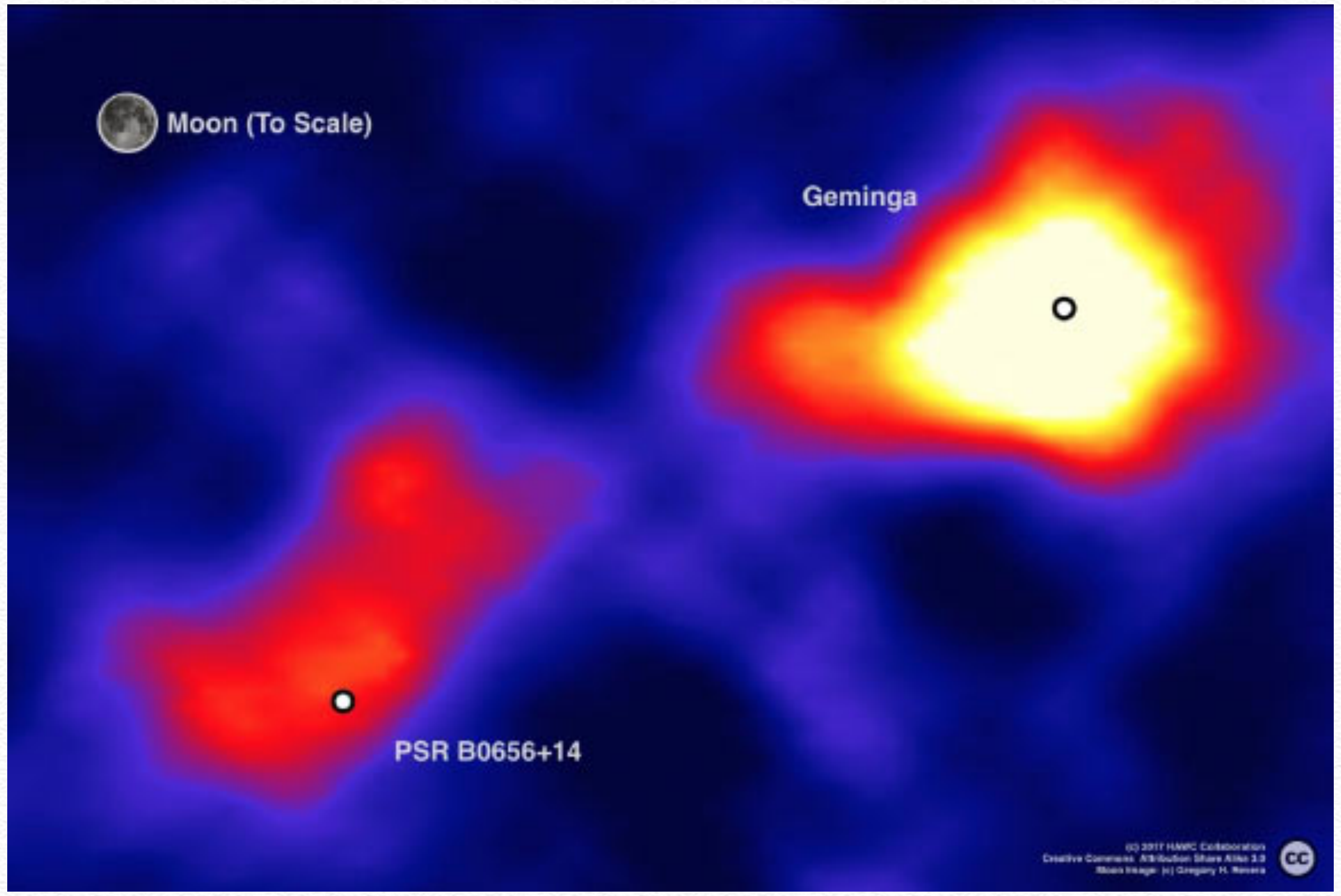


1st Workshop Gamma Ray Halos Around Pulsars

Dec1-3, 2020

conclusion from the meeting: **great meeting - congratulations!**

conclusion from the title: start of a new series of conferences? **excellent/timely initiative !**

great results, great science, great future

Felix Aharonian

great science

focused, at first glance, on a specific subject, but, in fact, covering two topical areas:

- new ingredient to the physics and astrophysics of the systems

pulsar/pulsar wind/pulsar-wind-nebulae

the most effective particle accelerators and most efficient gamma-ray emitters in the Universe !

- propagation of CRs in ISM , CR electrons…

- direct measurements of the diffusion coefficient
- interpretation of "positron excess, fluxes of multi-TeV electrons

(both in the context of general problem of origin of Galactic Cosmic Rays) *great results*　　H.E.S.S., HAWK, Fermi LAT: large sample - tens of sources

in some cases high quality data on “spectrometry-morphology”

sub-arcmin angular resolution of HESS, energy resolution better than 20 % - just perfect for such studies

robust (assumption-free!) derivation of spatial and energy distribution of multi-TeV electrons

unique for development of models, theories, concepts

great future

until mid 2020s: LHAASO-HESS, LHAASO CTA North, full coverage of the sky SWGO-STA South

MWL - most critical X-rays: eRosita: 0.2-10 keV (FoV 1 deg), 6-30 keV (0.5 deg), and sensitivity!

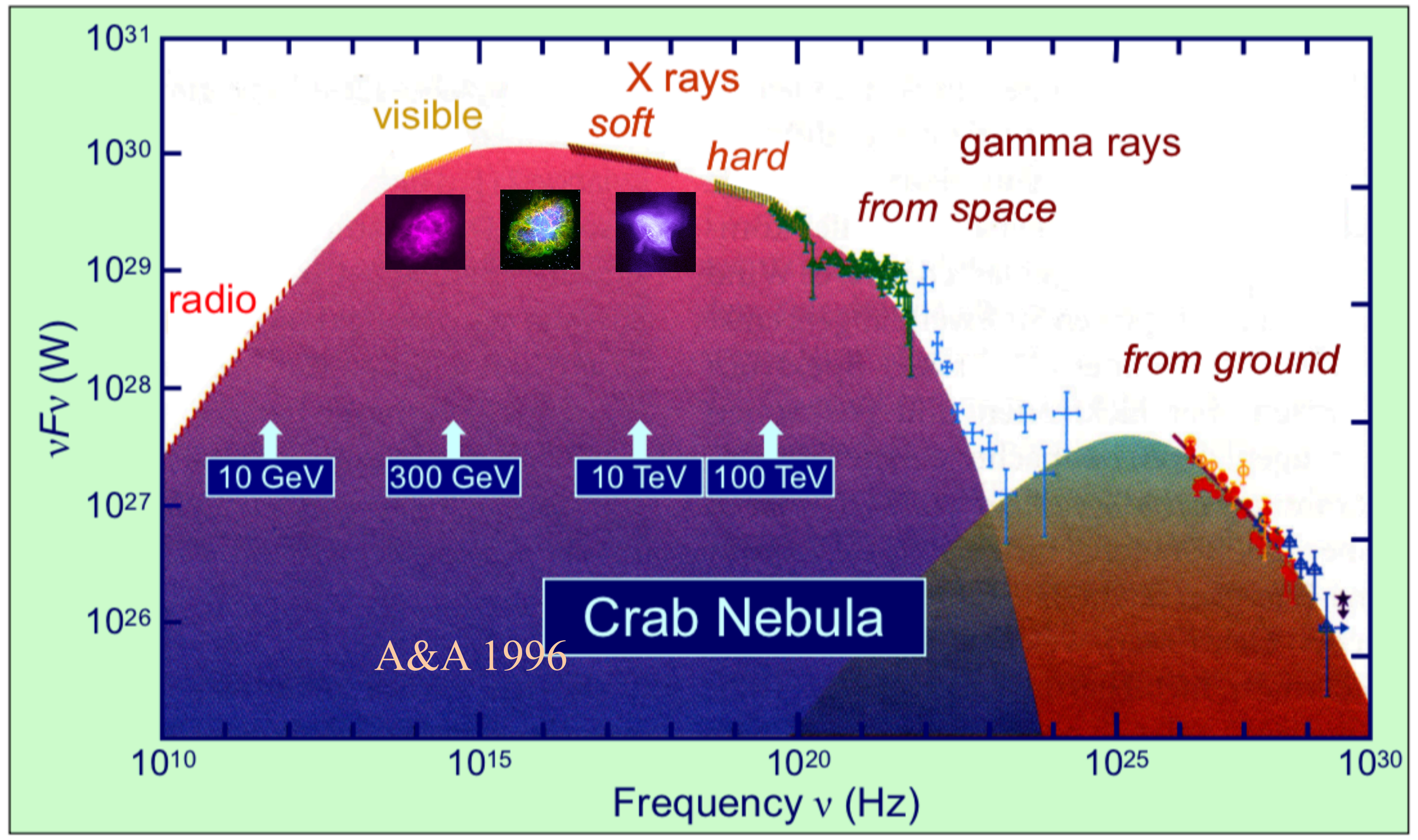
Crab pulsar/wind/nebula:

absolute extreme accelerator !

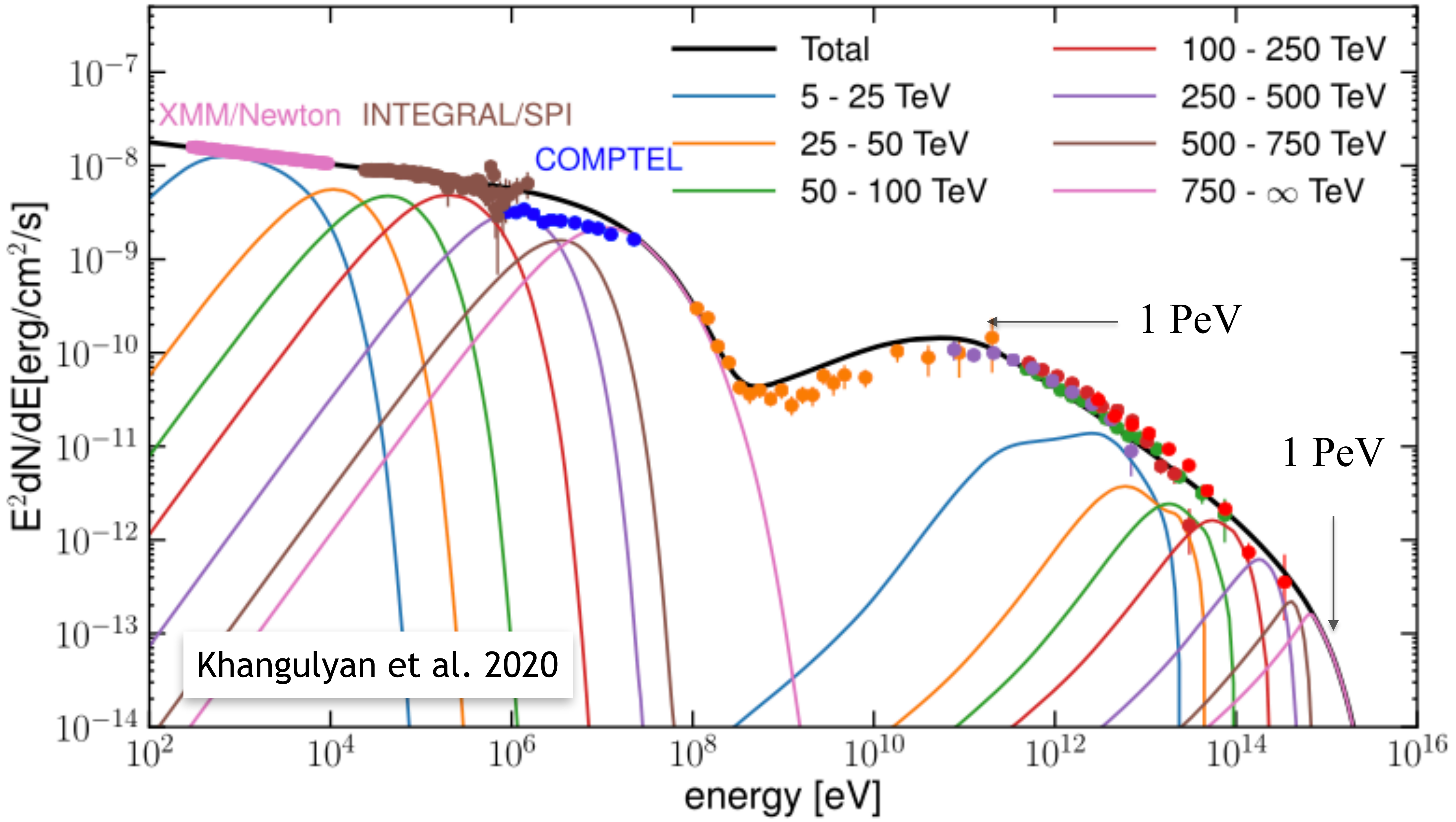
conversion of the rotational energy of pulsar to non-thermal energy with efficiency ~50 %

electron acceleration with 100 % efficiency

a non-thermal astrophysical object seen over 20 energy decades



R, mm, IR, O, UV,X — gamma-rays



~ half of rotational energy of pulsar is released in form of accelerated e^+e^- radiated away via synchrotron and IC channels of radiation over 20 decades !

e^+e^- are accelerated to >1 PeV (!) acceleration rate be at the margin allowed by theory ("ideal MHD")

Extreme Accelerators:

machines where acceleration proceeds with efficiency close to 100%

(i) fraction of available energy converted to nonthermal particles

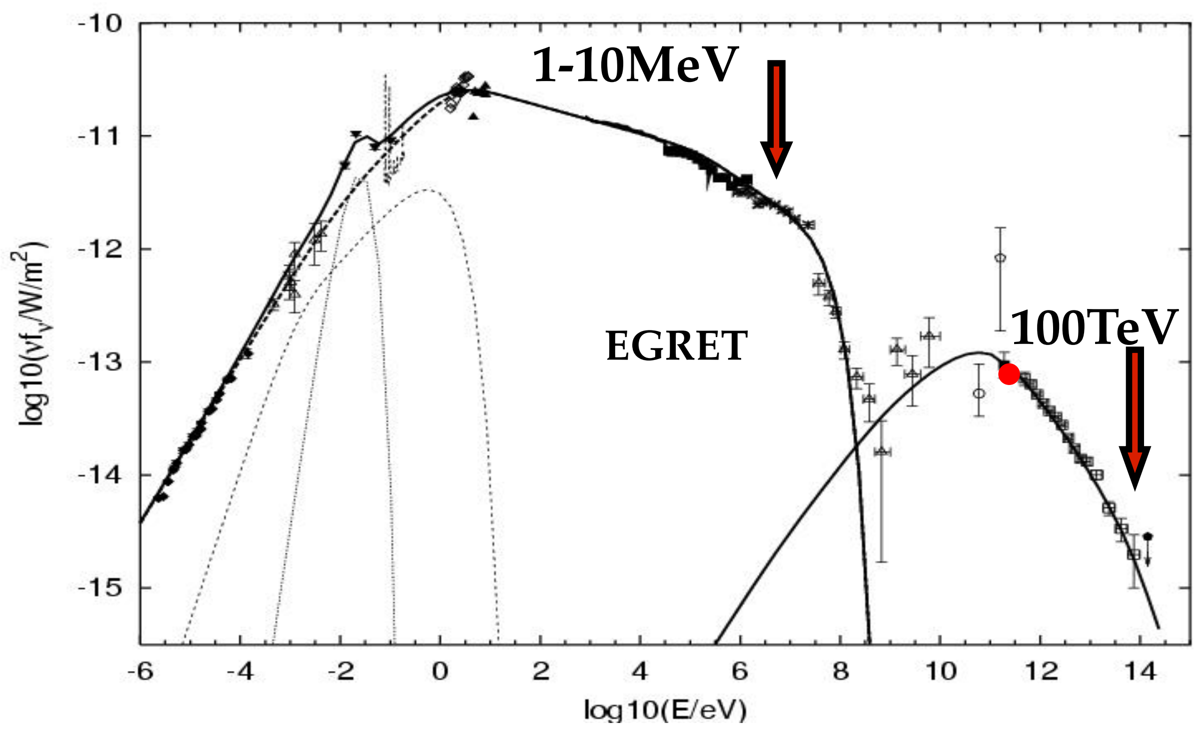
in PWNe and perhaps also in SNRs can be as large as 50 %

(ii) maximum possible energy achieved by individual particles

acceleration rate close to the maximum (theoretically) possible rate

sometimes efficiency can even "exceed" 100% ?
(no violation of conservation laws - but due to relativistic and non-linear effects)

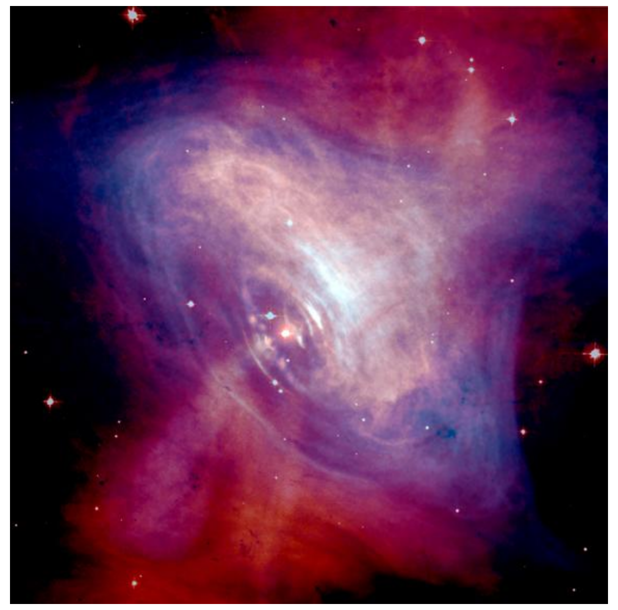
Crab Nebula – *a perfect electron PeVatron*



standard MHD theory (Kennel&Coroniti)

cold ultrarelativistc pulsar wind terminates by reverse shock resulting in acceleration of multi-TeV electrons

synchrotron radiation => nonthermal optical/X nebula
Inverse Compton => high energy gamma-ray nebula

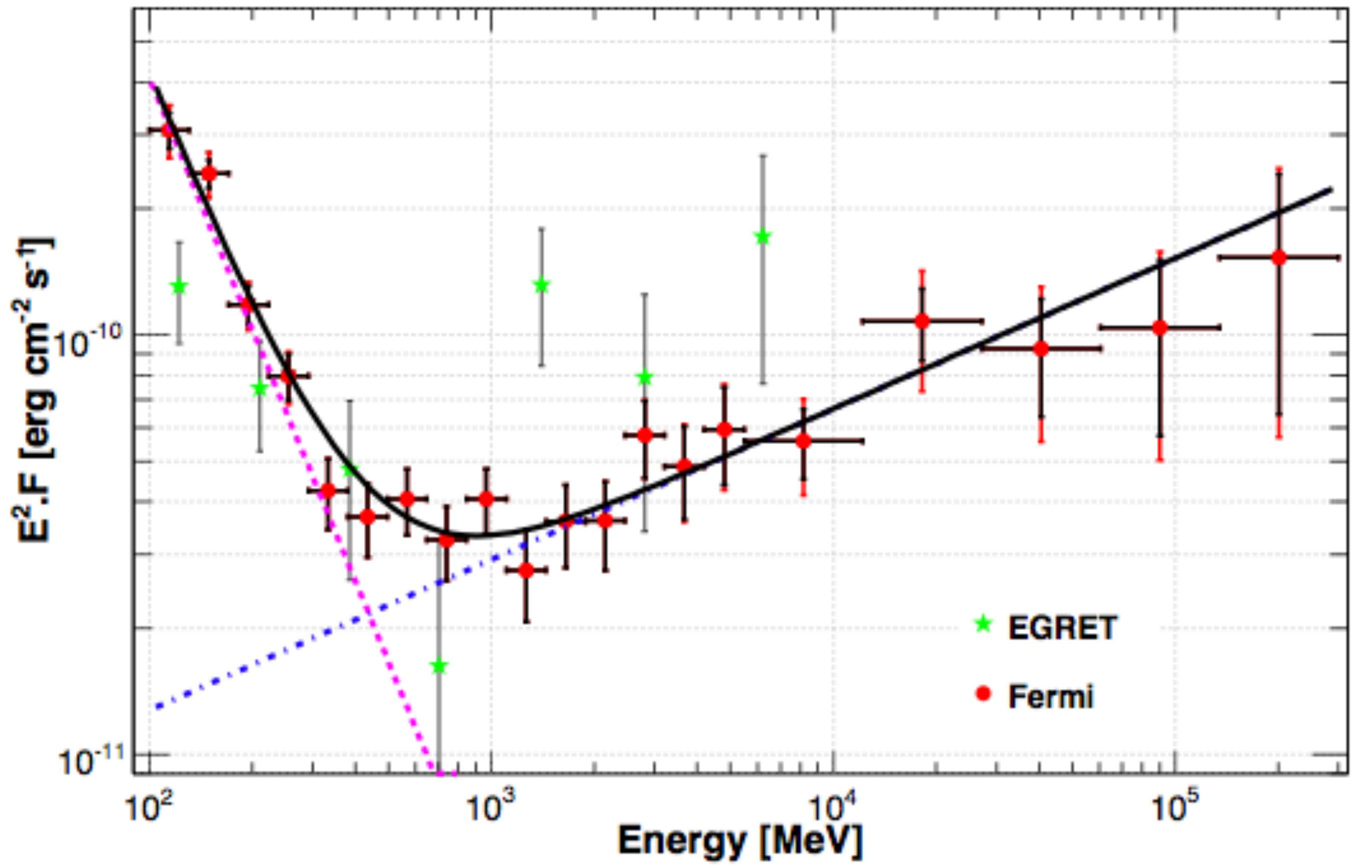


Crab Nebula – a powerful $L_e=1/5L_{rot} \sim 10^{38}$ erg/s
and extreme accelerator: Ee >> 100 TeV

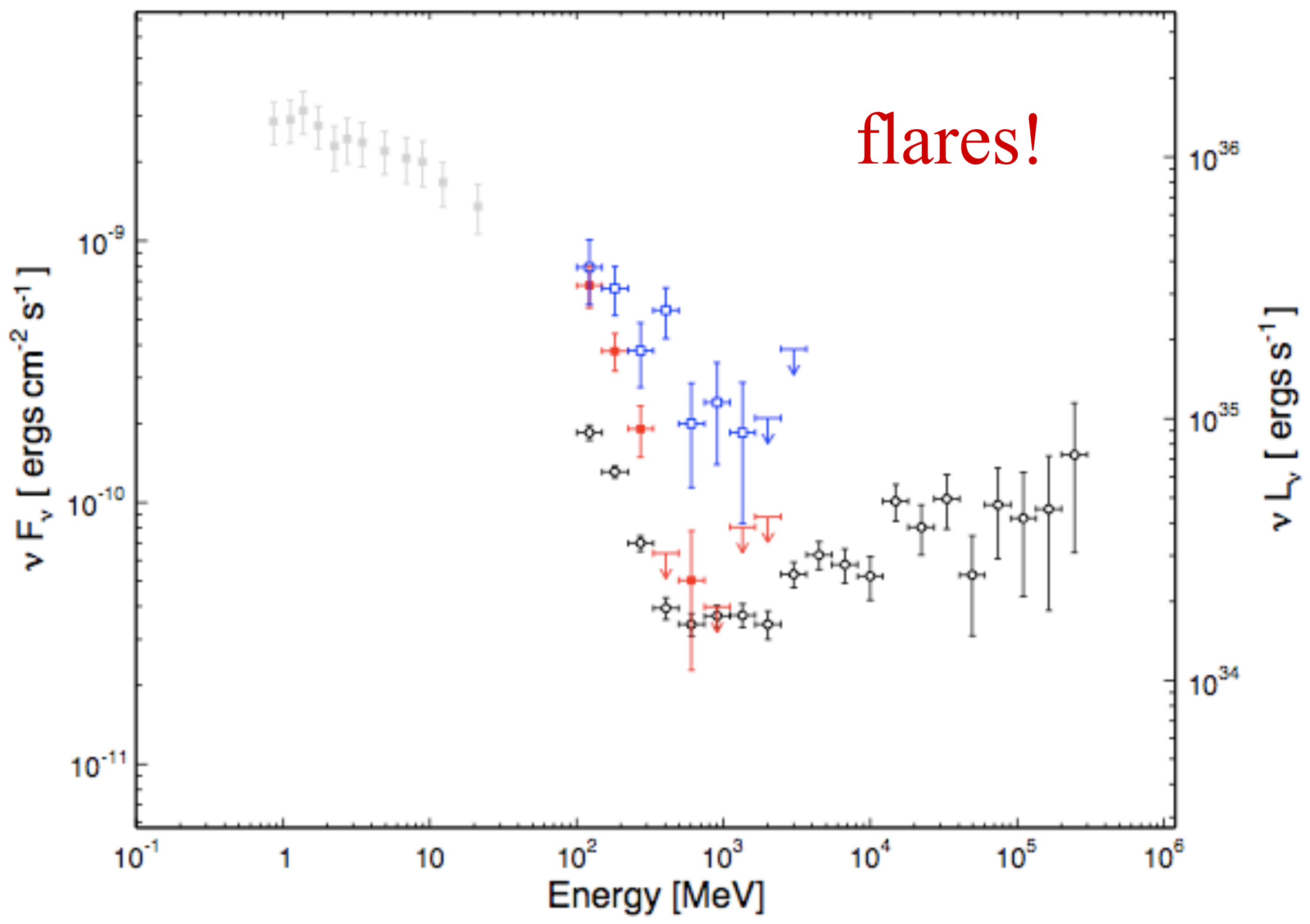
$E_{max}=60\ (B/1G)^{-1/2}\ \eta^{-1/2}$ TeV and $h\nu_{cut} \sim 150\eta^{-1}$ MeV

Cutoff at $h\nu_{cut} > 10 \Rightarrow \eta < 10$ - acceleration at 10 % of the maximum rate
γ-rays: $E_\gamma \sim 50$ TeV (HEGRA, HESS) => $E_e > 200$ TeV
B-field ~100 mG => $\eta \sim 10$ - independent and more robust estimate
1 mG => $\eta \sim 1$?

Flares of Crab (Nebula) :



IC emission consistent with average
nebular B-field: B ~ 100μG-150μG

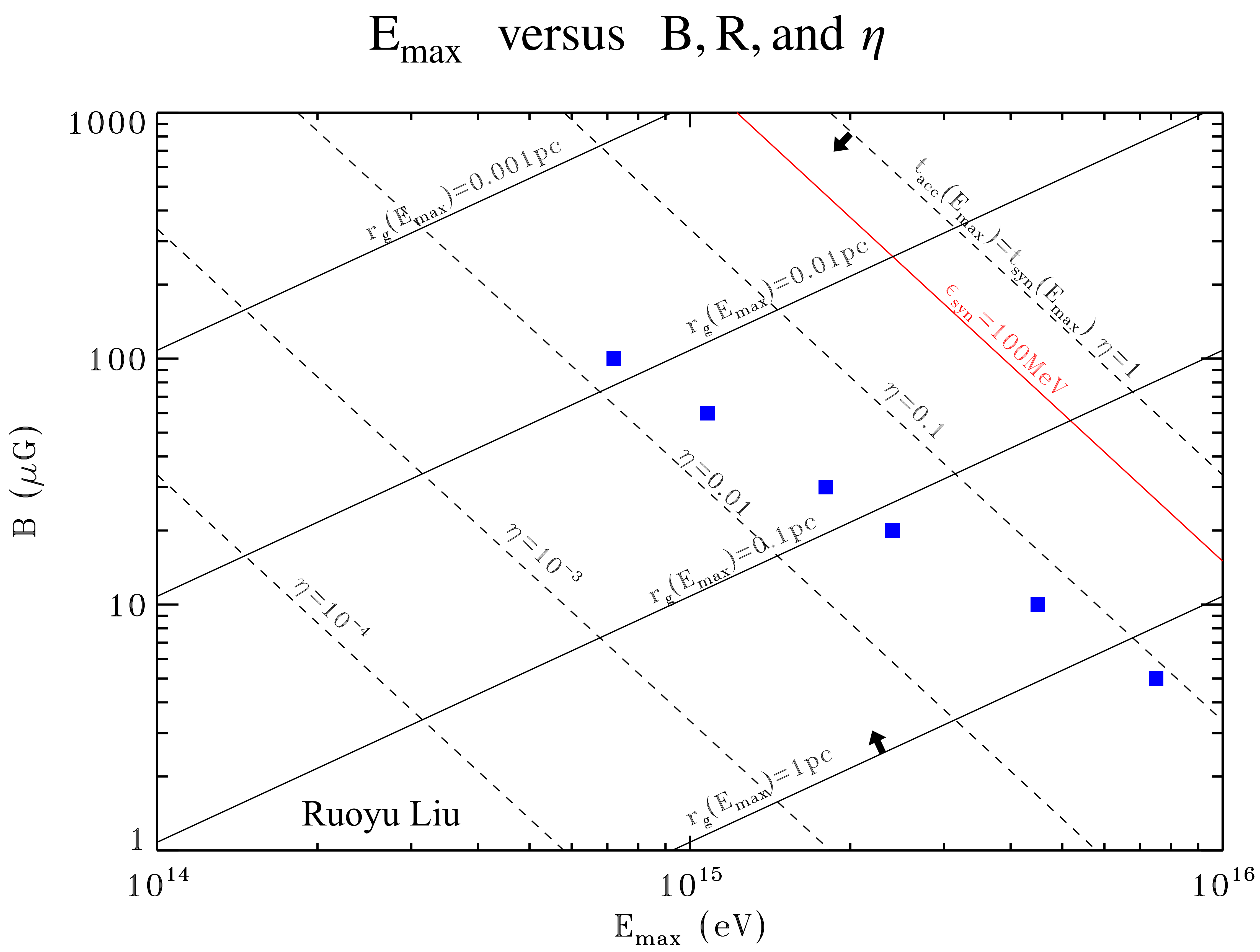


seems to be in agreements with the standard PWN picture, but … MeV/GeV flares!!

although the reported flares perhaps can be explained within the standard picture - no simple answers to several principal questions - extension to GeV energies, B>1mG, etc.

observations of 100TeV gamma-rays - IC photons produced by electrons responsible for synchrotron flares - a key towards understanding of the nature of MeV/GeV flares

PWNe as electron PeVatrons ?

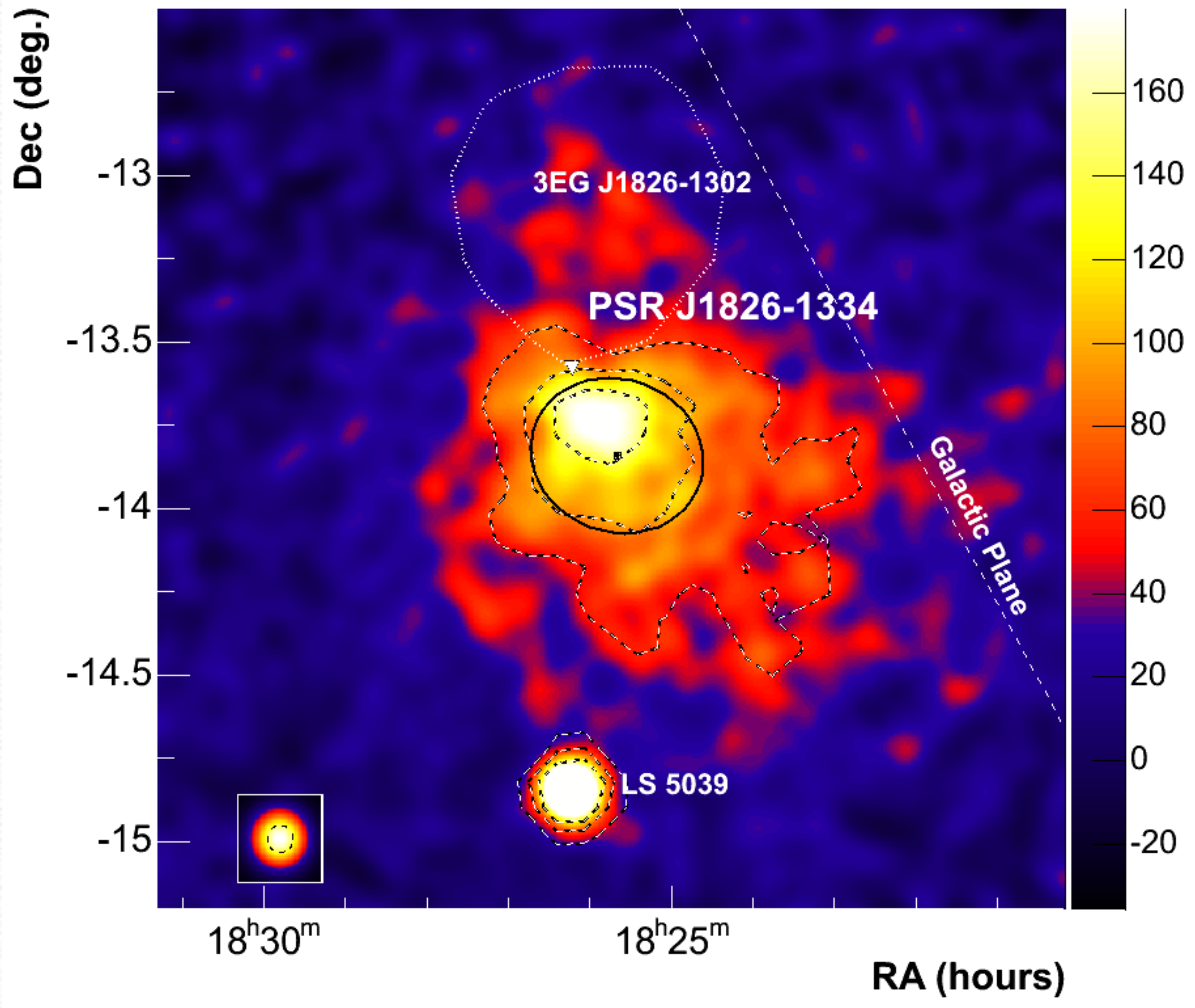


B $\leq$ 100μG -> E$_{max}$ $\rightarrow$ 1PeV

100 TeV - 1 PeV gamma-rays: critical and unbiased to find Emax

efficiency of gamma-ray production

Crab is effective electron accelerator but not effective gamma-ray emitter
because of $B \geq 100\mu G$, $\kappa \sim 10^{-3}$
other ("standard") PWNe are effective accelerators/effective gamma-ray emitters



$$t \geq t_{cool}, \quad \kappa = t_{Sy}/t_{IC} \approx 1(B/3\mu G)^{-2}$$

this compensates the smaller spin-down luminosities of "standard" PWNe

robust (assumption-free!) derivation of spatial and energy distribution of multi-TeV electrons
absolutely unique in astrophysics; great for development of models, theories, concepts

spatial- and energy- distributions of UHE electrons - direct measurement of of the diffusion coefficient

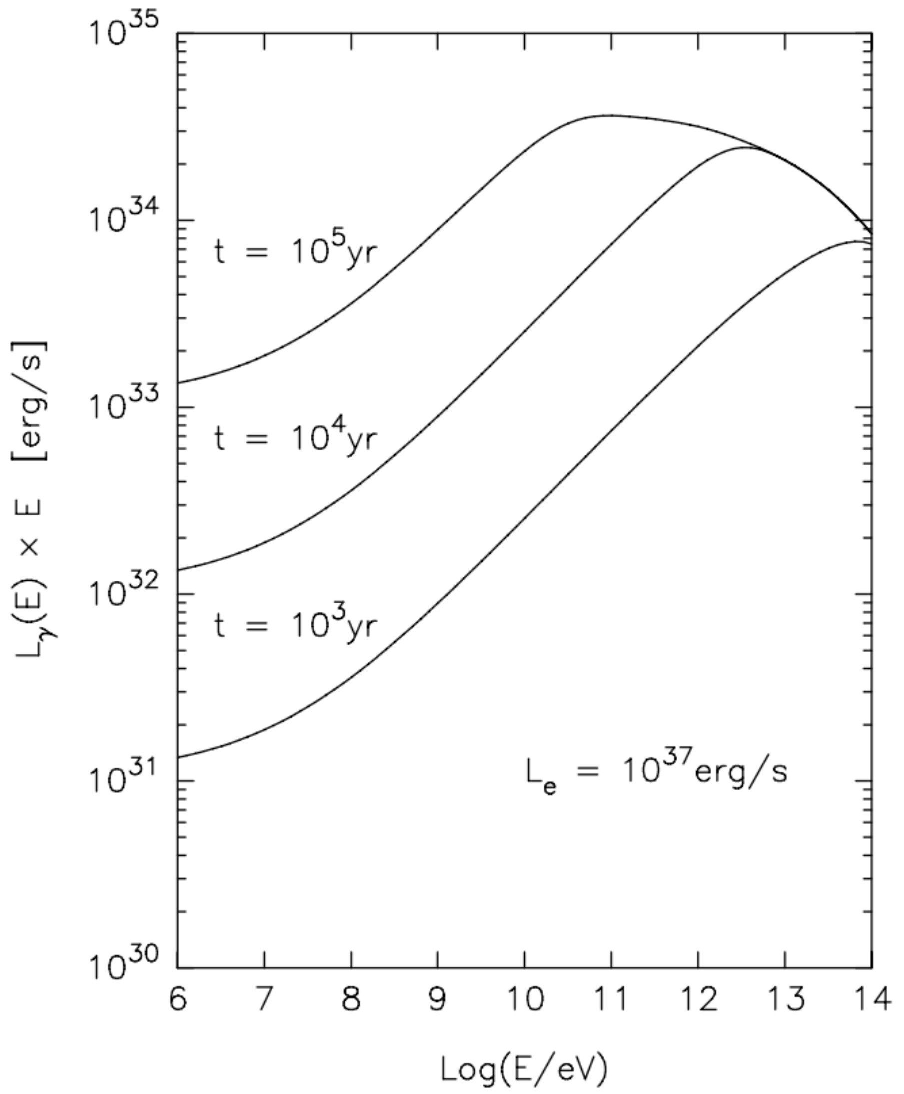


Fig. 4.14 The γ-ray luminosity of the expanding "cloud" of relativistic electrons at different epochs. A constant electron injection rate of $L_e = 10^{37}$ erg/s with a power-law acceleration spectrum ($\Gamma = 2$) extending up to 10^{15} eV is assumed. The magnetic field is $B_{\rm ISM} = 3\,\mu$G, the ambient gas density is $n = 1\,{\rm cm}^{-3}$, and energy density of O/IR starlight radiation is $w_{\rm IR} = 0.5\,{\rm eV/cm}^3$.

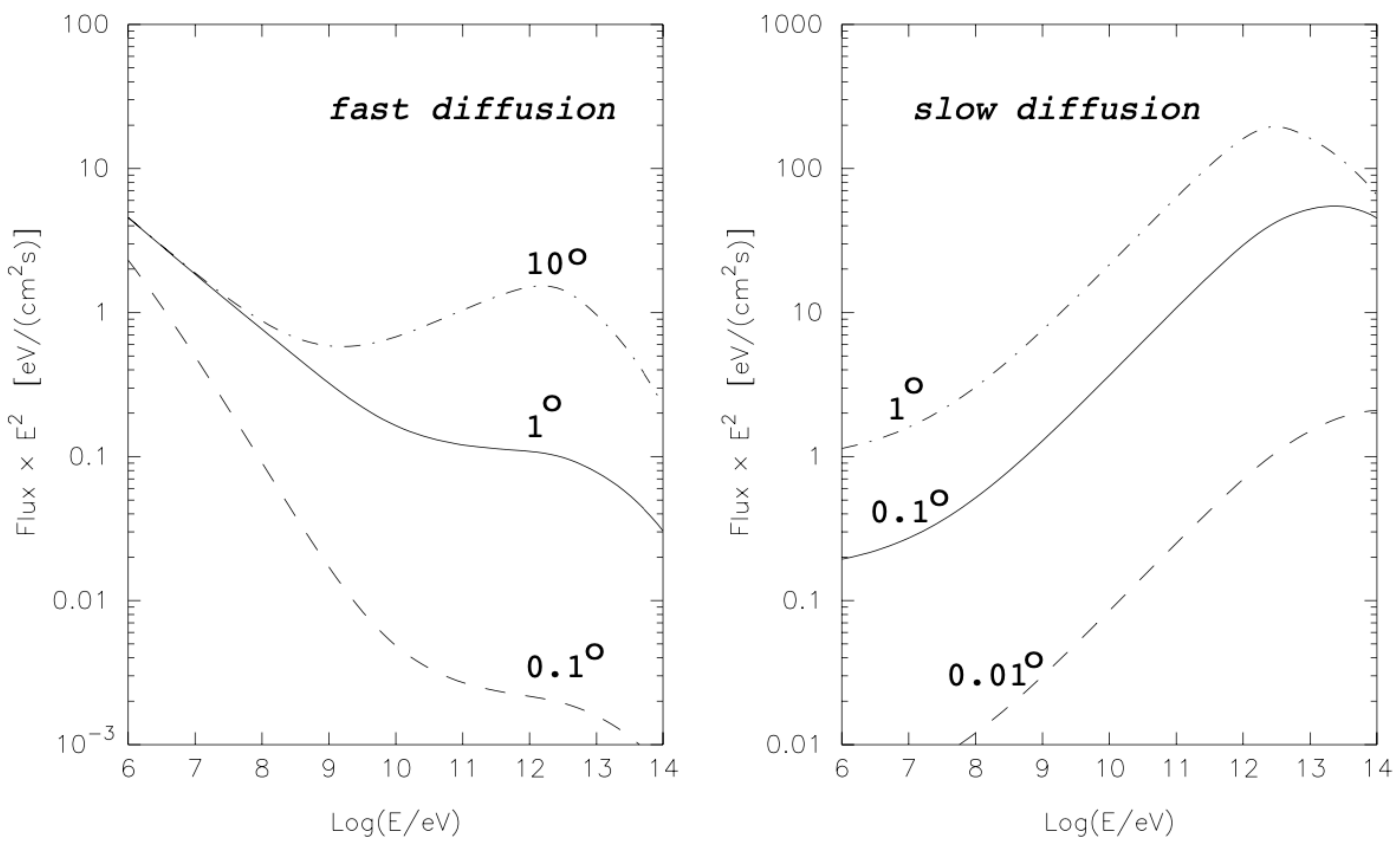
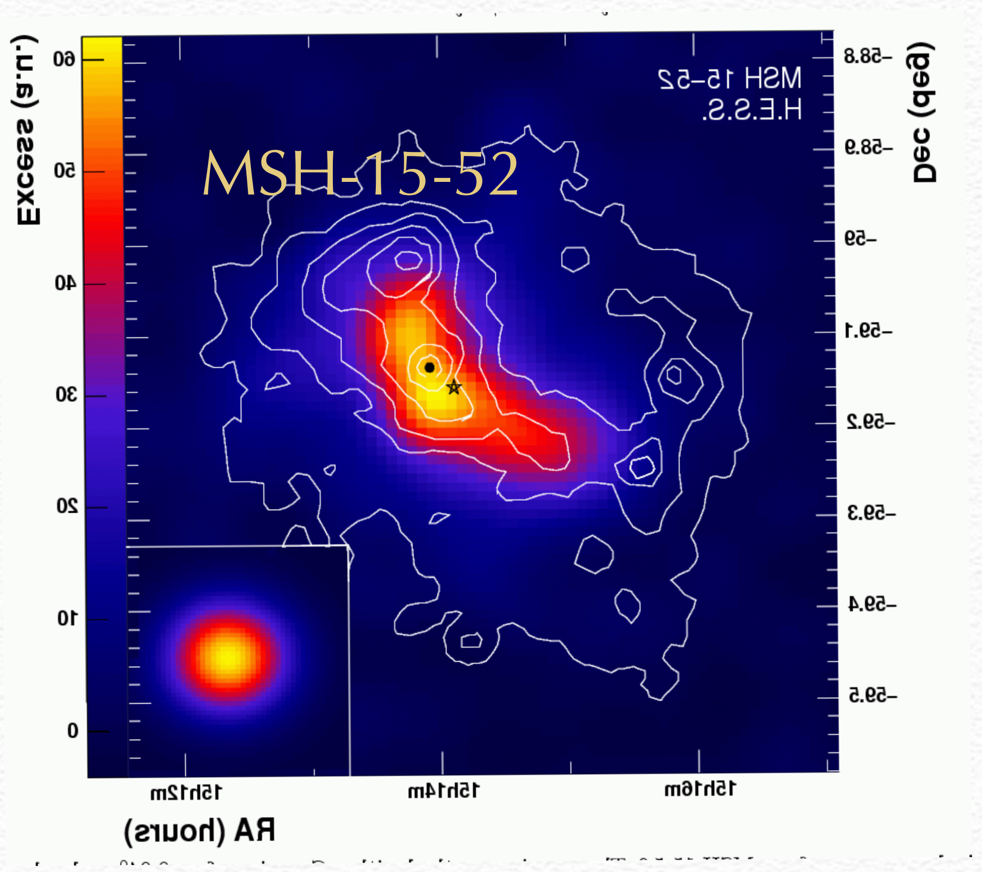
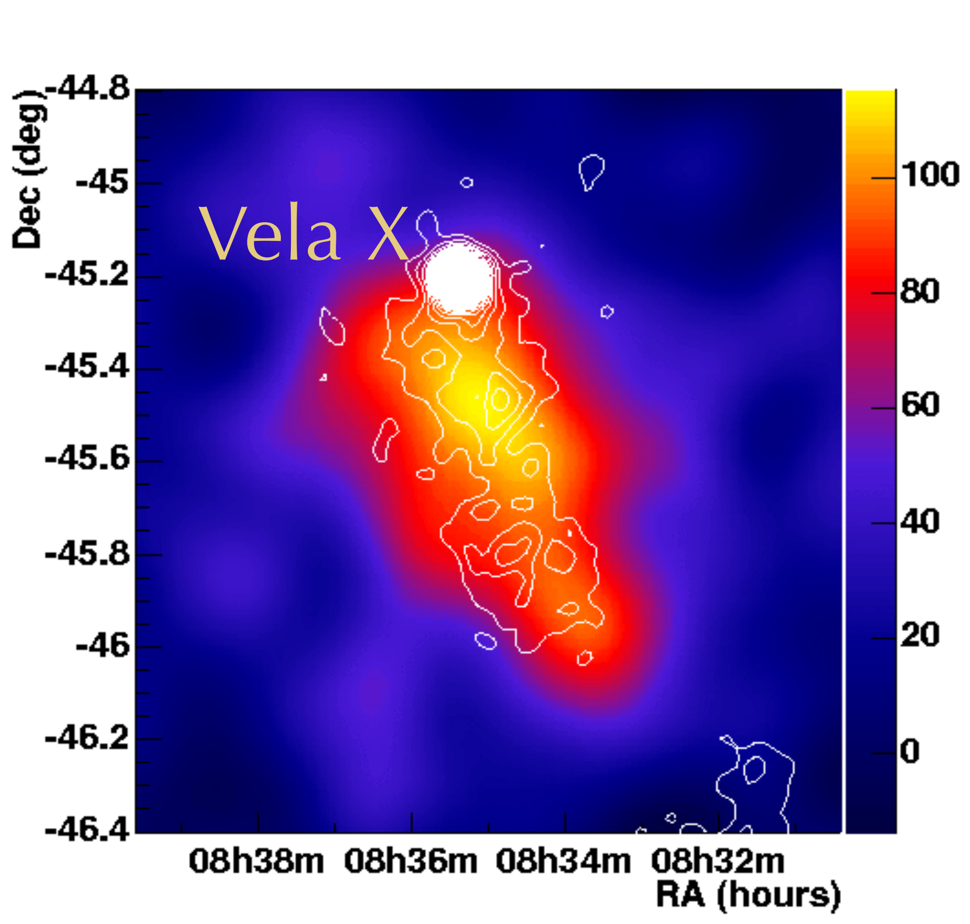


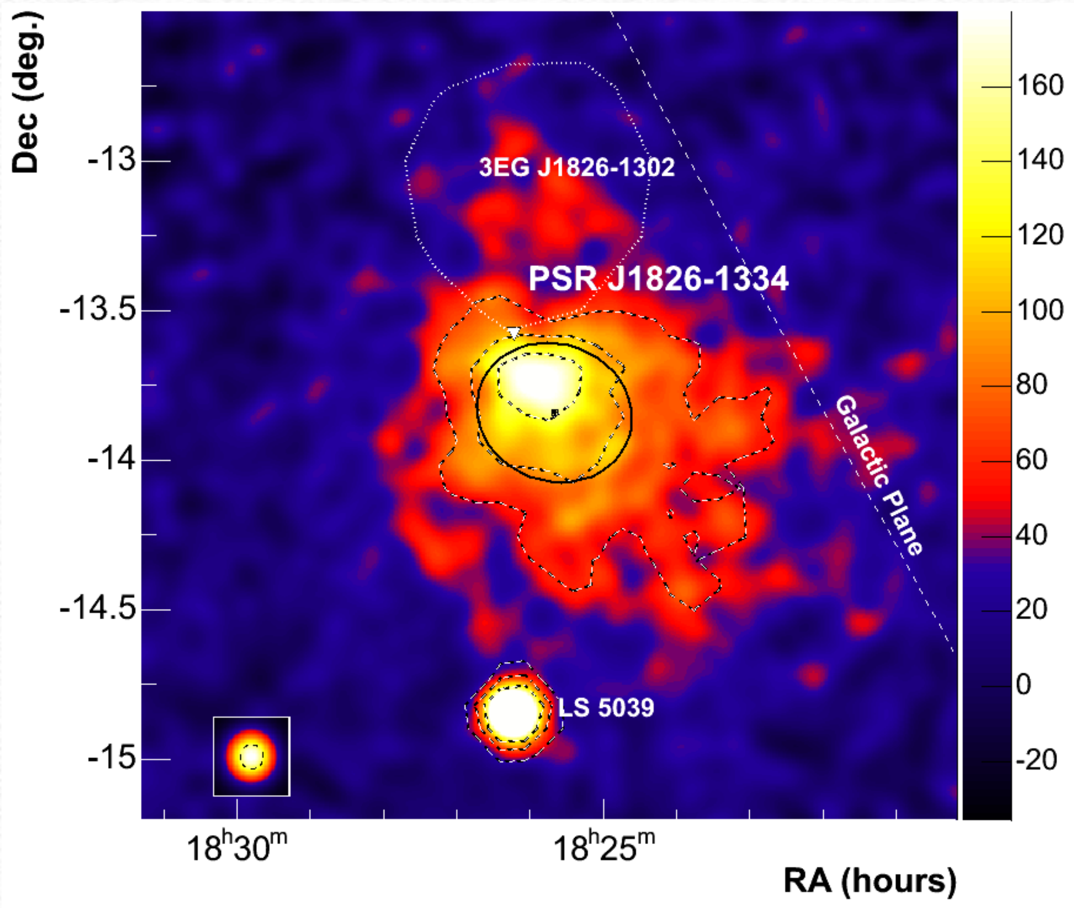
Fig. 4.15 IC γ-ray fluxes expected within different detection angles from an electron accelerator located at a distance of 0.5 kpc. The injection rate of electrons is $Le = 3.5 \cdot 10^{36}$ erg/s. **(a)** (left) fast diffusion – power-law diffusion coefficient $D(E) = D_*(E/10{\rm GeV})^{-\delta}$ with $D_* = 10^{27}\,{\rm cm}^2/{\rm s}$ and $\delta = 0.5$; steep spectrum of accelerated electrons with $\Gamma = 2.4$. **(b)** (right) slow diffusion – constant diffusion coefficient with $D_* = 10^{27}\,{\rm cm}^2/{\rm s}$ and $\delta = 0$; hard spectrum of accelerated electrons with $\Gamma = 2$.

H.E.S.S. “gems” - standard PWNe

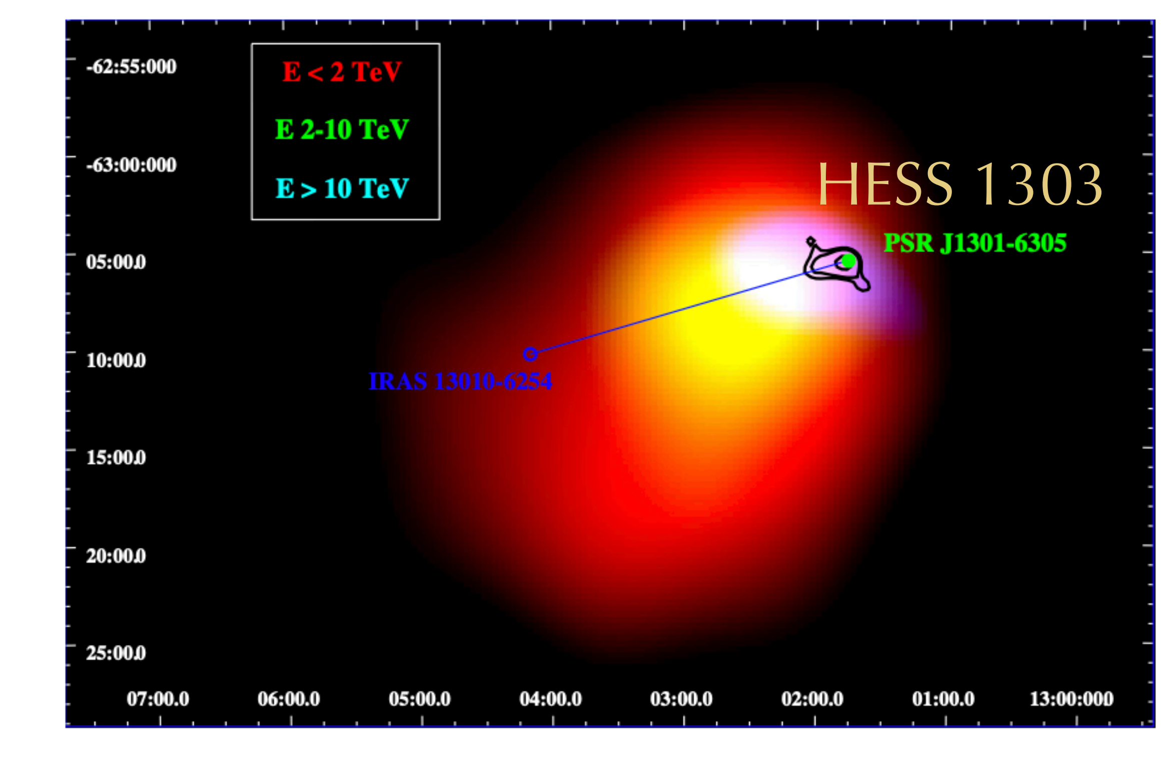


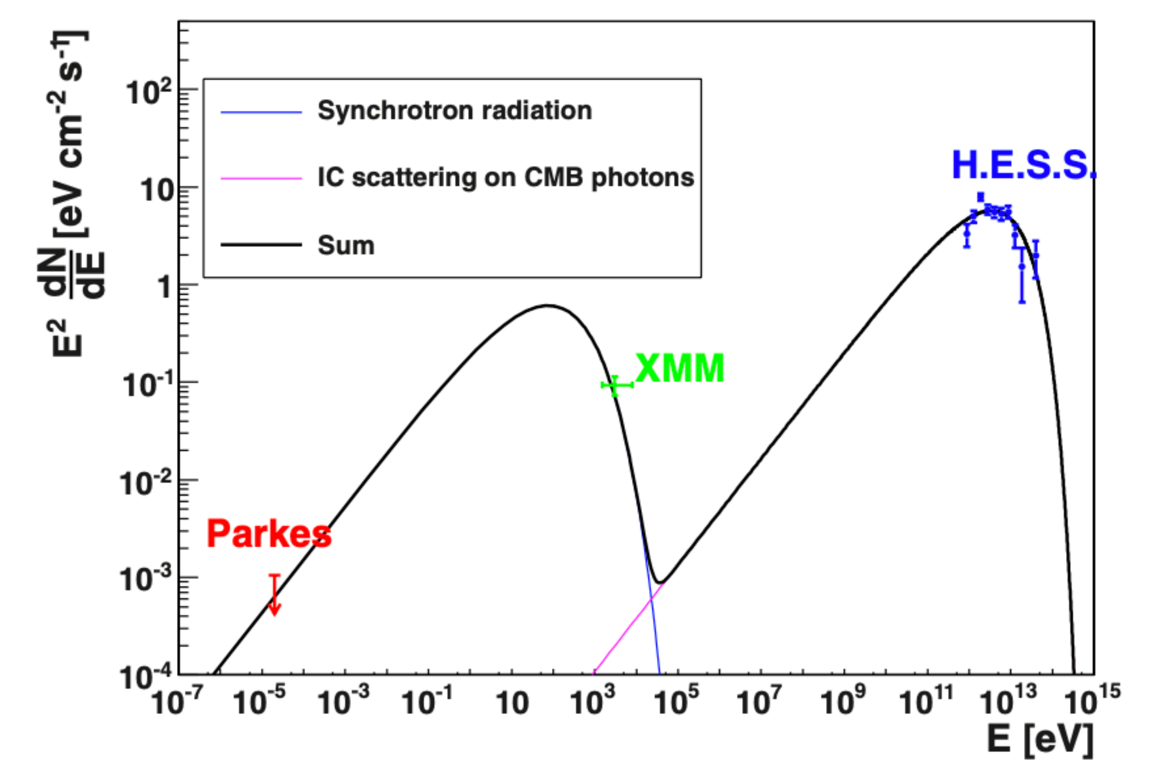


PWN+Halo?



“Classical” HESS PWNe





unusual/unexpected properties very low B-field energy dependent morphology >10 TeV around the pulsar; extended < 2 TeV

very low B-field: B ~ 1.4μG (one-zone model

PWN or a Halo ?

PWN or Halo ?   or   PWN+HALO ?

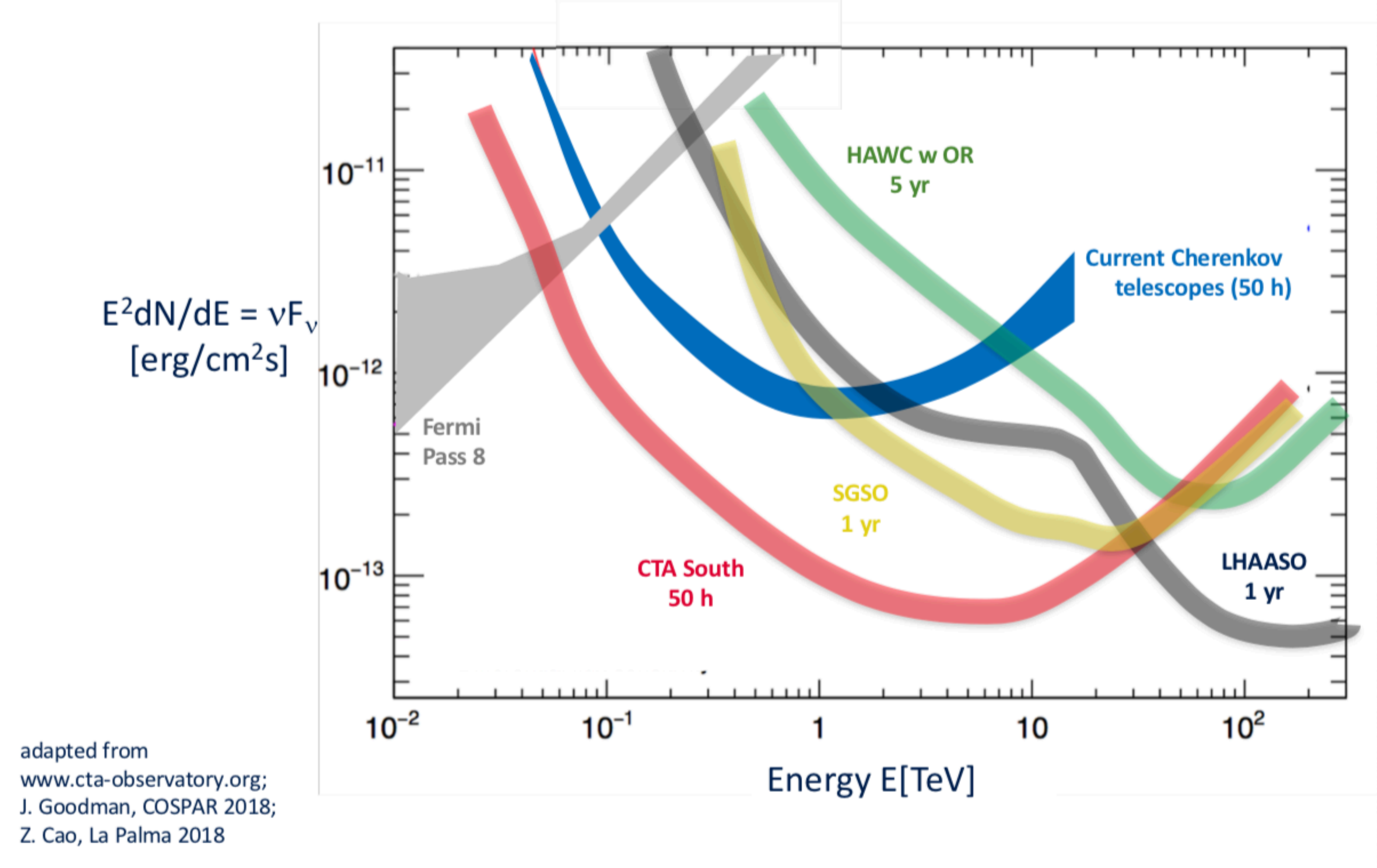
sources with linear size L~ 10-20 pc - a real problem to be interpreted as PWN,
only with J 1825 no problem with PWN

on the other hand for Geminga Halo is discussed as a Halo (“electron diffusion”)

other galactic extended sources different from Pulsar Halos?

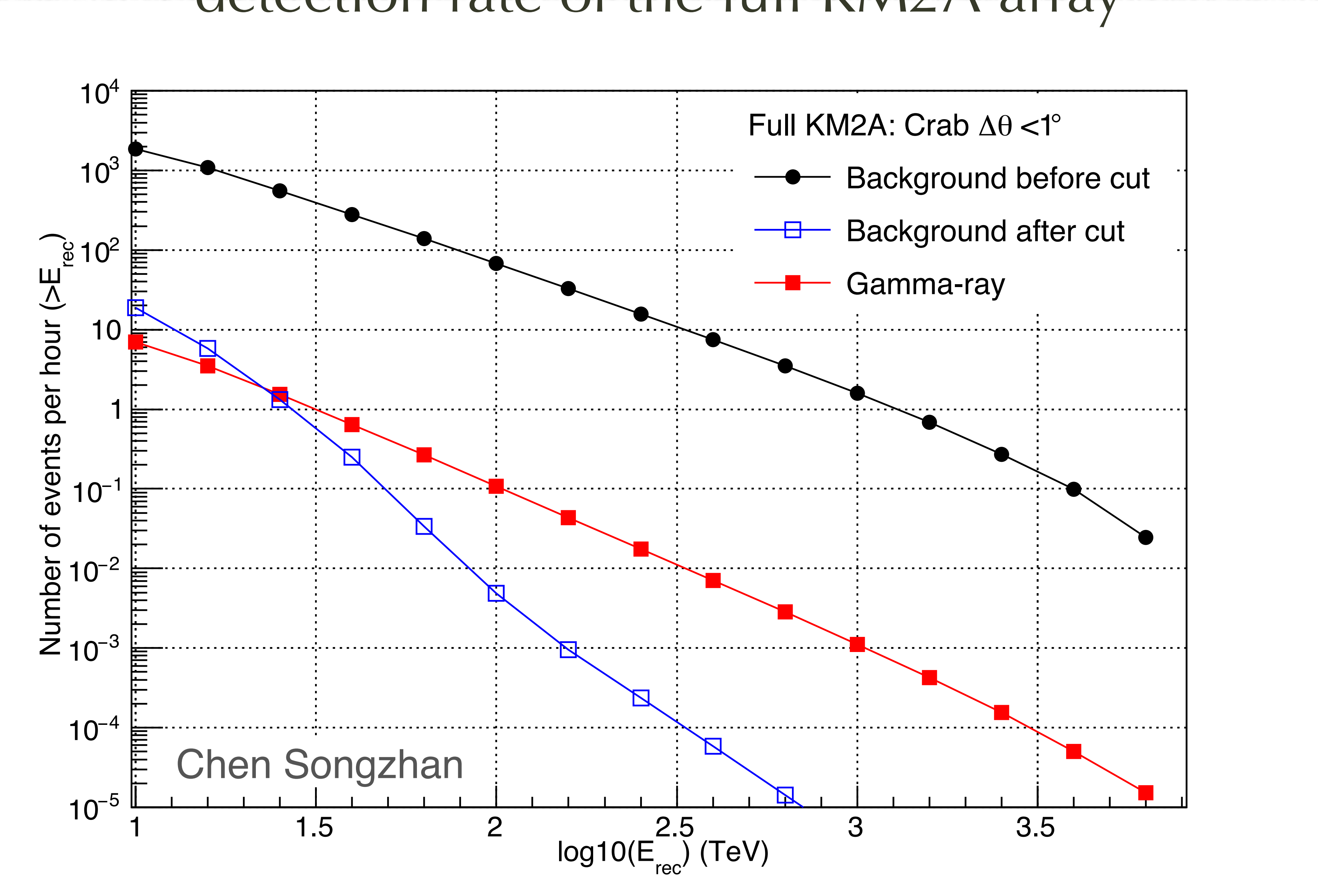
- leptonic or hadronic Halos around SNRs
- stellar clusters and related super bubbles
- giant molecular clouds
- Hadronic halos around pulsars?

current/future detectors and expectations



adapted from
www.cta-observatory.org;
J. Goodman, COSPAR 2018;
Z. Cao, La Palma 2018

detection rate of the full KM2A array



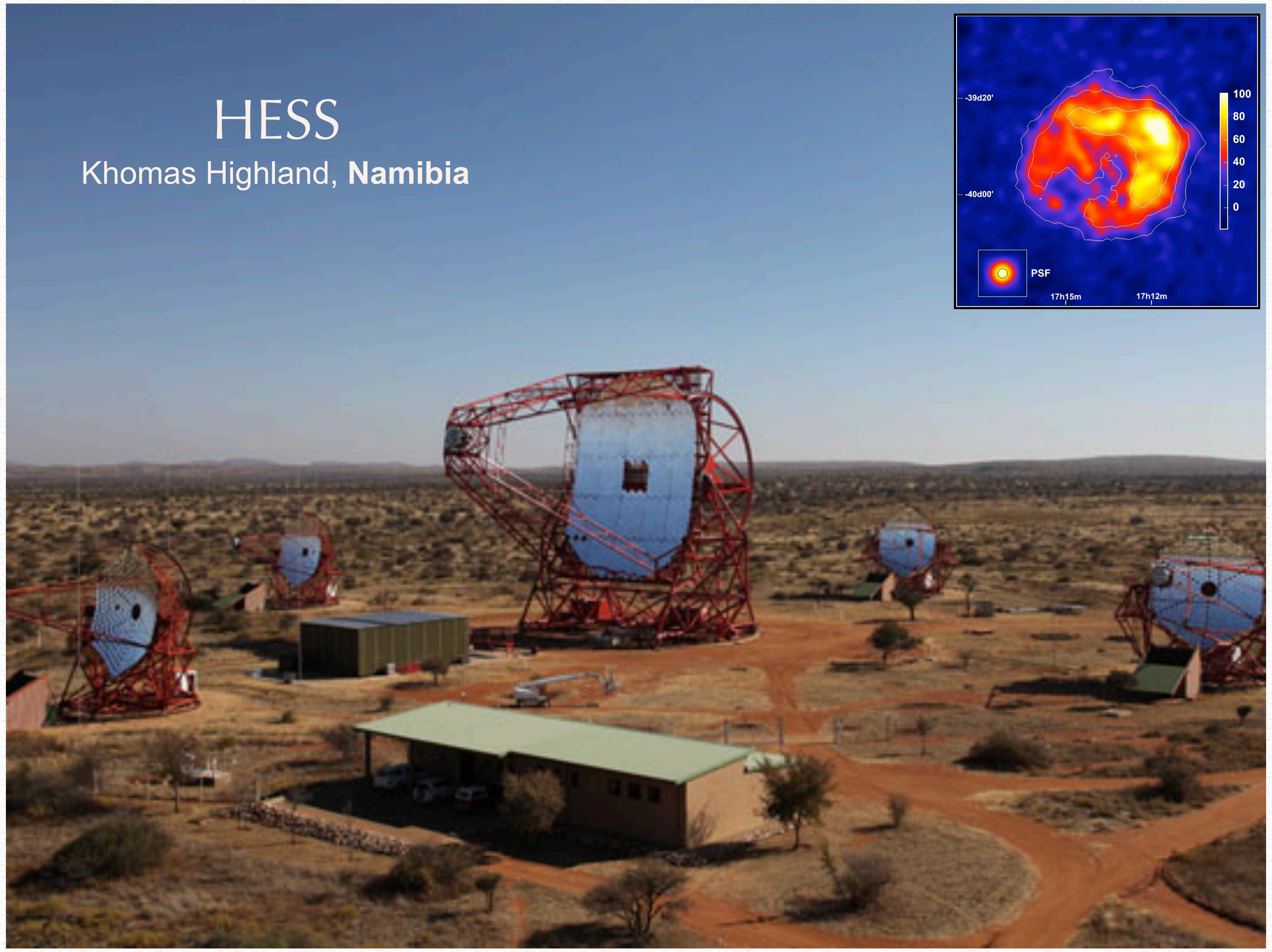
KM2A - PSF: 25 arcsin at 20 TeV, 12 arcsin at 100 TeV
KM2A - energy resolution around or less 20%

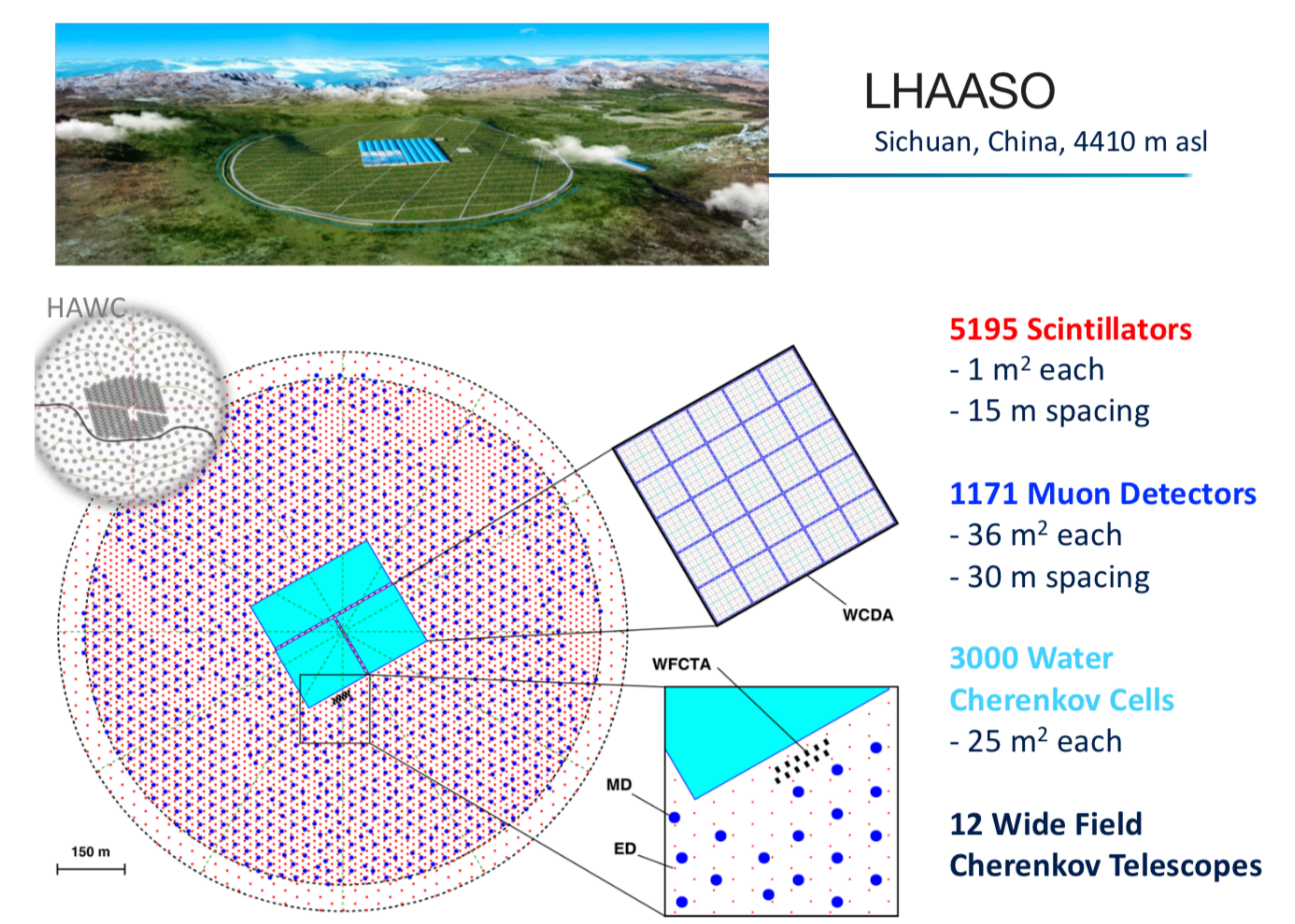
over next ~5 years	**LHAASO +HESS/VERITAS**	
	LHAASO+CTA North	**significant coverage of the sky**
after 2025	**SWGO+CTA South**	**full coverage**

HESS and LHAASO

TeV energies: VHE

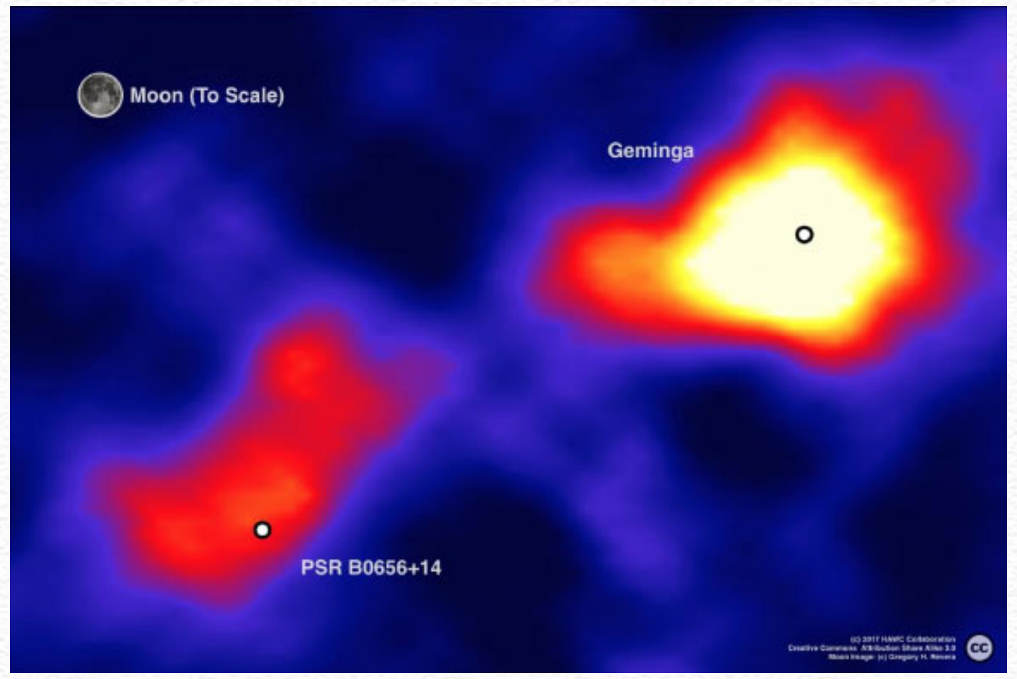
PeV energies: UHE

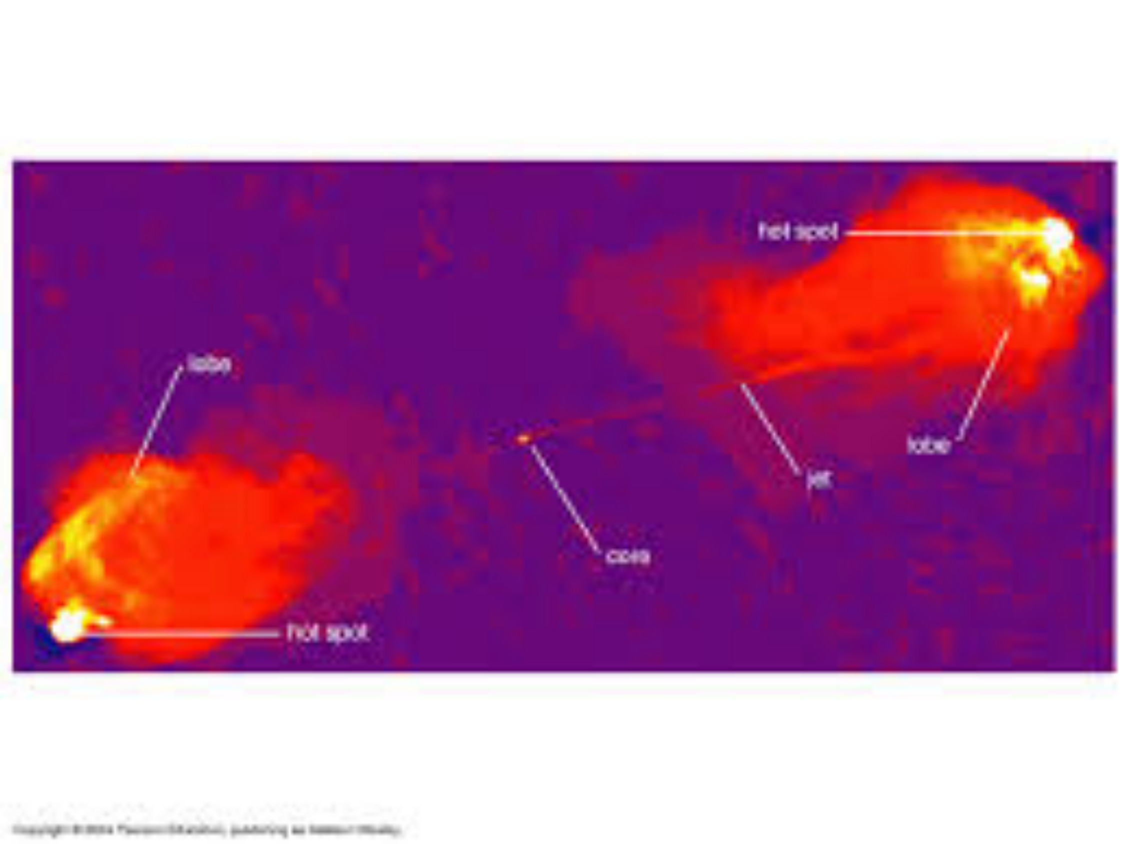




1 TeV=10^{12} eV

1PeV=10^{15} eV





Cygnus A in radio

imaging in VHE/UHE gamma-rays !

formation of Pulsar Halos are essentially TeV (PeV) phenomenon

Ground based gamma-ray detectors are perfectly designed for IC channel of radiation

synchrotron X-ray (also MeV?) for the Synchrotron channel of radiation

X-rays - current detectors (XMM, NuStar) and of course eRosita!
0.2-10 keV (FoV 1 deg), 6-30 keV (0.5 deg)

Diffuse TeV/PeV and hard X-ray background of the Galactic Plane ? (Aharonin&Atoyan 2000)

Broad-band diffuse gamma ray emission of the galactic disk

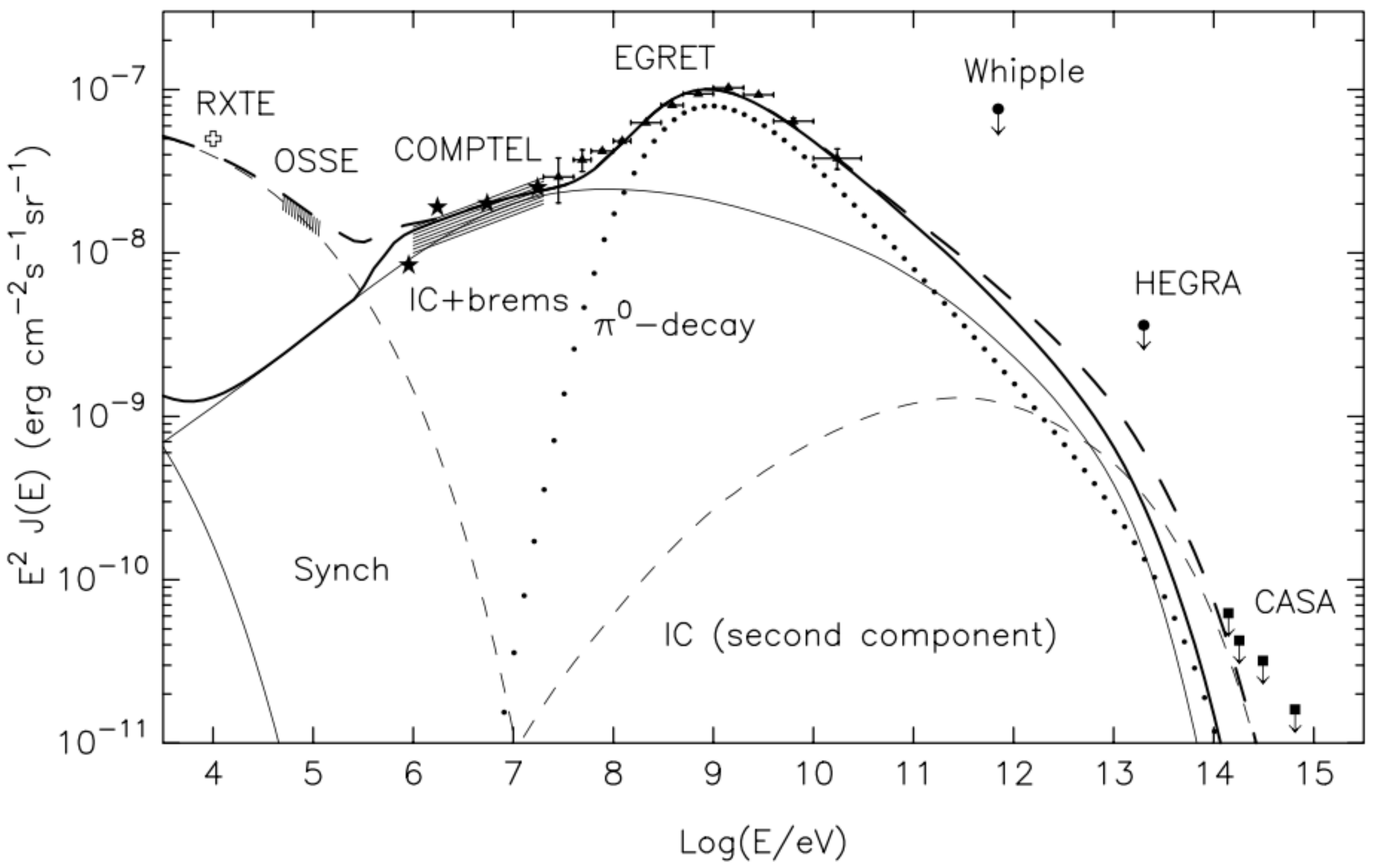


Fig. 7. The diffuse background radiation from the Galactic plane corresponding to the two-component model for the relativistic electrons. The heavy solid line corresponds to the fluxes produced by the electrons of the first (main) population, with the same model parameters as in Fig. 6, but for $\delta = 0.7$ and $C_+ = 0.3$, and the heavy dashed line shows the overall fluxes including the contribution from the second ('pulsar wind'– see text) population of electrons accelerated to energies $E_0 = 250\,\mathrm{TeV}$. The local mean magnetic field for the second electron population is $B_2 = 25\,\mu\mathrm{G}$. Besides the galactic diffuse background γ-radiation detected by COMPTEL and EGRET, the X-ray backgrounds detected by RXTE (Valinia & Marshall 1998) and OSSE (Kinzer et al. 1997), as well as the upper flux limits at very high energies (VHE) reported by Whipple, HEGRA, and CASA-MIA collaborations are also shown.

hard galactic diffuse X-ray emission can be explained by Pulsar Halos ?

F.A. Aharonian & A.M. Atoyan: Astron. Astrophys. 362, 937–952 (2000)

Broad-band diffuse gamma ray emission of the galactic disk