High Energy Astrophysics in Cosmic Structures (1)

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Outline

- Part 1: Historical remarks
- Part 2: Basics of high-E Astrophysics
  - Emission Mechanisms
  - Origin of particles: Leptons vs. hadrons
  - Condition in cosmic structures
- Part 3: High-E sources : Properties & Science
  - SNR, Pulsars, PWN
  - Galactic Center
  - AGNs
  - Galaxy clusters
  - DM annihilation and/or decay
  - Cosmology & Fundamental Physics
  - The highest-E particles
- Part 4: AstroParticle Physics in cosmic structure
  - An overall picture
- Part 5:Strategies: Observations, Theory, Data-analysis

An initial statement

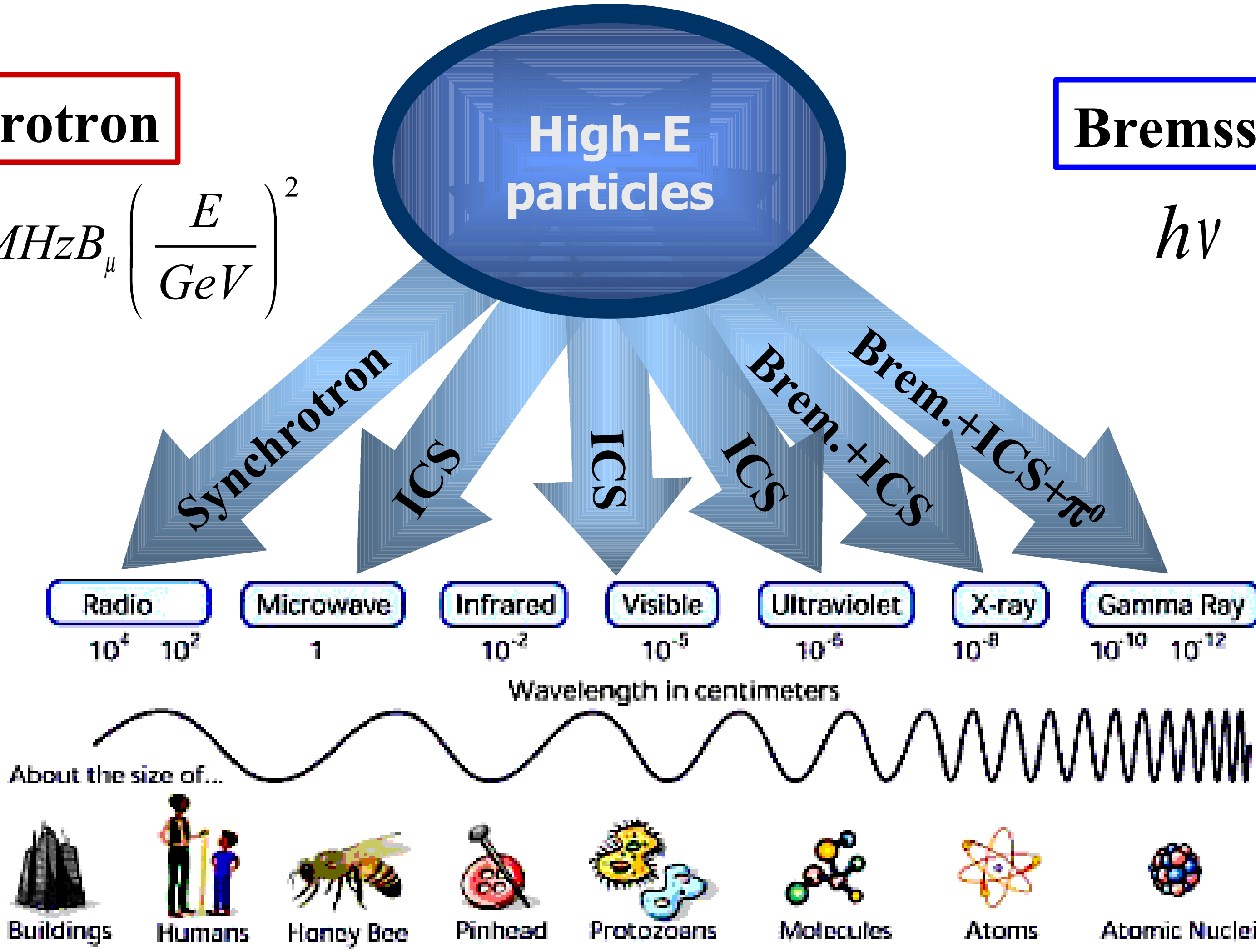
High-E particles vs. High-ν radiation

Synchrotron

$$\nu \approx 3.7 MHz B_{\mu} \left(\frac{E}{GeV} \right)^2$$

Bremsstrahlung

$$h\nu \approx E$$



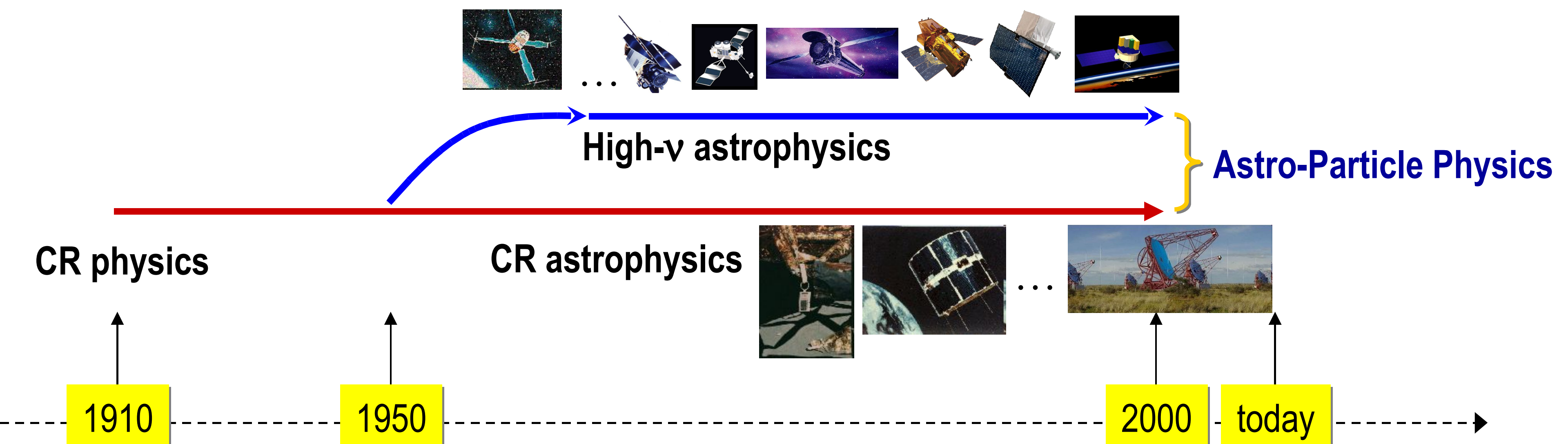
Part 1
Historical Remarks

The beginning

- The naissance of **high-E astrophysics** coincides with the study of cosmic rays (in the early 1910's) and then (in the 1950's) proceeds with the naissance of high-ν astrophysics (X-rays, γ-rays, TeVs, …)

- These two branches followed different paths…
  for a long time (~ 50 years) divided

- Today these two paths come together again…
  in the modern **Astro Particle Physics** approach.



CR physics begins

1900-1910: Measurements of ionization rates at increasing heights above the ground showed a decrease that could be explained as due to absorption of the ionizing radiation by the intervening air.

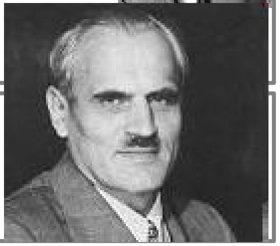
1912 Domenico Pacini observed simultaneous variations of the rate of ionization over a lake, and over the sea. He concluded that a certain part of the ionization must be due to sources other than the radioactivity of the Earth or air.

1912 Victor Hess carried three Wulf electrometers (a device to measure the rate of ion production inside a hermetically sealed container) to an altitude of 5300 meters in a free balloon flight. He found the ionization rate increased approximately fourfold over the rate at ground level. He concluded *“My observation are best explained by the assumption that a radiation of very great penetrating power enters our atmosphere from above."*

1913-14, **Werner Kolhörster** confirmed Victor Hess' results by measuring the increased ionization rate at an altitude of ~ 9 km.

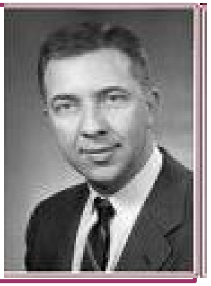
CR physics continues

The term "**cosmic rays**" was coined by **R. Millikan** who proved they were extra-terrestrial in origin, and not produced by atmospheric electricity as Hess thought. [*Millikan believed that cosmic rays were high-energy photons with some secondary electrons produced by Compton scattering of γ rays*.]



Compton himself held the (*correct*) belief that cosmic rays were primarily charged particles.

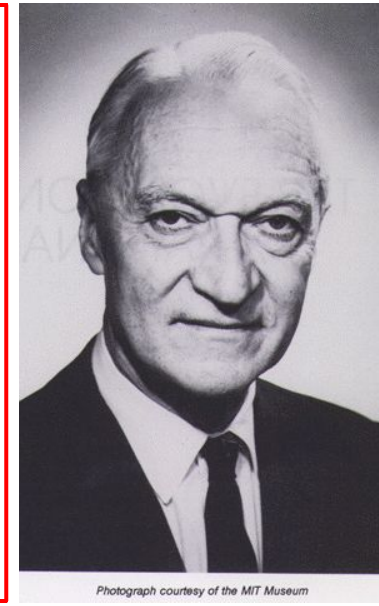
1927 – 1937: a wide variety of experimental investigations demonstrated that the primary cosmic rays are mostly positively charged particles, and the secondary radiation observed at ground level is composed primarily of a "soft component" of electrons and photons and a "hard component" of penetrating particles, (erroneously thought to be muons).



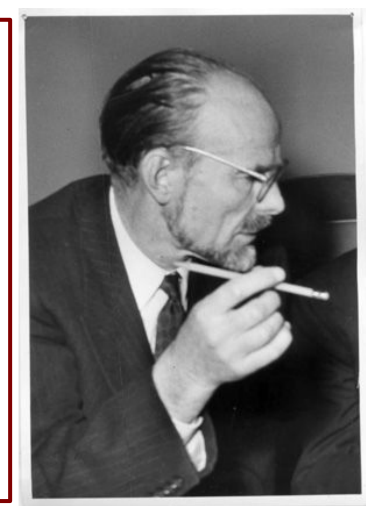
1948: observations with nuclear emulsions carried by balloons near the top of the atmosphere by **Gottlieb** & **Van Allen** showed that the primary cosmic particles are mostly protons with some helium nuclei (alpha particles) and a small fraction heavier nuclei.

CR astronomy begins

In **1934** **Bruno Rossi** reported an observation of nearly simultaneous discharges of two Geiger counters widely separated in a horizontal plane during a test of equipment he was using in a measurement of the so-called east-west effect. In his report on the experiment, Rossi wrote *"...it seems that once in a while the recording equipment is struck by very extensive showers of particles, which causes coincidences between the counters, even placed at large distances from one another"*. Unfortunately, he did not have the time to study this phenomenon more closely.



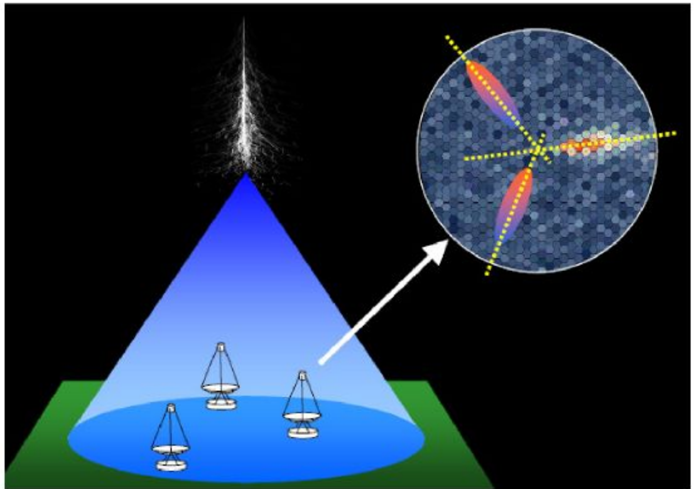
In **1937** **Pierre Auger**, unaware of Rossi's earlier report, detected the same phenomenon and investigated it in some detail. He concluded that extensive particle showers are generated by high-energy primary cosmic-ray particles that interact with air nuclei high in the atmosphere, initiating a cascade of secondary interactions that ultimately yield a shower of electrons, photons, and muons that reach ground level.

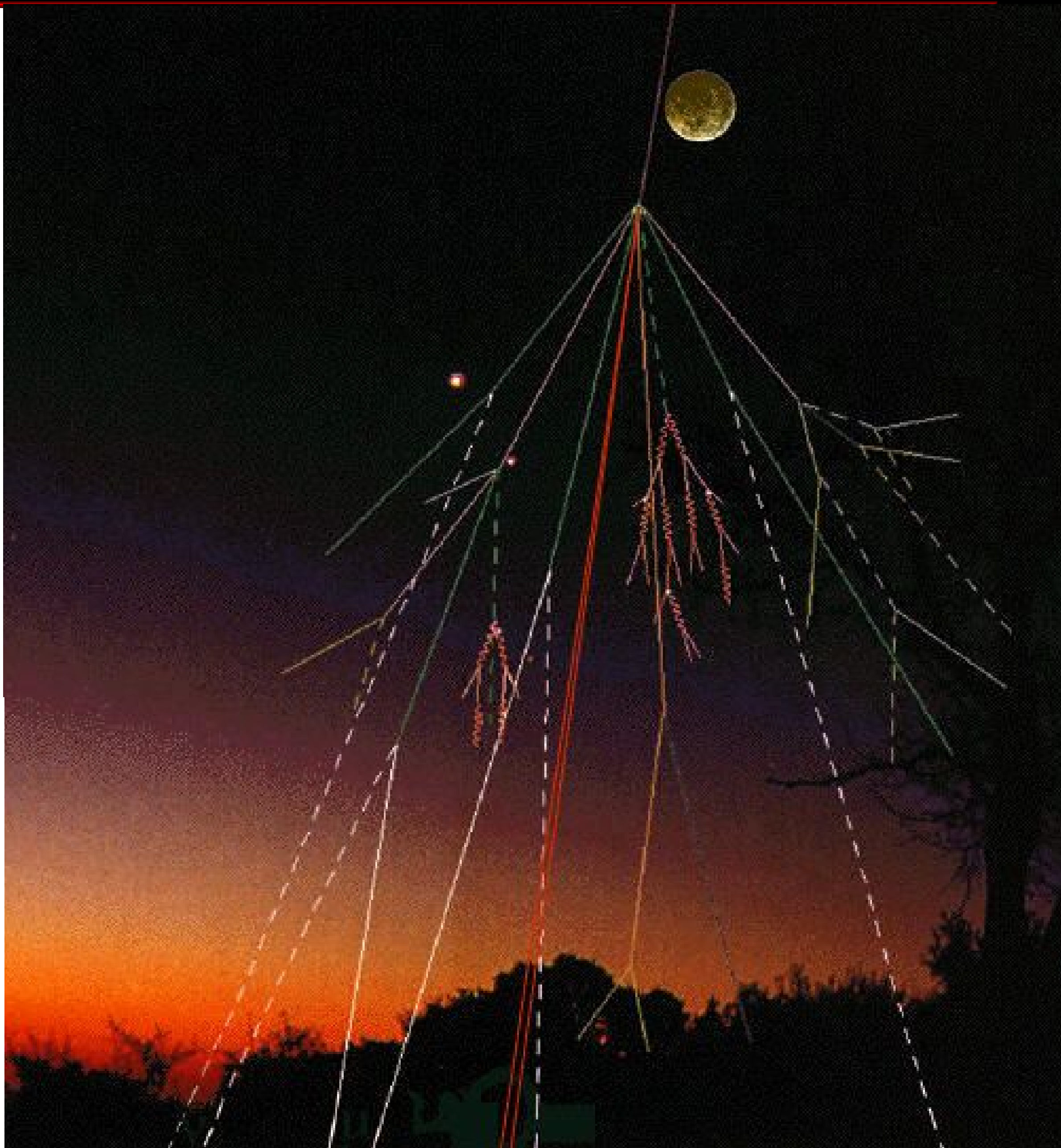


CR showers

Reconstructing the energy and the arrival direction of cosmic rays by studying the associated air shower

Cosmic Ray Astrophysics





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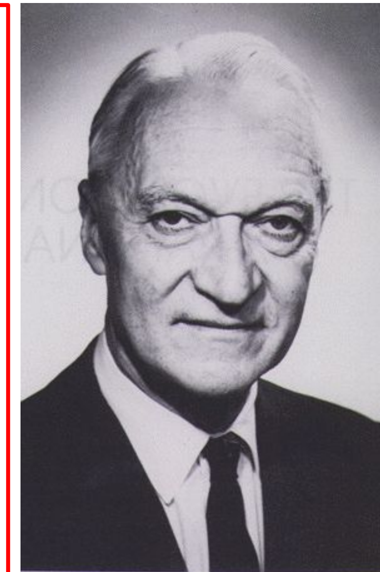
Photograph courtesy of the MIT Museum

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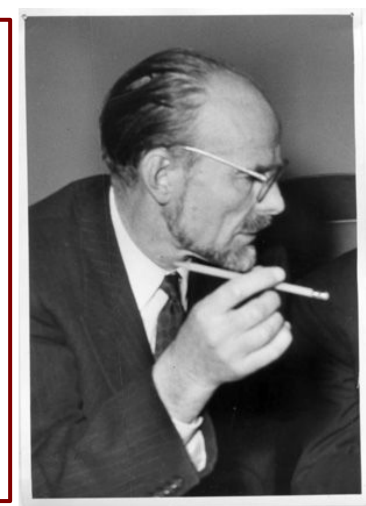


The parallel study of high-ν radiation

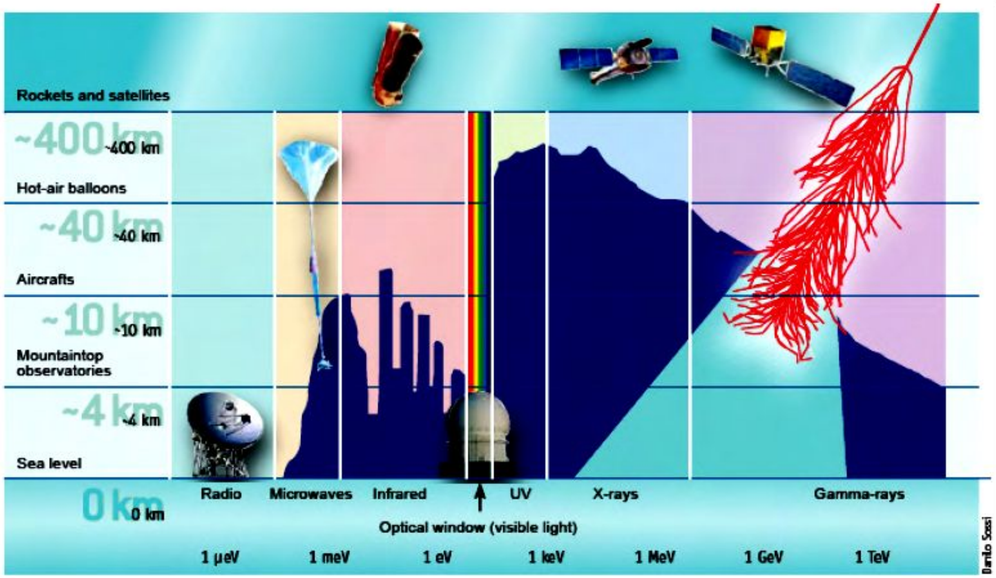
The existence of extra-terrestrial CRs led a number of scientists to envisage that the universe should be also producing high-E (X-ray, gamma) photons, long before experiments could detect gamma rays emitted by cosmic sources.

Work by Eugene Feenberg and H. Primakoff in 1948, Sachio Hayakawa and I.B. Hutchinson in 1952, and, especially, Morrison in 1958 had led scientists to believe that a number of different processes which were occurring in the universe would result in gamma-ray emission.

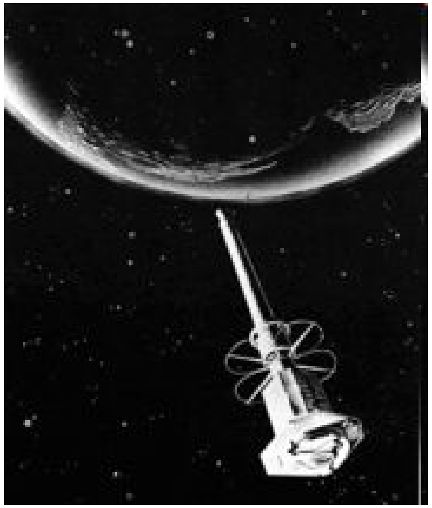
These processes included cosmic ray interactions with interstellar gas, supernova explosions, and interactions of energetic electrons with magnetic fields.

However, it was not until the 1960s that our ability to actually detect these emissions came to pass.

Need to go in space!

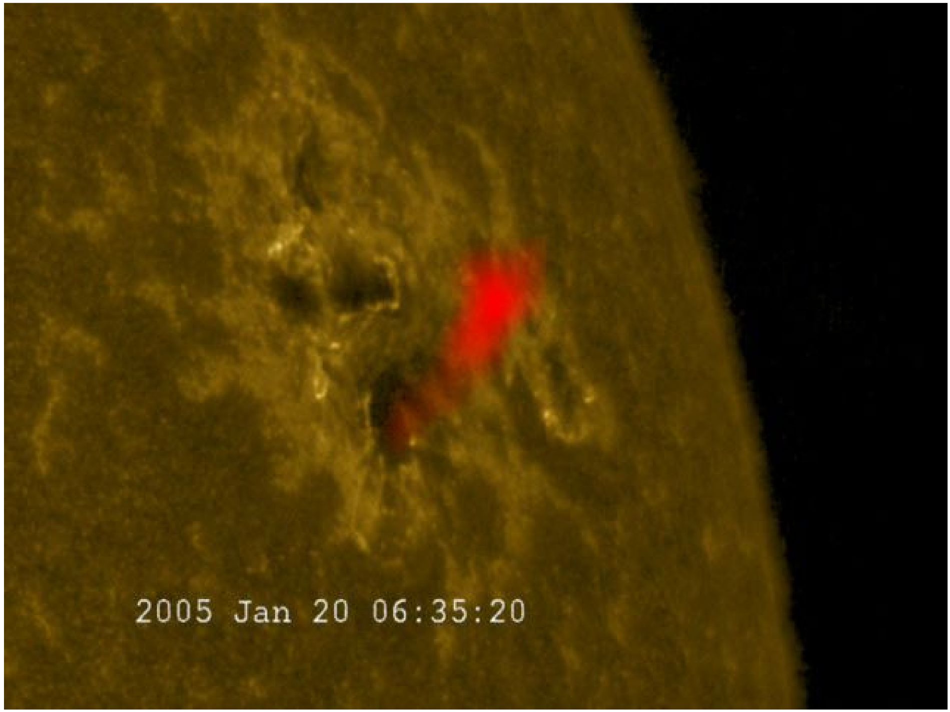


Gamma-ray astronomy



1961: the first gamma-ray telescope carried into orbit, on the Explorer 11 satellite, picked up ~ 100 cosmic γ-ray photons. These appeared to come from all directions in the Universe, implying some sort of uniform "gamma-ray background". Such a background would be expected from the interaction of cosmic rays (very energetic charged particles in space) with gas found between the stars.

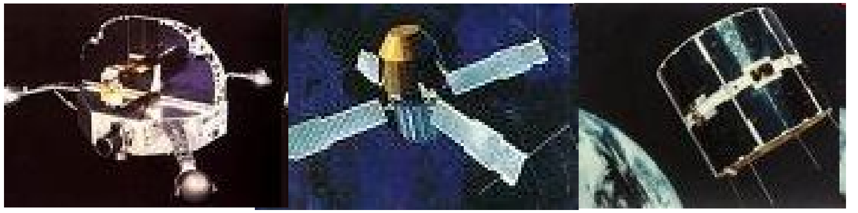
The first true astrophysical γ-ray sources were solar flares, which revealed the strong 2.223 MeV line predicted by Morrison. This line results from the formation of deuterium via the union of a neutron and proton; in a solar flare the neutrons appear as secondaries from interactions of high-energy ions accelerated in the flare process.



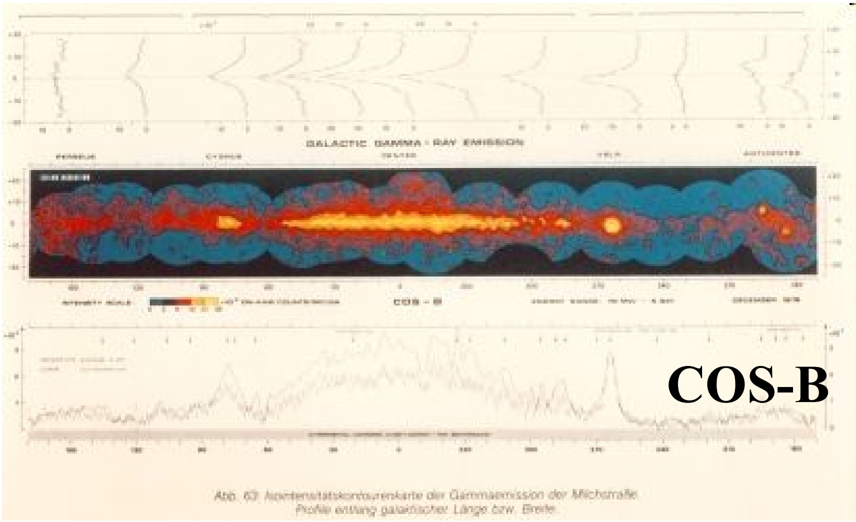
These first γ-ray line observations were from OSO-3 (1963), OSO-7 (1973), and the Solar Maximum Mission (1980). The solar observations inspired theoretical work by Reuven Ramaty and many others.

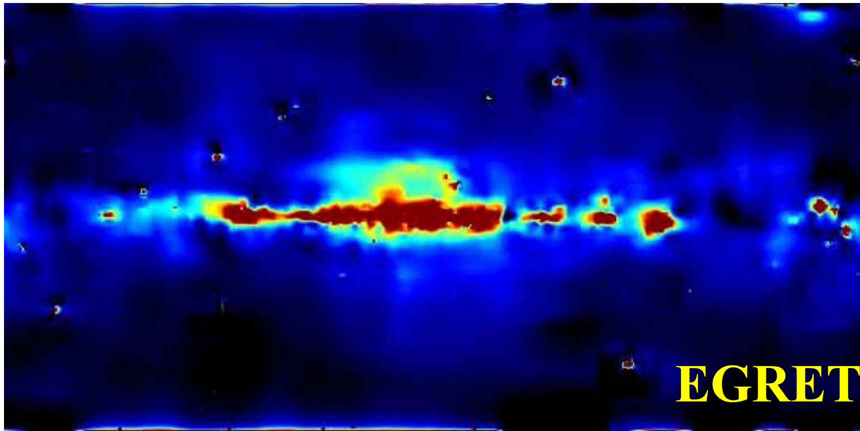
Gamma-ray astronomy

1967: significant γ-ray emission from our galaxy was first detected by the gamma-ray detector aboard the OSO-3 satellite.
It detected **621 events** attributable to cosmic gamma-rays.



1975-1982: The field of γ-ray astronomy took great leaps forward with the SAS-2 and the COS-B satellites.
These two satellites provided an exciting view into the high-energy universe. They confirmed the earlier findings of the γ-ray background, produced the **first detailed map of the sky at γ-ray wavelengths**, and detected a number of point sources. However, the poor resolution of the instruments made it impossible to identify most of these point sources with individual stars or stellar systems.





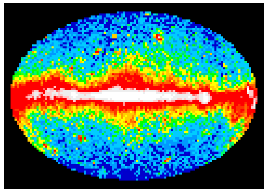
Gamma Ray Burts (GRBs)

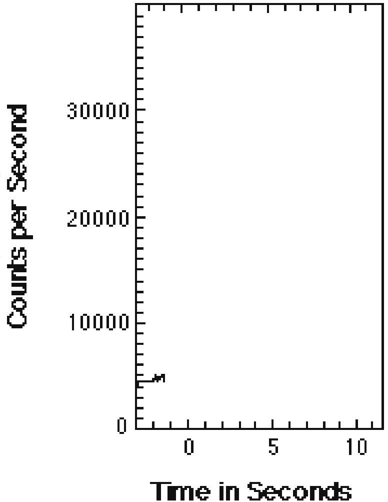
One of the most spectacular discovery in γ-ray astronomy came in the late 1960s - early 1970s from a constellation of defense satellites which were put into orbit for a “completely different” reason. Detectors on board the Vela satellite series, designed to detect flashes of γ-rays from nuclear bomb blasts, began to record bursts of gamma-rays, not from the vicinity of the Earth, but from deep space.

Today, these gamma-ray bursts are seen to last for fractions of a second to minutes, popping off like cosmic flashbulbs from unexpected directions, flickering, and then fading after briefly dominating the gamma-ray sky.

Studied for over 25 years now with instruments on board a variety of satellites and space probes, including Venera (CCCP) spacecraft and the Pioneer Venus Orbiter (USA) the sources of these high-E flashes remain a mystery.

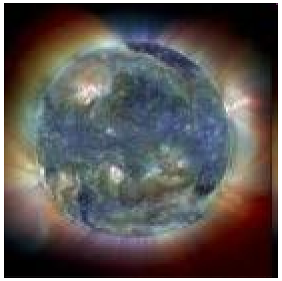
They appear to come from far away in the Universe at cosmological distances.
Current theories are able to explain many of their astrophysical and cosmological properties.
(see Meszaros 2002, Dar & DeRujula 2007 for reviews)

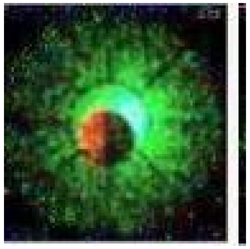


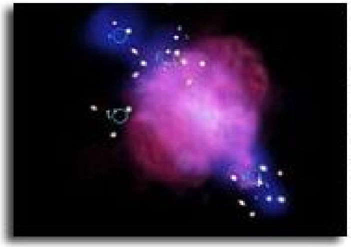


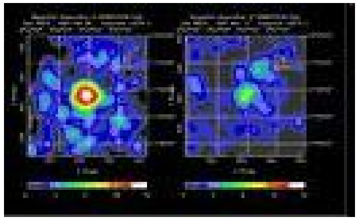
X-ray astronomy

Milestones





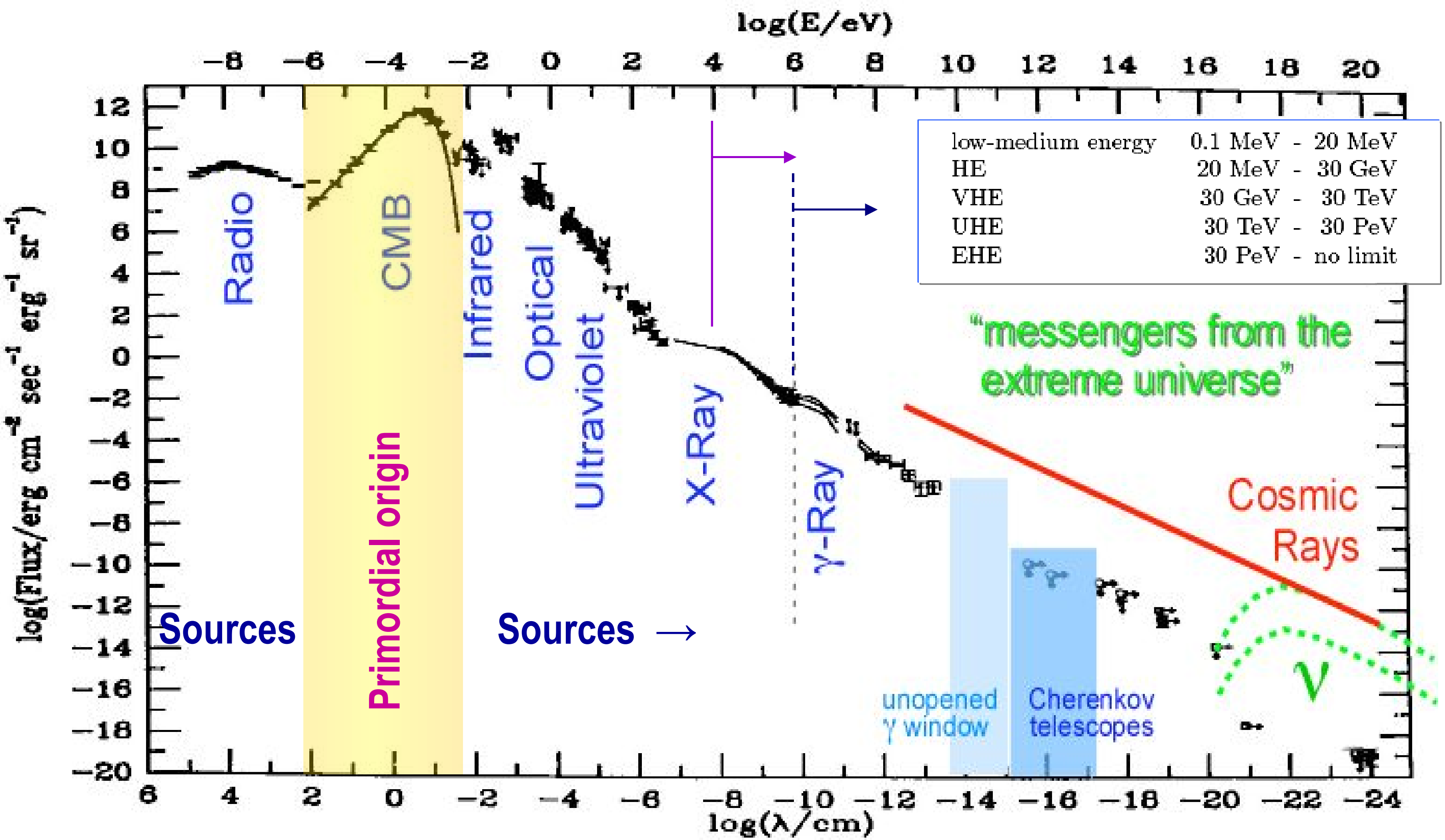




1949—the Sun is a weak X-ray star (H. Friedman)
1962—Scorpius X-1 discovered (R. Giacconi)
1970—First all-sky X-ray survey (Uhuru, R. Giacconi)
X-ray binaries and galaxy cluster X-ray sources discovered
1973—Announcement of discovery of Gamma-Ray Bursts
1974—Second all-sky X-ray survey (Ariel 5)
Presence of hot (10^7 K) intragalactic gas demonstrated
1978—First grazing incidence observatory (Einstein, Giacconi)
1996—Identification of the first GRB counterpart (BeppoSAX)
1999—Launch of Chandra
1999—Launch of XMM/Newton
2004—Launch of Swift
2008—New mission studies: SimbolX, nu-Star, NeXT, E-Rosita, IXO, …

→ towards Hard X-rays (E> 20 keV → 100 keV)

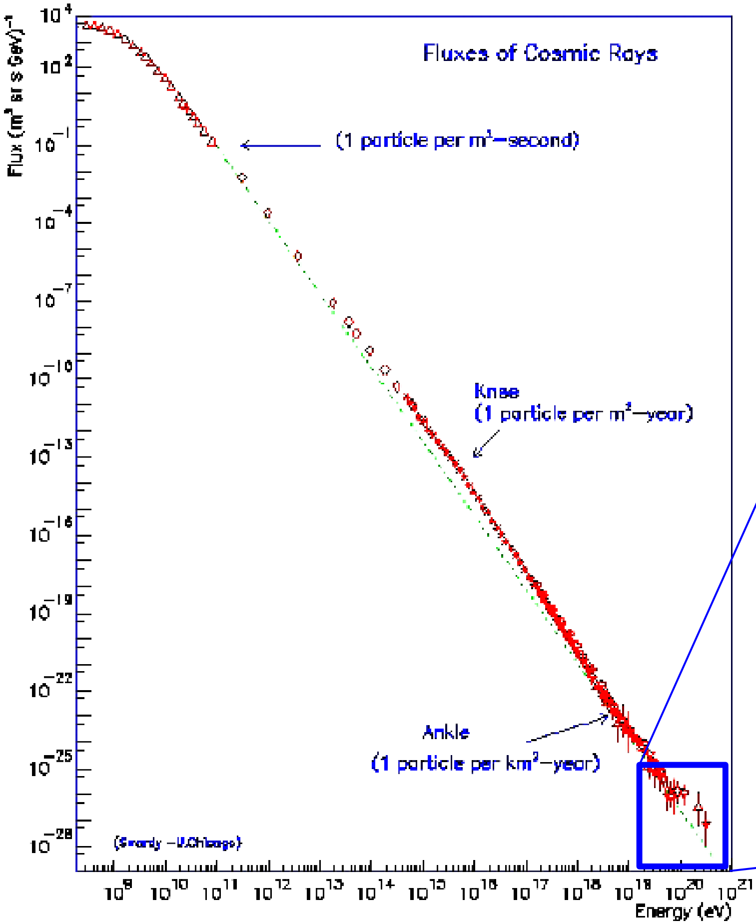
The cosmic photon backgrounds



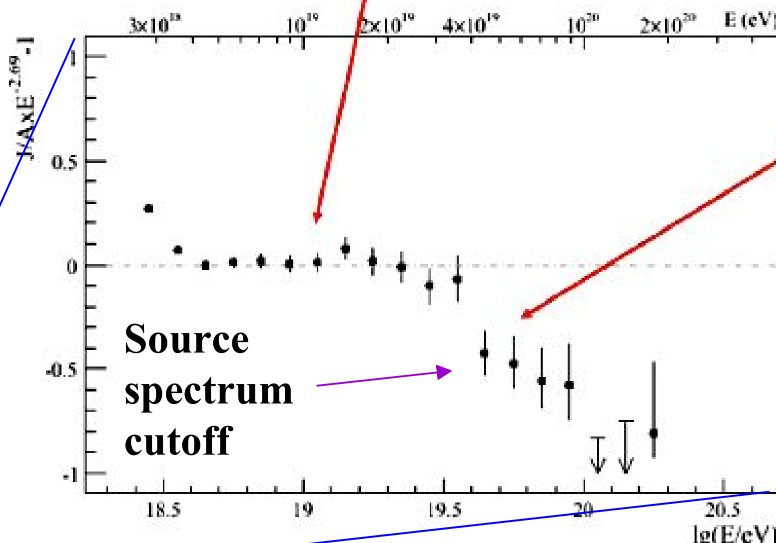
The cosmic particle background

$$\frac{dF}{dE} \propto E^{-\beta},$$

$$\begin{aligned}
\beta &\simeq 2.7; \quad E < E[\text{knee}] \sim 3 \times 10^{15}\ \text{eV}, \\
\beta &\simeq 3.0; \quad E[\text{knee}] < E < E[\text{knee2}] \sim 2 \times 10^{17}\ \text{eV} \\
\beta &\sim 3.1; \quad E[\text{knee2}] < E < E[\text{ankle}], \\
\beta &\sim 2.7; \quad E > E[\text{ankle}] \sim 3 \times 10^{18}\ \text{eV}.
\end{aligned}$$



$\beta = 2.69 \pm 0.02$



GZK suppression

Slope γ above 4×10^{19} eV:

4.2 ± 0.4

HiRes:

5.1 ± 0.7

Fron now on..

Facts:

- There is a high-E particle background out to very high-E

$$n(E) \sim E^{-p}$$

- There is a high-frequency radiation background out to very high-ν (…equivalent photon energies E_γ)
- The two backgrounds seem to be associated

$\rightarrow$ Backgrounds are made by Sources (… except CMB)

Aim: understand the high-E Universe

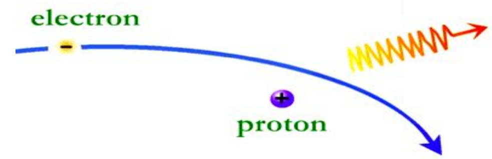
- Basics of high-E astrophysics
- High-E cosmic sources
- Constraints to Astro Particle Physics
- Strategies: Observations, Theory, Data Analysis

Part 2
Basics of High-E Astrophysics

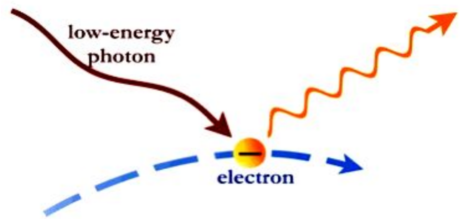
Emission mechanisms

Leptons

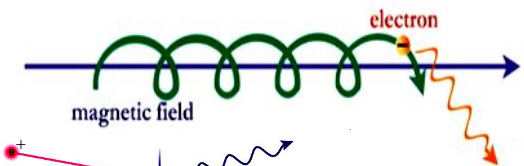
Bremsstrahlung



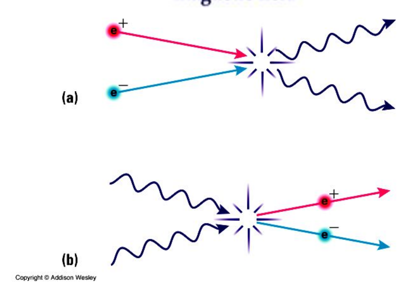
Inverse Compton



Synchrotron

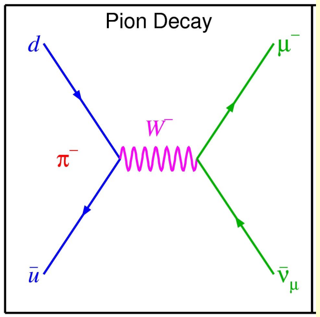


Pair production

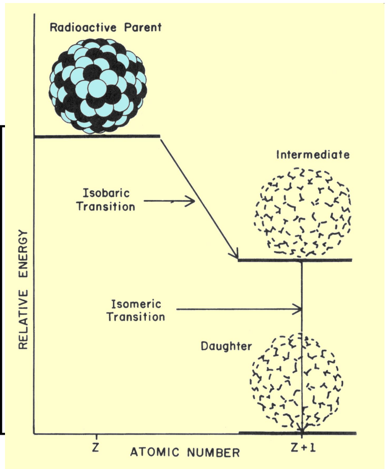


Hadrons

Pion decay



Nuclear transitions



A “compact” description

Electromagnetic (e.m.) radiation is a waggling of an e.m. field.
The only places where e.m. fields are attached to matter are called electric charges
So, there is really only **one radiation mechanism**: **waggle an electric charge**.

e.m. field responsible for waggling charged particles and produce e.m. radiation

Radioactivity

γ-rays

No strong G-field oscillating at ≥ 10^6 Hz !
G-field not responsible for e.m. radiation

Essentials…

Assume: electron in a plane e.m. wave with mean energy density **u_{light}**

Electron in a changing electric field has an equation of motion $\ddot{z} = \frac{e}{m_0} E$

(the e^- radiates like an Hertzian dipole)

Radiated power $\frac{2}{3}\frac{\ddot{p}}{c^3}$

$$\frac{2}{3c^3}\frac{e^4}{m_0^2}E^2 = \underbrace{\frac{8\pi}{3}\left(\frac{e^2}{m_0 c^2}\right)^2}_{\sigma_T}\underbrace{\left(\frac{E^2}{4\pi}\right)}_{u_{light}} c$$

$\sigma_T \quad u_{light} \quad c$ (1)

Which can be generalized as: $2\, c\, \sigma_T\, u_{electric\ field}$ (2)

Mean radiated power

Relativistic case

The following transformations must be taken into account:

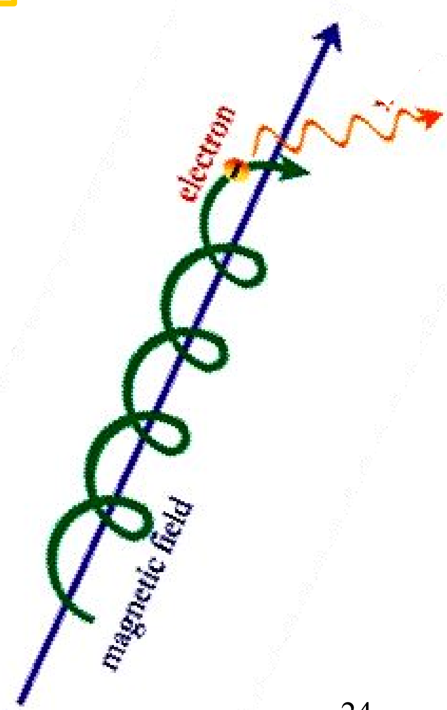
A) In eq.(2) we must use the electric field seen by the the elecron in its own rest frame

$$\boxed{\text{E seen by electron} = \frac{E + (v/c)\times B}{\sqrt{1 - v^2/c^2}} = \gamma\left(E + \frac{v}{c}\times B\right)}$$

so the electron radiates a power $\quad 2\gamma^2 c\sigma_T \dfrac{\overline{(E + (v/c)\times B)^2}}{8\pi}$

For example, if the field (in the lab. frame) is a static B-field, the power radiated by an electron is

$$\boxed{2\gamma^2 c\sigma_T \frac{v^2}{c^2}\frac{B_\perp^2}{8\pi} \approx 2\gamma^2 c\sigma_T u_B \sin^2\psi}$$



Where ψ is the angle between **B** and **v**, i.e. the pitch angle of the spiral path of the electron.

...continued

B) The energy radiated in Δt of the observer's time is radiated in only

$$\Delta t' = \Delta t\sqrt{1 - v^2/c^2} = \Delta t/\gamma \qquad \text{of the electron's proper time}$$

So that the amount of energy observed in Δt is: $2\gamma^2 c\sigma_T u_B \Delta t' = \frac{1}{\gamma} 2\gamma^2 c\sigma_T u_B \Delta t$

C) The radiation from the electron is observed with a Doppler shift.

Therefore the amount of radiation in the observer's frame is γ times greater .

Clearly, effects B) and C) cancel out, so that, when the field in the observer's frame is purely magnetic, the power radiated is given by:

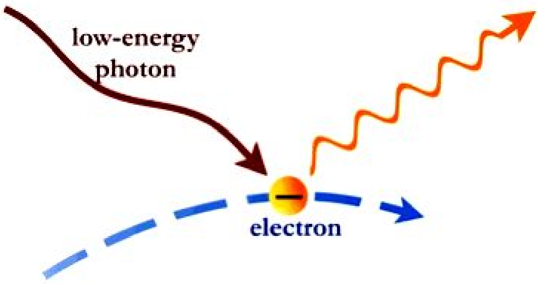
$$\boxed{\text{Power radiated} = 2\gamma^2 c\sigma_T u_B \sin^2\psi} \qquad (3)$$

This is the expression for the ***Synchrotron radiation***

Note: no approximation has been made: this is not an order of mag. calculation.

...continued

We may, as well, calculate the power emitted by **Inverse Compton Scattering** (ICS). This occurs when a a high-E electron scatters a low-E photon the photon is scattered with increased energy in a direction very close to the electron's direction of motion.



Suppose that there is an isotropic flux of photons in a region where there are fast electrons. Then:

$$\boxed{\text{mean radiated power} = 2c\sigma_T (u'_{electric-field})}$$

Observed from the electron's frame, the volume containing a given number of photons is contracted by a factor γ, and as they have no net momentum in the observer's frame, the effect of Doppler shifts is to increase the mean energy by a factor γ .
So:

$$\boxed{u'_{electric-field} = \gamma^2 u_{electric-field}}$$

$$\boxed{\text{mean radiated power} = 2c\sigma_T \gamma^2 (u_{electric-field}) = c\sigma_T \gamma^2 u_{light}}$$

Radiation spectra

$$F_\nu(E,\nu) \propto \frac{1}{4\pi D_L^2}\int dr^3 \quad n_{eq.}(E,r) \left.\frac{dE}{dt}\right|_{mechanism-i} \left.\frac{dE}{d\nu}\right|_{observed-\nu}$$

$F_\nu(E,\nu) \downarrow$ **E cm^{-2} s^{-1} ν^{-1}**

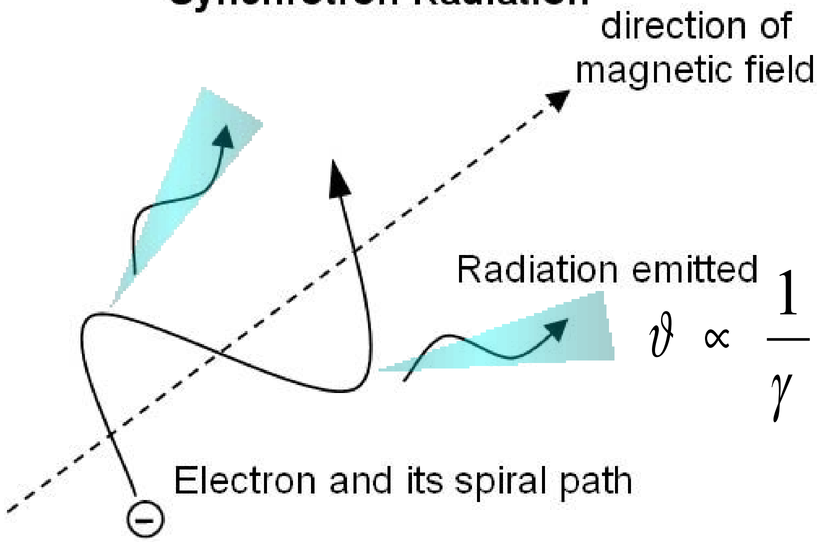
$n_{eq.}(E,r) \downarrow$ **E^{-1} cm^{-3}**

$\frac{dE}{dt} \downarrow$ **E s^{-1}**

$\frac{dE}{d\nu} \downarrow$ **E ν^{-1}**

Synchrotron

Synchrotron Radiation



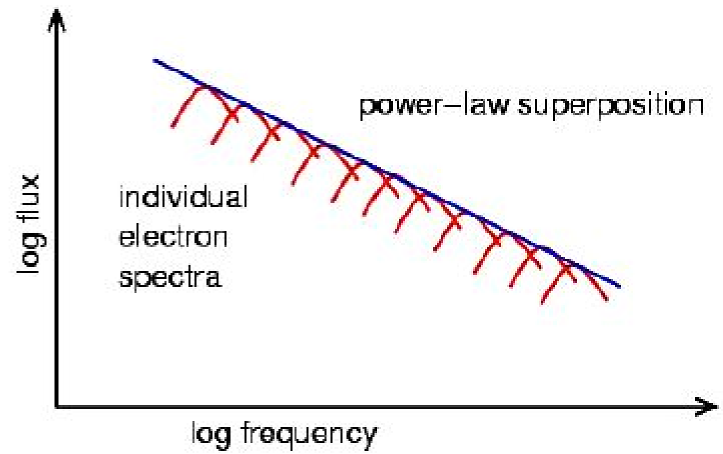
$$\vartheta \propto \frac{1}{\gamma}$$

Figure 3: Electrons spiralling along magnetic field lines emit radiation due to the acceleration (change in direction) of the electron. This radiation has an energy distribution dependent on the strength of the magnetic field. If the electron is travelling close to the speed of light the radiation emitted is 'beamed' in the forward direction and strongly polarised.

For a spectrum $n(\gamma)d\gamma = n_0 y^{-p} d\gamma$

Assume that photons are only emitted at frequency $\gamma^2\nu_L$ (good approximation since the spectrum has strong peak there), i.e.,

$$\phi_\nu(\gamma) \sim \delta(\nu - \gamma^2\nu_L) \quad (6.19)$$



$$\omega_c = \gamma^2\omega_L = \frac{eB}{m_e c}\left(\frac{E}{m_e c^2}\right)^2$$

$$\alpha_{synch} = \frac{p-1}{2}$$

$$P_\nu = \frac{2}{3} c\sigma_T n_0 \frac{U_B}{\nu_L}\left(\frac{\nu}{\nu_L}\right)^{-\frac{p-1}{2}}$$

The synchrotron spectrum of an electron power-law distribution is a power law

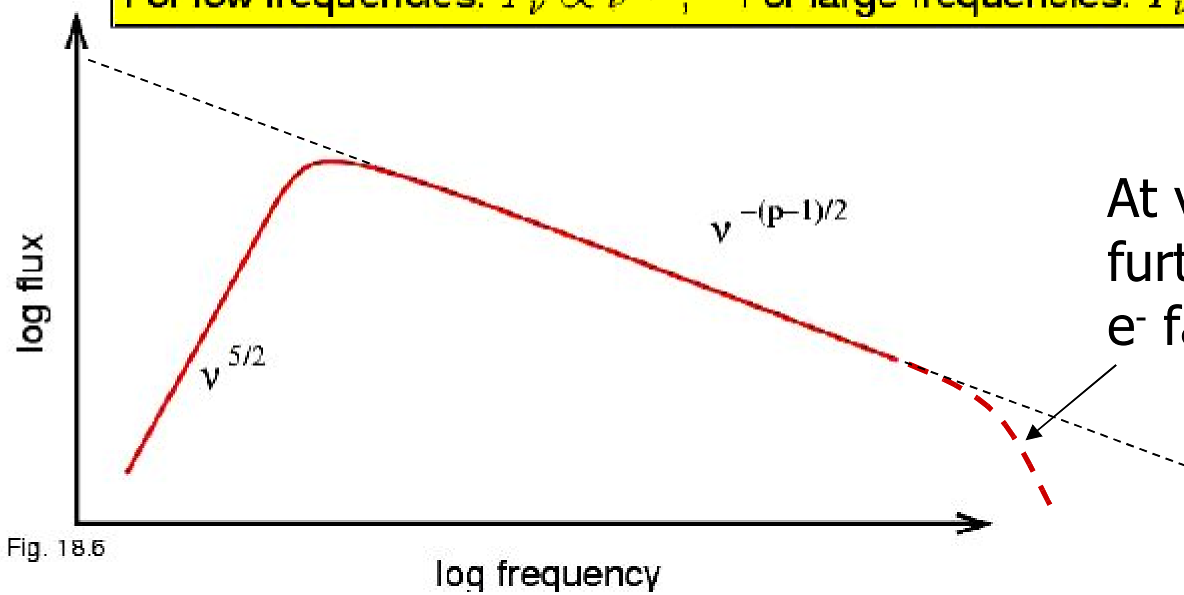
Synchrotron breaks

Below a typical cut-off frequency, the electrons are optically thick for the synchrotron radiation → Synchrotron Self-Absorption

For a power-law electron distribution the optically thick spectrum is

$\boxed{P_\nu \propto B^{-1/2}\nu^{5/2}}$ independent of the electron spectral index p !

For low frequencies: $P_\nu \propto \nu^{5/2}$, For large frequencies: $P_\nu \propto \nu^{-(p-1)/2}$.



after Shu, Fig. 18.6

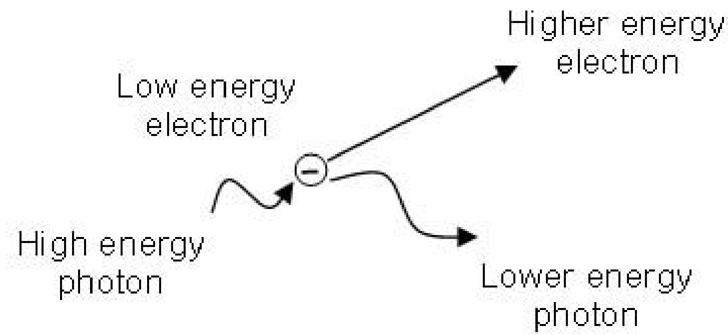
At very high-ν there are further breaks due to e^- fast energy losses

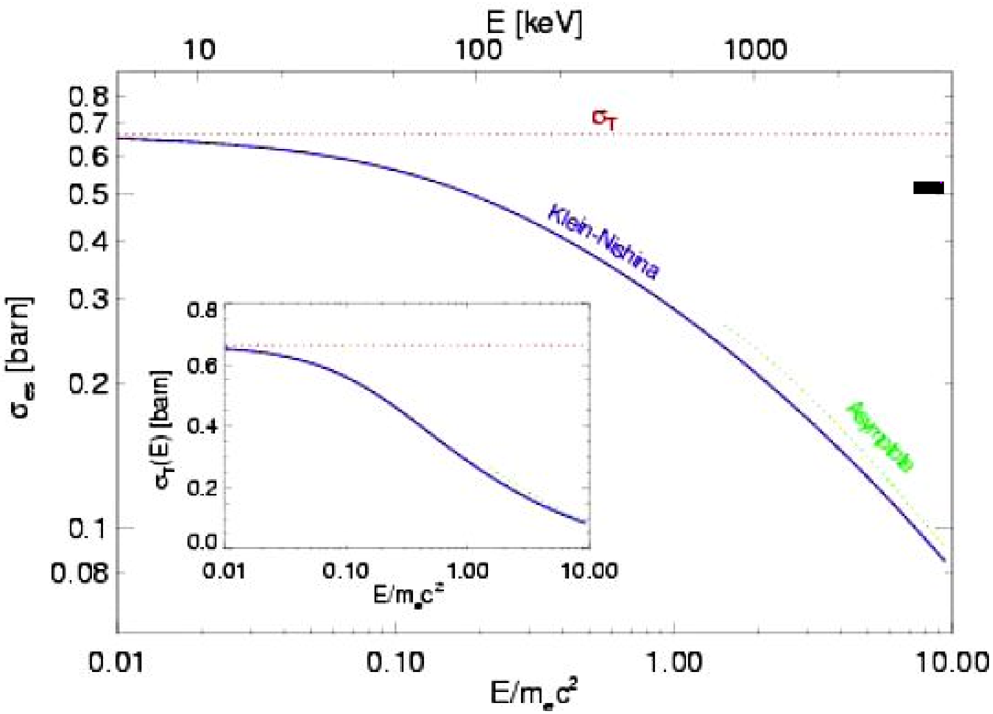
Inverse Compton Scattering (ICS)

Scattered radiation power: $P = \left|\vec{S}\right| \cdot \sigma$

with $\left|\vec{S}\right| = \dfrac{c}{4\pi}\left|\vec{E}\right| \times \left|\vec{H}\right| = \dfrac{c}{4\pi}\left|\vec{E}\right|^2$

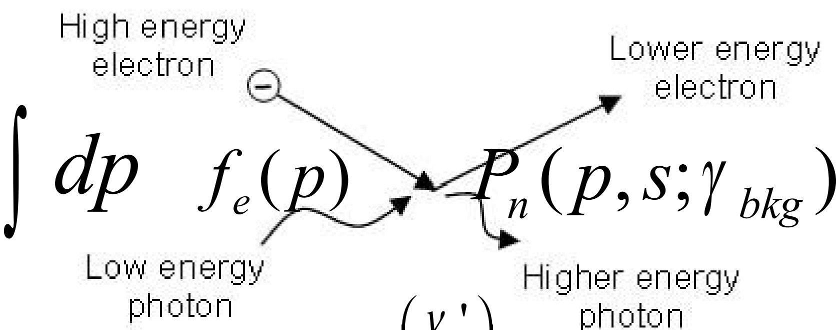
Compton scattering – photons loose energy





For x » 1 $\longrightarrow$ $\sigma \sim \frac{3}{8}\sigma_T \frac{1}{x}\left(\ln 2x + \frac{1}{2}\right)$

Inverse Compton scattering – photons gain energy



$$\int dp \quad f_e(p) \quad P_n(p, s; \gamma_{bkg})$$

$$s \equiv \ln\left(\frac{\nu'}{\nu}\right)$$

Figure 6: The two Compton scattering processes result in radiation being shifted to lower energies (Compton scattering) or higher energies (inverse Compton scattering). The essential factor differentiating these two processes is the kinetic energy of the electron involved.

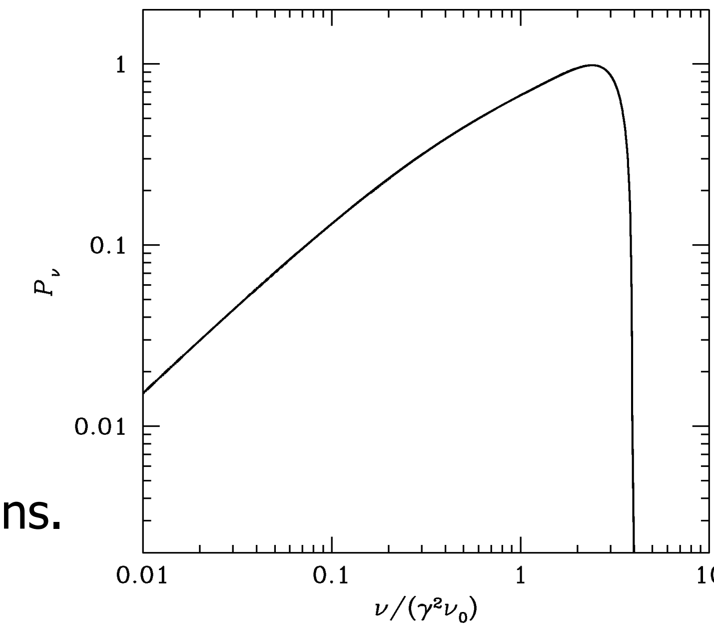
ICS (2)

Non-Thermal Comptonization

Average Energy gain
for relativistic electrons $\frac{\Delta\nu}{\nu} \approx \frac{4}{3}\gamma^2$

The ICS spectrum of electrons with energy γ irradiated by photons of frequency ν_0.

This spectrum is even more peaked than the synchrotron spectrum of mono-energetic electrons.



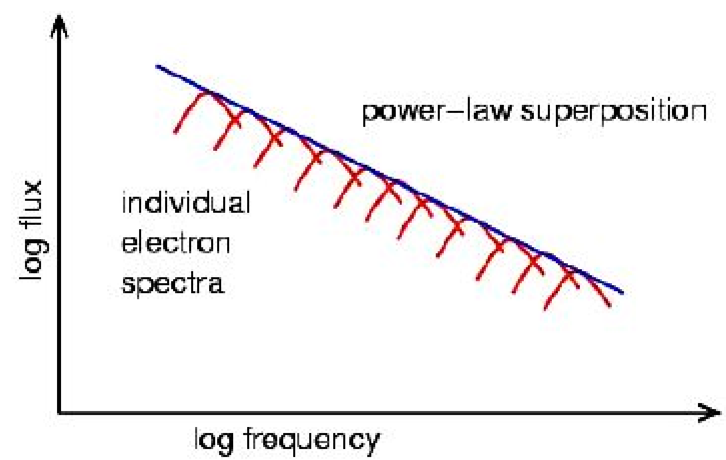
If the electron-energy distribution is

$$N(E)=KE^{-p}$$

the ICS spectrum is also a power law

$$P_\nu \sim \nu^{-\alpha}$$

with spectral index **$\alpha = (p-1)/2$**



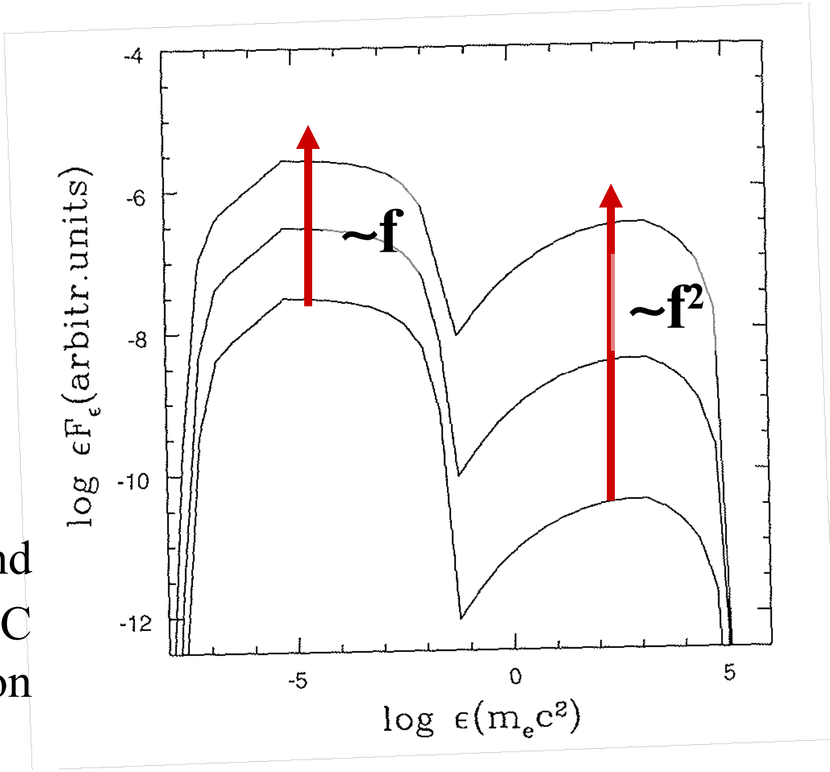
Synchrotron Self Compton

SSC radiation results from inverse-Compton scattering of synchrotron radiation by the same relativistic electrons responsible for the synchrotron radiation. Since

$$\frac{P_{ICS}}{P_{Synch}} = \frac{U_{light}}{U_B}$$

multiplying the density of relativistic electrons by a factor f multiplies both the synchrotron power and its contribution to U_{rad} by f, so

the SSC power scales as f^2.



Self-Compton radiation also contributes to $U_{\rm light}$ and leads to significant 2nd-order scattering as the SSC contribution to $U_{\rm light}$ approaches the synchrotron contribution. This runaway positive feedback (Compton Catastrophe) is a very sensitive function of the source brightness temperature, so IC losses very strongly cool the relativistic electrons if the source brightness temperature exceeds $T_{\rm max} = 10^{12}$ K in the rest frame of the source.

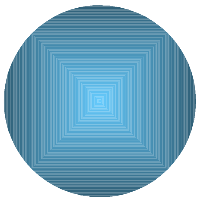
Radio sources with $T_b > T_{max}$ are either Doppler boosted or not-incoherent synchrotron sources (e.g. Pulsar or coherent RG)

ICS (3)

Thermal Comptonization:

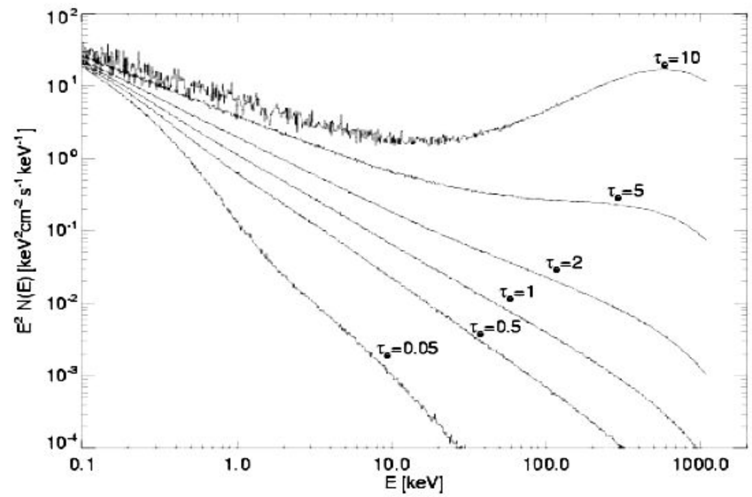
Average Energy gain of thermal NR e$^-$ $$\frac{\Delta \nu}{\nu} \approx 4 \frac{kT_e}{m_e c^2}$$

Case of BHs – thick plasmas



Sphere at kT=360 keV.
Seed photons come
from the sphere center.

y«1: pure power-law
y<1: power-law + exp. cutoff
y»1: saturated Comptonization



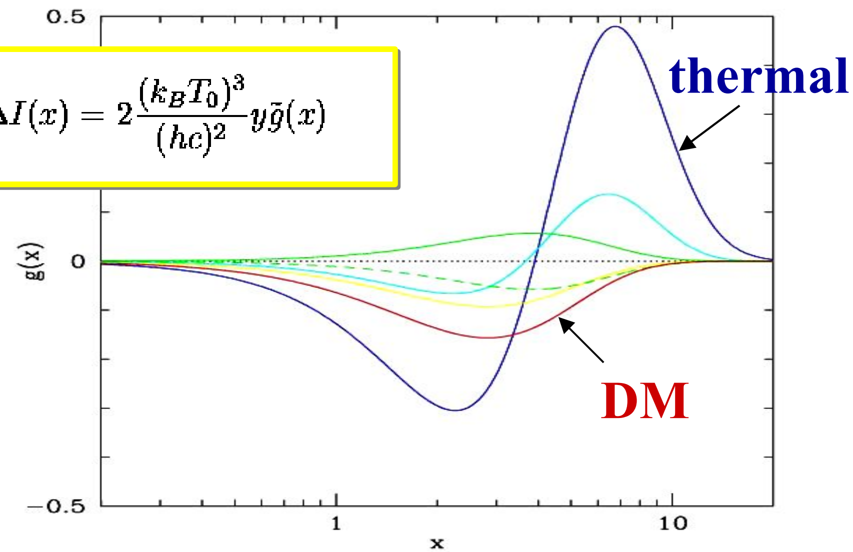
Case of clusters – thin plasmas

$$y = \frac{\sigma_T}{m_e c^2} \int P d\ell.$$

$$\tilde{g}(x) = \frac{m_e c^2}{\langle k_B T_e \rangle} \left\{ \frac{1}{\tau} \left[\int_{-\infty}^{+\infty} i_0(x e^{-s}) P(s) ds - i_0(x) \right] \right\}.$$

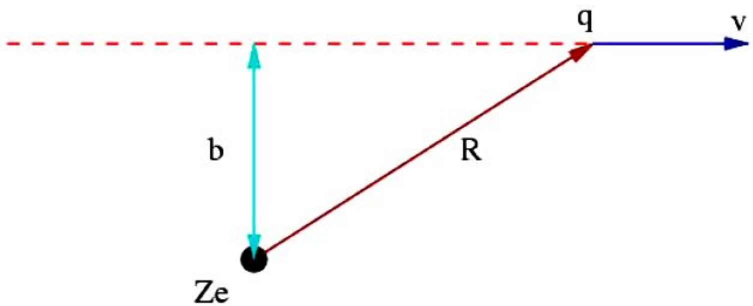
$$P(s) = \int_0^\infty dp f_e(p) P_s(s; p)$$

$$\Delta I(x) = 2 \frac{(k_B T_0)^3}{(hc)^2} y \tilde{g}(x)$$



Bremsstrahlung

Detailed understanding requires Quantum Electrodynamics (QED)! But one can have a good overview using Classical Electrodynamics.



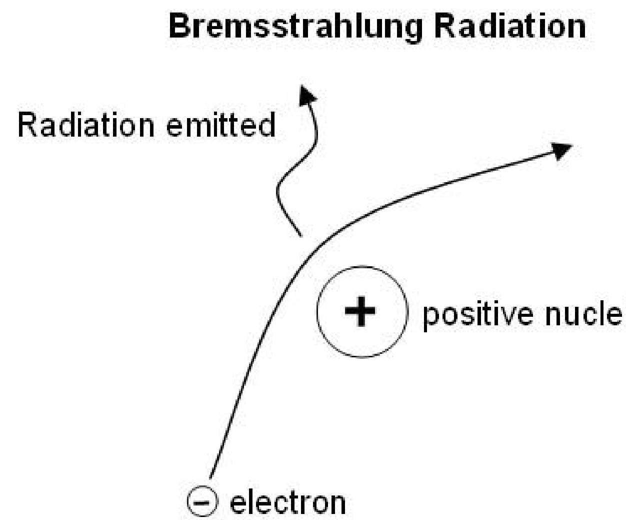


Figure 1: Bremsstrahlung (or 'braking') radiation is emitted when the path of a charged particle such as an electron is deviated by another charged particle. The acceleration of the electron causes it to emit a photon of light with an energy indicative of the electrons kinetic energy.

Work in classical Born approx. (small angles).
Path of the electron not influenced by the nucleus
Calculate motion along straight line → z=vt.
Acceleration is mainly ⊥ motion:

$$|\ddot{x}| = \frac{Z_i e^2}{m_e (b^2 + v^2 t^2)}$$

(Mainly produced by electrons)

$$E(t) = \frac{Z_i e^3 \sin\theta}{m_e c^2 R (b^2 + v^2 t^2)} \xrightarrow{\text{Fourier transform}} E(\omega) = \left(\frac{Z_i e^3 \sin\theta}{m_e c^2 R}\right)\left(\frac{\pi}{bv}\right) e^{-\omega b/v}$$

Bremsstrahlung (2)

Emitted E per unit area and frequency: $$\frac{\mathrm{d}W}{\mathrm{d}A\,\mathrm{d}\omega} = c|E(\omega)|^2$$

$$\frac{\mathrm{d}W(b)}{\mathrm{d}\omega} = \int_0^{\pi} c|E(\omega)|^2 R^2 2\pi \sin\theta\,\mathrm{d}\theta = \frac{8}{3\pi}\left(\frac{Z_i^2 e^6}{m_e^2 c^3}\right)\frac{1}{(bv)^2}\,e^{-2\omega b/v}$$

Assume: electron density n_e and ion density n_i

- flux of electrons with velocity v incident on ions: n_e v
- area element around each ions: $2\pi b\mathrm{d}b$

Emission per unit time, volume and frequency: $$\frac{\mathrm{d}W}{\mathrm{d}\nu\,\mathrm{d}V\,\mathrm{d}t} = n_e n_i 2\pi v \int_{b_{\min}}^{\infty} \frac{\mathrm{d}W(b)}{\mathrm{d}\nu} b\,\mathrm{d}b$$

- Straight line approximation (small Δv)
- Particle approximation (Quantum effects small)

$$b^1_{\min} = \frac{4Ze^2}{\pi m v^2}$$

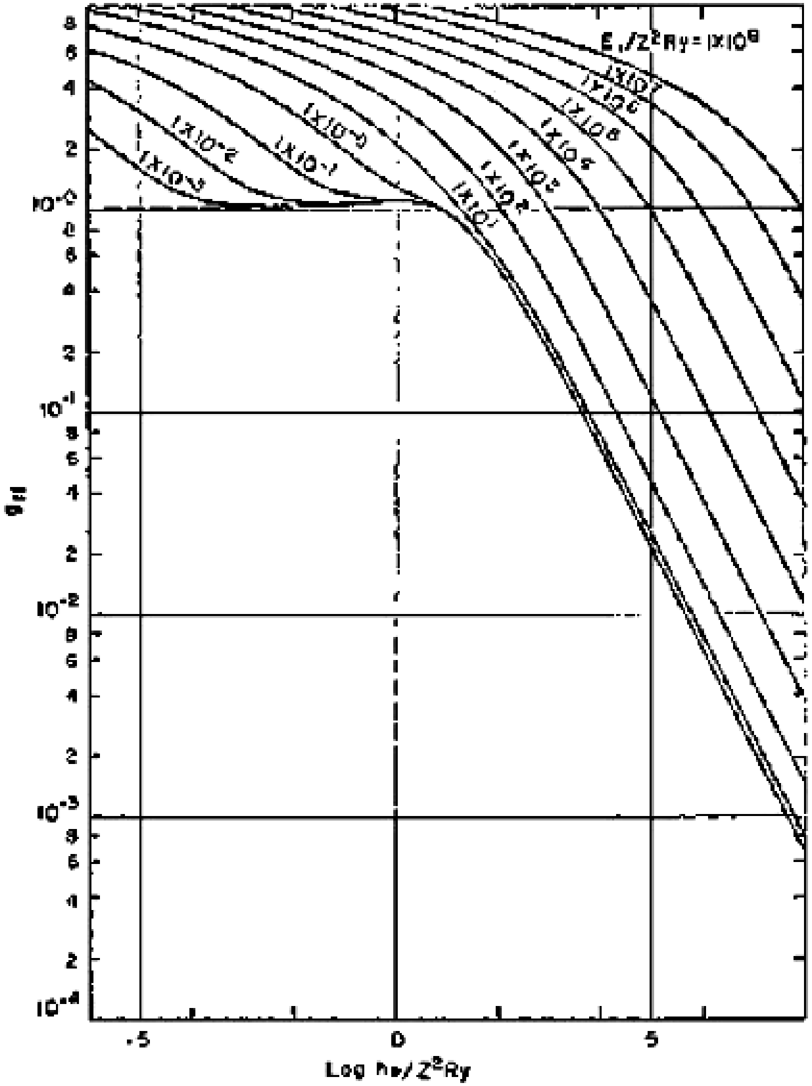
$$b^2_{\min} = \frac{h}{mv}$$

- Small angle collision → large contribution only up to b_{max}

$$b_{\max} = \frac{v}{\omega}$$

$$\frac{\mathrm{d}W}{\mathrm{d}\omega\,\mathrm{d}V\,\mathrm{d}t} = \frac{16e^6}{3c^3 m_e^2 v} n_e n_i Z^2 \int_{b_{\min}}^{b_{\max}} \frac{\mathrm{d}b}{b} = \frac{16e^6}{3c^3 m_e^2 v} n_e n_i Z^2 \ln\left(\frac{b_{\max}}{b_{\min}}\right)$$

Bremsstrahlung (3)



QED effects

In reality, perform QED computations. Result is

$$\frac{\mathrm{d}W}{\mathrm{d}\omega\,\mathrm{d}V\,\mathrm{d}t} = \frac{16\pi e^6}{3^{3/2} m_e^2 c^3 v} n_e n_i Z^2 g_{ff}(v,\omega) \qquad (5.11)$$

where g_{ff} is the Gaunt factor.

From the above, one can formally write

$$g_{ff}(v,\omega) = \frac{\sqrt{3}}{\pi} \ln\left(\frac{b_{max}}{b_{min}}\right) \qquad (5.12)$$

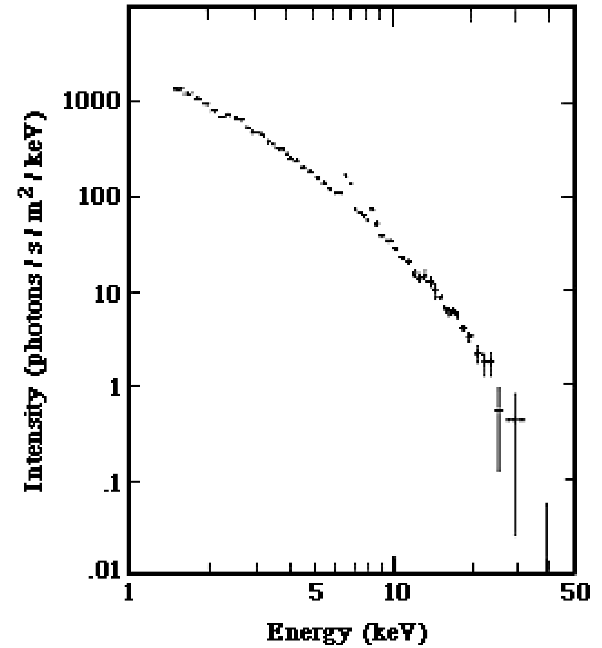
Karzas&Latter, 1961, Fig. 1

Bremsstrahlung (4)

Thermal bremsstrahlung

Electron distribution $\mathrm{d}P \propto v^2 \exp\left(-\frac{mv^2}{2kT}\right)$

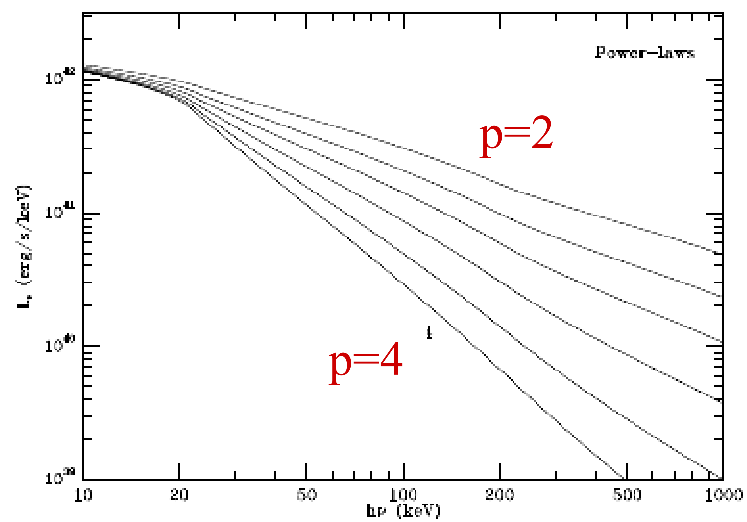
$$\frac{\mathrm{d}W}{\mathrm{d}V\,\mathrm{d}t\,\mathrm{d}\nu} = \frac{2^5 \pi e^6}{3 m_e c^3}\left(\frac{2\pi}{3 m_e k}\right)^{1/2} \cdot T^{-1/2} Z^2 n_e n_i e^{-h\nu/kT} \cdot \bar{g}_{\mathrm{ff}}$$



Non-Thermal bremsstrahlung

Electron distribution $n(\gamma)d\gamma = n_0 \gamma^{-p} d\gamma$

$$\frac{dW}{dVdtd\nu} \propto (h\nu)^{-p}$$

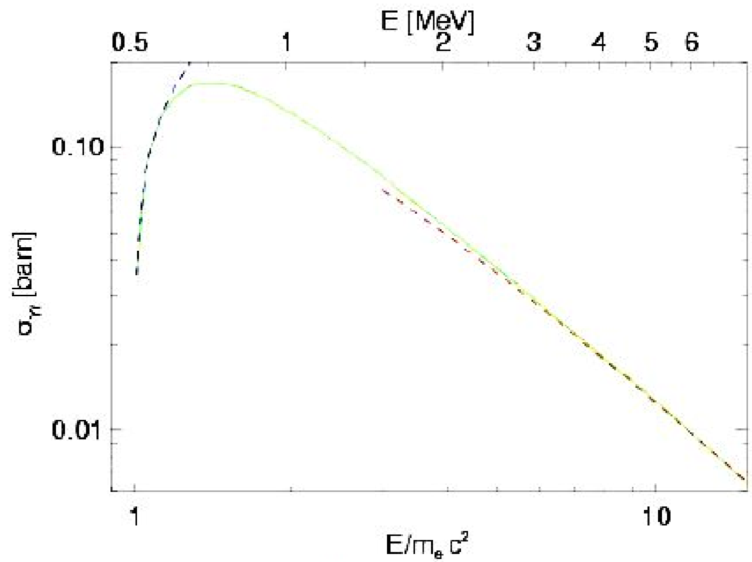


Other processes

γ–γ pair production Production of e± pairs in sites with high radiation energy density

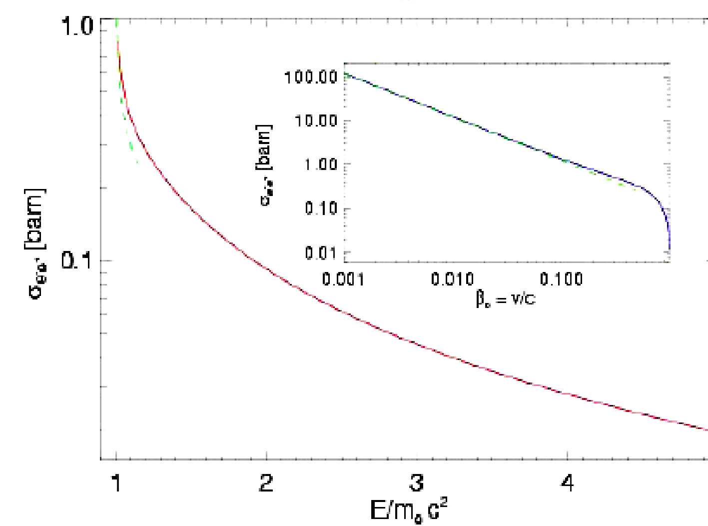
$$\gamma + \gamma \rightarrow e^{+} + e^{-}$$

$$\sigma_{\gamma\gamma} = \frac{\pi r_0^2}{\epsilon^2}\left(\left(2 + \frac{2}{\epsilon^2} - \frac{1}{\epsilon^4}\right)\ln\left(\epsilon + \sqrt{\epsilon^2 - 1}\right) - \sqrt{1 - \frac{1}{\epsilon^2}}\left(1 + \frac{1}{\epsilon^2}\right)\right)$$



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

$$\sigma_{e\,e'} = \pi r_0^2 \left(\frac{1 - \beta_c^2}{4\beta_c}\right)\left\{\frac{3 - \beta_c^4}{\beta_c}\ln\left(\frac{1 + \beta_c}{1 - \beta_c}\right) + 2\left(\beta_c^2 - 2\right)\right\}$$

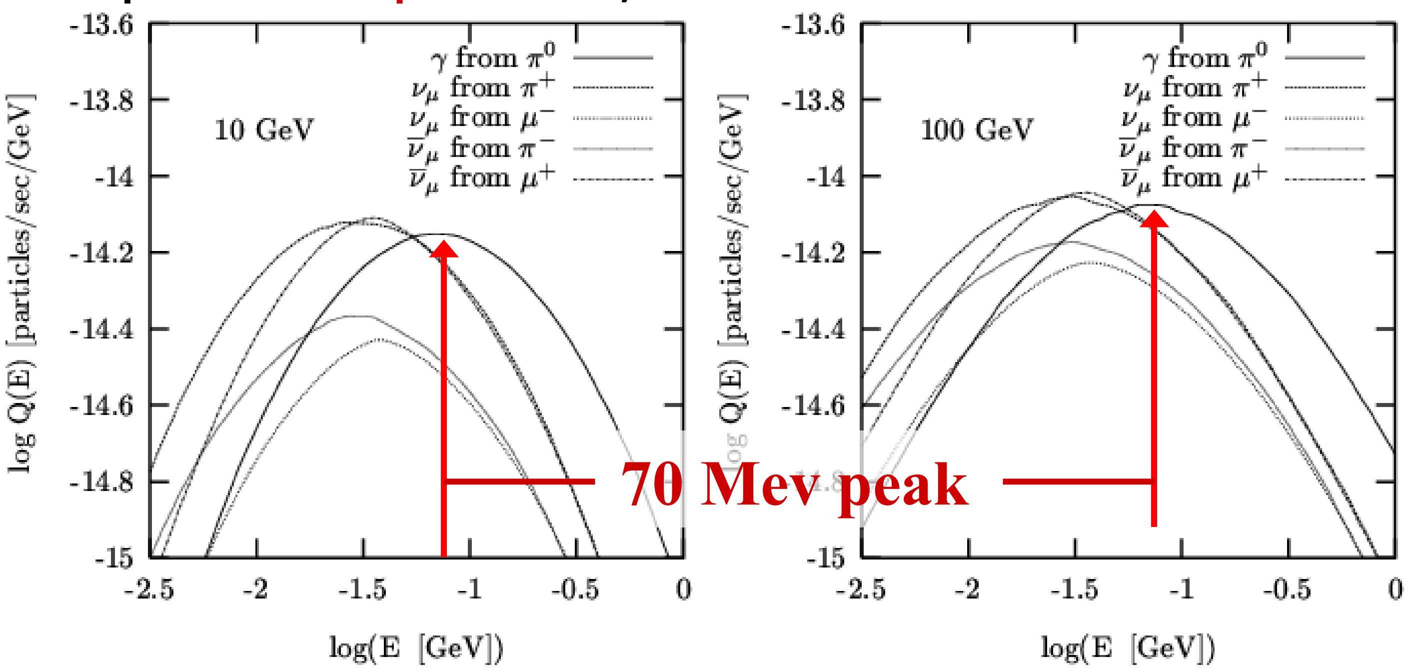


Pion decay

$$X + X \rightarrow \pi^{\pm} \rightarrow \mu^{\pm} + \nu_{\mu},\quad \mu^{\pm} \rightarrow e^{\pm} + \nu_e + \nu_{\mu}$$

$$X + X \rightarrow \pi^{0} \rightarrow \gamma\gamma$$

Spectra of photons, neutrinos & anti-neutrinos

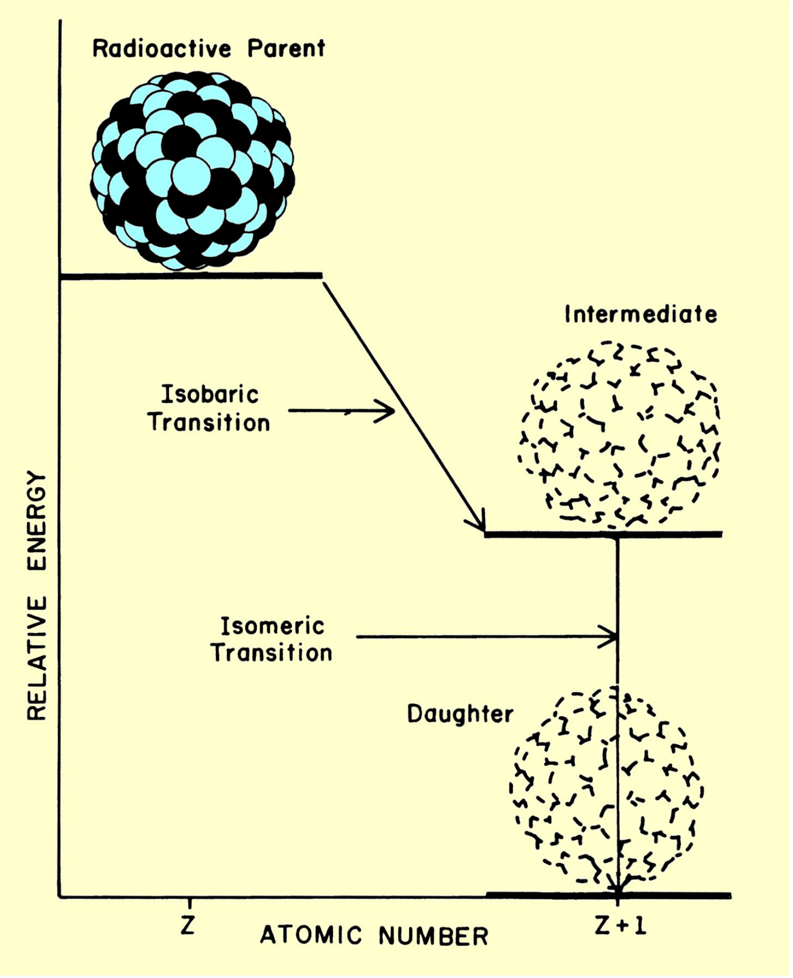


$M_\pi \approx 140$ MeV

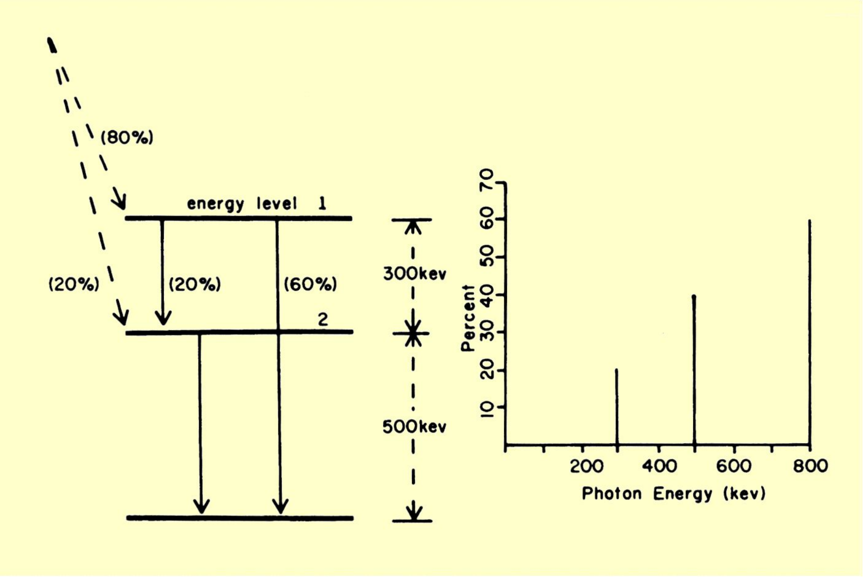
Nuclear transitions

ISOMERIC TRANSITIONS

After a radioactive nucleus undergoes an isobaric transition (beta emission, positron emission, or electron capture), it usually contains too much energy to be in its final stable or daughter state. Nuclei in these intermediate and final states are isomers, since they have the same atomic and mass numbers. Nuclei in the intermediate state will undergo an isomeric transition by emitting energy and dropping to the ground state.



In most isomeric transitions, a nucleus will emit its excess energy in the form of a gamma photon.



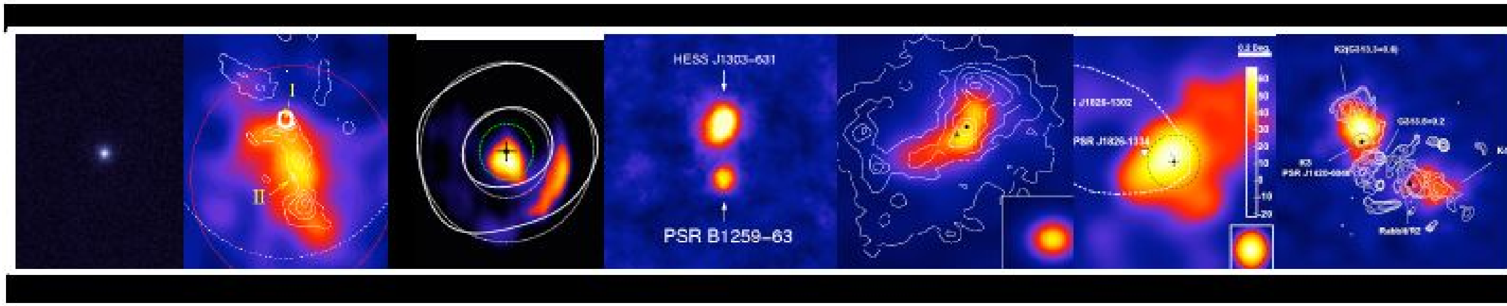
A Zoo of high-E cosmic sources

ASDC ASI Science Data Center

High-E radiation in cosmic sources: zoology

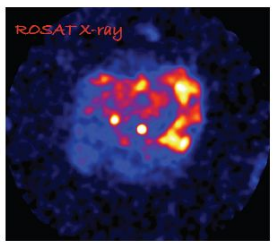
Pulsars

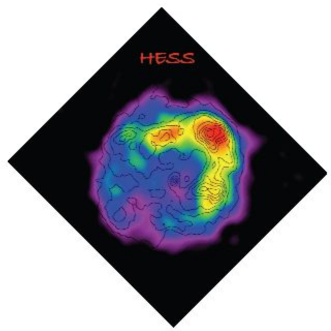
PWNe

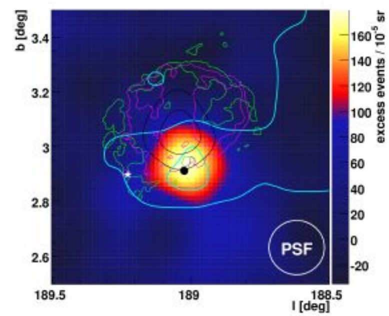


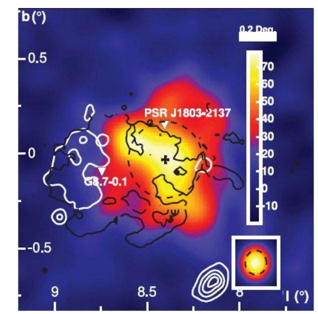
SNRs

Molecular Clouds



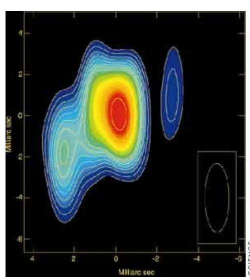


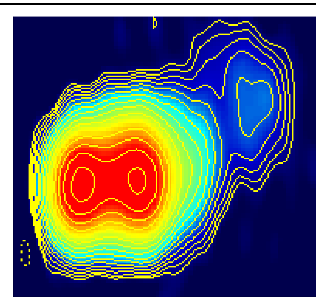


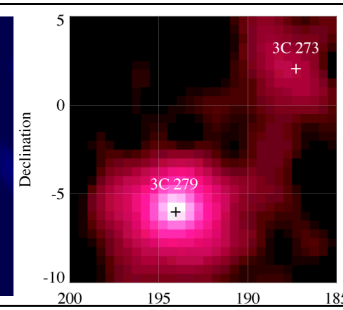


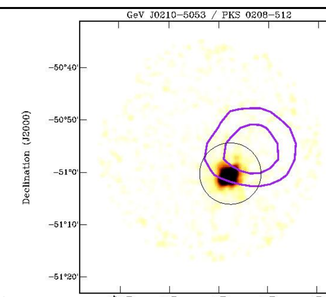
AGNs

μQSOs







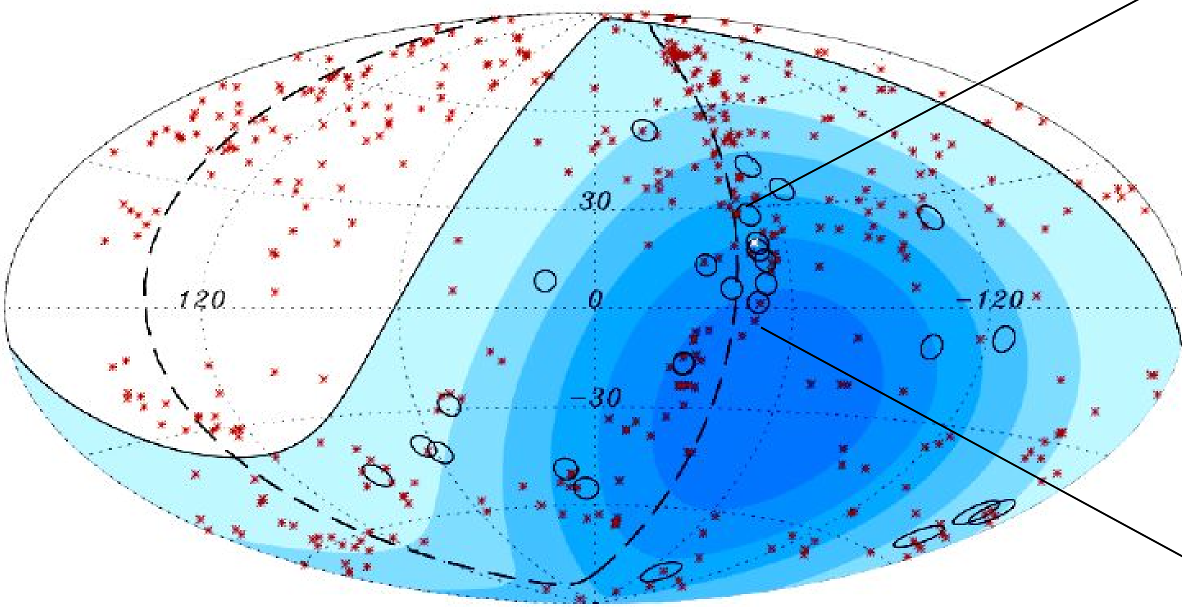


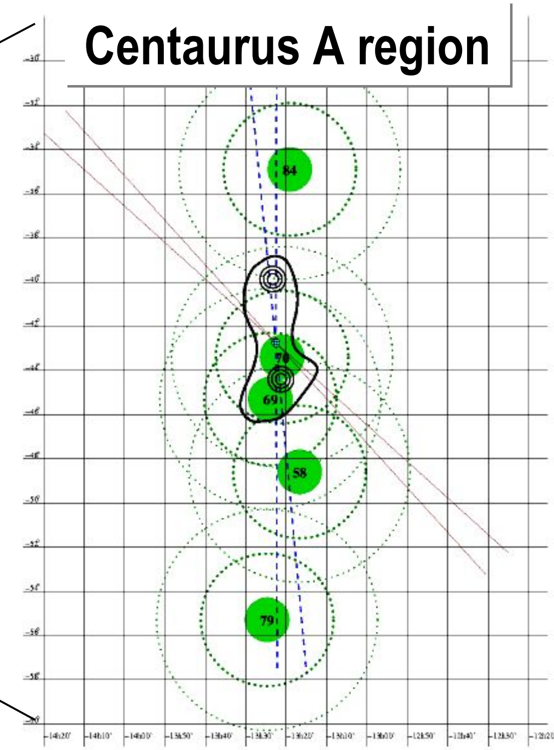
Radio Galaxies

Galaxy clusters

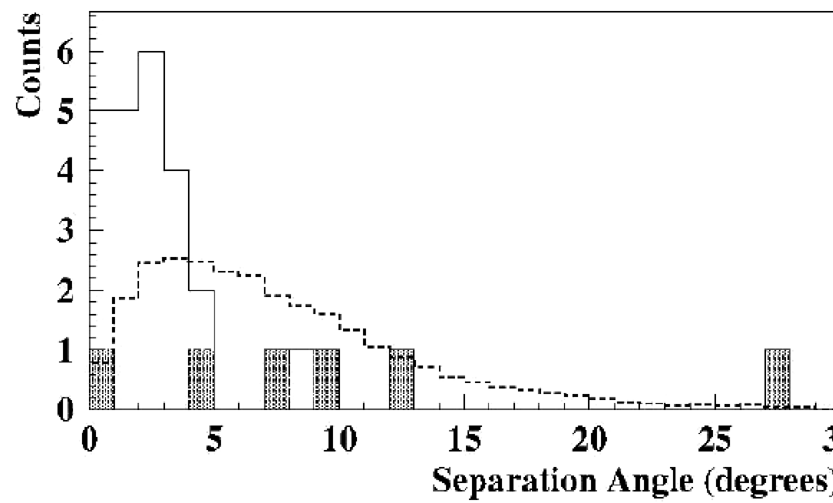
High-E particle in cosmic sources: zoology

P. Auger observatory - 2008



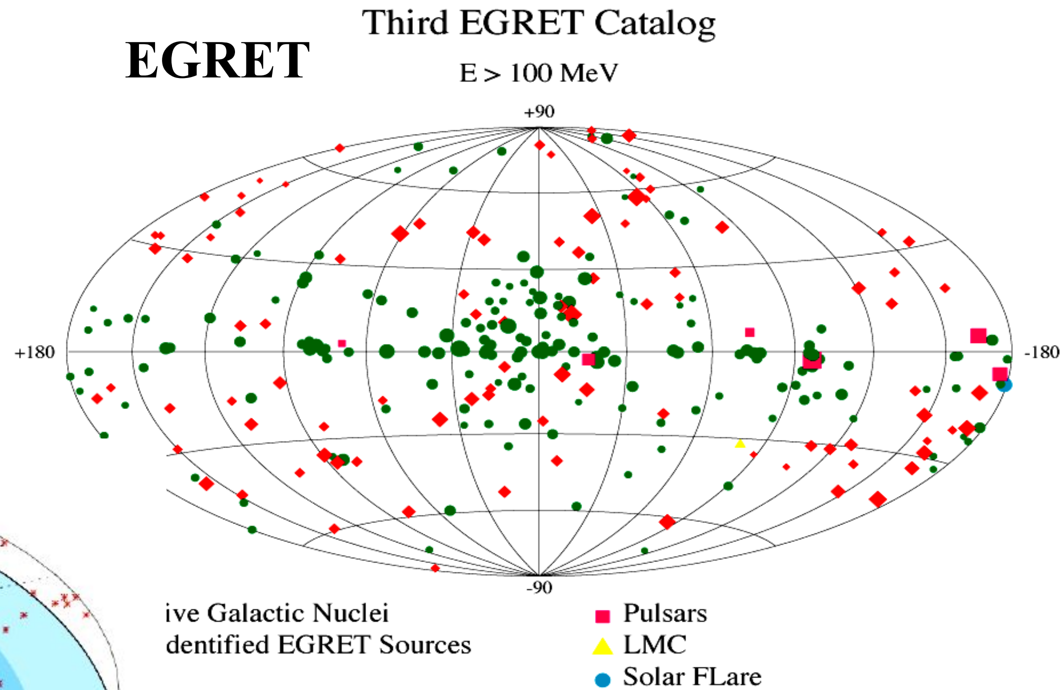


	Number of events E >57 EeV	Events correlated with AGN ψ = 3.1 degree	Events expected for isotropy
Exploratory scan 1 Jan 04- 27 May 06	15	12	3.2
Second independent set 27 May 06–31 Aug 07	13	8	2.7
Full data set (about 1.2 year full Auger)	27	20	5.6
Full data set excluding galactic plane region	21	19	5.0

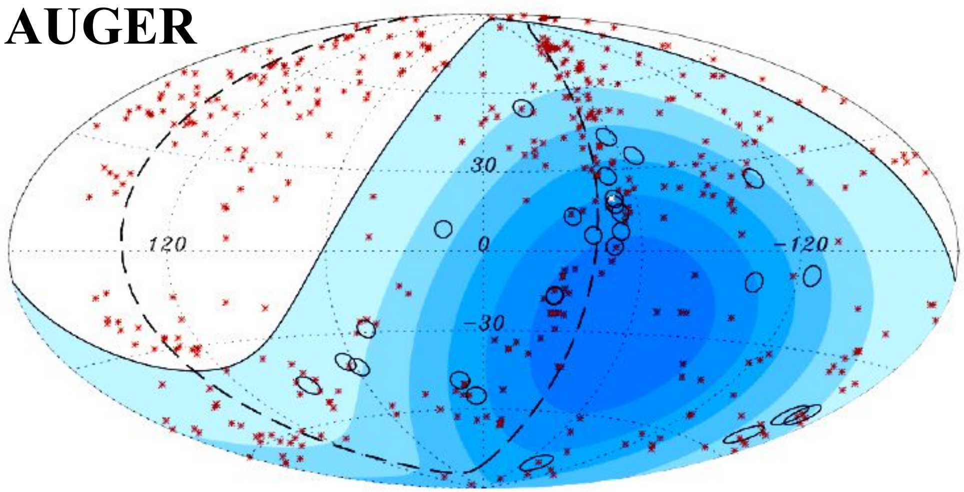


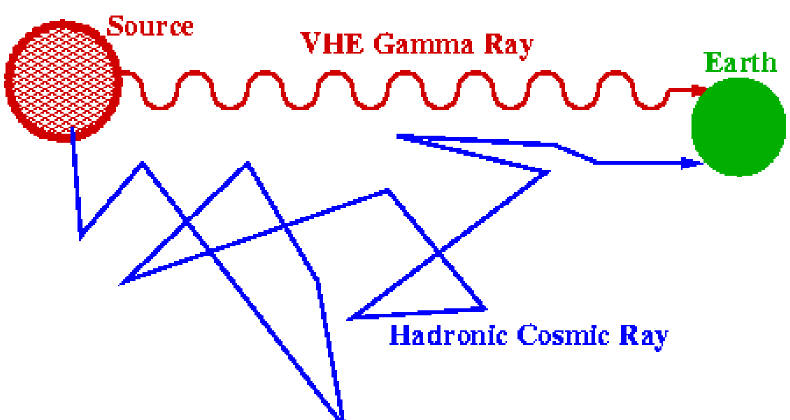
Sky maps

EGRET

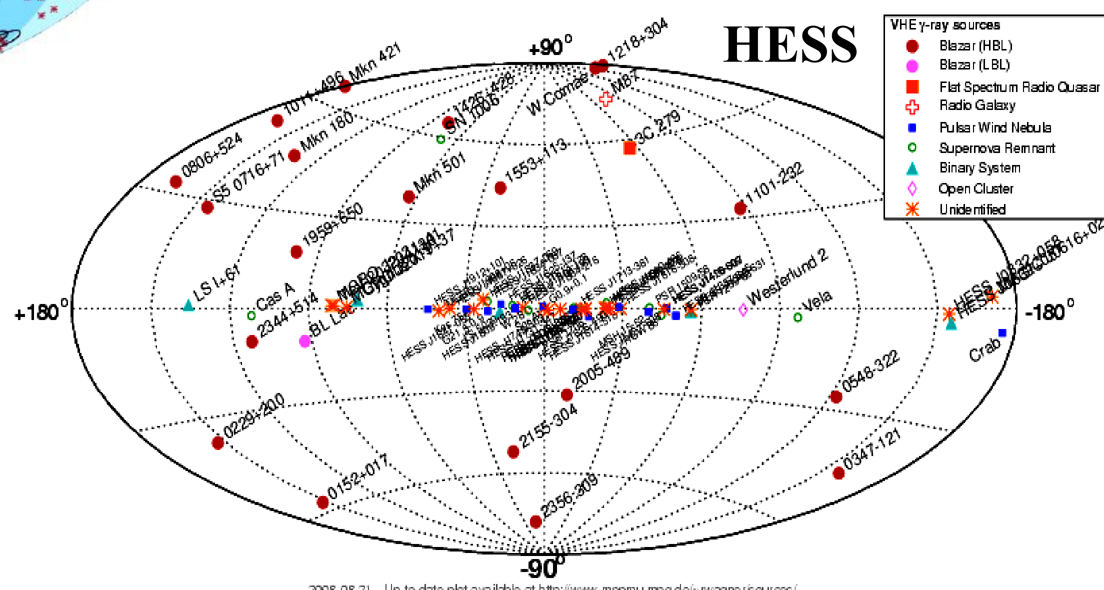


AUGER





HESS



Physical Conditions

in cosmic structures

Conditions in cosmic structures

In cosmic structures, the previous emission mechanisms require:

$$\frac{\partial n_e(E,r)}{\partial t} - \nabla\left[D(E)\nabla n_e(E,r)\right] - \frac{\partial}{\partial E}\left[b_e(E)n_e(E,r)\right] = Q_e(E,r)$$

1) Sources of particle distribution (leptons & hadrons)

- Acceleration
- Injection
- DM annihilation

$Q_e(E,r)$

2) Energy density fields

- Magnetic field
- Radiation field

U_B

U_{rad}

$$b(E) = b_{\rm IC}(E) + b_{\rm syn}(E) + b_{\rm Coul}(E) + b_{\rm brem}(E)$$
$$= b^0_{\rm IC}\left(\frac{E}{1\ {\rm GeV}}\right)^2 + b^0_{\rm syn}B^2_\mu\left(\frac{E}{1\ {\rm GeV}}\right)^2$$
$$+ b^0_{\rm Coul}n\left(1 + \log(\gamma/n)/75\right)$$
$$+ b^0_{\rm brem}n\left(\log(\gamma/n) + 0.36\right).$$

3) Equilibration mechanisms

- Thermalization processes
- Energy losses
- Diffusion
- Convection
- …

$$b_e(E) = b_{IC} + b_{sync} + b_{Coul} + b_{brem}$$

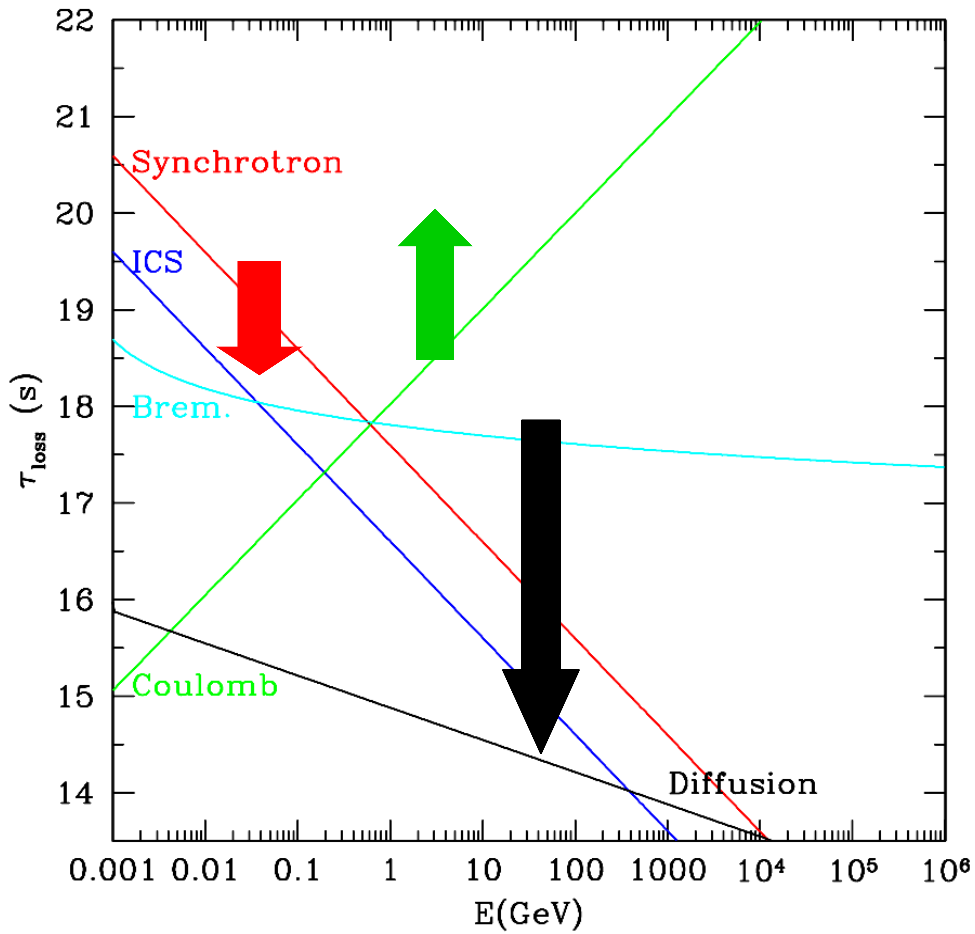
$$D(E) = D_0 E^{\gamma} B^{-\gamma}$$

Energy losses vs. Diffusion

$$\tau_{loss} = \frac{E}{b(E,B,n_{th})}$$

$$\tau_D = \frac{R_h^2}{D(E)}$$

B increase



n_{th} decrease

R_h decrease

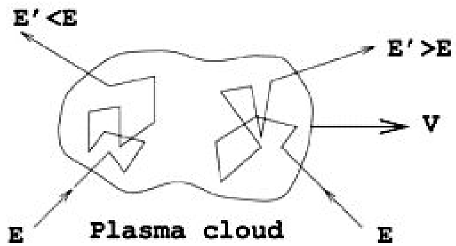
Particle production: acceleration

Basic idea

Fermi Acceleration Mechanism

Stochastic energy gain in collisions with plasma clouds

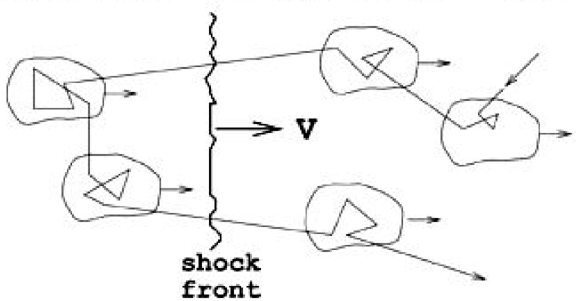
2nd order :
randomly distributed magnetic mirrors



$\frac{\Delta E}{E} \sim \beta^2 \qquad \beta = \frac{V}{c} \lesssim 10^{-4}$

[Slow and inefficient]

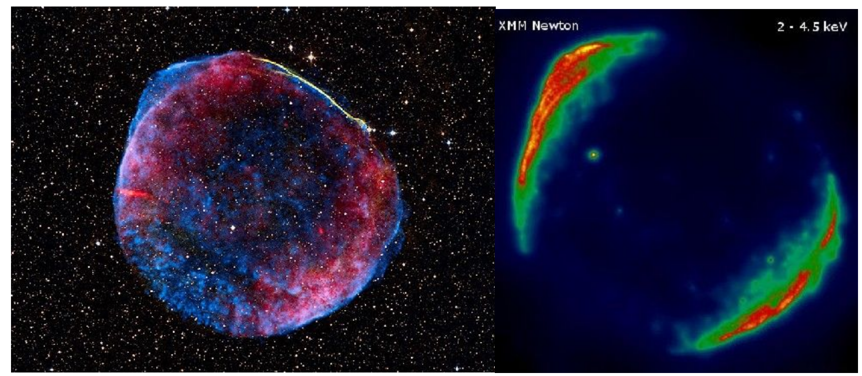
1st order :
acceleration in strong shock waves (supernova ejecta, RG hot spots...)



$\frac{\Delta E}{E} \sim \beta \qquad \beta = \frac{V}{c} \lesssim 10^{-1}$

The main reasons why SNRs are usually considered to accelerate particles (CRs) are:

3) the presence of shock waves
4) a simple argument about the energy required to sustain the CR population against losss by escape, nuclear interactions and ionization.



- Supernovae have enough power to drive CR acceleration if there exists a mechanism for channeling about 10% of the mechanical energy release into relativistic particles.
- The high velocity ejecta produced in the Supernova explosion interacts with the ambient medium to produce a strong blast wave.
- Such shock may accelerate a small suprathermal fraction of the ambient plasma to high energies

Stochastic acceleration: an example

Thermal

Quasi-thermal

Non-thermal

$$\frac{dN}{dE} \propto \exp\left(-\frac{E}{k_B T_e}\right)$$

$$f(\gamma) = \frac{\gamma^2\beta}{\theta K_2(1/\theta)}\exp\left(-\frac{\gamma}{\theta}\right)$$

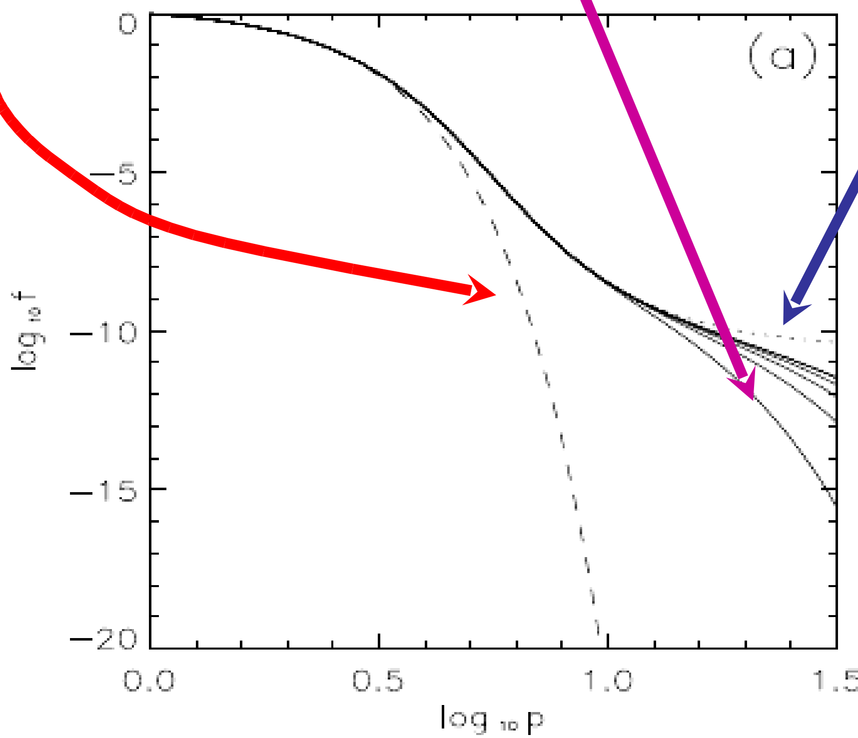
$$\beta = \frac{v}{c},$$

$$\gamma = \sqrt{1-\frac{1}{\beta^2}},$$

$$\theta = \frac{kT}{mc^2},$$

Maxwell-Juttner

$$\frac{dN}{dE} = n_0\left(\frac{E}{GeV}\right)^{-x}$$



Evolution of the particle distribution

The evolution of the distribution function of particles which are scattered by electromagnetic fluctuations is described by the Fokker-Planck equation which can be transformed to the diffusion type equation by integration over particle pitch-angles, if scattering is very effective and the distribution function is quasi-isotropic
(see Dogiel, Colafrancesco et al. 2007)

For the mechanism of the in-situ acceleration from background plasma, the equation can be written in the form

$$\frac{\partial f}{\partial t} + \frac{1}{p^2}\frac{\partial}{\partial p}p^2\left[\left(\frac{dp}{dt}\right)_C f - \{D_c(p) + D(p)\}\frac{\partial f}{\partial p}\right] = 0$$

where $(dp/dt)_C$ and $D_c(p)$ describe particle convection and diffusion in the momentum space due to Coulomb collisions, and $D(p)$ is the diffusion coefficient due to the stochastic acceleration
(see Wolfe & Melia 2006 for a relativistic covariant formulation)

The equilibrium distribution depends on the relative importance of the different time scales: t_{diff}, t_{conv}, t_{acc}, t_{loss}, …

Particle spectra: various regimes

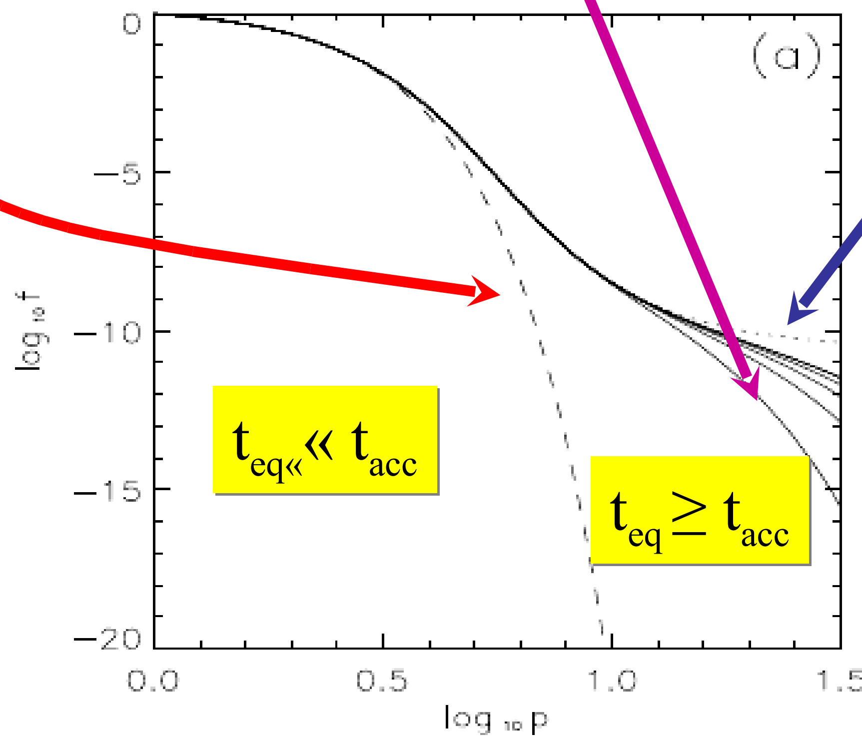
Thermal

Quasi-thermal

Non-thermal

$$\frac{dN}{dE} \propto \exp\left(-\frac{E}{k_B T_e}\right)$$

$$\frac{dN}{dE} = n_0 \left(\frac{E}{GeV}\right)^{-x}$$



$t_{eq} \ll t_{acc}$

$t_{eq} \geq t_{acc}$

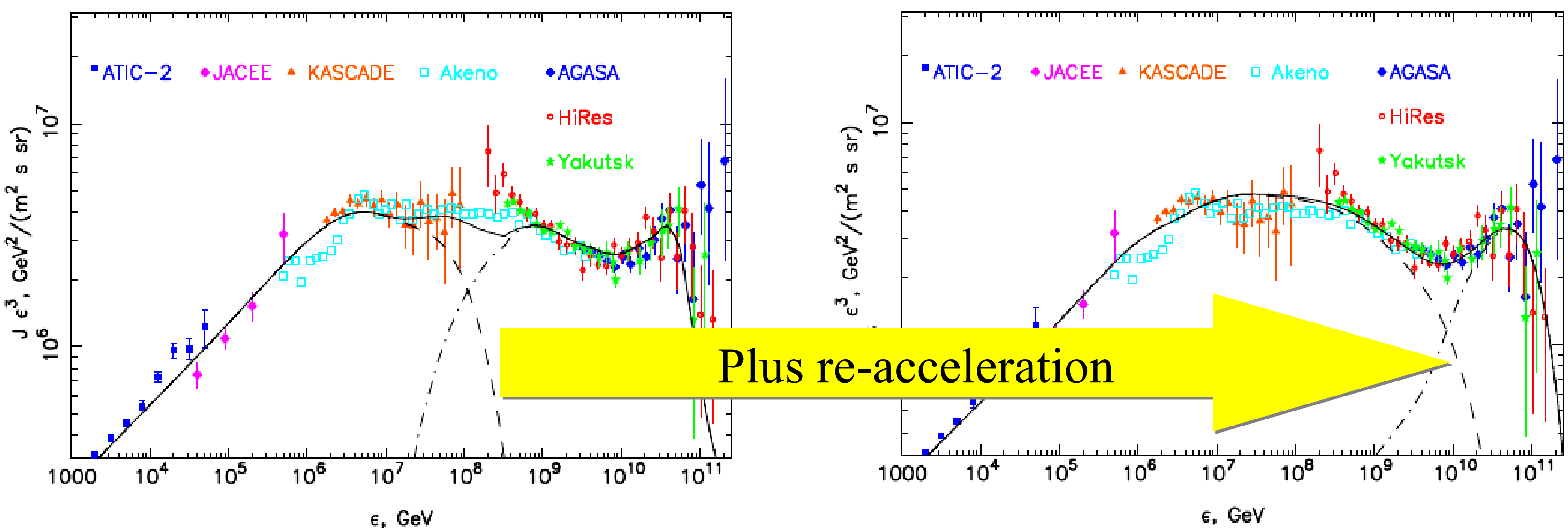
$t_{eq} \gg t_{acc}$

Acceleration: DSA

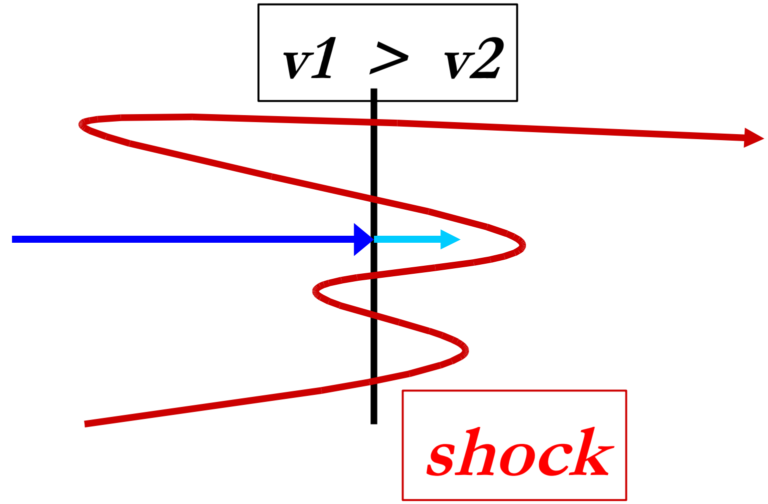
Another theory of particle acceleration which is sufficiently well developed and allow quantitative model calculations is **diffusive shock acceleration**. Considerable efforts have been made to empirically confirm the theoretical expectation that the main part (up to E ~10^{17} eV) of CRs indeed originates in SNRs.

Progress in the solution of this problem has been due to the development of a **kinetic nonlinear theory of diffusive shock acceleration**.

This theory includes all the most relevant physical factors, essential for the SNR evolution and CR acceleration in a SNR, at least in its early very energetic stages, and it is able to make quantitative predictions of the expected properties of CRs produced in young SNRs and their non-thermal radiation.



Acceleration models: limits



Conventional assumptions:

- maximal efficiency ($t_{acc} \sim \gamma/\omega_B$) is usually either assumed or put "by hand" by using (super)-Bohm cross-field diffusion
- so far NO self-consistent simulations produced required level of turbulence
- hardening of spectrum above E ~ 10^{18} eV indicates another acceleration mechanism

Constraints from UHERCs crucial! ⇒ **Extragalactic jetted sources**

1) high energy output > L_p $2\times10^{45} - 3.5\times10^{46}$ erg Mpc^{-3} yr^{-1} — **AGNs** **GRBs ?**

2) power-law spectrum up to $E_{max} = 10^{20}$ eV (>GZK-cutoff). — **AGNs**

$$\epsilon_{max} \approx 10^{20} Z \left(\frac{L_j}{10^{47}\ \mathrm{erg/s}}\right)^{3/4} \left(\frac{N_g}{10^{-4}\ \mathrm{cm}^{-3}}\right)^{-1/4} \left(\frac{V_h}{10^{10}\ \mathrm{cm/c}}\right)^{-1/4} \left(\frac{l_j}{1\ \mathrm{kpc}}\right)^{-1/2} \mathrm{eV}. \quad B^2/(8\pi) \sim 10^{-3}\rho V^2$$

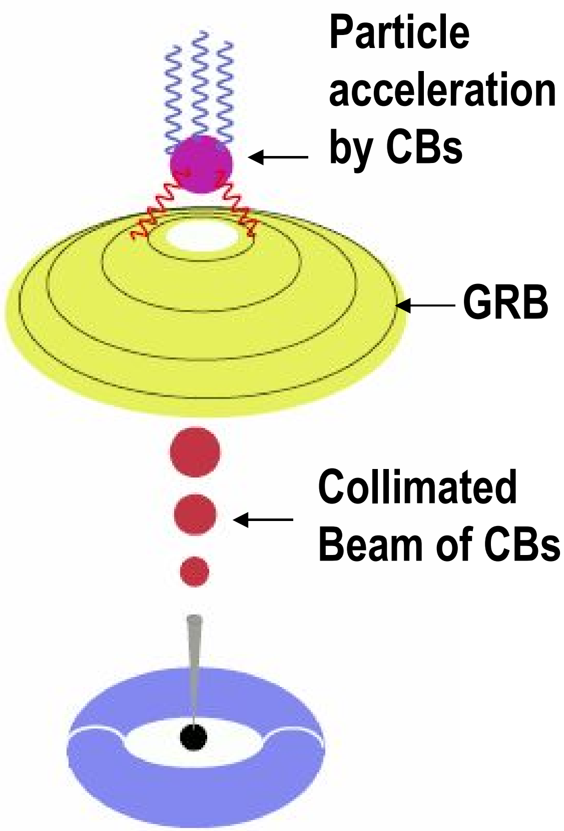
3) Shape of the power-law spectrum at > GZK-cutoff. — **AGNs**

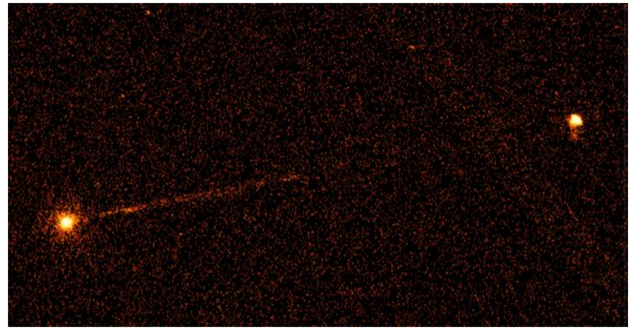
$$N(\epsilon) \propto \epsilon^{-\gamma} \quad \text{with} \quad \gamma = 1 + (2-\beta)/(2/\nu - 3)$$

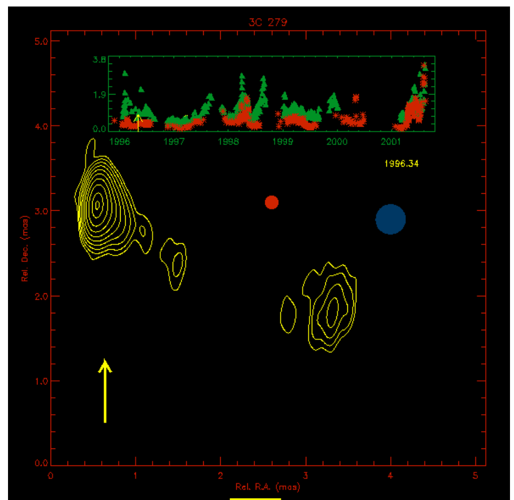
Particle production: injection

(common thread)

GRBs (CBs)

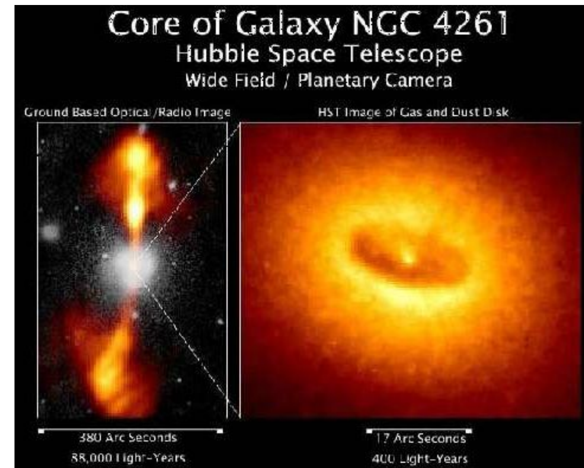


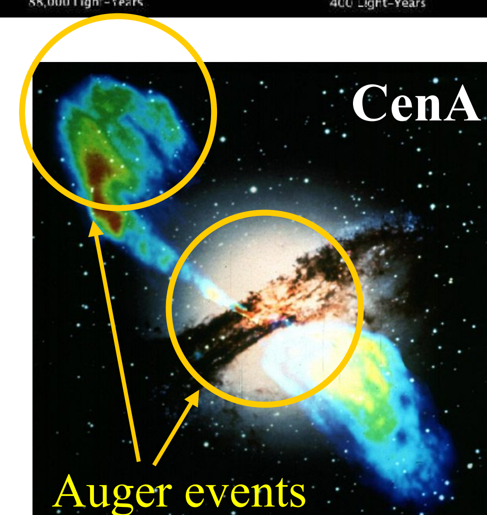




$$\frac{dN}{dE} = n_0 E_{e,p}^{-x}$$

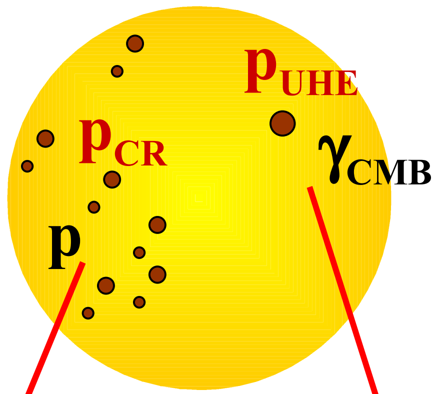
AGNs





Particle production: in situ

Stationary case



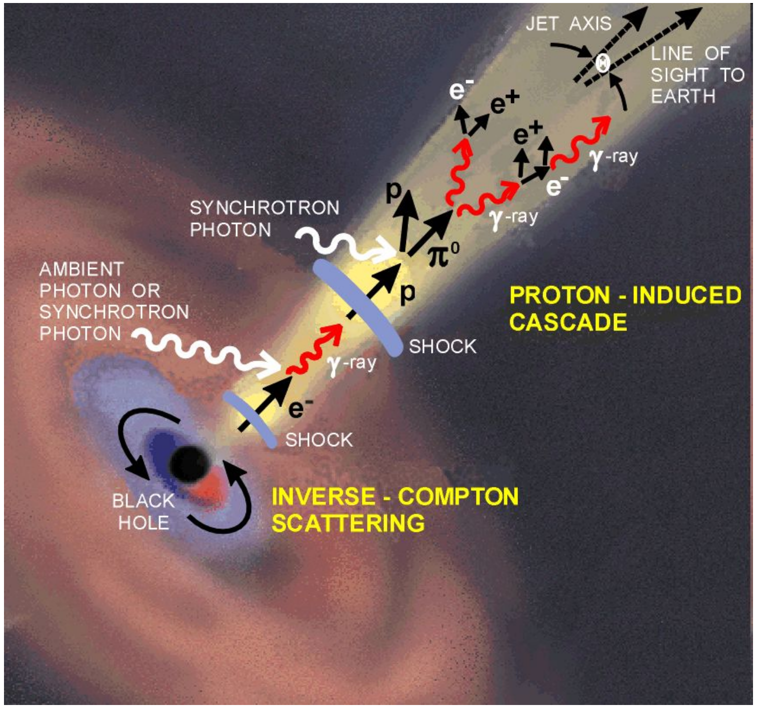
p_{CR} - p

p_{UHE} - γ_{CMB}

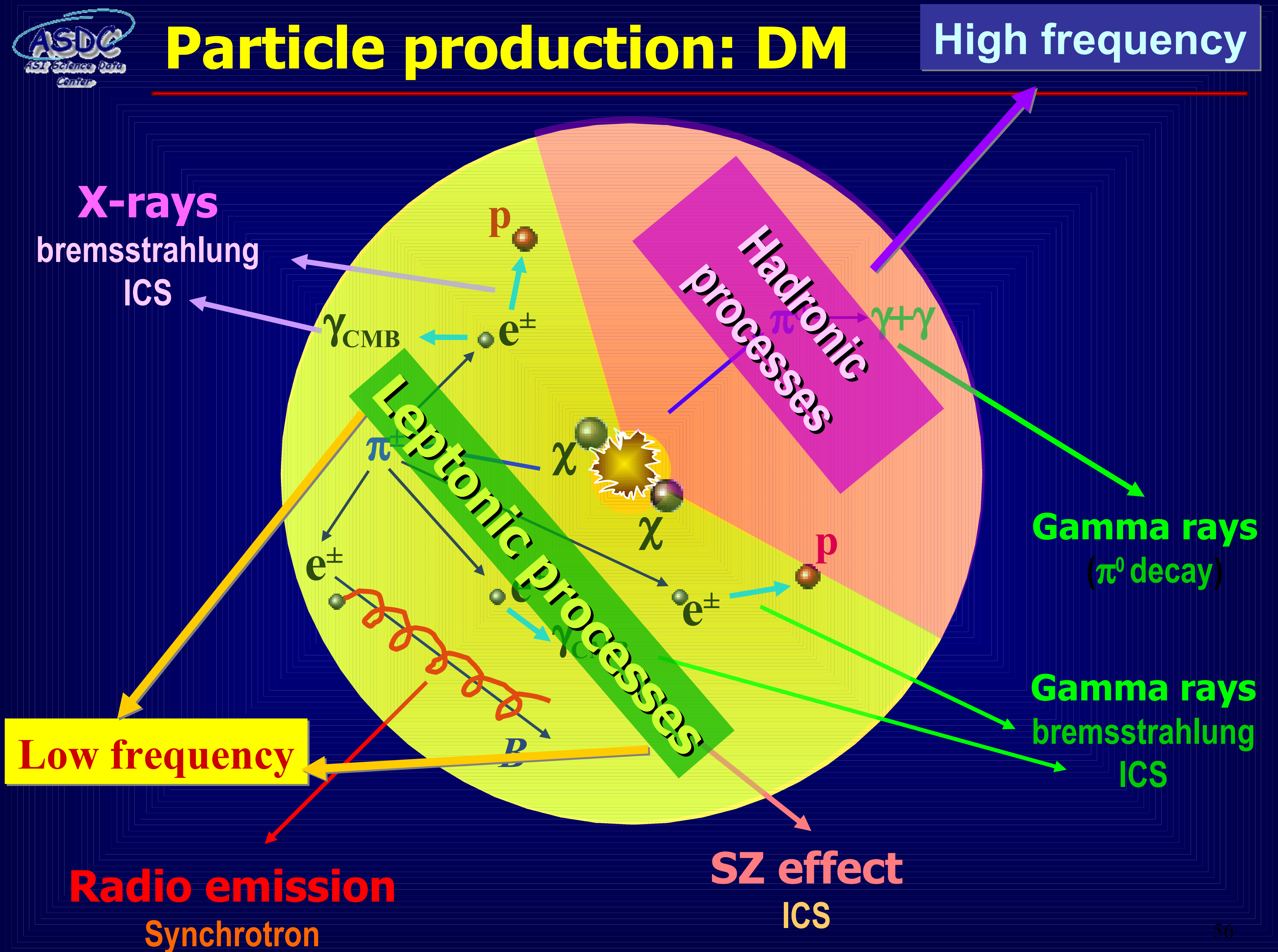
$$p_{CR} + p \rightarrow X + \pi^{\pm}$$
$$\pi^{\pm} \rightarrow X + e^{\pm}$$

$$p_{UHE} + \gamma \rightarrow p + e^{\pm}$$

Dynamical case



Particle production: DM



DM annihilation: where

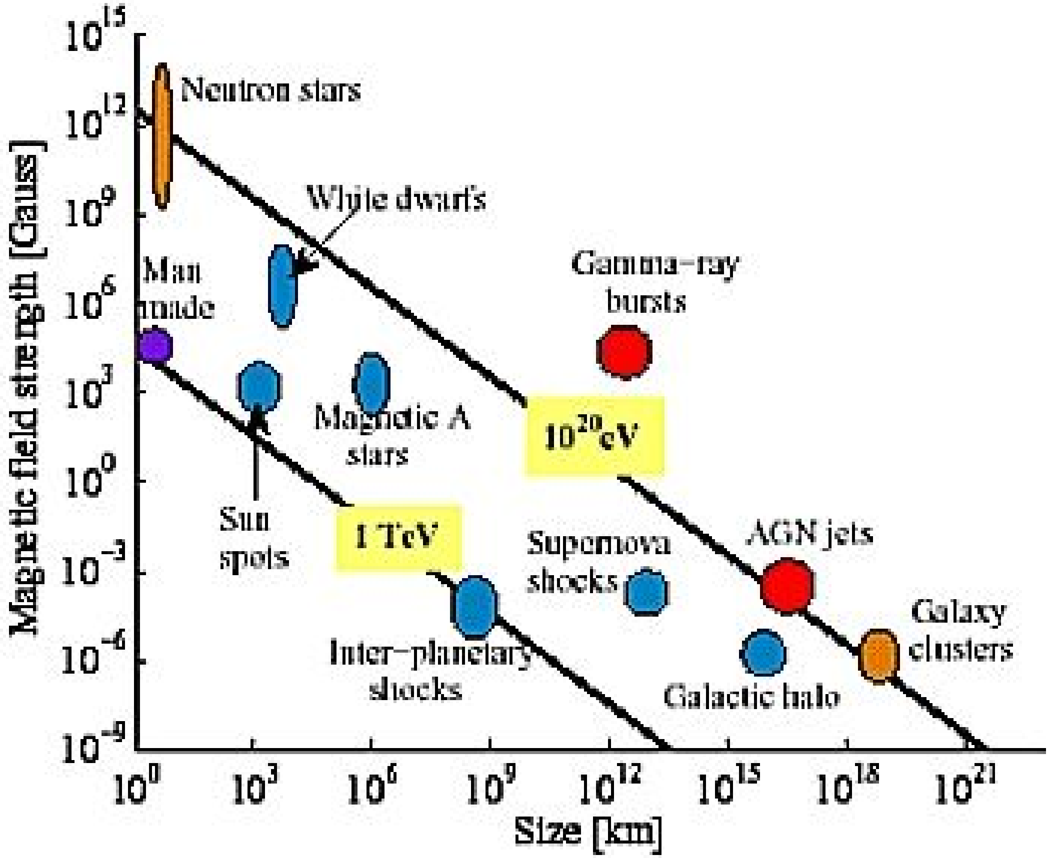
Dwarf Spheroidal galaxies

Galaxy centers

Galaxy clusters
With spatial offset
Betwen DM & baryons

Energy density fields: B-field

B-fields in cosmic structures



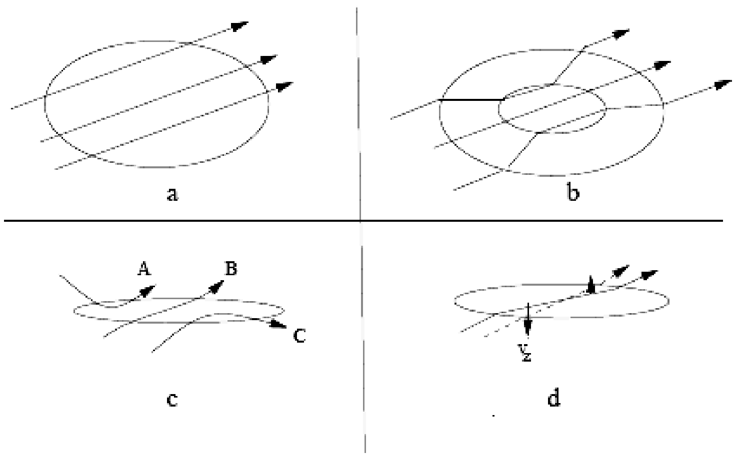
Origin of B-fields

Post-Recombination

- Biermann-battery (!)
- dynamo-disk model (?)
- amplification (?)

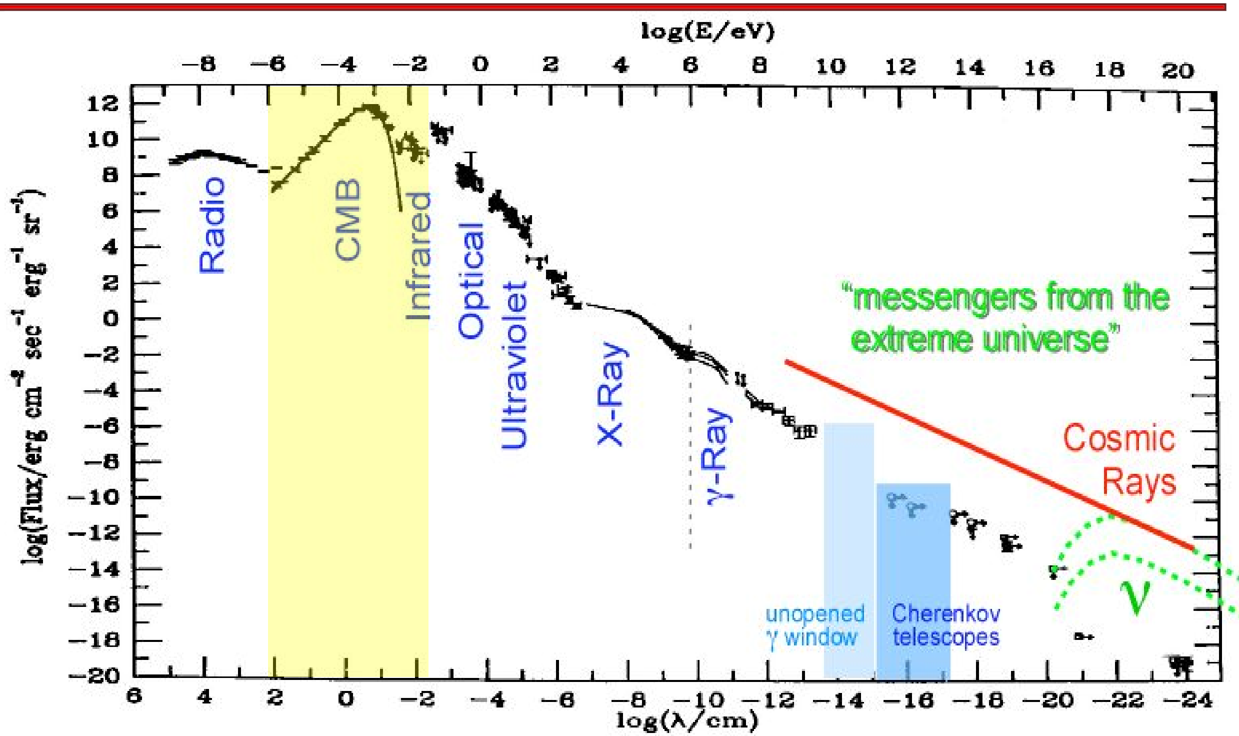
Primordial

- B-battery: 10^{-18} G
- proto-gal. Amplification
- saturation on gal. Scales
- gal. dynamo

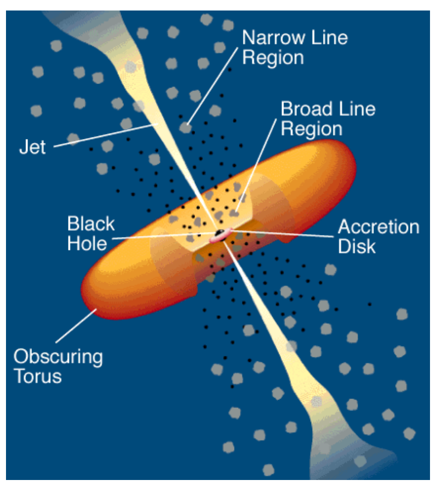


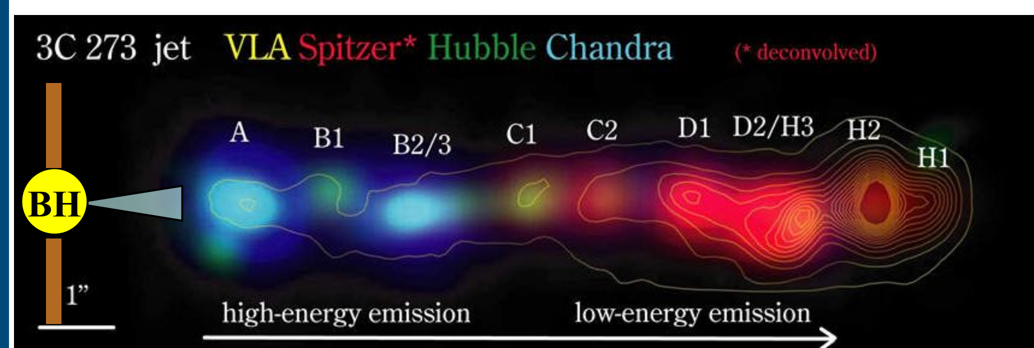
Energy density fields: Radiation

Universal fields
- CMB



Local (internal) fields
- Radio
- IR
- Optical
- X-ray
- γ-ray

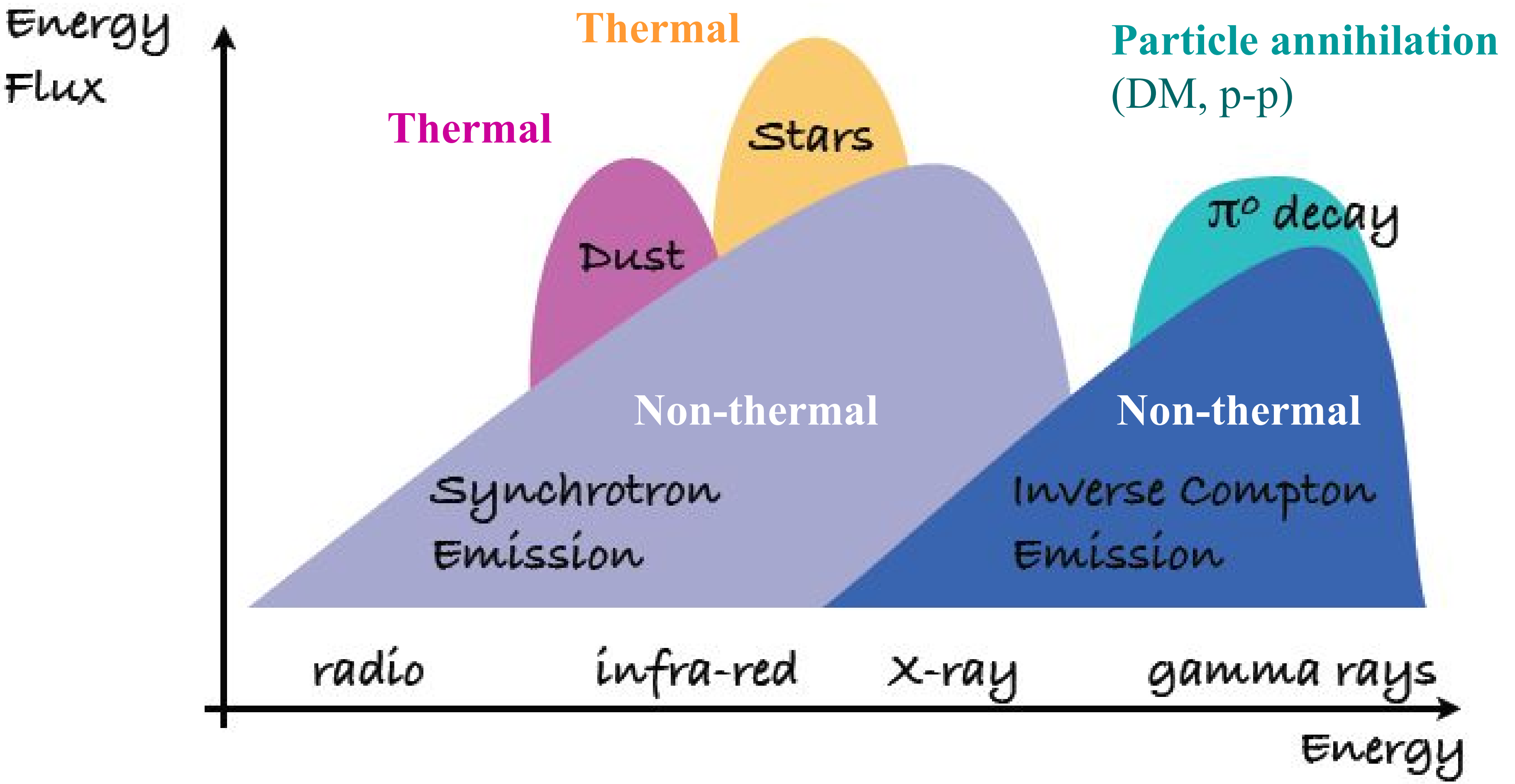




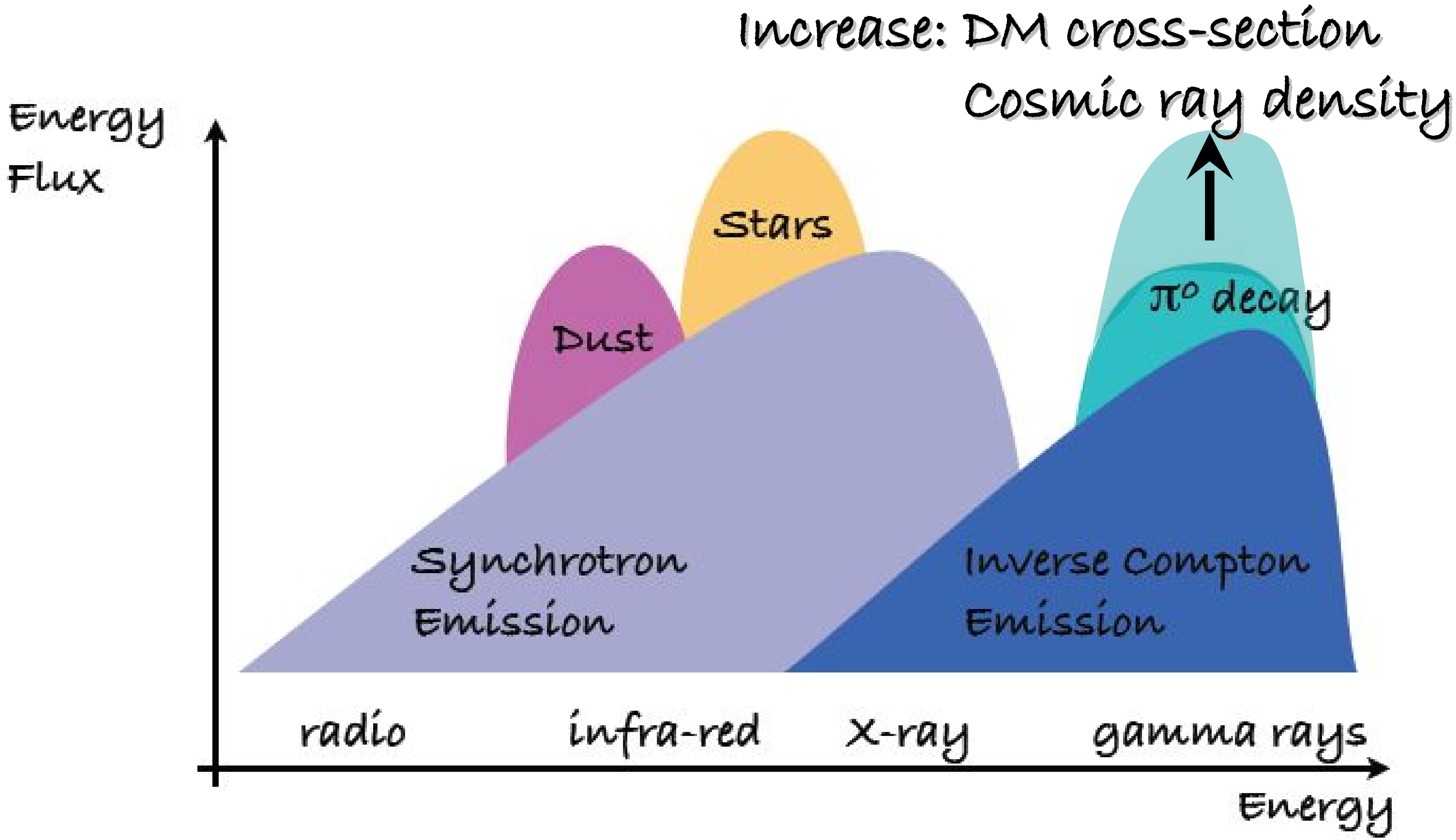
Putting all together

The E-spectrum of cosmic sources

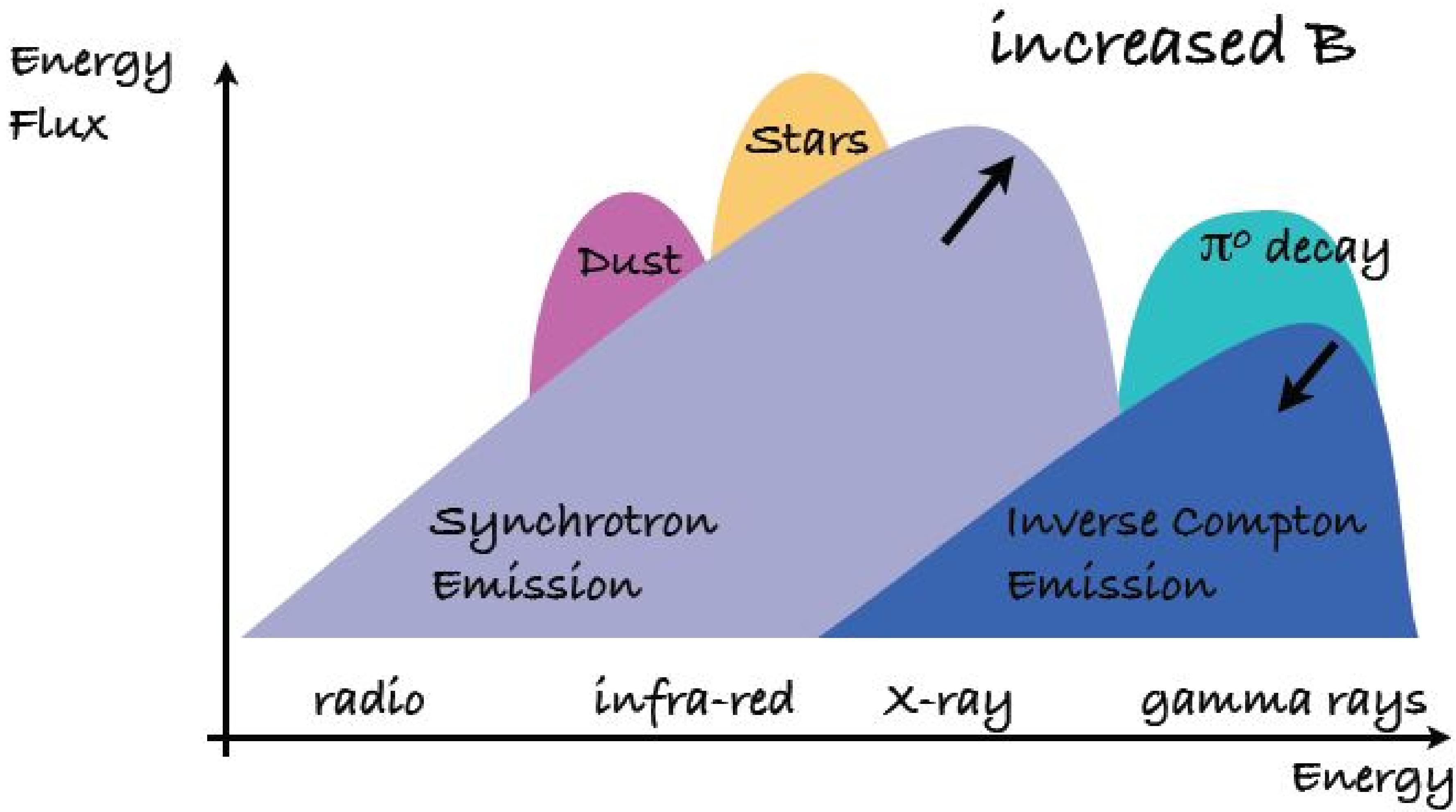
General Spectral Energy Distribution (SED)



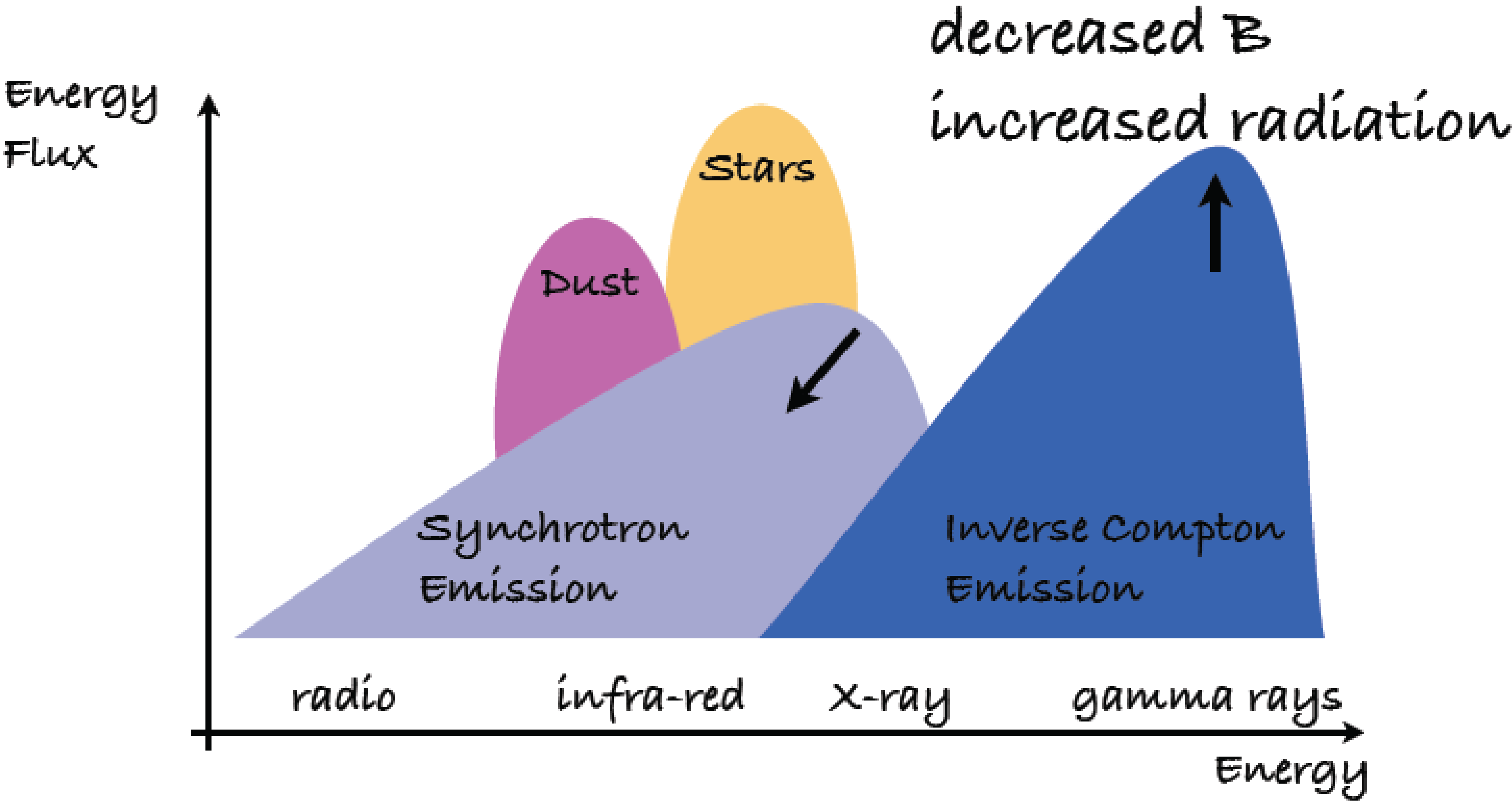
SED: non-thermal π^0 decay



SED: non-thermal



SED: non-thermal



GRBs

Dark Matter

Cosmology

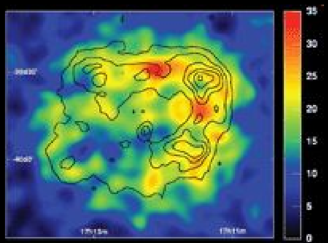
Space-Time

Part 3

Sources of High-E radiation

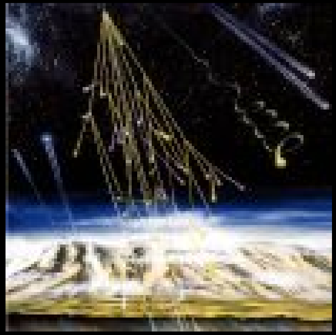
Properties

Science



SNR

Pulsars
PWN



Origin of
Cosmic Rays

AGNs