Friedrich-Alexander-Universität
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A template-based air shower reconstruction method for SWGO

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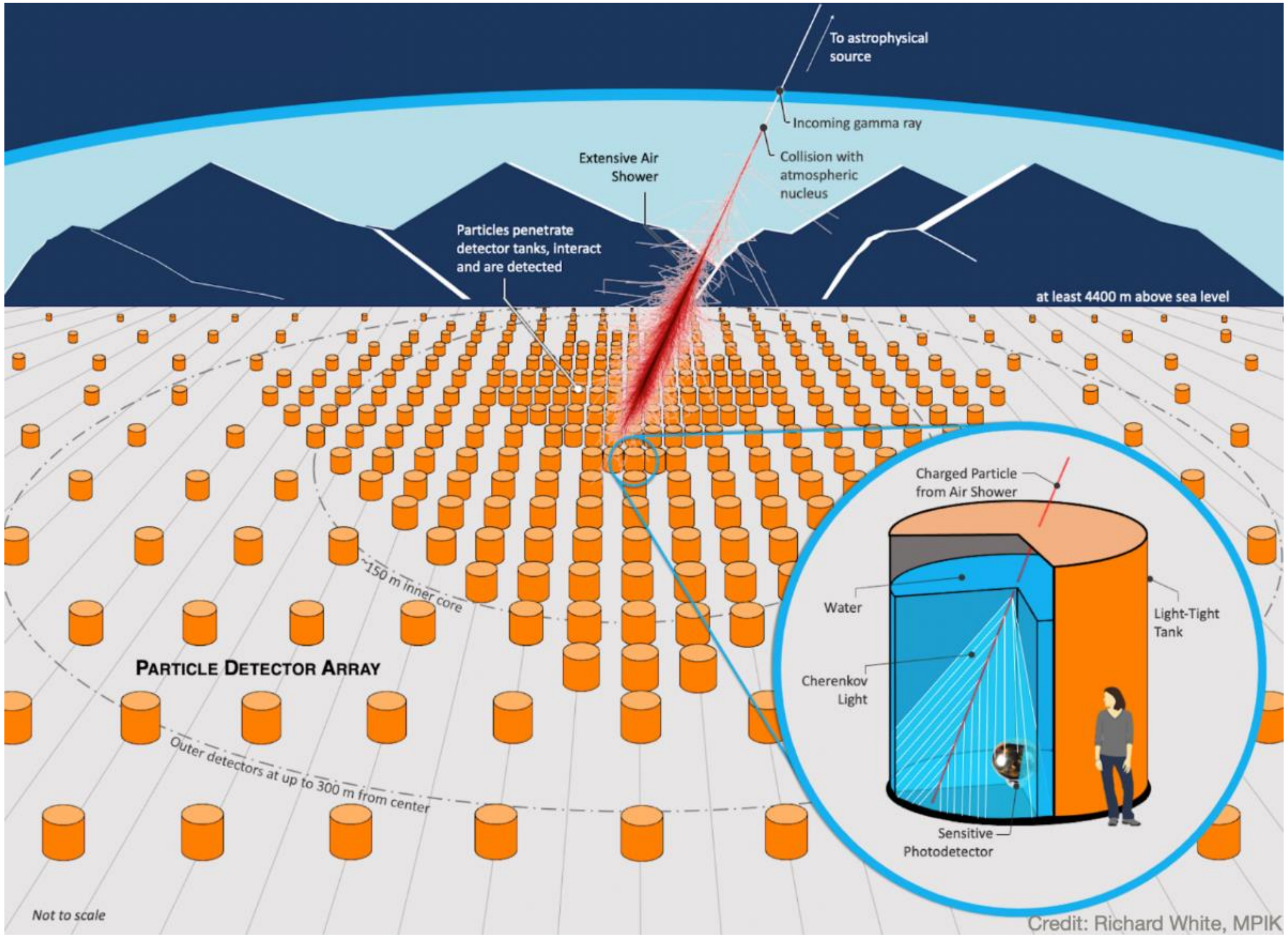
The Southern Wide-field Gamma-Ray Observatory (SWGO)

- Future particle detector array located in South America
- Ground-level water Cherenkov detector array
- Energy range from hundreds of GeV up to PeV
- Altitude above 4.4 km and latitude between 10° and 30° South

The Southern Wide-field Gamma-ray Observatory

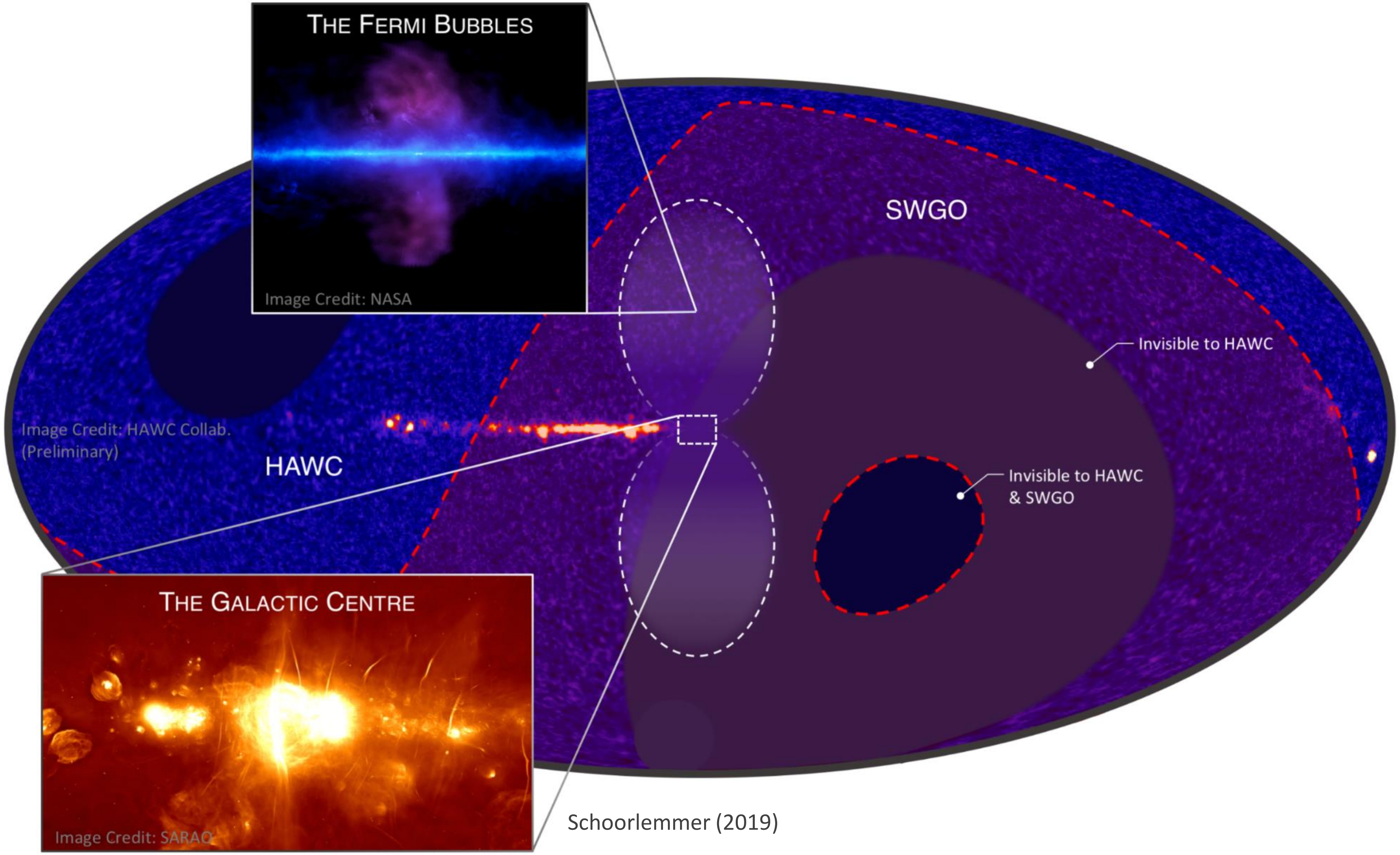
SWGO (2023)



The Southern Wide-field Gamma-Ray Observatory (SWGO)

Scientific prospects:

- Very extended gamma-ray emission sources
- Transient sources
- Primordial black holes
- Galactic accelerators
- And many more



Schoorlemmer (2019)

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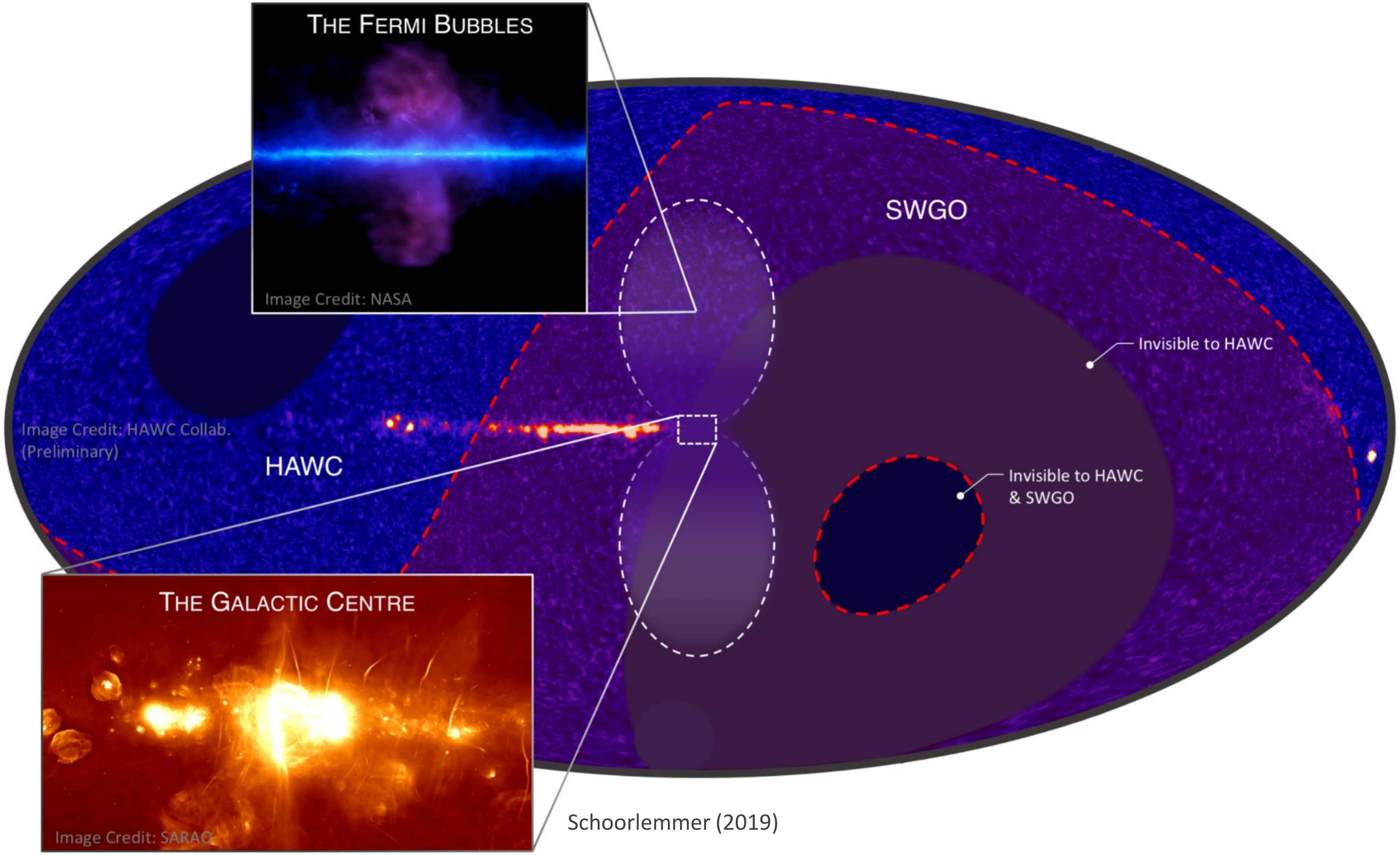
➢ Extending current generation instruments to the Southern hemisphere

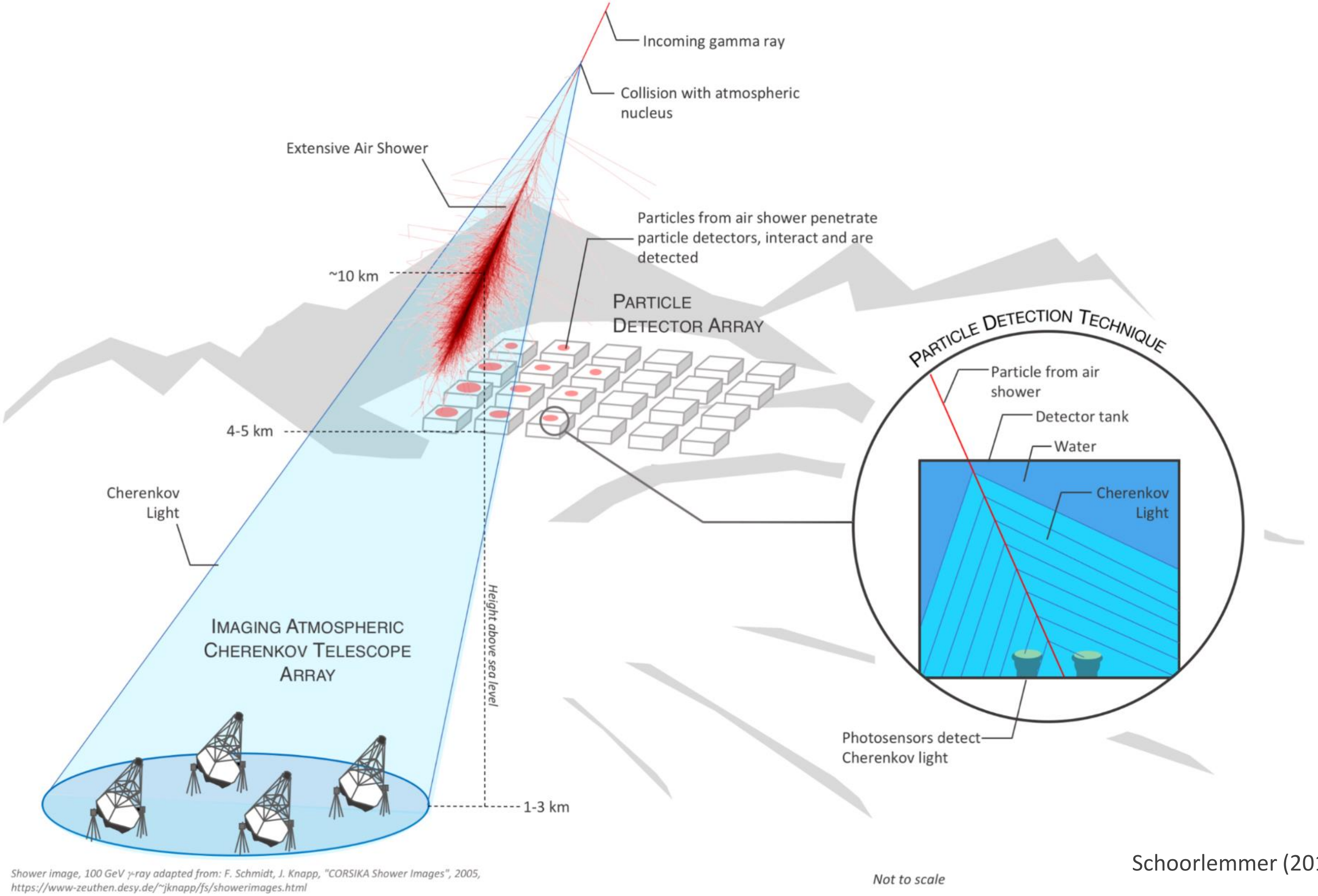


Schoorlemmer (2019)

Particle detection SWGO vs IACTs

<u>Advantages of SWGO:</u>

- Close to 100% duty cycle
- $\sim$2 sr field of view



Schoorlemmer (2019)

Template-based air shower reconstruction

What do we measure?

Secondary particles, induced by primary gamma rays that interacted with the nuclei in the atmosphere

What do we want to find out?

Information about these primary gamma rays → Information about their source (scientific prospects)

How do we characterize the primary gamma rays from our measurements?

Use info of secondaries to reconstruct the shower and therefore the primary particle

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CHARGE measured in the tanks

TIME measured in the tanks

Energy and core reconstruction

Direction reconstruction

→ Using a template-based approach for both

Core and energy reconstruction

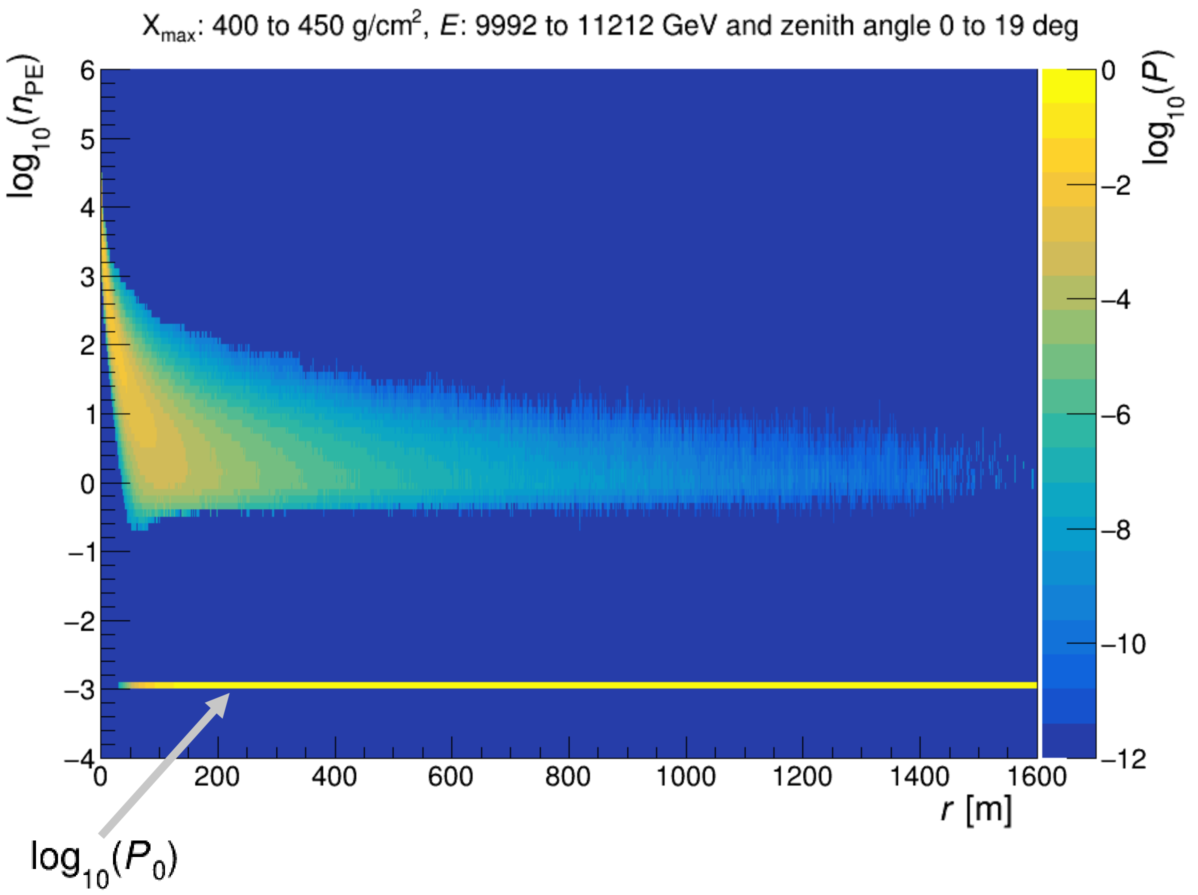
Core and energy reconstruction

- Templates:
  MC simulations of gamma-induced EAS binned in
  E, $X_{\max}$, θ

- Reconstruct incoming shower:
  Fit LDF of the shower to the templates

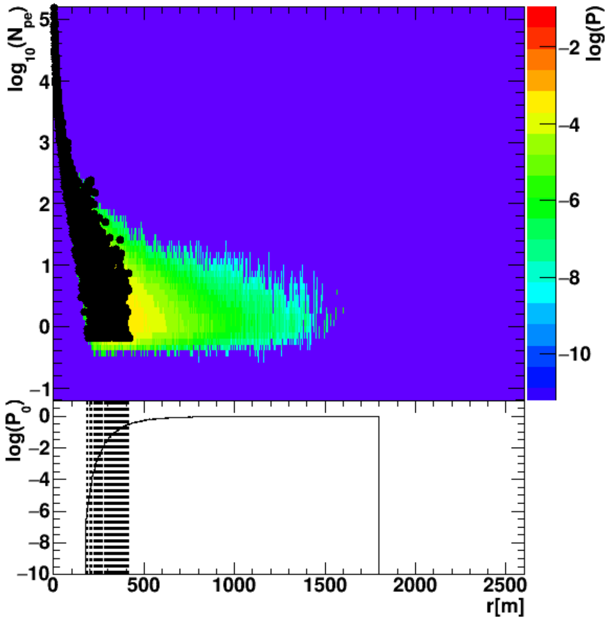
- Minimise log-likelihood to get best fit parameters

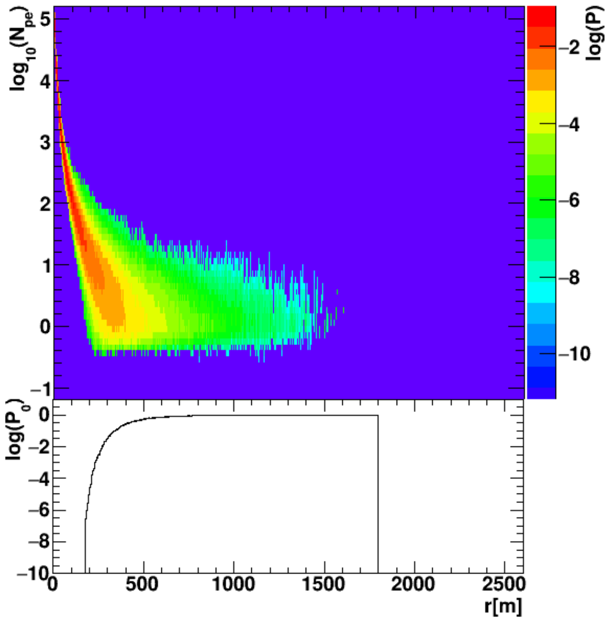
$$\log L = -2 \sum_i \log(F(\log_{10}(N_{\mathrm{PE}})_i, r_i, X_{\max}, E|\theta, \phi))$$



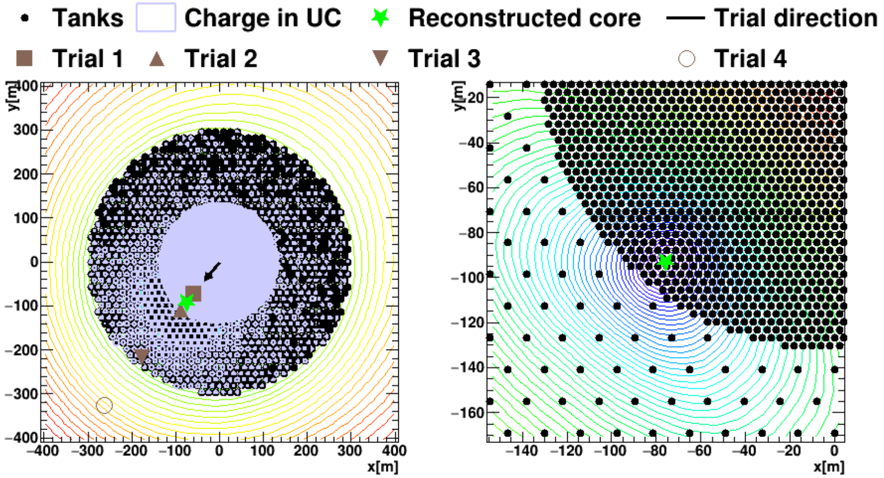
Example event reconstruction

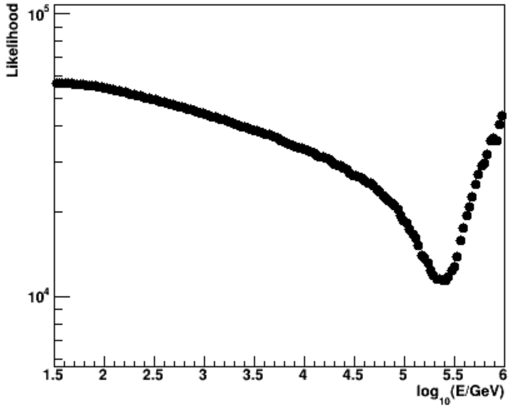
Binning: $E = 251.0$ TeV – 281.6 TeV; $X_{\max}$ = 500 g/cm² - 550 g/cm²; θ = 0° - 19°





Likelihood surface: minimum → maximum





	E [TeV]	X_{max} [g/cm²]	x [m]	y [m]
True	256.4	514	-75.9	-93.0
Reco	266.1	546	-75.7	-93.0

Reconstruction results

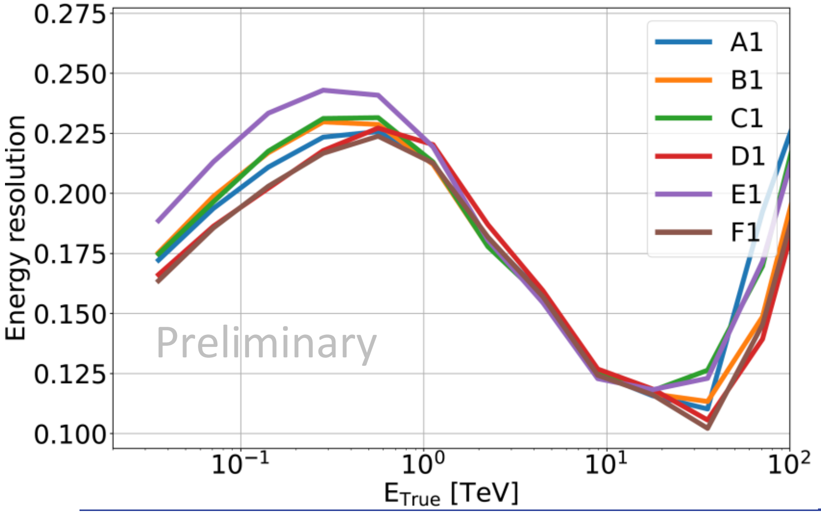
→ Can reliably reconstruct core resolution and energy bias and resolution for different array configurations

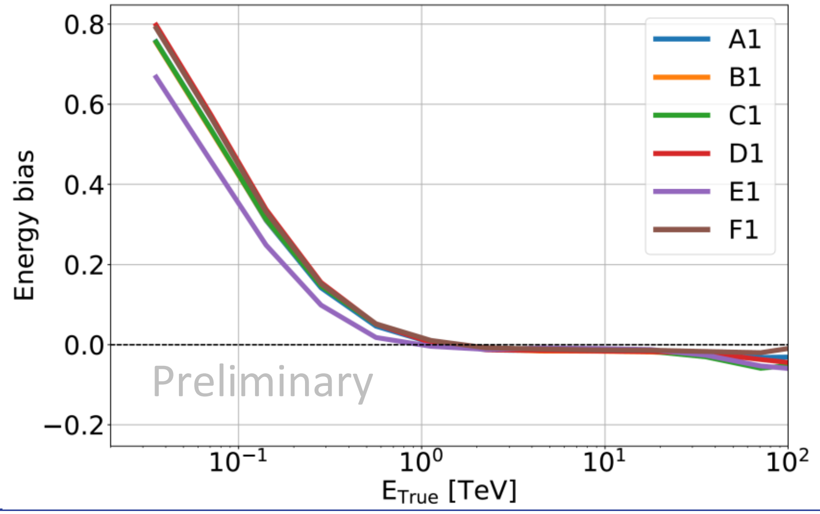
Reconstruction cuts for plots:

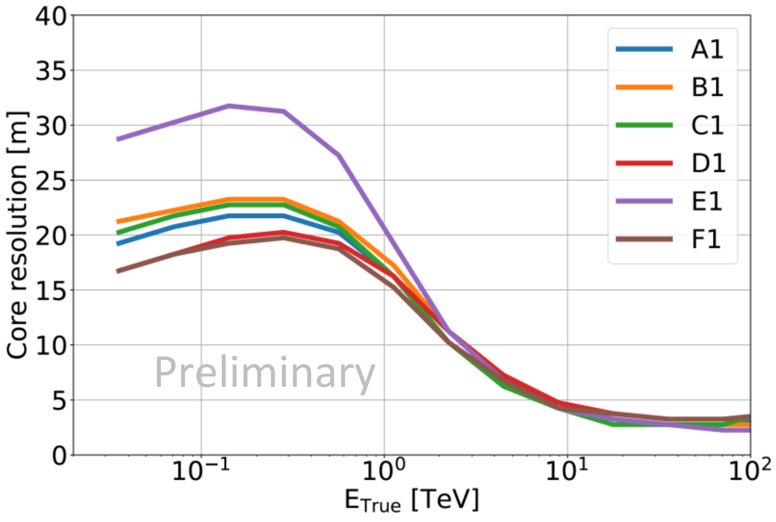
- Shower thrown within 300 m radius of the array centre
- $n_{\text{tanks hit}} > 25$
- Zenith angle $\theta < 45°$

- Use only upper cells from double-layered tanks
- No optimisation of $\#n_{\text{tanks hit}}$ and the radius in which showers should be thrown for each configuration yet

→ Need different reconstruction cuts before making comparisons between the performances of the configurations







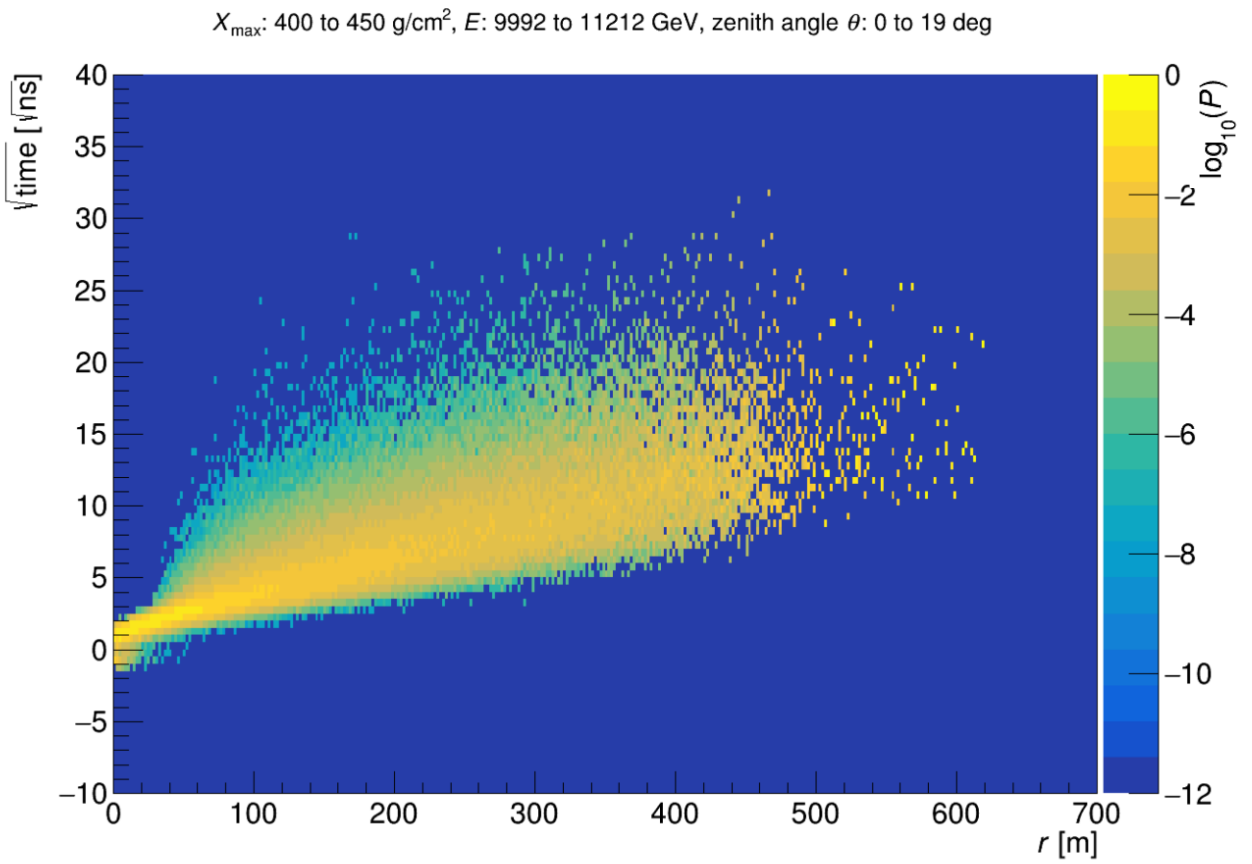
Direction reconstruction

Direction reconstruction

- Templates:
  MC simulations of gamma-induced EAS *preliminarily* binned in:
  $$E, \quad X_{\text{max}}, \quad \theta$$

- Reconstruct incoming shower:
  Fit LDF of the shower to the templates

- Minimise log-likelihood to get best fit parameters
  - Use a 3-parameter fit
    $$L = F(l, m, t_0 | x, y, E, X_{max})$$
  - Calculate θ, ϕ with fit parameters l, m



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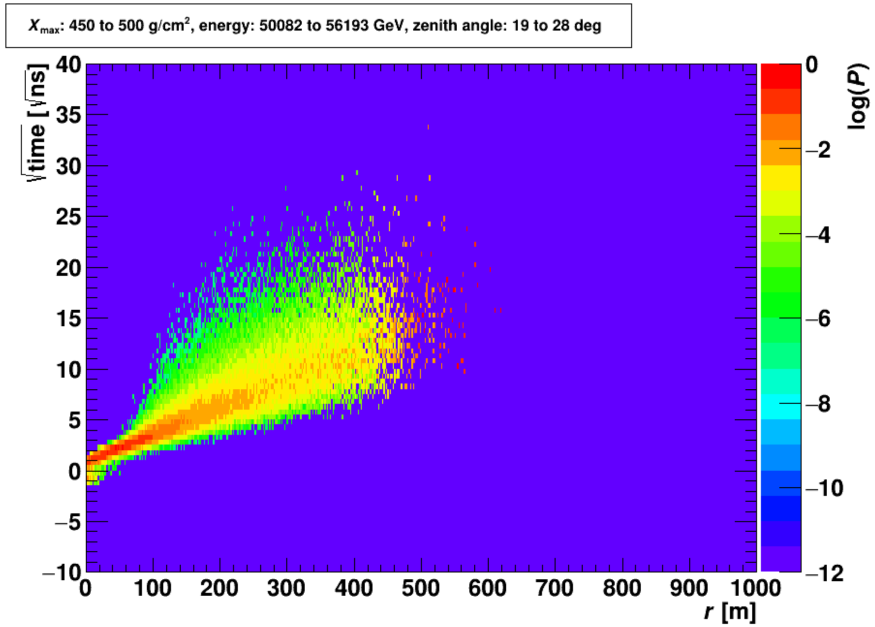
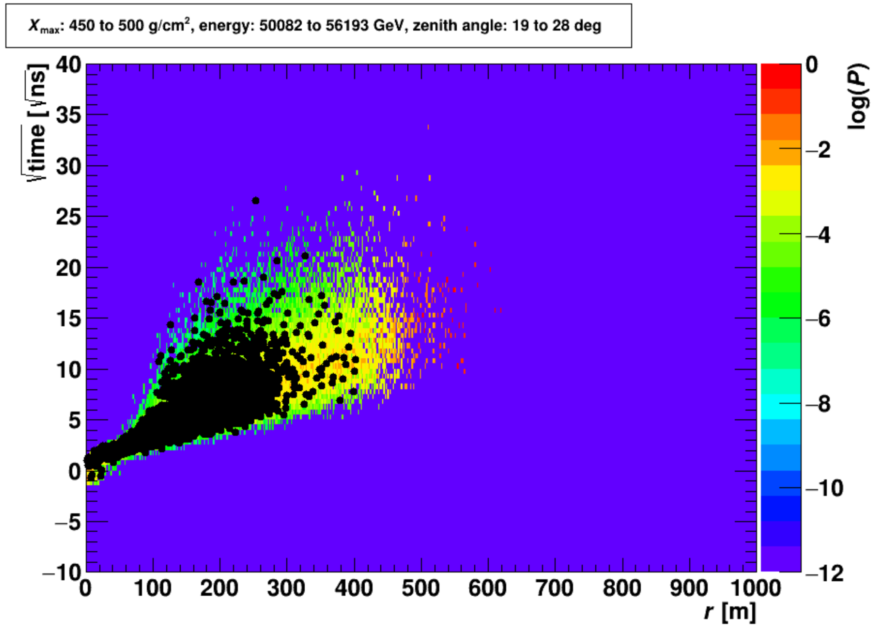
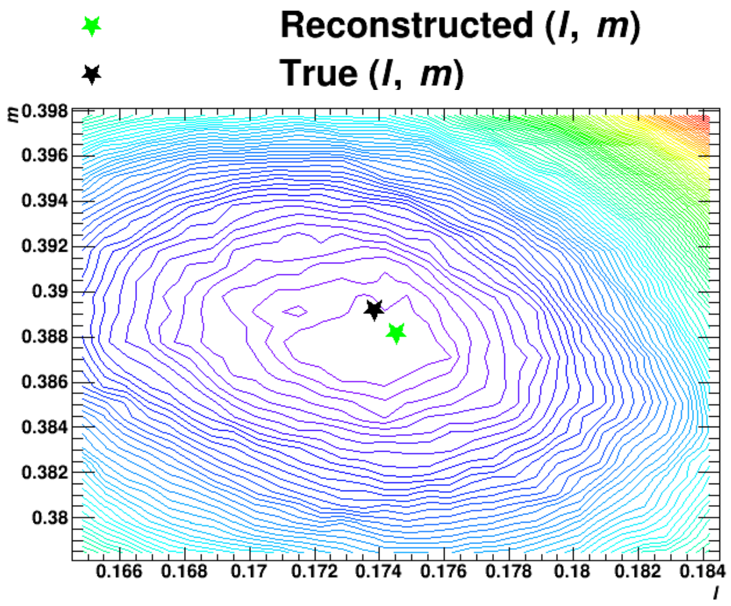
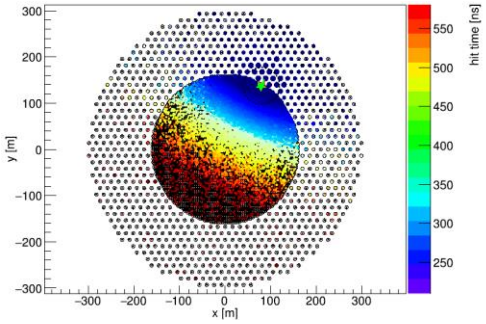


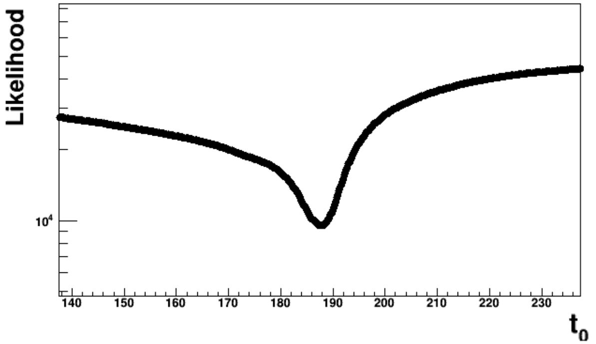


Likelihood surface: minimum → maximum



	l	m	θ [°]	ϕ [°]	$\Delta angle$ [°]	E [TeV]
True	0.173836	0.389146	25.23	65.93	-	56.5
Seed	0.17756	0.394607	25.64	65.77	0.42	53.1
Reco	0.174521	0.388119	25.19	65.79	0.07	53.1

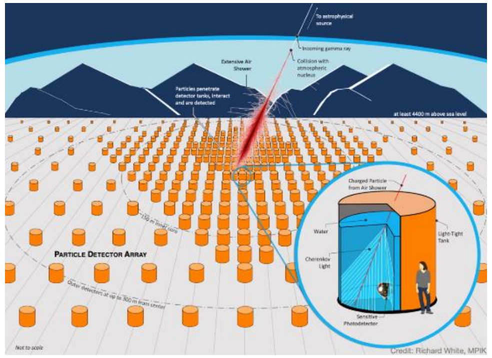




Summary

SWGO:

- Ground-based gamma-ray detection array that uses WCDs
- Close to 100% duty cycle and steradian field of view
- Extending current generation instruments to the Southern hemisphere



SWGO (2023)

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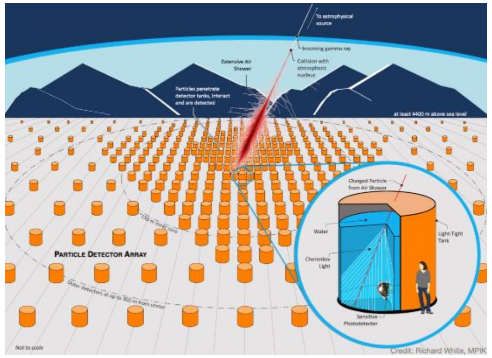

SWGO (2023)

Template-based reconstruction method:

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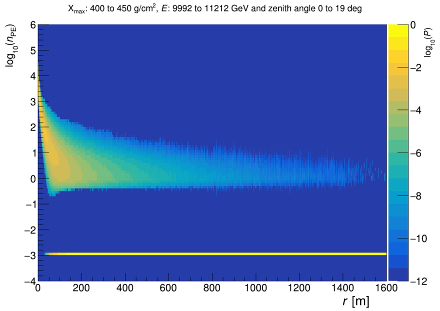
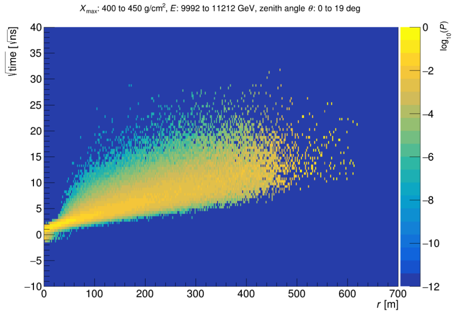
- Fit LDF of the shower to the templates and minimise the log Likelihood





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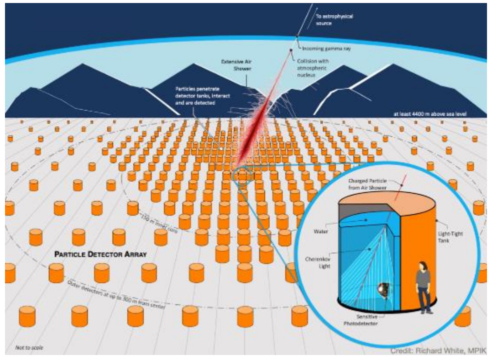

[SWGO](2023)

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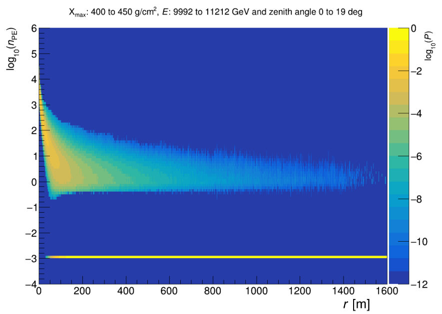

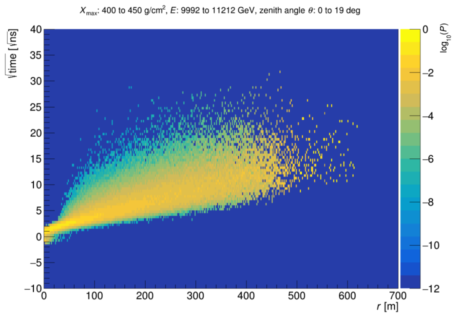

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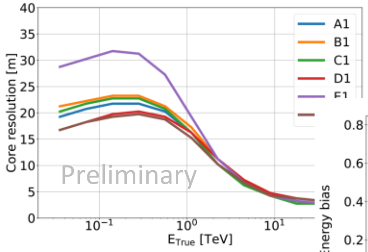
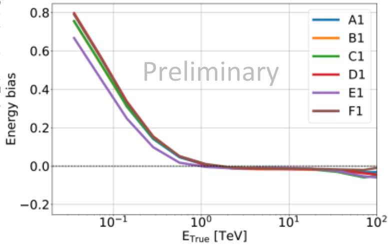
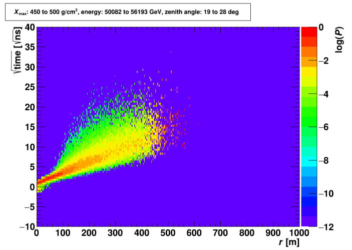
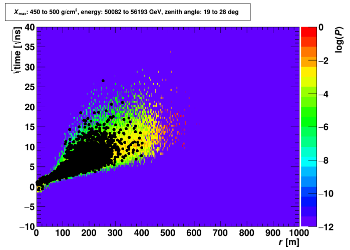


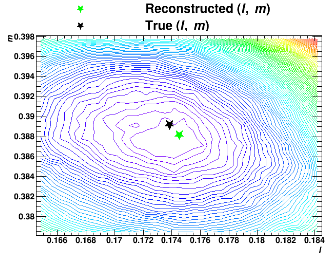


Reconstruction

- Core and energy (up and running)
- Direction (work in progress)







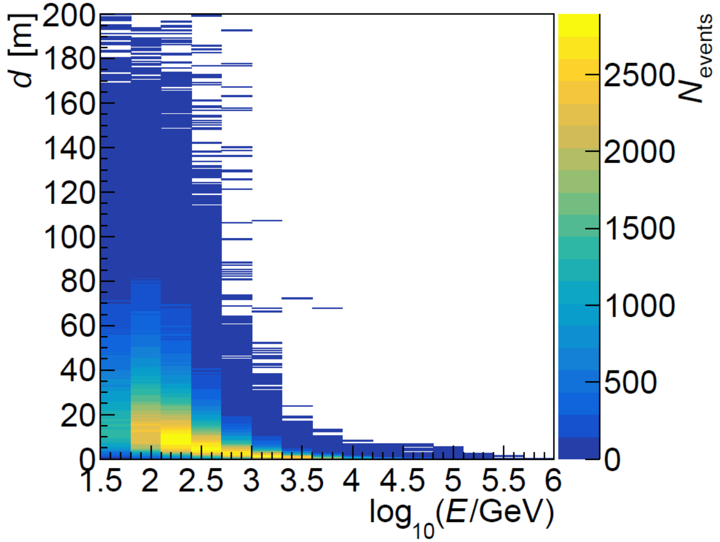
Thank you for your attention!

Backup

How to calculate bias and resolutions

<u>Core resolution:</u>

68% containment radius of the distribution of the distance between the reconstructed and true shower core

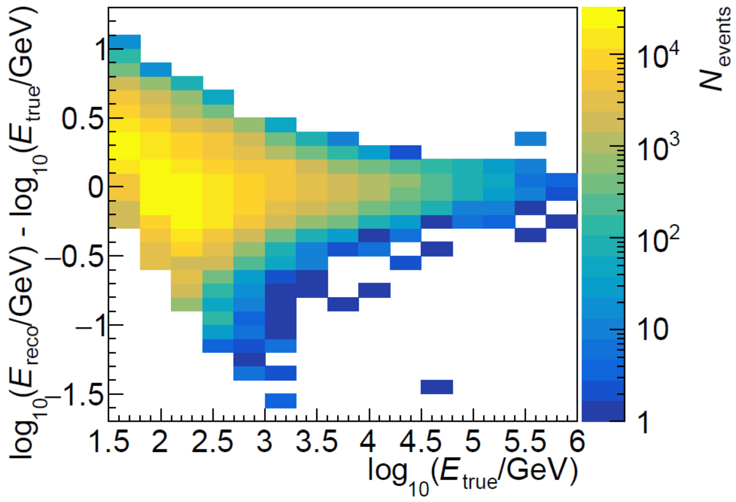


<u>Energy bias:</u>

mean of $(\log_{10}(E_{\mathrm{reco}}/\mathrm{GeV}) - \log_{10}(E_{\mathrm{true}}/\mathrm{GeV}))$

<u>Energy resolution:</u>

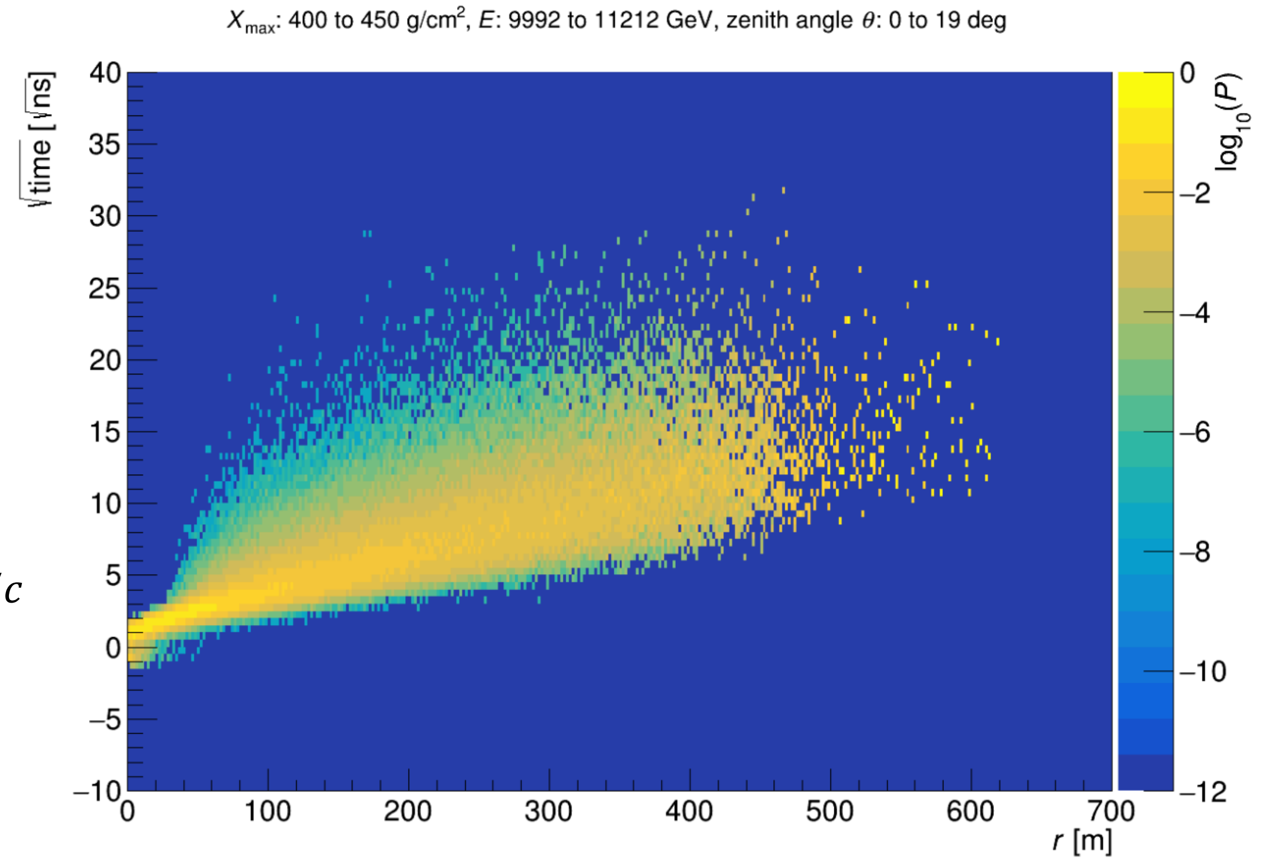
RMS of $(\log_{10}(E_{\mathrm{reco}}/\mathrm{GeV}) - \log_{10}(E_{\mathrm{true}}/\mathrm{GeV}))$



Current templates

Sqrt templates:

- Still unsmoothed
- Binning preliminary, taken from module for fitting core and energy



Fitting:

- 3-parameter fit, fitting t_0, l, m:

$$t_i = t_{\text{tank},i} - t_0 + \left(l \times (x_{\text{tank},i} - x_c) + m \times (y_{\text{tank},i} - y_c)\right)/c$$

- Get θ, ϕ with $n = \sqrt{1 - l^2 - m^2}$:

$$\theta = 90° - \text{atan}\left(\frac{n}{\sqrt{1-n^2}}\right); \qquad \phi = \text{atan2}(m, l)$$