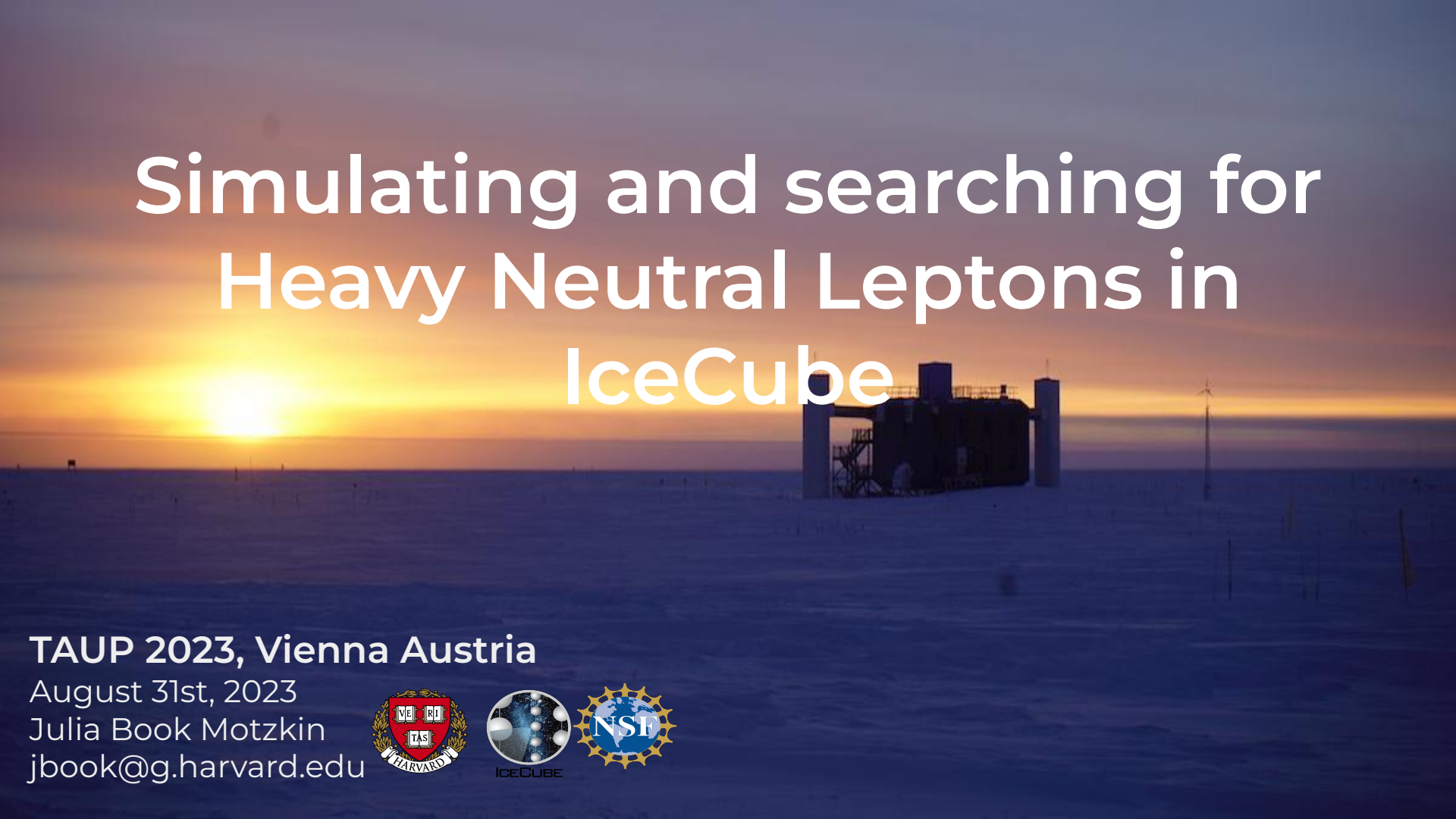
Simulating and searching for Heavy Neutral Leptons in IceCube



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Motivation: The search for Heavy Neutral Leptons

Image credit: Symmetry Magazine

Neutrino oscillations → neutrinos have mass

Neutrino mass + smallness of the mass = something funny going on

Possible explanation:
Seesaw mechanism, requiring a right-handed SU(2) singlet, the HNL

HNLs could then explain other issues, like matter antimatter asymmetry, Dark matter, oscillation anomalies

Motivation: The search for Heavy Neutral Leptons

Image credit: Symmetry Magazine

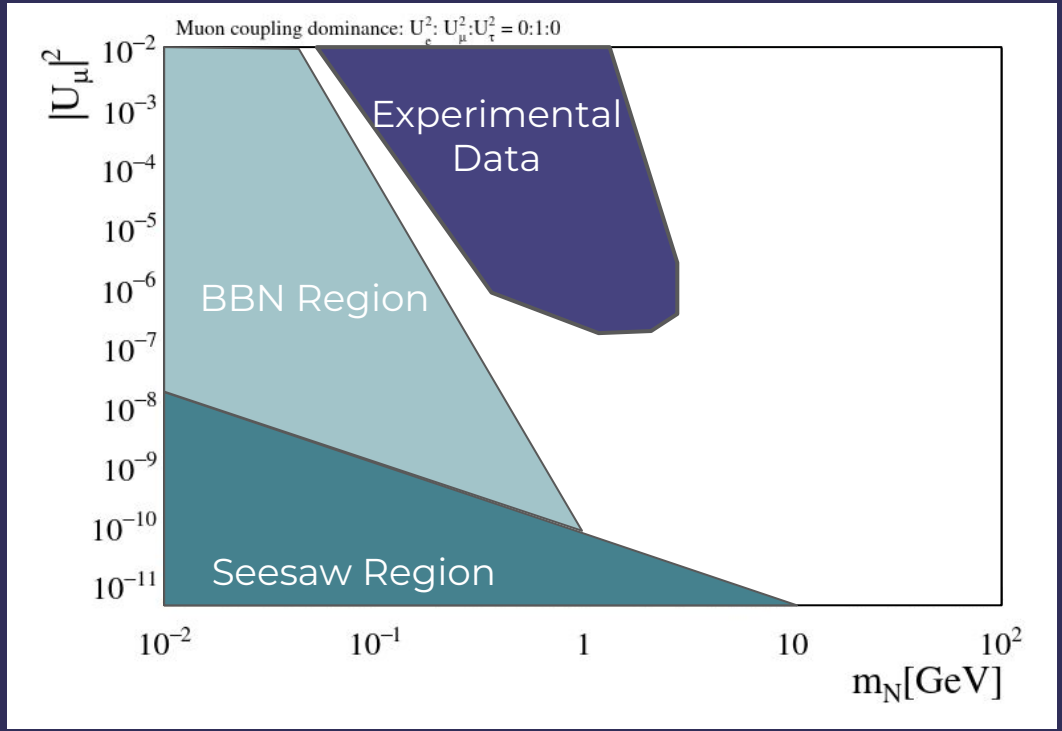
Searches for HNLs are occurring around the world at beamlines, neutrino observatories, and in evaluation of existing data

Existing event generators for neutrino observatories don't support many BSM scenarios, like HNLs

Robust searches for these scenarios demands working MC simulation tools

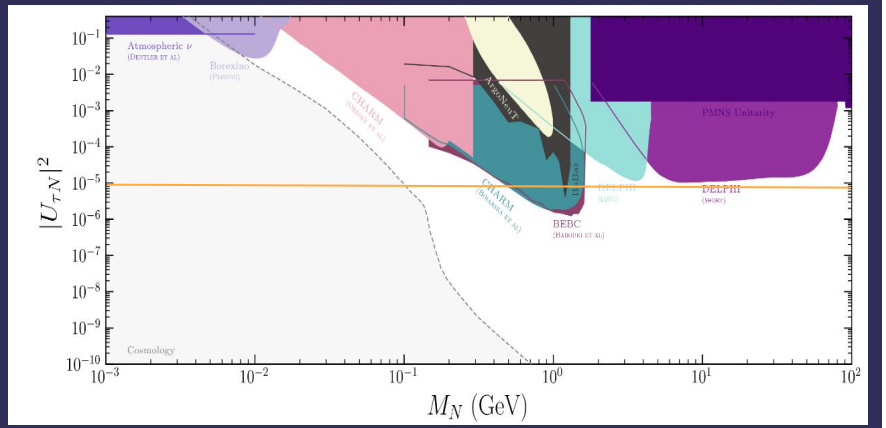
Bounds on HNL Searches

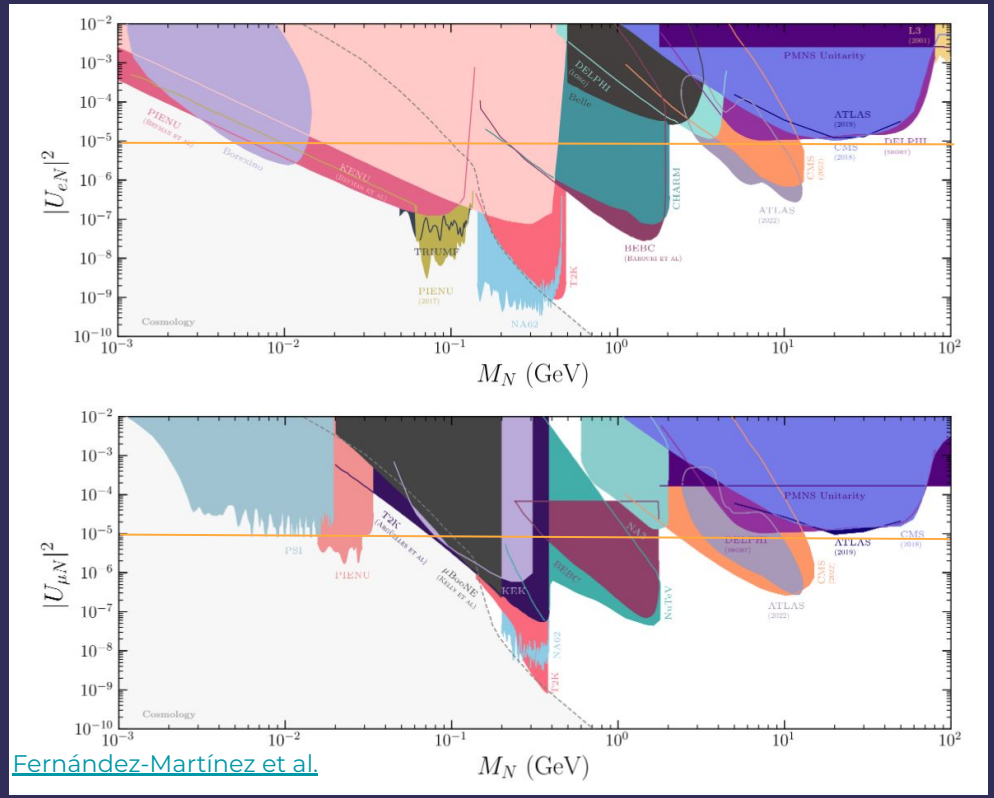
HNL bounds come from theory, cosmological observations, and a bevy of experiments



Experimental searches

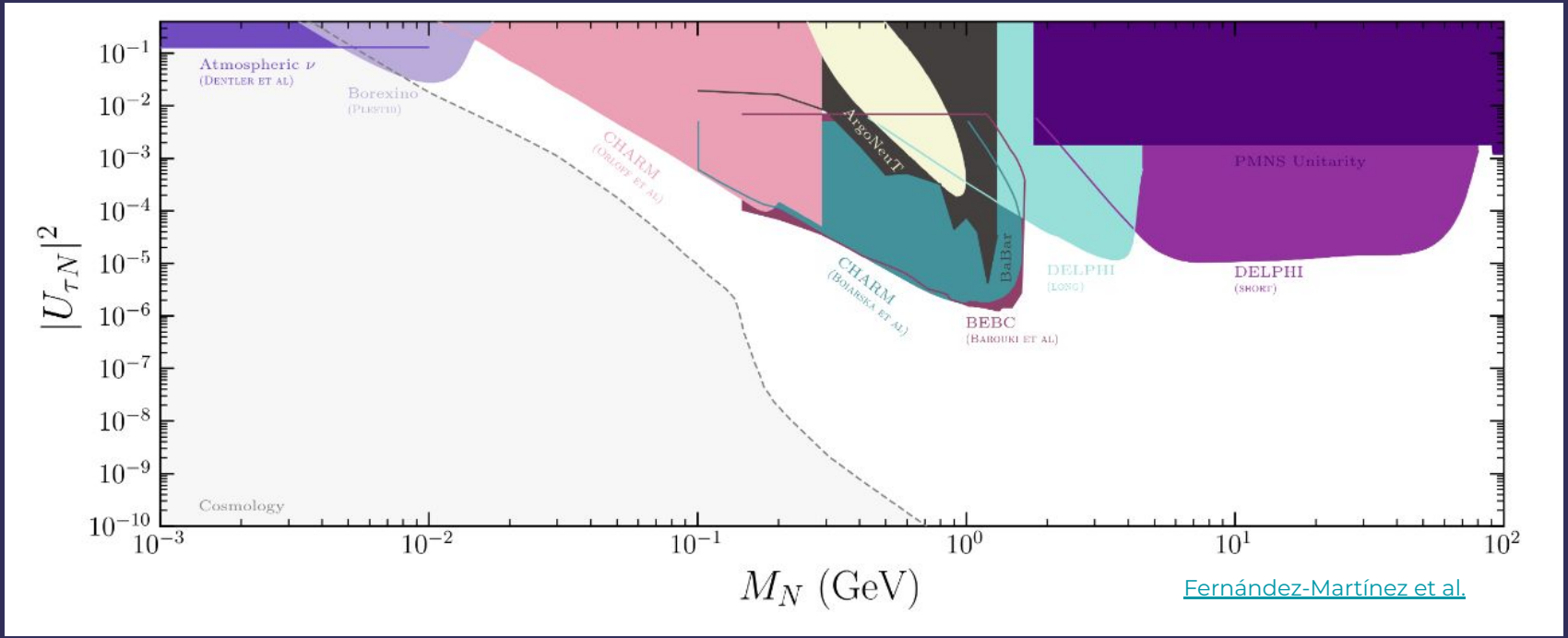
HNL mixings with the tau are less constrained





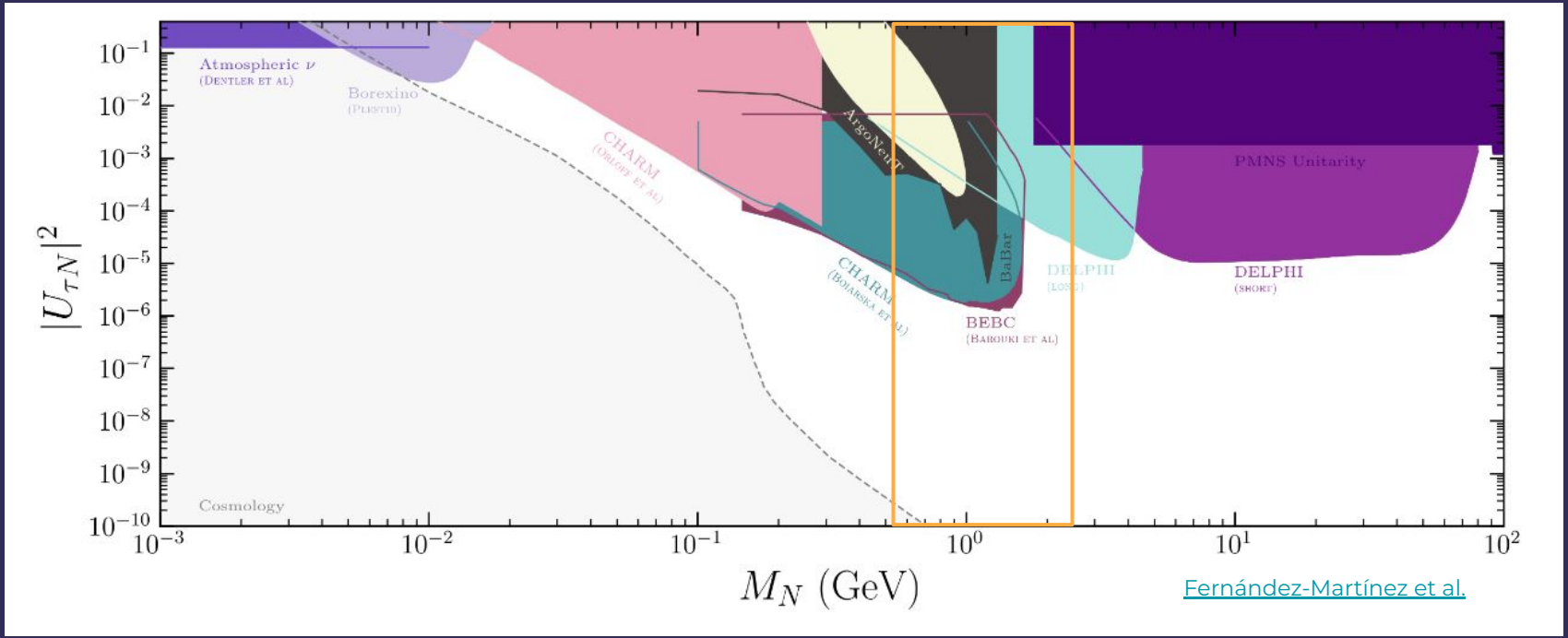
Fernández-Martínez et al.

Bounds on HNL-ν_τ Mixing

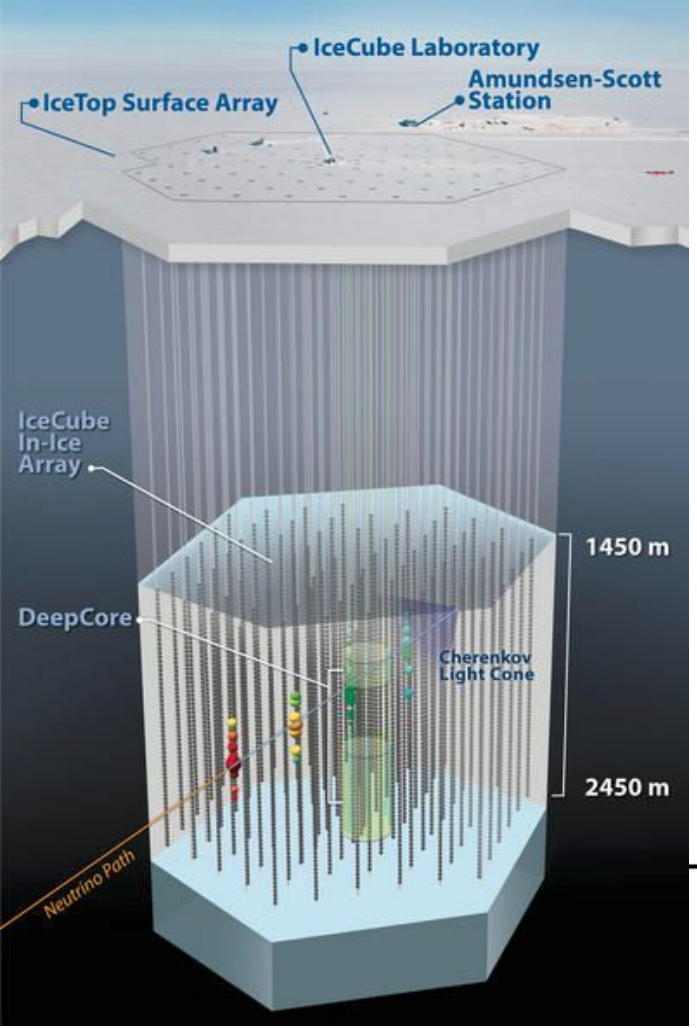


Fernández-Martínez et al.

IceCube Region of Interest



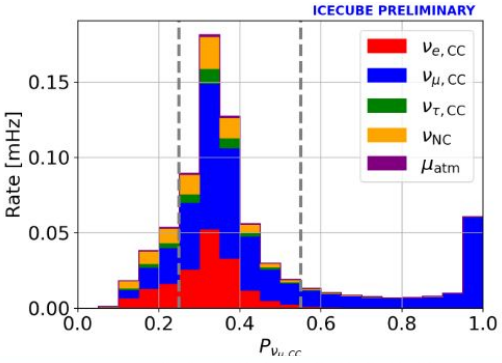
Region of interest first estimated in Coloma et al.

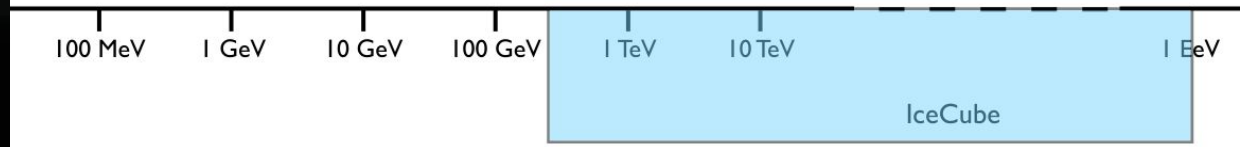


The IceCube Detector

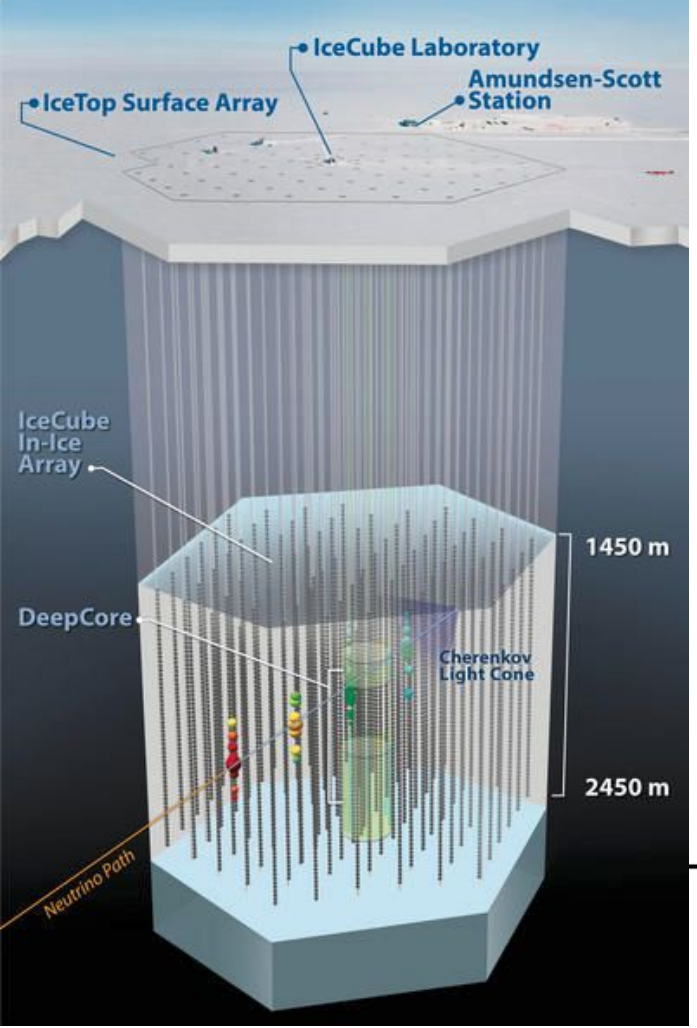
- Cubic km volume water Cherenkov detector
- In DeepCore, the DOMs are more densely spaced, giving greater sensitivity for short-lived HNLs
- ν_τ flux from oscillation of atmospheric ν_μ
- Event energies range from GeV to high TeV scales

As seen earlier in this session, shows ν_τ contribution to the atmospheric flux in DeepCore



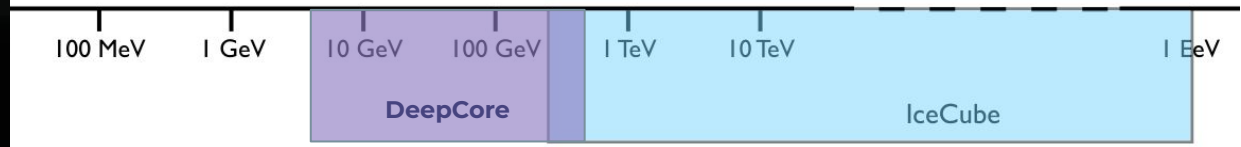


The IceCube Neutrino Observatory

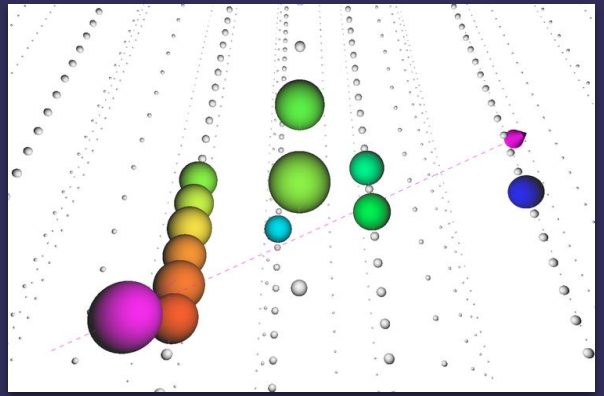


DeepCore: lowering the energy threshold

- 8 extra strings
- DOM spacing of 7m
- All below dust layer, plus dust layer veto

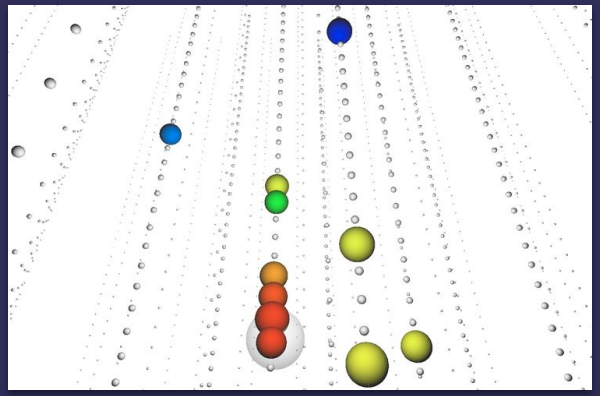


Low-energy Event Topologies



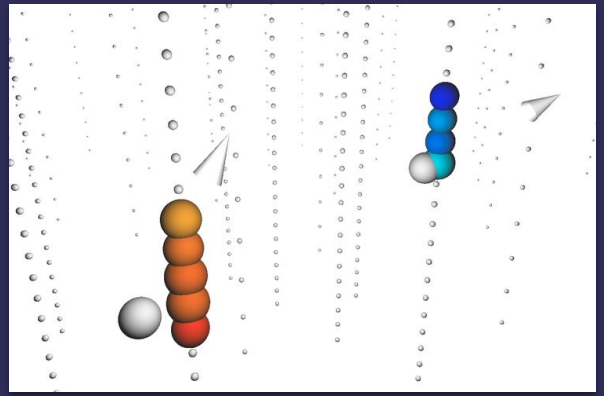
Track

Muons created in muon neutrino charged current events can propagate for a while before stopping, releasing cherenkov light as they go



Cascade

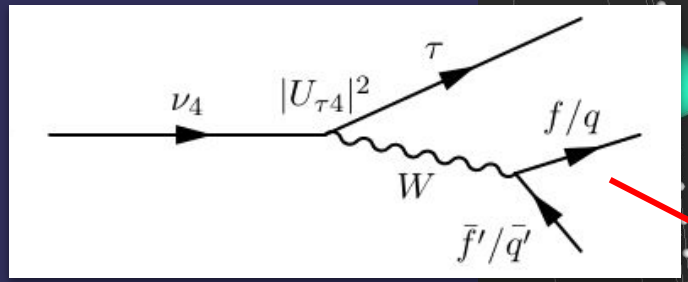
Result of a neutral current (Z exchange) or electron neutrino event



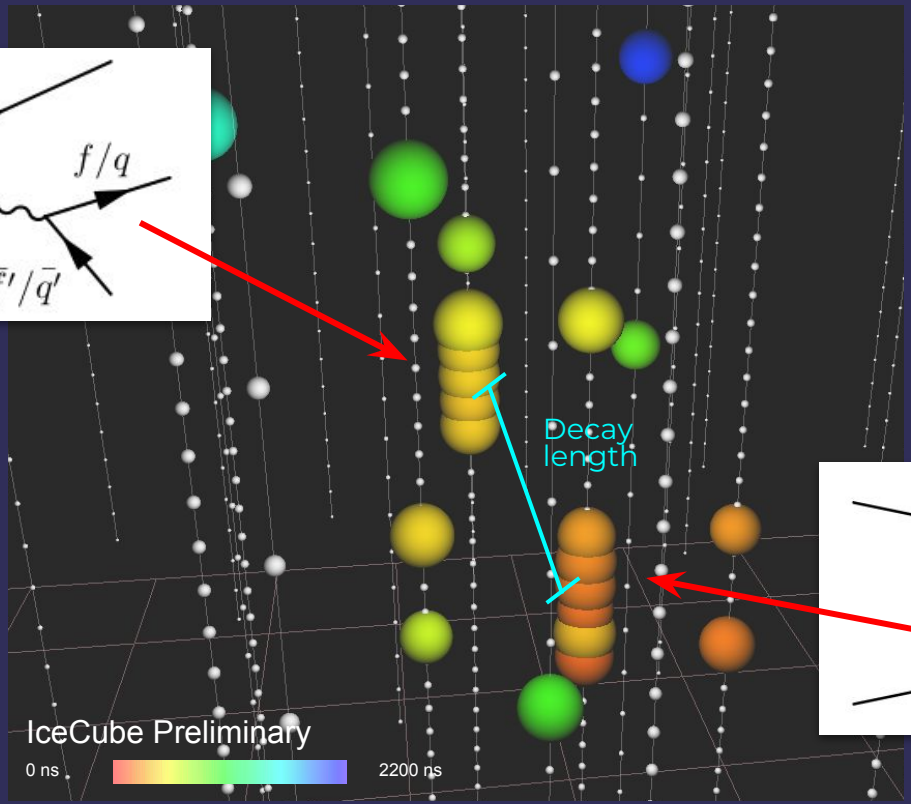
Double Cascade

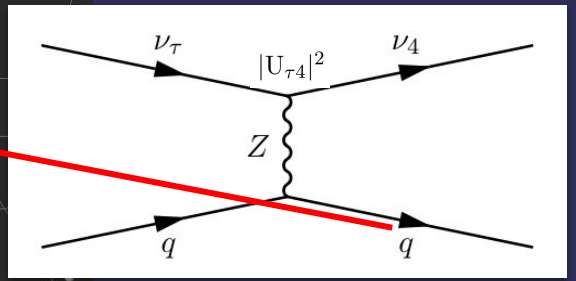
Tau or exotic signal - cascade at production and decay

Double Cascade HNL Production

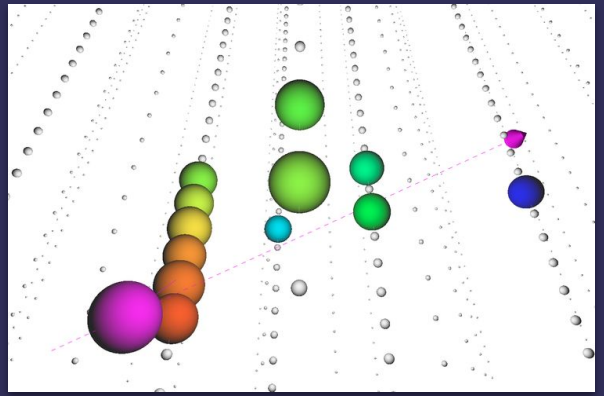


Tau neutrinos passing through the detector volume may scatter off ice nuclei, producing an HNL. HNLs then decay to leptonic or mesonic final states

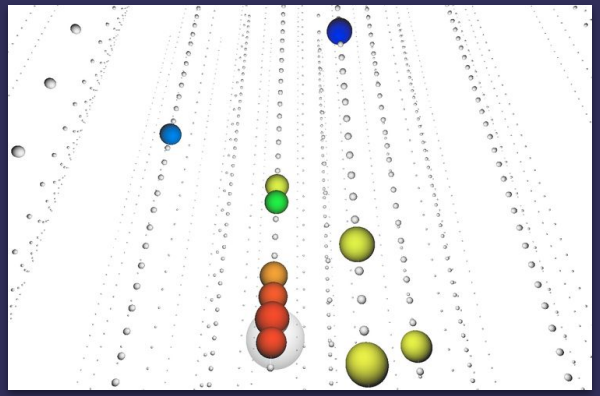




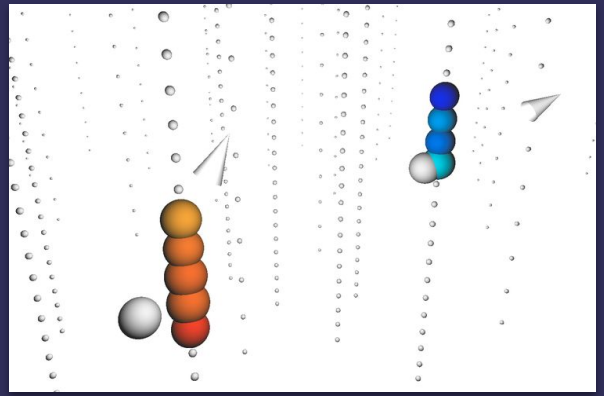
Low-energy Event Topologies



Track



Cascade

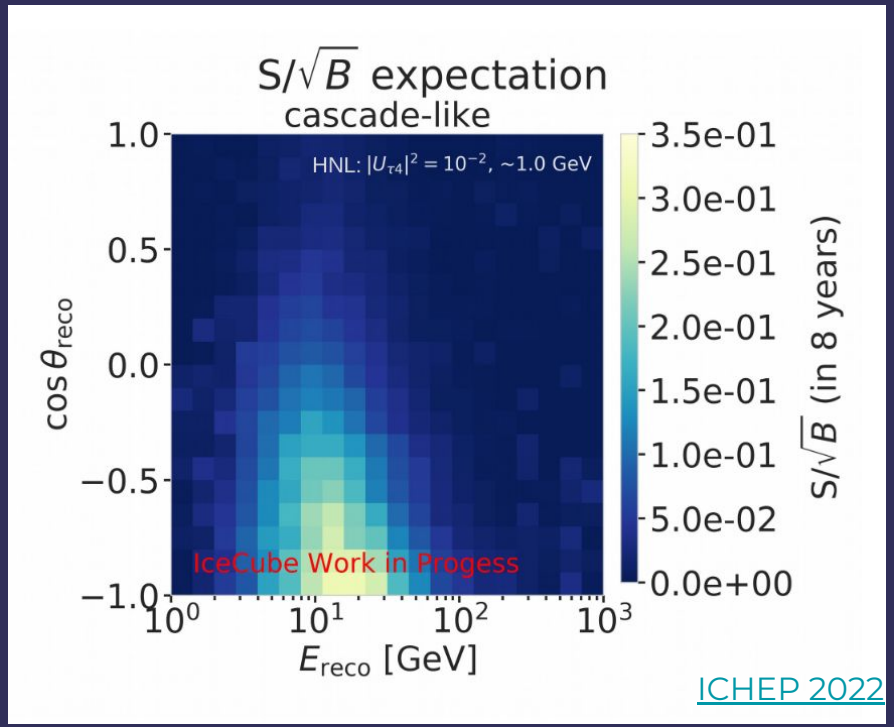


Double Cascade

The distinctive double-cascade shape has the potential to be a clear hallmark of an HNL signal - if we can resolve them

Current Searches

- At low energies, the double-cascade signature is currently unresolvable
- Using existing analysis and reconstruction tools, a search for a cascade-like excess is underway (led by Leander Fischer)
- Working towards a double-cascade analysis through development of tailored reconstruction tools
- All analyses make use of our custom generator



ICHEP 2022

LeptonInjector-HNL Overview

While some work has addressed HNLs in accelerator experiments, there is not yet an HNL event generator for neutrino observatories

We've produced an HNL simulator which is adaptable to a range of experiments and theoretical models

LeptonInjector-HNL Workflow

1) Choose injection parameters
   - Earth properties
   - Neutrino cross section
   - Atmospheric neutrino flux parameters
   - HNL mass
   - Number of events

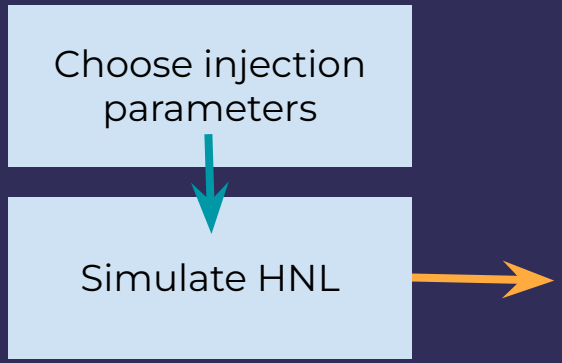
LeptonInjector-HNL Workflow

Choose injection parameters

2) Simulate each HNL

- Choose a vertex, direction, and energy for the initial particle (we use tau neutrinos)
- Use this to calculate the first final state particle (created along with the upscatter to HNL)
- Create HNL, sampling to get decay length, lifetime, decay mode

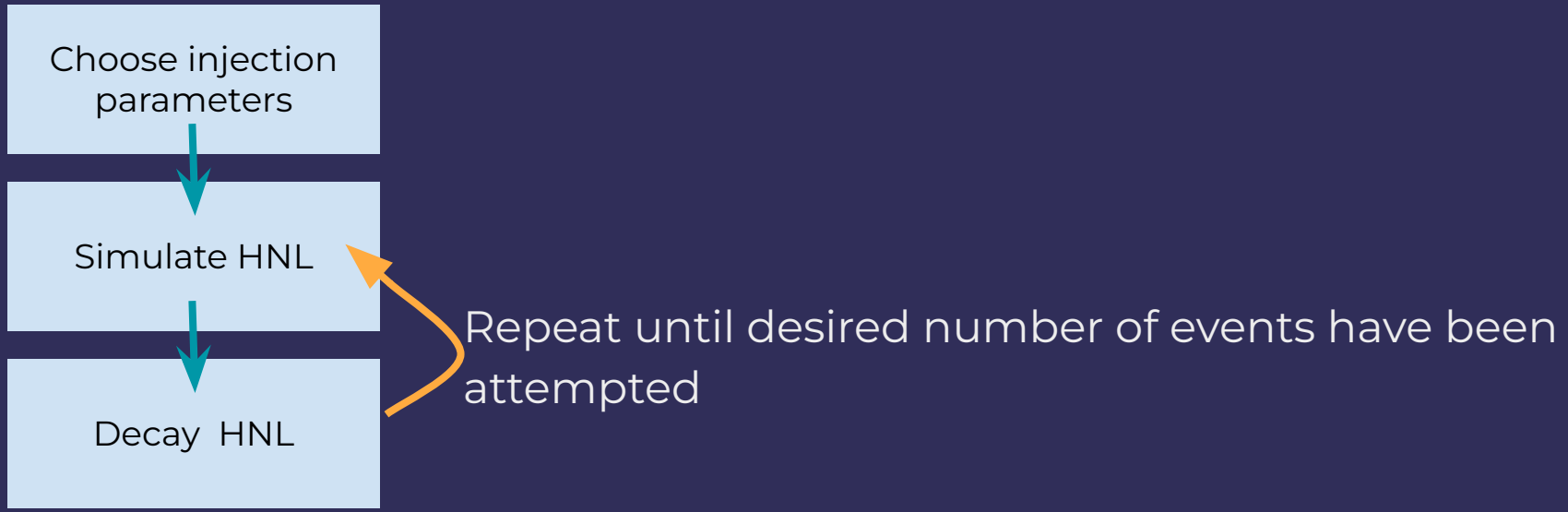
LeptonInjector-HNL Workflow



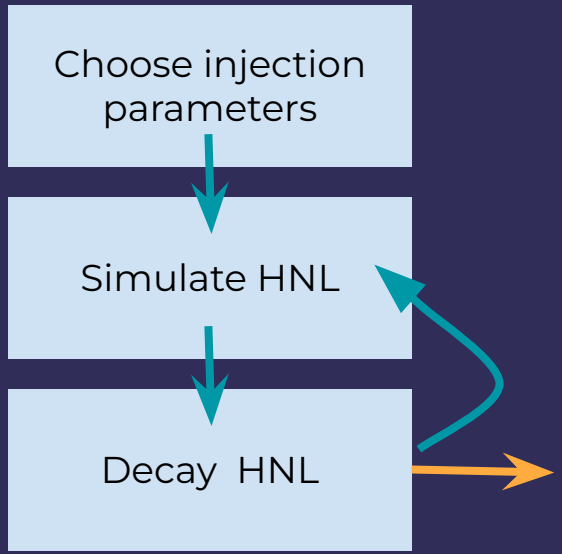
3) Decay HNL

- Choose a decay mode
- If 2-body, calculate kinematics directly
- If 3-body, choose a kinematic distribution from the pre-calculated distributions in the appropriate MadGraph file
- Return information about the decay products

LeptonInjector-HNL Workflow



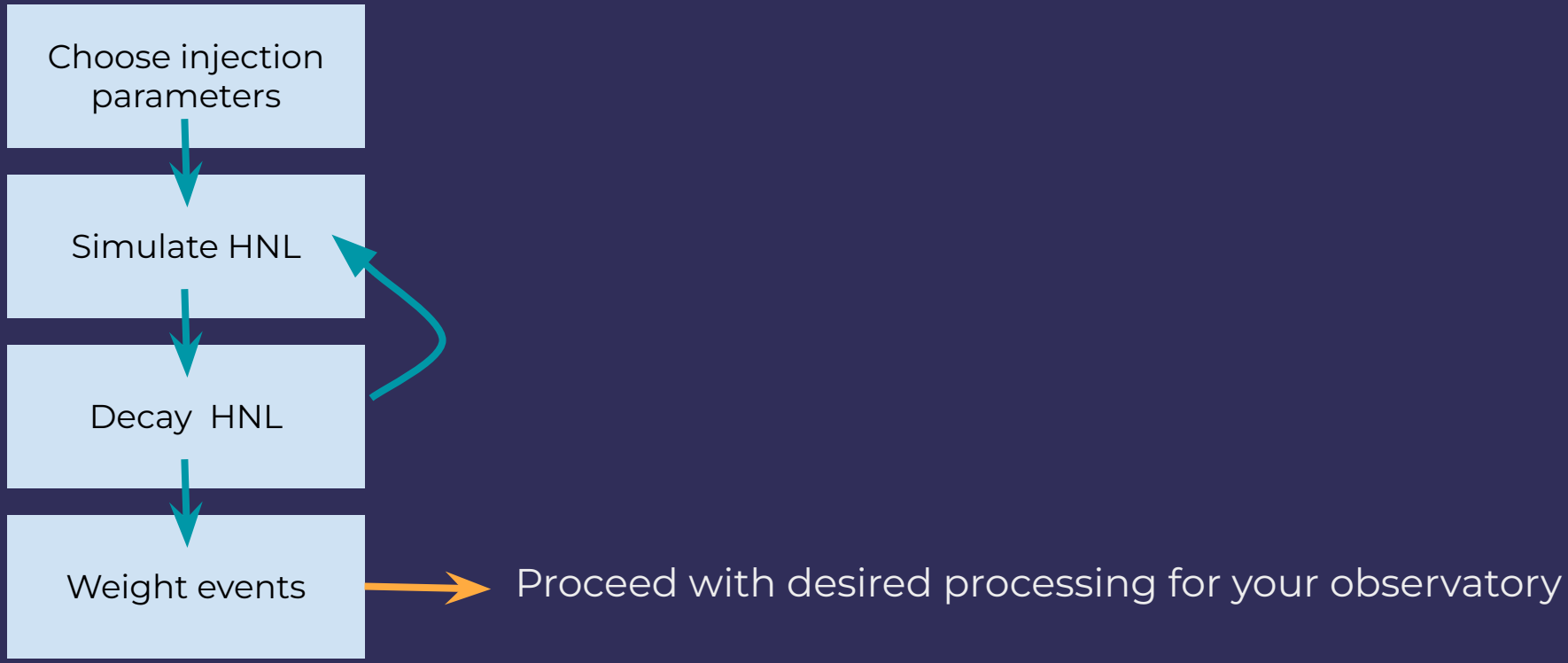
LeptonInjector-HNL Workflow



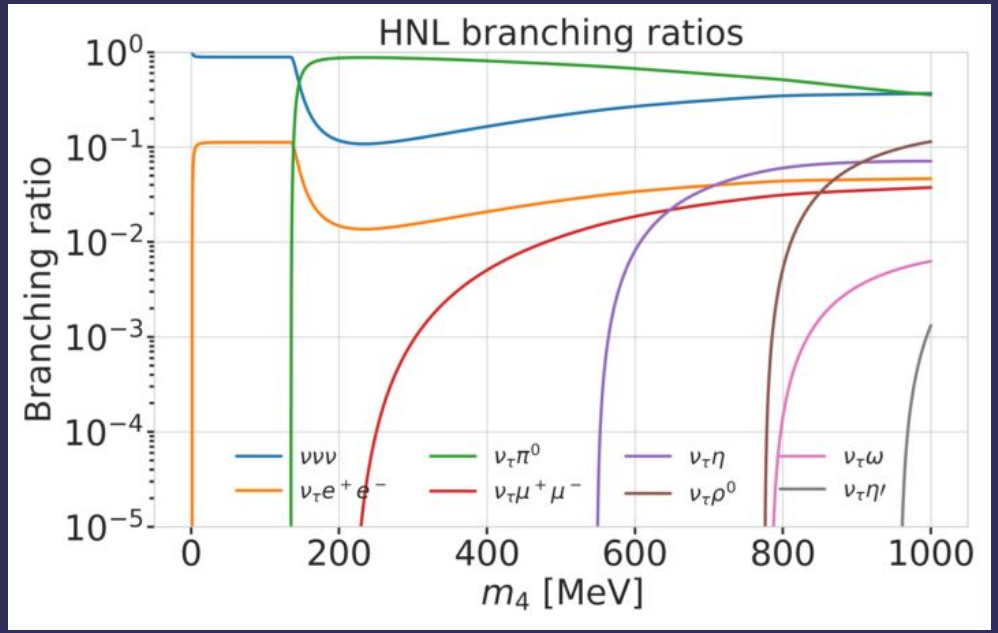
4) Weight each event

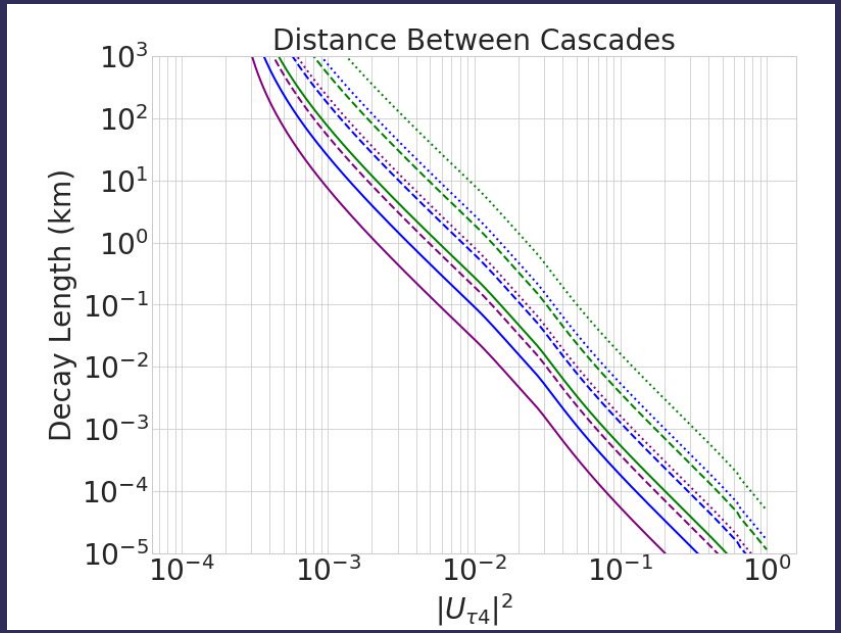
- For every frame, calculate weights using LeptonWeighter, taking events generated to a physical event distribution that accounts for flux, neutrino oscillations, and more

LeptonInjector-HNL Overview



Simulation Capabilities





➔ Using MadGraph5 (with HNL decay implemented in Feynrules, as described here)

➔ Working on adding support for simulating HNLs with m > 1 GeV

Take-home Message

1. New event generator based on LeptonInjector developed for Neutrino Telescopes
2. First generation analysis using track and cascade morphologies on going.
3. Continue developing our proof-of-concept - an HNL search in IceCube with GNN-based reconstruction methods

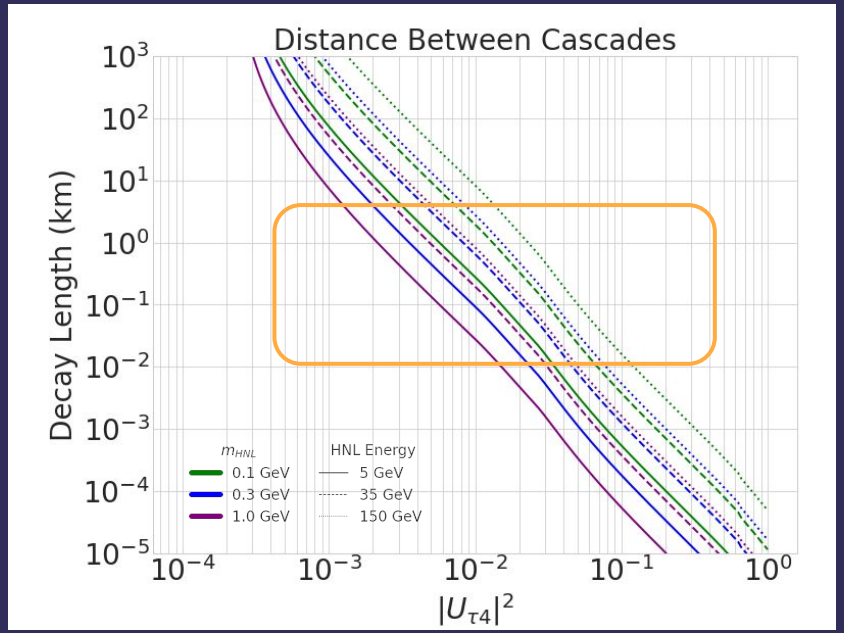
Thank you for listening!

Further thanks to Leander Fischer, Summer Blot, and Carlos Arguelles-Delgado - the rest of the HNLs in IceCube team.

Backup Slides

HNL Search: Current Status

- The decay length is determined mHNL, its mixing with the tau, and its overall energy
- IceCube's size allows us to search only in a particular region of phase space
- We tailor our simulation and reconstruction tools to decay lengths between cm and km scales
- IceCube is most sensitive to mixings above 10^{-4}, but is sensitive to smaller mixings at higher HNL masses



HNLs in IceCube

The dominant decay modes are to three neutrinos and to a tau neutrino and neutral pion

The proper lifetimes are closely bunched for all decay modes, especially above 1 GeV