Particle physics at extreme energies using neutrino telescopes
why detecting high energy neutrinos?
neutrino sources

- naturally occurring neutrinos can have extreme energies

- manmade beams can reach $E \sim 50$ GeV at most

- but the fluxes are low, so you need really large detectors
studying their sources
using $\nu$ as probes
neutrino telescope basics
interaction mainly with single quarks in nucleons – simple and well understood
detect neutrinos from all directions starting at a few GeV -atmospheric -astrophysical -cosmogenic -others
-muons travel from tens of meters to several km
-other particles shower

sparsely instrumented detectors work
-muons travel from tens of meters to several km

-other particles shower

sparsely instrumented detectors work
1978: 1.26 km³
22,698 OMs

DUMAND in Hawaii
first proposed in 1973
1978: 1.26 km³
22,698 OMs

1998
NT200
Lake Baikal

2000
AMANDA
South Pole

2008
ANTARES
Mediterranean
1978: 1.26 km³
22,698 OMs

IceCube 1km³
5,160 OMs
IceCube

the largest neutrino detector in the world

Deep Core

Penetrator

HV Divider

LED Flasher Board

DOM Mainboard

Mu-metal grid

Delay Board

PMT

RTV gel

Glass Pressure Housing
IceCube
the largest neutrino detector in the world

1 km³ of ice monitored by 5000+ photo-sensors
buried 1.5 km under the surface
IceCube

two regions

IceCube
17m spacing in z 125m in x-y

DeepCore
7m in z, 40-70m in x-y
Interaction:

Primary
- Type: NuMuBar
- Energy: 7.34e+01 GeV

Muon
- Type: MuPlus
- Energy: 5.22e+01 GeV

Cascade
- Type: PiPlus
- Energy: 9.93e+00 GeV
neutrino physics with IceCube
oscillation parameters

atmospheric neutrino oscillations
-crucial in discovery of neutrino mass
-Nobel prize 2015
-still being understood

\[ P_{\nu_\alpha \rightarrow \nu_\beta}^{2\nu}(L, E) = \sin^2(2\theta) \sin^2 \left( \frac{\Delta m^2}{4E} L \right) \]

\[
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau
\end{pmatrix} = \\
\begin{pmatrix}
U_{e1} & U_{e2} & U_{e3} \\
U_{\mu1} & U_{\mu2} & U_{\mu3} \\
U_{\tau1} & U_{\tau2} & U_{\tau3}
\end{pmatrix} \\
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3
\end{pmatrix}
\]
neutrino oscillations & DeepCore

\[ P_{\nu_\alpha \rightarrow \nu_\beta} (L, E) = \sin^2(2\theta) \sin^2\left(\frac{\Delta m^2}{4E}L\right) \]
\[ P_{\nu_\alpha \rightarrow \nu_\beta}^{2\nu}(L, E) = \sin^2(2\theta) \sin^2\left(\frac{\Delta m^2}{4E}L\right) \]
tau neutrino appearance

disappeared muon neutrinos mainly go to tau neutrinos
- tau lepton E threshold $\rightarrow$ only HE detection
- test of unitarity of PMNS matrix
- test of NuTau CC cross section
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\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3
\end{pmatrix}
\]

- HESE with ternary topology ID
- Best fit: 0.20 : 0.39 : 0.42
- Global Fit (IceCube, APJ 2015)
- Inelasticity (IceCube, PRD 2019)
- 3\nu-mixing 3\sigma allowed region

\(\nu_e : \nu_\mu : \nu_\tau\) at source \(\rightarrow\) on Earth:
- 0:1:0 \(\rightarrow\) 0.17 : 0.45 : 0.37
- 1:2:0 \(\rightarrow\) 0.30 : 0.36 : 0.34
- 1:0:0 \(\rightarrow\) 0.55 : 0.17 : 0.38
- 1:1:0 \(\rightarrow\) 0.36 : 0.31 : 0.33

\[\text{Atmospheric } \bar{\nu} \text{ from AGN}\]
\[\text{Cosmogenic } \nu \]
some **odd neutrino results** suggest **extra neutrinos** that you can obtain **via oscillations**, but do not interact directly with the world (**sterile**) 

NTs can probe this hypothesis with **high precision**
\[
\begin{pmatrix}
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\nu_2 \\
\nu_3
\end{pmatrix}
\]
EHE neutrino cross section

study of interactions of extreme high energy neutrinos using the Earth as the target

interaction rate

IceCube Preliminary

interaction properties

energy scale is inaccessible to man-made experiments
the challenges of IceCube data
the challenges to its operation & construction
Water $\text{km}^3$ scale neutrino telescopes under construction

- Km3NeT – Mediterranean sea
- GVD-Baikal – Lake Baikal

serious technical challenges in deployment and operations
– salt water is tough
enters Ocean Networks Canada

established in 2007
operates Ocean observatories
provides deep sea research infrastructure
UofA & TUM researchers established cooperation in 2017

“potential installation”
first step forward: P-ONE
Pacific Ocean Neutrino Explorer

- 200 modules
- 10 strings/lines
- order 100m spacing
- exploring potential for:
  - tau neutrinos
  - charm production
  - exotic oscillations
first step forward: P-ONE
Pacific Ocean Neutrino Explorer

- 200 modules
- 10 strings/lines
- order 100m spacing
- exploring potential for:
  tau neutrinos
  charm production
  exotic oscillations
and after P-ONE?

an array large enough to see TeV-PeV events with large statistics:
- do real neutrino astronomy
- study extreme high energy interactions

To know more, pay us a visit in http://www.pacific-neutrino.org/
thank you

questions?
backup
detect **muons** from cosmic ray showers “above” the detector

lots of them

2 kHz rate in IceCube
dominant interaction channel is deep inelastic scattering – well understood
non-standard interactions

mediated by non-SM bosons
modify neutrino rates at all energies
Coherent 2018 ($\epsilon^{\alpha\beta}_{e\mu} = \epsilon^{\alpha\beta}_{e\tau}$)
oscillation parameters
sterile neutrino searches

effects in low & high energy regions

\[ P_{\nu_\alpha \to \nu_\beta}^{2\nu}(L, E) = \sin^2 (2\theta) \sin^2 \left( \frac{\Delta m_{41}^2 L}{4E} \right) \]
sterile neutrino searches

Some experiments have obtained odd neutrino results - a potential explanation: extra neutrinos that you can obtain via oscillations, but do not interact directly with the world (sterile)

NTs can probe this hypothesis with high precision.
CR composition around the knee

origin of the CR knee is unknown
change in composition or acceleration mechanism?
CR composition around the knee

muon multiplicity can **differentiate** between heavy/light nuclei

![Graph showing muon multiplicity vs. cosmic ray energy per nucleon](Fedynitch)
prompt muon production

prompt decay of charm+unflavored mesons -still unobserved -main background for astrophysical neutrinos

Fedynitch, arXiv:1806.04140
neutrino detection

- $E_\nu = 0 \ldots 1$ MeV
  - Coherent scattering
  - Capture in radioactive nuclei
- $E_\nu = 1$-100 MeV
  - Inverse beta decay
- $E_\nu = 100$ MeV - 20 GeV
  - Quasi-elastic scattering
  - NC elastic scattering
  - Coherent, resonant pion production
- $E_\nu = 20^+$ GeV
  - Deep Inelastic Scattering
neutrino sources

- relic neutrinos from the early Universe
- solar neutrinos
- neutrinos from supernova
- atmospheric neutrinos
- cosmic HE neutrinos