Astroparticle Physics: γ–Rays

Lecture 2: Sources of γ-rays

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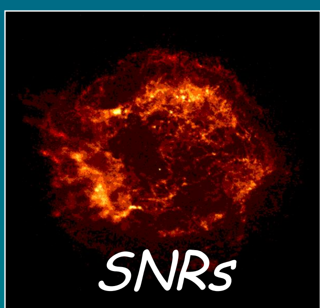
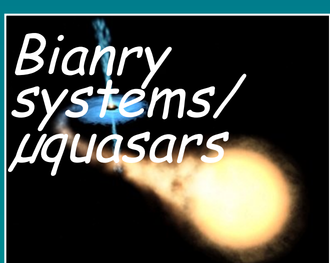
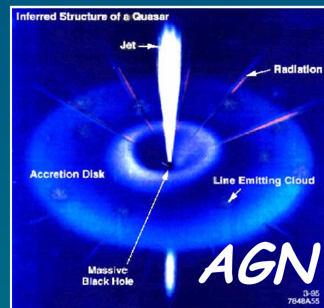
Sources of γ-rays

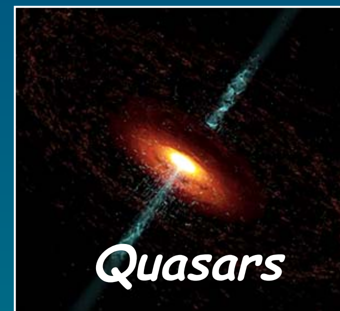
Galactic

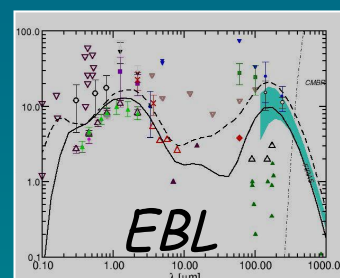


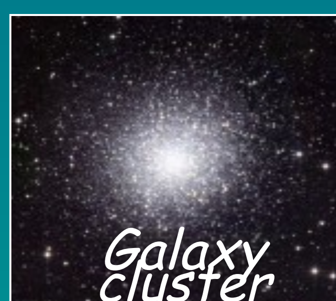


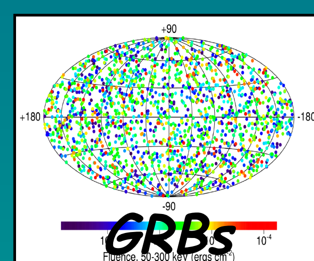
Extragalactic



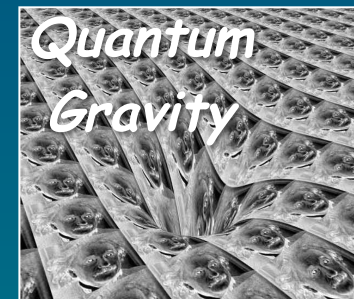


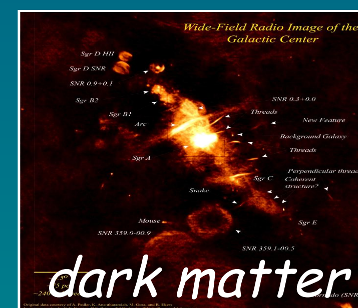


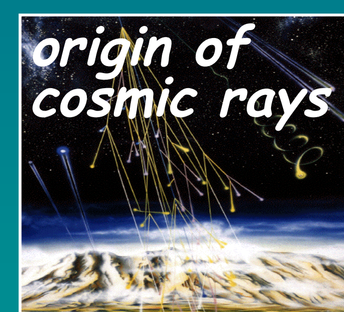




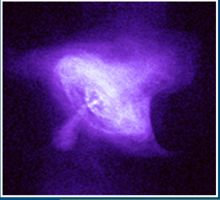
Fundamental Physics





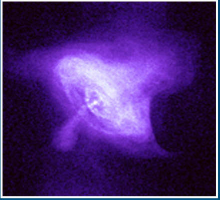


Galactic sources



Pulsars

- Pulsars are highly magnetized and rapidly rotating neutron stars
- Formation of a neutron star



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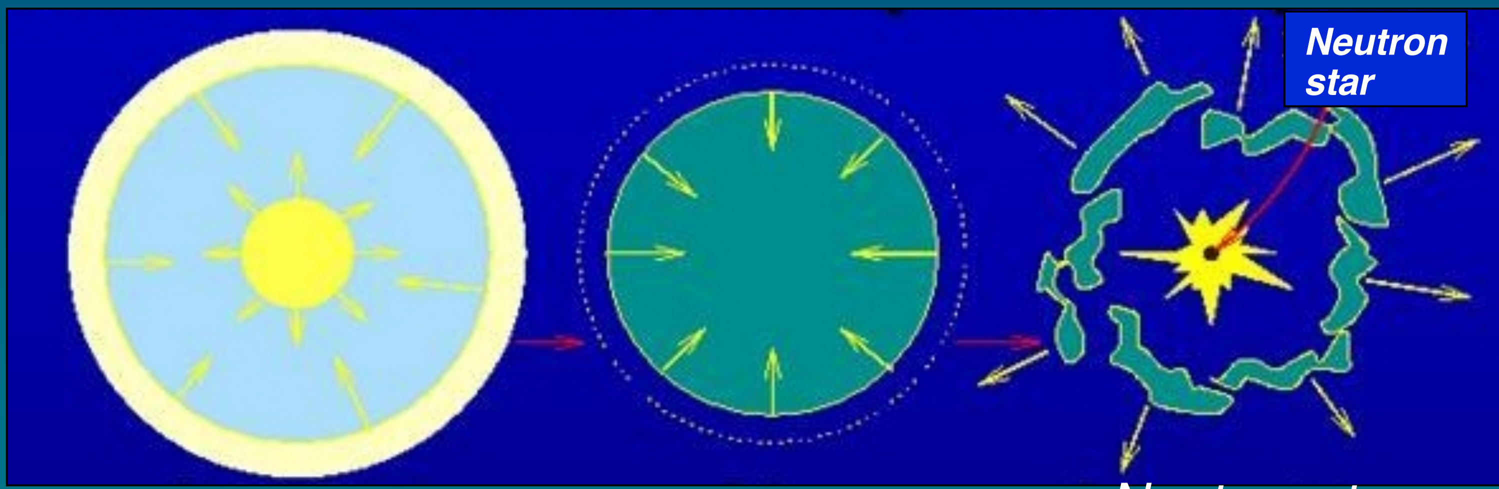


Star *Collapse* *Neutron star + Supernova Remnant*

- Typical mass : 1.4 M_{sun}
- Typical Radius: ~10 km
- Magnetic field: B ~10^{8-12} G

➔ *Extreme internal density*

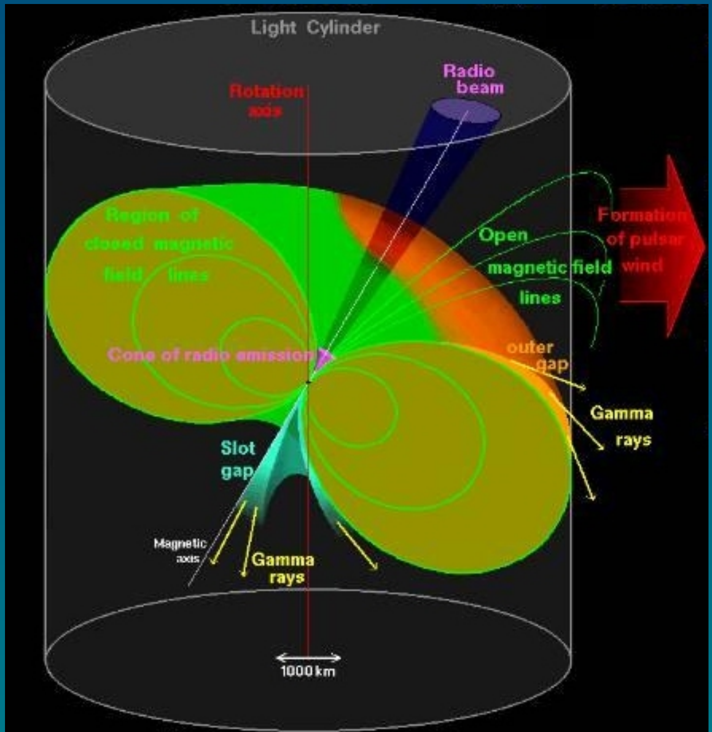
➔ *Unique labs for study the behavior of matter under extreme magnetic & gravitational fields*

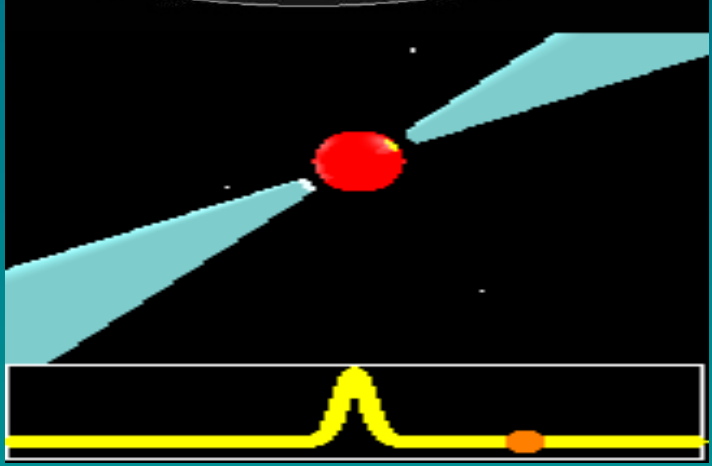
Pulsar models

Magnetosphere

- Fast rotation + huge B field ($B \sim 10^{12}$G) induces intense Electric field E
- E so intense that pull particles out of the stellar surface
- A dense plasma is co-rotating with the star:
  - Magnetosphere extends to the "light cylinder"
  - Non-thermal Emission (radio, optical, X-ray, γ-rays) produced in beams

➔ *Acts like a cosmic light-house*

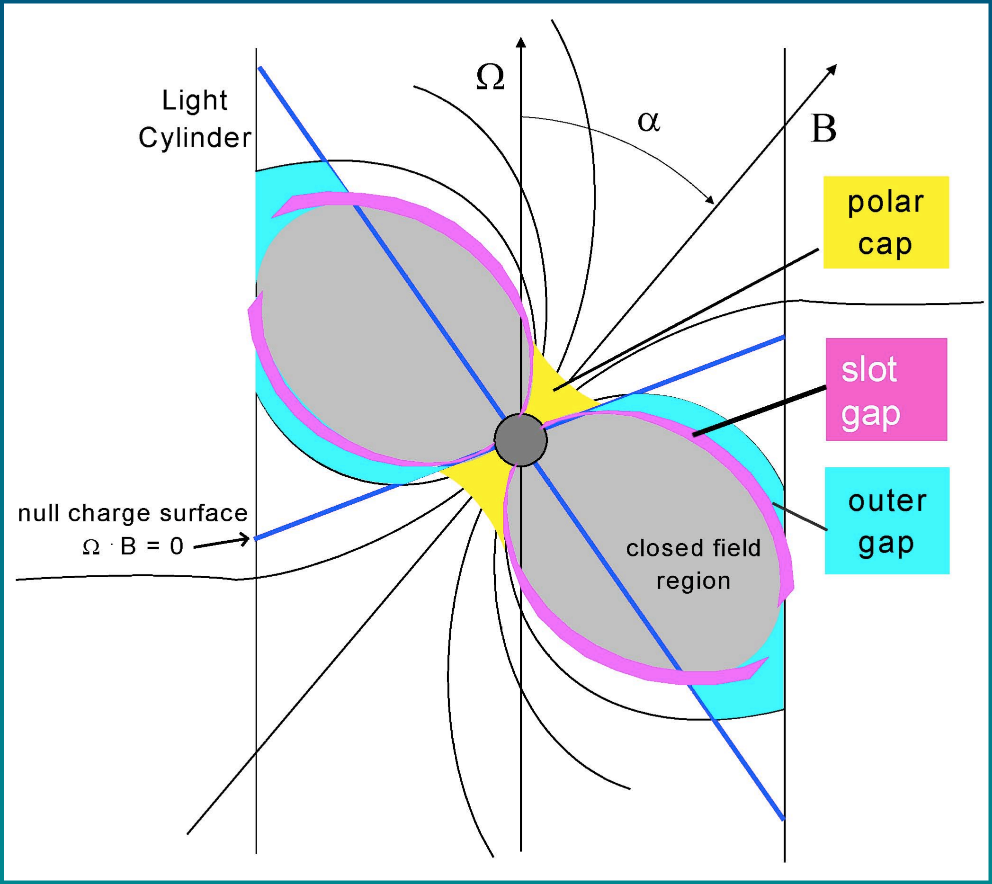




Pulsar models

Origin of γ-rays

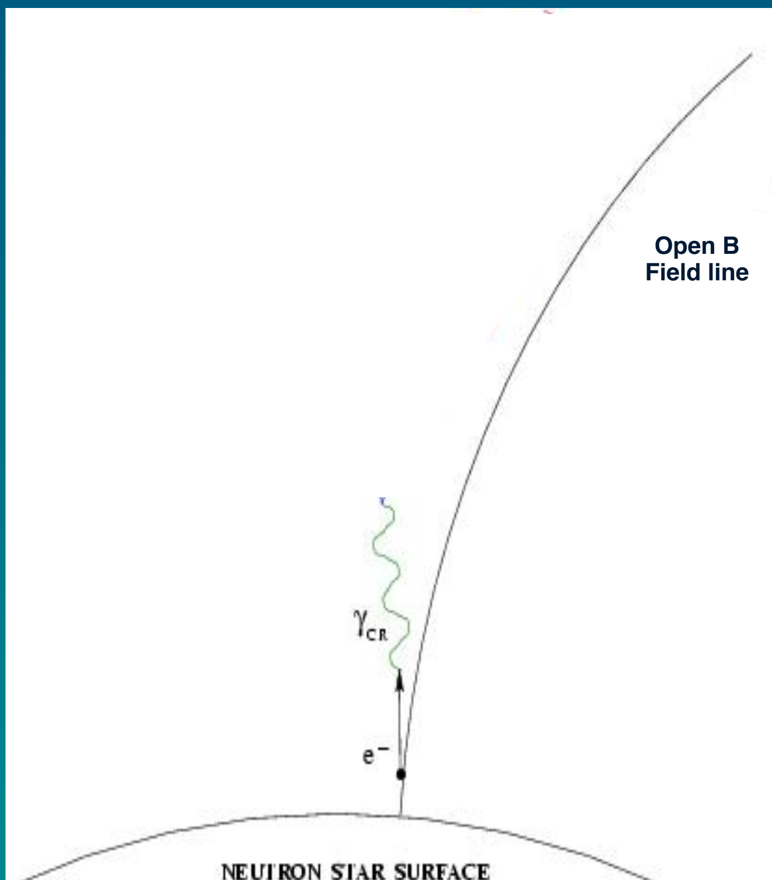
- Different models assume different emitting regions in the magnetosphere:
  - Polar cap
  - Outer gap
  - Slot gap
- Spectrum depends on the physics of the emitting region
- Light curves depend on geometry



Pulsar models: Polar Cap

Polar Cap Model

Sturrock (1971); Ruderman & Sutherland (1975); Harding (1981); Daugherty & Harding (1982)



- Acceleration of e- along B lines
- Accelerated particles emit γ-rays via:
  - a) Curvature radiation
  - b) Synchrotron, I.C. of X-rays
- γ-rays interact with magnetic field, via *Magnetic pair production*

$$\gamma + \vec{B} \rightarrow e^{+} + e^{-}$$

- An electromagnetic cascade develops
- The cross-section depends exponentially on the photon energy

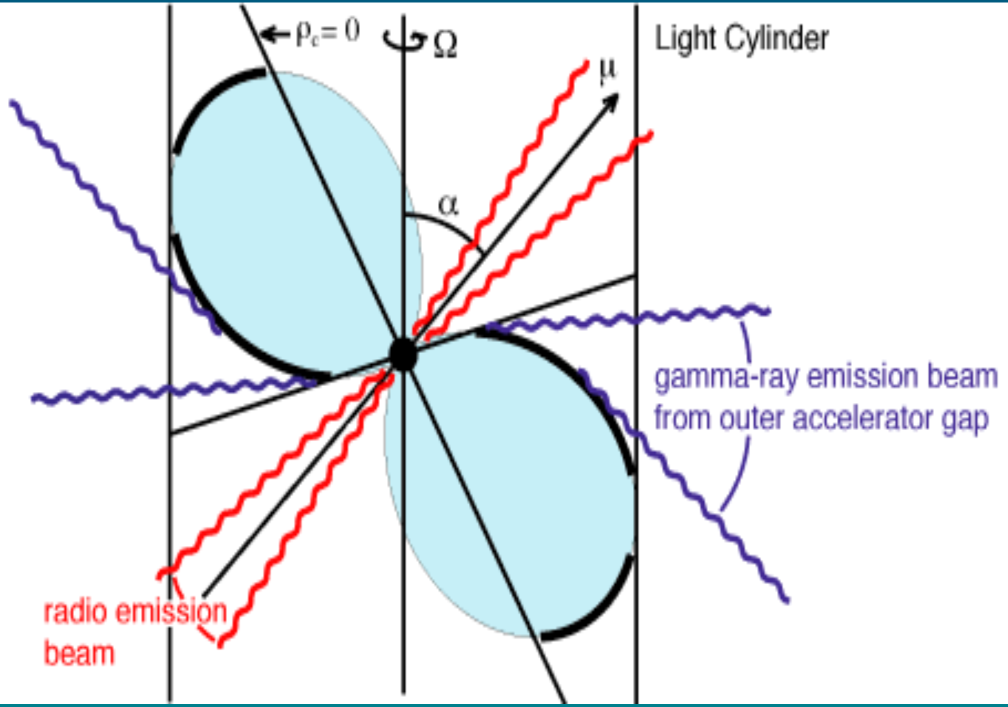
No se puede mostrar la imagen. Puede que su equipo no tenga suficiente memoria para abrir la imagen o que ésta esté dañada. Reinicie el equipo y, a continuación, abra el archivo de nuevo. Si sigue apareciendo la x roja, puede que tenga que borrar la imagen e insertarla de nuevo.

Polar Cap model predicts super-exponential cutoff in high energy γ-ray spectra

Pulsar models: Outer Gap

Outer Gap model

Cheng, Ho & Ruderman (1986); Romani (1996)



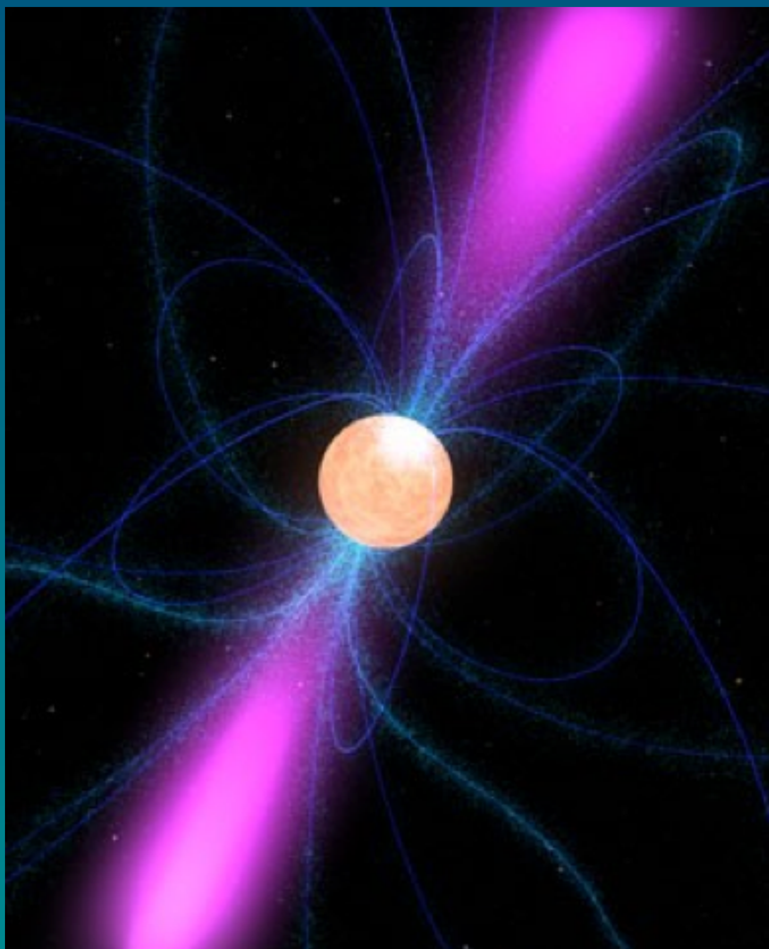
- γ-ray emission occurs near LC
- Charges accelerated in vacuum gap

  → *γ-rays via Curv. rad.*
- **B** not strong enough for pair-production.
- But in this case *γ-rays* can interact with ambient X-rays or IR photons

$$\gamma\gamma \rightarrow e^{+}e^{-}$$

Softer ***exponential cutoff*** in the high energy γ-ray spectra

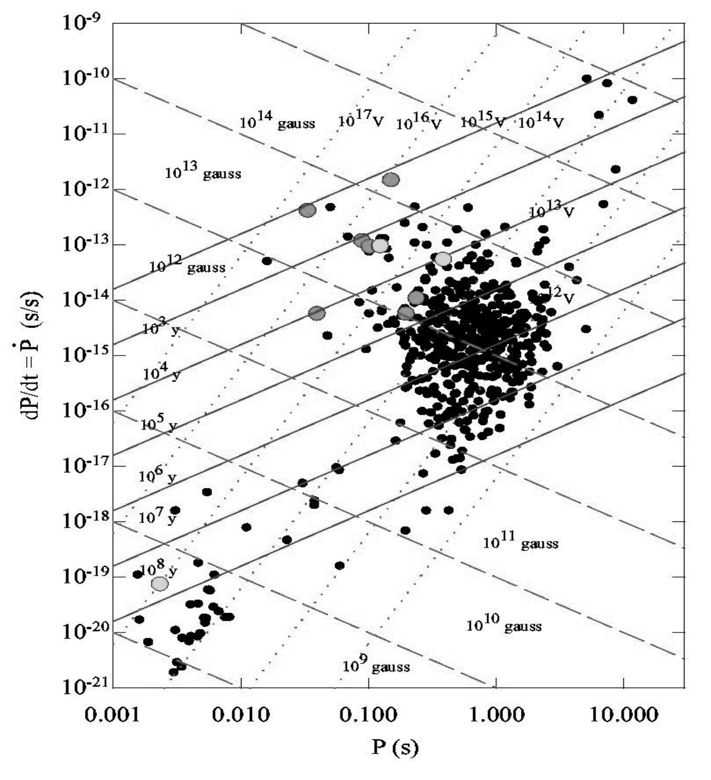
Where do γ-rays come from? Outer/slot gap,polar cap?

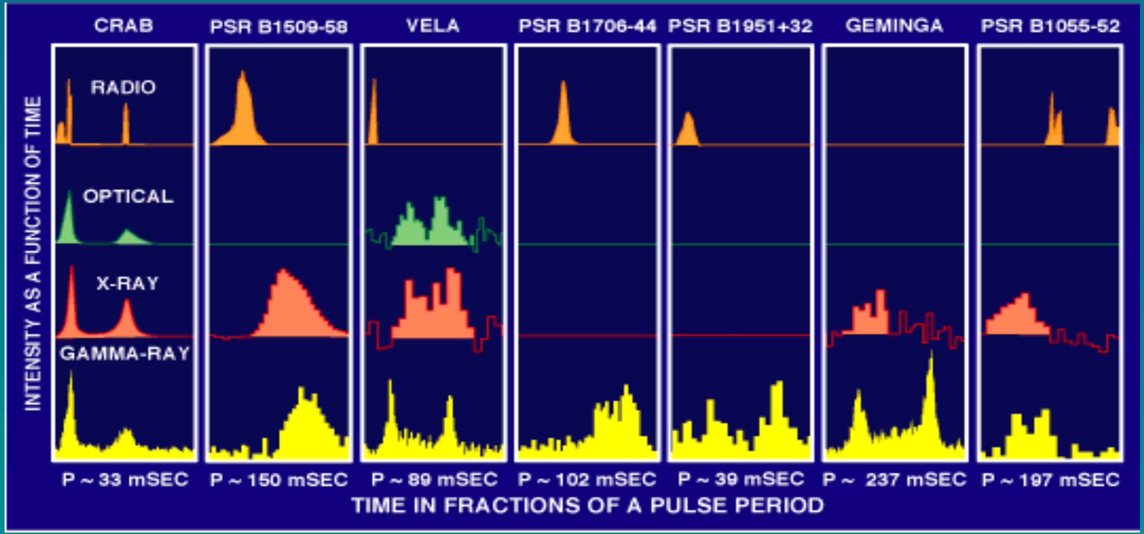


Vs.

Pulsar observations

- Radio: ~2000 radio pulsars known today
  - Can be grouped in normal and ms
- Optical: Just 7 (Crab,Vela,Geminga,…)
- γ-rays:
  - Only 7 seen by EGRET





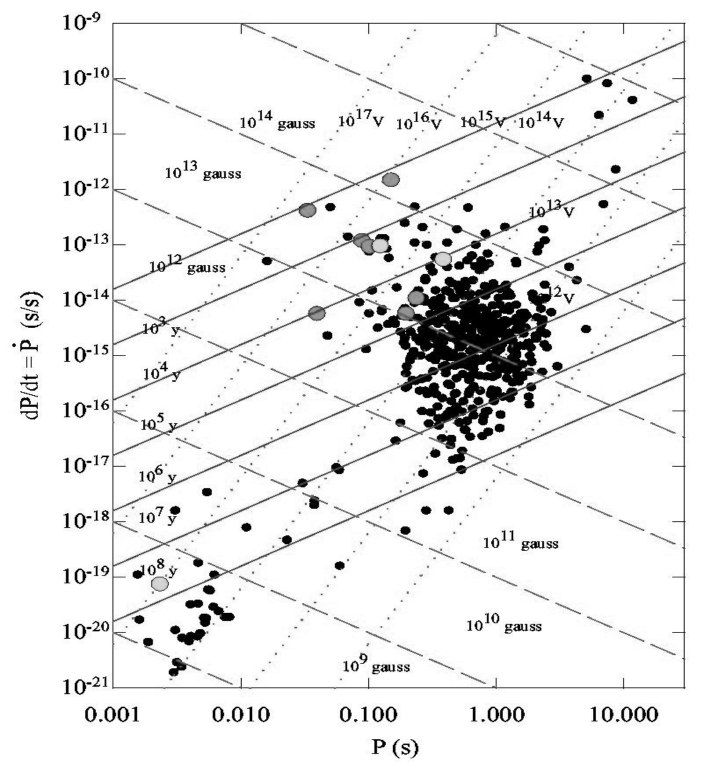
- Typically 2 peaks

- All, but Geminga, radio emitters

- Crab only pulsar which same behaviour at all wavelengths !

Pulsar observations

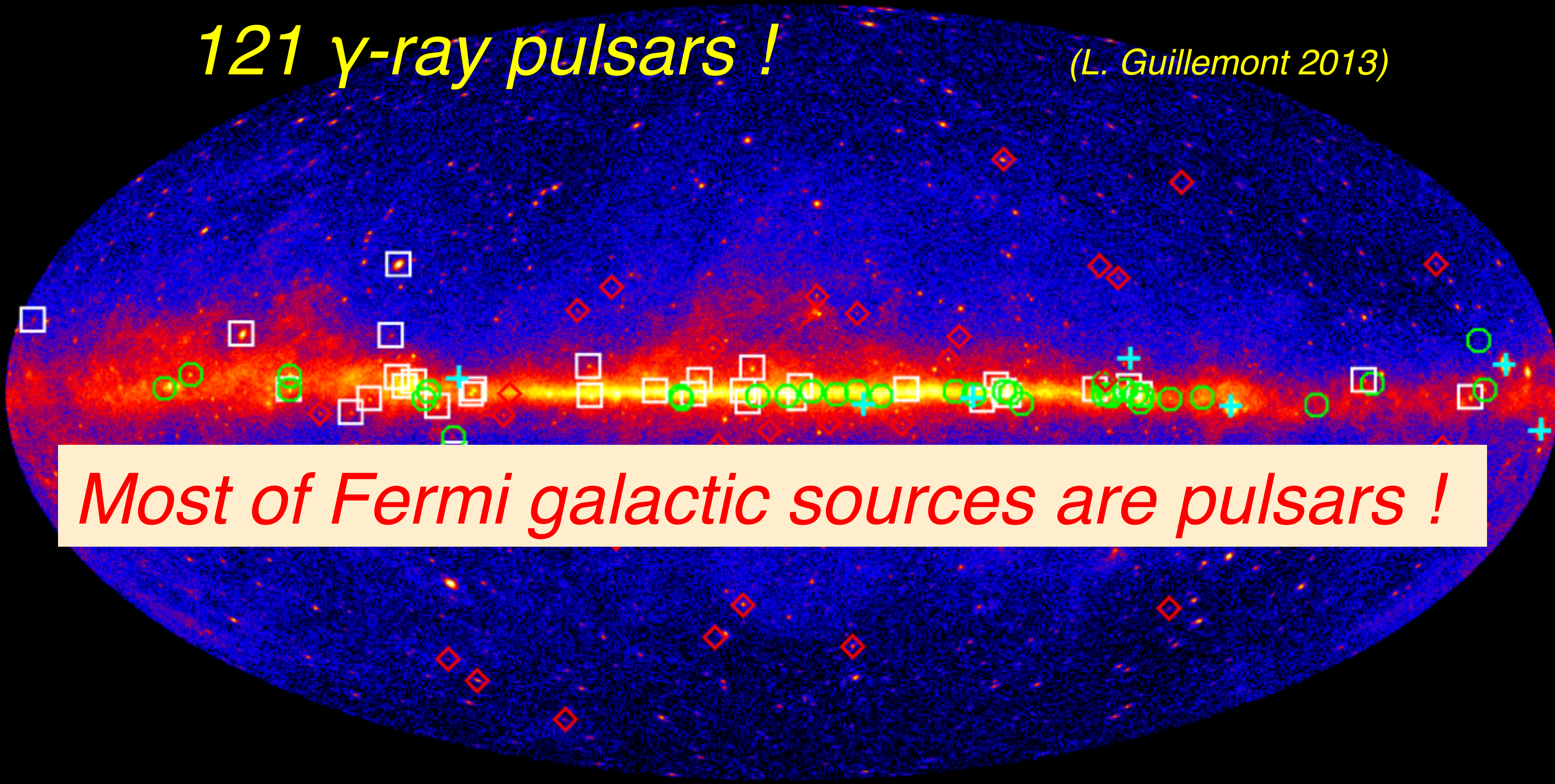
- Radio: ~2000 radio pulsars known today
  - Can be grouped in normal and ms
- Optical: Just 7 (Crab,Vela,Geminga,…)
- γ-rays:
  - Only 7 seen by EGRET
  - ~150 detected by Fermi !



- Fermi Pulsar Highlights:
  - Confirmed all EGRET pulsars and candidate ones
  - Discovered many geminga-like pulsars
  - Discovered new γ-ray pulsars in blind searches
  - Discovered a whole population of ms pulsars

The Fermi Pulsar Catalog

121 γ-ray pulsars ! *(L. Guillemont 2013)*



Most of Fermi galactic sources are pulsars !

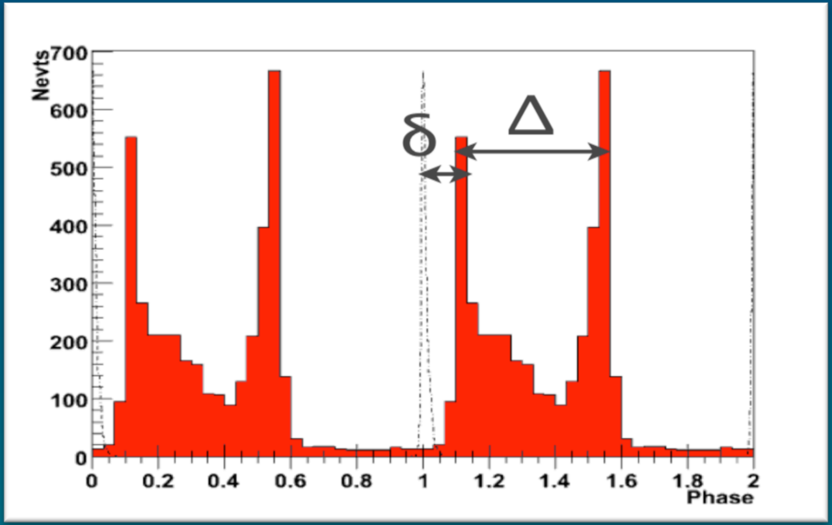
41 young radio- and X-ray-selected (green circles, cyan crosses)
36 young γ-ray-selected (white squares)
43 radio-selected MSPs (red diamonds) + 1 γ-ray-selected MSP (yellow diamond)

What do we learnt from Fermi zoo?

Light curves

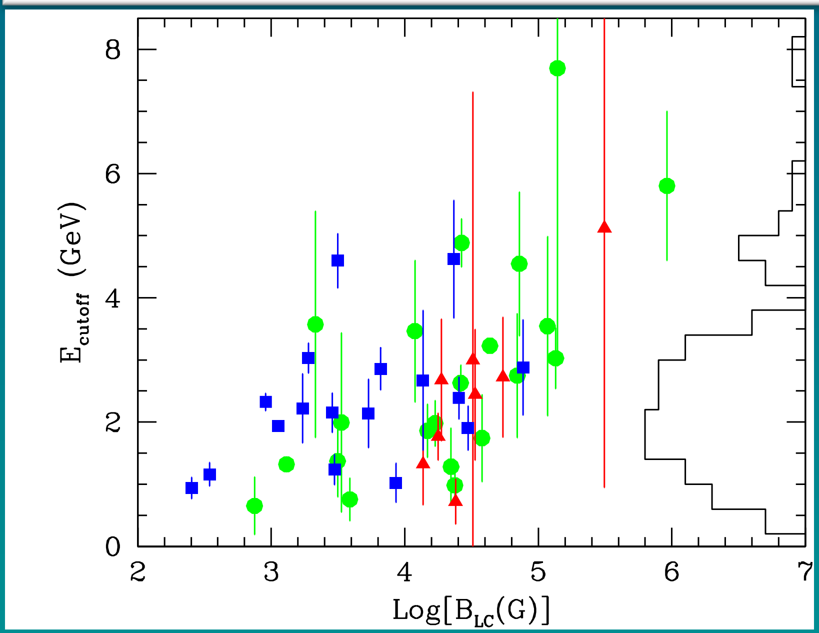
Typically 2 sharp peaks

- Separated by ~0.4-0.5 rotations
- Outer Gap (OG) provide good fit



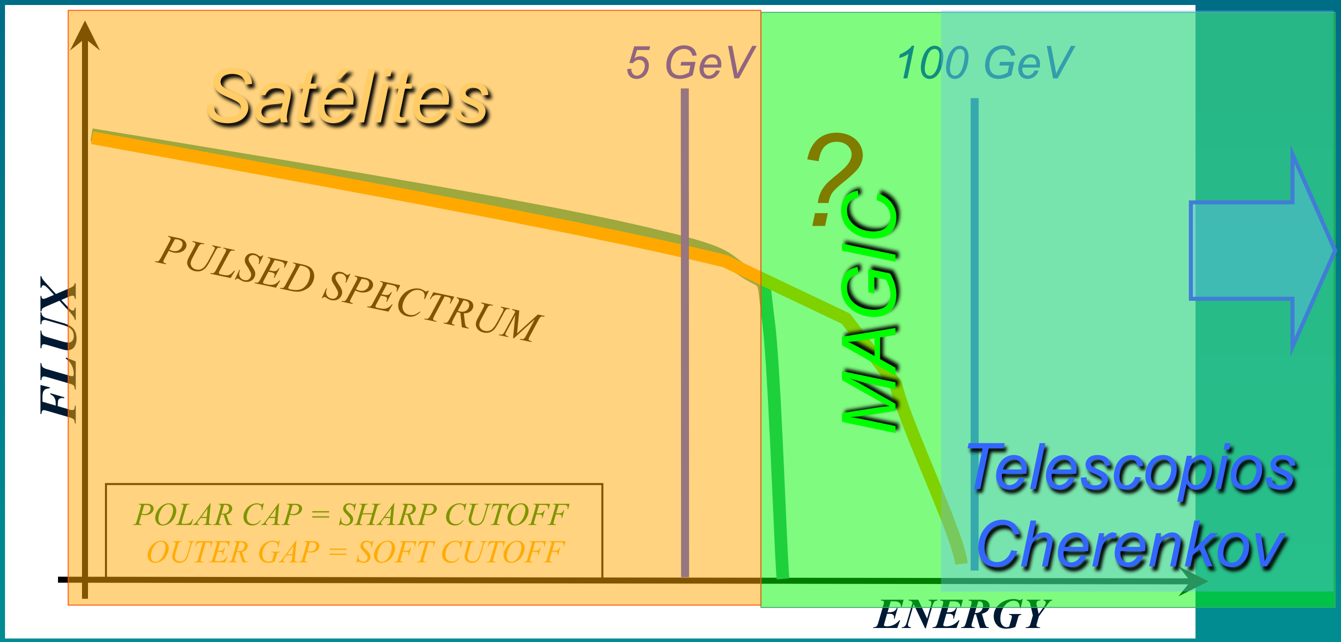
Spectra

- Consistent with power-laws + exponentially cutoff
- Cutoff energies < 10 GeV



Pulsars visible @ VHE ??

- All models predicted exp. o super exp cutoffs @ ~ GeV
- Measuring it will help to test the models
- But this energy region laid in the unexplored window of γ-ray astronomy until recently

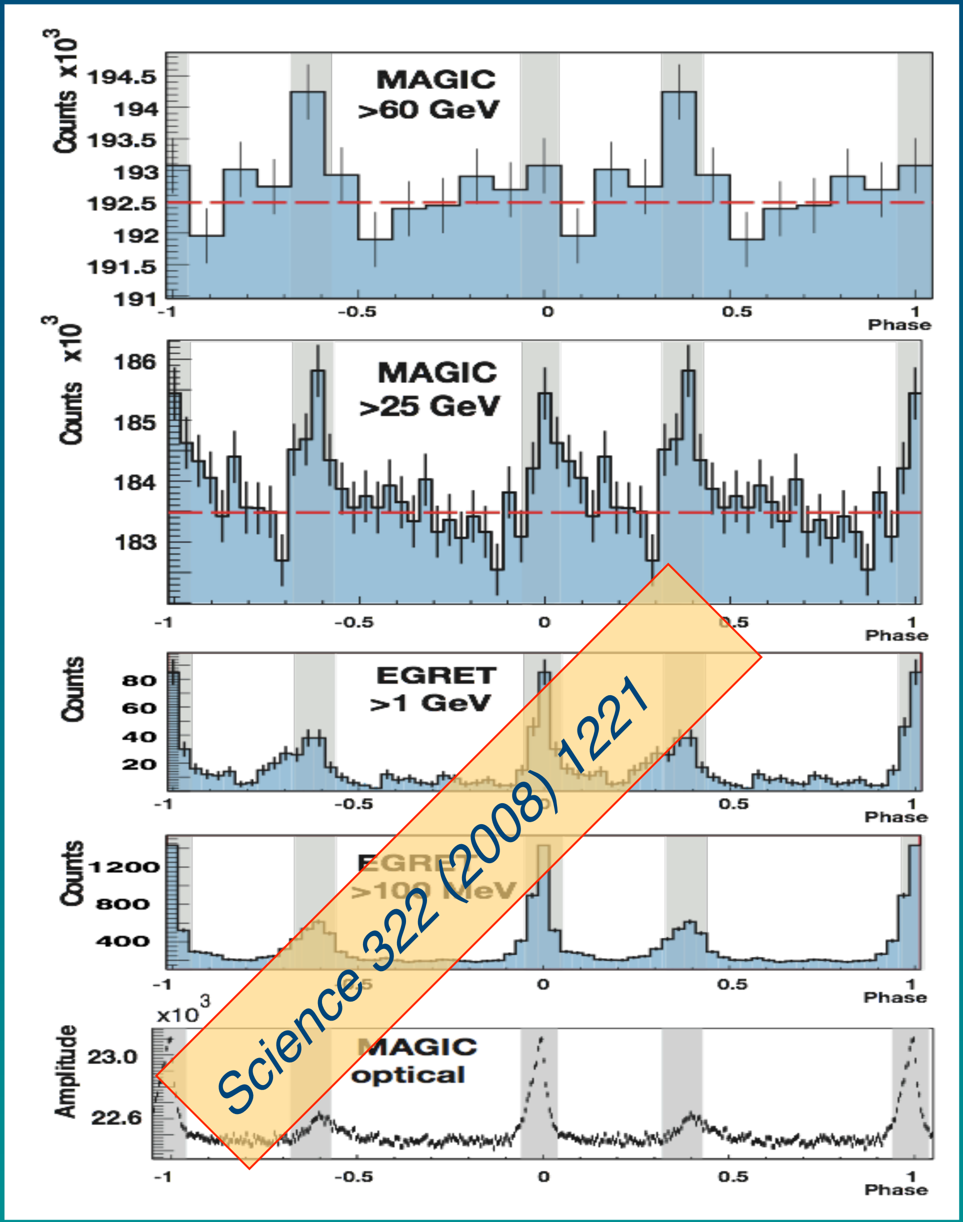


First pulsar detected @ VHE: MAGIC 2008

- The technical innovations of MAGIC allowed for the first time to detected VHE pulsed γ-rays

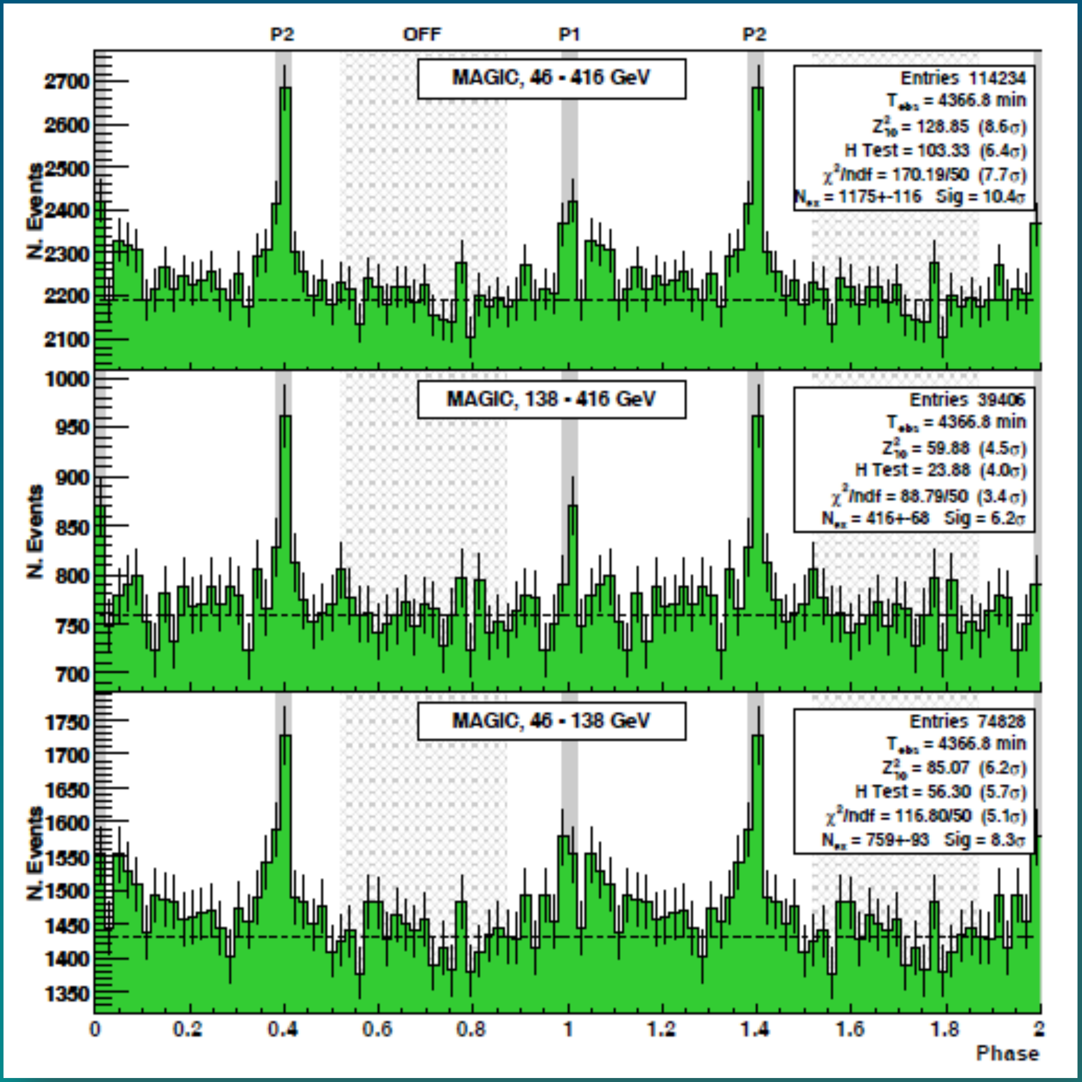
A break-through for ground-based γ-ray astronomy after more than 20 years chasing it

- Surprising discovery:
  - P1 clearly visible @25 GeV ➔First Surprise
  - Pulsed emission still visible > 60 GeV !



Crab pulsar @ VHE

- MAGIC continued observing Crab pulsar



Pulsed emission detected up to 400 GeV !!

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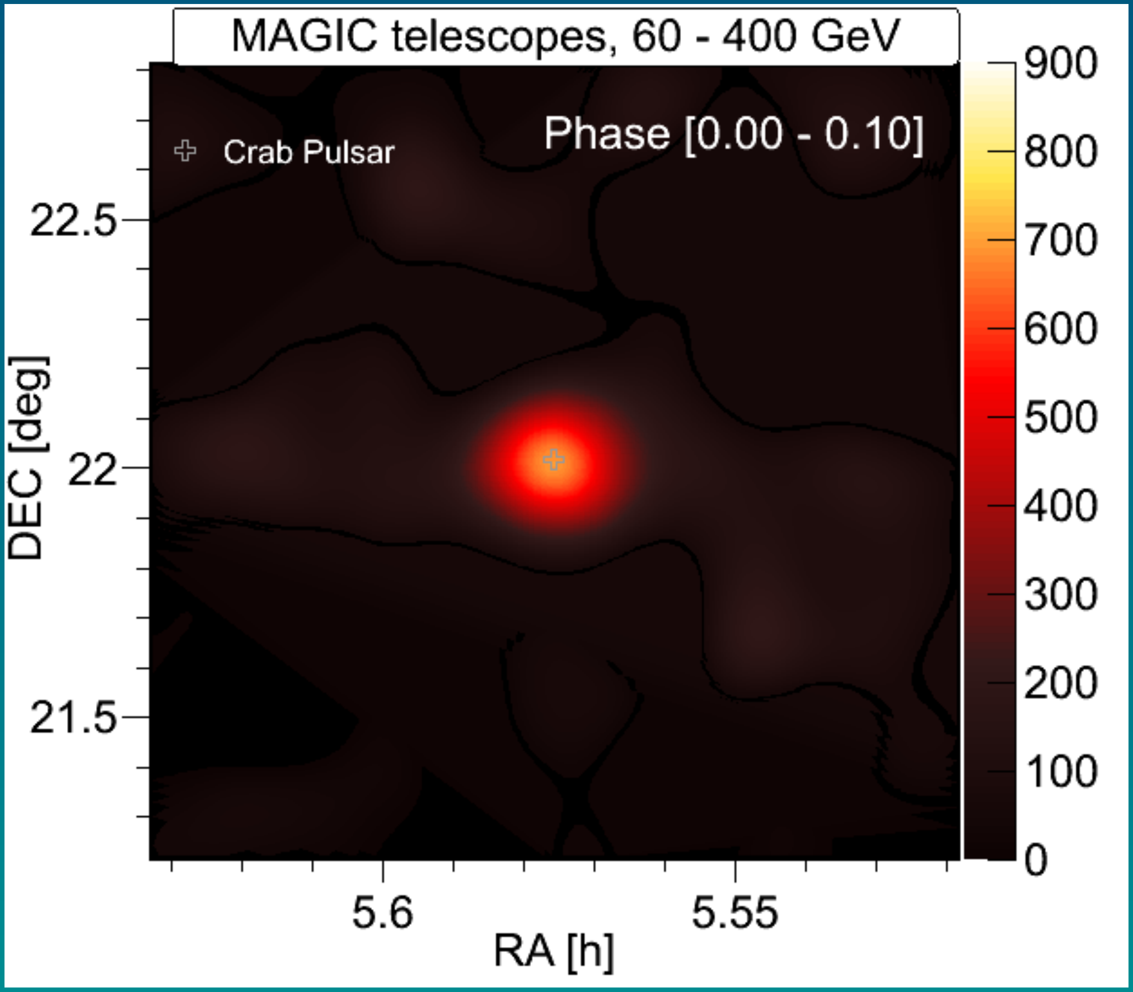
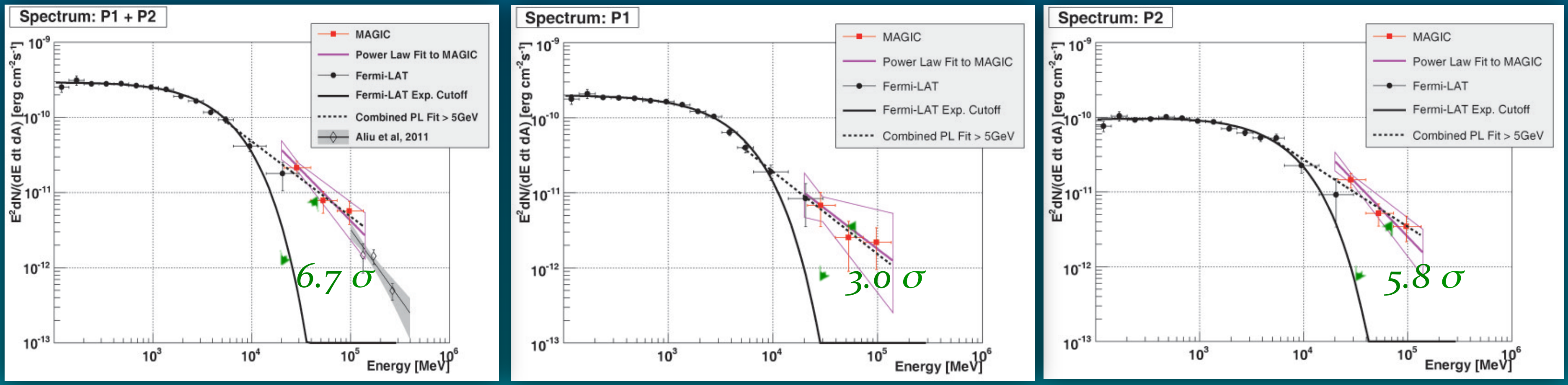


Pulsed emission detected up to 400 GeV !!

Crab pulsar @ VHE

First pulsar Phase-resolved spectrum > 100 GeV !



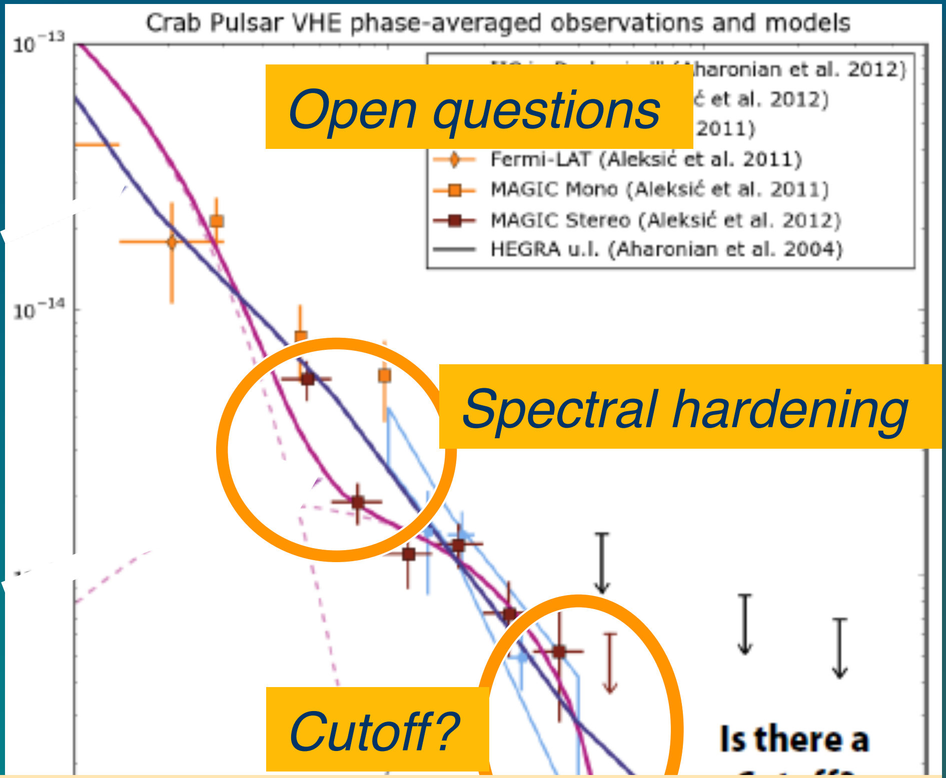
MAGIC results rule out extrapolation of Fermi exponential fit.

Unexpected detection of Crab pulsar @ VHE
➔ Re-thinking pulsar models

Possible explanations for a VHE tail

New models proposed to explain the unexpected Crab VHE:

1. **Extension of OG model (Hirotani)**
2. **Emission outside LC (Aharonian et al.)**
3. **Emission by secondary plasma in the OG (Lyutikov et al.)**
4. **Sync-Curvature emission by ultra-relativistic particles @ LC (Bednark)**
5. **IC of secondary pairs in Annular gap (Du et al.)**



None of them explains yet all the features:
Spectra + Light Curve + Ratio P1/P2

Supernnova Remnants

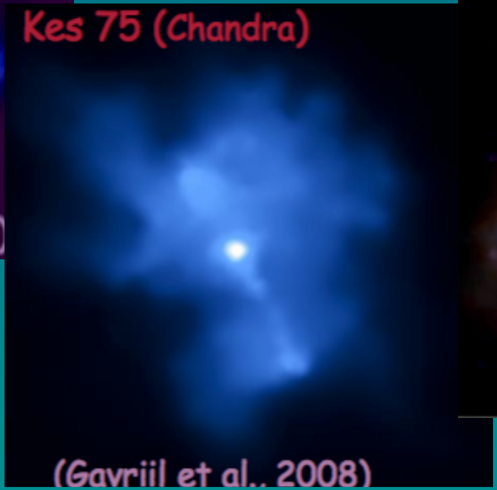
Types

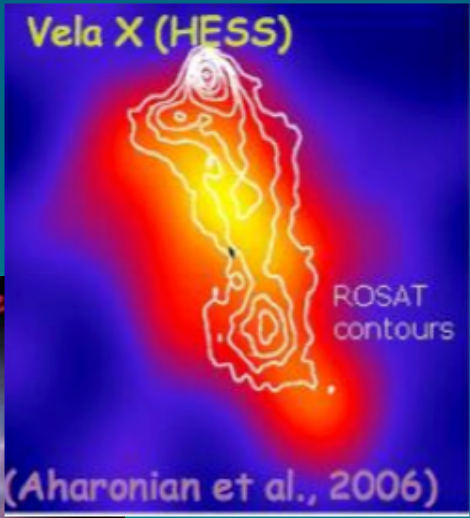
- Plerion (or Pulsar Wind Nebula): Host a pulsar inside
  - Emission: dominated by Synchrotron of the pulsar wind e^-

- Shell type: Without a pulsar inside:
  - Emission: Leptonic or hadronic

Pulsar Wind Nebulae (PWN)

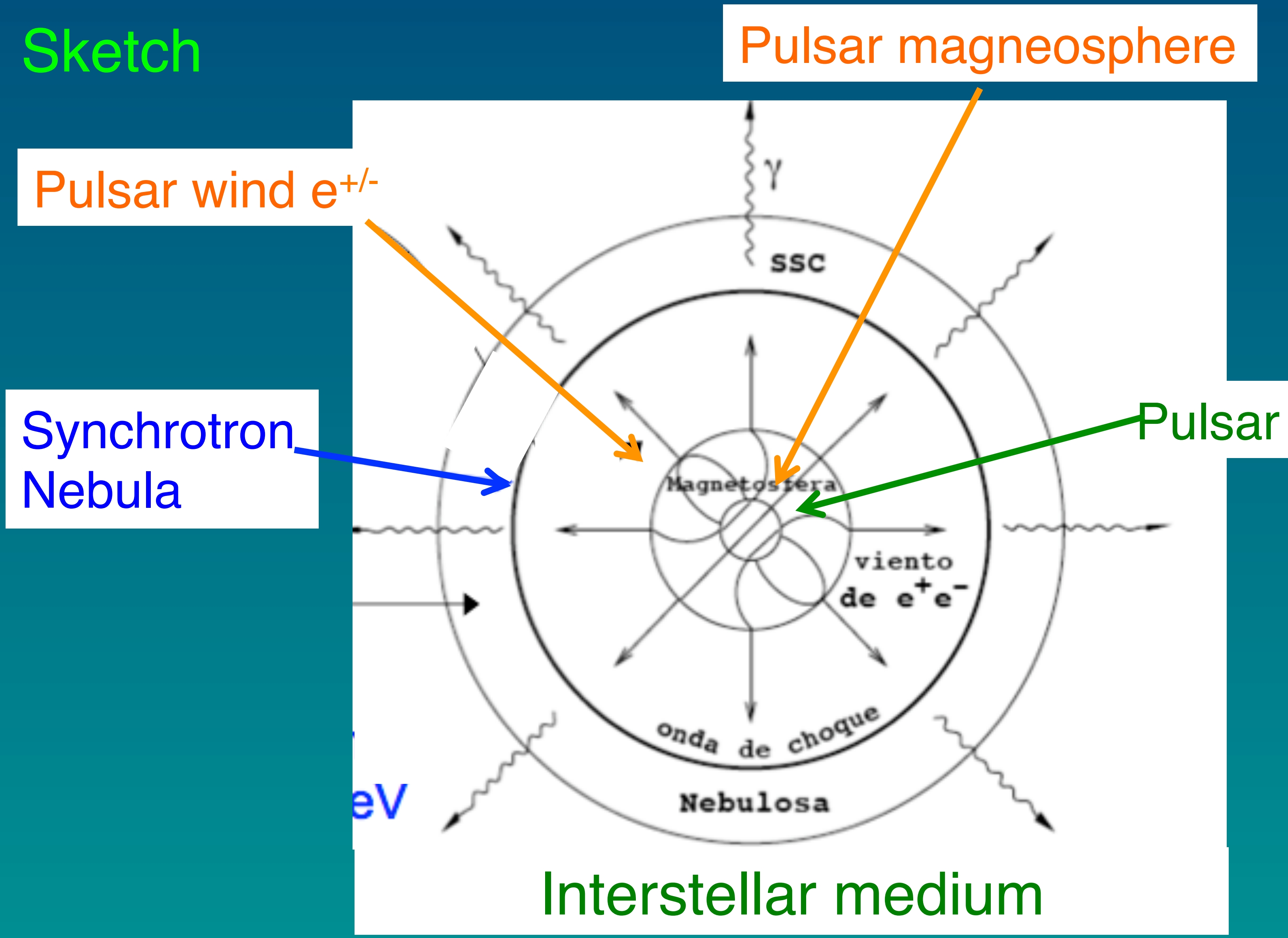
- ~15 discovered @ VHE
- They store most of energy lost by the pulsar
- Emitting over most of the electromagnetic spectrum: from radio to γ-rays





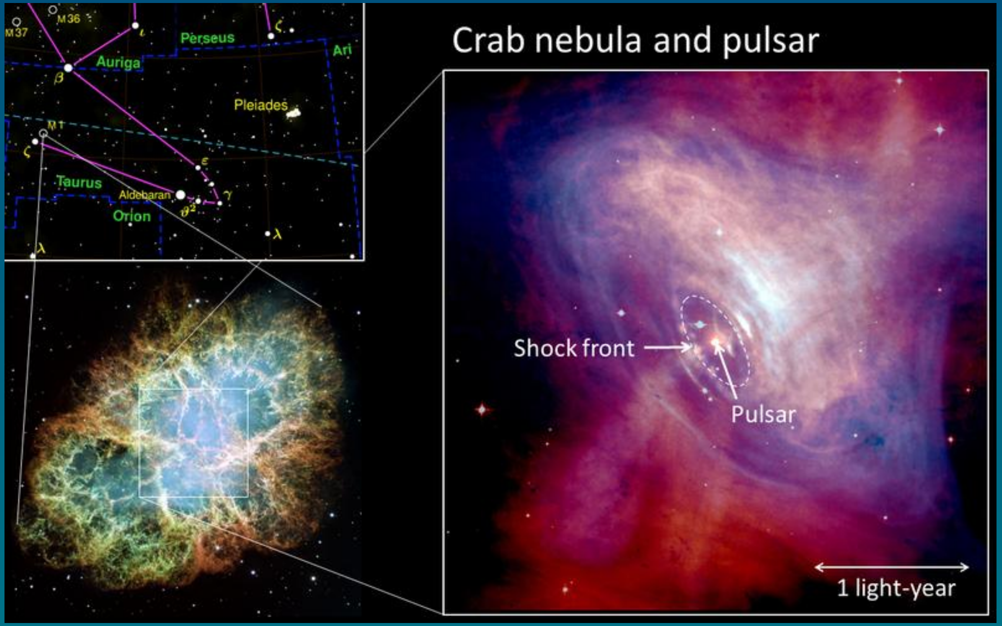
Pulsar Wind Nebulae (PWN)

Sketch



Crab Nebula

- The best known PWN
- Host the Crab Pulsar at its center
- Remnant of a supernova occurred in 1054 in the Taurus constellation
  – Event recorded by American natives and Chinese astronomers
  – 4x brighter than Venus

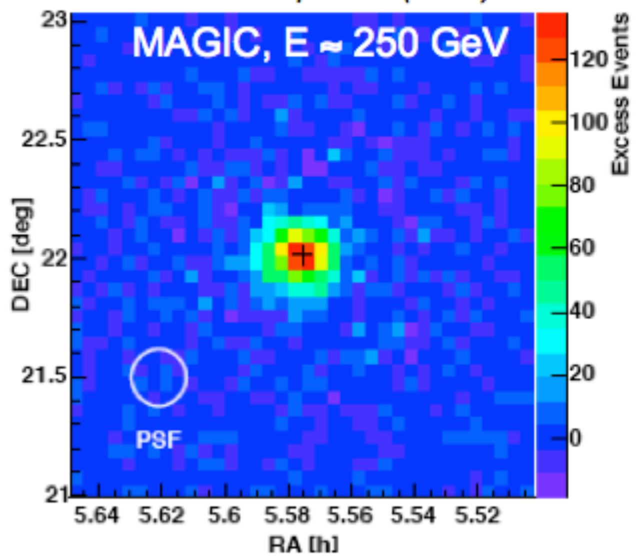


Crab Nebula

Crab @ VHE

- First γ-ray source detected from ground (Whipple Telescope, 1989)
- Emission@ TeV very intense and stable
  → "Standard candle of VHE Astronomy"
- Point-like source for Chrenkov telescopes (and also for Fermi)
  – instrumental PSF > nebula side

Albert et al ApJ 674 (2008)

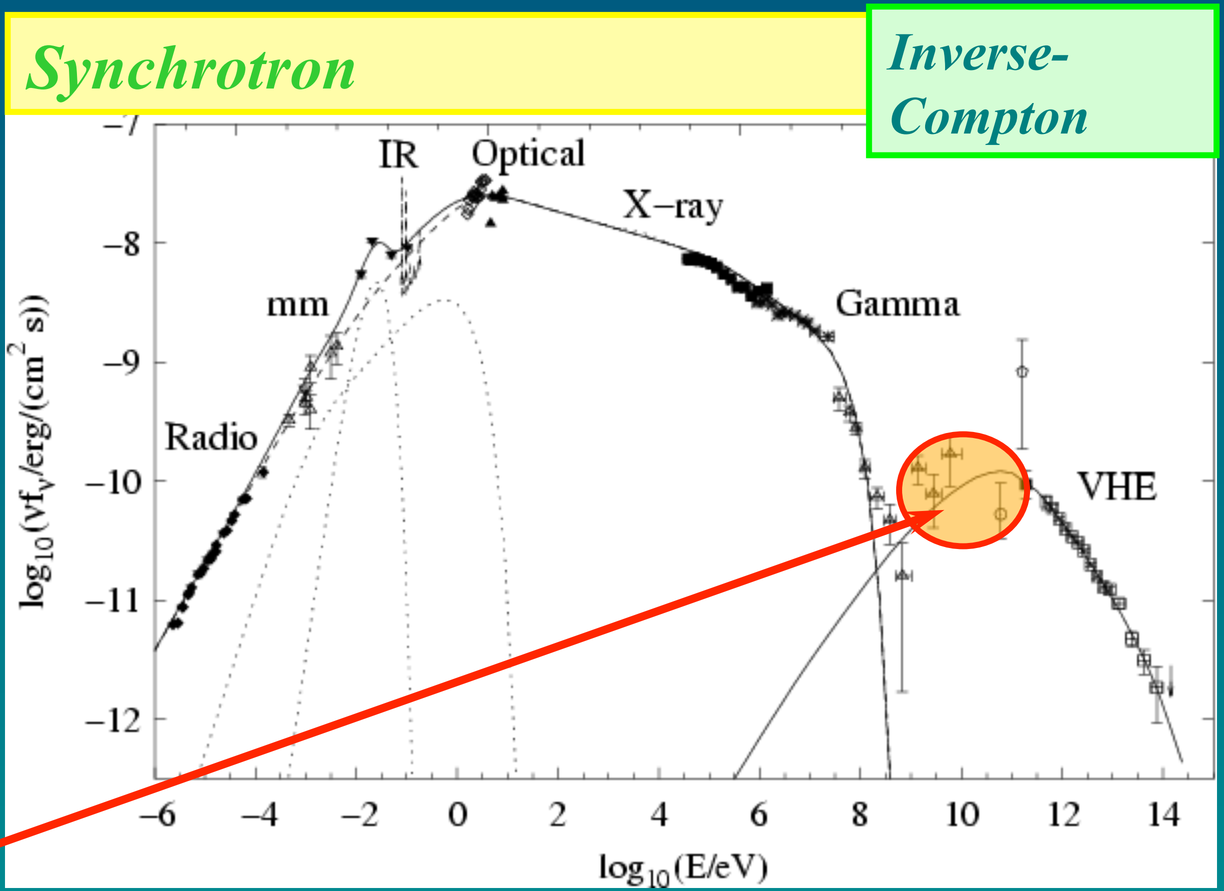


X-ray nebula at the same scale

Crab Nebula

Emission by leptonic model

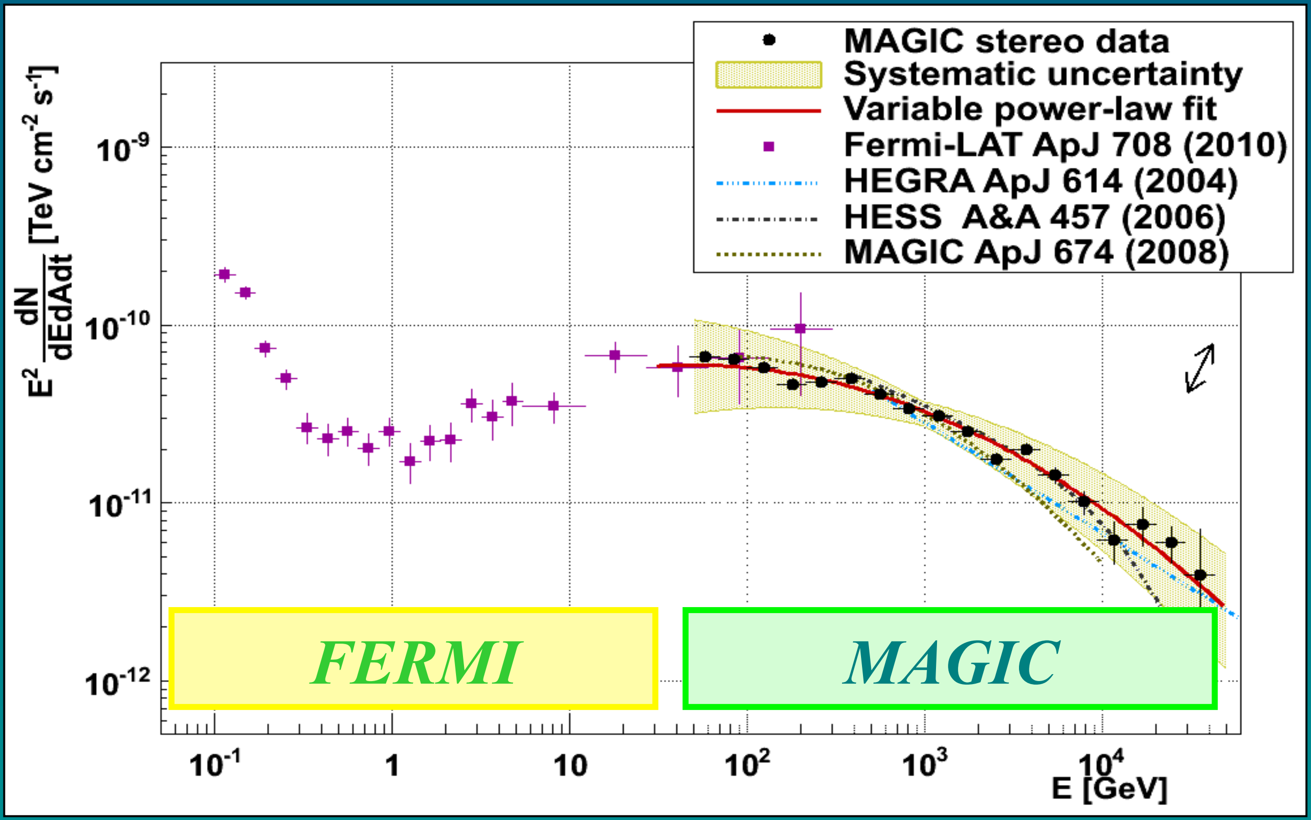
- By non-thermal processes
- Two components:
  - Synchrotron
  - Inverse Compton
- SSC model explains the observed spectrum
  - Inverse Compton peak expected below 100 GeV



Crab Nebula

VHE Spectrum

- Measurements by space and ground detectors agree very well
- Precise IC peak estimation (MAGIC+Fermi fit): **59 ± 6 GeV**



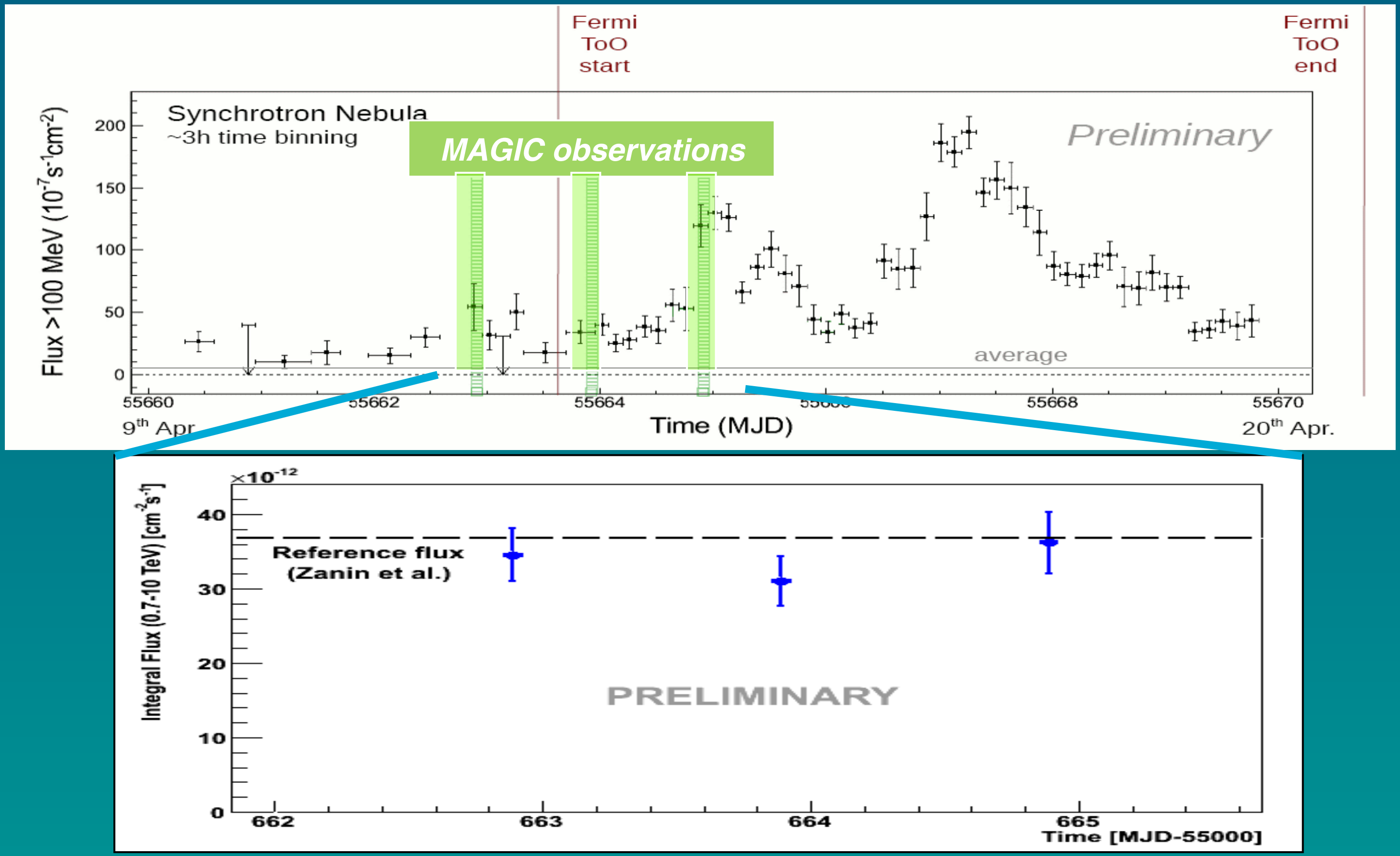
Crab Nebula

Flux variability

- GeV flares of hours/days seen by AGILE & Fermi and year-long variability in X-rays…
- No variability detected @ TeVs

FERMI

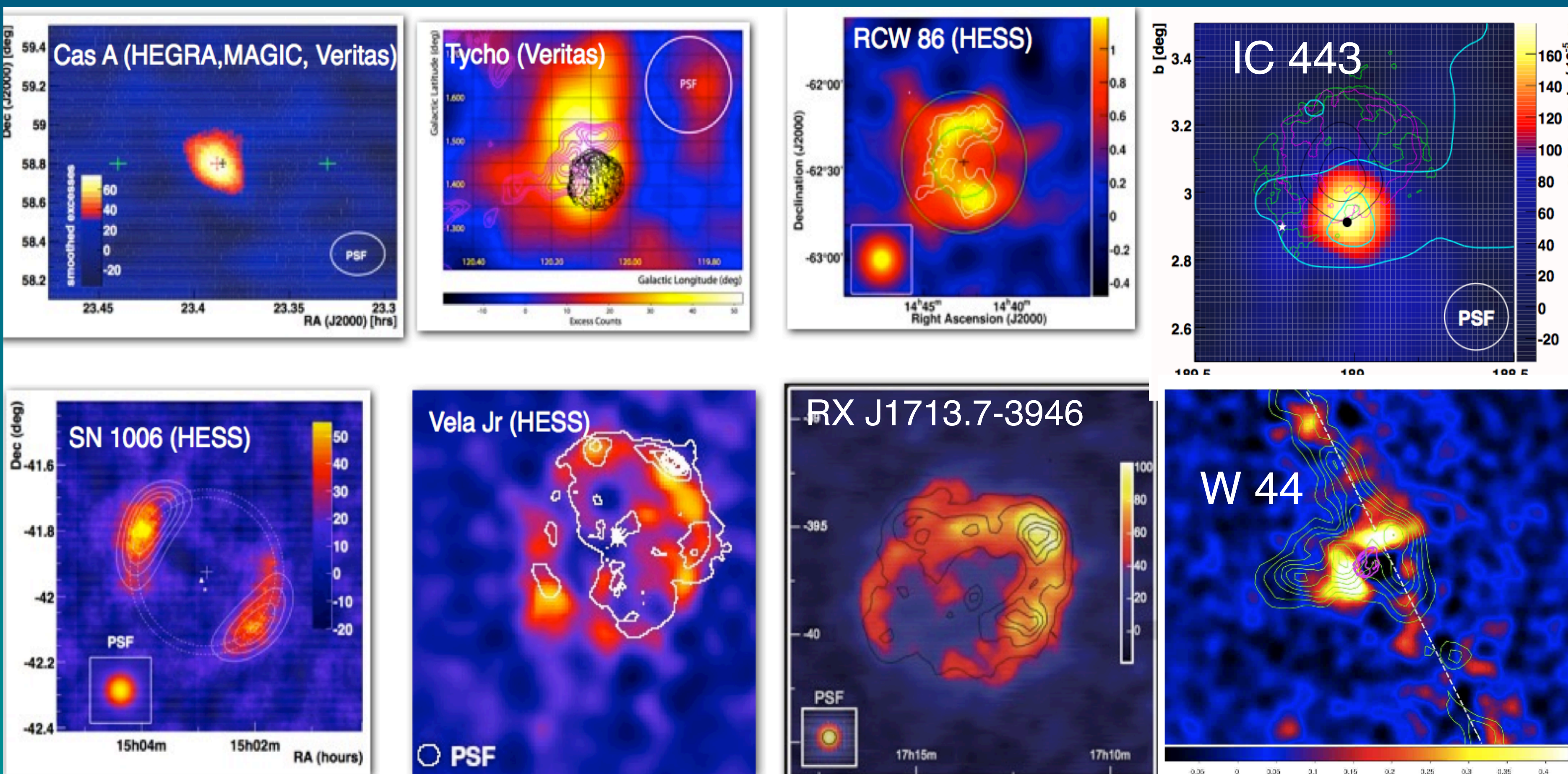
MAGIC



Fermi curve, Credits: Rolf Bueler for Fermi

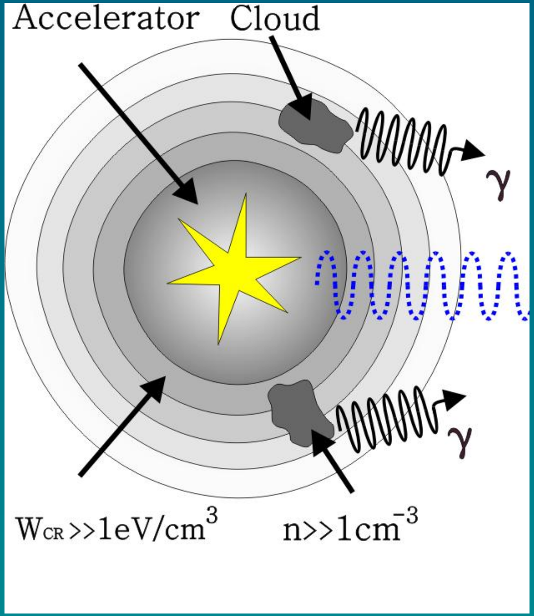
Supernova Remnants (SNRs)

- Considred as one the main site for production of CRs
- ~10 detected @ VHE γ-rays (some as extended sources



SNRs: Leptonic or hadronic origin?

- Leptonic: SSC model
  - Synchrotron emission by relativistic e^- accelerated in the shock wave
  - The same e^- population produc γ–rays via IC
  - γ-ray spectrum: $E^{-1,5}$
- Hadronic
  - Accelerated protons collide with clouds of interstellar material. π^0 are producd and they decay into γs
  - γ-ray spectrum: E^{-2}



Measuring their spectra at gamma-rays we could distinguish between models

SNRs: RX J1713.7-3946

X-Rays

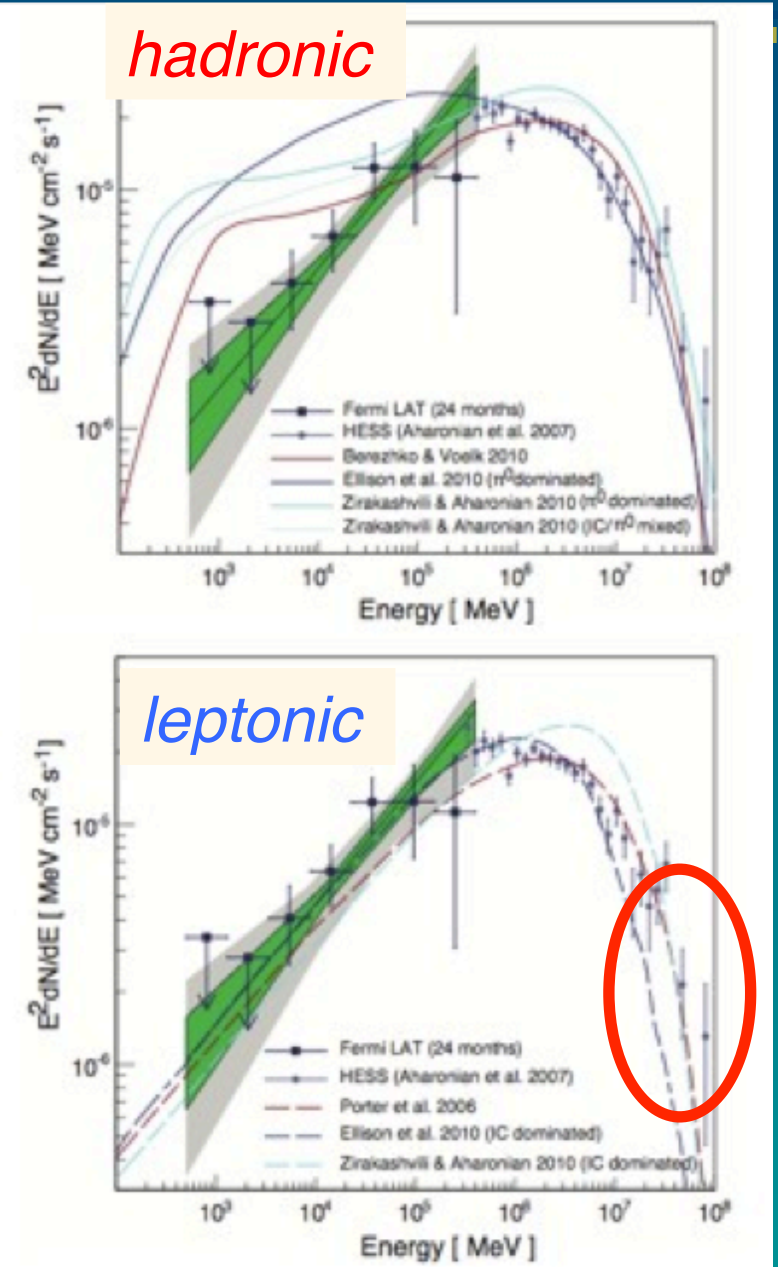
- Emission due to Synchrotron

TeV

- First resolved extended (~1°) source @ TeV
- Emission up to ~ 40TeV

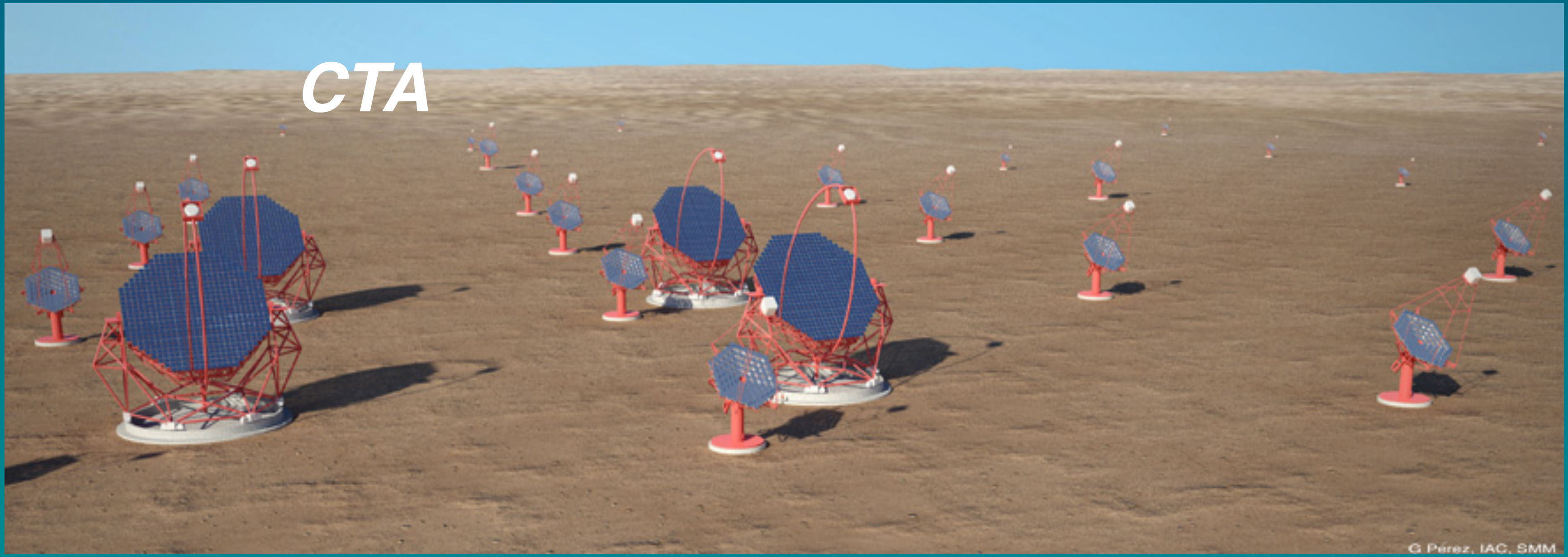
GeV

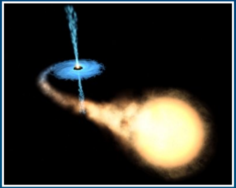
- Detected by Fermi
- First results suggested hadronic emission
- But latest results favors emission by IC, though leptonic scenario does not fiel well at TeVs



SNRs: Leptonic or hadronic origin?

- So far, the hadronic scenario has not been confirmed in SNRs (though last Fermi detections seem to favor it in some cases)
- The dilemma about the origin of CRs is still open…





Binary systems

Description: Systems of 2 stars

- The more massive evolves faster, giving rise to a:
  - **White dwarf** (WD)
  - **Neutron star** (NS) or **Black Hole** (BH)
- At the end we have a star orbiting around a compact object

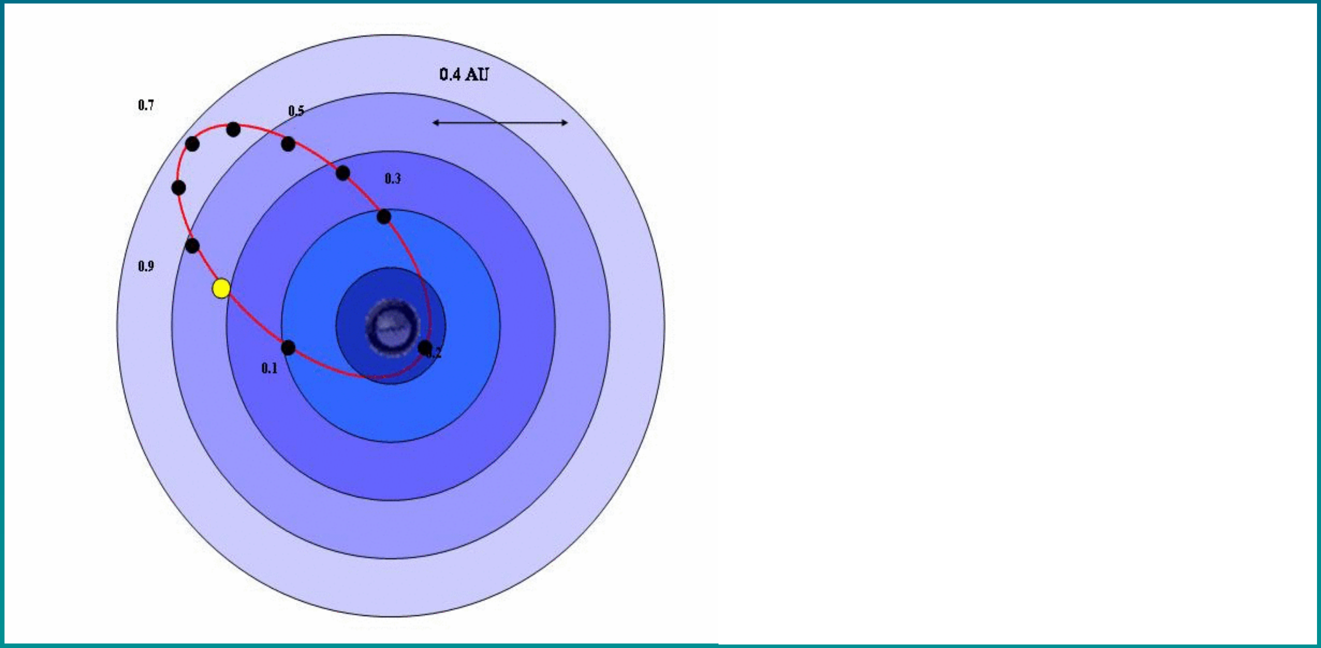
Types:

- Non-accreting binaries

  Emission from interaction with:
  - *Pulsar winds*
  - *Stellar winds of massive stars*
- Accreting binaries
  - *X-ray binaries*
  - *Microquasars with jets*

Non-accreting binary: LSI+61 303

- High mass x-ray binary system at 2 kpc., composed by:
  - Be star (13 $M_\odot$) around
  - unknown compact object (neutron start, BH?)
- TeV emission detected by MAGIC
  - only seen at some orbital phases (over a quarter of the orbit), when the compact object is far away from the stellar disc.



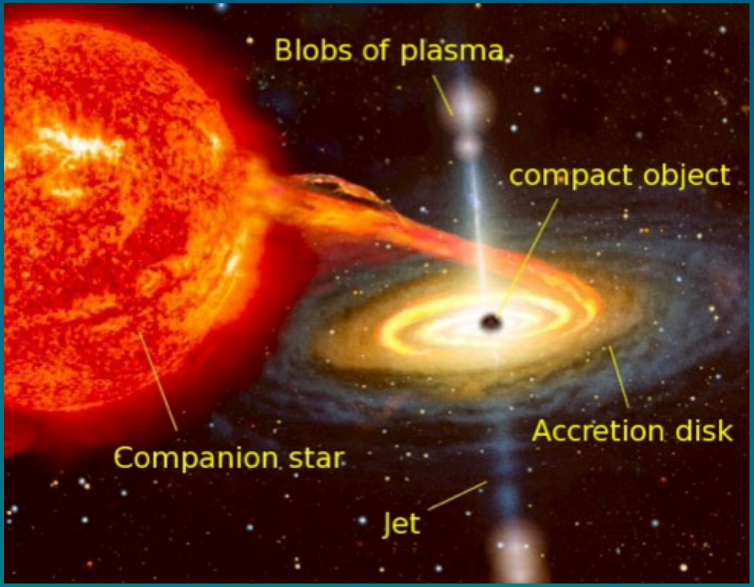
Accreting binaries: Microquasars

Composition

Star orbiting around a BH, NS, with accretion disk and jet

Emission mechanisms

- Synchrotron radiation by e- accelerated in the jet
- γ–rays via IC of stellar photons with the accelerated particles

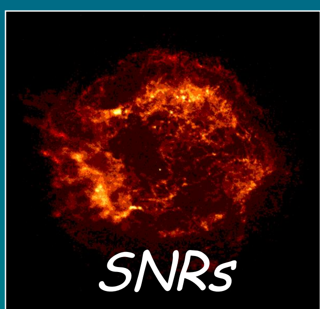


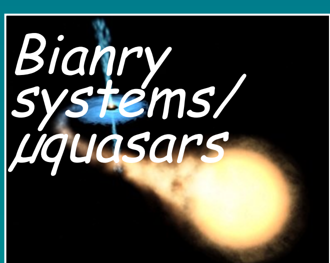
Microquasars @ VHE ?

- 15 microquasars known in X-rays
- Some detected @ GeV during flares
- But none yet detected at TeVs

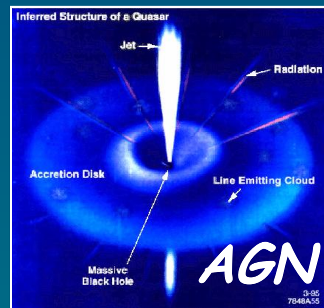
Sources of γ-rays

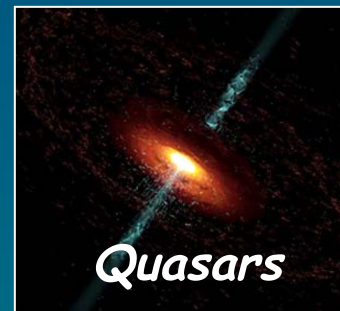
Galactic

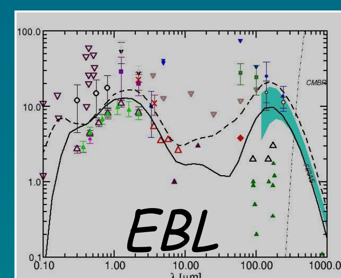


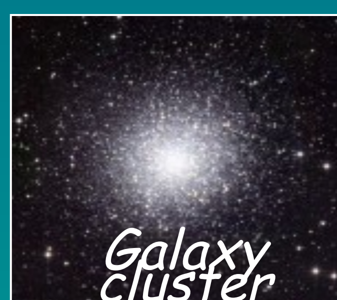


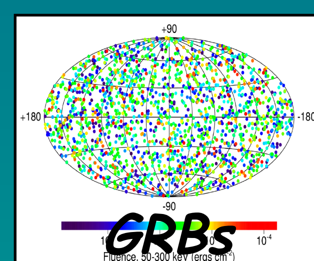
Extragalactic



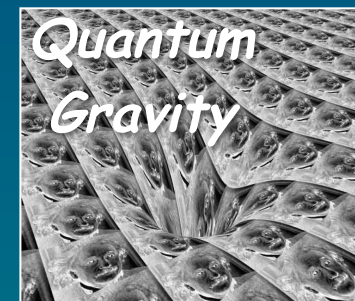


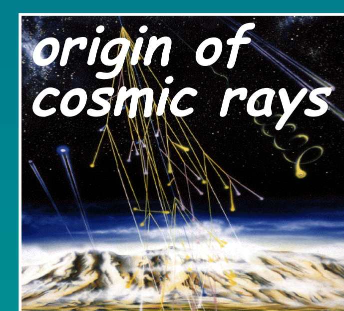






Fundamental Physics





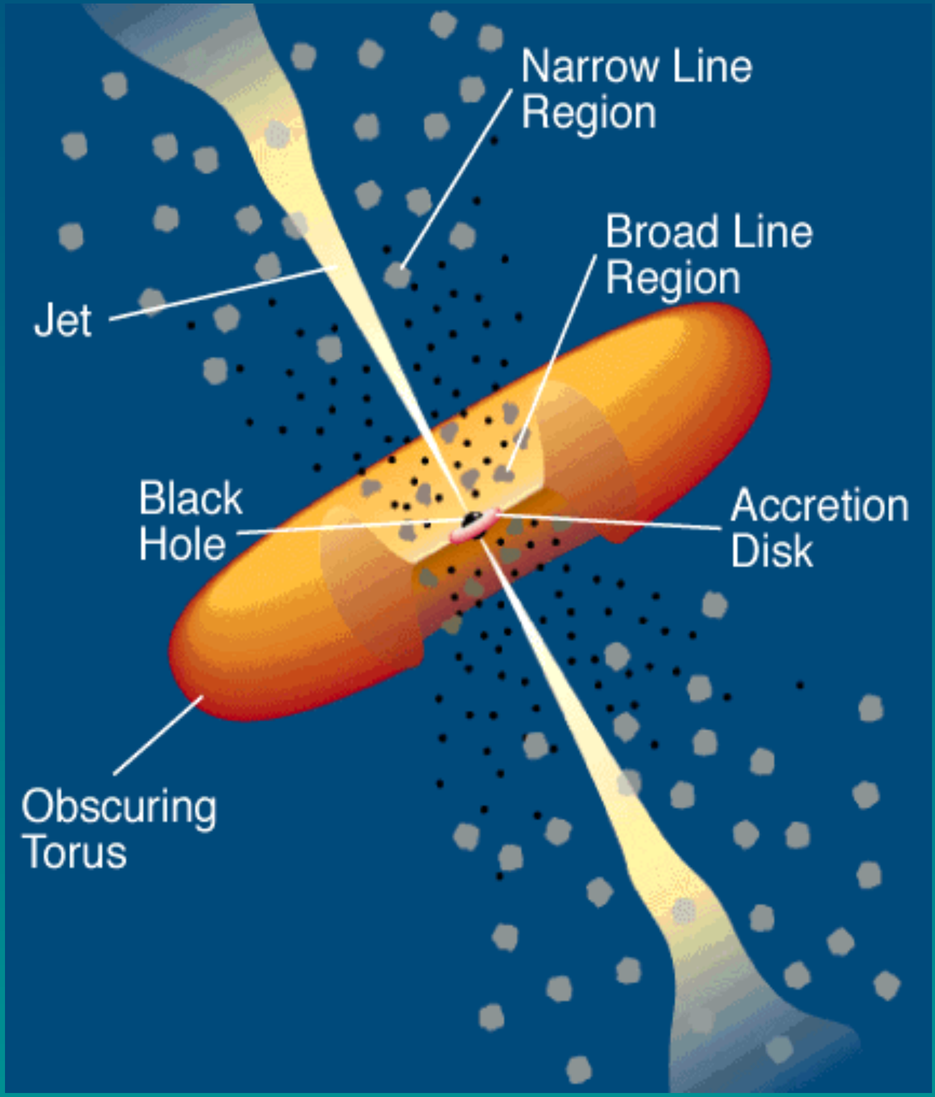
Active Galactic Nuclei (AGNs)

- ***Blazars***
- ***Quasars***
- ***Radio galaxies***

Active Galactic Nuclei

Composition

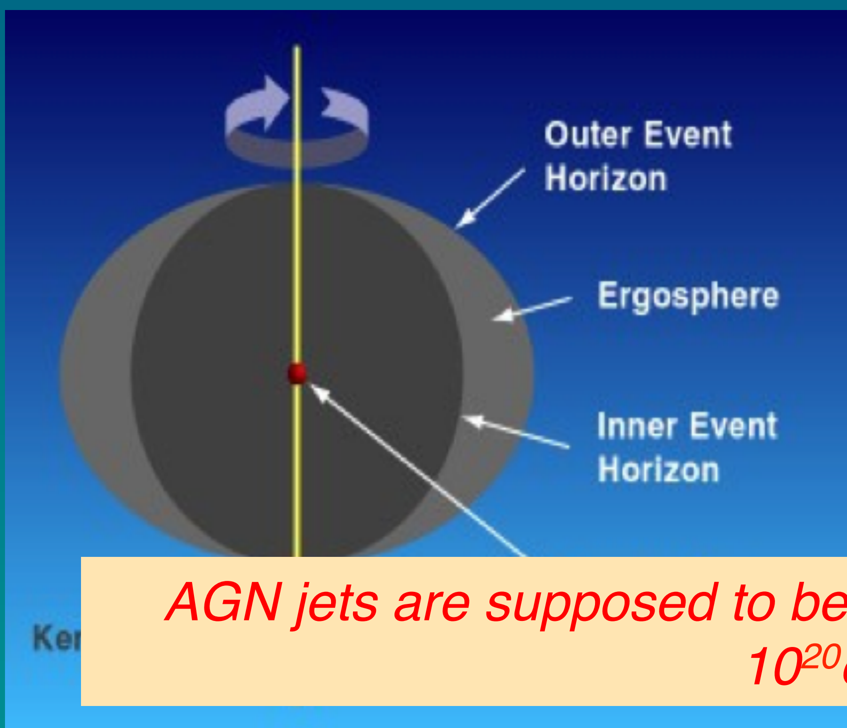
- Supermassive black hole ($>10^7 M_\odot$) in the galactic center
- Accretion
  - dust clouds and torus orbiting around the BH
- Relativistic jets emanating from the BH
  - Jet formation not yet understood

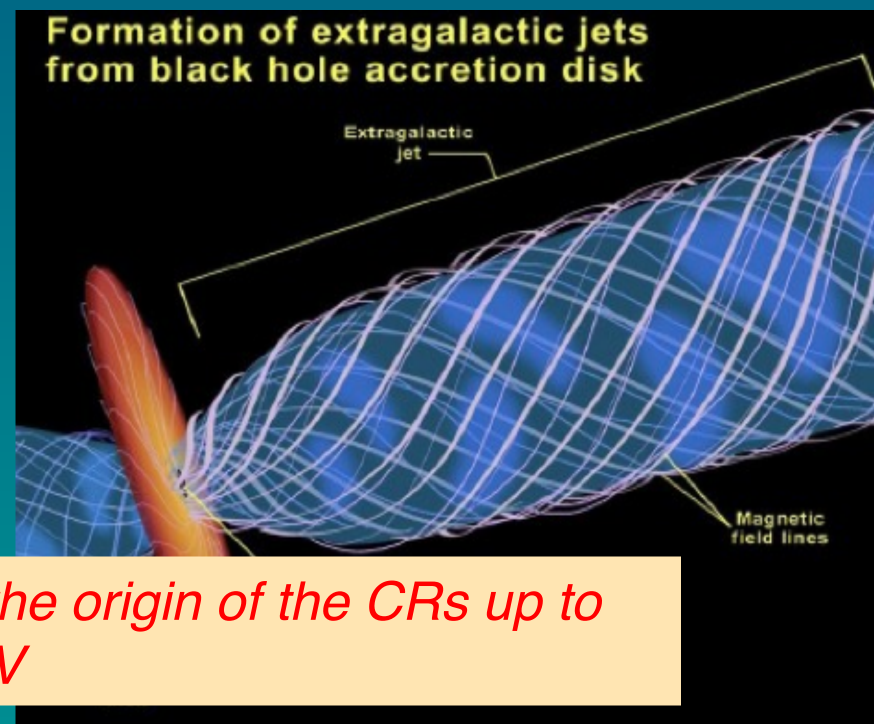


Active Galactic Nuclei

Jet formation theories

- Due to the BH rotation
  Blandford-Znajek (1977)
- Formed by the accreation disk
  Blandford-Payne (1982)

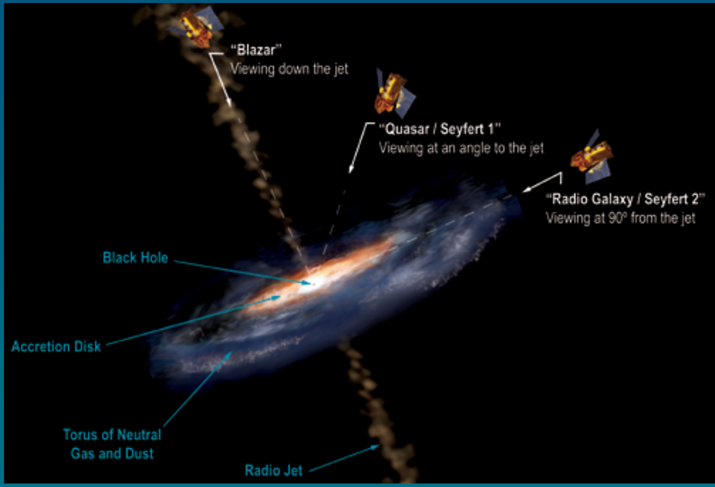




AGN jets are supposed to be the origin of the CRs up to 10^{20}eV

Types of AGNs seen in γ-rays

- The AGNs seen in γ-rays belong to 3 classes:
  - Blazars. With two sub-categories:
    - BL Lacs
    - Flat-Spectrum Radio Quasars
  - Radio galaxies

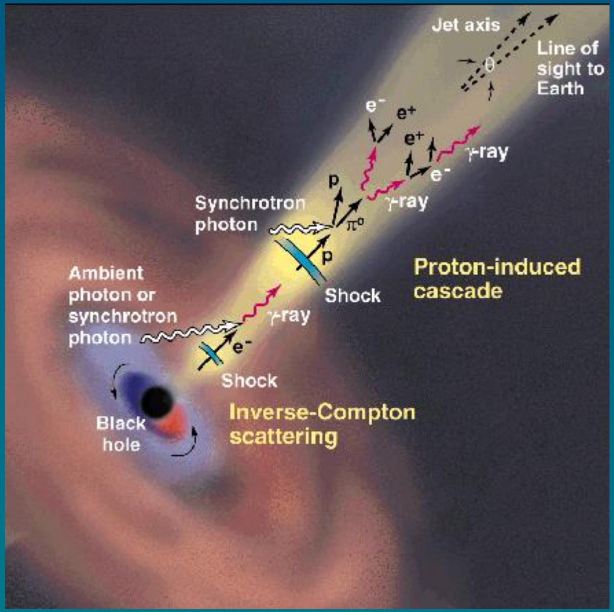


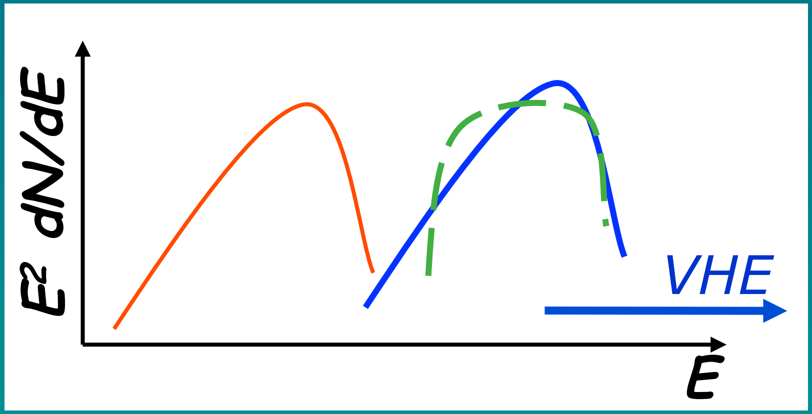
Blazars

- Most of the detected AGNs in γ-rays are Blazars
- But blazars are very rare among AGNs (only ~1%)
- The sample is biased due to the effect of the Doppler boosting in the direction of the jet:
  - Large apparent luminosity ➔the measured flux is higher than the emitted one

AGNs: Emission models in γ-rays

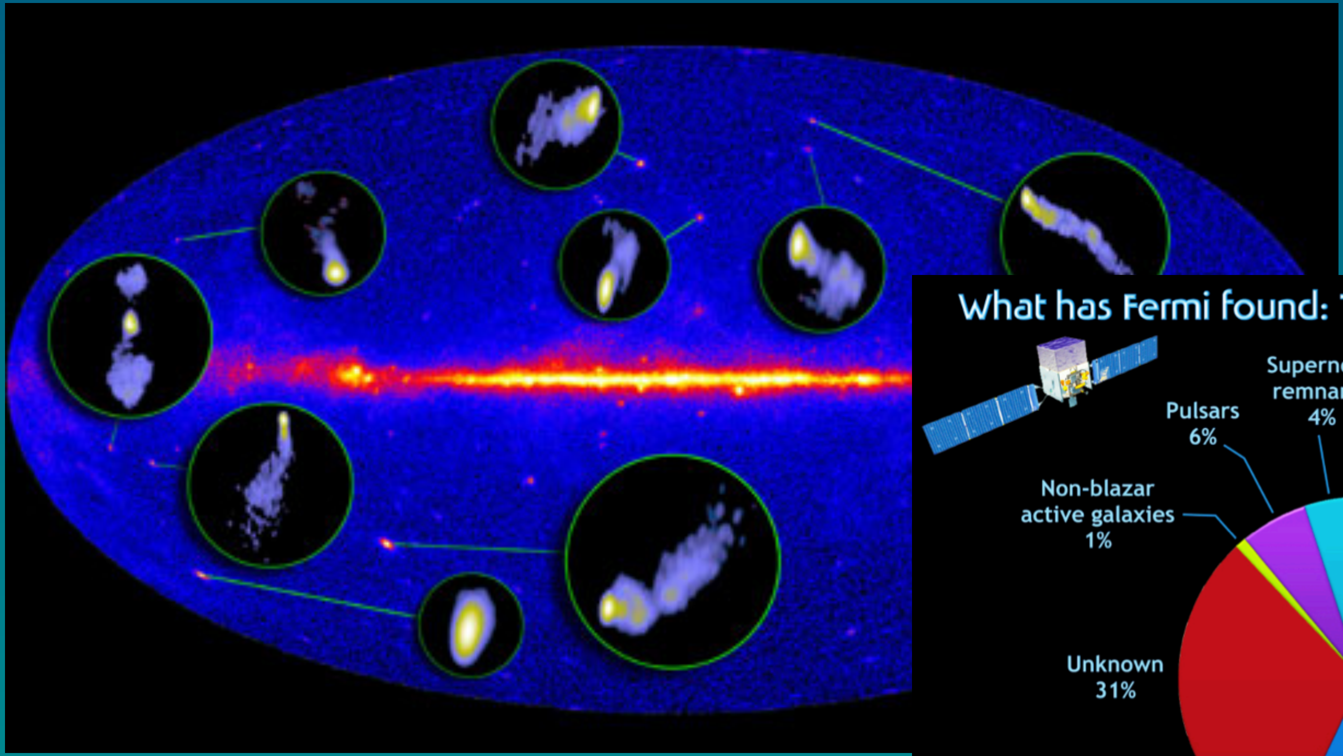
- Leptonic ➔SSC model
  - Produces spectra with 2 peaks:
    - Synchrotron peak (X-rays)
    - IC peak (γ-rays)
- Hadronic
  - Also produces spectra with 2 peaks, but in this case the γ peak due to π^0 decay

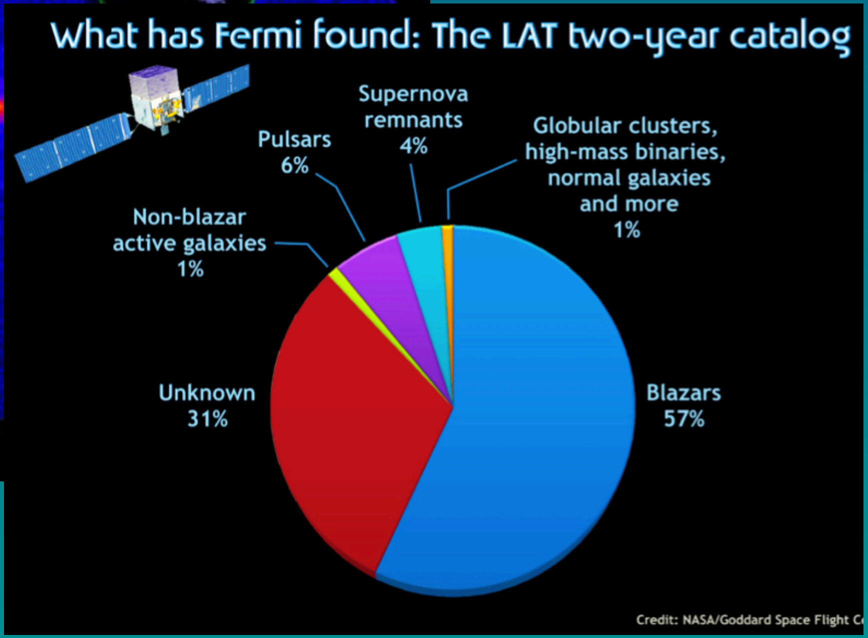




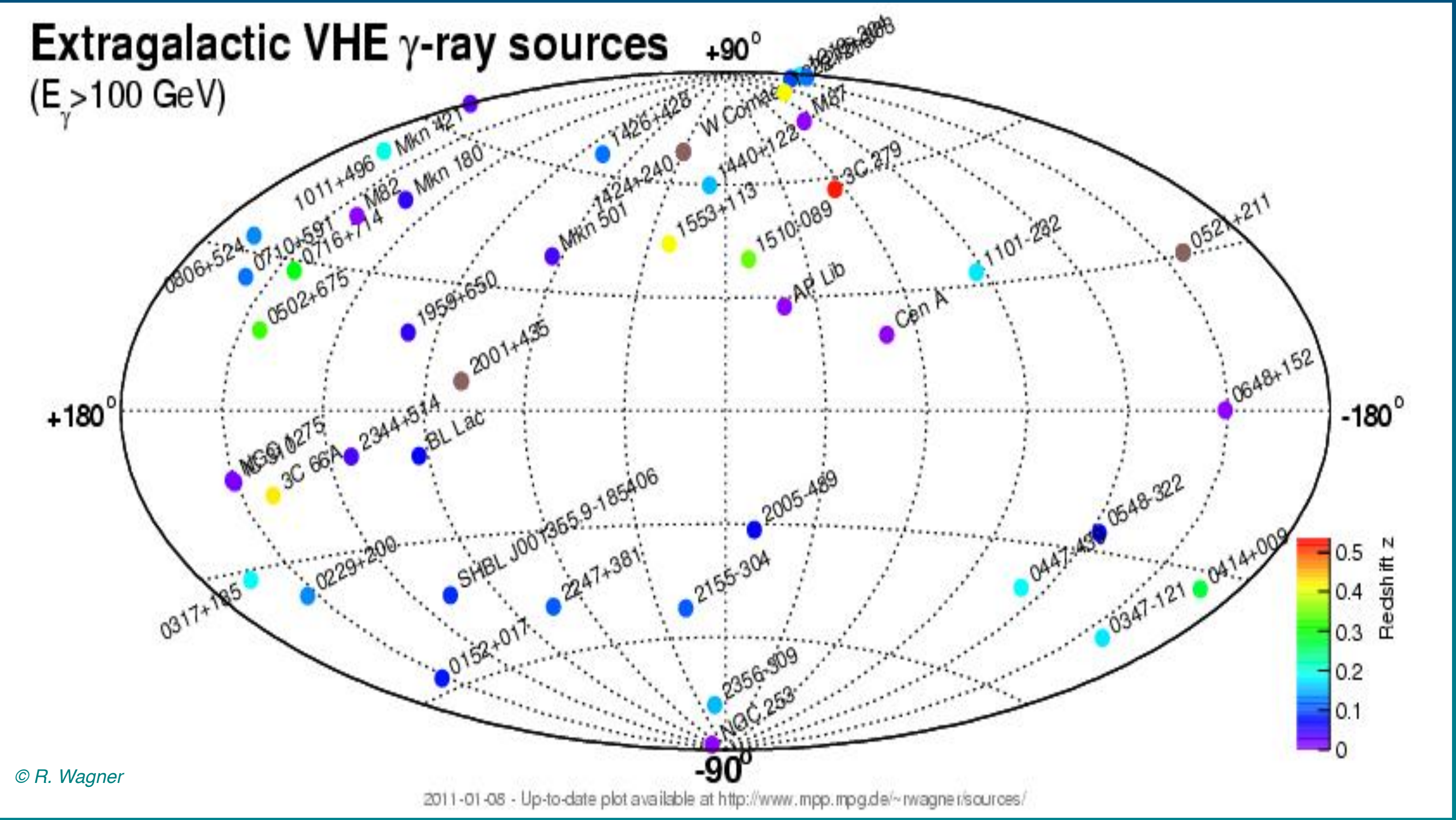
AGNs: Observations from space

- Fermi has detected >1000 AGNs
- Most of them are blazars





Extragalactic observations from ground

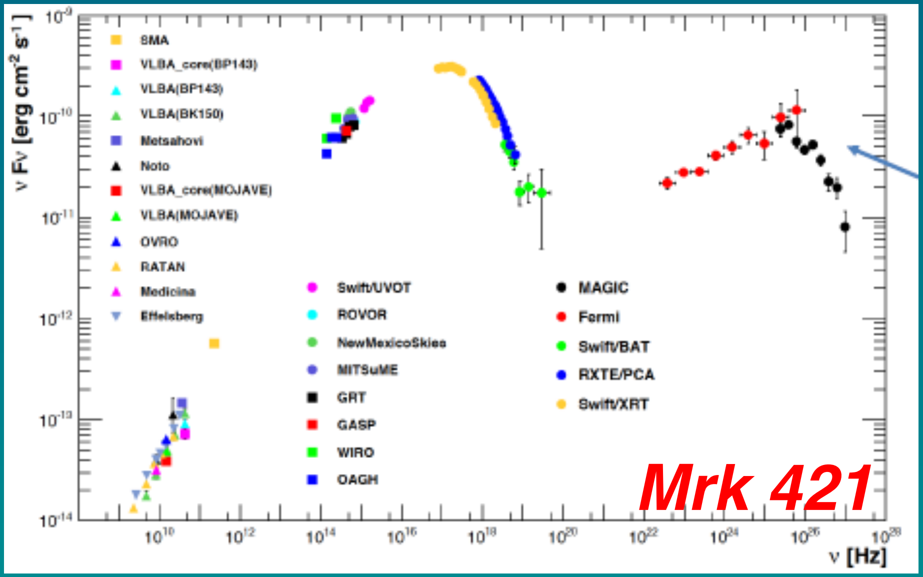


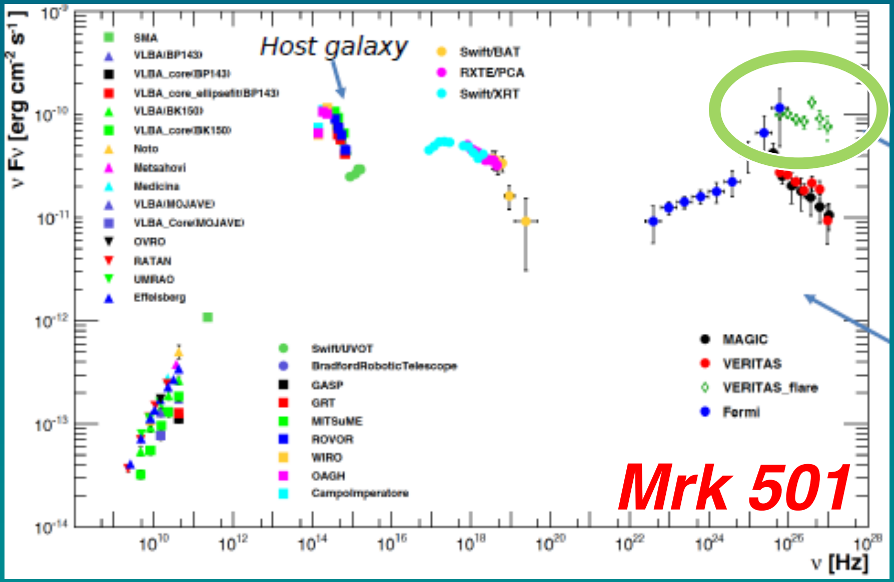
- **Currently > 50 sources (first discovered in 1992)**
- **most of them blazars**

Blazars / Bl Lacs: Mrk 421 & Mrk 501

- They were the first extragalactc TeV sources detected
- Multi-wavelength observations, involving many instruments, are needed to generate detailed SEDs of sources.

A 3 day flare



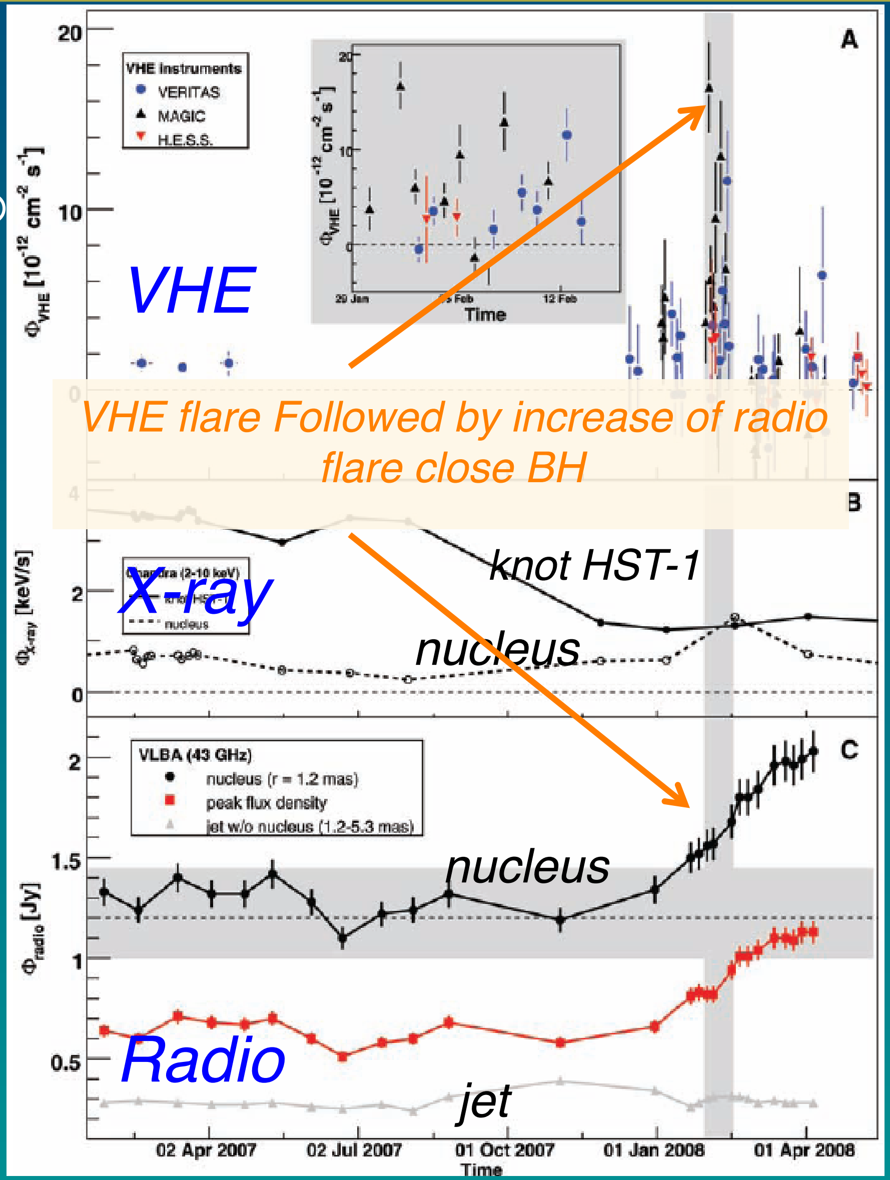


Radio galaxies: M87

- Radio galaxy with super massive black hole ~ 6·10^9 M$_\odot$ at ~16Mpc
- Jet structure with knots, sometimes brighter than nucleus

MWL campaign in 2008

- Discovered a VHE flare:
  - Fast (day-scale) variability
  - Correlated TeV flare with radio & X-rays
  - VHE emission originates very close to central BH



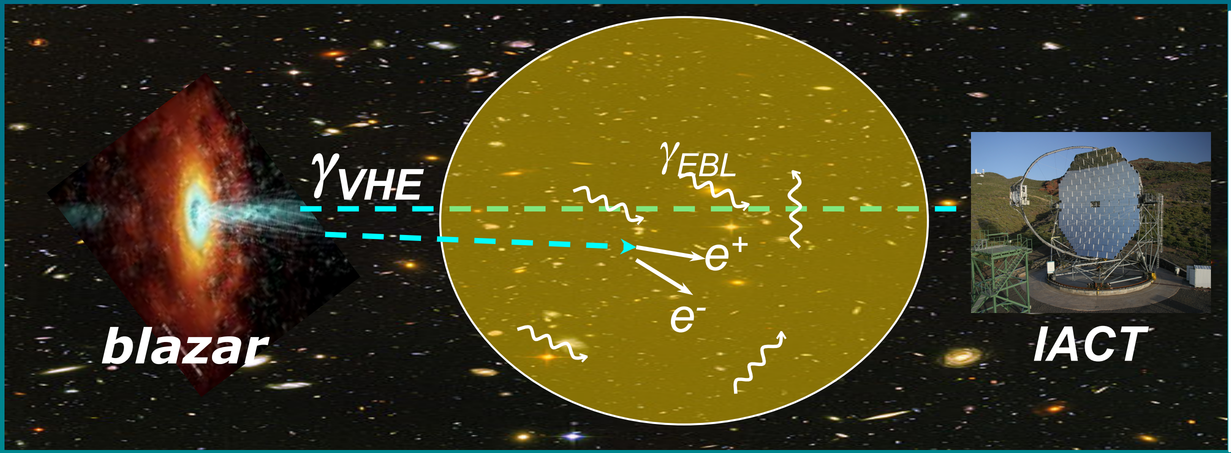
Absorption of γ-rays & the γ-ray horizon

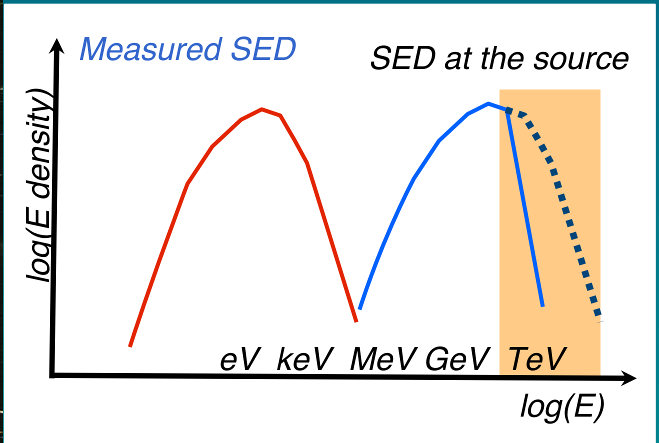
- γ-rays travelling long distances interact with the background photons of the EBL, producing e+/- pair.

$$\gamma_{HE}\,\gamma_{EBL} \rightarrow e^{+}\,e^{-}$$

EBL: Light emitted during formation and evolution of galaxies

- Essential for understanding the full energy balance of the Universe
- Direct measurement very difficult due to strong foreground





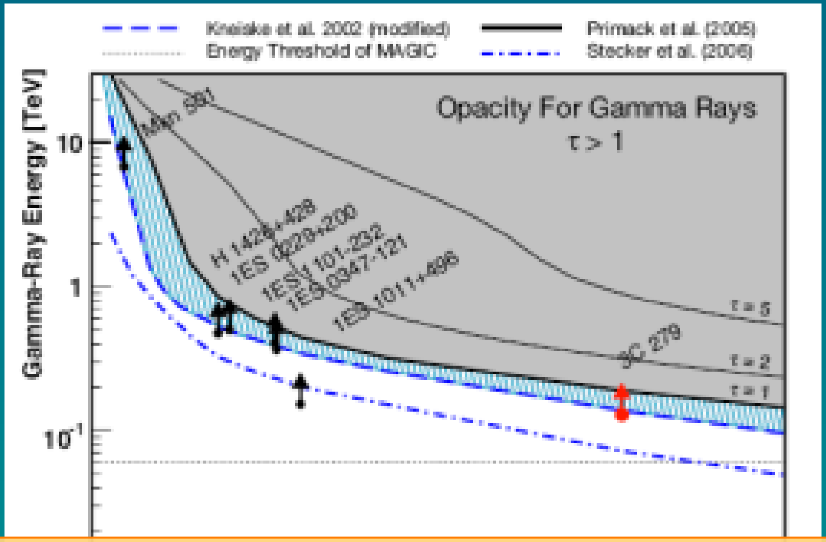
Measured spectrum differs from the emitted one

If we know source distant & intrinsic spectrum, we can constrain the EBL

Limits on the Extragalactic Background Light

MAGIC results with Quasar 3C 279 (z=0.54)

- A intense flare detected in 2006
- Spectrum follows a Power law Γ=- 4.11+/-0.68
- Assuming a reasonable index for the intrinsic spectrum one gets an Upper limit to the EBL close to lower limit from galaxy count
  - Ruled out the most accepted model so far

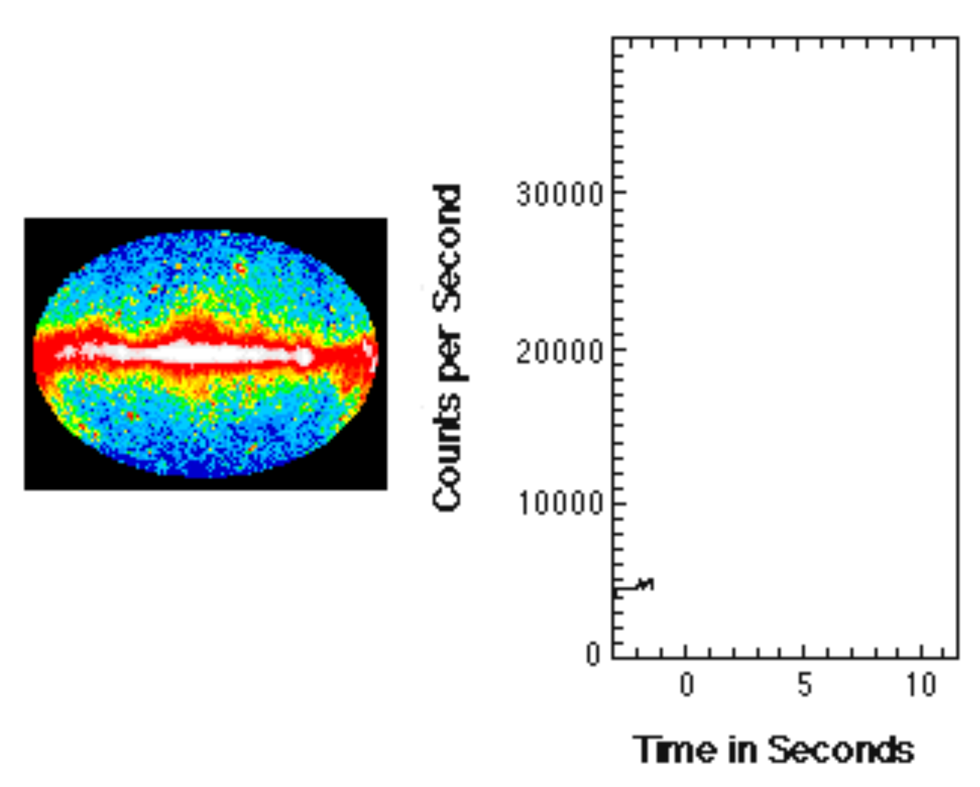


The Universe appears more transparent at cosmological distances than previously believed

Gamma-Ray Bursts

What are they?

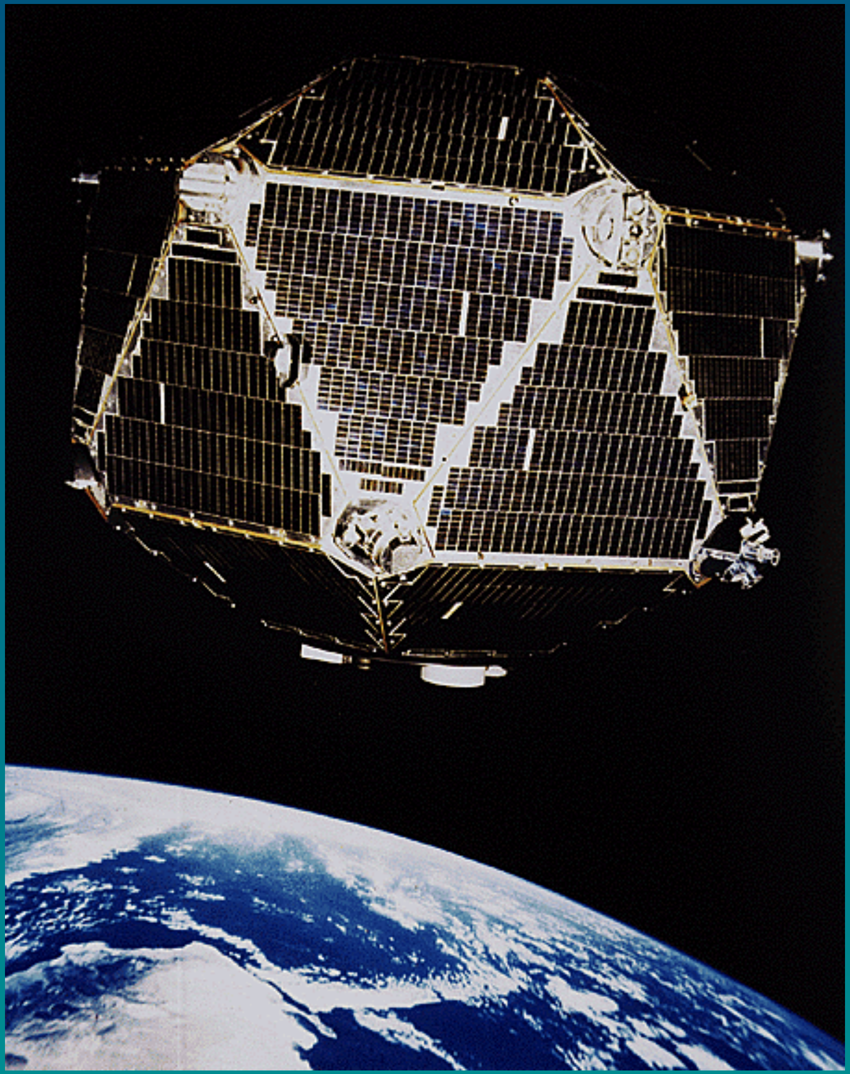
- Flashes of γ-rays occurring ~3 times per day at any position in the sky
- The released energy (~10^{53}erg=10^{7}J) is such that they often outshine all the other γ-ray sources



Gamma-Ray Bursts

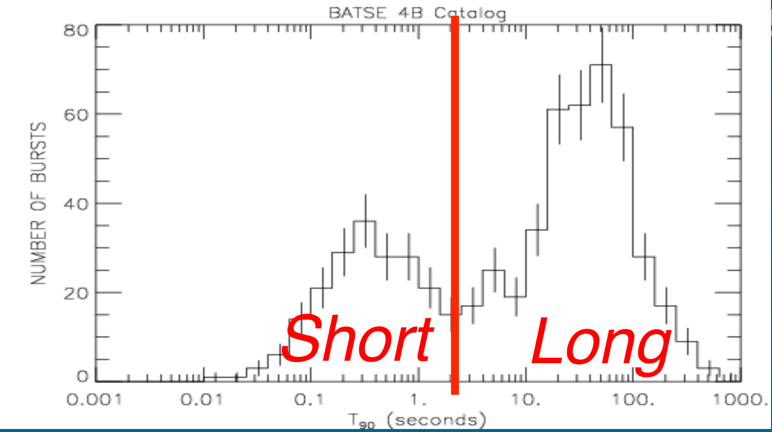
Discovery

- In the 60's, the U.S Vela satellites detected energetic flashes of γ-rays in the sky
  - The americans thought that they were caused by secret soviets atomic bombs tests

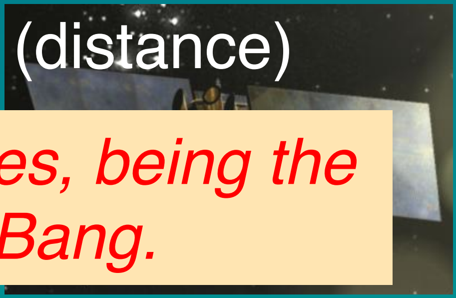


GRBs: The mystery about their origin

- Duration: two classes:
  - Short: 1ms - 2s
  - Long: 2s – 0.5h



- Location
  - First theories assumed nearby sources as galactic neutron stars ➔ GRBs should be distributed along galactic plane
  - But In the early 90's, BATSE detected that they were randomly distributed in the sky ➔ Extragalactic events
  - In the late 90's, Beppo-Sax led to the discovery counterparts and afterglows at other wavelengths
    - ➔ This allowed to measure their redshift (distance)

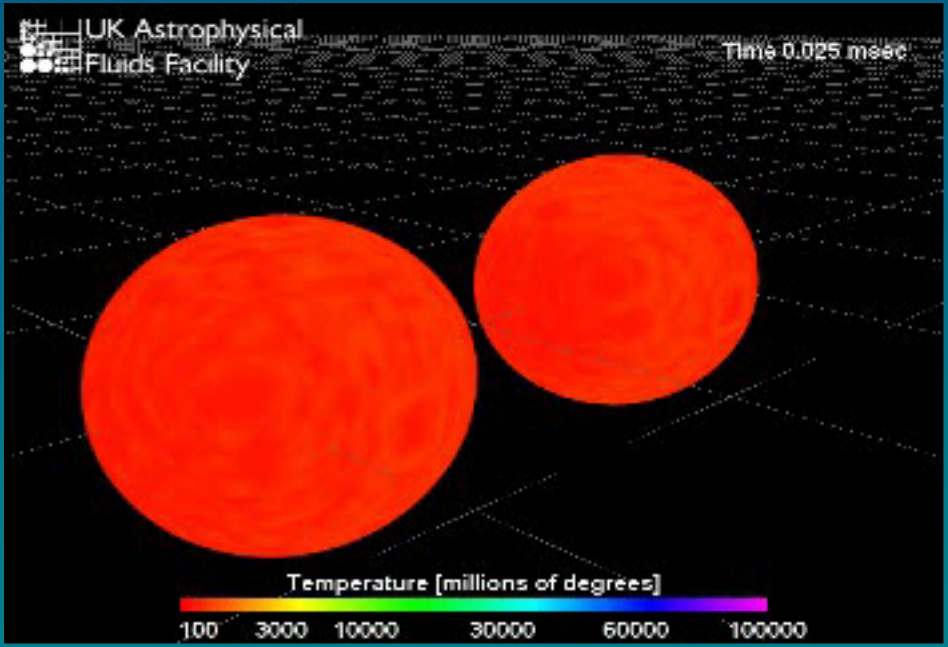


GRBs were located at cosmological distances, being the more energetic events since the Big Bang.

GRBs: Progenitors

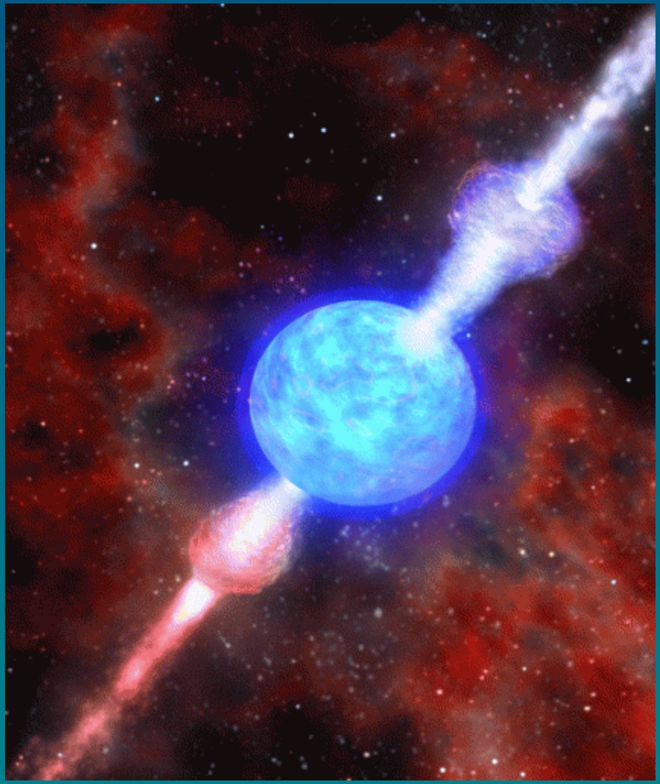
Short and long GRBs would have caused by different events

- Shorts: Merging of 2 neutron stars
  - The merging forms a massimve Black Hole
  - A Jet emerges from the BH
  - The GRB would be originated in the jet
  - Strong gravitational waves will be emitted as well



GRBs: Progenitors

Short and long GRBs would have caused by different events



- Shorts: Merging of 2 neutron stars
  - The merging forms a massimve Black Hole
  - A Jet emerges from the BH
  - The GRB would be originated in the jet
  - Strong gravitational waves will be emitted as well
- Longs: Hipernovae
  - Dead of a supermassive star ($M>40M_{\odot}$)
  - A jet of relativistic plasma emerges, which will originate the GRB

GRBs: Models

Independently of the progenitor, the favorite model is the “Fireball model”

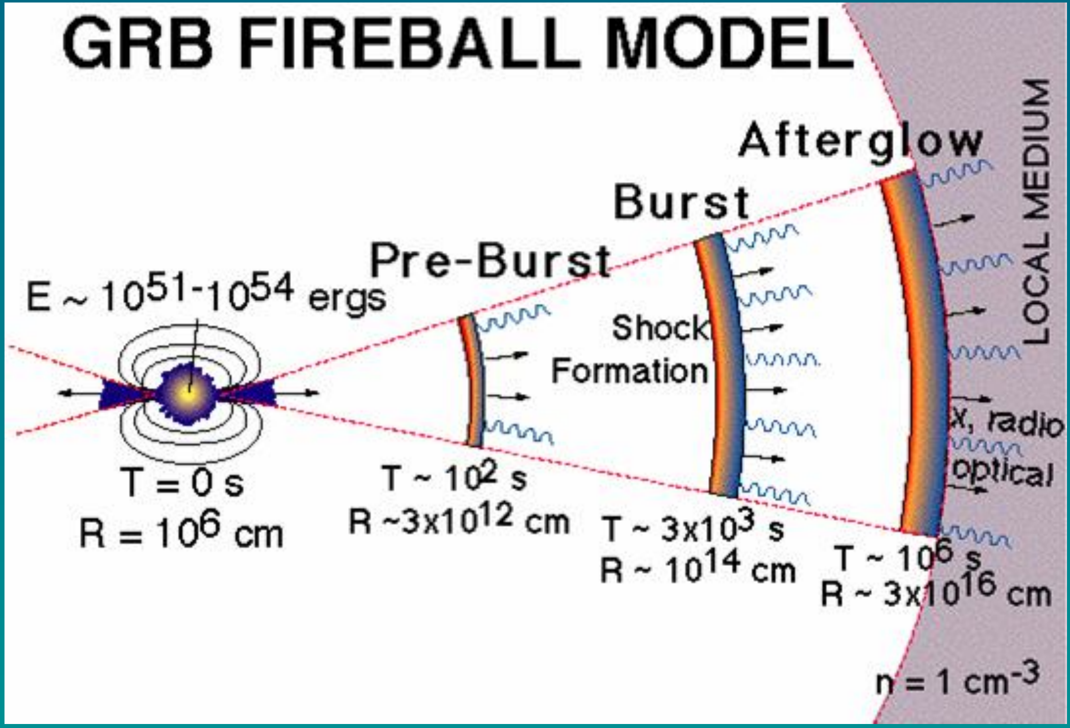
- **Jets** of relativistic particles ($\Gamma \sim 10^2 - 10^3$) are created
- These jets are the origin of the detected emission:

Burst

- Inner collisions between different shock waves
- X- and γ-ray emission

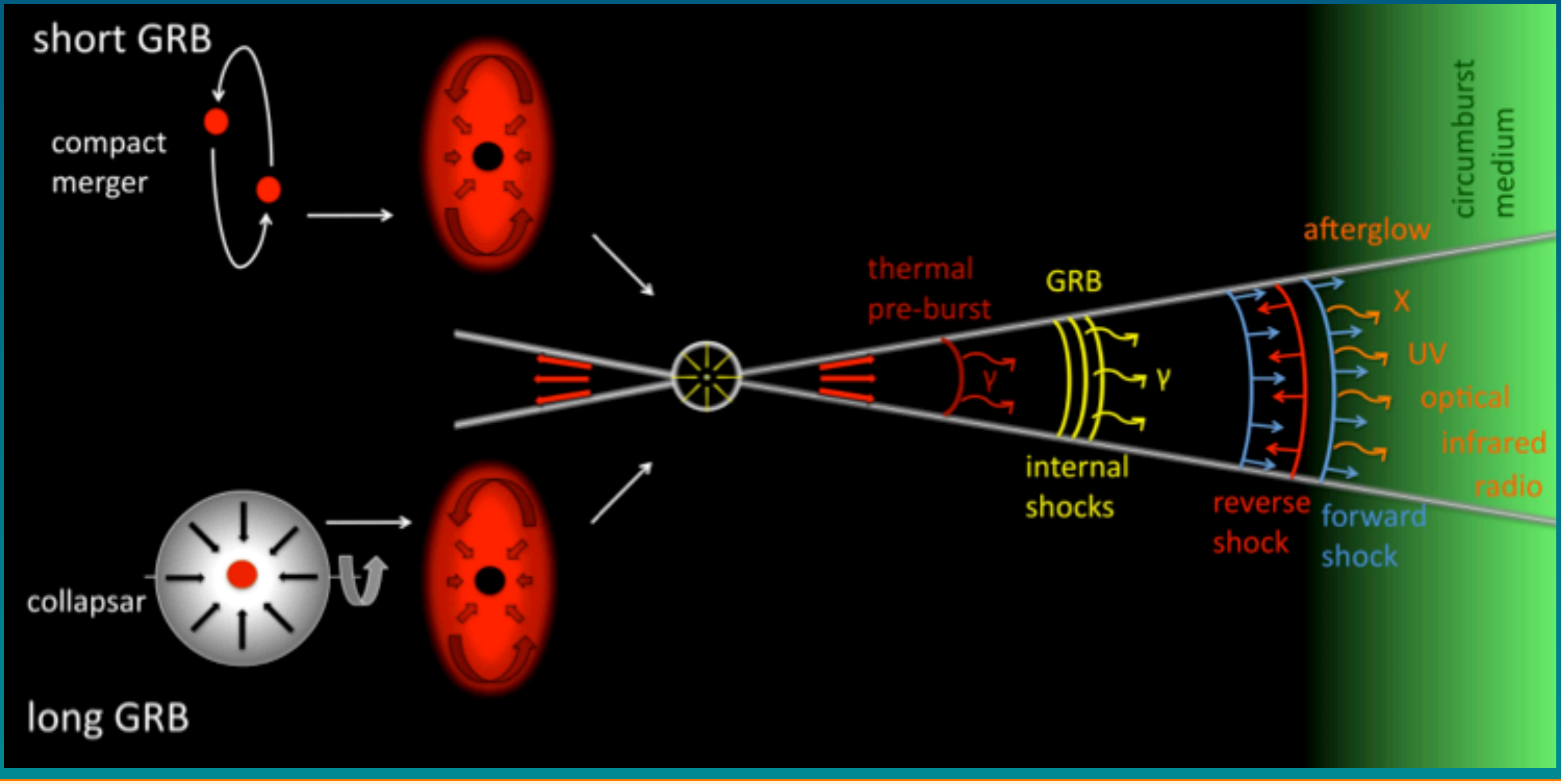
Afterglows

- Outer collisions with the interstellar medium
- Radio,optical and X-ray emission



GRBs: Models

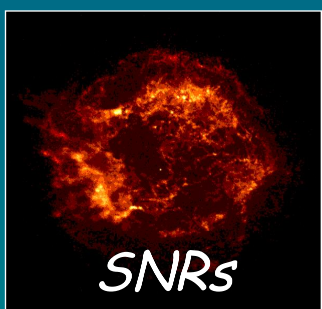
Summarising: In both caes (short,long) a jet is form where particles are accelerated

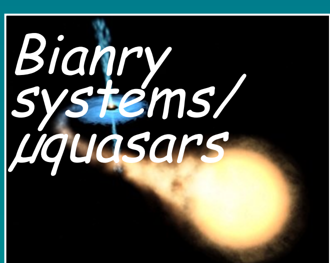


Only when the jet points towards us we can see the emission (in spite of the long distances) thanks to the Doppler Bossting.

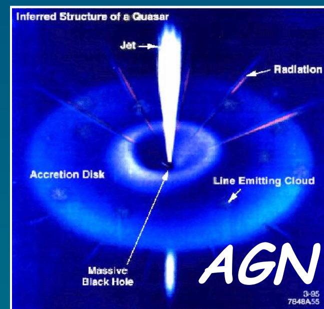
Sources of γ-rays

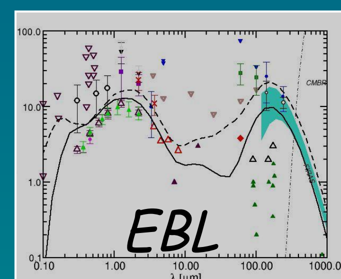
Galactic

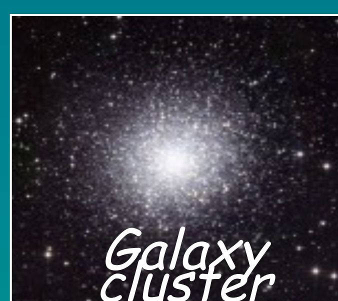


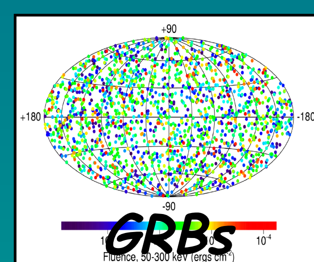


Extragalactic

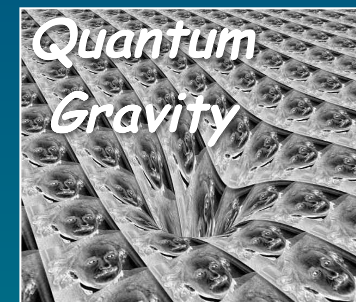


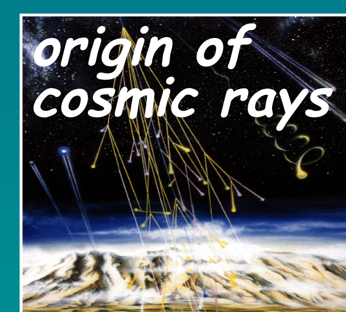


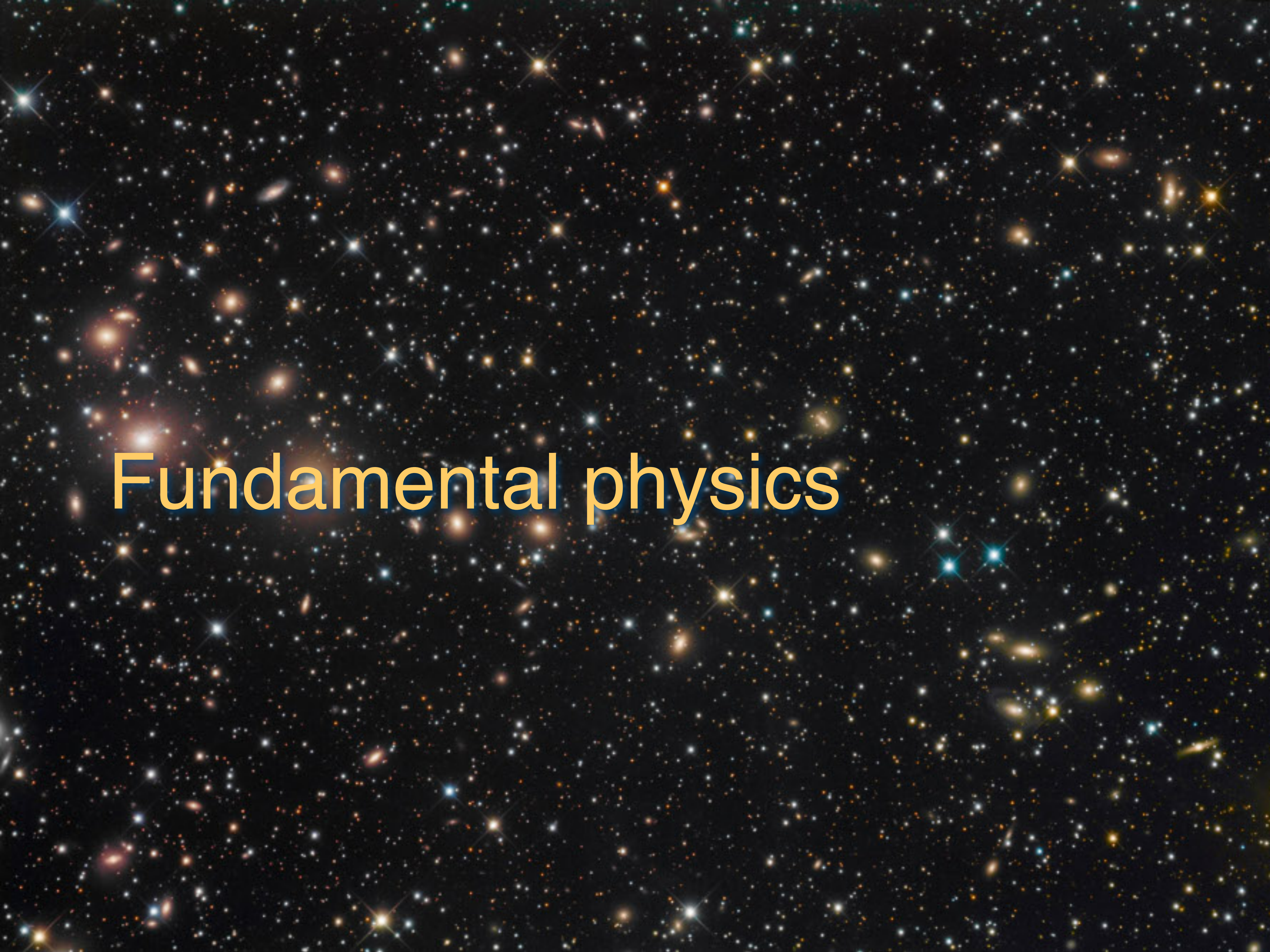




Fundamental Physics







Fundamental physics

Quantum gravity

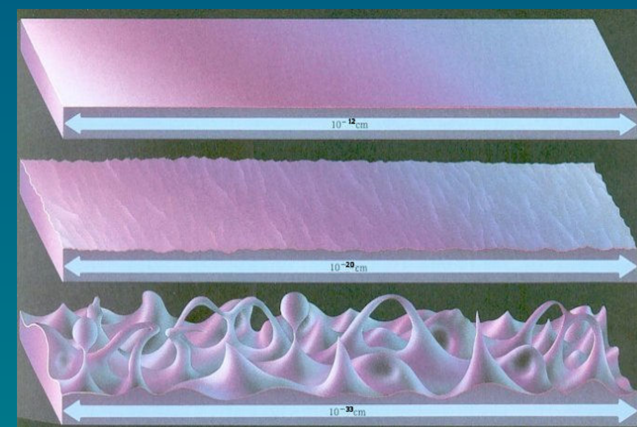
γ–rays allow us to investigate the space-time structure

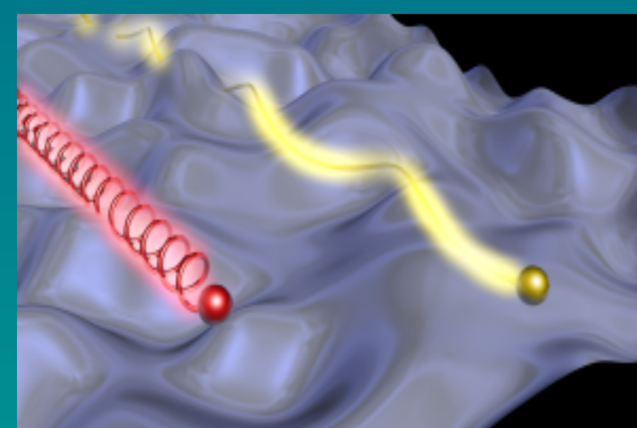
Quantum gravity and speed of light

- QC theories predict foamy space-time structure at low scales
- This would cause a dependency of the speed of light ***c*** with the photon energy:

$$\boldsymbol{c = c(E\gamma)}$$

  – High energy photons (small λ) would 'feel' more the foamy space-time structure and would travel slower than low energy ones





Quantum gravity

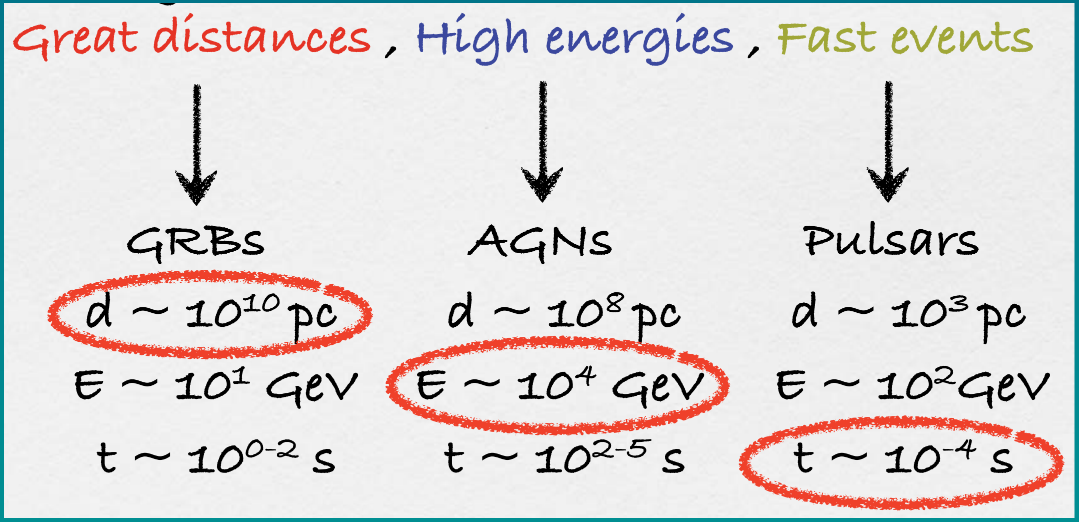
- Lorentz Invariance Violation (LIV):

$$c' = c\left[1 - \frac{E}{M_{QG1}^{LIV}} - \frac{1}{2}\left(\frac{E}{M_{QG2}^{LIV}}\right)^2 - \ldots\right]$$

- Observational implications:
  - Two photons with energies E_l, E_h, emitted simultaneously would be detected with a delay Δt:

$$\Delta t \approx \left(\frac{E_h - E_l}{M_{QG1}^{LIV}}\right)\frac{d}{c}$$

- We need:



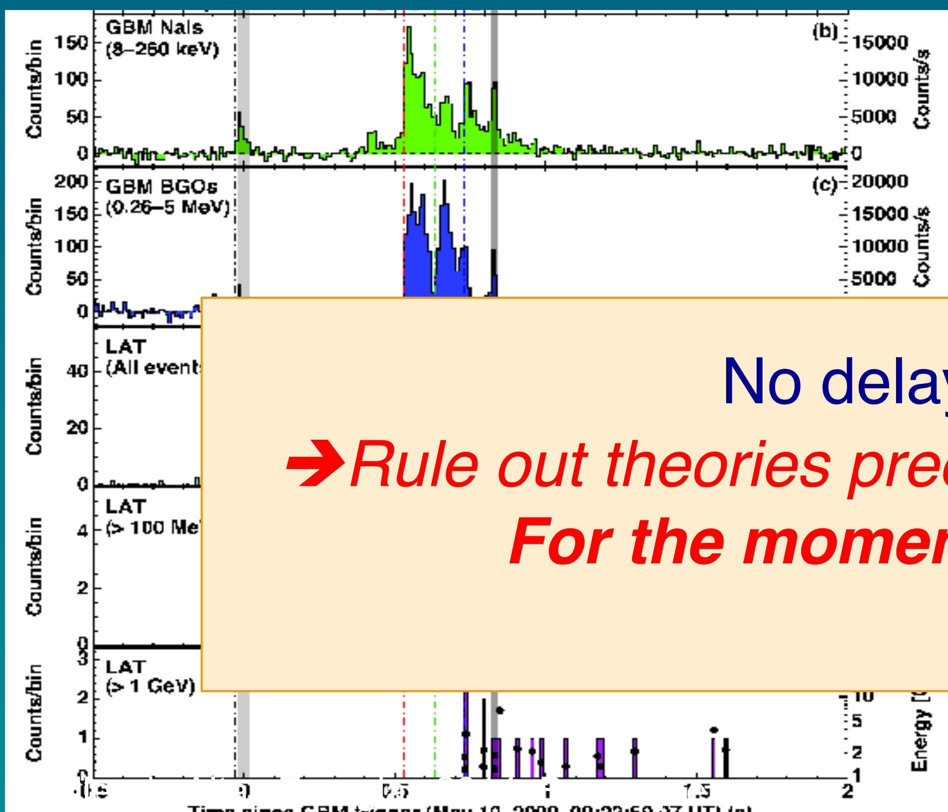
Quantum gravity

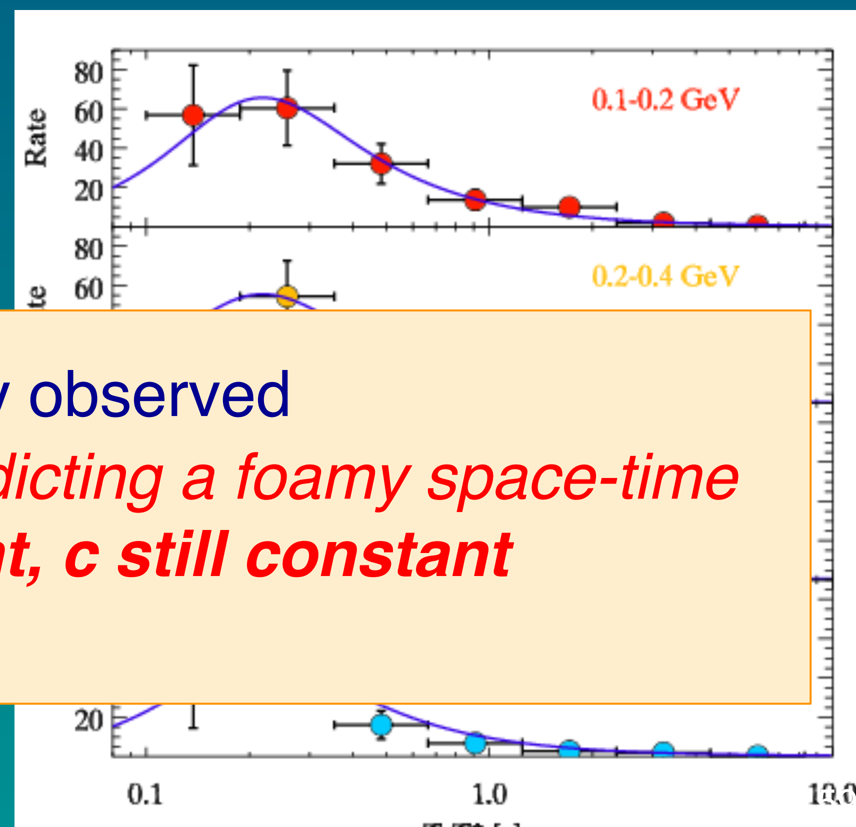
Limits from GRB's

In 2009 Fermi detected an extraordinary GRB, GRB090510:

- Very far away: d ~ 10^9 pc (~ $7 \cdot 10^9$ light-years)
- Photons up to 40 GeV

$M_{QG1} > 1.5 \cdot 10^{19}$ GeV

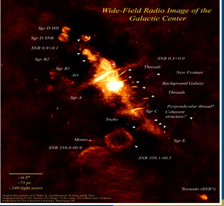




No delay observed

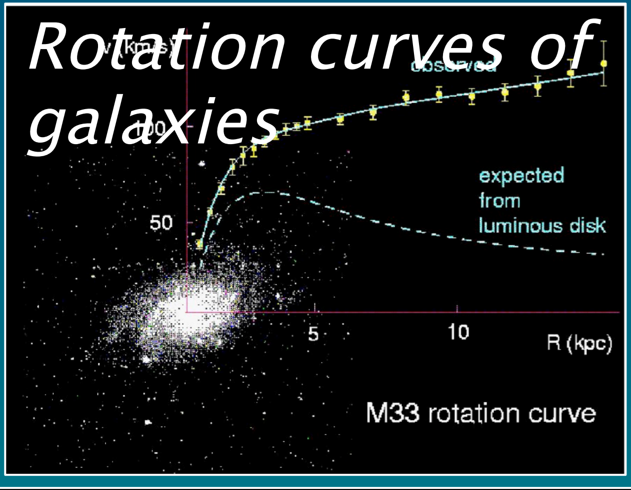
➔*Rule out theories predicting a foamy space-time*

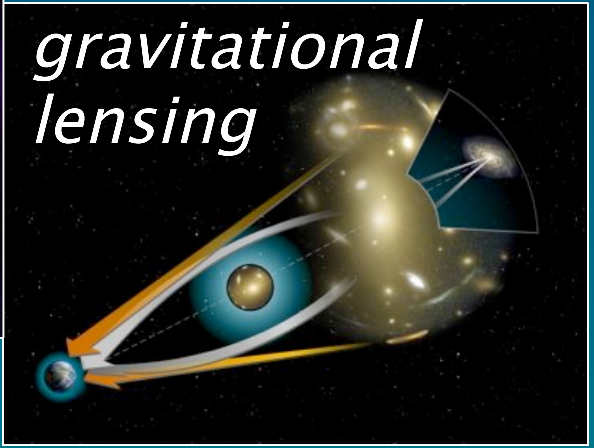
For the moment, c still constant

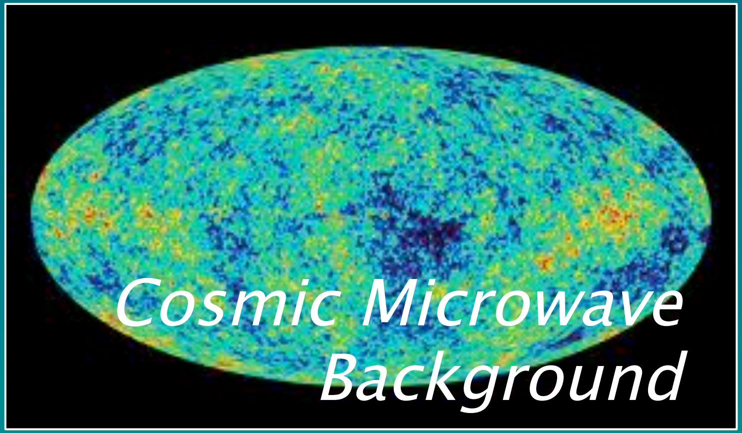


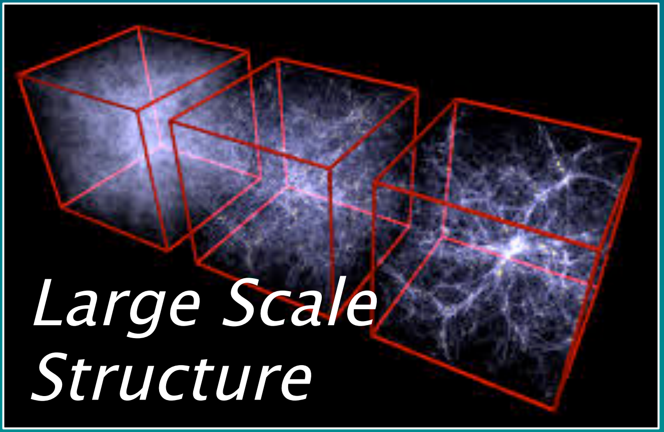
Indirect Dark Matter searches

Evidences for DM





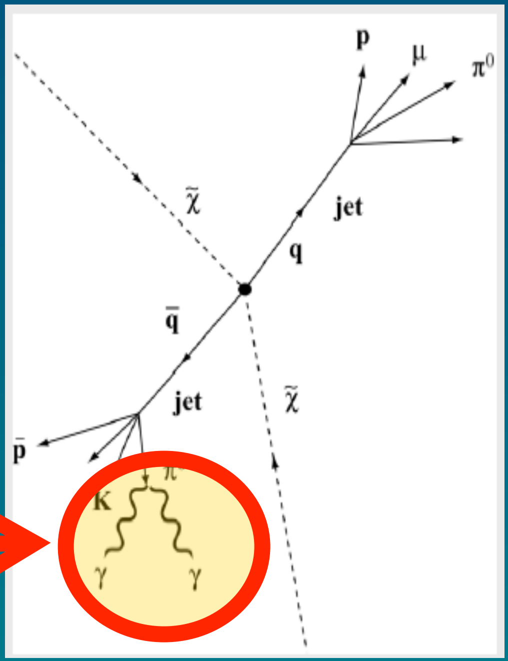




Indirect Dark Matter searches

Candidate particles

- The DM must be:
  - Massive (acts gravitationally)
  - Stable (justify abundances)
  - Neutral in charge and colour (no X ray emission)
  - Maybe weakly interacting
  - Non baryonic (no candidate)



- **Neutralino** χ
  - Is one of the best candidates
  - Majorana particle: annihilates with itself
  - Severla annihilation channels. Can be groupped according with expected spectrum
    - Broad band: $\chi\chi \rightarrow WW,\ b\bar{b},\ \tau\tau \rightarrow \ldots \rightarrow \pi_0, jets \rightarrow \gamma\gamma$
    - Line emission: $\chi\chi \rightarrow \gamma\gamma$ $\chi\chi \rightarrow \gamma Z$

Indirect Dark Matter searches

DM annihilation/decay can produce VHE γ-rays

Where to search for?

- **Galactic center?**

  obscured by strong VHE γ-ray source

- **Other galaxies/galaxy clusters?** expec[ted] DM signal much smaller than that coming from CR interactions

→

MAGIC obsevations

Perseus cluster

No detection. Derived U.L.'s orders of magnitude above mSUGRA expectations

→ Needed significant increase in sensitivity to come close to model predictions

Summary

- Astroparticle Physics is a fascinating research field in blooming expansion
  - Tries to understand the most energetic phenomena in the Universe
- Many different research topics, from galactic to extragalactic sources and fundamental physics
- Number of detected sources rapidly increasing

  >2000 GeV sources detected from space

  >150 TeV sources discovered from ground