Gamma-ray observations of the super-fast variability of IC310

ICRR spring school 2021.
Gamma group report

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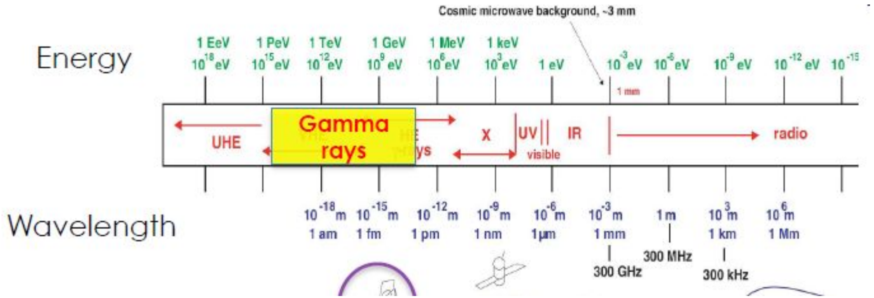
Outline

- **Introduction**
  - Our Universe, Active Galactic Nuclei, Perseus cluster
  - gamma-ray observation methods
- **γ-ray observations of AGNs in the Perseus cluster**
  - Fermi observations of IC310 - serendipitous discovery
  - MAGIC observations of IC310 - lightning-fast variability
- **Discussion and implications**
  - Eddington Limit
  - relativistic effects in the jets
  - measuring sizes of supermassive black holes
  - A possible model for IC310 variability

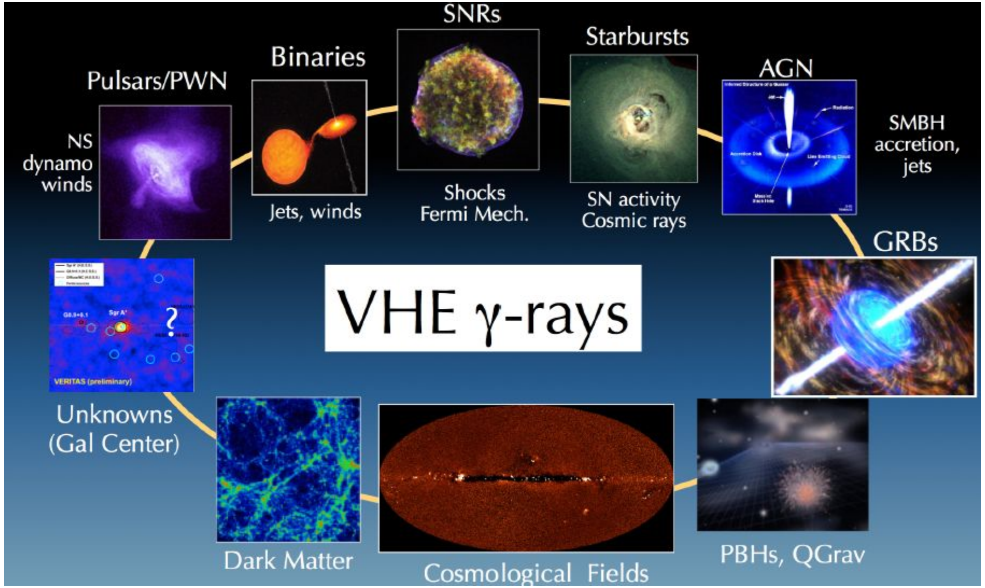
Introduction

Gamma Rays and Our Universe

Gamma Rays



Our Universe



- The energy range of γ ray is from 0.1MeV.

  We observe about TeV energy.
- Our universe has many high energy objects-pulsars, GRBs (Gamma Ray Burst), and **AGN (Active Galactic Nuclei)**.

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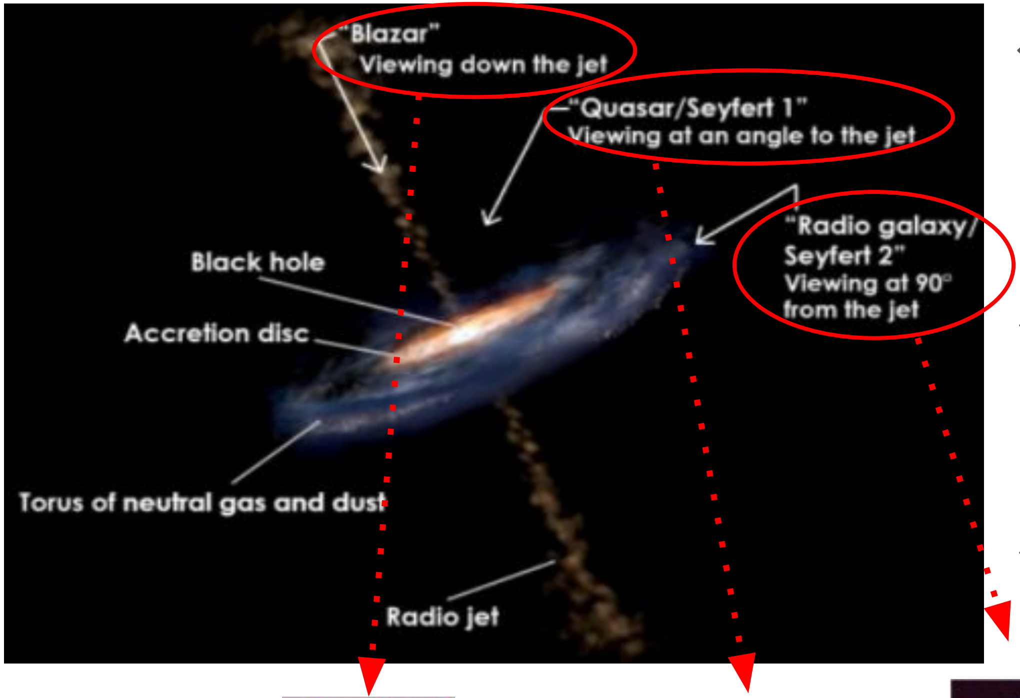
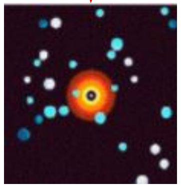
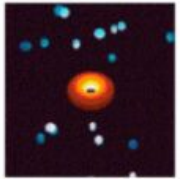
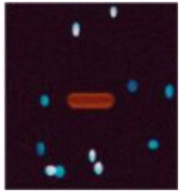
Active Galactic Nuclei









- Some galaxies have a brighter part in the center.
  - ➡ It is called AGN and it has supermassive black hole.
- AGN emits jets of relativistic particles from the center.
- AGN looks differently depending on the viewing direction.

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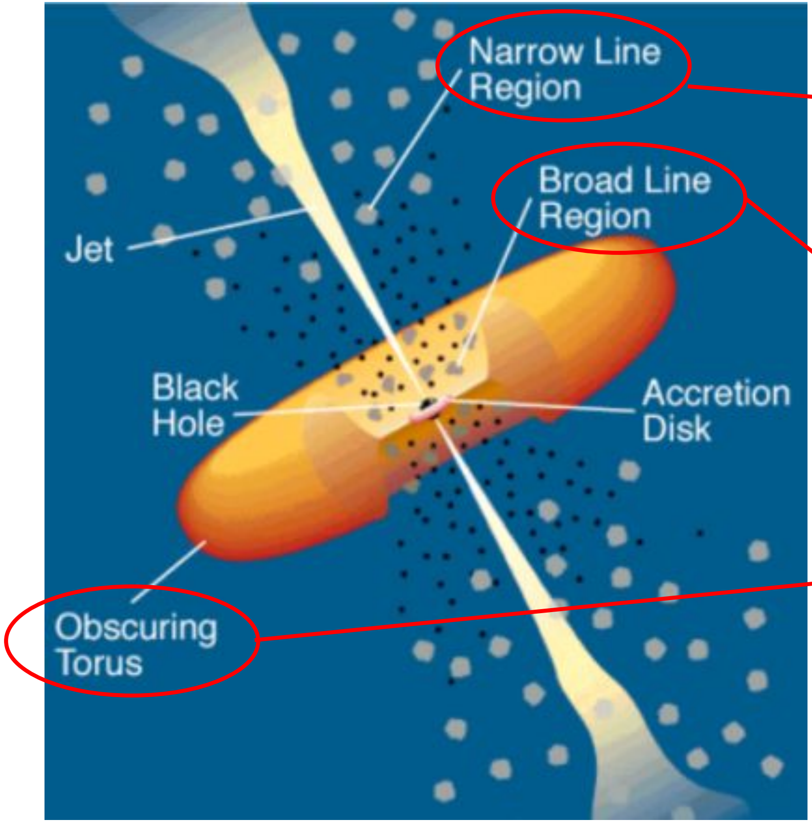
Structure of Active Galactic Nuclei



Cool, low velocity, low density gas clouds.

Hot, high velocity, dense gas clouds and hot electrons scatter.

Optical-thick dusty.

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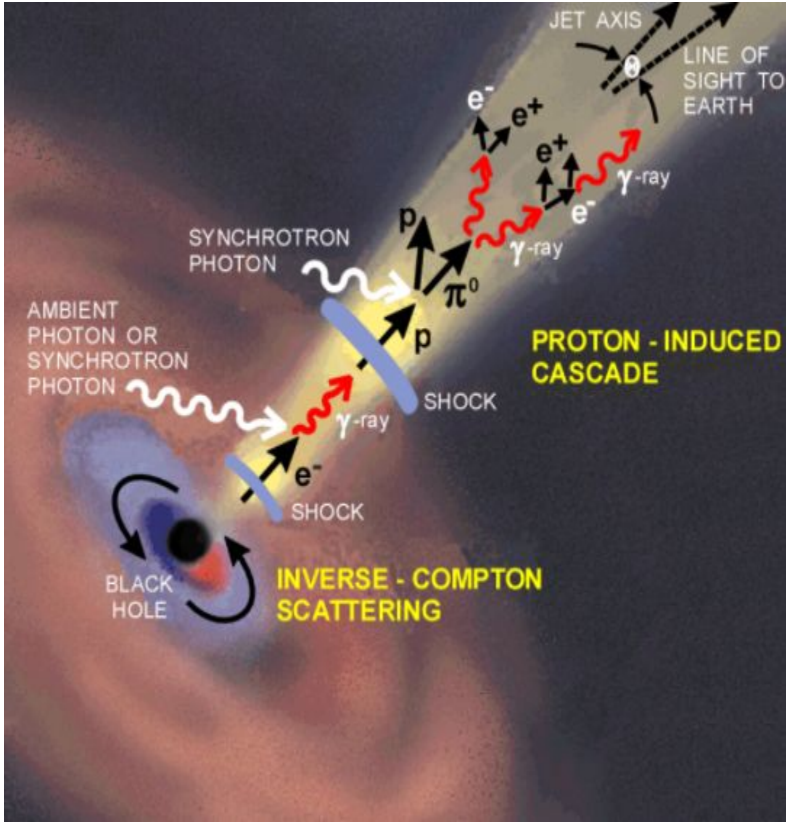
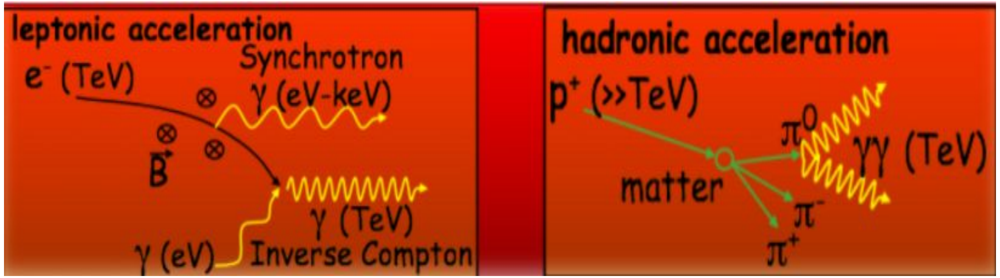
Blazar



- Blazar is a type of AGN with relativistic plasma jets pointing to our direction, highly variable
- Models of TeV blazars imply leptonic or hadronic particle acceleration.



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Motivation of our study

How are AGN jets formed?

⬇

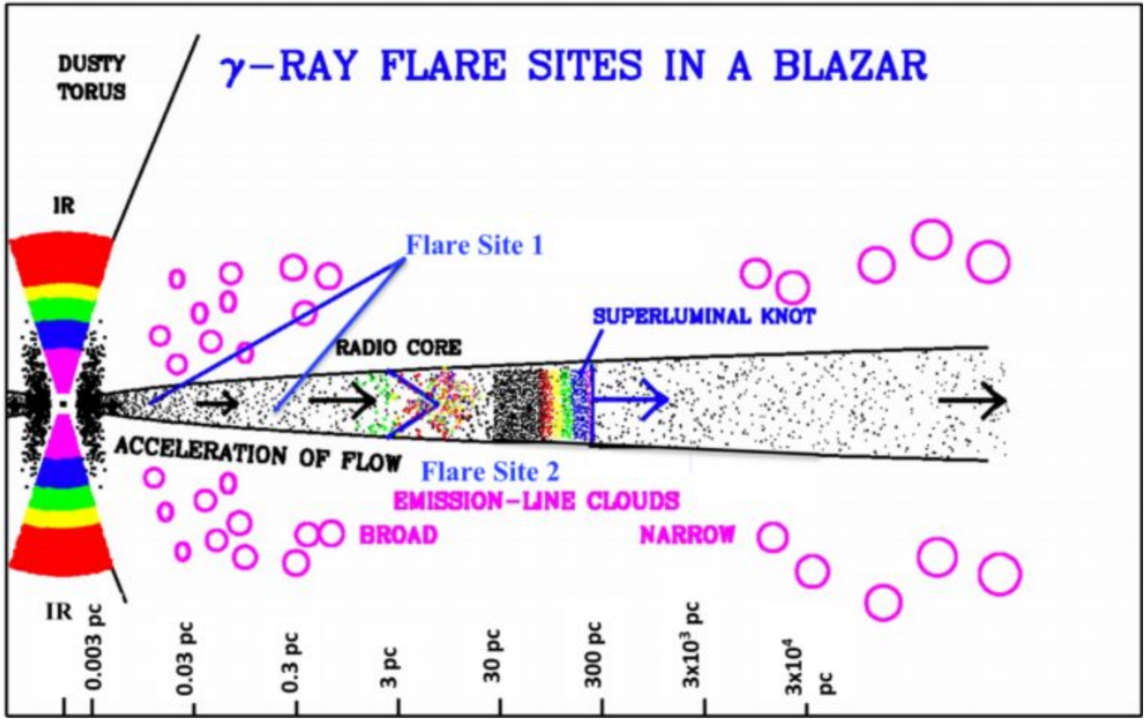
Gamma-ray flares are key to solve this problem.

⬇

Where are gamma-ray flares coming from?

⬇

Work out the jet generation mechanism and conditions in BH vicinity.



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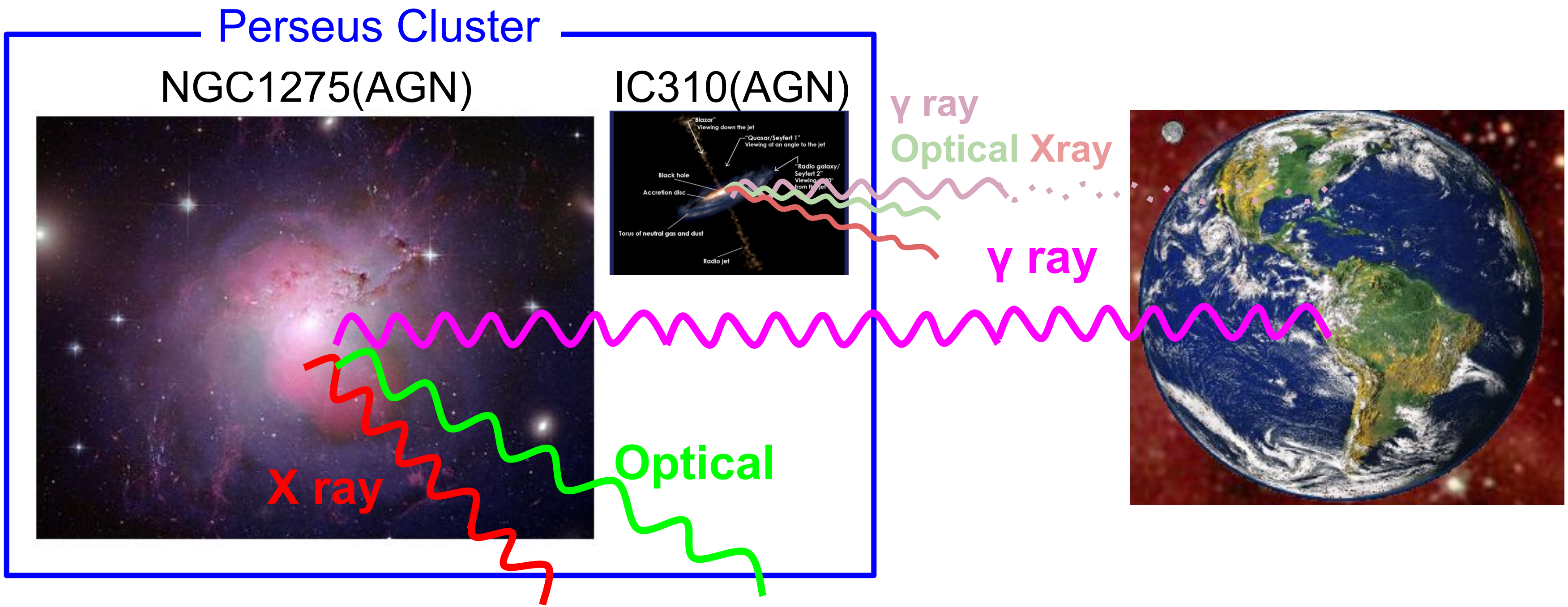
Perseus Cluster and IC310



- AGNs in Perseuse Cluster emit electromagnetic waves.
- We observe **IC310**'s γ ray , but NGC is so bright that we couldn't.

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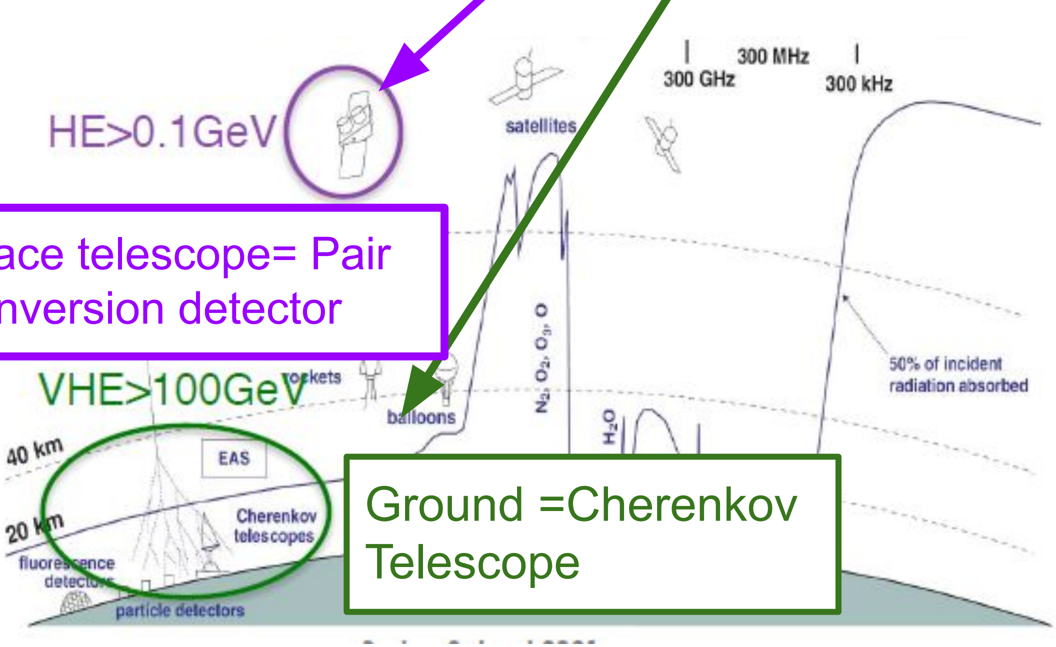
γ-ray observation techniques

Gamma ray with E >> 2x 0.5 MeV (double electron mass)

Space telescope= Pair Conversion detector



Ground =Cherenkov Telescope

- **2 ways** of γ ray detection

One is direct way which uses Space telescope-Fermi.

➡ HE(High Energy)>0.1GeV

The other is indirect way employing air showers.

➡ VHE(Very High Energy)>0.1TeV

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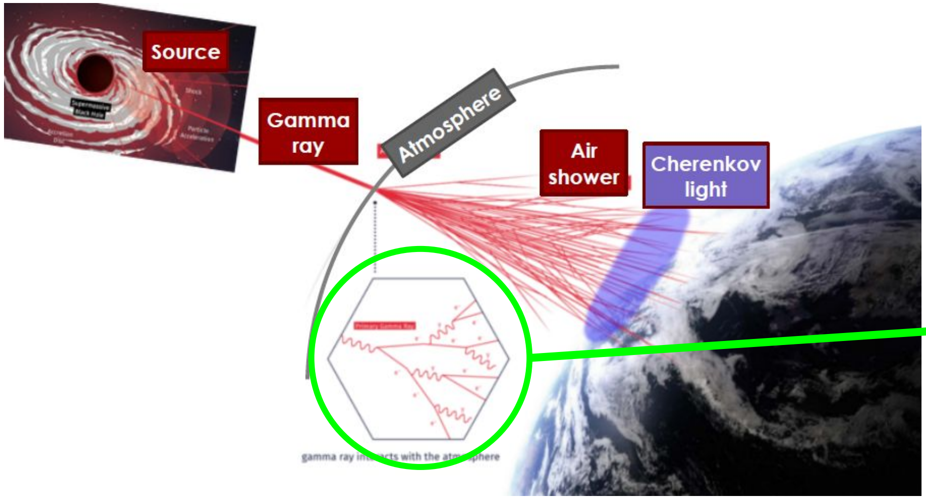
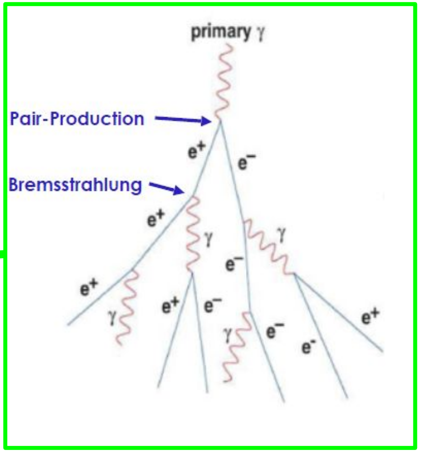
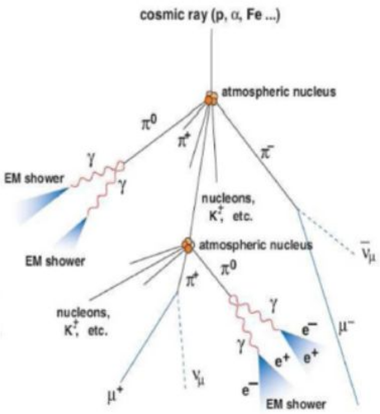
Air shower



In the atmosphere



Electromagnetic shower

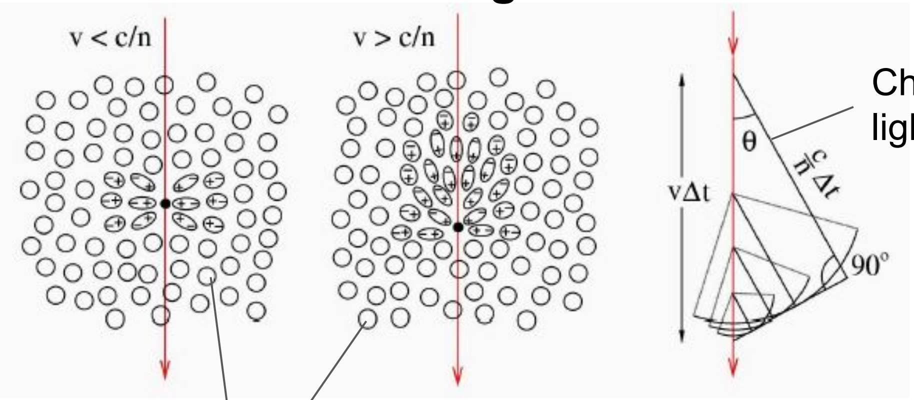


Hadronic shower

- Air shower is caused by (primary) **Gamma Rays**.
- Gamma rays → Pair-Production → Bremsstrahlung → Gamma rays → Pair-Production → Gamma rays

Cherenkov Light

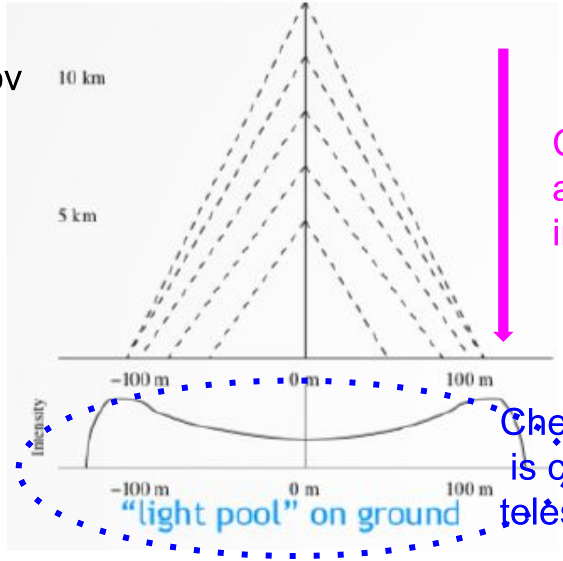
Cherenkov light



Cherenkov light

medium

Light Pool

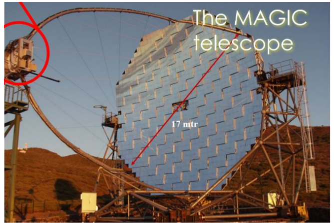


Cherenkov angle increases

Cherenkov light is collected by telescopes

- When traversed at v > c/n, the medium is polarized. Electromagnetic wave is generated, and it is Cherenkov light.

- At lower altitude, Cherenkov angle is larger. Cherenkov light is collected by telescopes, the light pool radius is 100m.



γ-ray observations of AGNs in the Perseus cluster

Fermi satellite

- Launched from Cape Canaveral Air Station on 11th June 2008 (NASA)
- Circular Orbit ~ 565 km
- Period ~ 95 min.

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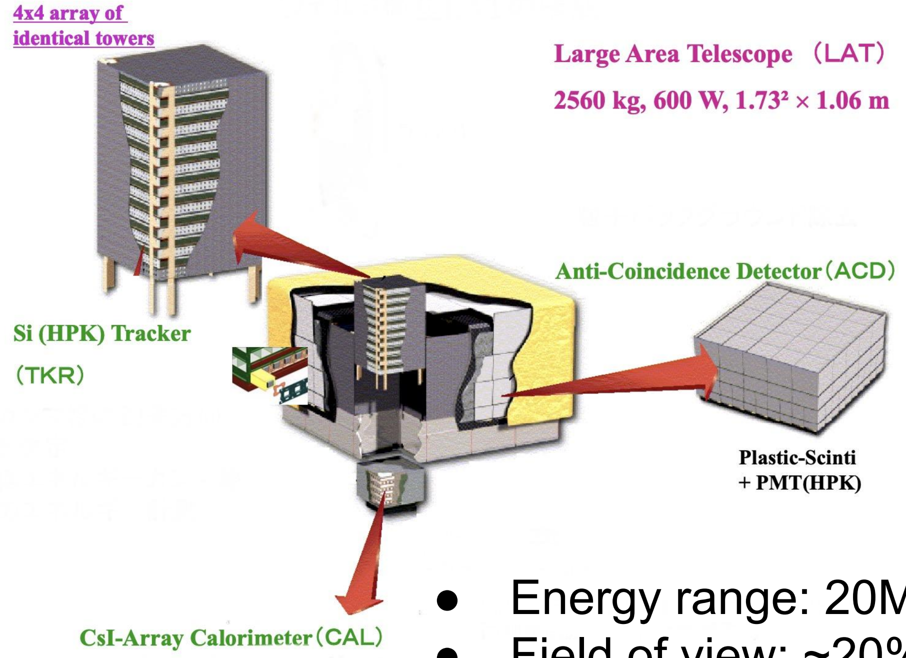
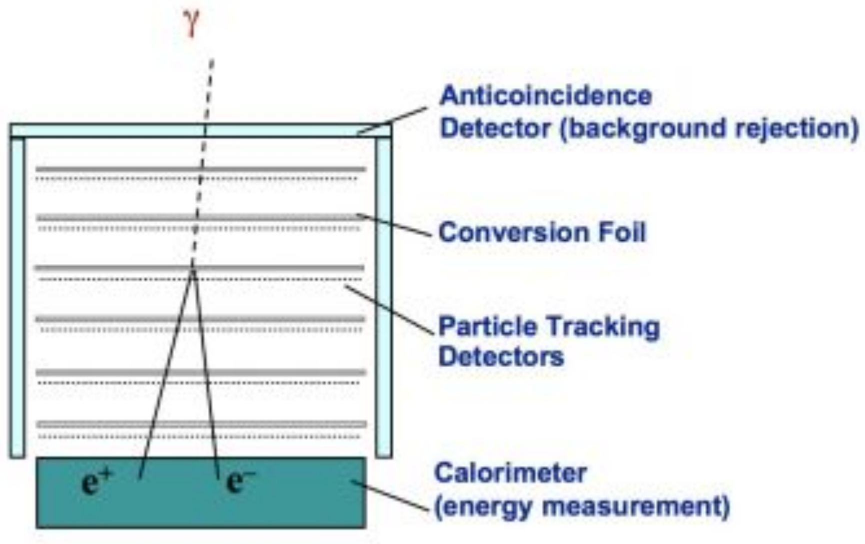
Large Area Telescope





- Energy range: 20MeV - 300GeV
- Field of view: ~20% of sky
- Effective area: >0.8m^2
- Time accuracy: <10μs

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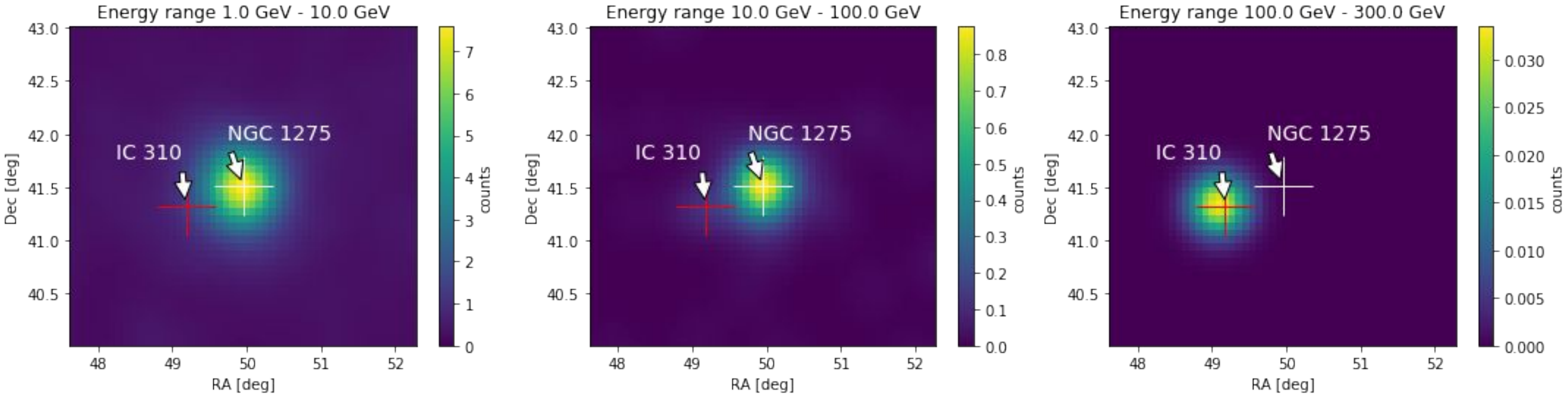
Fermi observations: IC 310 discovery >100 GeV



- Observed NGC 1275
- (1GeV-10GeV) → (10GeV-100GeV)→ (100Gev-300GeV)
- Energy range > 100GeV → IC 310 was discovered!

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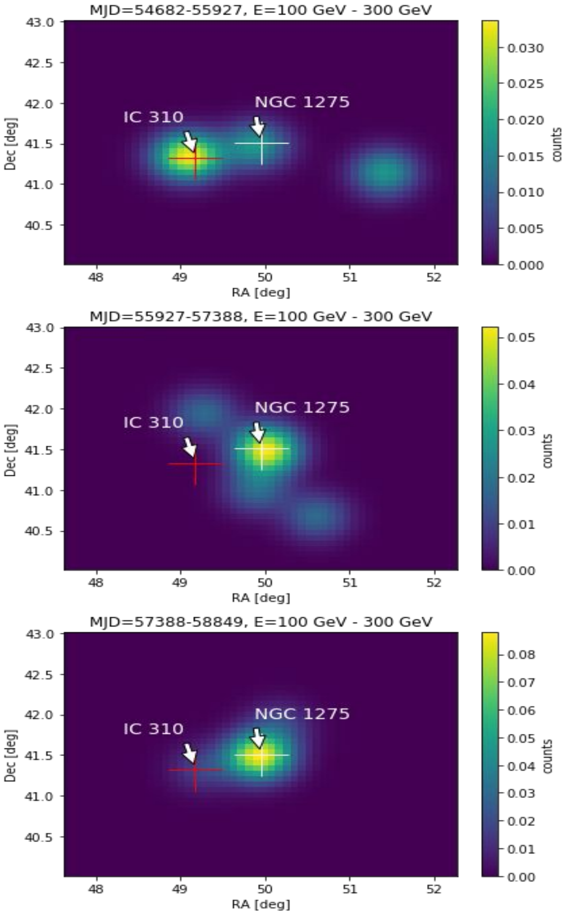
Fermi observations: IC 310 discovery >100 GeV



Observation Periods

1. 4th Aug 2008 - 1st Jan 2012
2. 1st Jan 2012 - 1st Jan 2016
3. 1st Jan 2016 - 1st Jan 2020

Modified Julian Date (MJD)

- 0(d) = 00:00:00, 17th Nov 1858
  e.g. 12:00:00, 5th Mar 2021
  ~ 59278.50(d)
  & 1000(d) ~ 3 yrs

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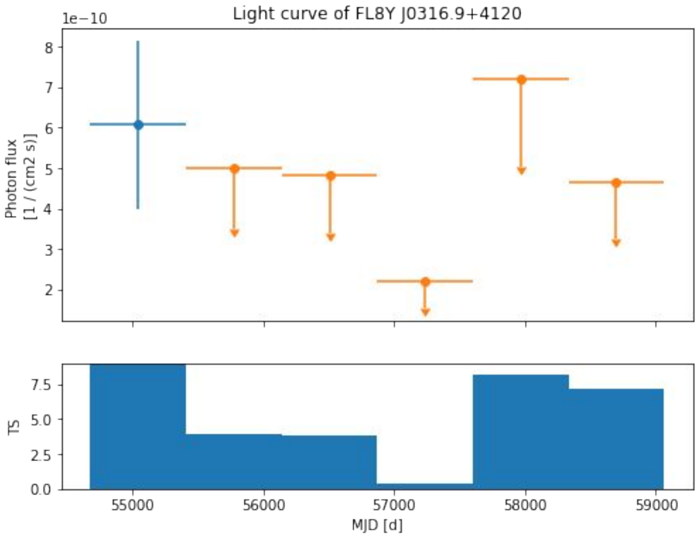
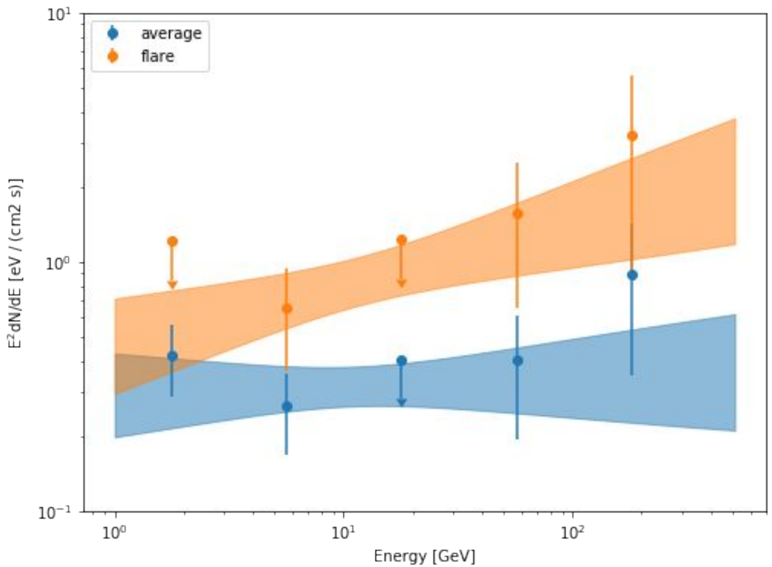
Fermi observations: IC 310 spectrum and variability

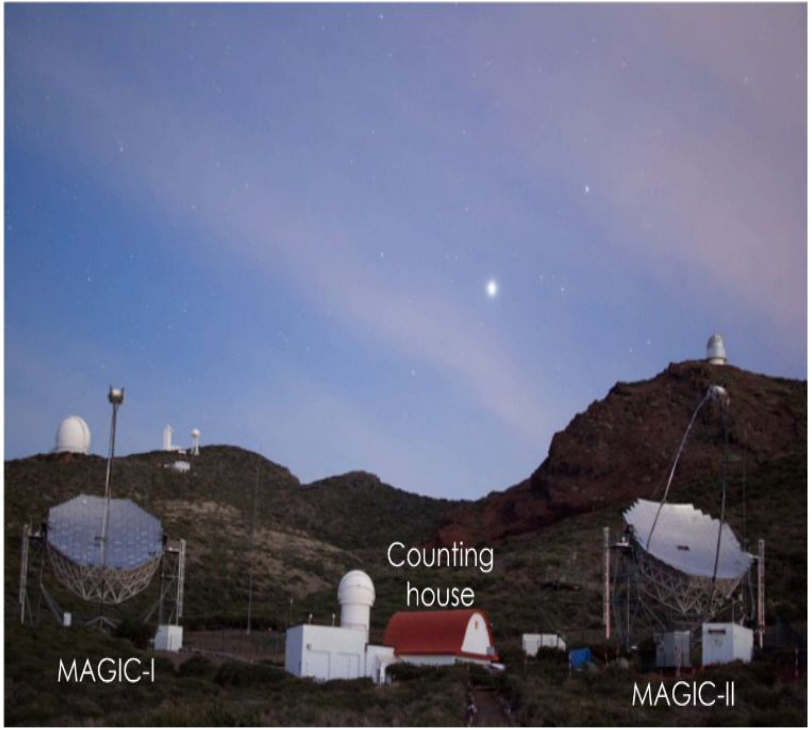




TS ≥ 9 → the emission is detected (false-alarm probability ≤ 0.3%)

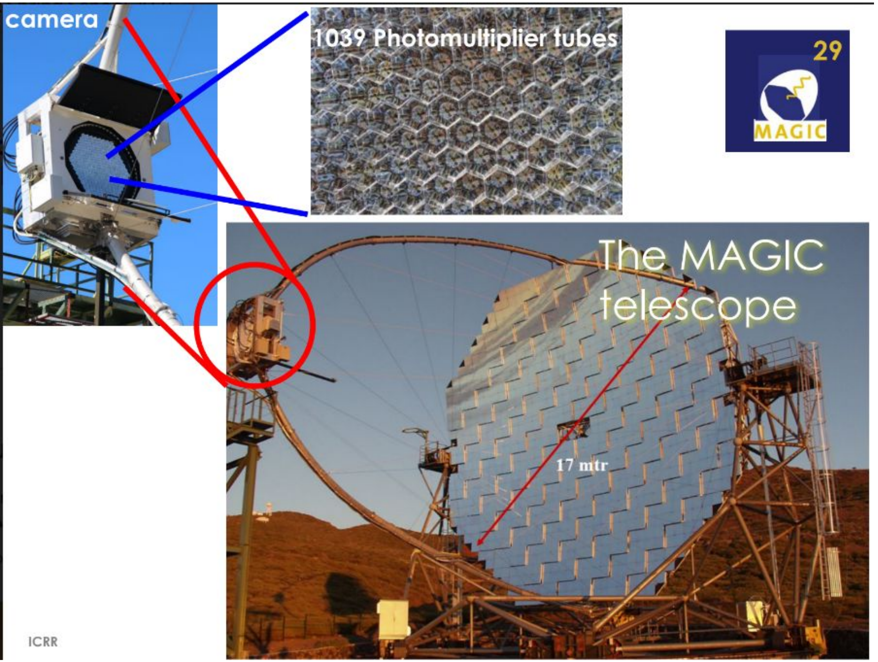
→ The source emission is not stable in time!

MAGIC telescopes



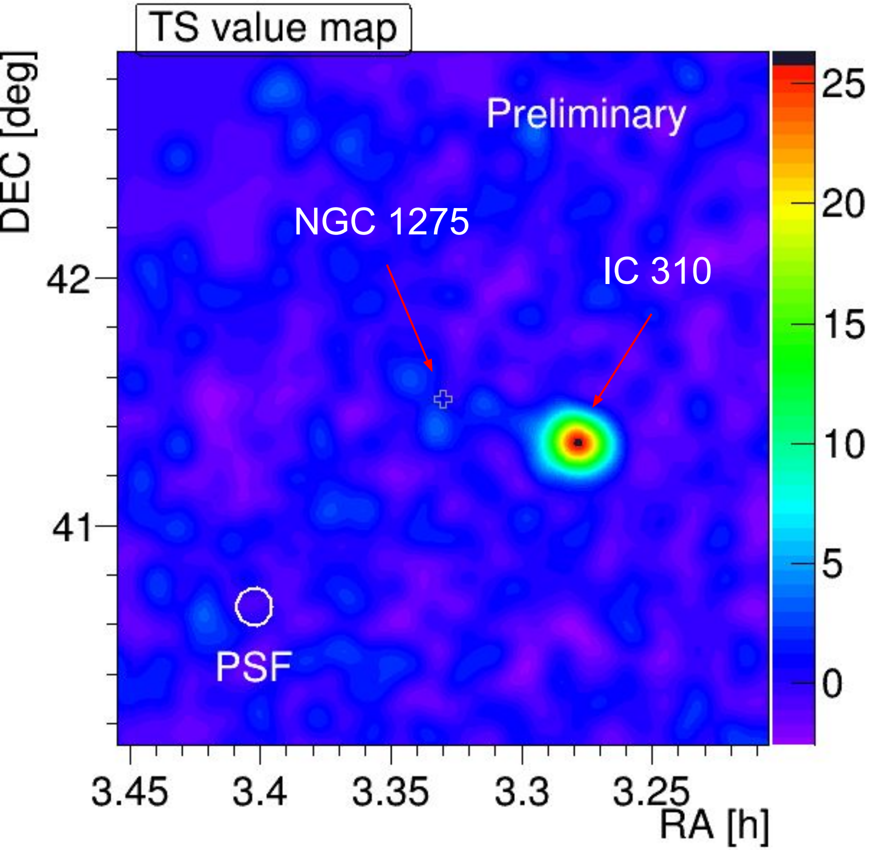
- Located on La Palma, 2200m above sea level
- 2 × 17m diameter mirror dishes
- Energy threshold: 50 GeV
- Energy resolution: 15% at 1 TeV

MAGIC telescopes

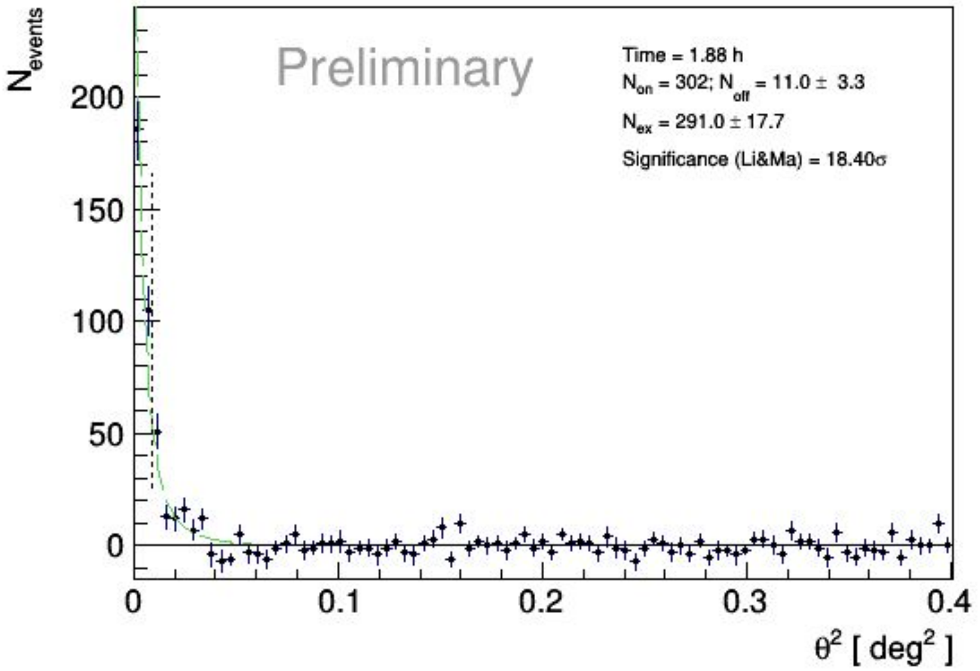


- Cherenkov light is reflected into the camera
- High sensitivity PMT
- Observed IC310 between 2012-11-12 and 13

Perseus cluster with MAGIC eyes



検出したガンマ線の角距離分布



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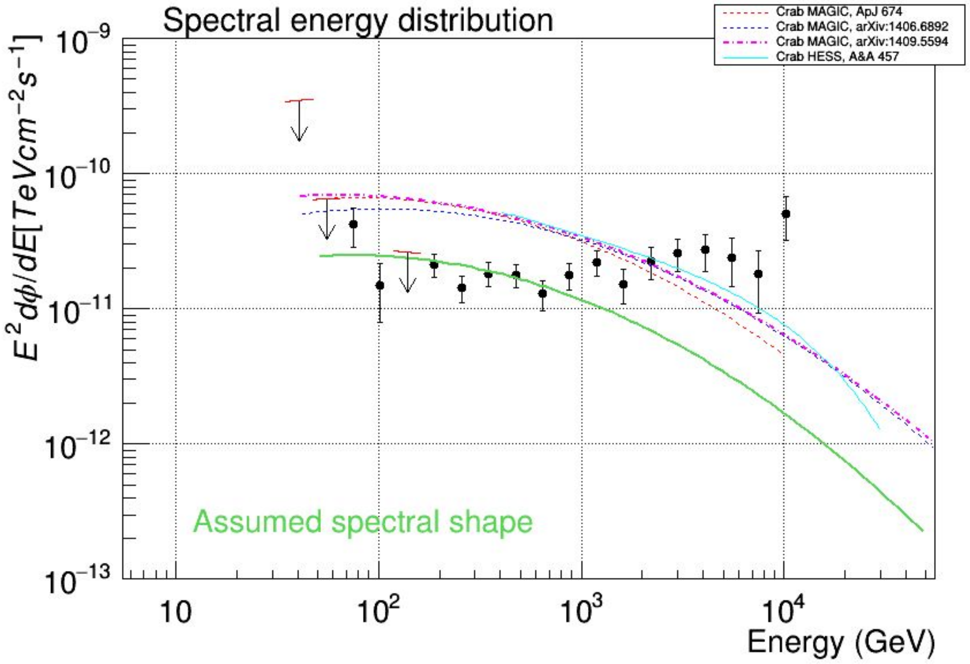
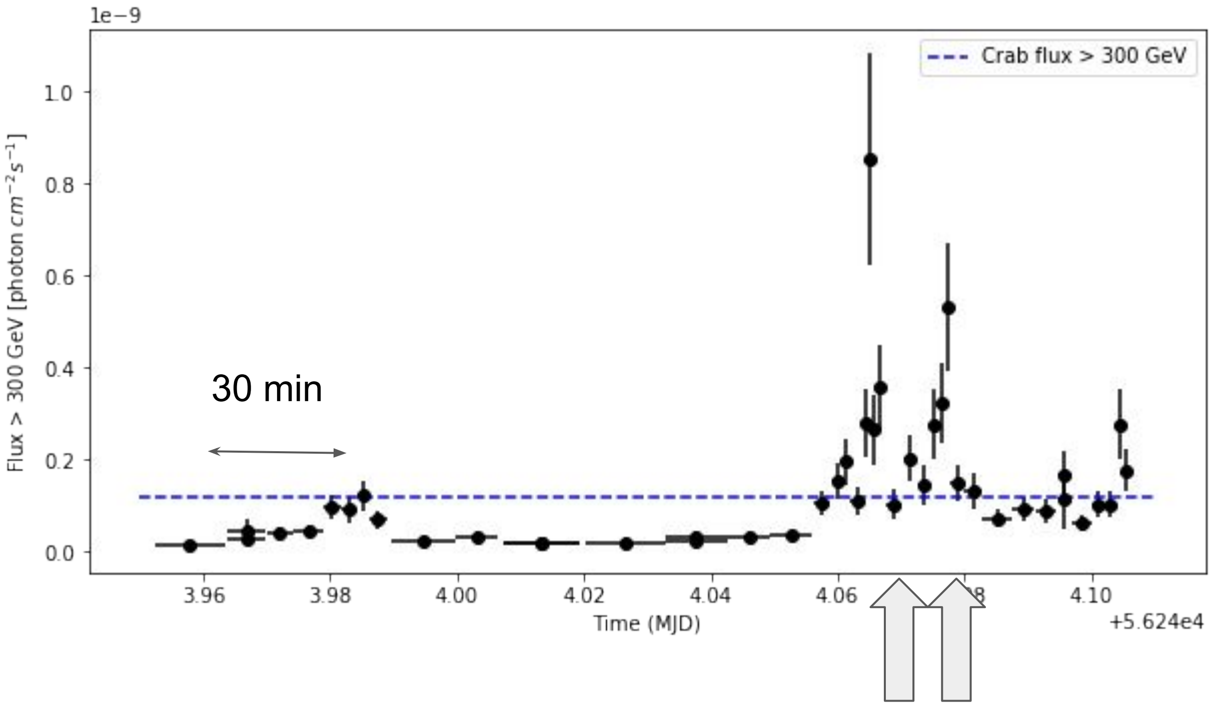
IC 310 spectrum and variability



- Different Spectrum from Crab
- IC 310 exceeds Crab at 10 TeV

MAGIC flare: IC 310 spectrum and light curve



used fit!

Total ~ 4 hours of observations

IC310 showed variability:
flux increase by a factor of 10
at a short time scale

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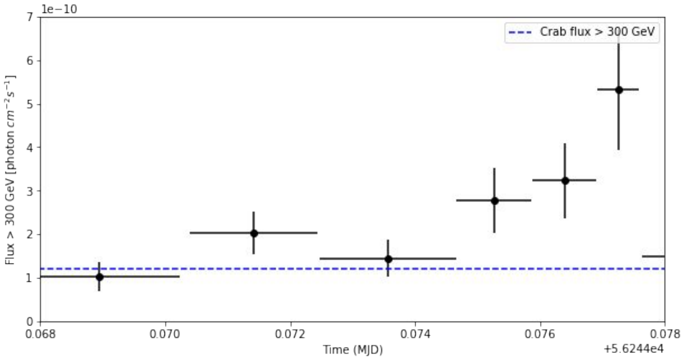
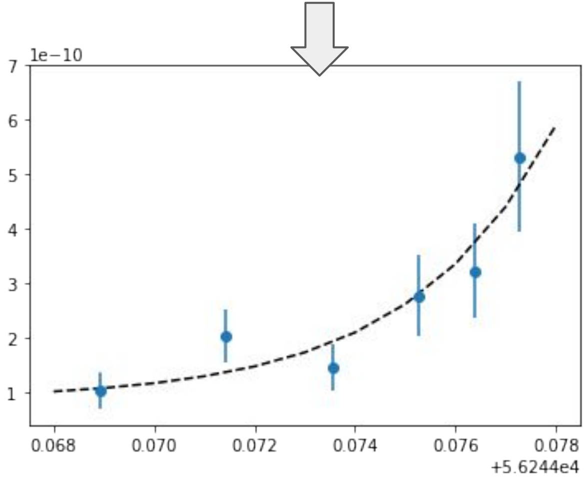
How to get timescale





$$f(x) = p_0 + p_1 \exp\left(\frac{x - p_2}{p_3}\right)$$

$$p_3 \sim 4.09[\mathrm{min}]$$

Parameter	Value	unit
p0	8.65*10^-11	flux
p1	2.04*10^-10	flux
p2	5.62*10^4	MJD
p3	2.84*10^-3	MJD
prob	0.164	

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Discussion and implications

Flux and Luminosity

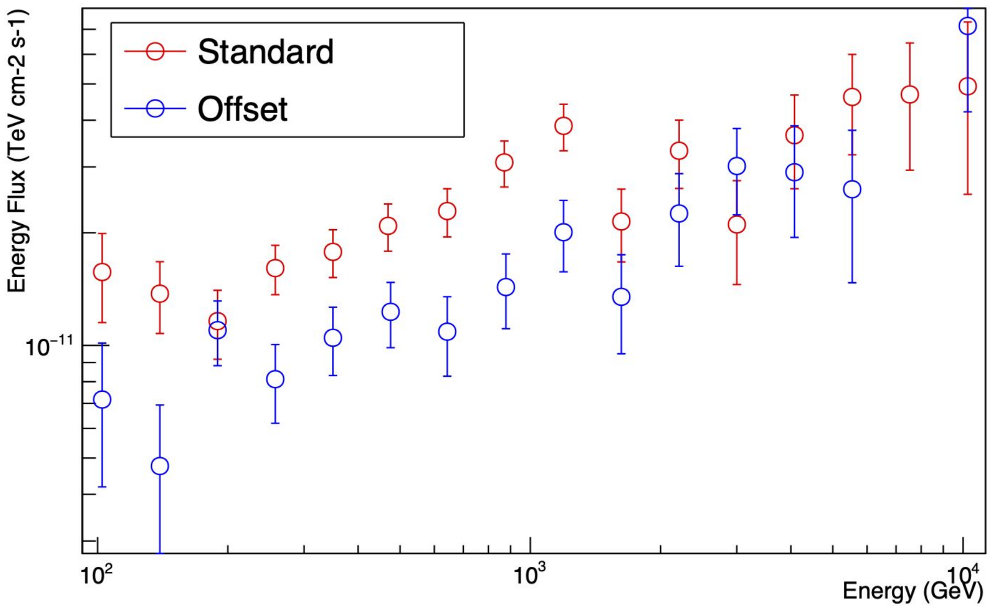


Fig:Energy Flux

- This graph is the data observed by the Magic Telescope

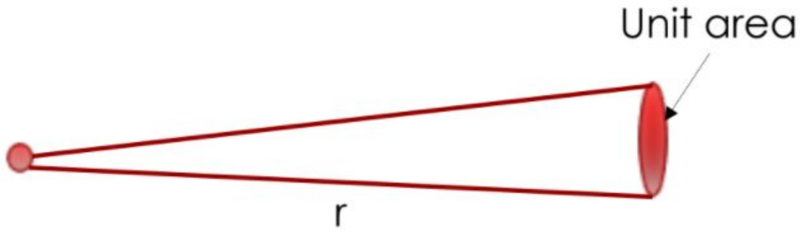
- ➢ The horizontal axis is Energy
- ➢ The vertical axis is Energy Flux per unit energy

This time we used 100 [GeV] to 10 [TeV] data

And we aimed to use this data to estimate the mass and size of black holes

Flux and Luminosity

$$S = \frac{L}{4\pi r^2}$$



$\frac{d\Phi}{dE}$: photon flux per unit energy

$E\frac{d\Phi}{dE}$: energy flux per unit energy

S :energy flux

$$S = \int E\frac{d\Phi}{dE}dE = \int E^2\frac{d\Phi}{dE}d\{ln(E)\}$$

fermi S = 6.24×10^{-12} [erg/s/cm^2]

magic S = 1.35×10^{-10}[erg/s/cm^2]

Combine fermi and magic

S = 1.41×10^{-10}[erg/s/cm^2]

Luminosity is

$$L = 4\pi r^2 \times S$$

$r = 81$ [Mpc] has already known

As a result,

$$L = 1.67 \times 10^{44} \text{ [erg/s]}$$

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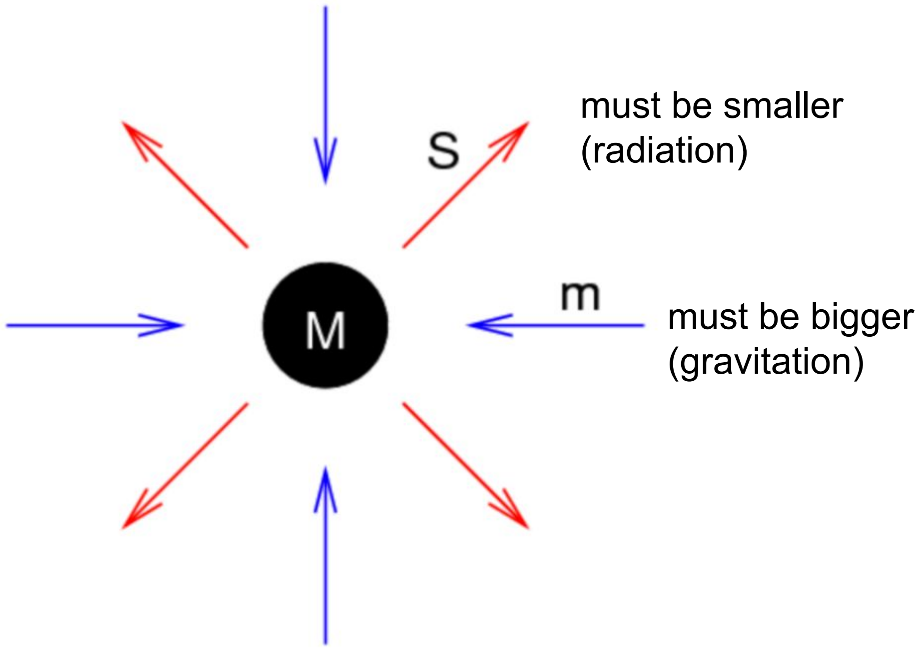
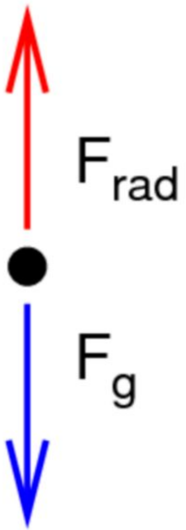
Eddington Luminosity

There is a maximum luminosity beyond which radiation pressure will overcome gravity,and material outside the object will be forced away from it rather than falling inwards



Eddington Luminosity



$$F_{rad} = \frac{\sigma_T S}{c}$$

$$F_g = \frac{GMm_p}{r^2}$$

σT：cross section

where energy flux S is given by

$$S = \frac{L}{4\pi r^2}$$

Accretion is only possible if gravitation dominates:

$$\frac{GMm_p}{r^2} > \frac{\sigma_T S}{c} = \frac{\sigma_T}{c} \cdot \frac{L}{4\pi r^2}$$

in astronomically meaningful units

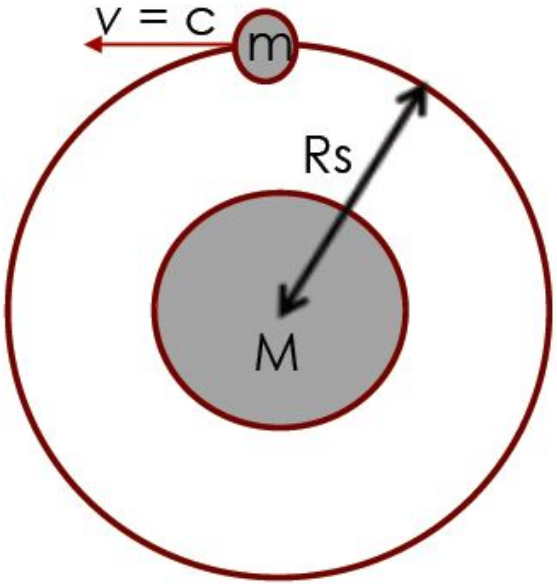
$$L < 1.3 \times 10^{38}\,\mathrm{erg\,s^{-1}} \cdot \frac{M}{M_\odot}$$

From using the result from experiment, we calculate

$$1.3 \times 10^6 M_\odot < M$$

cf） $M_{BH} = 3^{+4}_{-2} \times 10^8 M_{sun}$ which shows in relation with velocity dispersion of bludeg stars of host galaxy indicate validity of this result.

Schwarzschild Radius



- Do you know Schwarzschild radius ?

Schwarzschild radius is the minimum radius that light cannot escape

it is given this formula

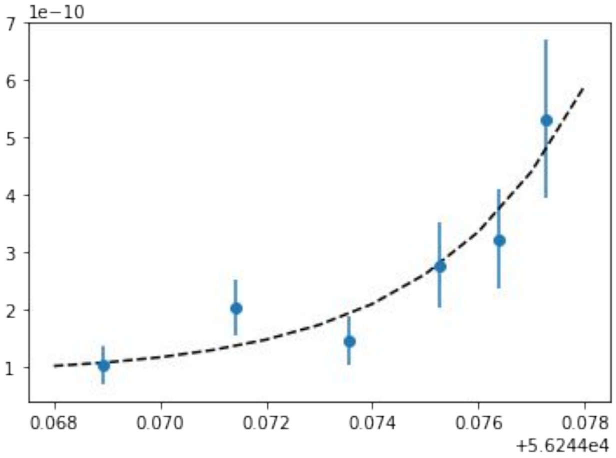
$$R_s = \frac{2GM_{BH}}{c^2}$$

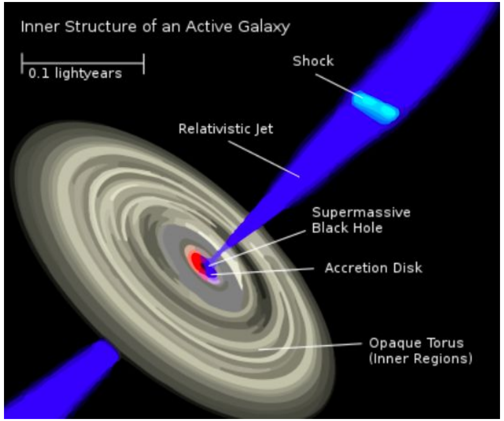
now M has estimated by relation with velocity dispersion of bulge stars of host galaxy

$$M_{BH} = 3^{+4}_{-2} \times 10^8 M_{sun}$$

consequently we get $R_s = 9 \times 10^{11}$ [m]

Size of Emission region





- We estimate the size of emission region inside the AGN jet.
- Variability Time scale Δt is ~4 min.
- The emission region changed its physical state within 4 min.
- Size of the emission region should be smaller than cΔt, because information cannot travel faster than the light.

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Doppler Effect

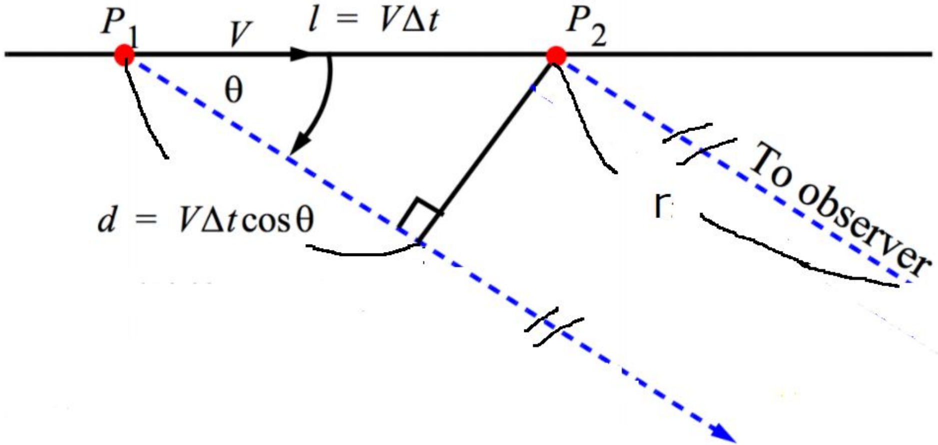
Time difference between P1 and P2(source):*Δt*
Time difference between P1 and P2(observer):*Δt'*
Form Lorenz transformation

$$\Delta t' = \gamma\Delta t - \frac{V\gamma\Delta t\cos\theta}{c}$$

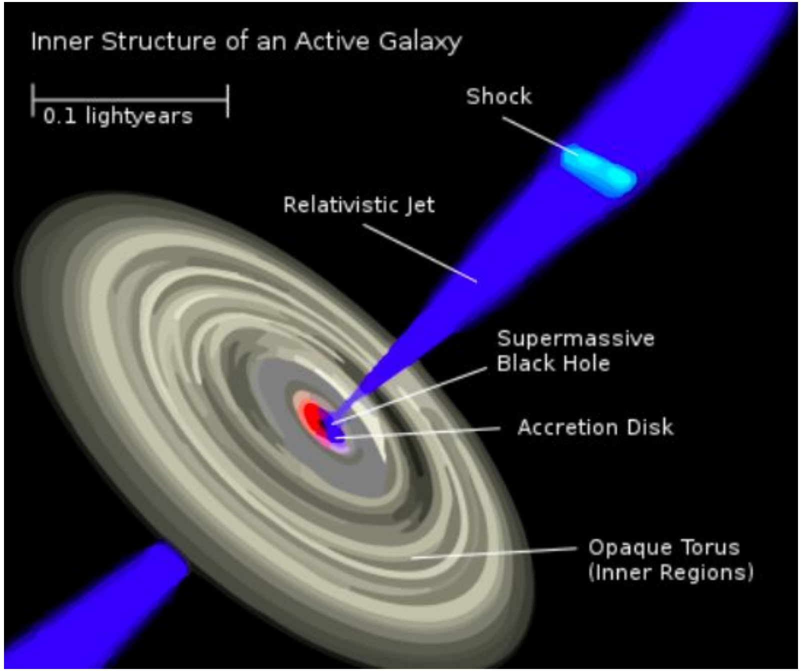
Therefore,frequency is $$f' = \frac{1}{\gamma(1-\beta\cos\theta)} f$$

Doppler factor is $$\delta = \frac{1}{\gamma(1-\beta\cos\theta)}$$

Also,θ＝15° and γ＝10 is already given. Thus, we calculated δ＝2.9



Size of Emission region



- Now we can calculate $c\Delta t_{\rm flar}$!

the observed time scale is 4 min
and doppler factor is $\delta \cong 3$

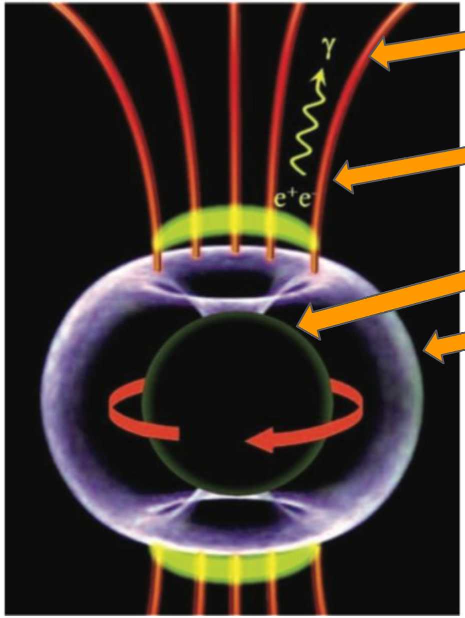
consequently $c\Delta t_{\rm flar} = 2.2 \times 10^{11}$ [m]

in other word $\mathrm{R} < 2.2 \times 10^{11}$ [m]

But $R_s = 9{\times}10^{11}$ [m]

It is strange that R is smaller than R_s

One model for IC 310 emission



magnetic field (red line)

size of emission region(polar vacuum gap regions,yellow area) R＜2.7× 10^{11}

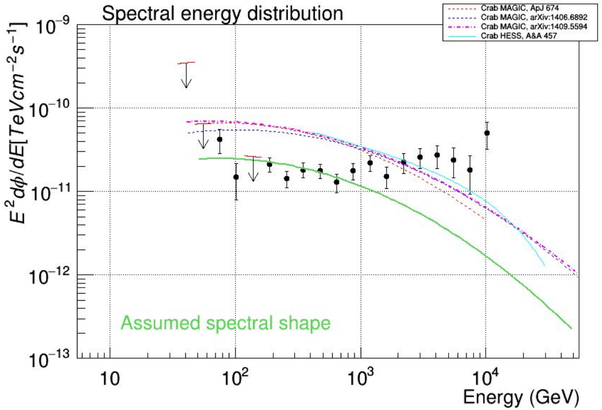
size of event horizon(black area) R＝9× 10^{11}

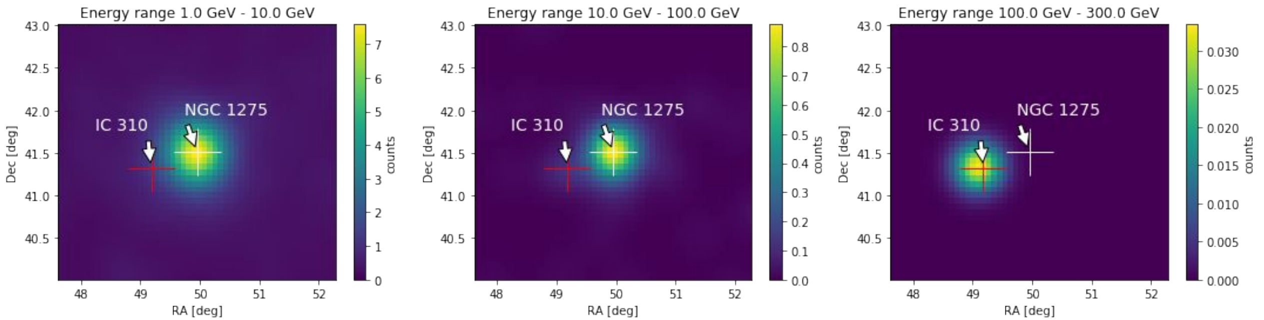
ergosphere(blue area)

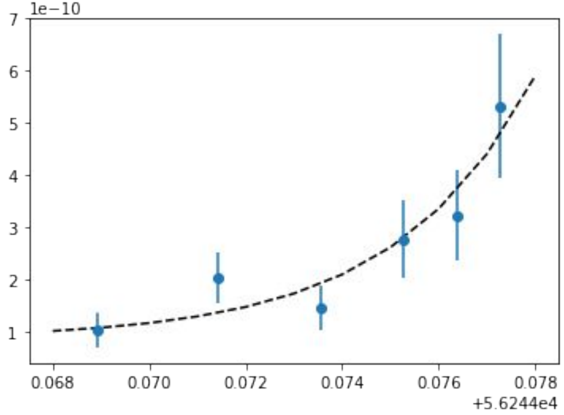
- Rotating black hole with event horizon accretes plasma.
- The rotation of the black hole induce charge-separated magneto-sphere(red) with polar vacuum gap regions(yellow area)
- magneto-sphere has a component parallel to the magnetic field.

This model can explain why size of emission region is smaller than size of event horizon！

Summary



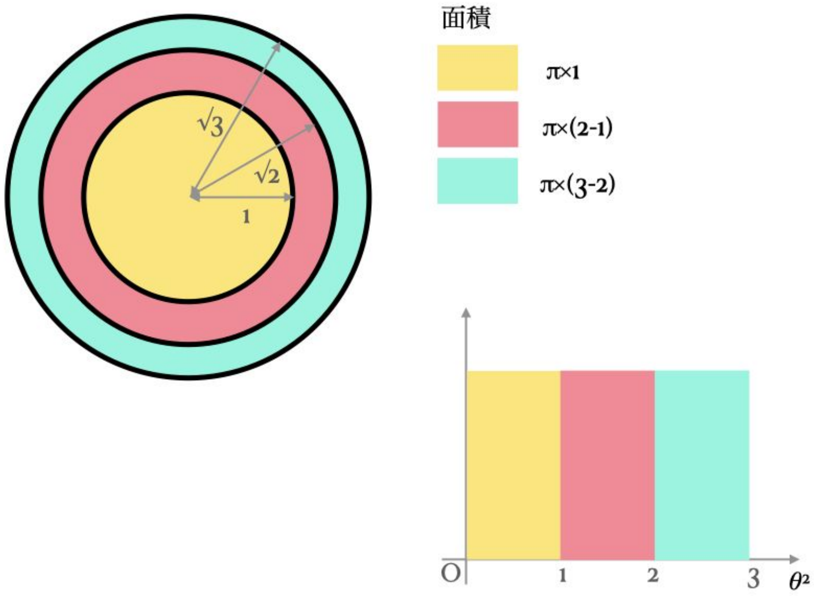




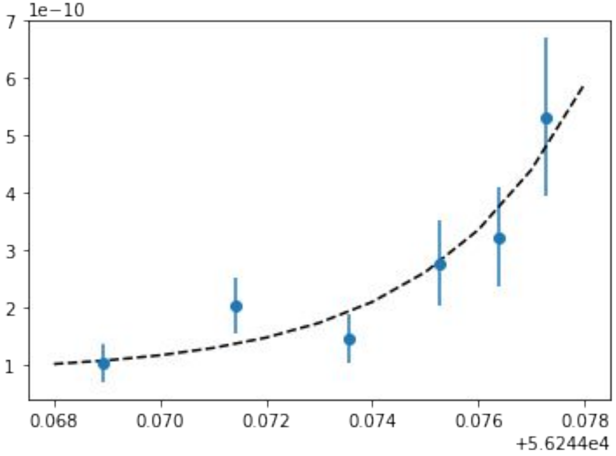
- We analyzed Fermi-LAT and MAGIC data of IC310.
- Very fast variability (~4min) was observed in November 12th. 2012.
- We found that flare luminosity is within the Eddington Limit.
- We also found that size of emission region is smaller than size of event horizon. It suggest that here is a little complex structure near the black hole.

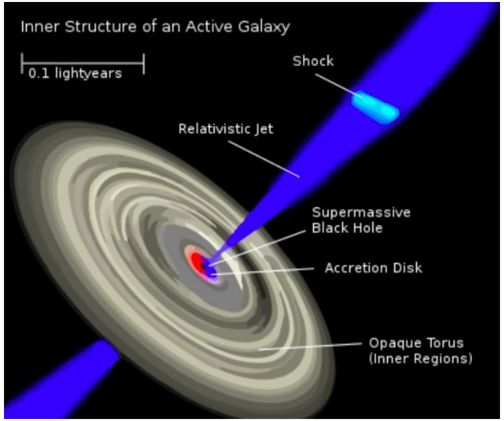
Appendix

Explanation of theta square



Size of Emission region





- we expected that black hole is limited size

- Δt_{ligt} is defined by the time scale of a light
- Δt_{flar} is defined by the time scale of a flare

So size of Δt_{ligt} is $R = c\Delta t_{\text{ligt}}$

(It's like the thickness of the time interval of light)

and $\Delta t_{\text{ligt}} < \Delta t_{\text{flar}}$

because Light has the maximum propagation speed

thus we get $\mathrm{R} < c\Delta t_{\text{flar}}$

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