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Exploring Nonthermal Universe with X-rays

Lecture 1: Introduction

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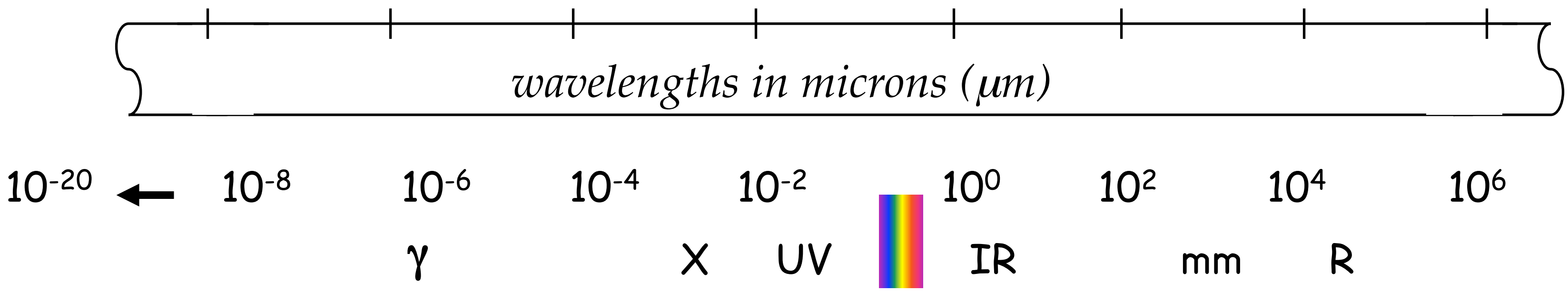
Cosmic EM radiation



radiation of most of astronomical objects, including stars and galaxies is generally dominated by emission of thermalized gas/plasma:

cold - e.g. molecular clouds T ~ 10 to 100 K,

hot - e.g. stars, $T \sim 10^4$ K

very hot - e.g. SNRs, Galaxy Clusters, accretion disks; $T \sim 10^6 – 10^8$ K

highest temperatures have been reported in X-ray binaries, $T \sim 10^9$ K;
in principle ion temperatures in accretion flows can achieve 10^{11} K (not detected yet)

nonthermal emission and particle accelerators

Presence of suprathermal particles in hot plasmas may lead to a non-negligible deviation from characteristics of radiation calculated for Maxwellian distribution of particles. The effect can be strong in high temperature turbulent plasmas. But it should be considered as a thermal rather than nonthermal radiation.

Generally, *nonthermal emission* is called the radiation component related to relativistic particles (electrons, proton, ions) produced by almost perfectly designed (by Nature) machines – the so-called *particle accelerators*.

The efficiency of some of these machines can be close to 100 % and particles can be boosted to energies close to the theoretical limit. These are the so called *extreme accelerators*.

nonthermal emission in Radio, X- and γ-rays

origin?

as a rule (with some exceptions) synchrotron in the R to X-ray band
bremsstrahlung, Inverse Compton and π^0-decay in the γ-ray band

a large fraction of astrophysical objects are characterized by synchrotron radio emission => presence of high energy (typically, GeV) electrons

relatively low luminosity of radio emission should not be misleading => the total energy of GeV electrons can dominate in the total energy budget of the source (e.g. in the Crab Nebula);

luminosities of related (bremsstrahlung) γ-rays can significantly exceed radio luminosities, but often γ-rays cannot be detected because of limited sensitivities of detectors in this (Mev/GeV) energy band

Synchrotron X-rays and VHE γ-rays

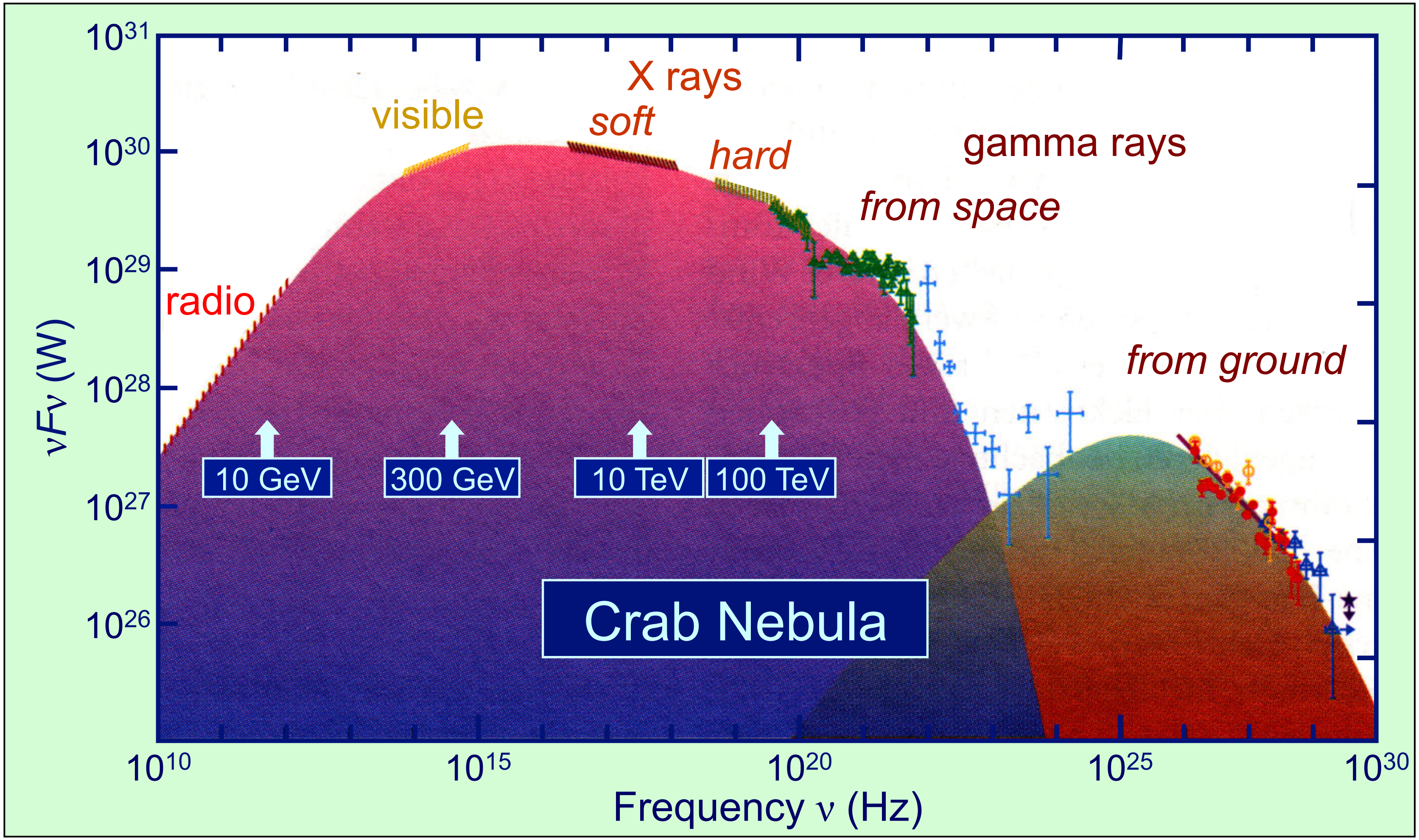
key (complementary) channels of information about the highest energy particles => crucial for understanding of complex processes in extreme accelerators

observations of recent years lead to a (quite surprise) conclusion:

like cosmic plasmas which are easily heated to keV temperatures - *almost everywhere*, particles (electrons/protons) can be easily accelerated to 10+ TeV and beyond (*almost everywhere*!), especially in objects containing relativistic outflows -jets & winds

in some of these sources, e.g. in Pulsar Wind Nebulae and Blazars, the entire energy budget can be contributed by relativistic particles and magnetic fields

a non-thermal astrophysical object seen over 20 energy decades



R, mm, IR, O, UV,X

gamma-rays

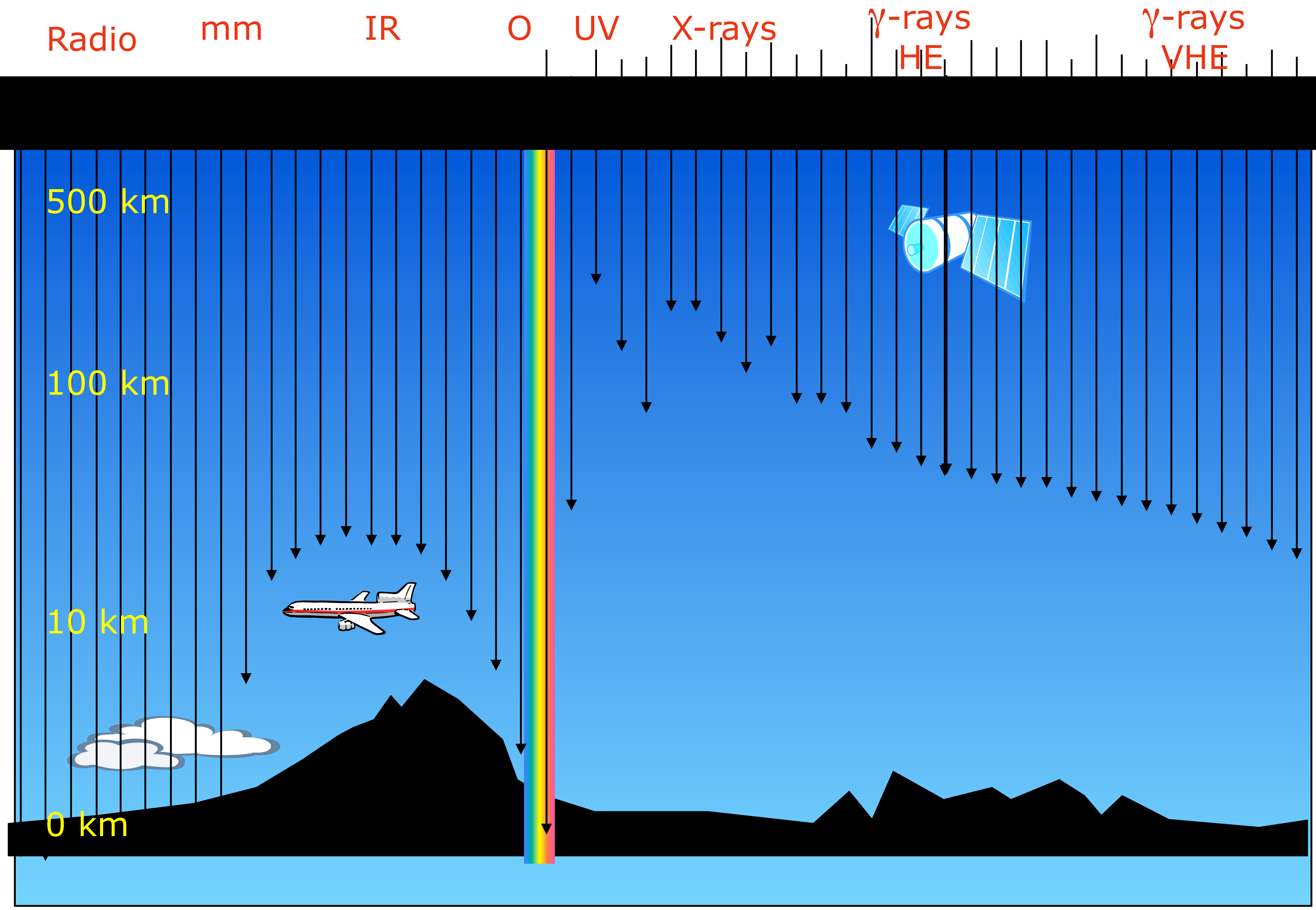
E-M radiation: from radio (MHz) to EHE gamma rays 26+ decades:

R	Radio, mm	$10^{-6} – 10^{-3}$ eV
IR	(FIR,MIR,NIR)	0.01- eV
O		1.5-3 eV
UV		3-100 eV
X	(soft, classical, hard)	0.1 keV – 100 keV

γ	LE	or	MeV :	0.1 -100 MeV	(0.1 -10 + 10 -100)
	HE	or	GeV :	0.1 -100 GeV	(0.1 -10 + 10 -100)
	VHE	or	TeV :	0.1 -100 TeV	(0.1 -10 + 10 -100)
	UHE	or	PeV :	0.1 -100 PeV	(*only hadronic*)
	EHE	or	EeV :	0.1 -100 EeV	(*unavoidable because of GZK*)

1keV=10^3 eV, 1MeV=10^6 eV, 1GeV=10^9 eV, 1TeV=10^{12} eV, 1PeV=10^{15} eV 1EeV=10^{18} eV

Transparency of the Earth's atmosphere for cosmic E-M radiation



X-Ray Astronomy

since 1960s - one of the most advanced astronomical disciplines, run by strong and large community

great instruments - surveys (ROSAT), imaging (Chandra) :
timing (RXTE), spectrometry (XMM) …

underdeveloped areas - polarization,
hard X-rays (NuSTAR is a great step forward and soon ASTRO-H will arrive)
fine spectroscopy (ASTRO-H !)

ambitious plans for future major X-ray missions, but…
unfortunately many uncertainties with funding

X-Ray Astronomy

a part of High Energy Astrophysics

traditional areas (since 1960s):

study of hot astrophysical plasmas with temperature 10^6 - 10^9 K which are formed effectively almost everywhere in the Universe from accreting flows (BHs and NSs) and shocks in SNRs to large scale cosmological structures (Clusters of Galaxies)

recent developments (since mid 1990s):

recognition of great potential of X-ray astronomy for study of nonthermal phenomena, first of all most effective particle accelerators in the Universe, through synchrotron X-ray emission – complementary to VHE *gamma-rays* and neutrinos

radiation and absorption processes

any interpretation of an astronomical observation requires

- ✓ unambiguous identification of radiation mechanisms and
- ✓ good knowledge of radiation and absorption processes

X- and gamma-ray production and absorption processes:

several but well studied

interactions with matter

E-M: VHE

bremsstrahlung: e N(e) => e' γ N (e) * $E\gamma \sim 1/2E_e$

pair production γ N(e) => e^+e^- N (e) *

e+e- annihilation e^+e^- => $\gamma\,\gamma$ (511 keV line)

Strong/week: pp (A) => π, K, Λ, … ** $E\gamma \sim 1/10E_p$

π, K, Λ => γ, ν, e, μ

μ => ν

also in the low energy region

Nuclear: p A => A* => A' γ, n

n p => D γ (2.2 MeV line)

interactions with radiation and B-fields

Radiation field		**VHE**	
E-M:			
inverse Compton:	e γ (B) => e' γ	**	$E\gamma \sim \varepsilon(Ee/mc^2)^2$ (T) to ~Ee (KN)
γγ pair production	γ γ (B) => e^+e^-	**	
Strong/week	p γ => π, K, Λ, …	*	
	π, K, Λ => γ, ν, e, μ		Eγ~ 1/10Ep
	μ => ν		
	A γ => A* => A' γ	*	Eγ~ 1/1000A Ep
B-field			
synchrotron	e (p) B => γ	*	$E\gamma \sim BE_e^2$; $h\nu_{max} \sim \alpha^{-1} mc^2$
pair production	γ B => e+e-	*	

leptonic or hadronic?

gamma-rays produced in interactions of electrons and protons/nuclei often are called leptonic and hadronic interactions
but it is more appropriate to call them as E-M (electromagnetic) and S (strong)

examples:

(i) synchrotron radiation of protons - pure electromagnetic process
interaction of hadrons without production of neutrinos

(ii) Synchrotron radiation of secondary electrons from $\pi^{+/-}$ *decays has hadronic origin*
and can be accompanied by TeV neutrinos

(iii) photon-photon annihilation => $\mu+\mu-$ *=> neutrionos, antineutrinos*
production of neutrinos by photons as parent particles

often several processes proceed together =>
cascades in matter, radiation and B-fields

Specifics

of high energy nonthermal radiation

extreme physical conditions

generally the phenomena relevant to HEA generally proceed under extreme physical conditions in environments characterized with

- *huge gravitational, magnetic and electric fields,*
- *very dense background radiation,*
- *relativistic bulk motions (black-hole jets and pulsar winds)*
- *shock waves, highly excited (turbulent) media, etc.*

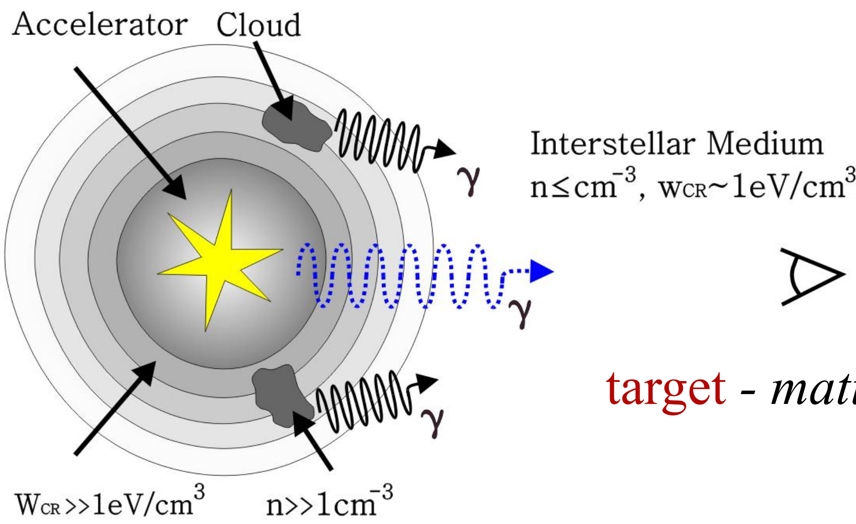
any coherent description and interpretation of phenomena related to high energy cosmic gamma-rays requires knowledge and deep understanding of many disciplines of experimental and theoretical physics, including

nuclear and particle physics,
quantum and classical electrodynamics,
special and general relativity,
plasma physics, (magneto) hydrodynamics, etc.

and (of course) Astronomy&Astrophysics

Production of nonthermal radiation requires accelerator+target

existence of a powerful particle accelerator by itself is not sufficient for radiation; an additional component – a dense target - is required

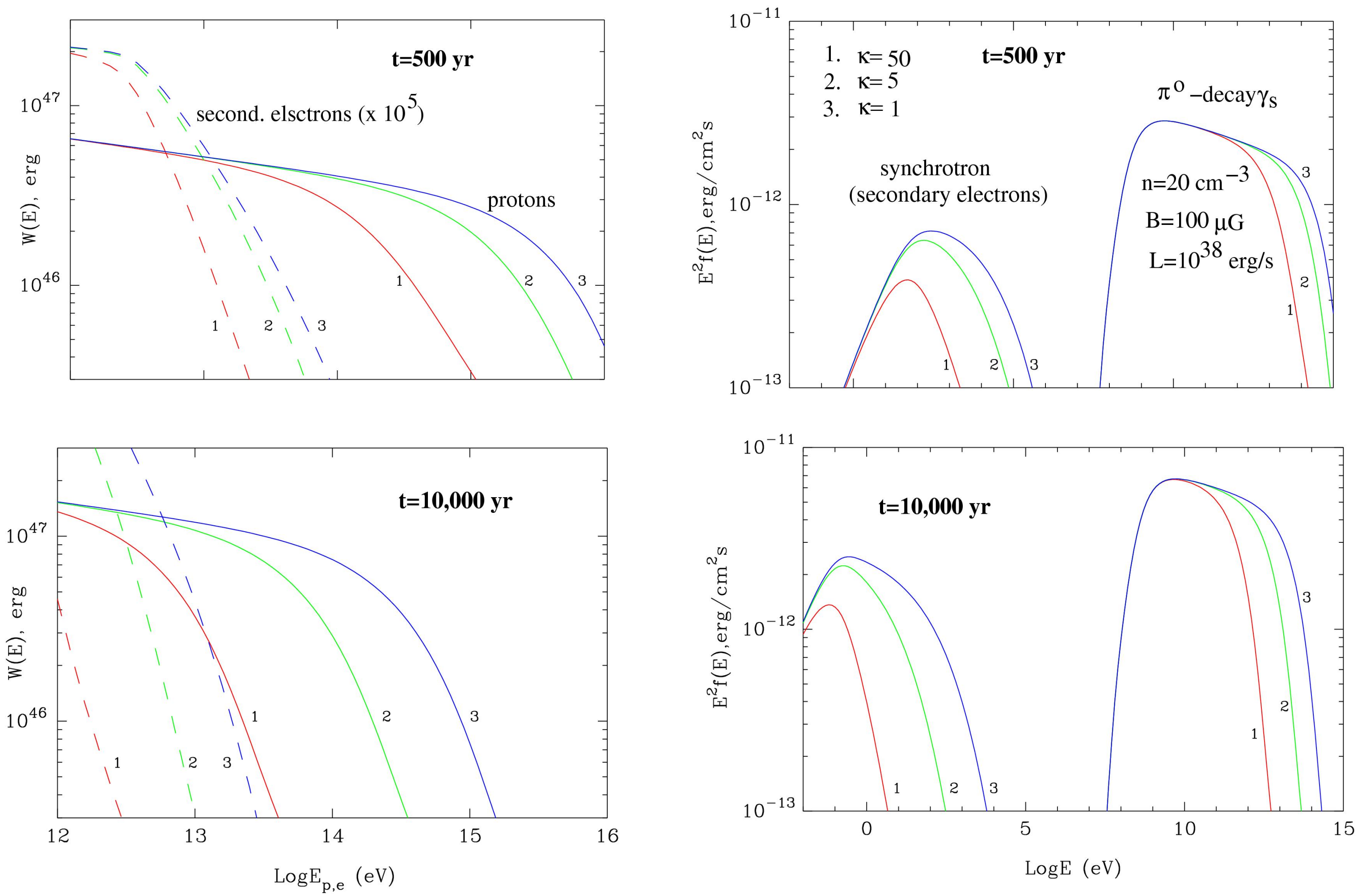


target - *matter, radiation, magnetic field*

any nonthermal emitter coincides with the target, but not necessarily with the "primary" source/particle-accelerator

the radiation spectrum depends not only on the acceleration spectrum and energy losses, , but also on propagation effects

older source – steeper γ-ray spectrum



$t_{esc}=4x10^5(E/1\ TeV)^{-1}\kappa^{-1}$ yr (R=1pc); κ=1 – Bohm Difussion

$Qp = k\ E^{-2.1} \exp(-E/1PeV)$ $Lp=10^{38}(1+t/1kyr)^{-1}$ erg/s

production of nonthermal X-rays

at interactions with matter,radiation, and magnetic-field

matter: *bremsstrahlung of subrelativistic suprathermal electrons;* always ***inefficient*** process (k ~ 10^{-6} - 10^{-5}) due to competing ionization loses (more general – Coulomb interactions)

radiation: inverse Compton scattering of relativistic but not very high energy (MeV/GeV) electrons; generally ***not efficient*** because of long cooling time ($t_{IC} \sim 1/E_e \sim 1/E_x^{1/2}$)

B-field: synchrotron radiation (magnetobremsstrahlung) of ultra relativistic electrons (sometimes also protons) – as a rule ***very effective*** both in regular and highly turbulent B-fields *inefficient!*

Nonthermal X-ray Bremsstrahlung

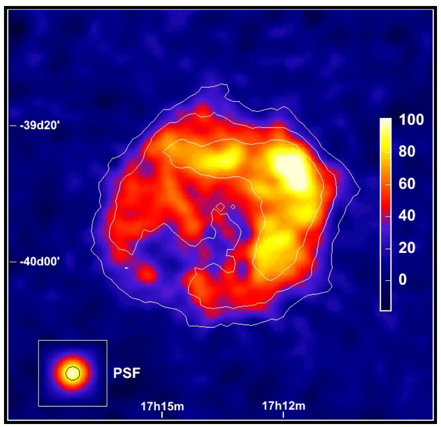
at first glance quite attractive (*"why should I invoke multi-TeV electrons to produce X-rays when can I use keV electrons to produce keV X photons?"*) in fact only less than 10^{-5} fraction of the kinetic energy of electrons (protons) is released in X-rays; 99.99…% goes to the ionization and heating of the gas

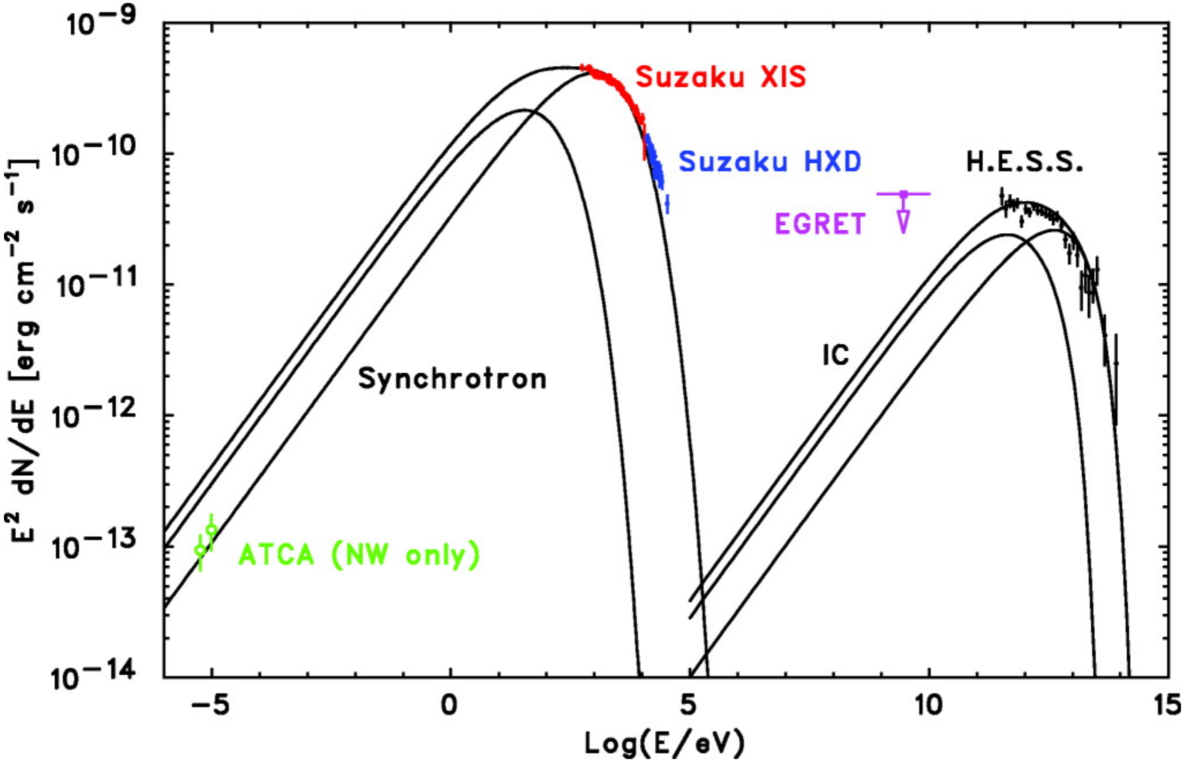
$$L_e > 10^5 L_X = 10^{37} (f_X/10^{-12} \text{ erg/s}) (d/1\text{kpc})^2 \text{ erg/s}$$

the same is true for <u>gamma-ray line emission due to excitation of nuclei</u> by sub-relativistic protons - both mechanisms "work" during Solar flares, otherwise it typically leads to unreasonably high requirements for production rate of sub-relativistic electrons - this makes the extremely interesting issues like detection of gamma-ray lines, in particular from ISM, SNRs, GMCs, etc (information about the sub-relativistic CRs !) observationally very difficult

1. synchrotron X-rays versus IC X-rays: *SNRs*

leptonic models: acceleration of electrons in SNR shells to energies up to 100TeV





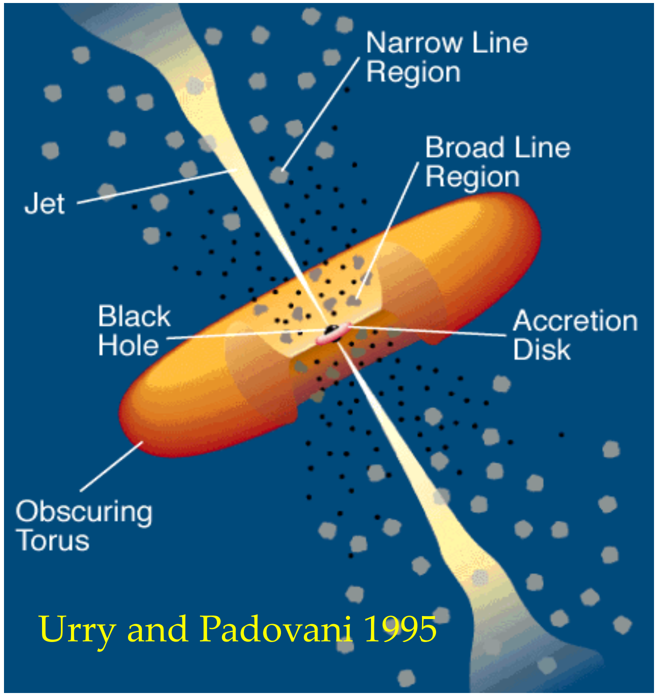
$e + 2.7K \Rightarrow \gamma$

B=15μG We ≈3 10^{47} erg

Synchrotron X-rays strongly dominate over IC hard X-rays

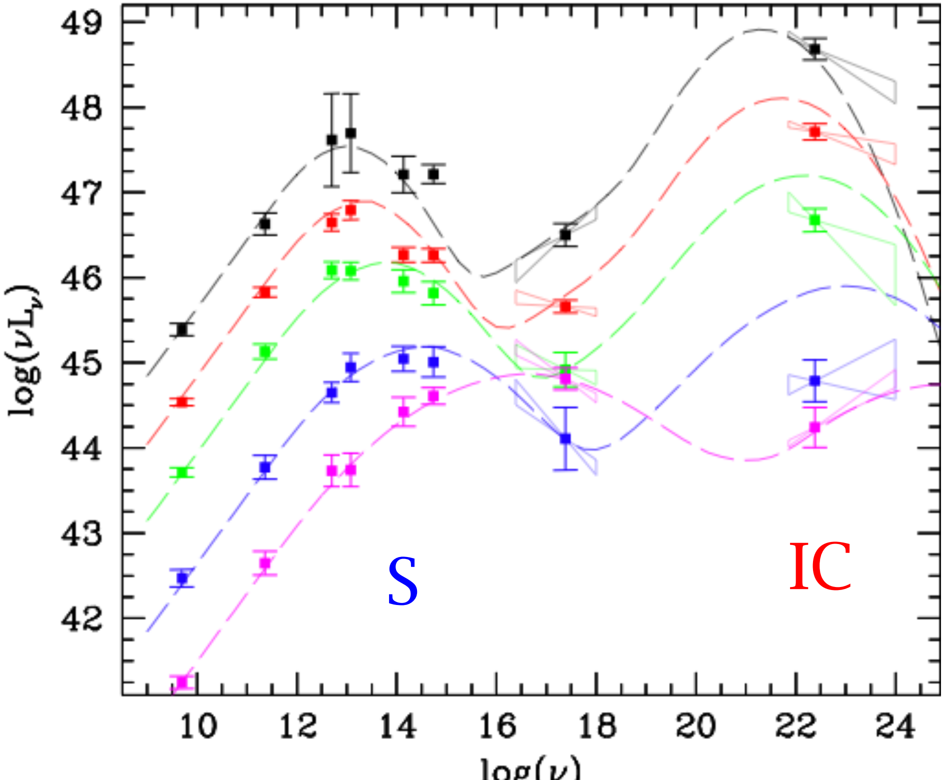
2. synchrotron X-rays versus IC X-rays: *blazars*

sub-class of AGN dominated by nonthermal broad band radiation produced in relativistic jets close to line of sight, with massive BHs as central engines



gamma- rays from >100 Mpc sources - detectable because of Doppler boosting

two-peaks (Synchrotron-IC) paradigm



Synchrotron X-rays strongly dominate over IC hard X-rays

3. Synchrotron versus IC: LS 5039

a nonthermal X/γ binary: works as perfect TeV clock and an extreme accelerator

electrons are accelerated to energies to 20 TeV in presence of dense radiation

more complex synchrotron-IC relations at different energies