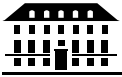


The Niels Bohr
International Academy

VILLUM FONDEN

Astro and Supernova Neutrinos: Particle Physics Questions

Irene Tamborra

Niels Bohr Institute, University of Copenhagen

CERN Theory Institute: “Neutrinos: the quest for a new physics scale”
CERN, March 30, 2017

Astro and SN Neutrinos

PeV Neutrinos

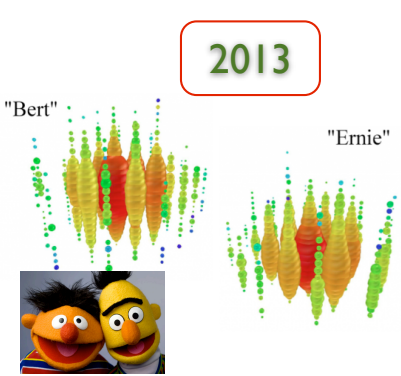
See talk by Walter Winter

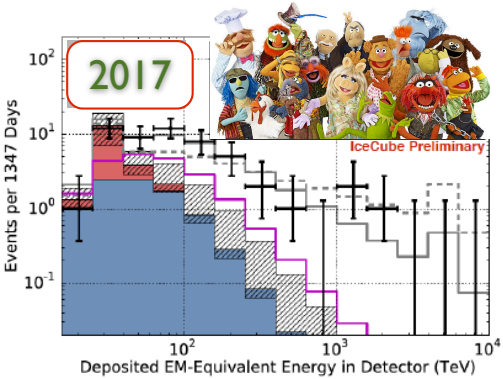
Supernova Neutrinos

See talk by Alessandro Mirizzi

PeV Neutrinos

High-Energy Neutrino Astronomy





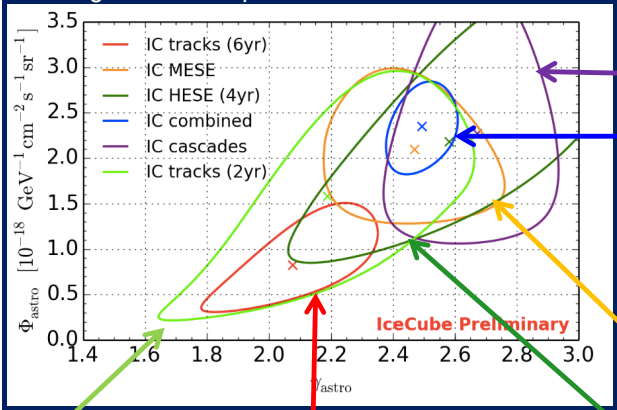
- ★ IceCube observed 54 events over four years in the 25 TeV-2.8 PeV range.
- ★ Zenith Distribution compatible with isotropic flux.
- ★ Flavor distribution consistent with $\nu_e : \nu_\mu : \nu_\tau = 1 : 1 : 1$.

7σ evidence for astrophysical flux

IceCube Collaboration, Science 342 (2013) 6161, PRL 113 (2014) 101101, PRD 91 (2015) 2, 022001.
IceCube Collaboration, ApJ 809 (2015) 1, 98; PRL 115 (2015) 8, 081102. M. Kowalski @ Neutrino 2016.

Measured Astrophysical Flux

Assumed equal ν flavor ratios $(f_e:f_\mu:f_\tau)_\oplus$ = 1:1:1 at Earth and single unbroken power-law fit



All Sky Cascades ($\nu_e+\nu_\tau$) 2yr
E>10 TeV
PoS (ICRC2015) 1109

Combined fit $\nu_e + \nu_\mu + \nu_\tau$
PoS(ICRC2015) 1066

All Sky MESE $\nu_e + \nu_\mu + \nu_\tau$ 2yr
E>1 TeV
PRD 91, 022001 (2015)

All Sky HESE $\nu_e + \nu_\mu + \nu_\tau$ 4yr
E>60 TeV
PoS(ICRC2015) 1081

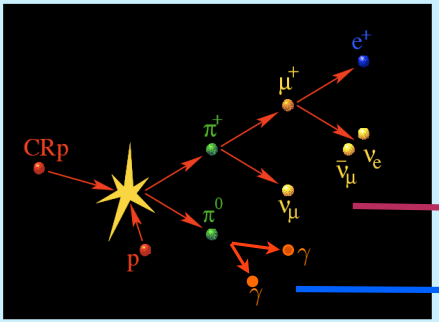
ν_μ (Northern Sky only) 2yr
PRL 115 (2015) 8, 081102

ν_μ (Northern Sky only) 6yr
PoS(ICRC2015) 1079

Slide adapted from J. Kiryluk @ NOW 2016.

Neutrino Production in Astro Sources

Hadronic interactions



Lepto-hadronic interactions

$$p + \gamma \rightarrow \Delta \rightarrow n + \pi^+, p + \pi^0$$
$$p + \gamma \rightarrow K^+ + \Lambda/\Sigma \ .$$

$$\begin{aligned}
\pi^+ &\rightarrow \mu^+ \nu_\mu \ , \\
\mu^+ &\rightarrow \bar{\nu}_\mu + \nu_e + e^+ \\
\pi^- &\rightarrow \mu^- \bar{\nu}_\mu \ , \\
\mu^- &\rightarrow \nu_\mu + \bar{\nu}_e + e^- \\
K^+ &\rightarrow \mu^+ + \nu_\mu \ , \\
n &\rightarrow p + e^- + \bar{\nu}_e
\end{aligned}$$

Anchordoqui et al., PLB (2004). Kelner, Aharonian, Bugayov, PRD (2006). Kelner, Aharonian, PRD (2008). Vissani, Astrop. Phys. (2006).

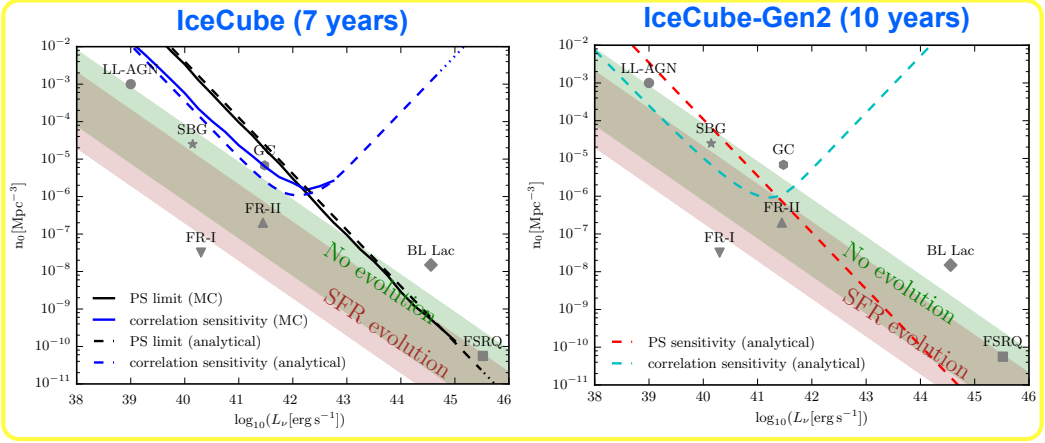
Where Are These Neutrinos Coming from?

- ★ New physics?
- ★ Galactic origin [sub-dominant contribution]
- ★ **Extragalactic origin [flux compatible with Waxman & Bahcall bound]**
  - Star-forming galaxies
  - Gamma-ray bursts
  - Active galactic nuclei
  - Low-power or choked sources

Warning: More statistics needed! No strong preference so far.

Anchordoqui et al., JHEAp (2014). Meszaros, arXiv: 1511.01396. Waxman, arXiv: 1511.00815. Murase, arXiv: 1511.01590.

Sources Parameter Space

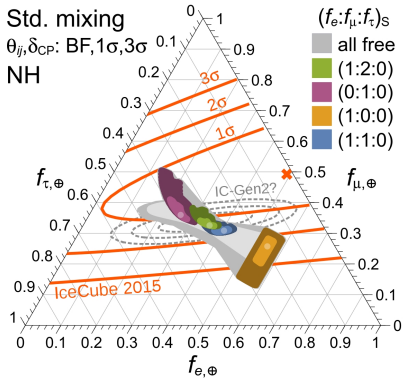


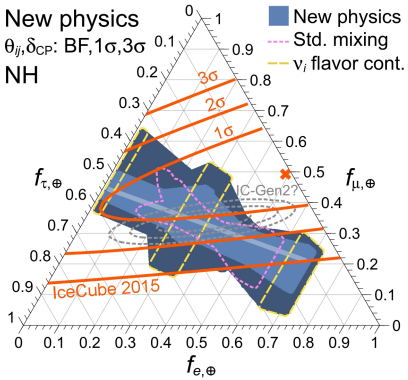
IceCube-Gen2 will probe ~half of parameter space of known sources (w/ nu data only).

- More than one source likely composes the flux we observe. What are the most powerful ways to disentangle pp from p-gamma contributions?

Mertsch, Rameez, Tamborra, JCAP (2017). Murase & Waxman PRD (2016). Biehl et al., JCAP (2017). Winter, PRD (2013). Murase, Ahlers, Lacki, PRD (2013).

Flavor Composition





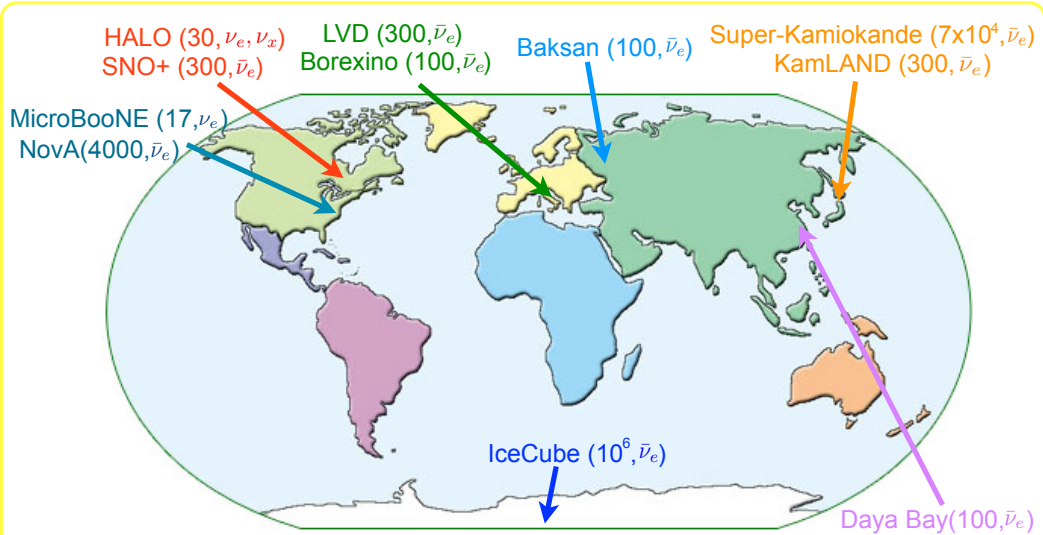
Not yet possible to pinpoint the production mechanism.

- Can we test non-standard physics despite uncertainty on flavor ratio (vs. multiple sources)?
- If IceCube/Gen2 won't pin down exact flavor ratio, how do we test BSM physics in source?

Bustamante, Beacom, Winter, PRL (2015). Arguelles, Katori, Salvado, PRL (2015). Palladino, Pagliaroli, Villante, Vissani, PRL (2015). IceCube Collaboration, ApJ (2015).

Supernova Neutrinos

Are We Ready For SN 20XXa?



Expected number of events for a SN at 10 kpc and dominant flavor sensitivity in parenthesis.

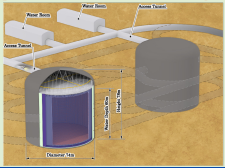
Fundamental to combine the SN signal seen in detectors employing different technologies.

Recent review papers: Scholberg (2012). Mirizzi, Tamborra, Janka, Scholberg et al. (2016).

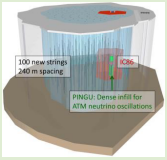
Next Generation Large Scale Detectors

Cherenkov telescopes ($\bar{\nu}_e$)

Hyper-Kamiokande (10^5)

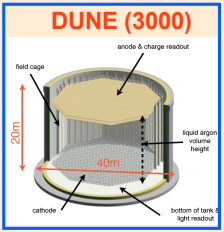


IceCube-Gen2 PINGU (10^6)



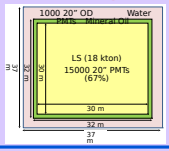
Liquid Argon detectors (ν_e)

DUNE (3000)

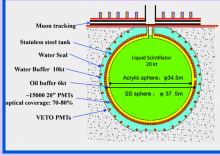


Scintillation detectors ($\bar{\nu}_e$)

RENO-50 (5400)



JUNO (6000)



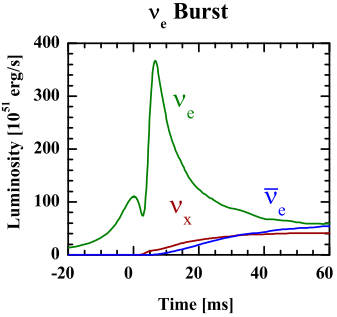
Dark Matter Detectors ($\nu_{e,x}$, $\bar{\nu}_{e,x}$)

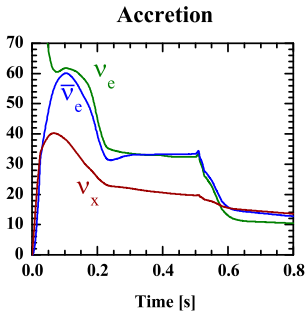
e.g., DARWIN (700)

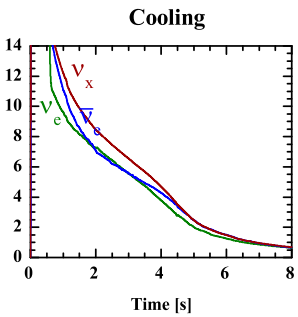
- Do we have under control cross-sections, systematics?

Recent review papers: Scholberg (2012). Mirizzi, Tamborra, Janka et al. (2016).

Neutrino Signal (SM Physics)







Signal independent on SN mass and EoS.

- SN distance.
- (Test oscillation physics.)

Signal has strong variations (mass, EoS, 3D effects).

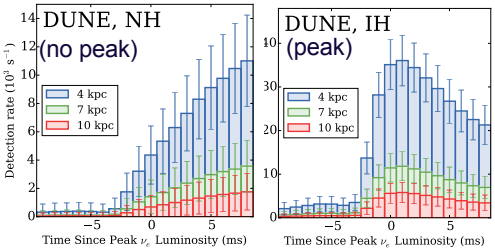
- Core collapse astrophysics.
- (Test oscillation physics.)

EoS and mass dependence.

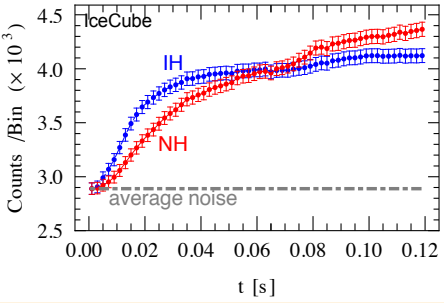
- Test nuclear physics.
- Nucleosynthesis.

Early SN Neutrino Signal

Neutrinos



Antineutrinos

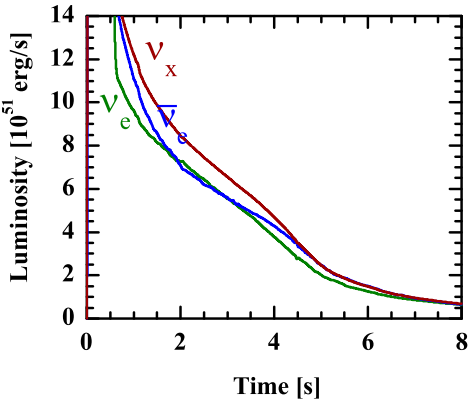


- Complementary test of mass ordering.
- If mass ordering known, test oscillations in dense media.
- keV sterile neutrino bounds, NSI.

- How do we plan to improve our understanding of oscillations in dense media?

Kachelriess et al., PRD (2005). Wallace, Burrows, Dolence, ApJ (2016). Serpico et al., PRD (2012). Stapleford et al., PRD (2016). Hidaka & Fuller, PRD (2006). Raffelt & Zhou, PRD (2011).

Cooling Neutrino Signal



Emission of BSM particles could steal energy from the burst and shorten it.

- How do we distinguish among sterile neutrinos, NSI, exotic DM particles?
- Which is the most promising method to avoid degeneracies with nuclear physics, astro?

Stapleford et al., PRD (2016). Payez et al., JCAP (2015). Kazanas et al., Nucl.Phys.B (2014).

Questions

- What are the most powerful ways to disentangle pp from p-gamma contributions?
- Can we test non-standard physics despite uncertainty on flavor ratio (vs. multiple sources)?
- If IceCube/Gen2 won't pin down exact flavor ratio, how do we test BSM physics in source?

- Do we have under control cross-sections, systematics?
- How do we plan to improve our understanding of oscillations in dense media?
- How do we distinguish among sterile neutrinos, NSI, exotic DM particles?
- Which is the most promising method to avoid degeneracies with nuclear physics, astro?

Thank you for your attention!