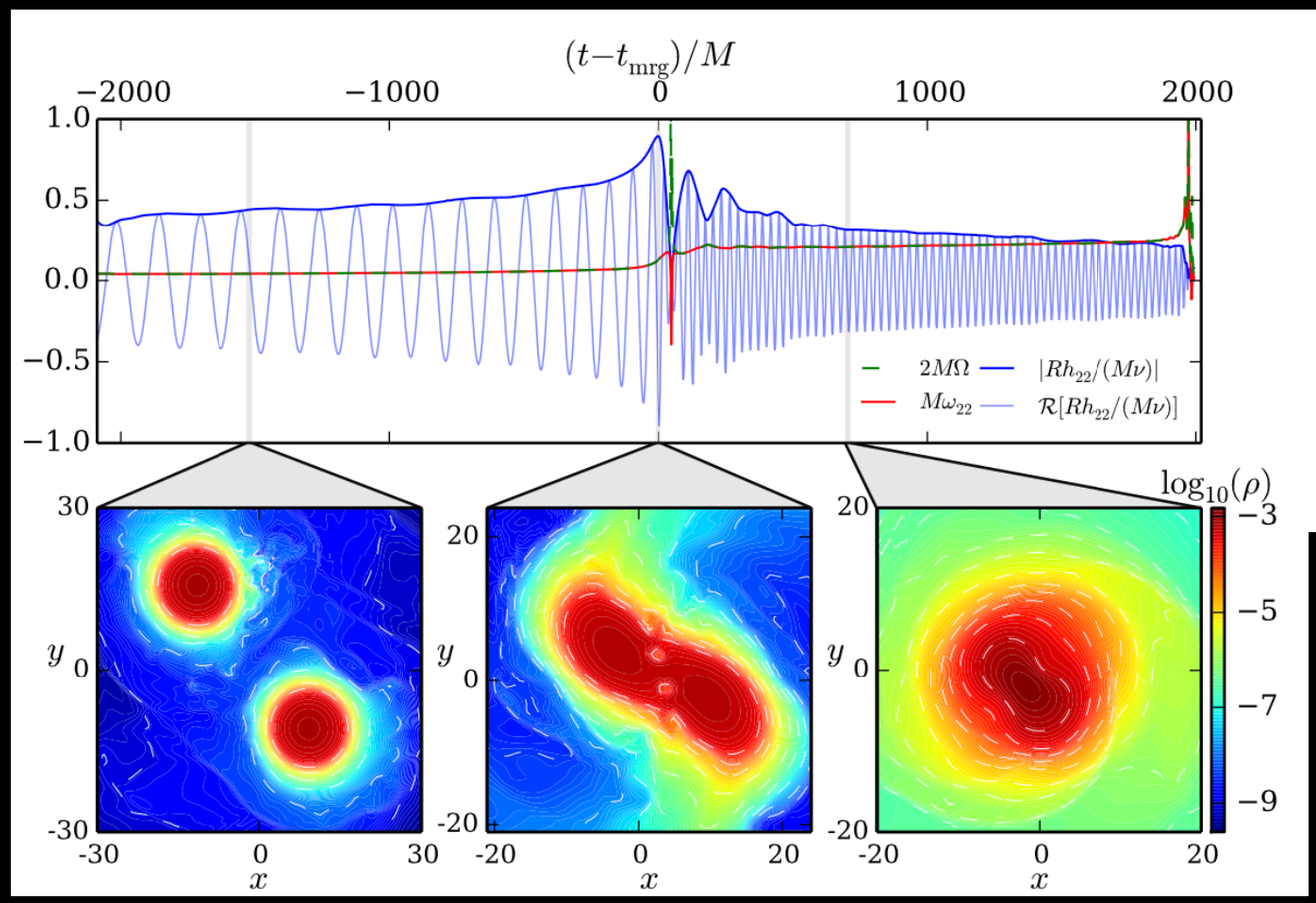
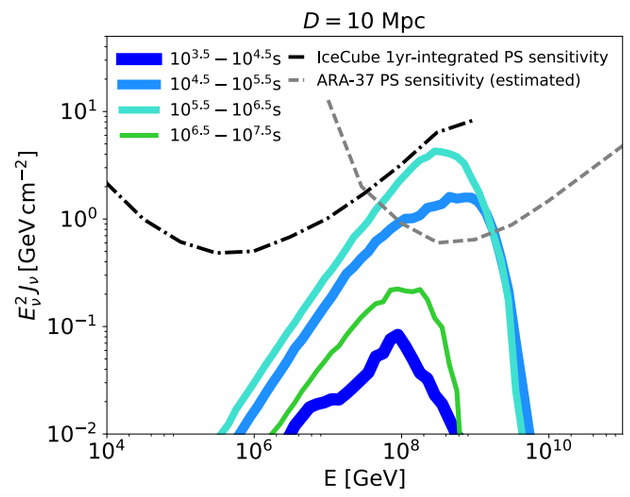
High-energy Neutrinos from Millisecond Magnetars from Mergers of Neutron Stars





Ke Fang
University of Maryland

KIAA Workshop, Aug 17, 2017

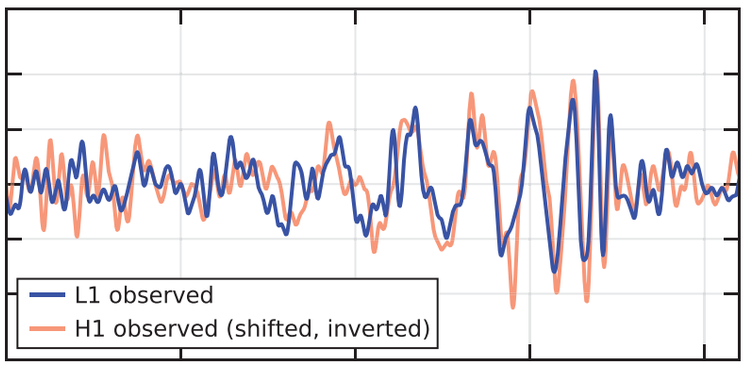
Searches for EM Counterparts of GW events



LIGO Hanford

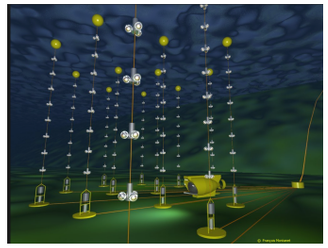


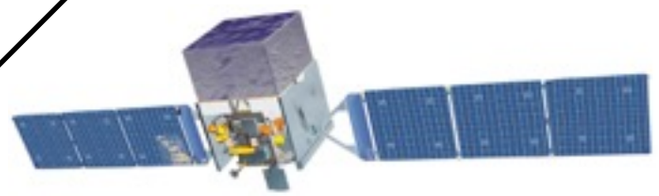
LIGO Livingston



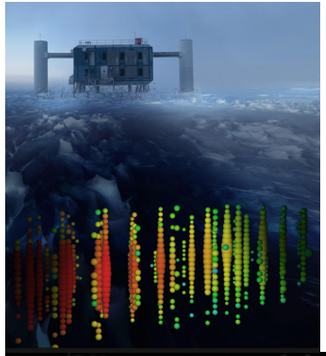
GW event

neutrinos





Fermi

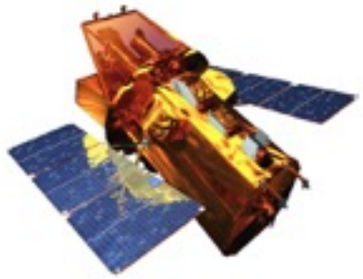




INTEGRAL

gamma rays

X-rays



Swift

optical



Pan-STARRS

NIR

radio

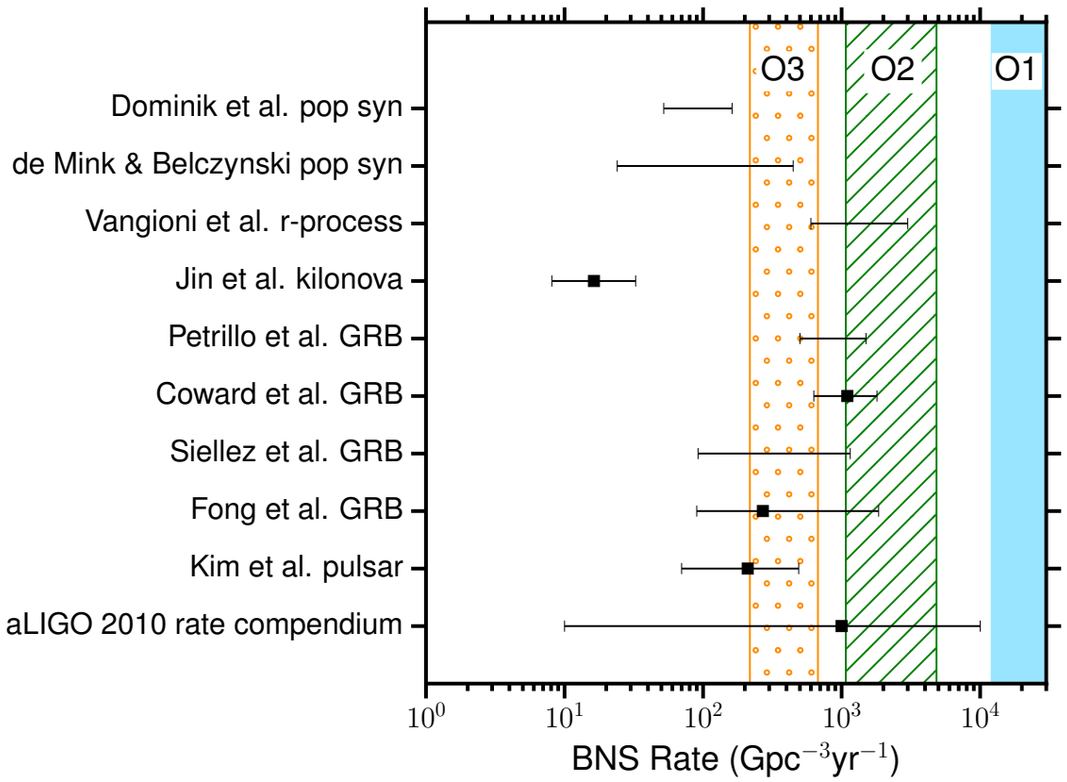


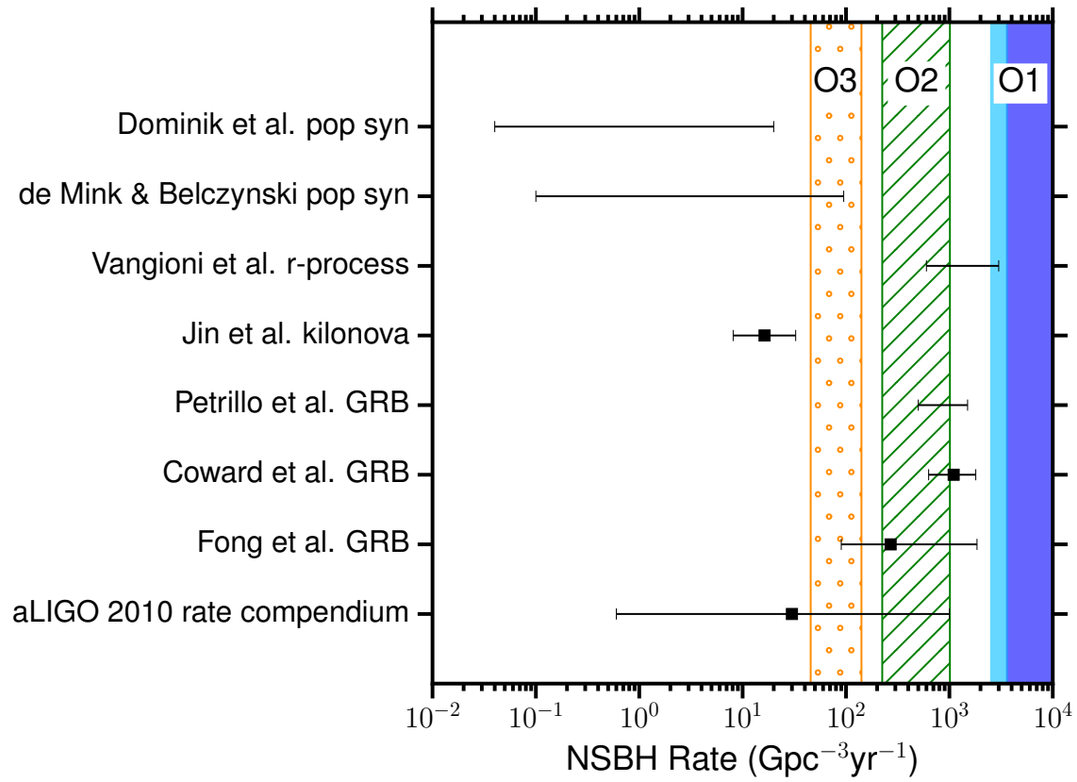
LOFAR



VISTA

NS Merger Rate vs LIGO Sensitivity





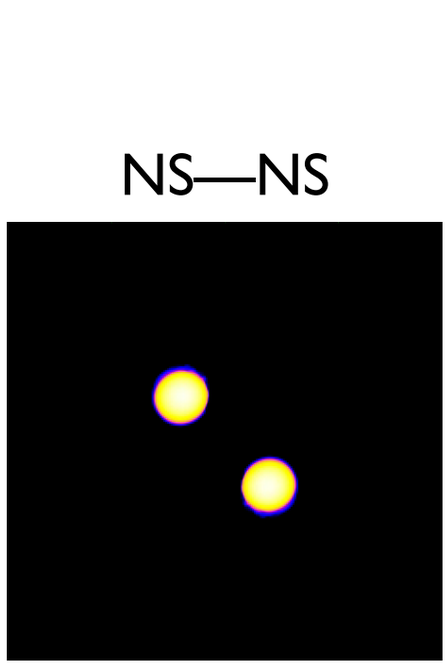
Abbott+ 2016c

O3 will perform a deep probe into BNS.

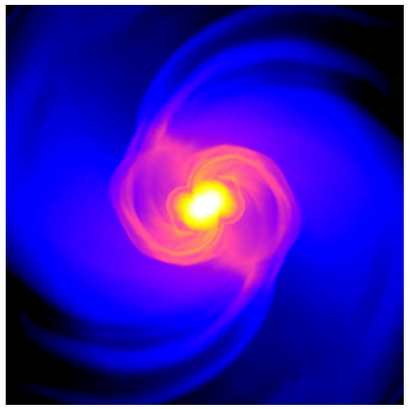
O2: Nov 2016 - Aug 2017

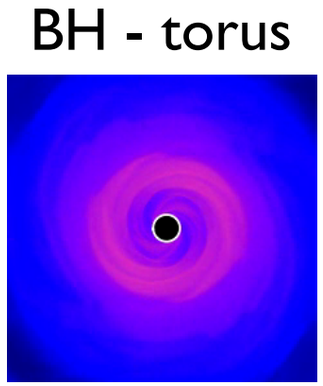
O3: scheduled to begin fall 2018

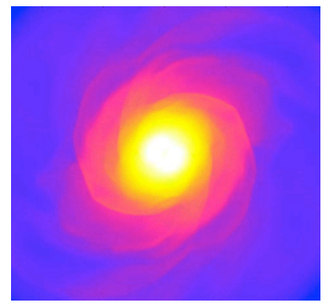
NS Merger Phenomenology

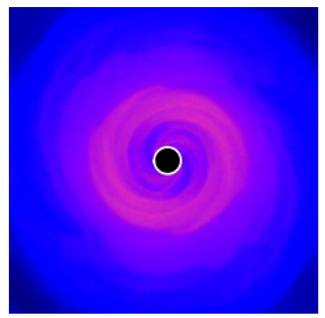


prompt collapse

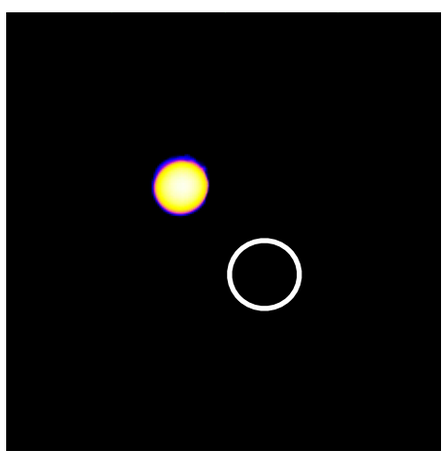


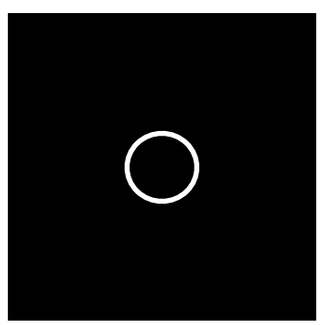






sim. & vis.: W. Kastaun



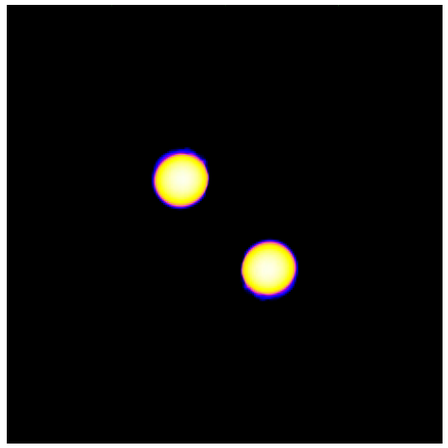


Outcome depends on EOS and binary parameters (masses, mass ratio, spin, …)

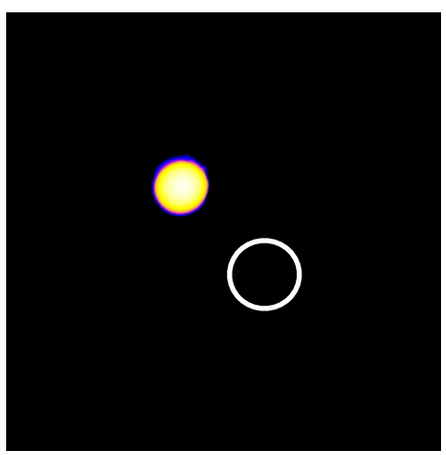
Slide from D. Siegel

NS Merger Phenomenology

NS—NS

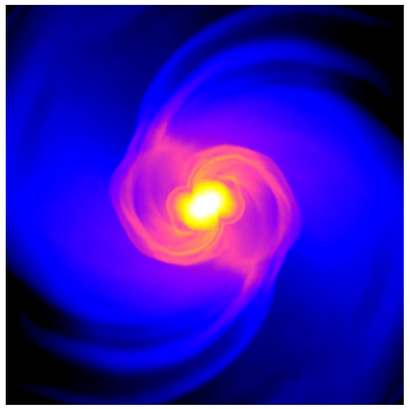


BH—NS

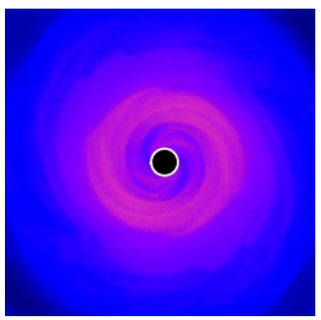


prompt collapse

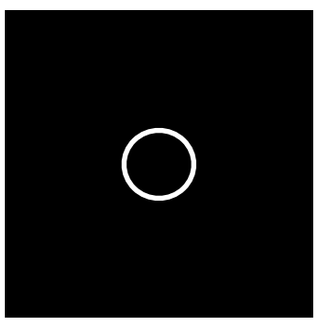
SMNS / HMNS



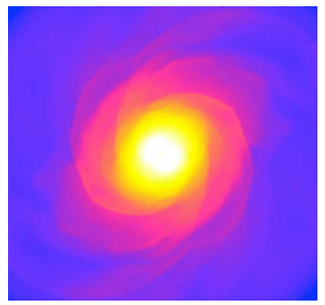
BH - torus



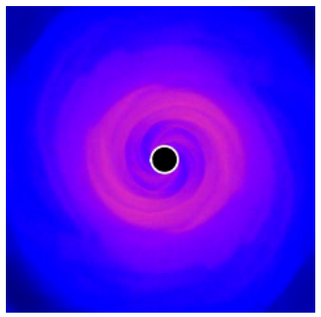
BH



long-lived NS



BH - torus

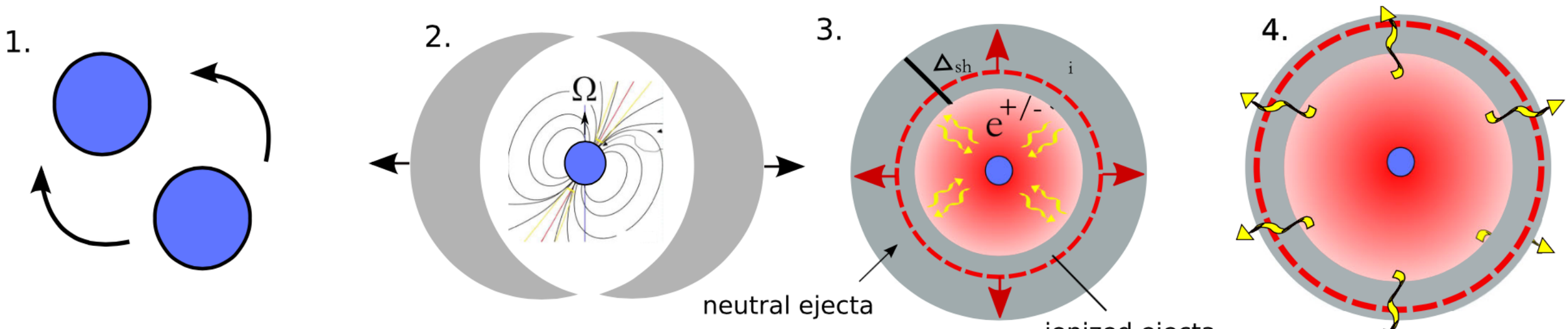


sim. & vis.: W. Kastaun

Outcome depends on EOS and binary parameters (masses, mass ratio, spin, …)

Slide from D. Siegel

Magnetar-powered Transients



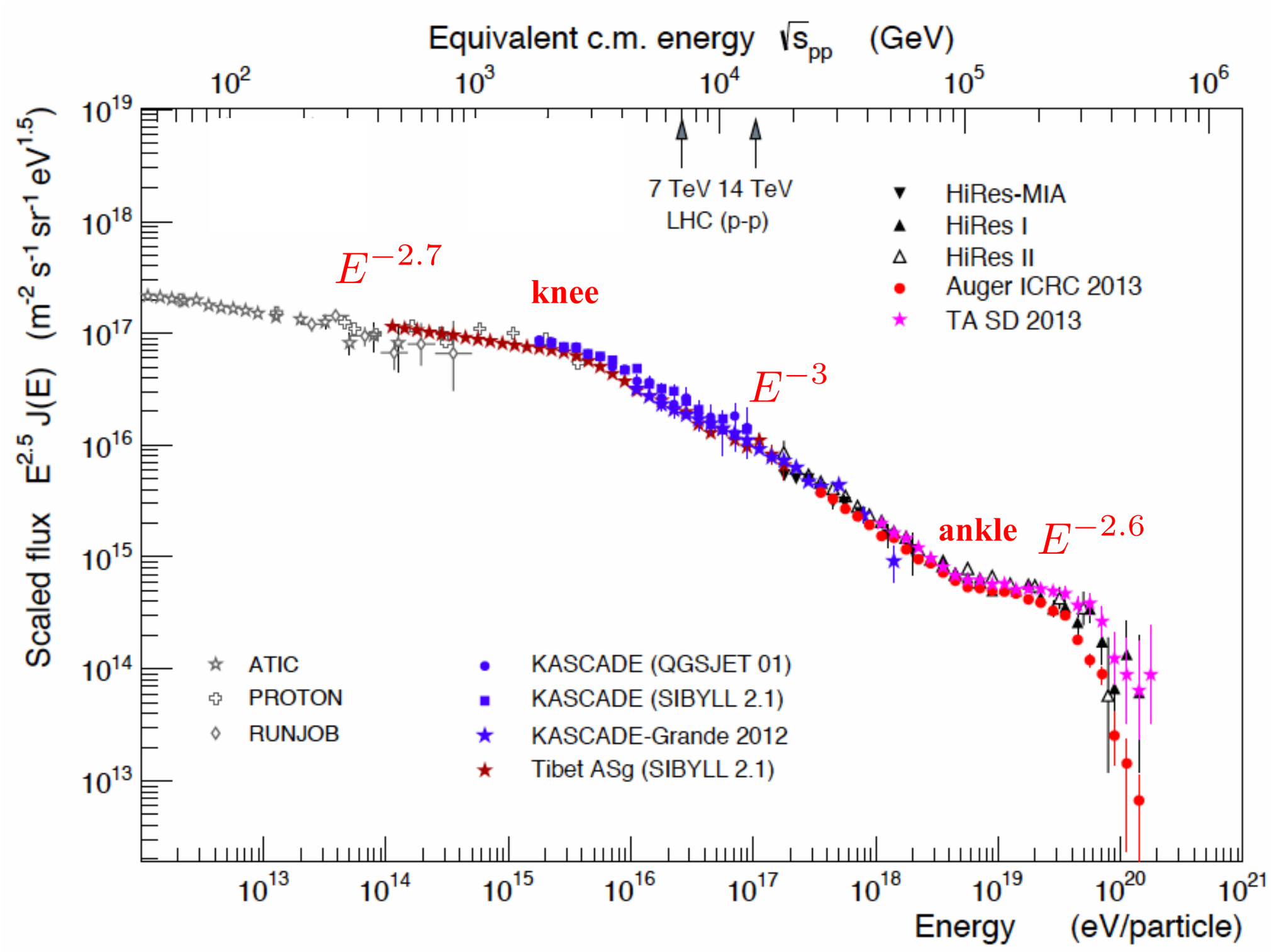
BNS merger leads a differentially rotating NS remnant —> electron positron pairs fill the nebula —> X-ray, UV, optical.. emission carry out spindown energy

EM counterparts from merger remnant provide crucial clues to locate the GW event

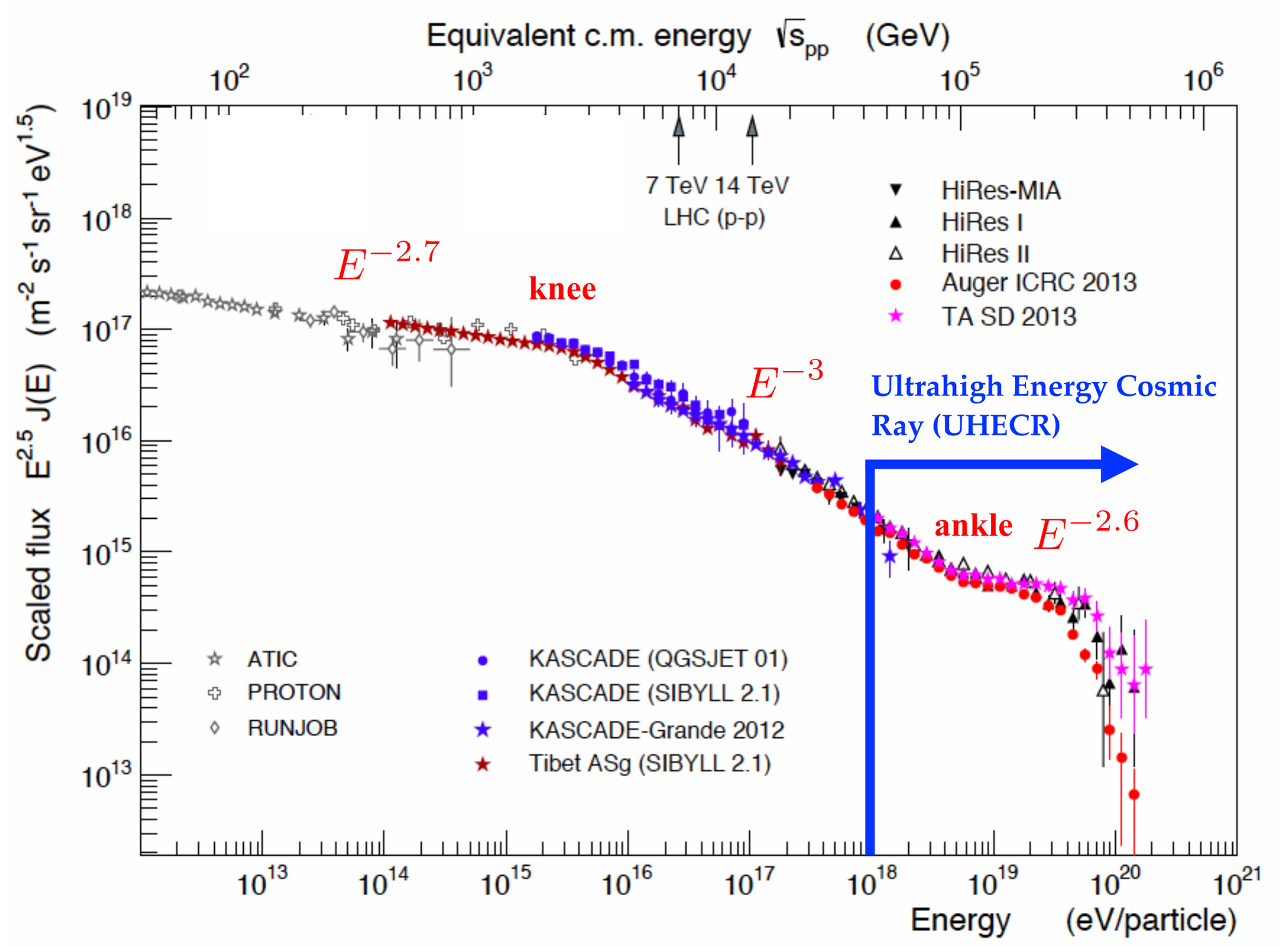
e.g.,Dai 2006, Gao & Fan 2006,

Giacomazzo & Perna, 2013; Metzger & Piro, 2014

Unknown Origin of UHECRs



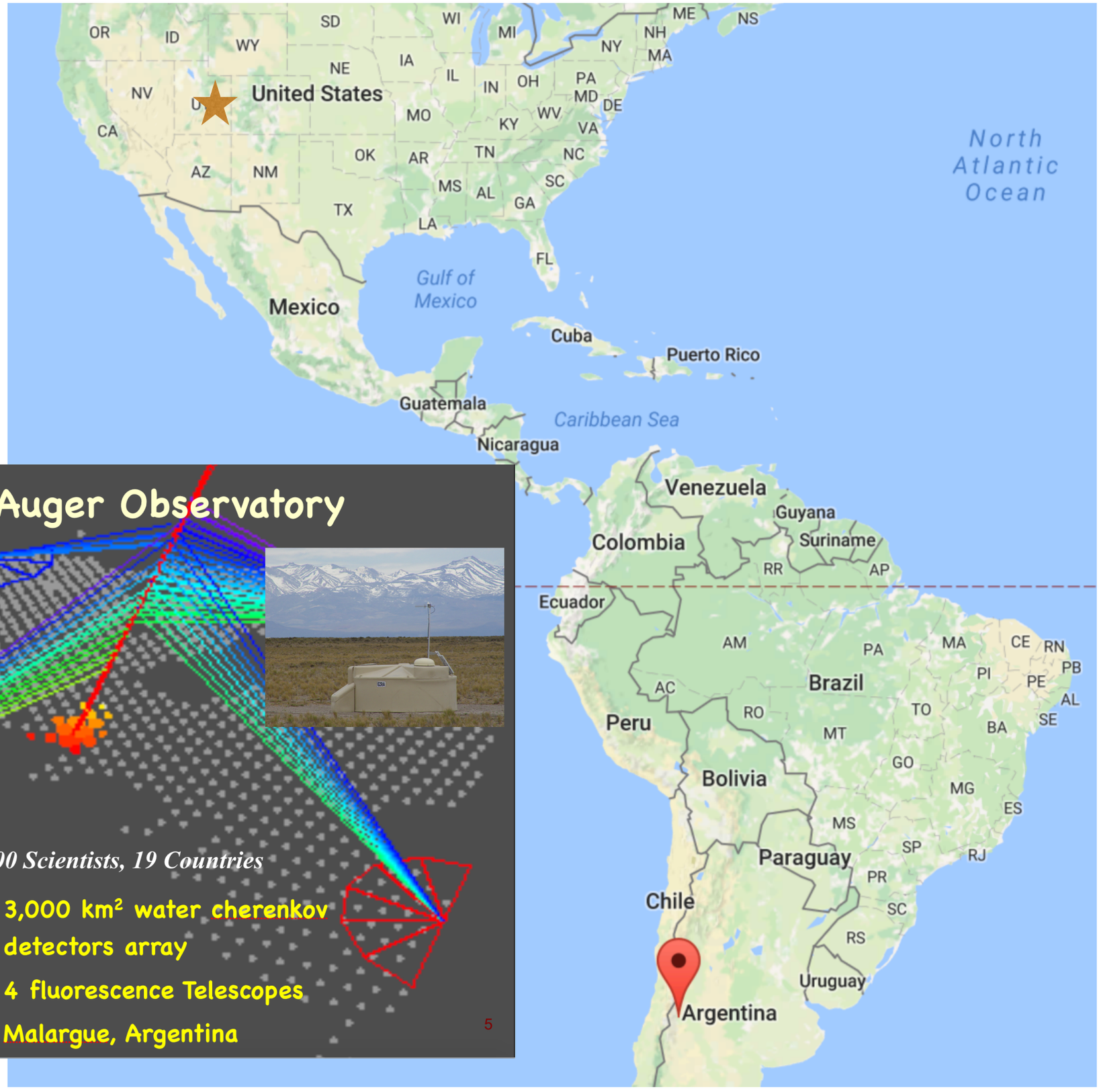
Unknown Origin of UHECRs



Detecting UHECRs



Detecting UHECRs



Pierre Auger Observatory

Argentina
Australia
Brasil
Bolivia*
Croatia
Czech Rep.
France
Germany
Italy
Mexico
Netherlands
Poland
Portugal
Romania*
Slovenia
Spain
UK
USA
Vietnam*
*Associate Countries

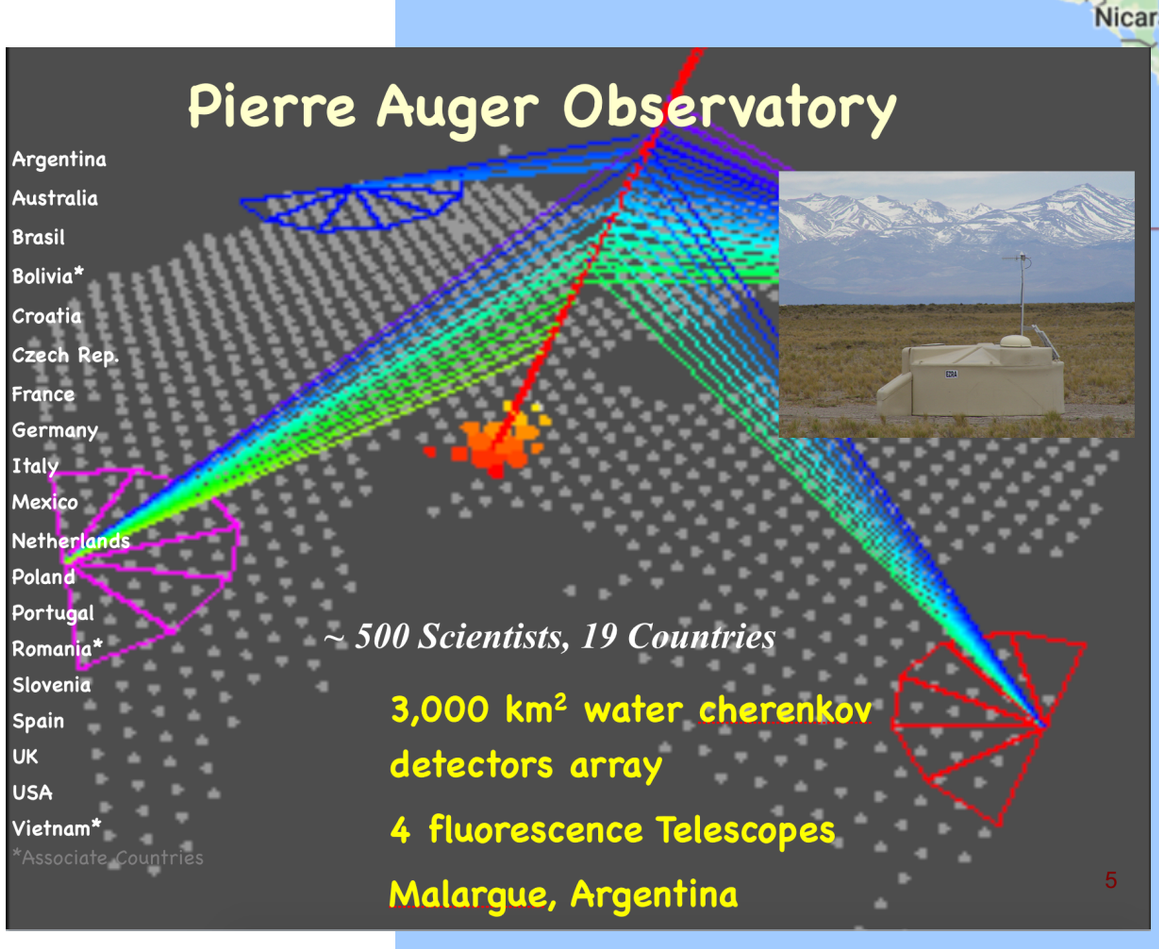
~ 500 Scientists, 19 Countries

3,000 km² water cherenkov detectors array

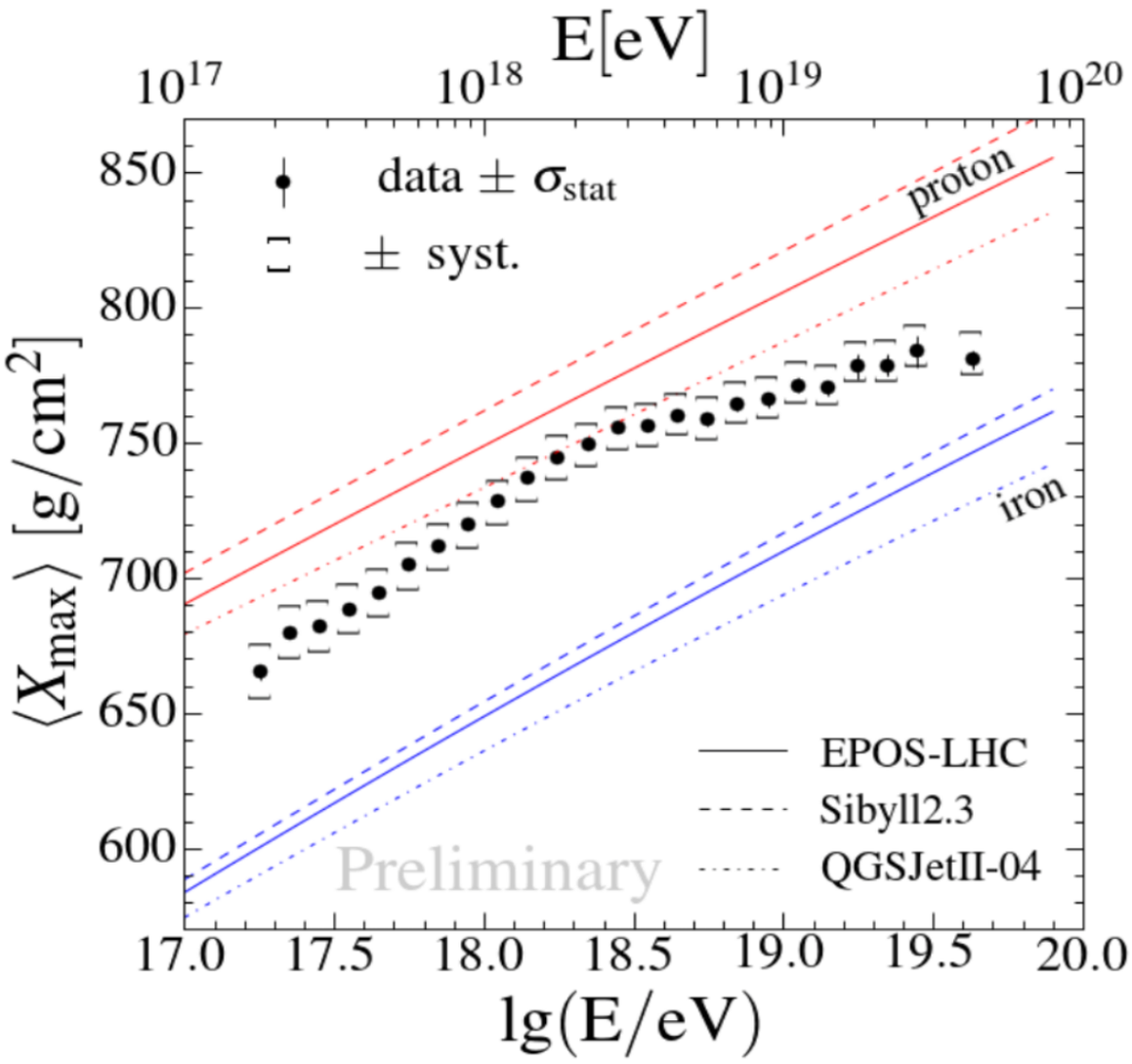
4 fluorescence Telescopes

Malargue, Argentina

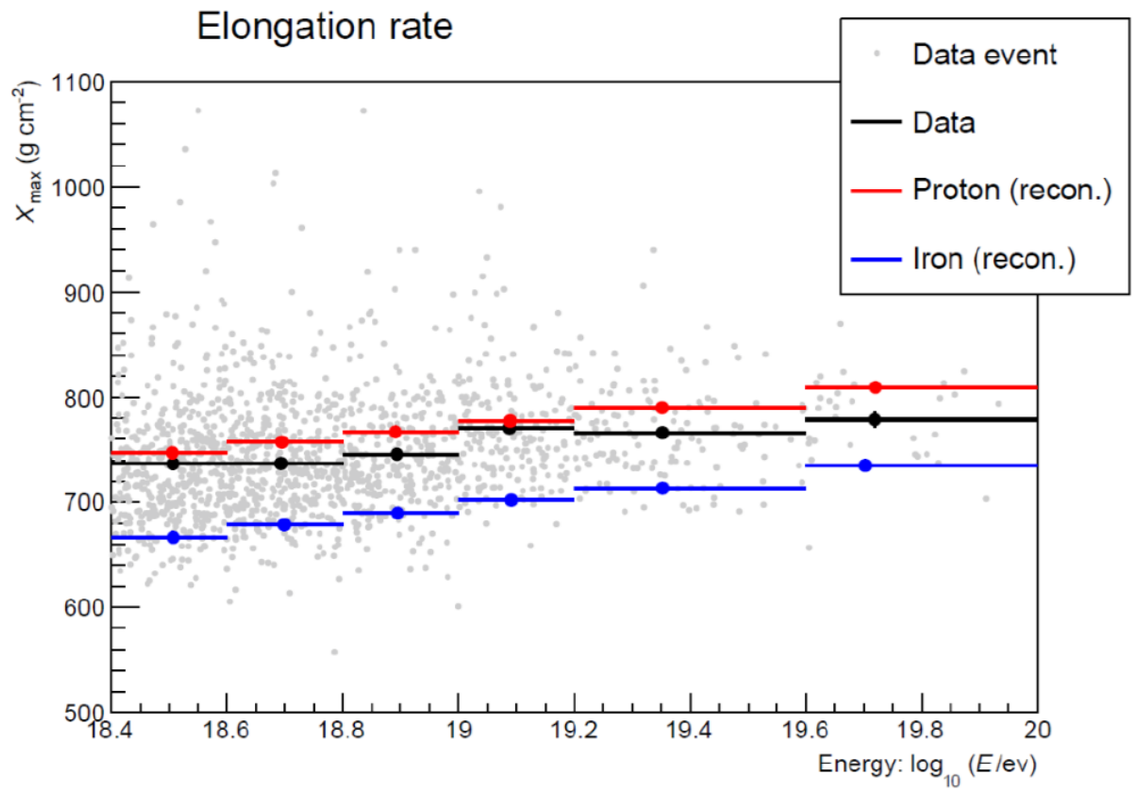
Detecting UHECRs



Hint of Intermediate-Heavy Composition



Auger Collaboration, ICRC2017

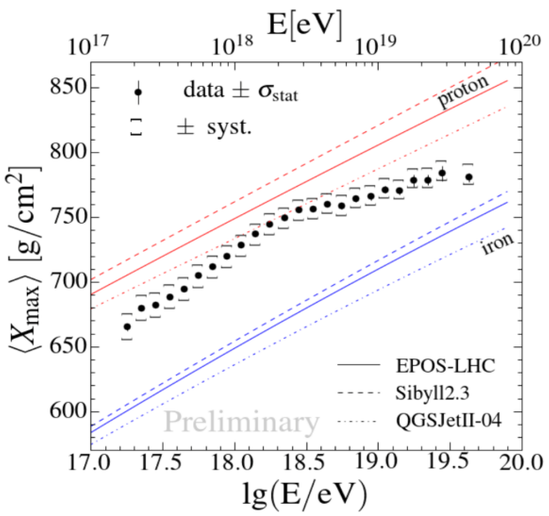


TA Collaboration, ICRC2017

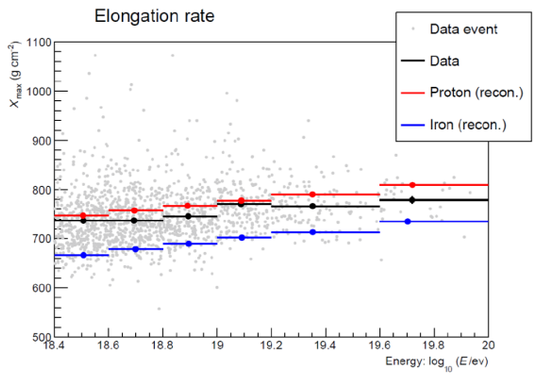
Auger -Transition toward heavy nuclei

TA - Protons; data consistent within error bars

Where to mine for gold?

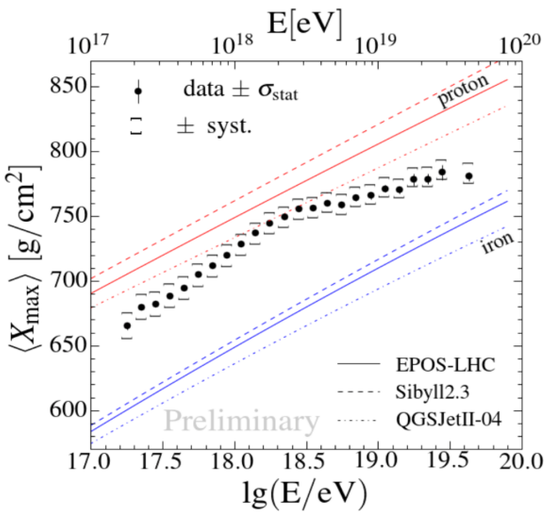


Auger Collaboration, ICRC2017

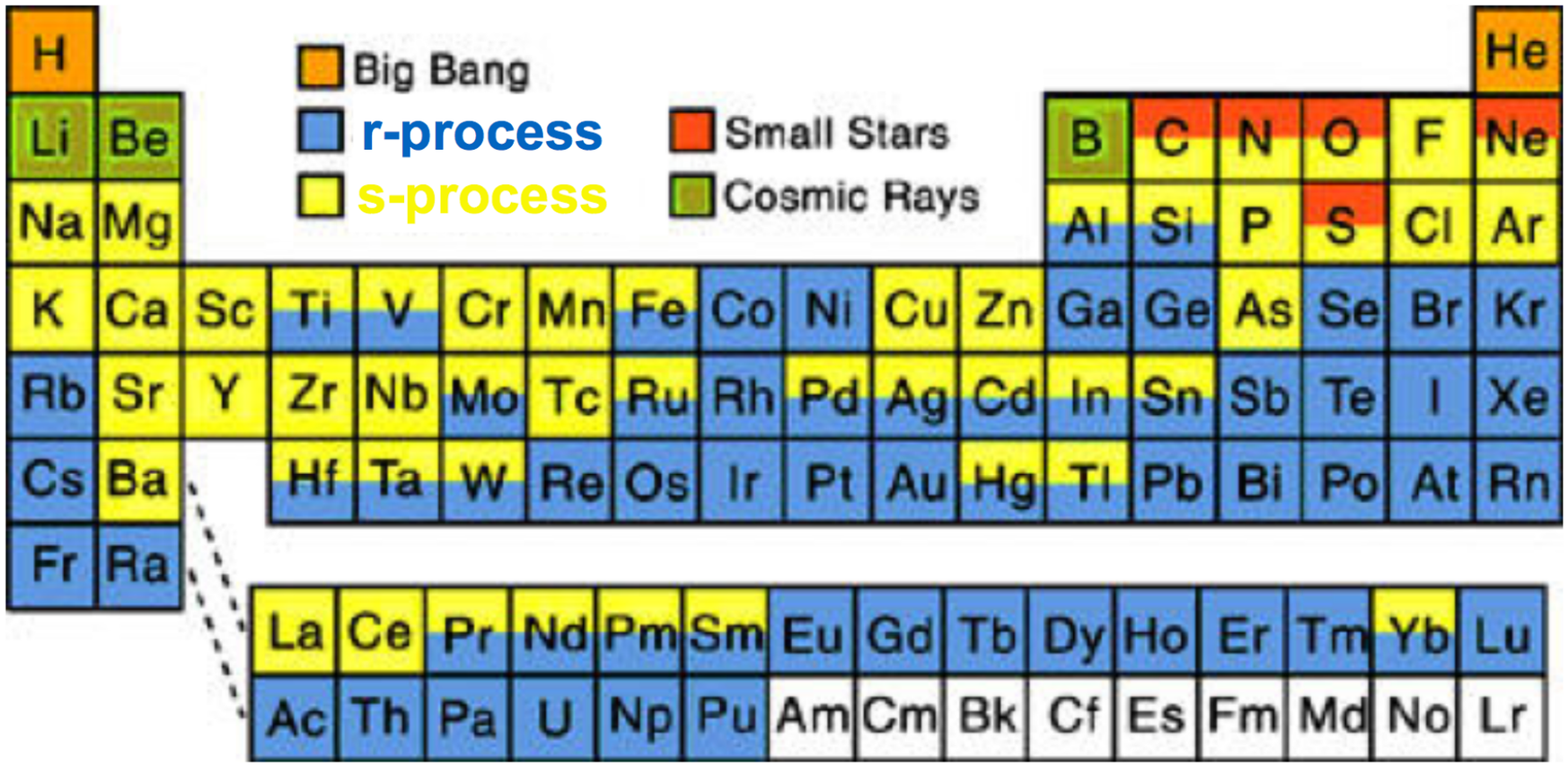


TA Collaboration, ICRC2017

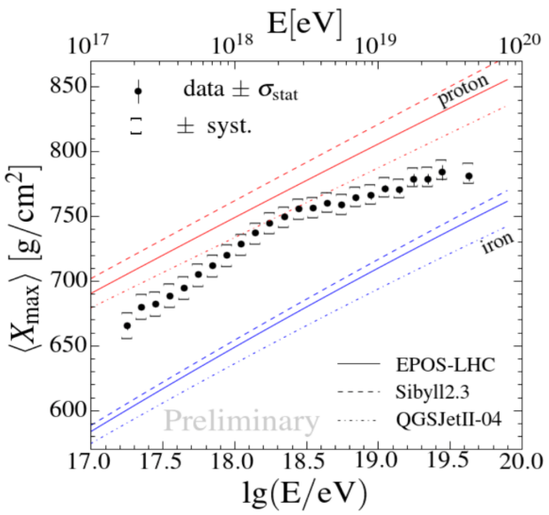
Where to mine for gold?



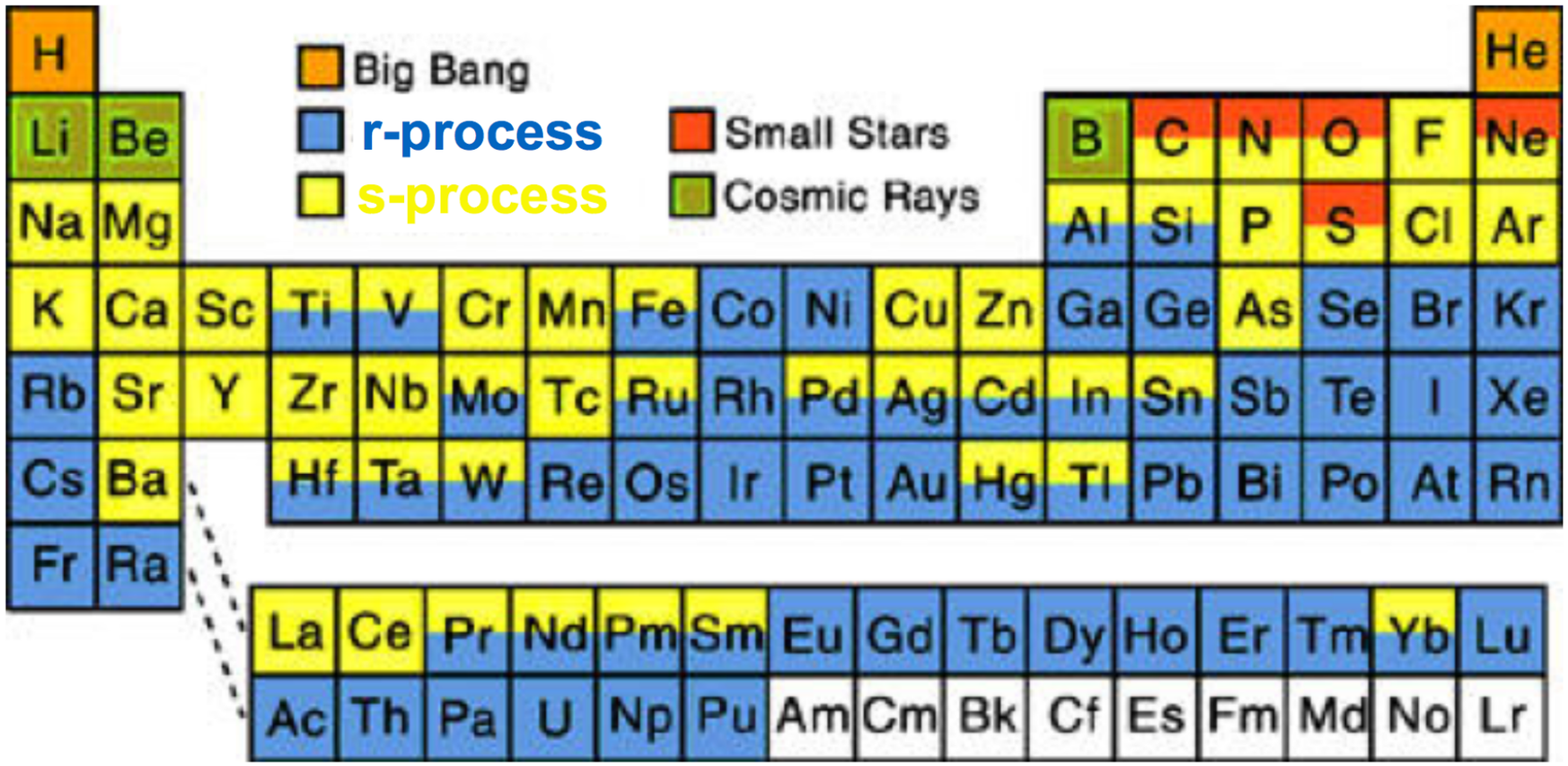
Auger Collaboration, ICRC2017



Where to mine for gold?

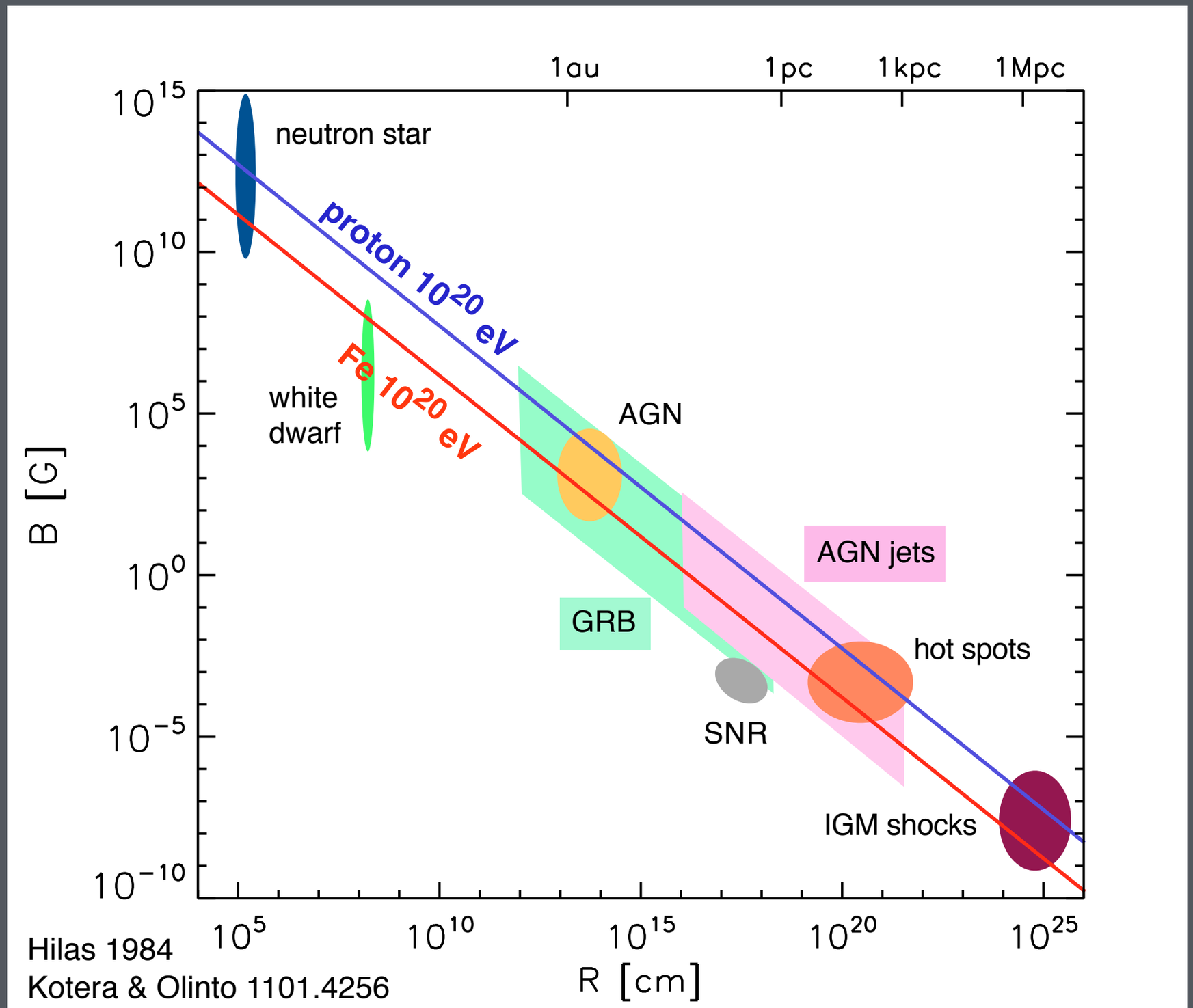


Auger Collaboration, ICRC2017

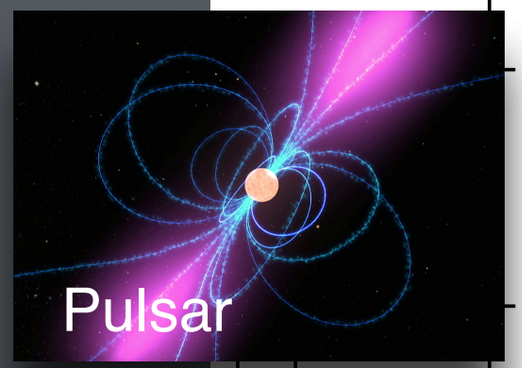


NS mergers are important, if not dominant, contributor of rapid neutron capture nucleosynthesis in the universe.

Sources that Can Accelerate UHECRs



Sources that Can Accelerate UHECRs



Hilas 1984
Kotera & Olinto 1101.4256

Pulsars: Cosmic Ray Acceleration

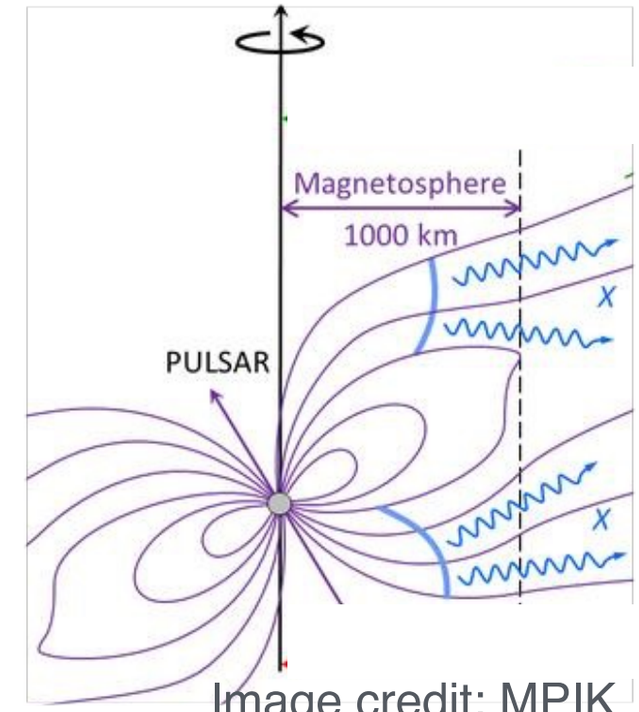


Image credit: MPIK

Venkatesan, Miller & Olinto ApJ 484 (1997)
Blasi, Epstein & Olinto ApJ 533 (2000)
Arons, ApJ 589 (2003)
Lemoine, Kotera & Petri 1409.0159

Pulsars: Cosmic Ray Acceleration

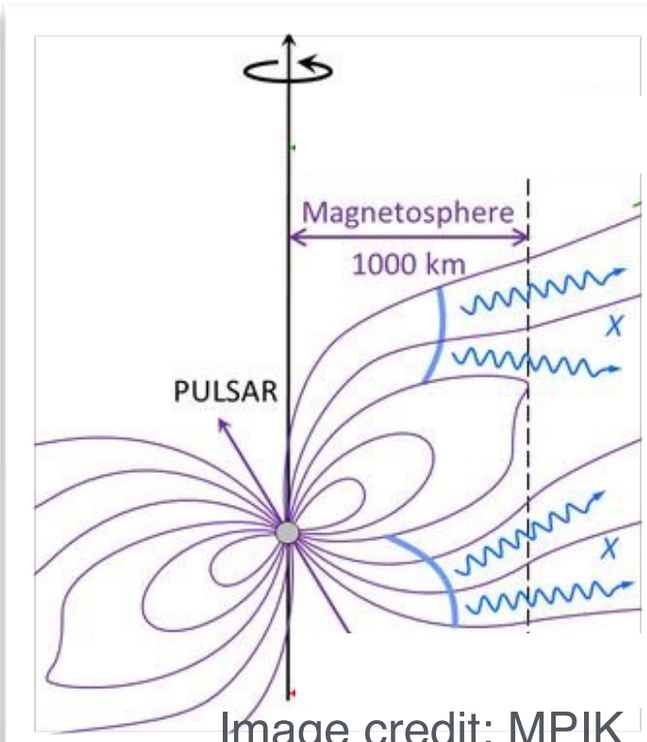


Image credit: MPIK

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

Venkatesan, Miller & Olinto ApJ 484 (1997)
Blasi, Epstein & Olinto ApJ 533 (2000)
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Pulsars: Cosmic Ray Acceleration

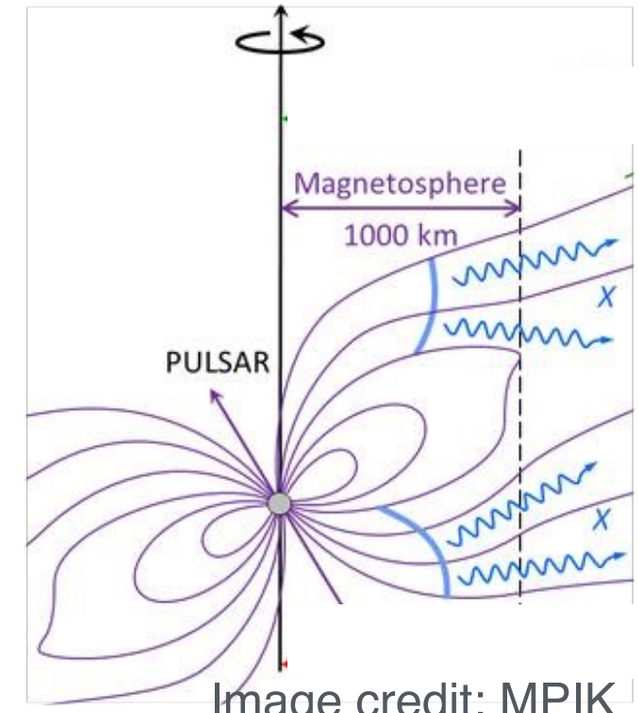


Image credit: MPIK

Magnetic Field

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

Venkatesan, Miller & Olinto ApJ 484 (1997)
Blasi, Epstein & Olinto ApJ 533 (2000)
Arons, ApJ 589 (2003)
Lemoine, Kotera & Petri 1409.0159

Pulsars: Cosmic Ray Acceleration

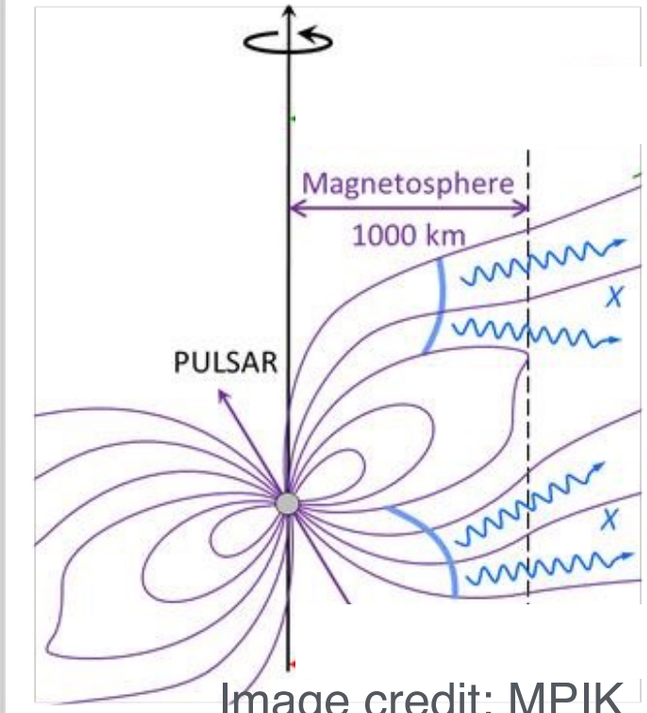


Image credit: MPIK

initial spin period

Magnetic Field

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

Venkatesan, Miller & Olinto ApJ 484 (1997)
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Lemoine, Kotera & Petri 1409.0159

Pulsars: Cosmic Ray Acceleration

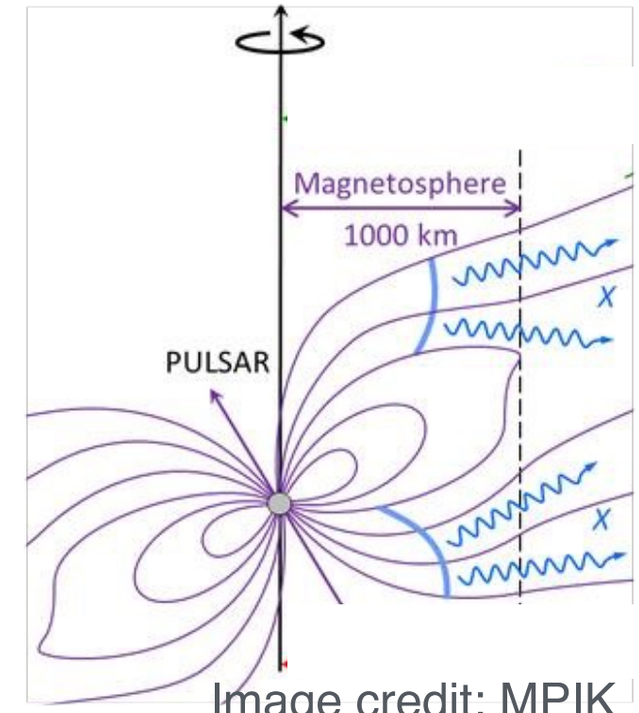


Image credit: MPIK

initial spin period

Magnetic Field

Wind efficiency

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

Venkatesan, Miller & Olinto ApJ 484 (1997)
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Arons, ApJ 589 (2003)
Lemoine, Kotera & Petri 1409.0159

Pulsars: Cosmic Ray Acceleration

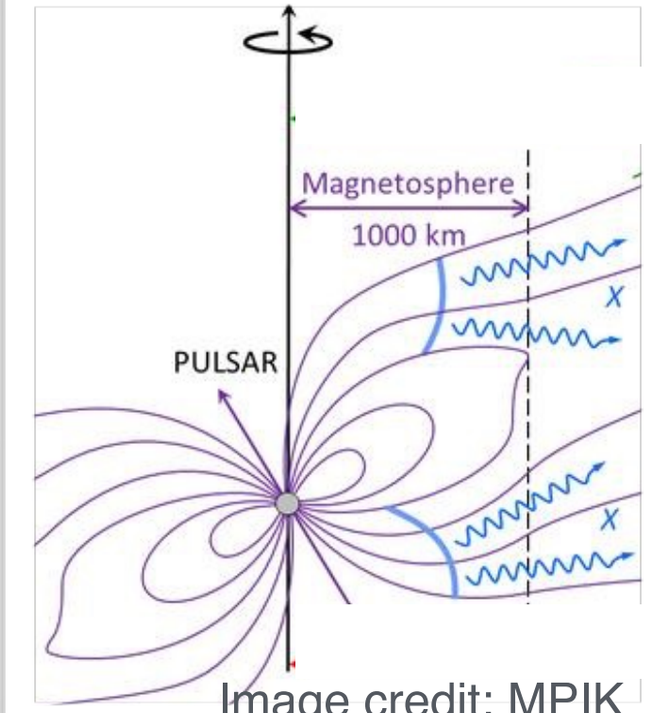


Image credit: MPIK

initial spin period

Magnetic Field

Wind efficiency

Multiplicity

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

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Pulsars: Cosmic Ray Acceleration

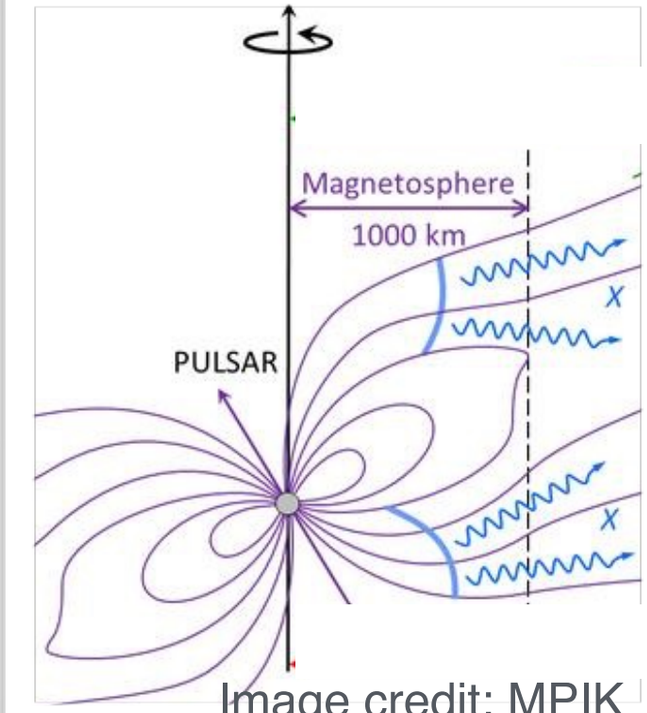


Image credit: MPIK

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 ↓

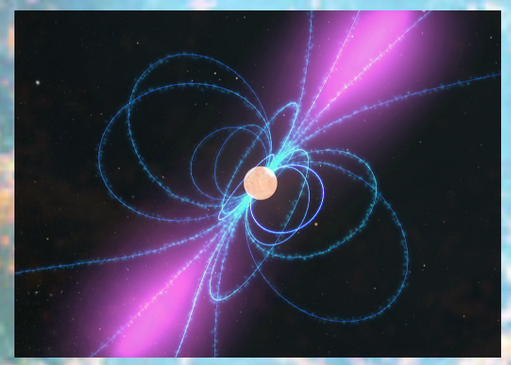
$$\tau_{\rm sd} = 1 B_{13}^{-2} P_{i,1{\rm ms}}^{2}\,{\rm yr}$$

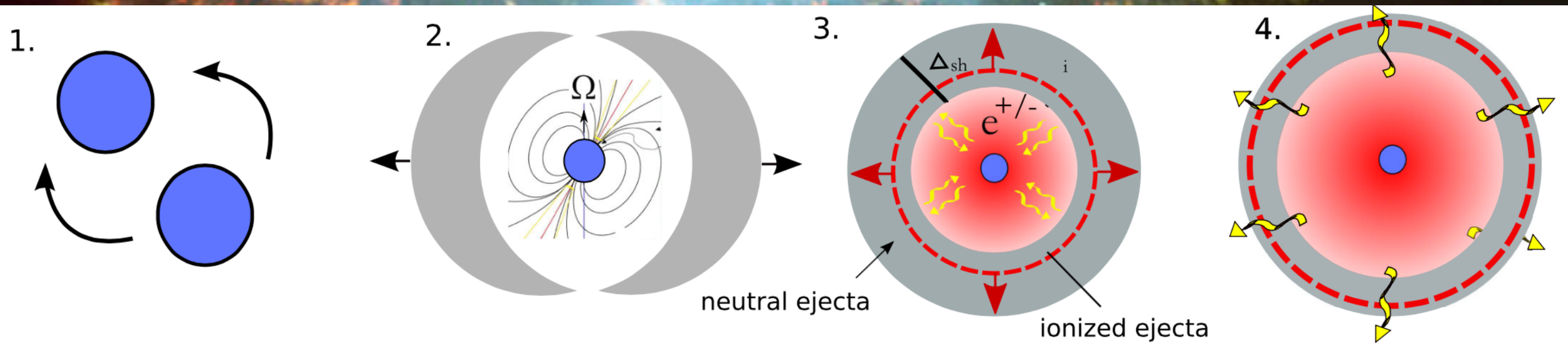
Venkatesan, Miller & Olinto ApJ 484 (1997)
Blasi, Epstein & Olinto ApJ 533 (2000)
Arons, ApJ 589 (2003)
Lemoine, Kotera & Petri 1409.0159

The pulsar sits in a nebula of dense plasma

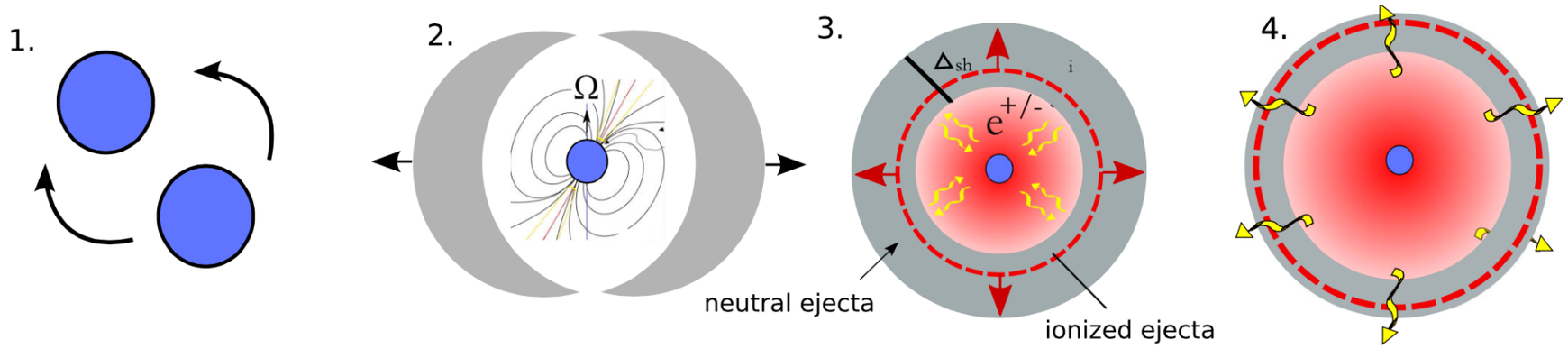
For CR production in millisecond pulsars from Type II SN, see also:

KF, Kotera, Olinto ApJ 2012
KF, Kotera, Olinto JCAP 2013
KF, Kotera, Murase, Olinto, PRD, 2014
KF, JCAP 2015
KF, Kotera, Murase, Olinto, JCAP 2016
IceCube Collaboration, PRL, 2016





Thermal and Non-thermal Radiation Background



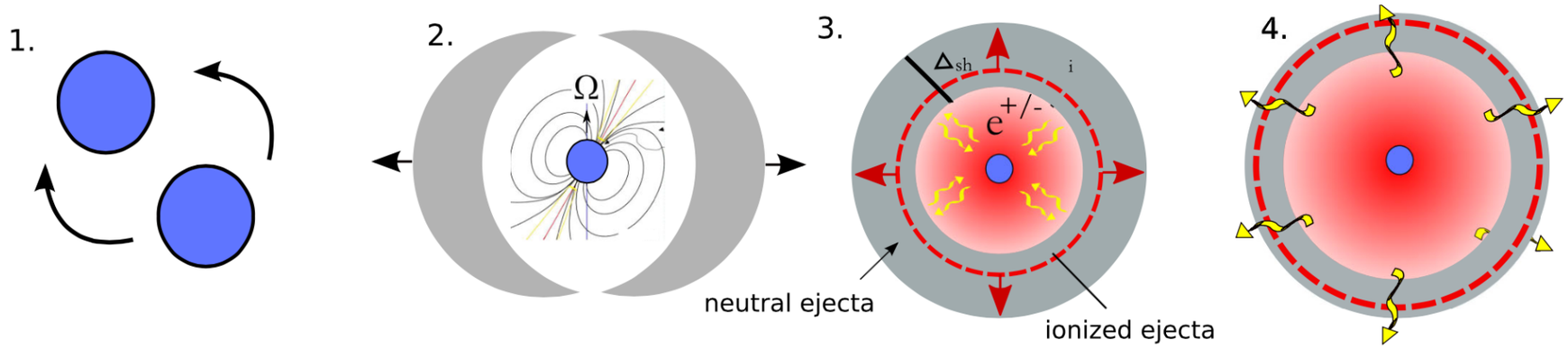
$$\frac{dE_{\rm nth}}{dt} = L_{\rm sd} - \frac{E_{\rm nth}}{R}\frac{dR}{dt} - (1-\mathcal{A})\,\frac{E_{\rm nth}}{t_d^n},$$

$$\frac{dE_{\rm th}}{dt} = (1-\mathcal{A})\,\frac{E_{\rm nth}}{t_d^n} - \frac{E_{\rm th}}{R}\frac{dR}{dt} - \frac{E_{\rm th}}{t_d^{\rm ej}}.$$

$$M_{\rm ej} v \frac{dv}{dt} = \frac{E_{\rm nth}}{R}\frac{dR}{dt} + \frac{E_{\rm th}}{R}\frac{dR}{dt}$$

$$\frac{dE_B}{dt} = \epsilon_B\, L_{\rm sd} - \frac{E_B}{R}\frac{dR}{dt}$$

Thermal and Non-thermal Radiation Background



Albedo of the ejecta wall

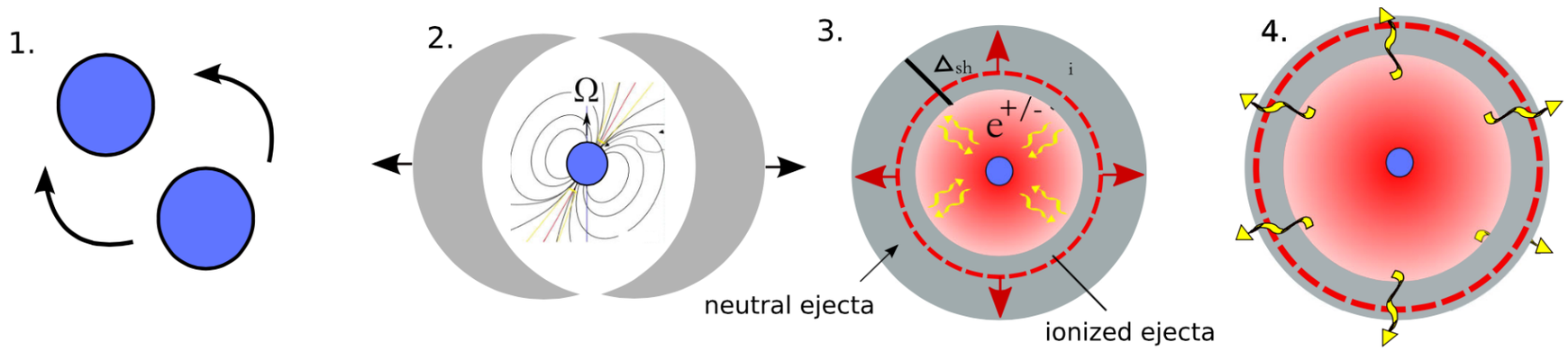
$$\frac{dE_{\rm nth}}{dt} = L_{\rm sd} - \frac{E_{\rm nth}}{R}\frac{dR}{dt} - (1-\mathcal{A})\frac{E_{\rm nth}}{t_d^n},$$

$$\frac{dE_{\rm th}}{dt} = (1-\mathcal{A})\frac{E_{\rm nth}}{t_d^n} - \frac{E_{\rm th}}{R}\frac{dR}{dt} - \frac{E_{\rm th}}{t_d^{\rm ej}}.$$

$$M_{\rm ej} v \frac{dv}{dt} = \frac{E_{\rm nth}}{R}\frac{dR}{dt} + \frac{E_{\rm th}}{R}\frac{dR}{dt}$$

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Thermal and Non-thermal Radiation Background



Albedo of the ejecta wall

$$\frac{dE_{\rm nth}}{dt} = L_{\rm sd} - \frac{E_{\rm nth}}{R}\frac{dR}{dt} - (1-\mathcal{A})\frac{E_{\rm nth}}{t_d^n},$$

time for photons to escape the nebula freely; determined by pair density

$$\frac{dE_{\rm th}}{dt} = (1-\mathcal{A})\frac{E_{\rm nth}}{t_d^n} - \frac{E_{\rm th}}{R}\frac{dR}{dt} - \frac{E_{\rm th}}{t_d^{\rm ej}}.$$

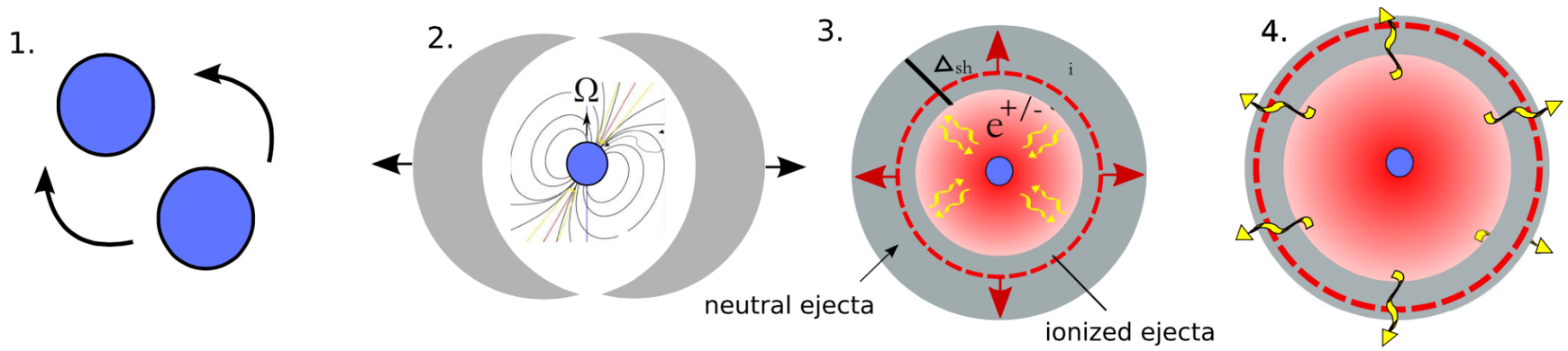
$$M_{\rm ej} v \frac{dv}{dt} = \frac{E_{\rm nth}}{R}\frac{dR}{dt} + \frac{E_{\rm th}}{R}\frac{dR}{dt}$$

$$\frac{dE_B}{dt} = \epsilon_B L_{\rm sd} - \frac{E_B}{R}\frac{dR}{dt}$$

$$\dot{N}_\pm^+ = Y L_{\rm sd}/(m_e c^2)$$

$$\dot{N}_\pm^- = (3/16)\,\sigma_T\, c\, n_\pm\, N_\pm$$

Thermal and Non-thermal Radiation Background



Albedo of the ejecta wall

$$\frac{dE_{\rm nth}}{dt} = L_{\rm sd} - \frac{E_{\rm nth}}{R}\frac{dR}{dt} - (1-\mathcal{A})\frac{E_{\rm nth}}{t_d^n},$$

time for photons to escape the nebula freely; determined by pair density

$$\frac{dE_{\rm th}}{dt} = (1-\mathcal{A})\frac{E_{\rm nth}}{t_d^n} - \frac{E_{\rm th}}{R}\frac{dR}{dt} - \frac{E_{\rm th}}{t_d^{\rm ej}}.$$

$$\dot{N}_{\pm}^{+} = Y L_{\rm sd}/(m_e c^2)$$

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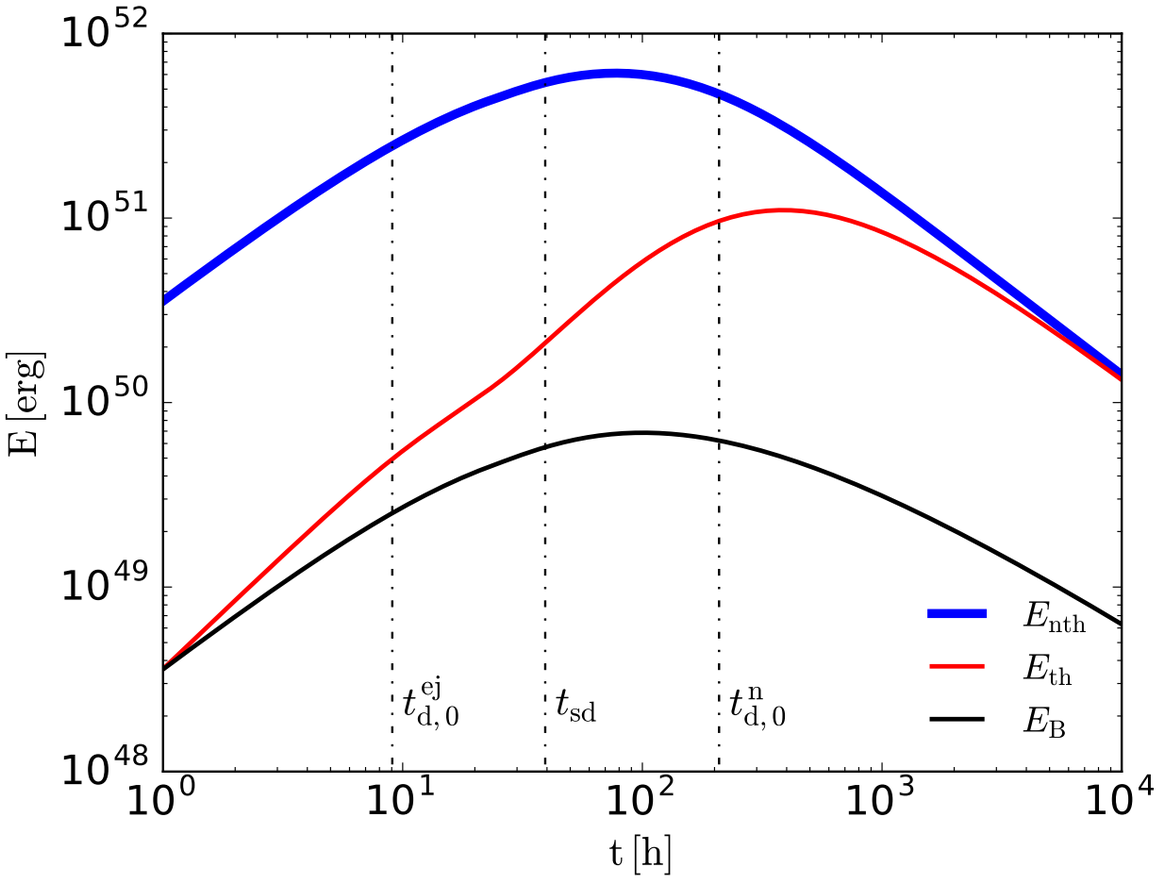
$$M_{\rm ej} v \frac{dv}{dt} = \frac{E_{\rm nth}}{R}\frac{dR}{dt} + \frac{E_{\rm th}}{R}\frac{dR}{dt}$$

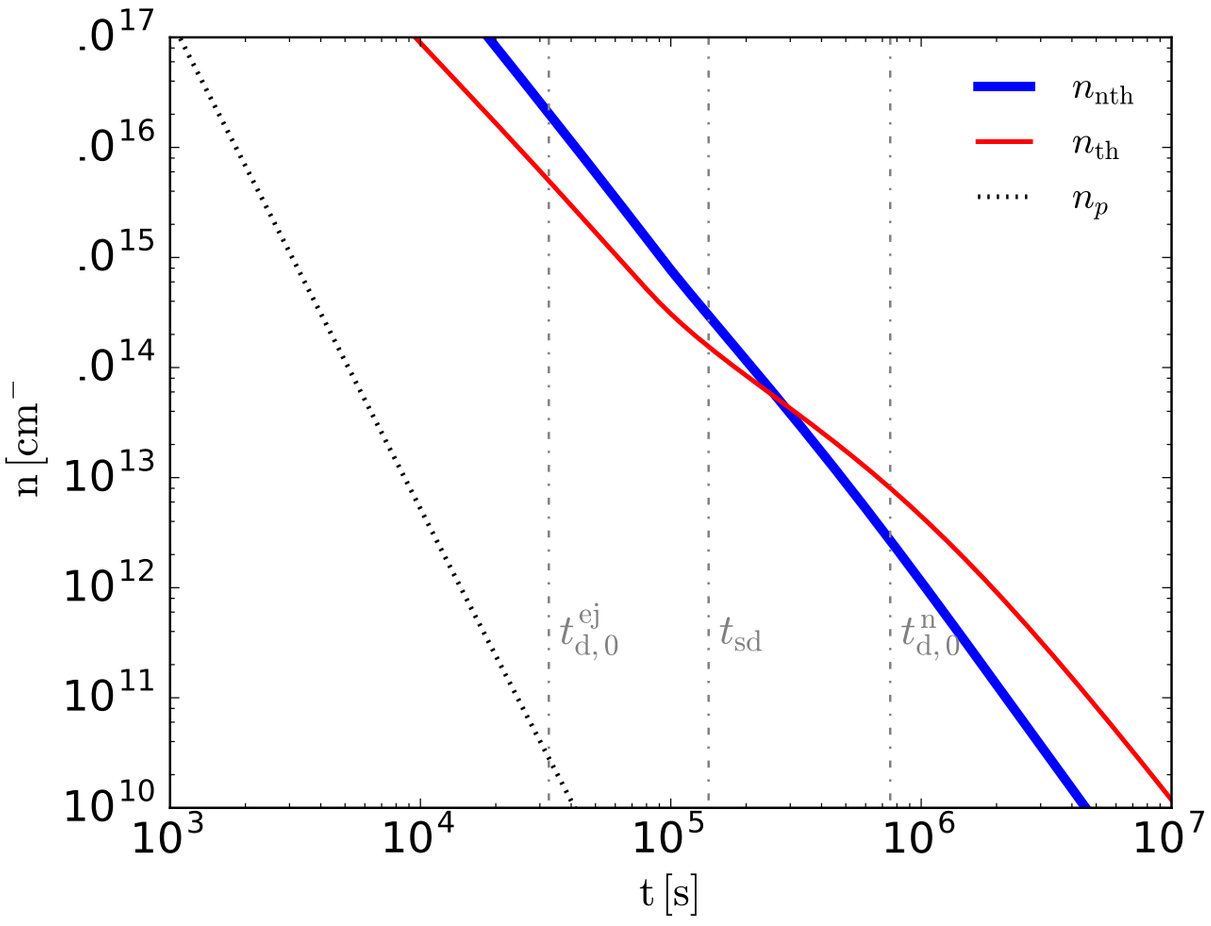
time for photons to leave the ejecta freely; determined by ejecta optical depth

$$\tau_{\rm es}^{\rm ej} = 3M\kappa/4\pi R^2$$

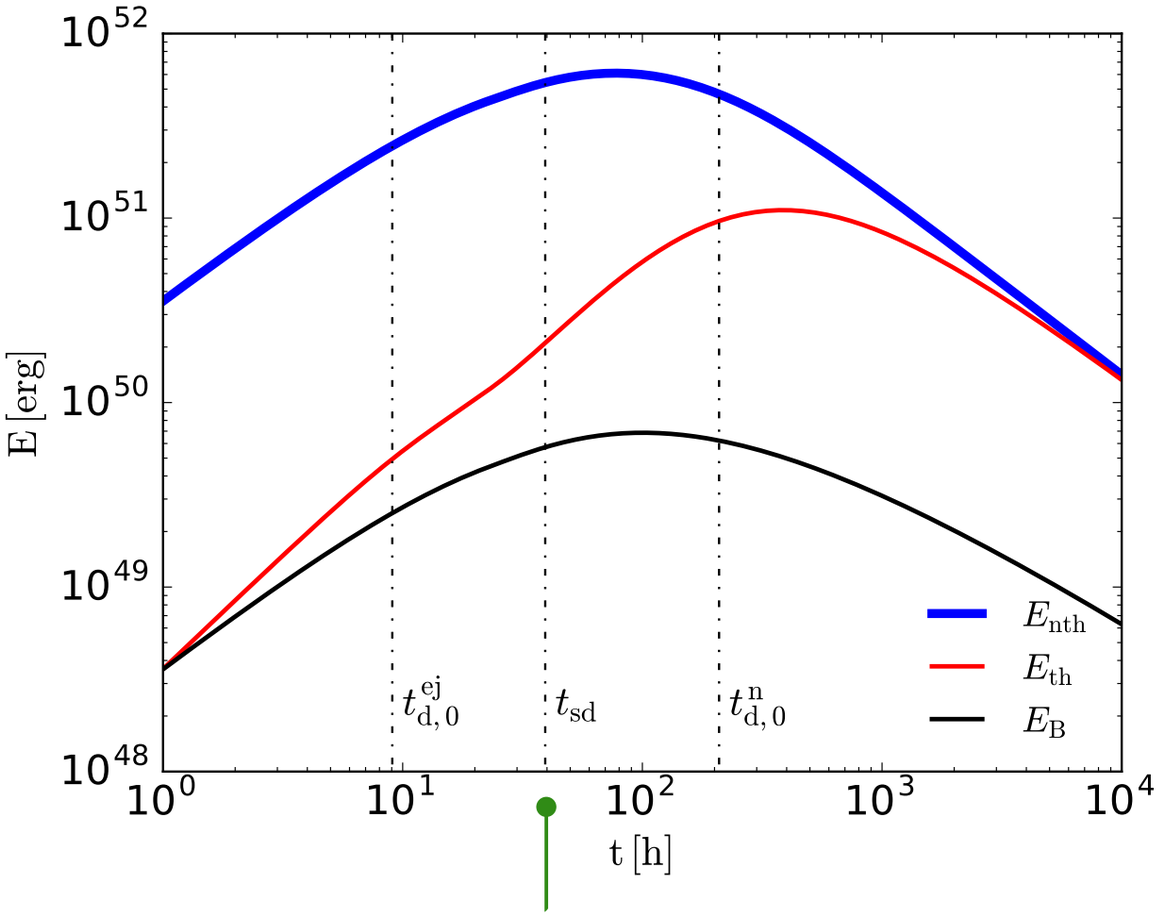
$$\frac{dE_B}{dt} = \epsilon_B L_{\rm sd} - \frac{E_B}{R}\frac{dR}{dt}$$

Background Density

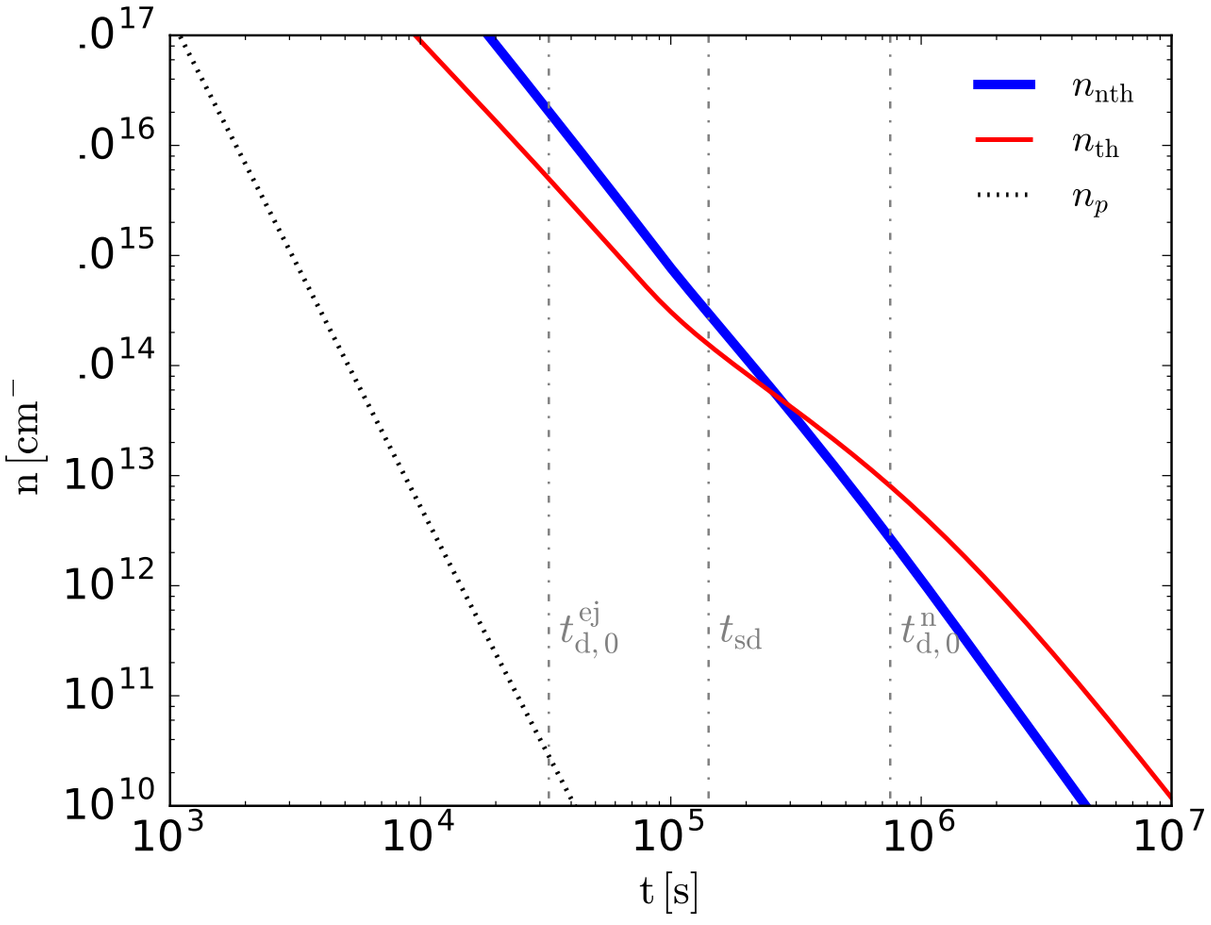




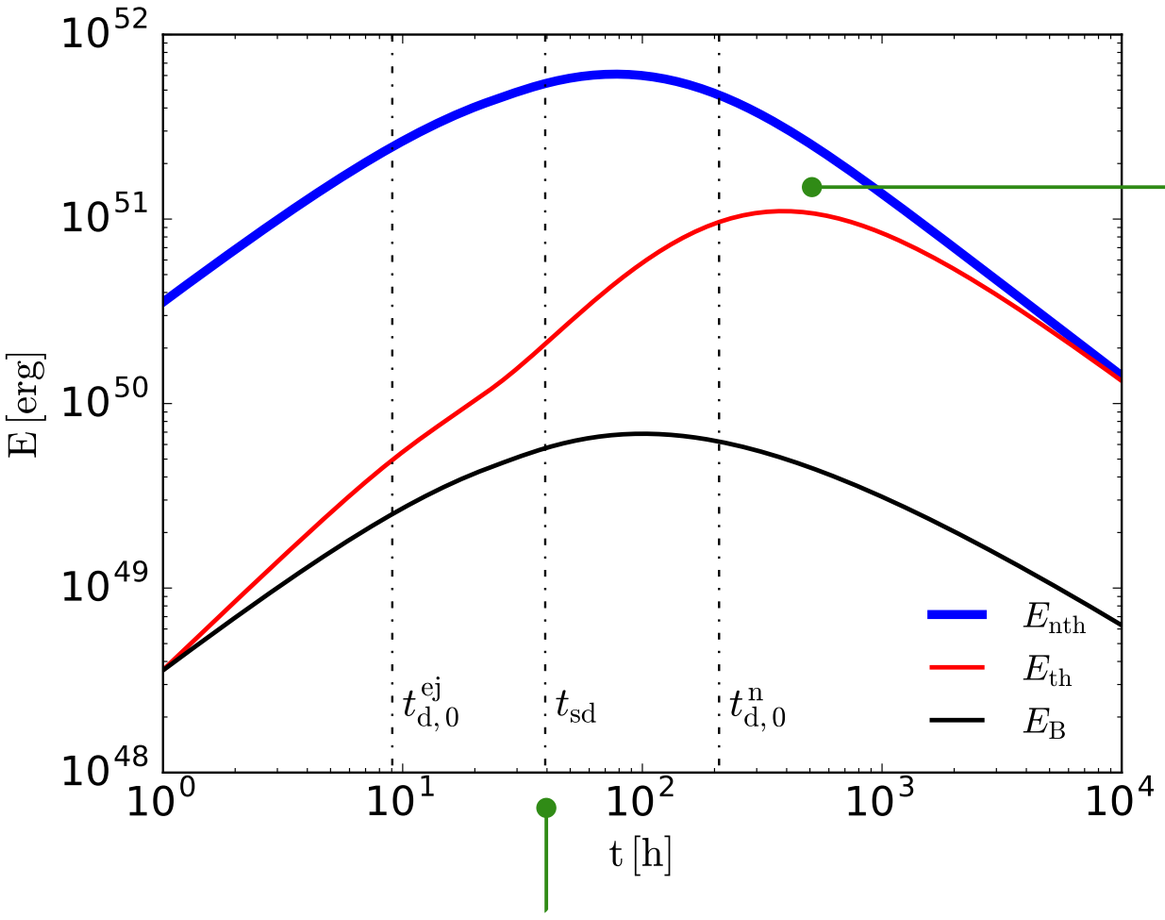
Background Density



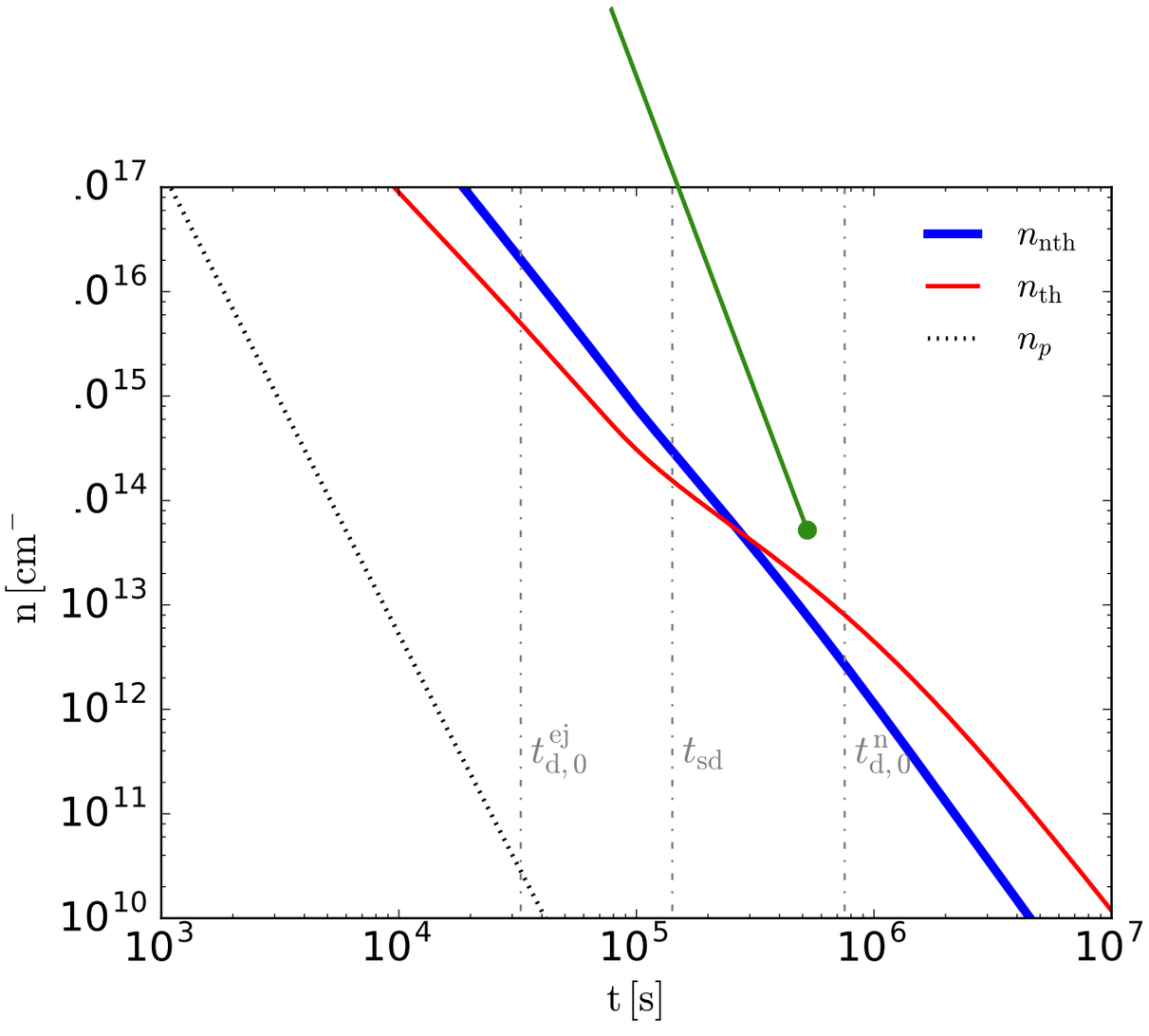
most rotational energy is released by the spin down time



Background Density

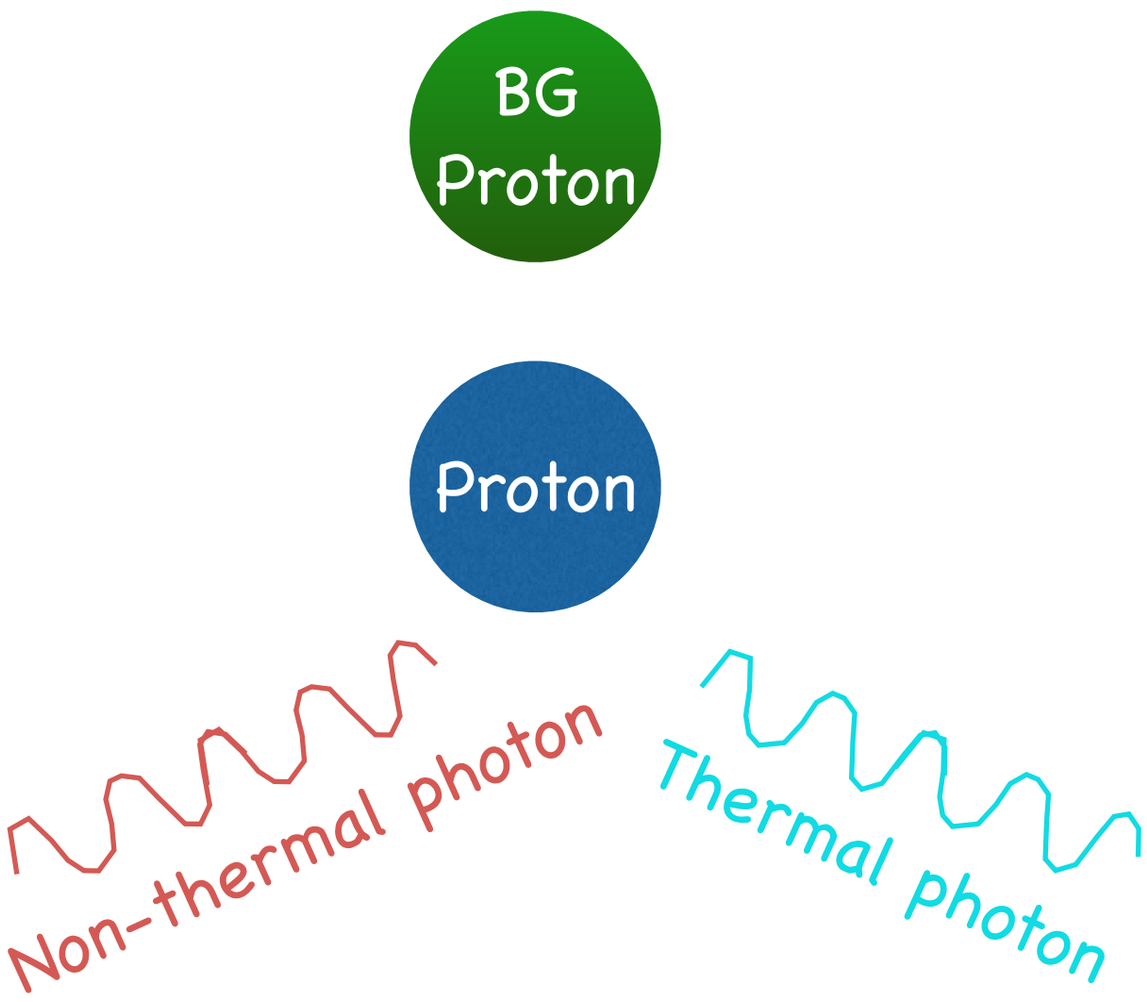


Boost of thermal background when photons are allowed to leave nebula freely

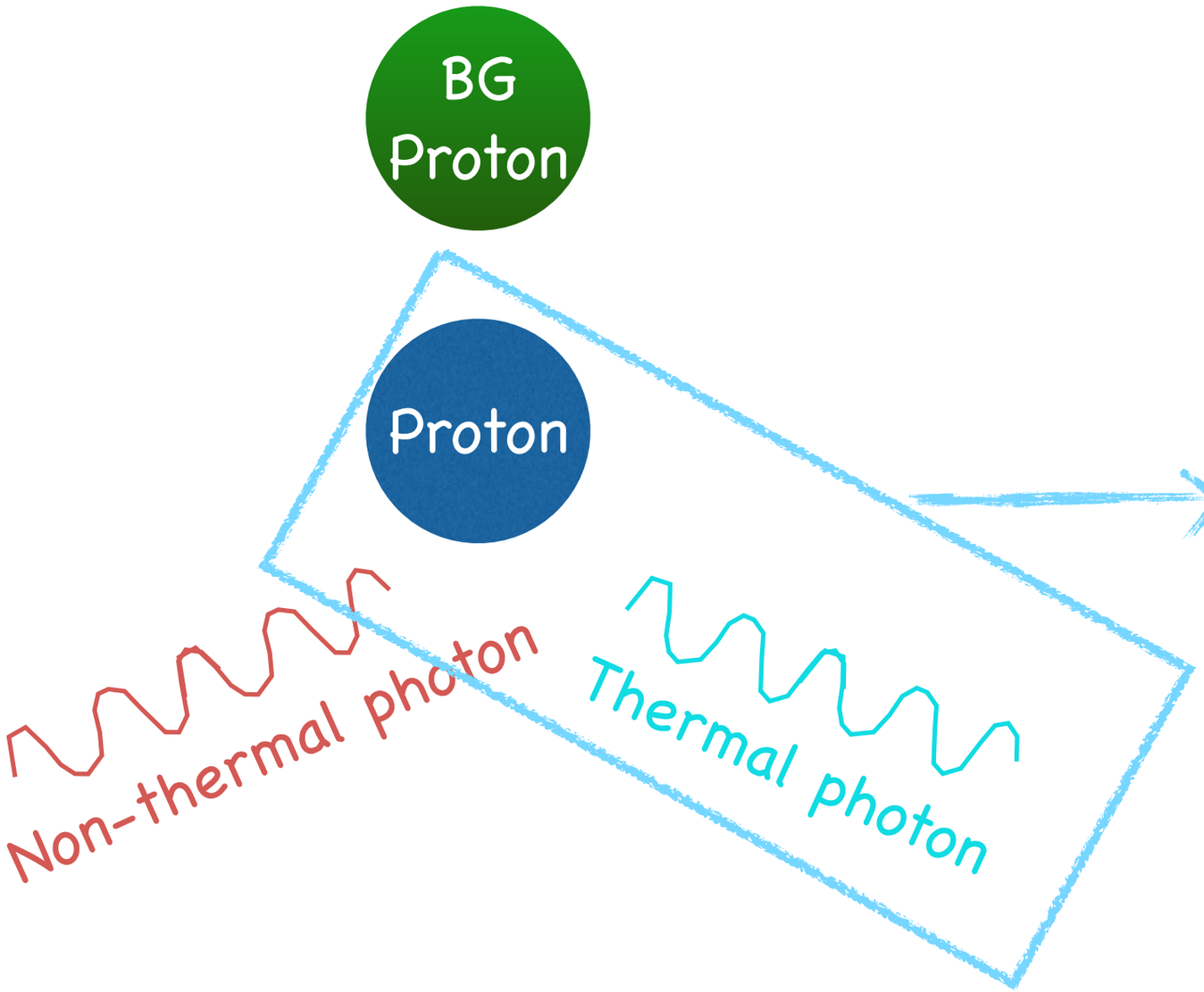


most rotational energy is released by the spin down time

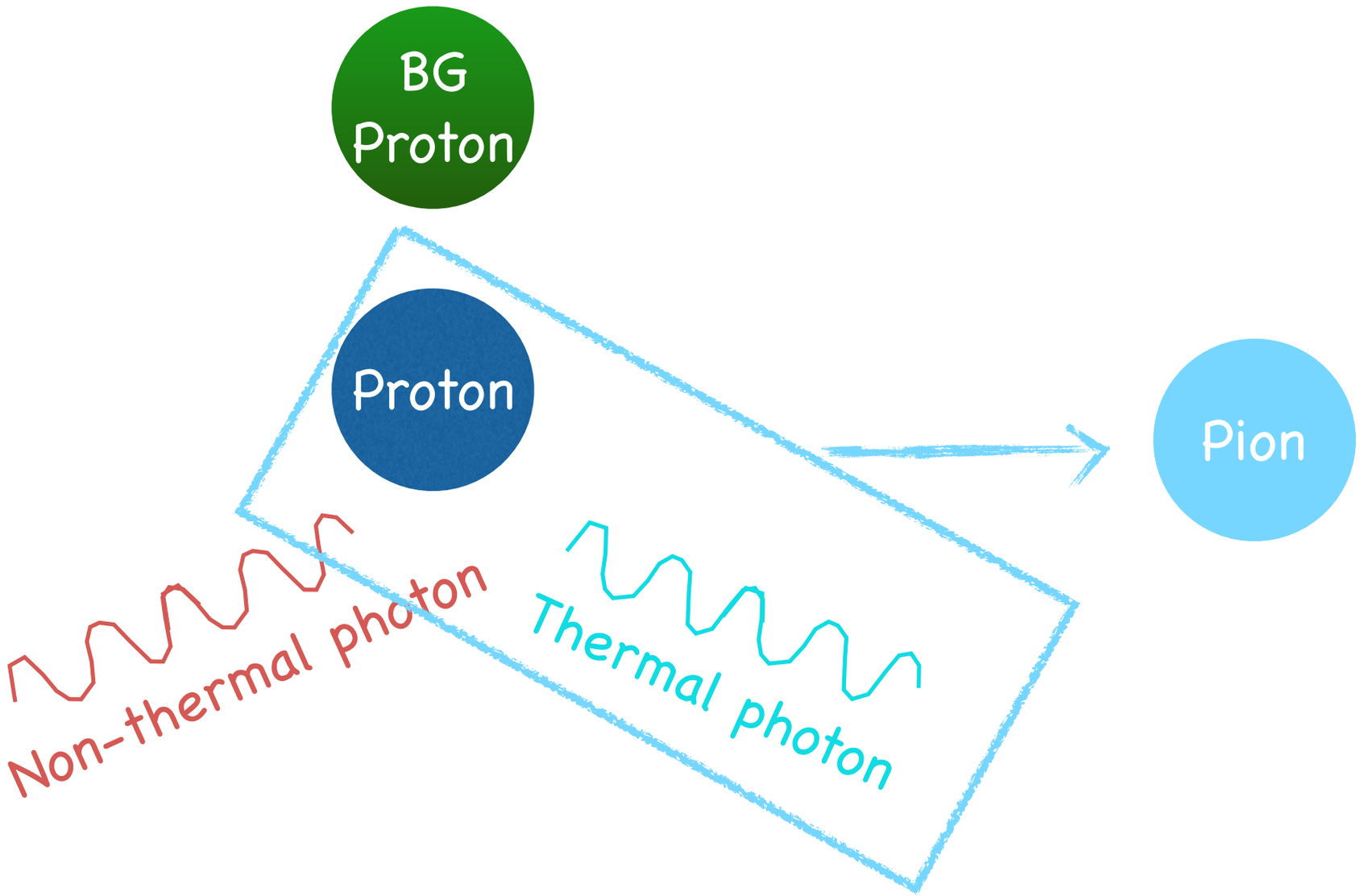
From Proton to Neutrino



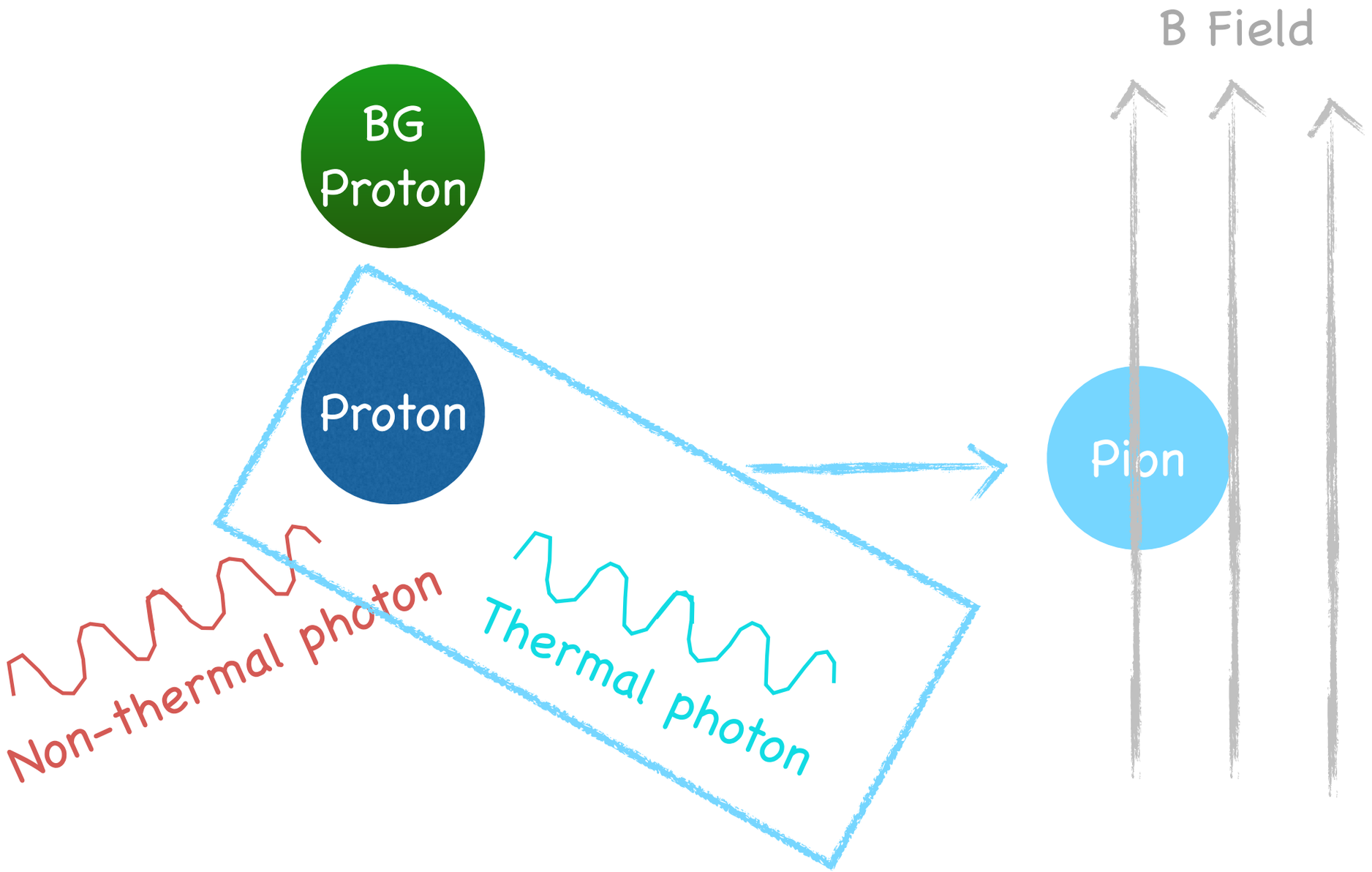
From Proton to Neutrino



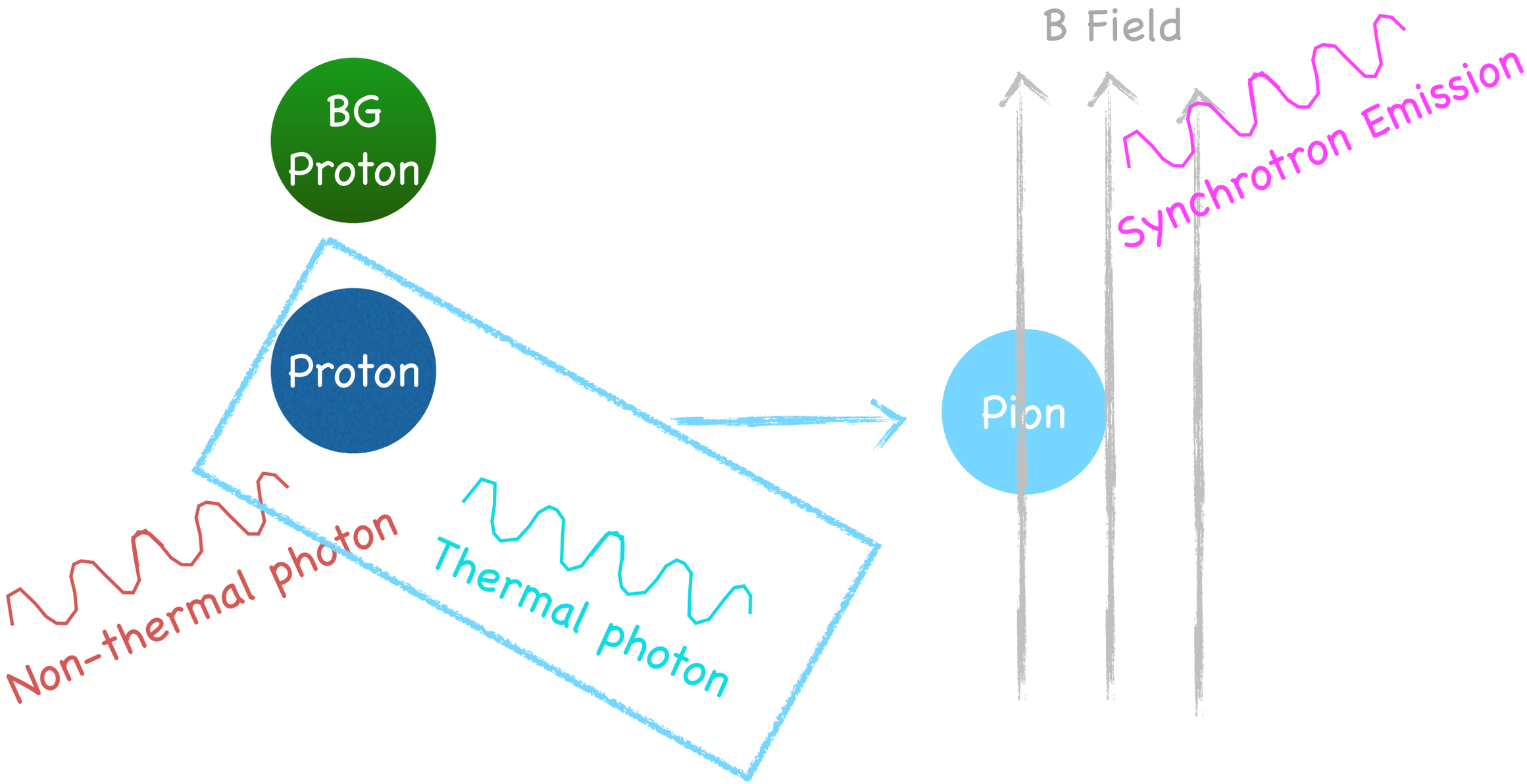
From Proton to Neutrino



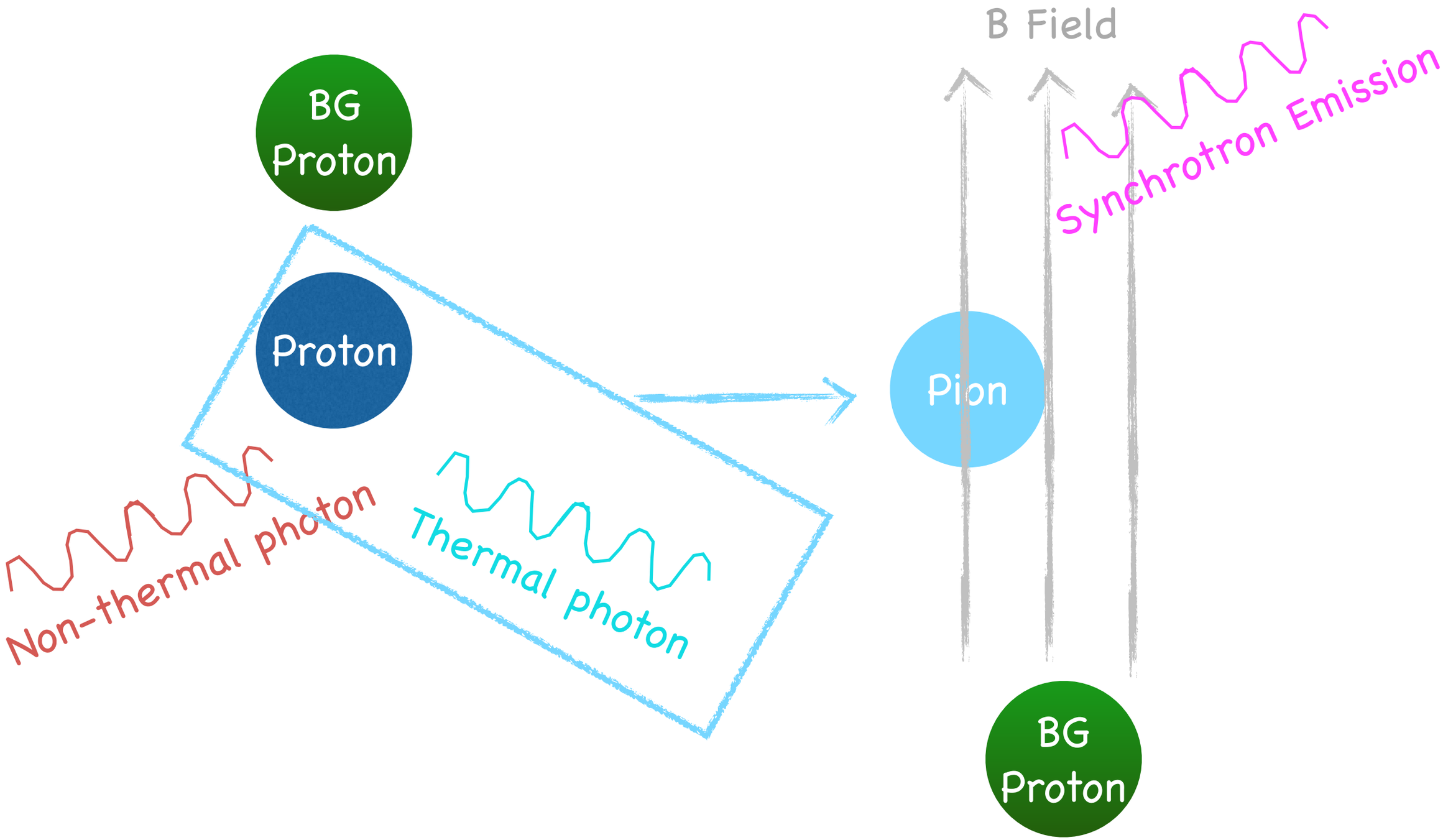
From Proton to Neutrino



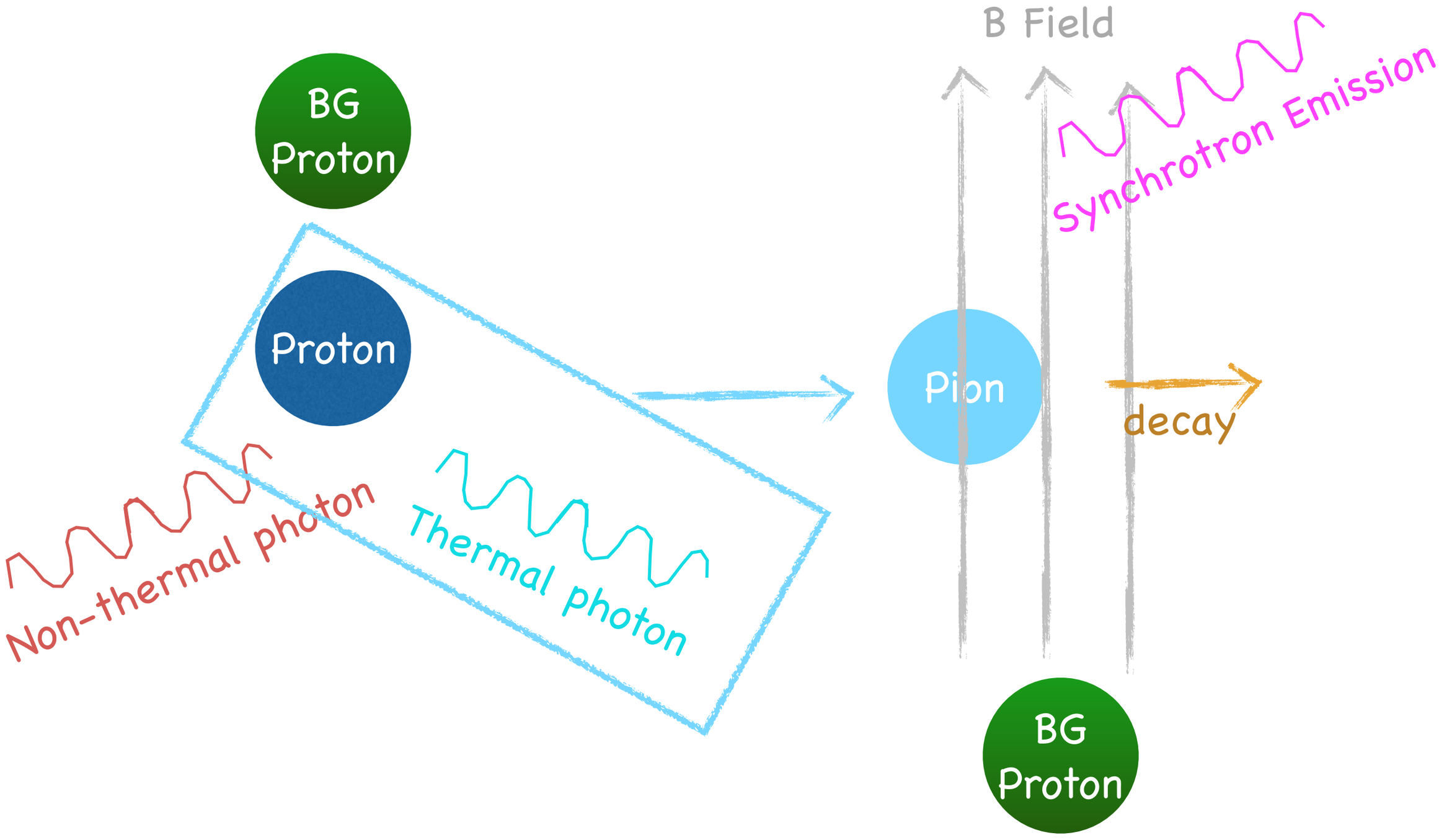
From Proton to Neutrino



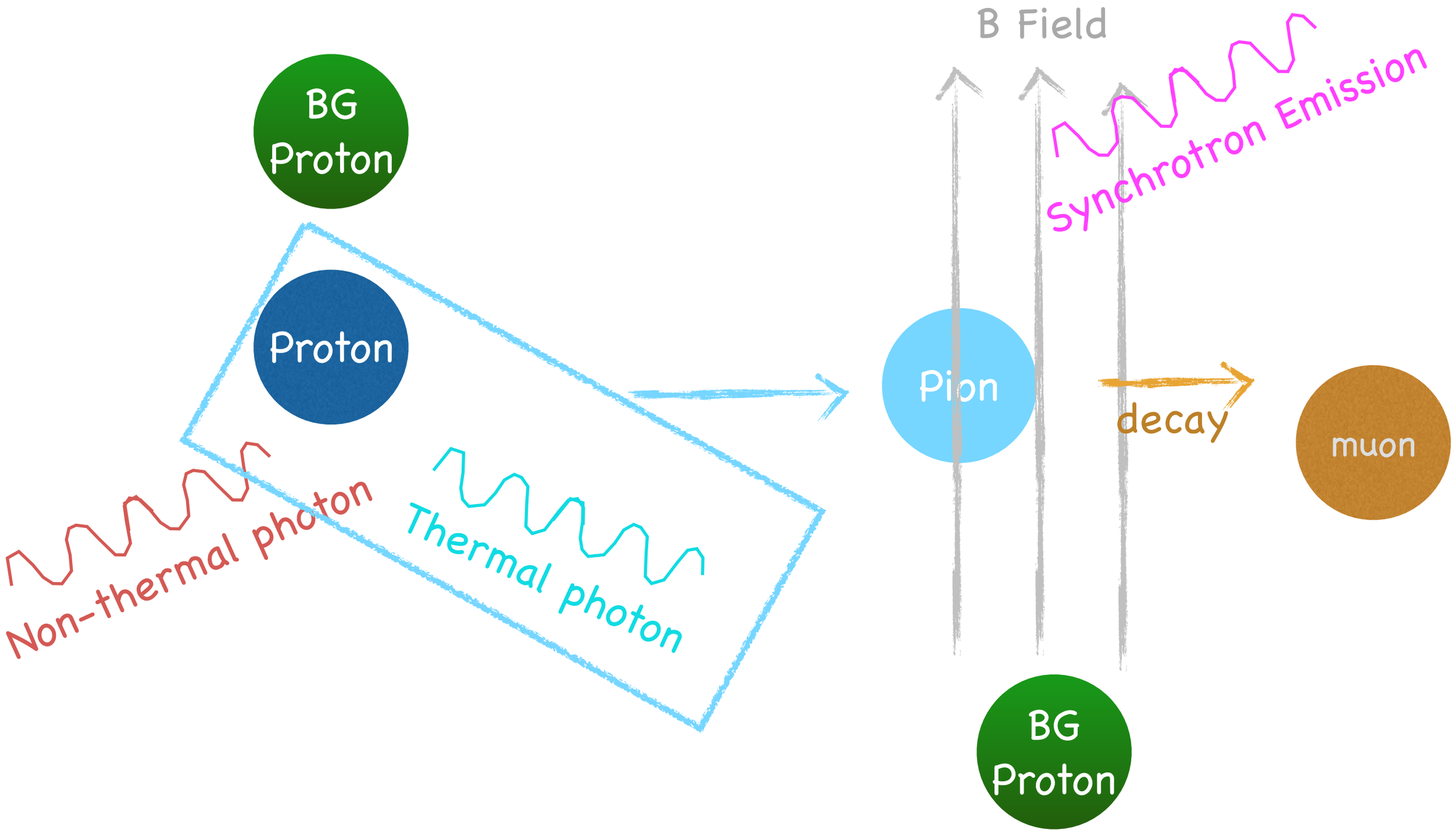
From Proton to Neutrino



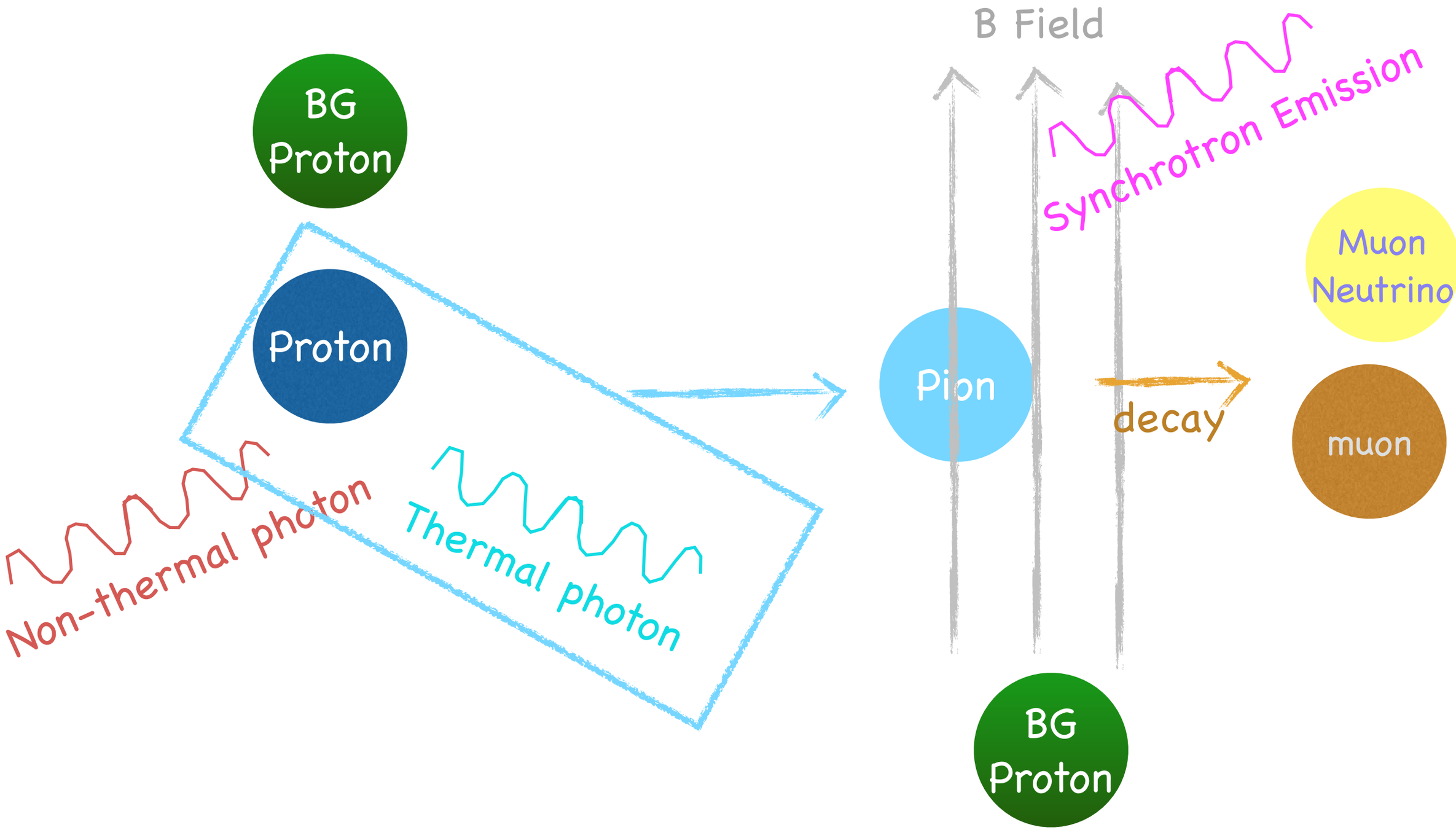
From Proton to Neutrino



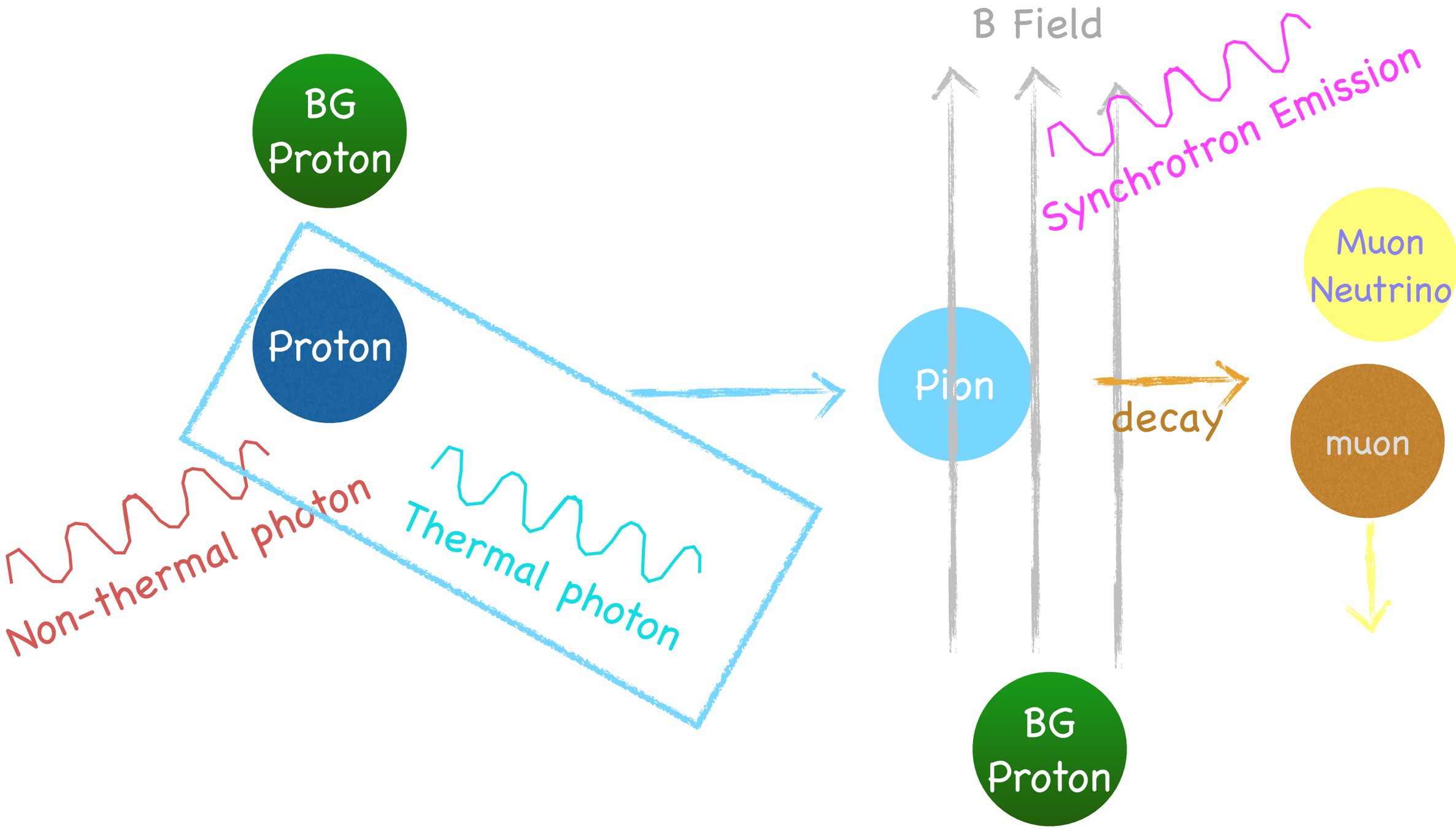
From Proton to Neutrino



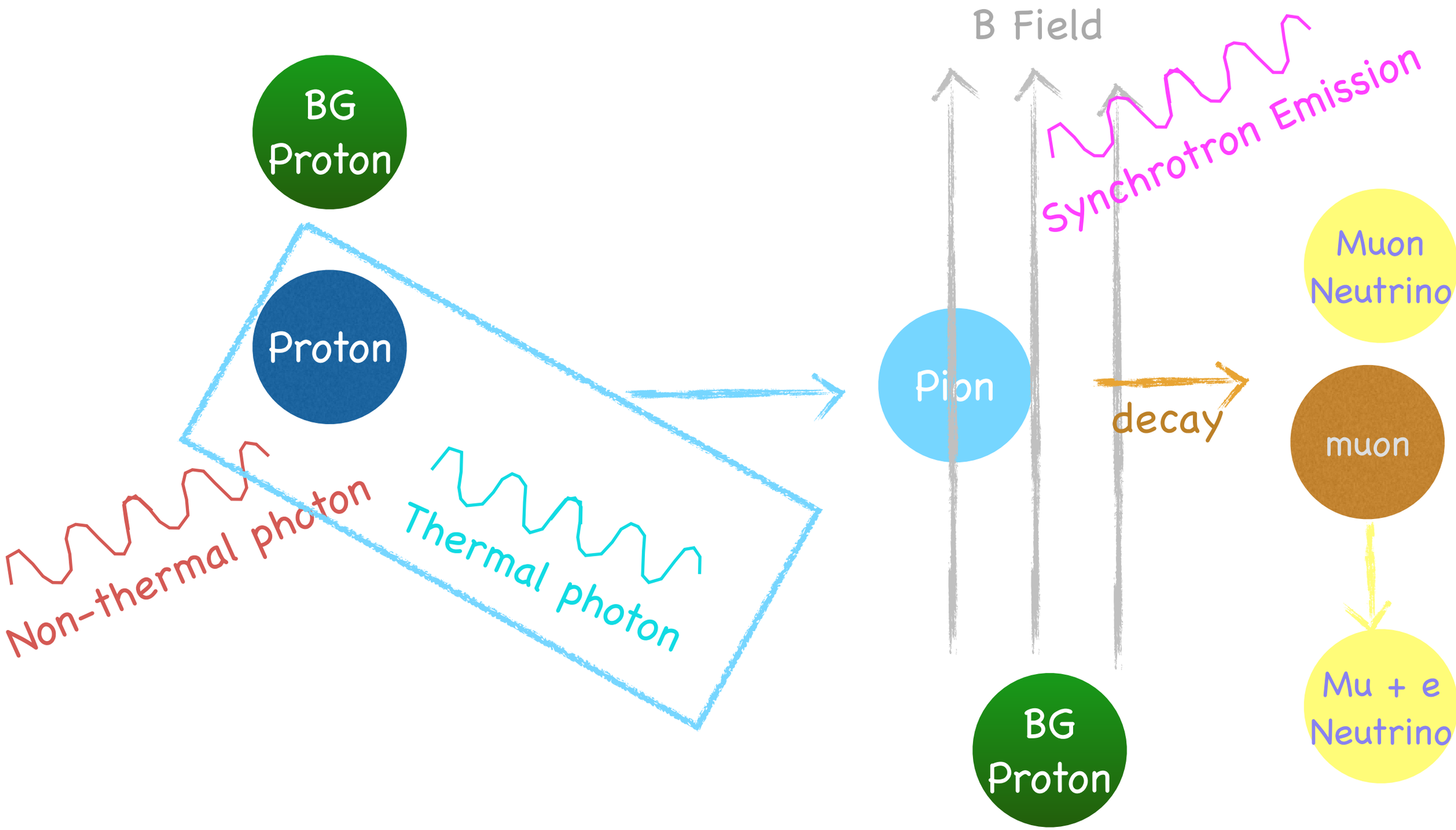
From Proton to Neutrino



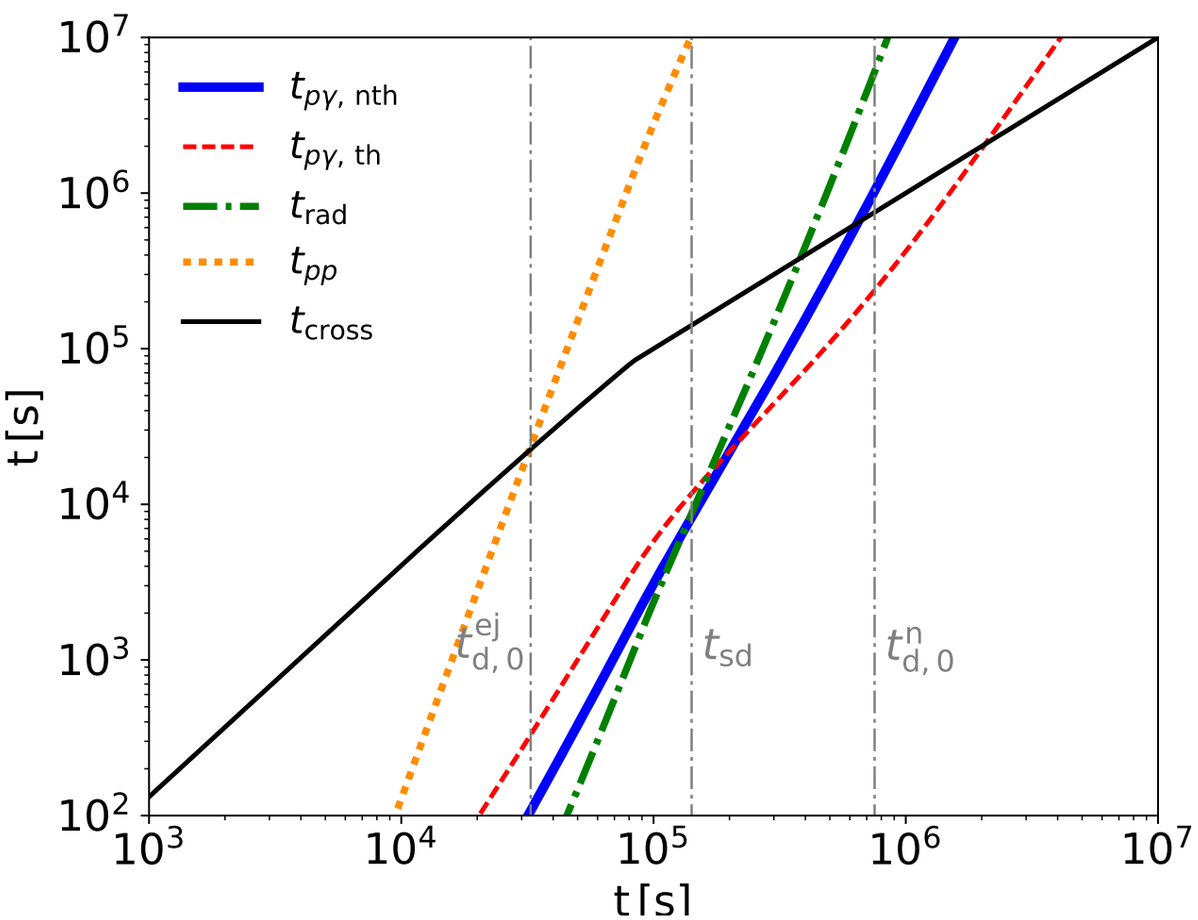
From Proton to Neutrino



From Proton to Neutrino



Interaction and Cooling Processes



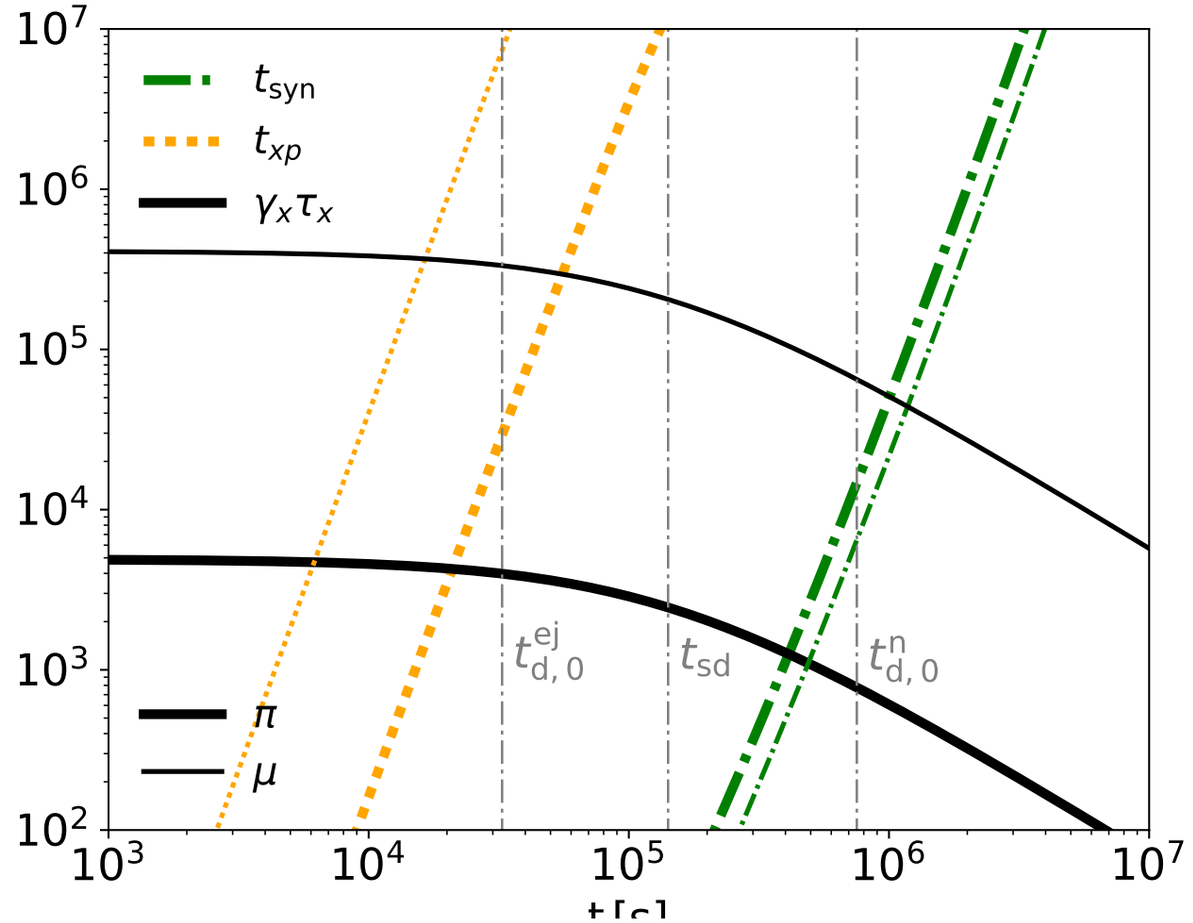


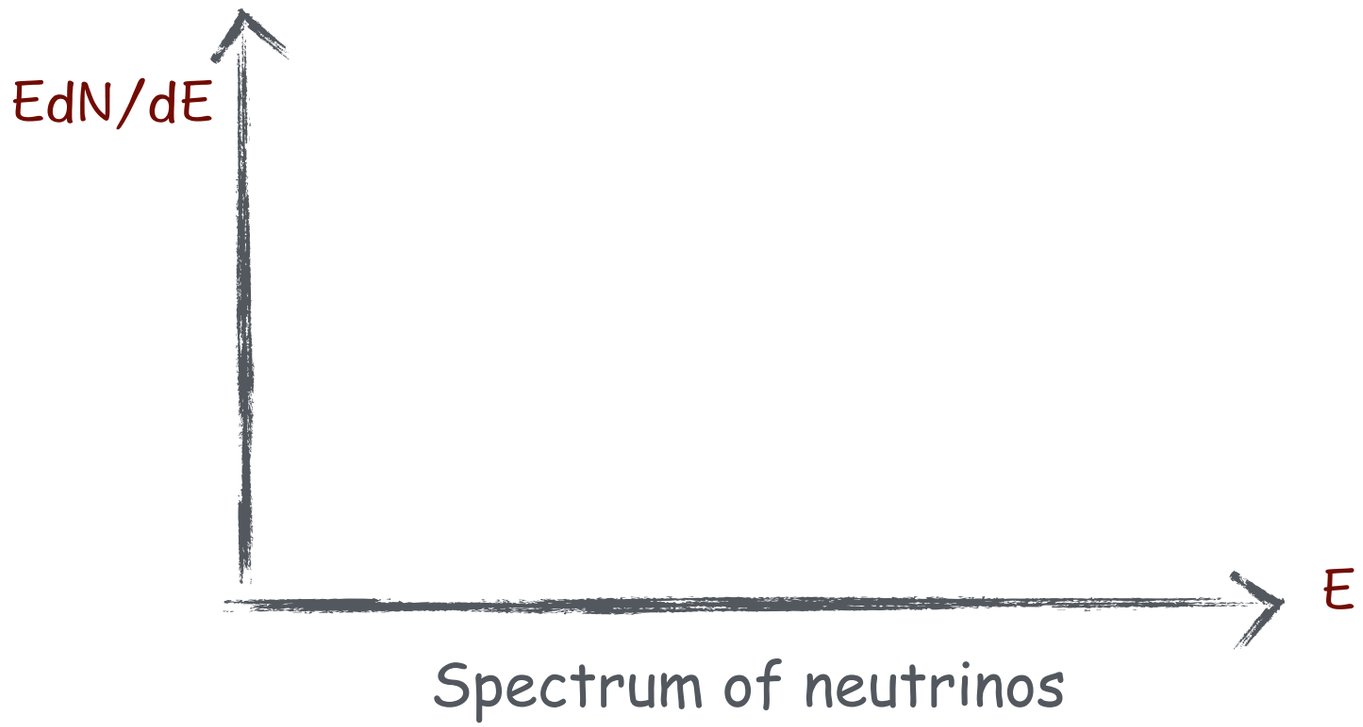
Table 1. Summary of characteristic timescales

time symbol	value [s] at $t_{\mathrm{sd}} \ll t \ll t^{n}_{d,0}$	description
$t^{\mathrm{ej}}_{d,0}$	$3.3 \times 10^{4}\, M_{-2}^{1/2}\, \beta^{-1/2}$	time after which photons escape the ejecta freely
t_{sd}	$1.4 \times 10^{5}\, P_{i,-3}^{2}\, B_{14}^{-2}$	spin-down time
$t^{p}_{\mathrm{sup},\,0}$	$1.4 \times 10^{5}\, \eta_{-1}^{8/25}\, B_{14}^{-18/25}\, \beta^{-9/25}\, \epsilon_{B,-2}^{8/25}$	time when an efficient photopion production starts
$t^{\pi}_{\mathrm{sup},\,0}$	$3.9 \times 10^{5}\, \eta_{-1}^{1/3}\, B_{14}^{-2/3}\, \beta^{-1/2}\, \epsilon_{B,-2}^{1/6}$	time when πs decay
$t^{n}_{d,0}$	$7.5 \times 10^{5}\, B_{14}^{-2/3} \beta^{1/3}$	time after which photons escape the nebula freely
$t^{\mu}_{\mathrm{sup},\,0}$	$9.3 \times 10^{5}\, \eta_{-1}^{1/3}\, B_{14}^{-2/3}\, \beta^{-1/2}\, \epsilon_{B,-2}^{1/6}$	time when μs decay
$t_{\pi,0}$	$1.2 \times 10^{7}\, \beta^{-23/7}\, B_{14}^{-6/7}$	time when neutrino production stops

Neutrino Production

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

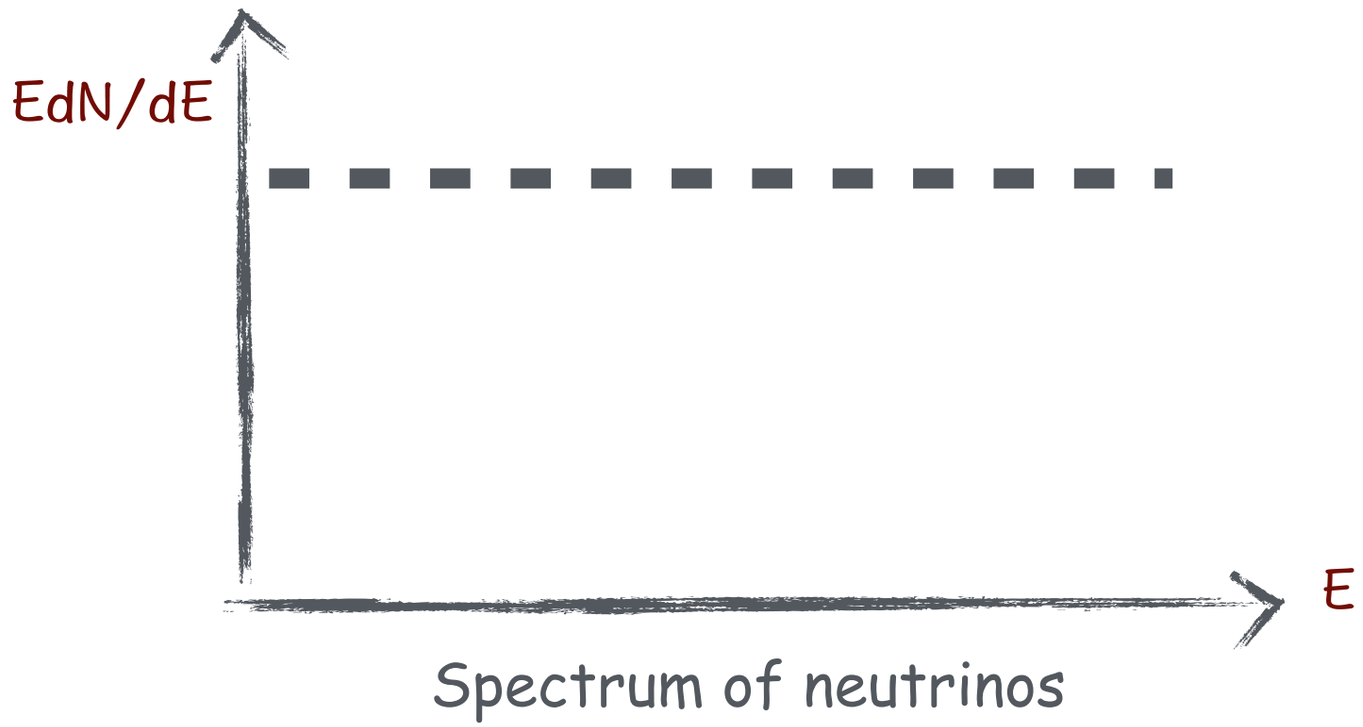
Charged pion products



Neutrino Production

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

Charged pion products



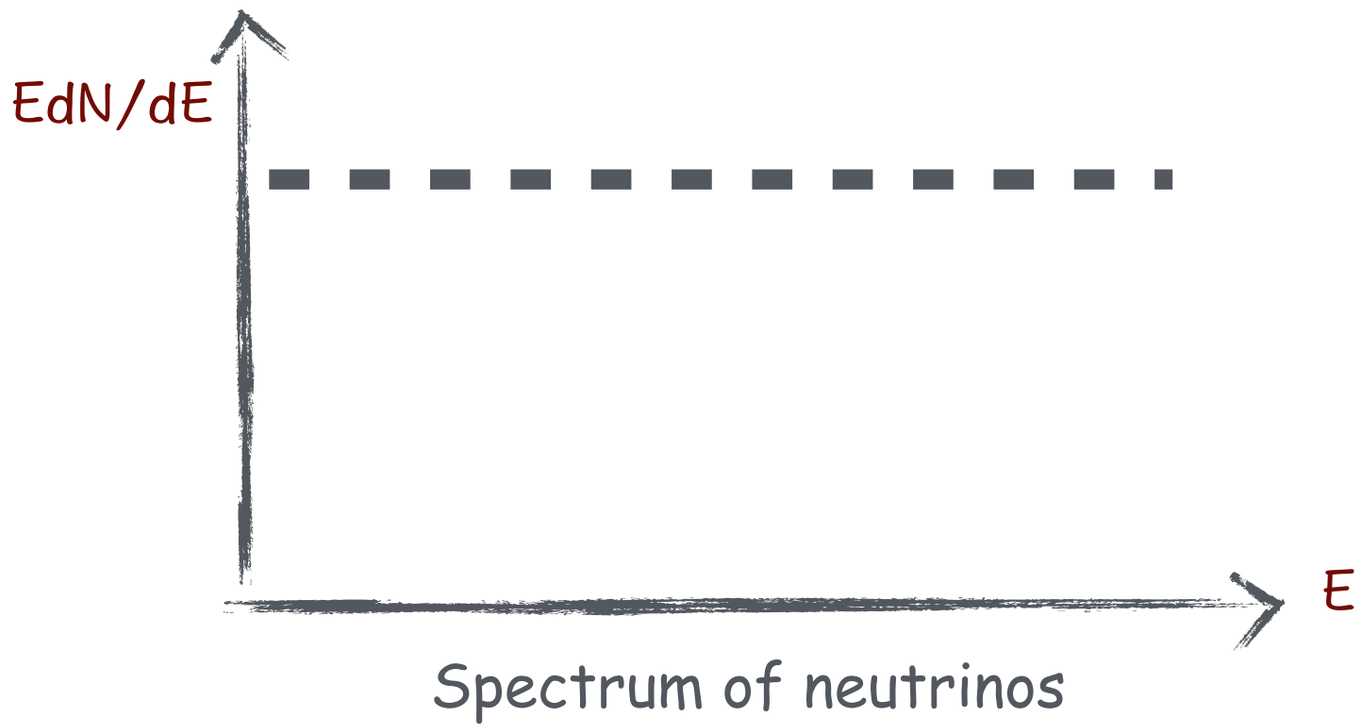
Neutrino Production

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

Charged pion products

Decay into leptons

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



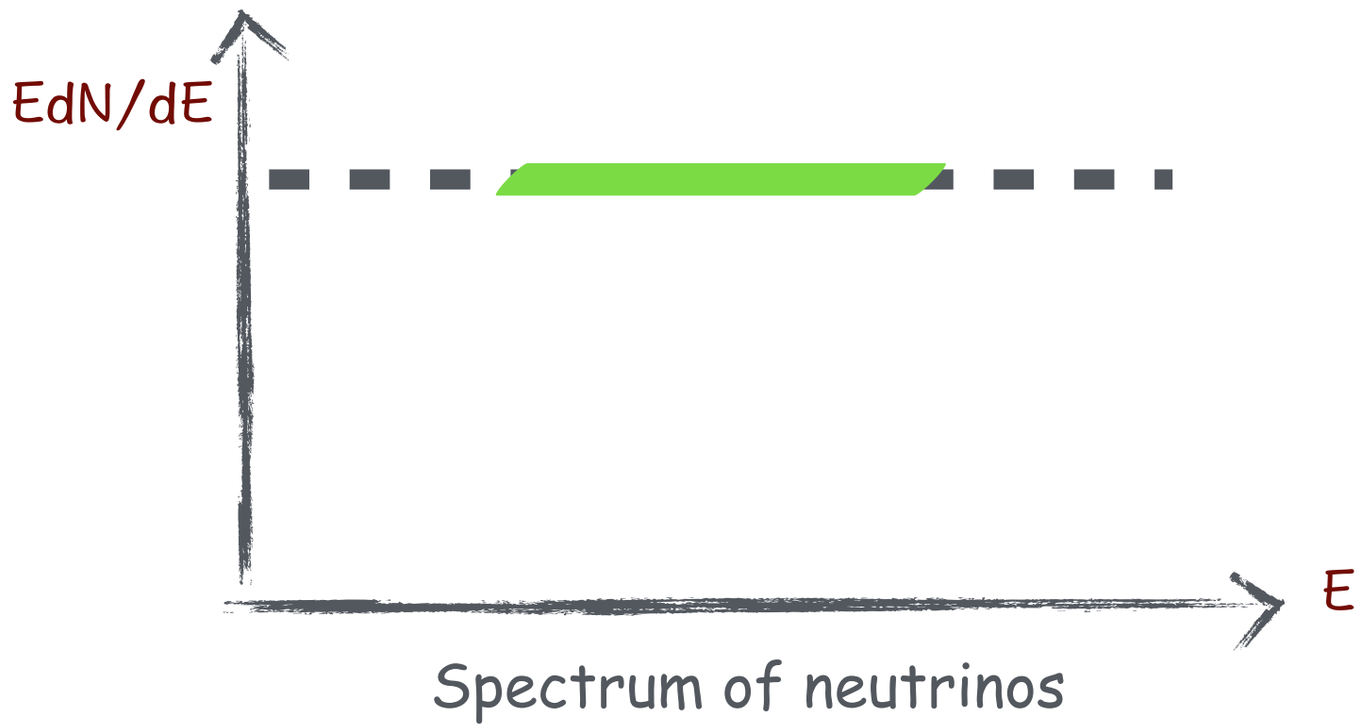
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Spectrum of neutrinos

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 or undergo synchrotron radiation

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



Spectrum of neutrinos

Neutrino Production

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

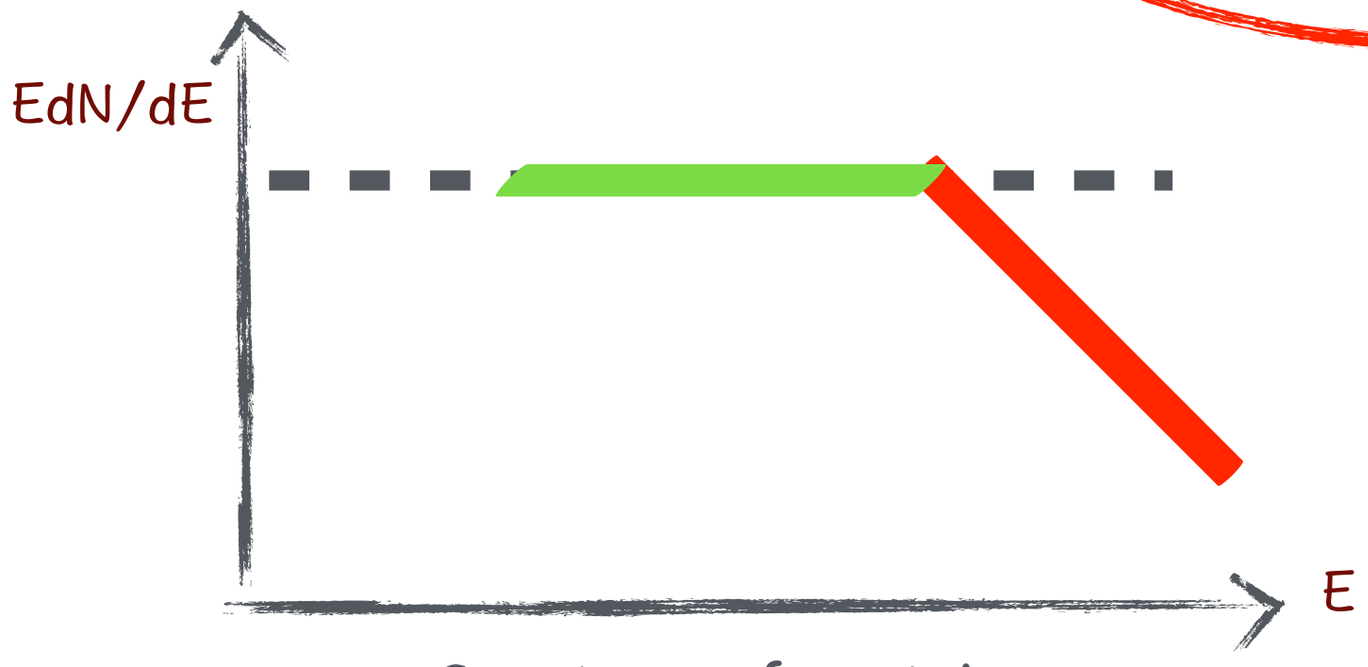
Charged pion products

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Spectrum of neutrinos

Neutrino Production

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

Charged pion products

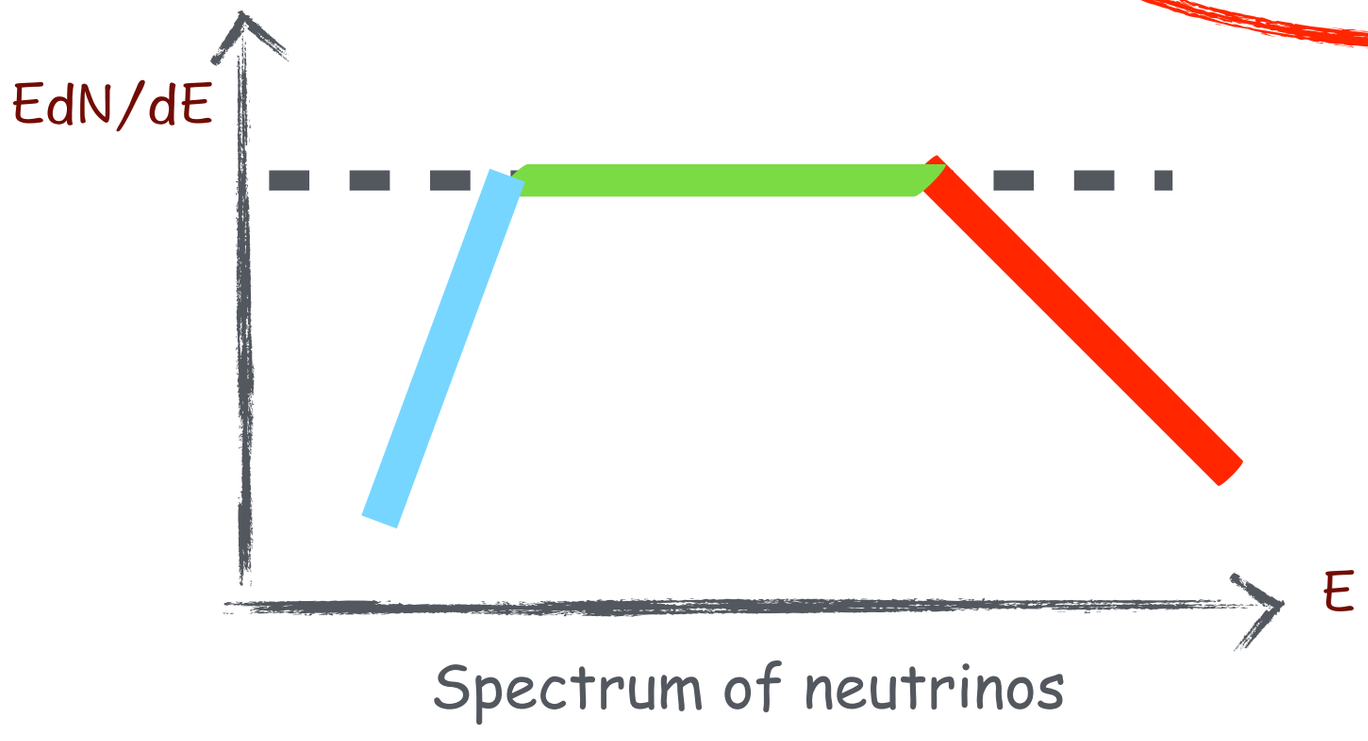
$f_\pi = \min(\tau_{Np}, 1)$

Decay into leptons

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

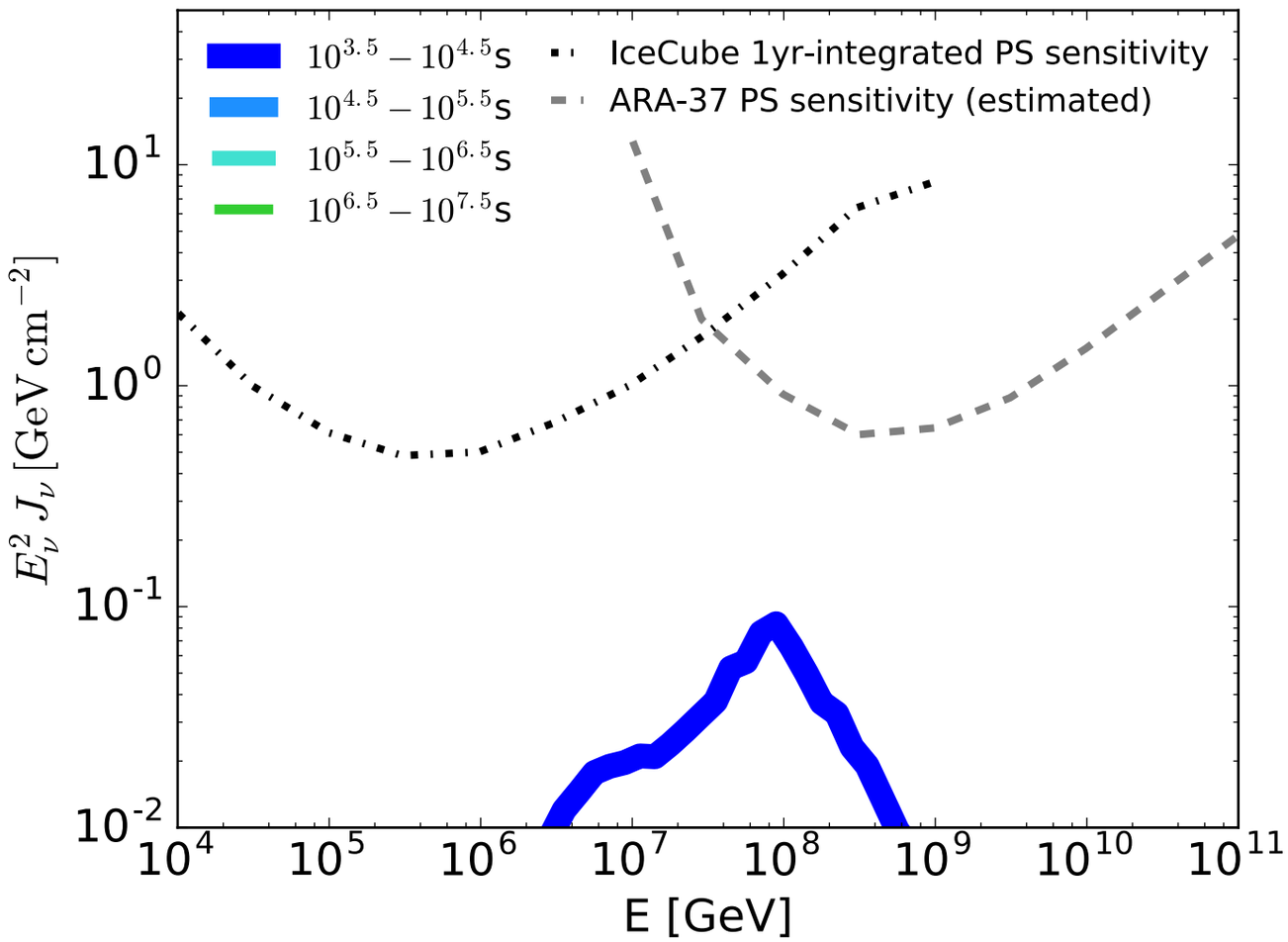
Interact with hadron background or undergo synchrotron radiation

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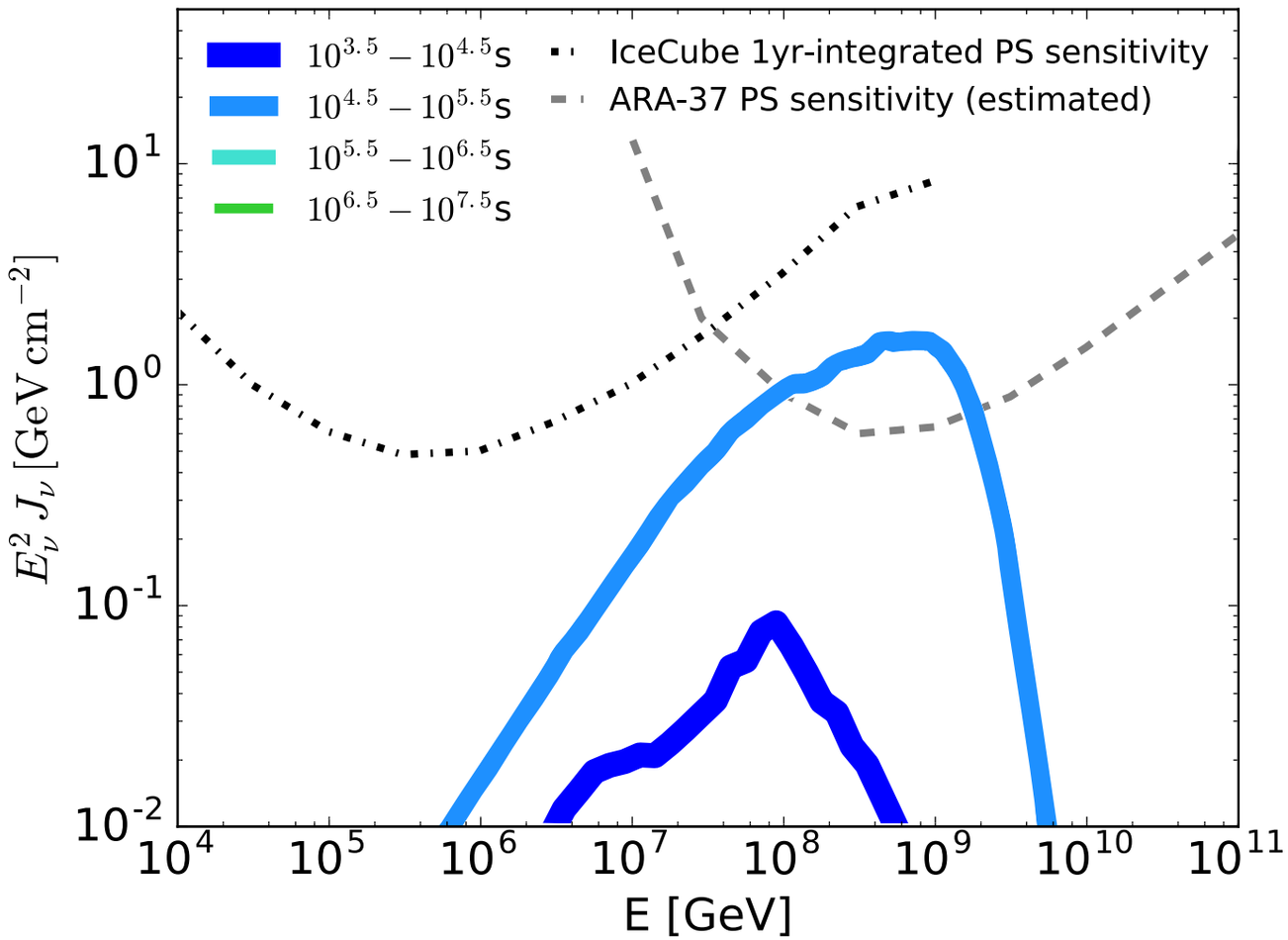
Spectrum of neutrinos

Neutrino light curves - Single Source



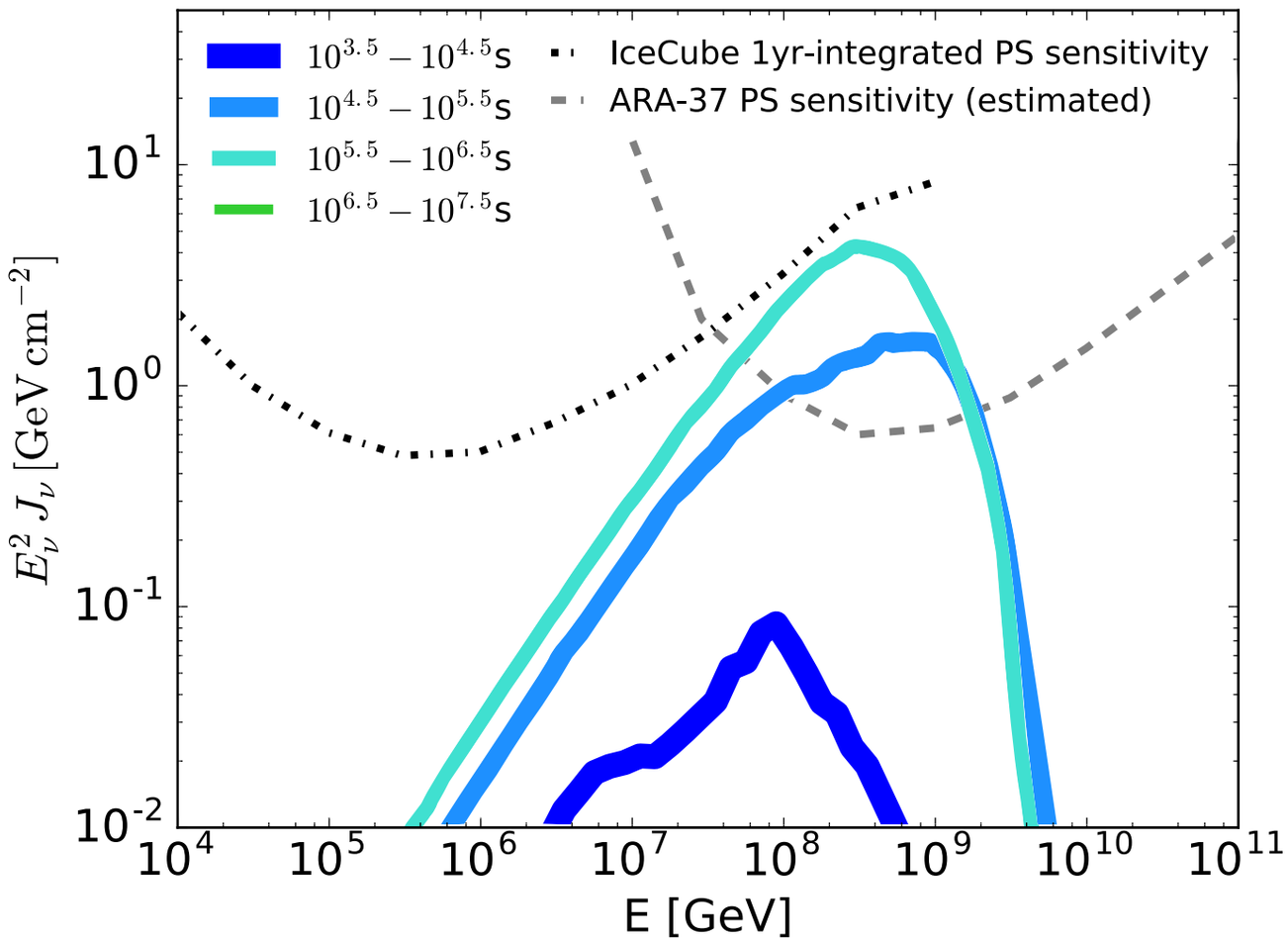
KF & Metzger 1707.04263

Neutrino light curves - Single Source



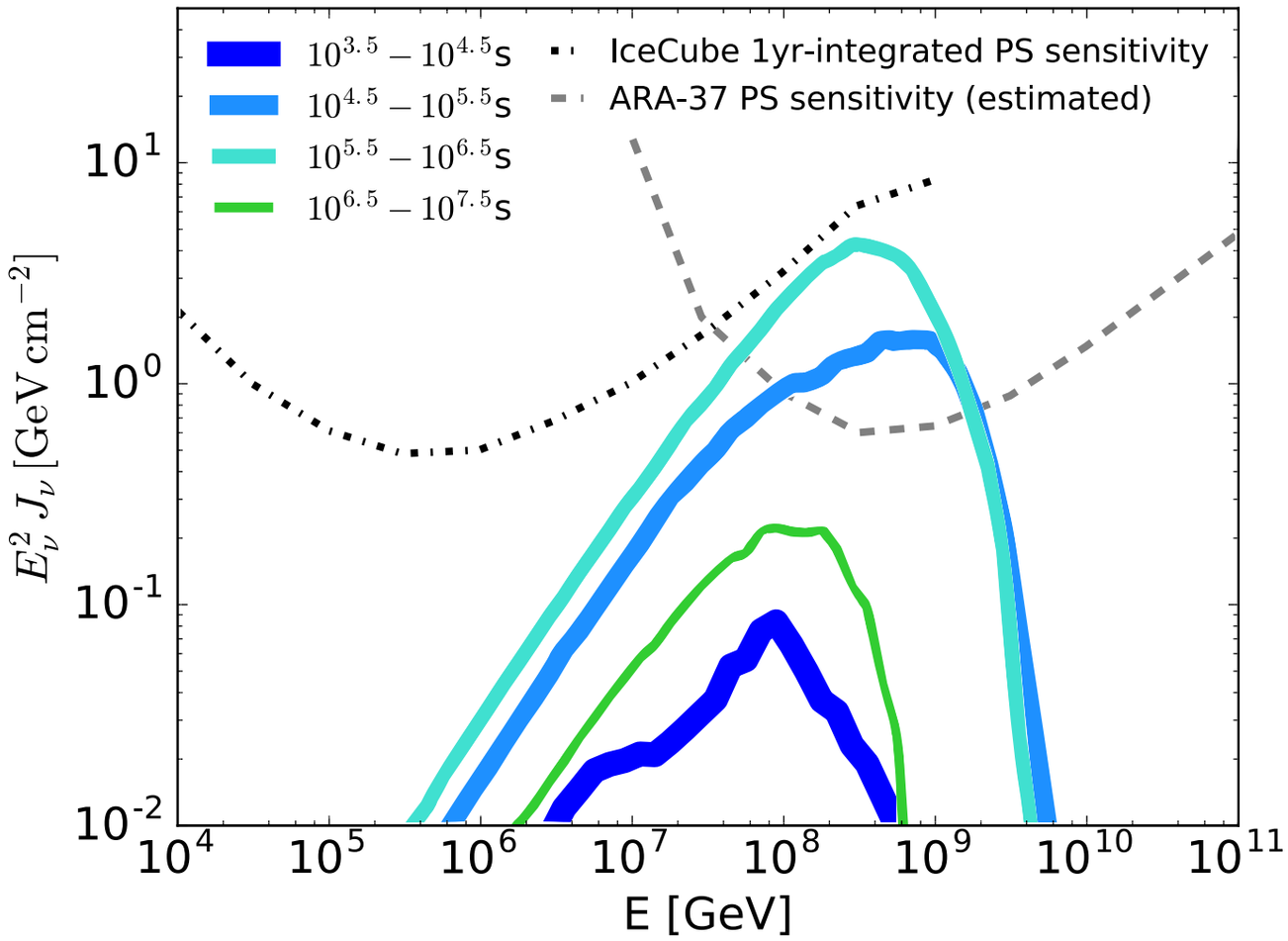
KF & Metzger 1707.04263

Neutrino light curves - Single Source



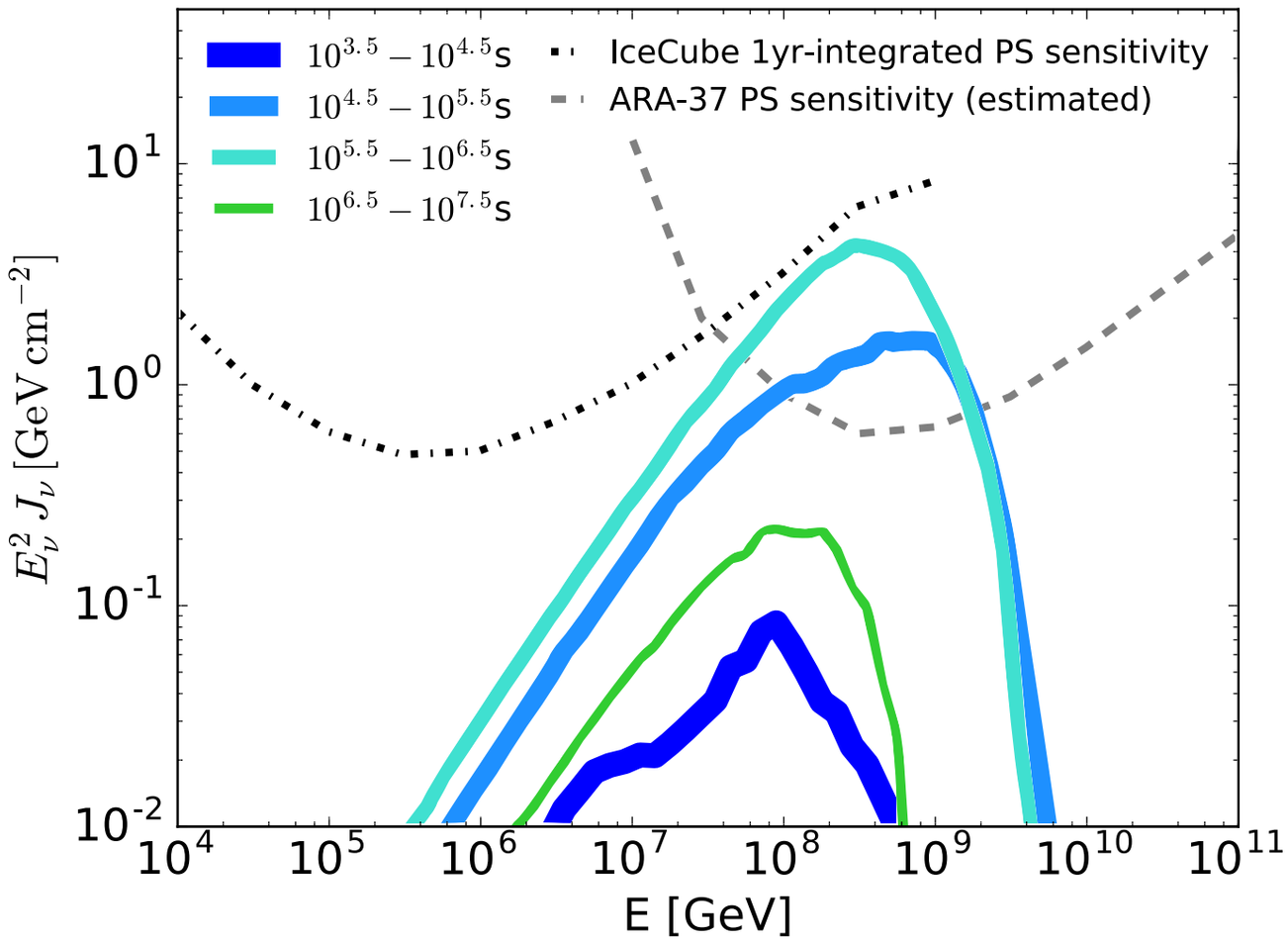
KF & Metzger 1707.04263

Neutrino light curves - Single Source



KF & Metzger 1707.04263

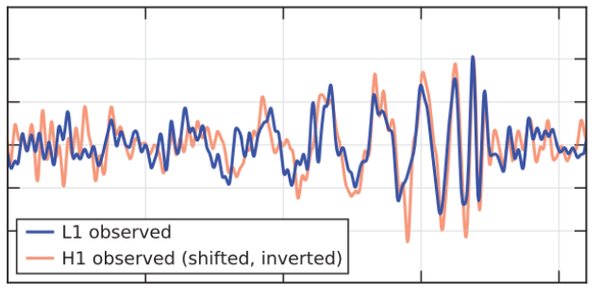
Neutrino light curves - Single Source

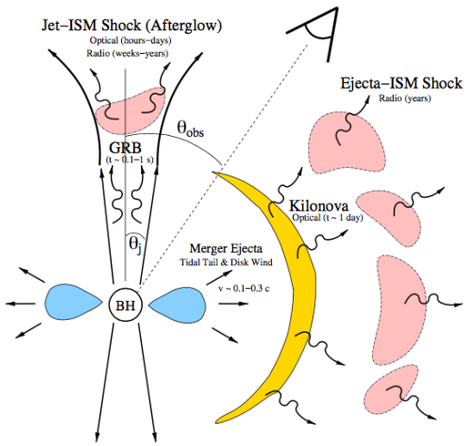


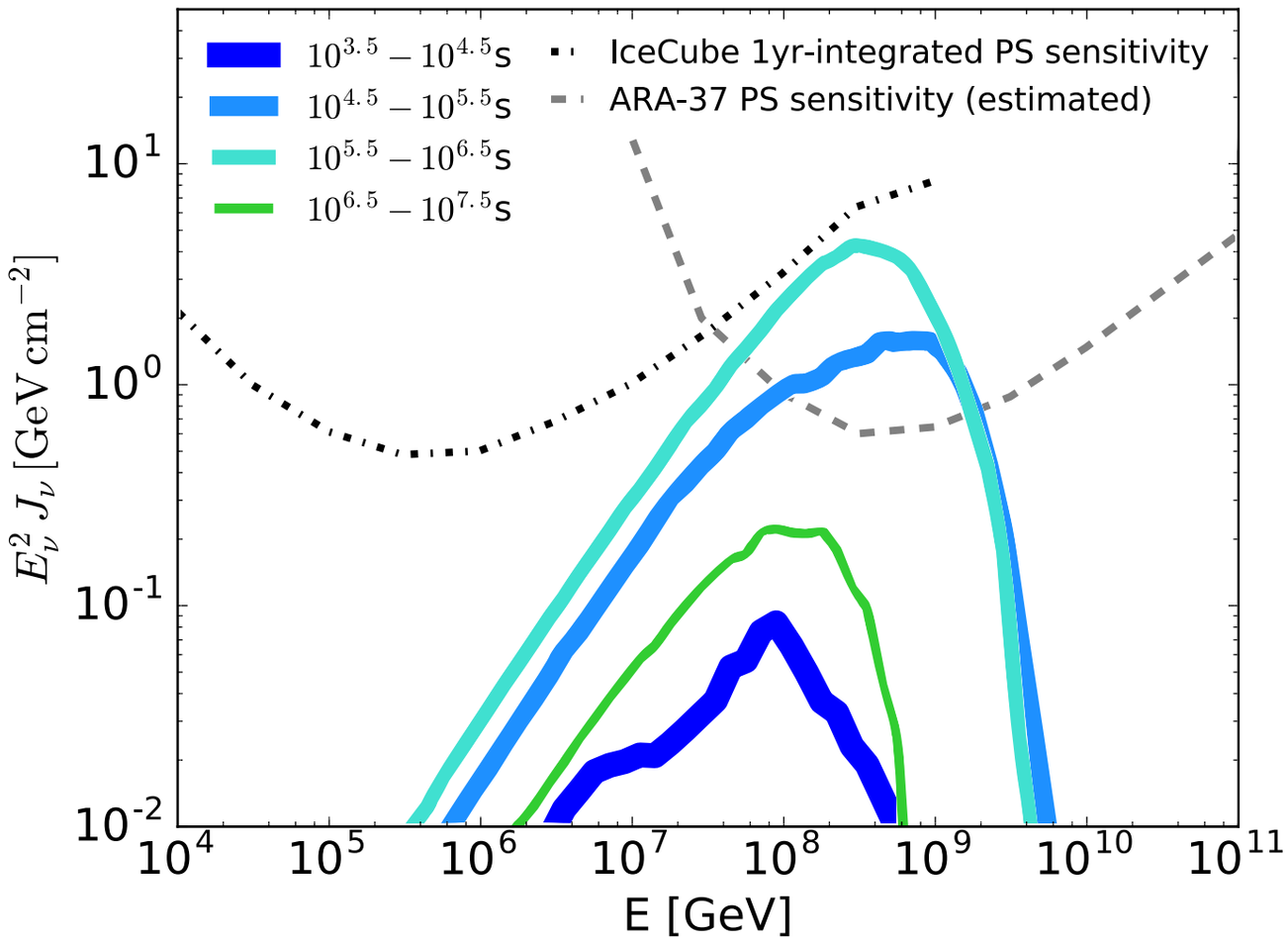
High-energy neutrinos may help localize the gravitational wave event, and provide clear evidence of the formation of a stable neutron star remnant.

KF & Metzger 1707.04263

Neutrino light curves - Single Source





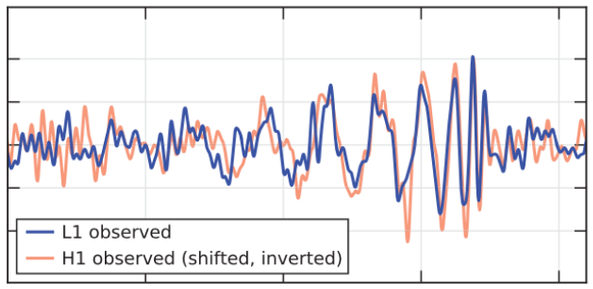


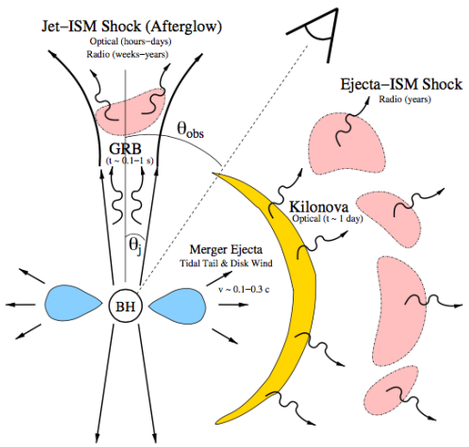
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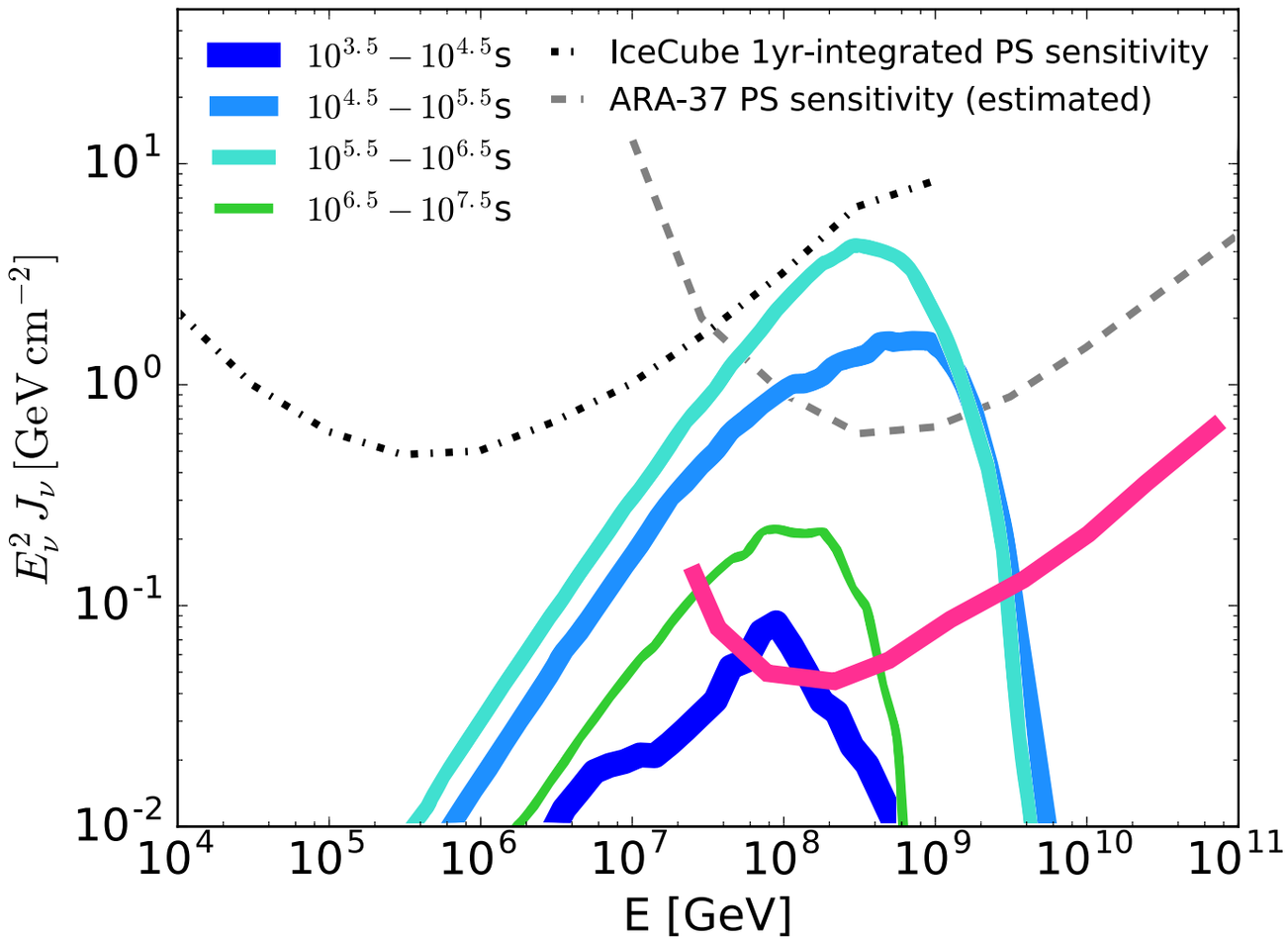
KF & Metzger 1707.04263

Neutrino light curves - Single Source

see talks by F. Schroeder and C. Timmermans







Future neutrino detectors with 10x better sensitivity can localize NS mergers in LIGO ranges. Be GRAND!

High-energy neutrinos may help localize the gravitational wave event, and provide clear evidence of the formation of a stable neutron star remnant.

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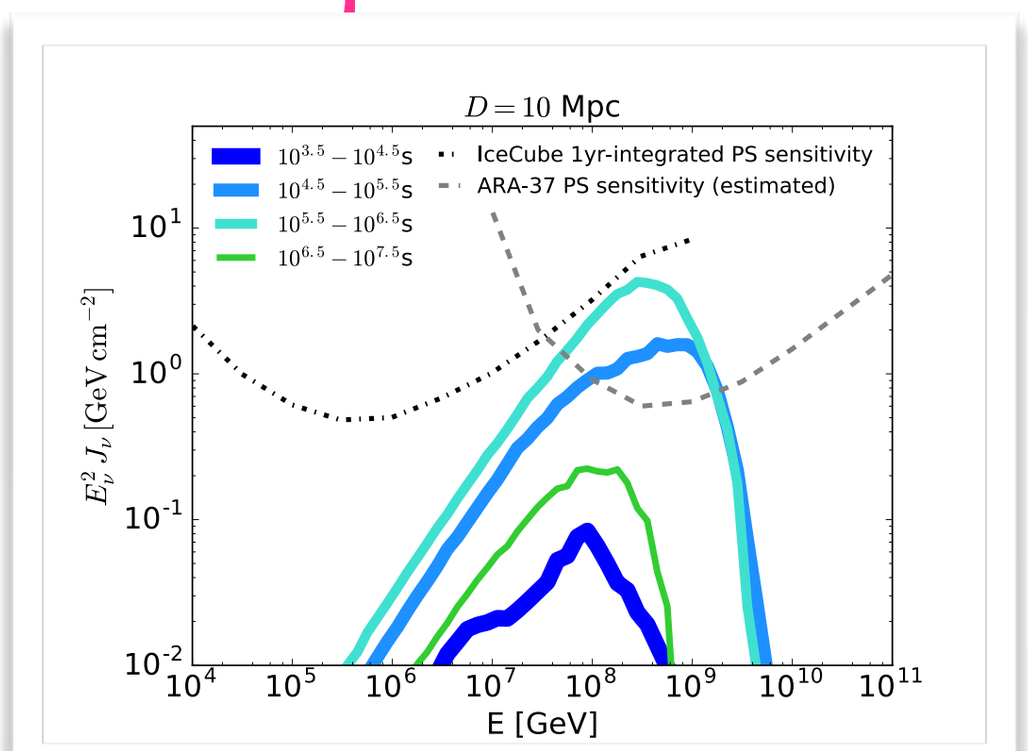
Cumulative Neutrino Background

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

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

Cumulative Neutrino Background

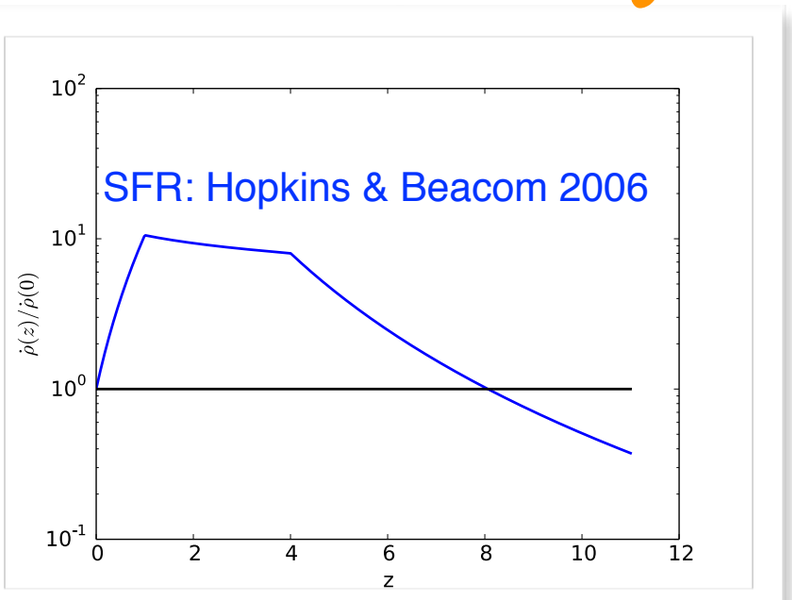
$$\Phi_\nu = \frac{dN}{dE dA dt d\Omega} = \frac{c}{4\pi} \int_0^{z_{\rm max}} \dot{\rho}_{\rm source}(z) \frac{dN[E(1+z)]}{dE'} (1+z) \frac{dt}{dz} dz$$

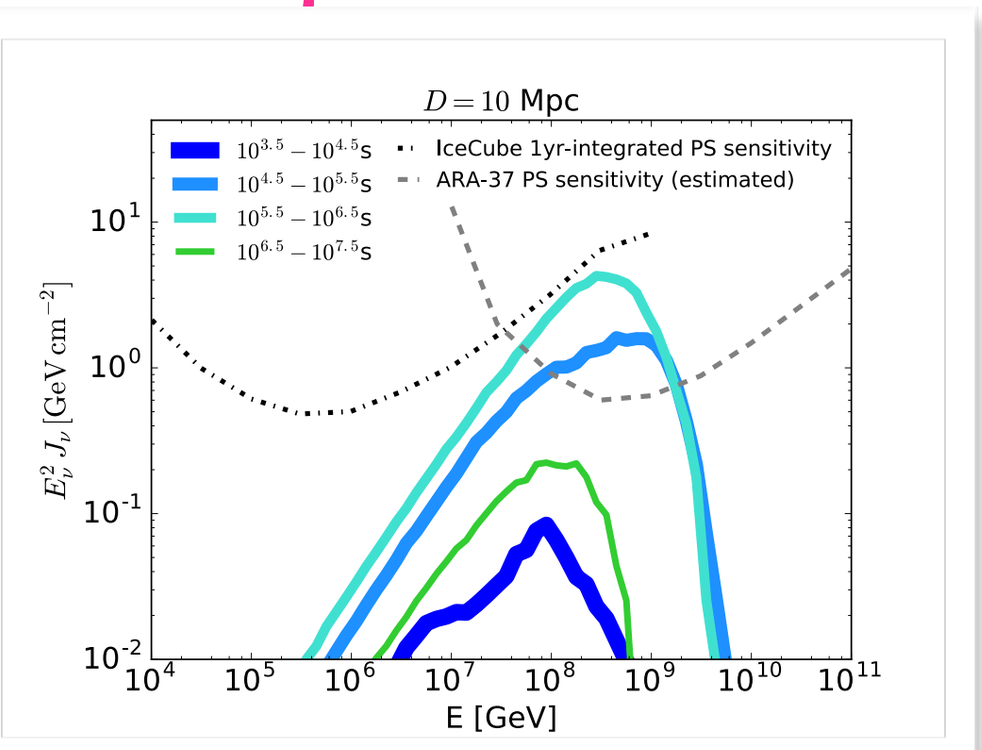


KF, Kotera, Murase & Olinto, PRD 90, 103005 (2014)

Cumulative Neutrino Background

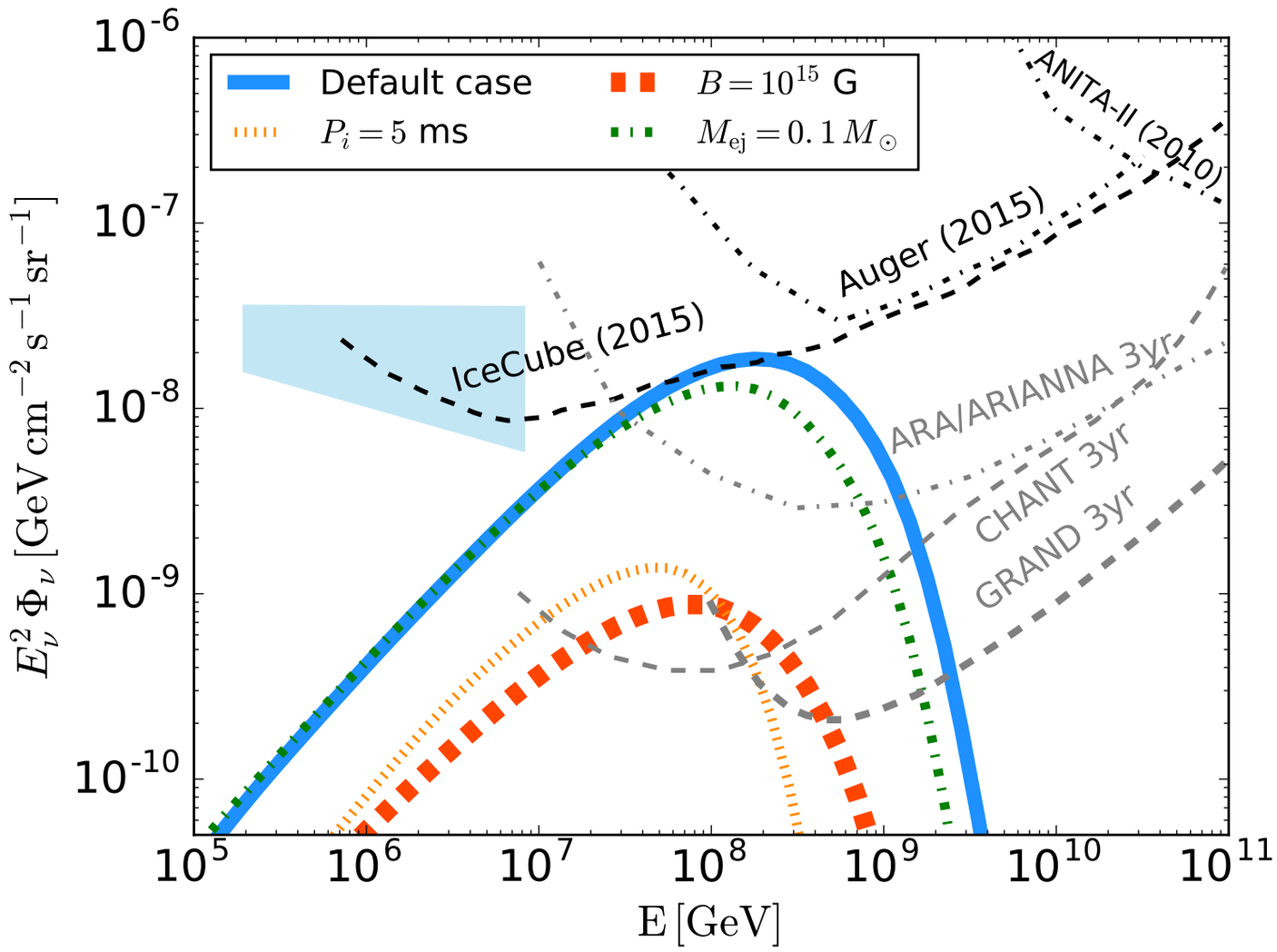
$$\Phi_\nu = \frac{dN}{dE dA dt d\Omega} = \frac{c}{4\pi} \int_0^{z_{\rm max}} \dot{\rho}_{\rm source}(z) \frac{dN[E(1+z)]}{dE'} (1+z) \frac{dt}{dz} dz$$





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

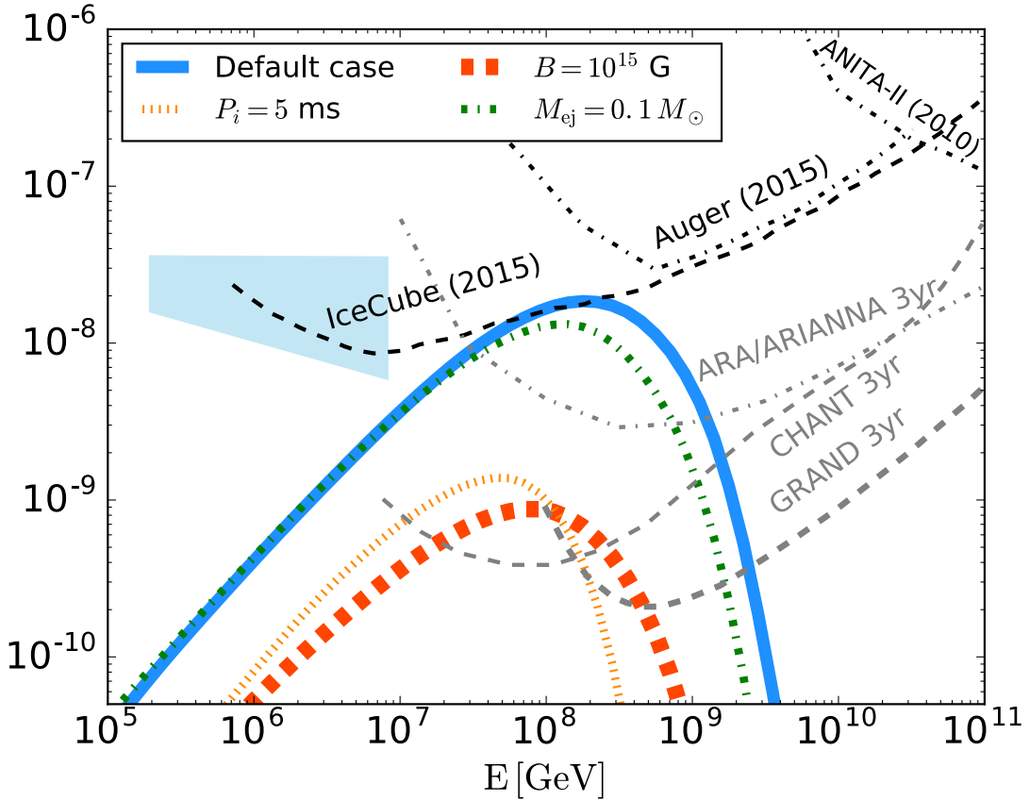
Cumulative Neutrino Background



Cumulative flux may be detectable by IceCube and next-generation telescopes

KF & Metzger 1707.04263

In Case of A Non-detection

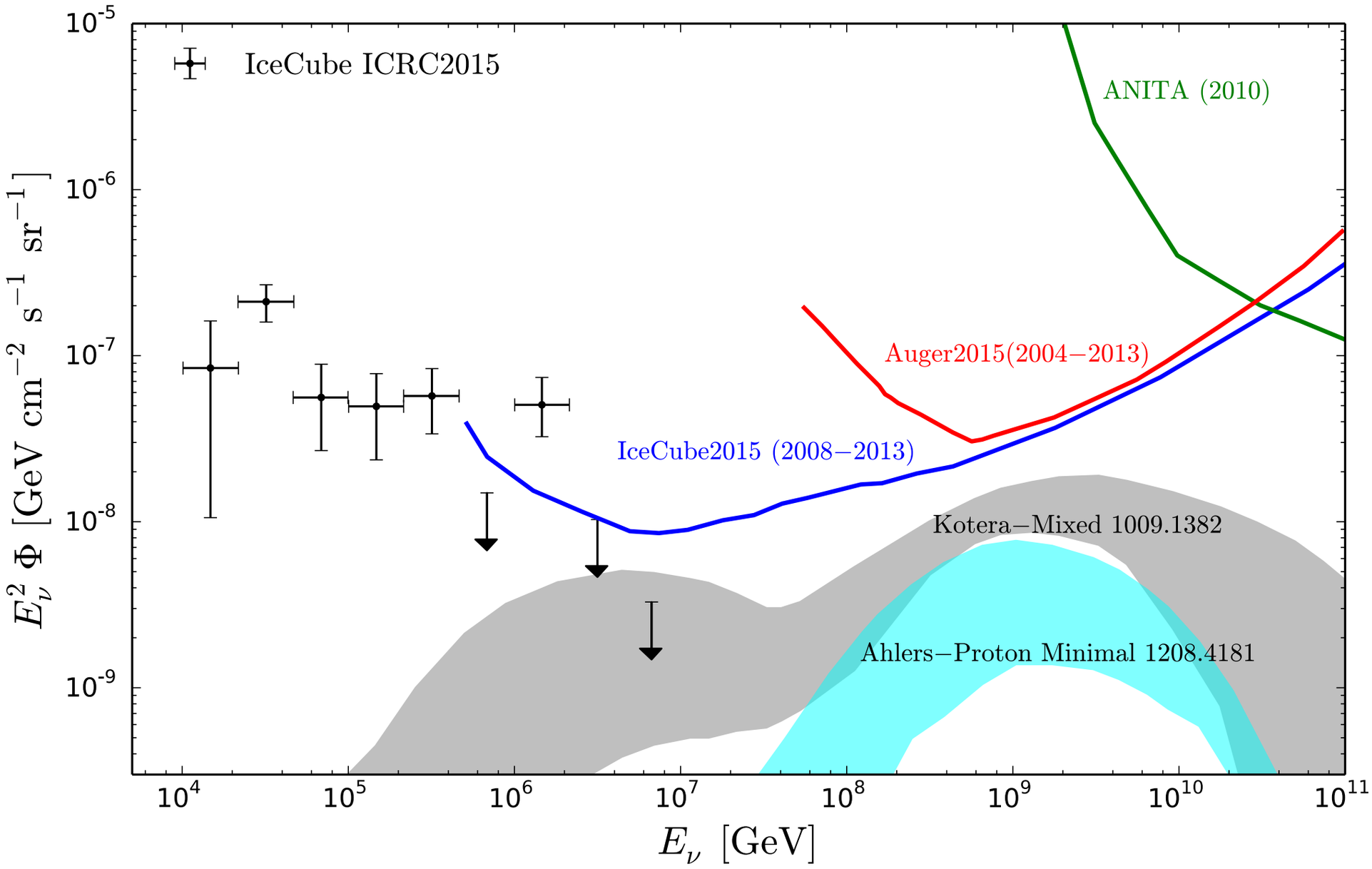


Non-detection can constrain

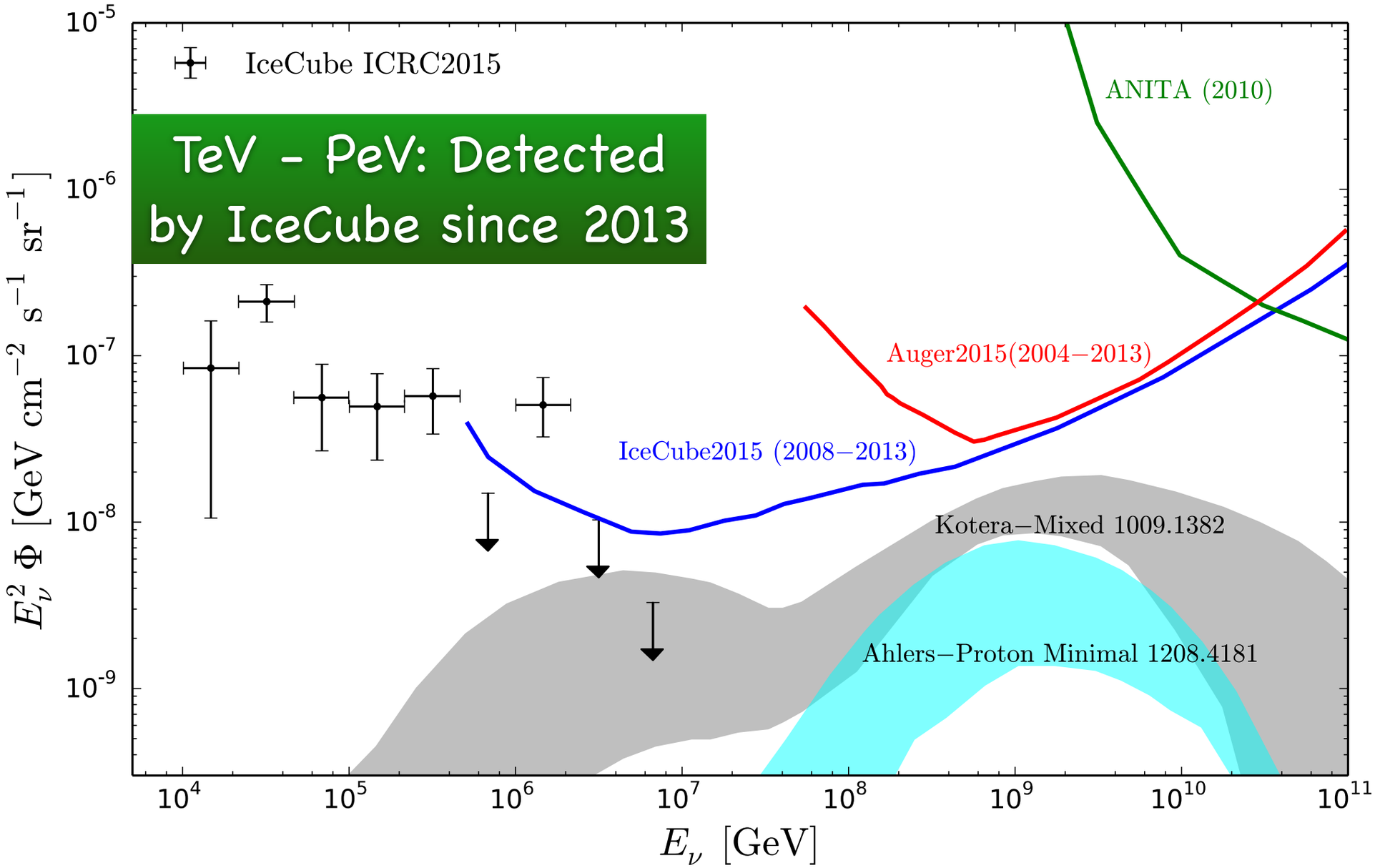
1. Fraction of NS mergers that produce a stable magnetar
2. Rate of NS mergers
3. Strength of dipole field

KF & Metzger 1707.04263

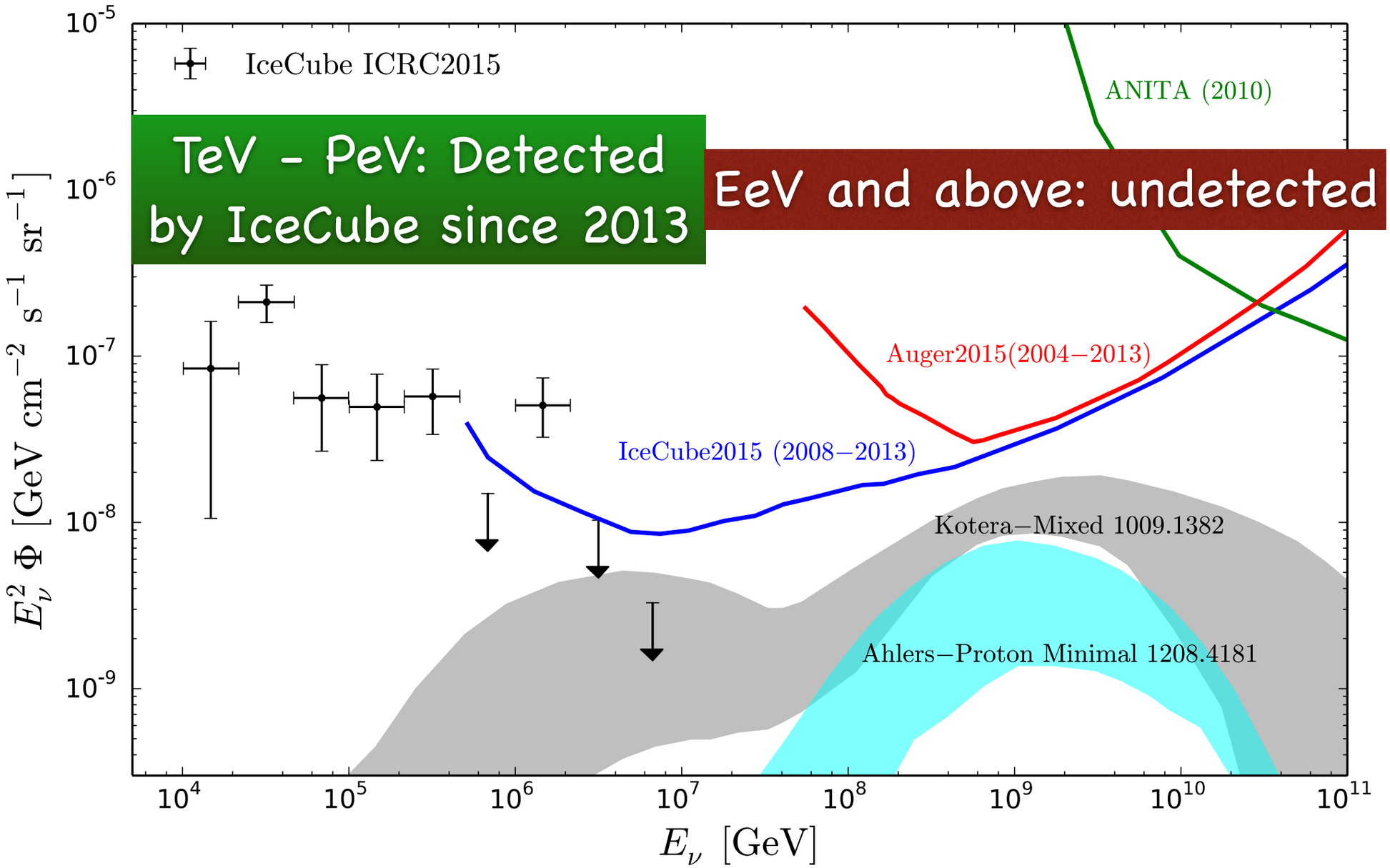
Summary


IceCube ICRC2015
ANITA (2010)
Auger2015(2004−2013)
IceCube2015 (2008−2013)
Kotera−Mixed 1009.1382
Ahlers−Proton Minimal 1208.4181
$E_\nu^2\ \Phi$ [GeV cm^{-2} s^{-1} sr^{-1}]
E_ν [GeV]
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^4
10^5
10^6
10^7
10^8
10^9
10^{10}
10^{11}

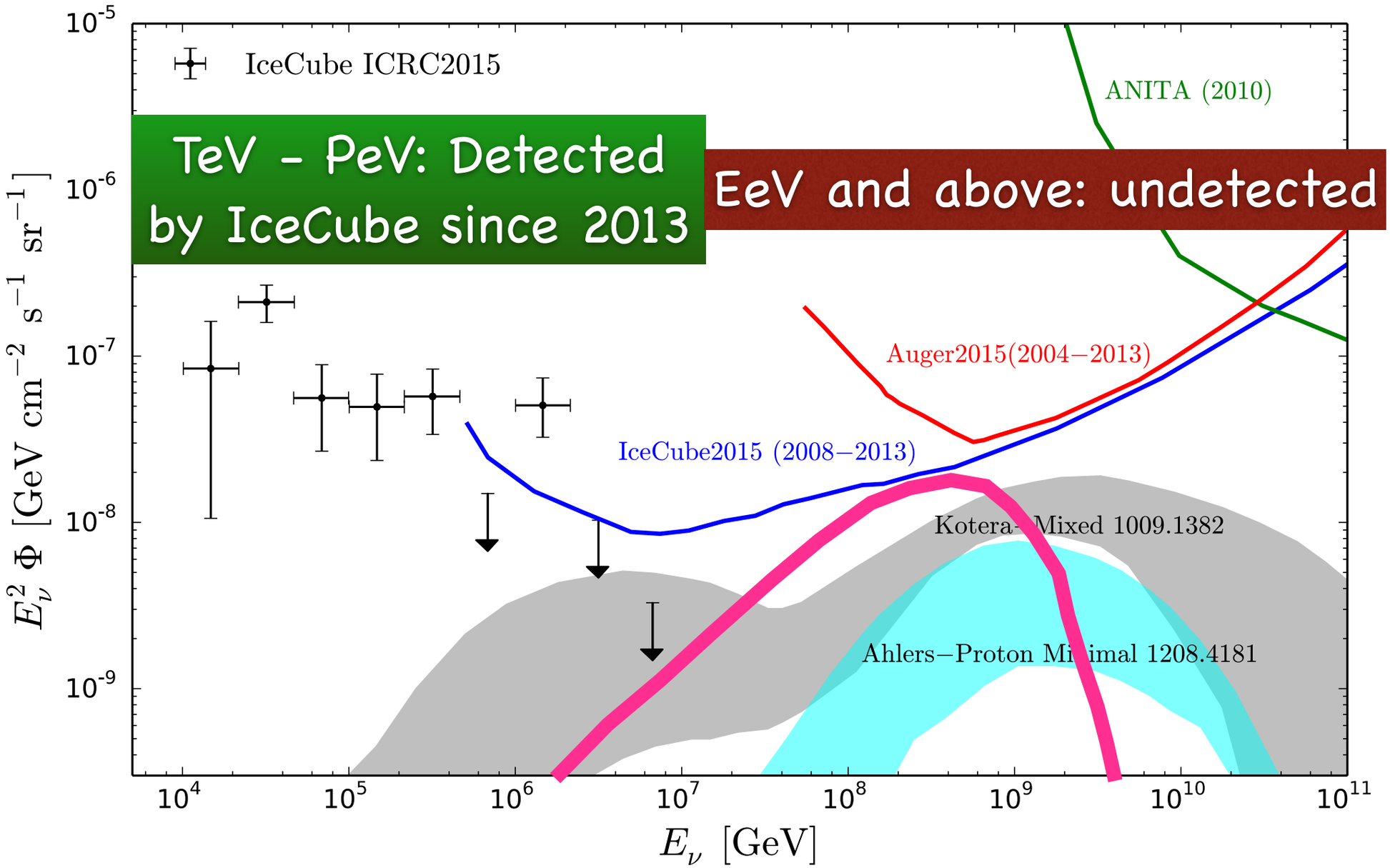
Summary


IceCube ICRC2015
TeV – PeV: Detected by IceCube since 2013
ANITA (2010)
Auger2015(2004−2013)
IceCube2015 (2008−2013)
Kotera−Mixed 1009.1382
Ahlers−Proton Minimal 1208.4181
$E_\nu^2\,\Phi$ [GeV cm^{-2} s^{-1} sr^{-1}]
E_ν [GeV]

Summary


IceCube ICRC2015
TeV – PeV: Detected by IceCube since 2013
EeV and above: undetected
ANITA (2010)
Auger2015(2004−2013)
IceCube2015 (2008−2013)
Kotera−Mixed 1009.1382
Ahlers−Proton Minimal 1208.4181
$E_\nu^2\,\Phi$ [GeV cm^{-2} s^{-1} sr^{-1}]
E_ν [GeV]

Summary



High-energy neutrinos may signal NS mergers led by GW emissions!

Additional Slides

r-process nucleosynthesis from NS mergers

NS merger (dynamical ejecta):

Radice+ 2016

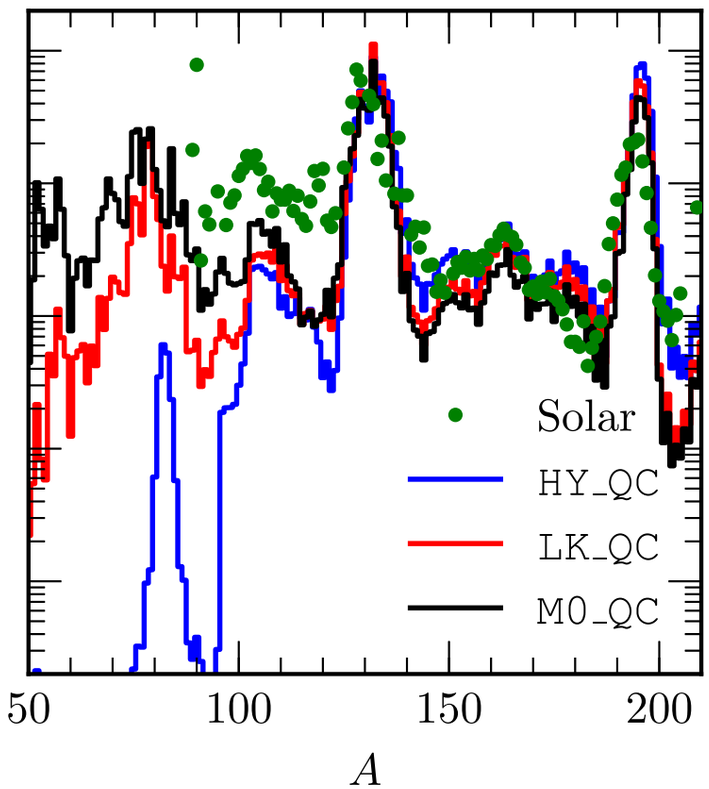


Fig.: production of r-process elements from early ejecta of a BNS merger (dynamical ejecta, neutrino-driven winds)

Post-merger accretion disk outflows:

Siegel & Metzger 2017a
Siegel & Metzger 2017b, in prep.

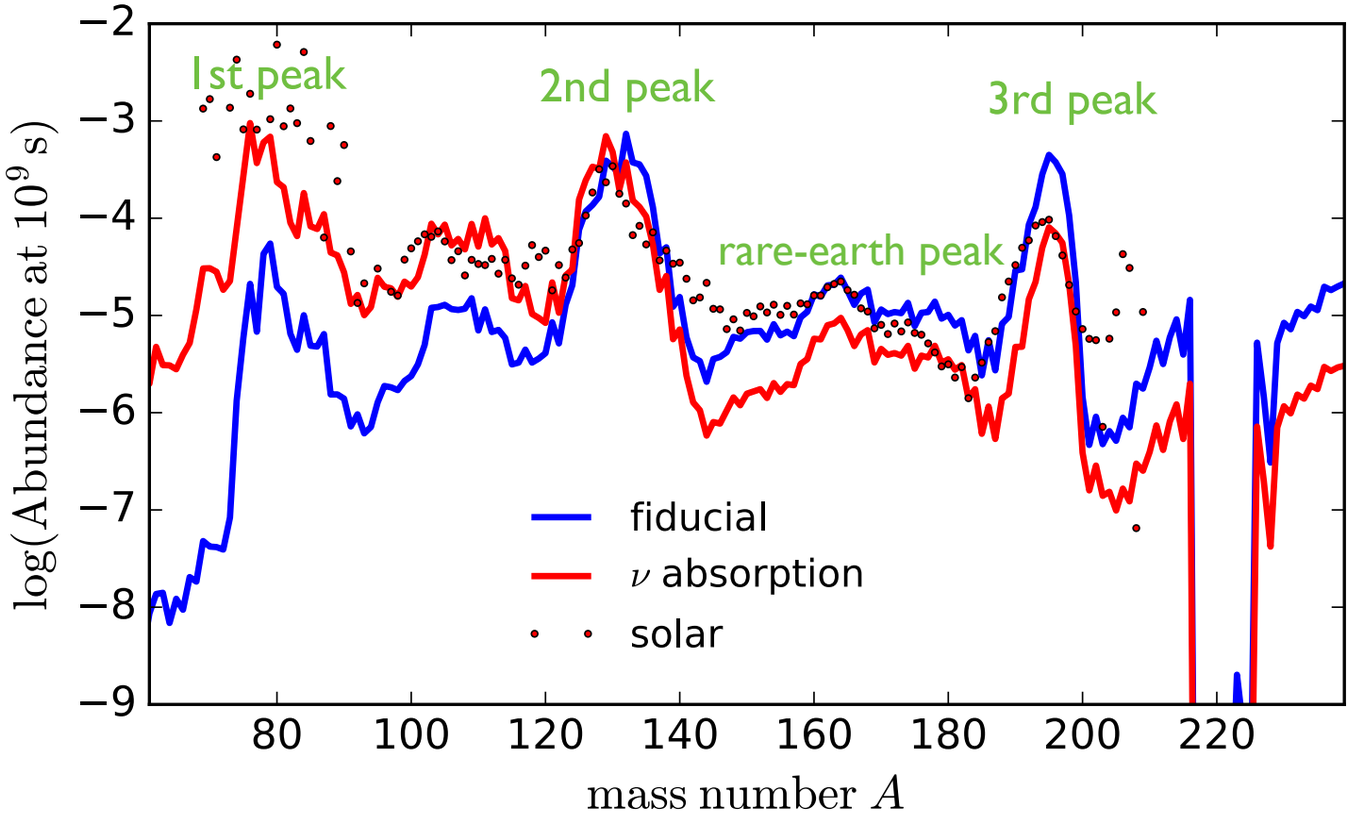


Fig.: production of all r-process elements from outflows of post-merger accretion disk

Overall ejecta mass per event:

$$\lesssim 10^{-3} - 10^{-2}\, M_\odot$$

strongly depends on EOS!

$$\gtrsim 0.4\, M_{\rm disk} \gtrsim 10^{-2}\, M_\odot$$

robust lower limit

Slide from D. Siegel

Short GRBs: Jet or no jet?

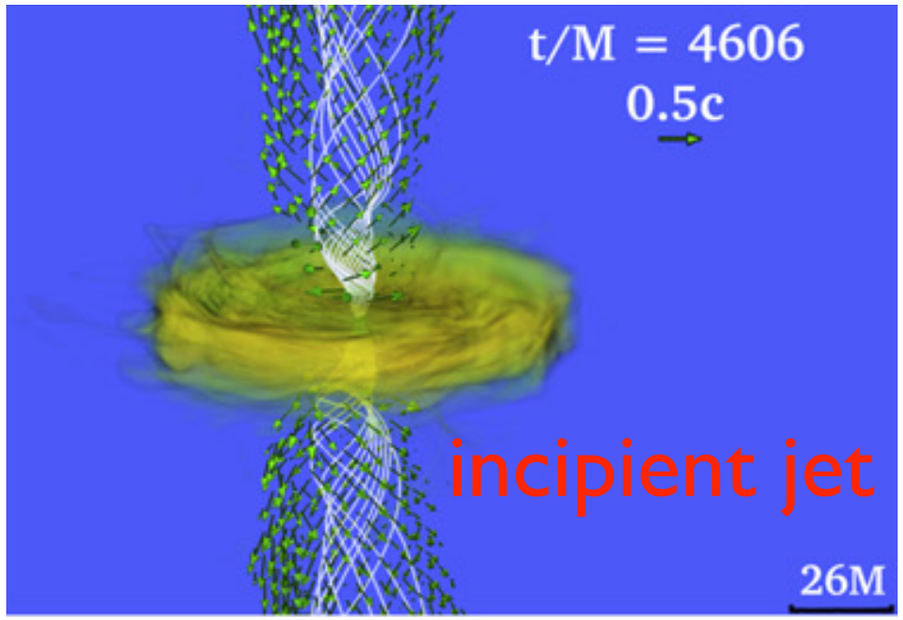


Fig.: Magnetic funnel ("incipient jet") emerging from a BH-torus system (BNS merger)

Ruiz+ 2016

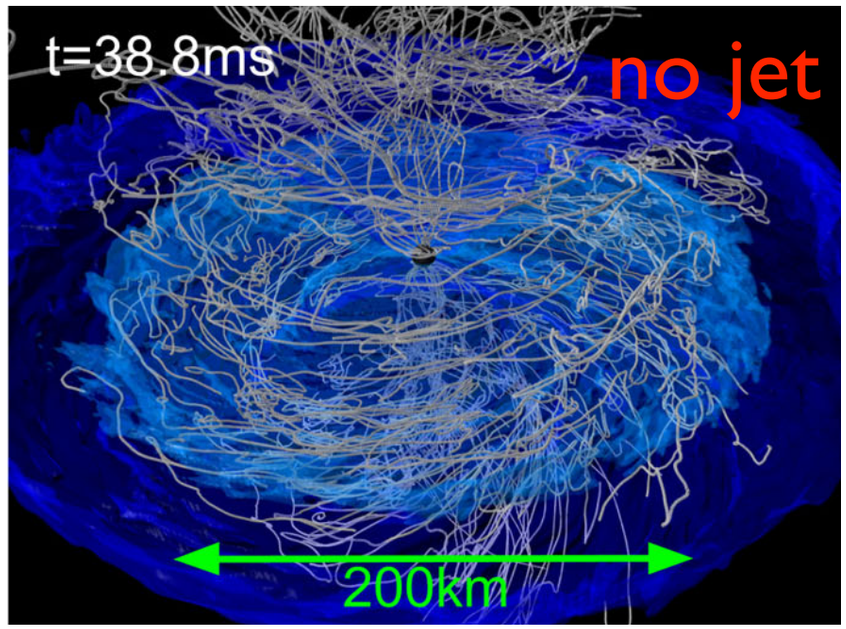


Fig.: Magnetic configuration from the highest resolution BNS simulations: no jet

Kiuchi+ 2017

→ jet formation in NS mergers not understood yet

no jet

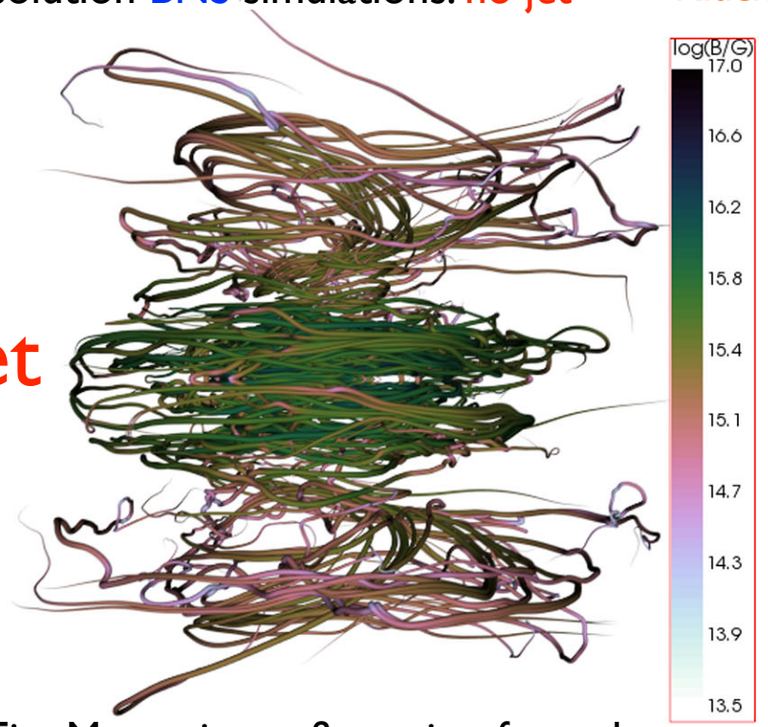
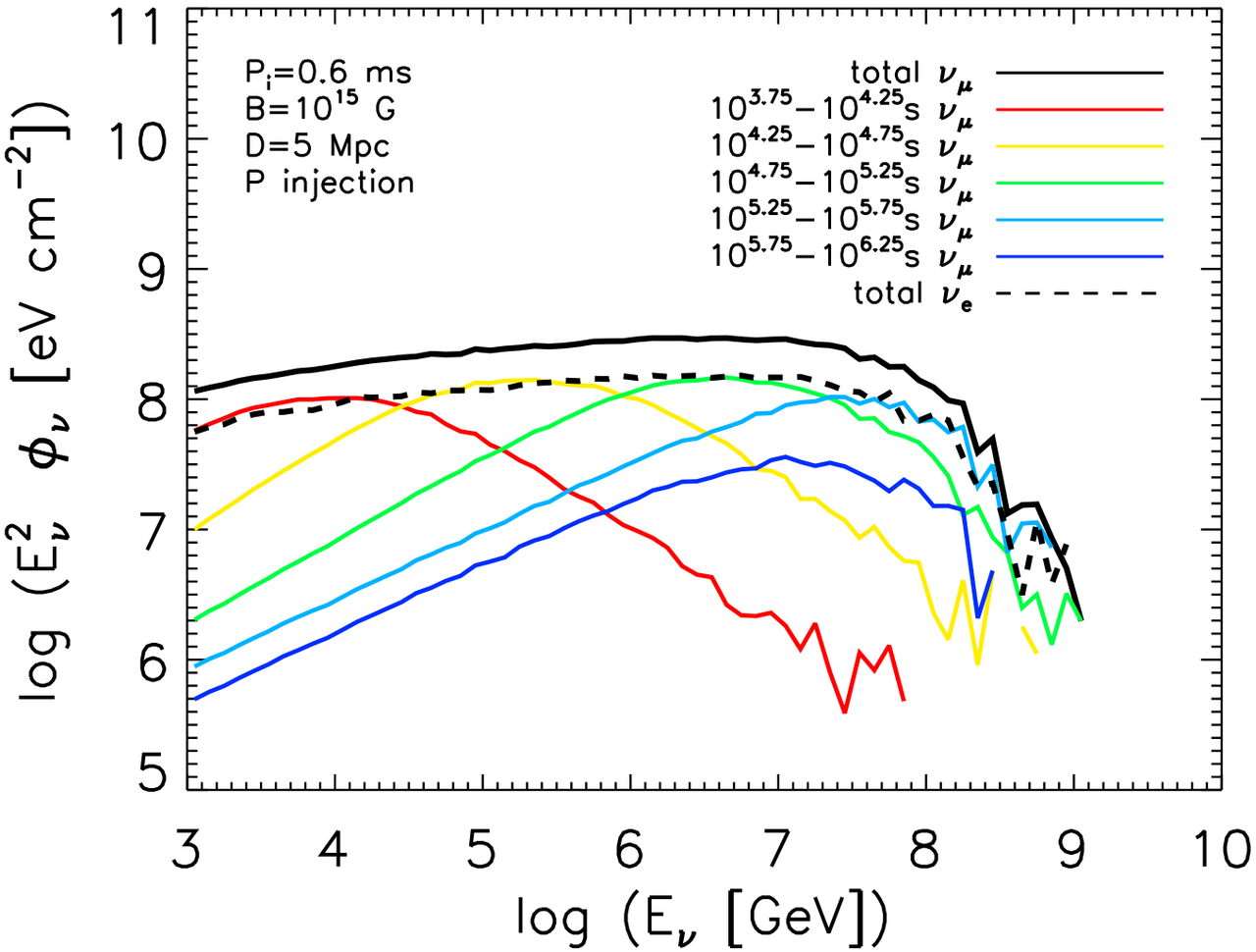


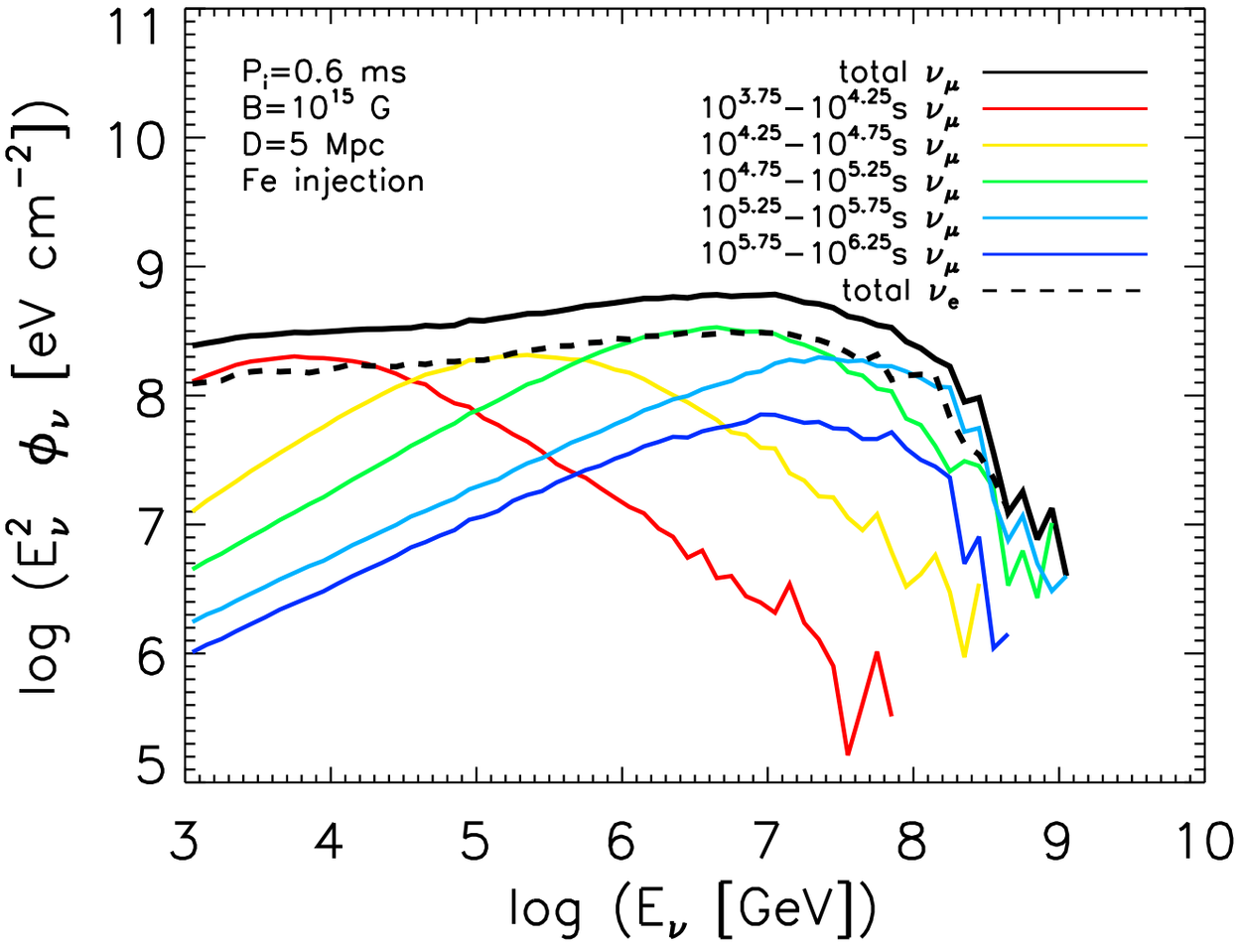
Fig.: Magnetic configuration from the latest BNS simulations: no jet

Ciolfi+ 2017

Slide from D. Siegel

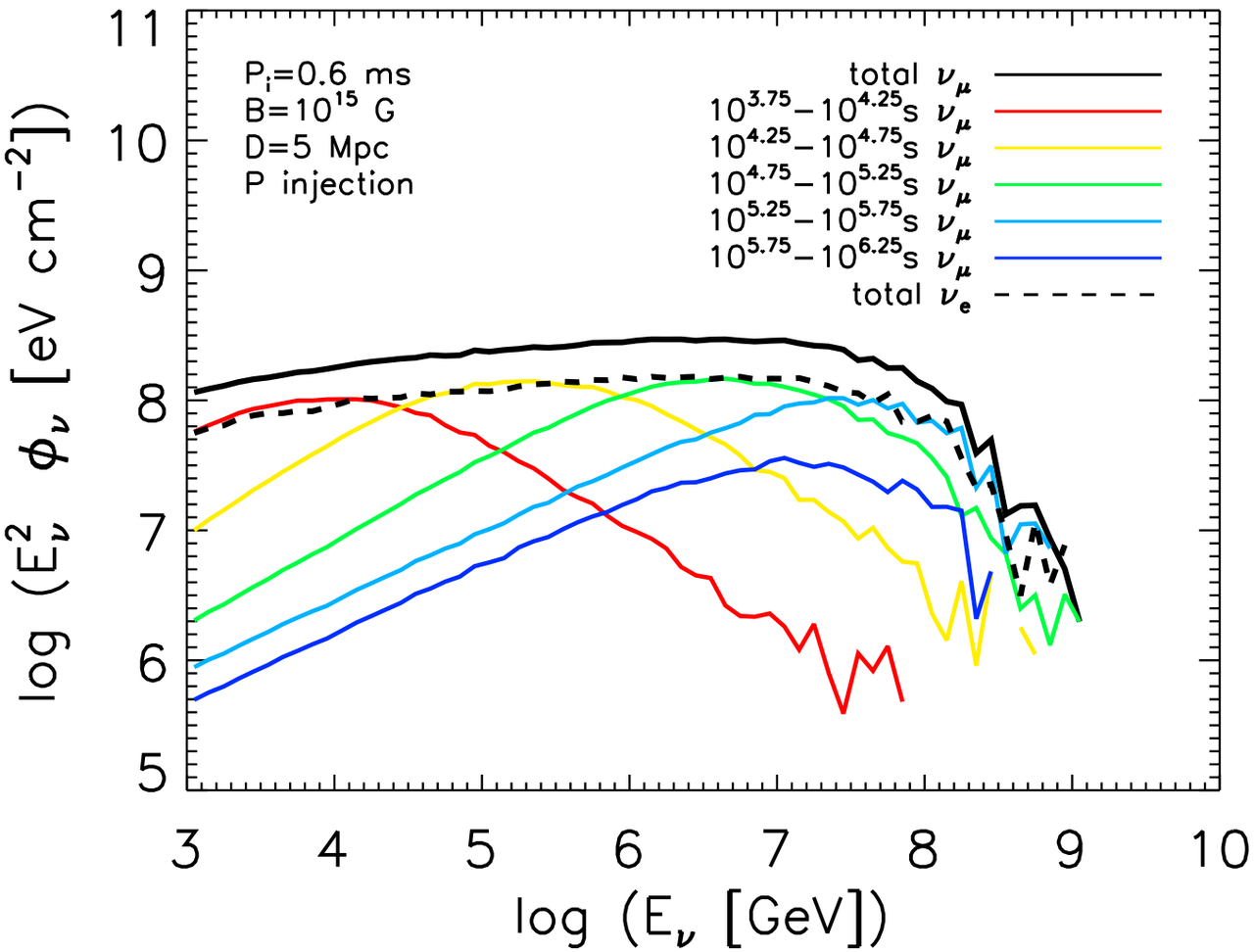
P vs. Fe

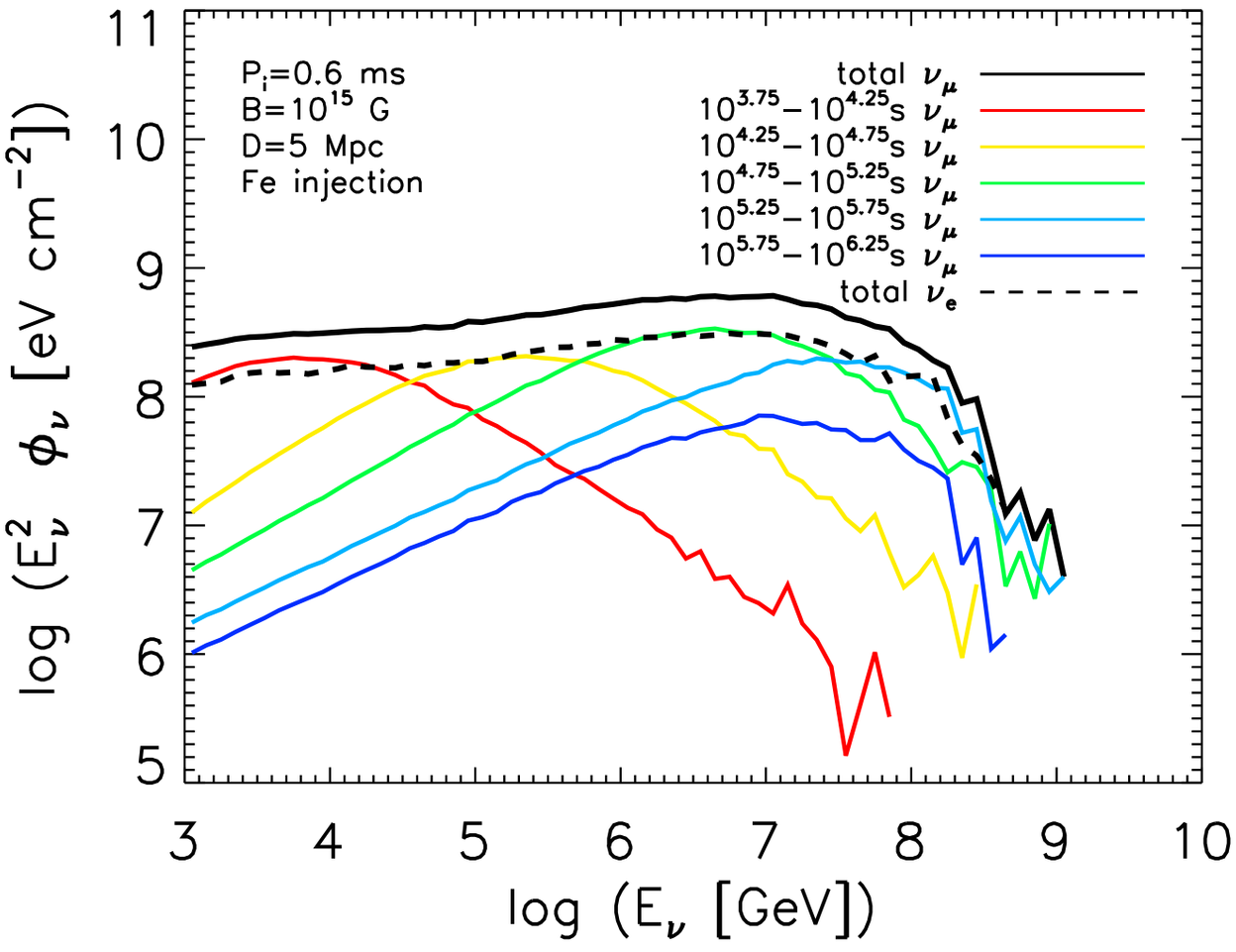




KF, JCAP 06(2015)004

P vs. Fe



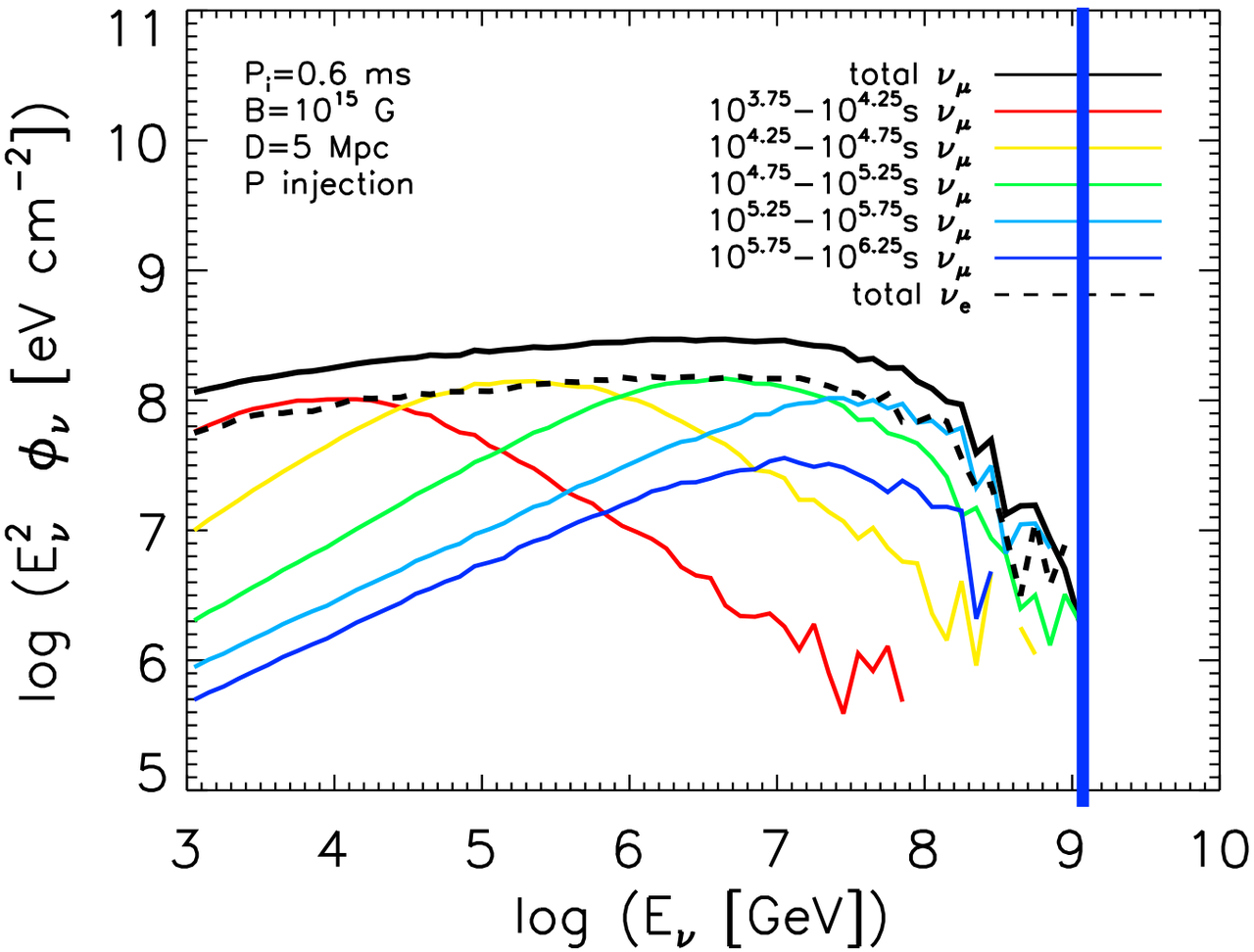


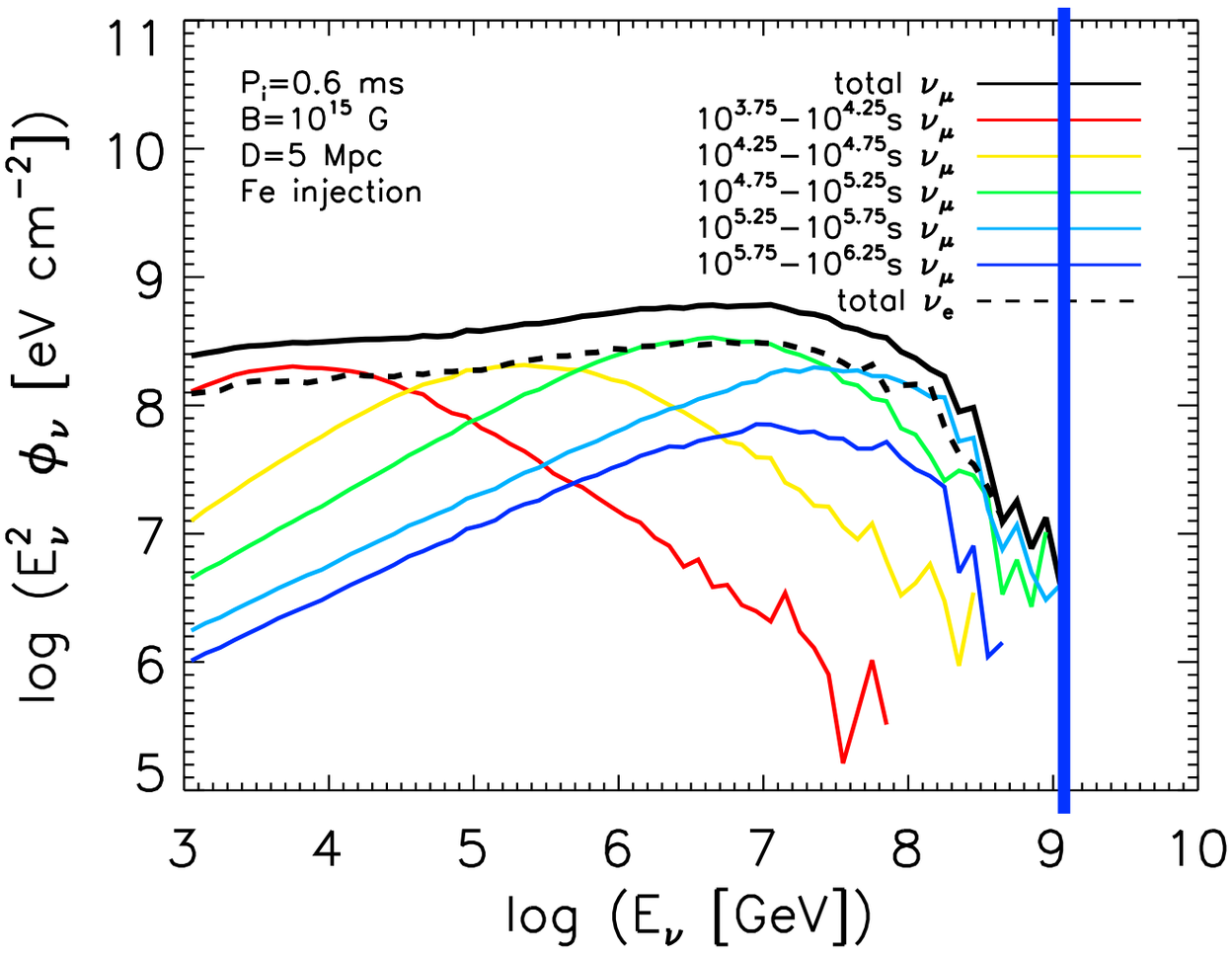
$$E_{\max} \propto A \Rightarrow E_{Fe} \approx 56 E_P$$

A/A = 1 times of Ev,max

KF, JCAP 06(2015)004

P vs. Fe



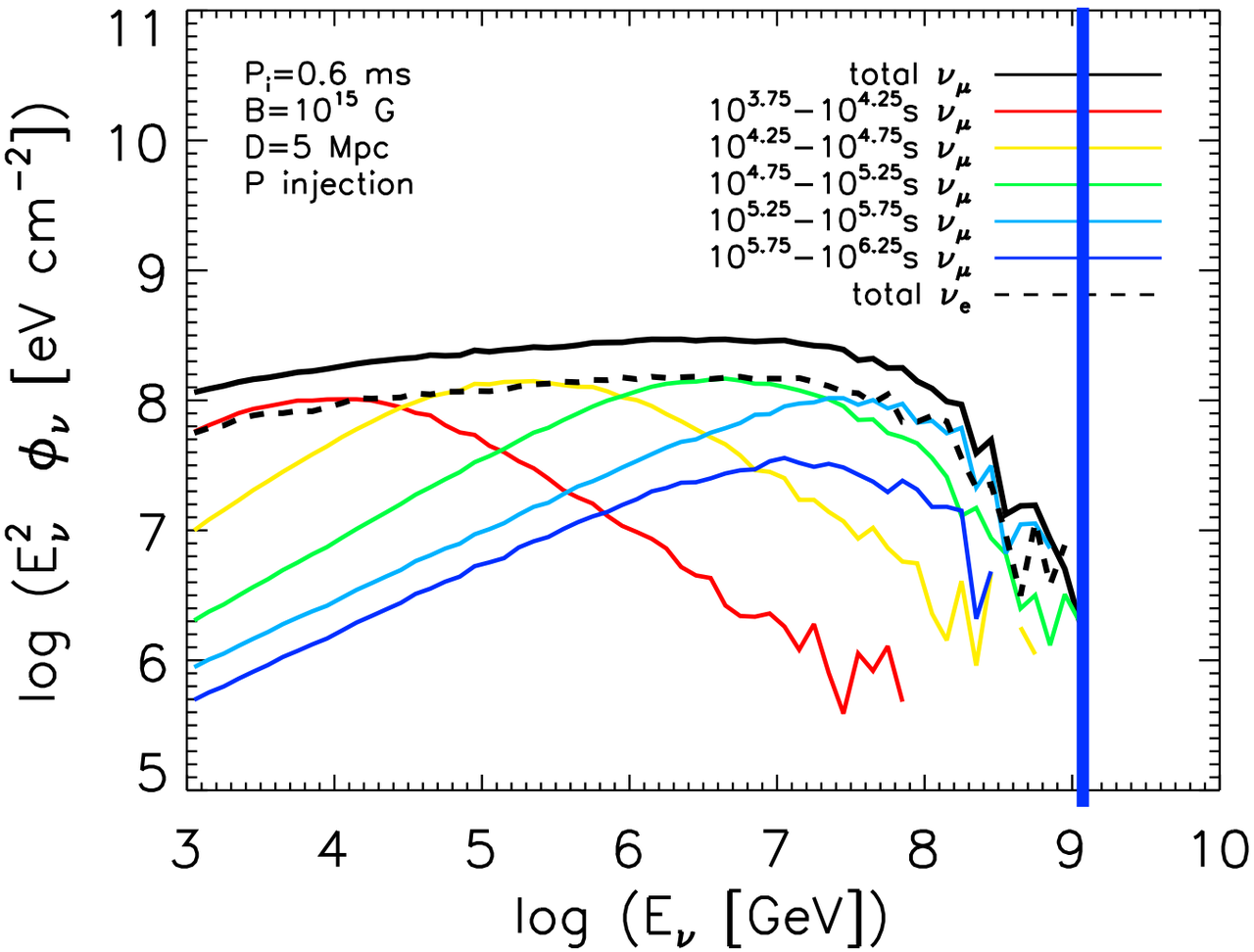


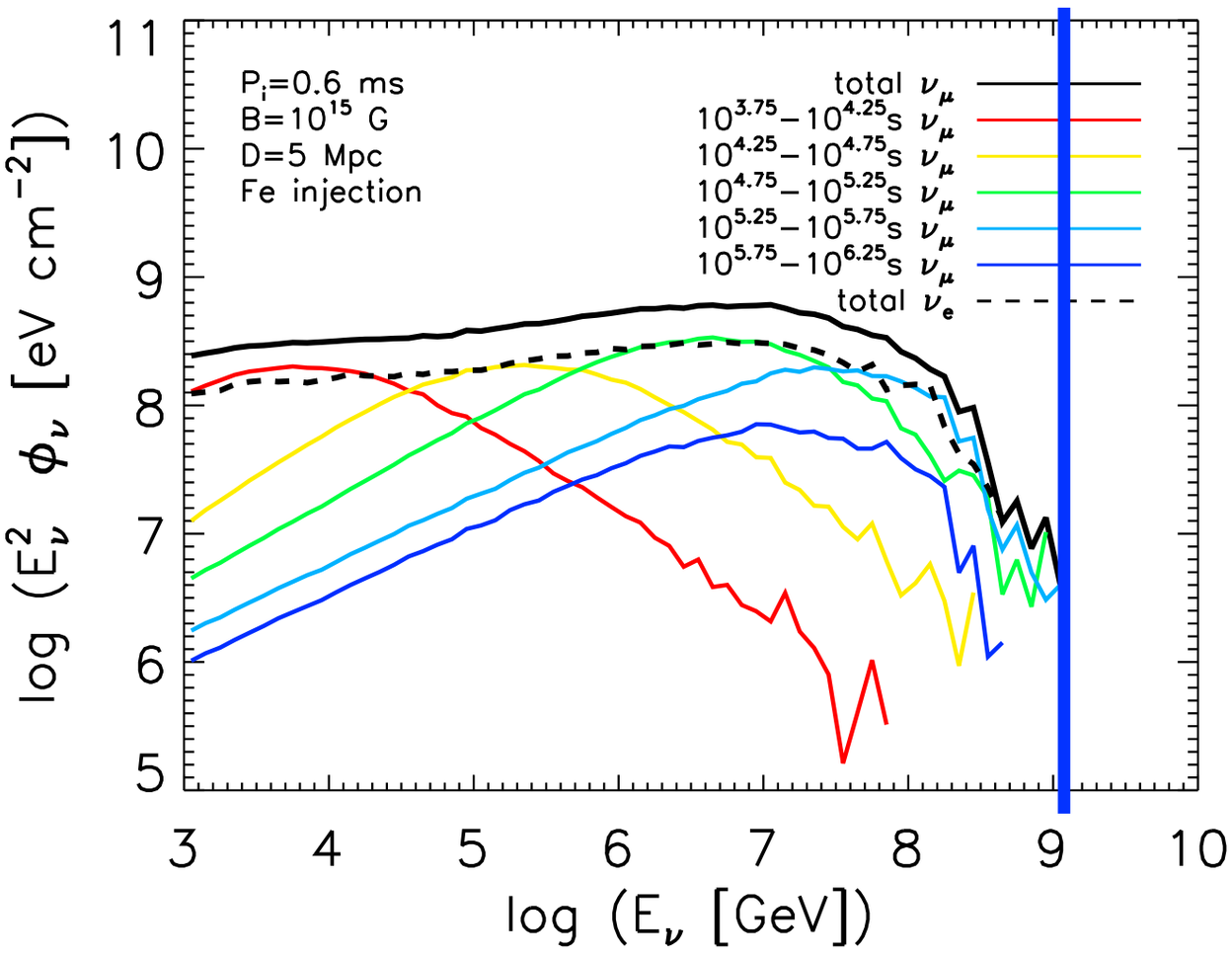
$$E_{\max} \propto A \Rightarrow E_{Fe} \approx 56 E_P$$

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KF, JCAP 06(2015)004

P vs. Fe





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

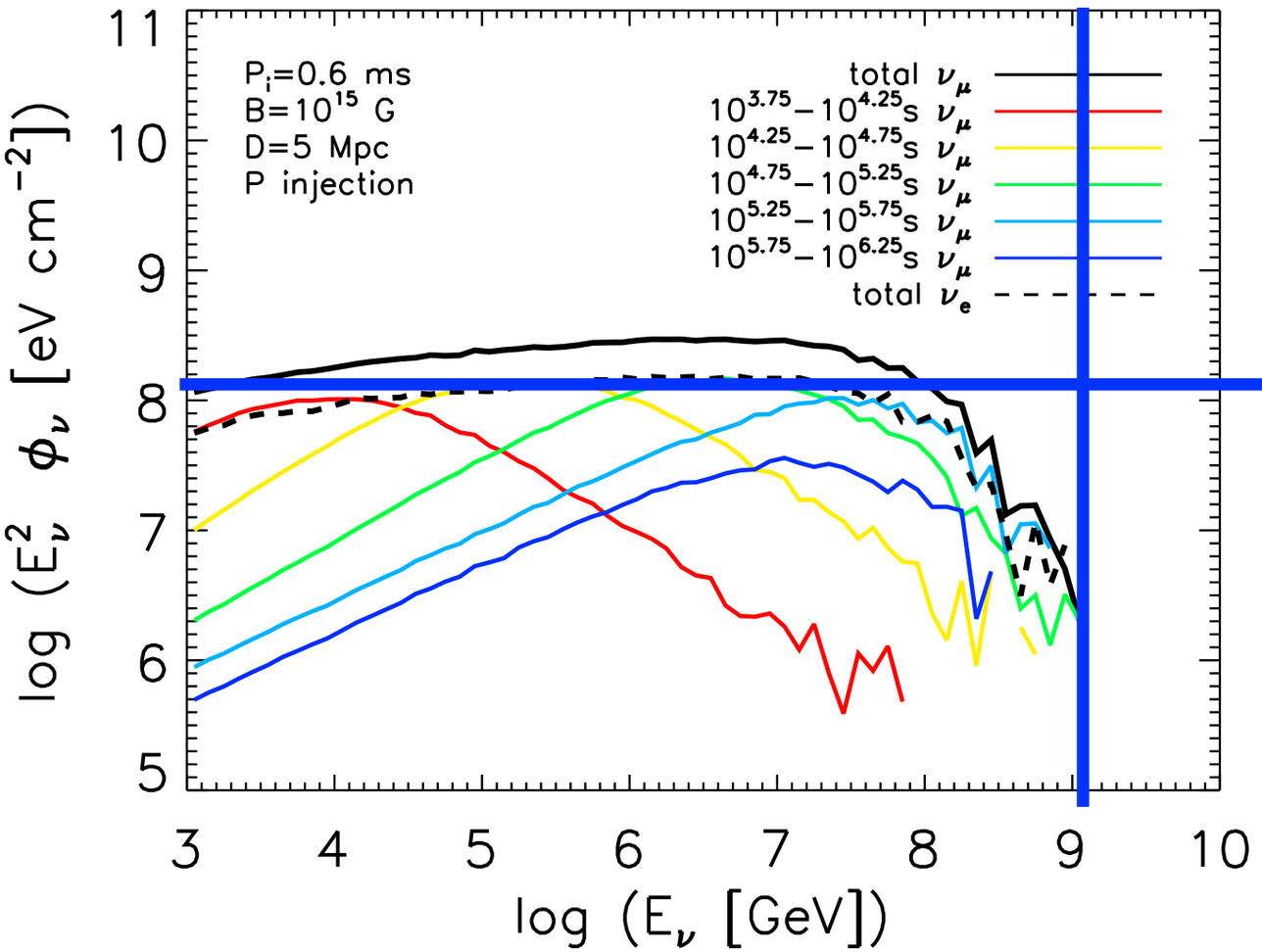
$$\dot{N} \propto \frac{1}{Z} \Rightarrow \dot{N}_{Fe} = \frac{\dot{N}_P}{26}$$

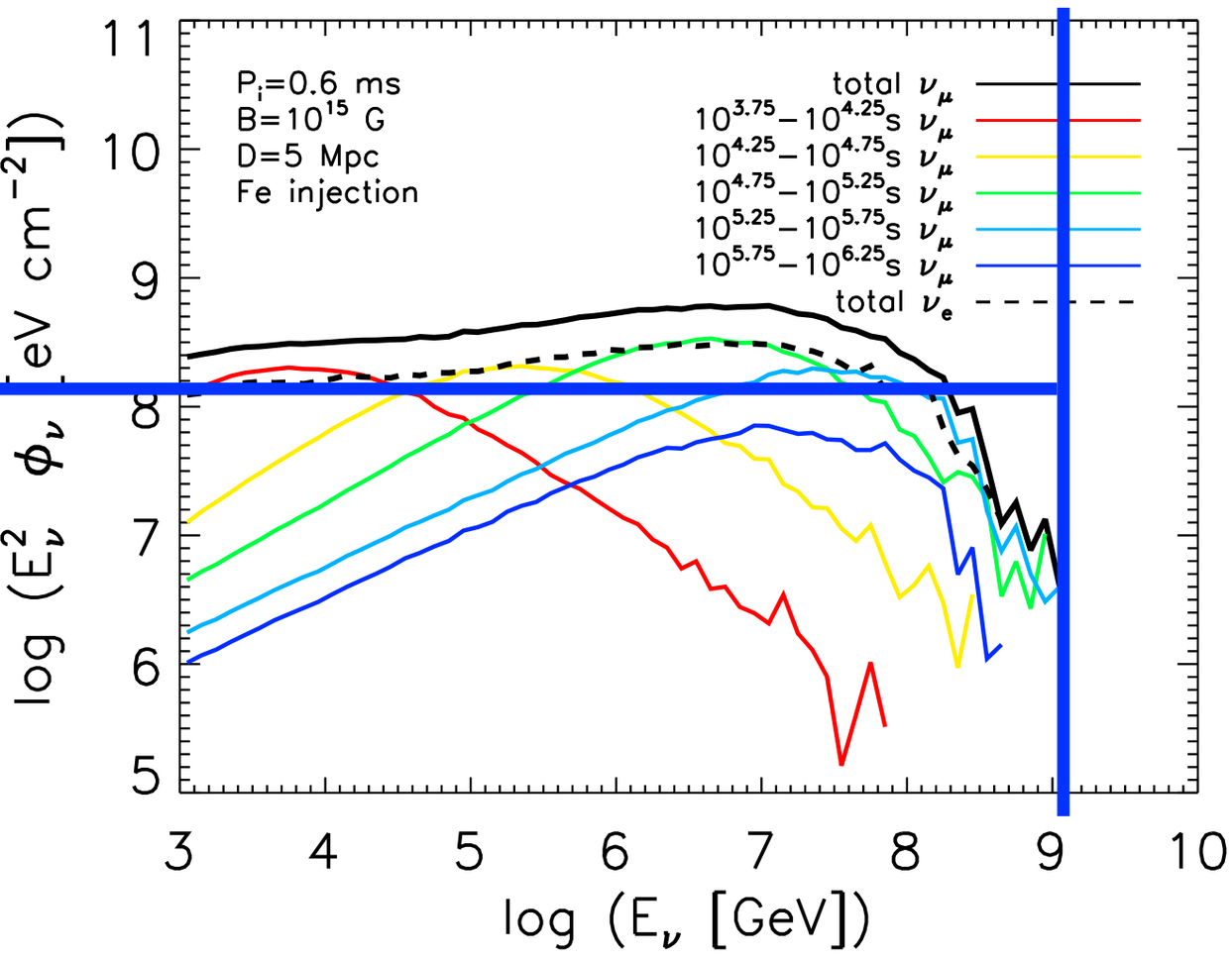
A/A = 1 times of $E_{\nu,\max}$

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