

# L'observatoire CTAO dans le VO

## *Cherenkov Telescope Array Observatory*

Journées ASOV – Paris, 24 Mars 2025



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Onur Ates  
Catherine Boisson  
+ équipe LUX, PADC, CTAO, IVOA !



# The Cherenkov Telescope Array Observatory (CTAO)

# Cherenkov Astronomy



**MAGIC**: located in La Palma, Spain

Since 2004: single 17m telescope

Since 2009: system of two 17m telescopes



**VERITAS**: located in Mt Hopkins, Arizona

Since 2007: four 12m telescopes

Since 2012: upgraded PMTs



**H.E.S.S.**: located in Khomas Highlands, Namibia

Since 2002: four 12m telescopes

Since 2012: added 32m by 24m telescope

Since 2015: camera upgrades on 12m telescopes

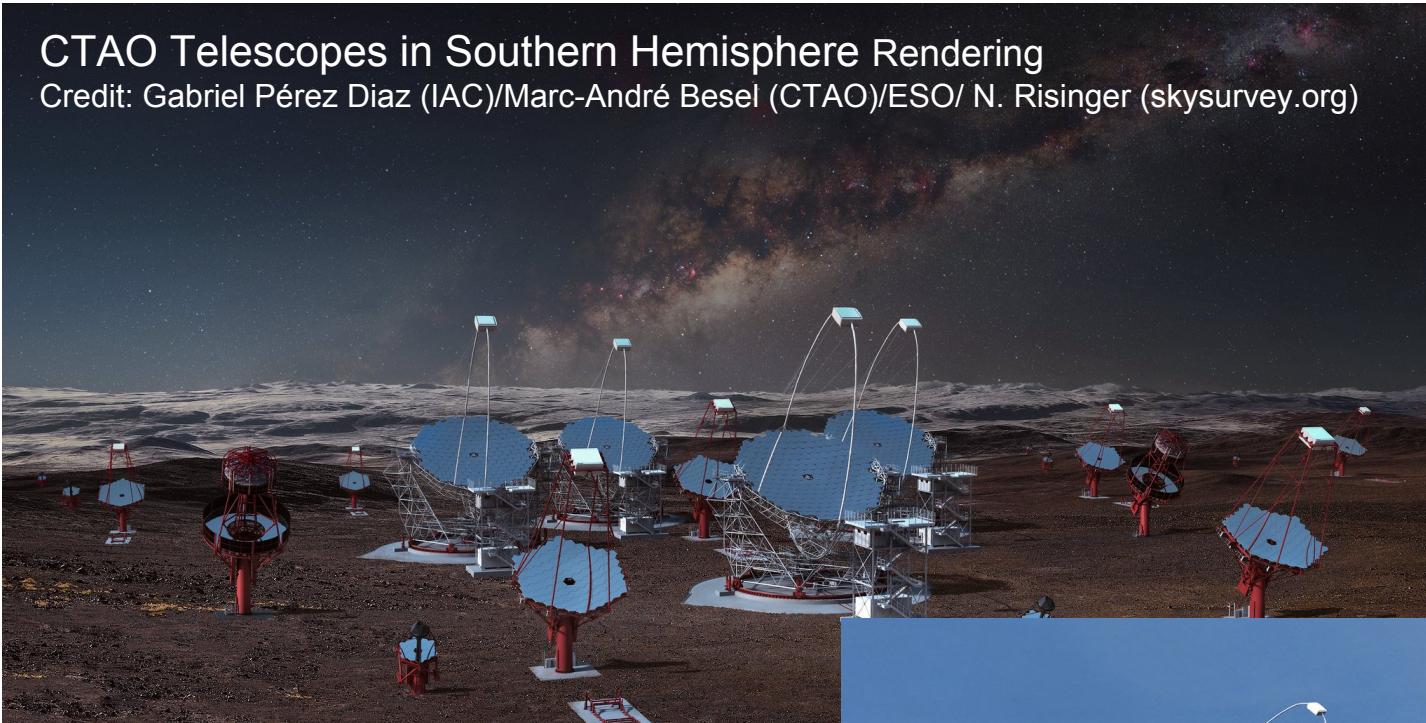
@ Jeff Grube

# The Cherenkov Telescope Array

**CTAO**

CTAO Telescopes in Southern Hemisphere Rendering

Credit: Gabriel Pérez Diaz (IAC)/Marc-André Besel (CTAO)/ESO/ N. Risinger (skysurvey.org)

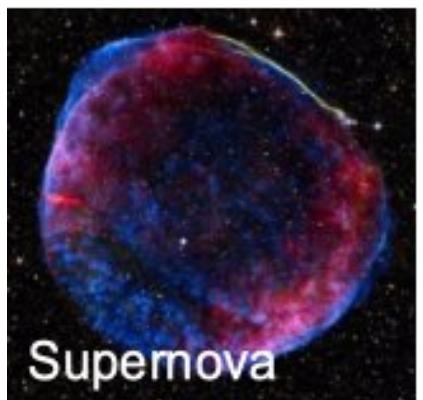


<https://www.ctao.org>

- Next generation ground-based gamma-ray observatory
- More than 60 telescopes (4m to 23m)
- South: 150 GeV to 300 TeV
- North: 20 GeV to 5 TeV



CTAO Northern Hemisphere Array Rendering - Credit: Gabriel Pérez Diaz, IAC

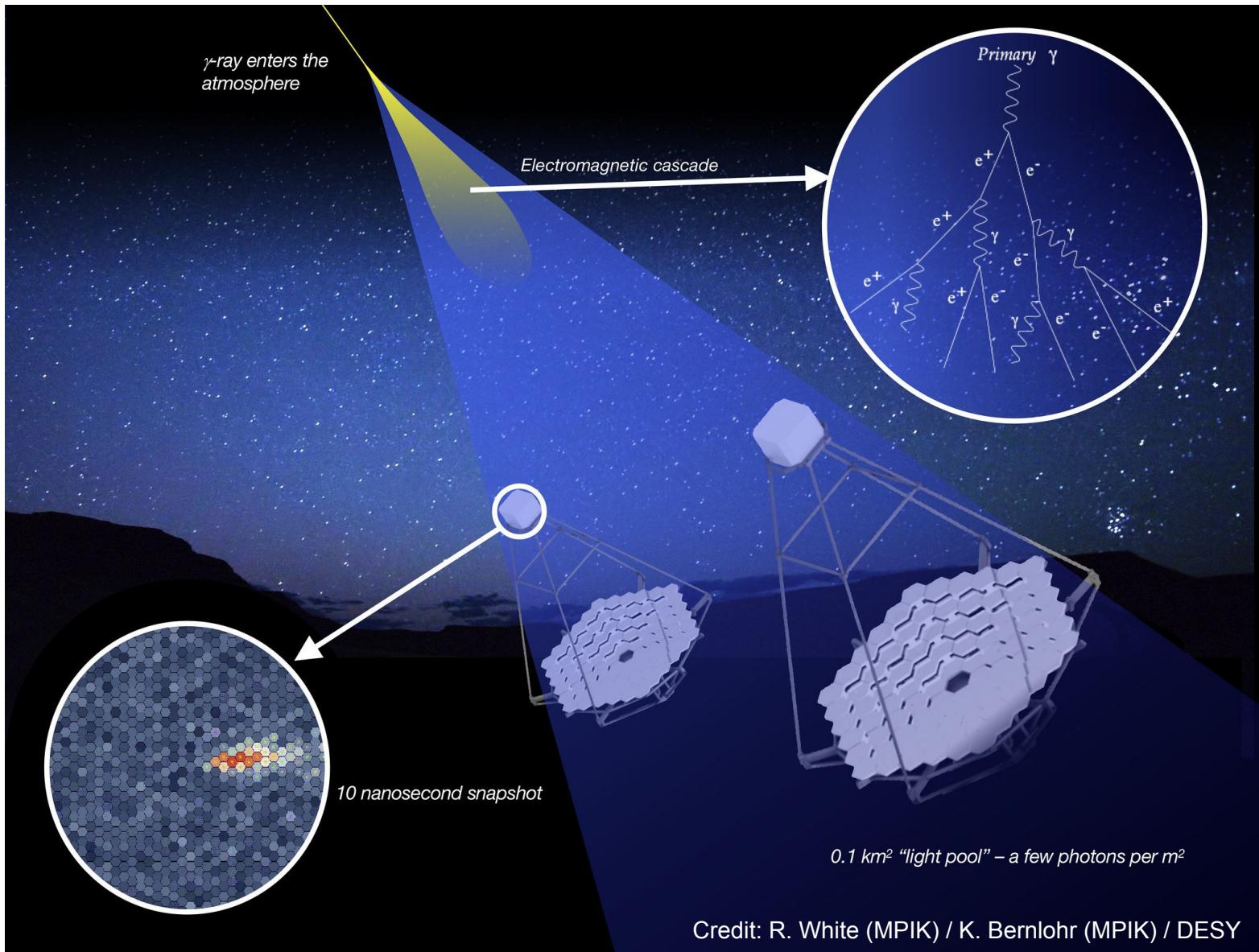


- ◆ Violent, transient, non-thermal phenomena
- ◆ Matter under extreme conditions
- ◆ Particle Acceleration
- ◆ Fundamental Physics
- ◆ Role of Black Holes in the structuration of the Universe

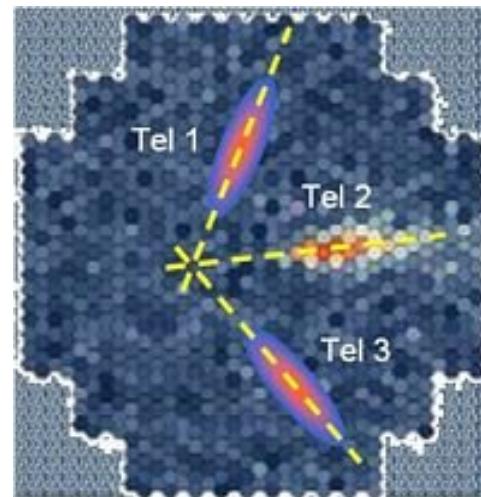


# Cherenkov Telescope observations

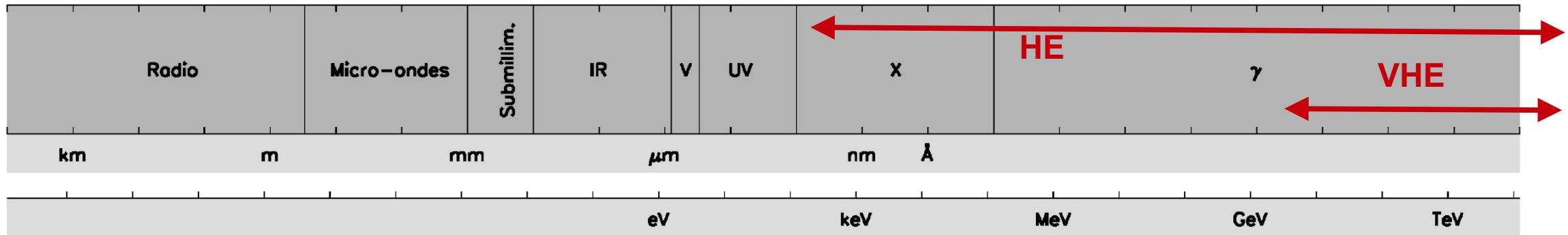
CTAO



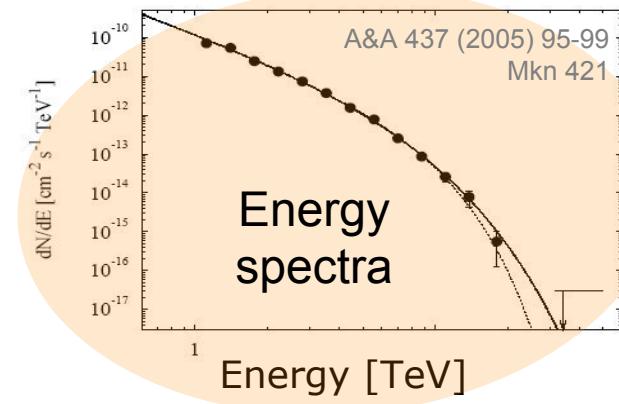
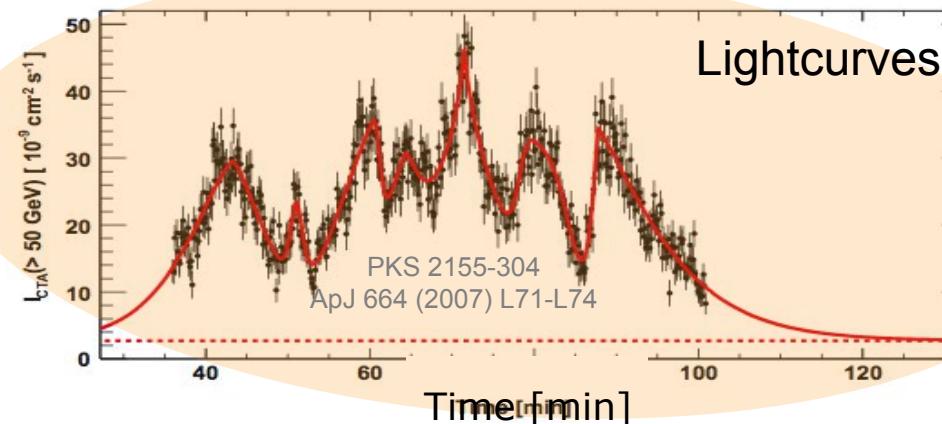
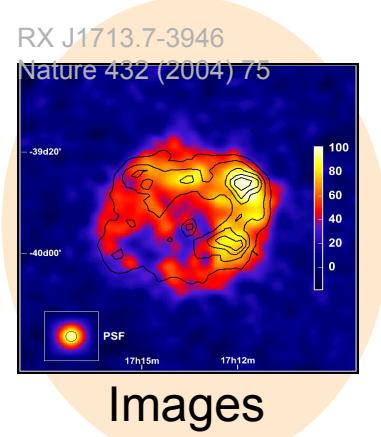
- Detection of "**events**"
- Each event is **probably** due to the interaction of a **particle** (photon, hadron, lepton) in the upper atmosphere (10 km altitude)
- This interaction emits Cherenkov light for a few **ns**
- **Indirect detection**



# High Energy Astrophysics



Several orders of magnitude - Event **counting**  
→ **Event lists** (coordinates, time, energy)



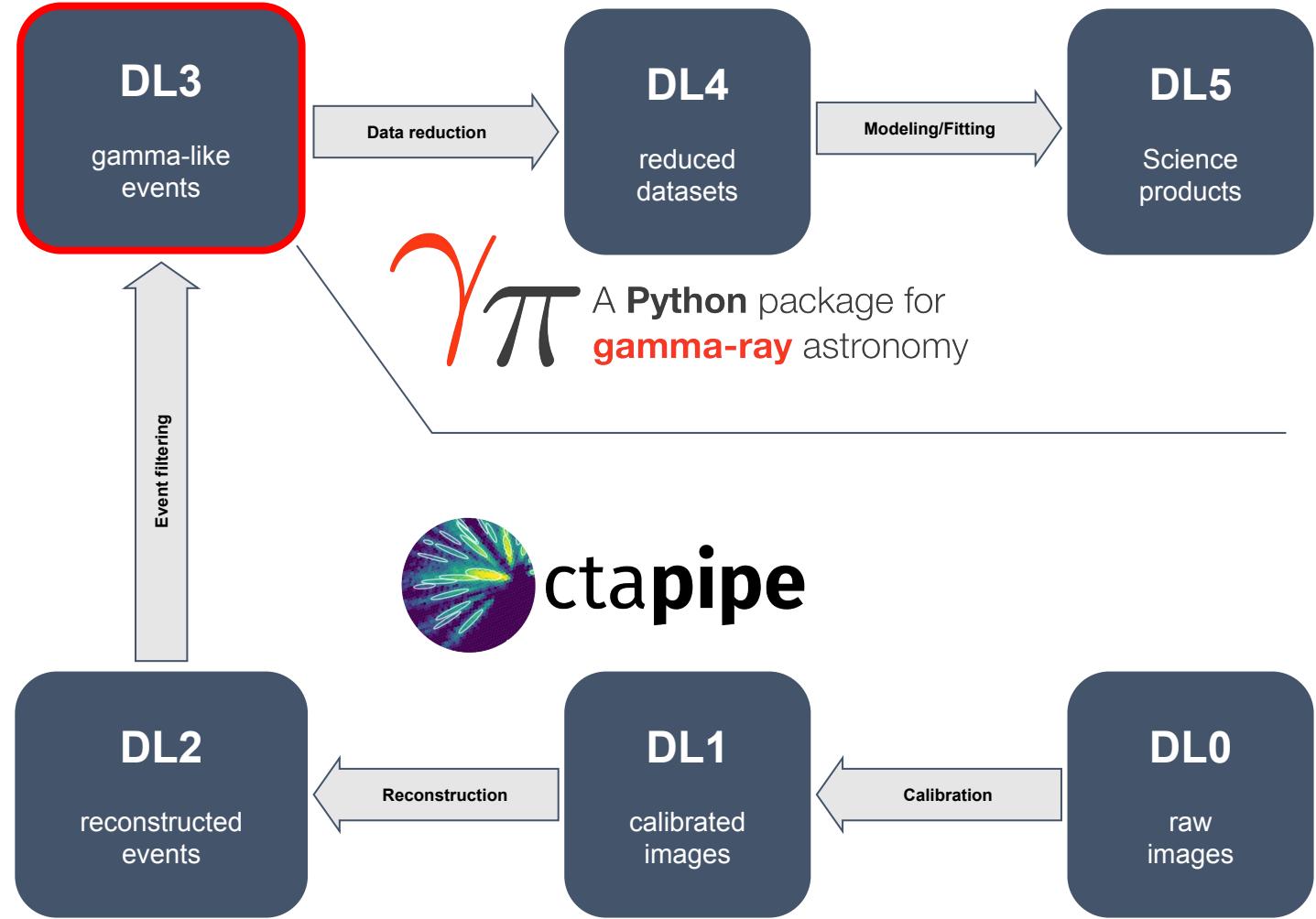
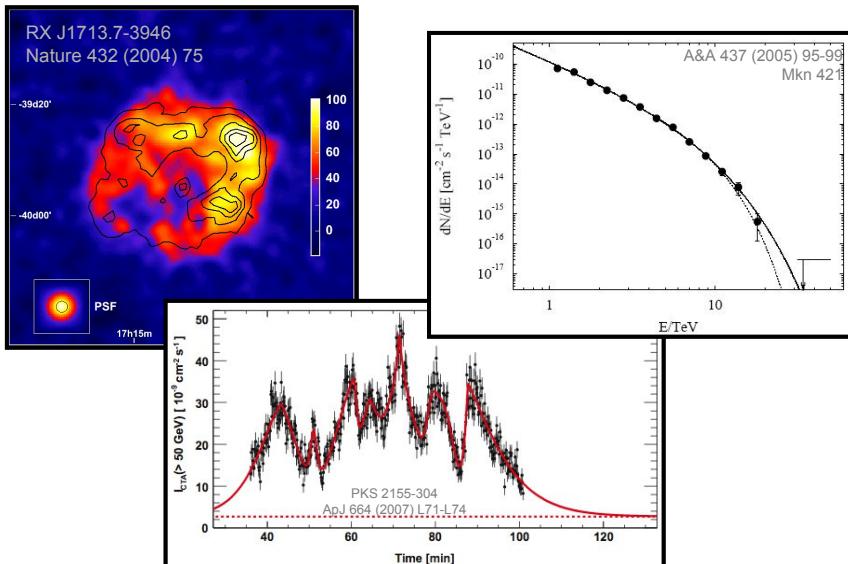
+ multi-messenger data (photons, cosmic rays, neutrinos, gravitational waves...)

# Data processing for imaging Cherenkov data

## Data Level 3 (DL3) event lists

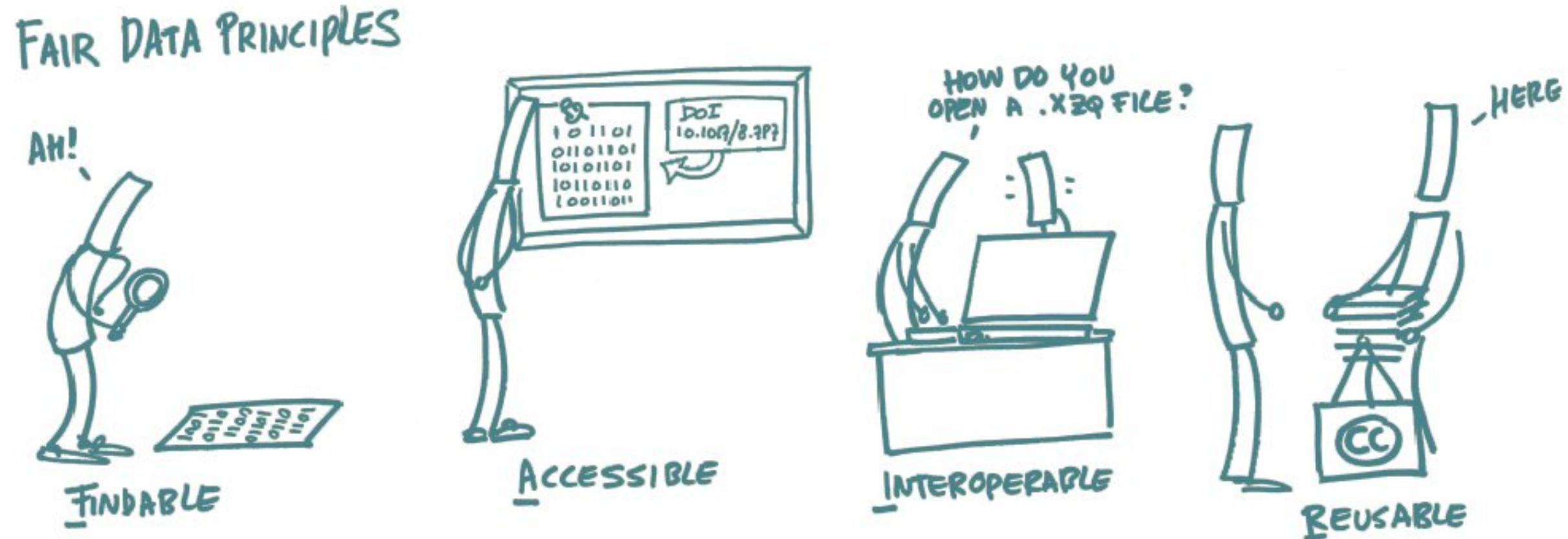
- TeV “candidate” photons (coordinates, time, energy)
- Low count statistics
- High background

## Science products (DL5):



# CTAO and the VO

# Open Science and data management



*The FAIR data principles. Image: <https://book.fosteropenscience.eu/>*  
*<https://www.go-fair.org/fair-principles>*

# A long way...

*It's a Long Way... from Private Ground-based Gamma-ray Data to Public Release: Open-data, Open-source Tools, First Real TeV Data Release from H.E.S.S.*  
[C. Boisson et al. 2020, ADASS XXVII Santiago, ASPC 522 497B]

- Imaging Atmospheric Cherenkov Telescopes
- Gamma **data format** initiative
- **Open tools** for analysis

→ A story of the relations  
between Cherenkov observatories and the IVOA  
via European projects



# A long way...

- **Provenance** of astronomy data products
  - Complex data processing, assumptions, statistics...
  - CTAO as a major use case
  - Several OV-France workshops
  - IVOA Provenance Data Model v1.0
- **OSTrails : Plan-Track-Assess and Open Science**
  - CTAO as a sub-pilot (see B. Cecconi presentation)
  - maDMP, SKG, FAIR assesment
- **High Energy in the VO**
  - Role of OV-France, workshops
  - Creation of an IVOA Interest Group in 2025



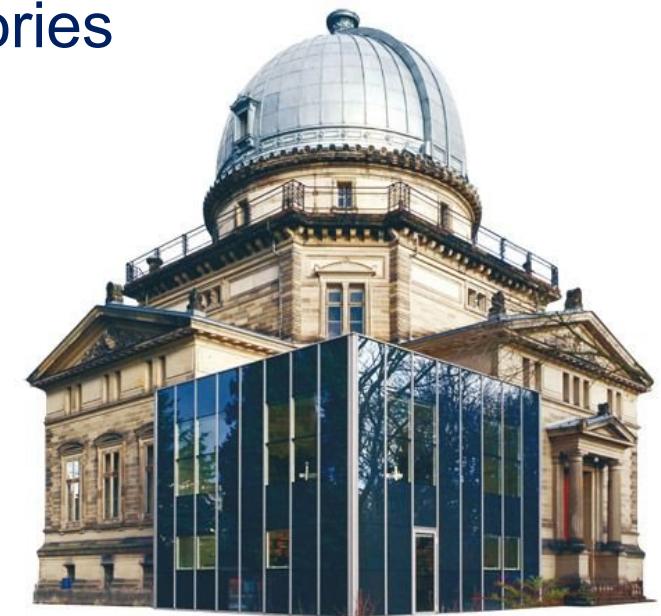
os~~t~~rails

:OV FRANCE

# First HE dedicated workshop



- **October 2022 in Strasbourg**
  - <https://indico.obspm.fr/event/1489>
- Continue activities of the **ESCAPE European project** that focused on High Energy Facilities (2019-2023 H2020 project)
- Bring together representatives of high energy observatories (VHE, HE, GW, neutrino)
- Presentations of HE observatory operations and data:
  - CTA (Mathieu Servillat)
  - Ligo Virgo Kagra (Pierre Chanial)
  - Neutrino (Damien Dornic)
  - XMM & SVOM (Laurent Michel)
  - GADF/VODF (Bruno Khelifi)



# HE meeting at IVOA Interop

- **May 2023 at the IVOA Bologna**
  - Dedicated talk at the DM session by M. Servillat:
    - [https://wiki.ivoa.net/internal/IVOA/InteropMay3023DM/2023-05-11\\_IVOA\\_meeting\\_-\\_VOHE.pdf](https://wiki.ivoa.net/internal/IVOA/InteropMay3023DM/2023-05-11_IVOA_meeting_-_VOHE.pdf)
  - Fruitful splinter IVOA meeting
- Creation of HE “Club”
  - IVOA mailing list and wiki page
    - <https://wiki.ivoa.net/twiki/bin/view/IVOA/HEGroup>
  - Several online meetings
    - IVOA data models (cube, dataset)
    - Detailed of HE data, with a focus on Instrument Response Functions



# Second HE workshop enlarged to IVOA : OV FRANCE

- **June 2023 in Paris**
  - *IVOA standards for High Energy Astrophysics*
  - <https://indico.obspm.fr/event/1963>
- Review of documents since 2021
- **Focus on user scenarios in HE**
  - Access and Analysis of HE data
  - Used IVOA standards
  - What specific developments are needed
- Prepare an IVOA Note to justify a HE Interest Group
  - <https://github.com/ivoa/HighEnergyDataNote>



# IVOA High Energy Interest Group (HEIG)

- HEIG web page: charter & meeting notes
  - Official IG created at the Malta IVOA meeting in Nov 2024
  - <https://wiki.ivoa.net/twiki/bin/view/IVOA/HEGroup>
- High Energy IVOA Note v1.0
  - Servillat et al. 2024 (with ~16 co-authors from ~10 Institutions)
  - <https://www.ivoa.net/documents/Notes/VOHE>
- Focus
  - Event-list level data access in the VO, and description
  - ObsCore extension for HE astronomy
  - Alerts and Time Domain relations (VOEvent)
- Next Workshop: 29-30 April 2025 in Paris !



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# IVOA standards, from TAP to Provenance, for Cherenkov Astronomy

# FAIR data management for Cherenkov Astronomy ?

## FAIR high level data for Cherenkov astronomy

Servillat, Boisson, Fuessling, Khelifi, ASPC 2021

<https://arxiv.org/abs/2201.03247>

Findable  
Accessible  
Interoperable  
Reusable?

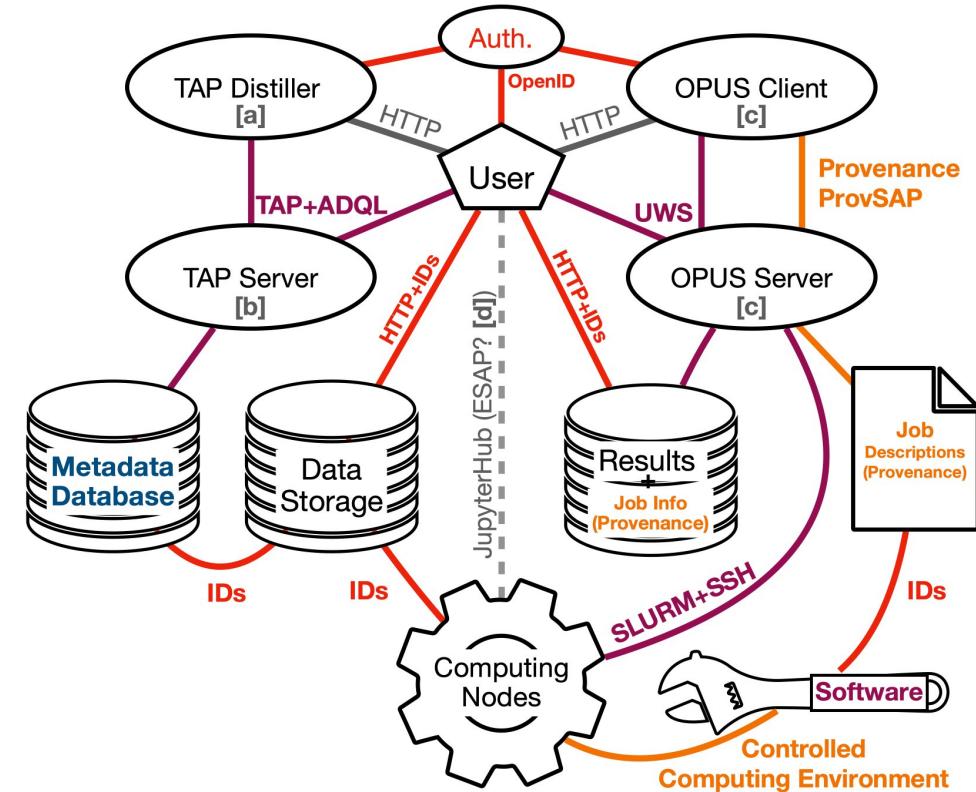
### Re-usable vs Re-producible

- Totally different concepts
- **Trust** is key:
  - licences, certifications
  - **metadata and provenance!**
- Also: Re-executable

## FAIR solutions for a science platform to analyse Cherenkov data online

Servillat, Boisson, Kornecki, ASPC 2023

[Link to poster](#)



# F = Findable

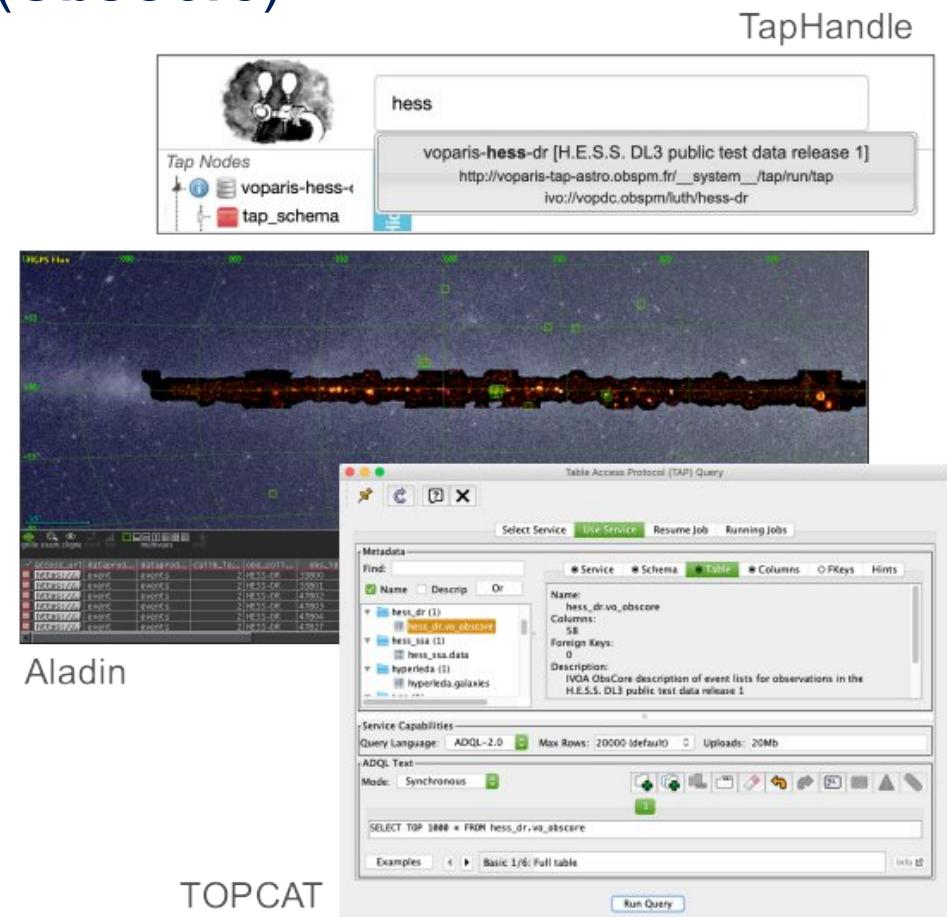


**International Virtual Observatory Alliance (IVOA) standards tailored to make data findable:**

- **IVOA Observation Data Model Core Components (**ObsCore**)**  
[\[link to IVOA REC\]](#) → adapted to Cherenkov data
- **IVOA Table Access Protocole (**TAP**)**  
[\[link to IVOA REC\]](#)
- **Deployed service at ObsParis**  
<https://hess-dr.obspm.fr>
- Registered in the VO **Registry** via PADC  
(Paris Astronomical Data Centre)

→ **Data widely findable**

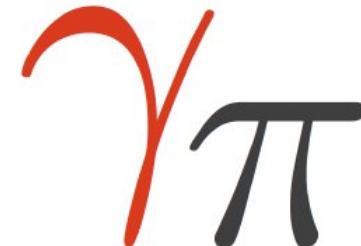
e.g. Aladin, TOPCAT, TapHandle, PyVO...  
+ dedicated web pages



# F = Findable : generation of an ObsCore Table

Module `ivoa.py` now included in **GammaPy**

Export of the DataStore into an IVOA ObsCore table  
with proper metadata to build an IVOA TAP service



dataproduct_type	calib_level	target_name	obs_id	obs_collection	obs_publisher_did	access_url	access_format	access_estsize	s_ra	s_dec	s_fov
								kbyte	deg	deg	deg
str10	int32	str25	str10	str10	str30	str30	str30	int32	float64	float64	float64
EVENTS	2	AGN monitoring	513837	DL3	ivo://ctao#<internal_id>	URL<internal_id>	application/fits	1797	327.5722	-14.7231	1.00
EVENTS	2	AGN monitoring	513839	DL3	ivo://ctao#<internal_id>	URL<internal_id>	application/fits	1785	356.2607	-16.4372	1.00
EVENTS	2	AGN monitoring	513833	DL3	ivo://ctao#<internal_id>	URL<internal_id>	application/fits	1664	262.7	-0.2026	1.00

# A = Accessible

- IVOA ObsCore **access\_url**

- Direct download link to the FITS file

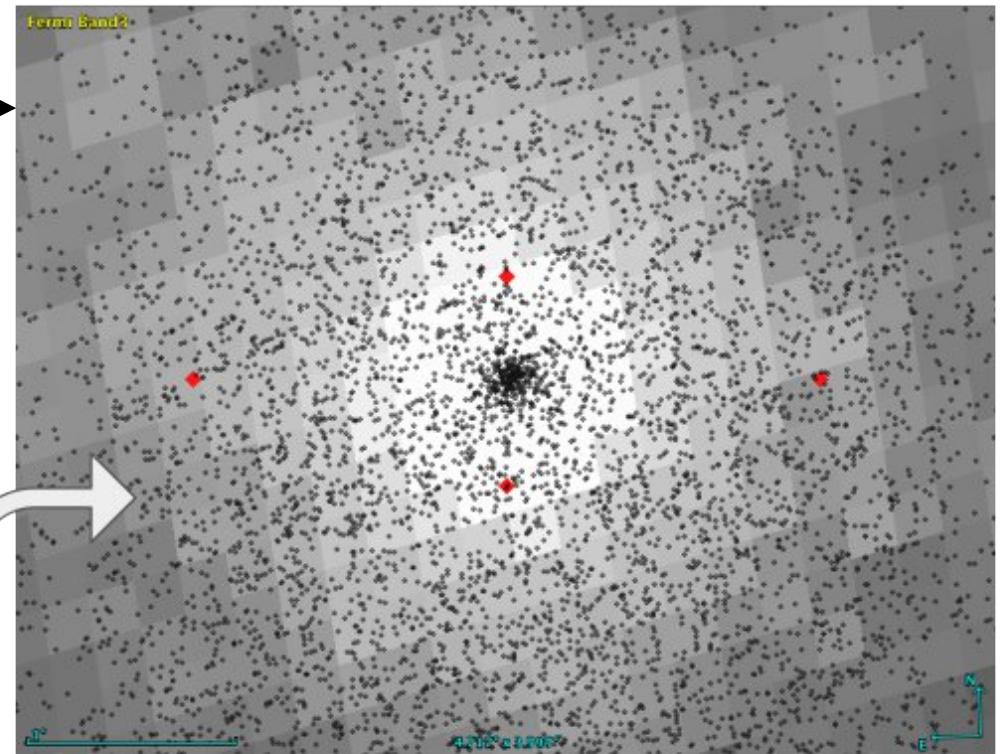
- IVOA DataLink:

- URL returning a list of connected dataset and services
  - Access to different storage services
  - Access to analysis services, previews

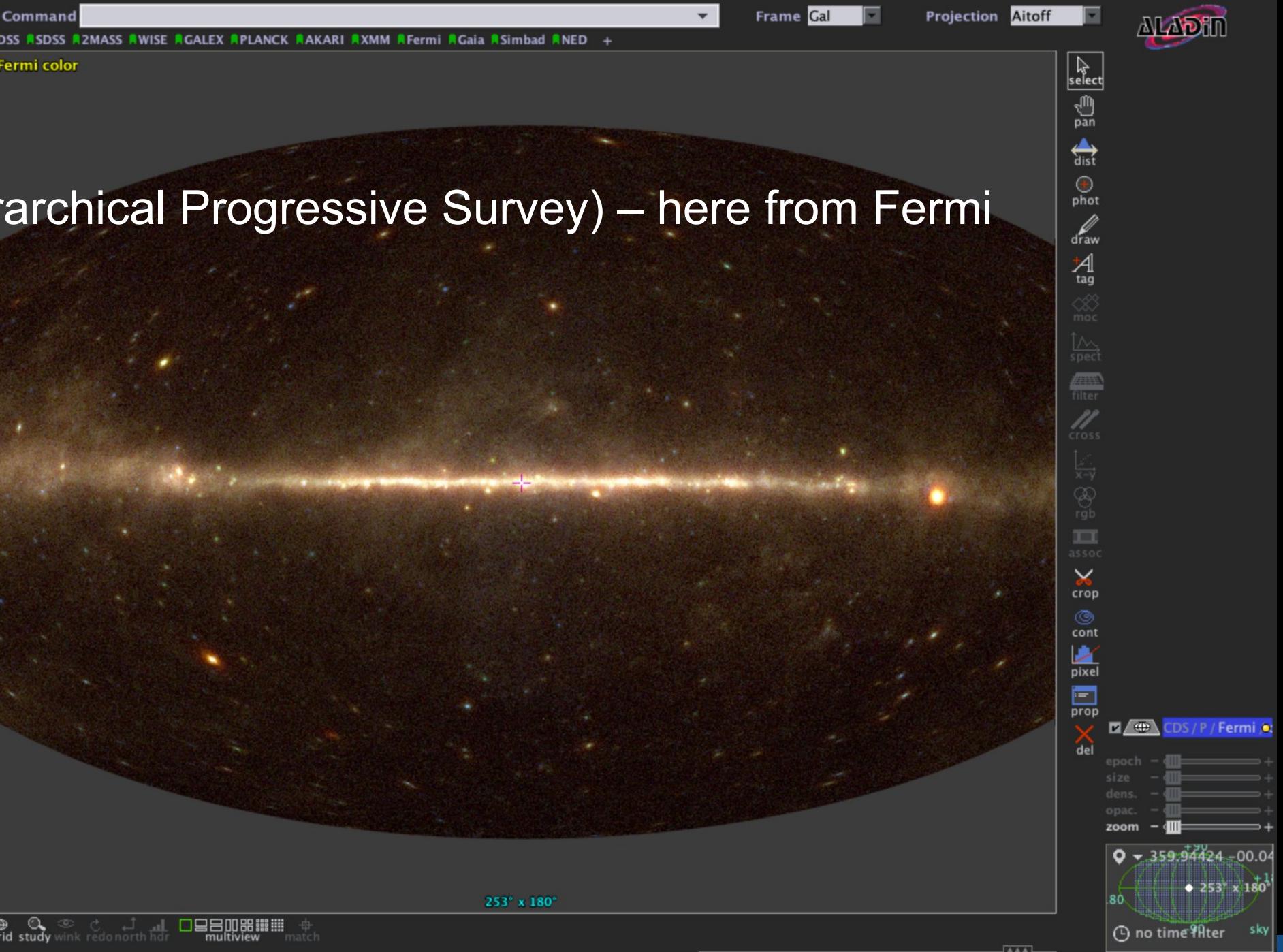
- **Access rights**

- Public data: no restrictions
  - Anticipating need for **permissions**:
    - PI proprietary period
    - Federation authentication

DL3 event list directly opened in Aladin  
(each black dot is an event)



access_url	data...	obs_colle...	obs_id	access_format	access...	target_name	s_ra	s_de
https://...	event	HESS-DR	23523	application/fits	285120	Crab Nebula	83.6333...	21.514
https://...	event	HESS-DR	23526	application/fits	282240	Crab Nebula	83.6333...	22.514
https://...	event	HESS-DR	23559	application/fits	285120	Crab Nebula	85.2533...	22.014
https://...	event	HESS-DR	23592	application/fits	273600	Crab Nebula	82.0133...	22.014



- ▼ Collections → 26 / 35132
  - ▼ Image → 2 / 620
    - ▼ Gamma-ray → 2 / 24
      - ▼ HESS → 2
        - HGPS significance
        - HGPS integral flux
  - Catalog → 20 / 33068
  - ▼ Others → 4 / 1262
    - ▼ SSA (spectrum) → 2 / 159
      - padc.obspm.astro → 1 /
        - hess\_ssa
    - ▼ vopdc.obspm → 1 / 3
      - High Energy Stereosc
  - ▼ TAP (table) → 2 / 220
    - nasa.heasarc → 1 / 35
      - RHESSI Gamma-Ray B
    - padc.obspm.he → 1 / 2
      - H.E.S.S. DL3 public te



DSS SDSS 2MASS WISE GALEX PLANCK AKARI XMM Fermi Gaia Simbad NED +

HGPS Flux



IVOA Registry (search for distribution services)

select   
 from

coll.  sort  view  scan  filter

grid  study  wink  redo  north  hdr

multiview  match

360° x 180°

select
pan
dist
phot
draw
tag
moc
spect
filter
cross
X-Y
rgb
assoc
crop
cont
pixel
prop
CDS / P / HGPS
CDS / P / Fermi

epoch - +

size - +

dens. - +

opac. - +

zoom - +

359.94023, -00.04

80

360° x 180°

no time filter

sky

Available data → 26 / 35132

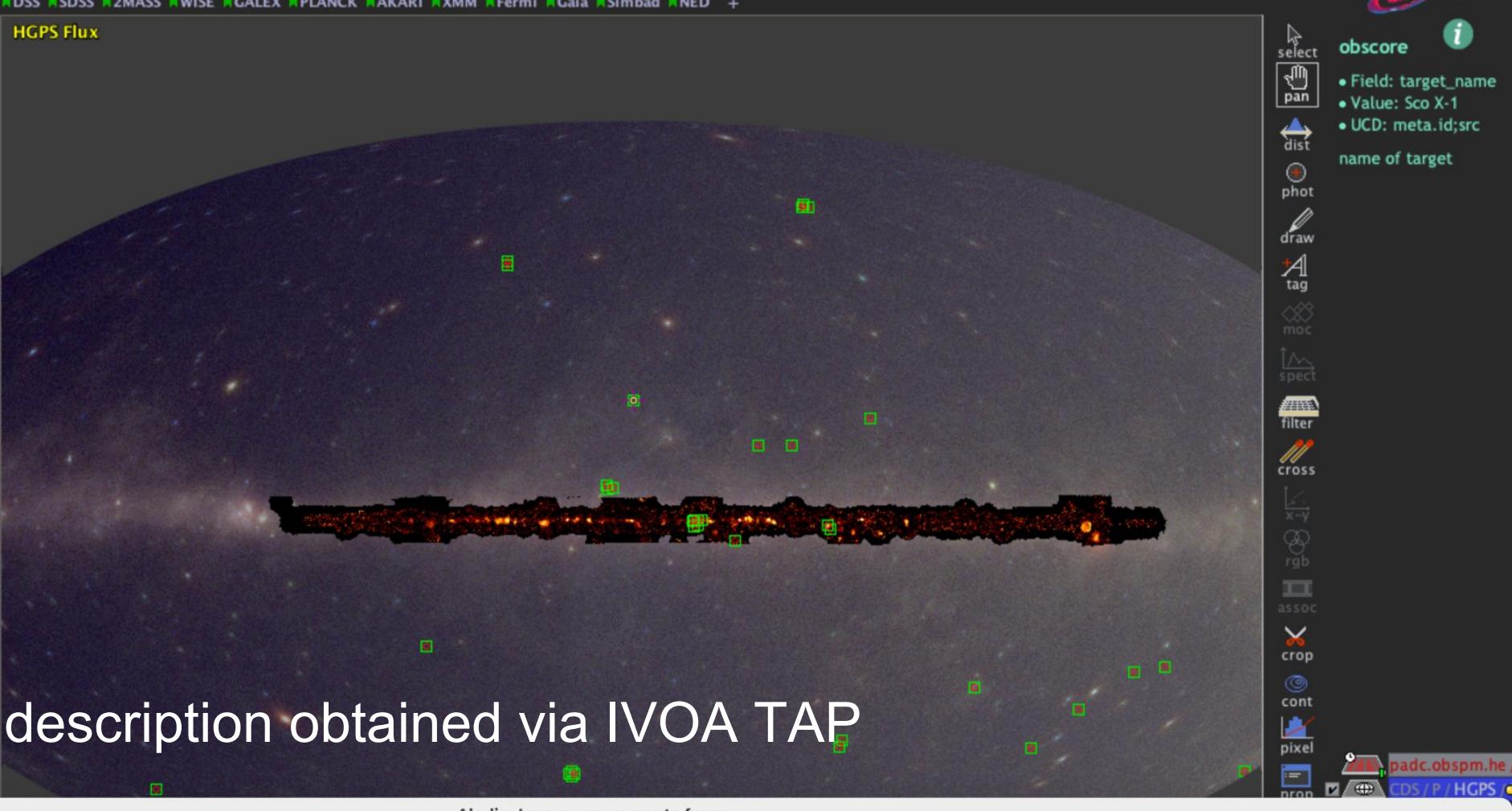
Command 359.6891364258 +24.2208343586

Frame Gal

Projection Aitoff



- ▼ Collections → 26 / 35132
  - ▼ Image → 2 / 620
    - ▼ Gamma-ray → 2 / 24
      - ▼ HESS → 2
        - GPS significance
        - GPS integral flux
  - Catalog → 20 / 33068
  - ▼ Others → 4 / 1262
    - ▼ SSA (spectrum) → 2 / 159
      - padc.obspm.astro → 1 /
        - hess\_ssa
    - ▼ vopdc.obspm → 1 / 3
      - MOC High Energy Stereoscopic
  - ▼ TAP (table) → 2 / 220
    - ▼ nasa.heasarc → 1 / 35
      - RHESSI Gamma-Ray B
    - ▼ padc.obspm.he → 1 / 2
      - H.E.S.S. DL3 public te



- obscore
- Field: target\_name
  - Value: Sco X-1
  - UCD: meta.id;src
- name of target
- select
- pan
- dist
- phot
- draw
- tag
- moc
- spect
- filter
- cross
- X-Y
- rgb
- ASSOC
- crop
- cont
- pixel
- prop
- CDS/P/HGPS

Available data → 26 / 35132

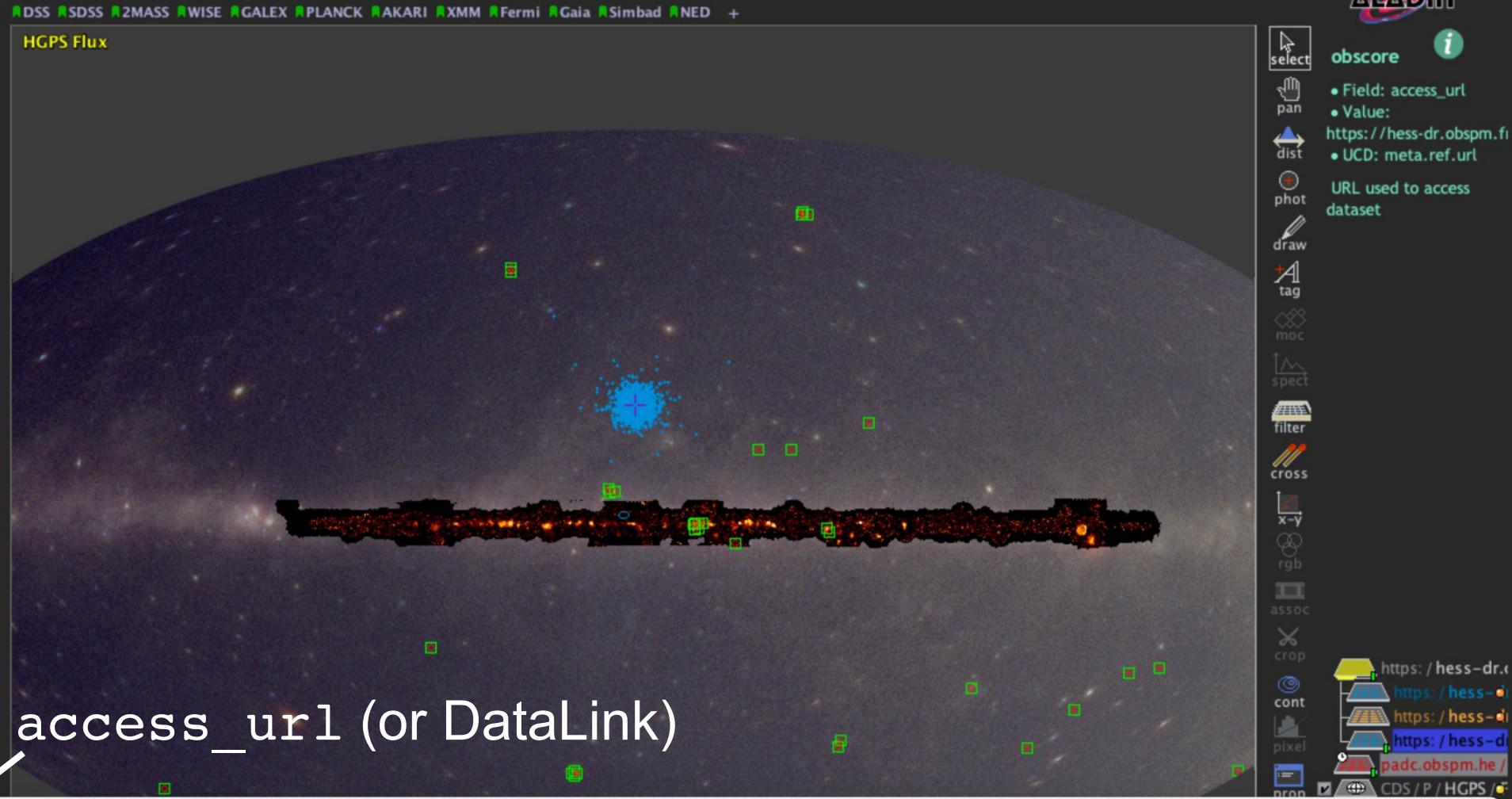
Command 359.6891364258 +24.2208343586

Frame Gal

Projection Aitoff



- ▼ Collections → 26 / 35132
- ▼ Image → 2 / 620
- ▼ Gamma-ray → 2 / 24
- ▼ HESS → 2
  - HGPS significance
  - HGPS integral flux
- Catalog → 20 / 33068
- ▼ Others → 4 / 1262
  - ▼ SSA (spectrum) → 2 / 159
    - padc.obspm.astro → 1 /
      - hess\_ssa
  - ▼ vopdc.obspm → 1 / 3
    - H.E.S.S. High Energy Stereoscopic System
- ▼ TAP (table) → 2 / 220
  - ▼ nasa.heasarc → 1 / 35
    - RHESSI Gamma-Ray Burst Catalog
  - ▼ padc.obspm.he → 1 / 2
    - H.E.S.S. DL3 public test catalog



## IVOA ObsCore access\_url (or DataLink)

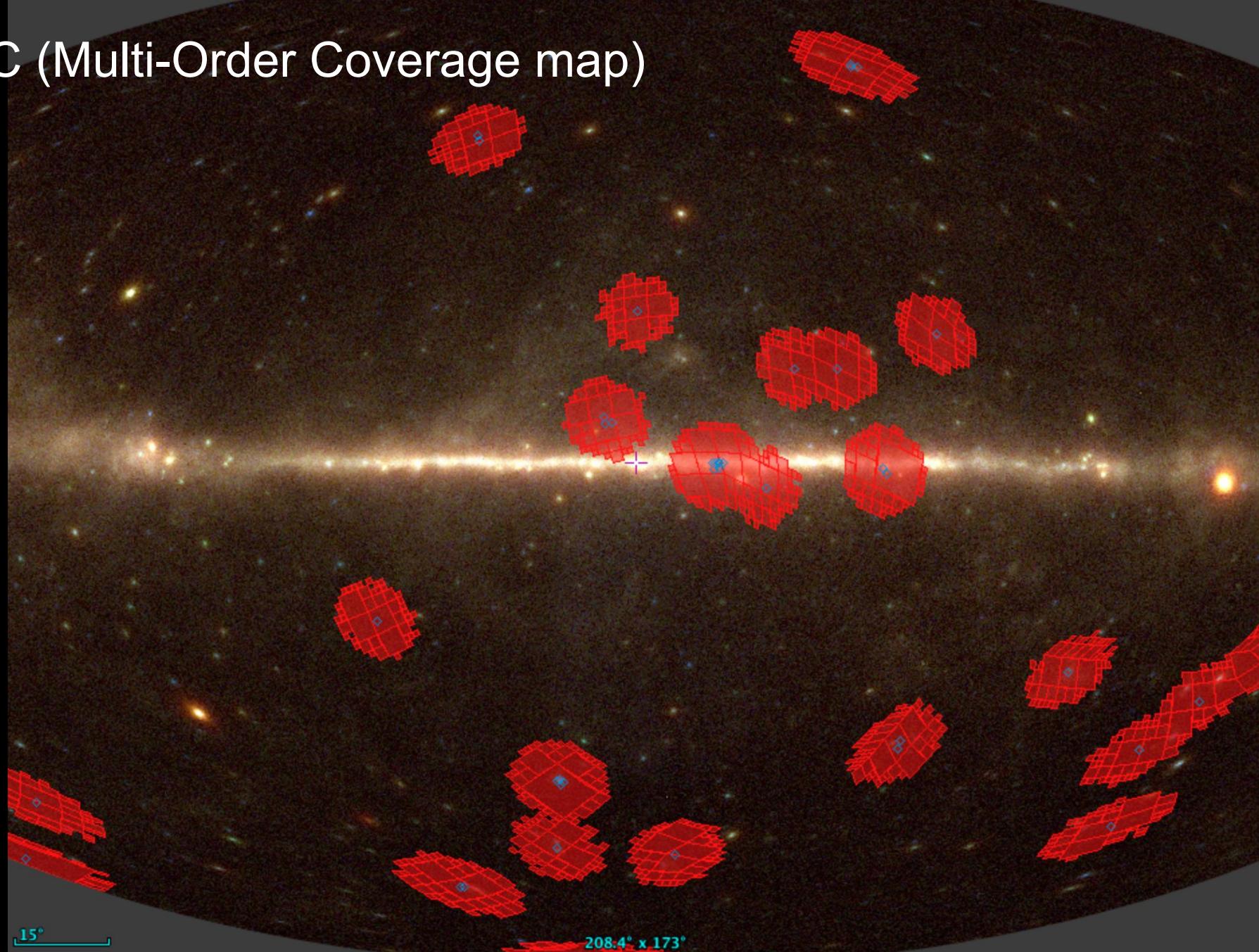
Aladin Java measurements frame

obscore – access\_url: URL used to access dataset

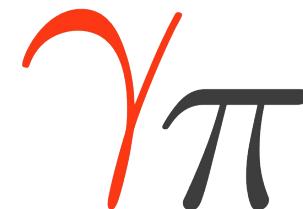
Search  Down Up

access_url	dataproduct_type	dataproduct_sub_id	calib_level	obs_collection	obs_id	obs_publisher_did	access_format	access_estsize	target_name	s_ra	dec
<a href="https://hess-dr.obspm.fr/">https://hess-dr.obspm.fr/</a>	event-list	events	2	HESS-DR	26827	ivo://padc.obspm/hess#...	application/fits	241920	Arp 220	234.5016784667...	-00.0000000000...
<a href="https://hess-dr.obspm.fr/">https://hess-dr.obspm.fr/</a>	event-list	events	2	HESS-DR	26791	ivo://padc.obspm/hess#...	application/fits	172800	Arp 220	233.7383728027...	-00.0000000000...
<a href="https://hess-dr.obspm.fr/retrieve/hess_dl3_dr1_obs_id_026077.fits.gz">https://hess-dr.obspm.fr/retrieve/hess_dl3_dr1_obs_id_026077.fits.gz</a>	event-list	events	2	HESS-DR	26077	ivo://padc.obspm/hess#...	application/fits	239040	Sco X-1	244.9916687011...	-00.0000000000...
<a href="https://hess-dr.obspm.fr/">https://hess-dr.obspm.fr/</a>	event-list	events	2	HESS-DR	25511	ivo://padc.obspm/hess#...	application/fits	233280	3C 273	187.77819824218...	-00.0000000000...
<a href="https://hess-dr.obspm.fr/">https://hess-dr.obspm.fr/</a>	event-list	events	2	HESS-DR	25443	ivo://padc.obspm/hess#...	application/fits	325440	3C 273	187.2778930664...	-00.0000000000...
<a href="https://hess-dr.obspm.fr/">https://hess-dr.obspm.fr/</a>	event-list	events	2	HESS-DR	25345	ivo://padc.obspm/hess#...	application/fits	334080	3C 273	187.2778930664...	-00.0000000000...
<a href="https://hess-dr.obspm.fr/">https://hess-dr.obspm.fr/</a>	event-list	events	2	HESS-DR	23736	ivo://padc.obspm/hess#...	application/fits	259200	SN 1987A	83.86775207519...	-00.0000000000...

# IVOA MOC (Multi-Order Coverage map)



# I = Interoperable



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

A community initiative to define **common data formats for gamma-ray astronomy** based on FITS

<https://vodf.readthedocs.io>

<https://gamma-astro-data-formats.readthedocs.io>

- Includes formats for: event lists, effective area, energy resolution, point spread function, instrumental background...
- More and more used by current instruments: Fermi-LAT, HESS, VERITAS, MAGIC, FACT, ...

**Open-source Python package** (Astropy affiliated package)

- Core library for the Science Tools of CTA
- Used in the analysis of existing gamma-ray instruments, such as H.E.S.S., MAGIC, VERITAS, HAWC...

**FAIR4RS:** FAIR Principles for Research Software  
→ <https://doi.org/10.15497/RDA00065>

[A&A 625, A10, 2019] [A&A 632, A72, 2019] [A&A 632, A102, 2019]

# From F-A-I to FAIR

## F-A-I

- Use the **Virtual Observatory standards**, protocols and services
- Define **community standards** where required
- To be discussed soon in projects, but **technical solutions exist**

## Reusability?

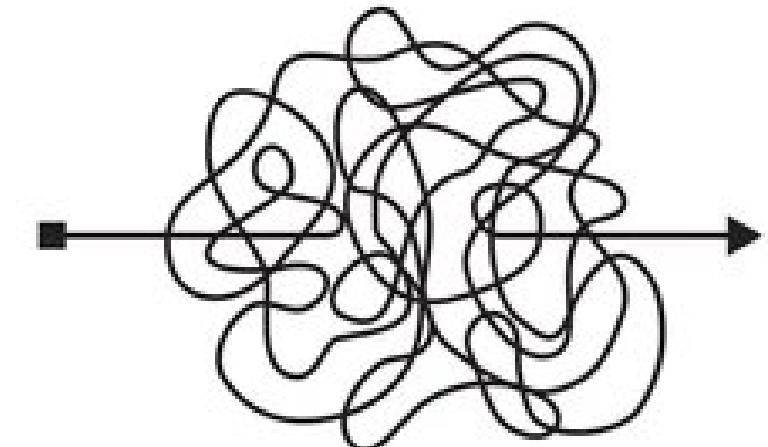
- Based on the **quality / reliability / trustworthiness** of the products
- What calibration was applied? What tools were used and how?  
What assumptions were made during the data preparation?
- **Sustainability:** with time, key information may disappear...

## Provenance information as an answer to reusability

- Need for the **origin, trace**, and detailed manipulations
- Need to **structure** this information
- Need to **keep** it and **link** it to the data

→ **IVOA Provenance standard data model!**

<https://www.ivoa.net/documents/ProvenanceDM/>



# IVOA Provenance Data Model story

<https://wiki.ivoa.net/twiki/bin/view/IVOA/ObservationProvenanceDataModel>

## Meetings

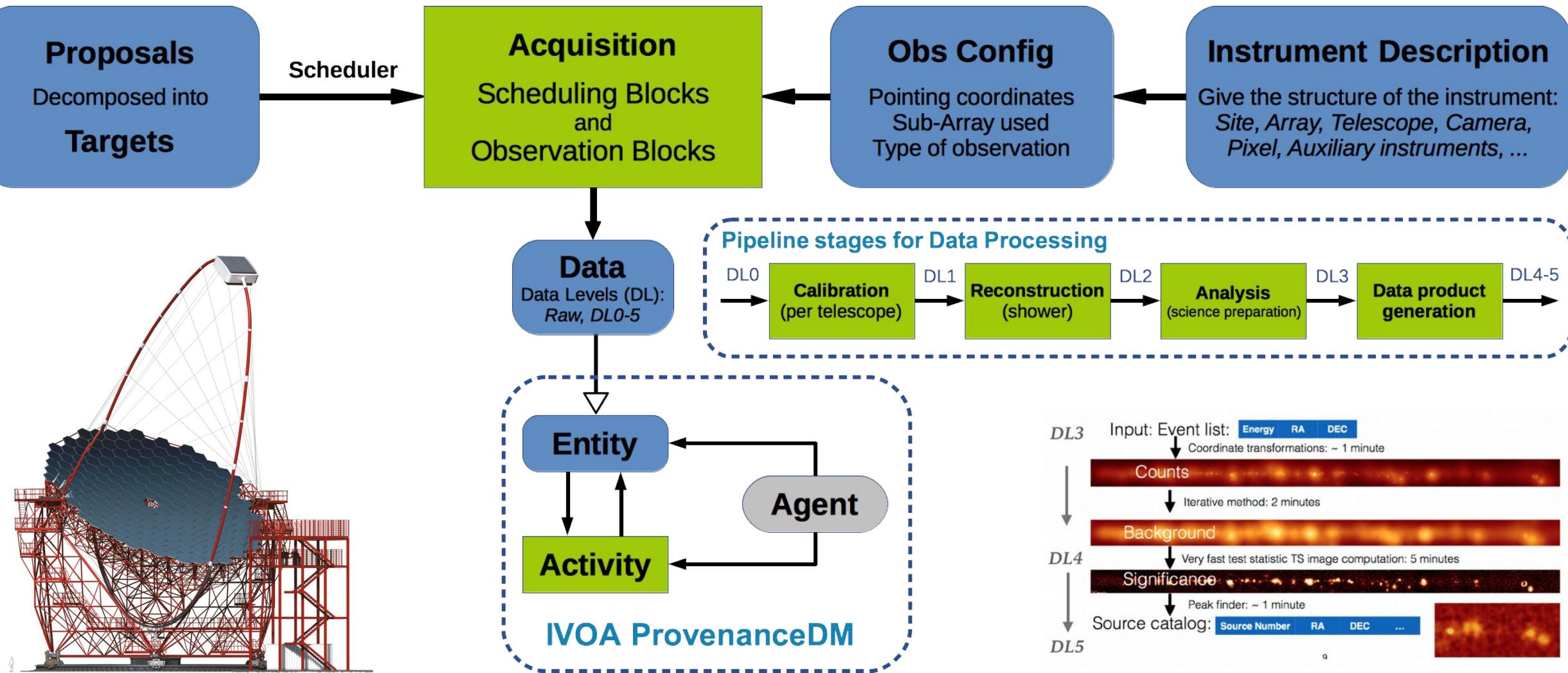
- Provenance discussions at IVOA Interop, May 2019; [Notes](#), [ChangeList](#)
- Provenance discussion for PR update / Asterics focus [ProvFocusAsterics](#) [ProvFocusAstericsExamples](#)
- Provenance meeting, Paris, August 28th - 30th [ProvDayAug2018](#)
- Participation to the [Provenance Week 2018](#), London, 2018, July 9-13 [ProvWeekJuly2018](#)
- Provenance discussions at [InterOp](#) Victoria, 2018, May 28th - June 1st [ProvDiscussionMay2018](#)
- Provenance telecon, 2018, May 2nd, [ProvTeleconMay2018](#)
- Provenance short Meeting in Edinburg during Asterics Tech Forum [see the Asterics Hackathon Page here](#)
- Provenance short Meeting in Postdam , before RDA meeting in Berlin [ProvDayMarch2018](#)
- Provenance meeting, Potsdam, January 18th - 19th [ProvDayJanuary2018](#)
- Provenance discussions at [InterOp](#) Santiago, 2017, October
- Provenance telecon, 2017, September 5th, [ProvTeleconSeptember2017](#)
- Provenance day, Paris, 2017, July 27th afternoon and 28th [ProvDayJuly2017](#)
- Provenance day, Montpellier, 2017, May 3rd afternoon and 4th [ProvDayMay2017](#)
- Provenance meeting, Strasbourg, 2017, March 23rd at the Asterics Tech Forum [ProvDayMarch2017](#)
- Provenance day, Strasbourg, 2016, December 13th [ProvDayDec2016](#)
- Provenance discussions at [InterOp](#) Trieste, 2016, October 16th - 23rd [ProvDiscussionOctober2016](#)
- Provenance telecon, 2016, October 12th [ProvTeleconOctober2016](#)
- Provenance telecon, 2016, September 14th [ProvTeleconSeptember2016](#)
- Provenance day, Paris , 2016, July 20th [ProvDayJuly2016](#)
- Provenance day, Heidelberg , 2016, June 14th [ProvDayJune2016](#)
- Provenance day, Paris , 2016, April 14th [ProvDayApril2016](#)

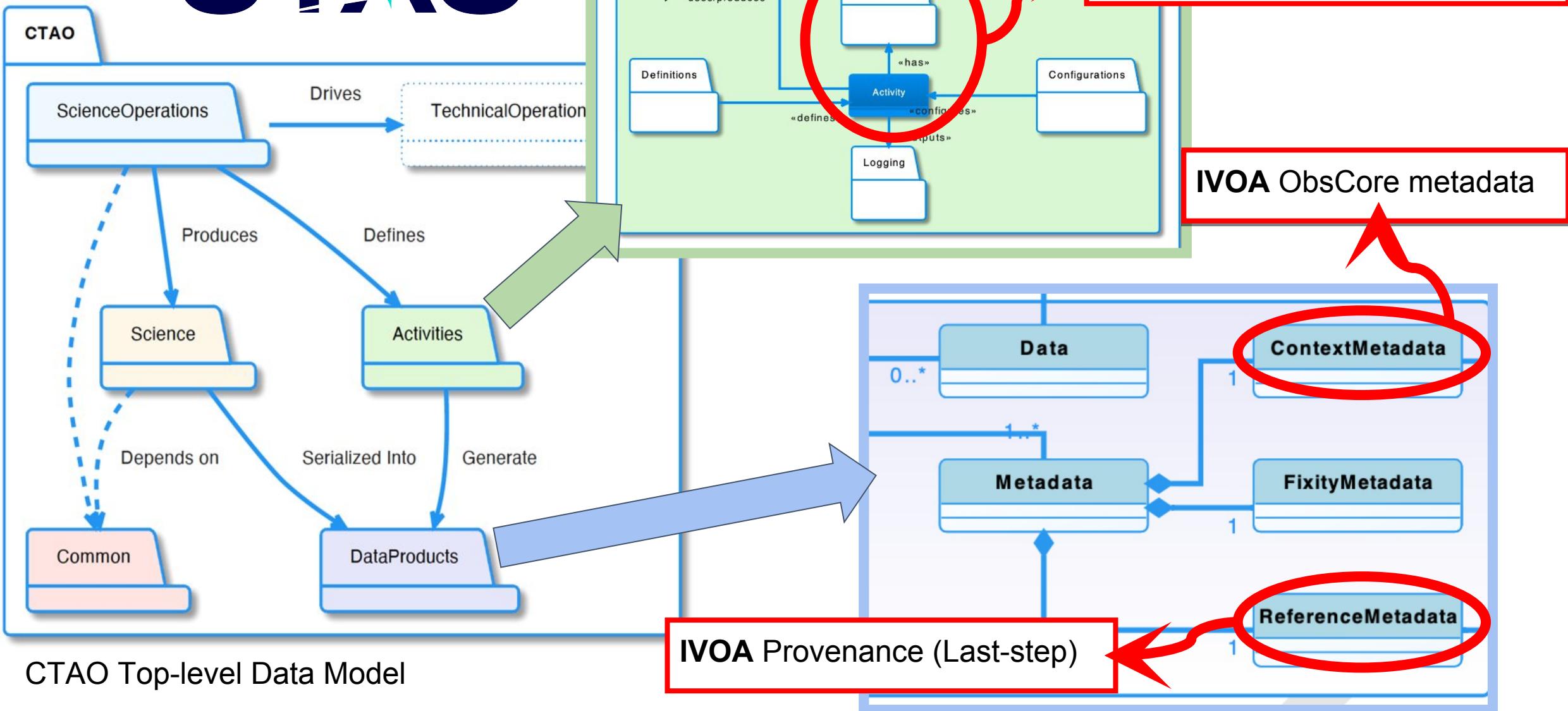


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# CTAO Master Configuration Data Model

Servillat et al. 2019 ([link](#))





# Implementing the IVOA standards

# CTAO web portal prototypes

**CTAO Data Explorer**

Search Results

Object Name (optional): m1

Use SIMBAD  
 Use NED

Coordinate System  
Equatorial (J2000)

RA (J2000) [deg]: 83,6324

Dec (J2000) [deg]: 22,0174

Observation Start (dd/mm/yyyy HH:MM:SS): dd/mm/yyyy HH:MM:SS

Observation End (dd/mm/yyyy HH:MM:SS): dd/mm/yyyy HH:MM:SS

Search Radius [deg]: 5

**Cherenkov Data Explorer**

- FastAPI + React.js using PyVO package
- Metadata hosted by VO compatible DaCHS server

**CTAO Data Explorer**

Sky Map

ICRS 05 34 32.00 +22 00 52.0

33.24° × 12.20°

ALADIN

Search Results

Action	DataLink	dataproduct_type	dataproduct_subtype	calib_level	obs_collection	obs_id	obs_publisher_did	access_url	access_format	access_est	
<input type="checkbox"/>	Add	DataLink	event-list	events	2	HESS-DR	23523	ivo://padc.obspm/hess...	https://platform.cta.cs...	application/fits	285120
<input type="checkbox"/>	Add	DataLink	event-list	events	2	HESS-DR	23526	ivo://padc.obspm/hess...	https://platform.cta.cs...	application/fits	282240
<input type="checkbox"/>	Add	DataLink	event-list	events	2	HESS-DR	23559	ivo://padc.obspm/hess...	https://platform.cta.cs...	application/fits	285120
<input type="checkbox"/>	Add	DataLink	event-list	events	2	HESS-DR	23592	ivo://padc.obspm/hess...	https://platform.cta.cs...	application/fits	273600

Rows per page: 10 ▾ 1-4 of 4 | < < > >|

Logged in as Mathieu Profile Logout

Charts

Timeline EM Range

Observation Timeline

Dec 5 2004 Dec 6 Dec 7 Dec 8 Dec 9 Time

# Online data analysis in the VO

**OPUS**

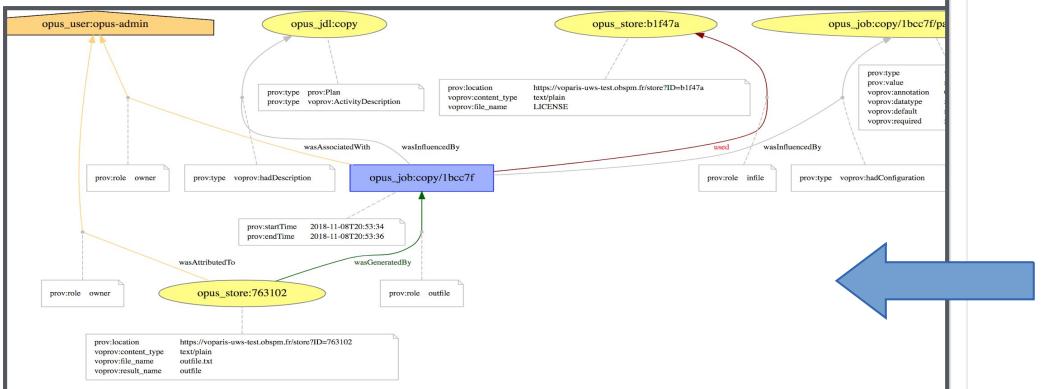
Job Definition Job List

Job List for **gammapy\_spectra**

Type	Start Time	Destruction Time	Phase
gammapy_spectra	2017-10-02 10:47:07	2017-11-01 10:47:05	COMPLETED
gammapy_spectra		2017-11-01 10:47:03	PENDING
gammapy_spectra	2017-09-29 15:07:52	2017-10-29 15:07:51	COMPLETED
gammapy_spectra	2017-09-29 14:55:10	2017-10-29 14:55:09	ABORTED
gammapy_spectra	2017-09-29 14:21:20	2017-10-29 14:21:19	COMPLETED

**OP UWS Service (OPUS at Observatoire de Paris)**

- Flask/Bottle.py, Bootstrap, SLURM cloud
- <https://voparis-uws-test.obspm.fr> – [ADASS XXX proceedings]
- Based on **IVOA UWS** (Universal Worker Service Pattern)
- Connection to **IVOA Provenance**



**Details**

Properties Parameters **Results** (Red Circled)

**Control**

Start Abort Delete

**Job Results**

spectrum: Download [image/fits]  
spectrum\_preview: Download [image/png]

**Figure**

Plot of  $dnde / (cm<sup>-2</sup> s TeV)$  vs Energy [TeV]. The plot shows a power-law decay with residuals below zero.

**Thank you for your attention !**