PYTHON FOR GAMMA-RAY ASTRONOMY

Christoph Deil (MPIK Heidelberg)

March 21, 2016
PyAstro15 in Seattle

GAMMA-RAY ASTRONOMY

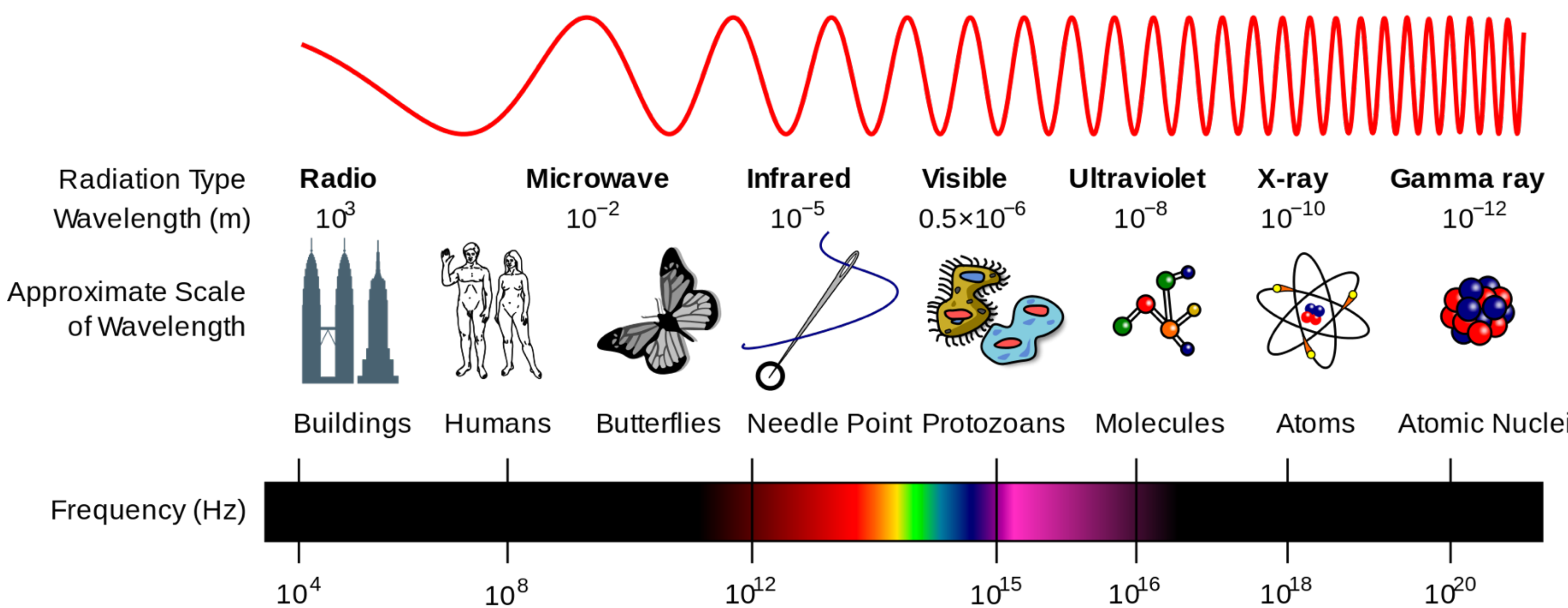
Space and ground telescopes

- Brief introduction to gamma-ray telescopes and data (will go very quickly over slides in this section)
- No time to cover astrophysics, if you're interested, here's a good recent review: 2015arXiv150805190F

Space- and Ground-Based
Gamma-Ray Astrophysics

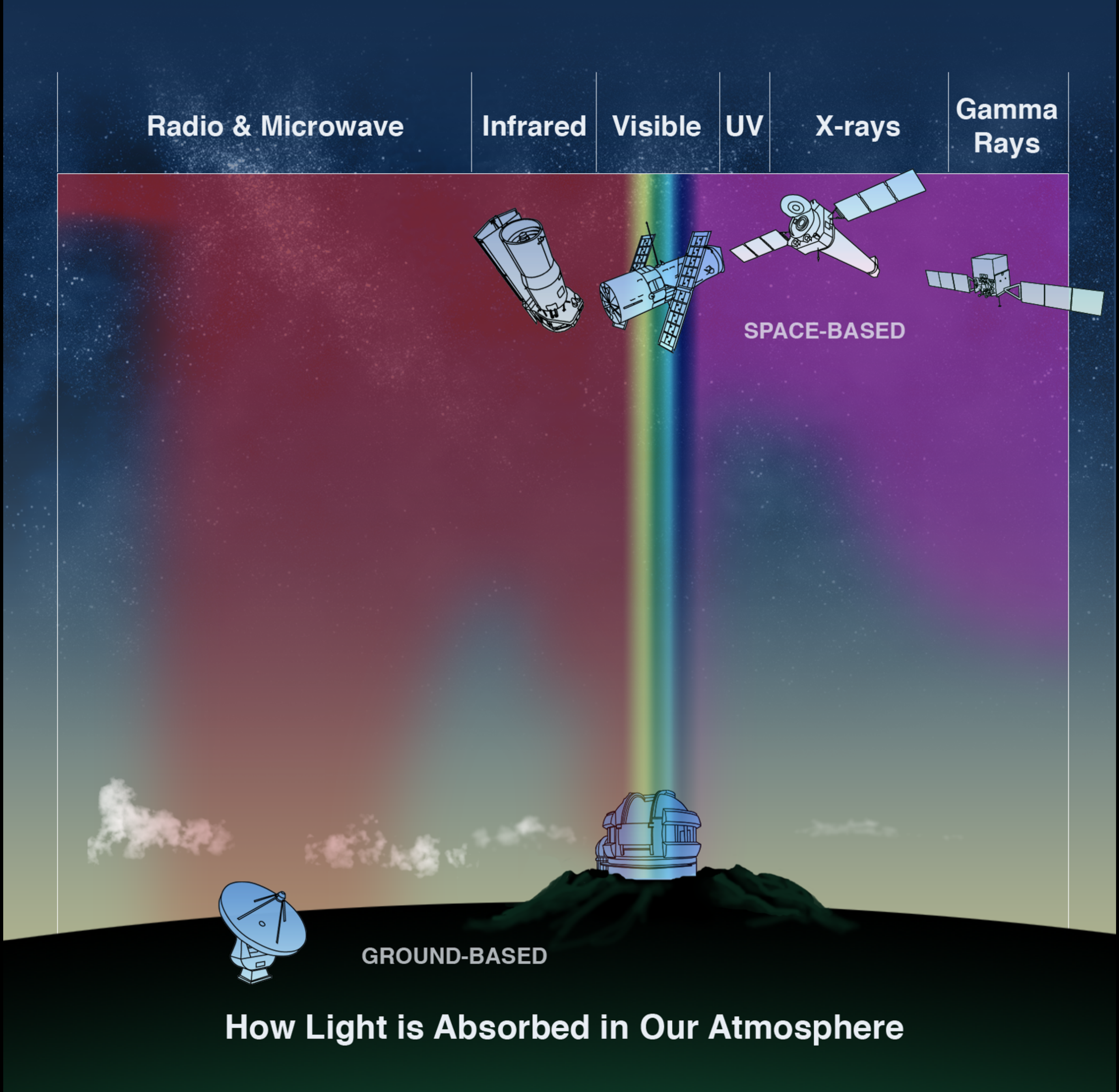
Stefan Funk [1], [2]

ELECTROMAGNETIC SPECTRUM

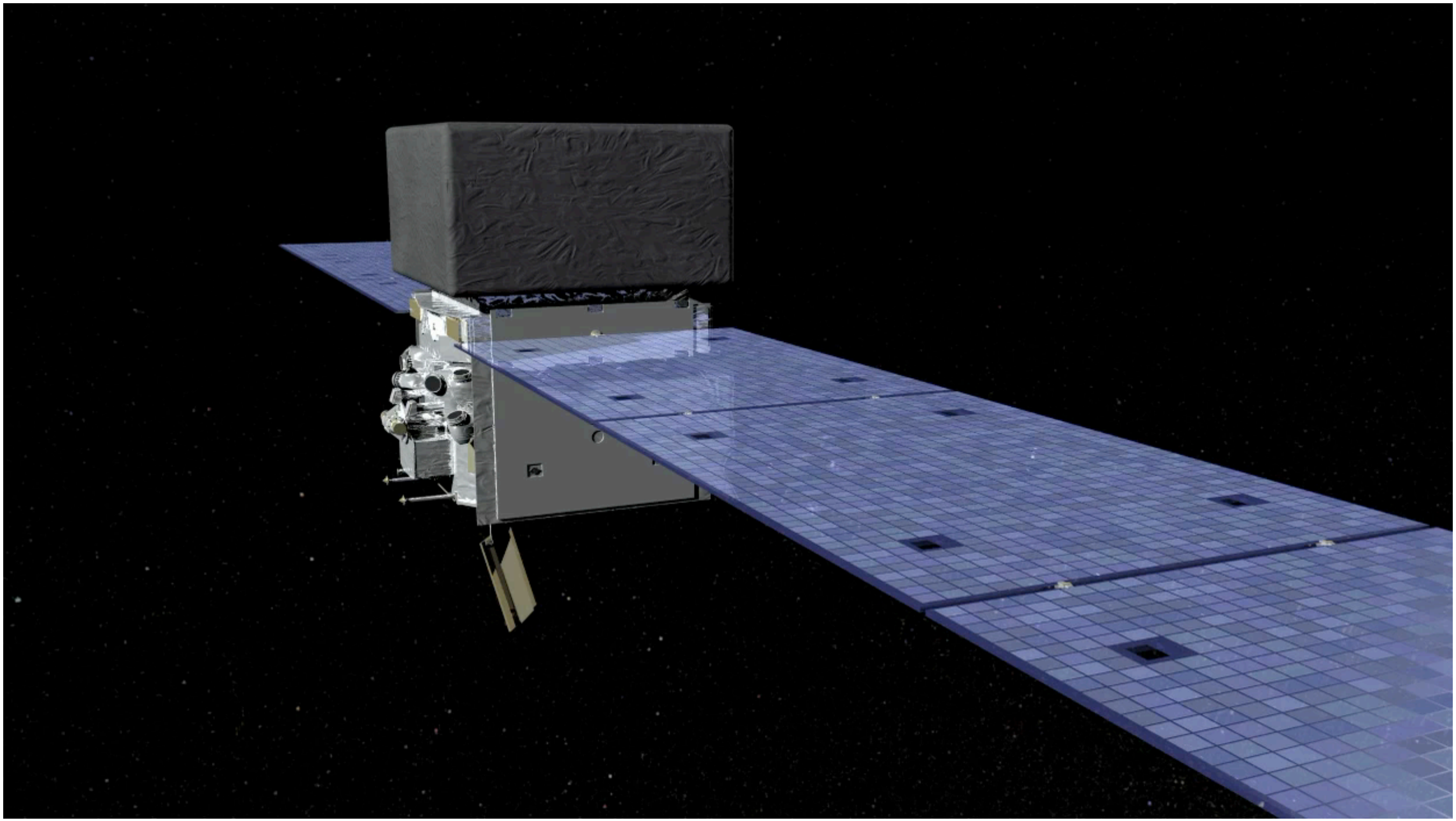


Gamma-rays are the high-energy end of the electromagnetic spectrum.

Observe photons of energy MeV to ~ 100 TeV
(optical light is ~ 1 eV, X-rays are ~ 1 keV)

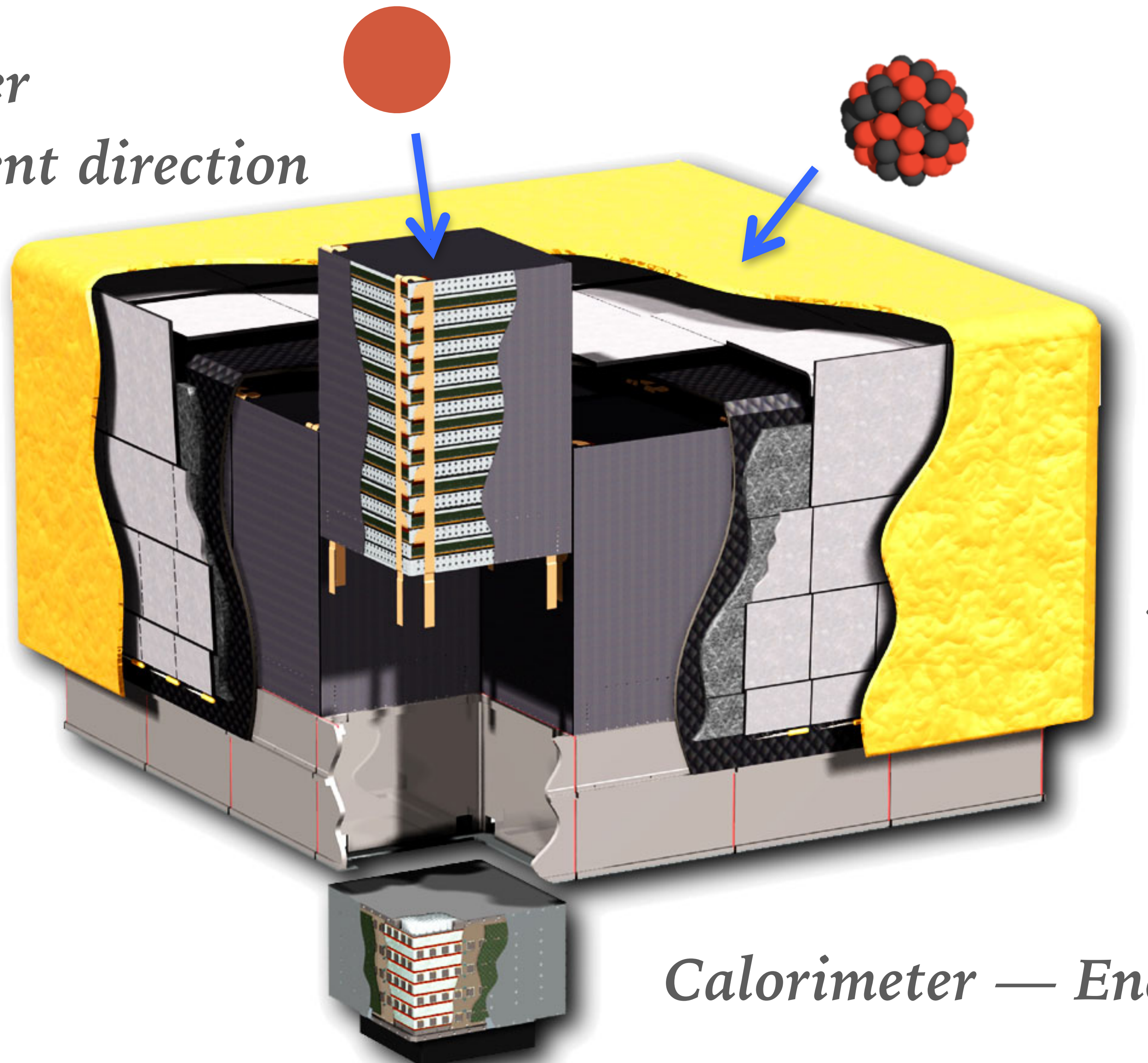

Radio & Microwave
Infrared
Visible
UV
X-rays
Gamma Rays
SPACE-BASED
GROUND-BASED
How Light is Absorbed in Our Atmosphere

FERMI-LAT PAIR PRODUCTION TELESCOPE



FERMI-LAT PAIR PRODUCTION TELESCOPE

Tracker
— Event direction

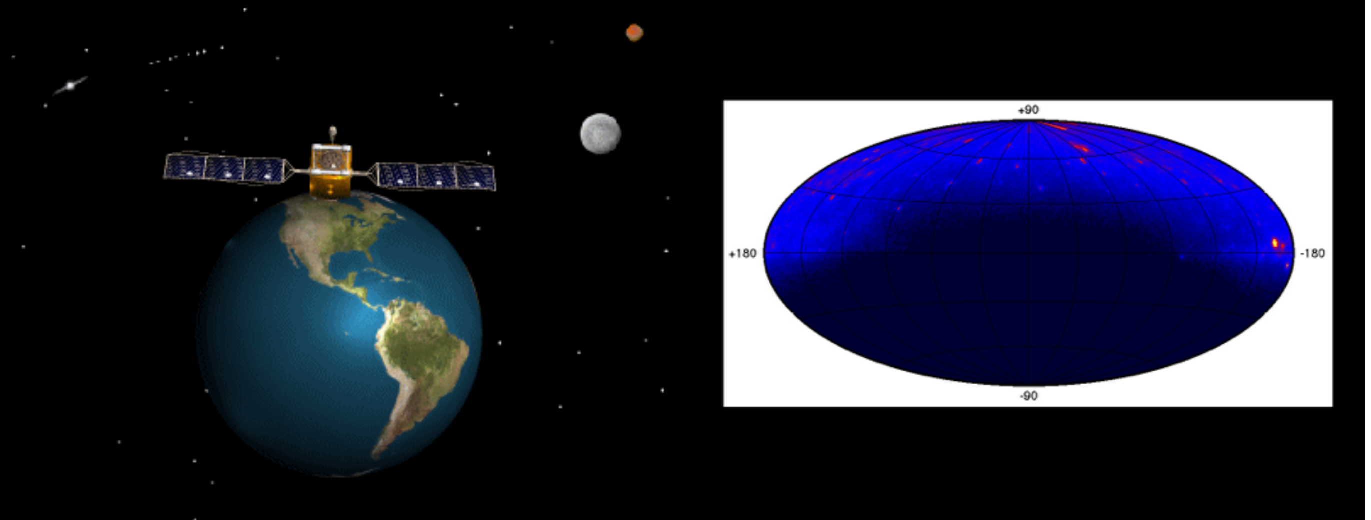


Anti-coincidence shield
— Particle type (proton, electron, photon, ...)

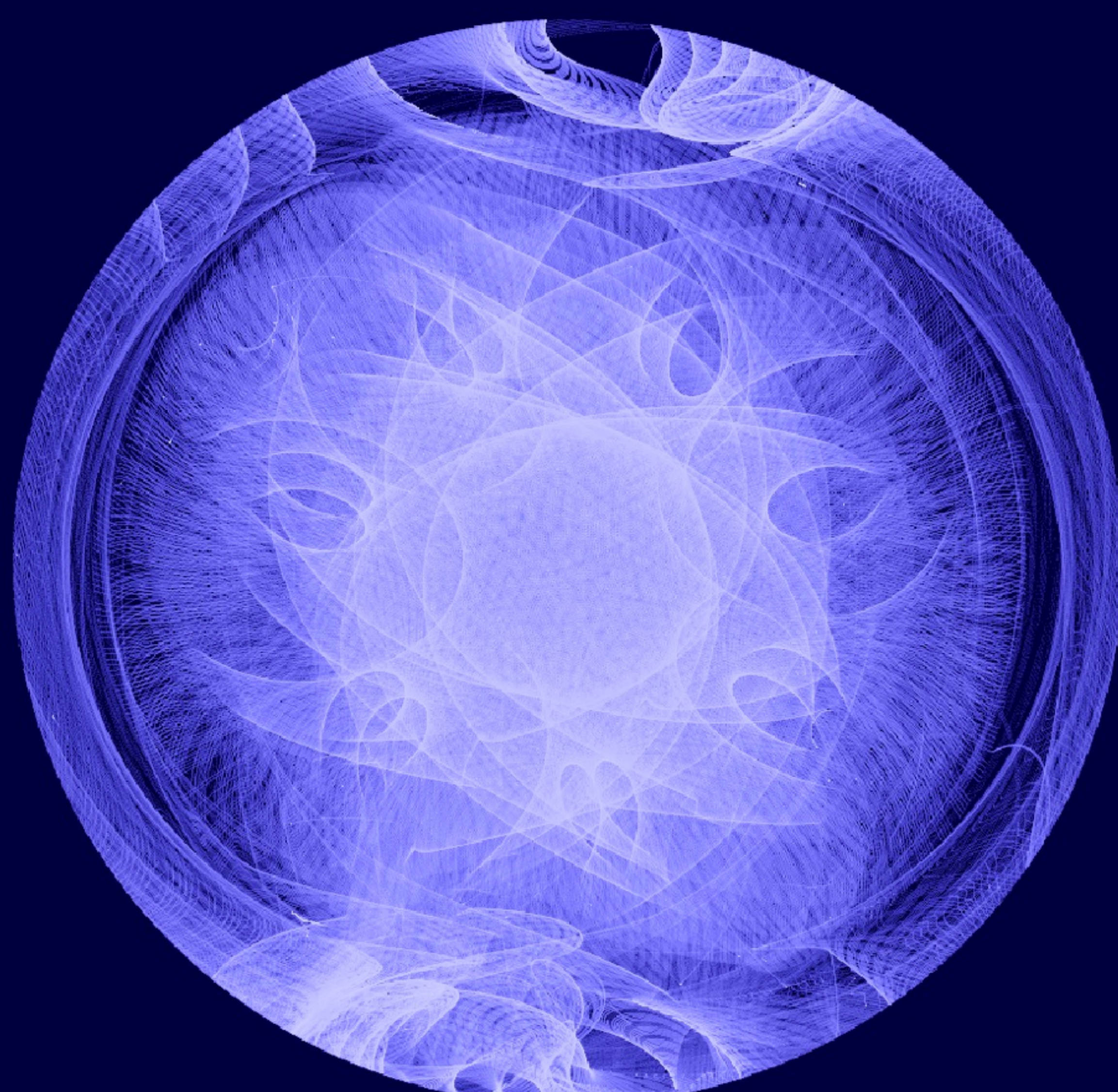
Needed to distinguish small fraction (1 in 10k) of photons among charged cosmic ray background.

Calorimeter — Energy

High-level data is basically an event list table (TIME, ENERGY, RA, DEC)
+ spacecraft file (GTIs, pointing)
+ instrument response functions (effective area, PSF)



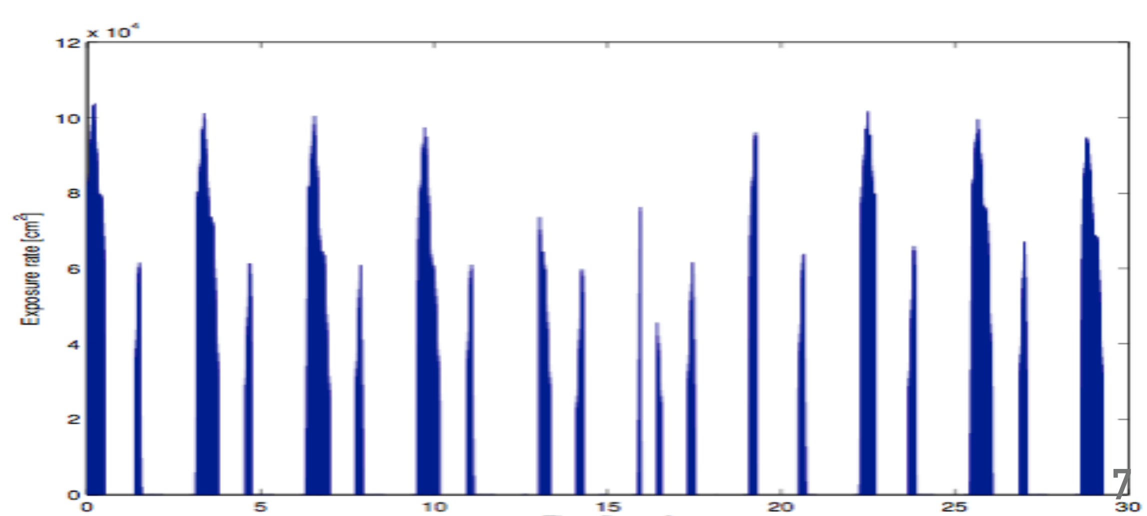
Vela pulsar location in Fermi-LAT field of view as a function of time



FERMI-LAT OBSERVATIONS

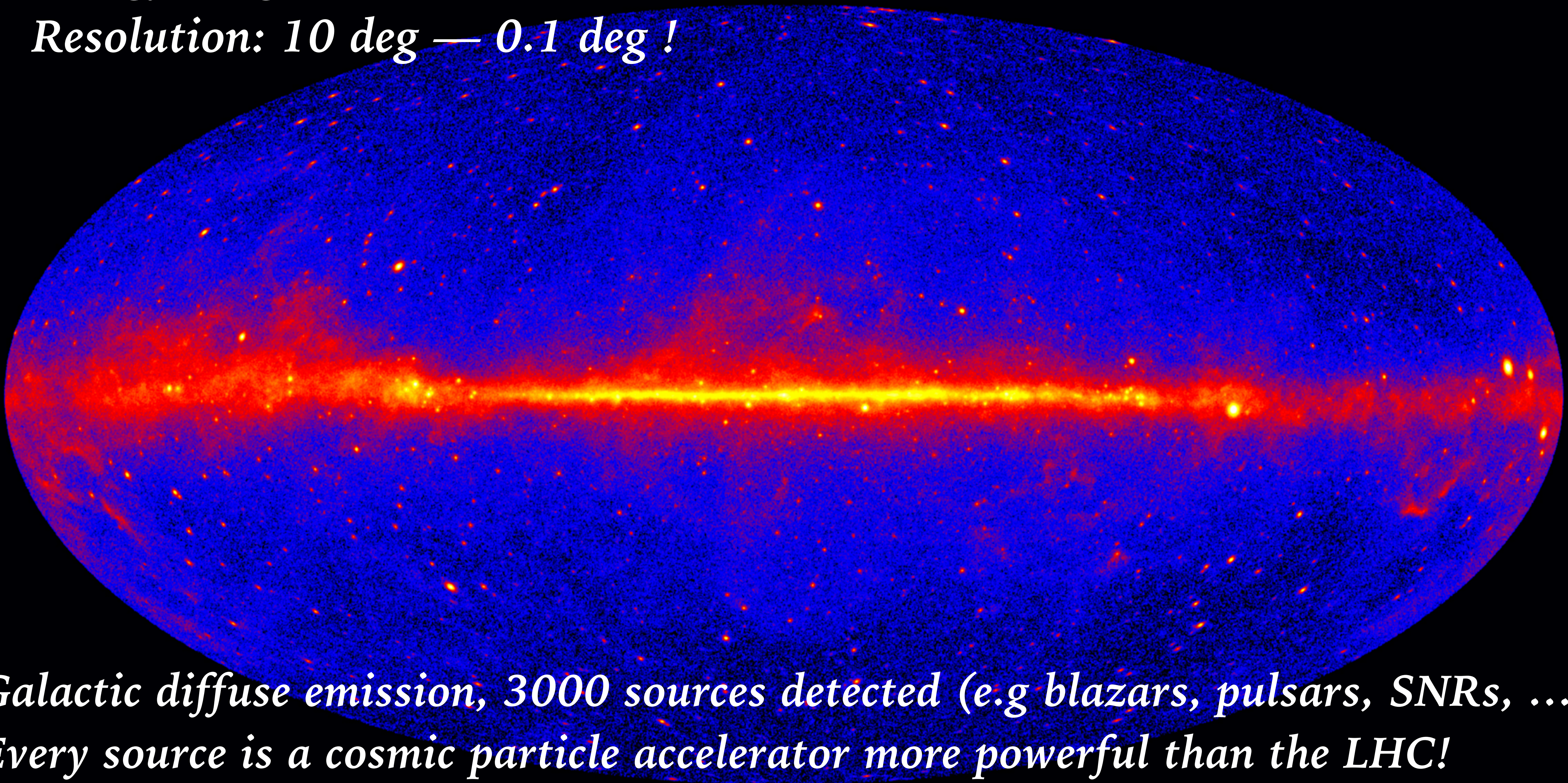
- Start: 2008. Continuous all-sky survey for past 7+ years
- Large field of view — observe good fraction of the whole sky at any given time
- Earth orbit + rocking pattern — observe every source every few hours

Exposure vs time for a given source on one day

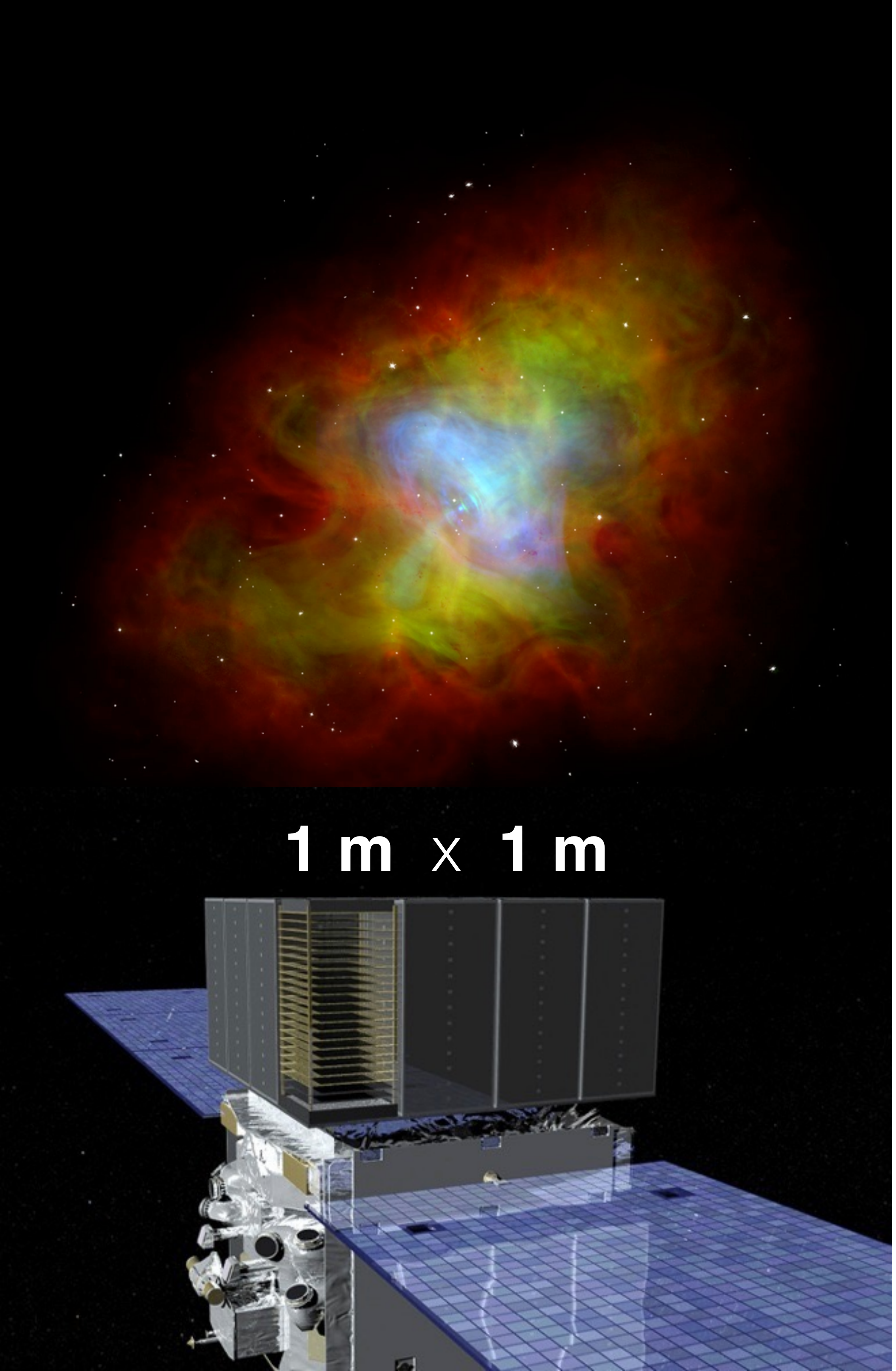


FERMI-LAT — FIRST GOOD VIEW OF THE GEV GAMMA-RAY SKY

Energy range: 100 MeV — 1 TeV
Resolution: 10 deg — 0.1 deg !

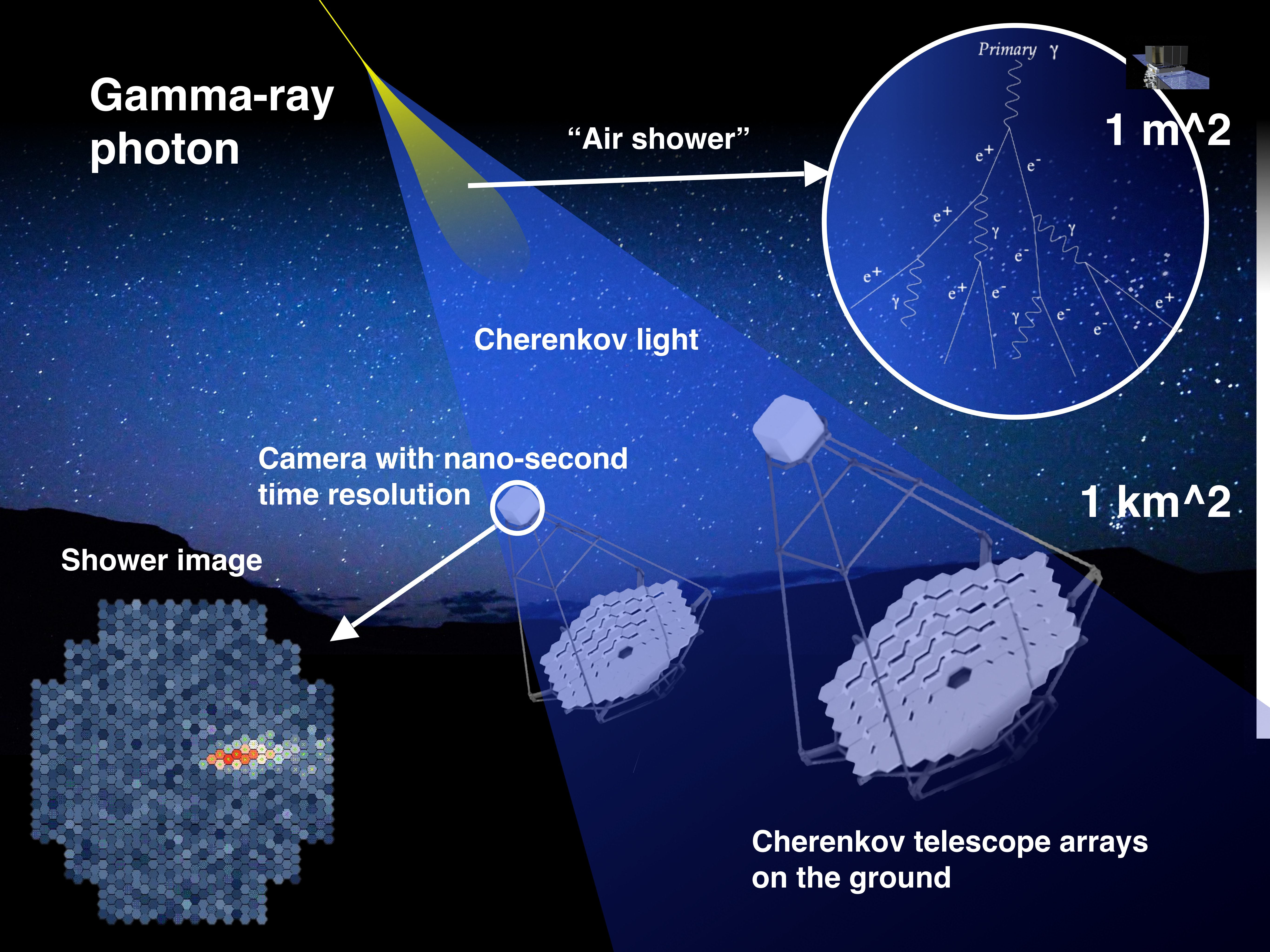


Galactic diffuse emission, 3000 sources detected (e.g blazars, pulsars, SNRs, …)
Every source is a cosmic particle accelerator more powerful than the LHC!



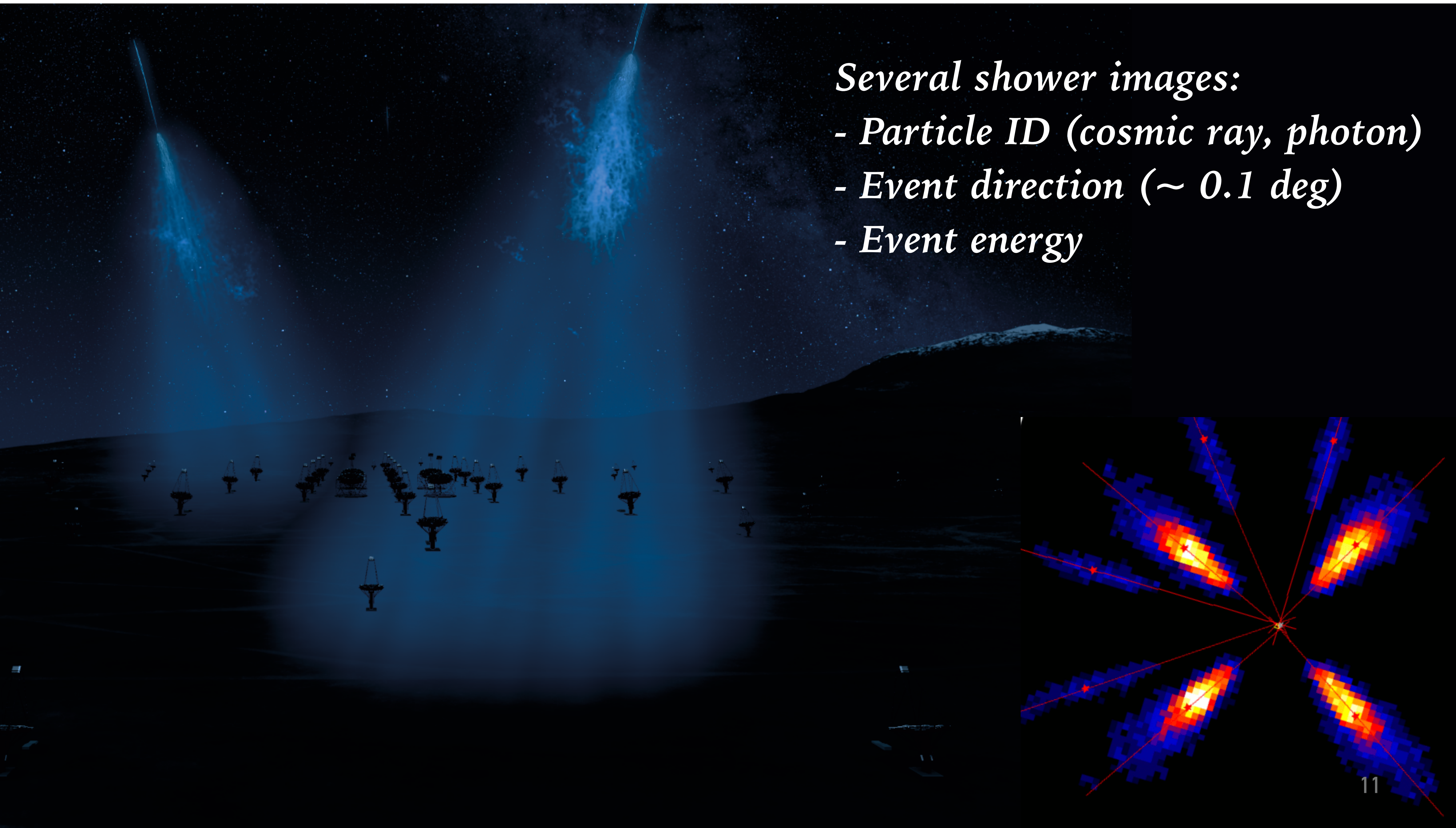
PHOTON STATISTICS

- The Fermi-LAT is an awesome gamma-ray telescope.
- But at ~ 1 TeV it runs out of statistics, because gamma-ray spectra are steep power-laws.
- Brightest sources observed for 10 years with a 1 m^2 detector yield a few photons.
- For very-high-energy gamma-ray astronomy (> 1 TeV), other telescopes are needed!

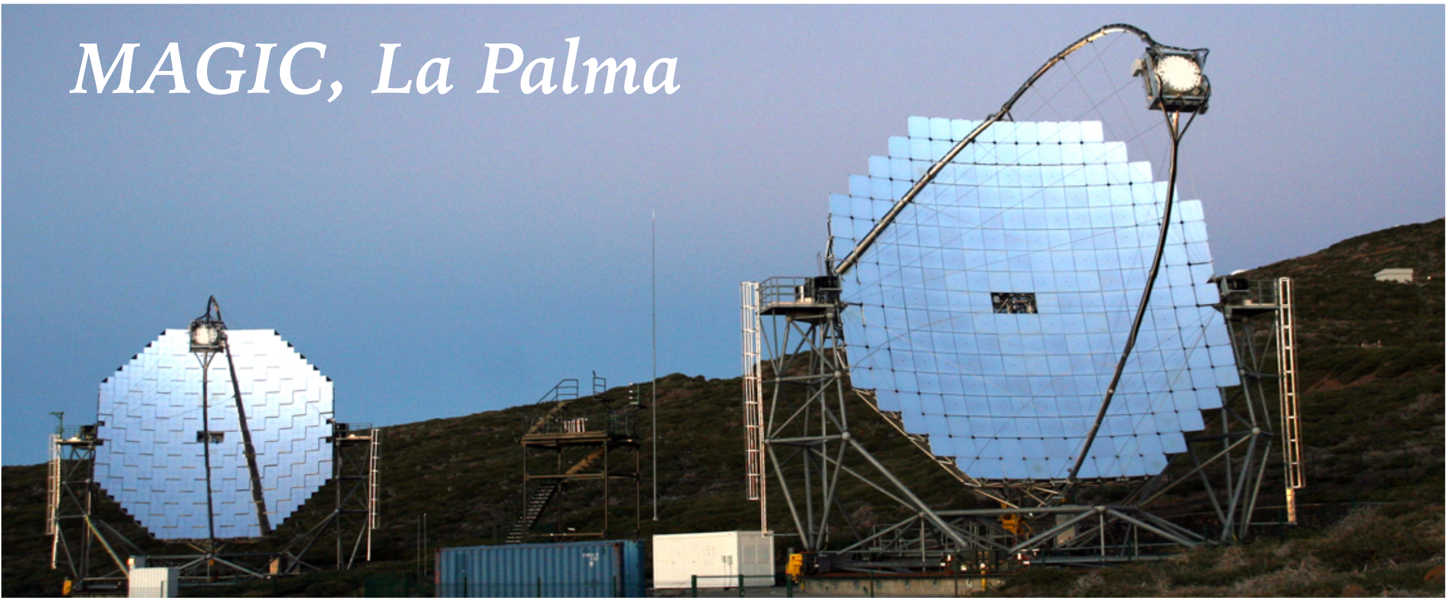

Gamma-ray photon
"Air shower"
Primary γ
1 m^2
Cherenkov light
Camera with nano-second time resolution
1 km^2
Shower image
Cherenkov telescope arrays on the ground

IMAGING ATMOSPHERIC CHERENKOV TELESCOPE ARRAY (IACT)

*Atmosphere is part of detector -> km**2 detection area -> TeV astronomy!*



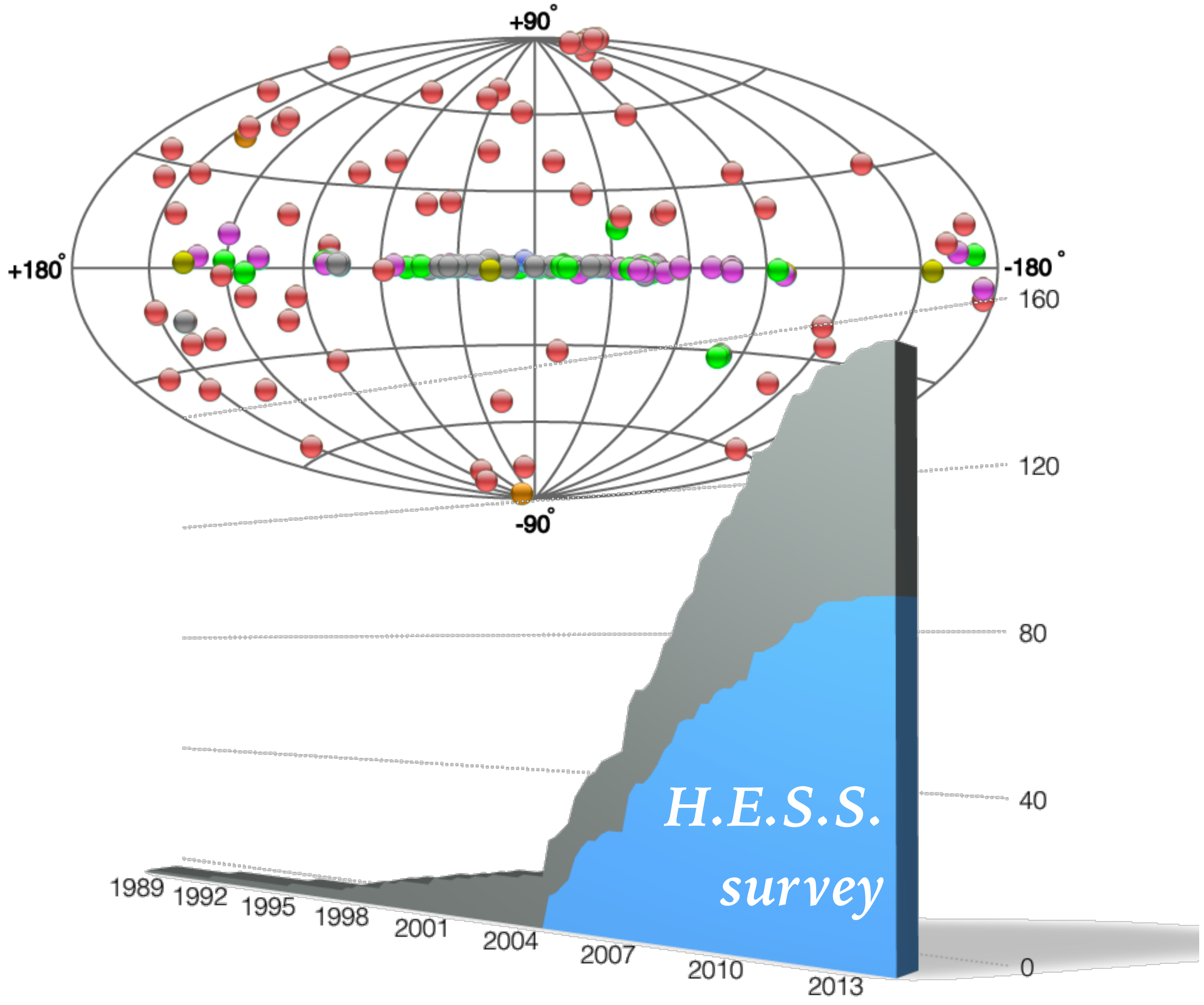
Several shower images:
- *Particle ID (cosmic ray, photon)*
- *Event direction (~ 0.1 deg)*
- *Event energy*



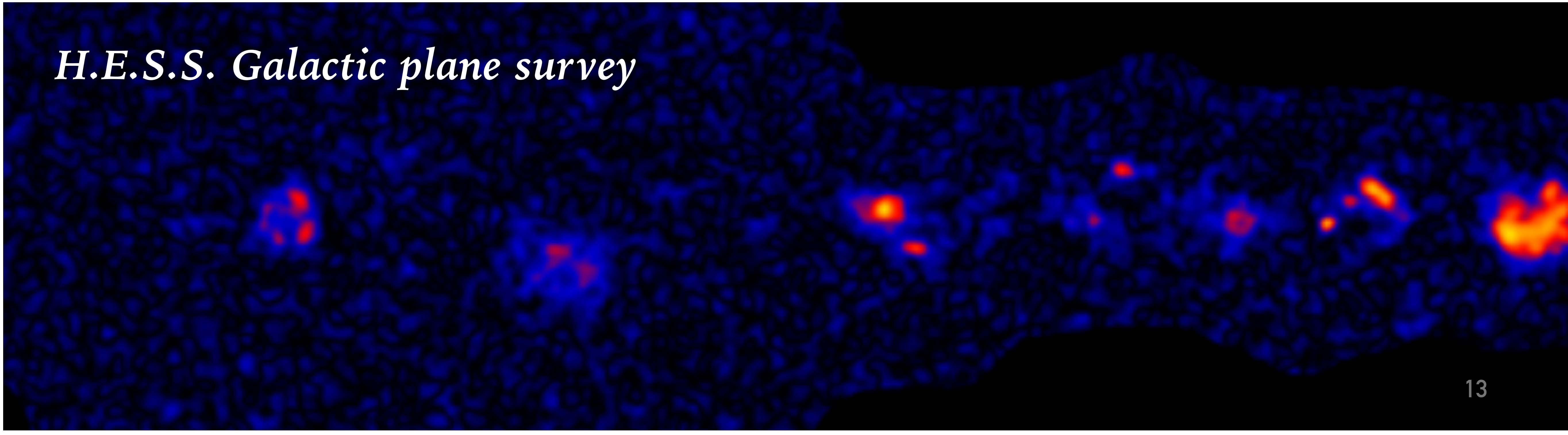
EXISTING IACTS

- Energy range roughly 100 GeV — 100 TeV
- Pointed observations with field of view of a few degrees.
- Each array has a few telescopes, total cost ~ 10 M$
- Built by collaborations of ~100 astronomers
- Data and software from current IACTs not publicly available.
- (Fermi-LAT is a NASA mission with ~ 600 M$. All data and software is publicly available!)

TEV GAMMA-RAY SOURCES

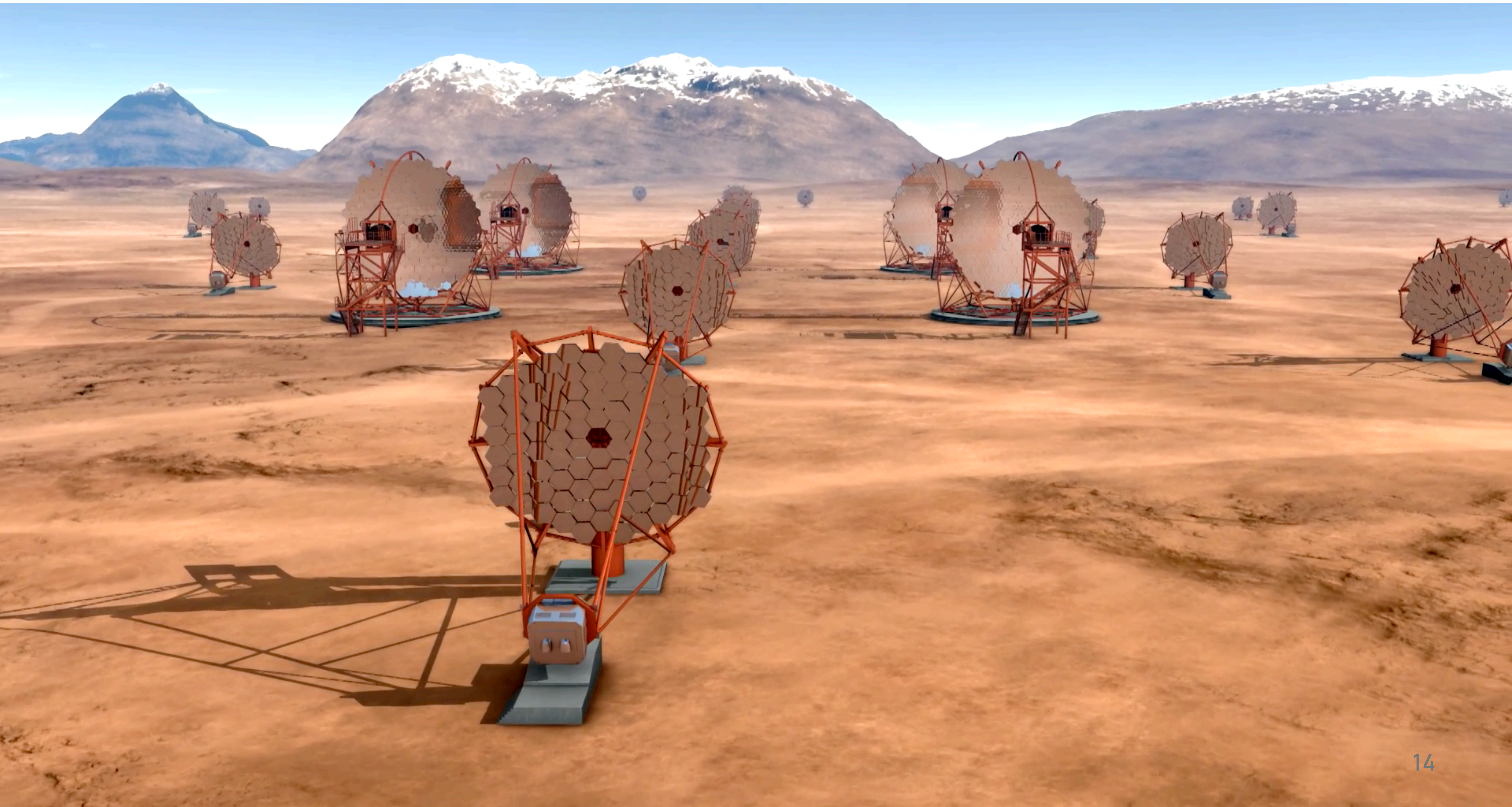


- First ground-based gamma-ray source detection: Crab nebula in 1989
- Already ~ 150 detected now! :-)
- Only a few % of the sky have been surveyed so far.



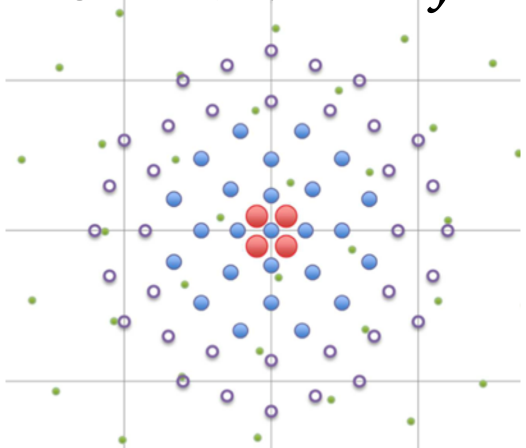
CHERENKOV TELESCOPE ARRAY (CTA)

Next step: build more and better Cherenkov telescopes!

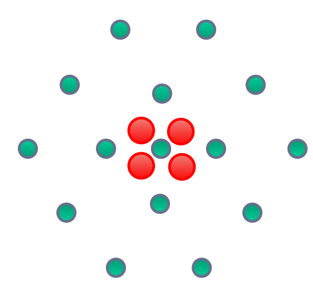


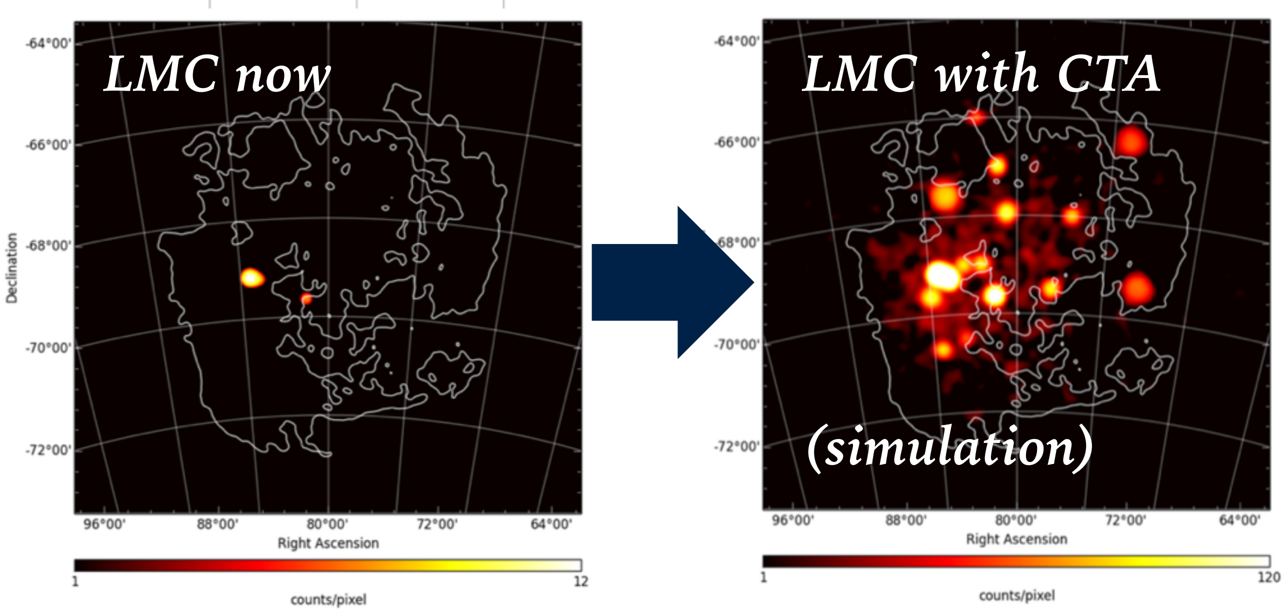
CHERENKOV TELESCOPE ARRAY

CTA south array



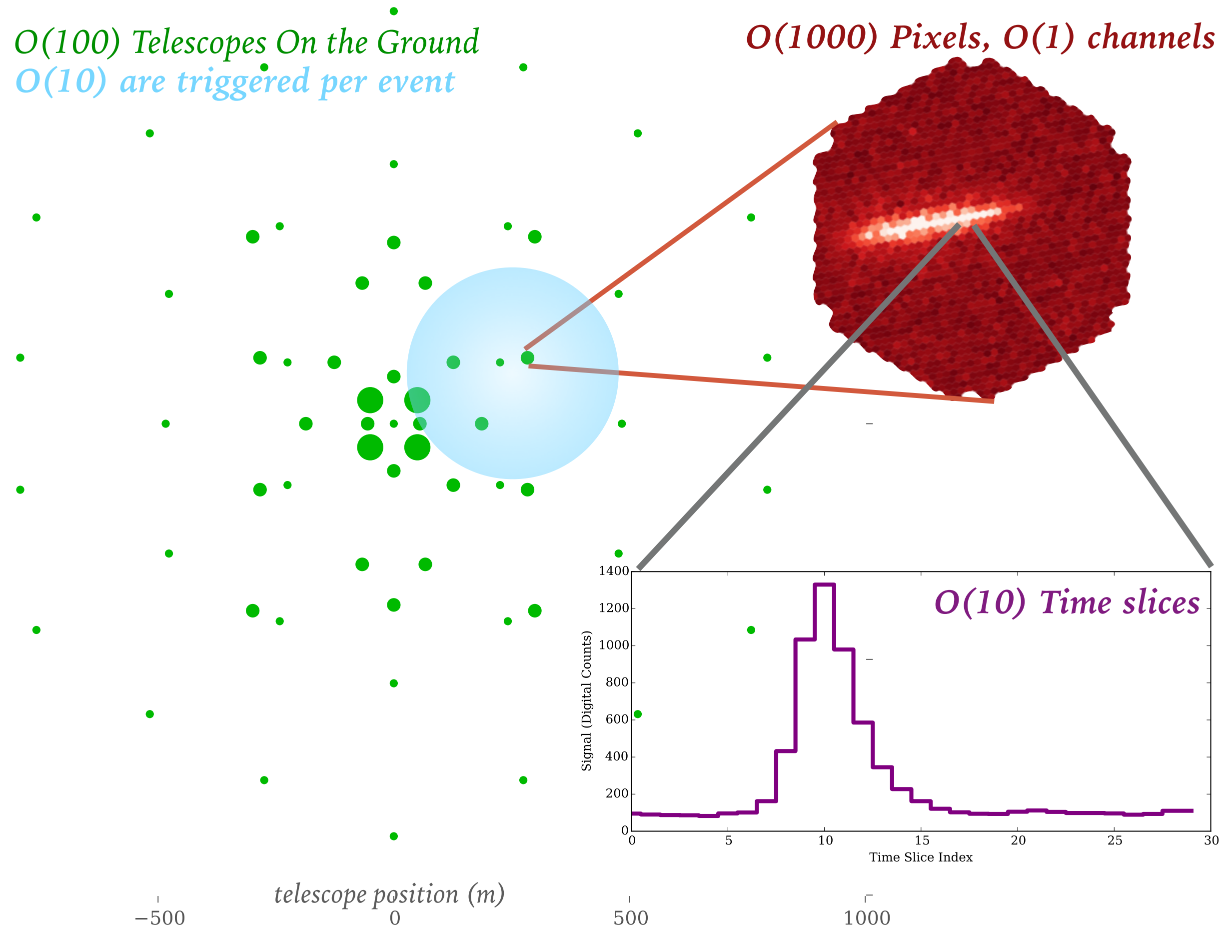
CTA north array



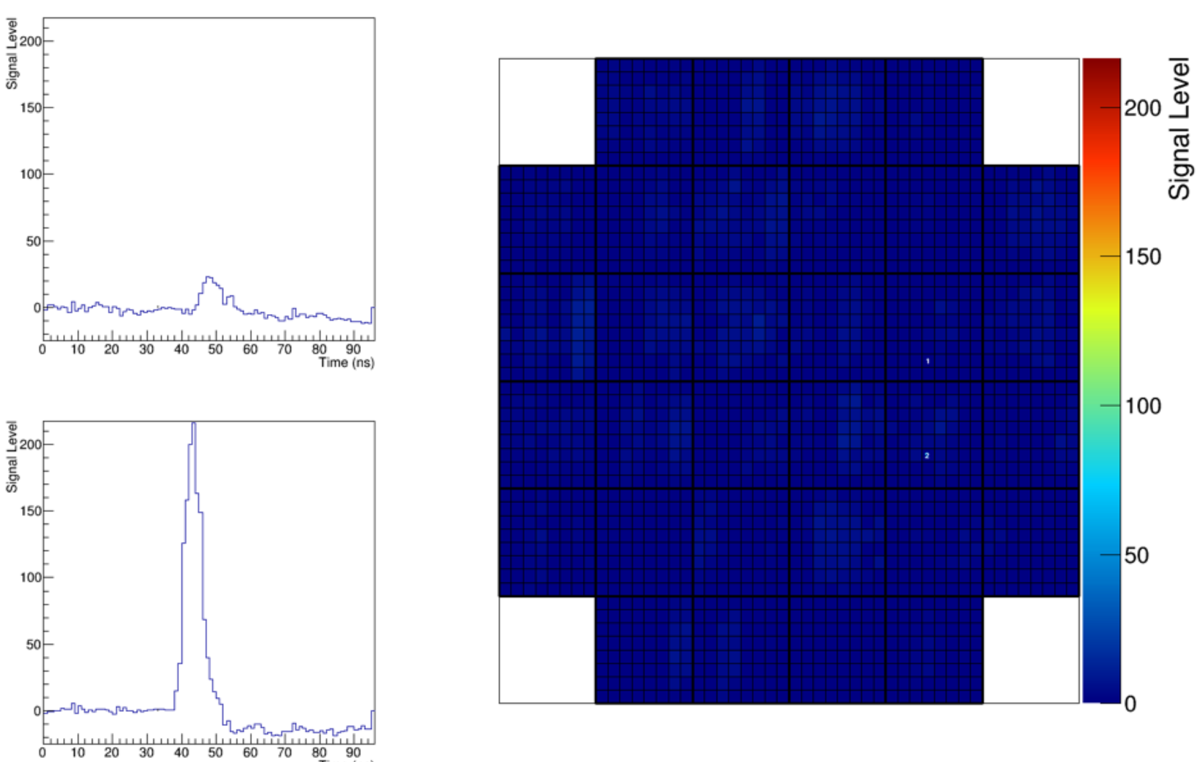


- 100 telescopes in Chile
  20 telescopes on La Palma
  (site negotiations still ongoing)
- International consortium with already 30 countries and 1000 astronomer members
- Cost ~ 300 M$
- **Open observatory with guest observers and archive**, as is common in other wavelengths.
- Prototype telescopes taking data. Array construction starts **2017**. Full array operational ~ **2024**.

CTA — BIG AND SMALL DATA



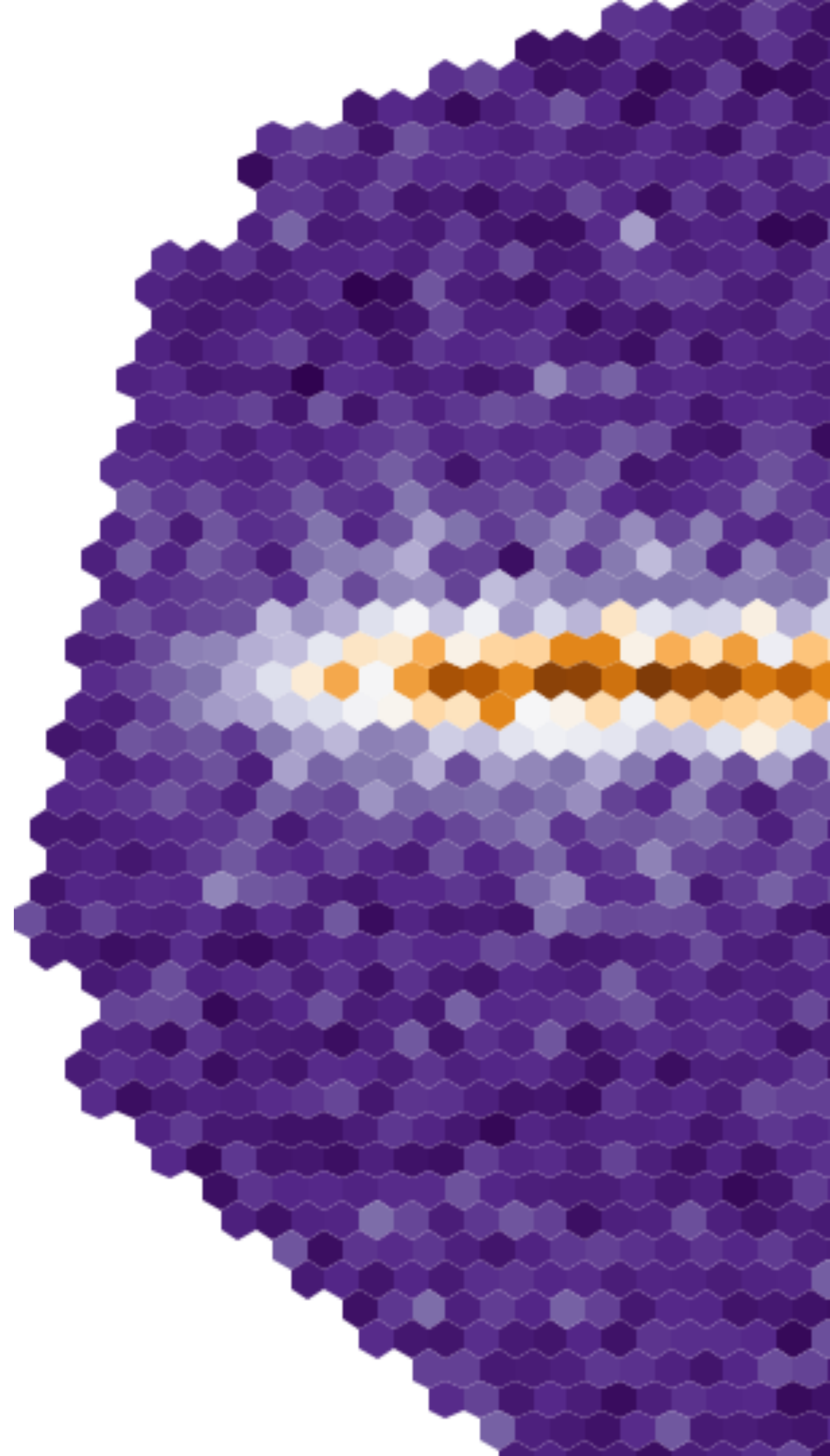
One of the first observed events from a CTA prototype telescope (~ ns time resolution)

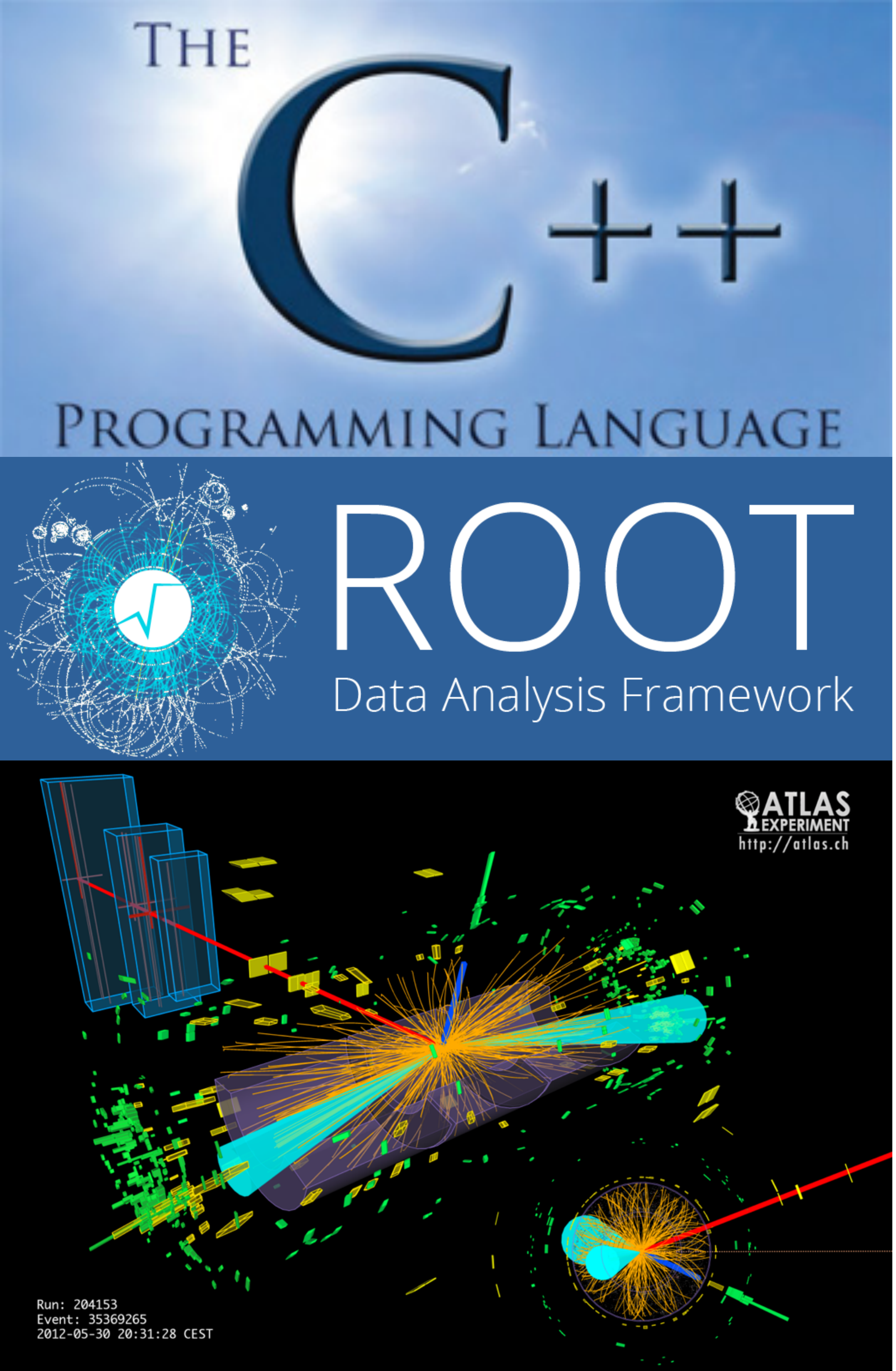


- Raw data consists of images or little movies of air showers
- Raw data rate is ~ 10 GB / s
  Big data!
- Data center: low-level **CTA pipeline** for calibration, event reconstruction, gamma-hadron separation.
- Results in much-reduced dataset: event list with just a few parameters per event (time, energy, RA, DEC)
  Small data!
- Astronomers, on their laptop with downloaded FITS data (like Fermi-LAT today): high-level **CTA science tools** for source detection as well as time, spatial and spectral analysis.

CODES
C++
PYTHON

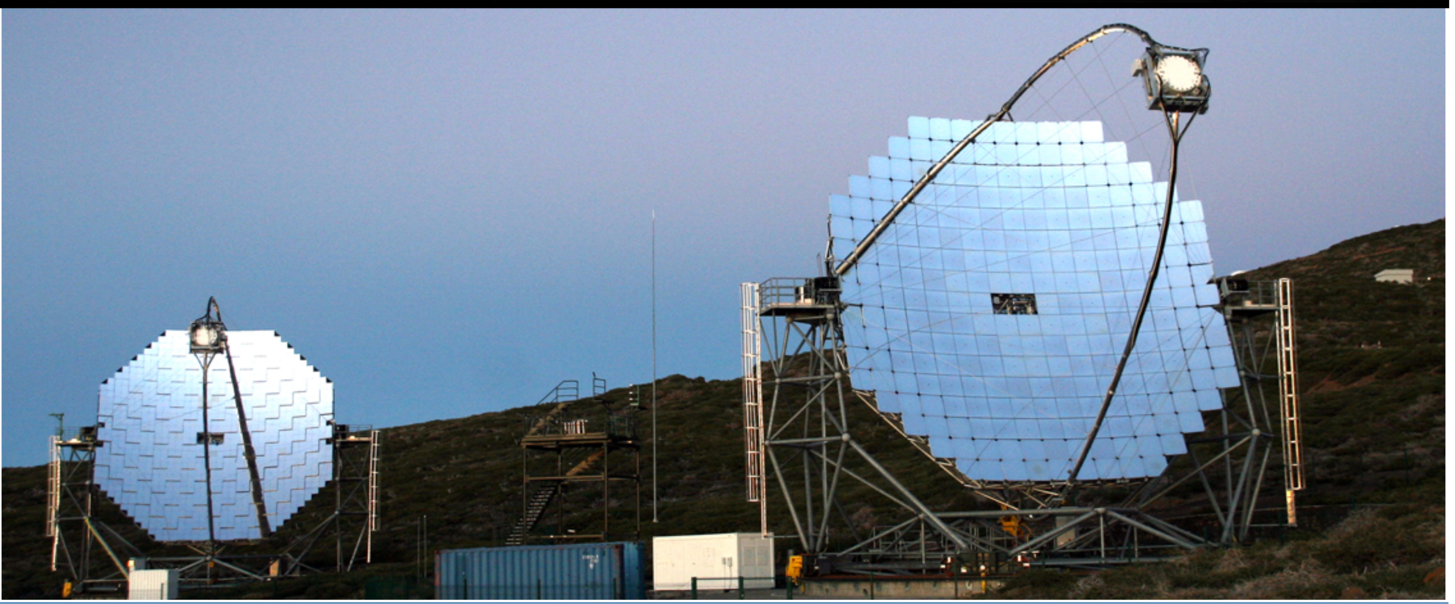
in gamma-ray astronomy





C++ & ROOT

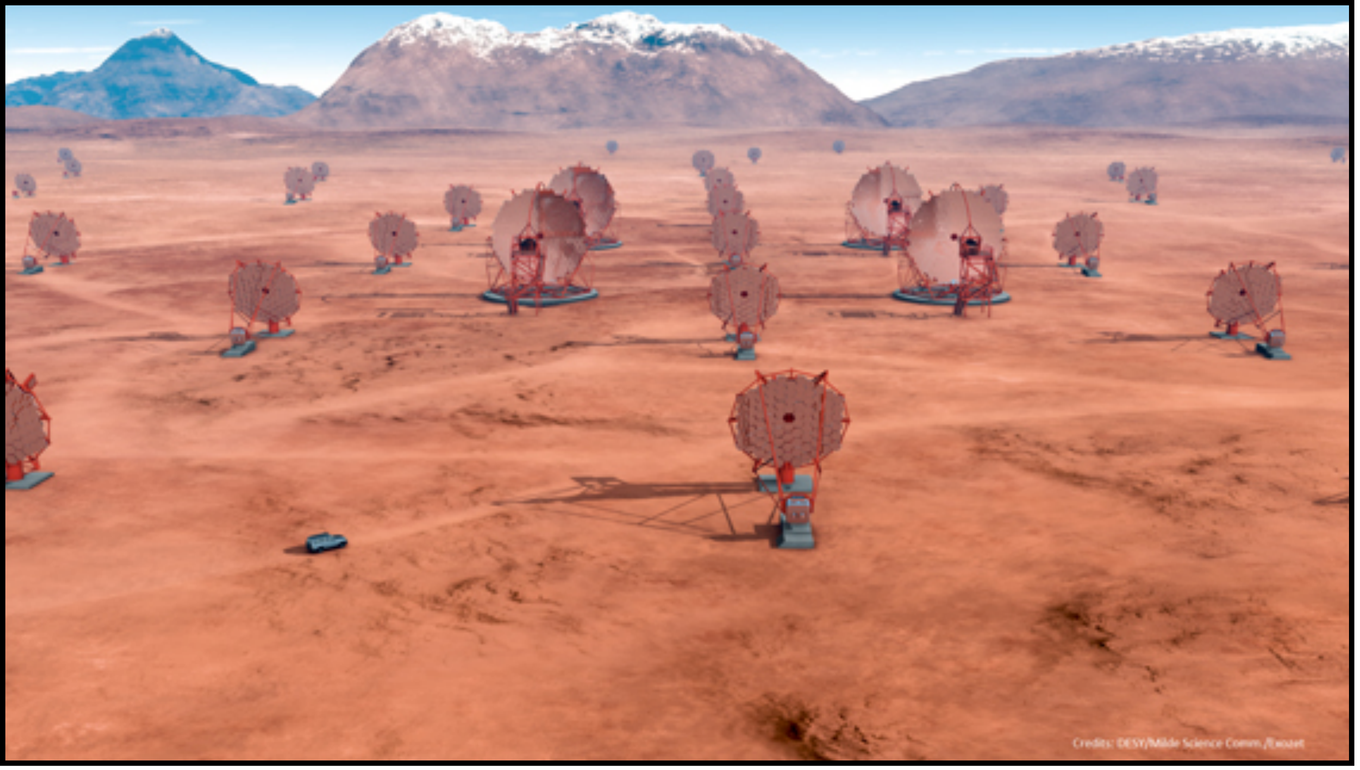
- For the past decades, gamma-ray astronomy was mostly done by people from high-energy physics.
- For the past ~ 20 years until very recently , this meant C++ & ROOT
- ROOT provides everything!
  - Scientific computing library
  - I/O (auto C++ object serialisation)
  - GUI framework
  - Interactive REPL and scripting (ACliC, now Cling)
  - Python interface PyROOT (fancy auto wrapper generator, using ROOT introspection, not SWIG).

STATUS

- Ground-based gamma-ray telescopes have proprietary software (C++ & ROOT, no Python) and data formats (serialised ROOT objects).
- Space-based gamma-ray telescopes (at least Fermi-LAT) have C++ & ROOT-based low-level pipeline, but the astronomer gets:
  - Data in FITS format
  - Science tools are C++ with SWIG Python wrapper

CTA SOFTWARE?



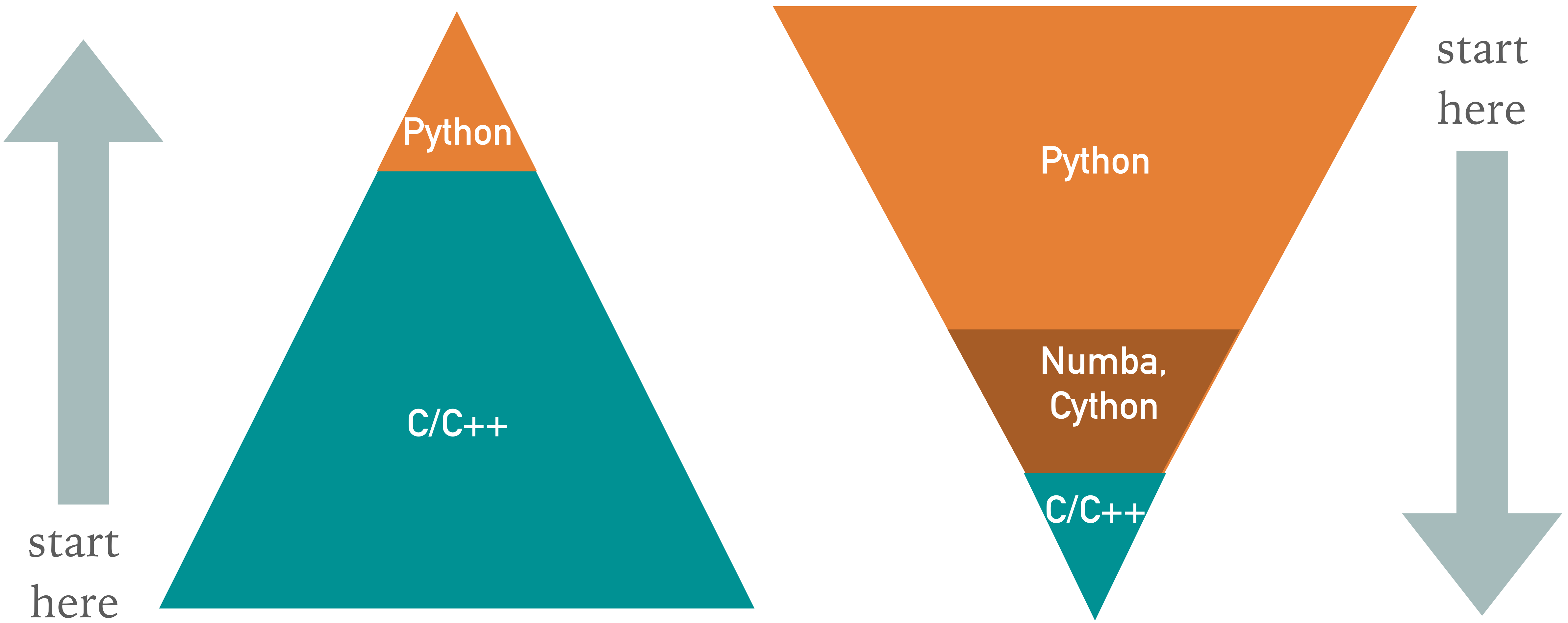
CTA SOFTWARE

- Very active development ongoing for low-level and high-level software.
- Many ideas and prototypes by different groups.
- Making decisions and going toward production codes is hard because so far no strong central management (CTA is not an ESO project).
- It looks like most CTA software will be **C, C++ or Python**.
  (Also Java used for array control.)
- Somewhat surprisingly: **not ROOT**!
  (HEP -> astro community change?)

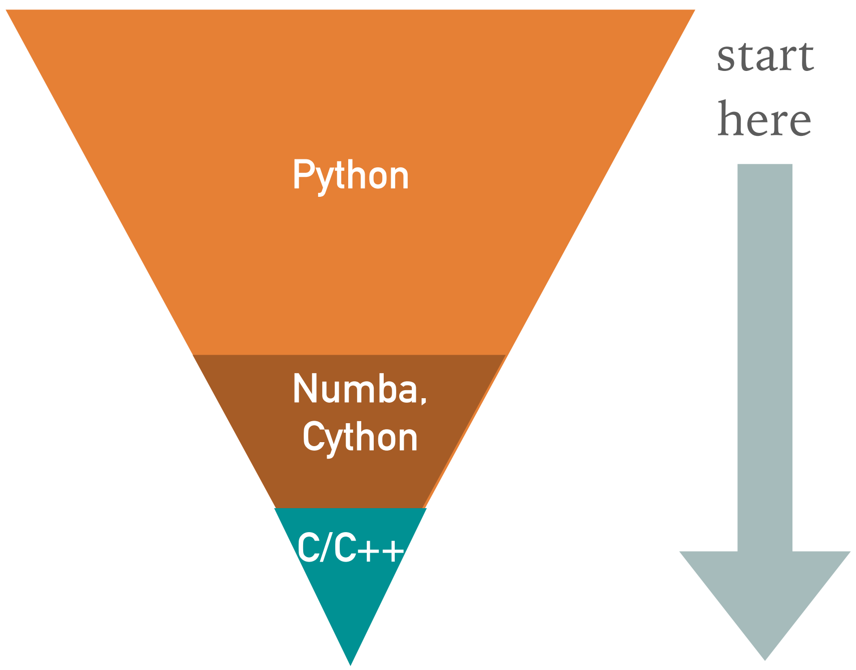
python™

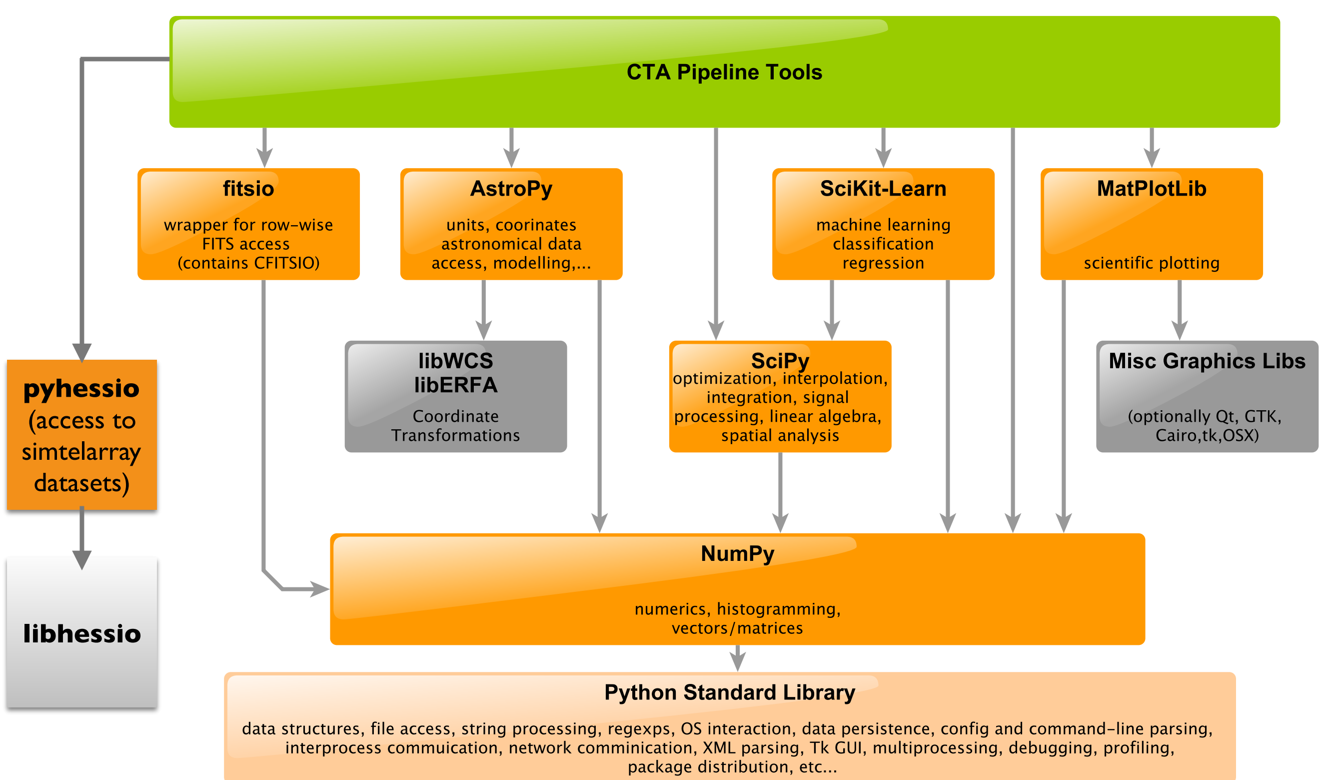
A MAJOR QUESTION FOR CTA

Bottom-Up approach **Top-Down approach**



Top-Down approach



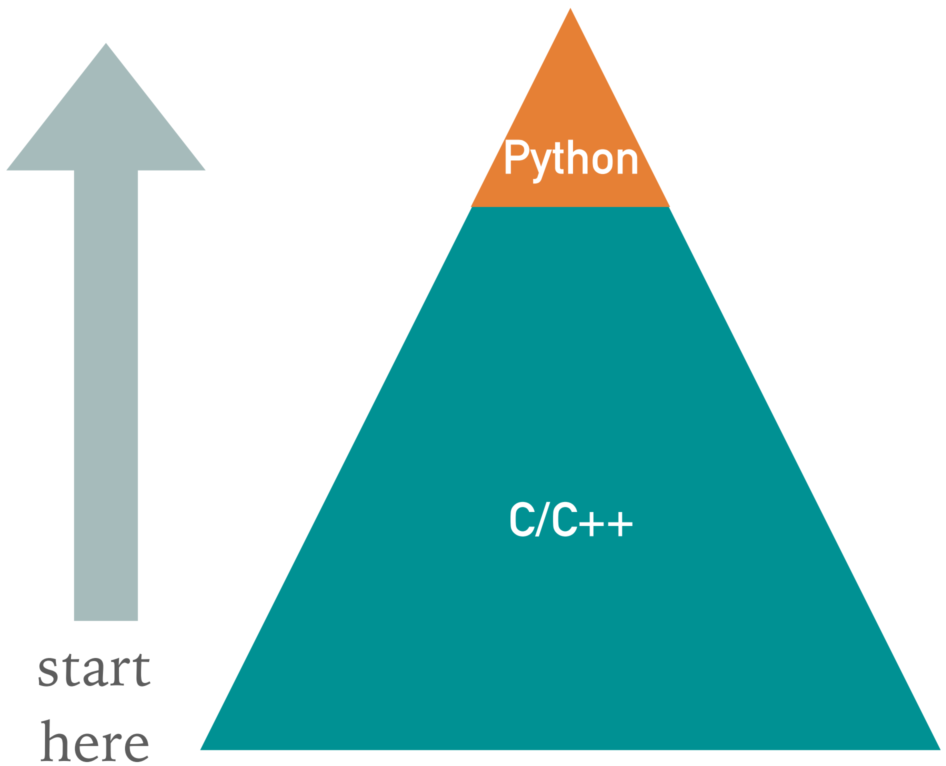


CTAPIPE

- CTA offline analysis Python pipeline prototype.
- Python package, built on Scientific Python stack and Astropy, started from Astropy affiliated package template.
- Open-source and on Github as cta-observatory/ctapipe.
- Chosen over many C and C++ based proposals and prototypes. Still a bit controversial if Python is efficient enough.
- Python 3 only!

GAMMALIB & CTOOLS

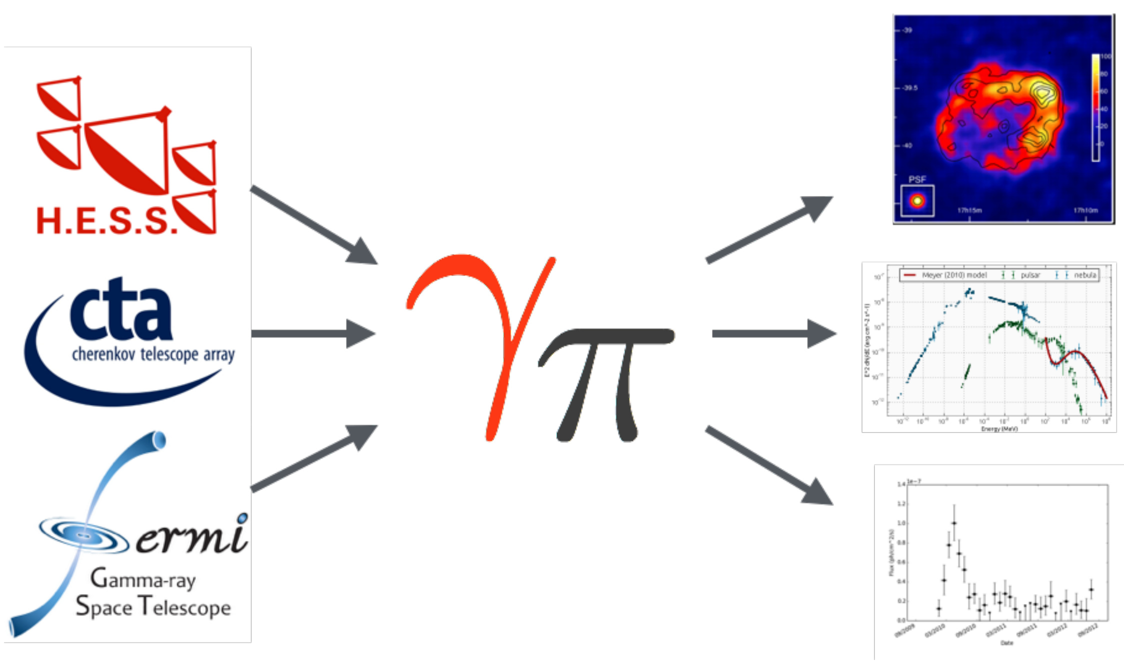
Bottom-Up approach



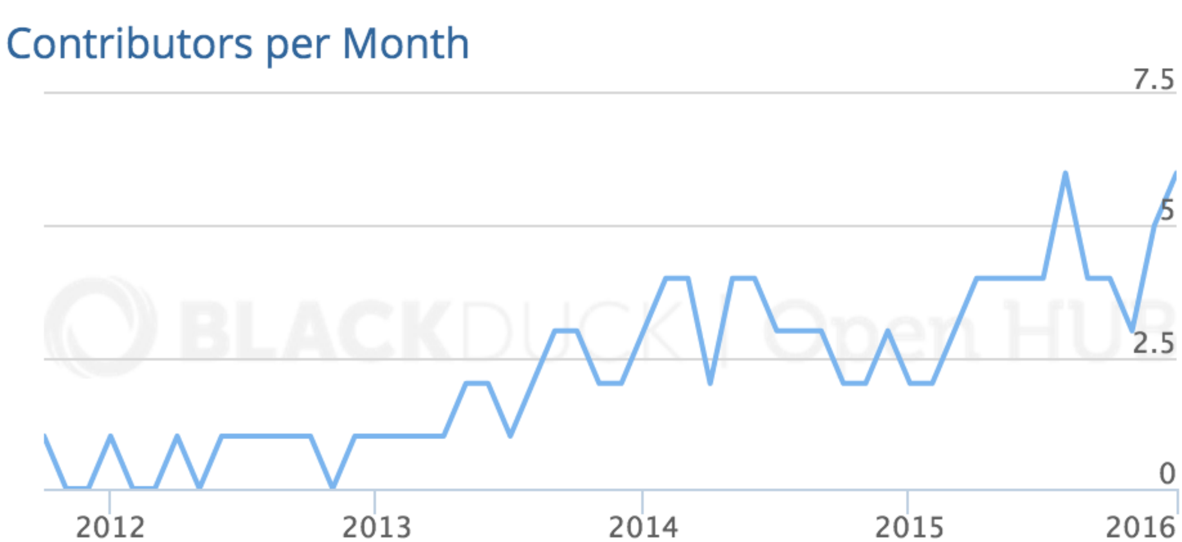
- C++ with SWIG Python wrapper
- Gammalib
  - generic library for gamma-ray event data, with instrument modules for CTA, Fermi-LAT, …
  - No dependencies (except CFITSIO) for easy long-term maintenance.
  - 120k SLOC
- ctools
  - software tools (like FTOOLS) for IACT analysis implemented using Gammalib
  - is being proposed as a prototype for the official CTA science tools

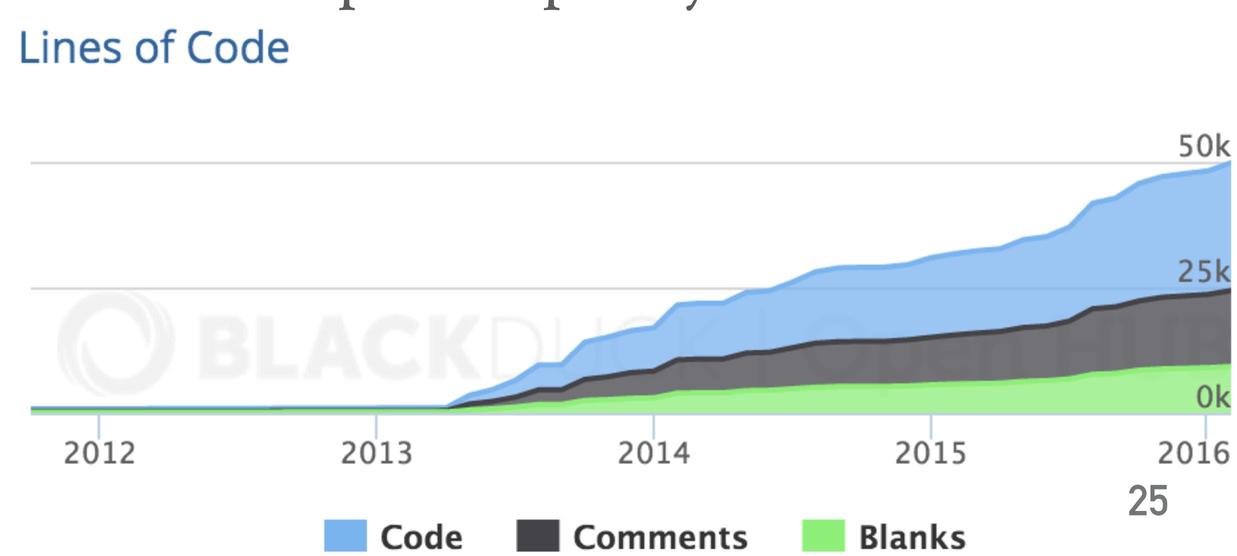
GAMMAPY

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



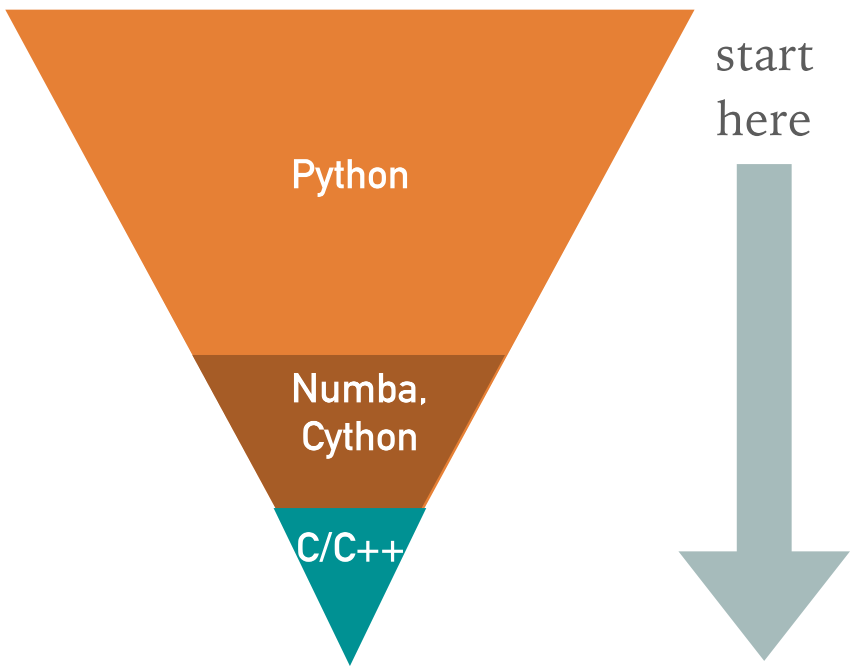
- Python package for gamma-ray science tools data analysis (provisionally accepted as an Astropy-affiliated package)
- Produce images, spectra, light curves for event data from telescopes such as H.E.S.S., CTA or Fermi-LAT.
- Fermi analysis directly or via Fermipy & Fermi ScienceTools.
- Development pretty active

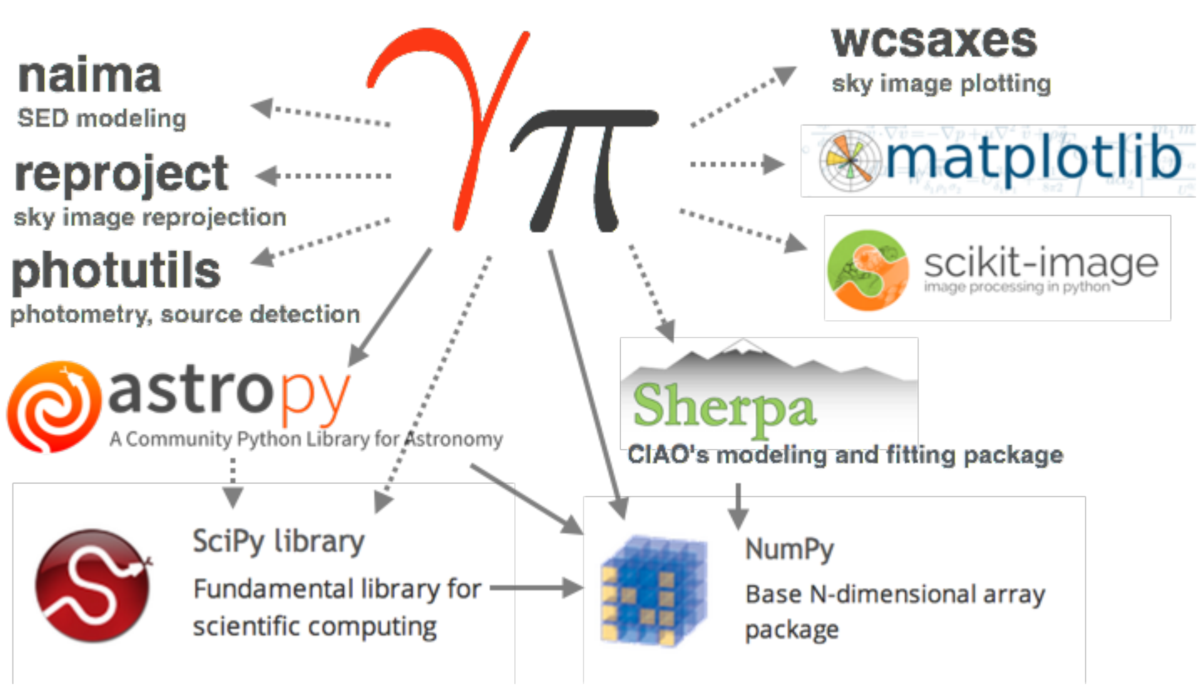




GAMMAPY

Top-Down approach





- Python first and use dependencies:
  - Builds on **Astropy** and **Sherpa**, as well as **Naima**, **Fermipy** and a few other packages like **reproject** or **photutils**.
  - Similar to ctapipe approach, different from Gammalib / ctools
- So far mainly used for research with H.E.S.S. data exported to FITS.
- Could propose as prototype for official CTA science tools.
- Plan: 1.0 release this summer, a paper in summer or fall.

GAMMAPY DEVELOPMENT

We use the awesome and free tools and infrastructure like Astropy and most open-source Python packages these days …

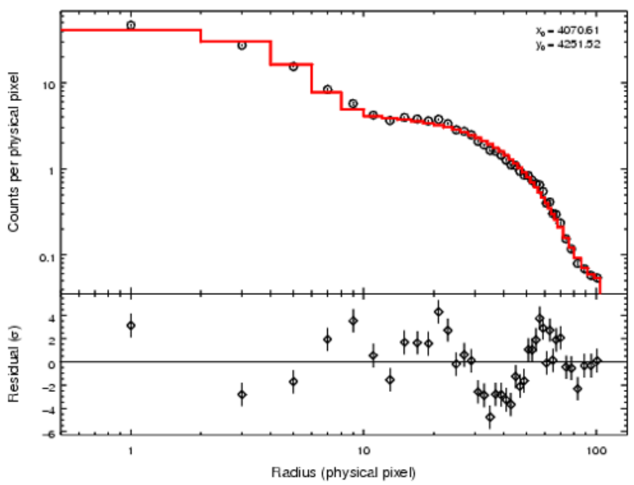
GitHub — Version control, issue tracker,
contributions via pull requests & code review

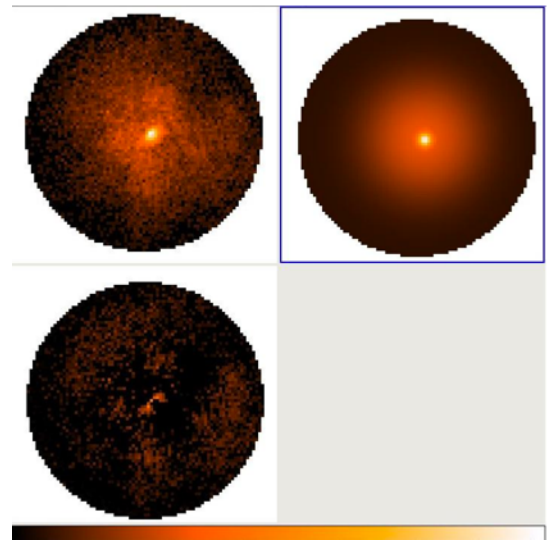
Tests automatically run on Linux & Mac
on each pull request and master branch — Travis CI

pytest — Python testing framework
(makes it easy to write and run tests)

Python documentation generator
API and narrative docs pages
cross-linked, full-text search — Sphinx

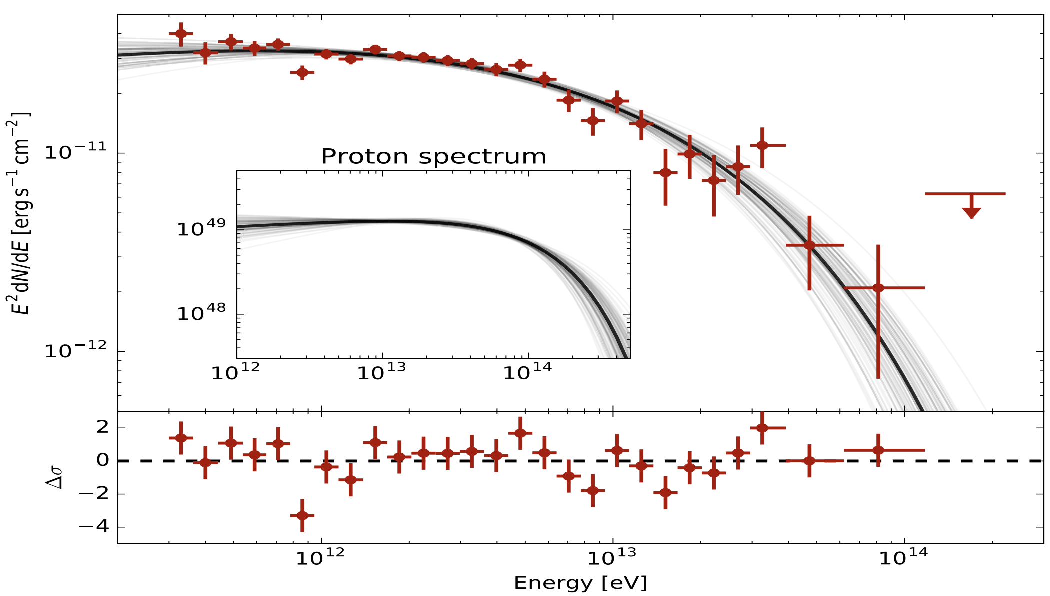
Anaconda — Binary cross-platform package manager.
Install Gammapy and all dependencies on any Linux & Mac box in $HOME in 10 min.





SHERPA

➤ Awesome general modeling and fitting package (similar, but different from astropy.modeling)



NAIMA

➤ Astropy-affiliated package for non-thermal SED modeling. Fitting using emcee or Sherpa

```
data:
  evfile : ft1.lst
  scfile : ft2.fits

binning:
  roiwidth   : 10.0
  binsz      : 0.1
  binsperdec : 8
```

```
from fermipy import GTAnalysis

gta = GTAnalysis('config.yaml')
gta.setup()
gta.fit()
gta.print_roi()
```

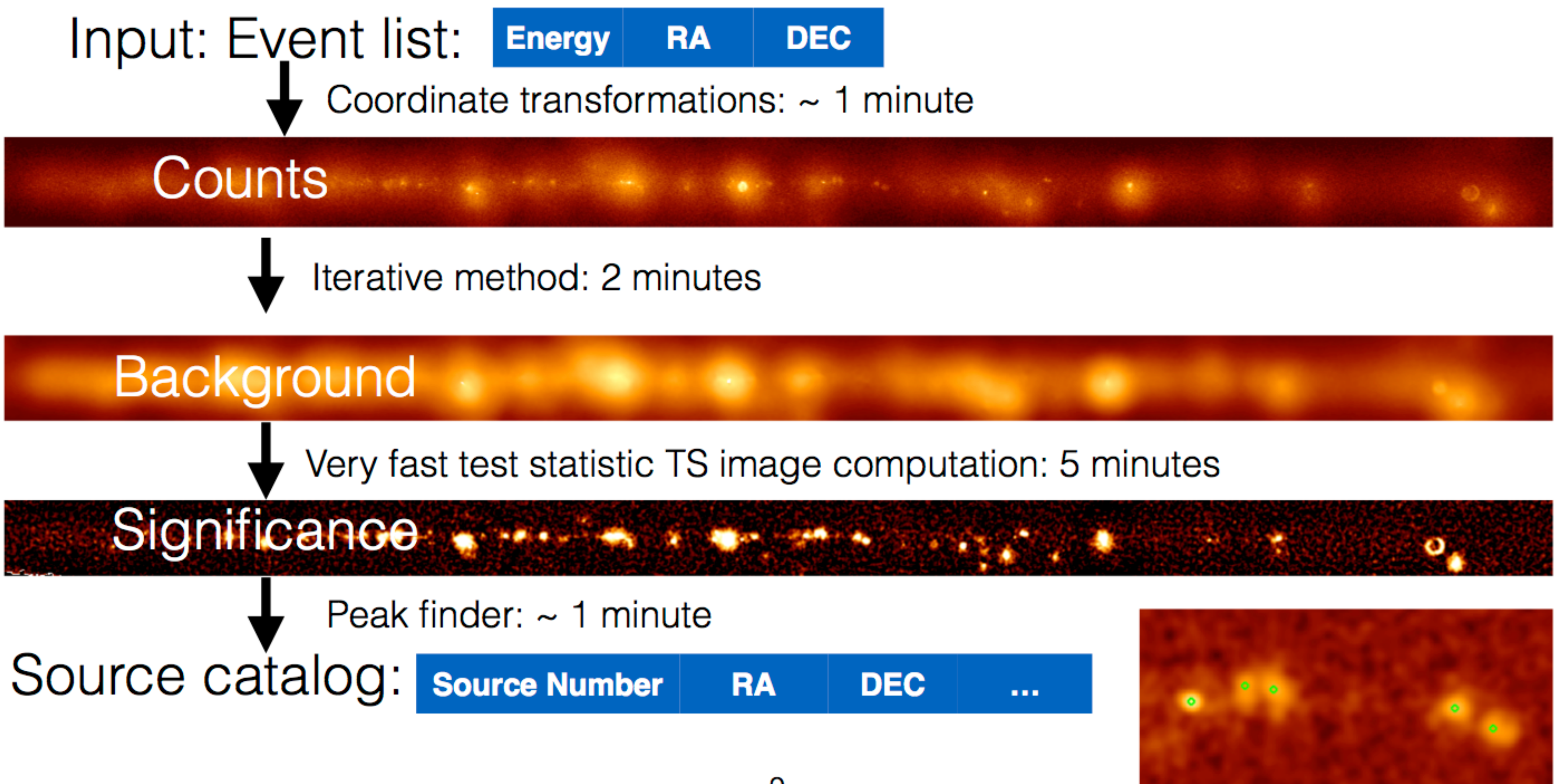
FERMIPY

➤ Fermi-LAT data analysis for humans (using Fermi ScienceTools SWIG Python interface in the background)

All open-source, open-development projects on Github!

GAMMAPY APPLICATION EXAMPLE

With very little Python code, go from an event list to a source catalog for the H.E.S.S. Galactic plane survey.

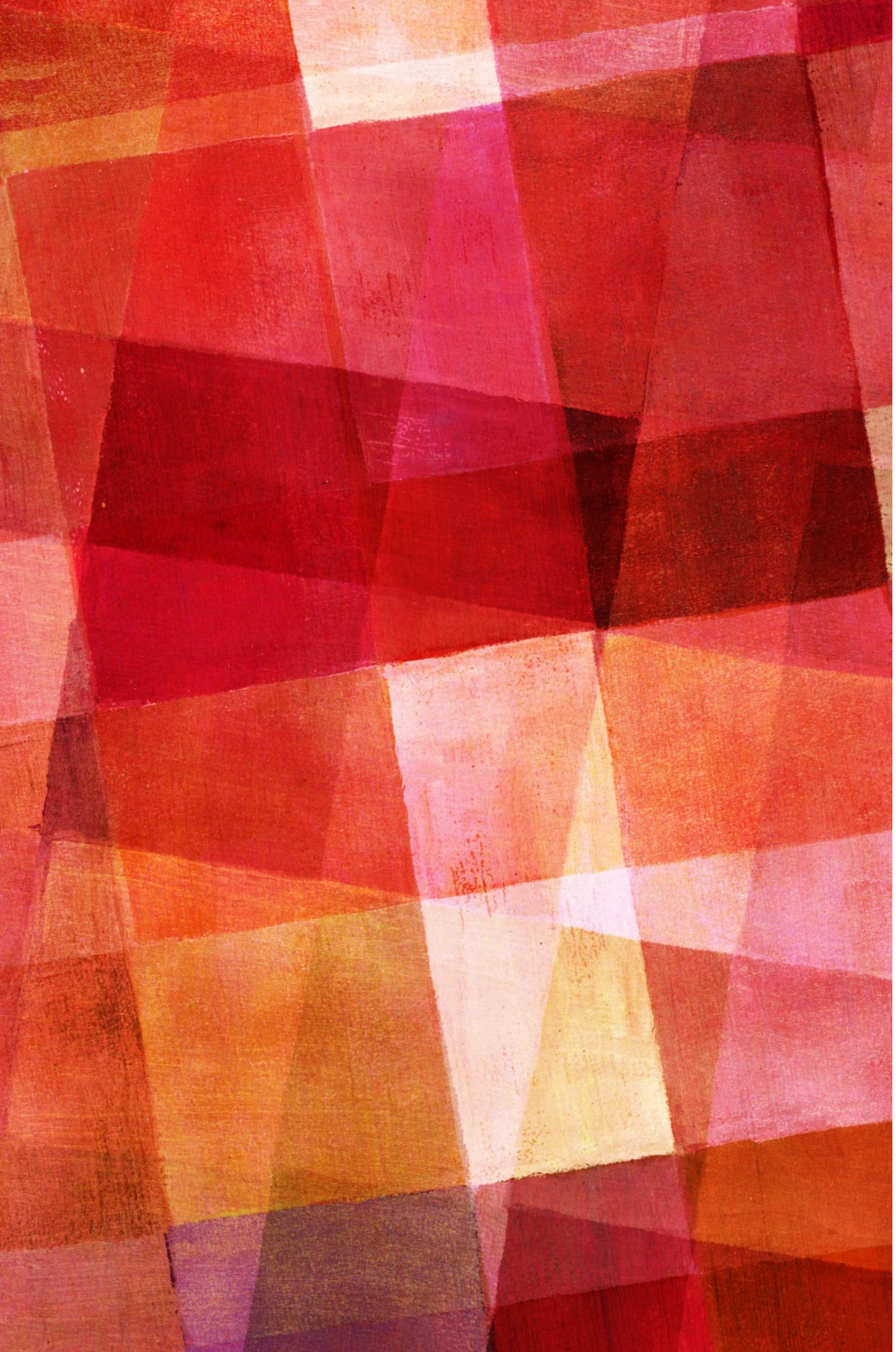


WRAP-UP

Python in gamma-ray astronomy

SUMMARY

- **Space- and ground-based gamma-ray observations are used to study cosmic particle accelerators and the non-thermal universe.**
- Ground-based gamma-ray astronomy is so far done with C++ / ROOT based codes in collaborations (no public data or software access).
- **The Cherenkov Telescope Array (CTA) is coming**
  - **Open observatory and data, open-source software.**
  - Competing concepts on C / C++ / Python software and dependency stack are being prototyped and proposed.
- Open-source codes using scientific Python stack and Astropy: ctapipe, Gammapy, Naima, Fermi



THANK YOU!

- For organising PyAstro16!
- For the opportunity to give this presentation.
- For building the Astropy package and community!
- For providing and maintaining important infrastructure for Python and astronomy
  - Astropy core
  - package template
  - ci-helpers
  - Astropy conda channel


Comments?
Questions?
(c) F. Acero & H. Gast

BACKUP SLIDES

SIDE COMMENT: OPEN IACT DATA EFFORT

- “Python in gamma-ray astronomy” workshop, November 16 — 20, 2015, MPIK Heidelberg http://gammapy.github.io/PyGamma15/
- Agreed to start an open gamma-ray astronomy effort: https://lists.nasa.gov/mailman/listinfo/open-gamma-ray-astro https://github.com/open-gamma-ray-astro
- Open IACT DL3 specifications (Github & Readthedocs)
- IACT DL3 meeting in Meudon in April 2016 (participants from all existing IACTs and CTA)

GAMMAPY SOFTWARE CHALLENGES

- Decide how to do modeling / fitting?
  Sherpa, or astropy.modeling, or roll our own?
- How to structure the functionality into sub-packages so that it makes sense and circular imports are avoided.
- Which patterns to use to implement analysis workflows?
  - Where to use functions? classes? config objects? results objects?
  - How to expose this both as a Python API and as command line tools?
- Software distribution (e.g. no conda package for Fermi ScienceTools yet, conda packages for Healpy, Sherpa, … changing).