Analyses in IceCube

Hannah Erpenbeck

IceCube Summer School, 8th June 2022

Content shamelessly "borrowed" from previous year's talks + other talks of collaborators

Working Groups in IceCube

Science in IceCube

IceCube does a lot of science!

→ Organization into Working Groups (WG)

• Each WG group covers one *large physics goal*

  • Some have a slight overlap in interest

  → Communication between WGs

• You will interact with your WG the most (in weekly or biweekly calls)

  • listen to other's work

  • present your analysis, updates on your work

  • receive feedback, etc.

• Majority of the details are discussed in the WGs

  • Only a subgroup of the collaboration will discuss an analysis in detail until it is ready to be presented to everybody
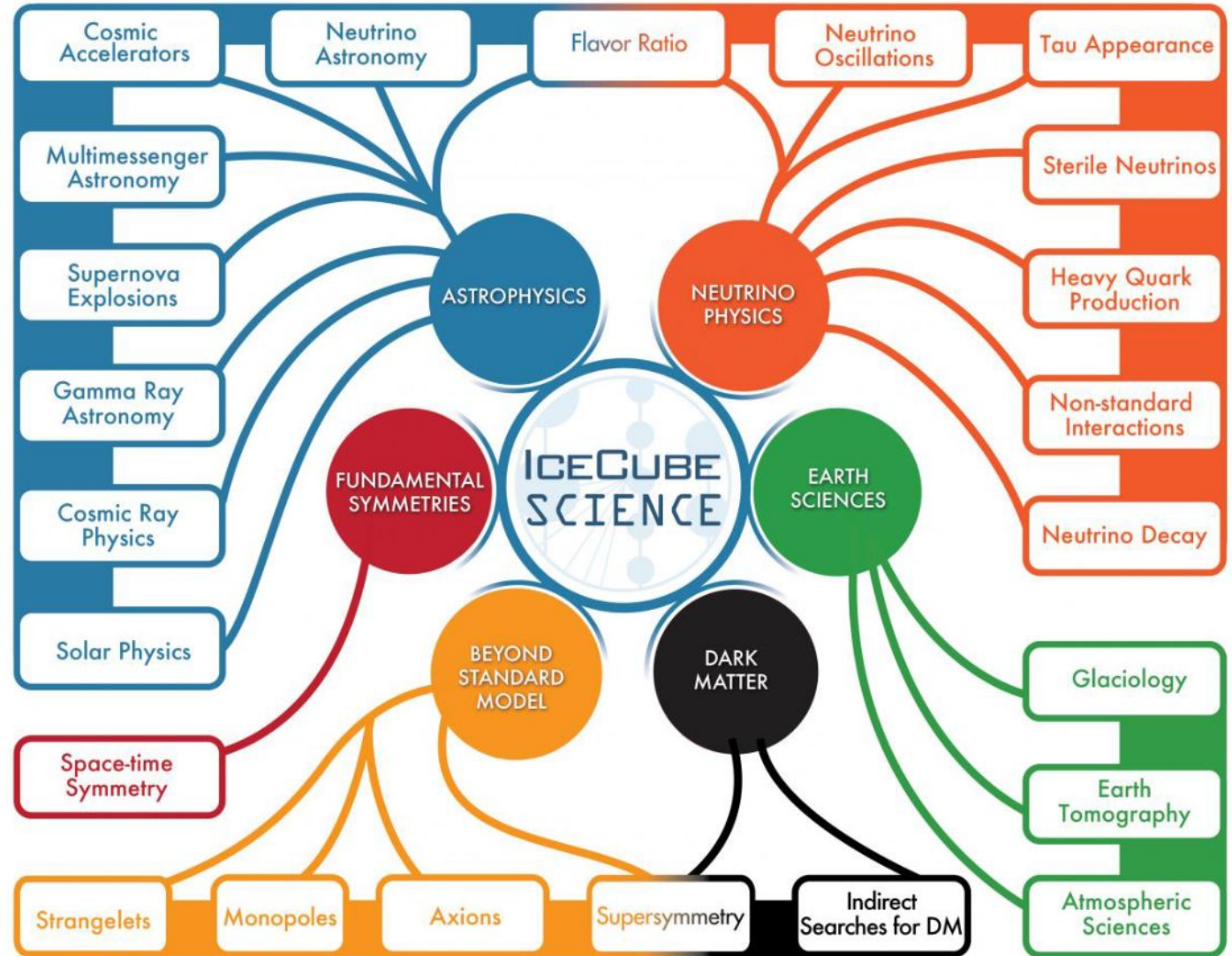
→ **Analysis Call**

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Working Groups

Working groups

Analysis		
Oscillations	(calls)	(mail)
Cosmic rays	(calls)	(mail)
Diffuse/Atmospheric ν	(calls)	(mail)
Supernova	(calls)	(mail)
Beyond the Standard Model	(calls)	(mail)
Neutrino Sources	(calls)	(mail)

High level physics goal

Technical Working Groups		
Reconstruction	(calls)	(mail)
Realtime	(slack)	(mail)
Calibration	(calls)	(mail)

Detector & Simulation	
Simulation	(mail)
Simulation Production	

R&D projects		
Acoustic	(calls)	(mail)
AURA		
RASTA	(calls)	(mail)
PINGU		
Proton Decay Simulation		
IceCube Extensions		(mail)
IceAct	(calls)	

Legacy working groups		
Neutrino Oscillations	(calls)	(mail)
Low-energy ν	(calls)	(mail)
Extreme energies	(calls)	(mail)
Tau & Composites	(calls)	(mail)
Exotic particles	(calls)	(mail)
WIMPs/Dark Matter	(calls)	(mail)
Transients	(calls)	(mail)
Point sources	(calls)	(mail)
Cascades/Taus	(calls)	(mail)
Muons	(calls)	(mail)
Verification		(mail)

Each WG has
- a wiki page
  - with links to the phone calls
  - With summaries of current ongoing analyses
- Two working group leads and a technical lead

Link to all working groups available here:
https://wiki.icecube.wisc.edu/index.php/Main_Page

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Tools for higher level physics

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Historic

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Analyses in IceCube

Selected analyses from each working group*

*Due to limited time, I will not cover everything. Apologies if I missed out your favorite analysis!

Cosmic Rays WG

- WG focuses on analyses with cosmic-ray air showers (see Paolo's talk yesterday)

  - When cosmic rays hit Earth's atmosphere, a particle air shower is created

- Uses **IceTop** (cherenkov tanks) + in-ice detectors

- Works on CR energy spectrum, CR composition, CR anisotropy, sun+moon shadow, **seasonal variations** (of atmospheric neutrinos)

- Uses MCEq, CORSIKA, FLUKA and GEANT4

- Also deals with surface enhancements (Surface array WG) with scintillators, radio, and IceACT
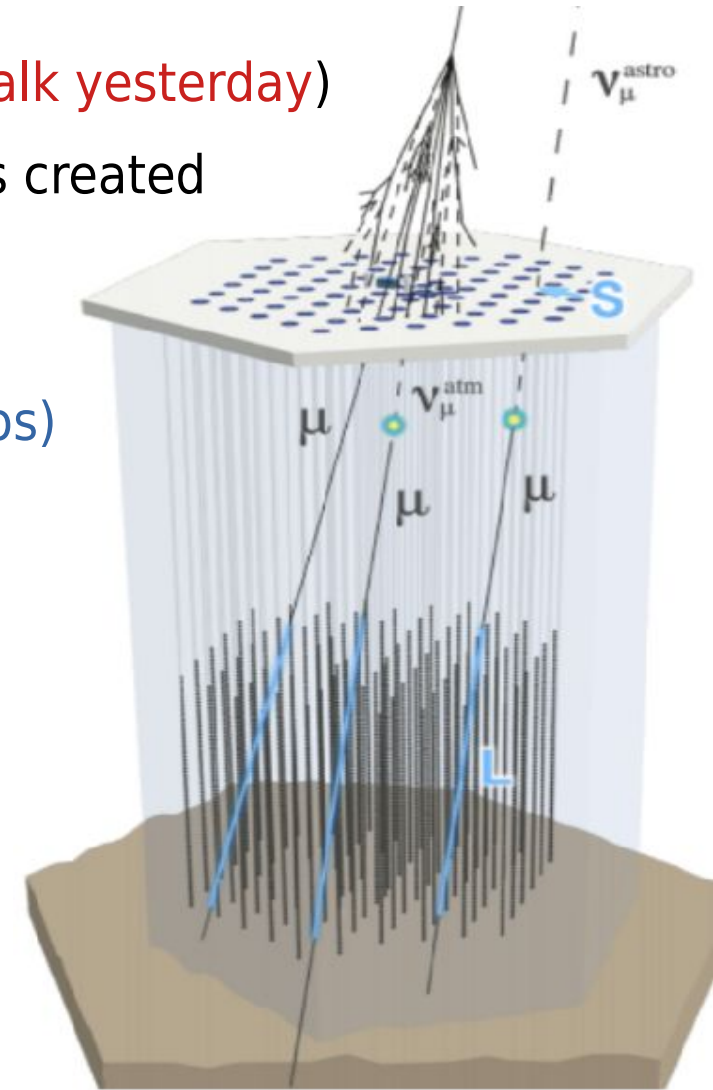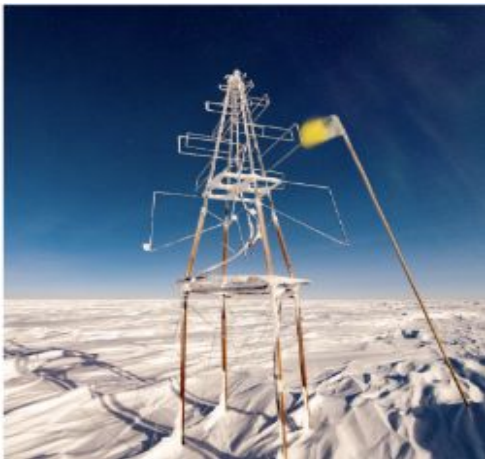
Cosmic Ray Analyses

Spectrum and composition

- Both low-energy and medium energy spectra
- Density of GeV muons of air showers in IceTop
- Seasonal variation of the muon and the mu-nu flux
- Upcoming analyses: Machine learning methods for composition, muon multiplicity, low energy extension, gamma-hadron separation

Anisotropy

- Small and large scale structures in the sky

Surface upgrade

- Air shower reconstructions and cross-calibrations of prototype stations
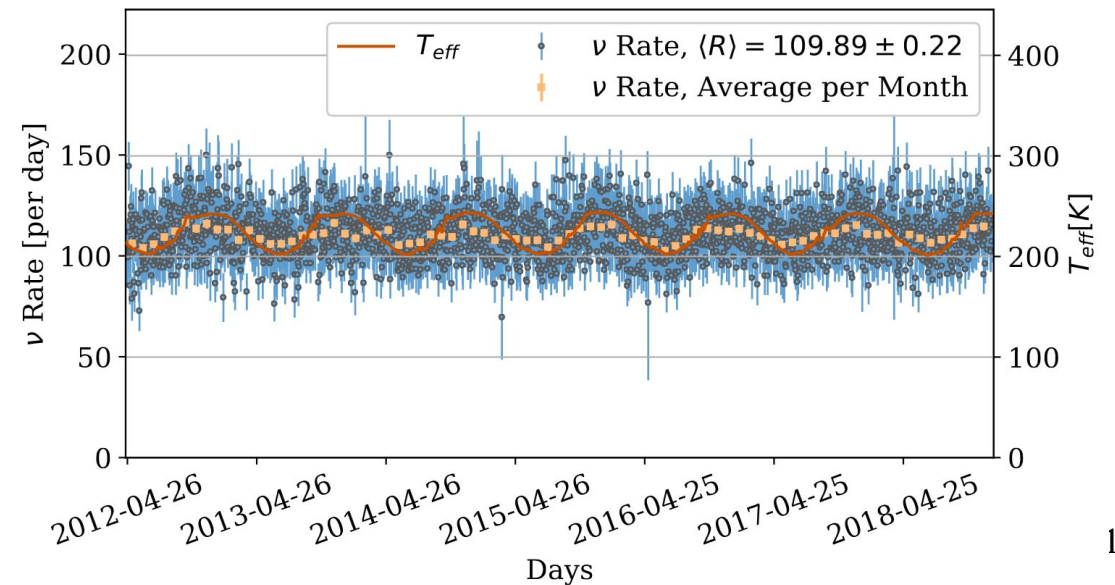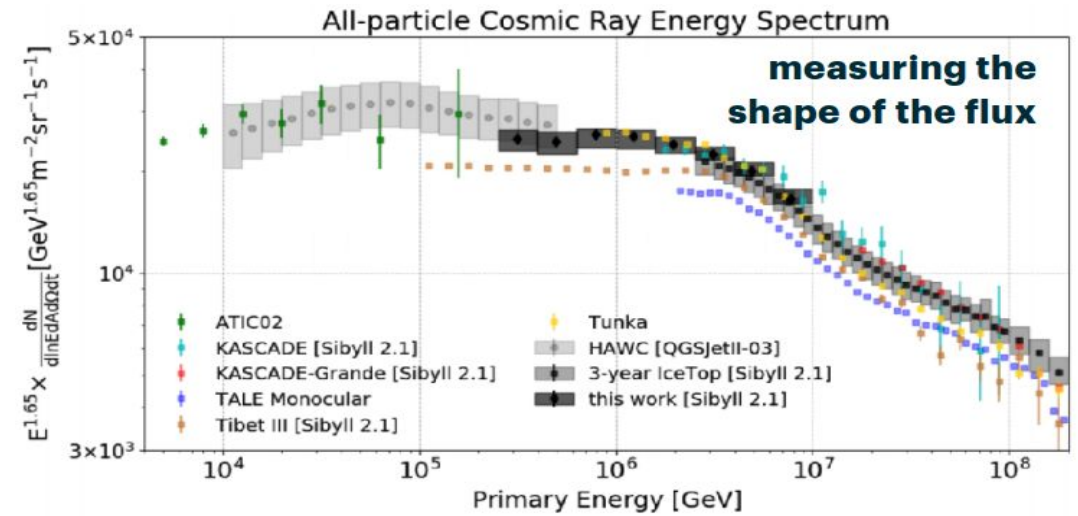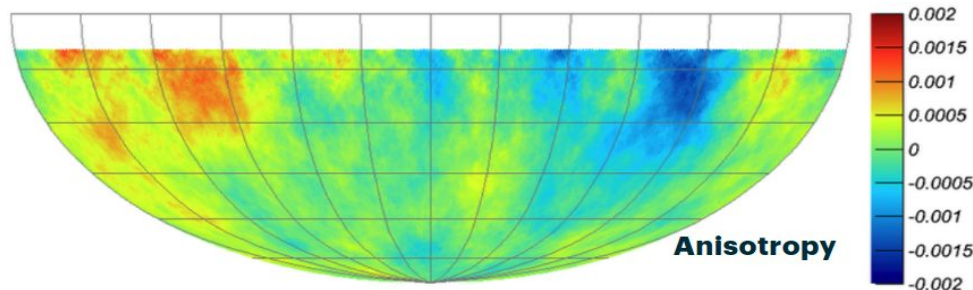
Diffuse WG

- Works on the diffuse (from all directions) flux of neutrinos observed on Earth

- Tries to measure the atmospheric and astrophysical spectrum of neutrinos in the energy range of TeV to EeV (see Lu's talk yesterday)

- Also deals with several particle-physics measurements such as cross-sections, nu/nu_bar ratio
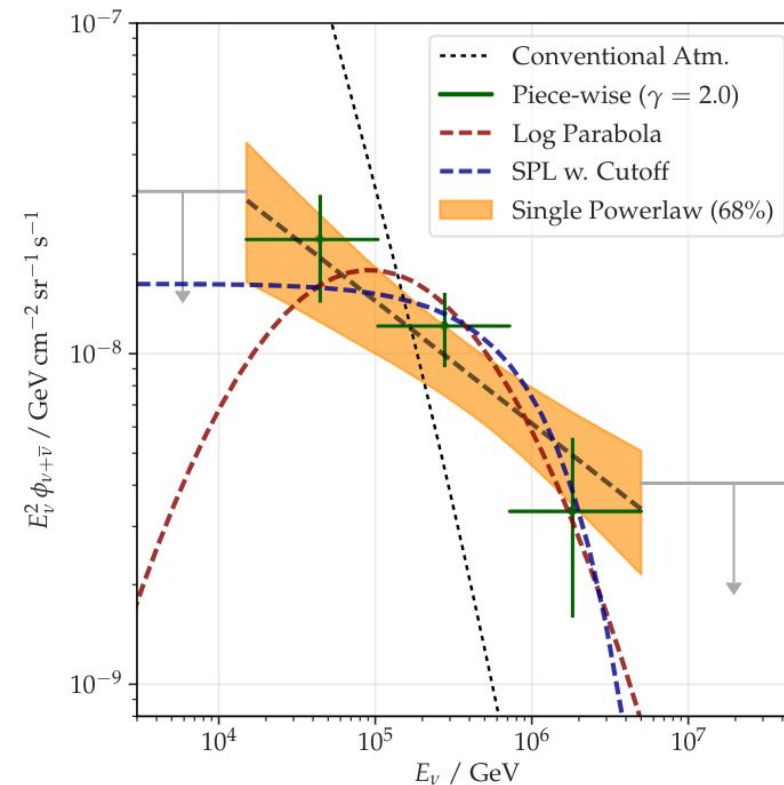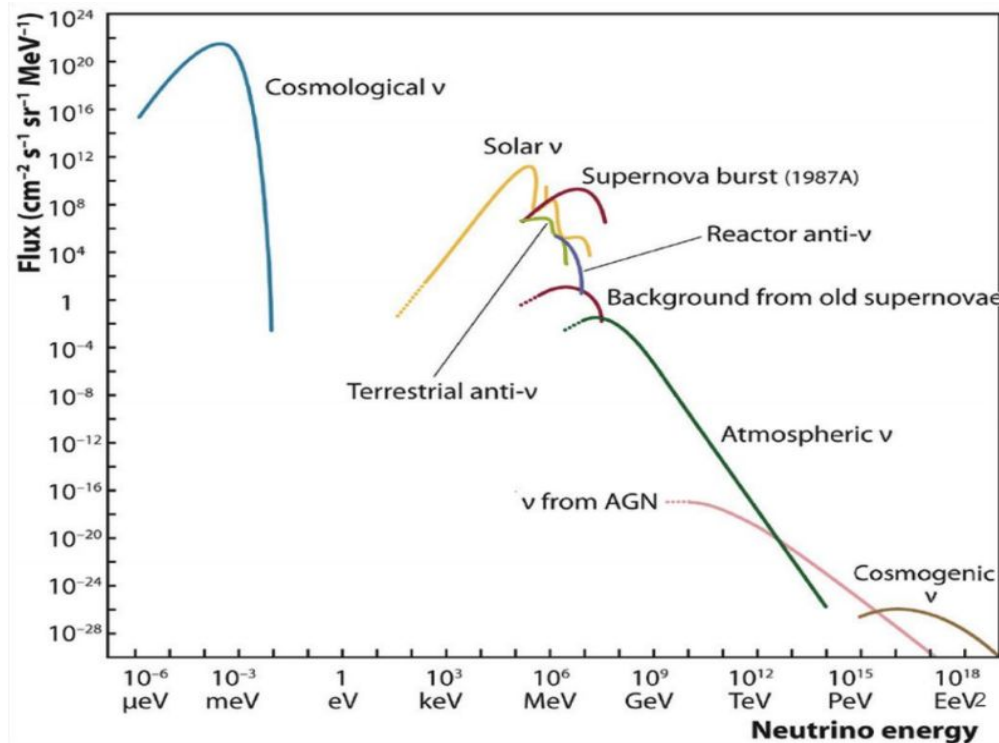
Diffuse Analyses

Astrophysical flux

- Event selections: (see talk by Marjon tomorrow morning)
  - HESE, MESE, Northern Tracks/Diffuse NuMu, ESTES, PEPE
  - Upcoming "GlobalFit": combining measurements
- Identification of tau neutrinos (double pulse, double cascade)
- Flavor ratio of astrophysical neutrinos (expectation: 1:1:1)
- **Particle physics**
- Inelasticity measurements - the ratio of hadronic cascade energy to total neutrino energy in νμ CC interactions
- Neutrino-nucleon cross section measurements
- Glashow resonance @ 6.3 PeV $\quad \bar{\nu}_e + e^- \to W^- \to X$
- **Atmospheric nu**
- Seasonal variations (also CR-WG)
- Measuring Earth's core density
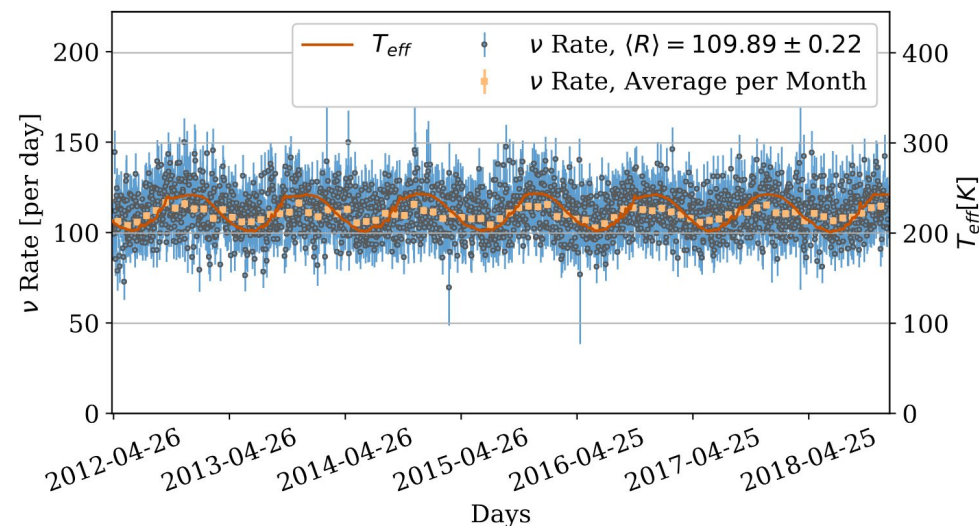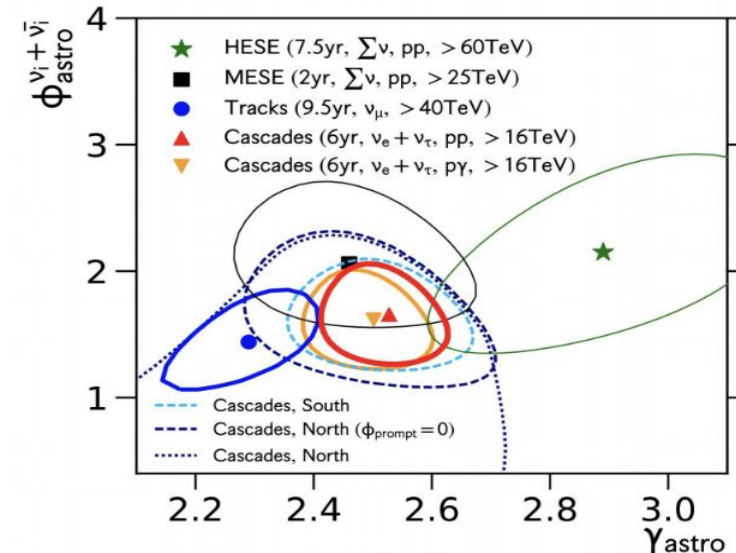
Neutrino Sources Working Group

- Main goal: to pinpoint the sources of astrophysical neutrinos

- Check for "hot spot" (clusters of neutrinos)

- Can have clusters in both time and space

- Can only explain ~1% of the total flux of neutrinos, so other sources must be dim

- Analyses are testing new hypotheses for correlating IceCube's neutrino data with possible sources

- WG has several tools to do these searches (Skylab, csky, FIRESONG, etc.)

- Main ingredients foe a nu-sources analysis:

  - Where are you looking? (source, region, whole sky, etc.)

  - When are you looking? (time integrated, transient or realtime etc.)
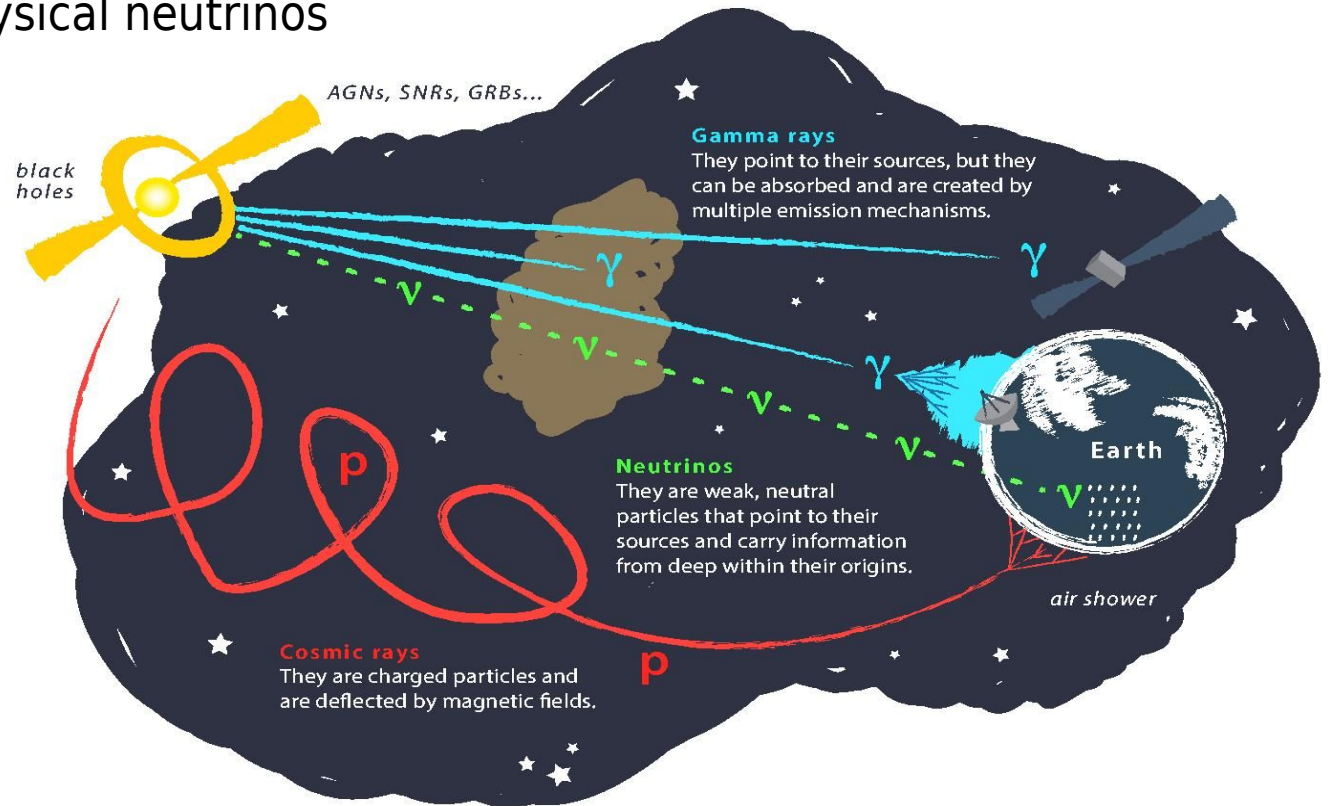
Neutrino Sources Analyses

Active Galaxy

- NGC 1068

- Published as
  Science paper

- Excess of neutrinos
  discovered with 4.2σ

- Used a skymap search from 2011 to 2020
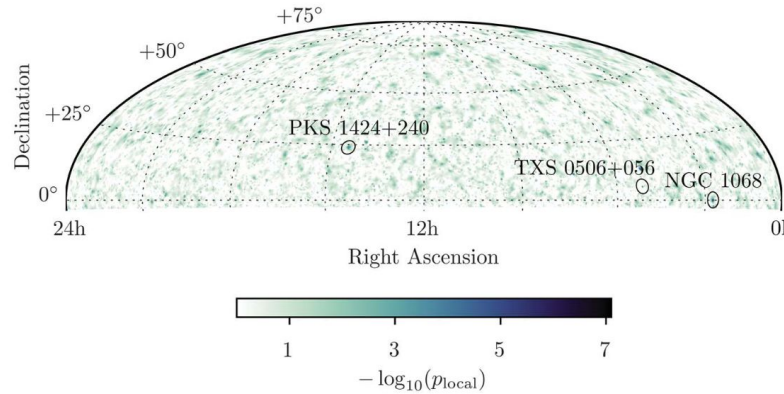
Gamma Ray Burst (GRB)

- GRB 221009A

- Brightest GRB observed by Fermi-GBM to date

- IceCube placed upper limits on the neutrino flux form this source

- After an alert: The analyzers looked at that source at the time surrounding the event

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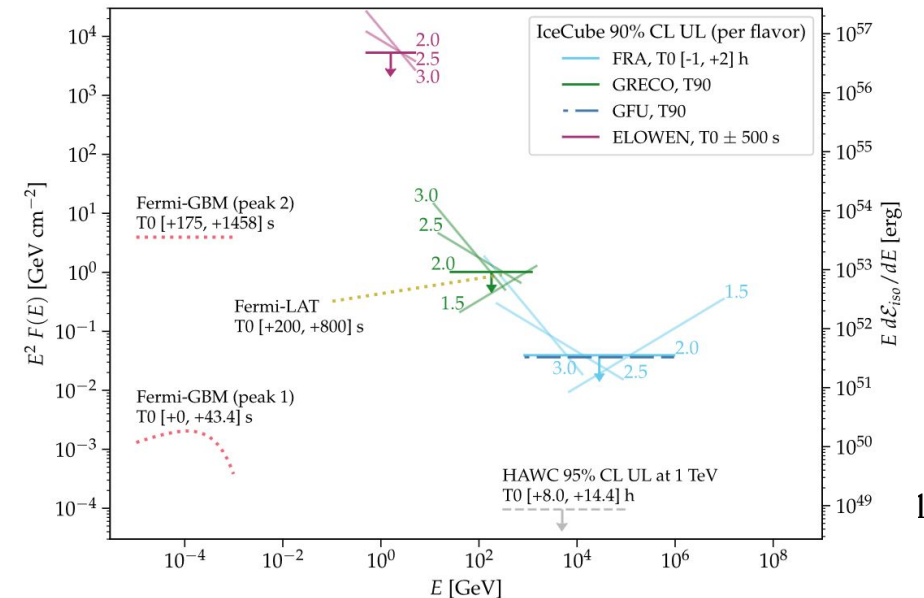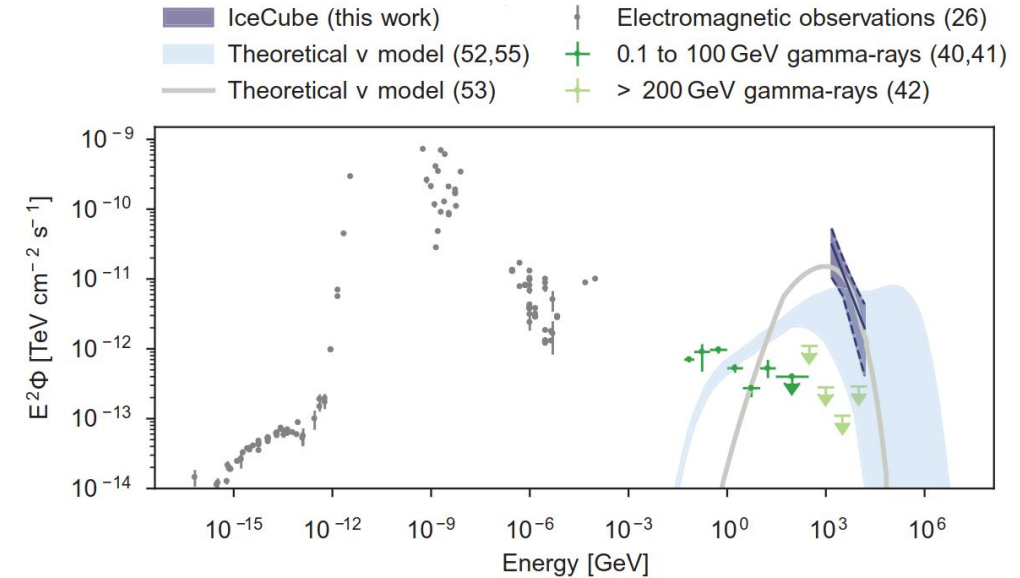
Realtime

- Technical WG, works closely with nu-sources WG

- Build tools for rapid identification of neutrino sources

- Sends alerts to the astro community

- Also receives alerts from the astro community and quickly searches for neutrinos in coincidence

- Analyses are presented in the nu-sources WG

- Three main strategies:

Alert generation, broadcasting and curation   Follow-up of external triggers   Self-triggers
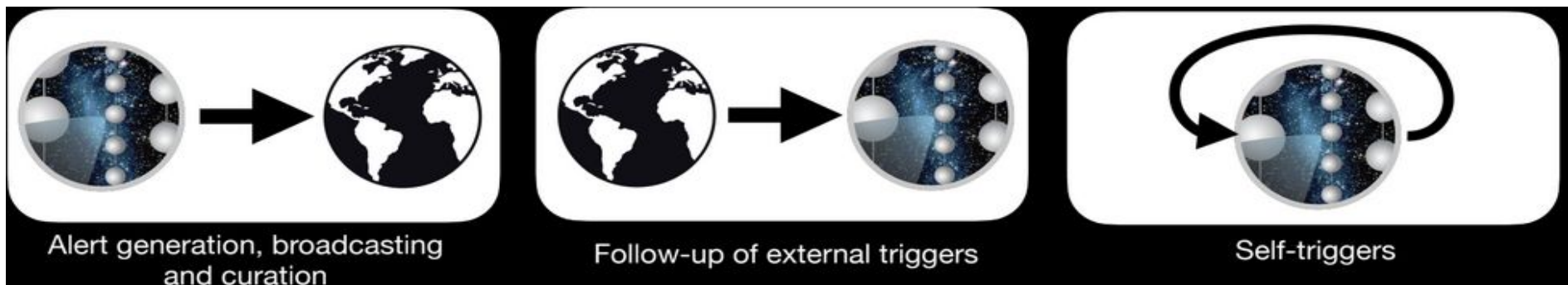
Realtime Alerts

TXS Follow-up: IceCube sent out an alert

- Alert from IceCube followed up by several observatories (astrobites article)

- Magic found a correlated flare of gamma rays, Fermi detects a flaring blazar: TXS 0506+056

IceCube alerts 2011-2020

- Skymap of all neutrino candidate alerts using this analysis

Oscillations WG

Oscillation probabilities for an initial electron neutrino
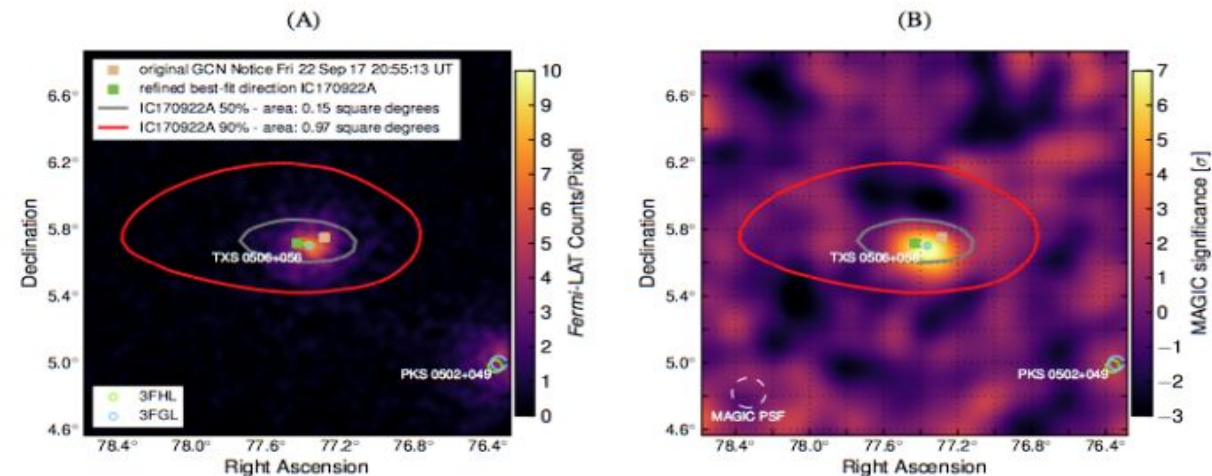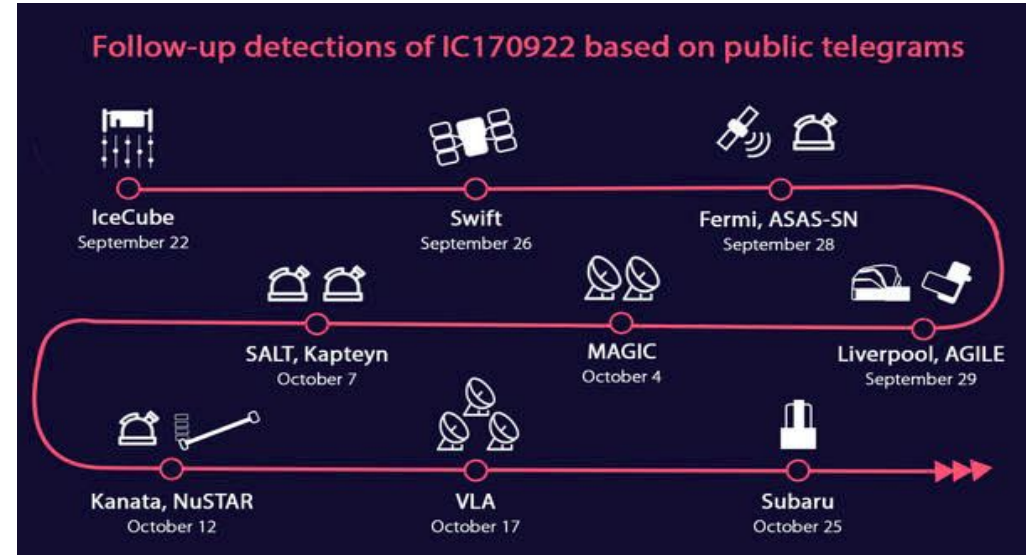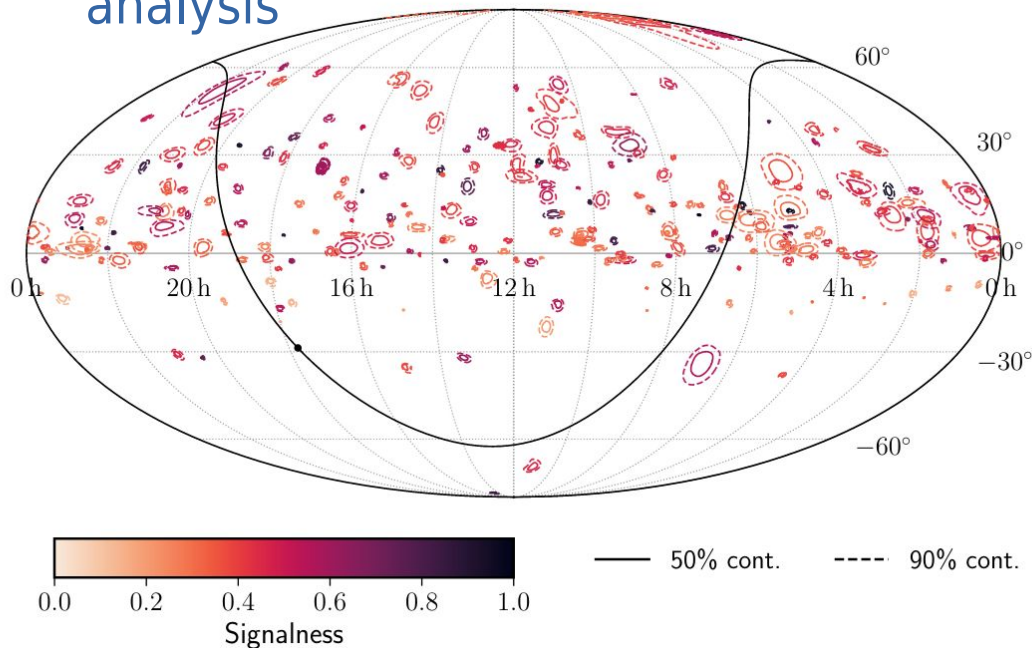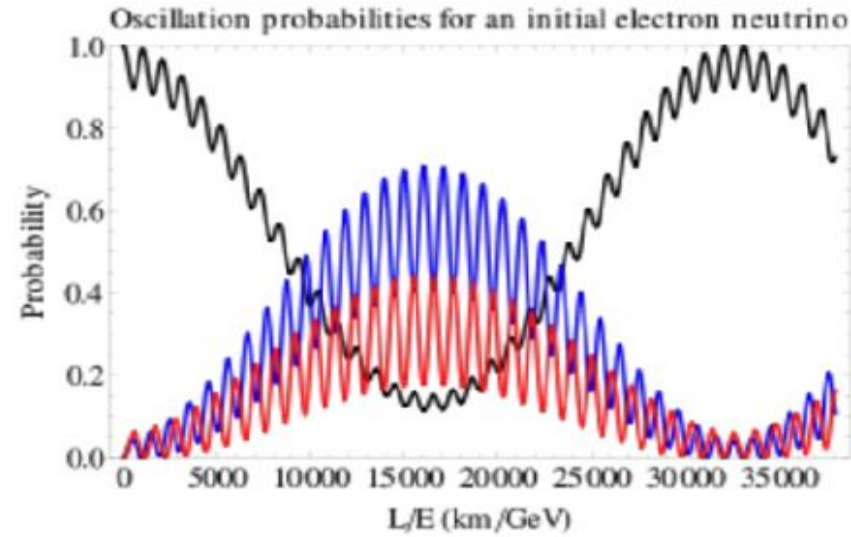
- "All analyses that focus on neutrinos changing flavor as they Cross the Earth"

- Oscillation probability

$$P_{\alpha \to \beta, \alpha \neq \beta} = \sin^2(2\theta) \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

- Oscillation parameters, tau neutrino appearance, neutrino mass ordering, non-standard interactions, sterile neutrinos

- (see Sanjib's talk Monday)

Oscillations Analyses

OscNext:

- Data selection using DeepCore

- Two samples: "high-stats" sample and "verification" sample (subset of golden events)

- Analysis using OscNext:

  - NuMu disappearance, NuTau appearance

  - Non standard neutrino interactions (NSI)

  - Neutrino mass ordering
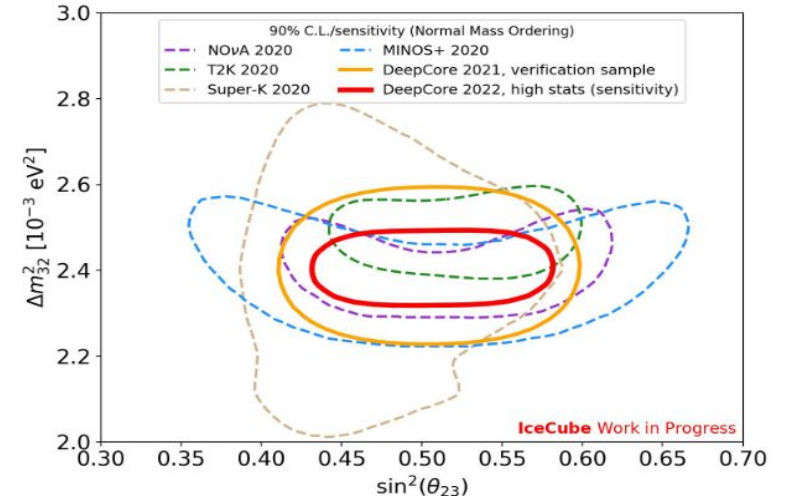
MEOWS

- Dataset for sterile neutrino search

  - Also used for NSI analysis

FLERCNN

- New reconstruction tool (fast) for low energies
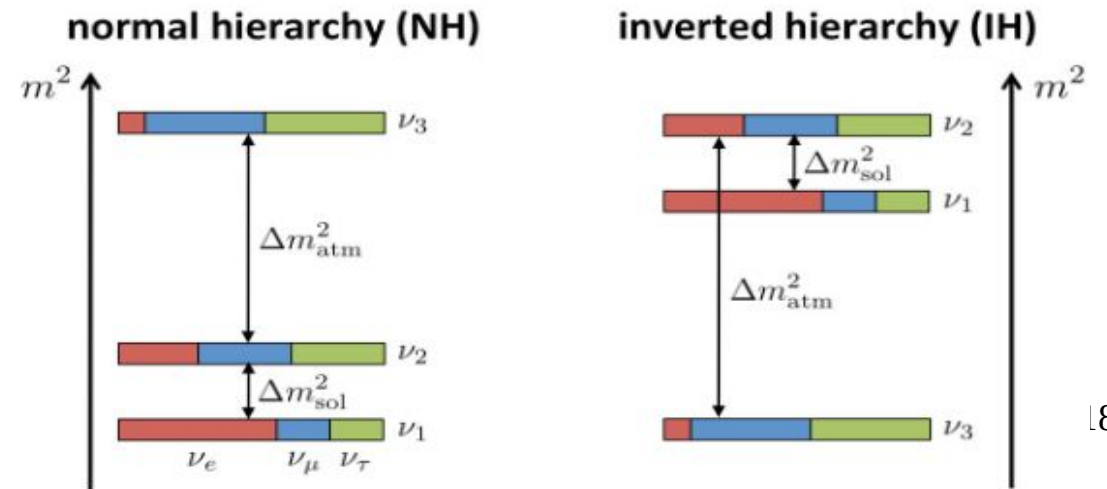
Beyond Standard Model WG

- WG focuses on new physics that could be out there (The 3-flavor model of neutrino oscillations is widely accepted, but what if that is not the whole story?)

- Interactions with new physics can cause distortions in the spectrum and flavor of both astrophysical and atmospheric neutrinos
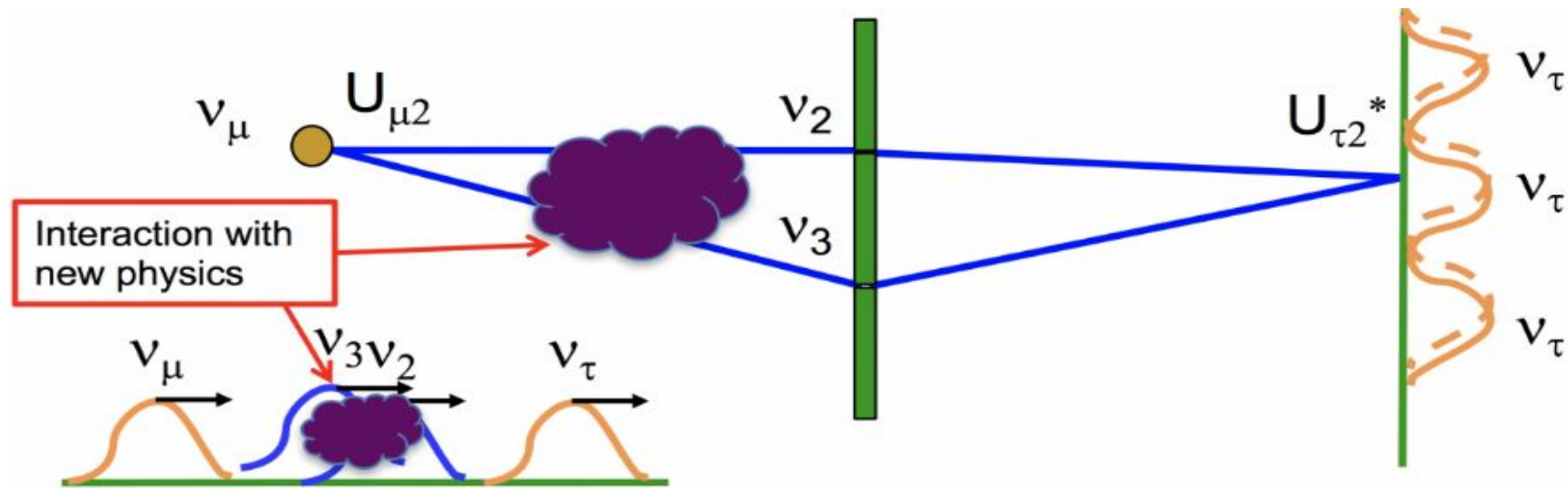
BSM Analyses

- **Sterile-neutrinos** (w/ decay): Do we see a signal consistent with that from a 4th neutrino flavor? Using MEOWS.

- **Magnetic monopoles**: Is there evidence for slow non-relativistic monopoles?

- **Diffuse DM**: could part of the diffuse spectrum be due to DM?

- **Solar/Earth DM**: Do we see an excess of neutrinos from the Sun/center of the Earth that could be from DM?

Exotics
Q-balls
Monopoles
Anomalous charged particles
...

Neutrinos
Sterile Neutrinos
Oscillations
Flavor ratio
Trident Production
...

Dark Matter
Earth WIMPs
Galactic Center
Solar Dark Matter
...

HALO   D
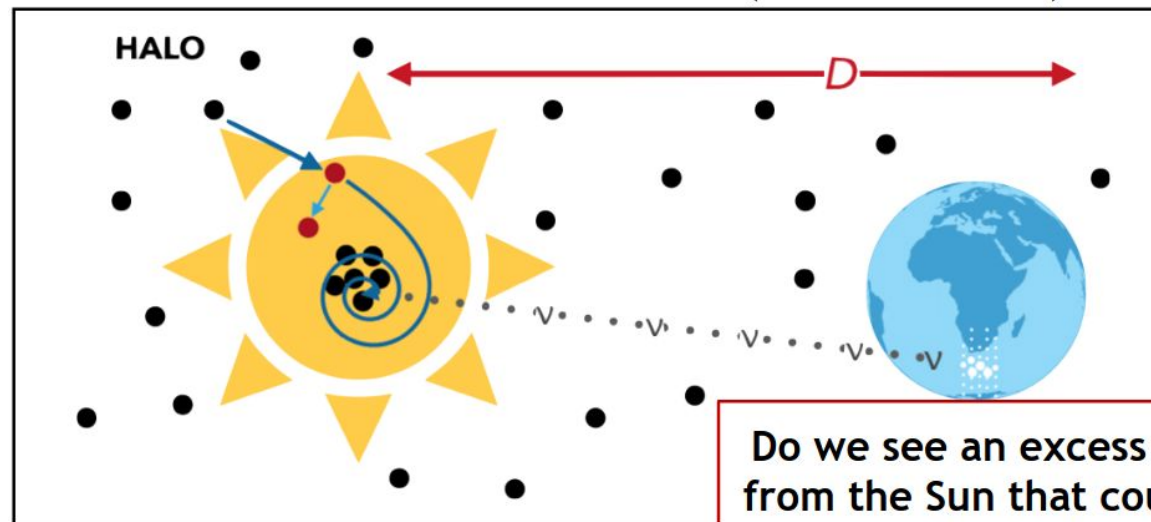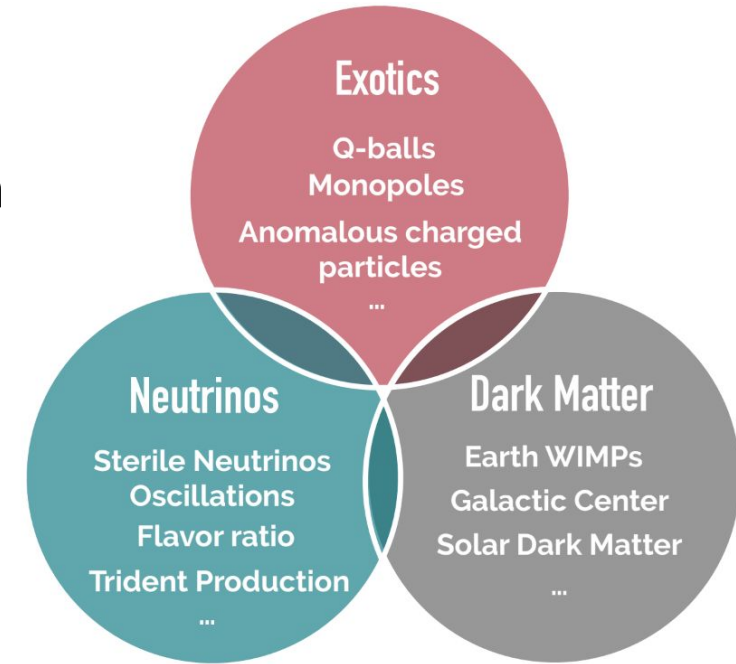
Do we see an excess of neutrinos from the Sun that could be due to solar dark matter?

Supernova WG

- Supernova (SN) neutrinos are at a very low energy compared to what IceCube normally sees.

- Therefore in a supernova, we would expect an overall rise in the "noise" rate of the detector, rather than identifying many individual events

- SN WG does online and offline SN analyses

- Conducts "fire drills" to test response

- ELOWEN analyses for GeV neutrinos: solar flare and GW

- Realtime alert within SNEWS

Collective rise in the DOM hit rate due to a nearby burst of MeV neutrinos
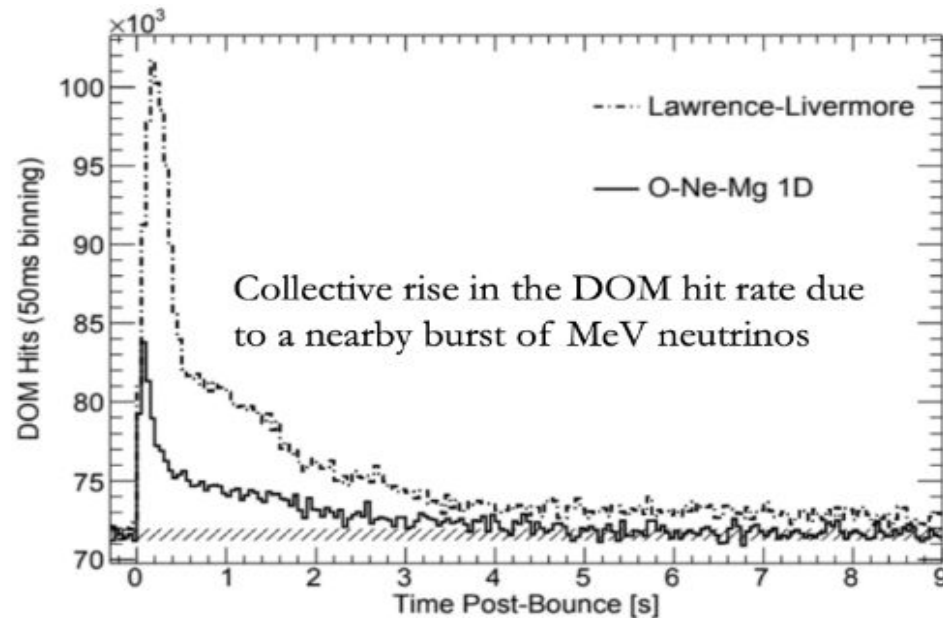
Other technical WGs

Calibration WG

- Deals with calibration of the detector

- Ice properties with LED flashers, using muon tracks, Sweden camera studies,

- DOM efficiency, IceTop calibration

Reconstruction WG

- Uses approximate models for photon timing distributions (SPICE-bfr, ftp)

- Some of the reconstructions are machine learning/deep learning based (see Tianlu's talk tomorrow)

- Physics analyses depend heavily on the calibration and reconstruction WG's

z=-540 m
main tilt gradient direction
ice flow direction (10 m/year)

Event 138005/24780443-0
Time 2023-06-03 05:00:47 UTC
Duration 22296.4 ns
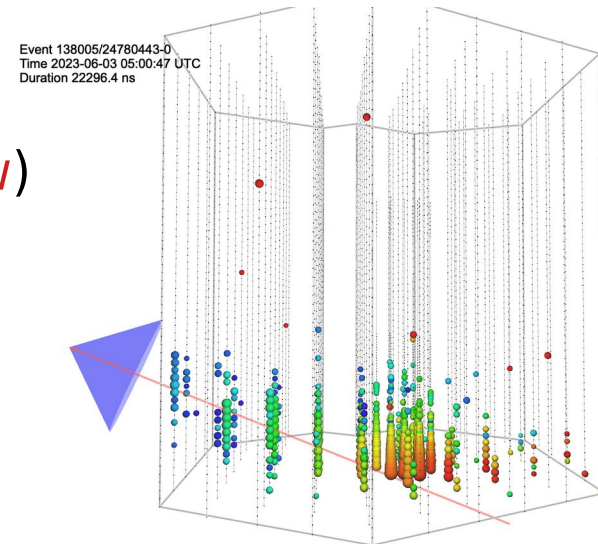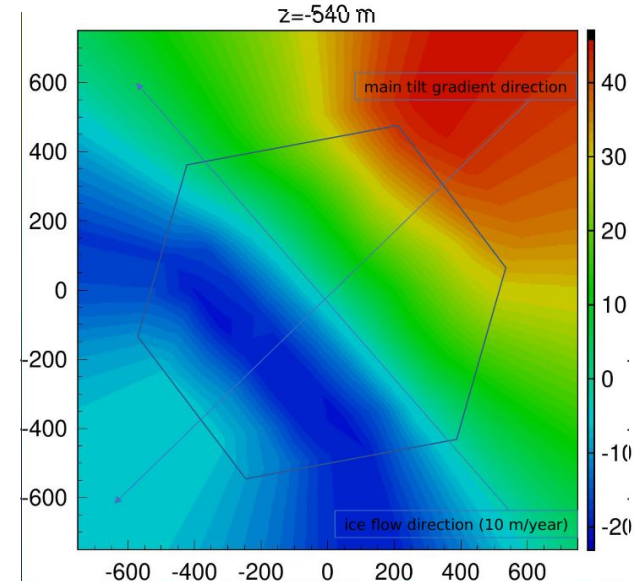
Bronze alert last Saturday

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Where everything comes together

- **Analysis Call on Thursdays at 9:00 am CST (~1 hour)**

- Most nearly-finished analyses are presented to the whole collaboration here

  - High-level description of the analyses

- Good for learning about other analyses in IceCube

- Also sometimes have WG summaries

- Collaboration-wide announcements, discussions and decisions happen here

https://wiki.icecube.wisc.edu/index.php/Analysis_calls_2023

How to Do Your Own Analysis in IceCube

How to publish an IceCube paper

Summary document

Develop analysis with simulation or scrambled data → Unblind Analysis → Write Paper Outline → Write Paper → Submit Paper

Develop analysis with simulation or scrambled data:
- Unblinding approval from working group
- Unblinding approval by analysis reviewers
- Unblinding approval on analysis call

Unblind Analysis:
- Present results on working group phone call

Write Paper Outline:
- Outline approval from working group
- Outline approval on analysis call

Write Paper:
- Paper draft approval from working group
- Paper approved by review committee (3)
- Paper circulated then approved by PubCom

Thank you for your attention.

Are there any questions?