Discussion of “ "Fundamental Physics With Neutrinos”

Spencer Klein, LBNL and UC Berkeley

Presented at the 2021 Intl. Cosmic Ray Conf.

- 16 talks to summarize
  - Diverse subjects and experiments
  - Compare and Contrast?
- Short notice
- I will try to be slightly provocative

Disclaimer: I am in IceCube, so may not be unbiased regarding IceCube contributions

The list…

The Future of High-Energy Astrophysical Neutrino Flavor Measurements	Ningqiang Song	Talk
Reaching the EeV frontier in neutrino-nucleon cross sections in upcoming neutrino telescopes	Victor Valera	Talk
Studying neutrinos at the LHC-FASER ~ its impact to the cosmic-ray physics	Akitaka Ariga	Talk
HE Neutrinos beyond Standard Model: steriles and secret interactions	Ninetta Saviano	Talk
Search for STaus in IceCube	Jan-Henrik Schmidt-Dencker	Poster
New flux limits in the Low relativistic Regime for Magnetic Monopoles in IceCube	Frederik Lauber	Talk
Search for Magnetic Monopoles with ten years of ANTARES data	Jihad Boumaaza	Talk
Measuring neutrino cross-section with IceCube at intermediate energies (~100 GeV to a few TeV)	Sarah Nowicki	Talk
IceCube constraints on Violation of Equivalence Principle	Damiano Francesco Giuseppe Fiorillo	Poster
Scalar Non Standard Interactions at long baseline experiments	Abinash Medhi	Poster
Potential for 3+1 and Lorentz violation measurements with DUNE	Austin Schneider	Talk
Search for nuclearites with the KM3NeT detector	Alice Paun	Poster
Search for exotic neutrino interactions by XMASS-I detector	hiroshi ogawa	Talk
Measuring the Neutrino Cross Section Using 8 years of Upgoing Muon Neutrinos	Sally Robertson	Talk
Sensitivity of the KM3NeT/ORCA detector to the neutrino mass ordering and beyond	Mathieu Perrin-Terrin	Talk
Rigorous predictions for prompt neutrino fluxes in view of VLVnT upgrades	Maria Vittoria Garzelli	Talk

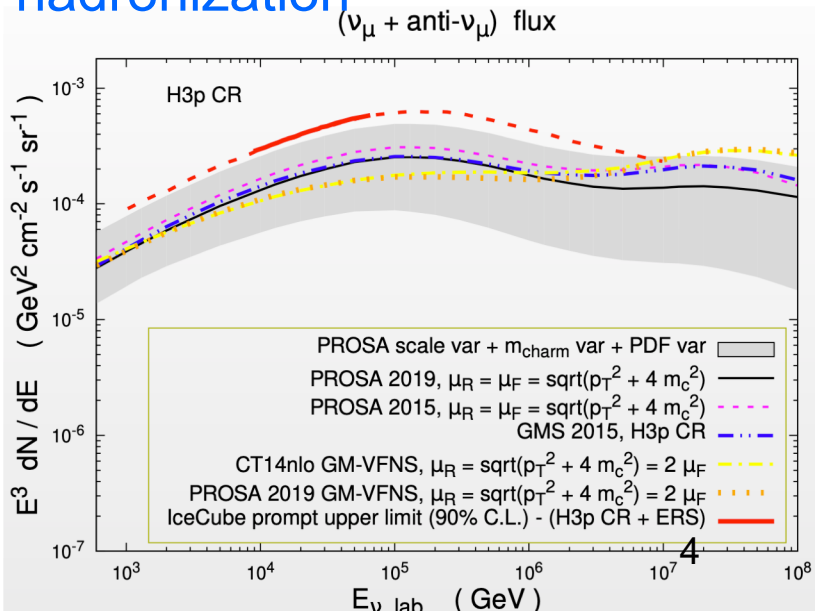
Some themes…

- Probe Beyond Standard Model physics
- Probe standard model physics – backgrounds to BSM physics
- Accelerators experiments and natural neutrinos
- Two approaches
  - Look for unusual/unexpected topology events
  - Count events as function of energy, zenith angle & flavor
    - Compare with models that include
      - Production models (π/K decay, neutron decay, μ decay, mixtures..)
      - Propagation (oscillation)
      - In-Earth propagation (absorption, matter-induced oscillations)
      - Detection in detector
    - Set limits on BSM processes

Rigorous predictions for prompt neutrino fluxes in view of VLVνT upgrades

Maria Vittoria Garzelli, with S. –O Moch and G. Sigl

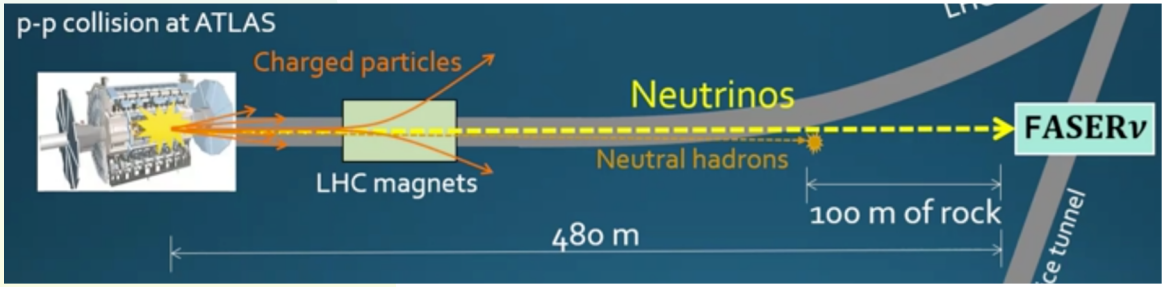
- Prompt neutrinos must exist, but have not been seen
  - IceCube limits challenge some earlier calculations.
  - Prompt ν have the potential to mimic astrophysical ν
- This motivates a new prompt ν calculation
  - Models for cosmic-ray energy and composition dependence +
  - Convolution of cross-sections with fragmentation functions, or
  - Fixed order pQCD + Parton Shower + hadronization
- Calculations is below IceCube limit
  - ~ similar to other newer calculations
  - Uncertainty is a factor of 4-10

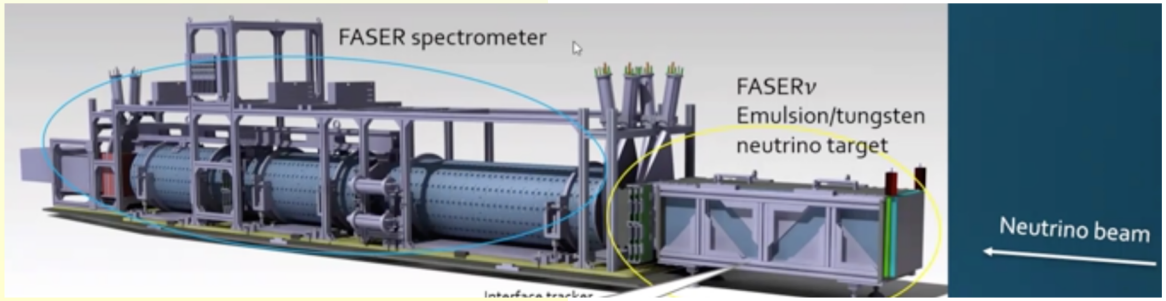


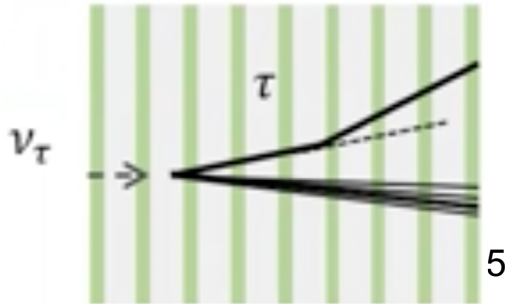
Studying neutrinos at the LHC-FASER ~ its impact to the cosmic-ray physics

Akitaka Ariga

- FASER-ν will study forward ν from the LHC
  - Asymmetric collision of high-x partons with low-x partons
  - $\sqrt{s_{pp}}$=14 TeV -> 10^{17} eV equiv. fixed target.
- Probes topics needed to tune cosmic-ray Monte Carlos
  - Forward ν production
  - Prompt production in the far-forward region

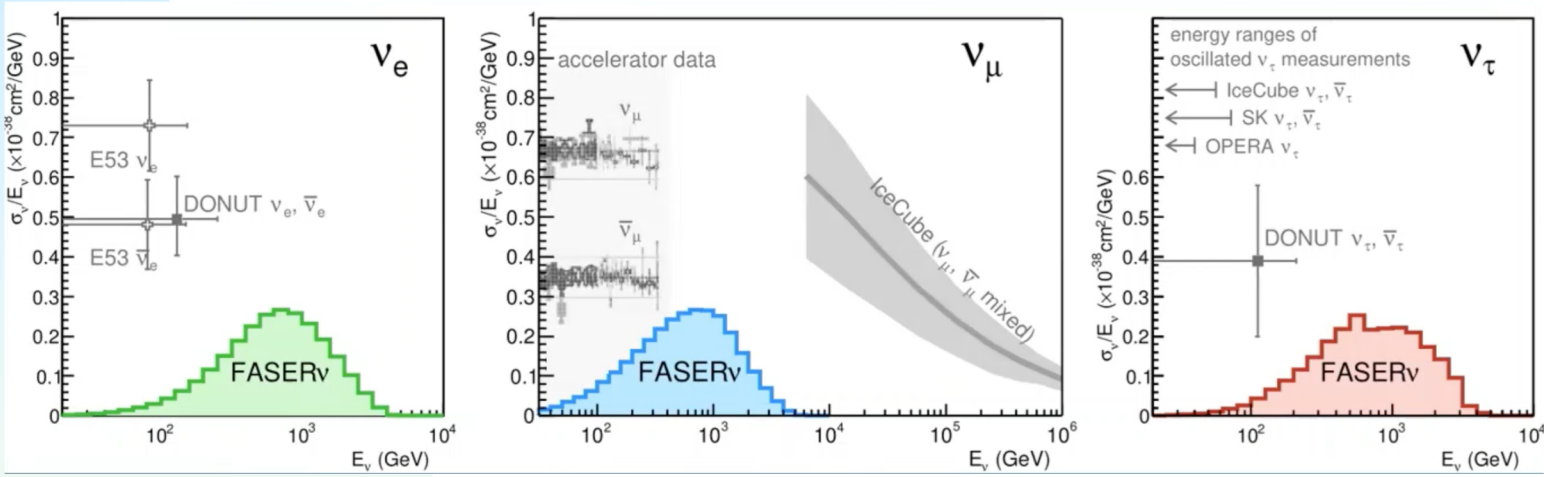




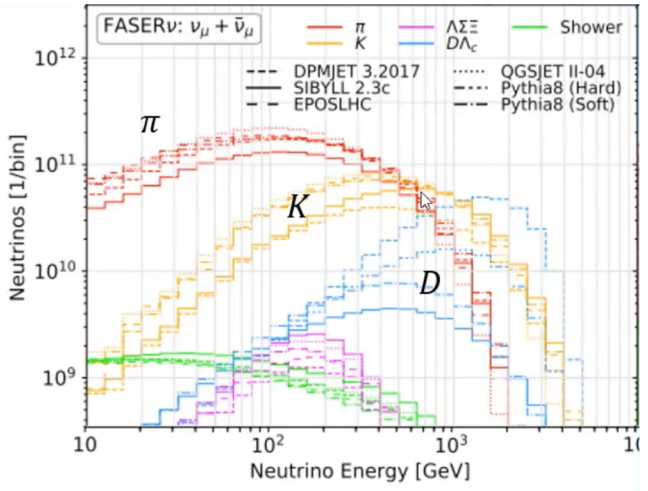


FASER…

- Energy spectrum extends well into TeV region



- π/K/charm have different energy spectra, flavor & p_T spectra
  - Can separate different components
  - Prompt measurements
  - Also ν_τ
- + cross-sections, BSM…

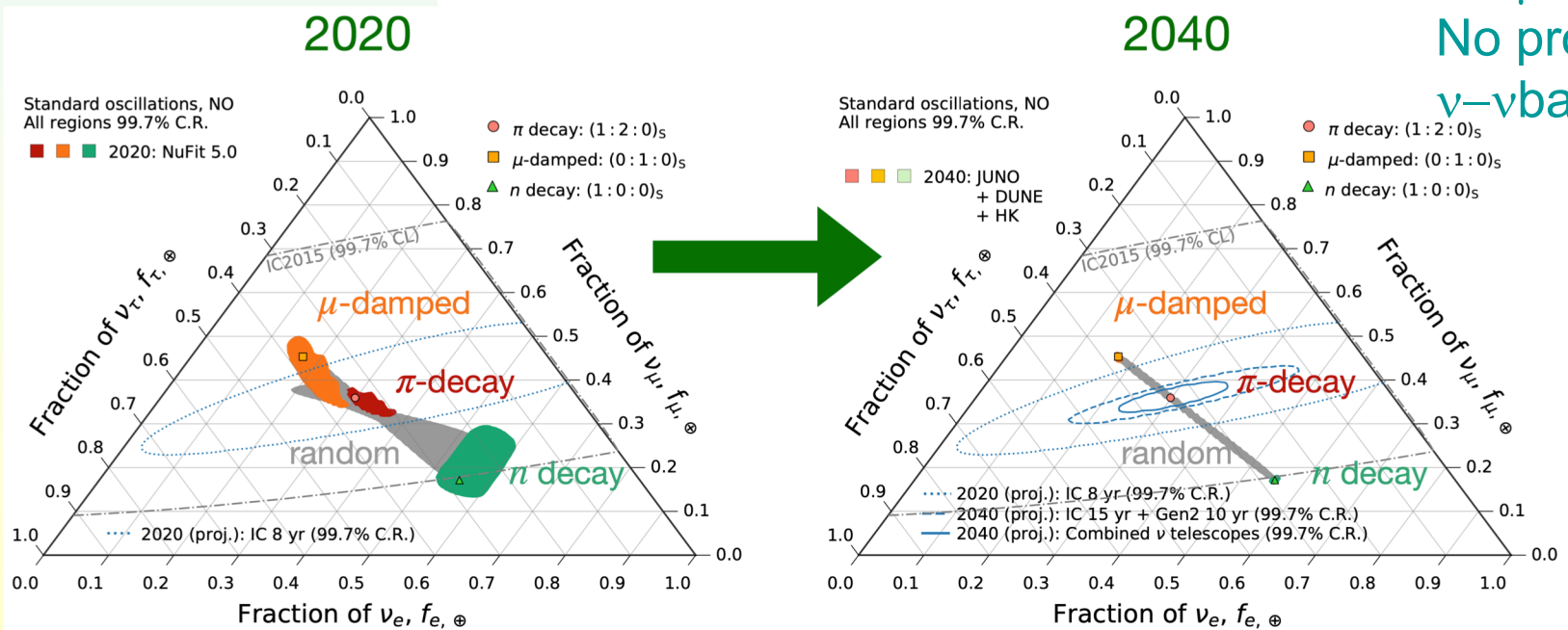


The Future of High Energy Astrophysical Neutrino Flavor Measurements

Ningqiang Song, with Shirley Li, Carlos Arguelles, Mauricio Bustamante, Aaron Vincent

- How well can future neutrino telescopes constrain the flavor content of astrophysical neutrinos?
  - TAMBO, P-ONE, KM3NeT, Baikal GVD, IceCube Gen2
  - Better oscillation data from JUNO, DUNE, Hyper-K
- What can we then say about BSM physics?

No μ decay
No prompt ν
ν–νbar ratio



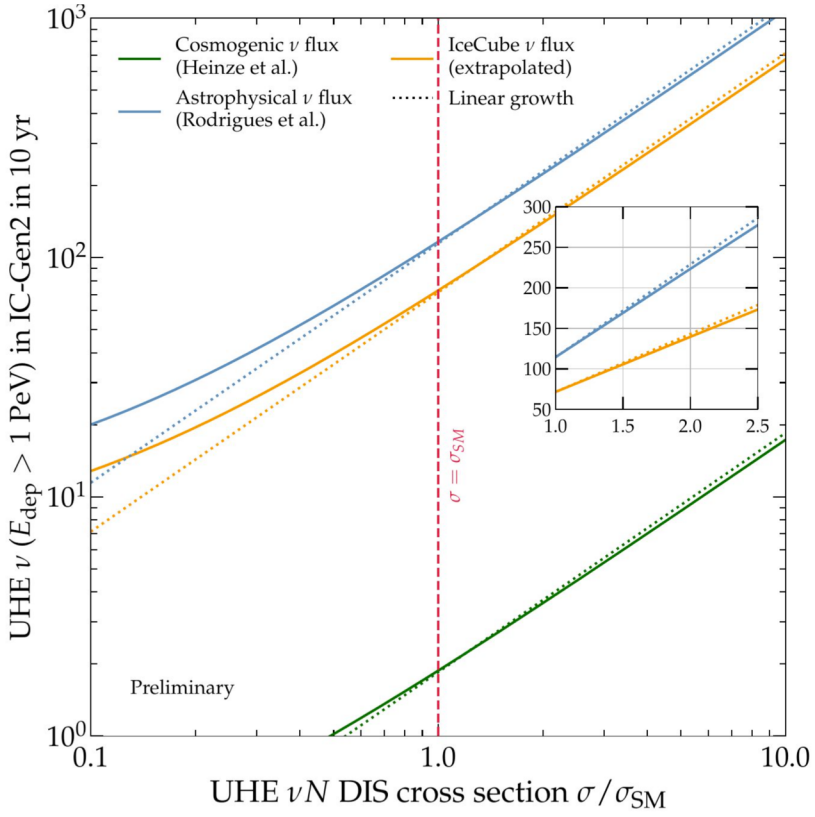
Reaching the EeV frontier in neutrino-nucleon cross section

Victor Valera with Mauricio Bustamante

- What can future radio experiments (IceCube Gen2 radio) tell us about the cross-section
- Focus on expected number of events
  - IceCube power law extrapolation + GZK ν
  - Angular resolution?
- Propagation in Earth, including τ regeneration

Rates vs. flux

- Linear regime
  - N ~ flux*σ
  - Reduced by absorption
- For counting, flux must be known
  - The IceCube power-law flux was determined assuming the standard model cross-section.
  - If $\sigma \neq \sigma_{SM}$, then the IceCube flux must be adjusted to match.
    - GZK measurements are OK.
- Zenith angle/energy fits are more robust – little flux sensitivity



$$N \sim \Phi_\nu \sigma_{\nu N} e^{-\tau(E,\,\theta)}.$$

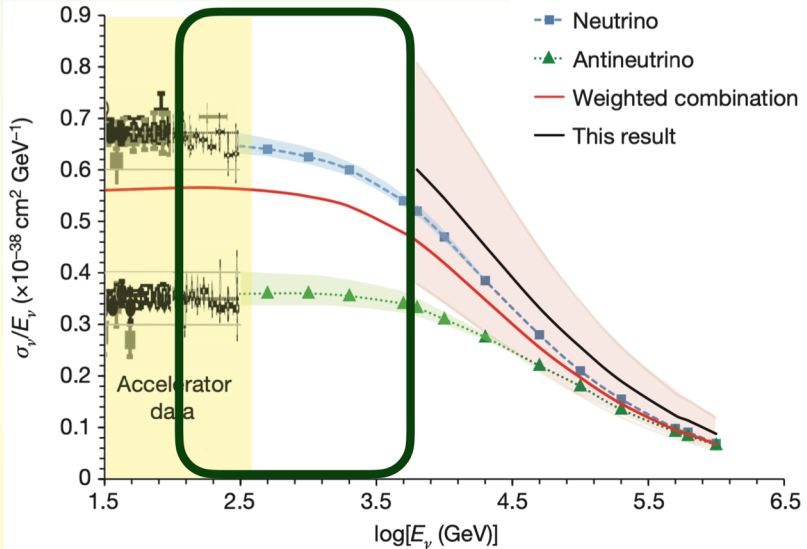
Increases the probability of a neutrino detection.

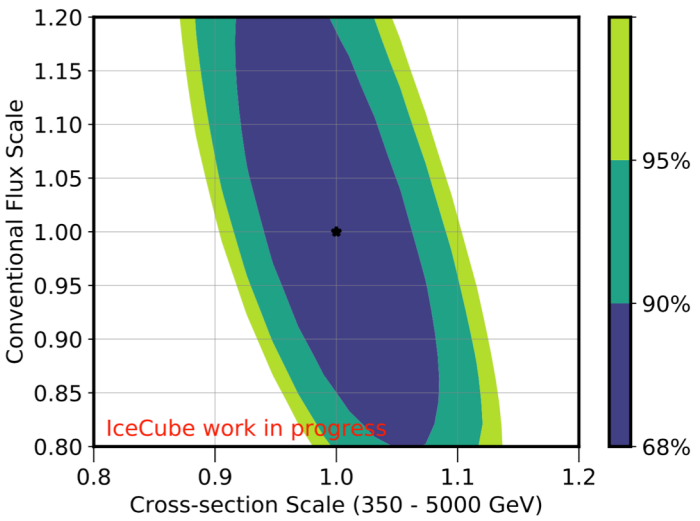
Decreases probability of a neutrino transmission

Measuring neutrino cross-section with IceCube at intermediate energies (~100 GeV to a few TeV)

Sarah Nowicki for the IceCube Collaboration

- Fills the gap from accelerator to Earth-absorption measurements
  - Two energy bins: 100 GeV – 350 GeV & 350 GeV – 5 TeV
    - 1st bin: overlap with accelerator studies
    - 2nd bin: similar energy region to FASER
  - Little absorption -> σ~ Number of events
    - Requires good knowledge of flux
    - The flux is constrained by by accelerator cross-section in priors
- Improved energy estimator for low-energy ν

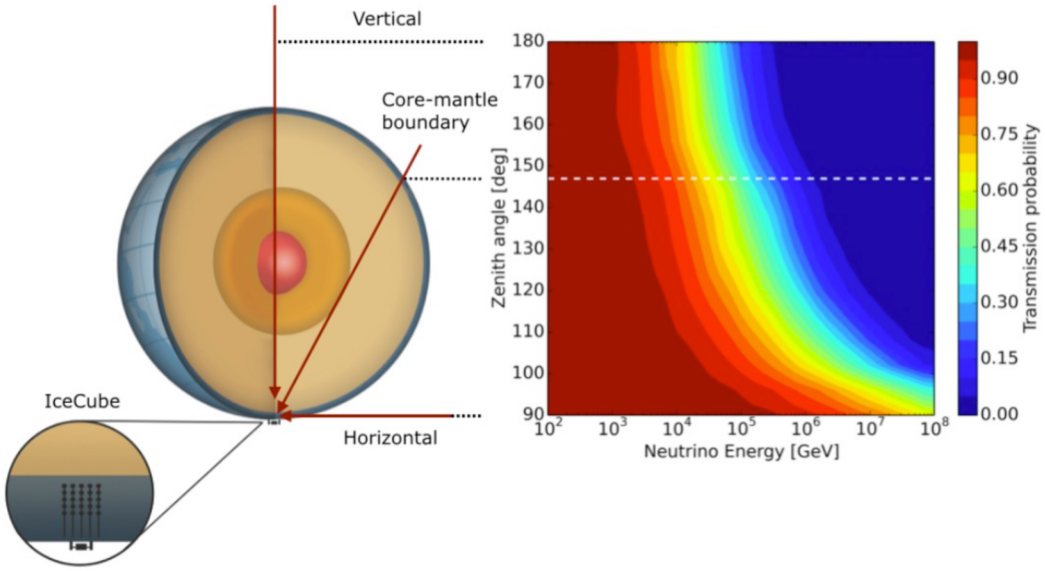


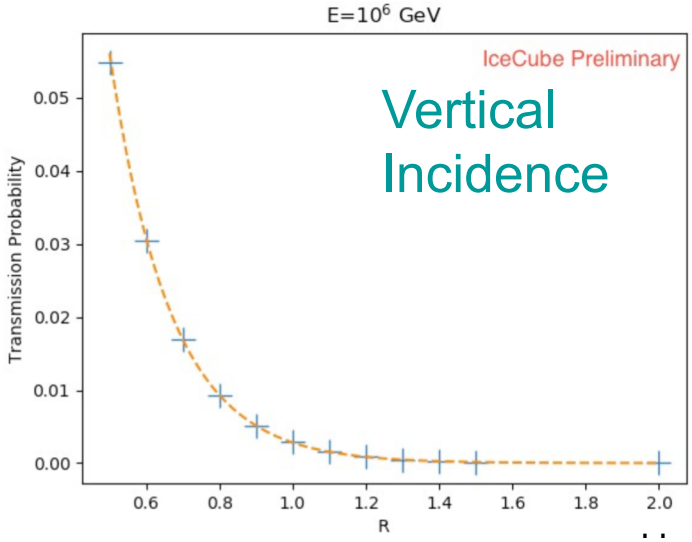


Measuring the Neutrino Cross Section Using 8 year of Upgoing Muon Neutrinos Observed with IceCube

Sally Robertson for the IceCube Collaboration

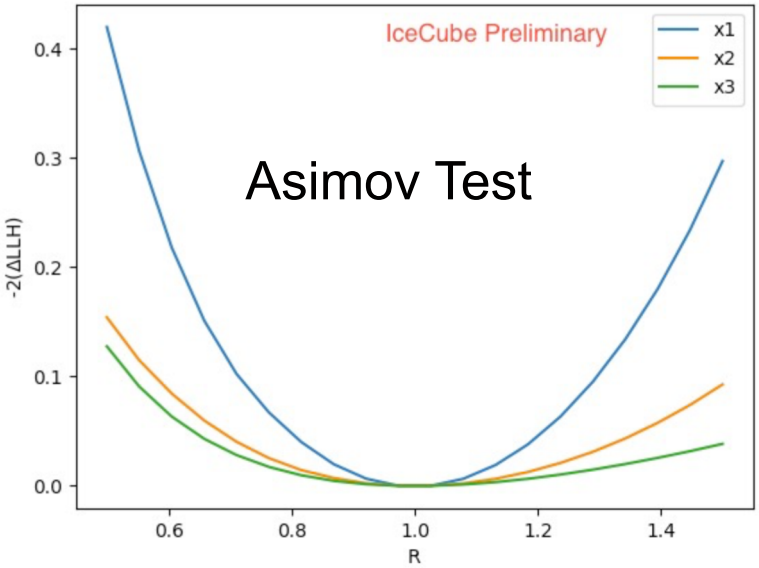
- Measures the upgoing ν_μ flux as a function of E_ν, zenith angle
- Fit with the cross-section multiple R as a free parameter
  - $R=\sigma/\sigma_{DIS}$; same for both charged current and neutral current
- Fit flux*R; decouple flux (i. e. $N_{events} = \phi\sigma$) and focus on absorption
- 10 X the statistical power of IC79 study + improved systematics

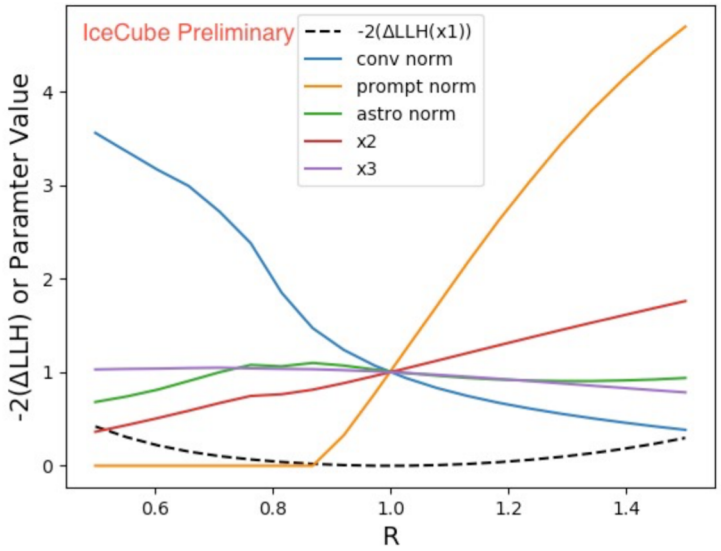




8-year analysis

- 3 energy bins from 1 -10 TeV, 10 TeV - 1 PeV, and 1 - 100 PeV
  - Few events above 10 PeV
- How much can the systematics be improved?
  - Better optical model of ice
  - Barr parameters for atmospheric ν
    - What is the ν/ν-bar ratio in the flux?
      - What are we measuring?
- Choice of priors is likely important to fit



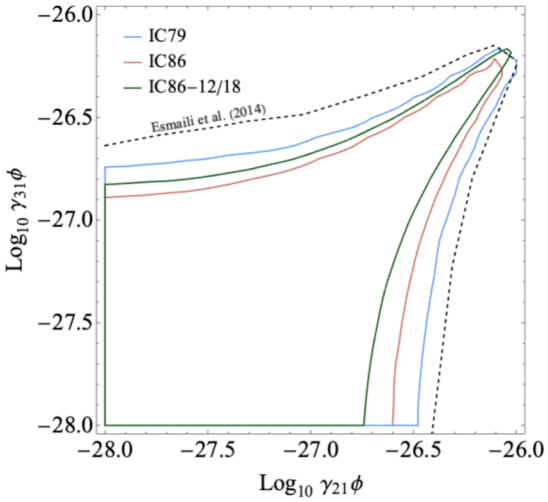


R for lowest energy bin

IceCube constraints on Violation of Equivalence Principle

Damiano F. G. Fiorillo with G. Mangano, S. Morisi and O. Pisanti

- Equivalence principle (EP): all particles couple equally to the gravitational field
  - All follow the same trajectory
  - Equality of gravitational and inertial mass
- Check if different ν flavors have the same coupling
  - Violation of the EP could introduce dephasing in ν oscillations
  - Characterized by γ_{ij}, where i, j are ν flavors
    - Physical meaning or scale?
- Used IceCube ν_μ data to constrain γ_{ij}



Sterile neutrino prospects with atmospheric neutrinos in DUNE

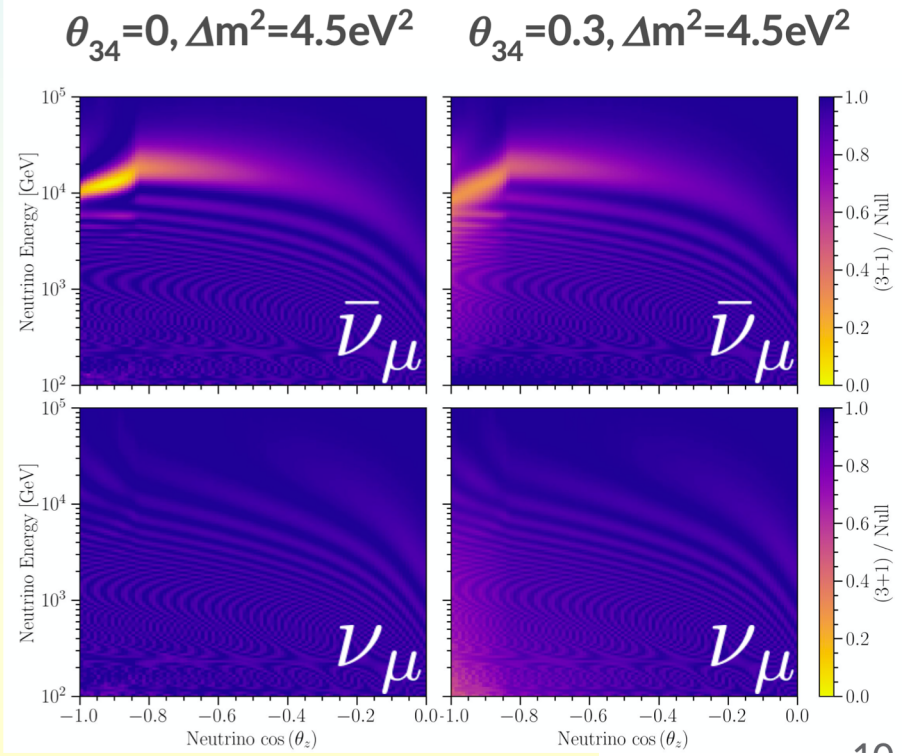
Austin Schneider with B. Skrzypek, C. Arguelles and J. Conrad

- Use through-going μ from atmospheric ν to search for the signature of sterile ν
- Use δ rays (high energy atomic excitation) to measure μ energy, especially in the 100 GeV to TeV range.
  - Still, need to go from μ energy to ν energy
- 9 module-years of data (1st 5 years of DUNE)
- Look for matter-induced resonant behavior
  - Similar to recent IceCube analyses
  - 3+1 flavor scenario
- Scan in $\sin^2(2\theta_{24})$ and Δm^2 with θ_{34}=0 or floating

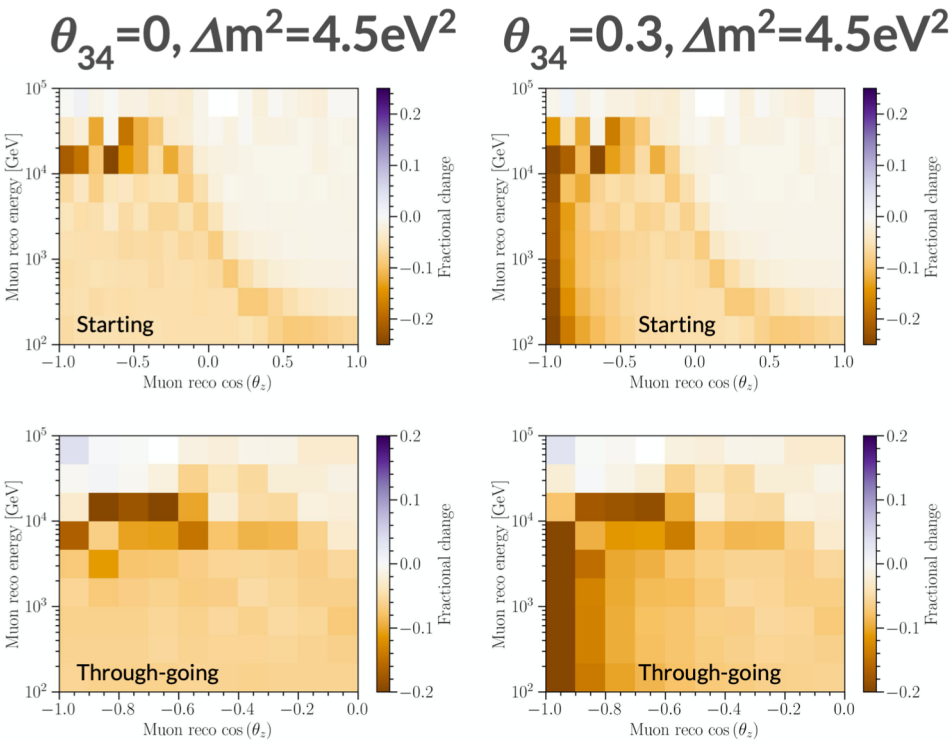
Oscillograms

- Nonzero θ_{34} 'fuzzes out' oscillation peaks and valleys
  - Deficit near $\cos(\theta_z)$ near -1
- DUNE's resolution is good; it preserves the primary ridge.
  - Surprising for through-going muons
- DUNE can test IceCube preferred point if θ_{34}=0.34, but not if θ_{34}=0

Raw



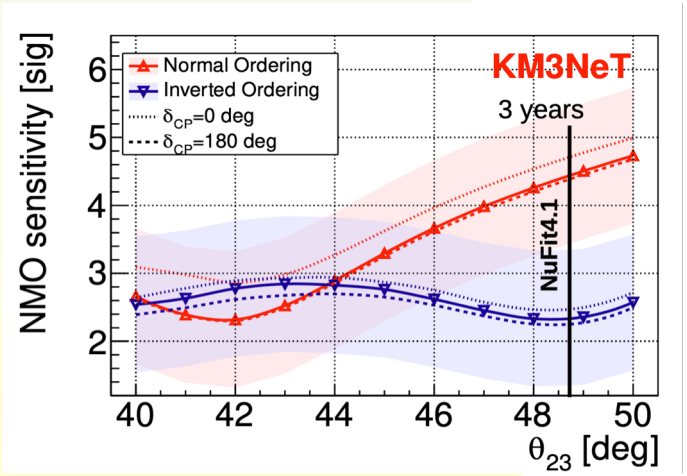
In DUNE

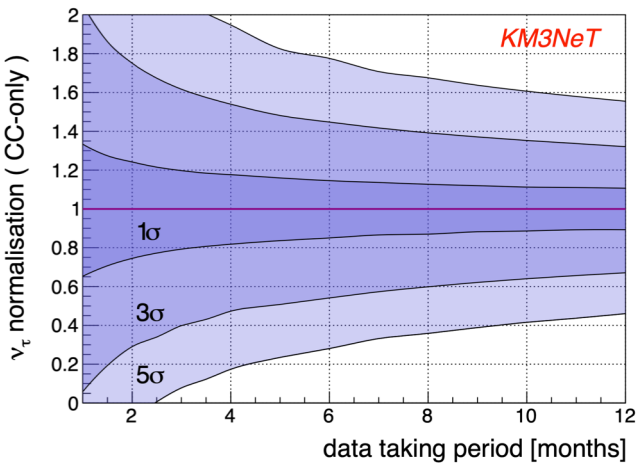


Sensitivity of the KM3NeT/ORCA detector to the neutrino mass mixing

Mathieu Perrin-Terrin for the KM3NeT Collaboration

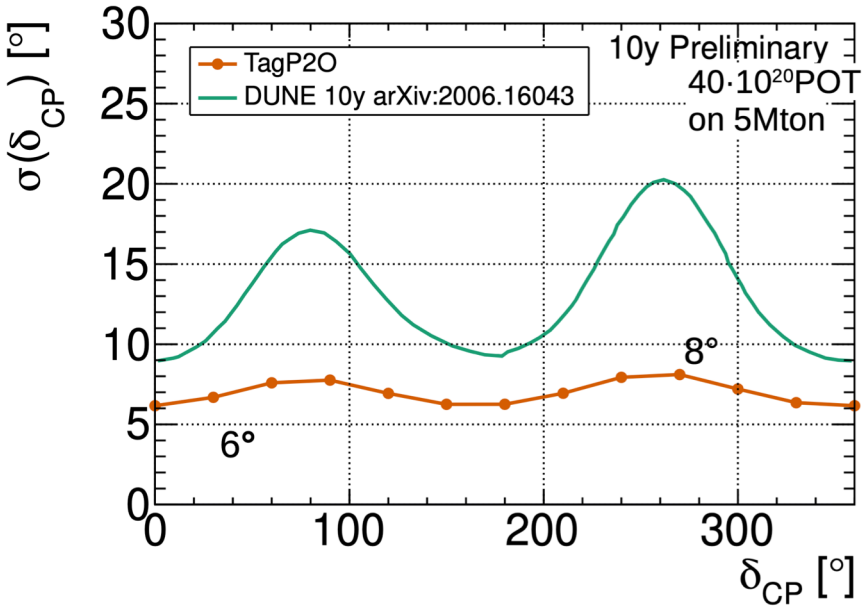
- KM3NeT/ORCA will densely instrument 5-6 Mm^3 of water with optical modules, to study ν in the energy range 3-100 GeV
- Main physics topics
  - Neutrino mass ordering
  - Measure θ_{23} and Δm^2_{23}, and determine the θ_{23} octant
  - Constrain the PMNS matrix unitarity using ν_τ
- Systematics are critical, and have received much attention

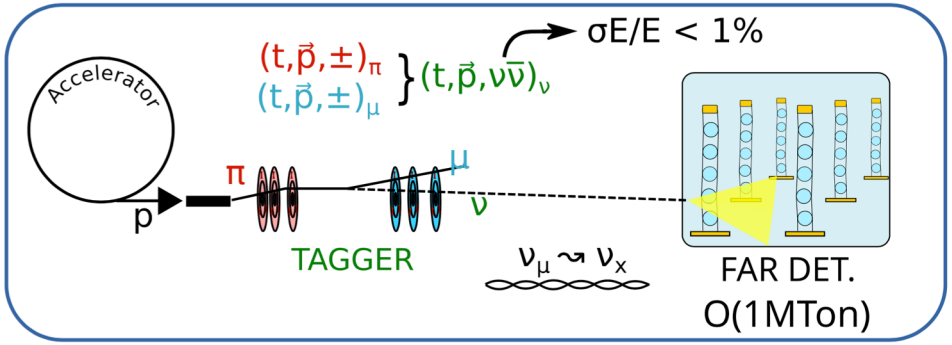




Looking ahead – beams from Protvino

- Shoot an accelerator beam from Protvino to ORCA
  - Large detector relaxes flux reqts.
- Systematics are limitation
- To reduce systematics, tag the neutrino events
- If feasible, this can beat DUNE
  - What is the tagger rate?





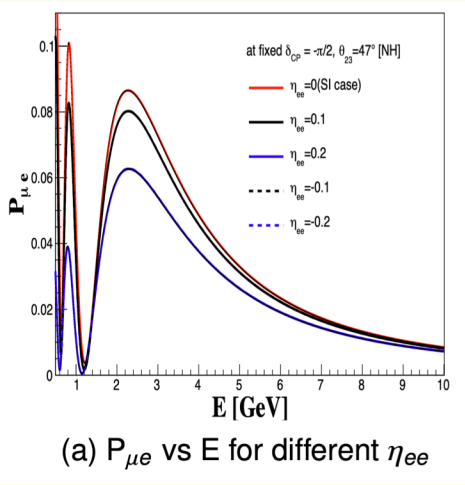
Scalar Non Standard Interactions at long baseline experiments

Abinash Medhi with D. Dutt and M. M. Devi

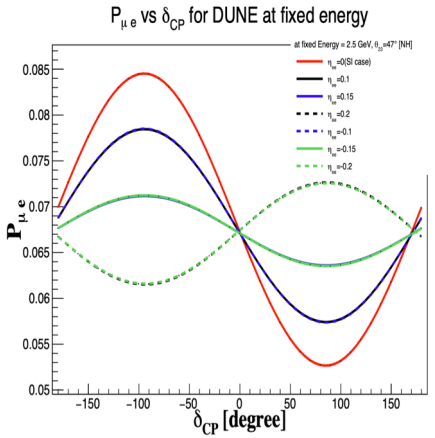
- Explored the effect of a BSM interaction between neutrinos and a new scalar field, with the Hamiltonian

$$\mathcal{H} \approx E_\nu + \frac{(M+\delta M)(M+\delta M)^\dagger}{2E_\nu} \pm V_{SI}$$

- The mass term is perturbed, and there is a new term, with different sign for ν and νbar
- Oscillation probabilities are reduced at DUNE (1300 km baseline)



(a) $P_{\mu e}$ vs E for different η_{ee}



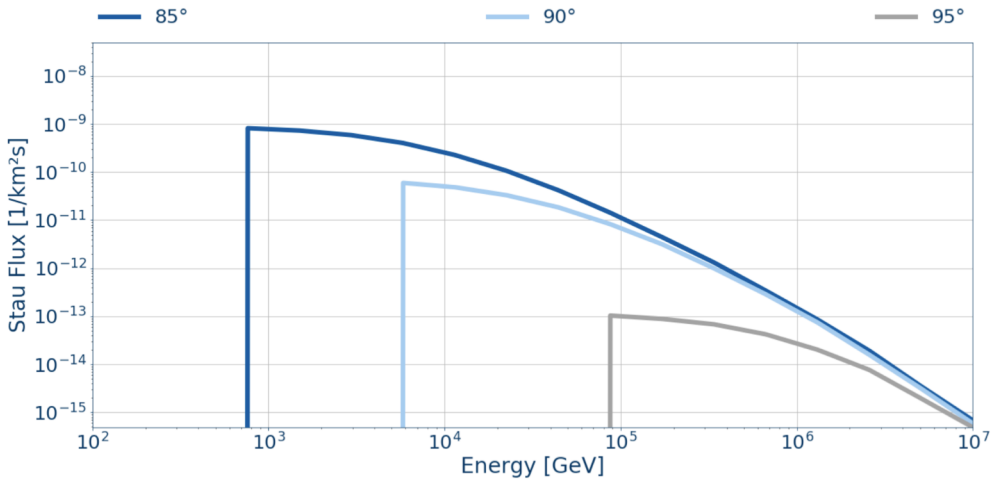
(a) $P_{\mu e}$ vs δ_{CP} for different η_{ee}

To what extent can existing data limit this new term?

Search for STaus ion IceCube

Jan-Henrik Schmidt-Denker for the IceCube Collaboration

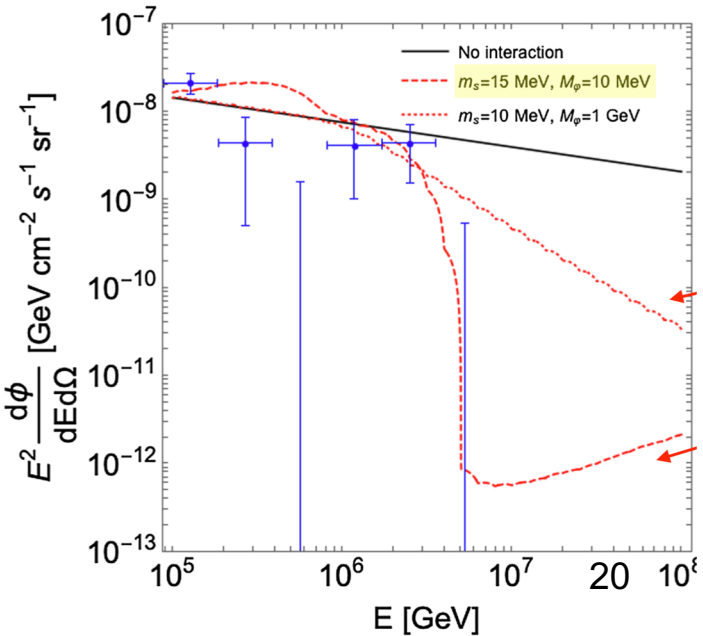
- Long lives stau (supersymmetric counterparts of the τ lepton) are produced in cosmic-ray air showers
  - Drell Yan process: q + qbar -> stau + stau-bar
- M(stau)>> M(μ), so staus are nearly minimum ionizing
- Look for minimum-ionizing particles near the horizon, where the few remaining muons are very high energy.
- Current sensitivity estimate:
  - excludes staus with M<63 GeV @ 90% CL
- Must do better to beat LHC
  - Try a stochasticity cut?



HE neutrinos beyond the standard model: steriles and secret interactions

Ninetta Saviano, with D Fiorillo, G. Miele and S. Morisi

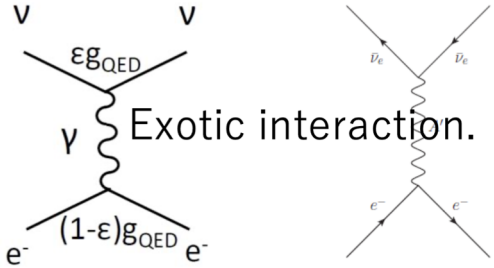
- Presented a BSM model with a new pseudoscalar-mediated interaction involving both active and sterile neutrinos
- Accelerator limits on Br($K^+ \to \mu\nu\nu\nu$) $< 2.4 * 10^{-6}$ can be repurposed to set limits on these new interactions
  - Can IceCube/future radio-detection do better?
- High energy ν en-route to Earth may interact with low-energy CMB ν, and turn into invisible sterile ν
- This introduces cuts-off the astrophysical power-law spectrum
- For heavier mediators, GZK ν may be cut off.
- The cutoff is flavor-dependent
  - E-dependent flavor ratio

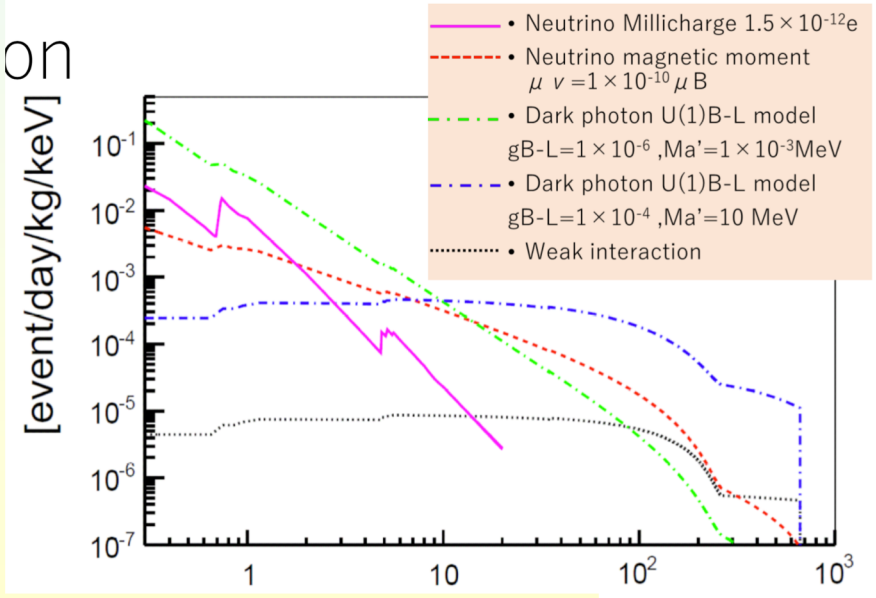


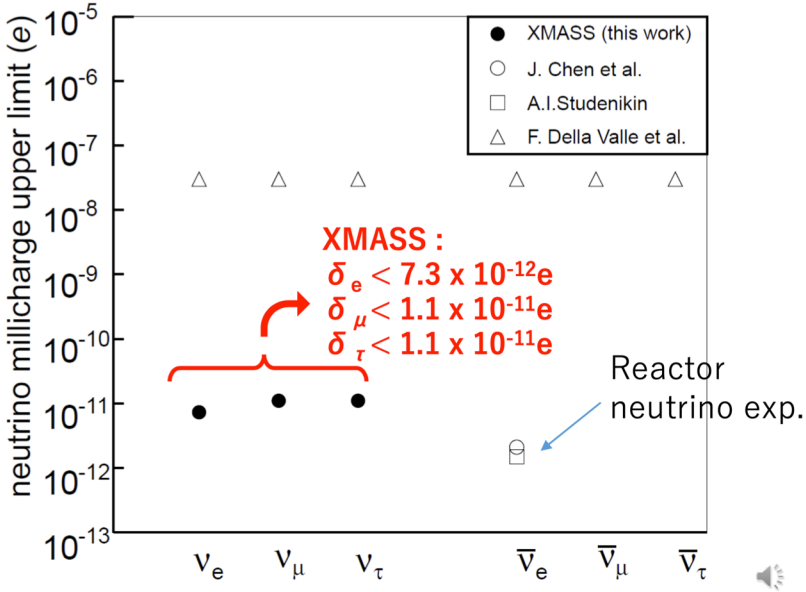
Search for exotic neutrino interactions by XMASS-I detector

Hiroshi Ogawa

- 832 kG single phase liquid Xe detector for dark matter, solar neutrinos, $0\nu\beta\beta$ etc.
- Sensitive to non-standard interactions of solar neutrinos
  - ν Millicharge
  - ν magnetic moment $\mu_\nu < 1.8 \times 10^{-10}\ \mu_B$
  - Dark Photons



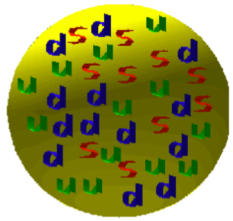


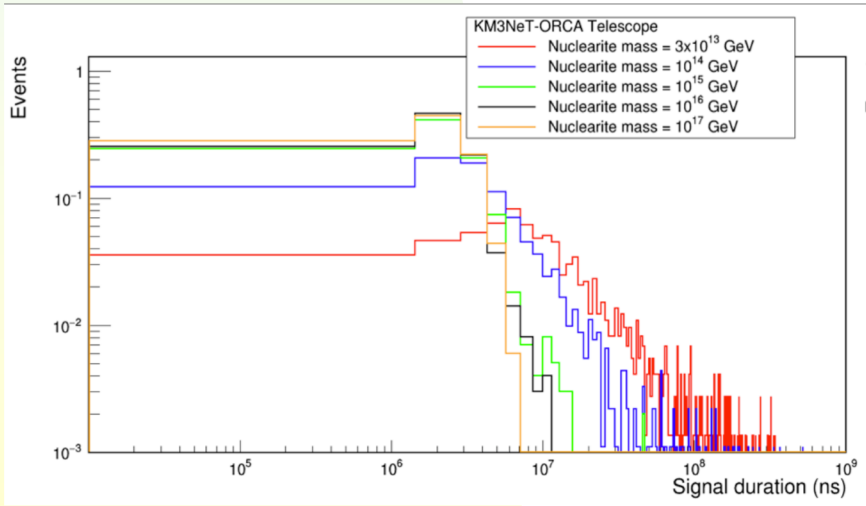


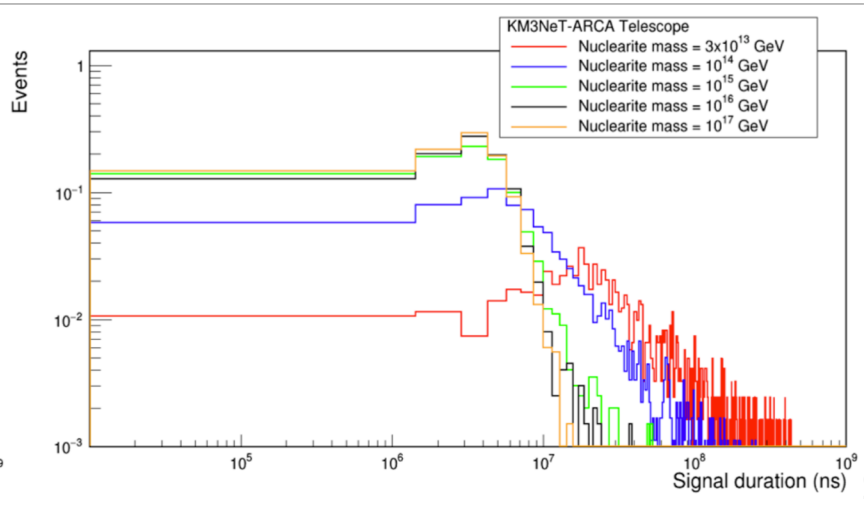
Search for nuclearites with the KM3NeT detector

Alice Paun, G. E. Pavalas and V. Popa for the KM3NeT Collaboration

- Nuclearites are objects that contain roughly equal (and large) numbers of up, down and strange quarks
  - Three flavors reduces effect of Pauli exclusion principle
- Simulated $\beta=10^{-3}$, and mass range $3*10^{13}$-10^{17} GeV
  - $dE/dx \sim k\beta^2$, by elastic and quasi-elastic interactions
- Studied possible cut variables, including time in detector
  - Both ORCA and ARCA considered



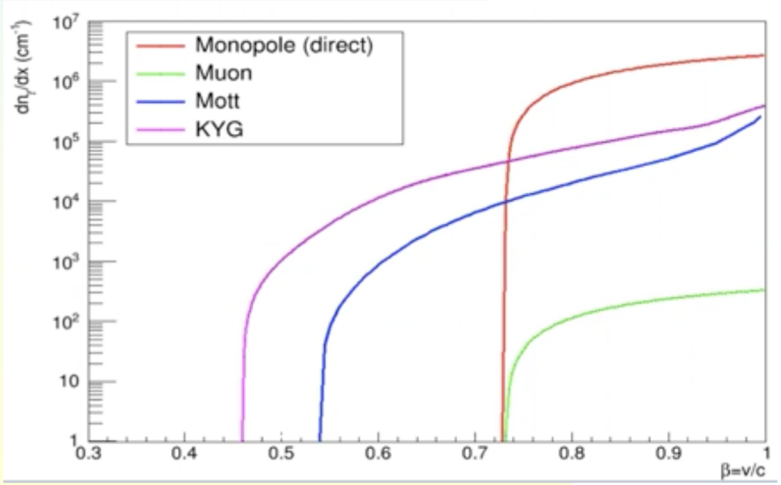


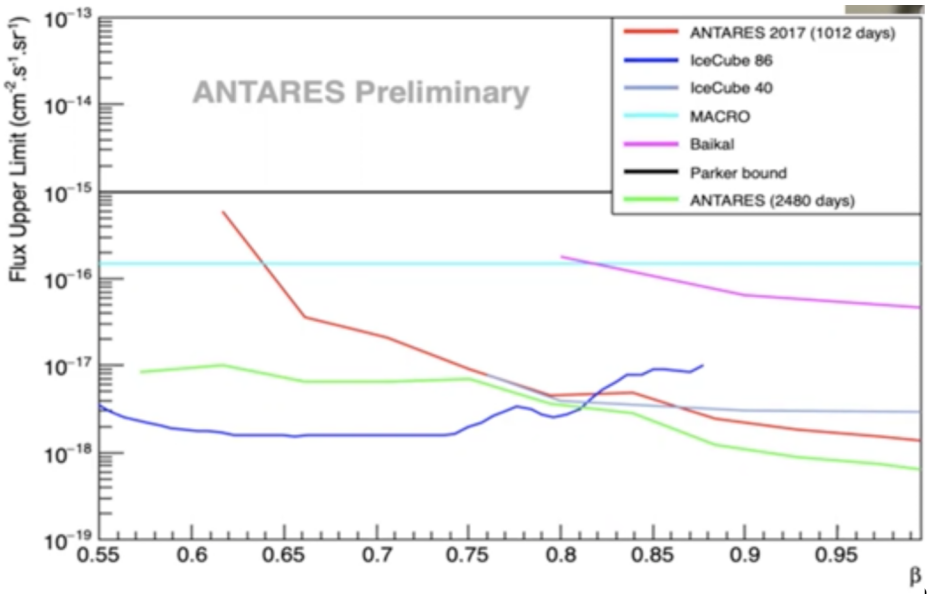


Search for Magnetic Monopoles with ten year of ANTARES data

Jihad Boumazza, with J. Brunner, A. Mousa and Y. Tayalati

- Searched for relativistic ($0.995 > \beta > 0.57$) monopoles
  - 10 years of ANTARES data
  - Direct light from monopoles + from δ rays
- Upward-going, so major background is high-energy neutrinos
  - Astrophysical ν uncertainty can influence monopole backgrounds

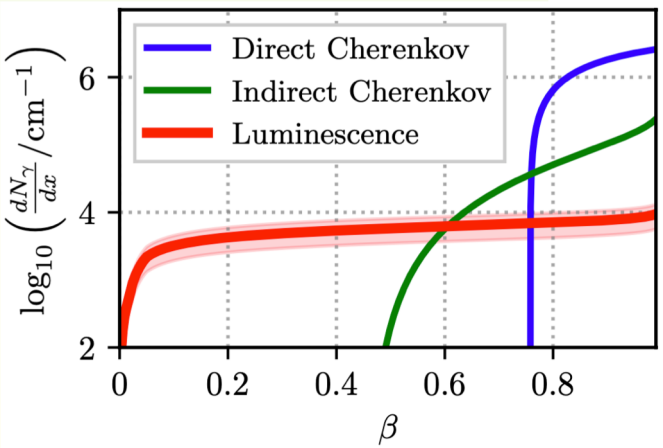


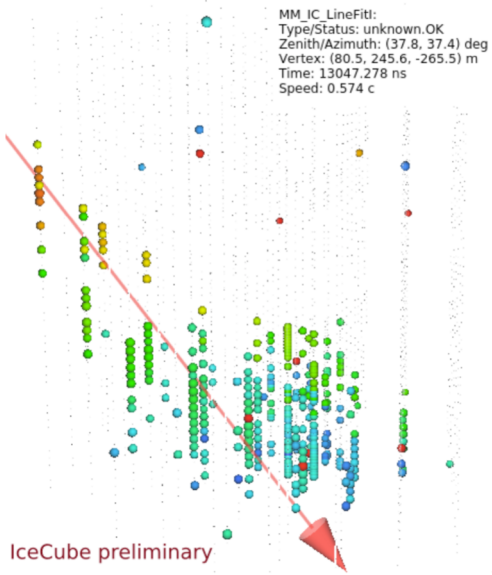


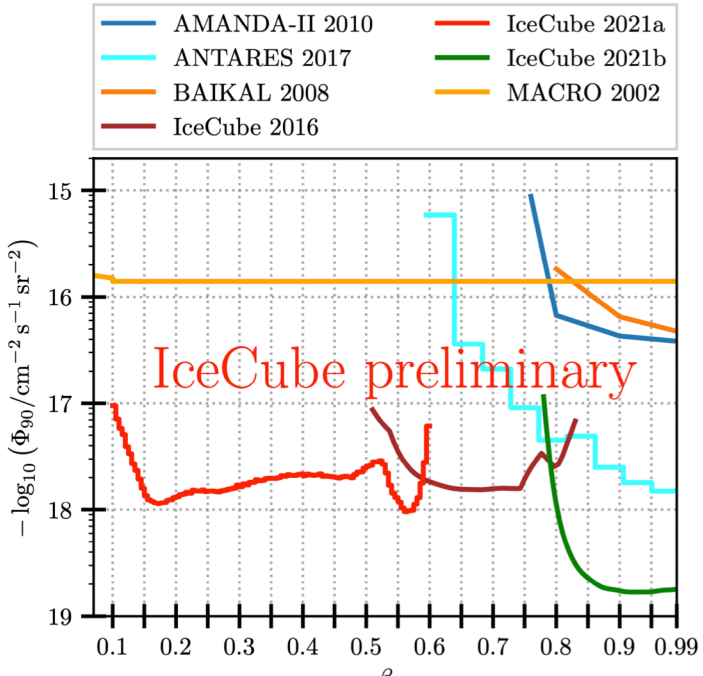
New flux limit in the low relativistic regime for magnetic monopoles at IceCube

Frederik Lauber for the IceCube Collaboration

- $0.10 < \beta < 0.55$
- Similar approach to ANTARES, but additional light source
  - Luminescence in the ice
    - Considerable effort to measure luminescence light output
- Two events found, consistent with coincident muon events







Second order standard-model effects?

- **To claim BSM physics, one needs to eliminate all reasonable standard model possibilities**
- Prompt ν production in sources -> some ν_τ
- Diffractive interactions in the Earth or the detector
  - Adds to cross-section, produces events with inelasticity~0
- Nuclear effects on cross-sections and inelasticity
  - Material-dependent alterations to cross-section, inelasticity dist.
- The ν/ν–bar ratio can affect aggregate behavior
  - Especially important for cross-section studies.

How flexible is the Astrophysical ν flux?

- The as-generated astrophysical flux is unlikely to be a perfect power law. Concavity or more complex behavior is likely.
  - It is risky to assume a single power law, and then take deviation from this as evidence for BSM physics
  - It is easy to generate a source cutoff, for example.
    - Multiple sources with different cutoffs could easily lead to complex behavior.
- Some variation in flavor ratio with energy is also likely.
  - Especially if there are multiple sources with different mechanisms.
  - The flux may not be isotropic.
- How flexible a model of astrophysical ν should we consider when searching for BSM physics?
  - Could a complex astrophysical flux hide BSM physics that is in our existing data?

System uncertainties

- As neutrino telescopes collect more data, systematic errors will become more important
  - Atmospheric flux models (Barr parameters), detector modelling etc.
- More sophisticated treatments are needed to model more complex systematic uncertainties.
  - More nuisance parameters to get acceptable quality fits.
- Current approaches seem to work for setting exclusion limits on BSM physics.
  - Could we trust them if they pointed toward BSM physics?
  - Could they be hiding BSM physics in our current data?
- There is much interplay between different measurements, especially if BSM phenomena are considered.
  - For example, if the cross-section R=2 (for a wide energy range), then the astrophysical ν flux would be ~ halved, and the atmospheric ν flux would be in severe tension with theoretical expectations.

Time for discussion