Development of the comprehensive analysis tools for Supernova neutrino detectors

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

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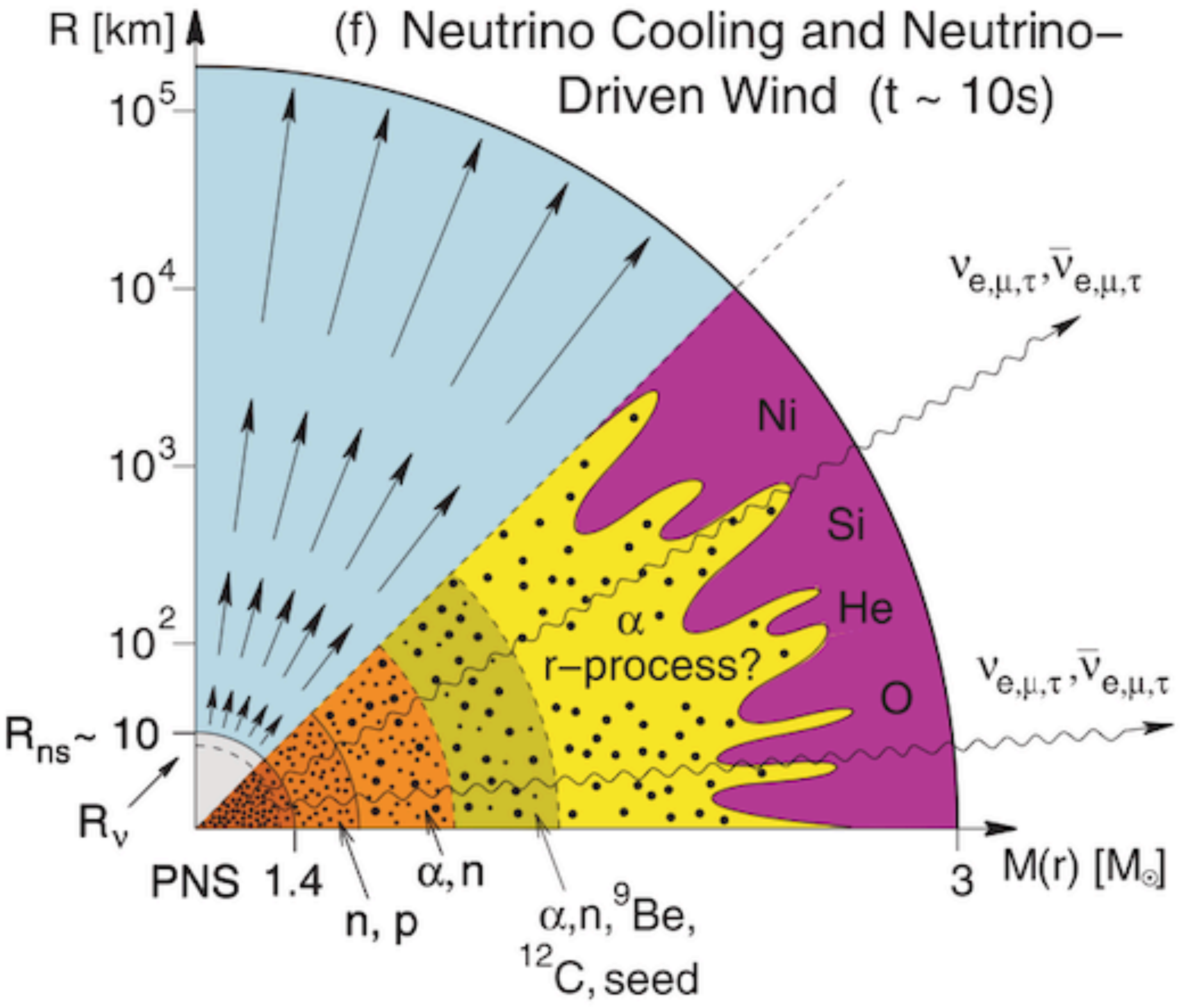
PRISMA

Motivation

- How does the SN explosion take place?
- What are the conditions inside massive stars during their evolution, collapse and explosion?
- Is the compact remnant after the SN explosion a neutron star or a black hole?
- Matter is too dense inside the core-collapsed star—> neutrinos are the most important tool to study physics at core!



SN 1987A

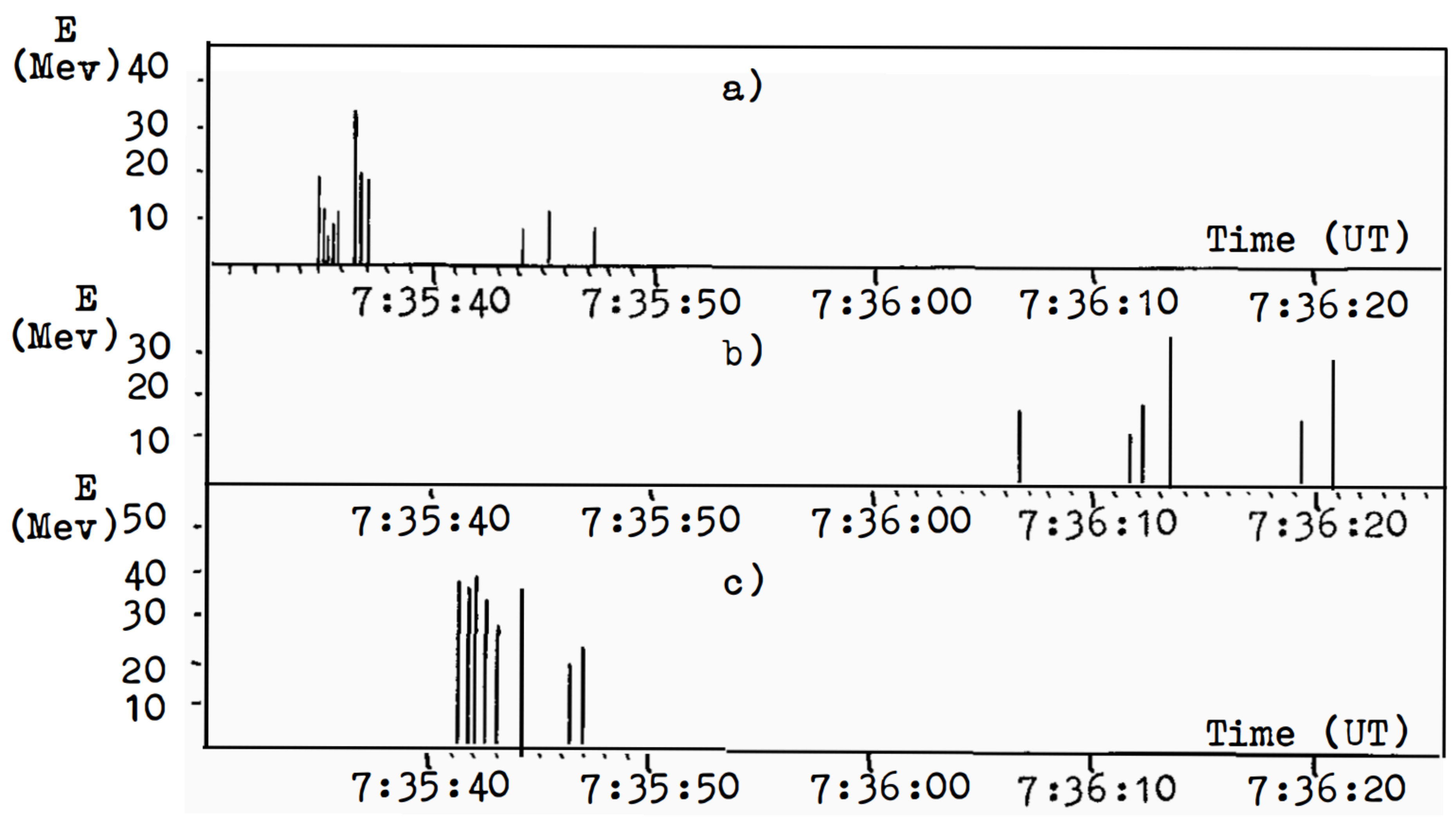
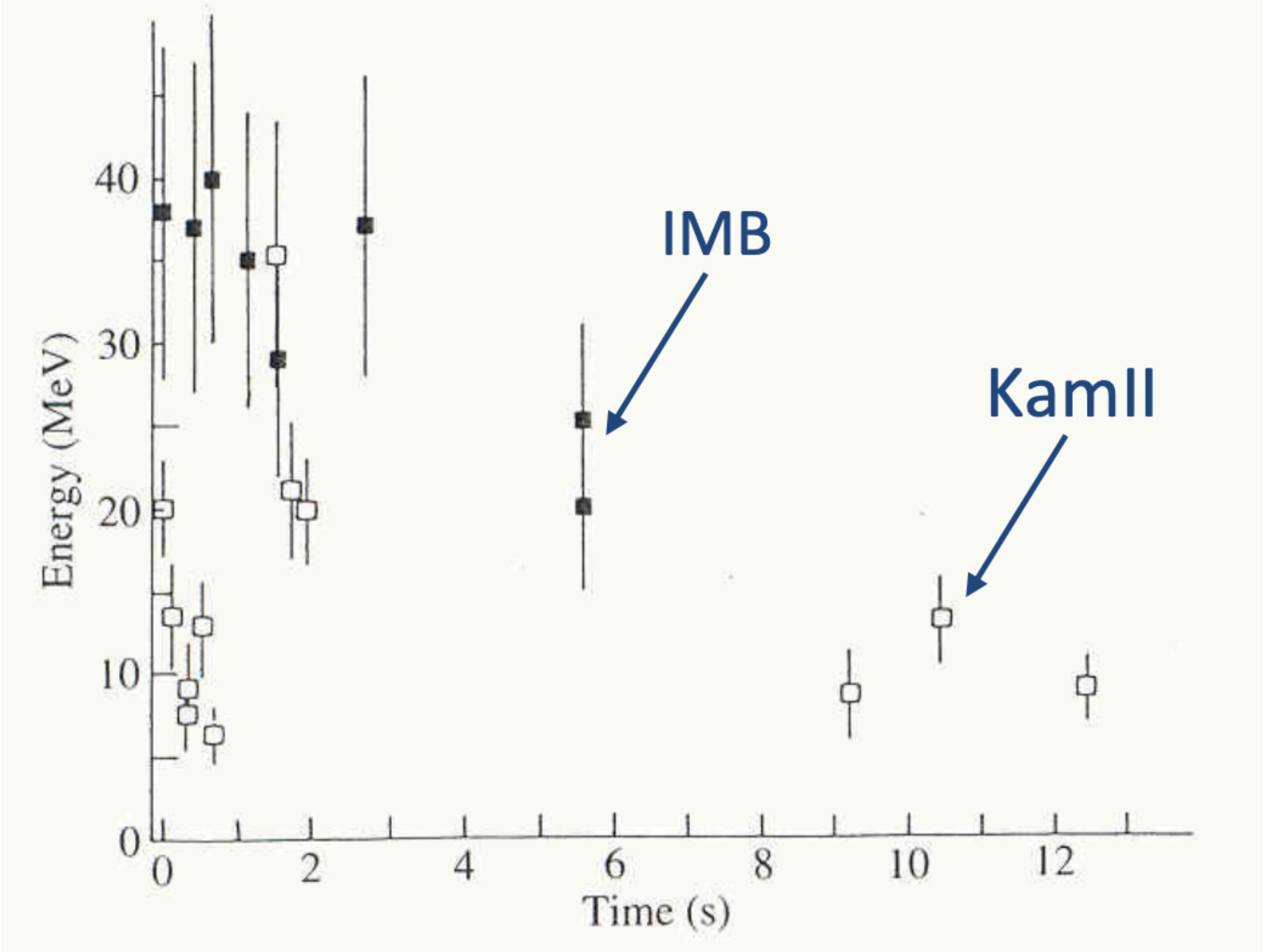


Fig.3 The time sequences of signals detected by the KAMIOKANDE II (a), the Baksan telescope (b) and the IMB detector (c) on February 23, 1987 at 7:35 UT.



- If a SN neutrino burst arrived at Earth today, it would be detected by a variety of ton to kiloton scale neutrino detectors based on different technologies and target media.

Multi-detector analysis

- Various experiments complement each other

- One could provide experiments with limited energy resolution, such as IceCube with spectral information from other detectors so that rates can be translated into fluxes

- As a result of limitations and peculiarities of different target media of the existing and future detectors, one would need a framework to analyse data from all of them simultaneously

- —-> My work is to develop this framework in order to take advantage of various experiments

$$R = N_p \cdot \Phi_{\bar{\nu}_e} \cdot \sigma(E)$$

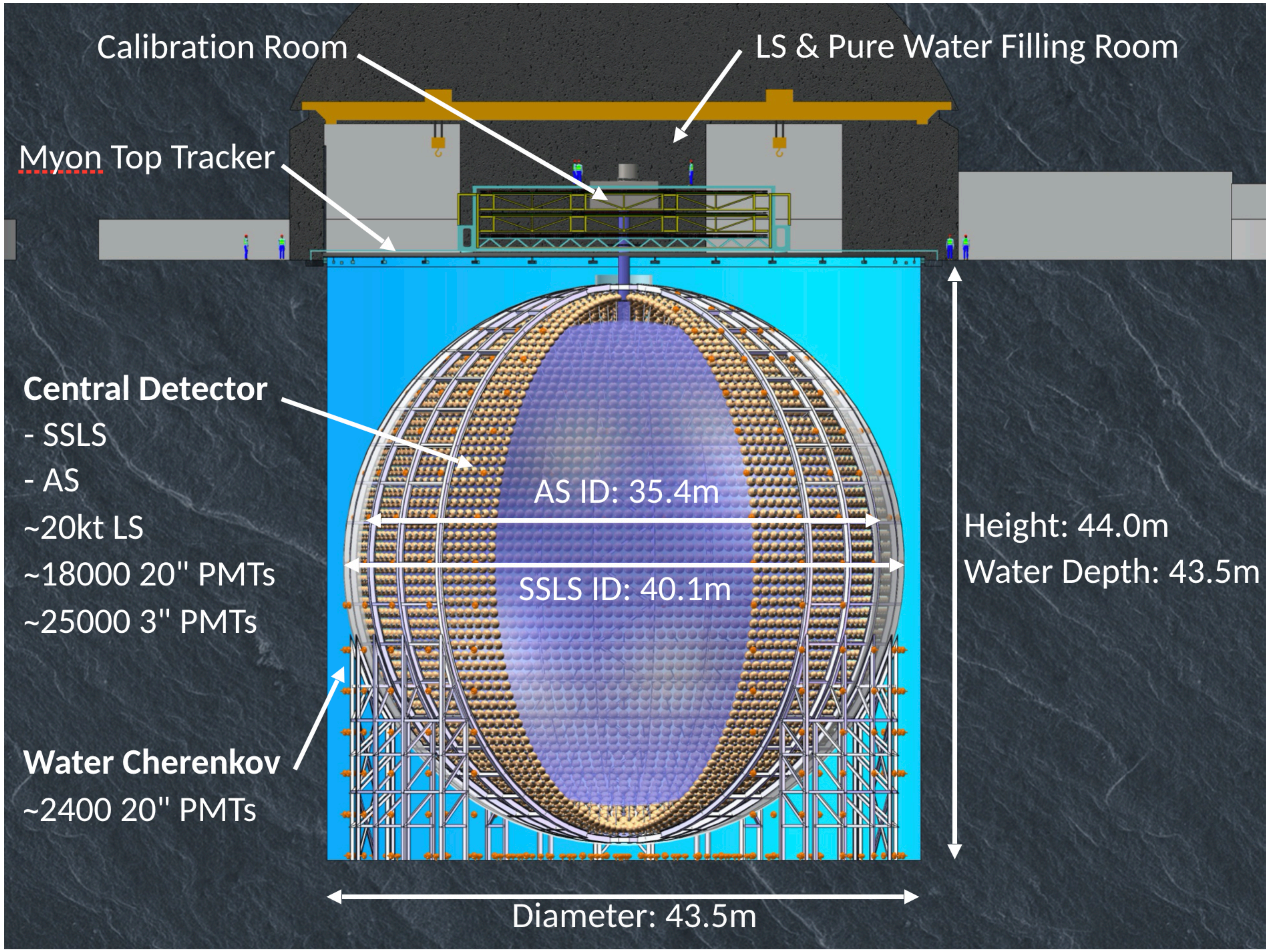
Icecube

JUNO (fit)

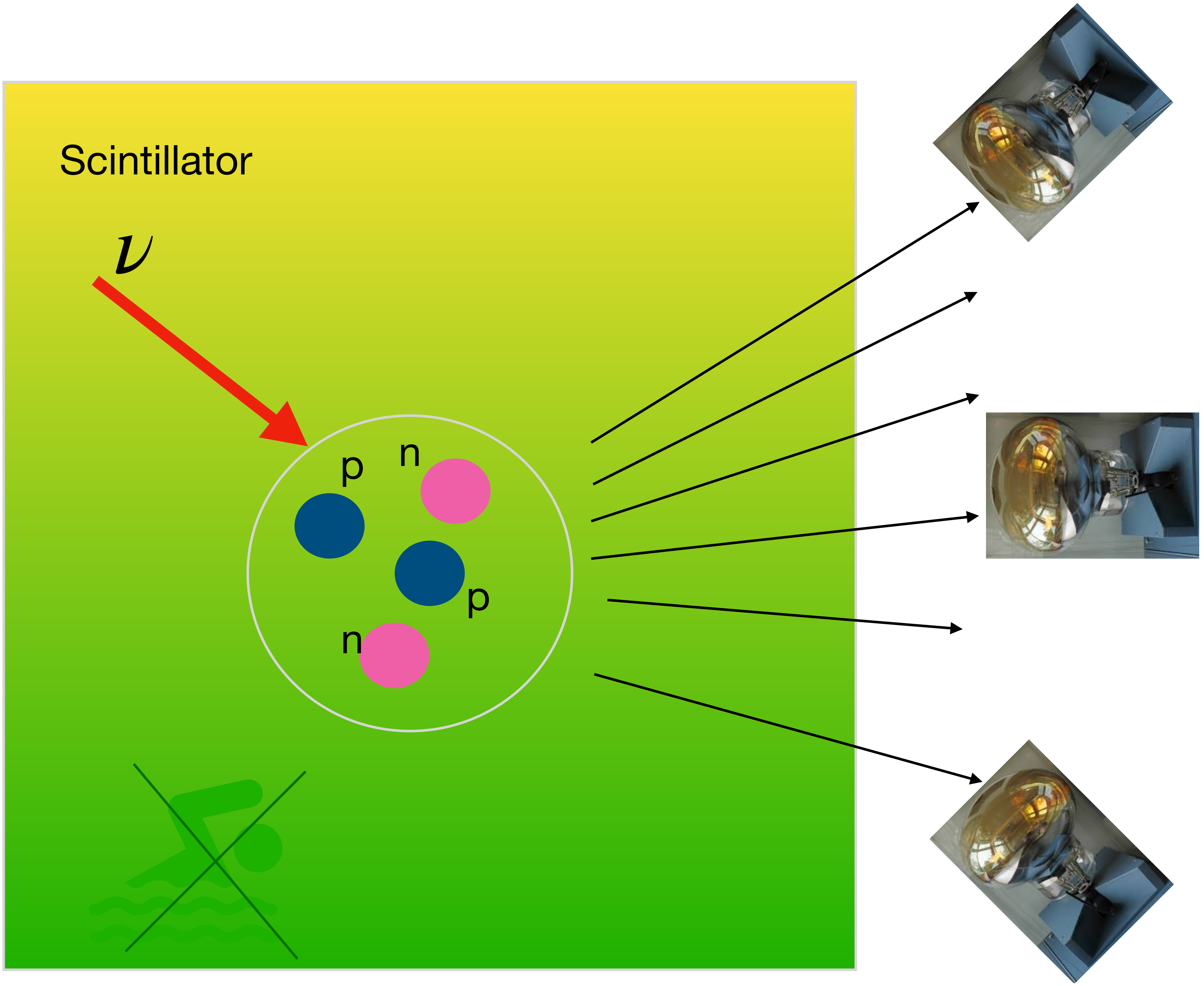
$$\chi^2 = \chi^2_{JUNO} + \chi^2_{IC}$$

- If a SN neutrino burst arrived at Earth today, it would be detected by a variety of ton to kiloton scale neutrino detectors based on different technologies and target media.

JUNO Experiment



Channels of interaction in scintillator



$$\bar{\nu}_e + p -> n + e^+$$

$$\nu_x + p -> \nu_x + p$$

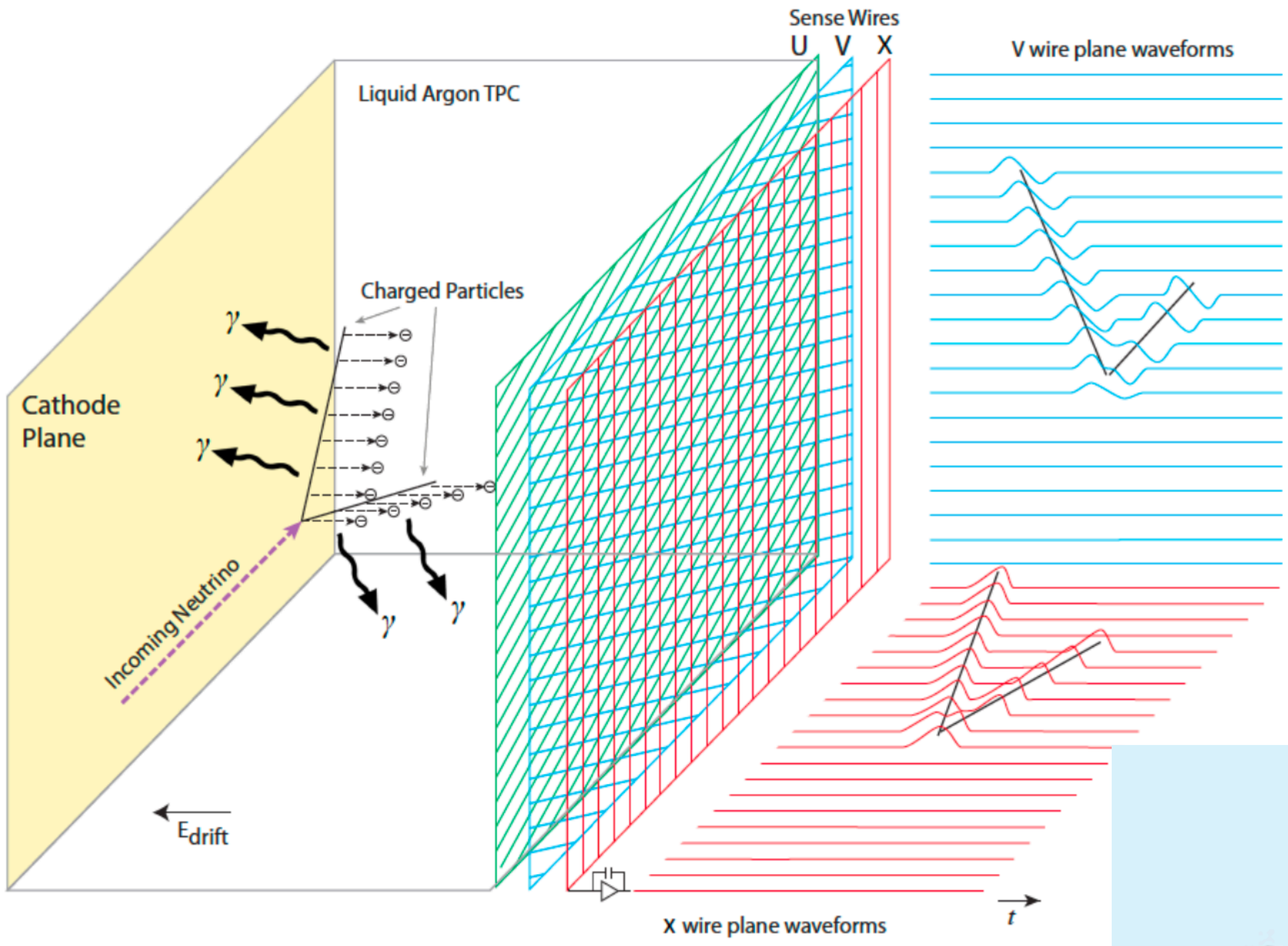
$$\nu_{e,x} + e^- -> \nu_{e,x} + e^-$$

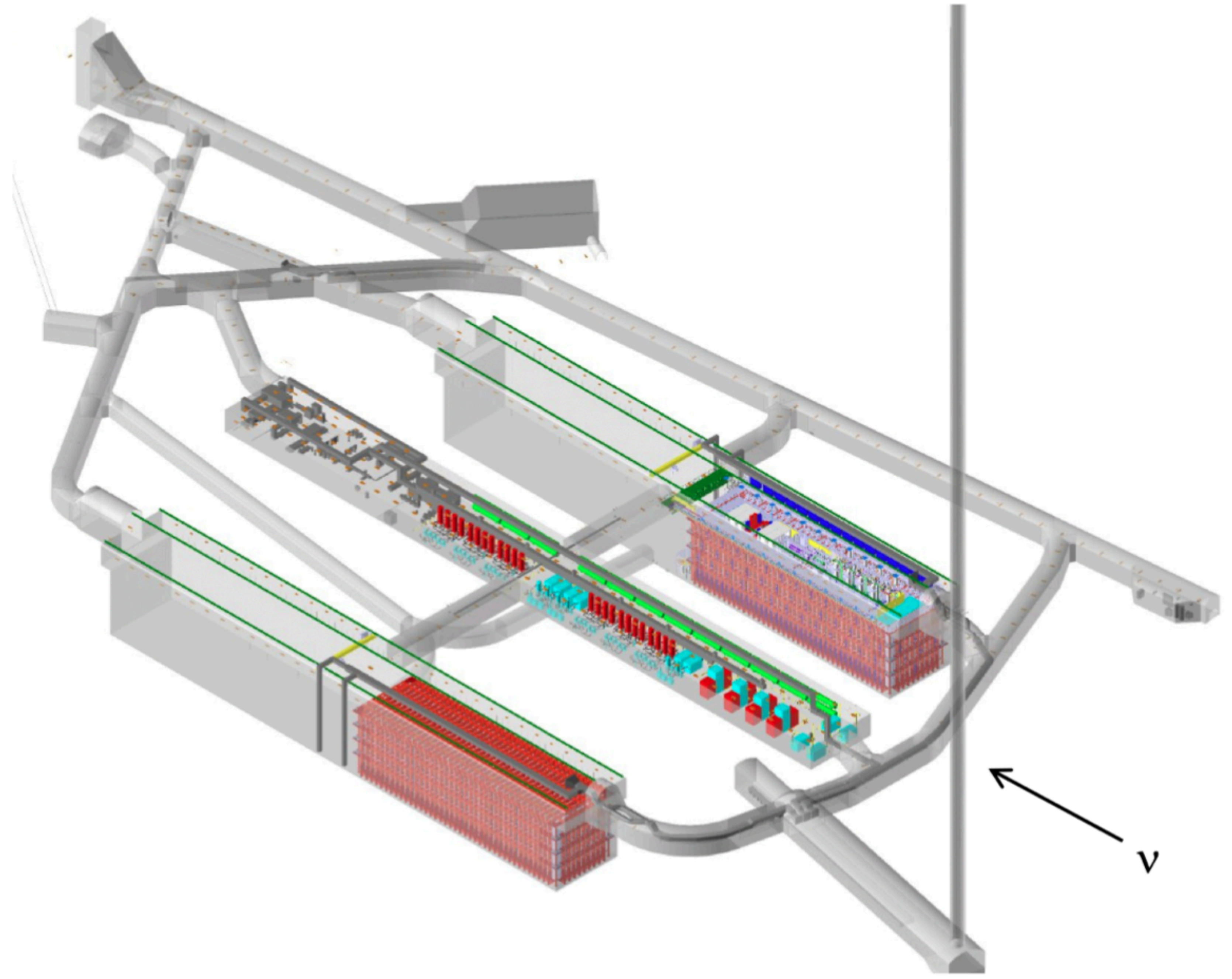
$$\nu_e +^{12} C ->^{12} N + e^-$$

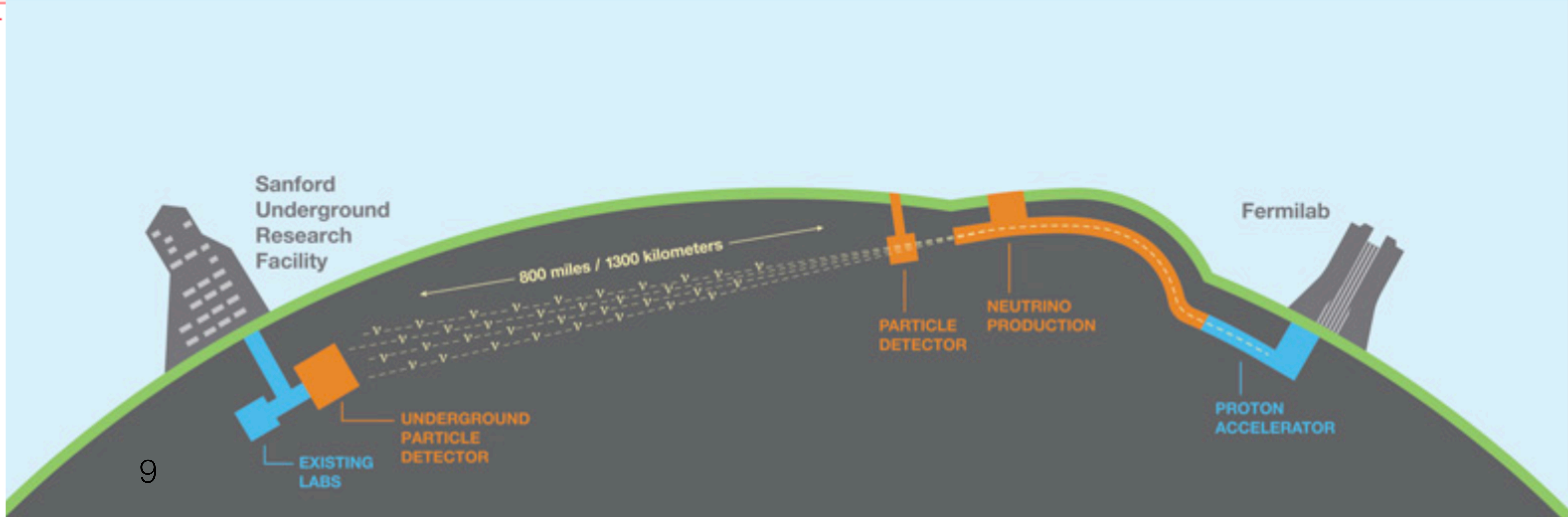
$$\bar{\nu}_e +^{12} C ->^{12} B + e^+$$

$$\nu_x +^{12} C -> \nu_x +^{12} C*$$

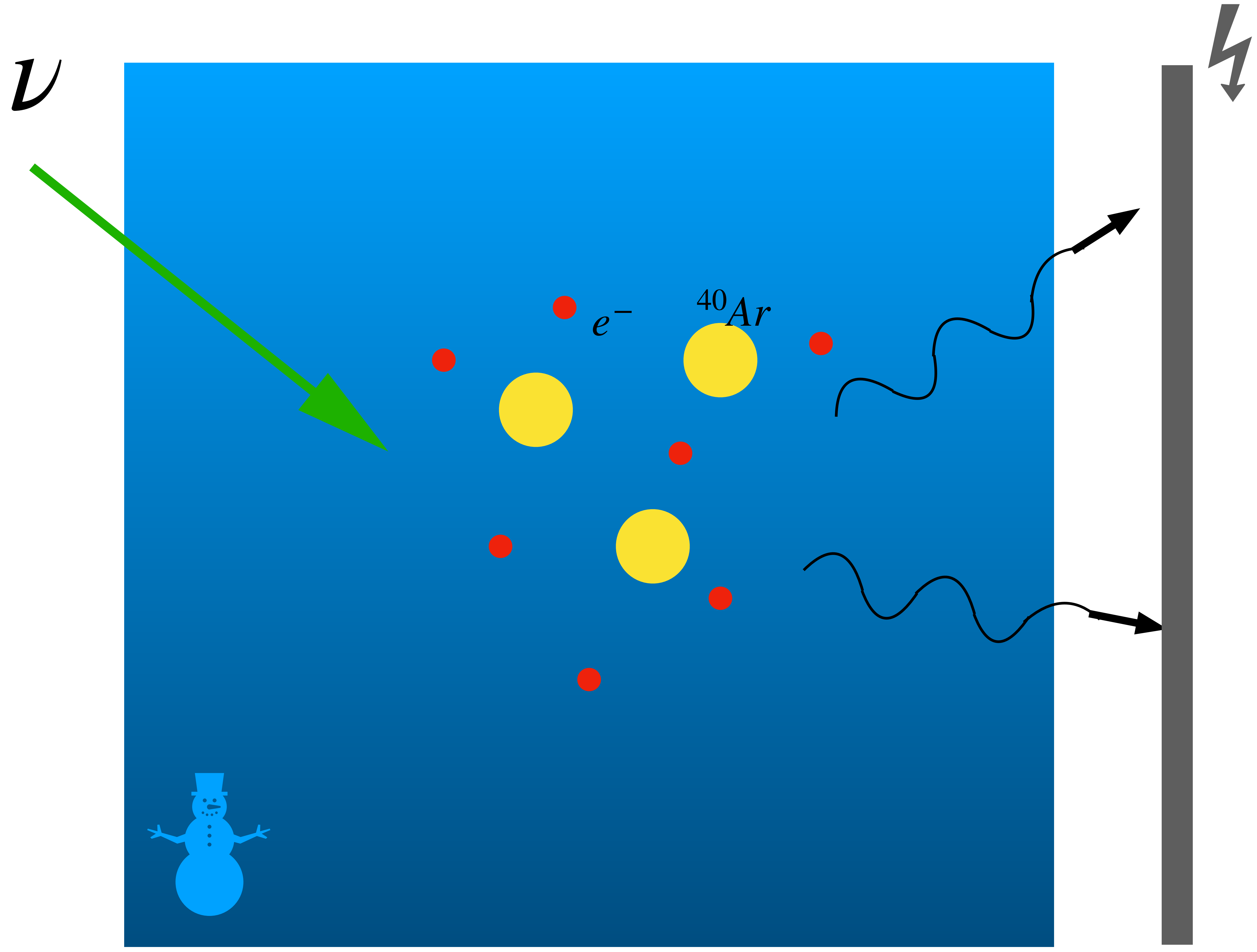
DUNE


Sense Wires
U V X
V wire plane waveforms
Liquid Argon TPC
Charged Particles
Cathode Plane
Incoming Neutrino
E_{drift}
X wire plane waveforms
t


ν


Sanford Underground Research Facility
800 miles / 1300 kilometers
Fermilab
PARTICLE DETECTOR
NEUTRINO PRODUCTION
PROTON ACCELERATOR
UNDERGROUND PARTICLE DETECTOR
EXISTING LABS

Channels of interaction in ^{40}Ar

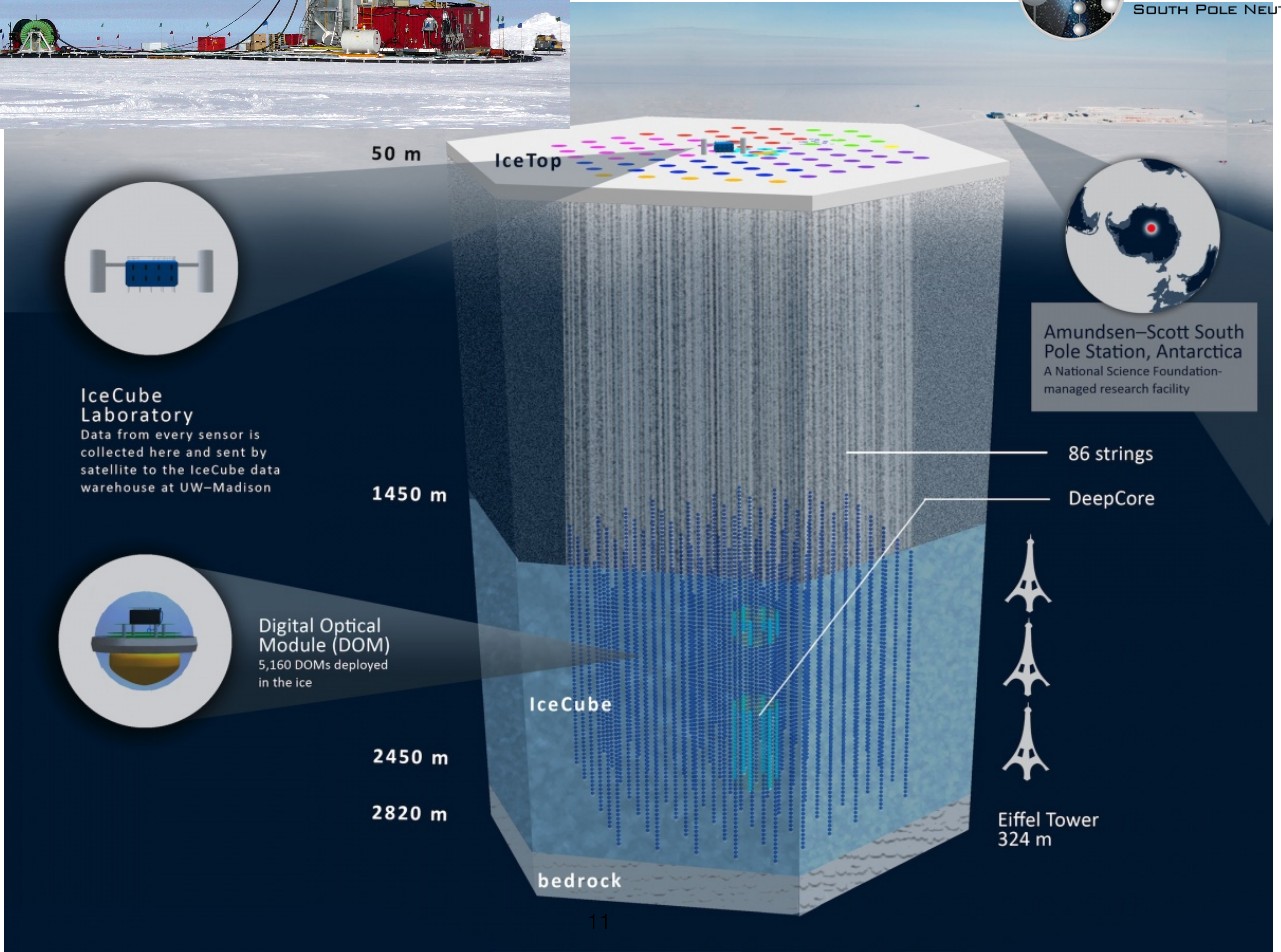


$$\nu_e +^{40} Ar -> e^- +^{40} K^*$$

$$\bar{\nu_e} +^{40} Ar -> e^+ +^{40} Cl^*$$

$$\nu_x + e^- -> \nu_x + e^-$$

$$\nu_x +^{40} Ar -> \nu_x +^{40} Ar*$$



ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY

Noise rate (avg) =
540 Hz

dead time = 250μs

$\varepsilon_{\text{noise}} \approx 0.87/(1+\tau \cdot r_{\text{SN}}(t)).$

SN neutrino rate in Icecube

Reaction	# Targets	# Signal hits	Signal fraction	Reference
$\bar{\nu}_e + p \to e^+ + n$	6×10^{37}	134 k (157 k)	93.8% (94.4%)	Strumia & Vissani (2003)
$\nu_e + e^- \to \nu_e + e^-$	3×10^{38}	2.35 k (2.25 k)	1.7% (1.4%)	Marciano & Parsa (2003)
$\bar{\nu}_e + e^- \to \bar{\nu}_e + e^-$	3×10^{38}	660 (720)	0.5% (0.4%)	Marciano & Parsa (2003)
$\nu_{\mu+\tau} + e^- \to \nu_{\mu+\tau} + e^-$	3×10^{38}	700 (720)	0.5% (0.4%)	Marciano & Parsa (2003)
$\bar{\nu}_{\mu+\tau} + e^- \to \bar{\nu}_{\nu+\tau} + e^-$	3×10^{38}	600 (570)	0.4% (0.4%)	Marciano & Parsa (2003)
$\nu_e + {}^{16}O \to e^- + X$	3×10^{37}	2.15 k (1.50 k)	1.5% (0.9%)	Kolbe et al. (2002)
$\bar{\nu}_e + {}^{16}O \to e^+ + X$	3×10^{37}	1.90 k (2.80 k)	1.3% (1.7%)	Kolbe et al. (2002)
$\nu_{all} + {}^{16}O \to \nu_{all} + X$	3×10^{37}	430 (410)	0.3% (0.3%)	Kolbe et al. (2002)
$\nu_e + {}^{17/18}O/{}^2_1H \to e^- + X$	6×10^{34}	270 (245)	0.2% (0.2%)	Haxton (1999)

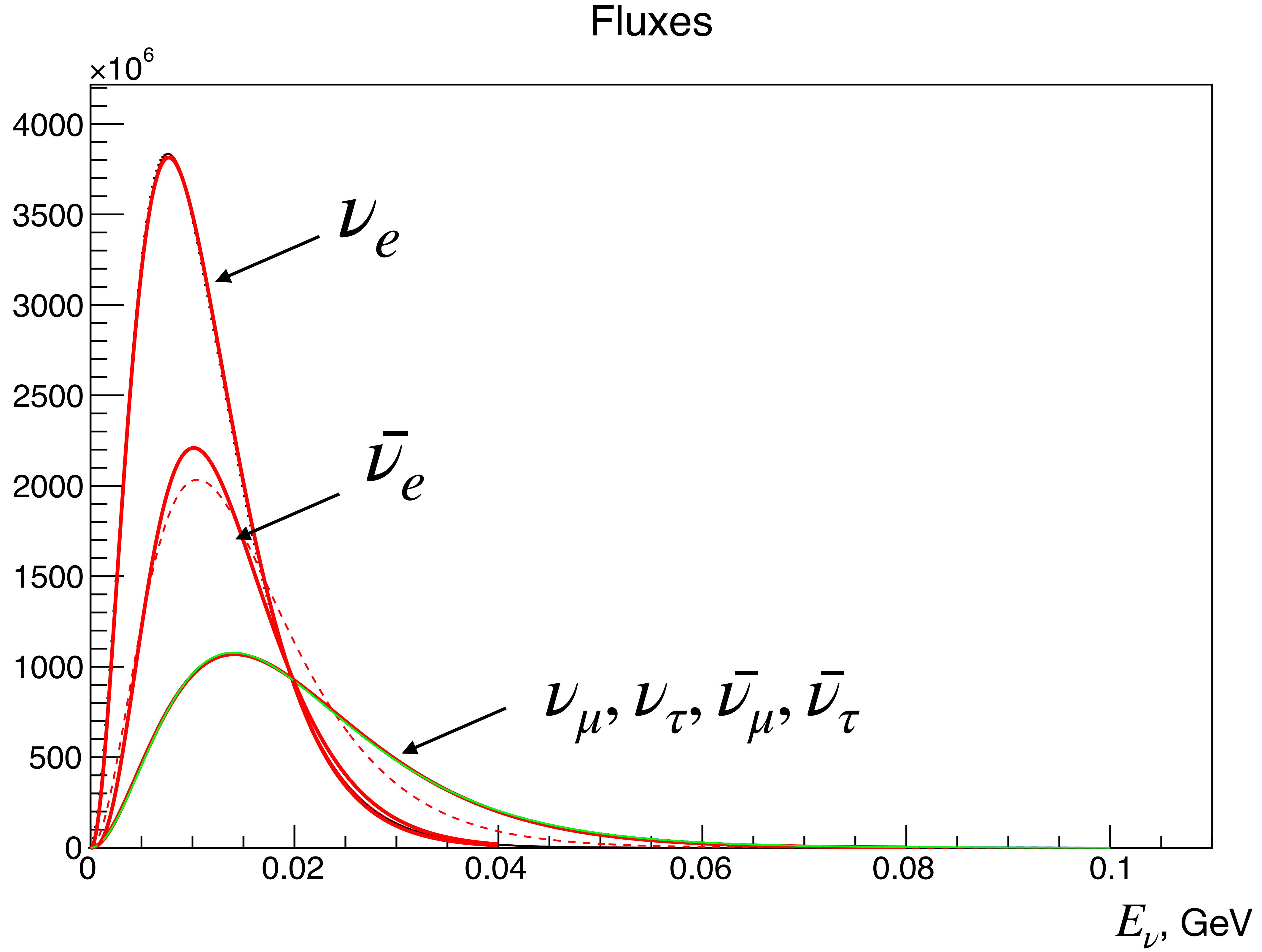
Notes. The approximate number of targets in a 1 km^3 ice detector, the detected number of hits at 10 kpc distance and their fraction in stars are given in the second, third and fourth column, respectively. In order to indicate the effect of neutrino oscillations in the star, signal hits and fractions are presented both assuming a normal neutrino hierarchy (Scenario A) and – in brackets – assuming an inverted hierarchy (Scenario B). The numbers are taken from the Garching model using the equation of state by Lattimer & Swesty (1991), integrating over 0.8 s and averaging over the neutrino incidence angle.

Common fit of all neutrino spectra

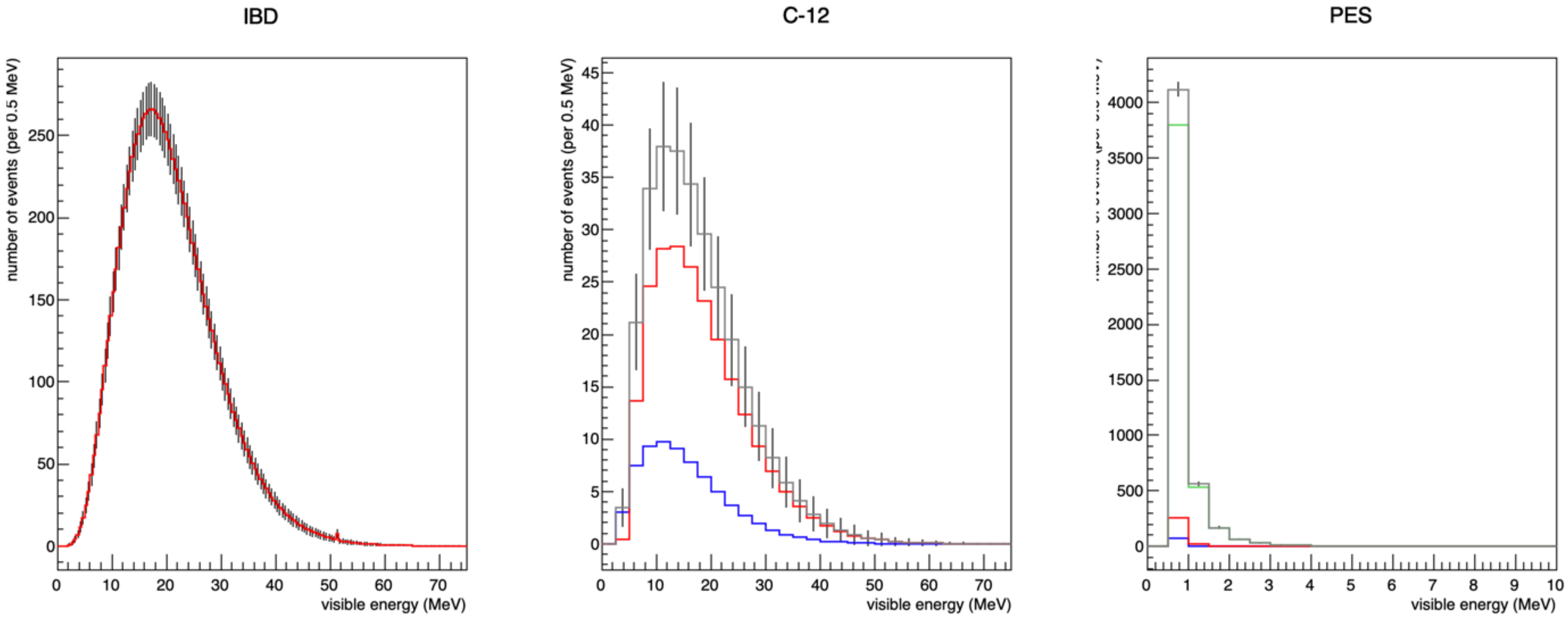
$$\frac{\mathrm{d}F_\alpha}{\mathrm{d}E_\alpha} = \frac{3.5 \times 10^{13}}{\mathrm{cm}^2\ \mathrm{MeV}} \cdot \frac{1}{4\pi D^2} \frac{\varepsilon_\alpha}{\langle E_\alpha \rangle} \frac{E_\alpha^{\gamma_\alpha}}{\Gamma(1+\gamma_\alpha)} \left(\frac{1+\gamma_\alpha}{\langle E_\alpha \rangle}\right)^{1+\gamma_\alpha} \exp\left[-(1+\gamma_\alpha)\frac{E_\alpha}{\langle E_\alpha \rangle}\right]$$

<u>Fit parameters</u>: <E> , γ, flux normalisation

- Histogram array of simulated data is pre-stored using SNOwGLoBES
- Fit uses it interpolating in-between histograms

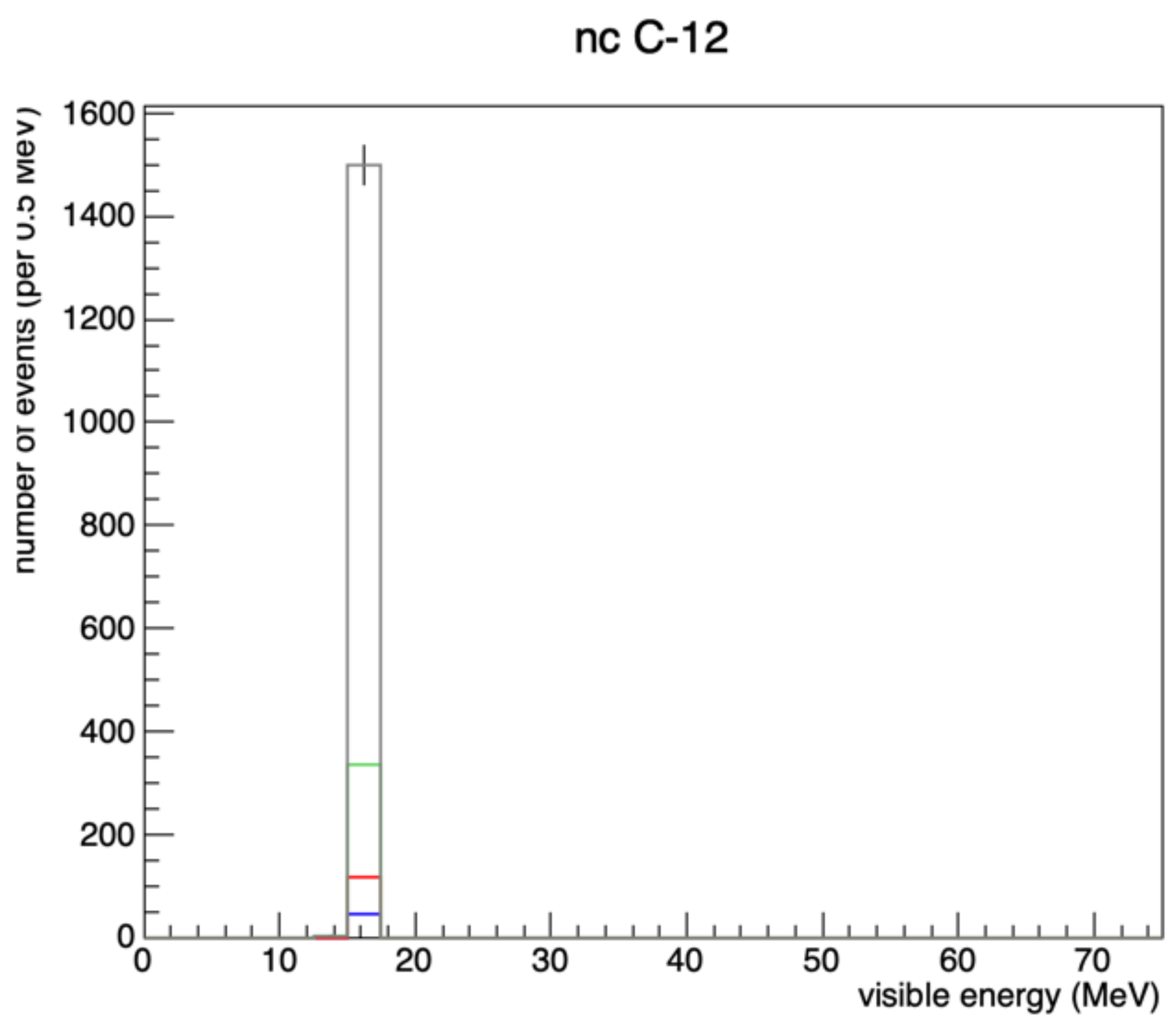


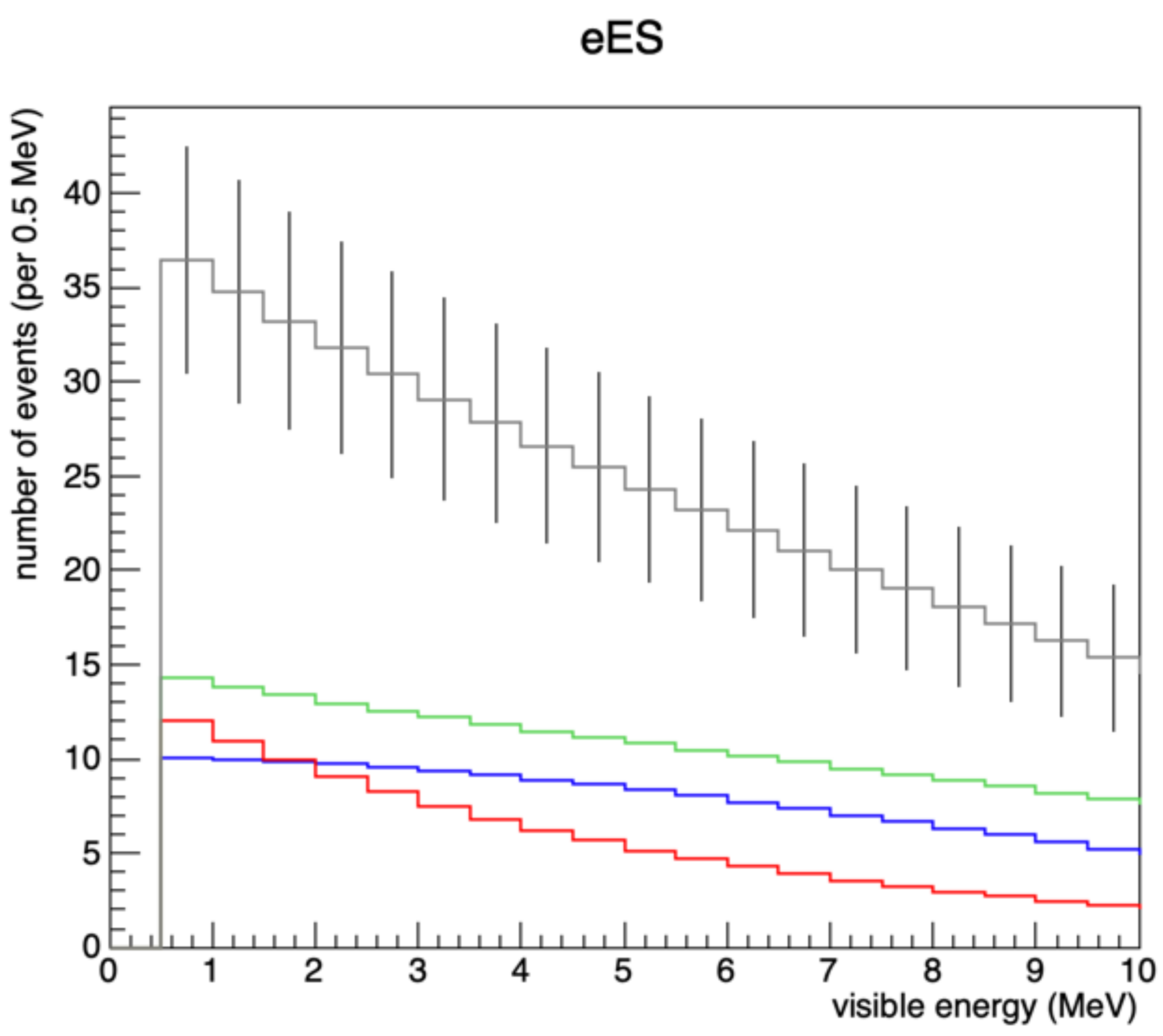
Fit to Asimov data sets returns median sensitivity/uncertainties + quenching



- $\bar{\nu}_e$
- ν_e
- $\nu_\mu, \nu_\tau, \bar{\nu}_\mu, \bar{\nu}_\tau$
- *total*

Fit to Asimov data sets returns median sensitivity/uncertainties + quenching





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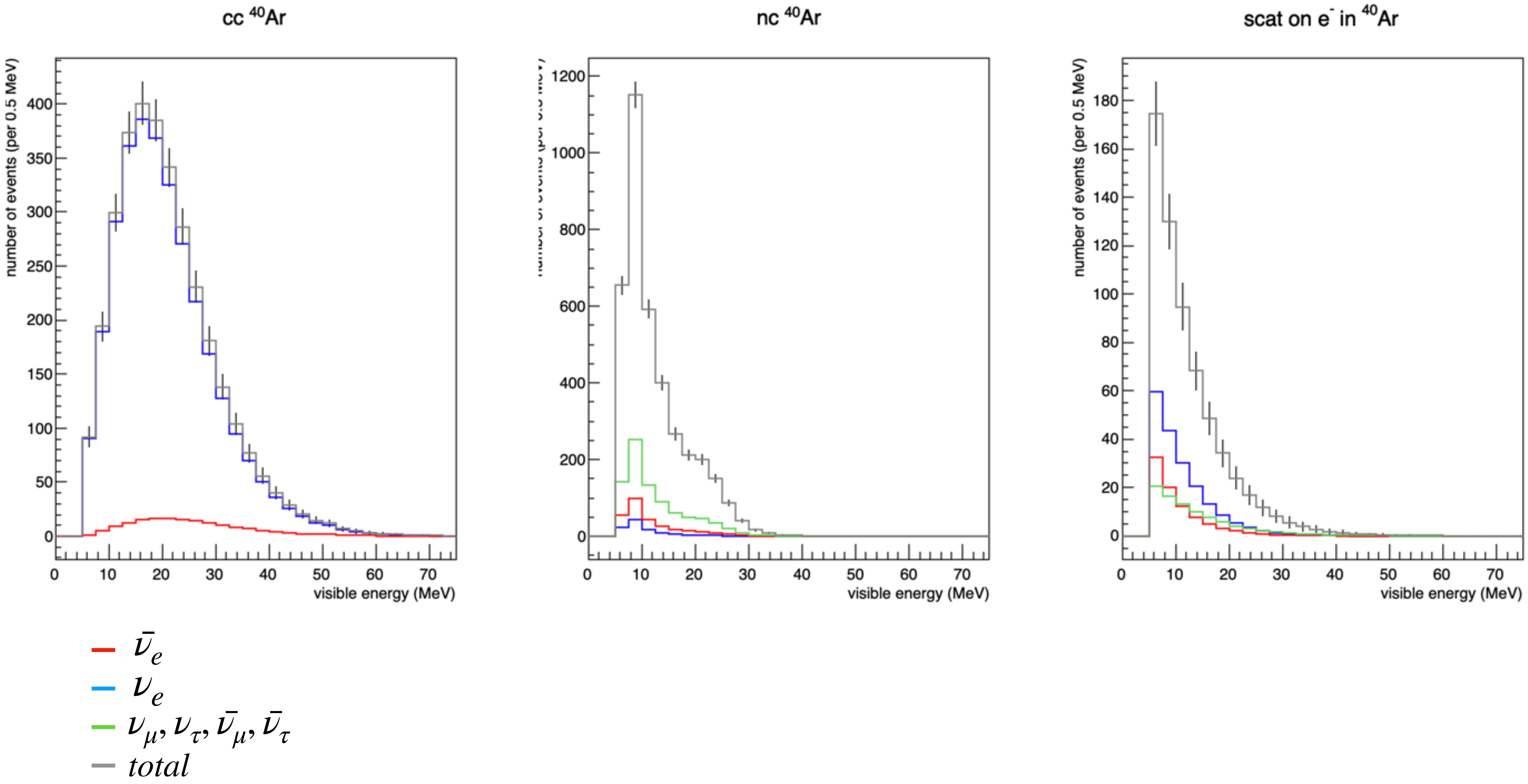
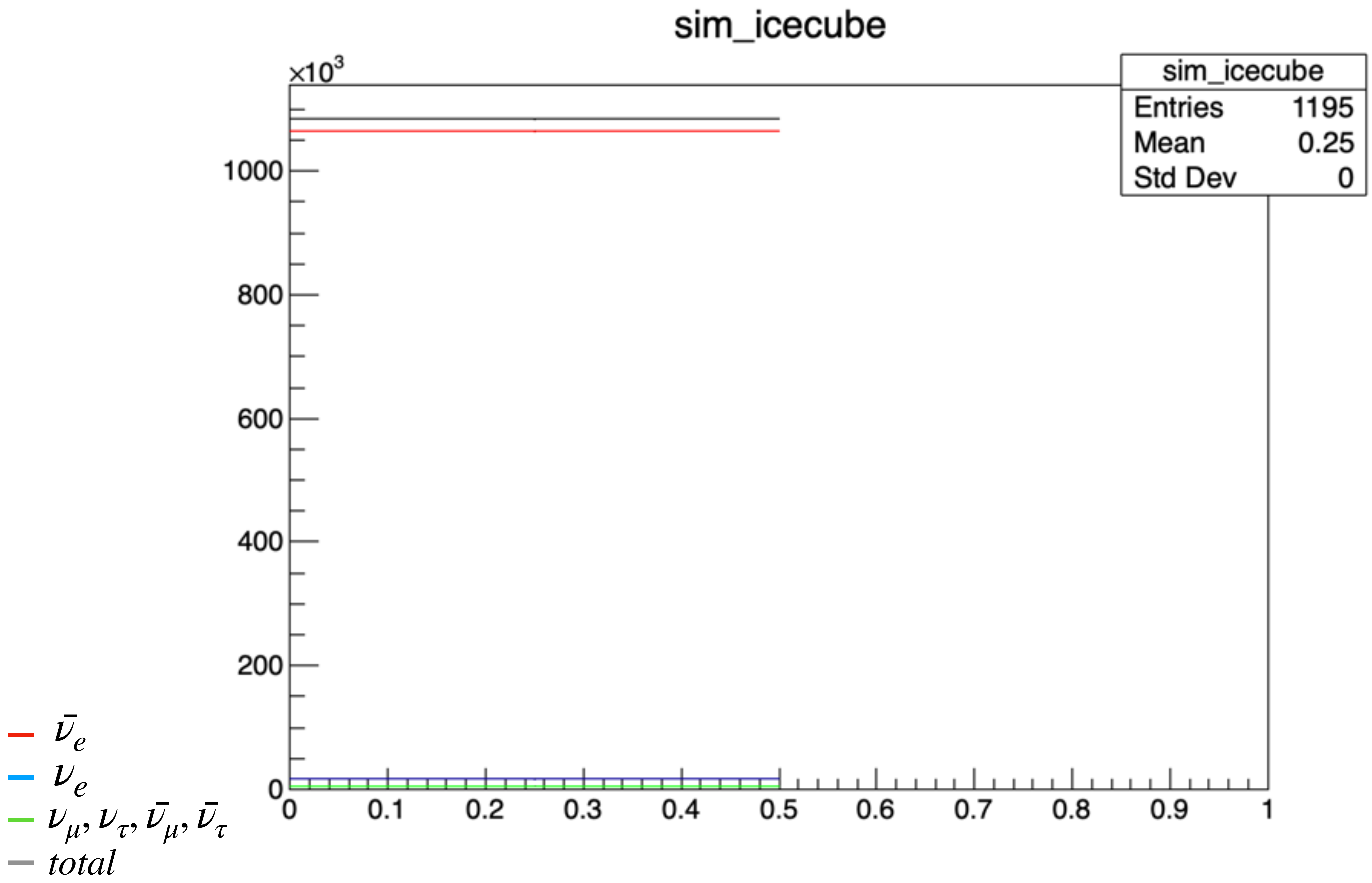
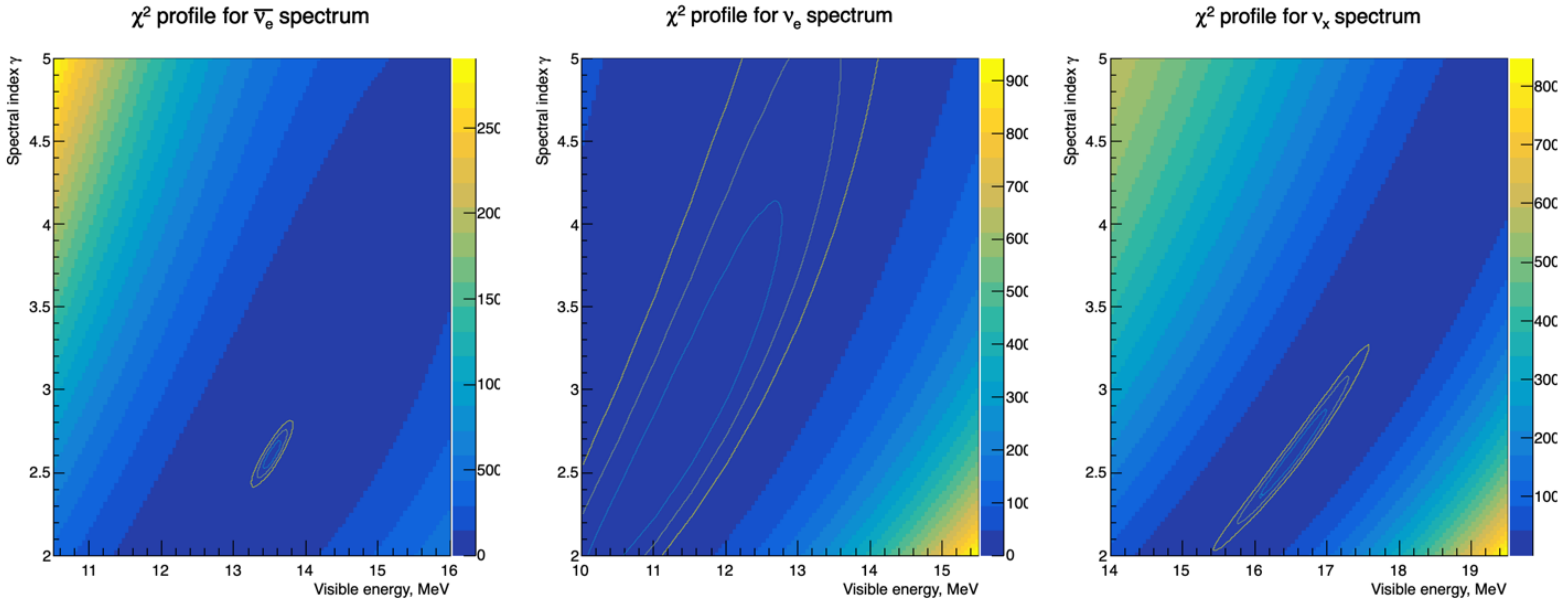


Icecube fit

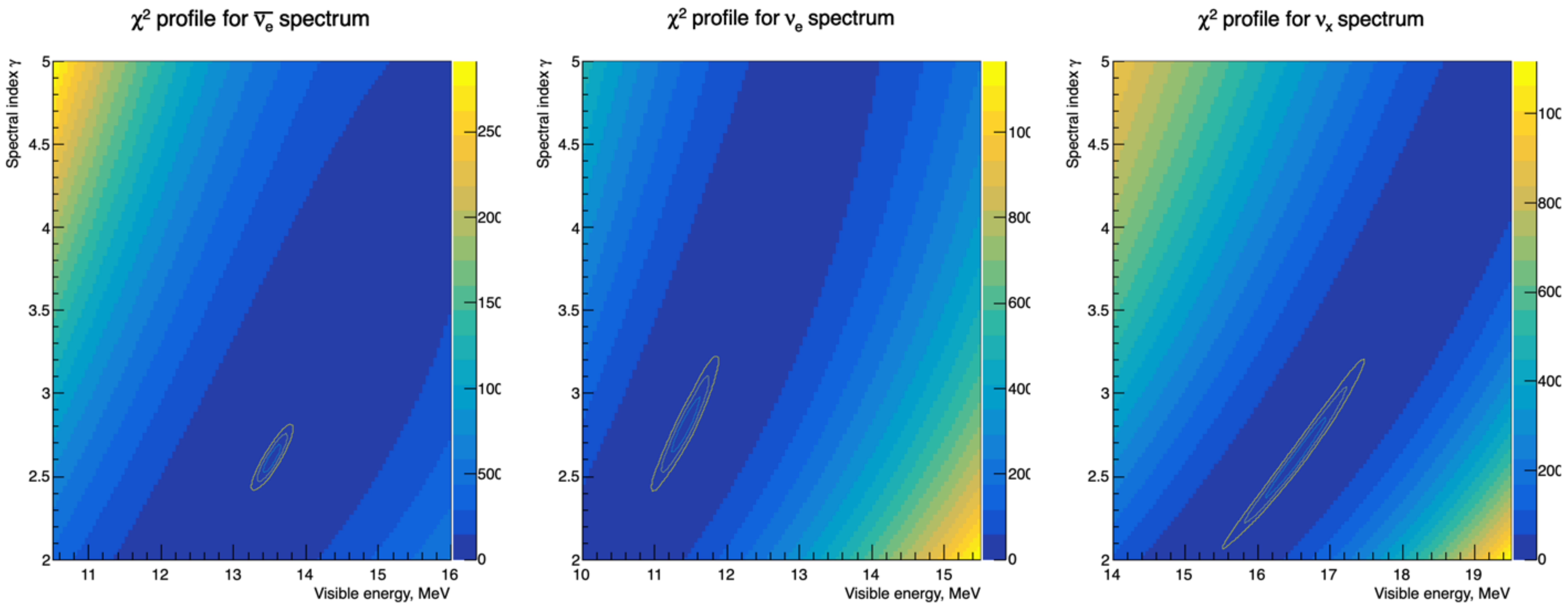


sim_icecube
×10^3
1000
800
600
400
200
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
sim_icecube
Entries 1195
Mean 0.25
Std Dev 0
$\bar{\nu}_e$
ν_e
$\nu_\mu, \nu_\tau, \bar{\nu}_\mu, \bar{\nu}_\tau$
total

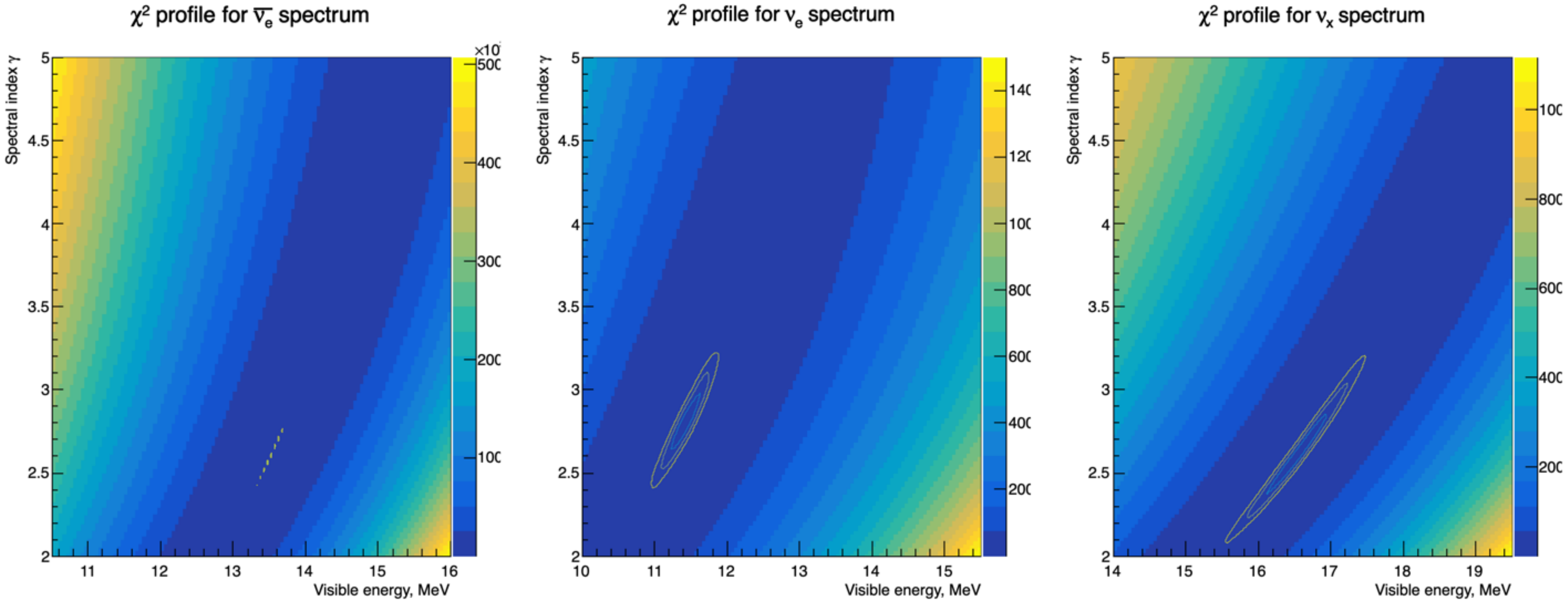
Mean energy - γ correlation



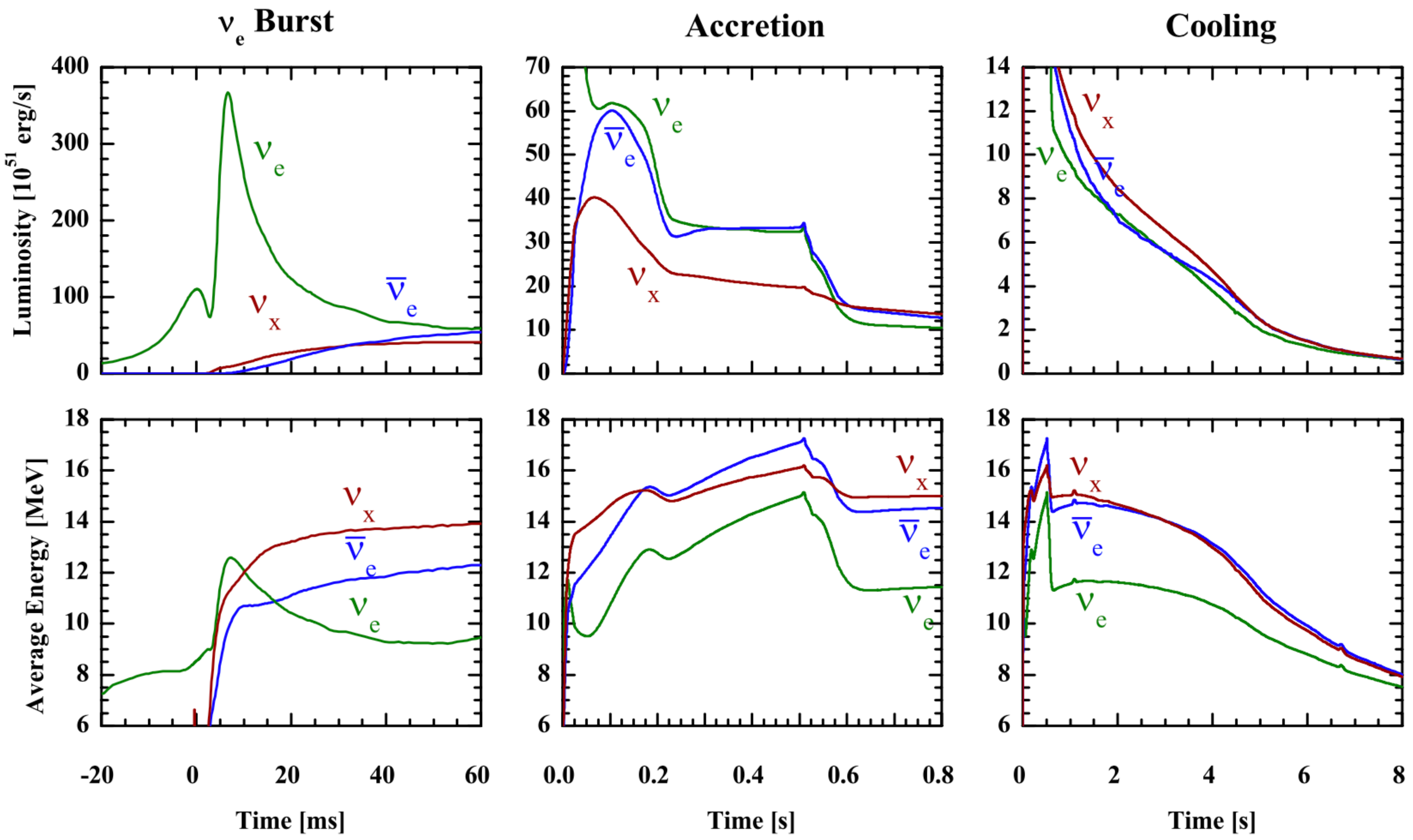
Mean energy - γ correlation



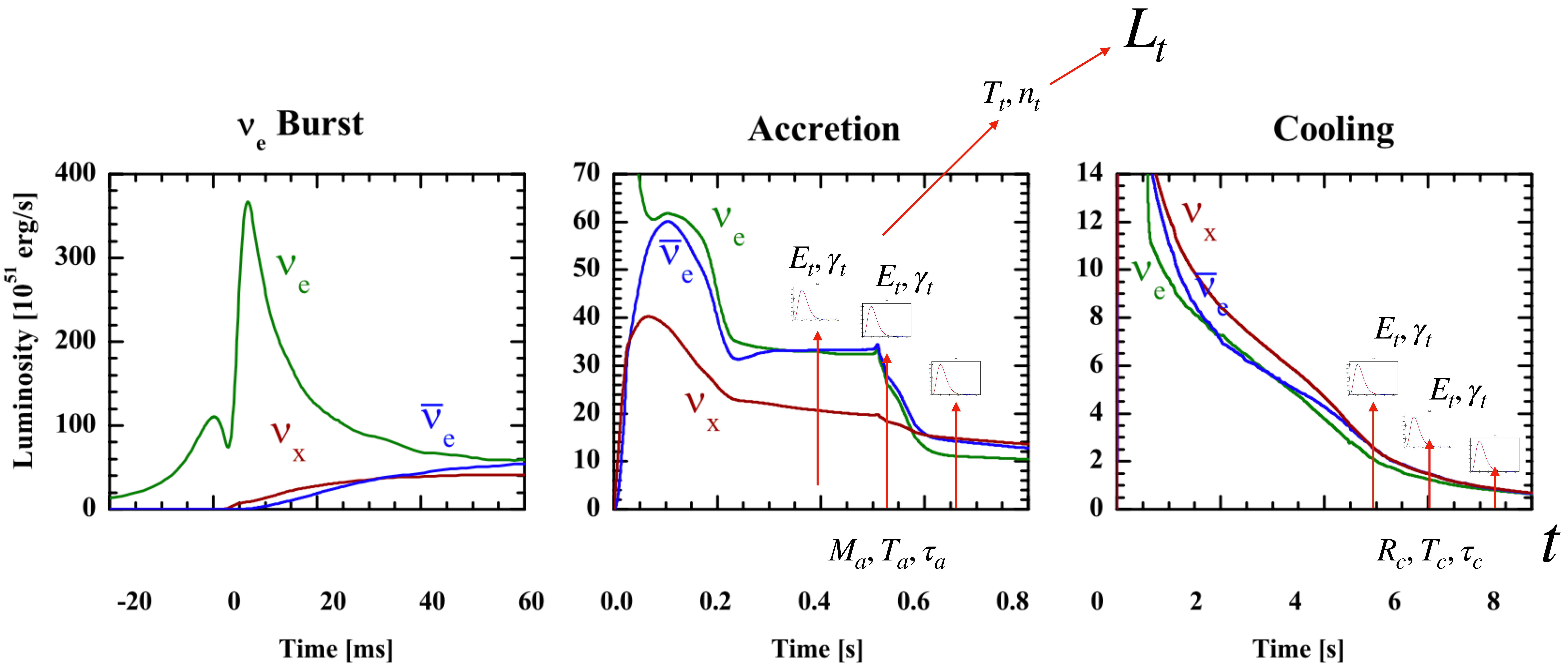
Mean energy - γ correlation



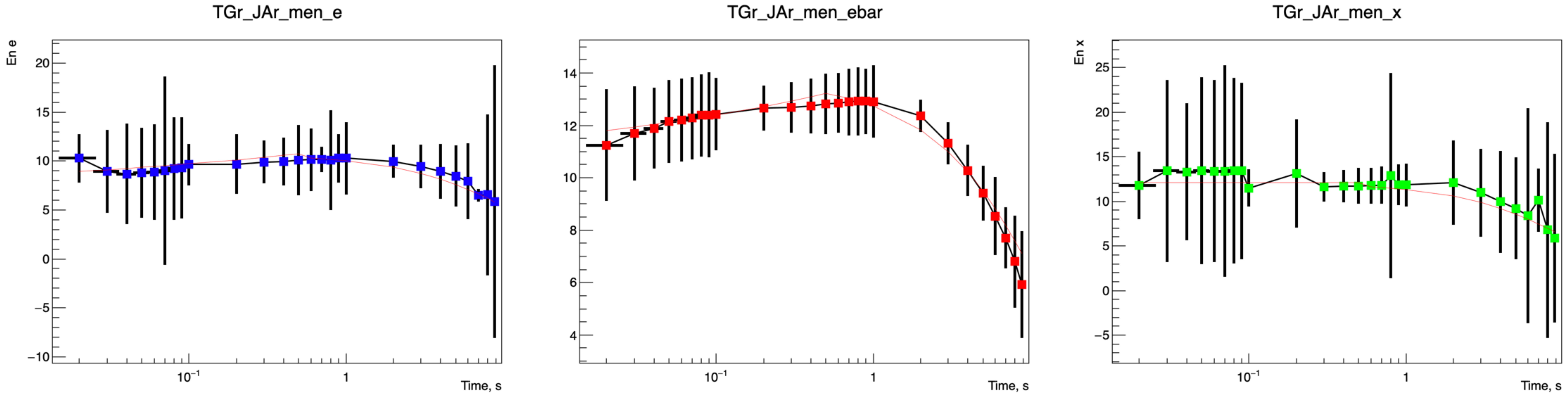
Time-dependent neutrino flux



Time-dependent neutrino flux



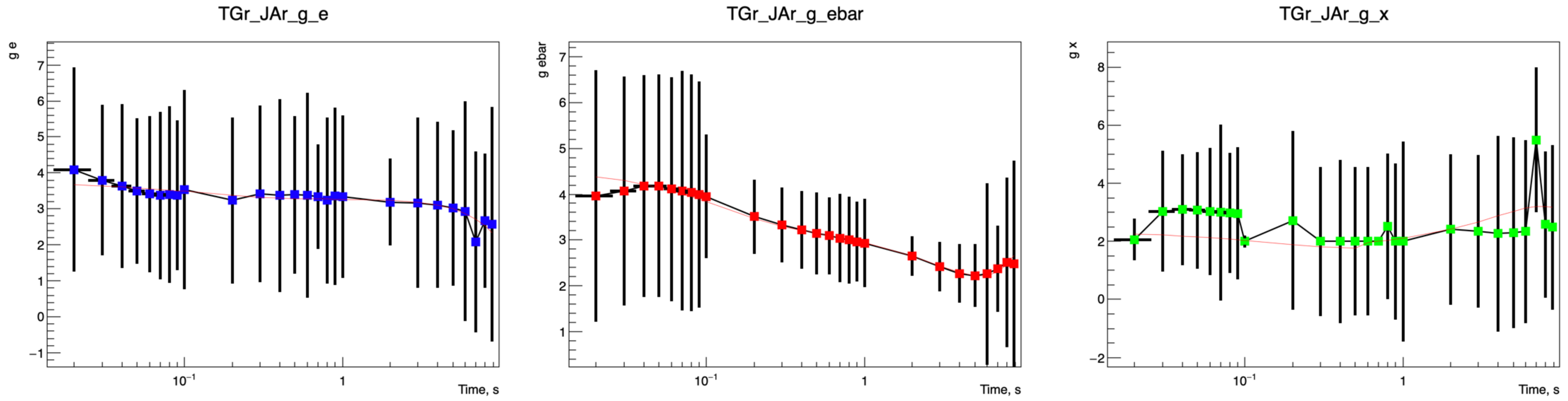
Time-dependent parameters. Fit results



— $\bar{\nu}_e$
— ν_e
— $\nu_\mu, \nu_\tau, \bar{\nu}_\mu, \bar{\nu}_\tau$

8.8 Solar mass model

Time-dependent parameters. Fit results



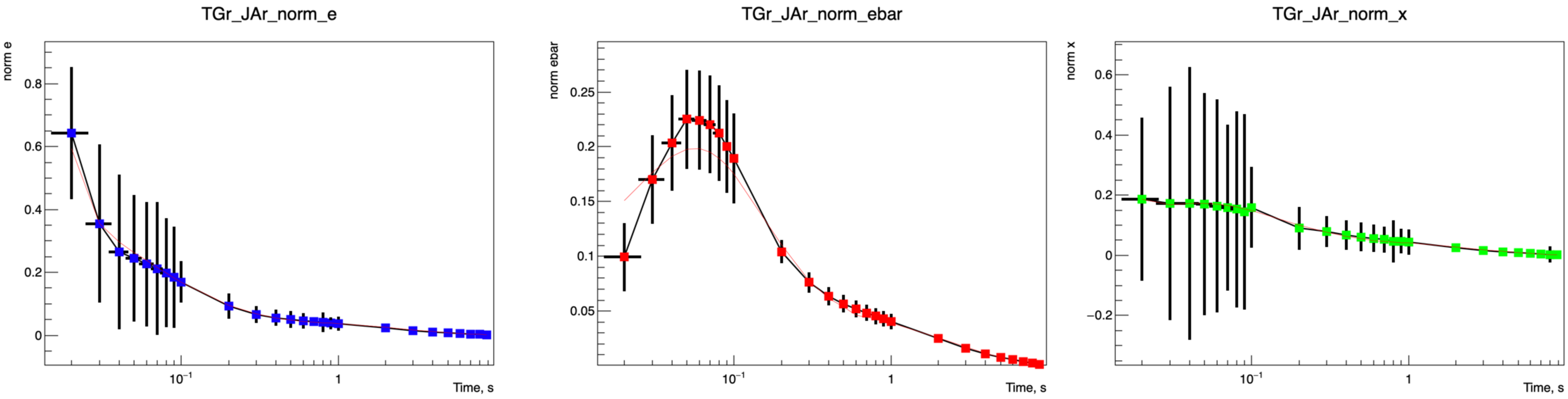
$-\ \bar{\nu}_e$

$-\ \nu_e$

$-\ \nu_\mu, \nu_\tau, \bar{\nu}_\mu, \bar{\nu}_\tau$

8.8 Solar mass model

Time-dependent parameters. Fit results



— $\bar{\nu}_e$
— ν_e
— $\nu_\mu, \nu_\tau, \bar{\nu}_\mu, \bar{\nu}_\tau$

8.8 Solar mass model

Summary

- Basic framework is working fine
- SN explosion is a unique astrophysical event:
  - Visible in the sky! (if it is close enough)
  - Astrophysics
    - Supernova explosion mechanism?
    - Heavy elements production?
    - Neutron star or a blackhole?
  - Particle physics
    - Total energy emitted in neutrinos?
    - Partition between flavours?
    - Emission in other particles?
    - Spectrum of neutrinos?
    - Neutrino mixing effects?

It will offer unprecedented opportunities for diverse neutrino detectors around the world to gather critical information about astrophysics and particle physics!

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PRISMA

Thank you for your attention!


Betelgeuse