FERMIPY HANDS-ON SESSION

MANUEL MEYER

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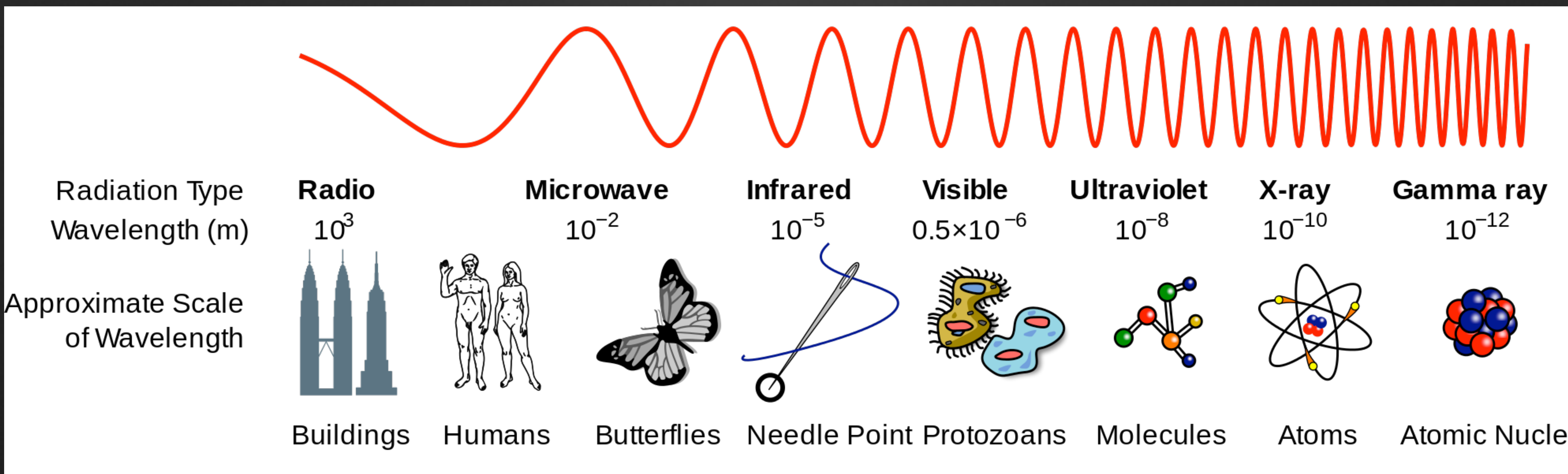
ISAPP21 FERMIPY HANDS-ON

MANUEL.MEYER@DESY.DE

OUTLINE

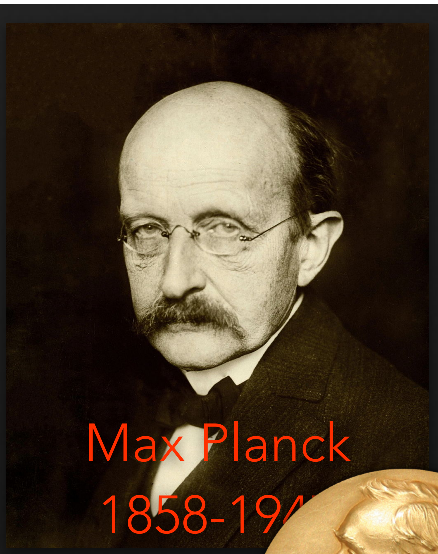
- How Does the LAT work?
- Analyze! (What are the common steps of a LAT analysis?)

THE ELECTROMAGNETIC SPECTRUM



λ	Wavelength
ν	Frequency
c	Speed of light
E	Energy

$$\nu = \frac{c}{\lambda}$$



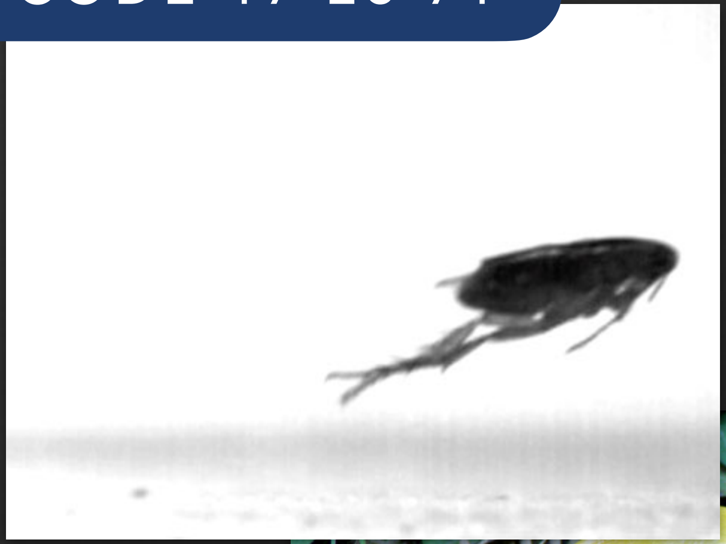
$$E = h\nu$$

$$h = 6.62607004 \times 10^{-34}\ \mathrm{J\ s}$$

WHAT DOES THE ENERGY OF A GAMMA-RAY WITH $\lambda = 10^{-19}$ m CORRESPOND TO?

PLEASE GO TO WWW.MENTI.COM AND ENTER CODE 17 26 71

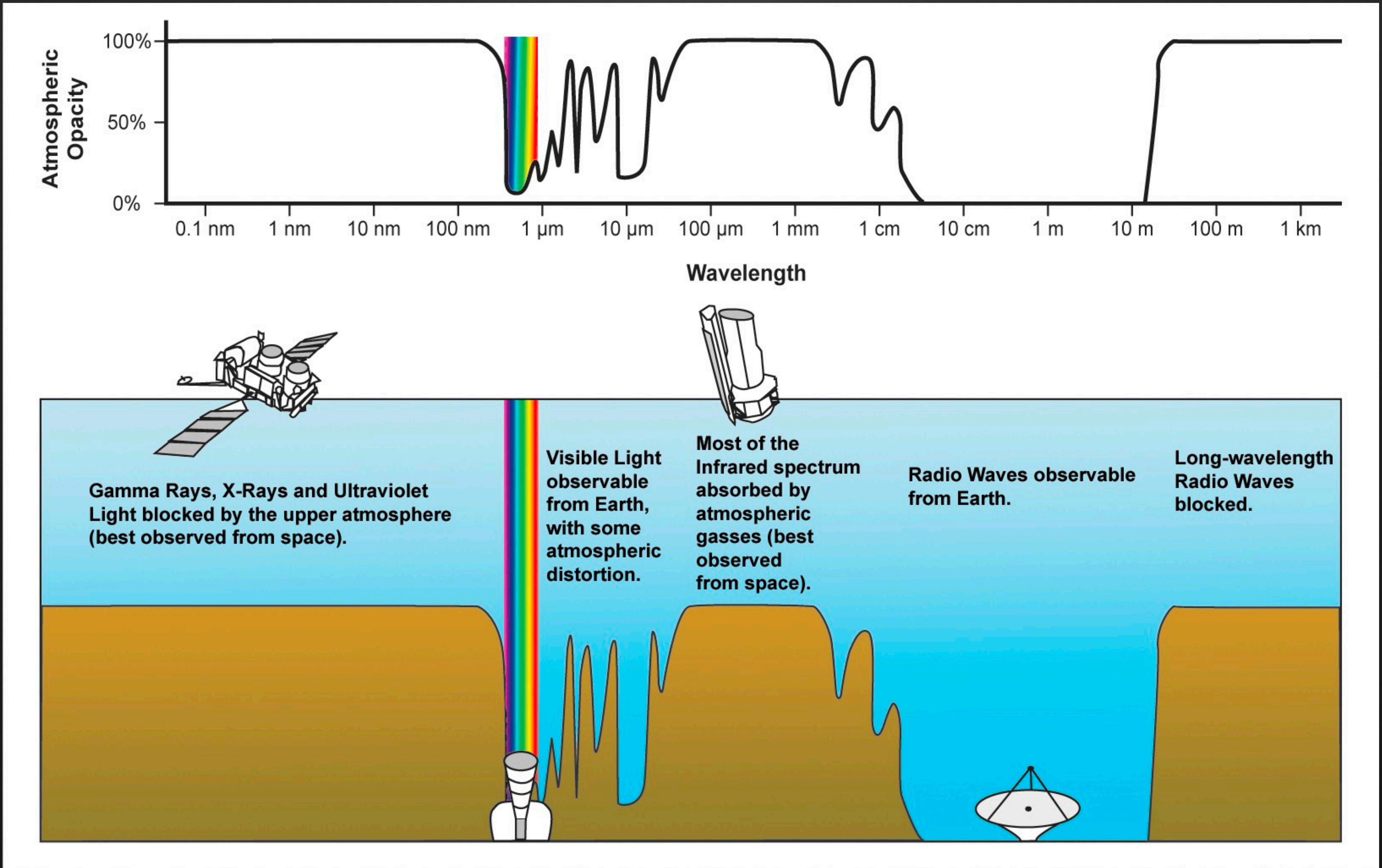
- A flea jumping 20 cm high (m=0.5mg)



- A moving banana slug (m = 115g, v = 0.003 m/s)

- A running cheetah (m=50 kg, v = 120 km/h)

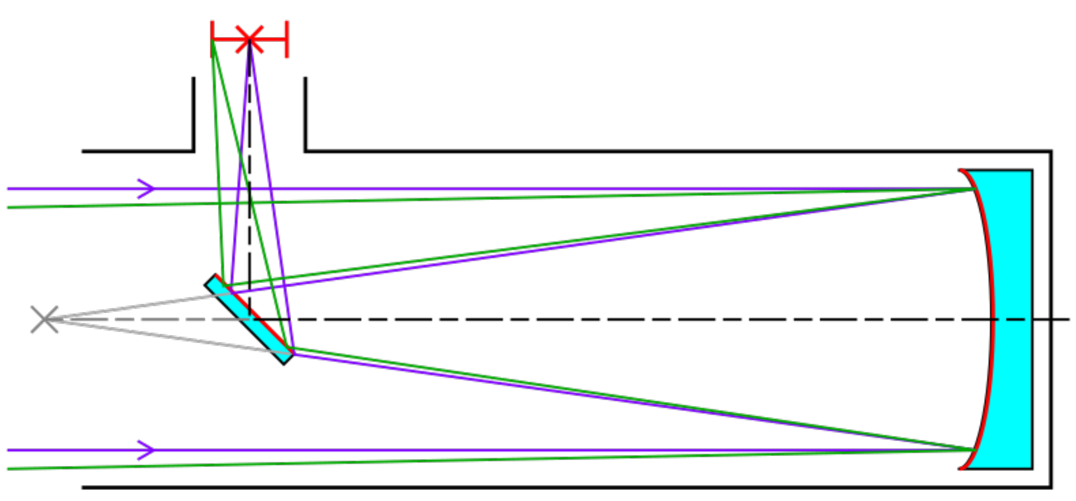
CHALLENGE 1: OPACITY OF THE EARTH'S ATMOSPHERE



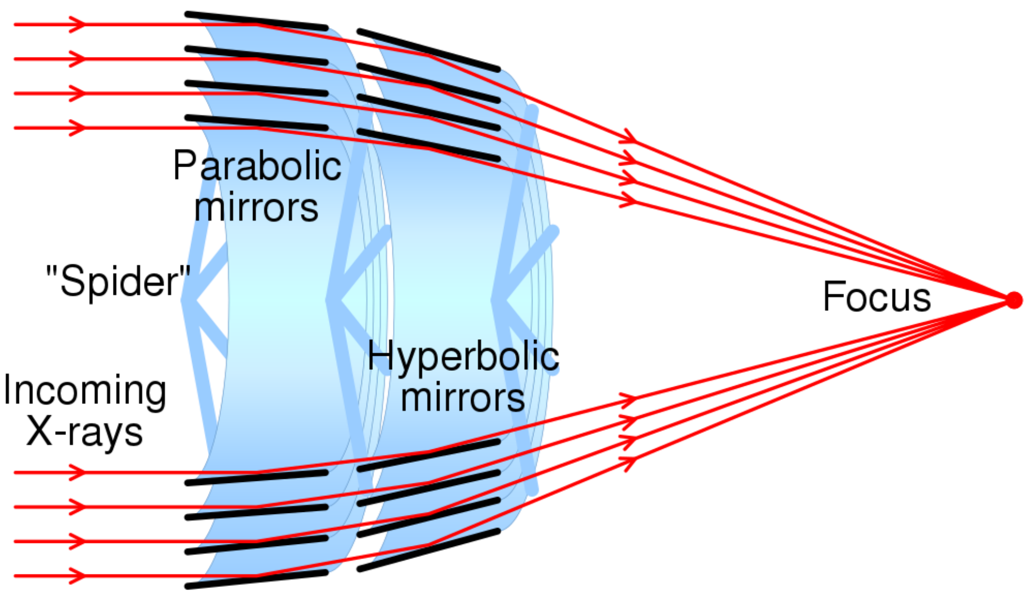
CHALLENGE 2: FOCUSSING LIGHT

- With increasing energy / frequency it becomes more difficult to focus electromagnetic radiation as it penetrates matter
- X-ray optics use grazing incidence
- Gamma-rays penetrate material even further than X-rays, impossible to focus

NEWTON TELESCOPE

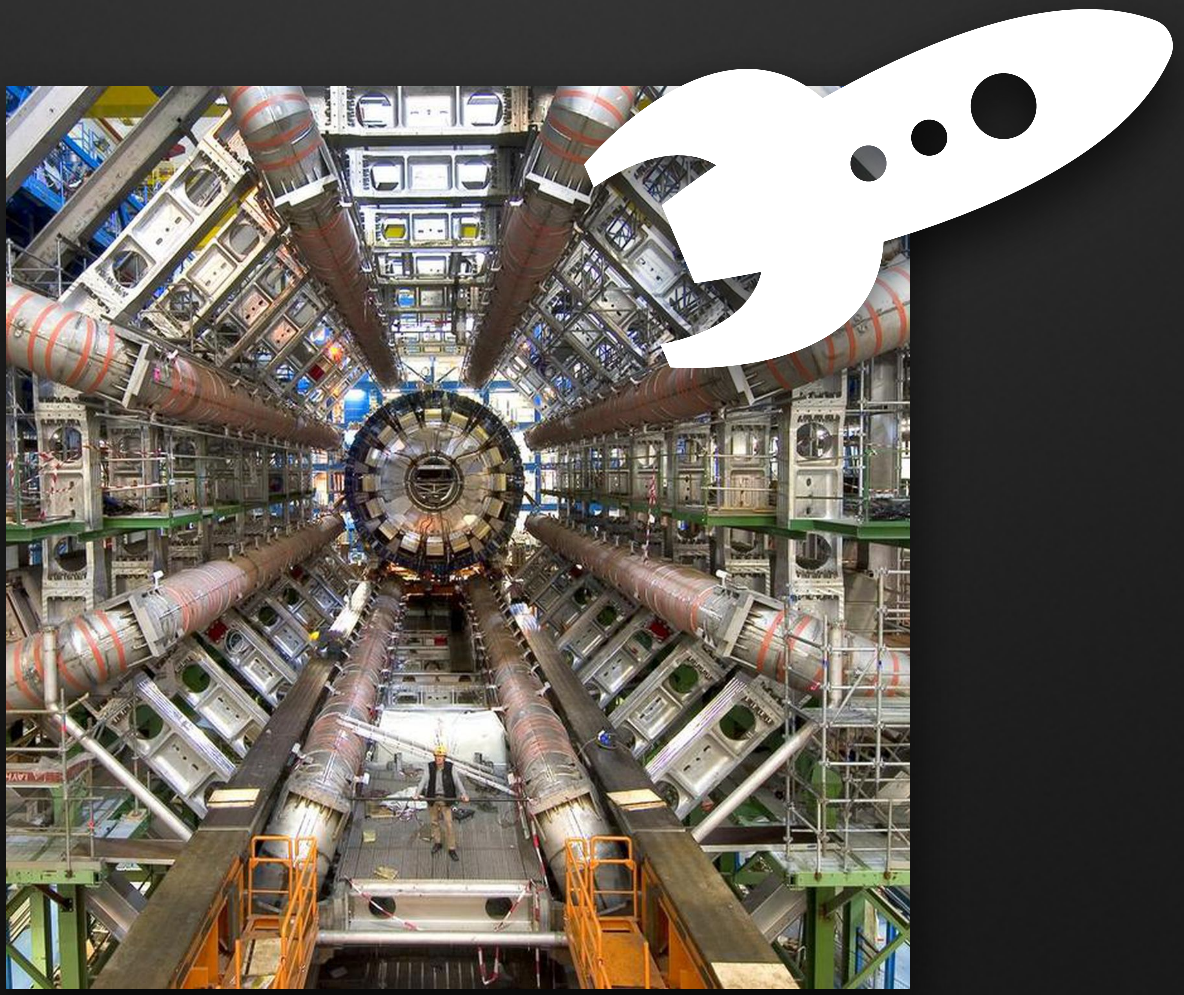


X-RAY TELESCOPE



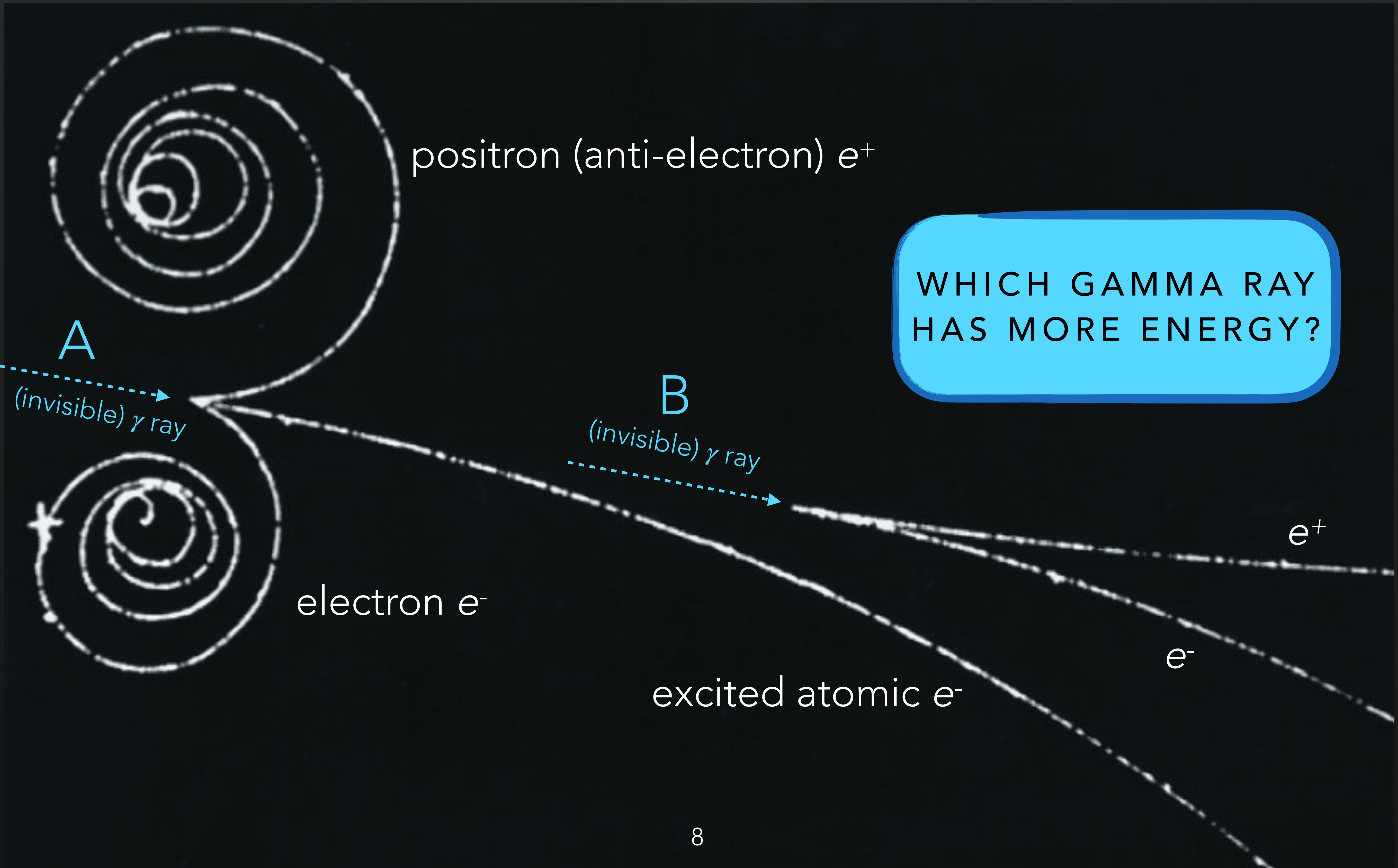
SOLUTION

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



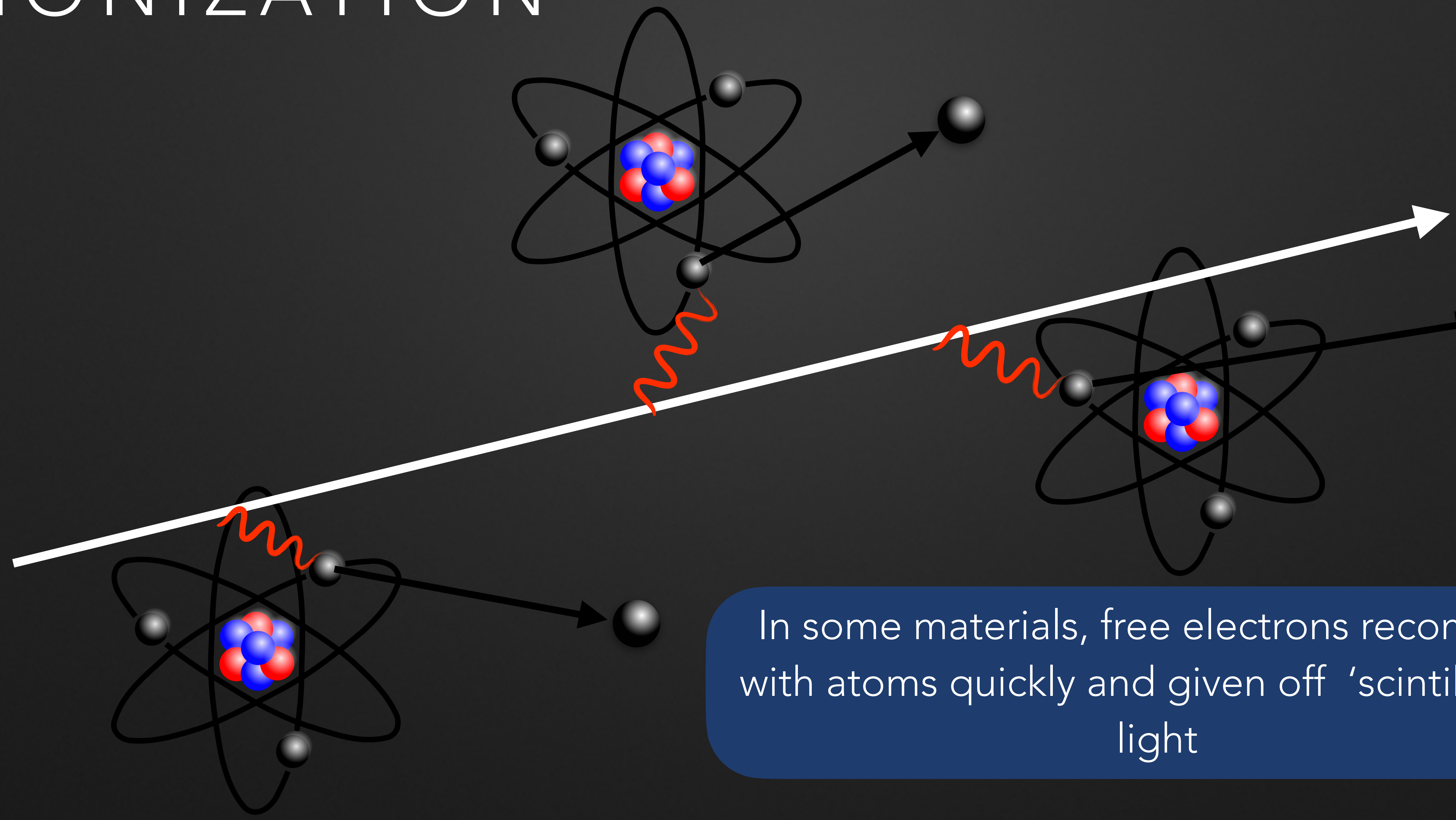
PARTICLE DETECTION

— MAKING HIGH ENERGY PARTICLES VISIBLE



WHICH GAMMA RAY HAS MORE ENERGY?

IONIZATION



In some materials, free electrons recombine with atoms quickly and given off 'scintillation' light

- A high-energy charged particle going through material will kick loose lots of electrons for atoms near its path
  - The electric field from the charged particle transfers energy to the atomic electrons and unbinds them

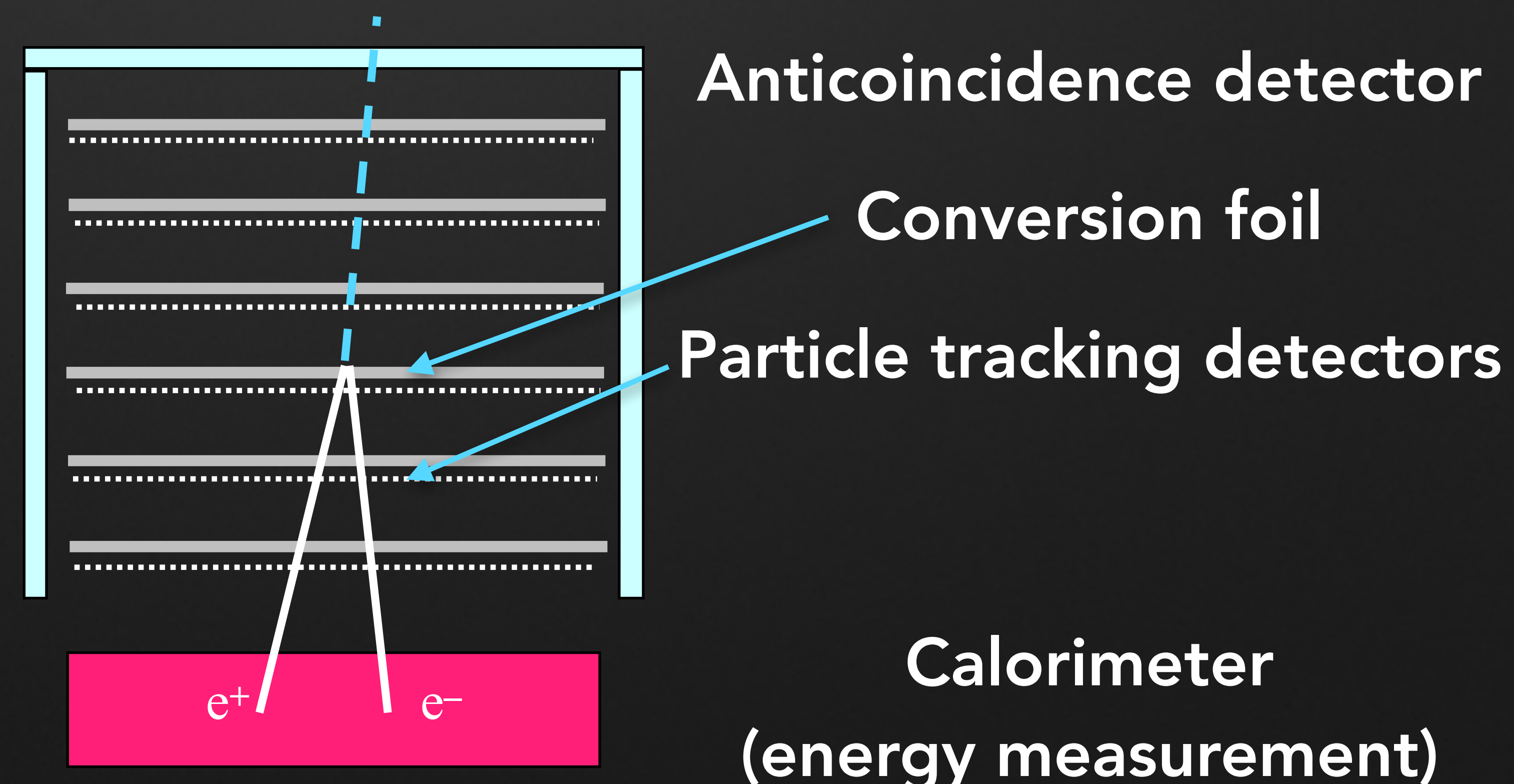
BUILDING A GAMMA RAY TELESCOPE

— WHAT DO WE WANT TO KNOW ABOUT THE PARTICLES THAT HIT THE TELESCOPE?

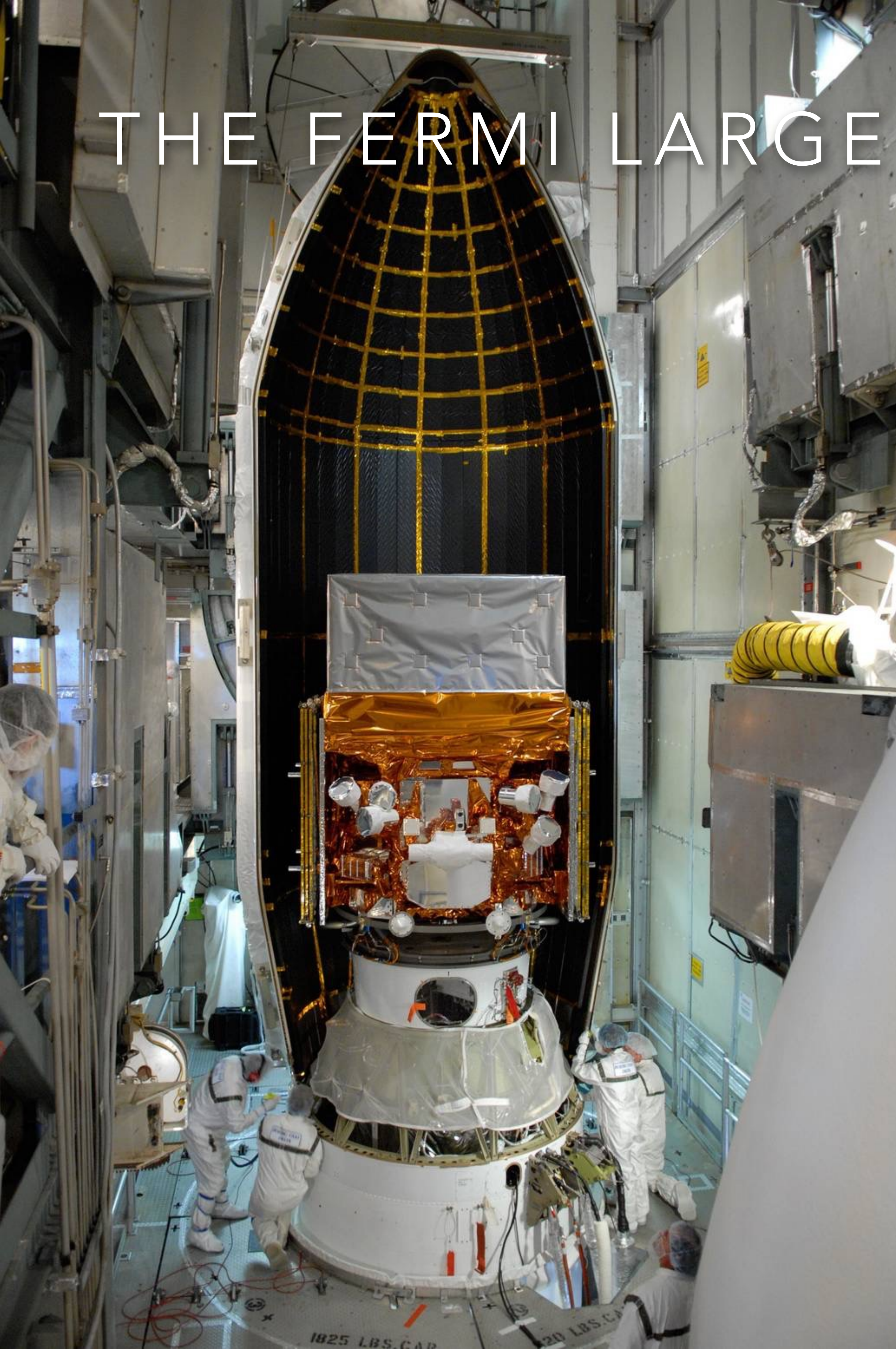
BUILDING A GAMMA RAY TELESCOPE

— 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 cosmic rays)



THE FERMI LARGE AREA TELESCOPE



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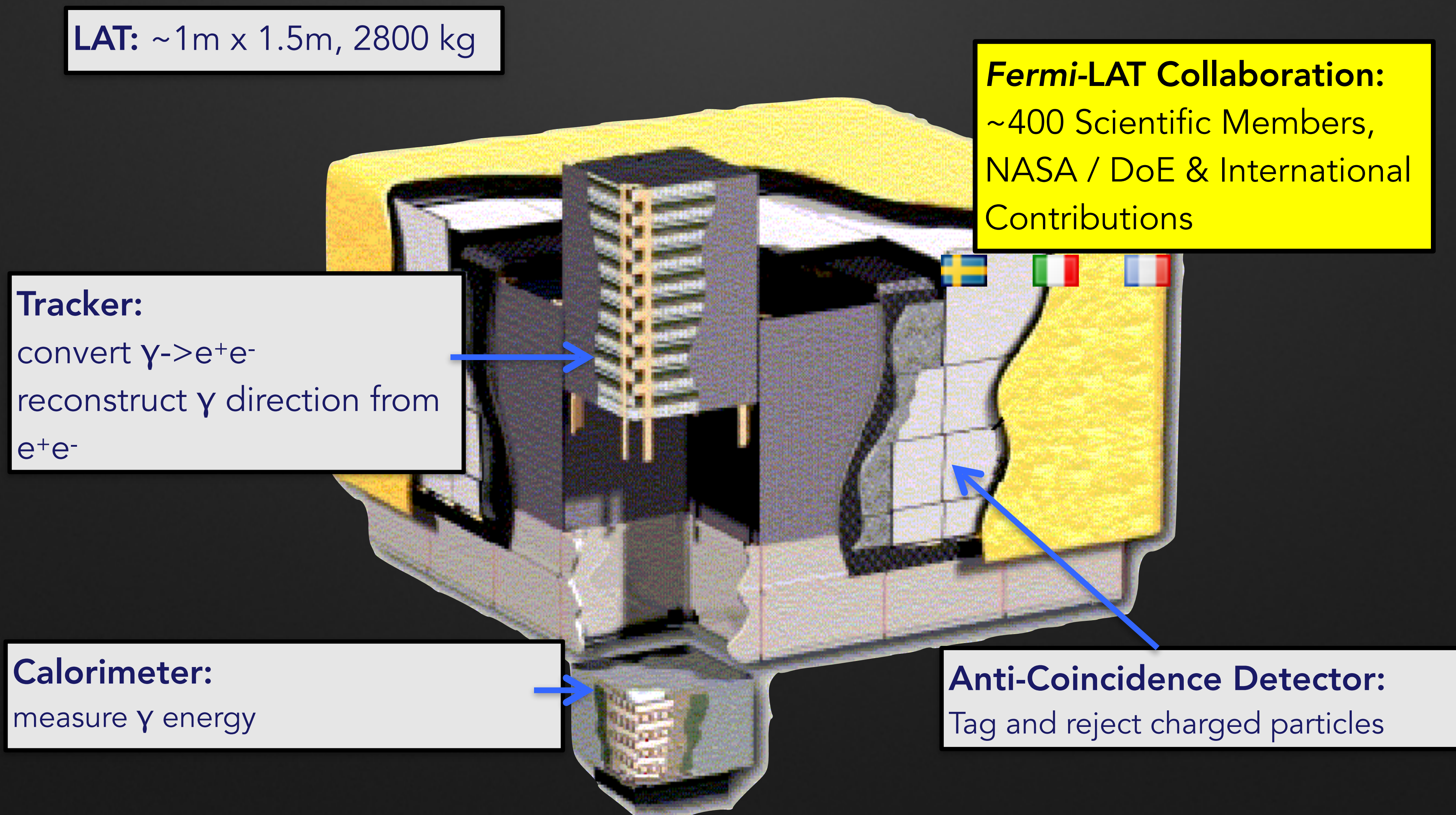
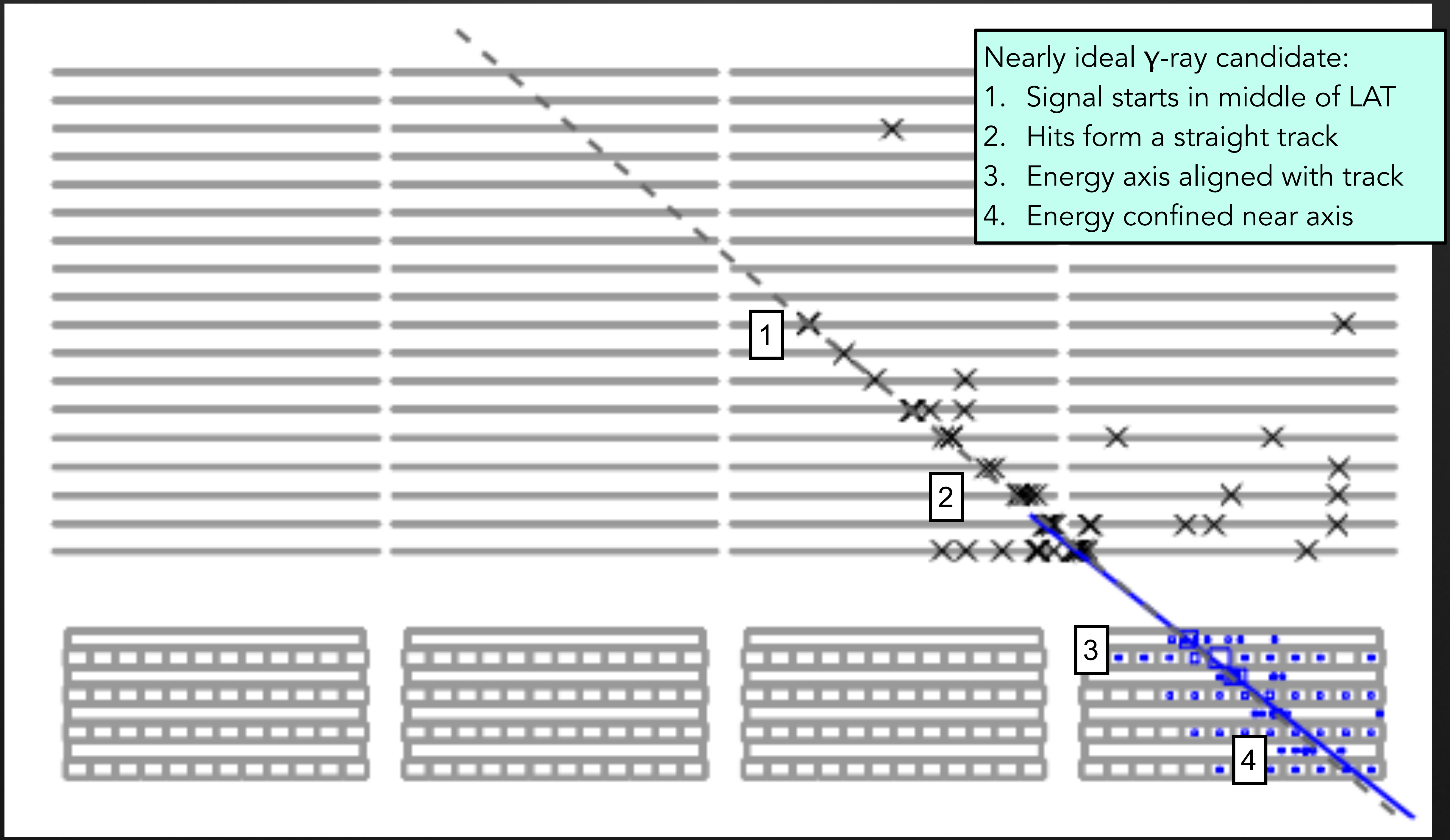
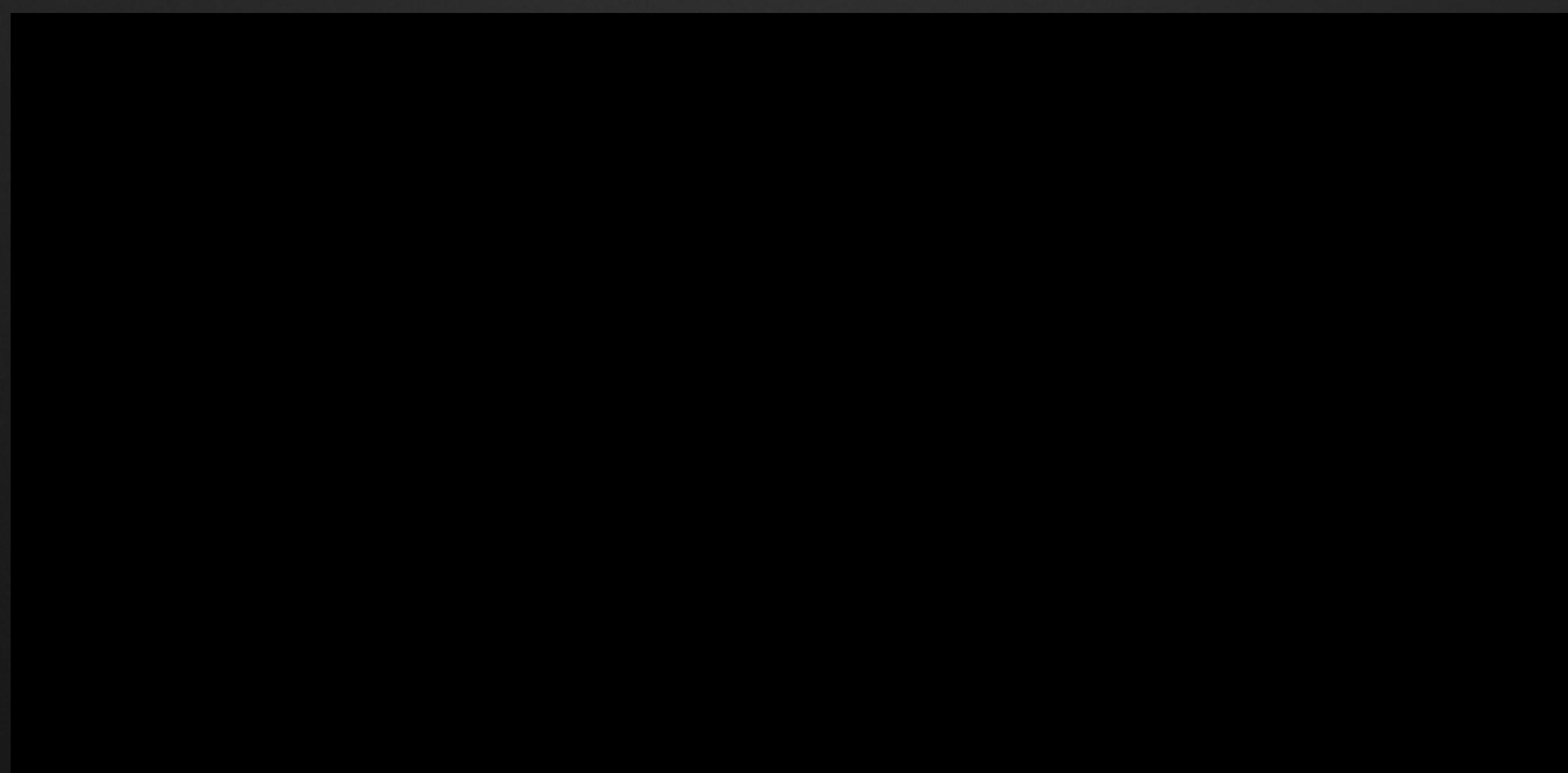


LAT DETECTS INDIVIDUAL GAMMA RAYS



OBSERVING THE FULL SKY WITH FERMI

- Fermi satellite orbital period ~ 90 minutes
- Satellite alternates between looking south and north every orbit
- Sees the whole sky every 3 hours



Fisheye view of bright point source in 51 months

BASIC WORKFLOW

WHAT'S YOUR RESEARCH QUESTION?

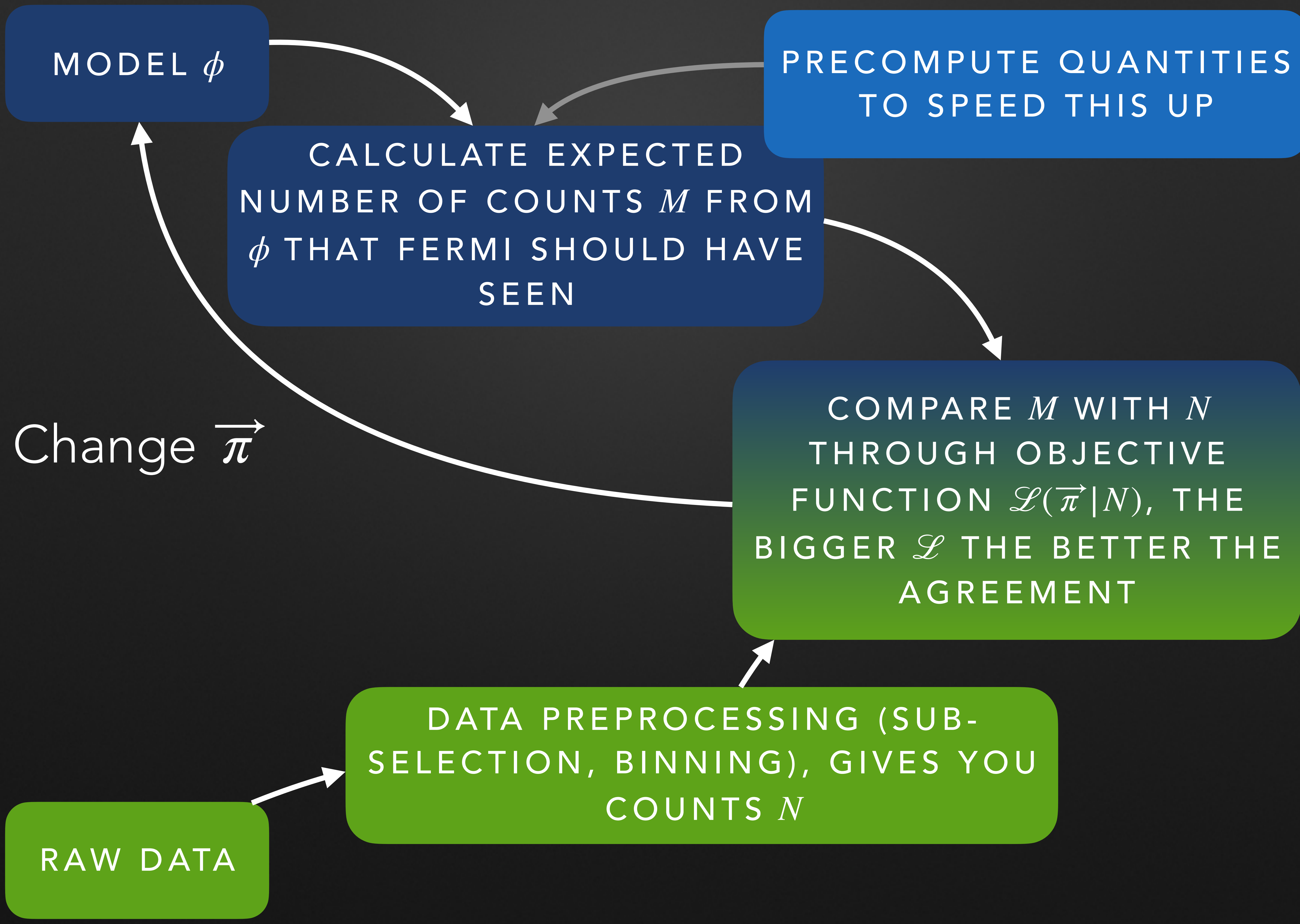
- Is my source of interest detected at γ energies?
- If it is detected what is its average spectrum (=photon flux as a function of energy) over some time range?
- Is its spectrum compatible with some theoretical shape (e.g., dark matter annihilation)?
- What is the source morphology? Point-like? Extended?
- What is the evolution of the source flux vs time?
- …

LIKELIHOOD FITTING

- No matter what your question is, in the end it boils down to fitting a model ϕ for your source(s) to the data
- Most generally, model will depend on energy E, time t, solid angle Ω, and model parameters $\vec{\pi}$:

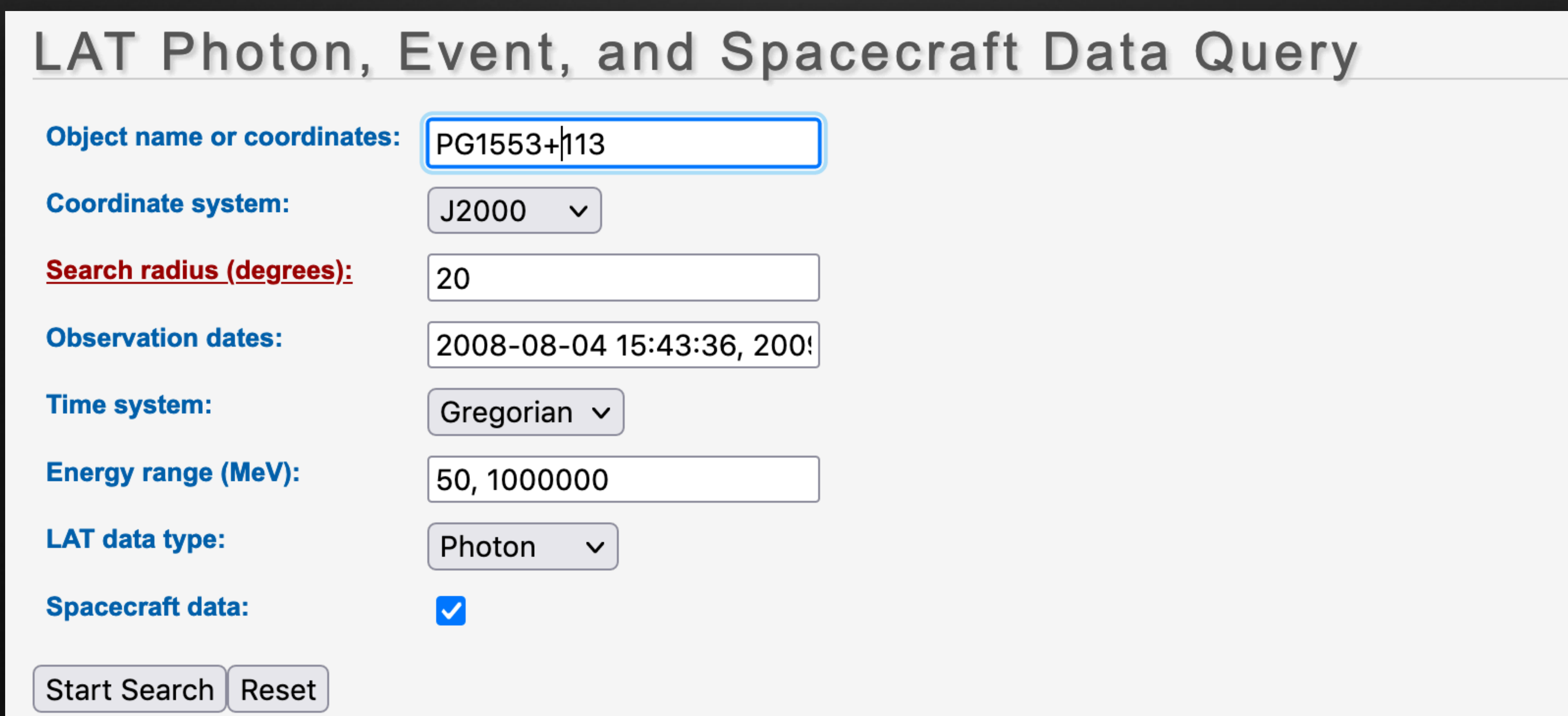
$$\phi \equiv \phi(E, t, \Omega, \vec{\pi}) = \frac{dN}{dE\ dt\ dA\ d\Omega}$$

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


MODEL ϕ
PRECOMPUTE QUANTITIES TO SPEED THIS UP
CALCULATE EXPECTED NUMBER OF COUNTS M FROM ϕ THAT FERMI SHOULD HAVE SEEN
Change $\overrightarrow{\pi}$
COMPARE M WITH N THROUGH OBJECTIVE FUNCTION $\mathscr{L}(\overrightarrow{\pi}|N)$, THE BIGGER $\mathscr{L}$ THE BETTER THE AGREEMENT
DATA PREPROCESSING (SUB-SELECTION, BINNING), GIVES YOU COUNTS N
RAW DATA

GET THE DATA

- You can download data from https://fermi.gsfc.nasa.gov/cgi-bin/ssc/LAT/LATDataQuery.cgi
- Data starts at 2008-08-04 15:43:36 UTC
- Useful tool: xTime convert mission elapsed time (MET) to UTC, MJD, …



DOWNLOAD DATA

- If you downloaded the latest version of fermipy and the fermitools, you are all set
- Otherwise, you need to get the catalog files and templates for extended sources, available here

Your search criteria were:

Equatorial coordinates (degrees)	(238.929,11.1901)
Time range (MET)	(239557417,271093418)
Time range (Gregorian)	(2008-08-04 15:43:36,2009-08-04 15:43:36)
Energy range (MeV)	(50,1e+06)
Search radius (degrees)	20

The state of your query is 2 (Query complete)

Server	Position in Queue	Estimated Time Remaining (sec)
Photon Server	Query complete	N/A
Spacecraft Server	Query complete	N/A

The filenames of the result files consist of the query ID string with an identifier appended to indicate which database the file came from. The identifiers are of the form: _DDNN where DD indicates the database and NN is the file number. The file number will generally be '00' unless the query resulted in a large data volume. In that case the data is broken up into multiple files. The values of the database field are:

- PH - Photon Database
- SC - Spacecraft Pointing, Livetime, and History Database
- EV - Extended Database

In the event that you do not see any files with the data type you requested listed below, you should try resubmitting your query as there may have been a problem.

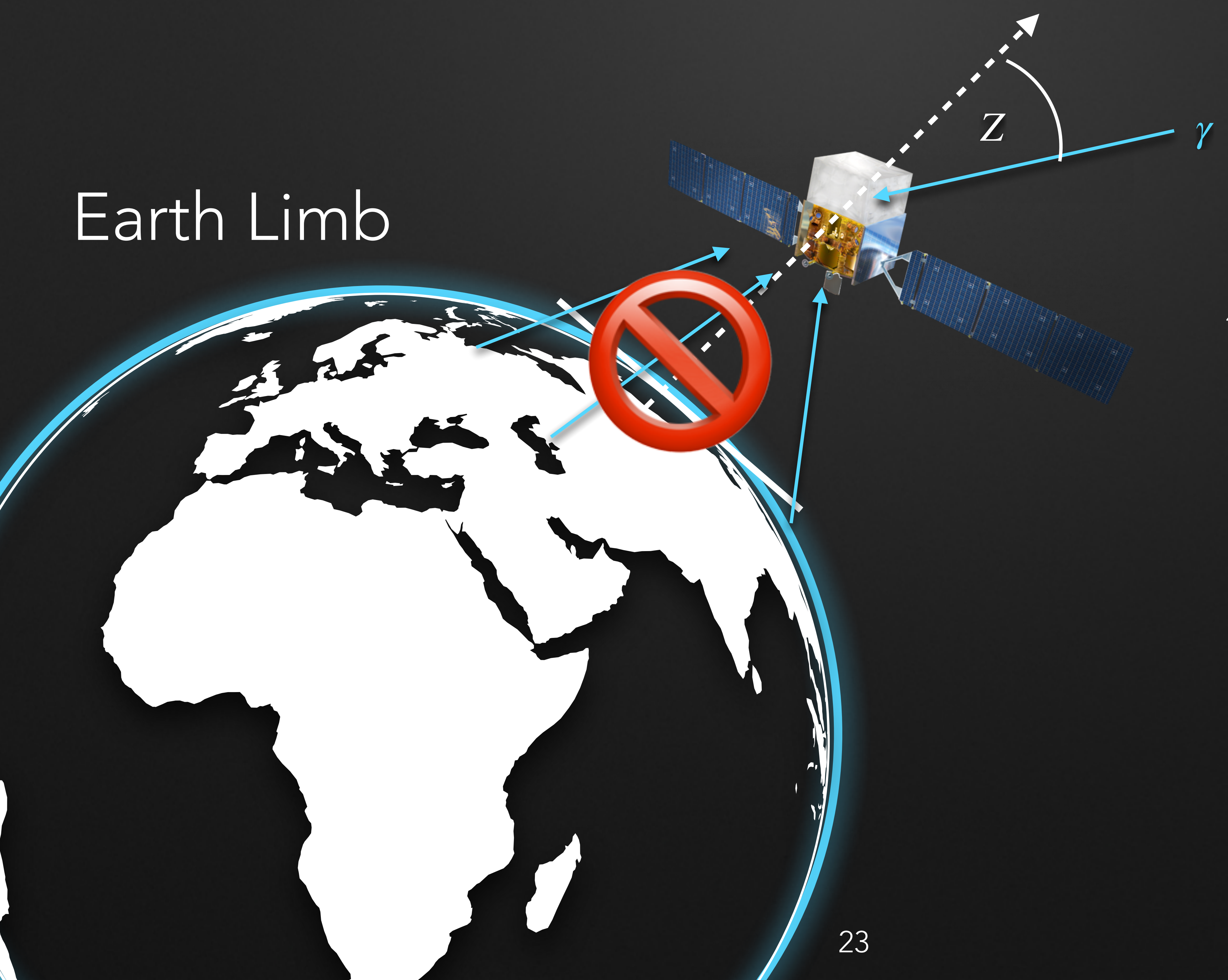
Filename	Number of Entries	Size (MB)	Status
L210621085941F357373F60_PH00.fits	231862	21.73	Available
L210621085941F357373F60_PH01.fits	179612	16.84	Available
L210621085941F357373F60_SC00.fits	876471	137.11	Available
L210621085941F357373F60_PH02.fits	135830	12.74	Available

If you would like to download the files via wget, simply copy the following commands and paste them into a terminal window. The files will be downloaded to the current directory in the terminal window.

```
wget https://fermi.gsfc.nasa.gov/FTP/fermi/data/lat/queries/L210621085941F357373F60_PH00.fits
wget https://fermi.gsfc.nasa.gov/FTP/fermi/data/lat/queries/L210621085941F357373F60_PH01.fits
wget https://fermi.gsfc.nasa.gov/FTP/fermi/data/lat/queries/L210621085941F357373F60_SC00.fits
wget https://fermi.gsfc.nasa.gov/FTP/fermi/data/lat/queries/L210621085941F357373F60_PH02.fits
```

SWITCH TO PG1553 NOTEBOOK: [HTTPS://NBVIEWER.JUPYTER.ORG/GITHUB/ME-MANU/FERMIPY-EXTRA/BLOB/MASTER/NOTEBOOKS/PG1553.IPYNB](https://nbviewer.jupyter.org/github/me-manu/fermipy-extra/blob/master/notebooks/PG1553.ipynb)

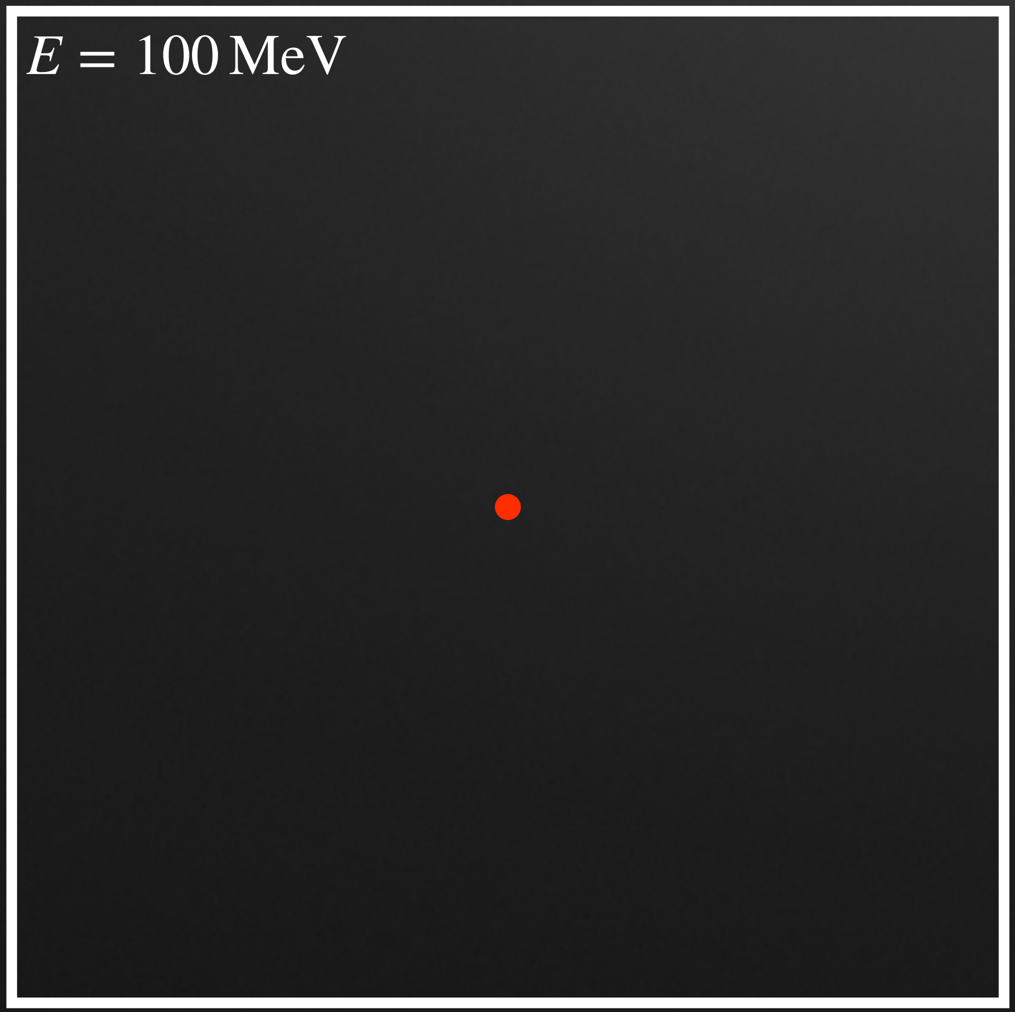
WHY A CUT ON ZENITH ANGLE?



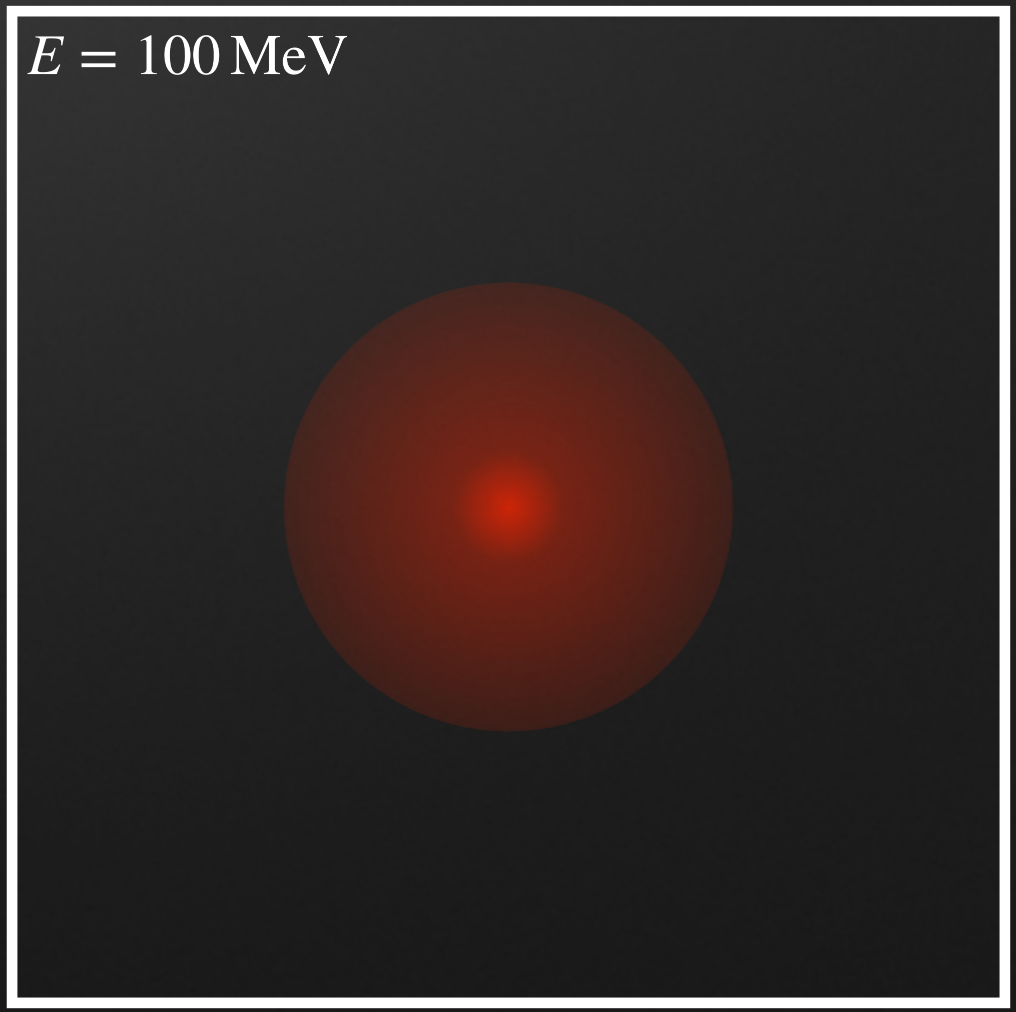
$$Z \leqslant 90°$$

WHY SELECTING EVENTS FROM A REGION OF INTEREST (ROI)?

- LAT has large point spread function, which depends on energy



Truth



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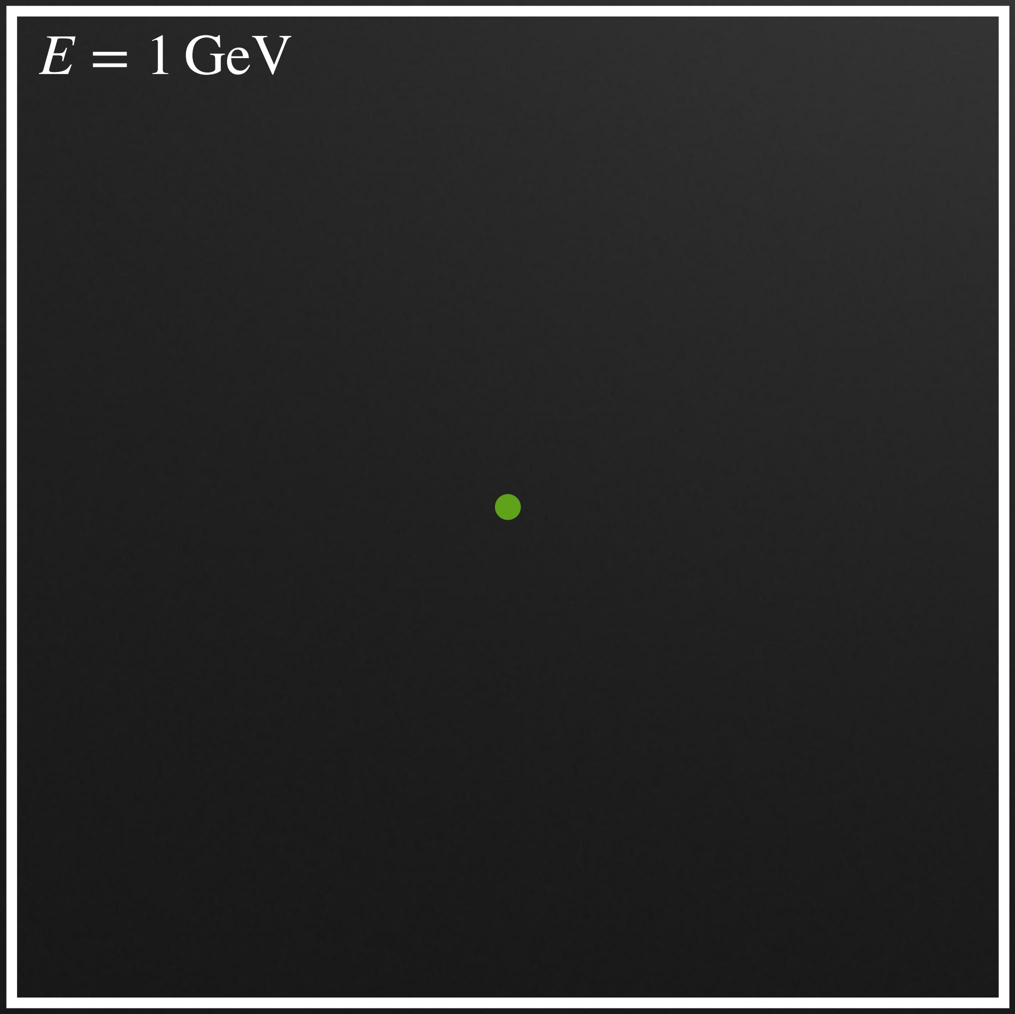

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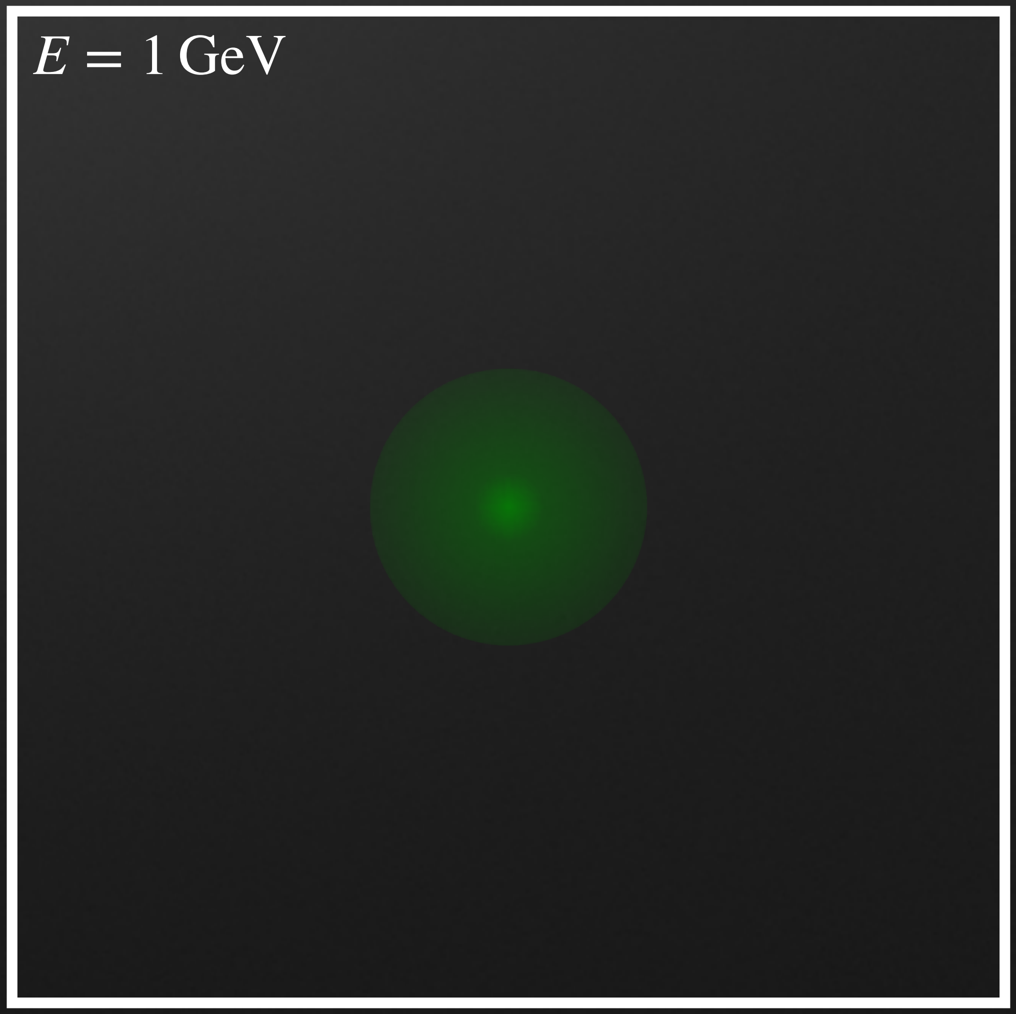

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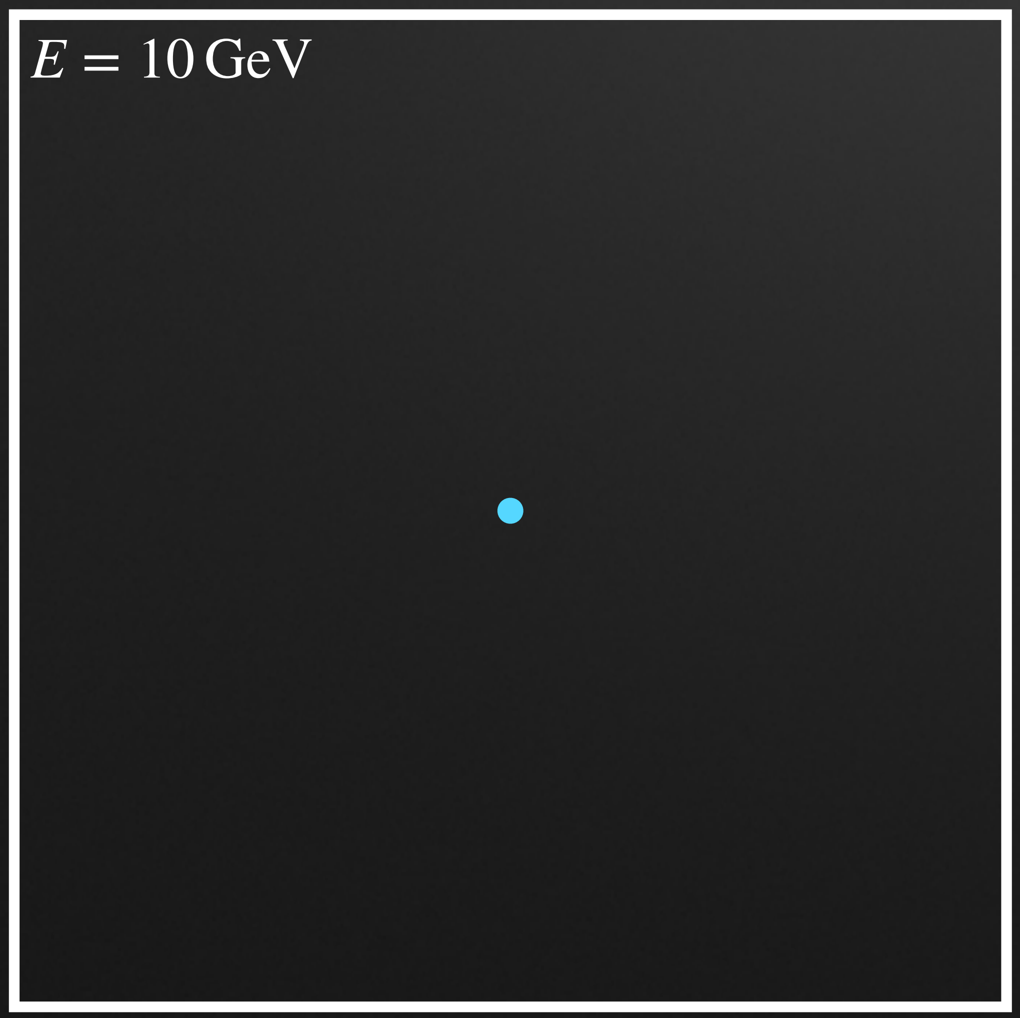

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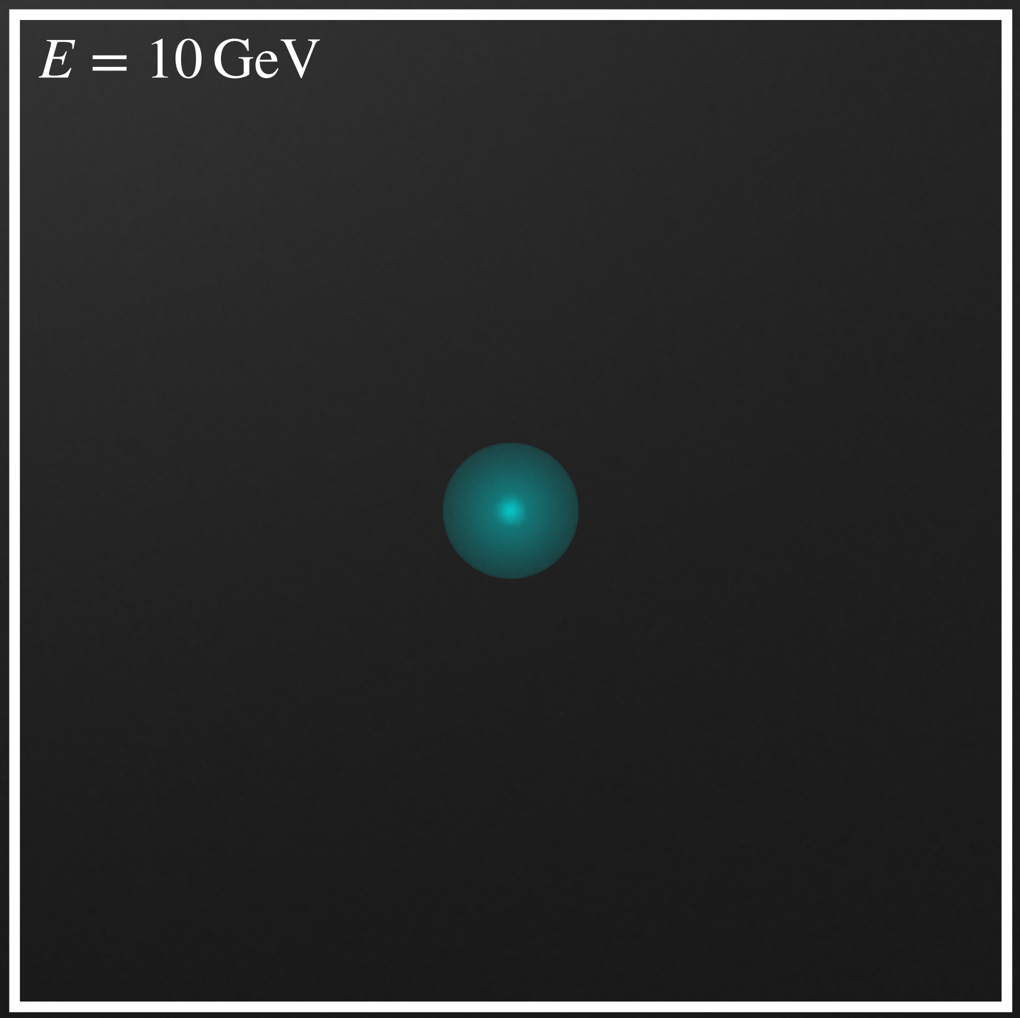

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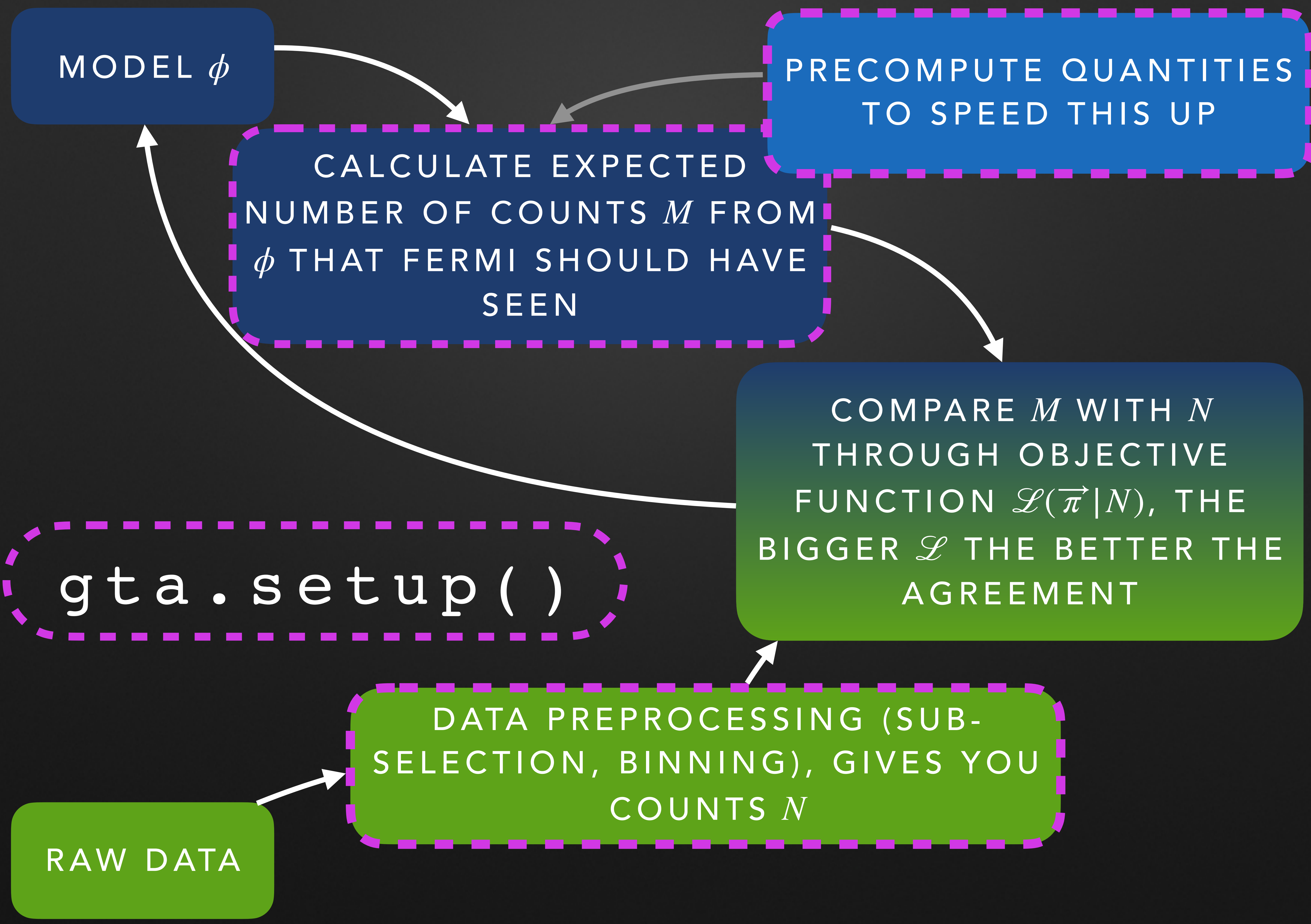
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COMPUTE EXPECTED COUNTS M

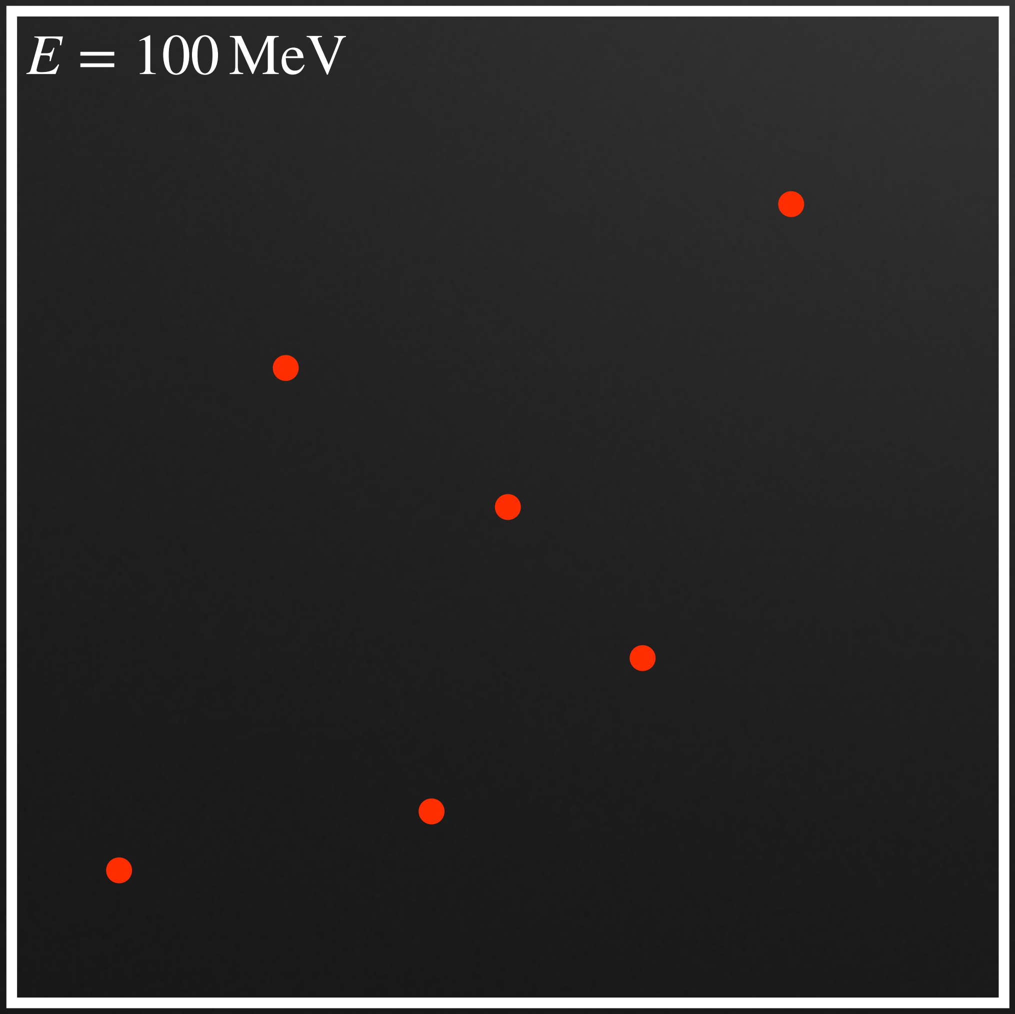
- Expected counts obtained from convolution of model flux ϕ with instrumental response function R

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

- Instrumental response function factors into:
  - Point spread function $\mathrm{PSF}(\vec{p}, \vec{p}\,', E)$, 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 $A_{\mathrm{eff}}(E, \vec{p})$ of the detector at energy E and direction $\vec{p}$ (multiplied with T_{obs} this is called exposure)

WHY SO MANY SOURCES IN MY MODEL?

- Broad PSF makes it necessary to not only model your source of interest but all sources in the vicinity as well!



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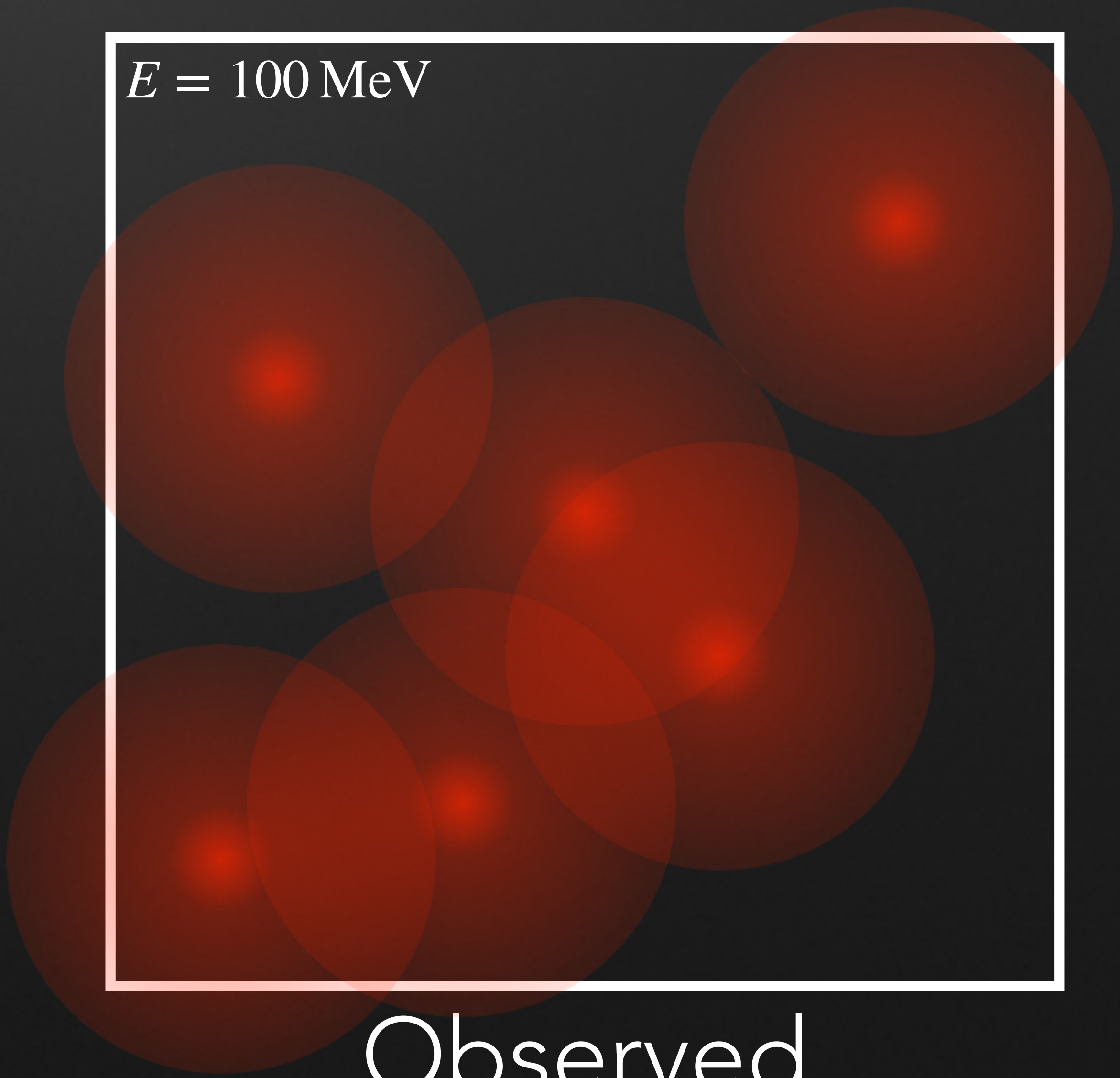
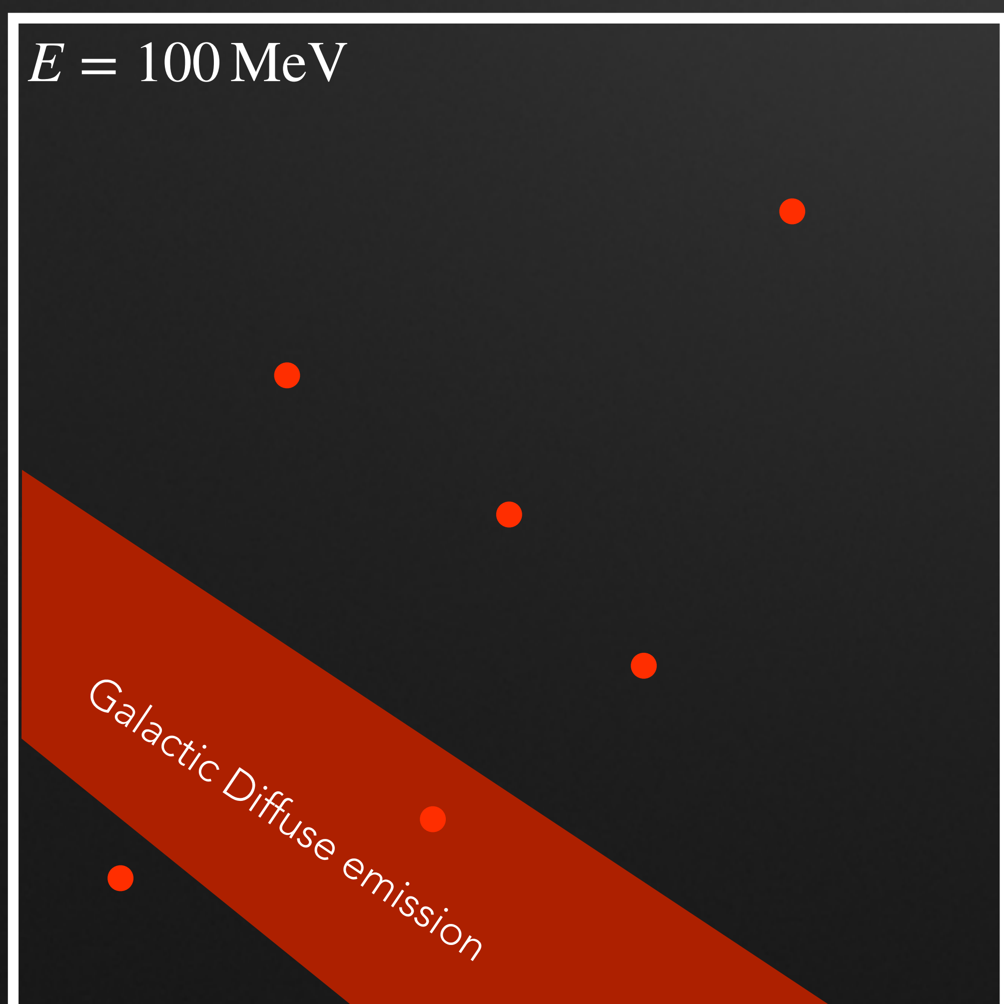


Observed

WHY SELECTING EVENTS FROM A REGION OF INTEREST (ROI)?

- Also backgrounds like Galactic and Extragalactic diffuse emission need to be included



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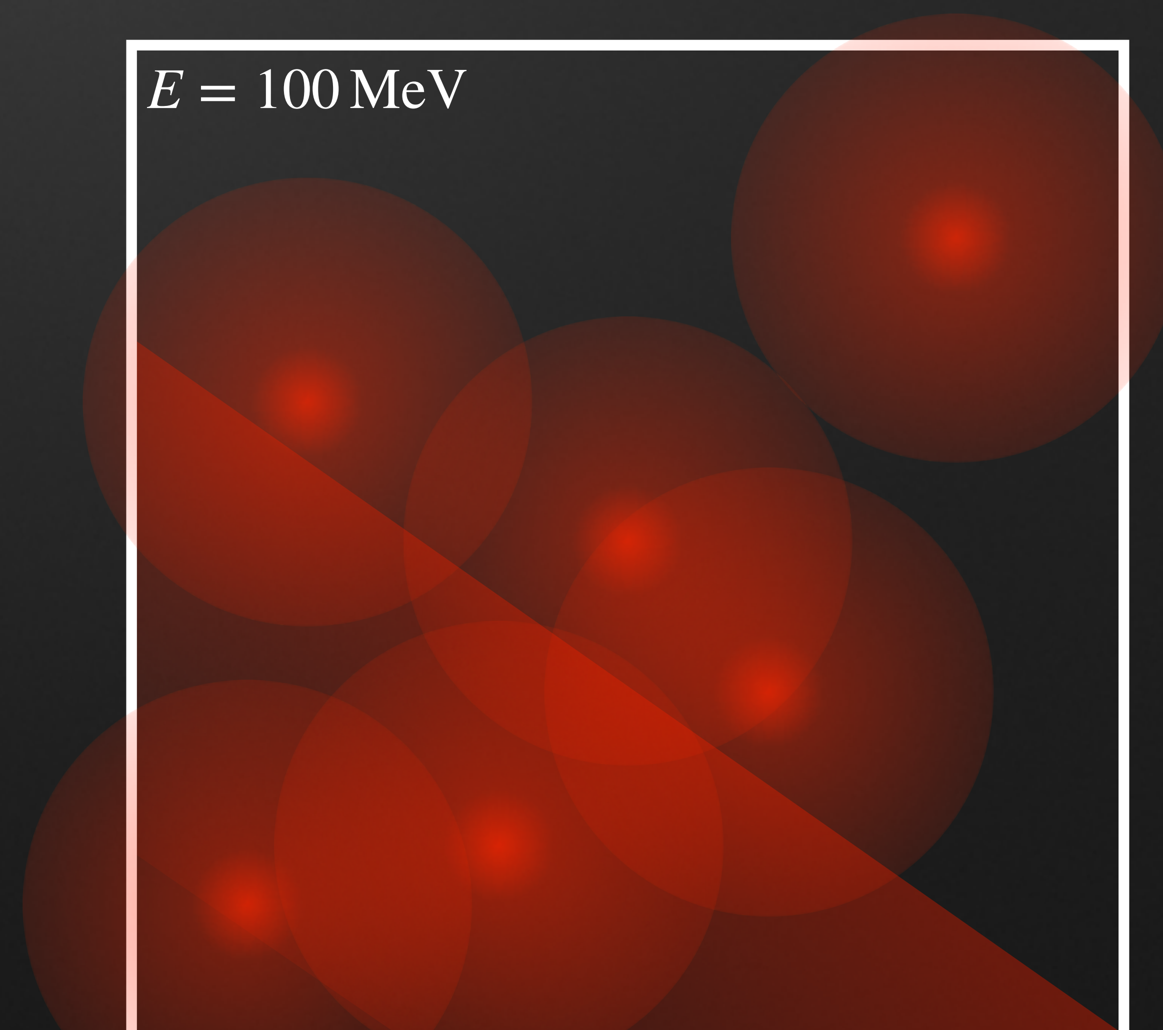

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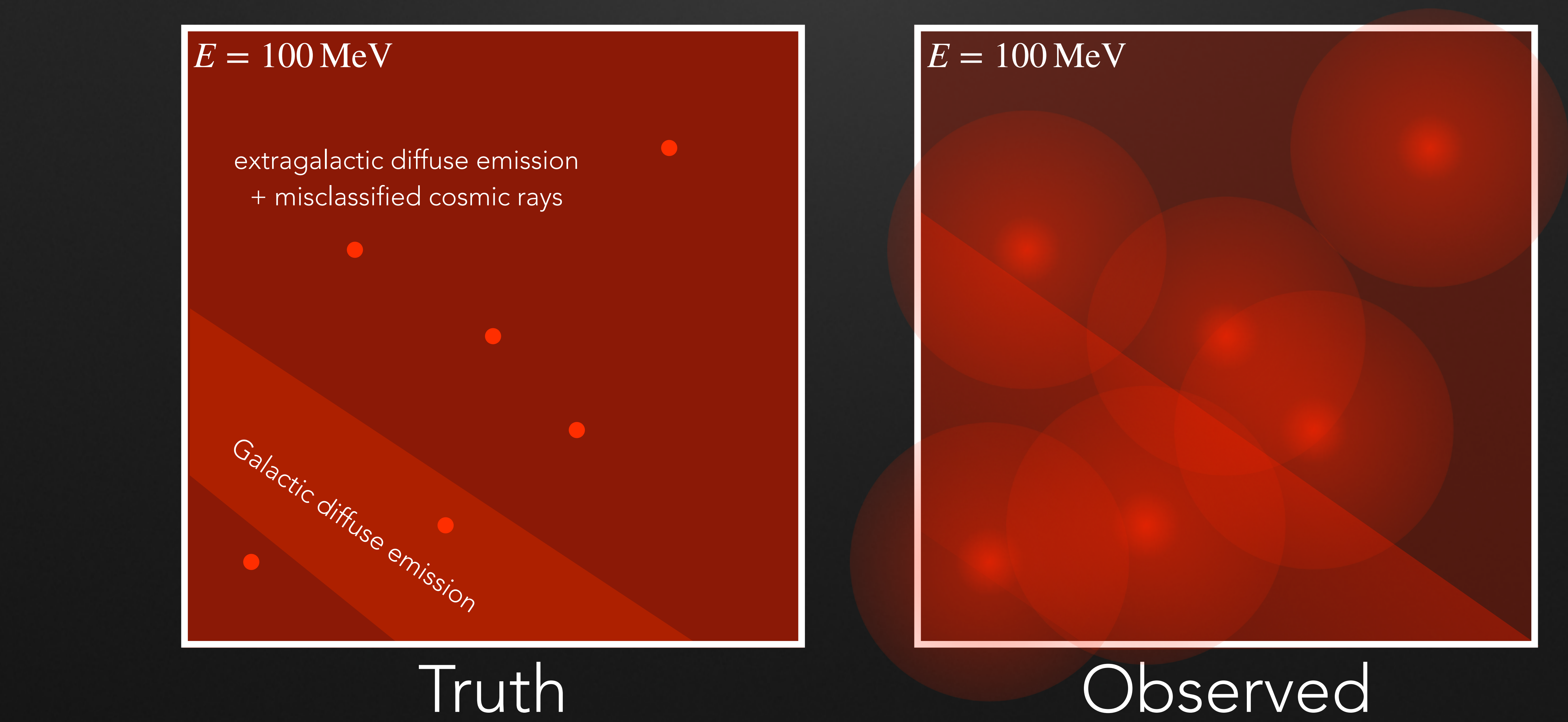


OBJECTIVE FUNCTION: POISSON LIKELIHOOD

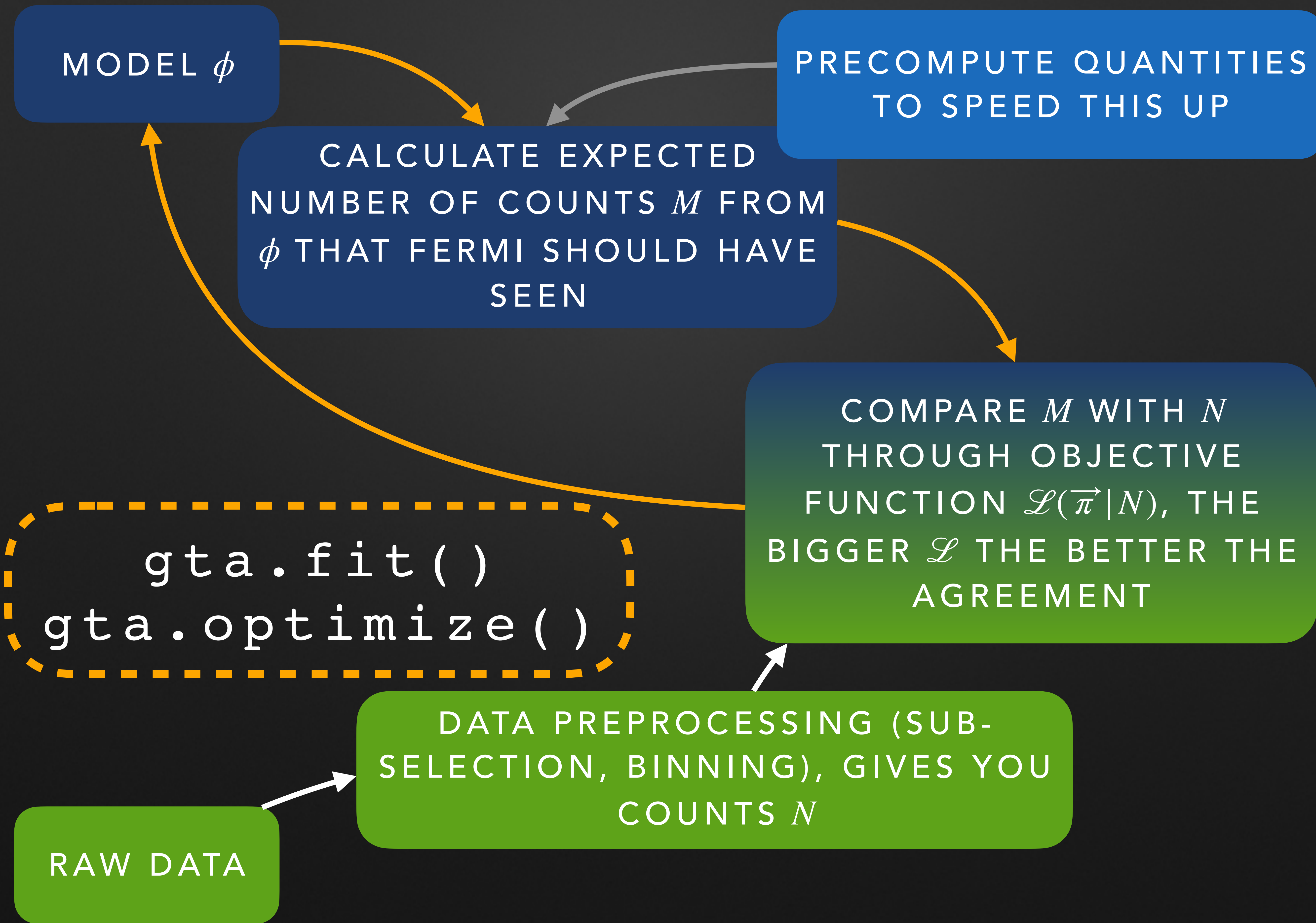
- Poisson statistics applies when we have a photon counting experiment
- Probability to observe N events given a constant rate M:

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

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

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

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

- If you want to know what's going on "behind the scenes" consider doing the binned analysis tutorial using only the fermitools and not fermipy
- A full description of the individual analysis steps and what they do and the files that are created is given here
    - If you are planning to do more Fermi analysis in the future, I strongly suggest that you read this and do do the binned analysis tutorial once
- You can also do an unbinned analysis of LAT data, this is, however, not supported by fermipy. In any case, a tutorial is provided here