Software development in Astroparticle Physics

APC 13

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April 2025

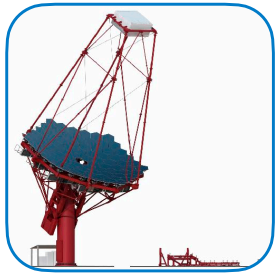
HELMHOLTZ

DESY.

We need software to...

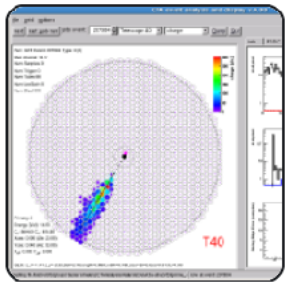
Operate the instruments we build

CTAO ACADA



CTAO MST Structure Control

Analyze the data we collect

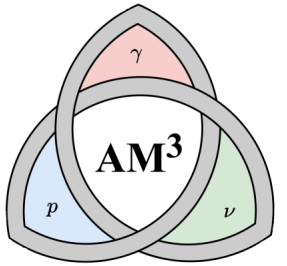


Eventdisplay

Ampel

Make predictions that connect observations with physical processes

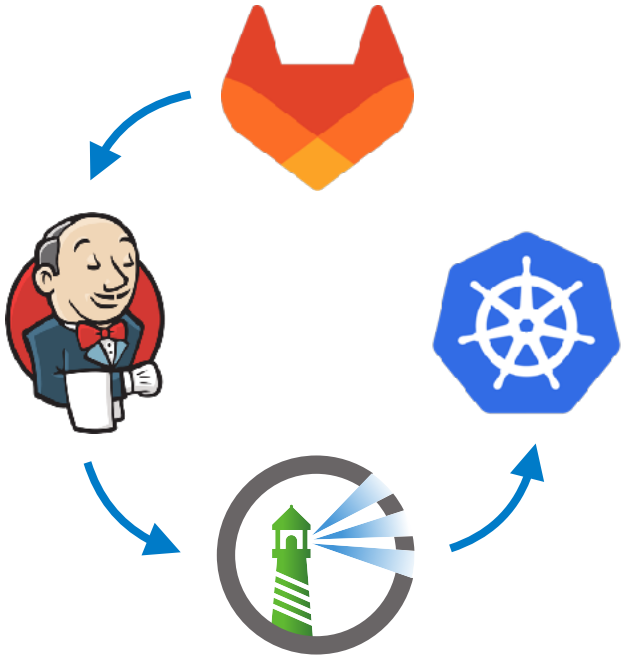
CTAO SimPipe



Astrophysical Multi-Messenger Modelling

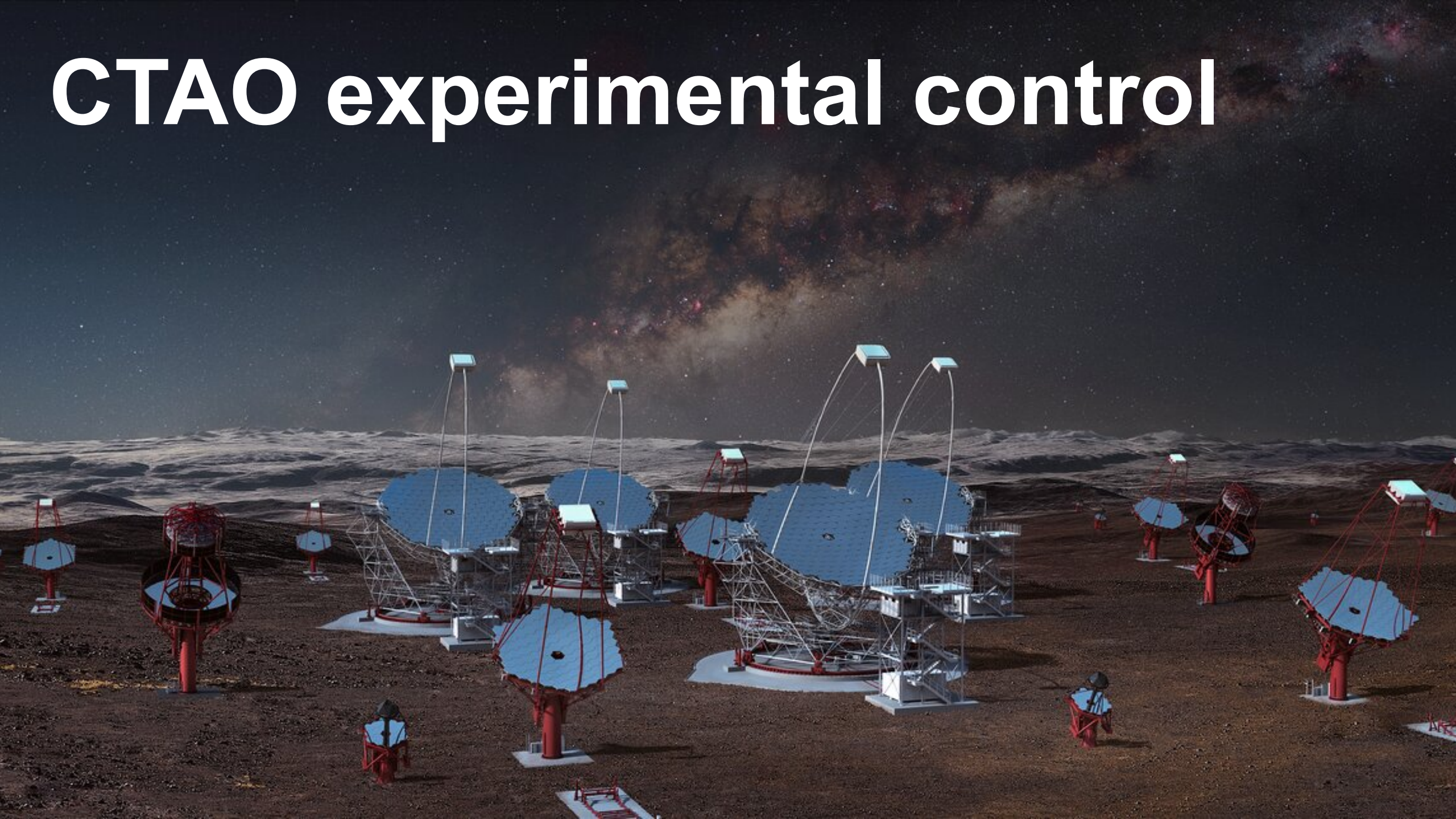
We support software development with...

Tools and services



Networking and training

CTAO experimental control



Array Control and Data Acquisition

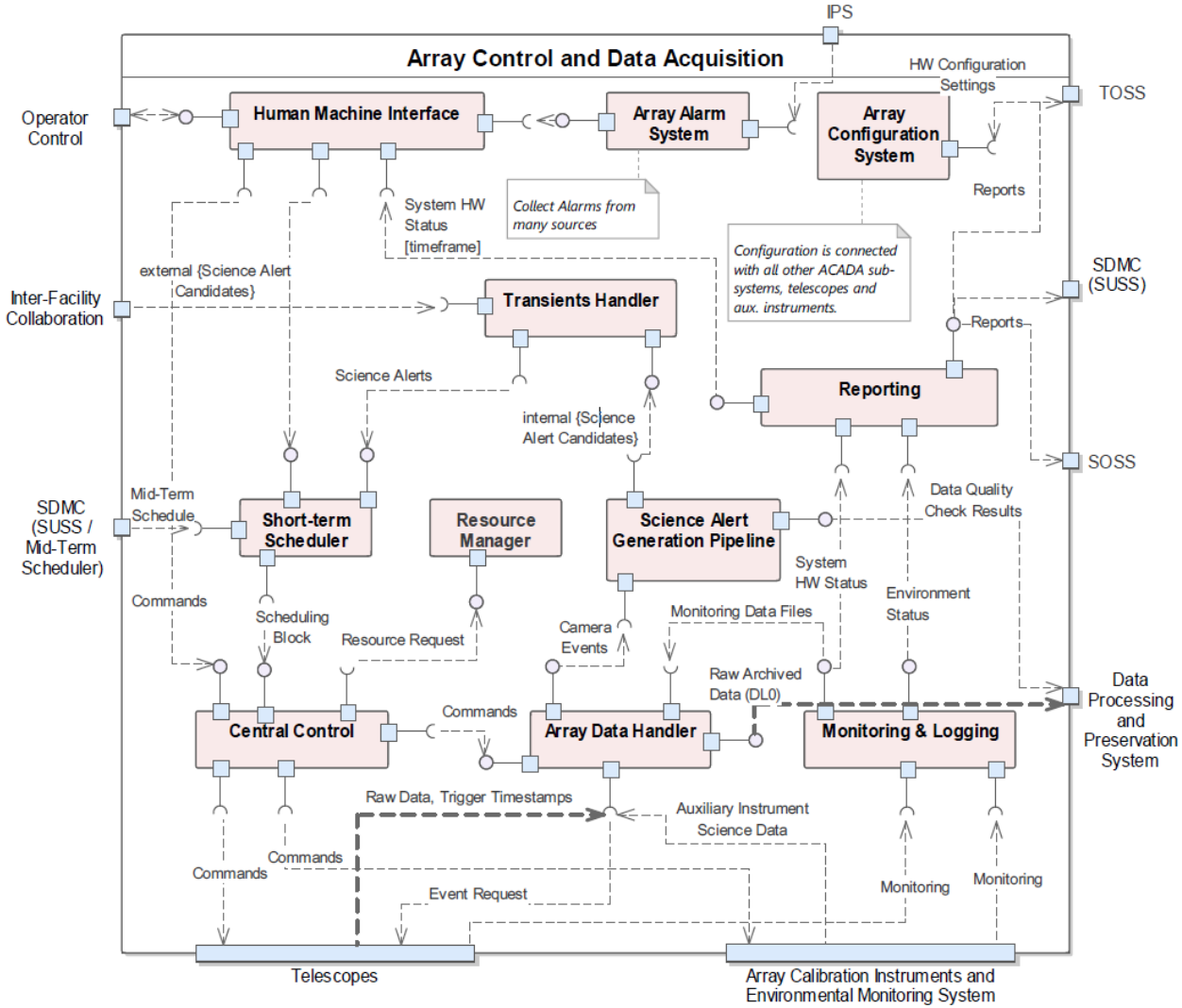
Supervisory control and data acquisition system for CTAO-North, CTAO-South

ACADA makes it possible to operate the observatory

- Many interconnected components
- Must operate reliably and safely for the lifetime of the observatory

DESY is the largest in-kind contributor to ACADA

- **Resource Manager:** top-level supervision
- **Central Control:** executes observation requests (pointing, data acquisition, analysis)
- **Human Machine Interface:** how observers control the array
- **Array Configuration System:** distributes configurations to components
- ~5.8 FTE (3.8 DESY, 2 external)

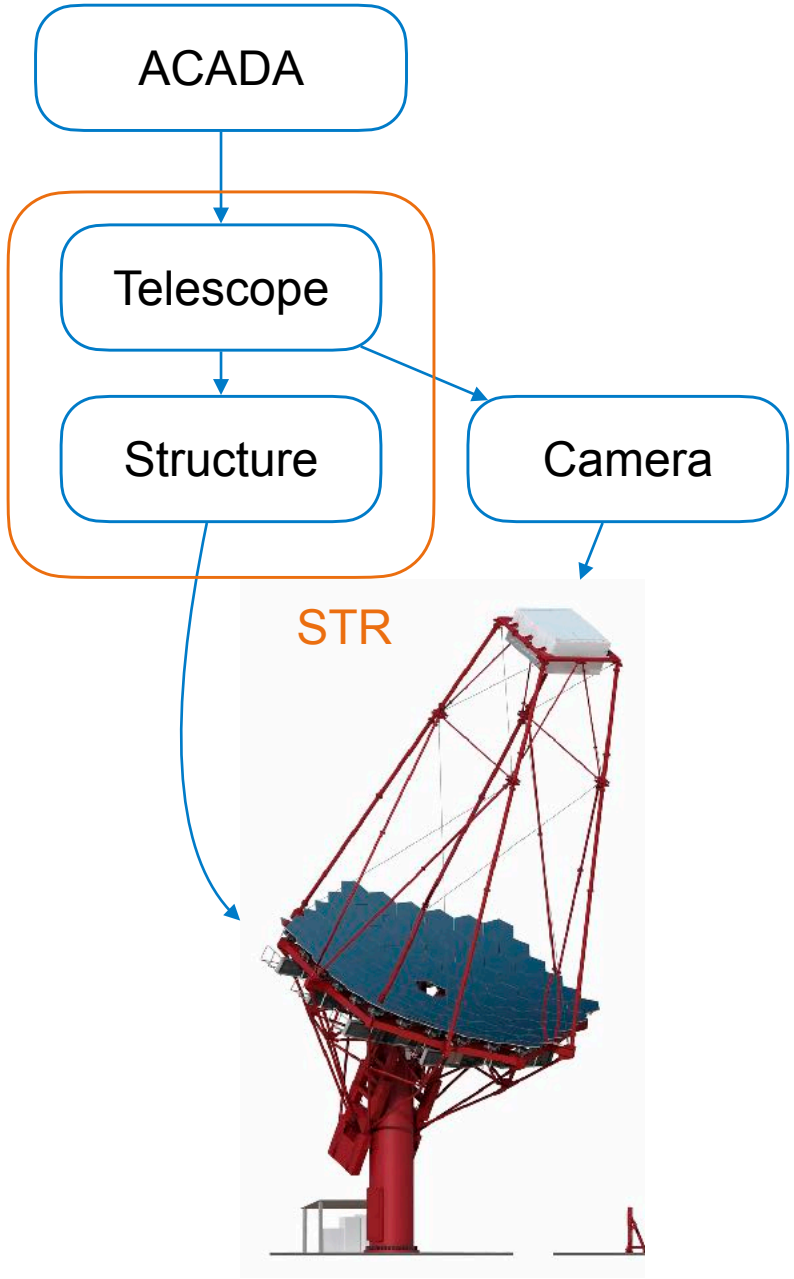


The logical view of the ACADA, representing the main components of the system.
Source: The Architecture Design Document of ACADA (I. Oya et al.) -

MST Structure Control software

DESY in-kind contribution to MST sub-project

- Control software for individual telescopes
  - ACADA sends commands
  - Structure control coordinates low-level hardware components (mount drives, mirror control, etc) to steer the telescope
  - ~20k lines of Java, Python
- Must operate safely and reliably for the lifetime of the observatory
- Must not damage people or the instrument
- ~4.5 FTE (1 permanent staff, 1 temporary staff, 0.5 external contractor, 2 postdocs)



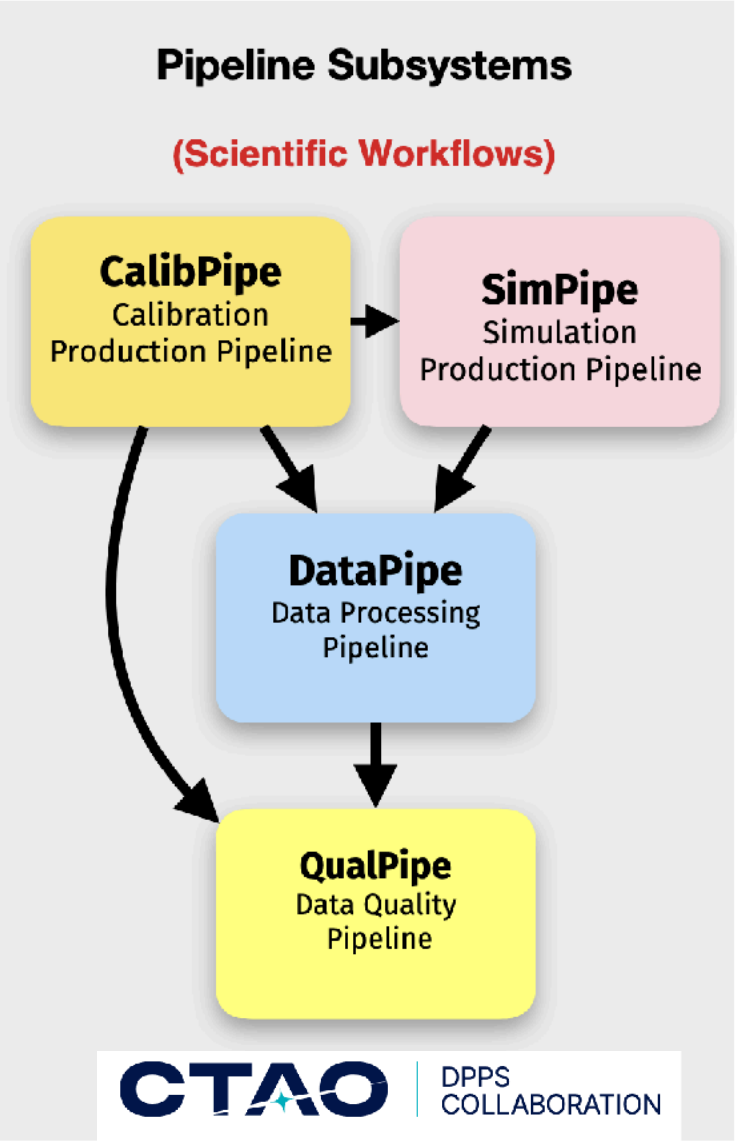
CTAO science

CTAO Simulation Pipeline

DESY in-kind contribution to Data Processing and Preservation System

- **Simtools**: main tool providing access to all functionality (production configuration, production manager, model parameter setting/derivation tools)
- Air shower (**CORSIKA**) and telescopes simulations (**sim_telarray**)
- Input/output tools for data access

- Developed as FAIR data pipeline in the context of Punch4NFDI
- 1-2 FTE (1 staff, 2 postdocs)
- In collaboration with MPIK Heidelberg

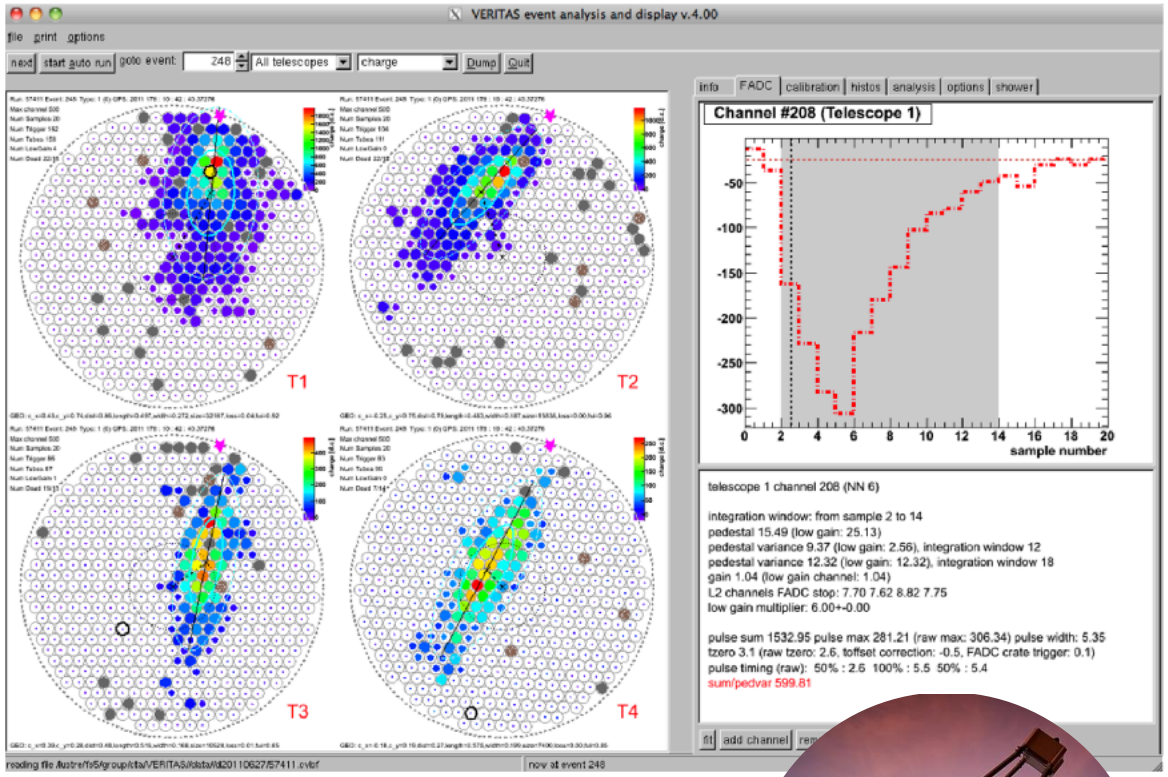


https://github.com/gammasim/simtools/
https://gitlab.cta-observatory.org/cta-computing/dpps/simpipe/simpipe/

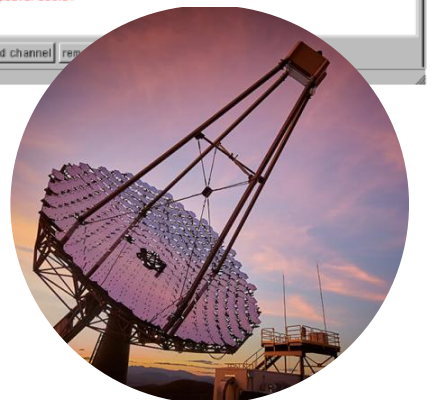
Eventdisplay

Proven visualization and analysis tool

- Includes calibration, reconstruction, science analysis
- Well-aged software started in 2004 (C++/ROOT based); public!
- Used for pre-processing of all VERITAS observations; easy-accessible [internal] archive
- Used to analyze CTAO Simulations
  - All CTAO instrument/array optimization and sensitivity estimates based on Eventdisplay
  - CTAO-compatible converters provide bridges to CTAO Software (DL3, DL3)



https://github.com/Eventdisplay



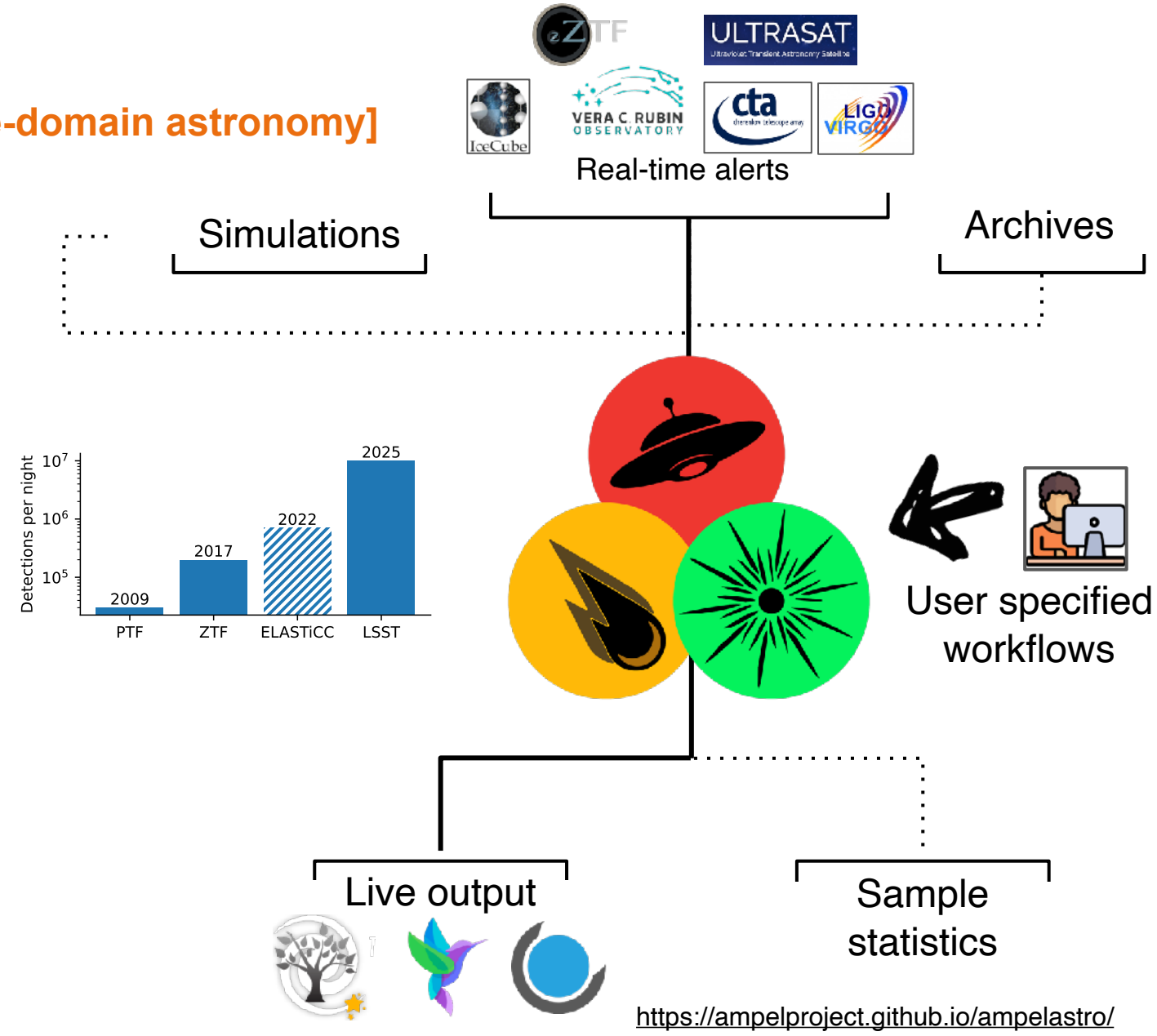
Credit: CfA/Rick Peterson

Analysis and modeling for multi-messenger astronomy

AMPEL

Streaming data analysis platform [for time-domain astronomy]

- Developed to support SNIa cosmology and multi-messenger astronomy with ZTF. ~30k lines of Python.
- Novel in astronomy: proactive analysis, code-to-data, built-in provenance tracking
- User (scientist) specifies a workflow of self-contained units
- Framework handles the boring stuff: orchestration, storage, provenance tracking, de-duplication, etc.
- Gearing up for Rubin Observatory alerts (Q4 2025), ULTRASAT



Numerical Tool: AM^3 (Astrophysical Multi-Messenger Modeling)

Numerically solving the coupled PDEs for electron, proton, neutrons, neutrino and photon distributions.

$$\partial_t n_i = Q_{i,ext} + \sum_k Q_{int,k\to i} - \partial_E(\dot{E}\cdot n_i) - (\alpha_{i,esc} + \alpha_{i,adv})n_i$$

Injection | Cooling | Escape/Advection

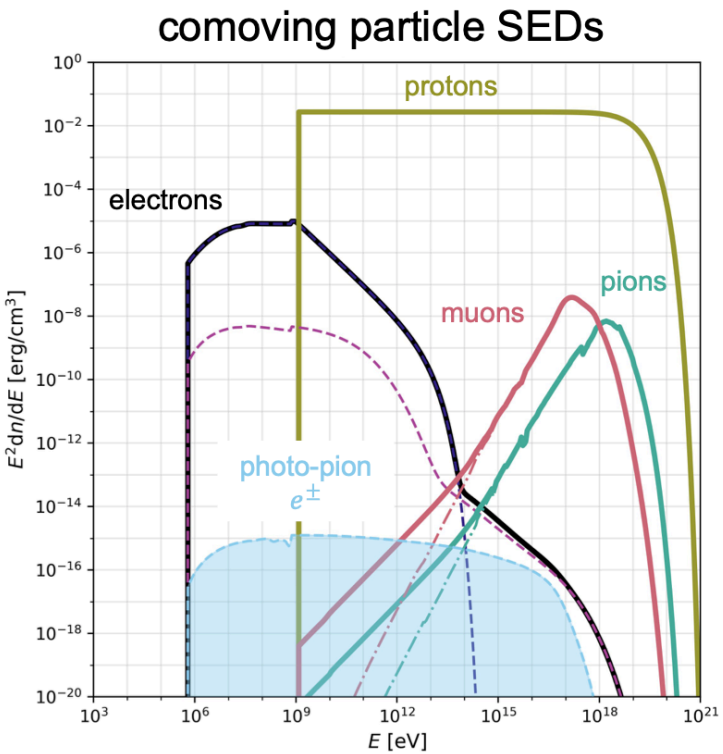
- An ***Open-Source*** Tool for ***Time-Dependent*** Lepto-Hadronic Modeling of Astrophysical Sources
- Blazars, GRBs, TDEs, etc

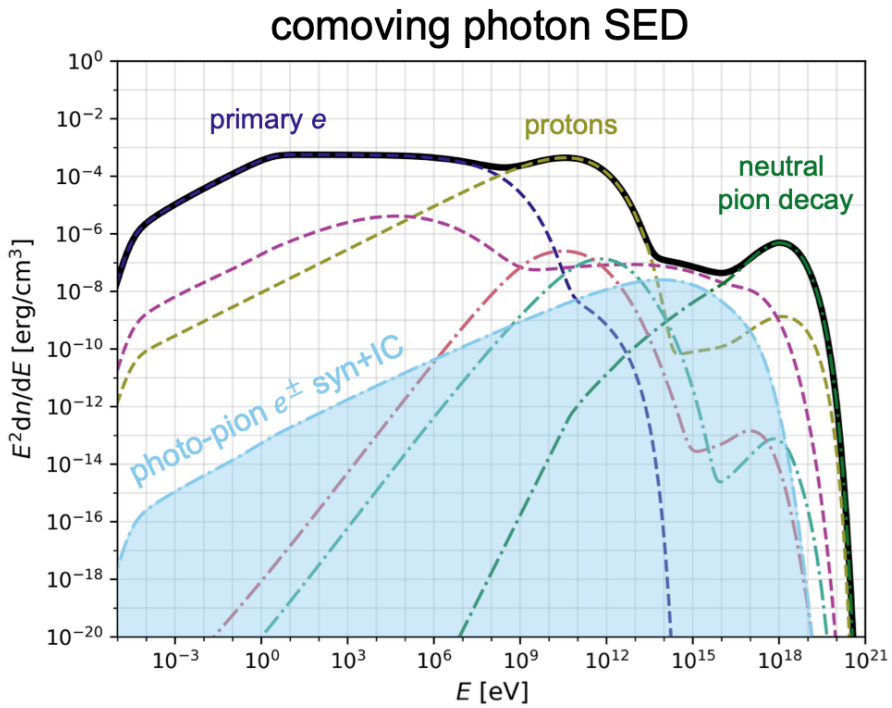
(Klinger, Rudolph, Rodrigues, CY +, arXiv: 2312.13371, ApJS)

Trackable photo-pion cascade:

$p\gamma \to \pi \to \mu \to e / \gamma$

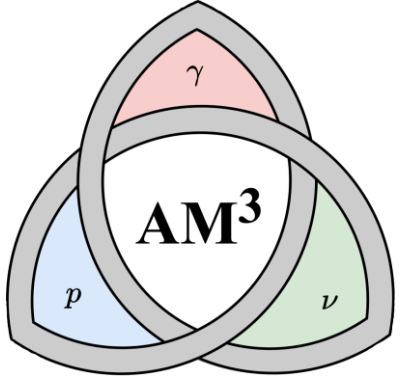
- Injected protons
- pions
- muons
- primary electrons, secondary electrons
- Photon components

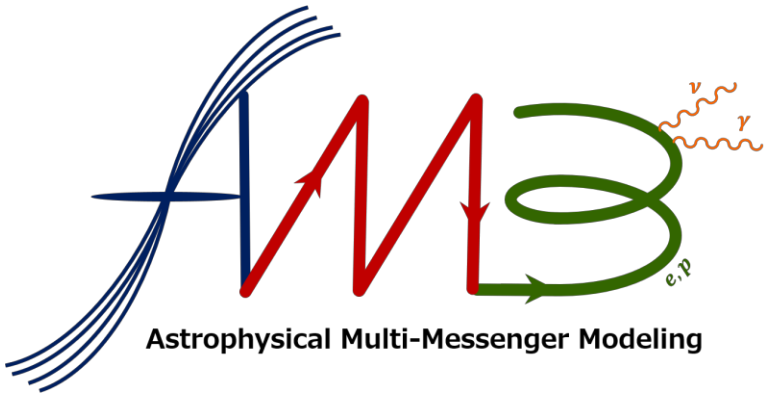




AM³ - finally public!

Astrophysical Multi-Messenger Modeling

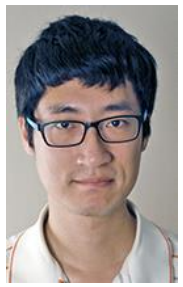




- solve transport equations - time dependent!
- for protons, electrons, photons
  + pions, muons, neutrinos
- Syn, IC, pair-prod., $p\gamma$, pp, Bethe-Heitler, decays,..
- speed optimized (steady state in ~10s)
- written in C++, interface to python
- used already for blazars (initially Gao++ 2017), GRBs, TDEs

Gao++ APJ 843 (2017)

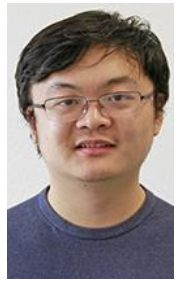
- including documentation!


Gao

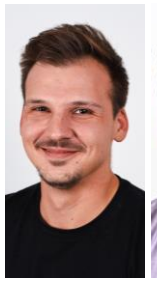

Klinger


Rudolph


Rodrigues


Yuan


Fichet De Clairfontaine


Fedynitch


Winter


Pohl

https://gitlab.desy.de/am3/am3

Software development ecosystem in AP

Services

Provided by DV and IT

GitLab
Version control, continuous integration

ACADA, MST STR, SimPipe, Ampel, AM^3, (everyone)

Jenkins
Continuous integration

ACADA

Kubernetes
Container orchestration

SimPipe, Ampel

SonarQube
Code quality and security

ACADA, MST STR

Nexus
Artifact repository

ACADA

MinIO
Object store

ACADA

Harbor
Container registry

ACADA, SimPipe

Zeuthen Data and Software Seminar

~Everyone needs to write software. ~Everyone could be better at it.

- Since 2020, ~monthly talks on:
  - Useful tools
  - Fundamental techniques
  - Lessons learned
- In person and online: https://indico.desy.de/category/713/
- Target audience: PhD students and postdocs
- Open to all divisions
- Coordinated by neutrino, gamma groups; computer center (G. Maier, T. Murach, D. Parsons, JvS)

If loosely connected series of talks were a picture, what picture would it be? Not this one, for sure.

Software development in AP

- We build software to:
  - Operate the instruments we build
  - Analyze the data we collect
  - Make predictions that connect observations with physical processes
- "We" are mostly physicists (staff, postdocs, PhDs), some with software engineering or computer science background
- DESY supports software development in AP through
  - Services provided by DV and IT
  - Training and networking

Thank you