Sub-GeV atmospheric neutrinos background in organic liquid scintillator mediums

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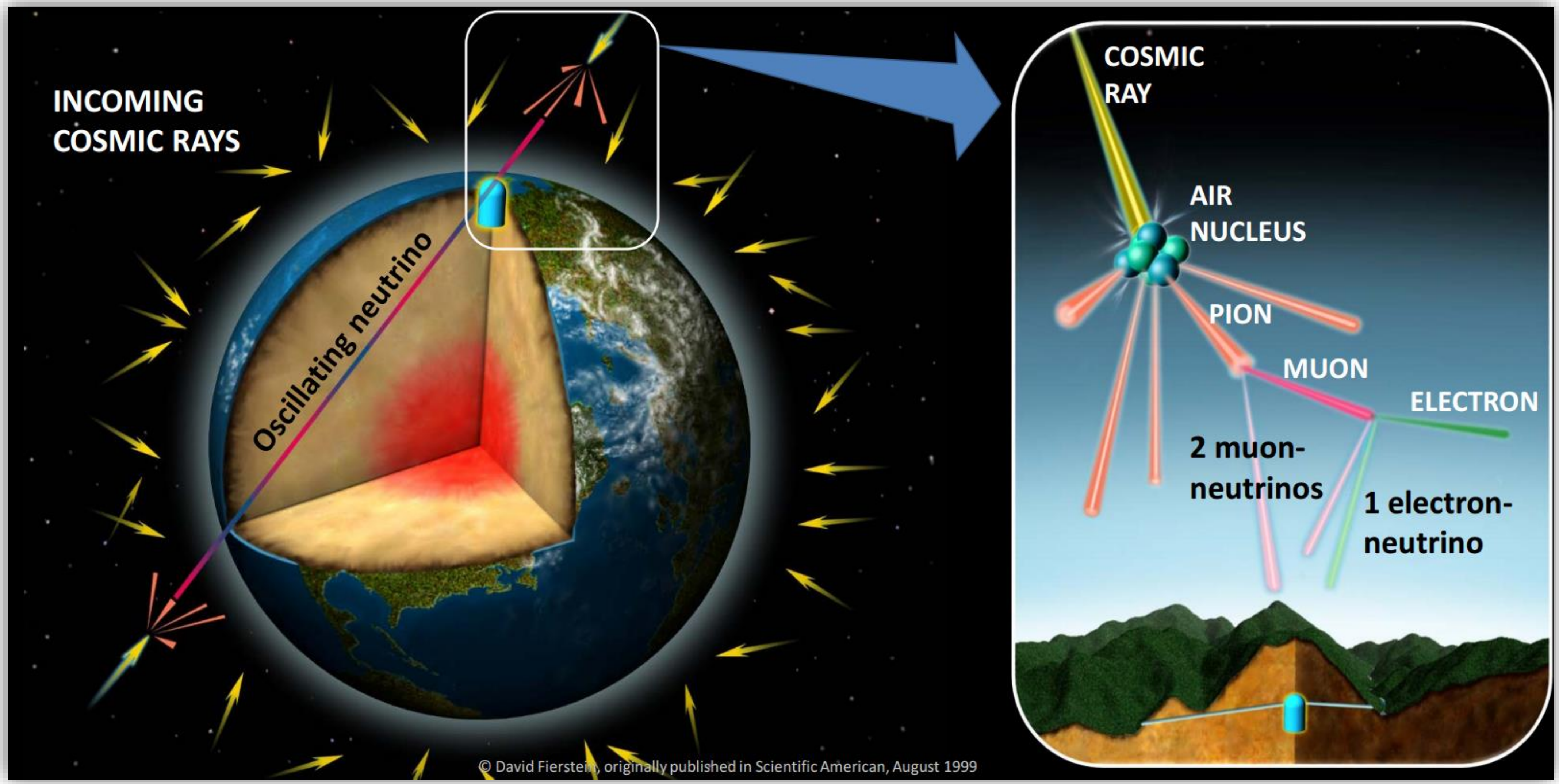

INCOMING
COSMIC RAYS
Oscillating neutrino
COSMIC
RAY
AIR
NUCLEUS
PION
MUON
ELECTRON
2 muon-
neutrinos
1 electron-
neutrino
© David Fierstein, originally published in Scientific American, August 1999

Atmospheric neutrinos

- Cosmic rays interactions with atomic nuclei in atmosphere
- $\pi^{\pm}/K^{\pm} \rightarrow \mu^{\pm} + \nu_{\mu}(\overline{\nu}_{\mu})$
- $\mu^{-} \rightarrow e^{-}\overline{\nu}_{e}\nu_{\mu}$
  $\mu^{+} \rightarrow e^{+}\nu_{e}\overline{\nu}_{\mu}$
- $\frac{\nu_{\mu}+\overline{\nu}_{\mu}}{\nu_{e}+\overline{\nu}_{e}} \approx 2, \quad E_{\nu} \lesssim 1\ \text{GeV}$

For $E_{\nu} \leq 100$ MeV:

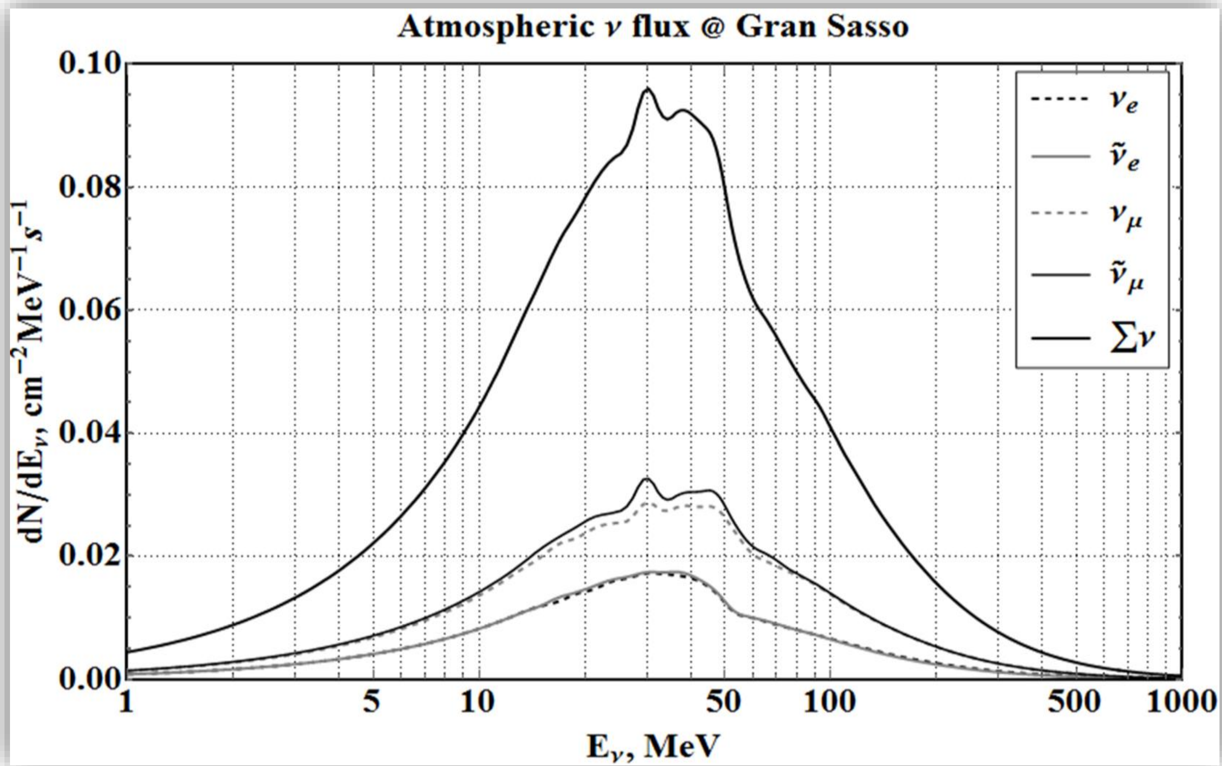
G. Battistoni, A. Ferrari, T. Montaruli, P.R. Sala

The atmospheric neutrino flux ***below 100 MeV****: The FLUKA results*

Astroparticle Physics, volume 23 issue 5, pp. 526–534, June 2005

Background for:

- DSNB
- proton decay (e.g. $\nu_{\mu}p \rightarrow \mu^{-}K^{+}p$ for $p \rightarrow \bar{\nu}K^{+}$)
- any processes with up to few expected events per year



Logarithmic quadratic spline interpolation

Atmospheric neutrinos

Different locations

- Borexino @ Gran Gasso, Italy
- KamLAND @ Kamioka, Japan
- SNO+ @ Sudbury, Ontario, Canada
- JUNO @ Jiangmen, China

Different magnetic field
Different atmosphere density profile

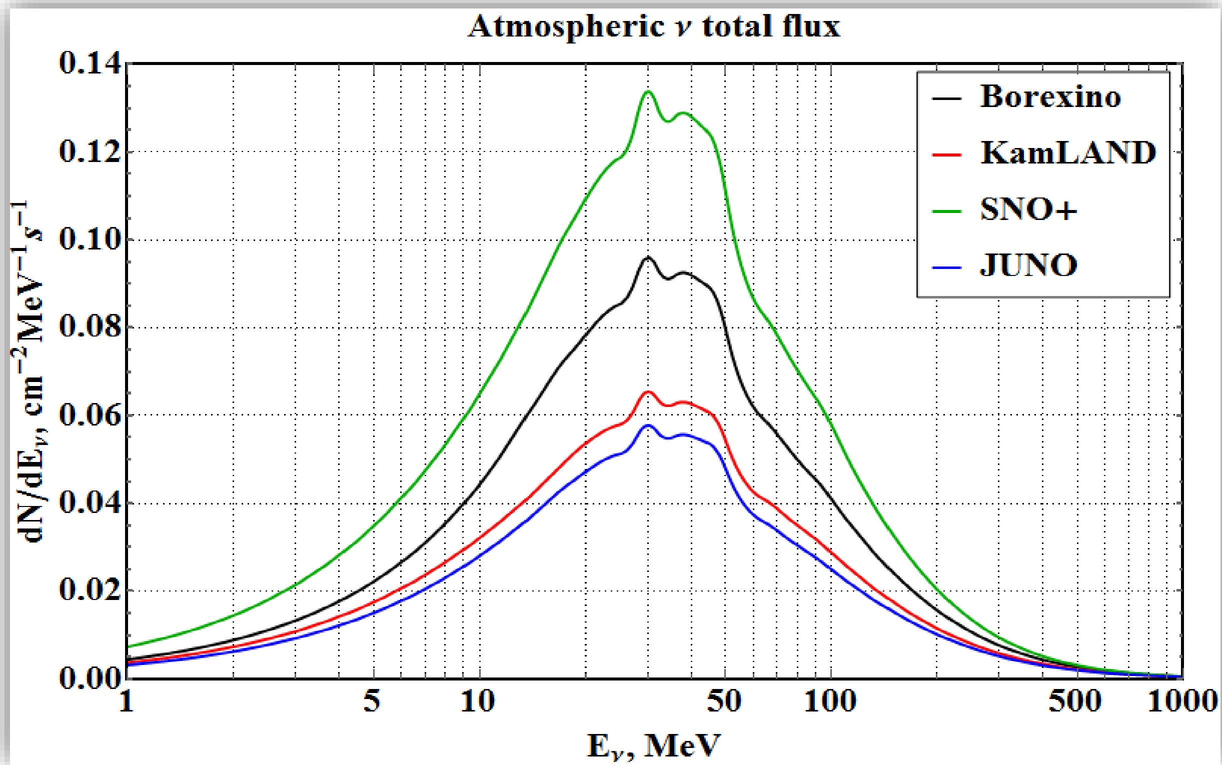
Different flux

For 100 MeV $< E_\nu \leq$ 10 GeV:

M. Honda, M. Sajjad Athar, T. Kajita, K. Kasahara, and S. Midorikawa

Atmospheric neutrino flux calculation using the NRLMSISE-00 atmospheric model

Phys. Rev. D 92, 023004 – Published 7 July 2015



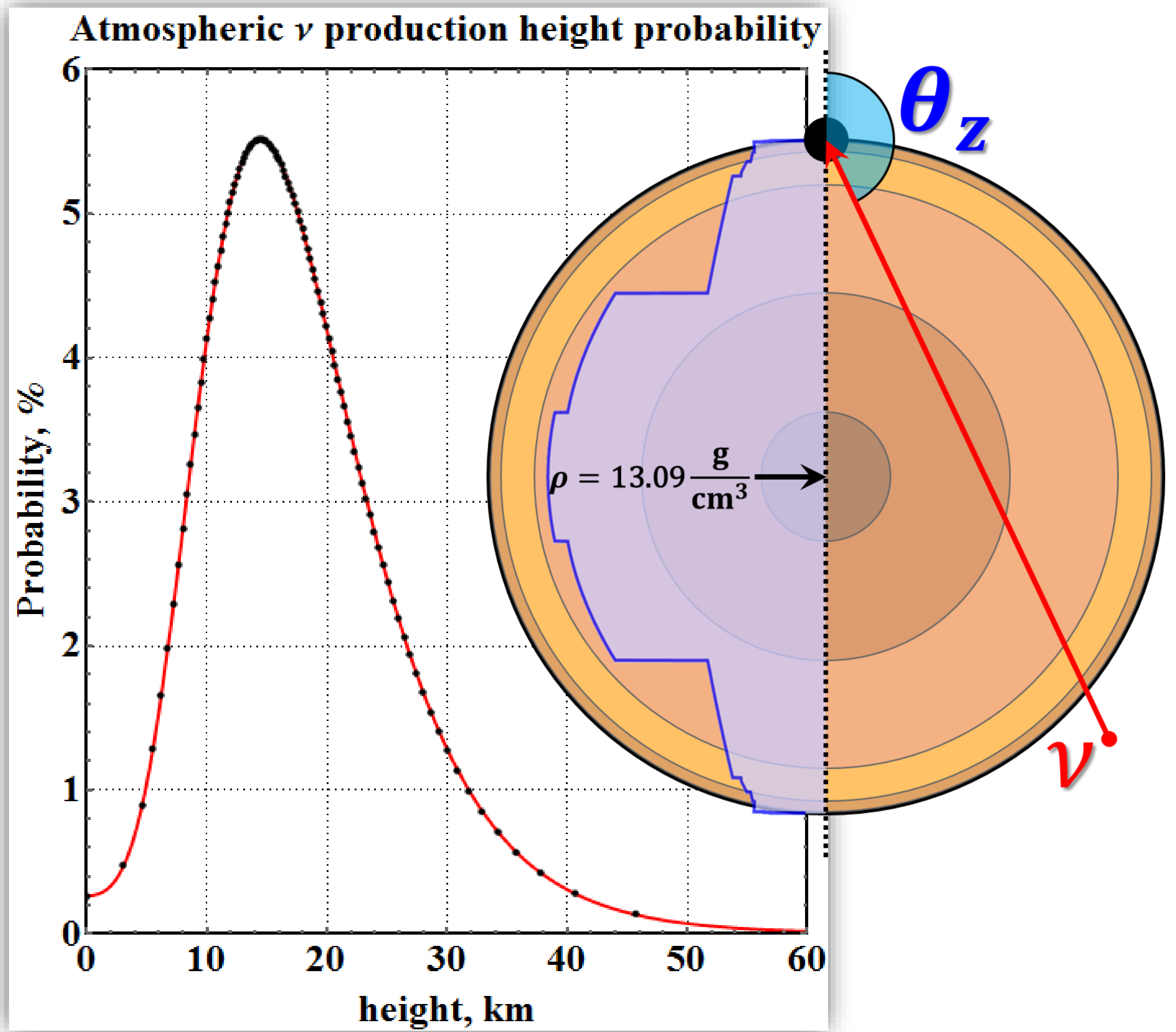
Integrated oscillated flux calculation

- Software used:
  - modified **Prob3++**
- Earth density profile:
  - **PREM** model
  - Constant density layers
  - ***1 km step***
- Mimic integration
  - Height profile
    - 101 points taken uniformly in CDF ordinate
  - Zenith angle
    - 181 points uniformly in $[0, \pi]$
  - Energy
    - Logaritmic scale
    - 10000 points per decade
    - 70000 points total

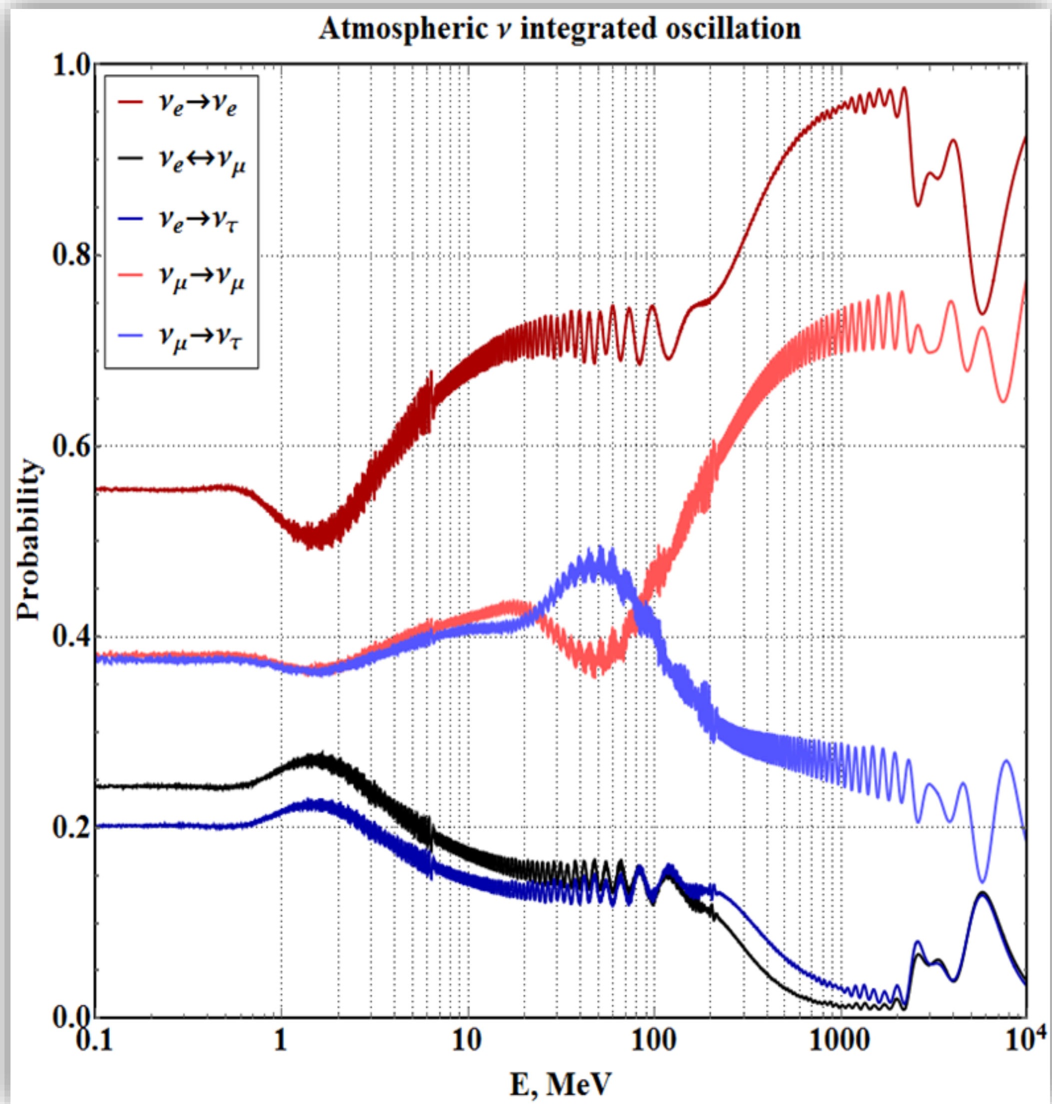
Very time consuming!

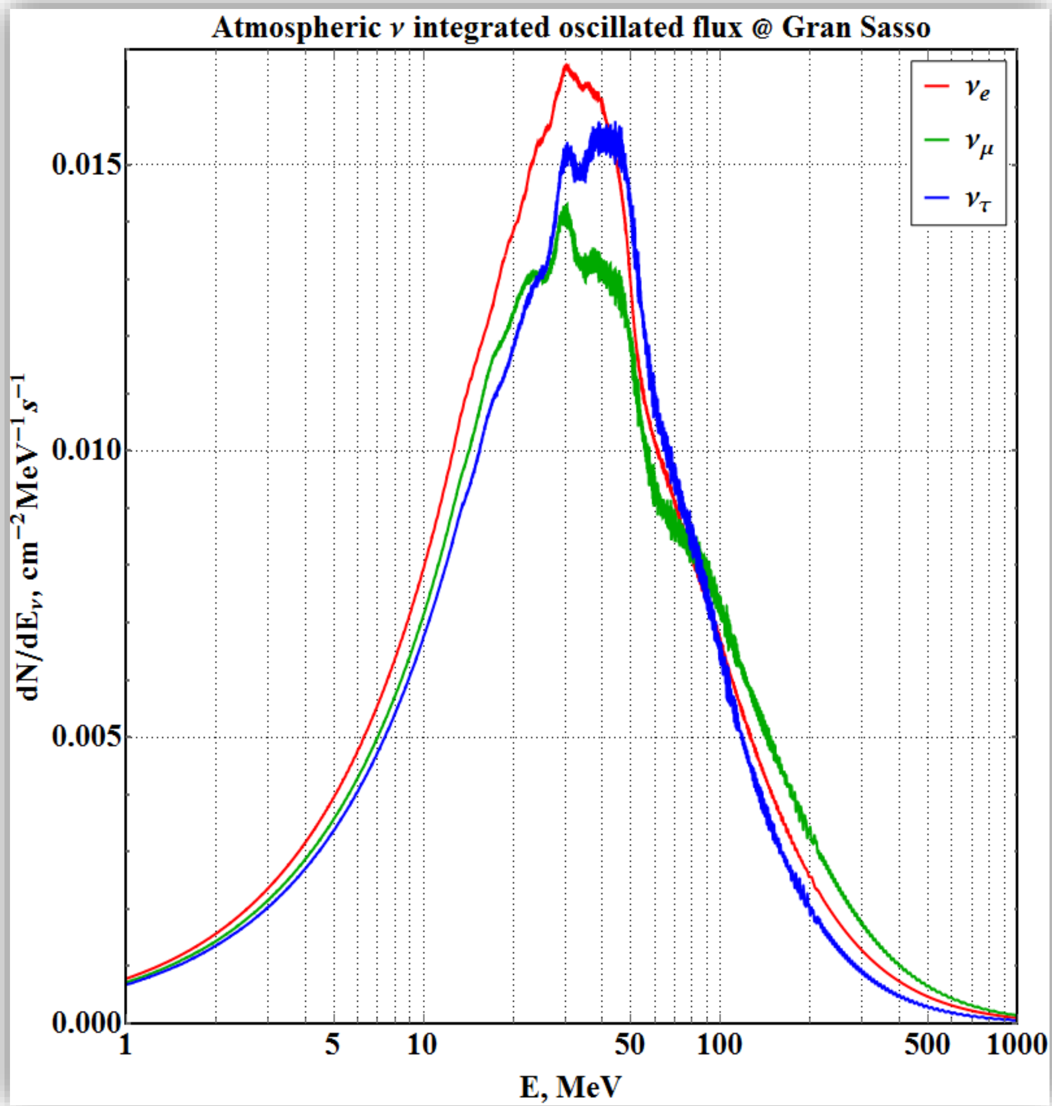
- 80 days @ 2.5GHz CPU

But more is needed for more fine grid over height and zenith angle



Integrated oscillated flux calculation





Scintillators properties

	Borexino	KamLAND	SNO+	JUNO
Composition	PC + 1.5 g/l PPO	Dodecane 80% + PC 20% + PPO 1.36 g/l	LAB + 2 g/l PPO + 15mg/l bis–MSB	LAB + 3 g/L PPO + 15 mg/L bis-MSB
Density, g/cm^3	0.876	0.780	0.86	0.86
Target mass, tons	278	900	780	20000
Energy resolution	5% @ 1 MeV	6.4% @ 1 MeV	5% @ 1 MeV	3% @ 1 MeV
kB, μm/MeV	e/γ : 115 α : 92 p : 115	e/γ : 138 α : 148 p : 100	e/γ : 74 α : 76 p : 97	e/γ : 74 α : 74 p : 98

Scintillation quenching
Birk's law:

$$\frac{dL}{dx} = S\frac{dE/dx}{1 + \mathrm{kB}\ dE/dx}$$

L – light yield, S – scintillation efficiency,
kB – Birks' constant, which depends on the material,
dE/dx – energy loss of the particle per path length.
dE/dx calculation:

- **ESTAR** for ***e***
- **SRIM** for ***p*** and **α**

Organic scintillators

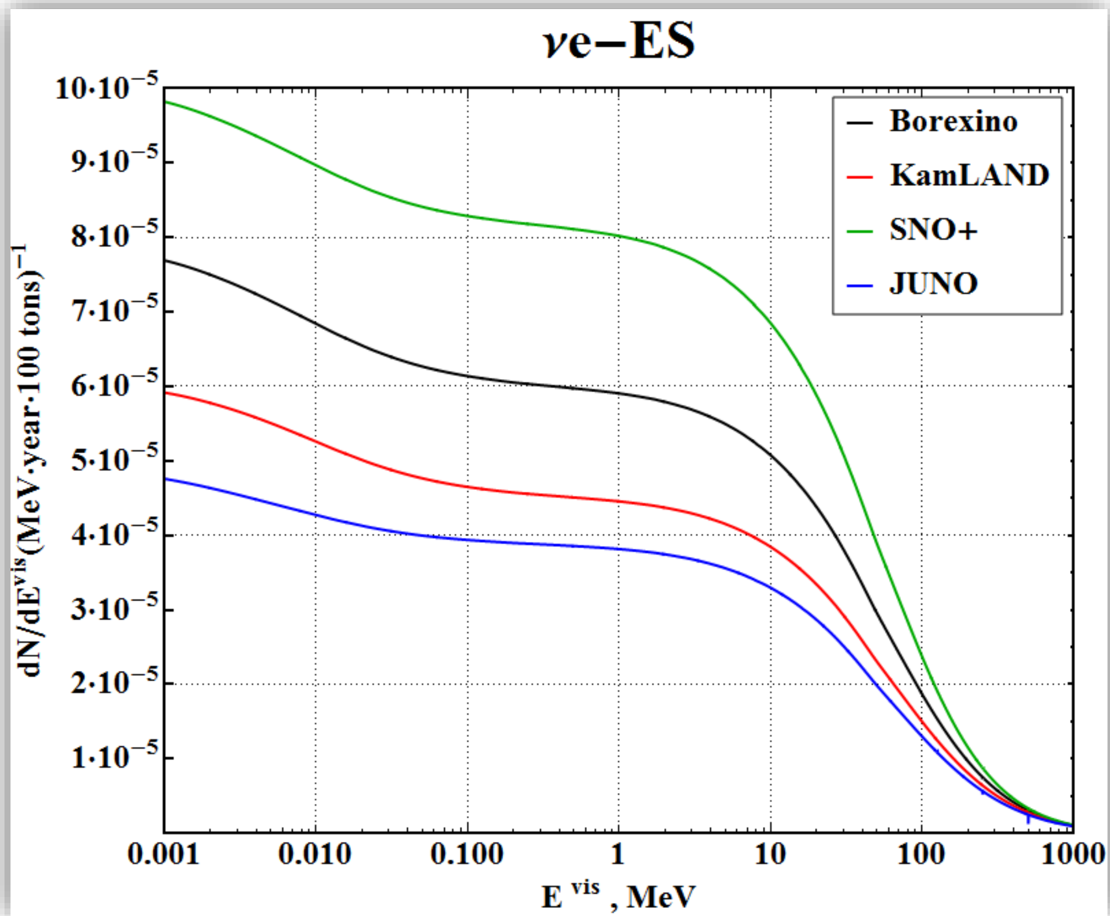
- Most common particles: $\boldsymbol{e, p, {}^{12}C}$
- $^{14}C\ \ \beta - \mathrm{decay} \quad \Rightarrow$
  $\mathrm{low\ energy\ threshold}\ \mathbf{250\ keV}$

Neutrino electron elastic scattering

$$\nu + e \rightarrow \nu + e$$

$$\frac{d\sigma}{dT_e} = \frac{2G_F^2 m_e}{\pi E_\nu^2}\left(g_L^2 E_\nu^2 + g_R^2 (E_\nu - T_e)^2 - g_L g_R m_e T_e\right)$$

10^{-5} electrons / year / 100 tons				
$0.25 < E^{vis} <$ … MeV	1	10	100	1000
Borexino	4.469	53.626	325.865	710.593
KamLAND	3.373	40.531	252.143	585.813
SNO+	6.068	72.603	431.313	875.546
JUNO	2.885	34.724	216.861	512.466



Inverse beta-decay

$$\bar{\nu}_e + p \rightarrow e^+ + n$$
$$E_{thr} = 1.806 \text{ MeV}$$

$$\frac{d\sigma}{dT_e} = \frac{G_F^2 \cos^2\theta_C}{4\pi m_p E_\nu^2}\left(A(Q^2) - (s-u)B(Q^2) + (s-u)^2 C(Q^2)\right)$$

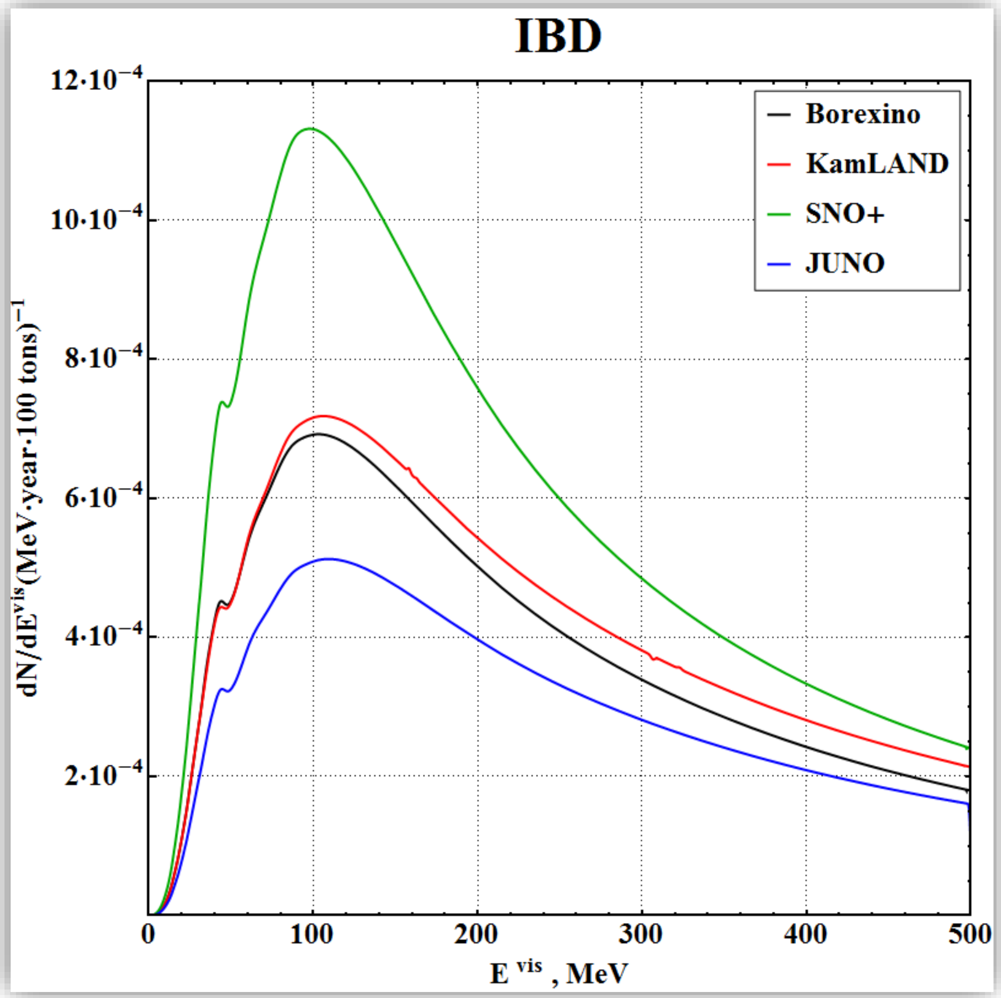
Strumia, A. and Vissani, F.

Precise quasielastic neutrino/nucleon cross-section

Phys. Lett. B 564, pp. 42-54, 2003

Double event signature	
Prompt	e^+ annihilation
Delayed	*n* capture

Positrons / year / 100 tons			
0.25<E^{vis}< … MeV	10	100	1000
Borexino	4.535×10^{-5}	0.0408	0.2439
KamLAND	4.991×10^{-5}	0.0413	0.2717
SNO+	7.936×10^{-5}	0.0667	0.3586
JUNO	3.499×10^{-5}	0.0295	0.2002



Neutrino proton elastic scattering

$$\nu + p \rightarrow \nu + p$$

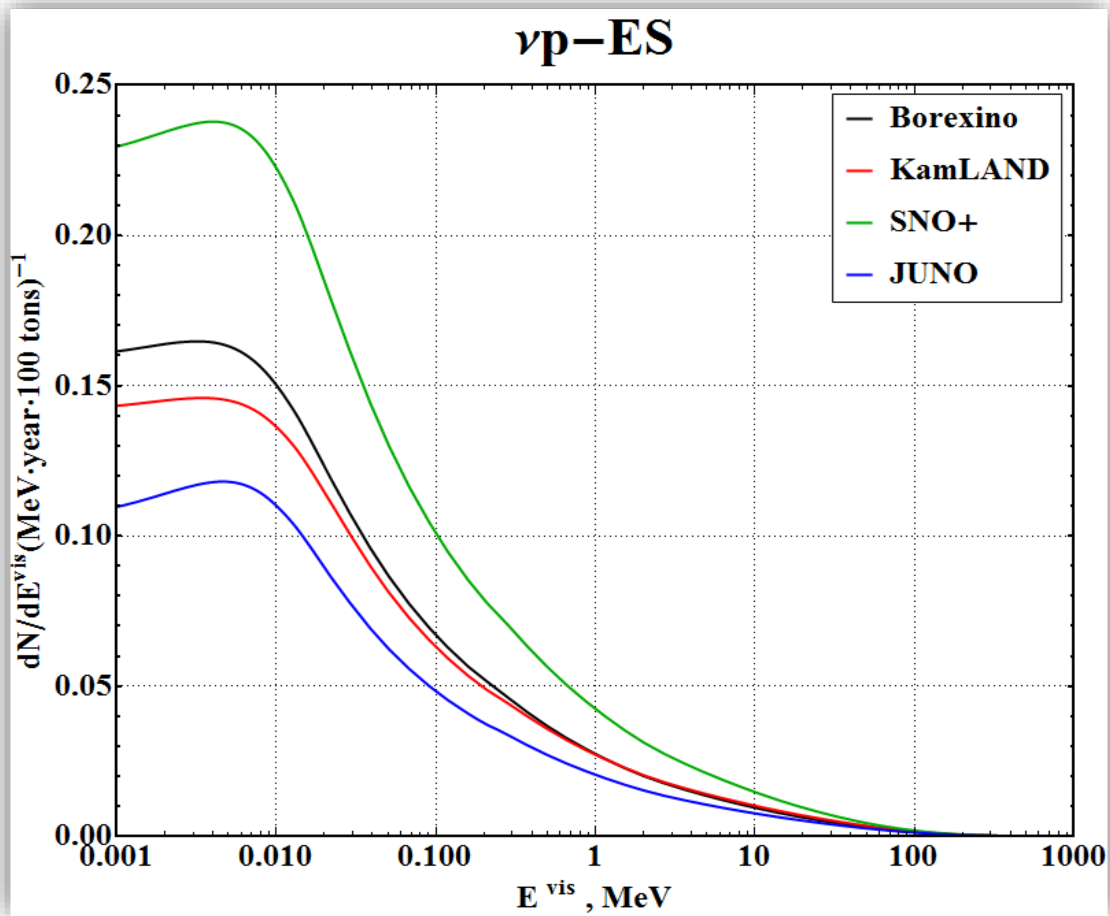
Ahrens, L. A. *et al.*

Measurement of neutrino-proton and antineutrino-proton elastic scattering

Phys. Rev. D 35, pp. 785-809, 1987

$$\frac{d\sigma}{dT_p} = \frac{G_F^2 m_p^3}{4\pi E_\nu^2}\left(A(Q^2) \mp \frac{(s-u)}{m_p^2} B(Q^2) + \frac{(s-u)^2}{m_p^4} C(Q^2)\right)$$

Recoil protons / year / 100 tons				
$0.25 < E^{vis} <$ … MeV	1	10	100	1000
Borexino	0.0261	0.1533	0.4594	0.5917
KamLAND	0.0254	0.1572	0.5045	0.6704
SNO+	0.0401	0.2380	0.6926	0.8721
JUNO	0.0193	0.1181	0.3797	0.5073



Neutrino carbon-12 reactions

$$\nu + {}^{12}C \rightarrow \nu + {}^{12}C^*$$
$$ {}^{12}C^* \rightarrow {}^{12}C + \gamma(15.11\ \mathrm{MeV})$$

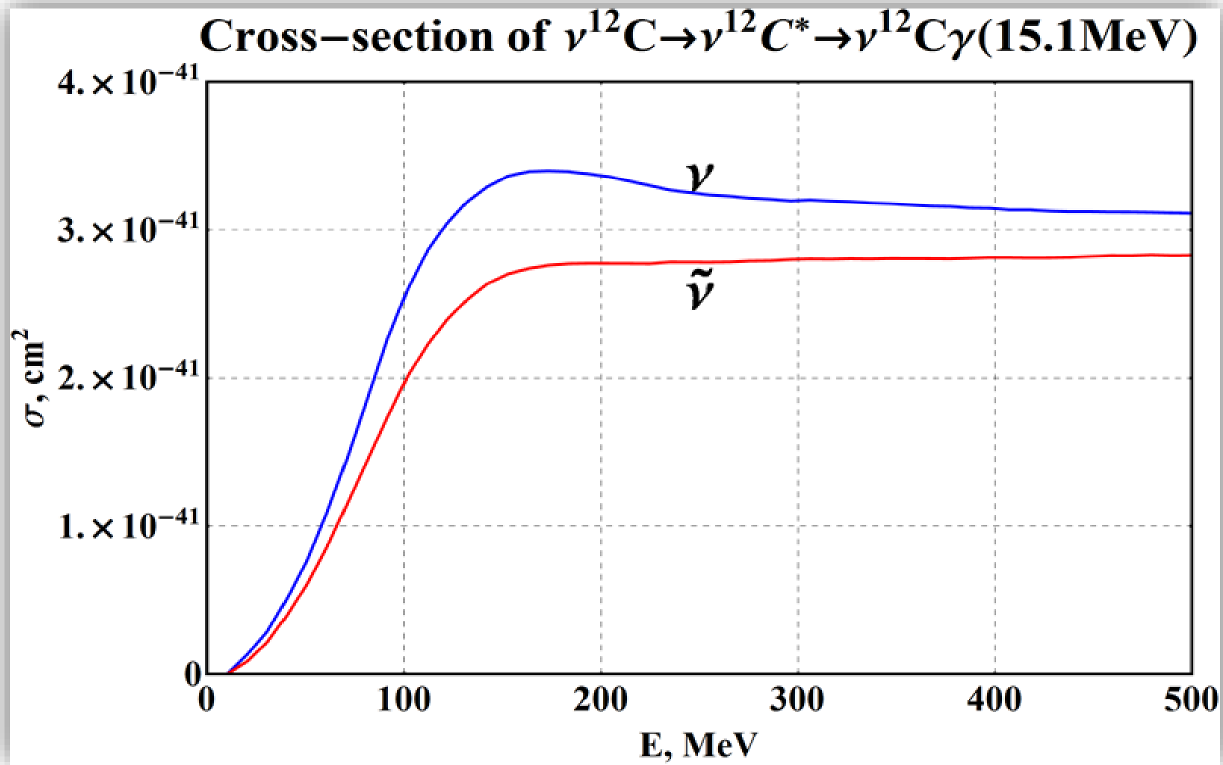
Donelly, T. W. and Peccei, R. D.

Neutral current effects in nuclei

Physics Reports, vol. 50, iss. 1, 1979

$$year \cdot N_{^{12}C} \cdot \sum_{i=\nu,\bar{\nu}} \int dE_i\, flux_i(E_i)\sigma_i(E_i)$$

Gammas / year / 100 tons	
Borexino	0.0293
KamLAND	0.0208
SNO+	0.0371
JUNO	0.0189



Neutrino carbon-12 reactions

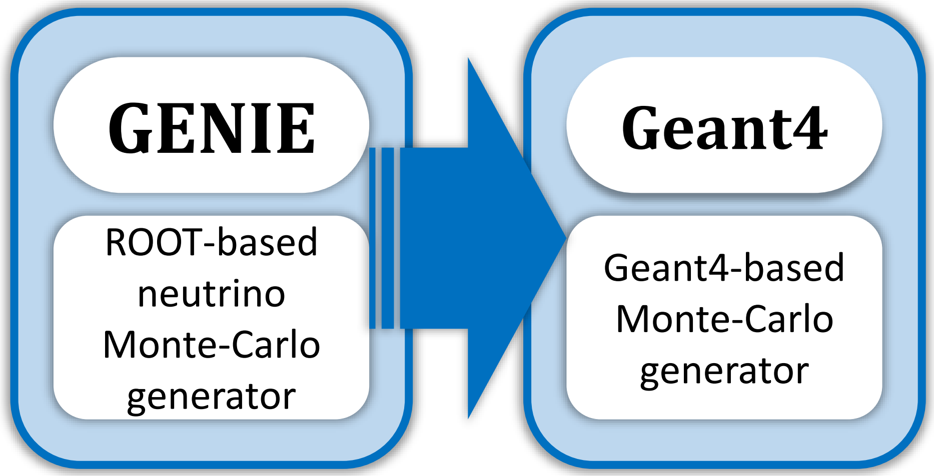
CC: $\nu + {}^{12}C \rightarrow e^{\pm}/\mu^{\pm} + \cdots + X$

NC: $\nu + {}^{12}C \rightarrow \nu + \cdots + X$

$$\sum_{\nu=\nu_e,\bar{\nu}_e,\nu_\mu,\bar{\nu}_\mu,\nu_\tau,\bar{\nu}_\tau} \int dE_\nu flux(E_\nu)\sigma_{tot}^{GENIE}(E_\nu)$$

Total number of events with GENIE cross-sections

Events/ year/ 100 tons	$E_\nu \leq 1$ GeV	$E_\nu \leq 10$ GeV
Borexino	**11.326**	**19.311**
KamLAND	**8.534**	**15.632**
SNO+	**13.074**	**21.100**
JUNO	**7.892**	**14.834**



- 2×10^6 events normalized by $\sum_{i,j} \int dE_{\nu_i} flux_i(E_{\nu_i})\sigma_j(E_{\nu_i})$
- Double events mimic IBD

Double event signature	
Prompt	e^+ annihilation
Delayed	*n* capture

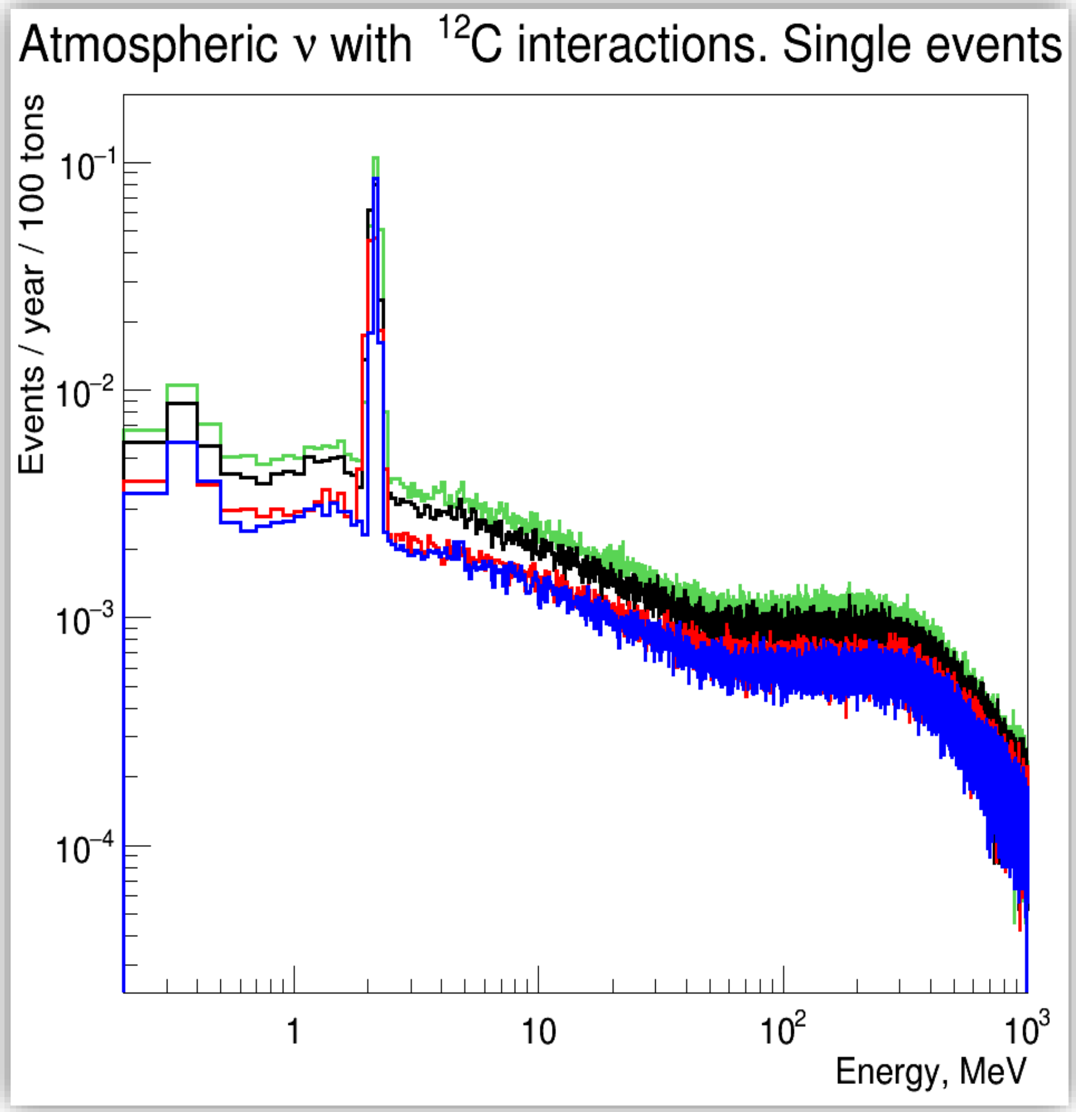
Neutrino carbon-12 reactions

$GENIE \rightarrow Geant4$ $simulated$

Atmospheric $\nu - {}^{12}C$ interactions

Single events

Events / year / 100 tons				
0.25<E^{vis}< … MeV	**1**	**10**	**100**	**1000**
Borexino	**0.04127**	**0.4619**	**1.420**	**5.736**
KamLAND	**0.02825**	**0.3252**	**1.035**	**4.401**
SNO+	**0.04939**	**0.5546**	**1.699**	**6.596**
JUNO	**0.02612**	**0.3036**	**0.9522**	**4.055**



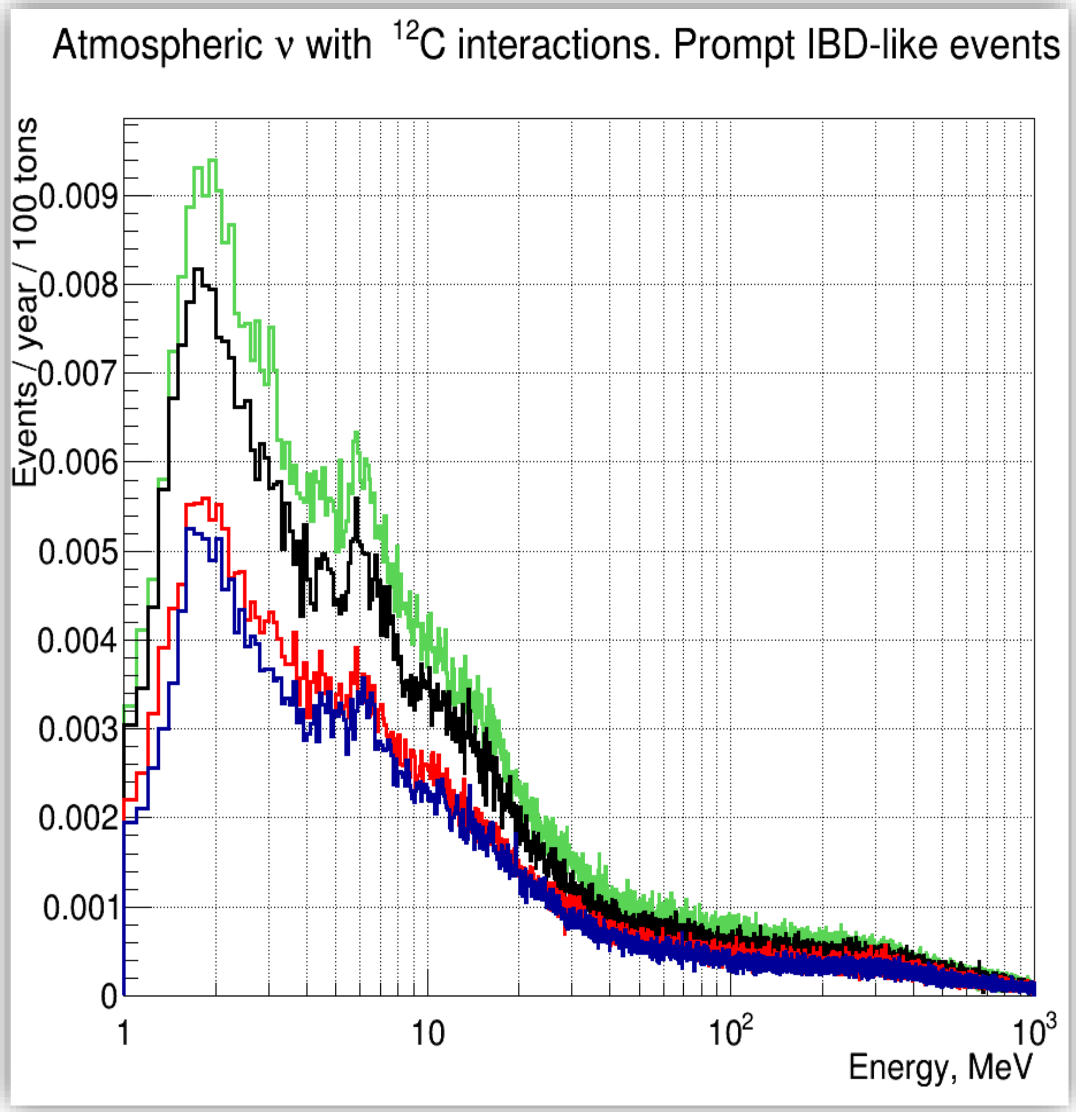
Neutrino carbon-12 reactions

$GENIE \rightarrow Geant4\ \ simulated$

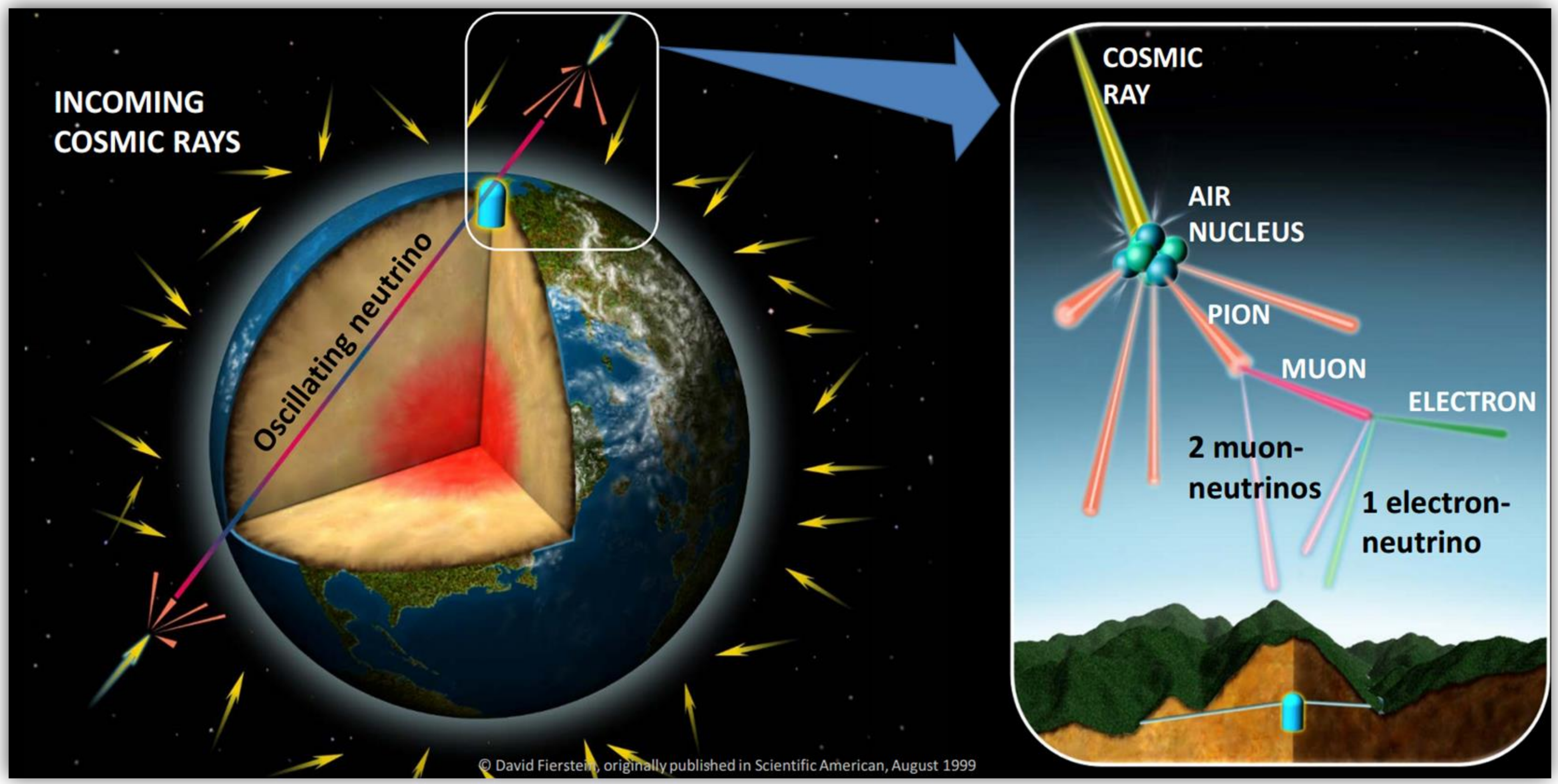
Atmospheric $\nu - {}^{12}C$ interactions

IBD-like events

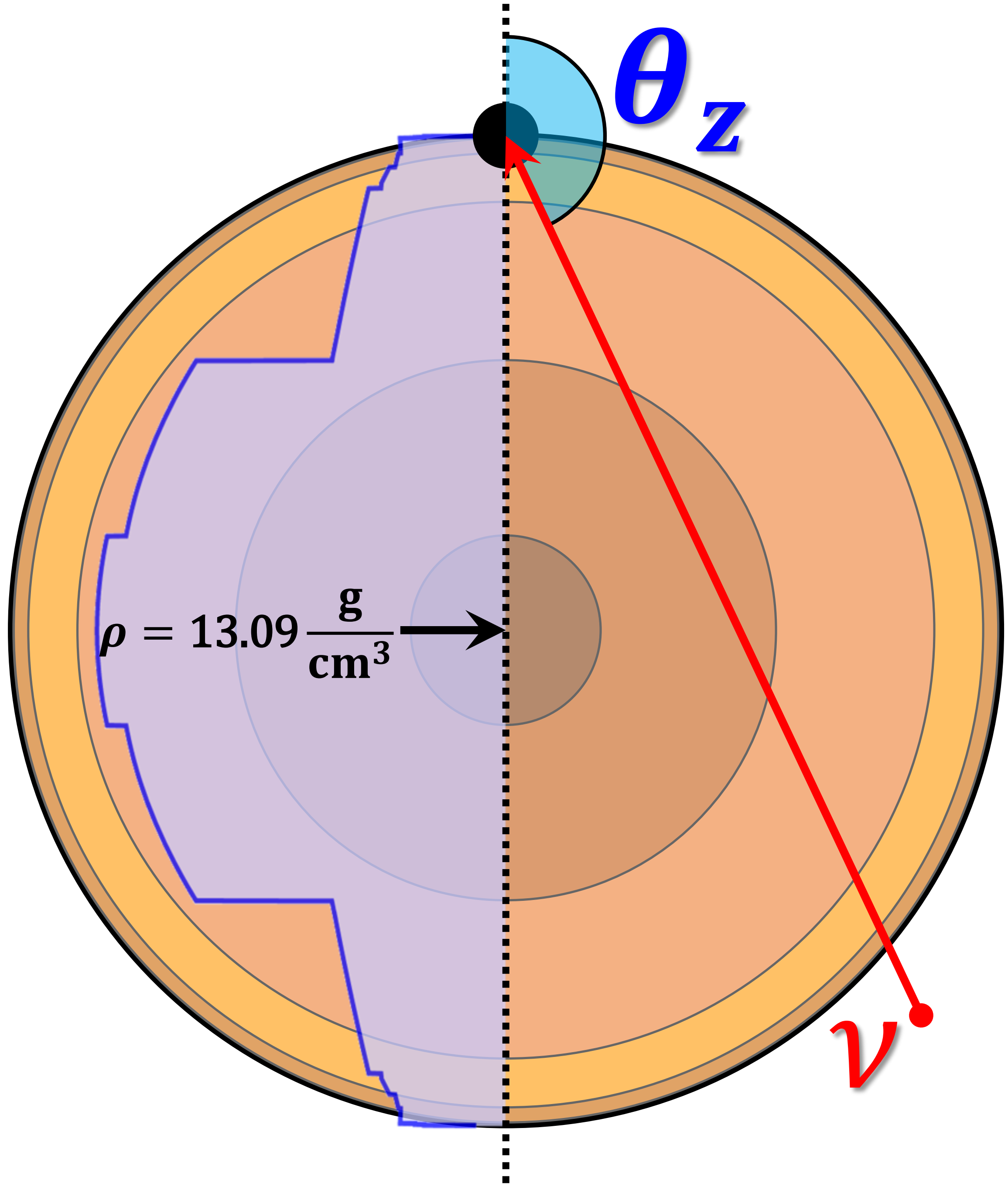
Events / year / 100 tons			
0.25<E^{vis}< … MeV	10	100	1000
Borexino	0.4352	1.362	3.711
KamLAND	0.3104	1.031	2.955
SNO+	0.5107	1.633	4.300
JUNO	0.2823	0.9387	2.681



Thanks for your attention!



Backup


θ_z
$\rho = 13.09 \frac{g}{cm^3}$
ν