40th Saas-Fee Course: Astrophysics at Very High Energies

Course 1:
Very High Energy Gamma Ray Domain:

Lecture 1: Introduction: *Why VHE Gamma Rays?*

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Les Diablerets, March 15-20, 2010

Gamma-Ray Astronomy

a modern interdisciplinary research field at the interface of *astronomy, physics and cosmology,* a branch of

High Energy Astrophysics - in the context of studies of high energy nonthermal processes in Universe

Astroparticle Physics - as one of the cosmic messengers (together with cosmic rays, neutrinos, gravitational waves) as well as in the context of indirect search of Dark Matter, challenging basic laws in different arras of physics

Relativistic Astrophysics - the parents of gamma-rays - relativistic electrons, protons, nuclei are related, in one way or another, to particle acceleration close to relativistic objects: black holes, neutron stars/pulsars, SN explosions …

Golden age of VHE (ground-based) gamma-ray astronomy

(i) strongly support by (Astro) Particle Physics (APP) community, for several objective and subjective reasons:

objective - *perspectives of fundamental particle physics and cosmology*
subjective - *it is not clear what can be done with accelerators after LHC; VHE GA projects are dynamical and cost-effective; can be realized by relatively small groups on quite short timescales*, …

for Particle Physics Community APP was (first of all) "*Particle Physics Without accelerators*" but Particle physicists started to realize the potential and beauty of astrophysics - basically because of the recent great success of VHE GA

(ii) Astronomers finally accepted VHE GA as a branch of modern Astrophysics (in 2008 HESS appeared in the list of the top-10 most cited/influential astronomical telescopes - together with giants like Hubble, Chandra, VLT, etc.)

CTA - accepted as a very high rank project within the "Roadmaps" of both European Astroparticle and Astronomical Communities

Gamma-Ray Astronomy

provides crucial window in the cosmic E-M spectrum for exploration of non-thermal phenomena in the Universe in their most energetic, extreme and violent forms

'the last window' *in the spectrum of cosmic E-M radiation* …

the last E-M window ... 15+ decades:

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*)

low bound - nuclear gamma-rays, upper bound - highest energy cosmic rays

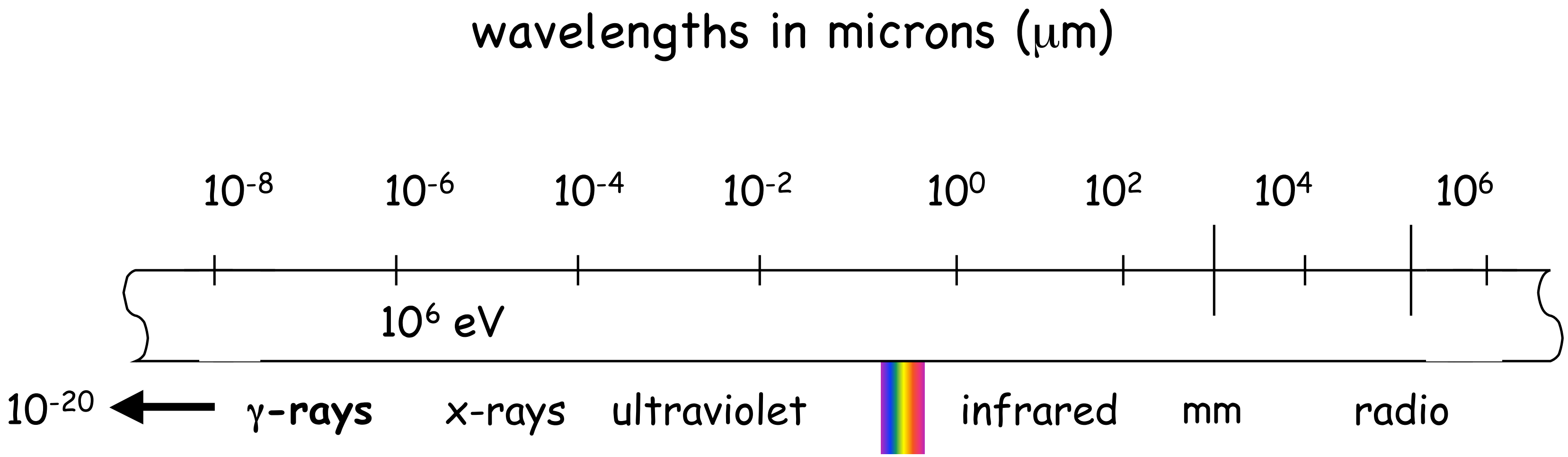
the window is opened in MeV, GeV, and TeV bands:

LE,HE *domain of space-based astronomy*
VHE, ... *domain of ground-based astronomy*

potentially 'Ground-based γ-ray astronomy' can cover five decades (from 10 GeV to 1 PeV) , but presently it implies 'TeV γ-ray astronomy'

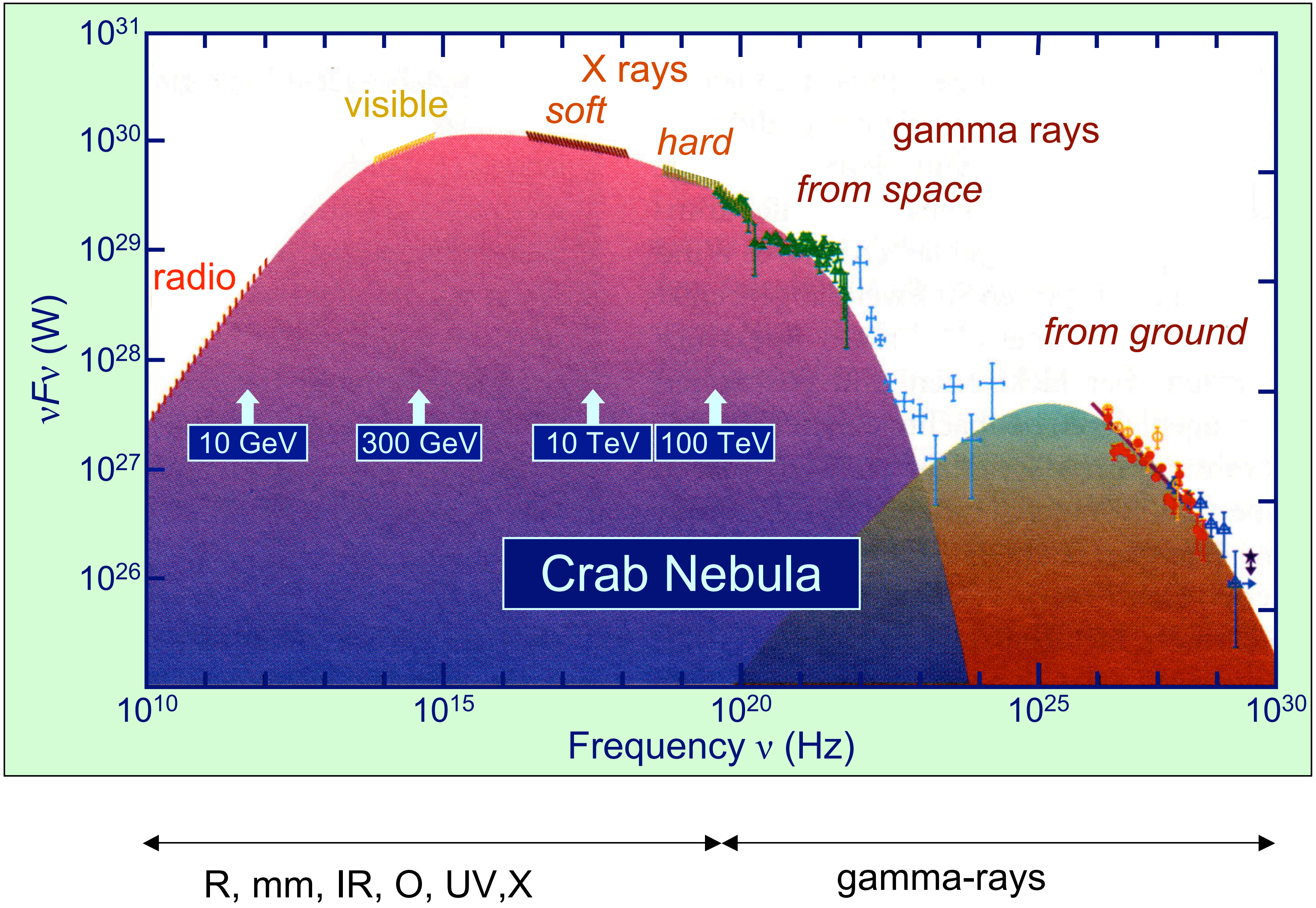
1MeV=10^6 eV, 1GeV=10^9 eV, 1TeV=10^{12} eV, 1PeV=10^{15} eV 1EeV=10^{18} eV

γ-rays: photons with wavelengths less than 10^{-6} μm



gamma-rays are detected from 10^5 eV to 10^{14} eV

a non-thermal astrophysical object seen over 20 energy decades



why gamma-rays?

gamma-rays – unique carriers of information about <u>high energy processes</u> in the Universe

- ✓ are effectively produced
  in both electromagnetic and hadronic interactions
- ✓ penetrate (relatively) freely throughout
  intergalactic and galactic magnetic and photon-fields
- ✓ are effectively detected
  by space-based and ground-based detectors

high energy cosmic gamma-rays

a few general remarks …

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

radiation and absorption processes

any interpretation of an astronomical observation requires

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

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:	$e\ \gamma\ (B) \Rightarrow e'\ \gamma$	**	$E\gamma \sim \varepsilon(Ee/mc^2)^2$ (T) to $\sim Ee$ (KN)
$\gamma\gamma$ pair production	$\gamma\ \gamma\ (B) \Rightarrow e^+e^-$	**	
Strong / week	$p\ \gamma \Rightarrow \pi, K, \Lambda, \ldots$	*	
	$\pi, K, \Lambda \Rightarrow \gamma, \nu, e, \mu$		$E\gamma \sim 1/10Ep$
	$\mu \Rightarrow \nu$		
	$A\ \gamma \Rightarrow A* \Rightarrow A'\ \gamma$	*	$E\gamma \sim 1/1000A\ Ep$
B-field			
synchrotron	$e\ (p)\ B \Rightarrow \gamma$	*	$E\gamma \sim BE_e^2$; $h\nu_{max} \sim \alpha^{-1}\ mc^2$
pair production	$\gamma\ B \Rightarrow e+e-$	*	

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) photon-photon annihilation => $\mu+\mu-$ => neutronos, antineutrinos

production of neutrinos by photons as parent particles

E-M are calculated with high accuracy and confirmed experimentally

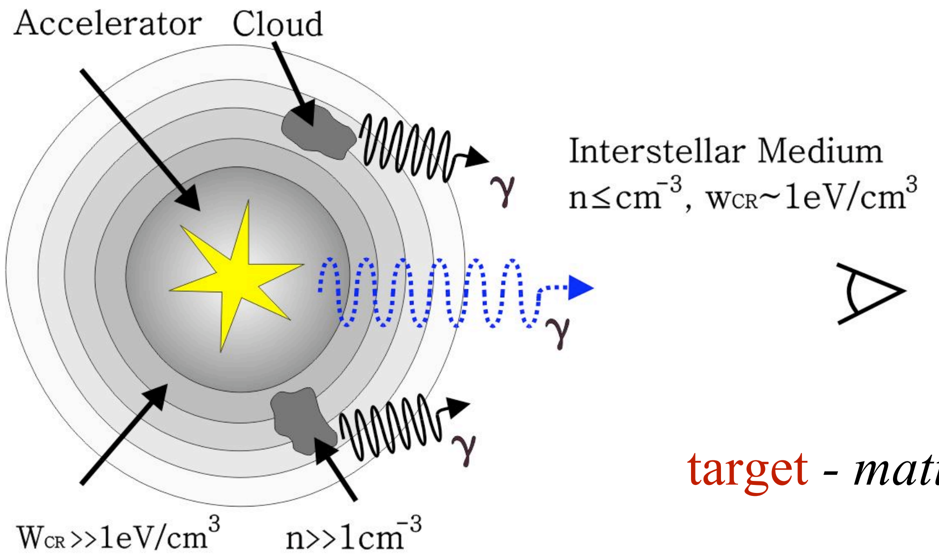
S are well studied experimentally and explained theoretically

often several processes proceed together =>

cascades in matter, radiation and B-fields

gamma-ray production: accelerator+target

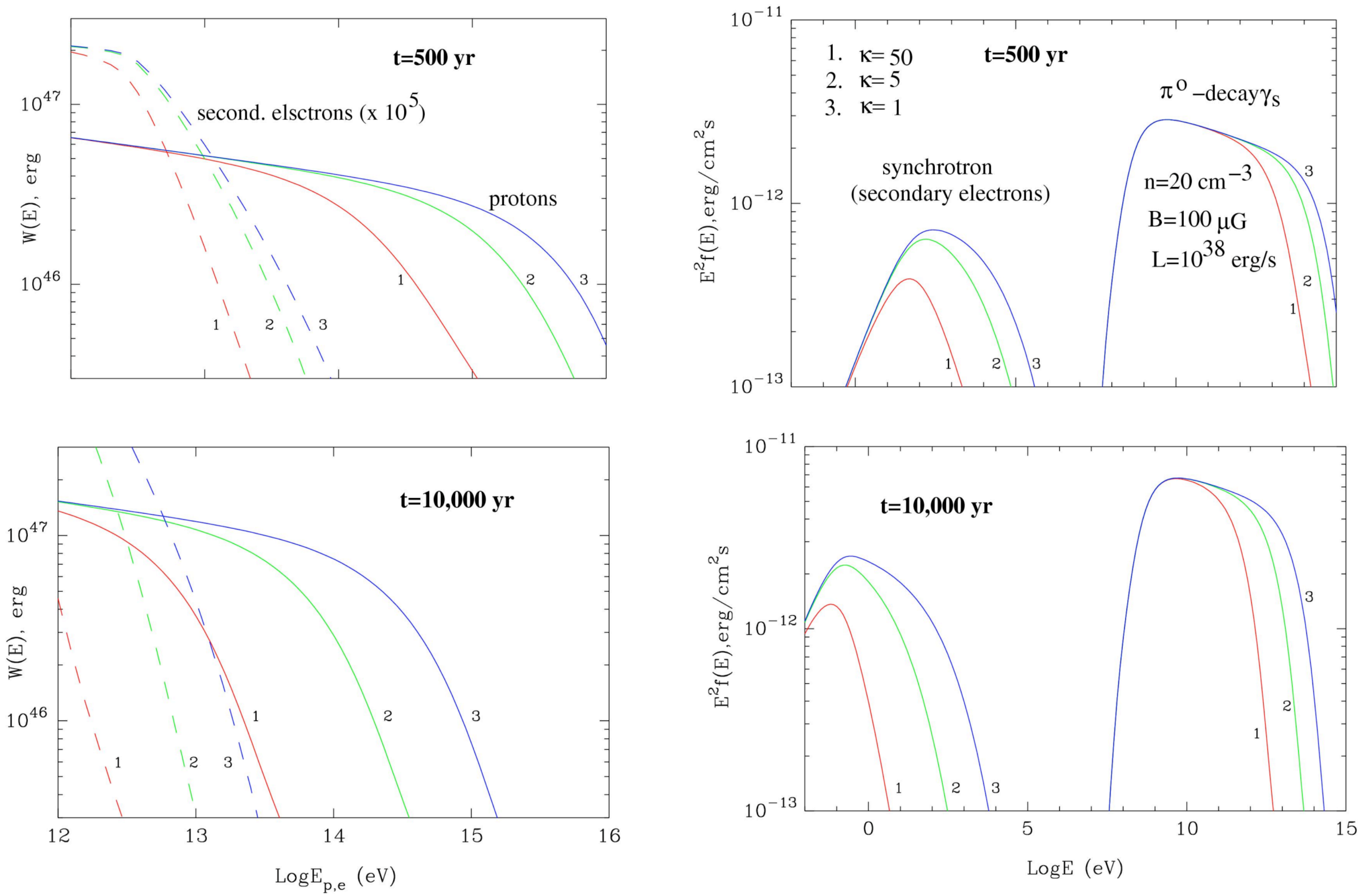
existence of a powerful particle accelerator by itself is not sufficient for γ-radiation; an additional component – a dense target - is required



target - *matter, radiation, magnetic field*

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

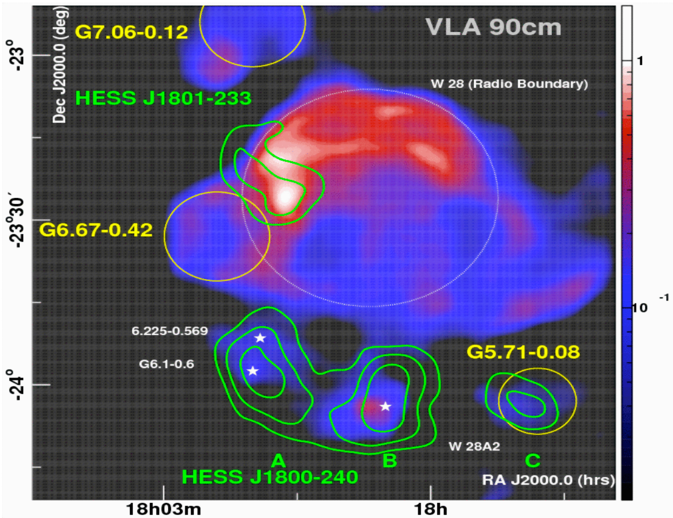
older source – steeper γ-ray spectrum

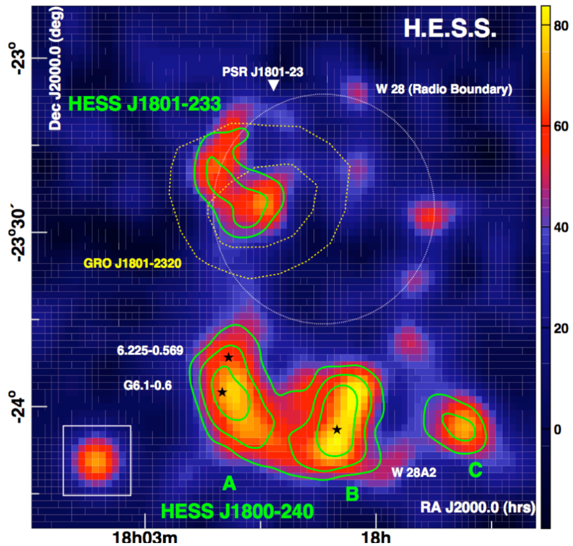


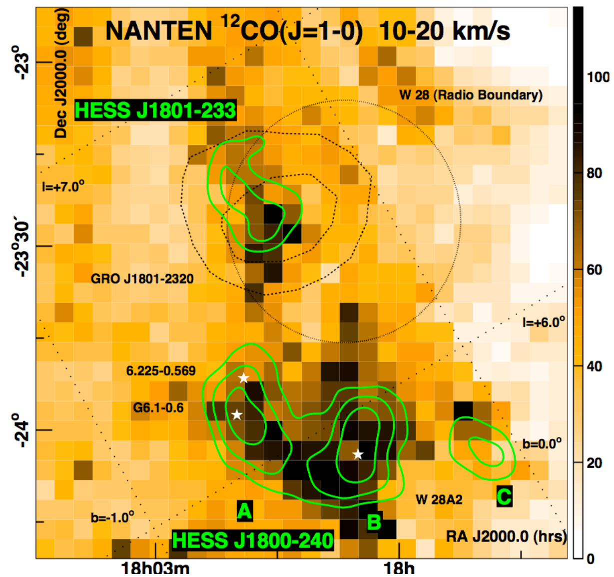
t_{esc}=4x10^5(E/1 TeV) $^{-1}\kappa^{-1}$ yr (R=1pc); κ=1 – Bohm Difussion

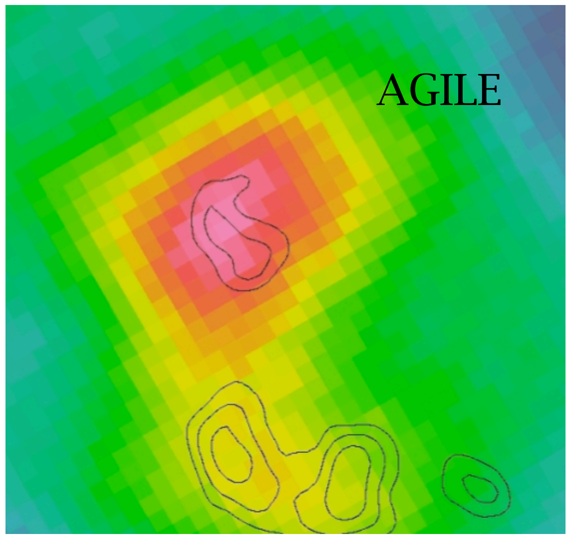
Qp = k $E^{-2.1}$ exp(-E/1PeV) Lp=10^{38}(1+t/1kyr) $^{-1}$ erg/s

1. TeV gamma-ray sources around W28: CRs from an old SNR interacting with nearby clouds?

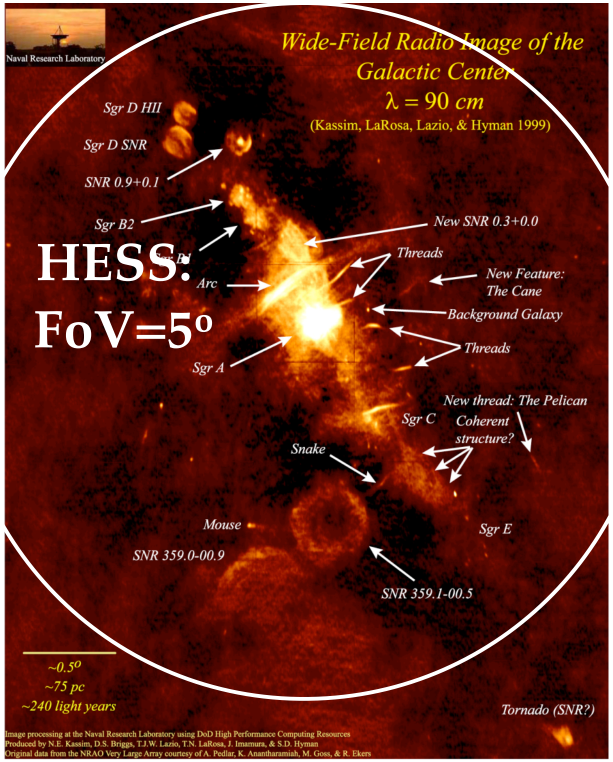








2. Galactic Center



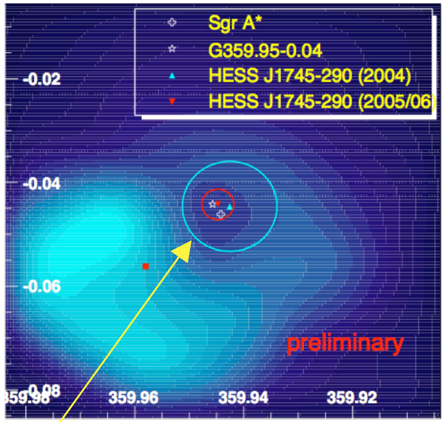
GC – a unique site that harbors many interesting sources packed with unusually high density around the most remarkable object $3\text{x}10^6$ Mo SBH – Sgr A*

*many of them are potential γ-ray emitters - Shell Type SNRs Plerions, Giant Molecular Clouds Sgr A * itself, Dark Matter …*

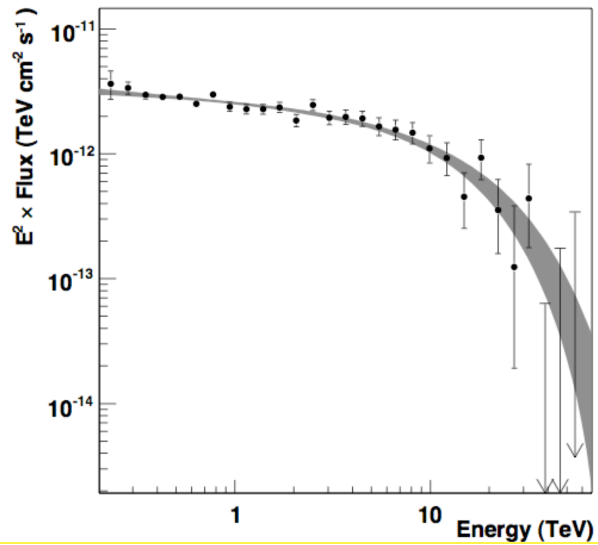
all of them are in the FoV an IACT, and can be simultaneously probed down to a flux level 10^{-13} erg/cm^{2}s and localized within << 1 arcmin

Galactic Center

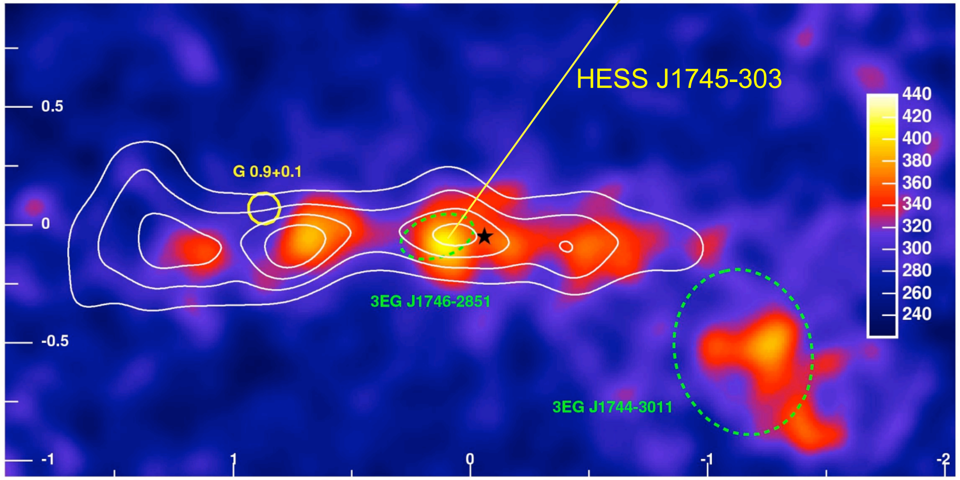
90 cm VLA radio image



Sgr A* or the central diffuse < 10pc region or a plerion? [no indication for variation]



γ-ray emitting clouds



Energy spectrum:

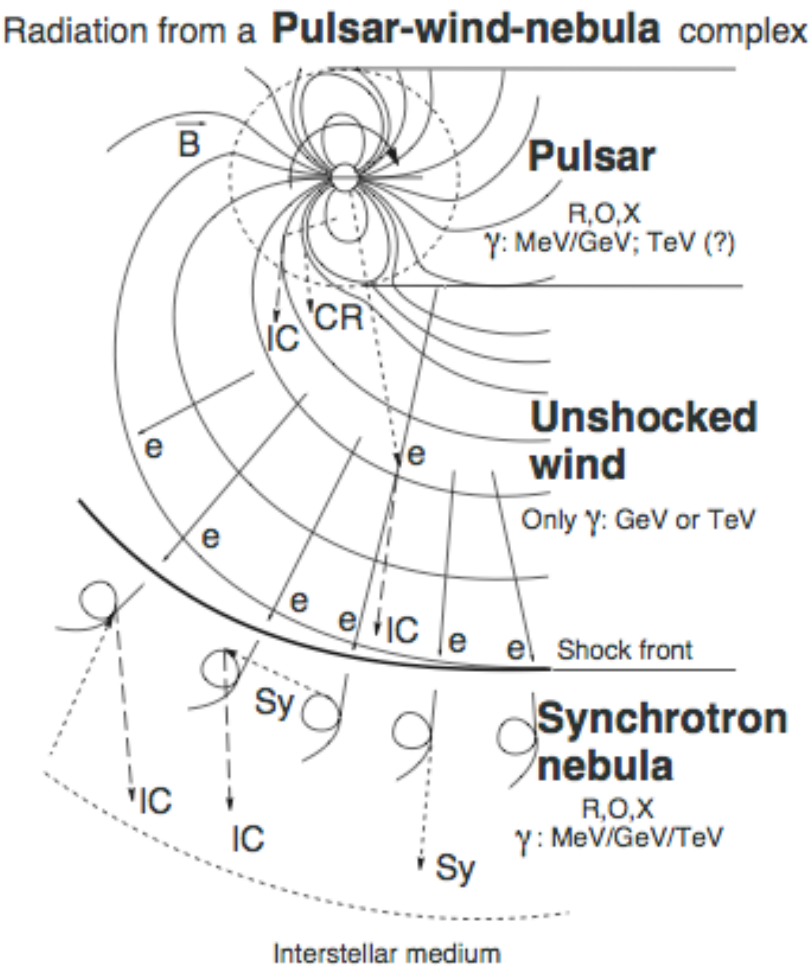
$dN/dE = AE^{-\Gamma} \exp[(-E/E_{0)})^{\beta}]$

$\beta=1$ $\Gamma=2.1$; $E_0=15.7$ TeV

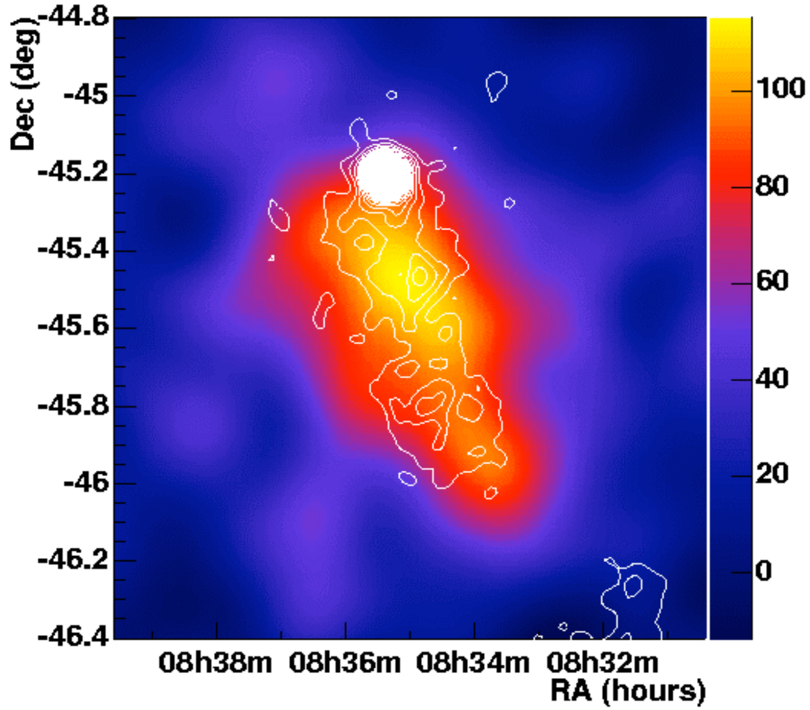
$\beta=1/2$ $\Gamma=1.9$ E0=4.0 TeV

γ-rays from GMCs in GC: a result of an active phase in Sgr A* with acceleration of CRs some 10^4yr ago?

3.



HESS J0835-456 (Vela X)



2.7 K MBR is the main target field; TeV images reflect spatial distributions of electrons Ne(E,x,y); coupled with synchrotron X-rays, this allow measurements of B(x,y)

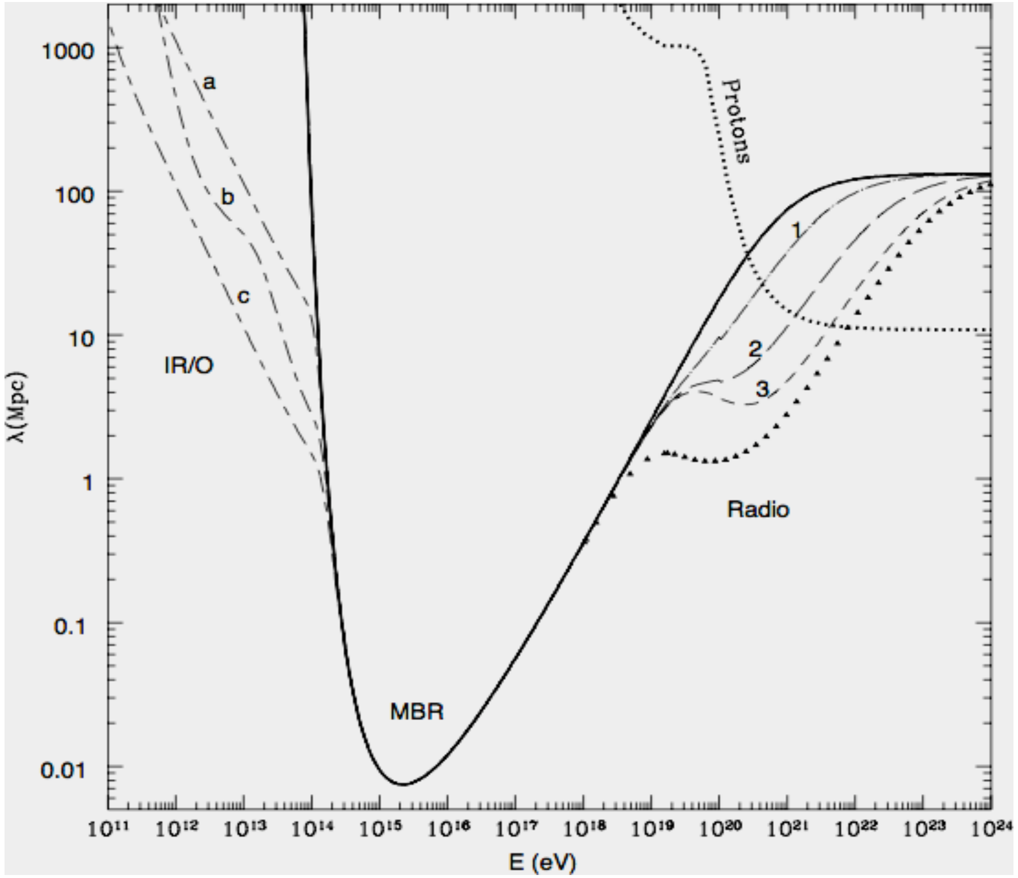
Gamma-Ray Horizon caused by interactions with radiation fields

VHE (TeV) gamma-rays interact effectively with EBL: 0.1-100 μm
100Mpc<d<1Gpc

UHE (PeV) gamma-rays interact effectively with 2.7K MBR: ~1mm
10kpc<d<1Mpc

EHE (EeV) gamma-rays interact with Radio emission:1-10MHz:
1Mpc<d<10Mpc

mean free path of cosmic gamma-rays



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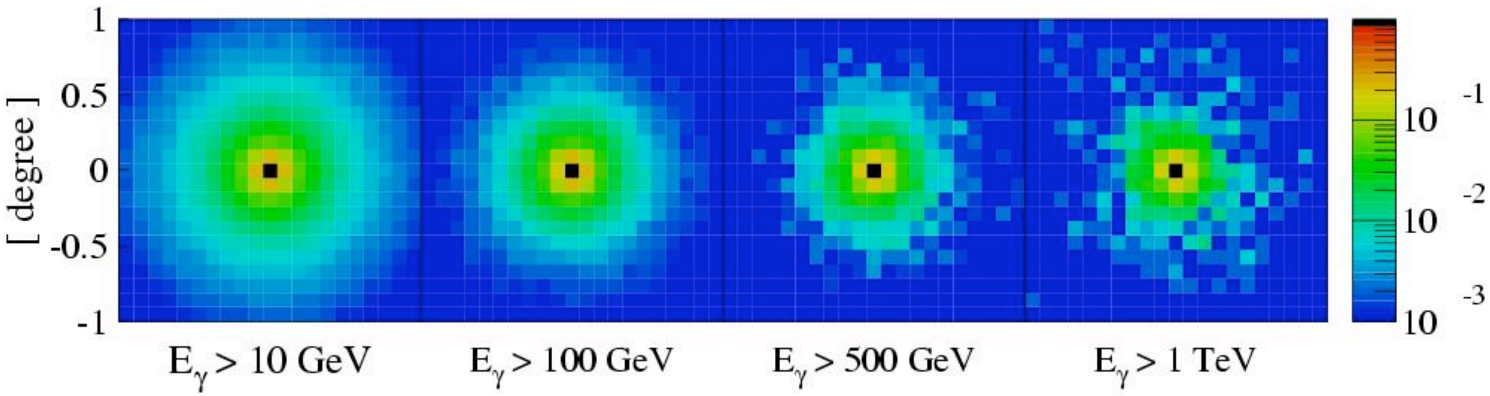
4. Giant Pair Halos

when a gamma-ray is absorbed its energy is not lost !
absorption in EBL leads to E-M cascades suppoorted by

- Inverse Compton scattering on 2.7 K CMBR photons
- photon-photon pair production on EBL photons

if IGM is sufficiently strong, B > 10^{-11} G, the e^+e^- pairs are promptly isotropised => formation of extended (relic) structures – Pair Halos

unique cosmological candles with or without the central sources



z=0.129

B-fields and VHE sources

B-field:

- ❑ *a key parameter for acceleration/confinement of multi-TeV particles*

$t_{acc} = \eta R_L/c \sim E/B \qquad t_{esc} \sim R^2/D(E) \sim R^2B/E$

diffusion in PeVatrons cannot be far from Bohm regime, $D(E)=cR_L/3$,

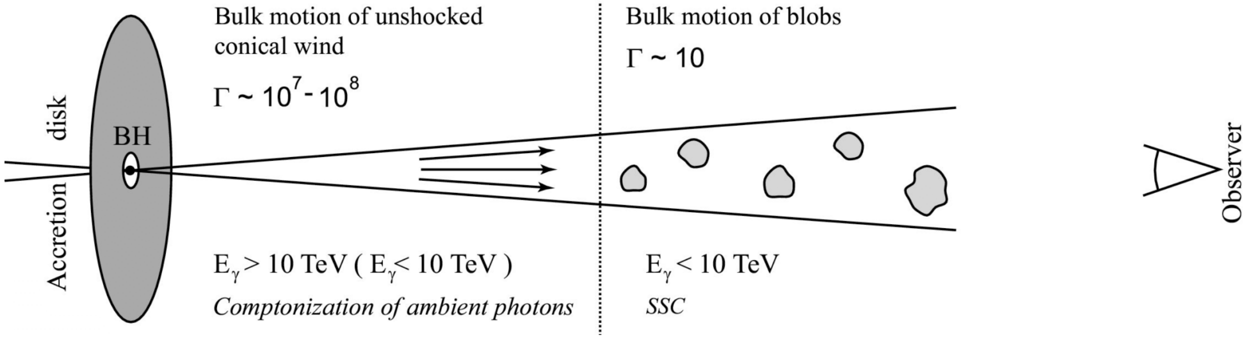
in many cases we have to invoke relativistic bulk motions (shocks with v~c)

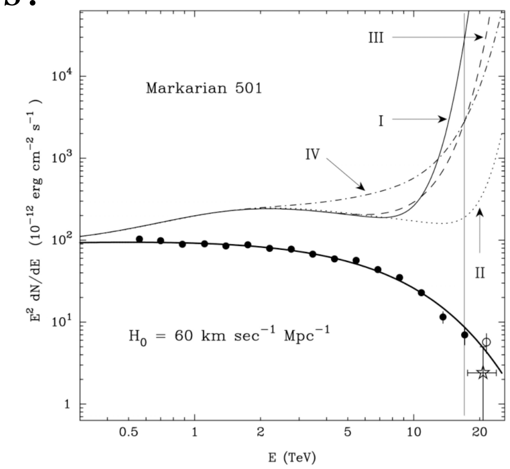
for electrons: $E_{max} \sim 60\ (B/kG)^{-1/2}\eta^{-1/2}$ TeV

- ❑ *a key parameter for effective gamma-ray production: for example:*

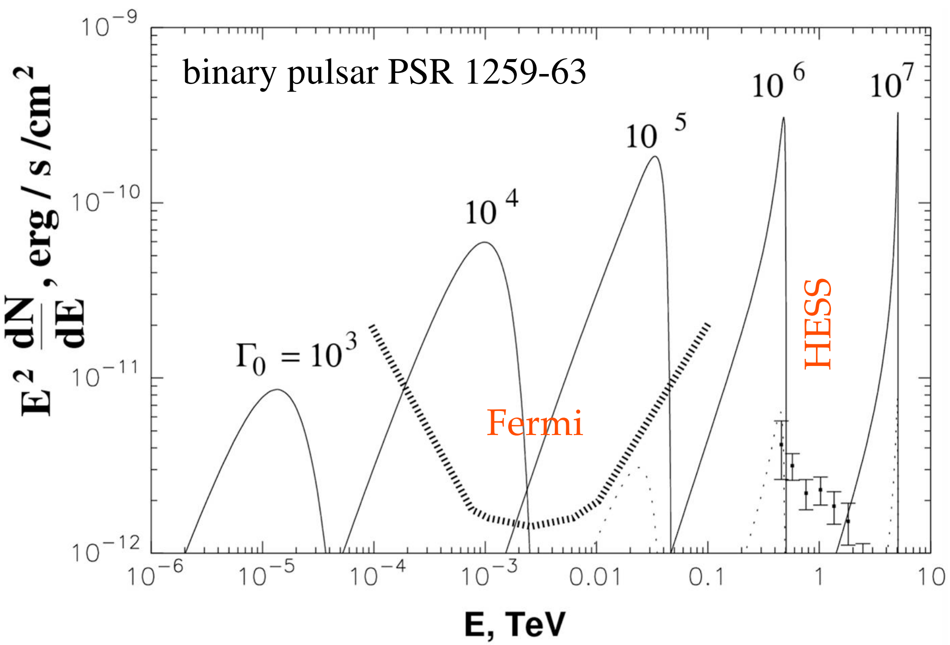
- ✓ very small for γ-ray production through IC scattering:
- ✓ large in young SNRs for production of “hadronic” γ-rays up to 100 TeV
- ✓ very large - for production of γ-rays through synchrotron radiation of protons
- ✓ not very large and not very small in TeV binaries

Unique! *IC Gamma Rays from Cold Ultrarelativistic Outflows?*





proposed to explains unususal spectral shapes of TeV emission of blazars… in fact it is not a very-exotic-scenario - it constitutes the basis of paradigm of pulsar winds and PWNe



when $\Gamma\varepsilon > m_e c^2$, $E_\gamma = \Gamma m_e c^2$ (IC in (K-N regime)
=> direct measurement of the bulk Lorentz factor

Loretz factors exceeding 10^6 are already excluded, very important - Fermi observations in Dec 2010

other astronomical messengers?

astronomical messengers should be neutral & stable:

photons and neutrinos satisfy fully to these conditions*

partly also ultra-high energy neutrons and protons …

neutrons: $d < (E_n/m_n c^2)\, c\, \tau_0 \;\Rightarrow\; E_n > 10^{17}(d/1\ \mathrm{kpc})$ eV
galactic astronomy with $E > 10^{17}$ eV neutrons

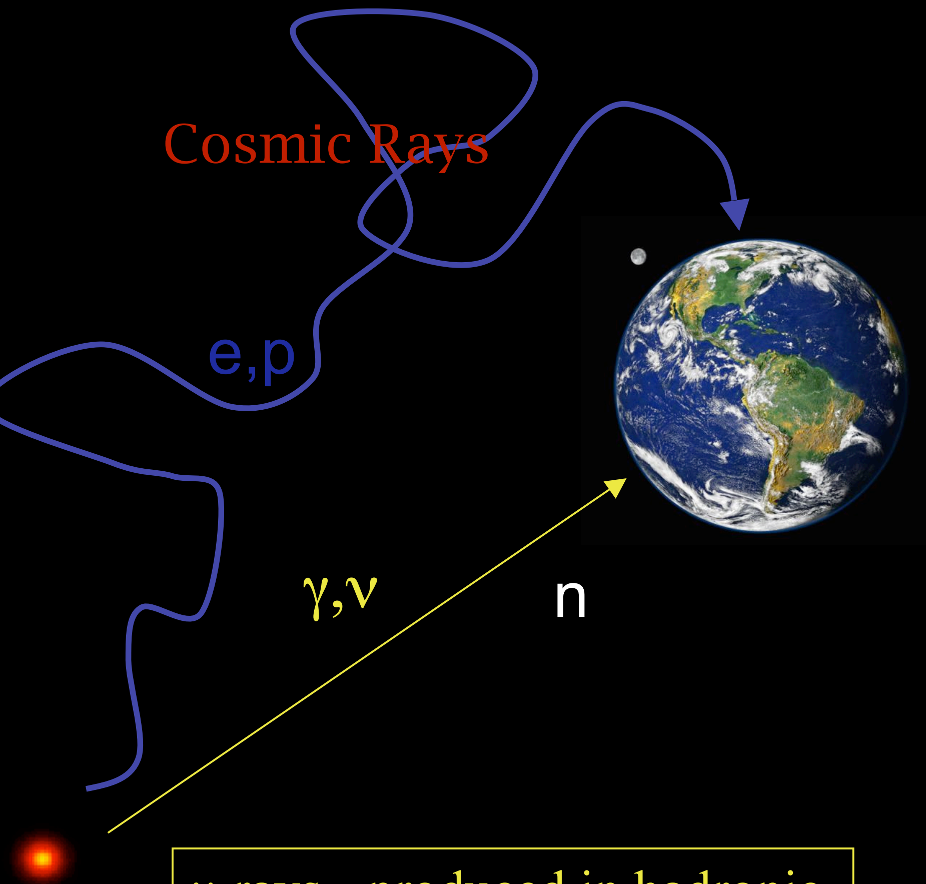
protons: $\phi \sim 1^o$ if $E > 10^{20}$ for IGMF $B < 10^{-9}$G eV
extragalactic astronomy with $E > 10^{20}$ eV protons

**) not only gamma-rays but also X-rays from both primary (directly accelerated) and secondary ($\pi^{+/-}$ decay) electrons*

carriers of information about
Nature's Particle Accelerators

neutral/stable secondary products
of EM and hadronic interactions
of electrons, protons and nuclei
with plasma, radiation and B-fields

photons and neutrinos

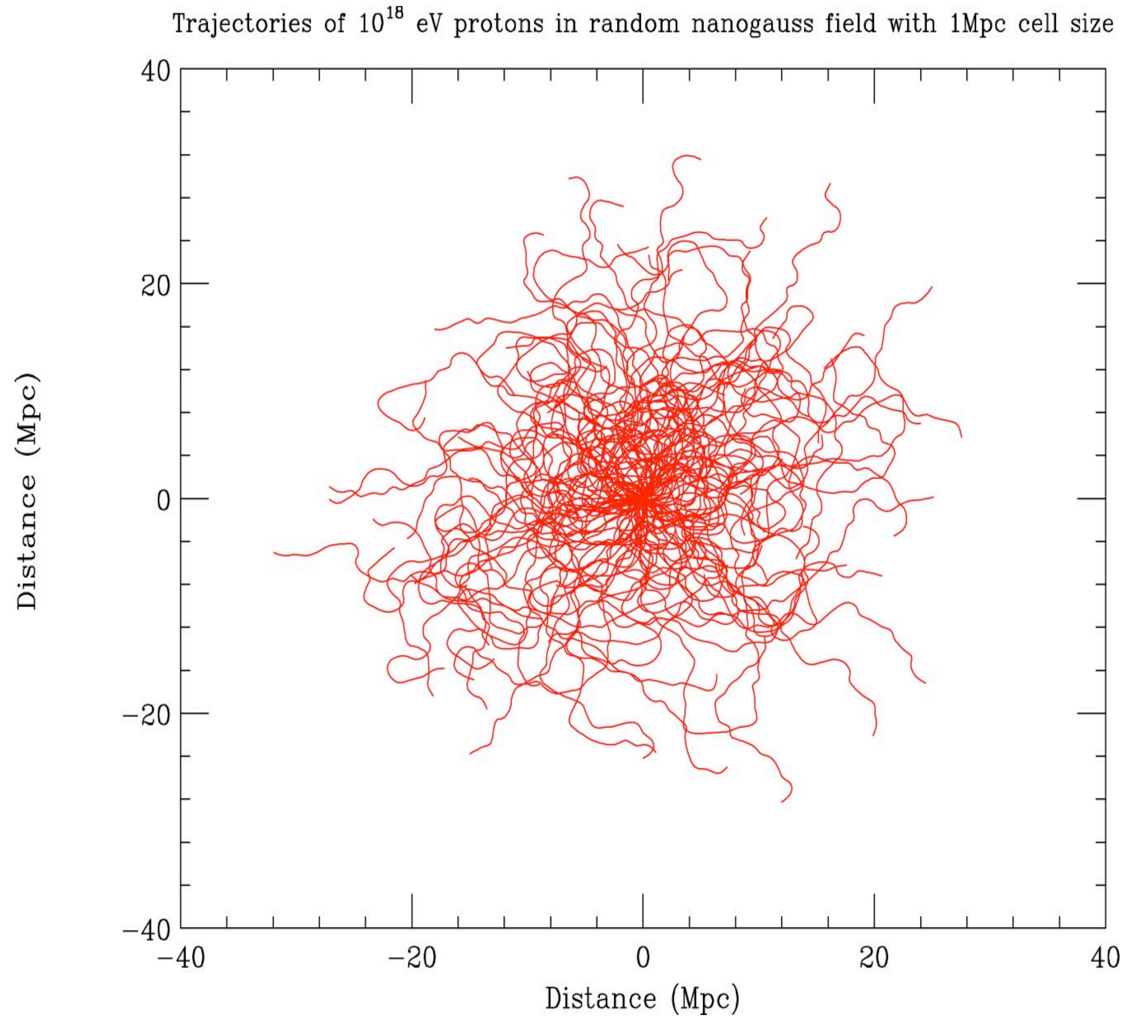


cosmic accelerator

γ-rays - produced in hadronic and E-M interactions

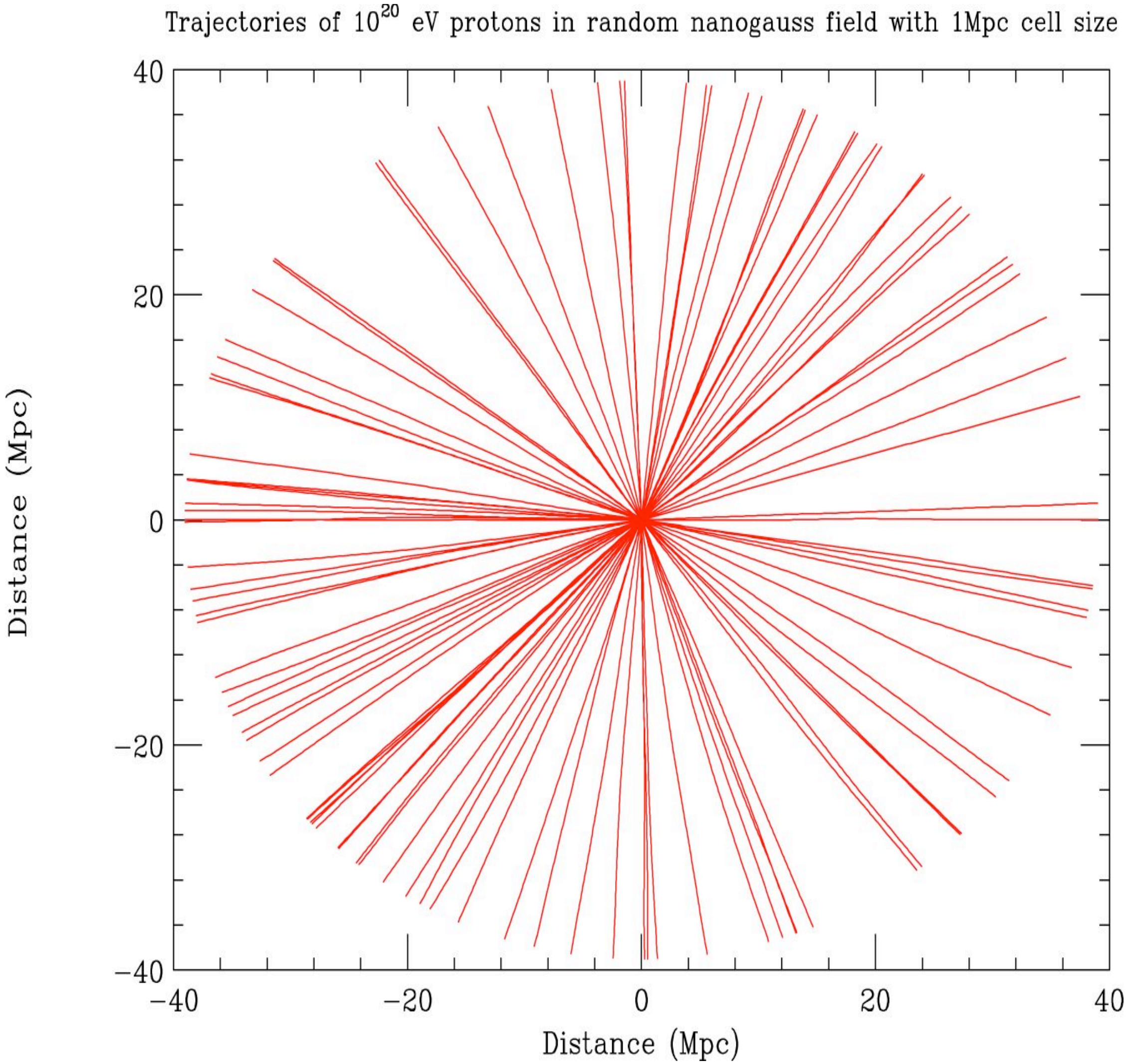
ν_μ, ν_e - produced only in hadronic interactions

astronomy with protons ?



J. Cronin

astronomy with protons ?



J. Cronin

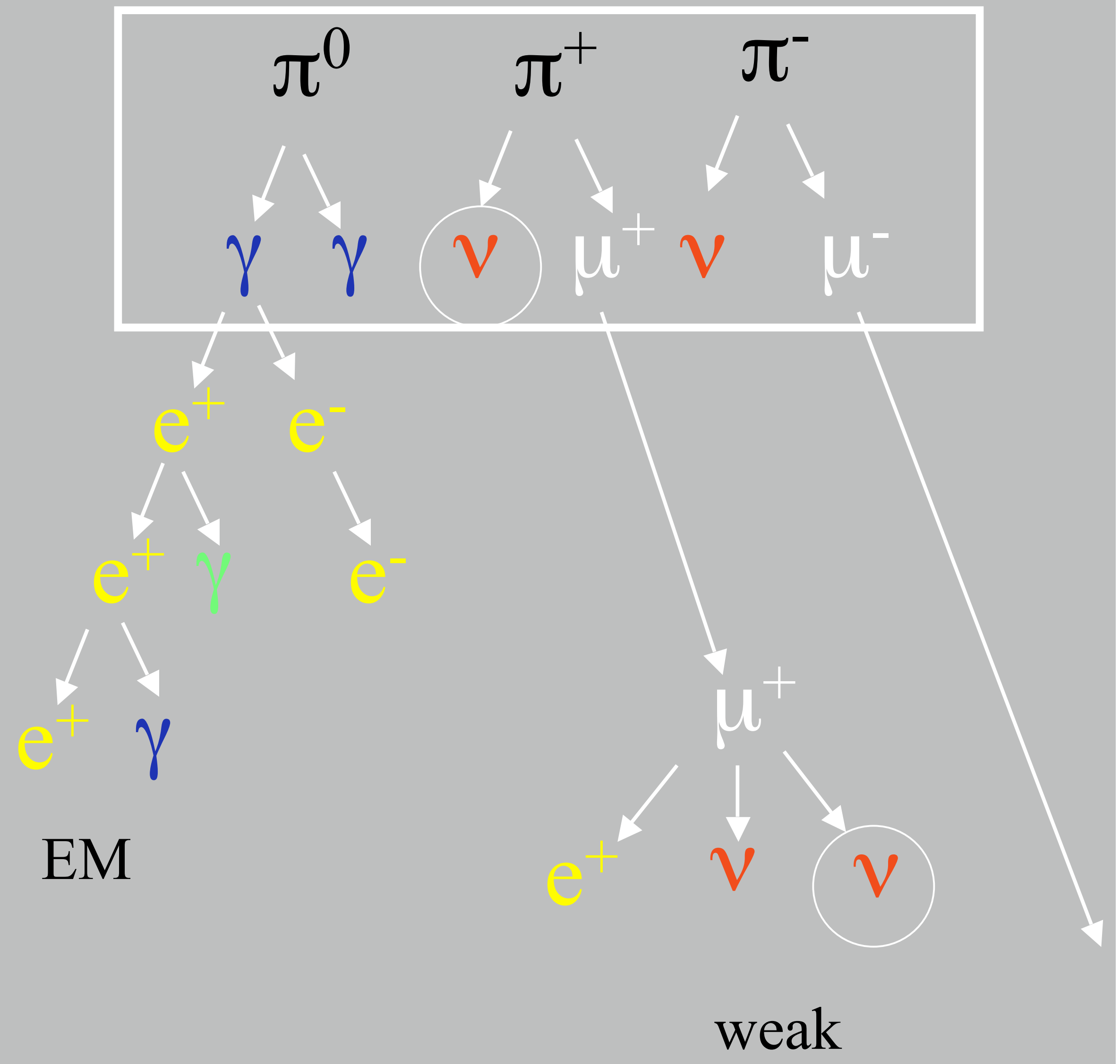
neutrinos

$p+p(\gamma) \rightarrow \pi^0, \pi^+, \pi^-$

strong interactions

γ-rays and neutrnos
neutral&stable !

unique particles
for astrophysics



gamma-ray astronomy

versus

neutrino astronomy

presently: TeV γ-ray astronomy -- a truly astronomical (*observational)* discipline

why TeV γ-rays ?

TeV γ-rays - *unique carriers of astrophysical/cosmological information about non-thermal phenomena in many galactic and extragalactic sources*

✓ are effectively produced in E-M and hadronic interactions ("good and bad")

✓ are effectively detected by space- and ground-based instruments

but… are fragile - effectively interact with matter, radiation and B-fields

(1) information arrives after significant distortion, (2) often - sources are opaque

presently: TeV neutrino astronomy -- "astronomy" *without sources*

why TeV neutrinos ?

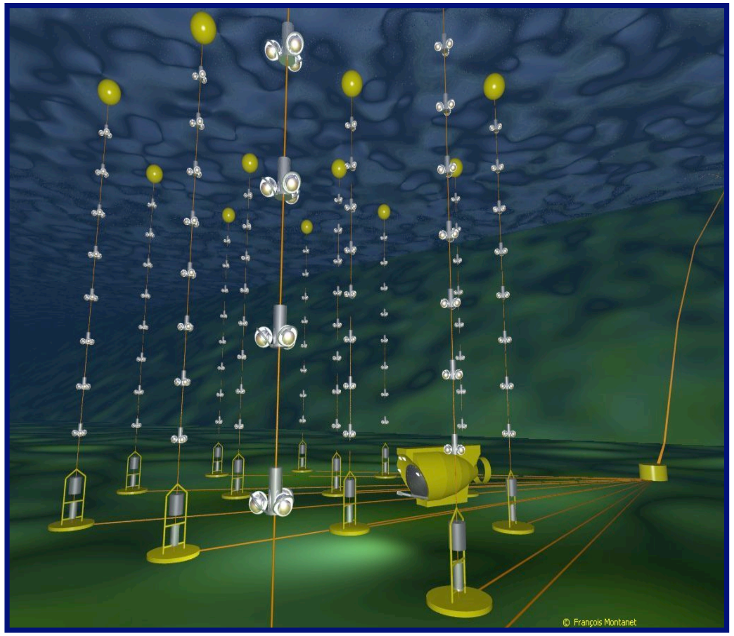
TeV neutrinos - *unique carriers of astrophysical/cosmological information about non-thermal phenomena in many galactic and extragalactic sources*

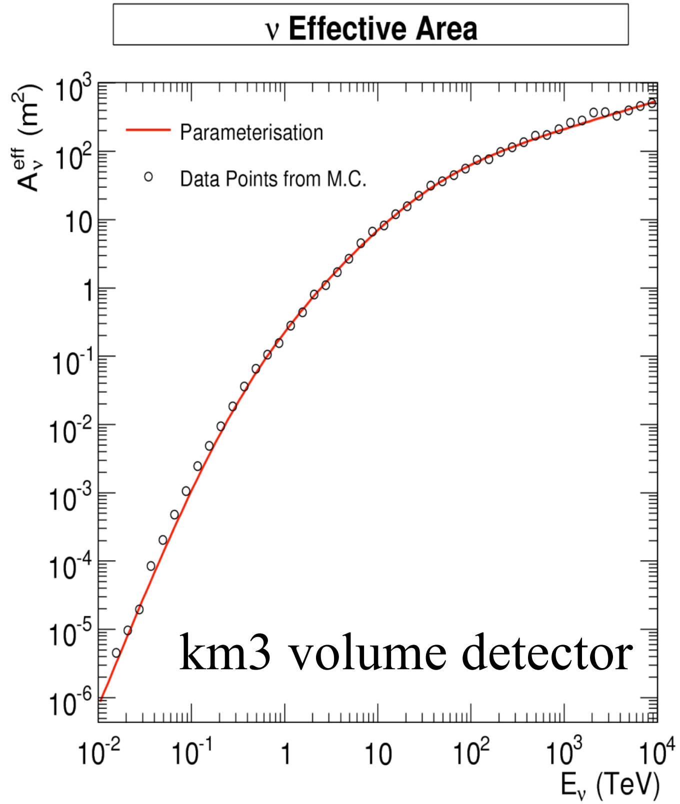
✓ are effectively produced in hadronic interactions ("good and bad")

✓ do not interact with matter, radiation and magnetic fields:

(1) information without distortion; (2) "hidden accelerators" available

but… cannot be effectively detected -- even huge "1km^3 volume" class detectors have limited performance *neutrino telescopes*





effective area: $0.3m^2$ at 1 TeV
$10m^2$ at 10 TeV

=> several events from a "1Crab" source per 1year

compare with detection areas of gamma-ray detectors:

Fermi - $1m^2$ but at GeV energies, ground-based $>10^4m^2$ at same energies

Potential TeV neutrino sources

TeV gamma-ray sources as potential TeV neutrino sources?

yes, if γ-rays of hadronic (*pp* or $p\gamma$) origin

Detectable (by km^3 class) neutrino detectors ?

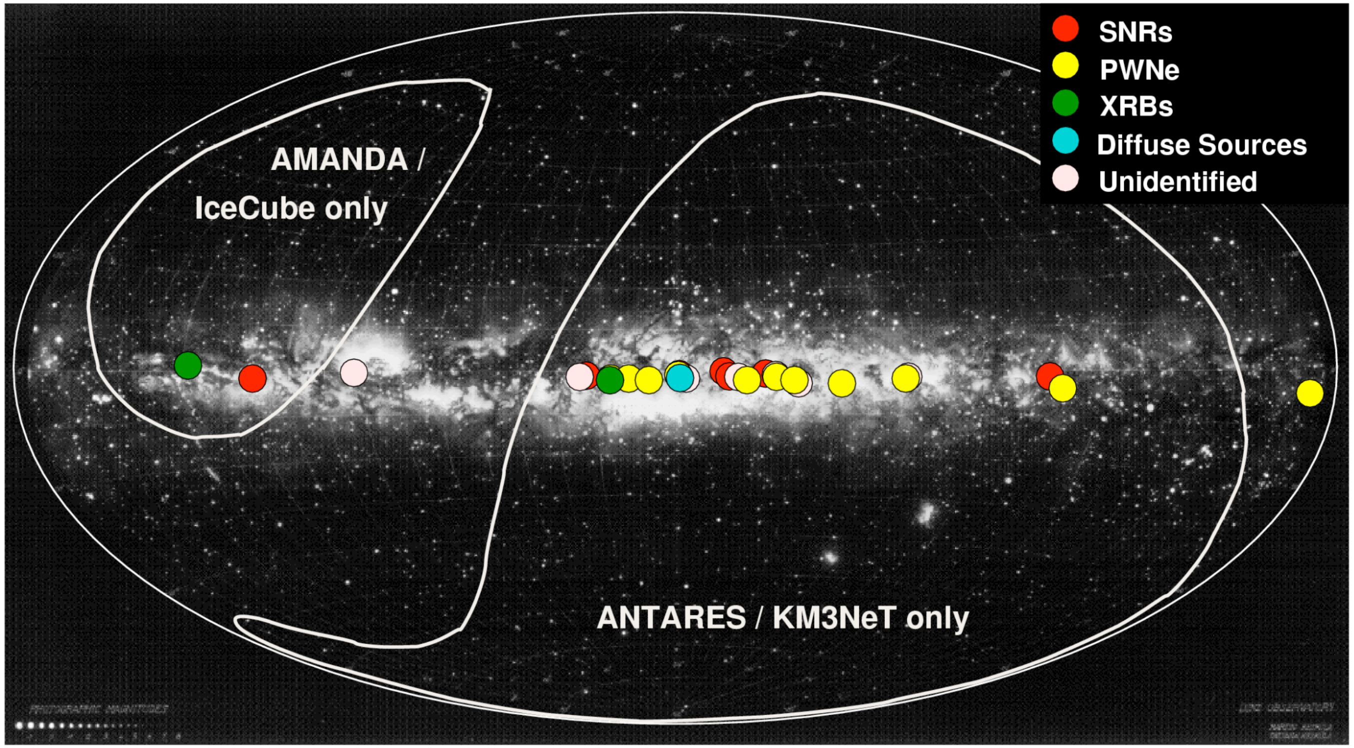
yes, if TeV γ-ray flux exceeds $2\text{x}10^{-11}$ ph/cm^2 s (~1 Crab)

(so far Crab Nebula, Vela X and and two SNRs)

or weaker sources if γ-rays are severely absorbed

(e.g. mQSOs LS 5039 and LS I +61 301, blazars!?)

Visibility of Galactic neutrino sources –
counterparts of TeV γ-ray sources



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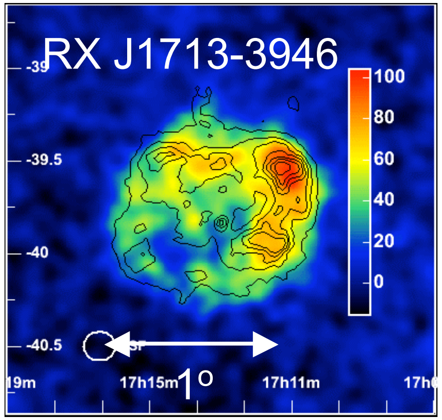
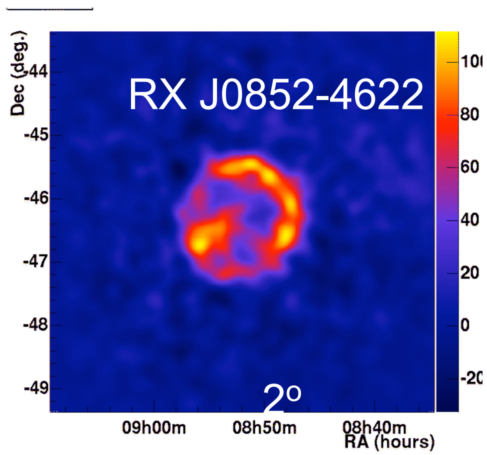
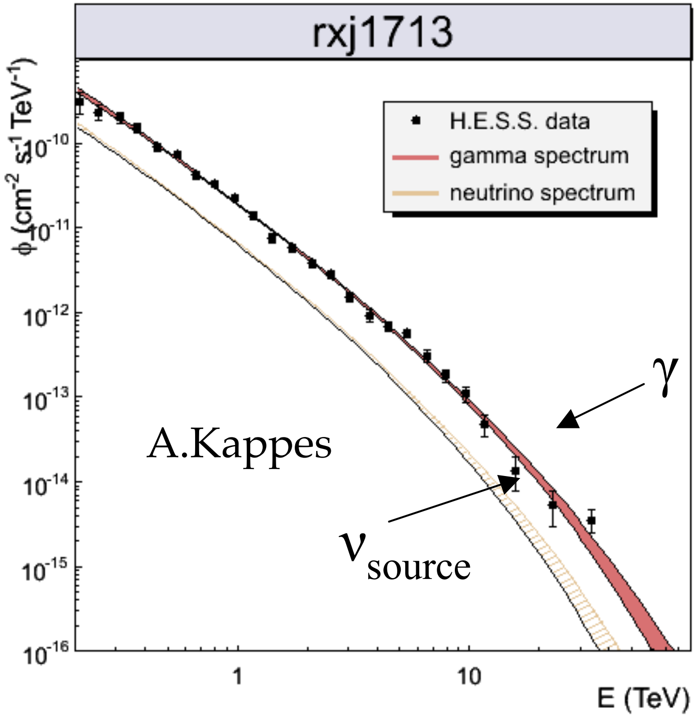
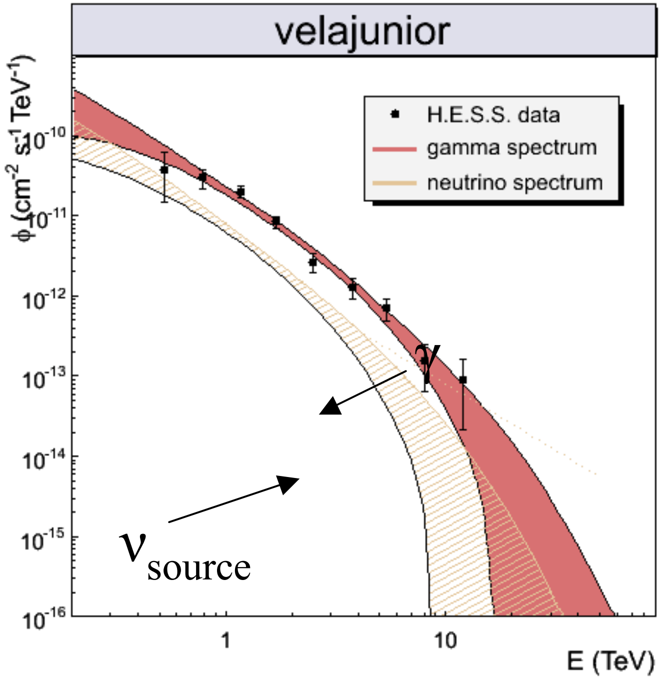


two brightest TeV SNRs

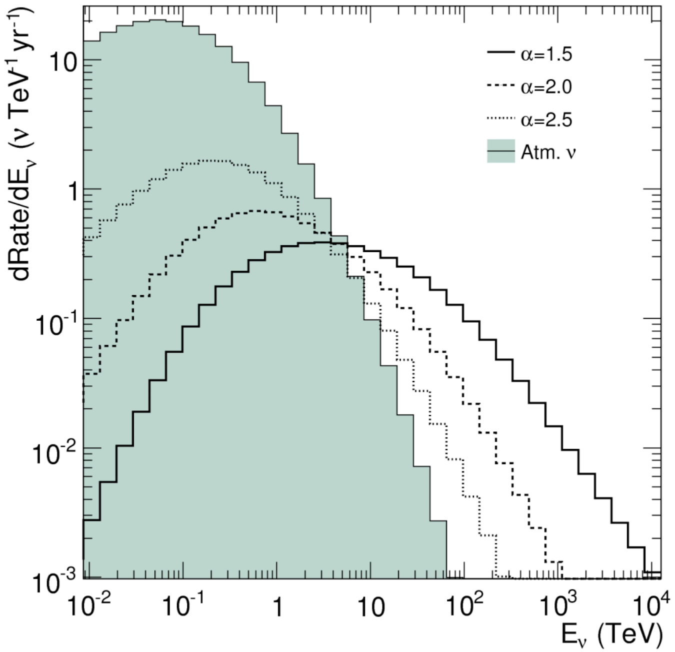


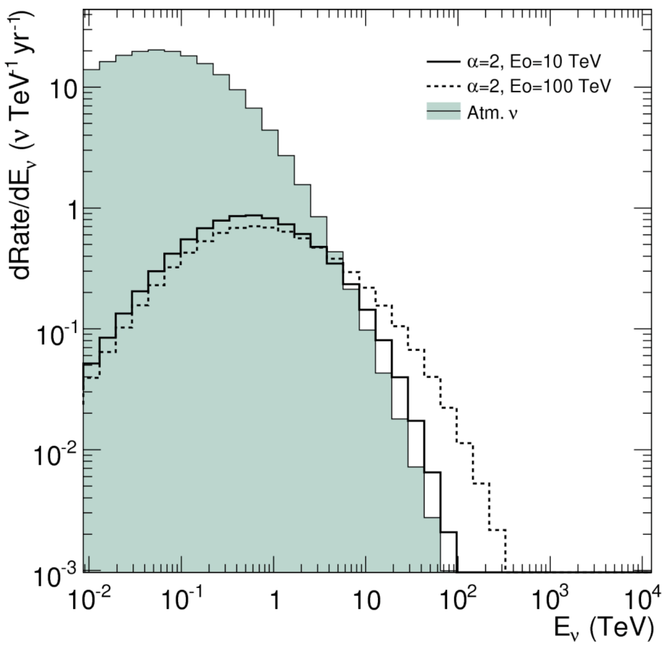




several neutrinos from SNRs per year against several background events by KM3NeT

detection rate of neutrinos with KM3NeT





R.White/A.Taylor

$$\mathrm{J}(\mathrm{E}_\nu) = \mathrm{A}\mathrm{E}_\nu^{-\alpha} \quad \text{with} \quad \mathrm{J}(>1\mathrm{TeV}) = 10^{-11}\ \nu/\mathrm{cm}^2\mathrm{s}$$

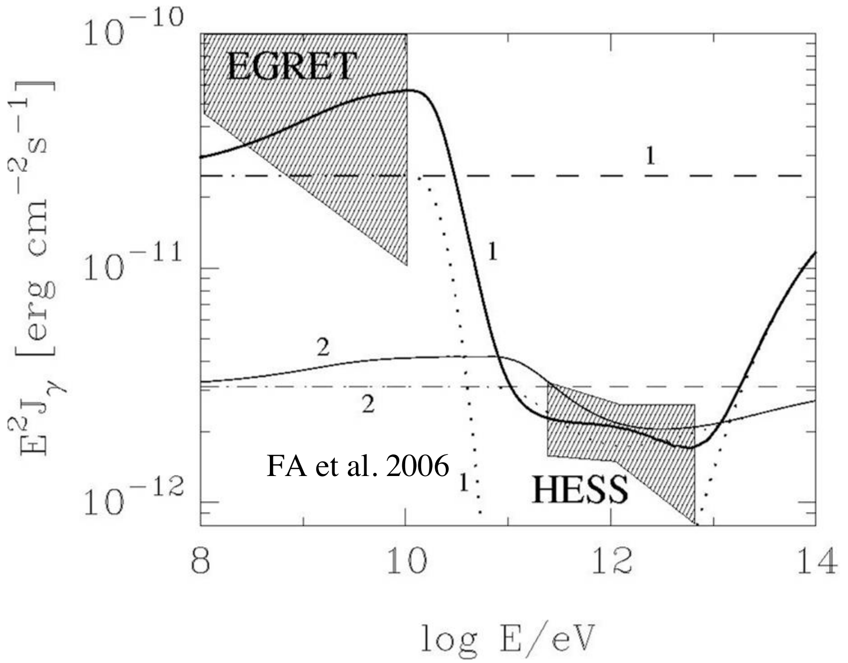
a few neutrinos per year at presence of comparable background events

γ–Binaries as potential neutrino sources ?

if TeV gamma-rays are produced within the binary system ($R < 10^{12}$cm)

- severe absorption of >100 GeV gamma-rays (γ + starlight -> e^+e^-)
  up to a factor of 10 to 100 higher initial luminosity

- severe radiative losses
  acceleration of electrons to multi-TeV energies difficult



Conclusions ? TeV gamma-rays of hadronic origin with high luminosity, and consequently high (detectable!) TeV neutrino fluxes

TeV neutrino fluxes strongly depend o the production site of γ-rays: the base of the jet/accretion disk and/or wind/atmosphere of the star

a more specific/detailed treatment

LS I 61 303

Neronov&Ribordy 2009

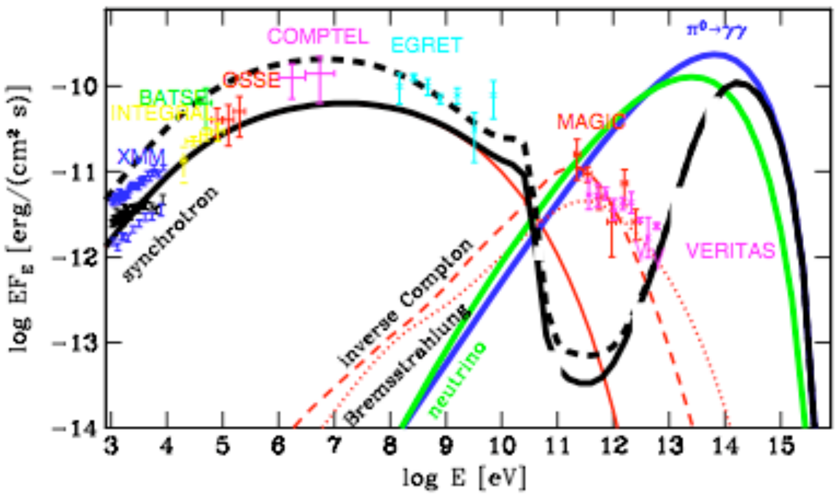


FIG. 4 (color online). Same as in Fig. 3, but for $\Gamma_p = 1$. The thick short dashed line shows the overall spectrum calculated taking into account the tertiary e^+e^- pairs from $\gamma\gamma$ interactions.

NEUTRINO SIGNAL FROM γ-RAY-LOUD BINARIES ...

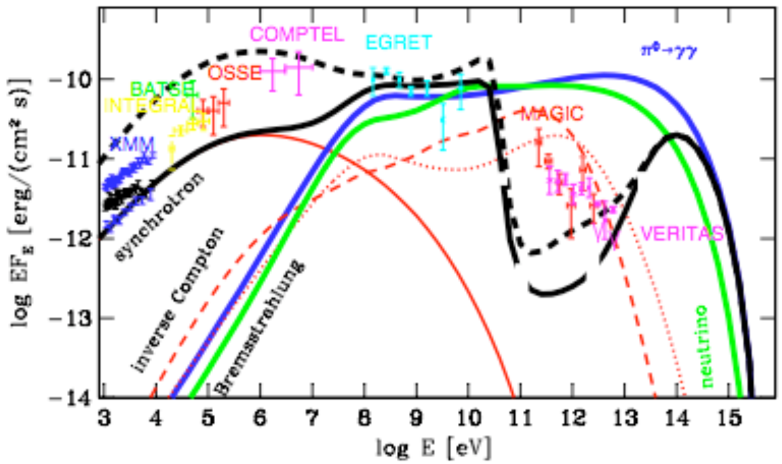


FIG. 5 (color online). Same as in Fig. 4 but for the proton injection spectrum $\Gamma_p = 2$. The magnetic field is assumed to be $B_0 = 0.5$ G.

"right" flux at right "energies" to be detected by IceCube!

some critical remarks concerning both gamma-rays and neutrinos

TeV, PeV, EeV - gamma rays and neutrinos: carriers of information about hadronic colliders, but

TeV γ-rays: effectively produced/detected, but it is not an easy task to identify the "hadronic" origin

PeV/EeV γ-rays: (i) difficult to detect (limited detection areas)
(ii) fragile (absorption in radiation and B-fields)

TeV/PeV/EeV neutrinos: difficult to detect

alternatives? - *hard X-rays of secondary electrons!*

hard X-rays - “hadronic” messengers?

the idea:

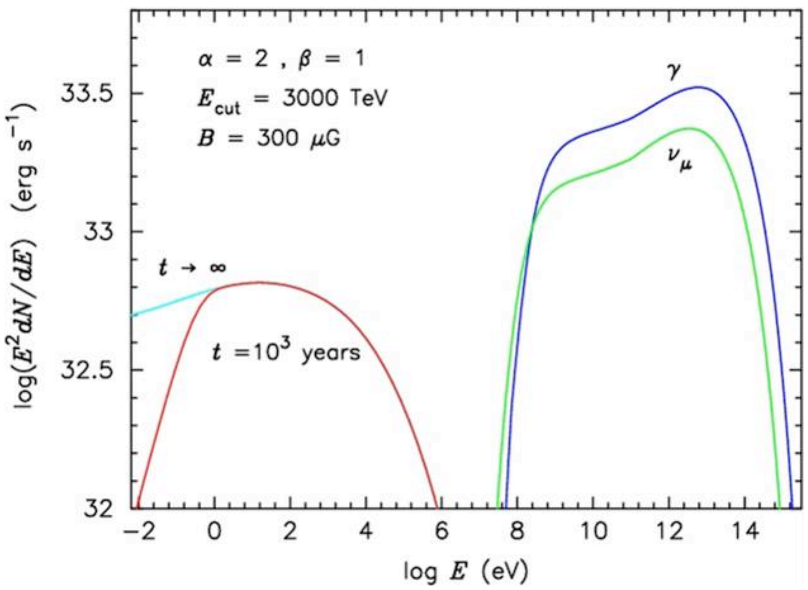
synchrotron radiation of secondary multi-100 TeV electrons produced at interactions of protons with ambient gas or radiation fields

- (1) $p\,p\,(\gamma) \Rightarrow \pi, K, \Lambda,$ (2) $\pi, K, \Lambda \Rightarrow \gamma, \nu, e, \mu$ (3) $e\,B \Rightarrow X$
- (1) $p\,\gamma \Rightarrow e^+\,e^-$ (2) $e\,B \Rightarrow X$

why hard X-rays/low energy gamma-rays?

- ✓ radiation often peaks in the hard X-ray band
- ✓ not many competing production mechanisms
- ✓ no absorption in radiation and magnetic fields
- ✓ good sensitivity/good spectrometry/good morphology

a Galactic PeVatron: E~10^{15}eV

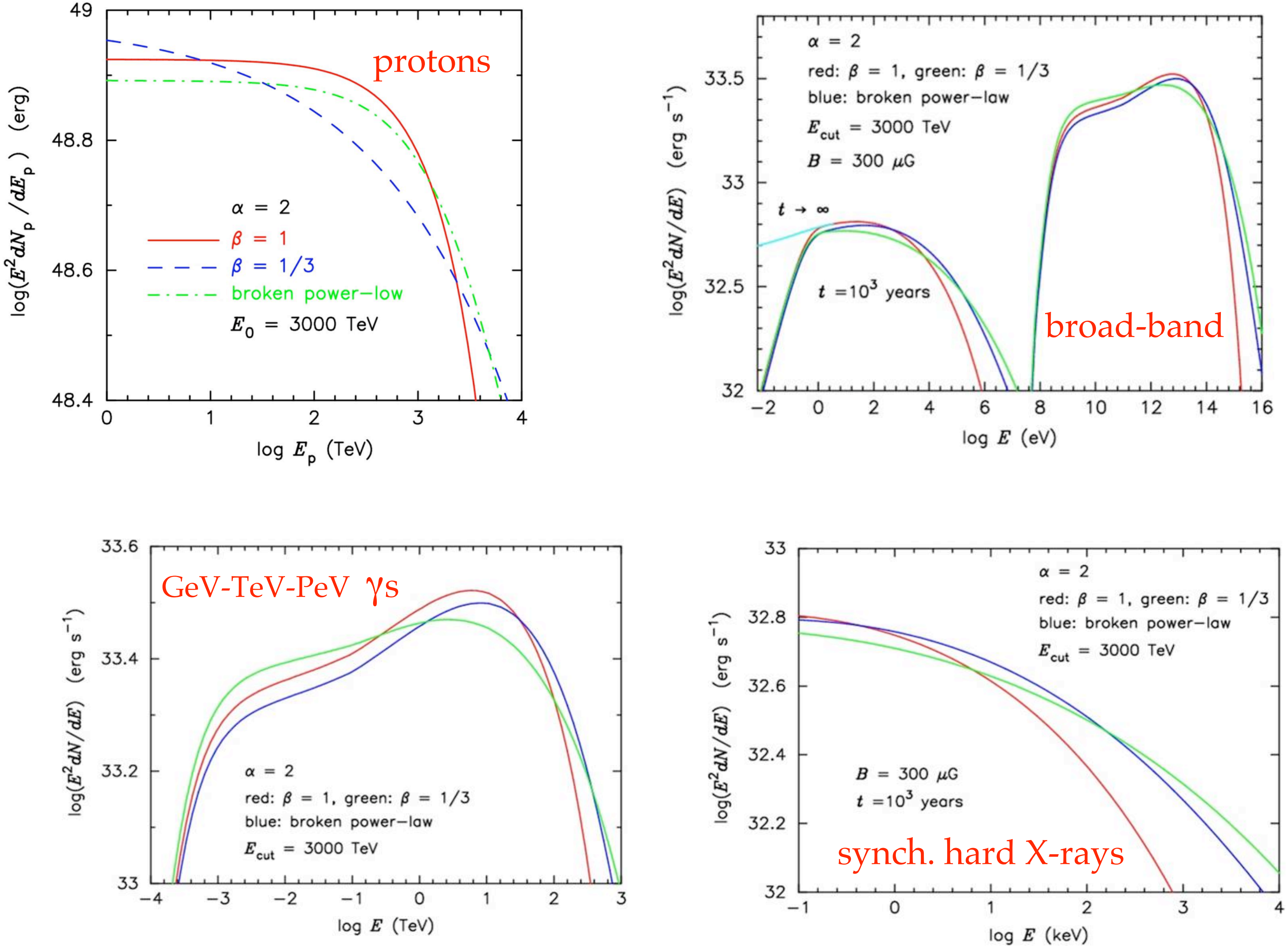


three channels of information
about cosmic PeVatrons:

10-1000 TeV gamma-rays
10-1000 TeV neutrinos
10 -100 keV hard X-rays

- γ-rays: difficult, but possible with future “10km^2“ area multi-TeV IACT arrays
- neutrinos: marginally detectable by IceCube, Km3NeT - don’t expect spectrometry, morphology; uniqueness - unambiguous signatute!
- “prompt“ synchrotron X-rays: smooth spectrum
  a very promising channel - quality!

$\sim \varepsilon^{-(\alpha/2+1)} \exp[-(\varepsilon/\varepsilon_0)^{1/5}]$



broad-band emision initiated by pp interactiosn : Wp=10^{50} erg, n=$1cm^{-3}$

Clusters of Galaxies accelerating protons to 10^{18}eV

DSA acceleration of protons=> interactions of protons with 2.7K CMBR
=> e^+e^- pair production => Synchrotron and IC of secondary electrons

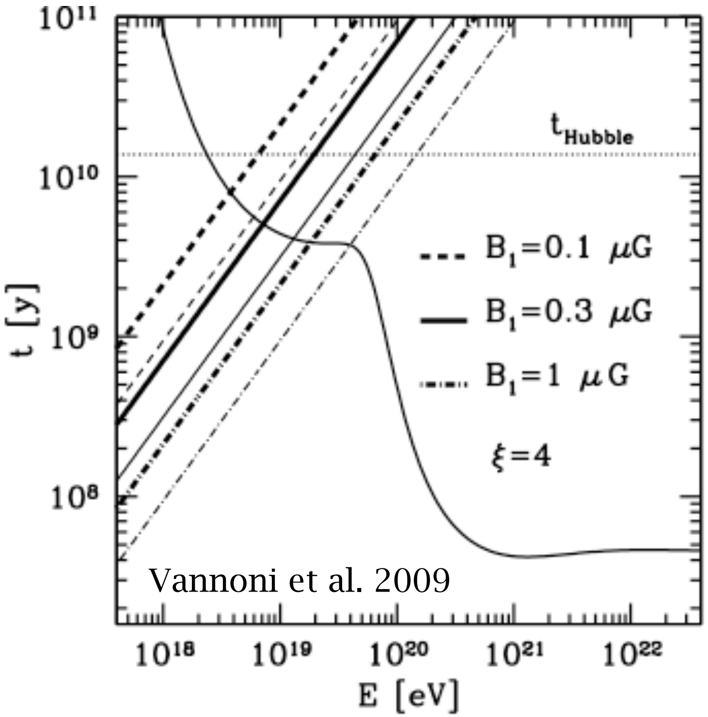


Fig. 1. Acceleration and energy loss time scales as a function of the proton energy. The acceleration time scales are obtained for the values of the upstream magnetic field B_1 reported in figure and a downstream magnetic field $B_2 = 4B_1$. The thick lines correspond to a shock velocity of 2000 km/s, the thin lines to a velocity of 3000 km/s. As an horizontal dotted line we report the estimated age of the Universe, for comparison.

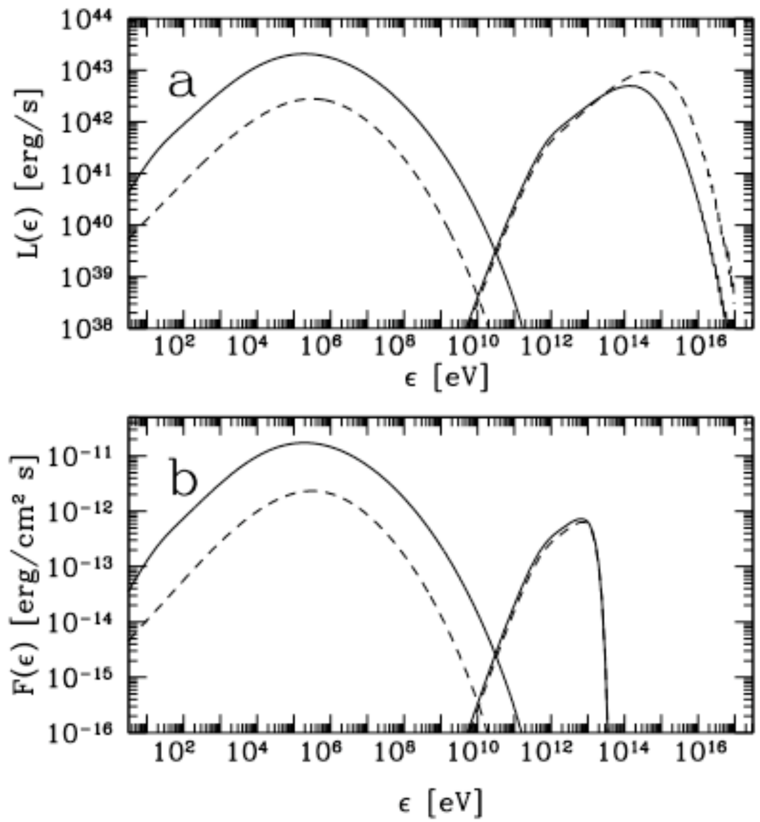
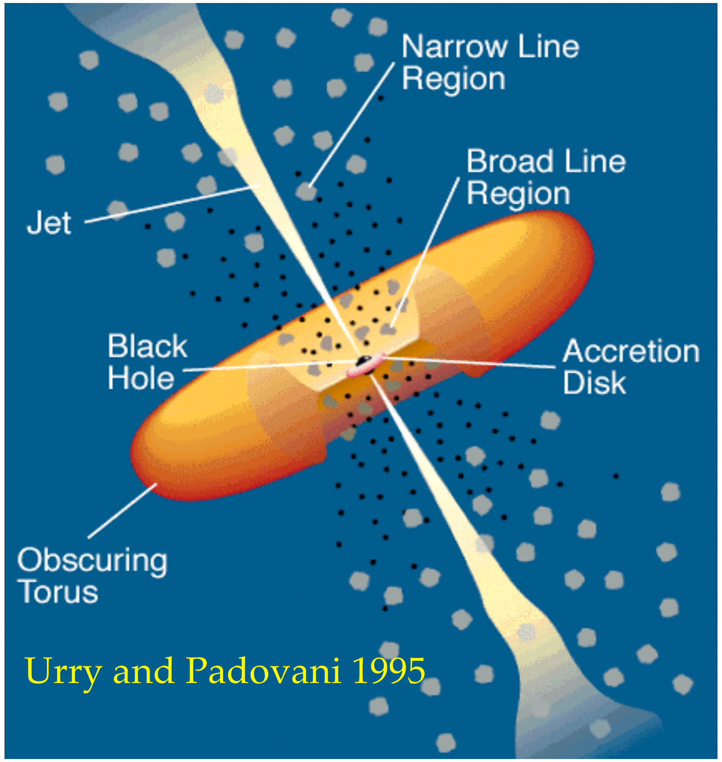
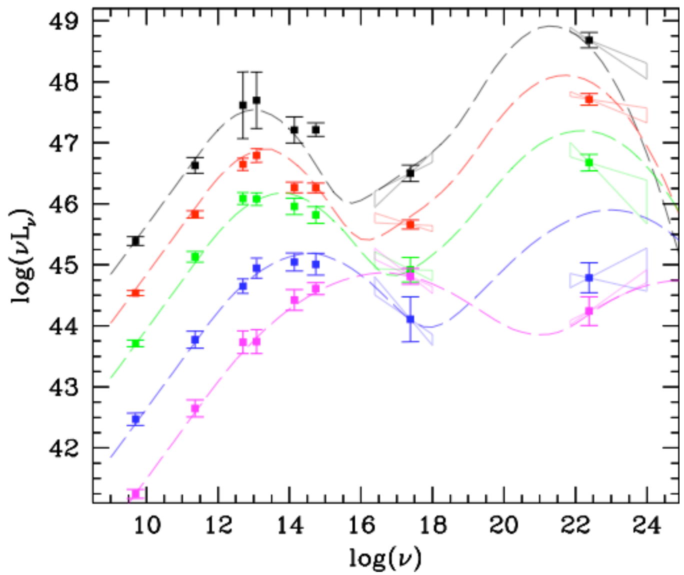


Fig. 13. a) Broadband radiation spectra produced at the source by the electron distributions in Fig. 12**b**, downstream (solid line) and upstream (dashed line). **b)** Energy flux at the observer location, after absorption in the EBL, for a source distance of 100 Mpc.

Blazars - sub-class of AGN dominated by nonthermal/variable broad band (from R to gamma) adiation produced in relativistic jets close to the line of sight, with massive Black Holes as central engines

two-peaks (Synchrotron-IC) paradigm

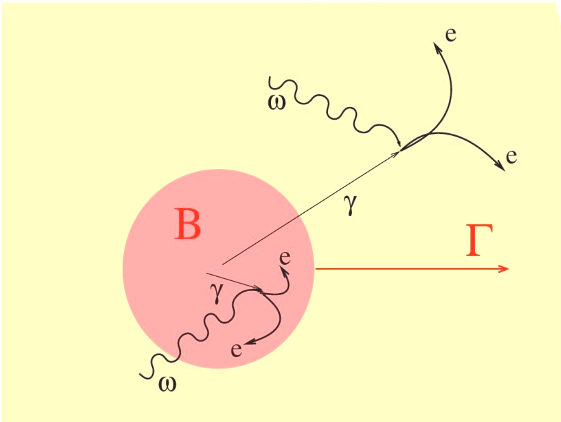




typically small B-field, B <1G

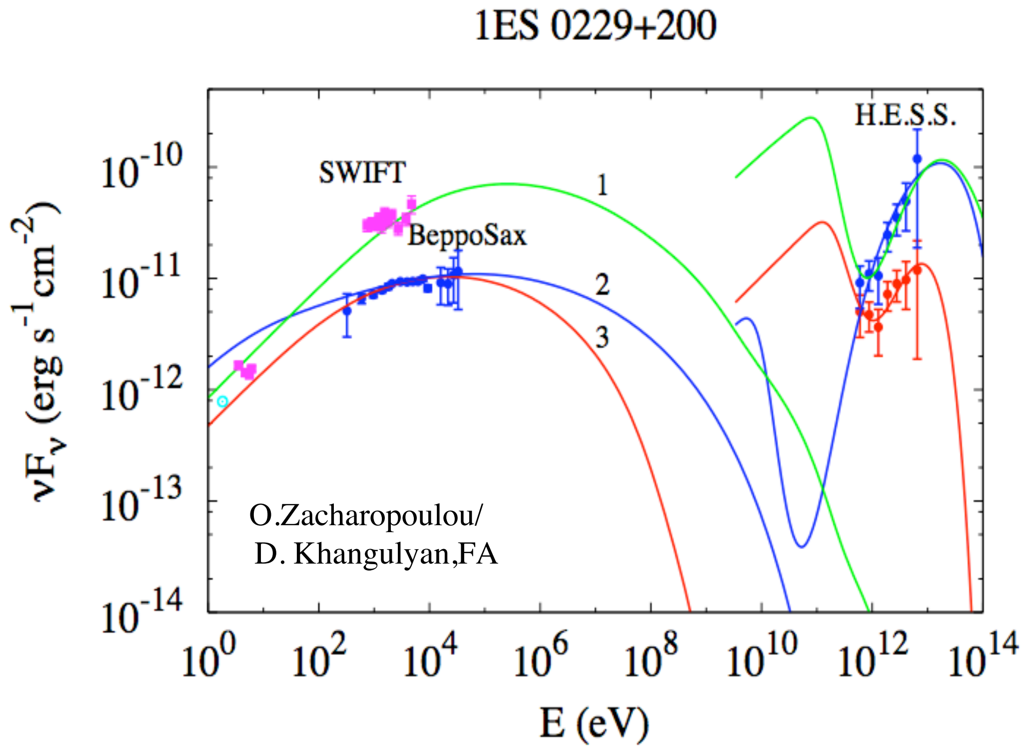
gamma- rays from >100 Mpc sources - detectable because of Doppler boosting

problem - extremely hard γ-ray spectra after correction for the EBL absorption
B-field:10^{-3}G - strong departure from equipartition- can be that easily accepted?



magnetized compact blobs (B~100G) in blazar jets with Γ~10 as accelerators of protons to E~10^{20} eV ?

- gamma-ray spectrum partly absorbed inside the source and in IGM
- X-ray emission from synchrotron radiation of secondary e+e- pairs



assuming optical depth $\tau_{\gamma\gamma}$ ~ 3-7, Γ ~ 10, one can explain not only gamma-ray spectra (after) correction for intergalactic absorption), but also the synchrotron emission by secondary e^+e^-

Model: *internal γ−γ absorption inside and outside the blob* (Aharonian et al. 2008) probing hadrons with secondary hard X-rays with NASA-JAXA ASTRO-H

the JAXA-NASA mission ASTRO-H will provide X-ray imaging and spectroscopy in the hard X-ray band with angular resolution as good as one arcmin and minimum detectable energy flux down to 10^{-14} erg/cm^{2}s !

complementary to gamma-ray and neutrino telescopes

advantage - (a) comparable or better performance
(b) compensates lack of neutrinos and gamma-rays at “right energies”

disadvantage - ambiguity of origin of X-rays