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

The perspective of CTAO, HESS, and beyond

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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

✦ measure Energy, Position, Time of individual *photons, [and likelihood]*

✦ but *also* from irreducible cosmic ray detections

✦ **Data Cubes: 1D-5D!** (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:

✦ 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, ...)

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

Provenance important here...

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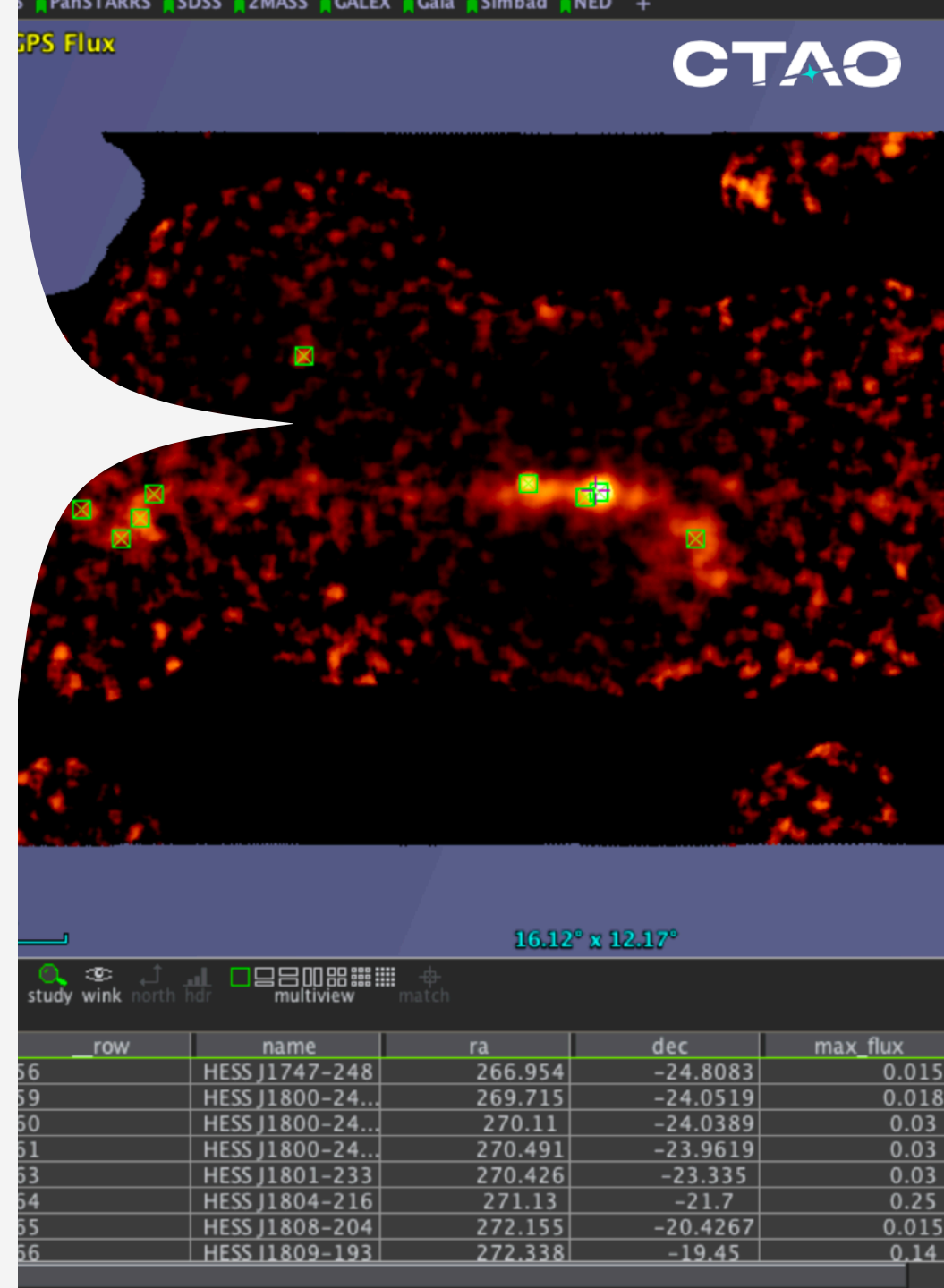4. Observation Planning

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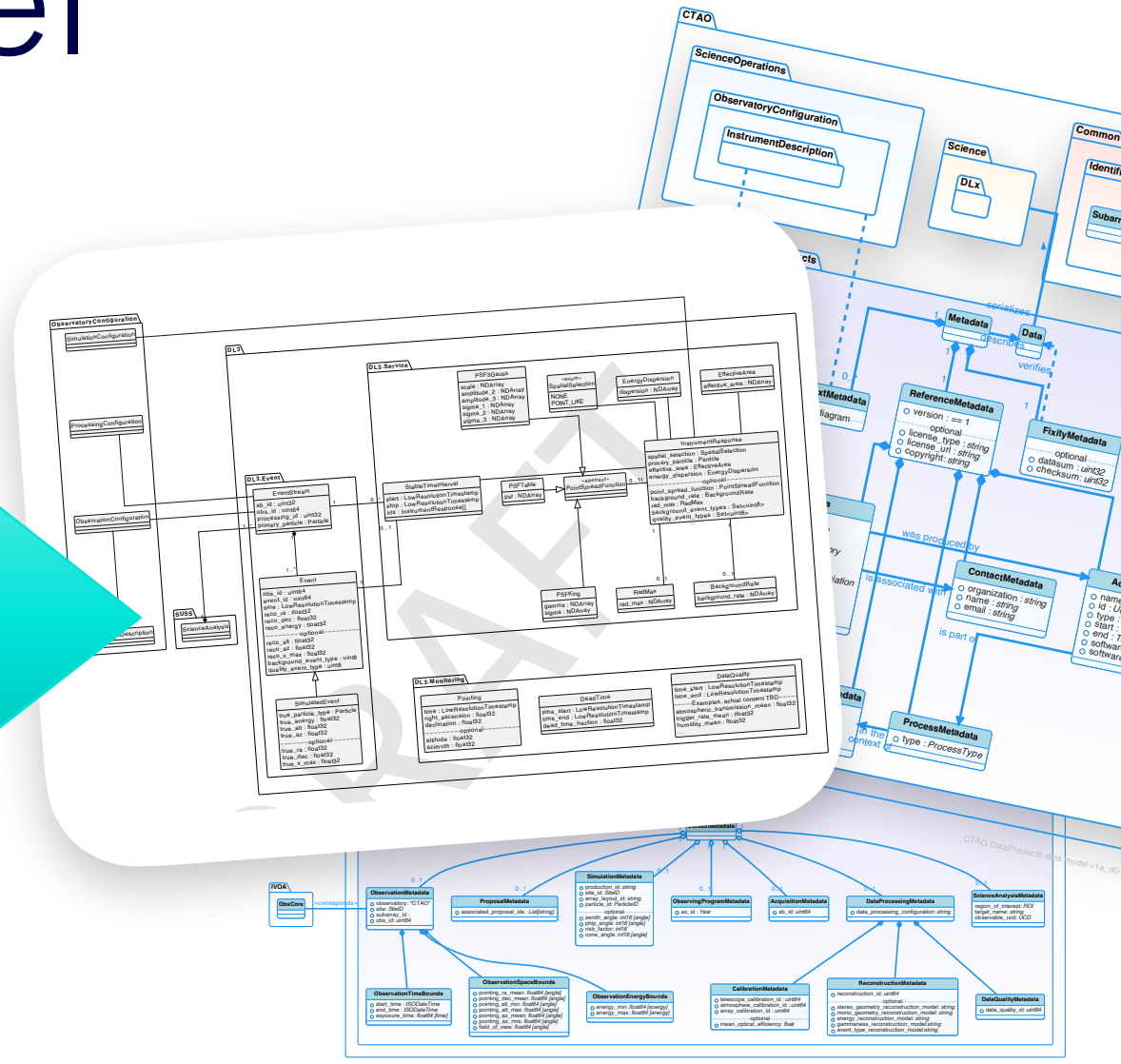
✦ **CTAO:**
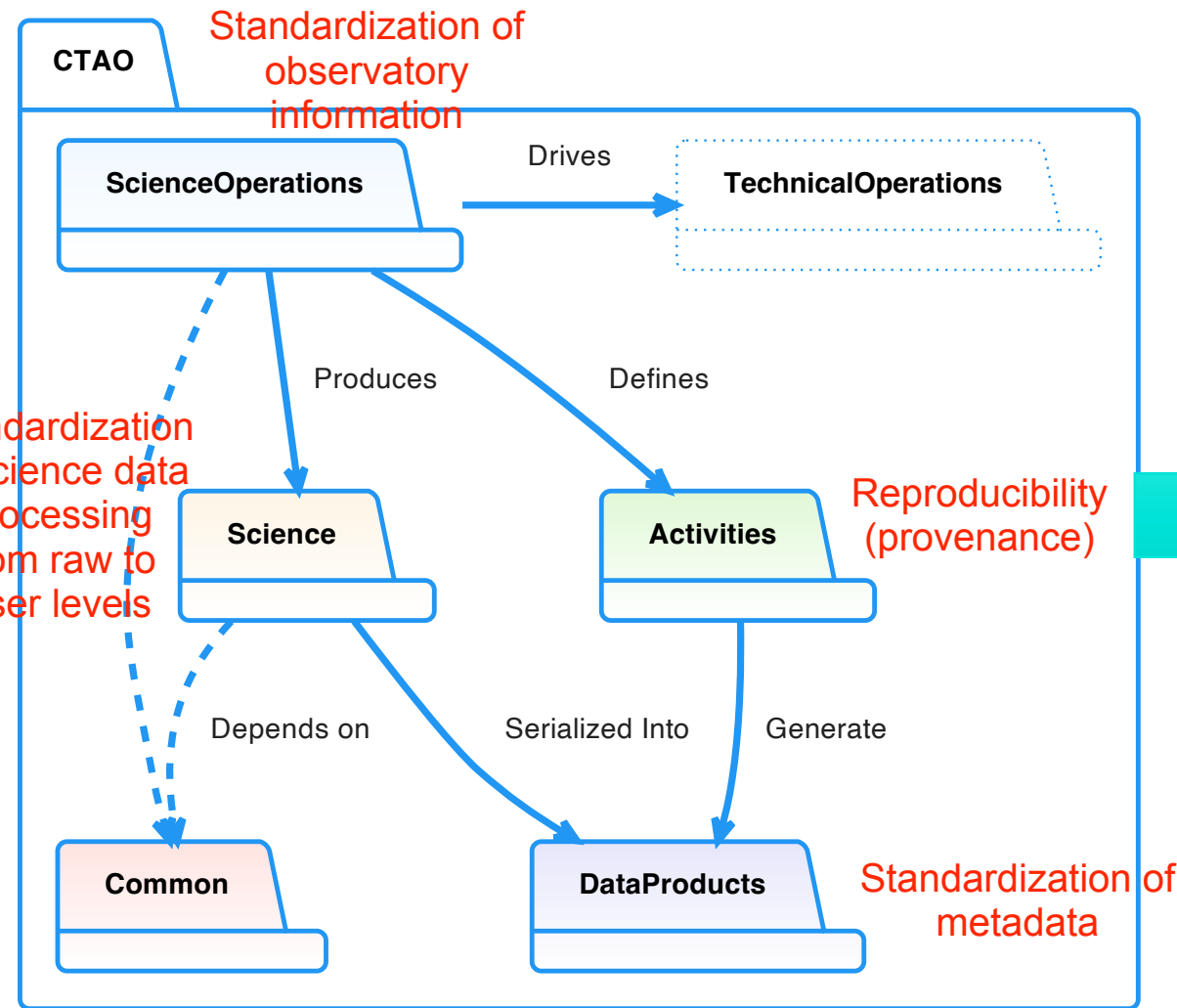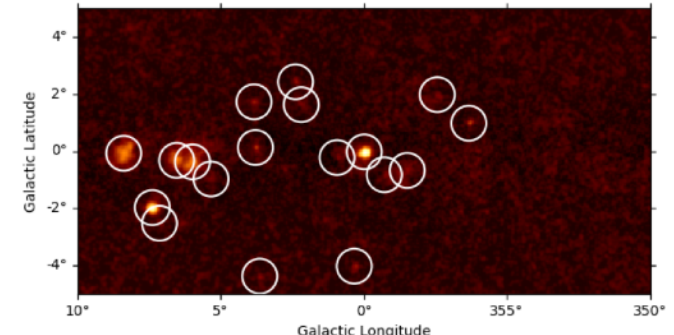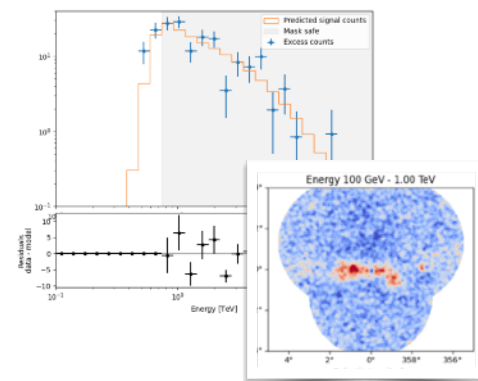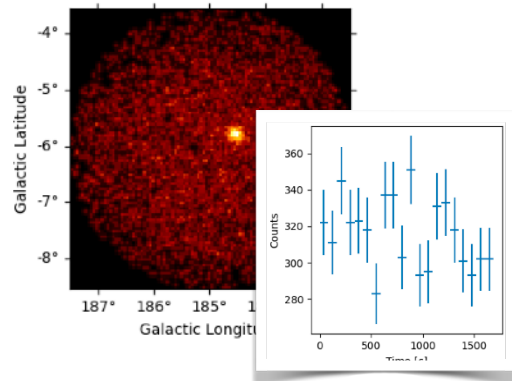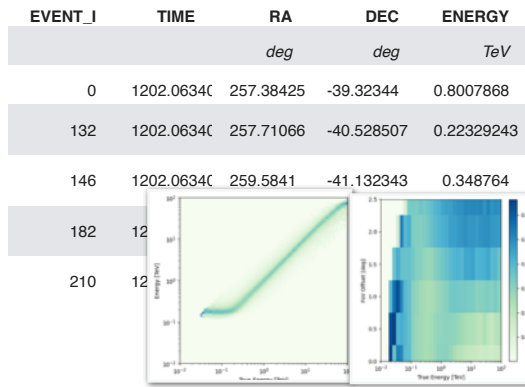
- **Observation Catalog**:
  - ObsCore compliance
- **Science results (quicklook and user data?)**:
  - hope for full VO access via TAP services

1. Differences?
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CTAO Data Model

EVENT_I	TIME	RA	DEC	ENERGY
		deg	deg	TeV
0	1202.06340	257.38425	-39.32344	0.8007868
132	1202.06340	257.71066	-40.528507	0.22329243
146	1202.06340	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

Data Cubes

Time — Space — Energy

- 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, ...)

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
SWGO	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 (≈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
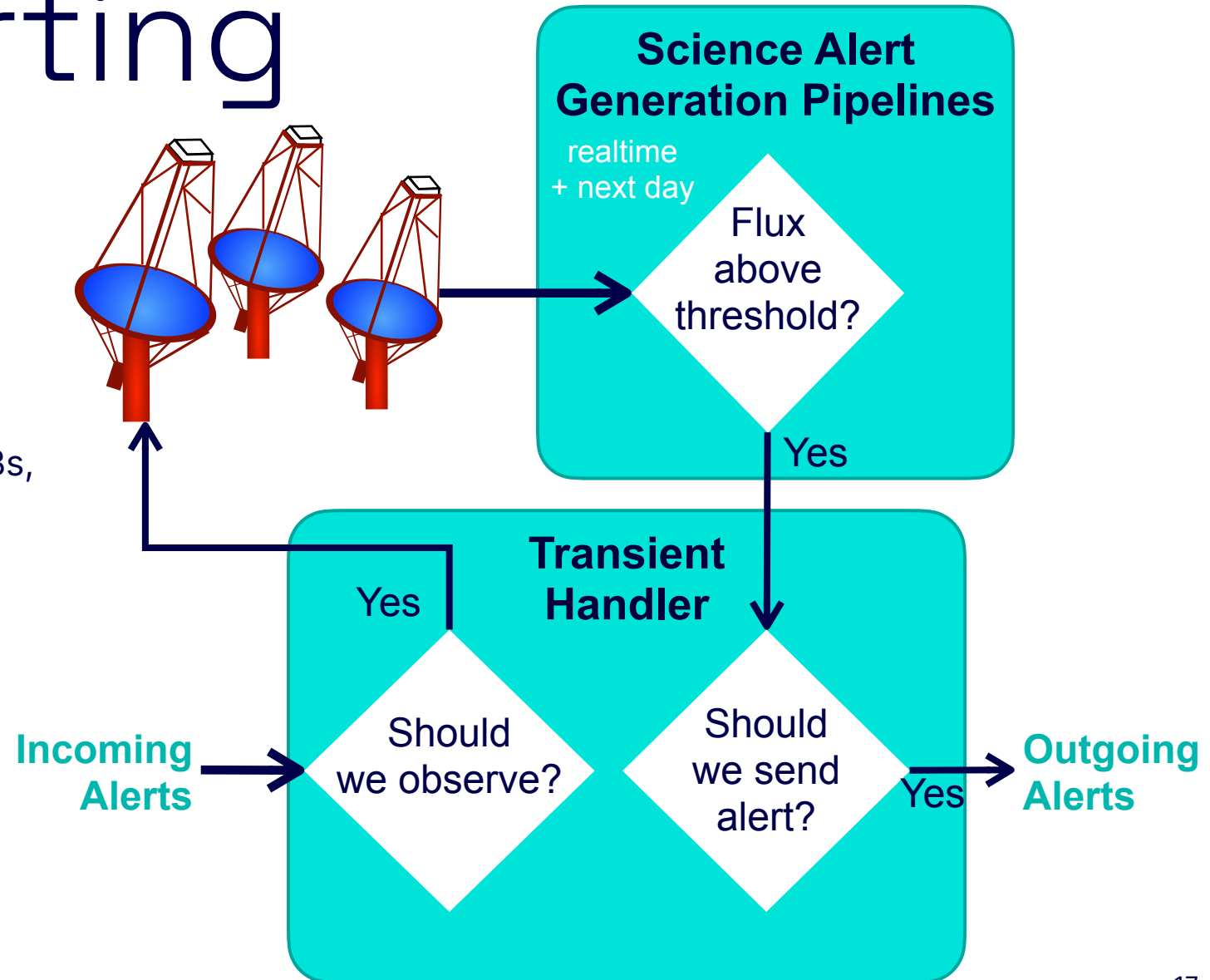
Science Alerting

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

Science Alert Generation Pipelines

realtime + next day

Flux above threshold?

Yes

Transient Handler

Yes

Incoming Alerts

Should we observe?

Should we send alert?

Yes

Outgoing Alerts

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*
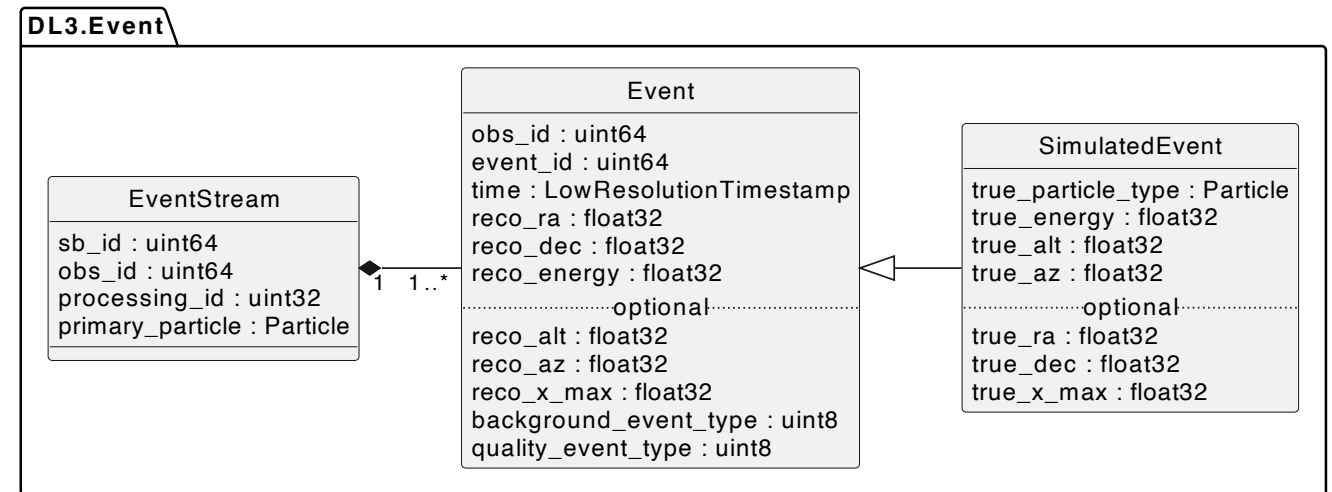 - high-level analysis of many Cherenkov Events, transformed into a flux exstimate....

DL3.Event

EventStream
sb_id : uint64
obs_id : uint64
processing_id : uint32
primary_particle : Particle

1   1..*

Event
obs_id : uint64
event_id : uint64
time : LowResolutionTimestamp
reco_ra : float32
reco_dec : float32
reco_energy : float32
optional
reco_alt : float32
reco_az : float32
reco_x_max : float32
background_event_type : uint8
quality_event_type : uint8

SimulatedEvent
true_particle_type : Particle
true_energy : float32
true_alt : float32
true_az : float32
optional
true_ra : float32
true_dec : float32
true_x_max : float32

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*