

IVOA and High-Energy Gamma-Rays: Ground-based IACTs

The perspective of CTAO, HESS, and beyond

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From Closed Experiments...



...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

- ◆ measure Energy, Position, Time of individual *photons*
- ◆ but *also* from irreducible cosmic ray detections
- ◆ → **Data Cubes** are important (image, lightcurve, spectrum, spatial-spectro cube, spatial-time cube, spatial-spectral-time)
- ◆ Source models are also $F(\text{ra}, \text{dec}, E, t)$

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.

Energy-dependent optical characteristics:

- ◆ Field of view: 5-20°
- ◆ PSF: 0.1 - 0.01°
- ◆ Performance varies with offset from center, zenith/azimuth angle, atmosphere changes,

From Events \rightarrow Physics

Events on their own are not enough:

- ◆ Events *counts in region* (space/time) - *background estimate* \rightarrow
 - Excess counts above background
 - Detection Significance

Typical IRF Decomposition:

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

Instrumental Response Functions (IRFs)

- ◆ Matrices to transform between *counts in region* \rightarrow **Flux**
- ◆ Derived from detailed simulations + observations
- ◆ Events \otimes IRFs \rightarrow Fluxes (Images, Spectra, Light-curves, ...)

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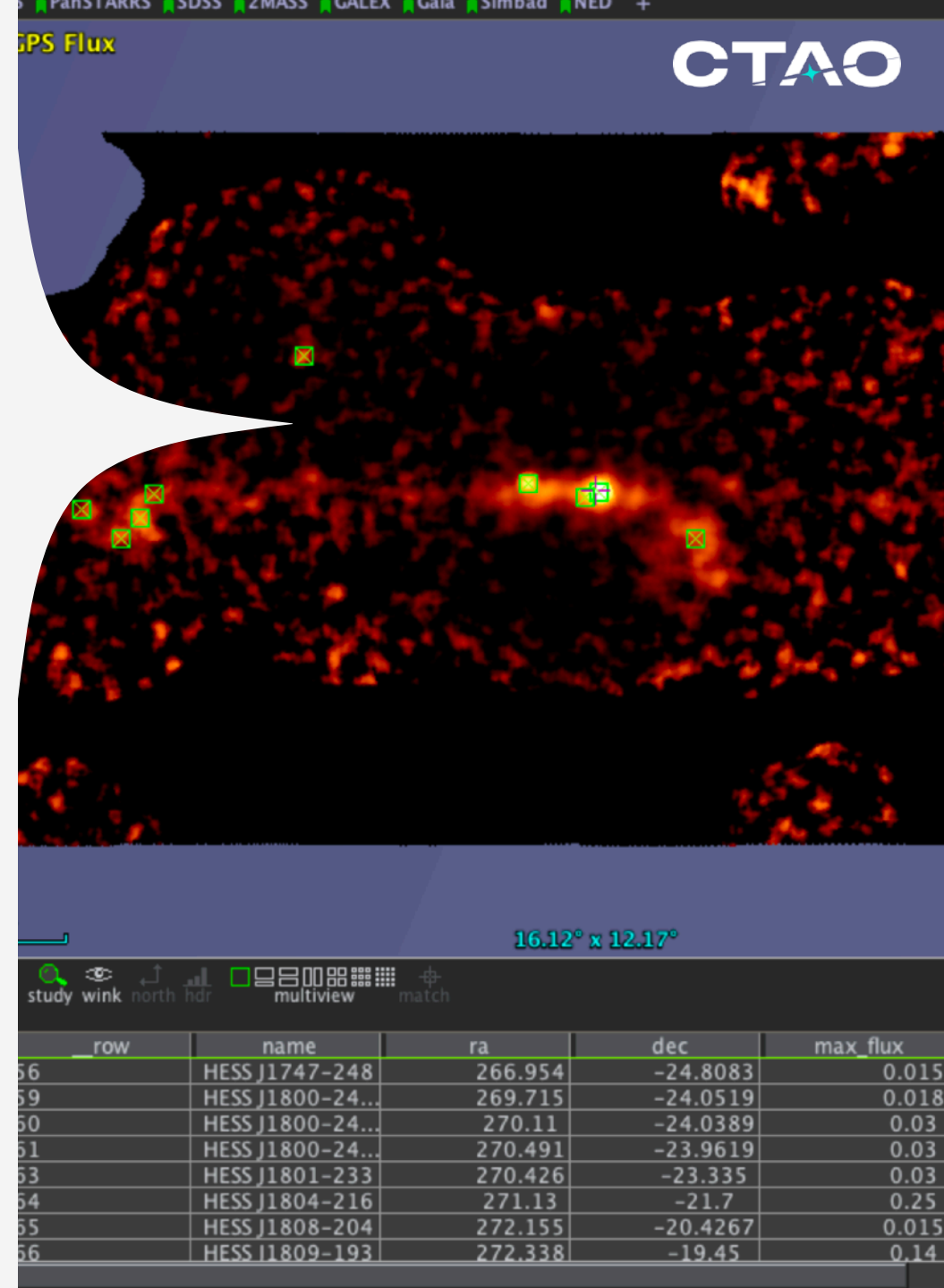
Data Discoverability

◆ 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

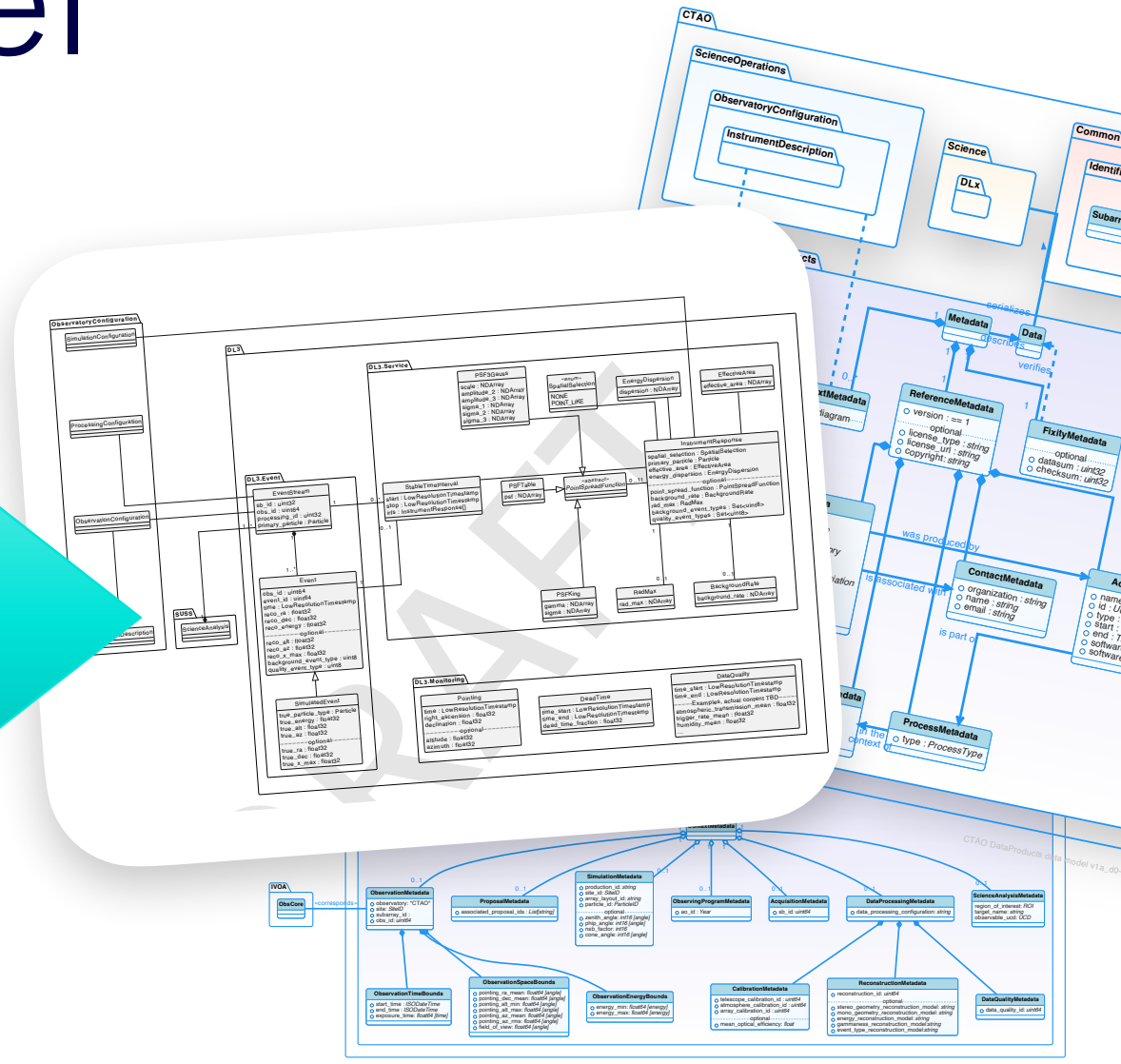
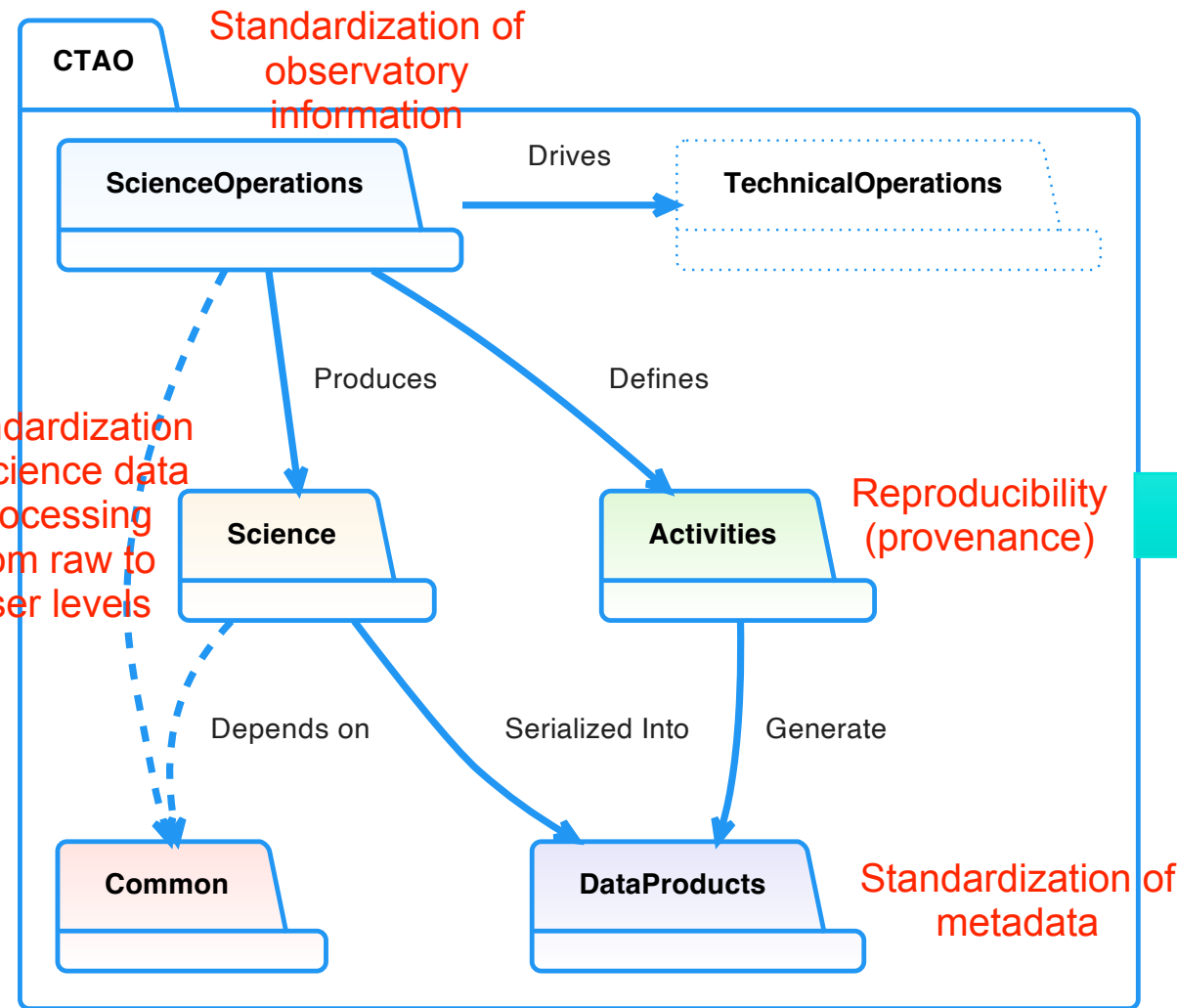
◆ CTAO:

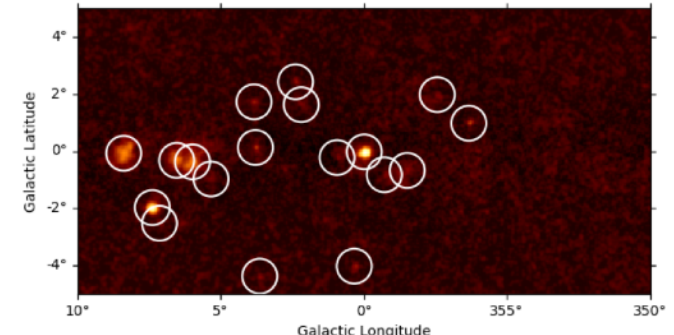
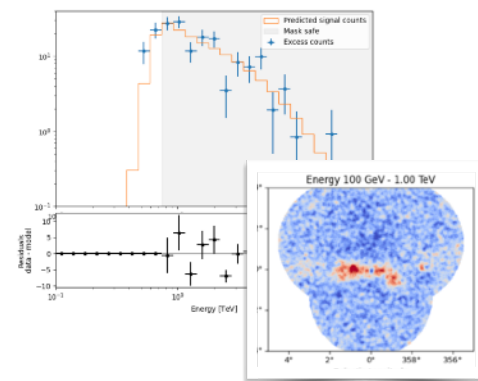
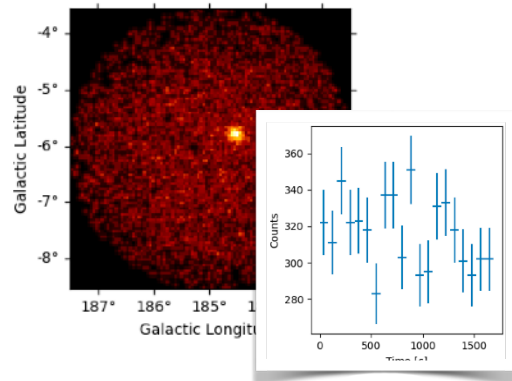
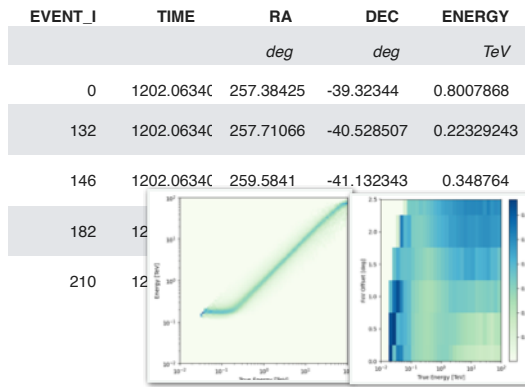
- **Observation Catalog:**
 - **ObsCore** compliance
- **Science results (quicklook and user data?):**
 - hope for full VO access via TAP services



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CTAO Data Model





Science-Ready Products
DL3

Binned Science Products
DL4

Advanced Science Products
DL5

High-Level Catalog Products
DL6

Event Lists

Counts, Exposure, Background Data Cubes

Flux Data Cubes

Source Catalog

Instrument Response Functions

Excess, Significance Data Cubes

Likelihood Data Cubes

Source Component Catalog

Instrument Monitoring Tables

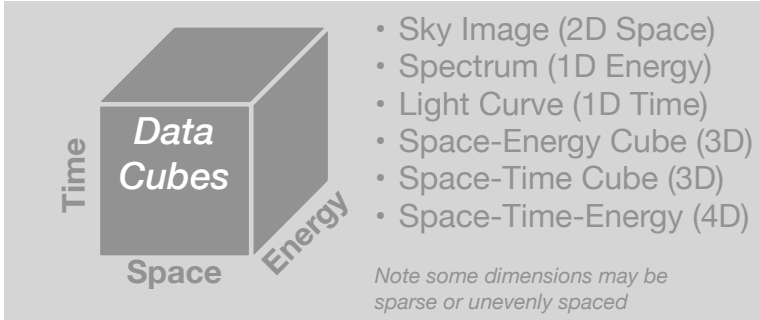
Sky Regions

Model Fit Metrics

Time Intervals (stable, good)

Sky Models

Observation Catalogs / Coverage Maps



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, ...)

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?

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
SWG0	Slewing γ -ray instrument
VERITAS	Pointing γ -ray instrument

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.

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Scheduling for CTAO

Schedules are similar to other instruments:

- ◆ Long-term schedule (at start of Observing Year)
- ◆ Medium-term schedule (\approx 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:

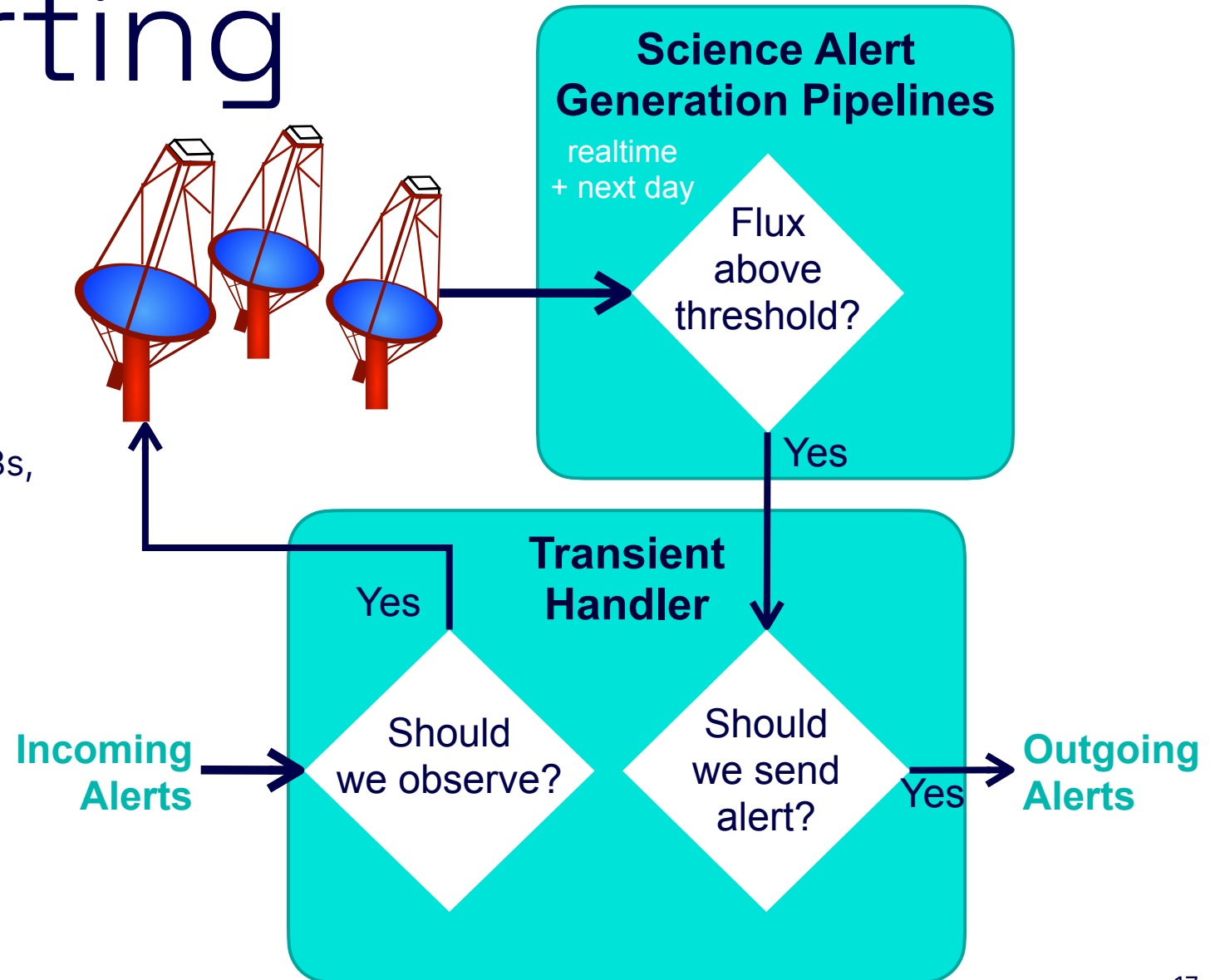
- ◆ GCN
- ◆ VOEvent (2.0)
- ◆ Astronomer's Telegrams
- sufficient for many!

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
- ◆ $\approx 10,000$ events/s for CTAO!

Event = Photon?

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

Confusion: Event \neq Transient Source outburst

- ◆ Event \rightarrow *Cherenkov Event*:
 - detection of photon or background
- ◆ Alert \rightarrow *Transient Event*
 - high-level analysis of many Cherenkov Events, transformed into a flux estimate....

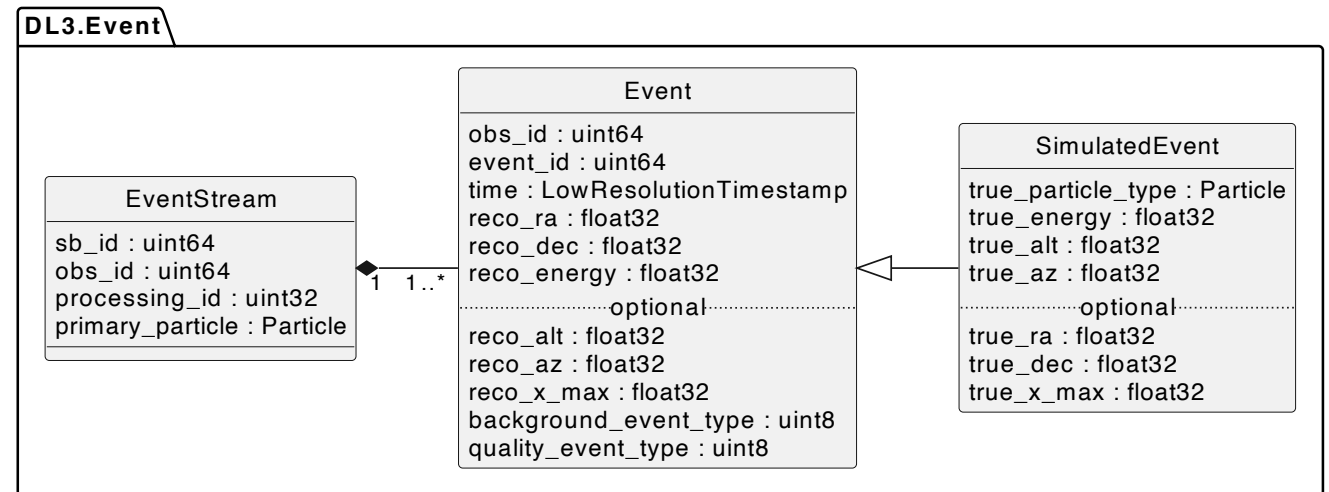


Figure 2.2 – UML Diagram of the DL3/Event Data Model.

Data Formats and Models Overview

	Instrumental, internal →			Disseminated to users →			
	DL0: Raw Archived	DL1: Reduced Instrument	DL2: Reconstructed showers	DL3: Science-Ready	DL4: Binned Science	DL5: Advanced Science	DL6: High-level
Primary / Example Contents	<ul style="list-style-type: none"> ▸ Per-telescope raw event waveforms 	<ul style="list-style-type: none"> ▸ Per-telescope processed event images and image features 	<ul style="list-style-type: none"> ▸ reconstructed event parameters (energy, position, classification info) 	<ul style="list-style-type: none"> ▸ γ-like event lists (time, position, energy) ▸ associated IRF matrices 	<ul style="list-style-type: none"> ▸ data cubes in instrumental units (e.g. counts) 	<ul style="list-style-type: none"> ▸ data cubes in physics units (e.g. flux) 	<ul style="list-style-type: none"> ▸ 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*,
Software	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