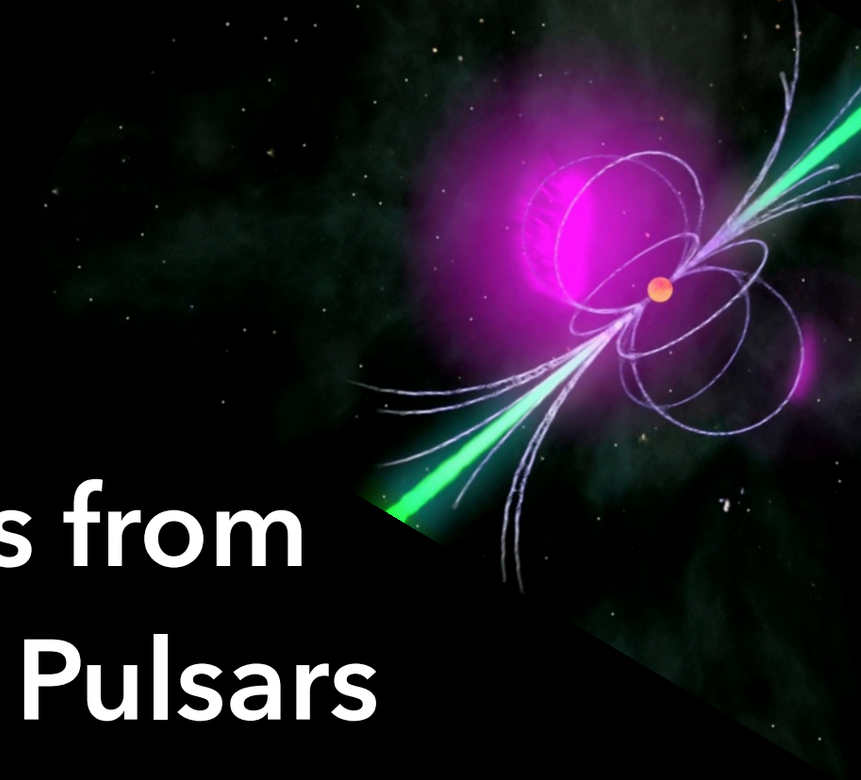


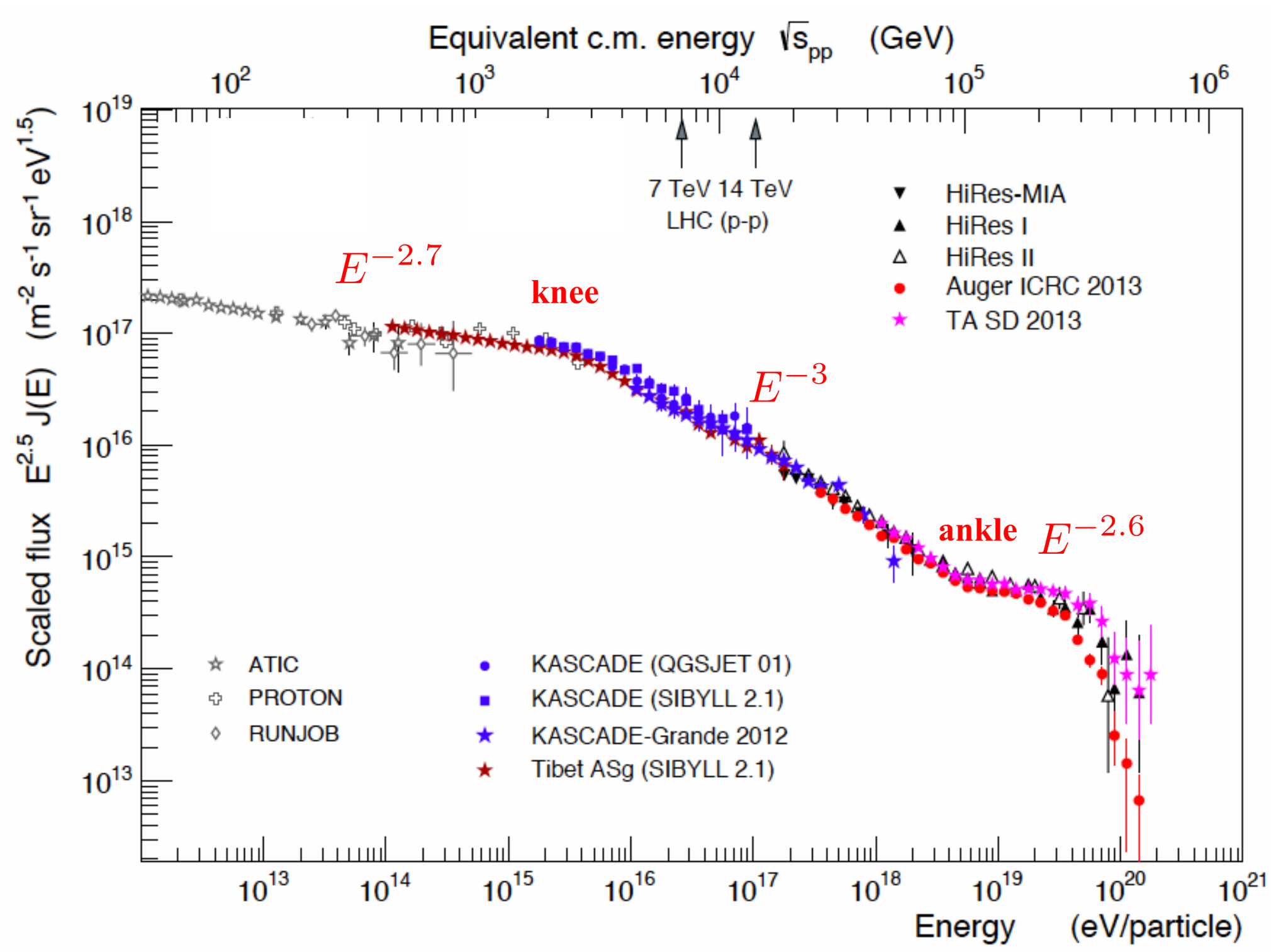
High-Energy Neutrinos from Fast-spinning Newborn Pulsars

Ke Fang

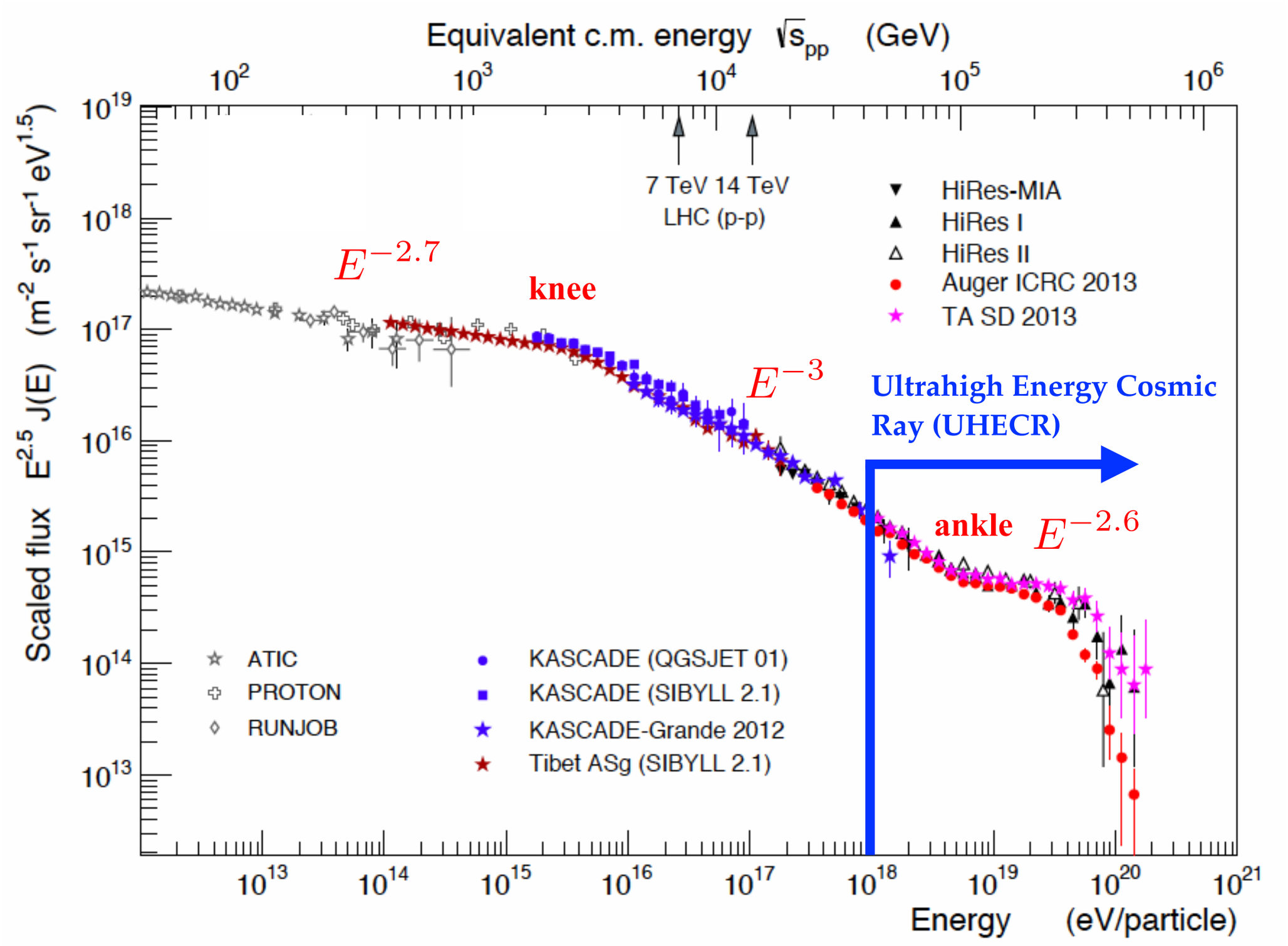
JSI Fellow @ University of Maryland & NASA GSFC

Oct 29, 2015

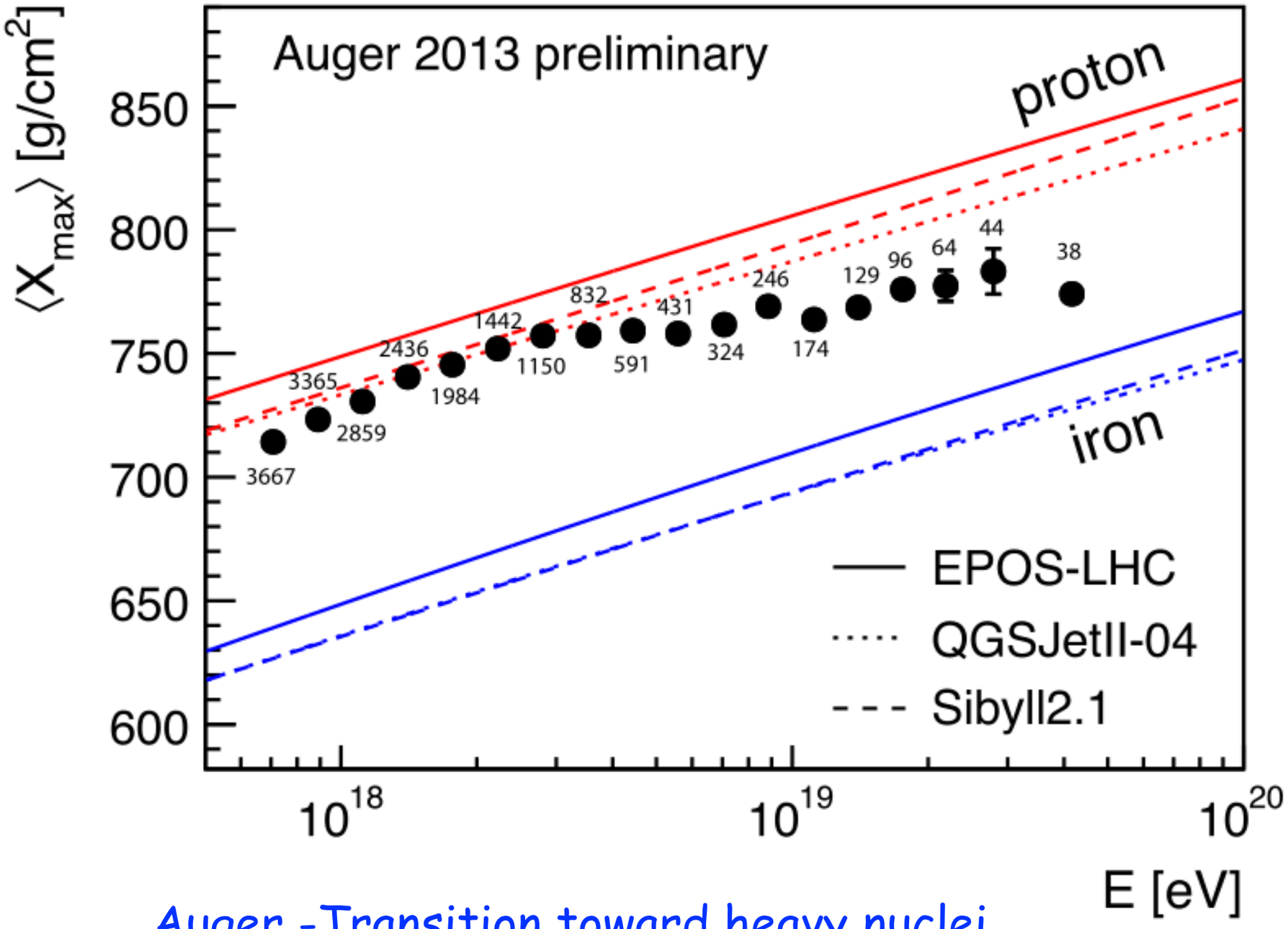
Unknown Origin of UHECRs



Unknown Origin of UHECRs



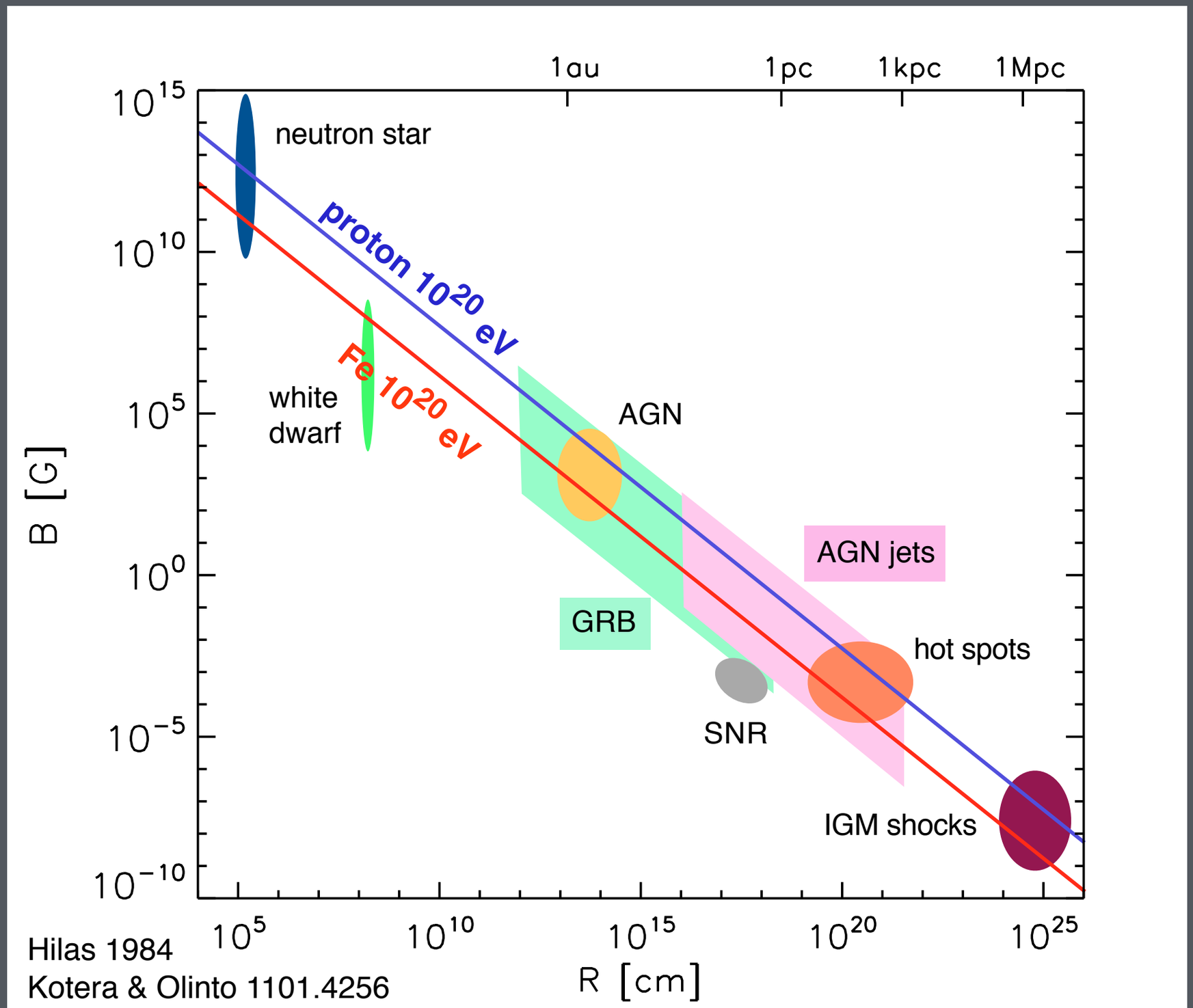
Hint of Heavy Composition



Auger -Transition toward heavy nuclei

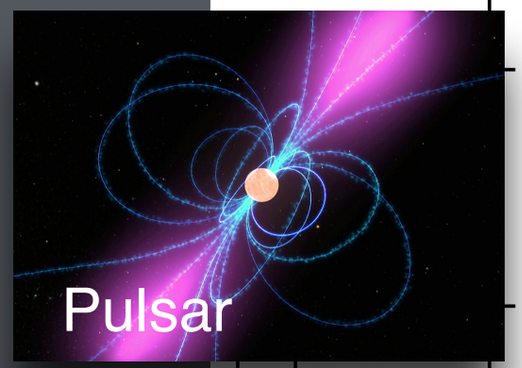
TA - Protons; data consistent within error bars

Pulsars as Sources of UHECRs



Hilas 1984
Kotera & Olinto 1101.4256

Pulsars as Sources of UHECRs



Hilas 1984
Kotera & Olinto 1101.4256

Pulsars: Cosmic Ray Acceleration

Particle injection rate $\propto \frac{\sqrt{\dot{E}_{\rm rot} c}}{e}$

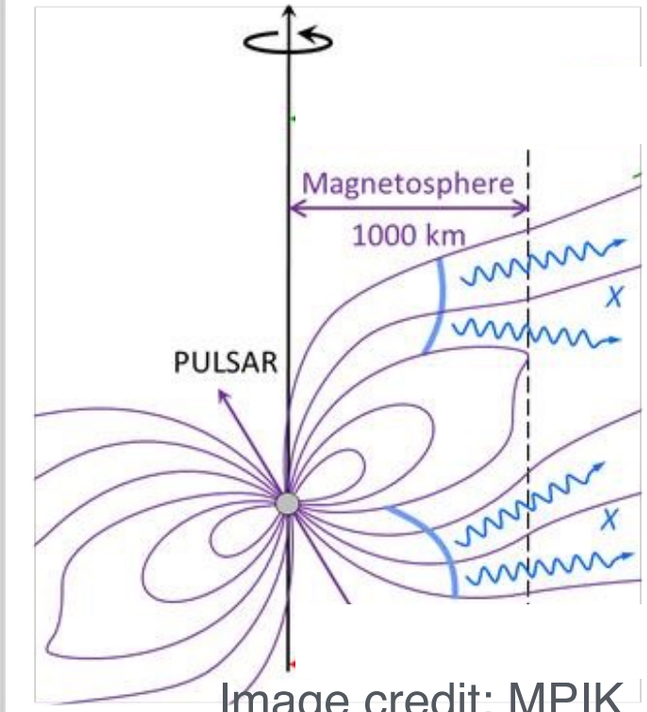


Image credit: MPIK

Blasi, Epstein & Olinto ApJ 533 (2000)
Arons, ApJ 589 (2003)
Lemoine, Kotera & Petri 1409.0159

Pulsars: Cosmic Ray Acceleration

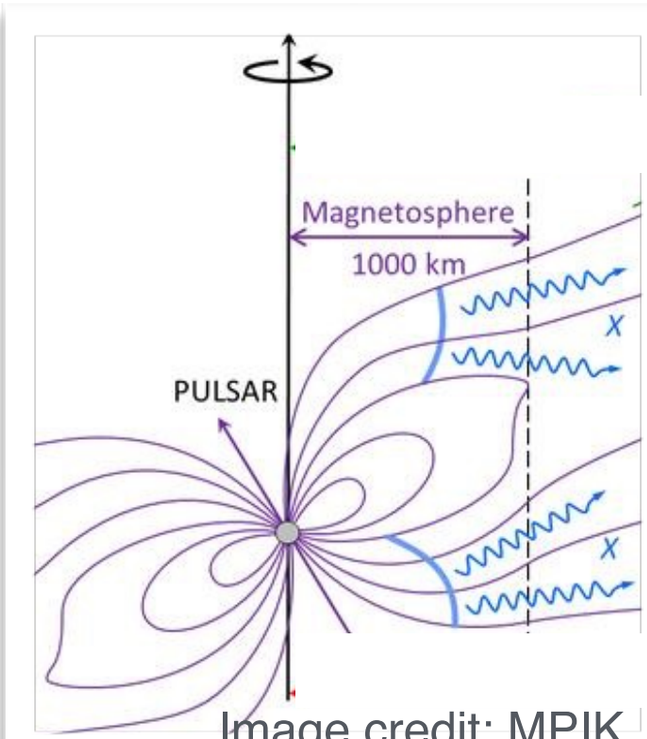


Image credit: MPIK

Particle injection rate $\propto \frac{\sqrt{\dot{E}_{\rm rot} c}}{e}$

$$E_{\rm CR} = 10^{18}\, A \left(\frac{B}{10^{13}\,{\rm G}}\right) \left(\frac{P_i}{1\,{\rm ms}}\right)^{-2} \left(\frac{\eta}{0.3}\right) \left(\frac{\kappa}{10^4}\right)^{-1} \left(1+\frac{t}{\tau_{\rm sd}}\right)^{-1} {\rm eV}$$

Blasi, Epstein & Olinto ApJ 533 (2000)
Arons, ApJ 589 (2003)
Lemoine, Kotera & Petri 1409.0159

Pulsars: Cosmic Ray Acceleration

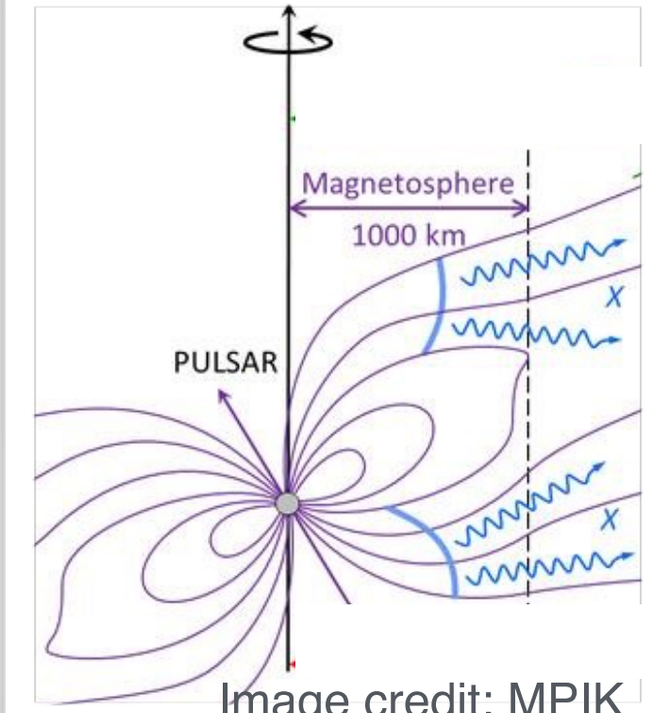


Image credit: MPIK

Particle injection rate $\propto \frac{\sqrt{\dot{E}_{\rm rot} c}}{e}$

Magnetic Field

$$E_{\rm CR} = 10^{18}\, A \left(\frac{B}{10^{13}\,{\rm G}}\right) \left(\frac{P_i}{1\,{\rm ms}}\right)^{-2} \left(\frac{\eta}{0.3}\right) \left(\frac{\kappa}{10^4}\right)^{-1} \left(1+\frac{t}{\tau_{\rm sd}}\right)^{-1} {\rm eV}$$

Blasi, Epstein & Olinto ApJ 533 (2000)
Arons, ApJ 589 (2003)
Lemoine, Kotera & Petri 1409.0159

Pulsars: Cosmic Ray Acceleration

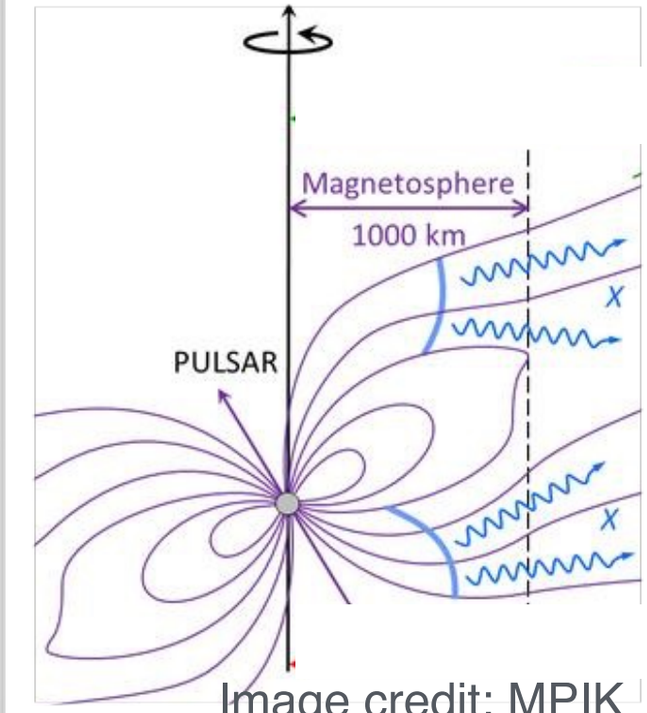


Image credit: MPIK

Particle injection rate $\propto \dfrac{\sqrt{\dot{E}_{\rm rot} c}}{e}$

initial spin period

Magnetic Field

$$E_{\rm CR} = 10^{18}\, A \left(\frac{B}{10^{13}\,{\rm G}}\right) \left(\frac{P_i}{1\,{\rm ms}}\right)^{-2} \left(\frac{\eta}{0.3}\right) \left(\frac{\kappa}{10^4}\right)^{-1} \left(1+\frac{t}{\tau_{\rm sd}}\right)^{-1} {\rm eV}$$

Blasi, Epstein & Olinto ApJ 533 (2000)
Arons, ApJ 589 (2003)
Lemoine, Kotera & Petri 1409.0159

Pulsars: Cosmic Ray Acceleration

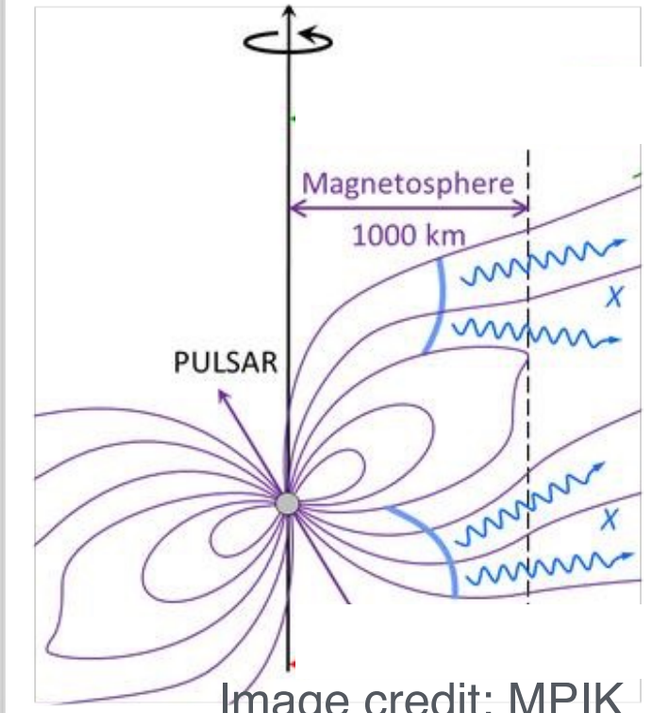


Image credit: MPIK

Particle injection rate $\propto \frac{\sqrt{\dot{E}_{\rm rot} c}}{e}$

initial spin period

Magnetic Field

Wind efficiency

$$E_{\rm CR} = 10^{18}\, A \left(\frac{B}{10^{13}\,{\rm G}}\right) \left(\frac{P_i}{1\,{\rm ms}}\right)^{-2} \left(\frac{\eta}{0.3}\right) \left(\frac{\kappa}{10^4}\right)^{-1} \left(1+\frac{t}{\tau_{\rm sd}}\right)^{-1} {\rm eV}$$

Blasi, Epstein & Olinto ApJ 533 (2000)
Arons, ApJ 589 (2003)
Lemoine, Kotera & Petri 1409.0159

Pulsars: Cosmic Ray Acceleration

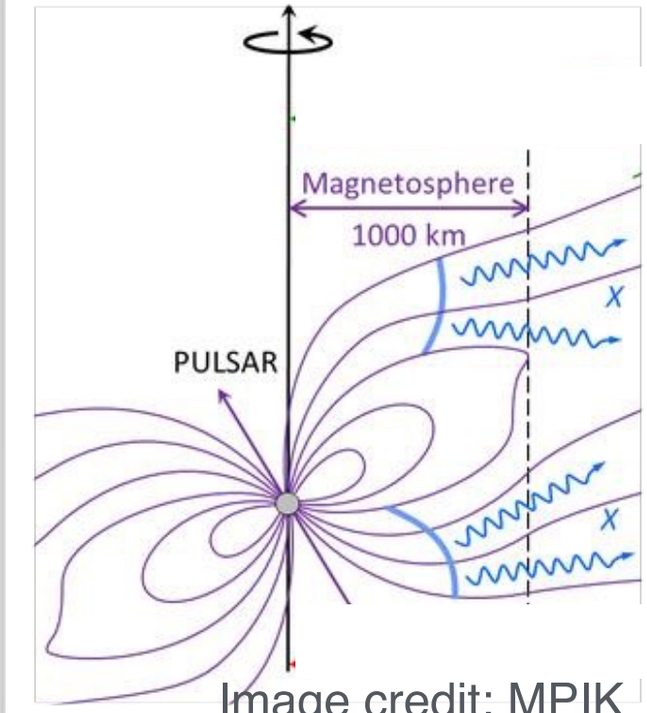


Image credit: MPIK

Particle injection rate $\propto \dfrac{\sqrt{\dot{E}_{\rm rot} c}}{e}$

initial spin period

Magnetic Field | Wind efficiency | Multiplicity

$$E_{\rm CR} = 10^{18}\, A \left(\frac{B}{10^{13}\,{\rm G}}\right) \left(\frac{P_i}{1\,{\rm ms}}\right)^{-2} \left(\frac{\eta}{0.3}\right) \left(\frac{\kappa}{10^4}\right)^{-1} \left(1+\frac{t}{\tau_{\rm sd}}\right)^{-1} {\rm eV}$$

Blasi, Epstein & Olinto ApJ 533 (2000)
Arons, ApJ 589 (2003)
Lemoine, Kotera & Petri 1409.0159

Pulsars: Cosmic Ray Acceleration

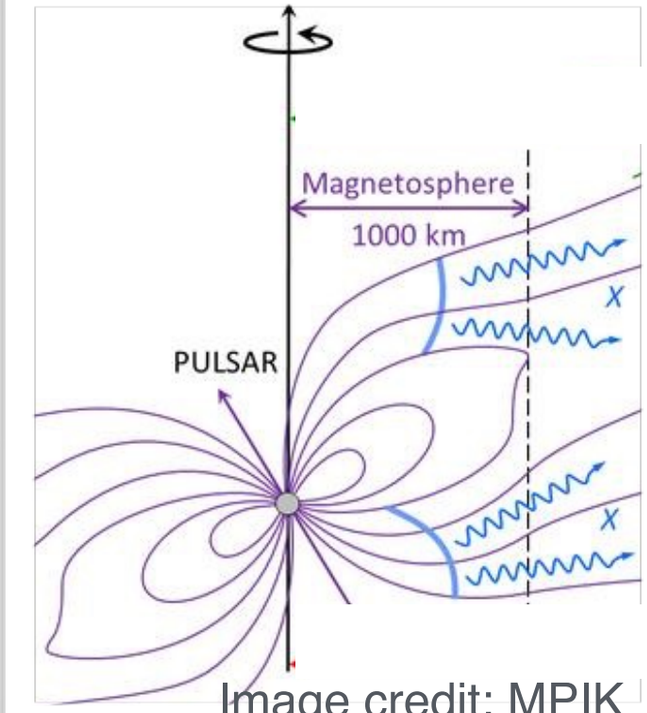


Image credit: MPIK

Particle injection rate $\propto \frac{\sqrt{\dot{E}_{\rm rot} c}}{e}$

initial spin period

Magnetic Field

Wind efficiency

Multiplicity

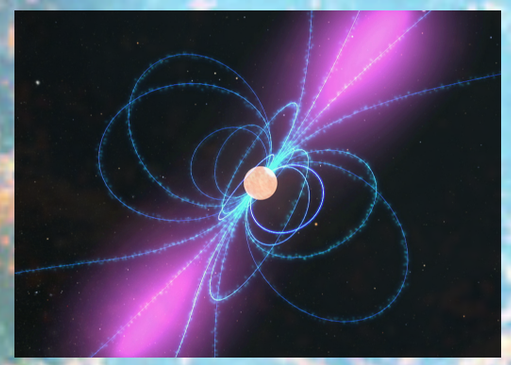
$$E_{\rm CR} = 10^{18}\, A \left(\frac{B}{10^{13}\,{\rm G}}\right) \left(\frac{P_i}{1\,{\rm ms}}\right)^{-2} \left(\frac{\eta}{0.3}\right) \left(\frac{\kappa}{10^4}\right)^{-1} \left(1 + \frac{t}{\tau_{\rm sd}}\right)^{-1} {\rm eV}$$

t ↑ E ↓

$$\tau_{\rm sd} = 1 B_{13}^{-2} P_{i,1{\rm ms}}^{2}\,{\rm yr}$$

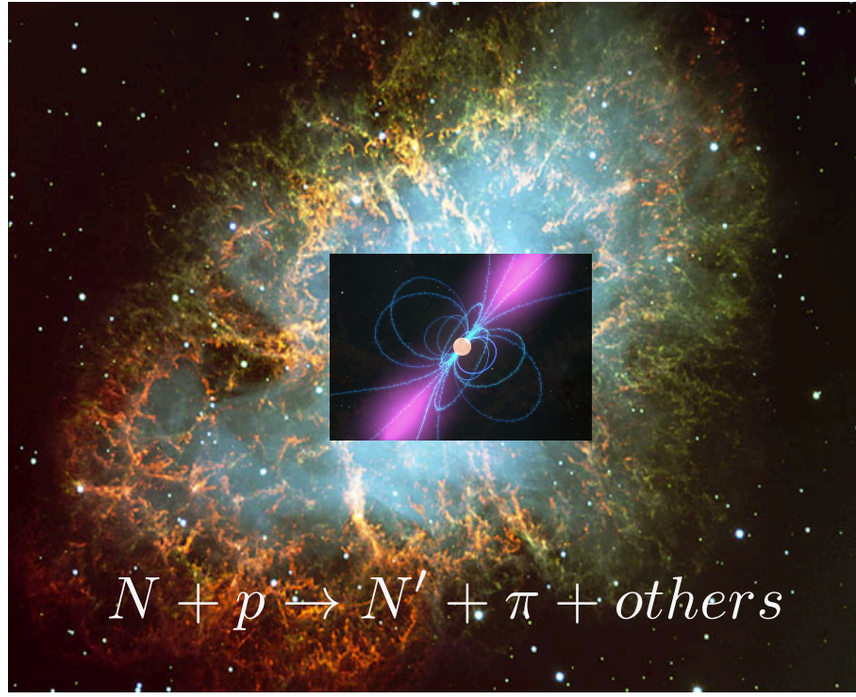
Blasi, Epstein & Olinto ApJ 533 (2000)
Arons, ApJ 589 (2003)
Lemoine, Kotera & Petri 1409.0159

Cosmic ray particles interacting
with hadronic supernova ejecta



Interaction with Ejecta

$$\tau_{pp} = 0.2 \left(\frac{M_{\rm ej}}{10 M_\odot} \right) \left(\frac{v_{\rm ej}}{10^4 {\rm km/s}} \right)^{-2} \left(\frac{t}{1 {\rm yr}} \right)^{-2}$$

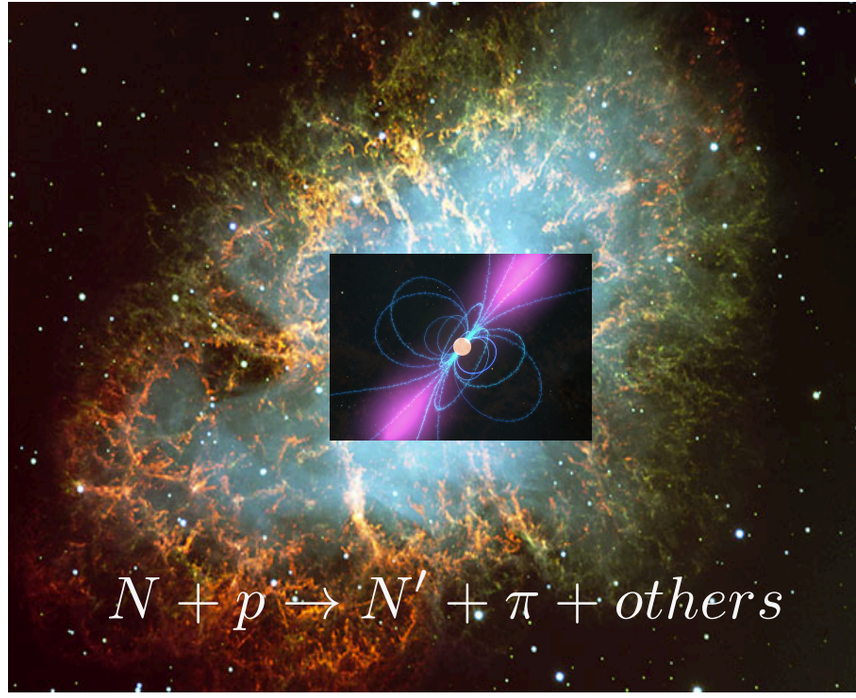


KF, Kotera & Olinto, ApJ, 750, 118, 2012

Interaction with Ejecta

$$\tau_{pp} = 0.2 \left(\frac{M_{\rm ej}}{10 M_\odot} \right) \left(\frac{v_{\rm ej}}{10^4 {\rm km/s}} \right)^{-2} \left(\frac{t}{1 {\rm yr}} \right)^{-2}$$

Monte Carlo simulation tracking particle propagation



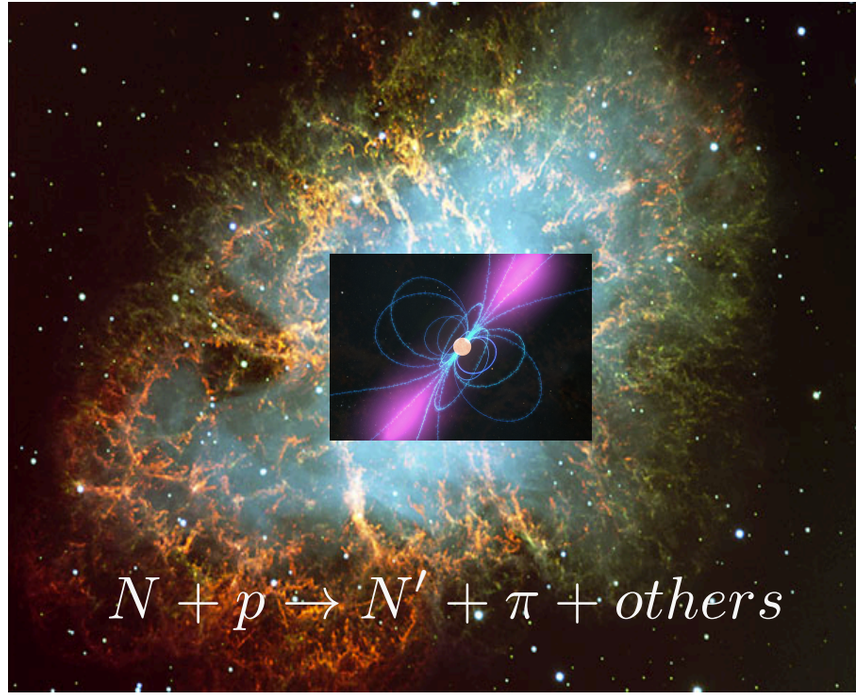
$$B = 10^{13}\,{\rm G}, {\rm P_i} = 0.6\,{\rm ms}$$

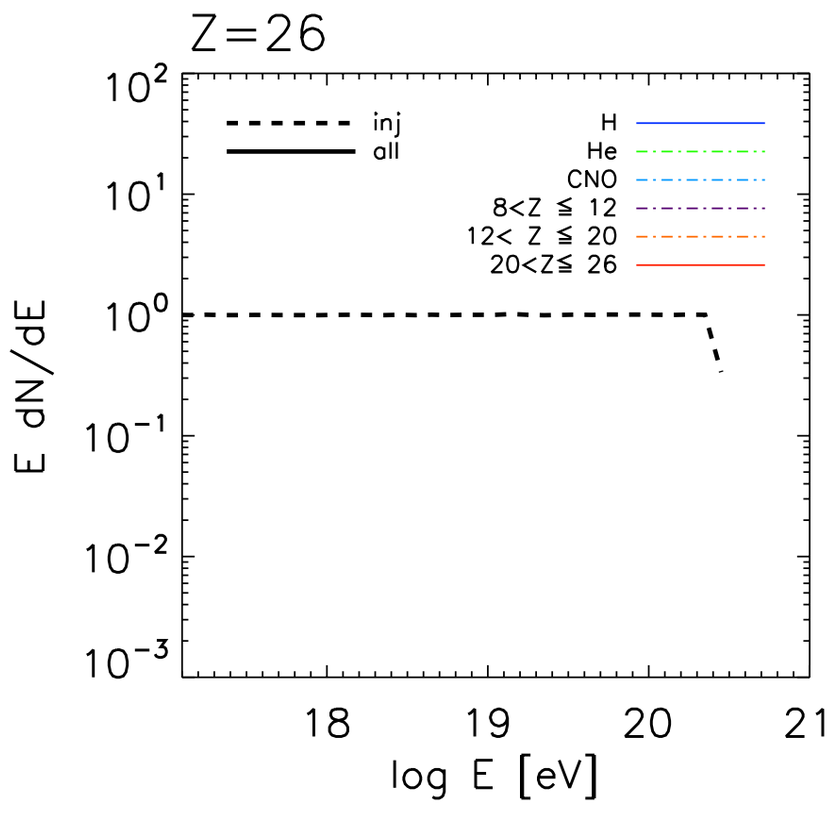
KF, Kotera & Olinto, ApJ, 750, 118, 2012

Interaction with Ejecta

$$\tau_{pp} = 0.2 \left(\frac{M_{\rm ej}}{10 M_\odot} \right) \left(\frac{v_{\rm ej}}{10^4 {\rm km/s}} \right)^{-2} \left(\frac{t}{1 {\rm yr}} \right)^{-2}$$

Monte Carlo simulation tracking particle propagation





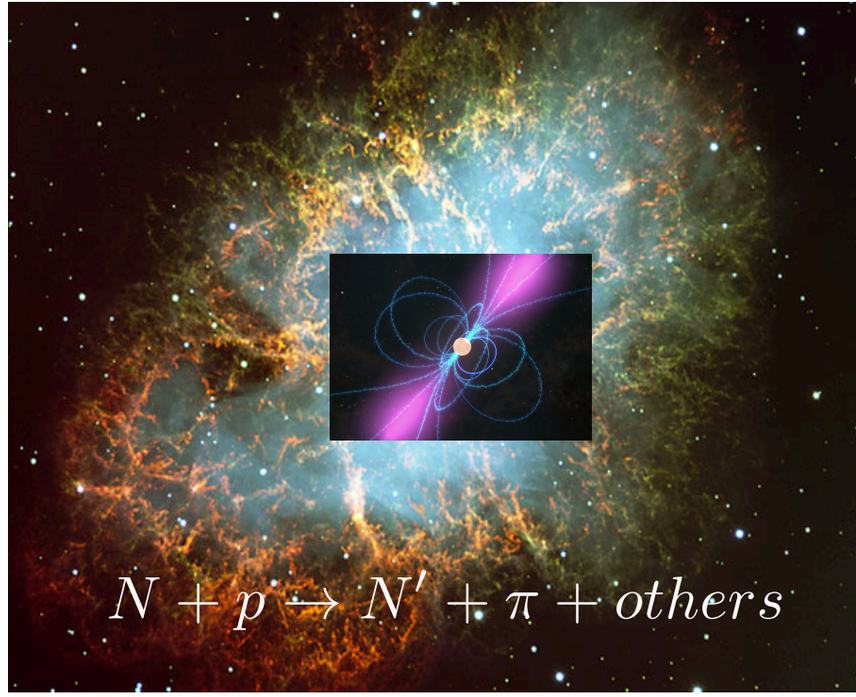
$$B = 10^{13}\,{\rm G}, {\rm P_i} = 0.6\,{\rm ms}$$

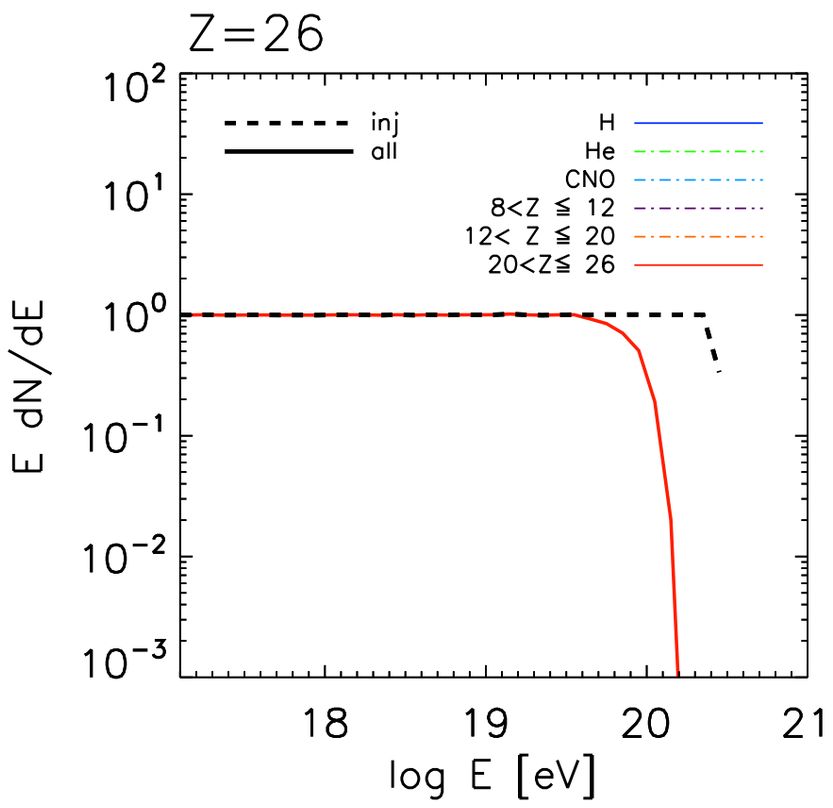
KF, Kotera & Olinto, ApJ, 750, 118, 2012

Interaction with Ejecta

$$\tau_{pp} = 0.2 \left(\frac{M_{\rm ej}}{10 M_\odot} \right) \left(\frac{v_{\rm ej}}{10^4 {\rm km/s}} \right)^{-2} \left(\frac{t}{1 {\rm yr}} \right)^{-2}$$

Monte Carlo simulation tracking particle propagation





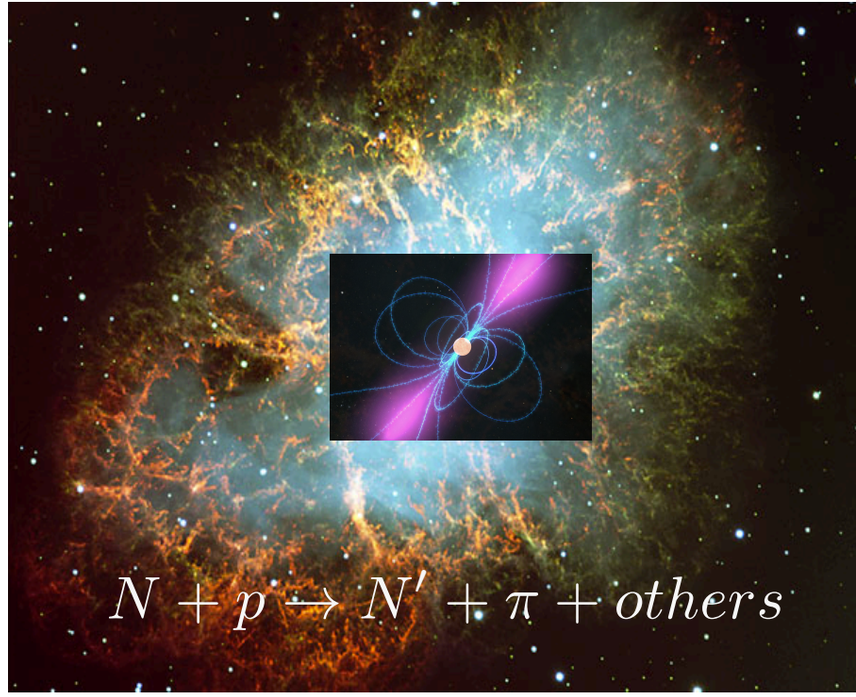
$$B = 10^{13}\,{\rm G}, {\rm P_i} = 0.6\,{\rm ms}$$

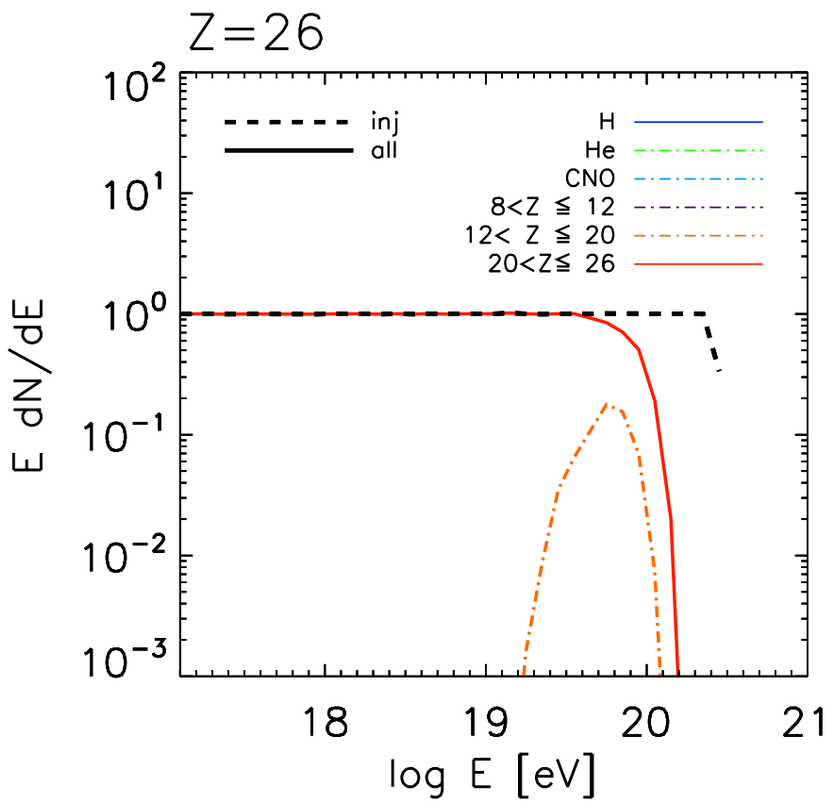
KF, Kotera & Olinto, ApJ, 750, 118, 2012

Interaction with Ejecta

$$\tau_{pp} = 0.2 \left(\frac{M_{\rm ej}}{10 M_\odot} \right) \left(\frac{v_{\rm ej}}{10^4 {\rm km/s}} \right)^{-2} \left(\frac{t}{1 {\rm yr}} \right)^{-2}$$

Monte Carlo simulation tracking particle propagation





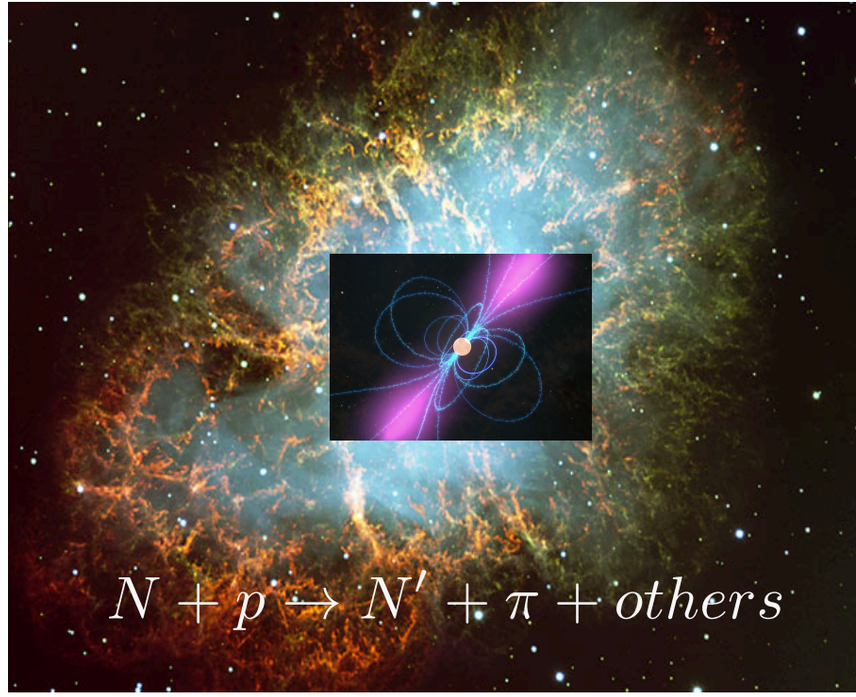
$$B = 10^{13}\,{\rm G}, {\rm P_i} = 0.6\,{\rm ms}$$

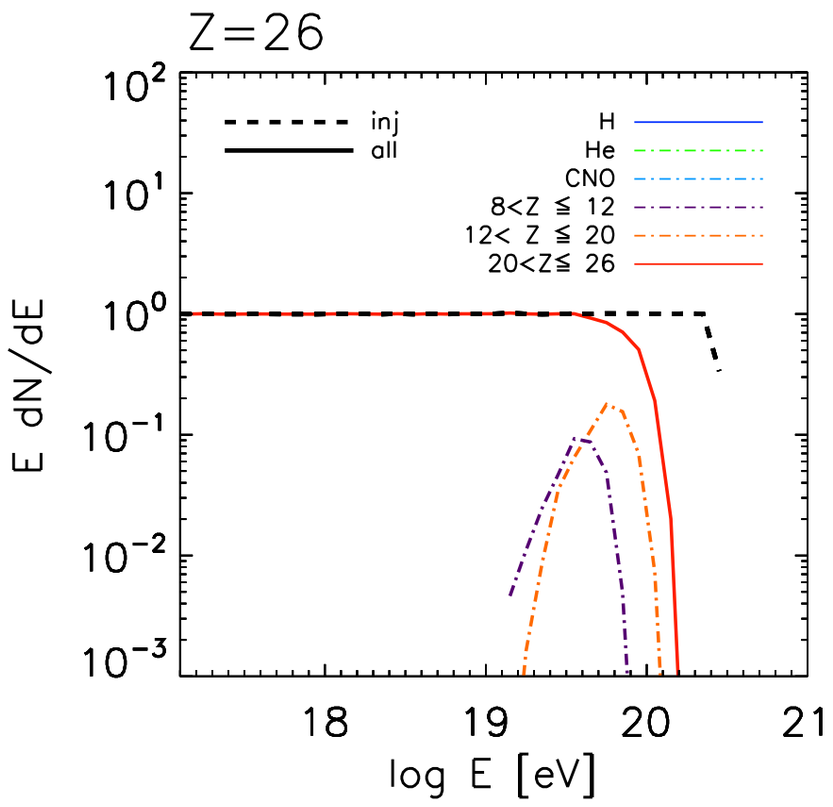
KF, Kotera & Olinto, ApJ, 750, 118, 2012

Interaction with Ejecta

$$\tau_{pp} = 0.2 \left(\frac{M_{\rm ej}}{10 M_\odot} \right) \left(\frac{v_{\rm ej}}{10^4 {\rm km/s}} \right)^{-2} \left(\frac{t}{1 {\rm yr}} \right)^{-2}$$

Monte Carlo simulation tracking particle propagation





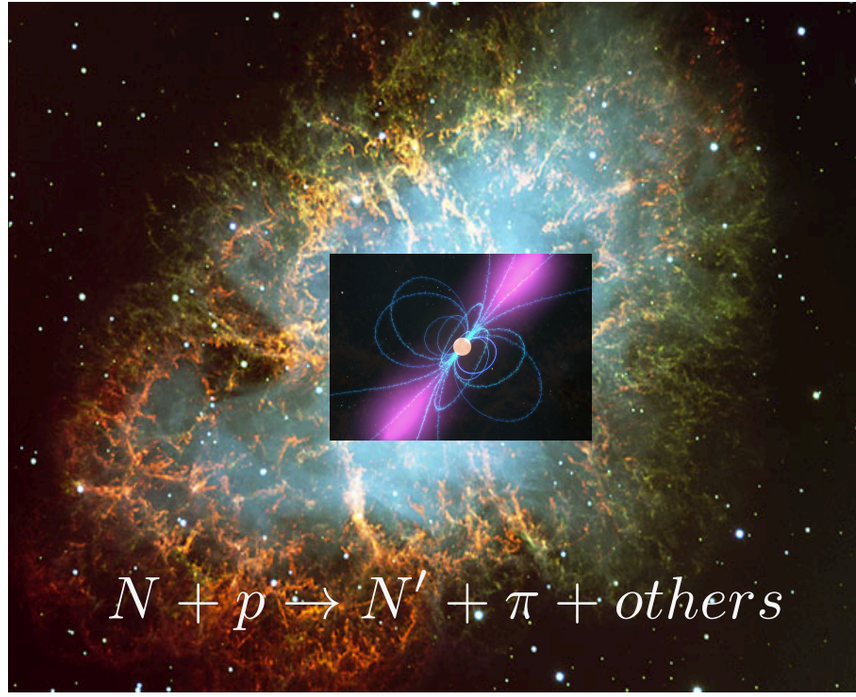
$$B = 10^{13}\,{\rm G}, {\rm P_i} = 0.6\,{\rm ms}$$

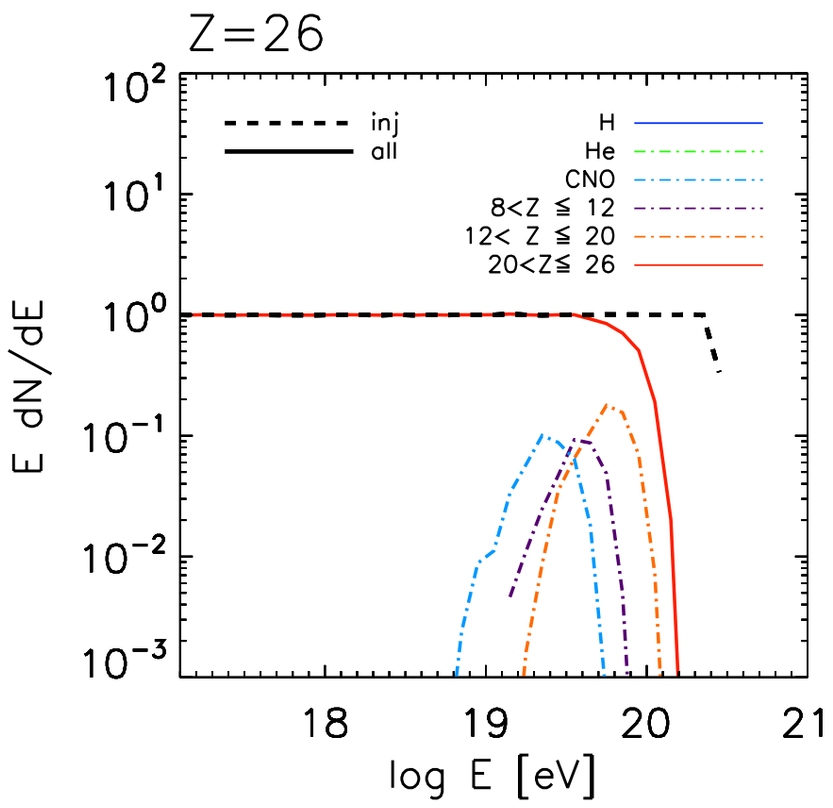
KF, Kotera & Olinto, ApJ, 750, 118, 2012

Interaction with Ejecta

$$\tau_{pp} = 0.2 \left(\frac{M_{\rm ej}}{10 M_\odot} \right) \left(\frac{v_{\rm ej}}{10^4 {\rm km/s}} \right)^{-2} \left(\frac{t}{1 {\rm yr}} \right)^{-2}$$

Monte Carlo simulation tracking particle propagation





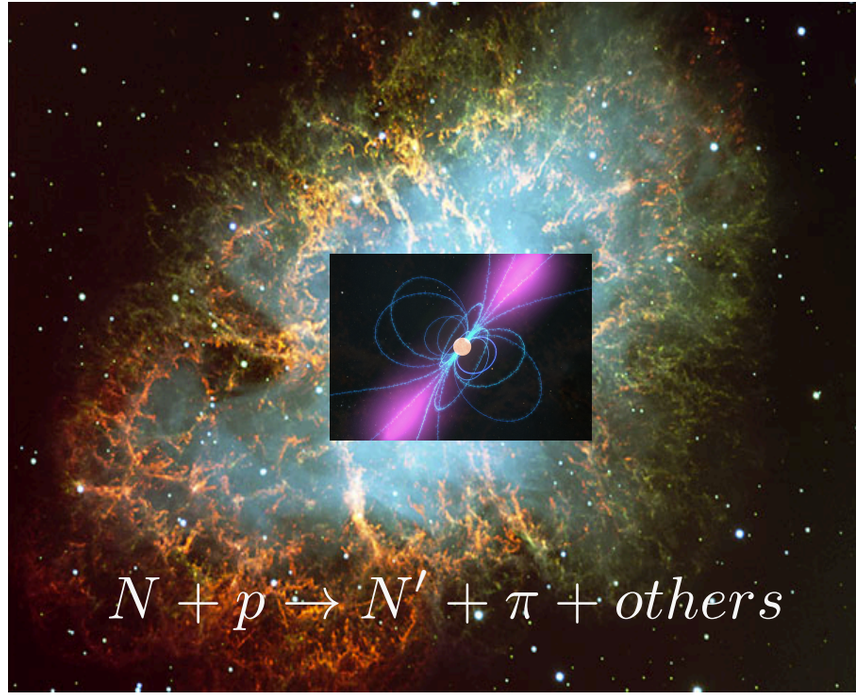
$$B = 10^{13}\,{\rm G}, {\rm P_i} = 0.6\,{\rm ms}$$

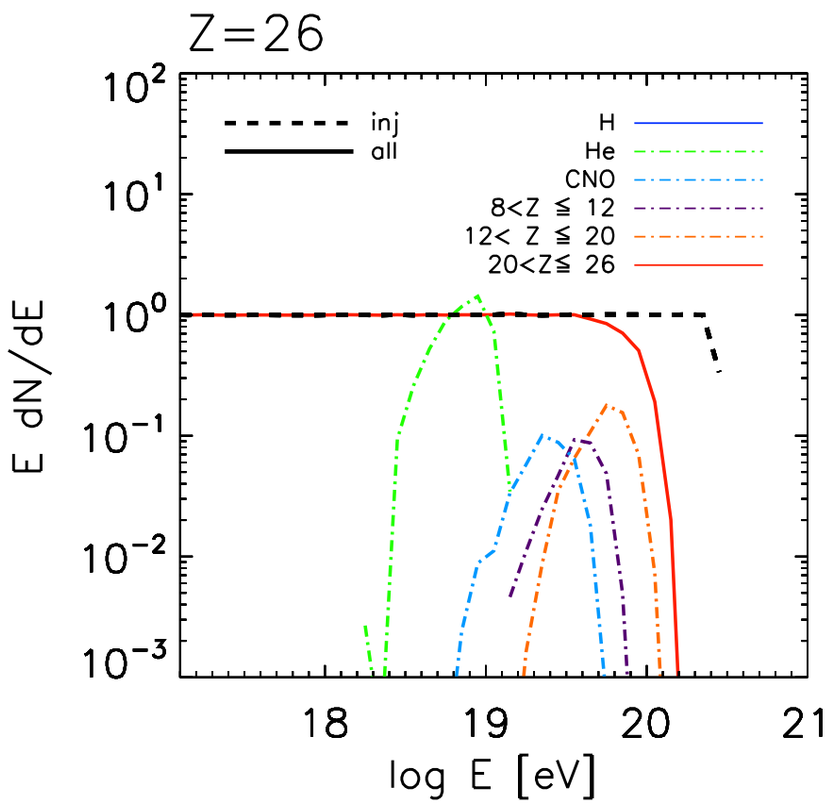
KF, Kotera & Olinto, ApJ, 750, 118, 2012

Interaction with Ejecta

$$\tau_{pp} = 0.2 \left(\frac{M_{\rm ej}}{10 M_\odot} \right) \left(\frac{v_{\rm ej}}{10^4 {\rm km/s}} \right)^{-2} \left(\frac{t}{1 {\rm yr}} \right)^{-2}$$

Monte Carlo simulation tracking particle propagation





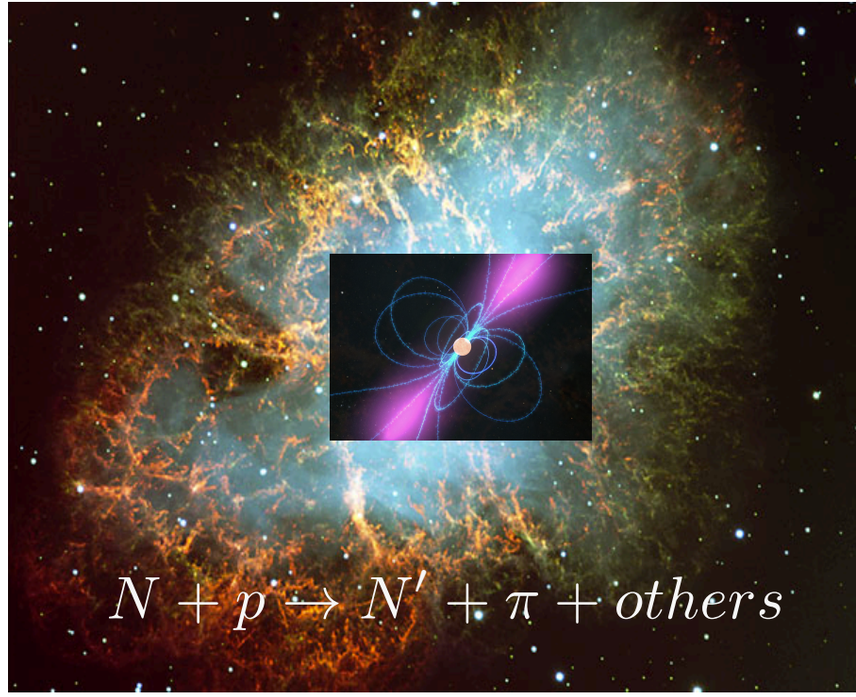
$$B = 10^{13}\,{\rm G}, {\rm P_i} = 0.6\,{\rm ms}$$

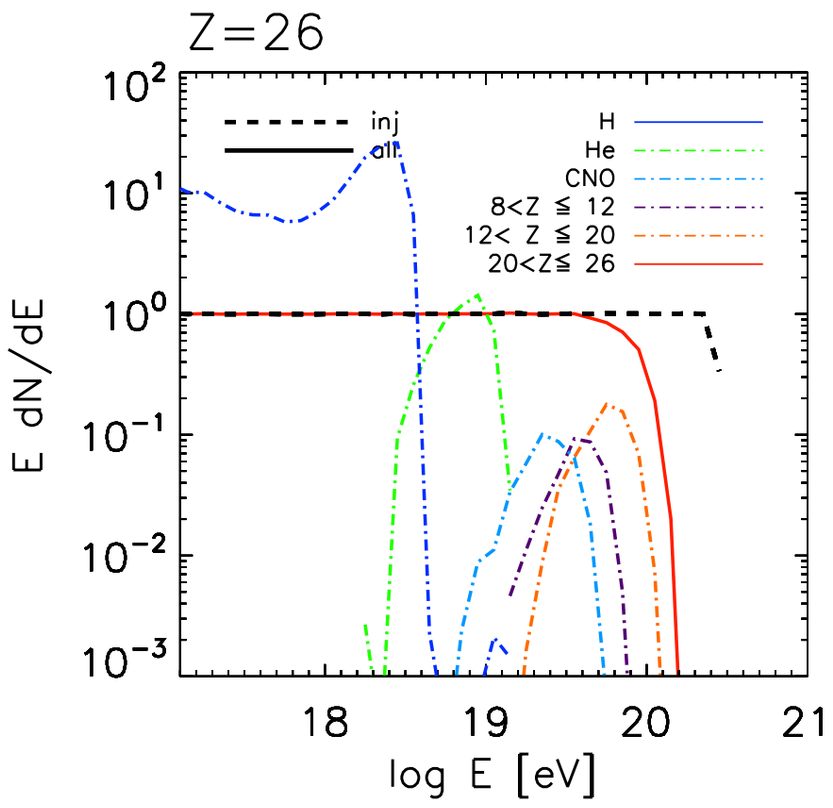
KF, Kotera & Olinto, ApJ, 750, 118, 2012

Interaction with Ejecta

$$\tau_{pp} = 0.2 \left(\frac{M_{\rm ej}}{10 M_\odot} \right) \left(\frac{v_{\rm ej}}{10^4 {\rm km/s}} \right)^{-2} \left(\frac{t}{1 {\rm yr}} \right)^{-2}$$

Monte Carlo simulation tracking particle propagation





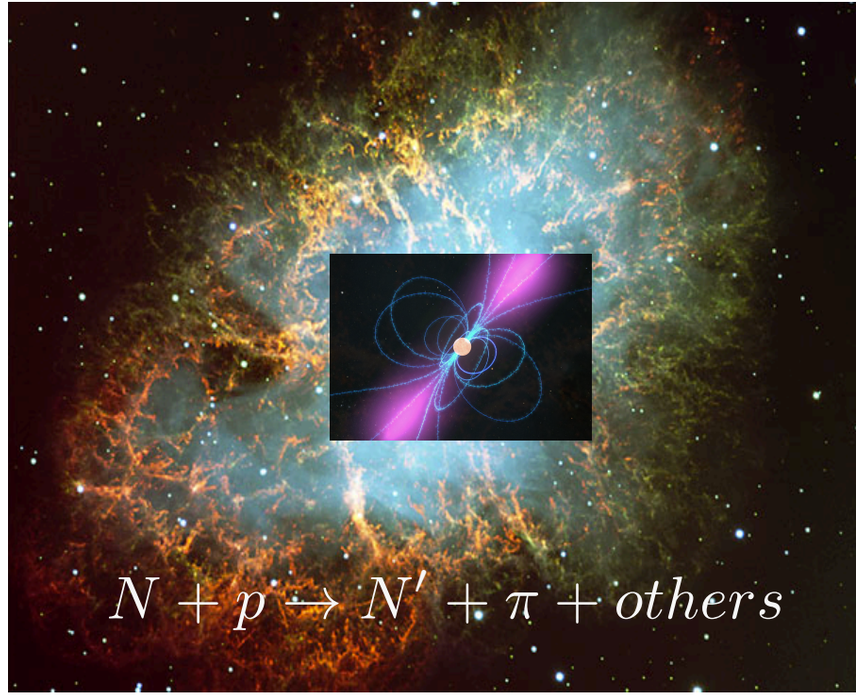
$$B = 10^{13}\,{\rm G}, {\rm P_i} = 0.6\,{\rm ms}$$

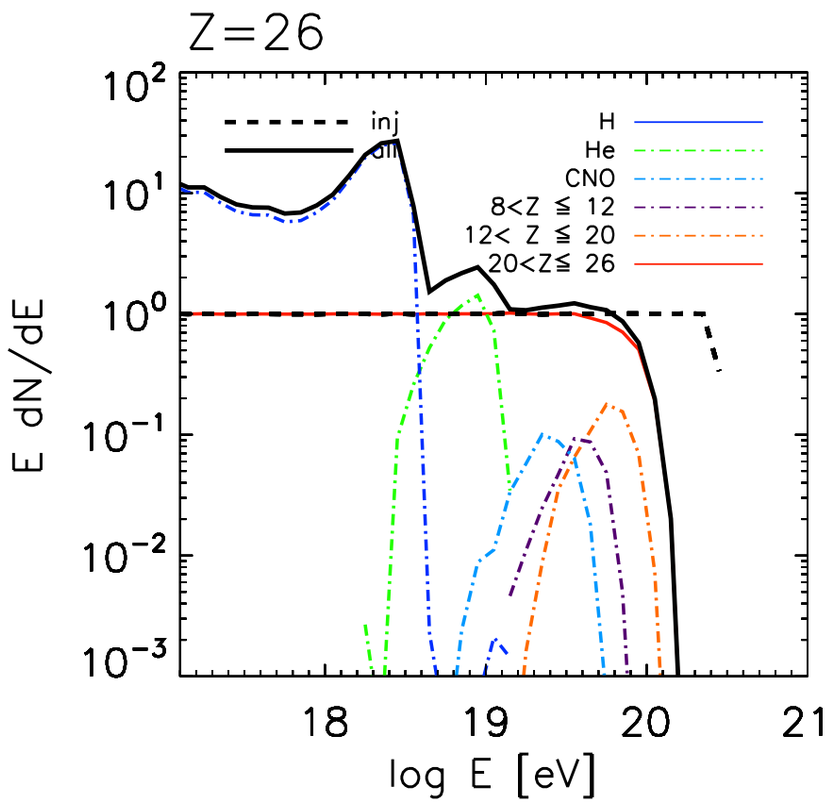
KF, Kotera & Olinto, ApJ, 750, 118, 2012

Interaction with Ejecta

$$\tau_{pp} = 0.2 \left(\frac{M_{\rm ej}}{10 M_\odot} \right) \left(\frac{v_{\rm ej}}{10^4 {\rm km/s}} \right)^{-2} \left(\frac{t}{1 {\rm yr}} \right)^{-2}$$

Monte Carlo simulation tracking particle propagation





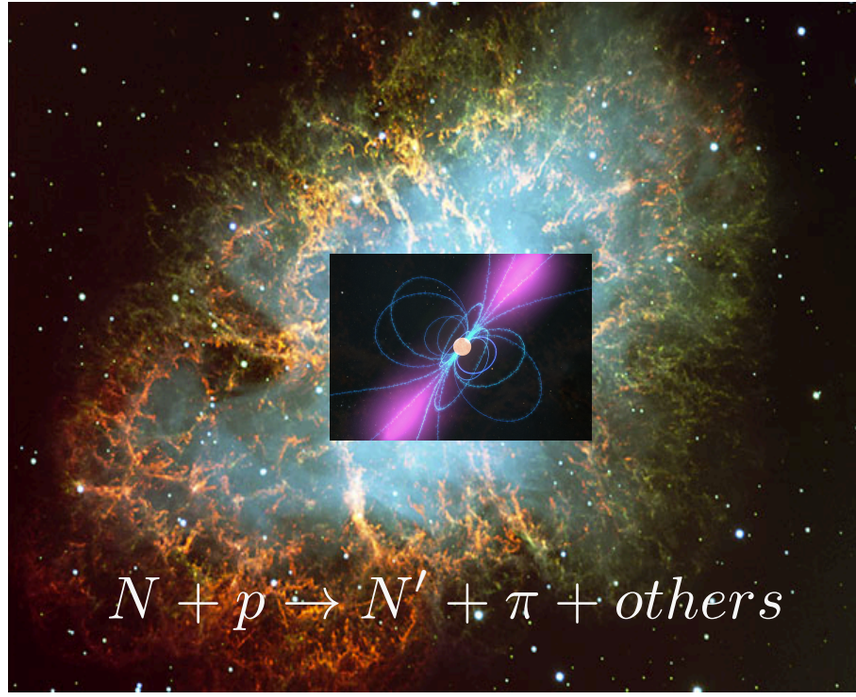
$$B = 10^{13}\,{\rm G}, {\rm P_i} = 0.6\,{\rm ms}$$

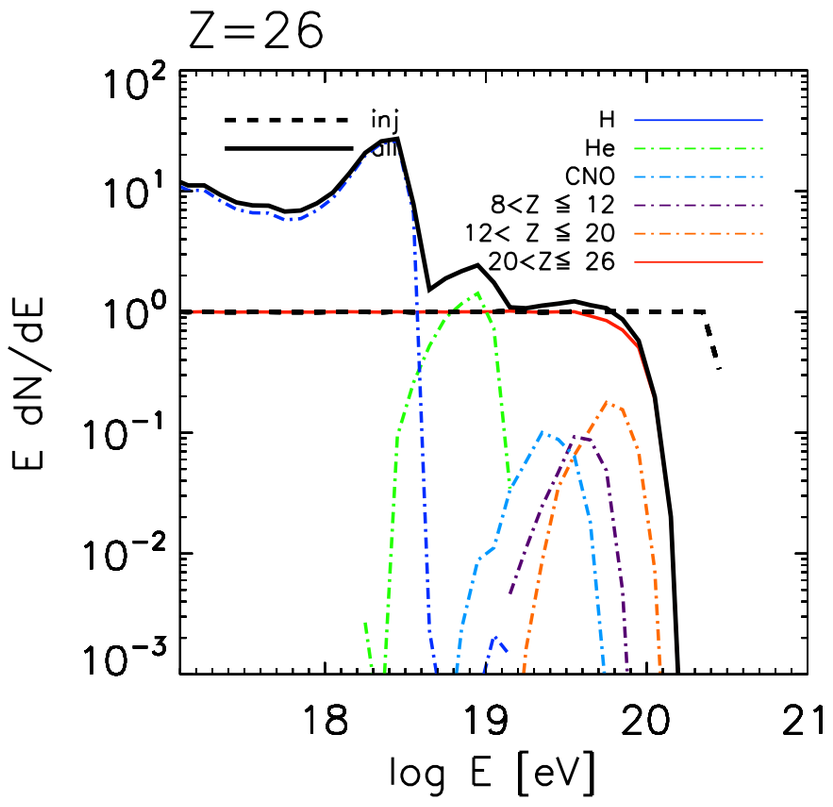
KF, Kotera & Olinto, ApJ, 750, 118, 2012

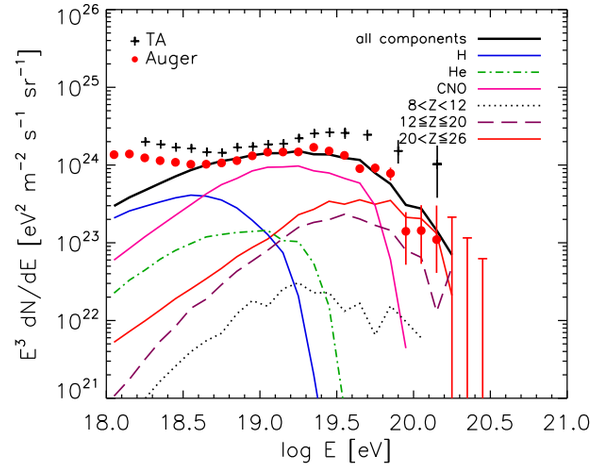
Interaction with Ejecta

$$\tau_{pp} = 0.2 \left(\frac{M_{\rm ej}}{10 M_\odot} \right) \left(\frac{v_{\rm ej}}{10^4 {\rm km/s}} \right)^{-2} \left(\frac{t}{1 {\rm yr}} \right)^{-2}$$

Monte Carlo simulation tracking particle propagation







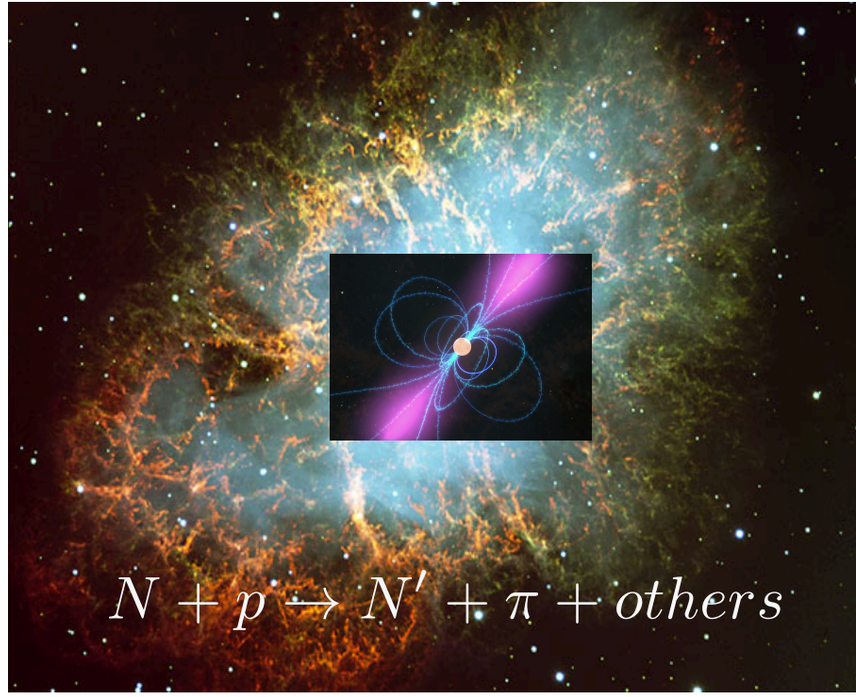
$$B = 10^{13}\,{\rm G}, {\rm P_i} = 0.6\,{\rm ms}$$

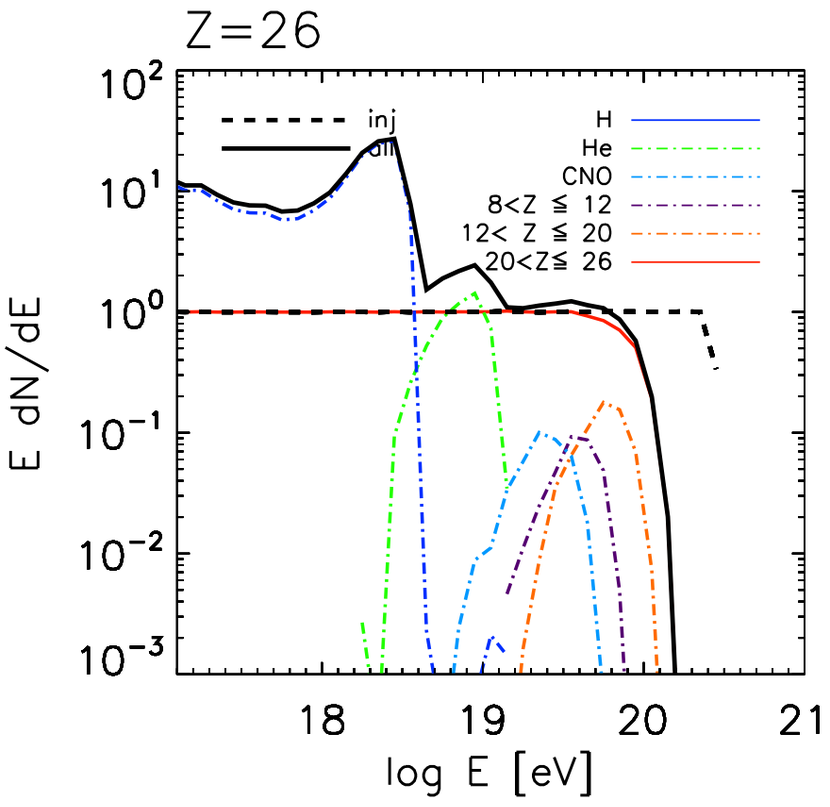
KF, Kotera & Olinto, ApJ, 750, 118, 2012

Interaction with Ejecta

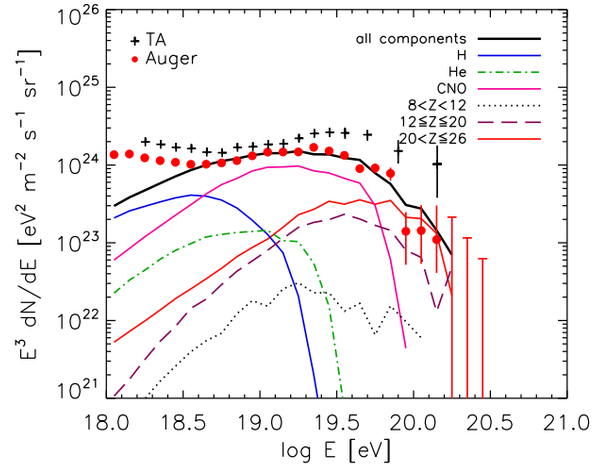
$$\tau_{pp} = 0.2 \left(\frac{M_{\rm ej}}{10 M_\odot}\right) \left(\frac{v_{\rm ej}}{10^4 {\rm km/s}}\right)^{-2} \left(\frac{t}{1{\rm yr}}\right)^{-2}$$

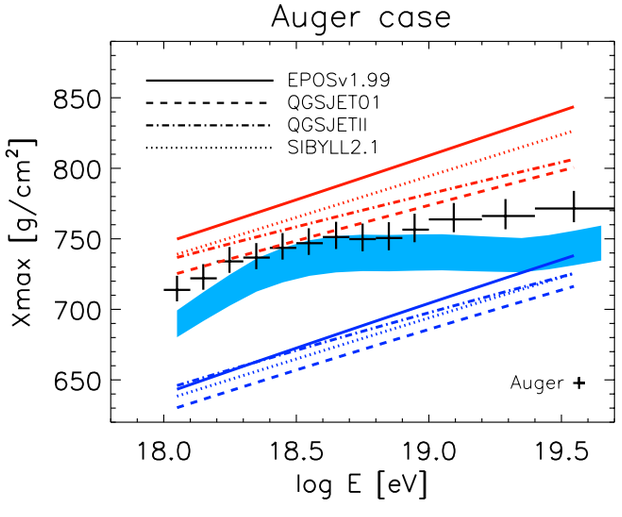
Monte Carlo simulation tracking particle propagation





$$B = 10^{13}\,{\rm G}, {\rm P_i} = 0.6\,{\rm ms}$$



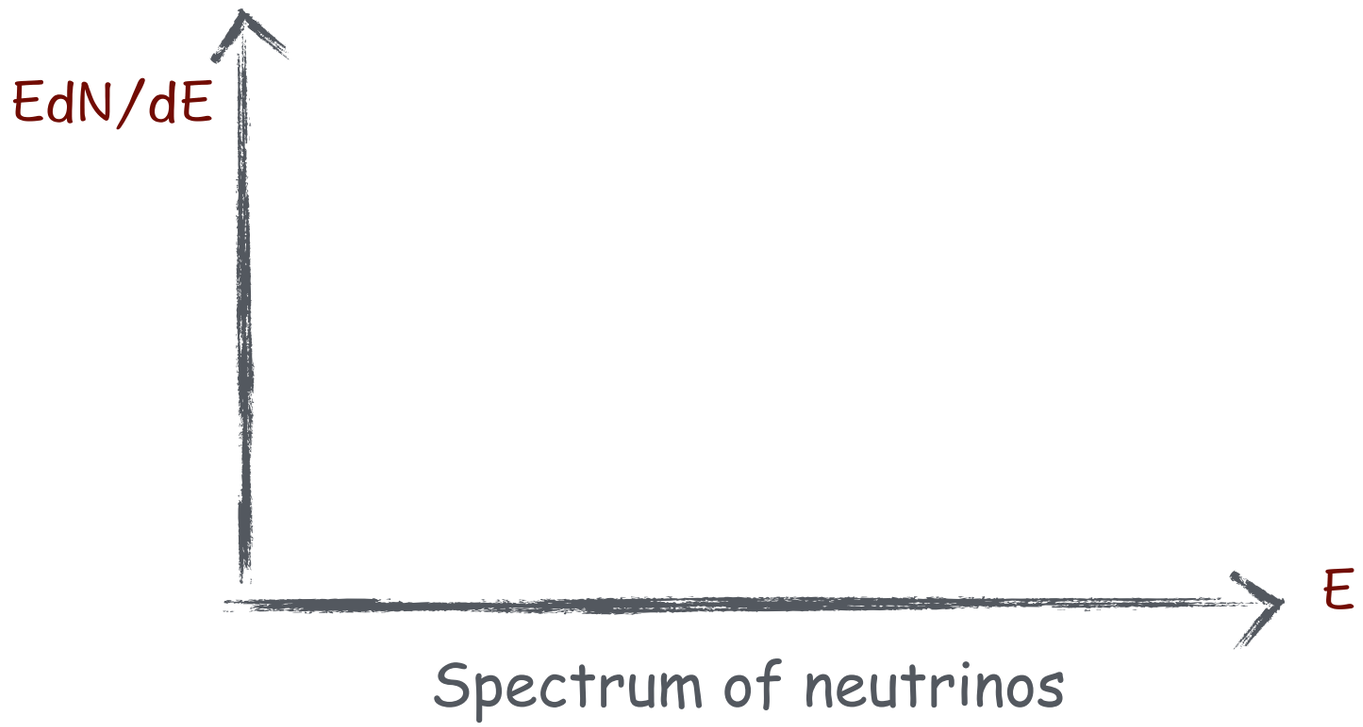


KF, Kotera & Olinto, ApJ, 750, 118, 2012

Neutrino Production

$$N + p \rightarrow N' + \pi + others$$

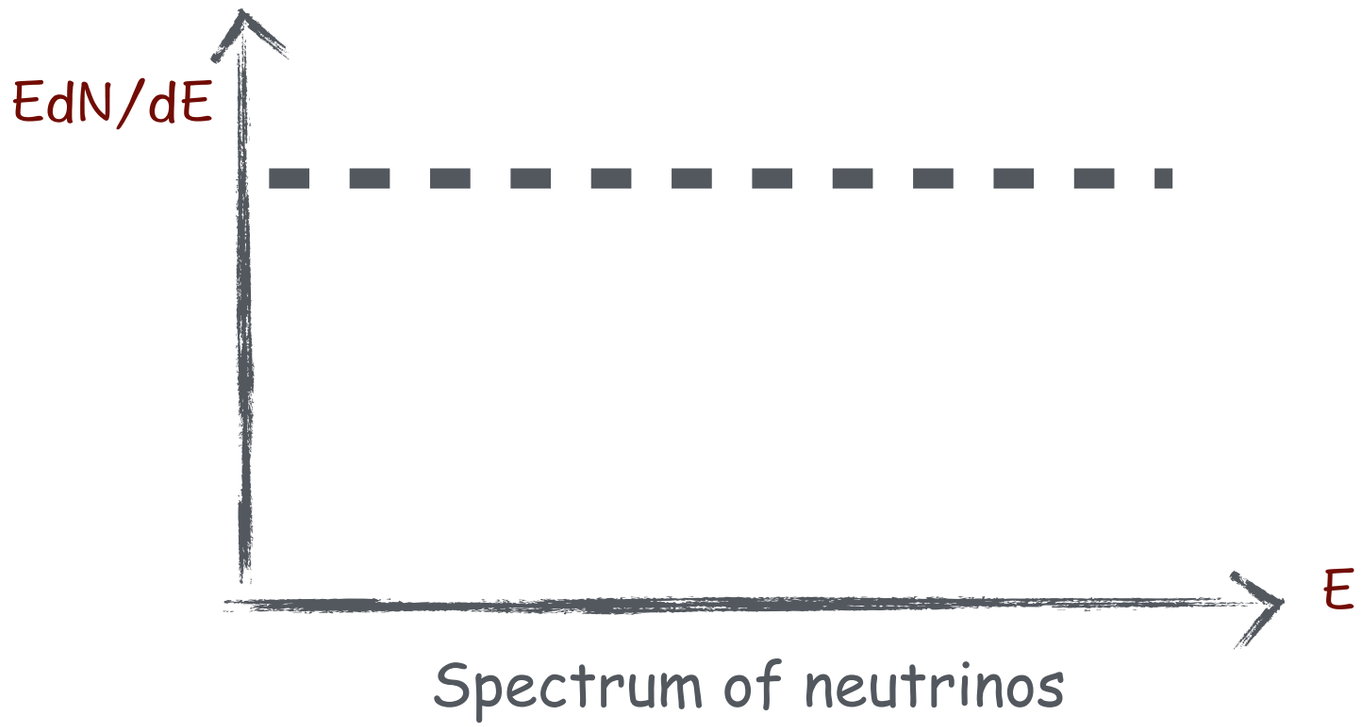
Charged pion products



Neutrino Production

$$N + p \rightarrow N' + \pi + others$$

Charged pion products



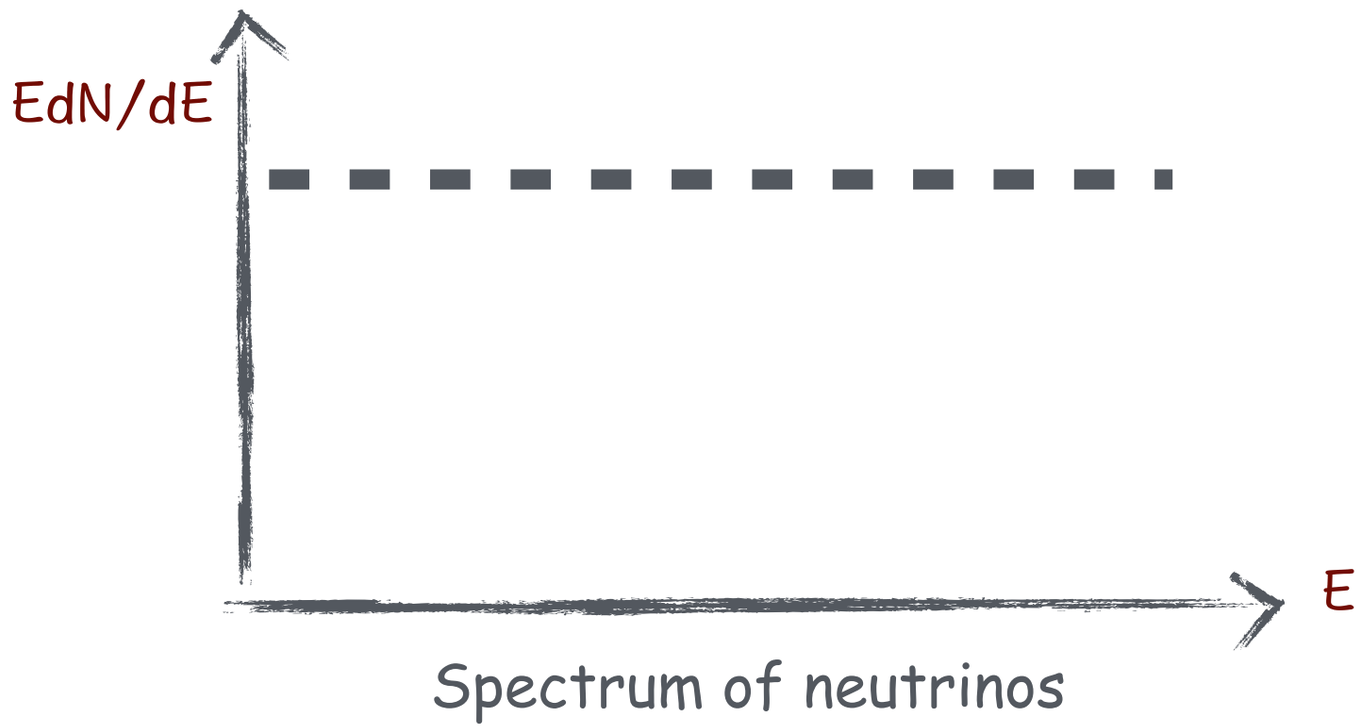
Neutrino Production

$N + p \rightarrow N' + \pi + others$

Charged pion products

Decay into leptons

$\pi^{\pm} \rightarrow e^{\pm} + \nu_e(\bar{\nu}_e) + \bar{\nu}_\mu + \nu_\mu$



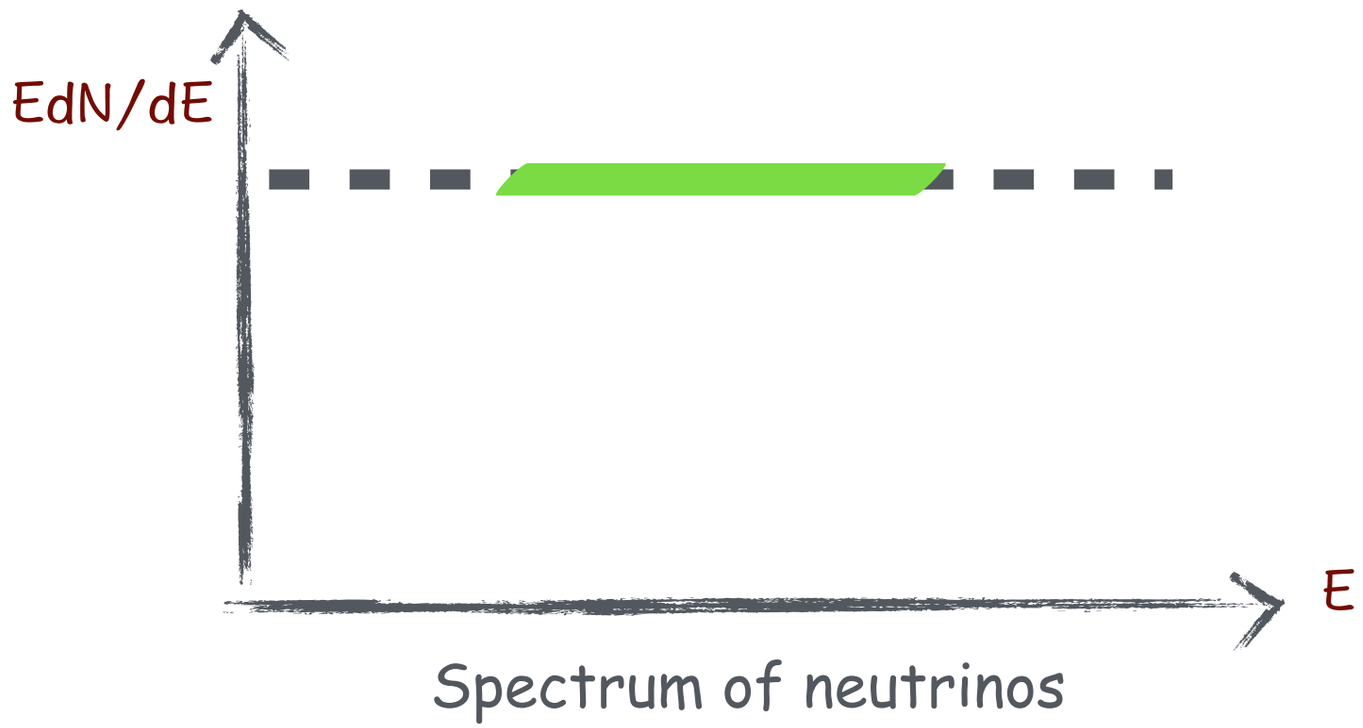
Neutrino Production

$N + p \rightarrow N' + \pi + others$

Charged pion products

Decay into leptons

$\pi^{\pm} \rightarrow e^{\pm} + \nu_e(\bar{\nu}_e) + \bar{\nu}_\mu + \nu_\mu$



Neutrino Production

$N + p \rightarrow N' + \pi + others$

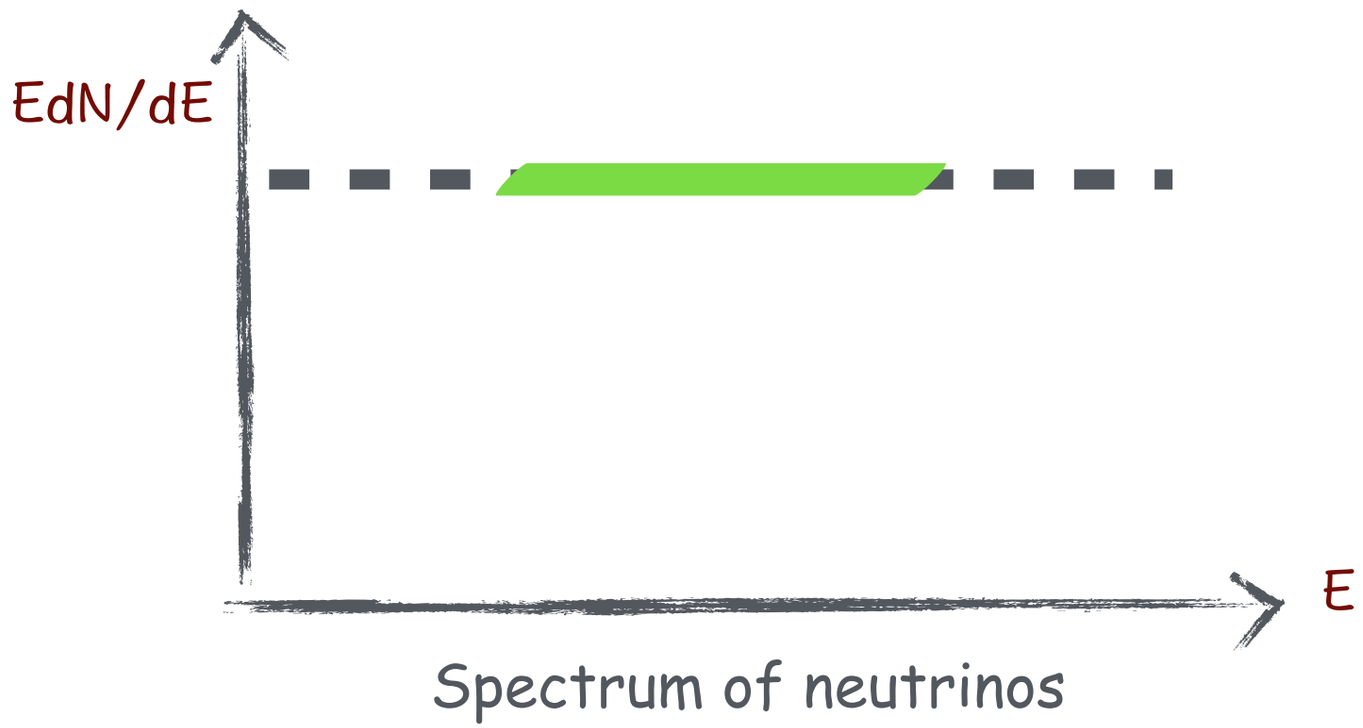
Charged pion products

Decay into leptons

$\pi^{\pm} \rightarrow e^{\pm} + \nu_e(\bar{\nu}_e) + \bar{\nu}_\mu + \nu_\mu$

Interact with hadron background

$\pi + p \rightarrow \pi' + others$



Neutrino Production

$N + p \rightarrow N' + \pi + others$

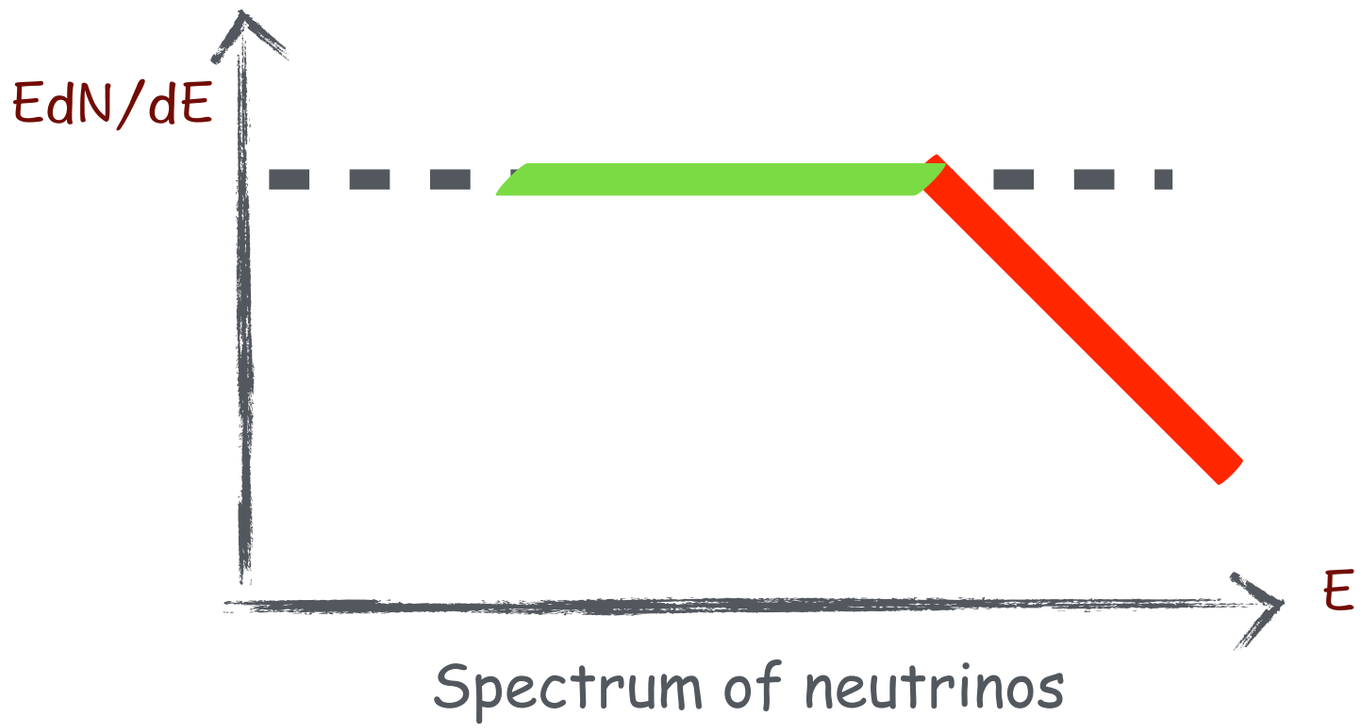
Charged pion products

Decay into leptons

$\pi^{\pm} \rightarrow e^{\pm} + \nu_e(\bar{\nu}_e) + \bar{\nu}_\mu + \nu_\mu$

Interact with hadron background

$\pi + p \rightarrow \pi' + others$



Neutrino Production

$N + p \rightarrow N' + \pi + others$

Charged pion products

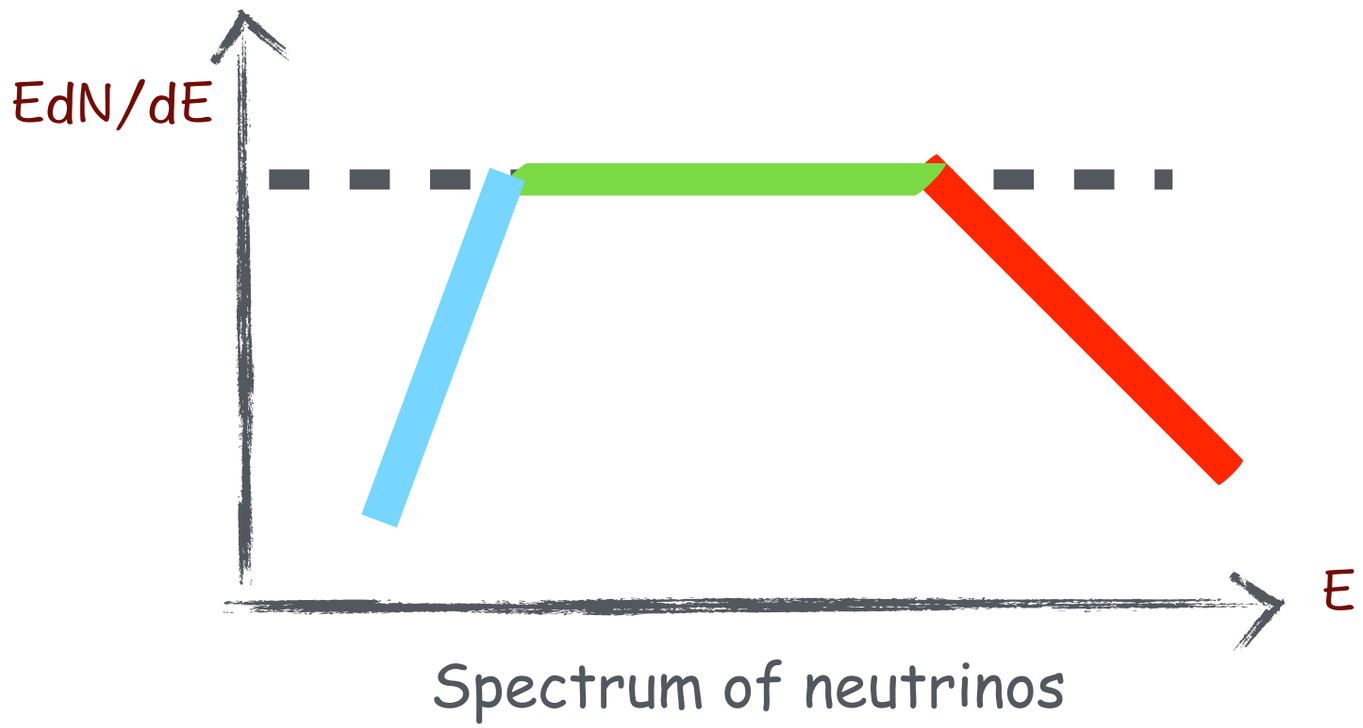
$f_\pi = \min(\tau_{Np}, 1)$

Decay into leptons

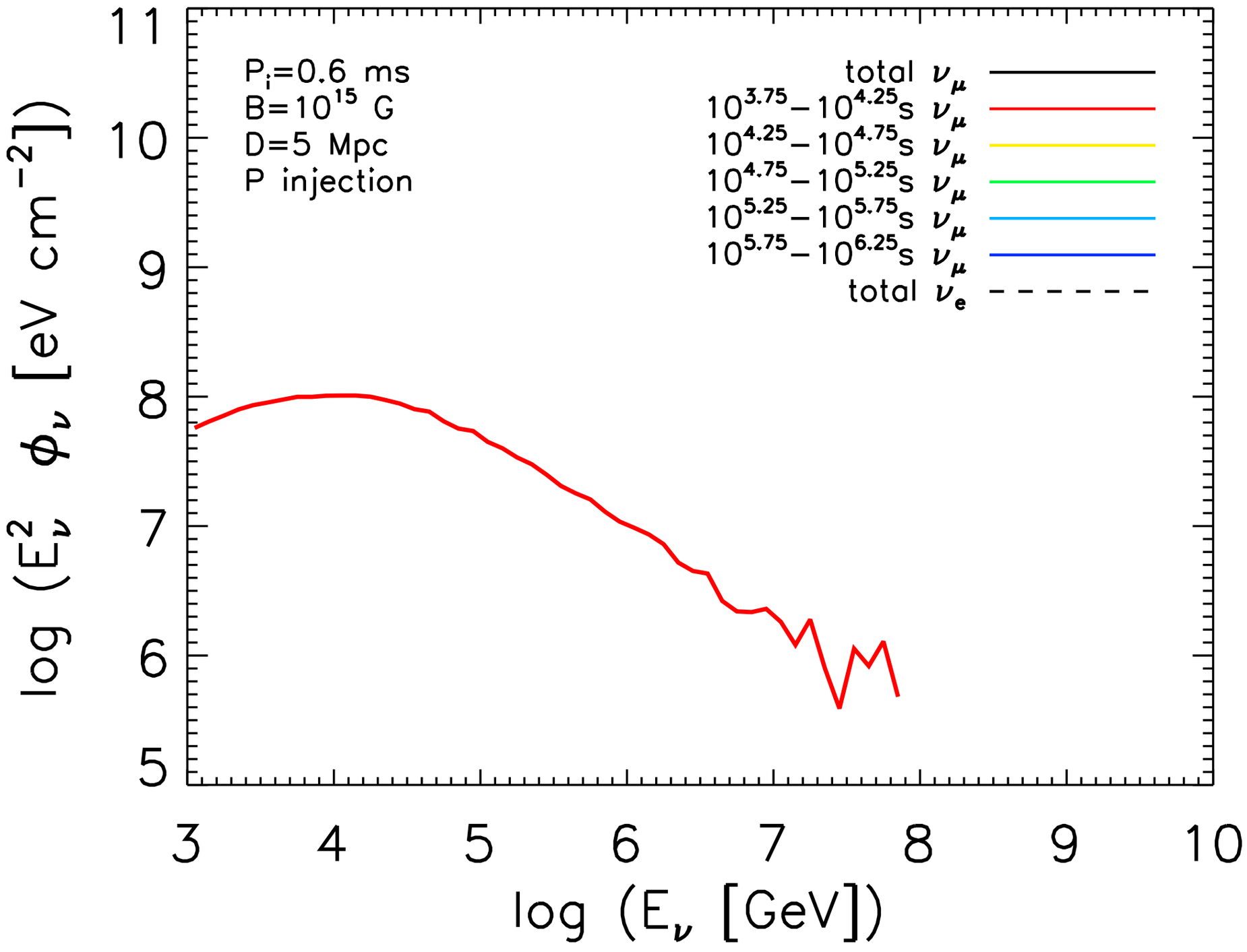
$\pi^\pm \rightarrow e^\pm + \nu_e(\bar{\nu}_e) + \bar{\nu}_\mu + \nu_\mu$

Interact with hadron background

$\pi + p \rightarrow \pi' + others$

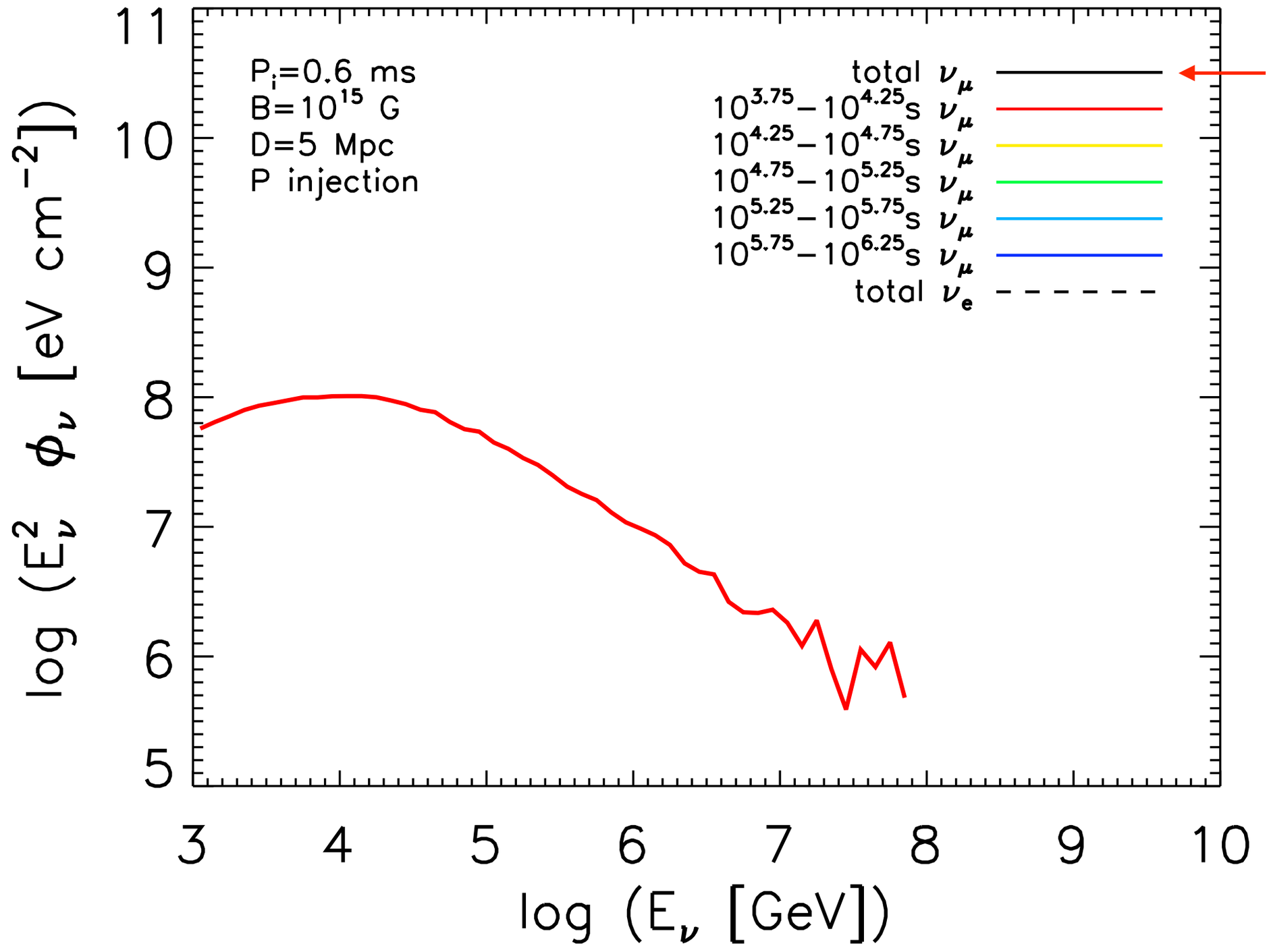


Neutrino spectrum - Single Source



KF, JCAP 06(2015)004

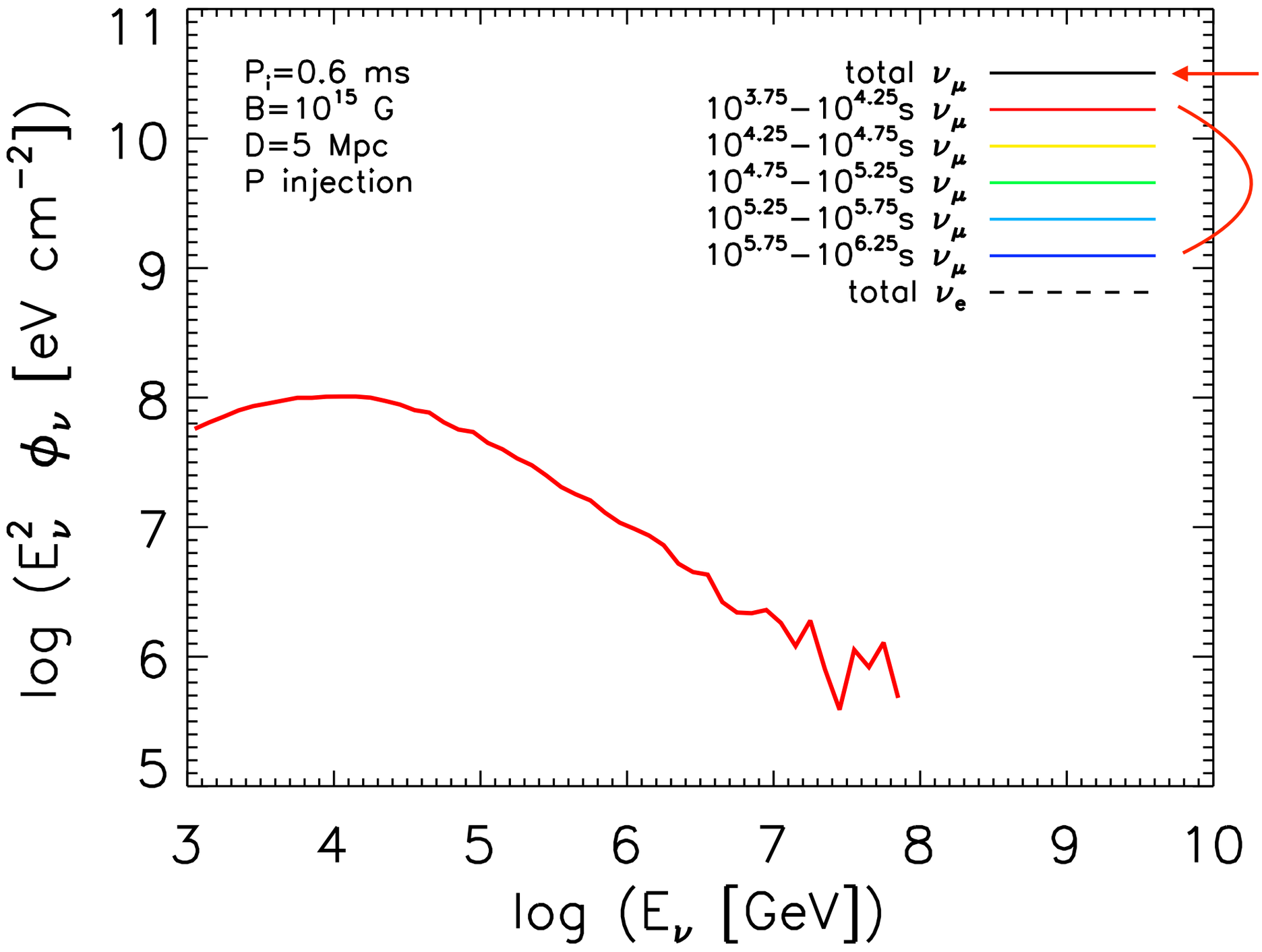
Neutrino spectrum - Single Source



muon neutrino

KF, JCAP 06(2015)004

Neutrino spectrum - Single Source

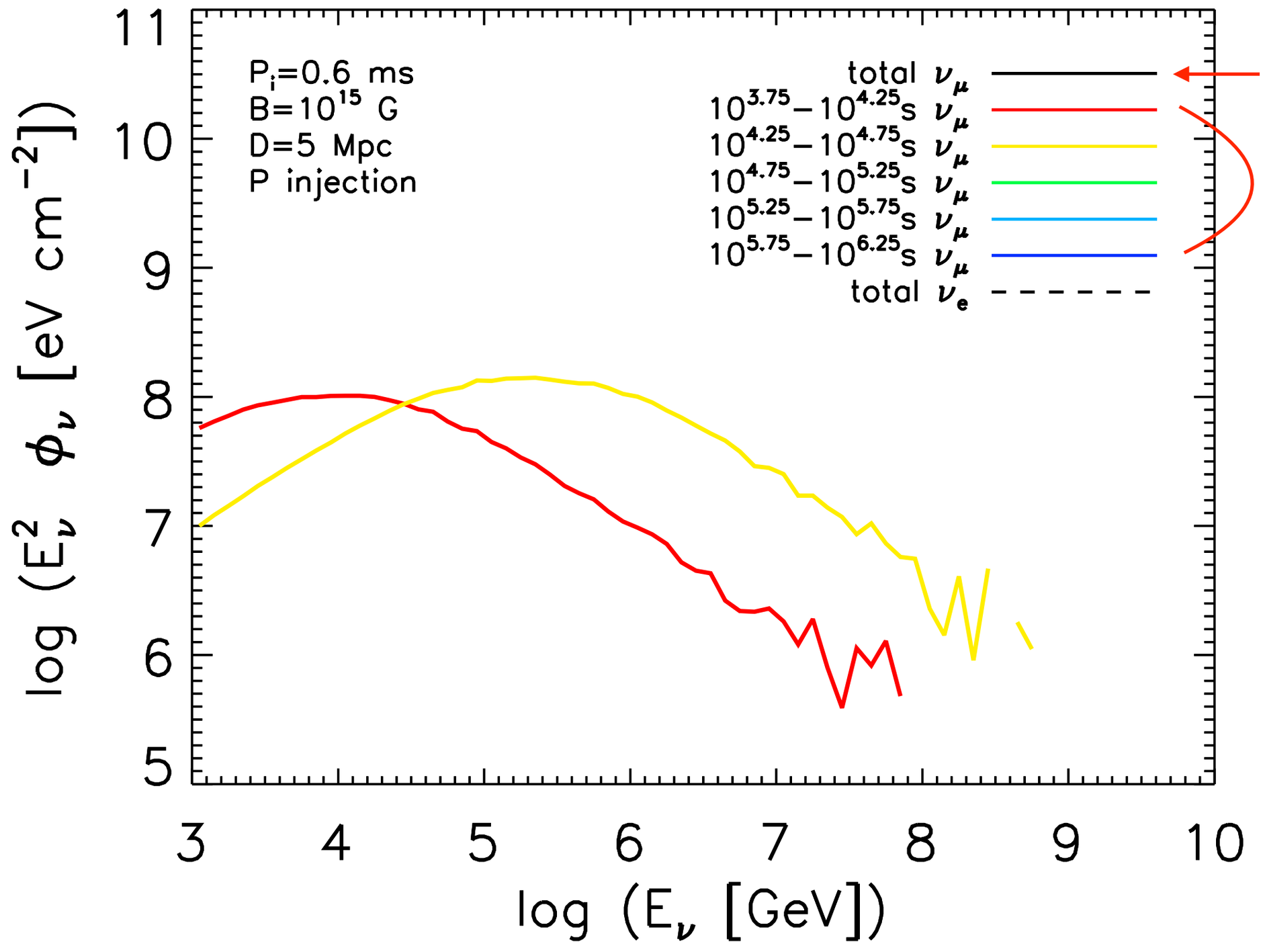


muon neutrino

system time

KF, JCAP 06(2015)004

Neutrino spectrum - Single Source

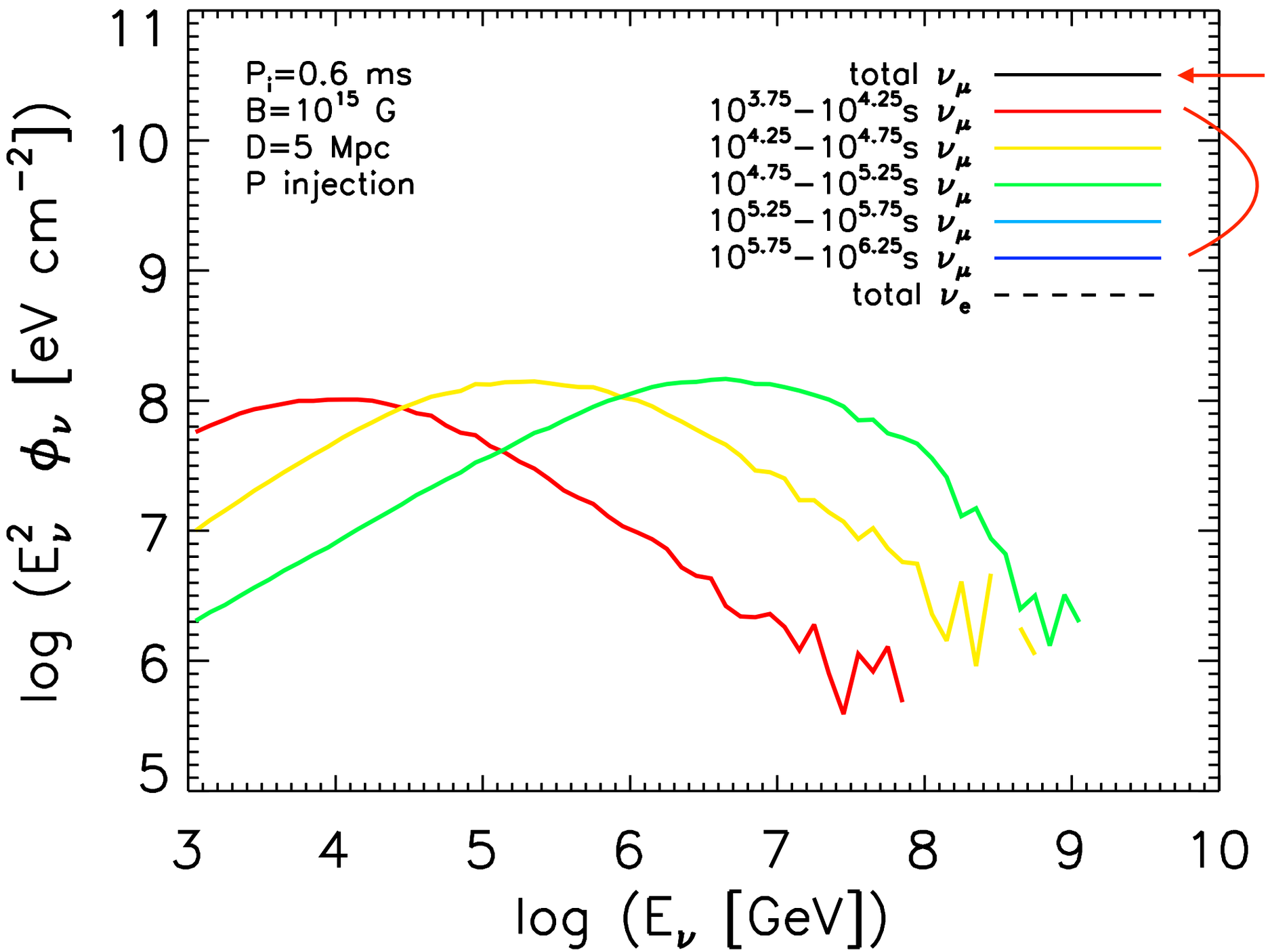


muon neutrino

system time

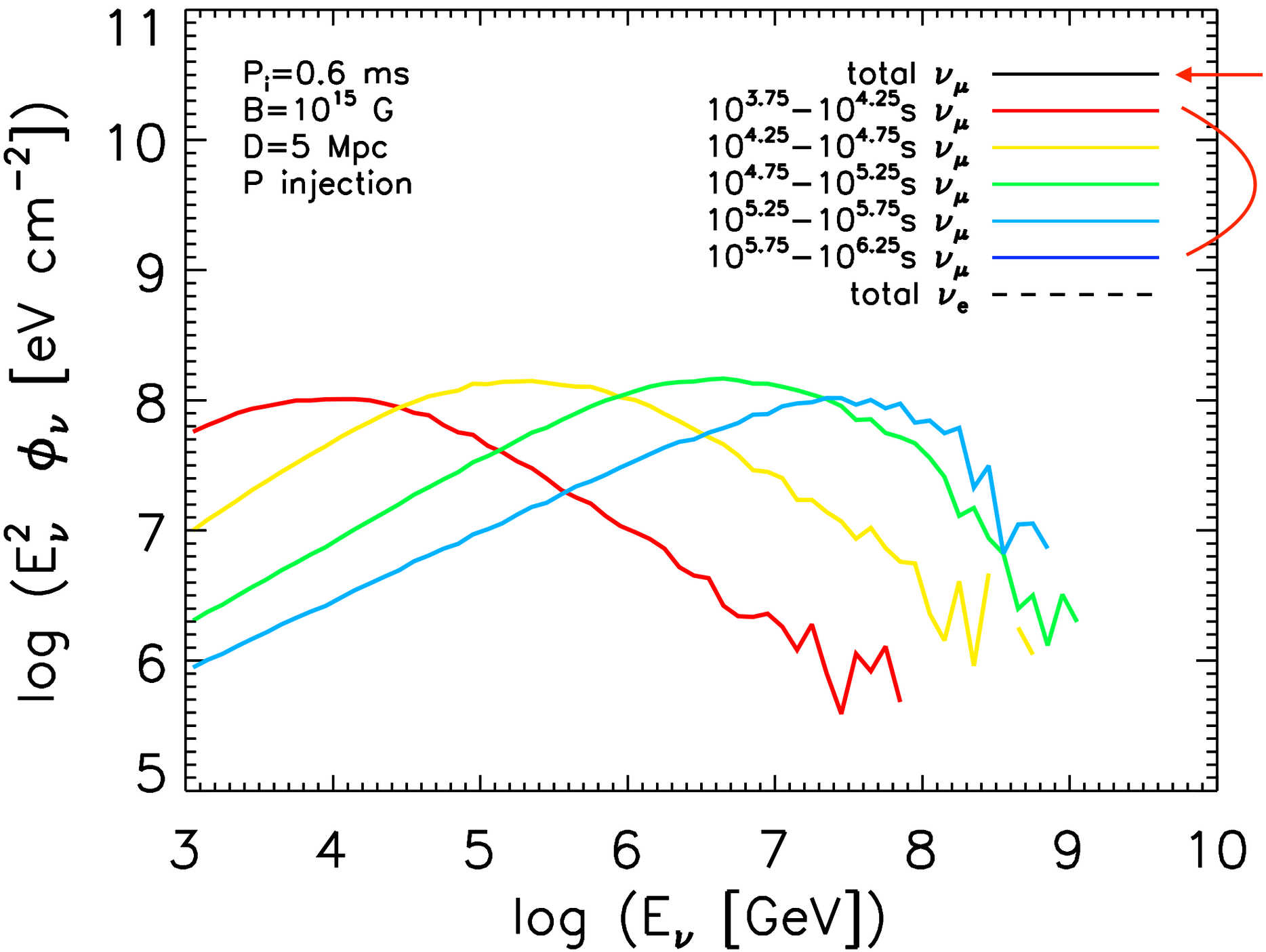
KF, JCAP 06(2015)004

Neutrino spectrum - Single Source



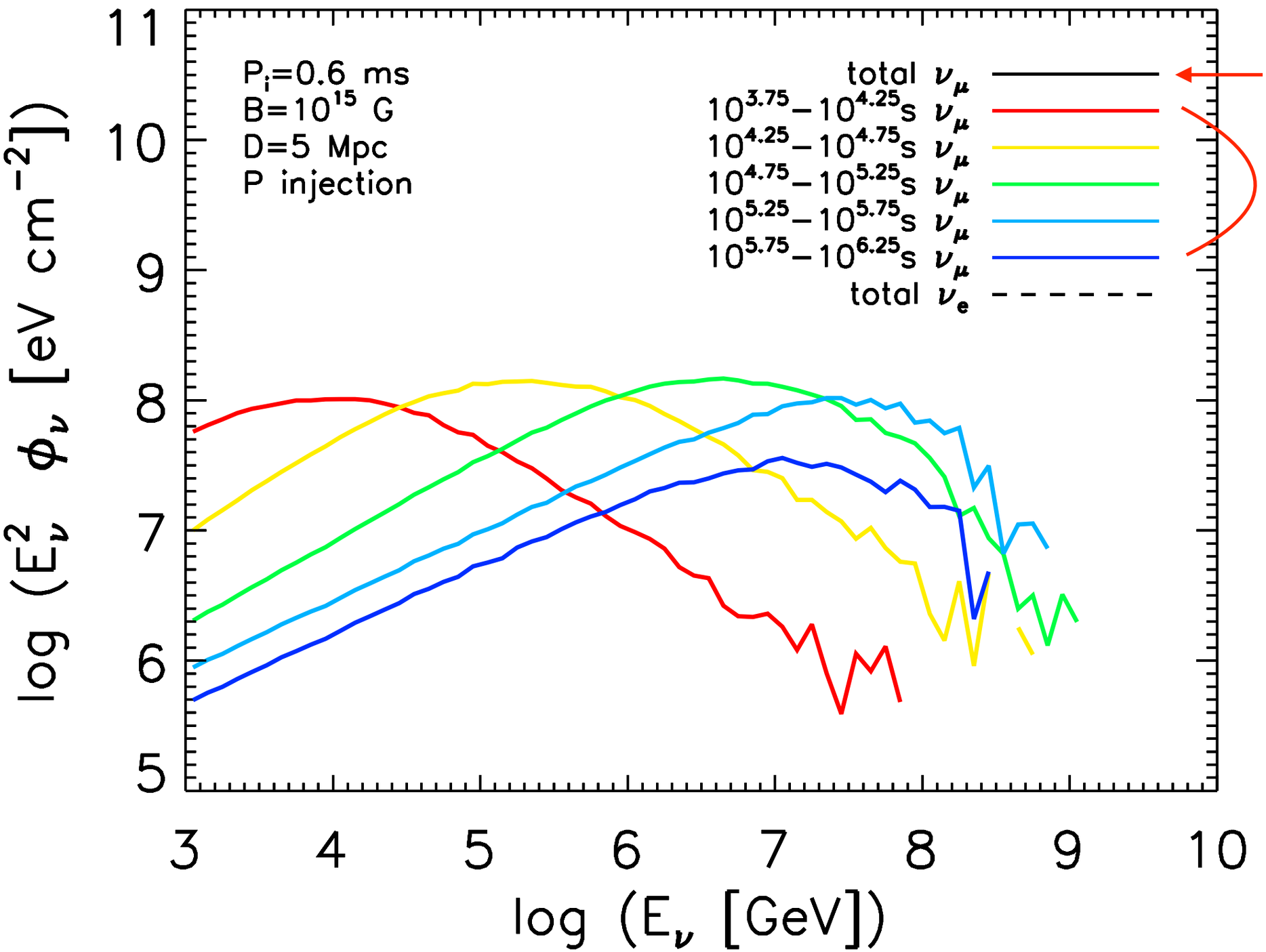
KF, JCAP 06(2015)004

Neutrino spectrum - Single Source



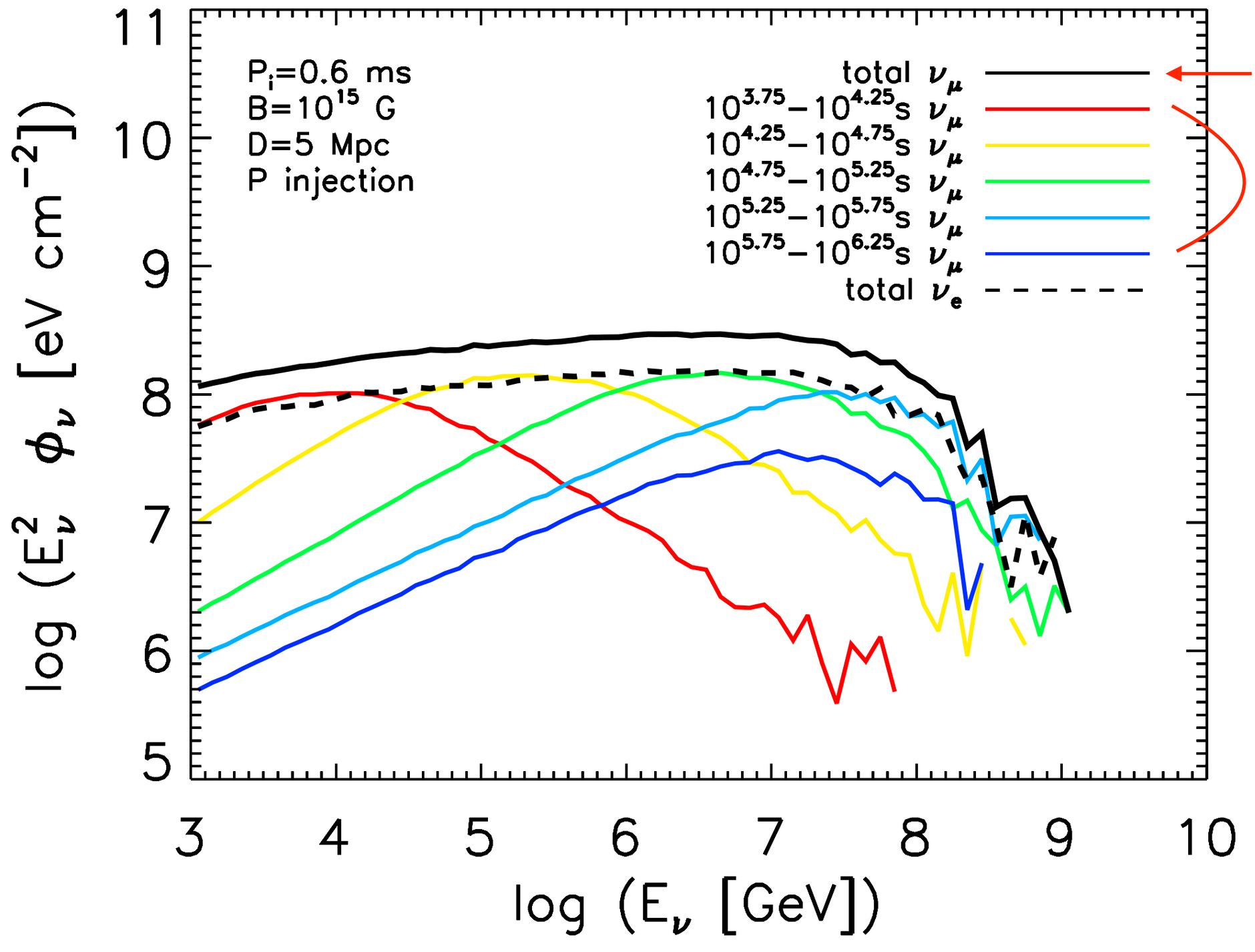
KF, JCAP 06(2015)004

Neutrino spectrum - Single Source



KF, JCAP 06(2015)004

Neutrino spectrum - Single Source

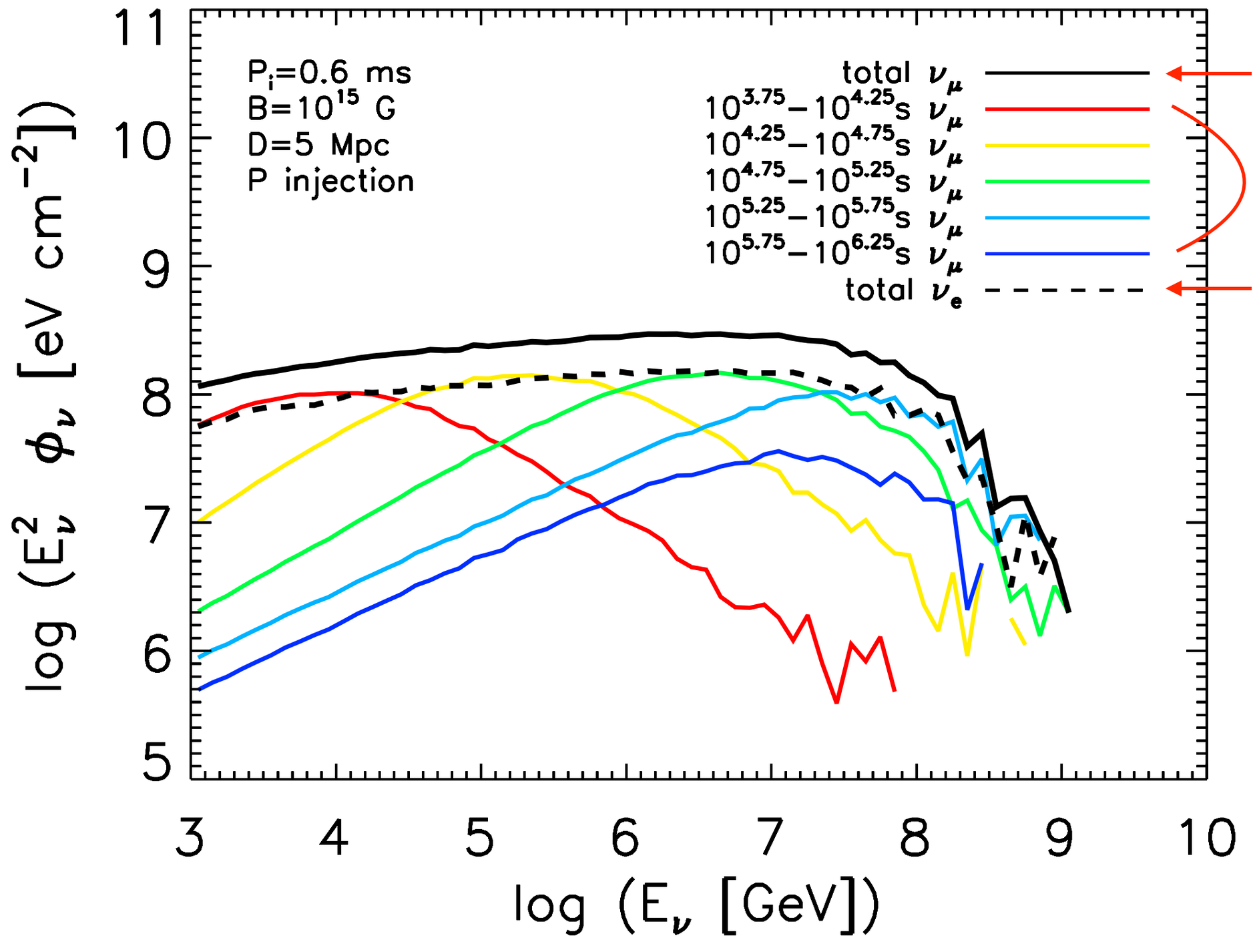


muon neutrino

system time

KF, JCAP 06(2015)004

Neutrino spectrum - Single Source



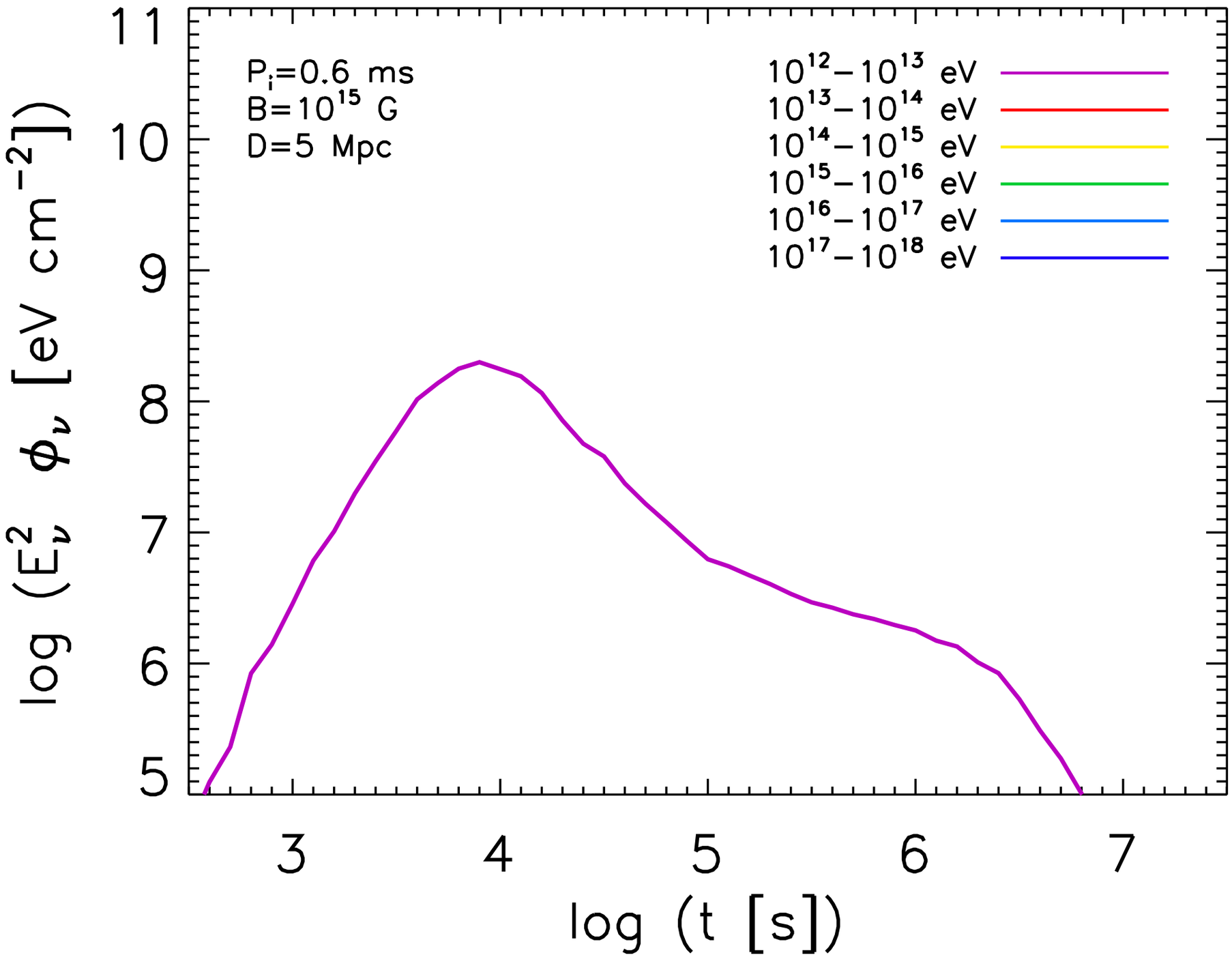
muon neutrino

system time

electron neutrino

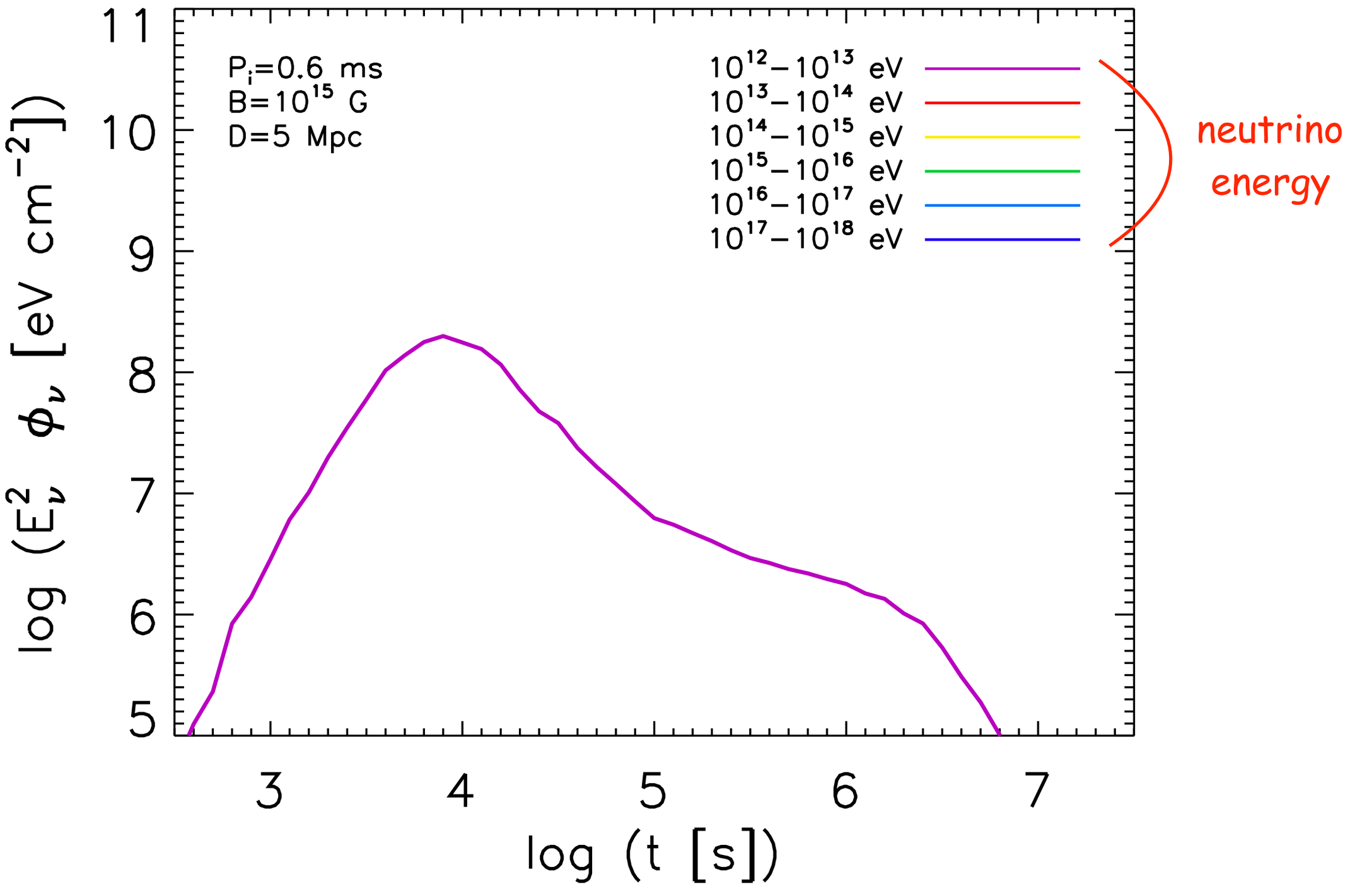
KF, JCAP 06(2015)004

Neutrino light curves - Single Source



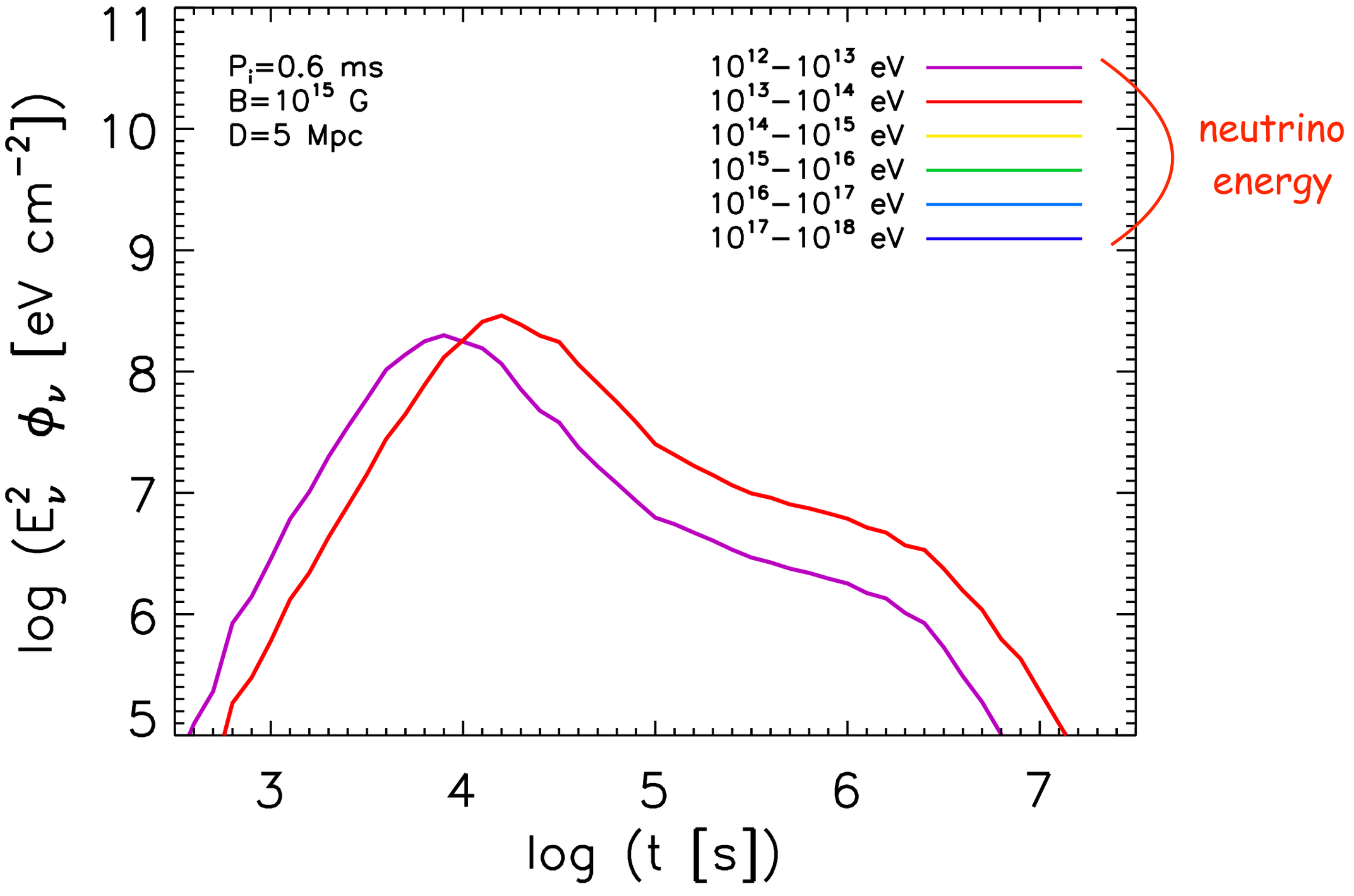
KF, JCAP 06(2015)004

Neutrino light curves - Single Source



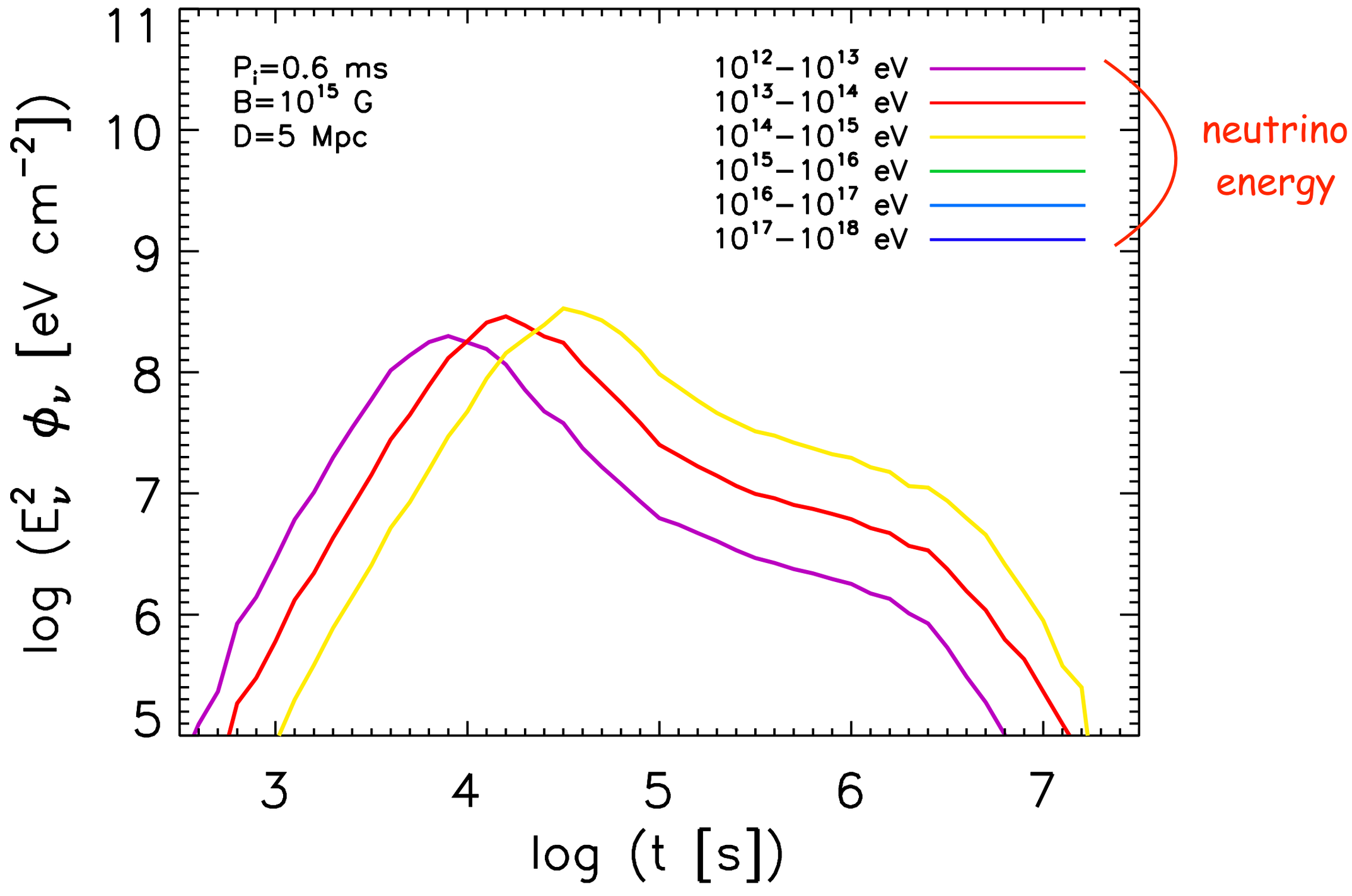
KF, JCAP 06(2015)004

Neutrino light curves - Single Source



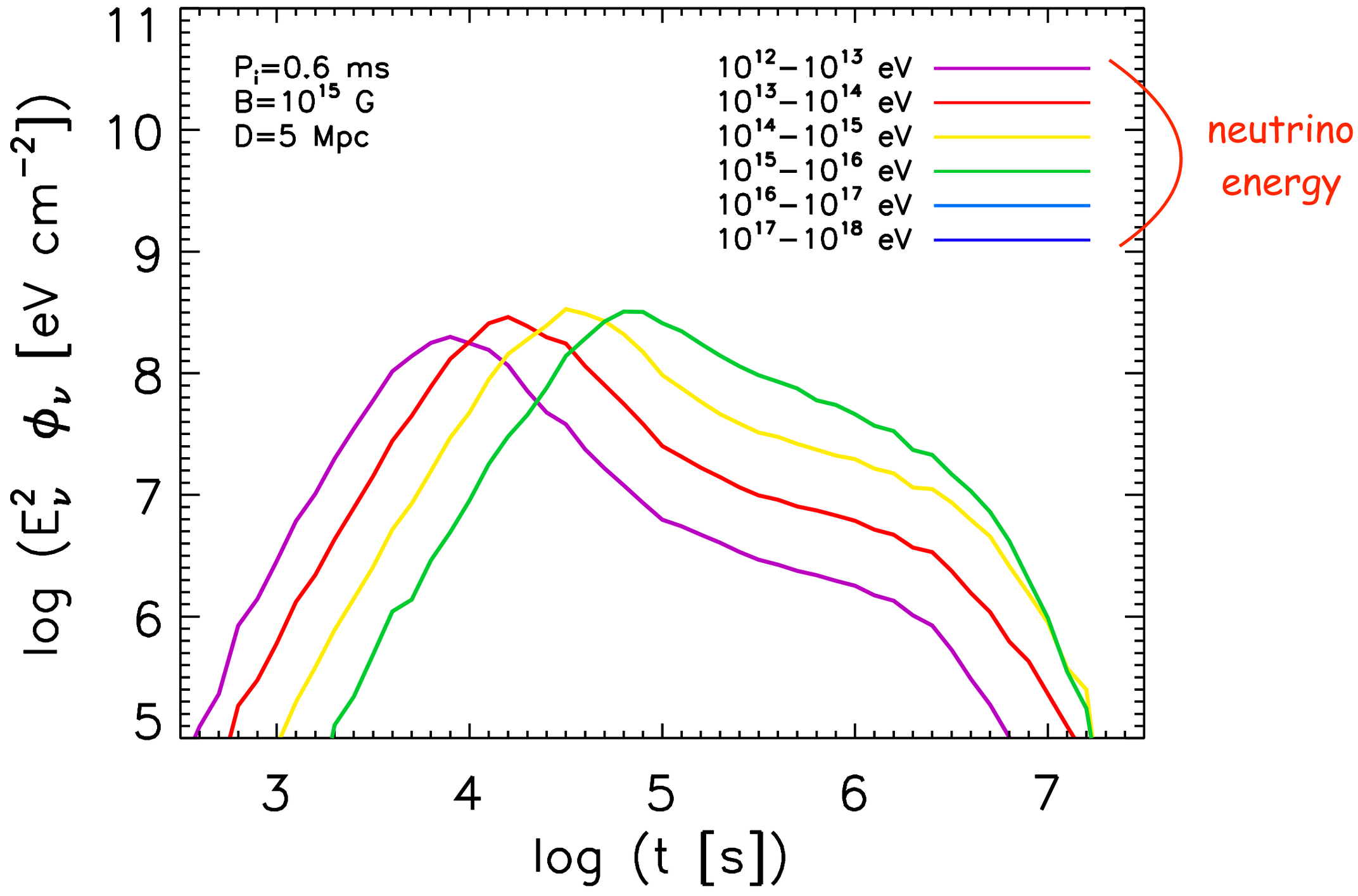
KF, JCAP 06(2015)004

Neutrino light curves - Single Source



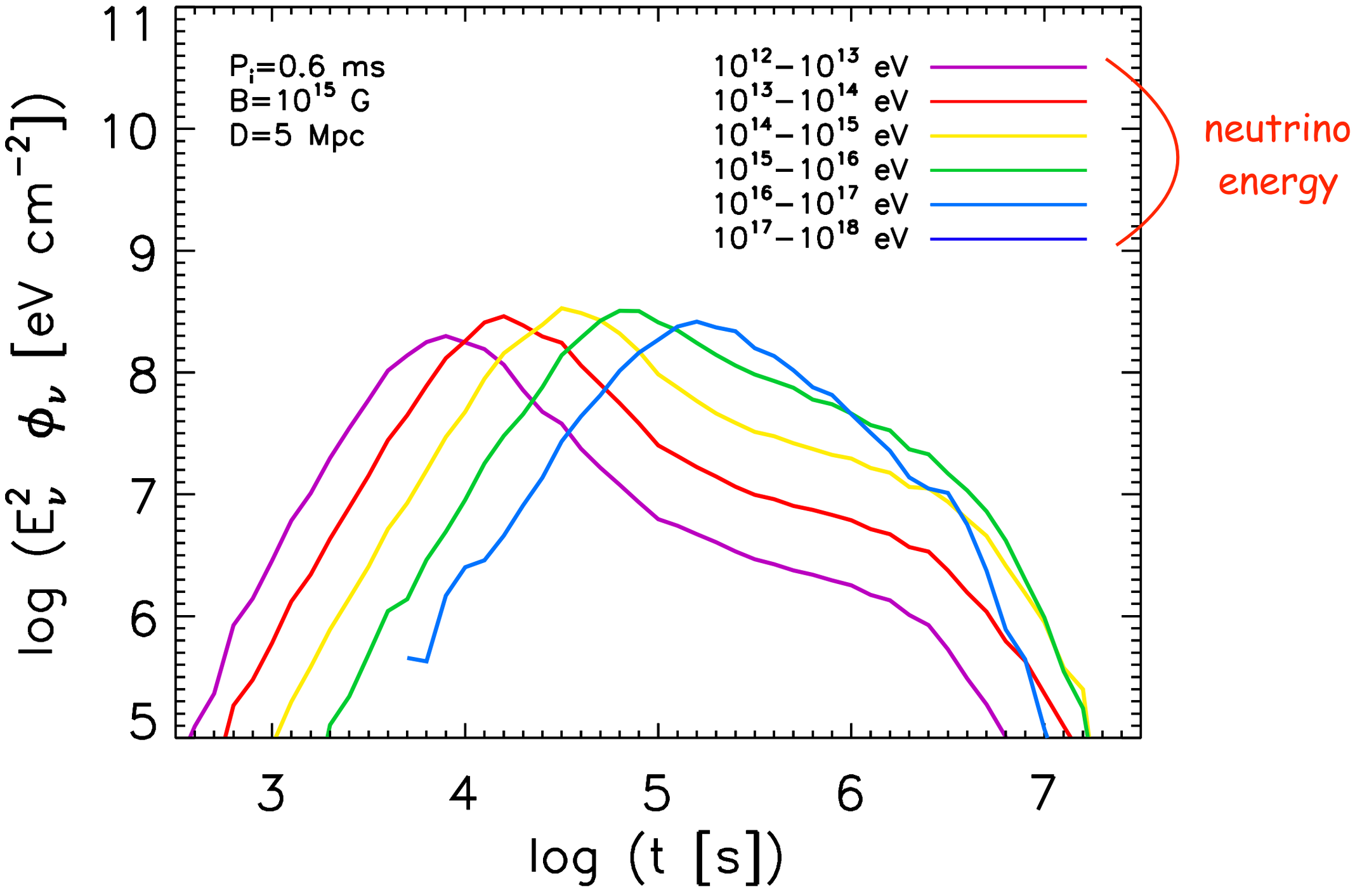
KF, JCAP 06(2015)004

Neutrino light curves - Single Source



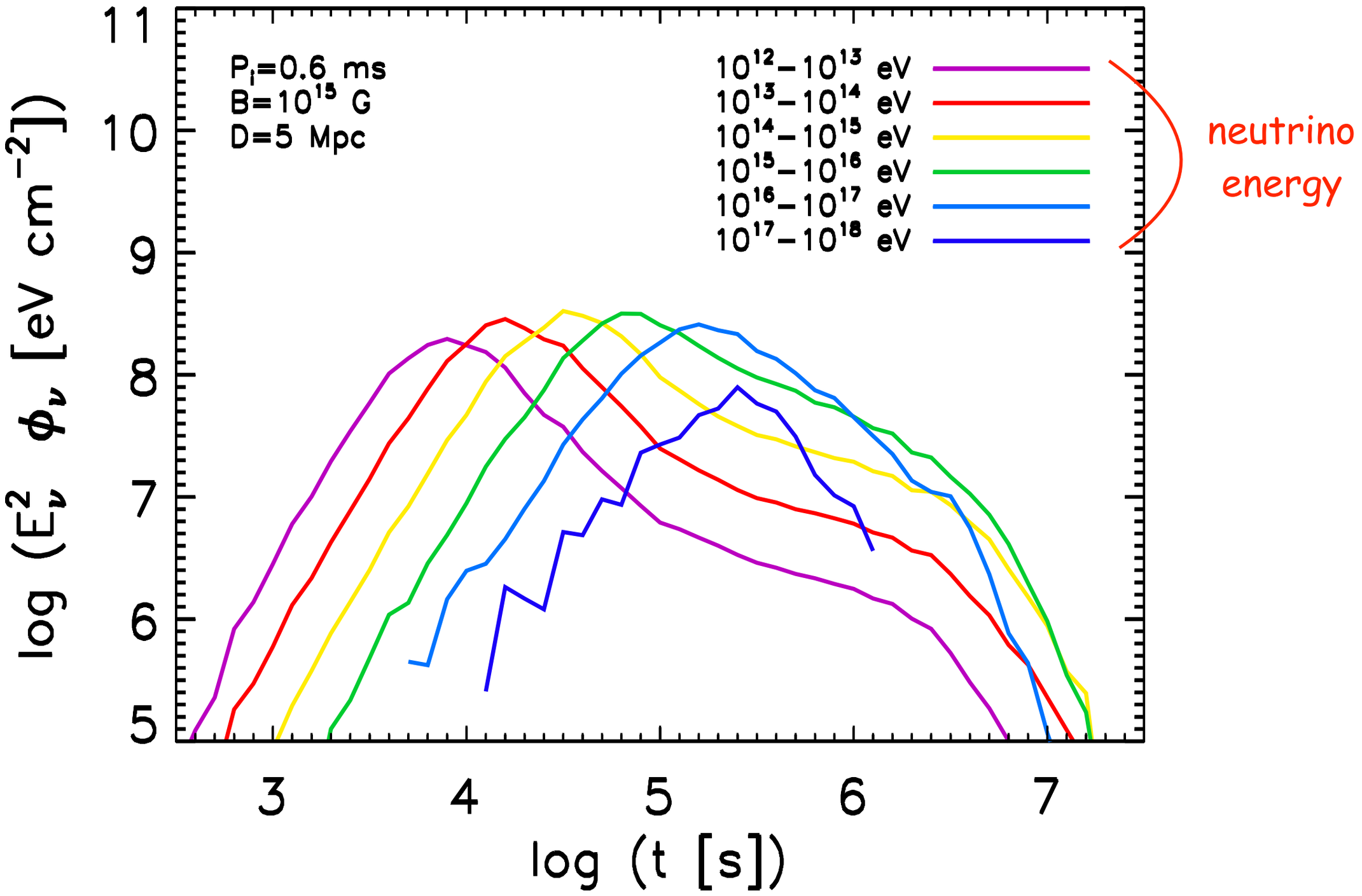
KF, JCAP 06(2015)004

Neutrino light curves - Single Source



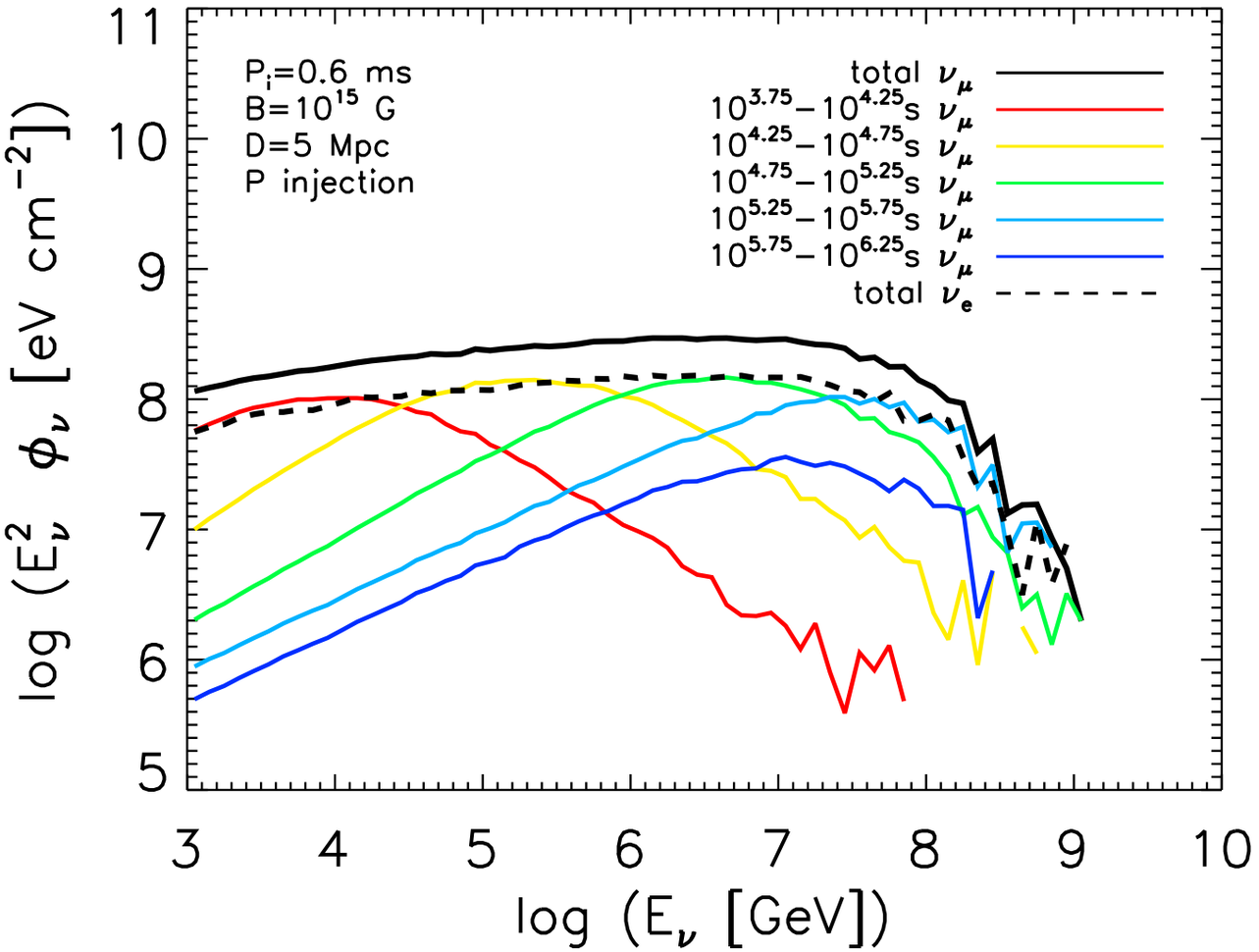
KF, JCAP 06(2015)004

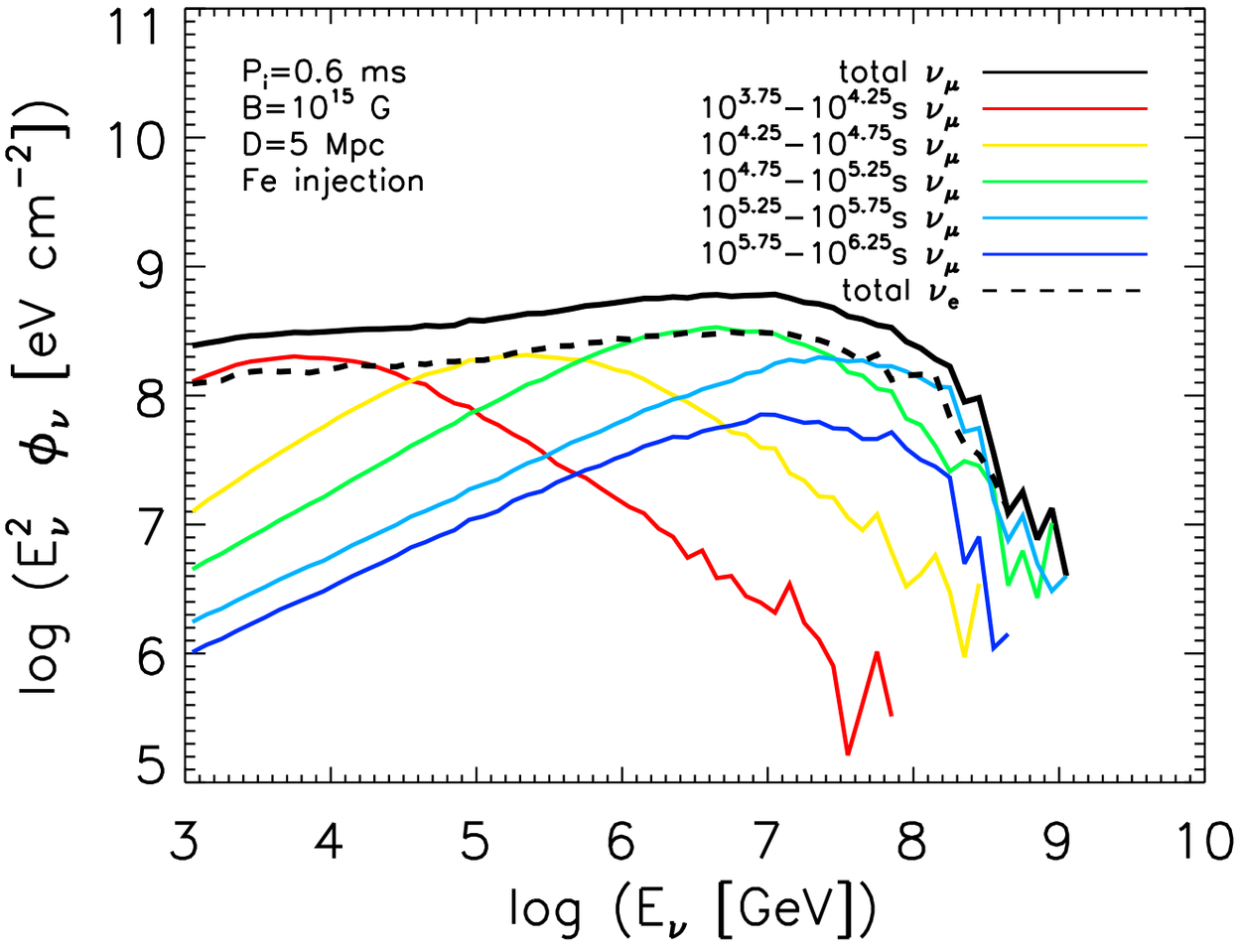
Neutrino light curves - Single Source



KF, JCAP 06(2015)004

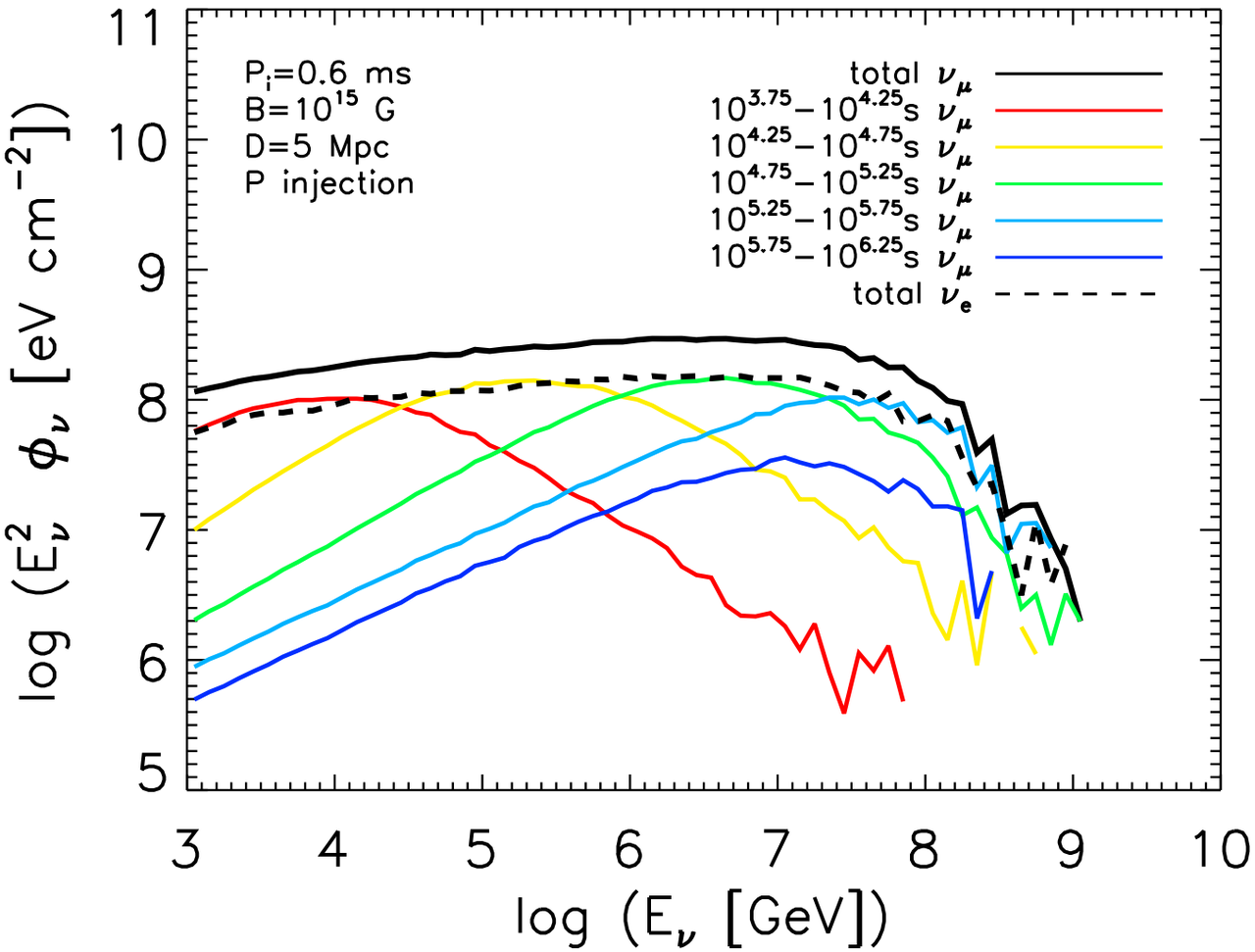
P vs. Fe

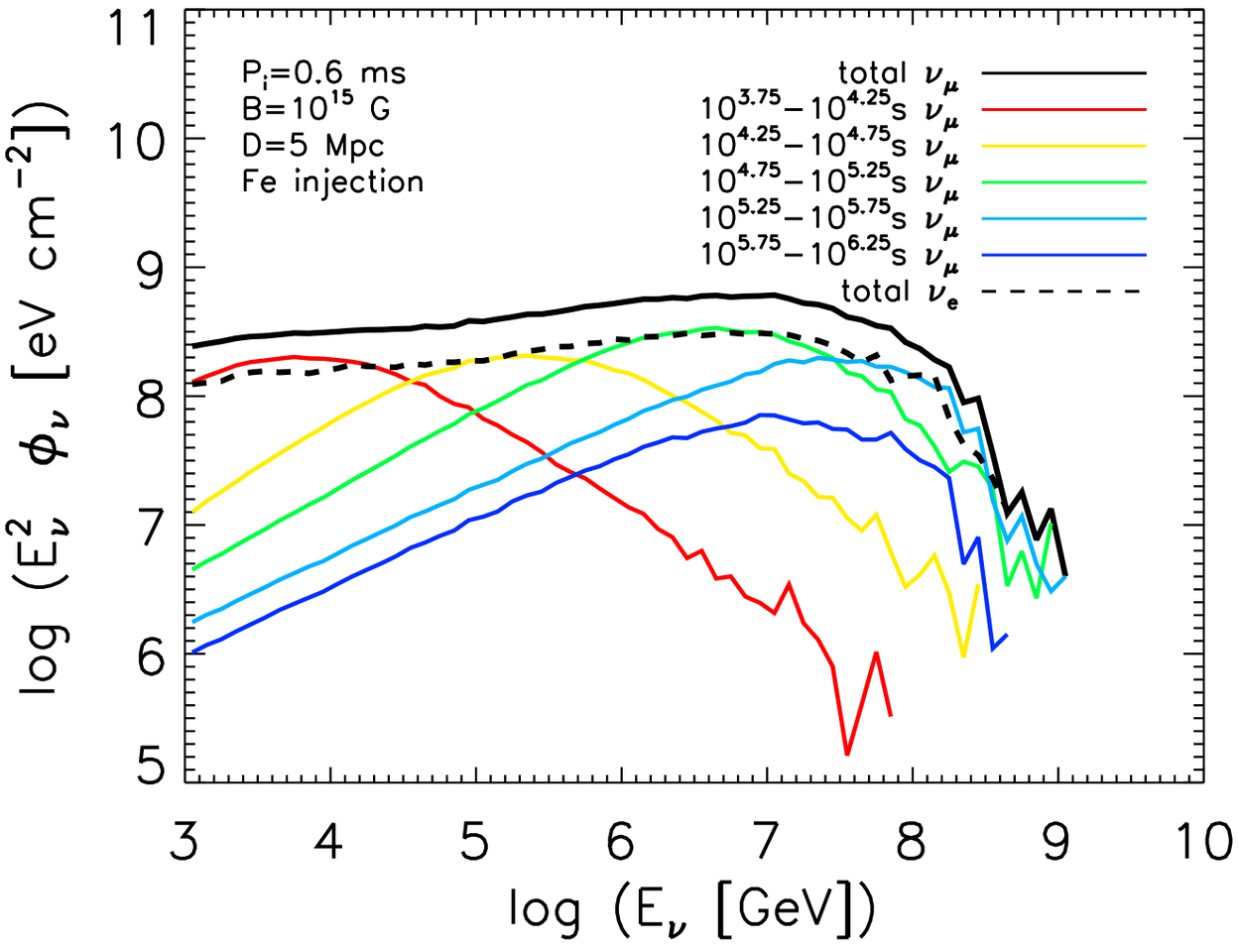




KF, JCAP 06(2015)004

P vs. Fe



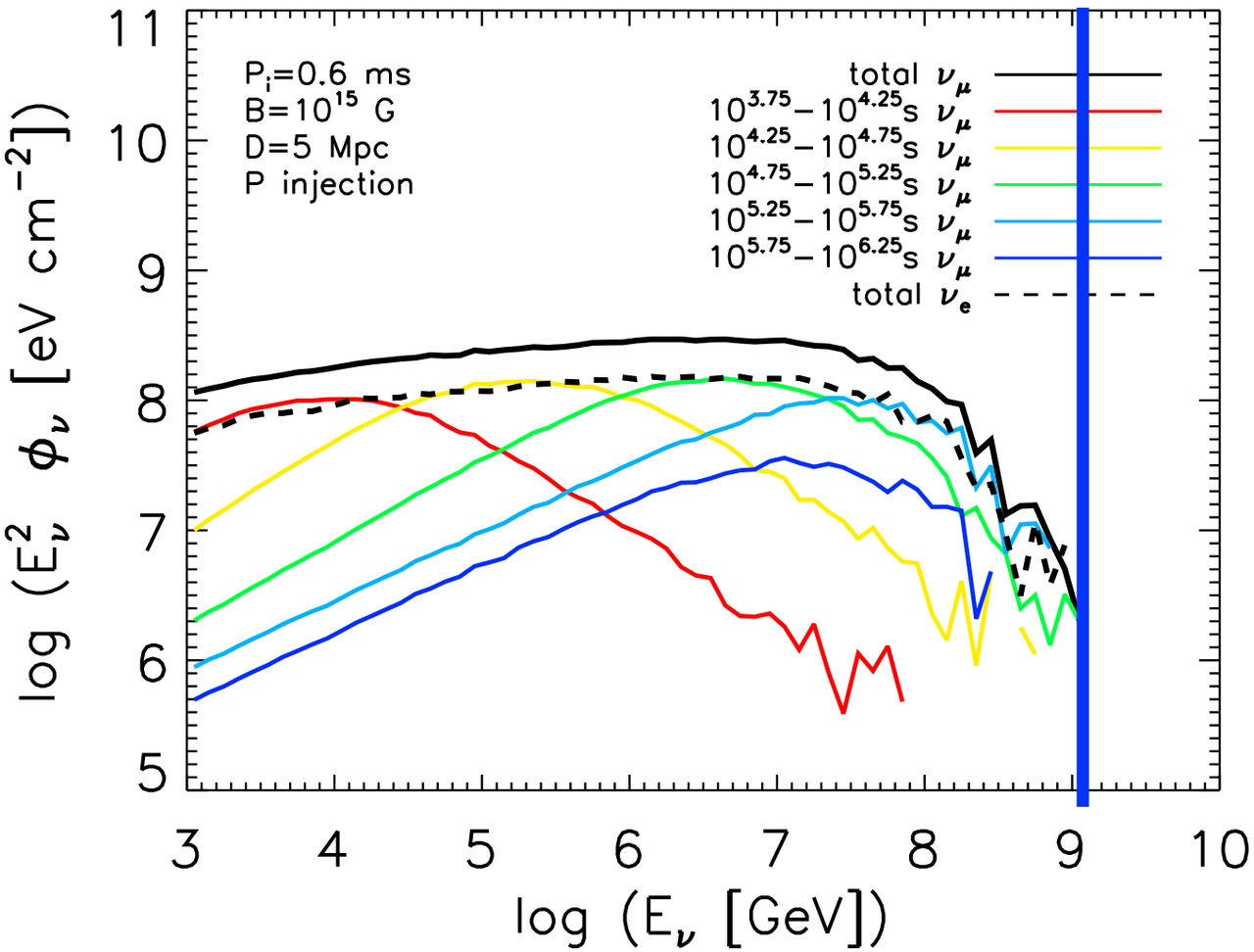


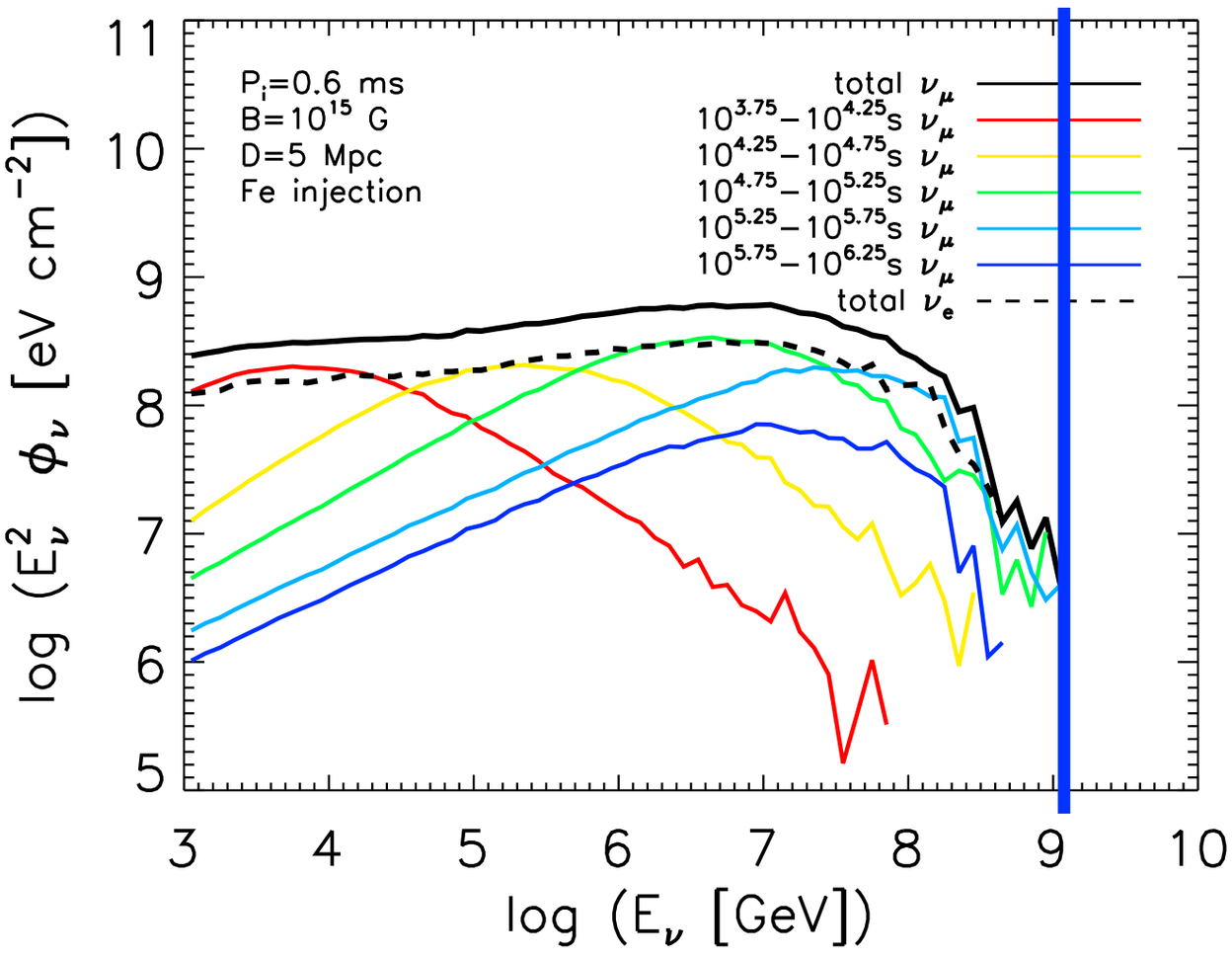
$$E_{\max} \propto A \Rightarrow E_{Fe} \approx 56 E_P$$

A/A = 1 times of Ev,max

KF, JCAP 06(2015)004

P vs. Fe



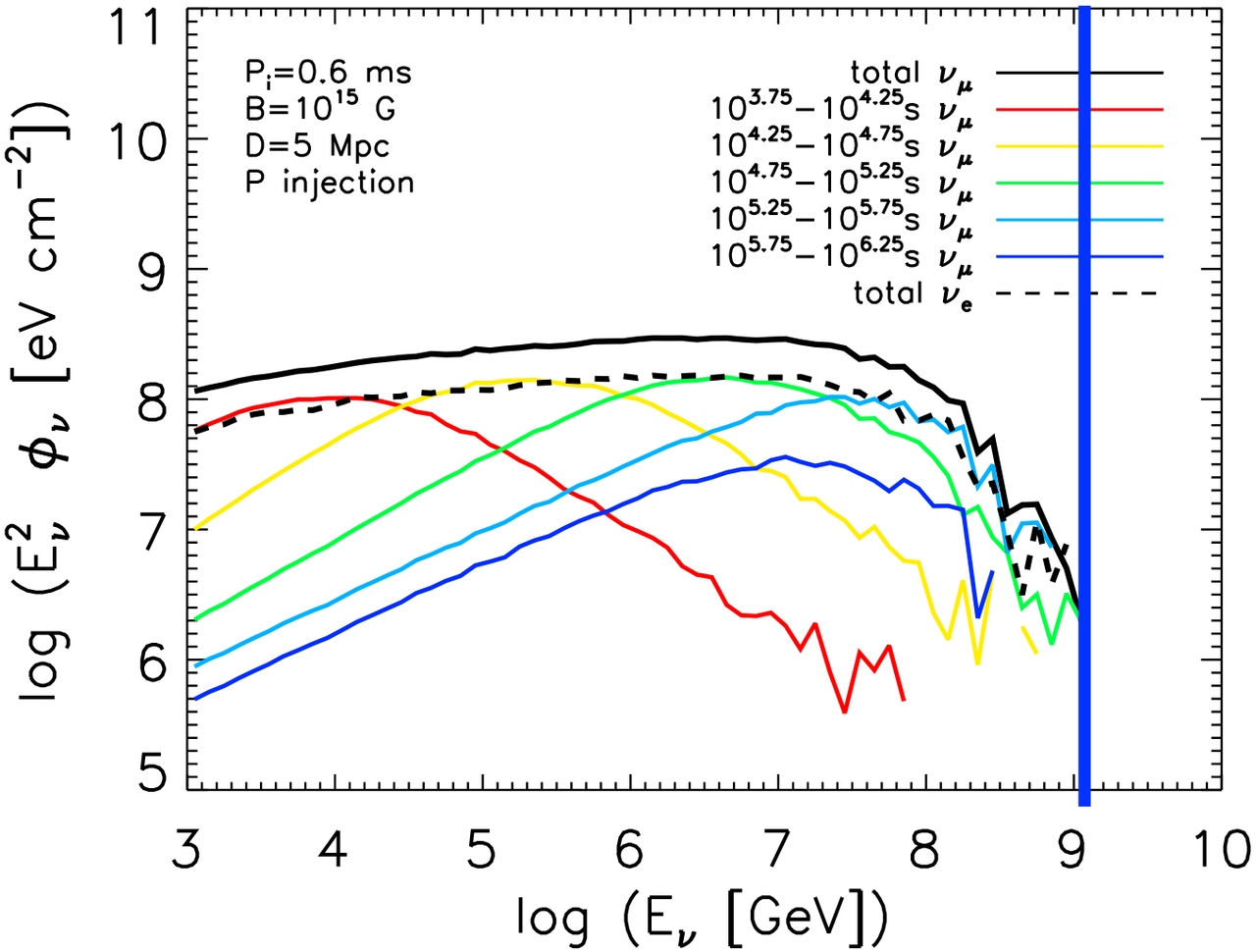


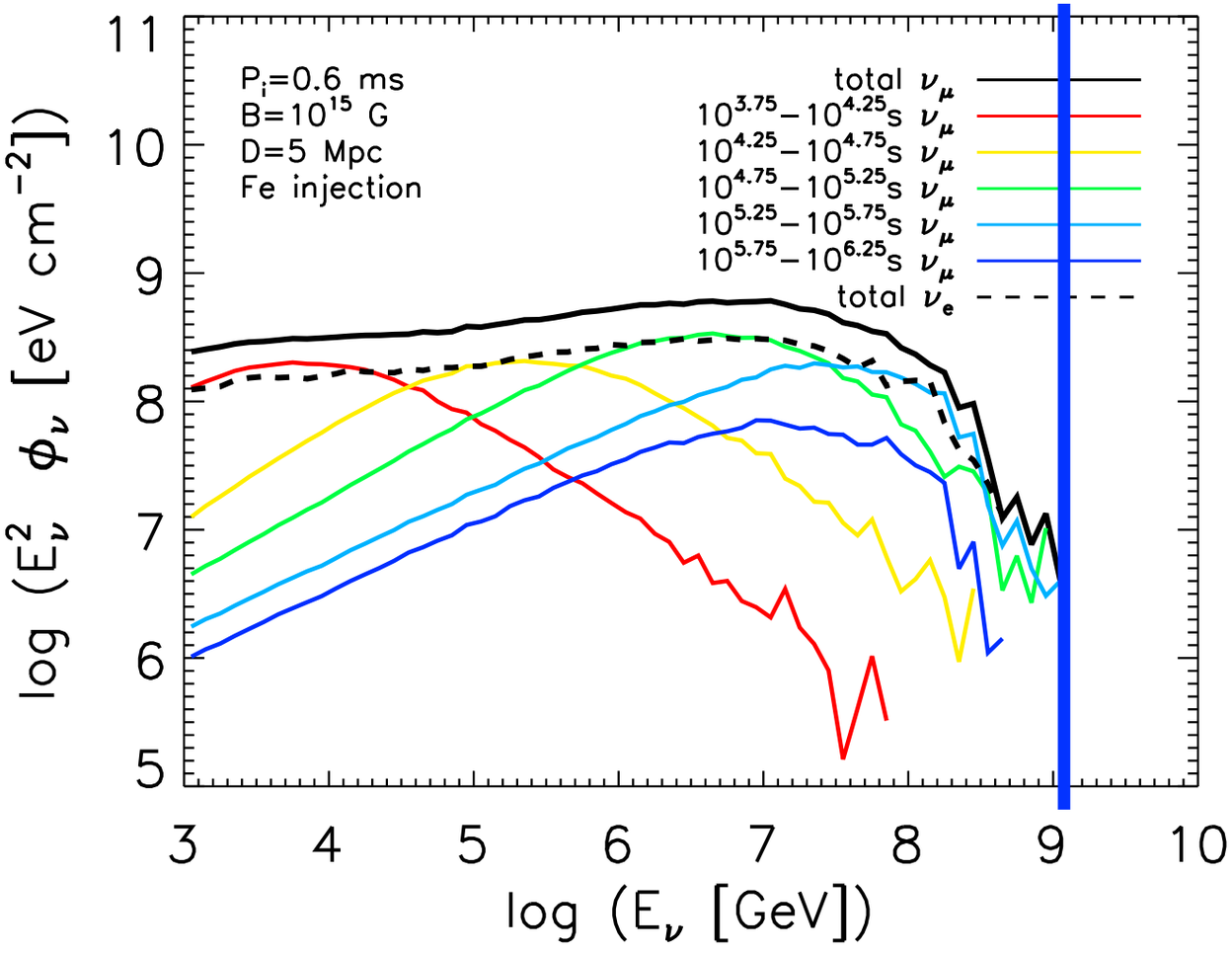
$$E_{\max} \propto A \Rightarrow E_{Fe} \approx 56 E_P$$

A/A = 1 times of Ev,max

KF, JCAP 06(2015)004

P vs. Fe





$$E_{\max} \propto A \Rightarrow E_{Fe} \approx 56 E_P$$

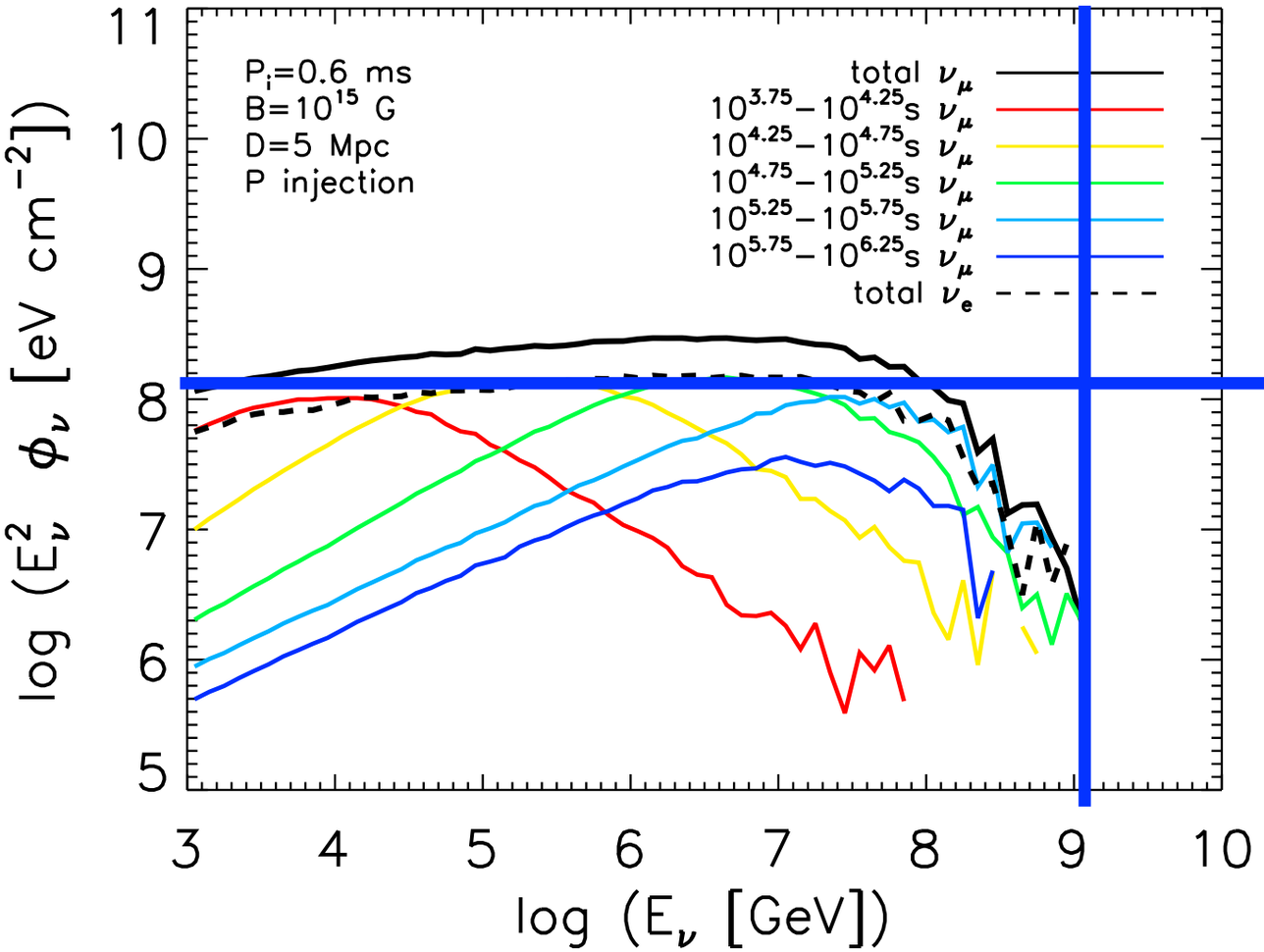
$$\dot{N} \propto \frac{1}{Z} \Rightarrow \dot{N}_{Fe} = \frac{\dot{N}_P}{26}$$

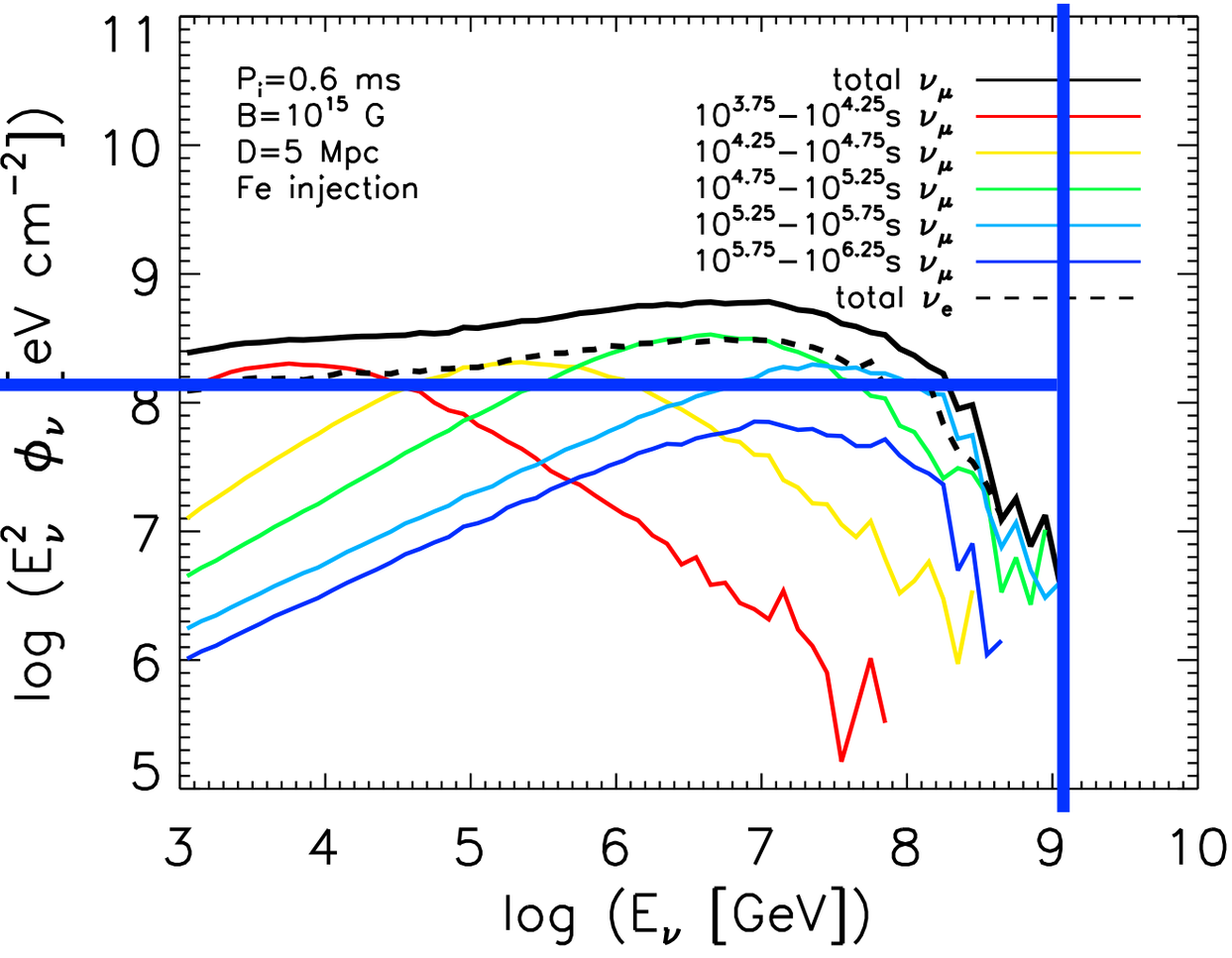
A/A = 1 times of $E_{\nu,\max}$

A/Z = 2 times of neutrino flux

KF, JCAP 06(2015)004

P vs. Fe





$$E_{\max} \propto A \Rightarrow E_{Fe} \approx 56 E_P$$

$$\dot{N} \propto \frac{1}{Z} \Rightarrow \dot{N}_{Fe} = \frac{\dot{N}_P}{26}$$

A/A = 1 times of $E_{\nu,\max}$

A/Z = 2 times of neutrino flux

KF, JCAP 06(2015)004

Cumulative Neutrinos from Pulsars

$$\Phi_\nu = \frac{dN}{dE dA dt d\Omega} = \frac{c}{4\pi} \int_0^{z_{\max}} \dot{\rho}_{\rm source}(z) \frac{dN[E(1+z)]}{dE'} (1+z) \frac{dt}{dz} dz$$

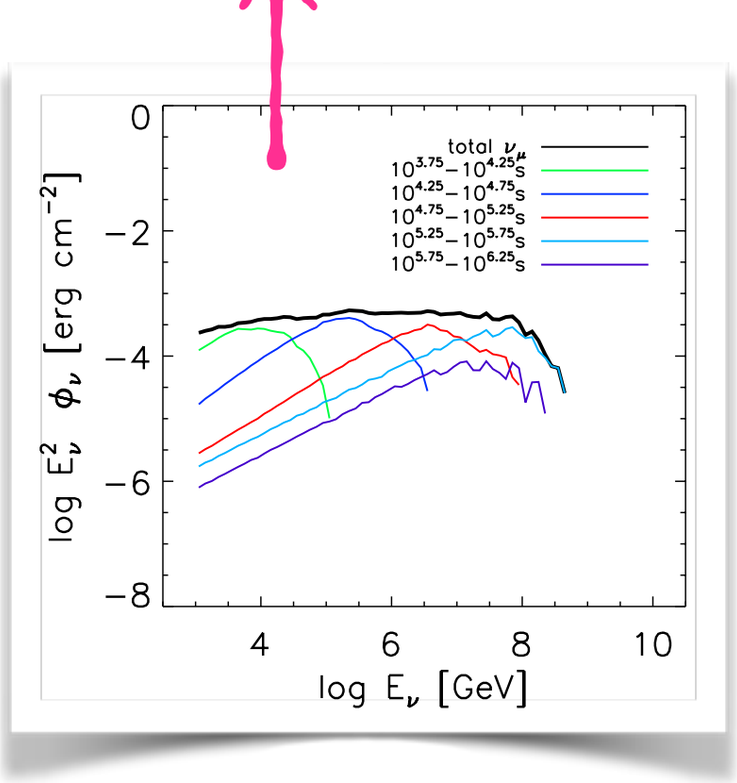
$$\frac{dN}{dE'} = f_s \int dP_i dB \, \frac{dN}{dE'}(P_i, B) f(P_i, B)$$

KF, Kotera, Murase & Olinto, PRD 90, 103005 (2014)

Cumulative Neutrinos from Pulsars

$$\Phi_\nu = \frac{dN}{dE dA dt d\Omega} = \frac{c}{4\pi} \int_0^{z_{\rm max}} \dot{\rho}_{\rm source}(z) \frac{dN[E(1+z)]}{dE'} (1+z) \frac{dt}{dz} dz$$

$$\frac{dN}{dE'} = f_s \int dP_i dB \frac{dN}{dE'}(P_i, B) f(P_i, B)$$

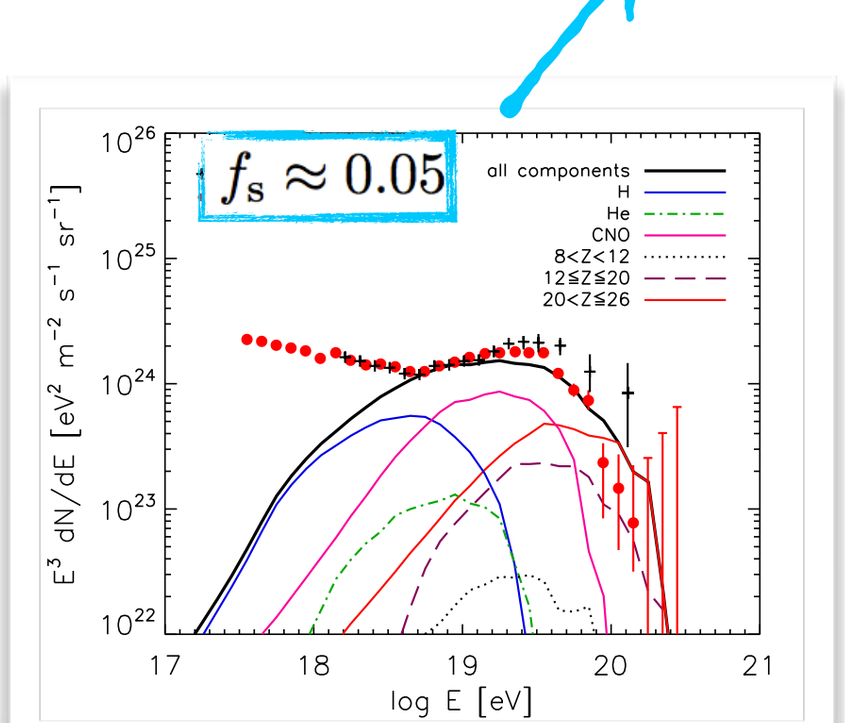


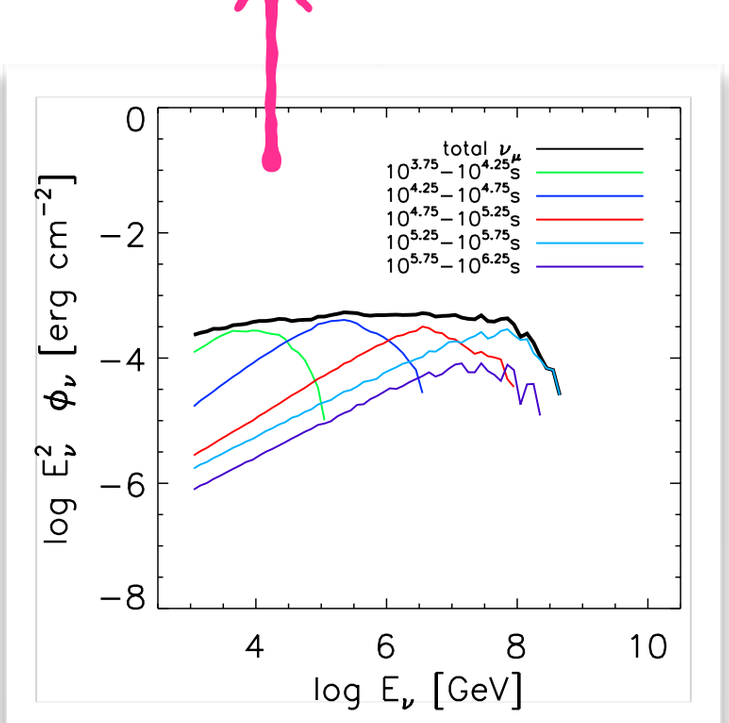
KF, Kotera, Murase & Olinto, PRD 90, 103005 (2014)

Cumulative Neutrinos from Pulsars

$$\Phi_\nu = \frac{dN}{dE dA dt d\Omega} = \frac{c}{4\pi} \int_0^{z_{\max}} \dot{\rho}_{\rm source}(z) \frac{dN[E(1+z)]}{dE'} (1+z) \frac{dt}{dz} dz$$

$$\frac{dN}{dE'} = f_s \int dP_i dB \frac{dN}{dE'}(P_i, B) f(P_i, B)$$



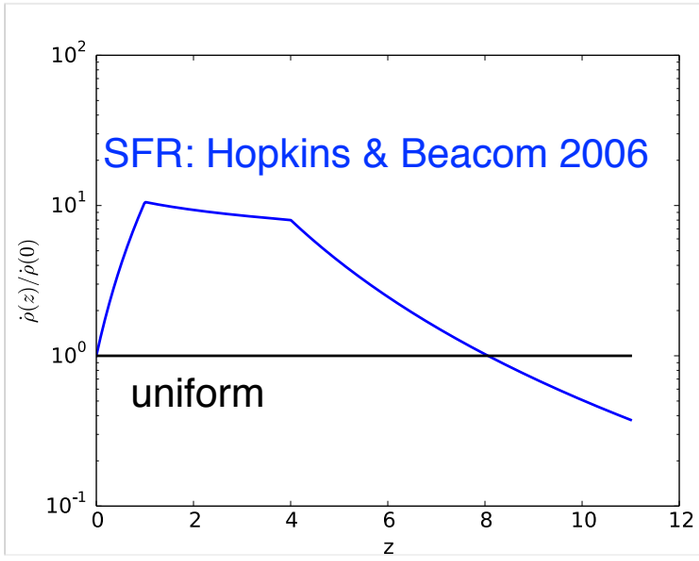


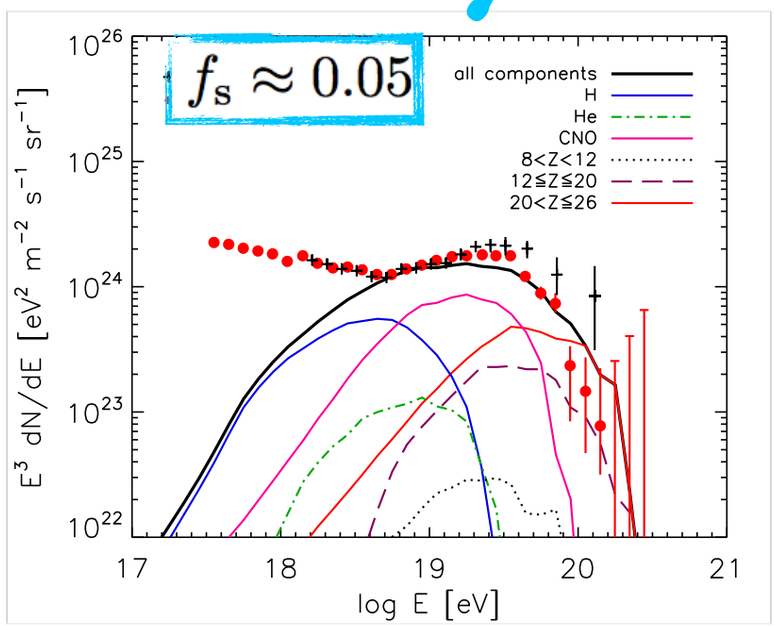
KF, Kotera, Murase & Olinto, PRD 90, 103005 (2014)

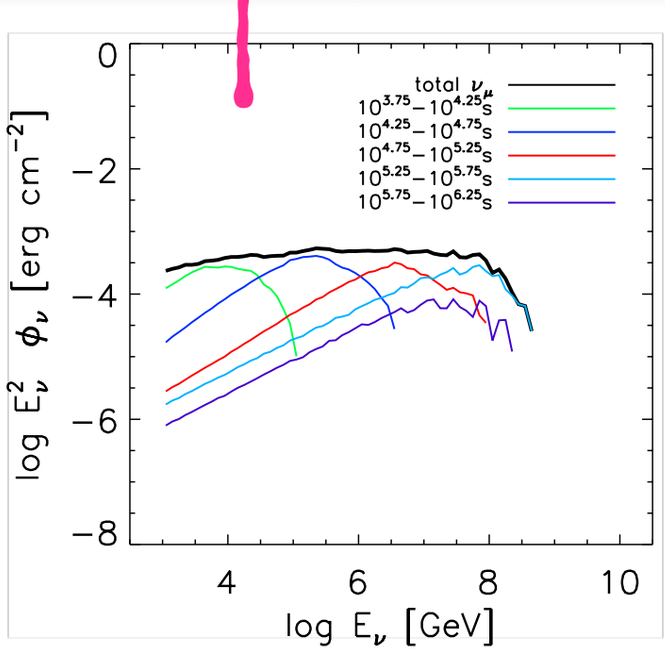
Cumulative Neutrinos from Pulsars

$$\Phi_\nu = \frac{dN}{dE dA dt d\Omega} = \frac{c}{4\pi} \int_0^{z_{\max}} \dot{\rho}_{\rm source}(z) \frac{dN[E(1+z)]}{dE'} (1+z) \frac{dt}{dz} dz$$

$$\frac{dN}{dE'} = f_s \int dP_i dB \frac{dN}{dE'}(P_i, B) f(P_i, B)$$







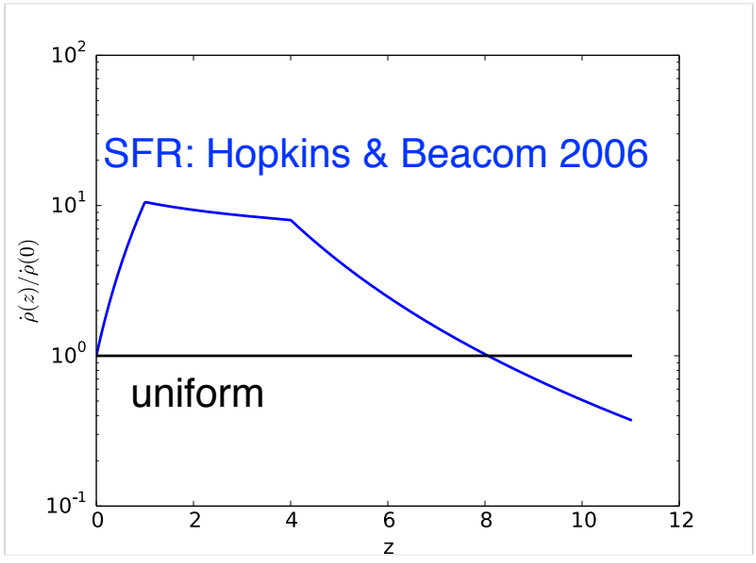
KF, Kotera, Murase & Olinto, PRD 90, 103005 (2014)

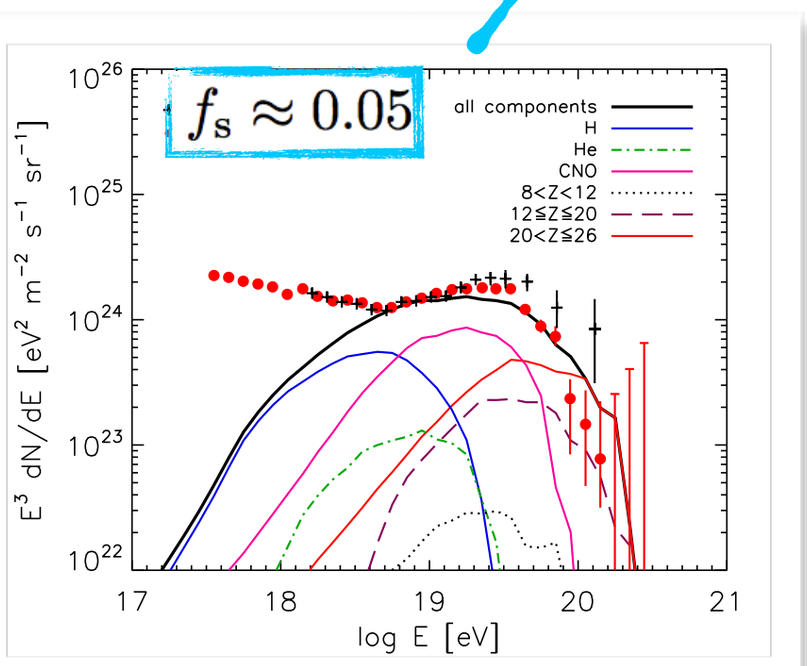
Cumulative Neutrinos from Pulsars

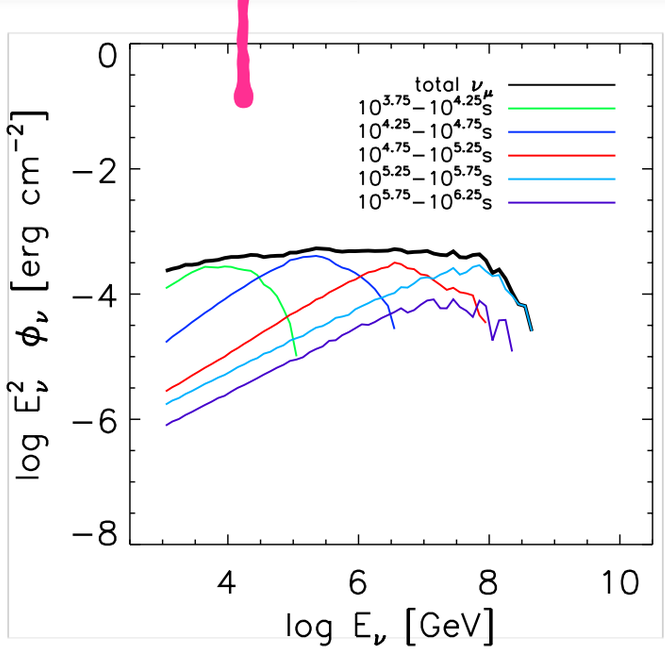
Correction to original work: redshift dependence!

$$\Phi_\nu = \frac{dN}{dE dA dt d\Omega} = \frac{c}{4\pi} \int_0^{z_{\max}} \dot{\rho}_{\rm source}(z) \frac{dN[E(1+z)]}{dE'} (1+z) \frac{dt}{dz} dz$$

$$\frac{dN}{dE'} = f_s \int dP_i dB \frac{dN}{dE'}(P_i, B) f(P_i, B)$$

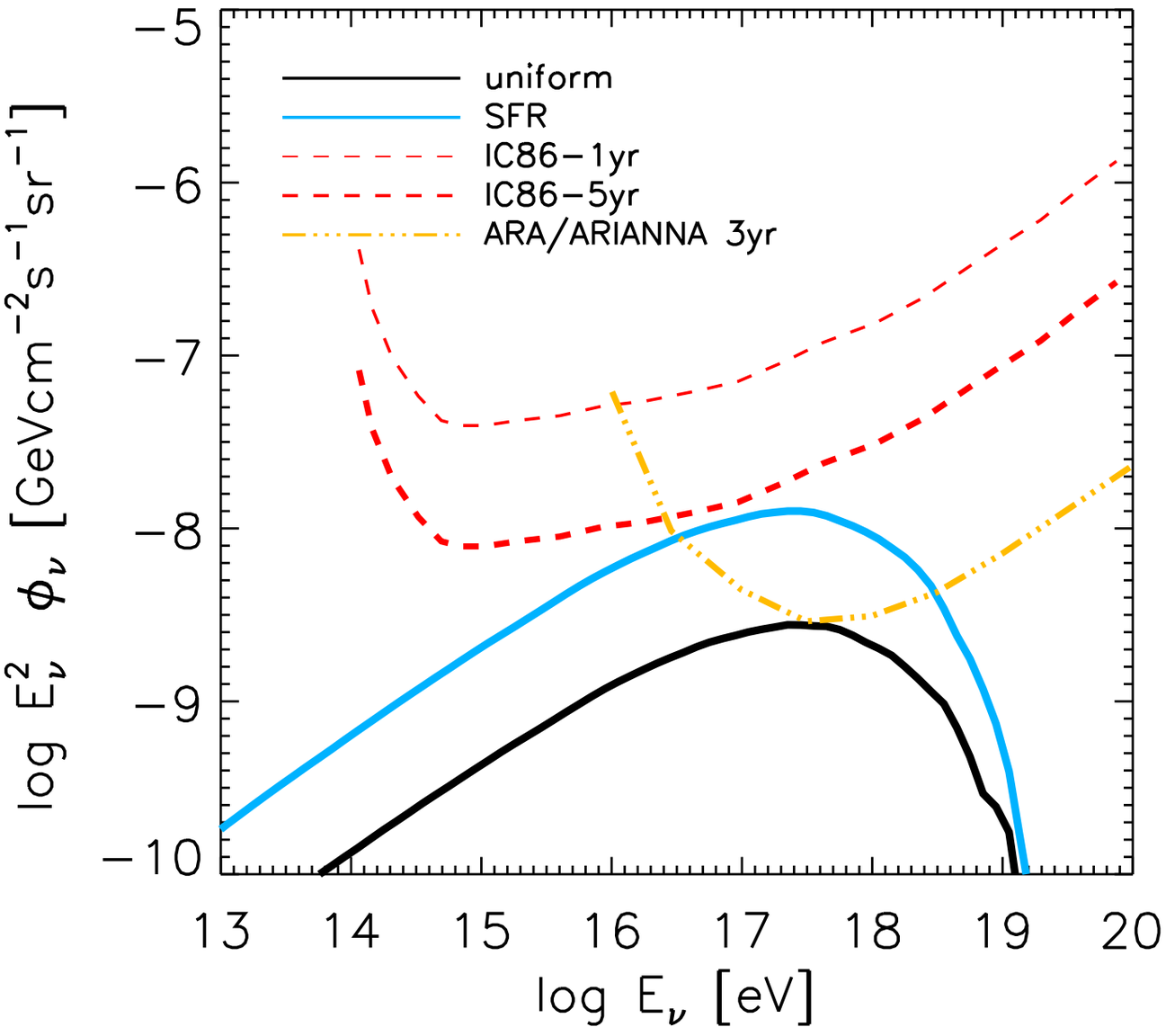






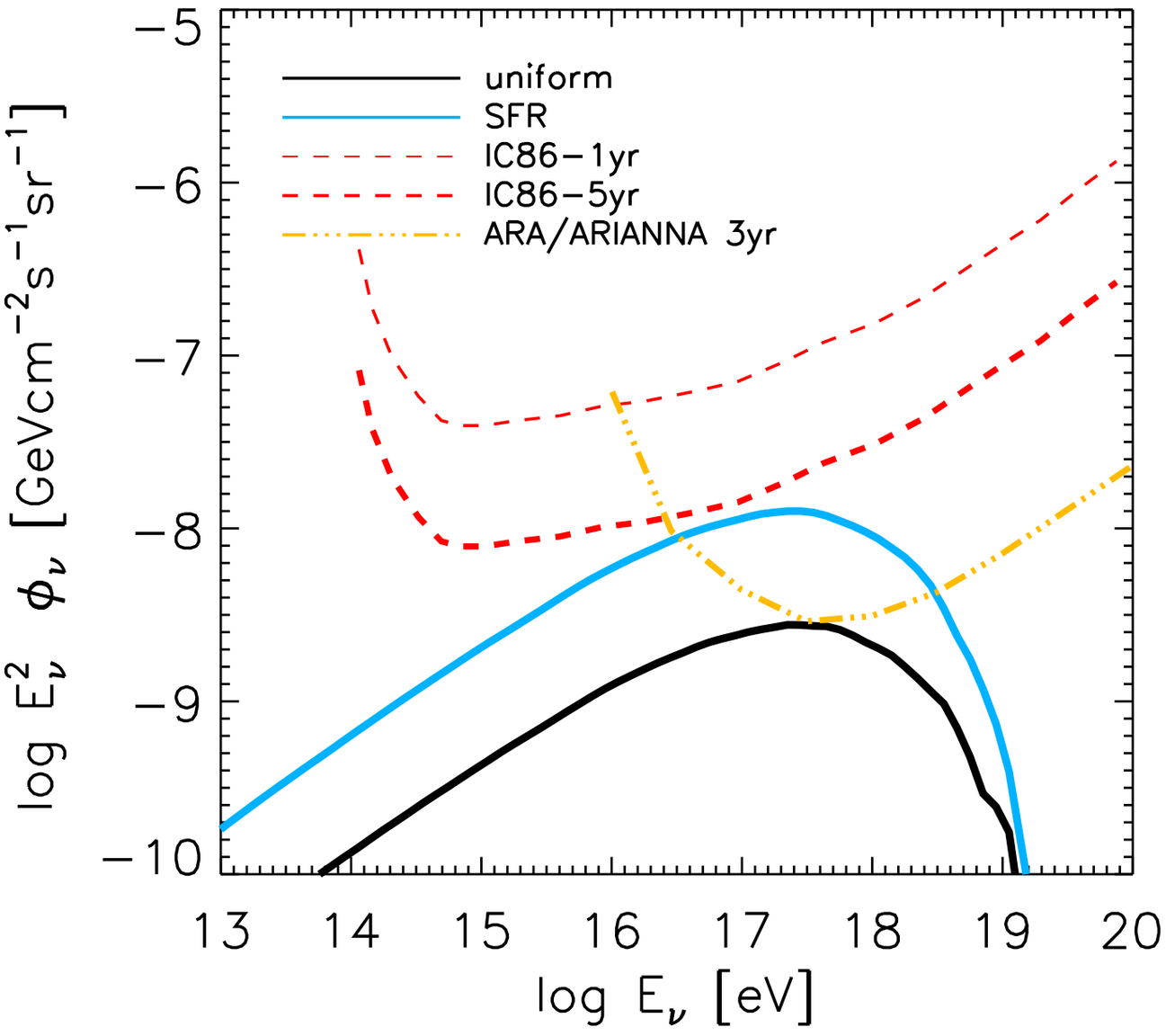
KF, Kotera, Murase & Olinto, PRD 90, 103005 (2014)

Cumulative Neutrinos - Result



KF, Kotera, Murase & Olinto, PRD 90, 103005 (2014)

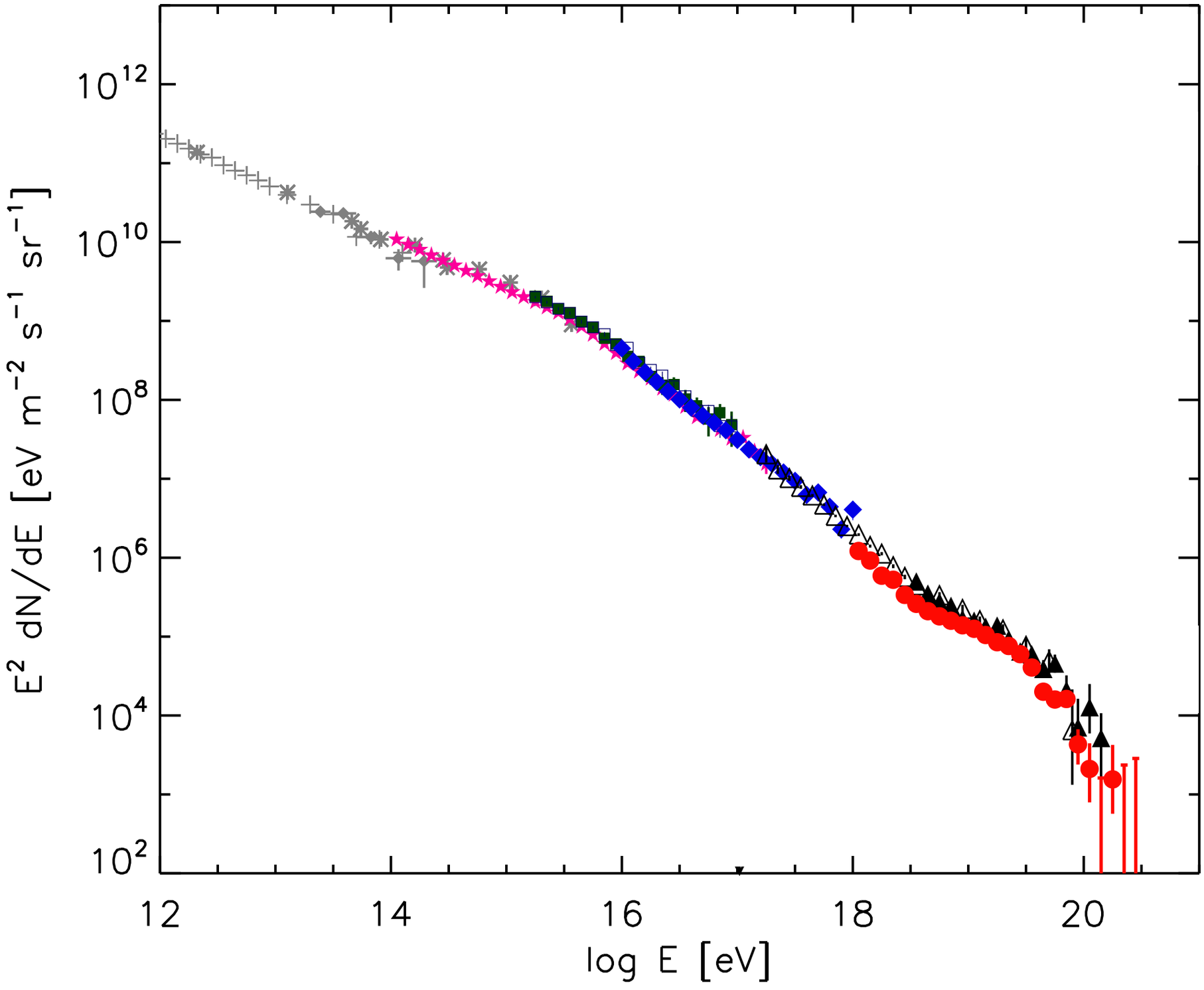
Cumulative Neutrinos - Result



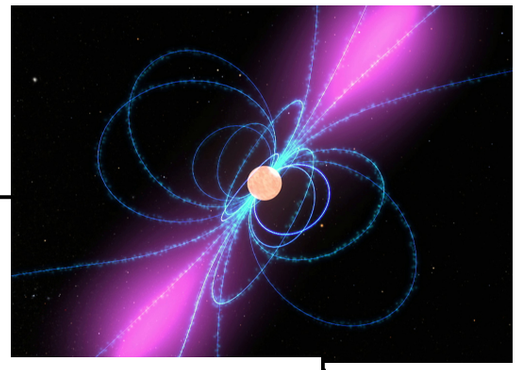
Comparable to IceCube 5-year and ARA-37 3-year sensitivities

KF, Kotera, Murase & Olinto, PRD 90, 103005 (2014)

Summary


10^{12}
10^{10}
10^{8}
10^{6}
10^{4}
10^{2}
E^2 dN/dE [eV m^{-2} s^{-1} sr^{-1}]
12
14
16
18
20
log E [eV]

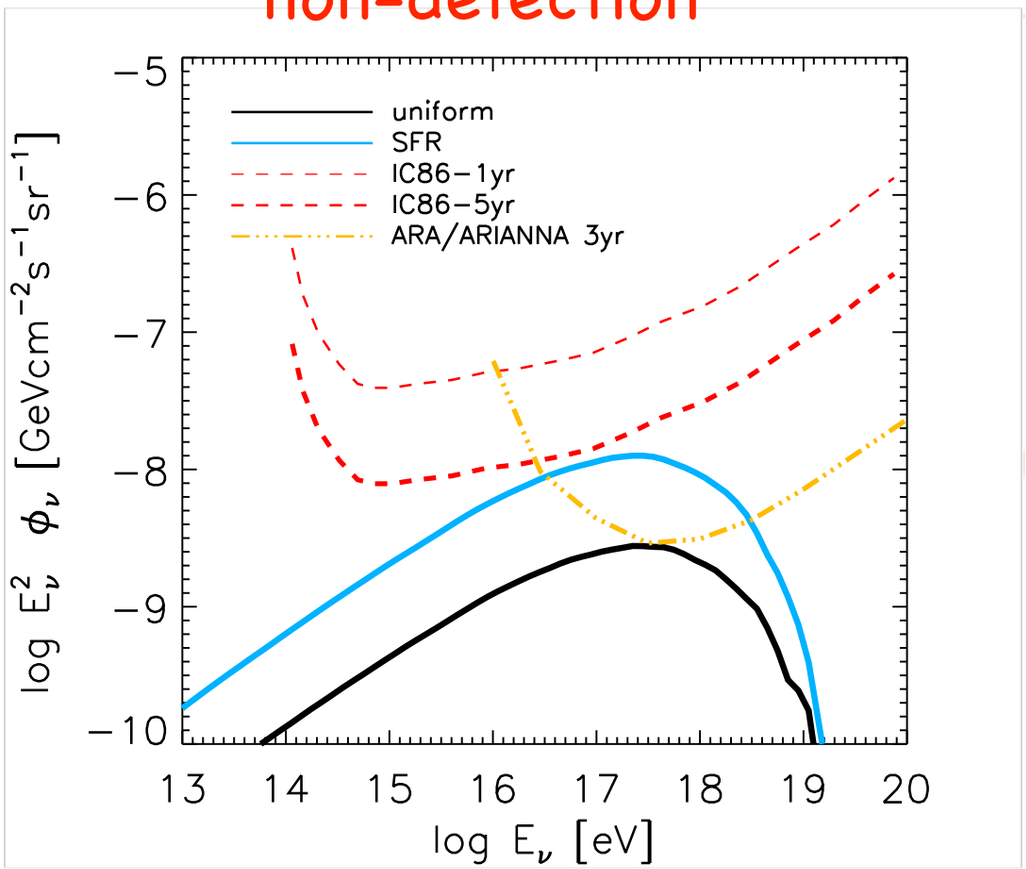
Summary

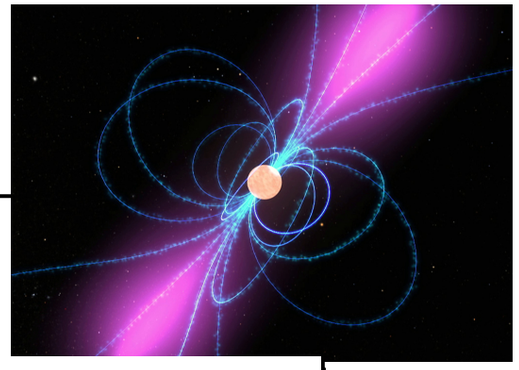


Galactic newborn pulsars
above the knee,
Extragalactic newborn pulsars
above the ankle

Summary

Neutrinos consistent with non-detection





Galactic newborn pulsars above the knee,
Extragalactic newborn pulsars above the ankle