CTAO
Cherenkov Telescope Array Observatory

IVOA and High-Energy Gamma-Rays:

Ground-based IACTs

The perspective of CTAO, HESS, and beyond

Karl KOSACK

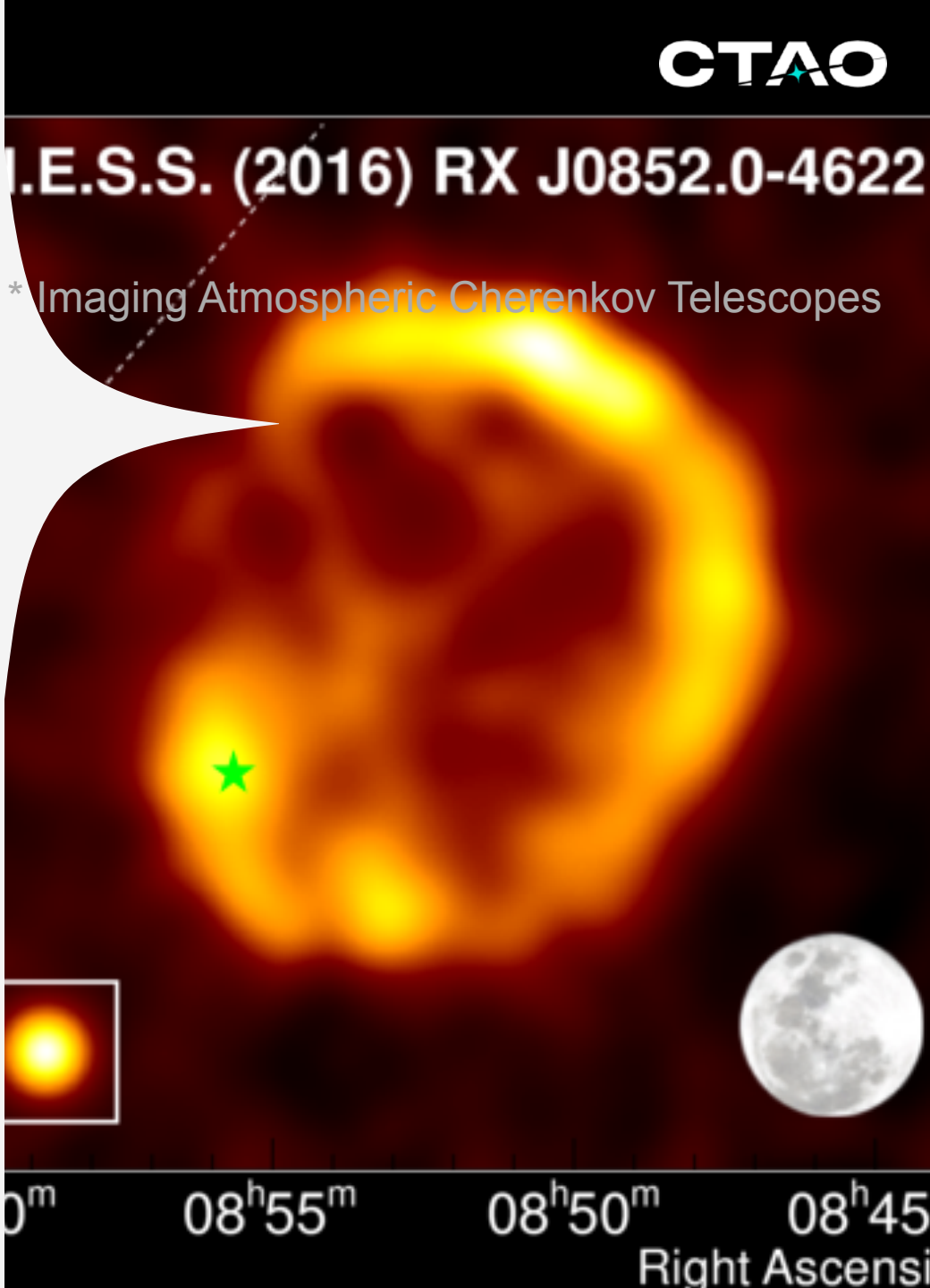
CEA Paris-Saclay / CTAO


From Closed Experiments...
H.E.S.S.
VERITAS
..to an Open Observatory
CTAO
Cherenkov Telescope Array Observatory

1. Differences?
2. Discoverability
3. Data Models
4. Observation Planning

Characteristics of IACTs*

- **"Event"-counting instruments**
  - Energy, Position, Time of individual *photons, [and likelihood]*
  - but *also* from irreducible cosmic ray detections
  - **Data Cubes: 1D-2D-3D... 6D?**
    - (image, lightcurve, spectrum, spatial-spectro cube, spatial-time cube, spatial-spectral-time) + optional likelihood axes...
  - Source models are also F(ra, dec, E, t)
- **Pointed Instruments**
  - Alt/Az mounts
  - Track Ra/Dec → (field rotation) or can "drift" in fixed Alt/Az
  - Complex pointing patterns: "wobbles" to avoid source at center, survey grids, etc.
  - Atmosphere is part of instrument → "GTI"-like intervals linked to different instrument response functions
- **Energy-dependent optical characteristics:**
  - E = 30 GeV - 300 TeV
  - Field of view: 5-20°
  - PSF: 0.1 - 0.01°
  - Performance varies with offset from center, zenith/azimuth angle, atmosphere changes,
- **Many "instruments":** subarray choice and analysis configurations $\approx 10 \rightarrow \infty$



From Events → Physics

Need additional linked information…

Instrumental Response Functions (IRFs)

- Matrices to transform between ***counts in region*** → **Flux**
- Derived from detailed simulations + observations
- Events ⊗ IRFs → Fluxes (Images, Spectra, Light-curves, …)

Time evolution… Data Quality…

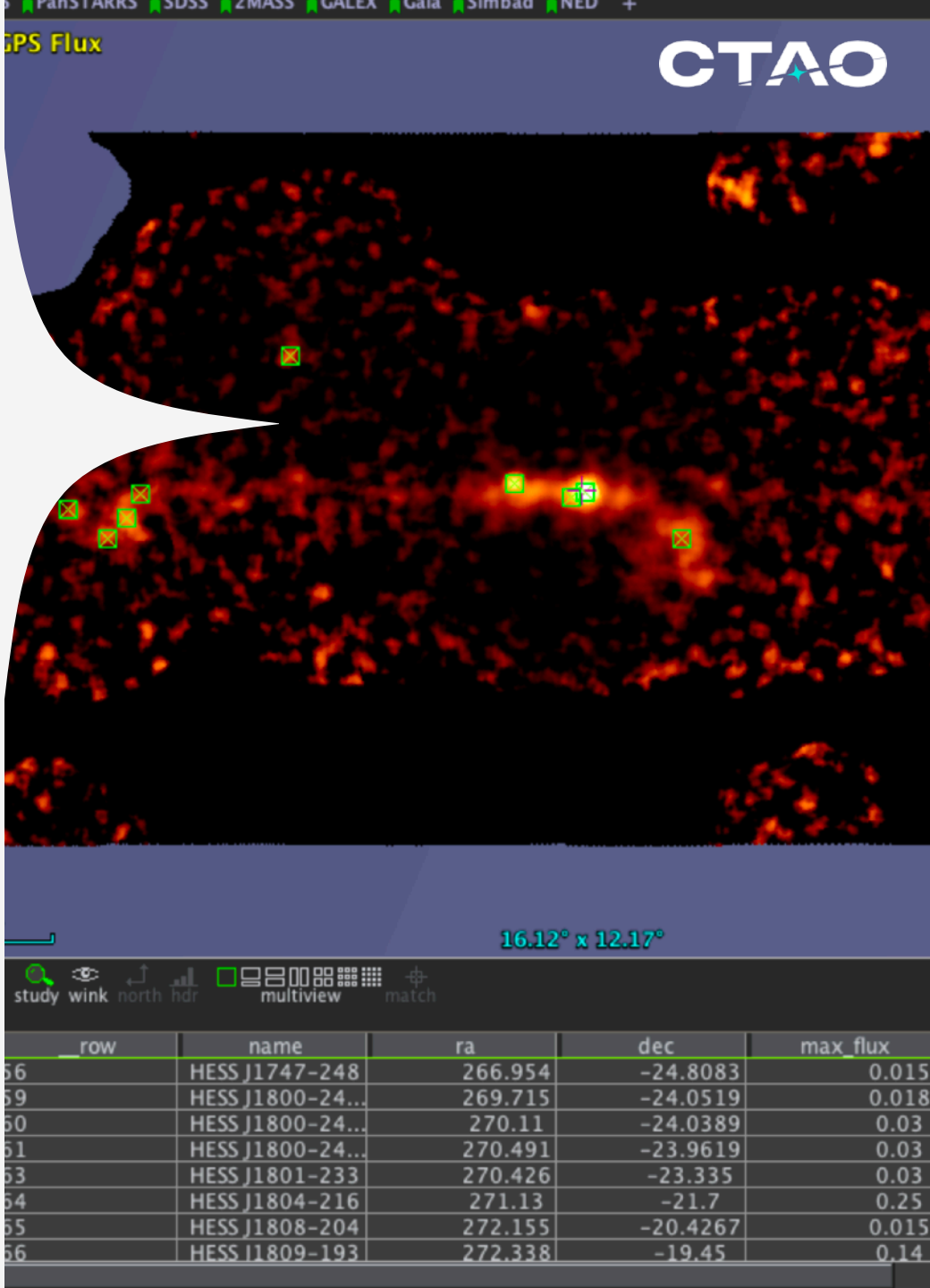
- **Provenance important here…**

Typical IRF Decomposition:
- Effective Collection Area (efficiency)
- Energy Migration ($E_{true} \rightarrow E_{reco}$)
- PSF ($P_{true} \rightarrow P_{reco}$)
- Background Model (subtractive)

1. Differences?
2. **Discoverability**
3. Data Models
4. Observation Planning

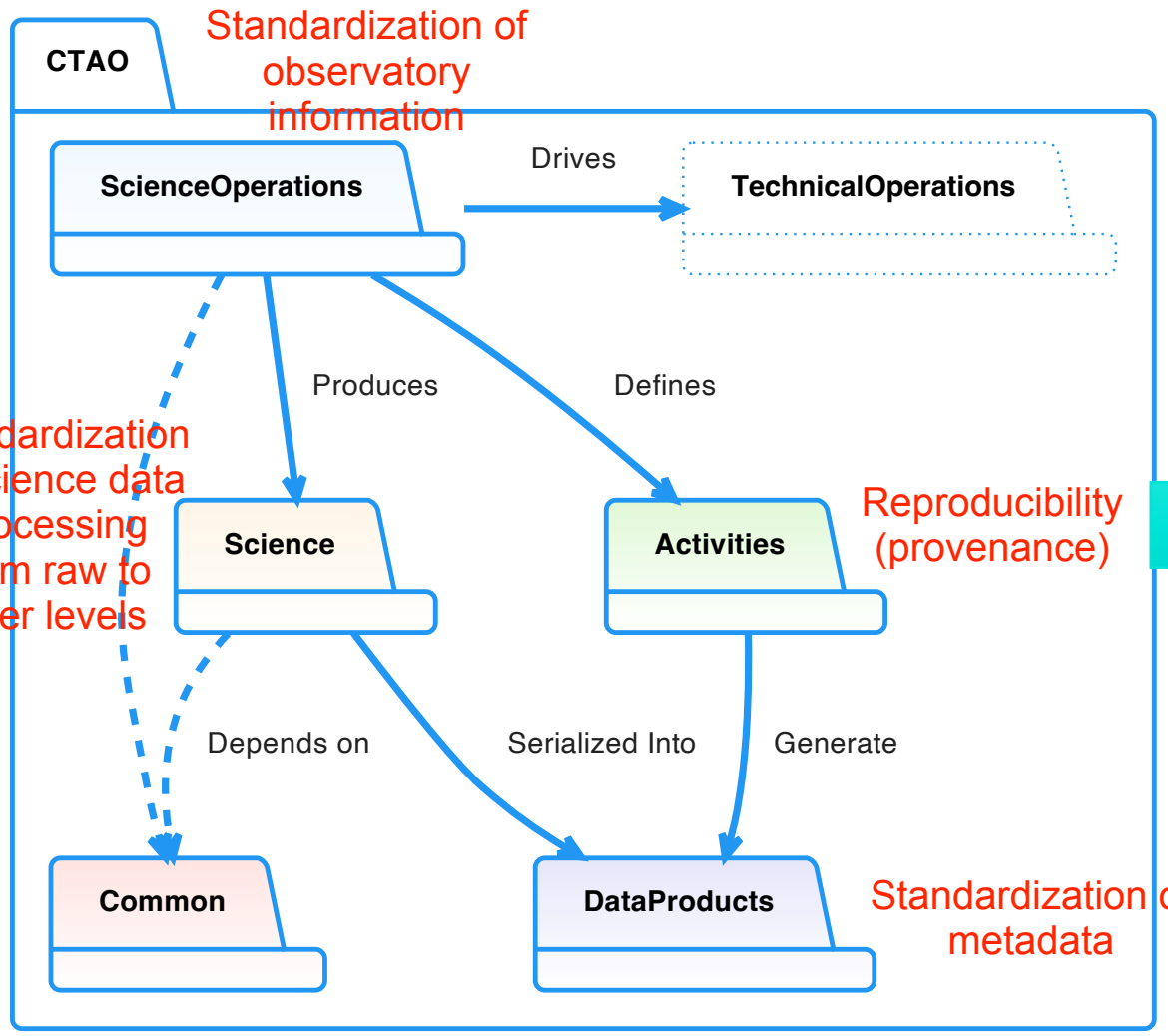
Data Discoverability

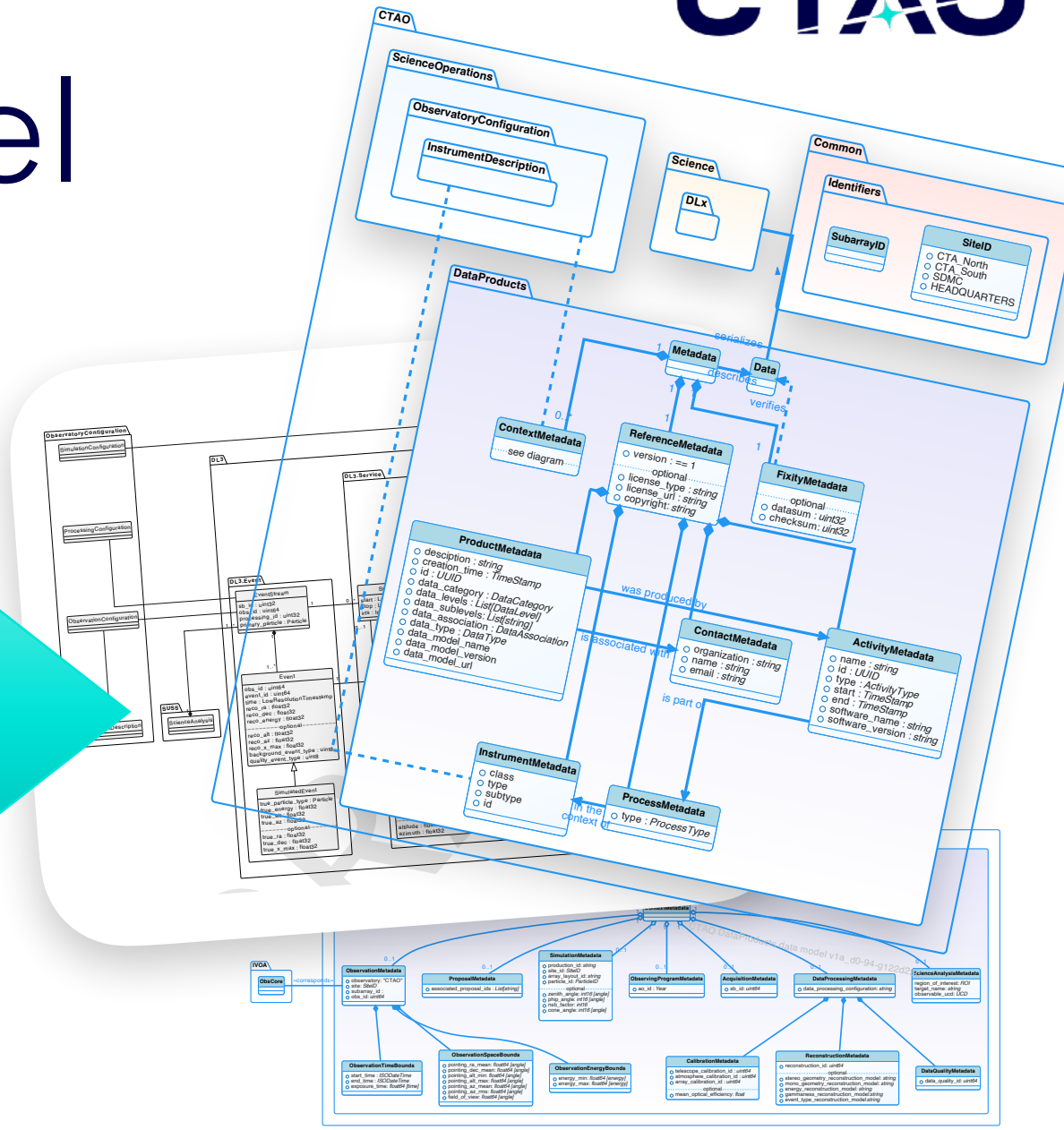
- **Current Instruments:**
  - **Catalogs**: HESS, VERITAS
    - → VO via HEASEARC
  - **Surveys**:
    - HESS Galactic Plane: VO image access
  - **Proof-of-concept event-level**:
    - small sample of public DL3 HESS data (no IRFs) available via TAP
- **CTAO:**
  - **Observation Catalog**:
    - ObsCore compliance
  - **Science results (quicklook and user data?)**:
    - hope for full VO access via TAP services



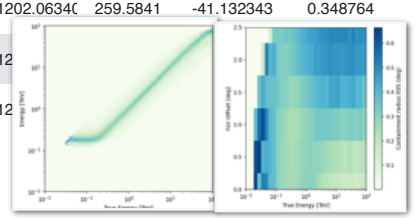
1. Differences?
2. Discoverability
3. **Data Models**
4. Observation Planning

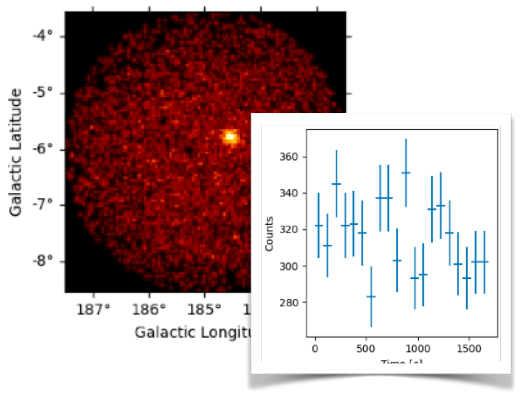
CTAO Data Model

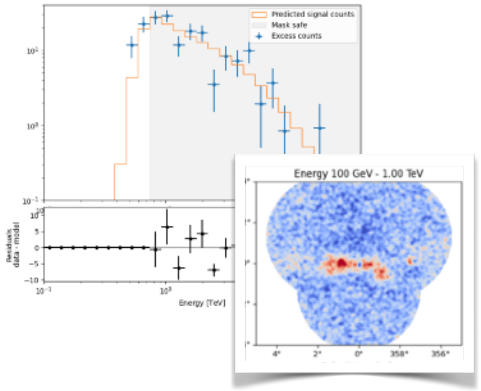


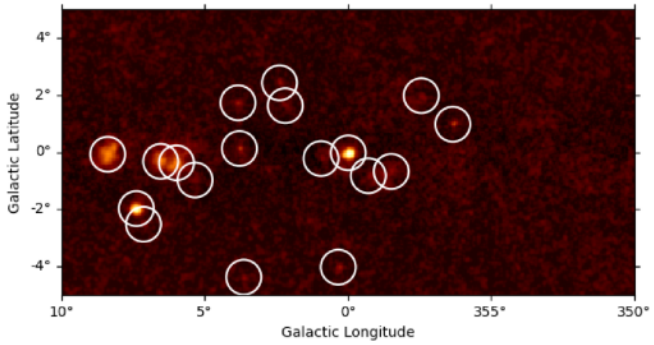


EVENT_I	TIME	RA	DEC	ENERGY
		deg	*deg*	*TeV*
0	1202.0634(	257.38425	-39.32344	0.8007868
132	1202.0634(	257.71066	-40.528507	0.22329243
146	1202.0634(	259.5841	-41.132343	0.348764
182	12			
210	12			









Science-Ready Products DL3

- Event Lists
- Instrument Response Functions
- Instrument Monitoring Tables
- Time Intervals (stable, good)
- Observation Catalogs / Coverage Maps

Binned Science Products DL4

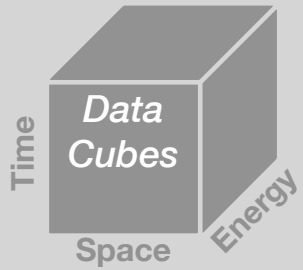
- Counts, Exposure, Background Data Cubes
- Excess, Significance Data Cubes
- Sky Regions
- Sky Models

Advanced Science Products DL5

- Flux Data Cubes
- Likelihood Data Cubes
- Model Fit Metrics

High-Level Catalog Products DL6

- Source Catalog
- Source Component Catalog



- Sky Image (2D Space)
- Spectrum (1D Energy)
- Light Curve (1D Time)
- Space-Energy Cube (3D)
- Space-Time Cube (3D)
- Space-Time-Energy (4D)

Note some dimensions may be sparse or unevenly spaced

Science Data **Formats**

High-level data models driven by CTAO, but shared by the VHE community!

✦ **GADF: Gamma-ray Astronomy Data Format**

- FITS-based Data format created by IACT community
- Inspiration from existing X-ray standards (e.g. OGIP)
- No formal model, ad-hoc set of standards
- Only partial coverage of CTAO data model, and needs improvement

✦ **VODF: Very-high-energy Open Data Format** (under development)

- evolution of GADF, To be *model-driven*, verifiable
- Wider scope of instruments with similar needs:
  - IACTs (CTAO, HESS, MAGIC, VERITAS...),
  - WCTs (HAWC, SWGO,... ; wide-field water-Cherenkov)
  - Neutrino telescopes (km3Net, ...)

VODF

very-high-energy open data format

Facility	Category
ASTRI	Pointing γ-ray instrument
CTAO	Pointing γ-ray instrument
FACT	Pointing γ-ray instrument
Fermi-LAT	Slewing γ-ray instrument
HAWC	Slewing γ-ray instrument
H.E.S.S.	Pointing γ-ray instrument
IceCube	Neutrino detector
KM3Net	Neutrino detector
MAGIC	Pointing γ-ray instrument
SWGO	Slewing γ-ray instrument
VERITAS	Pointing γ-ray instrument

Work currently stalled for technical reasons

How to define down a model that supports:

- Automatic documentation with diagrams
- Validation (at least FITS)
- Tables with rich column metadata
- Cubes that support our IRFs
- Units, UCDs, descriptions,
- Relationships! (not just structure)
- mapping to FITS (headers, structures, standards) and IVOA standards?

Things we've tried:

- Pure documentation / UML diagrams
- FITS TPLs (not sufficient)
- ASDFSchema / JSONSchema (ran into missing features)
- Custom in-house prototypes
  - FITSSchema (used for GADF, but needs improvement)
  - Prototype based on Pydantic

are we missing something?

Provenance

- **Reproducibility a top-level requirement of CTAO**
  - IVOA **VOProv** Developed by CTAO members!
  - Parts included in our Data Product metadata...
  - Still need to see at what level of detail we apply for pipeline workflows
    - likely to be part of our Workflow Management System
    - connection to CWL standards, etc.

1. Differences?
2. Discoverability
3. Data Models
4. **Observation Planning**

Scheduling for CTAO

Schedules are similar to other instruments:

- Long-term schedule (at start of Observing Year)
- Medium-term schedule (≈monthly updates)
- Short-term schedule (< Daily)
  - re-generated during observations
  - Adapt to changes in weather, hardware, real-time analysis results

Under development

- automatic and constraint based, solver realtime-rescheduling possible
- Detailed data model model (linked also to Proposal model)
- Evaluation of IVOA model (only recently discovered)

Observation Coordination

Current instruments:

- MoUs and *human interaction*
- For some campaigns, sharing of "observing slots"

CTAO (intentions/wishlist)**:**

- Automated schedule sharing for ToO/MWL coordination
- use standardized model and platform for sharing (ObsLocTAP?)
  - Currently evaluating standards
  - Mapping to our preliminary data model
  - Defining policies
  - Discussing with other instruments

Science Alerting

Receive and Send:

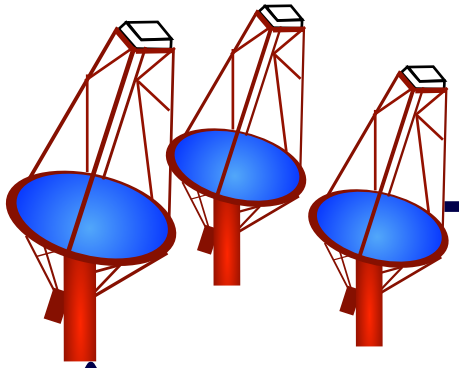
- GCN
- VOEvent (2.0)
- Astronomer's Telegrams
  - sufficient for many!

Criteria:

- Inputs from high-energy astronomy , GRBs, neutrinos, cosmic rays (e.g. ICECube), Gravitational Waves
- Visibility window

Followups:

- Automatic (e.g. GRBs)
- Human-in-the-loop
- Complex pointing strategy (e.g. GWs)



- HESS Alert System (2022, A&A)
- CTAO Transient Handler

Backup info

Event-counting instruments

"Events": detections of a single *photon* or *cosmic ray* background particle

- space + time (i.e. "event") info
- + other associated parameters
- ≈ 10,000 events/s for CTAO!

Event = Photon?

- Dominated by *irreducible* background.
- We *can't say* "photon list" (but analogous!)

Confusion: Event ≠ Transient Source outburst

- Event → *Cherenkov Event*:
  - detection of photon or background
- Alert → *Transient Event*
  - high-level analysis of many Cherenkov Events, transformed into a flux exstimate....

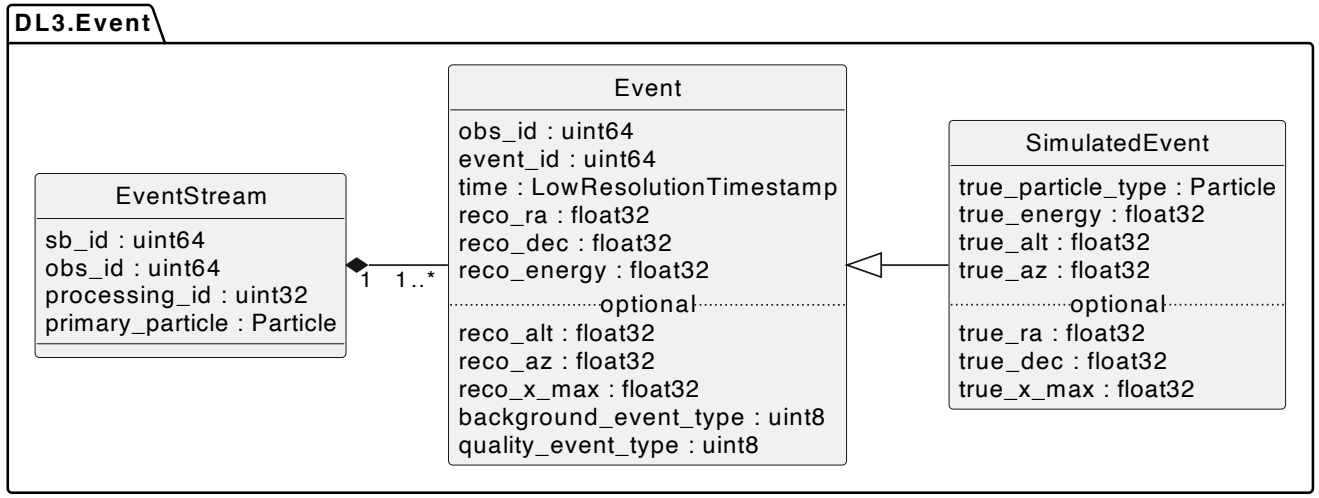


Figure 2.2 – UML Diagram of the DL3/Event Data Model.

CTAO DL3 Data Model Specification, v1b

Data Formats and Models Overview

	Instrumental, internal →			Disseminated to users →			
	DL0: Raw Archived	**DL1:** Reduced Instrument	**DL2:** Reconstruct-ed showers	**DL3:** Science-Ready	**DL4:** Binned Science	**DL5:** Advanced Science	**DL6:** High-level
Primary / Example Contents	‣ Per-telescope raw event waveforms	‣ Per-telescope processed event images and image features	‣ reconstructed event parameters (energy, position, classification info)	‣ γ-like event lists (time, position, energy) ‣ associated IRF matrices	‣ data cubes in instrumental units (e.g. counts)	‣ data cubes in physics units (e.g. flux)	‣ Source catalogs ‣ Observatory-produced background models
Data model & Format	**Current instruments**: **closed**: internal model, ROOT format **CTAO**: **open**: model, FITS + HDF5 format			**Current Instruments**: **open**: *GADF* model in FITS format **closed**: proprietary formats, internal **CTAO**: **open**: *VODF** model in FITS format			**Current**: FITS, no common model **CTAO**: **open**: *VODF**,
Soft-ware	**Current instruments**: **closed**: proprietary, internal **CTAO**: **open**:			**Current Instruments:** **open:** gammapy **CTAO**: **open**:science tools based on gammapy			*VODF will be a formal evolution of GADF that complies with the CTAO data model