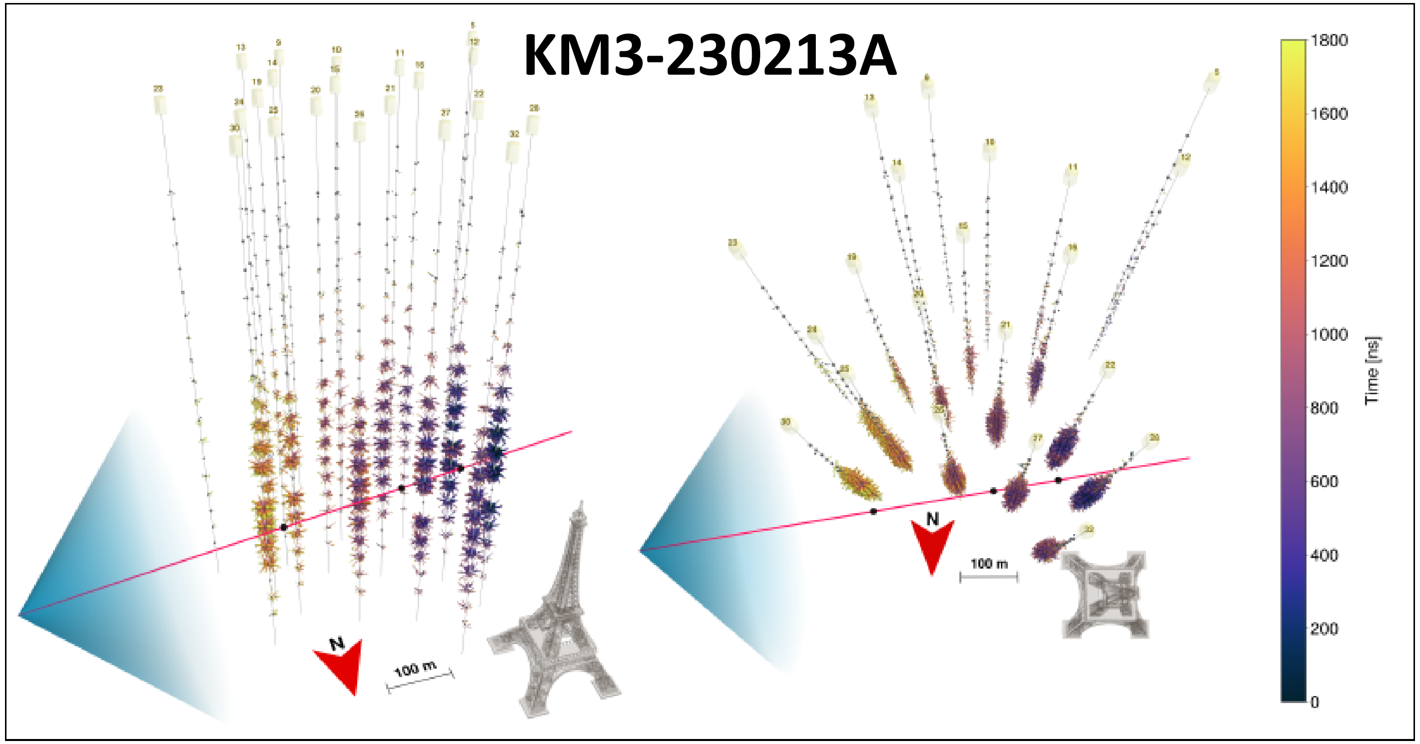
KM3-230213A

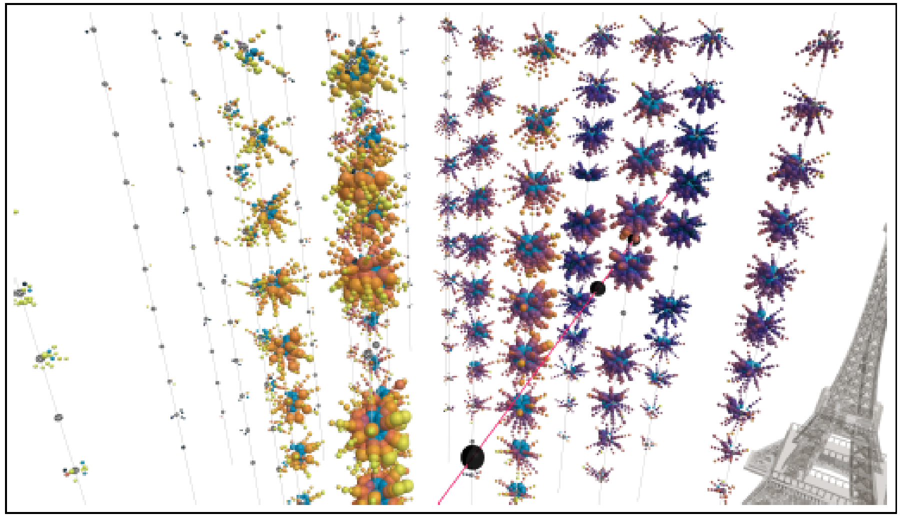
Nikhef topical lectures

Maarten de Jong (Nikhef/Leiden University)

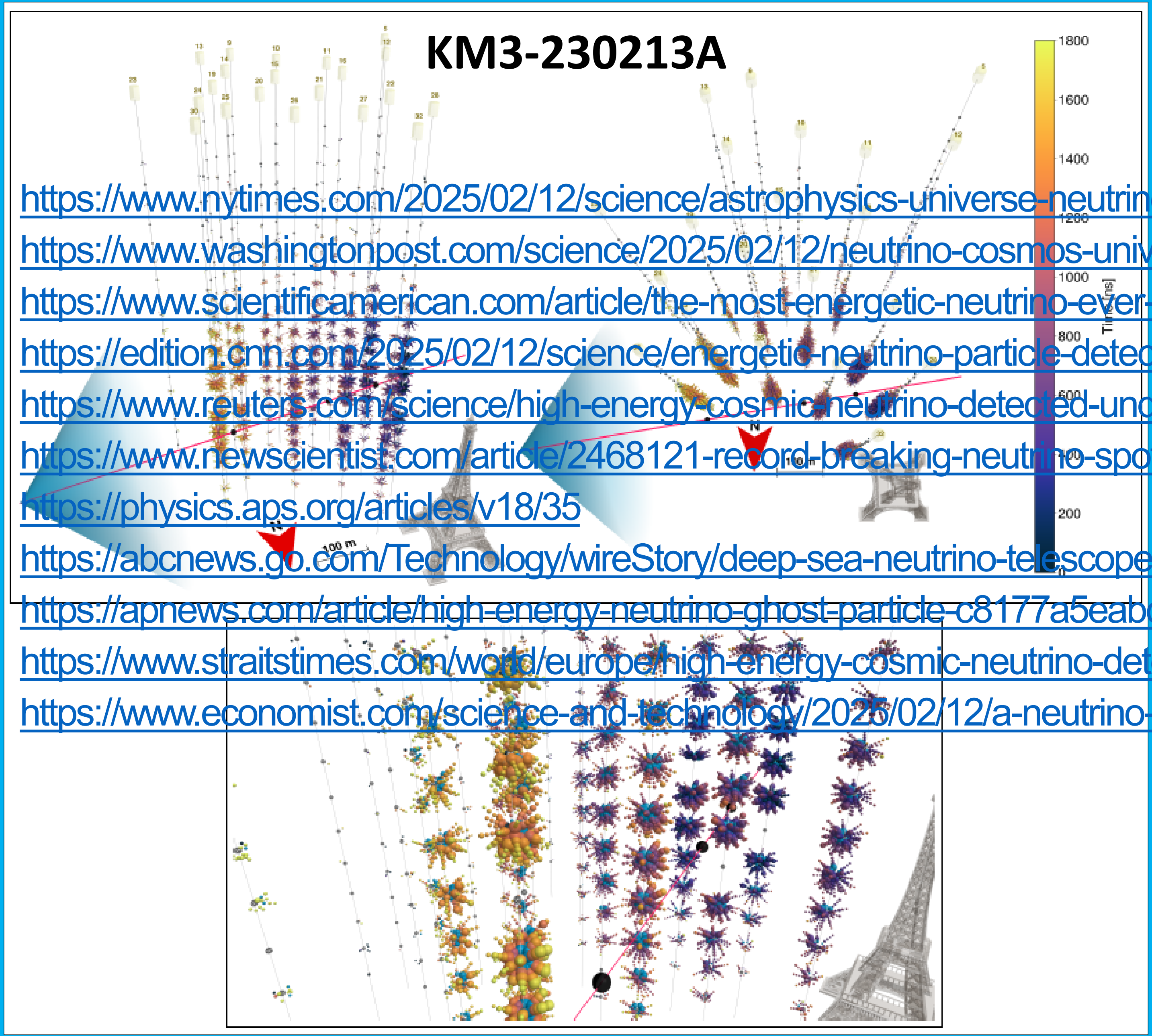
KM3-230213A

KM3NeT year month day counter


KM3-230213A
N
100 m
N
100 m
1800
1600
1400
1200
1000
800
600
400
200
0
Time [ns]




The international journal of science / 13 February 2025
nature
COSMIC CATCHER
Deep-sea telescope detects neutrino with highest energy ever recorded



https://www.nytimes.com/2025/02/12/science/astrophysics-universe-neutrinos.html
https://www.washingtonpost.com/science/2025/02/12/neutrino-cosmos-universe-astonomers/
https://www.scientificamerican.com/article/the-most-energetic-neutrino-ever-seen-makes-a-mediterranean-splash/
https://edition.cnn.com/2025/02/12/science/energetic-neutrino-particle-detection/index.html
https://www.reuters.com/science/high-energy-cosmic-neutrino-detected-under-mediterranean-sea-2025-02-12/
https://www.newscientist.com/article/2468121-record-breaking-neutrino-spotted-tearing-through-the-mediterranean-sea/
https://physics.aps.org/articles/v18/35
https://abcnews.go.com/Technology/wireStory/deep-sea-neutrino-telescope-spots-energetic-ghost-particle-118738655
https://apnews.com/article/high-energy-neutrino-ghost-particle-c8177a5eabdcab2fd045d92e872e1fb1
https://www.straitstimes.com/world/europe/high-energy-cosmic-neutrino-detected-under-mediterranean-sea
https://www.economist.com/science-and-technology/2025/02/12/a-neutrino-telescope-spots-the-signs-of-something-cataclysmic

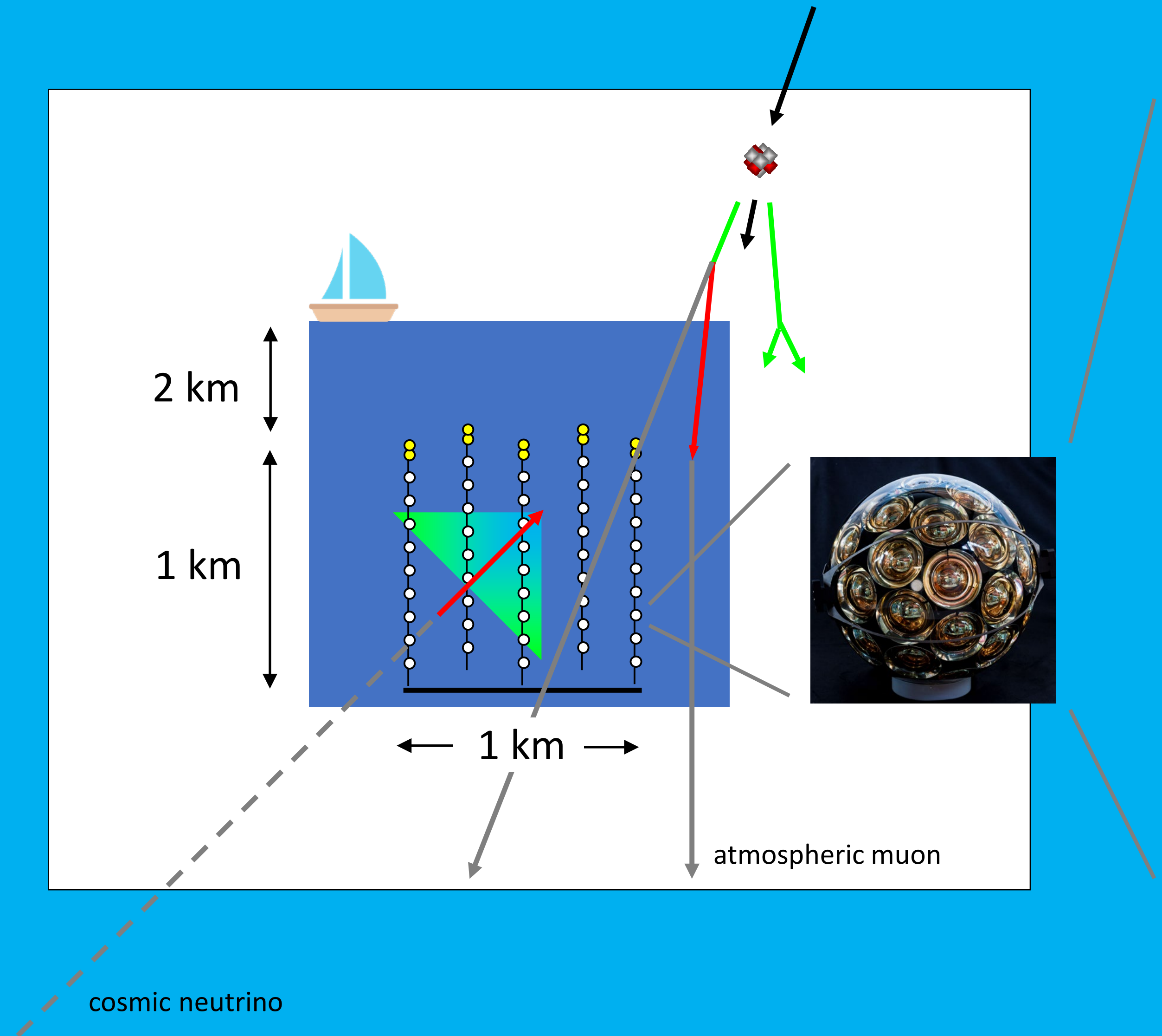
Recap

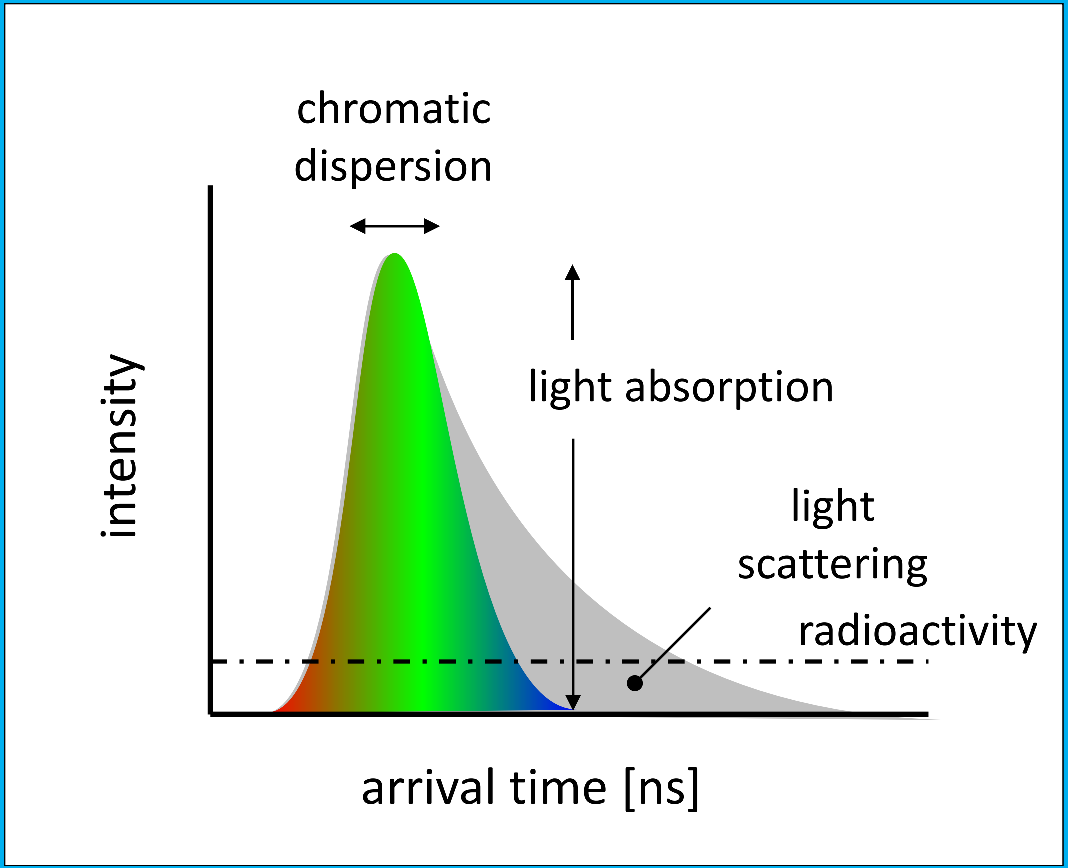
1. Precision of estimation of parameters increases with more information
2. For a given set of data (i.e. amount of information),
   maximum likelihood yields smallest variance of parameters
3. If data are normally distributed and χ^2 depends linearly on parameters,
   smallest χ^2 can be obtained by solving matrix equation $Ax = b$
4. Else, determination of maximum likelihood involves iterative procedure

PDF describing data

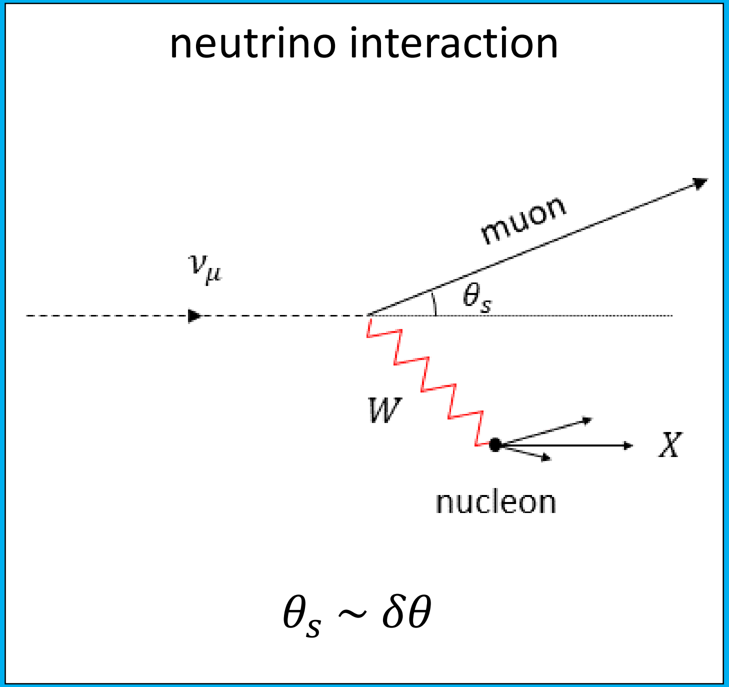
$$\nabla \chi^2 = \nabla f \times \frac{\partial \chi^2}{\partial f}$$

KM3NeT neutrino telescope

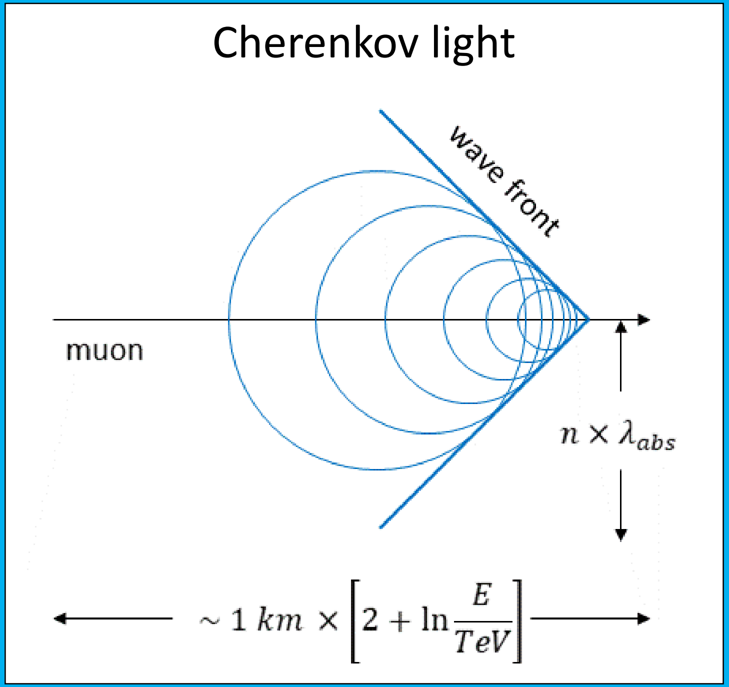




“golden” channel



+



=

1. Target mass

   overcome small cross section

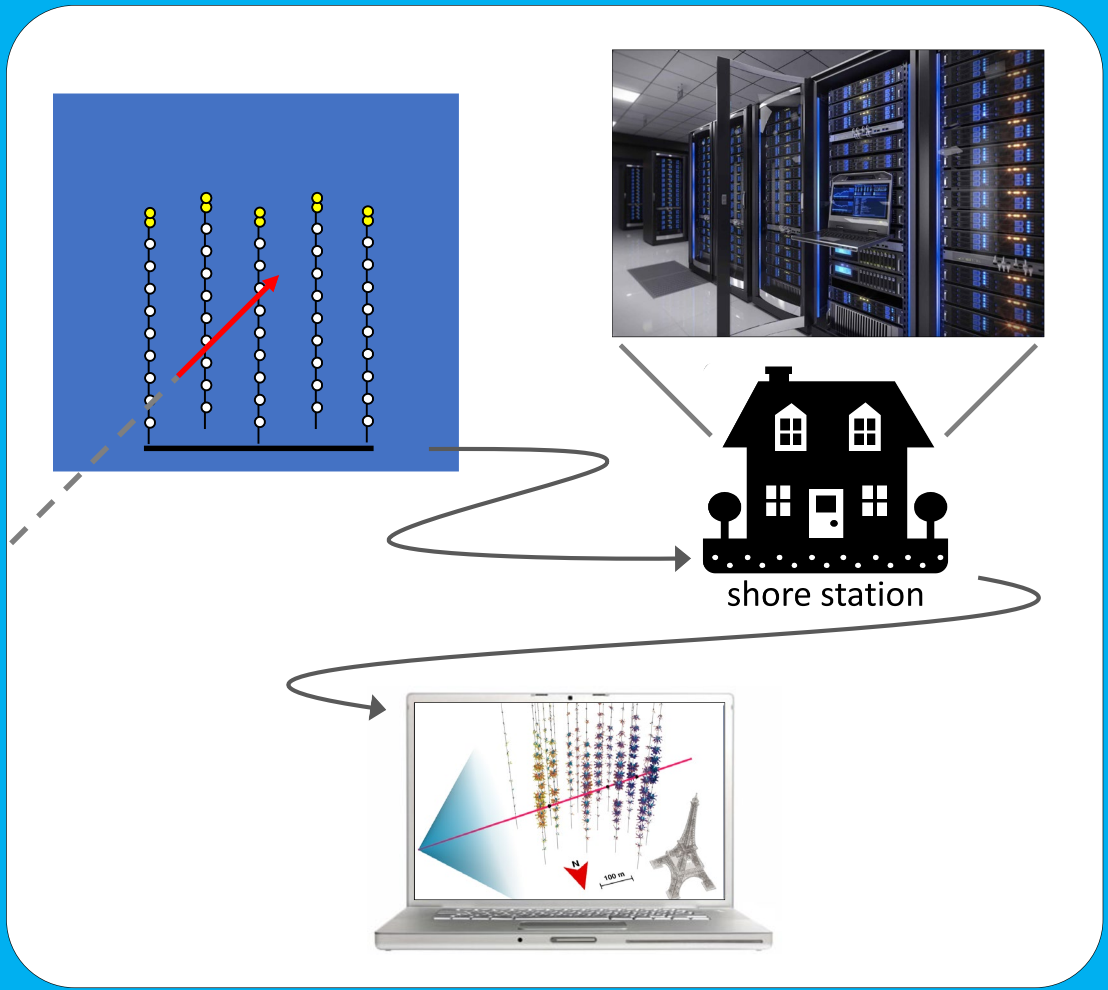
2. Transparency

   sparse sensor array

3. Muon range

   good angular resolution

All-data-to-shore



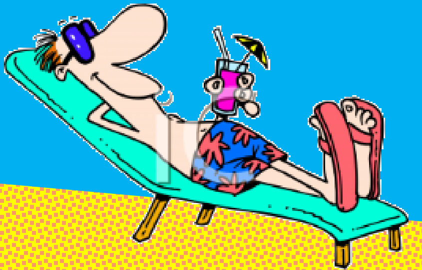
25 Gb/s

⇓

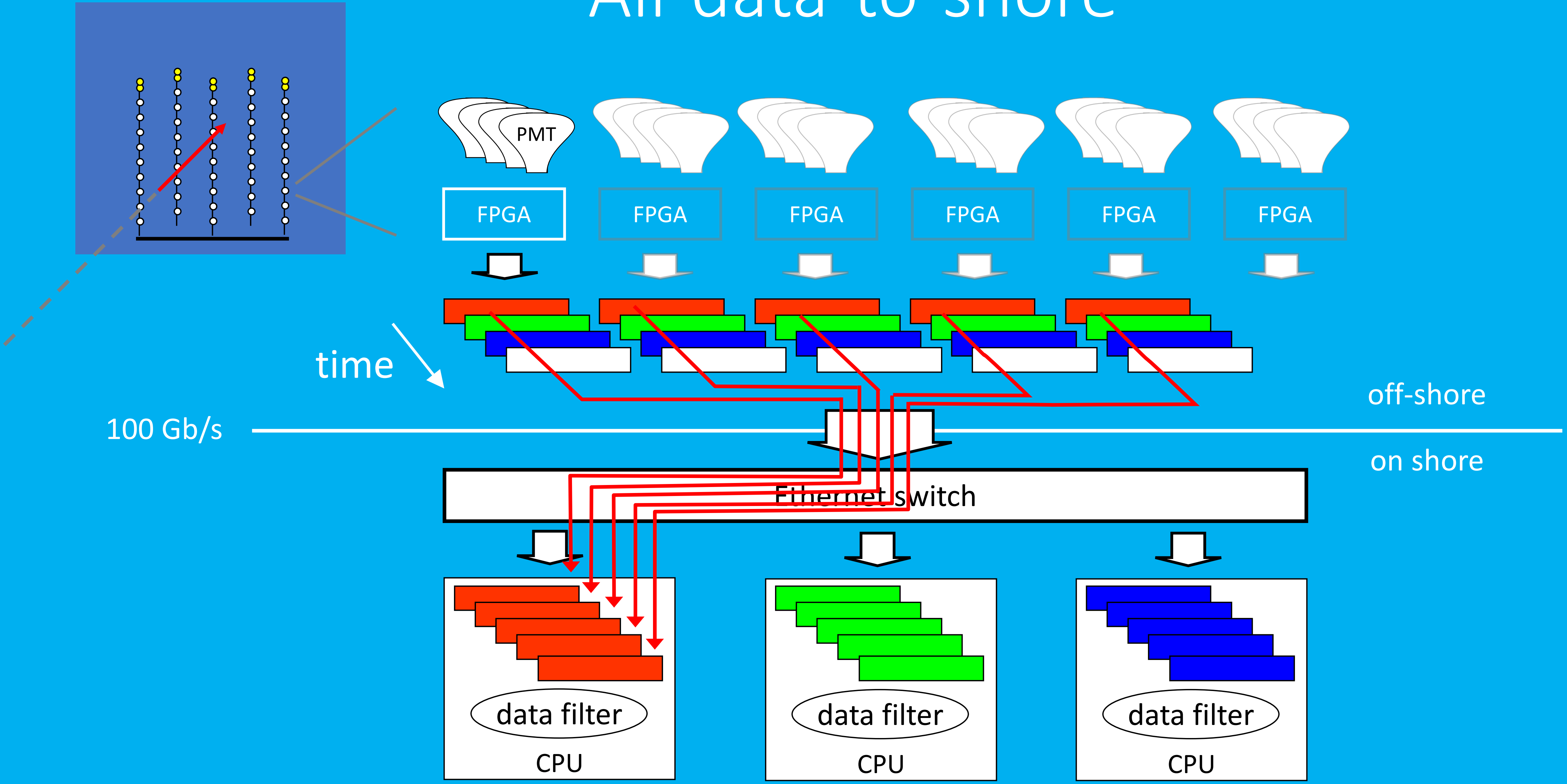
“something happens”

⇓

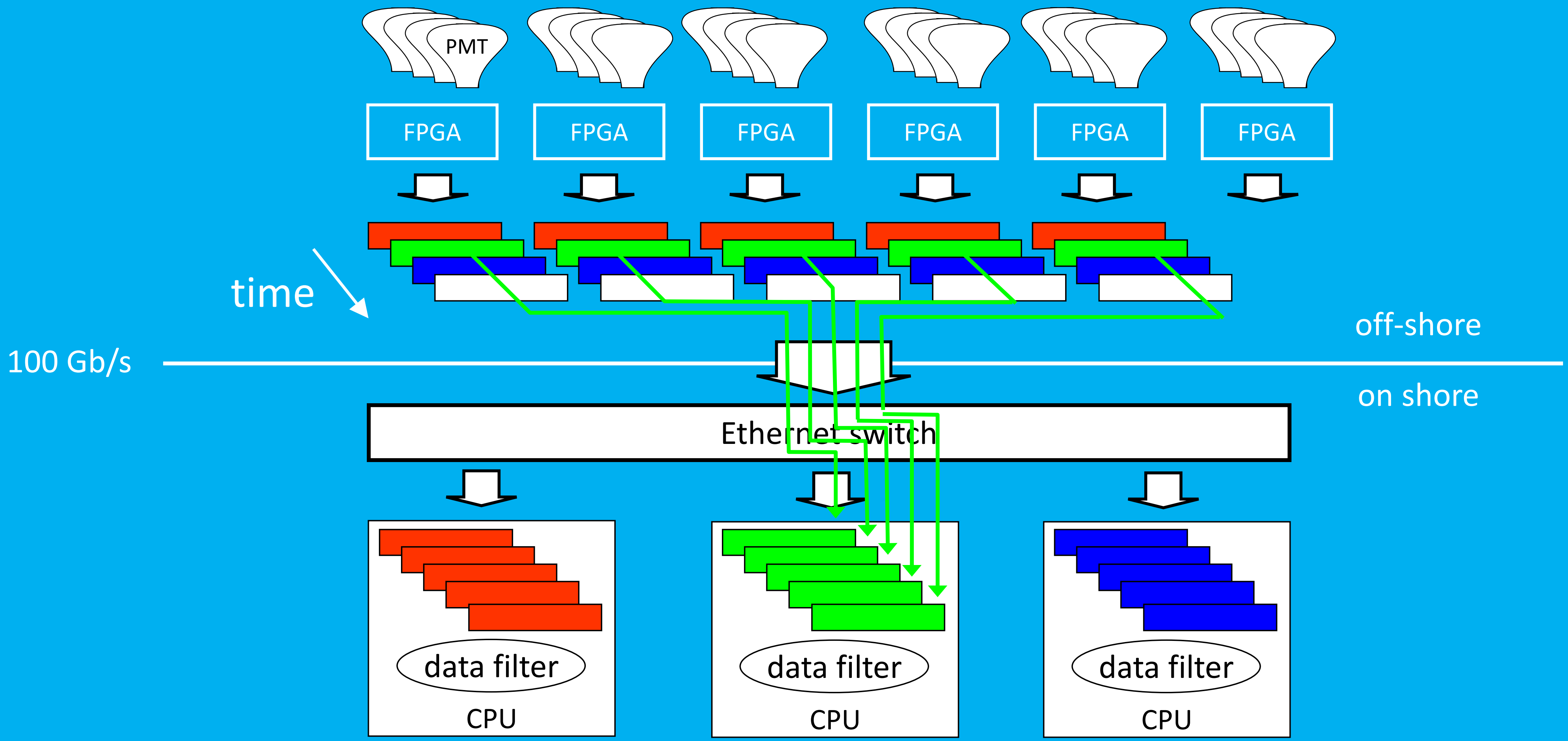
10 Mb/s



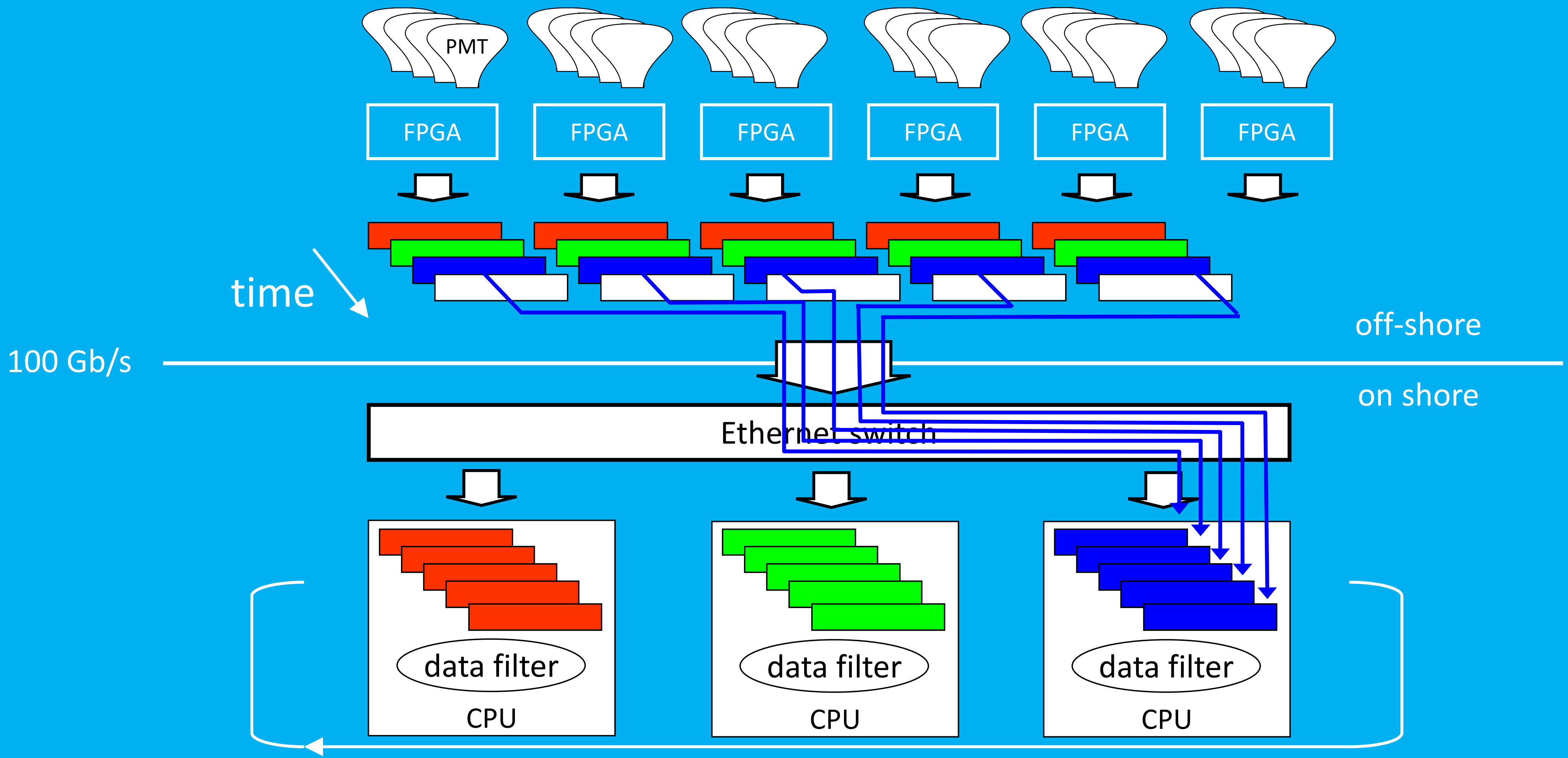
All-data-to-shore



All-data-to-shore



All-data-to-shore



Data filter

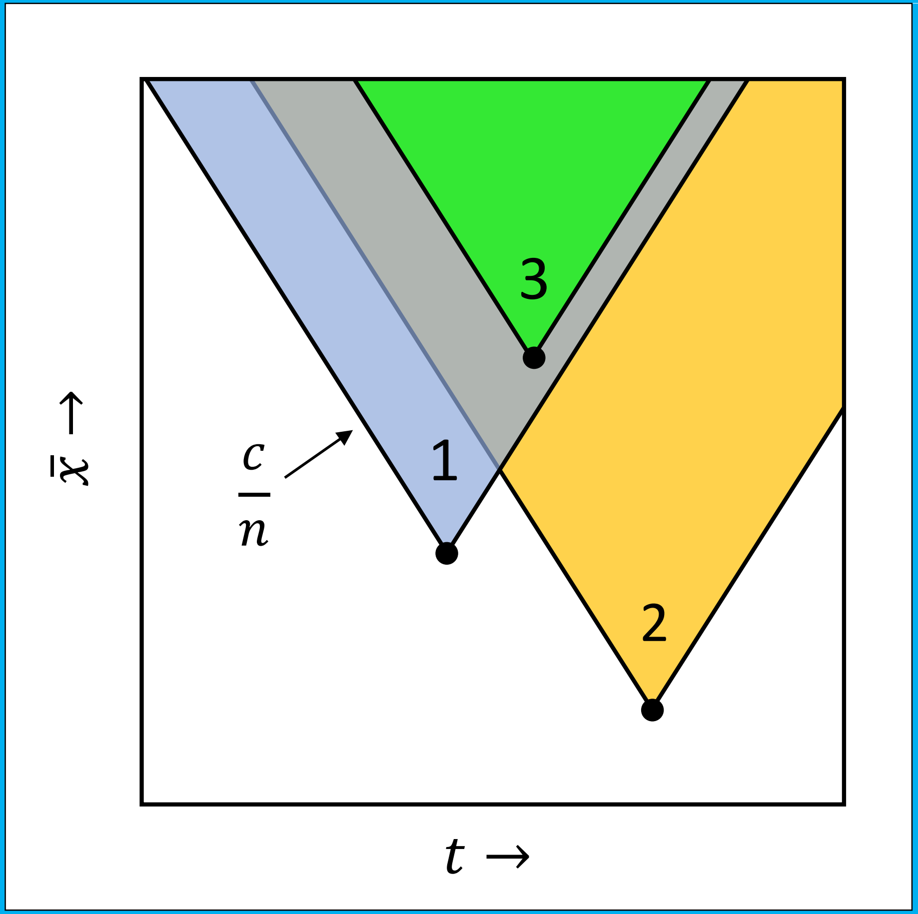
- Level 1
  - local coincidence of two (or more) L0 hits in same optical module
    - typical time window 20 ns
- Level 2
  - subset of L1 hits with additional criteria
    - typical opening angle between PMTs ≤ 90 deg.
    - typical time window 15 ns
- Level 3
  - minimal subset of L2 hits that are causally related
    - typical minimal number of L2 hits is 5 (= 10 photo-electrons)
    - write "snapshot" to disk (no loss of data)

100% purity
photon counting

$$\frac{c}{n}|\Delta t| \leq |\Delta \bar{x}|$$

causality

Causality



- hit (1,3) and (2,3) are causally related
- hit (1,2) are not causally related ☹

⇩

$n!$ problem

⇩

"clique" algorithm (n^2)

number of modules — L2 rate — time window

$$R(m) \simeq \binom{N}{m} \times r \times (r\Delta T)^{m-1}$$

number of coincidences

$$\simeq \frac{N^m}{m!} \times r \times (r\Delta T)^{m-1}$$

$$= \frac{1}{m!} \times (Nr) \times (Nr\Delta T)^{m-1}$$

total rate — probability of coincidence

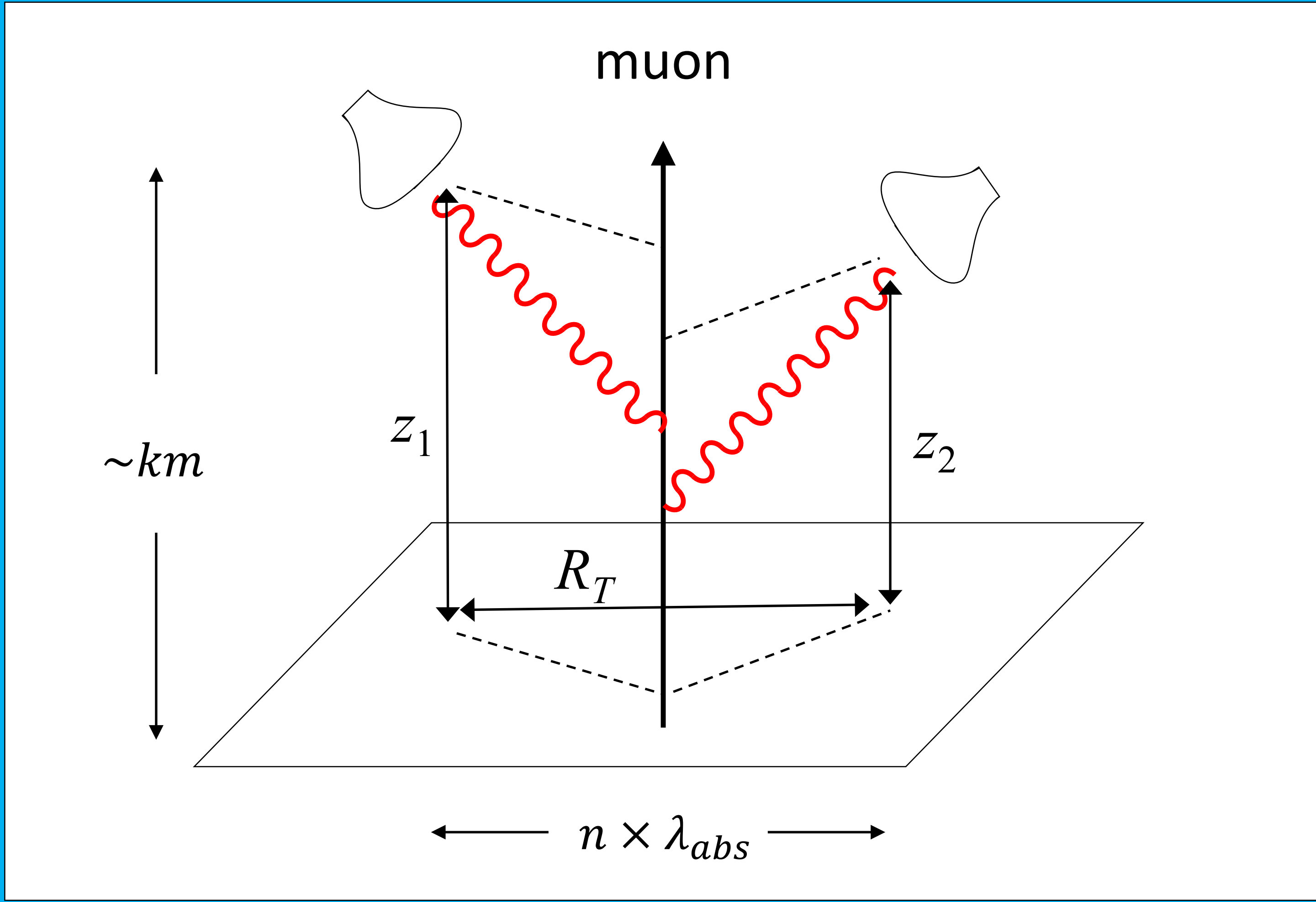
$N \cong 2000$

$r \cong 1\ kHz$

$\Delta T \cong 10\ \mu s$

$P \gg 1$

Beaming



Beaming

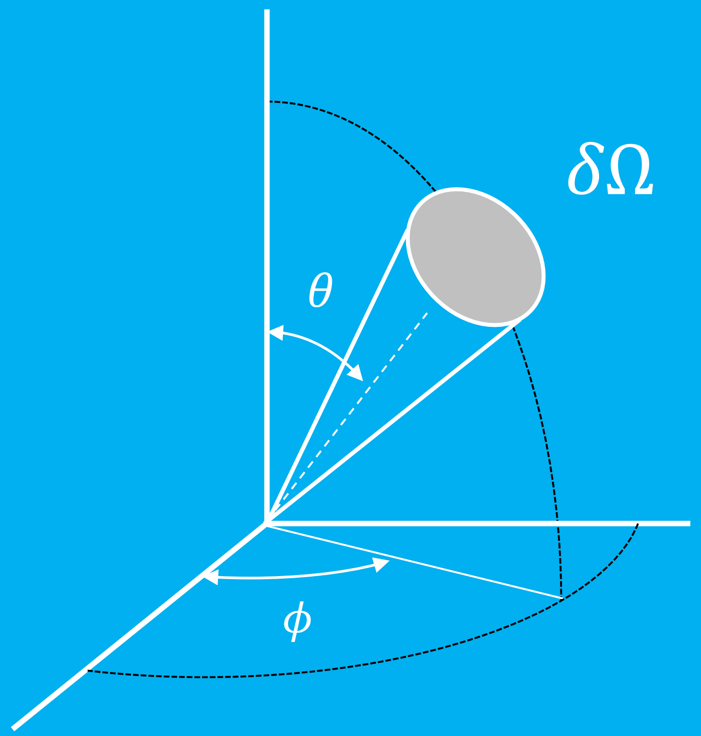
$$R(m) \simeq \frac{1}{m!} \times Nr \times (Nr\Delta T)^{m-1}$$

$$\Delta T = \frac{n}{c} D \Rightarrow \frac{1}{c} R_T \tan \theta_c$$

$$N \times \left(\frac{R_T}{D}\right)^2$$

$$R'(m) \simeq (10^{-3} - 10^{-2})^{m-1} \times R(m)$$

Full sky coverage



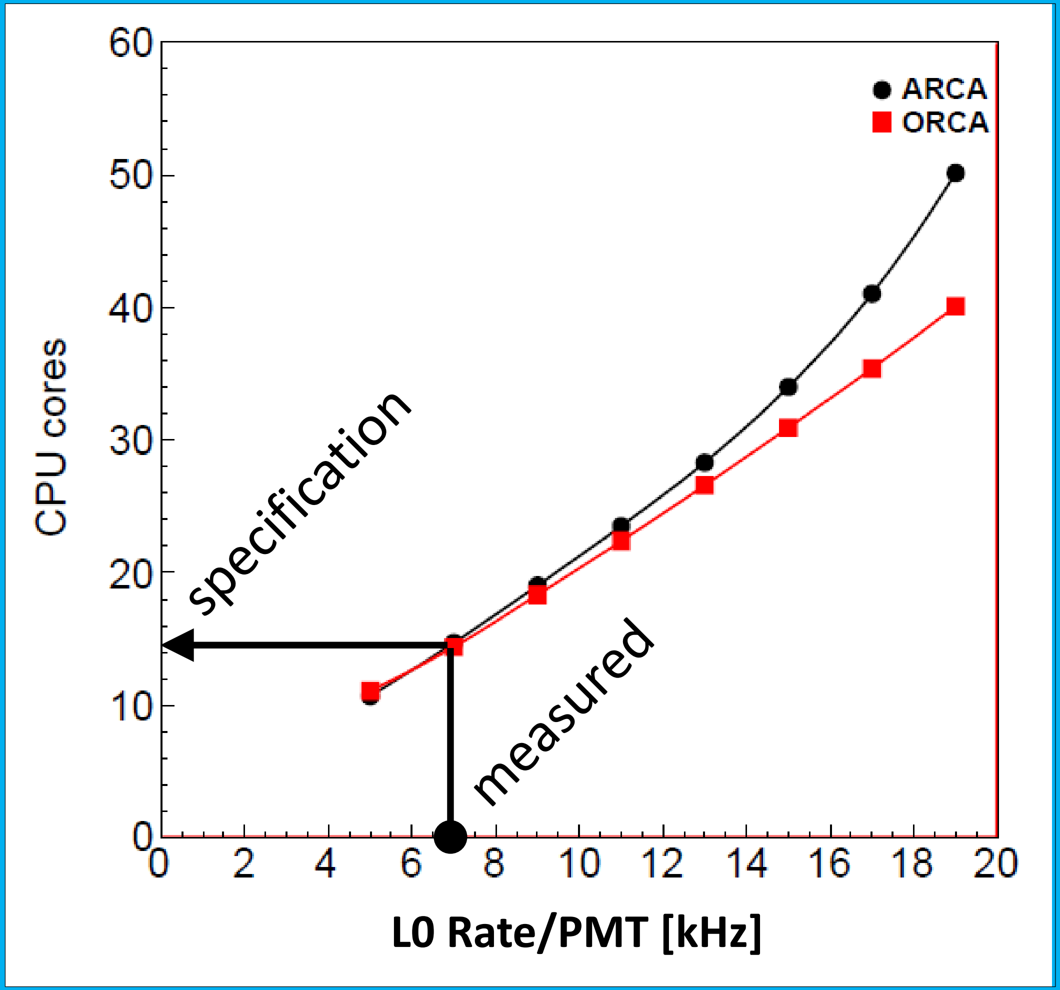
$$\delta\Omega \cong 0.06$$

$$N^{\bullet} = \frac{4\pi}{\delta\Omega} \simeq 200$$

$$R'' \simeq N^{\bullet} \times R'$$

$$\simeq N^{\bullet} \times (10^{-3} - 10^{-2})^{m-1} \times R \ll R$$

CPU usage



60
50
40
30
20
10
0
CPU cores
ARCA
ORCA
specification
measured
0
2
4
6
8
10
12
14
16
18
20
L0 Rate/PMT [kHz]

Start value problem

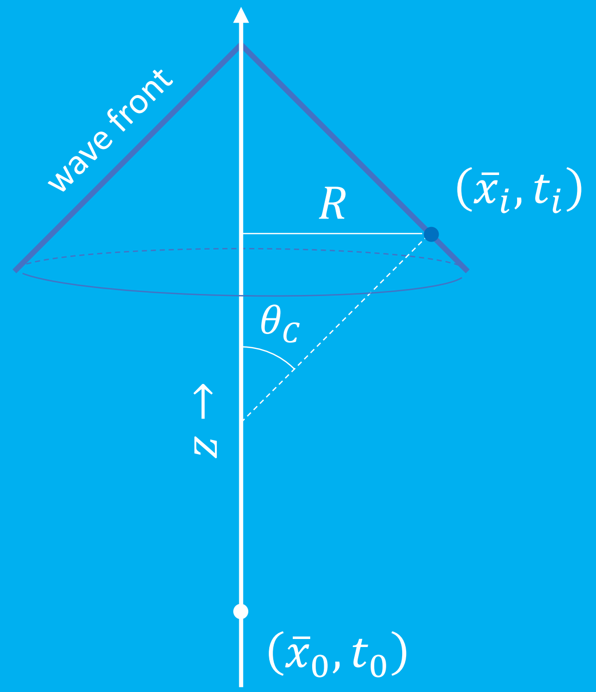
$$5D = 3D \otimes 2D$$

position-time direction

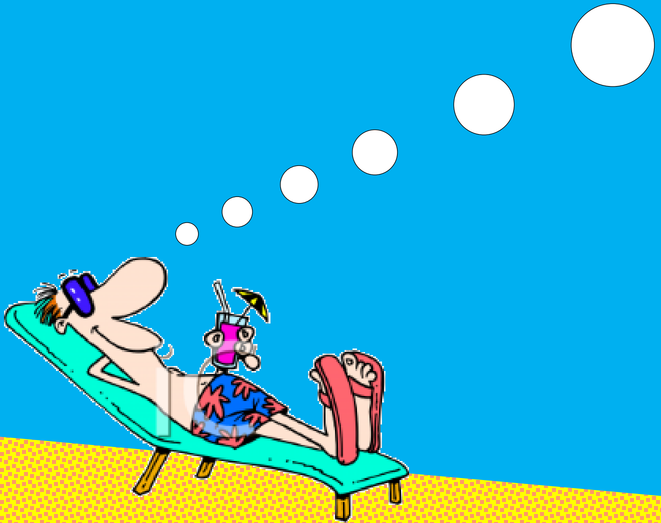
linear fit (x_0, y_0, t_0) scan (θ, φ)

$$\bar{t}_j^2 - \bar{t}_i^2 - 2(\bar{t}_j - \bar{t}_i)\,\boldsymbol{\bar{t}_0} \;=\; x_j^2 - x_i^2 - (x_j - x_i)\,\boldsymbol{x_0} \;+\; y_j^2 - y_i^2 - (y_j - y_i)\,\boldsymbol{y_0}$$

$$\bar{t}_i \equiv \frac{ct_i}{\tan\theta_C} - \frac{z_i}{\tan\theta_C} \qquad \bar{t}_0 \equiv \frac{ct_0}{\tan\theta_C}$$



$$ct_i \;\cong\; ct_0 + \Delta z + R\tan\theta_C$$



Linear fit

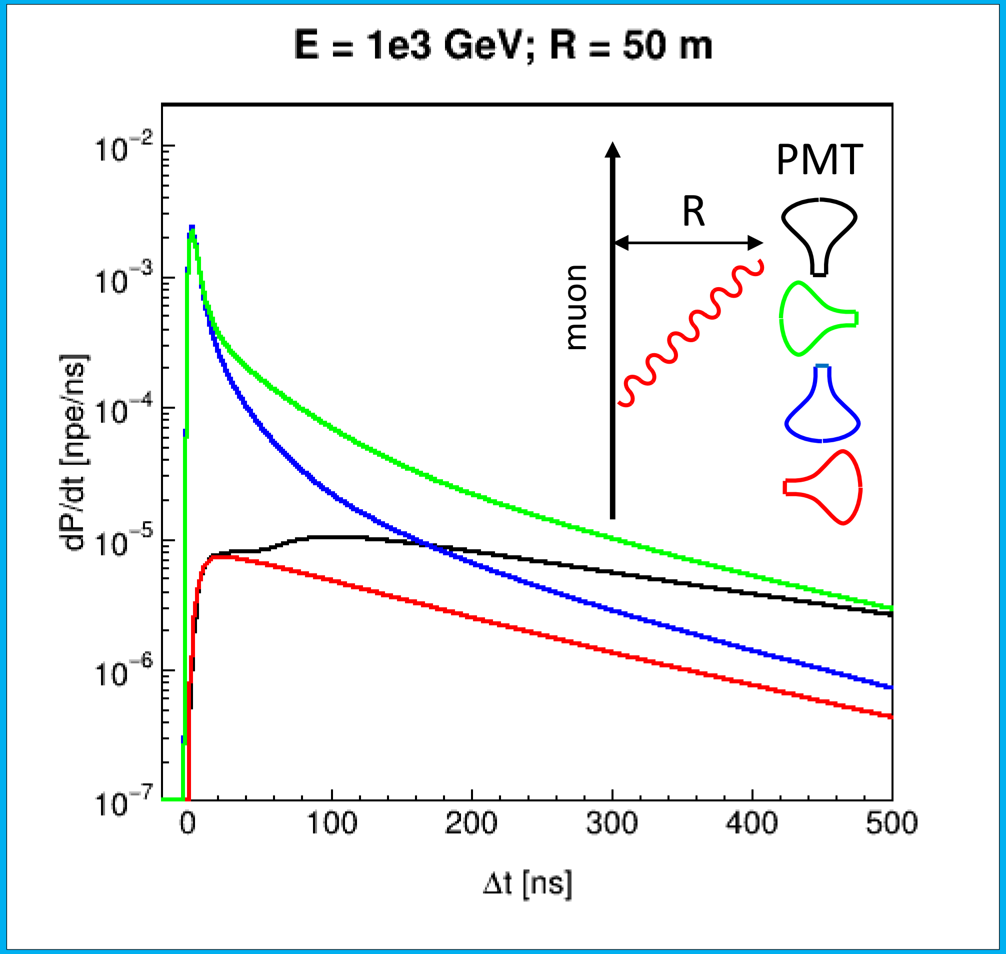
$$y = H\,\theta$$

$(n \times 1)$ $(n \times k)$ $(k \times 1)$

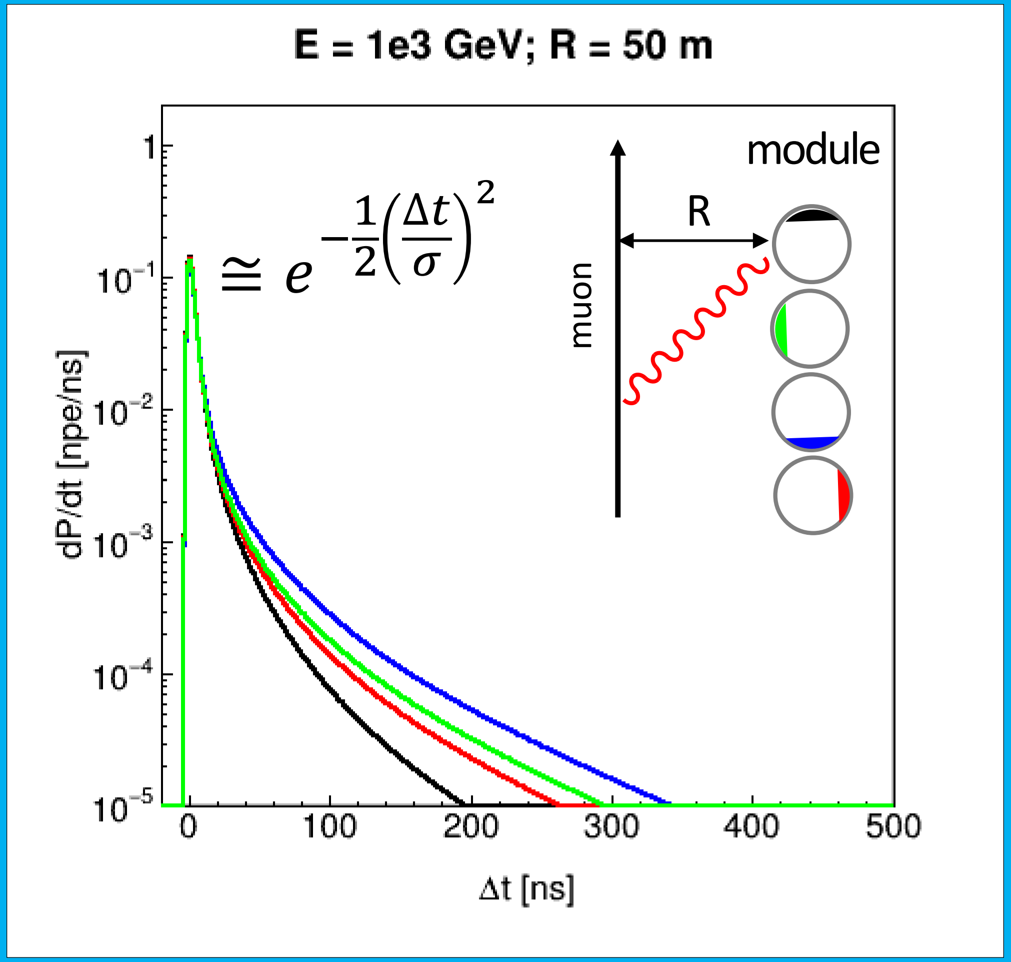
1 (0) solution

Gaussian PDF

L0



L1



Scan (θ, φ)

$1°$ grid of directions

⇩

keep N best solutions

Which N best?

$$\underset{(k\times 1)}{\hat{\theta}} = (\underset{(k\times n)}{H^T}\ \underset{(n\times n)}{V^{-1}}\underset{(n\times k)}{H})^{-1}\underset{(k\times n)}{H^T}\underset{(n\times n)}{V^{-1}}\underset{(n\times 1)}{y}$$

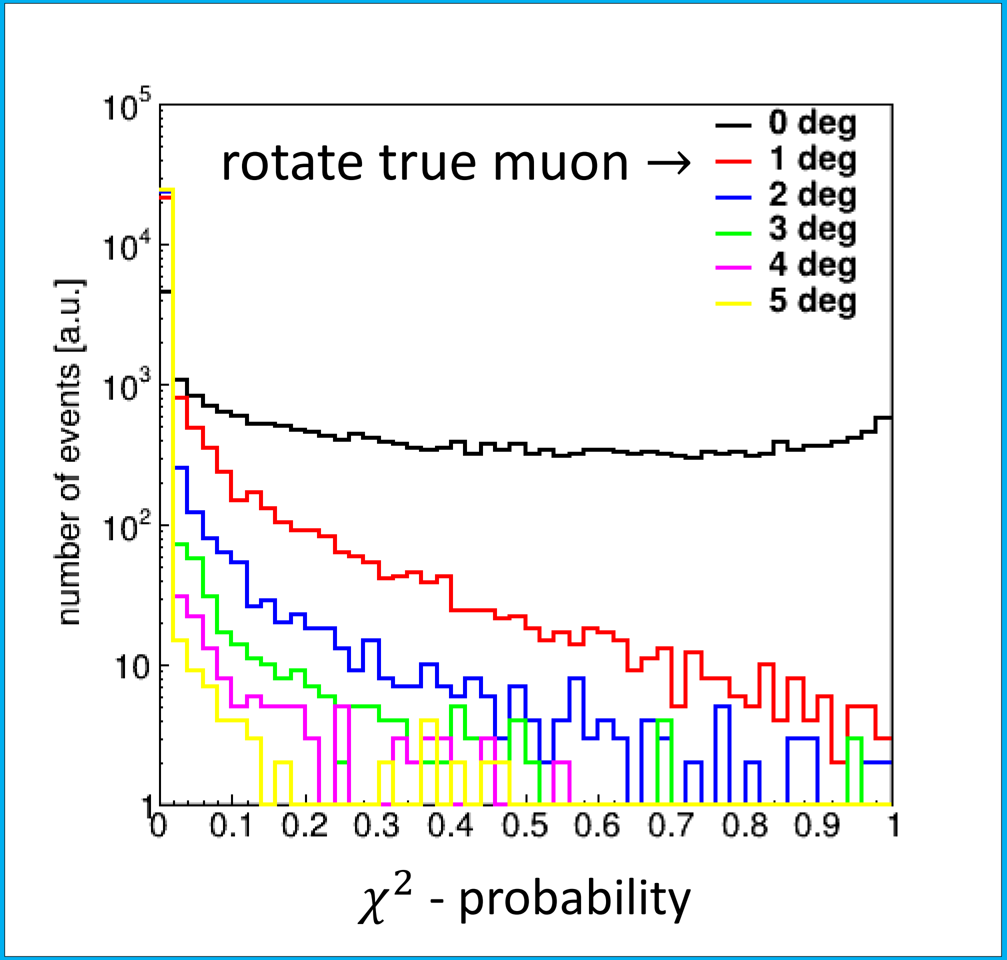
$$V = \begin{pmatrix} \sigma_1^2 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & \sigma_n^2 \end{pmatrix}$$

grid angle ⇨

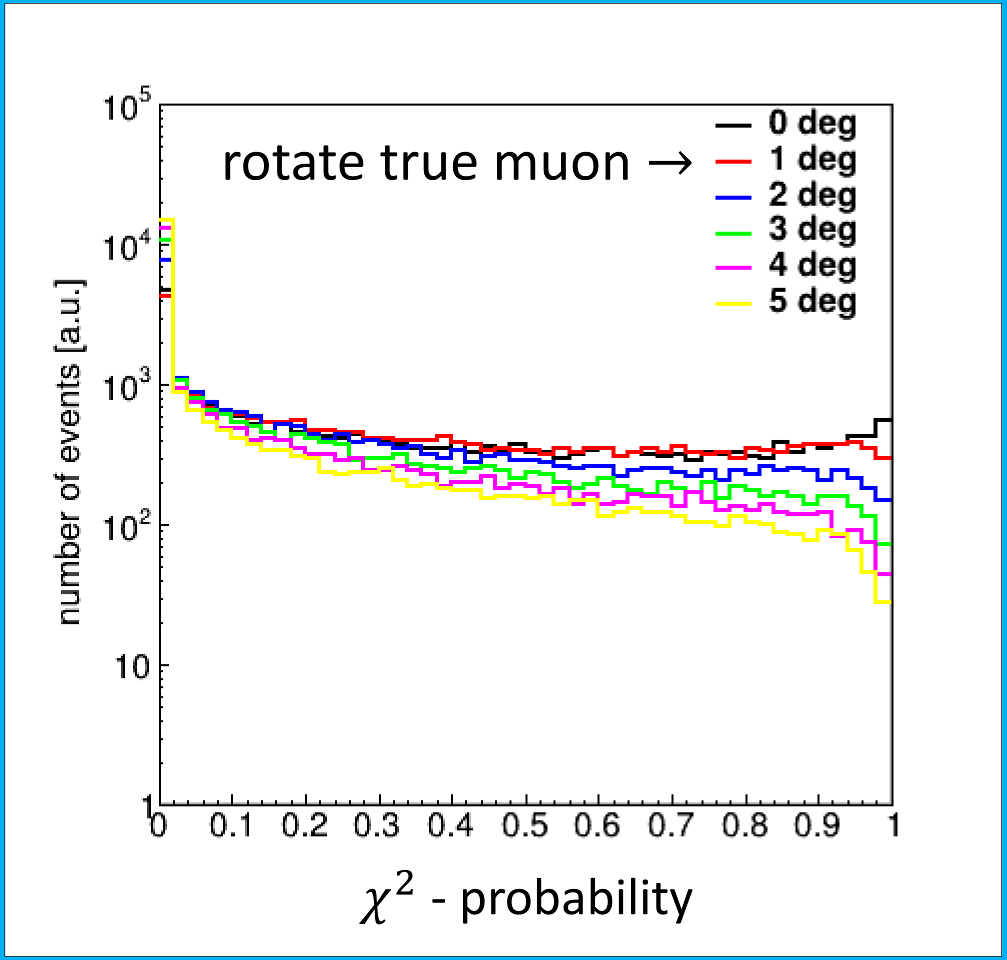
$$V_{ij} \mathrel{+}= \delta\alpha^2 \frac{\partial t_i}{\partial \alpha}\frac{\partial t_j}{\partial \alpha}$$

Which N best?

w/o co-variances



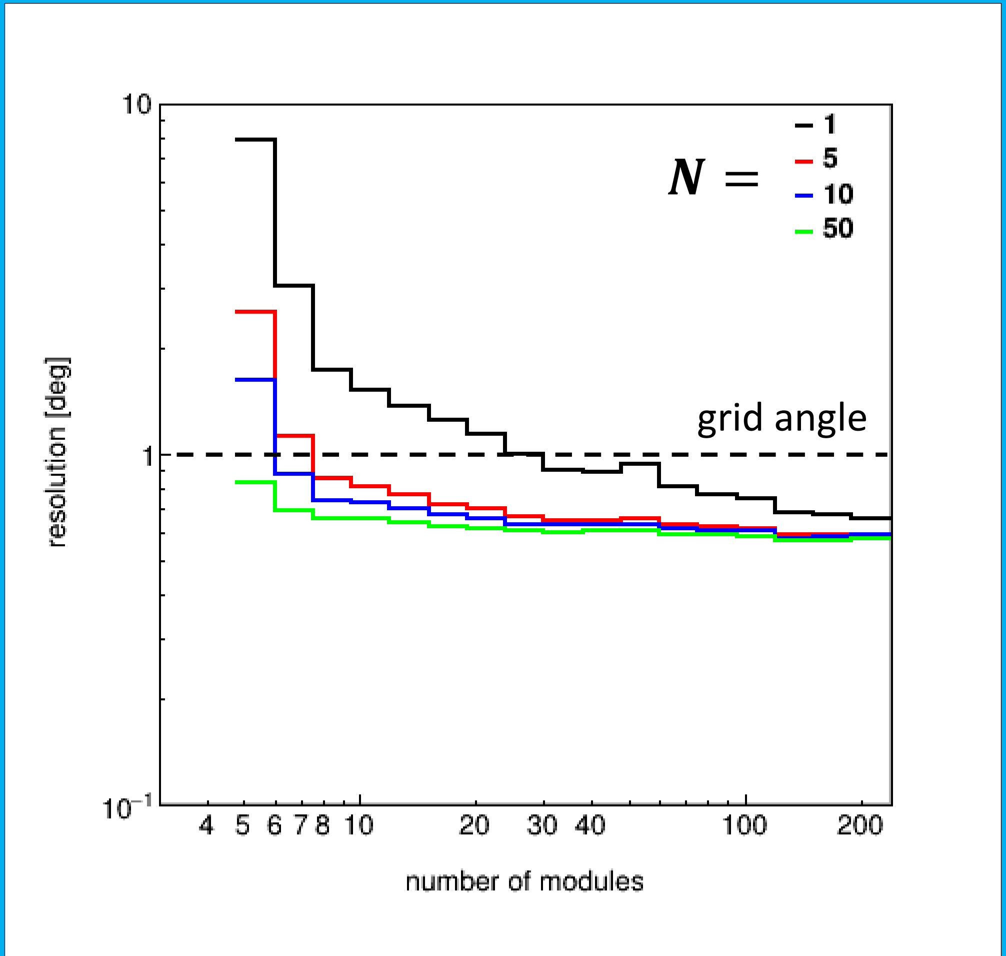
with co-variances



Which N best?

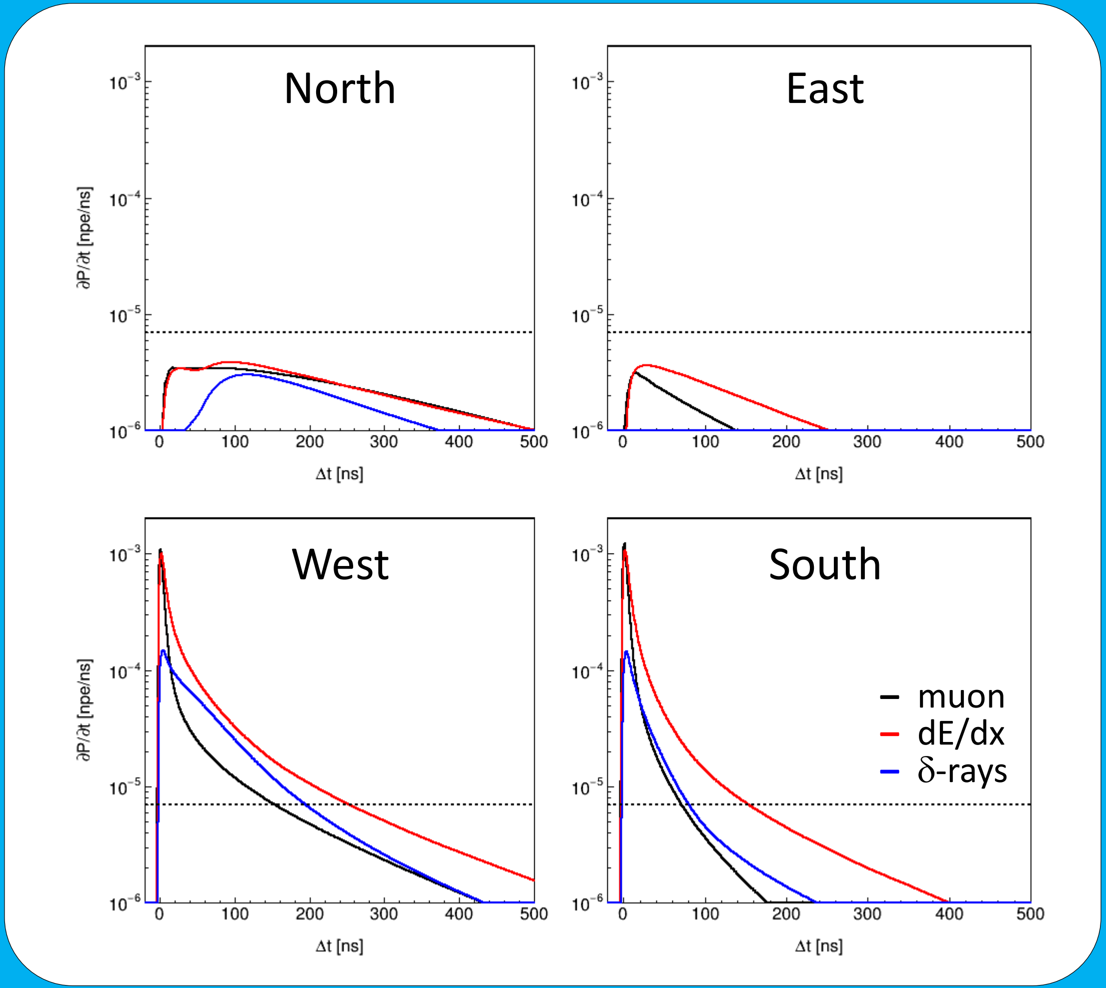
$$Q \equiv n - 0.25\frac{\chi^2}{\mathrm{NDF}}$$

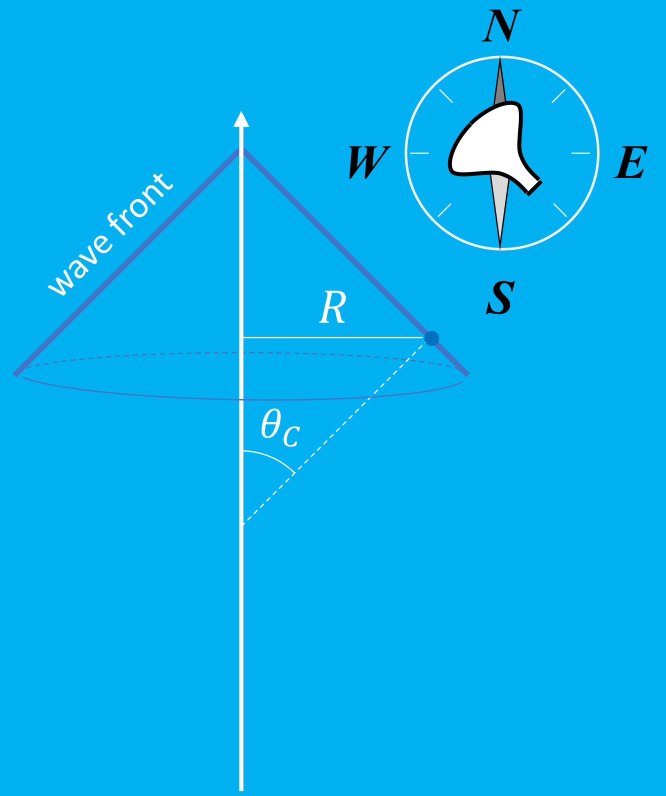
⇨

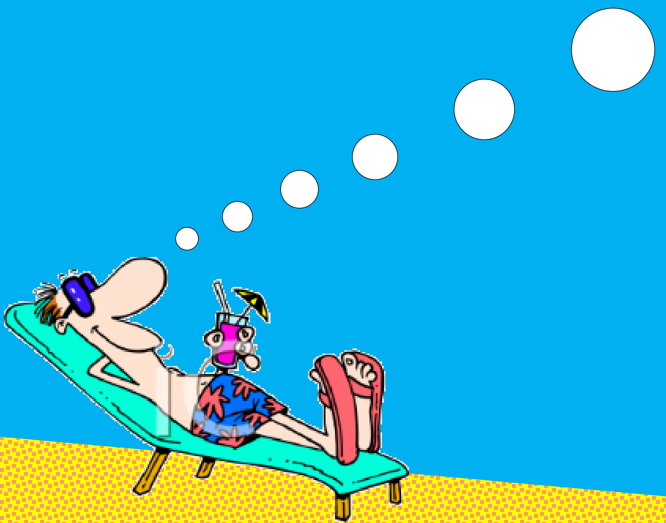


⇨ ✓ $N = 50$

PDF of Cherenkov light







PDF of Cherenkov light

- PDF can be calculated from first principles when [effective] scattering length is much larger than absorption length (see documentation)

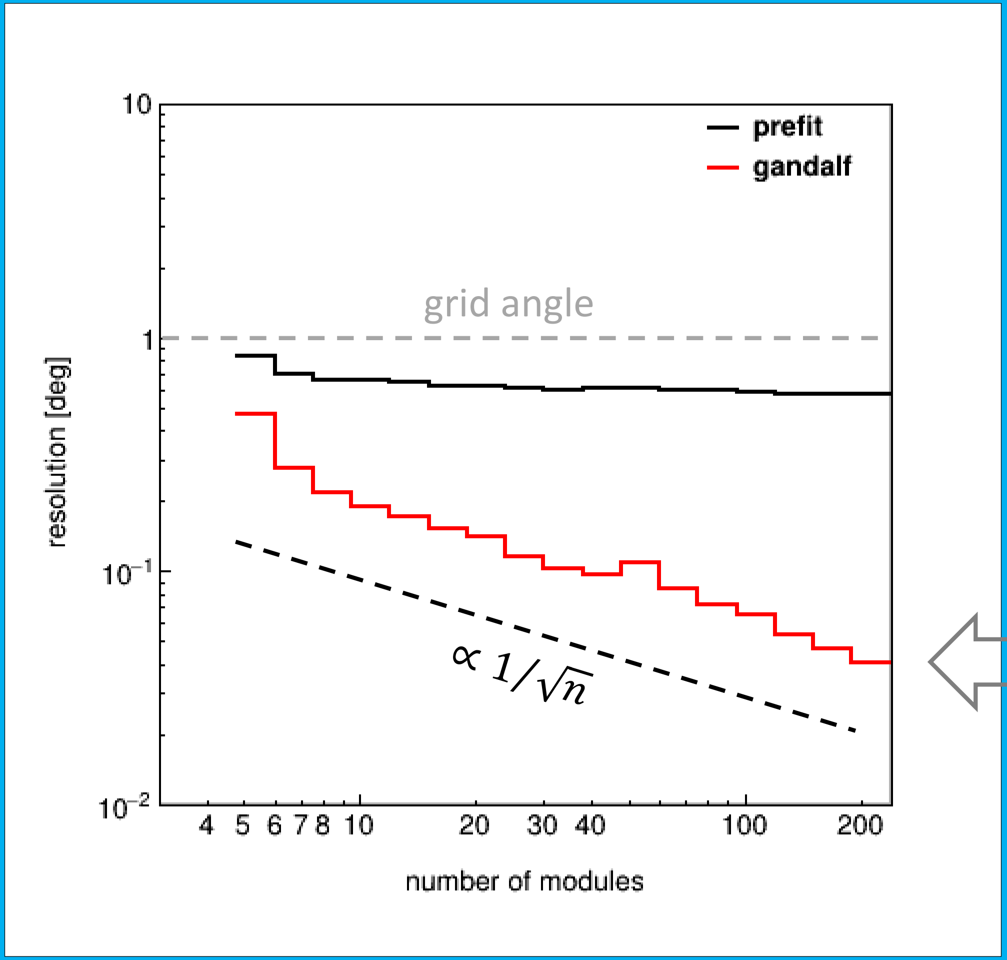
$\frac{1}{R} \propto$ $\qquad$ $\propto \frac{1}{R}$

$$\frac{d\mathcal{P}}{dt} = \Phi_0(R,\lambda)\, A \left(\frac{\partial t}{\partial \lambda}\right)^{-1} \varepsilon(\cos\theta_\oslash)\, QE(\lambda)\, e^{-d/\lambda_{abs}}\, e^{-d/\lambda_s}$$

$$\frac{d\mathcal{P}}{dt} = \iiint d\lambda\, dz\, d\phi_0\, \frac{1}{2\pi} \frac{dN}{dx} \frac{1}{\lambda_s} \left(\frac{\partial t}{\partial u}\right)^{-1} \varepsilon(\cos\theta_\oslash)\, QE(\lambda)\, e^{-d/\lambda_{att}} \frac{dP_s}{d\Omega_s}\, d\Omega$$

$\frac{\partial N_s}{\partial u}$ $\qquad$ $\frac{1}{1-\cos\theta_s}$

Performance



world's best!

$0.05° \cong 1\ mrad \cong 3\ arcmin$

“intelligent lockdown”

Dear Dorothea and Robert,¶

3 March 2020

I would like to suggest that the acoustic position calibration is approached from a data analysis perspective. If I correctly understood, there are various emitters on the seabed. The acoustic signals are regularly produced but the actual time of the emission is not directly recorded. These signals are synchronously detected in different optical modules located on different strings. Furthermore, the positions of the modules are constraint by the mechanics of the string. To make optimal use of the available information, the shapes of the different strings should simultaneously be reconstructed from the measured times-of-arrival of the acoustic signals. In this, the time of emission of the acoustic signal is a free parameter. To further constrain the system, signals from different emitters should be joint.

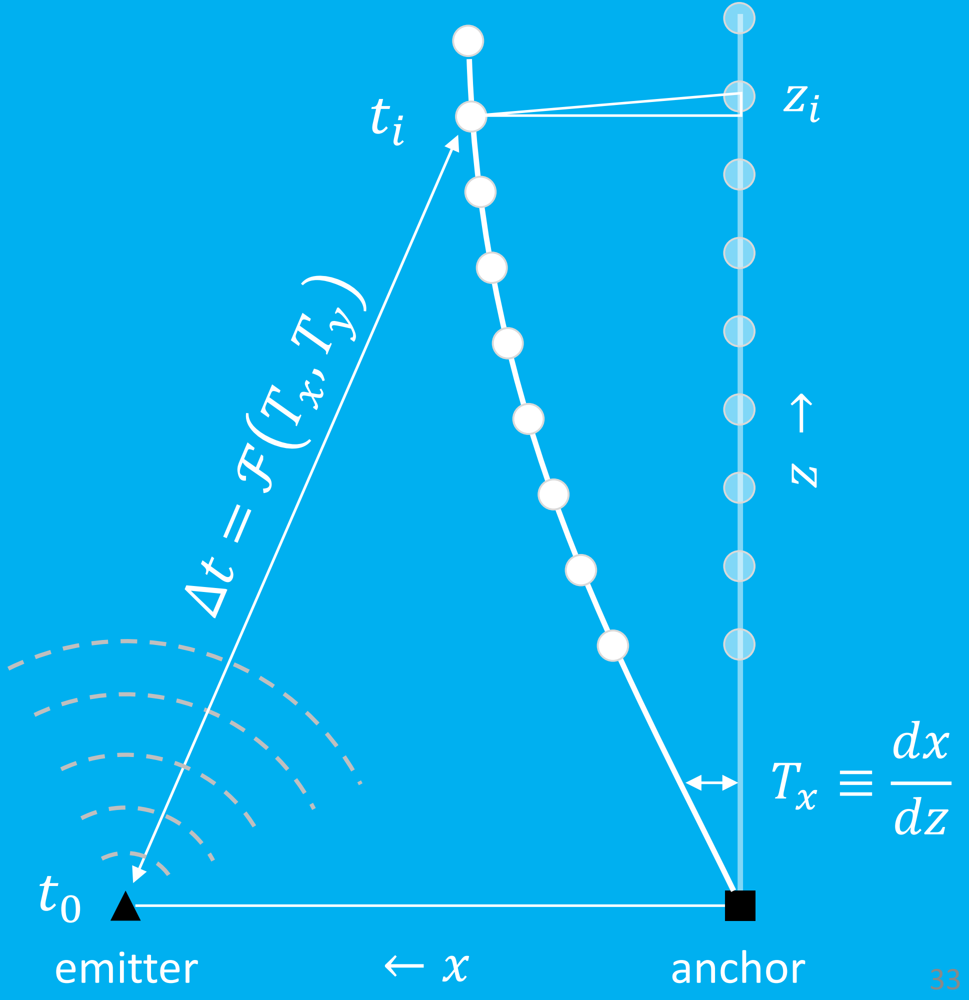
Regards,

Maarten

¶ Convenors of KM3NeT calibration working group.

Concept

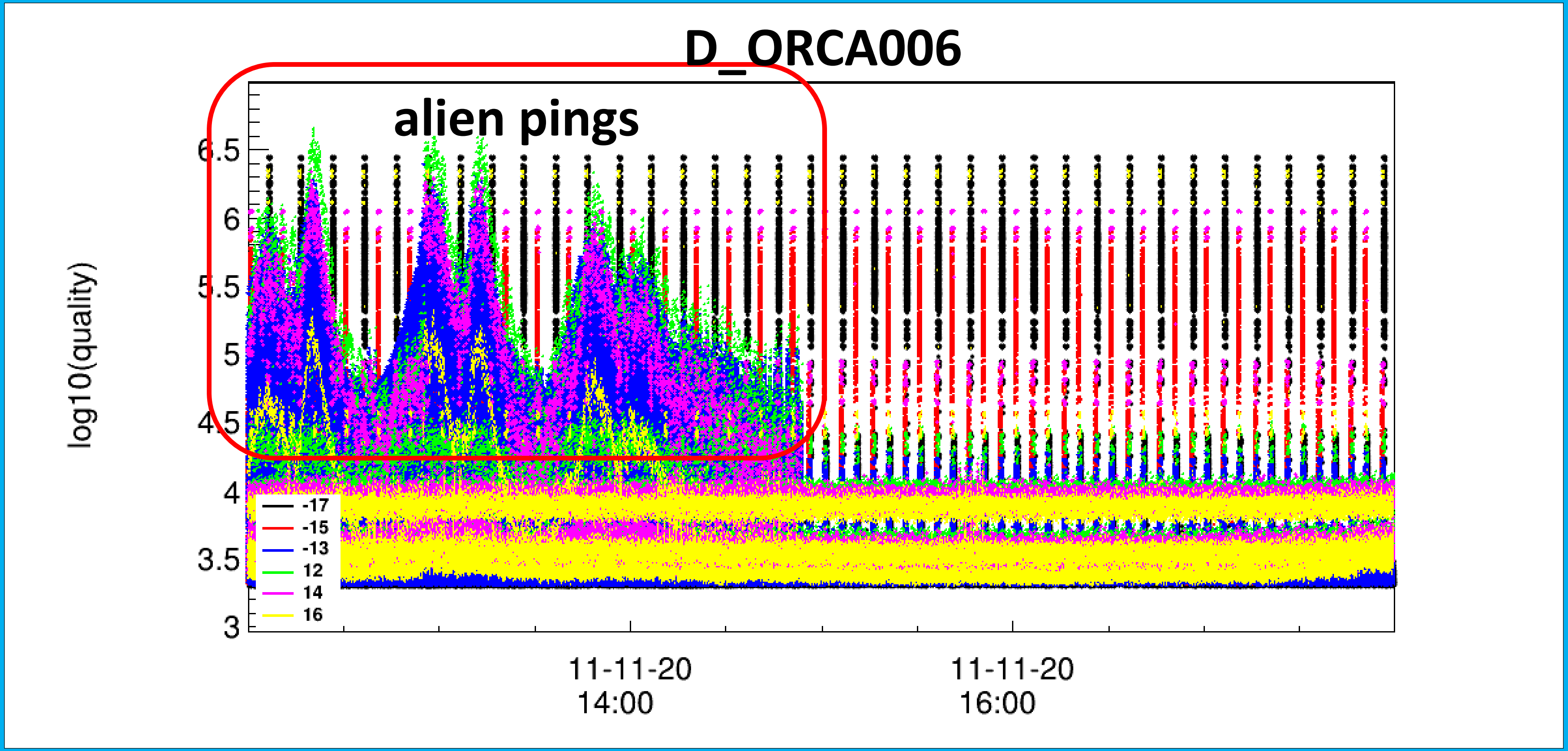
- model
  - mechanical constraints
  - shape of string $=$ drag $+$ buoyancy
- parameters
  - string: 2 tilt angles (T_x, T_y)
  - ping: 1 time of emission (t_0)
- data
  - time of arrival t_i in optical module



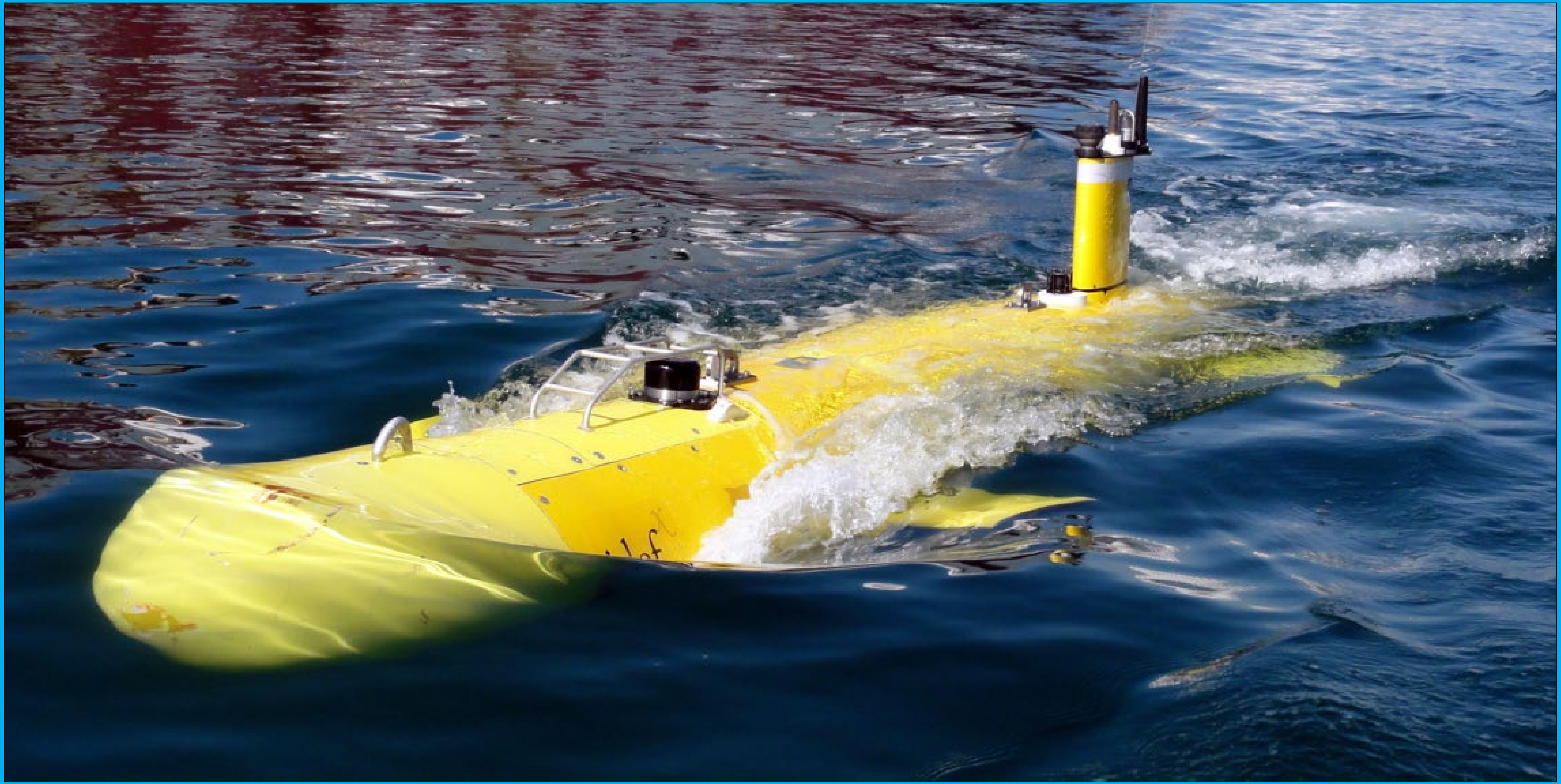
Implementation

1. event builder
   - correlate times of emission from given emitter (referred to as “event”)
2. fit
   - combine events within fixed time intervals (typically 10 mins.)
   - simultaneously fit all model parameters to data
3. dynamical calibration of detector
   - interpolate fitted model parameters and correct detector geometry on-the-fly (typically every minute)

Event builder



Culprit



Fit

- Levenberg-Marquardt algorithm (text book)
  - repeatedly solve curvature matrix equation

$$A\ \bar{x} = \bar{b}$$

$$(n \times n)\ (n \times 1) \qquad (n \times 1)$$

$$A_{ij} \equiv \sum_{N} \frac{\partial \chi^2}{\partial x_i} \frac{\partial \chi^2}{\partial x_j} \qquad b_i \equiv \sum_{N} \frac{\partial \chi^2}{\partial x_i}$$

Fit

- Number of parameters $n \sim 300$
- Number of data points $N \sim 100{,}000$

$$A_{ij} \equiv \sum_{N} \frac{\partial \chi^2}{\partial x_i} \frac{\partial \chi^2}{\partial x_j} \qquad i \in \{1, 2, \cdots, n\}$$

$\sum \Rightarrow$ CPU

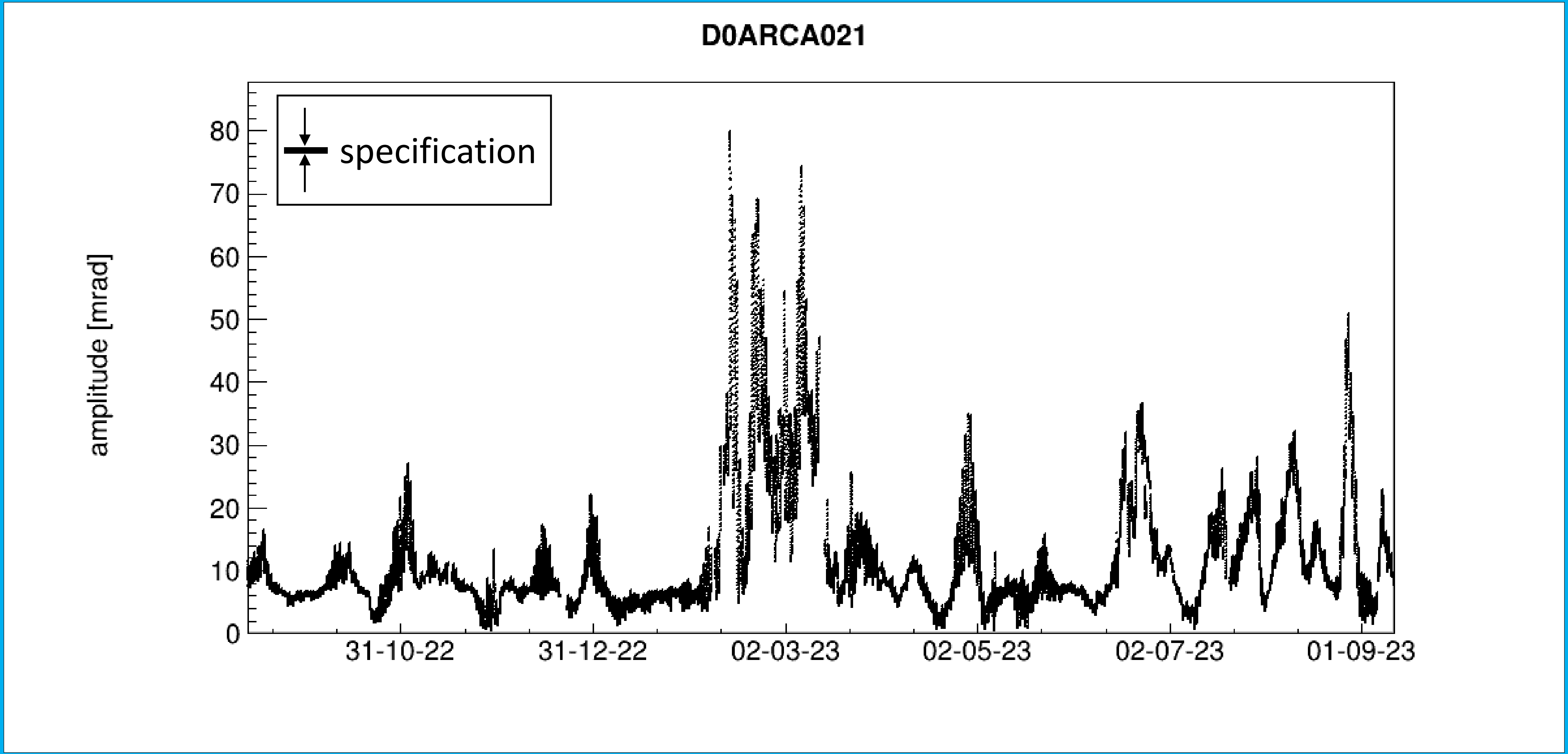
Fit

- Each data point affects only one ping and one string (= 3 parameters)
  - $i \notin \{i_1, i_2, i_3\} \Rightarrow \frac{\partial \chi^2}{\partial x_i} = 0$

$$A_{ij} \equiv \sum_N \frac{\partial \chi^2}{\partial x_i} \frac{\partial \chi^2}{\partial x_j} \qquad i \in \{i_1, i_2, i_3\}$$

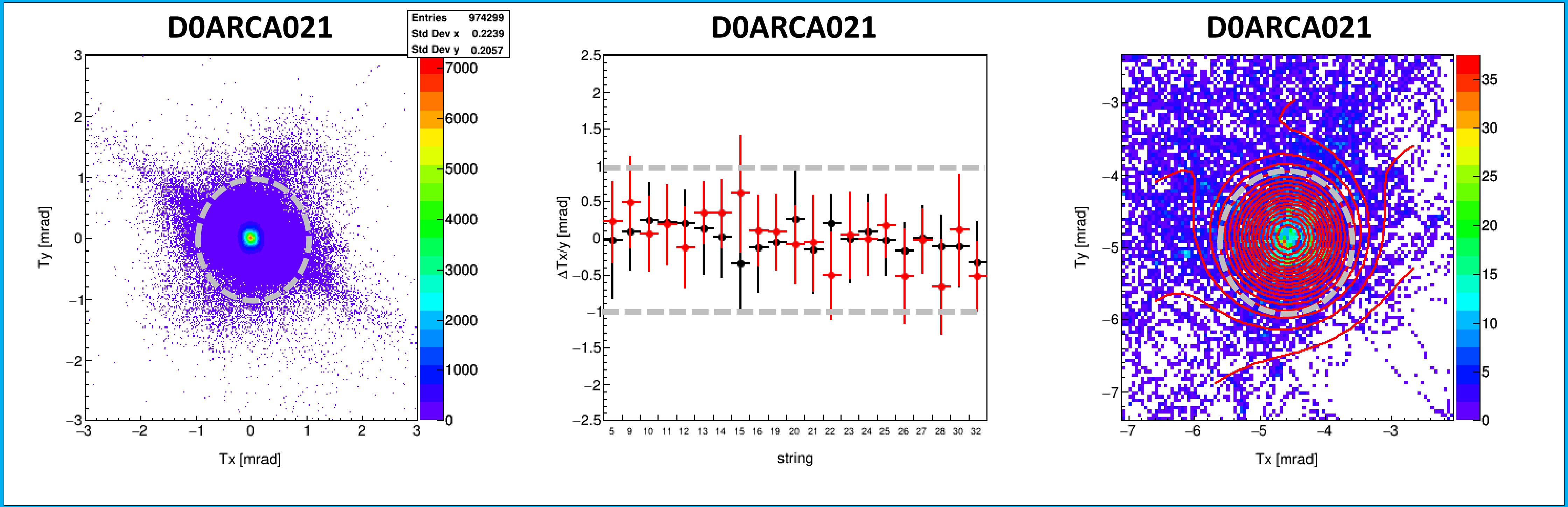
customisation $\Rightarrow$ 1000 x faster

Results



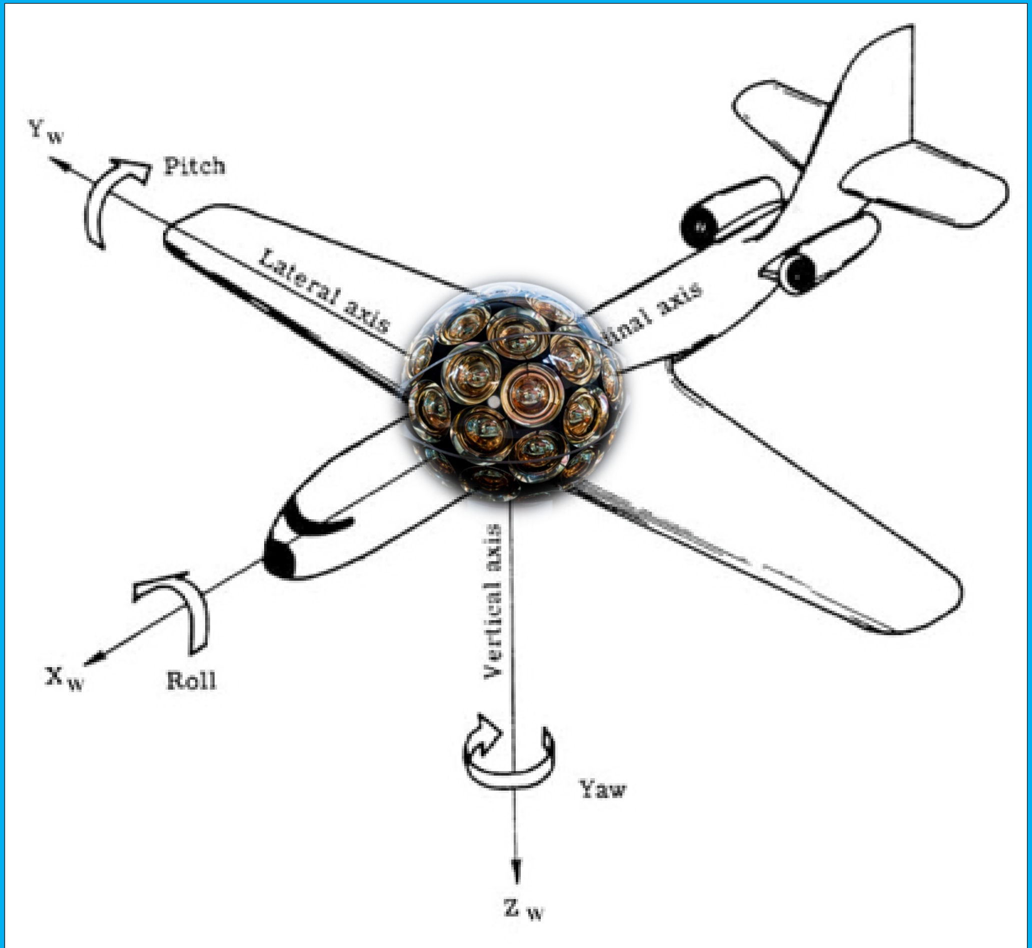
D0ARCA021
specification
amplitude [mrad]
0
10
20
30
40
50
60
70
80
31-10-22
31-12-22
02-03-23
02-05-23
02-07-23
01-09-23

Resolution

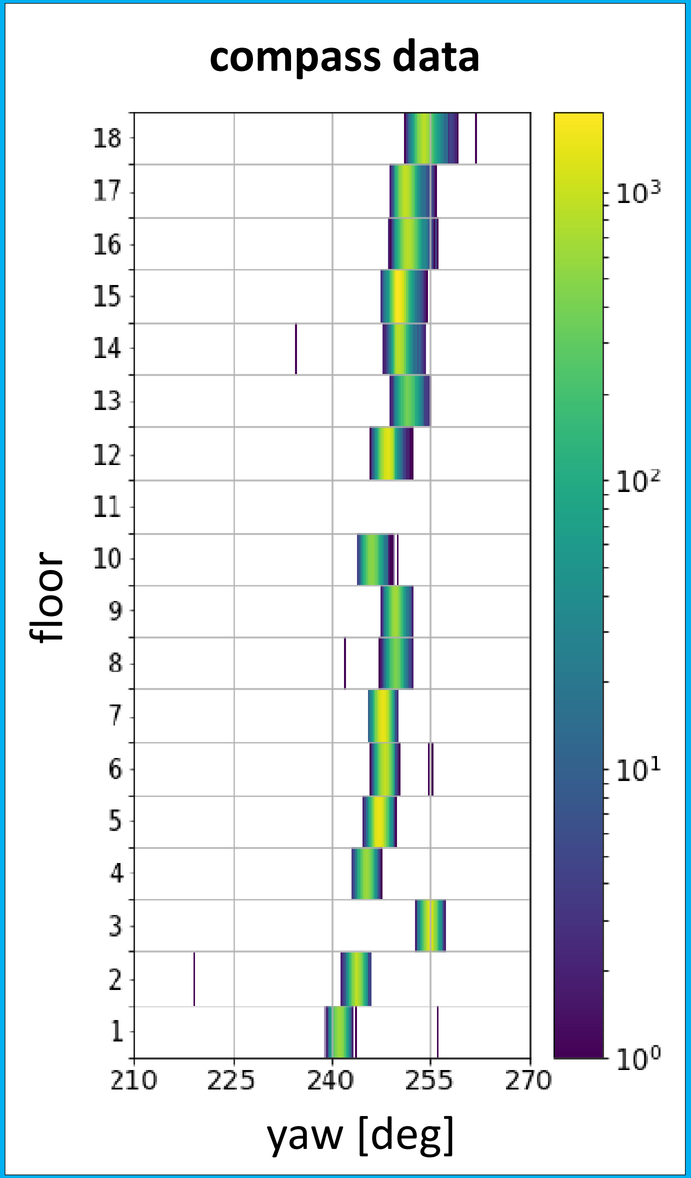


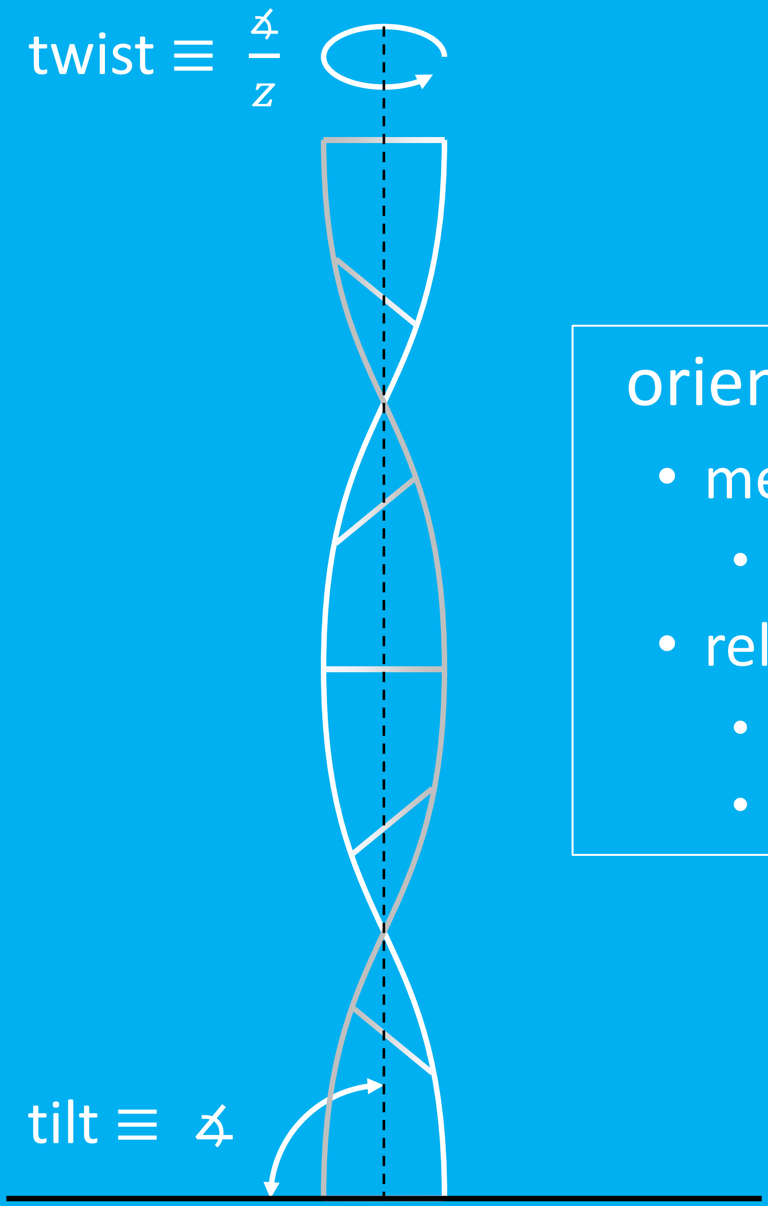
resolutions within 1 mrad

Orientation calibration



Here as he walked by
on the 16th of October 1843
Sir William Rowan Hamilton
in a flash of genius discovered
the fundamental formula for
quaternion multiplication
$\mathbf{i}^2 = \mathbf{j}^2 = \mathbf{k}^2 = \mathbf{i\,j\,k} = -1$
& cut it on a stone of this bridge.





idea

orientation of optical modules

- measured by 3D-compass
  - yaw, pitch and roll
- related through string mechanics
  - tilt
  - twist

Fit

- model
  - $Q_i = Q_0 Q_1^{z_i}$
    - Q_0 tilt of the string
    - Q_1 twist of string
    - z_i height floor i
- data
  - yaw, pitch and roll → quaternion

Fit
polynomial of quaternions
to
quaternions

"Easier said than done."

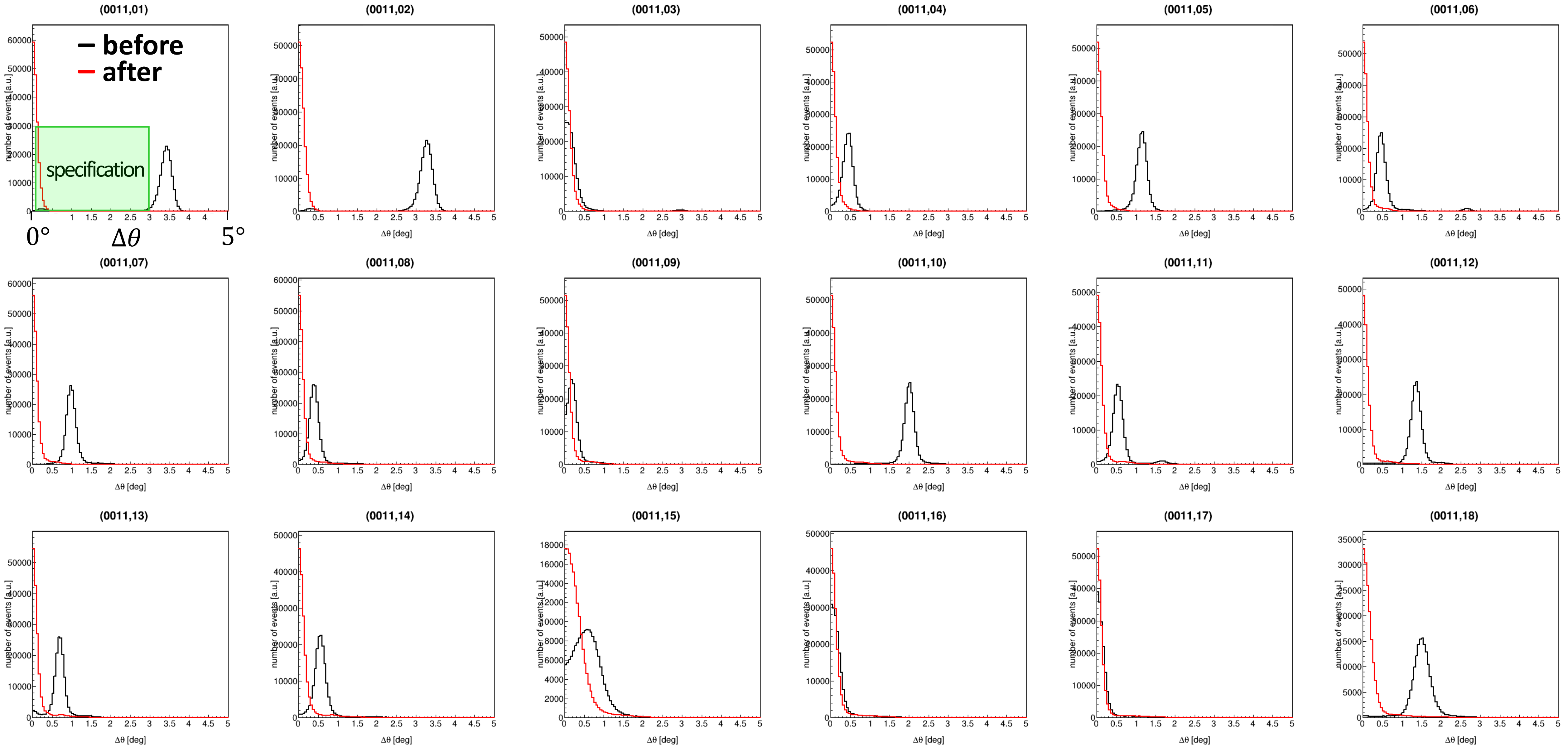
Fit

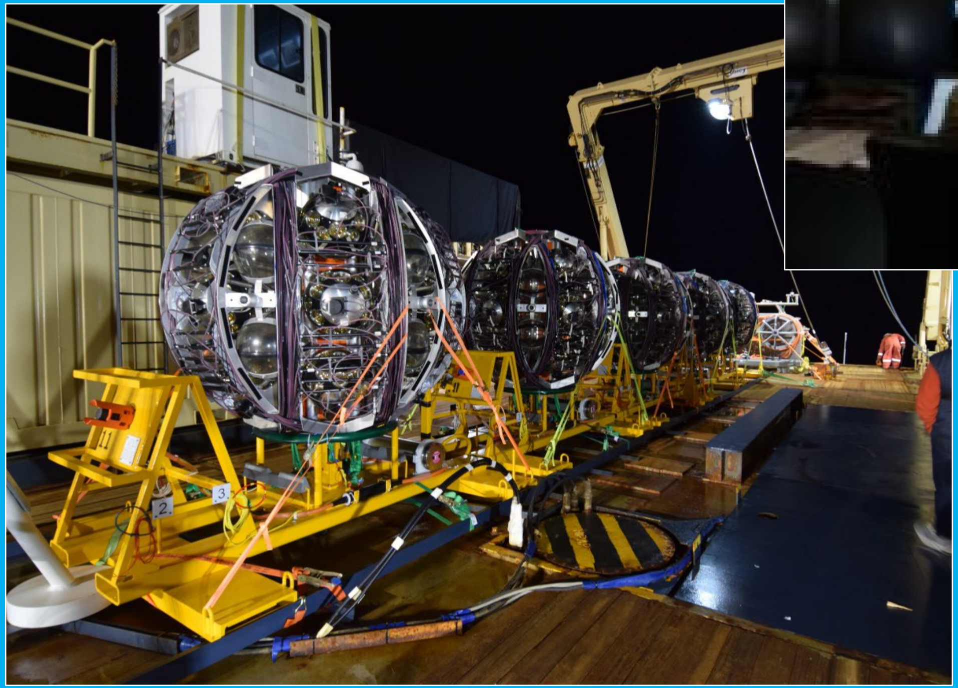
- Metric
  - geodesic distance between two quaternions
- Resolution for χ^2 evaluation
  - $\sigma \equiv \frac{1}{2}\sqrt{\sigma_x^2 + \sigma_y^2 + \sigma_z^2}$
- Minimiser
  - JSimplex¶ works out-of-the-box
    - step corresponds to multiplication $Q \pm \Delta Q \quad \Rightarrow \quad Q\,\Delta Q^{\pm 1}$
    - scaling corresponds to power $Q \times y \quad \Rightarrow \quad Q^y$

✓ Euler's theorem

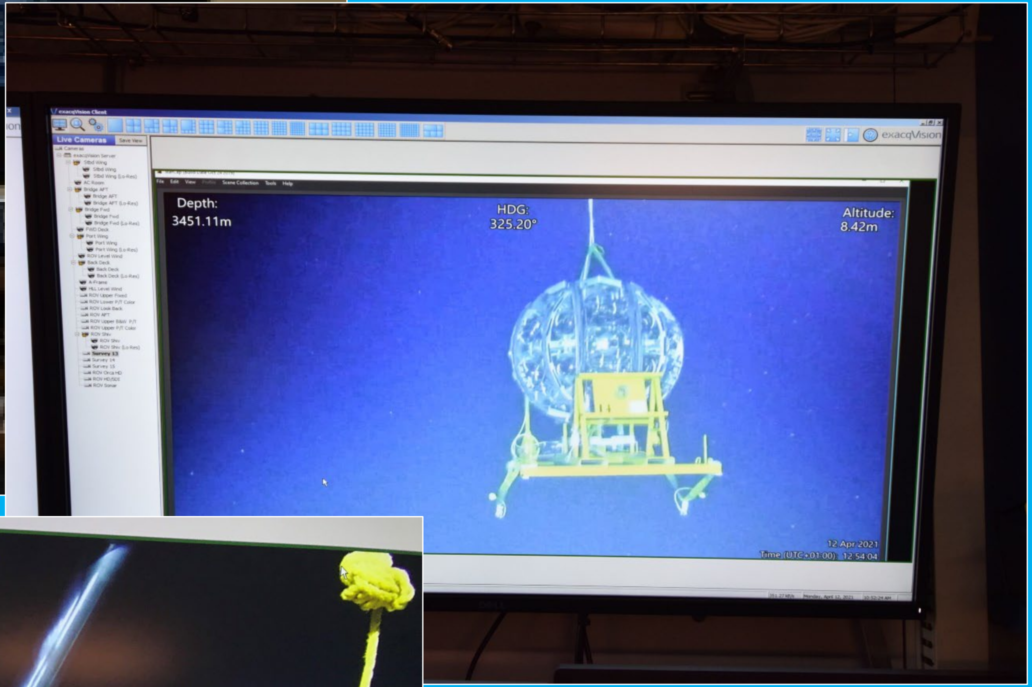
"Easier done than said."

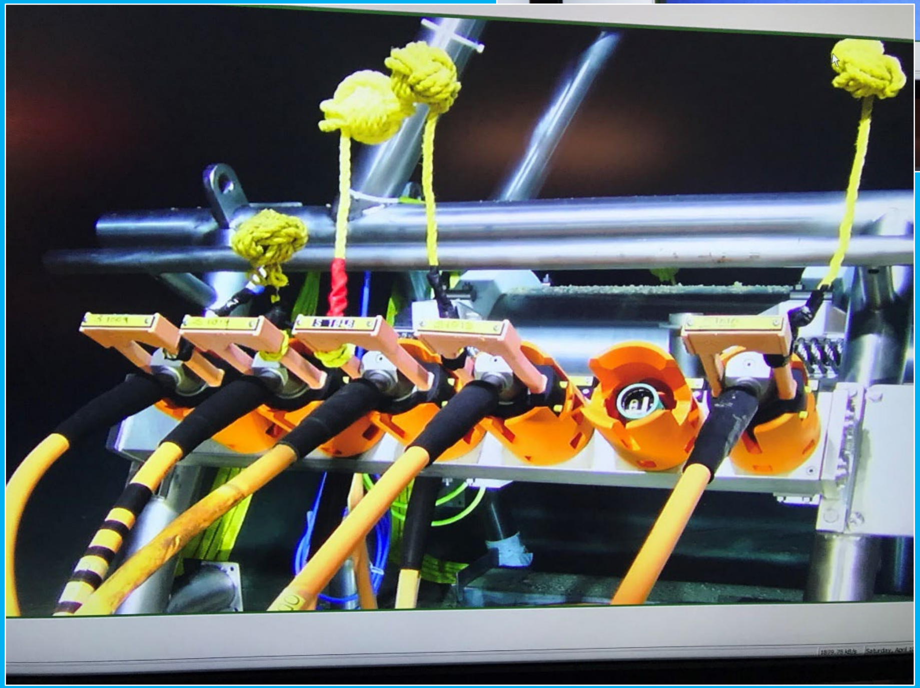
¶ JSimplex is a custom-made minimiser in C⁺⁺.

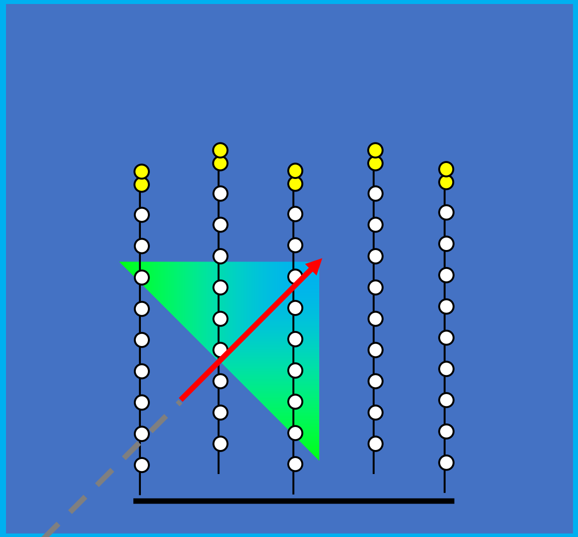

(0011,01)
before
after
specification
0°
Δθ
5°
(0011,02)
(0011,03)
(0011,04)
(0011,05)
(0011,06)
(0011,07)
(0011,08)
(0011,09)
(0011,10)
(0011,11)
(0011,12)
(0011,13)
(0011,14)
(0011,15)
(0011,16)
(0011,17)
(0011,18)
number of events [a.u.]
Δθ [deg]




IDMAR


exacqVision
Live Cameras
Depth:
3451.11m
HDG:
325.20°
Altitude:
8.42m
12 Apr 2021

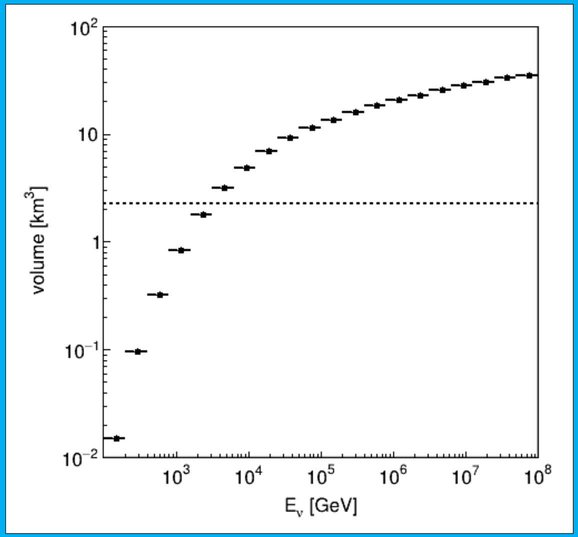




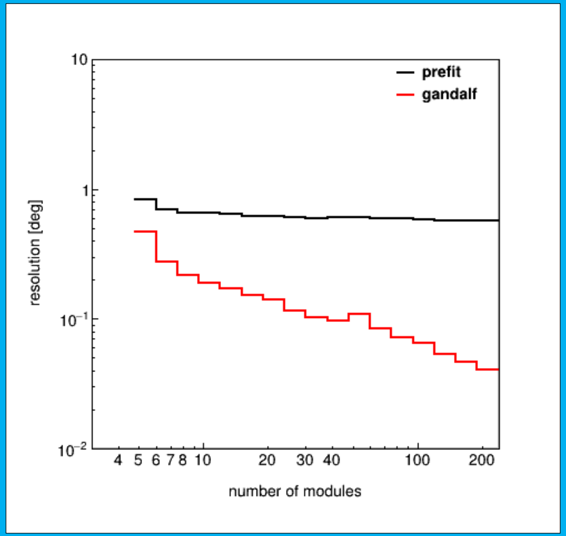
data filter

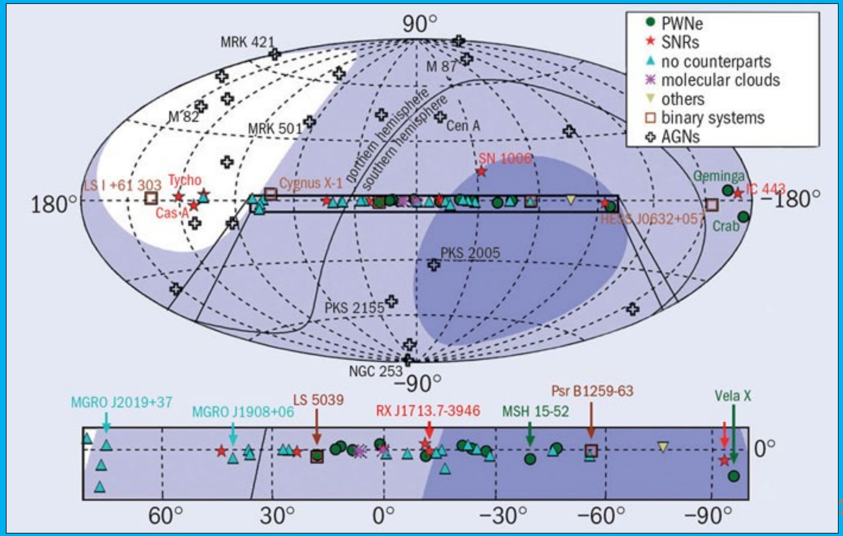
event reconstruction

event analysis

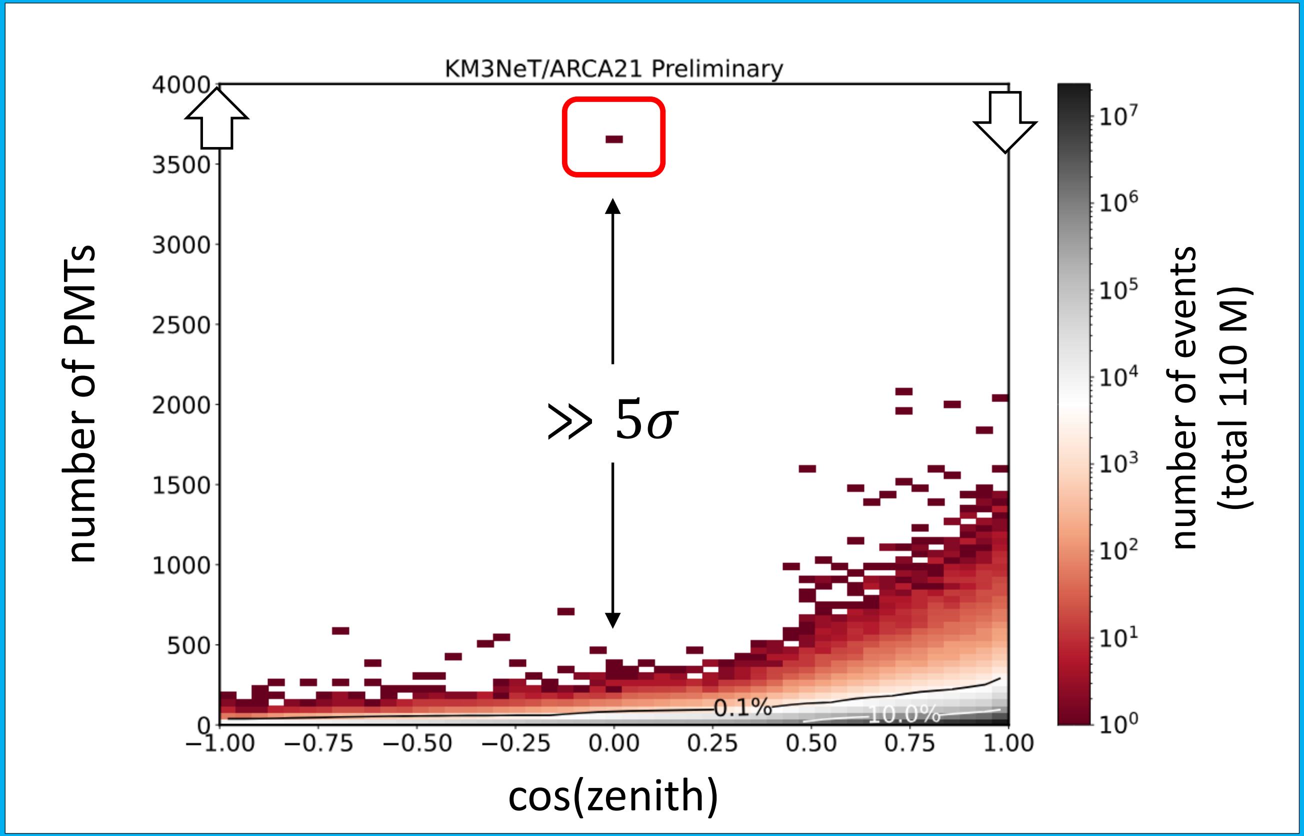


Search for hot spots...



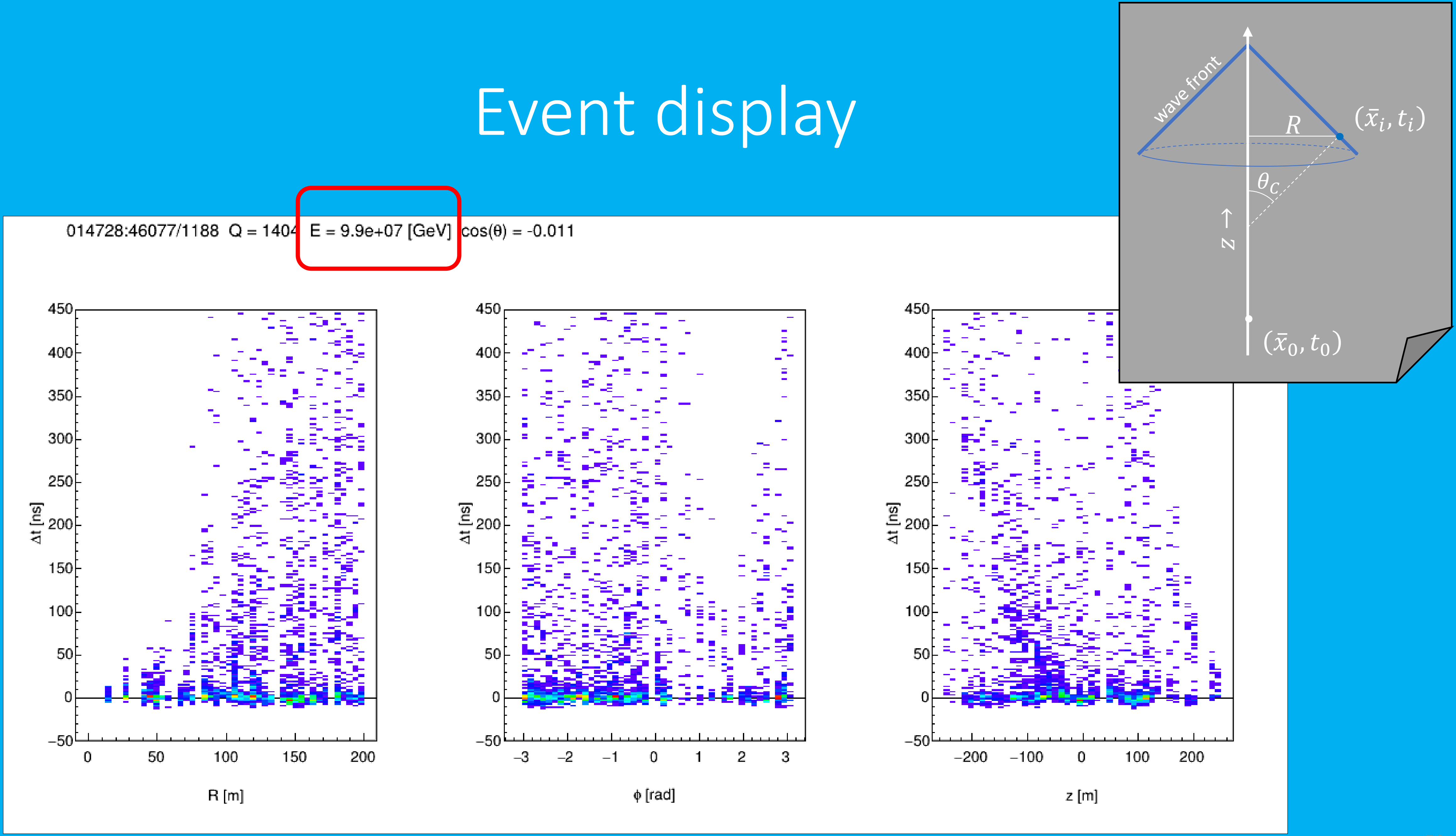


KM3-230213A

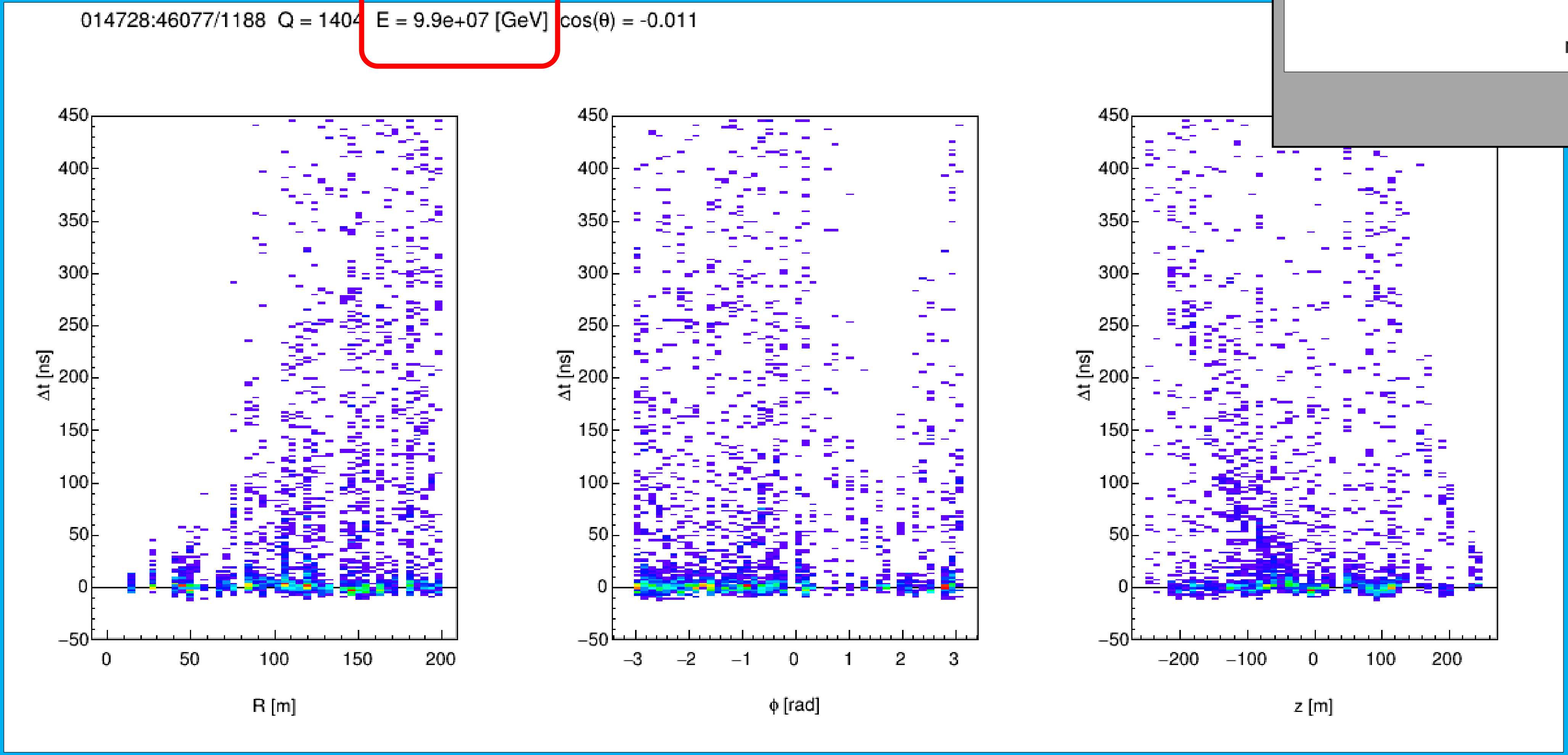


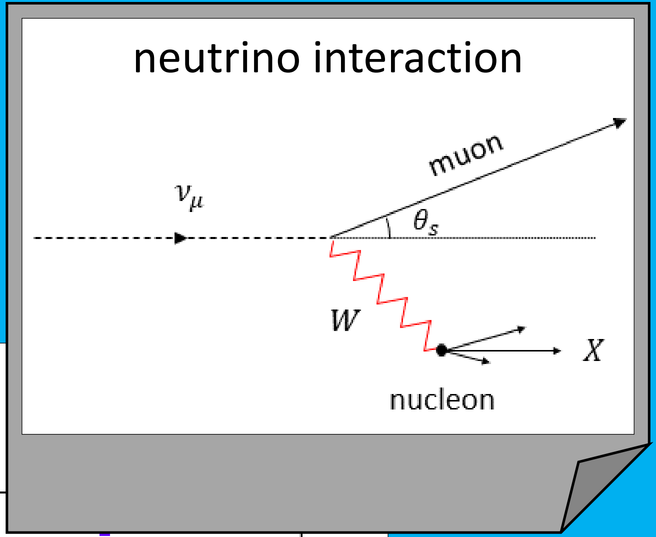
KM3NeT/ARCA21 Preliminary
number of PMTs
4000
3500
3000
2500
2000
1500
1000
500
0
−1.00
−0.75
−0.50
−0.25
0.00
0.25
0.50
0.75
1.00
cos(zenith)
≫ 5σ
0.1%
10.0%
10^7
10^6
10^5
10^4
10^3
10^2
10^1
10^0
number of events
(total 110 M)

Event display

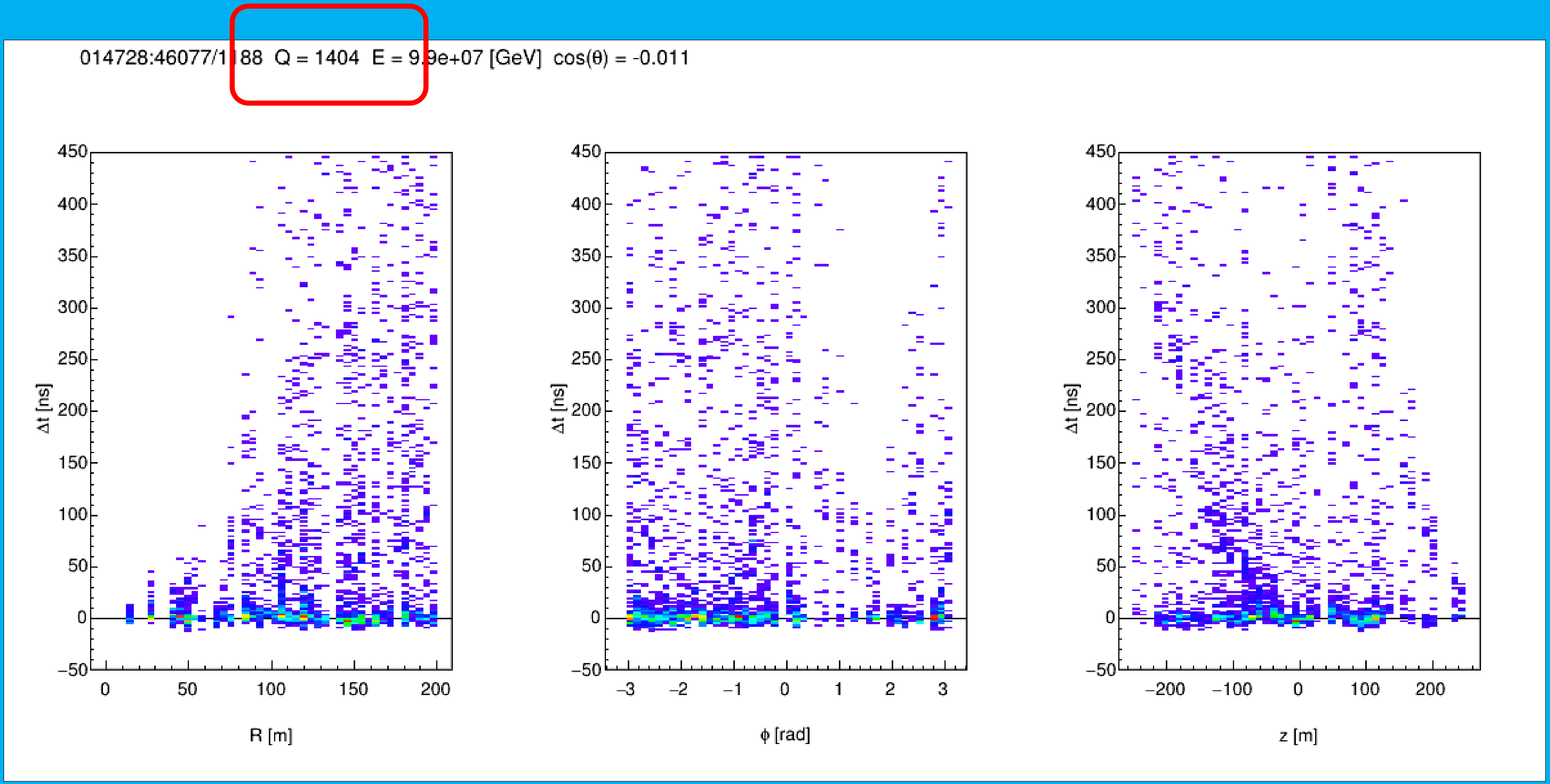


$$E_\nu \geq E_\mu \geq E_{\text{measured}}$$

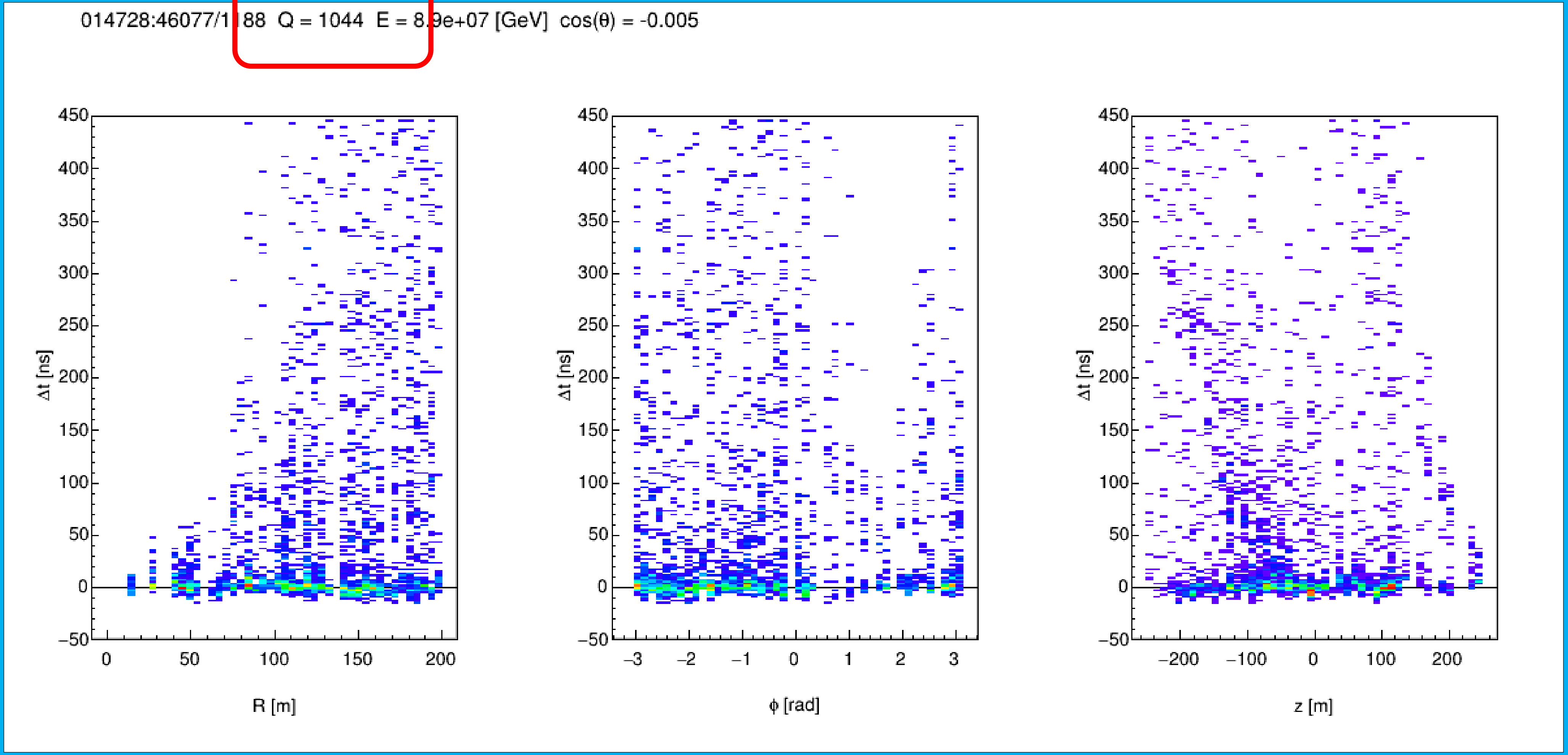




Event display - dynamic calibrations



Event display - static calibrations



Q/A

- Why is direction of this neutrino close to horizon?
- Do we know [astrophysical] origin of neutrino?
- Could it be a tau?
- Could it be a charged-current interaction of a tau neutrino?
- Is observation [in]compatible with IceCube results?

Summary & Outlook

- KM3NeT construction [now] proceeds as planned
  - time to completion about 5 years
  - **deployment of hardware for absolute pointing of KM3NeT/ARCA 2025/2026**
- KM3NeT operation ongoing
  - data are being recorded 24/7
  - **neutrino physics with KM3NeT/ORCA**
- KM3NeT science output depends on:
  - **calibration = data analysis**
  - **reconstruction = data analysis**