Physics 290E - 11/3/21

High-energy neutrino interactions with IceCube

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Outline

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2. Physics behind IceCube
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Part 1: The IceCube Experiment

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What is IceCube?

IceCube
South Pole Neutrino Observatory

- Centered around IceCube Neutrino Observatory
  - Cherenkov detector in Antarctica
  - Started data taking in 2008
- Focus on **neutrino astronomy**
  - General idea: observe the universe by looking at neutrinos rather than photons
  - Useful for observing distant phenomena since they scatter very rarely

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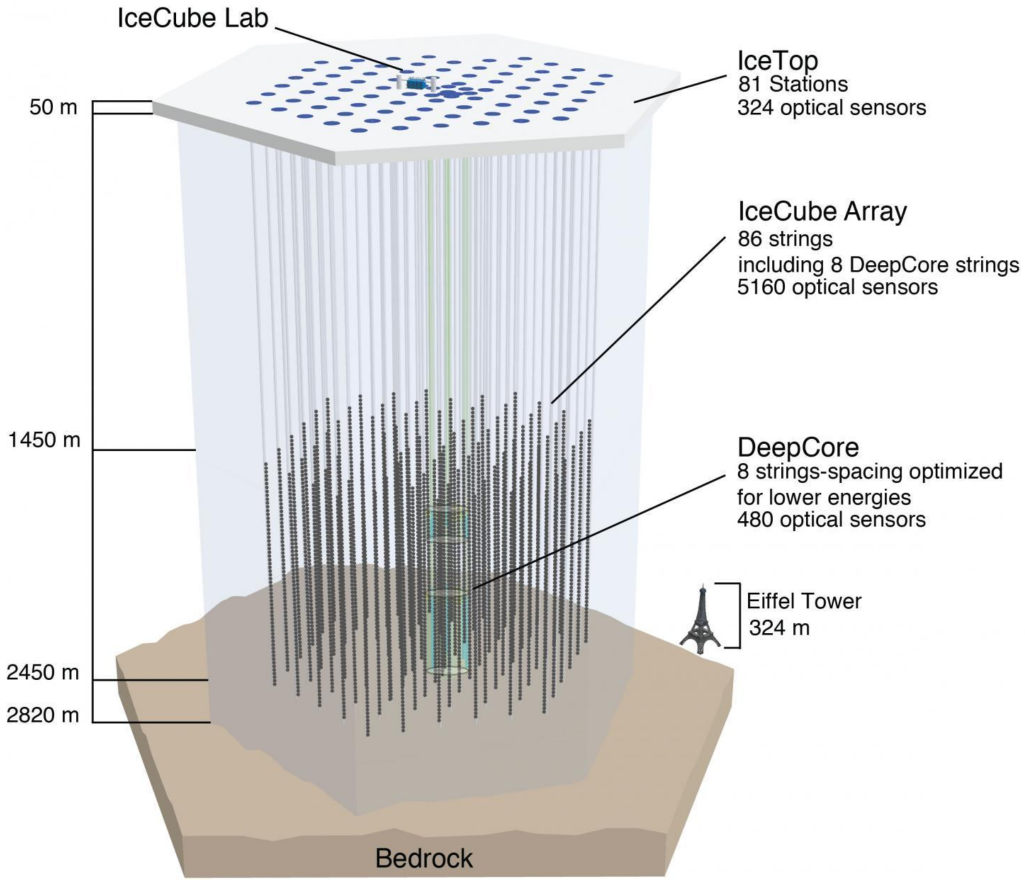
The IceCube detector

- Detector encompasses 1 km^3 of ice
- 86 strings with 5160 total Digital Optical Modules (DOMs) containing PMTs
- DeepCore: set of 8 central, densely-spaced strings



Experimental focus

- **High-energy neutrinos** (~TeV-PeV scale) created by violent interstellar events of particular interest for **astronomy**
  - Allow for identification of point sources in the sky (supernovae, gamma-ray bursts, black hole mergers, etc.)
- Can also detect **lower-energy neutrinos** created by cosmic ray interactions in the atmosphere (~GeV scale)
  - More interesting for **particle physics** purposes since travel distance is known (WIMPs, sterile neutrinos, oscillations, etc.)

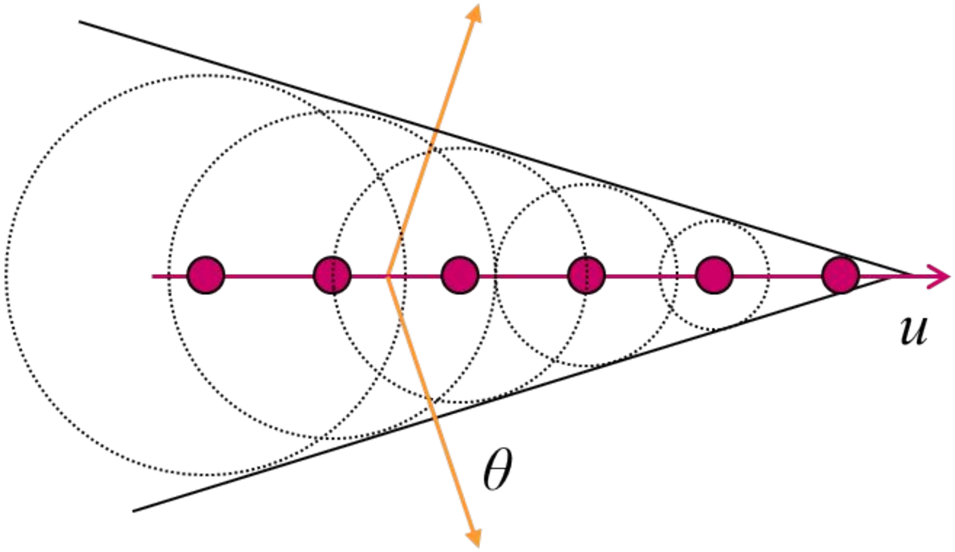
Detecting neutrinos

- Neutrinos only interact weakly -> **cannot measure directly**
  - Need to examine products of their interactions
- IceCube detects **Cherenkov radiation** (photons) originating from particles produced in neutrino interactions via its array of PMTs
  - Incoming neutrinos interact with protons/neutrons in the ice
- Antarctic ice allows photons to travel relatively undisturbed (minimal scattering)

Part 2: Physics behind IceCube

Cherenkov radiation

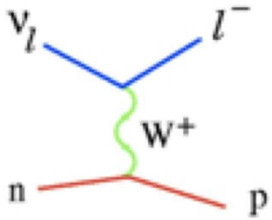
- Occurs when charged particles travel through medium at **v > c/n**
- Particle propagates faster than its own EM field -> interference
- Manifests as light cones along trajectory



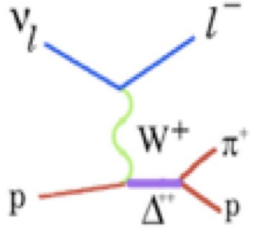
Neutrino scattering

- Three main types of neutrino-nucleon interactions:
  - Quasi-elastic scattering (QE)
  - Resonance production (RES)
  - Deep inelastic scattering (DIS)
- IceCube probes **deep inelastic neutrino-nucleon scattering**
  - High-energy neutrino “tears apart” nucleon

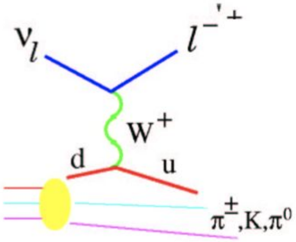
QE:

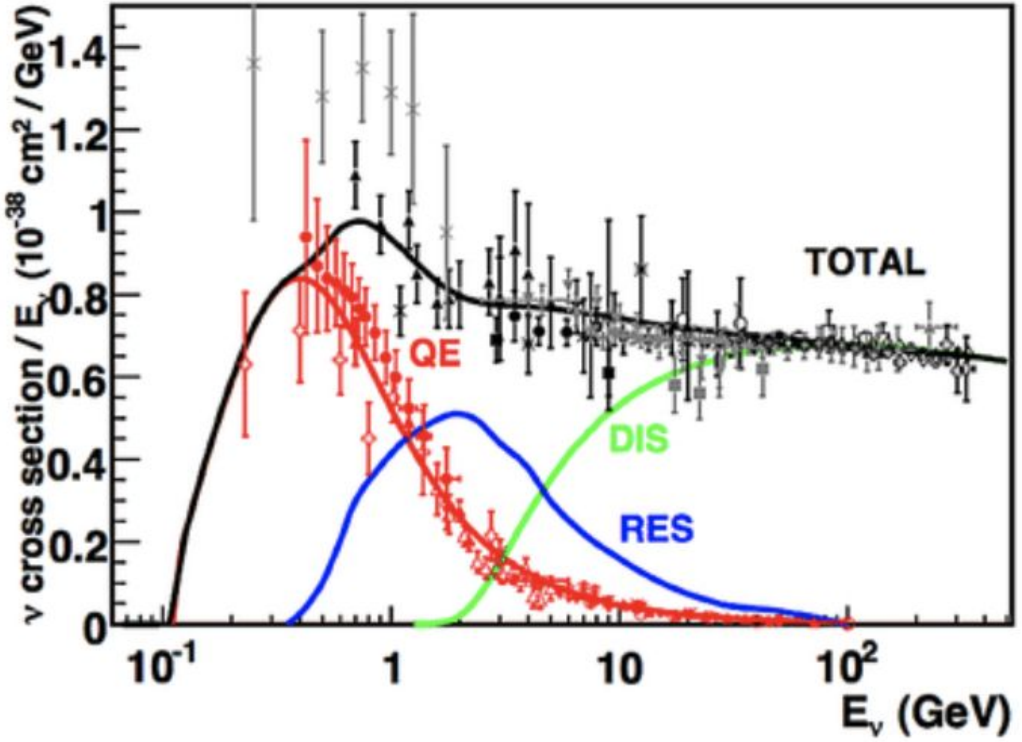


QE:



DIS:





Deep inelastic scattering (DIS) dominates at high neutrino energies

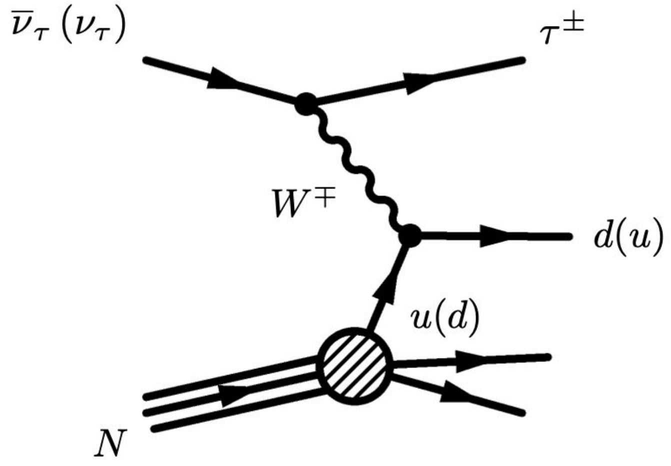
Charged vs. neutral current

Charged-current (CC) interactions mediated by W± bosons, **neutral-current** (NC) interactions by Z boson

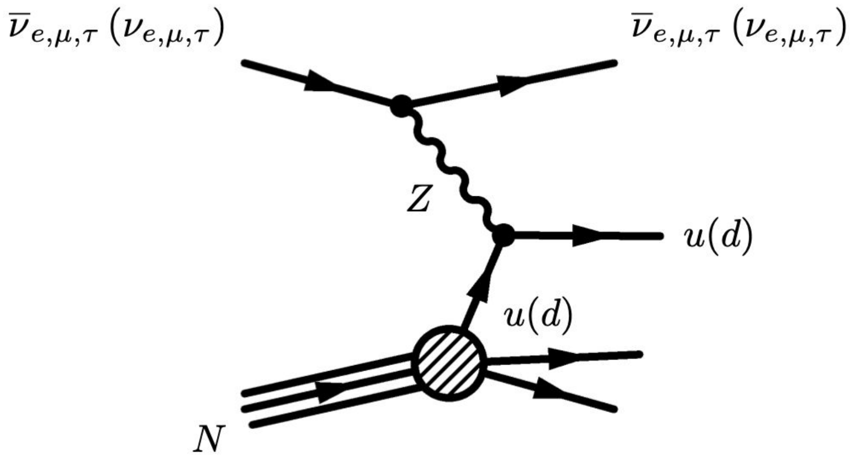
$$NC : \nu_\alpha + N \rightarrow \nu_\alpha + X$$

$$CC : \nu_\alpha + N \rightarrow l_\alpha^- + X$$

N = nucleon
X = hadronic shower
l = charged lepton



Charged-current interaction



Neutral-current interaction

Detector signatures

- Hadronic cascades usually difficult to resolve due to sparse detector grid
  - Can't probe structure of hadronic showers
- Two primary event types: **tracks** and **cascades**
  - Electrons scatter easily and produce electromagnetic cascades
  - Muons are easiest to identify since they don't scatter as easily and produce tracks
  - Taus decay quickly and so are hard to distinguish from electrons -> given enough energy they could produce "double bang" signature (two cascades connected by a track)
- Tracks useful for finding point sources, cascades for energy studies

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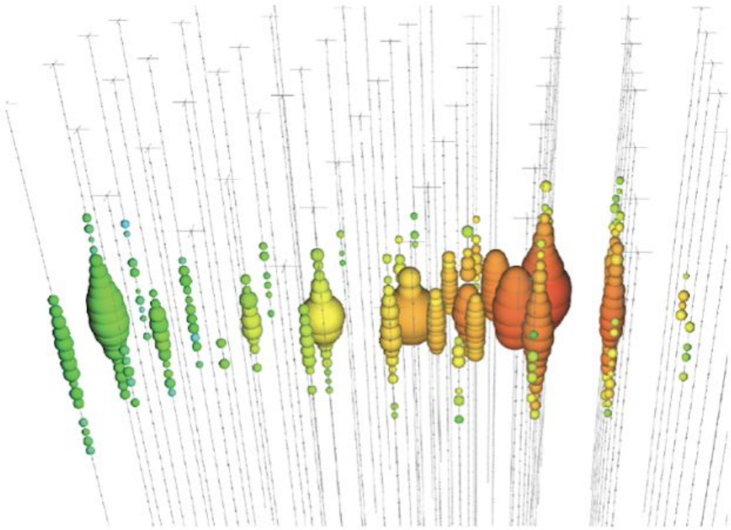
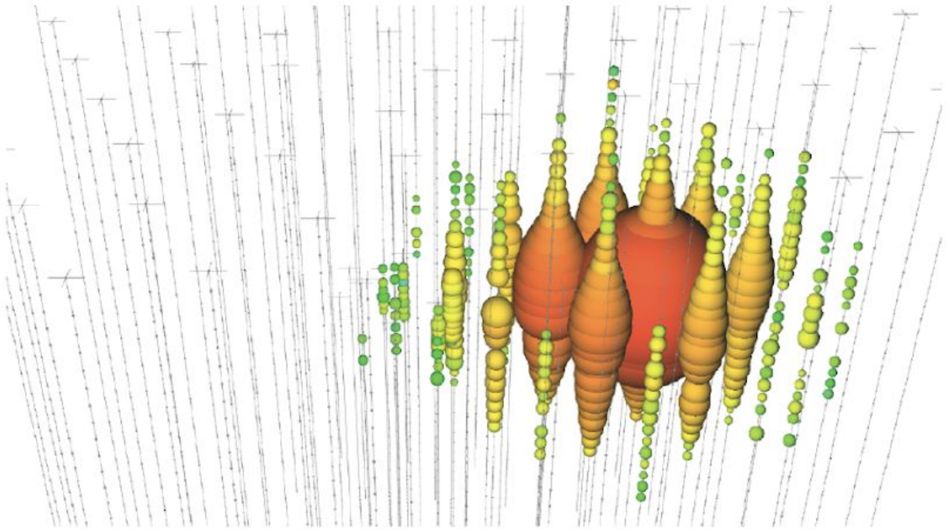


Tracks (produced by muons)



Cascades (produced by electrons, taus, hadronic showers)

Important backgrounds

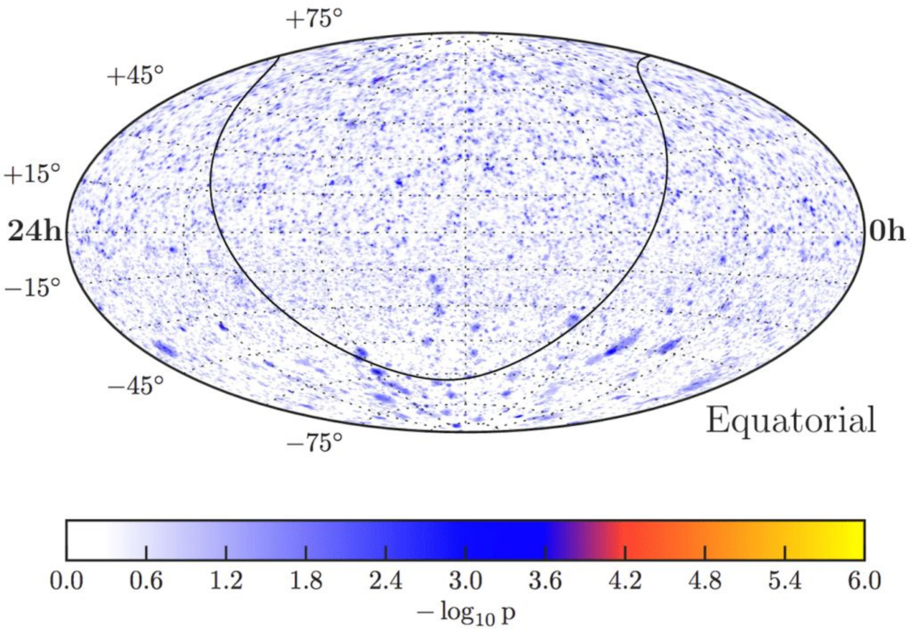
- Two main backgrounds: atmospheric muons and atmospheric neutrinos
  - Produced by cosmic ray interactions in the atmosphere
- **Atmospheric muons** vetoed by only considering events originating from below the horizon (“upgoing”) or cutting events not originating in detector
  - Rate is ~100 billion per year
- **Atmospheric neutrinos** are dominant at lower energies
  - Rate is ~100,000 per year
  - Relevant for particle physics analyses

Part 3: Interesting results

Astrophysics

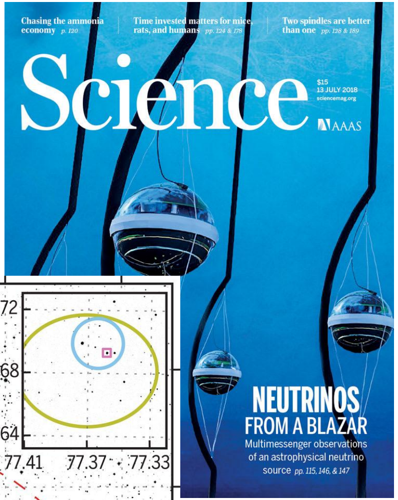
- IceCube has produced **neutrino sky maps** in search for point sources
- Resolution for northern hemisphere is much better than southern hemisphere
  - Due to cut on “downgoing” events

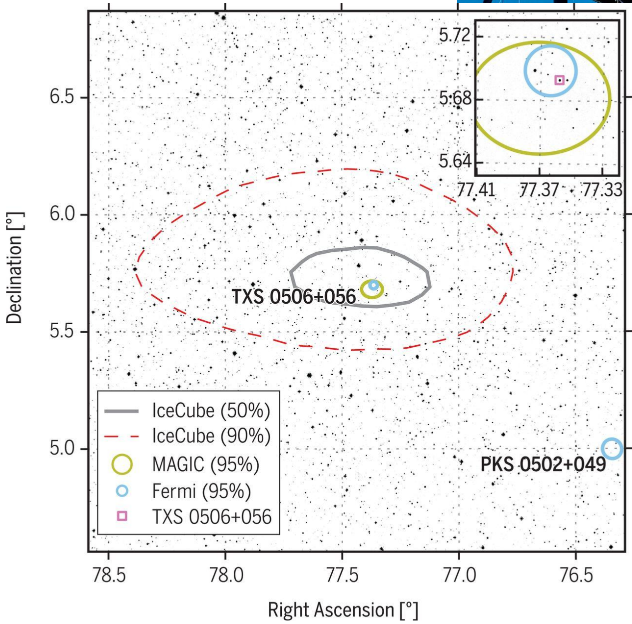
2015 sky map (7 years of data)



Multi-messenger astronomy

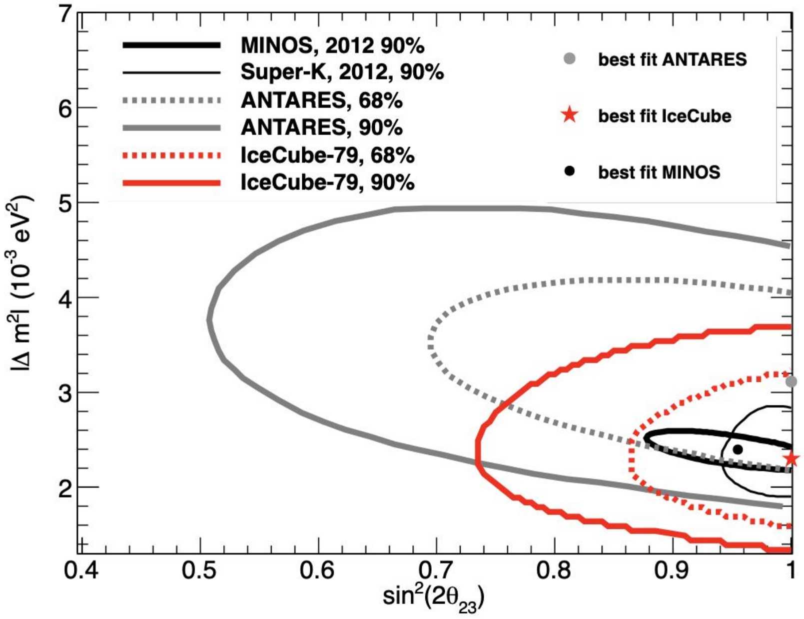
- In 2018 IceCube found excess in high-energy neutrino flux from Blazar TXS 0506+056
- First time high-energy neutrinos were matched to known astronomical source
- Observations made during period of enhanced gamma-ray emission





Neutrino oscillations

- IceCube set limits on neutrino oscillation parameters (plot from 2013)
- Can measure muon neutrino disappearance from atmospheric neutrino events
  - Dependent on incident angle
  - Can compare to survival probability



$$P_{\nu_\mu \to \nu_\mu} = 1 - \sin^2 2\theta_{\mathrm{atm}} \sin^2 \Delta_{\mathrm{atm}}$$

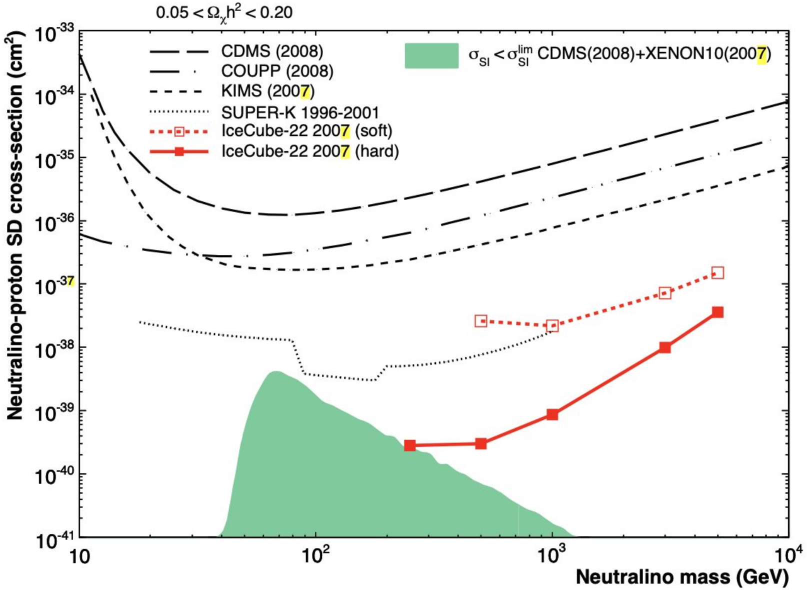
$$\Delta_{ij} = \frac{\Delta m_{ij}^2 L}{4E_\nu}$$

atm = 23

Other results

- Detection of Glashow resonance event in 2020
- Search for neutralino (WIMP dark matter candidate) annihilation in the sun to set limit on WIMP mass

Limits on neutralino mass



Glashow resonance

$$\bar{\nu}_e + e^- \rightarrow W^- \rightarrow X$$

References

[1] https://iopscience.iop.org/article/10.1088/1742-6596/718/6/062027

[2] https://user-web.icecube.wisc.edu/~jvansanten/lit/jvs_diplom.pdf

[3] https://npc.fnal.gov/wp-content/uploads/2017/06/2016-CrossSections-Minerba.pdf

[4] https://arxiv.org/pdf/1806.05696.pdf

[5] https://icecube.wisc.edu/news/research/2016/09/searching-for-point-like-sources-with-seven-years-of-icecube-data/

[6] https://arxiv.org/pdf/1807.08816.pdf

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