Bundesministerium für Bildung und Forschung

RWTH AACHEN IceCube

Measurement of Neutrino Oscillations with IceCube

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- Astroteilchenschule Bärnfels -

DFG Deutsche Forschungsgemeinschaft

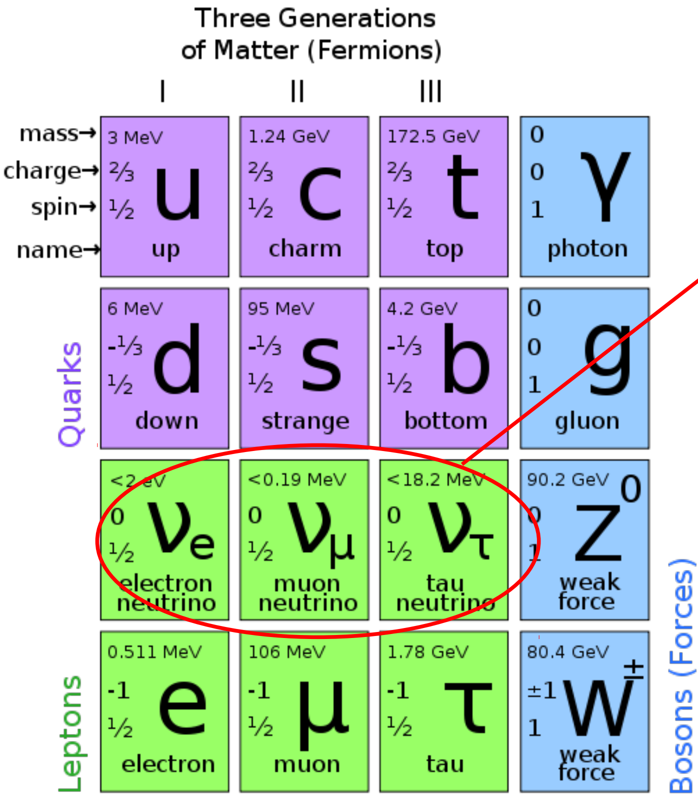
HELMHOLTZ | GEMEINSCHAFT

Allianz für Astroteilchenphysik

Outline of Talk

- **Introduction**
  - *What is neutrino oscillation?*
  - *What are atmospheric neutrinos?*
- **The IceCube Neutrino Observatory**
- **Idea of oscillation analyses**
  - *Energy and zenith observables*
  - *Log-likelihood test*
- **Current performance of IceCube analyses**
- **Improvements within my work**
  - *Dealing with low statistic Monte-Carlo simulations*
  - *Improving current reconstruction of observables*
  - *Neutrino flavor identification for multi-flavor analysis*
- **Summary and outlook**

Theory of Neutrino Oscillation



Why do neutrinos oscillate?

- **Flavor eigenstates**($\nu_{e,\mu,\tau}$) do not match **mass eigenstates** of neutrinos($\nu_{1,2,3}$):

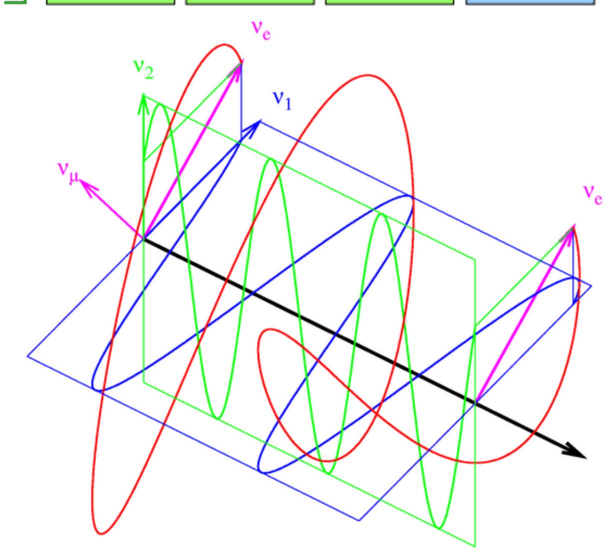
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U \cdot \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

- *Pontecorvo-Maki-Nakagawa-Sakata* Matrix U given by product of 3 U(3) matrices:

$$U = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{U_{23}} \underbrace{\begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix}}_{U_{13}} \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{U_{12}}$$

- Parameters: $s_{ij} = \sin(\theta_{ij})$ $c_{ij} = \sin(\theta_{ij})$ $(\delta = 0)$

called *mixing angles* (3 params.)



Theory of Neutrino Oscillation

Why do neutrinos oscillate?

$k = 1,2,3$ $\quad E$: neutrino energy
$\alpha = e, \mu, \tau$ $\quad L$: travelled distance
Δm_{ij}^2: squared mass diff. of states i & j

- Time expansion: $$|\nu_k(t)> = e^{-iE_k t}|\nu_k>$$

$$\Rightarrow |\nu_\alpha(t)> = \sum_{\beta=e,\mu,\tau} \left(\sum_k U_{\alpha k}^* e^{-iE_k t} U_{\beta k} \right) |\nu_\beta>$$

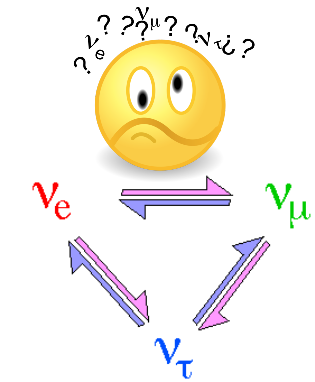
- Likelihood for flavor change after distance $L = c \cdot t$:

$$\Rightarrow P_{\nu_\alpha \to \nu_\beta}(L,E) = \sum_{k,j} U_{\alpha k}^* U_{\beta k} U_{\alpha j} U_{\beta j}^* \exp\left(-i \frac{\Delta m_{kj}^2 L}{2E} \right)$$

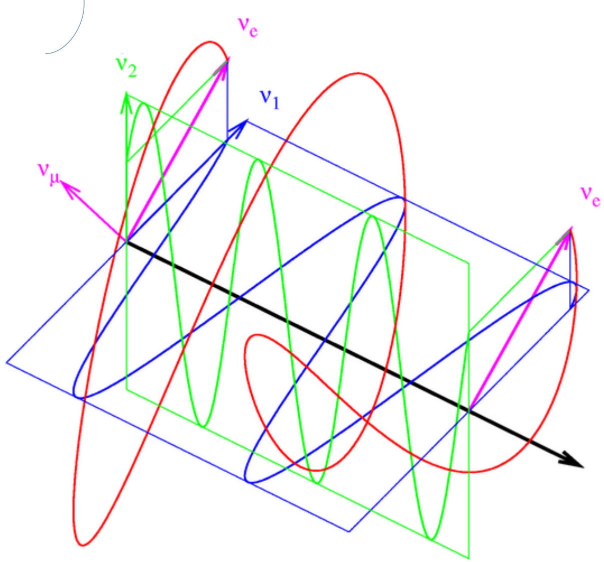
- 5 oscillation parameters: $\theta_{12}, \theta_{23}, \theta_{13}, \Delta m_{12}^2, \Delta m_{32}^2$
- In simplified 2-flavor model:

$$P_{\nu_\alpha \to \nu_\beta}(L,E) = \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E} \right)$$

(in many cases sufficient to understand the dominant effects)



"Neutrino Oscillation"



Theory of Neutrino Oscillation

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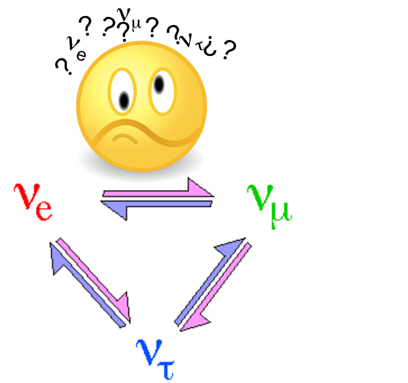
$$\rightarrow \quad |\nu_\alpha(t)\rangle = \sum_{\beta=e,\mu,\tau} \left(\sum_k U^*_{\alpha k} e^{-iE_k t} U_{\beta k} \right) |\nu_\beta\rangle$$



"Neutrino Oscillation"

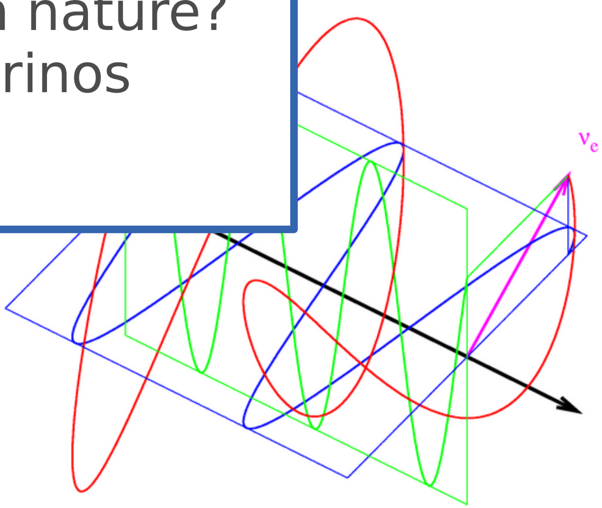
- Likelihood for flavor change after distance L = c*t:

- 5 Oscilla

- In simpl

Ok, but where does this happen in nature? Where can we get oscillating neutrinos from?

$$P_{\nu_\alpha \rightarrow \nu_\beta}(L,E) = \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$



(in many cases sufficient to understand the dominant effects)

Atmospheric Neutrinos

Where do we get the neutrinos from?

- Primary cosmic rays interact with atmosphere
- Generate light mesons (pions, kaons)
- Decay of mesons results in neutrino production:

$$\pi^{\pm} \longrightarrow \mu^{\pm} + \overset{(-)}{\nu}_{\mu} \longrightarrow e^{\pm} + \overset{(-)}{\nu}_{e} + \nu_{\mu} + \bar{\nu}_{\mu}$$

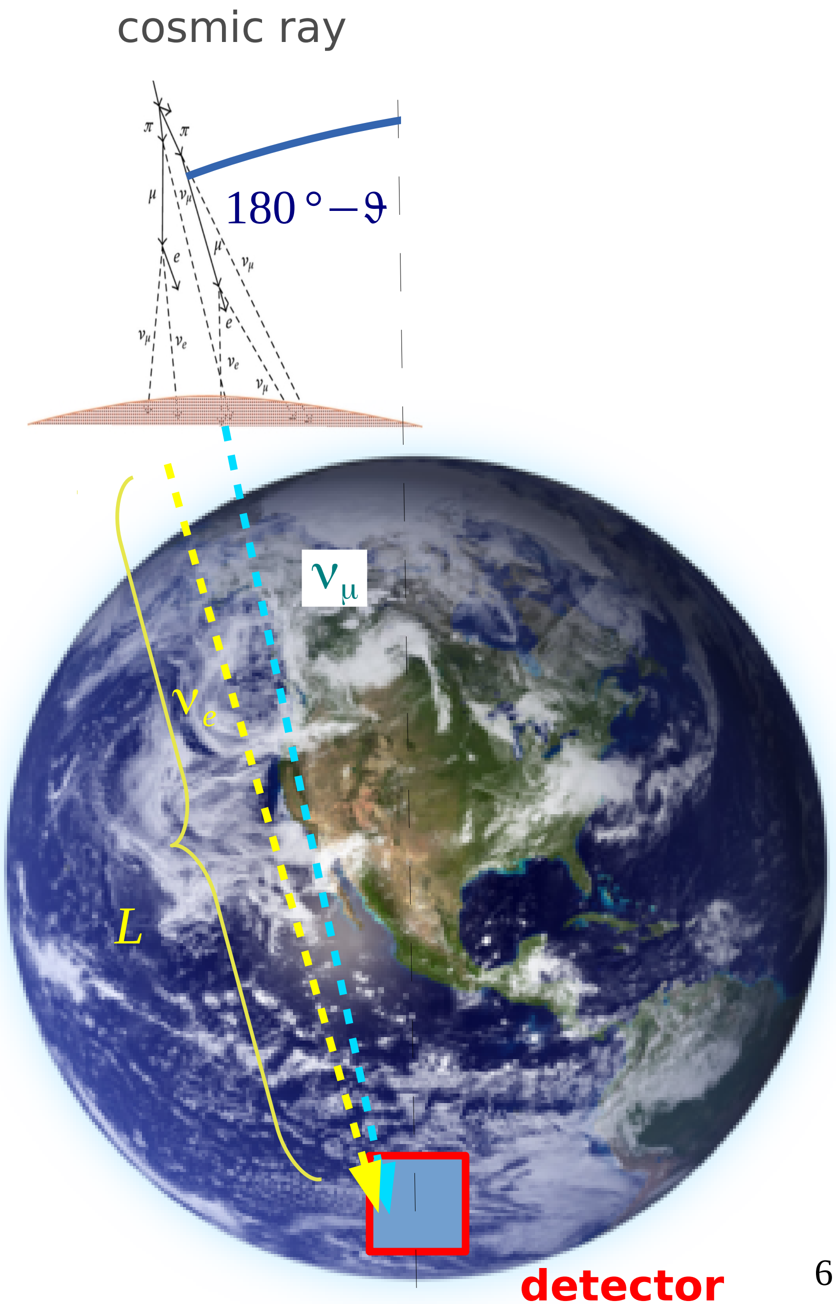
$$K^{\pm} \longrightarrow \mu^{\pm} + \overset{(-)}{\nu}_{\mu} \longrightarrow e^{\pm} + \overset{(-)}{\nu}_{e} + \nu_{\mu} + \bar{\nu}_{\mu}$$

- Derive distance L from zenith angle theta:

$$L \approx D \cdot \cos(\vartheta)$$

ϑ: zenith angle of incoming neutrino

D: diameter of Earth



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$K^{\pm}$

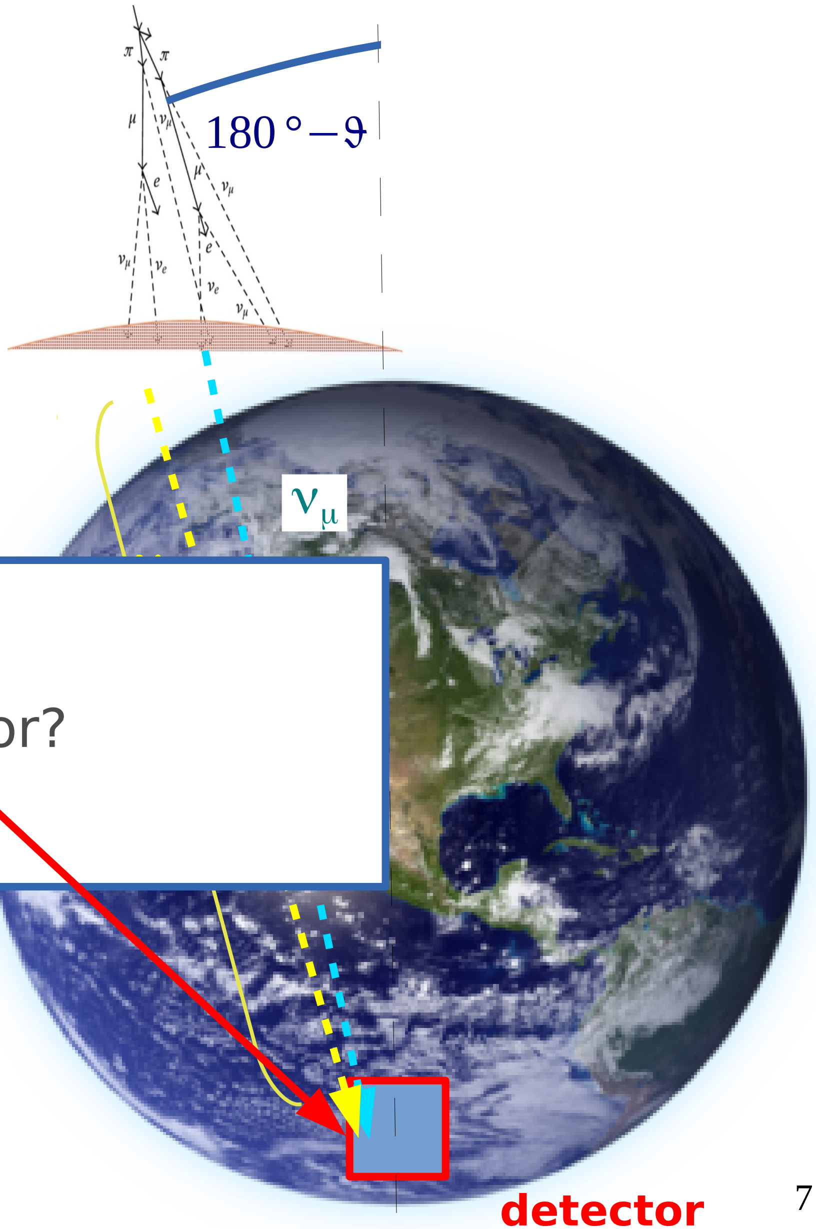
- De

Do we have such a detector?

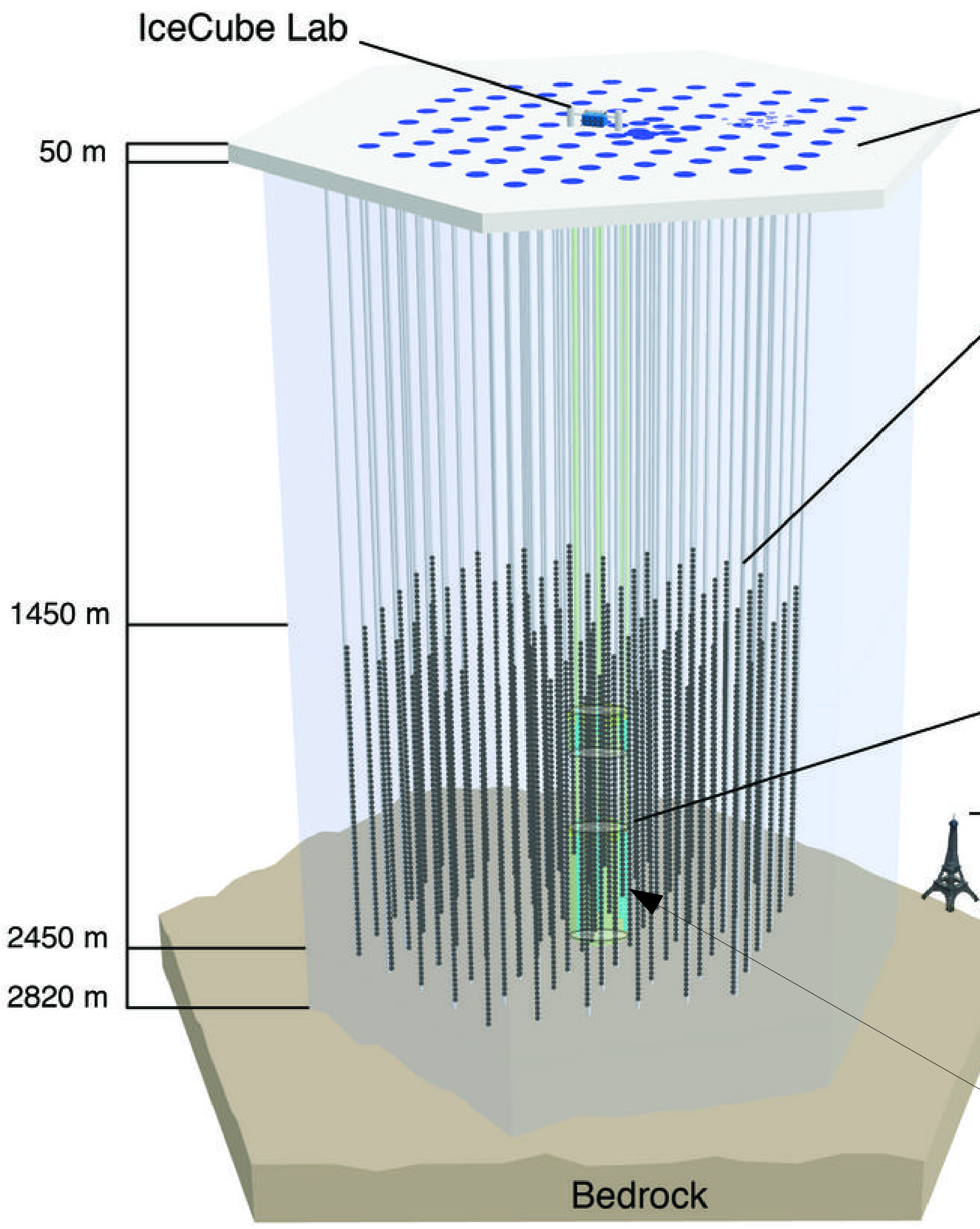
$$L \approx D \cdot \cos(\vartheta)$$

ϑ: zenith angle of incoming neutrino

D: diameter of Earth



IceCube Neutrino Observatory



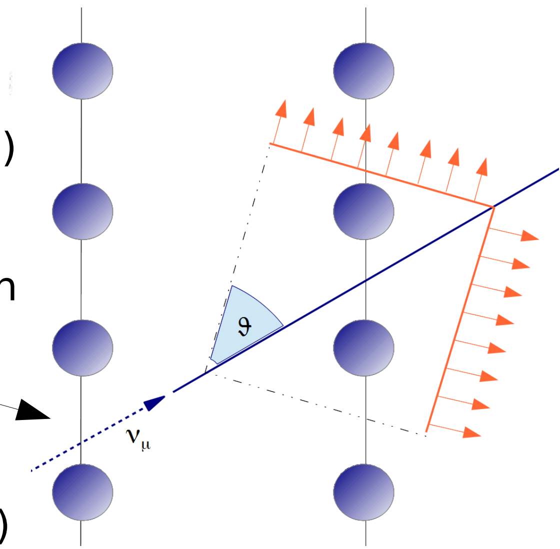
IceTop

What is IceCube?

At geographic South Pole,
finished 2010
~ 1km³ neutrino detector

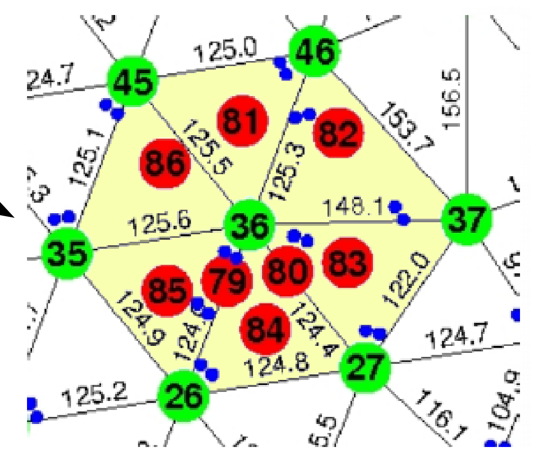
IceCube Array

- 86 strings
- 5160 opt. sensors(DOMs)
- 1.5 - 2.5km depth
- detects above ~100GeV
- uses Cherenkov radiation



DeepCore

- 8 additional strings
- 460 opt. sensors(DOMs)
- High-QE DOMs
- detects above ~10GeV



clear glacial ice

Idea of Oscillation Analyses

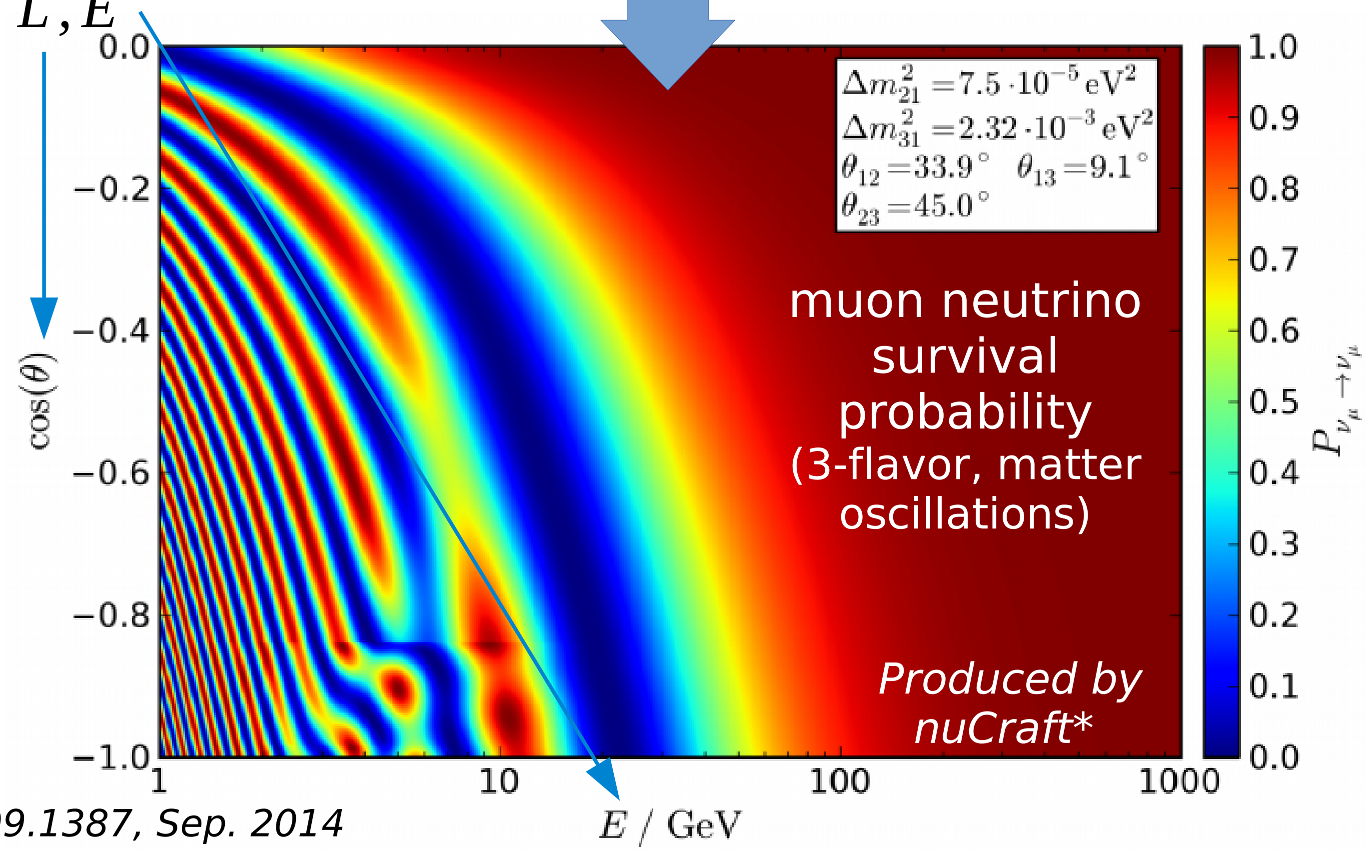
How can we measure the oscillation parameters?

- Remember 2-flavor approximation: $P_{\nu_\alpha \to \nu_\beta}(L, E) = \sin^2 2\theta \sin^2 \left(\frac{\Delta m^2 L}{4E} \right)$
- ν_μ -disappearance analysis:

$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2(2\theta) \cdot \sin^2[1.27 \cdot \Delta m^2(\text{eV}^2) \frac{L(\text{km})}{E_\nu(\text{GeV})}]$$

- Two observables needed: L, E

Measure zenith angle and energy for each neutrino and apply log-likelihood analysis (LLH) to 2D histogram

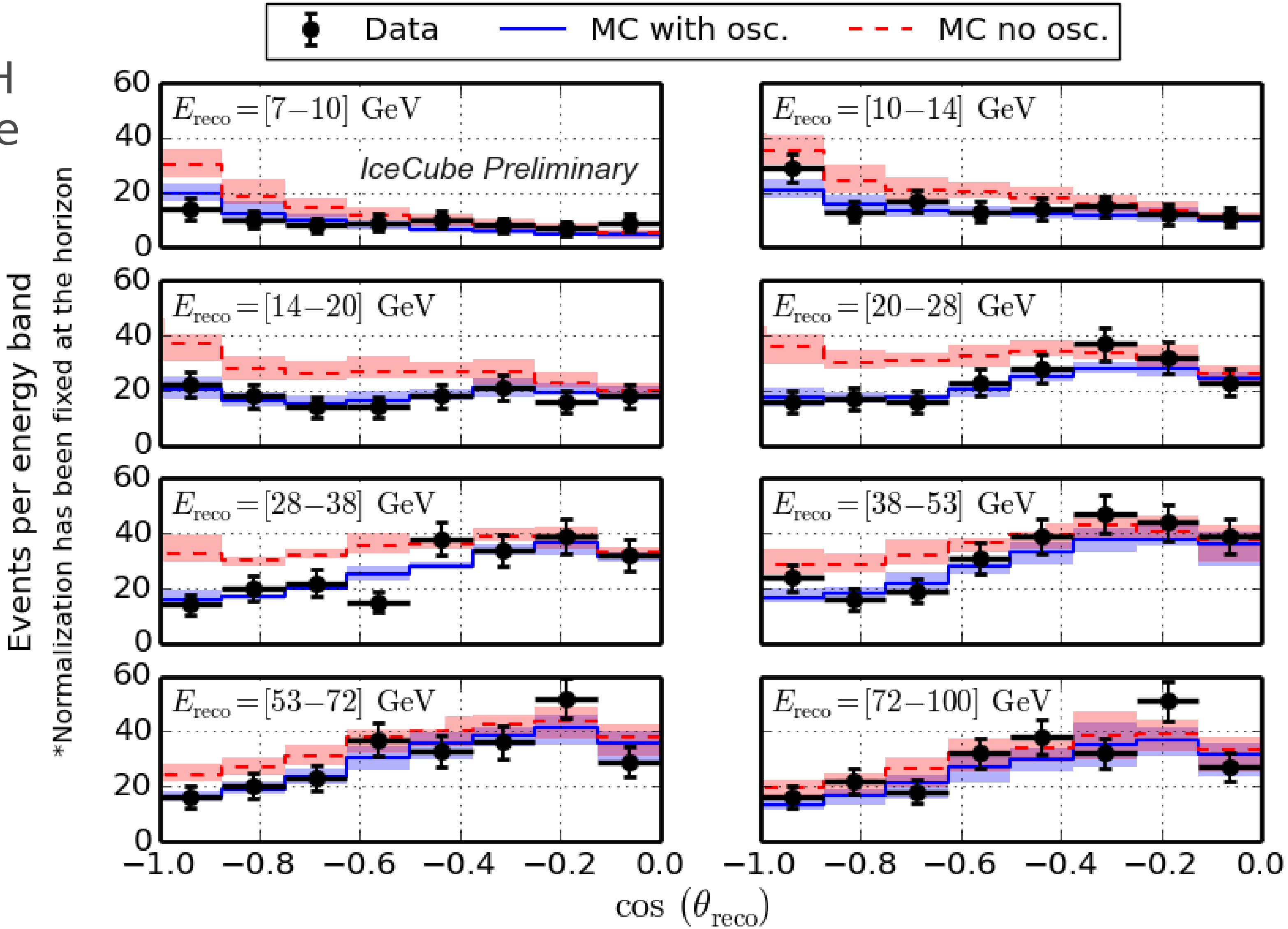


* *M. Wallraff, C. Wiebusch, arXiv:1409.1387, Sep. 2014*

Current Status in IceCube

- Based on: *IceCube Collaboration, The measurement of neutrino oscillation with the full IceCube detector, ICRC 2013 Proceedings, arXiv:1309.7008*

- **8x8 Bins** for LLH
- IC86 data sample
- High ν_μ-purity
- Contamination:
  - → e-neutrinos
  - → atm. muons
- Poissonian likelihood fct.
- Best fit(blue) vs null-hypothesis

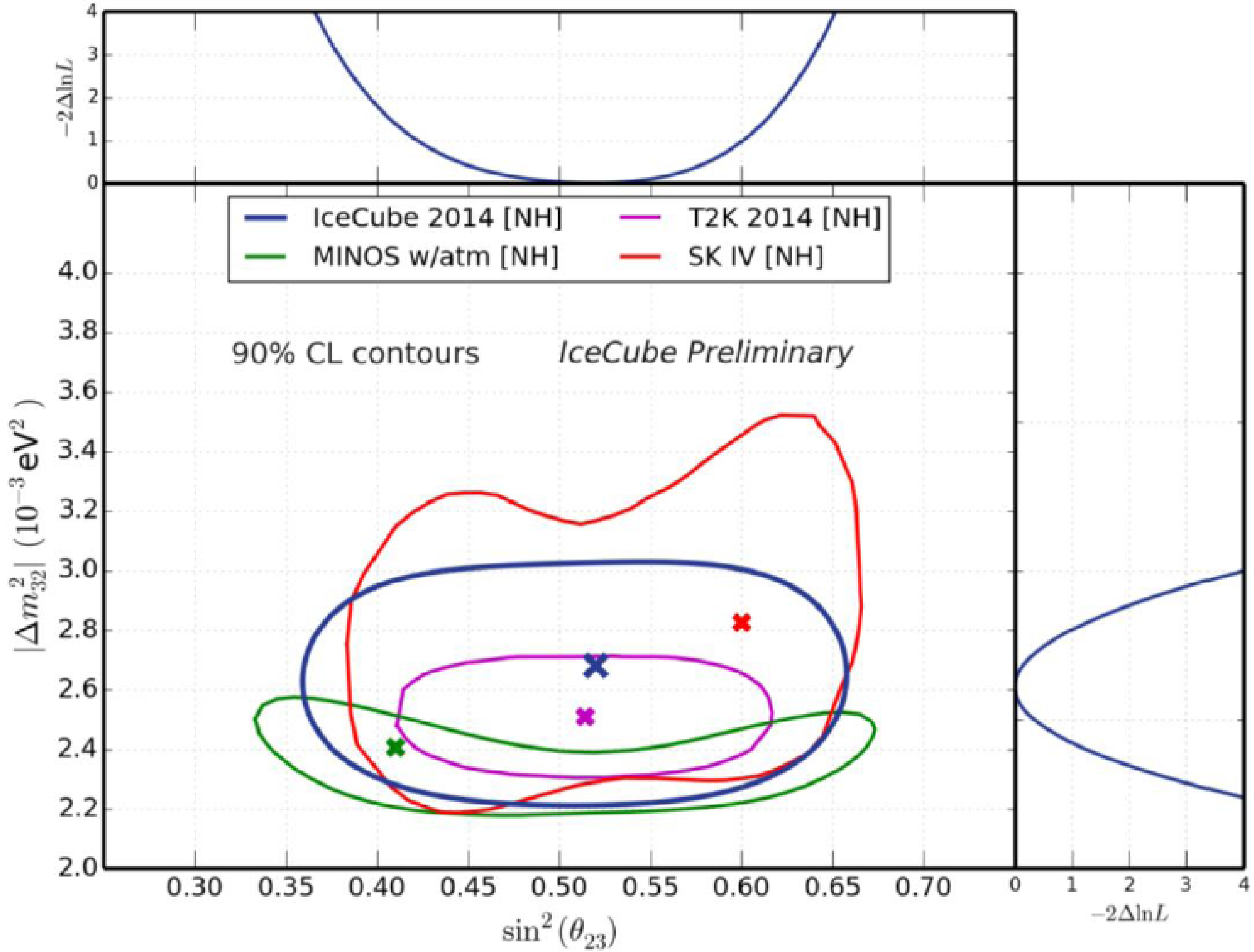


Current Status in IceCube

- Based on:

J.P. Yanez (IceCube Collaboration), Results from atmospheric neutrino oscillation with IceCube/DeepCore, Proceedings, Neutrino 2014, June 2014

- Fit of: $\Delta m^2_{32}, \theta_{23}$
- Other oscil. params. treated as nuisance parameters
- Competitive to world leading measurements



Best fit:

$$\Delta m^2_{23} = (2.68 \pm 0.20) \cdot 10^{-3}\, eV^2$$

$$\sin^2(\theta_{23}) = 0.51 \pm 0.09$$

- Based on:

J.P. Yanez (IceCube Collaboration), Results from atmospheric neutrino oscillation with IceCube/DeepCore, Proceedings, Neutrino 2014, June 2014

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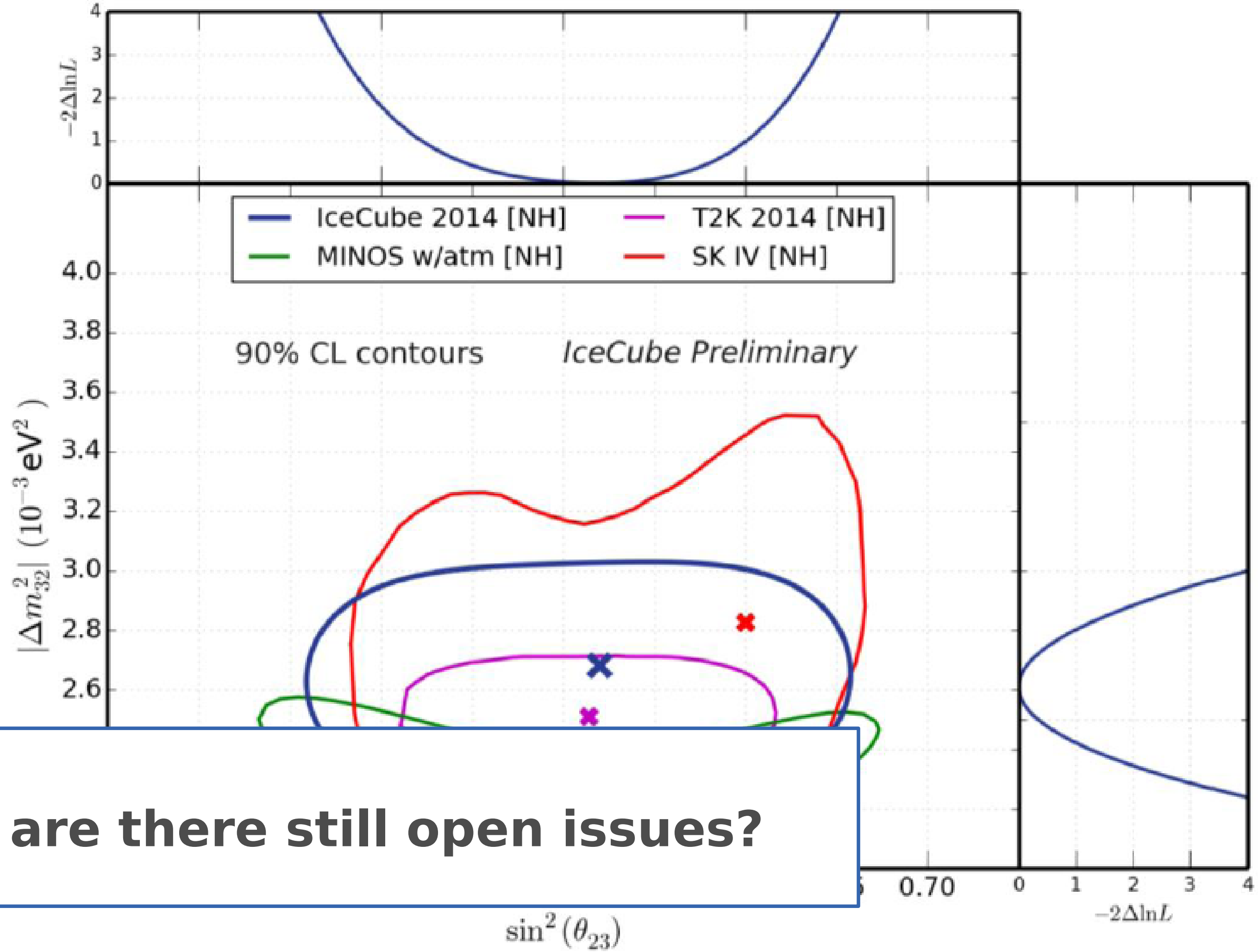


Best fit:

$\Delta m^2_{23} = (2.68 \pm 0.$

$\sin^2(\theta_{23}) = 0.51 \pm$

So, are there still open issues?

Improvements within my Work

So, are there still open issues?

1) Low Monte-Carlo statistics – how to deal with?

2) Reconstruction of low-energy events challenging

Improvements within my Work

So, are there still open issues?

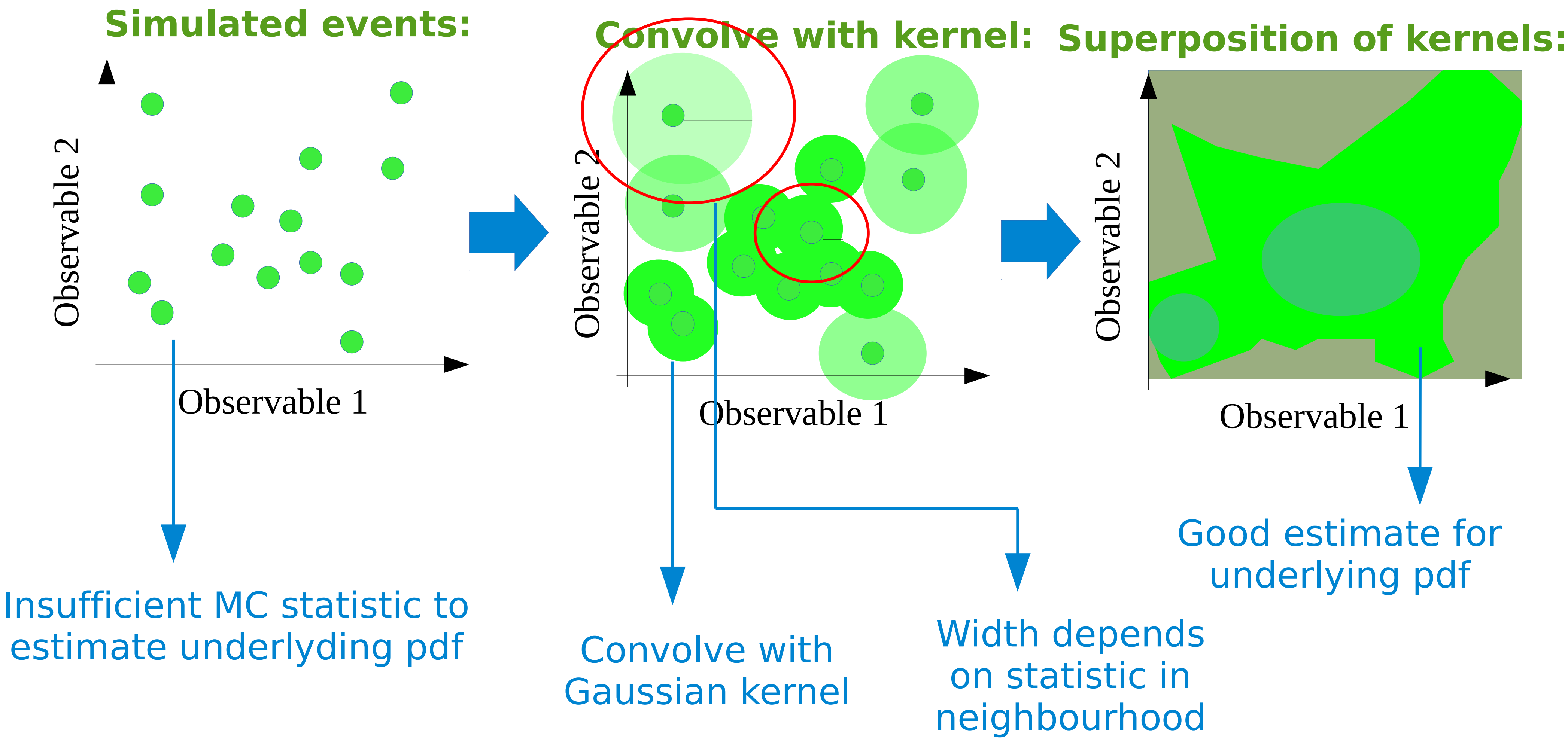
1) Low Monte-Carlo statistics – how to deal with?

→ **Kernel Density Estimation (KDE)**

2) Reconstruction of low-energy events challenging

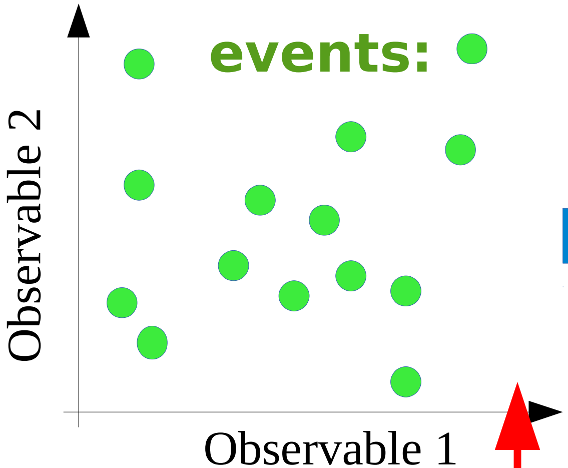
Idea of KDE

So, how can we deal with our limited knowledge of the pdf due to too low MC statistics?

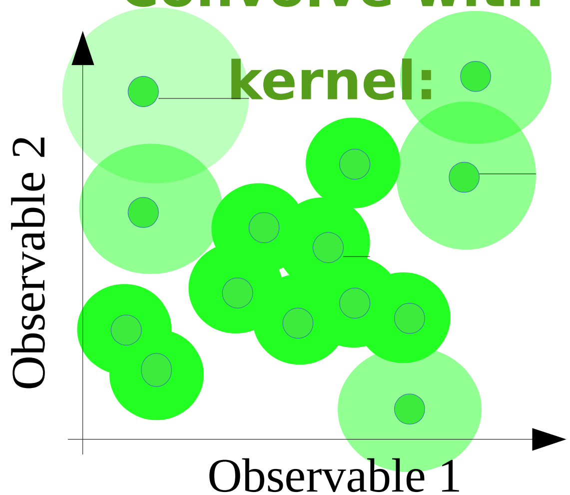


Reconstruction Performance

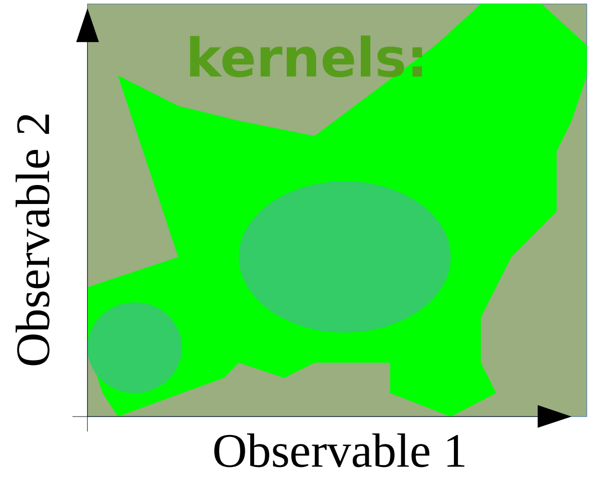
Simulated events:

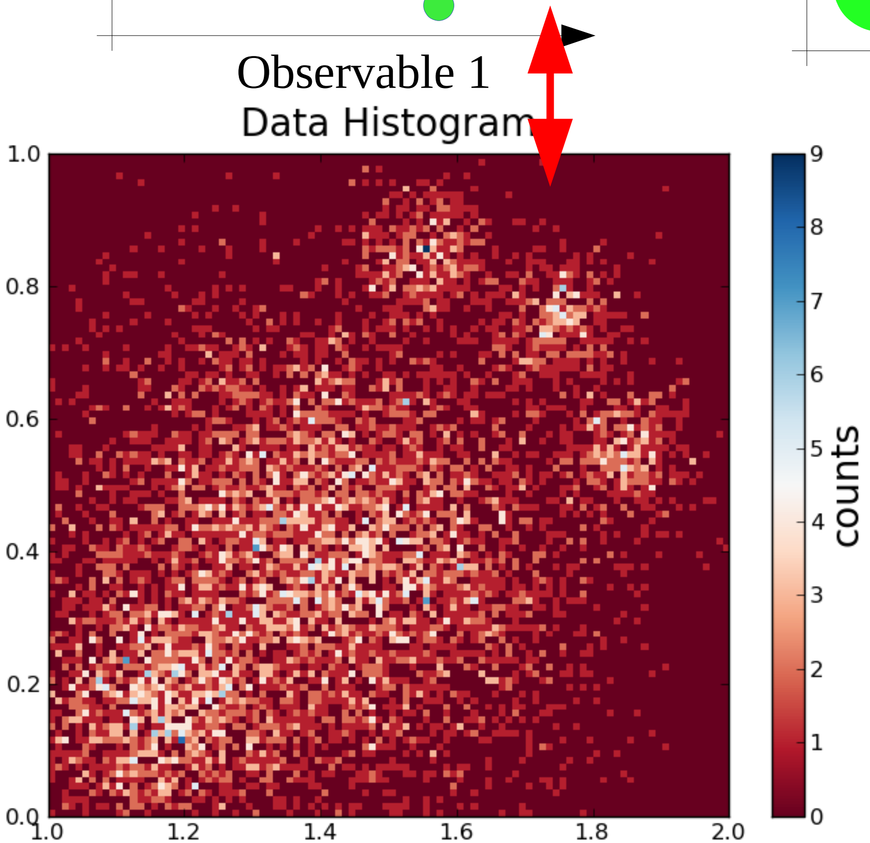


Convolve with kernel:

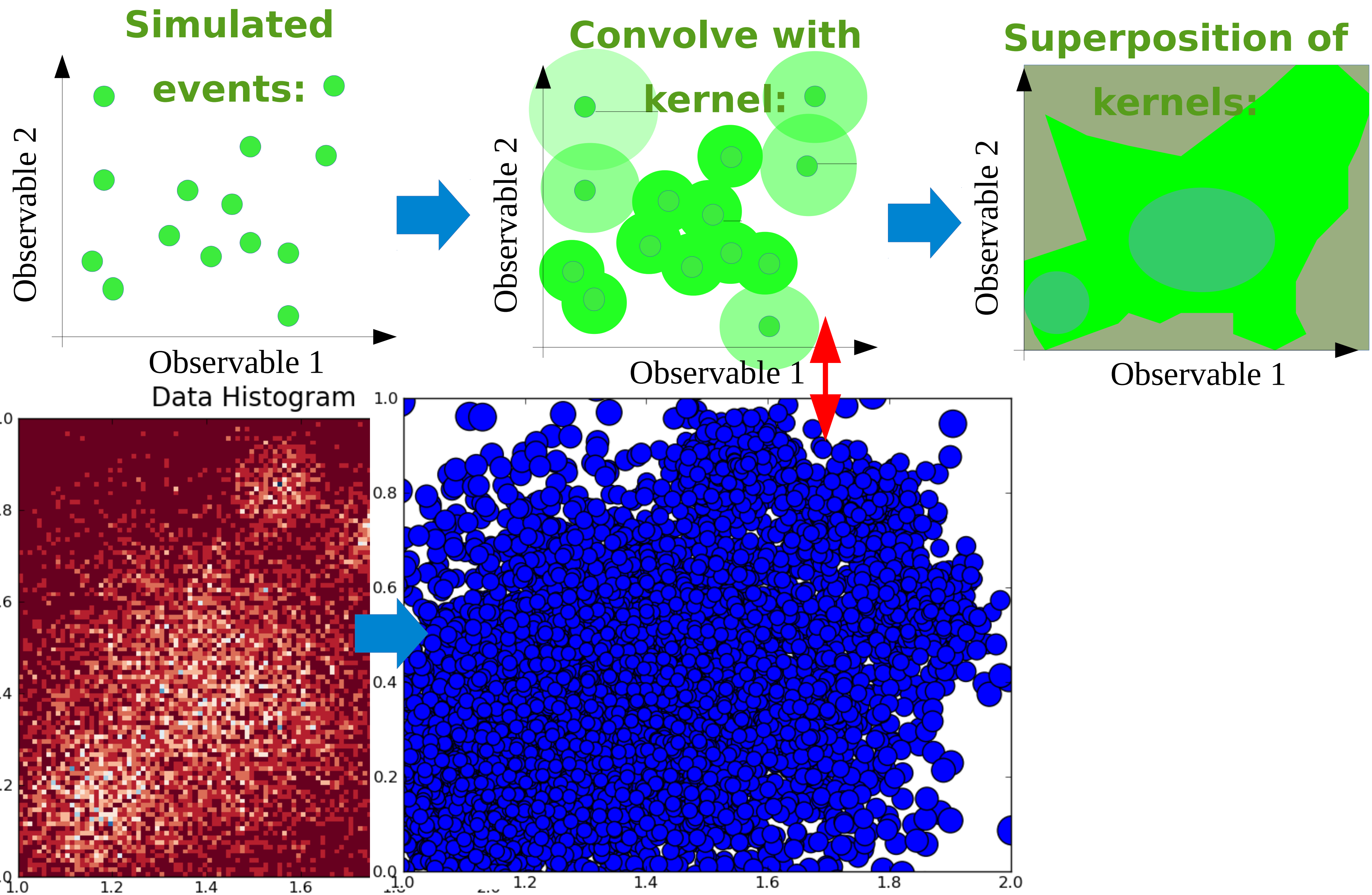


Superposition of kernels:

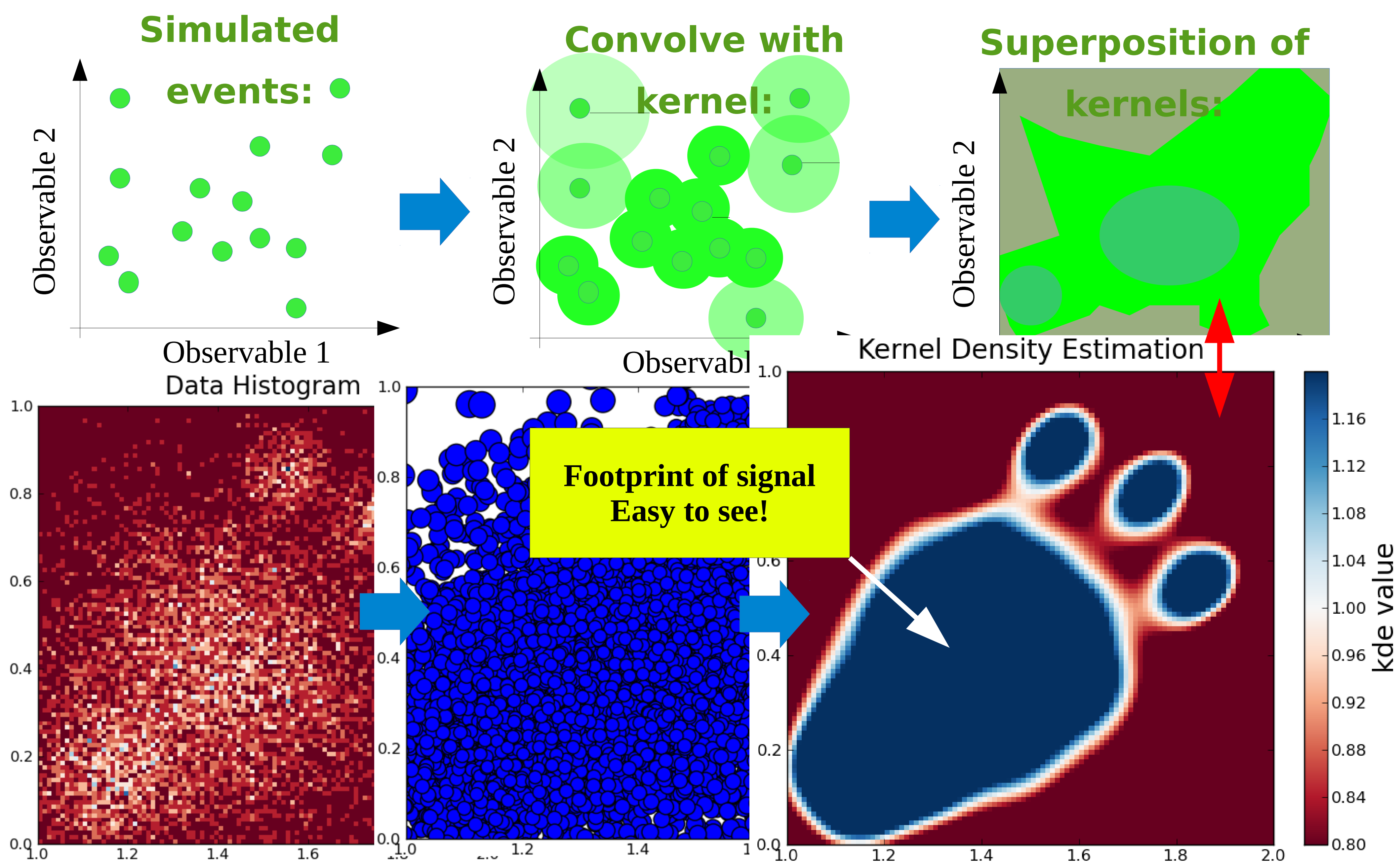




Reconstruction Performance



Reconstruction Performance



Improvements within my Work

So, are there still open issues?

1) Low Monte-Carlo statistics – how to deal with?

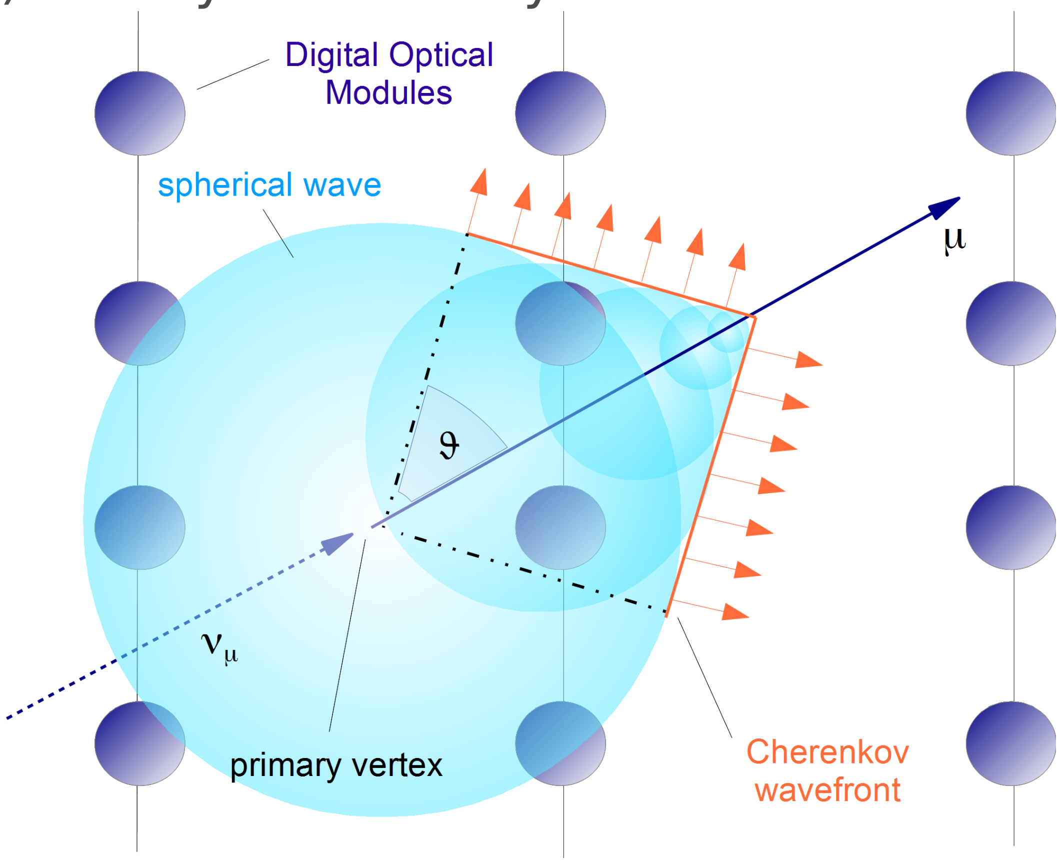
→ Kernel Density Estimation

2) Reconstruction of low-energy events challenging

→ **Improved reconstruction algorithm**

Idea of Current Recos.

1.) What you have in your data:



seen charge at DOM 1

position of DOM 1

time of seen charge

$$\begin{pmatrix} q_1(\vec{x}_1, t_1) \\ q_2(\vec{x}_2, t_2) \\ q_3(\vec{x}_3, t_3) \\ \ldots \end{pmatrix}$$

pulse map/
charge distribution

2.) What you know about the ice:

sim. light propagation properties of the ice

LLH of $E(\vec{y}_1)$ to cause $q(\vec{x}_1)$:

$$\Lambda(\vec{x}_1, \vec{y}_1, q(\vec{x}_1), E(\vec{y}_1))$$

Idea of Current Recos.

1.) special feature of LLH:

$$\Lambda\left(\vec{x}_1, \vec{y}_1, q\left(\vec{x}_1\right), E\left(\vec{y}_1\right)\right) \Rightarrow \underbrace{q\left(\vec{x}_1\right)}_{\text{<expected charge> at x}} = \Lambda\left(\vec{x}_1, \vec{y}_1\right) \cdot \underbrace{E\left(\vec{y}_1\right)}_{\text{Caused by energy dep. at y}}$$

<expected charge> at x

Caused by energy dep. at y

2.) For a given set of sources $\left\{\left(E_i, \vec{y}_i, t_i\right)\right\}$, we can rewrite this:

$$\underbrace{\begin{pmatrix} q_1\left(\vec{x}_1, t_1\right) \\ q_2\left(\vec{x}_2, t_2\right) \\ q_3\left(\vec{x}_3, t_3\right) \\ \ldots \end{pmatrix}}_{\vec{Q}} = \underbrace{\begin{pmatrix} \Lambda\left(\vec{x}_1, \vec{y}_1\right) & \Lambda\left(\vec{x}_1, \vec{y}_2\right) & \ldots \\ \Lambda\left(\vec{x}_2, \vec{y}_1\right) & \Lambda\left(\vec{x}_2, \vec{y}_2\right) & \ldots \\ \ldots & \ldots & \ldots \end{pmatrix}}_{\Lambda} \cdot \underbrace{\begin{pmatrix} E_1\left(\vec{y}_1, t_1\right) \\ E_2\left(\vec{y}_2, t_2\right) \\ E_3\left(\vec{y}_3, t_3\right) \\ \ldots \end{pmatrix}}_{\vec{E}} \Rightarrow \vec{Q} = \Lambda \cdot \vec{E}$$

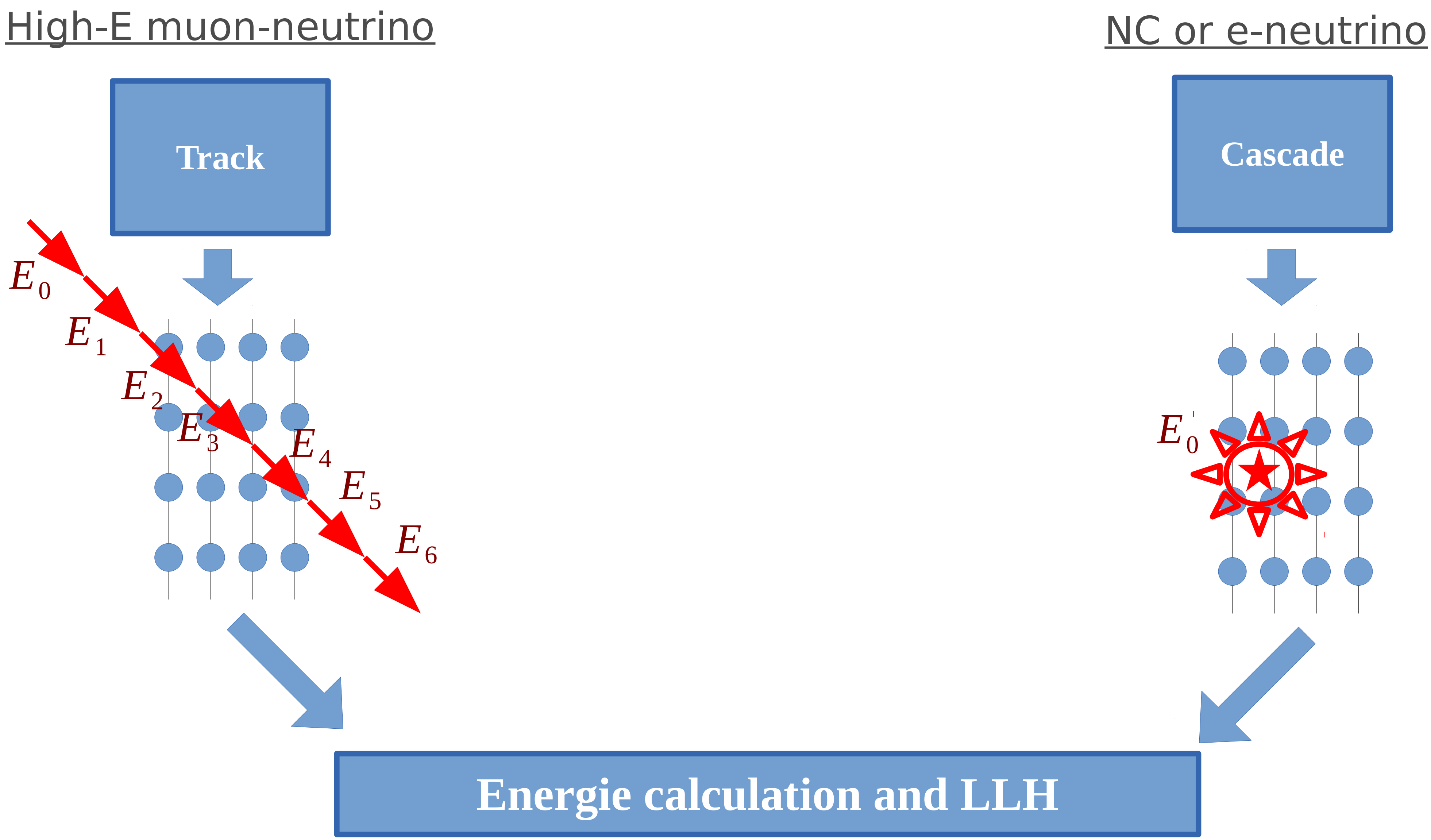
$$\Rightarrow \vec{E} = \Lambda^{-1} \cdot \vec{Q}$$

$\vec{Q}$: (measurement)

Λ: (different for each set of Qs and Es)

$\vec{E}$: (hypothesis)

Existing Reconstructions

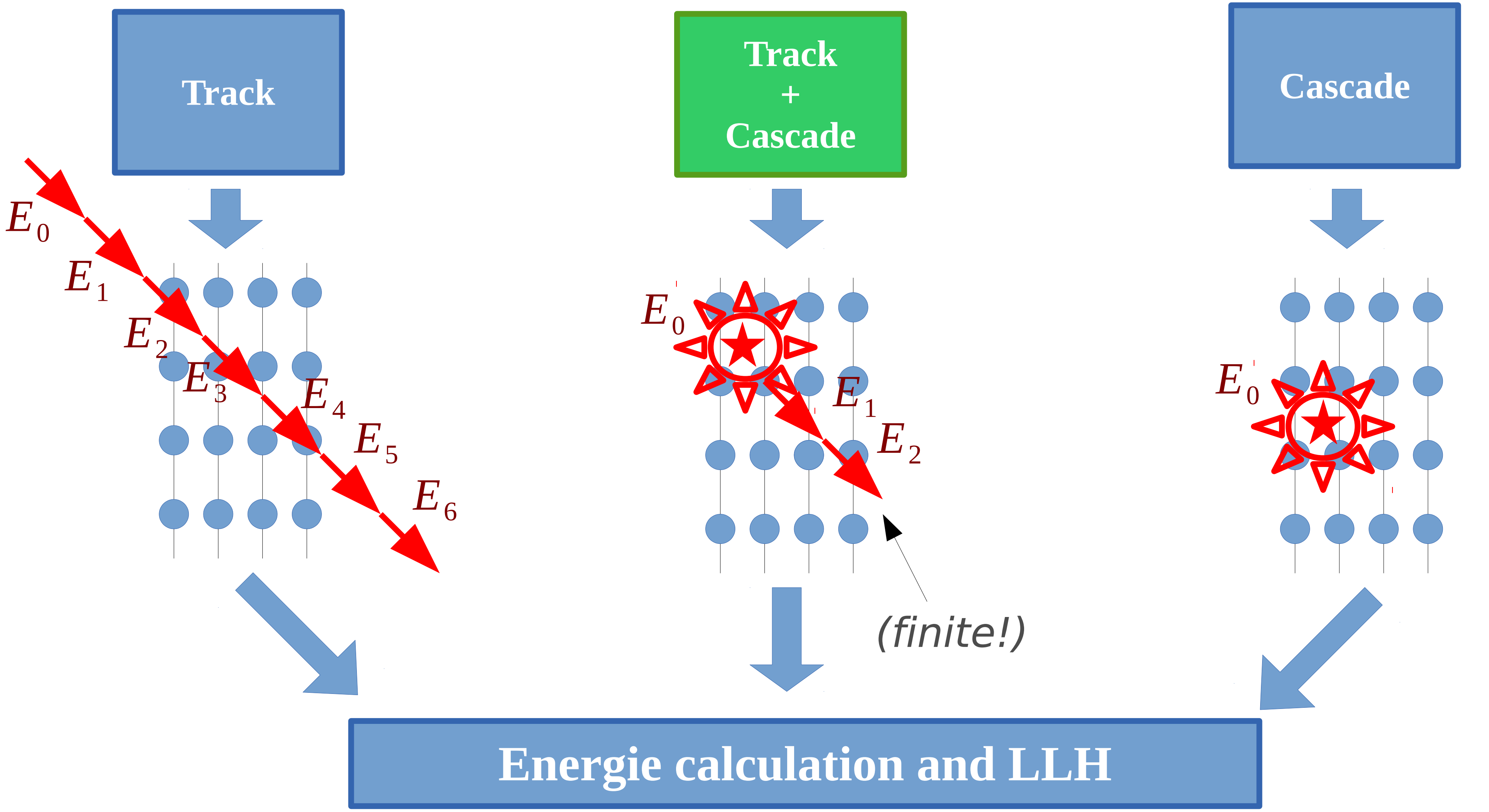


Existing Reconstructions

High-E muon-neutrino

Low-E muon-neutrinos:

NC or e-neutrino



Improvements within my Work

So, are there still open issues?

1) Low Monte-Carlo statistics – how do deal with?

→ Kernel Density Estimation

2) Reconstruction of low-energy events challenging

→ Improved reconstruction algorithm

Summary

Summary:

- Neutrino oscillation of atmospheric neutrinos is measured by IceCube-DeepCore

- IceCube is/becomes competitive to world leading measurements (additional tau- and e-appearance analyses / sterile neutrinos, ...)

- Still space for improvements (**my work/outlook**):
    - Dealing with low statistics => K.D.E.
    - Improving reconstruction algorithms
    - Other ideas to be developed

References

Content references:

IceCube Collaboration, The measurement of neutrino oscillation with the full IceCube detector, ICRC 2013 Proceedings, arXiv:1309.7008

Dmitry Chirkin, Likelihood description for comparing data with simulation of limited statistics, arXiv:1304.0735

Graphics references:

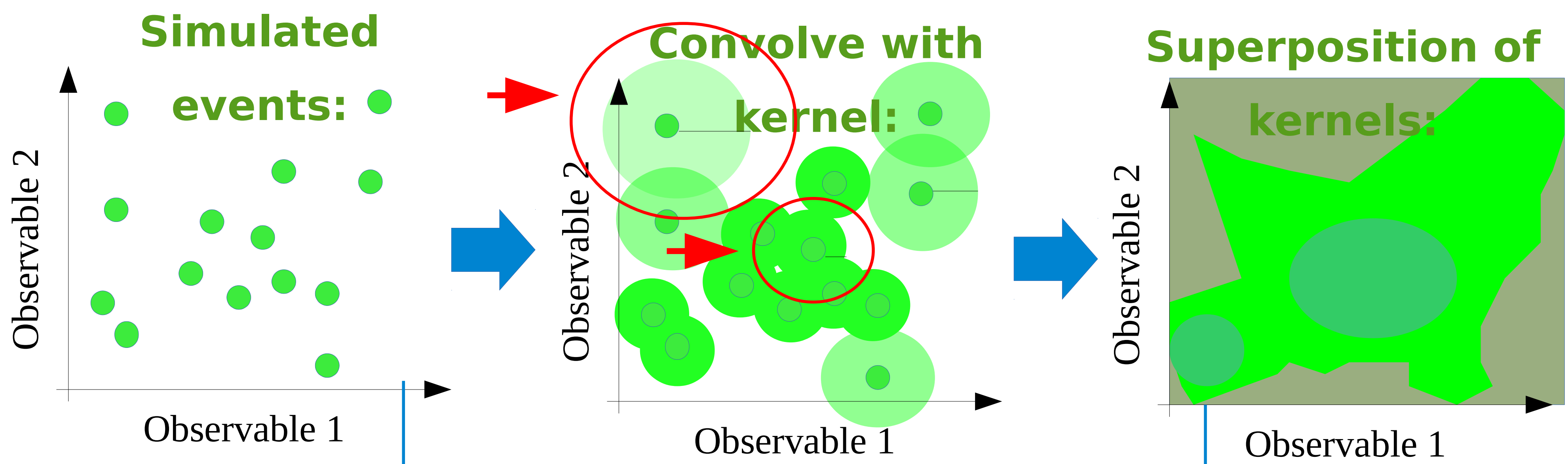
http://lappweb.in2p3.fr/neutrinos/neutimg/nkes/oscill.gif
http://www.newworldencyclopedia.org/entry/Elementary_particle
http://www.lead-conduct.de/wp-content/uploads/2012/05/Motivation-vs.-Desinteresse.png
http://commons.wikimedia.org/wiki/File:1_Earth_(blank_2).png

Thanks for listening

Backup

Idea of KDE

So, how can we deal with our limited knowledge of the pdf due to too low MC statistics?



Gaussian Kernel:

$$KDE(\vec{y}) = \sum_{i=1}^{i=N} A_i \cdot \exp\left(\frac{-1}{2}(\vec{x}_i - \vec{y})^T C^{-1} (\vec{x}_i - \vec{y}) / (h \cdot \lambda_i)^d\right)$$

- KDE can be evaluated everywhere!
- Gaussian norm.
- covariance of data
- width of Gaussians
- pdf dimensions

Implementation of KDE

Gaussian Kernel:

pdf dimensions

$$KDE(\vec{y}) = \sum_{i=1}^{N} A_i \cdot \exp\left(\frac{-1}{2}(\vec{x}_i - \vec{y})^T C^{-1} (\vec{x}_i - \vec{y}) / (h \cdot \lambda_i)^d\right)$$

KDE can be evaluated everywhere!

Gaussian norm.

covariance of data

width of Gaussians

Seed bandwidth:

$$h = \left(\frac{N(d+2)}{4}\right)^{\frac{-1}{d+4}}$$

(„Silverman“ normalization)

Adaptive factor:

$$\lambda_i = \left(\frac{kde_i}{glob}\right)^{-\alpha}$$

$$glob = \exp\left(\frac{1}{N}\sum_{i=1}^{N} \ln(kde_i)\right)$$

$$kde_i = KDE(\vec{x}_i)\Big|_{\lambda_i = 1, \forall i}$$

What about simulations that require a weight to be introduced for every data point?

Implementation of KDE

Gaussian Kernel:

$$KDE(\vec{y}) = \sum_{i=1}^{N} w_i \cdot A_i \cdot \exp\left(\frac{-1}{2}(\vec{x}_i - \vec{y})^T C_w^{-1} (\vec{x}_i - \vec{y}) / (h \cdot \lambda_i)^d\right)$$

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pdf dimensions

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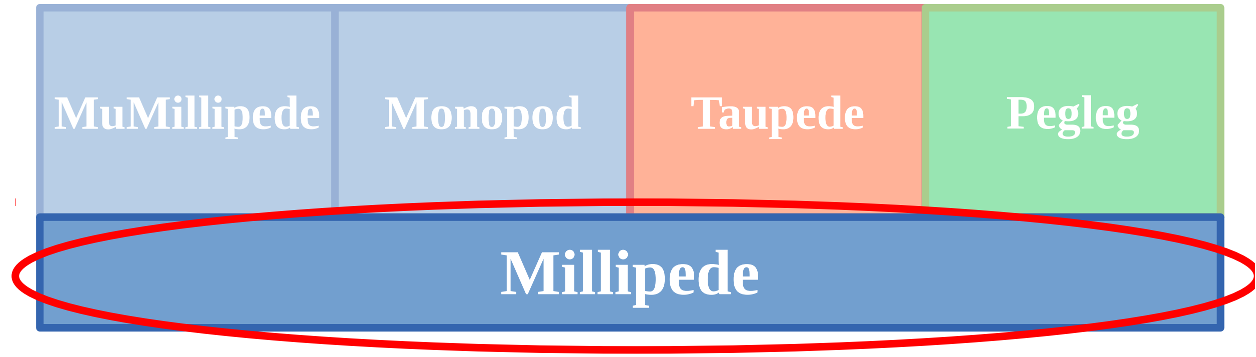
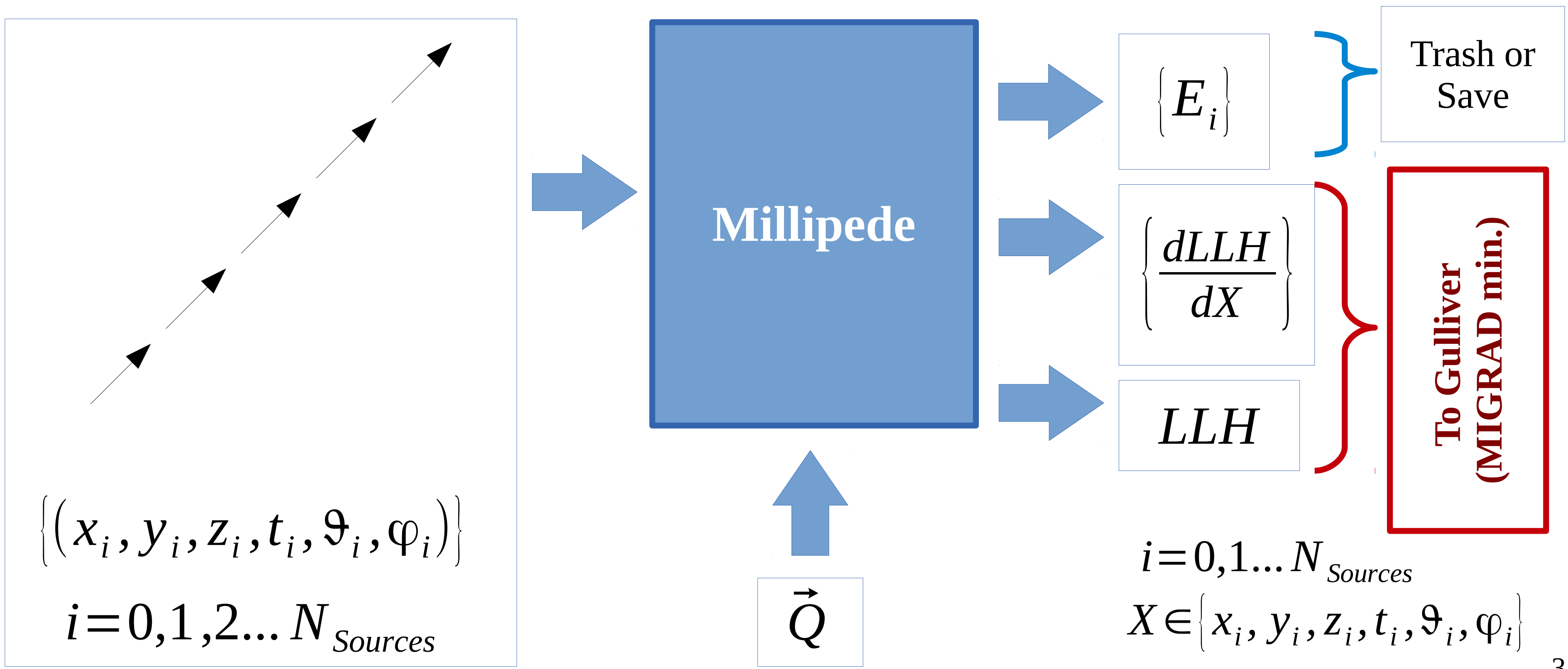
For more details on the method see: arXiv:0709.1616

Millipede Introduction

So, what the key-element of all modules, **"Millipede"**, does is:





Pegleg

Hypothesis:
Cascade
+
<u>FINITE</u> track