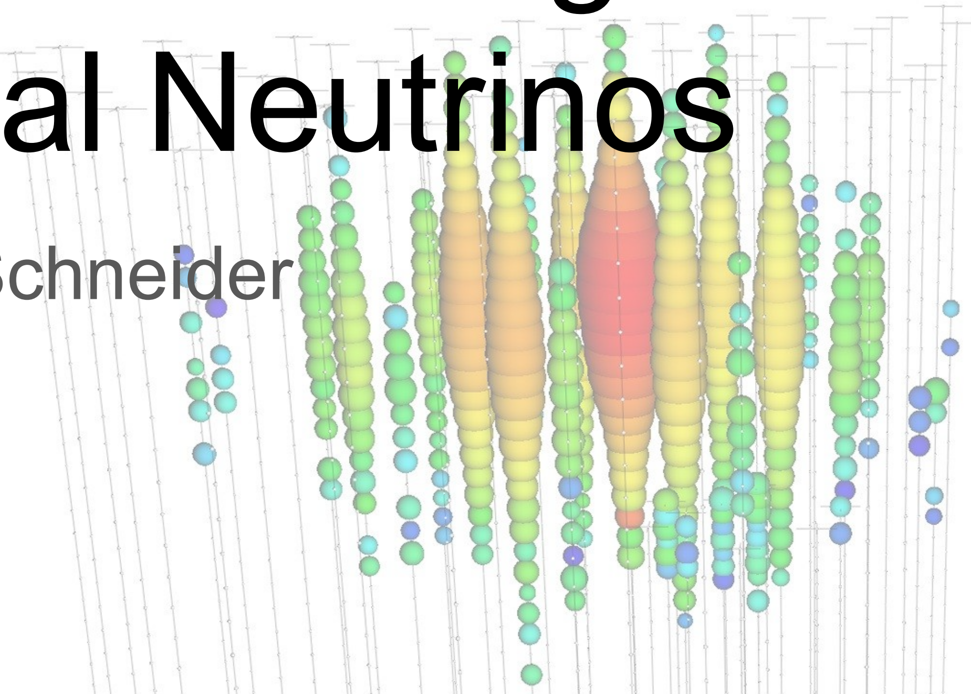
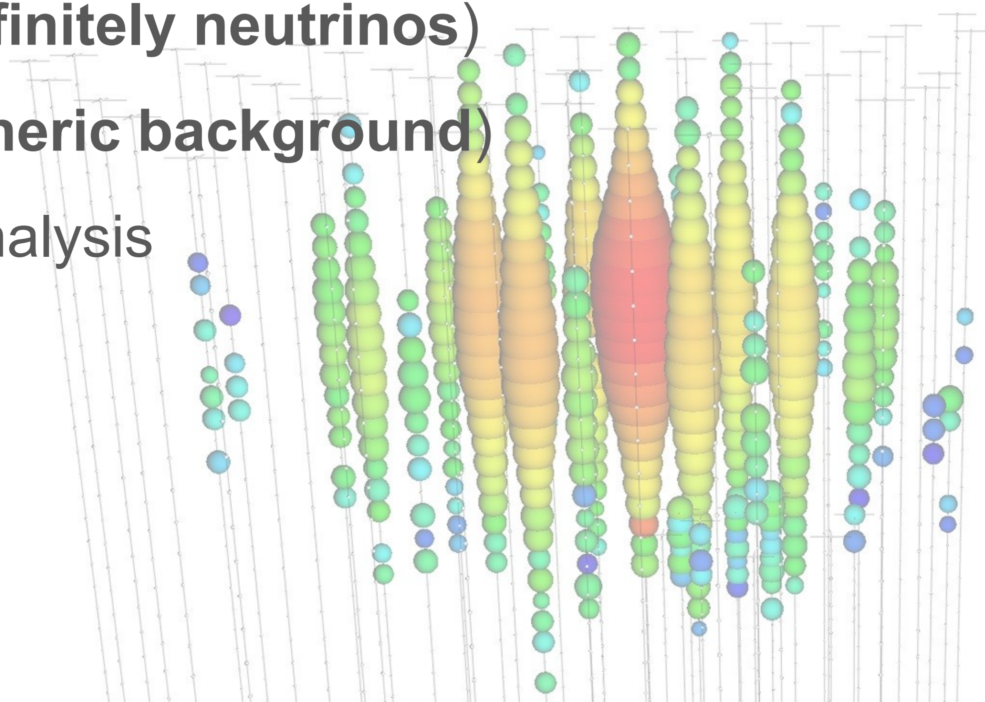
HESE - Discovering Astrophysical Neutrinos

Austin Schneider



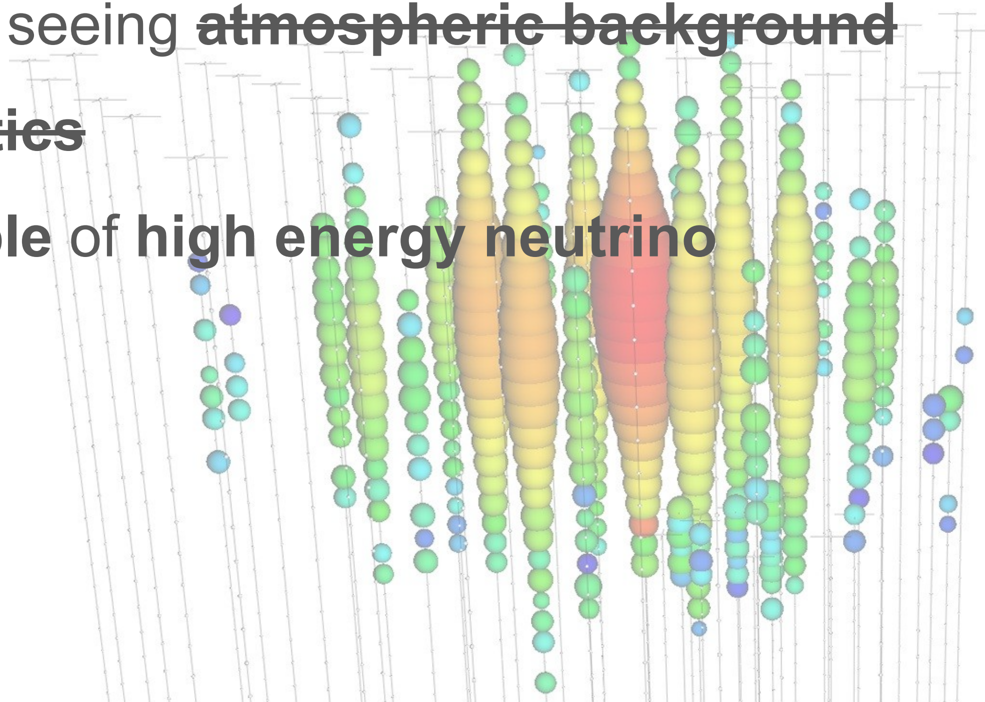
What is HESE?

- **H**igh **E**nergy **S**tarting **E**vent (Selection / Search)
- Looks for starting events (**definitely neutrinos**)
- High in energy (**low atmospheric background**)
- A **simple** event selection / analysis



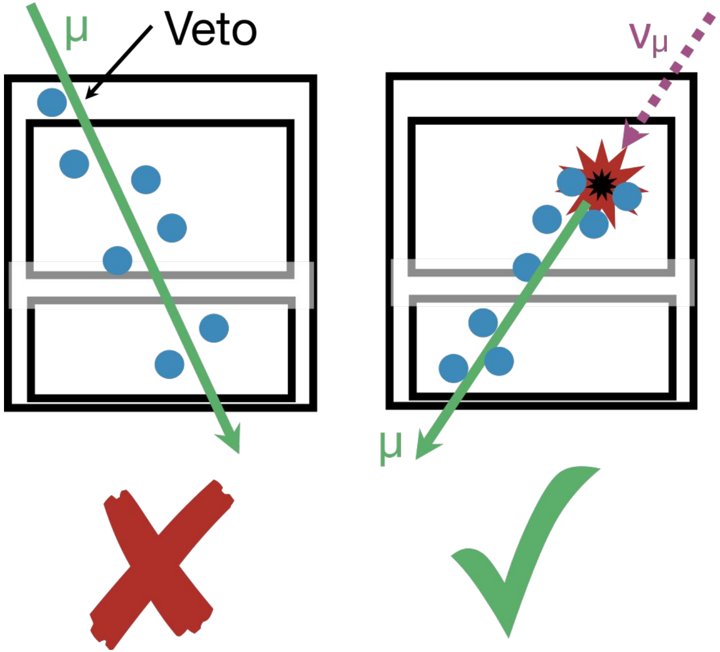
What is HESE designed to do?

- **Detect** a **diffuse flux** of astrophysical neutrinos
- **Convince** us that we are not seeing ~~**atmospheric background**~~
- Not designed for ~~**high statistics**~~
- Provide us with a **pure sample** of **high energy neutrino events** to do physics with



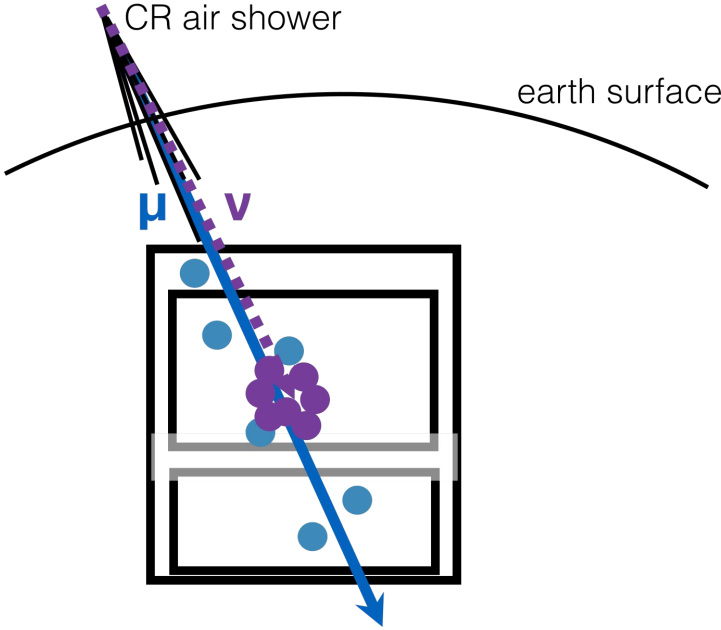
How do we accomplish this?

- Make a charge cut → **High Energy**
- Define a veto region → ~~**background**~~
  - Gets rid of incoming muons
- Reject events that deposit enough charge in the veto region



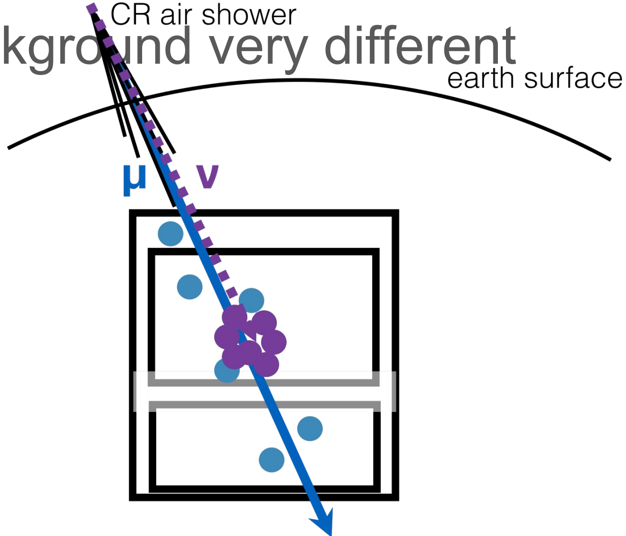
What about the atmospheric neutrinos?

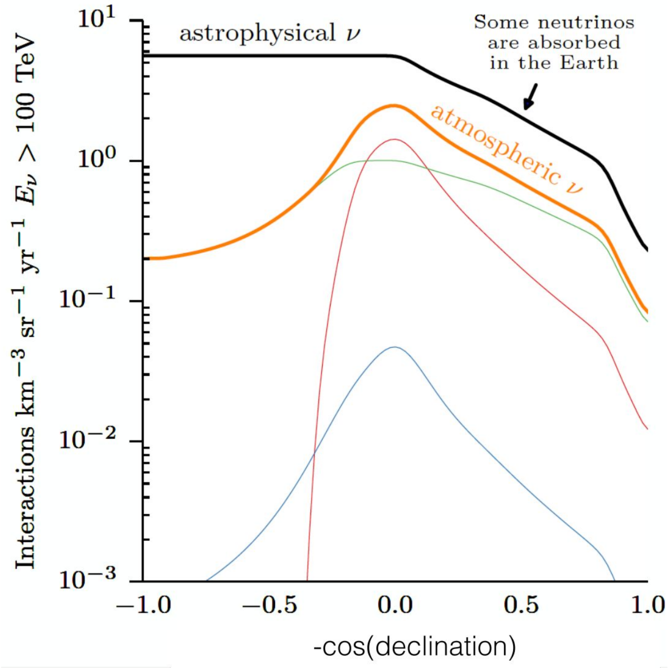
- Atmospheric neutrinos come from showers
- Showers contain lots of muons
- An accompanying muon will not pass the veto
- Any neutrino from a shower has a chance to get vetoed by an accompanying muon
- “Atmospheric Neutrino Veto Probability”



What about the atmospheric neutrinos?

- "Atmospheric Neutrino Veto Probability" depends on the overburden (and therefore zenith)
- Makes the zenith distribution of signal and background very different



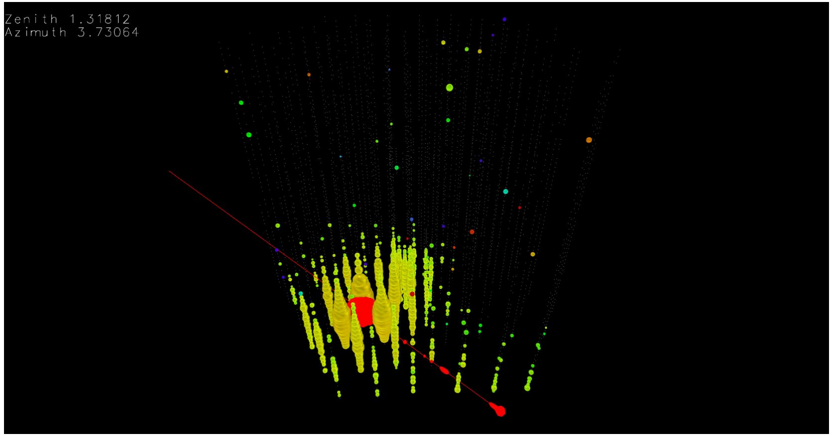


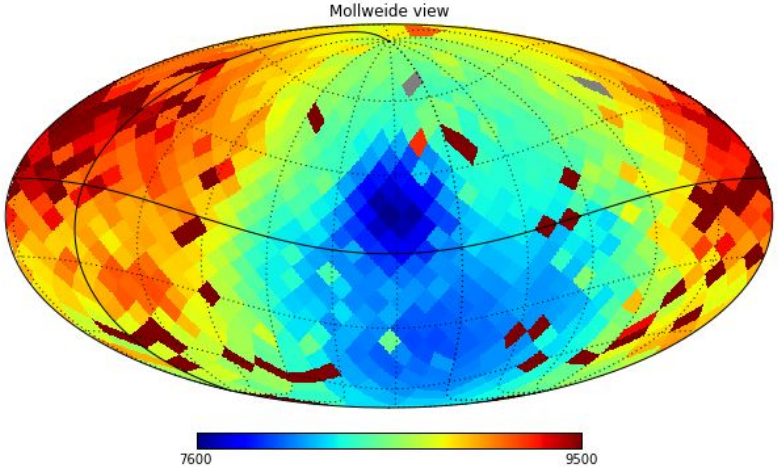
How are we doing on technical details?

- Veto ✔
- Cuts ✔
- Reconstruction ?
- Systematics ?

Reconstruction

- Our measurement depends on **energy** and **zenith**
- Need these for data and simulation
- **Monopod** / **Millipede / Taupede** scans can fit a cascade / track hypothesis
- Run expensive sky scans on the data events
- What about simulation?





Reconstruction - Changing approaches

- Running **detailed reconstructions** on the simulation sets is **computationally prohibitive**
- Previously we ran a **different reco** on data and sim

- This is bad since our fits assume that we are doing the same things to data and simulation
- **So what now?**
- Use iterative monopod/millipede/taupede
    - Worse angular resolution
    - **Fits have valid assumptions**

Systematics

- Parameters that affect our observables that we may not be interested in measuring
  - DOM efficiency
  - Hole ice parameters
  - Ice anisotropy

- How to account for them?
- Parameterize the effect in some way
- Allow the systematics as free parameters in the fit
- Parameterization is analytic in some cases
- Approximations can be made by comparing simulation sets with different systematic parameters

We have data/simulation/systematics now what?

- Try to figure out what the astrophysical component is.
- How can we do that
- Perform forward folding likelihood fit! (more details here: goo.gl/WbiWcy)

Performing a fit:

- Choose physics model
- Choose observables
- Choose binning
- Choose likelihood
- Minimize -log(L)
- Report parameters

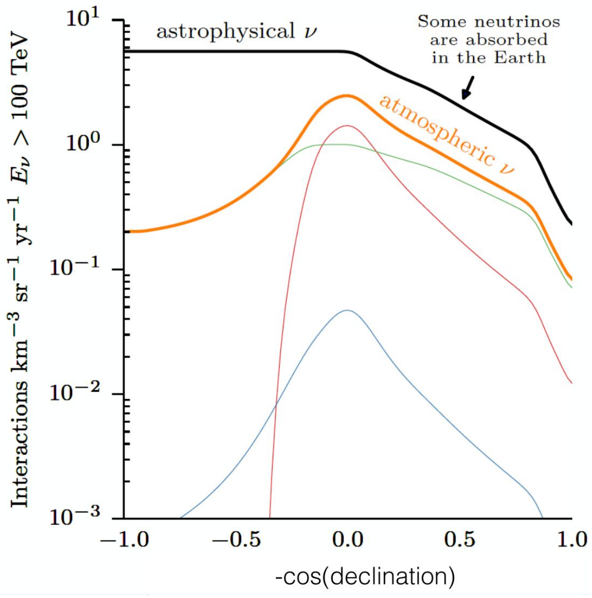
Fit - Physics model

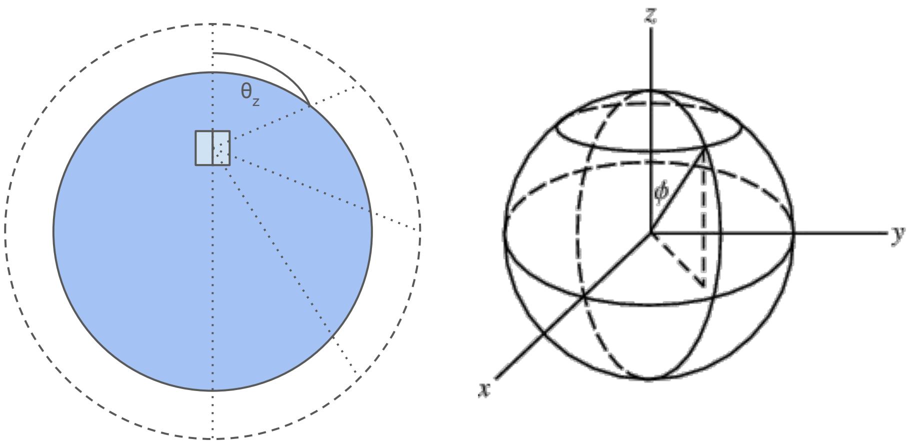
- Isotropic astrophysical neutrino flux
  - Normalization
  - Power law index
  - Flavor ratio 1
  - Flavor ratio 2
  - Neutrino anti neutrino ratio
- Atmospheric neutrino flux
  - Conventional normalization (flux from pions and kaons)
  - Prompt normalization (flux from charmed hadrons)
  - Pion Kaon ratio
  - Neutrino anti neutrino ratio
  - Cosmic ray spectral index
- Atmospheric muons
  - Normalization
- Detector systematics
  - DOM efficiency
  - Hole ice
  - Ice anisotropy magnitude

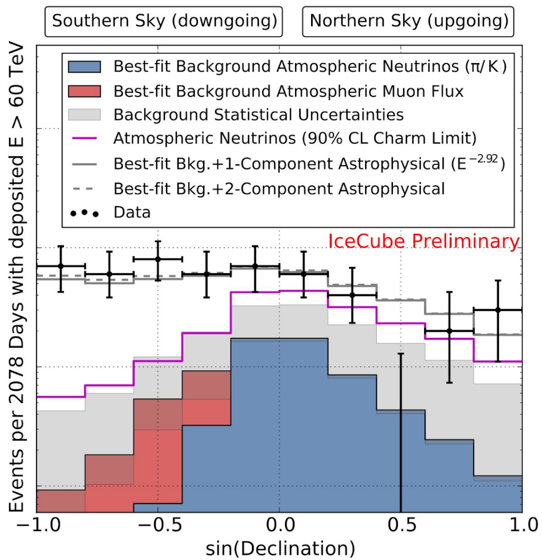
Observables - Zenith

Angle measured from directly overhead

Atmospheric and astrophysical components have different zenith distributions

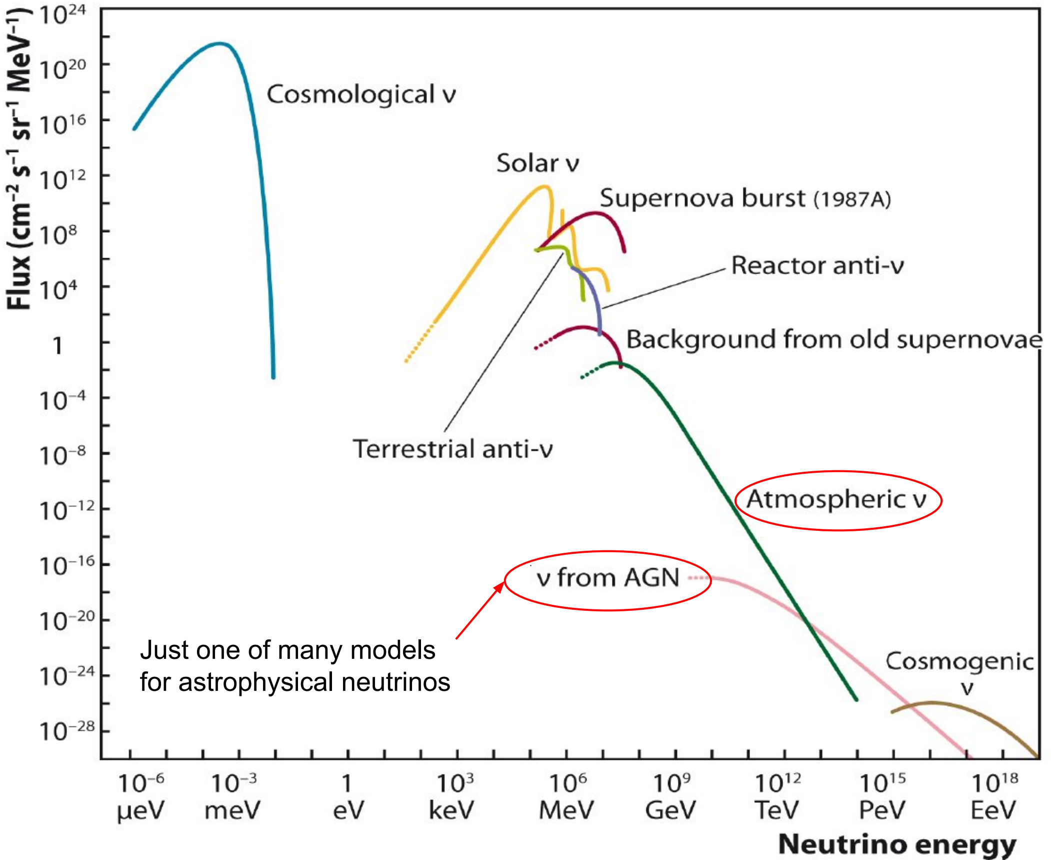






Observables - Energy

Energy is important because we expect different spectra from the atmosphere and a diffuse astrophysical flux



Constructing the binning

So because both energy and zenith are important, we bin our data in reconstructed zenith and reconstructed energy

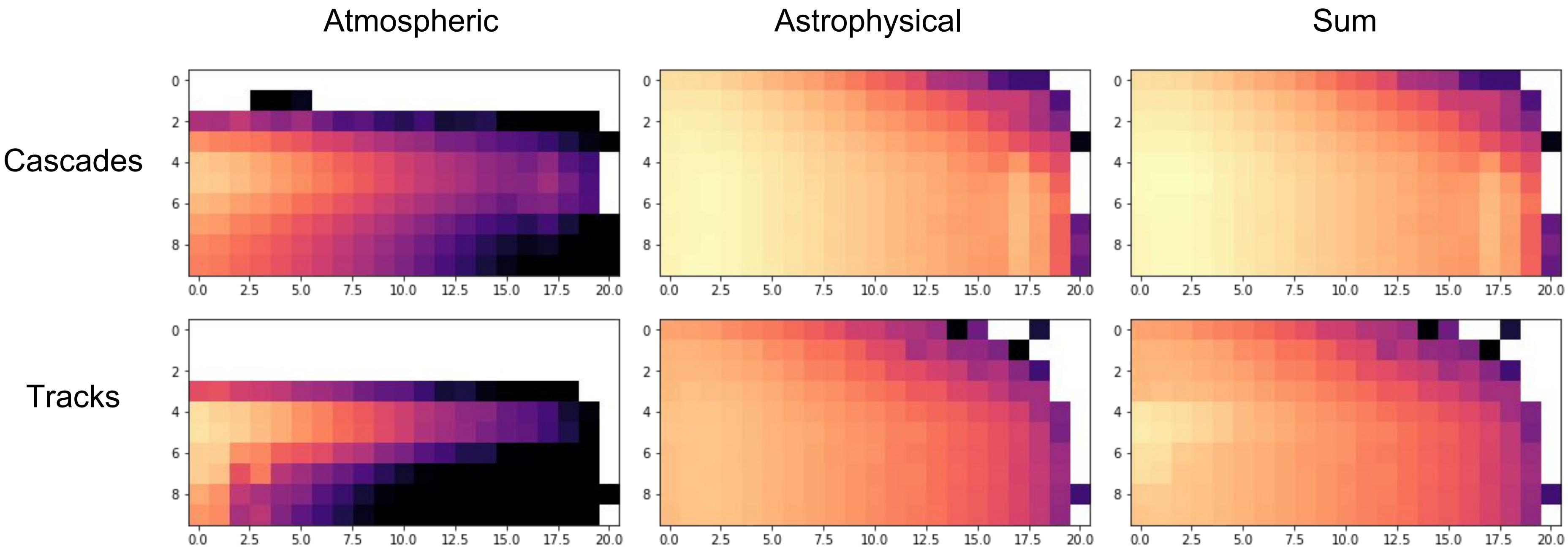
We also separate the three event topologies (cascades, tracks, double cascades)

Logarithmically energy bins are appropriate for measuring a power law

Bins in Cos(Zenith) are appropriate for the observed flux at IceCube

The number of bins is tuned so that the fit is stable and we have good MC coverage (gives us ~600 bins)

Monte Carlo



Fit - Likelihood

We have a likelihood that is a product of poisson terms $\mathcal{L}(\vec{\theta}|\vec{d}) = \prod_i \frac{(\lambda_i)^{k_i} e^{-\lambda_i}}{k_i!}$

Where each $\boldsymbol{\lambda}_i$ is the expectation in a bin, which is a function of the nuisance parameters

$$\mathcal{L}(\vec{\theta}|\vec{d}) = \prod_i \frac{(\lambda_i(\vec{\theta}))^{k_i} e^{-\lambda_i(\vec{\theta})}}{k_i!}$$

If we consider that our expectation comes from simulation then we know

$$\mathcal{L}(\vec{\theta}|\vec{d}) = \prod_i \frac{(\sum_j w_j(\vec{\theta}))^{k_i} e^{-\sum_j w_j(\vec{\theta})}}{k_i!} \qquad \lambda_i(\vec{\theta}) = \sum_j w_j(\vec{\theta})$$

Which we maximize to obtain an estimate for $\vec{\theta}$

Poisson Likelihood With Monte Carlo

- Poisson Likelihood

$$P(\lambda|k) = \frac{\lambda^k e^{-\lambda}}{k!}$$

- Classic way in which monte carlo is used to specify the expectation

$$P(\theta) = \frac{\left(\sum_i w_i(\theta)\right)^k e^{-\left(\sum_i w_i(\theta)\right)}}{k!}$$

- Is equivalent to specifying a delta function prior on the expectation

$$P(\theta) = \int_0^\infty \frac{\lambda^k e^{-\lambda}}{k!} \delta\left(\lambda - \sum_i w_i(\theta)\right) d\lambda$$

- In general we can choose any prior that is a function of the monte carlo

$$P(\theta) = \int_0^\infty \frac{\lambda^k e^{-\lambda}}{k!} P\left(\lambda|\vec{w}(\theta)\right) d\lambda$$

- Specifying this prior is how all modifications to the poisson likelihood work

Modifications To The Poisson Likelihood

- Bohm Zech
- Barlow
- Dima (arXiv:1304.0735)
  - Log normal gaussian
  - [Multinomial likelihood] similar to Bohm Zech treatment
- Thorsten (arXiv:1712.01293)
  - Convolution of gamma distributions (one for each weight)
- SAY
  - Gamma distribution (with statistical properties drawn from the distribution of weights)

$$P(\theta) = \int_0^\infty \frac{\lambda^k e^{-\lambda}}{k!} \boxed{P(\lambda|\vec{w}(\theta))} \, d\lambda$$

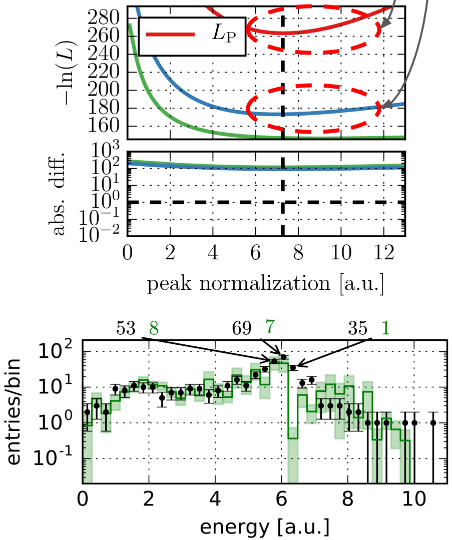
Comparison: Poisson -- Thorsten

Toy fitting scenario
Comparing the thorsten likelihood to the poisson likelihood with varying MC statistics

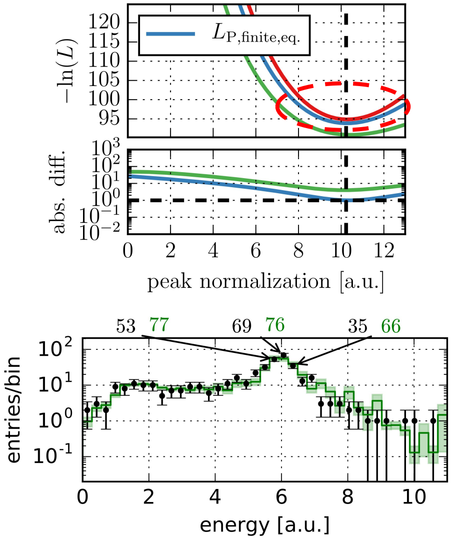
Low statistics limit:
Thorsten: biased but with appropriate significance
Poisson: biased with incorrect significance

High statistics limit:
Both recover the parameter of interest with similar significance

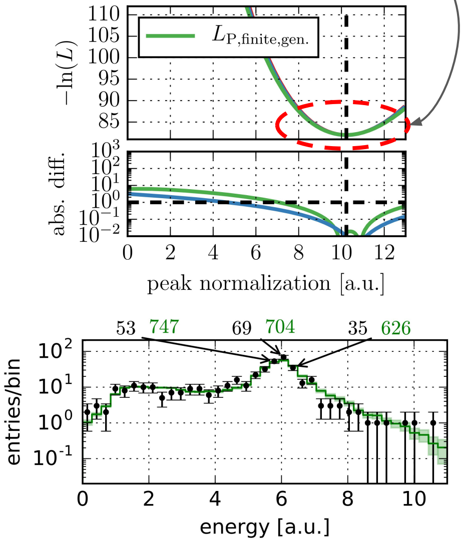
268 MC Events



2682 MC Events



26821 MC Events



Obtaining results from likelihood

- Maximum likelihood fit

$$\hat{\lambda} = \arg\max_{\lambda} \mathcal{L}(\lambda|k)$$

- Maximum likelihood scan
  - Same as above but fix some parameters and scan over those fixed parameters
  - Examine likelihood at each point
- Markov chain monte carlo (useful for Bayesian techniques)
  - Technique for characterizing large multidimensional space
  - Likelihood exists in 14+ dimensional space

$$\mathcal{L}(\vec{\theta}|\vec{d}) = \prod_i \frac{(\sum_j w_j(\vec{\theta}))^{k_i} e^{-\sum_j w_j(\vec{\theta})}}{k_i!}$$

Bayes Theorem

Analysis wiki: https://wiki.icecube.wisc.edu/index.php/IC86LV_atmo
Paper wiki: https://wiki.icecube.wisc.edu/index.php/IC86LV_atmo_paper

$$p\left(D\right) = \int p\left(D \mid \Theta, \alpha\right) \cdot p\left(\Theta, \alpha\right)\, d\Theta\, d\alpha$$

The goal is to obtain the posterior distribution marginalised over your nuisance parameters

Joint Posterior — Likelihood — Prior

$$p\left(\Theta, \alpha \mid D\right) = \frac{p\left(D \mid \Theta, \alpha\right) \cdot p\left(\Theta, \alpha\right)}{p\left(D\right)}$$

Marginal Likelihood

$$p\left(\Theta \mid D\right) = \int p\left(\Theta, \alpha \mid D\right) d\alpha$$

Marginalised Posterior

Problem: In a multidimensional space, the integral over the nuisance parameters is difficult to perform directly

Instead: Use an MCMC to sample over the joint posterior, after which the sampled points can be integrated over in a more straightforward way to obtain the marginalised posterior

MCMC

Analysis wiki: https://wiki.icecube.wisc.edu/index.php/IC86LV_atmo
Paper wiki: https://wiki.icecube.wisc.edu/index.php/IC86LV_atmo_paper

Definitions

Markov Chain:
Predictions which satisfy the Markov process depend solely on the present state of the system, and hence are independent of the system's full history.

Markov Chain Monte Carlo:
A class of algorithms for sampling from a PDF based on constructing a Markov Chain whose desired distribution approximates the PDF.

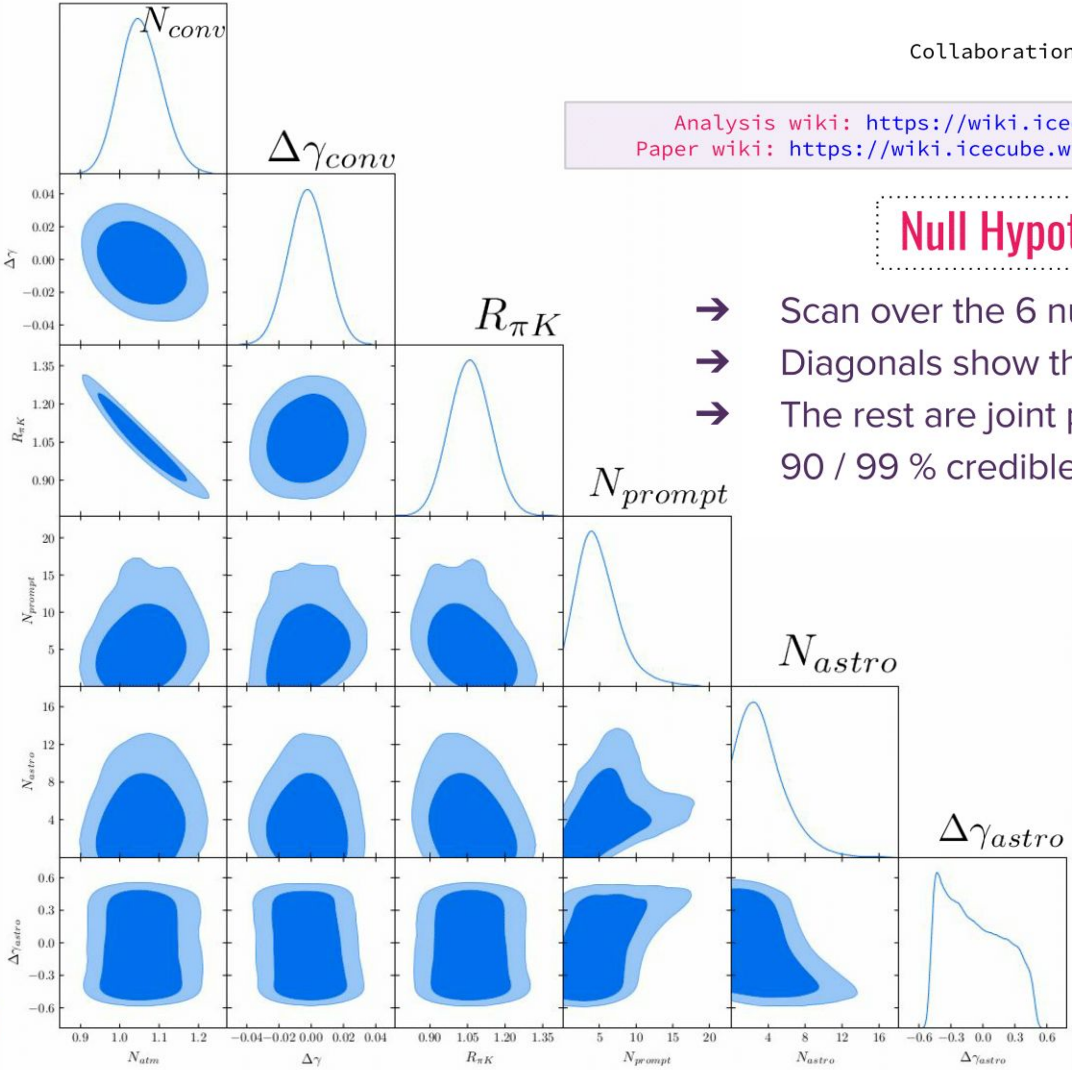
Metropolis-Hastings (M-H) Algorithm:
A simple MCMC algorithm which generates a random walk using a proposal PDF which is iteratively updated in a Markovian way using a method of rejection for some of the proposed moves, such that the distribution of walks closely approximates the desired PDF.

MCMC can be used to sample points whose distribution approximates the joint posterior in a Bayesian setup

Results

Analysis wiki: https://wiki.icecube.wisc.edu/index.php/IC86LV_atmo
Paper wiki: https://wiki.icecube.wisc.edu/index.php/IC86LV_atmo_paper

$$\Delta\gamma = \gamma_i - \gamma_{nominal}$$



Null Hypothesis (No LV)

- ➔ Scan over the 6 nuisance parameters
- ➔ Diagonals show the marginalised posterior
- ➔ The rest are joint posteriors, for which the 90 / 99 % credible region shown

Results

Analysis wiki: https://wiki.icecube.wisc.edu/index.php/IC86LV_atmo
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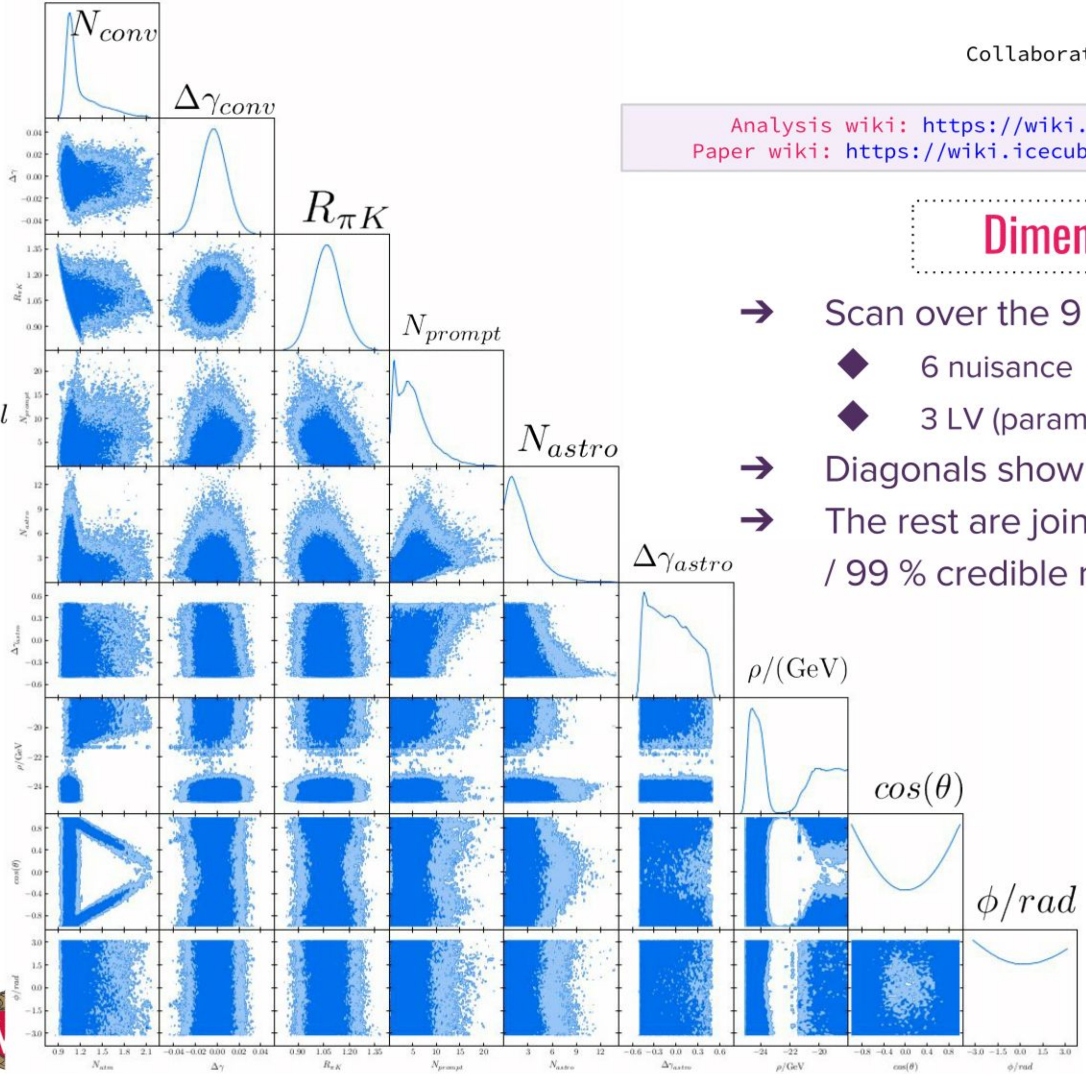
$$\Delta\gamma = \gamma_i - \gamma_{nominal}$$



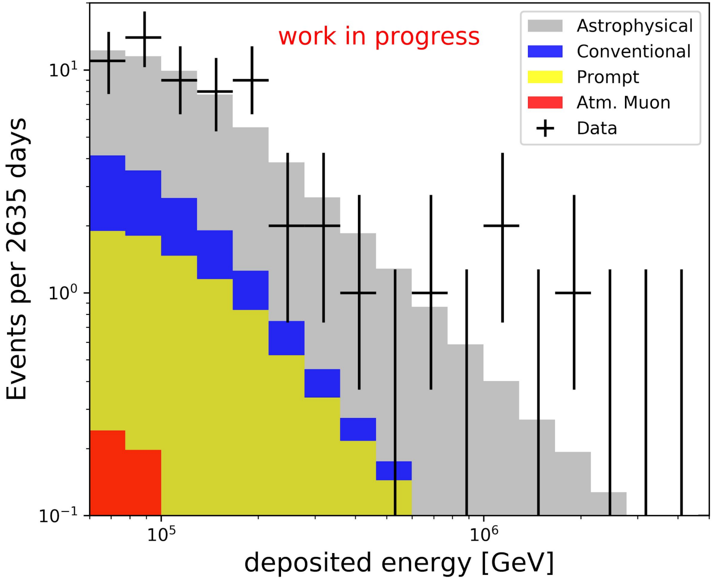
Dimension 3 Term

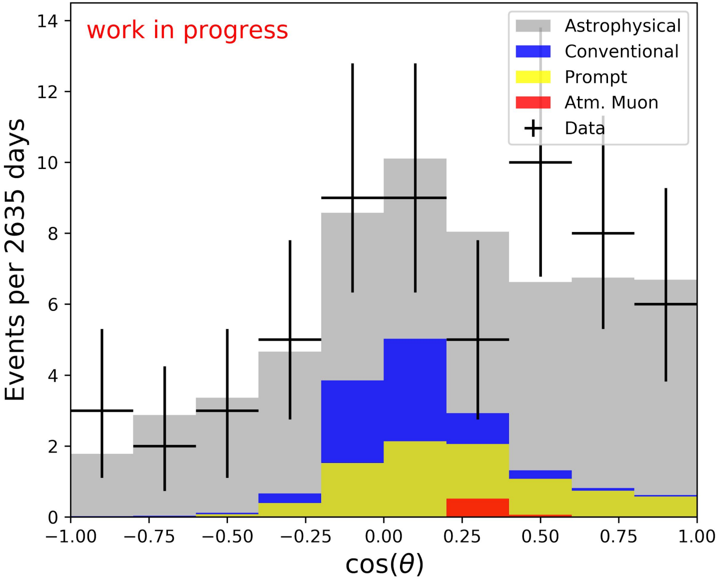
- Scan over the 9 parameters
  - 6 nuisance
  - 3 LV (parameterised in spherical coordinates)
- Diagonals show the marginalised posterior
- The rest are joint posteriors, for which the 90 / 99 % credible region shown

Queen Mary University of London

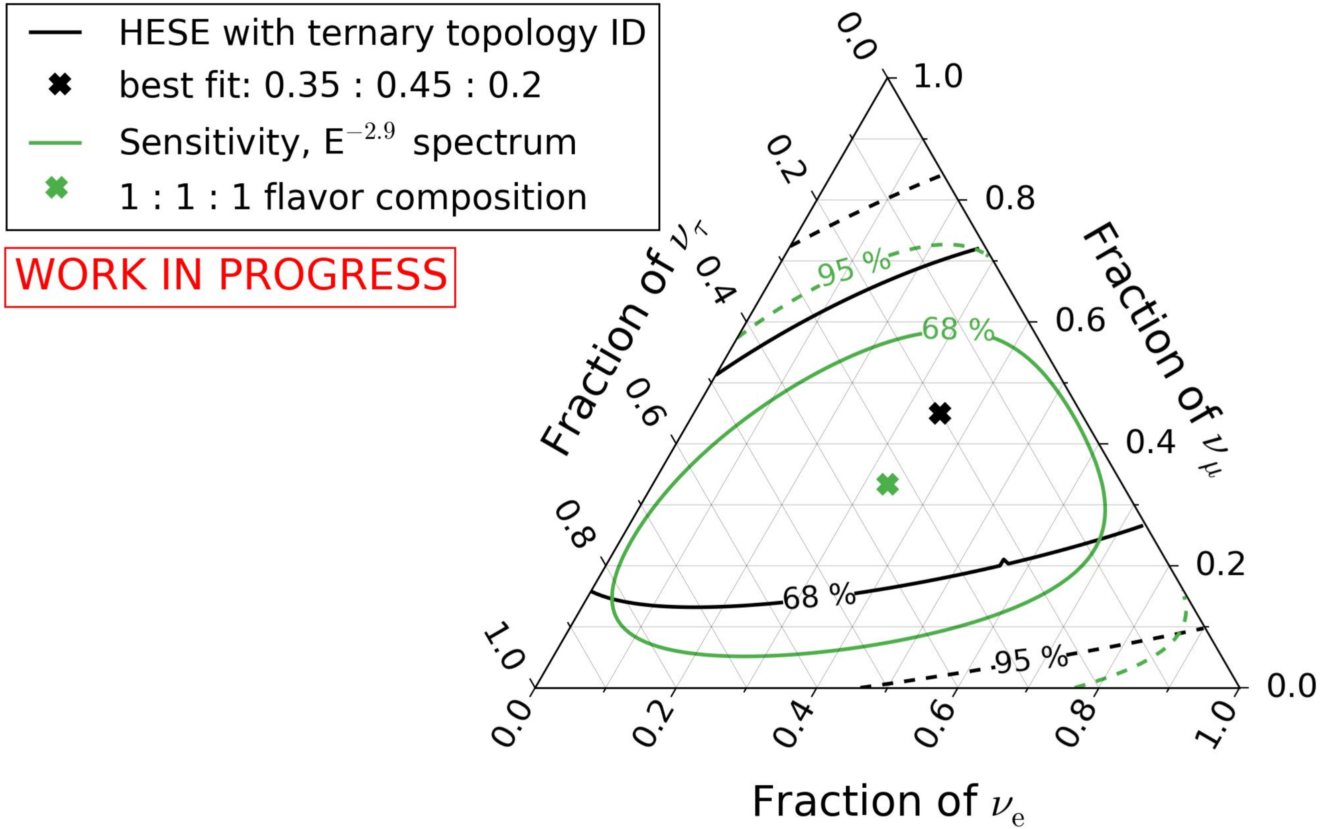
Results from fit

Astro index	2.87
Astro norm	1.9
Conv norm	1
Prompt norm	8.0
Muon norm	1.1

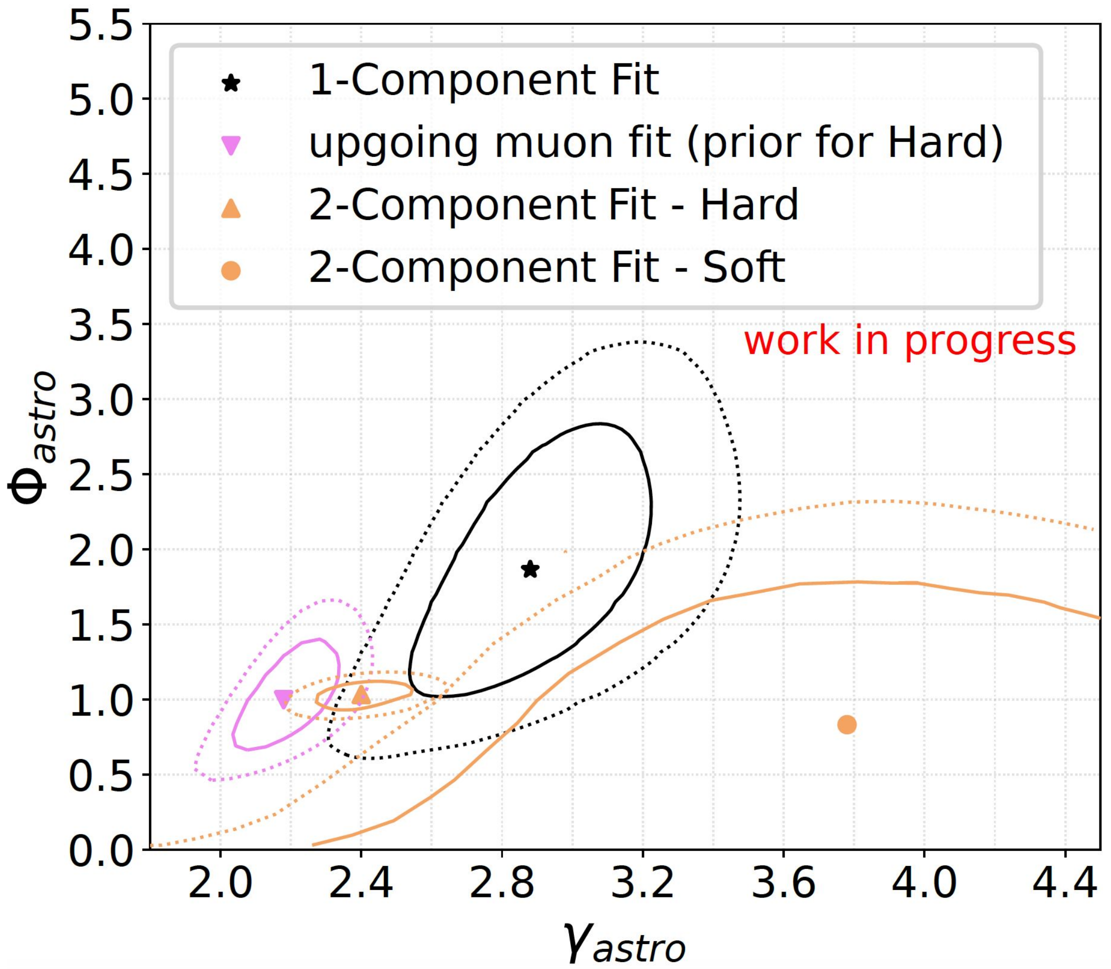




Results from fit



Results from fit



Data Sample

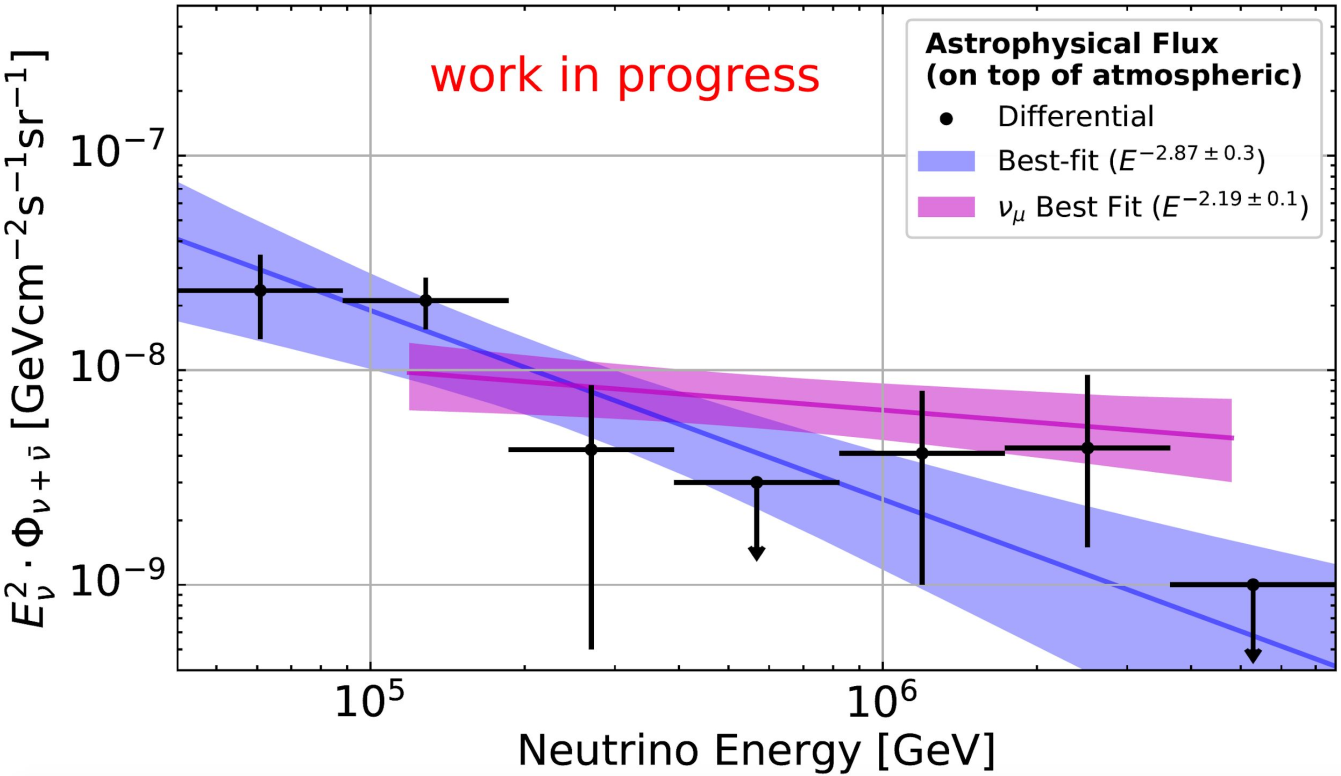
Unfolded spectrum

No detector systematics

No flux systematics beyond normalization

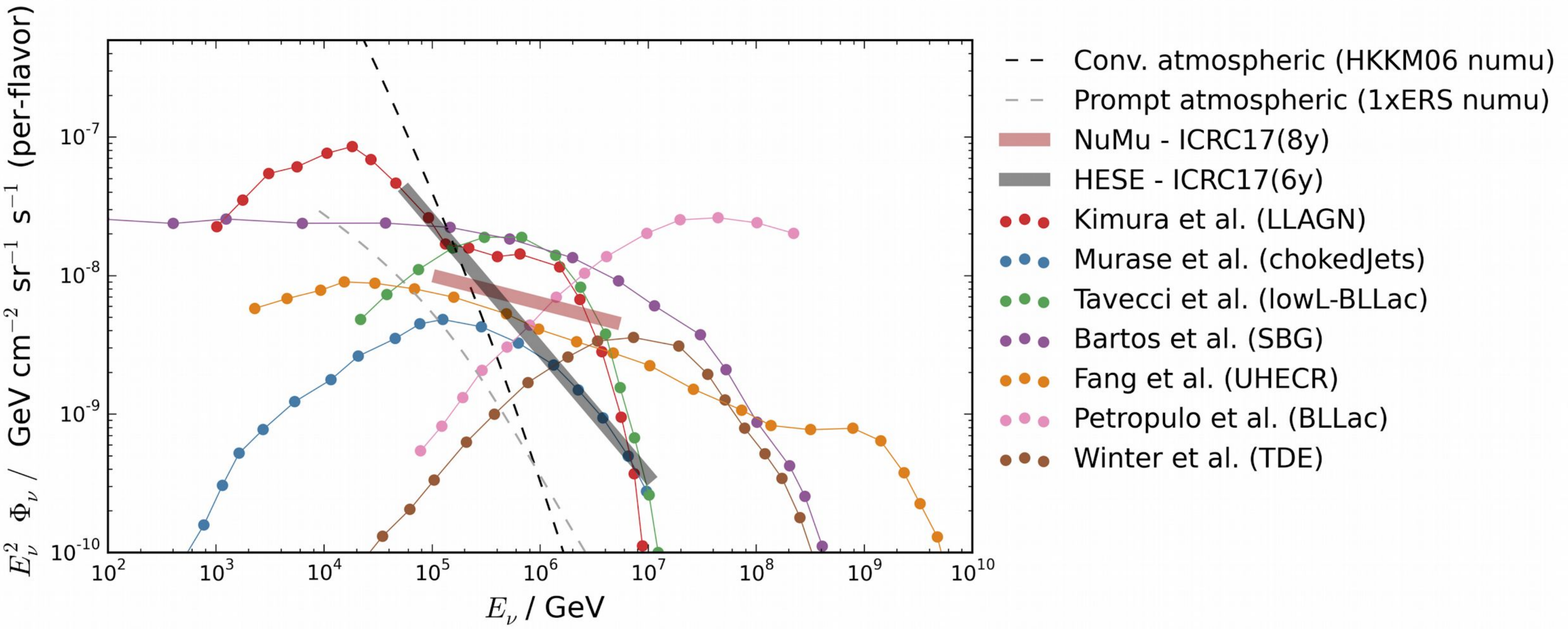
Working on the updated unfolding

Challenging because of many dimensions



Diffuse Models to Test

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



Flavor

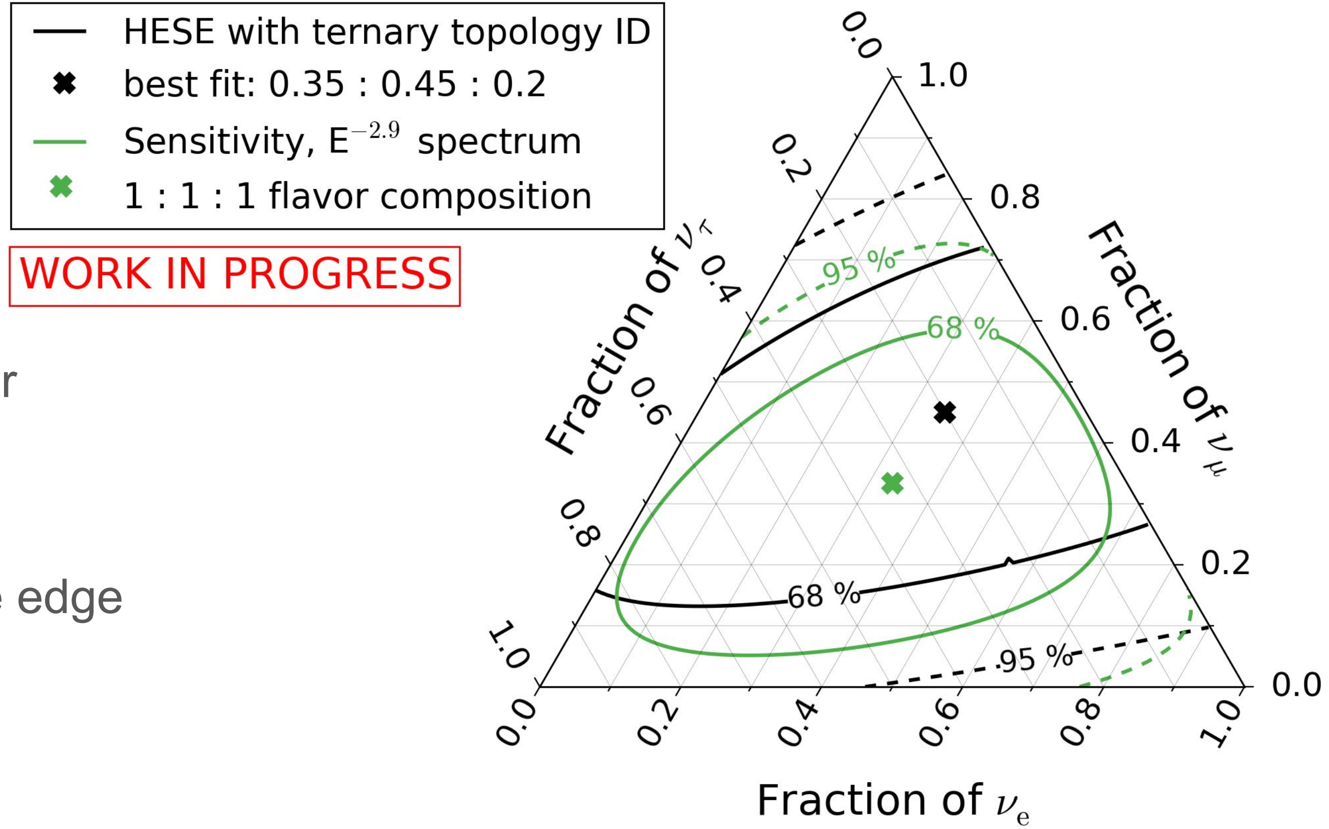
Black shows data

Green shows Asimov

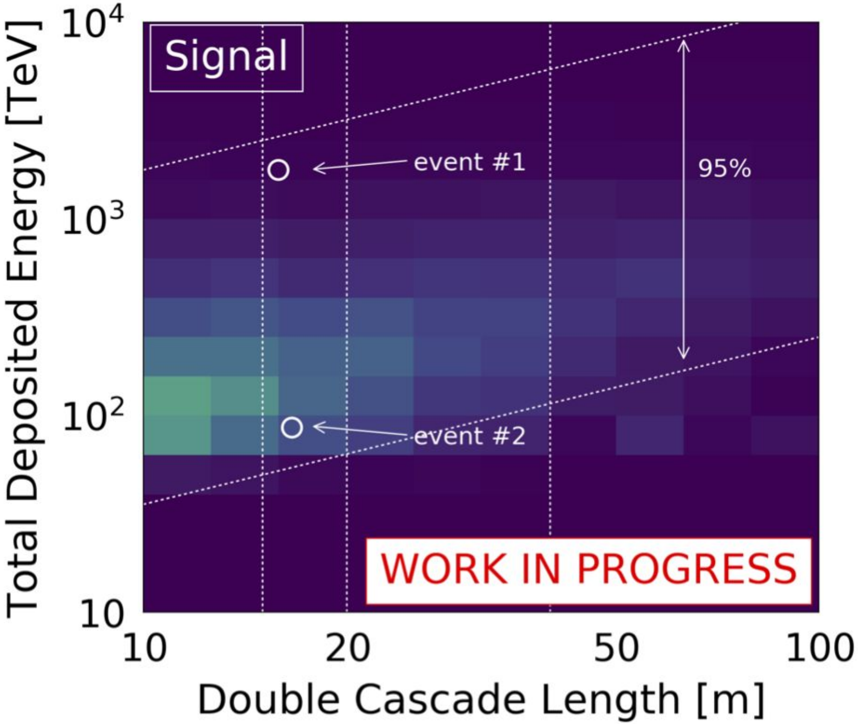
Contours getting smaller

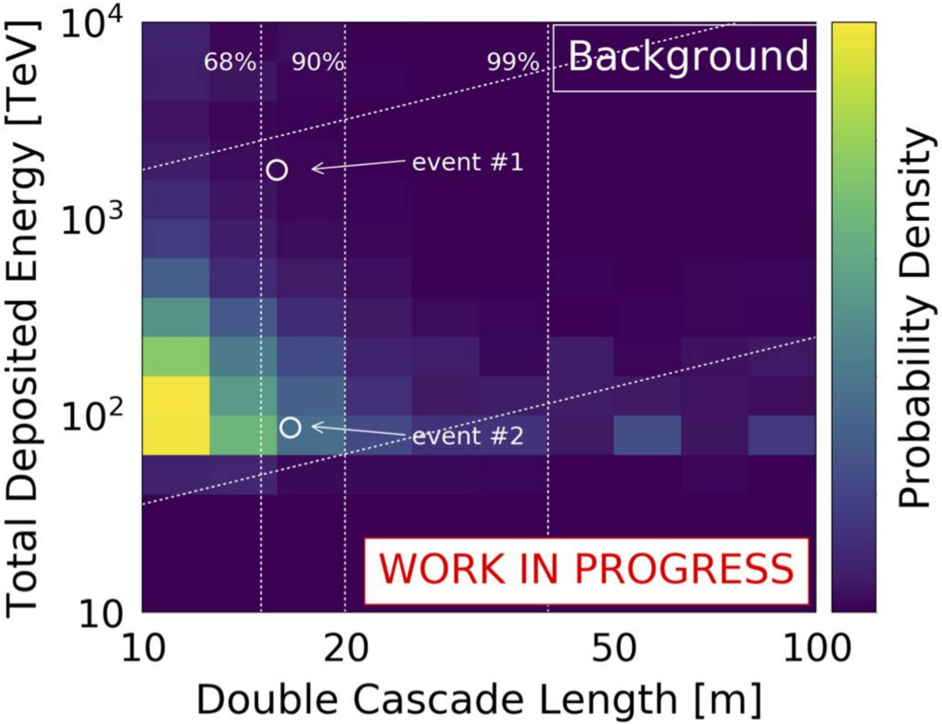
Ternary PID helps a lot

Best fit no longer on the edge



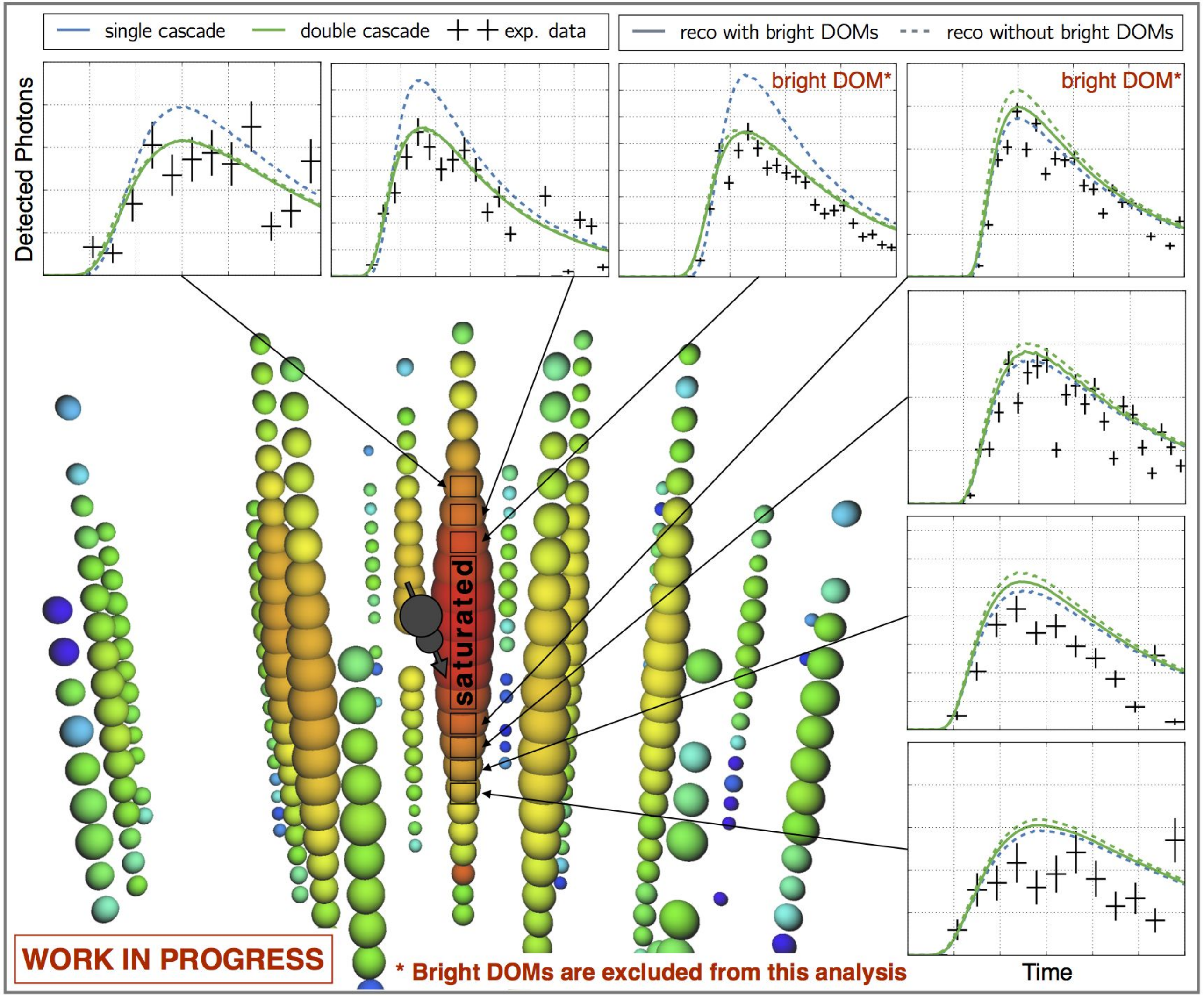
Flavor - Double Cascades





Big Bird

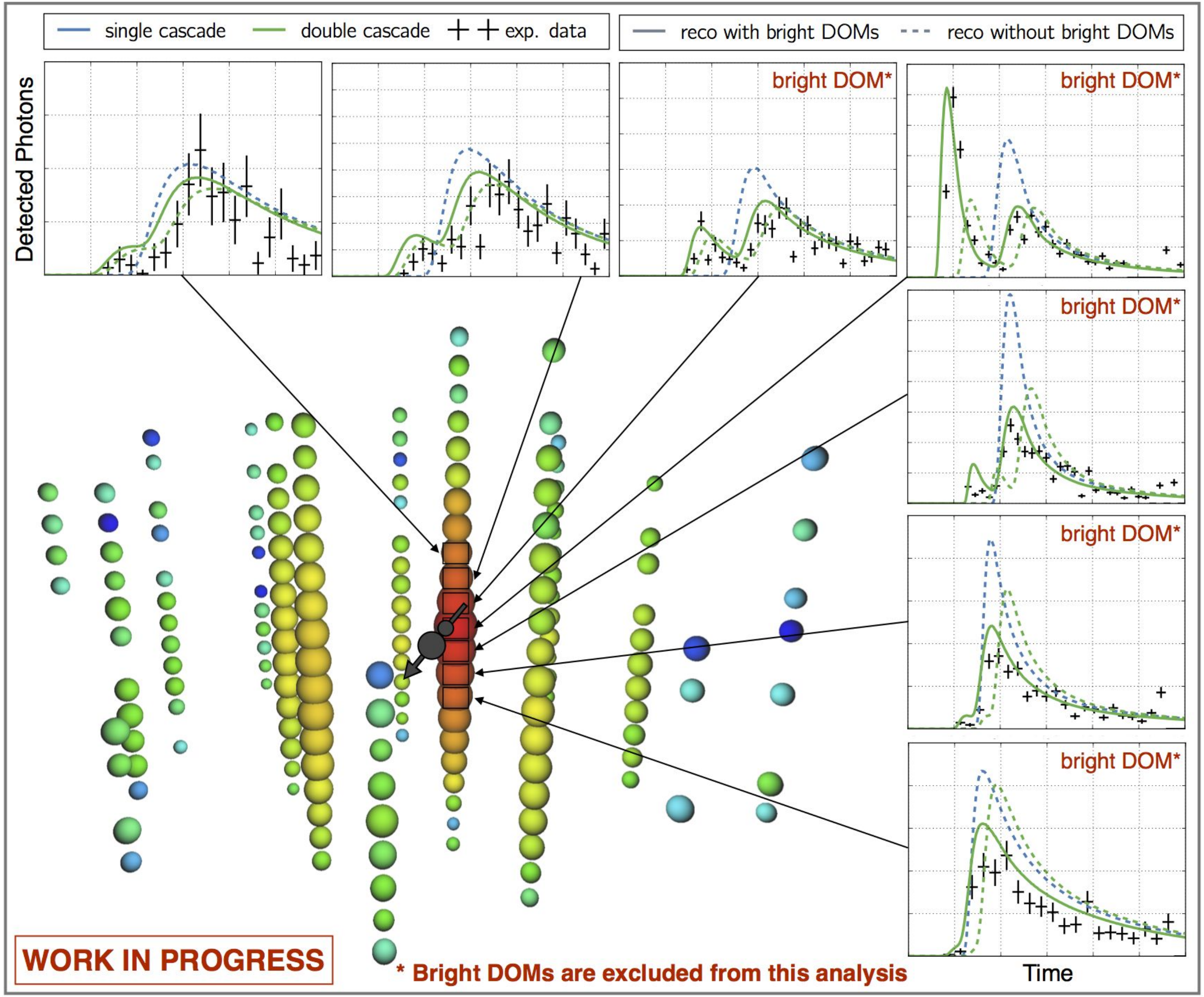
Compatible with double cascade and single cascade



Doppio

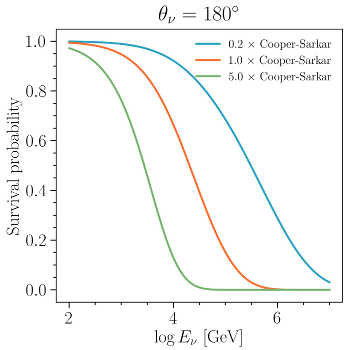
Double cascade

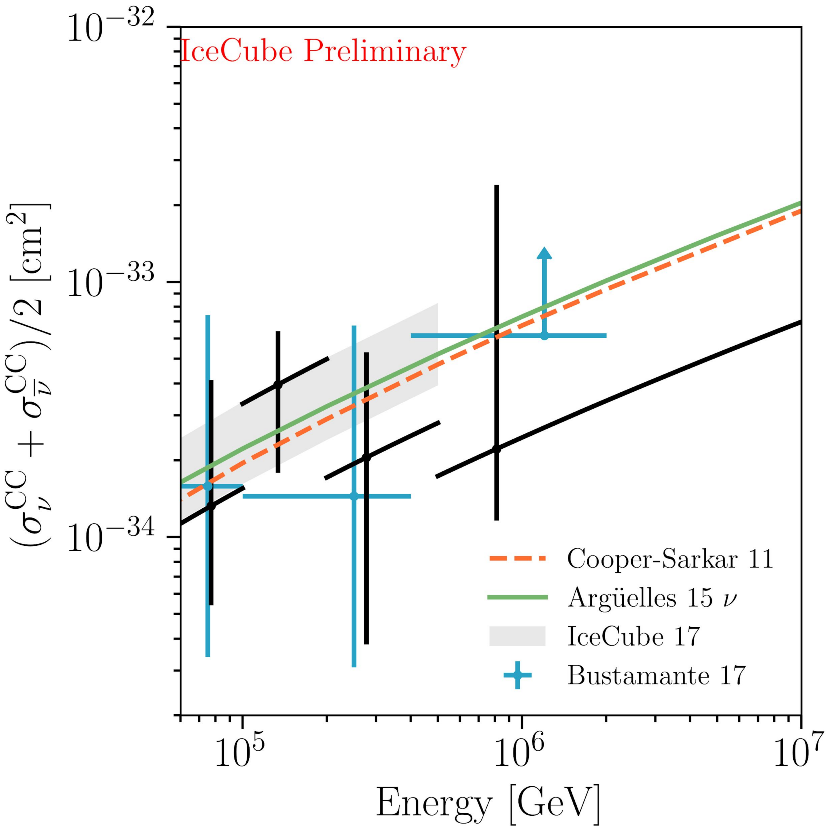
Not compatible with single cascade



Cross Section

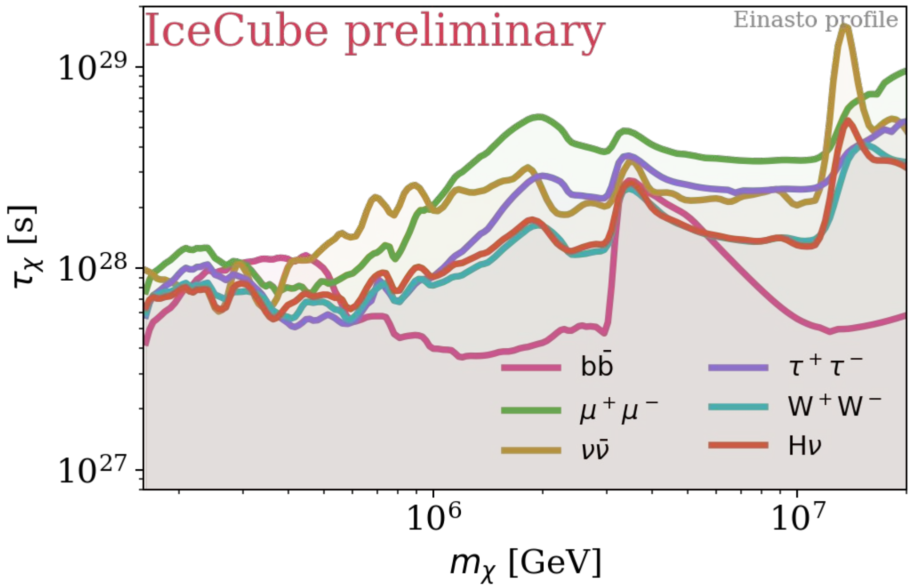
- For charge-current interactions, neutrinos are either lost or regenerated via tau decay
- For neutral-current interactions, neutrinos are not destroyed but cascade down in energy
- 7.5 year High-energy Starting Events (HESE) sample
- Forward-folded fit in energy and zenith; different from IC-Cascade measurement with unfolding

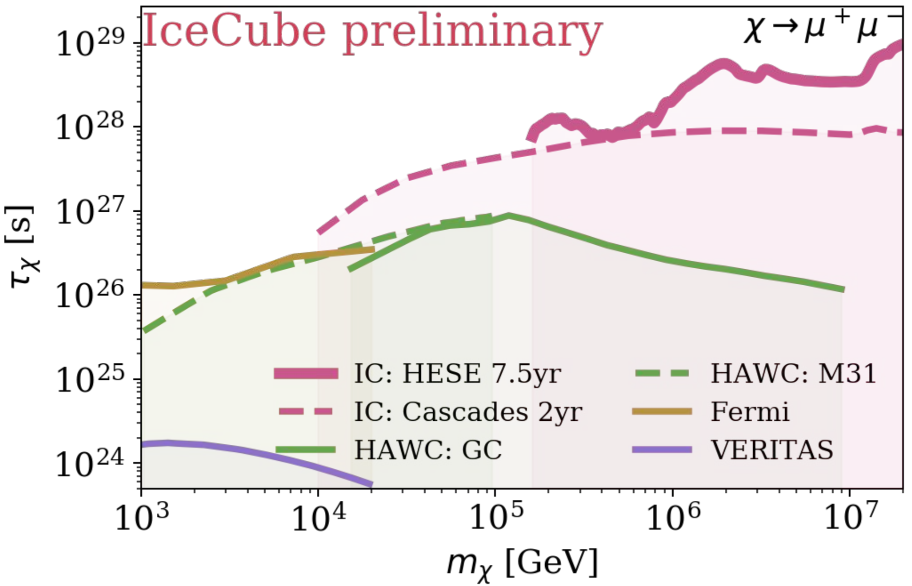




Dark Matter Decay

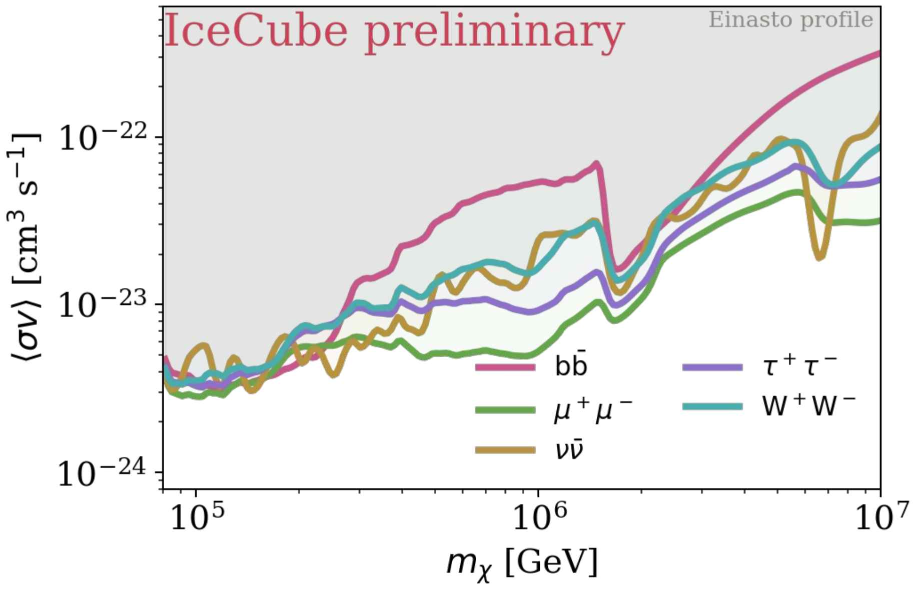
Great new limits in the mass range we look at!

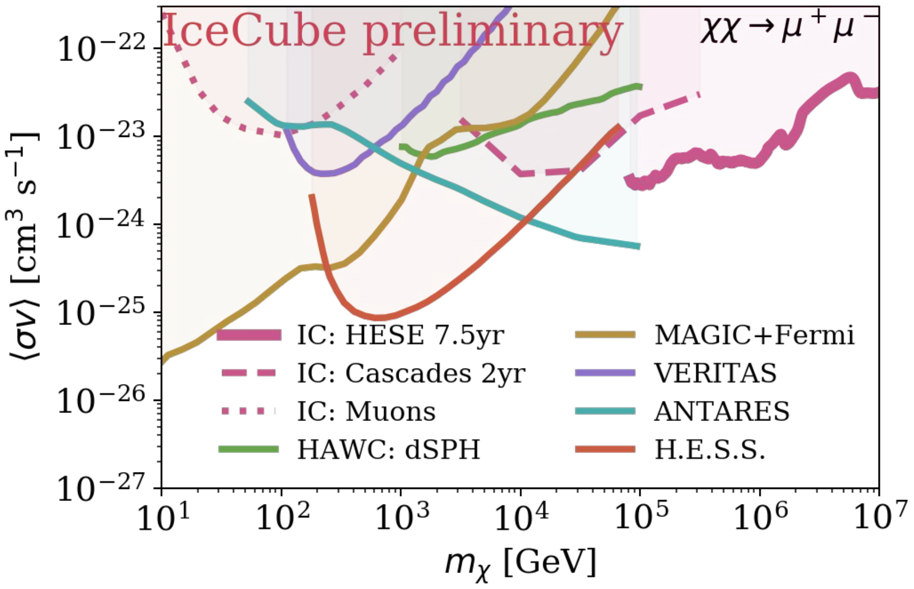




Dark Matter Annihilation

New limits in the energy range we look at

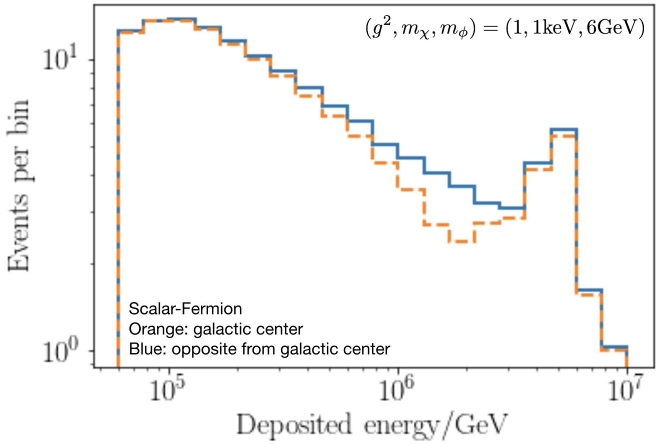


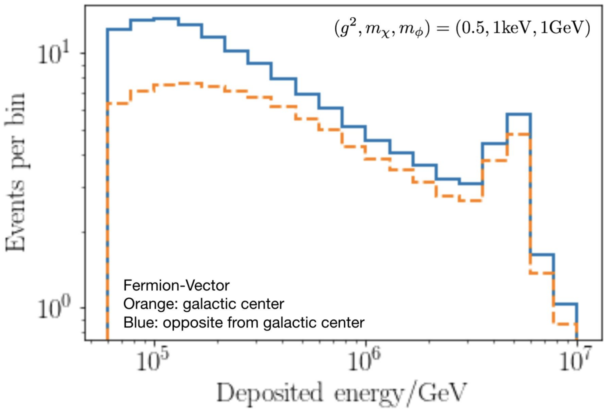


Dark Matter Scattering

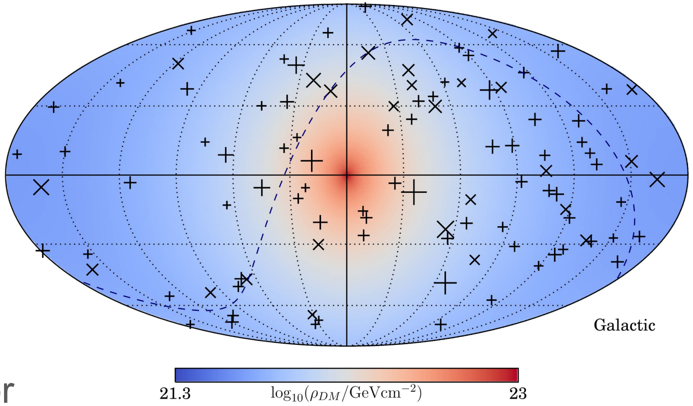
Assume an isotropic power-law neutrino spectrum incident on the galaxy. Dark matter-neutrino interactions introduces a deficit in the direction of DM over densities.

The color plots show the maximum allow coupling given for given dark matter and mediator masses. The bright pink line signals the region where IceCube bounds are stronger with respect to cosmological observations.



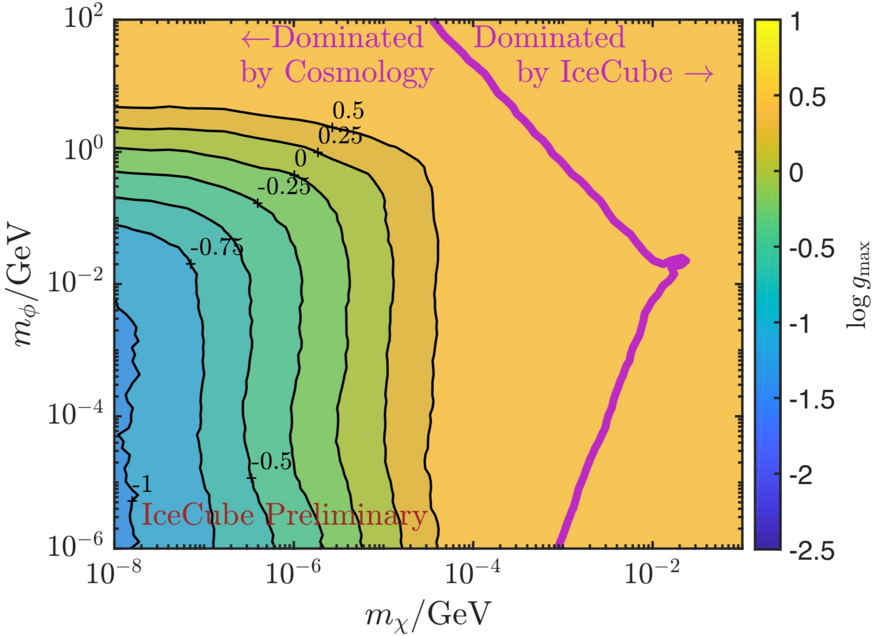


Dark Matter Scattering

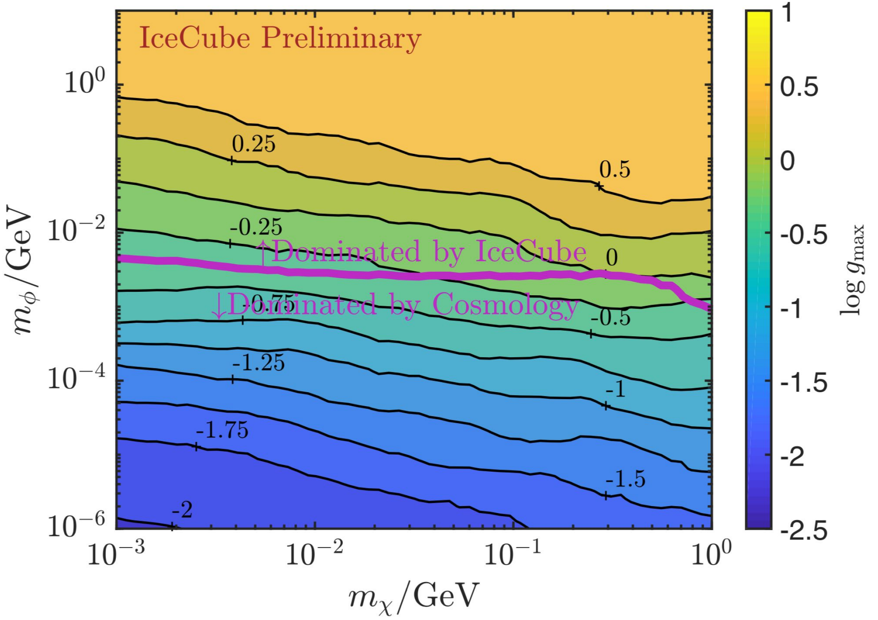


The color plots show the maximum allowed coupling for given dark matter and mediator masses.

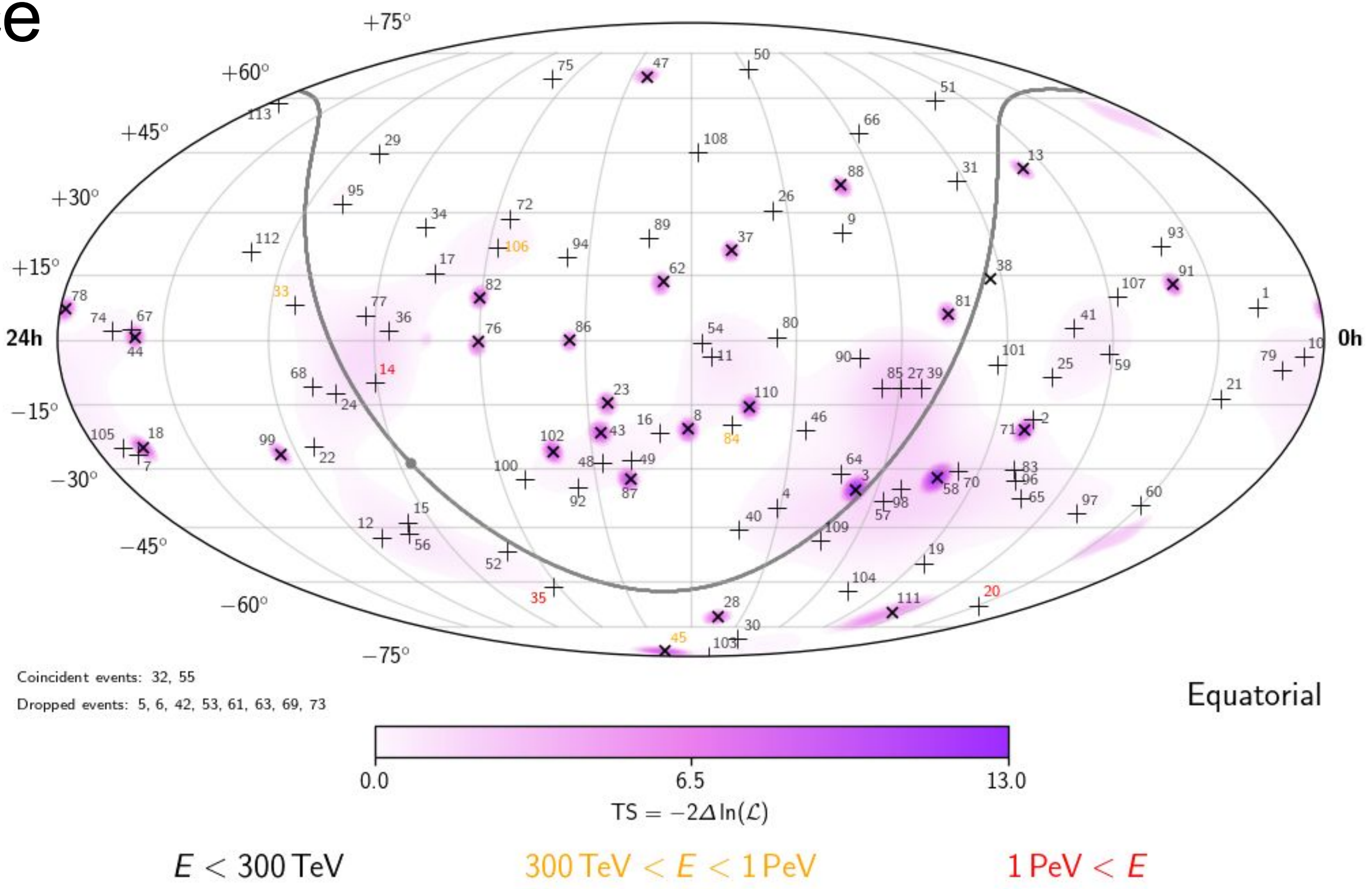
Scalar - Fermion



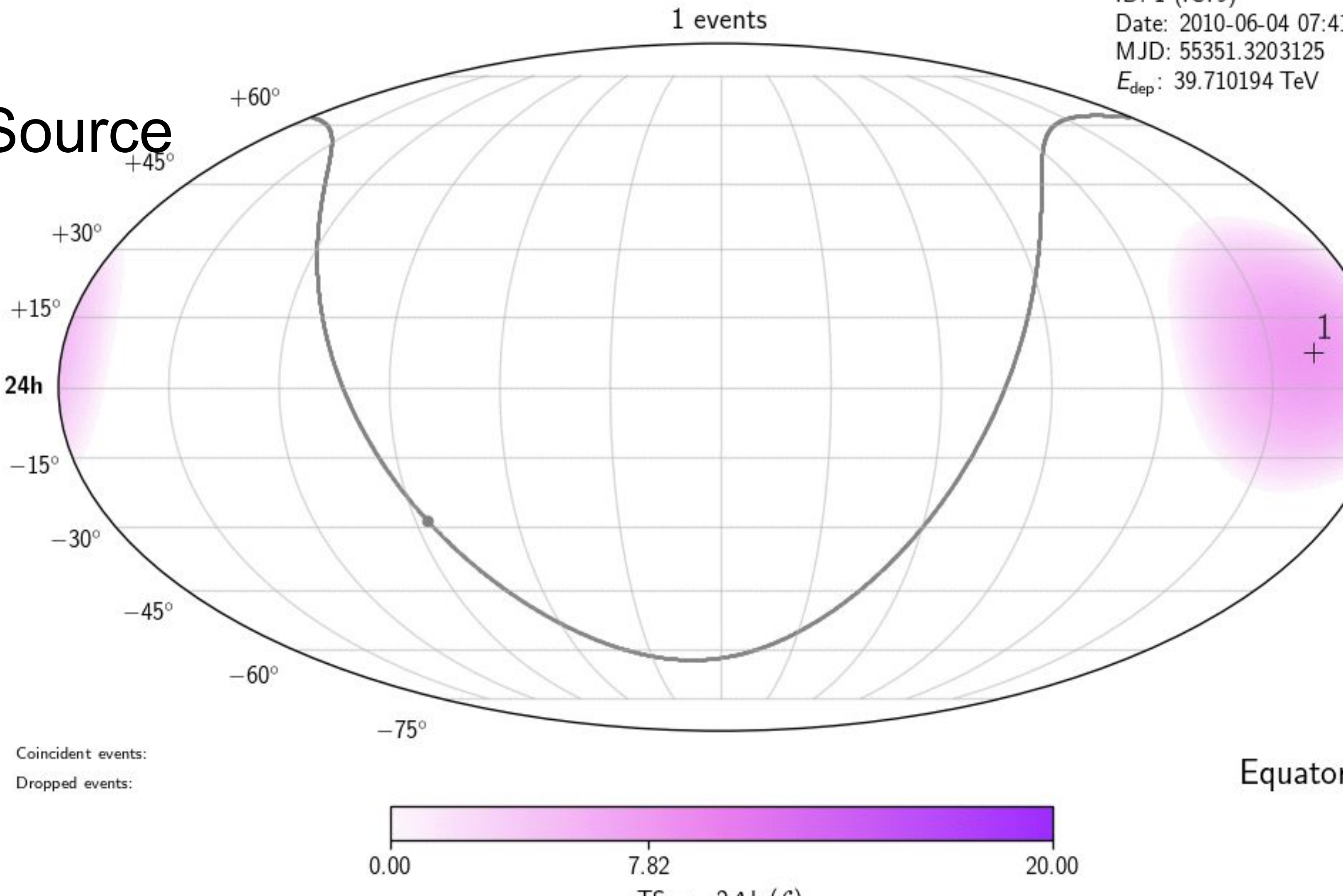
Fermion - Vector



Point Source



Point Source



Analyses / Results from HESE-7

- Diffuse → standard diffuse + many model tests — Austin / Nancy
- Cross section → measurement of \nu cross section — Tianlu
- Double cascade events → event studies — Tianlu / Nancy / Juliana
- Flavor → ternary PID + flavor triangle
- BSM flavor → limits on NSI and LV (best in the world!) — Shivesh
- Dark matter → limits for all channels — Carlos / Hrvoje
- Point source → PS / galactic plane search — Mike

Final words

- Sample discovered astrophysical neutrino flux
- Many analyses are using this data
- All using the same software
- Trying to get all the physics we can out of the sample
- Move on to bigger and better samples → MESE, MEOWS

Thanks!