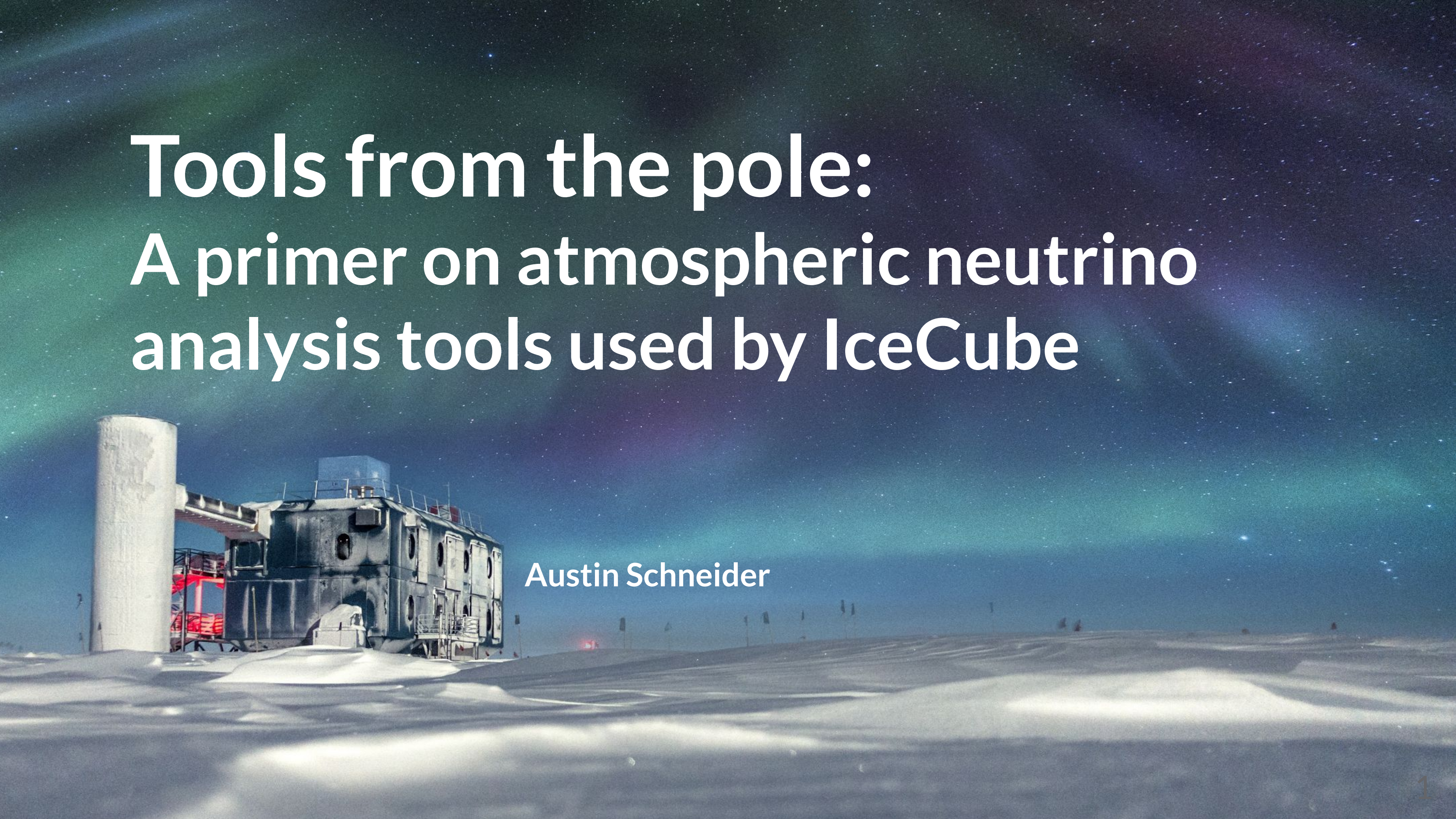
Tools from the pole:
A primer on atmospheric neutrino analysis tools used by IceCube

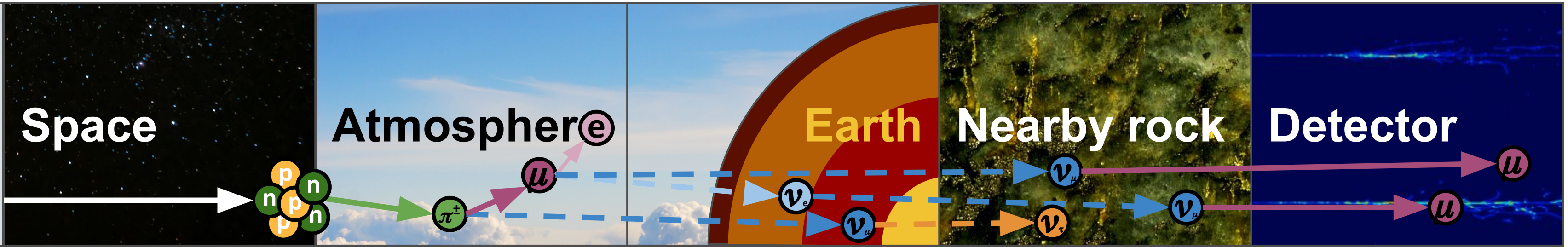


Austin Schneider

Goals of this talk

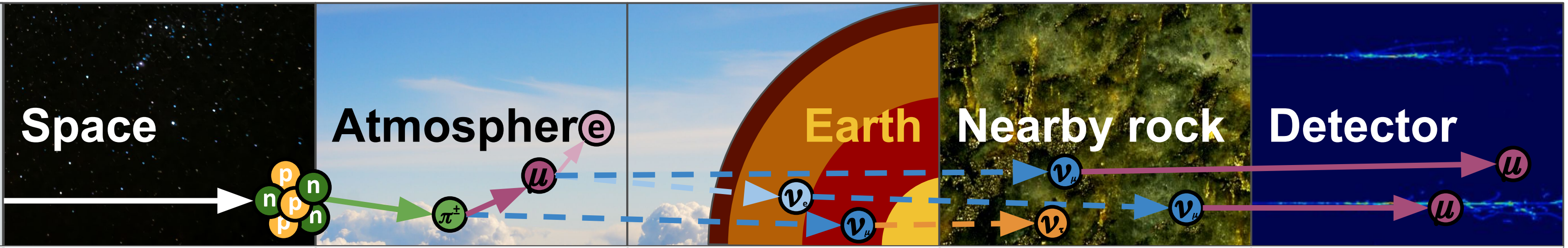
- Outline the “big picture” for atmospheric neutrino analyses
  - Break down into smaller problems
- Describe the software solutions used by IceCube
  - What they are
  - How they work
  - Why we use them
  - Pros / cons
  - Who maintains them
- Gain feedback from the group
  - Are these tools of interest?
  - Would you like a more in-depth tutorial on any of them?
  - Are there other topics you would like to see covered?
  - Are there any useful pieces of software we should all know about?

Big picture



Physical region	Space	Atmosphere	Earth	Nearby rock	Detector
Modeling	Cosmic ray flux and composition	Cosmic ray showers and neutrino production	Neutrino oscillations and interactions	Neutrino interactions and charged lepton propagation	Detector response
Analysis needs	Query or vary cosmic ray flux model	Query or compute atmospheric neutrino flux at surface	Solve oscillation / interaction problem Surface → detector	Inject neutrino interactions Simulate muons	Simulate the detector response
Software solution	MCEq	nuflux MCEq	nuSQuIDS	LeptonInjector PROPOSAL	GEANT4 LArSoft

Physical regions



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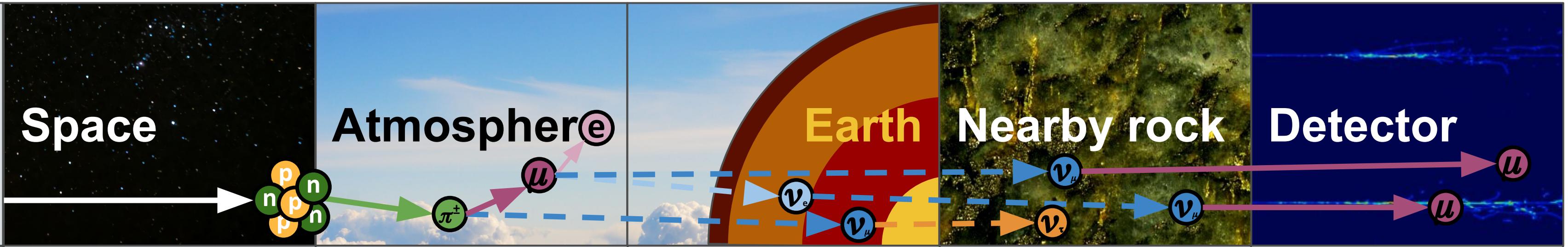
Modeling



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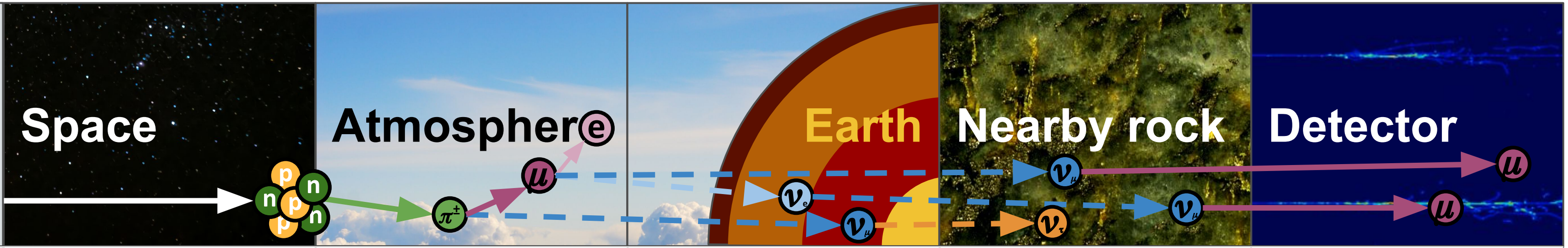
Analysis needs



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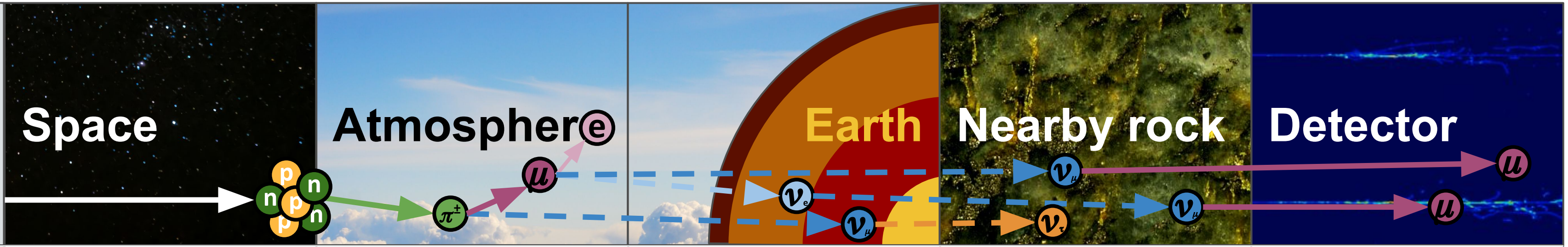
Software solutions



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Cosmic rays and air showers

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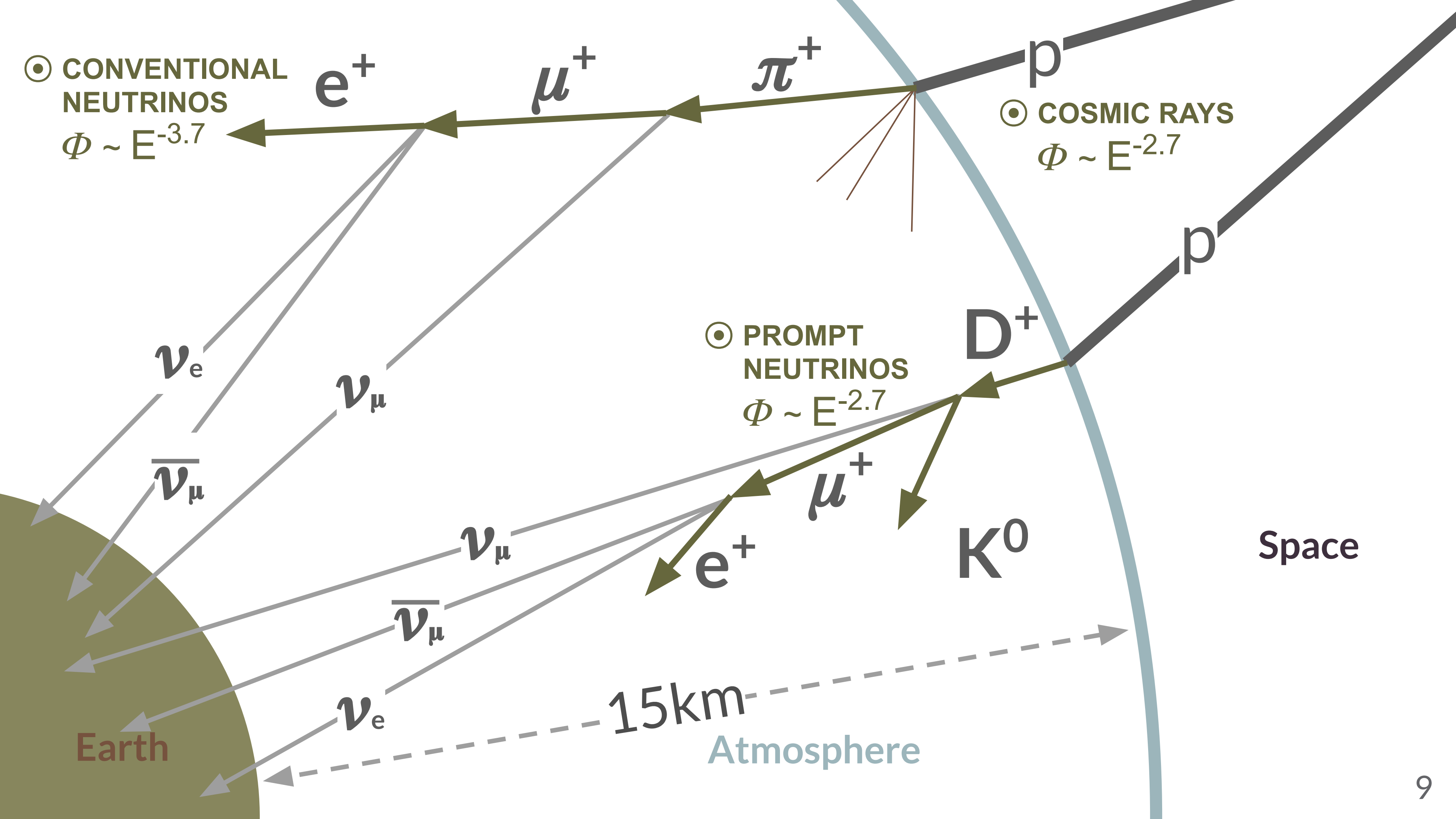
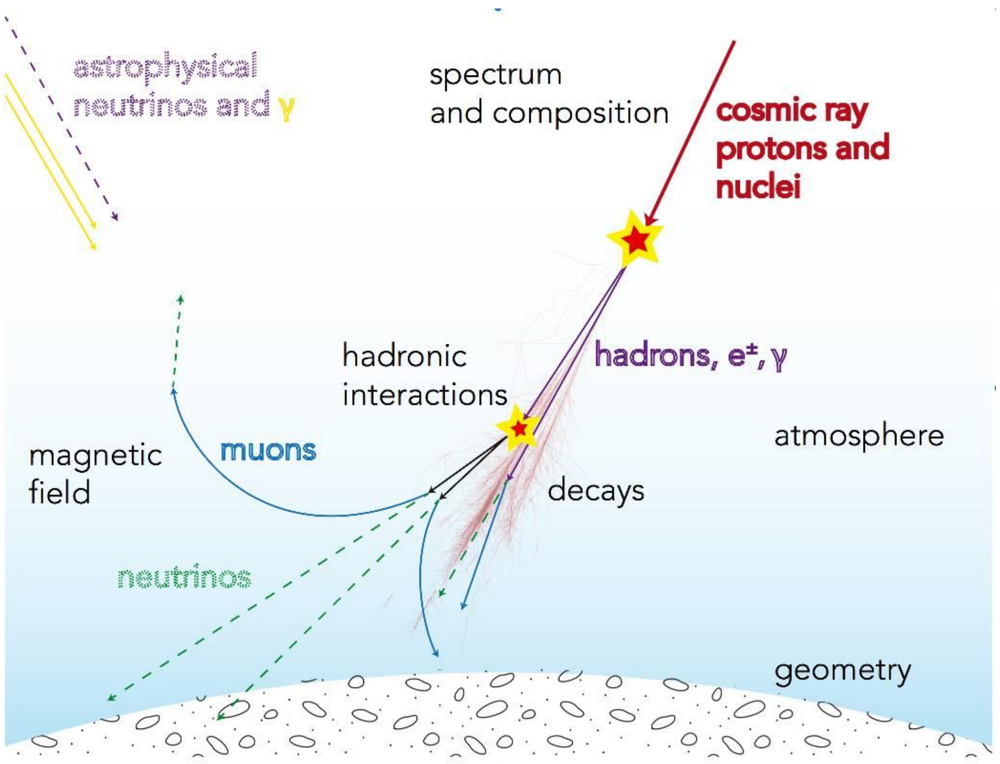


CONVENTIONAL NEUTRINOS
$\Phi \sim E^{-3.7}$
e+
μ+
π+
p
COSMIC RAYS
$\Phi \sim E^{-2.7}$
p
ν_e
ν_μ
$\bar{\nu}_\mu$
PROMPT NEUTRINOS
$\Phi \sim E^{-2.7}$
D+
μ+
K0
ν_μ
e+
$\bar{\nu}_\mu$
ν_e
15km
Space
Earth
Atmosphere

Cosmic rays

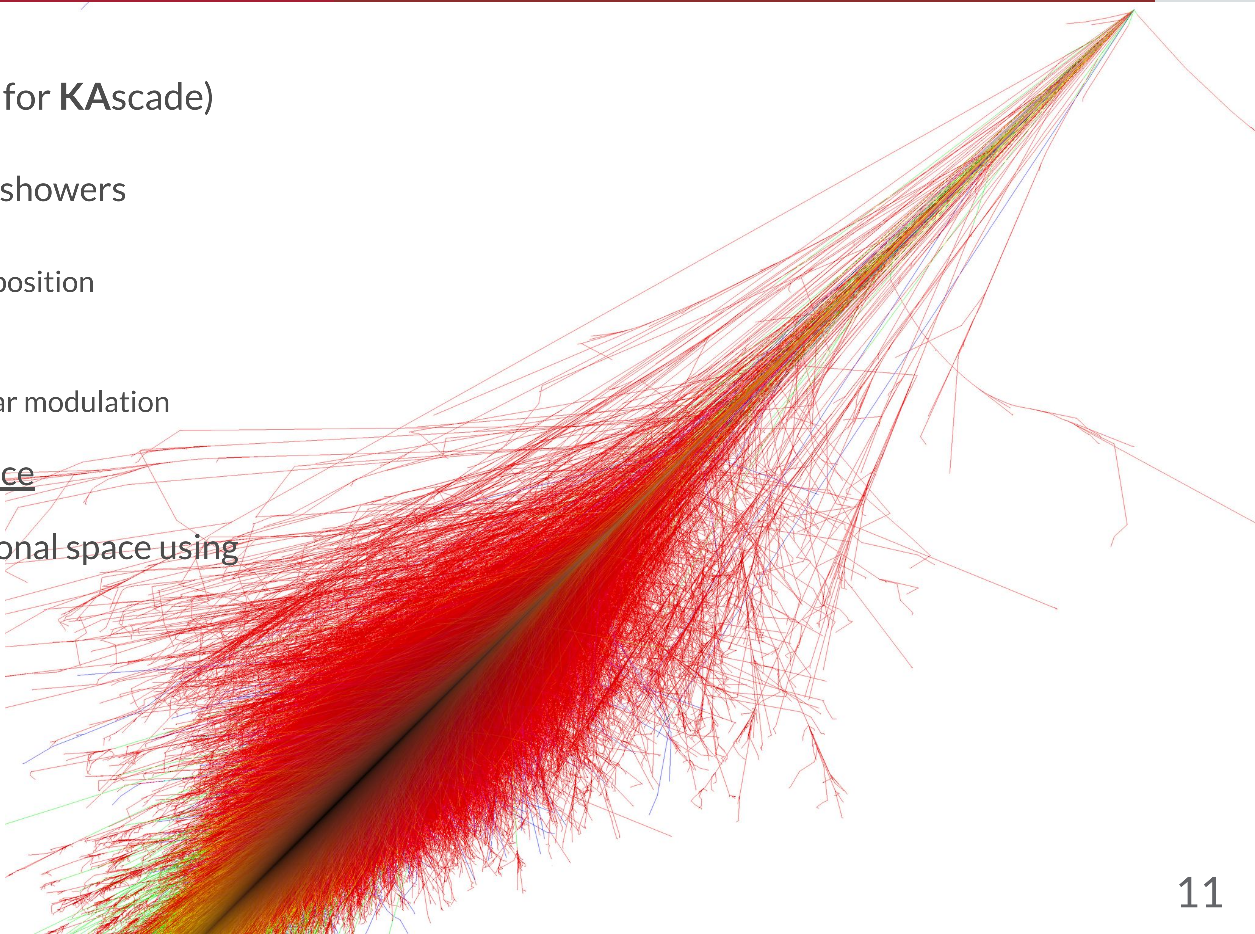
- Uncertain elements
  - Cosmic ray spectrum and composition
  - Hadronic interactions
  - Atmosphere
  - Geometry, magnetic fields, solar modulation
- Air showers are complex
- Currently no consistent error treatment
- **Neutrino and muon fluxes** depend on these uncertain elements
- Analytic approximations don't capture all the physics



Cosmic-ray air-shower simulation

CORSIKA (**CO**smic **R**ay **SI**mulations for **KA**scade)

- A complete simulation of the air showers
- Lots of knobs to turn
  - Cosmic ray spectrum and composition
  - Hadronic interactions
  - Atmosphere
  - Geometry, magnetic fields, solar modulation
- High dimensional parameter space
- Difficult to explore high dimensional space using expensive simulation



MCEq - Matrix cascade equations

- Compute the flux numerically!
- https://github.com/afedynitch/MCEq
- Solves matrix cascade equations that govern the average behavior of cosmic-ray air-showers
- Allows us to compute the neutrino flux at the Earth's surface!

System of PDE for each particle species h ($\leq 62 \times$ #E-bins in MCEq) :

$$\frac{\mathrm{d}\Phi_h(E,X)}{\mathrm{d}X} = -\frac{\Phi_h(E,X)}{\lambda_{\mathrm{int},h}(E)} - \frac{\Phi_h(E,X)}{\lambda_{\mathrm{dec},h}(E,X)} - \frac{\partial}{\partial E}(\mu(E)\Phi_h(E,X)) + \sum_k \int_E^\infty \mathrm{d}E_k \frac{\mathrm{d}N_{k(E_k)\to h(E)}}{\mathrm{d}E}\frac{\Phi_k(E_k,X)}{\lambda_{\mathrm{int},k}(E_k)} + \sum_k \int_E^\infty \mathrm{d}E_k \frac{\mathrm{d}N^{\mathrm{dec}}_{k(E_k)\to h(E)}}{\mathrm{d}E}\frac{\Phi_k(E_k,X)}{\lambda_{\mathrm{dec},k}(E_k,X)}$$

cosmic ray physics

atmospheric physics

particle physics

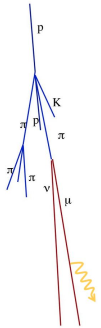
Interactions with air

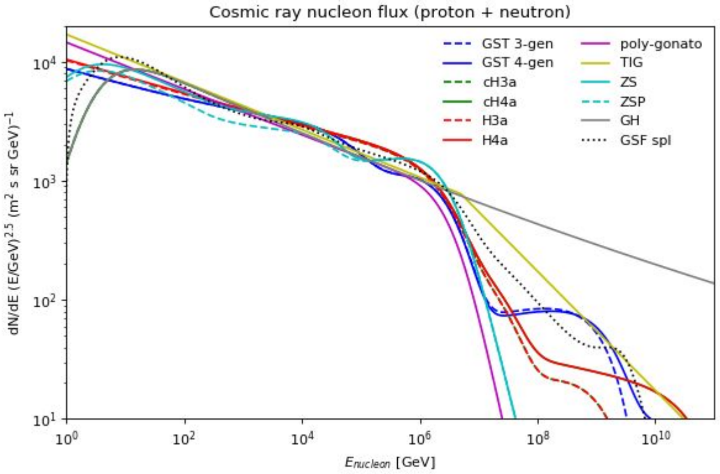
Decays

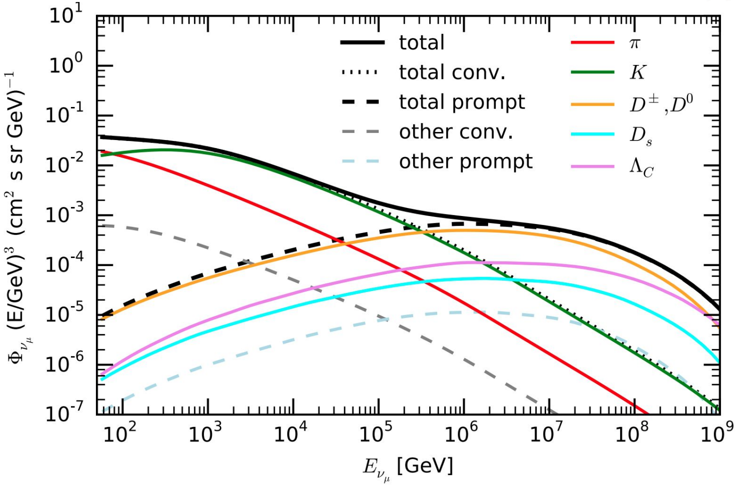
Energy losses (radiative)

Re-injection from interactions

Re-injection from decays

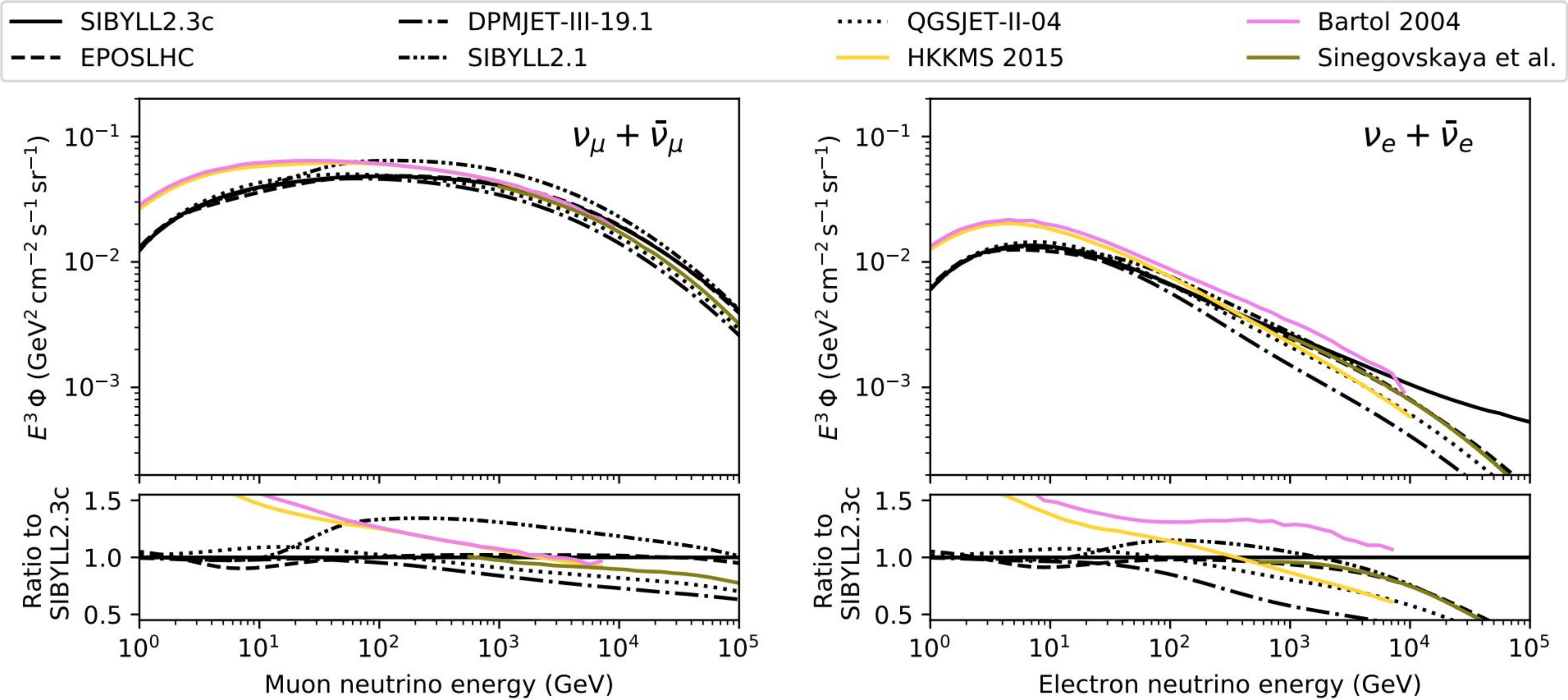






MCEq: Hadronic models

arxiv:1806.04140



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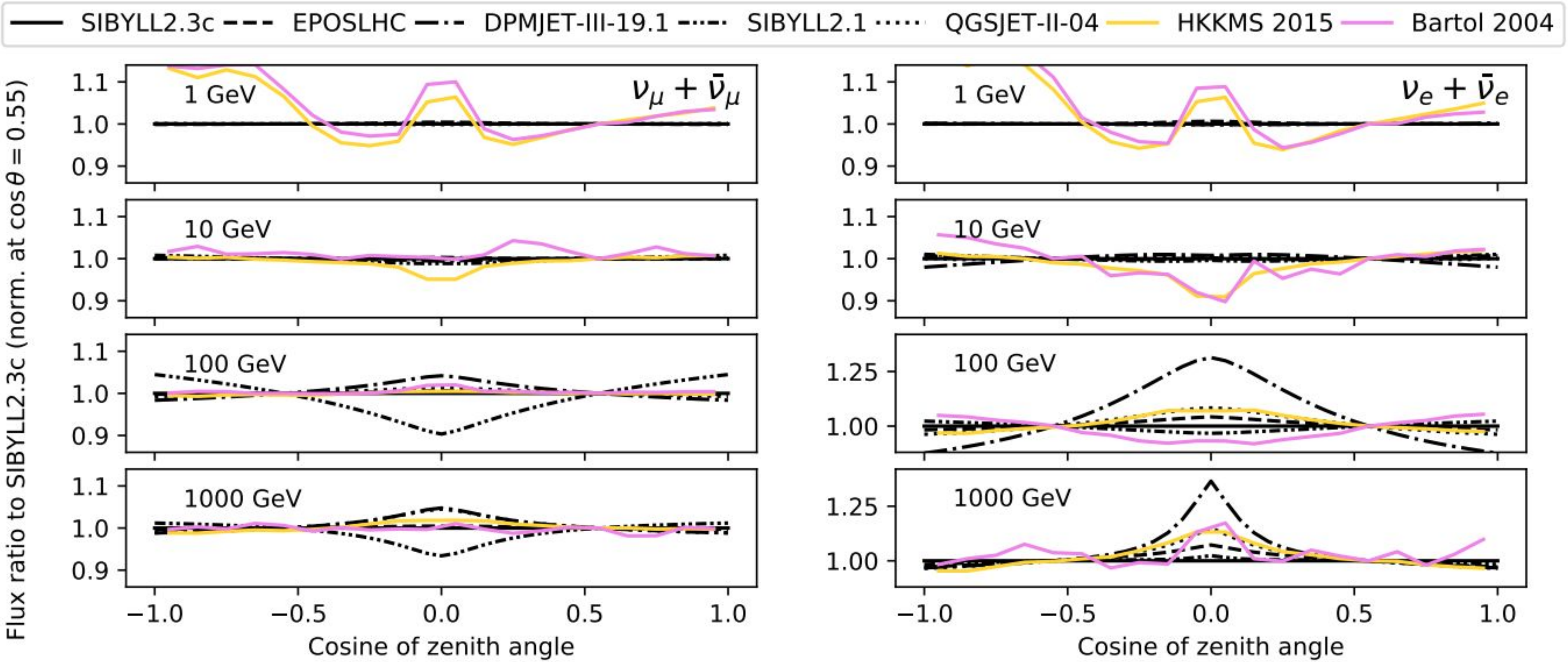

MCEq - Matrix cascade equations

- https://github.com/afedynitch/MCEq
- Pros
  - Implements many modern cosmic ray models (https://github.com/afedynitch/crflux)
  - Modeling of the atmospheric density profile with seasonal variations
  - Accounts for decays (fast and slow timescale), energy losses, interactions, reinjection
  - Wide variety of modern hadronic interaction models with direct input from modelers
  - Support from 1e-1 GeV to 1e12 GeV
  - Optimized for performance
  - Options to use Intel MKL or cuda
  - Fast enough that you can vary these parameters in analysis
- Cons
  - Does not model correlated arrival of particles from the same air-shower
  - There are a lot of knobs to turn
  - Perhaps you want something simpler
- Project maintained by hadronic models developers and cosmic ray model fitters
  - Written in python

nuflux

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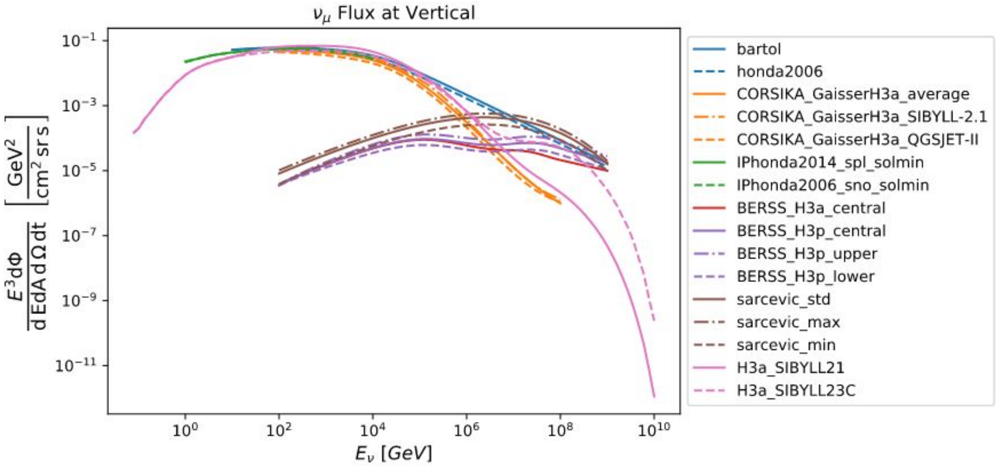
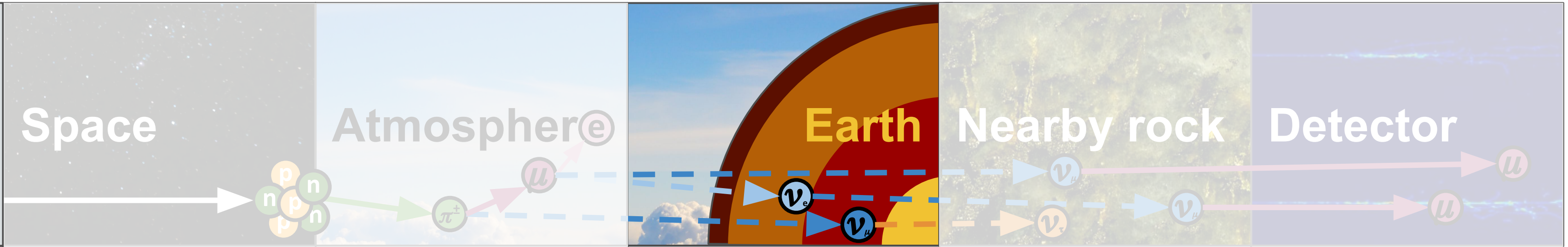
nuflux

- https://github.com/icecube/nuflux
- Sometimes we don’t need fine control of the atmospheric neutrino production
- Nominal and historical neutrino flux models are tabulated in this repository
- MCEq fluxes at Earth’s surface are stored as splines
- Some fluxes have analytic implementations
- Project maintained by IceCube analyzers and staff software developers
    - C++ implementation with python interface


```
import nuflux
flux = nuflux.makeFlux(H3a_SIBYLL23C)
Nu_type = nuflux.NuMu
Nu_energy = 1e3 # in GeV
nu_cos_zenith = 0.5
print(flux.getFlux(nu_type,nu_energy,nu_cos_zenith))
```



nuSQuIDS - Insert BSM physics here!



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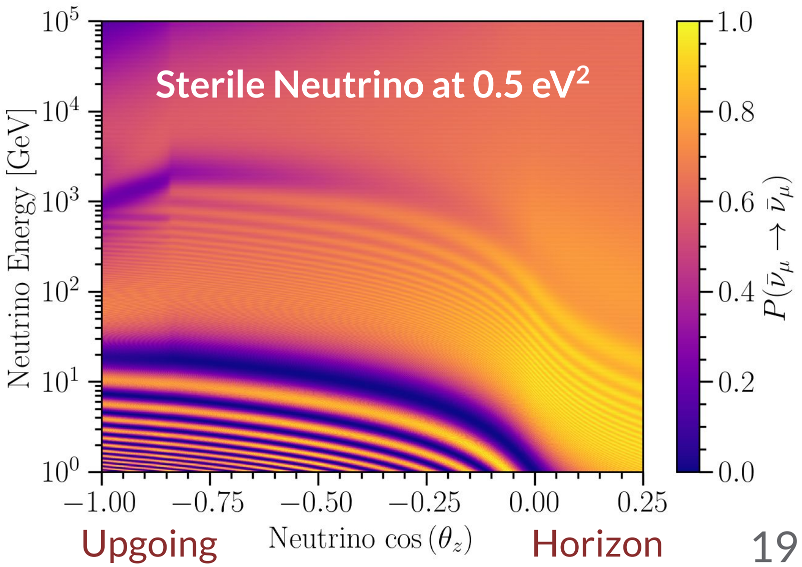
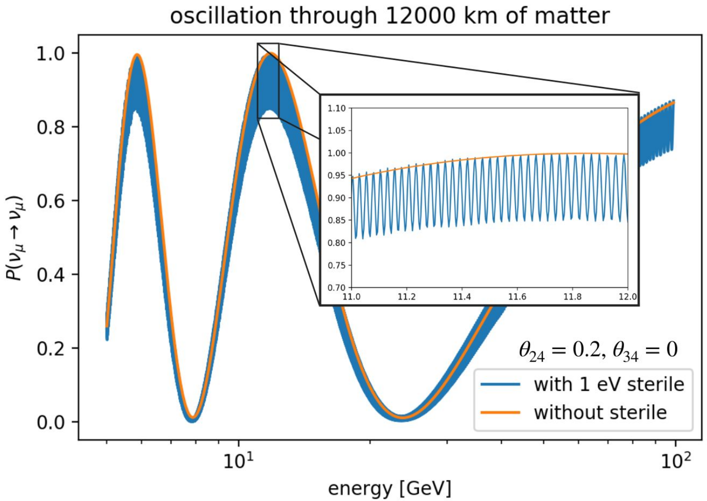
nuSQuIDS - Insert BSM physics here!

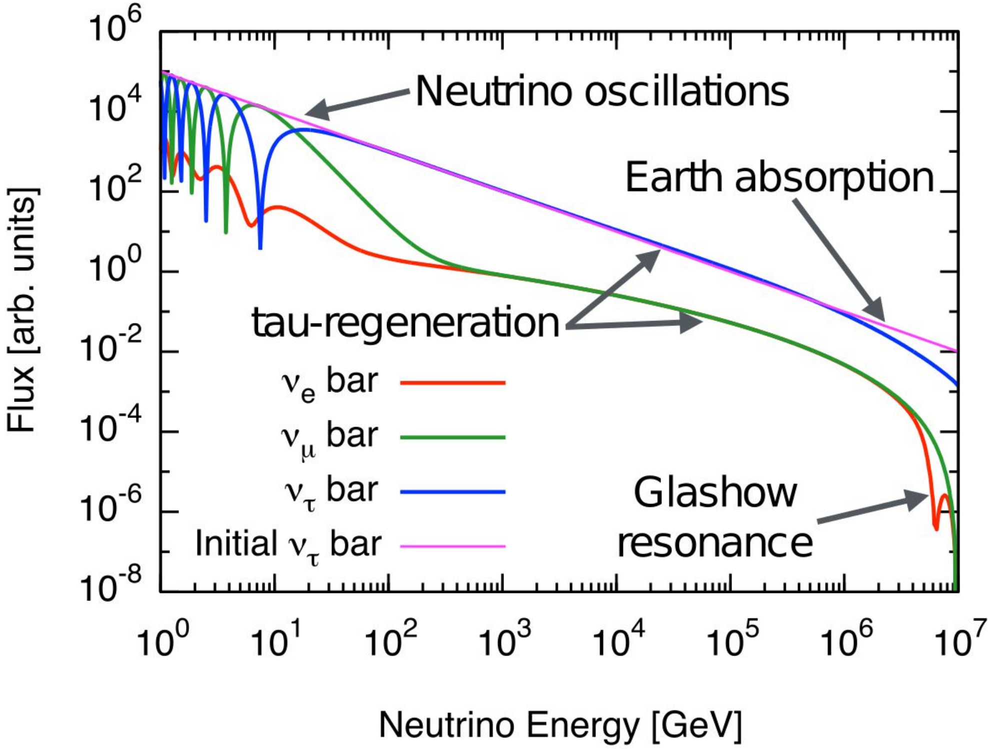
- https://github.com/arguelles/nuSQuIDS
- Neutrino oscillation software using SQuIDS (Simple Quantum Integro Differential Solver)
- Computes neutrino oscillations through the Earth and other dense bodies
- Uses the density matrix formalism
- Differential equations solved through numerical integration
- Lots of BSM physics implemented
    - N steriles, neutrino decay, lorentz violation, NSI
    - Easy to extend, just add new terms to the Hamiltonian



Why solve numerically or use nuSQuIDS at all?

- Quantum system is not closed at high energies
- Non-coherent neutrino interactions
- Neutrino production region in the atmosphere extends up to 340 km across
- Fast oscillations





nuSQuIDS in one slide

> formulate problem in interaction (Dirac) picture

$$H_s(t) = H_0 + H_1(t)$$

> operators evolve with H_0 (exactly solvable part)*

$$\bar{O}_I(t) = e^{iH_0 t} O_S e^{-iH_0 t}$$

> state densities evolve with $H_1(t)$

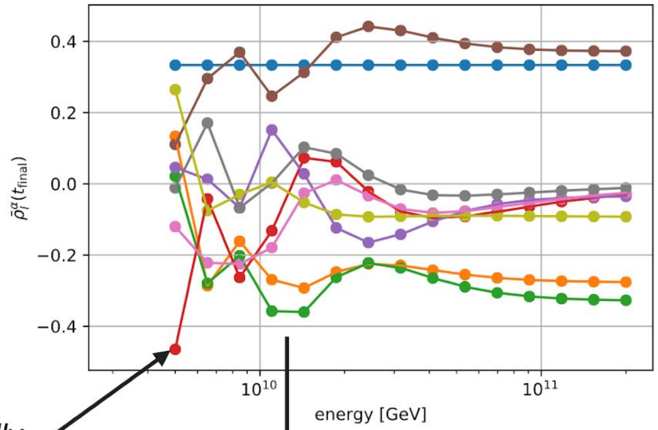
$$\partial_t \bar{\rho}_I(t) = -i[\bar{H}_{1,I}(t), \bar{\rho}_I(t)]$$

> probability to arrive in flavor state i :

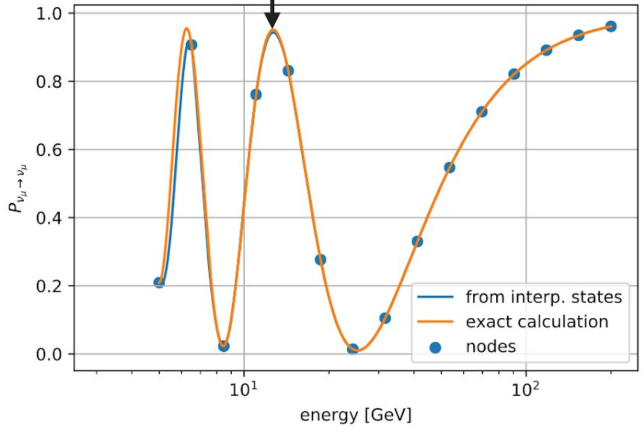
$$p_i(t) = \mathrm{Tr}(\underbrace{\bar{\Pi}^{(i)}(t)}\, \bar{\rho}_I(t))$$

projection operator on flavor state i evolved with H_0

solve numerically at each node



calculate $p_i(t)$ from interpolated $\bar{\rho}_I(t_{\mathrm{f\ nal}})$ between nodes



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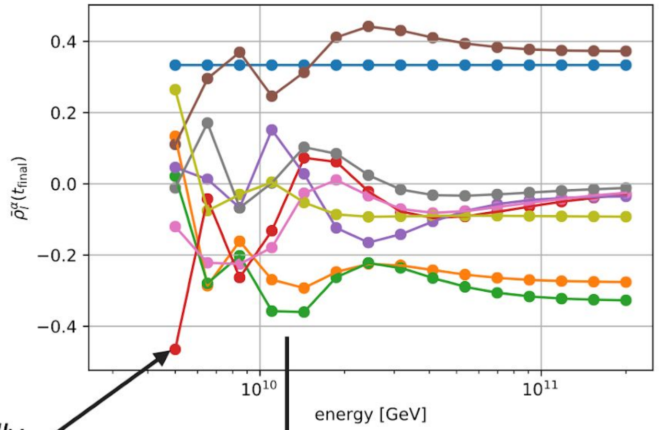
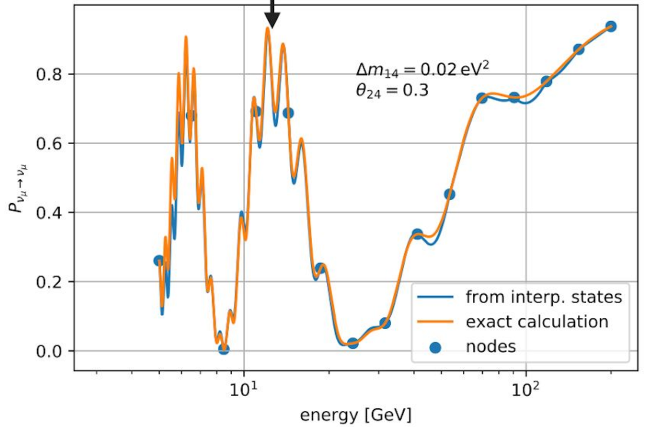
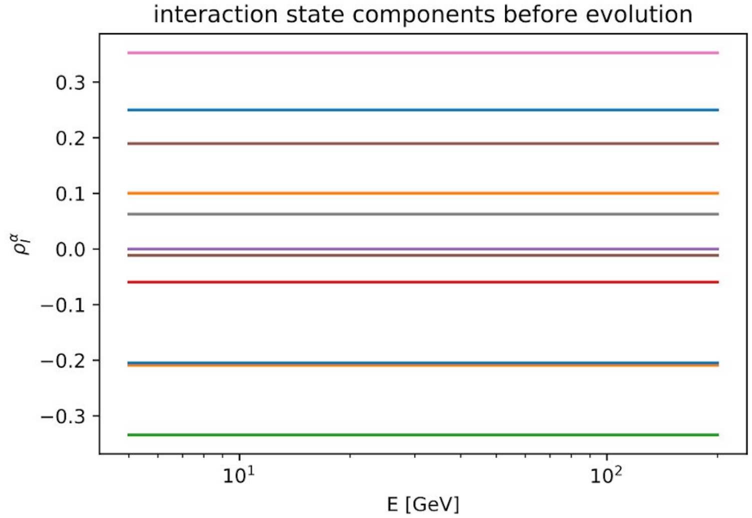


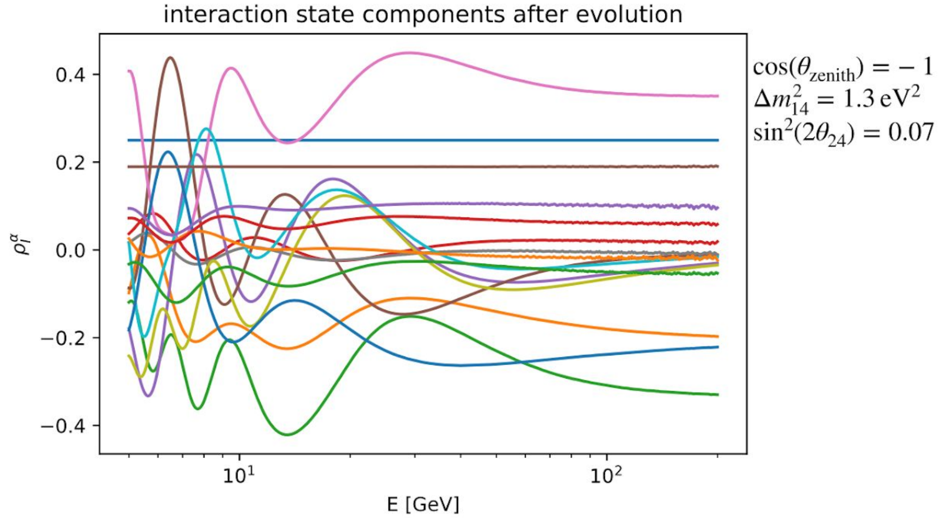
calculate $p_i(t)$ from interpolated $\bar{\rho}_I(t_{\rm final})$ between nodes



Ok, but what does that *look* like?



Coefficients of ρ_I after initialization with pure ν_μ states

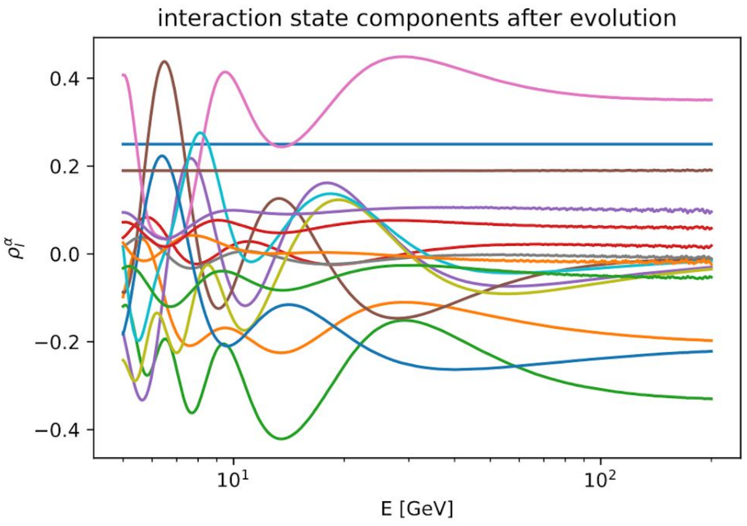


coefficients after evolution directly up-going through the Earth

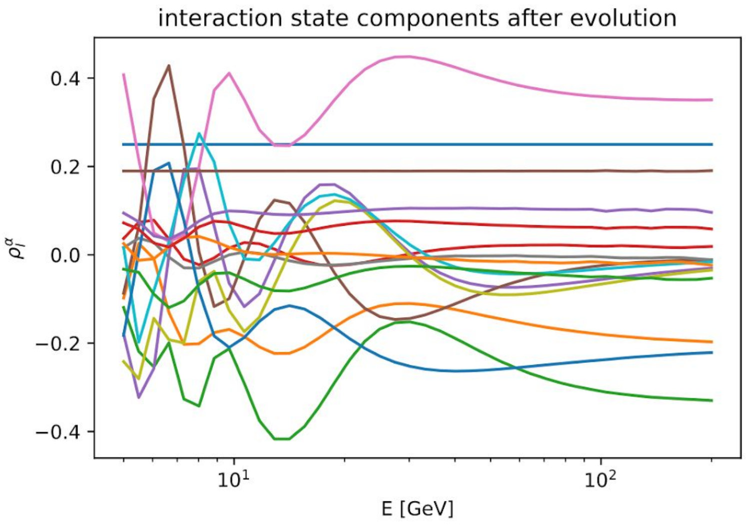
> note length scale of changes in energy: much slower than sterile oscillations!

Why νSQuIDS wins for large MC sets

- numerical integration is *slow*, using νSQuIDS for single events very inefficient
- the trick: use linear interpolation on *interaction picture density*

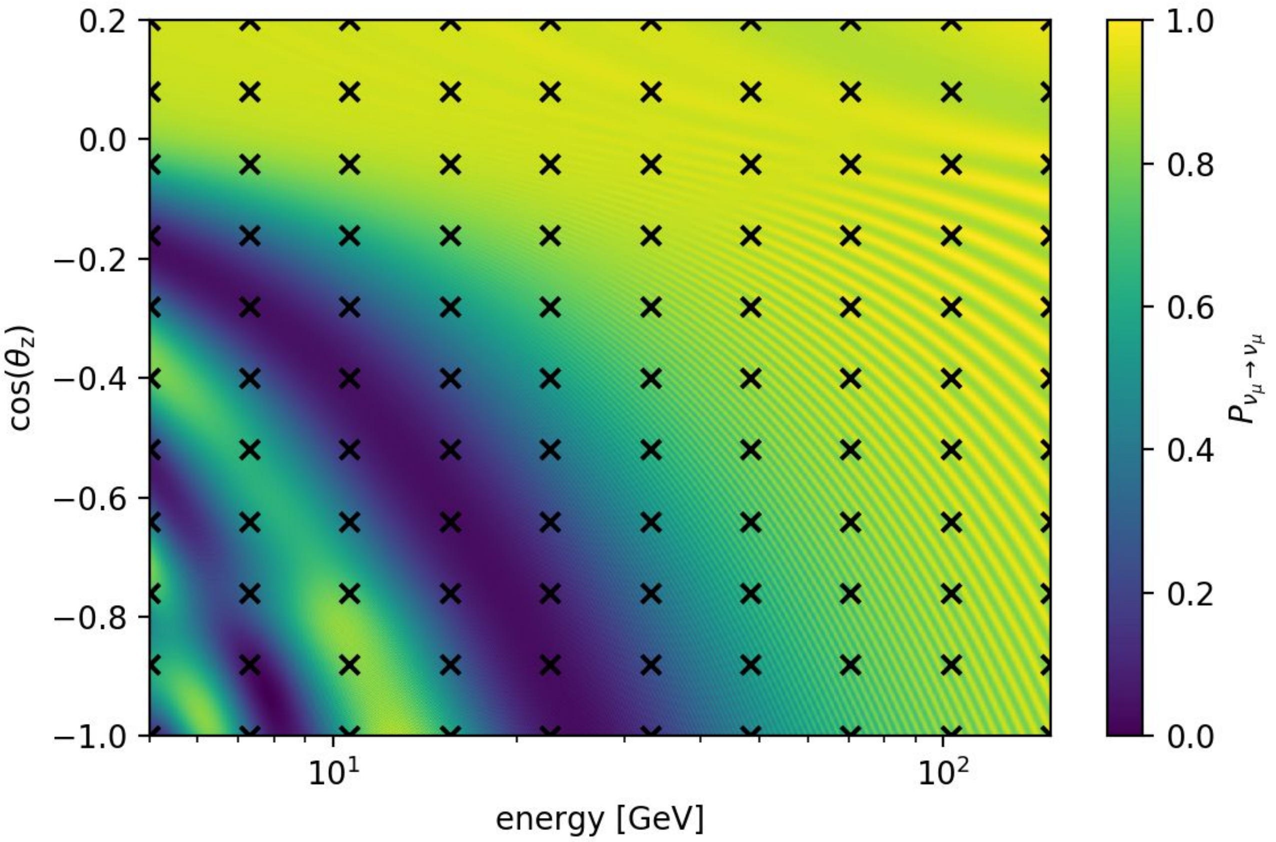


state evaluated at 400 nodes in plotted range



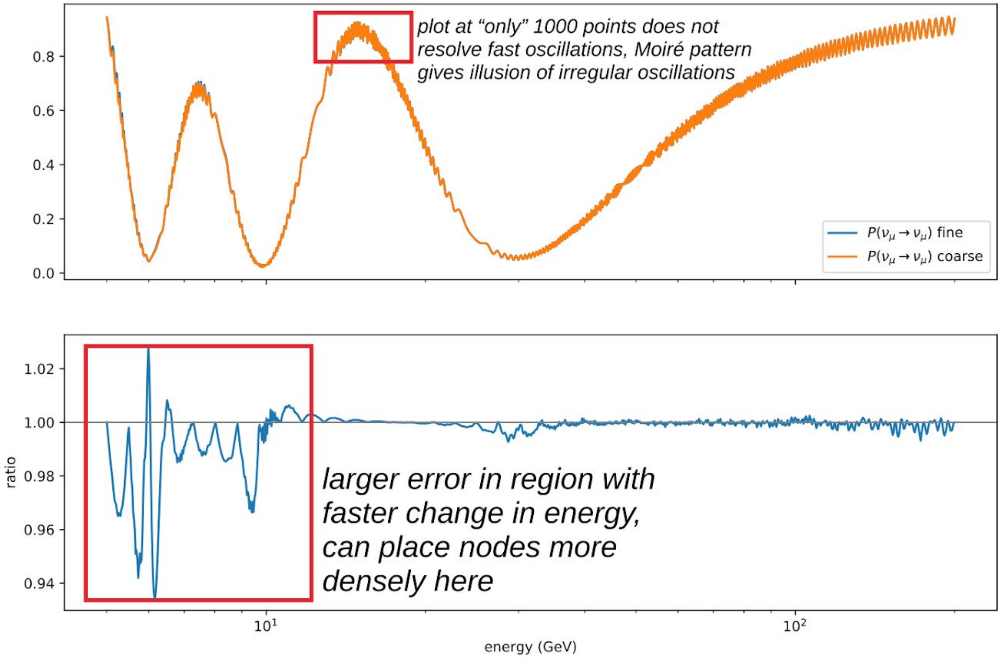
state evaluated at 40 nodes in plotted range w/ linear interpolation in $\log(E)$

Sparse grid in 2D



Why νSQuIDS wins for large MC sets

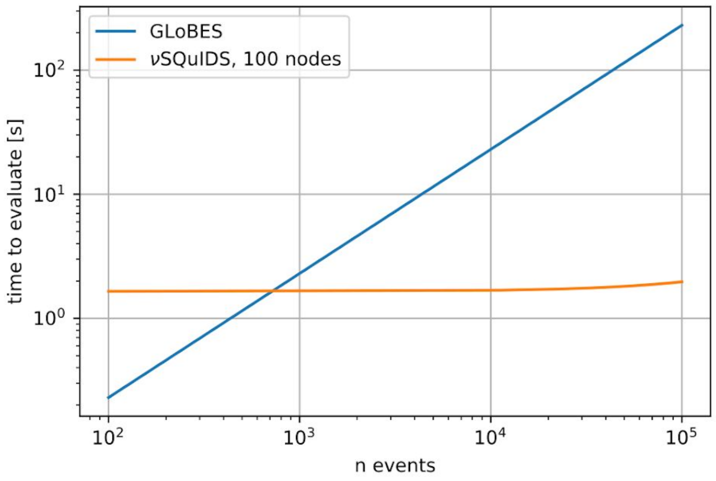
- works because fast oscillations induced by H_0
- fast oscillations accurately projected out from interpolated states even when very coarsely interpolated
- evaluation very fast
- **νSQuIDS wins if calculating grid of nodes is faster than evaluating all single events in GLoBES**

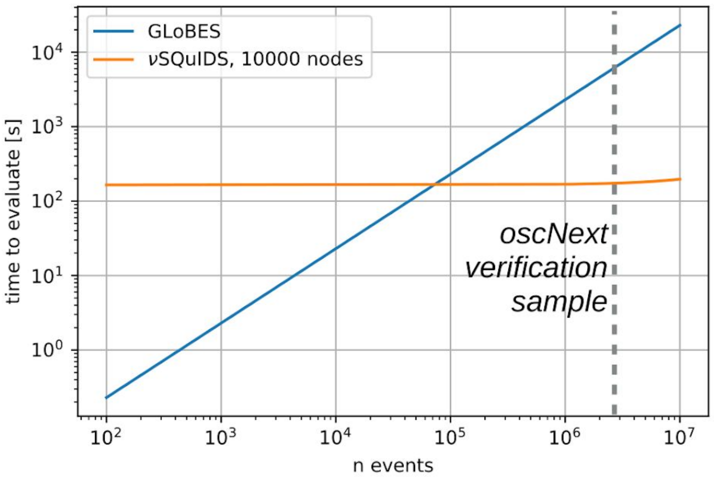


comparison between neutrino oscillation probabilities estimated using fine (400 nodes) and coarse (40 nodes) interpolation of states

Timing experiment for sterile oscillations through Earth

- GLoBES: 2.3 s for 1000 evaluations
- νSQuIDS: 1.65 s for 100 nodes, 3.5 ms for 1000 interpolated evaluations





- can confirm statement from https://arxiv.org/pdf/1902.00517.pdf that νSQuIDS starts being efficient at 1000 events when interpolating in 1D, need more nodes for 2D grid

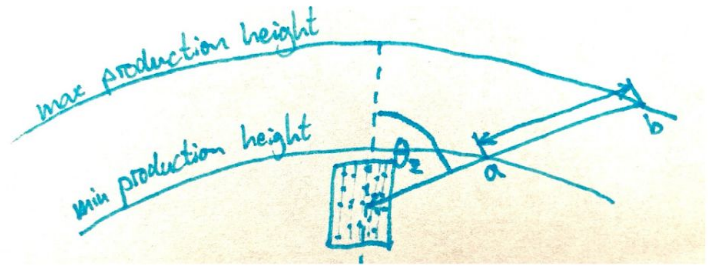
Distance averaging

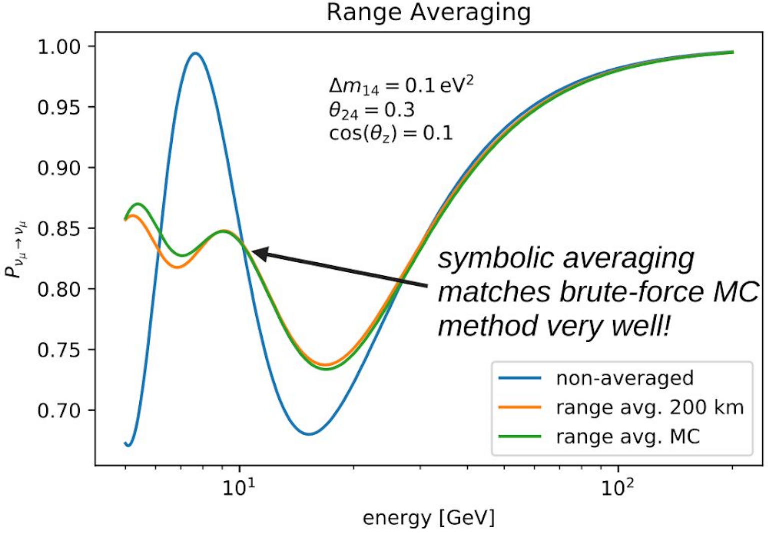
> Replace sines and cosines with their average!

> assumption: uniform distribution in interval $[a, b]$

$$\int_a^b \mathrm{d}t \frac{1}{b-a} \sin(\alpha t) = \frac{[\cos(\alpha a) - \cos(\alpha b)]}{\alpha(b-a)}$$

> calculate interval from minimum to maximum production height

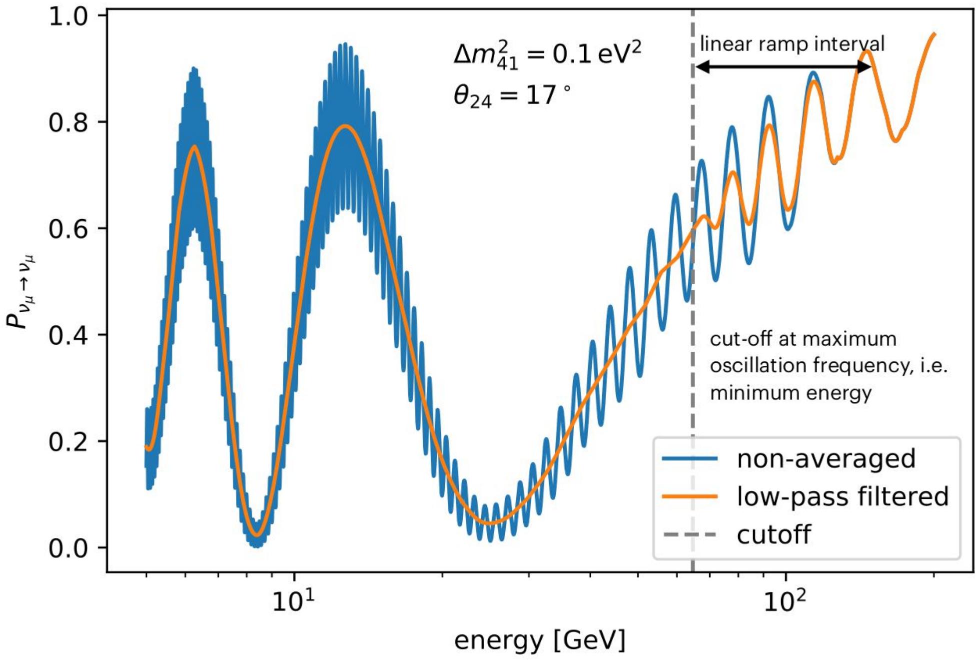




Oscillation probabilities in the presence of a sterile neutrino with averaging over a range of 200 km.

Fast Oscillations

- Same approach as production height averaging
- Linear ramp is added to avoid sharp transitions



Oscillations probability in the presence of 0.1 eV sterile neutrinos with low-pass filtering applied. The filter's linear ramp extends down to half of the cut-off frequency.

nuSQuIDS

- Pros
  - The Earth density profile with with PREM is implemented
  - Fast for large monte carlo sizes (integration cost is amortized)
  - Good for fast oscillations: interpolation between energies and baselines
  - Neutrino interactions in the Earth
  - Tau regeneration
  - Averaging: fast oscillations and atmospheric production height
    - done at evaluation for small additional cost [not during evolution]
  - Supports direct modification of Hamiltonian and modification of cross sections
- Cons
  - Slow for small monte carlo sizes
  - Fast oscillations due to non-vacuum oscillations will require a dense grid (killing the speed improvements)
- Project maintained by active phenomenologists and IceCube research scientists
  - C++ / GSL implementation and interface with python bindings

LeptonInjector

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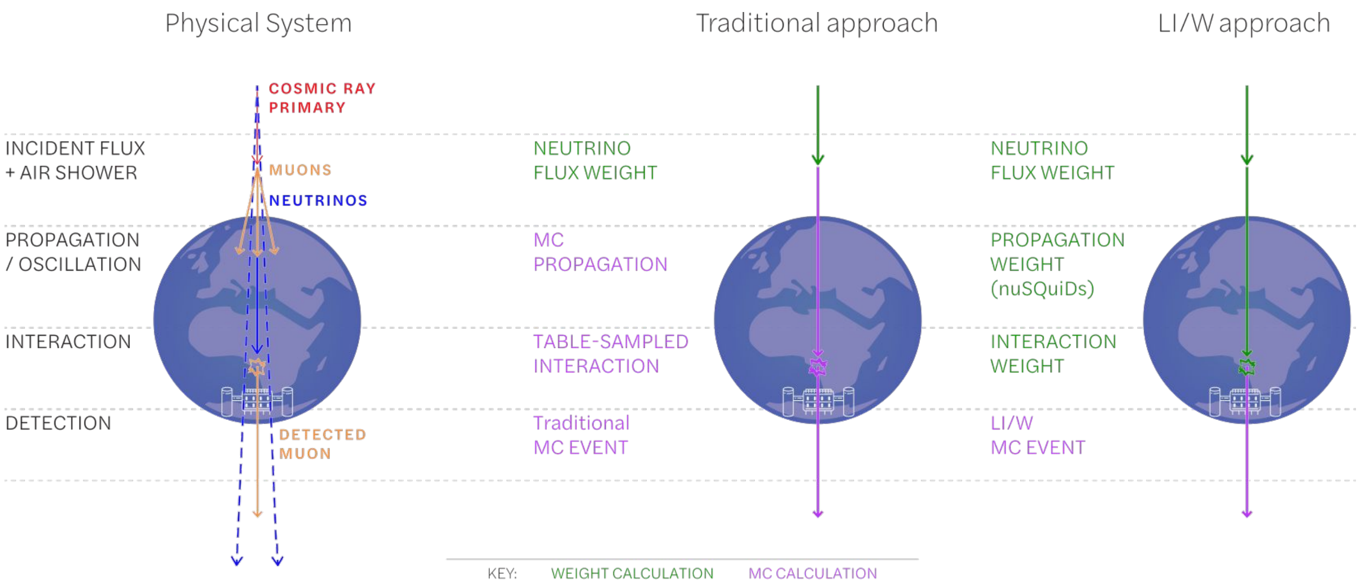
LeptonInjector

https://arxiv.org/abs/2012.10449

- https://github.com/icecube/LeptonInjector
- A standalone injector of leptons for large-volume neutrino observatories
  - What IceCube *mostly* uses in place of GENIE
- Sampling is appropriate for atmospheric fluxes and long ranged muons
- Designed with reweighting in mind
  - Cross sections, atmospheric flux, Earth model, detector density profiles, etc.

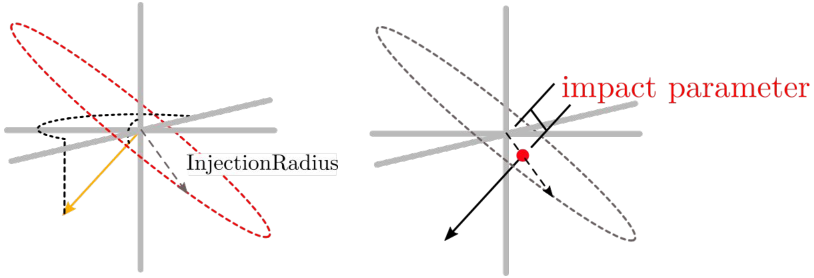


A simple injection model

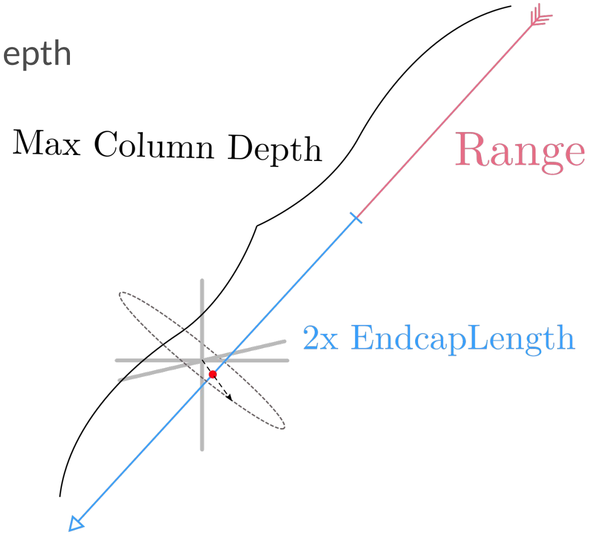
https://arxiv.org/abs/2012.10449

1. Sample neutrino energy and direction
2. Sample kinematic parameters of interaction
3. Choose point on injection disk
4. Bound segment such that it encompasses the detector and maximum muon range
5. Sample uniformly in column depth

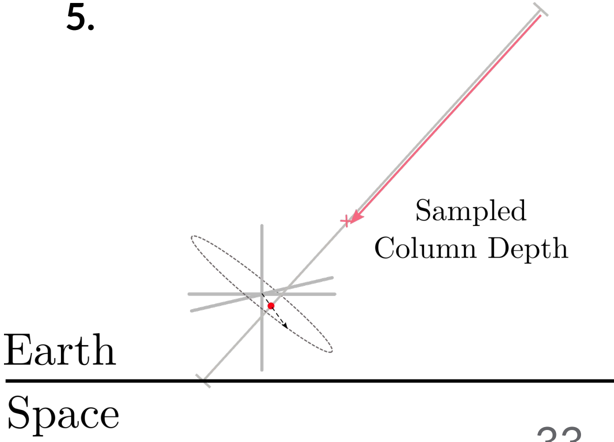
3.



4.



5.



Lepton Injector/Weighter

https://arxiv.org/abs/2012.10449

- https://github.com/icecube/LeptonInjector
- https://github.com/icecube/LeptonWeighter
- Weights injected neutrino final states to neutrino fluxes
  - The companion to LeptonInjector
- Enables the weighting of simulation produced with LeptonWeighter
- Computes generation probabilities and provides implementations for complete event weighting

- Pros
  - Designed with reweighting in mind
  - Cross sections, atmospheric flux, Earth model, detector density profiles, etc.
- Cons
  - Cross section sampling is currently done via splines (CSMS splines defined down to ~100 GeV)
  - Supported interactions are CC/NC DIS and Glashow resonance

- Projects maintained by IceCube pheno group and myself
  - C++ interface with python bindings
  - New features coming soon
    - More advanced geometry support
    - GENIE and Madgraph interfaces
    - Support for lower energies

PROPOSAL

Physical region	Space	Atmosphere	Earth	Nearby rock	Detector
Modeling	Cosmic ray flux composition	Cosmic ray showers and neutrino production	Neutrino oscillations and interactions	Neutrino interactions and charged lepton propagation	Detector response
Analysis needs	Query or vary cosmic ray flux model	Query or compute atmospheric neutrino flux at surface	Solve oscillation / interaction problem Surface → detector	Inject neutrino interactions Simulate muons	Simulate the detector response
Software solution	MCEq	nuflux MCEq	nuSQuIDS	LeptonInjector **PROPOSAL**	GEANT4 LArSoft

PROPOSAL

https://doi.org/10.1016/j.cpc.2013.04.001
https://doi.org/10.1016/j.cpc.2019.03.021

- https://github.com/tudo-astroparticlephysics/PROPOSAL
- A tool for propagation of charged leptons
- Used in IceCube to avoid running GEANT for multi-TeV muons
- Treats the stochastic energy losses but neglects tracking the secondaries
- Pros
  - Very fast for high energies and long distances
  - Configurable granularity for stochastic energy losses
  - Configurable material / density model
  - Also works for taus and gamma rays
- Cons
  - Secondaries not tracked
  - Lacks the latest photo-nuclear interaction models
- Maintained by Dortmund TU Astroparticle Physics group (used in all IceCube simulation)
  - C++ implementation / interface with extensive python bindings

Detector

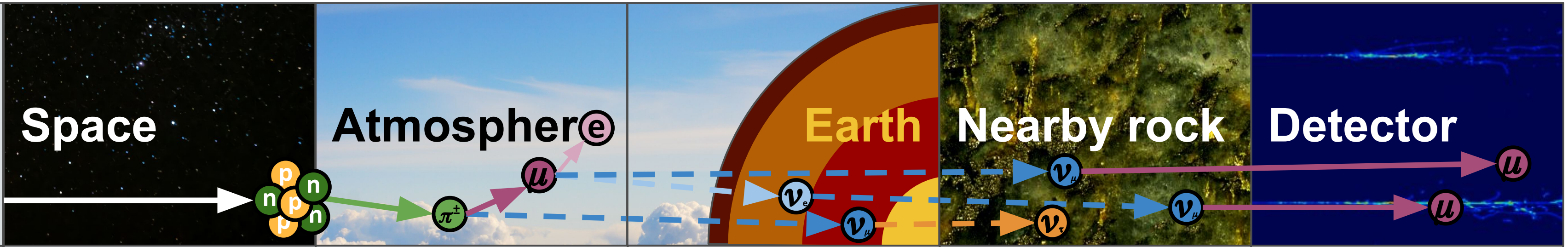
Physical region	Space	Atmosphere	Earth	Nearby rock	Detector
Modeling	Cosmic ray flux composition	Cosmic ray showers and neutrino production	Neutrino oscillations and interactions	Neutrino interactions and charged lepton propagation	Detector response
Analysis needs	Query or vary cosmic ray flux model	Query or compute atmospheric neutrino flux at surface	Solve oscillation / interaction problem Surface → detector	Inject neutrino interactions Simulate muons	Simulate the detector response
Software solution	MCEq	nuflux MCEq	nuSQuIDS	LeptonInjector **PROPOSAL**	GEANT4 LArSoft

Detector

Not a lot of overlap...

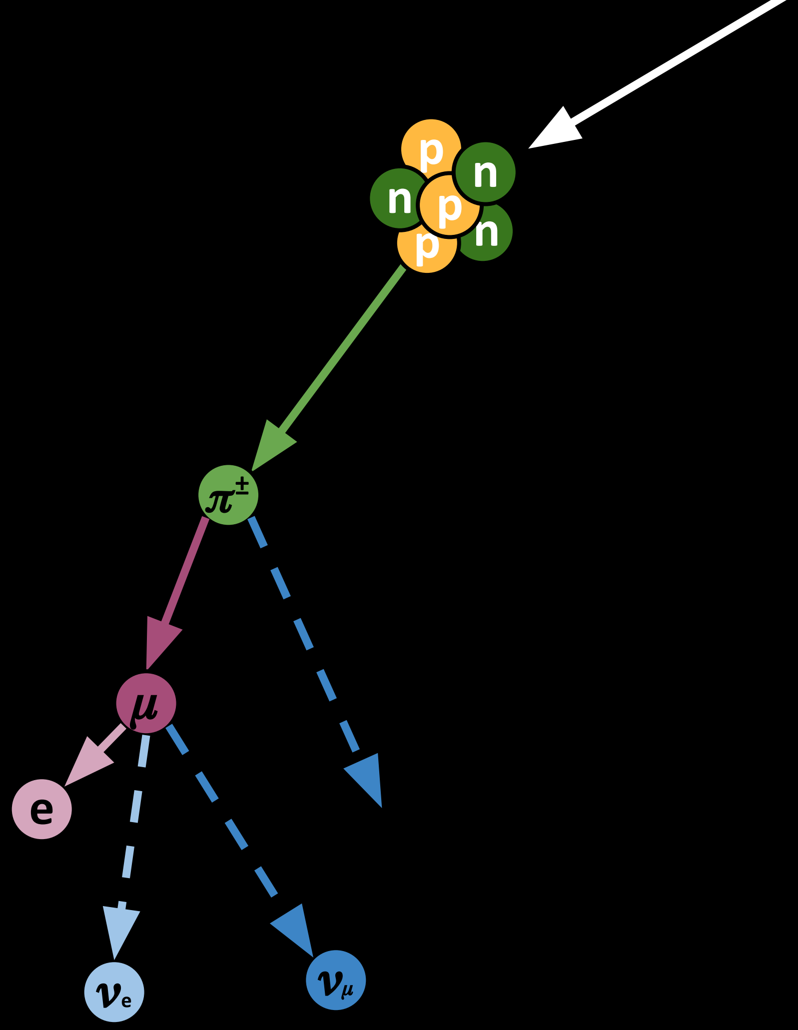
(unless you need photon propagation code)

Summary



Physical region	Space	Atmosphere	Earth	Nearby rock	Detector
Software solution	MCEq	nuflux MCEq	nuSQuIDS	LeptonInjector PROPOSAL	-

- Open source software solutions for a variety of problems related to atmospherics
  - C++ / python interfaces
- Gets you from cosmic rays to muons and neutrinos in the detector
- Major physical effects are accounted for along the way
  - Particularly those that are relevant for high energies
- MIT/Harvard hosting a workshop for investigating DUNE/IceCube(upgrade) synergies [**June 16th-18th**]
  - Attendance will be virtual



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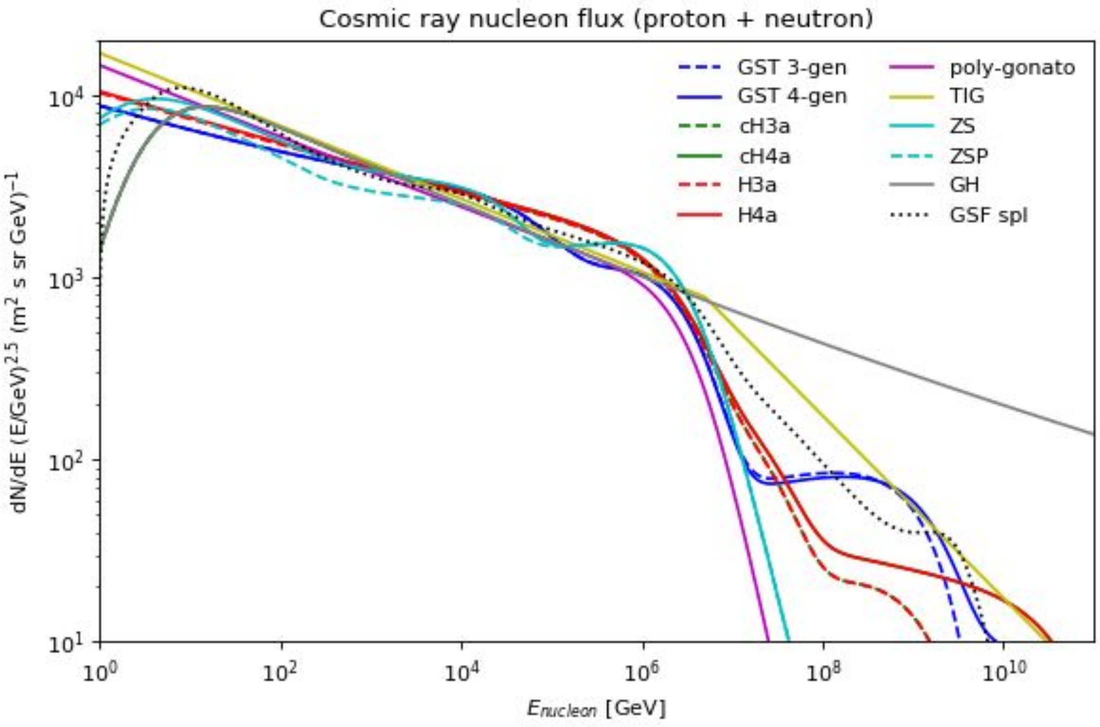
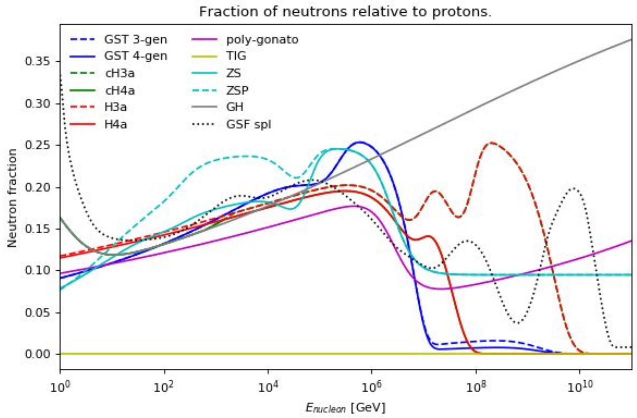
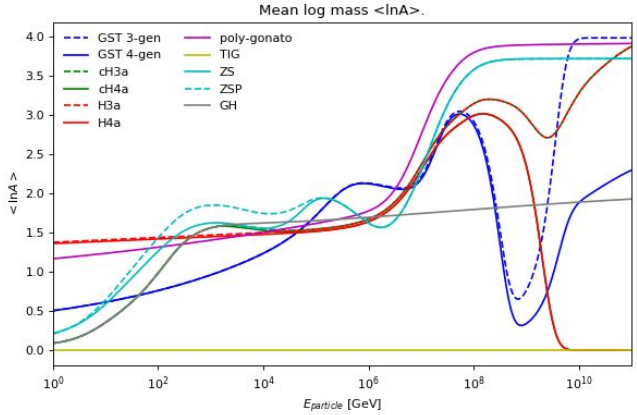
Cosmic ray fluxes







$$H_s(t) = H_0 + H_1(t)$$
$$\bar{O}_I(t) = e^{iH_0 t} O_S e^{-iH_0 t}$$
$$\partial_t \bar{\rho}_I(t) = -i[\bar{H}_{1,I}(t), \bar{\rho}_I(t)]$$
$$p_i(t) = Tr(\bar{\Pi}^{(i)}(t)\bar{\rho}(t))$$

$$\rho(t) = \rho^{\alpha}(t)\lambda_{\alpha}$$

$$H(t) = H^{\alpha}(t)\lambda_{\alpha}$$

$$i[\lambda_{\alpha}, \lambda_{\beta}] = -f^{\gamma}_{\alpha\beta}\lambda_{\gamma}$$

$$\partial_t \bar{\rho}_I(t) = \bar{H}^{\beta}_I(t)\bar{\rho}^{\gamma}_I(t) f^{\alpha}_{\beta}$$