Short Course on High Energy Astrophysics

Exploring the Nonthermal Universe with High Energy Gamma Rays

Lecture 2: **Why gamma-rays?**

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VHE gamma-ray astronomy - *a success story*

over last several years the field has bee revolutionized

before – <u>“astronomy with several sources”</u>

(an activity related to *Astroparticle Physics rather than Astronomy*)

now – a <u>truly astronomical discipline</u>

more than 150 reported VHE gamma-ray sources representing more than 10 Galactic & Extragalactic populations in the energy interval 0.1 TeV to 100 TeV

first surprises and conclusions from VHE gamma-ray observations:
protons/electrons are effectively accelerated to multi-TeV energies in diverse astronomical environments - almost in all nonthermal source populations

<u>analogy with X-ray Astronomy:</u>
as cosmic plasmas are heated up to keV temperatures - almost everywhere, particles (electrons/protons) can be easily accelerated to TeV energies - almost everywhere, especially in objects with relativistic outflows – jets&winds

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

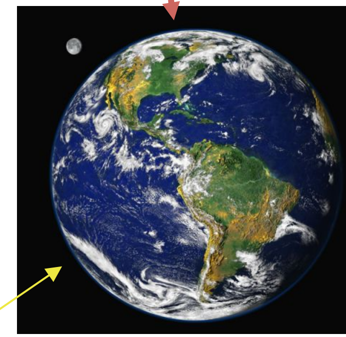
**) not only gamma-rays but also X-rays from both primary (directly accelerated) and secondary ($\pi^{+/-}$ decay) electrons*

Nature's Particle Accelerators

Cosmic Rays

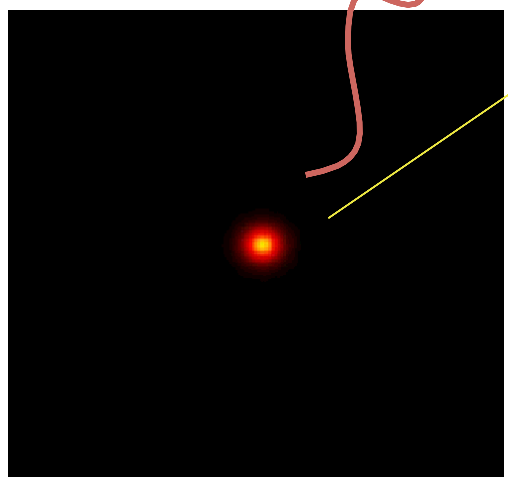
neutral/stable secondary products
of EM and hadronic interactions
of electrons, protons and nuclei
with plasma, radiation and B-fields

e,p



photons and neutrinos

γ, ν

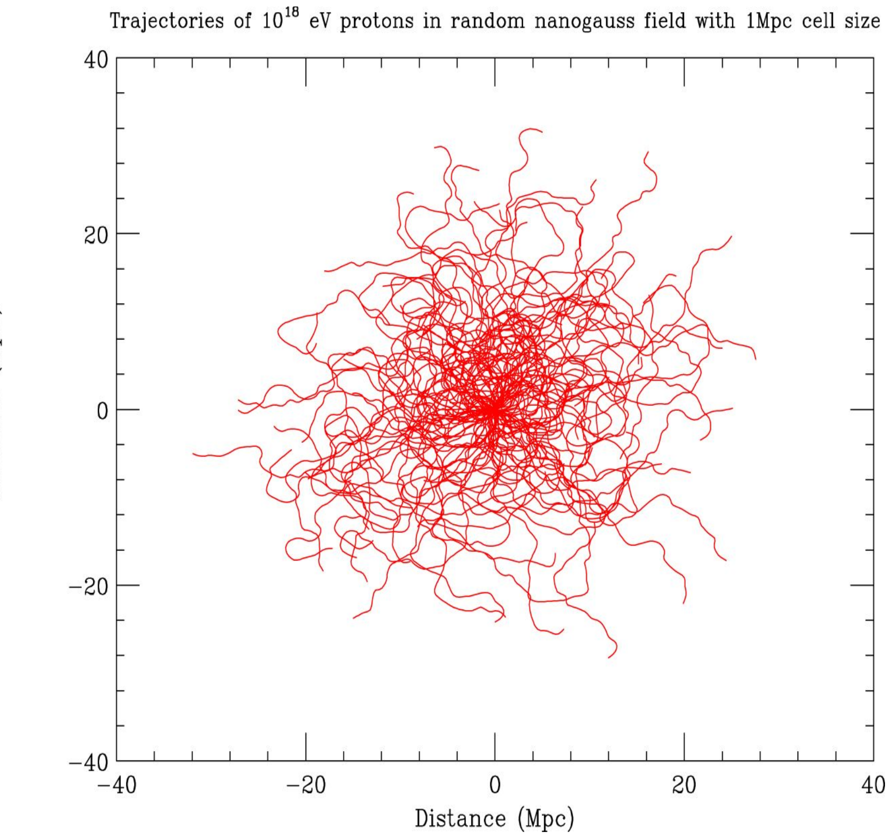


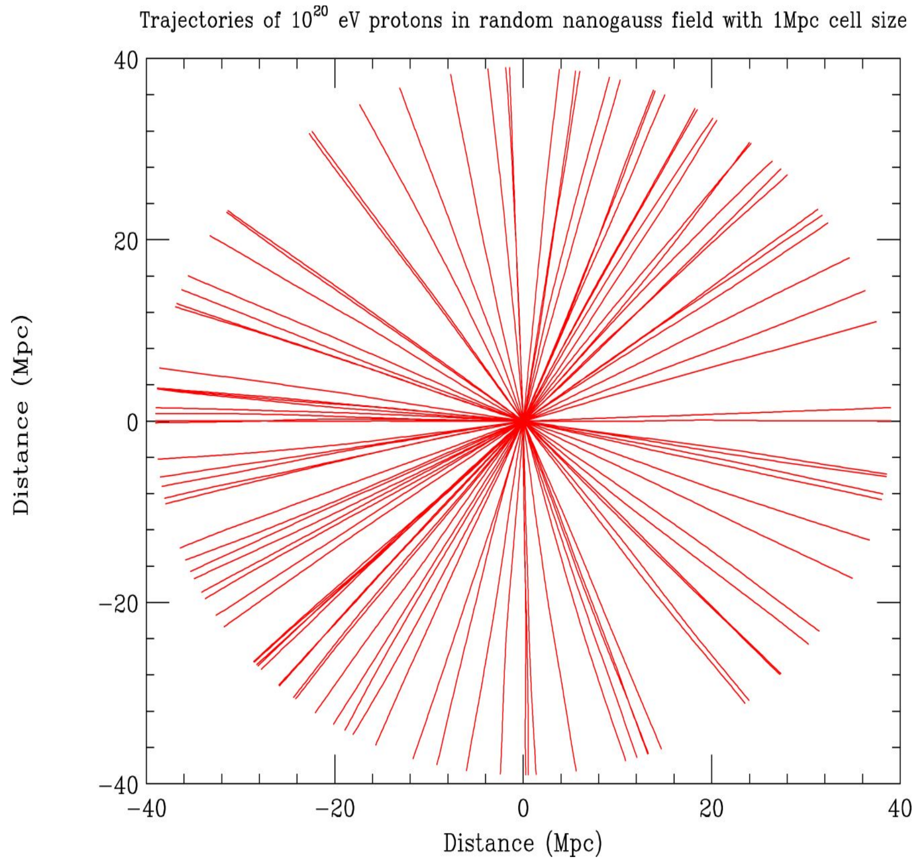
cosmic accelerator

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

ν_μ, ν_e - produced only in hadronic interactions

astronomy with protons ?





10^{18} eV

10^{20} eV

J. Cronin

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")

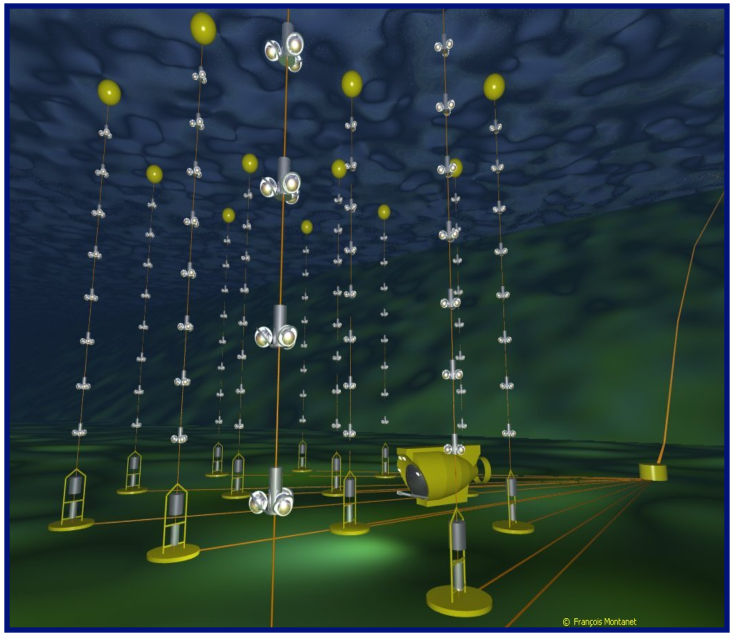
✓ do not interact with matter, radiation and magnetic fields:

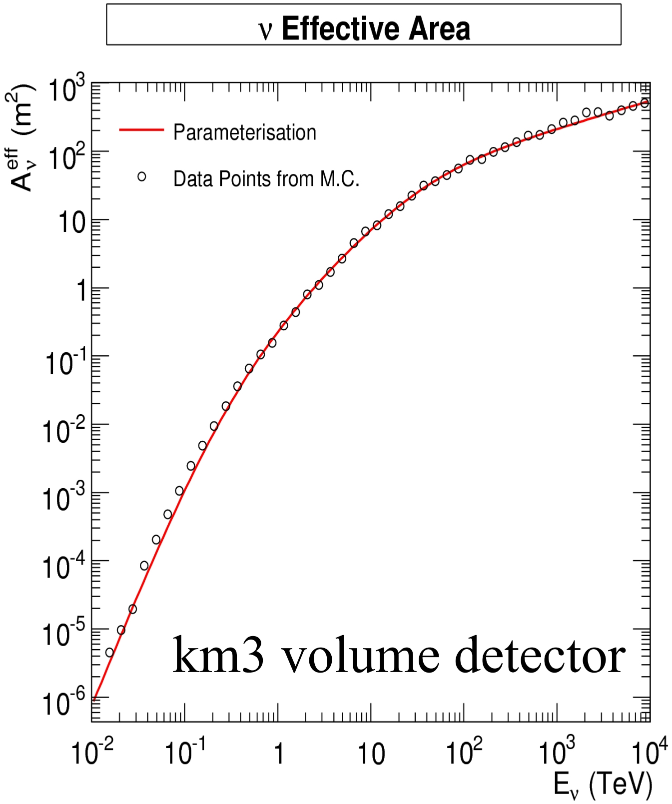
(1) information without distortion; (2) "hidden accelerators" available

but... cannot be effectively detected -- even huge "1km^3 volume" class detectors have limited performance

*) good news! Recently Ice Cube has detected tens of neutrino events of non-atmospheric origin

neutrino telescopes





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

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

compare with detection areas of gamma-ray detectors:

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

Potential TeV neutrino sources

TeV gamma-ray sources as potential TeV neutrino sources?

yes, if γ-rays of hadronic (*pp* or *pγ*) origin

Detectable (by km^3 class) neutrino detectors ?

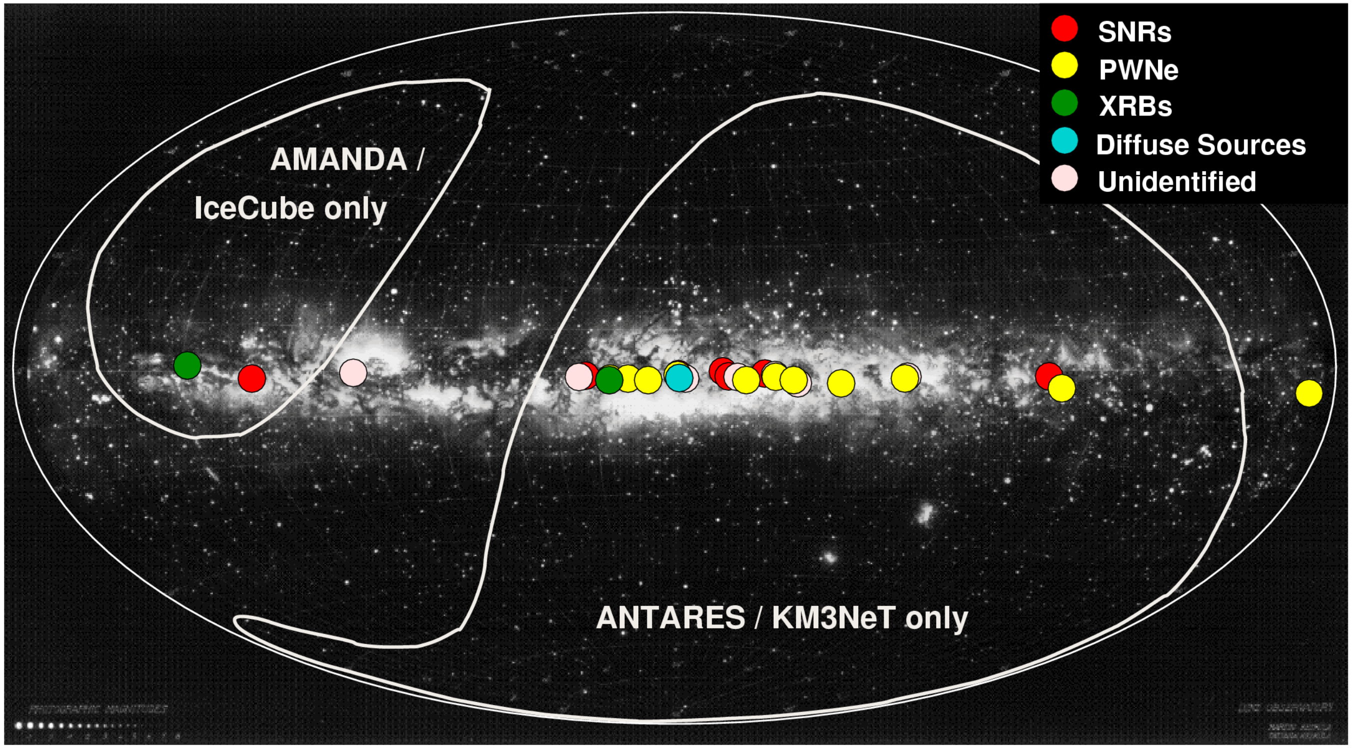
yes, if TeV γ-ray flux exceeds 2x10^{-11} ph/cm^2 s (~1 Crab)

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

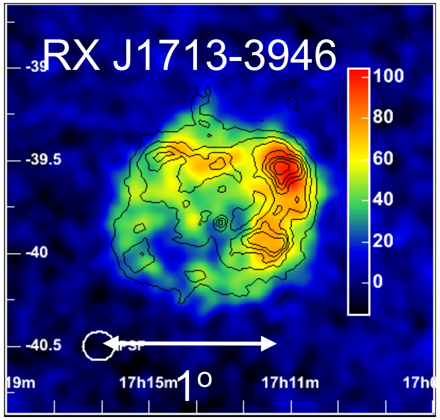
or weaker sources if γ-rays are severely absorbed

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

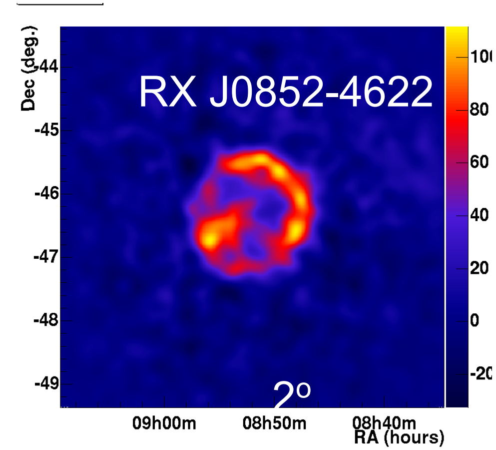
Visibility of Galactic neutrino sources – counterparts of TeV γ-ray sources

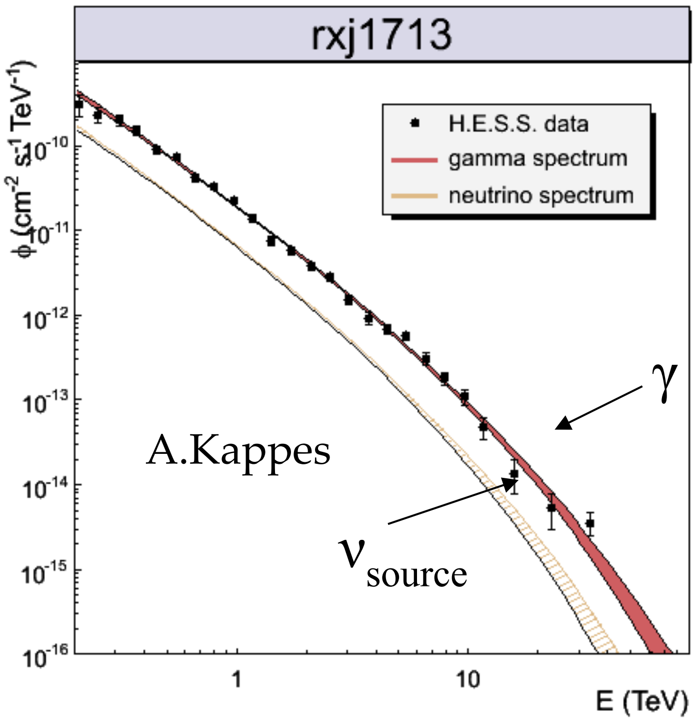


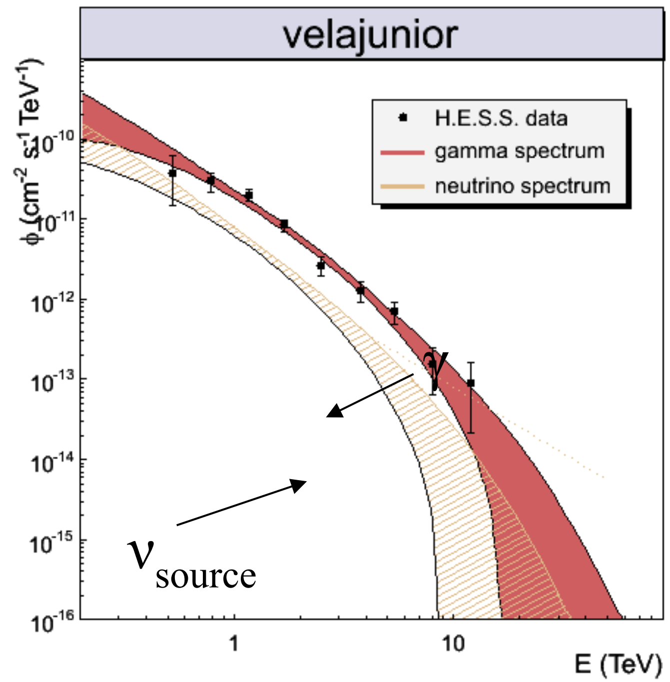
A.Kappes



two brightest TeV SNRs

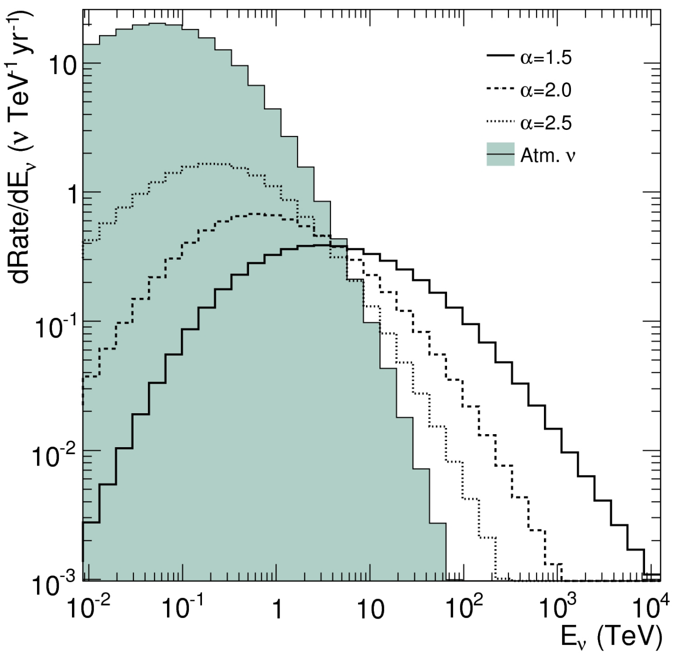


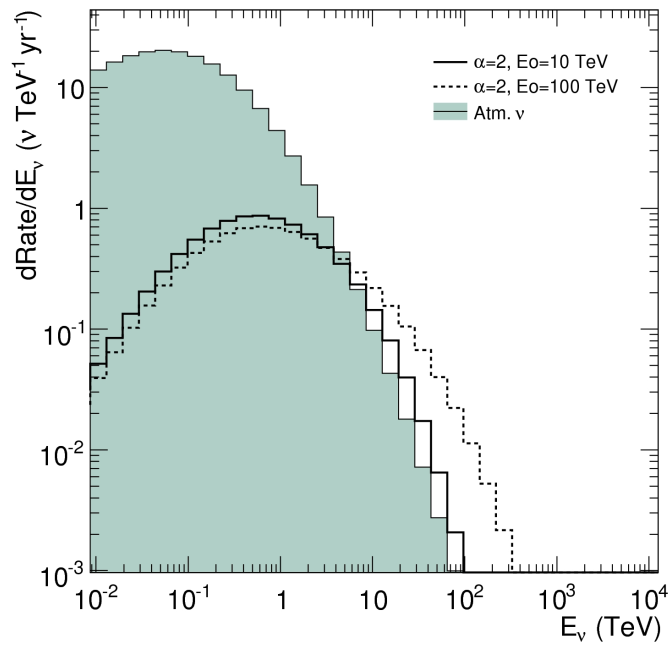




several neutrinos from SNRs per year against several background events by KM3NeT

detection rate of neutrinos with KM3NeT





R.White/A.Taylor

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

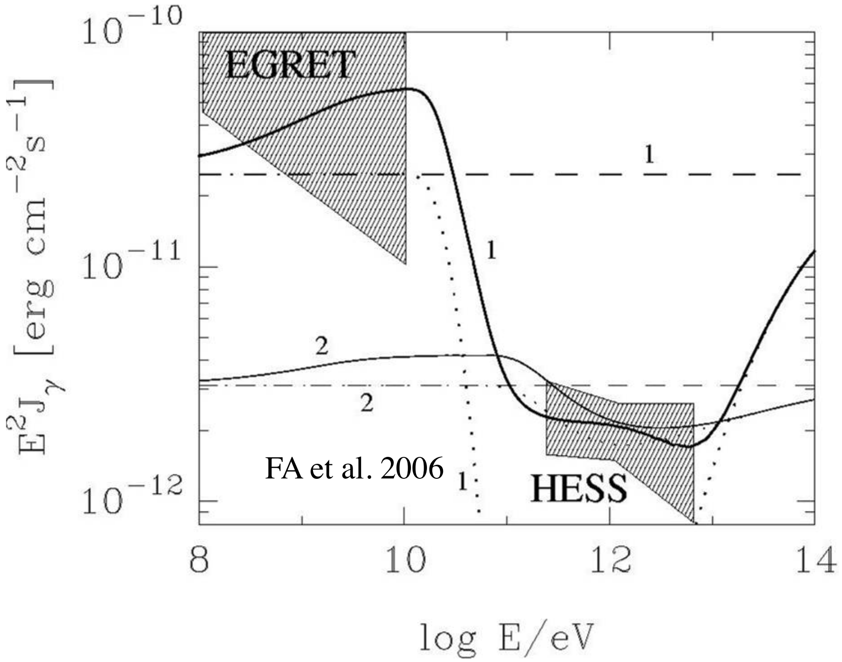
a few neutrinos per year at presence of comparable background events

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 *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:

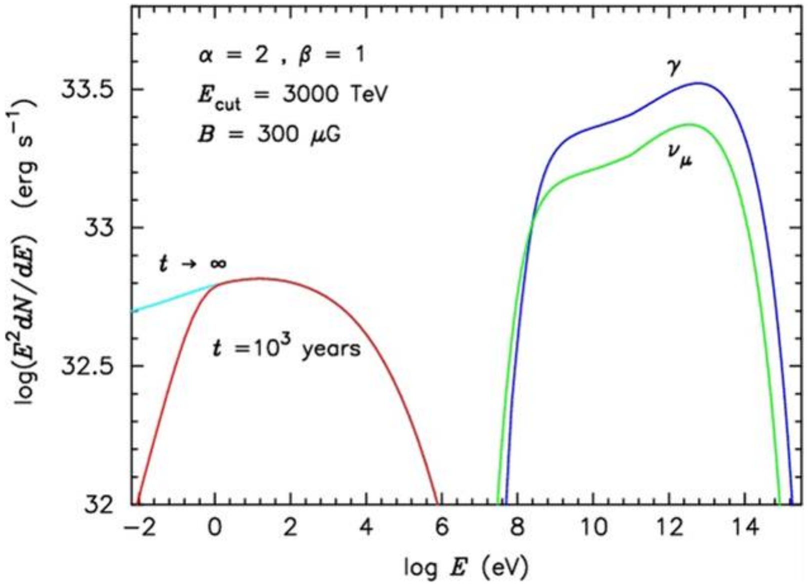
synchrotron radiation of secondary multi-100 TeV electrons produced at interactions of protons with ambient gas or radiation fields

- (1) p p (γ) => π, K, Λ, (2) π, K, Λ => γ, ν, e, μ (3) e B => X
- (1) p γ => e+ e- (2) e B => 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: $E \sim 10^{15}$eV



three channels of information
about cosmic PeVatrons:

10-1000 TeV gamma-rays
10-1000 TeV neutrinos

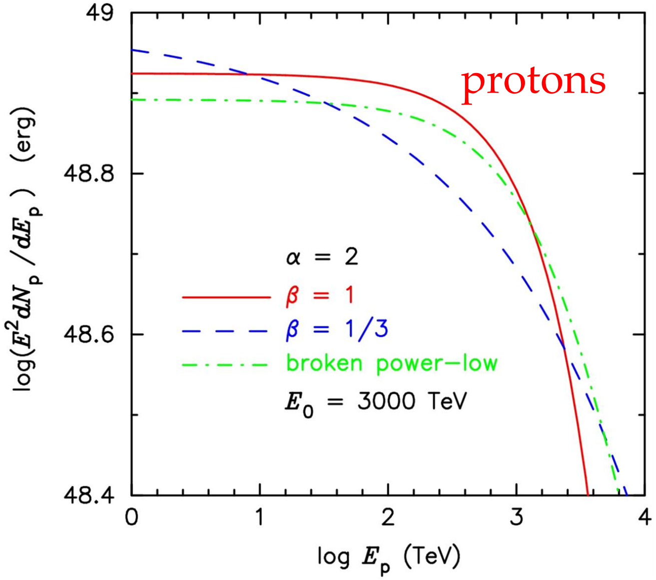
10 -100 keV hard X-rays

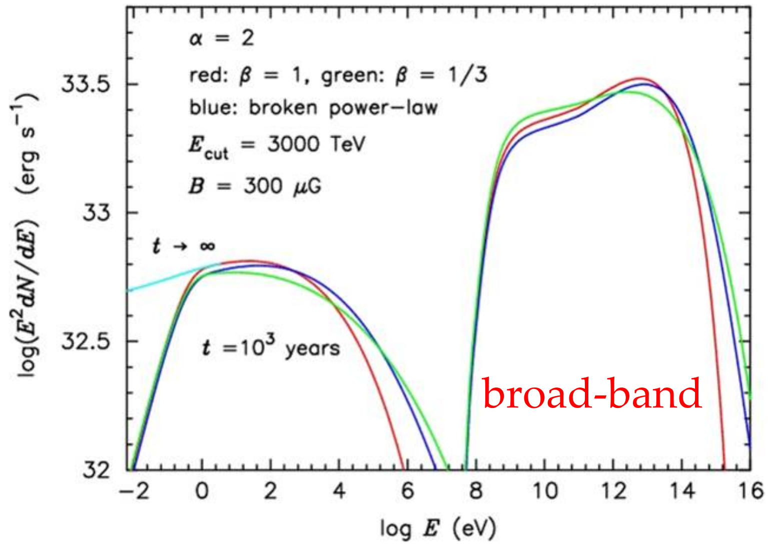
- γ-rays: difficult, but possible with future "10km^2" area multi-TeV IACT arrays

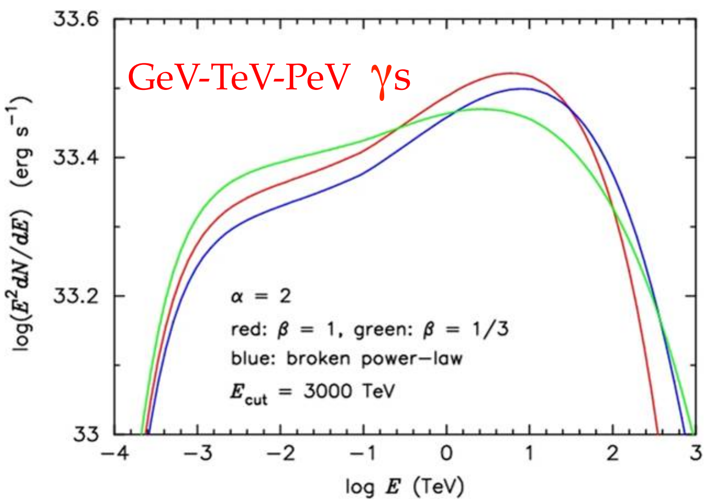
- neutrinos: marginally detectable by IceCube, Km3NeT - don't expect spectrometry, morphology; uniqueness - unambiguous signatute!

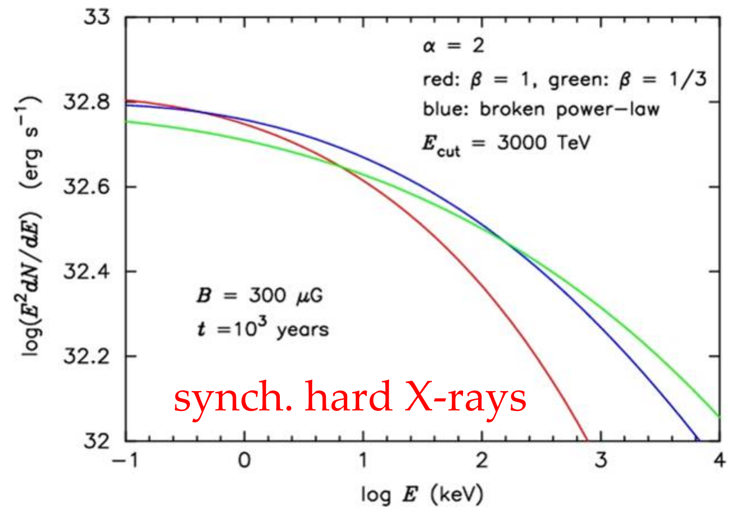
- "prompt" synchrotron X-rays: smooth spectrum a very promising channel - quality!

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









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

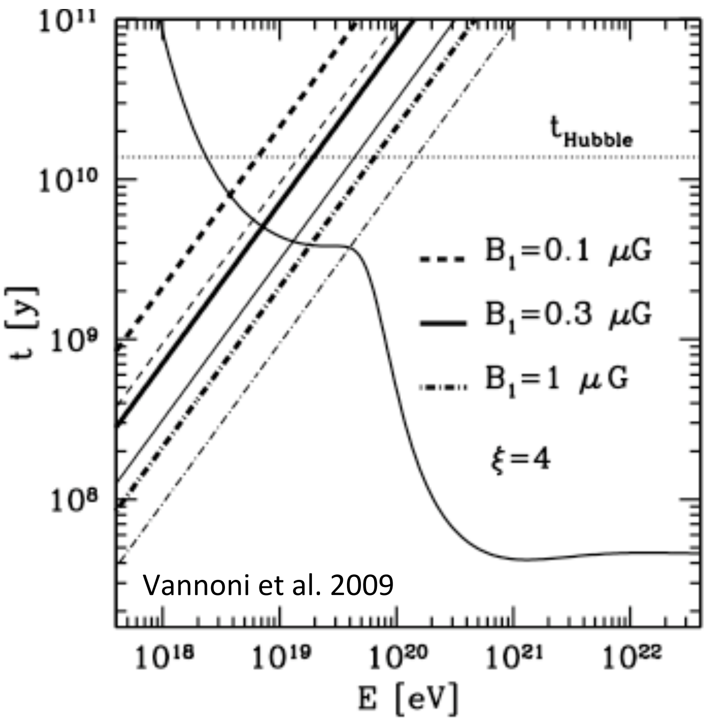


Fig. 1. Acceleration and energy loss time scales as a function of the proton energy. The acceleration time scales are obtained for the values of the upstream magnetic field B_1 reported in figure and a downstream magnetic field $B_2 = 4B_1$. The thick lines correspond to a shock velocity of 2000 km/s, 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.

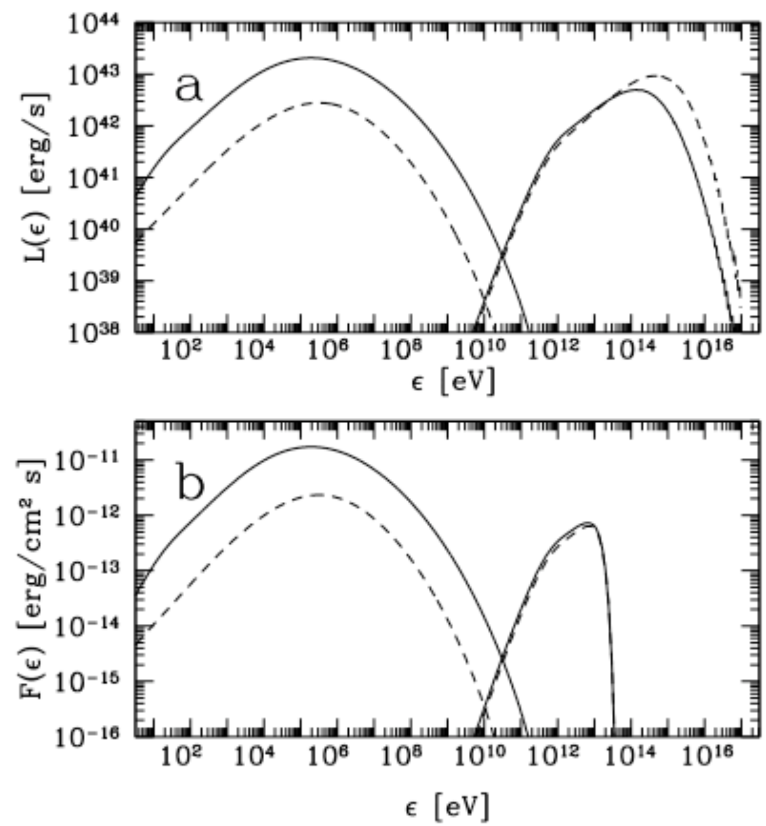
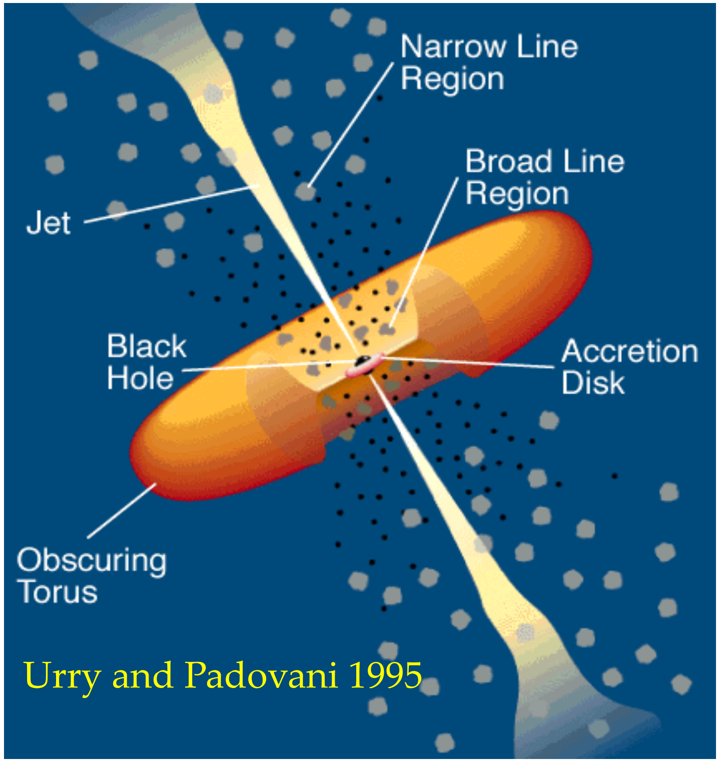
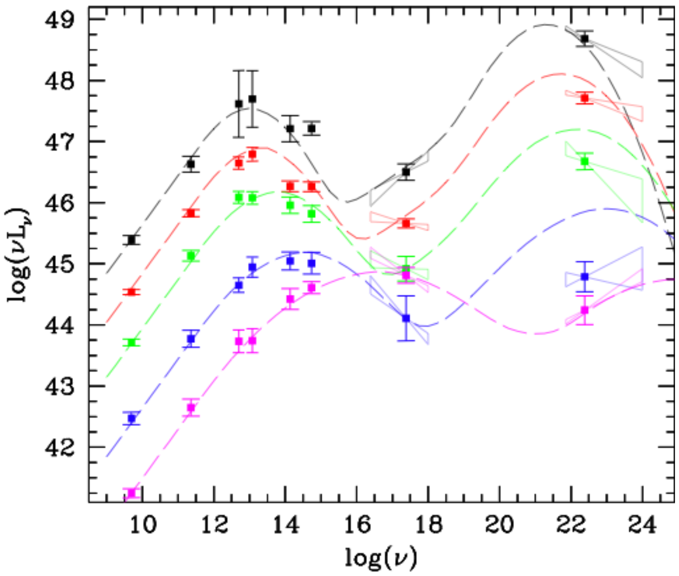


Fig. 13. a) Broadband radiation spectra produced at the source by the electron distributions in Fig. 12**b**, downstream (solid line) and upstream (dashed line). **b)** Energy flux at the observer location, after absorption in the EBL, for a source distance of 100 Mpc.

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



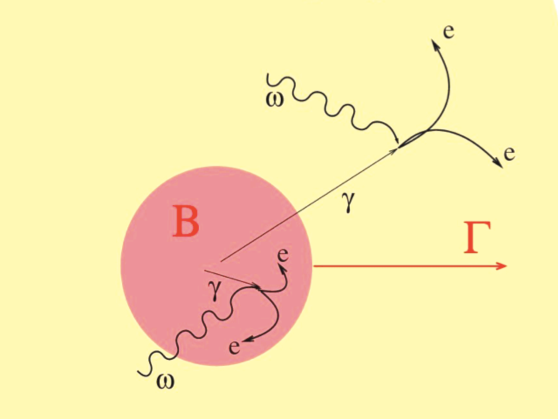
two-peaks (Synchrotron-IC) paradigm



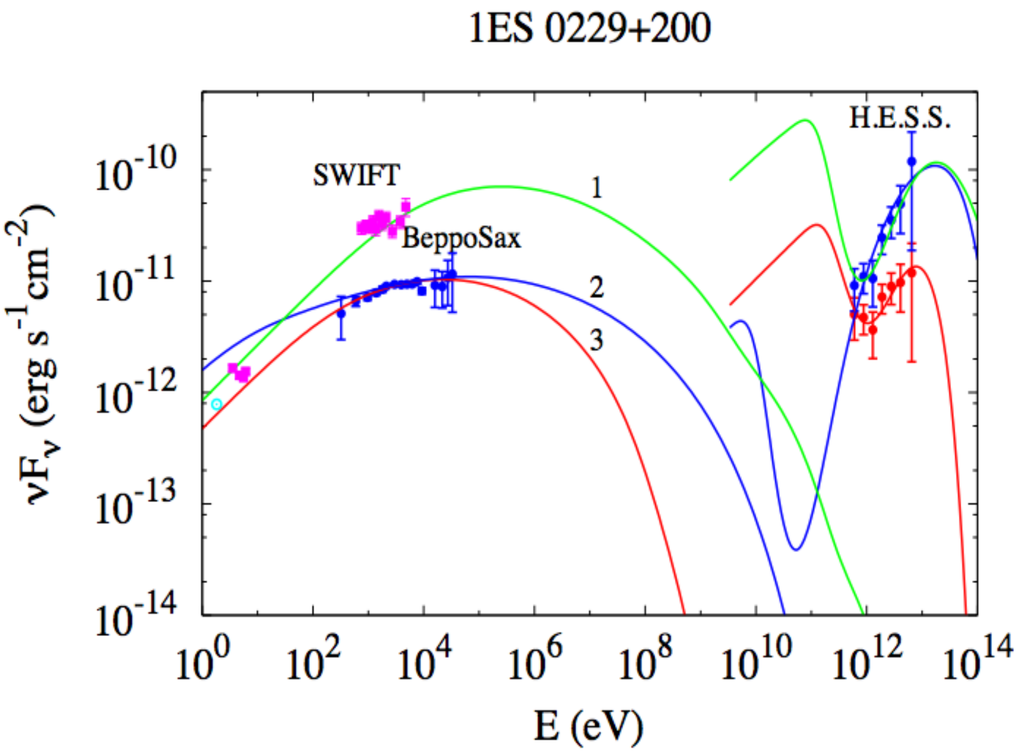
typically small B-field, B <1G

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*

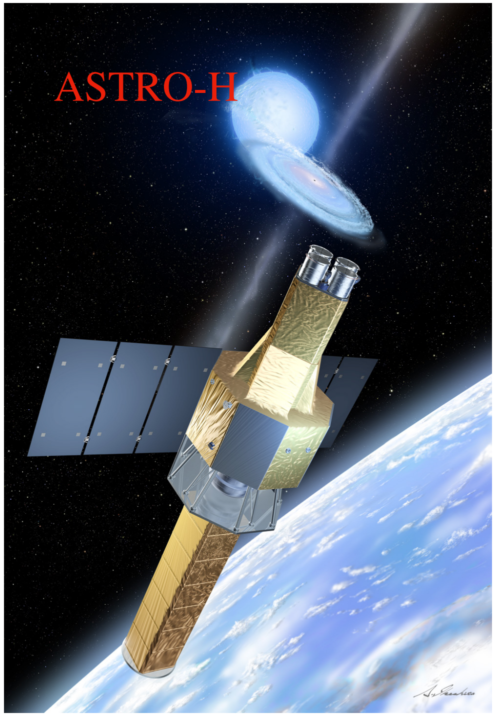
Probing hadrons with secondary hard X-rays

complementary to gamma-ray and neutrino telescopes

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

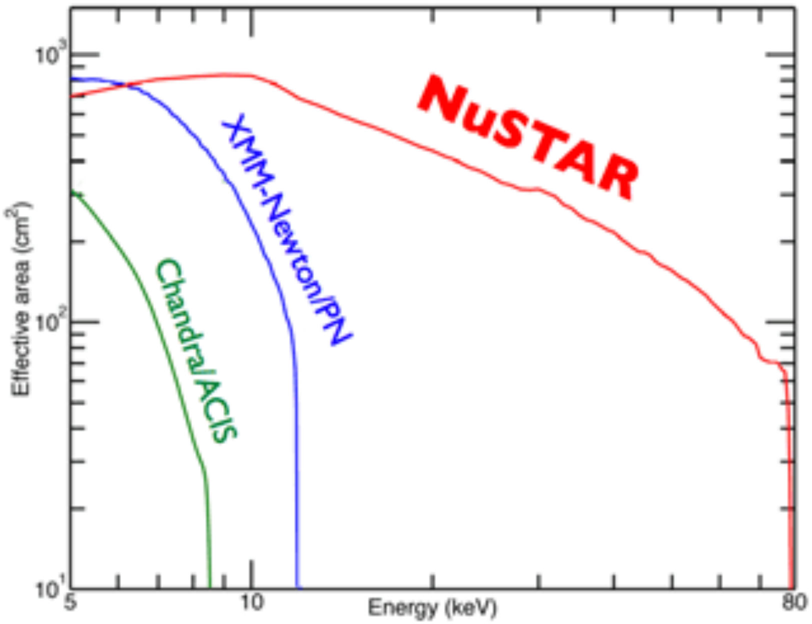
disadvantage - ambiguity of origin of X-rays

Energy Band: 3 - 80 keV
Angular resolution : 58" (HPD), 18" (FWHM)
Energy Resolution: 0.4 keV at 6 keV, 0.9 keV at 60 keV (FWHM)

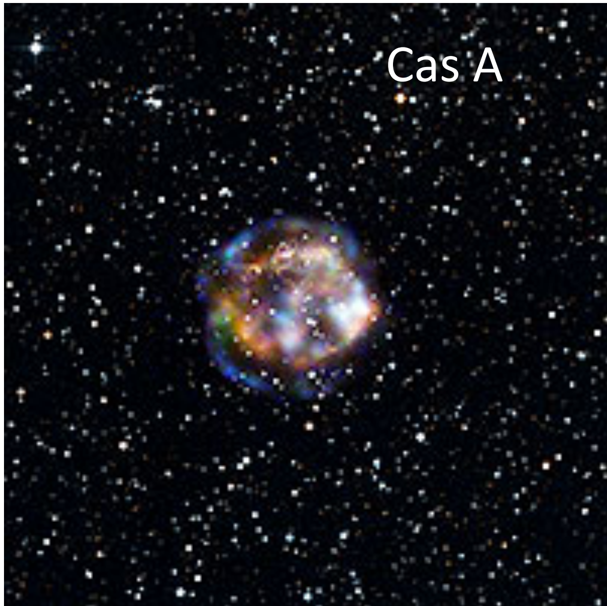


Hitomi!

- X-ray imaging and spectroscopy in the hard X-ray band
- angular resolution one arcmin (10")
- Minimum detectable energy flux down to 10^{-14} erg/cm^{2}s !



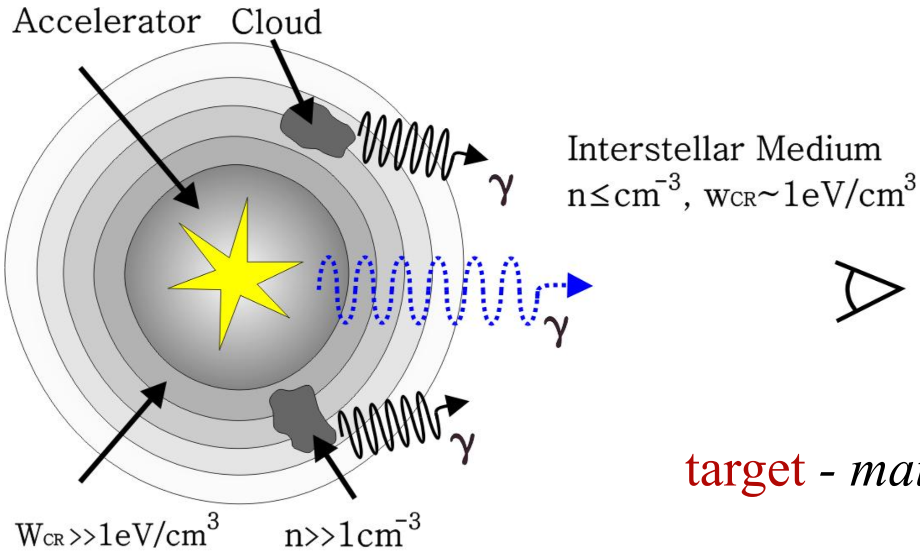
Nustar Gallery



some more specifics of cosmic gamma-rays

gamma-ray production: accelerator+target

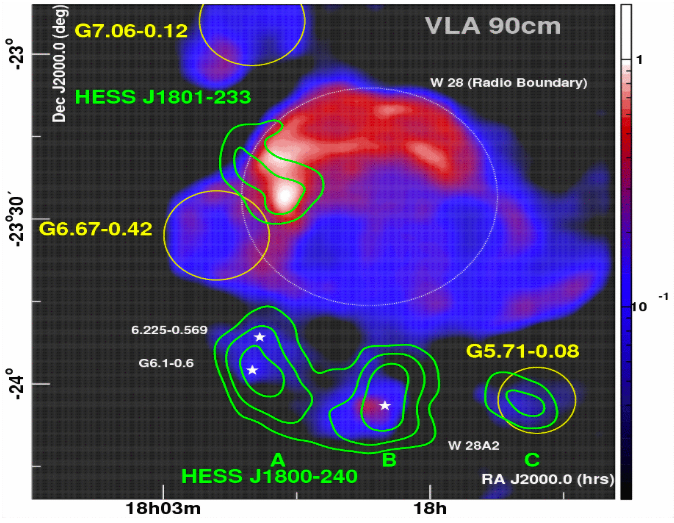
existence of a powerful particle accelerator by itself is not sufficient for γ-radiation; an additional component – a dense target - is required

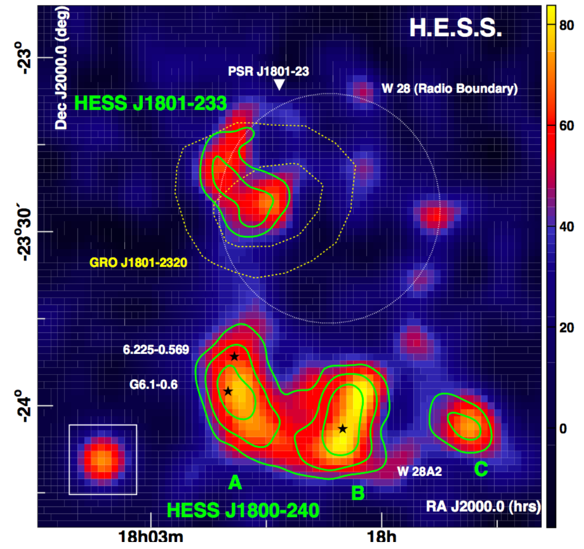


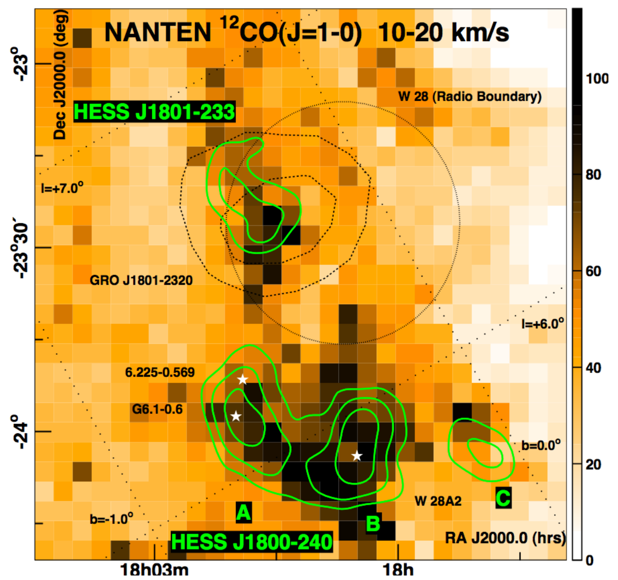
target - *matter, radiation, magnetic field*

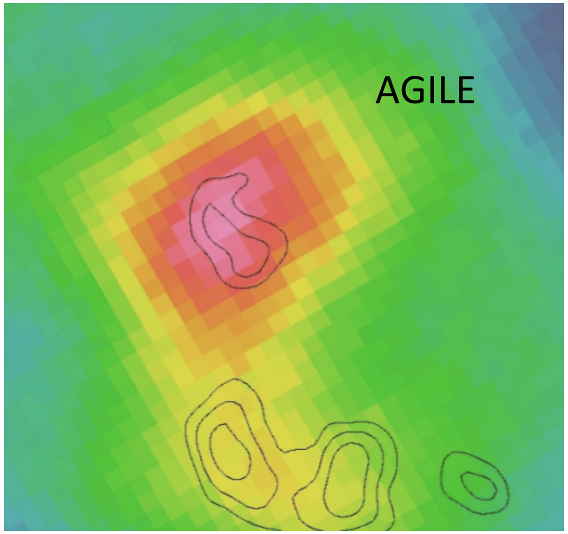
any gamma-ray emitter coincides with the target, but not necessarily with the "primary" source/particle-accelerator

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

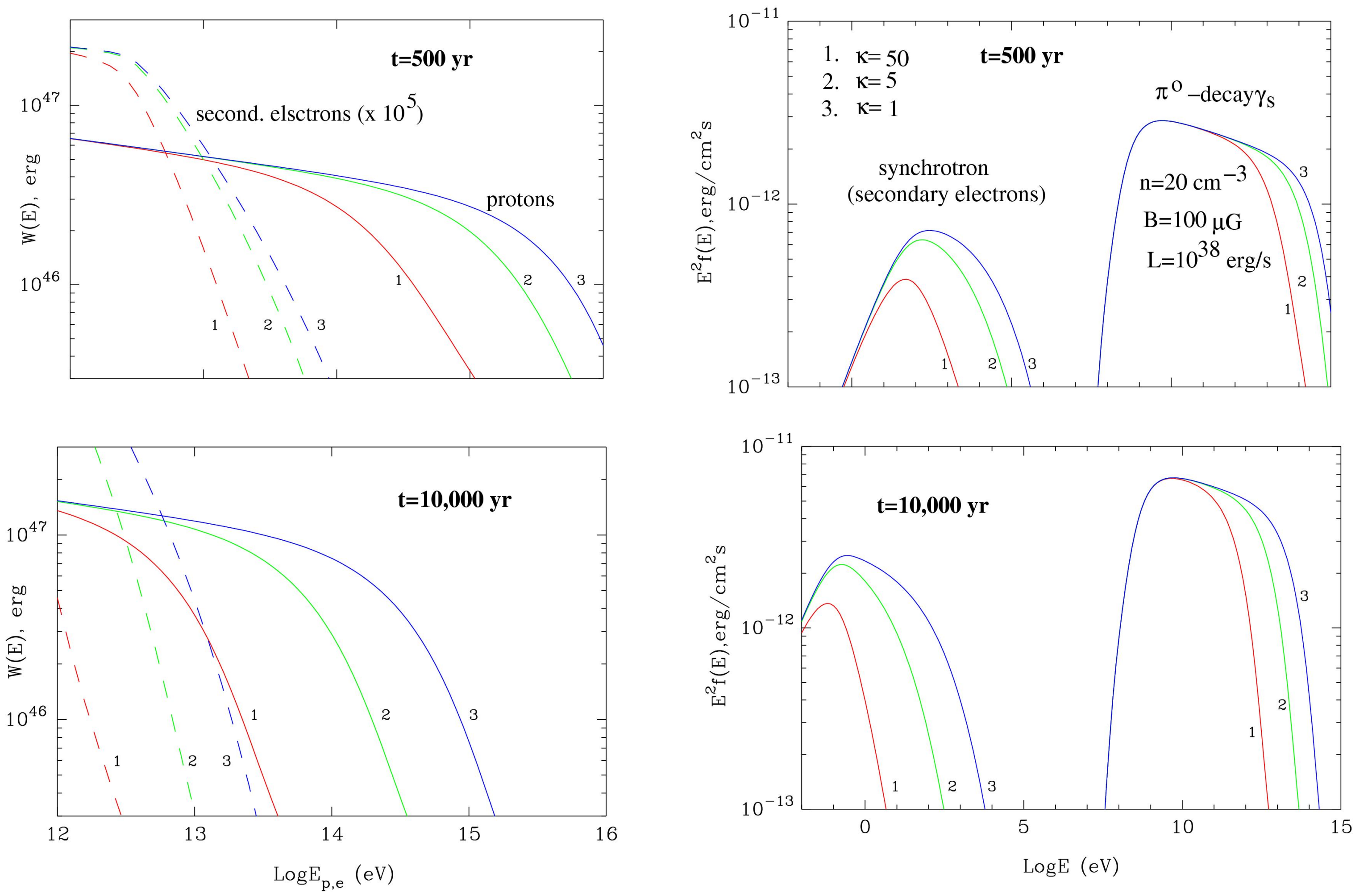








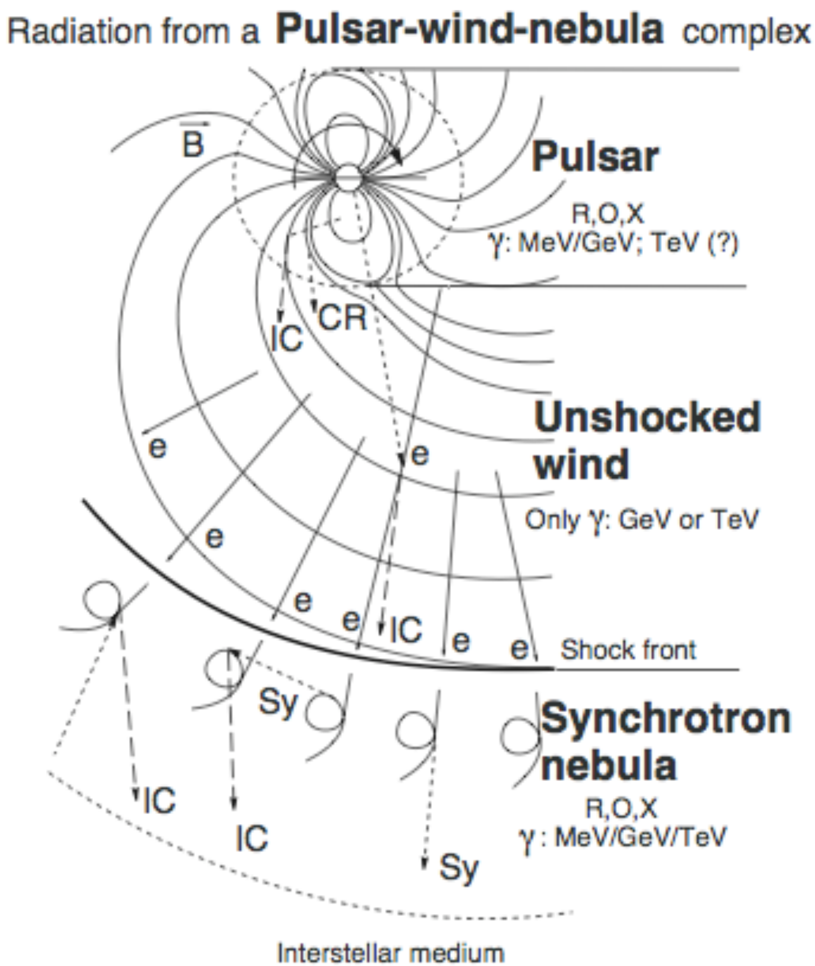
older source – steeper γ-ray spectrum

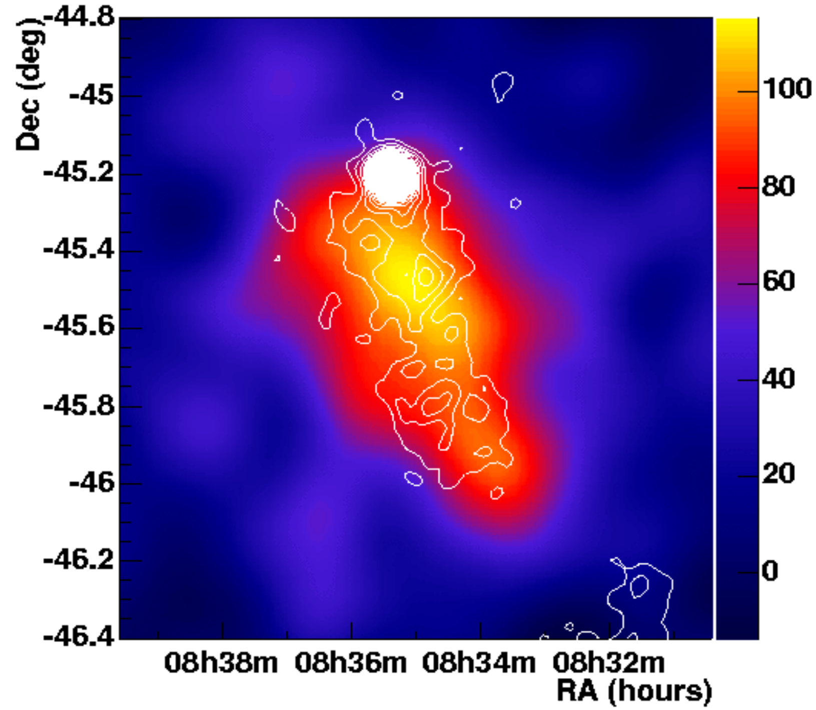


t_{esc}=4x10^5(E/1 TeV) $^{-1}\kappa^{-1}$ yr (R=1pc); κ=1 – Bohm Difussion

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

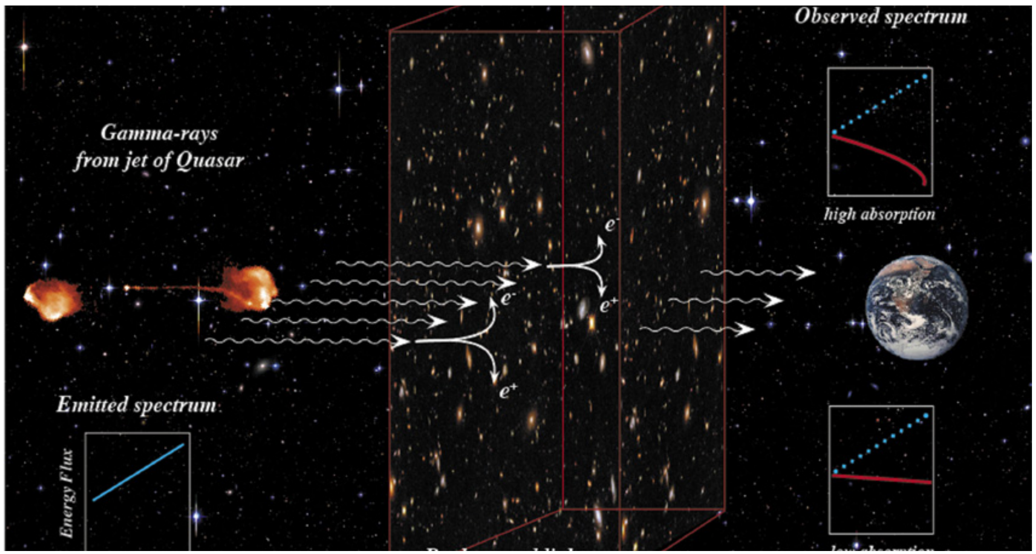
Inverse Compton on 2.7K – a major mechanism of gamma-ray production

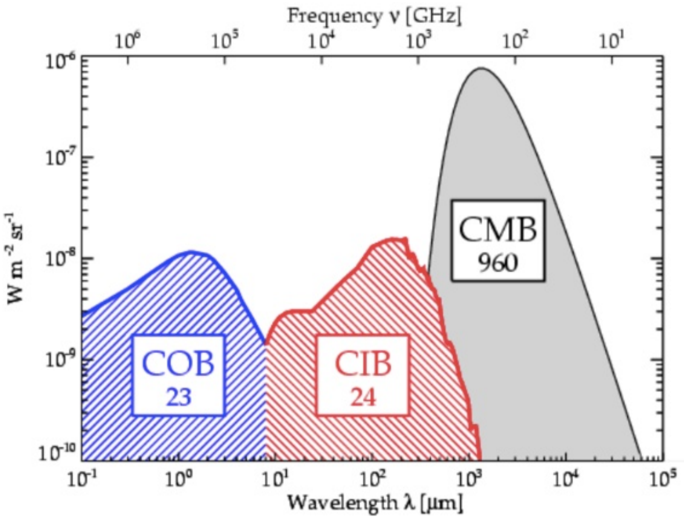




2.7 K MBR is the main target field; TeV images reflect spatial distributions of electrons Ne(E,x,y); coupled with synchrotron X-rays, this allow measurements of B(x,y) γγ -> e+e- as a major gamma ray absorption mechanism

extragalactic gamma-rays and EBL





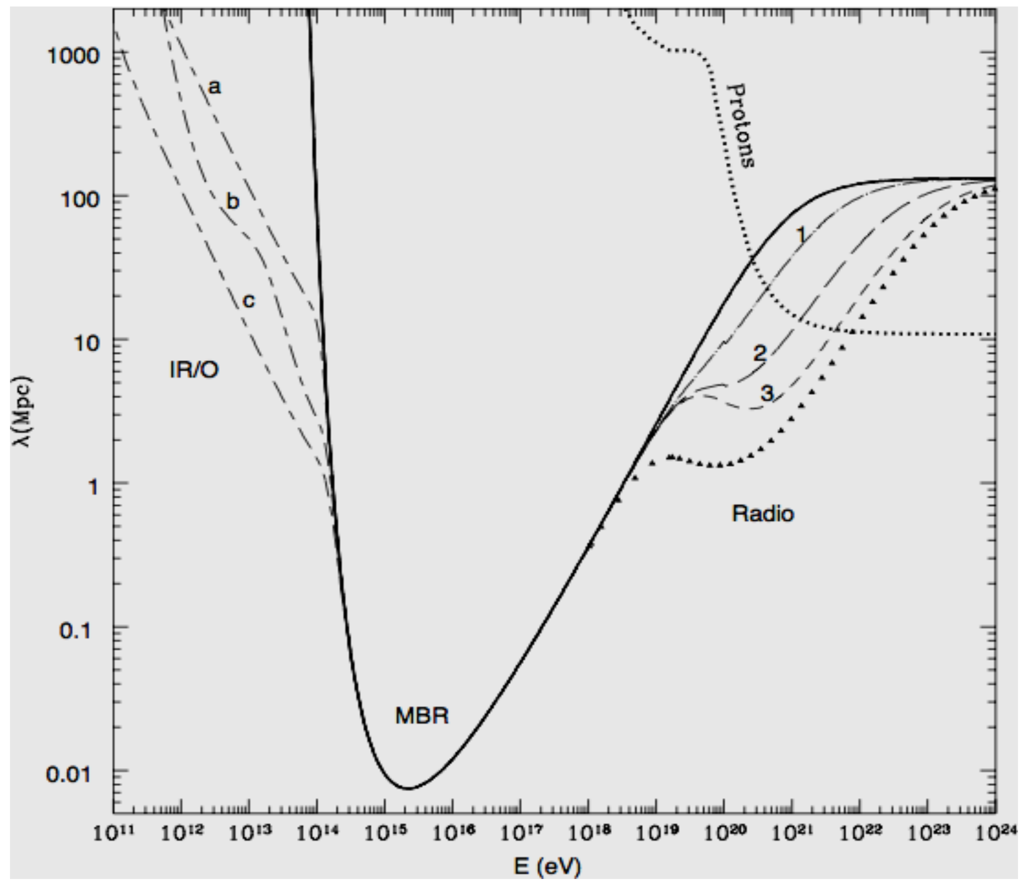
Nearby Universe

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

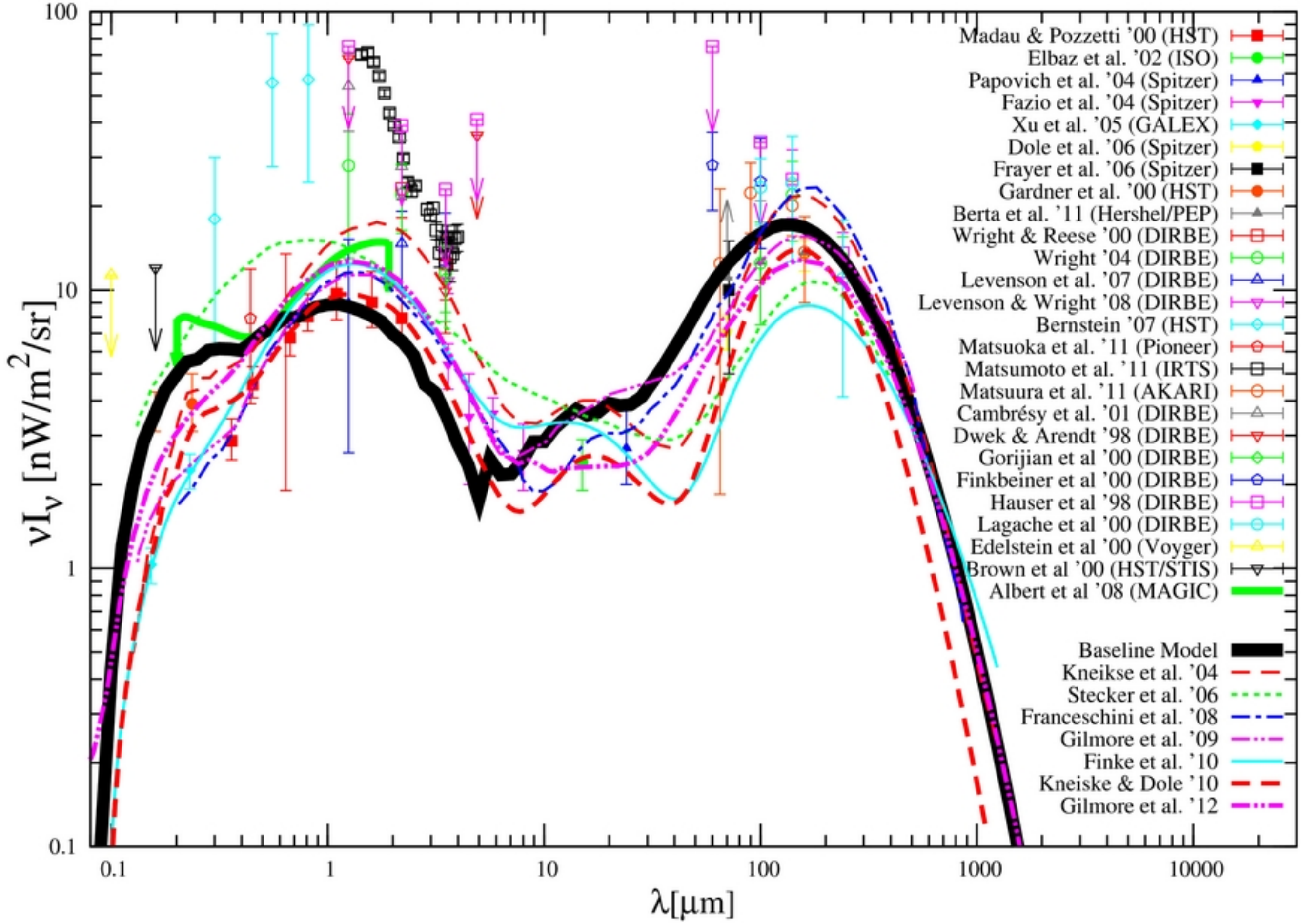
EHE (EeV) gamma-rays interact with Radio emission:1-10MHz:
1Mpc<d<10Mpc

mean free path of cosmic gamma-rays



Coppi,FA 97

EBL – history of evolution of Universe after Big Bang



Inoue et al, 2013

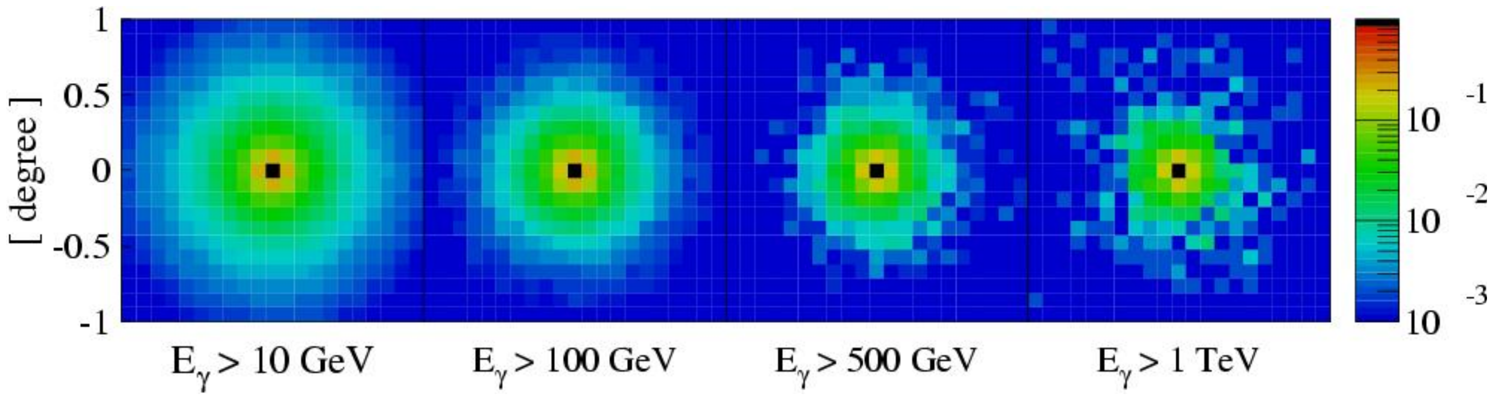
Giant Pair Halos

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

Magnetic 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:*

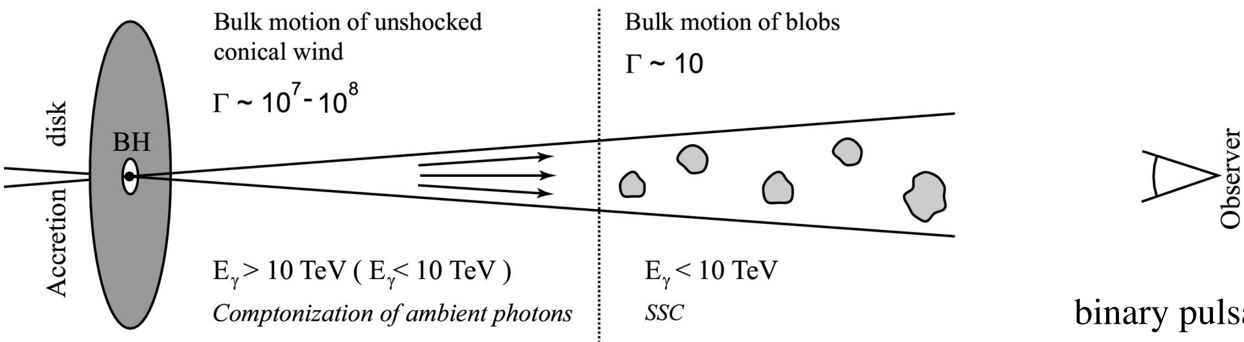
✓ very small for γ-ray production through IC scattering:

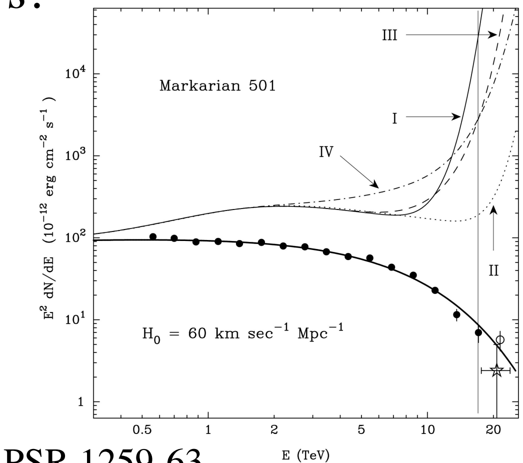
✓ large in young SNRs for production of "hadronic" γ-rays up to 100 TeV

✓ 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?*



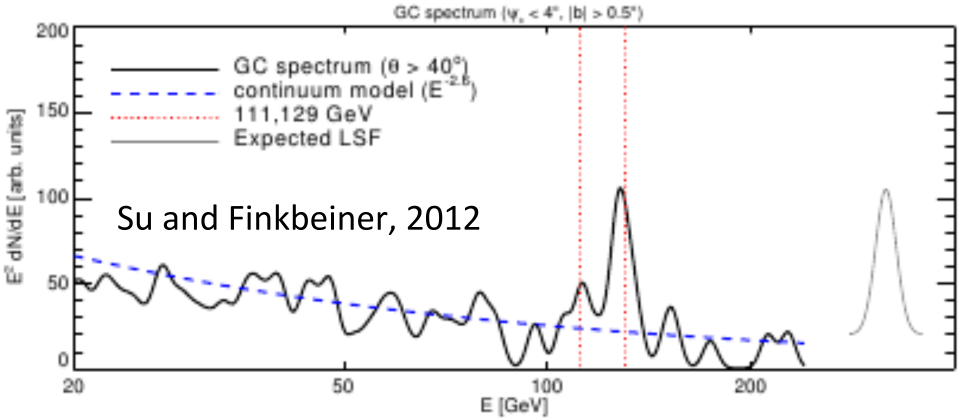


binary pulsar PSR 1259-63

proposed to explain unusual 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

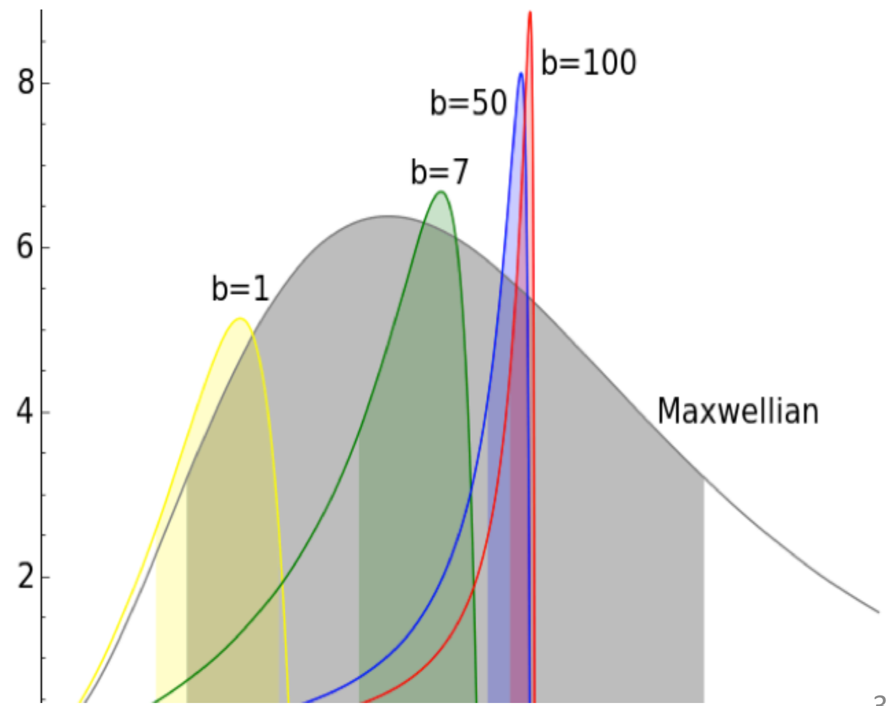
when $\Gamma\varepsilon > m_e c^2$, $E_\gamma = \Gamma m_e c^2$ (IC in (K-N regime) => direct measurement of the bulk Lorentz factor

Gamma-ray line emission seen by Fermi-LAT?

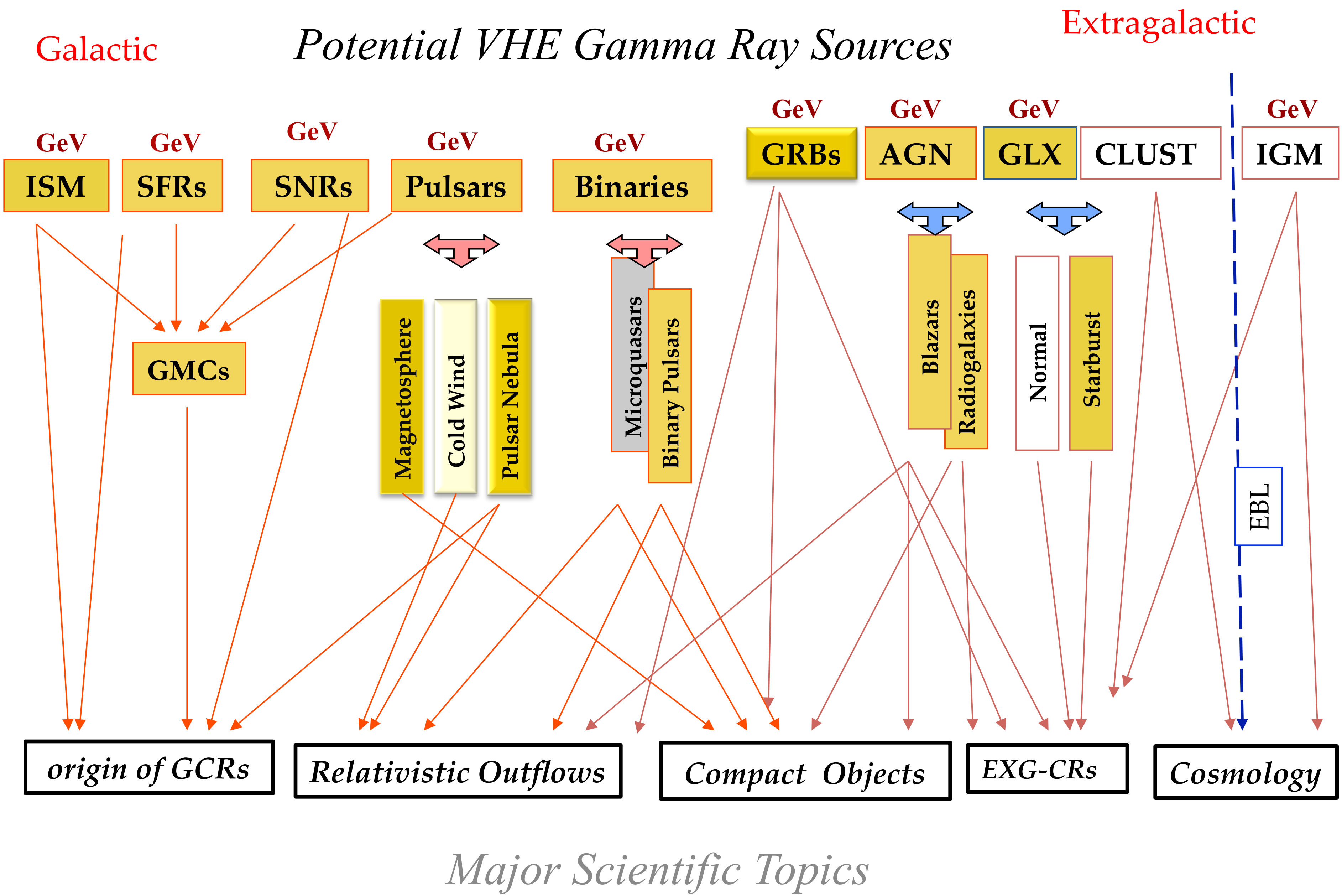


Cosmological interpretaion

Annihilation of DM as the only option?



can be also interpreted as
Inverse Compton scattering of
monoenergetic electrons in cold
ultrarelativistic pulsar winds
In the Klein-Nishina regime



Galactic
Potential VHE Gamma Ray Sources
Extragalactic
GeV
ISM
GeV
SFRs
GeV
SNRs
GeV
Pulsars
GeV
Binaries
GeV
GRBs
GeV
AGN
GeV
GLX
CLUST
GeV
IGM
GMCs
Magnetosphere
Cold Wind
Pulsar Nebula
Microquasars
Binary Pulsars
Blazars
Radiogalaxies
Normal
Starburst
EBL
origin of GCRs
Relativistic Outflows
Compact Objects
EXG-CRs
Cosmology
Major Scientific Topics