Atreyee Sinha
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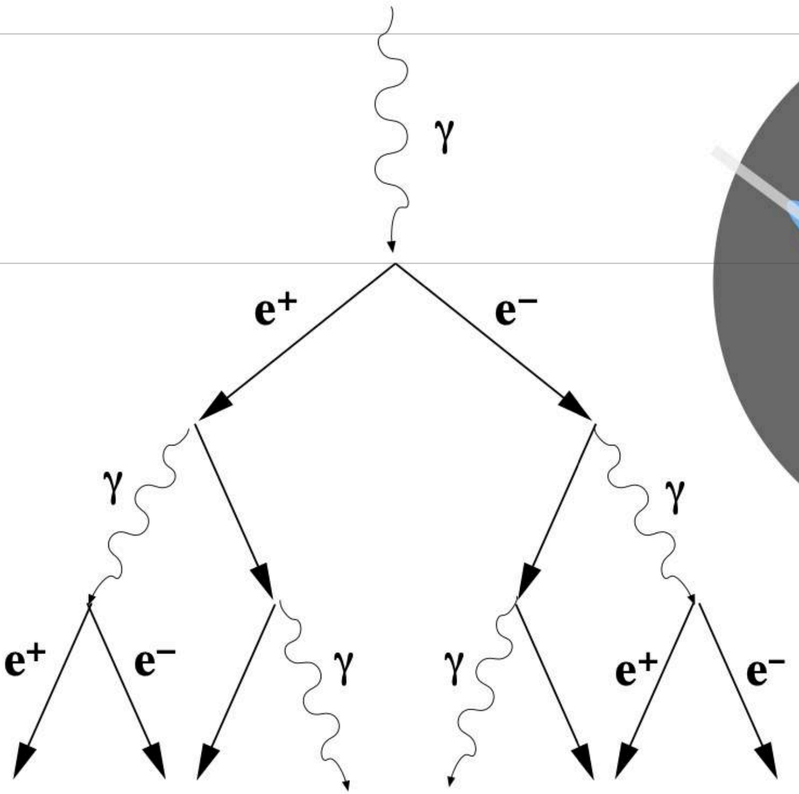
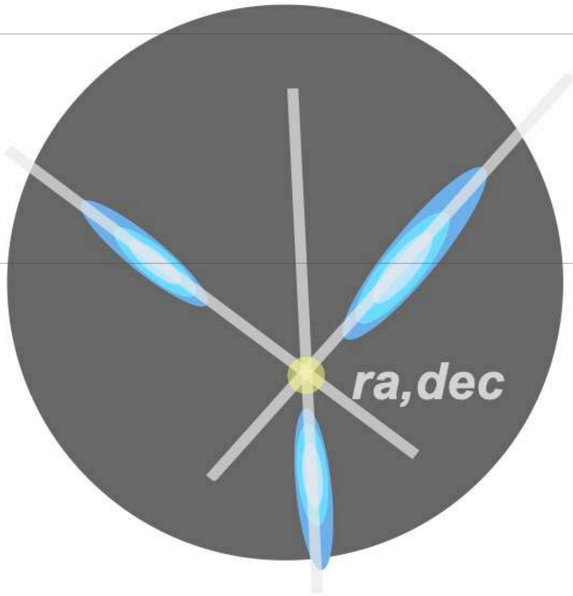
For the Gammapy-dev team

A short introduction to VHE gamma-ray detection techniques

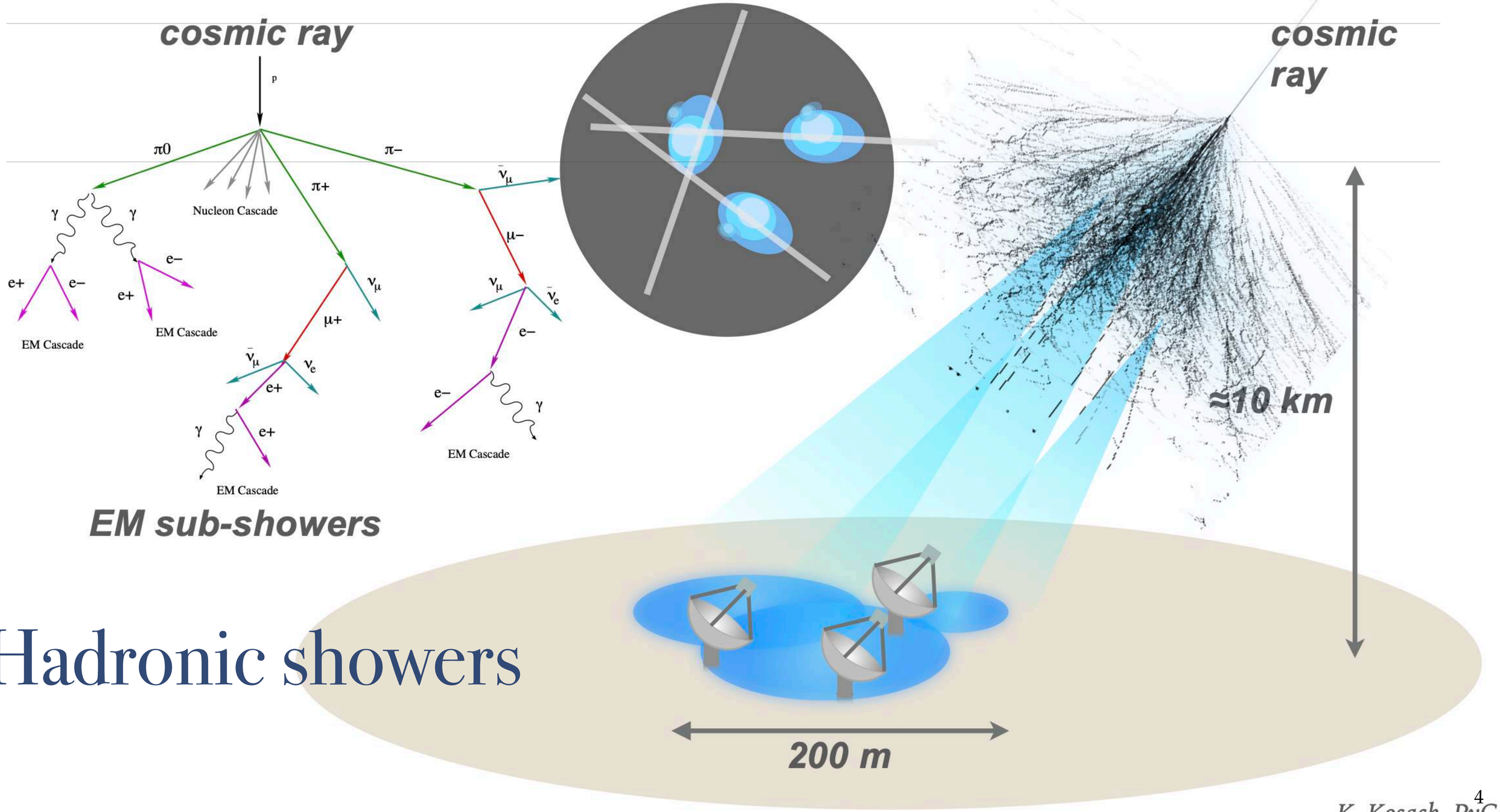




Photon showers

effective area *≈ size of light pool (small array)*

≈ size of array (large array)

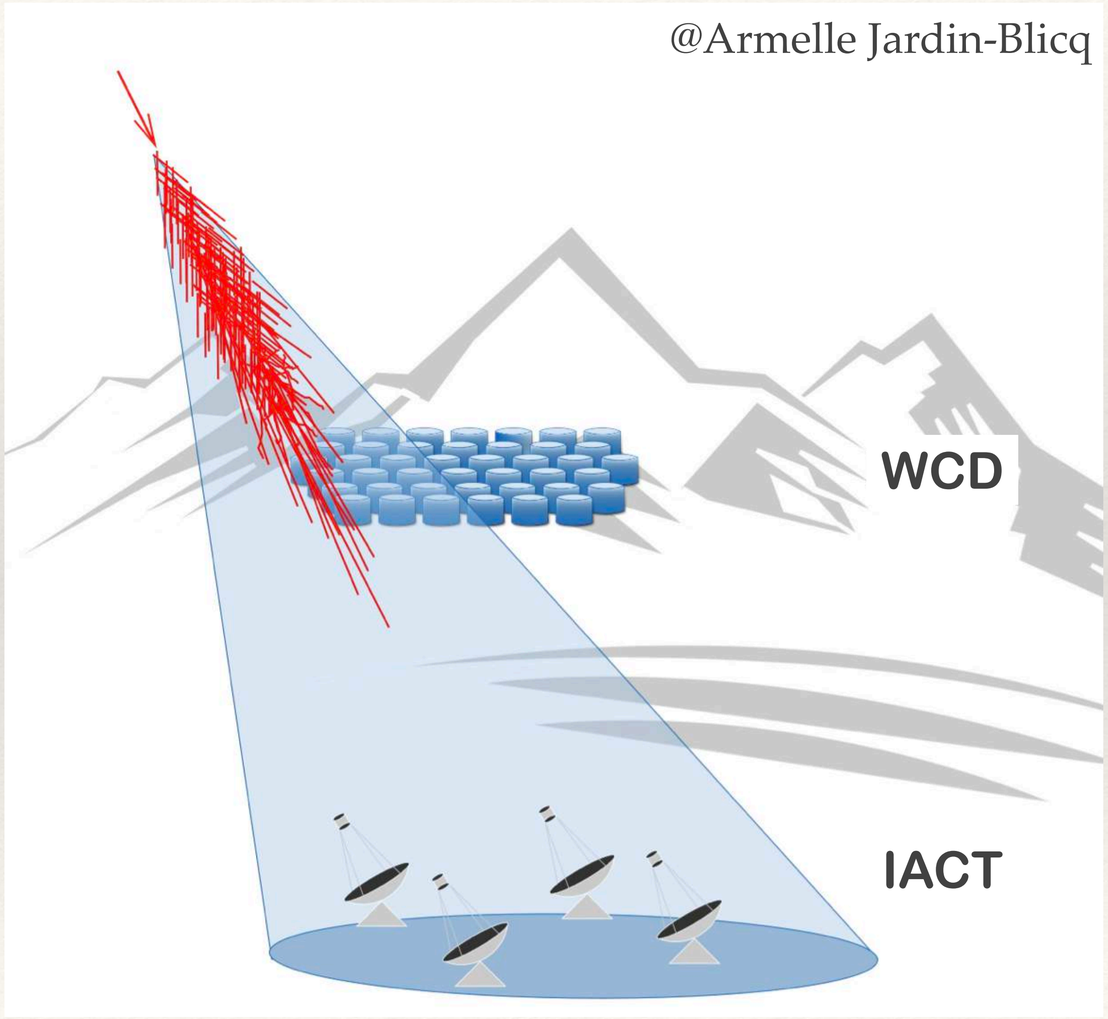


Hadronic showers

K. Kosack, PyG

Detection techniques

	IACT	WCD
Type	Pointing	All Sky
Energy threshold	~100 GeV	TeV
Energy resolution	~10%	40%
Angular Resolution	~0.1 deg	~0.5 deg
FoV	~5 deg	~ 90 deg
Duty Cycle	10%	~100%
Current instruments	H.E.S.S. , VERITAS, MAGIC, FACT	HAWC
Future Instruments	CTA	SWGO



Challenge: Atmosphere and Observation Condition

- Instrument response changes with
  - Gamma-ray **energy**
  - **Position** in Camera Field of View
  - **Zenith Angle** of observation (atmospheric thickness)
  - **Azimuth**: Earth's magnetic field orientation
  - **Telescopes triggered**
  - **Subarray choice**
  - Atmospheric Density profile
  - Optical **Night-Sky-Background** light level (Moon, Zodiacal light, Light pollution)
  - Detector Configuration
  - …

Challenge: Atmosphere and Observation Condition

- Instrument response changes with

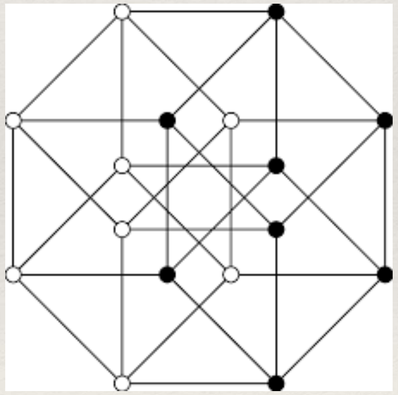
Change during an observation

- Gamma-ray **energy**
- **Position** in Camera Field of View
- **Zenith Angle** of observation (atmospheric thickness)
- **Azimuth**: Earth's magnetic field orientation
- **Telescopes triggered**

Change between observations

- **Subarray choice**
- Atmospheric Density profile
- Optical **Night-Sky-Background** light level (Moon, Zodiacal light, Light pollution)
- Detector Configuration
- …

- Potentially very high dimensional Instrument Response Functions
- Lots of custom simulations



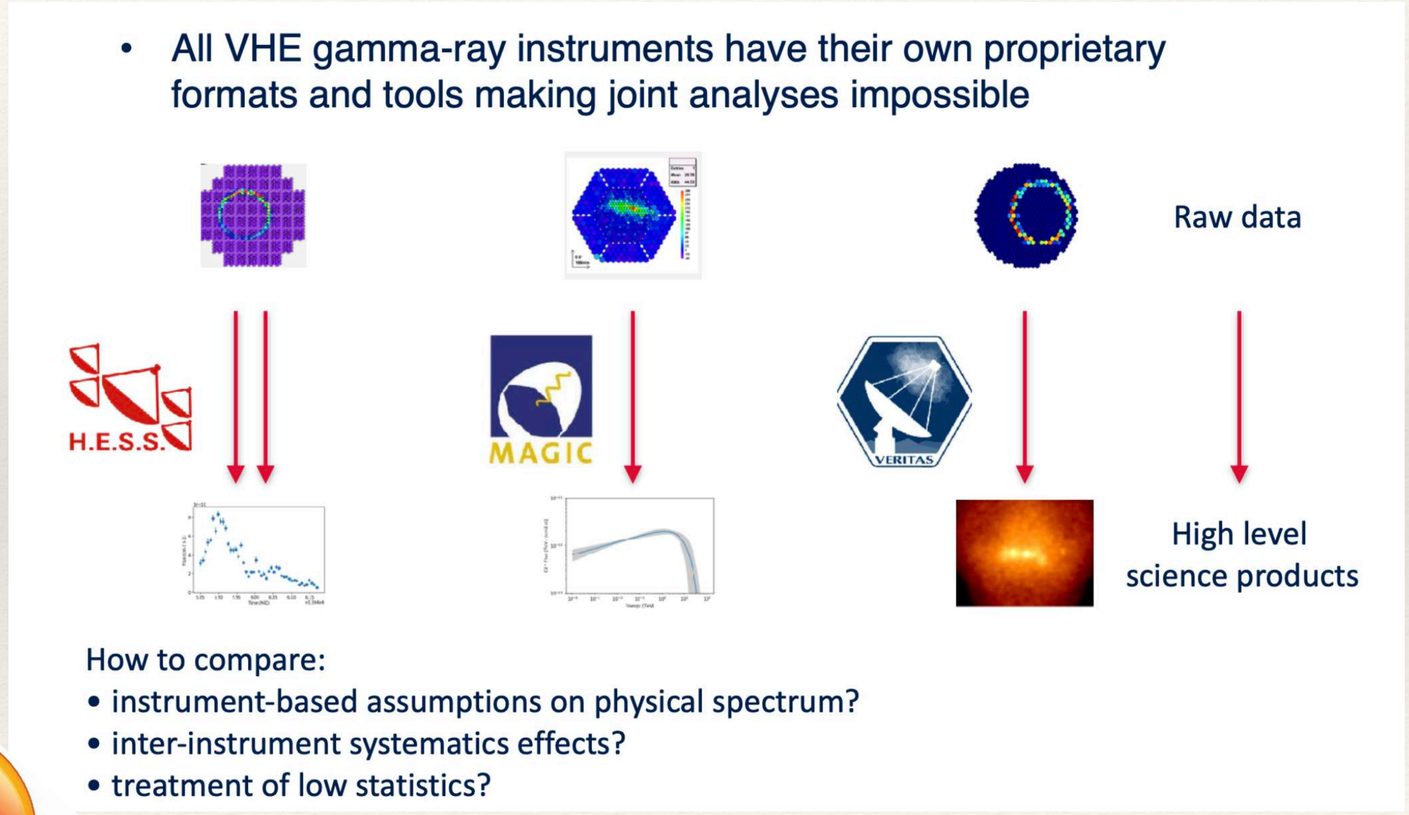
- Need good parametrisation and data model

Challenge: Strong residual hadronic background

- 10^4 hadronic triggers for 1 photon trigger
- ~98-99% rejected by present gamma-hadron separation techniques
- Still residual background is ~100 times of signal strength
  - **"90-99% of gamma-like particles are actually hadrons"**

Proprietary approaches

- Each telescope has its own data format and software
  - Multiple analysis chains within each collaboration
  - Cross checking analysis is a never-ending issue
- Combination of data from different experiments needs hacking into proprietary analysis s/w - terrible experience



Towards open VHE data analysis

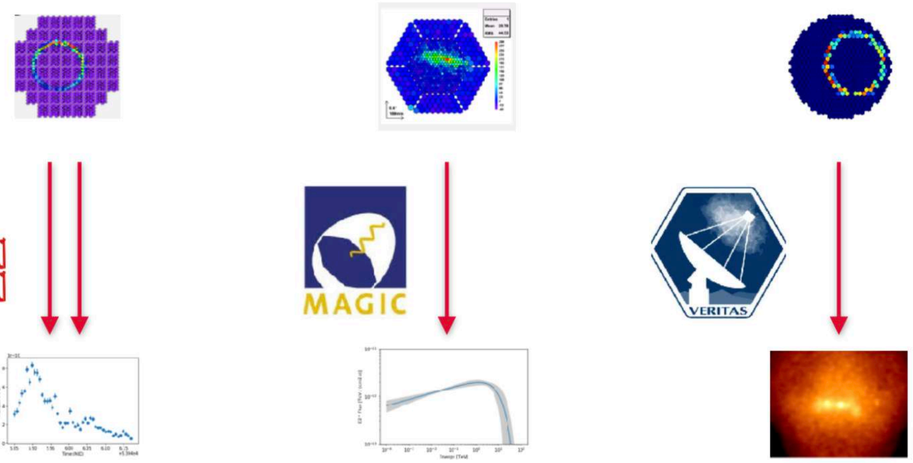
➡CTA will operate as **open observatory**

➡**Public legacy data release** of current instruments

➡Multi-instrument analysis necessary

◉VHE analysis needs common **open data formats** and **common open tools**

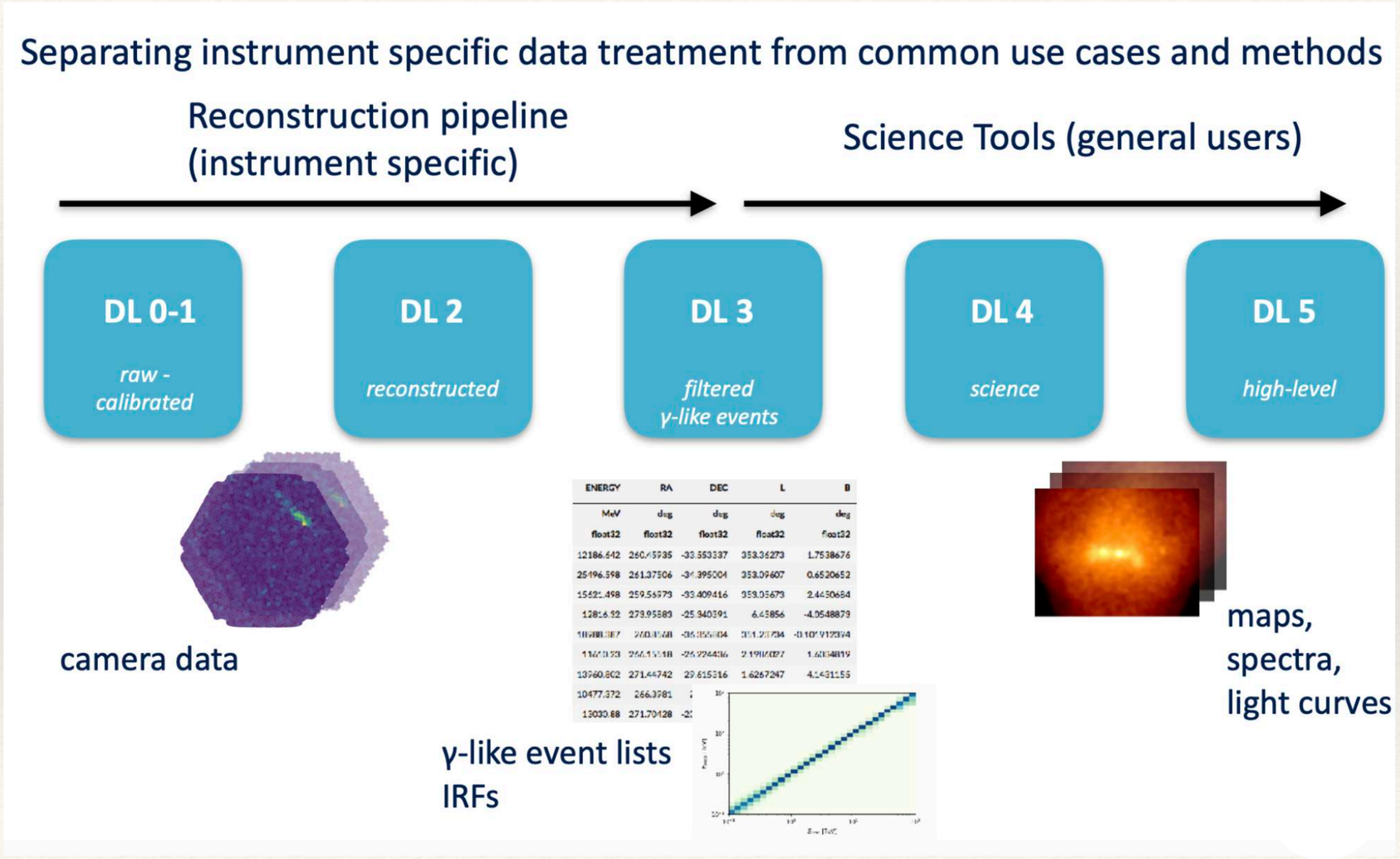
- All VHE gamma-ray instruments have their own proprietary formats and tools making joint analyses impossible



How to compare:
- instrument-based assumptions on physical spectrum?
- inter-instrument systematics effects?
- treatment of low statistics?

GammaAstroData formats & Gammapy

The GADF initiative



- Gamma Astro Data Formats (GADF)
- Based on the Fermi-LAT format Proposed in 2016
- Adopted by CTA
- H.E.S.S. DL3 DR1
- MAGIC data release

The Gammapy concept

A high level gamma-ray astronomy package based on common data formats

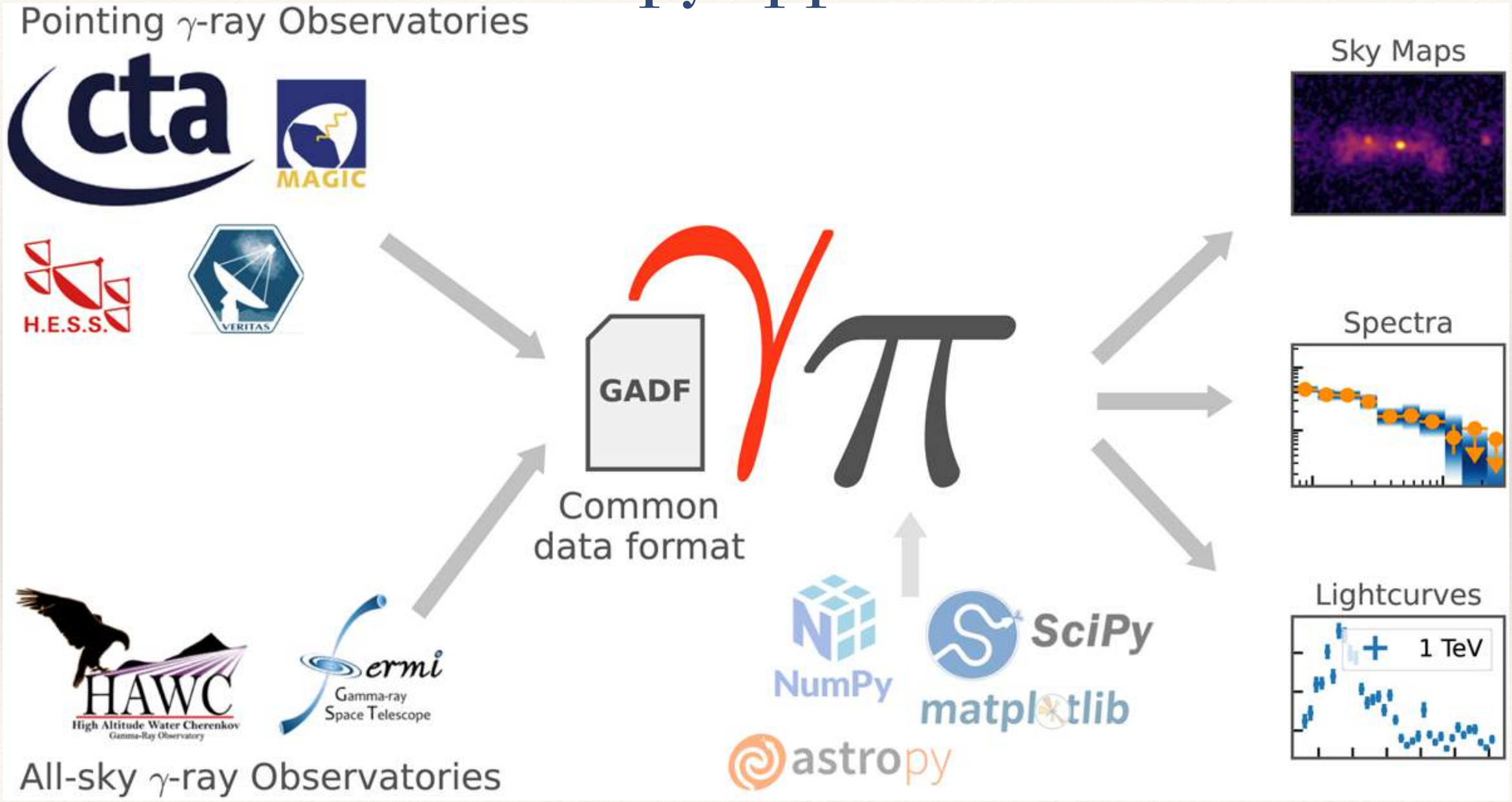
+

A flexible, open source, community driven python library

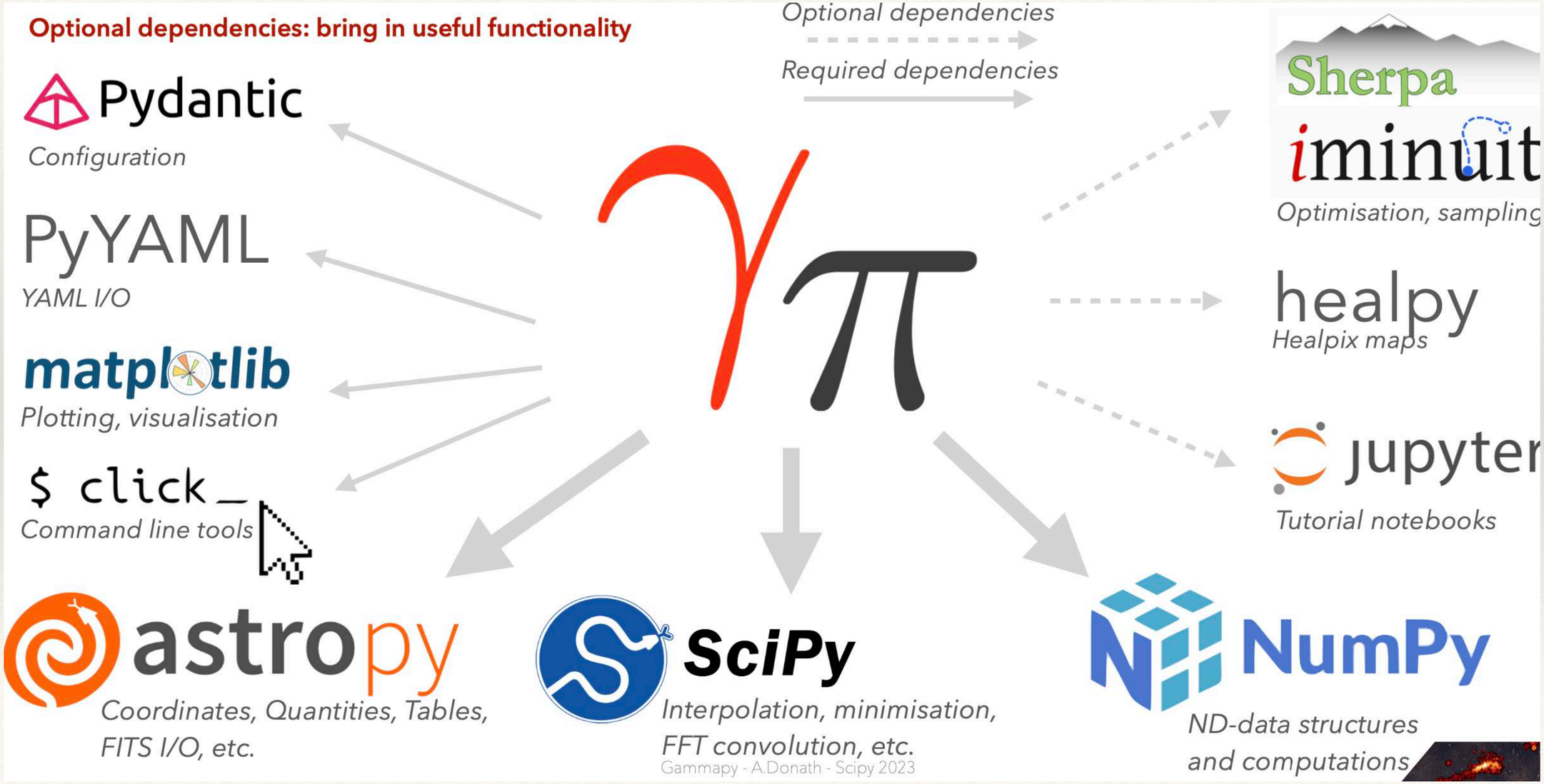
+

Science tools for the CTA

Gammapy approach

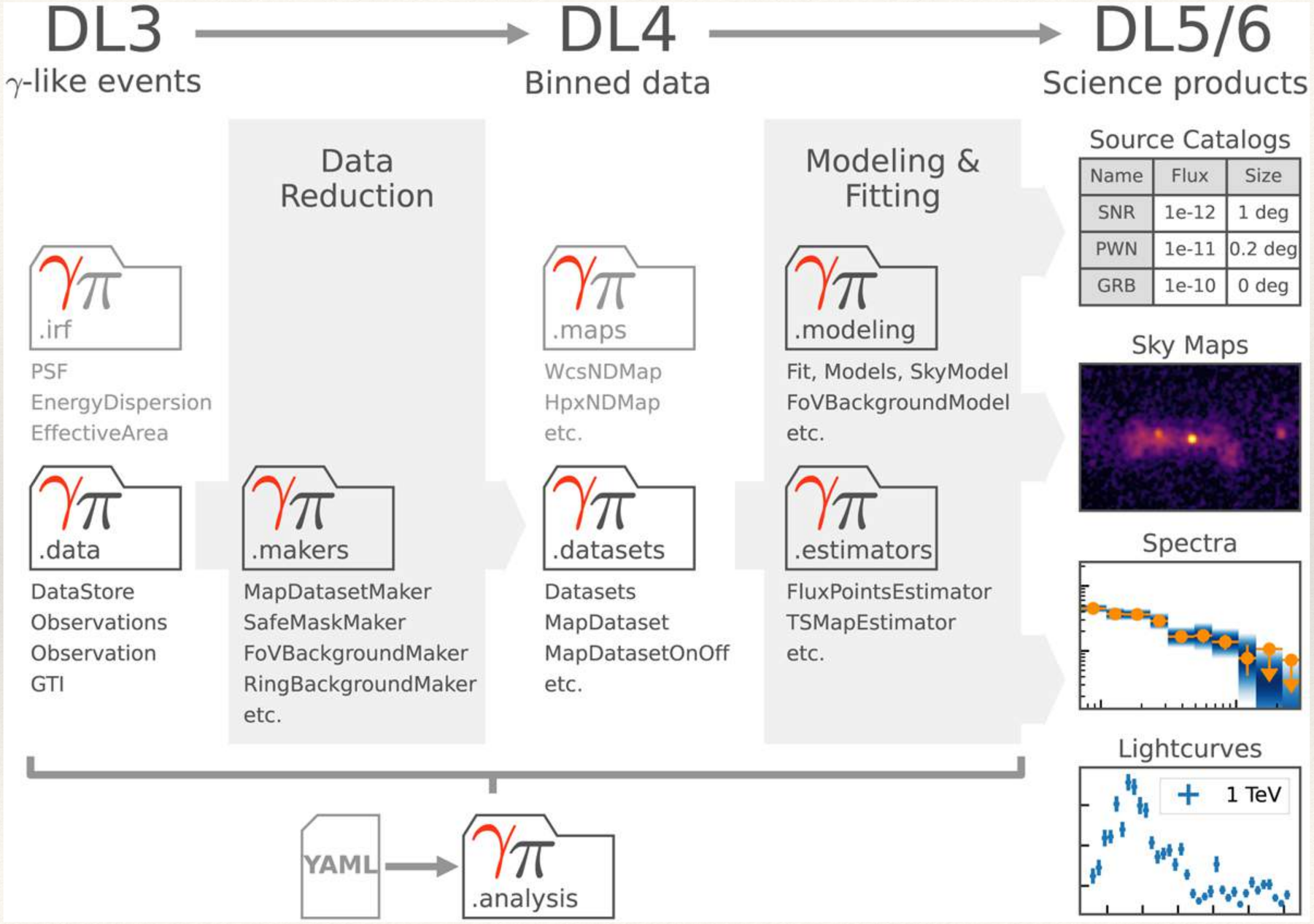


Dependencies



Internal workflow

- 2 step workflow
  - Data reduction (DL3 - DL4)
  - Modelling and fitting (DL4 - DL5)



Data reduction

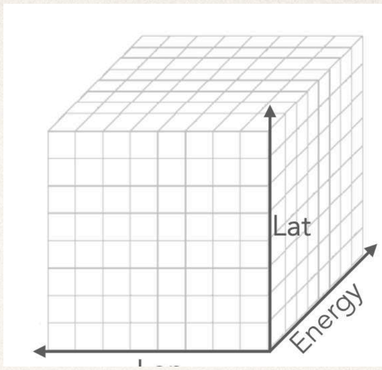
DL3 ⟶ DL4 ⇢ DL5

Dataset

- Bin events (and IRFs) into n-dim sky maps
  - Apply event selections (time, offset, etc)
  - Spatial and energy binning
- Generalised case: 3D maps
  - Image analysis: cube with one energy bin
  - Spectral analysis: Cube with one spatial bin

EVENT_ID	TIME	RA	DEC	ENERGY
	s	deg	deg	TeV
int64	float64	float32	float32	float32
5407363825684	123890826.66805482	84.97964	23.89347	10.352011
5407363825695	123890826.69749284	84.54751	21.004095	4.0246882
5407363825831	123890827.23673964	85.39696	19.41868	2.2048872
5407363825970	123890827.79615426	81.93147	20.79867	0.69548655
5407363826067	123890828.26131463	85.98302	21.053099	0.86911184
5407363826095	123890828.41393518	86.97305	21.837437	4.1240892
5407363826128	123890828.52555823	83.40073	19.771587	1.6680022
5407363826168	123890828.6829524	82.25036	19.22003	4.7649446
5407363826383	123890829.53362775	83.18322	22.008213	0.7920148
...	...	...	...	...

3D analysis



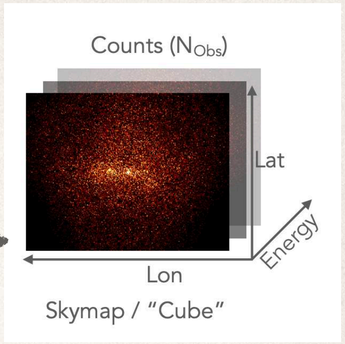
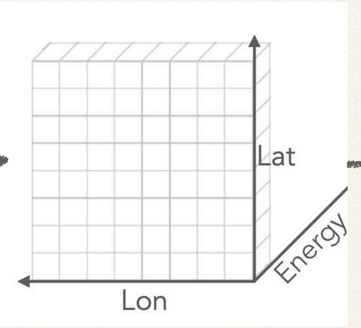
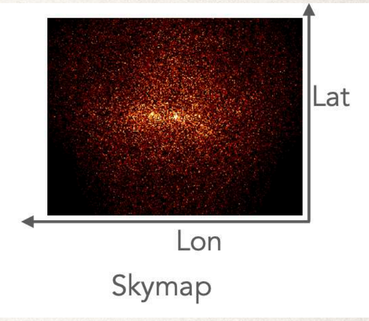
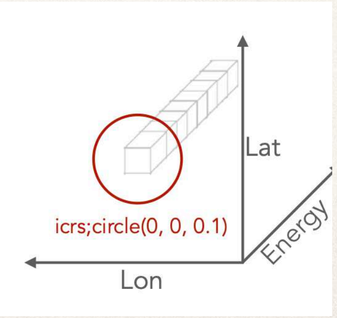


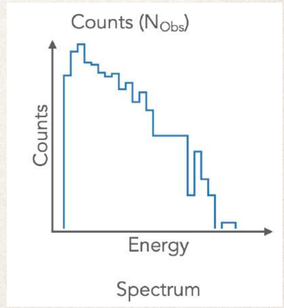
Image analysis





Spectral analysis analysis





Data fitting
DL4 ⟶ DL5

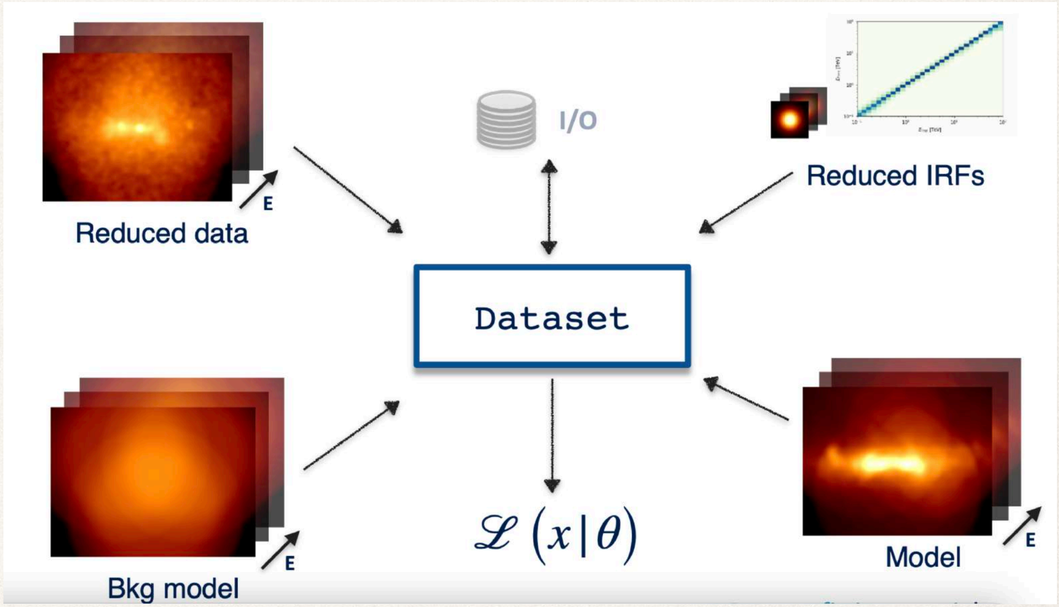
- Fitting on pre-computed datasets
  - eg: From HAWC, Fermi-LAT, OGIP files, etc
- Forward folding with maximum likelihood estimation

$$N_{Pred}(p,E) = N_{bkg}(p,E) + \Sigma_{src} N_{src}(p,E)$$

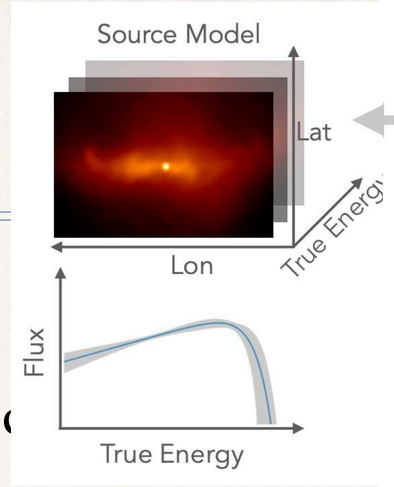
Cash: known background

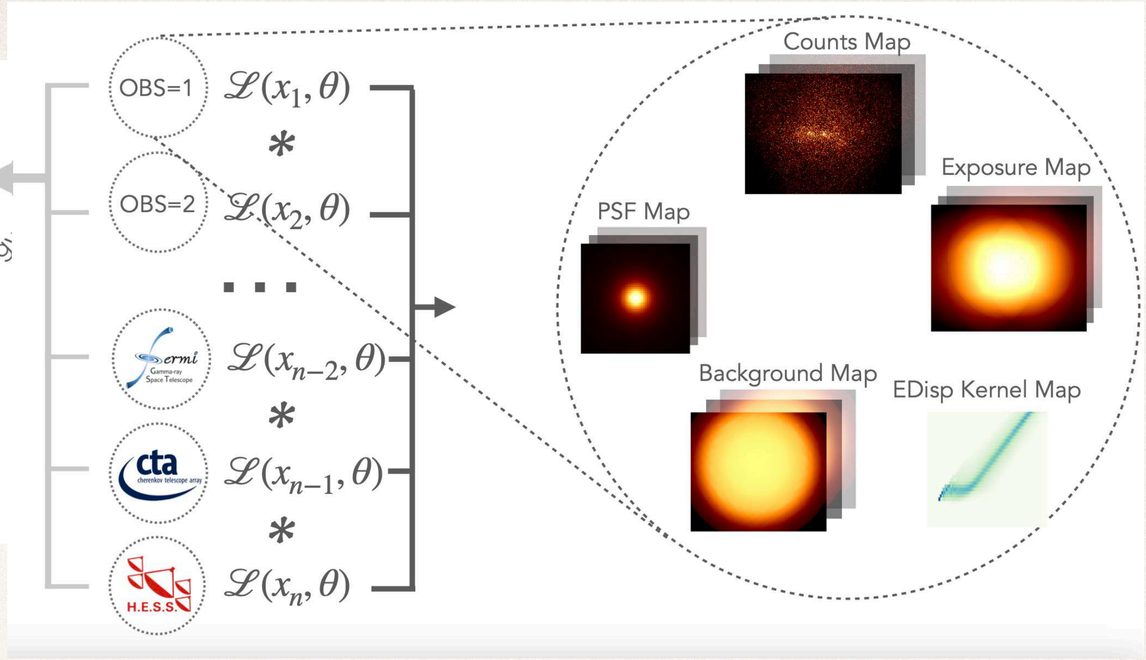
$$TS = -2\ logL = 2\Sigma\ (\ N * logN_{pred} - N_{pred}\ )$$

Wstat: counts with measured background

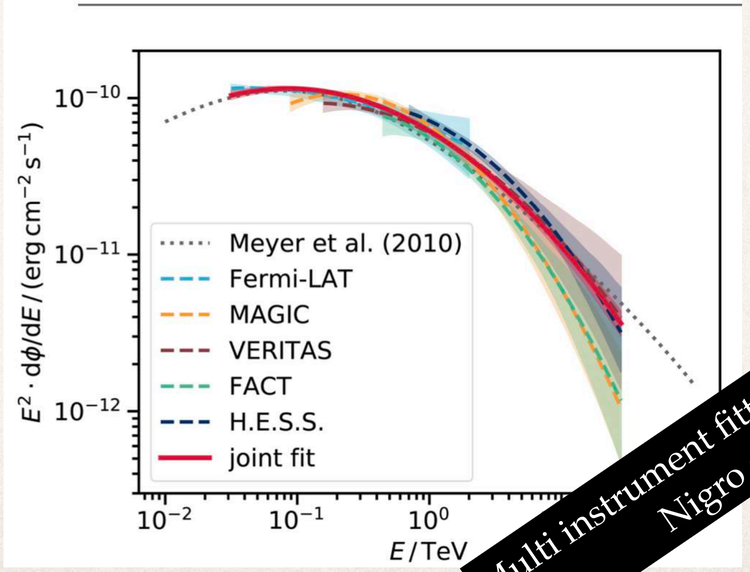


Joint likelihood





- Simultaneous fitting of various d
- Likelihood evaluated per dataset, individual likelihoods combined to get global likelihood
- May come from the same or different instruments
- Possible to combine DL4 and DL5 data

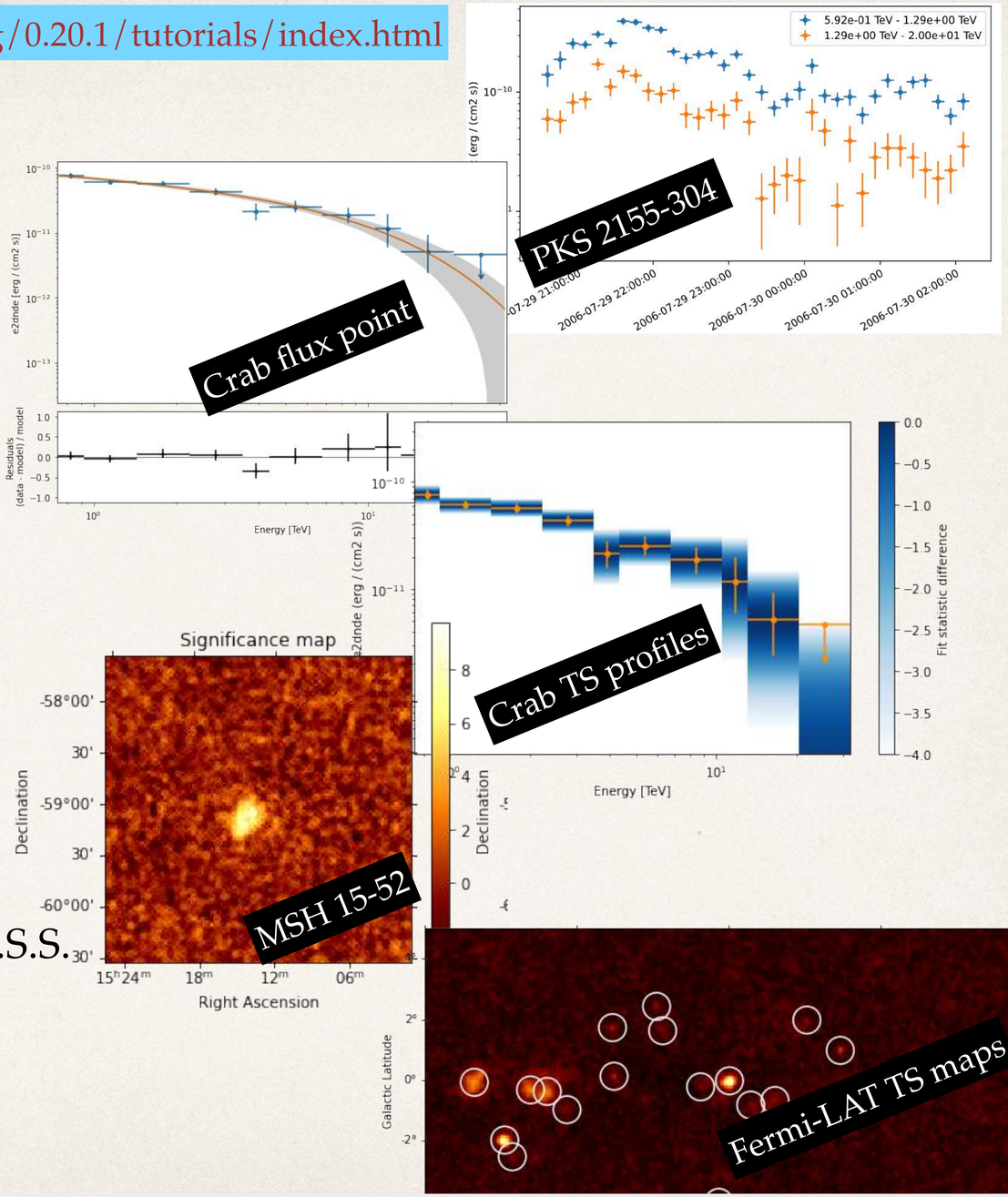


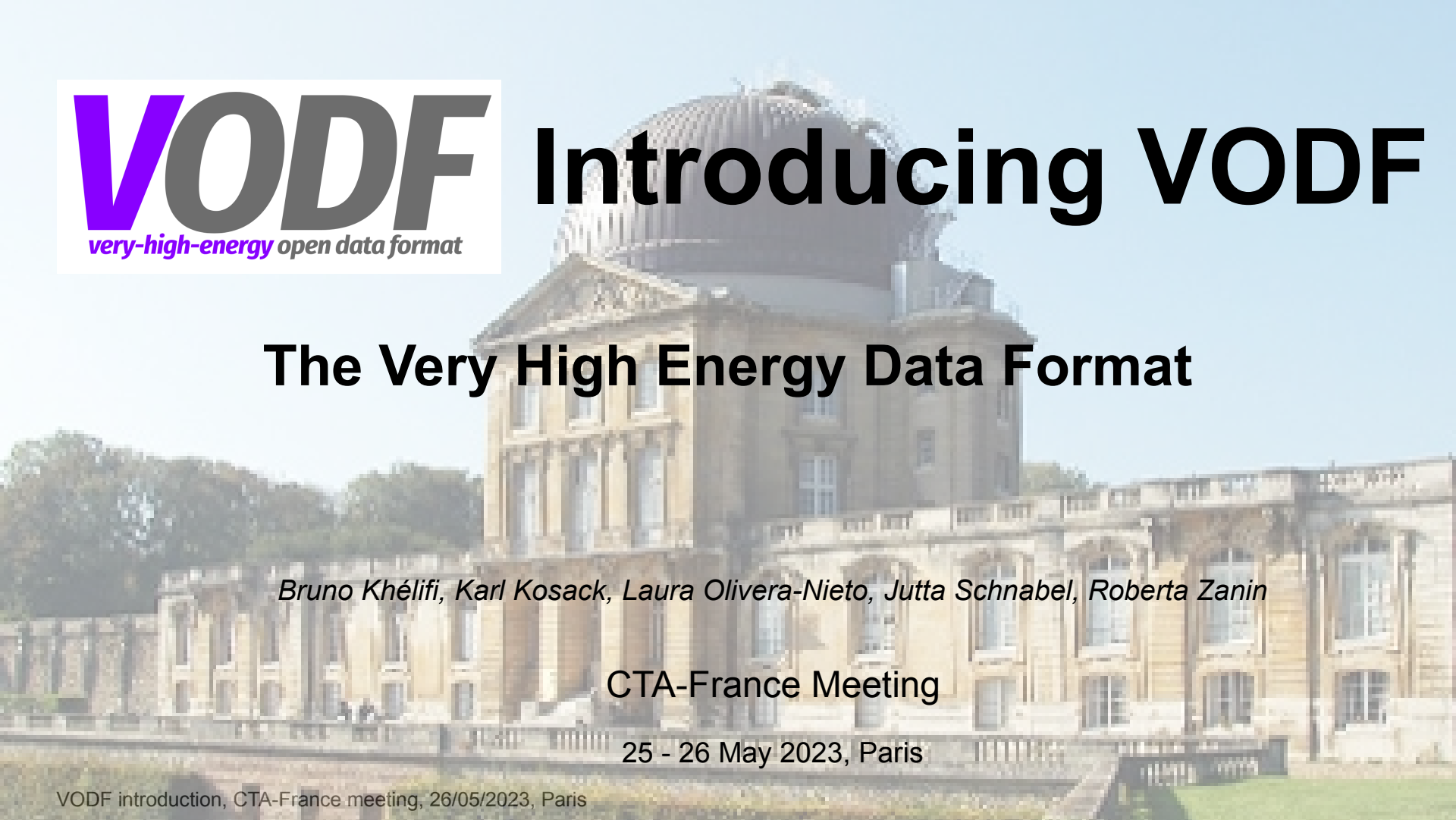
Multi instrument fitting of Crab Nebula
Nigro et al, 2019

End products: DL5 and DL6

See: https://docs.gammapy.org/0.20.1/tutorials/index.html

- DL5: Flux points, light curves and flux/TS maps
- Possible to fit DL5 data
  - Eg: published flux points, lightcurves
  - Chi2 statistics used
- DL6: catalogs
  - Support provide for common catalogs: Fermi 4FGL, H.E.S.S. galactic plane survey, HAWC catalog, etc
  - Create your own catalogs…





Introducing VODF

The Very High Energy Data Format

Bruno Khélifi, Karl Kosack, Laura Olivera-Nieto, Jutta Schnabel, Roberta Zanin

CTA-France Meeting

25 - 26 May 2023, Paris

What is it about: Data levels...

from Karl Kosack

Science Analysis: DL3-DL5

Happens at CTA data centers (automatic) + by users on user's laptops or e.g. ESCAPE science platform

Search for data
covering region of interest in space, time, maybe other parameters

VO tools?

DL3
Science-Ready

Retrieve Event Lists and IRFs that cover region of interest

obs_id = 84753

event_id	Time	Energy	RA	Dec
12351	55933.30	0.03	53.6	-29.2

obs_id = 99584

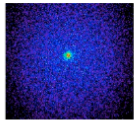
event_id	Time	Energy	RA	Dec
12351	55933.30	0.03	53.6	-29.2
12356	55933.31			
12378	559			
12389	559			

obs_id = 100207

event_id	Time	Energy	RA	Dec
12351	55933.30	0.03	53.6	-29.2
12356	55933.31	0.1	53.2	-29.3
12378	55933.36	12.0	53.8	-29.5
12389	55933.45	0.2	53.7	-28.7

DL4
Science-Binned

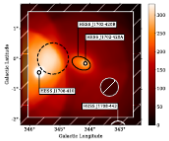
Use *Science Tools* to make intermediate Binned Data Products



Exposure Cube
Counts Cube
Exclusion Map
...

DL5
Science-Quicklook

Use *Science Tools* to Fit models to binned data (forward-folding) and make Flux cubes



Sky model
Light-Curve
Spectra
Flux Map/Cube

DL6
Science-Observatory

Observatory or CTAC produces some legacy products

Catalogs,
Survey Products

CTA Data Model

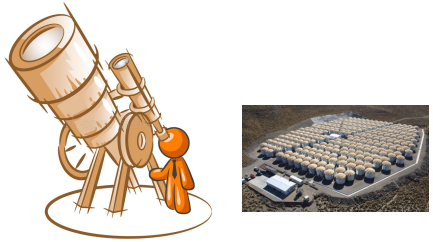
Karl Kosack

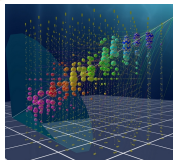
1

Outline: from gamma rays to high energies particles

GADF
Data Formats for
Gamma-Ray Astronomy

VODF
Very-high-energy
Open Data Format





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

Some history: GADF

A (short History of GADF)

2011 Prototypes for the CTA data format and science tools

2016
- Establishment of the Gamma-ray Astronomy Data Formats (GADF) initiative
- First preliminary release version (0.1), mainly focused on IACTs

2018
- Version 0.2 released
- Support implemented in the science tools Gammapy and ctools
- H.E.S.S. releases ≈ 50 h of observations of different sources using the format

2019
- FACT, Fermi-LAT, H.E.S.S. MAGIC and VERITAS observations of the Crab Nebula are used to perform the first multi-instrument analysis
  [doi:10.1051/0004-6361/201834938]
  `https://github.com/open-gamma-ray-astro/joint-crab`
- `ctools` based analysis of the H.E.S.S. data release
  [doi:10.1051/0004-6361/201936010]
- Comparison of Gammapy and ctools using the H.E.S.S. data release
  [doi:10.1051/0004-6361/201936452]

from Maximilian Linhoff

VODF, an open initiative around 11 large facilities

ASTRI - Astronomia a Specchi a Technologica Replicante Italiana, (IACT telescope)

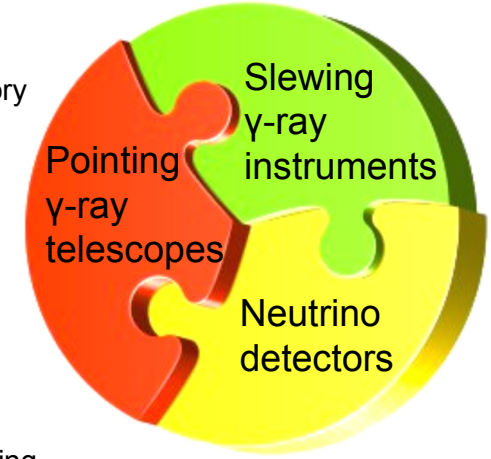
CTAO - Cherenkov Telescope Array Observatory (IACT observatory)

FACT - First APD Cherenkov Telescope (IACT telescope)

H.E.S.S. - High Energy Stereoscopic System (IACT Array)

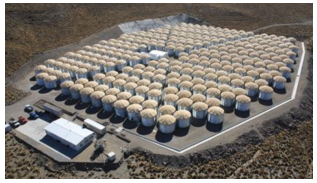
MAGIC - Major Atmospheric Gamma-ray Imaging Cherenkov telescope (IACT array)

VERITAS - Very High Energy Radiation Telescope Array System (IACT array)



Fermi-LAT - Large Area Telescope on the Fermi Space Telescope (High-energy Space Observatory)

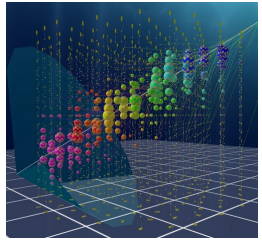
HAWC - High-Energy Water Cherenkov telescope (WCT)



SWGO - Southern Wide-Field Gamma-Ray Observatory (WCT)

IceCube - Neutrino Observatory

KM3NeT - The Cubic Kilometre Neutrino Telescope (neutrino telescope)



VODF: new structure for new open science

VODF Steering committee

Established in 2022

one representative per experiment, defining roadmap & goals

VODF Lead Editors (3)

Format development

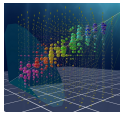
Conveners (2)

Organization & Coordination of work

Documentation: https://vodf.readthedocs.io
Source & Community: https://github.com/VODF/

Validation of standardized data formats and tools for ground-level particle-based gamma-ray observatories
doi:10.1051/0004-6361/202243527

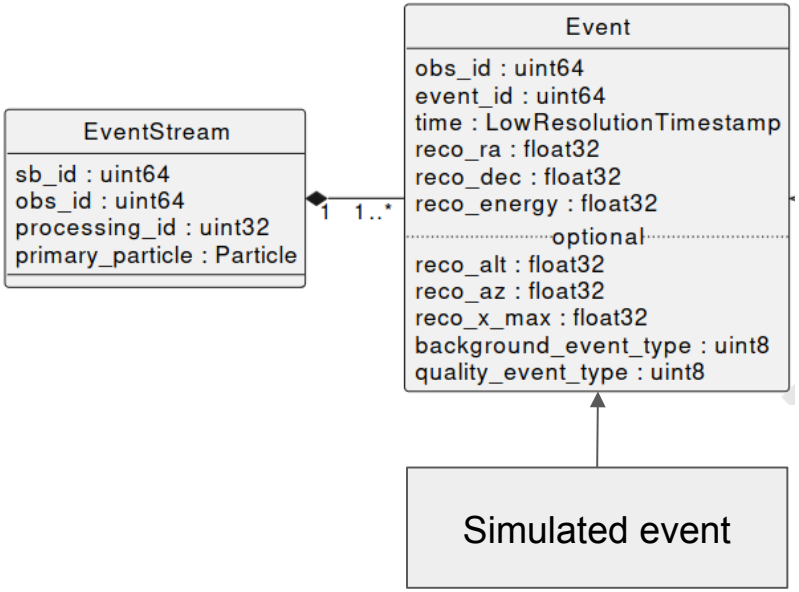
GADF @Gammapy



Models of Galactic Source Emissions with CTA and KM3NeT (in preparation)

Basic data format: “Events” and “service data” (DL3)

event = particle detection (gamma, neutrino)



Information derived from simulation: Instrument Response Functions (IRFs)

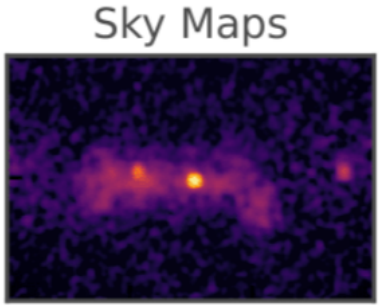
- Stable Time Interval
- Effective Area
- Energy Dispersion
- Point Spread Function
- Background
- Radius of On region for point-like IRFs

From CTA DL3 data model

Higher levels: Science results

DL4 (Science binned)

- exposure maps
- counts maps
- exclusion maps
- significance maps
- excess maps



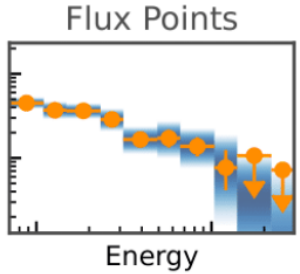
DL5/6 (Science products)

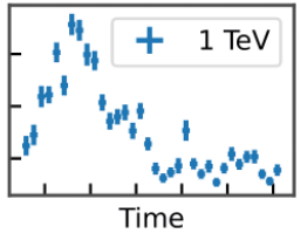
- Flux maps & fit models
  - data cube (3D,4D)
  - 2D sky map
  - light curve
  - spectrum
  - spatio-spectral cube
  - …

Potential future developments with VODF

Source Catalogs

Name	Flux	Size
SNR	1e-12	1 deg
PWN	1e-11	0.2 deg
GRB	1e-10	0 deg





Next steps & open questions

- Starting with a format definition: the one of CTAO, strongly inspired by GADF
  - Allow for multiple IRFs
  - Including different event categories (event types)
  - Choose metadata standards
- Ensuring interoperability (especially with IVOA)
  - Make data discoverable via VO (ObsCore?)
  - Could contribute to an interest group if it happens
  - Current considerations (see contribution by Mathieu Servillat)
    - CTAO Data Model group & DM for High Energy astrophysics
  - Further workshop prepared for June 28/29 (French VO, extending WP4 ESCAPE)