Moon & Sun shadow KM3NeT/ORCA

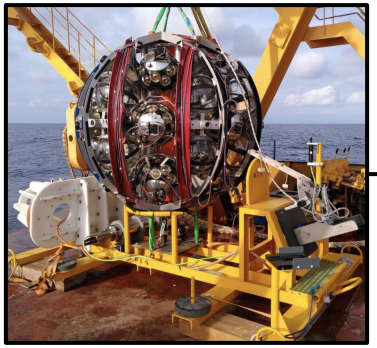
Luc C. · 17/11/2022 · IRN · IJCLab

KM3NeT

x31

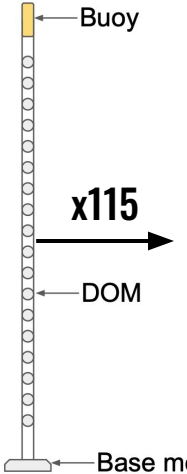
Digital Optical Module (DOM)

x18



unfurl

Detection Unit (DU)



x115

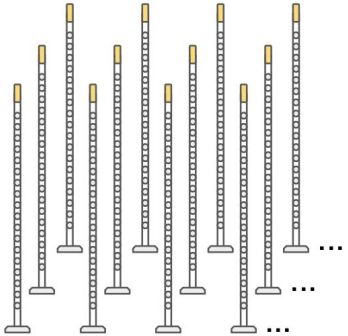
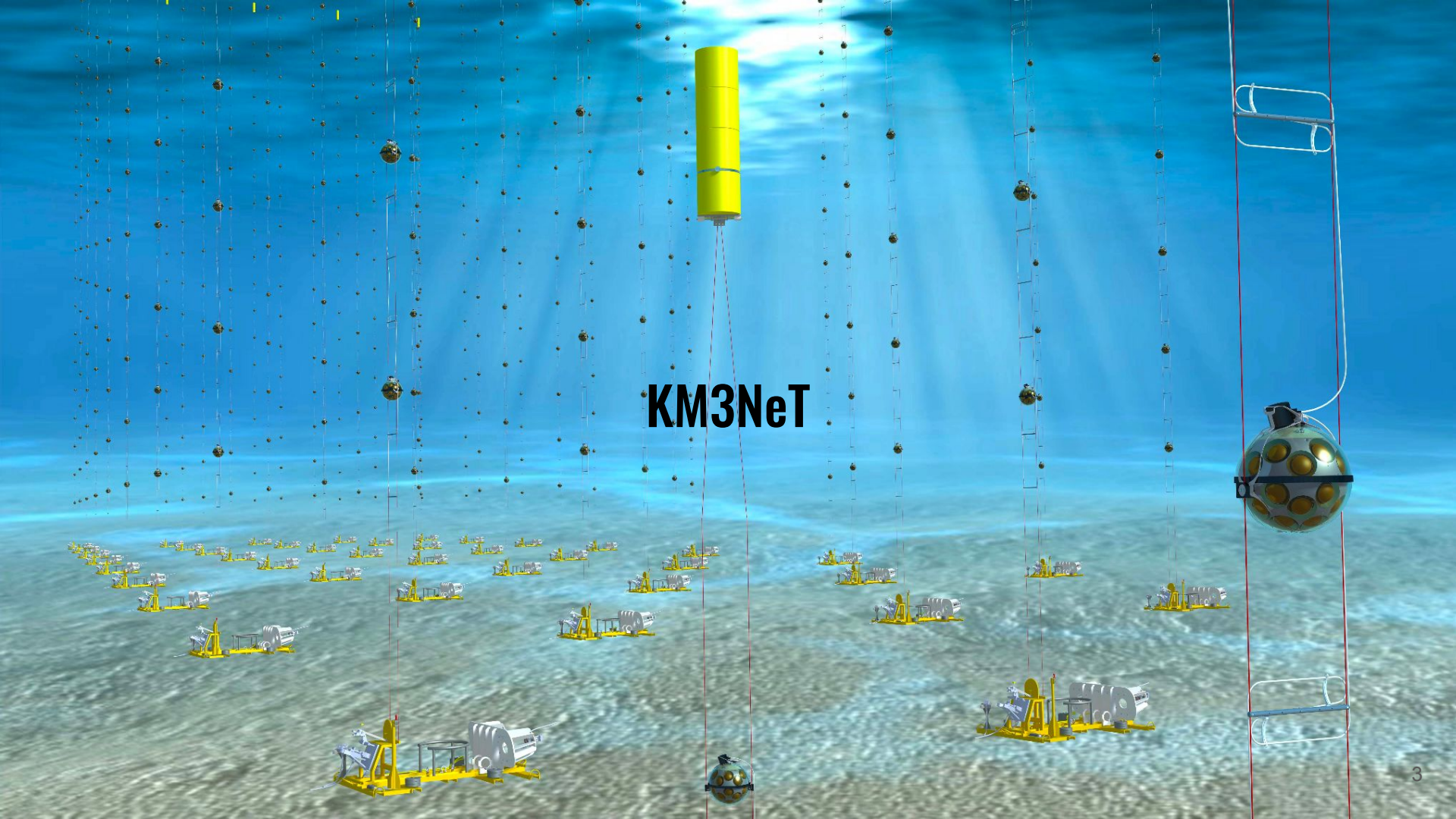


Photo-multiplier tubes (PMT)

detect cherenkov light from the charged products of neutrino interactions in sea-water

Launcher Optical Modules (LOM)

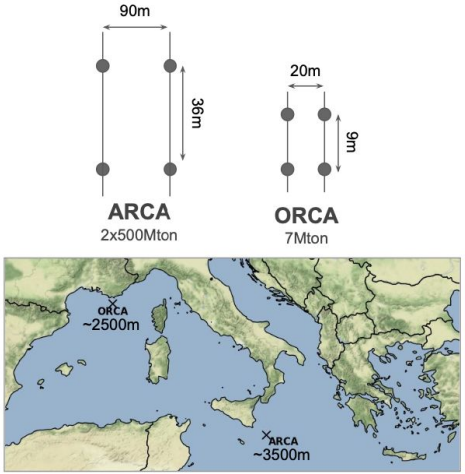
Building Block (BB)


KM3NeT

- Large array (2BB) optimized for [1TeV:10PeV]
- Neutrino astronomy: diffuse flux, **point source search**
- goal: **< 0.1°** angular resolution

→ knowledge of relative DOM position ~ 10cm

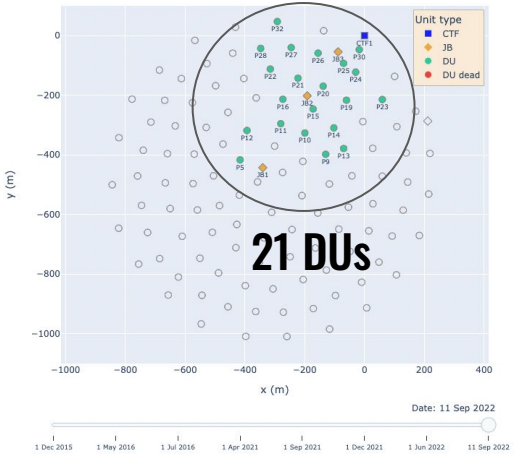
→ knowledge of absolute orientation < 0.1°



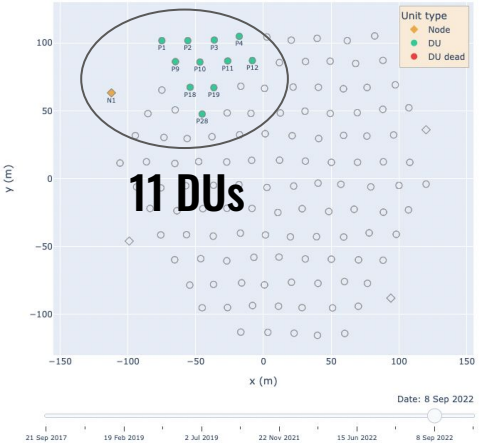
KM3NeT

ARCA

ORCA



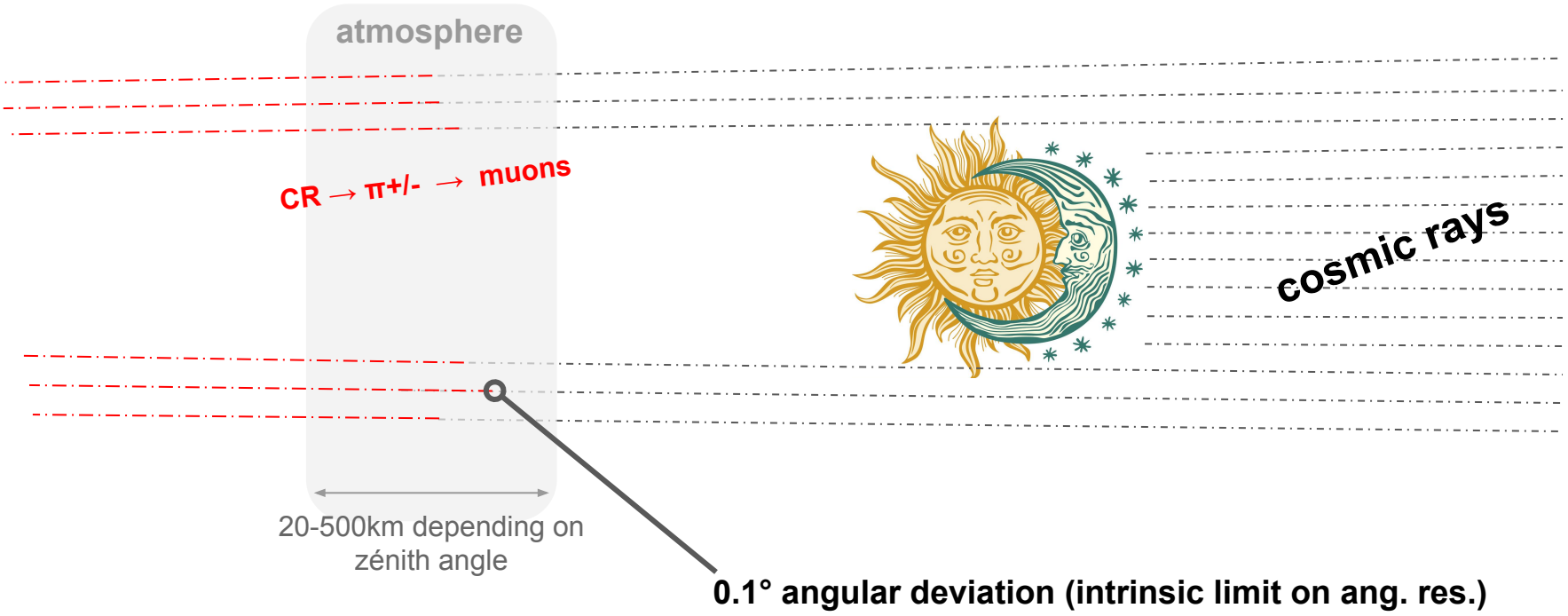
today

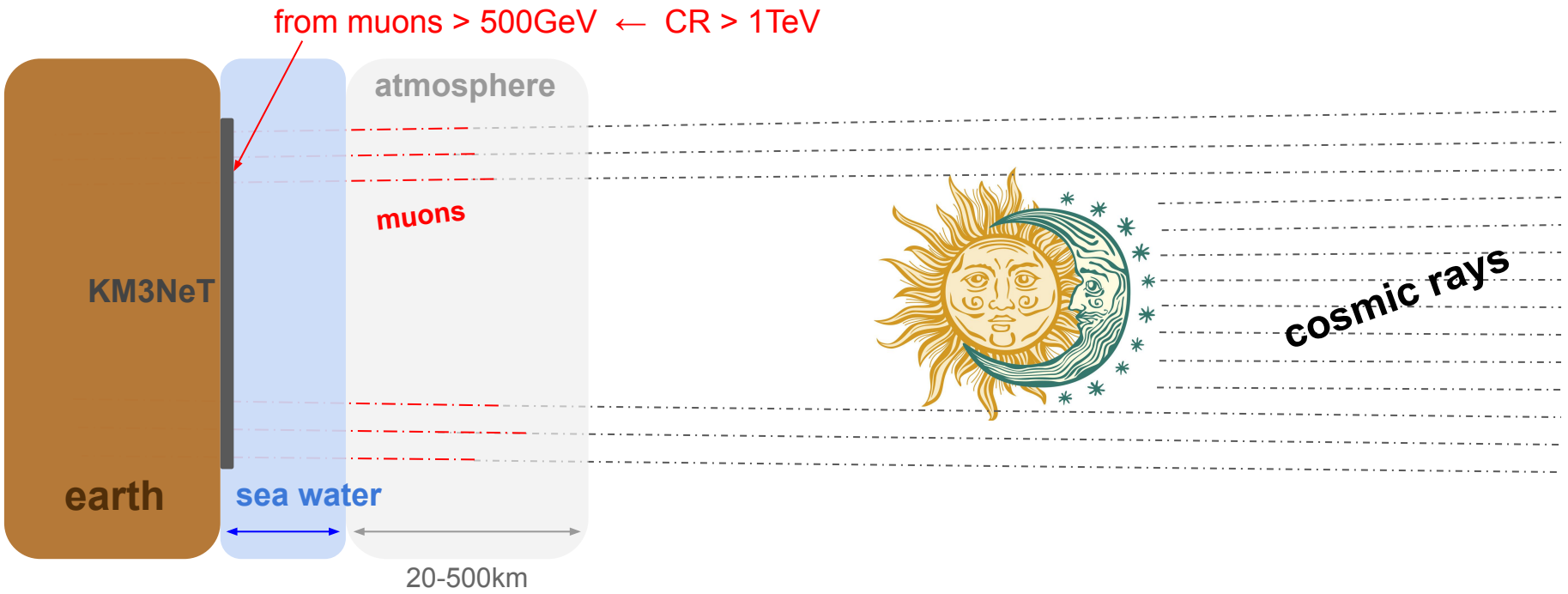


- Dense array (1BB) optimized for [1GeV:100GeV]
- Atmospheric neutrino **oscillation**
- GeV/MeV neutrino astronomy
- < 0.5° angular resolution

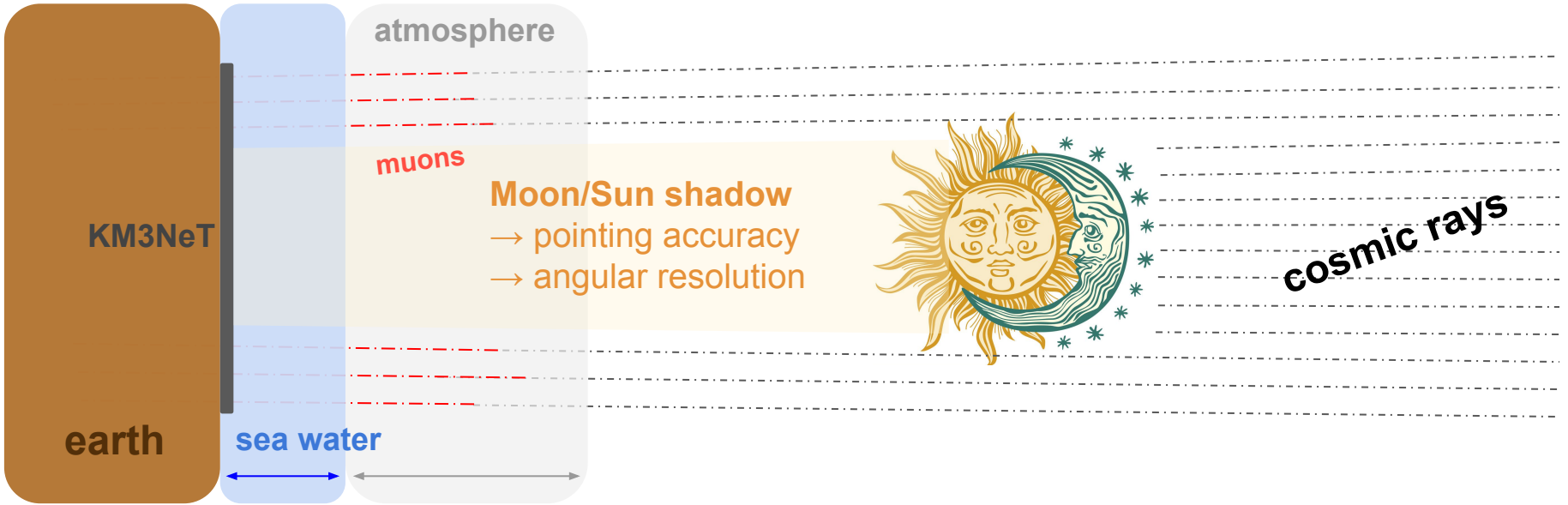
Moon/Sun cosmic ray shadow

~0.26° mean apparent angular radius seen from earth


atmosphere
CR → π+/- → muons
cosmic rays
20-500km depending on zénith angle
0.1° angular deviation (intrinsic limit on ang. res.)



→ ORCA (-2500m)
→ ARCA (-3500m)

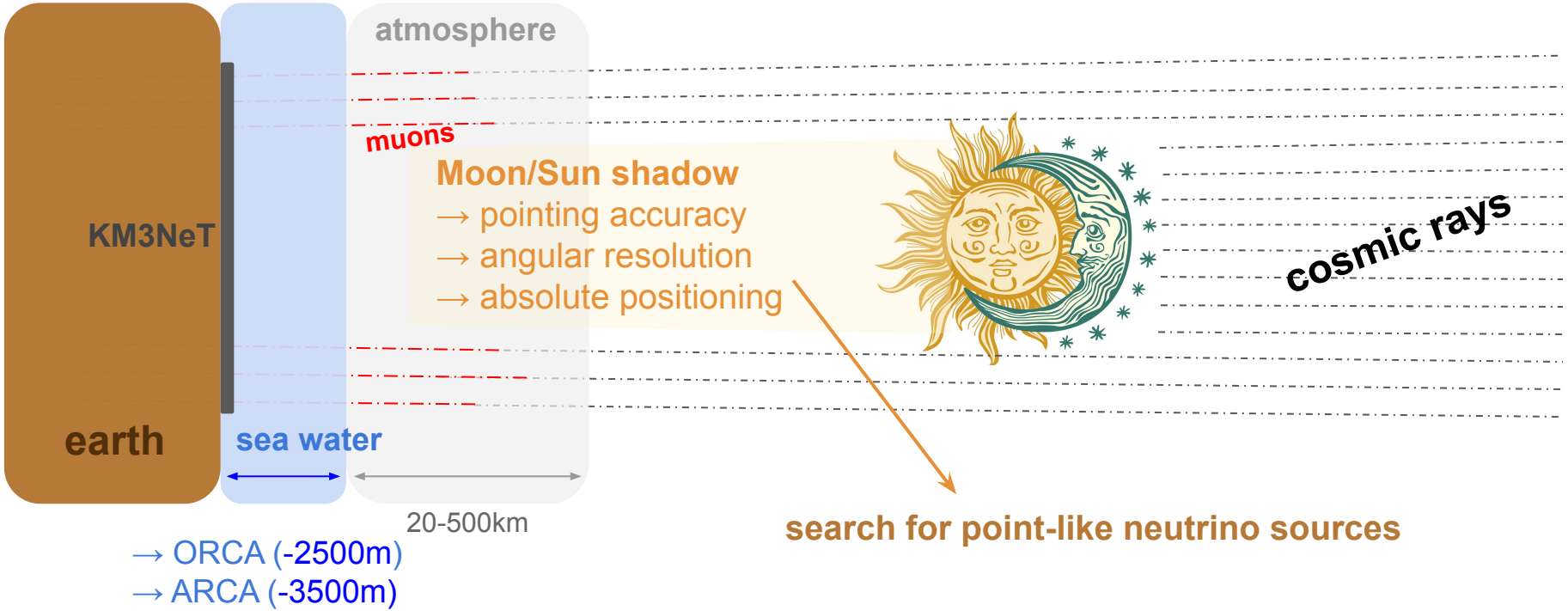


→ ORCA (-2500m)
→ ARCA (-3500m)

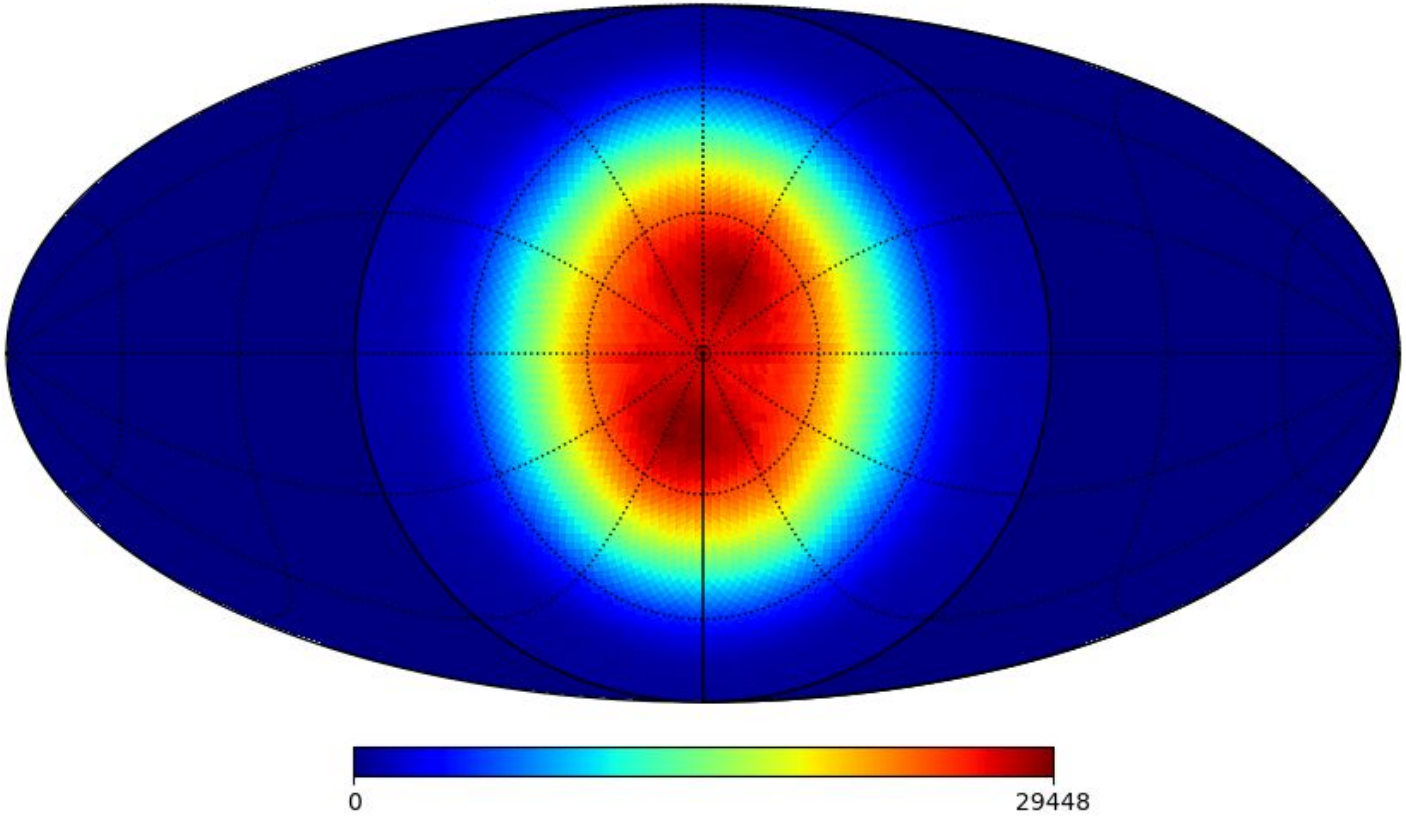
Moon/Sun cosmic ray shadow

Statistics:

- for 2000 CR in a 12° window around Sun/Moon → 1 blocked by Sun/Moon
  - we need 500 CR blocked to see a shadow → ~ 1 year of ORCA6

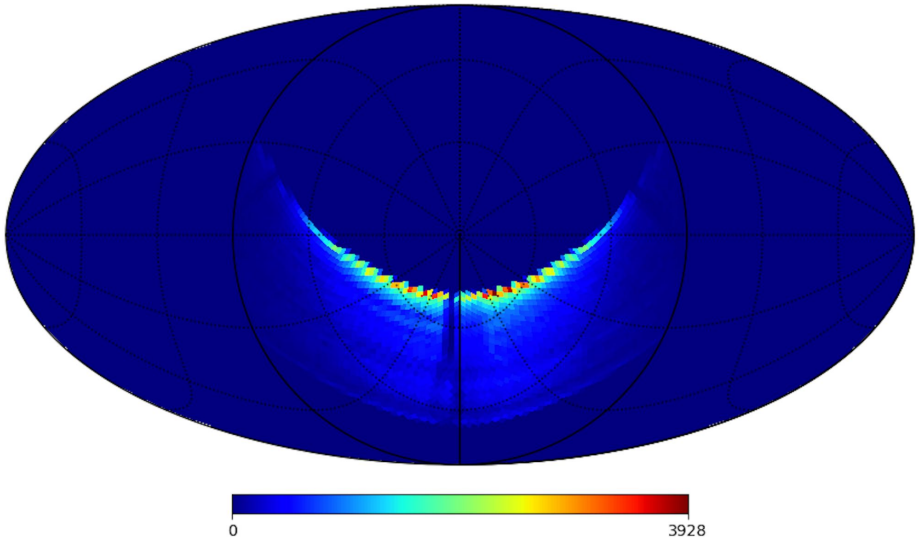


Local coordinates (azimuth - zenith) - all events - ORCA

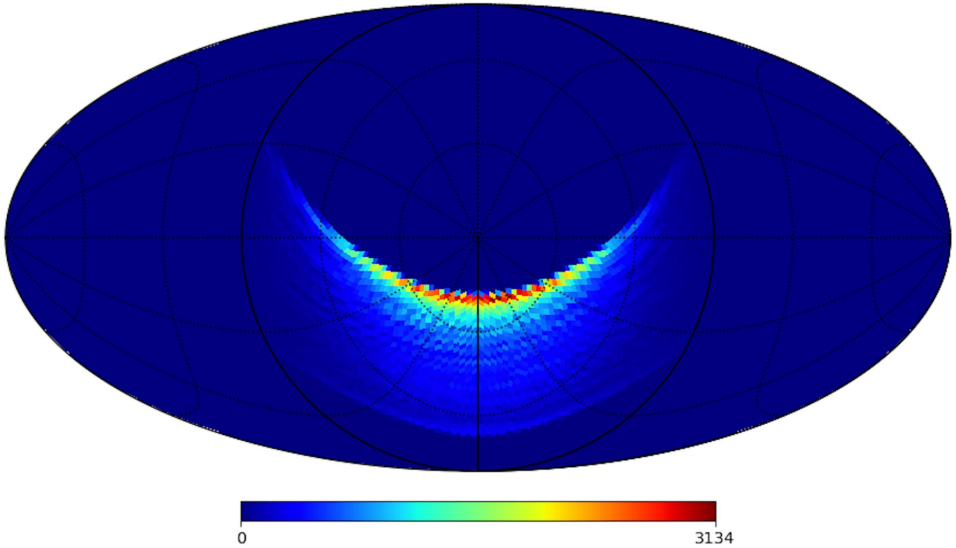


Local coordinates - Moon/Sun position

Sun

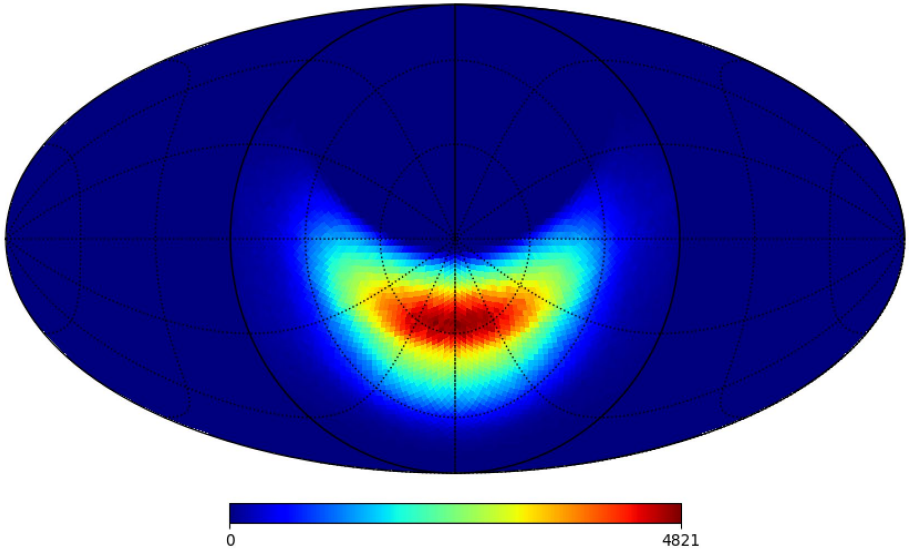


Moon

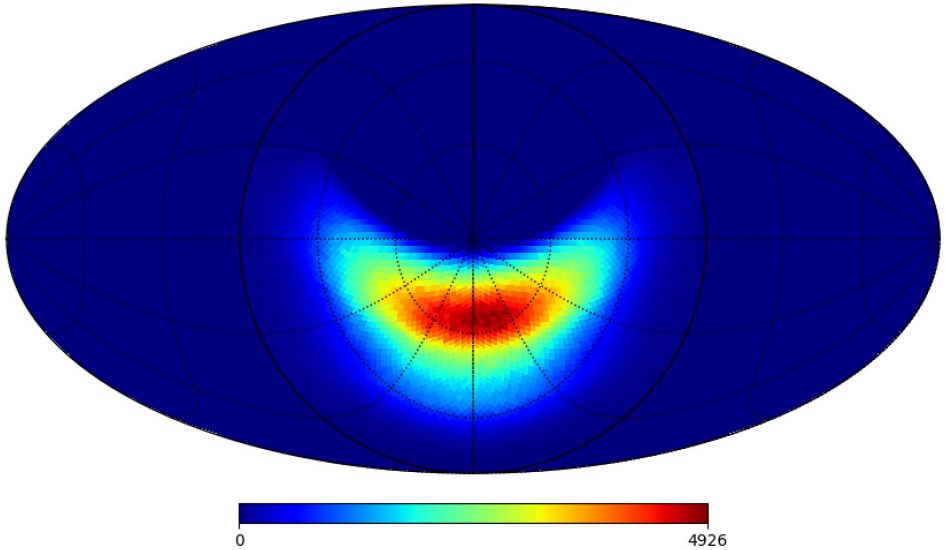


Local coordinates - events < 12° wrt. Moon/Sun position

Sun

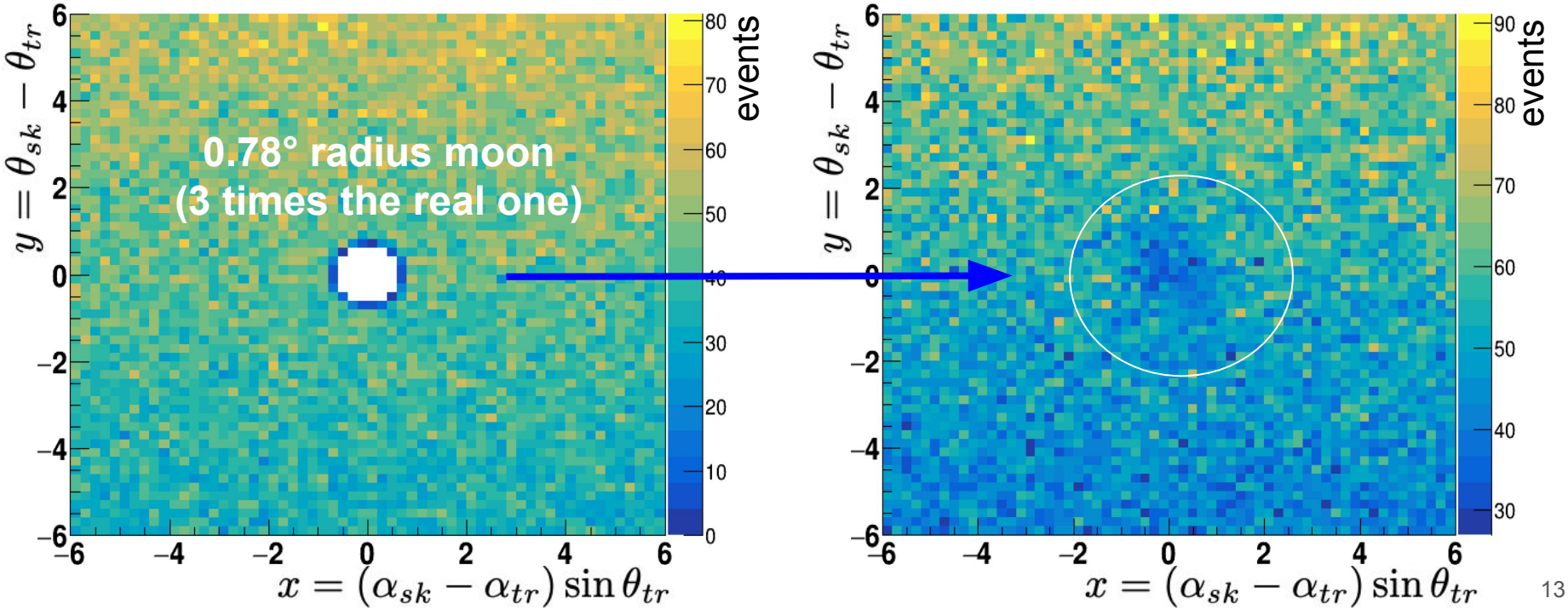


Moon



Simulation of the shadow on MC

mc **true** without moon disk → mc **reco**
→ perform a chi square scan



Fitting model

(x, y) coordinates from the zenith and azimuth angles:
sky object (θ_{sk} , α_{sk}) and tracks (θ_{tr} , α_{tr})

$$x = (\alpha_{sk} - \alpha_{tr}) \sin \theta_{tr}$$
$$y = \theta_{sk} - \theta_{tr}$$

parameterization of the track distribution in the absence of the shadow:

$$P_z(n_z) = 1 + \sum_{i=1}^{n_z} h_{zi} z^i \ ; \ z = [x, y]$$

H_0 : no-shadow hypothesis

$$H_0 = \rho \cdot P_x(n_x) \cdot P_y(n_y)$$

G : bi-dimensional Gaussian to fit the deficit of secondary cosmic ray events due to the shadowing effect

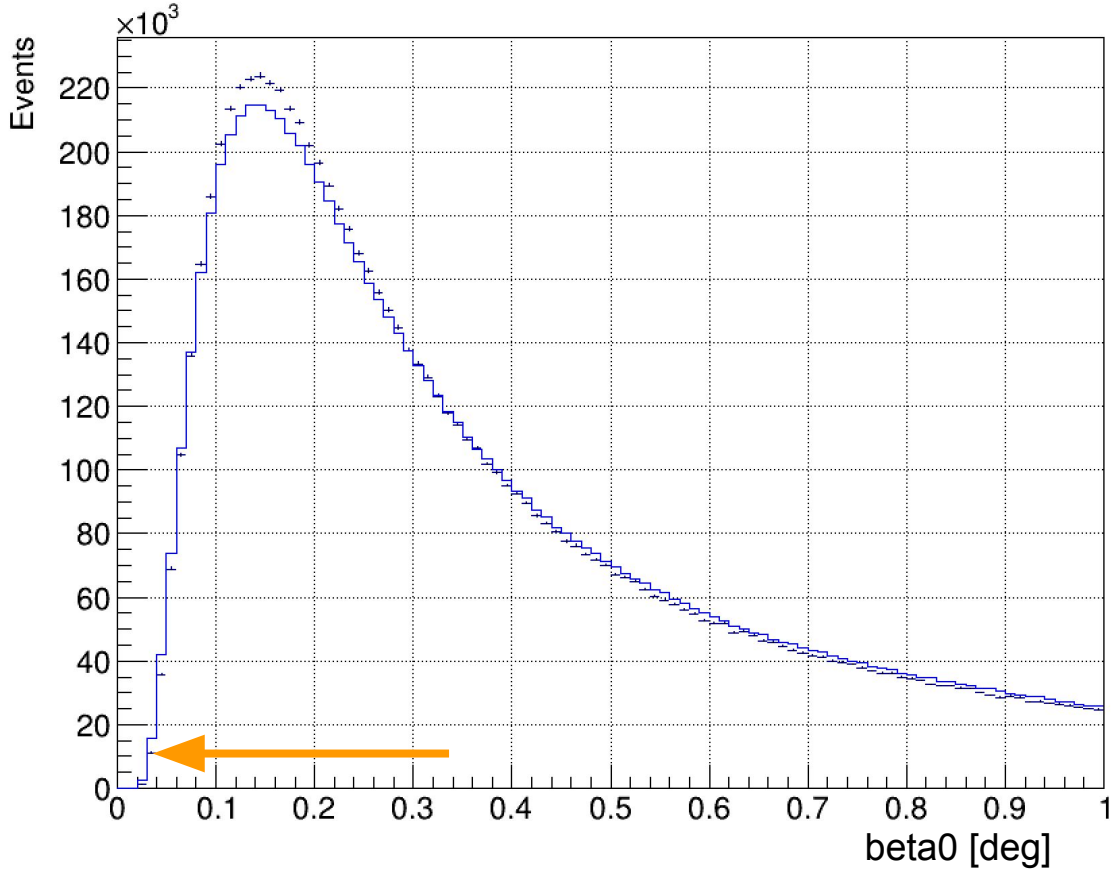
$$G(A, \sigma_{res}, x_s, y_s) = \frac{A {R_s}^2}{2\sigma_{res}^2} \exp\left[- \frac{(x - x_s)^2 + (y - y_s)^2}{2\sigma_{res}^2} \right]$$

H_1 : shadow hypothesis

$$H_1 = H_0 - \rho \cdot G$$

Preparation on MC:

data/MC angular error estimate distribution

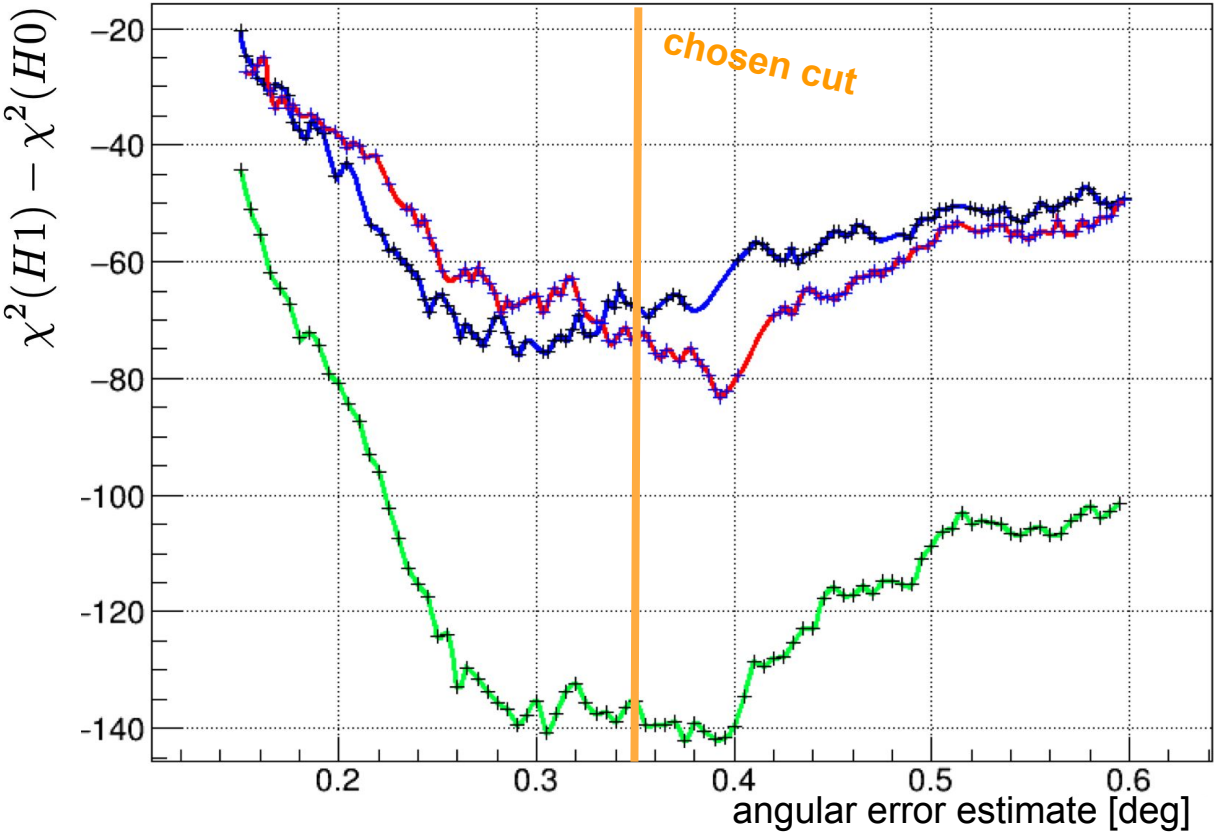


DATA

MONTE CARLO

Preparation on MC:

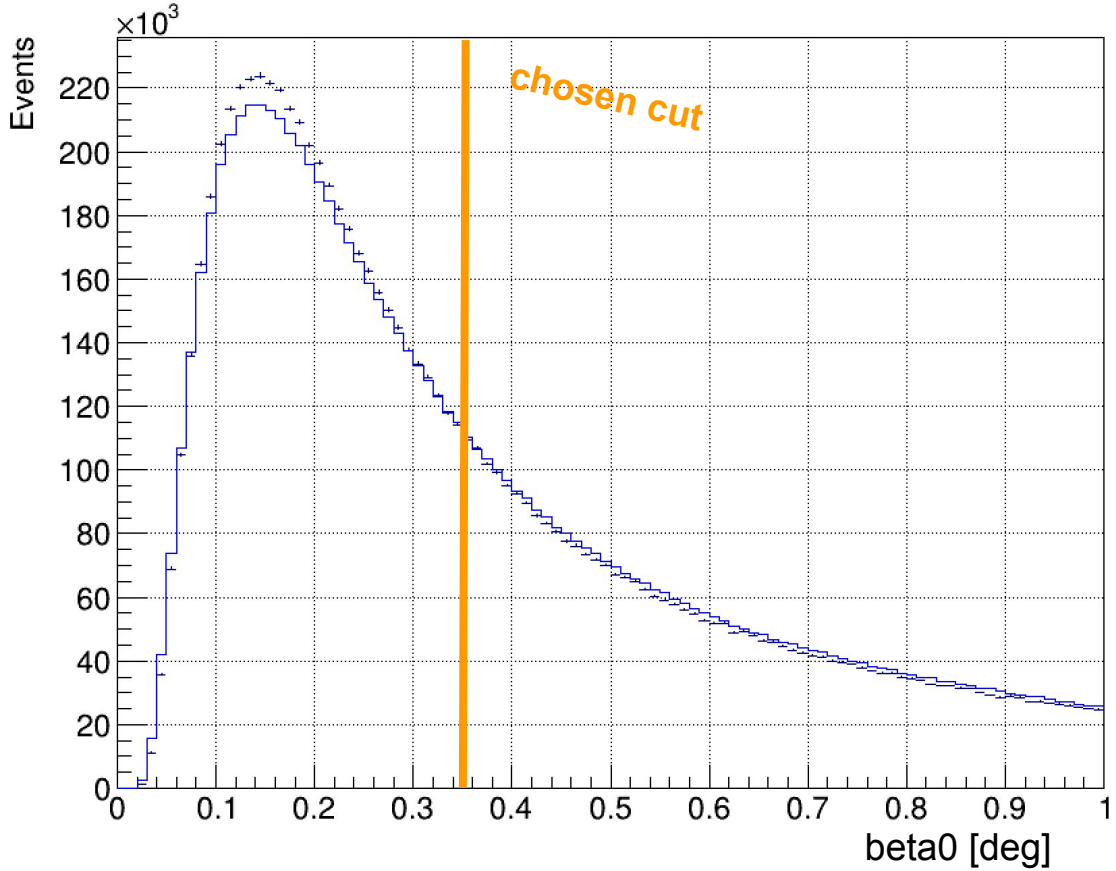
angular error estimate scan to optimize track selection



sun
moon
sun+moon

Preparation on MC:

data/MC angular error estimate distribution



DATA

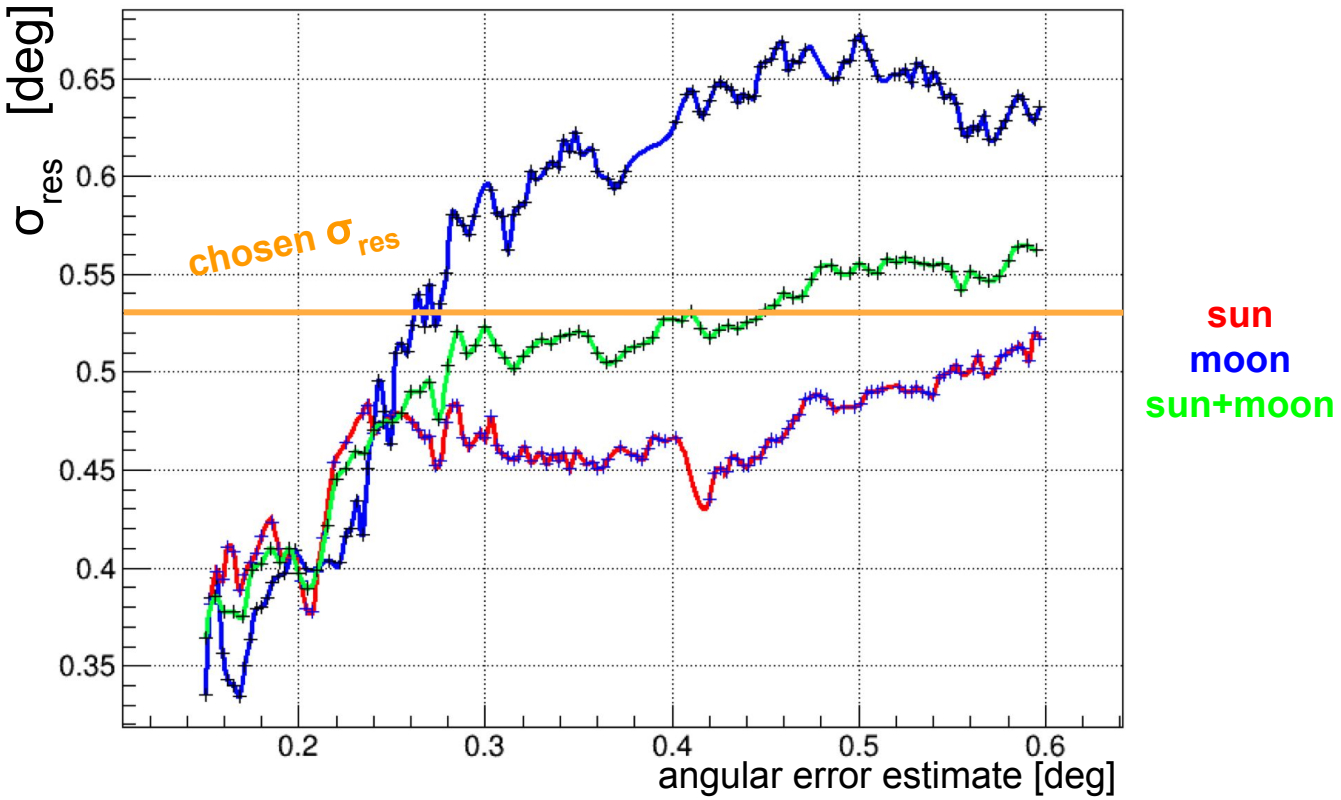
- data events: **3.2 million**
- fraction of sel. events: **45%**

MONTE CARLO

- MC events: **11 million**
- fraction of sel. events: **45%**

Preparation on MC:

angular error estimate scan to optimize track selection



Application to Data

Verify background model

$$H_0 = \rho \cdot P_x(n_x) \cdot P_y(n_y)$$

Fit at nominal Moon/Sun position **(xs,ys) = (0,0)**

with **free** amplitude, width → significance

$$G(A, \sigma_{res}, x_s, y_s) = \frac{A{R_s}^2}{2\sigma_{res}^2} \exp\left[- \frac{(x - x_s)^2 + (y - y_s)^2}{2\sigma_{res}^2} \right]$$

Determine shadow shape and pointing accuracy

with **fixed width (σ_{res})**

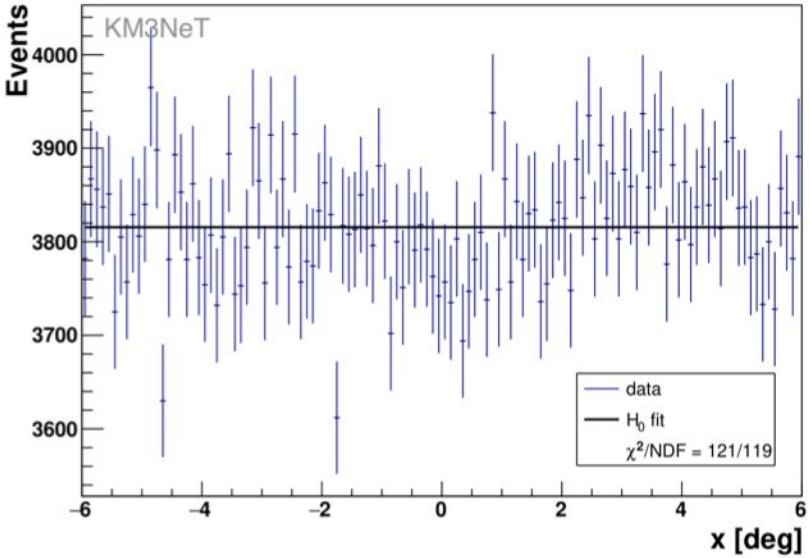
→ shadow position with respect to nominal + contours

Crosscheck with fake sources

Application to data:

Verify background model: $n_x = 0 \cdot n_y = 2$

$$H_0 = \rho \cdot P_x(n_x) \cdot P_y(n_y)$$



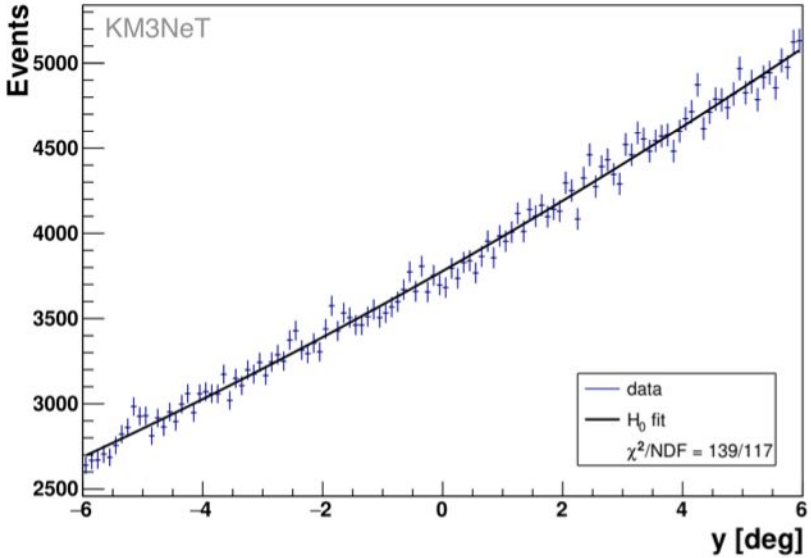


Figure 1: Event distribution in x and y for the Sun data sample (blue crosses) compared to the polynomial fits from the H_0 hypothesis (black lines).

Results ORCA6 - 499 days

from fit at nominal position: (xs, ys) = (0, 0)

Parameters	Moon 1D	Moon 2D	Sun 1D	Sun 2D
σ_{res}	$0.49° \pm 0.11°$	$0.49° \pm 0.15°$	$0.66° \pm 0.08°$	$0.65° \pm 0.13°$
A	0.69 ± 0.17	0.71 ± 0.27	1.38 ± 0.31	1.31 ± 0.34
$\Delta\chi^2_{H1/H0}$	-20.7	-21.3	-47.2	-43.0
Significance	4.2σ	4.2σ	6.5σ	6.2σ
Events/deg^2	2886	2892	3166	3161

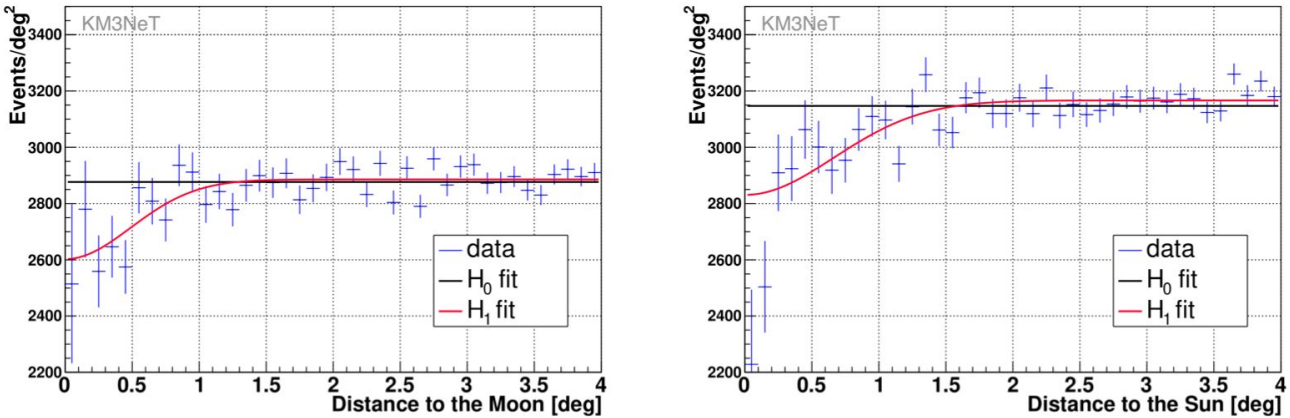


Figure 2: Event density as a function of the distance to the Moon on the left and the Sun on the right. Data (blue crosses) are compared to the H_0 fit (black) and the H_1 fit (red).

Results ORCA6 - 499 days

from fit at nominal position (up): (xs, ys) = (0, 0) + fit with fixed width (σ_{res}) (down)

σ_{res}

- 0.53° +/- 0.04° **MC**
- 0.49° +/- 0.15° **Moon**
- 0.65° +/- 0.13° **Sun**

Parameters	Moon 1D	Moon 2D	Sun 1D	Sun 2D
σ_{res}	$0.49° \pm 0.11°$	$0.49° \pm 0.15°$	$0.66° \pm 0.08°$	$0.65° \pm 0.13°$
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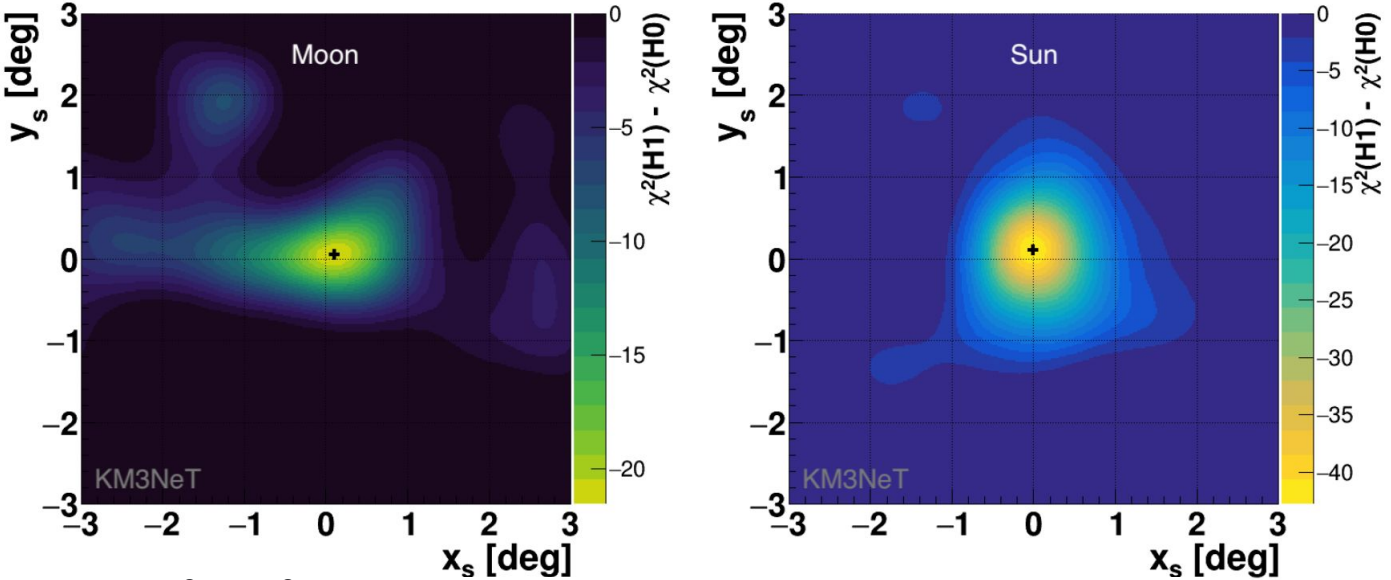
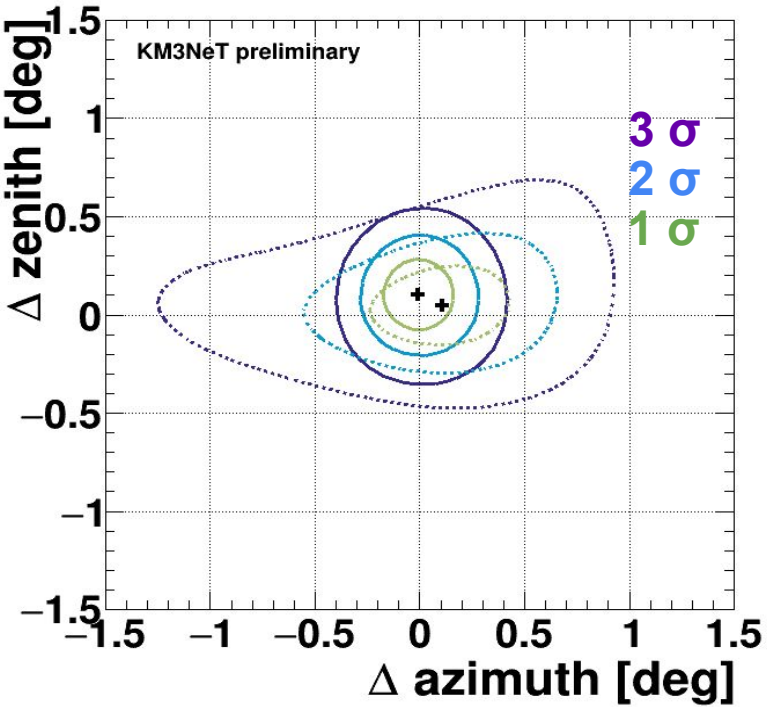


χ^2_{H1} - χ^2_{H0} scan wrt. local angular distance from the Sun/Moon in azimuth, zenith: [x_s,y_s]

Results ORCA6 - 449 days

from fit with fixed width (σ_{res})



1σ 2σ 3σ contour wrt. local angular distance from the Sun/Moon in azimuth, zenith: [x_s,y_s]

- Compatible with nominal position
  → > 60% compatibility with nom. position
- Best fit position compatible between Moon & Sun
  → no significant shift observed
- Sun - pointing results
  - xs (deg) = -0.01 +/- 0.11
  - ys (deg) = 0.10 +/- 0.12
- Moon - pointing results
  - xs (deg) = 0.11 +/- 0.21
  - ys (deg) = 0.04 +/- 0.13

Summary

Moon (Sun) cosmic ray shadows were observed with a **4.2σ (6.2σ)** statistical significance using 499 days of 6 DUs KM3NeT/ORCA data

.

→ good compatibility with the nominal positions of Moon/Sun, **no significant shift** in the absolute orientation was observed

→ good understanding of the detector positioning and orientation after deployment and after the several acoustic calibration stages

→ The shadow observed in data is **compatible with expectations** from MC concerning the significance, angular width and amplitude

→ The Sun shadow amplitude is **consistent** with the effects of the Sun's magnetic field in times of low activity

→ Promising future studies with ARCA and ORCA

Astrophysics > Instrumentation and Methods for Astrophysics

[Submitted on 15 Nov 2022]

First observation of the cosmic ray shadow of the Moon and the Sun with KM3NeT/ORCA

KM3NeT Collaboration

This article reports the first observation of the Moon and the Sun shadows in the sky distribution of cosmic-ray induced muons measured by the KM3NeT/ORCA detector. The analysed data-taking period spans from February 2020 to November 2021, when the detector had 6 Detection Units deployed at the bottom of the Mediterranean Sea, each composed of 18 Digital Optical Modules. The shadows induced by the Moon and the Sun were detected with a statistical significance of 4.2{\sigma} and 6.2{\sigma}, respectively, at their nominal position. This early result confirms the effectiveness of the detector calibration, in time, position and orientation and the accuracy of the event direction reconstruction. This also demonstrates the performance and the competitiveness of the detector in terms of pointing accuracy and angular resolution.

Comments: 14 pages, 8 figures
Subjects: **Instrumentation and Methods for Astrophysics (astro-ph.IM)**; High Energy Astrophysical Phenomena (astro-ph.HE)
Cite as: arXiv:2211.08977 **[astro-ph.IM]**
(or arXiv:2211.08977v1 **[astro-ph.IM]** for this version)
https://doi.org/10.48550/arXiv.2211.08977

Submission history

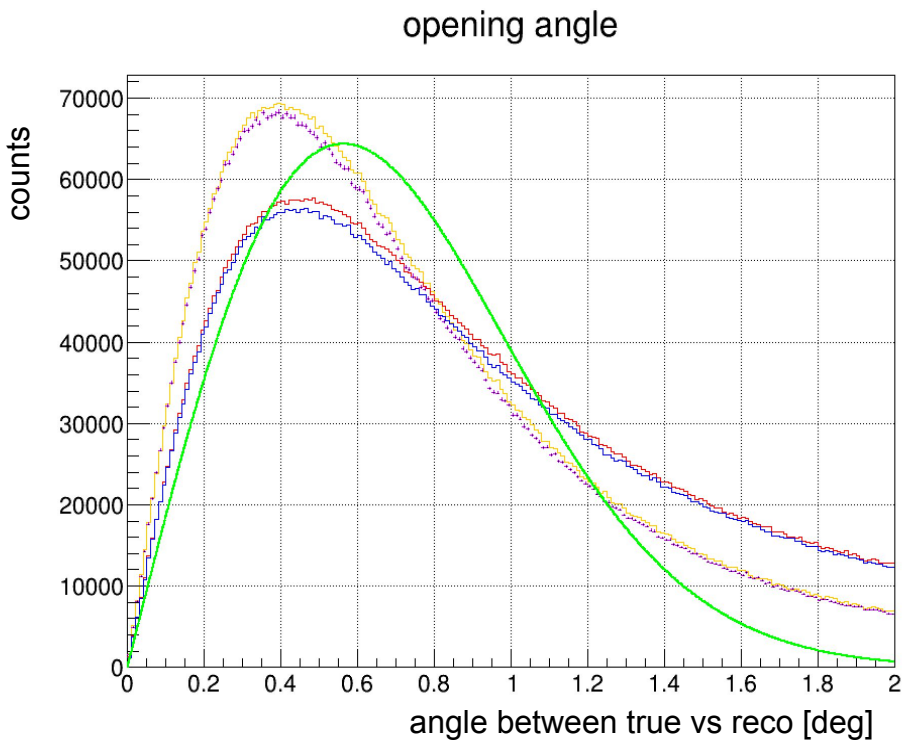
From: Luc Cerisy [view email]
[v1] Tue, 15 Nov 2022 14:48:34 UTC (394 KB)

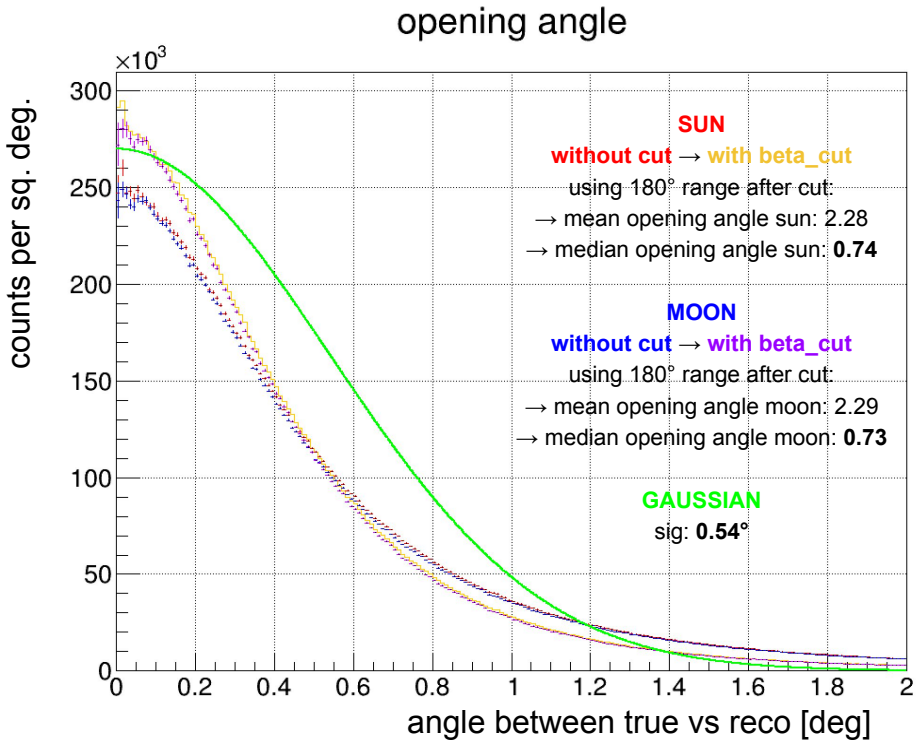
THANKS

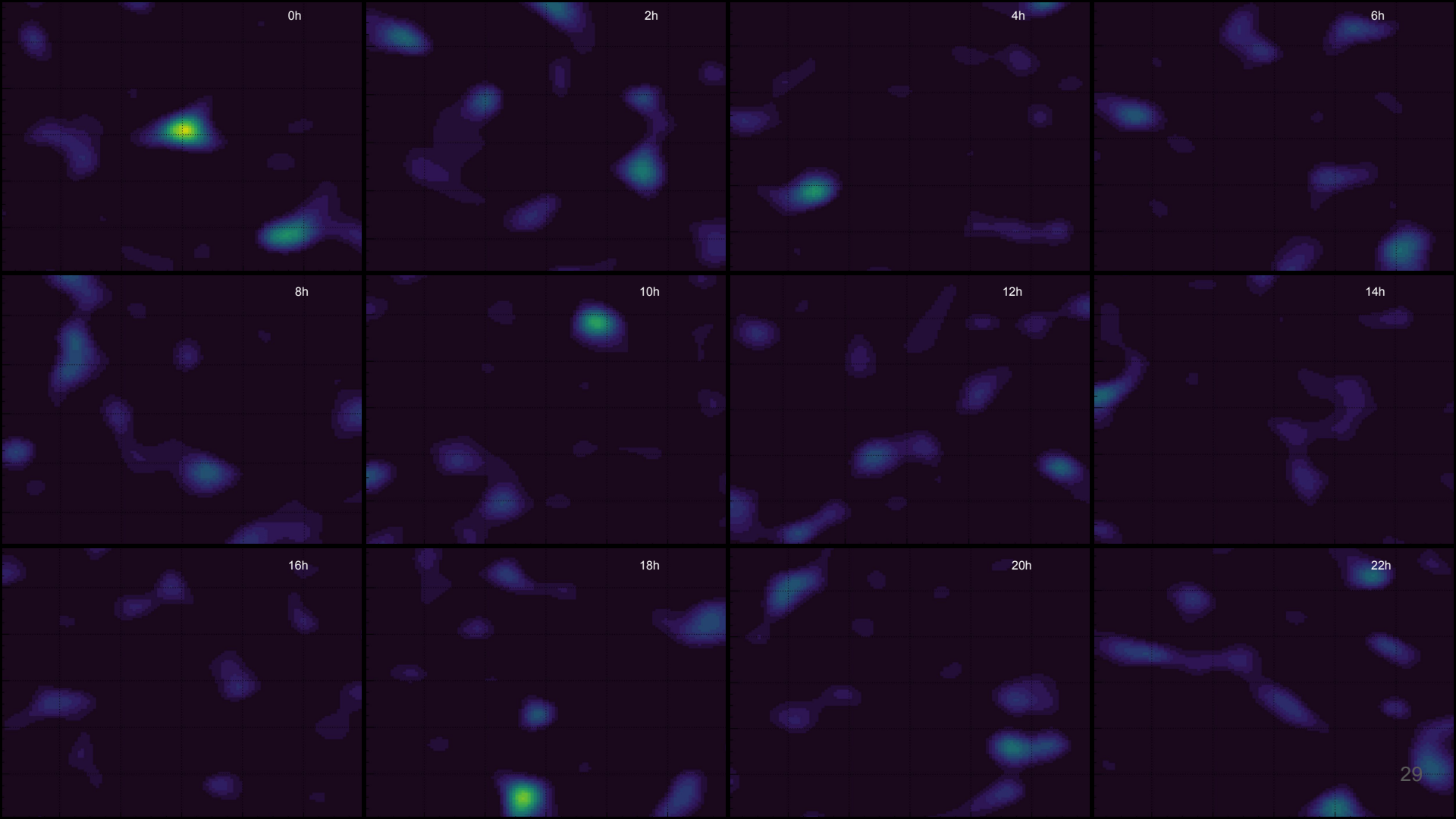
BACKUP

Preparation on MC:

comparison between actual angular resolution and used gaussian function



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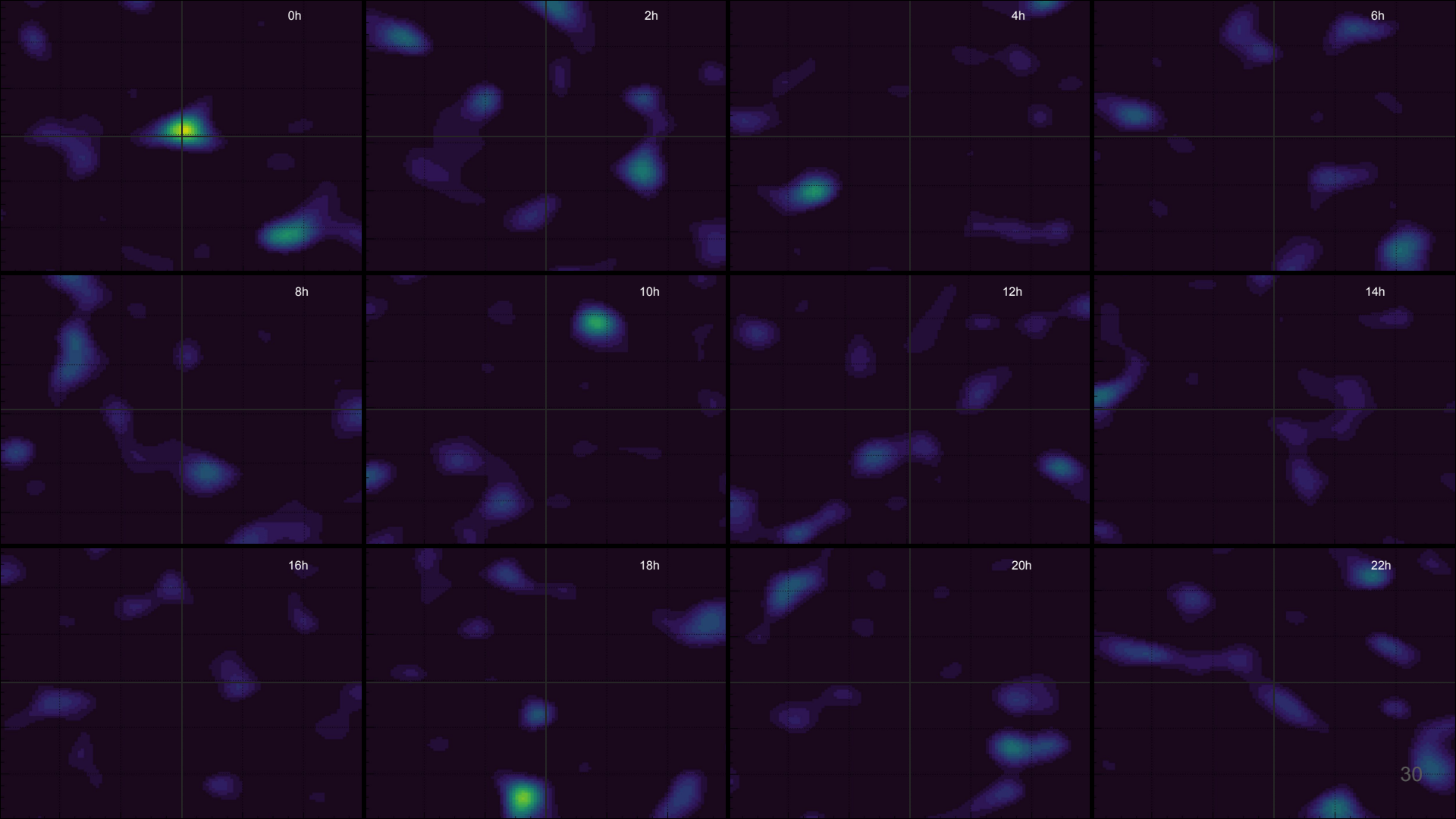
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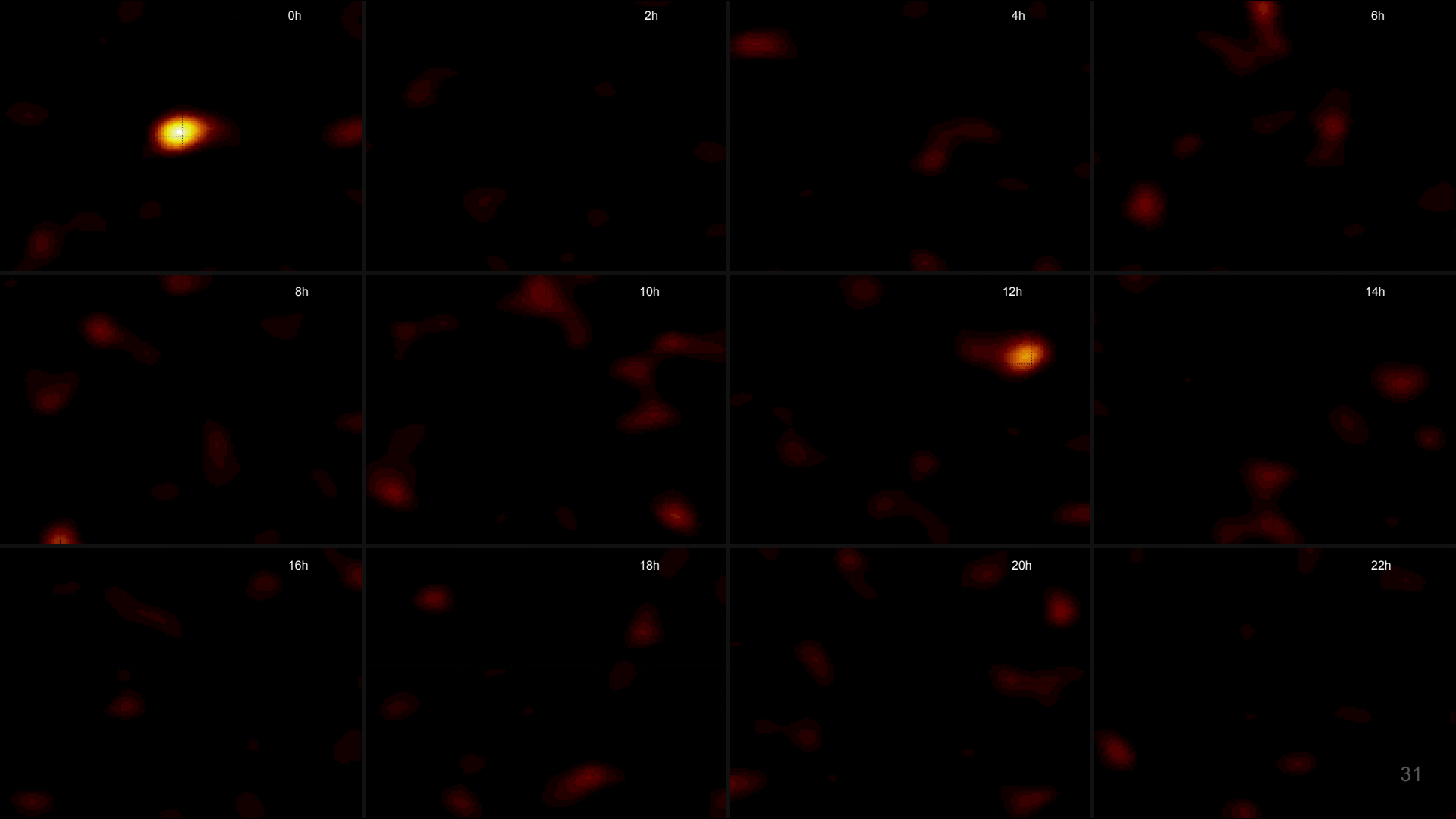
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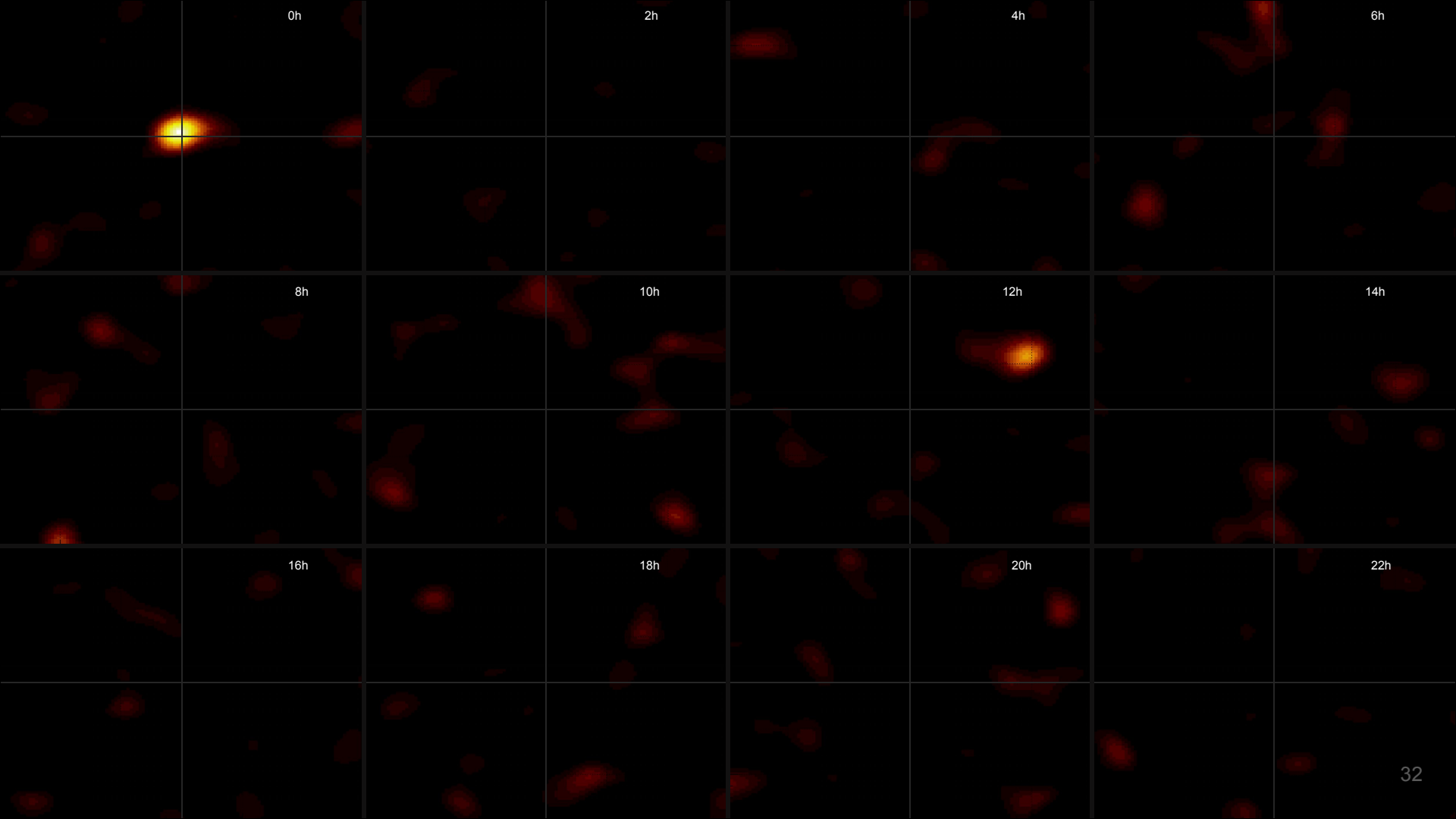
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