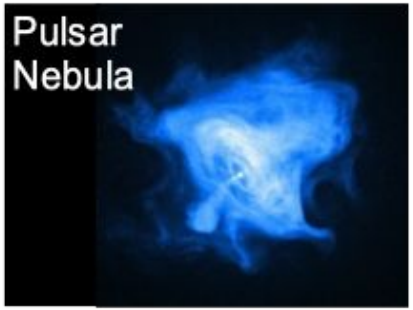
High Energy data in the Virtual Observatory

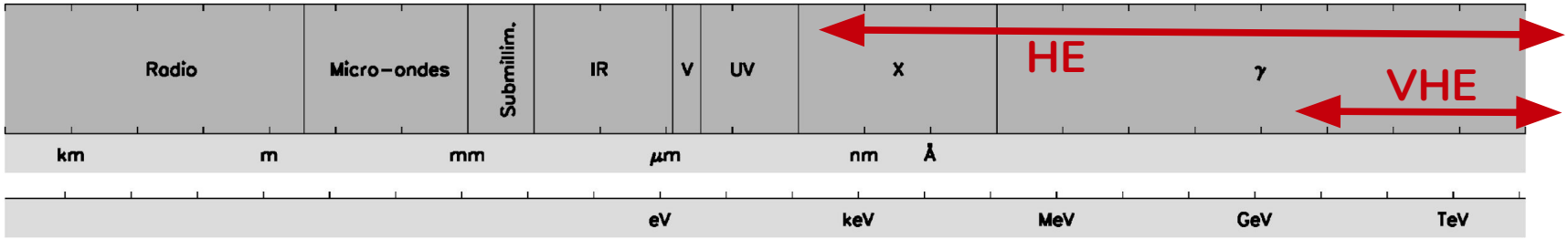
Mathieu Servillat (LUTH - Observatoire de Paris / CNRS - CTAO)
with work at the IVOA HE Club
with work during several European projects

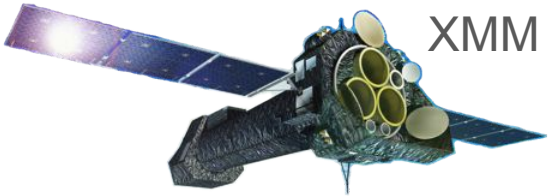
ASOV Strasbourg
2024-03-18



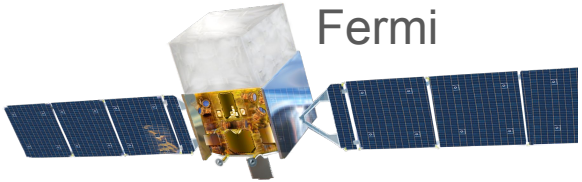
- Violent, transient, non-thermal phenomena
- Matter under extreme conditions
- Particle Acceleration
- Fundamental Physics
- Role of Black Holes in the structuration of the Universe

High Energy Astrophysics



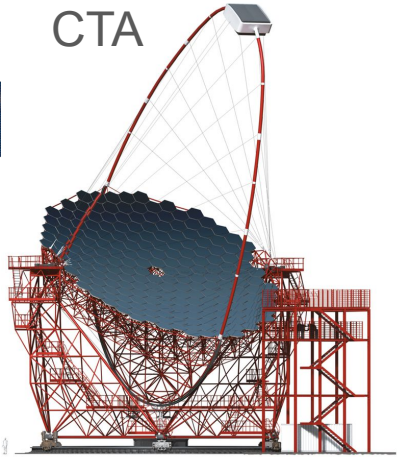


XMM

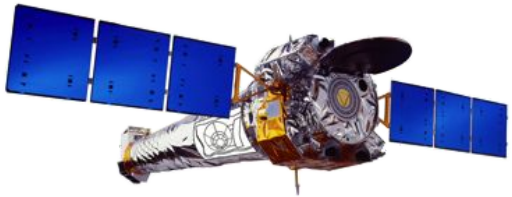


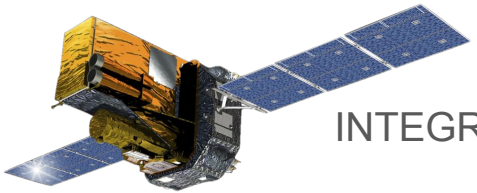
Fermi

CTA



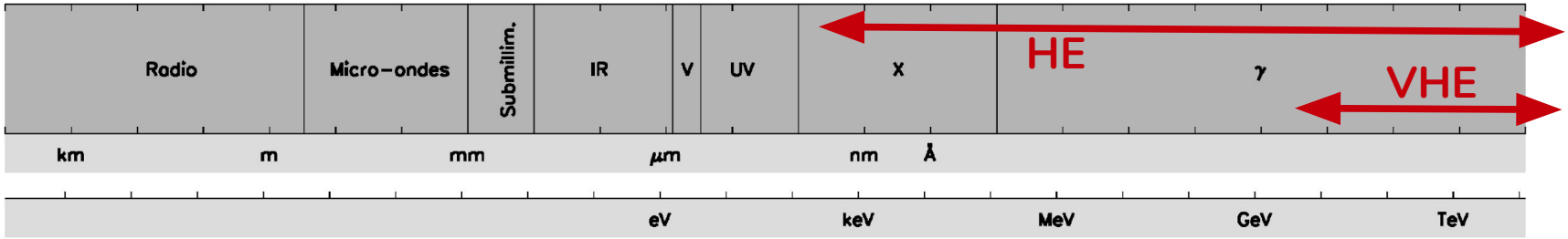
Chandra





INTEGRAL

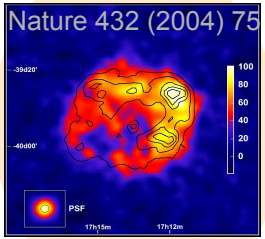
High Energy Astrophysics



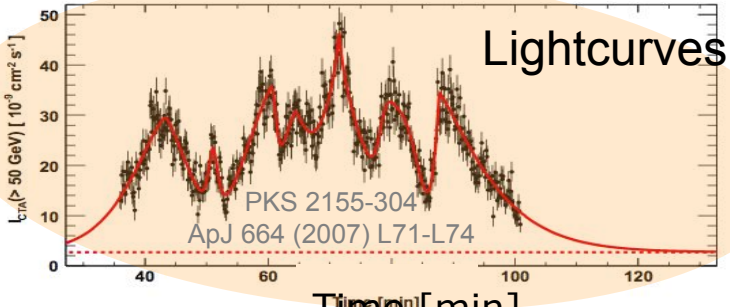
Several orders of magnitude - Event **counting** - Low count **statistics** - High background

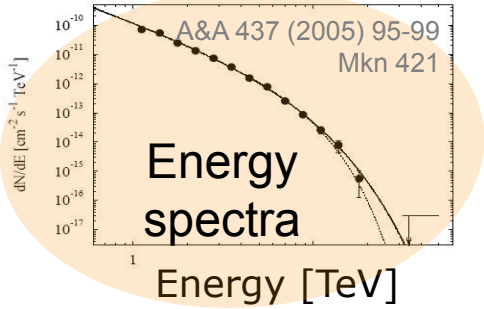
→ **Event lists** (coordinates, time, energy)

RX J1713.7-3946
Nature 432 (2004) 75



Images



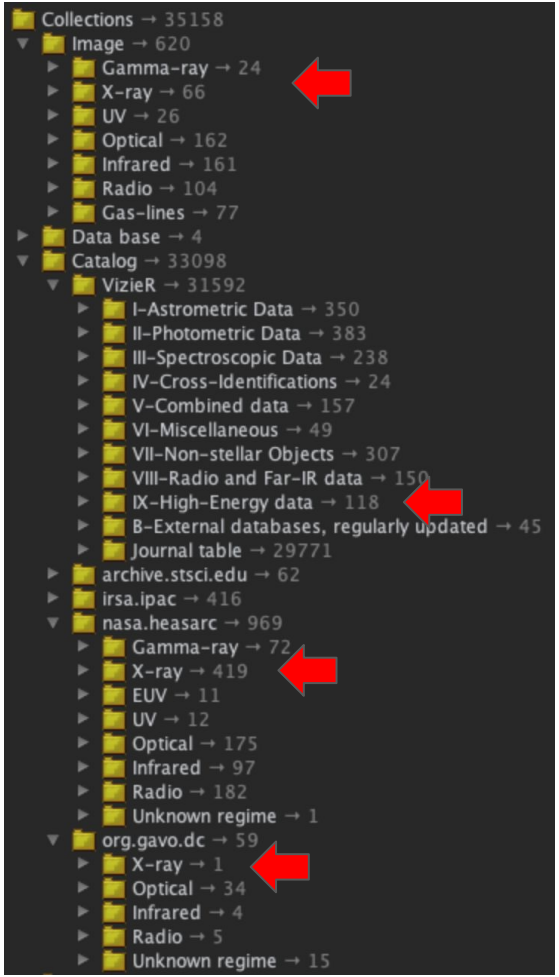


+ **multi-messenger data** (photons, cosmic rays, neutrinos, gravitational waves...)

Current High Energy data in the VO

- Images
  - Fermi Full Sky, eRosita, XMM-Newton, H.E.S.S. galactic plane
- Catalogs
  - Vizier dedicated section
  - NASA HEASARC (many legacy archives)
  - Generally catalogs of sources
- SIA/TAP services
  - High level data, catalogs, proposals, …

Aladin Search Tree



CHANDRA SOURCE CATALOG
Table Access Protocol

IVOA

XMM-Newton Science Archive
TAP queries to the XSA database

NASA's HEASARC
High Energy Astrophysics Science Archive Research Center

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

H.E.S.S.

cta cherenkov telescope array

EURO VO CoSADIE Collaborative and Sustainable Astronomical Data Infrastructure for Europe

2012-2014

Asterics Astronomy ESFRI & Research Infrastructure Cluster

2015-2019

ESCAPE European Science Cluster of Astronomy & Particle physics ESFRI research Infrastructures

2019-2023

Cherenkov Astronomy

MAGIC: located in La Palma, Spain
Since 2004: single 17m telescope
Since 2009: system of two 17m telescopes

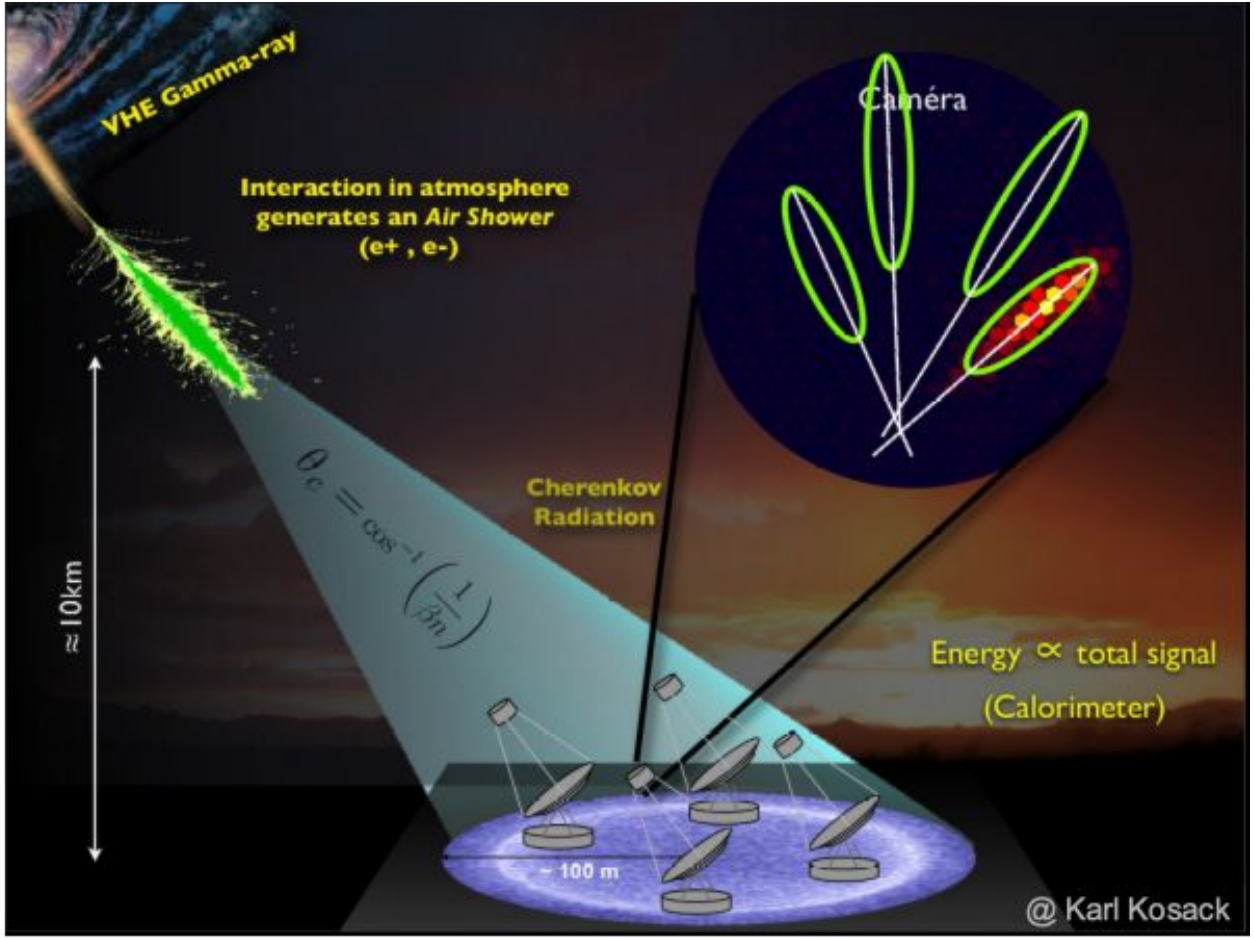
VERITAS: located in Mt Hopkins, Arizona
Since 2007: four 12m telescopes
Since 2012: upgraded PMTs

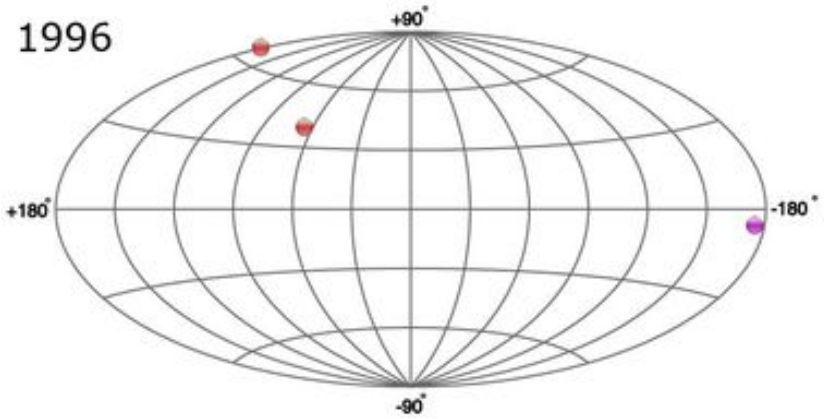
H.E.S.S.: located in Khomas Higlands, Namibia
Since 2002: four 12m telescopes
Since 2012: added 32m by 24m telescope
Since 2015: camera upgrades on 12m telescopes

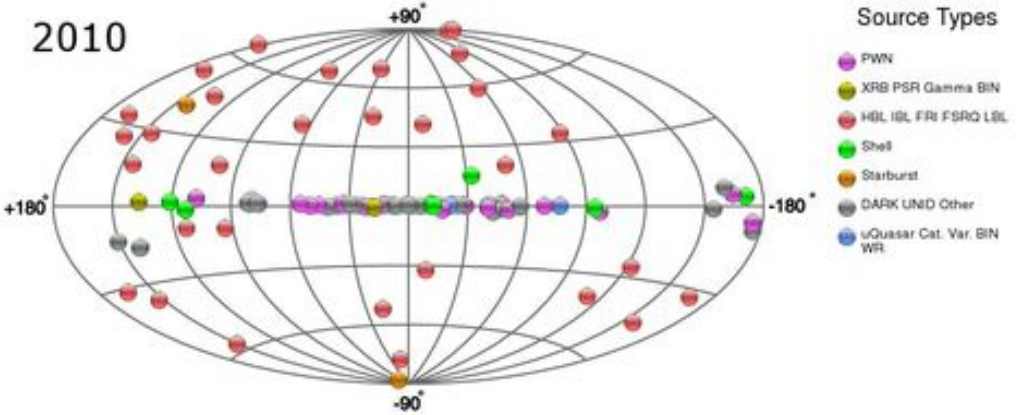
@ Jeff Grube

Cherenkov Astronomy Principles

- **Dark nights** (small duty cycle)
- **Event Reconstruction**: photon, particle shower, Cherenkov light (faint, few nanoseconds)
- **Atmosphere** = calorimetre Simulations, assumptions
- **Complex Metadata**, need to be structured

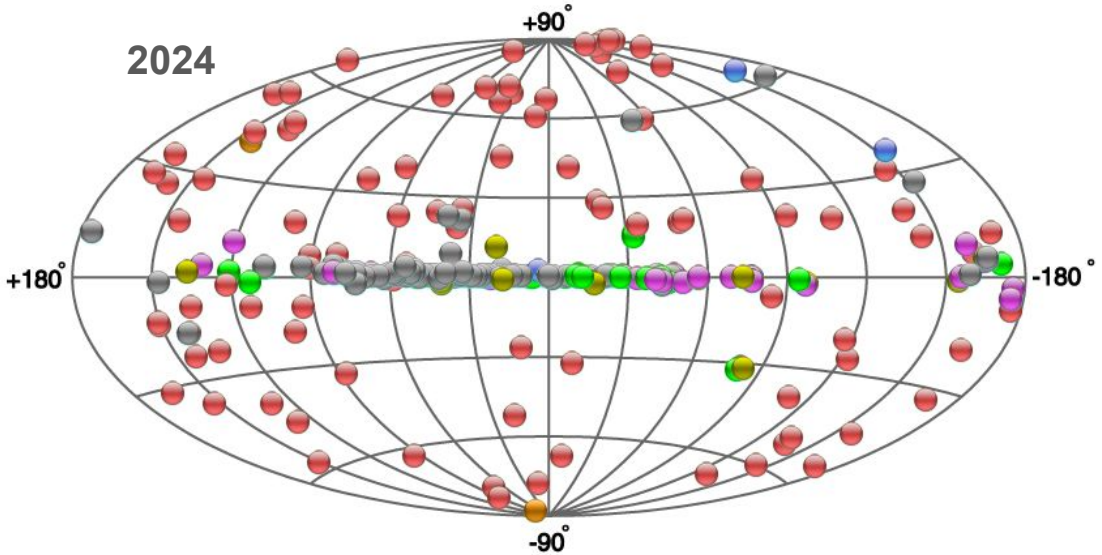


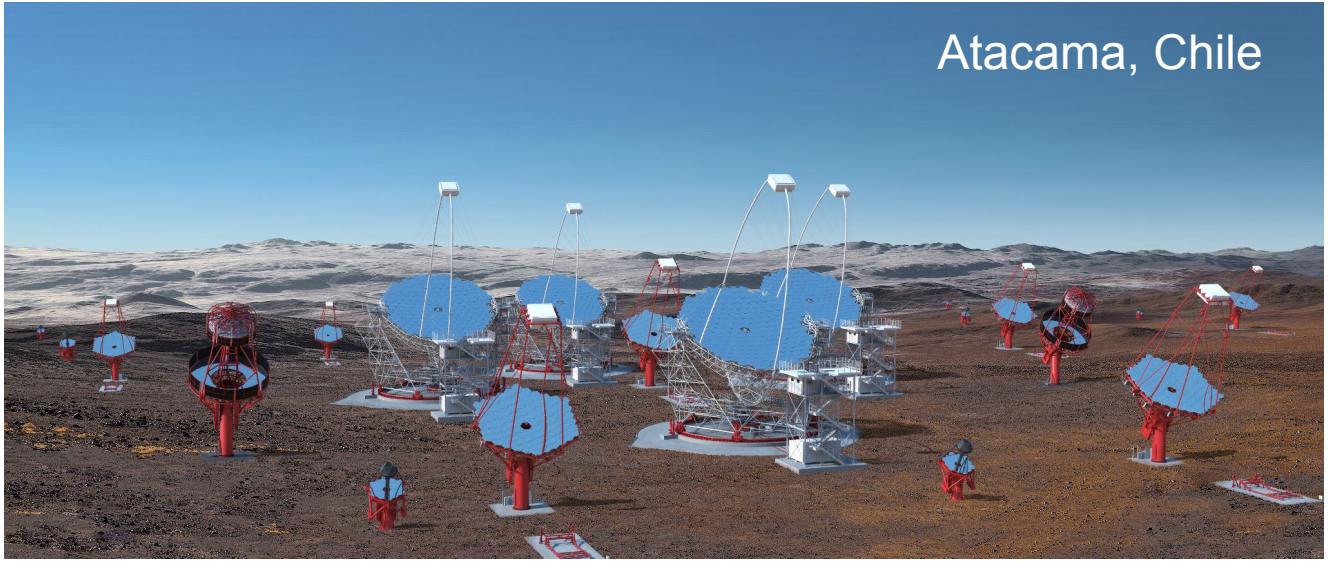




TeVCat2
http://tevcat2.uchicago.edu/

H.E.S.S., MAGIC, VERITAS
> 200 sources
energy > 100 GeV





Alpha configuration

CTAO Southern array

51 telescopes over a ~3 km2 area

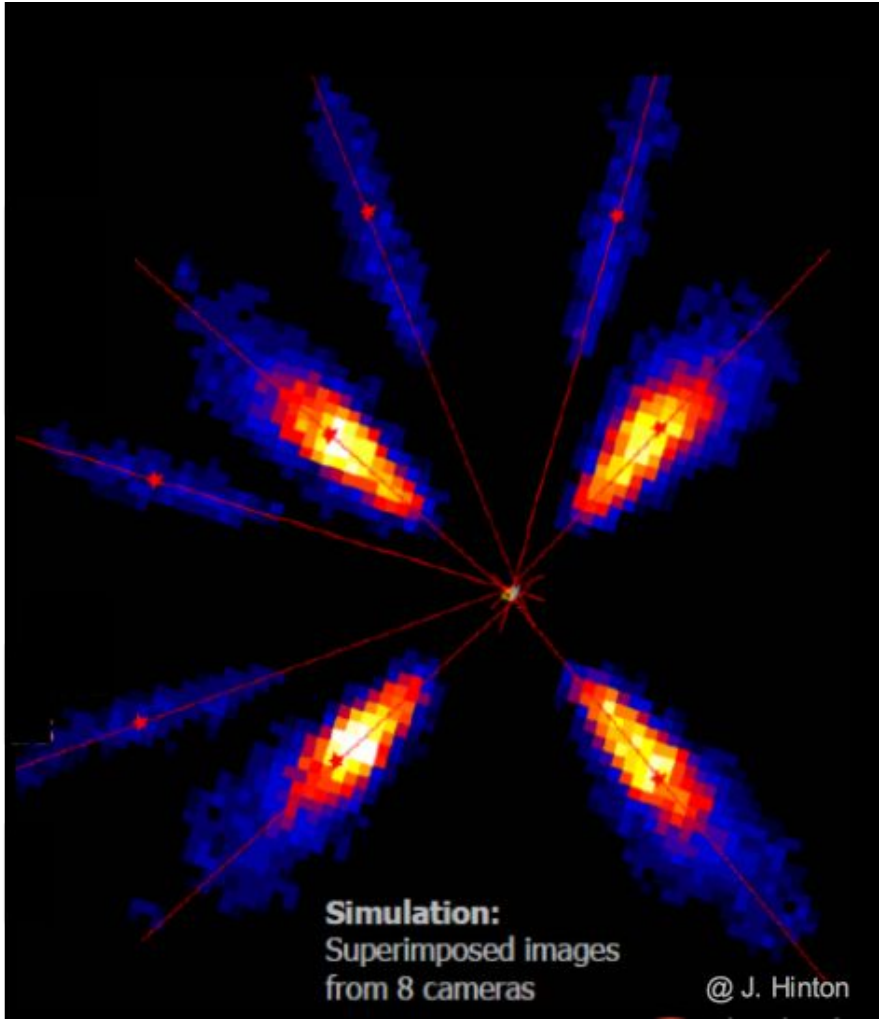
14 Medium-Sized Telescopes (MST)
37 Small-Sized Telescopes (SST)

CTAO Northern array

13 telescopes distributed over an area of about 0.5 km2

4 Large-Sized Telescopes (LSTs)
9 Medium-Sized Telescopes (MSTs)

- **Larger** collection area for gamma-rays
  - More events, more photons
  - Better spectra, images, fainter sources
- **Better** events
  - More precise measurements of atmospheric cascades and hence primary gammas
  - Improved angular resolution
  - Improved energy resolution
  - Improved background rejection power



CTA Master Configuration Data Model

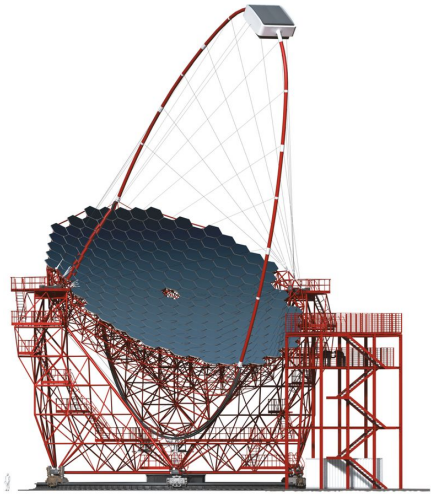
Proposals
Decomposed into
Targets

Scheduler

Acquisition
Scheduling Blocks
and
Observation Blocks

Obs Config
Pointing coordinates
Sub-Array used
Type of observation

Instrument Description
Give the structure of the instrument:
Site, Array, Telescope, Camera, Pixel, Auxiliary instruments, ...

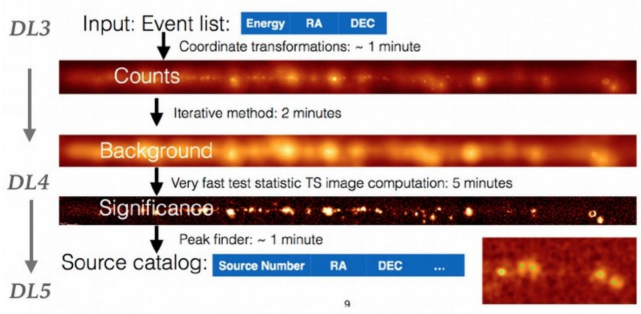


Data
Data Levels (DL):
Raw, DL0-5

Pipeline stages for Data Processing

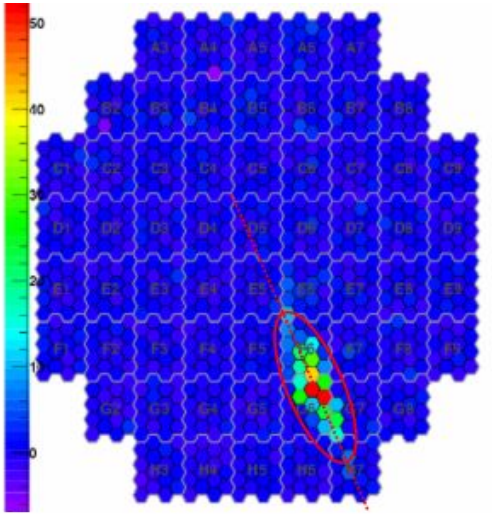
DL0 → **Calibration** (per telescope) → DL1 → **Reconstruction** (shower) → DL2 → **Analysis** (science preparation) → DL3 → **Data product generation** → DL4-5

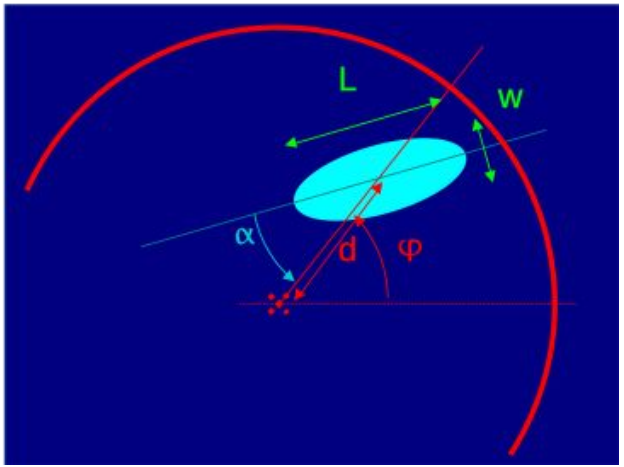
Entity
Agent
Activity
IVOA ProvenanceDM



Reconstruction phase

- **Hillas Parameters** (1984)
  - Shower images are **elliptical**
  - A **few** parameters:
    - Length (L) & Width (W)
    - Nominal Distance (d)
    - Azimuthal angle (φ)
    - Orientation angle (α)
    - Amplitude (size)
  - Additional parameters: asymmetry, …
- **Advanced methods**
  - 3D model
  - Fit to simulated images



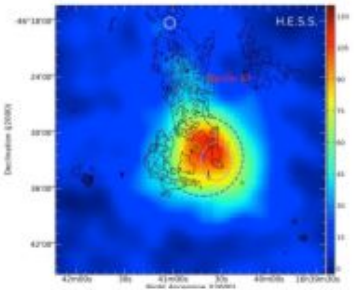


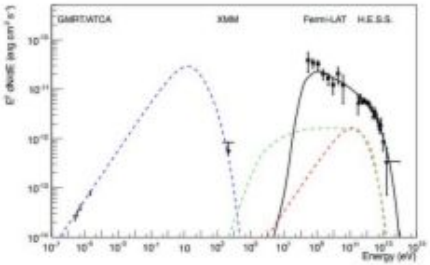
Analysis: producing images, spectra, light-curves

- Event lists (not necessarily gamma-rays!)
- Instrument Response Function
- TECH tables: atmosphere and data-quality measurements, → good time intervals, ...

- **Background dominated**
  - Even after stereo-reconstruction, hadron rejection is not 100% efficient
  - Therefore we can only talk **statistically** about gamma rays!
  - Use **likelihood** methods: model background, source assumption, Poisson statistics...
- **Source confusion**
  - Large PSF
  - Many sources are not point-like

t	RA	Dec	az	alt	E
501	128.2	-37.1	321.1	45	0.112
600	130.23	-36.2	322.1	45.1	0.242
620	120.124	-33.33	312	45.7	0.434
640	121.1	-34.1	323.4	43.0	35.0
720	123.23	-28.1	322.1	43.5	0.401
900	100.0	-31.2	32.2.	45.3	1.23
..	..	..		..	..
..	..	..		..	..

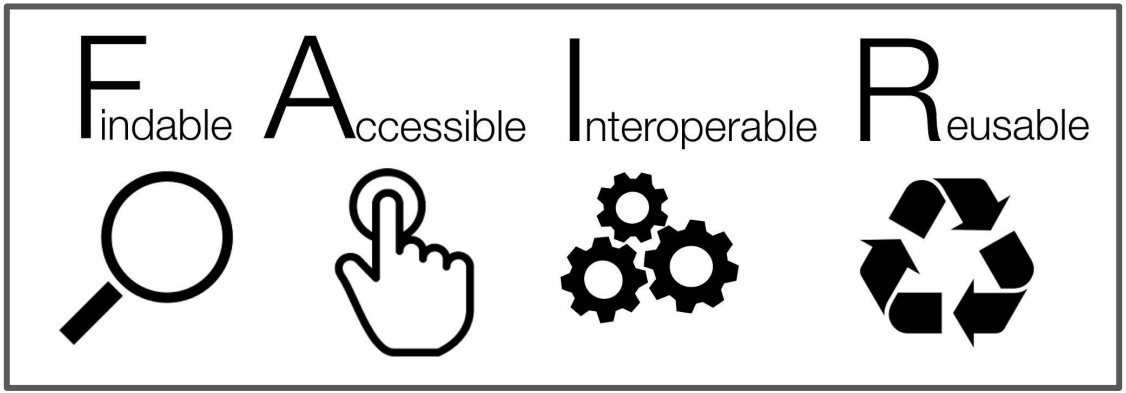




Open Observatory and Open Science

CTA will operate as an **open observatory** and will provide data to the scientific community. In the context of **Open Science**, the data provided by CTA must follow the **FAIR Guiding Principles** for scientific data management:

cherenkov telescope array



See e.g. Servillat et al. 2022, ADASS XXXI, ASP Conference Series
"FAIR high level data for Cherenkov astronomy"
https://hal-obspm.ccsd.cnrs.fr/obspm-03516688

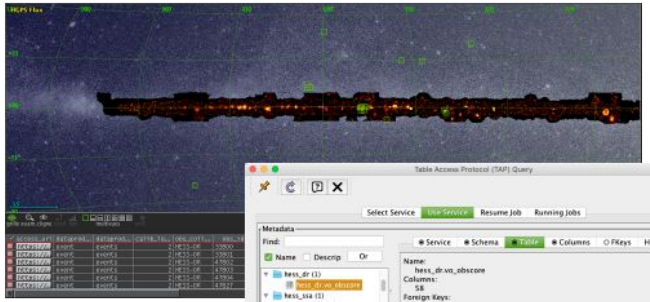
F = Findable

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

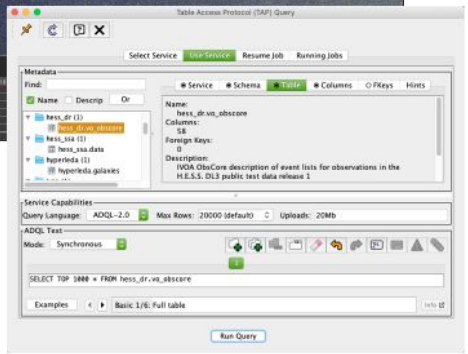
- **IVOA** Observation Data Model Core Components (**ObsCore**)
  [link to IVOA REC] → adapted to Cherenkov data
- **IVOA** Table Access Protocole (**TAP**)
  [link to IVOA REC]
- **Deployed service** at ObsParis
  https://hess-dr.obspm.fr
- Registered to the VO **Registry** via PADC
  (Paris Astronomical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

→ **Data widely findable**
e.g. Aladin, TOPCAT, TapHandle, PyVO…
+ dedicated web pages

TapHandle



Aladin



TOPCAT

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

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								kbyte	deg	deg	deg
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EVENTS	2	AGN monitoring	513839	DL3	ivo://ctao#<internal_id>	URL<internal_id>	application/fits	1785	356.2607	-16.4372	0.0
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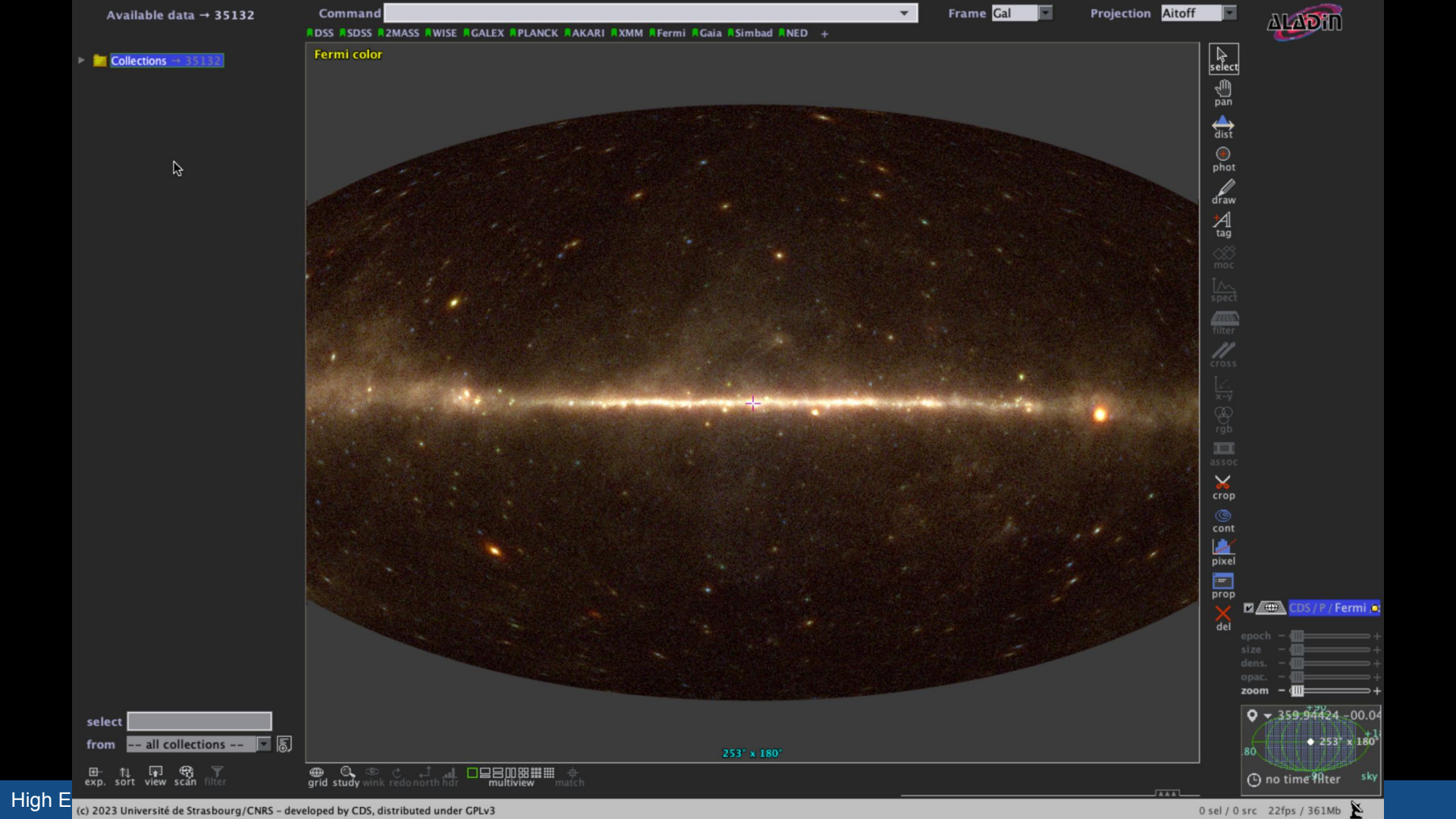
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Frame Gal
Projection Aitoff
DSS SDSS 2MASS WISE GALEX PLANCK AKARI XMM Fermi Gaia Simbad NED +
Collections → 35132
Fermi color
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253° x 180°
no time filter
sky
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from -- all collections --
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(c) 2023 Université de Strasbourg/CNRS - developed by CDS, distributed under GPLv3
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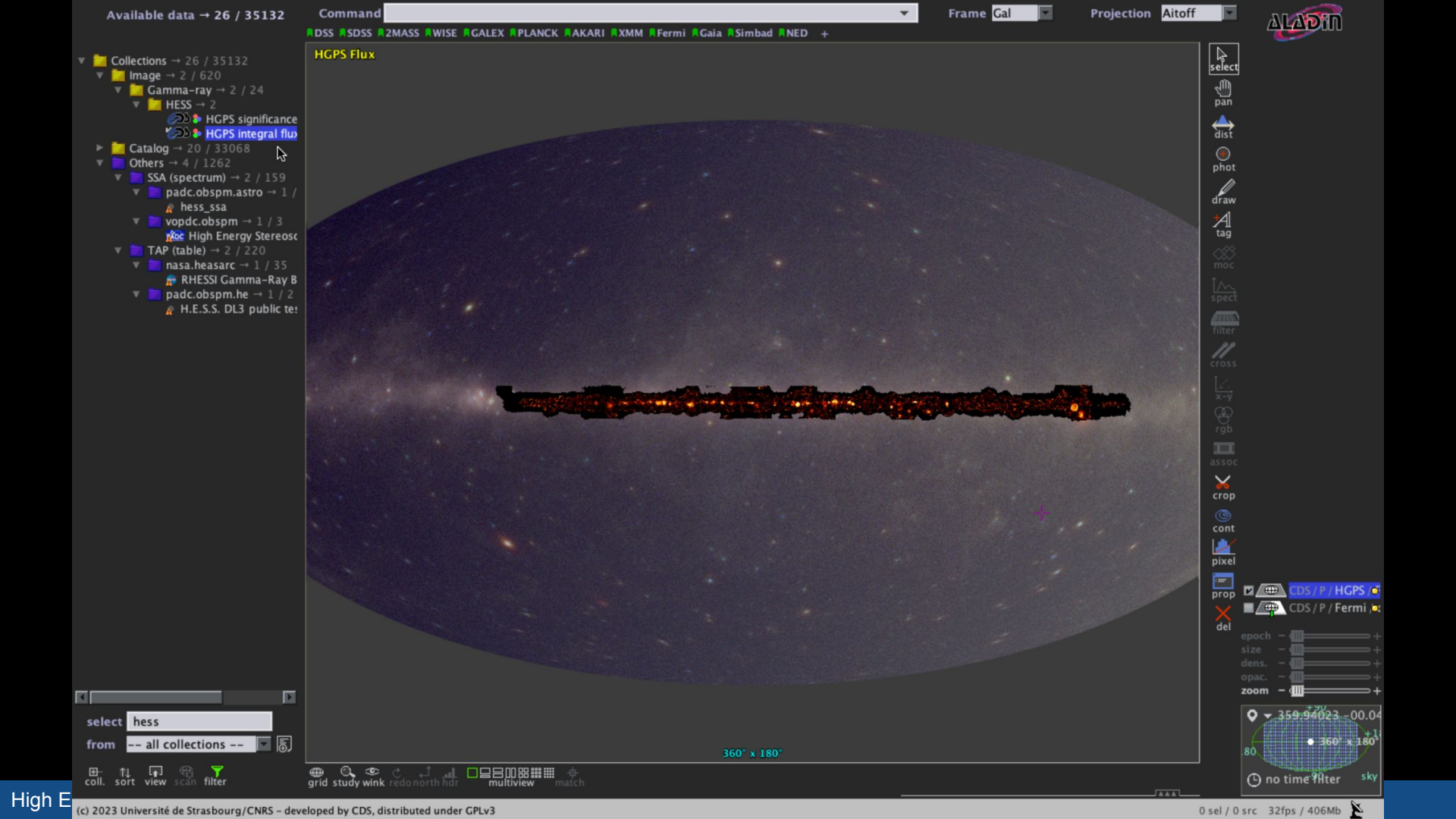
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Command
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Projection Aitoff
DSS SDSS 2MASS WISE GALEX PLANCK AKARI XMM Fermi Gaia Simbad NED
HGPS Flux
Collections → 26 / 35132
Image → 2 / 620
Gamma-ray → 2 / 24
HESS → 2
HGPS significance
HGPS integral 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
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CDS / P / HGPS
CDS / P / Fermi
epoch size dens. opac. zoom
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no time filter sky
(c) 2023 Université de Strasbourg/CNRS – developed by CDS, distributed under GPLv3
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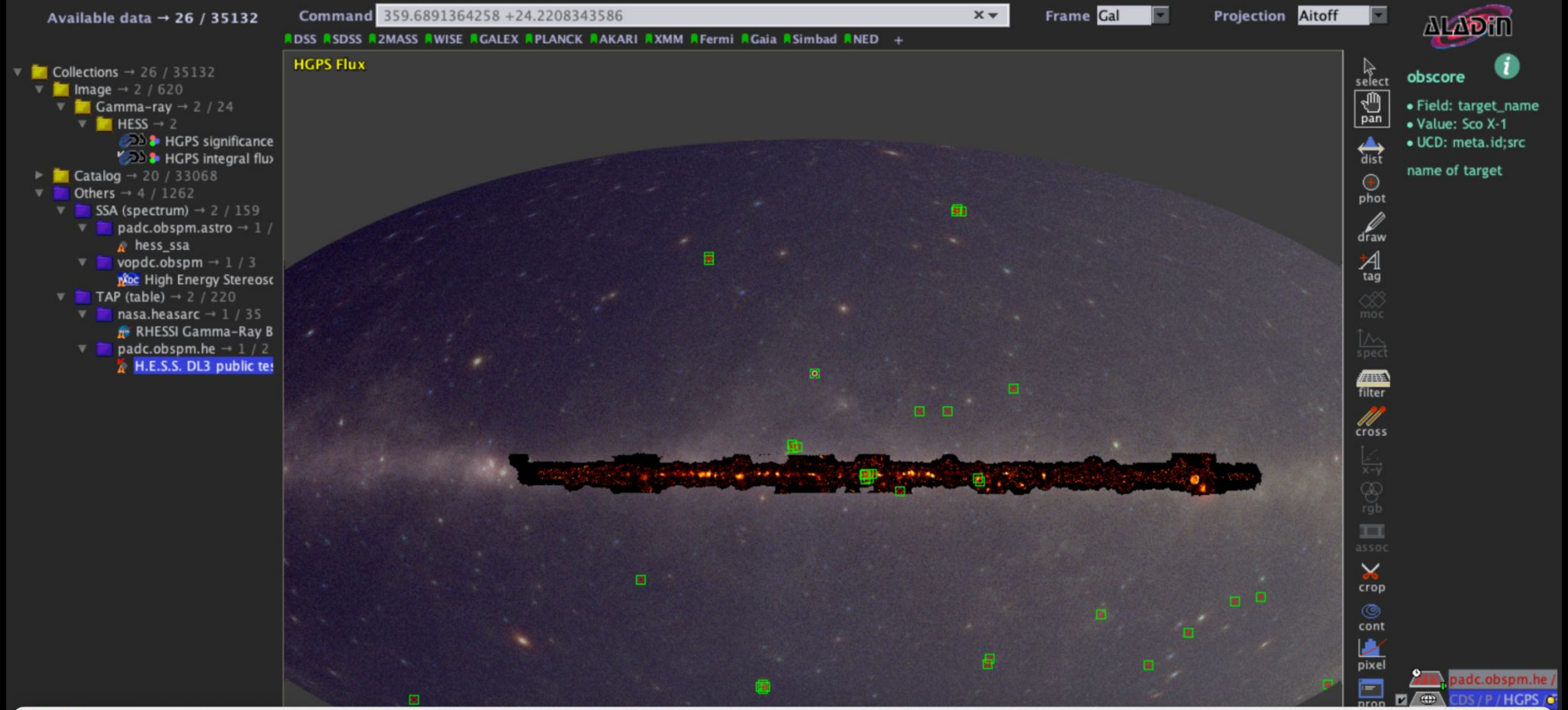

Aladin Java measurements frame

obscore – target_name: name of target

Search

access_url	dataproduct_type	dataproduct_sub...	calib_level	obs_collection	obs_id	obs_publisher_did	access_format	access_estsi...	target_name	s_ra	s
https://hess-dr.obspm.fr/	event-list	events	2	HESS-DR	26827	ivo://padc.obspm/hess#...	application/fits	241920	Arp 220	234.5016784667...	
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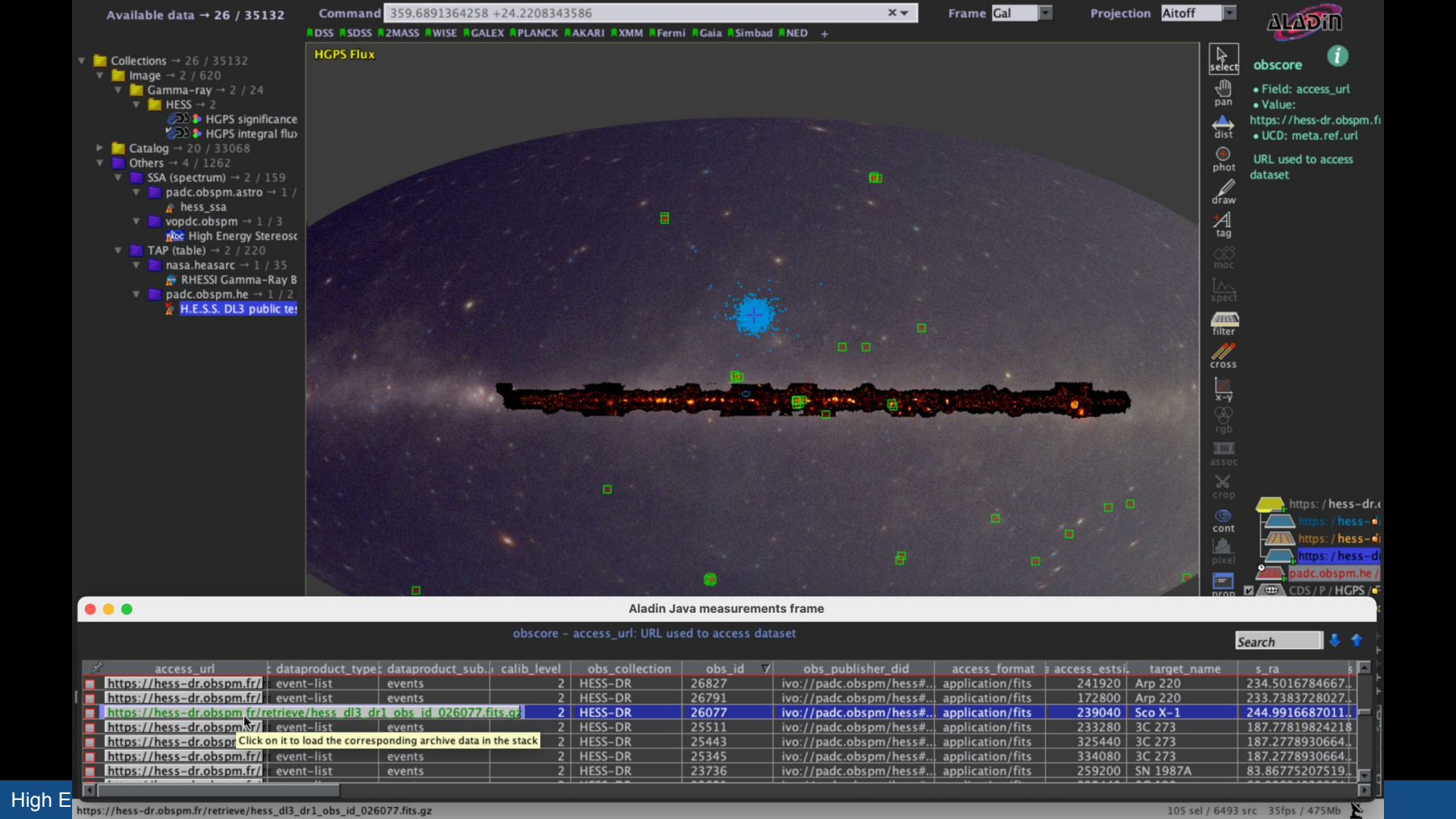
https://hess-dr.obspm.fr/	event-list	events	2	HESS-DR	25345	ivo://padc.obspm/hess#...	application/fits	334080	3C 273	187.2778930664...	
https://hess-dr.obspm.fr/	event-list	events	2	HESS-DR	23736	ivo://padc.obspm/hess#...	application/fits	259200	SN 1987A	83.86775207519...	

105 sel / 105 src 872Mb

High E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DSS SDSS 2MASS WISE GALEX PLANCK AKARI XMM Fermi Gaia Simbad NED
HGPS Flux
Collections → 26 / 35132
Image → 2 / 620
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nasa.heasarc → 1 / 35
RHESSI Gamma-Ray B
padc.obspm.he → 1 / 2
H.E.S.S. DL3 public te
select
pan
dist
phot
draw
tag
moc
spect
filter
cross
x-y
rgb
assoc
crop
cont
pixel
prop
obscore
• Field: access_url
• Value:
https://hess-dr.obspm.fr
• UCD: meta.ref.url
URL used to access dataset
Aladin Java measurements frame
obscore – access_url: URL used to access dataset
Search
access_url
dataproduct_type
dataproduct_sub.
calib_level
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obs_id
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access_estsi.
target_name
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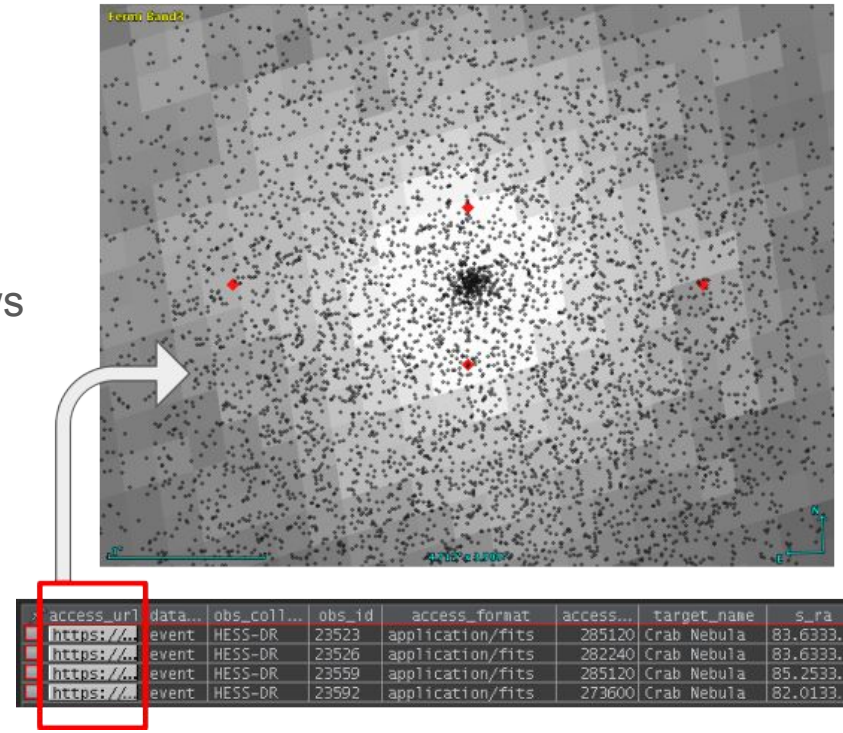
https://hess-dr.obspm.fr/retrieve/hess_dl3_dr1_obs_id_026077.fits.gz 2 HESS-DR 26077 ivo://padc.obspm/hess#.. application/fits 239040 Sco X-1 244.9916687011
https://hess-dr.obspm.fr/ event-list events 2 HESS-DR 25511 ivo://padc.obspm/hess#.. application/fits 233280 3C 273 187.7781924218
https://hess-dr.obspm.fr/ event-list events 2 HESS-DR 25443 ivo://padc.obspm/hess#.. application/fits 325440 3C 273 187.2778930664
https://hess-dr.obspm.fr/ event-list events 2 HESS-DR 25345 ivo://padc.obspm/hess#.. application/fits 334080 3C 273 187.2778930664
https://hess-dr.obspm.fr/ event-list events 2 HESS-DR 23736 ivo://padc.obspm/hess#.. application/fits 259200 SN 1987A 83.86775207519
Click on it to load the corresponding archive data in the stack
https://hess-dr.obspm.fr/retrieve/hess_dl3_dr1_obs_id_026077.fits.gz
105 sel / 6493 src
35fps / 475Mb
High E

A = Accessible

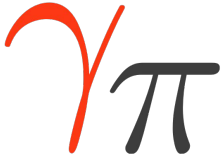
- ObsCore `access_url`
  - Direct download link to the FITS file
- IVOA **DataLink** (to be implemented):
  - Access to different storage services
  - Access to analysis services, previews
- **Access rights**
  - Public data: no restrictions
  - Anticipating need for **permissions**:
    - PI proprietary period
    - Federation authentication
  - e.g. IAM ESCAPE service

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



access_url	data...	obs_coll...	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

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 an more used by current instruments: Fermi-LAT, HESS, VERITAS, MAGIC, FACT, ...

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

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

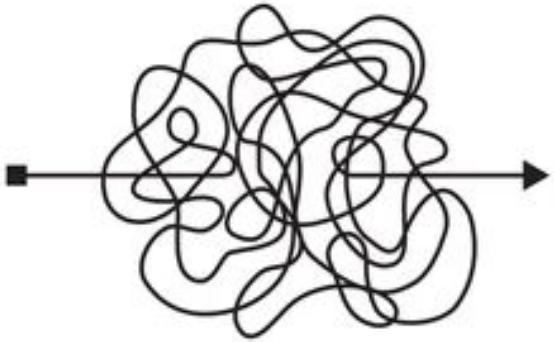
From F-A-I to FAIR

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?

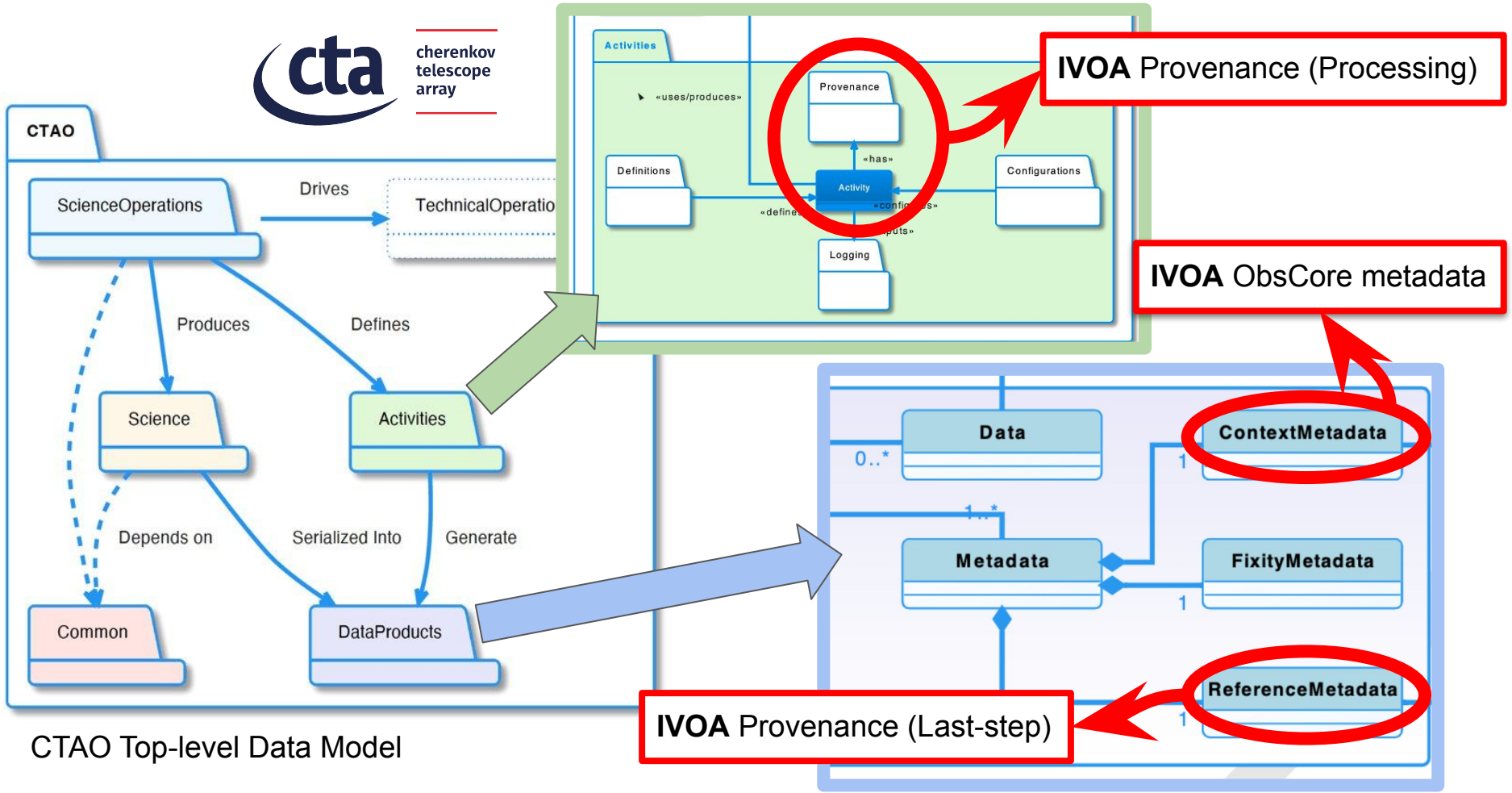
- Based on the **quality** / **reliability** / **trustworthiness** of the products
- What calibration was applied? What tools were used and how?
  What assumptions were made during the data preparation?
- **Sustainability**: with time, key information may disappear...



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!**



CTAO Top-level Data Model

A long way…

- Interactions between observatories and the IVOA
  - Astronomers and engineers need to be part of IVOA
  - They then need to convince their organisation!
  - And maintain the momentum!
- Early engagement of observatories/facilities
  - Construction and operations = different priorities
  - Seeds in the CTA requirements and data models
  - CTAO involved in ESCAPE open collab., OSTrails…
  - Role of European Projects
  - Role of **OV-France**

HE dedicated workshop at OV-France

- **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/IntropMay3023DM/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
  - Next call: **April 3rd 16h30**

Second OV-France workshop enlarged to IVOA

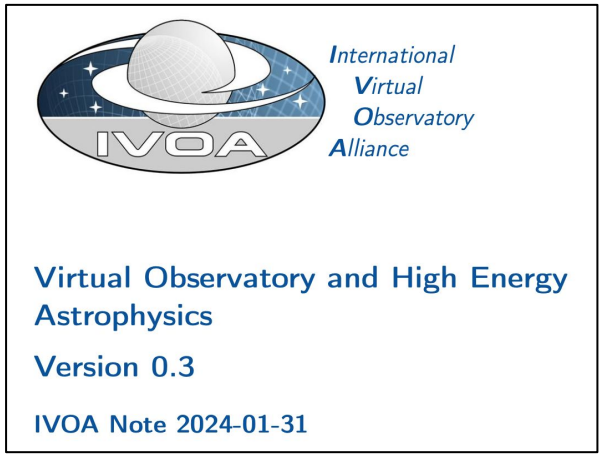
- **June 2023 in Paris**
  - *IVOA standards for High Energy Astrophysics*
  - https://indico.obspm.fr/event/1963

- Review of previous 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

Content of the Note

- Common practices and concept of event-list
  - **Lower level** dataset, used to generate images, lightcurves, spectra
  - Generally **reprocessed** from **event lists** for a dedicated analysis
  - Calibrated data, but instrument signature not totally removed
  - **Instrument Response Functions** (**IRFs**) are tightly connected
- Data Discovery
  - **ObsCore** for a HE event list?
  - Possible extension for HE
- An event-ist context data model
  - **Relations** to IRF and Instrument Configuration
- Modelling the content of an event-list
  - Cube and Dataset Data Model



HE “event” in the VO

a HE event is **not** a VOEvent

https://www.ivoa.net/documents/ObsCore

event: An event-counting (e.g. X-ray or other high energy) dataset ***of some sort***. Typically this is instrumental data, i.e., "event data". An event dataset is ***often a complex object*** containing multiple files or other substructures. An event dataset ***may contain*** data with spatial, spectral, and time information for each measured event, although the spectral resolution (energy) is sometimes limited. Event data may be used to produce higher level data products such as images or spectra.

http://www.ivoa.net/rdf/product-type (Preliminary)

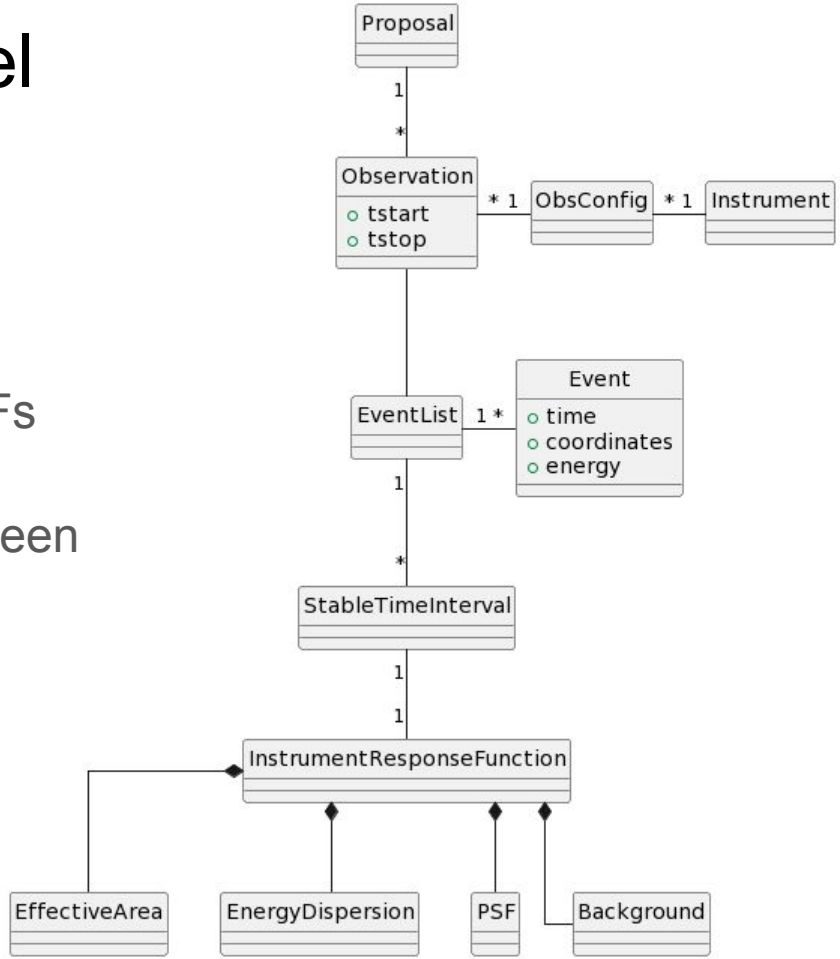
event-list: A collection of observed events, such as incoming high-energy particles. A row in an event list is typically characterised by a spatial position, a time and an energy.

Event-list Context Data Model

- Issue
  - What is really in the event-list dataset?
  - Does it include IRFs? only an event-list?
  - Where can one find the corresponding IRFs?
- Need a way to link an event-list to its IRFs

⟶ A proper **data model** with relations between those elements would help

⟶ Possible **ObsCore extension** fields would appear in this data model



Summary and conclusions

- **HE data available** through the VO
- HE domain have **specificities**
  - In particular the concept of **event-list**
  - and **Instrument Response Functions** (IRFs)
- Very limited number of VO services giving access to event-lists
- On the path to build an **HE Interest Group** at IVOA
  - **Session at IVOA Sydney** in May (plenary or with data model)
  - Next call: April 3rd 16h30