第21回理論懇シンポジウム＠国立天文台
2008年12月16日（火）

非熱的ニュートリノで探る星の強磁場

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MNRAS, 391, 1893 (2008)

Magnetic Fields

In Early-type stars:

- **Recently, $B \sim 10^3$ G**
  [Donati et al. 2006, etc]

Origin scenarios:

- **Fossil field ?**

stellar magnetic field inputs

In Neutron stars:

- **Typically $B \sim 10^{11} – 10^{14}$ G**
- **SGRs, AXPs,… $B \sim 10^{15}$ G**

Origin scenarios:

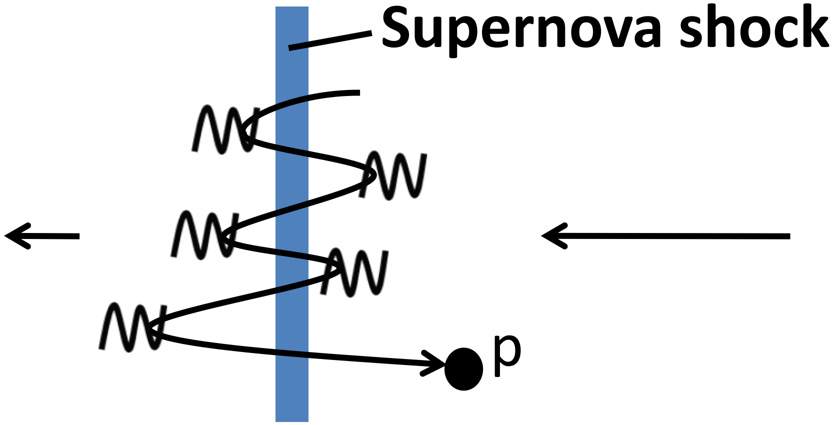
- **Dynamo ?**
  [Thompson&Duncan1993]
- **Fossil field ?**
  [Ruderman1972,Ferario2006]

Source	Surface B-field [G]	Radius [cm]	B-flux [G cm^2]
O stars	? – 10^3	10^{12}	$< 10^{28}$
Neutron stars	$10^{11} – 10^{15}$	10^6	$< 10^{28}$

Use neutrinos to see inside

Adopt the fossil scenario and investigate neutrino emission

First-order Fermi acceleration at supernova shock



[Blandford&Eichler 1987]
[Drury 1983

High-energy proton + target proton/photon

$$pp \longrightarrow pn\pi^+$$

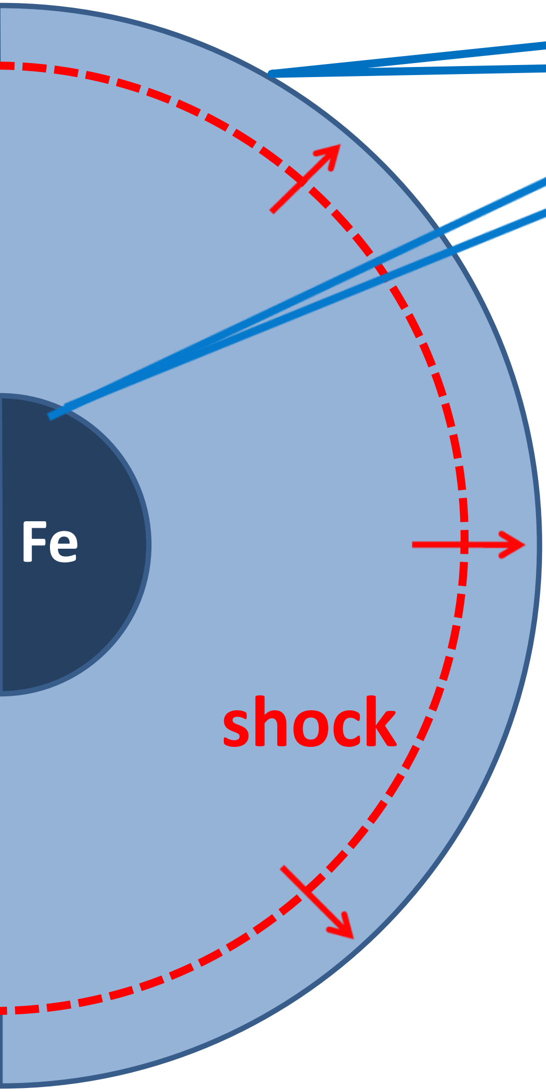
$$p\gamma \longrightarrow \Delta \longrightarrow n\pi^+$$

Secondary π decay

$$\pi^+ \longrightarrow \boxed{\nu_\mu}\mu^+$$

$$\mu^+ \longrightarrow \boxed{\bar{\nu}_\mu \nu_e} e^+$$

Supernova of a Magnetic star



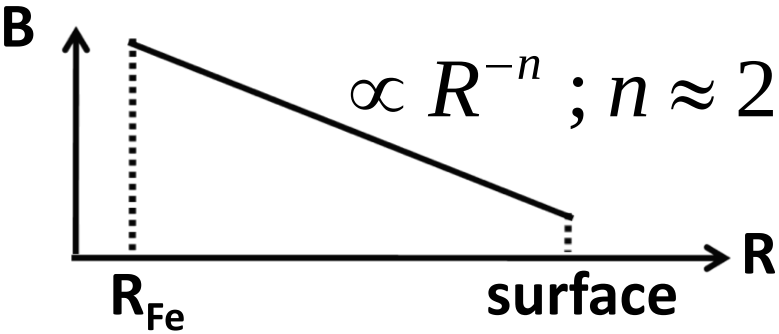
Surface B-field: observed

Eventually becomes magnetar B-field

Assuming fossil field hypothesis, the Fe core B-field is given by conservation of Br^2 :

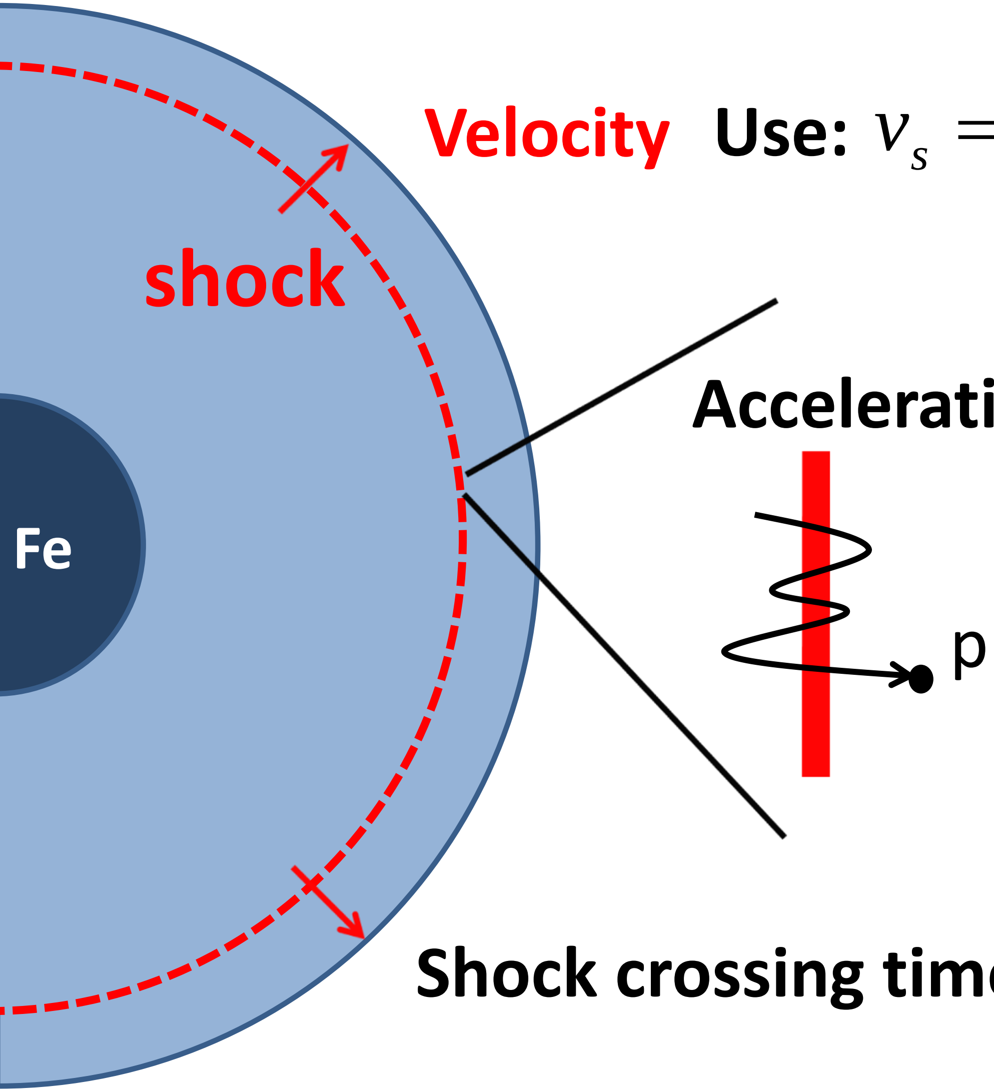
$$B_{\rm core} = 10^{15} \left(\frac{R_{\rm Fe}}{10^6 \ {\rm cm}} \right)^{-2} = 10^{11} \ {\rm G}$$

Assume a power-law :



$$\propto R^{-n} \, ; n \approx 2$$

Acceleration (timescale)



Velocity **Use:** $v_s = 10^{9.5}\,\mathrm{cm/s}$

e.g. [Kitaura et al. 2006]

Acceleration time (Bohm limit $\xi \to 1$) :

$$t_{acc} \approx \frac{10}{v_s^2}\frac{\xi r_g c}{3} \approx 10^{-5}\,\mathrm{sec}$$

Shock crossing time : $\dfrac{R}{v_s} \approx$ **minutes – hours**

Maximum Proton energy

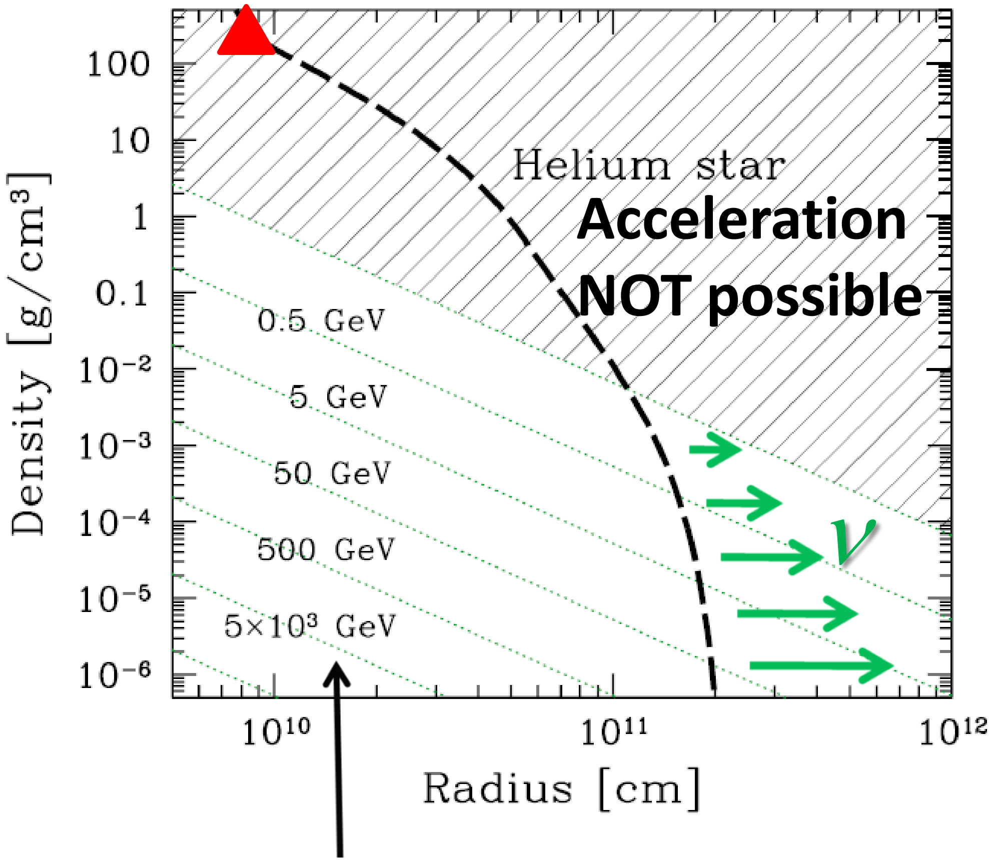
Proton cooling includes

1. **pair-production**
2. **synchrotron**
3. **inverse-Compton**

(include effects of electron synchrotron photons)

4. **proton-proton collision**

Fastest



[Horiuchi et al. 2008]

$$\boxed{t_{acc} = t_{cool}}$$ **yields the maximum proton energy**

Total neutrino event

Fluence:

$$\frac{dF_\nu}{d\epsilon_\nu} \approx \frac{1}{4\pi D^2} \frac{\xi_{\rm th}\xi_\nu \xi_p E_{\rm exp}}{\ln(\epsilon_{p,\rm max}/\epsilon_{p,\rm th})\epsilon_\nu^2}\zeta(\epsilon_\nu)$$

are fractions of the total energy:

$$\xi_p \sim 0.1$$

μ **event number, for 10^{51} ergs Supernova at 10 kpc :**

Soure	Neutrino E-max	@ Super-K	@ IceCube
Type II	20 GeV	130	200
Type Ib	400 GeV	160	6000
Type Ic	600 GeV	70	600

Background ~ 10/day

Background ~ 100 /day

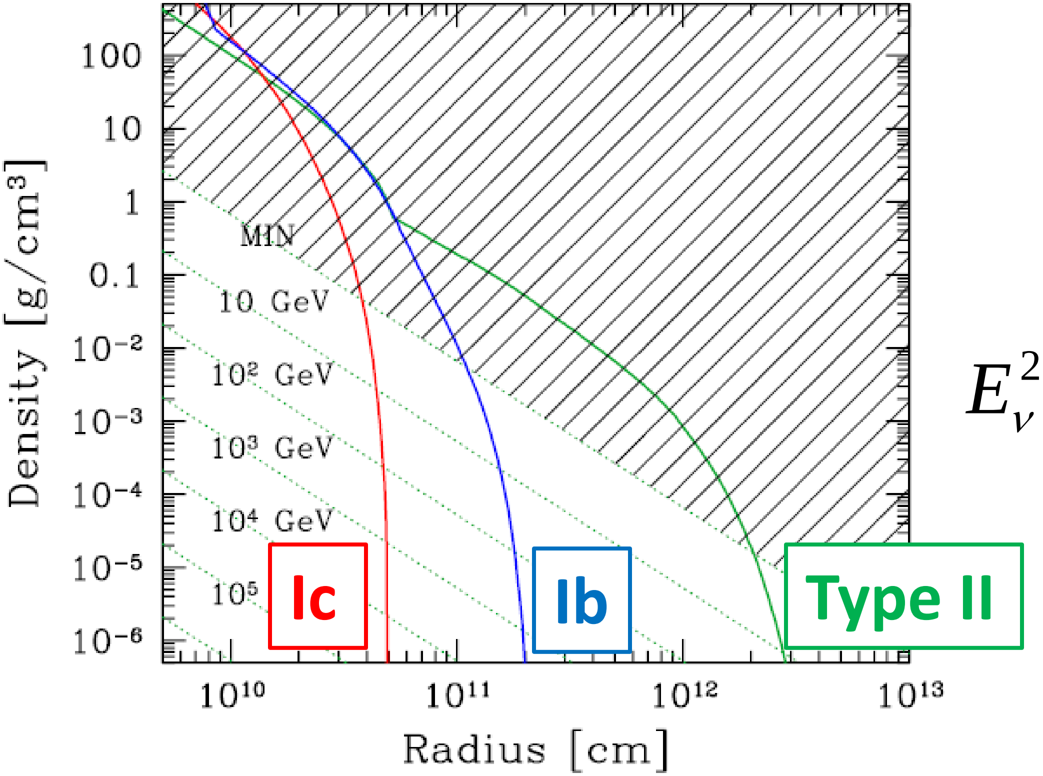
Detectable above background.

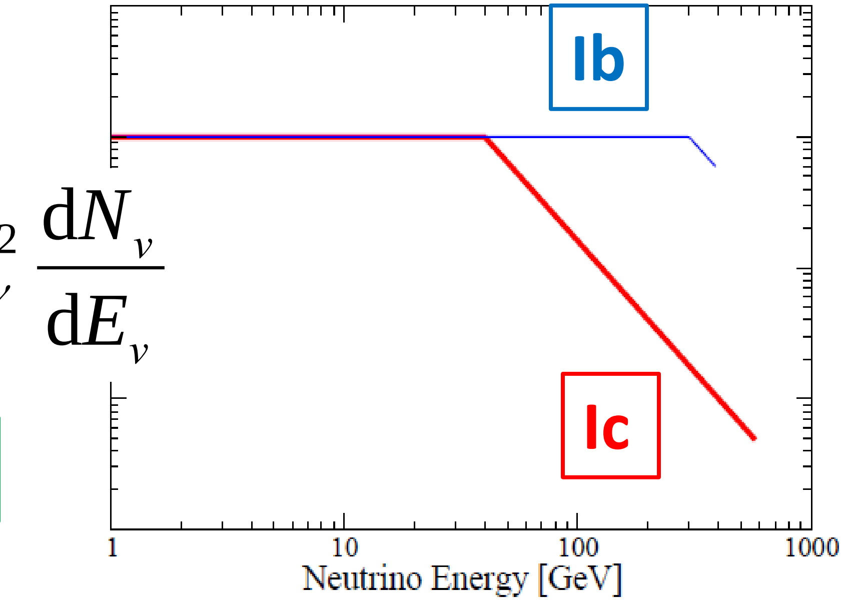
Discussion of event numbers

Source	@ Super-K	@ IceCube
Type II	130	200
Type Ib	160	6000
Type Ic	70	600

due to weak acceleration

due to energy loss of pions





Summary

- **Magnetic fields inside stars provides information for field origins [e.g., fossil scenario]**
- **Non-thermal neutrinos from supernovae of strongly magnetic stars:**
  - **Energy: ~ GeV**
  - **Time: ~ hours after thermal neutrinos**
- **Neutrinos observable above background from Galactic supernovae.**
- **Future work**
  - **Stellar magnetic field configuration**
  - **Acceleration efficiency with geometry**

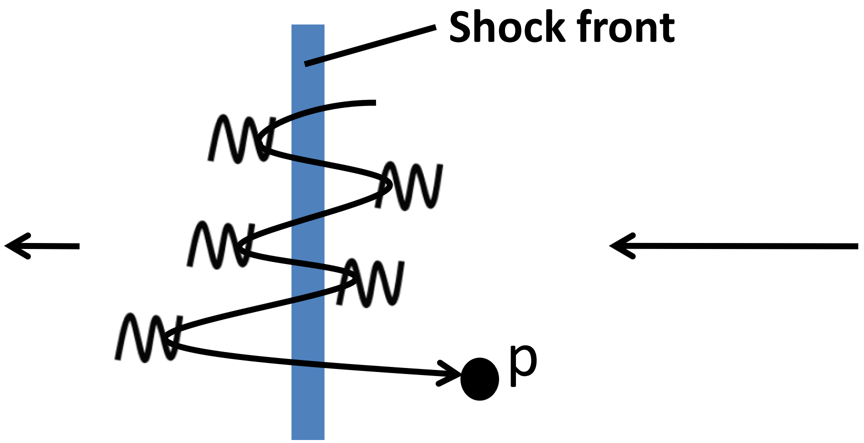
Future

- **Future work**
  - **Stellar magnetic field configuration**
  - **Acceleration efficiency with geometry**

Particle Acceleration

First order Fermi acceleration is a favourite. Shocks are efficient proton accelerators.

Drury, PhyRep (1983)
Blandford, Eichler ,PhyRep (1987)



Particles are deflected by plasma wave-particle interactions.
Does photons prohibit this?

Photon-electron collision frequency : $\nu_{e\gamma} = c\sigma_T n_e \approx 3\times10^8 s^{-1}$

Plasma frequency : $\nu_p = \sqrt{\frac{q^2 n_e}{m_e \varepsilon_0}} \approx 2\times10^{13} s^{-1}$

Gyrofrequency : $\nu_g = \frac{qB}{2\pi\varepsilon_p} \approx 5\times10^5 s^{-1}$

No.

Acceleration time

Solve the diffusion-convection equation

$$\underbrace{\boxed{\frac{\partial f}{\partial t}+U\frac{\partial f}{\partial x}}}_{\text{d/dt}}-\underbrace{\boxed{\frac{\partial}{\partial x}\kappa\frac{\partial f}{\partial x}}}_{\text{diffusion}}=\underbrace{\boxed{\frac{1}{3}\frac{\partial U}{\partial x}p\frac{\partial f}{\partial p}}}_{\text{convection}}$$

f: dist. func. for accelerated particles

Test-particle approx (reaction is ignored). The residence time *t* are

downstream | ***upstream***

$u_2 \leftarrow$ | $\leftarrow u_1$

$$t_2=\frac{4\kappa_2}{u_2 v}$$

$$t_1=\frac{\kappa_1 n}{u_1}\left(\frac{nv}{4}\right)^{-1}=\frac{4\kappa_1}{u_1 v}$$

In each cycle:

$$\Delta p=\frac{4\Delta U}{3v}p$$

Acceleration time

$$t_{acc}=\frac{p\Delta t}{\Delta p}=\frac{3}{\Delta U}\left(\frac{\kappa_1}{u_1}+\frac{\kappa_2}{u_2}\right)\sim\frac{3}{u_1}\frac{\kappa_1}{u_1}$$

(Limit of $u_1 >> u_2$ and dropping T_2)