Earth Matter Effect on SN Neutrinos
in large-volume detectors

based on arXiv:1207.5049

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During the last ten years the Earth Matter Effect (EME) on the observed spectrum of SN $\nu$ has been considered as a guaranteed signature to determine the $\nu$ mass hierarchy.

This is actually the case for large differences among the fluxes of the different $\nu$ species.

According to the state of the art of SN simulations these differences are much smaller than it was thought ten years ago.

We reevaluate the EME and the chances for next-generation underground detectors of observing it.
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**Supernova Neutrinos**

**SN Explosion**  
8 + $M_{\odot}$

Core collapse SN: terminal phase of a massive star.  
Shock wave driven explosion ejecting the outer mantle of the star.

**Energy Scale**  
$\sim 10^{53}$ erg

99% of the released energy ($\sim 10^{53}$ erg):  
$\sim O(10 \text{ MeV})$ neutrinos.

**$\nu$ Flux**  
$\sim 10^{57}$

$\sim 10^{57}\nu$ are emitted during a SN explosion.

**Time Scale**  
10 s

Neutrino emission lasts $\sim 10$ s.

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*SN 1604, the first observed galactic SN*  
-Kepler, 1604
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Three Phases of $\nu$ Emission

10. 8 $M_{\text{sun}}$ progenitor mass
(spherically symmetric with Boltzmann $\nu$ transport)

**Neutronization burst**
- Shock breakout
- De-leptonization of outer core layers

**Accretion**
- Shock stalls ~ 150 km
- $\nu$ powered by infalling matter

**Cooling**
- Cooling on $\nu$ diffusion time scale

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Earth Matter Effect on SN Neutrinos
Large Detectors for Supernova Neutrinos

- MiniBooNE (200)
- LVD (400)
- Borexino (80)
- Super-Kamiokande (10^4)
- KamLAND (330)

In brackets events for a “fiducial SN” at distance 10 kpc

IceCube (10^6)
Next-generation large-volume detectors might open a new era in SN neutrino detection:

**MEMPHYS**
400 kton water Cherenkov detector ($\bar{\nu}$ flux)

**LENA**
50 kton scintillator ($\bar{\nu}$ flux)

**GLACIER**
100 kton Liquid Ar TPC ($\nu$ flux)
Global 3ν Oscillation Analysis

e.g. Fogli et al. 2012

Earth Matter Effect on SN Neutrinos

\begin{align*}
\delta m^2 / 10^{-5} \text{ eV}^2 & \quad \Delta m^2 / 10^{-3} \text{ eV}^2 & \quad \delta / \pi \\
\sin^2 \theta_{12} & \quad \sin^2 \theta_{23} & \quad \sin^2 \theta_{13}
\end{align*}
Earth Matter Effect

Neutrino Oscillations in Earth

Modulations in the SN neutrino energy spectra.

Measurement of $\theta_{13}$

$\theta_{13} \sim 8^\circ$ large

SN accretion Phase
Chakraborty et al. 2011

Only MSW matter effects.
No collective

Only one possible scenario compatible with a detection of the EME:

Normal Hierarchy
The effect appears in the spectrum of antineutrinos.

Inverted Hierarchy
The effect appears in the spectrum of neutrinos.
Earth Matter Effect

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Earth Matter Effect

### Normal Hierarchy

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

### Inverted Hierarchy

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

#### Detectors

- **Water Cherenkov** (MEMPHYS)
- **Liquid scintillators** (LENA)

#### Detectors

- **LAr time projection chambers** (GLACIER)

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Earth Matter Effect

Modulated (Anti)Neutrino Flux

\[ F_{\tilde{e}}^D = \sin^2 \theta_{12} F_{\tilde{x}}^0 + \cos^2 \theta_{12} F_{\tilde{e}}^0 + \Delta F_{\tilde{e}}^0 \tilde{A}_\oplus \sin^2 (12.5 \Delta m^2_\oplus L/E) \]

Flux Difference

\[ \Delta F^0(E) = F_{\tilde{e}}^0(E) - F_{\tilde{x}}^0(E) \]

“Inverse-Energy”

\[ y = \frac{12.5}{E} \]

Fourier Transform (FT)

\[ k_\oplus = 2\Delta m^2_\oplus L \]

do not depend on the incoming \( \nu \) spectrum and has to contribute to the FT of the observed spectrum.
**Earth Matter Effect**

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Trend of SN $\nu$ Average Energy

$\nu_x \approx \bar{\nu}_x$

$\bar{\nu}_e$

$\nu_e$

$\langle E_{\bar{\nu}_e} \rangle - \langle E_{\nu_e} \rangle$

$0.0$ $0.5$ $1.0$ $1.5$ $2.0$ $2.5$ $3.0$ $3.5$ $4.0$

$k$

$20$ $40$ $60$ $80$ $100$ $120$
The EME is visible in the energy spectrum.

The EME IS visible in the power spectrum of the “inverse-energy” spectrum.

The EME MAY BE visible in the power spectrum of the “inverse-energy” spectrum.
Livermore 1997 ("Traditional" Simulation)

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## Detector Characteristics

### Water Cherenkov

\[ \bar{\nu}_e + p \rightarrow n + e^+ \]

- e.g.: MEMPHYS
- mass: 400 kton
- energy resolution:
  \[ \frac{\Delta}{\text{MeV}} = 0.47 \sqrt{\frac{E_e}{\text{MeV}}} \]

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- # of events:
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### Liquid scintillator

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### LAr TPC

\[ \nu_e + ^{40}\text{Ar} \rightarrow ^{40}\text{K}^* + e^- \]

- e.g.: GLACIER
- mass: 100 kton
- energy resolution:
  \[ \frac{\Delta}{\text{MeV}} = 0.11 \sqrt{\frac{E_e}{\text{MeV}}} + 0.02 \frac{E_e}{\text{MeV}} \]

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- e.g.: MEMPHYS
- mass: 400 kton
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![Energy resolution plot](image1.png)

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**Liquid Scintillator**

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- **Reaction:** $\bar{\nu}_e + p \rightarrow n + e^+$
- **Example:** MEMPHYS
- **Mass:** 400 kton
- **Energy Resolution:**
  \[
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- **Energy Resolution Distribution**
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- **e.g.:** GLACIER
- **mass:** 100 kton
- **energy resolution:**
  \[ \frac{\Delta}{\text{MeV}} = 0.11 \sqrt{\frac{E_e}{\text{MeV}}} + 0.02 \frac{E_e}{\text{MeV}} \]

![Energy resolution plot](image3)

- **exp. # of events:**
  - 10 kpc: $3 \times 10^3$
  - 1 kpc: $3 \times 10^5$
  - 0.2 kpc: $8 \times 10^6$

Enrico Borriello  |  Earth Matter Effect on SN Neutrinos
400 kton Water Cherenkov (MEMPHYS)

10 kpc

model: Garching 2011
detector: MEMPHYS
events: 17144
simulat.: 100

0 20 40 60 80 100 120
0
2
4
6
8
10
model: Garching 2011
detector: MEMPHYS
events: 17144
simulat.: 100

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detector: MEMPHYS
events: 17144
simulat.: 100

power spectrum

frequency

model: Garching 2011
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events: 17144
simulat.: 100

Enrico Borriello
Earth Matter Effect on SN Neutrinos
400 kton Water Cherenkov (MEMPHYS)

1 kpc

model: Garching 2011
detector: MEMPHYS
events: 17,144
simulat.: 100

model: Garching 2011
detector: MEMPHYS
events: 1,714,400
simulat.: 49

model: Garching 2011
detector: MEMPHYS
events: 42,860,000
simulat.: 10

power spectrum
frequency

Enrico Borriello
Earth Matter Effect on SN Neutrinos
400 kton Water Cherenkov (MEMPHYS)

model: Garching 2011
detector: MEMPHYS
events: 17 144
simulat.: 100

model: Garching 2011
detector: MEMPHYS
events: 1 714 400
simulat.: 50

model: Garching 2011
detector: MEMPHYS
events: 42 860 000
simulat.: 10

EME − no EME
**400 kton Water Cherenkov (MEMPHYS)**

0.2 kpc

**Power Spectrum**

Model: Garching 2011
Detector: MEMPHYS
Events: 17144
Simulation: 100

Model: Garching 2011
Detector: MEMPHYS
Events: 1714400
Simulation: 49

Model: Garching 2011
Detector: MEMPHYS
Events: 17144000
Simulation: 10

Model: Garching 2011
Detector: MEMPHYS
Events: 42860000
Simulation: 10

Enrico Borriello
Earth Matter Effect on SN Neutrinos
**50 kton Liquid scintillator (LENA)**

**10 kpc**

- Model: Garching 2011
- Detector: LENA
- Events: 1587
- Simulat.: 100

- Model: Garching 2011
- Detector: LENA
- Events: 158700
- Simulat.: 50

- Model: Garching 2011
- Detector: LENA
- Events: 3,967,500
- Simulat.: 10

**Power spectrum**

**Frequency**

**Enrico Borriello**

**Earth Matter Effect on SN Neutrinos**
50 kton Liquid scintillator (LENA)

1 kPC

model: Garching 2011
detector: LENA
events: 1587
simulat.: 100

model: Garching 2011
detector: LENA
events: 158700
simulat.: 50

model: Garching 2011
detector: LENA
events: 3967500
simulat.: 10

power spectrum

frequency

Enrico Borriello  Earth Matter Effect on SN Neutrinos
50 kton Liquid scintillator (LENA)

0.2 kpc

- **Model**: Garching 2011
- **Detector**: LENA
- **Events**: 1587
- **Simulation**: 100

- **Model**: Garching 2011
- **Detector**: LENA
- **Events**: 158700
- **Simulation**: 50

- **Model**: Garching 2011
- **Detector**: LENA
- **Events**: 3967500
- **Simulation**: 10

**Power Spectrum**

**Frequency**

**Enrico Borriello** | **Earth Matter Effect on SN Neutrinos**
null
100 kton LAr TPC (GLACIER)

0.2 kpc

model: Garching 2011
detector: GLACIER
events: 3039
simulat.: 100

model: Garching 2011
detector: GLACIER
events: 7597500
simulat.: 10

power spectrum

frequency

Enrico Borriello
Earth Matter Effect on SN Neutrinos
Galactic SN Distribution

Mirizzi, Raffelt & Serpico 2006

SN probability distribution

99% 56%

distance (kpc)

0 5 10 15 20 25 30

0.00 0.02 0.04 0.06 0.08

0.00 0.02 0.04 0.06 0.08

SN probability distribution

99% 56%
According to current SN simulations:

- 100 kton WC EME from few very close-by galactic SN
- 50 kton SC EME from few very close-by galactic SN
- 100 kton LAr TPC EME from $\mathcal{O}(10\%)$ galactic SN
According to current SN simulations:

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According to current SN simulations:

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According to current SN simulations:

- **100 kton WC**
  EME from few very close-by galactic SN

- **50 kton SC**
  EME from few very close-by galactic SN

- **100 kton LAr TPC**
  EME from $\mathcal{O}(10\%)$ galactic SN
Conclusions

EME seems to be less promising than what traditional SN simulations suggested.

However, SN $\nu$ can still be a valuable tool to get the $\nu$ mass hierarchy.

How?

Neutronization burst
Kalcheriess et al. 2006

Inverted hierarchy: MEMPHIS and GLACIER may see the peak.

Rise-time Serpico et al. 2012

MEMPHIS, LENA, GLACIER: Different Rise-times for $\nu$ species during the accretion phase.
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**CONCLUSIONS**

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Appendix: Flux Ratio & Pinching Trends

Enrico Borriello  Earth Matter Effect on SN Neutrinos
Appendix: Double Peak

Earth Matter Effect on SN Neutrinos
Appendix: Some Useful Formulae

Discrete FT

\[ g_N(k) = \frac{1}{\sqrt{N}} \sum_i e^{iky_i} = \sqrt{N} \langle e^{iky} \rangle \]

\[ \langle e^{iky} \rangle \simeq \int f(y) e^{iky} \, dy = g(k) \]

Continuous FT

\[ g_N(k) \simeq \sqrt{N} g(k) \]

\[ P_N(k) = |g_N(k)|^2 \simeq N |g(k)|^2 = NP(k) \]