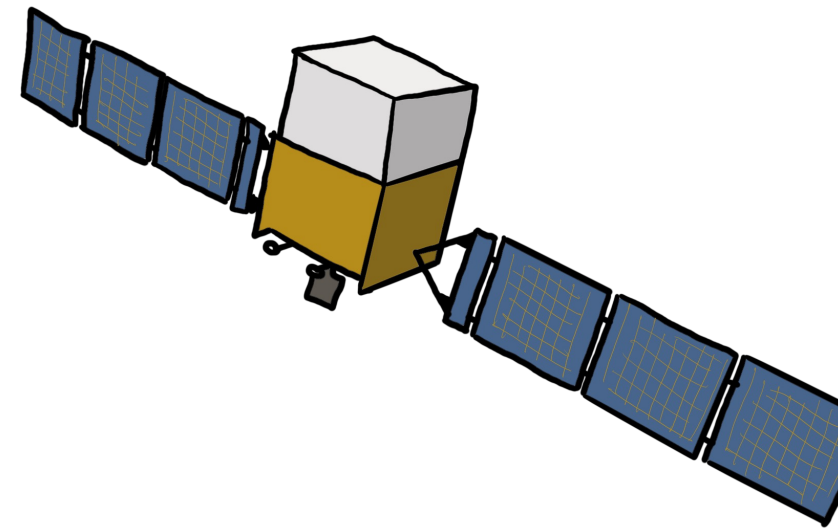


Lecture 11.



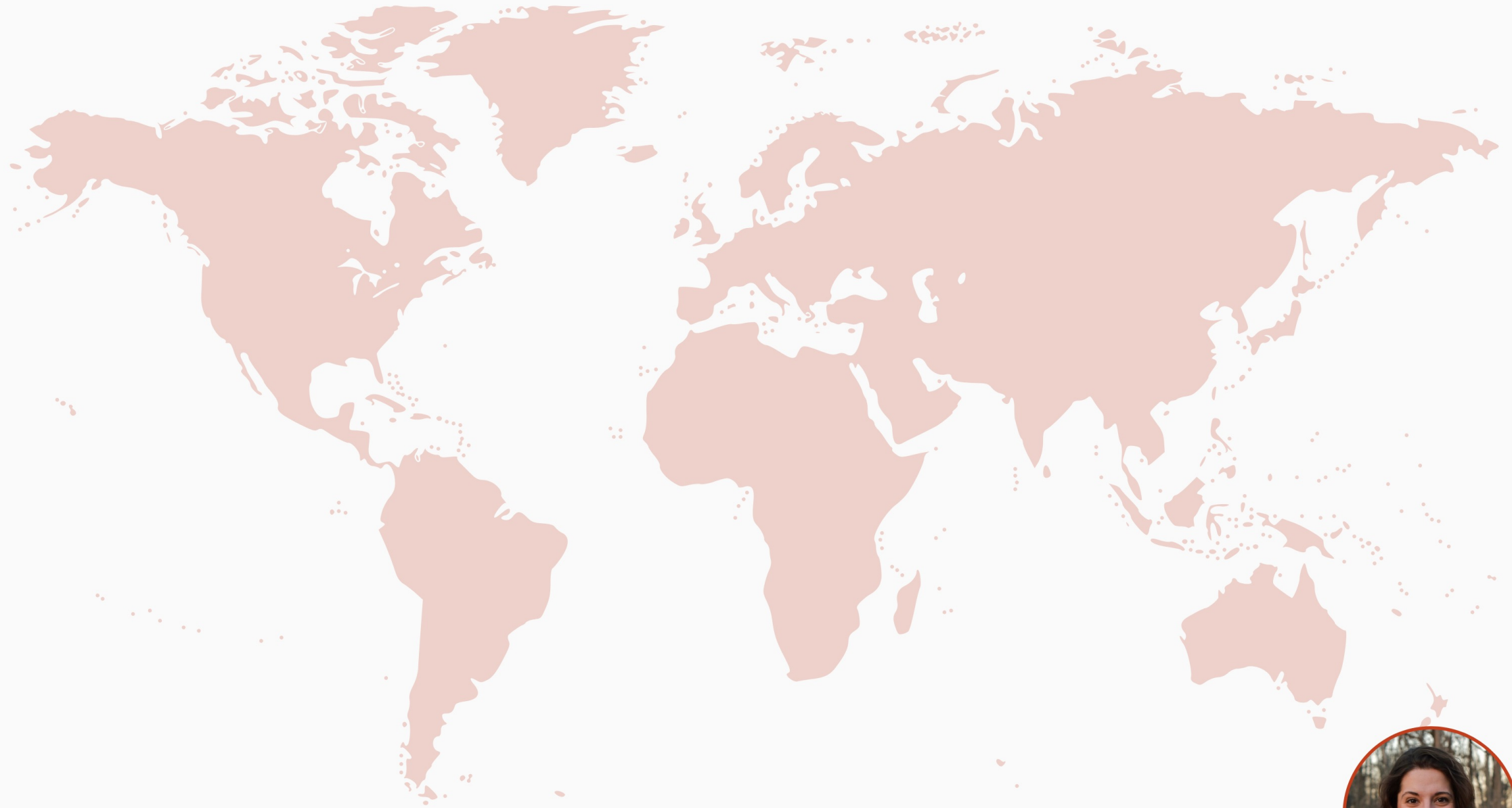
Analyzing Gamma-Ray Data

using `fermipy` and `gammapy`

Milena Crnogorčević

Guest Lecturer

milena.crnogorcevic@fysik.su.se





**BORN IN
MONTENEGRO**



1994





*BORN IN
MONTENEGRO*

*HIGH SCHOOL
IN HONG KONG*



1994

2011





MIDDLEBURY COLLEGE

First research experiences:

- QFT in curved geometries
- Galaxy/SMBH coevolution

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IN HONG KONG

1994

2011

2013

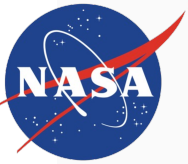


MIDDLEBURY COLLEGE

UNIVERSITY OF MARYLAND

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MONTENEGRO

HIGH SCHOOL
IN HONG KONG



1994

2011

2013

2017

MIDDLEBU

UNIVERSITY OF MARYLAND



PhD Advisors:
Dr. Regina Caputo
Prof. Manuel Meyer

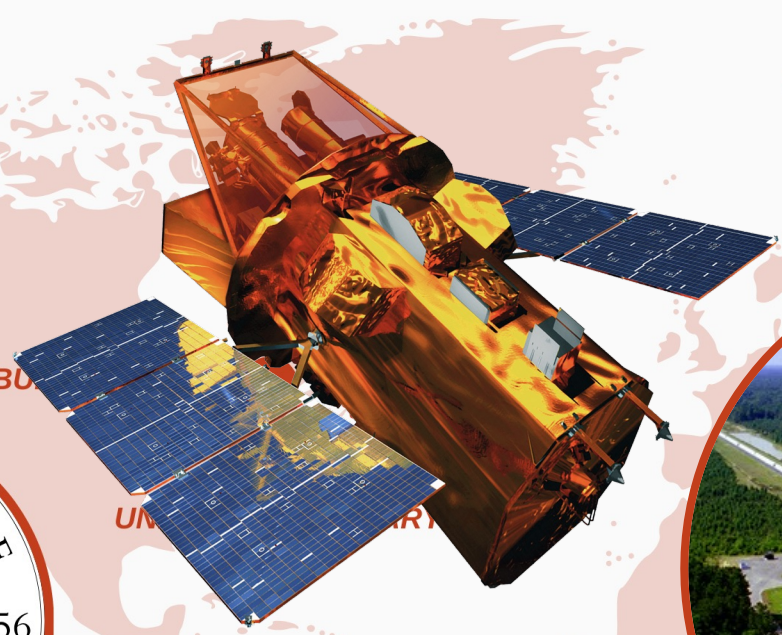


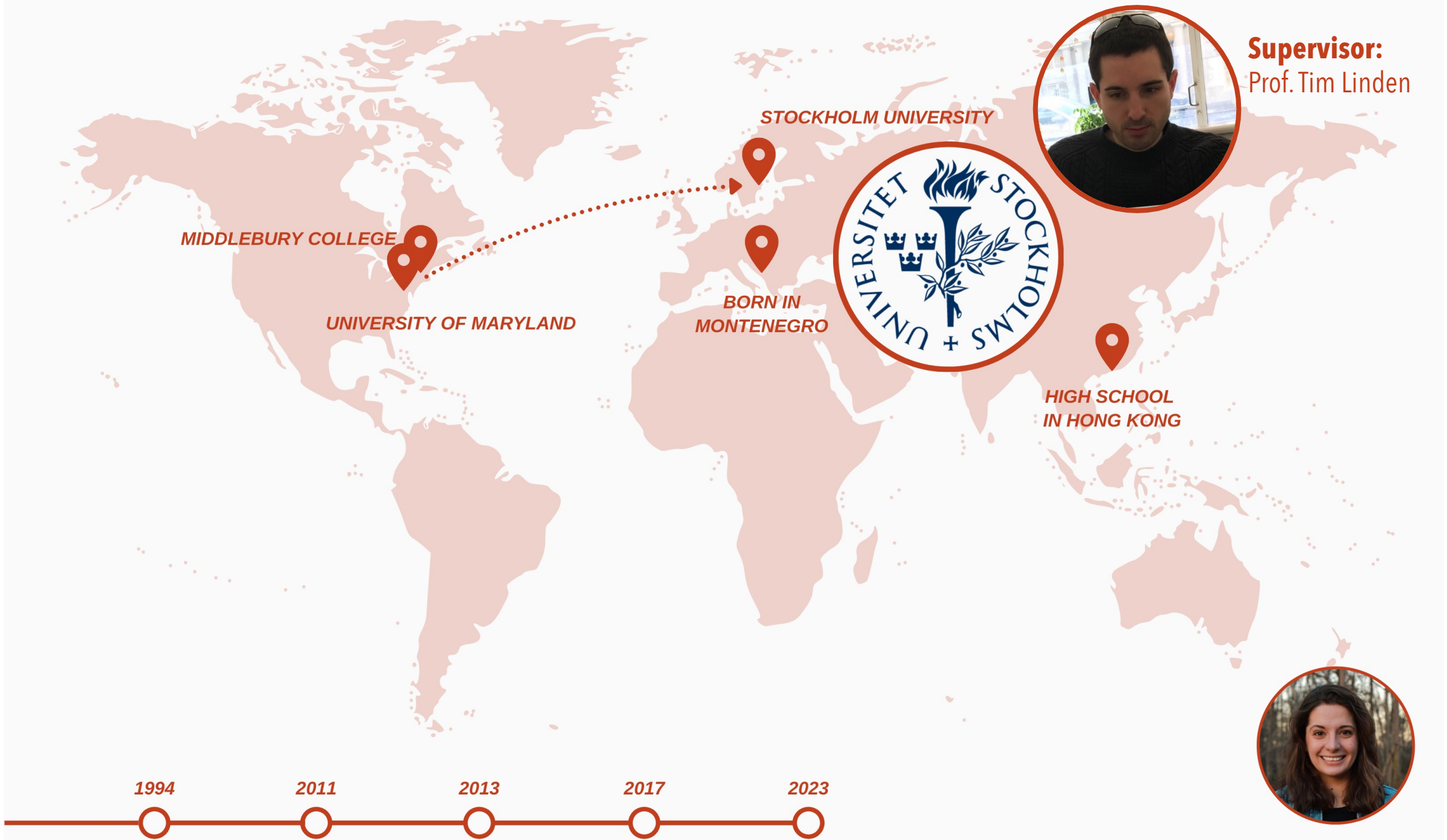
1994

2011

2013

2017





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BORN IN
MONTENEGRO

STOCKHOLM UNIVERSITY



HIGH SCHOOL
IN HONG KONG



Supervisor:
Prof. Tim Linden



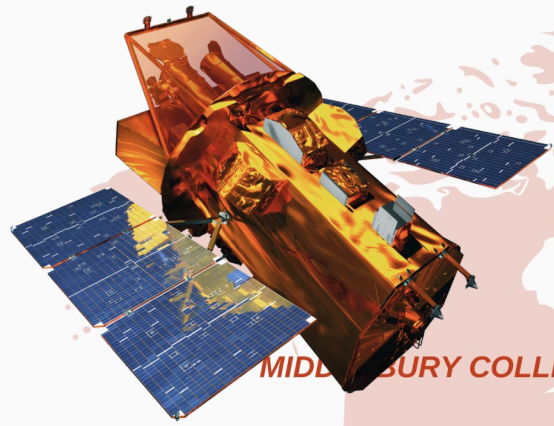
1994

2011

2013

2017

2023



MIDDLEBURY COLLEGE

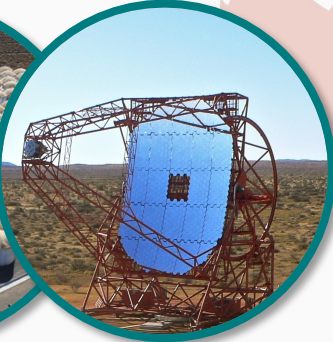
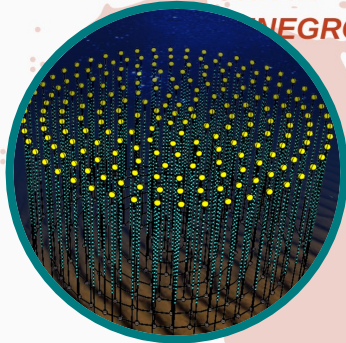
UNIVERSITY

STOCKHOLM UNIVERSITY

BORN IN
NEGRO



Supervisor:
Prof. Tim Linden



1994

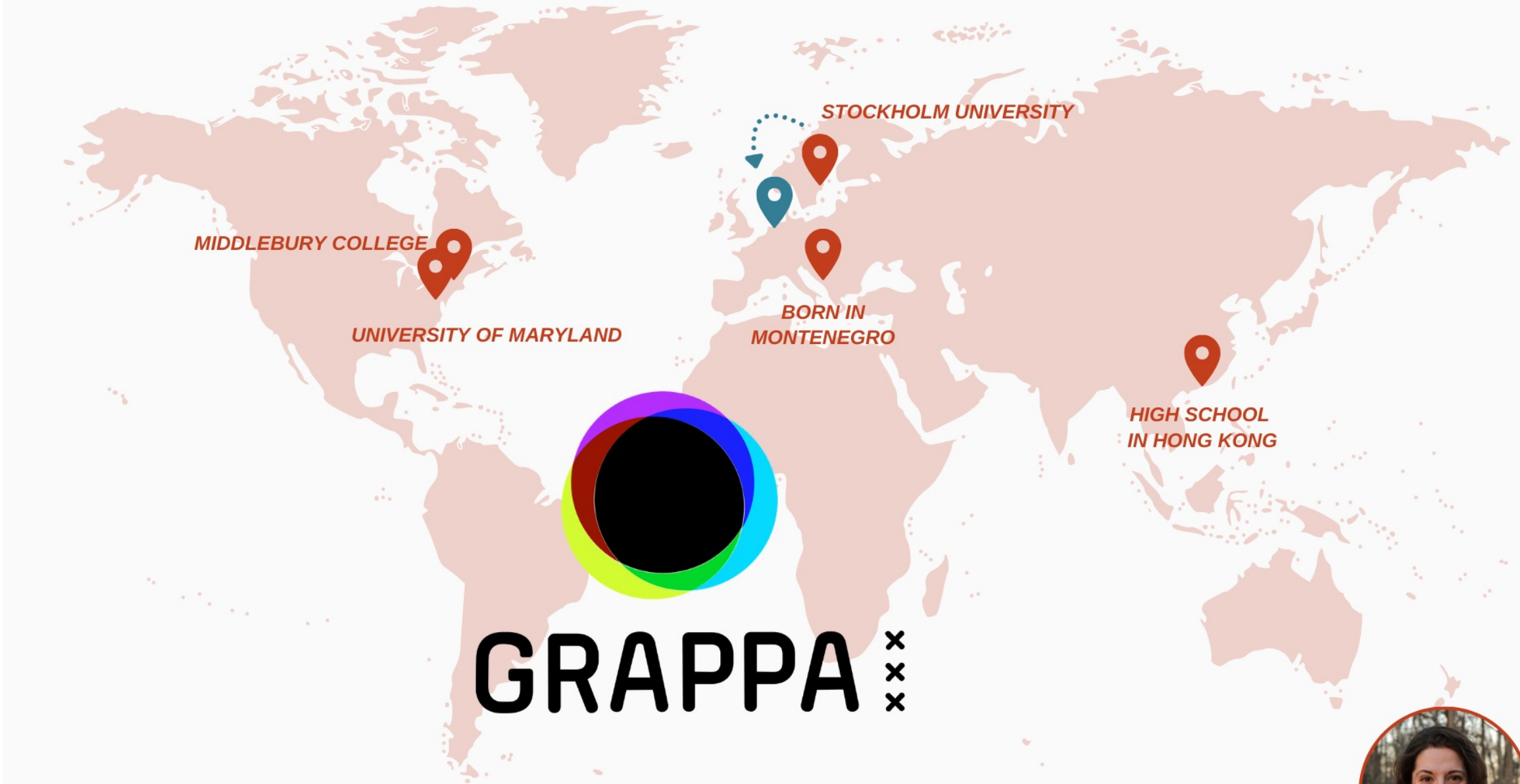
2011

2013

2017

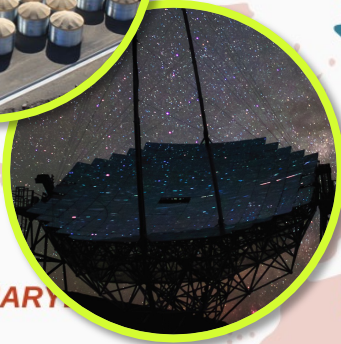
2023





GRAPPA ^x_x_x





Prof. Shin'ichiro Ando



Prof. Christoph Weniger



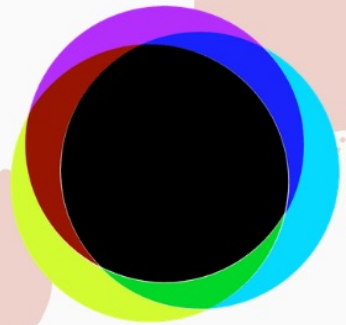
Prof. Gianfranco Bertone



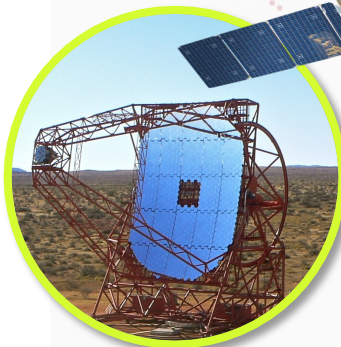
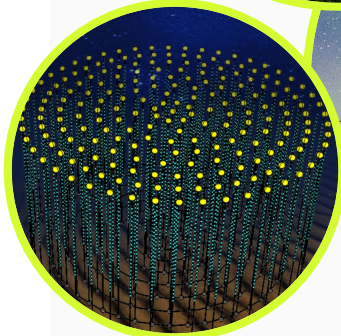
STOCKHOLM

BORN IN MONTENEGRO

HIGH SCHOOL IN HONG KONG



GRAPPA ^x_x_x



1994

2011

2013

2017

2023

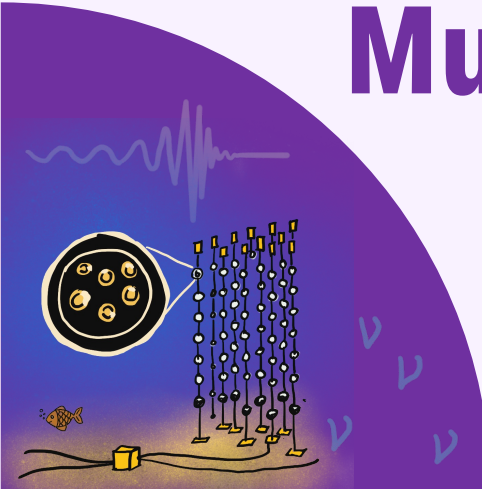
October 2026



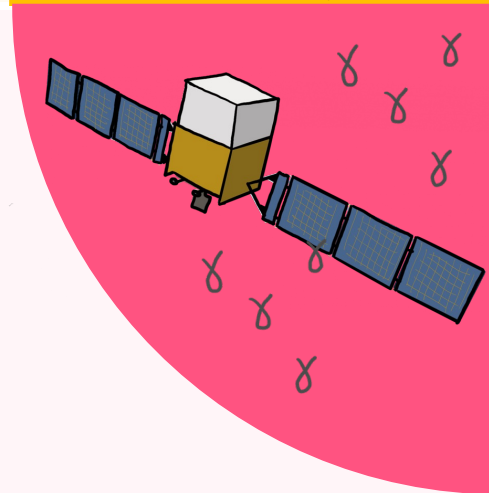
**Dark Matter
& New Physics**



**Multimessenger
astronomy**



**Gamma-ray
astronomy**



**Service
& Outreach**



Today:

1. Understanding of how a gamma-ray analysis is actually done
2. Getting familiar with the *Fermi*-LAT data and where to go if you want to find more information
3. Knowing which tool to reach for: Science Tools/Fermipy/Gammapy/else
4. Perform your own (customized) analysis

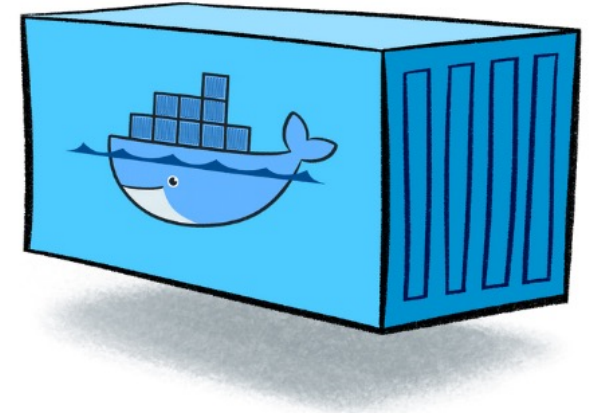
Today:

1. Understanding of how a gamma-ray analysis is actually done
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3. Knowing which tool to reach for: Science Tools/Fermipy/Gammapy/else
4. Perform your own (customized) analysis

We will analyze three real sources:

- **PG 1533+113** --- bright BL Lac (clean + isolated, end-to-end)
- **TXS 0506+056** --- the *neutrino* blazar (IceCube-170922A)
- **Crab** --- standard gamma-ray source (glimpse)

Today:



More info how to use Docker containers:
<https://docs.docker.com/get-started/>

The screenshot shows the GitHub interface for the repository 'mcrnogor / fermipy-lecture'. At the top, there are navigation tabs for 'Code', 'Issues', 'Pull requests', 'Agents', 'Actions', 'Projects', 'Wiki', 'Security and quality', 'Insights', and 'Settings'. Below the repository name, there are buttons for 'Pin' and 'Watch 0'. The main content area shows a commit history table with columns for the commit message, the commit hash and time, and the number of commits. The most recent commit is by 'mcrnogor' with the message 'cleaned up some more', hash '2d9b497', and 'now' time, containing 5 commits. The commit details table is as follows:

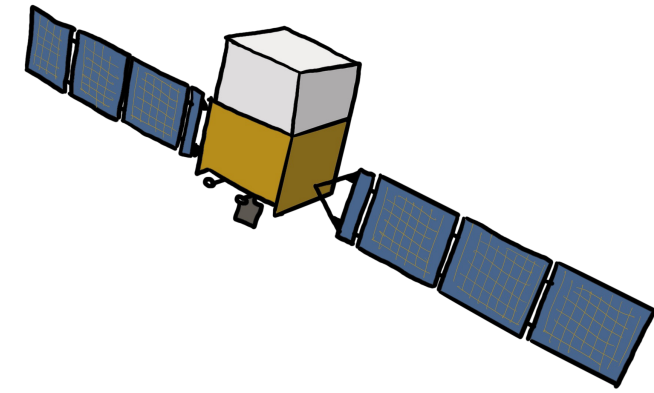
File	Commit Message	Time
lecture	cleaned up some more	now
student-environment	cleaned up	2 minutes ago
.gitignore	Initial lecture materials	39 minutes ago
LICENSE	Initial lecture materials	39 minutes ago
README.md	cleaned up	2 minutes ago

Below the commit history, there is a section for the 'README' file, which is licensed under 'MIT license'. The README content includes a link to 'Fermi-LAT analysis with fermipy and gammapy'.

<https://github.com/mcrnogor/fermipy-lecture>



Roadmap



I. recap & primer on data

Fermi-LAT
data product levels

II. Fermipy

PG 1533+113 (end-to-end)
TXS 0506+056 (lightcurve)

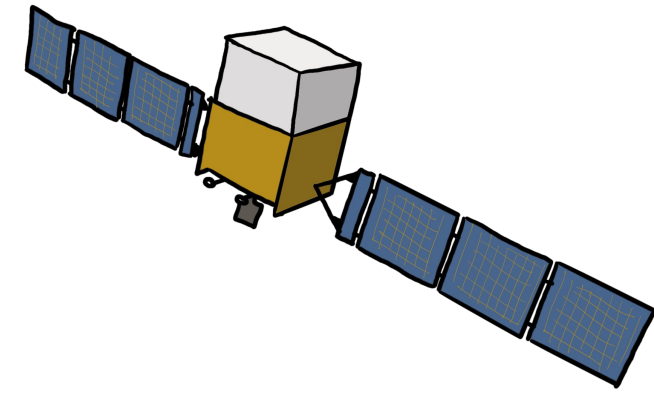
III. Gammapy

Crab

IV. Wrap-up

Big picture, when-to-use-what,
wrap-up, resources

Roadmap



I. recap & primer on data

Fermi-LAT
data product levels

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PG 1533+113 (end-to-end)
TXS 0506+056 (lightcurve)

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Crab

IV. Wrap-up

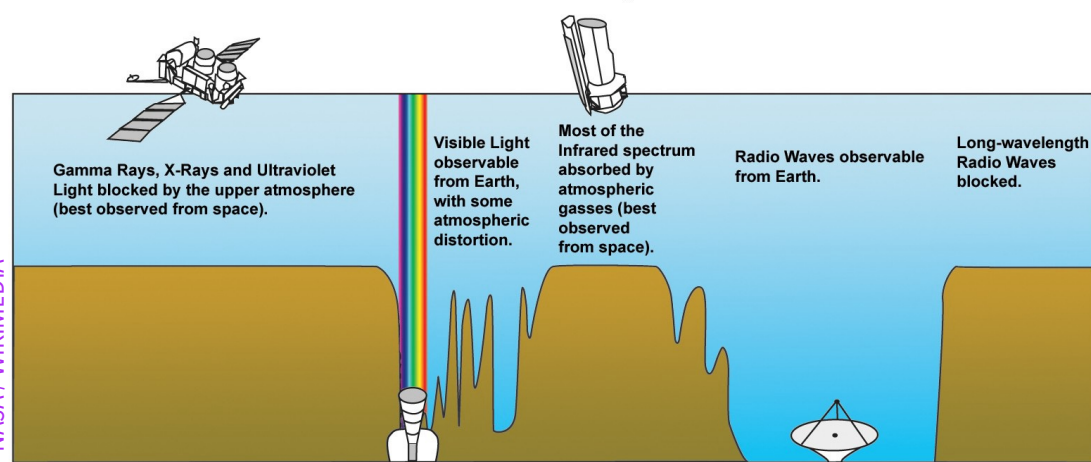
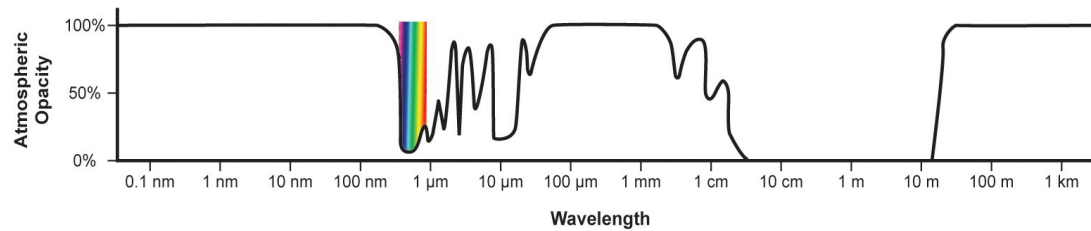
Big picture, when-to-use-what,
wrap-up, resources

Stop me. Always.

Detecting gamma rays

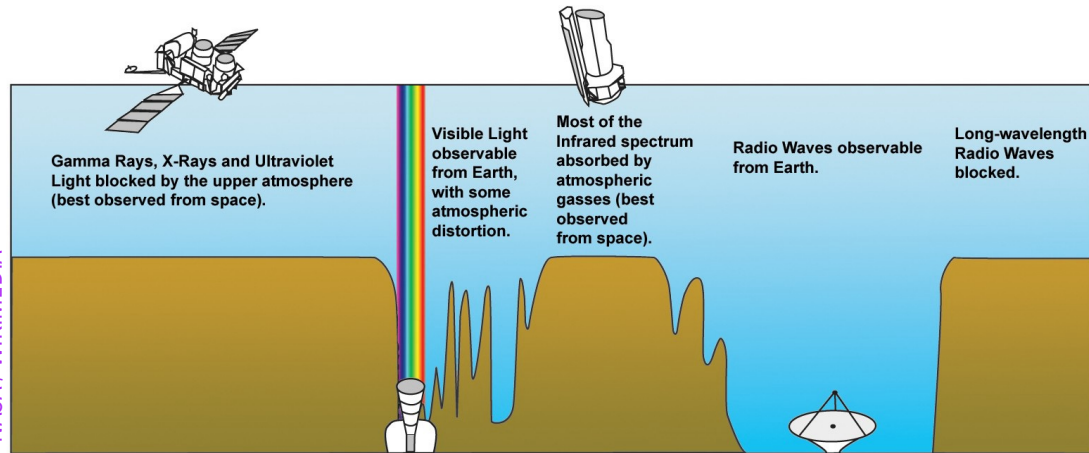
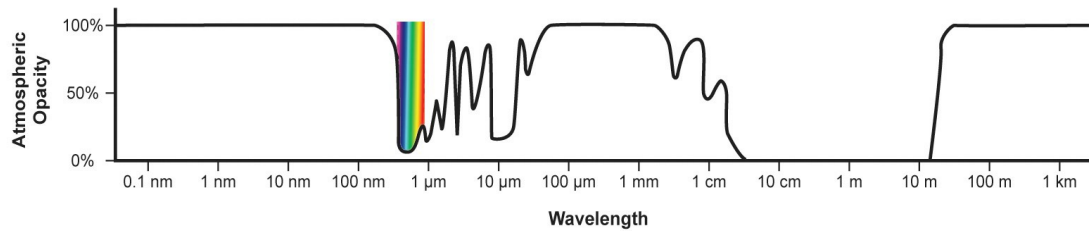
Detecting gamma rays

Challenge I. Opacity of the Earth's atmosphere



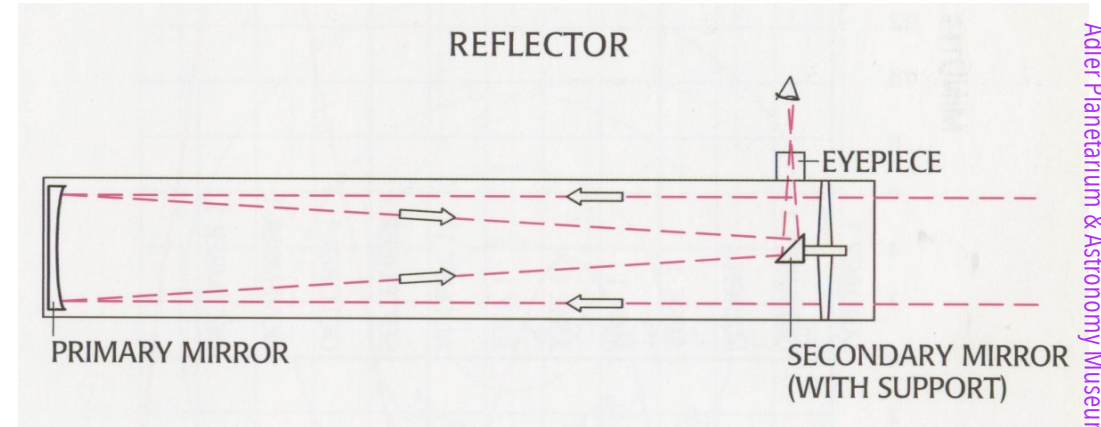
Detecting gamma rays

Challenge I. Opacity of the Earth's atmosphere

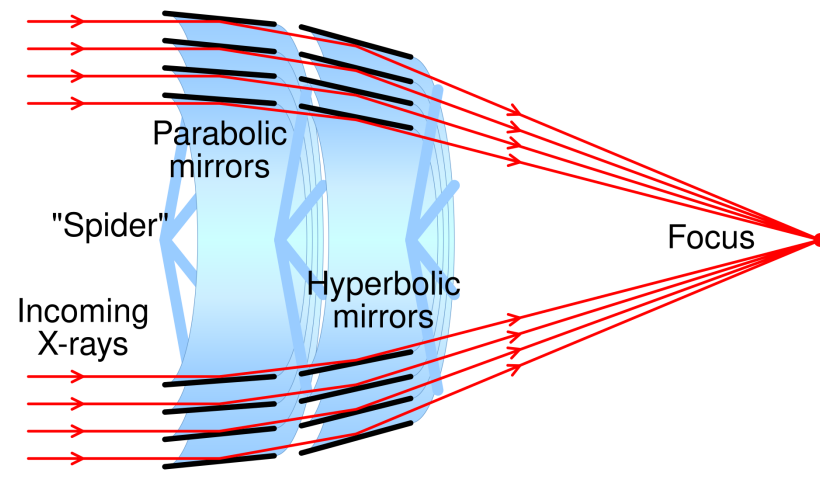


NASA / WIKIMEDIA

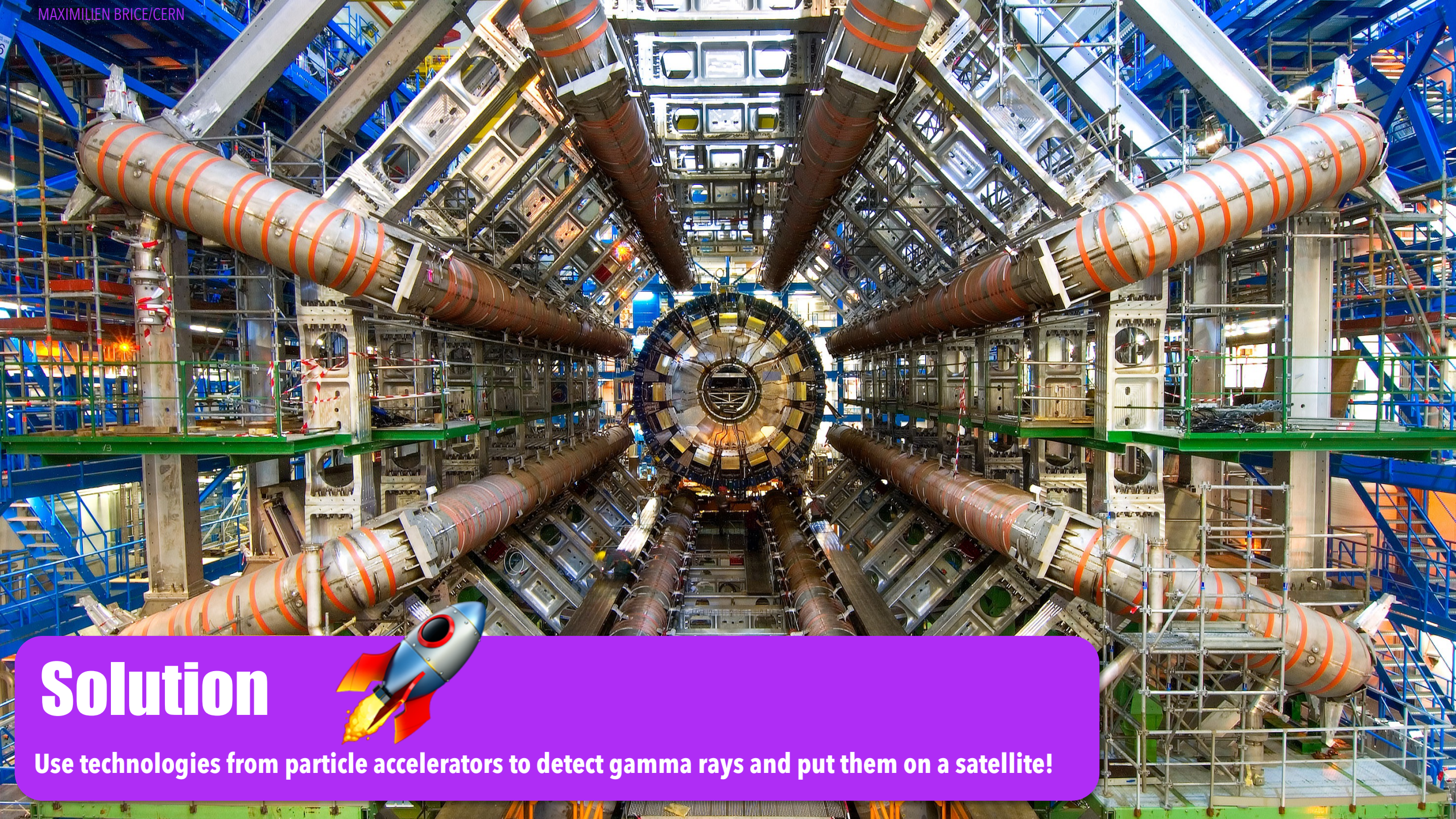
Challenge II. Focusing light



Adler Planetarium & Astronomy Museum



Cmglee/WIKIMEDIA

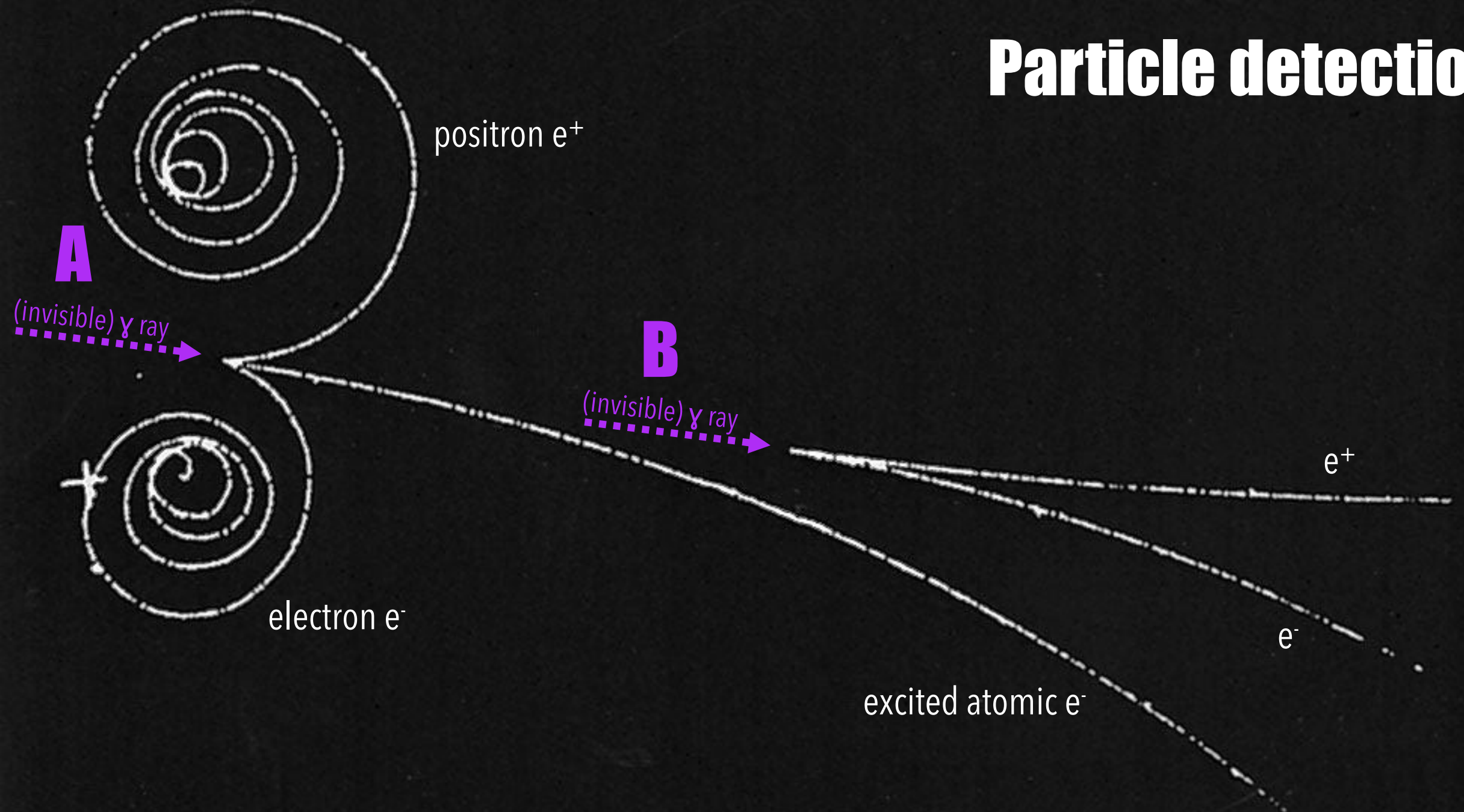


Solution

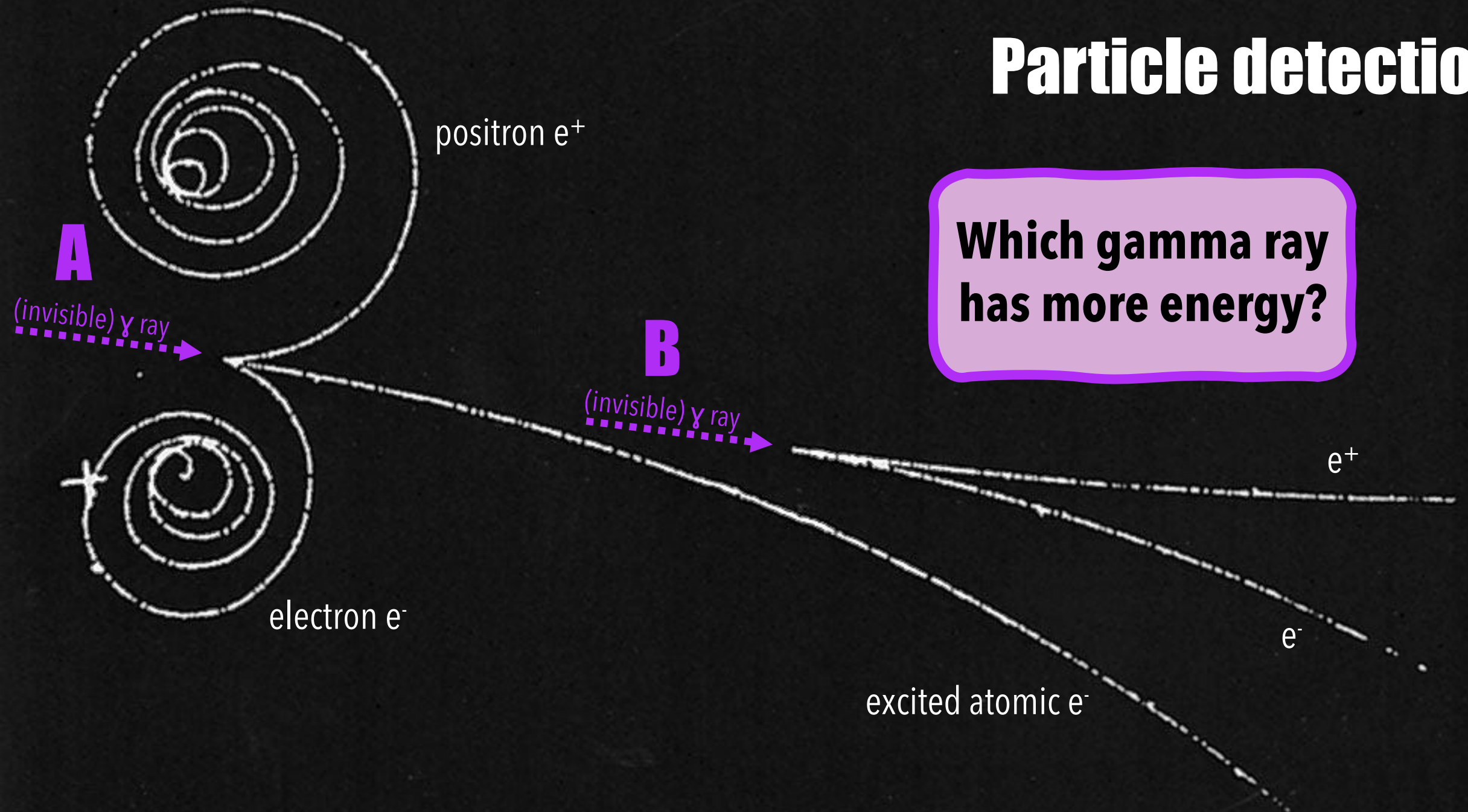


Use technologies from particle accelerators to detect gamma rays and put them on a satellite!

Particle detection



Particle detection



Which gamma ray has more energy?

Building a gamma-ray telescope

i.e. what do we want to know about the particles that hit the telescope?

Building a gamma-ray telescope

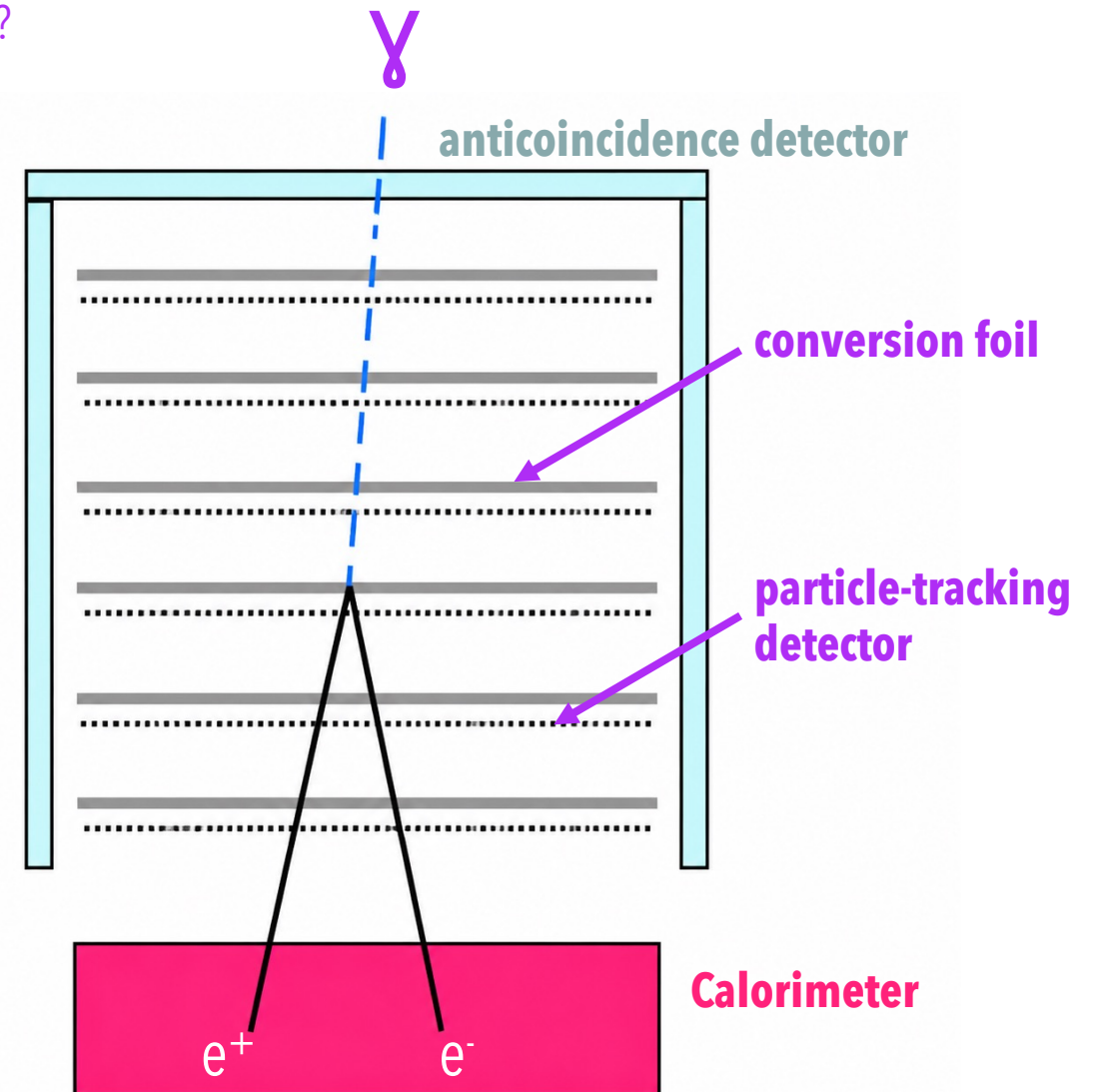
i.e. what do we want to know about the particles that hit the telescope?

- Where they are coming from (**direction**)
- How energetic they are (**energy**)
- That they are **really gamma rays** (and not, e.g., cosmic rays)
- When do they arrive (**timing**)

Building a gamma-ray telescope

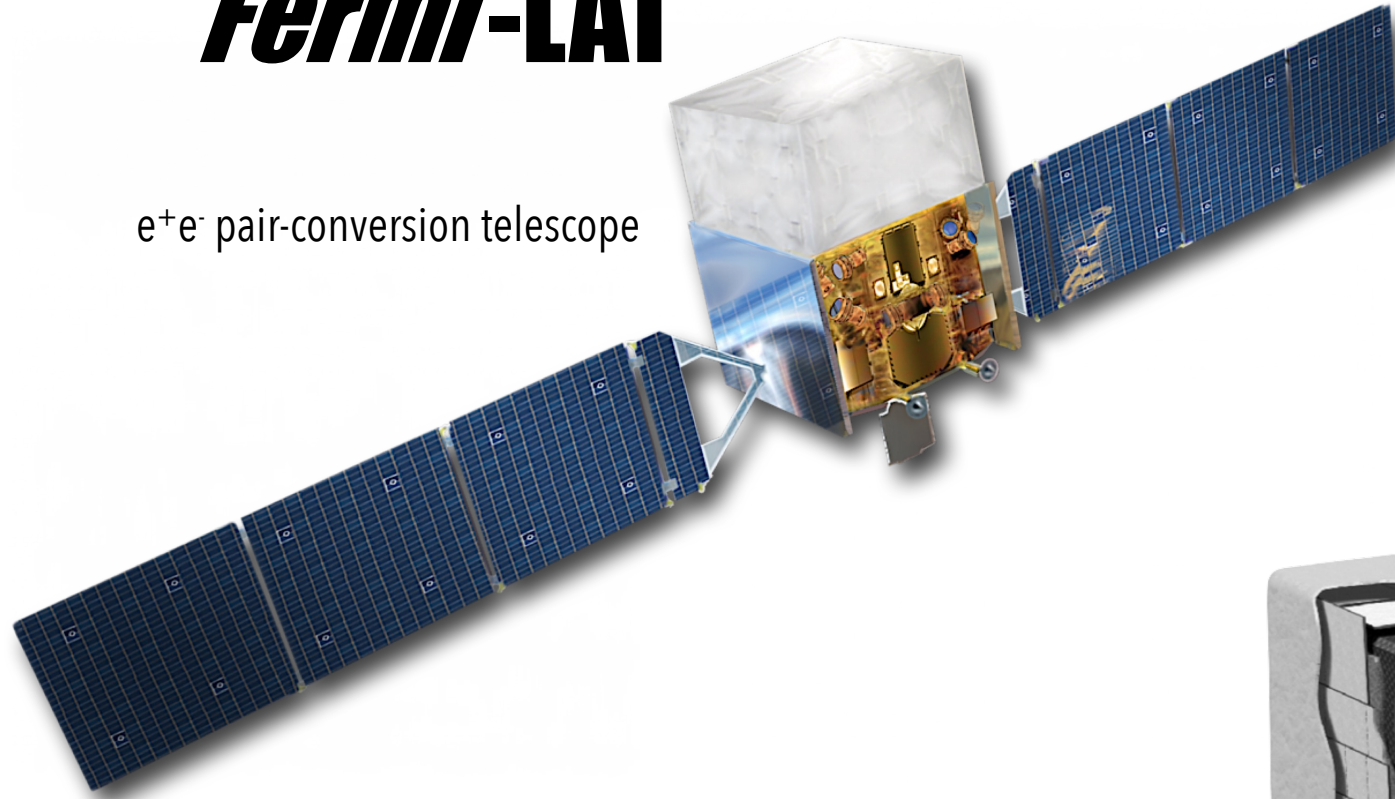
i.e. what do we want to know about the particles that hit the telescope?

- Where they are coming from (**direction**)
- How energetic they are (**energy**)
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- When do they arrive (**timing**)



Fermi-LAT

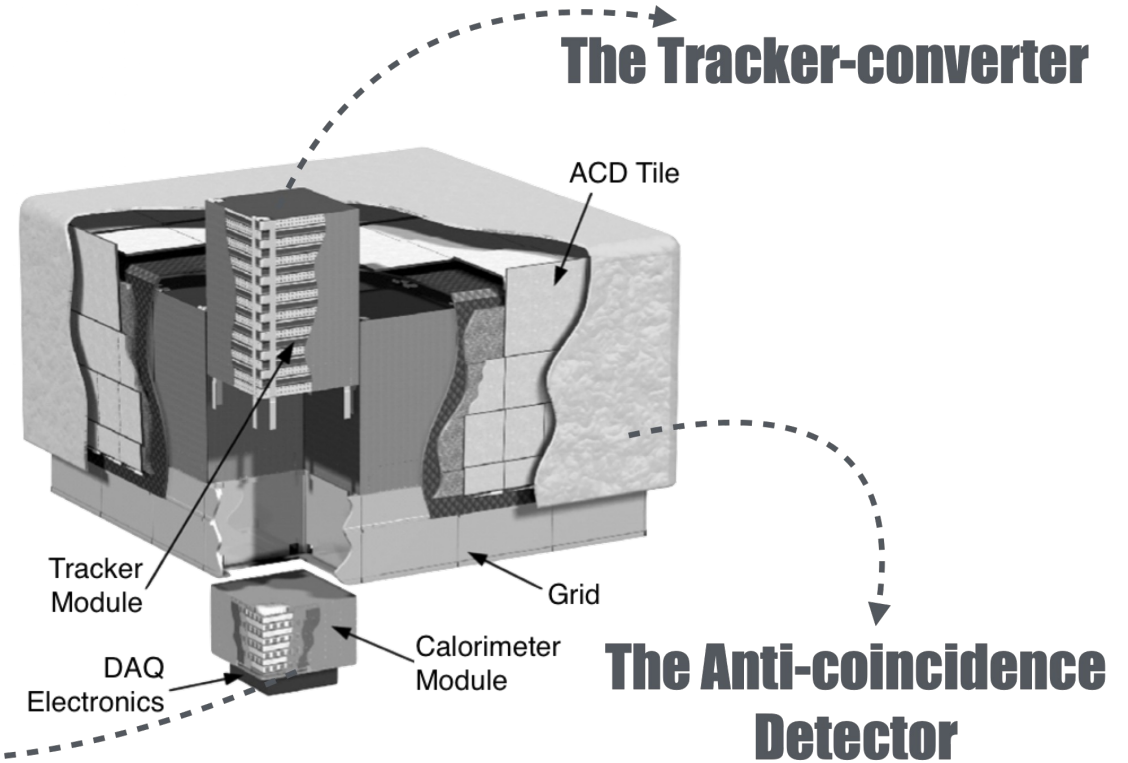
e^+e^- pair-conversion telescope



individual γ rays convert into e^+e^- pairs
→ tracks (localization) & deposited energy

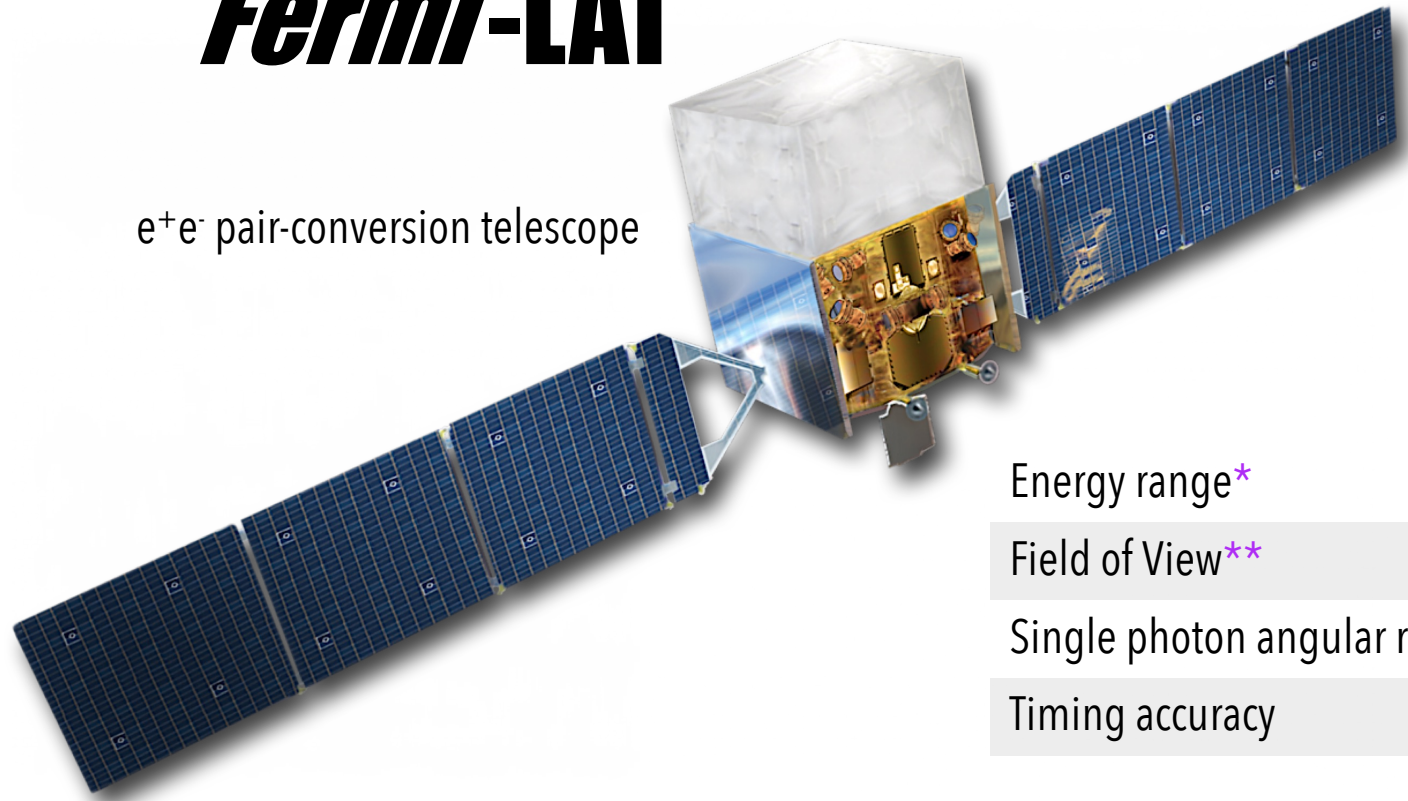
...it also detects electrons.

The Calorimeter



Fermi-LAT

e^+e^- pair-conversion telescope



Energy range^{*}

20 MeV to > 300 GeV

Field of View^{**}

2.4 sr (~ 1/5 of the whole sky)

Single photon angular resolution^{***}

< 1 deg at 1 GeV

Timing accuracy

1 microsecond

individual γ rays convert into e^+e^- pairs
 → tracks (localization) & deposited energy

...it also detects electrons.

^{*}ideally suited for WIMP searches

^{**}whole sky every ~3 hours

^{***}point-source localization < 0.5 arcmin

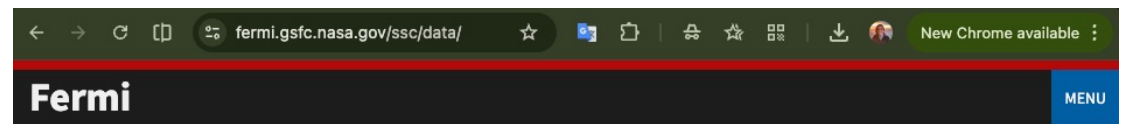
The hierarchy of gamma-ray data products

Level	Content	<i>Fermi</i> name	Who handles it
L0	Raw telemetry	-	Mission Ops
L1	Calibrated, reconstructed events with all variables	"Pass 8"	LAT Team
L2	Public event list + spacecraft pointing	FT1, FT2	You
L3	Binned counts/exposure cubes, IRFs, livetime	"intermediate".fits	You (via tools)
L4	Source catalogs (4FGL-DR4, 4LAC, etc.)	Catalog FITS	LAT team

You start at L2. Everything we do today is L2 → L3 → science.

Where the data actually lives

fermi.gsfc.nasa.gov/ssc/data/




Data & Products

The Fermi mission provides an extensive array of data products, with [no proprietary period](#) and minimal latency between observation and public release. Primary products are [all-sky survey data](#) from the LAT and [transient event data](#) (e.g., GRBs) from the GBM. Derived products include the [LAT Point Source Catalog](#), and specialized catalogs for active galactic nuclei, pulsars, gamma-ray bursts, and high-energy sources, as well as [light curves](#) and variability information for [monitored sources](#). You should have a [basic familiarity](#) with Fermi before proceeding further. Tools to analyze Fermi data and documentation (e.g., how-to guides) are available under the [Data Analysis](#) section. Note that the LAT and GBM data are accompanied by [caveats](#) about their use.

- All-Sky Survey Data** +
- Transient and Time Domain Data** +
- General Source Catalogs** +
- Source Specific Catalogs and Data** +

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 Site Editor: [J.D. Myers](#)
 Last Updated: 9-Mar-2026

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The LAT Data Server query page

<https://fermi.gsfc.nasa.gov/cgi-bin/ssc/LAT/LATDataQuery.cgi>

- Data starts at 2008-08-04 15:43:36 UTC
- Useful tool: [HEASARC xTime](#) to convert mission elapsed time (MET) to UTC, MJD, ...
- Two FITS file "types" per analysis (can be divided into multiple files for longer exposure times):
 - **FT1 --- photon event list**
(time, RA, Dec, energy, conversion type, event class, ...)
 - **FT2 --- spacecraft history (in 30-s increments)**
(time, position, pointing, livetime fraction, ...)
- You will also need (included w/ FermiTools/Fermipy):
 - **Galactic diffuse model:** `gll_iem_v07.fits`
 - **Isotropic diffuse template:** `iso_P8R3_SOURCE_V3_v1.txt`
 - **Latest catalog (4FGL-DR4):** `gll_psc_v32.fit`
 - **IRFs:** `P8R3_SOURCE_V3`
- Note: <https://fermi.gsfc.nasa.gov/ssc/> is your best friend.

LAT Photon, Event, and Spacecraft Data Query

Object name or coordinates:
Coordinate system:
Search radius (degrees):
Observation dates:
Time system:
Energy range (MeV):
LAT data type:
Spacecraft data:

Query L2605041143326812327D88 submitted.

Please see [LAT Data Caveats](#) for important information about Fermi LAT data.

Your search criteria were:

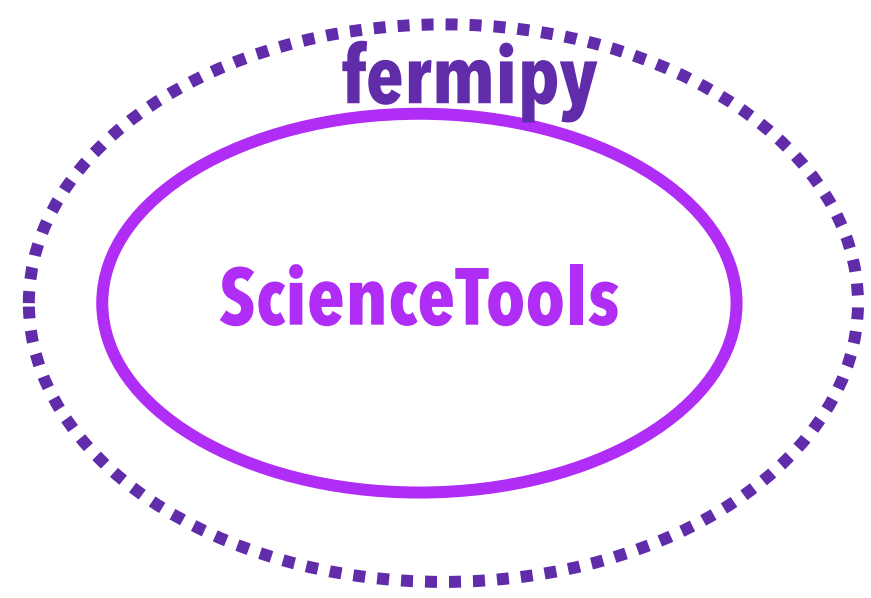
Query Parameters	
Equatorial coordinates (degrees)	RA = 238.929, Dec = 11.1901
Time range (MET)	(239557417, 776015021)
Time range (Gregorian)	(2008-08-04 15:43:36, 2025-08-04 15:43:36)
Energy range (MeV)	(50, 1000000)
Search radius (degrees)	20

The estimated time for your query to complete is 703 seconds. The results of your query may be found at <https://fermi.gsfc.nasa.gov/cgi-bin/ssc/LAT/QueryResults.cgi?id=L2605041143326812327D88>.

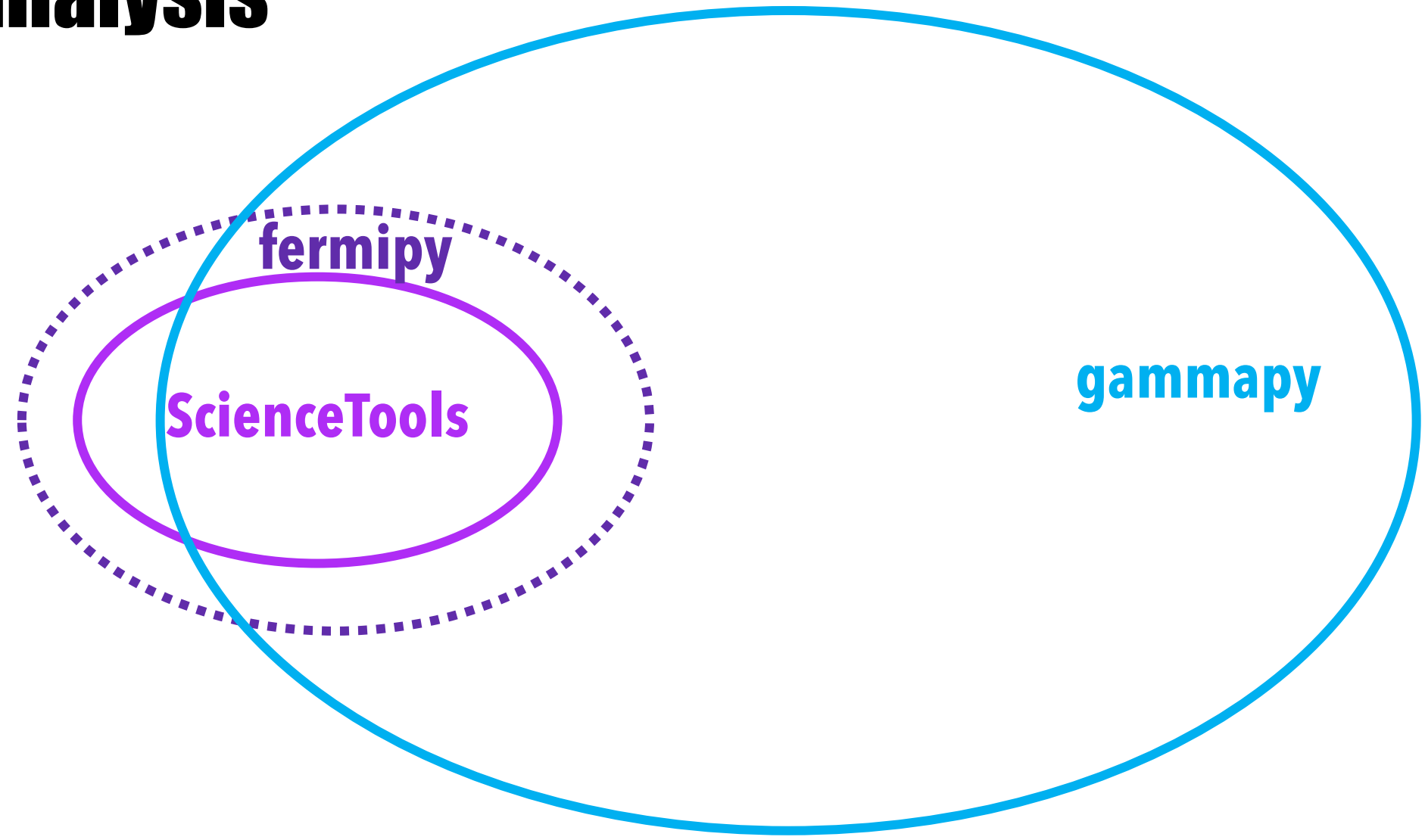
Data analysis



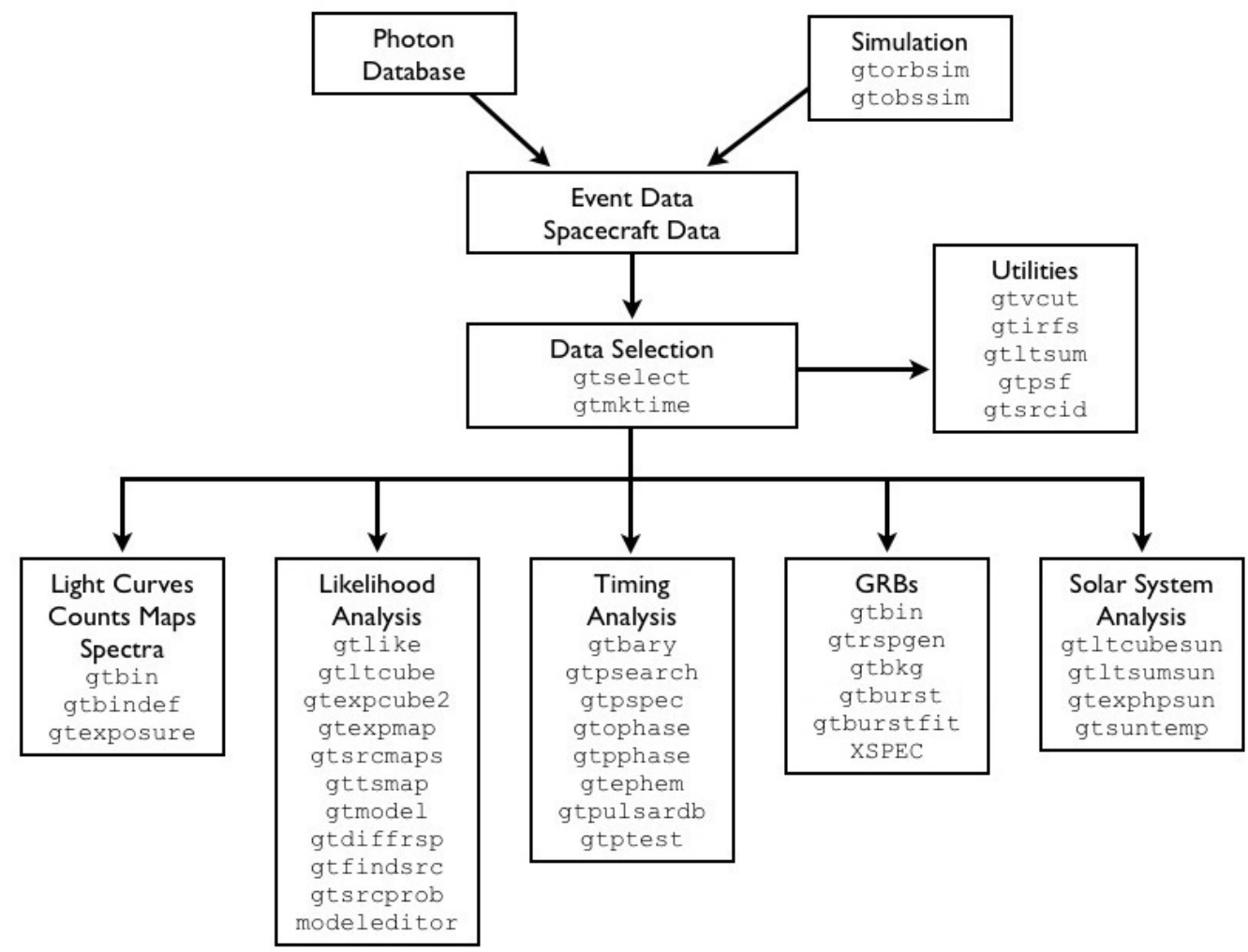
Data analysis



Data analysis



The Fermi Science Tools ecosystem



The LAT Data Server query page

Let's take a look at our data products.
(NB: `00_data_levels.ipynb`)

LAT Photon, Event, and Spacecraft Data Query

Object name or coordinates:
Coordinate system:
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Observation dates:
Time system:
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What is your research question?

Is [insert source of interest] detected at gamma-ray energies?

What is your research question?

Is [insert source of interest] detected at gamma-ray energies?

YES

Characterize the source!

- What is its average spectrum (= photon flux as a function of energy) over some time range?
- Is its spectrum compatible with some theoretical shape (e.g., dark matter annihilation, synchrotron radiation, etc.)?
- What is the source morphology? Point-like? Extended?
- How does the source flux change in time (i.e., is it variable)?

What is your research question?

Is [insert source of interest] detected at gamma-ray energies?

YES

NO

Characterize the source!

- What is its average spectrum (= photon flux as a function of energy) over some time range?
- Is its spectrum compatible with some theoretical shape (e.g., dark matter annihilation, synchrotron radiation, etc.)?
- What is the source morphology? Point-like? Extended?
- How does the source flux change in time (i.e., is it variable)?

Constrain physics & guide next steps!

- How bright it can be without being detected? (i.e., upper limits)
- Do these limits constrain theoretical models? (e.g., rule out certain dark matter properties, emission mechanisms, etc.)?
- Should we search at other wavelengths?
- Would longer exposure help? Or, are there some transient signals we might have missed?

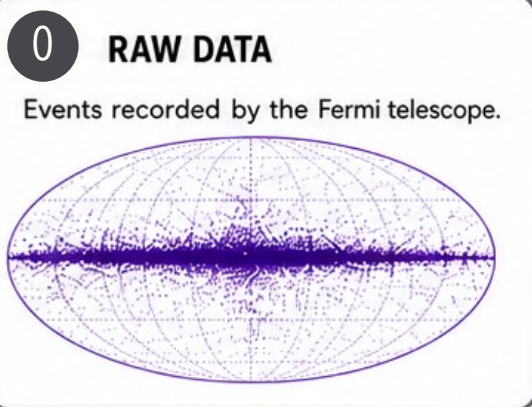
What is your research question?

No matter the question, the answer is **likelihood fitting**.

- Fitting a model ϕ for your source(s) to the observed data
- Most generally, the model will depend on energy E , time t , solid angle Ω , and model parameters $\vec{\pi}$:

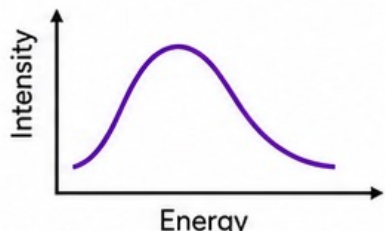
$$\phi \equiv \phi(E, t, \Omega, \vec{\pi}) = \frac{dN}{dE dt dA d\Omega}$$

- For LAT data, model parameters $\vec{\pi}$ are optimized through a **likelihood maximization**.



1 CHOOSE A MODEL ϕ

Your hypothesis about the source (e.g., its spectrum, shape, parameters π).

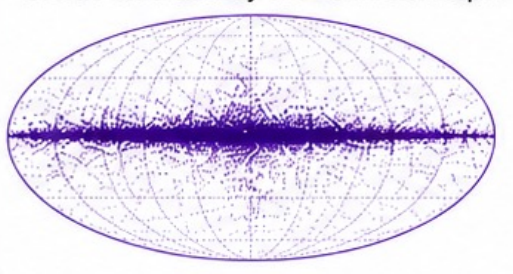


The graph shows a smooth, bell-shaped curve representing a model. The vertical axis is labeled 'Intensity' and the horizontal axis is labeled 'Energy'.



0 RAW DATA

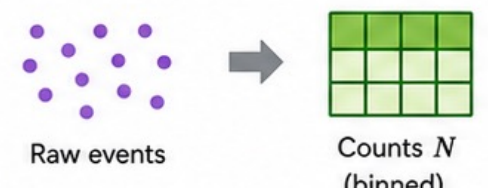
Events recorded by the Fermi telescope.



The visualization shows a dense collection of purple dots representing individual events, plotted on a grid of latitude and longitude lines on a sphere.

1' DATA PREPROCESSING

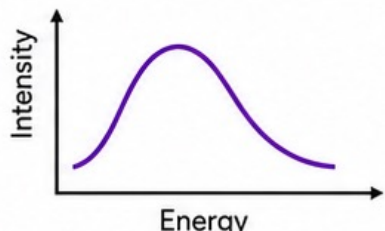
Process the raw data: event selection, background rejection, binning, etc. This gives the observed counts N .



The diagram shows a group of purple dots labeled 'Raw events' on the left. An arrow points to a 3x3 grid of green squares labeled 'Counts N (binned)' on the right.

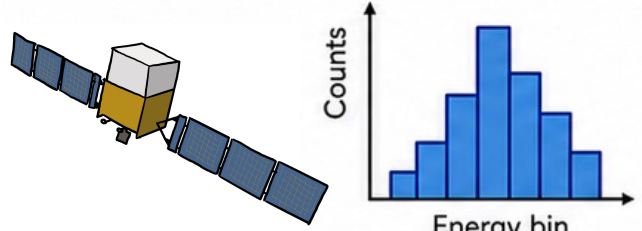
1 CHOOSE A MODEL ϕ

Your hypothesis about the source (e.g., its spectrum, shape, parameters π).



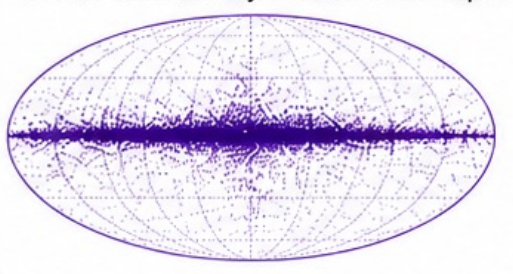
2 PREDICT COUNTS M

Calculate how many counts Fermi should detect if the model ϕ is true. (Uses instrument response, exposure, etc.)



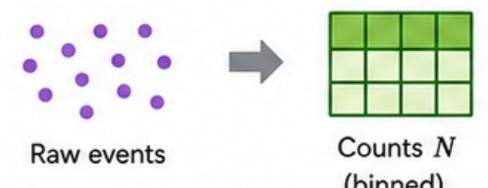
0 RAW DATA

Events recorded by the Fermi telescope.



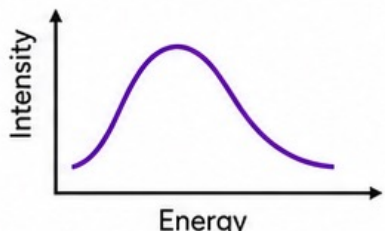
1' DATA PREPROCESSING

Process the raw data: event selection, background rejection, binning, etc. This gives the observed counts N .



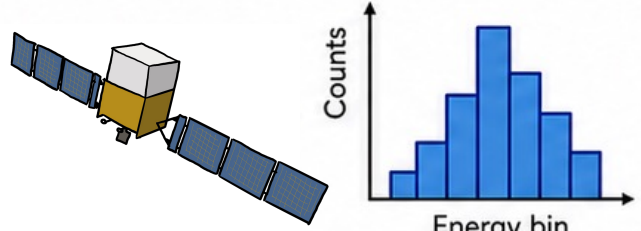

1 CHOOSE A MODEL ϕ

Your hypothesis about the source (e.g., its spectrum, shape, parameters π).



2 PREDICT COUNTS M

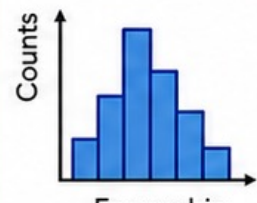
Calculate how many counts Fermi should detect if the model ϕ is true. (Uses instrument response, exposure, etc.)



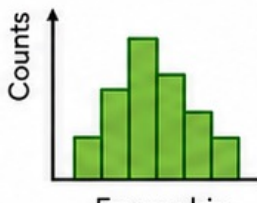
3 COMPARE MODEL TO DATA

Use an objective function (likelihood) $\Sigma(M|N)$ to quantify the agreement between predicted counts M and observed counts N .

Predicted M

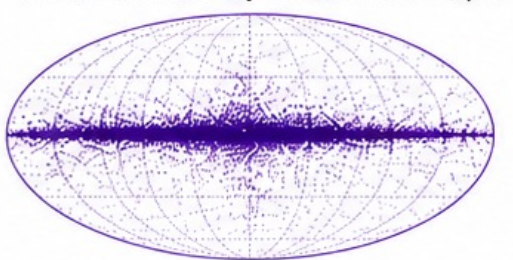


Observed N





0 RAW DATA

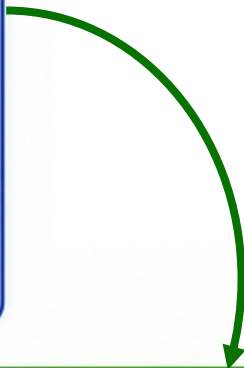
Events recorded by the Fermi telescope.



1' DATA PREPROCESSING

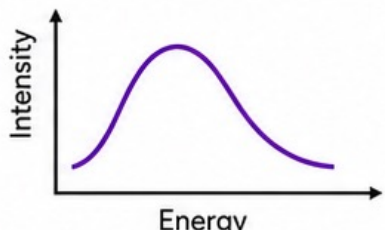
Process the raw data: event selection, background rejection, binning, etc. This gives the observed counts N .


→




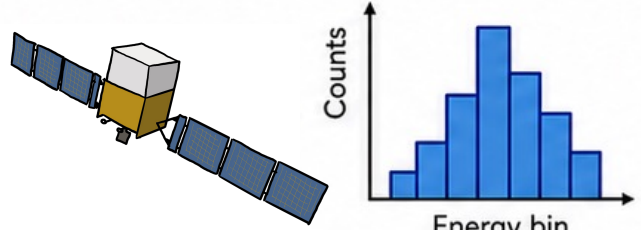
1 CHOOSE A MODEL ϕ

Your hypothesis about the source (e.g., its spectrum, shape, parameters π).



2 PREDICT COUNTS M

Calculate how many counts Fermi should detect if the model ϕ is true. (Uses instrument response, exposure, etc.)

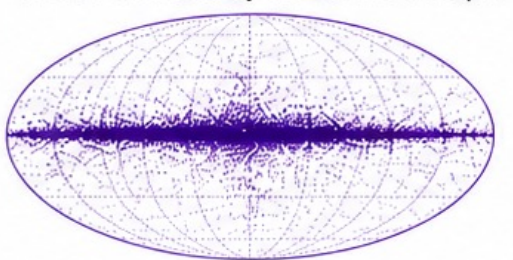


UPDATE MODEL PARAMETERS π

Try new values and repeat the loop.

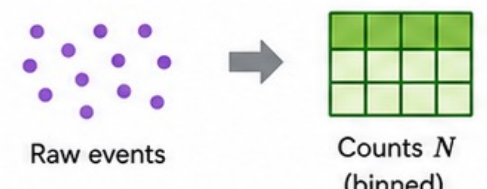
0 RAW DATA

Events recorded by the Fermi telescope.



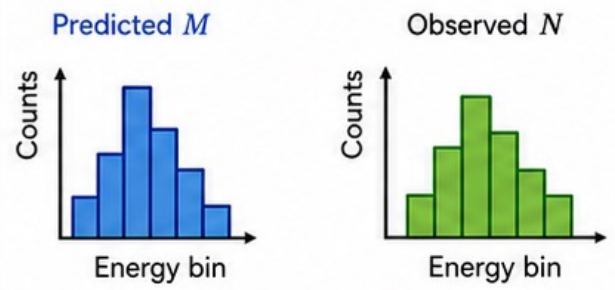
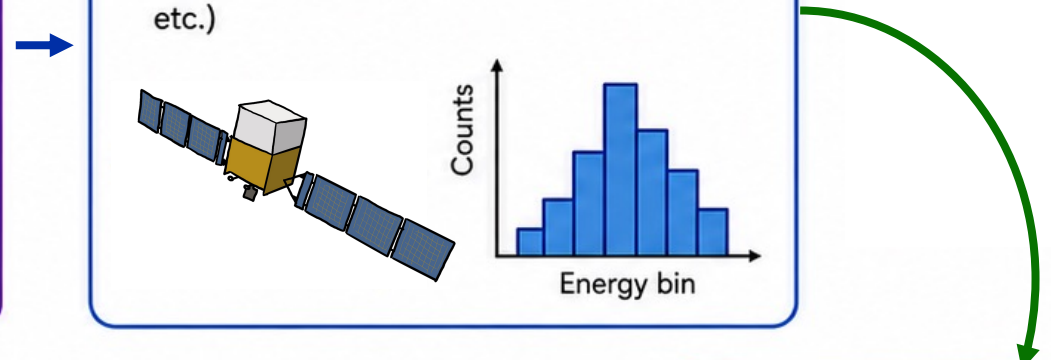
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Process the raw data: event selection, background rejection, binning, etc. This gives the observed counts N .



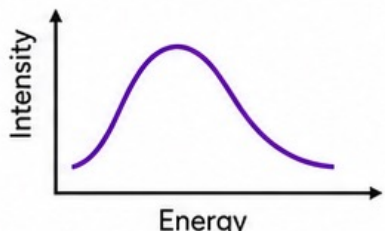
3 COMPARE MODEL TO DATA

Use an objective function (likelihood) $\Sigma(M|N)$ to quantify the agreement between predicted counts M and observed counts N .

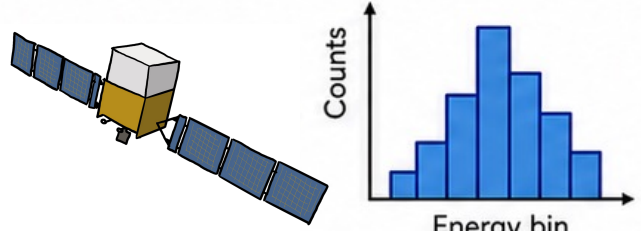
1 CHOOSE A MODEL ϕ

Your hypothesis about the source (e.g., its spectrum, shape, parameters π).




2 PREDICT COUNTS M

Calculate how many counts Fermi should detect if the model ϕ is true. (Uses instrument response, exposure, etc.)



SPEED IT UP

Precompute instrument quantities (exposure, responses, templates,...) so this step is faster.

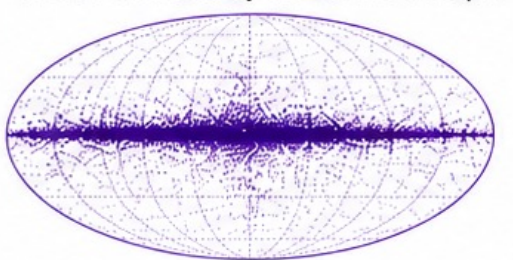


UPDATE MODEL PARAMETERS π

Try new values and repeat the loop.

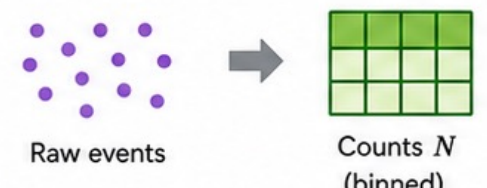
0 RAW DATA

Events recorded by the Fermi telescope.



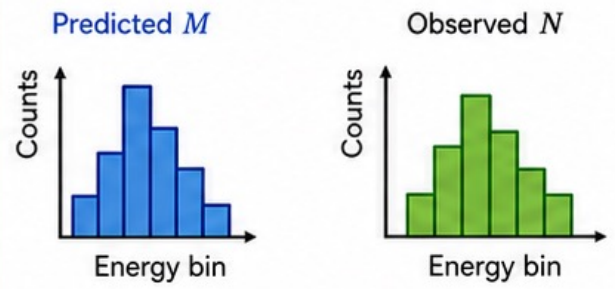
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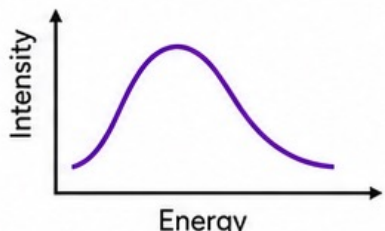
3 COMPARE MODEL TO DATA

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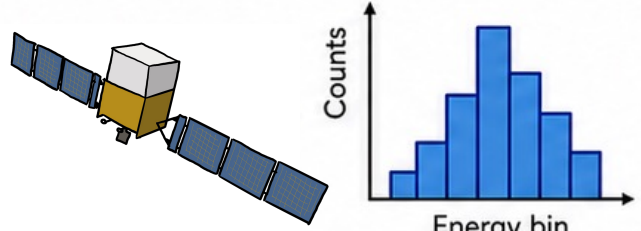
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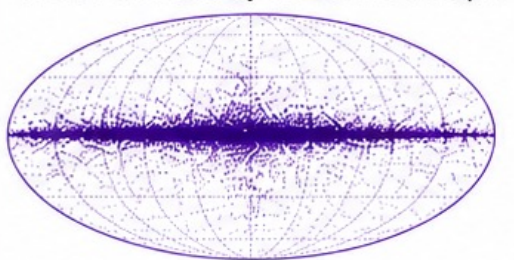


UPDATE MODEL PARAMETERS π

Try new values and repeat the loop.

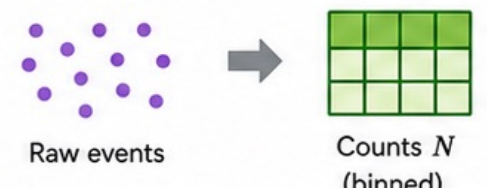
0 RAW DATA

Events recorded by the Fermi telescope.



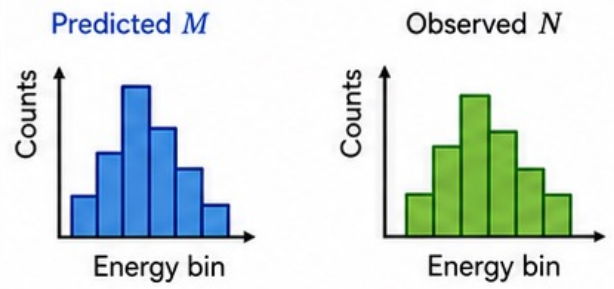
1' DATA PREPROCESSING

Process the raw data: event selection, background rejection, binning, etc. This gives the observed counts N .



3 COMPARE MODEL TO DATA

Use an objective function (likelihood) $\Sigma(M|N)$ to quantify the agreement between predicted counts M and observed counts N .



BEST FIT MODEL
(maximum \mathcal{L})



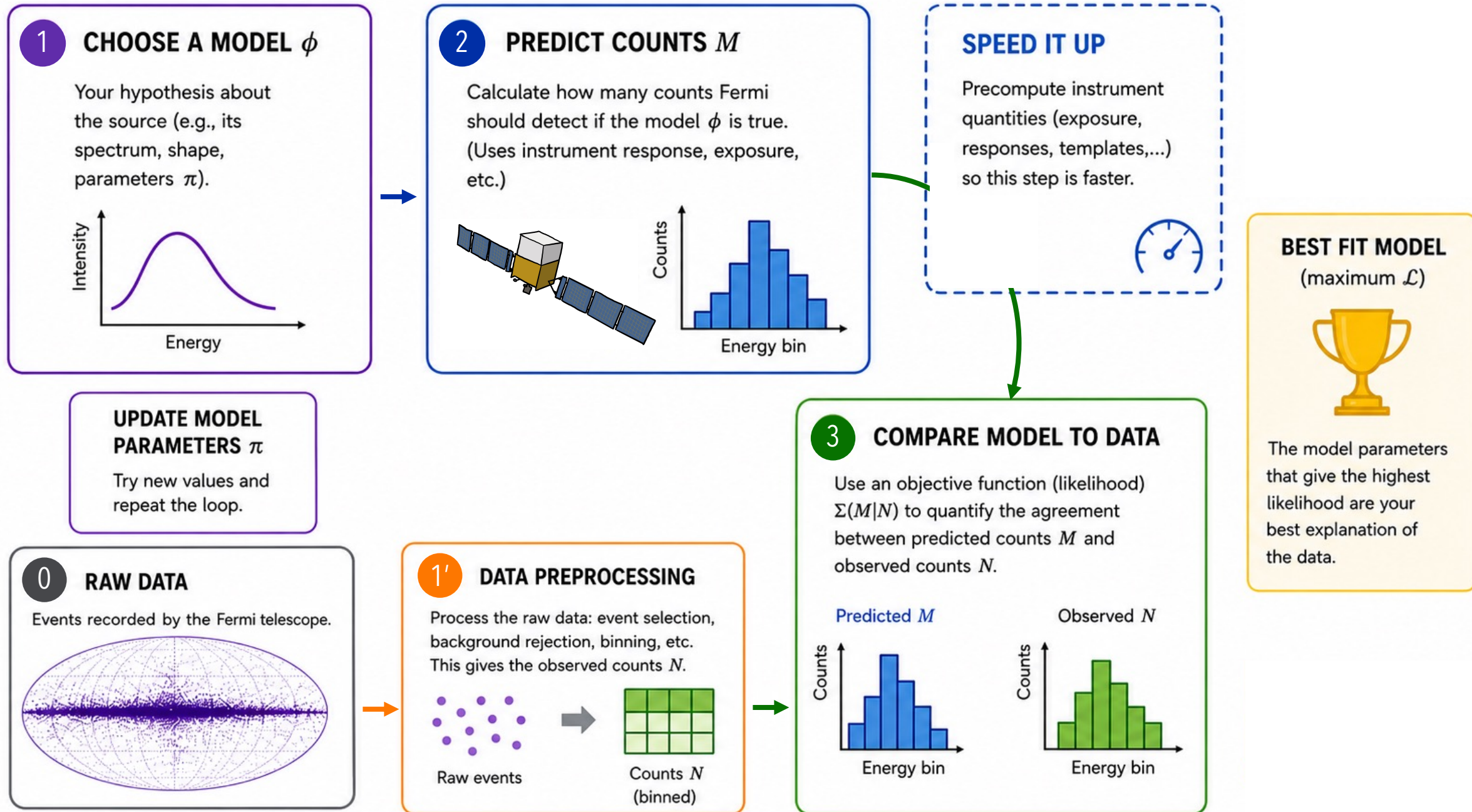
The model parameters that give the highest likelihood are your best explanation of the data.

fermipy

Relevant notebooks:

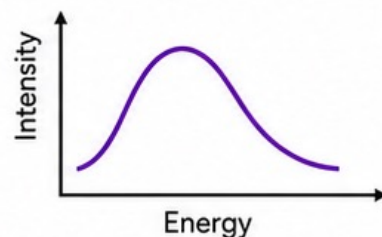
01_fermipy_pg1553.ipynb

02_fermipy_txs0506.ipynb



1 CHOOSE A MODEL ϕ

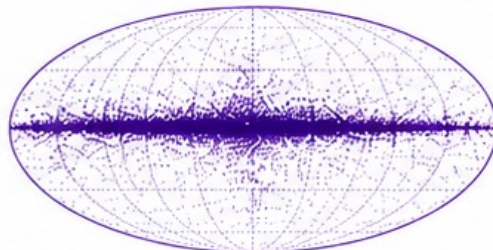
Your hypothesis about the source (e.g., its spectrum, shape, parameters π).

**UPDATE MODEL PARAMETERS π**

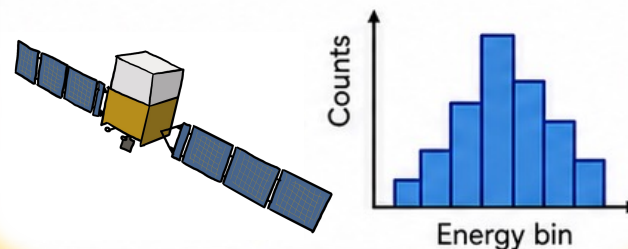
Try new values and repeat the loop.

0 RAW DATA

Events recorded by the Fermi telescope.

**2 PREDICT COUNTS M**

Calculate how many counts Fermi should detect if the model ϕ is true. (Uses instrument response, exposure, etc.)

**SPEED IT UP**

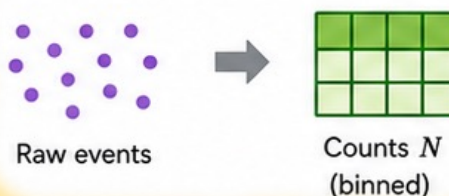
Precompute instrument quantities (exposure, responses, templates,...) so this step is faster.



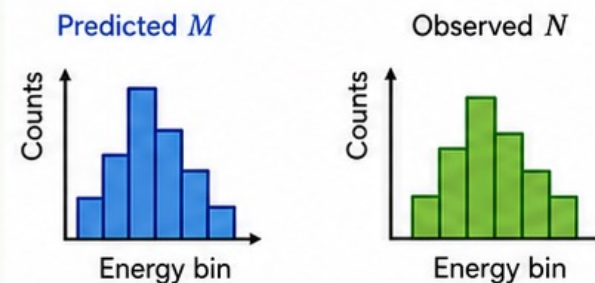
gta.setup()

1' DATA PREPROCESSING

Process the raw data: event selection, background rejection, binning, etc. This gives the observed counts N .

**3 COMPARE MODEL TO DATA**

Use an objective function (likelihood) $\Sigma(M|N)$ to quantify the agreement between predicted counts M and observed counts N .

**BEST FIT MODEL**
(maximum \mathcal{L})

The model parameters that give the highest likelihood are your best explanation of the data.

Computing expected counts M

- Expected counts obtained from convolution of model flux ϕ with instrumental response function R

$$M_{ijk}(E, \vec{\pi}) = \int_{\Delta E'_i} dE' \int_E dE \int_{\Omega_{jk}} d\vec{p}' \int_{\vec{p}} d\vec{p} T_{\text{obs}} R(E, E', \vec{p}, \vec{p}') \phi(E, \vec{p}, \vec{\pi})$$

- Instrumental response function factors into:
 - Point spread function $PSF(\vec{p}, \vec{p}', E)$, gives probability that true arrival direction \vec{p} is mapped onto observed arrival direction \vec{p}'
 - Energy dispersion matrix $D(E, E')$, gives probability that true energy E is mapped onto observed energy E'
 - Effective area $A_{\text{eff}}(E, \vec{p})$ of the detector at energy E and direction \vec{p} (multiplied with T_{obs} = exposure)

Objective function: Poisson Likelihood

- Poisson statistics applies when we have a photon counting experiment
- Probability to observe N events given a constant rate M :

$$P(N|M) = \frac{M^N \exp(-M)}{N!}$$

- In *Fermi* analysis, objective function is the corresponding log likelihood (up to a constant):

$$\log \mathcal{L}(\vec{\pi}|N) = \sum_{i,j,k} \left(-M_{ijk}(\vec{\pi}) + M_{ijk}(\vec{\pi}) \ln N_{ijk} \right) = -M_{\text{tot}} + \sum_{i,j,k} N_{ijk} \log M_{ijk}$$

- Where the summation runs over the energy bins i and spatial bins j, k

Gammapy

Why Gammapy at all?

The Science Tools and Fermipy *only* analyze *Fermi*-LAT.

Why Gammapy at all?

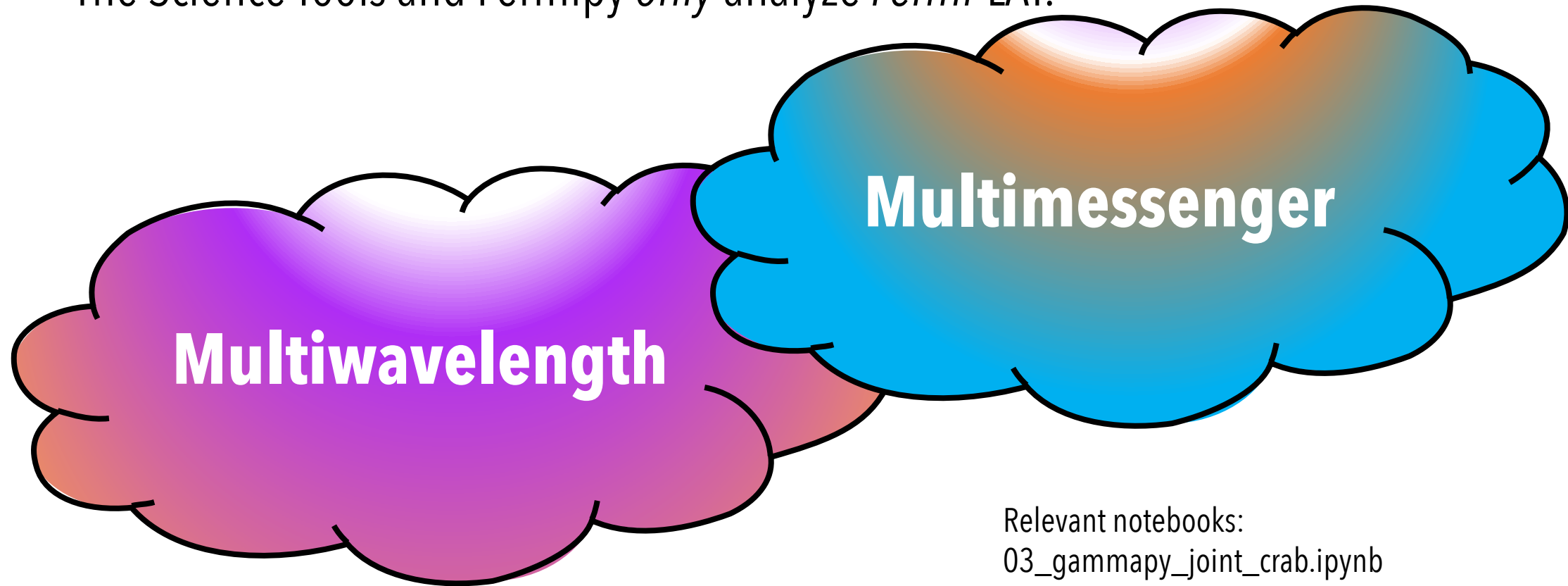
The Science Tools and Fermipy *only* analyze *Fermi*-LAT.



Multiwavelength

Why Gammapy at all?

The Science Tools and Fermipy *only* analyze *Fermi-LAT*.



Big picture

You want to...	Use...
Reproduce a published Fermi-LAT result, official catalog work	Science Tools (+ Fermipy for sanity)
Standard Fermi-LAT science: SED, lightcurve, TS map, source finding	Fermipy
Combine Fermi-LAT with H.E.S.S./MAGIC/CTA/HAWC into one SED	Gammapy
Modern likelihood (MCMC, nested sampling), custom spectral models	Gammapy
Just inspect/plot the FT1, no fitting	astropy + matplotlib
GRB / transient (loose cuts, all-sky)	Science Tools + gtburst

Resources:

Fermi Science Tools – <https://fermi.gsfc.nasa.gov/ssc/data/analysis/software/>

Fermipy – Wood+ 2017, ICRC; <https://fermipy.readthedocs.io/>

Gammapy – Donath+ 2023, A&A 678 A157; <https://docs.gammapy.org/>