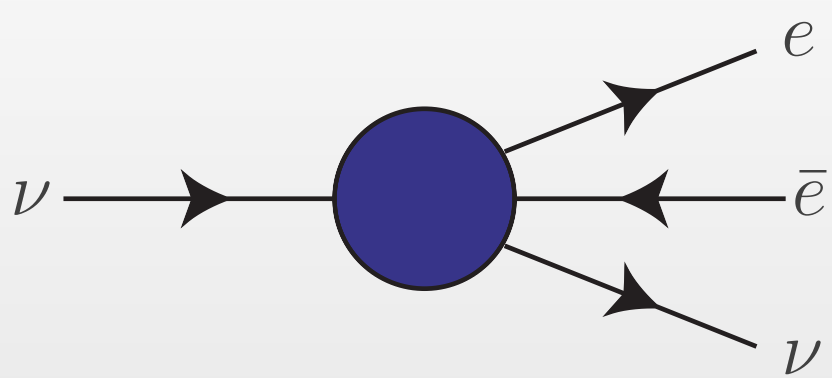
Mystery Title Here:

Pair production with neutrinos and intense magnetic fields

Todd M. Tinsley
Hendrix College

Duane A. Dicus — University of Texas @ Austin
Wayne W. Repko — Michigan State University

THE PROCESS: $\nu \longrightarrow \nu e \bar{e}$



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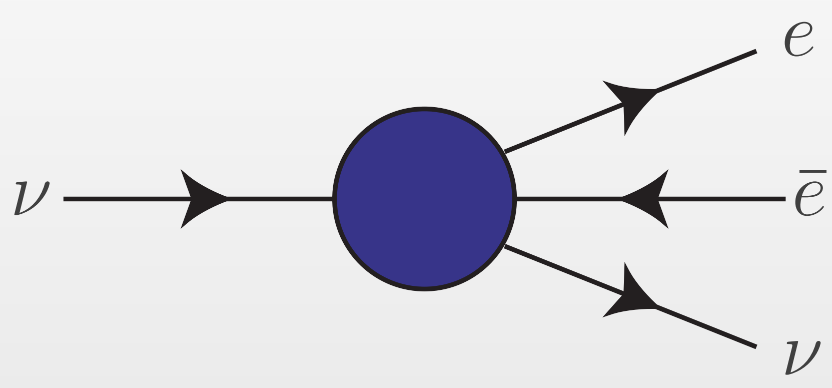
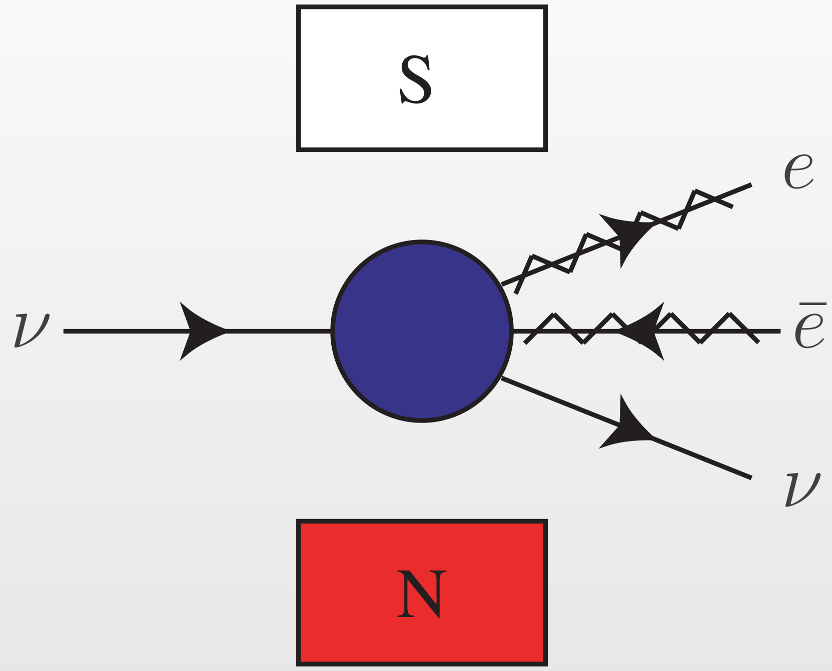


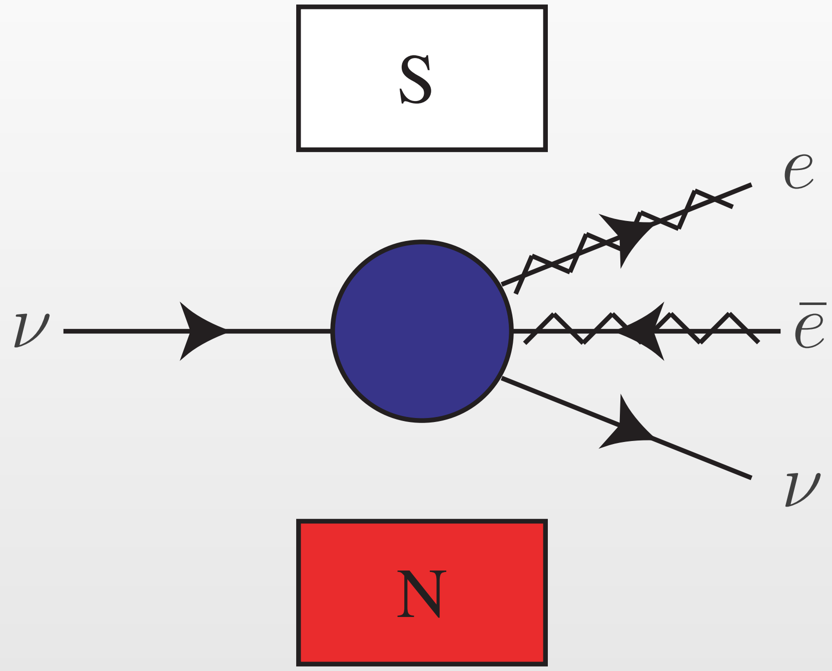
- This process is kinematically forbidden!

The Process: $\nu \longrightarrow \nu e \bar{e}$



- So we turn on a magnetic field.

The Process: $\nu \longrightarrow \nu e \bar{e}$



- So we turn on a magnetic field.
- This is not new:
  neutrino-electron scattering, neutrino-nucleus scattering, electron-positron pair annihilation, Urca processes ($pe \longrightarrow n\nu_e$, $n \longrightarrow pe\bar{\nu}_e$), neutrino absorption by nucleons, etc.

Terrestrial Detection?

What would you need?

Terrestrial Detection?

What would you need?

1. A neutrino source

Terrestrial Detection?

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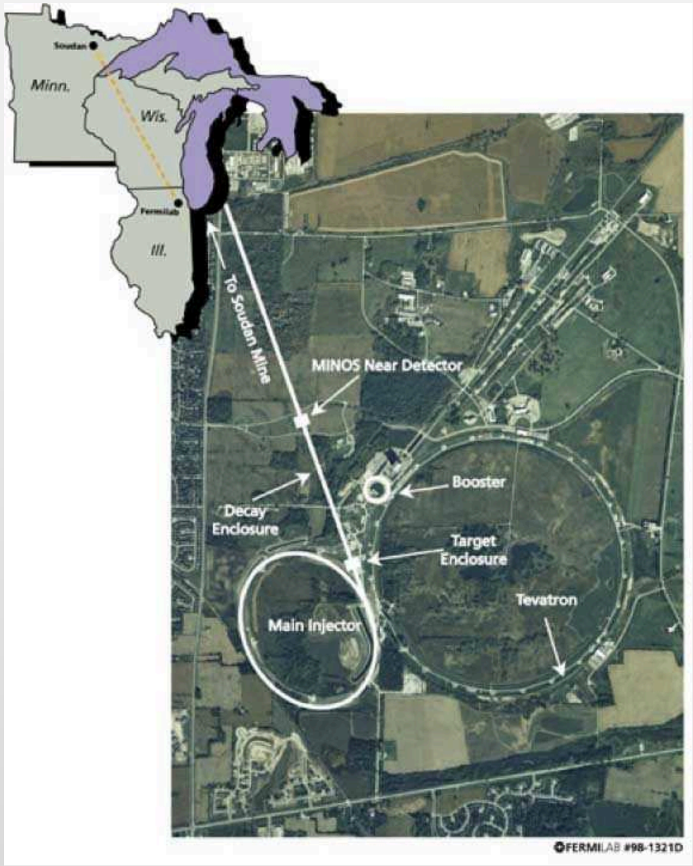


NuMI-MINOS

- Protons leave main injector
- Hit a target and produce mesons
- π^+ decay into μ and ν_μ
- $E_{\nu_\mu} \simeq 0 - 25$ GeV

Terrestrial Detection?

What would you need?

1. A neutrino source
2. Strong source of field

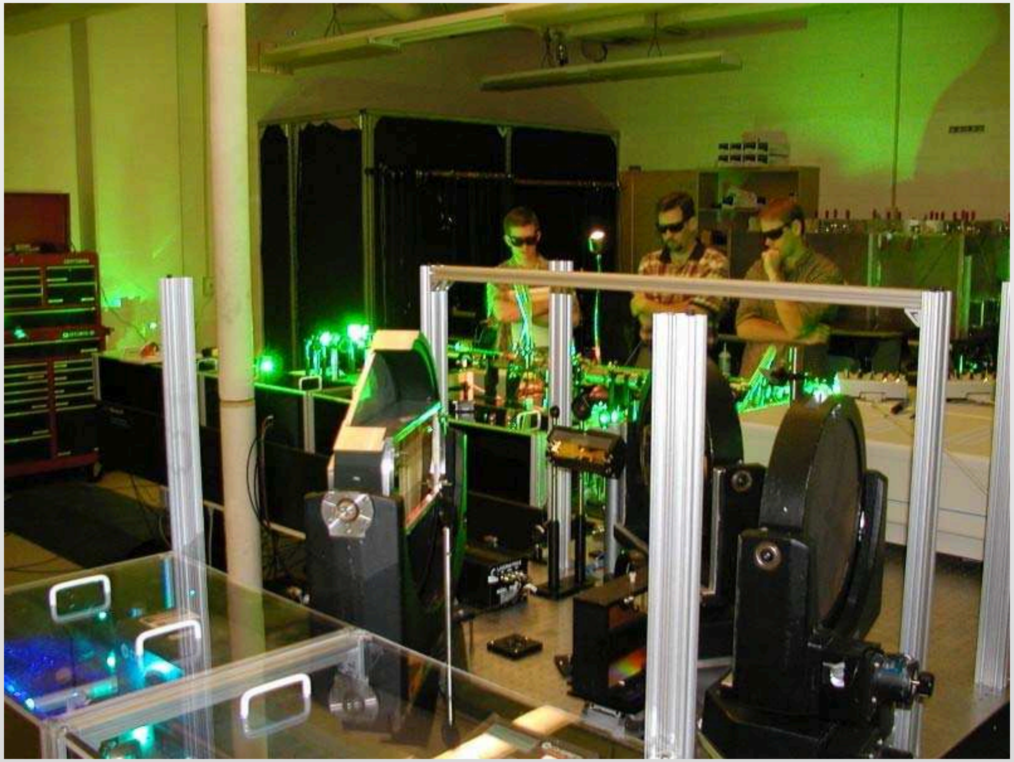
TERRESTRIAL DETECTION?

What would you need?

1. A neutrino source
2. Strong source of field

TW Lasers

- 20 TW Laser
- 35 fs, 0.7 J/pulse
- 10 Hz
- $E \approx 10^{11}$ V/cm
- $B \approx 10^{9}$ G



Results

What would you need?

1. A neutrino source
2. Strong source of field

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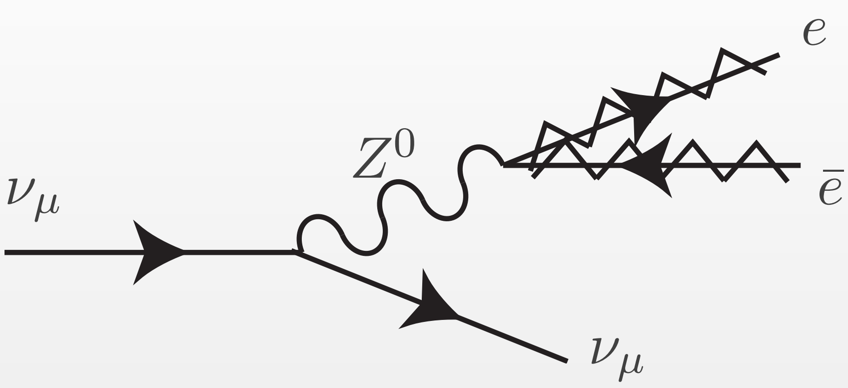
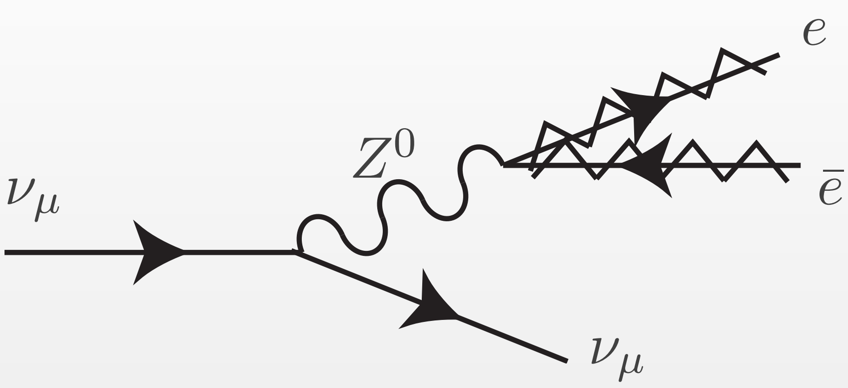
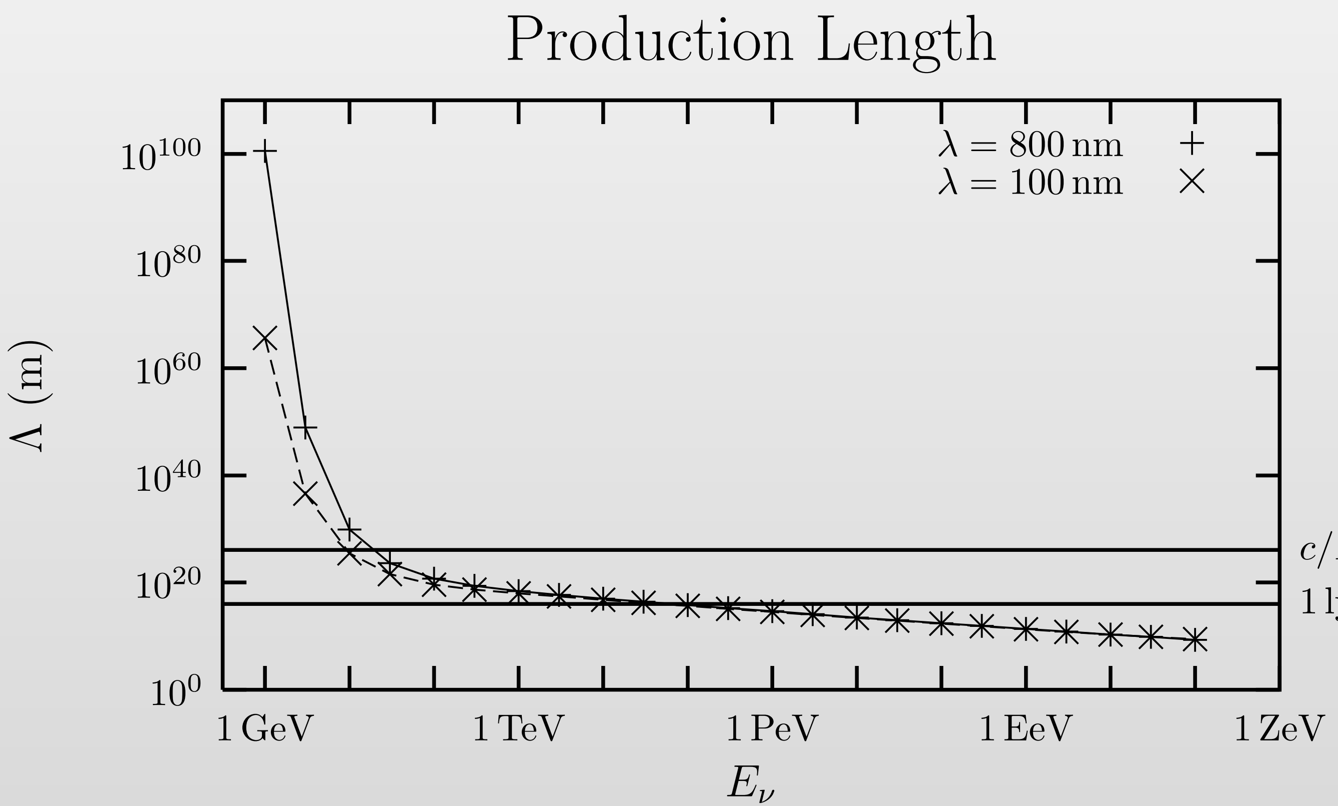


Results

What would you need?

1. A neutrino source
2. Strong source of field

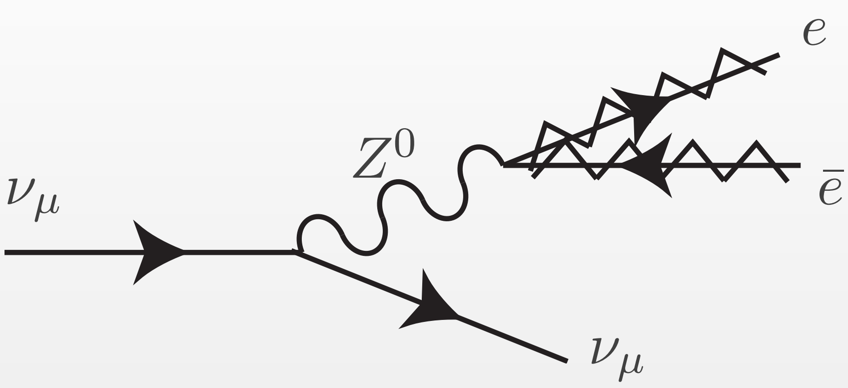


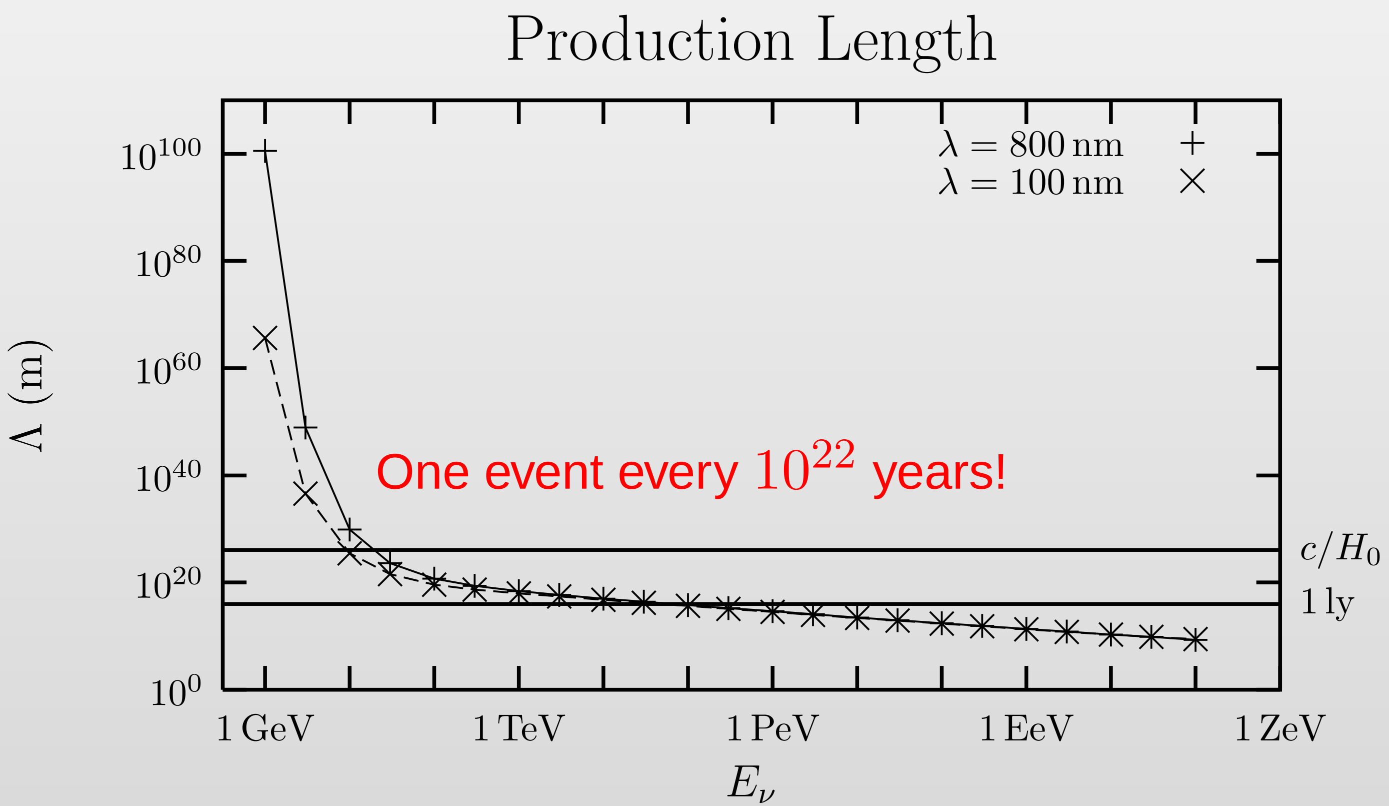


Results

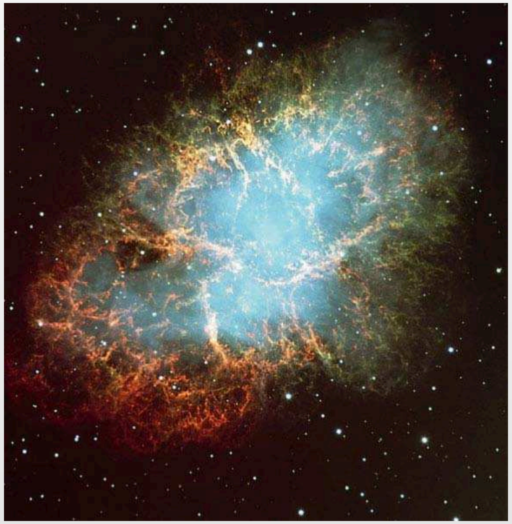
What would you need?

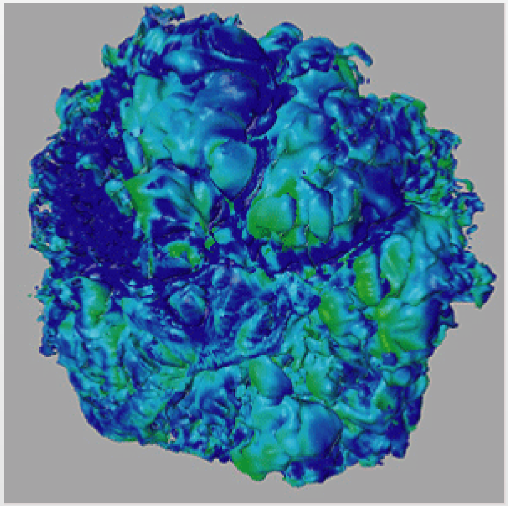
1. A neutrino source
2. Strong source of field
3. A dedicated student!

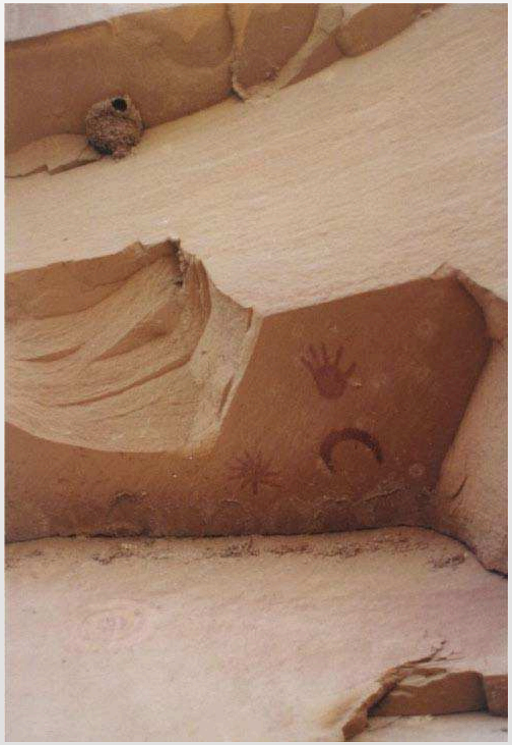




CORE-COLLAPSE SUPERNOVAE

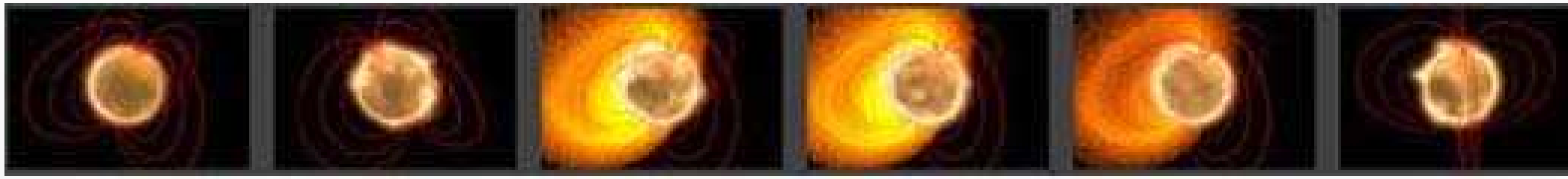






- A precise mechanism is unknown.
- Neutrinos are overwhelmingly favored for energy transfer
- Very large magnetic fields $B \approx 10^{12}$–10^{14} G.

Magnetars



The New York Times
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February 20, 2005

Dying Star Flares Up, Briefly Outshining Rest of Galaxy

By KENNETH CHANG

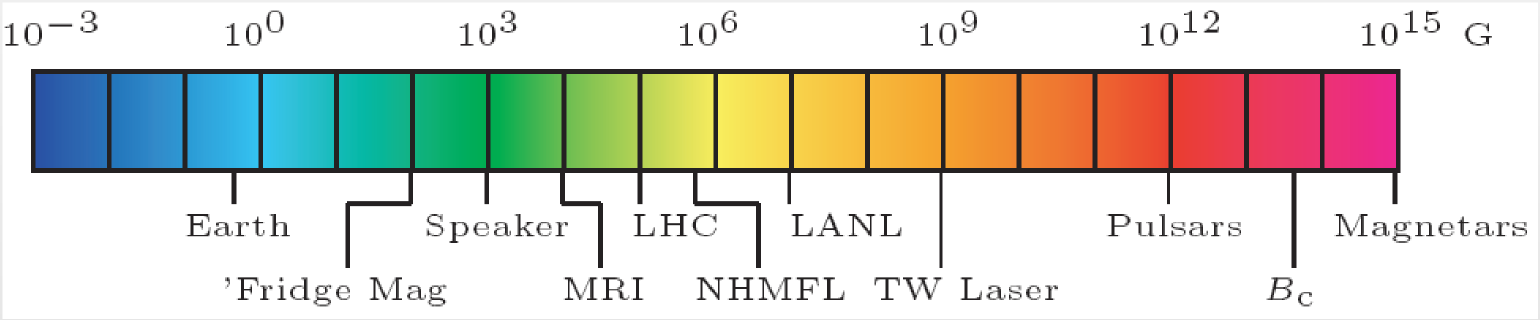
For a fraction of a second in December, a dying remnant of an exploded star let out of a burst of light that outshone the Milky Way's other half-trillion stars combined, astronomers announced Friday.

Even on Earth, half a galaxy away, the starburst was one of the brightest objects ever observed in the sky, after the Sun and perhaps a few comets. The magnitude of the event caught most astronomers by surprise.

"Whoppingly bright," said Dr. Bryan M. Gaensler, an astronomer at the Harvard-Smithsonian Center for Astrophysics in Cambridge, Mass. "It gave off more energy in 0.2 seconds than the Sun does in 100,000 to 200,000 years."

- Pair production as a mechanism for observed x-ray production
- $B \lesssim 10^{15}$ G.

Magnetic Field Scale



Solutions for homogeneous field

$$(\imath\not{\partial} + e\not{A}(x) - m_e)\,\psi_e(x) = 0 \qquad A(x) = (0, -yB, 0, 0)$$

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$$(\imath \not\partial + e \not{A}(x) - m_e)\, \psi_e(x) = 0 \qquad A(x) = (0, -yB, 0, 0)$$

$$\psi_e(x) = \sum_{n=0}^{\infty} \sum_{s=\pm} \int \frac{\mathrm{d}^2 \vec{p}_{\not y}}{(2\pi)^2} \sqrt{\frac{E_n + m_e}{2E_n}} u^s(\vec{p}_{\not y}, n, y)\, e^{-\imath p \cdot \not y}\, \hat{a}^s_{e\, \vec{p}_{\not y}, n} + \ldots$$

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Solutions for homogeneous field

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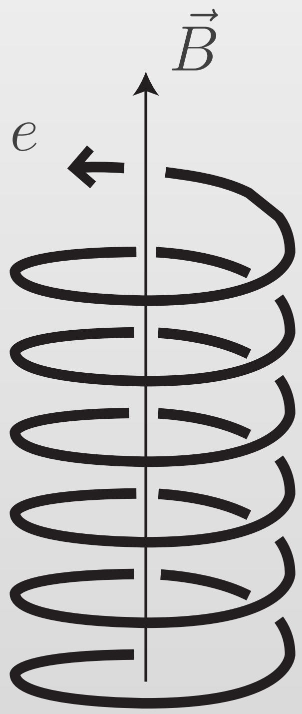
SOLUTIONS FOR HOMOGENEOUS FIELD

$$(\imath \not\partial + e \not A(x) - m_e)\, \psi_e(x) = 0 \qquad A(x) = (0, -yB, 0, 0)$$

$$\psi_e(x) = \sum_{n=0}^{\infty} \sum_{s=\pm} \int \frac{\mathrm{d}^2 \vec{p}_{\not y}}{(2\pi)^2} \sqrt{\frac{E_n + m_e}{2E_n}}\, u^s(\vec{p}_{\not y}, n, y)\, e^{-\imath p \cdot \not y}\, \hat{a}^s_{e\, \vec{p}_{\not y}, n} + \ldots$$

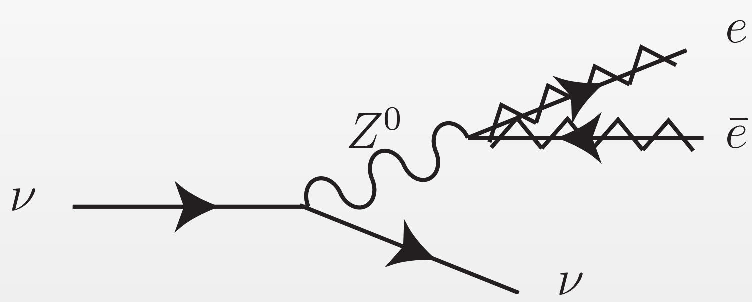
Landau Levels



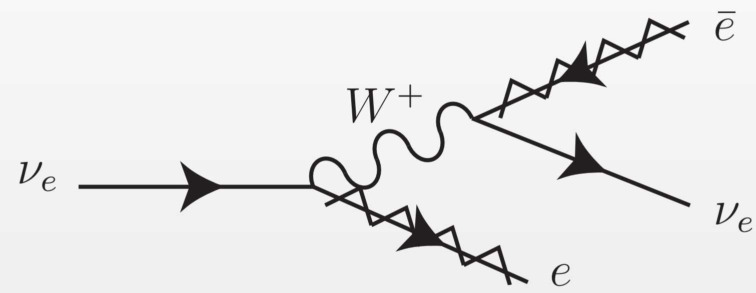
$$E_n = \sqrt{m_e^2 + p_z^2 + 2neB}$$

$$u^s(\vec{p}_{\not y}, n, y) \propto H_n(p_x, y)$$

Scattering Amplitude

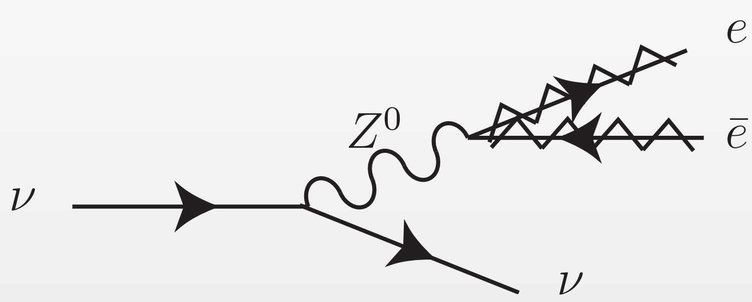


$$\mathcal{M}_{\nu_\mu} = \mathcal{M}_Z$$



$$\mathcal{M}_{\nu_e} = \mathcal{M}_Z + \mathcal{M}_W$$

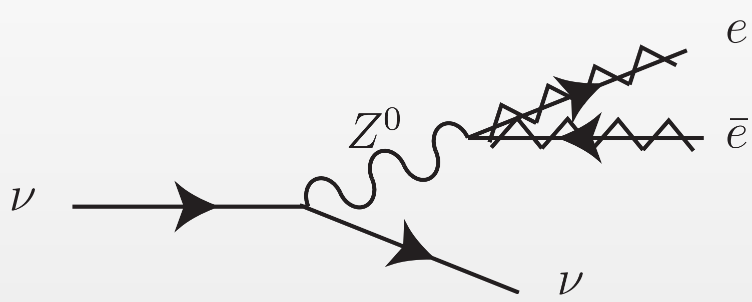
Scattering Amplitude

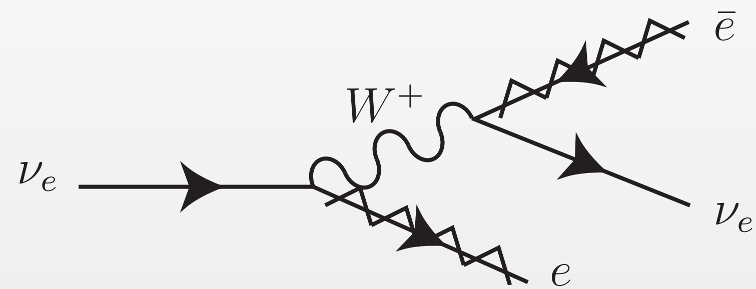


$$\mathcal{M}_{\nu_\mu} = \mathcal{M}_Z \qquad \mathcal{M}_{\nu_e} = \mathcal{M}_Z + \mathcal{M}_W$$

$$\mathcal{M}_{\binom{\nu_e}{\nu_\mu}} = \frac{-\imath G_F}{2^3\sqrt{2}} \sqrt{\frac{(E_{n_e}+m_e)(E_{n_{\bar{e}}}+m_e)}{EE'E_{n_e}E_{n_{\bar{e}}}}}\, \bar{u}^{s'}(p')\gamma_\mu\left(1-\gamma^5\right)u^s(p)$$
$$\times \int \mathrm{d}y\, e^{\imath(p_y-p'_y)y}\, \bar{u}^{s_1}\left(\vec{p}_{e\not{y}}, n_e, y\right)\gamma^\mu\left(G_V^{\binom{+}{-}} - \gamma^5\right) v^{s_2}\left(\vec{p}_{\bar{e}\not{y}}, n_{\bar{e}}, y\right)$$

Scattering Amplitude





$$\mathcal{M}_{\nu_\mu} = \mathcal{M}_Z \qquad \mathcal{M}_{\nu_e} = \mathcal{M}_Z + \mathcal{M}_W$$

$$\mathcal{M}_{\binom{\nu_e}{\nu_\mu}} = \frac{-\imath G_F}{2^3\sqrt{2}} \sqrt{\frac{(E_{n_e}+m_e)(E_{n_{\bar{e}}}+m_e)}{E E' E_{n_e} E_{n_{\bar{e}}}}}\; \bar{u}^{s'}(p')\gamma_\mu \left(1-\gamma^5\right) u^s(p)$$
$$\times \int \mathrm{d}y\, e^{\imath(p_y - p'_y)y}\, \bar{u}^{s_1}\left(\vec{p}_{e\not{y}}, n_e, y\right)\gamma^\mu \left(G_V^{\binom{+}{-}} - \gamma^5\right) v^{s_2}\left(\vec{p}_{\bar{e}\not{y}}, n_{\bar{e}}, y\right)$$

$$G_V^{\pm} = 1 \pm 4\sin^2\theta_W$$

The rate of pair production

$$\Gamma = \sum_{n_e, n_{\bar{e}}=0}^{\infty} \int \mathrm{d}\Phi \, \delta^3_{\not{y}} \left(p - p' - p_e - p_{\bar{e}} \right) \overline{|\mathcal{M}|^2}$$

THE RATE OF PAIR PRODUCTION

$$\Gamma = \sum_{n_e, n_{\bar{e}}=0}^{\infty} \int d\Phi \, \delta^3_{\not{y}} \left(p - p' - p_e - p_{\bar{e}}\right) \overline{|\mathcal{M}|^2}$$

- Sums over Landau levels are constrained by energy conservation.
- As initial energy is increased the number of states contributing increases very rapidly.

THE RATE OF PAIR PRODUCTION

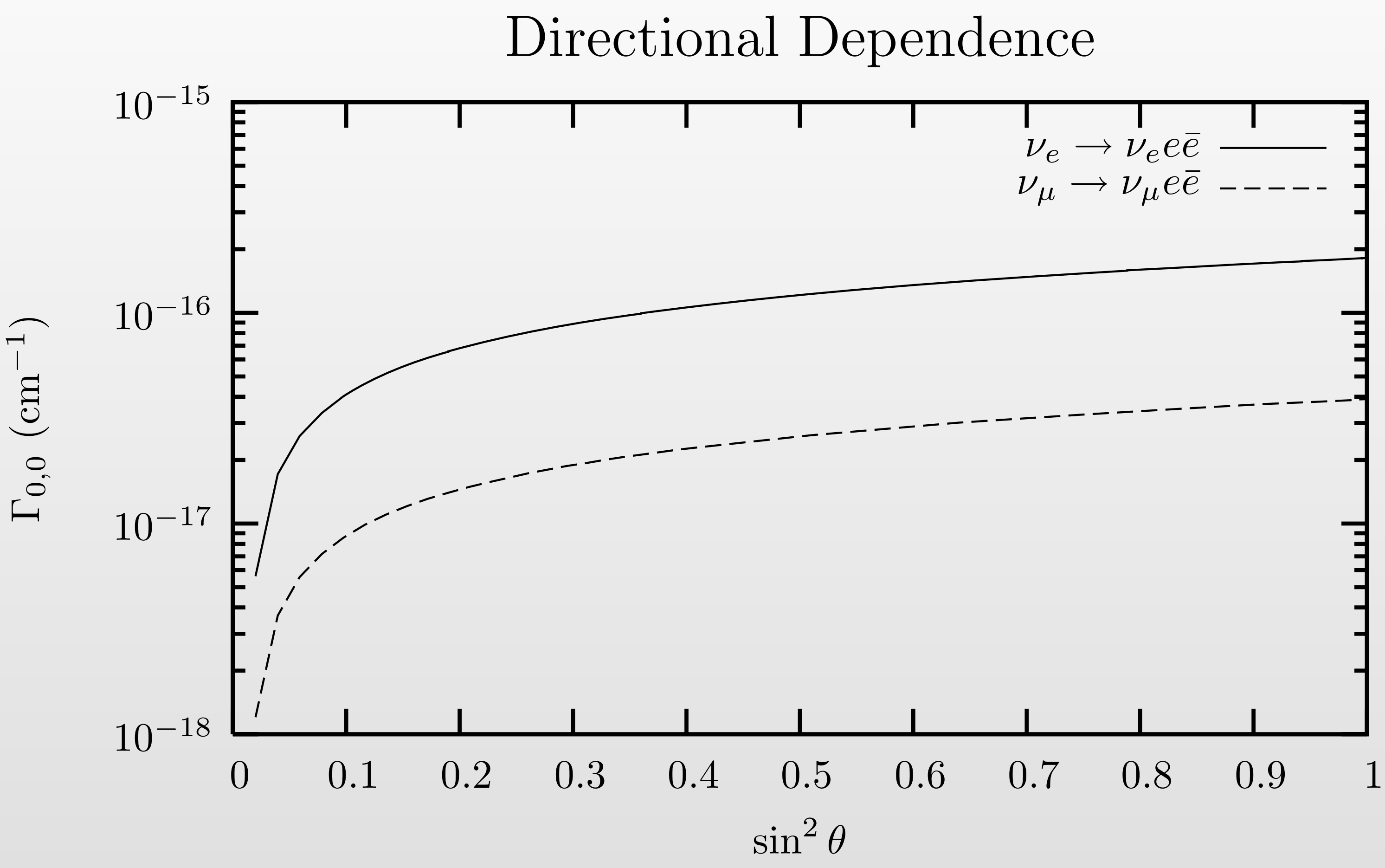
$$\Gamma = \sum_{n_e, n_{\bar{e}}=0}^{\infty} \int \mathrm{d}\Phi \, \delta^3_{\not{y}} \left(p - p' - p_e - p_{\bar{e}}\right) \overline{|\mathcal{M}|^2}$$

The rate of pair production

$$\Gamma = \sum_{n_e, n_{\bar{e}}=0}^{\infty} \int \mathrm{d}\Phi \, \delta^3_{\not{y}} \left(p - p' - p_e - p_{\bar{e}}\right) \overline{|\mathcal{M}|^2}$$

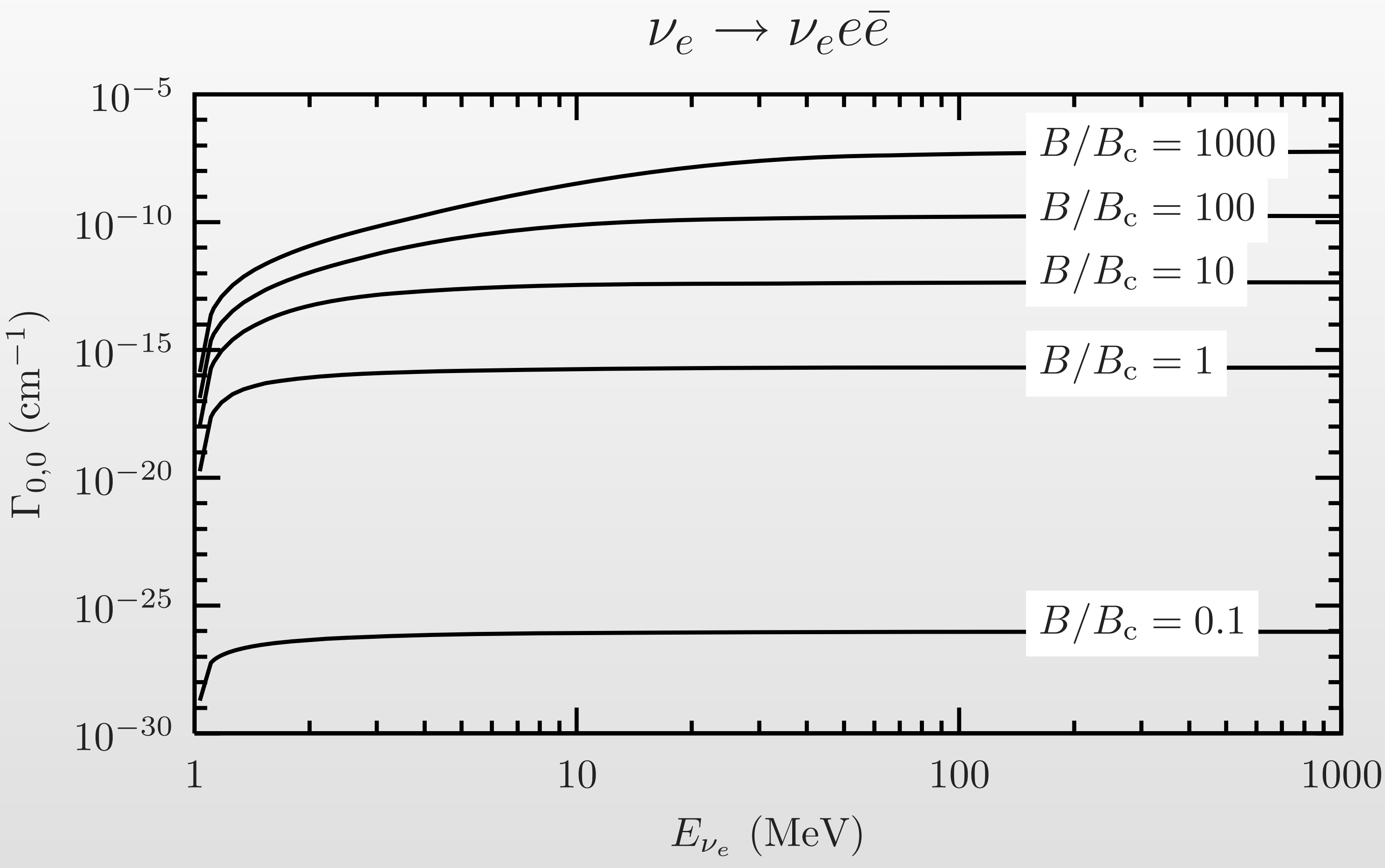
- Spin sums produce a result dependent on 16 different combinations of the Landau levels
- Integration over products of Hermite functions produces combinations of associated Laguerre polynomials that depend on the Landau levels

Angular dependance



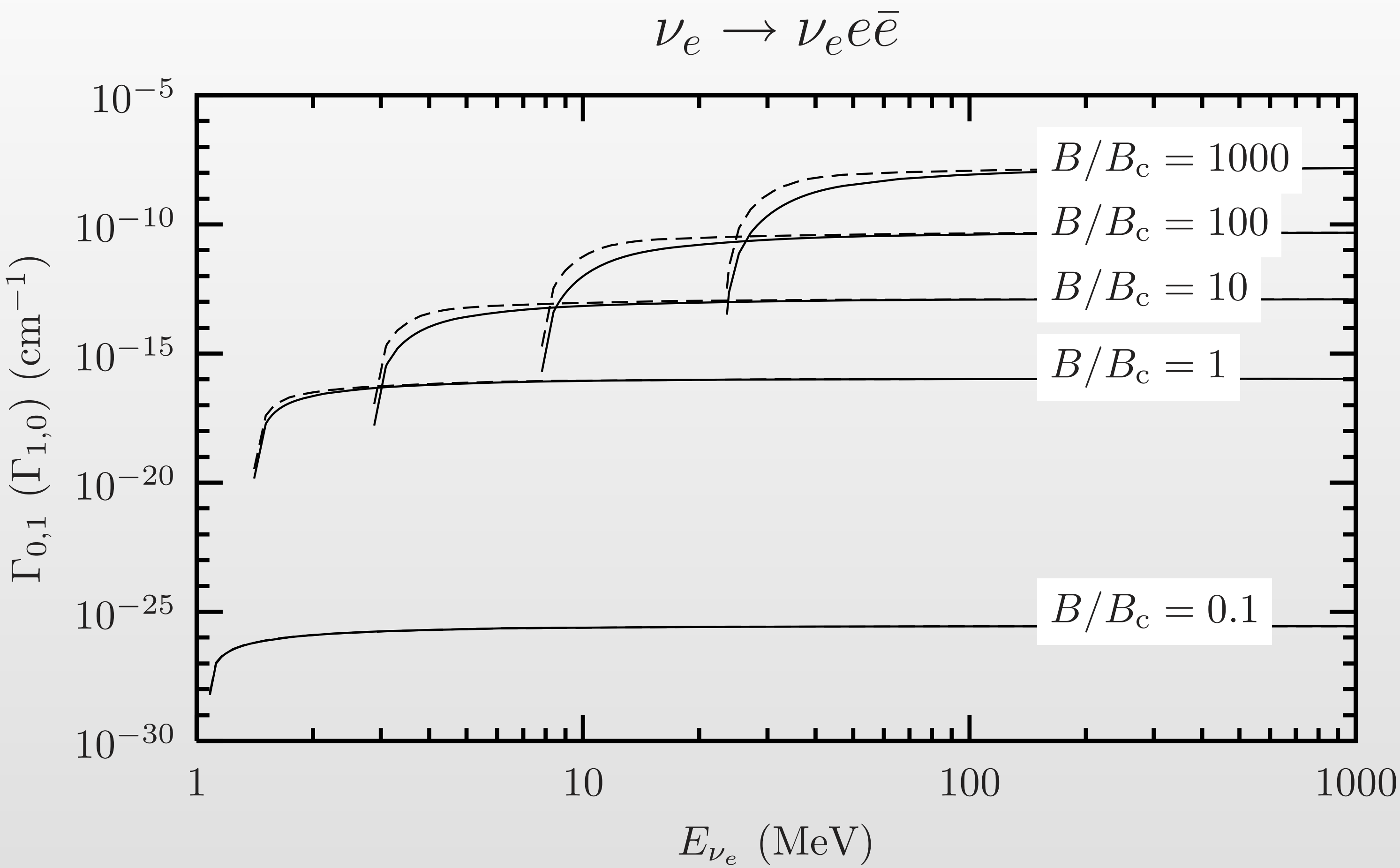
$$E_\nu = 20m_e, \quad B = B_c$$

$\nu_e \ \Gamma_{0,0}$



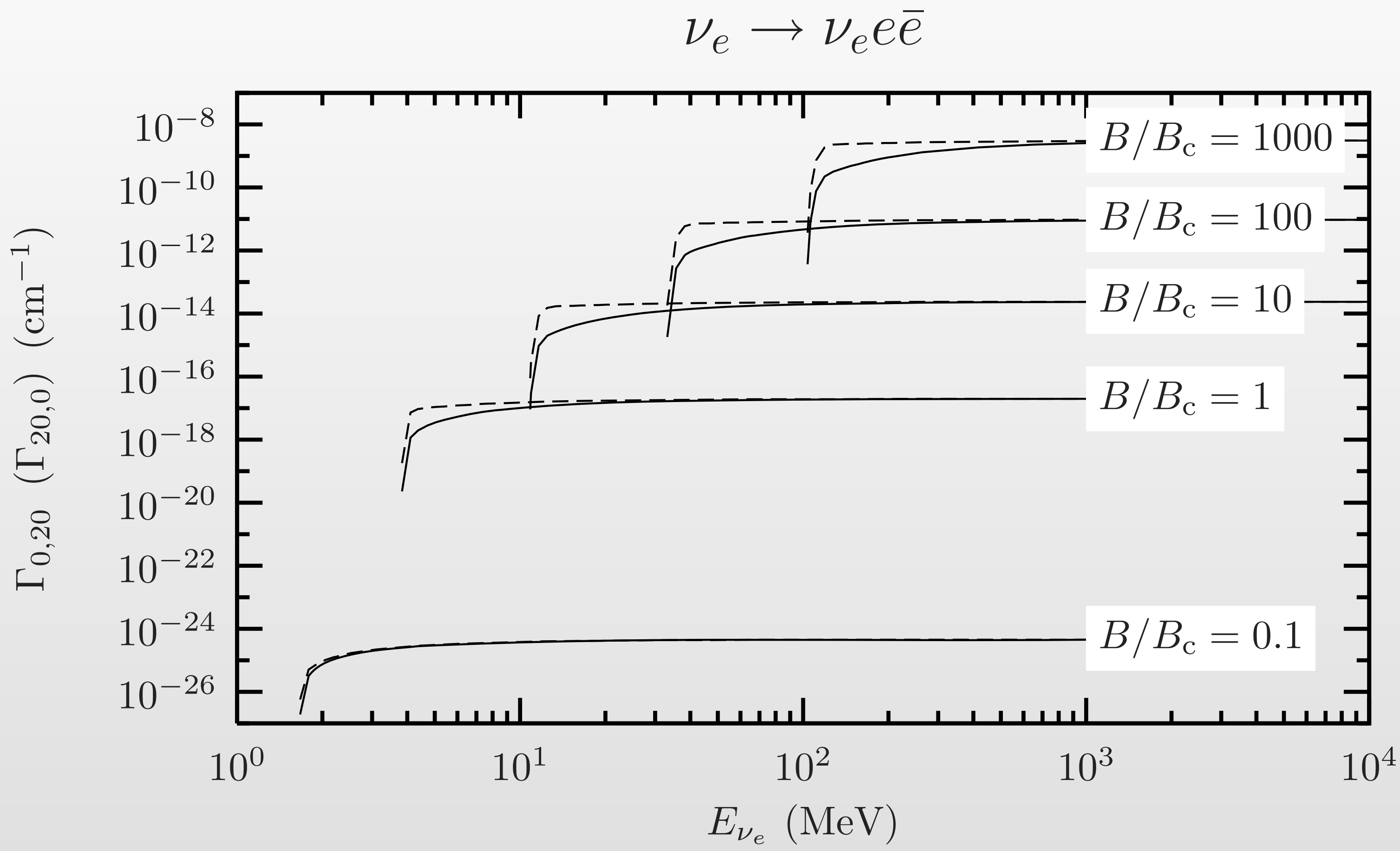
$\nu_e \longrightarrow \nu_e e \bar{e}$
10^{-5}
10^{-10}
10^{-15}
10^{-20}
10^{-25}
10^{-30}
$\Gamma_{0,0}$ (cm^{-1})
$B/B_c = 1000$
$B/B_c = 100$
$B/B_c = 10$
$B/B_c = 1$
$B/B_c = 0.1$
1
10
100
1000
E_{ν_e} (MeV)

$\nu_e\ \Gamma_{0,1}$

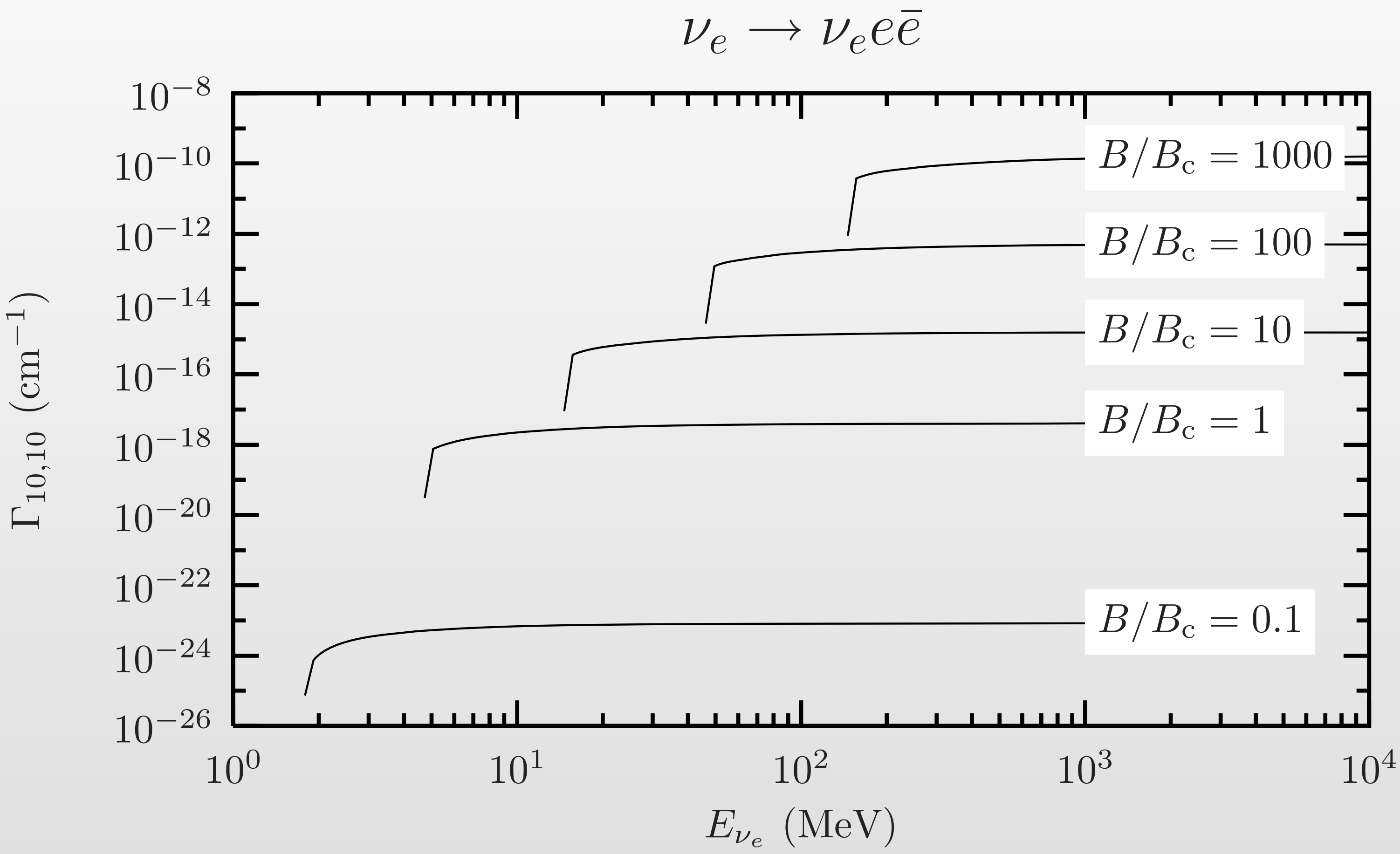


$\nu_e \longrightarrow \nu_e e\bar{e}$
$\Gamma_{0,1}\ (\Gamma_{1,0})\ (\mathrm{cm}^{-1})$
E_{ν_e} (MeV)
$B/B_c = 1000$
$B/B_c = 100$
$B/B_c = 10$
$B/B_c = 1$
$B/B_c = 0.1$
10^{-5}
10^{-10}
10^{-15}
10^{-20}
10^{-25}
10^{-30}
1
10
100
1000

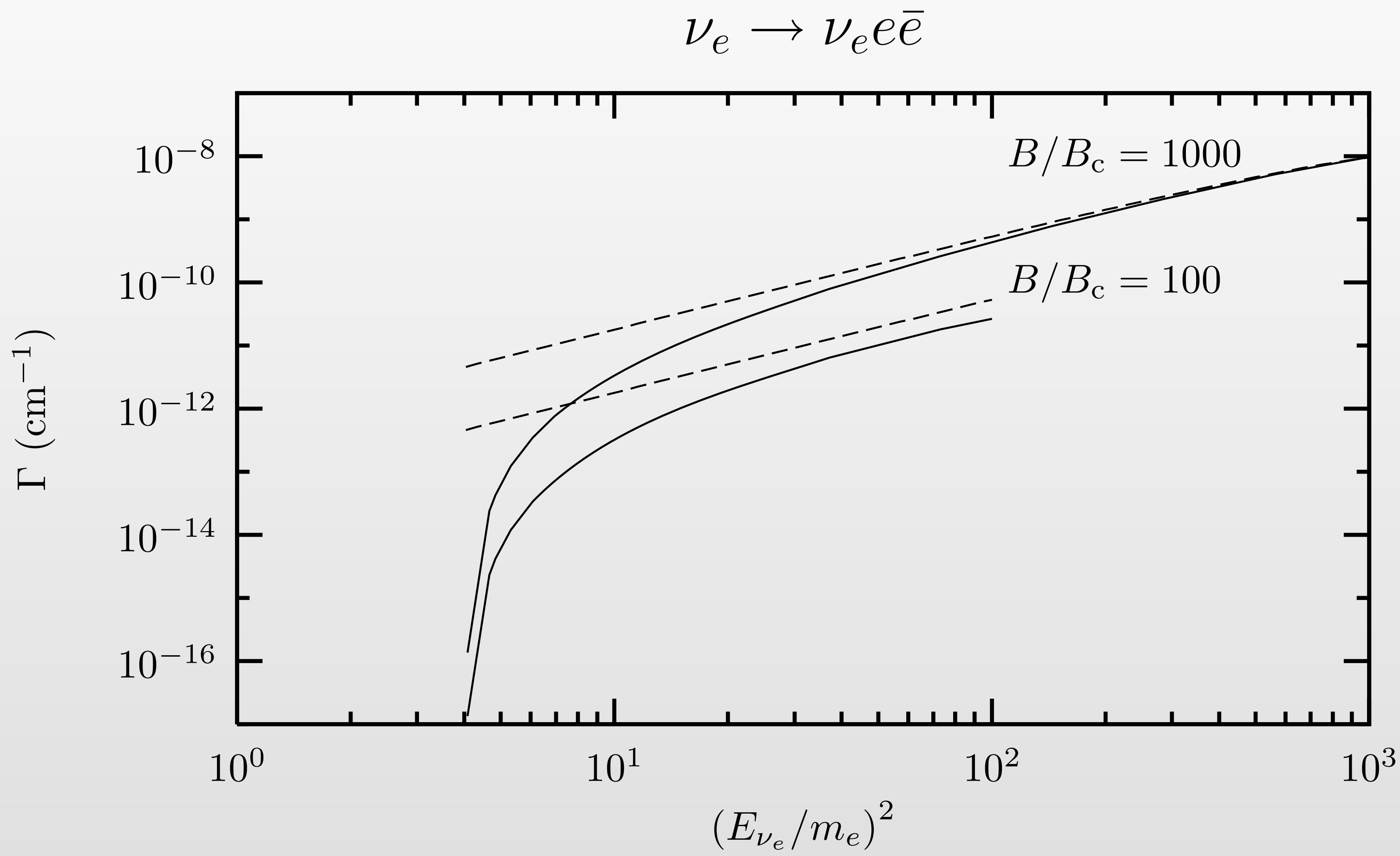
$\nu_e\ \Gamma_{0,20}$



$\nu_e\ \Gamma_{10,10}$

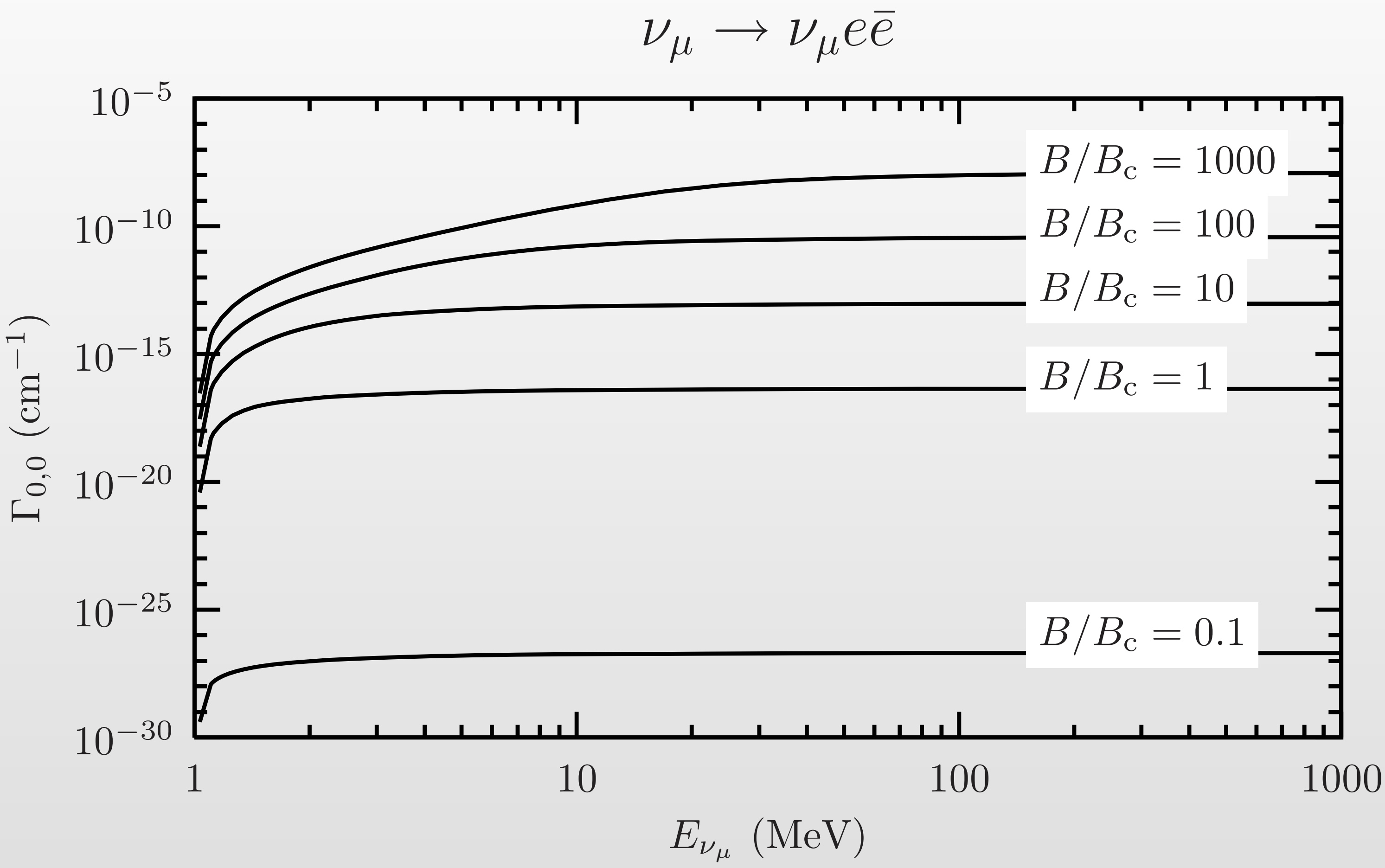


$\nu_e \approx$

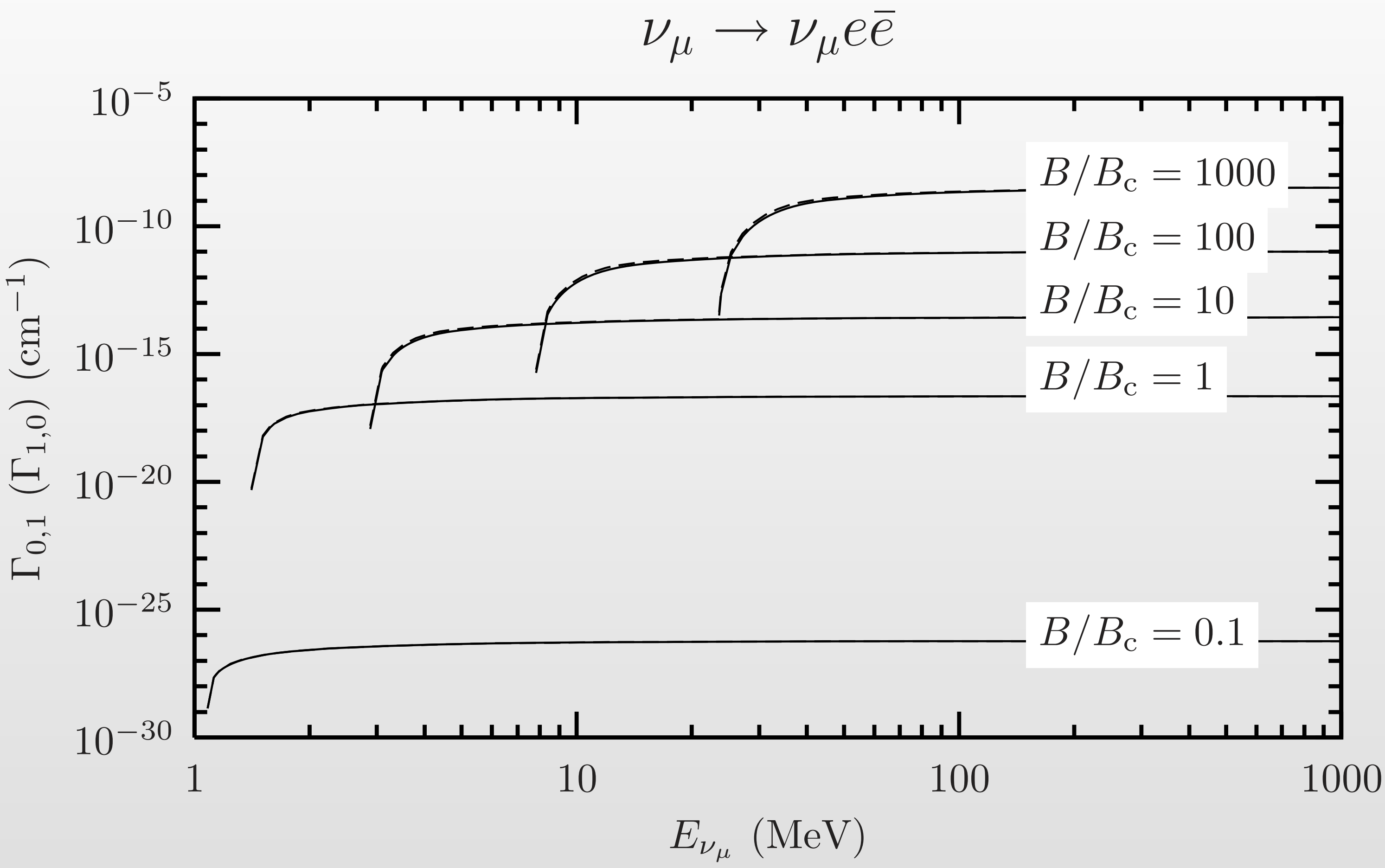


$\nu_e \to \nu_e e \bar{e}$
$B/B_c = 1000$
$B/B_c = 100$
Γ (cm^{-1})
10^{-8}
10^{-10}
10^{-12}
10^{-14}
10^{-16}
10^0
10^1
10^2
10^3
$(E_{\nu_e}/m_e)^2$

$\nu_\mu\ \Gamma_{0,0}$

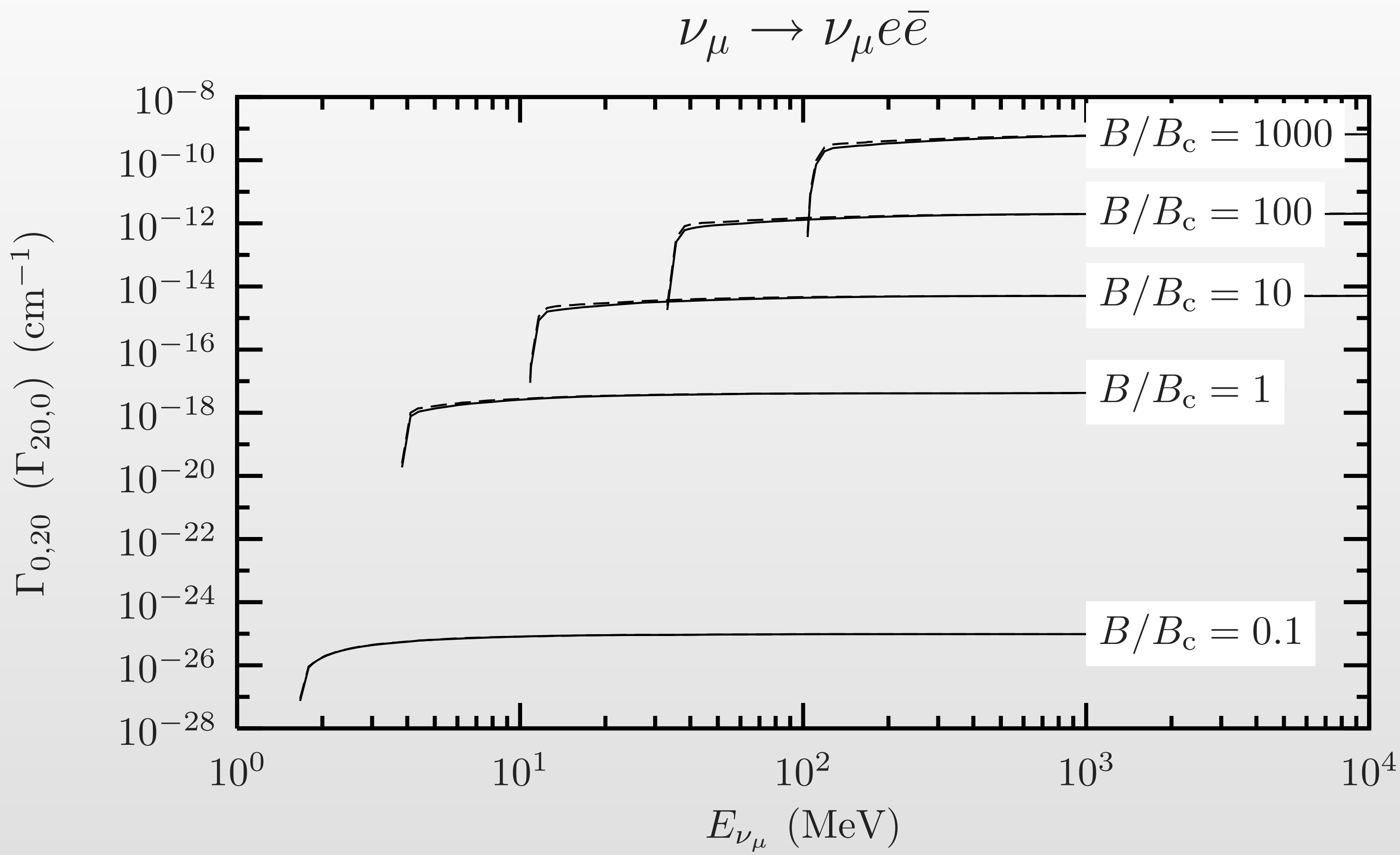


$\nu_e\ \Gamma_{0,1}$

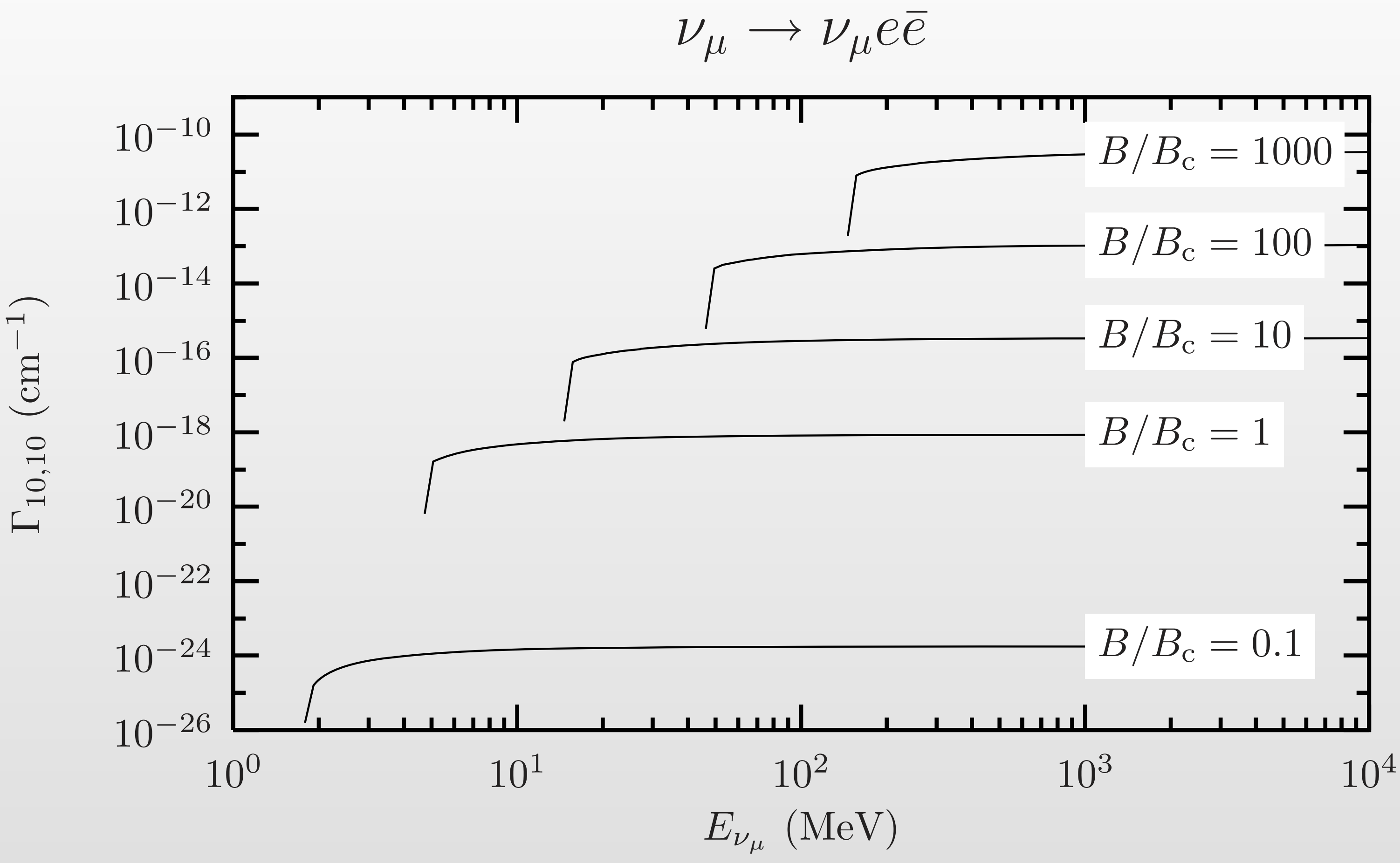


$\nu_\mu \to \nu_\mu e\bar{e}$
$\Gamma_{0,1}\ (\Gamma_{1,0})\ (\mathrm{cm}^{-1})$
10^{-5}
10^{-10}
10^{-15}
10^{-20}
10^{-25}
10^{-30}
1
10
100
1000
E_{ν_μ} (MeV)
$B/B_c = 1000$
$B/B_c = 100$
$B/B_c = 10$
$B/B_c = 1$
$B/B_c = 0.1$

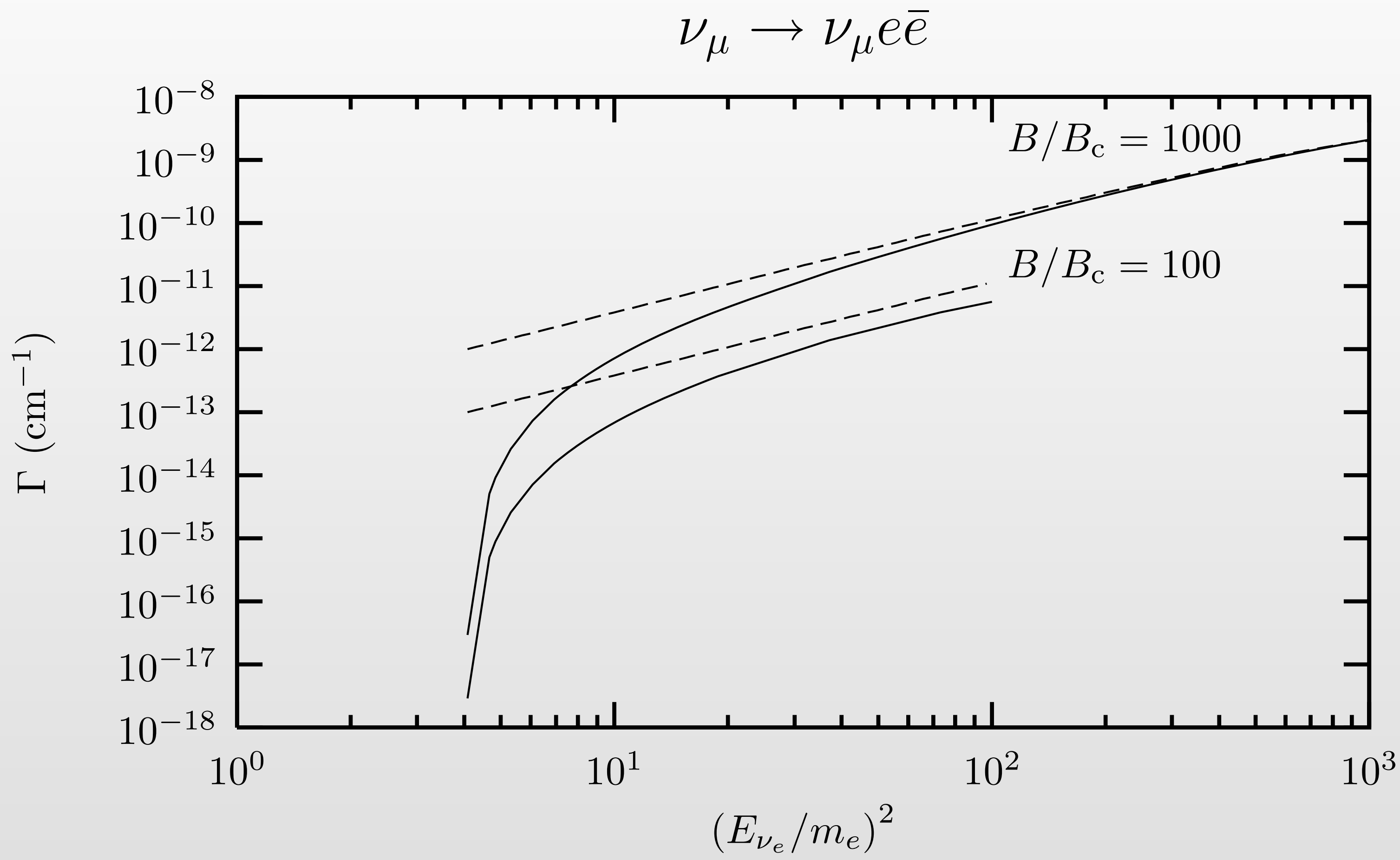
$\nu_e \; \Gamma_{0,20}$



$\nu_e\ \Gamma_{10,10}$



$\nu_e \approx$



$\nu_\mu \to \nu_\mu e\bar{e}$
$B/B_c = 1000$
$B/B_c = 100$
$\Gamma\ (\mathrm{cm}^{-1})$
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^0
10^1
10^2
10^3
$(E_{\nu_e}/m_e)^2$

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- National Science Foundation under Grants No. PHY-0244789 and No. PHY-0555544

More information:

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