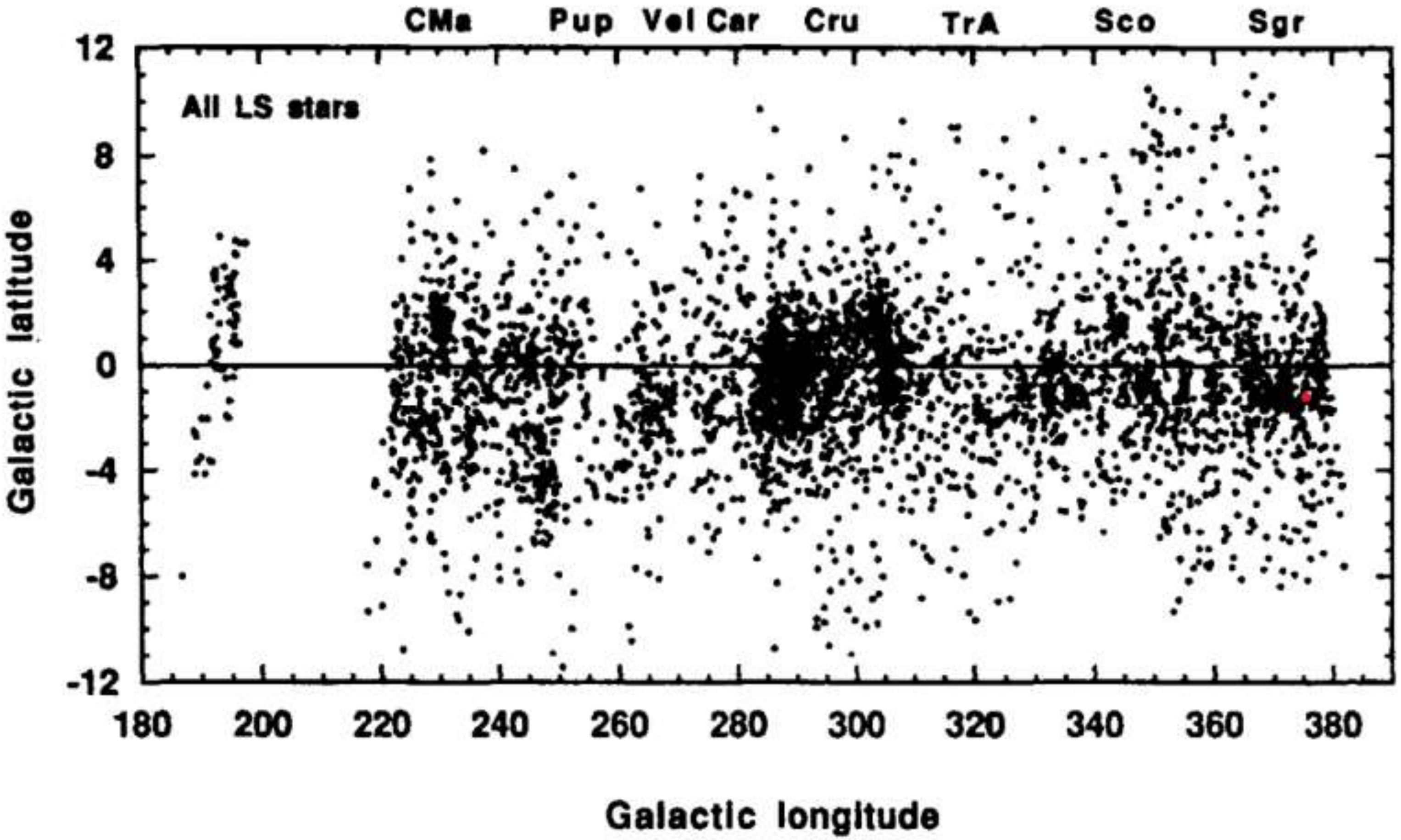
STUDY OF THE BINARY SYSTEM LS 5039

COMPUTATION OF THE ORBITAL PERIOD EVOLUTION USING GAMMA-RAYS

JOLAN LAVOISIER

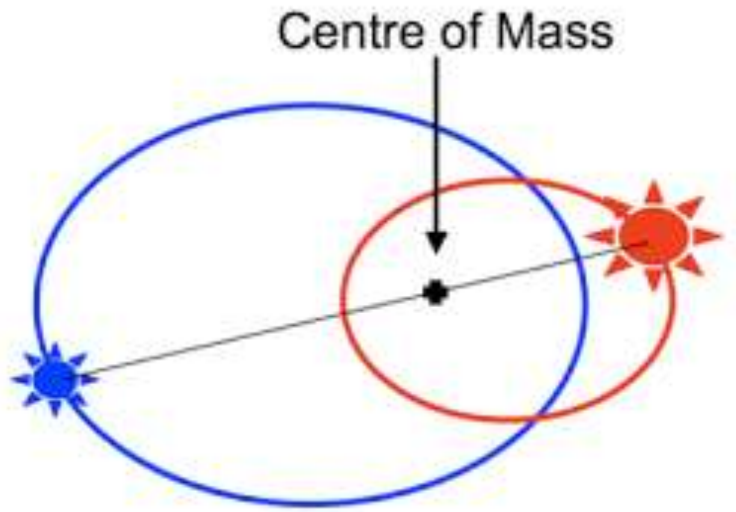
HISTORICAL FACTS ABOUT LS 5039

- First catalogued in **Luminous Stars in the Southern Milky Way** in 1971 by Sanduleak and Stephenson.



WHAT IS A BINARY SYSTEM

- A binary system is a gravitational system that is comprised of 2 massive objects
- 70 % of stars are in binary systems
- The center of mass is closer to the more massive object



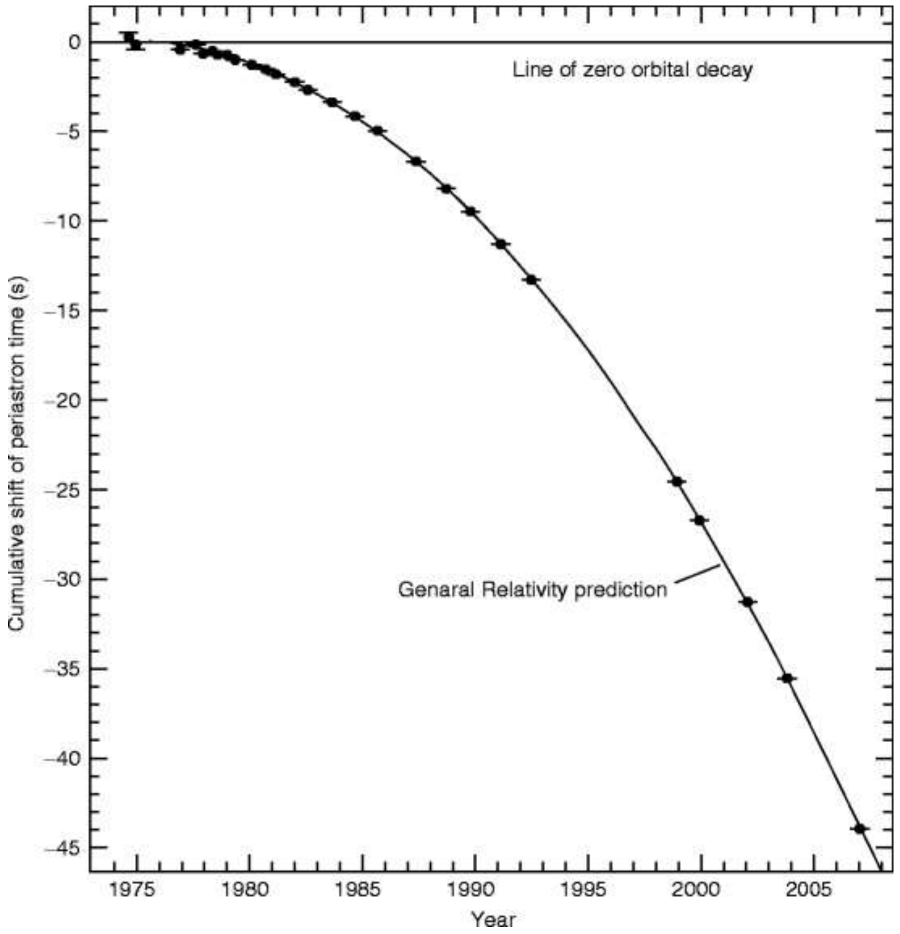
- LS 5039 is a binary system, comprised of a really luminous star, with a radius $R = 10\ R_\odot$, and a compact object (i.e. BH or NS, but in our case, could be a magnetar), at a distance of $0.13 \times A.U.$ (one Astronomical Unit is the distance between the Sun and Earth)
- As an idea of the scales : if the sun was that big and that close (we would burn, yes, not the point), it would have an angular diameter of 40°

WHAT WE EXPECT FROM THE STUDY

- In 2018, it was hinted that the period of LS 5039 could evolve in an unexpected manner
- Usually (Hulse-Taylor, Nobel Prize 1993), General Relativity effects will tend to approach the two objects of a binary system, hence diminishing the period
- According to them, the change in period would be $\dot{P} = -1.11 \cdot 10^{-13}\ s/s$ (after 10 years, 0.06s in difference)

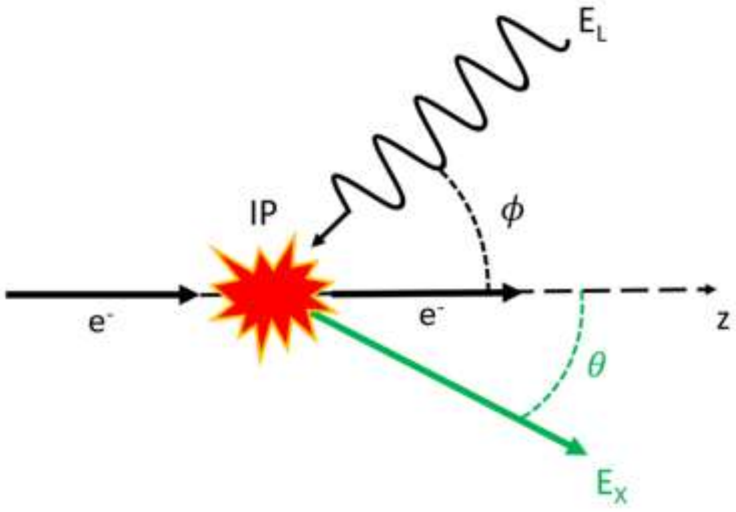
- But Christian Mariaud found in his thesis that the apparent evolution was in the other way around
- Our goal is to verify this result

Evolution of the period of the Hulse-Taylor Pulsar with time, under the effects of GR



HOW DOES LS5039 CREATE GAMMA RAYS ?

- For this study, we are going to use high-energy gamma rays emitted by LS 5039
- High-energy gamma rays are usually produced by inverse Compton scattering : electrons with high energies lose energy by emission of a photon



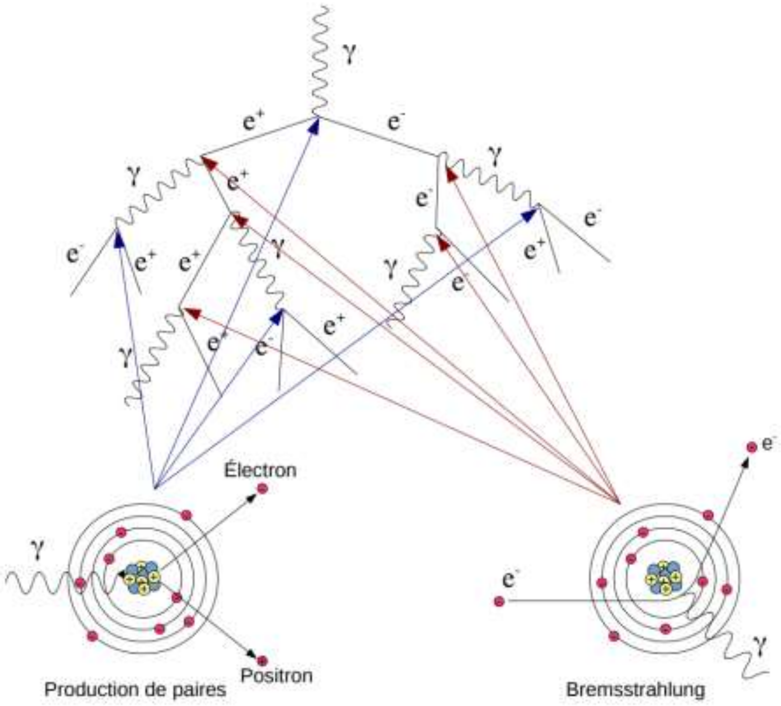
GAMMA ASTRONOMY

- Two types of gamma rays observation :
  - Low energy gamma rays : fairly common, so can be observed in space
    - Examples : EGRET (Energetic Gamma Ray Experiment Telescope – from 30 MeV to 30 GeV), Fermi LAT (its successor)
  - High energy gamma rays : more rare, so less easy to observe, we need to observe them on the ground
    - Examples : Pierre Auger Observatory (Argentina), HESS (Namibia)

GAMMA ASTRONOMY

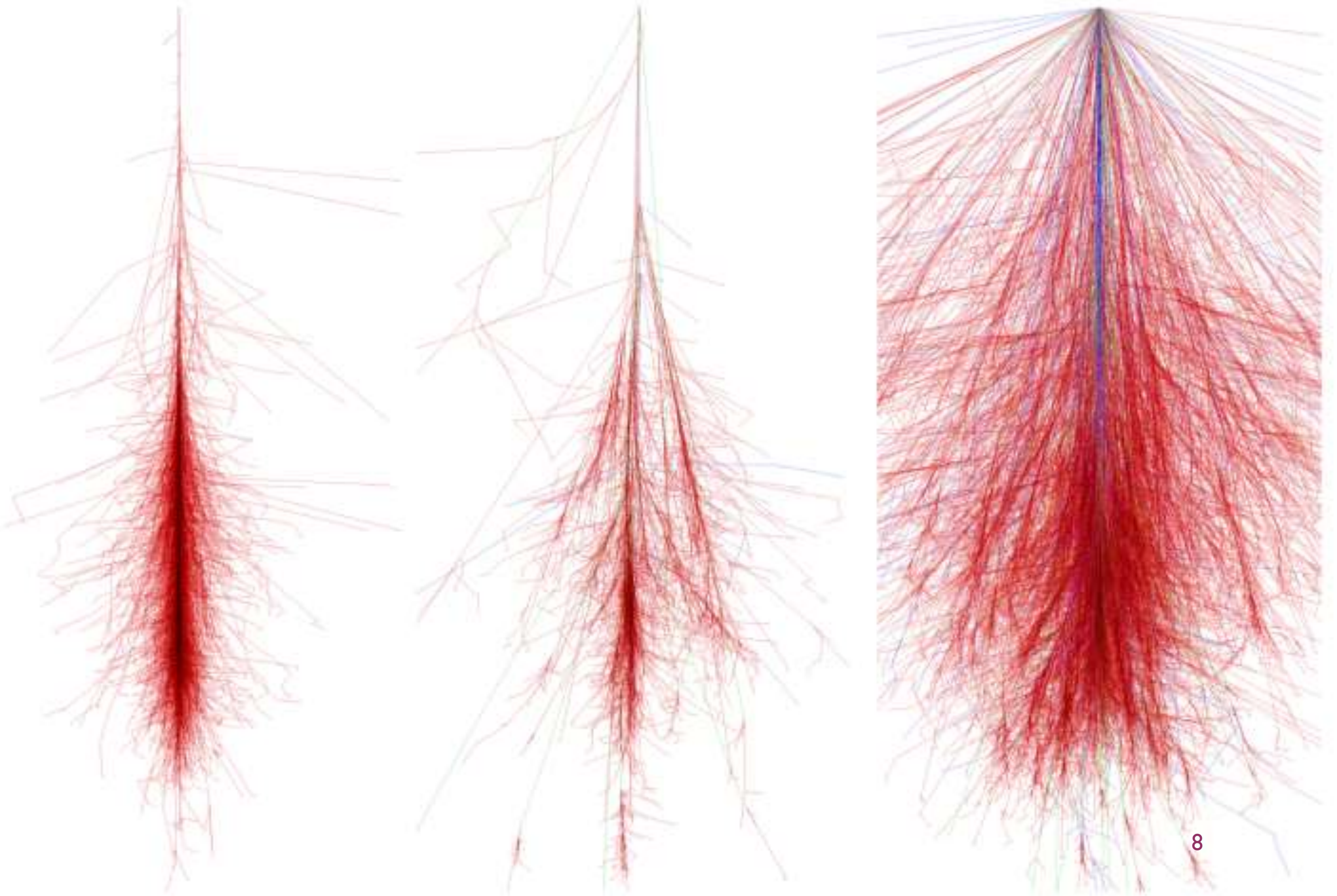
- If it is easy to observe gamma rays from space, since we can catch the primary particle, it is another game on the ground…

- Since high energy gamma rays have a high energy (if you hadn't guessed it), they interact with the particle of the atmosphere to create Extended Air Showers, with 2 different reactions



GAMMA ASTRONOMY

- Mind you, photons are not the only high-energy particles observed on the ground, other types of particles also enter the atmosphere and create EAS
- 99% of EAS are produced by protons, while 0.1% originate from photons
- To distinct them (other than the fact they contain different types of particles), we pay attention to their form

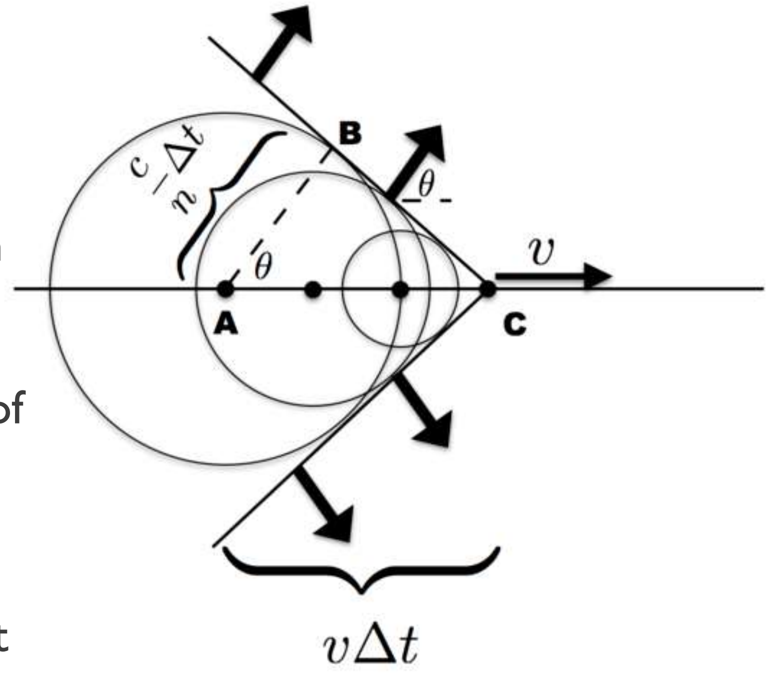


100 GeV γ 100 GeV proton 1 TeV iron nucleus

IMAGING ATMOSPHERIC CHERENKOV TELESCOPES

- How to differentiate their form ?

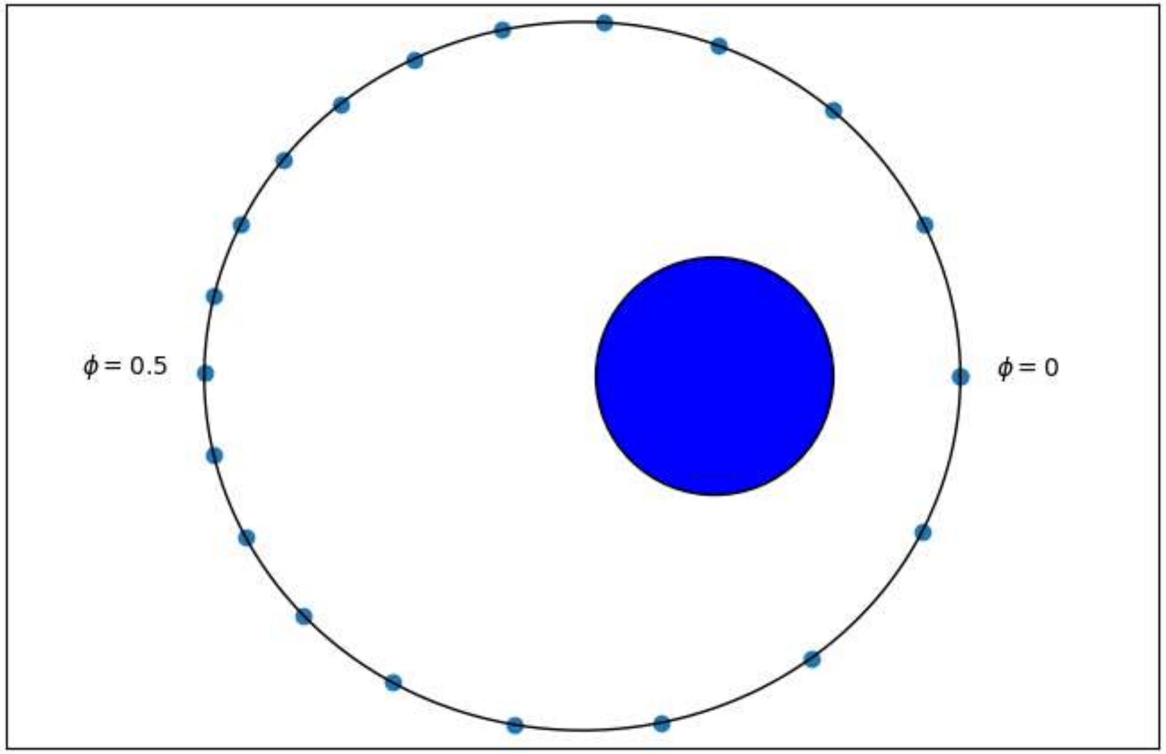
$\Rightarrow$ **Cherenkov light**

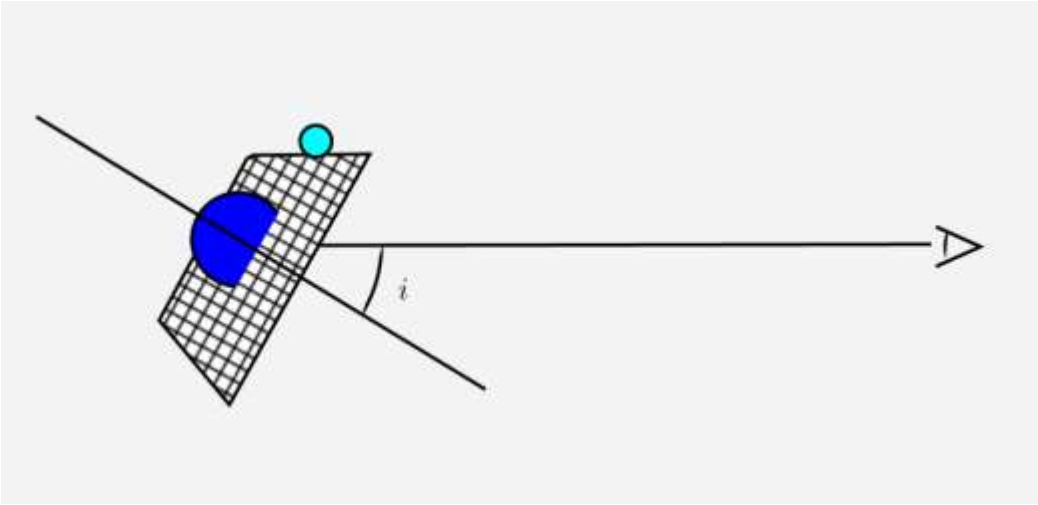


- Light emitted in a cone by particles going faster than the speed of light in the medium (i.e. not c, but rather $\frac{c}{n}$)
- The angle of the cone depends on the index of the medium. In the case of the air, we have $\theta \simeq 1.4°$
- Able to reconstruct the EAS to have its form and thus try to reconstruct the energy of the primary particle !

INFORMATION ON LS 5039

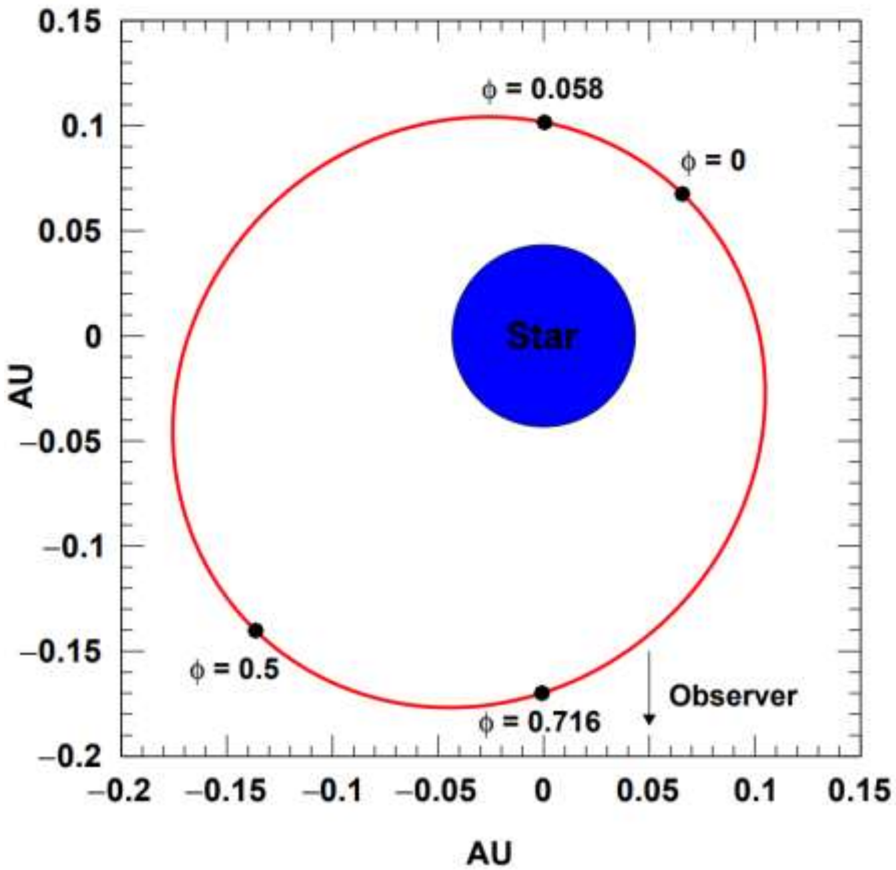
- Inclination plays a major role : angle at which we see the plan of orbit. In our case : $i = 24.9\,°$
- Allows us to define geometrically the conjunctions





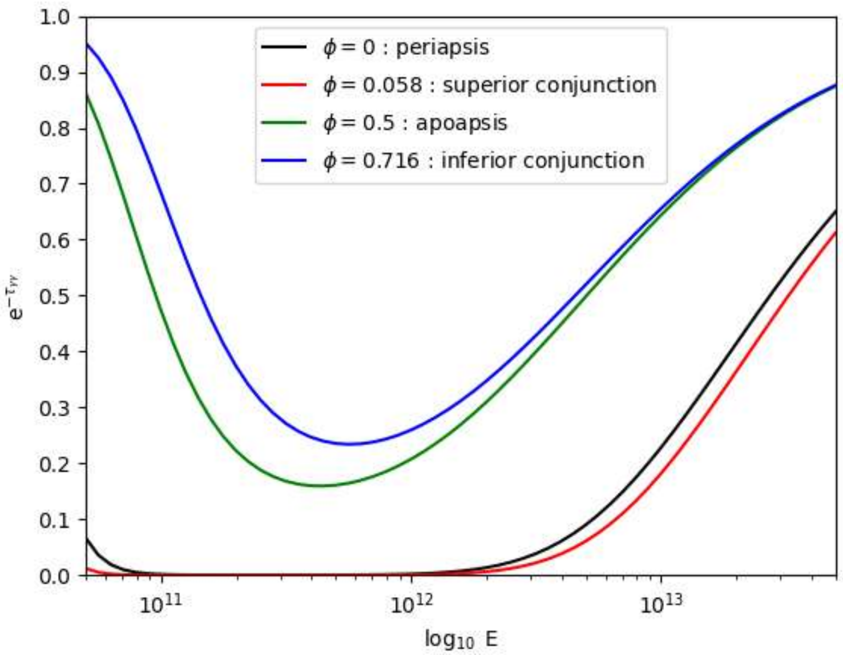
INFORMATION ON LS 5039

- Conjunction are really important



- The photons created in the cosmic accelerator can interact with a photon emitted from the star to induce a pair creation
- The cross section for this interaction (namely, $\gamma + \gamma \rightarrow e^- + e^+$) is more important when both photons come from opposite direction (angle between them close to 180°)

- This interaction acts as an absorption, and thus differs with the phase.

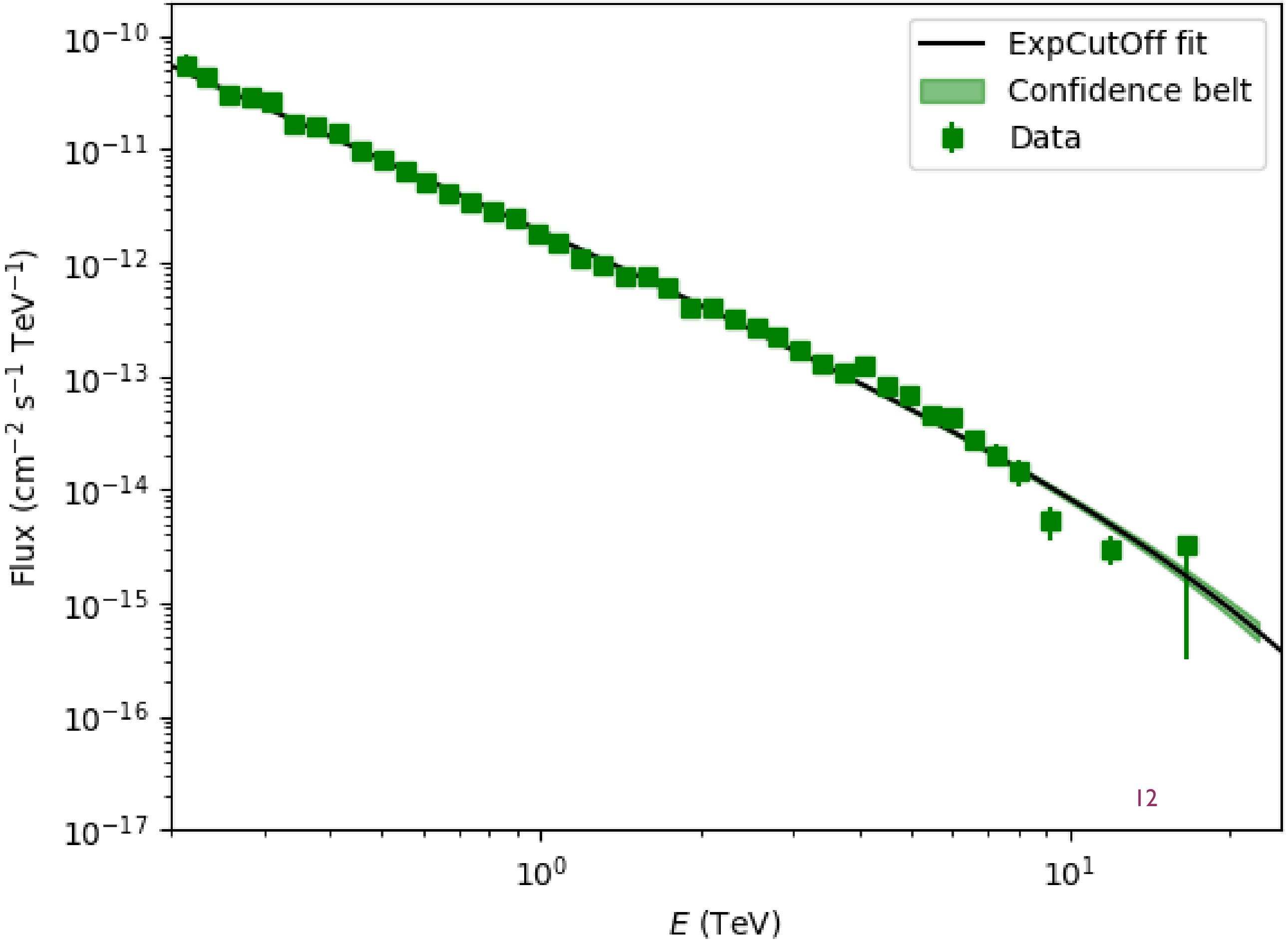


HOW TO MEASURE THE PERIOD

- Spectrum : Spectral shape, expected number of events

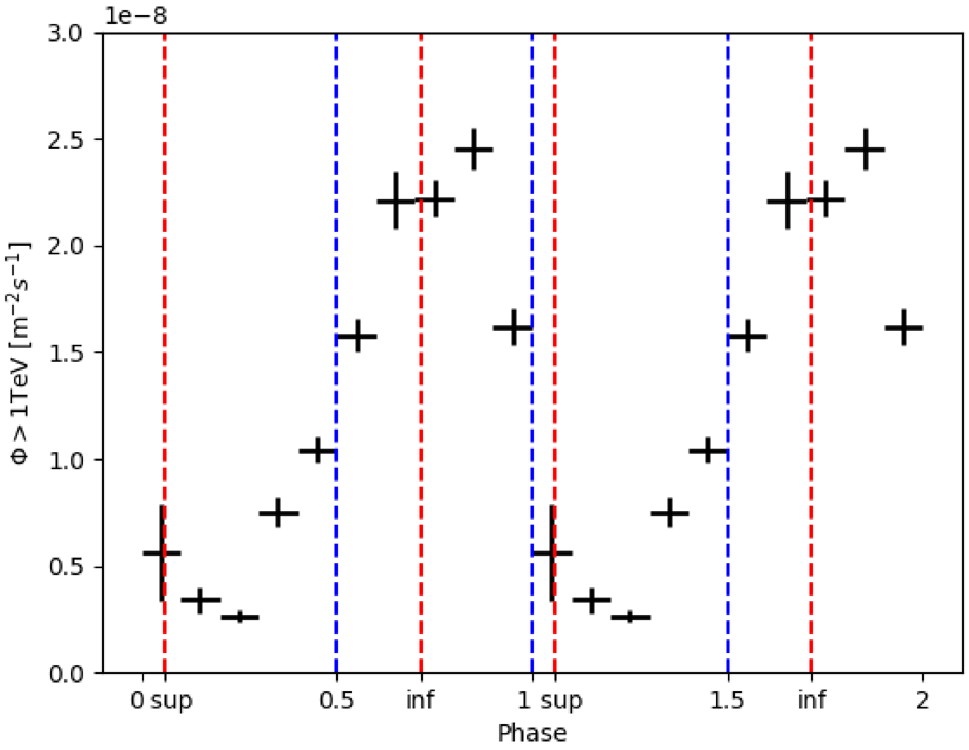
$$n_\gamma = \int_{E_{rec1}}^{E_{rec2}} dE \int_0^\infty dE_{true}\, R(E_{rec}, E_{true}) A(E_{true}) \Phi(\mathrm{E_{true}}|\vec{\alpha})$$

$$\Phi = \frac{dN}{dE} = \Phi_0 \left(\frac{E}{E_0}\right)^\alpha exp\left(-\frac{E}{E_{cut}}\right)$$



HOW TO MEASURE THE PERIOD

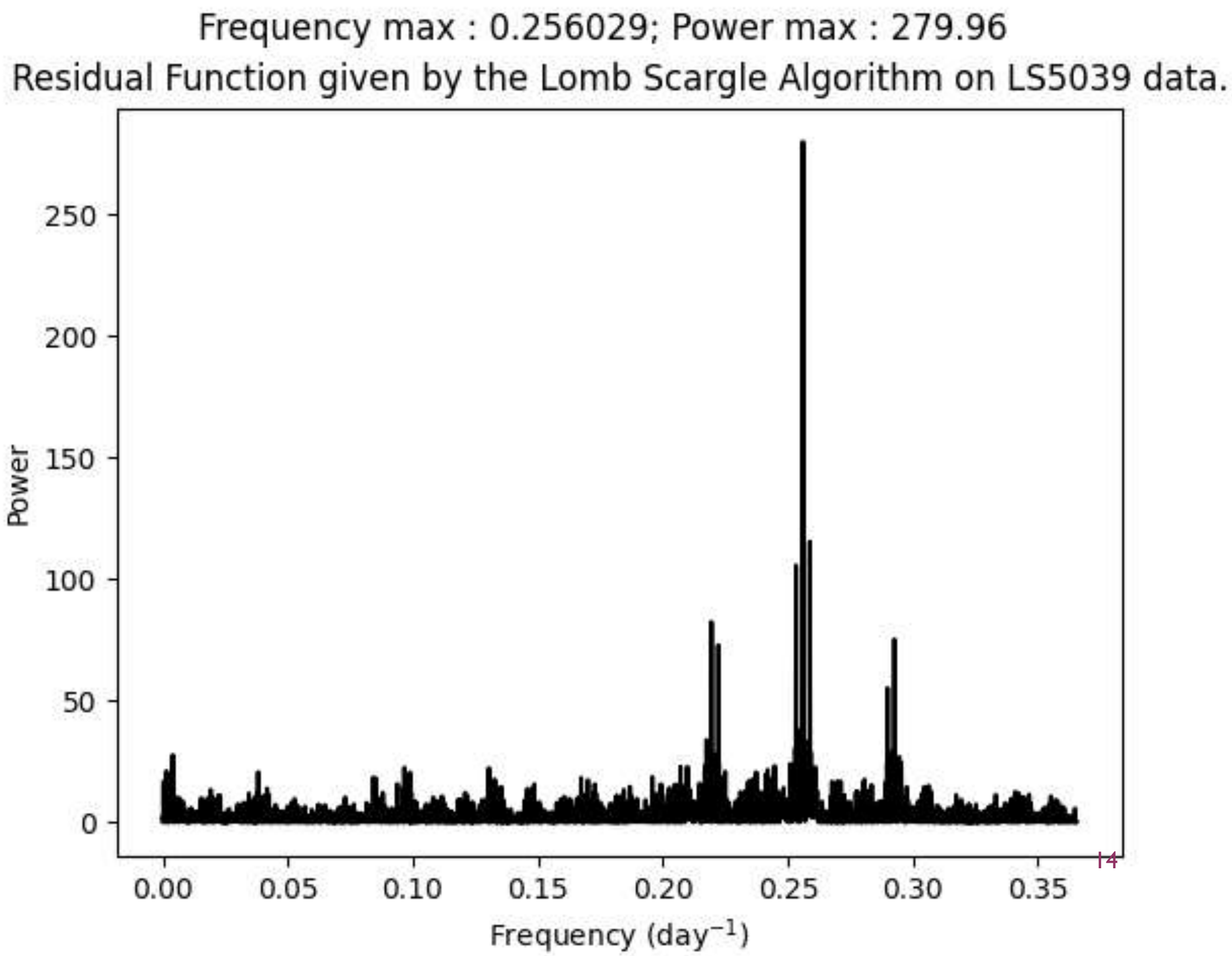
- Light curves : expected number of photon with time
- Here, I will use Phasograms (or folded light curves) : flux depending on the phase of the binary



HOW TO MEASURE THE PERIOD

- Lomb-Scargle periodogram : principle
  - "FFT for astronomers"
  - Light curves : discontinued observations
  - Associating a power to each frequency
  - The higher the power, the more likely we are to have a signal with the associated frequency

$$z(\omega) = \sum_{j=1}^{N} \frac{1}{\sigma_j} \left[X_j - C\right]^2 - \chi^2(\omega)$$

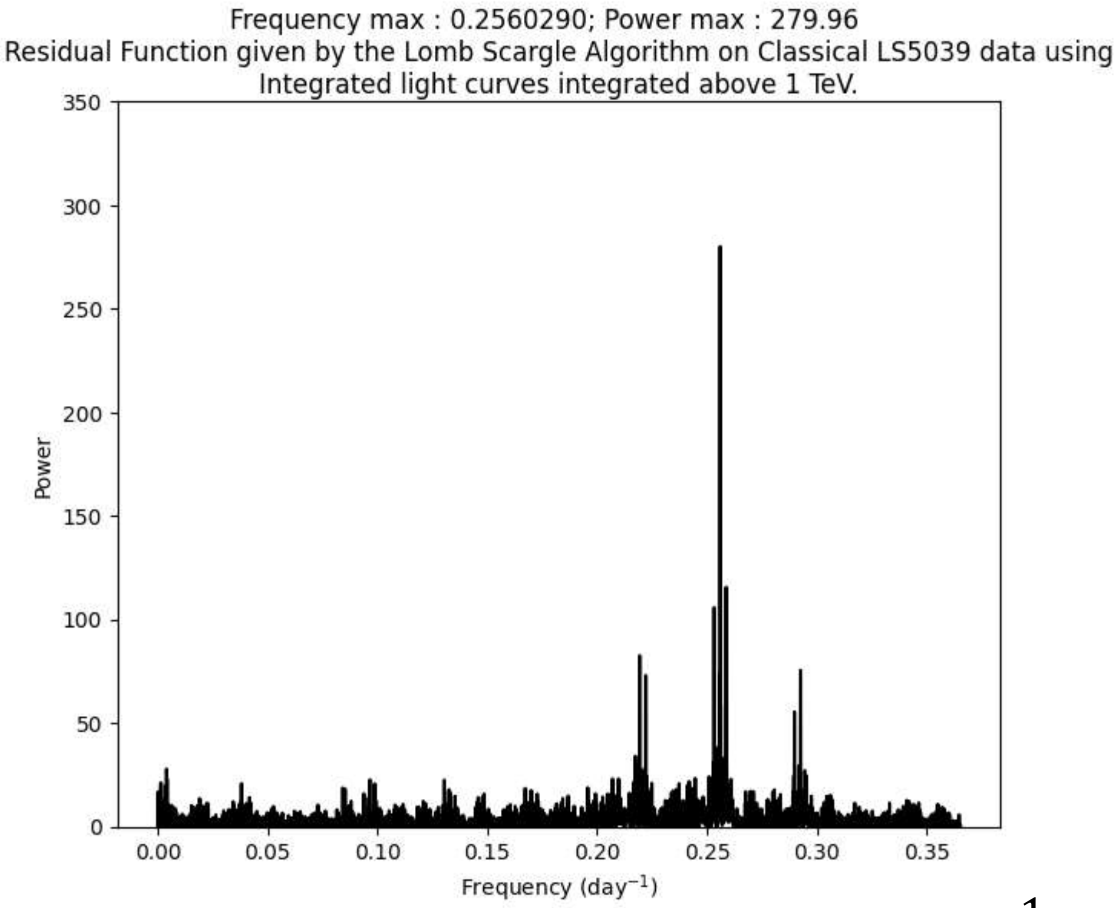


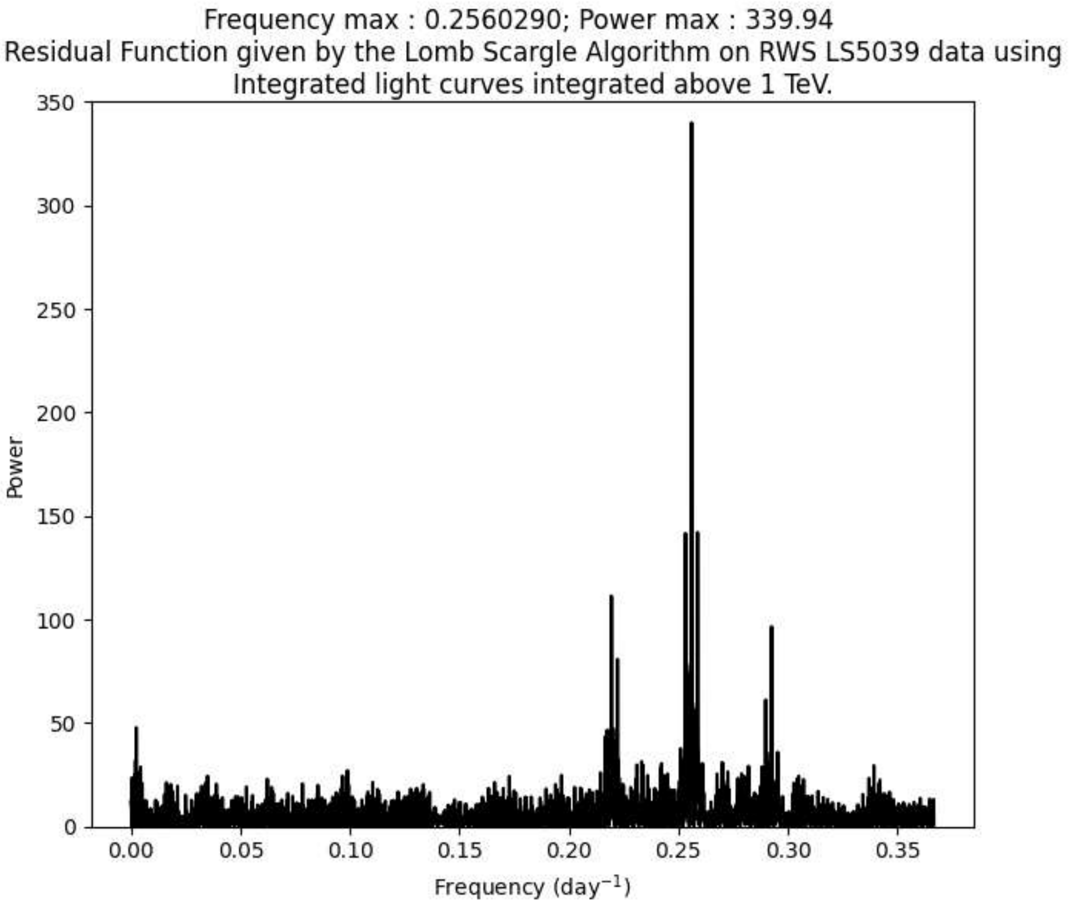
RUN WISE SIMULATIONS

- Systematic error induced by the atmosphere

- We use MC simulations, taking into account the atmosphere, the weather conditions during the run, and the configuration of the telescopes
- We get the Run Wise Simulation = the result we'd get in perfect conditions

CLASSIQUE VS. RUN WISE





Classical

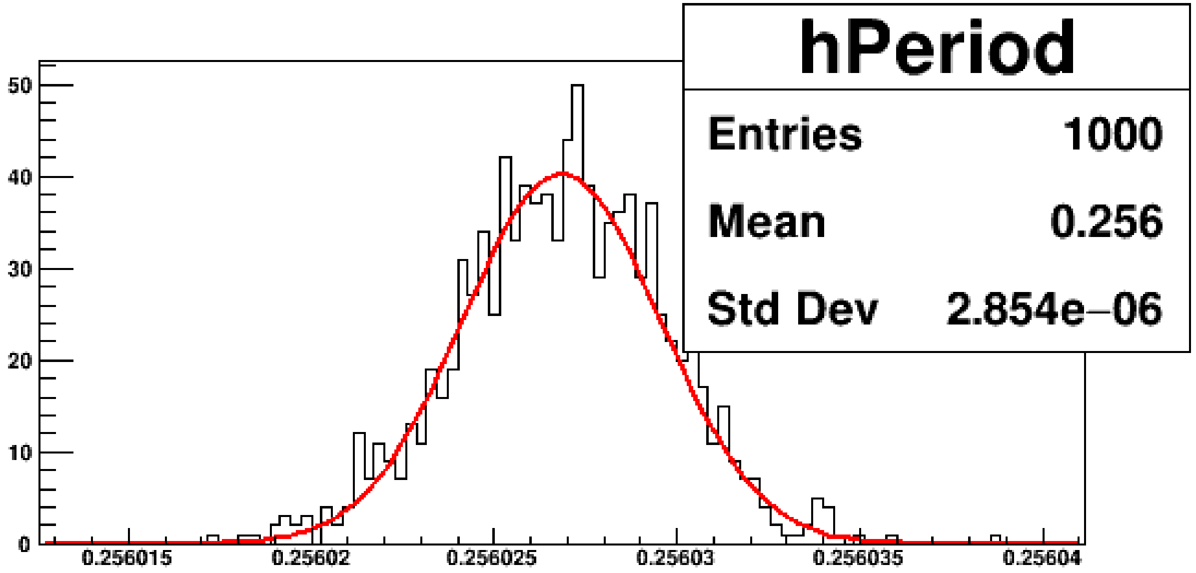
$$P = \frac{1}{f} = 3.905876\ day$$

RWS

UNCERTAINTY ON THE PERIOD

- Construct random light curves built from the model and pass them through the Lomb Scargle algorithm
- We take the frequency for which the power is maximal, and build a histogram from that.

- In our case :



$$u(f) = 2.854 \cdot 10^{-6}\ days^{-1}$$

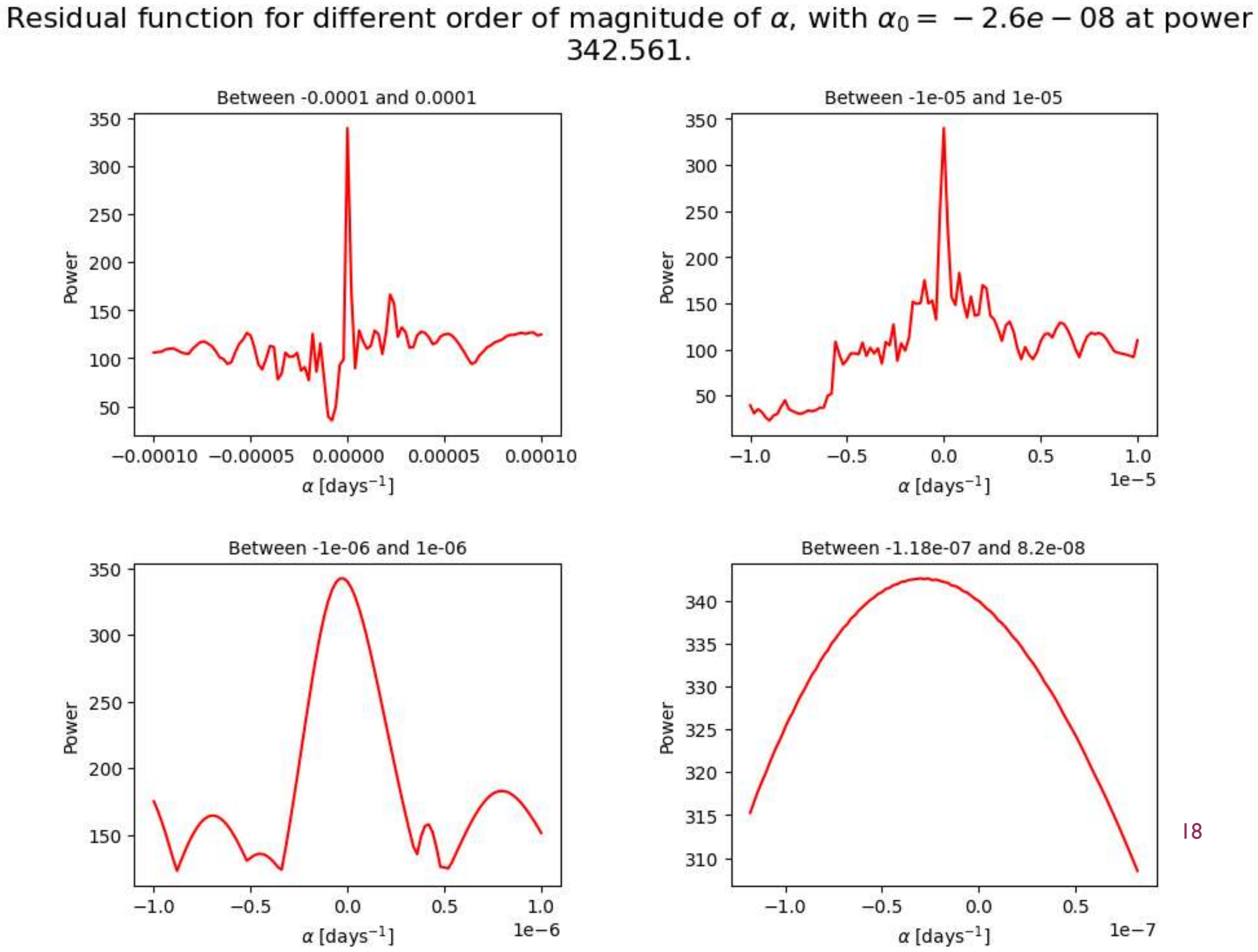
$$\Rightarrow \boldsymbol{u(P) = 3.76\ s}$$

HOW TO MEASURE THE PERIOD EVOLUTION ?

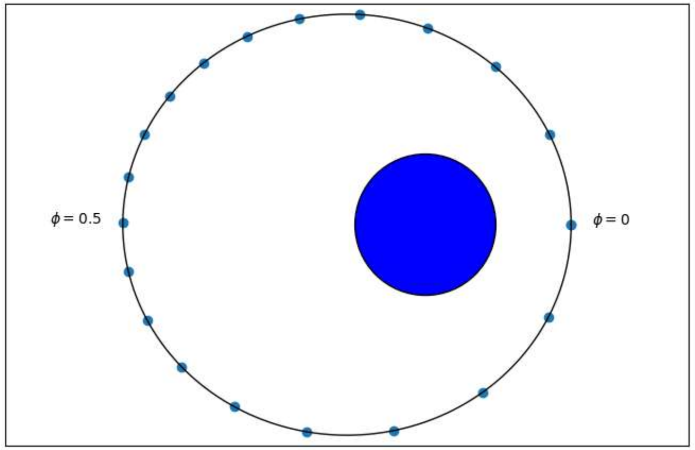
- Change the $\omega = \omega_0$ into $\omega = \omega_0(1 + \alpha t)$, and try with multiple α

$$z(\omega) = \sum_{j=1}^{N} \frac{1}{\sigma_j} [X_j - C]^2 - \chi^2(\omega + \alpha t)$$

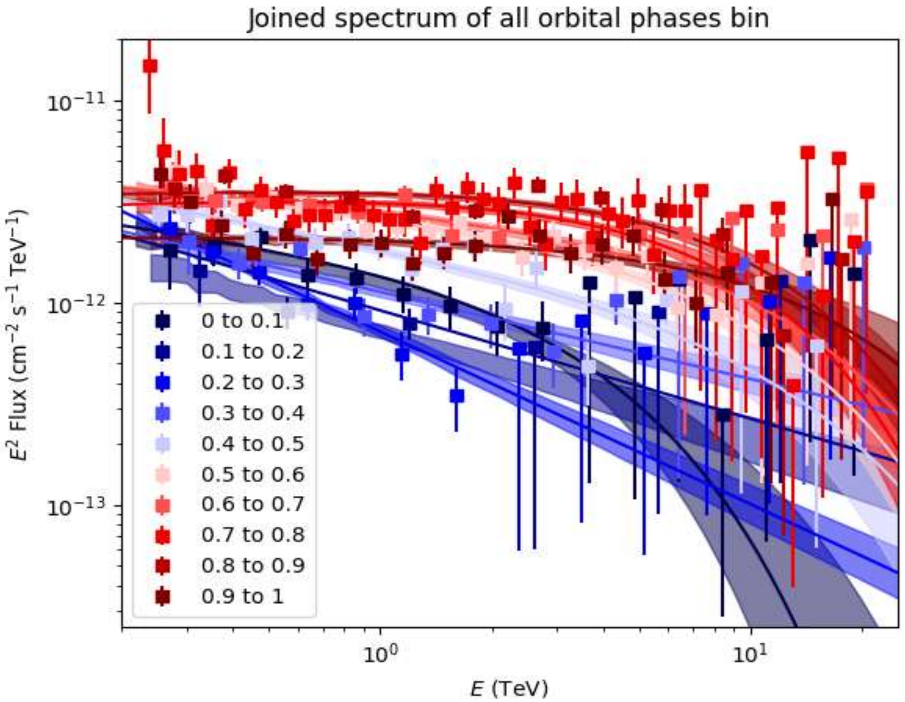
- We then take the maximum power for each value of α tested, and look for the maximum of those values to have the proper α_0

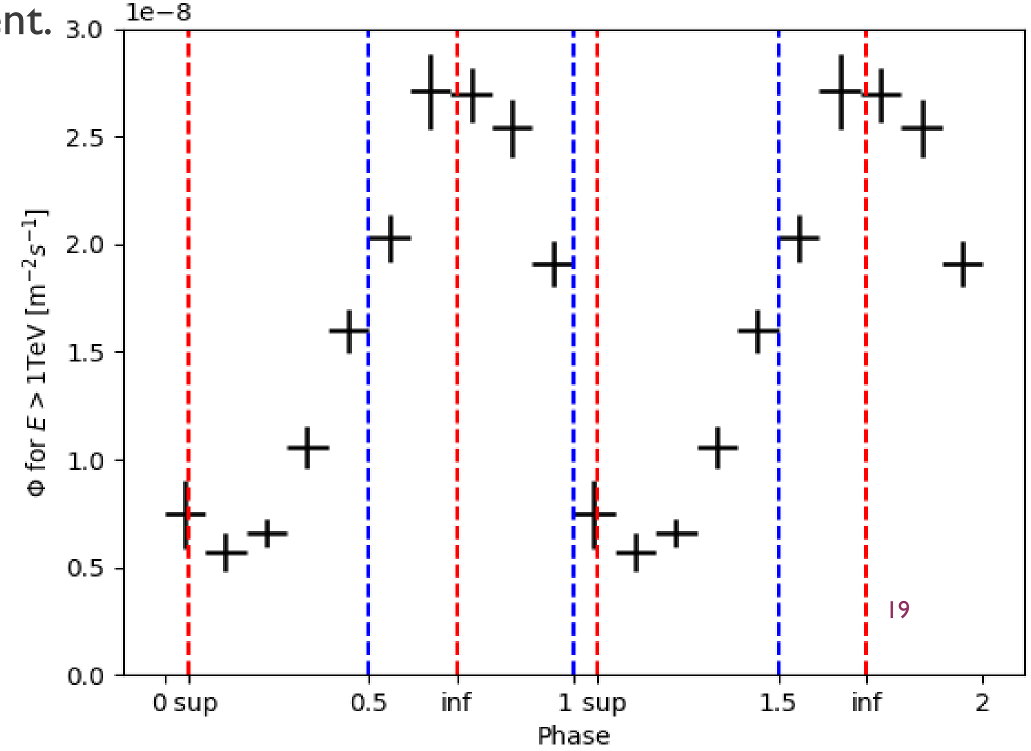


ANOTHER WAY TO MEASURE ALPHA



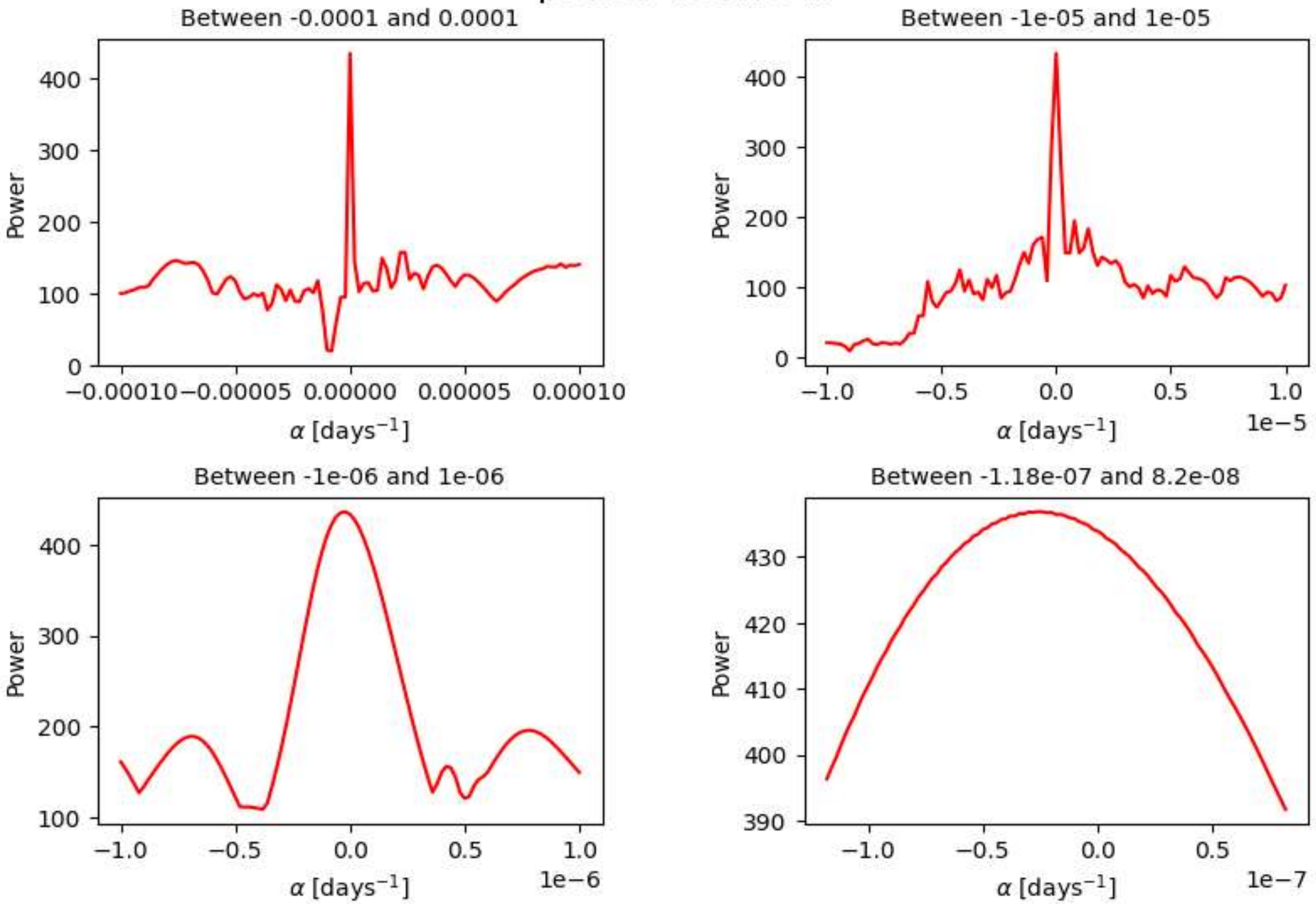
- Split the data into n different bins (in our case, $n = 10$) according to the phase of the system at this time.
- For each of the bins, apply a different spectrum : this allows a better flexibility, and for a more precise characterization of the fluxes at each moment.





NEW ALPHA

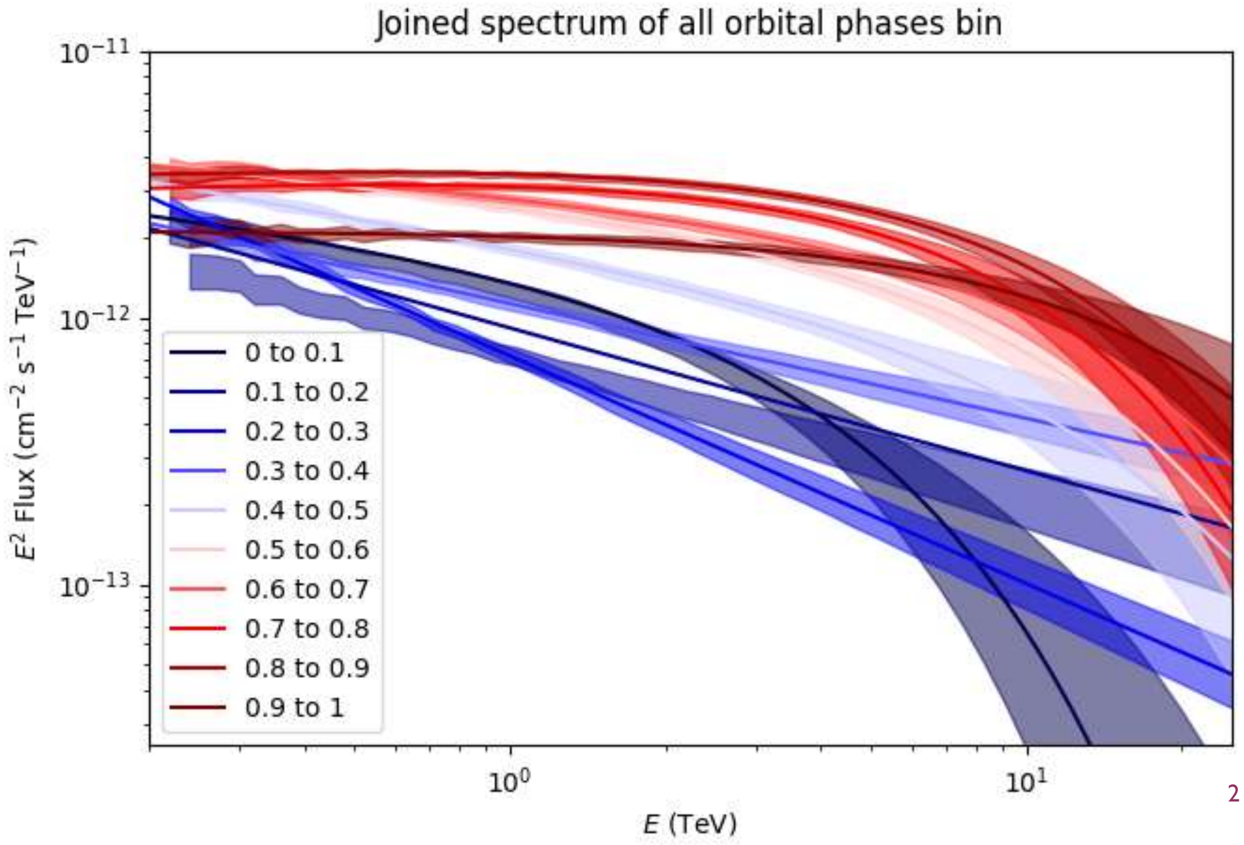
Residual function for different order of magnitude of α, with $\alpha_0 = -2.6e-08$ at power 436.794.



HOW DO WE USE THIS SEPARATION TO GET BETTER RESULTS ?

- Using the differential fluxes at our advantage : there is a big difference in fluxes around 1-10 TeV between the phases 0.45 to 0.9 and the rest

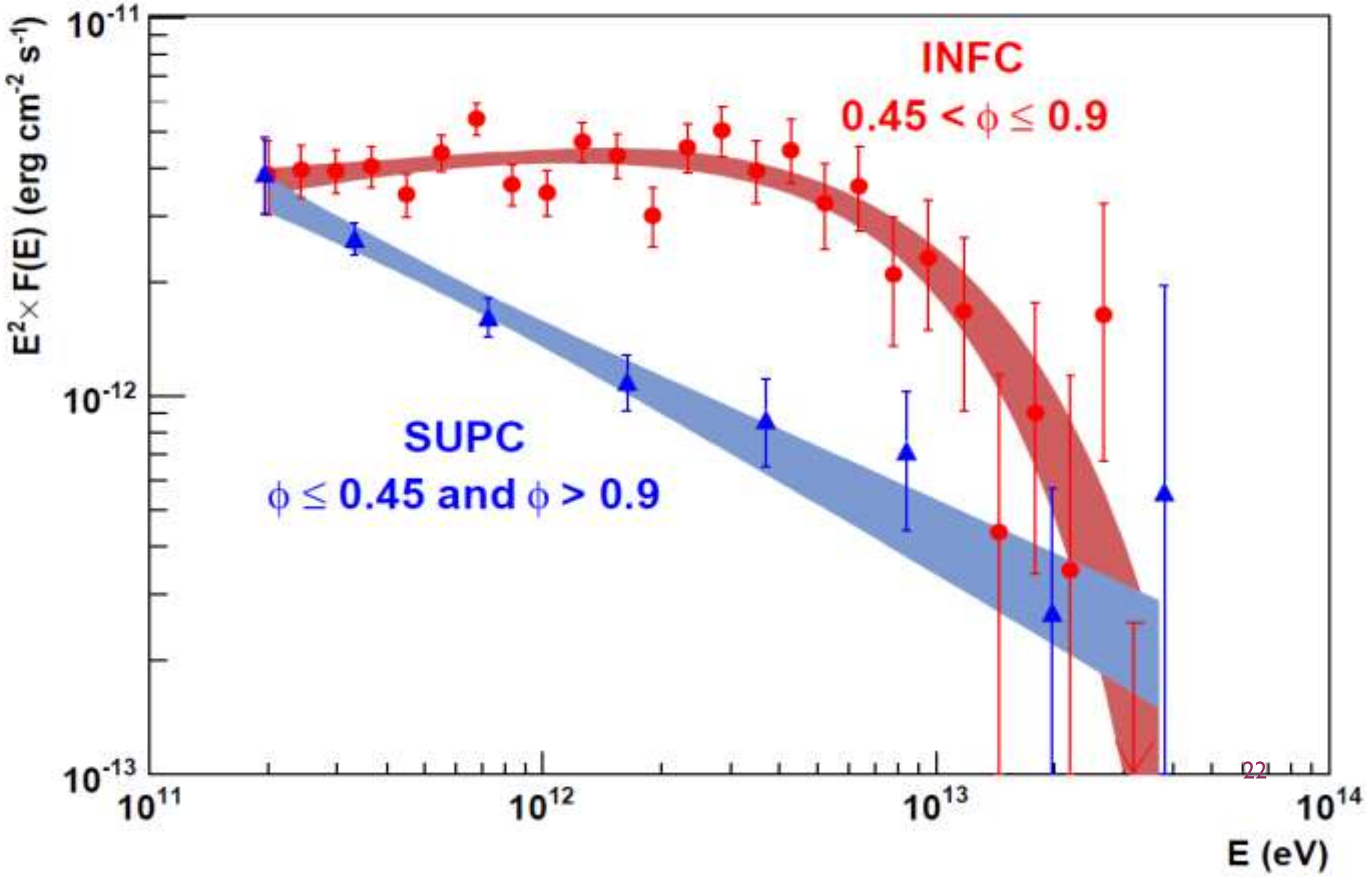
- We can compute the light curves at different energy references, and see which one gives the highest power



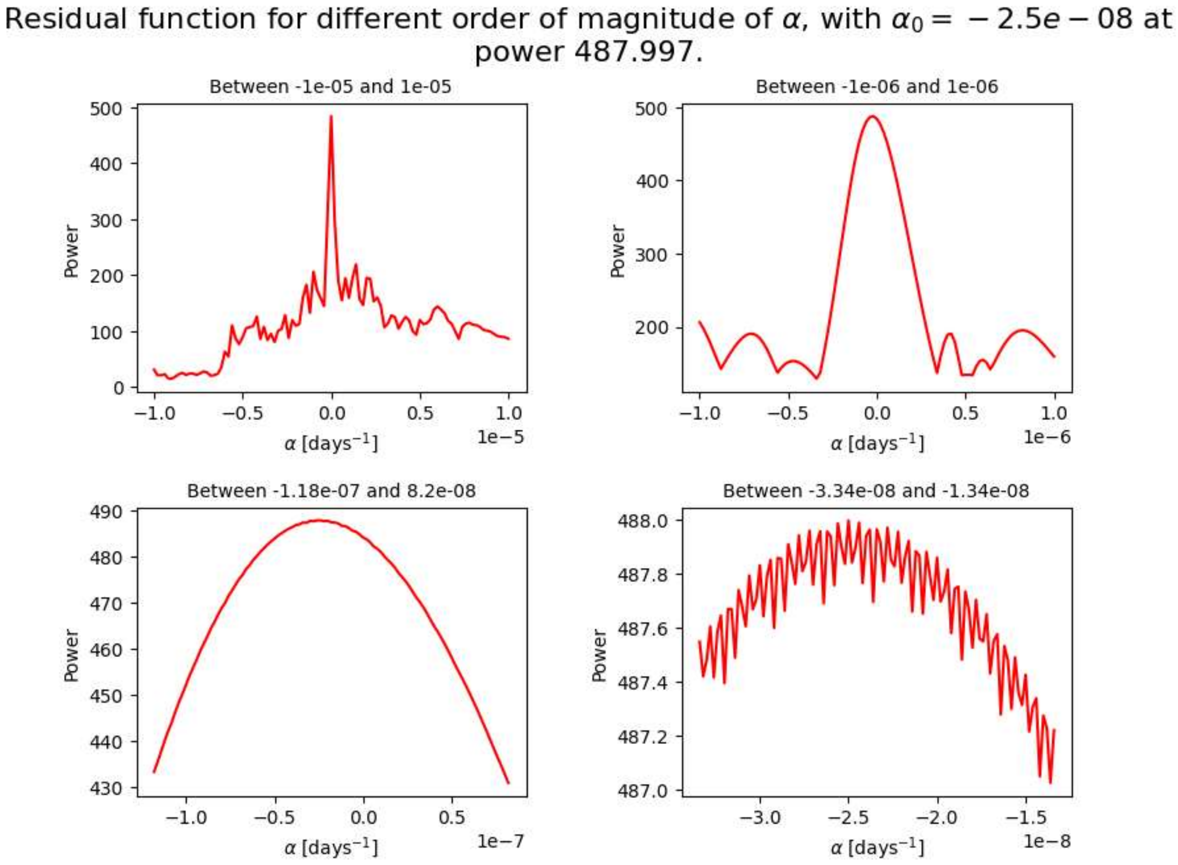
HOW DO WE USE THIS SEPARATION TO GET BETTER RESULTS ?

- Using the differential fluxes at our advantage : there is a big difference in fluxes around 1-10 TeV between the phases 0.45 to 0.9 and the rest

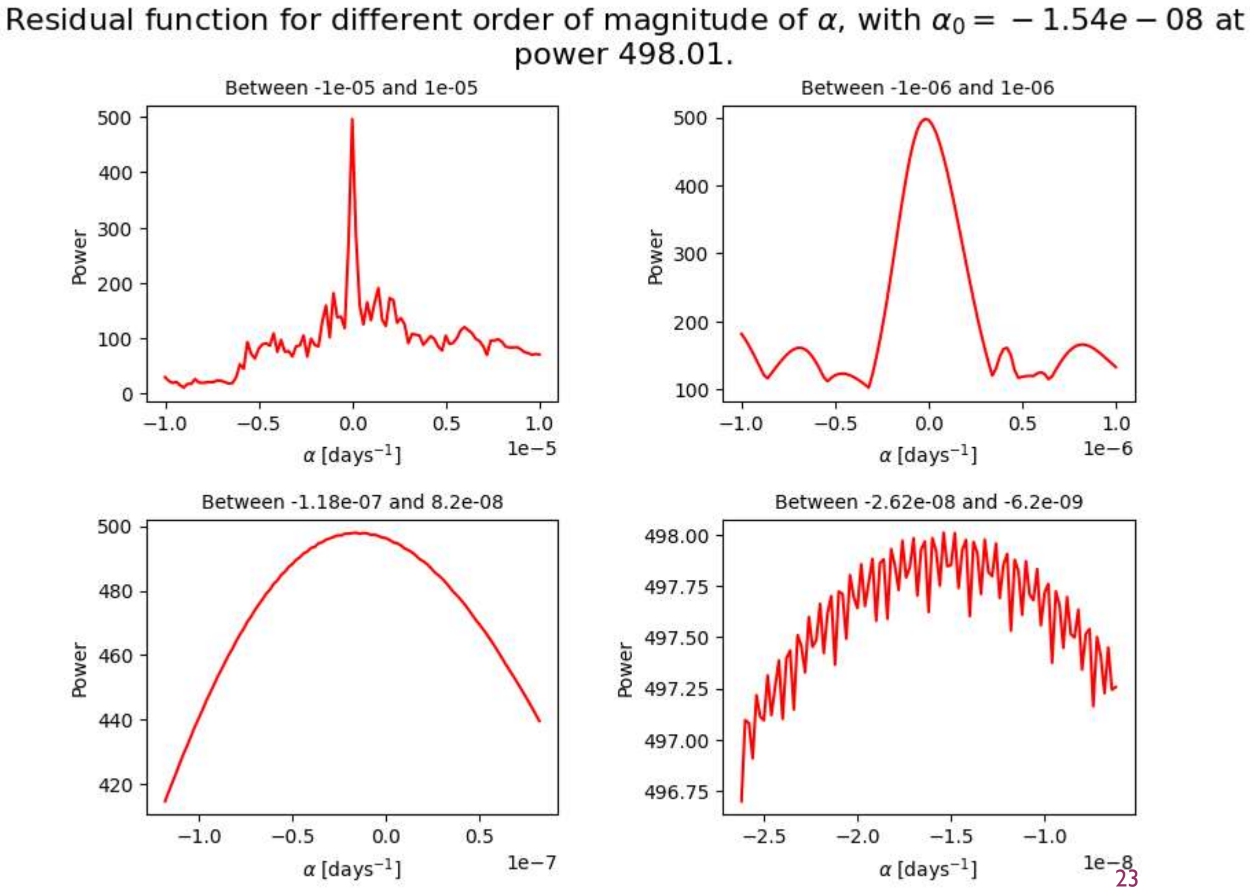
- We can compute the light curves at different energy references, and see which one gives the highest power



FOR EXAMPLE, WITH 2 AND 4 TEV

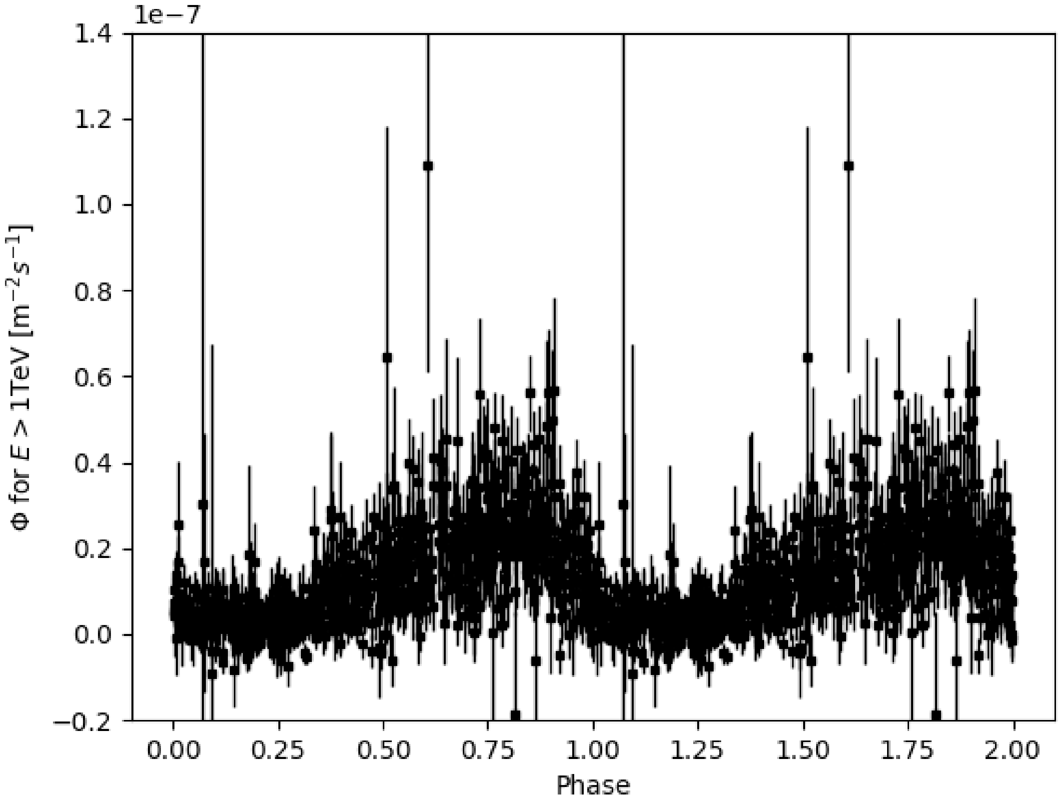


2 TeV

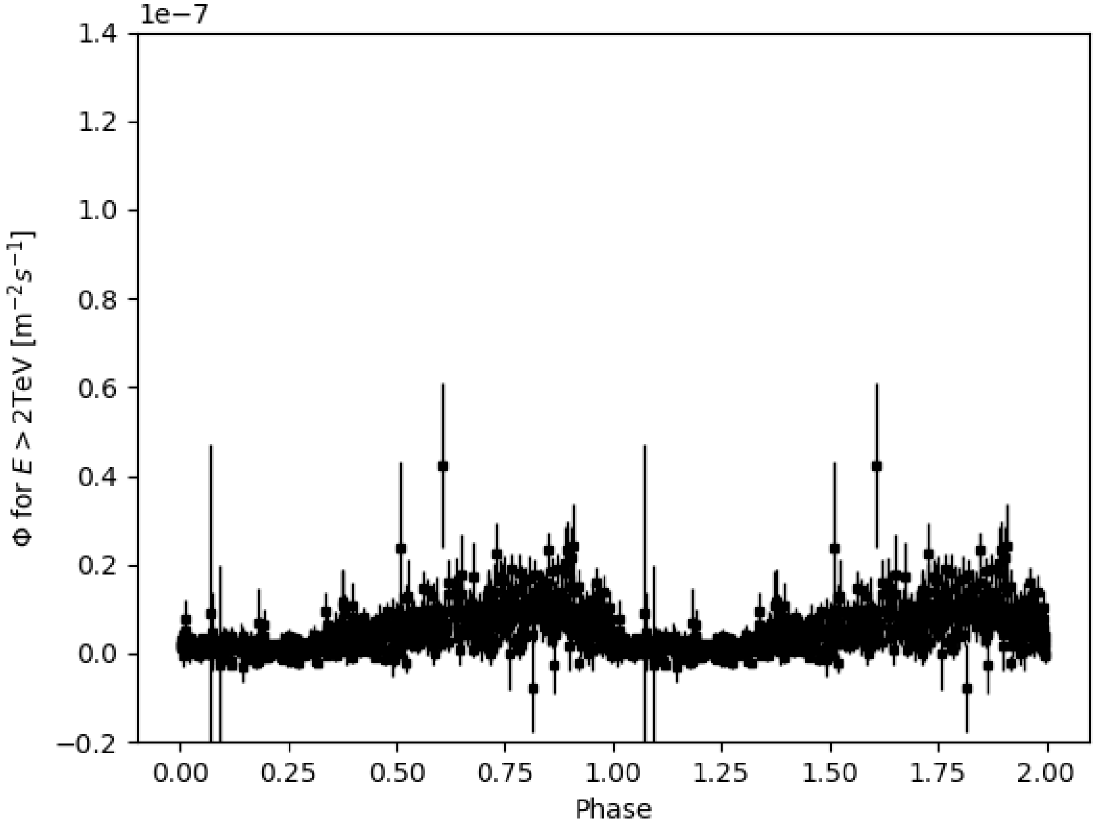


4 TeV

PROBLEM WITH THAT : FLUXES OF RUNS



1 TeV



2 TeV

WHAT'S NEXT ?

- The next part of the plan concerns uncertainties :
  - With each computation, α changes, so we need an uncertainty to see if we can expect to have something stable
  - We'll use the same algorithm as the uncertainty on the period
  - Problem : really long (usually done over 1000 random light curves, loop over the different values of α, loop over the different values of the frequency… -> on 32 hearts, it would take 4 days to run)
- Solution : optimization of the codes, and estimation of the best energy reference for the light curve used (by looking at the maximum power)

CONCLUSION

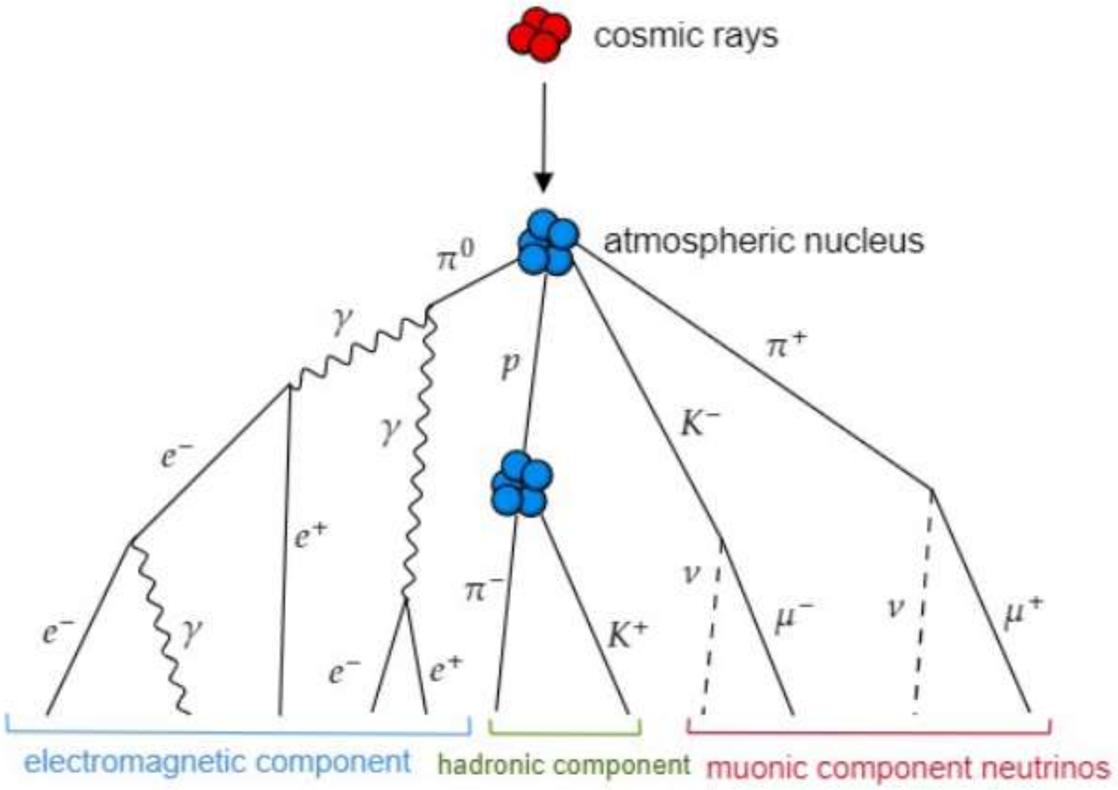
- α_0 is always negative, which is not expected (usually the inverse !)
- Theory said the period lost $0.06\ s$ each 10 years.
- Each day, the period grows by (first order Limited development, for $\alpha_0 = 2.4 \cdot 10^{-8} days^{-1}$)

$$\text{P} \times (-\alpha_0) \times 1\ day = 9.374 \cdot 10^{-8}\ day$$

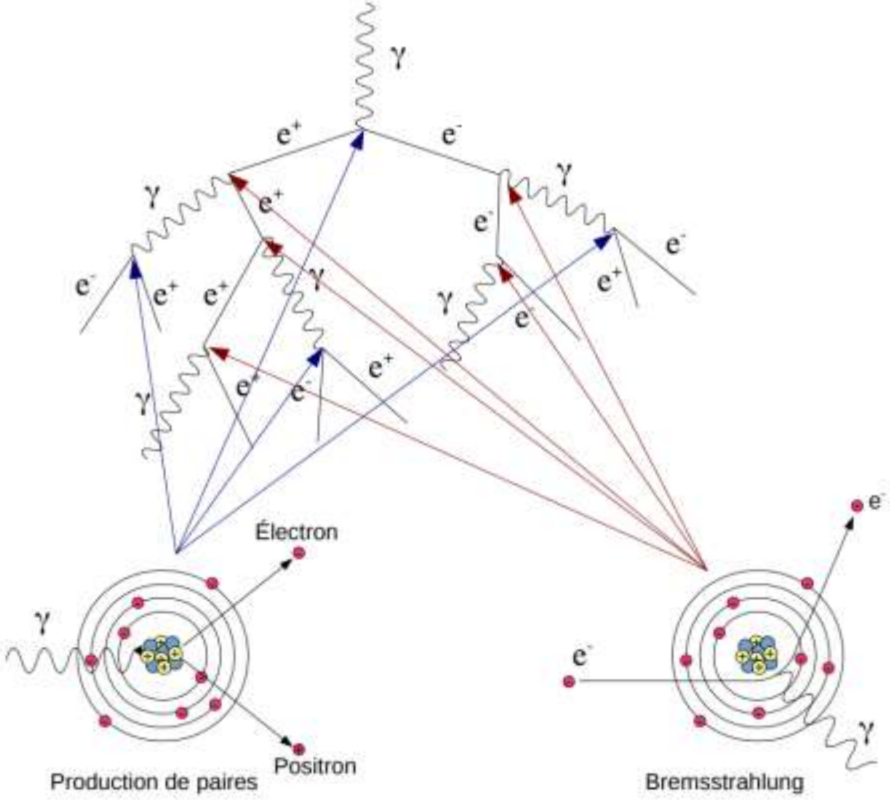
$$\Rightarrow 29.4\ s \text{ after 10 years}$$

- Bigger than the uncertainty for P ?
- Other question we could ask ourselves : Could we have a stable system ?

UHECR VS GAMMA RAYS



UHECR

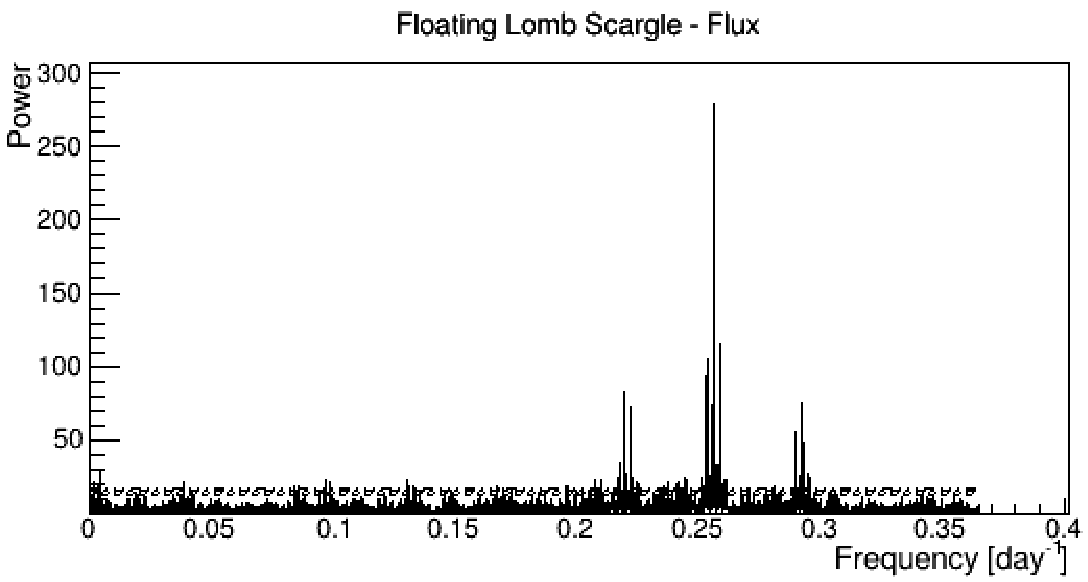


Gamma rays

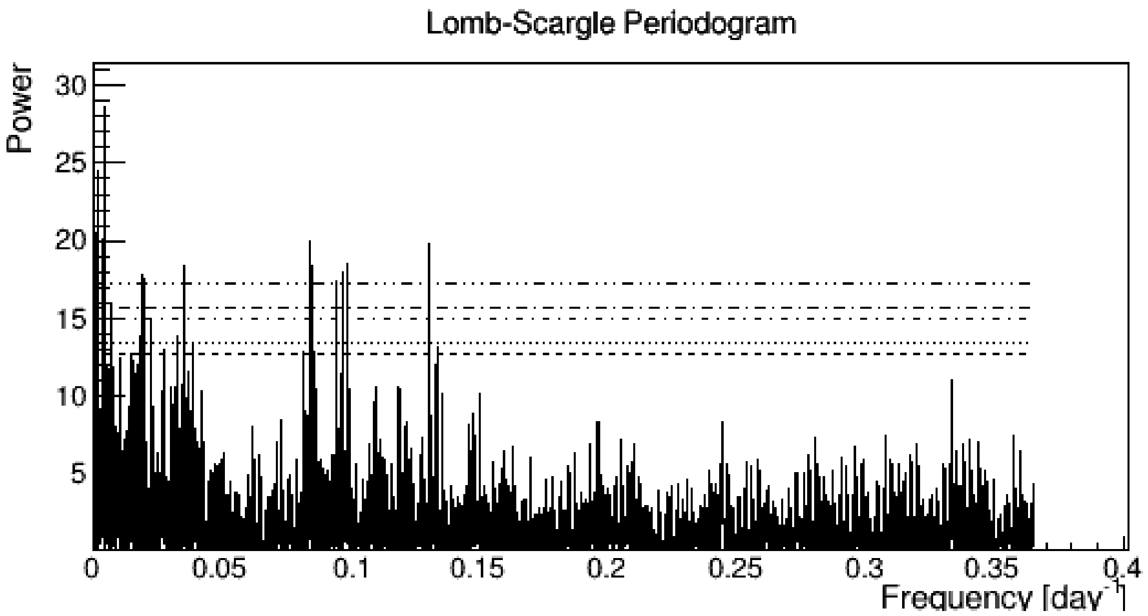
LOMB SCARGLE

- We look for a frequency of the form $f(t) = A\cos\omega t + B\sin\omega t + C$
- We try to get them from diagonalizing a matrix which elements depend on the fluxes obtained in the light curve associated.
- We get a model for $f(t)$, and plug it into $$\chi^2 = \sum_{j=1}^{N} \frac{1}{\sigma_j^2}\left(X(t_j) - f(t_j)\right)^2$$

LOMB SCARGLE PEAKS



Obtained Lomb Scargle from data



Highest peaks subtraction

Window effect