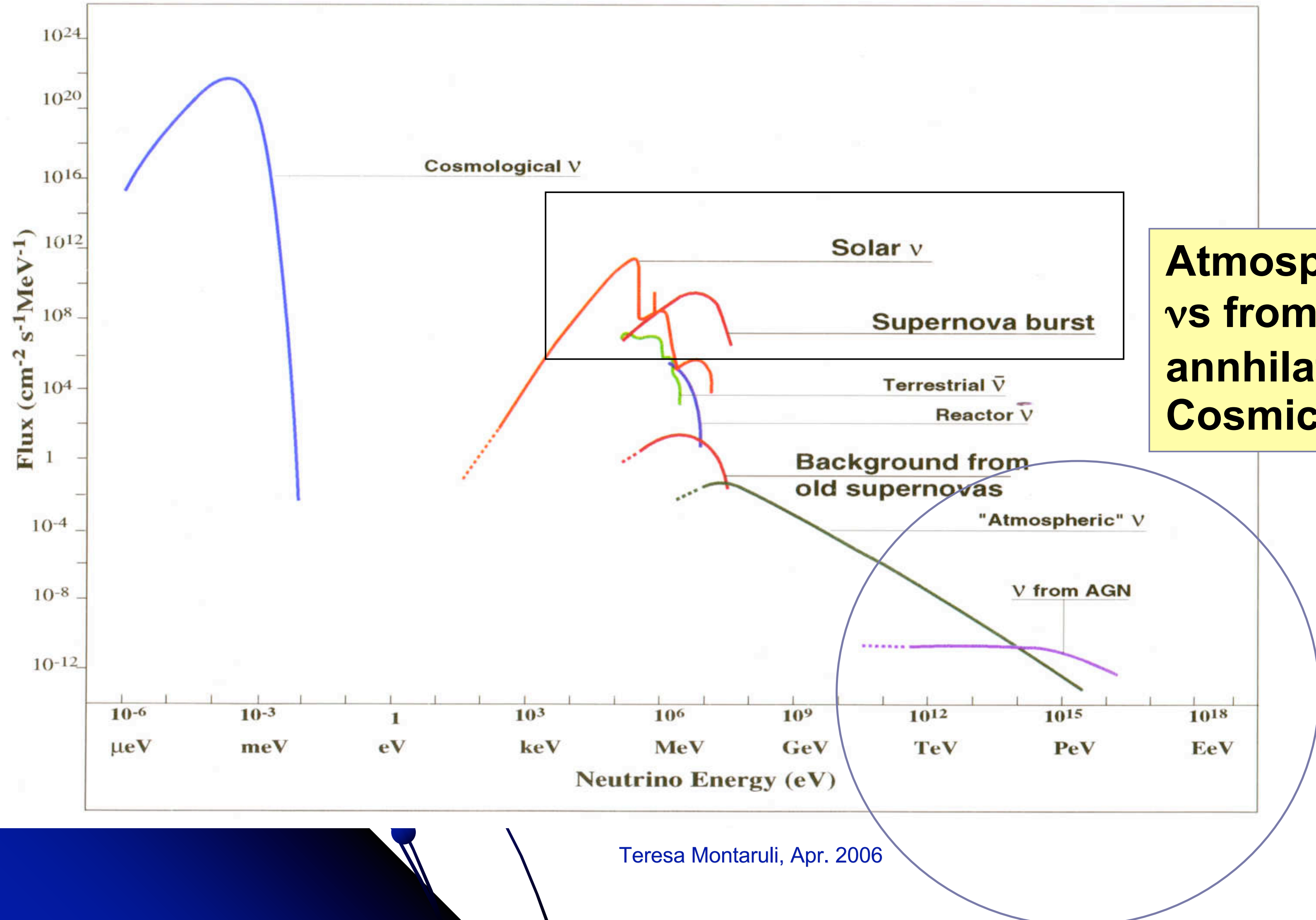
$$\bar{\nu}_e + p \rightarrow n + e^+$$

Fig. 3. Energies of all events detected at 7:35 UT on February 23, 1987 versus time. t=0.0 is set as to be the time of the first event of each signal observed.



Supernova 1987A Ring
Hubble Space Telescope WFPC2

Neutrino Fluxes



Atmospheric νs
νs from WIMP annhilation
Cosmic νs

Astronomy with particles

- straight line propagation to point back to sources
- Photons: reprocessed in sources and absorbed by extragalactic backgrounds

For E_γ > 500 TeV do not survive journey from Galactic Centre

- Protons: directions scrambled by galactic and intergalactic magnetic fields (deflections <1° for E>50 EeV)

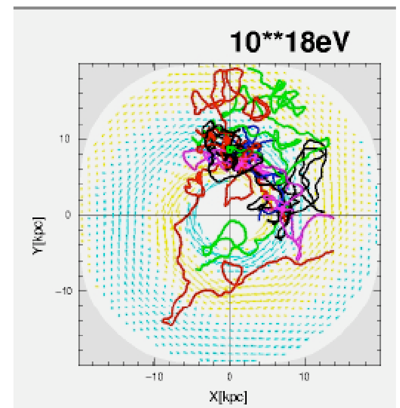
$$\vartheta \cong \frac{d}{R_{gyro}} = \frac{dB}{E} \Rightarrow \frac{\vartheta}{0.1°} = \frac{\left[\frac{d}{1Mpc}\right]\left[\frac{B}{1nG}\right]}{\left[\frac{E}{3\times10^{20}eV}\right]}$$

θ

d

R_{gyro}

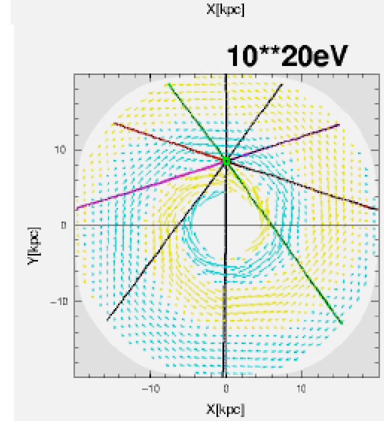
$evB = mv^2/R_{gyro} \Rightarrow eB = p/R_{gyro} \Rightarrow 1/R_{gyro} = B/E$



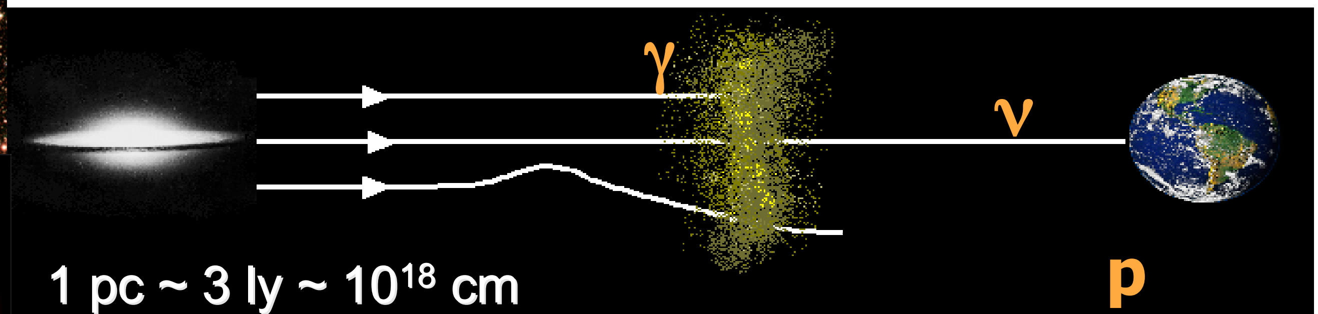
- Interaction length $p + \gamma_{CMB} \rightarrow \pi + n$

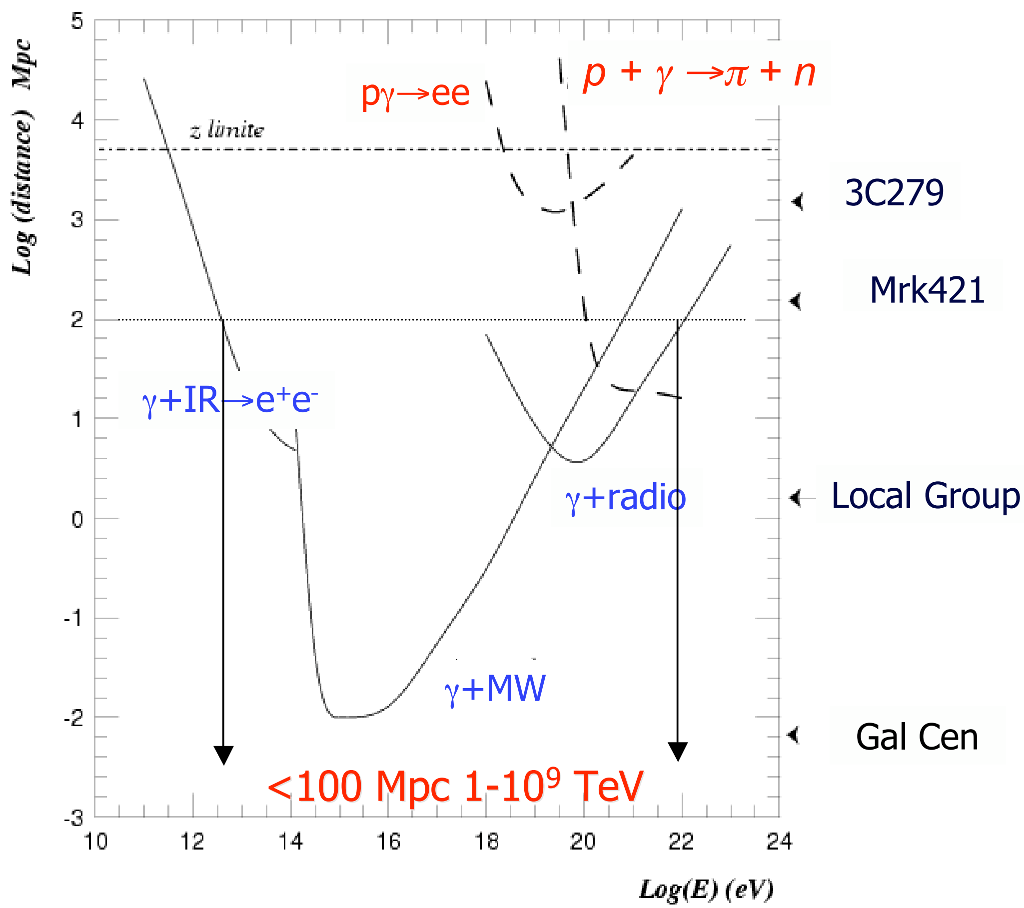
$\lambda_{\gamma p} = (n_{CMB}\, \sigma)^{-1} \sim 10$ **Mpc**

- Neutrons: decay $\gamma ct \sim E/m_n\, ct$ ~10kpc for E~EeV



Messengers from the Universe





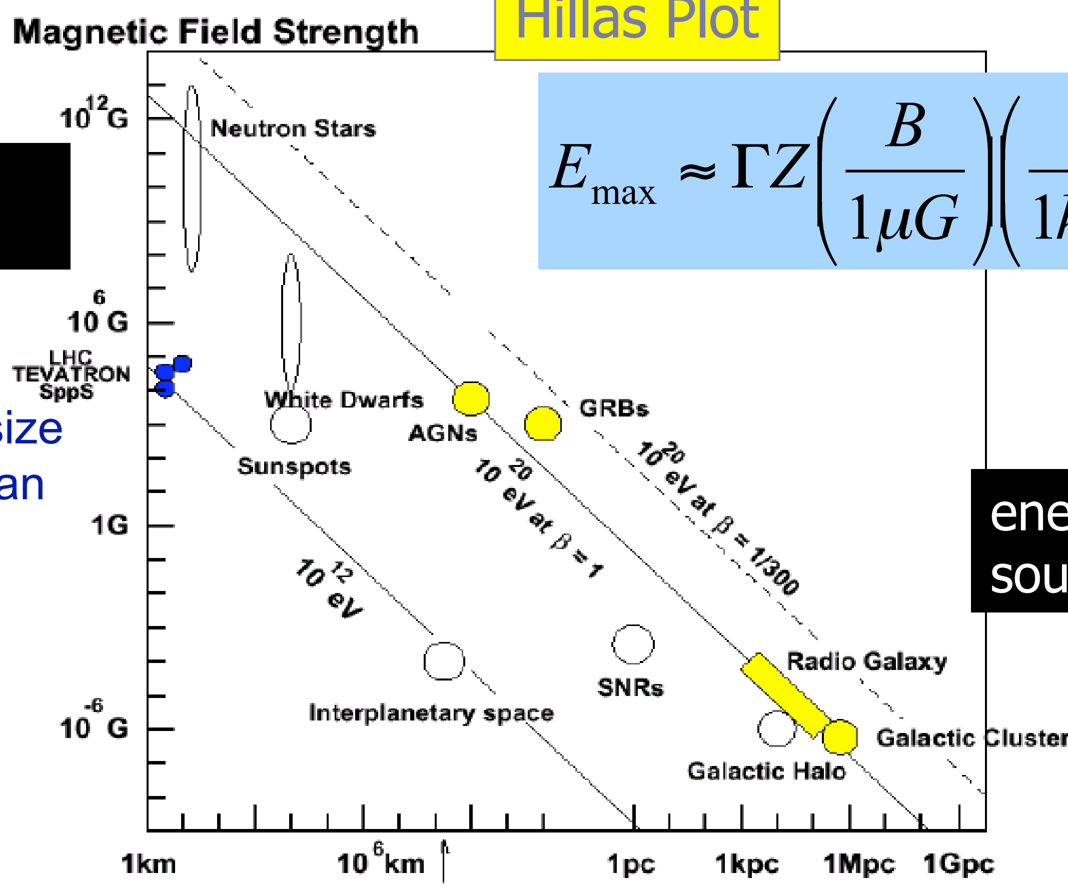
Photons currently provide all information on the Universe but interact in sources and during propagation

Neutrinos and gravitational waves have discovery potential because they open a new window on the universe

CR acceleration at sources

Hillas Plot

$$E_{\max} \approx \Gamma Z \left(\frac{B}{1\mu G} \right) \left(\frac{R}{1kpc} \right) 10^{18} eV$$

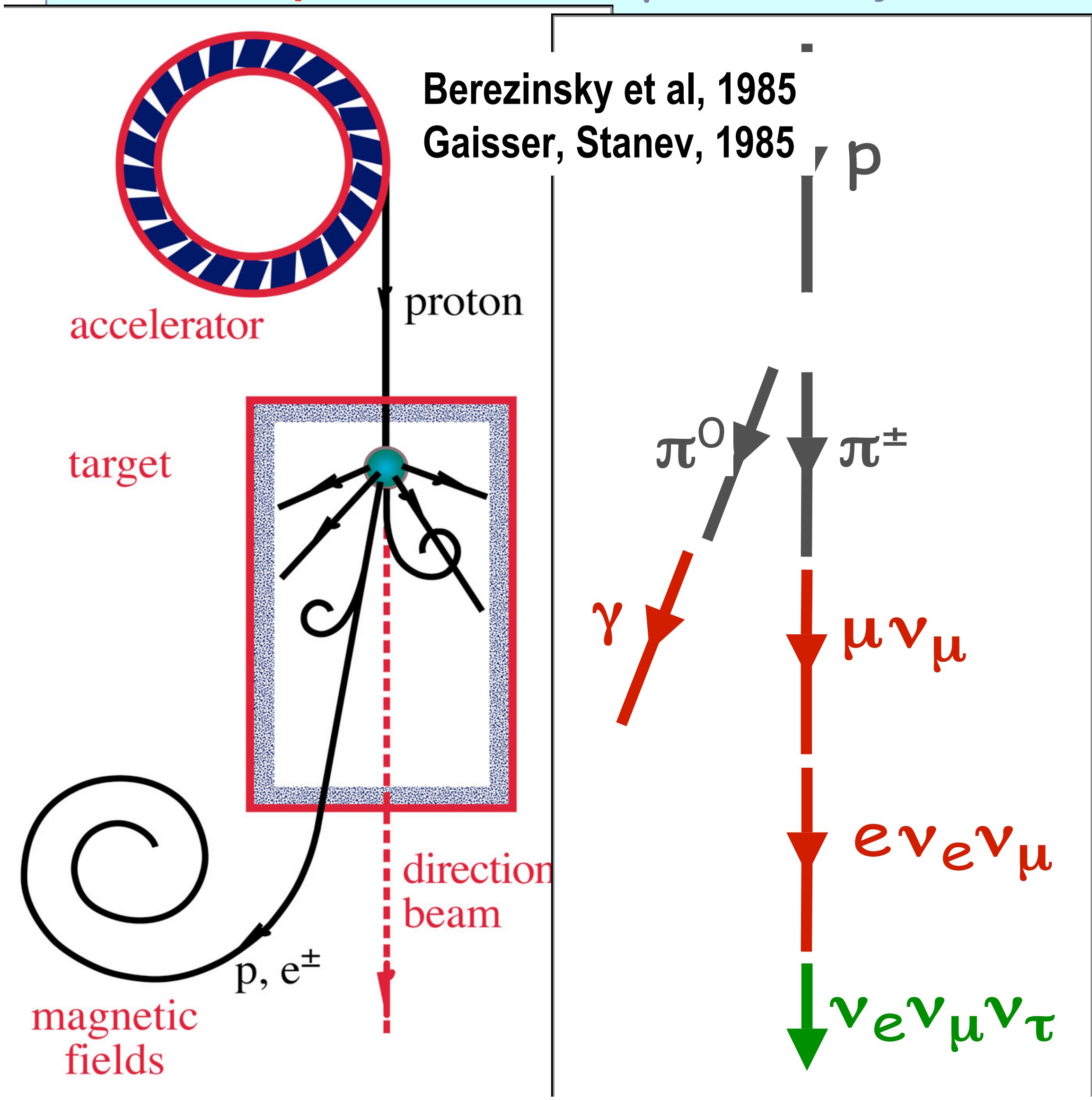


The accelerator size must be larger than R_{gyro}

energy losses in sources neglected

Neutrino production: bottom up

Beam-dump model: $\pi^0 \rightarrow \gamma$-astronomy $\pi^\pm \rightarrow \nu$-astronomy



Neglecting γ absorption (uncertain) $\varphi_\nu \sim \varphi_\gamma$
Targets: p or ambient γ

From photon fluxes to ν predictions:pp

$$\int_{E_{\gamma\,\min}}^{E_{\gamma\,\max}} E_\gamma \frac{dN_\gamma}{dE_\gamma} dE_\gamma = K \int_{E_{\nu\,\min}}^{E_{\nu\,\max}} E_\nu \frac{dN_\nu}{dE_\nu} dE_\nu$$

K = 1 pp

2 photons with

$$E_\gamma \approx {E_\pi}/{2} \approx {E_p}/{6}$$

$$\begin{array}{llll} p + A,\ \gamma \longrightarrow & \pi^0 & +\pi^+ & +\pi^- \\ & \downarrow & \downarrow & \downarrow \\ & \gamma+\gamma & \mu^+ + \nu_\mu & \mu^- + \bar{\nu}_\mu \\ & & \downarrow & \downarrow \\ & & e^+ + \nu_e + \bar{\nu}_\mu & e^- + \bar{\nu}_e + \nu_\mu \end{array}$$

$$E_\pi \approx {E_p}/{3}$$

2ν_μ and 1 ν_e with

$$E_\nu \approx {E_\pi}/{4} \approx {E_p}/{12}$$

2ν_μ 1ν_e 0ν_τ for 1γ

$$E_p^{\min} = \Gamma \frac{(2m_p + m_\pi)^2 - 2m_p^2}{2m_p}.$$

$$p + p \rightarrow p + p + \pi^0$$

$$p + p \rightarrow p + n + \pi^+$$

K = 1 since energy in photons matches that in ν_μs
2ν_μs with $E_p/12$ for each γ $E_p/6$

Minimum proton energy fixed by threshold for π production (Γ =E/m is the Lorentz factor of the p jet respect to the observer)

The energy imported by a ν in π decay is 1/4E_π

Exercises!

From photon fluxes to ν predictions: pγ

$$\int_{E_{\gamma\,\min}}^{E_{\gamma\,\max}} E_\gamma \frac{dN_\gamma}{dE_\gamma} dE_\gamma = K \int_{E_{\nu\,\min}}^{E_{\nu\,\max}} E_\nu \frac{dN_\nu}{dE_\nu} dE_\nu$$

K = 4 pγ

$$E_\gamma = \frac{E_p < x_{p\to\pi} >}{2} = 10\% E_p$$

$$E_\nu = \frac{E_p < x_{p\to\pi} >}{4} = 5\% E_p$$

$$1)\, p + \gamma \to \Delta^+ \to p\pi^0$$ BR = 2/3

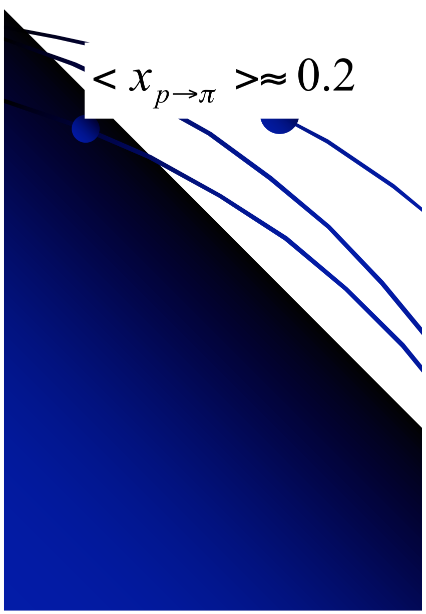
$$2)\, p + \gamma \to \Delta^+ \to n\pi^+$$ BR = 1/3

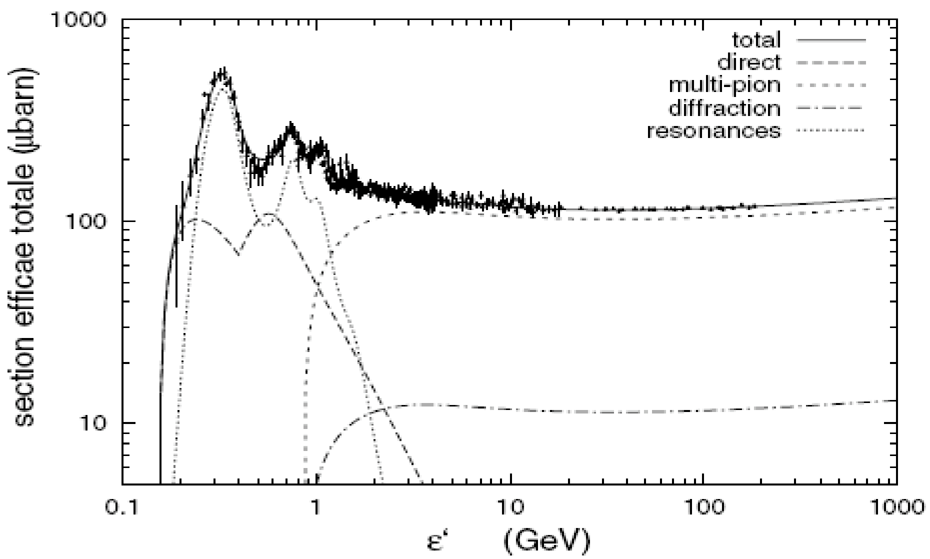
1) 2γs with $2/3 E_\gamma = 2/3 \cdot 0.1 E_p$

2) $2\nu_\mu$s with $1/3 E_\nu = 1/3\ 0.1 \cdot E_p\ /2$

→ K = 4

$< x_{p\to\pi} > \approx 0.2$





Astrophysical Neutrino Oscillations

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{13}s_{23}e^{i\delta} & c_{12}c_{23} - s_{12}s_{13}s_{23}e^{i\delta} & c_{13}s_{23} \\ s_{12}s_{23} - c_{12}s_{13}c_{23}e^{i\delta} & -c_{12}s_{23} - s_{12}s_{13}c_{23}e^{i\delta} & c_{13}c_{23} \end{pmatrix}$$

$$U = \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12}c_{23} & c_{12}c_{23} & s_{23} \\ s_{12}s_{23} & -c_{12}s_{23} & c_{23} \end{pmatrix} = \begin{pmatrix} c_{sol} & s_{sol} & 0 \\ -s_{sol}c_{atm} & c_{sol}c_{atm} & s_{atm} \\ s_{sol}s_{atm} & -c_{sol}s_{atm} & c_{atm} \end{pmatrix}$$

$$\theta_{12} \approx 35\deg \Rightarrow c_{sol} = 0.82 \text{ and } s_{sol} = 0.57$$

$$\theta_{23} \approx 45\deg \Rightarrow s_{atm} = c_{atm} = 1$$

$$U = \begin{pmatrix} c & s & 0 \\ -sx & cx & x \\ sx & -cx & x \end{pmatrix} = \begin{pmatrix} 0.82 & 0.57 & 0 \\ -0.4 & 0.58 & 1/\sqrt{2} \\ 0.4 & -0.58 & 1/\sqrt{2} \end{pmatrix}$$

Astrophysical Neutrino Oscillations

Hence for astrophysical sources L>kpc: the uncertainties on distances to sources and on their dimensions eliminate the effect of the phase term.

$$P(\nu_\alpha \rightarrow \nu_\beta) = \sum_{i,j} U_{\alpha,i} U^*_{\beta,i} U^*_{\alpha,j} U_{\beta,j} e^{-i\Delta m^2_{i,j} L/2E} \Rightarrow P(\nu_\alpha \rightarrow \nu_\beta) = \sum_i |U_{\alpha,i}|^2 |U_{\beta,i}|^2$$

$$P(\nu_e \rightarrow \nu_e) = \sum_i |U_{ei}|^2 |U_{ei}|^2 = |U_{e1}|^4 + |U_{e2}|^4 + |U_{e3}|^4 = 0.82^4 + 0.57^4 + 0 = 0.56$$

$$P(\nu_e \rightarrow \nu_\mu) = \sum_i |U_{ei}|^2 |U_{\mu i}|^2 = |U_{e1}|^2 |U_{\mu 1}|^2 + |U_{e2}|^2 |U_{\mu 2}|^2 + |U_{e3}|^2 |U_{\mu 1}|^2 = 0.82^2 \cdot 0.4^2 + 0.57^2 \cdot 0.58^2 + 0 = 0.22$$

$$P(\nu_e \rightarrow \nu_\tau) = \sum_i |U_{ei}|^2 |U_{\tau i}|^2 = |U_{e1}|^2 |U_{\tau 1}|^2 + |U_{e2}|^2 |U_{\tau 2}|^2 + |U_{e3}|^2 |U_{\tau 1}|^2 = 0.82^2 \cdot 0.4^2 + 0.57^2 \cdot 0.58^2 + 0 = 0.22$$

$\nu_\alpha \backslash \nu_\beta$	ν_e	ν_μ	ν_τ
ν_e	60%	20%	20%
ν_μ	20%	40%	40%
ν_τ	20%	40%	40%

$$\nu_e : \nu_\mu : \nu_\tau = 1:2:0$$

$$\Downarrow$$

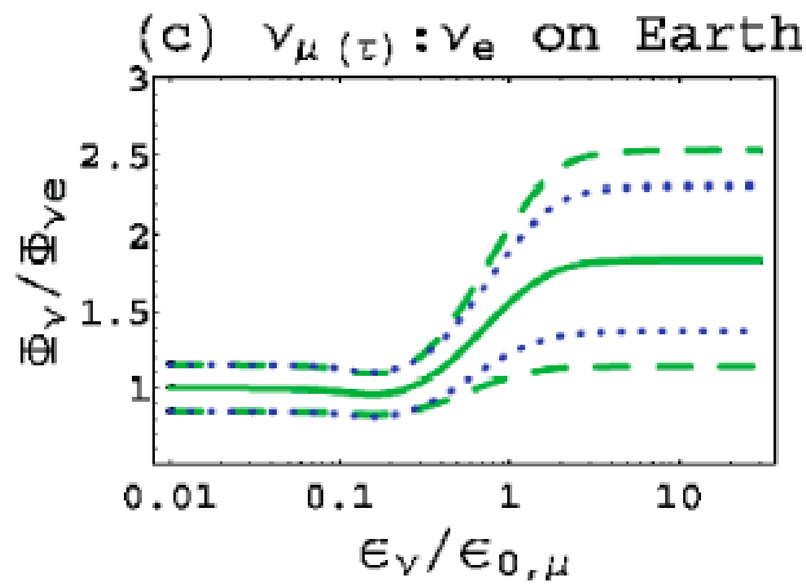
$$\nu_e : \nu_\mu : \nu_\tau = 1:1:1$$

But: energy losses in sources

At high energy this ratio modifies into 1:1.8:1.8 since pions/muons may suffer significant energy losses prior to decay. Since pion lifetime 2.6×10^{-8} s < muon one 2.2×10^{-6} s , it can decay more easily before losing significant energy compared to muons. This leads to a suppressed contribution of ν_e and ν_μ from μ decay. When muons do not decay at source 0:1:0 and the ratio is modified by oscillations into 1:1.8:1.8. Transition at about 10^6 TeV for AGNs, for GRBs associated to collapse of massive stars transition at 1 TeV due to intense inverse Compton losses

(Kashti & Waxman, PRL95 (2005

ϵ_0 = energy at which $\tau_{x,\mathrm{cool}} = \tau_{x,\mathrm{decay}}$



Neutrino production: top down

Decay of neutrons in sources

Decay or annihilation of supermassive relic of Big Bang 10^{24} eV = 10^{15} GeV ~ M_{GUT} (monopoles, topological defects, vibrating strings…)

Resonant UHE neutrino interactions on relic neutrinos (Z-bursts)

$$\nu\bar{\nu} \rightarrow Z \rightarrow p\gamma\ldots \qquad E_{\rm res} = \frac{M_Z^2}{2\,m_\nu} = 4\times10^{21}{\rm eV}\left(\frac{\rm eV}{m_\nu}\right)$$

Gelmini et al, PRD70, 2004

Can explain EHECR

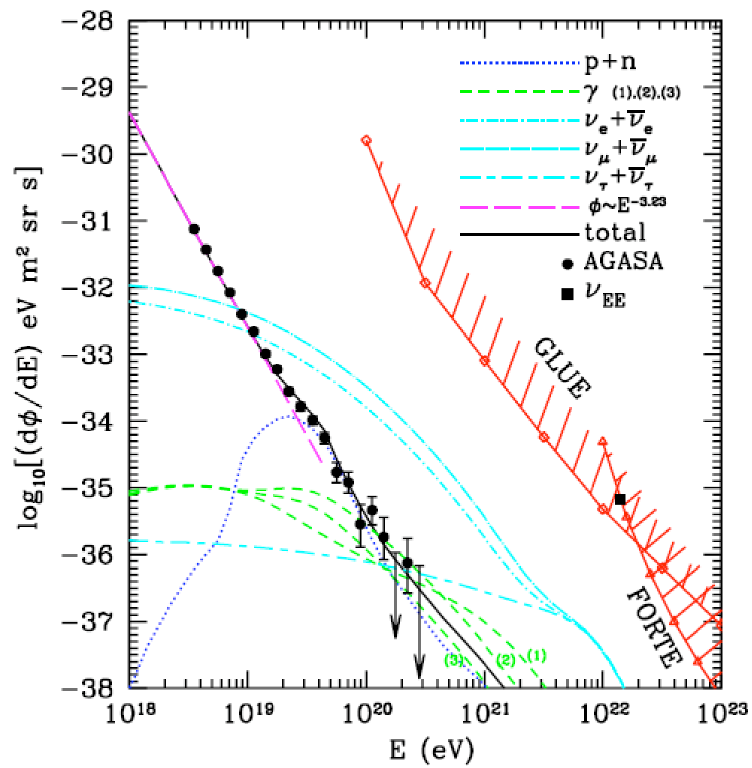


Figure 2: Predicted spectra for m_ν =0.3 eV from Z-bursts with a uniform distribution up to $z = 2$, added to a power law spectrum which fits the data below the ankle $\sim 10^{19}$ eV, and terminates at 4×10^{19} eV. It is seen that EECR primaries above the ankle are nearly 100% nucleons up to 10^{20} eV, and photons plus nucleons at higher energies. Also shown is the EE neutrino flux at the unique resonance energy which produces the required Z-burst rate.

Guaranteed neutrinos: GZK νs

UHECR produce πs →νs

νs from CR interactions in the Galactic plane

Teresa Montaruli, Apr. 2006

Supernovae and gravitational collapse

Stars are in hydrostatic equilibrium: equilibrium between the gravitational force towards the core and the pressure opposing to I: For spherical symmetry:

Mass inside radius r= distance from the centre of the star

Pressure

density

$$\frac{dP(r)}{dr} = -\frac{GM(r)\rho(r)}{r^2}$$

$$M(r) = 4\pi \int_0^r dr' \, (r')^2 \, \rho(r')$$

The layer between r and r+dr contains $dm(r) = 4\pi r^2 \rho(r) \, dr$

The gravitational force on this layer is:

$$F_{grav} = -G\frac{M(r)dm(r)}{r^2}$$

While the pressure force is:

$$\left[P(r) - P(r+dr)\right] \times (4\pi r^2) = \frac{dP}{dr} \times (4\pi r^2 dr)$$

CVD

Pressure in stars

In normal stars the source of pressure is the thermal motion of the material. In degenerate stars (n stars or white dwarfs) it is a quantum mechanical effect. Given Heisenberg uncertainty principle

$$\Delta p \, \Delta x \sim \hbar$$

A particle cannot be compressed in a volume $(\Delta x)^3$ without having a Momentum

$$p \sim \frac{\hbar}{\Delta x}$$

For a system of N particles confined in a volume Vwith particle density n = N/V Each particle has an available volume of $(\Delta x)^3 \sim 1/n$ and so a momentum

$$\langle p \rangle \sim \hbar \, n^{\frac{1}{3}} \sim \hbar \, \frac{N^{\frac{1}{3}}}{R}$$

The Chandrasekar mass

In the non relativistic case:

$$F_{\rm kin} \simeq \frac{\langle p\rangle^2}{2m} \simeq\sim \hbar^2 \ \frac{N^{\frac{2}{3}}}{2\,m}\ \frac{1}{R^2}$$

In the relativistic case:

$$\frac{E^{\rm rel}_{\rm kin}}{N} \simeq \langle p\rangle c$$

In the non relativistic case the total energy is

$$E = -G\frac{Nm^2}{R} + \frac{N^{2/3}\hbar^2}{2mR^2}$$

The equation has the form:

That has a min for

$$E = -\frac{a}{R} + \frac{b}{R^2}$$

$$\frac{dE}{dR} = \frac{a}{R^2} - \frac{2b}{R^2} = 0 \Rightarrow R^* = \frac{2b}{a} = \frac{h^2}{Gm^3N^{1/3}}$$

For R>R* the gravitational effect dominates and the system contracts.

For R<R* the repulsive effect of the Fermi momentum dominates

The Chandrasekar mass

When N increases the system becomes unavoidably relativistic:

$$R^* \to N^{-1/3} \text{ and } \qquad \langle p \rangle \sim \hbar \frac{N^{\frac{1}{3}}}{R^*} \propto N^{\frac{2}{3}}$$

And the total energy is:

$$E = -\frac{G\,N\,m^2}{R} + \frac{N^{\frac{1}{3}}\,\hbar c}{R}$$

This equation has no equilibrium position. The energy is positive or negative.

For N sufficiently small E>0 and the repulsive effect wins and the star expands until it becomes non relativistic. For N sufficiently large the system collapses to R->0.

The critical condition that separates the collapse from the existence of a stable solution is

$$G\,N\,m^2 \simeq N^{\frac{1}{3}}\;\hbar\,c \qquad N^* \simeq \left(\frac{\hbar\,c}{G\,m^2}\right)^{\frac{3}{2}} \simeq 2.2\times 10^{57}$$

And if fermions have nucleons

$$M^* \simeq N^* m_p \simeq 1.85\; M_\odot$$

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The Chandrasekar mass

A more detailed calculation includeing the density profile of the star would give

$$M_{\rm max} = M_{\rm Chandra} = 1.457 \left(\frac{Z/A}{1/2}\right) M_\odot$$

$$N_{\rm max} = \frac{M_{\rm Chandra}}{m_p} = 1.82 \times 10^{57}$$

Which is the max mass of a Carbon white dwarf (in this case the pressure is generated by electrons that have a smaller mass and so a larger velocity for the same momentum and a larger pressure P.

The corresponding radius is given by the condition where fermions become relativistic

$$\langle p \rangle \approx mc \approx \hbar \frac{N^{1/3}}{R^*} \qquad R^* \simeq \frac{\hbar}{mc}(N^*)^{\frac{1}{3}}$$

For $m = m_e$ $\quad R^* \simeq 4000$ Km

For $m = m_p$ $\quad R^* \simeq 20$ Km

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Core Collapse

A star passes most of its lifetime burning H (main sequence). The resulting He builds up in the core and its mass increase, heating and contracting under the pressure of outer layer. The star contraction pauses as nuclear fusion provides the energy necessary to replenish the energy the star loses in radiation and neutrinos. When the T in the core is sufficiently large, He burning begins. After He burning the evolution is greatly accelerated by neutrino losses The scheme repeats for different stages

(i) Hydrogen burning $4p \rightarrow {}^{4}\mathrm{He} + 2\,e^{+} + 2\nu_e$
(ii) Helium burning $3\alpha \rightarrow {}^{12}\mathrm{C} + 2\gamma$
(iii) Carbon burning ${}^{12}\mathrm{C} + {}^{4}\mathrm{He} \rightarrow {}^{16}\mathrm{O} + \gamma$

Million yrs

(iv) Oxygen burning ${}^{16}\mathrm{O} + {}^{16}\mathrm{O} \rightarrow {}^{28}\mathrm{Si} + \alpha$
(iv) Iron burning ${}^{28}\mathrm{Si} + {}^{28}\mathrm{Si} \rightarrow {}^{56}\mathrm{Fe} + \gamma$

Few weeks