Neutrino Astrophysics

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- Outline of the talk

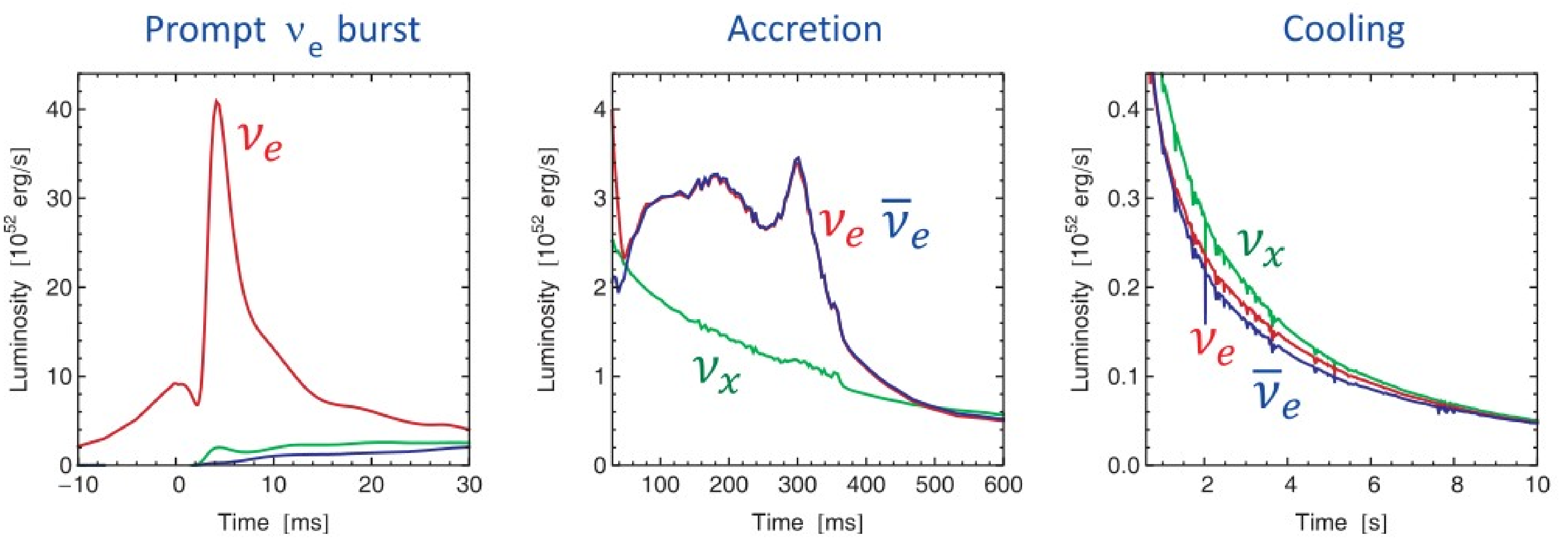
  - Supernova Neutrino Detection
  - Diffuse Supernova Neutrinos
  - High-Energy Neutrinos

Supernova Neutrinos

Supernova Neutrinos

- <u>Supernova Neutrino Emission</u>

  - strong emission of neutrinos from colapsing stars

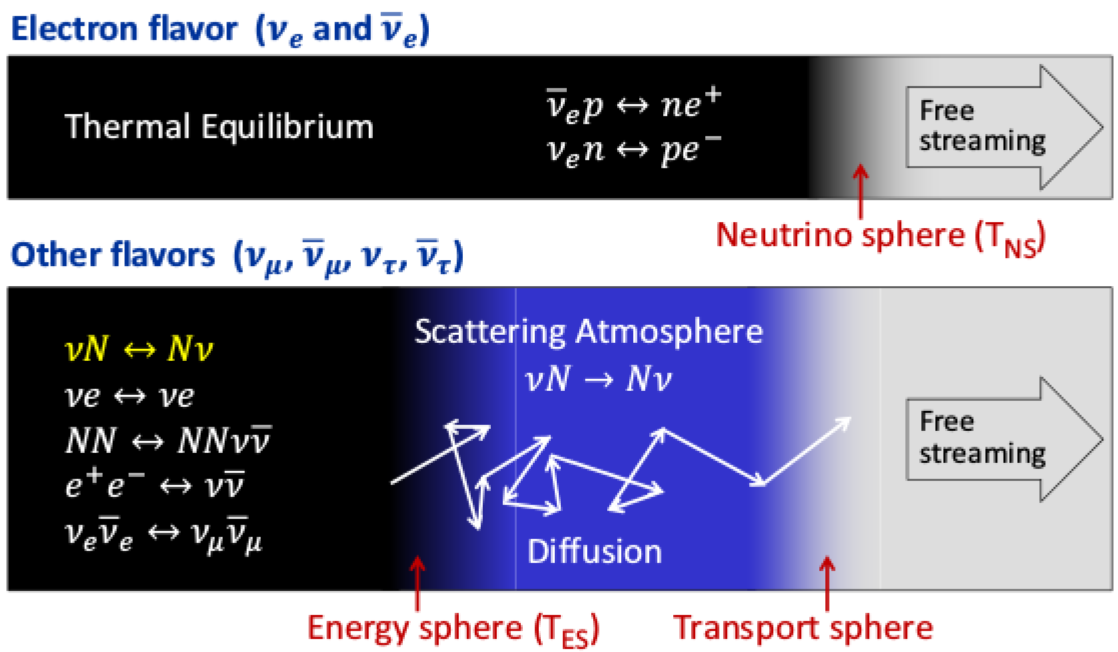


Raffelt, 1201.1637

Supernova Neutrinos

- Supernova Neutrino Emission

  - close to thermal emission, with $\langle E_{\nu_e} \rangle < \langle E_{\bar{\nu}_e} \rangle < \langle E_{\nu_x} \rangle$

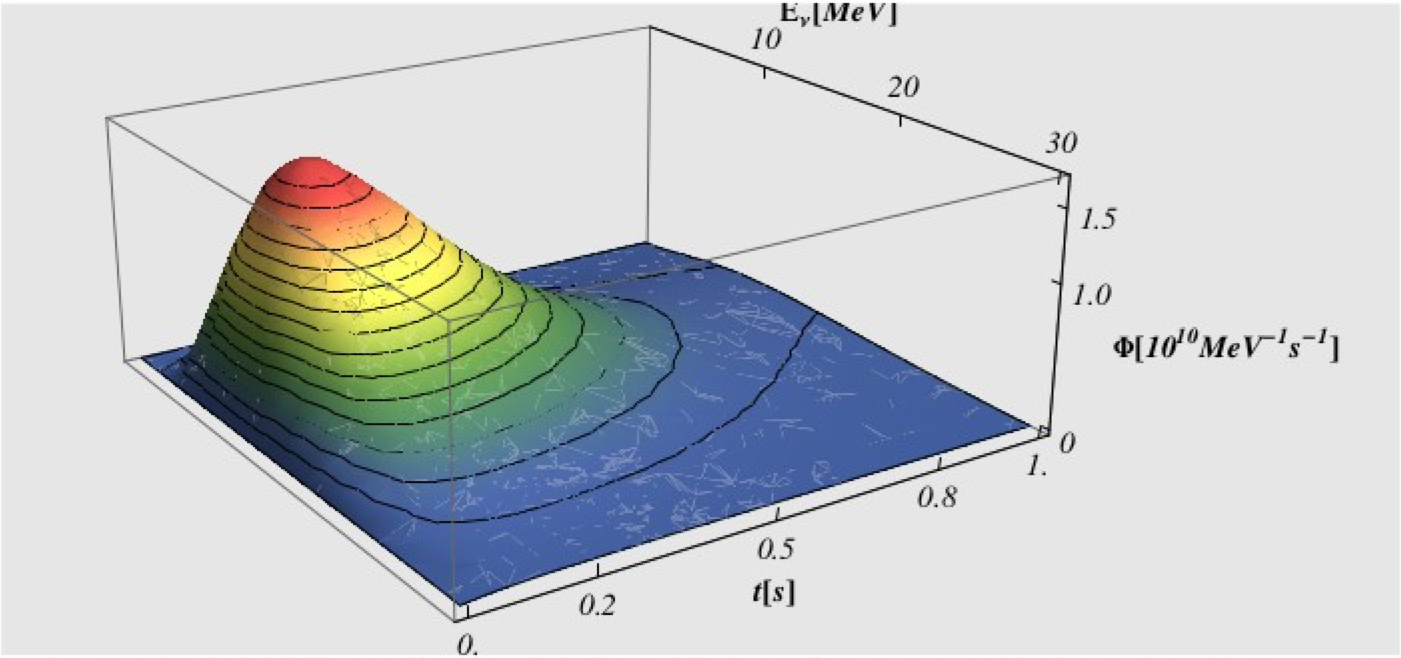


Raffelt, 1201.1637

Supernova Neutrinos

- Supernova Neutrino Emission

  - importance features on time and energy structure!

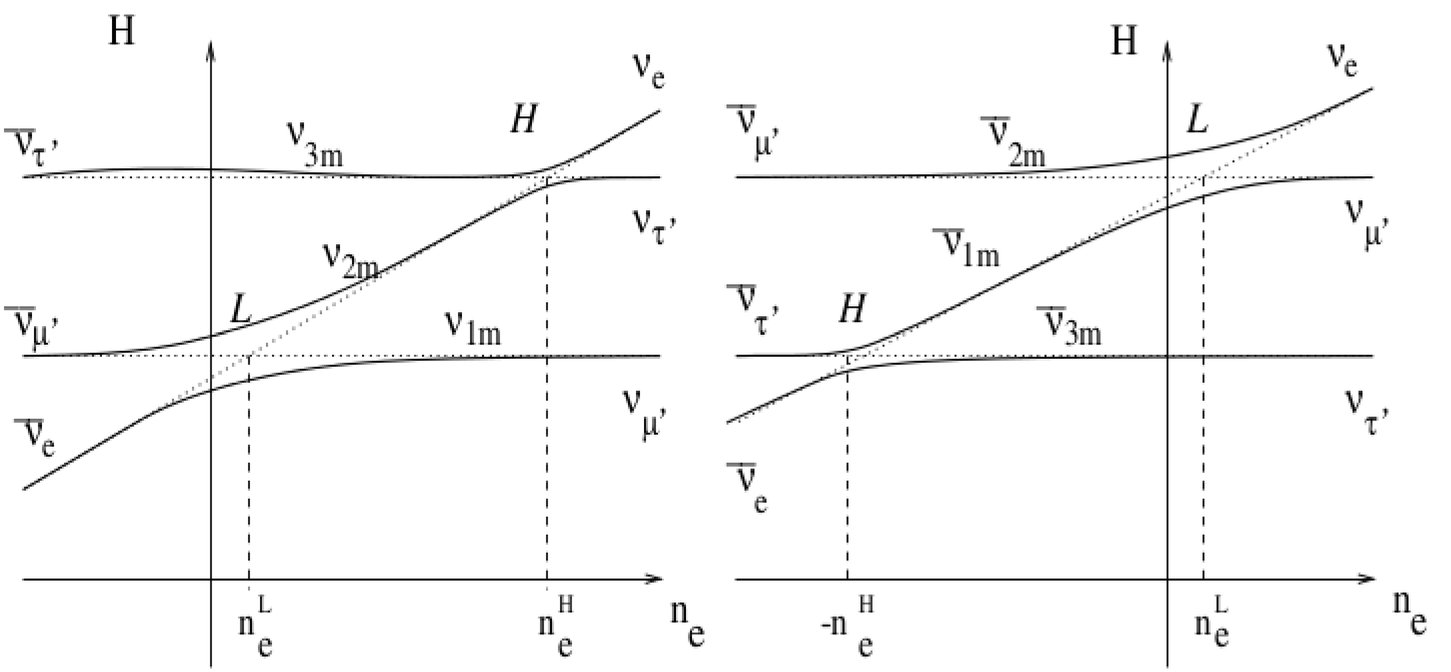


from Vissani's talk, Paris 2011.

Supernova Neutrinos

- <u>Supernova Neutrino Conversion</u>

- like solar neutrinos, supernova neutrinos are produced in a dense medium, in flavour eigenstates that relates to mass eigenstates through proper diagonalization of the Hamiltonian.



normal inverted

Supernova Neutrinos

- Supernova Neutrino Conversion

  - survival probability depends on hierarchy

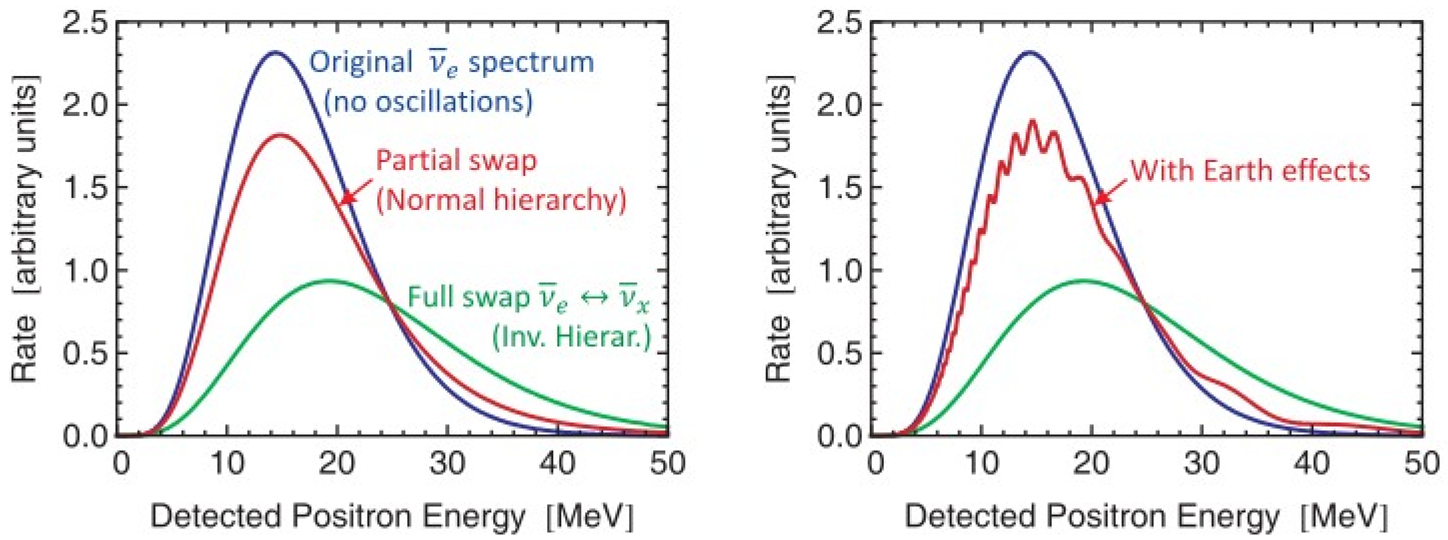
Scenario	Hierarchy	p	$\bar{p}$	Earth effects
A	Normal	0	$\cos^2\theta_{12}$	$\bar{\nu}_e$
B	Inverted	$\sin^2\theta_{12}$	0	ν_e

  - large fraction of electronic anti-neutrinos flux with normal hierarchy.

Supernova Neutrinos

- Supernova Neutrino Conversion

Detection rate:



Supernova Neutrinos

But things are more complicated:

- very dense medium, flavour freeze, neutrino-neutrino interaction

$$\varrho_{\mathbf{p},\mathbf{x}} = \begin{pmatrix} \varrho_{ee} & \varrho_{e\mu} & \varrho_{e\tau} \\ \varrho_{\mu e} & \varrho_{\mu\mu} & \varrho_{\mu\tau} \\ \varrho_{\tau e} & \varrho_{\tau\mu} & \varrho_{\tau\tau} \end{pmatrix}$$

$$\mathbf{v}_{\mathbf{p}} \cdot \nabla_{\mathbf{x}} \varrho_{\mathbf{p},\mathbf{x}} = -i[\Omega^{\mathrm{vac}}_{\mathbf{p}}, \varrho_{\mathbf{p},\mathbf{x}}] - i[\Omega^{\mathrm{ref}}_{\mathbf{p},\mathbf{x}}, \varrho_{\mathbf{p},\mathbf{x}}]$$

$$\mathbf{v}_{\mathbf{p}} \cdot \nabla_{\mathbf{x}} \overline{\varrho}_{\mathbf{p},\mathbf{x}} = +i[\Omega^{\mathrm{vac}}_{\mathbf{p}}, \overline{\varrho}_{\mathbf{p},\mathbf{x}}] - i[\Omega^{\mathrm{ref}}_{\mathbf{p},\mathbf{x}}, \overline{\varrho}_{\mathbf{p},\mathbf{x}}]$$

$$\Omega^{\mathrm{vac}}_{\mathbf{p}} = U \frac{M^2}{2p} U^\dagger$$

$$M^2 = \mathrm{diag}\left(m_1^2, m_2^2, m_3^2\right) = \left(-\frac{\delta m^2}{2}, +\frac{\delta m^2}{2}, \pm\Delta m^2\right)$$

Supernova Neutrinos

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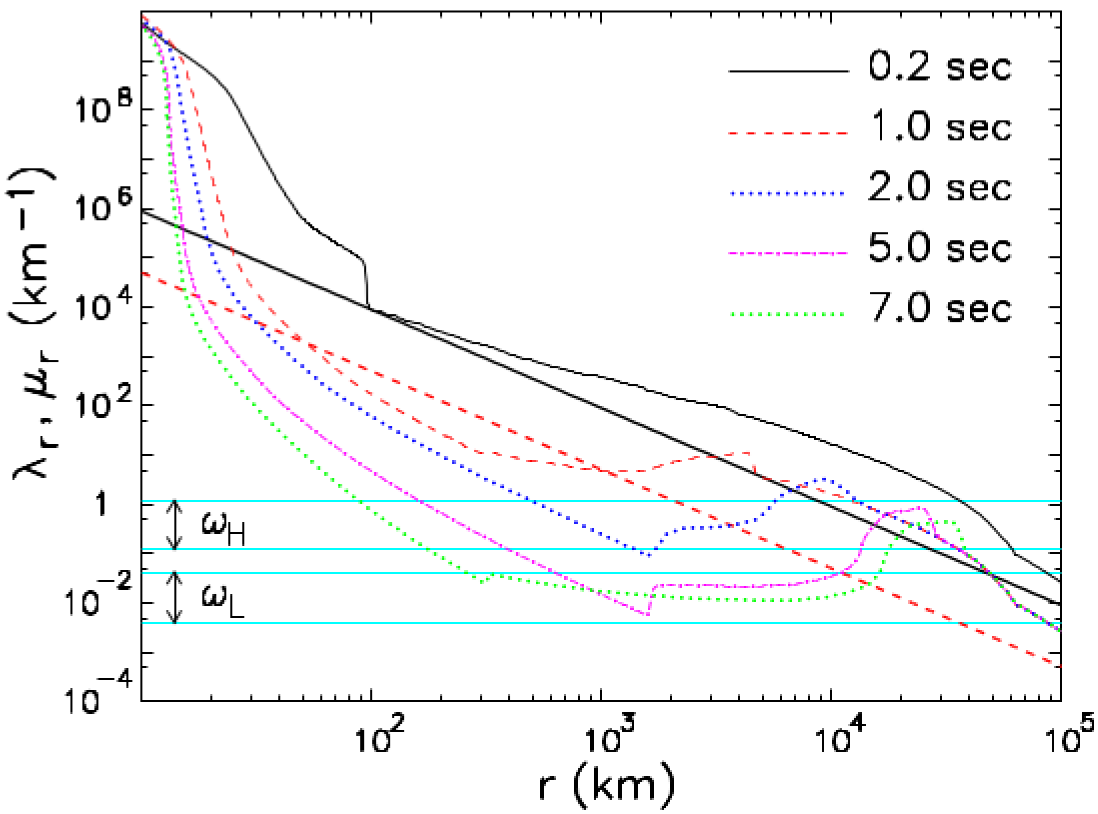

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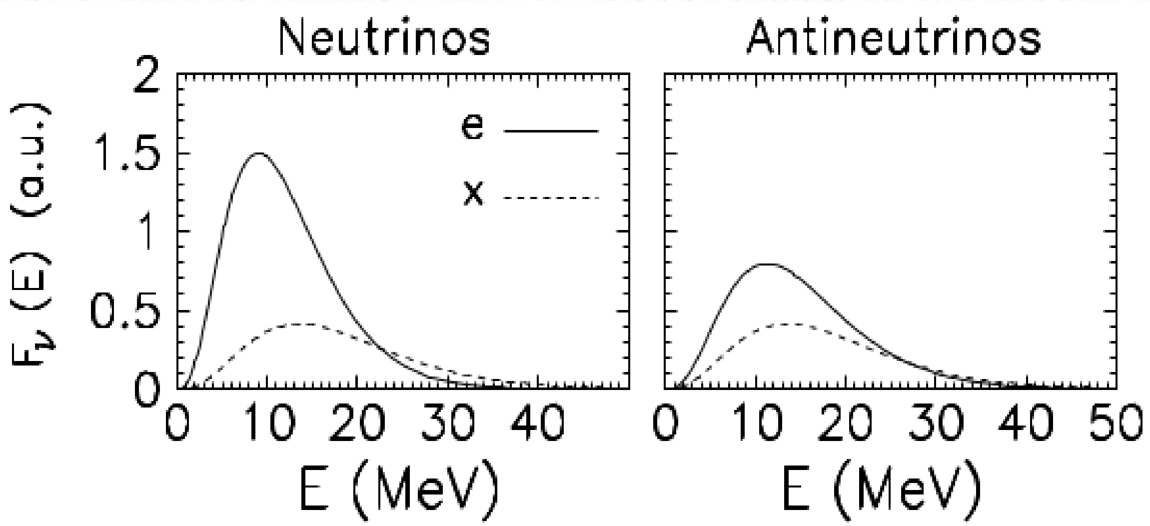

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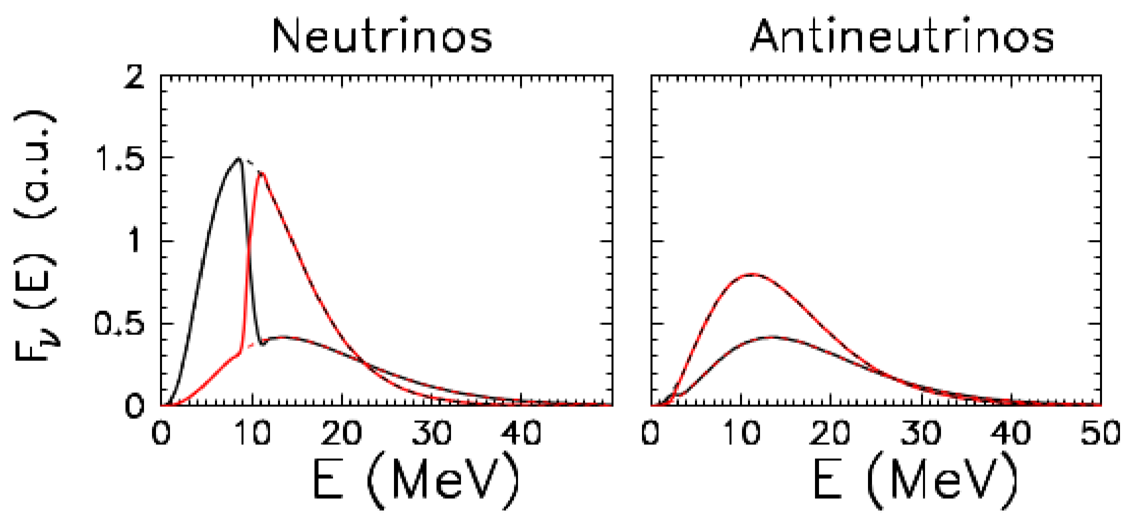
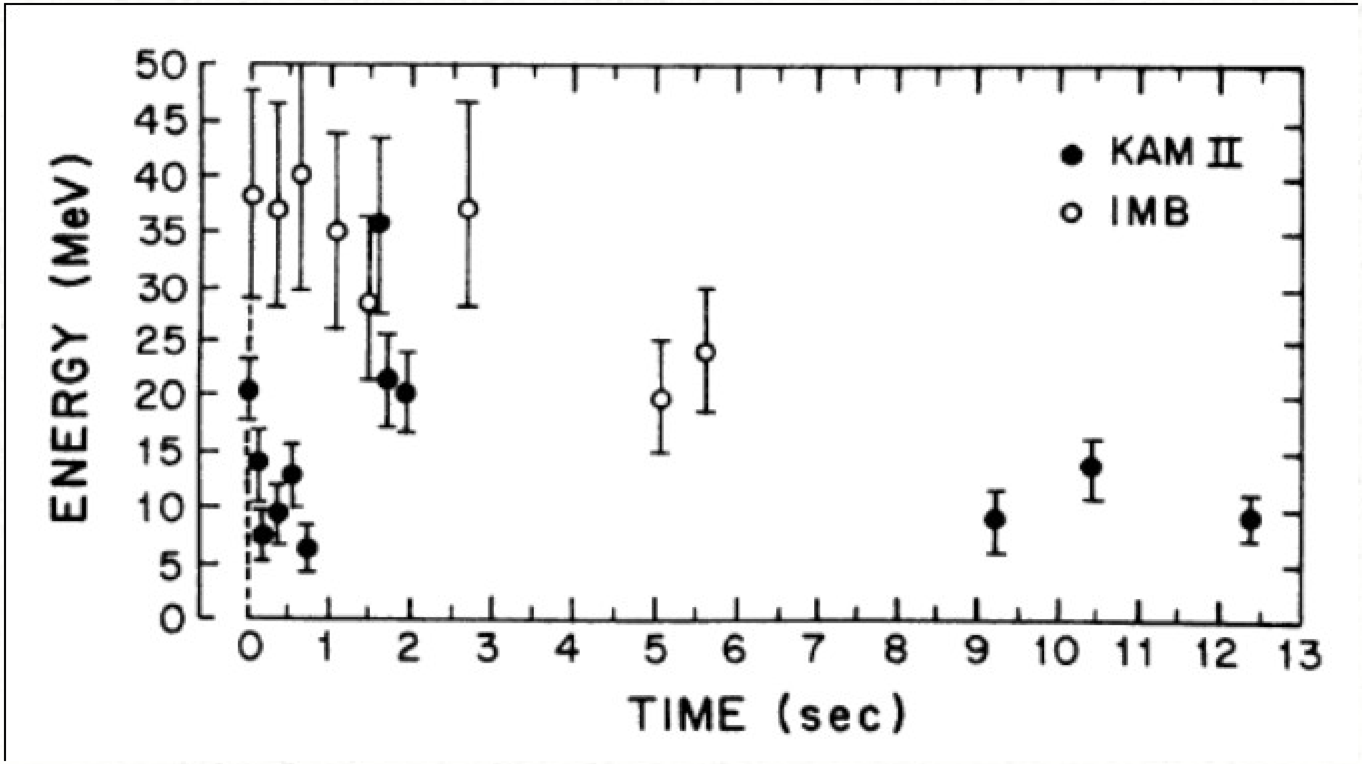


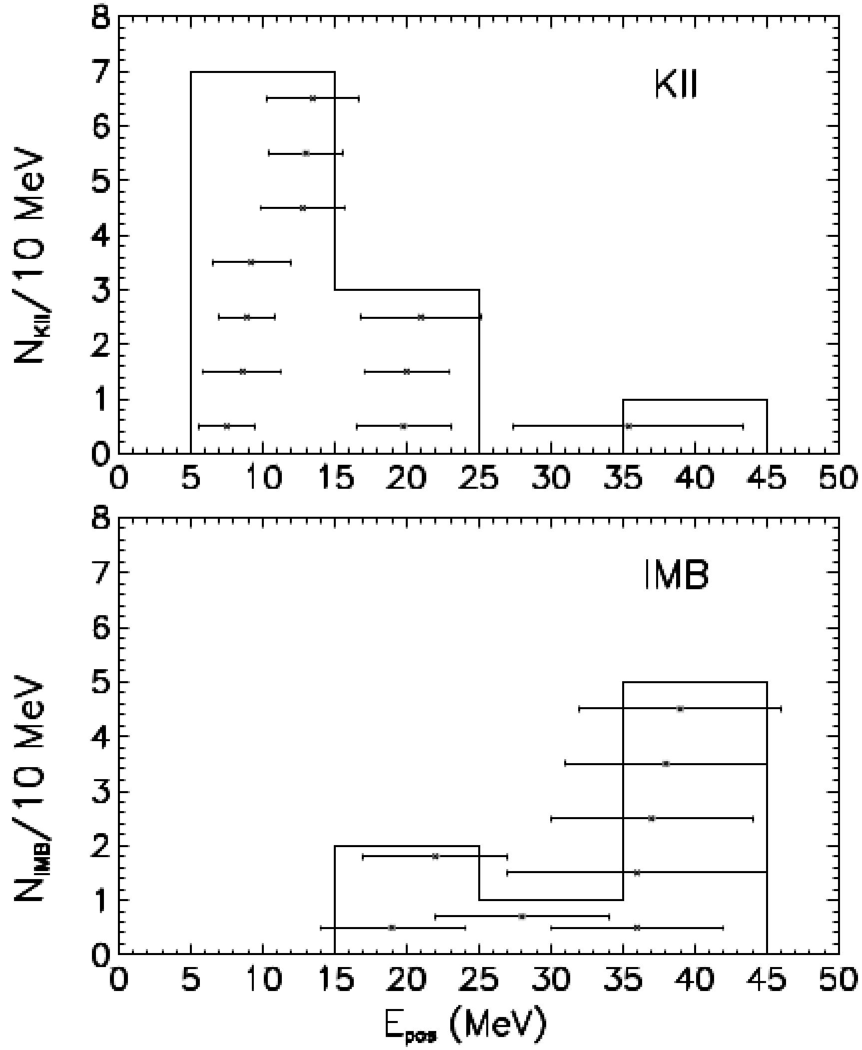
Supernova Neutrinos

SN 1987A: a succesfull case for Supernova Neutrino detection



Supernova Neutrinos

SN 1987A



Supernova Neutrinos

Next Galactic Supernova will provide great statistics, > 1000 articles in the first month, dedicated conferences in nice places and a lot of learning opportunities.

Fortunately, it will happen in our lifetime.

Diffuse Supernova Background DSNB

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- Why waiting for a gallactic SN, if somewhere else in the Universe a SN is exploding every second?

Diffuse Supernova Background DSNB

- Why waiting for a gallactic SN, if somewhere else in the Universe a SN is exploding every second?

$$1/r^2$$

worse then that, we have to account redshift and space expansion!

- But what if we integrate the signal of all neutrinos from SN explosions?

Diffuse Supernova Background DSNB

Related question: **Olbers' paradox.**

Diffuse Supernova Background DSNB

Related question: Olbers' paradox.

Why is the night dark?

$$L(t) = \int_0^\infty \frac{L_s(t)}{r^2} 4\pi r^2 dr \to \infty$$

We should have a bright sky!

Diffuse Supernova Background DSNB

Related question: Olbers' paradox.

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- Universe is expanding, so photons redshift.

Diffuse Supernova Background DSNB

- Back to DSNB:

$$\Phi_{(}\nu_\alpha) = \frac{c}{H_0}\int_{M_0}^{M_{max}}\int_0^{z_{max}} dz \frac{\dot{\rho}_{SN}(z,M)F_{\nu_\alpha}(E(1+z),M)}{\sqrt{\Omega_M(1+z)^3+\Omega_\Lambda}}$$

Diffuse Supernova Background DSNB

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► - SN explosion rate

Diffuse Supernova Background DSNB

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- SN explosion rate
- neutrino energy redshifted

Diffuse Supernova Background DSNB

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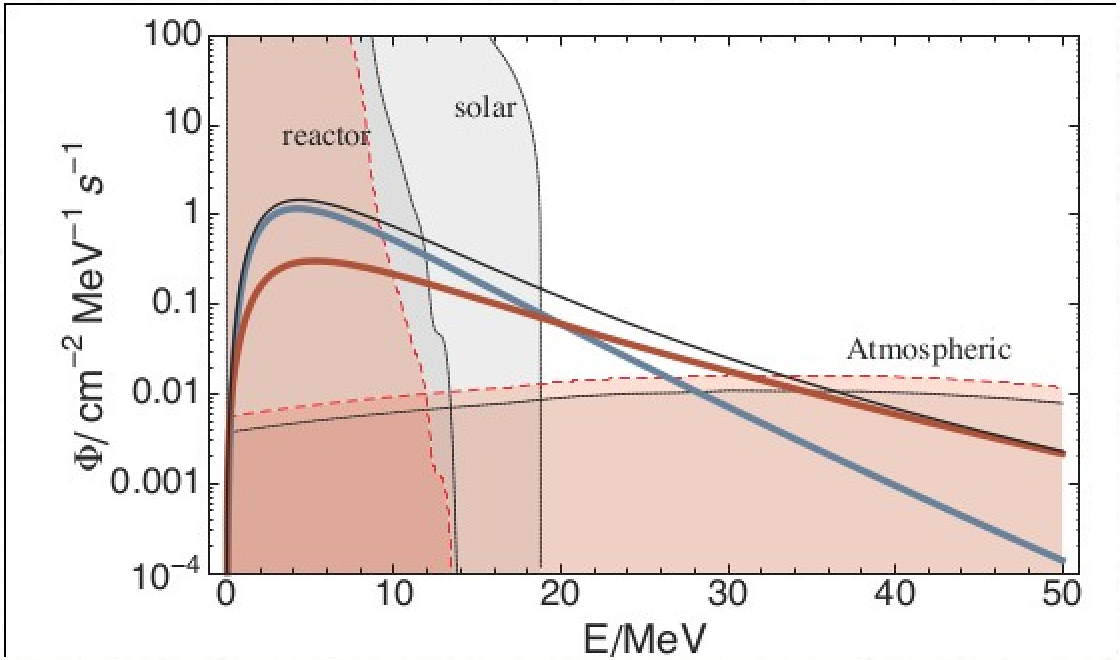
- SN explosion rate
- neutrino energy redshifted
- universe expansion

Diffuse Supernova Background DSNB

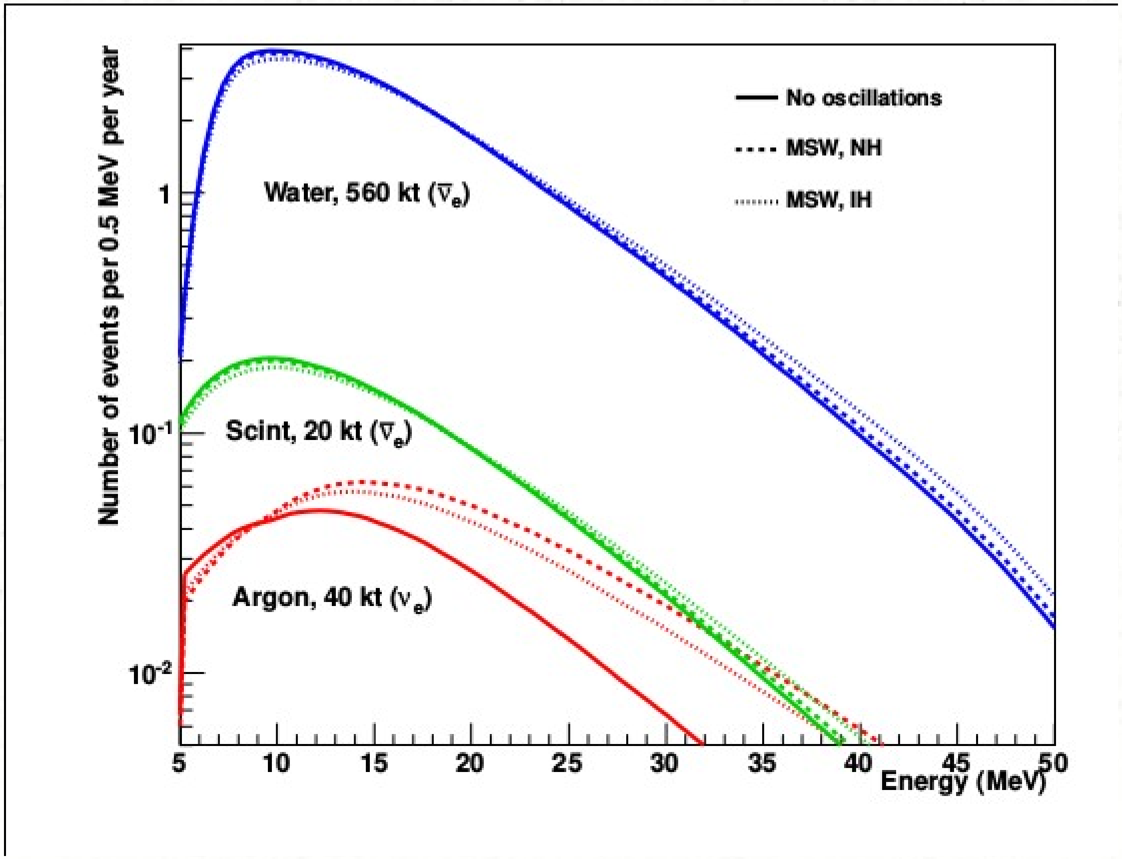
- Small window between solar and atmospheric neutrinos to search for DSNB.



Lunardini et al., ArXiV:1012.1274

Diffuse Supernova Background DSNB

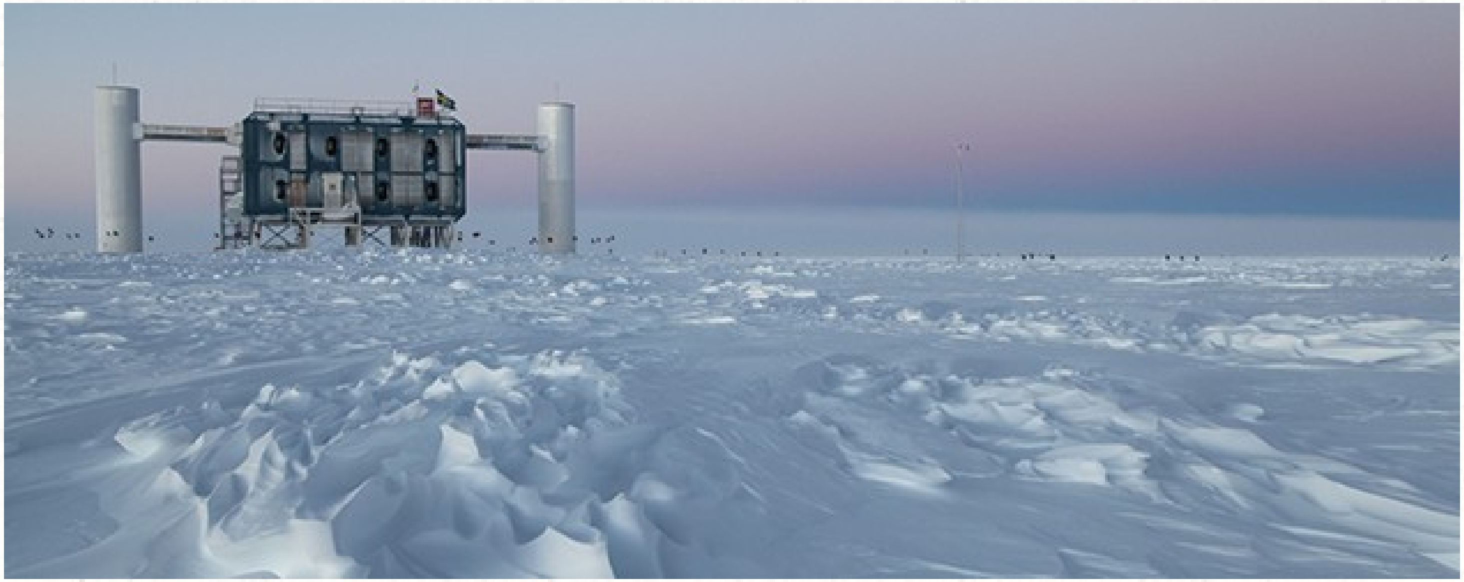
- but with a chalenging event rate...



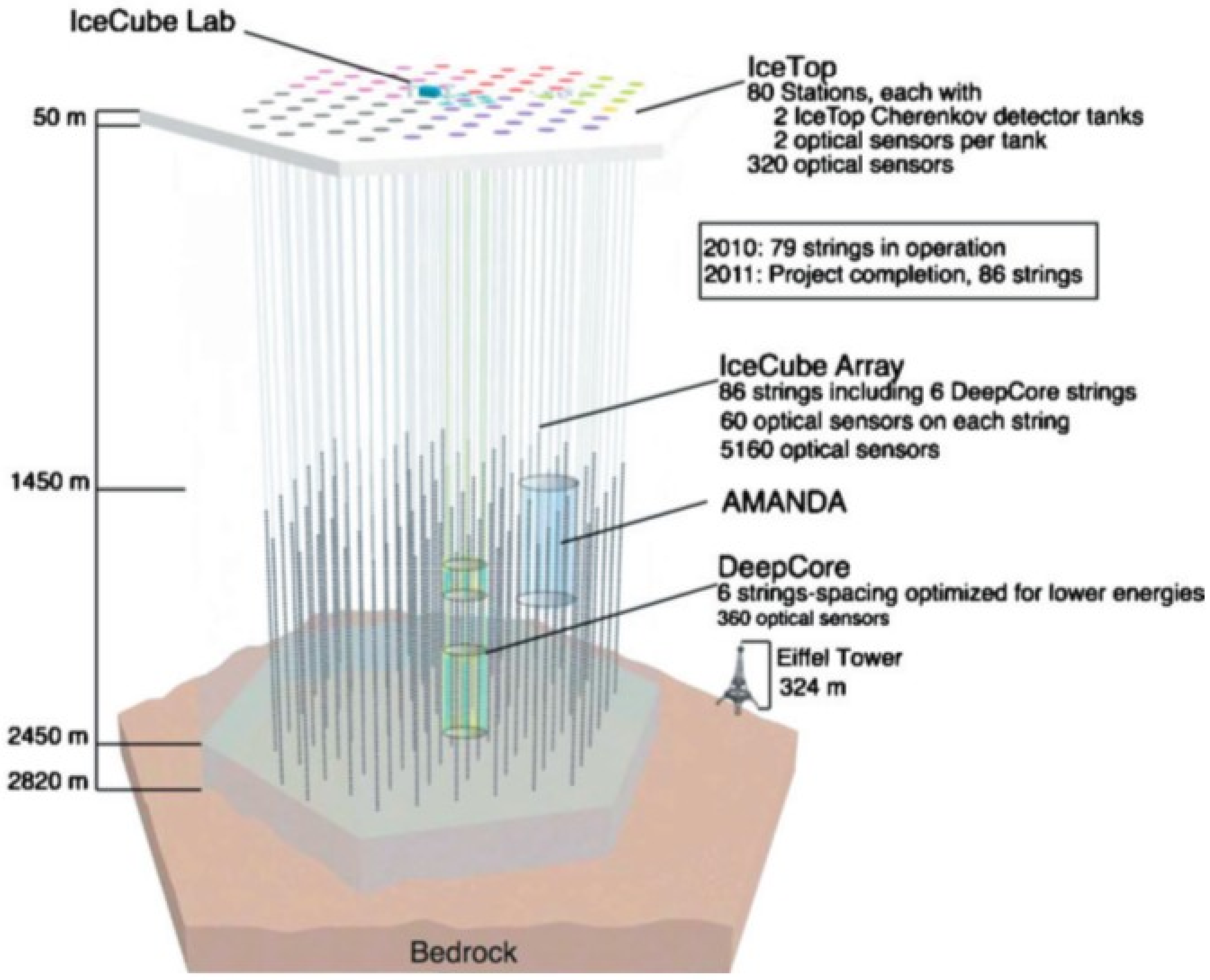
From ArXiV:1508.00785

Icecube

Icecube



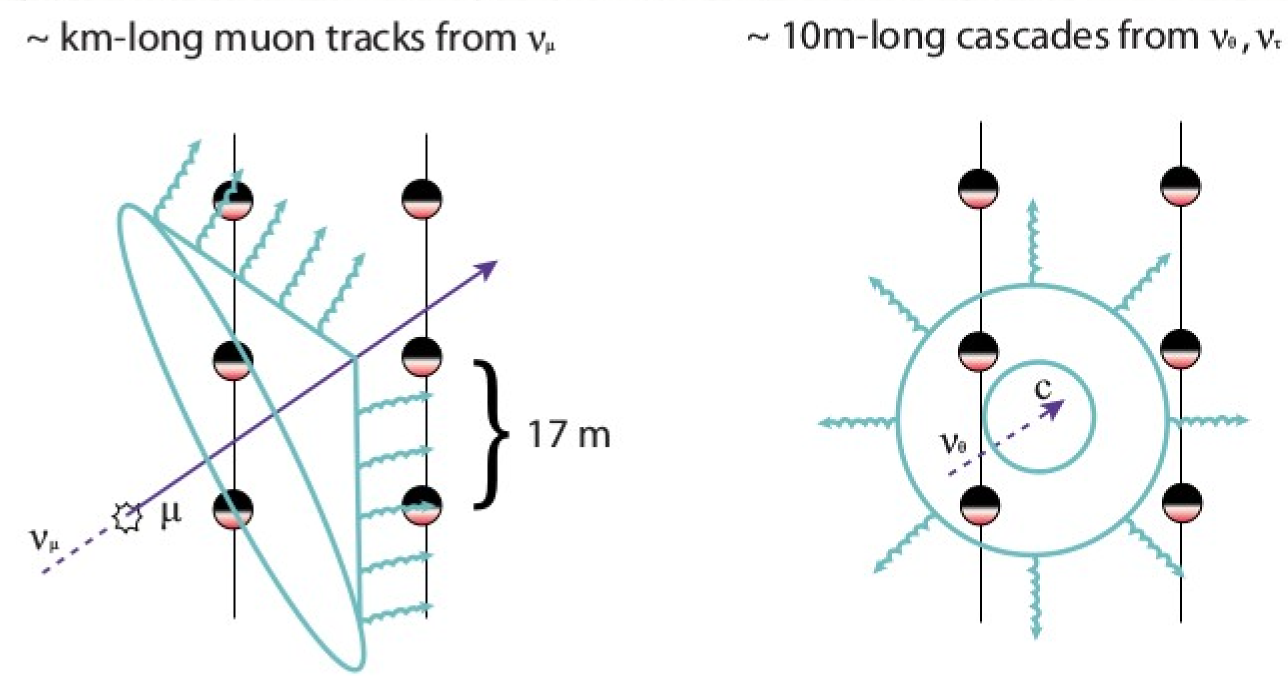
Icecube



IceCube Lab
IceTop
80 Stations, each with
2 IceTop Cherenkov detector tanks
2 optical sensors per tank
320 optical sensors
2010: 79 strings in operation
2011: Project completion, 86 strings
IceCube Array
86 strings including 6 DeepCore strings
60 optical sensors on each string
5160 optical sensors
AMANDA
DeepCore
6 strings-spacing optimized for lower energies
360 optical sensors
Eiffel Tower
324 m
50 m
1450 m
2450 m
2820 m
Bedrock

Icecube

- detect cherenkov light from charged particles.
- incoming neutrino produces the associated charged lepton through charged current.
    - Muon neutrinos leave a track + a hadronic shower
    - Electron and (low energy) tau neutrinos produce only a shower
- neutral currents produces only the hadronic shower.



Icecube

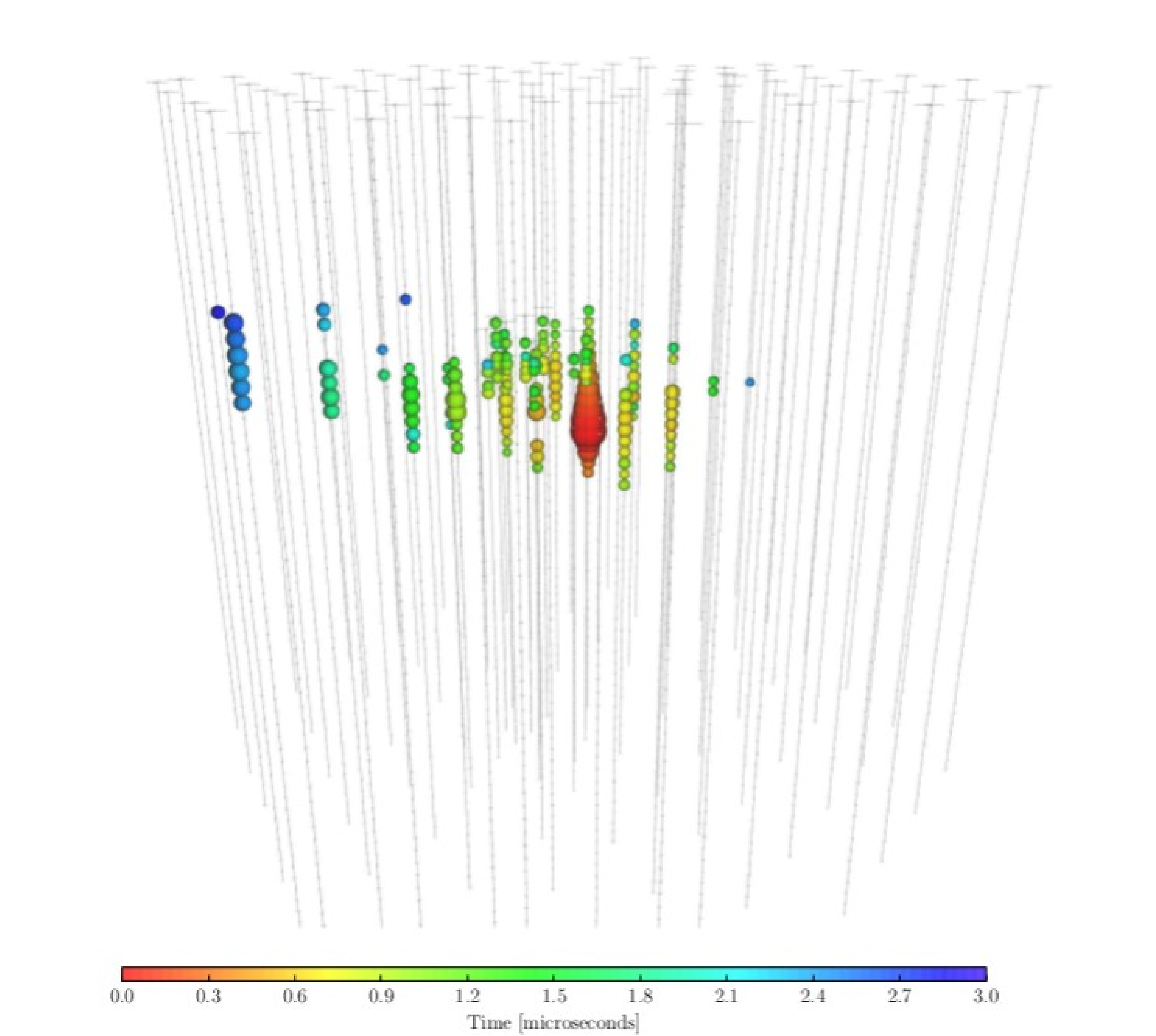
- events with muon tracks has an excelent angular resolution < 1º.

- But events are not contained, so energy leaks out of the detector, making it difficult to find original neutrino energy.
- Huge atmospheric background, difficult (but not impossible) to distinguish non-atmospheric neutrinos.
- At such high energies, neutrino absortion on Earth is relevant, so more sensible to downgoing neutrinos: south hemisphere

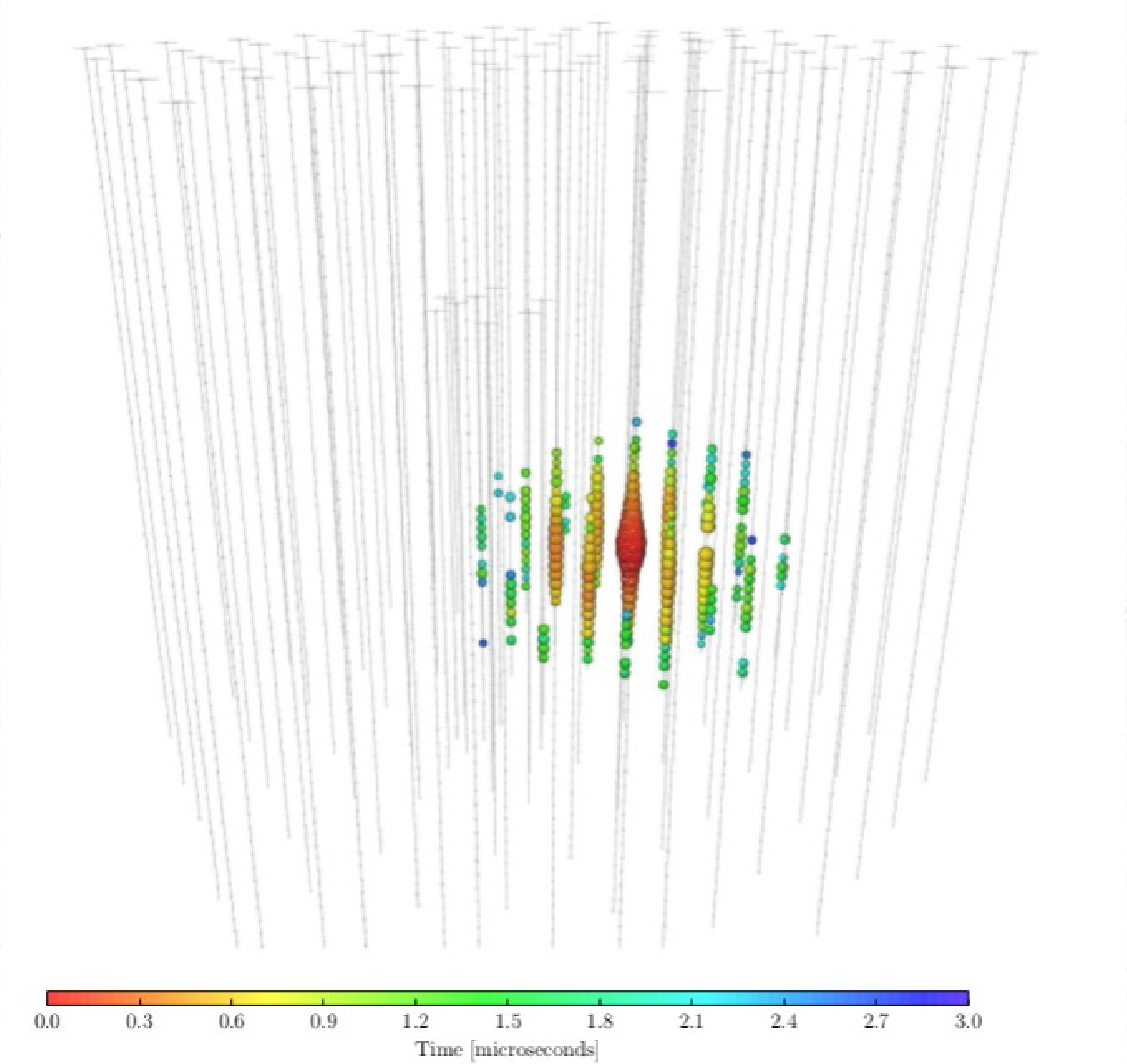
- Shower events can do a better job in reconstructing neutrino energy, but with poor direccionality: < 30º

- Sensible to electronic and tauonic neutrinos, not present in atmospheric neutrino flux for high energies → cleaner background

Track event

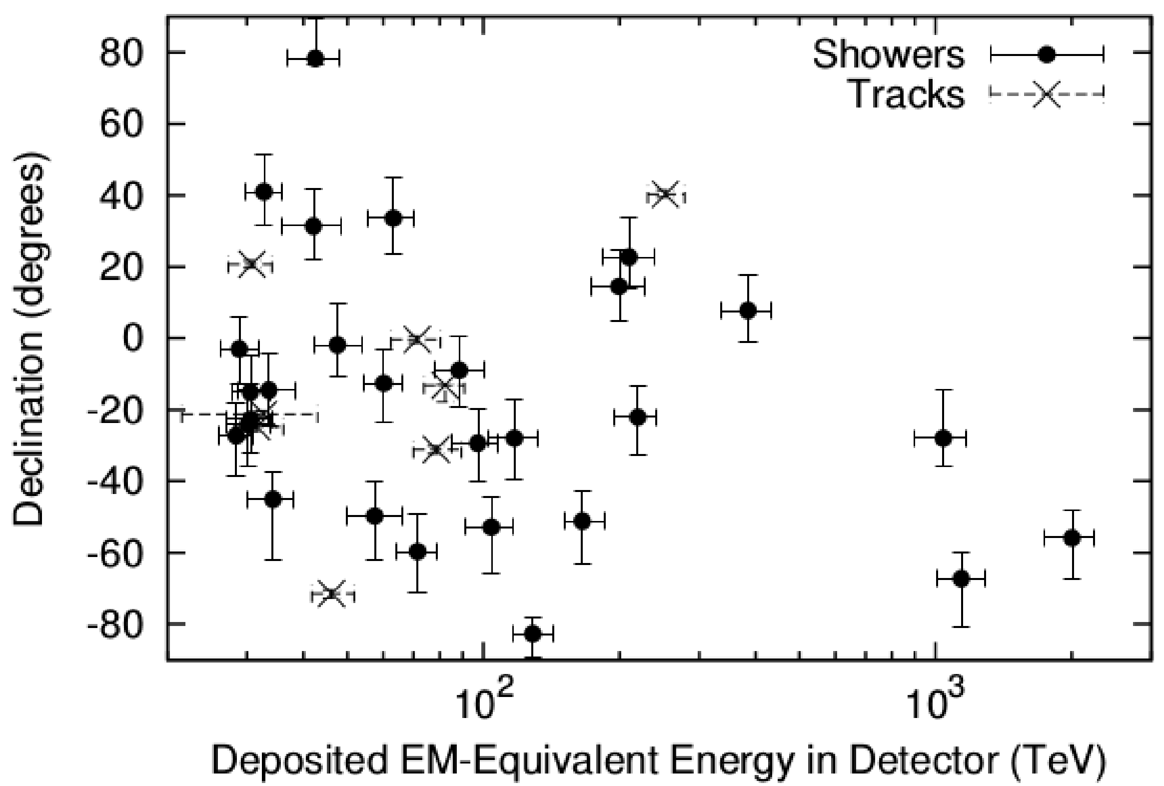


Shower event



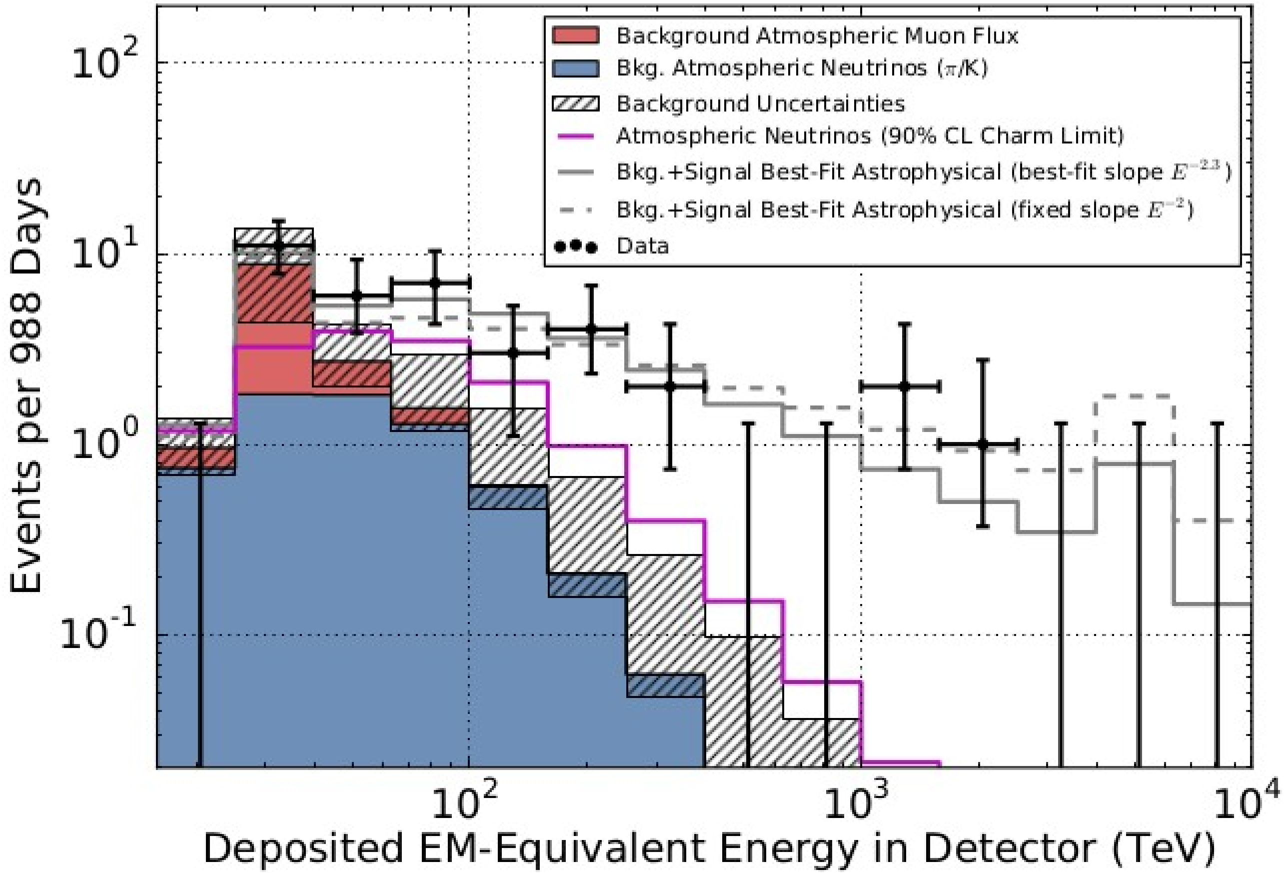
Icecube, track x showers

- Selection Criteria: only events that originated inside the detector
- 37 events from 30 to 2000 TeV
- only atmospheric excluded at 5.7 sigma



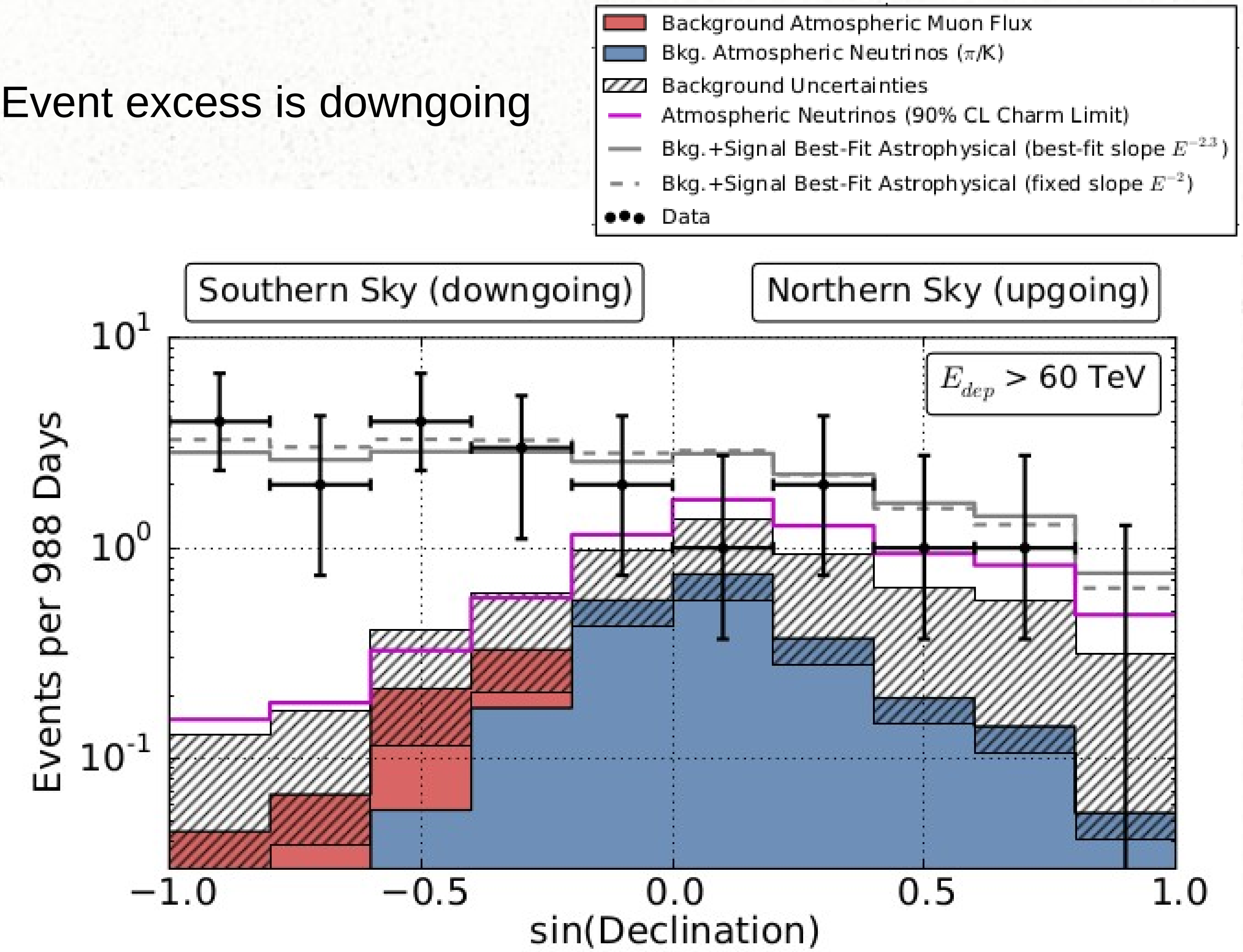
Icecube, track x showers

Event excess in high-energy.



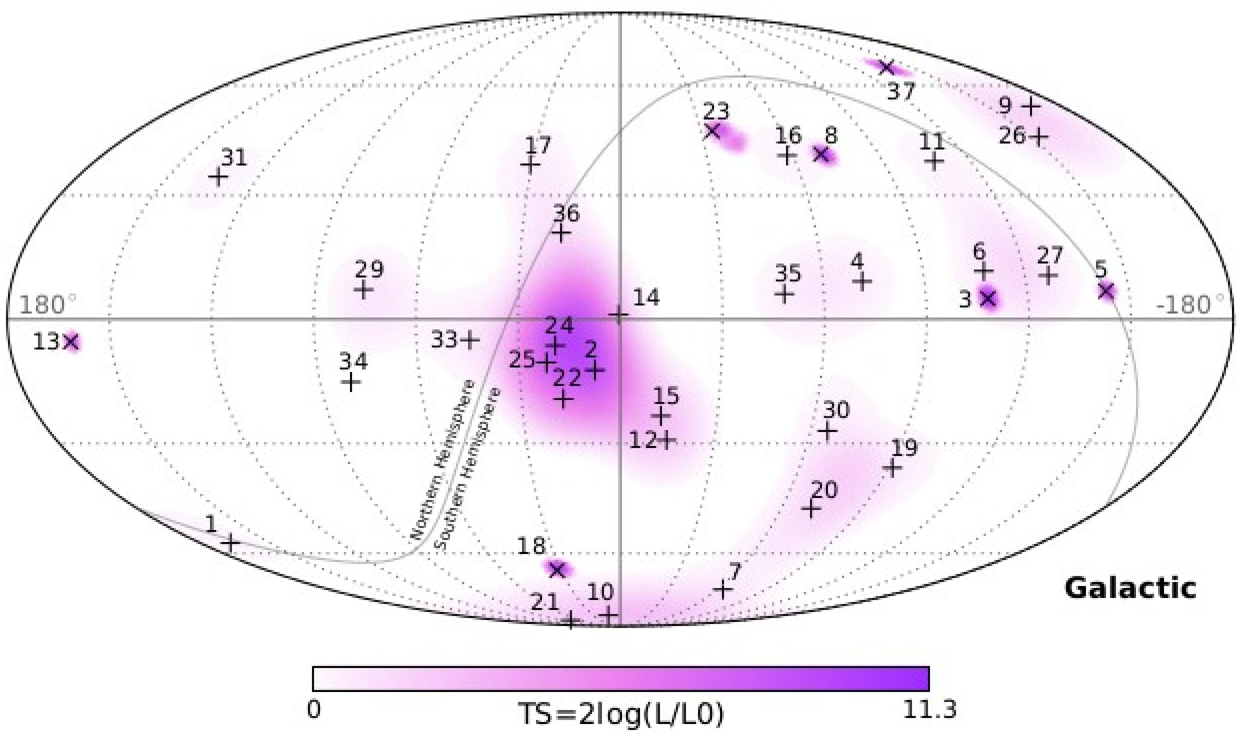
Icecube, track x showers

Event excess is downgoing



Icecube, track x showers

No directionality



Flavor composition

Flavor composition

Due to large mixing angles, flavour distribution in initial neutrino fluxes changes with neutrino evolution.

$$(\nu_e : \nu_\mu : \nu_\tau) = (2 : 1 : 0) \xrightarrow[\text{evolution}]{\text{neutrino}} (0.93 : 1.05 : 1.02)$$

$$(\nu_e : \nu_\mu : \nu_\tau) = (1 - 0 : 0 - 1 : 0)$$

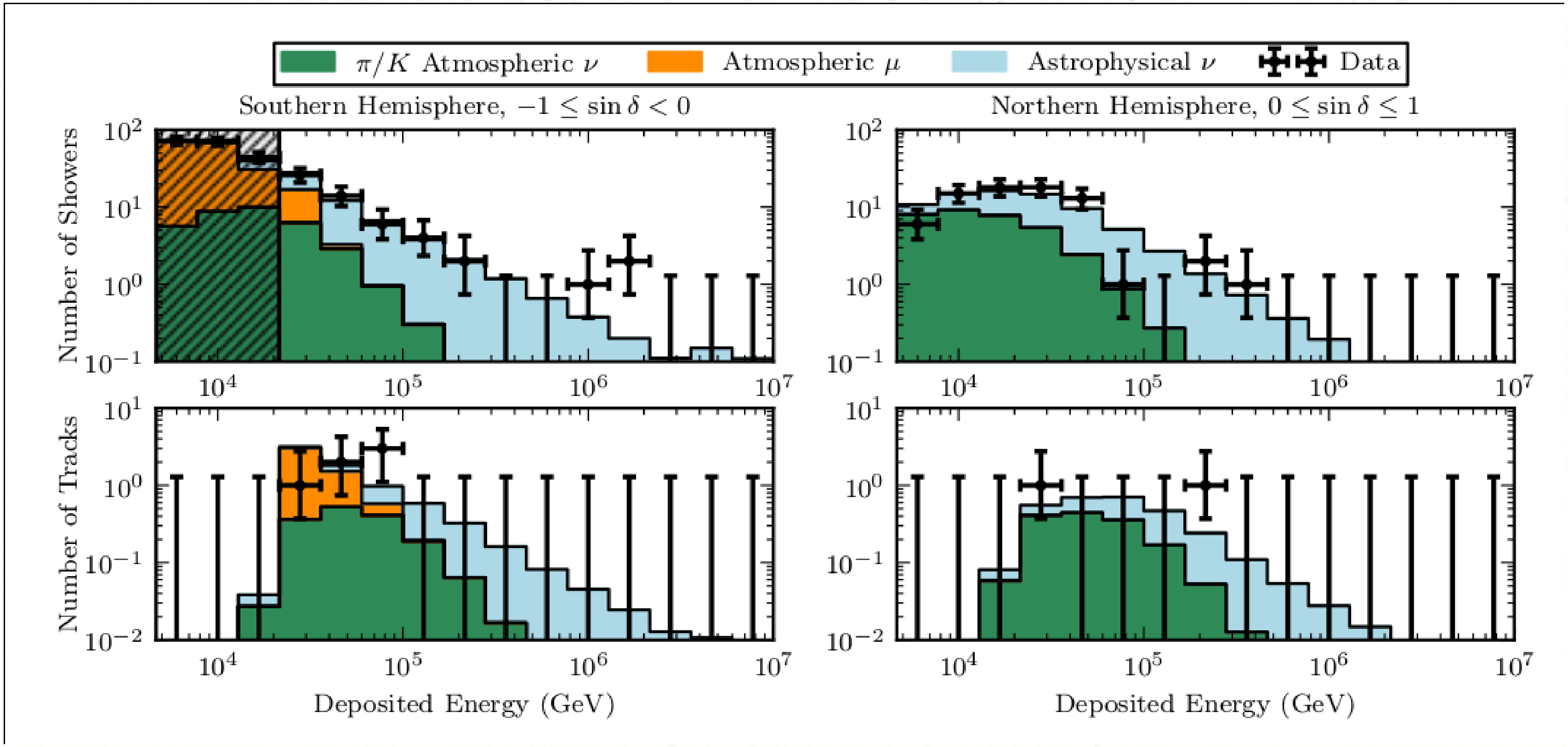
$$\xrightarrow[\text{evolution}]{\text{neutrino}} \begin{cases} (0.6 : 1.3 : 1.1) \\ (1.6 : 0.6 : 0.8) \end{cases}$$

It is reasonable to expect something close to (1:1:1) on Earth.

Flavor composition

Physical quantities to be considered:

- event topology
- deposited energy and arrival direction

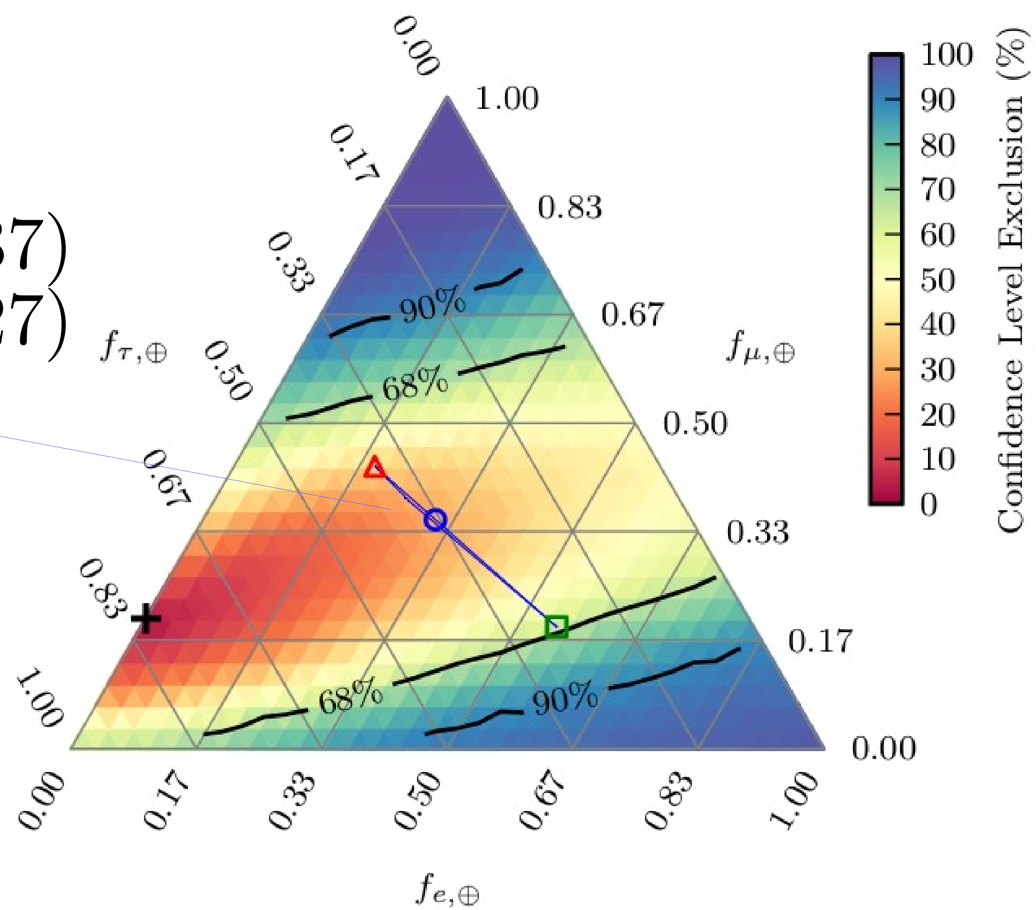


Flavor composition

Results (arxiv:1502.03376)

$$(0.2 : 0.43 : 0.37)$$
$$(0.53 : 0.2 : 0.27)$$

Compatible with equipartition



ν_μ from northern hemisphere

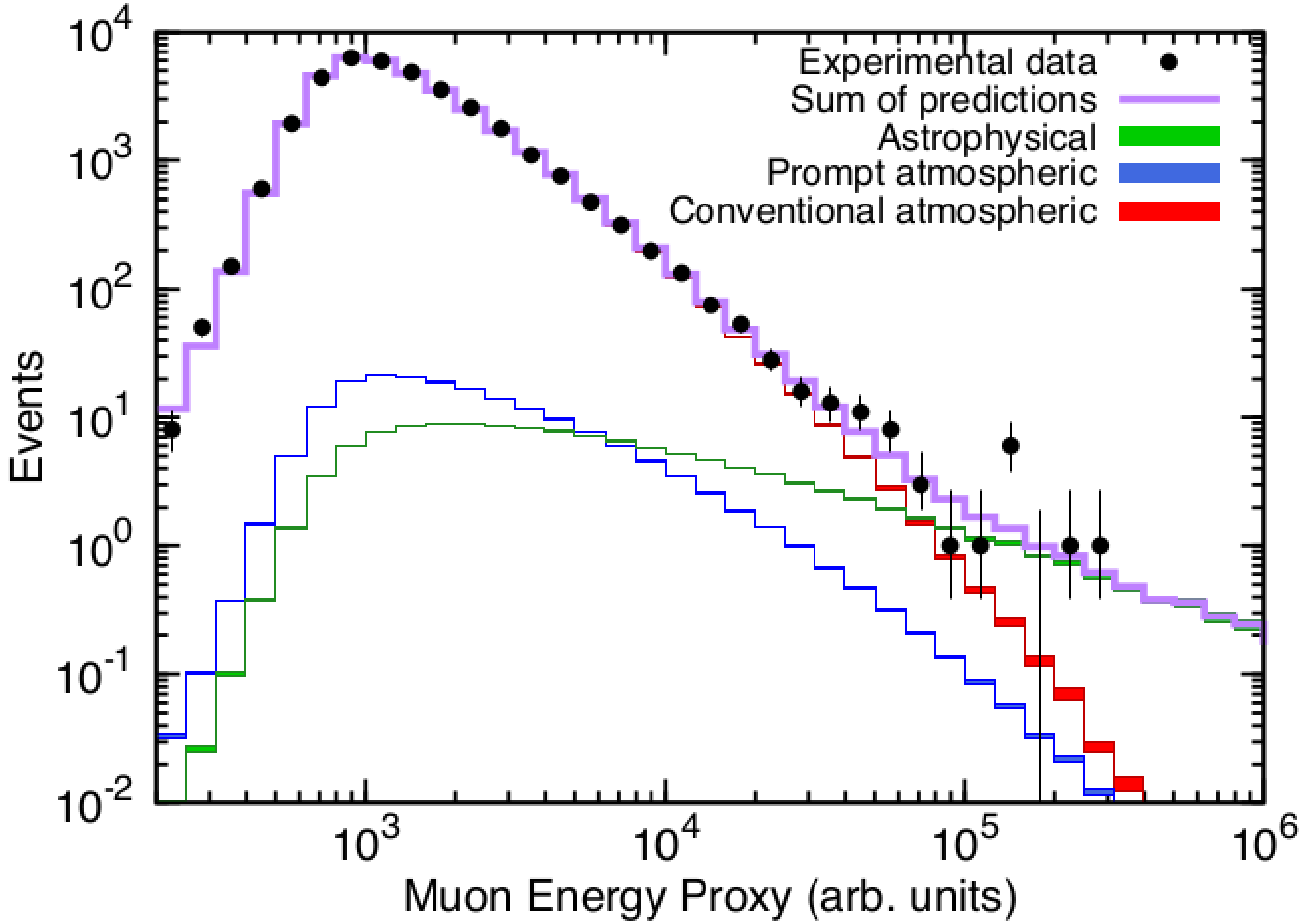
- Recent analysis relax the requirement that the event begins inside the detector → ***sensible only to ν_μ***.

- Selection of muons that could not have survived all the way to the detector → must have been created through a neutrino interactions halfway.

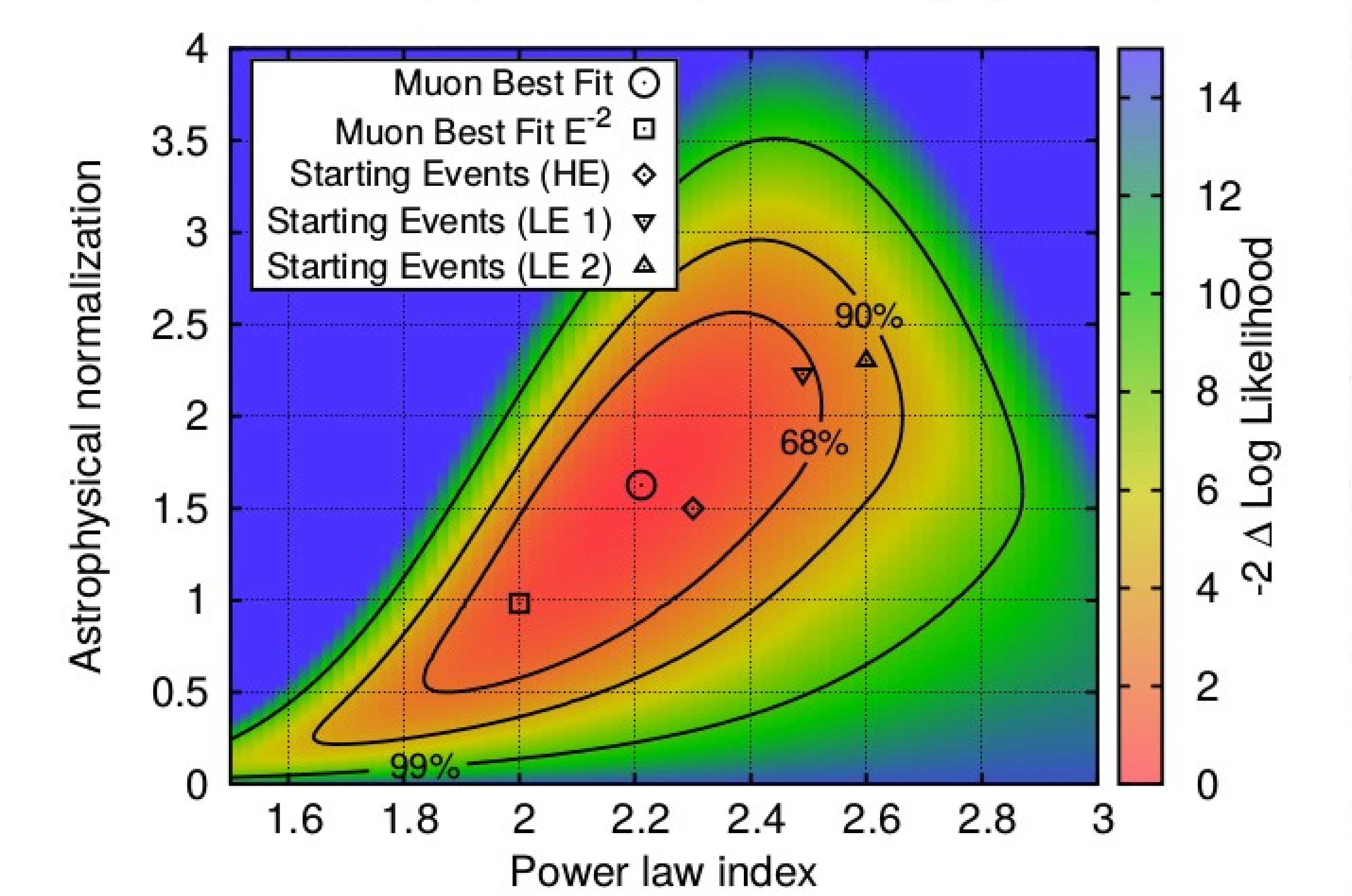
- Zenith angle > 85 degrees.

- Energy loss before entering the detector.

ν_μ from northern hemisphere



ν_μ from northern hemisphere



ν_μ from northern hemisphere

- ***"While this work represents the first strong evidence for an astrophysical numu flux in Northern Hemisphere, the sources producing these neutrinos remain unknown."***

- starting events:

$$\phi = (9.5 \pm 3) \times 10^{-19}\,\mathrm{GeV\,cm^{-2}\,sr^{-1}s^{-1}}$$

- "northern hemisphere" events:

$$\phi = (9.9^{+3.9}_{-3.4}) \times 10^{-19}\,\mathrm{GeV\,cm^{-2}\,sr^{-1}s^{-1}}$$

- complete analysis is sensible to different flavours, indicating a (1:1:1) flavour distribution

- compatible with some models, incompatible with others.

Final Conclusions

- other lectures: rich phenomenology involving neutrinos theory, production, evolution and detection.

- these lectures:

- which science can we do if we have no control on **neutrino production**

  Neutrino Astrophysics

- Which science can we do if we can't have a direct **neutrino detection**

  Neutrino Cosmology

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Thank you!