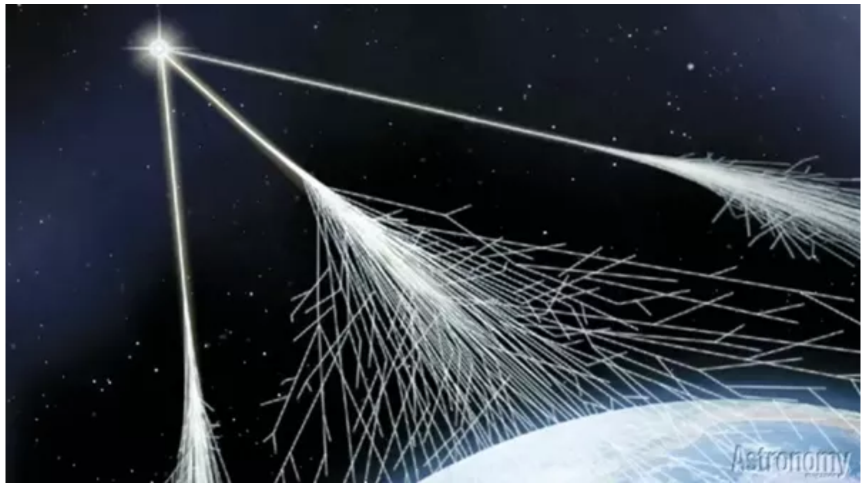
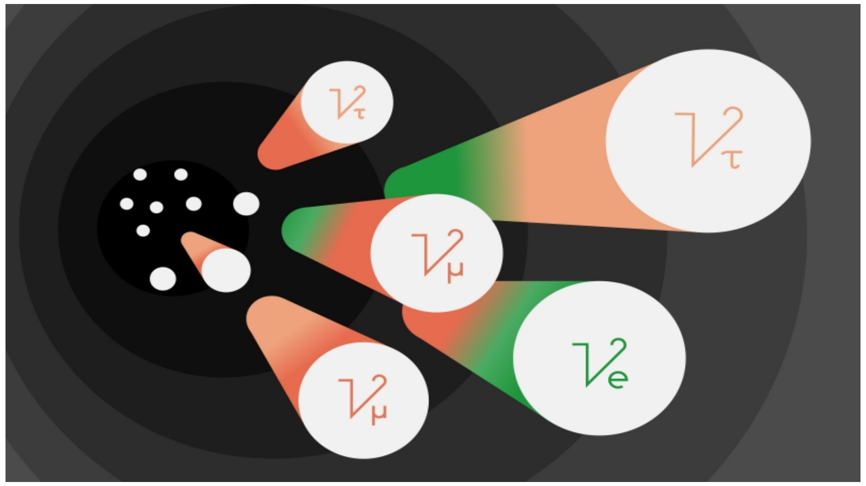
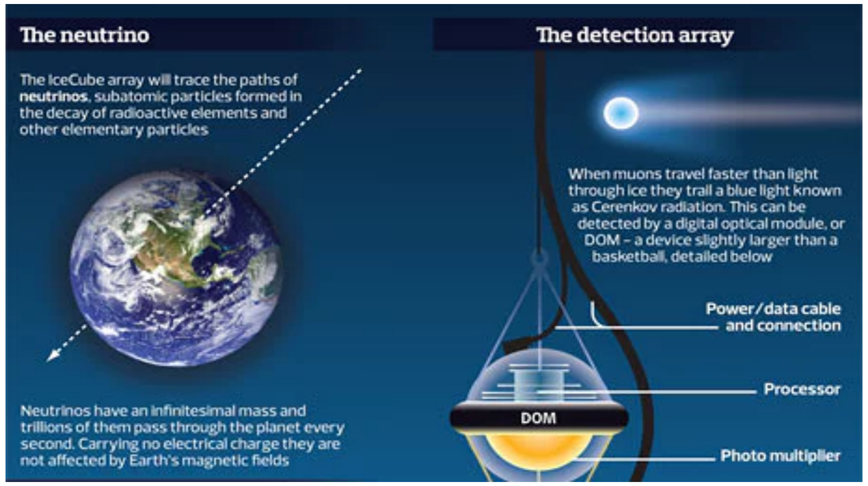
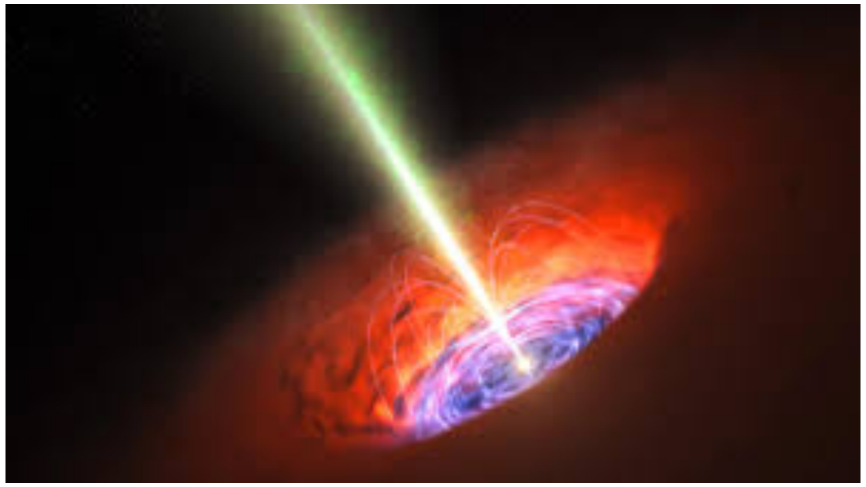
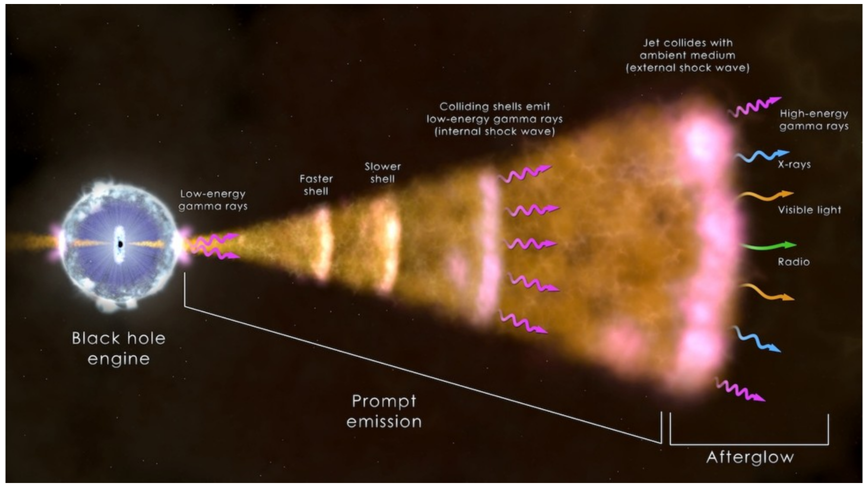
High Energy Universe
Cosmic Rays & Neutrinos & Gamma Rays

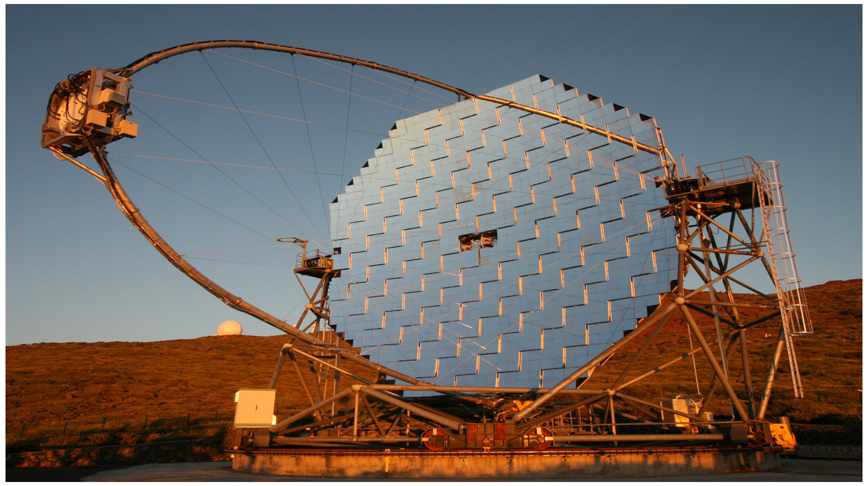












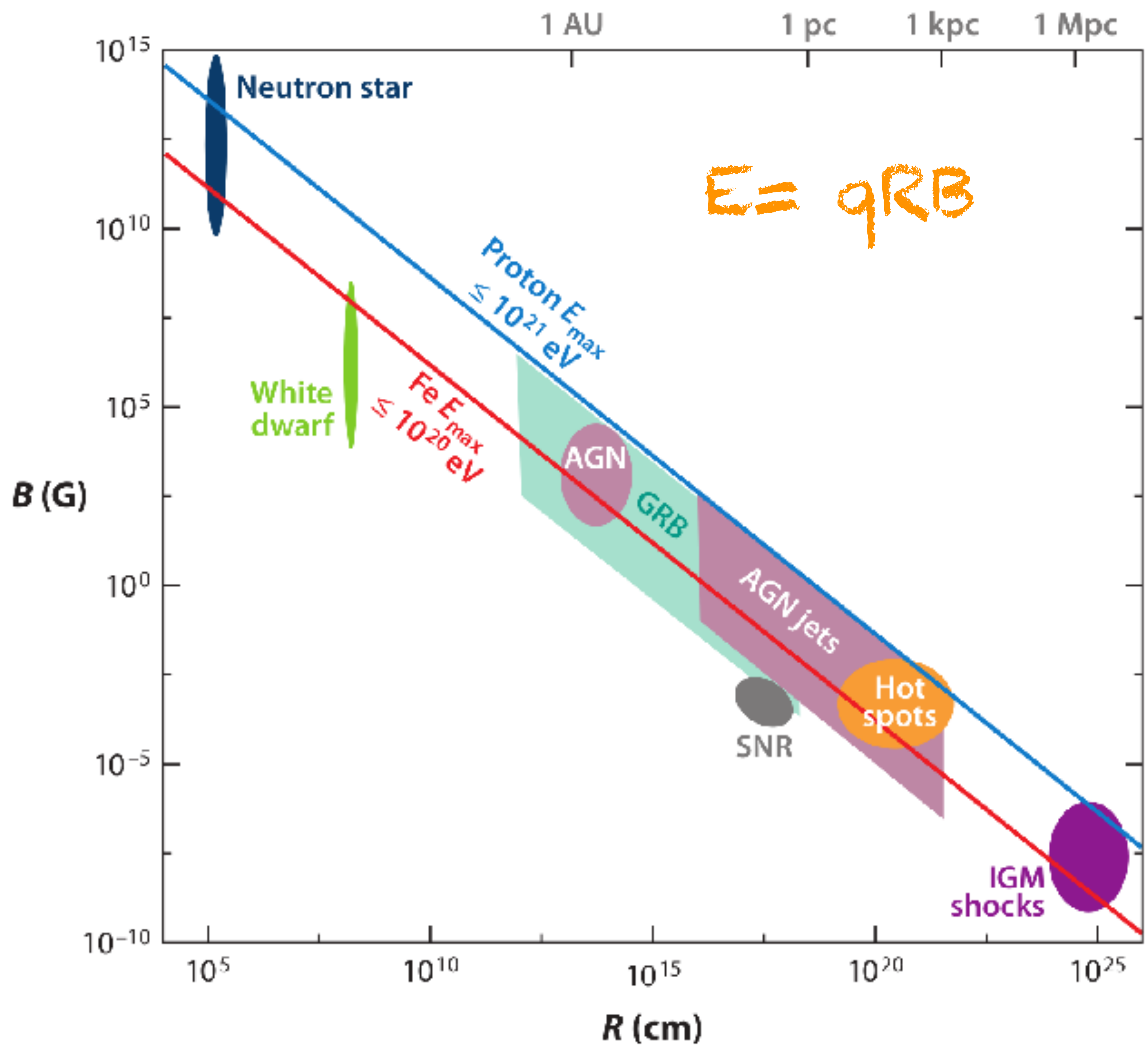
Debanjan Bose [debaice@gmail.com]

Lecture 2 [11.04.2019]

Possible Sources of Cosmic Rays

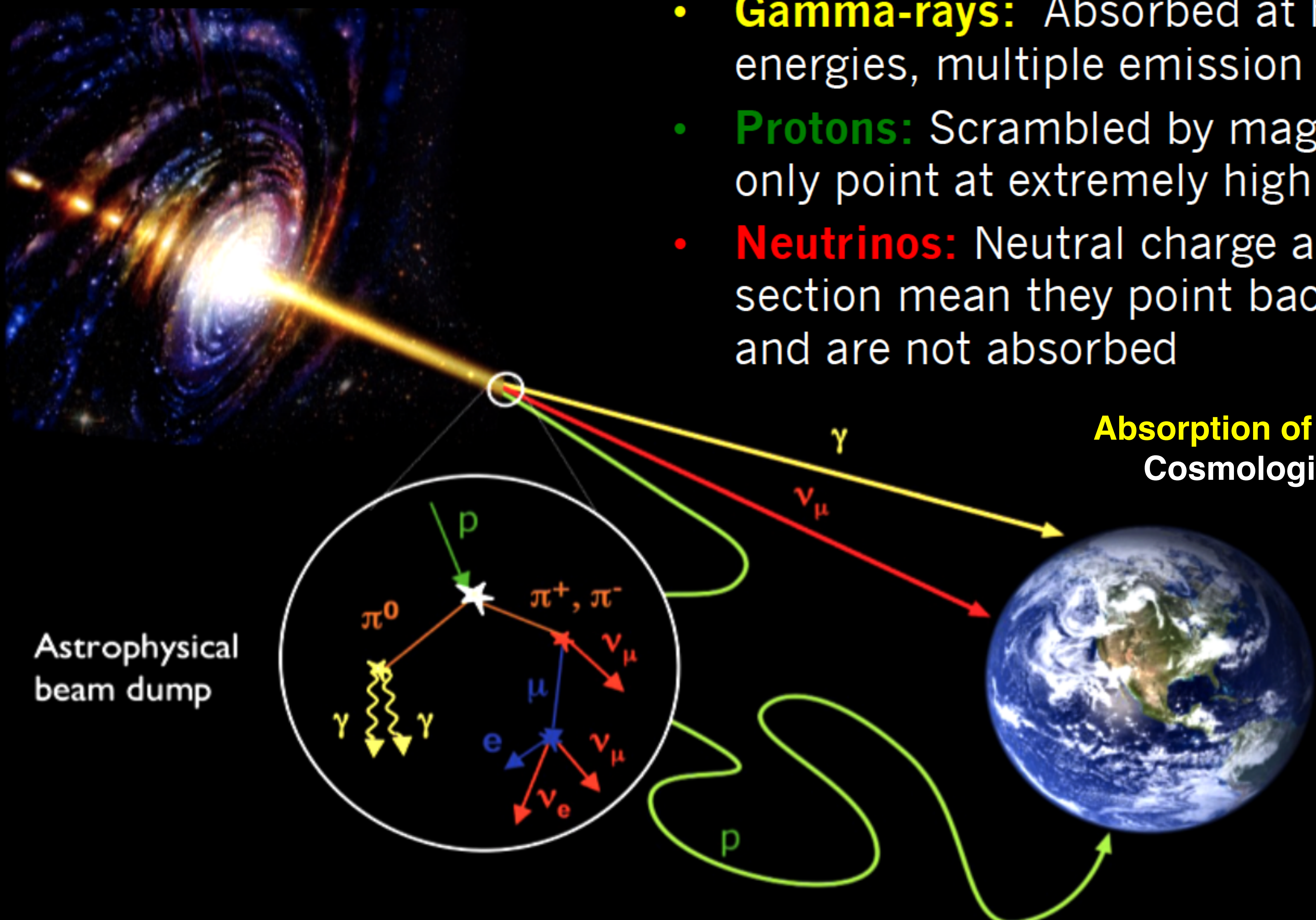
General Principle of Acceleration & Probabale Sources (Hillas Plot)

Magnetic fields themselves do not work therefore can not be directly responsible for accl. But changing magnetic field leads to inductive electric field



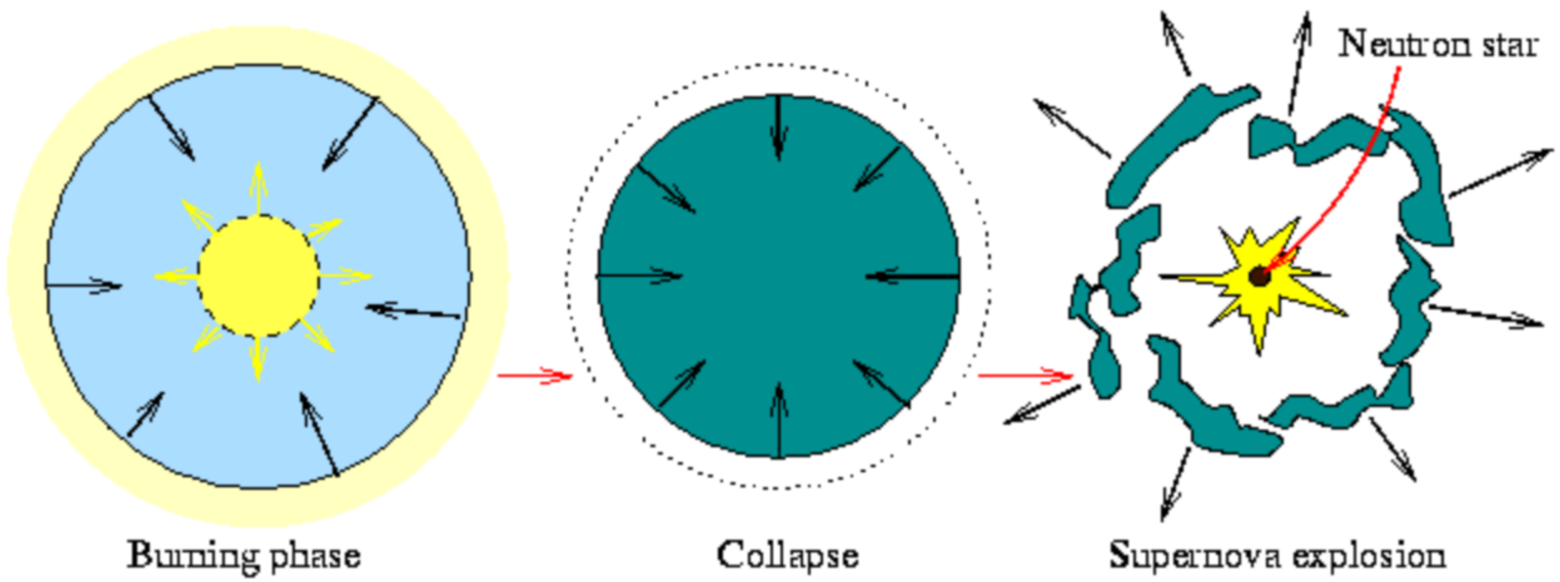
Cosmic Messengers @ High Energies

- **Gamma-rays:** Absorbed at highest energies, multiple emission mechanisms
- **Protons:** Scrambled by magnetic fields, only point at extremely high energies
- **Neutrinos:** Neutral charge and low cross-section mean they point back to source and are not absorbed



Absorption of Gamma-rays :
Cosmological Studies

Neutron Stars



$$Density \sim 10^{14} g/cm^3, \; Radius \sim 10km, \; Mass \sim 1.5 M_{\odot}$$

Once the Star completes all its nuclear burning - core collapses under the gravitational force produced by its own mass : Supernova Explosion

SN explosion decreases star radius by 5 orders of magnitude, increases magnetic field strength to 10^8 to 10^{12} G : conservation of angular momentum and magnetic flux

Shortest known period of a pulsar is 1 ms. In that time light can travel 300 km. So emission region must be smaller than that.. compact region.

SN - Source of Galactic CRs (Upto Knee)

Energy Density of CRs in our Galaxy 1 eV/cm^3

Milky way has radius 20 kpc and height 200 pc

Total CR energy in the galaxy $E_{G,CR} = \pi R^2 h \rho = 5X10^{54}$ ergs

On an avg a CR spends 10^{14} secs in the Galaxy confined to its magnetic field 3μG. Therefore there should be astronomical objects which has accleration power 10^{40} erg/sec.

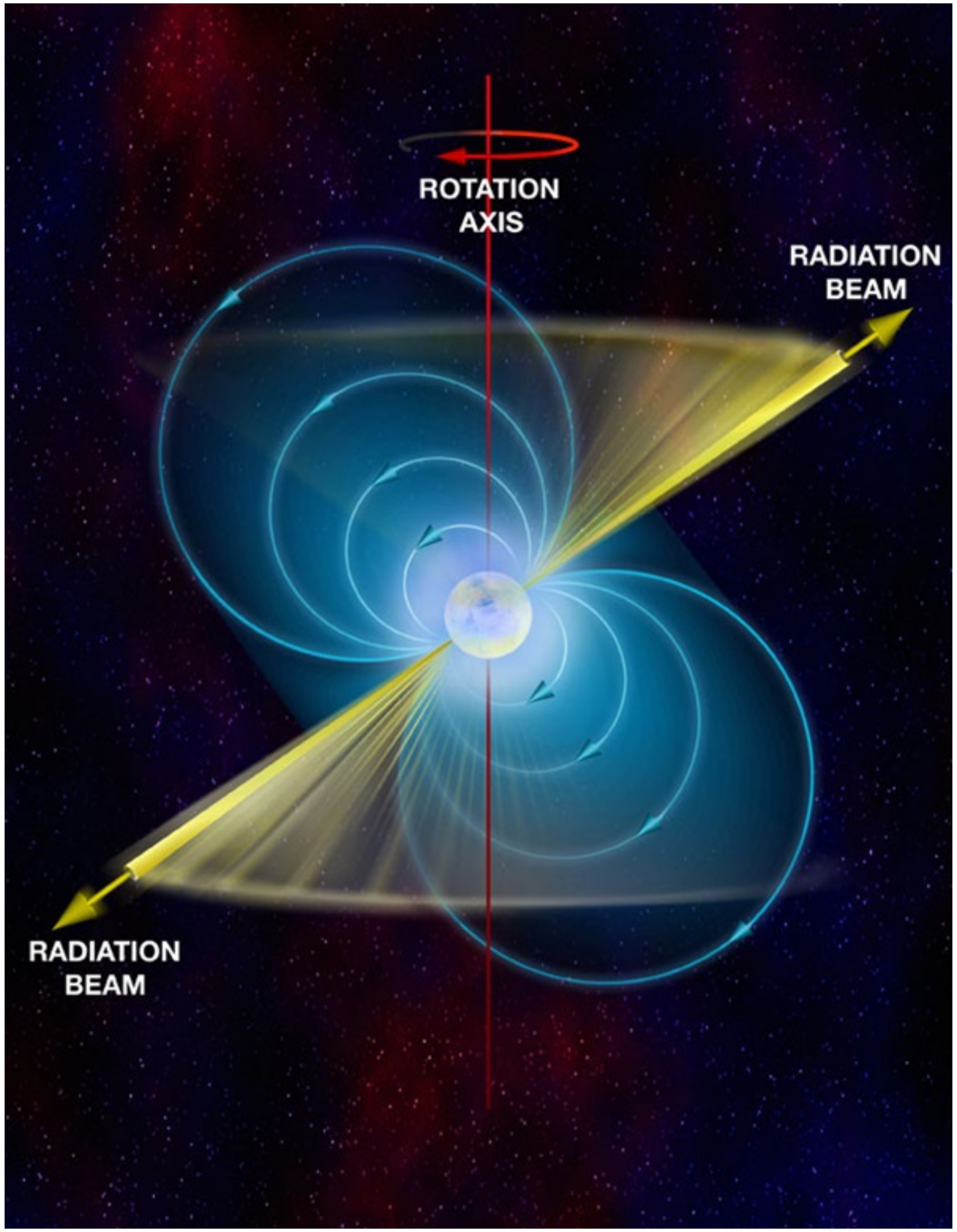
Avg total energy in SN explosion $E_{SN} = 10^{51}$ erg

If 0.01% transferred to CR particles by Fermi Acceleration

And if there is 1 SN every 30 years then accleration power

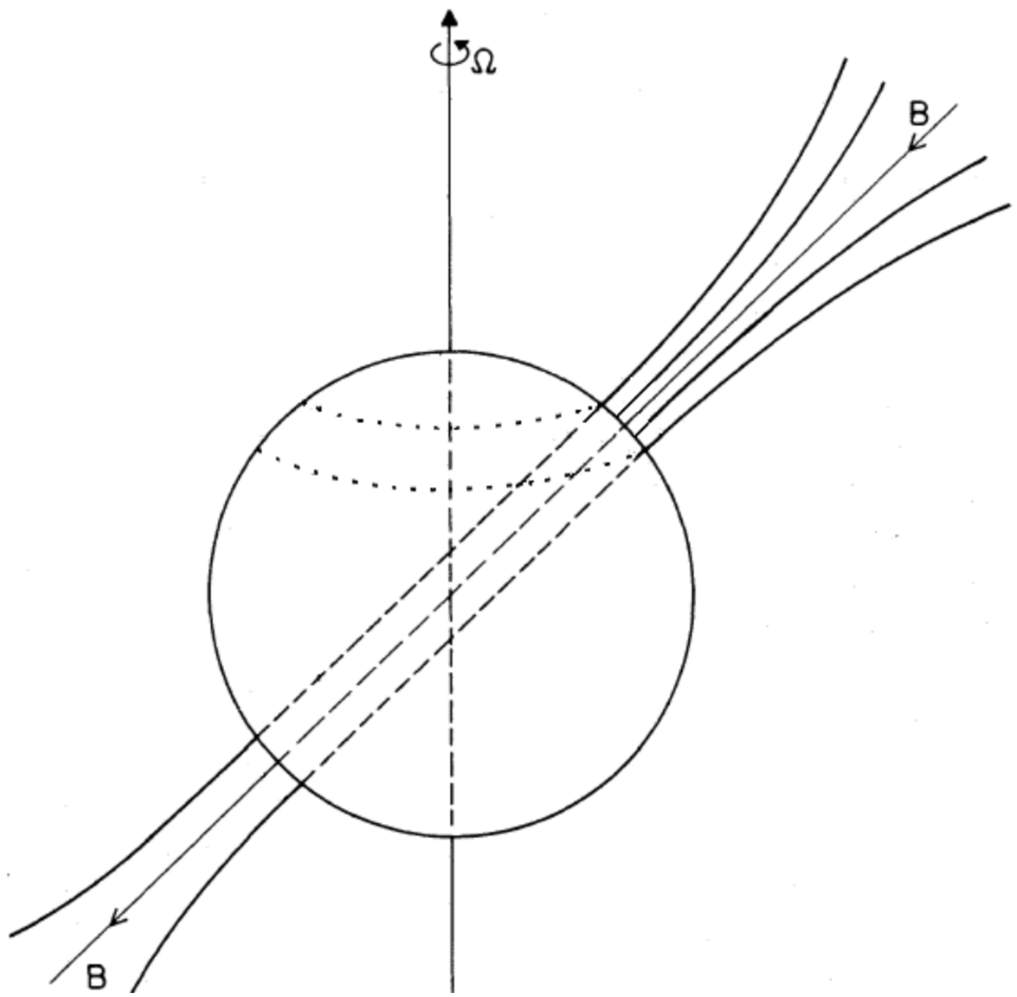
$P = 0.01\ E_{SN}/30 = 10^{40}$ erg/sec

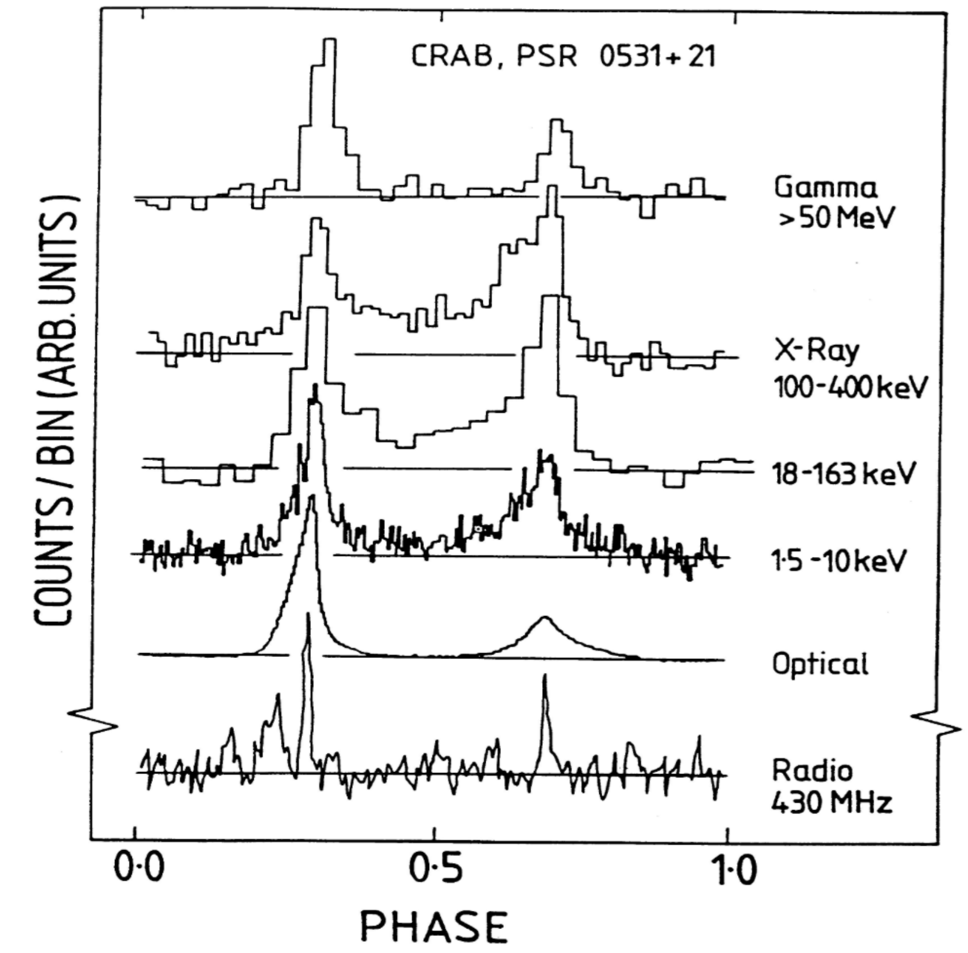
Pulsars

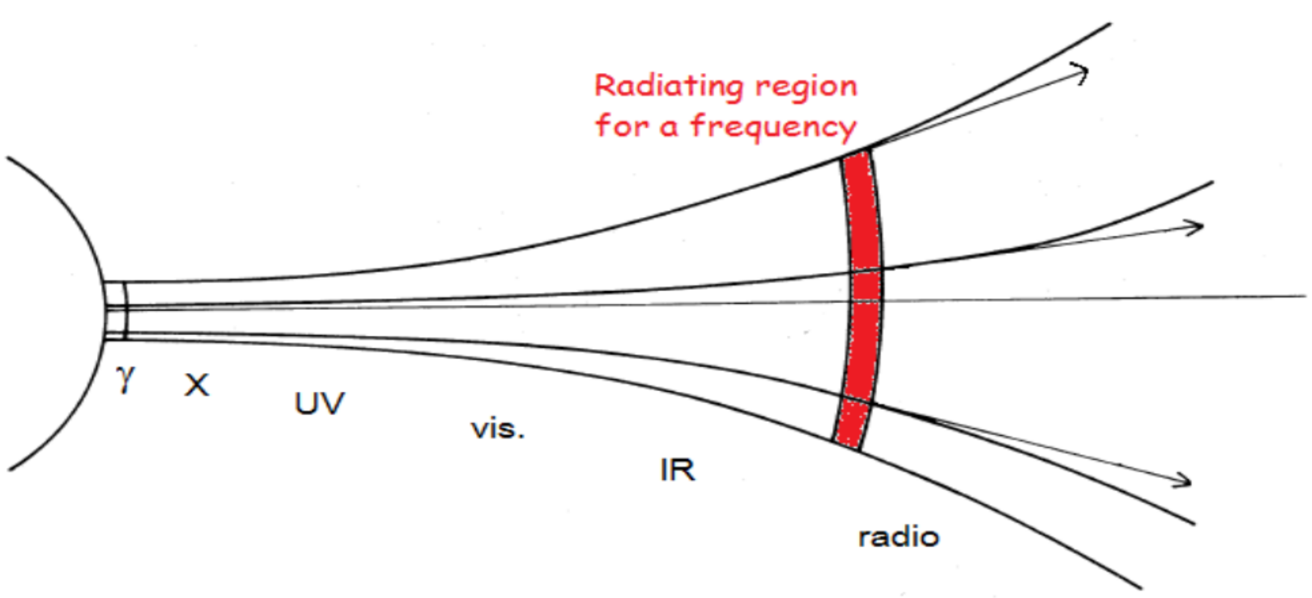


- A Pulsar - A pulsating Object [Pulsating EM radiation]
- Pulsar Period 1 ms to 10 secs
- Rapidly rotating Neutron Stars (NS)
- Most of the pulsars detected in radio emission : electrons & positrons are accelerated along the magnetized field lines of the NS

HE Pulsed Emission from Crab Pulsar



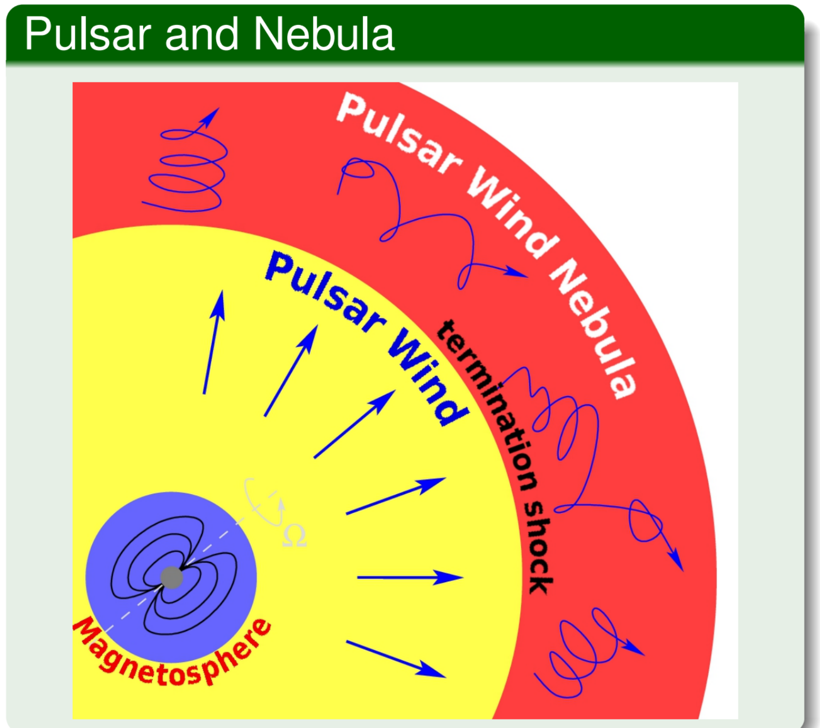


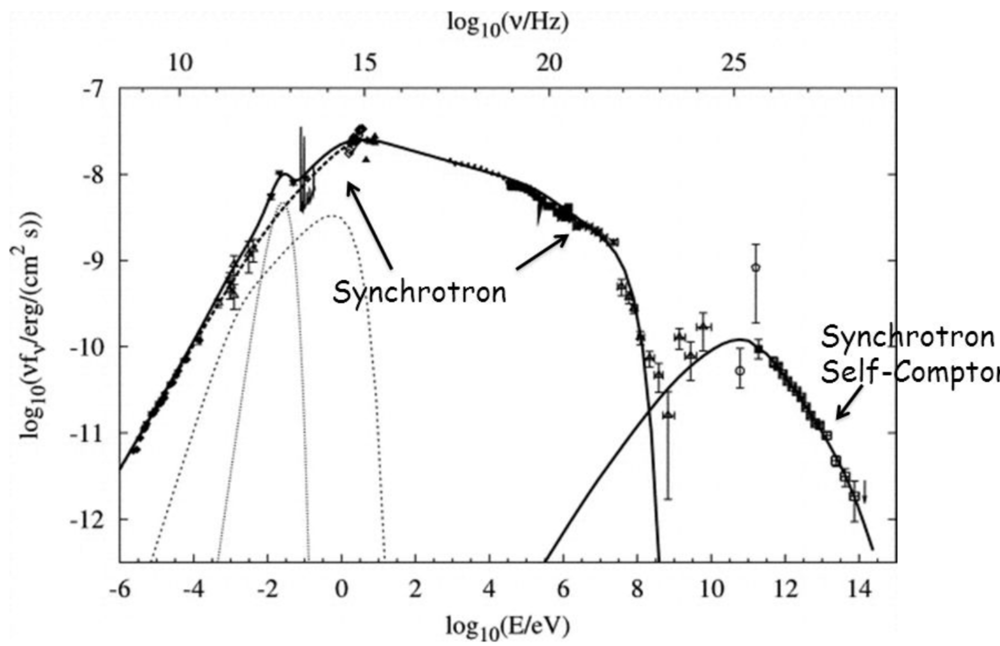


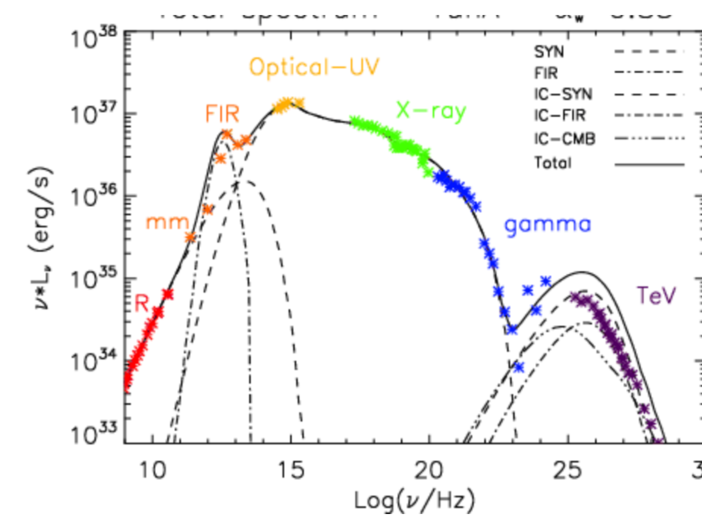
Due to rapid rotation of very strong magnetic field huge electric field is induced 10^{11} V/m.

And they pull $e^{\pm}$ away from NS surface overcoming gravitational pull. These particles move along magnetic limes and emit EM radiation.

HE Continuous Emission from Crab Pulsar





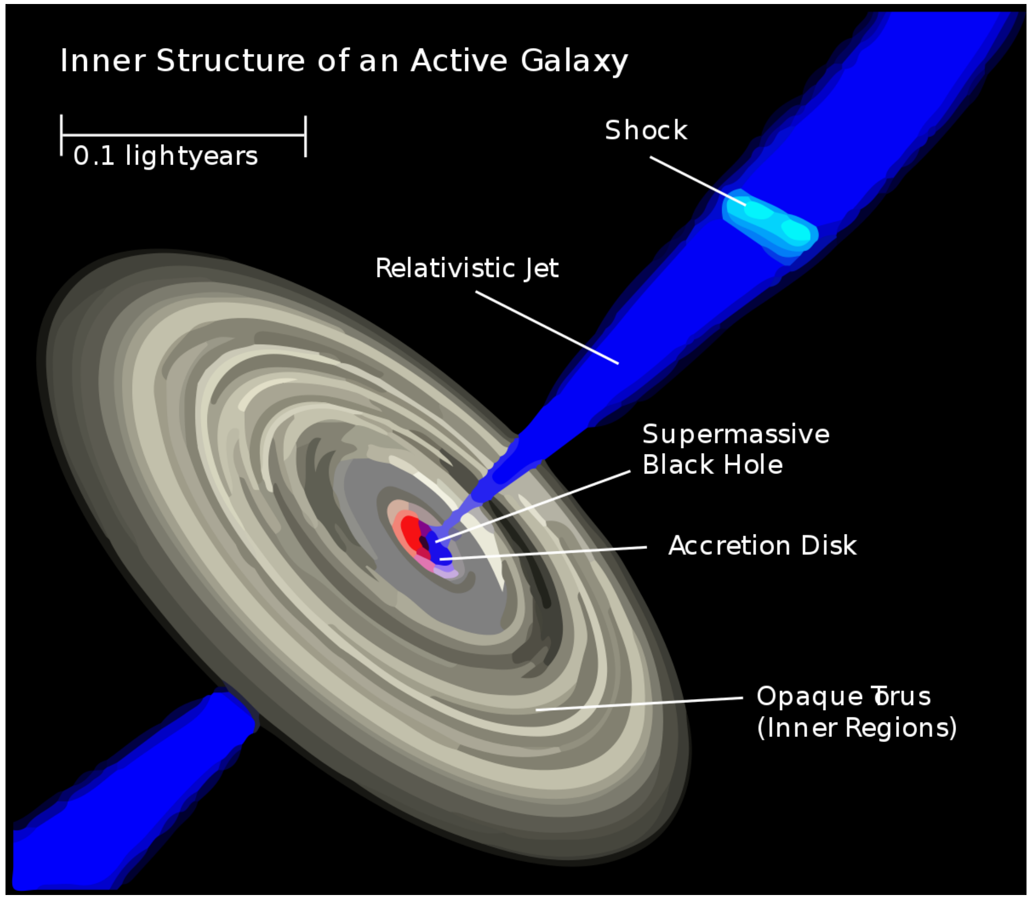


Ground based gamma-ray telescopes have detected both pulsed and continuous emission from Crab. Continuous emission comes from pulsar win nebula. This continuous emission is used as candle to calibrate telescopes.

According to some models protons are also presents along with in the magnetized wind of relativistic plasma, p-p and p-γ processes produce

γ and ν

Sources of Extra-Galactic Cosmic rays
Active Galactic Nuclei (AGN)



Energy density of extra-galactic cosmic ray :

$$10^{36} erg Mpc^{-3} s^{-1}$$

In order to maintain this density total power requirement for a source with spectrum of E^{-2} would be :

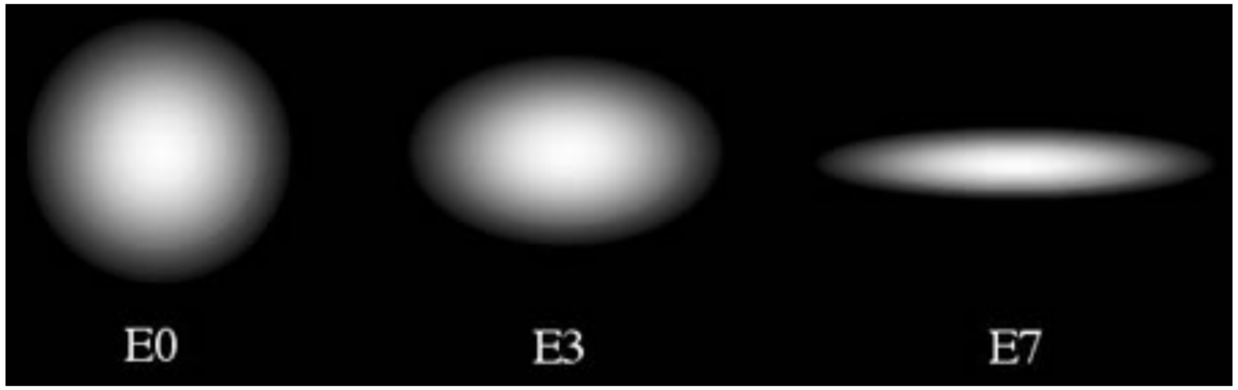
$$2 \times 10^{37} erg Mpc^{-3} s^{-1}$$

AGNs with following source density and emission power has right ingredients to maintain observed CR_{EG} density

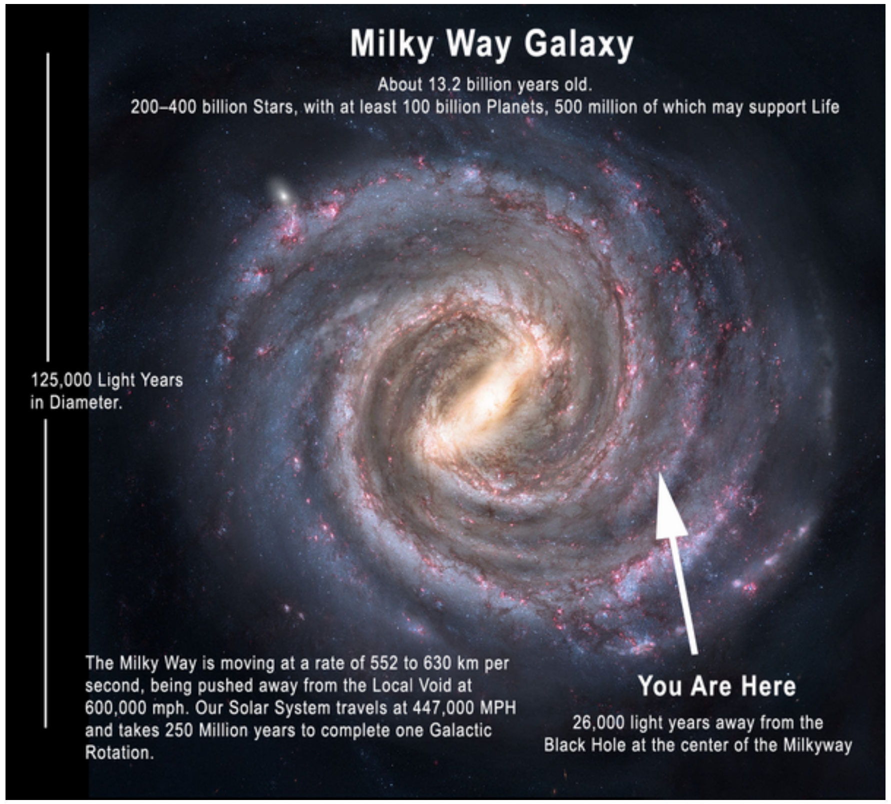
$$1 \times 10^{-7} Mpc^{-3} \qquad 10^{44} erg/s$$

Normal Galaxy

Characterised by Thermal Emission



Elliptical Galaxy



Spiral Galaxy

Normal Galaxies has total mass : 10^7 - 10^{12} solar masses. Contains 100 billion stars.

Luminositiy 10^8 to 10^{11} times the Sun.

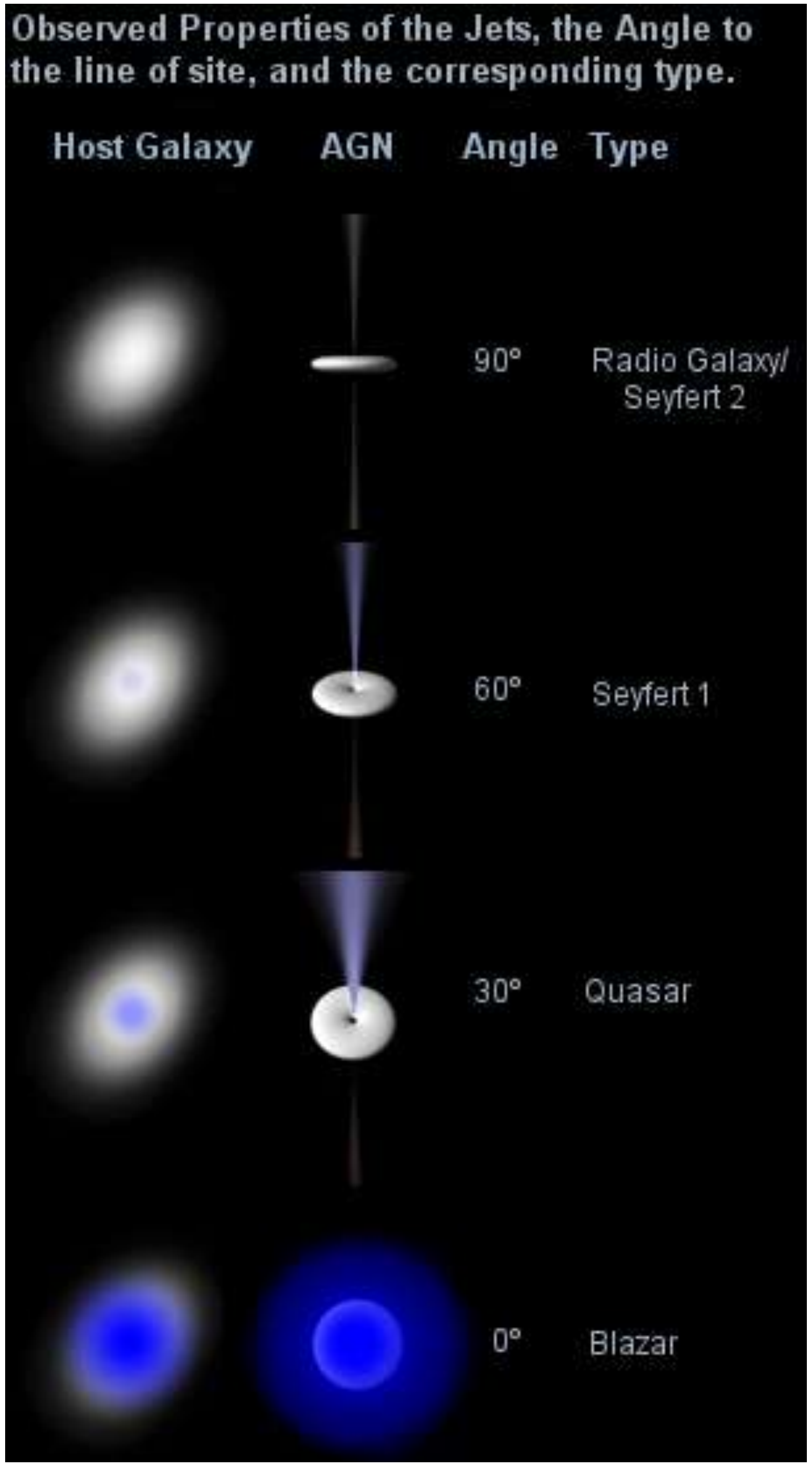
Our Milky Way is a Spiral Galaxy. Diameter 50 kpc. Thickness 200 pc.

1 pc = 3.26 light-year or 30 trillion kms

Solar System is located almost 27000 light-years from the galactic center.

Active Galaxy

Characterised by Non Thermal Emission



- Very Bright , brightness >> luminosity of normal galaxies
- Detected across EM spectrum from radio to gamma-rays
- Powered by accretion of mass onto a supermassive BH (Black Hole) 10^9-10^{11} solar masses

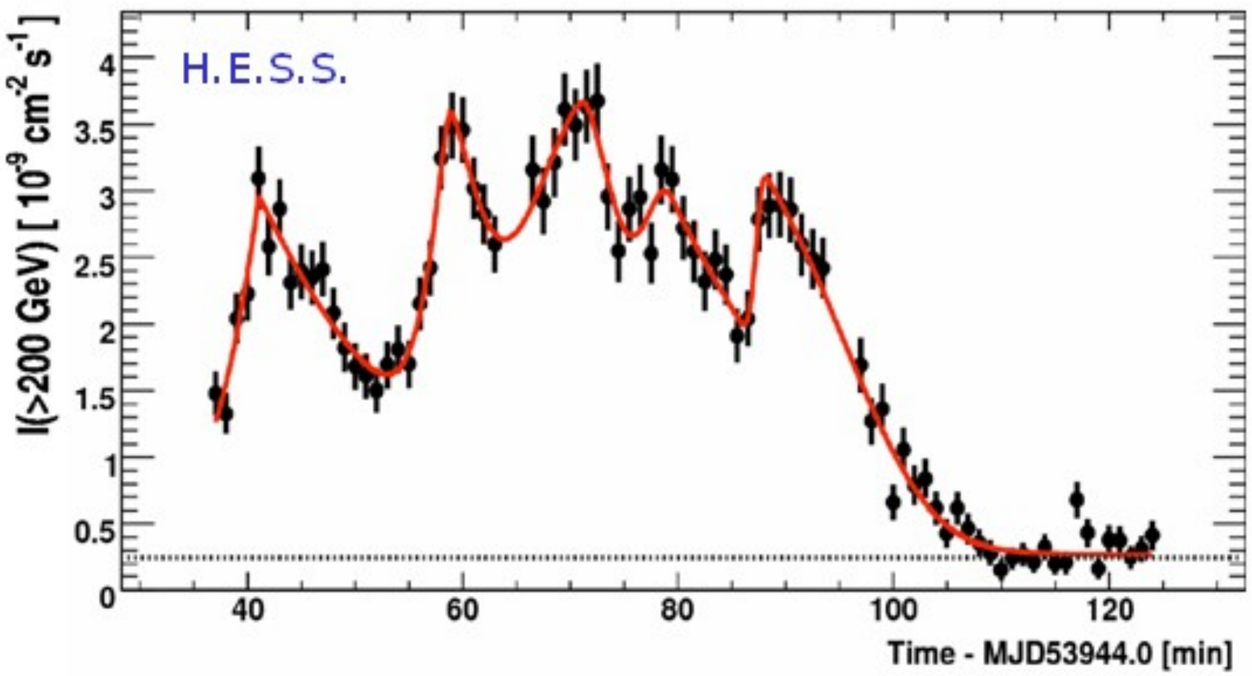
Radius SMBH : 10^{13} cm

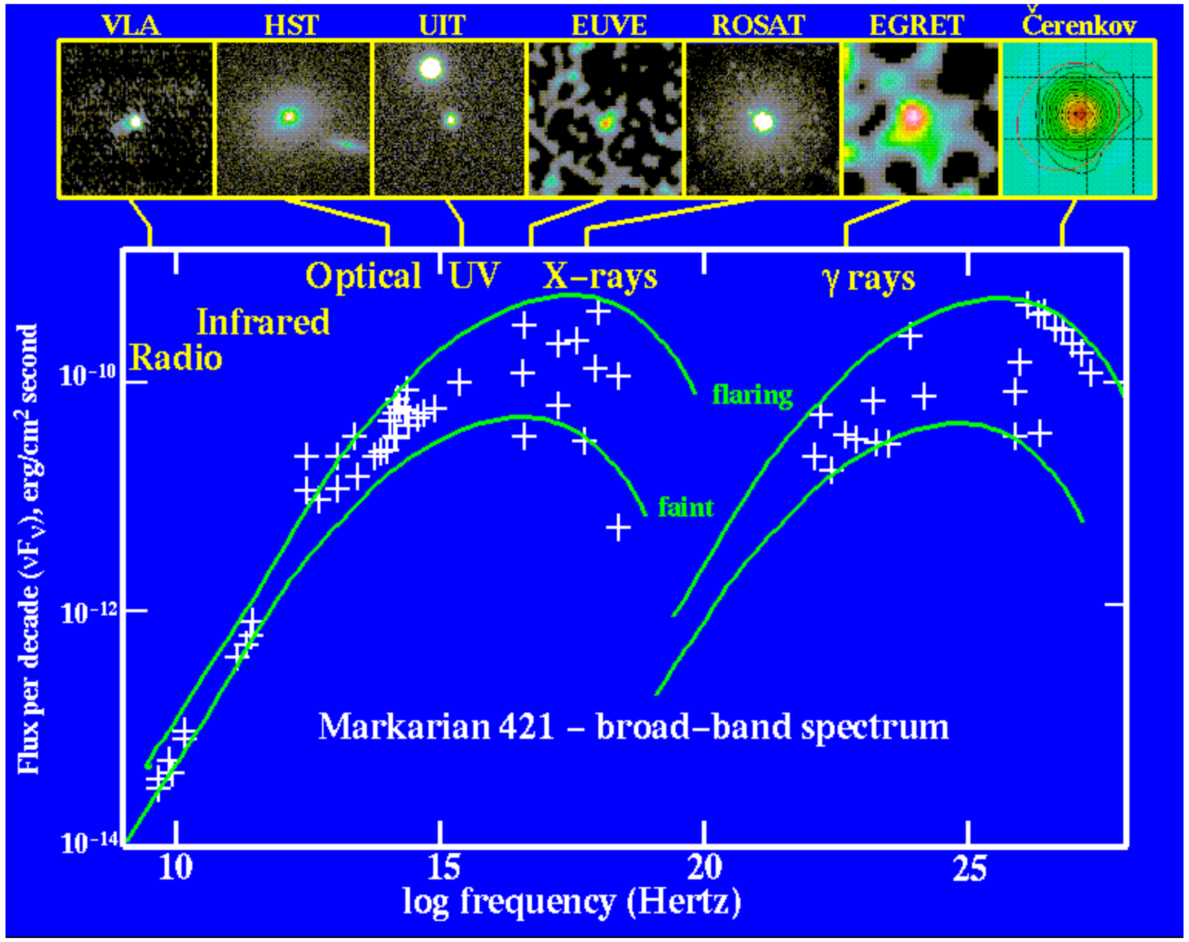
Radius of accretion disk : 10^{14} cm

Extension of jet : 10^{24} cm

1-2% of all galaxies

Blazar a class of AGN





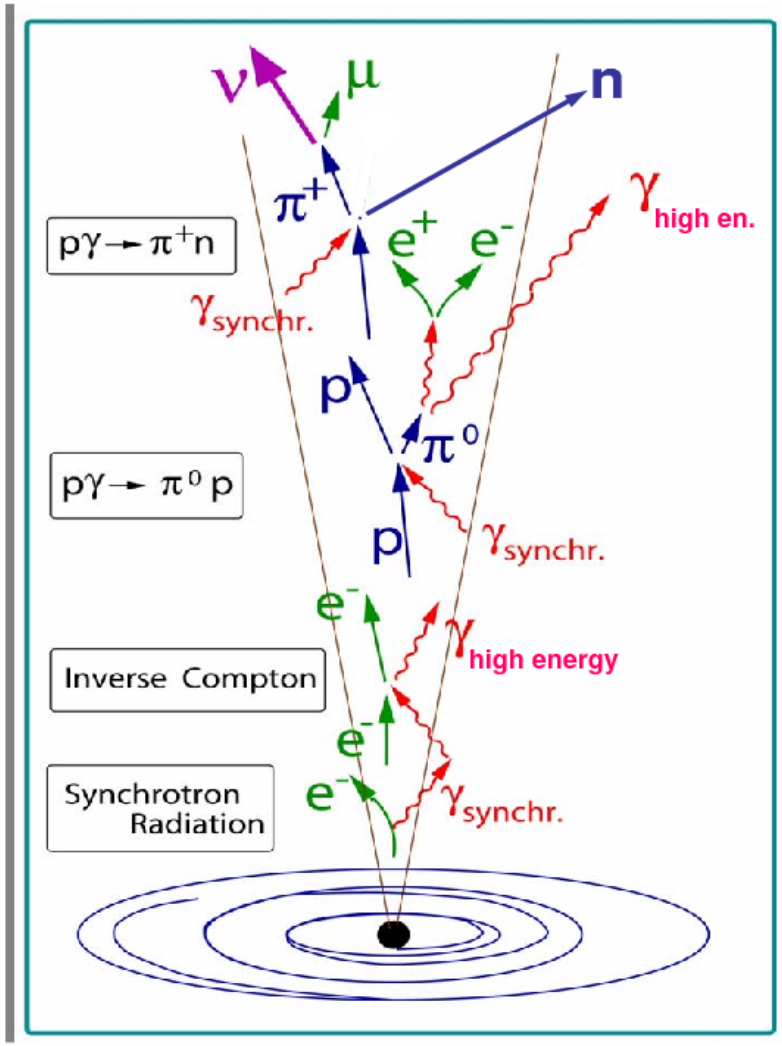
They are extremely interesting astrophysical laboratories - studying physical laws under relativistic conditions

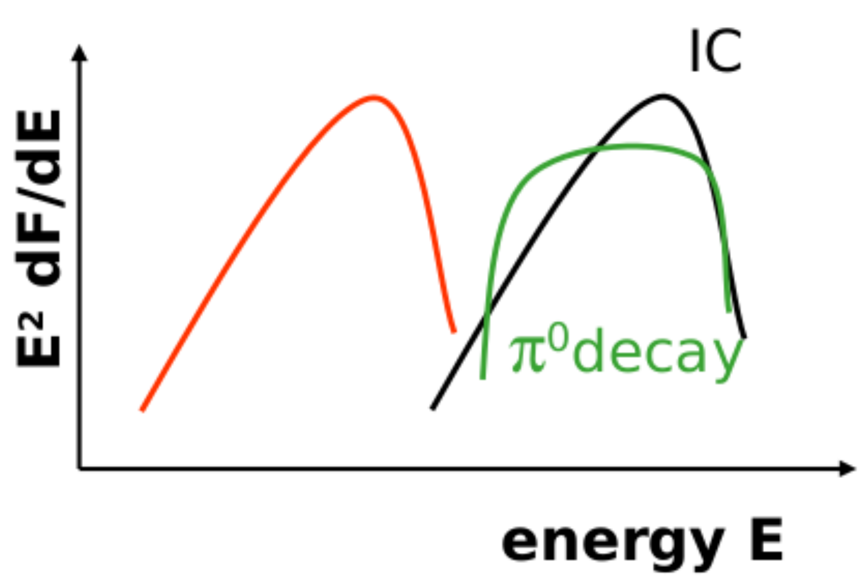
Excellent probe of the Early Universe and everything between us and them

Less than 5% of all AGN

Origin of cosmic rays above 10^{19} eV

Emission Mechanisms @ Very High Energies





Leptonic Models

Synchrotron-Self Compton

External Compton

VHE γ-rays from Blazars

Space-borne and ground based telescopes has detected VHE γ-rays : can be explained by leptonic models

If they are source of cosmic rays

then protons are also accelerated

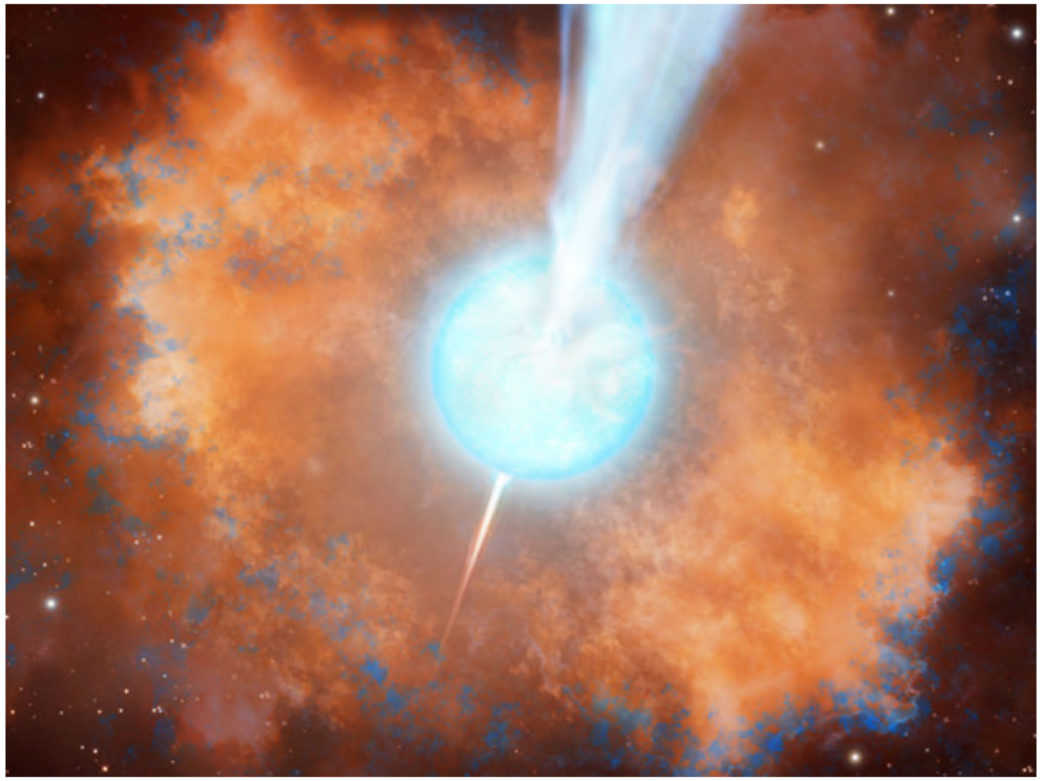
Hadronic Models

Proton-Proton Collisions

Proton-Photon Collisons

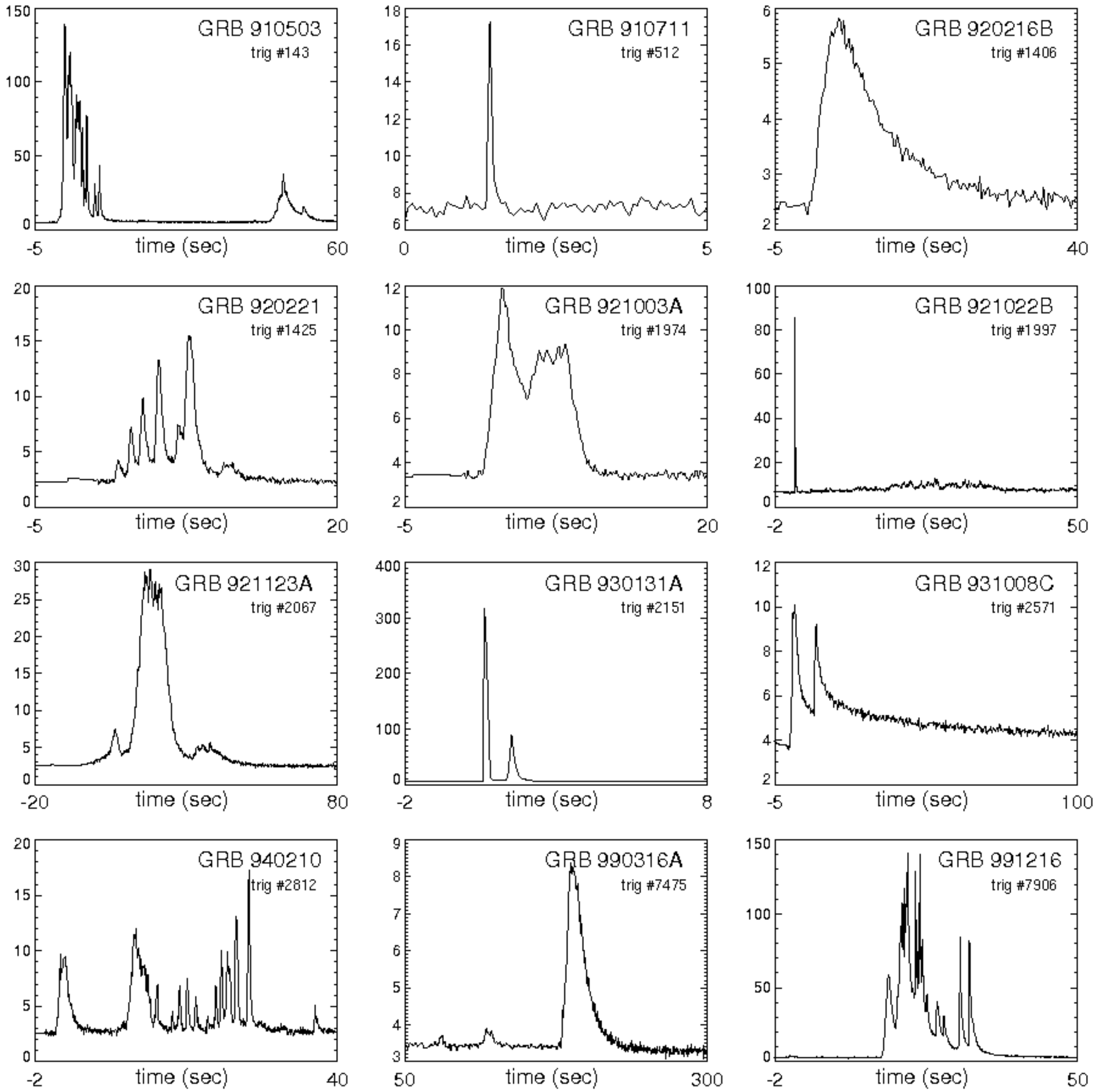
By Product **Neutrinos**

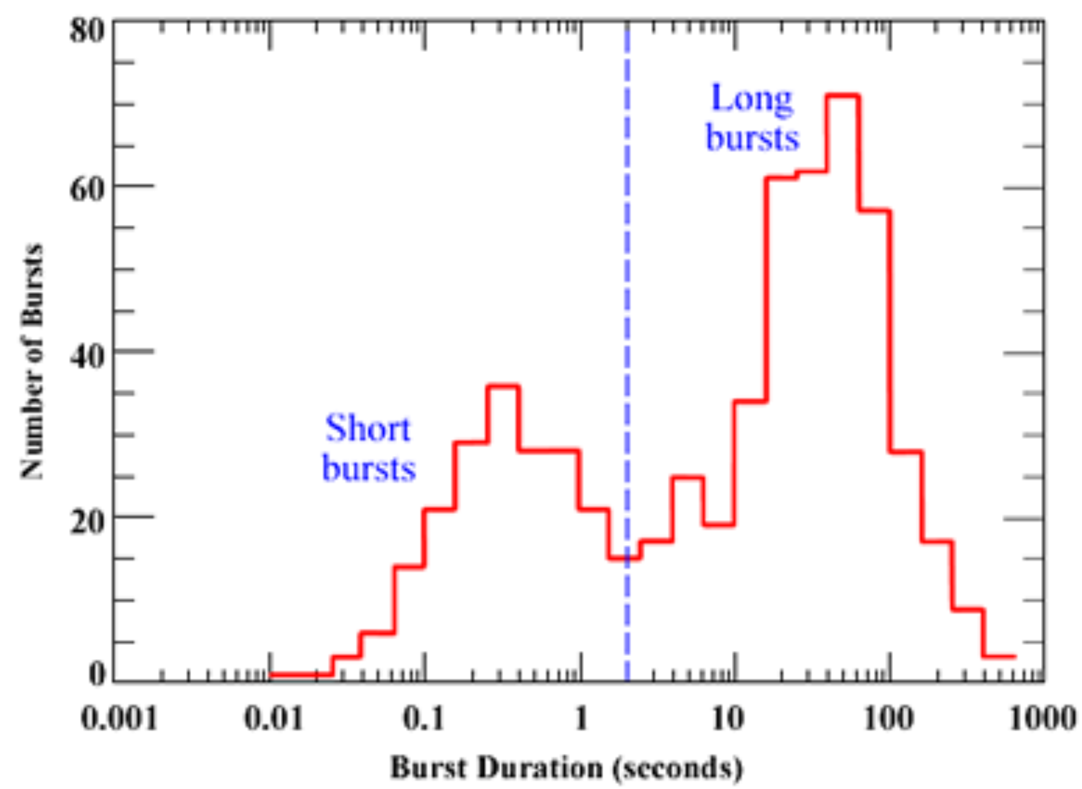
Gamma Ray Burst (GRB)



- GRBs are sudden, intense and non-repetitive flashes of gamma-rays
- They are the most luminous, most energetic events in the Universe, outshines everything else
- They lasts only for few seconds and release 10^{54} ergs; comparable to SN, comparable to optical light emission by Sun over the lifetime of the Universe
- Non-thermal emission

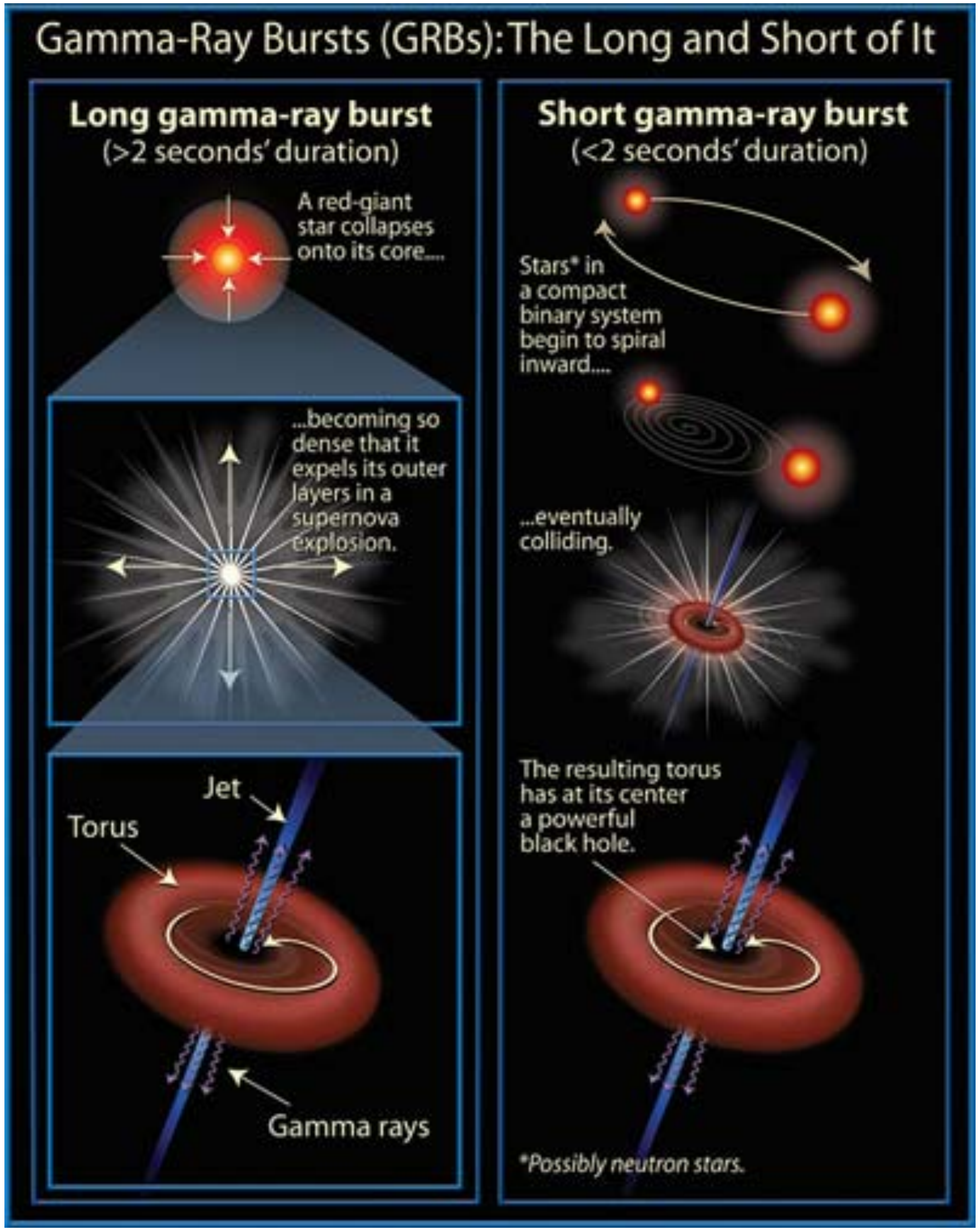
Variability of GRBs





Rapid Variability and short timescales implies compact region and relativistic motion

Long & Short GRBs



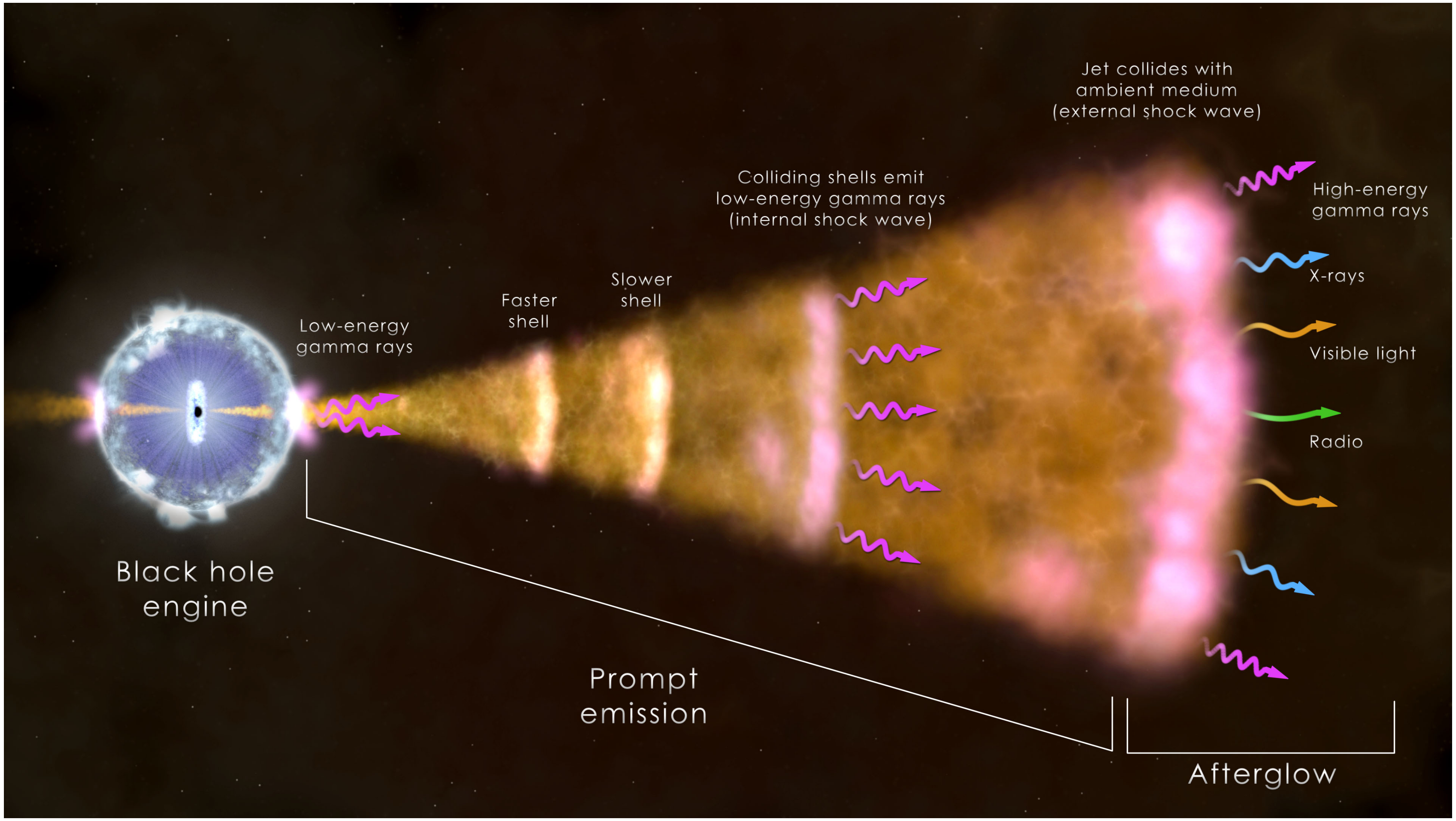
Upto 30 years after discovery only "prompt" emissions were detected from GRBs. Thus Location of these objects and nature of compact objects not known

Observation of afterglow changed that scenario

Long GRBs - core of massive star collapse [Evidence - absorption due to Fe in x-ray continuum spectrum.. associated with SN]

Short GRBs - Merger of NS-NS, NS-BH [Never associated with SN; fond in elliptical galaxies- compact binaries most abundant]

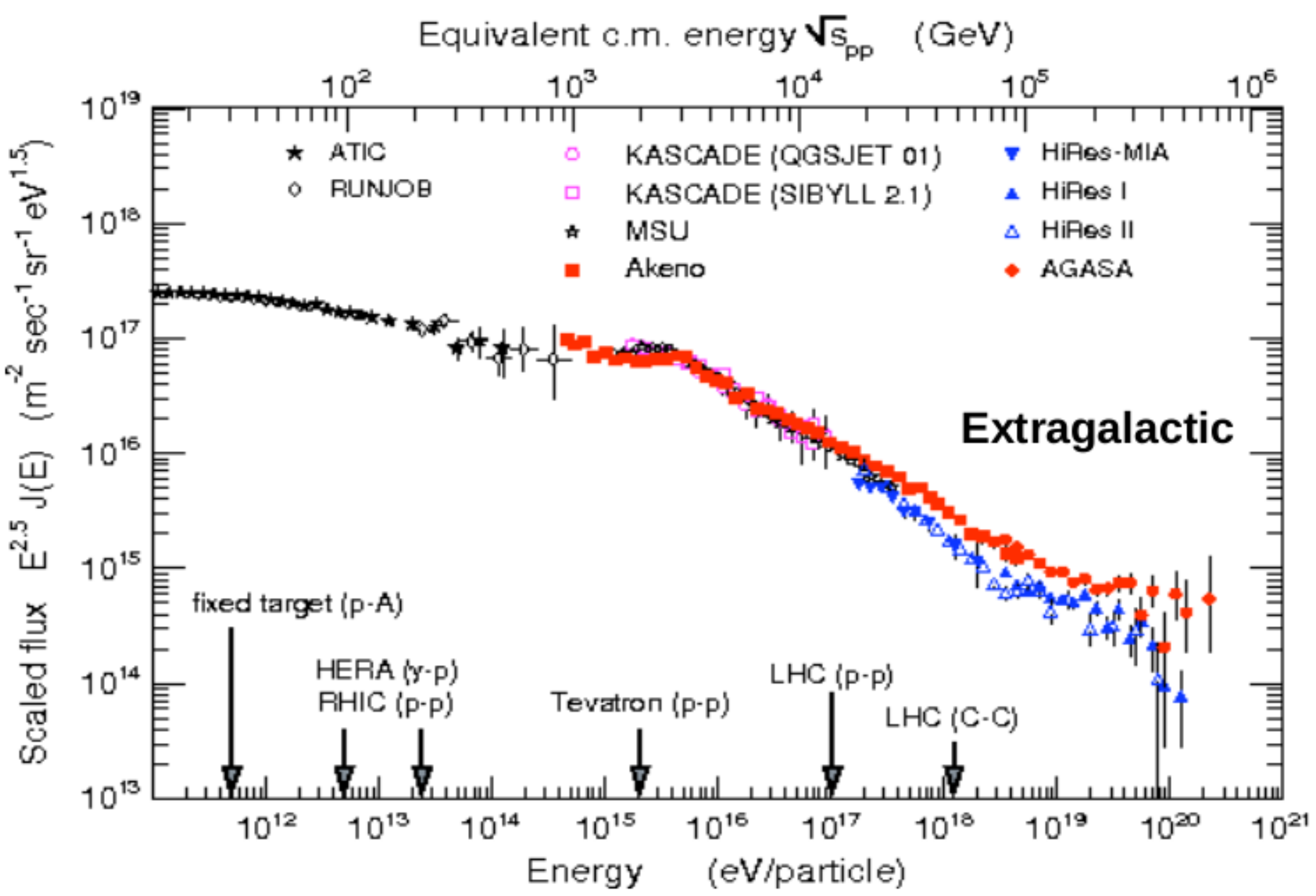
Fireball Mechanism



The enormous energy release in a such a short time from very compact region produces tremendous luminosity which overwhelms gravity.

This outward pressure flings out matter, which gets heated up into a fireball made of electrons, positrons, gamma-rays, protons, neutrons

Models Sugegsted GRBs only Source of VHE CRs



Energy Density of EG CR

$\rho_{CR} \sim 10^{45}\ ergs/yr/Mpc^3$

Gamma-ray Bursts

$\rho_{GRBs} \sim 10^{45}\ ergs/yr/Mpc^3$

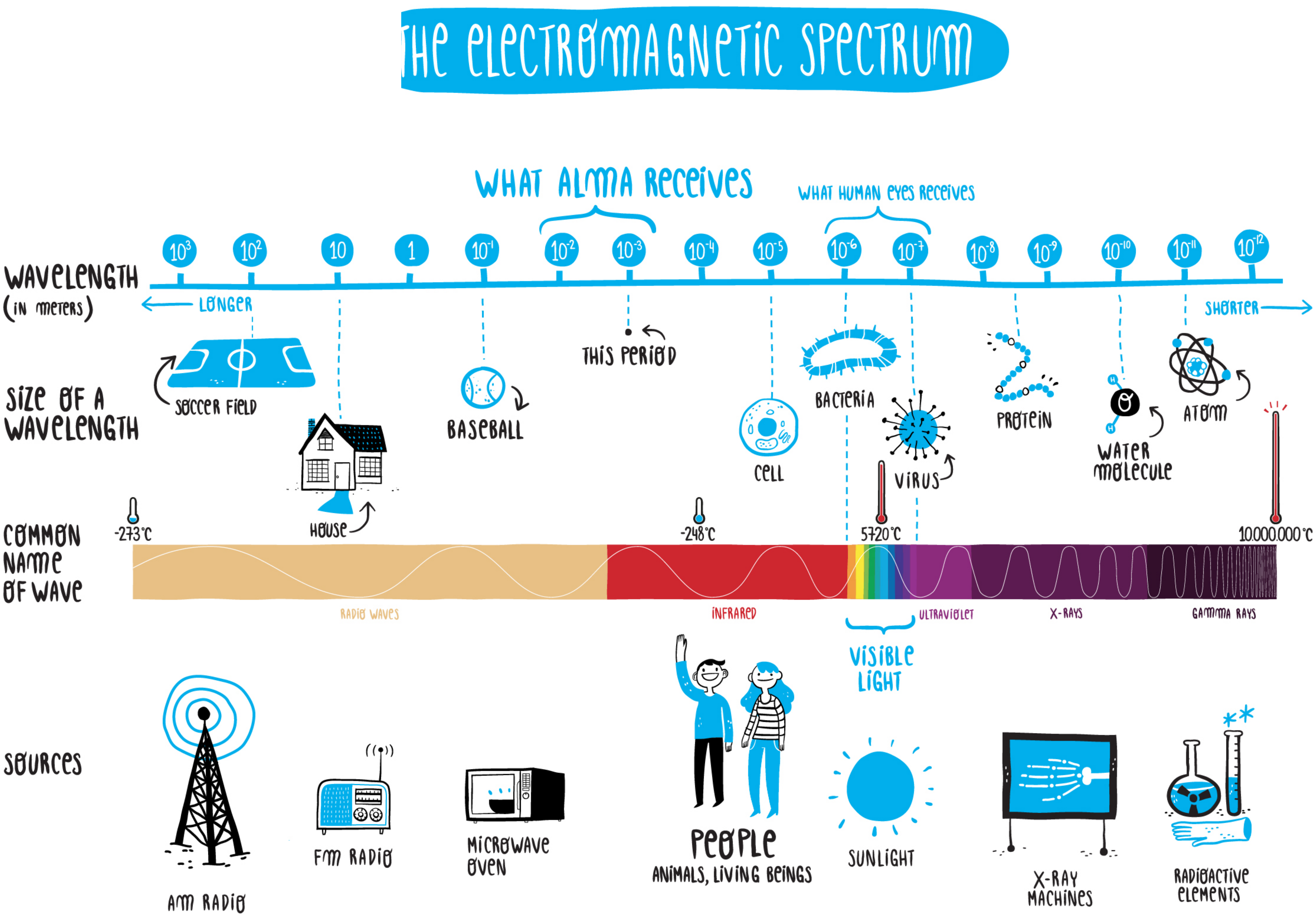
From :

$(2\text{-}3)10^{51} ergs \times 300/yr/Gpc^3$

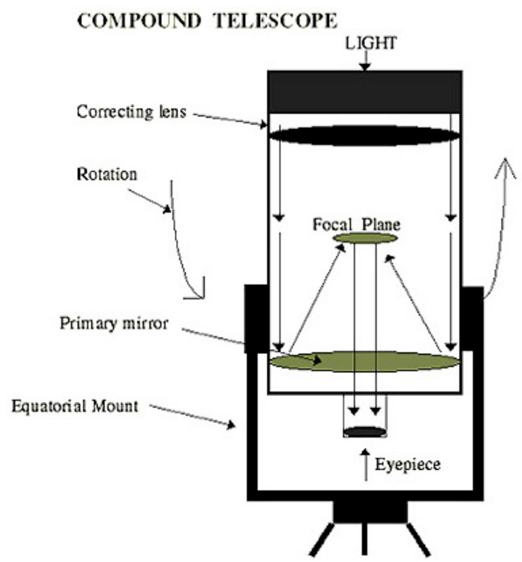
This Possibility is ruled out by IceCube Neutrino Telescope

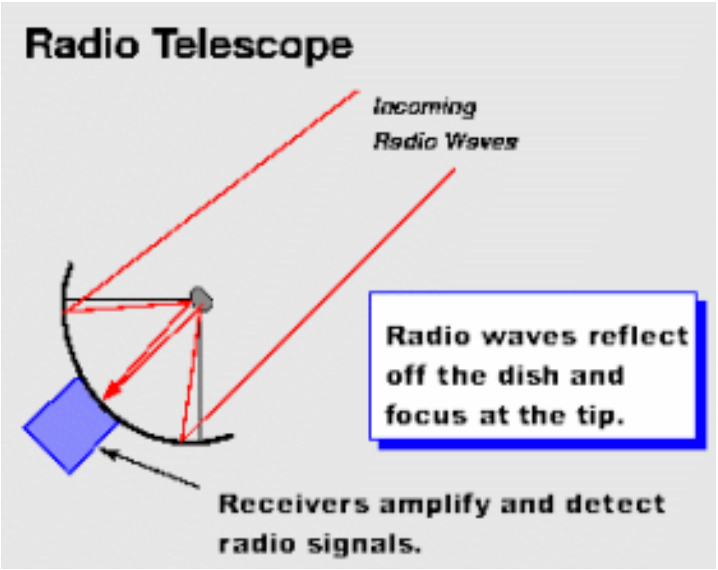
How to Detect Gamma-rays & Neutrinos From Astrophysical Sources

Gamma Ray Astronomy

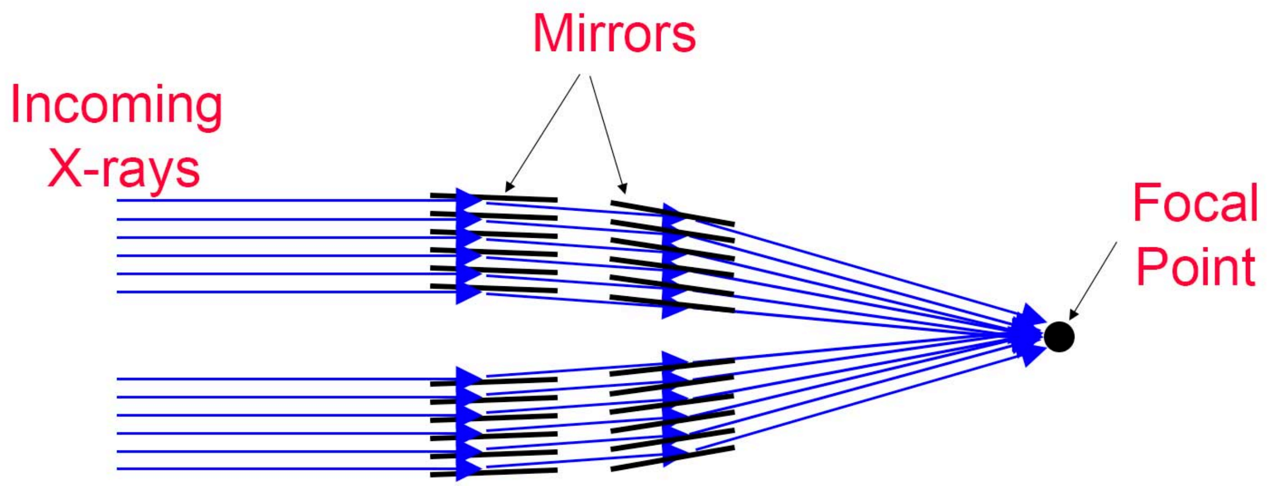


Comparison : Optical/X-ray/Gamma-ray

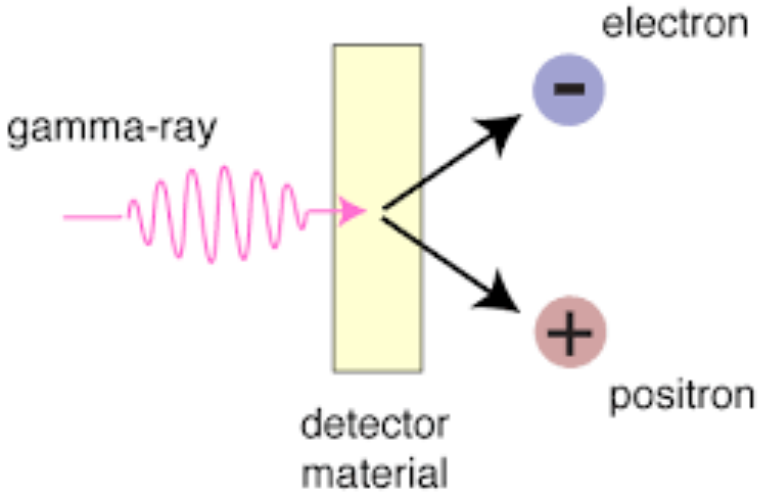




Optical/radio wave is focused using a reflector : Reflection is caused by e-s reacting to EM field oscillating with same frequency and emits radiation with same frequency



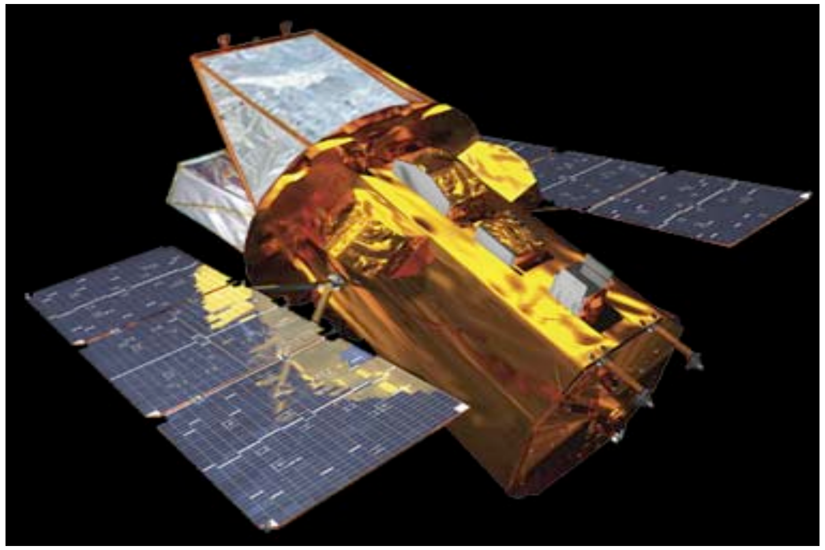
X-rays can not be reflected like visible light, as index of refraction is close to 1 focal length becomes impractically long. However they can be reflected at shallow angle.



None of the above works for gamma-rays as they have very small wavelength they simple passes through matter. So they can be detected by pair production.

Resolution : Optical/X-ray/Gamma-ray

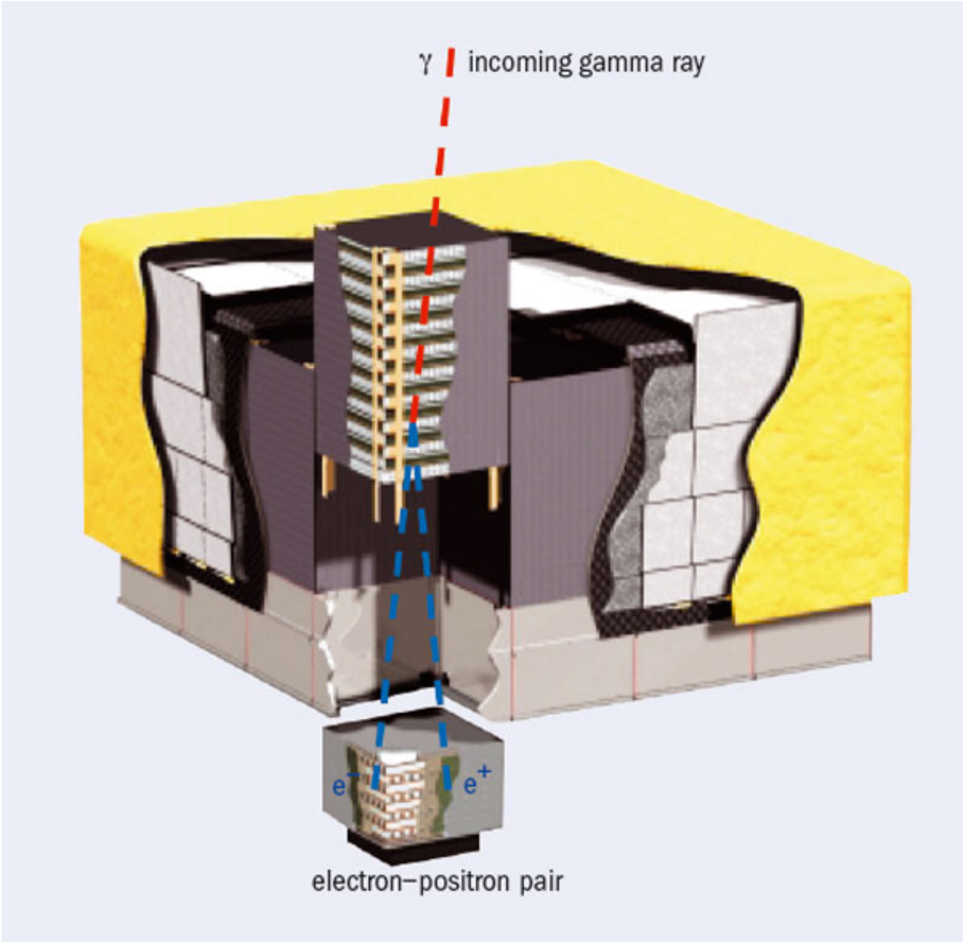
Hubble Space telescope (Visible light) - 1/20th of arc second

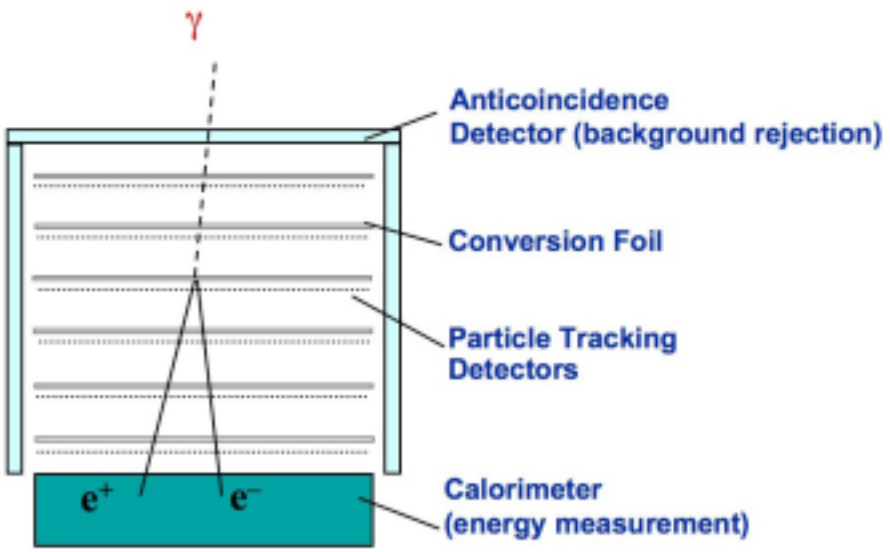


Swift X-ray telescope - 18 arc second

Fermi Gamma-ray telescope - 1°

Fermi Gamma ray Space Telescope

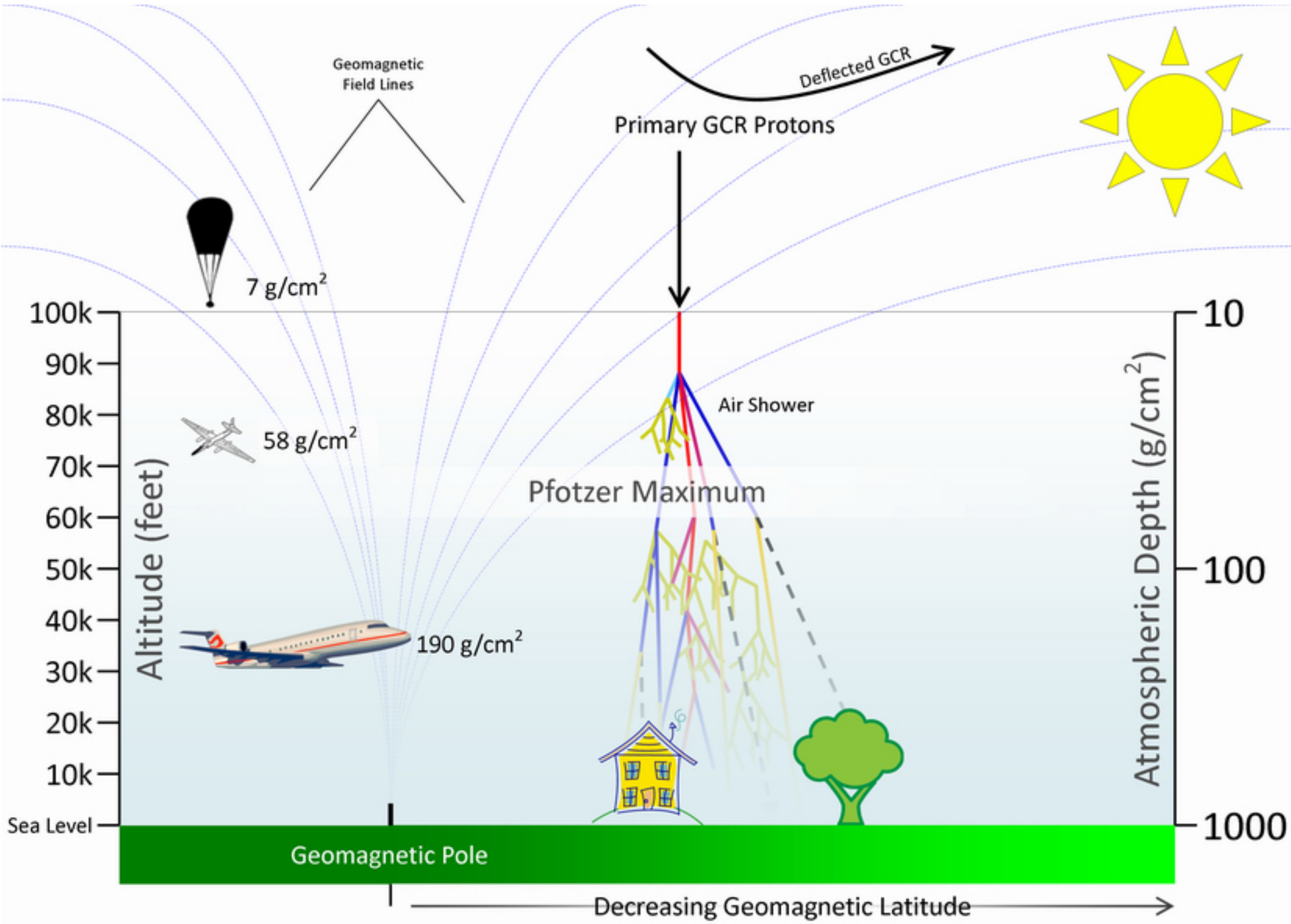


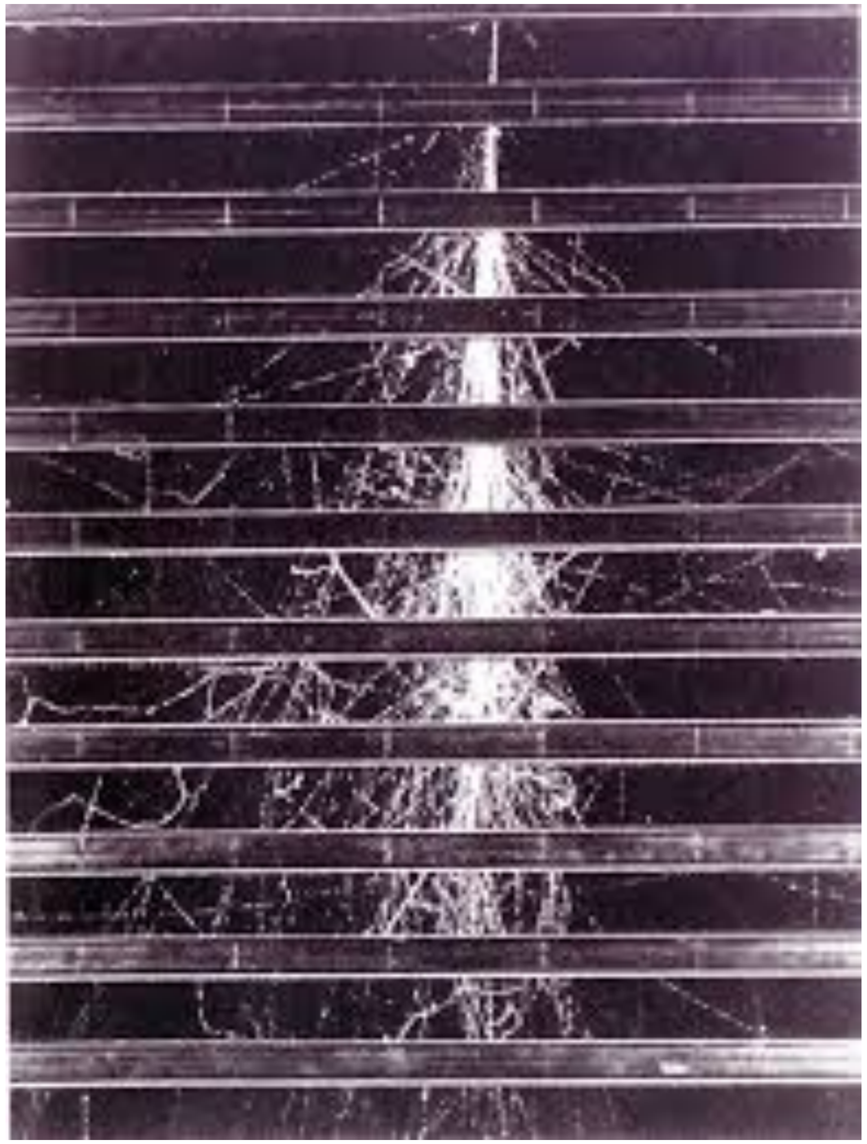


Area $1 m^2$

Energy range MeV to GeV

Gamma-ray Detection Technique @ Ground





~130 cm of Iron