# The IceCube Realtime Program


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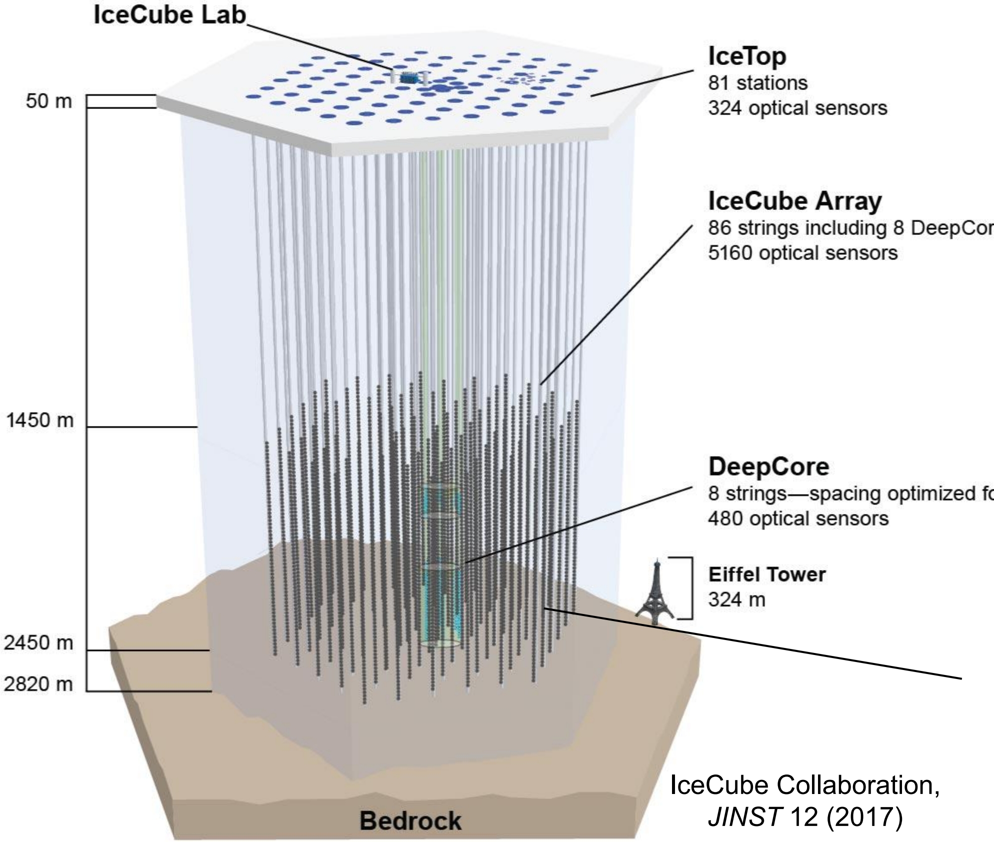
ICECUBE NEUTRINO OBSERVATORY

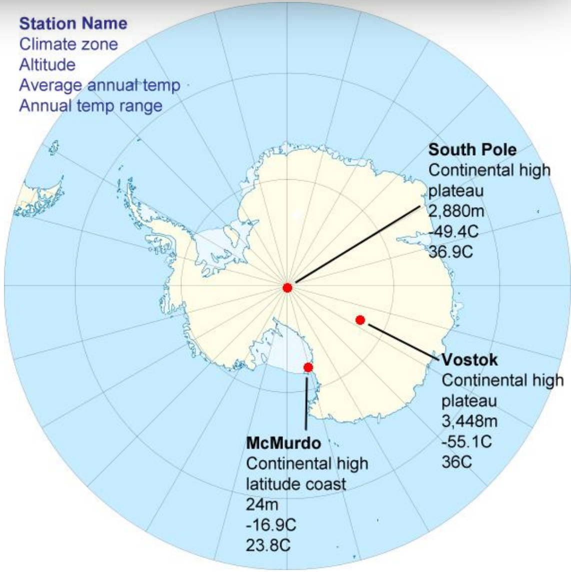
# Summary

- Introduction (what is IceCube? What and how does it detect?)
- The Realtime Alerts
- IC170922A coincidence with TXS 0506+056

# The IceCube Neutrino Observatory




IceCube Collaboration, *JINST* 12 (2017)



Incident neutrino (several TeV)

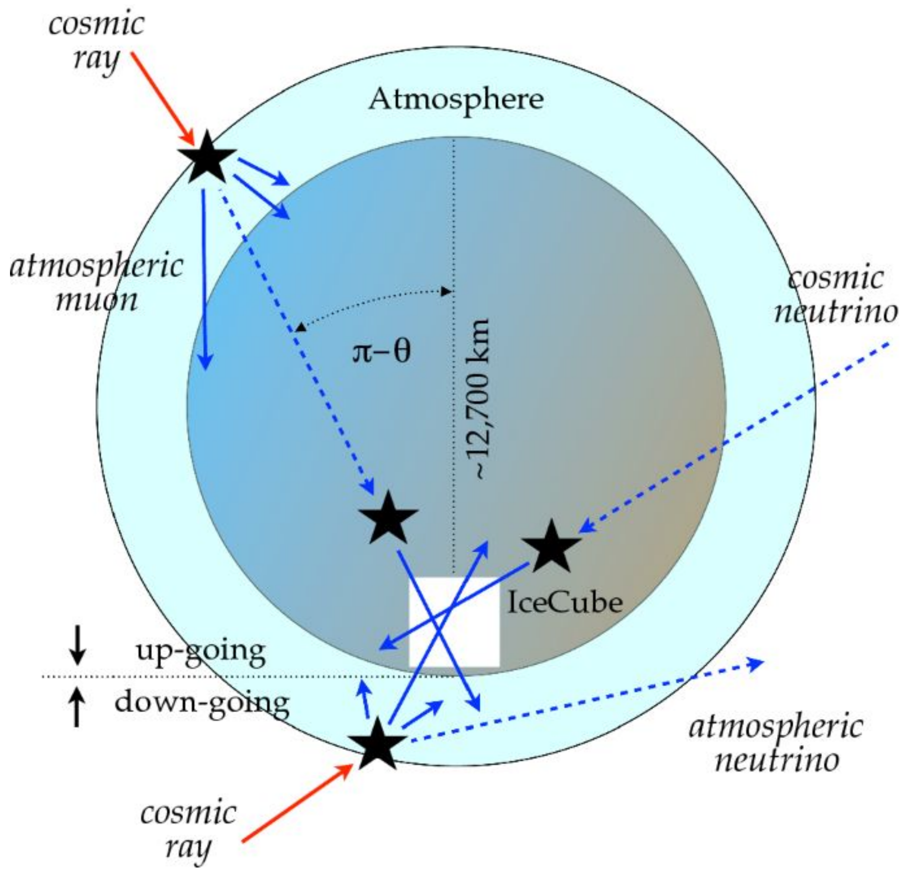
Hadronic cascade (destroyed nucleus)

$$\nu_\ell + N \to X + \ell/\nu_\ell$$

Nucleus in the antarctic ice

- If Charged Current (CC), lepton $\ell$;
- If Neutral Current (NC), neutrino $\nu_\ell$.

$$\ell = \begin{cases} e & \text{Produces electromagnetic cascades} \\ \mu & \text{Best angular reconstructions} \\ \tau & \end{cases}$$

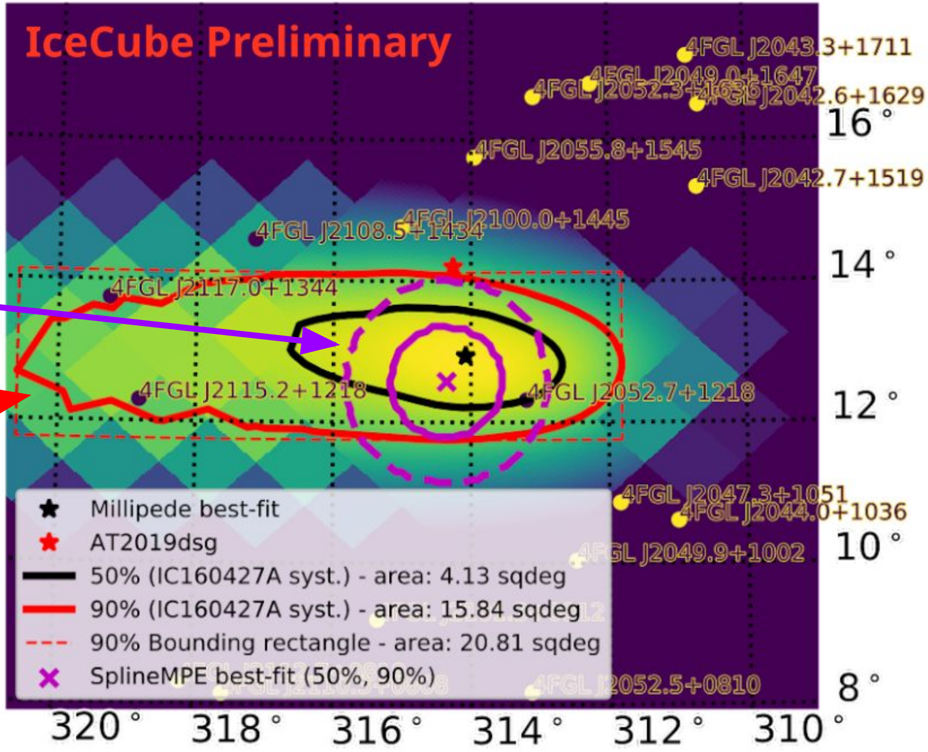



- In 2013, the IceCube collaboration announced the detection of a diffuse astrophysical neutrino flux.
- Origin of these neutrinos is still unknown.
- **Realtime alerts** to identify possible sources. **The angular reconstruction is extremely important.**

# Realtime Alerts,
## current status

Neutrinos with a high probability of being astrophysical.

- <u>First rough estimation</u>:
  - It uses **SplineMPE**, <u>fast and robust</u>).
- <u>Updated alert</u>:
  - It uses **Millipede + likelihood scan**, (<u>slow and very systematics-dependent</u>).




C. Lagunas Gualda and G. Sommani, Presentation, *Presented at the IceCube spring Collaboration meeting* (2022)

Ref: C. Lagunas Gualda et al., *arXiv:2107.08670* (2021)

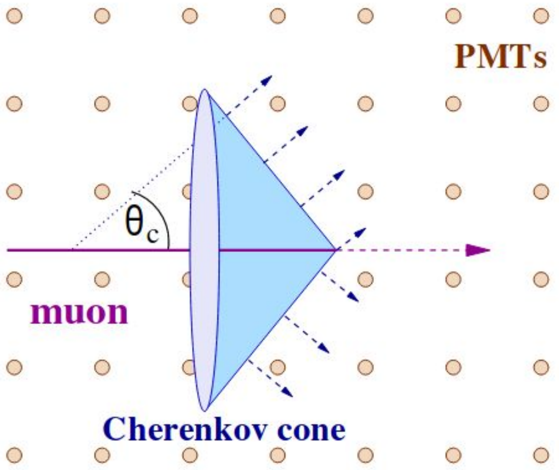
The data consists of **hits** registered by the **Digital Optical Modules (DOMs)**

# SplineMPE

It reconstructs the muon track assuming a continuous emission. **Fast and uses few data.**

Parameters: direction and vertex.

**First update of the realtime alerts. No likelihood scan.**



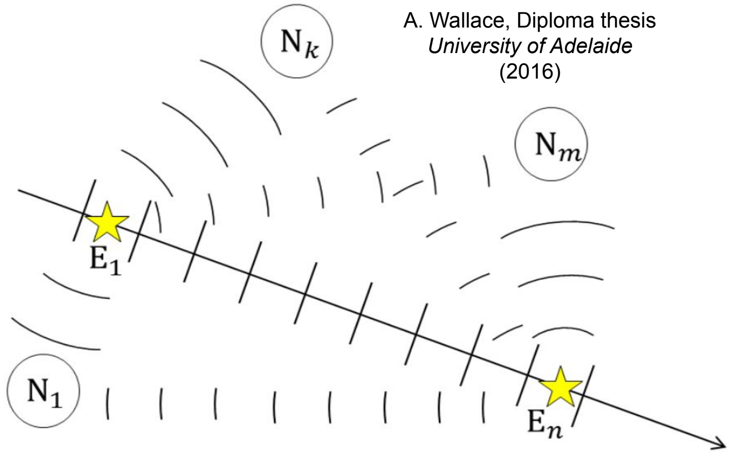

AMANDA Collaboration and J. Ahrens. *Nucl. Instrum.* 524.1-3 (2004)

# Millipede

It reconstructs the muon track assuming a stochastic emission. **Slow and uses a lot of data.**

Parameters: direction, vertex, and energy.

**Second update of the realtime alerts. It uses the likelihood scan**.



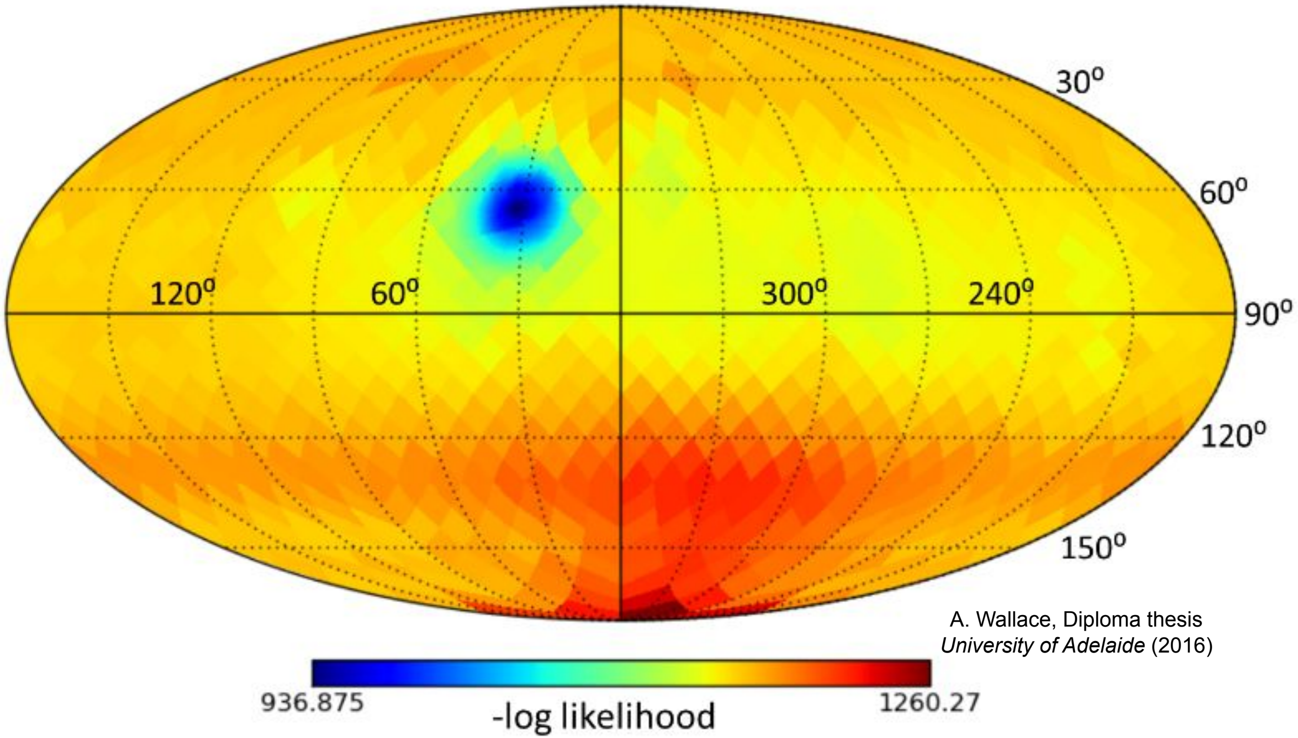

A. Wallace, Diploma thesis *University of Adelaide* (2016)

# The likelihood scan (or likelihood landscape)

Millipede already used it to reconstruct the direction.

I developed it for SplineMPE too.

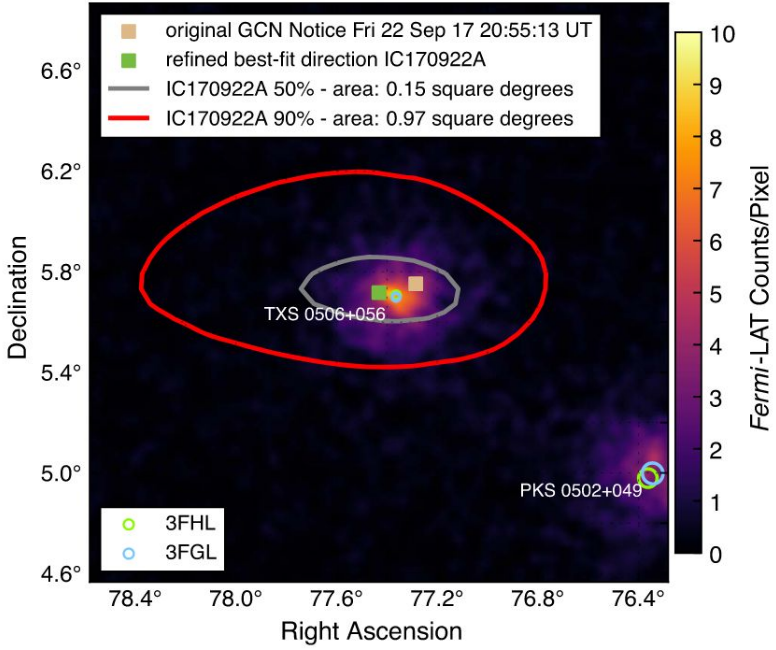
Goal: to compare SplineMPE with Millipede.

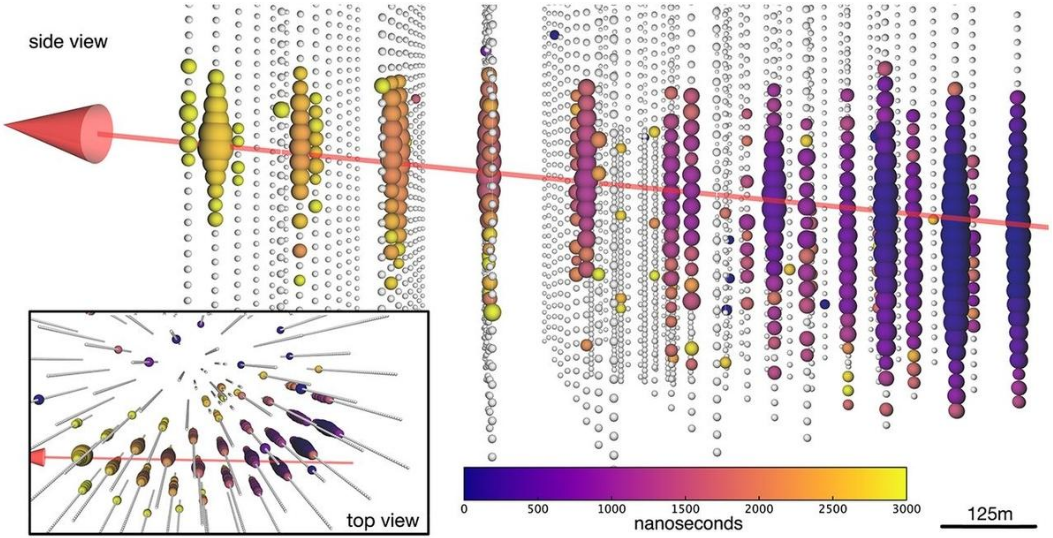



A. Wallace, Diploma thesis
*University of Adelaide* (2016)

# IC170922A
# 290 TeV neutrino

IceCube Collaboration et al.
*Science* 361 (2018), eaat1378.



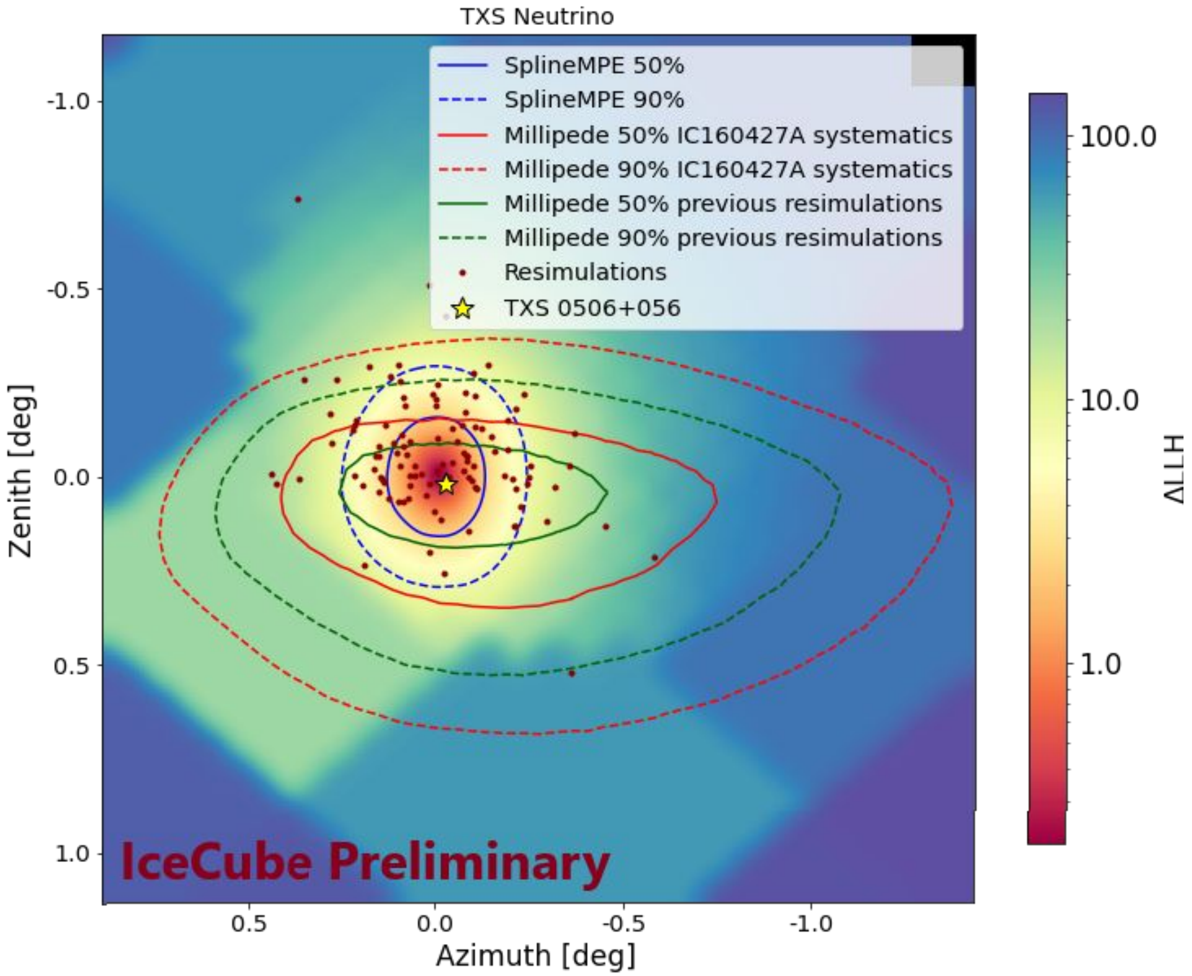




Neutrino coincident with a flaring blazar (TXS 0506+056).

Switching from Millipede to SplineMPE, how would the contours change?

# IC170922A reconstructed with SplineMPE

- Combined SplineMPE with the likelihood scan;
- SplineMPE much more precise than Millipede;
- TXS still in central position.



# Conclusions

- The realtime alerts select neutrinos with a high probability of being astrophysical.

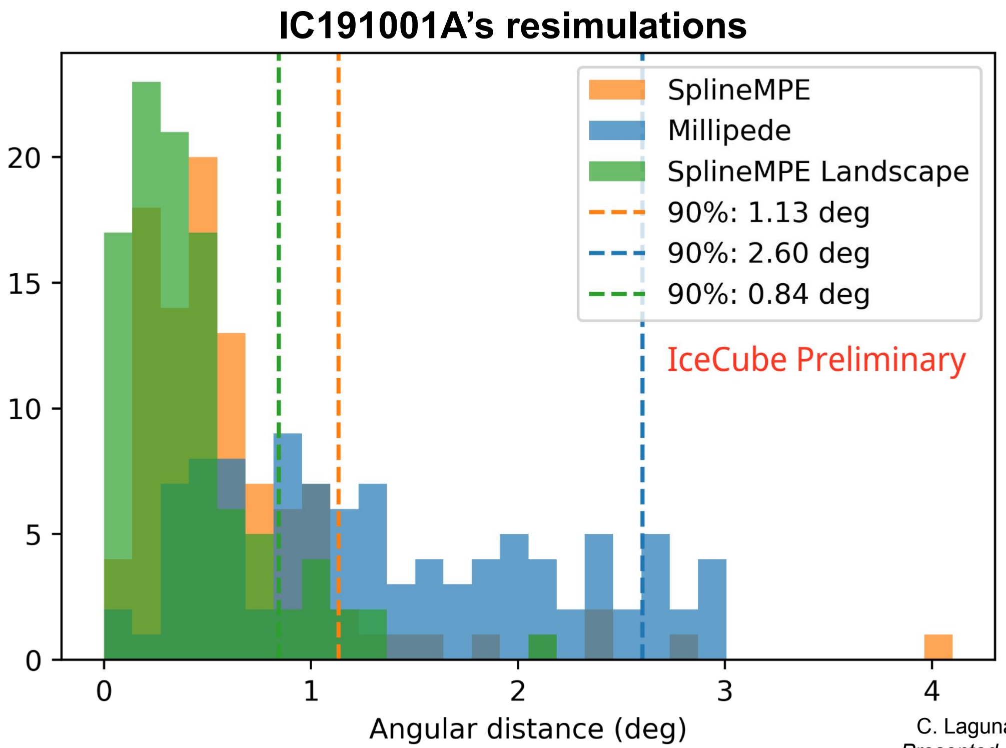
- IceCube sends two updated for each alert, using two different algorithms:
  - First update: SplineMPE **without** likelihood scan;
  - Second update: Millipede **with** likelihood scan

- SplineMPE with the likelihood scan is faster and more precise.


Thank you for listening!

# Backup Slides

# Improvements with the likelihood scan




C. Lagunas Gualda and G. Sommani, Presentation, *Presented at the IceCube spring Collaboration meeting* (2022)

## The Problem:

Millipede results depend strongly on systematic uncertainties
(one of the most important is the ice model)

## Possible Solution:

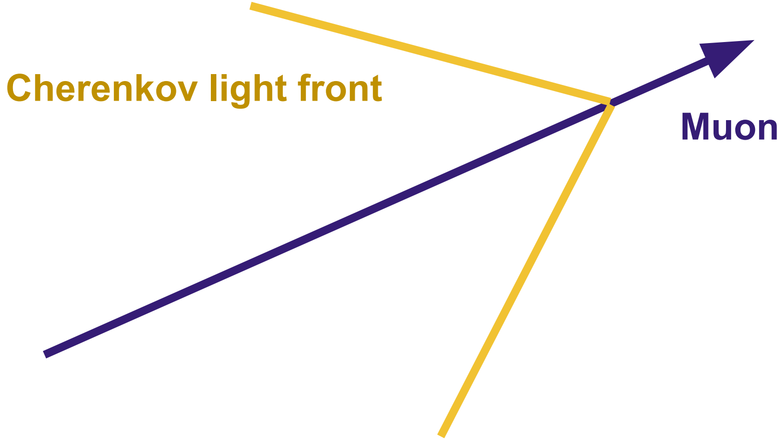
An alternative reconstruction algorithm: SplineMPE,
its results depend less on systematics because it uses fewer data.

## My work:

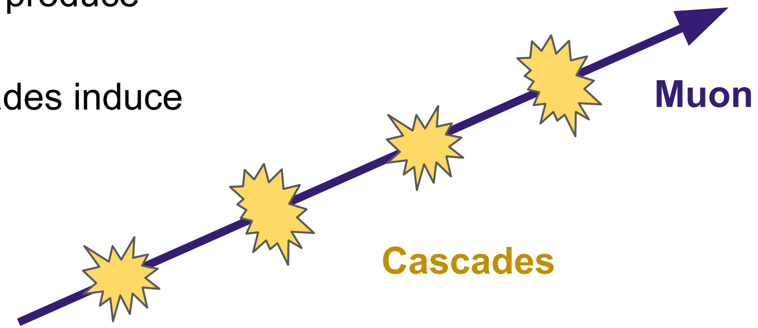
- Develop a unique configuration of SplineMPE for the likelihood scans.
- Study SplineMPE dependence on systematic uncertainties.

# Muon’s light emissions

- **Continuous light emission:**
  - Cherenkov effect induced by the Muon.




- **Stochastic light emission:**
  - Stochastic energy losses along the muon track produce secondary cascades.
  - The relativistic particles in the secondary cascades induce Cherenkov effect.



$$\mathcal{L}(x, \mathbf{a})$$

$$\max_{\mathbf{a}} \mathcal{L}(x, \mathbf{a})$$

**The log-likelihood ratio**:

$$\lambda(x, \mathbf{a}) = -2 \log \left( \frac{\mathcal{L}(x, \mathbf{a})}{\max_{\mathbf{a}} \mathcal{L}(x, \mathbf{a})} \right)$$

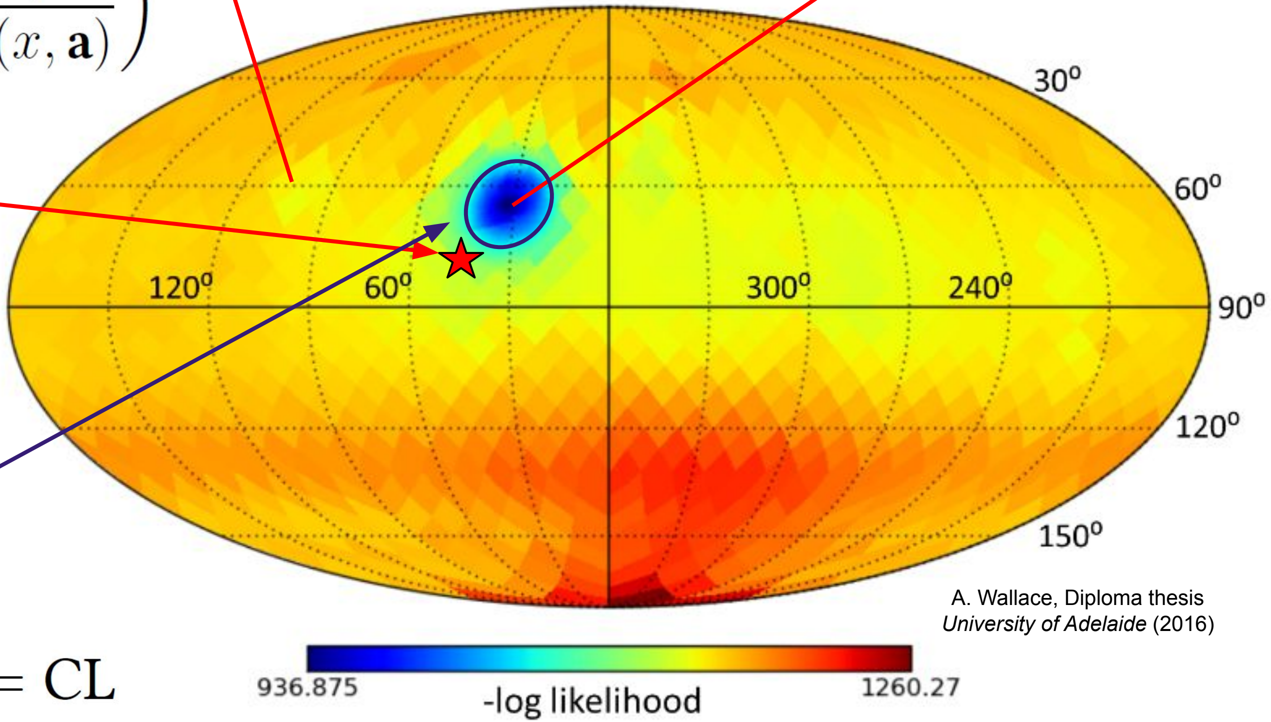
$\mathbf{a}_{\mathrm{True}}$

**Wilks' theorem:**

$\lambda(x, \mathbf{a}_{\mathrm{True}})$ has a **universal** distribution:

$$p(\lambda) = \chi^2_{\nu=2}(\lambda)$$

$$\int_0^{\lambda_{\mathrm{CL}}} p(\lambda) d\lambda = \mathrm{CL}$$




A. Wallace, Diploma thesis
*University of Adelaide* (2016)

**The log-likelihood ratio:**

$$\mathcal{L}(x, \mathbf{a}) \qquad \max_{\mathbf{a}} \mathcal{L}(x, \mathbf{a})$$

$$\lambda(x, \mathbf{a}) = -2 \log \left( \frac{\mathcal{L}(x, \mathbf{a})}{\max_{\mathbf{a}} \mathcal{L}(x, \mathbf{a})} \right)$$

**Because of systematic uncertainties!**

$\mathbf{a}_{\mathrm{True}}$

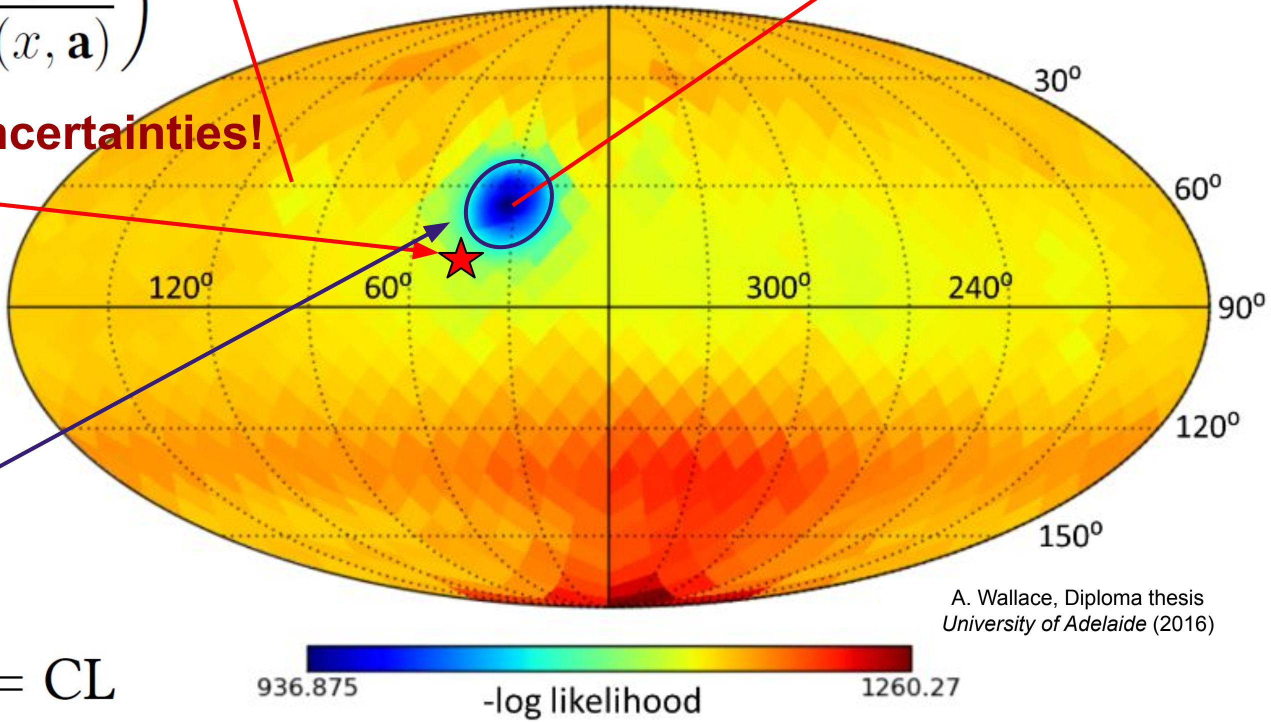
**Wilks' th... orem:**

$\lambda(x, \mathbf{a}$ ...

**universa... ...tion:**

$p(\lambda$ ... $\chi_{\nu=}$ ... $)$

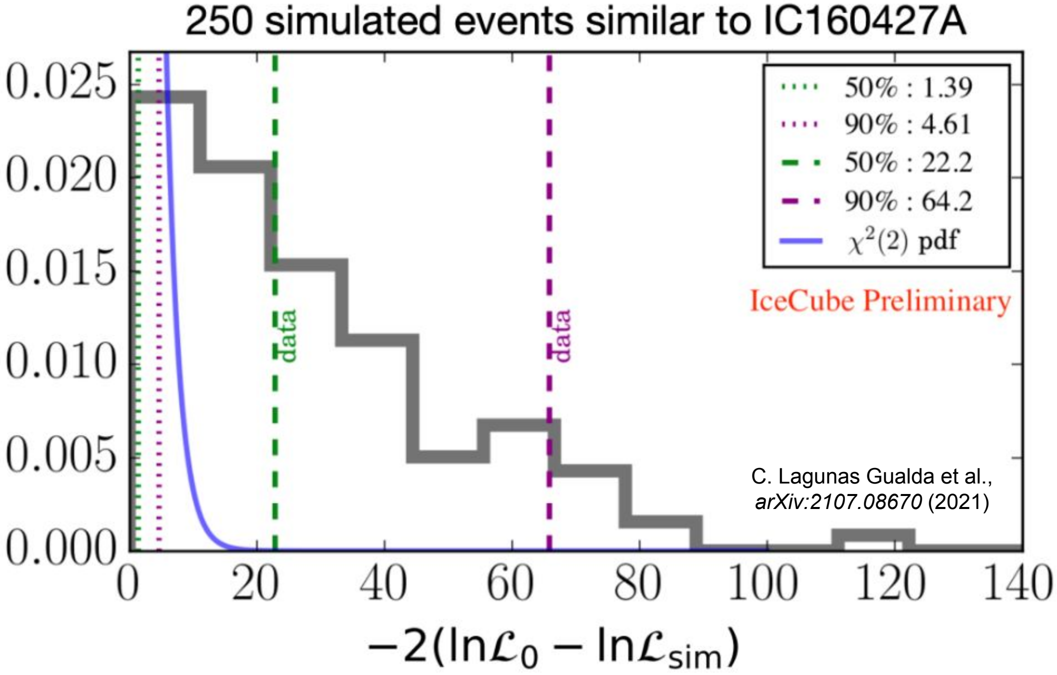
$$\int_0^{\lambda_{\mathrm{CL}}} p(\lambda) d\lambda = \mathrm{CL}$$




A. Wallace, Diploma thesis
*University of Adelaide* (2016)

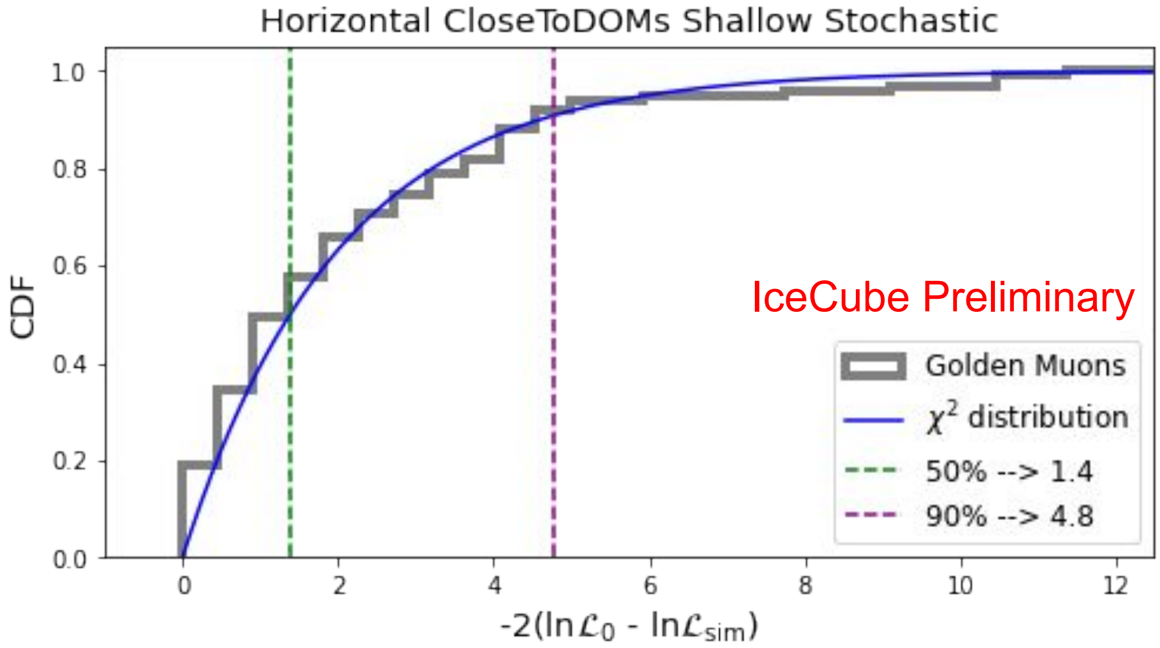
# The current solution (IC160427A resimulations)

One event, resimulated (simulating events *similar* to the original one) to investigate **the log-likelihood-ratio distribution** $p(\lambda)$**.**




**The resulting levels are currently used in realtime alerts.**

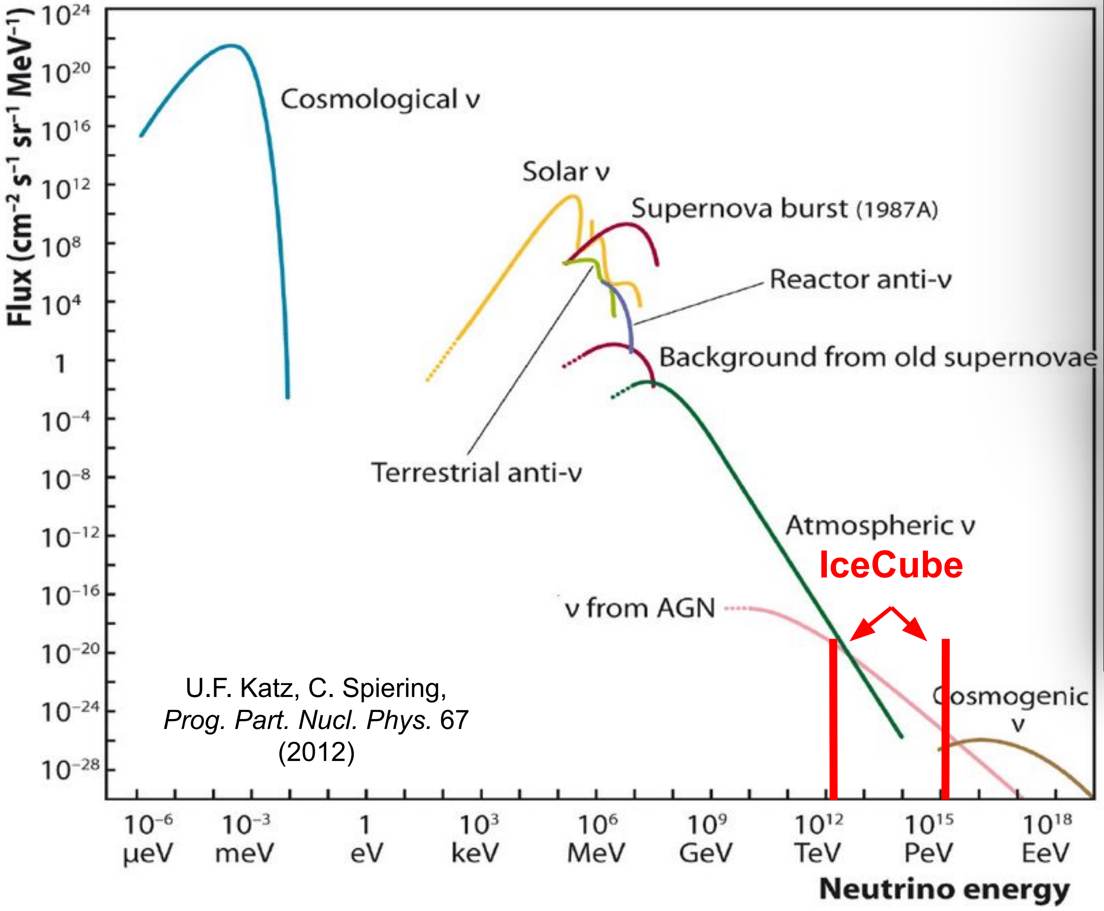
# My results using SplineMPE's likelihood scans (on Golden Muons)

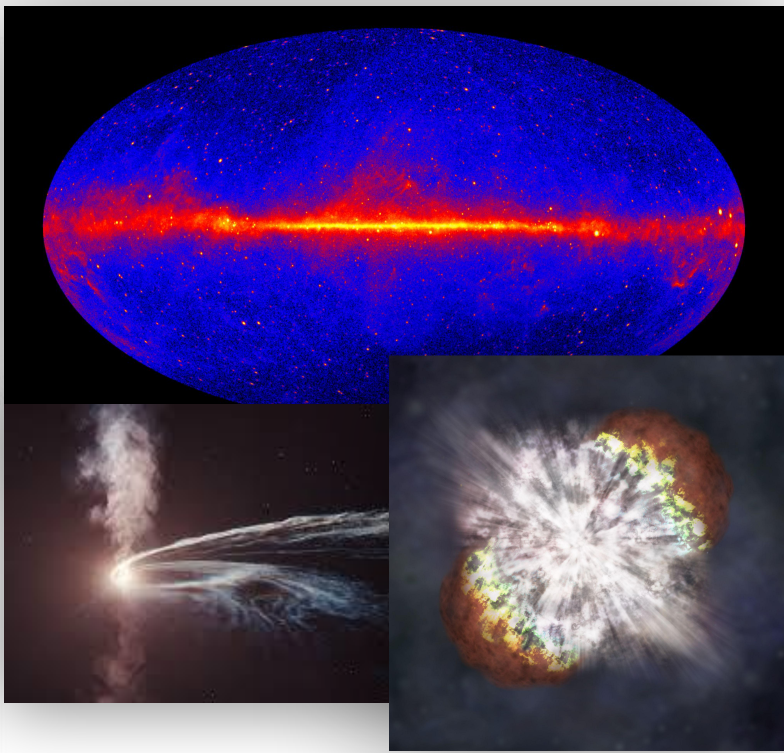



- Levels much smaller than with Millipede.
- Not so different from one category to another.
- Not so far from Wilks' theorem.

**This is the case for most of the Golden Muons categories.**

# High-Energy Astrophysical Neutrinos

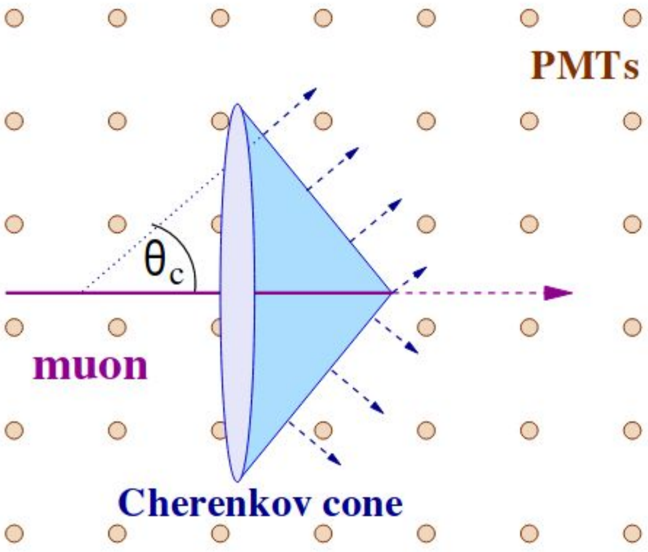


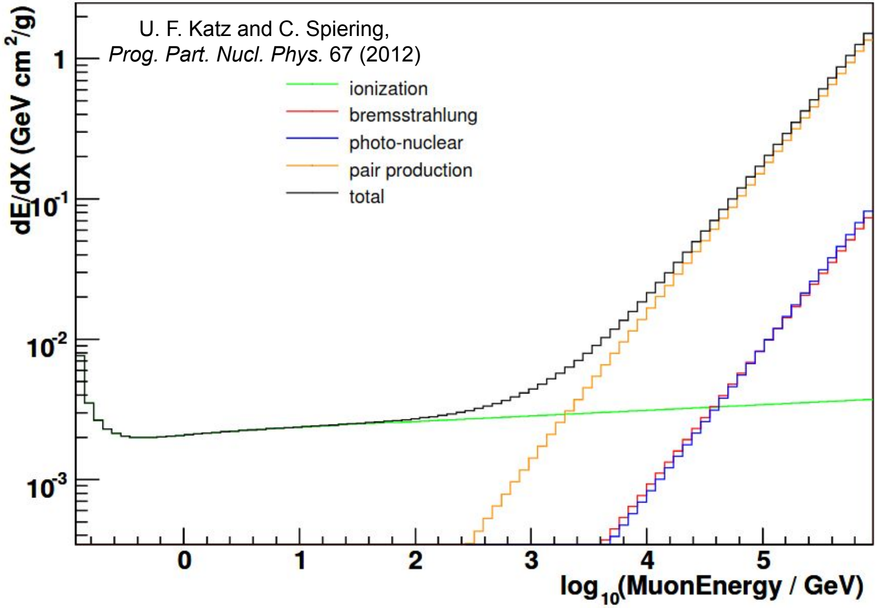
**AGNs, TDEs, SLSNs, the galactic plane,** are just some examples…

# The Muon Track light emission

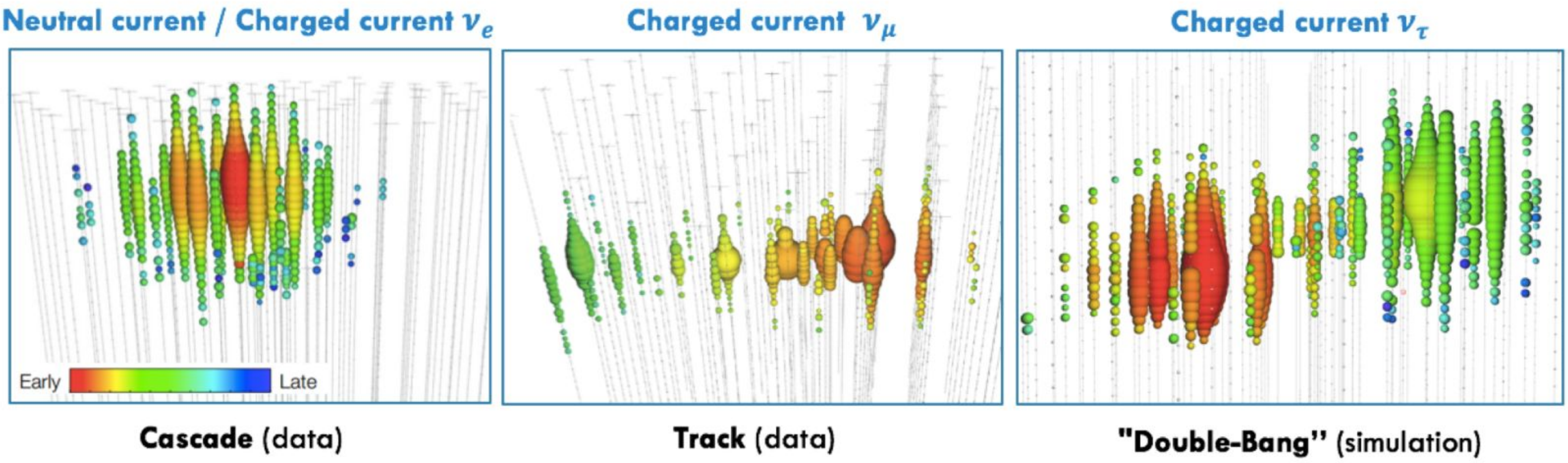
- Continuous emission:
  - Muon's Cherenkov effect.
- Stochastic emission:
  - Bremsstrahlung;
  - Pair production;
  - Photo-nuclear interactions.




AMANDA Collaboration and J. Ahrens.
*Nucl. Instrum.* 524.1-3 (2004)



# The Signatures




N. Iovine, Master thesis, *Université de Mons,* (2017)

- The detected light is emitted via Cherenkov effect by relativistic particles
- Track signatures are the most promising to reconstruct the direction