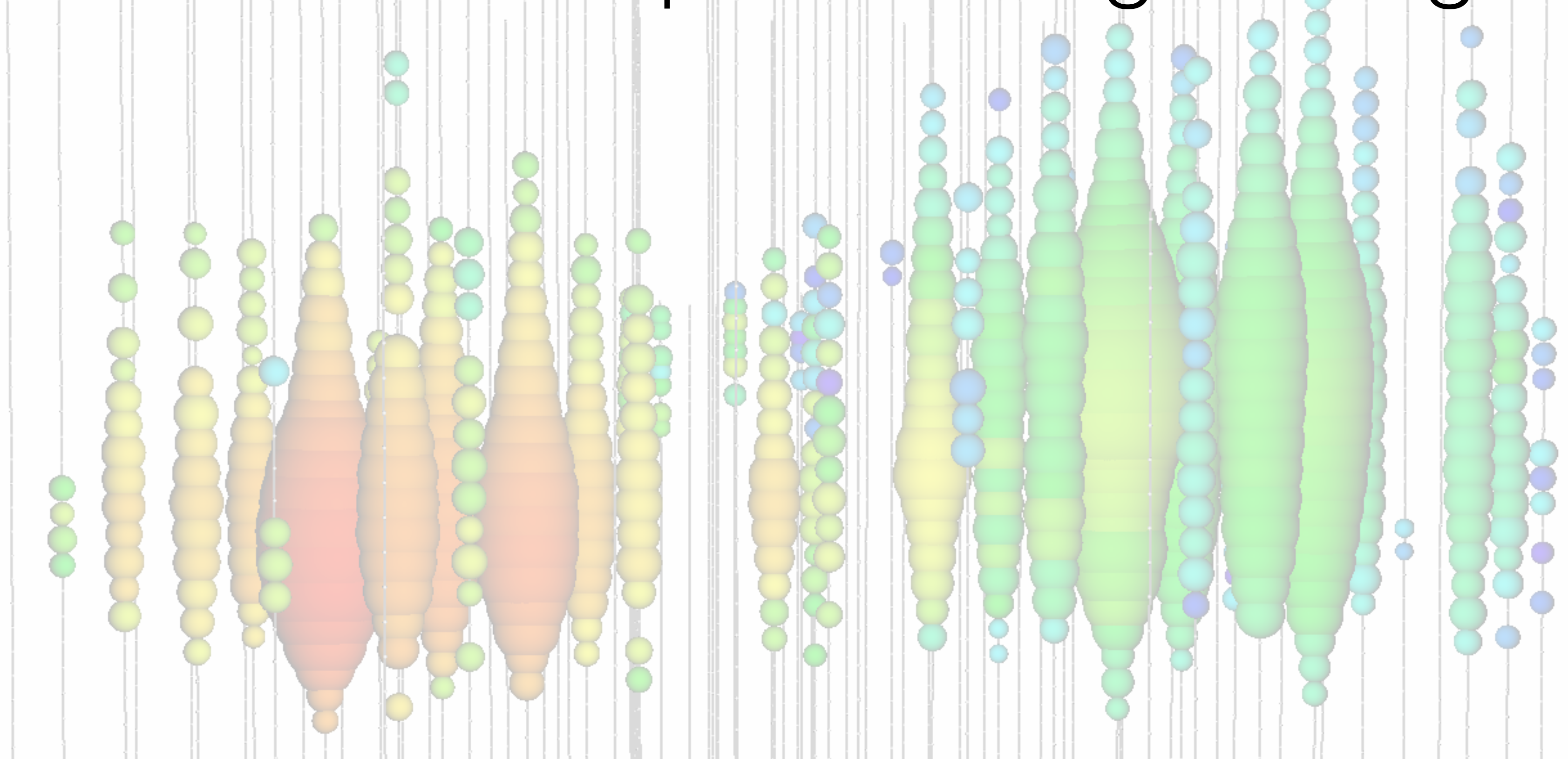
Reconstruction, Flavor Identification and Future Prospects at High Energies

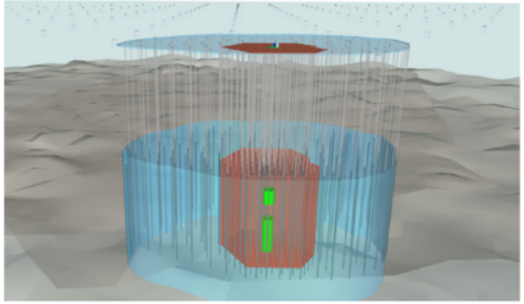


NuTau 2021
September 30 2021
Juliana Stachurska

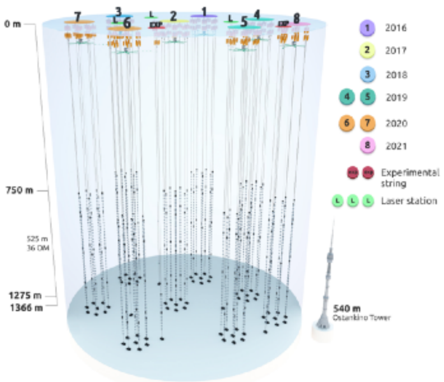
Massachusetts Institute of Technology

Experiments Covered

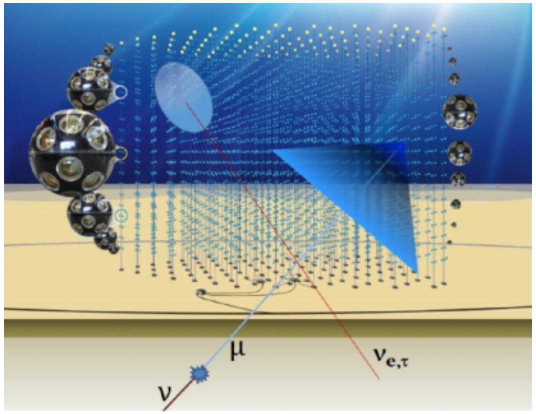
- IceCube / IceCube-Gen2:
  Ice Cherenkov



- Baikal-GVD:
  (Lake) water
  Cherenkov



- KM3NeT/ARCA:
  (Salt) Water
  Cherenkov



Experiments Covered

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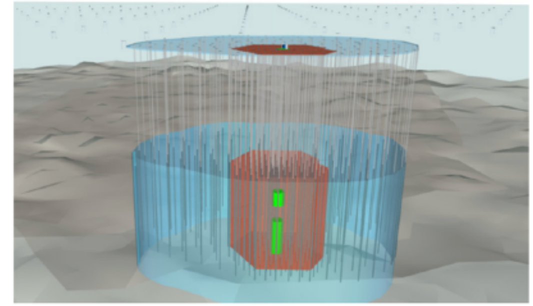

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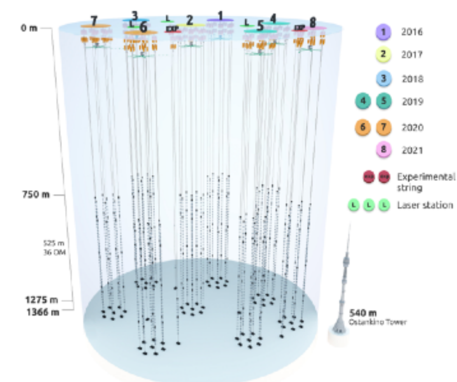

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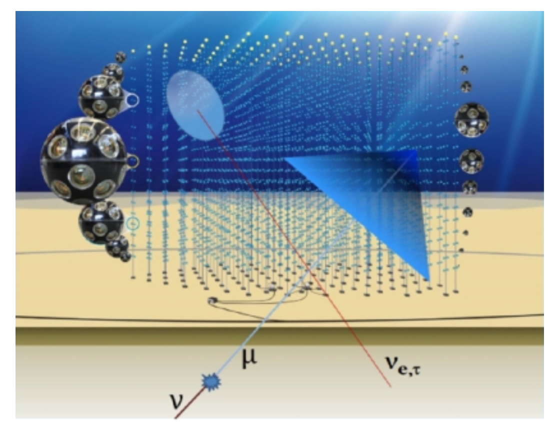
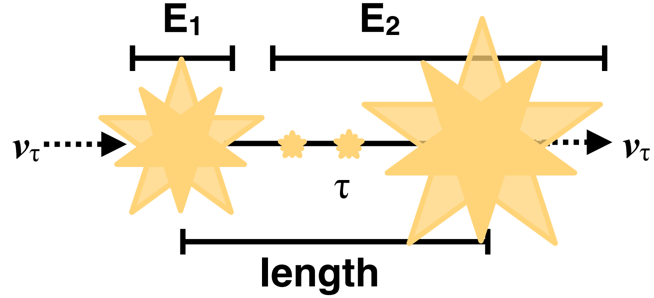
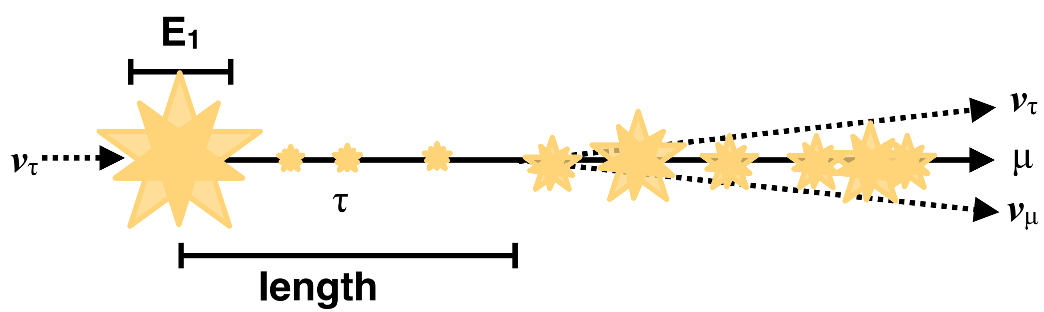


See talk by Dawn Williams

Tau Neutrino Signatures

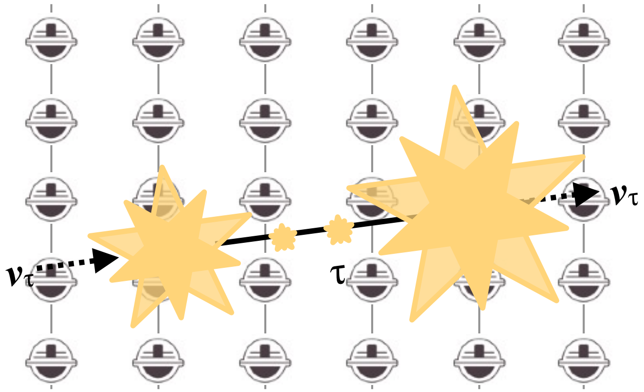


→ Double Bangs,
Double Cascades,
Double Pulses
(83% branching ratio)



→ Tracks (not unique)
(17% branching ratio)

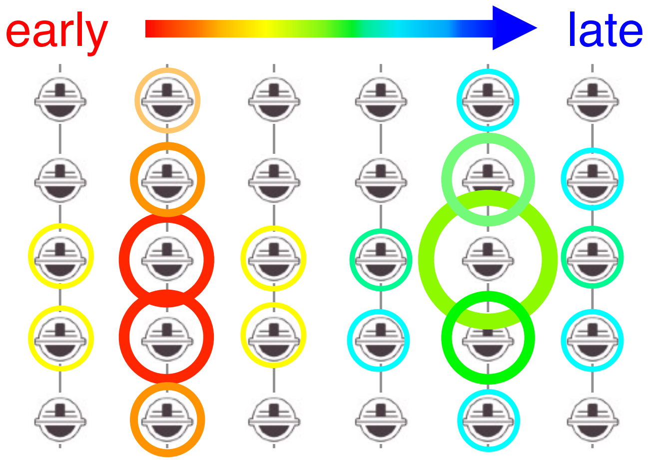
Double Bang



- 2 clearly separated energy depositions*
- Identification by-eye
- Maximum likelihood cascade reconstruction

*Learned, Pakvasa: Astropart. Phys. 3, 267–274 (1995)

Double Bang



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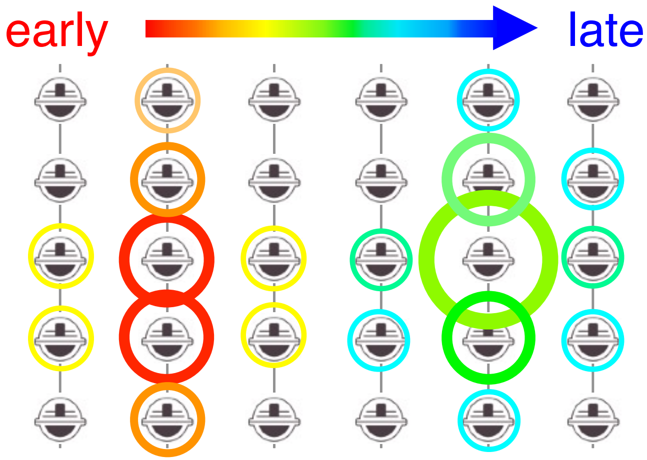

- 2 clearly separated energy depositions*
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- Maximum likelihood cascade reconstruction

"At a few PeV these cascades would be separated by roughly 100 m, and thus be easily resolvable in DUMAND and similar detectors."*

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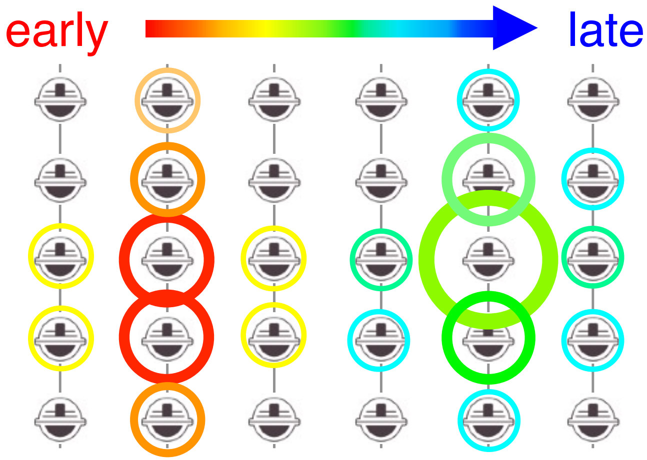
Double Bang



- 2 clearly separated energy depositions*
- Identification by-eye
- Maximum likelihood cascade reconstruction

"At a few PeV these cascades would be separated by roughly 100 m, and thus be easily resolvable in DUMAND and similar detectors."*

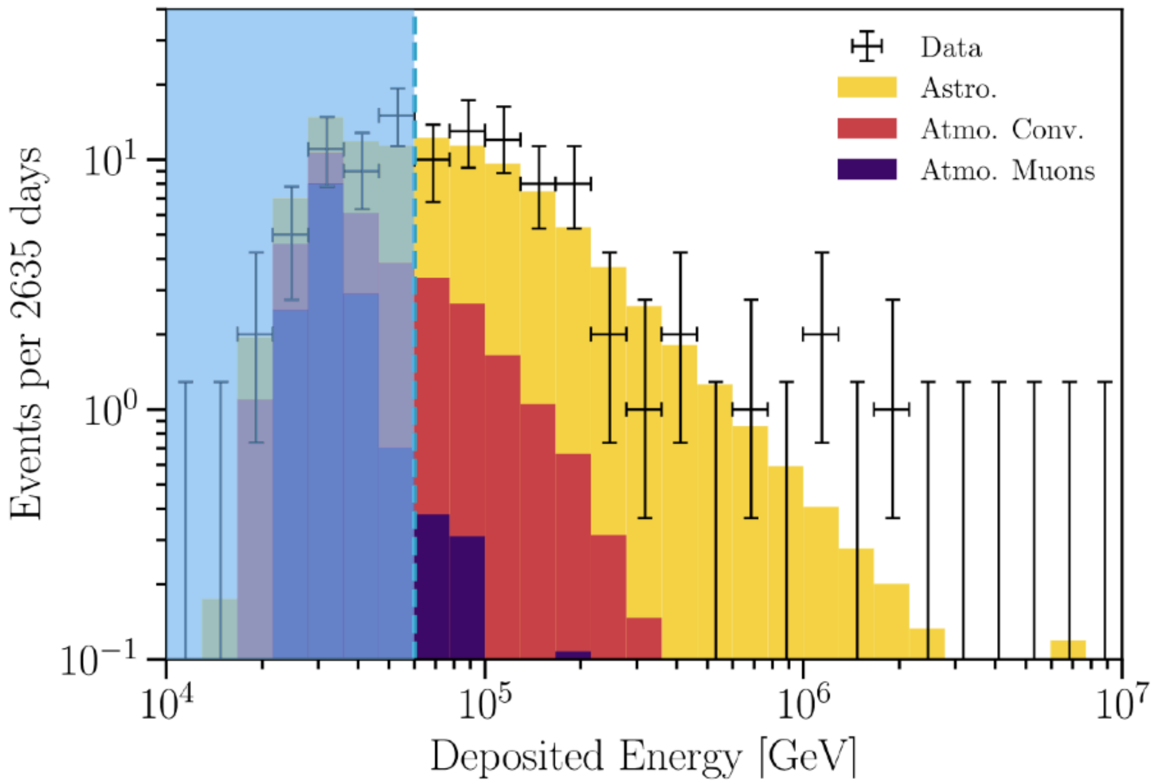
+ Simple, robust

− Large separations = high energies: $\langle L_\tau \rangle \sim 50\,\mathrm{m} \cdot E_\tau$ [PeV] extremely rare events!

Background: almost none* (note: coincident events, muons hiding in sparse detectors)

***Learned, Pakvasa: Astropart. Phys. 3, 267–274 (1995)**

Astrophysical Neutrino Spectrum

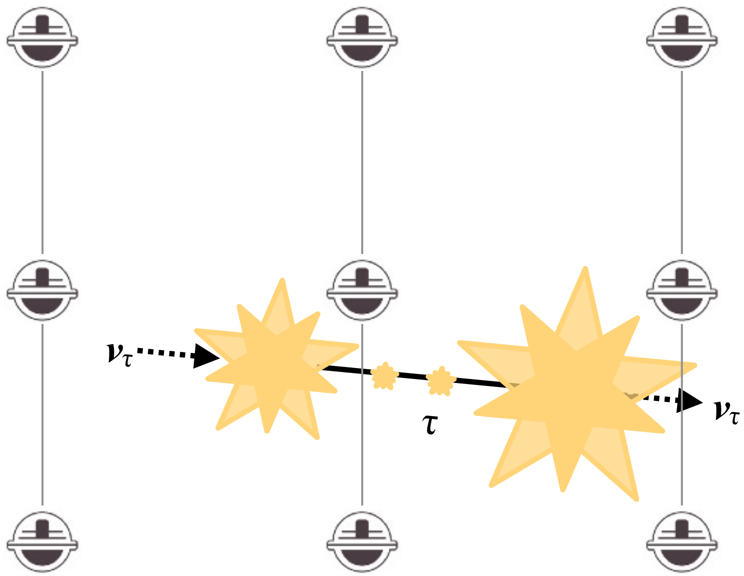


- Latest all-flavor spectral measurement: HESE 7.5 years*
- 60 events > 60 TeV
- Spectrum: $E^{-\gamma}$ with $\gamma = 2.87^{+0.20}_{-0.19}$

- Need to wait for many more years for Double Bang
- Or: lower the thresholds, understand backgrounds & systematic uncertainties

***R. Abbasi et al., PRD 104 (2021)**

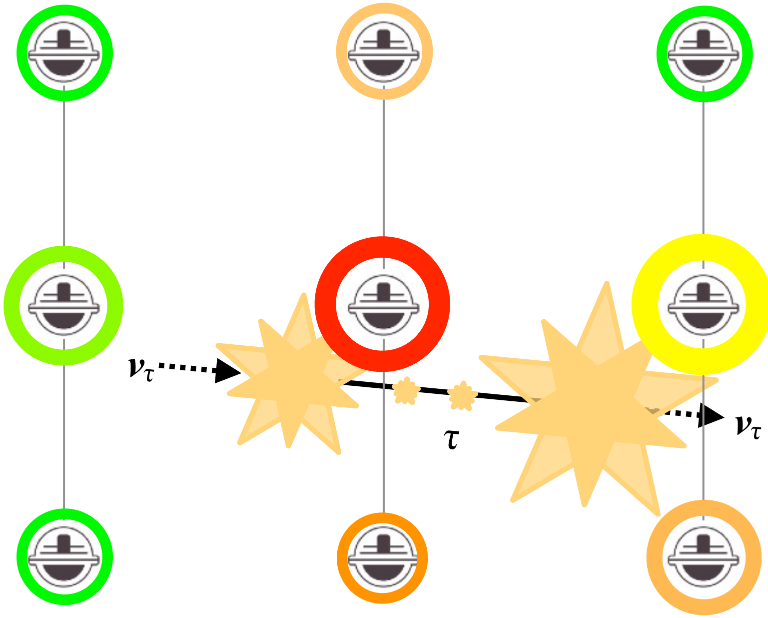
Double Cascade



- 2 separated energy depositions, but typically not visible by-eye
- Direct maximum likelihood (ML) reconstruction for double cascade hypothesis*

***M. Usner, PoS(ICRC2017) 974**

Double Cascade



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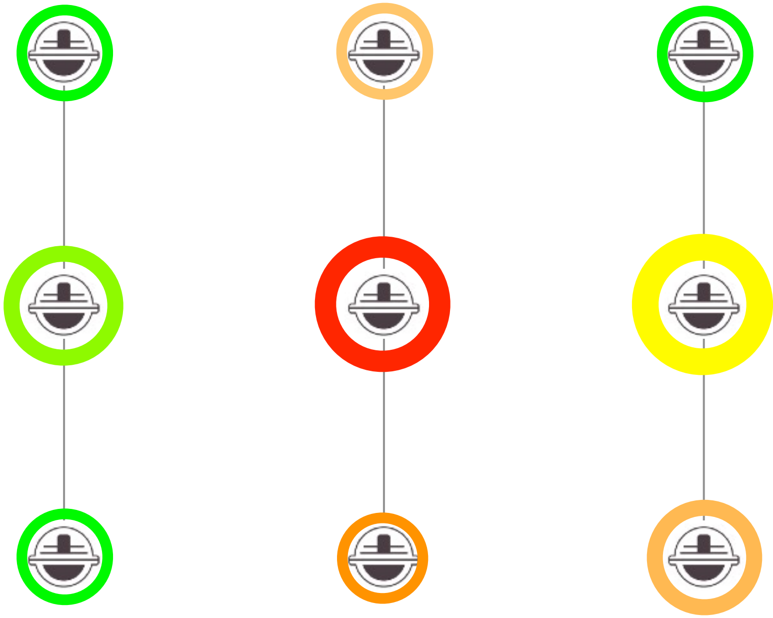

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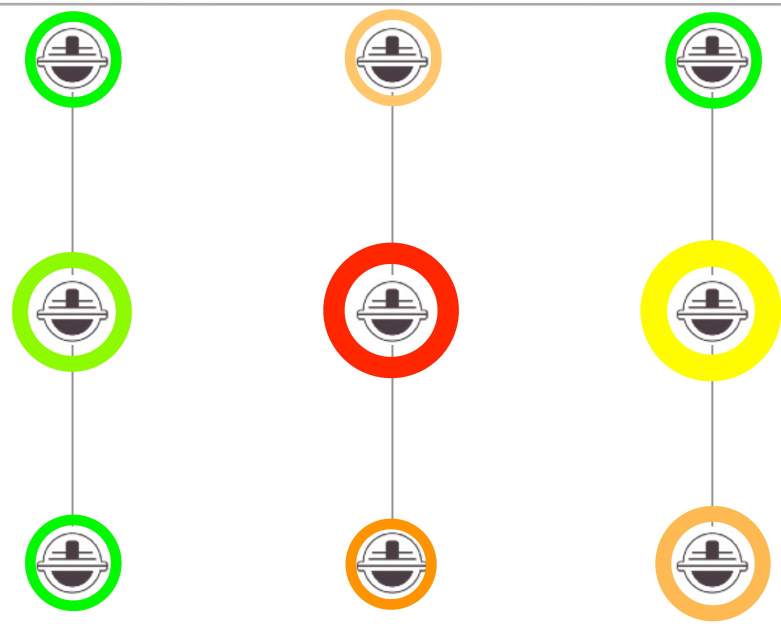
Double Cascade



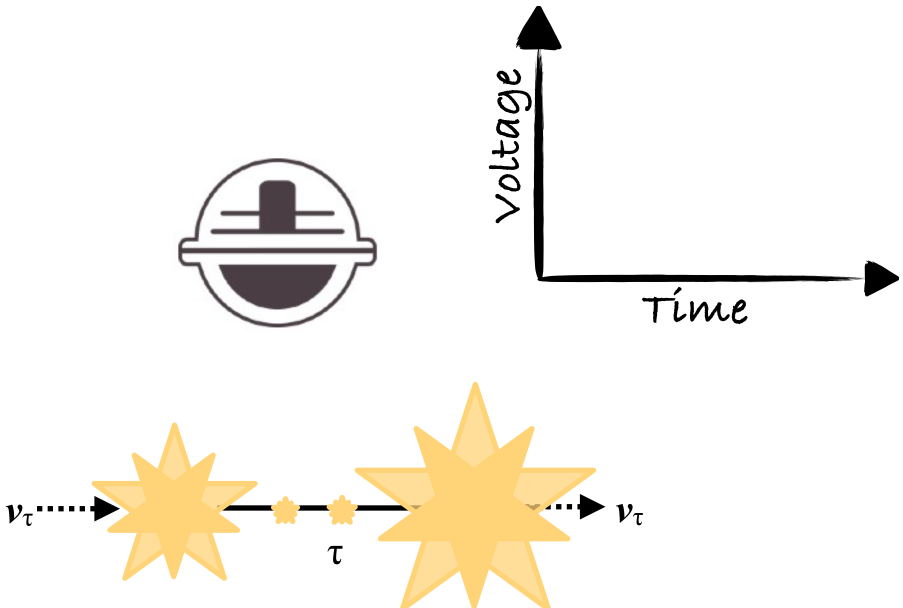
- 2 separated energy depositions, but typically not visible by-eye
- Direct maximum likelihood (ML) reconstruction for double cascade hypothesis*

+ Lower energy threshold: larger statistics
  Same ML framework used for all flavors for flavor composition

− Timing of arriving photons critical: sensitive to knowledge of photon propagation through medium
  Background: single cascades close to analysis threshold

*M. Usner, PoS(ICRC2017) 974

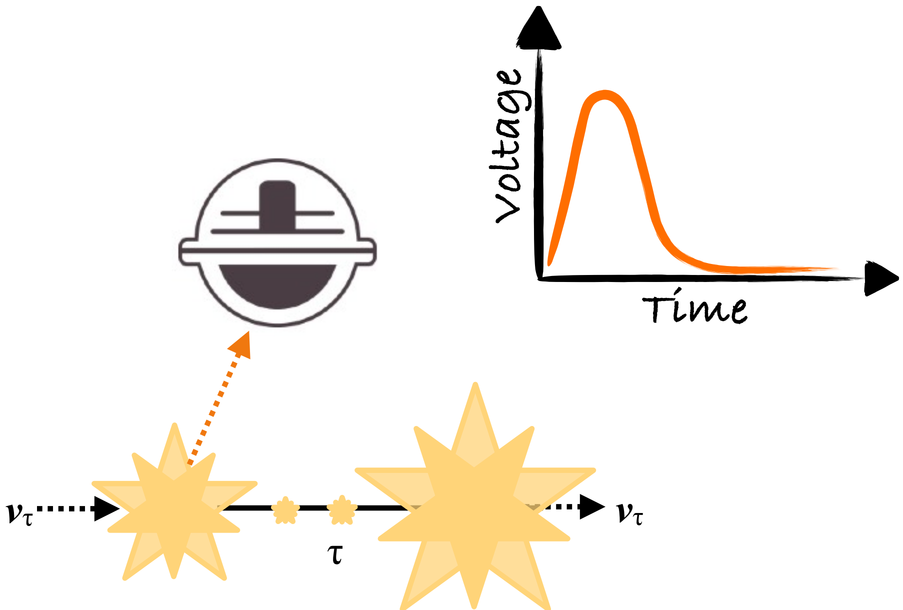
Double Pulse



- 2 energy depositions, typically with small distances, identified on one PMT*
- Only created for events with both energy losses close to PMT
- Needs time-binned readout

*M. Aartsen et al., PRD 93 (2016)

Double Pulse



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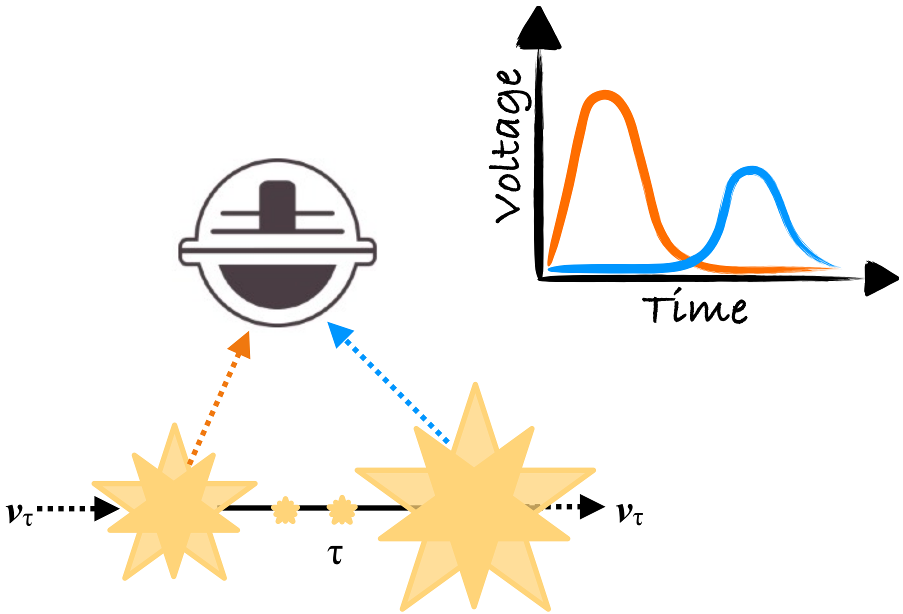

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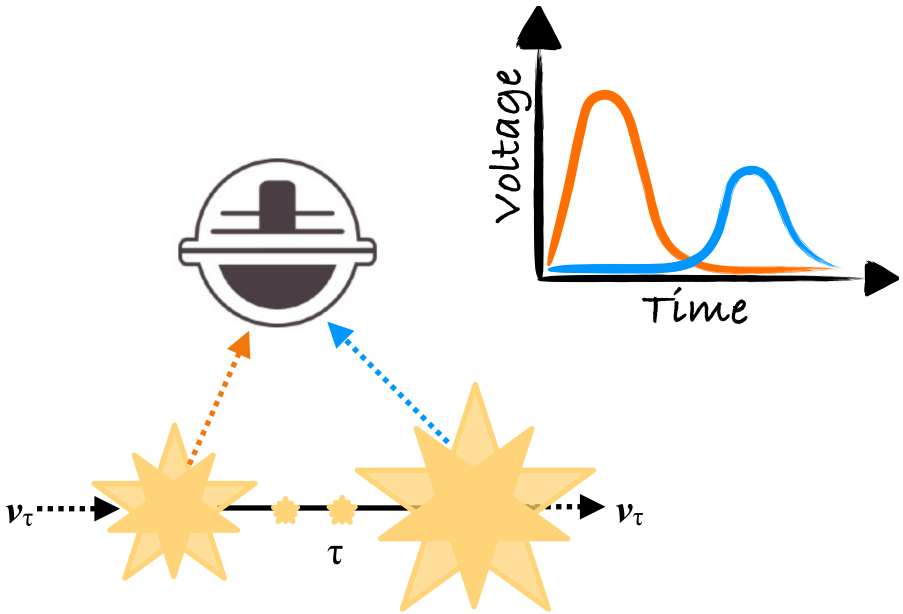


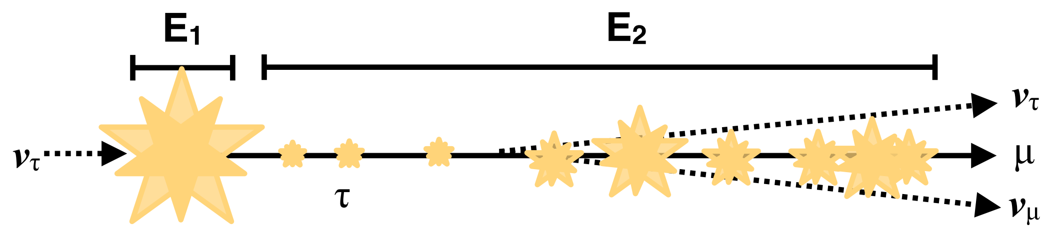
- 2 energy depositions, typically with small distances, identified on one PMT*
- Only created for events with both energy losses close to PMT
- Needs time-binned readout

\+ Can in principle have lower length end energy threshold

− Depends highly on event happening close to PMT
Background: muons create Double Pulses
No reconstruction, just identification of interesting events

*M. Aartsen et al., PRD 93 (2016)

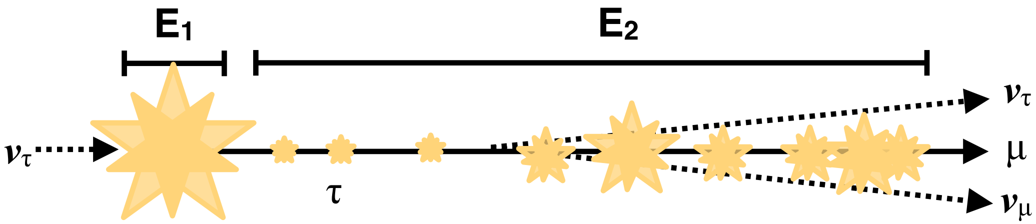
Starting Tracks



- Inelasticity distribution different for ν_τ than ν_μ*
- Statistic method to measure contributions to starting tracks

*M. Aartsen et al., PRD 99 (2019)

Starting Tracks



See talk by Spencer Klein

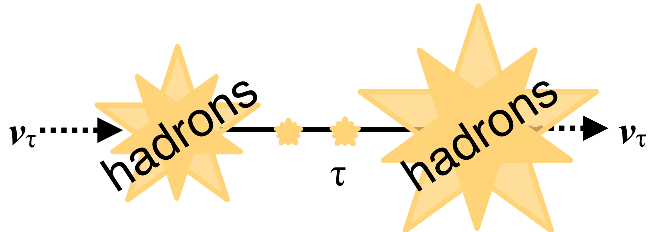
- Inelasticity distribution different for ν_τ than ν_μ*
- Statistic method to measure contributions to starting tracks

+ Low energy threshold

− Indirect method, limited sensitivity to ν_τ
  Relies on good modeling of energy losses
  Low branching fraction

*M. Aartsen et al., PRD 99 (2019)

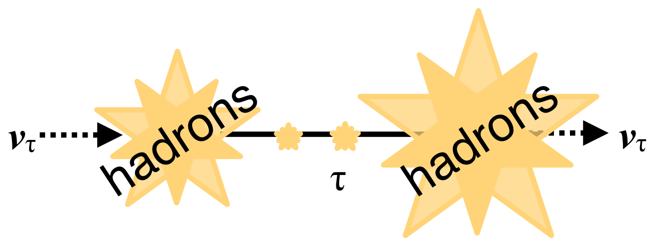
Echoes[1]



- Hadronic cascade contains muons and neutrons
- Muons decay, neutrons get captured on H
- Search for afterglows[1,2]

1. S. Li et al., PRL 123 (2019)
2. A. Steuer, PoS(ICRC2017) 1008
3. A. Pollmann, PoS(ICRC2021) 1093

Echoes[1]



- Hadronic cascade contains muons and neutrons
- Muons decay, neutrons get captured on H
- Search for afterglows[1,2]

\+ Low energy threshold

\- Indirect method, NC cascades are also hadronic
Relies on good modeling of energy losses & medium properties[2], e.g. luminescence[3]
Late data typically not saved

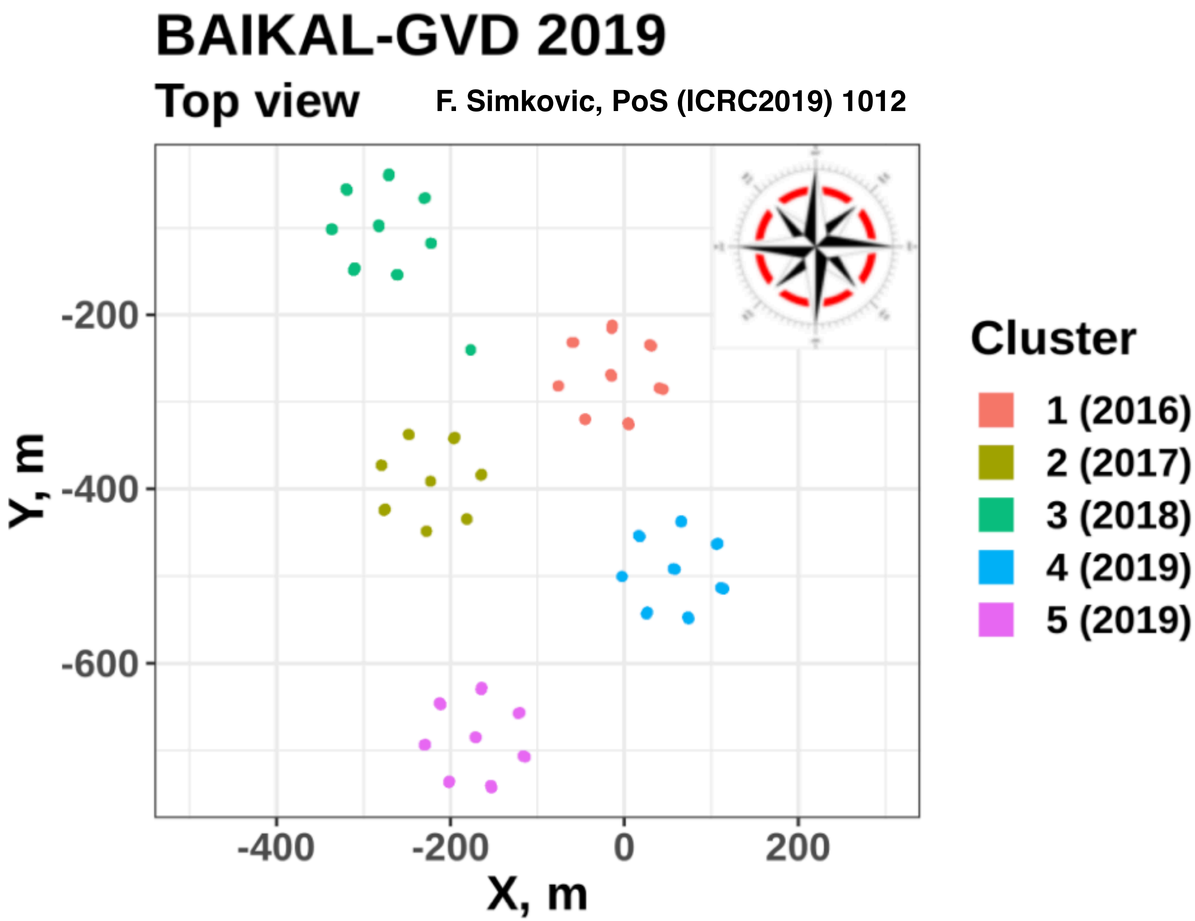
1. S. Li et al., PRL 123 (2019)
2. A. Steuer, PoS(ICRC2017) 1008
3. A. Pollmann, PoS(ICRC2021) 1093

Current Status

- **IceCube**:
  - ~1km^3 instrumented volume, 10 years of full operations
  - 0 Double Bangs, 2 Double Cascades[1], 2 Double Pulses[2,3]
  - Enhanced Double Pulse analysis in pipeline
- **Baikal GVD**:
  - under construction, 8 clusters of 8 strings installed, 0.4km^3
  - 1 Double Bang[4]
  - Double Cascade and Double Pulse methods tested on simulation[4]
- **KM3NeT / ARCA**:
  - under construction, 9 DUs (strings) installed - 3 this month!
  - Double Cascade reconstruction method tested on simulation[5]

1. JS, PoS(ICRC2019) 1015
2. D. Xu, L. Wille, PoS(ICRC2019) 1036
3. M. Meier, J. Soedingrekso, PoS(ICRC2019) 960
4. Eeden et al., PoS(ICRC2021) 1089
5. E. Eckerova, PoS(ICRC2021) 1167

Caveat: Sparse Layout



- Double Bang: two cascades in two clusters
- Signature can be mimicked by horizontal muon
- Sparse layout: blind spots (will improve with more clusters)

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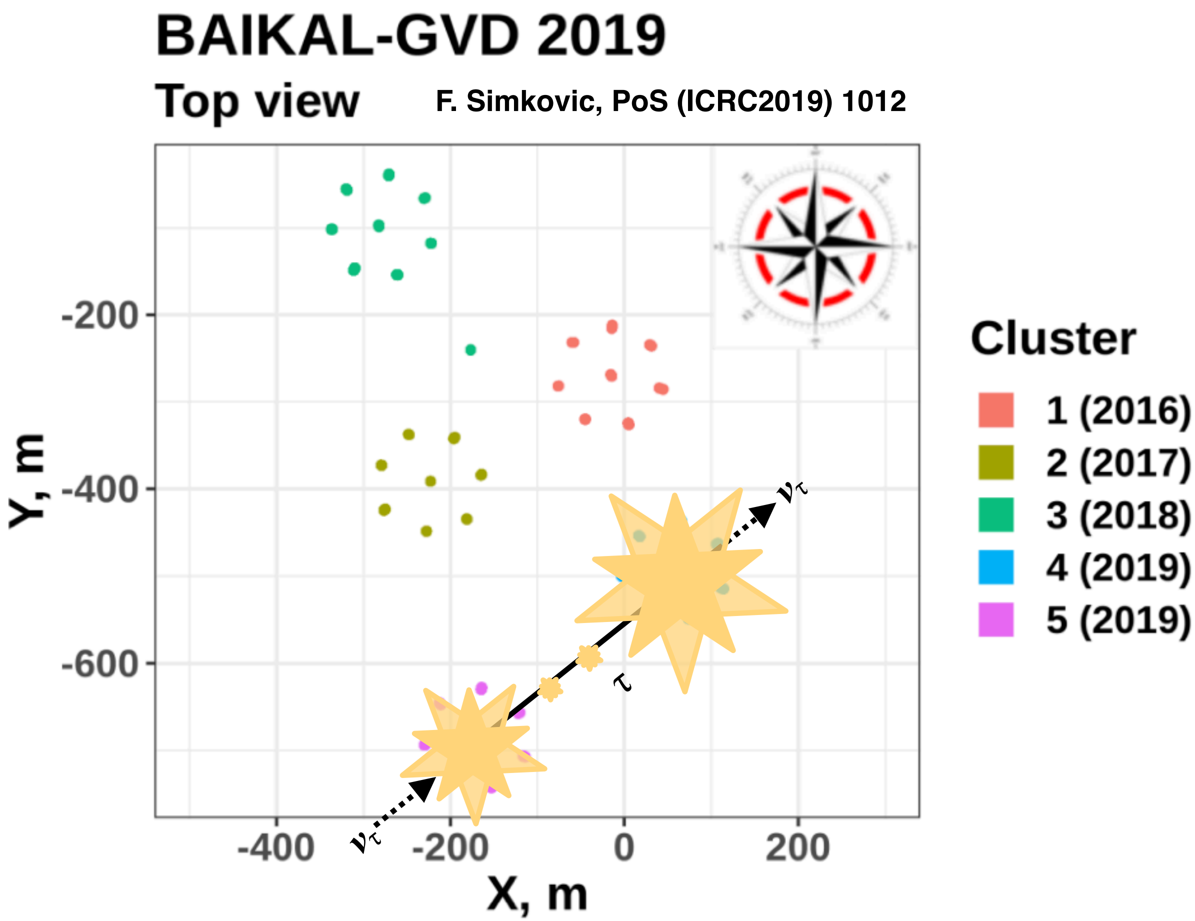

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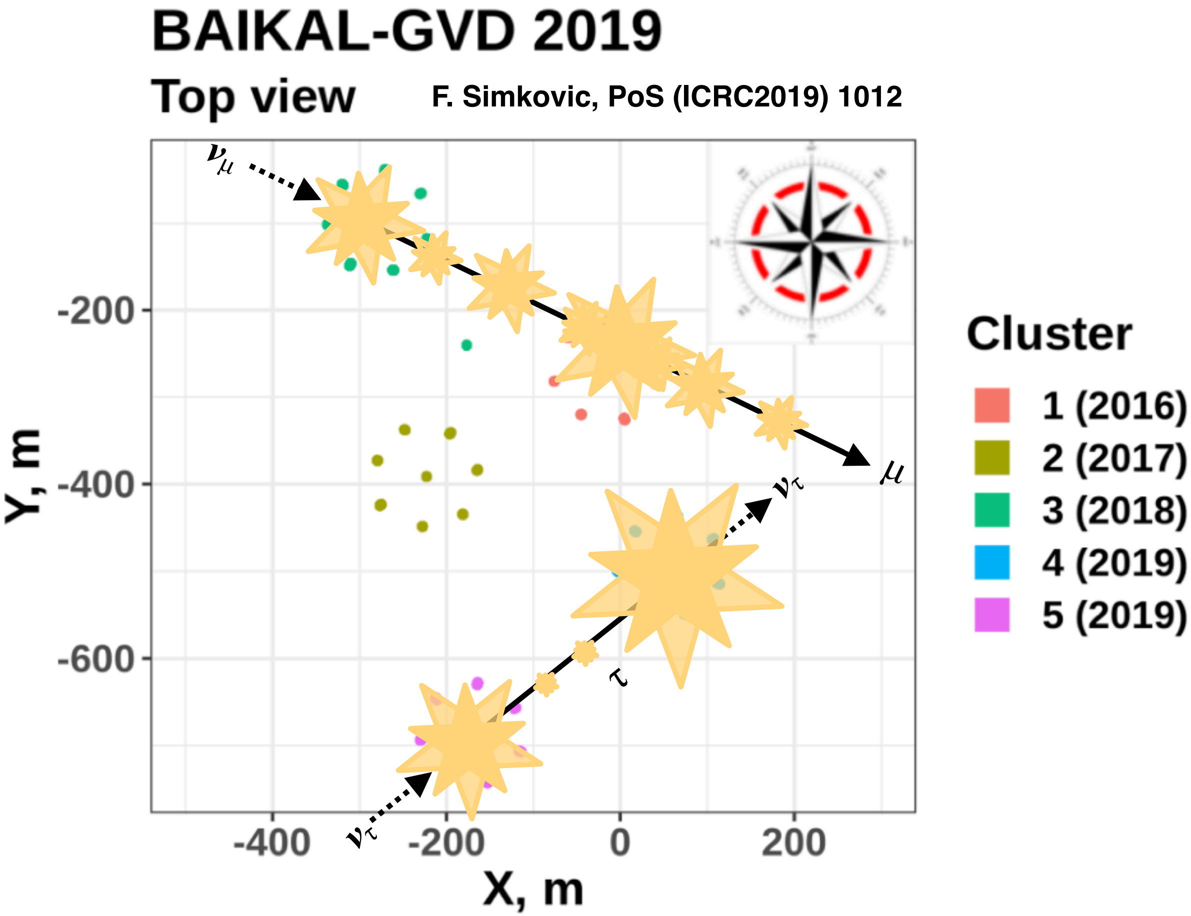

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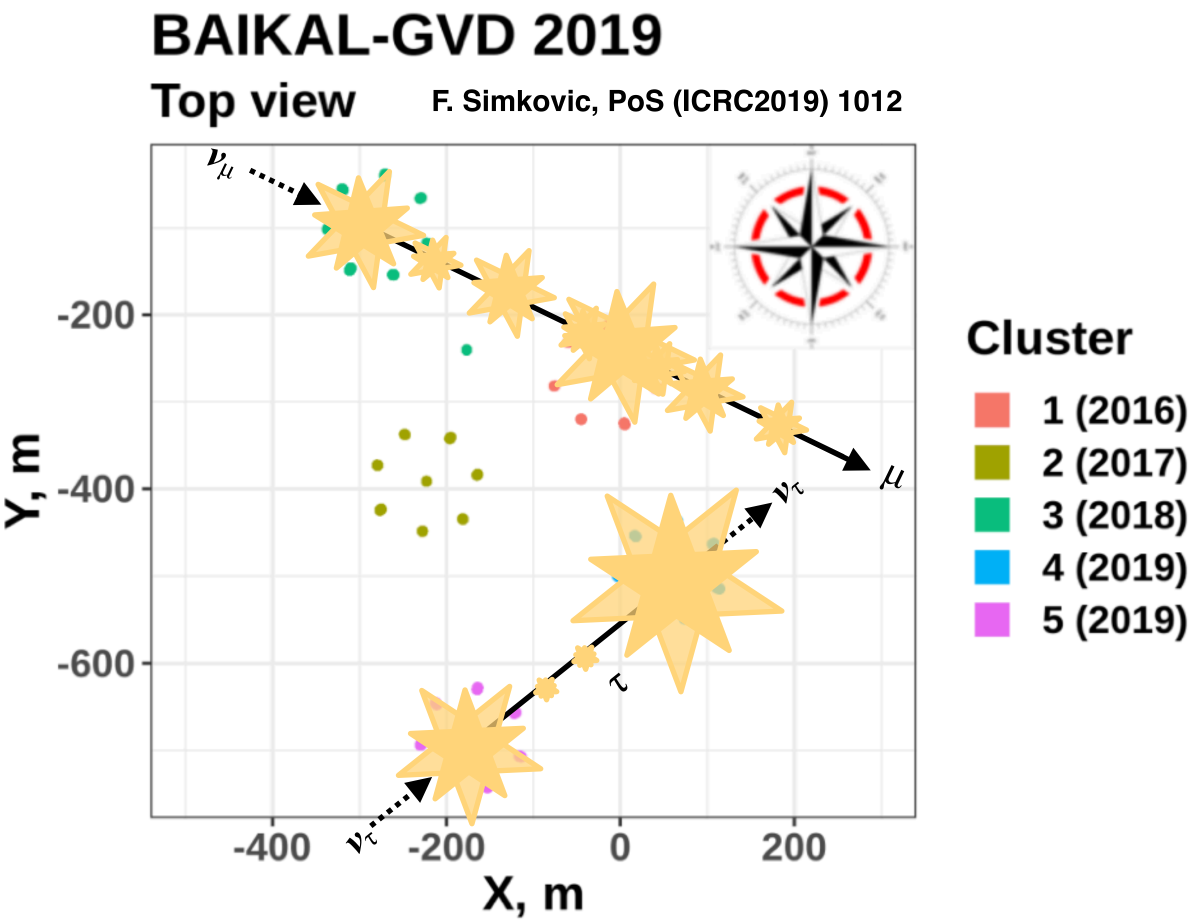

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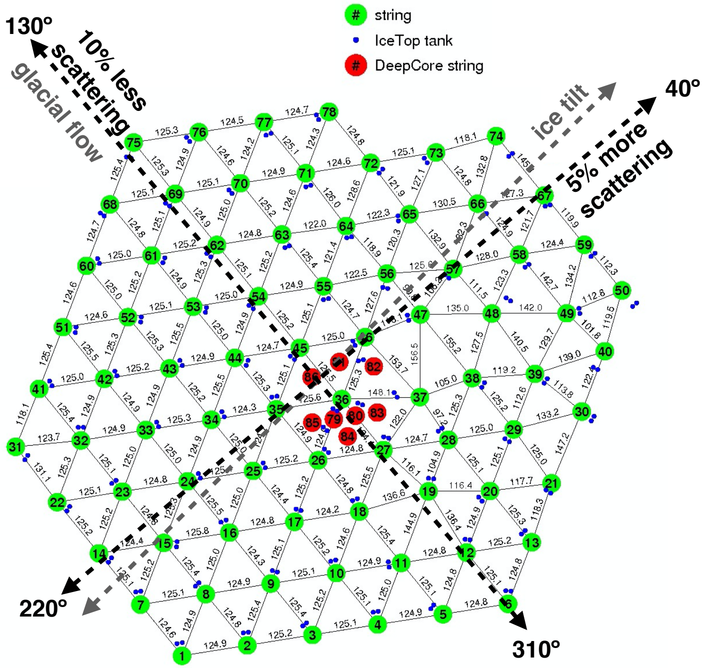
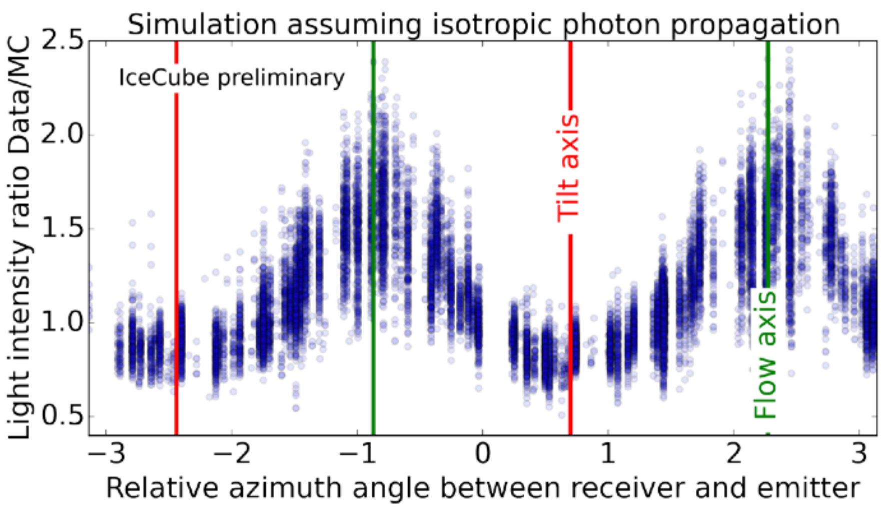
Baikal-GVD: E_1 = 8 TeV, E_2 = 4.7 TeV, L = 330m. Not a ν_τ.*

*E. Eckerova, PoS(ICRC2021) 1167

Caveat: Photon Propagation



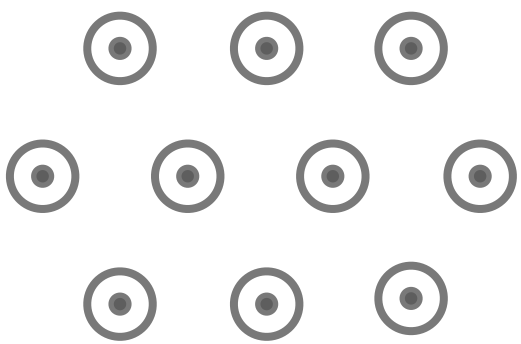


D. Chirkin, M. Rongen, PoS(ICRC2021) 1119

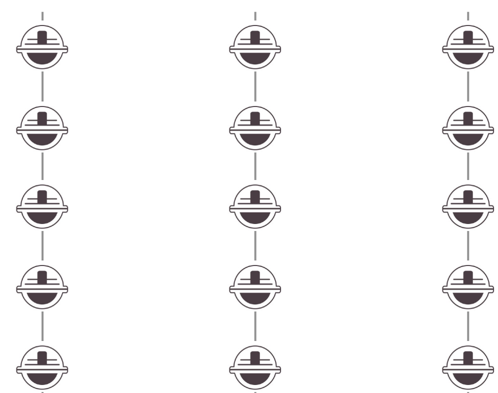
- IceCube: natural glacier
- Photons propagate further along glacial flow
- Can lead to cascade elongation
- Layers tilted, "dust" layer
- Reconstruction: isotropic photon propagation

Caveat: Photon Propagation

- Can’t break symmetries of photon propagation
- But can assume detector to be stretched*!



Anisotropy



Tilt

*M. Usner, PhD thesis (2018)

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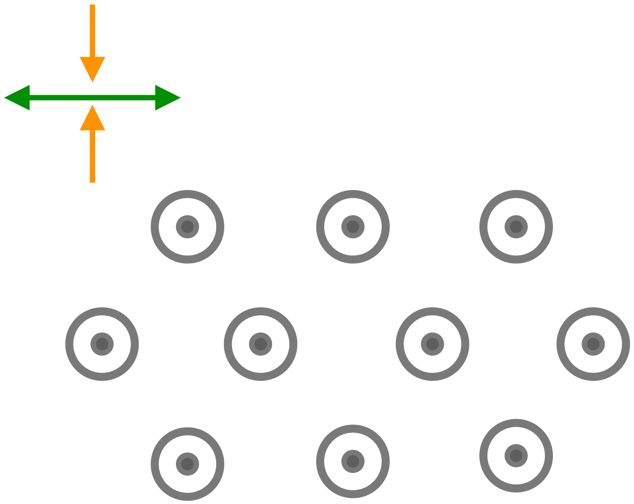

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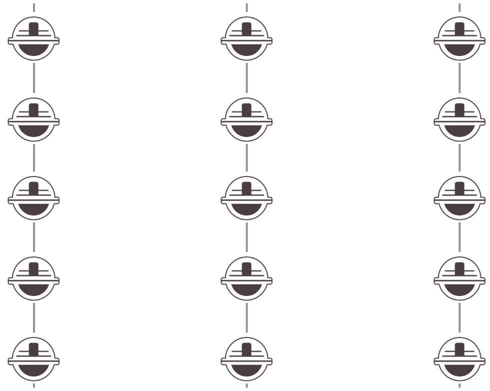

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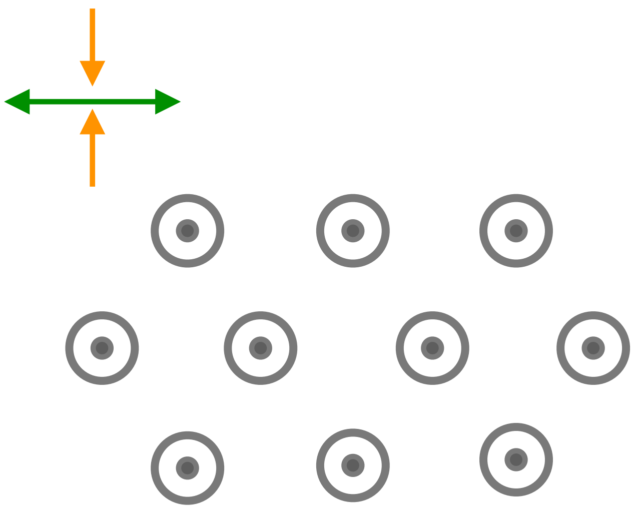

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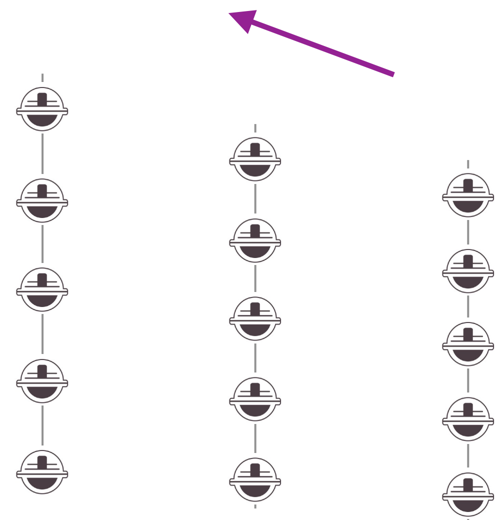

Tilt

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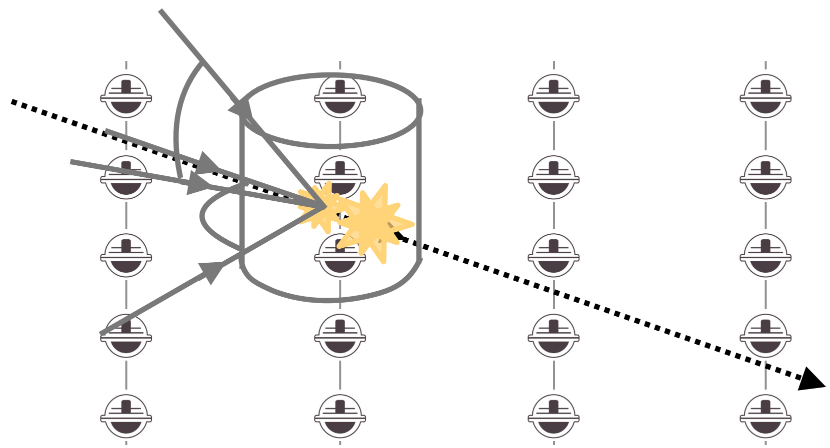
Follow-up: Targeted MC Method

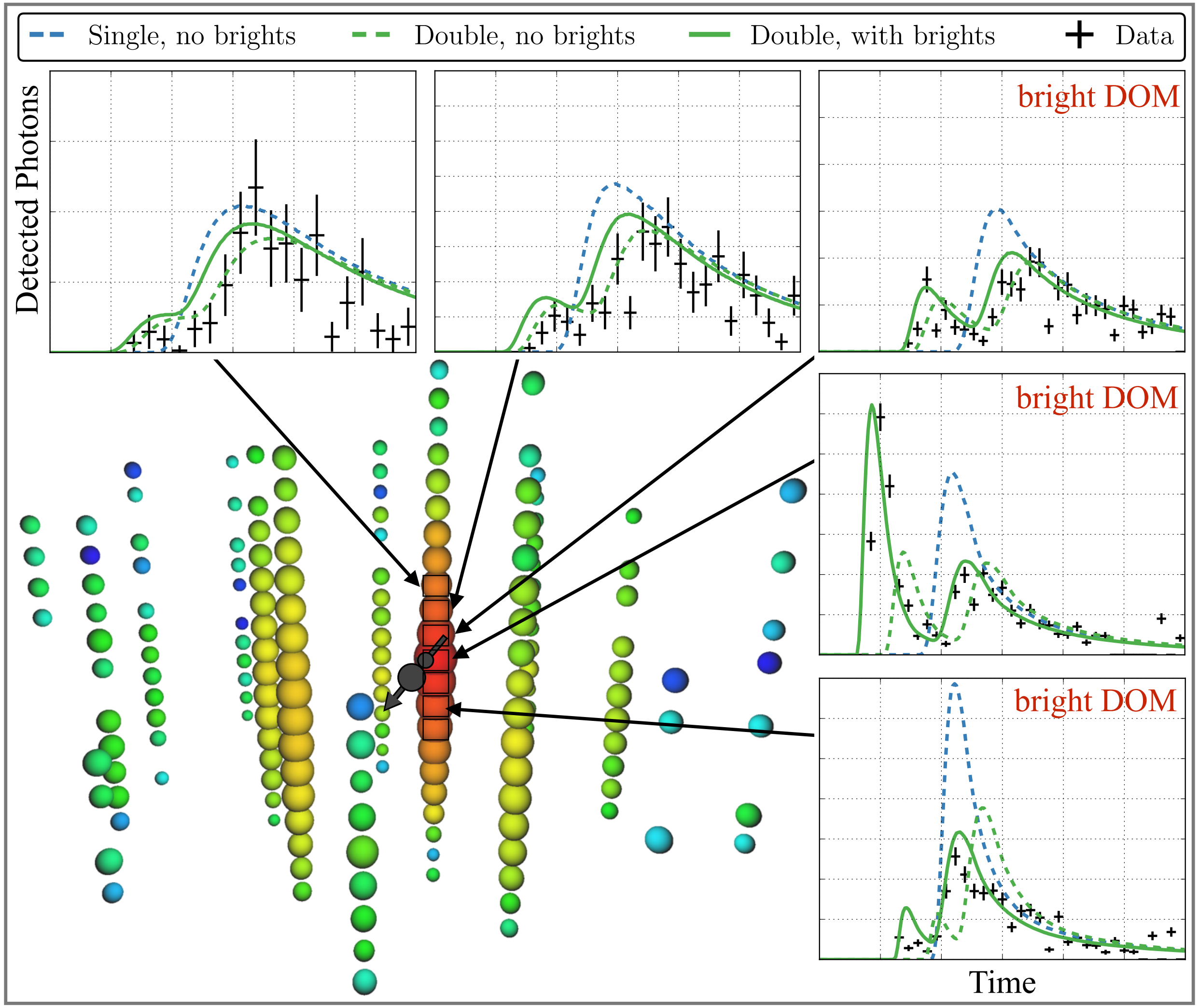
- Targeted MC production for ν_τ candidates in restricted parameter-space (energy, direction, interaction vertex) as
  - ν_e, ν_μ, ν_τ
  - atmospheric μ (Double Cascade)
- Double Cascade: Evaluation using multidimensional KDE,
  DC #1: ~75% likely ν_τ, 25% likely ν_e
  DC #2: ~98% likely ν_τ[1]
- Double Pulse: count number of events passing Double Pulse selection, using $E^{-2.5}$ spectrum & ice model variations
  best DP: >90% likely ν_τ[2]

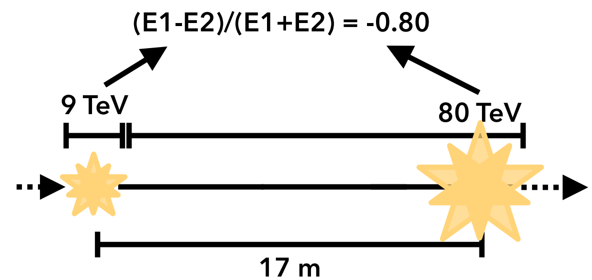


Rare events need targeted simulation!

1. R. Abbasi et al., arXiv:2011.03561
2. W. Tian et al., PoS(ICRC2021) 1146

First astrophysical ν_τ: Double Double



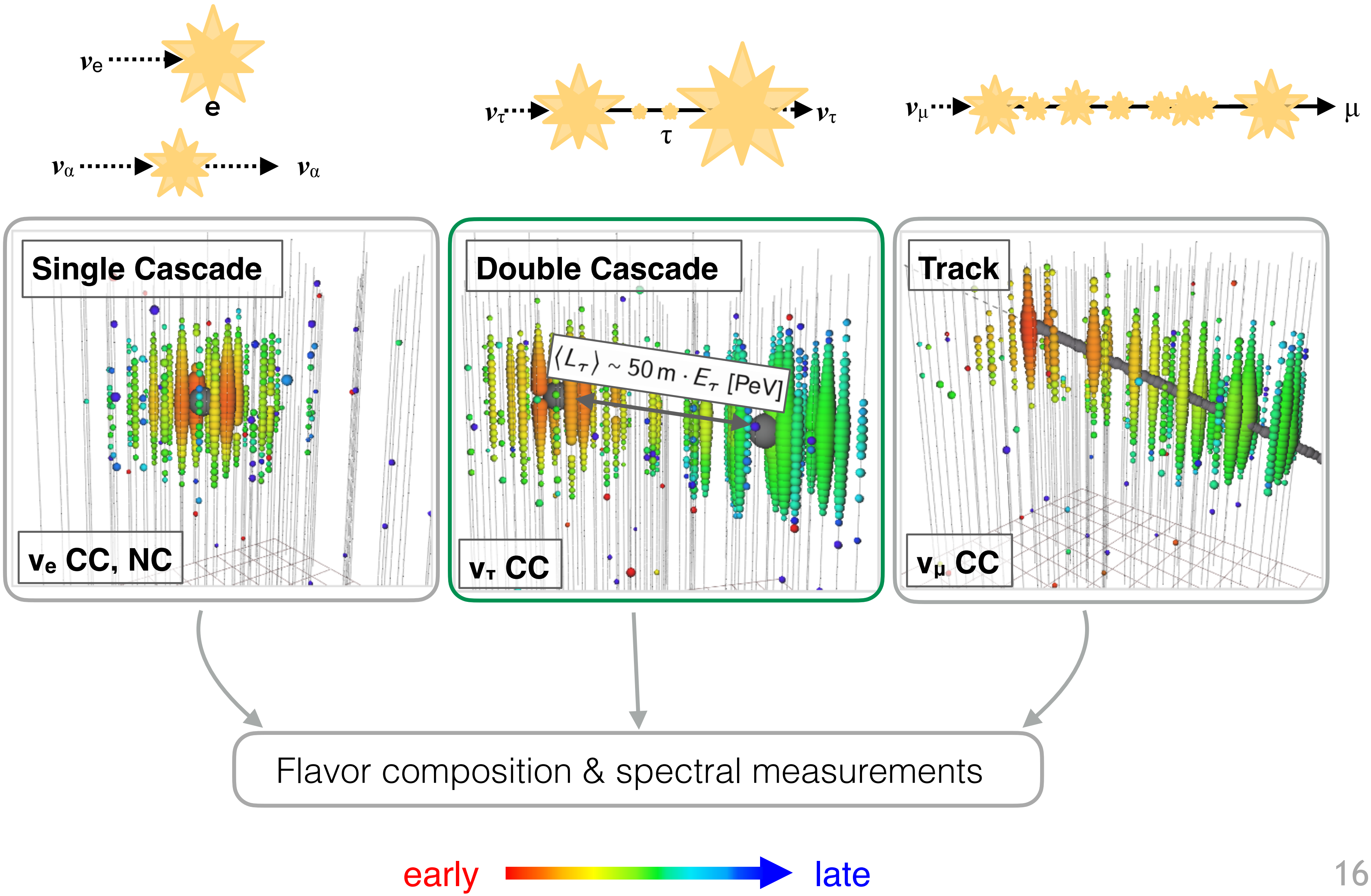


- Observed 2014
- Found in complementary Double Cascade and Double Pulse searches
- Independent follow-up analyses confirm likely ν_τ origin, with different systematics, backgrounds etc.

R. Abbasi et al., arXiv:2011.03561

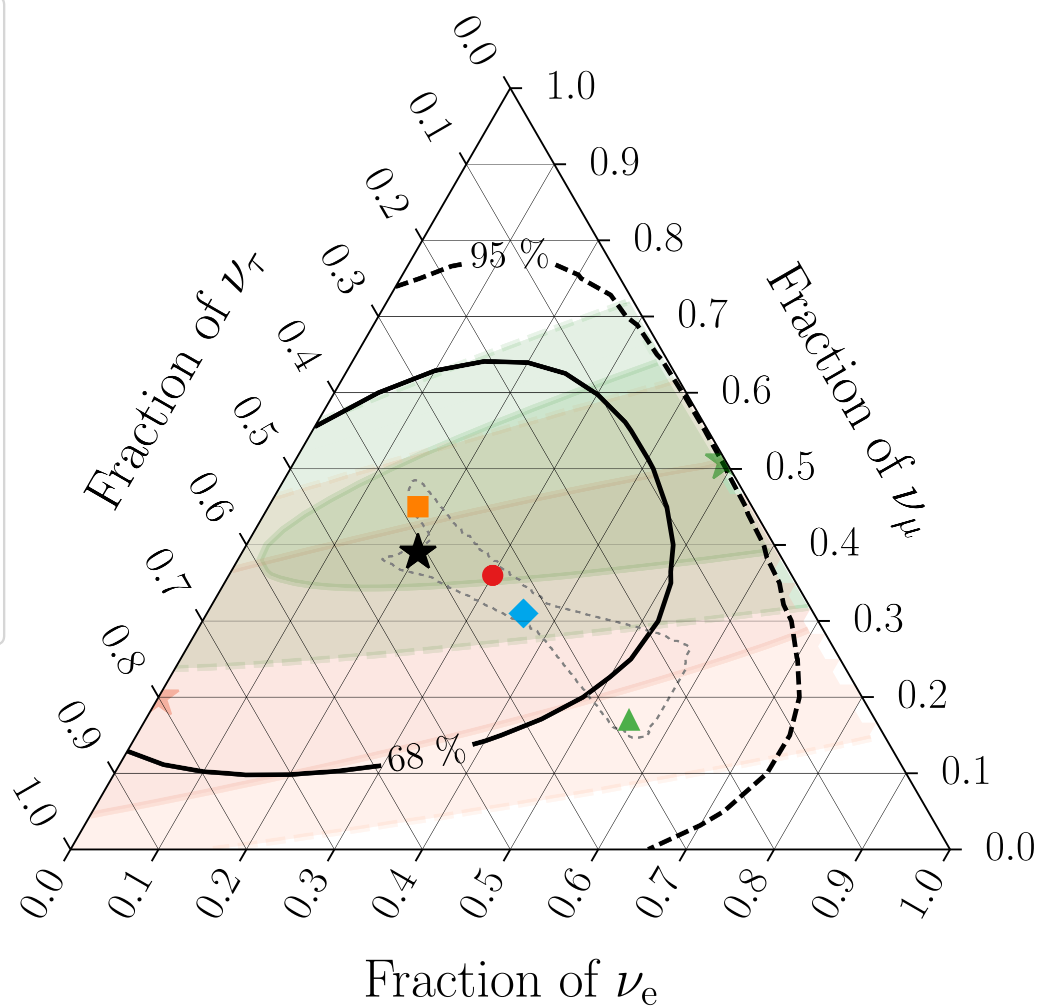
early → late

Flavor Composition Measurement



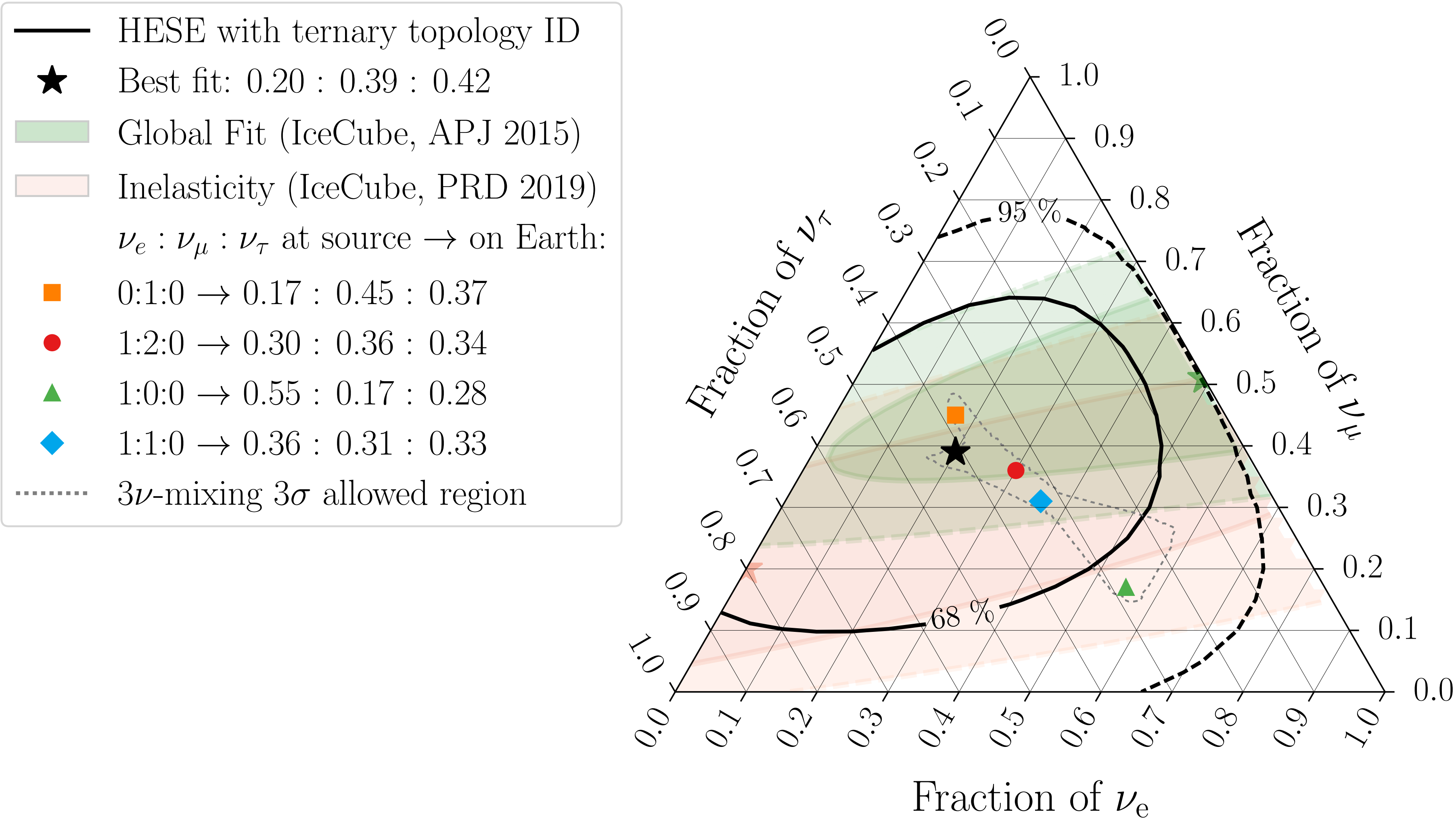
Neutrino Flavor Composition

- HESE with ternary topology ID
- ★ Best fit: 0.20 : 0.39 : 0.42
- Global Fit (IceCube, APJ 2015)
- Inelasticity (IceCube, PRD 2019)
- $\nu_e : \nu_\mu : \nu_\tau$ at source → on Earth:
  - 0:1:0 → 0.17 : 0.45 : 0.37
  - 1:2:0 → 0.30 : 0.36 : 0.34
  - 1:0:0 → 0.55 : 0.17 : 0.28
  - 1:1:0 → 0.36 : 0.31 : 0.33
- 3ν-mixing 3σ allowed region



R. Abbasi et al., arXiv:2011.03561

Neutrino Flavor Composition

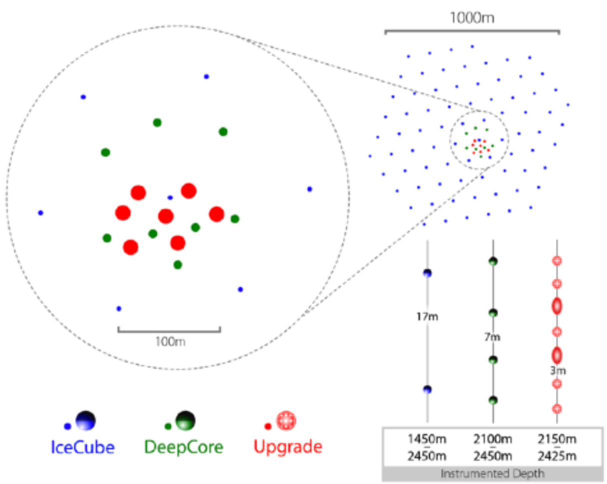


Astrophysical ν_τ flux indicated at 2.8 σ level

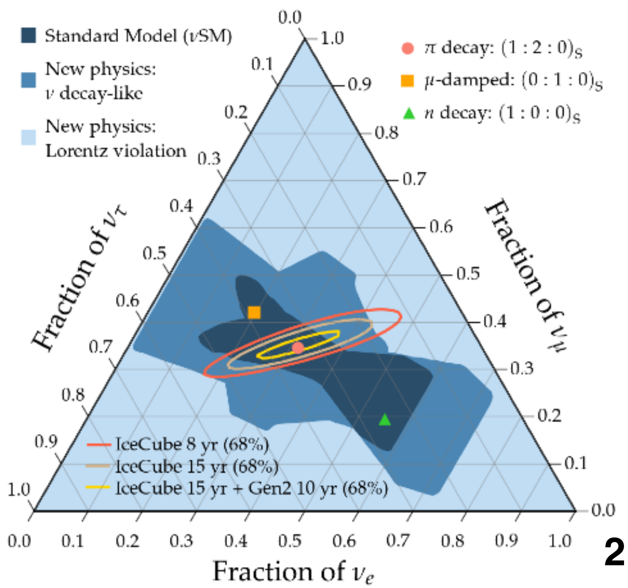
R. Abbasi et al., arXiv:2011.03561

Near-Future Prospects: The 20s

IceCube Upgrade



1



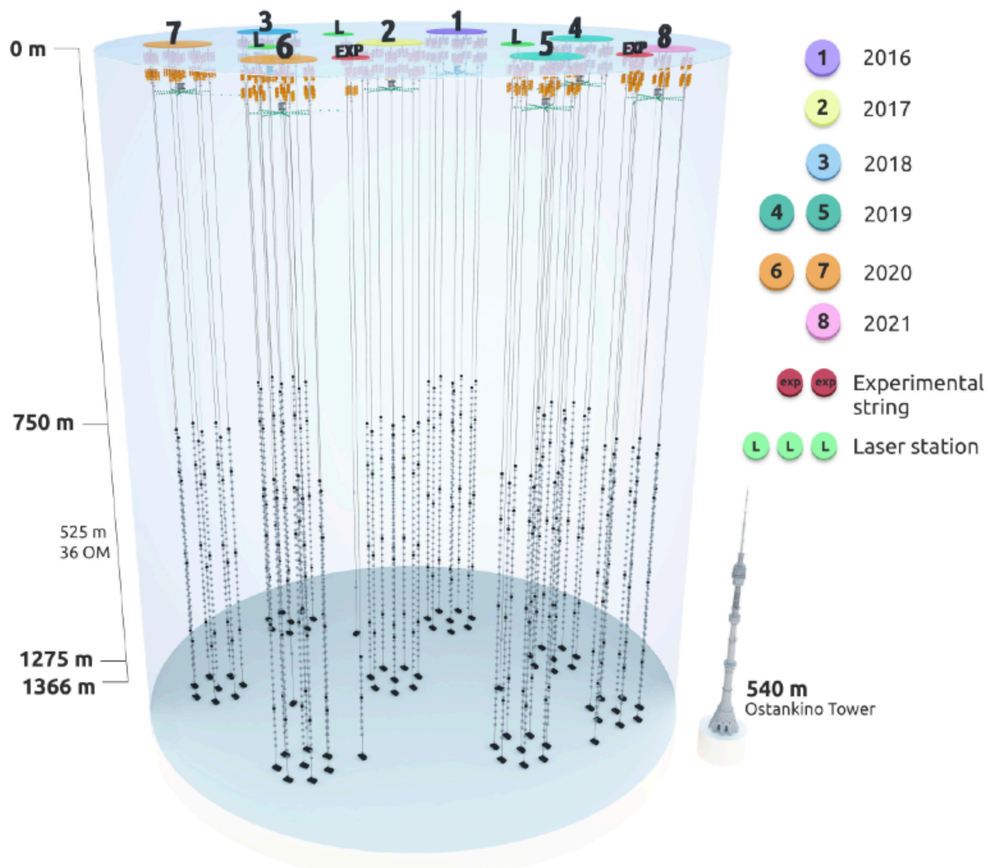
2

- Combination of multiple ν_τ identifiers?
- "Global Fit" of different event selections in a supersample, unified systematics treatment & reconstruction procedures
- Combination of multiple flavor-sensitive features
- Upgrade: new ice model: reduce systematic uncertainty, better ν_τ identification

1. A. Ishihara., PoS(ICRC2019) 1039
2. M. Aartsen et al., J. Phys. G: Nucl. Part. Phys. 48 060501 (2021)

Near-Future Prospects: The 20s

Baikal-GVD

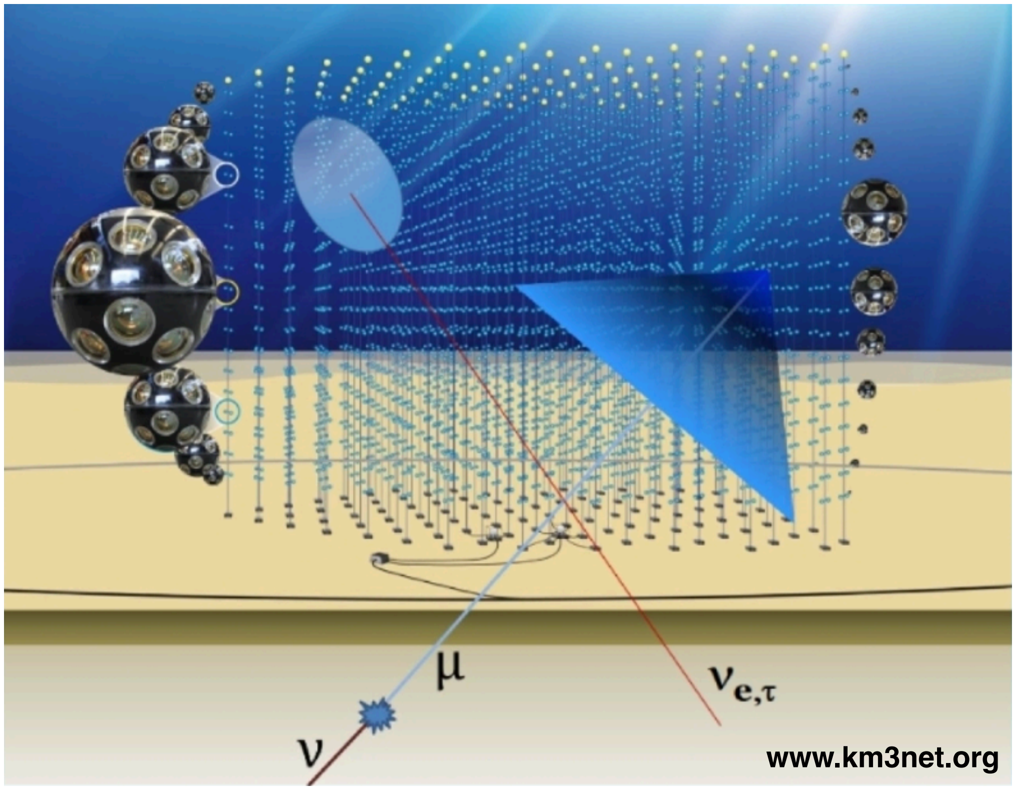


- 14 clusters with 0.8km^3 instrumented volume[1]
- Completion expected ~2024[1]
- Methods and Analyses are being developed
- Changing optical properties of lake water are studied[2,3]
- First results from construction phase

1. I. Belolaptikova, Zh.-A. Dzhilkibaev et al., PoS(ICRC2021) 002
2. E. Ryabov, B. Tarashanski, VLVnT2021
3. E. Eckerova, VLVnT2021

Near-Future Prospects: The 20s

KM3NeT/ARCA

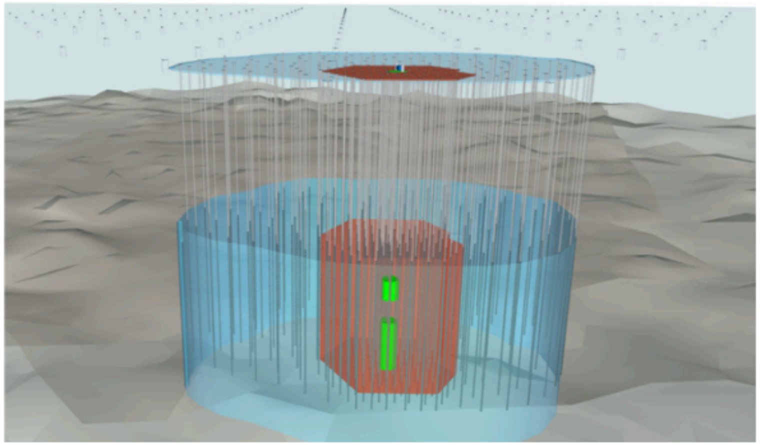


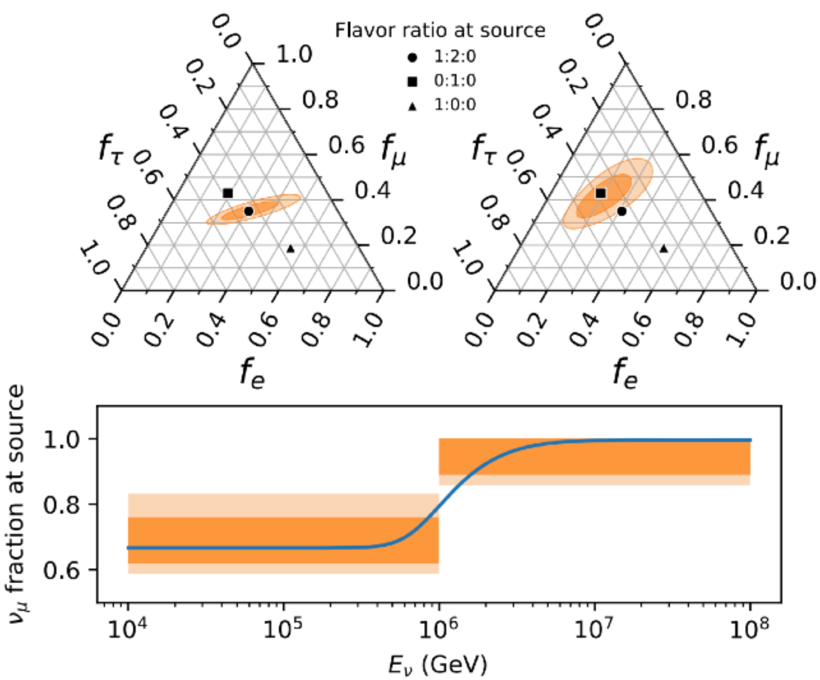
- 2 blocks with 115 DUs and 0.5km^3 instrumented volume each*
- Segmented sensors with directionality*
- Methods and Analyses are being developed
- First results from construction phase

*S Adrián-Martínez et al., J. Phys. G: Nucl. Part. Phys. 43 084001 (2016)

The Next Decade

IceCube-Gen2





- 120 new strings
- Order of magnitude more volume
- At least 5 times more ν_τ expected
- Better, segmented sensors with directionality
- Will be able to find transition in source flavor composition

M. G. Aartsen et al., J. Phys. G: Nucl. Part. Phys. 48 060501 (2021)

The Next Decade

- **KM3NeT/ARCA**: 3rd building block planned
- **Baikal-GVD**: extensions planned
- **P-ONE**: currently pathfinder mission for km^3 experiment

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- Truly global fit to spectrum, flavor?

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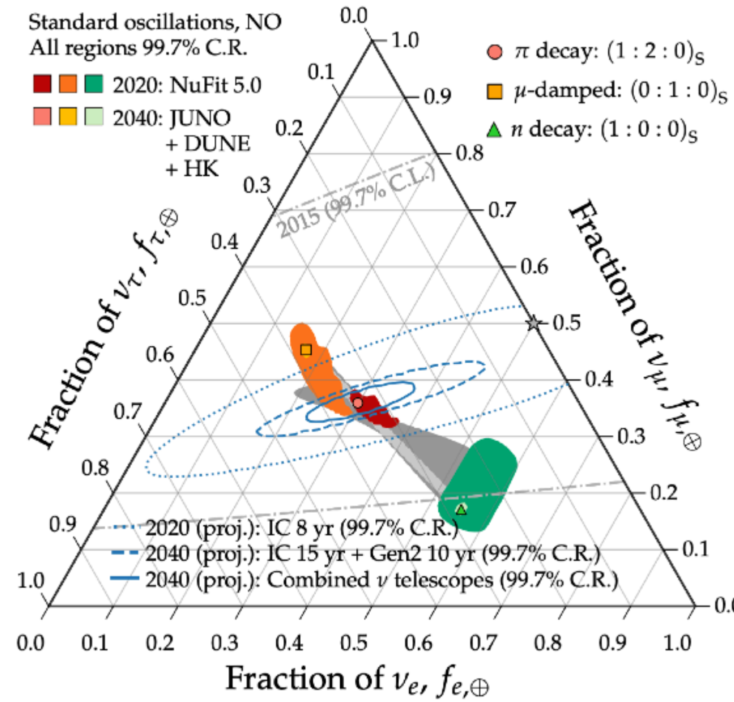

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Song et al., arXiv:2012.12893

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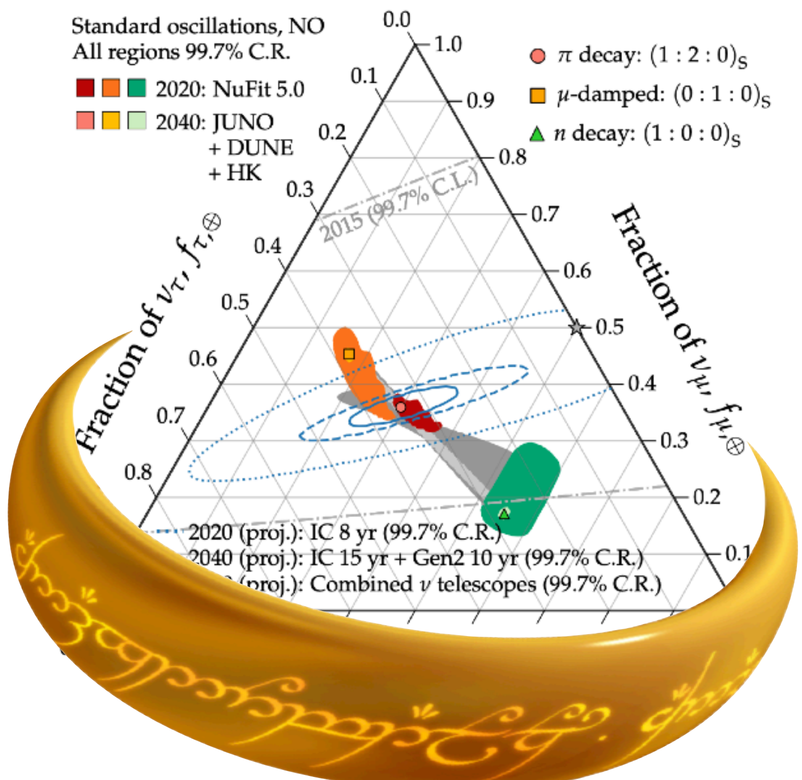

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Takeaway

- Reconstruction of ν_τ signatures is hard
- Currently only sensitive to signatures at high energies / lengths
- First astrophysical ν_τ seen in IceCube, first spectrum measured
- 2 detectors under construction, with ν_τ detection methods being established
- Next years: better understanding of systematic uncertainties, unified treatment of all-flavor, all-topology neutrinos (IceCube + Upgrade)
- Next decade: Combination of several telescopes for precise flavor composition measurement & BSM constraints, ν_τ astronomy, cross-section measurement

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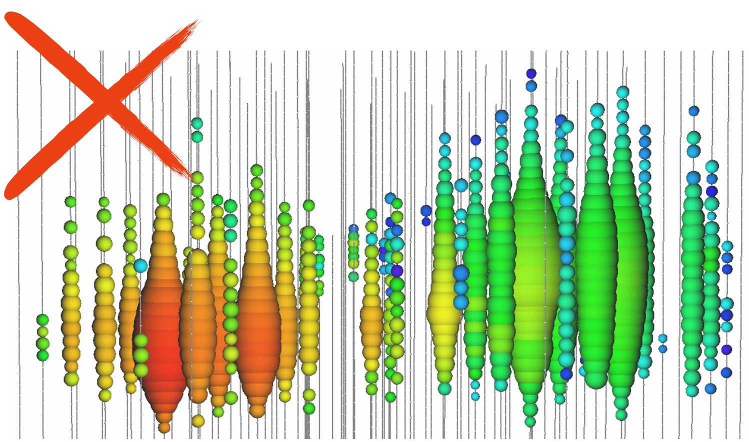

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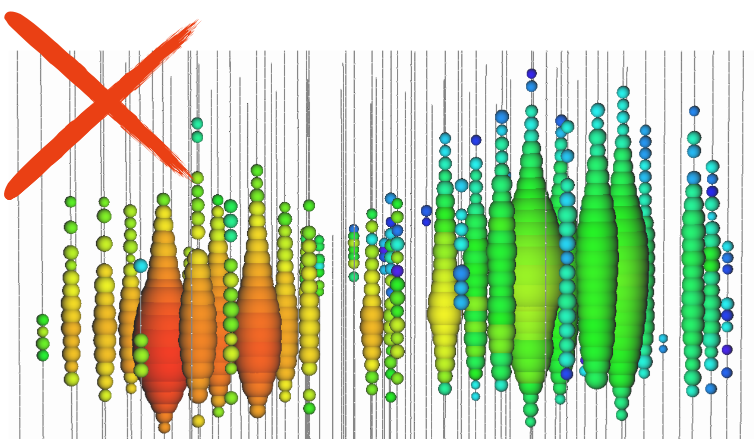
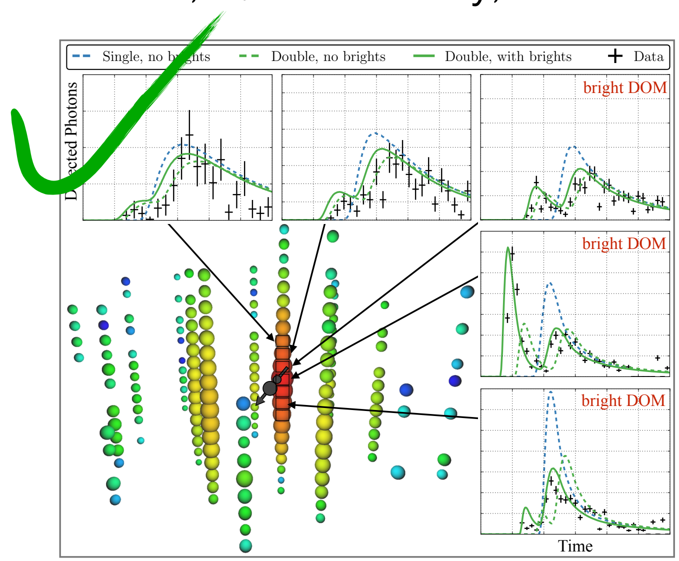
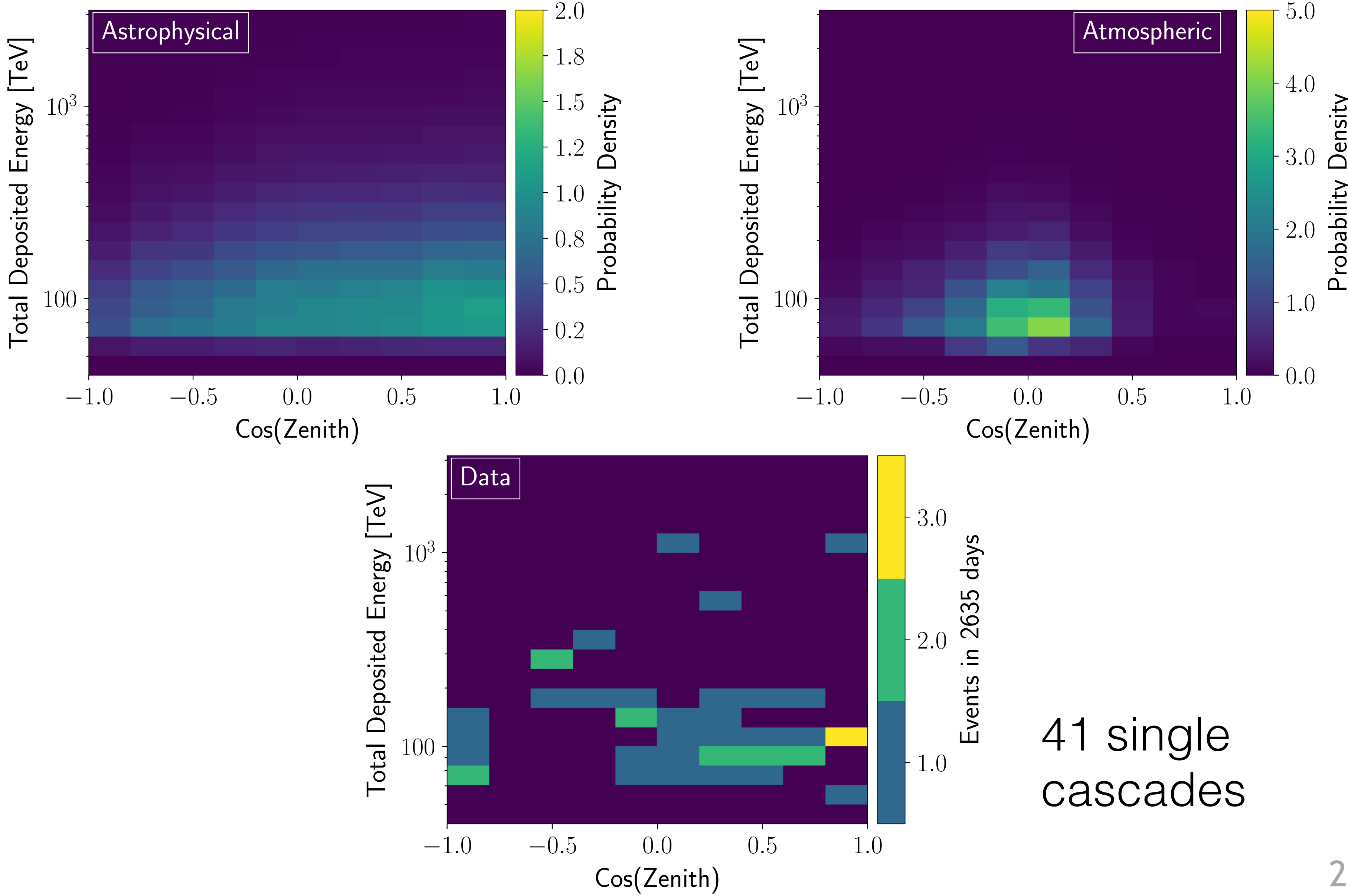




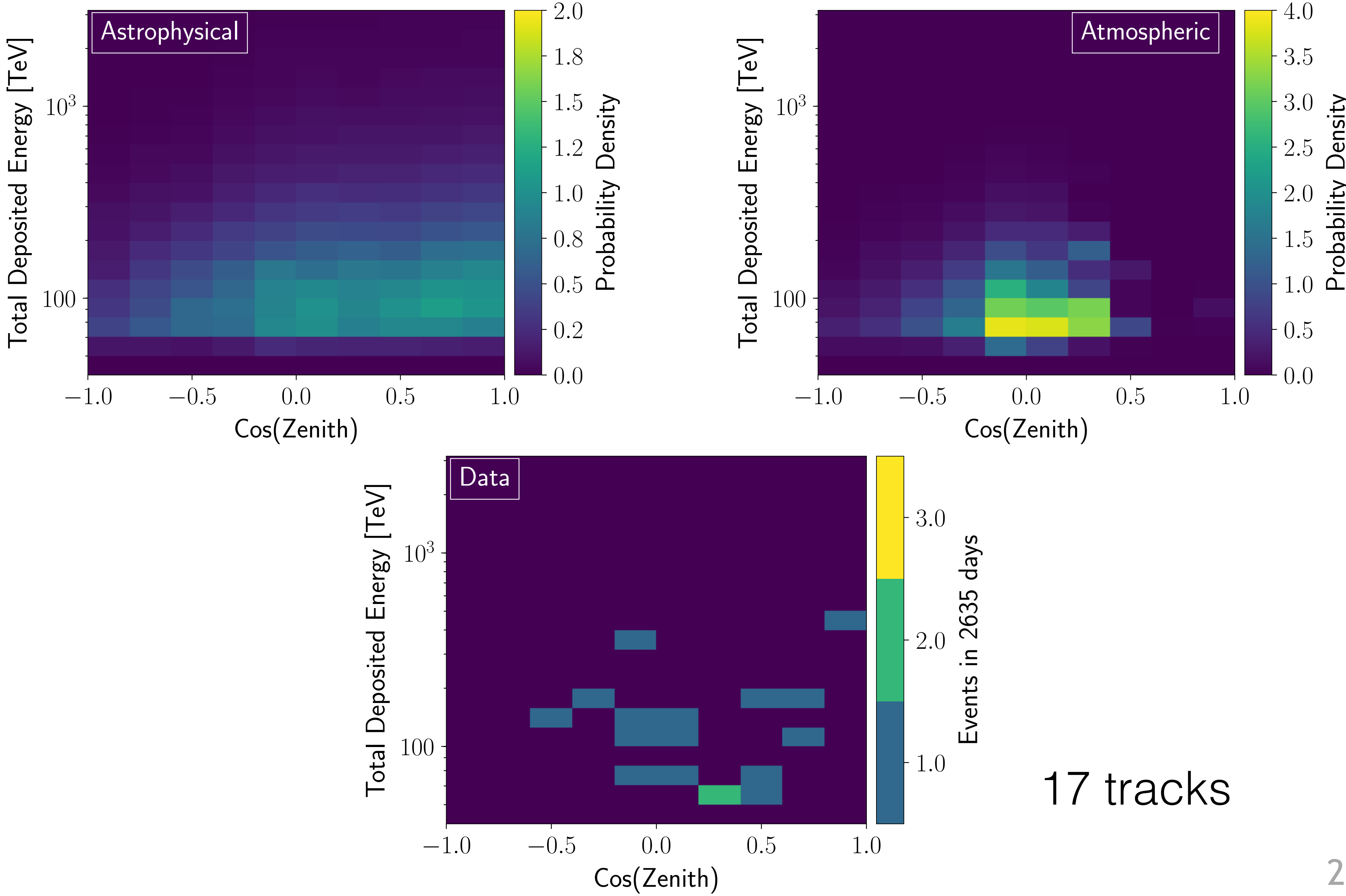
Back up

Single Cascades



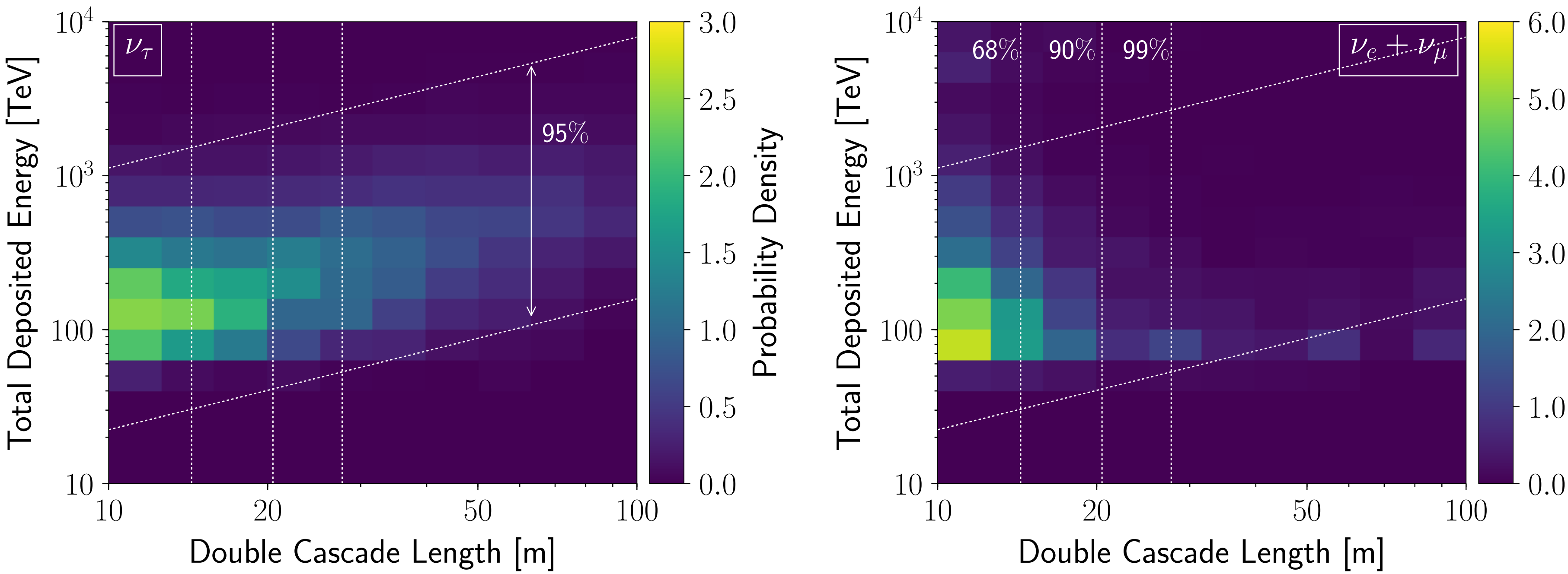
41 single cascades

Tracks



17 tracks

Double Cascades



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1. R. Abbasi et al., arXiv:2011.03561
2. R. Abbasi, PRD 104, 022002 (2021)

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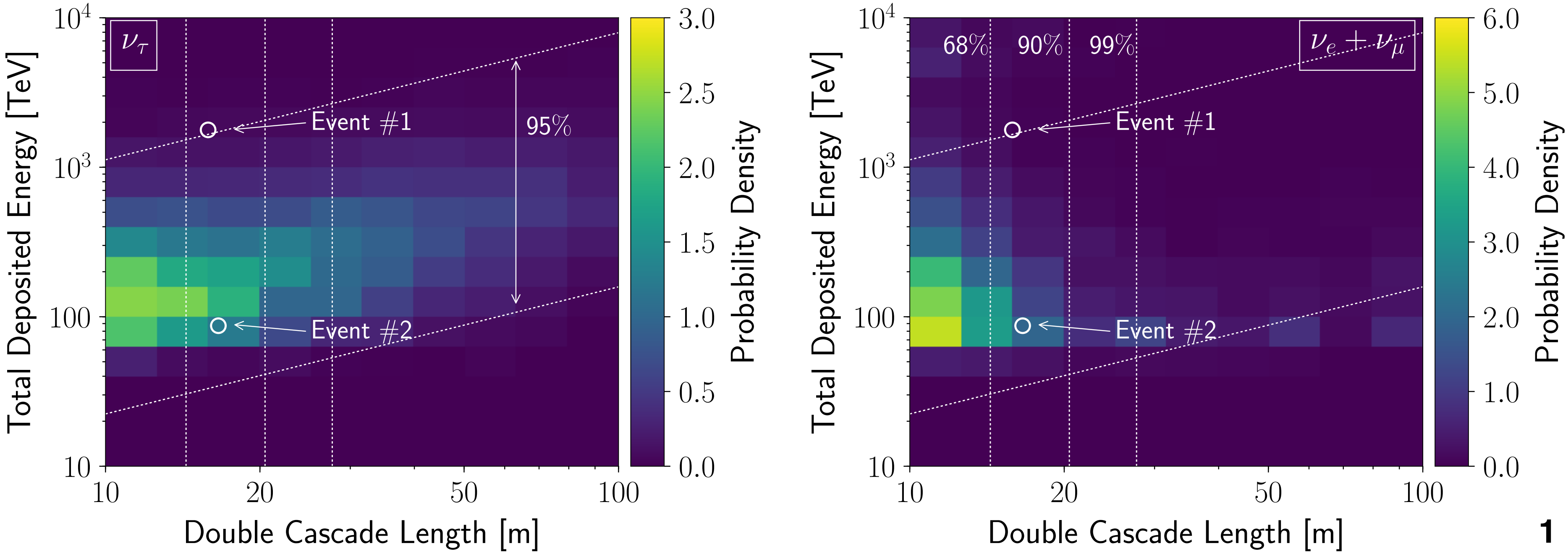

- 2 double cascades
- ν_τ probability: ~0.6 per event, large uncertainties
- At spectral index 2.87, 1:1:1 flavor ratio[2] → expect ~2.3 events (~1.5 signal + ~0.8 background)

1. R. Abbasi et al., arXiv:2011.03561
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