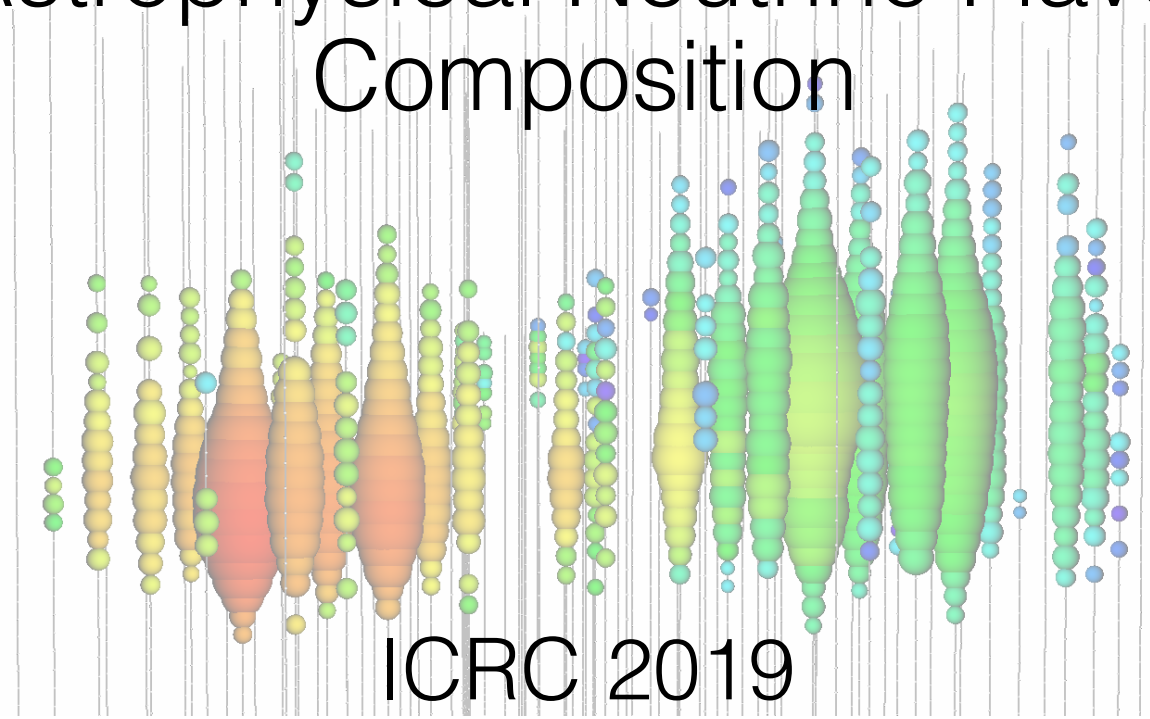
Cosmic Tau Neutrinos and the Astrophysical Neutrino Flavor Composition



ICRC 2019

July 30, 2019

Juliana Stachurska

Astrophysical Tau Neutrinos

- Measure spectrum and flavor composition → learn about environment at cosmic accelerators → constrain production mechanisms
- ν_τ needed for flavor composition measurement
- Negligible atmospheric ν_τ flux
- Guaranteed astrophysical ν_τ flux due to neutrino mixing
- Finding cosmic ν_τ:
  - Another confirmation of the astro-physical content of diffuse neutrino flux
  - Finding last SM cosmic messenger
  - Verification of neutrino mixing at largest baselines, highest energies

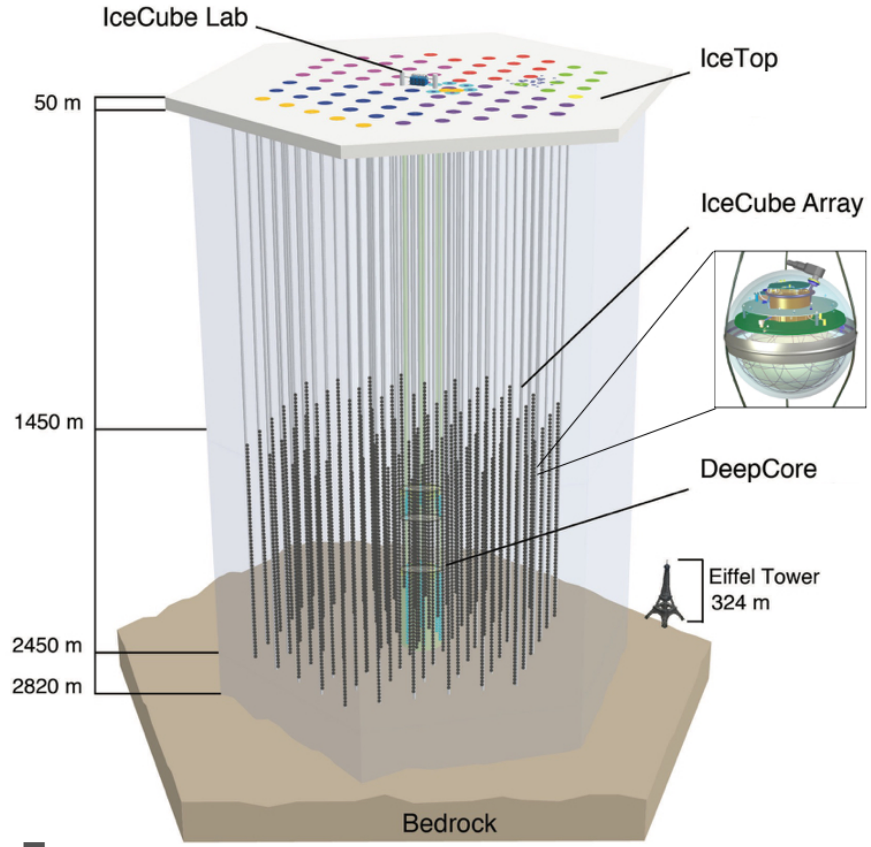
Complementarity

Discovery

Universality & BSM constraints

IceCube

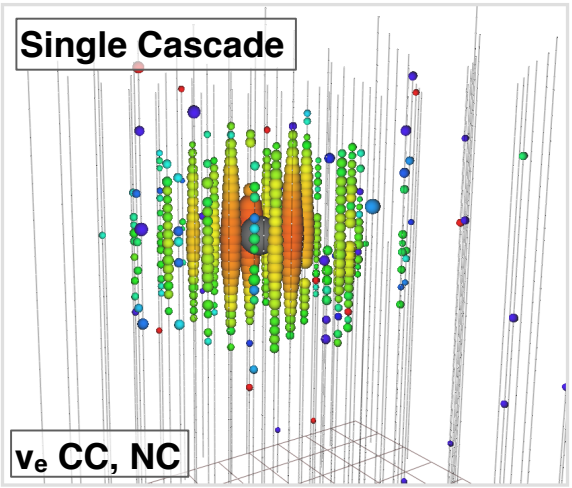
- km^3 scale Cherenkov detector
- At South Pole
- Instrumented Antarctic ice in 1.5-2.5km depth
- 5160 Digital Optical Modules (DOMs)
- ~1 ns time resolution



	Horizontal spacing [m]	Vertical spacing [m]	Energy threshold [GeV]	
IceCube	125	17	~100	Astrophysical neutrinos
DeepCore	50	7	~5	Atmospheric oscillations

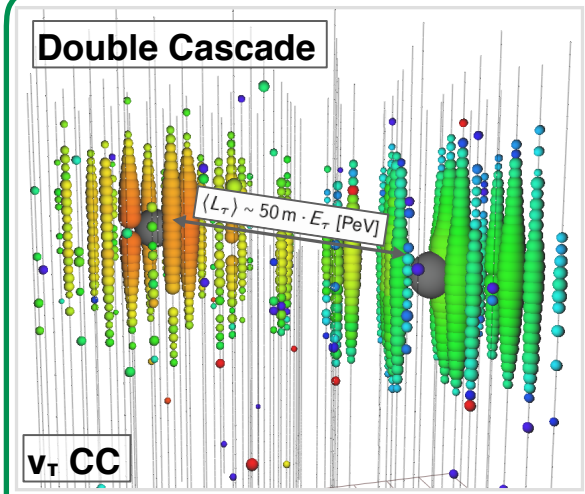
Topologies in IceCube

early → late



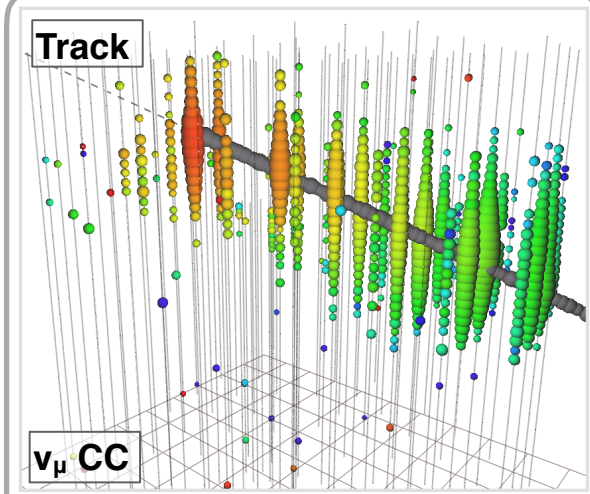
All NC interactions
ν_e CC interactions

Good energy resolution
Bad angular resolution



ν_τ CC interactions with hadronic / electronic tau decay

Good energy resolution
Angular resolution gets better with larger lengths

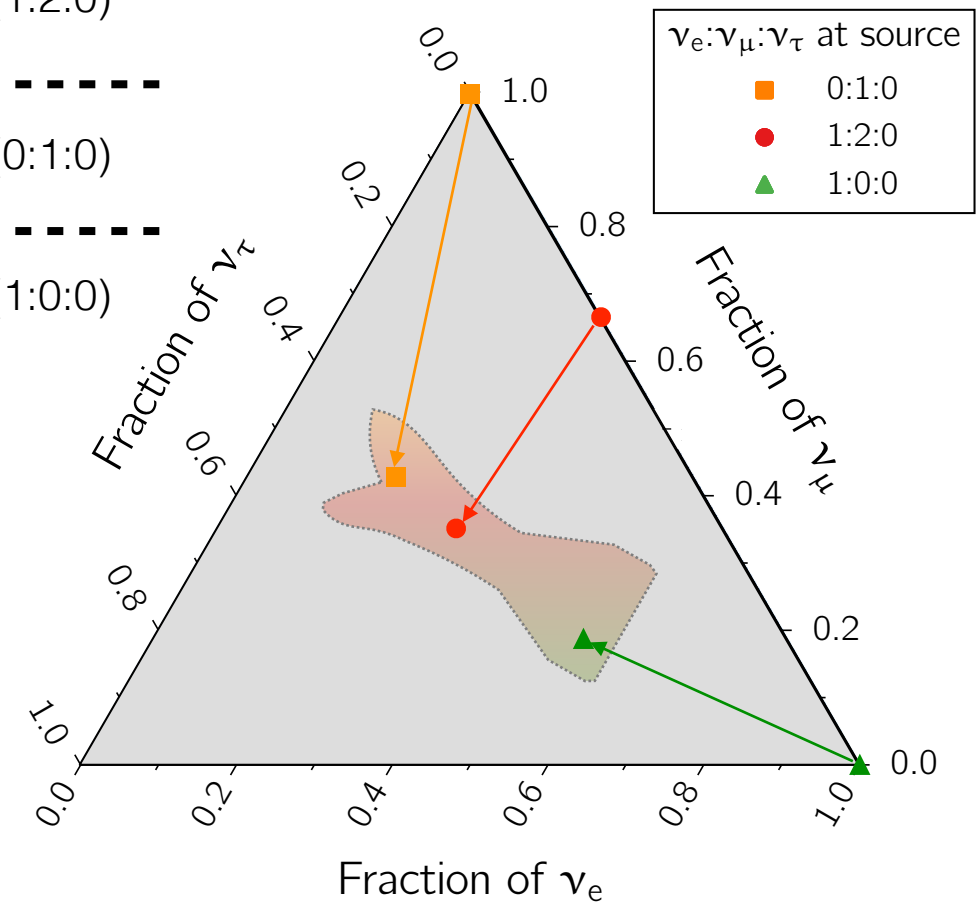


ν_μ CC interactions
Atmospheric μ
ν_τ CC interactions with muonic tau decay

Bad energy resolution
Good angular resolution

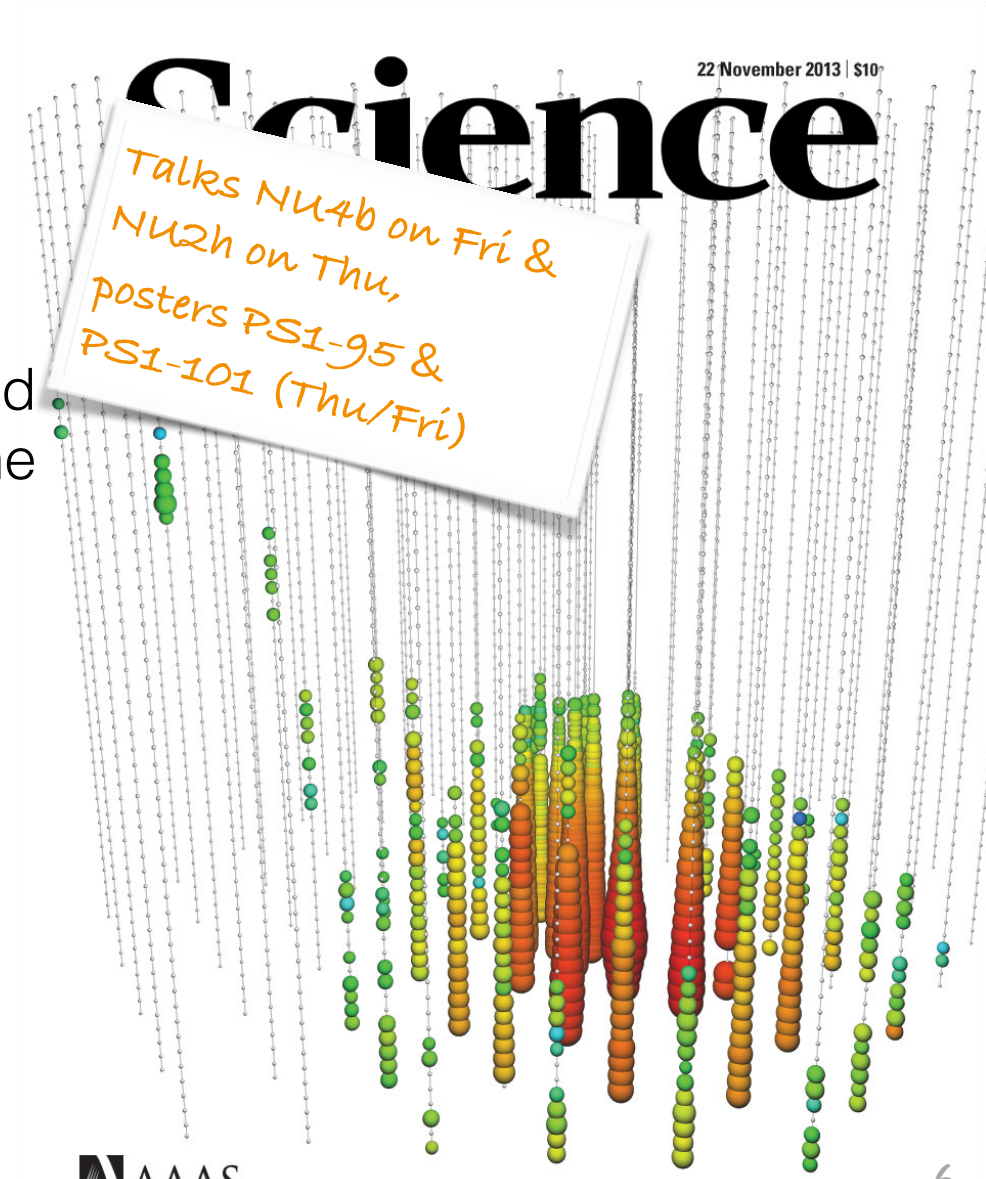
Flavor Composition

Cosmic particle accelerator		$\nu_e:\nu_\mu:\nu_\tau$
● Pion decay	$\pi^+ \to \mu^+ + \nu_\mu$, $\mu^+ \to e^+ + \nu_\mu + \bar{\nu}_e$	(1:2:0)
■ Muon-damped	$\pi^+ \to \cancel{\mu^+} + \nu_\mu$	(0:1:0)
▲ Neutron decay	$n \to p + e^- + \bar{\nu}_e$	(1:0:0)



High-Energy Starting Events (HESE)

- Evidence of diffuse astrophysical neutrino flux with 2 years livetime
- All-flavor event selection
- Revisit of HESE and associated analyses with 7.5 years livetime
- Ternary topology ID algorithm added
  - Cascades
  - Tracks
  - Double Cascades



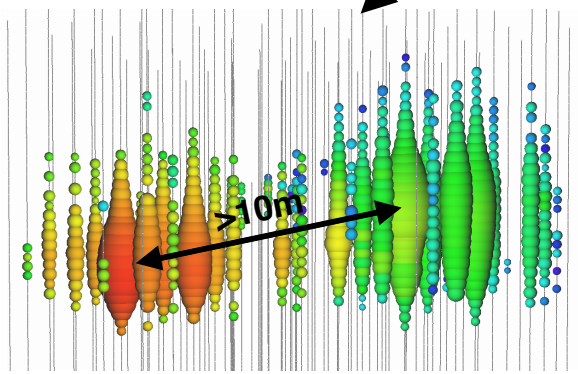
Science 342 (2013)

Flavor Analysis Overview

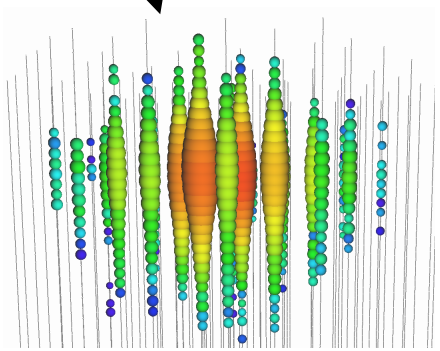
60 HESE events in 7.5 years of data above 60 TeV

↓

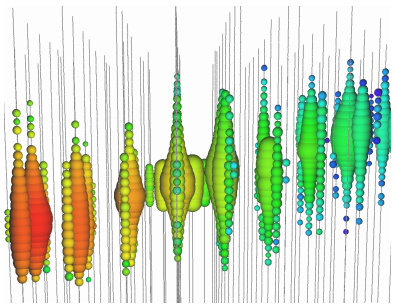
Observables from direct double-cascade reconstruction



Double cascade (2):
ν_τ + N → τ + hadrons $\xrightarrow{>10m}$ hadrons / electrons



Single cascade (42):
not well-reconstructable ν_τ – CC interactions, all other cascades

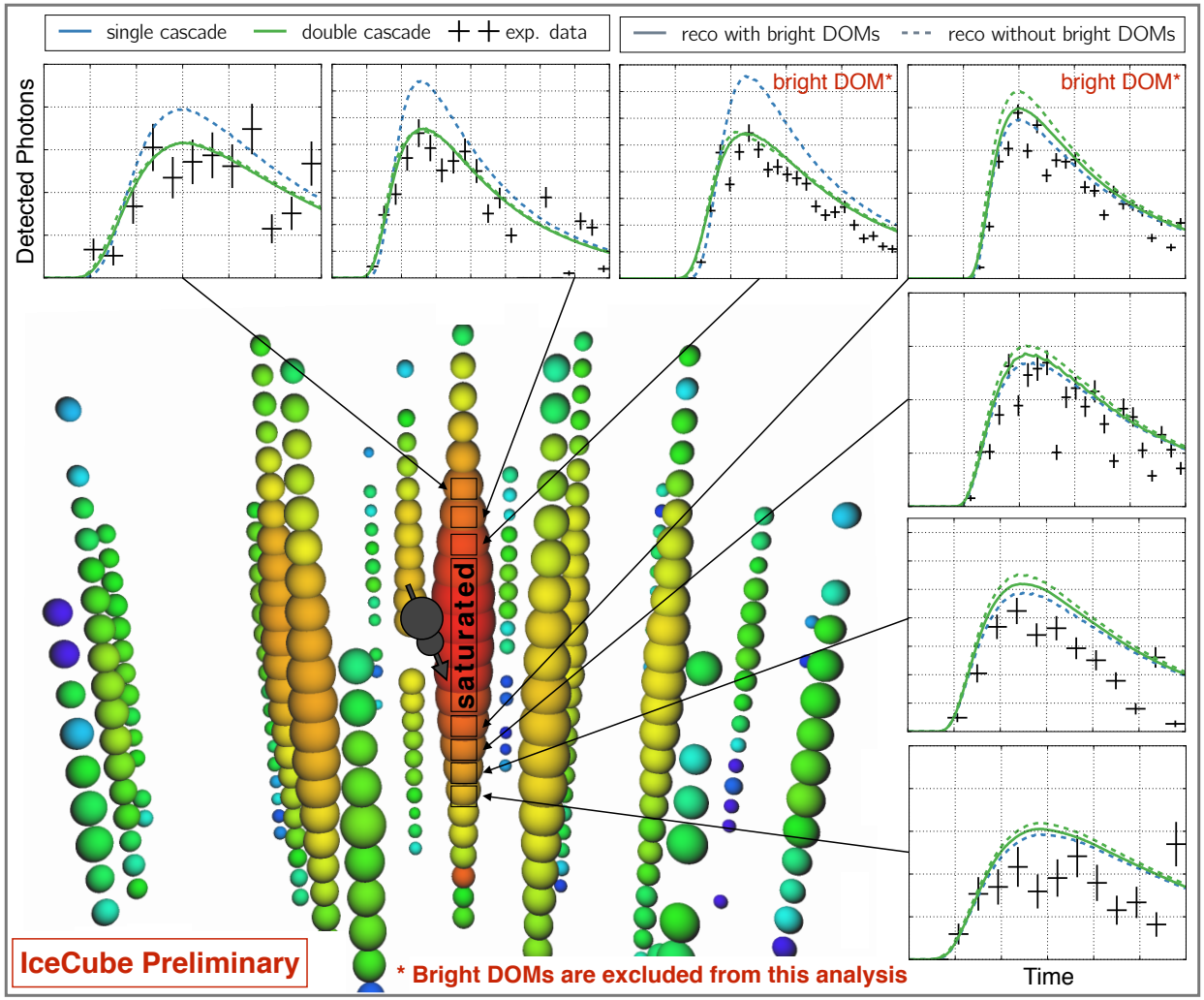


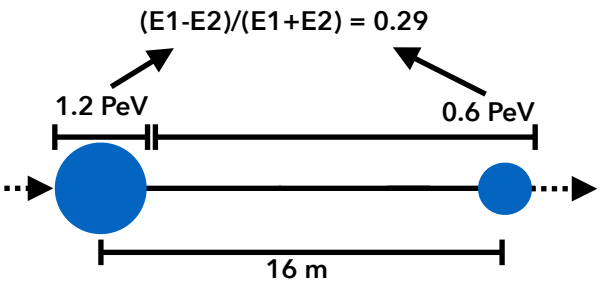
Track sample (16):
ν_τ – CC interactions creating μ, ν_μ – and atm. μ – tracks

↓

Flavor composition

Event #1 (Big Bird)

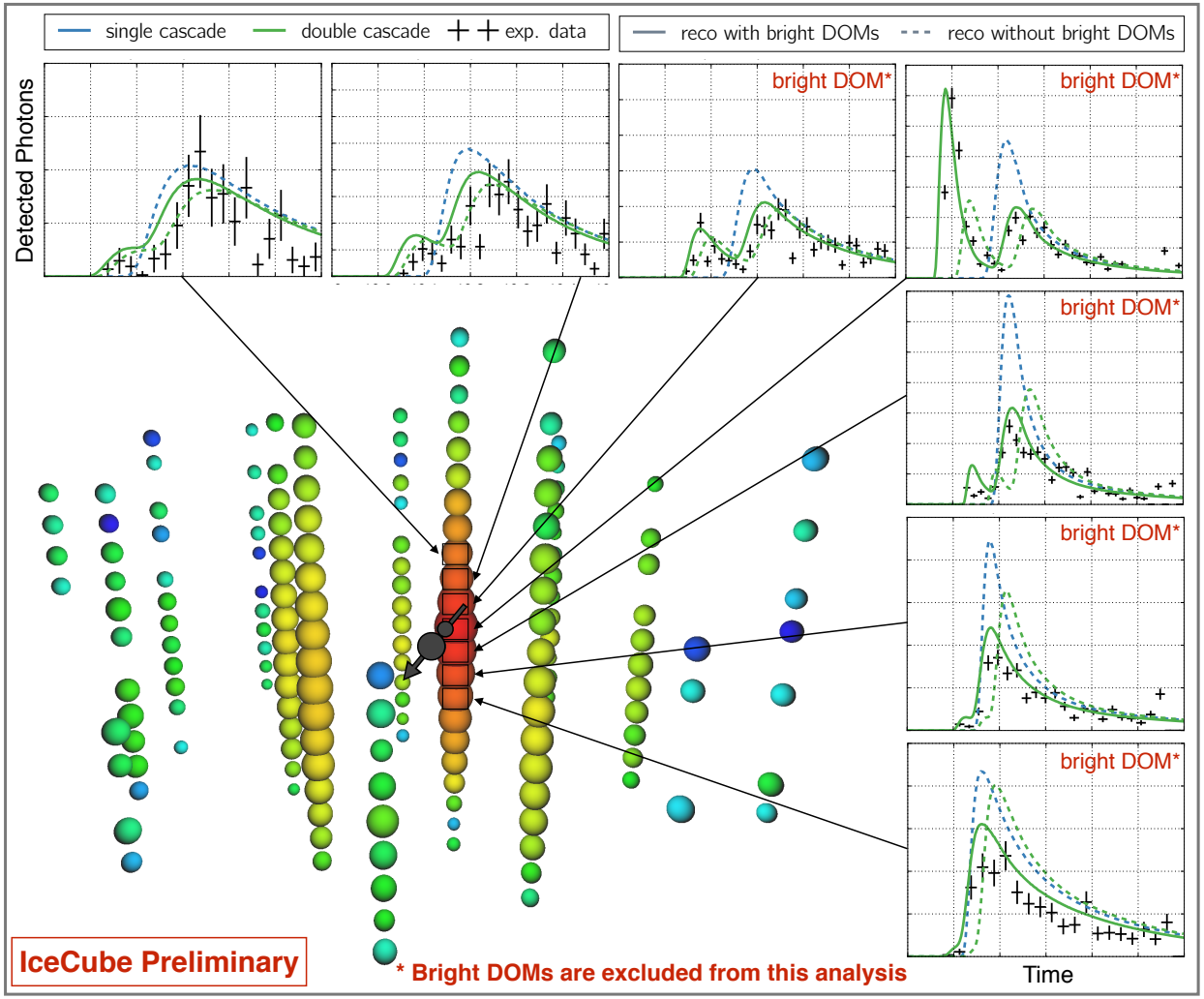


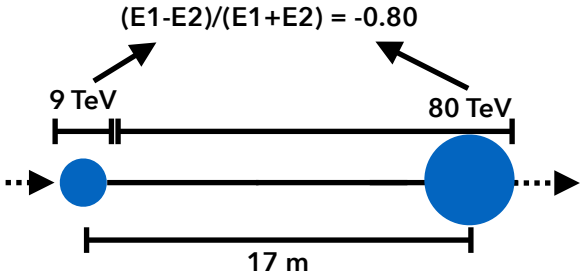


- Observed 2012
- Shows no clear preference between a single cascade and double cascade hypothesis

early → late

Event #2 (Double Double)

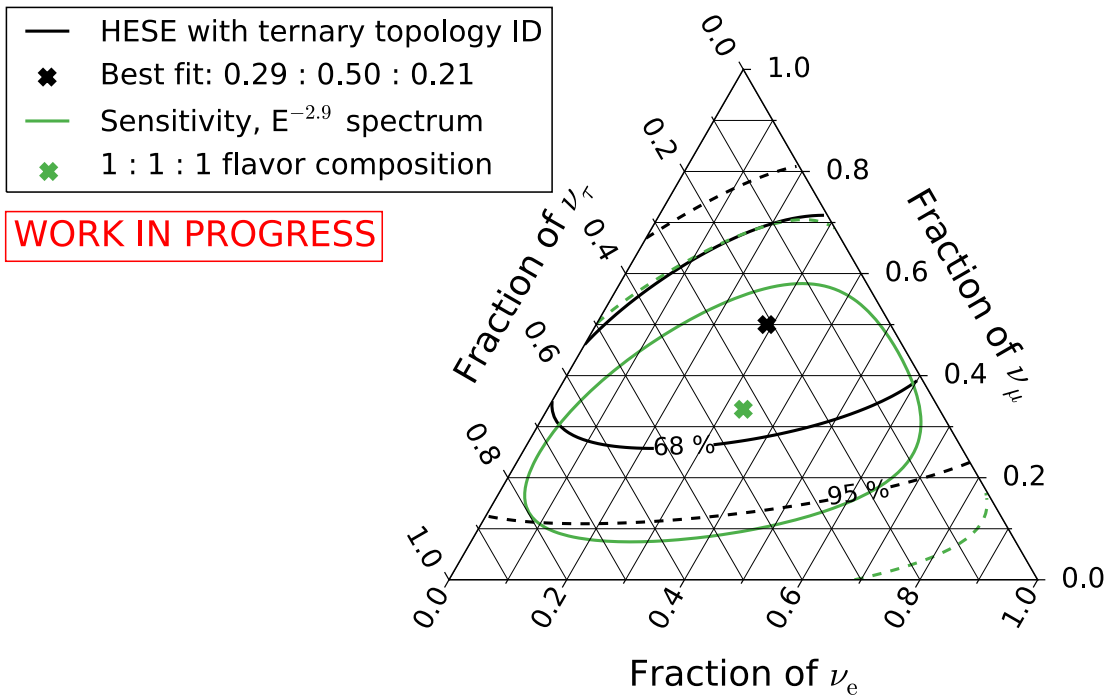




- Observed 2014
- Observed light arrival pattern clearly favors double cascade hypothesis

early → late

Flavor Composition

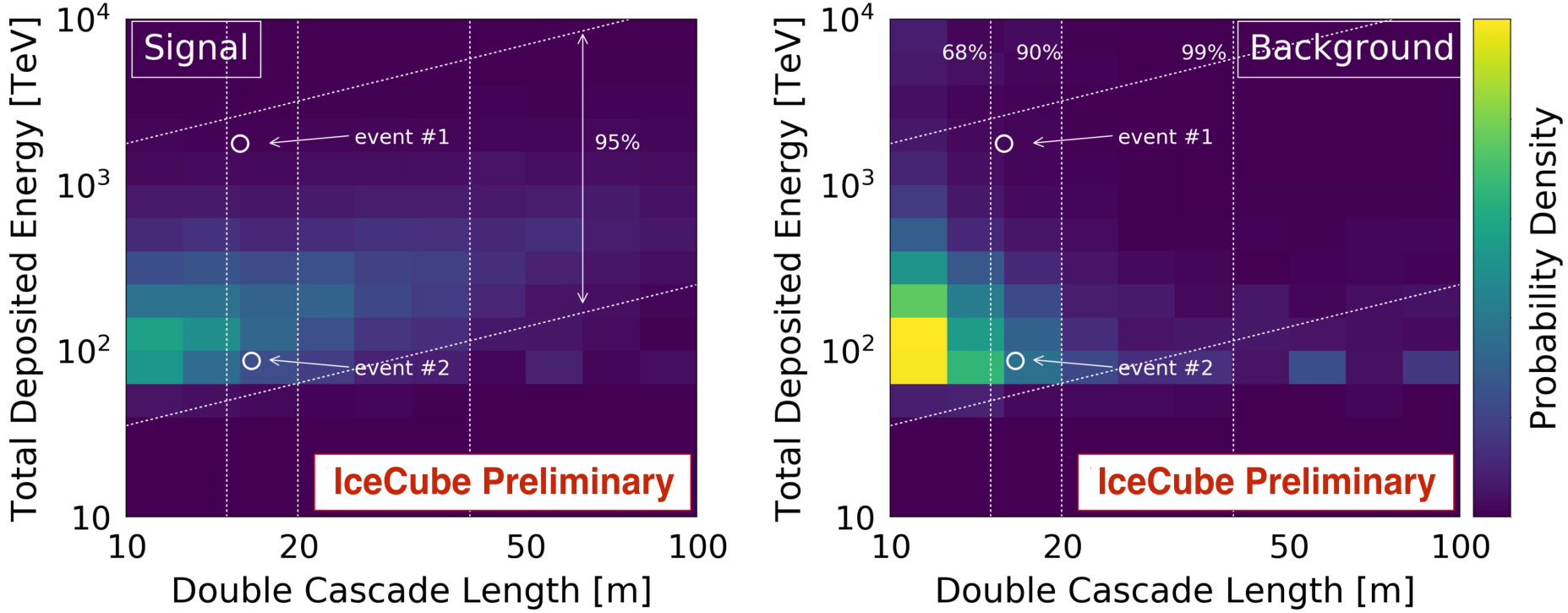


First probe of neutrino oscillations over cosmological baselines and at TeV energies!

First best fit non-zero in each flavor component!

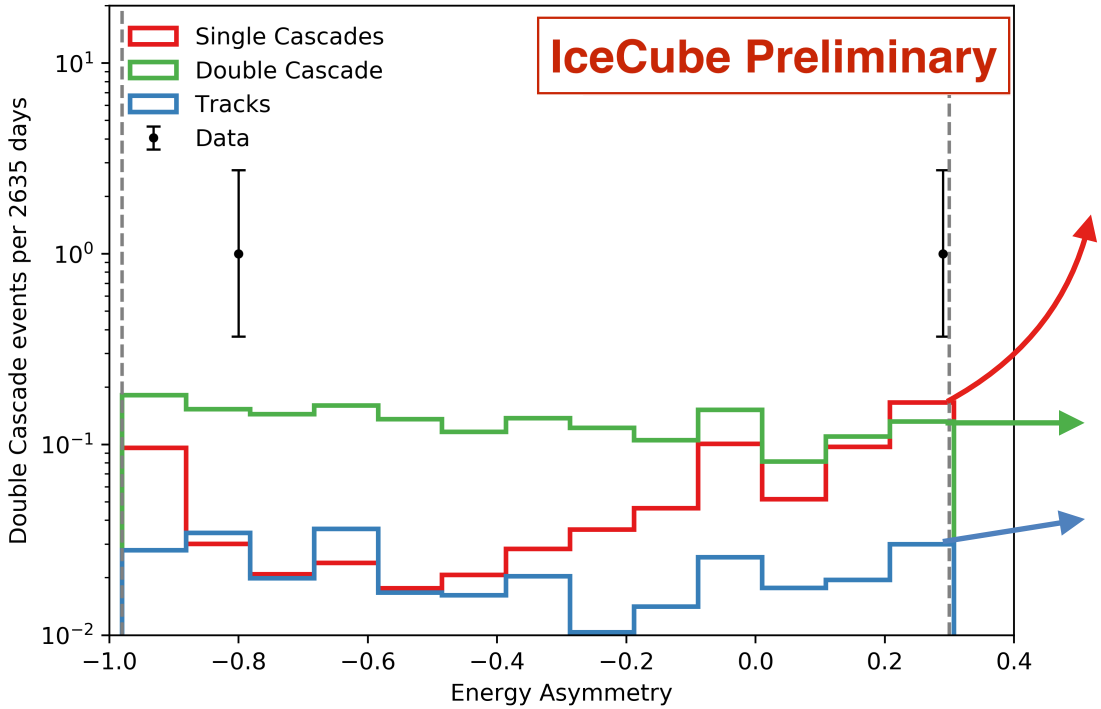
- Best-fit ν_e:ν_μ:ν_τ = 0.29:0.50:0.21
- Consistent with previous measurements and expectation of ~1:1:1 for astrophysical neutrinos
- Zero ν_τ flux cannot be excluded
- Systematic errors not included

Energy & Length



- 2 events with Double Cascade topology
- Soft spectral index: 2.9 → expect ~2.1 events (~1.4 signal + ~0.7 background)

Energy Asymmetry

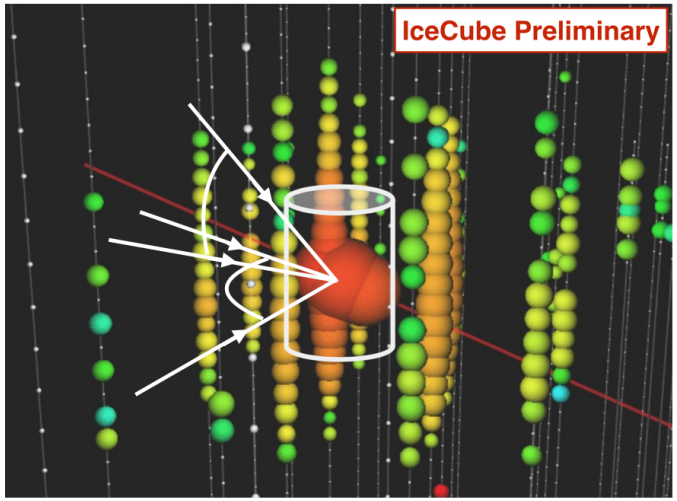


- $A_E=(E_1-E_2)/(E_1+E_2)$
- Only a straight cut was used
- Mainly due to computational issues
- Want to use all event properties

Energy asymmetry for best-fit spectrum, and a $\nu_e:\nu_\mu:\nu_\tau$ = 1:1:1 composition

Follow-Up

- $P(\nu_\tau|\boldsymbol{x})$ for Big Bird / Double Double?
  → Resimulate!
- Save computational power
  → Restrict parameter space
- Simulate ν_e, ν_μ, ν_τ and atmospheric μ (Double Double)
- 13M Double-Double-like events & 1M Big-Bird like events pass HESE selection
- Evaluate! → Tauness



Tauness:

differential signal event rates

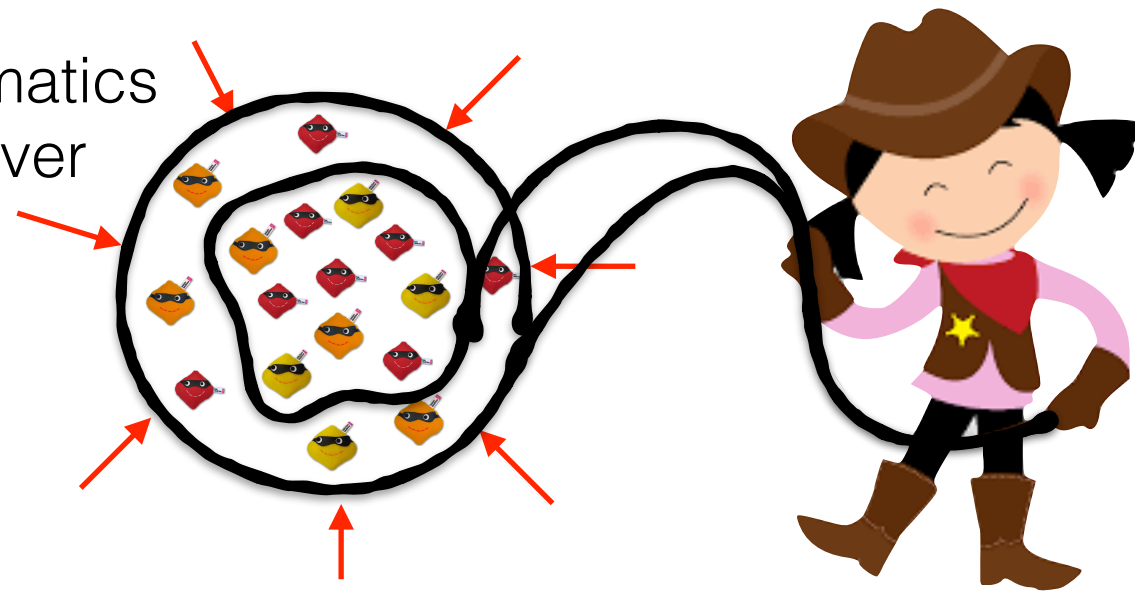
$$P(\nu_\tau|\boldsymbol{x}) \approx \frac{\mathrm{d}N_S^{DC}/\mathrm{d}\boldsymbol{x}}{\mathrm{d}N_S^{DC}/\mathrm{d}\boldsymbol{x} + \mathrm{d}N_B^{DC}/\mathrm{d}\boldsymbol{x}} \equiv \tau$$

differential background event rates

with $\boldsymbol{x} = (x, y, z, \theta, \phi, E_{tot}, L, A_E)$

Follow-Up Results

- Use 6D KDE with Rodeo* algorithm & ROI in A_E, L
- Assume best-fit $E^{-2.89}$ spectrum, 1:1:1 flavor composition (see talk NU4b on Fri)
- Uncertainties & systematics not yet marginalized over

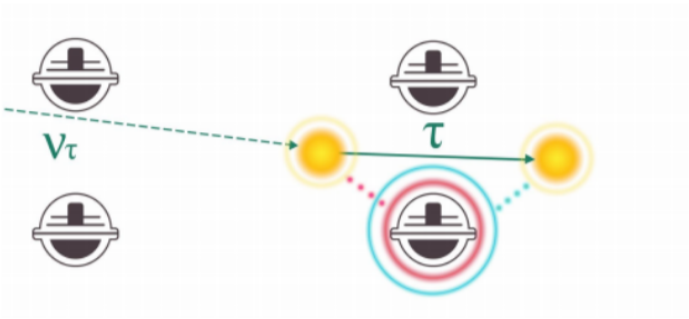


- **≥97% of Double-Double-like events are ν_τ-induced**
- **~75% of Big-Bird-like events are ν_τ-induced**
- Statistics still limiting factor

Proceedings of the Eleventh International Conference on Artificial Intelligence and Statistics (2007)

Double Pulse

- Another feature of ν_τ CC interactions
- Analyze waveform on brightest DOMs
- No full reconstruction of event
- Information used complementary to Double Cascade method presented here
- 2 analyses presented here:
  - Results using straight cuts
  - Results using machine learning

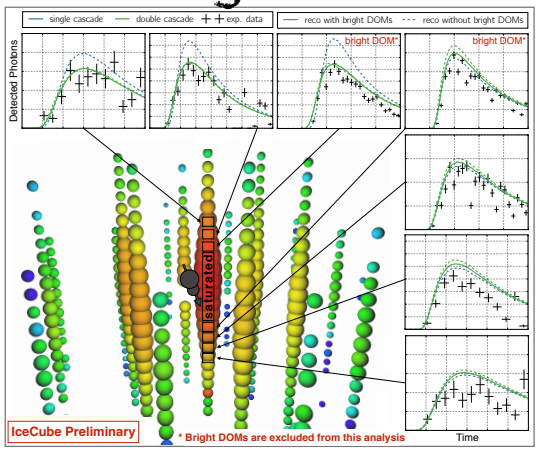


Talk NU11c on Wed

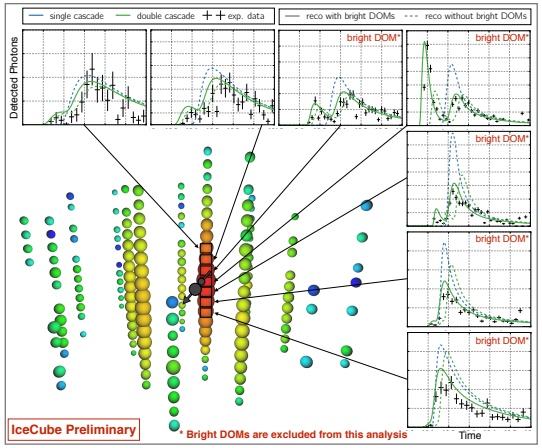
Poster PS1-117 (Thu/Fri)

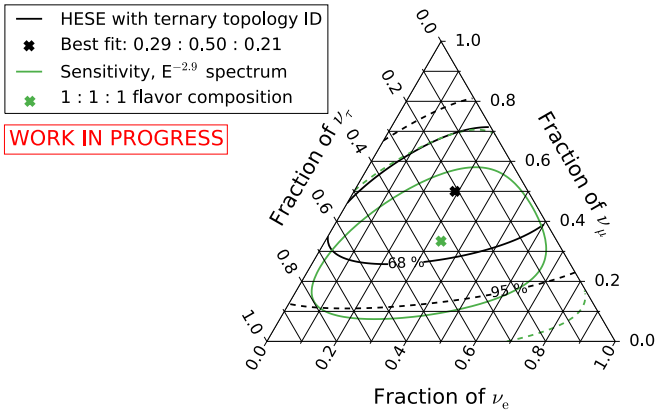
Summary

Big Bird



Double Double





Best fit ≠0 in all flavors!

(≈75% ν_τ)

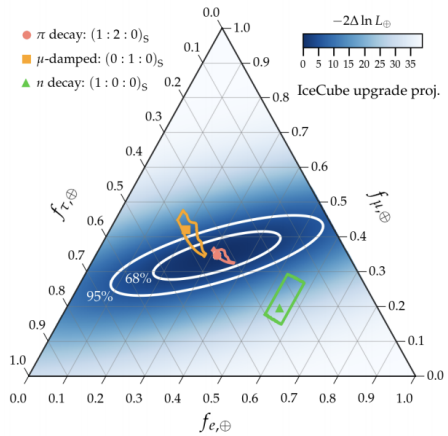
(≥97% ν_τ)

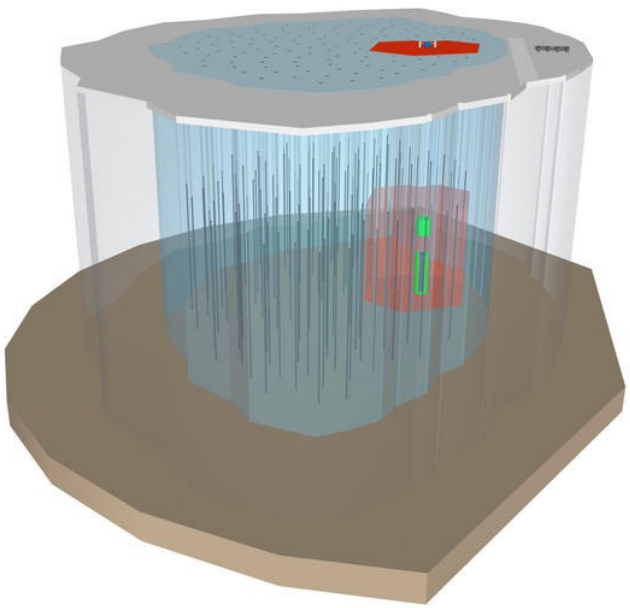
SM Cosmic messengers:

e, p, A ✔	ν_e ✔
γ ✔	ν_μ ✔
GW ✔	ν_τ ✔

Back up

The Future of Astrophysical ν_τ

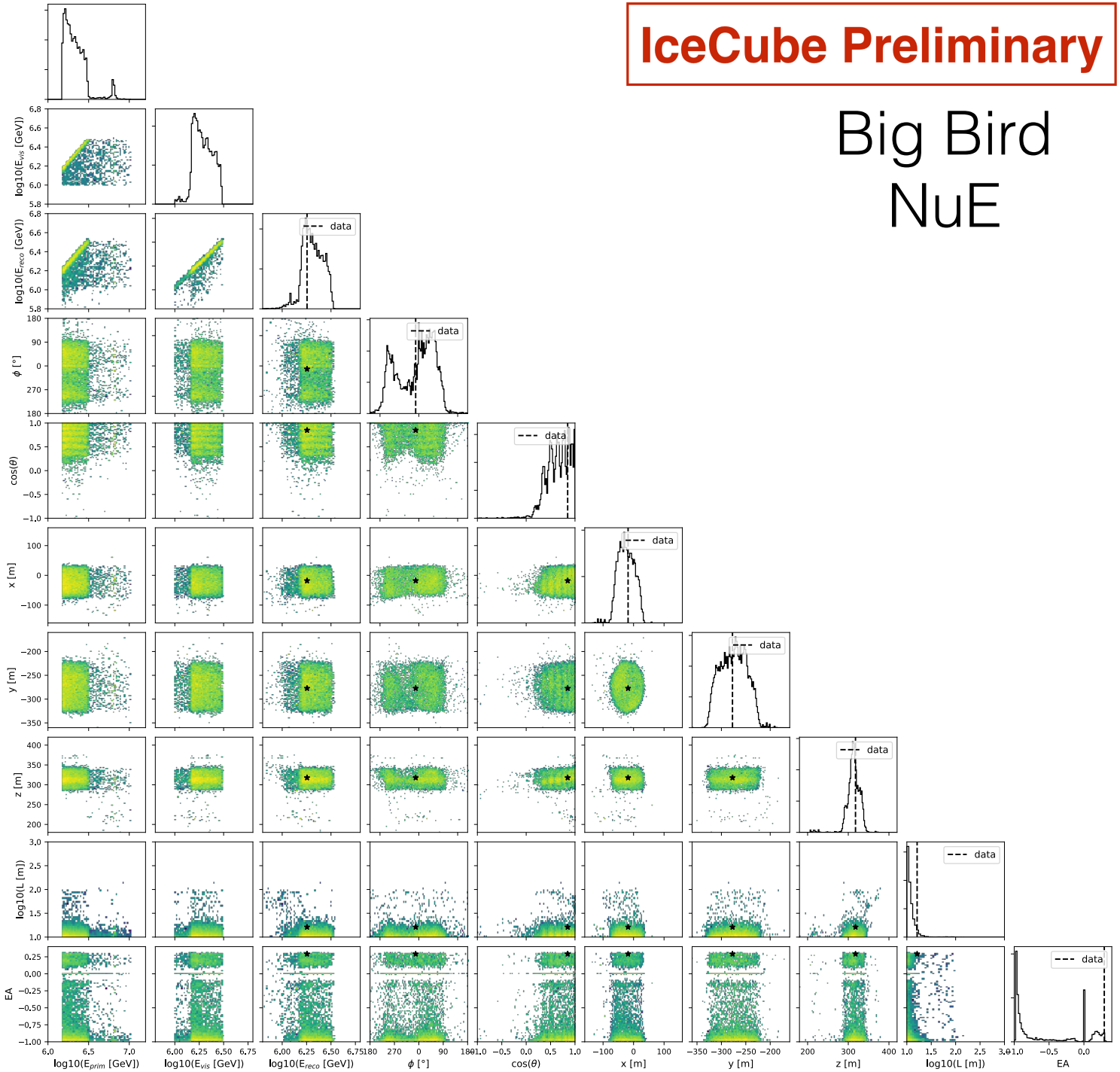




- IceCube Upgrade
  - Precision measurements of ice optical properties
  - In-situ verification of ν_τ reconstruction at ~20 m baselines
- IceCube Gen2
  - More volume
  - More identifiable ν_τ expected
- Higher precision for flavor composition measurement

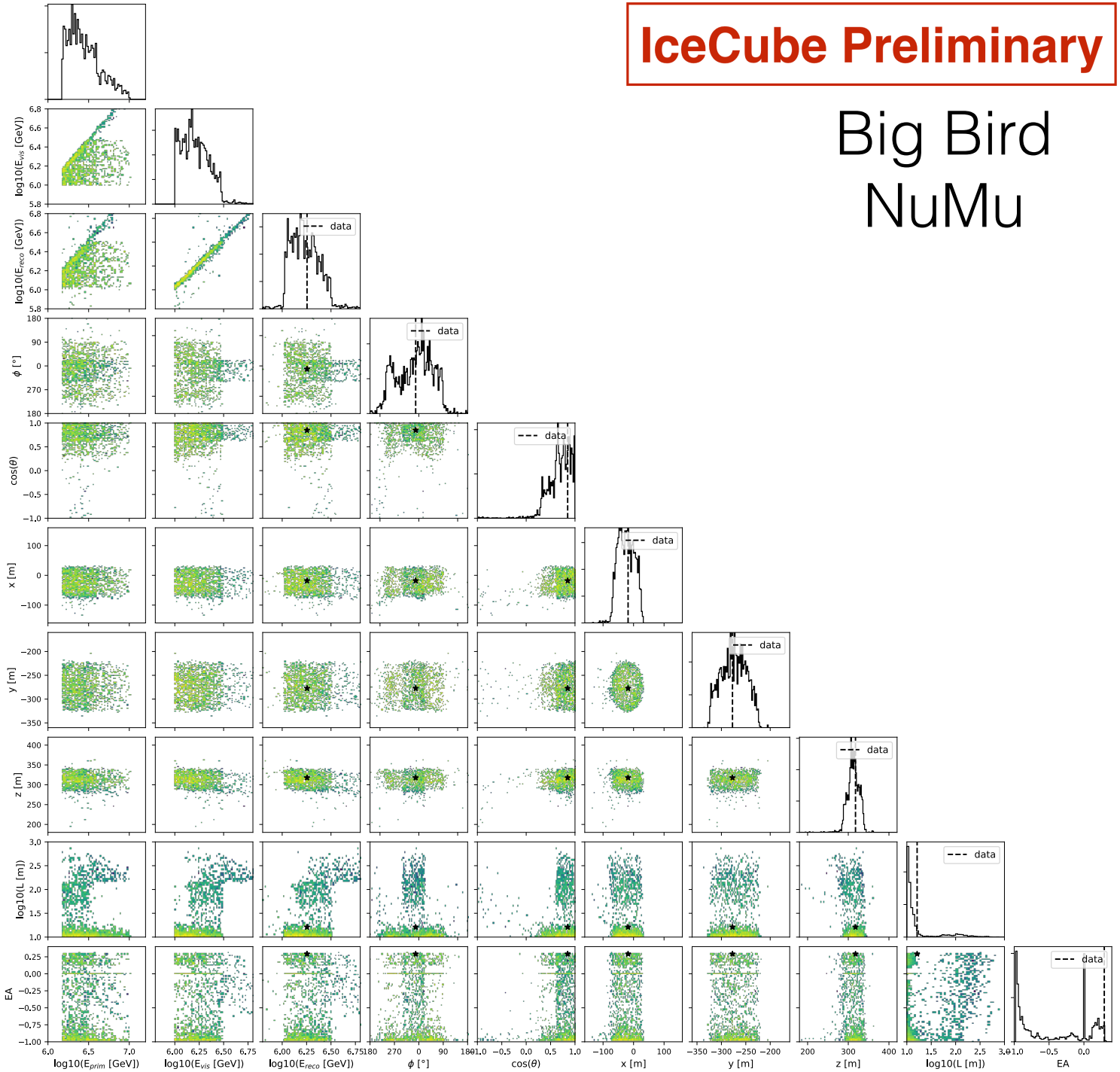
IceCube Preliminary

Big Bird NuE



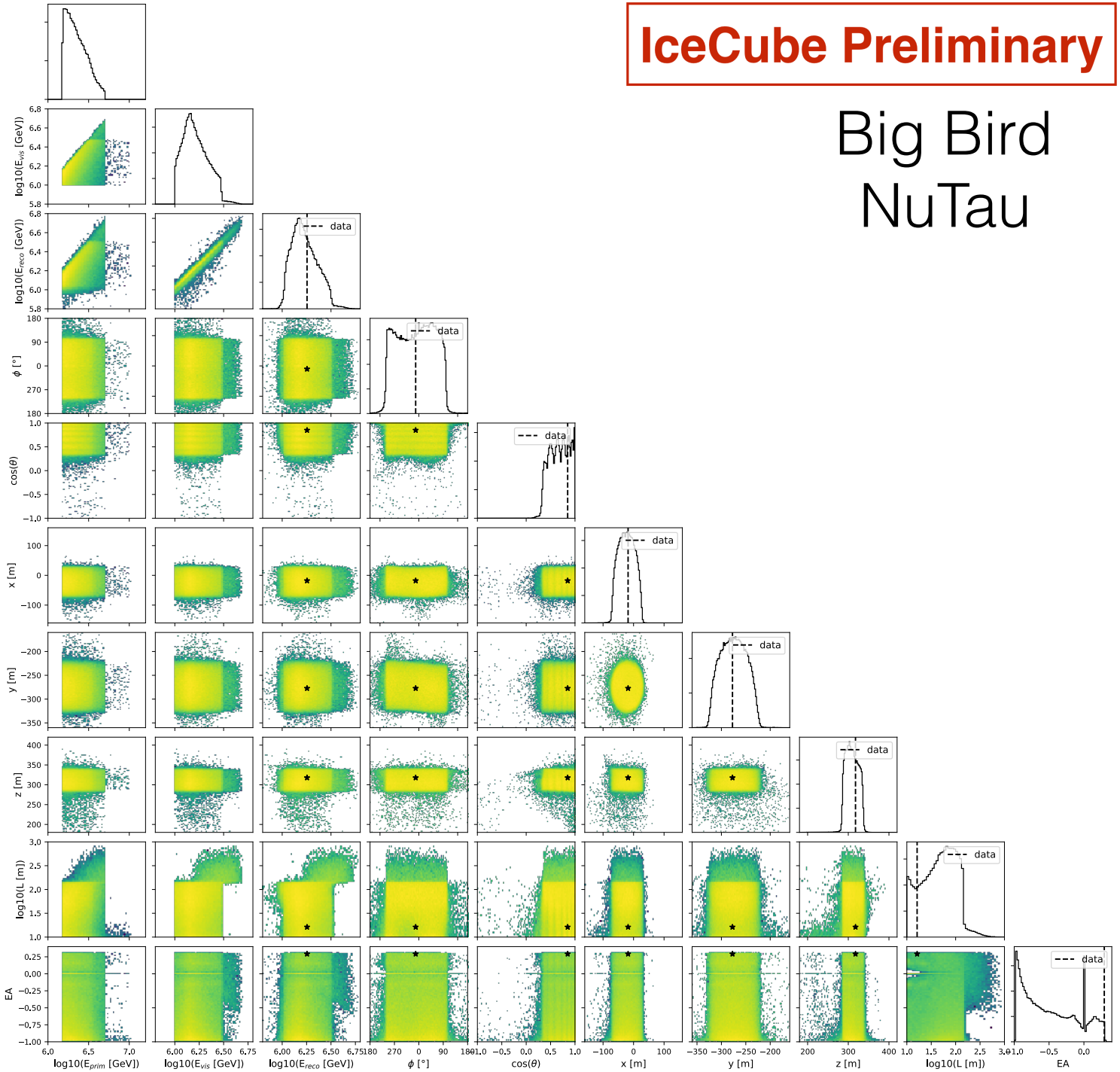
IceCube Preliminary

Big Bird NuMu



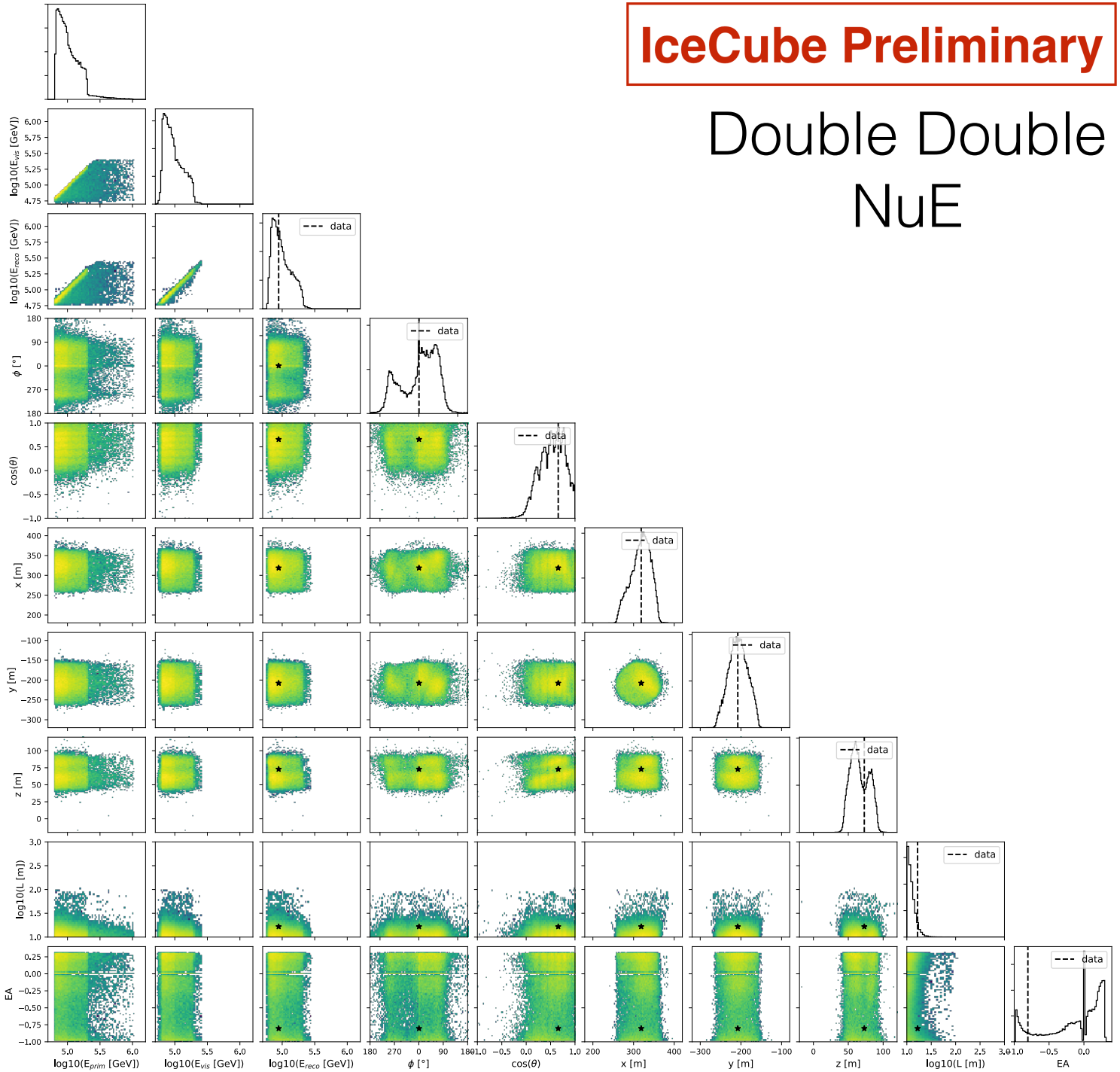
IceCube Preliminary

Big Bird NuTau



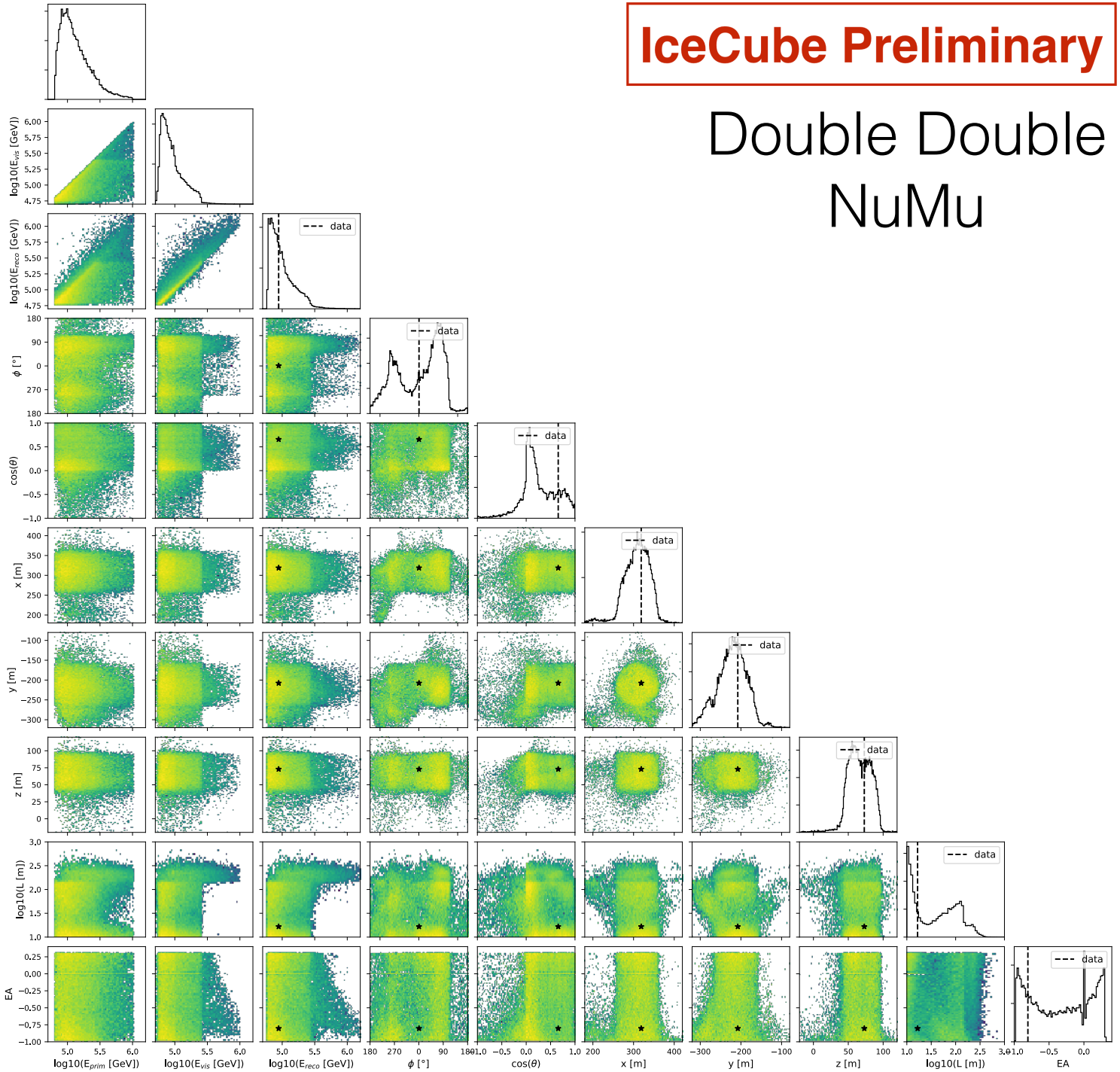
IceCube Preliminary

Double Double NuE



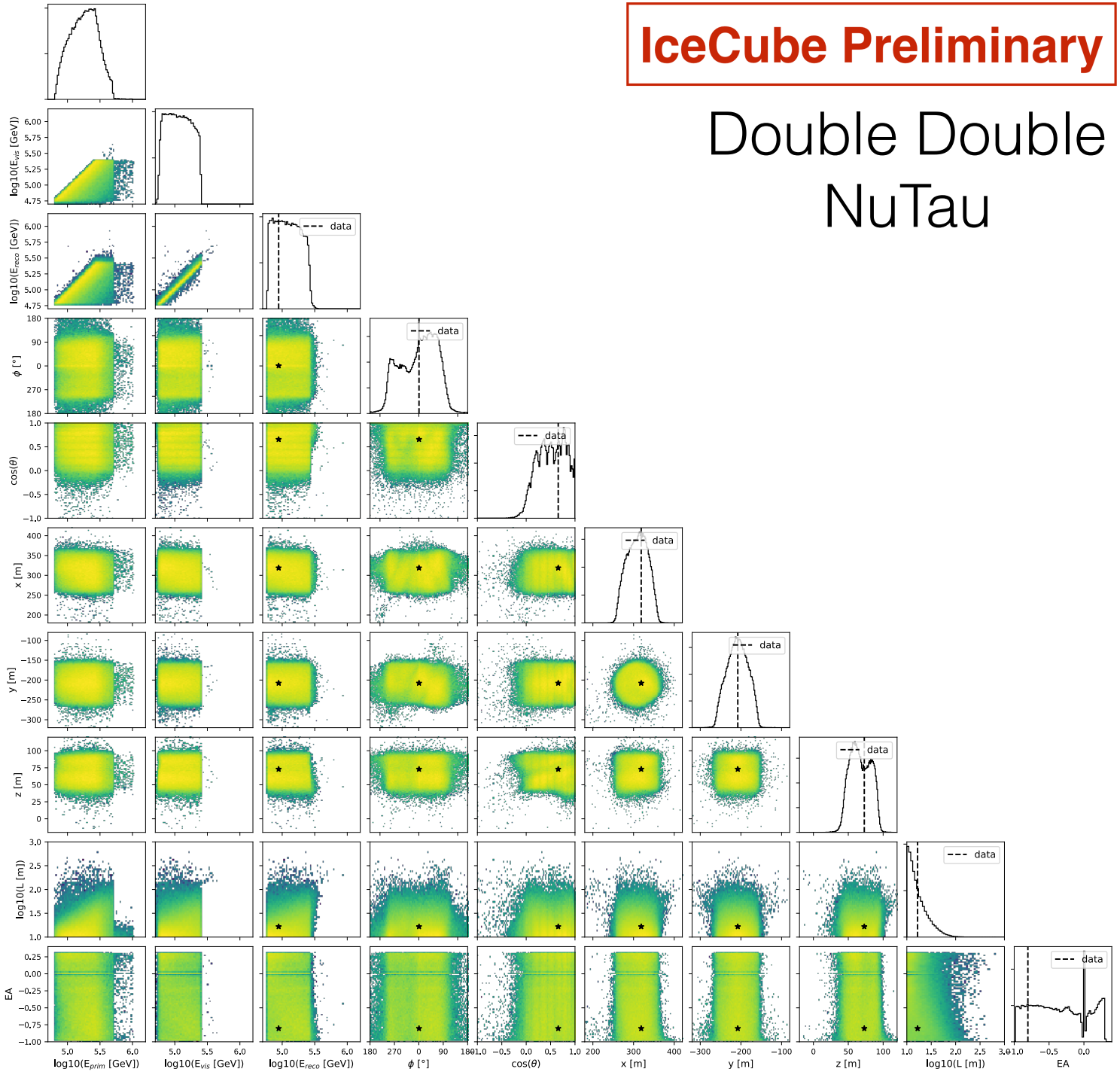
IceCube Preliminary

Double Double NuMu

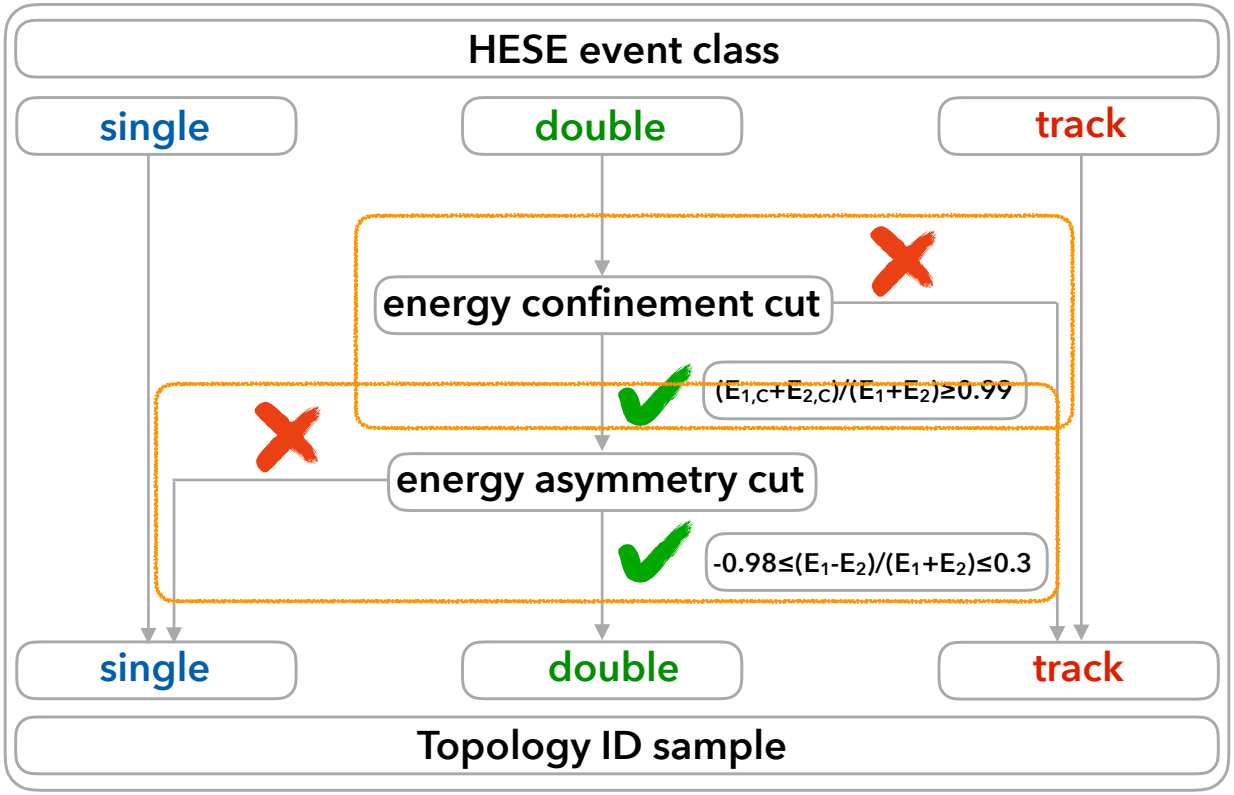


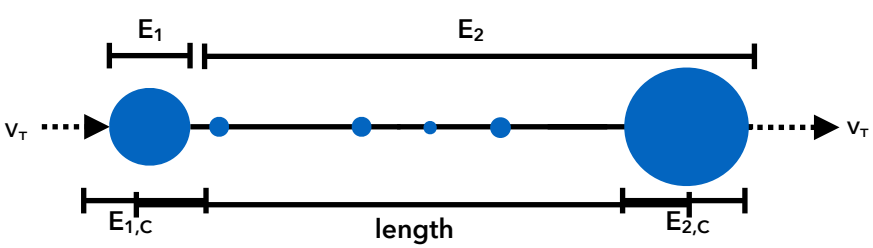
IceCube Preliminary

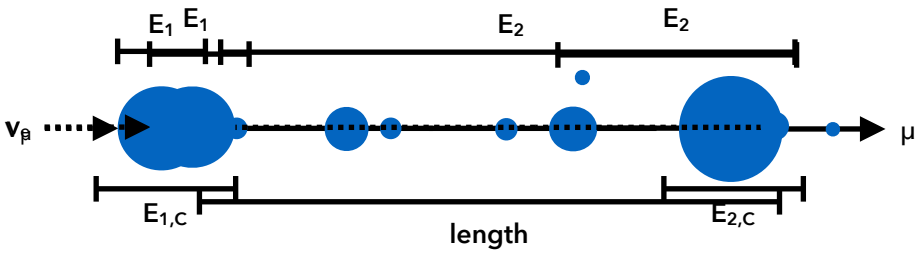
Double Double NuTau



Selection

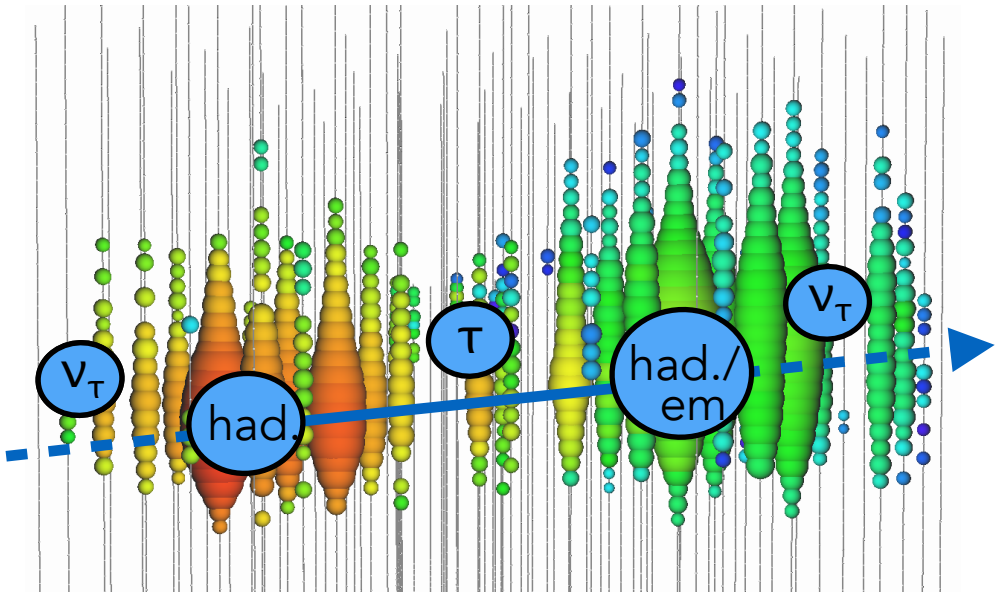

HESE event class
single
double
track
energy confinement cut
$(E_{1,C}+E_{2,C})/(E_1+E_2)\geq 0.99$
energy asymmetry cut
$-0.98\leq(E_1-E_2)/(E_1+E_2)\leq 0.3$
single
double
track
Topology ID sample


E_1
E_2
ν_τ
ν_τ
$E_{1,C}$
length
$E_{2,C}$


E_1 E_1
E_2
E_2
ν_μ
μ
$E_{1,C}$
length
$E_{2,C}$

Double Cascade Signal

- ν_τ interaction
- Charged current (71%)
- Tau decays into hadrons / electrons (83%)
- Mean length: 50m x energy/1PeV

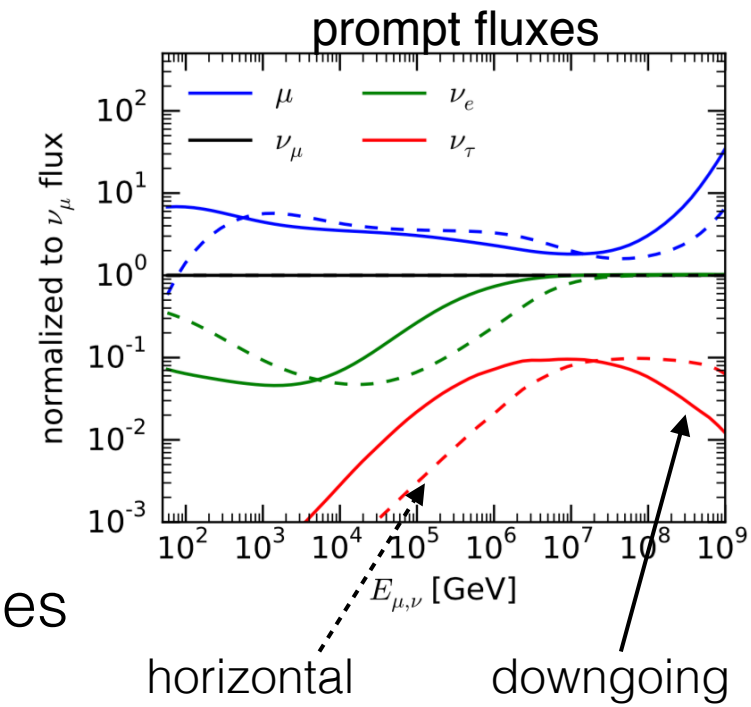


simulated 10PeV Double Cascade event

Astrophysical Tau Neutrinos

- Tau neutrinos needed for flavor composition measurement
- Negligible atmospheric ν_τ flux
- Guaranteed astrophysical ν_τ flux due to neutrino mixing
- Finding cosmic ν_τ:
  - Finding the last SM cosmic messenger
  - Yet another confirmation of the diffuse neutrino flux being astrophysical
  - on of neutrino mixing at aselines, highest energies

- Discovery
- Complementarity
- Universality
- BSM constraints



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