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

HET Lunch Discussion

April 29, 2022

2203.05591

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

PDG PTEP 2020

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- Tau neutrino (2000)

  DONuT hep-ex/0012035

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

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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

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

- Higgs boson (2012)

  ATLAS 1207.7214

  CMS 1207.7235

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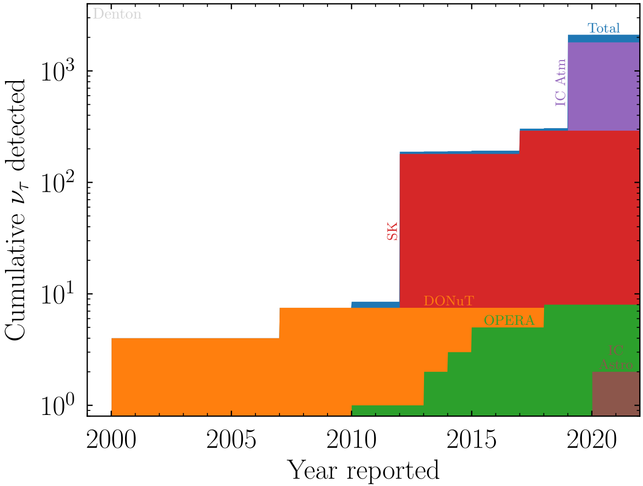
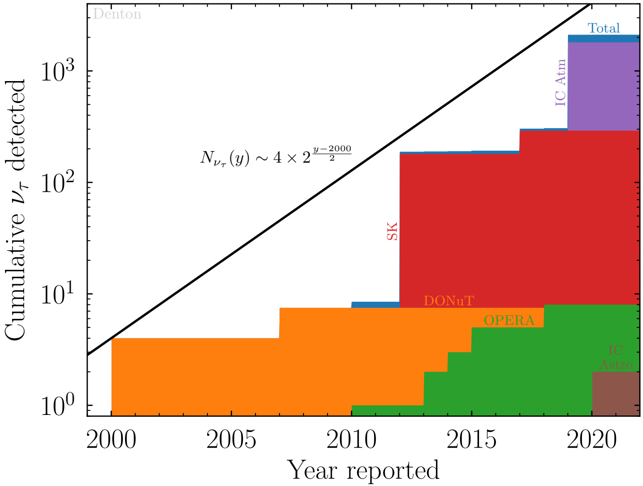
  PDG PTEP 2020

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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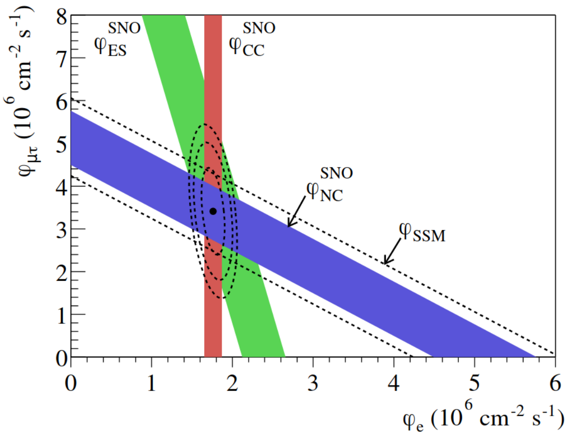
IceCube	Astro decoh	2

Doubles every two years!

Overlooked tau neutrinos from the Sun



SNO nucl-ex/0204008

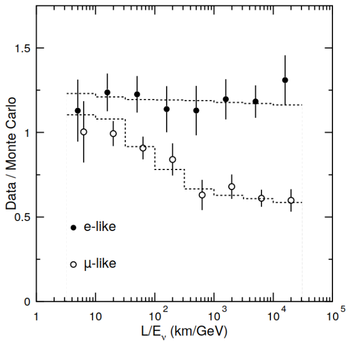
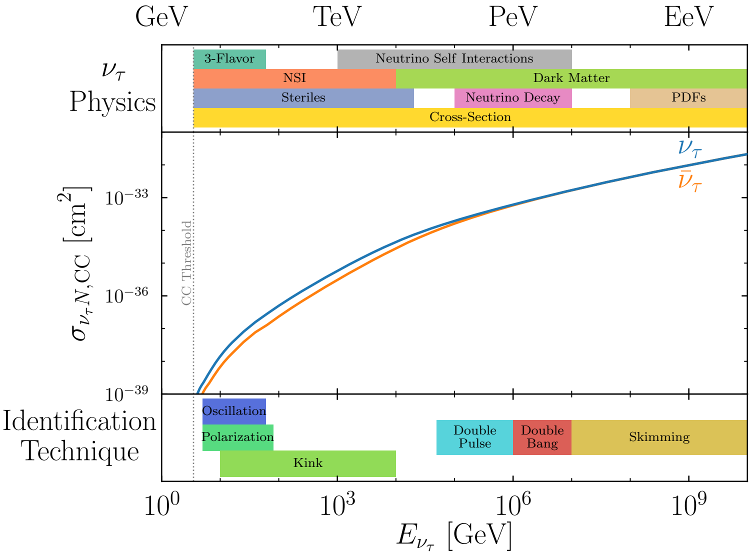


FIG. 4. The ratio of the number of FC data events to FC Monte Carlo events versus reconstructed L/E_ν. The points show the ratio of observed data to MC expectation in the absence of oscillations. The dashed lines show the expected shape for $\nu_\mu \leftrightarrow \nu_\tau$ at $\Delta m^2 = 2.2 \times 10^{-3}\text{eV}^2$ 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

Tau neutrinos: from GeV to EeV



Outline

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

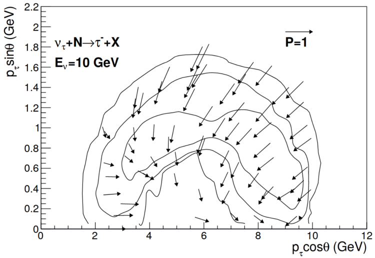
Reconstructs full event; uses oscillations

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*



Oscillations

Given τ properties
Neutrino oscillations
ν_τ identification is possible

T. Stanev astro-ph/9907018

Regardless of nature of oscillations

PBD 2109.14576

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PBD 2109.14576

Works by:

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

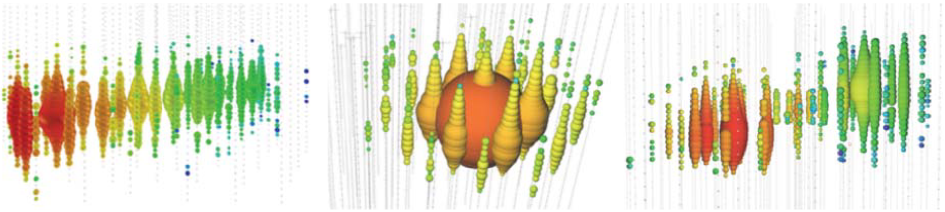
Criticism: is statistical

Every technique including emulsion is statistical

Double 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	

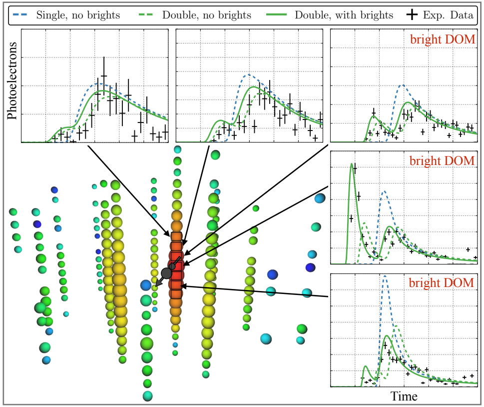
No double bangs detected

Double pulse

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

M. Meier, J. Soedingrekso 1909.05127

Two candidates!



IceCube 2011.03561

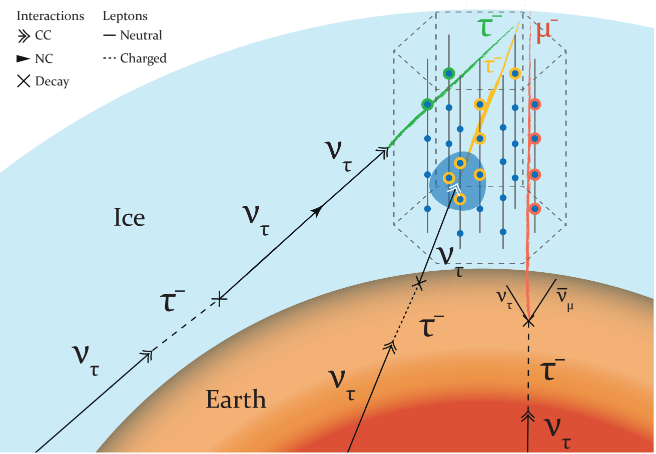
Tau neutrino regeneration

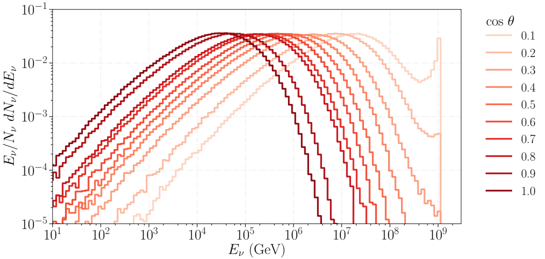
1. High energy tau neutrinos propagating in the Earth
2. Interact:
   2.1 NC: outgoing tau neutrino at lower energy
   2.2 CC: produces a tau which then decays back to a tau neutrinos
3. Still have a tau neutrino

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

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

Tau neutrino regeneration

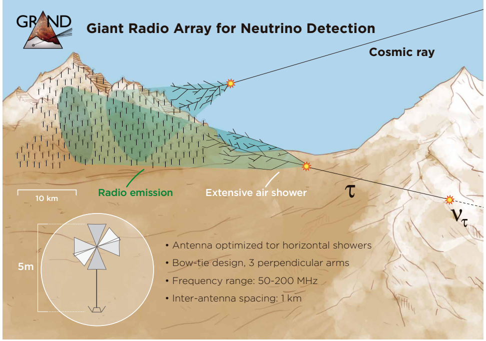




I. Safa, et al 1909.10487

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

High energy experiments

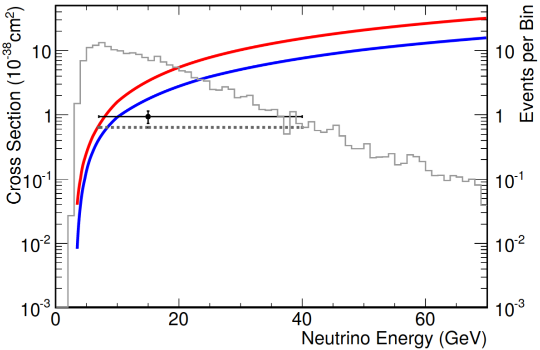
				Flavor		Technique			Neutrino Target					Geometry					
Experiments	Phase & Online Date	Energy Range	Site	Tau	All Flavor	Optical / UV	Radio	Showers	H_2O	Atmosphere	Earth's limb	Topography	Lunar Regolith	Embedded	Planar Arrays	Valley	Mountains	Balloon	Satellite
IceCube	2010	TeV-EeV	South Pole		✓	✓			✓					✓					
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

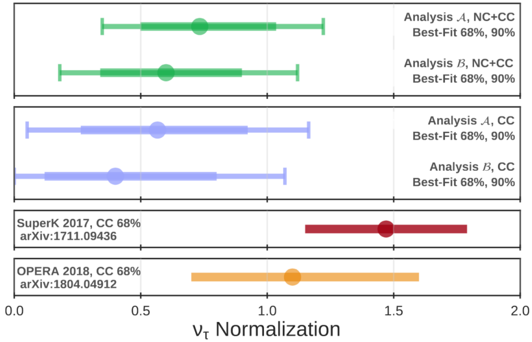
Physics opportunities

ν_τ cross section: GeV

From oscillations and polarization



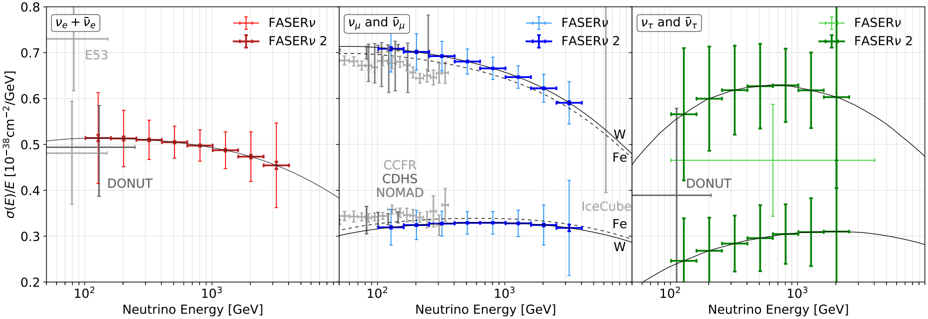
SuperK 1711.09436



IceCube 1901.05366

ν_τ cross section: TeV

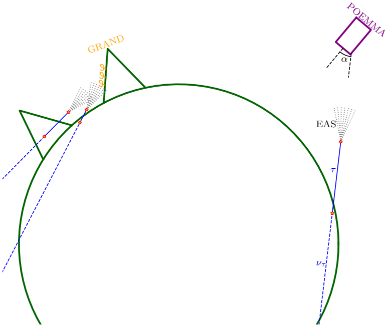
No neutrino cross section measurements at these energies

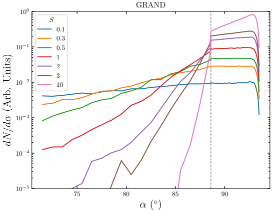


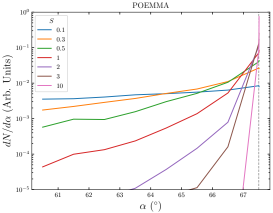
PBD, et al 2109.10905

ν_τ cross section: PeV-EeV

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



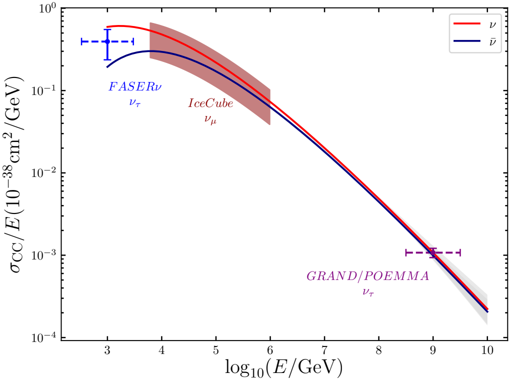




PBD, Y. Kini 2007.10334

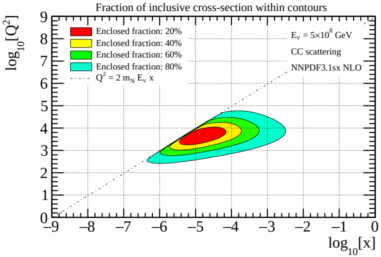
ν_τ cross section: PeV-EeV

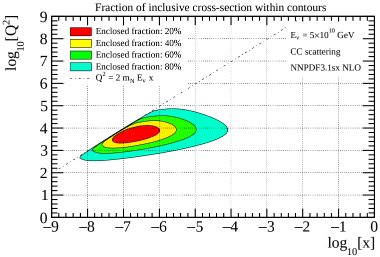
Flux unknown $\Rightarrow$ assume 100 events

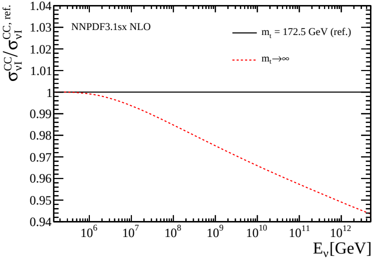


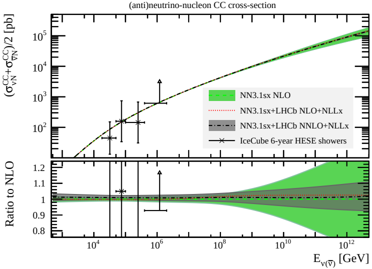
PBD, Y. Kini 2007.10334

ν_τ cross section: PeV-EeV: PDF connection









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

2203.05591

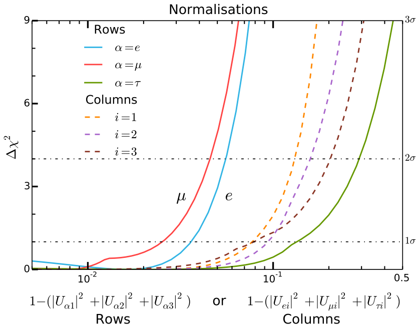
Unitarity Constraints on Tau Neutrinos

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

New interactions with matter particles

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

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

Tight constraints:

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

IceCube 2106.07755

Weak constraints:

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

IceCube 2106.07755

$|\epsilon_{e\tau}^\oplus|\sim0.2?$ (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

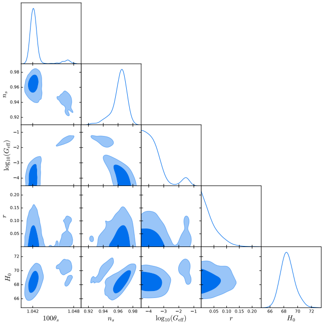
IceCube 2106.07755

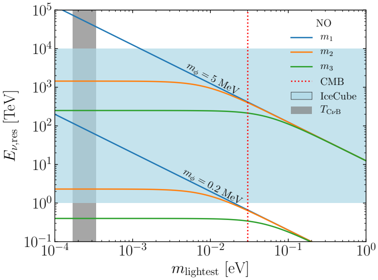
New self interactions: cosmology

- 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?)
- $C\nu B$ scattering $\Rightarrow$ dips at IceCube

G. Barenboim, PBD, I. Oldengott 1903.02036

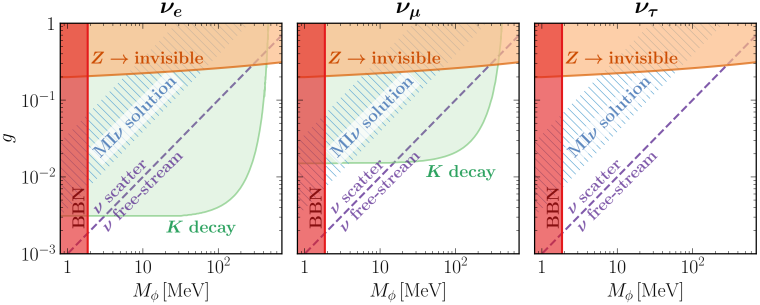
C. Kreisch, F. Cyr-Racine, O. Doré 1902.00534





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

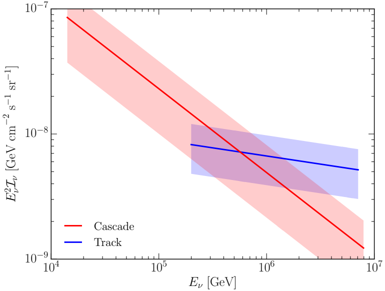
N. Blinov, et al 1905.02727

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

Next gen IceCube can cover the space

Neutrino decay

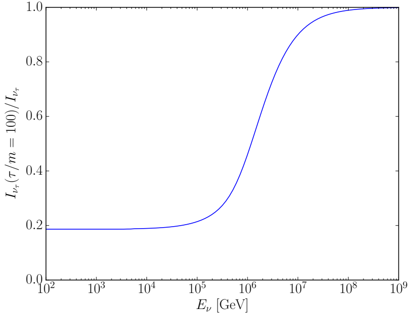
$$\mathcal{L} \supset \frac{g_{ij}}{2}\bar{\nu}_j\nu_i\phi + \frac{g'_{ij}}{2}\bar{\nu}_j i\gamma_5\nu_i\phi$$



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

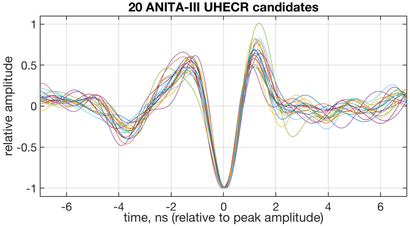
A. Abdullahi, PBD 2005.07200

ANITA anomaly

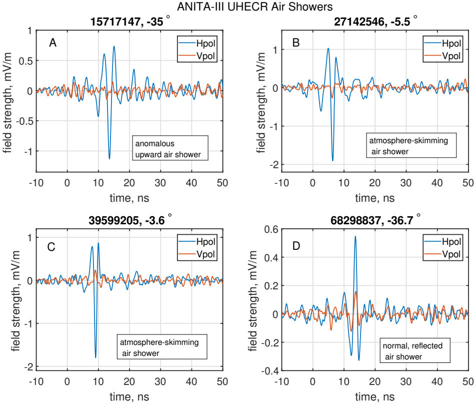
- Balloon-borne radio experiment over Antarctica
- Detected few dozen CR showers reflected off ice
- Detected several unreflected signals
- Some unreflected signals deep into the Earth $\sim 30^\circ$
- Energies $\sim 0.1 - 10$ EeV: ν's readily absorbed in the Earth
- Would expect $\sim 10^6$ more events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

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$\rightarrow \nu_R$

  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

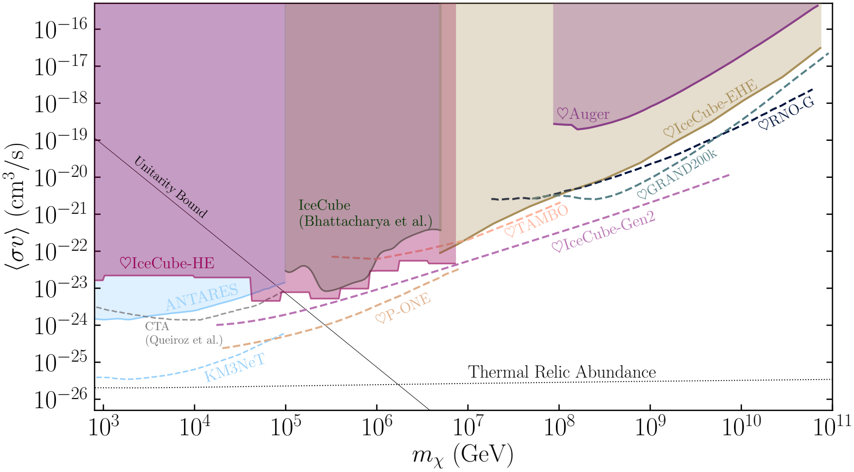
  D. Fox, et al 1809.09615
- Boosted DM

  L. Heurtier, et al 1905.13223

No conclusive answer to ANITA exists

Need PUEO/IceCube-Gen2/...

Dark matter



C. Argüelles, et al 1912.09486

Others

- 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
- ANITA?¿?
- Will be entering a golden age of tau neutrinos: DUNE, FASERν, IceCube, GRAND

Thanks!

Backups

Inflation meet neutrinos