Abstract

Tau neutrinos are the least well understood particle in the Standard Model. I will discuss the existing and upcoming experimental techniques to study this particle across a large range of energies. I will also discus various standard and new physics motivations to study this particle.

Tau Neutrinos: from GeV to EeV

Peter B. Denton

Snowmass

July 24, 2022

2203.05591

Brookhaven National Laboratory

Brookhaven NDI Neutrino Discovery Initiative

Speaking from Setauket land

Recent particle discoveries

- Top quark (1995)

  CDF hep-ex/9503002

  D0 hep-ex/9503003

- m_t has 0.2% precision

  PDG PTEP 2020

- Higgs boson (2012)

  ATLAS 1207.7214

  CMS 1207.7235

- m_H has 0.14% precision

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Recent particle discoveries

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  PDG PTEP 2020

- Tau neutrino (2000)

  DONuT hep-ex/0012035

- $m_{\nu_\tau} =?$

- Higgs boson (2012)

  ATLAS 1207.7214

  CMS 1207.7235

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Recent particle discoveries

- Top quark (1995)

  CDF hep-ex/9503002

  D0 hep-ex/9503003

- m_t has 0.2% precision

  PDG PTEP 2020

- Neutrino oscillations (1998)
  - Guarantees 2+ new particles

  SuperK hep-ex/9807003

- ???

- Tau neutrino (2000)

  DONuT hep-ex/0012035

- $m_{\nu_\tau} =?$

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  ATLAS 1207.7214

  CMS 1207.7235

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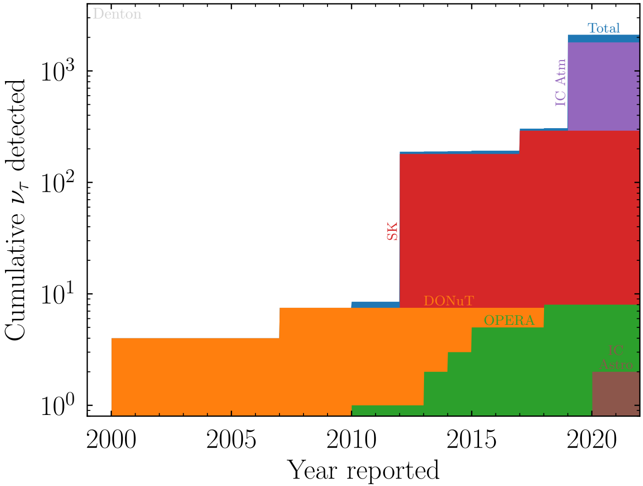
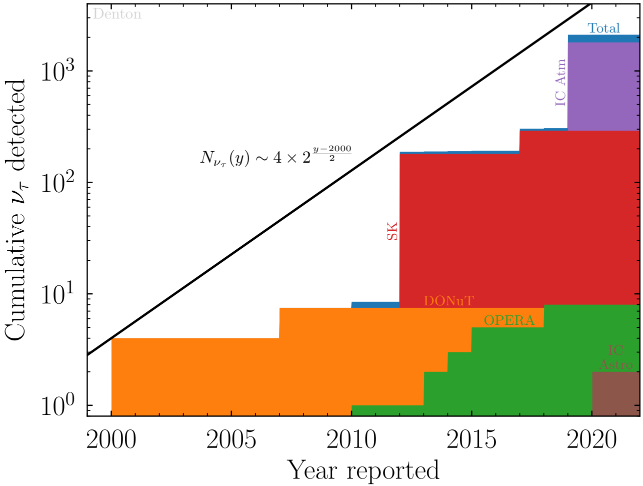
  PDG PTEP 2020

Cumulative tau neutrino data set



Experiment	Source	~Detected
DONuT	Prod	7.5
OPERA	LBL osc	8
SK	Atm osc	291
IceCube	Atm osc	1804
IceCube	Astro decoh	2

Cumulative tau neutrino data set



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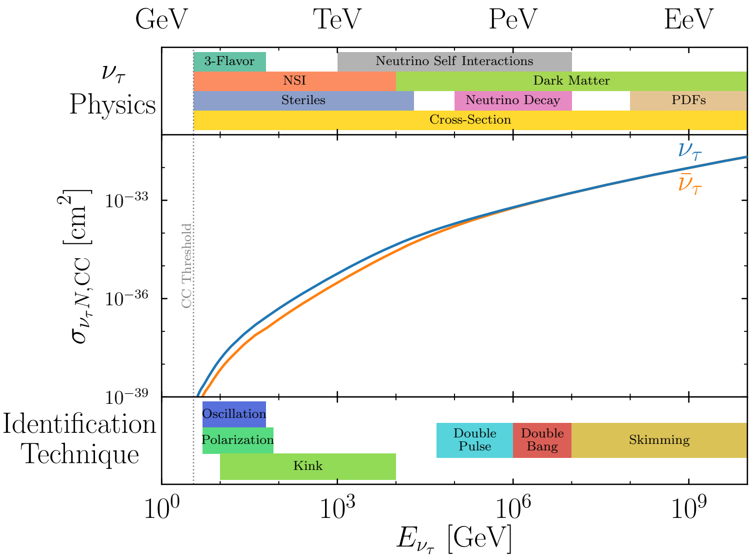
IceCube	Atm osc	1804
IceCube	Astro decoh	2

Doubles every two years!

Tau neutrinos: from GeV to EeV



Detection techniques

Kink

Taus are like muons: dE/dX, decay, but much shorter lifetime
Near threshold ν_τ CC τ large p_T
Need to know source direction

Leveraged by:

1. NOMAD (low density spectrometer): 0 events detected
2. OPERA (emulsion): ~ 8 events detected
3. FASERnu (emulsion): running now
4. SND@LHC (emulsion): running now
5. DUNE ND: SAND (straw tube tracker): future
6. DUNE FD (LArTPC): future

Reconstructs full event; uses oscillations

Oscillations

Given τ properties
Neutrino oscillations
$\Rightarrow \nu_\tau$ identification is possible

T. Stanev astro-ph/9907018

Regardless of nature of oscillations

PBD 2109.14576

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T. Stanev astro-ph/9907018

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PBD 2109.14576

Works by:

1. Biased reconstruction
2. Tau production threshold
3. NC

Criticism: is statistical

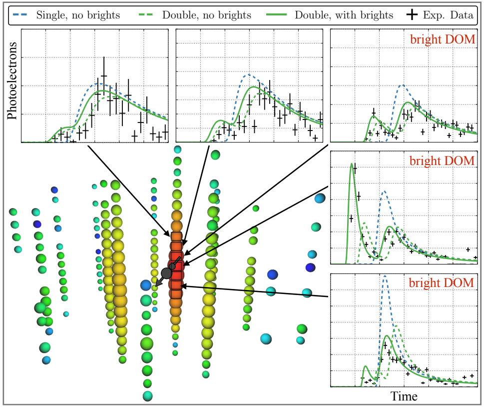
Every technique including emulsion is statistical

Double pulse

Relevant at $E_{\nu_\tau} \gtrsim 100$ TeV

M. Meier, J. Soedingrekso 1909.05127

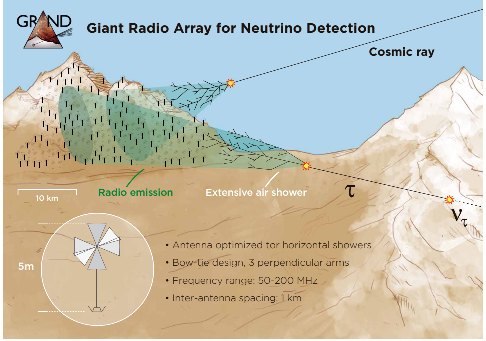
Two candidates!



IceCube 2011.03561

Skimming

Any air shower coming up from the Earth/mountain *must* be a tau neutrino

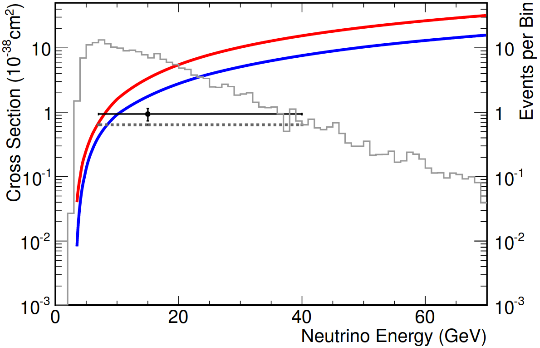


- Relevant at $E_{\nu_\tau} \gtrsim 10-100$ PeV
- At these energies we'll know about ν_τ than ν_e and ν_μ

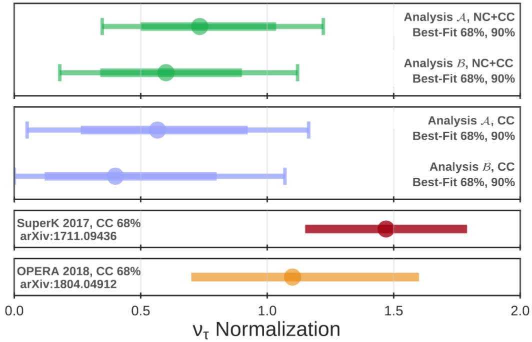
Physics opportunities

ν_τ cross section: GeV

From oscillations and polarization



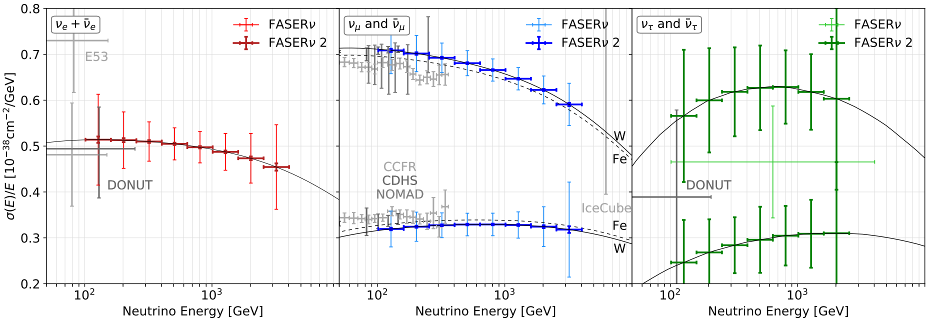
SuperK 1711.09436



IceCube 1901.05366

ν_τ cross section: TeV

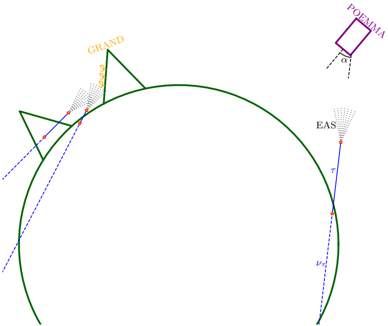
No neutrino cross section measurements at these energies

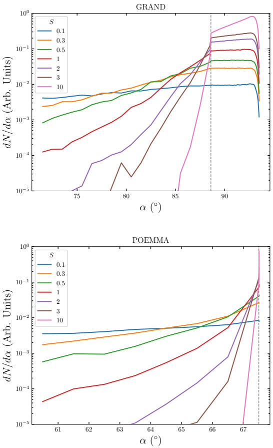


FASERnu 2109.10905

ν_τ cross section: PeV-EeV

Earth-/mountain-skimming provides information about ν_τ *only*

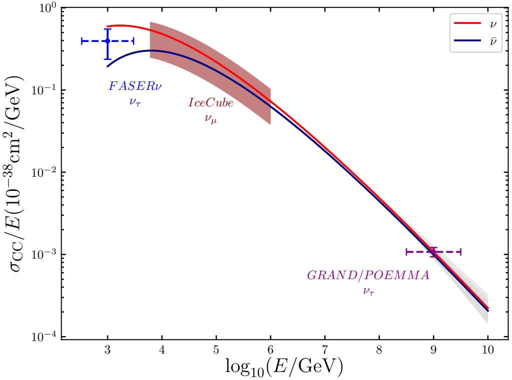




PBD, Y. Kini 2007.10334

ν_τ cross section

Flux unknown $\Rightarrow$ assume 100 events



PBD, Y. Kini 2007.10334

See also I. Esteban, S. Prohira, J. Beacom 2205.09763

- PDF uncertainties become relevant
- UHE neutrinos can constrain PDFs

  V. Bertone, R. Gauld, J. Rojo 1808.02034
- Only possible with tau neutrinos!

New interactions with matter particles

$$\mathcal{L}_{\rm NSI} = -2\sqrt{2}G_F \sum \epsilon_{\alpha\beta}^f (\bar\nu_\alpha \gamma^\mu \nu_\beta)(\bar f \gamma_\mu f)$$

$$H = \frac{1}{2E}\left[U \begin{pmatrix} 0 & & \\ & \Delta m_{21}^2 & \\ & & \Delta m_{31}^2 \end{pmatrix} U^\dagger + a \begin{pmatrix} 1+\epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon_{e\mu}^* & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon_{e\tau}^* & \epsilon_{\mu\tau}^* & \epsilon_{\tau\tau} \end{pmatrix}\right]$$

Tight constraints:

$|\epsilon_{\mu\tau}^\oplus| < 0.004$ (atmospheric)

IceCube 2106.07755

Weak constraints:

$|\epsilon_{e\tau}^\oplus| < 0.17$ (atmospheric)

IceCube 2106.07755

$|\epsilon_{e\tau}^\oplus| \sim 0.2?$ (long-baseline accelerator)

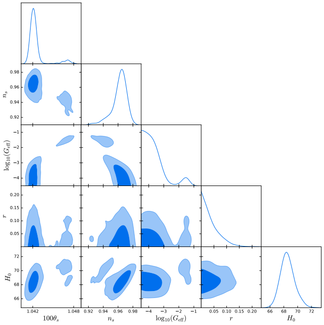
PBD, J. Gehrlein, R. Pestes 2008.01110

$|\epsilon_{\tau\tau}^\oplus| < 0.2$ (atmospheric + scattering)

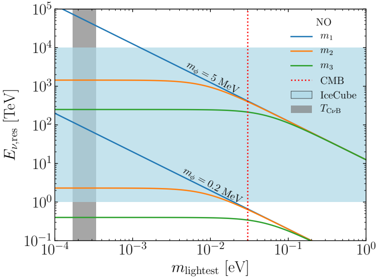
PBD, I. Shoemaker, Y. Farzan 1804.03660

IceCube 2106.07755

New self interactions: cosmology



- New $\nu-\nu$ interaction allowed (preferred?) by cosmology
- Re-allows several minimal inflation models
- Partially solves Hubble tension
- May prefer one new light dof (sterile?)
- CνB scattering $\Rightarrow$ dips at IceCube

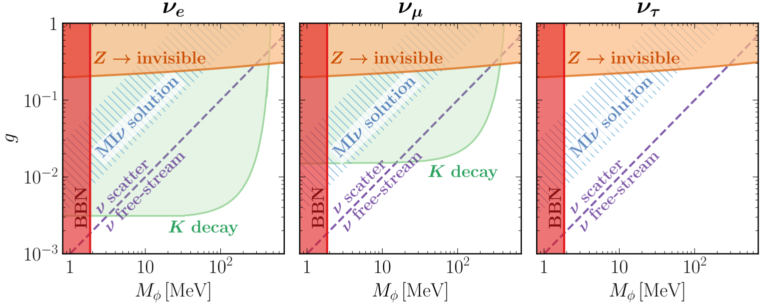


G. Barenboim, PBD, I. Oldengott 1903.02036

C. Kreisch, F. Cyr-Racine, O. Doré 1902.00534

New self interactions: cosmology implies tau neutrinos

BBN/CMB, kaons, and Z decays push the new physics to the ν_τ sector



I. Esteban, et al 2107.13568

N. Blinov, et al 1905.02727

C. Creque-Sarbinowski, J. Hyde, M. Kamionkowski 2005.05332

Next gen IceCube can cover the space

ANITA anomaly

- Balloon-borne radio experiment over Antarctica
- Detected few dozen CR showers reflected off ice
- Detected several unreflected signals
- Some unreflected signals deep into the Earth $\sim 30^\circ$
- Energies $\sim 0.1 - 10$ EeV: ν's readily absorbed in the Earth
- Would expect $\sim 10^6$ more events at smaller angles
- IceCube, Auger, and Telescope Array should have seen this flux

No conclusive answer to ANITA exists

Need PUEO/IceCube-Gen2/...

Others

- Tau neutrinos from the Sun
- Detect tau neutrinos via polarization of decays
- High energy tau neutrinos are regenerated in the Earth at lower energies
- Unitarity violation
- Neutrino decay
- Dark matter decay/annihilation
- Dipole portal
- Models for neutrinos scattering: $B-L$, $B-3L_\tau$, $L_\mu-L_\tau$
- HNLs
- Flavor anomalies

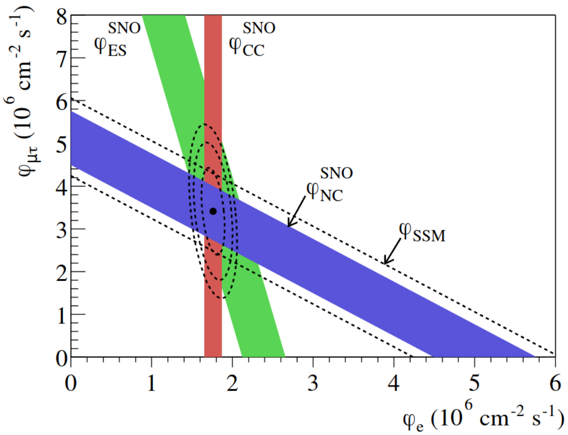
Summary

- Tau neutrinos are the least constrained particle
- More information in the data than people realize
- Many models need testing in ν_τ sector
- Connections across ~ 8 orders of magnitude in energy
- ANITA?¿?
- Entering a golden age of tau neutrinos: FASERν, IceCube, DUNE, HK, GRAND, …

Thanks!

Backups

Overlooked tau neutrinos from the Sun



SNO nucl-ex/0204008

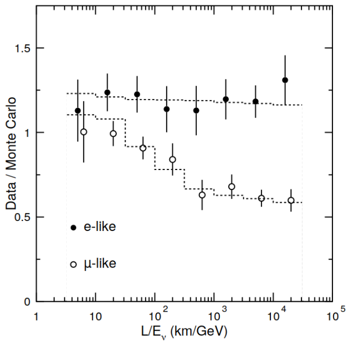
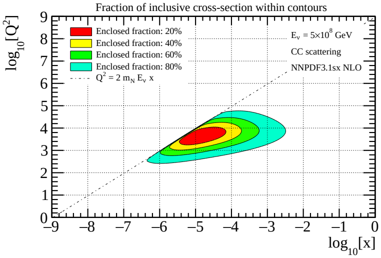
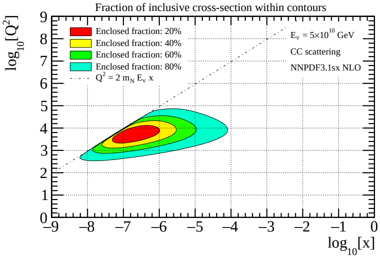


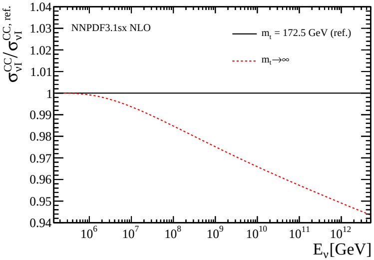
FIG. 4. The ratio of the number of FC data events to FC Monte Carlo events versus reconstructed L/E_ν. The points show the ratio of observed data to MC expectation in the absence of oscillations. The dashed lines show the expected shape for $\nu_\mu \leftrightarrow \nu_\tau$ at $\Delta m^2 = 2.2 \times 10^{-3}\text{eV}^2$ and $\sin^2 2\theta = 1$. The slight L/E_ν dependence for e-like events is due to contamination (2-7%) of ν_μ CC interactions.

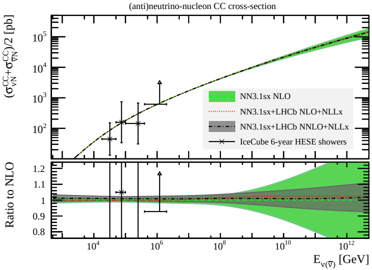
SuperK hep-ex/9807003

ν_τ cross section: PeV-EeV: PDF connection









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V. Bertone, R. Gauld, J. Rojo 1808.02034

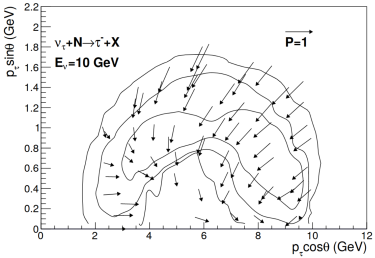
Polarization

SuperK used:

1. Hadronic tau decay information
2. Tau polarization information
3. Simulated with TAUOLA

   Z. Was, P. Golonka hep-ph/0411377

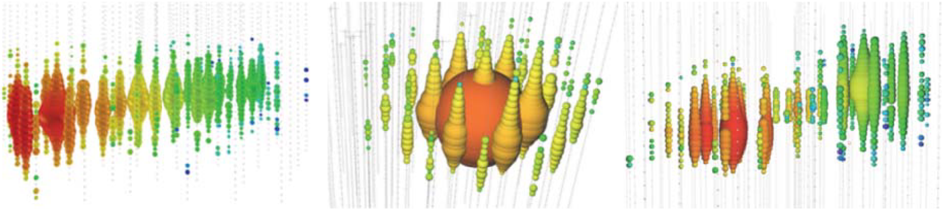
4. Backgrounds are atmospherics: NC and ν_e, ν_μ CC
5. Neural net
6. *and standard oscillations*



Double bang

Relevant at $E_{\nu_\tau} \gtrsim 10$ PeV

J. Learned, S. Pakvasa hep-ph/9405296



Track	Cascade	Double bang
ν_μ CC	ν_e CC	ν_τ CC $\tau \to e, X$ HE
ν_τ CC $\tau \to \mu$	ν_τ CC $\tau \to e, X$ LE	
	ν_α NC	

No double bangs detected

High energy experiments

Experiments	Phase & Online Date	Energy Range	Site	Flavor: Tau	Flavor: All Flavor	Technique: Optical / UV	Technique: Radio	Technique: Showers	Neutrino Target: H_2O	Neutrino Target: Atmosphere	Neutrino Target: Earth's limb	Neutrino Target: Topography	Neutrino Target: Lunar Regolith	Geometry: Embedded	Geometry: Planar Arrays	Geometry: Valley	Geometry: Mountains	Geometry: Balloon	Geometry: Satellite
IceCube	2010	TeV-EeV	South Pole		✓	✓			✓					✓					
KM3NeT	2021	TeV-PeV	Mediteranean		✓	✓			✓					✓					
Baikal-GVD	2021	TeV-PeV	Lake Baikal		✓	✓			✓					✓					
P-ONE	2020	TeV-PeV	Pacific Ocean		✓	✓			✓					✓					
IceCube-Gen2	2030+	TeV-EeV	South Pole		✓	✓	✓		✓					✓					
ARIANNA	2014	>30 PeV	Moore's Bay		✓		✓		✓					✓					
ARA	2011	>30 PeV	South Pole		✓		✓		✓					✓					
RNO-G	2021	>30 PeV	Greenland		✓		✓		✓					✓					
RET-N	2024	PeV-EeV	Antarctica		✓		✓		✓					✓					
ANITA	2008,2014,2016	EeV	Antarctica	✓	✓		✓		✓		✓							✓	
PUEO	2024	EeV	Antarctica	✓	✓		✓		✓		✓							✓	
GRAND	2020	EeV	China / Worldwide	✓			✓			✓	✓	✓			✓		✓		
BEACON	2018	EeV	CA, USA/ Worldwide	✓			✓				✓	✓					✓		
TAROGE-M	2018	EeV	Antarctica	✓			✓				✓	✓					✓		
SKA	2029	>100 EeV	Australia		✓		✓						✓		✓				
Trinity	2022	PeV-EeV	Utah, USA	✓		✓					✓						✓		
POEMMA		>20 PeV	Satellite	✓	✓	✓				✓	✓								✓
EUSO-SPB	2022	EeV	New Zealand	✓		✓					✓							✓	
Pierre Auger	2008	EeV	Argentina	✓	✓			✓		✓	✓	✓			✓				
AugerPrime	2022	EeV	Argentina	✓	✓		✓	✓		✓	✓	✓			✓				
Telescope Array	2008	EeV	Utah, USA	✓	✓			✓		✓					✓				
TAx4		EeV	Utah, USA	✓	✓			✓											
TAMBO	2025-2026	PeV-EeV	Peru	✓				✓				✓				✓			

Operational		Date full operations began
Prototype		Date protoype operations began or begin
Planning		Projected full operations

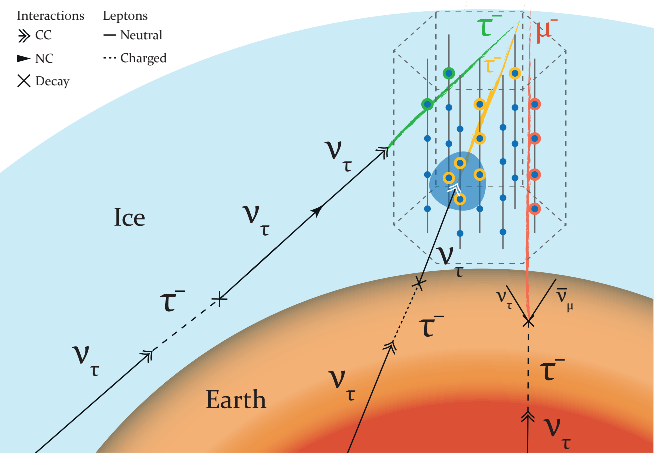
Tau neutrino regeneration

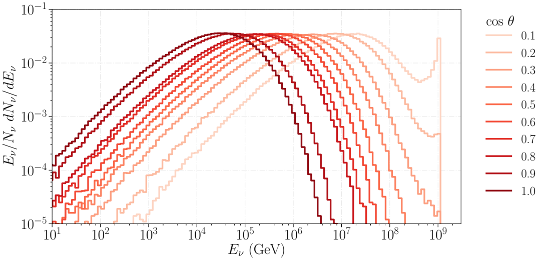
1. High energy tau neutrinos propagating in the Earth
2. Interact:
   2.1 NC: outgoing tau neutrino at lower energy
   2.2 CC: produces a tau which then decays back to a tau neutrinos
3. Still have a tau neutrino

S. Ritz, D. Seckel Nucl. Phys. B 1988

F. Halzen, D. Saltzberg hep-ph/9804354

Tau neutrino regeneration





I. Safa, et al 1909.10487

Unitarity Constraints on Tau Neutrinos

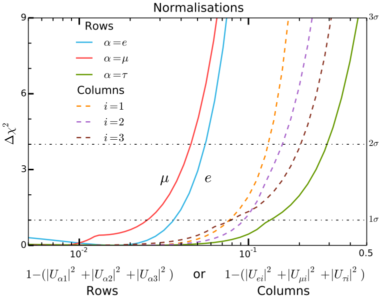
BSM scenario with extra neutrinos,
with no direct Δm^2_{41} probe

Past studies used:

1. $\nu_\mu \to \nu_\tau$ at OPERA
2. SNO NC and CC data

S. Ellis, K. Kelly, S. Li 2008.01088

Z. Hu, J. Ling, J. Tang, T. Wang 2008.09730



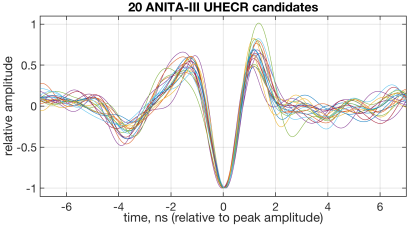
S. Parke M. Ross-Lonergan 1508.05095

$\sim 30\%$ of the ν_τ row could be missing
Atmospheric ν_τ appearance helps

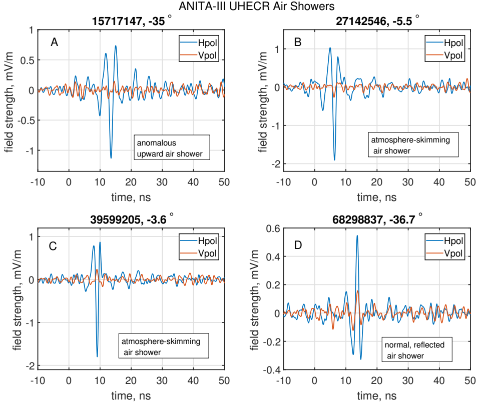
PBD, J. Gehrlein 2109.14575

ANITA anomaly

Typical reflected CR waveforms



a) Anomalous b,c) above horizon CRs
d) reflected CR



ANITA 1803.05088

ANITA 2008.05690

Possible resolutions of ANITA

- Regular CR interactions + ice properties
  - Tranition radiation

    K. de Vries, S. Prohira 1903.08750
  - Subsurface reflections

    I. Shoemaker, et al 1905.02846

  Disfavored

  ANITA 2009.13010
- Sterile mixing reduces absorption

  J. Cherry, I. Shoemaker 1802.01611

  Y. Farzan 2105.03272
- DM scattering in ice

  D. Hooper et al 1904.12865
- Heavy DM→ ν_R

  L. Heurtier, Y. Mambrini, M. Pierre 1902.04584

  D. Borah et al 1907.02740
- Sterile with leptoquark

  B. Chauhan, S. Mohanty 1812.00919
- RPV SUSY

  J. Collins, B. Dev, Y. Sui 1810.08479
- $L_e - L_\tau$ from in Earth

  A. Esmaili, Y. Farzan 1909.07995
- Axion-photon conversion in ionoshpere

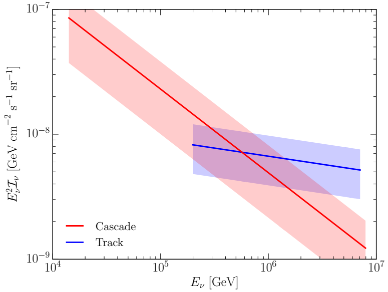
  I. Esteban et al 1905.10372
- Stau, IceCube data also

  D. Fox, et al 1809.09615
- Boosted DM

  L. Heurtier, et al 1905.13223

Neutrino decay

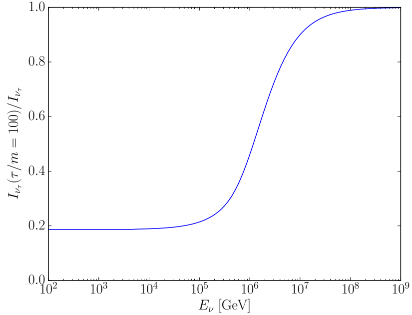
$$\mathcal{L} \supset \frac{g_{ij}}{2}\bar{\nu}_j\nu_i\phi + \frac{g'_{ij}}{2}\bar{\nu}_j i\gamma_5\nu_i\phi$$



IceCube 1607.08006

$$\tau_2/m_2 \sim \tau_3/m_3 \sim 100 \text{ s/eV}$$

preferred at $3-3.5\sigma$

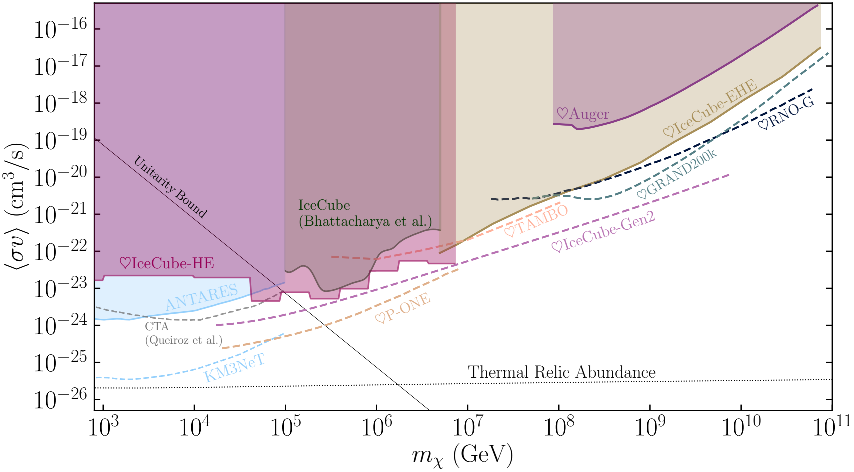


Predict deficit in ν_τ flux at lower energies

PBD, I. Tamborra 1805.05950

A. Abdullahi, PBD 2005.07200

Dark matter



C. Argüelles, et al 1912.09486