MAX-PLANCK-INSTITUT FÜR KERNPHYSIK

# HAWC analysis with gammapy

## Progress report and proposed features


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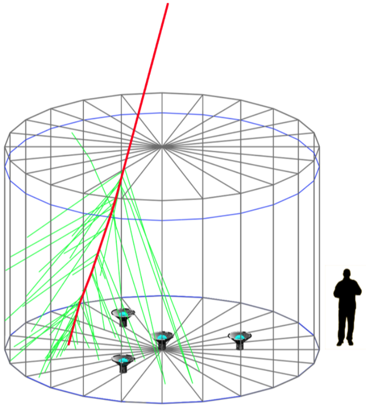
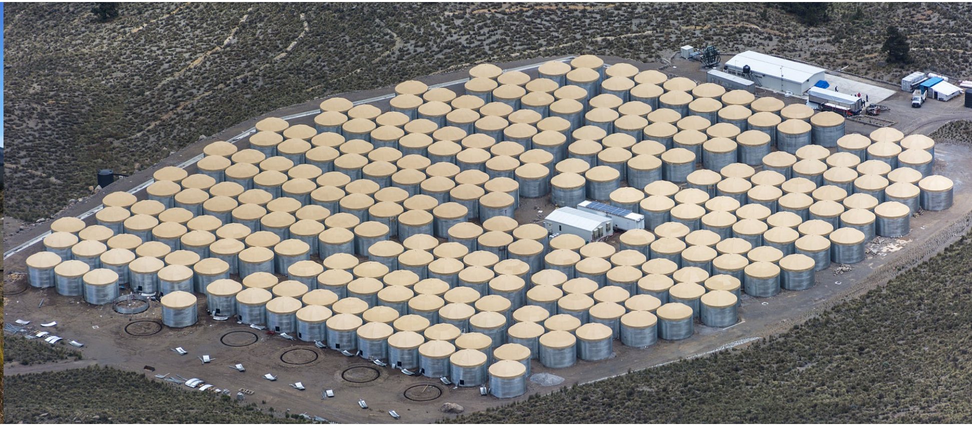
A **Python** package for **gamma-ray** astronomy

HAWC High Altitude Water Cherenkov Gamma-Ray Observatory

# The HAWC observatory

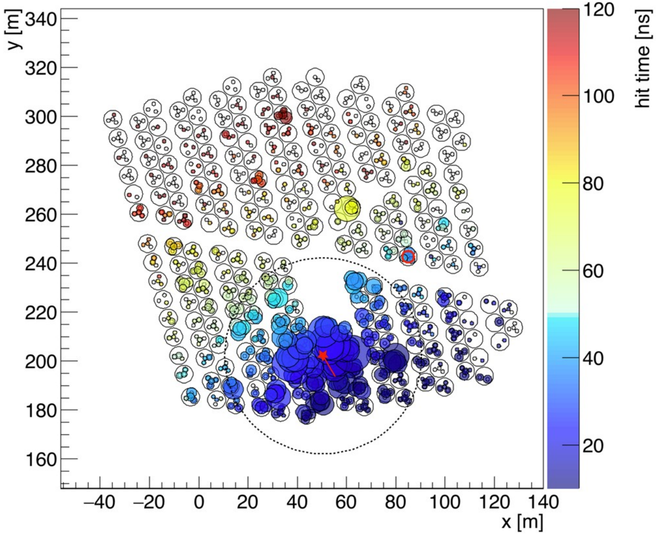
- High Altitude Water Cherenkov Observatory, located in Mexico
- Continuous, wide-field observations
- Energy range between 100 GeV and 100 TeV
- Complimentary to pointed IACT observations





# The nHit binning scheme

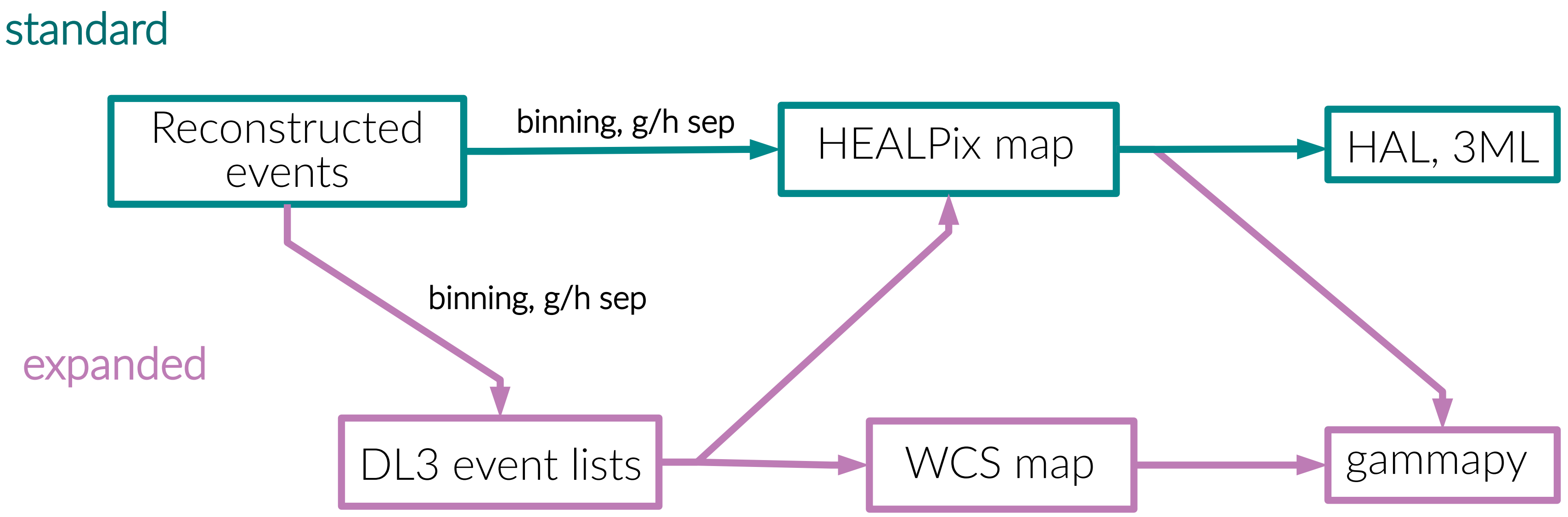
- Properties of reconstructed events in HAWC depend very strongly on the **number of tanks that were triggered** → **nHit** parameter
- Very different PSF and G/H separation threshold between bins
- Together with energy axis → 2D bins.
- In DL3 format: nHit bin → **different event classes, different datasets**




| Bin number | Low fraction hit | High fraction hit |
|---|---|---|
| 1 | 0.067 | 0.105 |
| 2 | 0.105 | 0.162 |
| 3 | 0.162 | 0.247 |
| 4 | 0.247 | 0.356 |
| 5 | 0.356 | 0.485 |
| 6 | 0.485 | 0.618 |
| 7 | 0.618 | 0.740 |
| 8 | 0.740 | 0.840 |
| 9 | 0.840 | 1.00 |

| Bin | $\hat{E}$ energy range (TeV) |
|---|---|
| c | 1-1.78 |
| d | 1.78-3.16 |
| e | 3.16-5.62 |
| f | 5.62-10.0 |
| g | 10.0-17.8 |
| h | 17.8-31.6 |
| i | 31.6-56.2 |
| j | 56.2-100 |
| k | 100-177 |
| l | 177-316 |

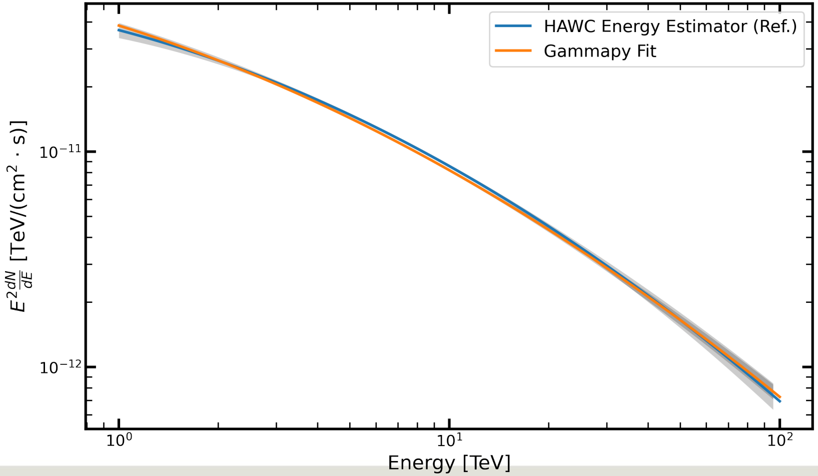
# The HAWC data analysis workflow




Scripts to go from usual HAWC data format and IRFs to DL3 compatible event lists and gammapy IRFs already available to the HAWC collaboration

# HAWC data analysis with gammapy

- Is it possible? YES 🙂 but I can't show you many details because data is not public.
- Successfully reproduced published Crab spectrum using gammapy.
- Results shown in the November HAWC collaboration meeting.




```
%%time
fit = Fit(hawc_datasets_nHitBin[1:])
result = fit.run()
```

```
CPU times: user 2min 41s, sys: 1min 1s, total: 3min 42s
Wall time: 3min 42s
```

# HAWC data analysis with gammapy

- Key difference with IACT analysis: IRFs are given as a whole-sky map in RA, Dec.

  → IRFs depend on declination, usually given in bins of 5°

  → made changes to `MapDatasetMaker`: if IRF inputs are maps (`Map`, `EdispKernelMap`, `PSFMap`), interpolate to analysis geometry (#3007)

- Another difference: PSF in HAWC is given in $E_{reco}$ and not in $E_{true}$

  → changes made by Axel in #3072: define

  `SkyModel.apply_irf["psf_after_edisp"]=True`

- nHit event classes → one `MapDataset` per nHit bin with $E_{reco}$ axis

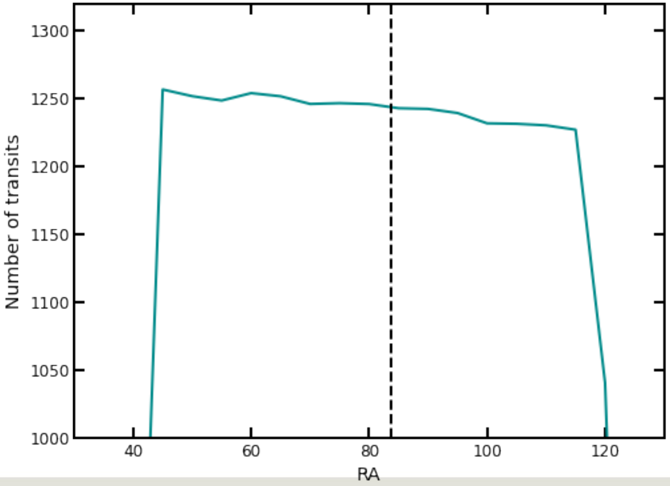
# ON Time

- Information about the ONTIME of the detector is stored in **GTIs** (Good Time Intervals), a table associated to each event list.

$$GTI_{subrun} = [t_{\text{first event, no cuts}}, t_{\text{last event, no cuts}}]$$

| START | STOP |
|---|---|
| float64 | float64 |
| 1168135330.0 | 1168135455.0 |
| 1168135455.0 | 1168135580.0 |

- For each GTI, compute the R.A. of zenith and fill a histogram




Right now done in separate step, could be done inside gammapy?

# HAWC IRFs

- **Effective area** → from detector response file, number of events that are reconstructed in each bin.

  $$\text{effective\_area}(E_{true}) = \text{expected\_counts}(E_{true})/(\Delta E_{true} \cdot dN/dE_{true})$$

  This corresponds to 1 transit → need to multiply by histogram in slide before to get effective exposure. Depends on declination: Fill a whole-sky **gammapy.maps.WcsNDMap** with the right value in each dec band and an energy true axis

- **Energy dispersion** → Shape of the normalized distributions in detector response file. Answer to the question *"For each event with energy $E_{true,}$ what is the probability that it is reconstructed with a certain $E_{reco}$?"*.

  Again it depends on declination: Fill a **gammapy.irf.EdispKernelMap**, a 4D matrix (ra, dec, $E_{true}$, $E_{reco}$)

- **PSF** → From detector response file, fill in a **PSFMap** → (ra, dec, radial offset, $E_{reco}$)

**Note:** in the HAWC analysis with energy estimators, some energy bins are not considered (e.g. 1a and 1b). This is taken into account adding to each of our nHit datasets a **MapDataset.mask_safe**, which is a **gammapy.Map** with the same dec binning, an $E_{reco}$ axis and boolean values indicating the right energy bins at each sky position.

# The future of detector arrays

- SWGO: proposed wide-field observatory in the Southern hemisphere
- Observation mode similar to HAWC → tools developed for HAWC can be used
- Interest in adopting open-source tools and GADF data formats

The Southern Wide-field Gamma-ray Observatory

# Things that would be nice to have

- Right now the usual HAWC workflow is completely based in HEALPix maps, improving support of HpxNDMap in the analysis would be good to bridge between both approaches.

- The possibility to have an asymmetric PSF would be very interesting

- Right now IRFs are given in declination for one transit, but another possibility is to have them in local coordinates (zenith bands). This would require projecting them into sky coordinates at the data reduction step. This is specially relevant for transient analysis.
    → "3D PSF": energy, theta, zenith
    → IRFs in zenith bands would then need to be convolved with source trajectory.