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Gamma Rays: overview of the status

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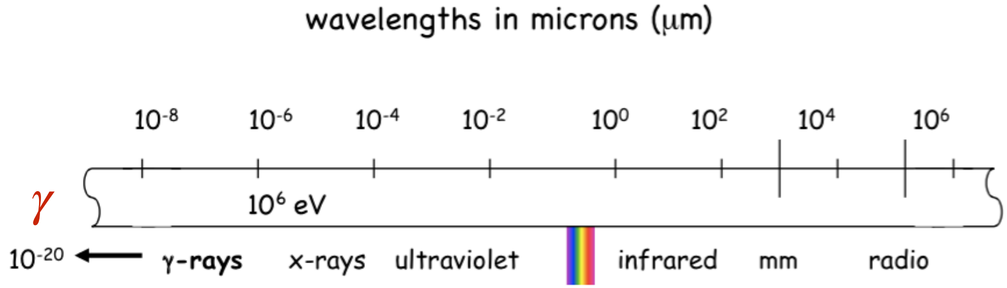
Gamma-rays: ‘the last window’ in the cosmic EM spectrum



MeV-GeV-TeV-PeV

LE	or	MeV :	0.1 -100 MeV	
HE	or	GeV :	0.1 -100 GeV	
VHE	or	TeV :	0.1 -100 TeV	
UHE	or	PeV :	0.1 -100 PeV	new!

…

window is opened in MeV, GeV, TeV bands

UHE gamma-rays: “the last window in the last window

we are at the threshold of UHE gamma-ray astronomy

MeV   Status of the Field

was at the forefront of gamma astronomy in the 1970s to 1990s, but now is stalled …

- no new remarkable results since Compton GRO (OSSE, COMPTEL) except for 0.511 MeV from GC and Milky Way map in 1.8 MeV (^{16}Al) lines (INTEGRAL)

- no significant progress with proposed space missions (NASA, ESA) despite several tries; efforts continue in Europe and US, new initiatives in Japan, China…

reasons? - high competition in space programs

- difficult energy band - "no breakthrough in the detection technique" nevertheless improvement of the performance (sensitivity can be improved by two orders of magnitude (eASTROGAM)

- exciting science in the the MeV band is not fully recognised and appreciated

despite the dramatic interest to gamma-ray astronomy in general, less interest to MeV band and related science (e.g. gamma-ray lines) than 40-50 years ago

MeV

Status of the Field

a few topical research areas:

Gamma-Tay Line Astronomy - nucleosynthesis (stellar evolution)
Solar flares
sub-relativistic CRs (heating/ionization, star formation)
$> 10^{9\text{-}10}$ K two-temperature plasma around BHs (ADAF, etc.)

Astrophysics of annihilation lines - positrons in pulsars, black holes, radioactive nuclei…

1-100 MeV continuum astronomy - unique to probe <100 MeV electrons (through bremsstrahlung), and measurements of the B-field

MeV synchrotron sources - extreme synchrotron blazers, Crab flares, …

GRBs and GRB afterglows - a part of MeV astronomy

Future ? instruments with performance of eASTROGAM can provide a breakthrough but strong efforts are needed for getting a dedicated MeV gamma-ray satellite

Status of the Field

GeV

consistent progress over 50 years (SAS-II/COS B/EGRET GRO/AGILE/Fermi LAT) and finally breakthrough thanks to Fermi LAT and AGILE:

- *detection of thousands of galactic and extragalactic sources*: dramatic increase of gamma-ray emitting Pulsars and AGN; SNRs, GMCs, Stellar Clusters, PWNs, Binary Pulsars, Microquasars, Normal Galaxies, Starburst Galaxies, …

- *galactic and extragalactic diffuse backgrounds*

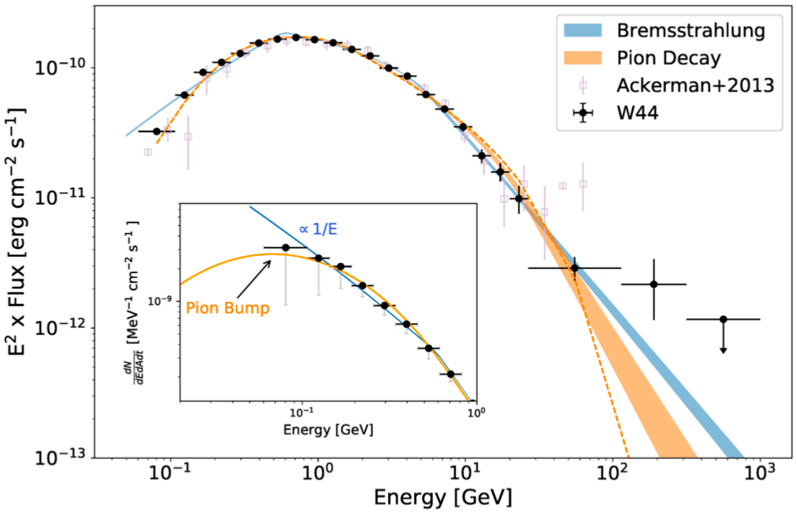
- *discoveries of new phenomena* - Fermi flares, and Fermi Bubbles, etc…

- *detection of the kinematic* π^0 *- decay bump* in the gamma-ray spectra of SNRs

- detection of 100 MeV gamma-ray counterparts of GRBs/GRB-afterglows

- some exciting results of *recent years* - (tentative) detections of gamma-rays from famous astronomical objects - SS 433, Coma, Arp 220

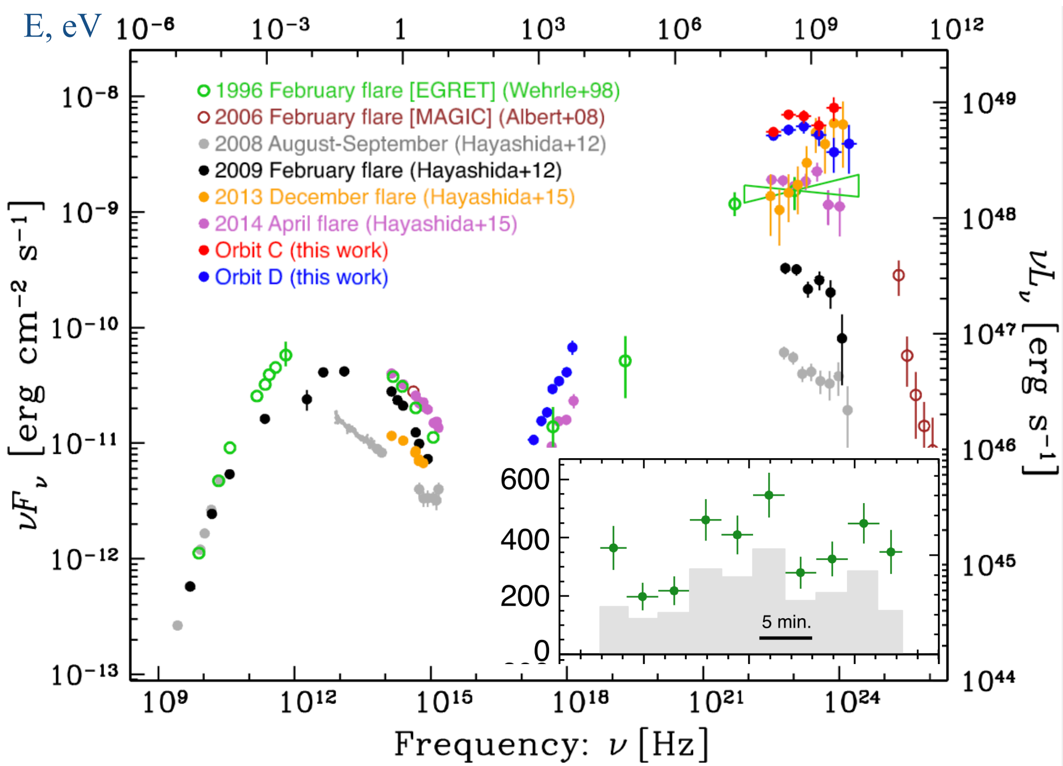
SNR W44



unambiguous detection of kinematic ‘π^0 bump’ at 67 MeV in spectrum of SNR W44: measured differential spectrum harder than : $dN/dE \propto E^{-1}$

the only alternative for very hard spectrum: bremsstrahlung but cannot be harder than E^{-1}

3C 279: z=0.54



$t_{var} \approx 5$ min variability during flare $F_\gamma \sim 3F_{Crab}$, $L^{(iso} = 10^{49}$ erg/s

challenges:

standard IC models require
- jet's Lorentz factor ≥ 50
- magnetisation $\leq 10^{-3}$
- $L \geq L_{Edd}$
- $M_{BH} \approx 5 \times 10^8 M_\odot \rightarrow r_g/c \sim 1$ h
- by order of magnitude larger t_{var}

GeV

Status of the Field

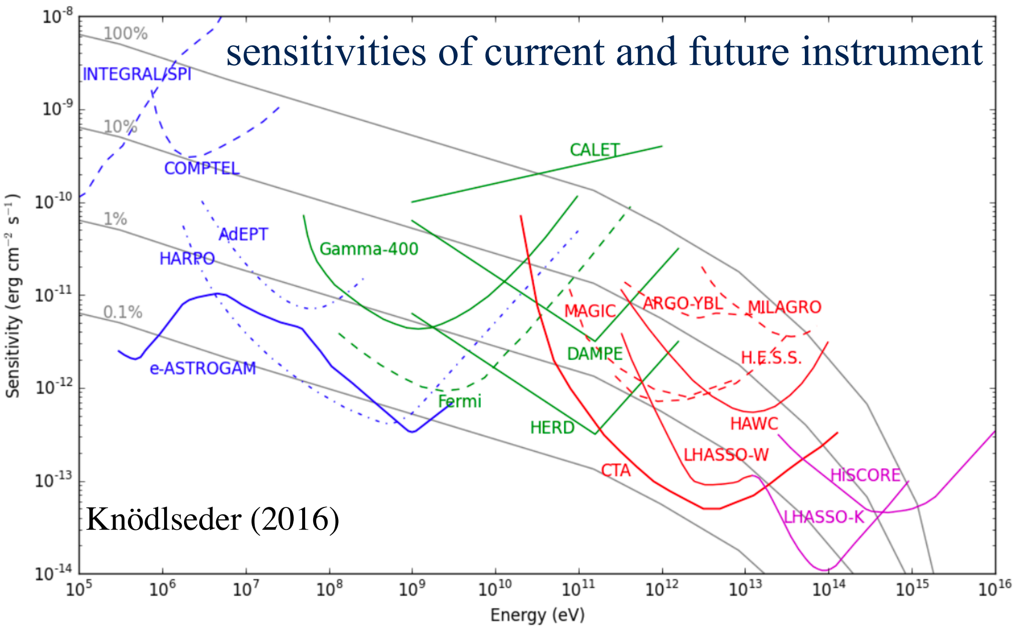
Satellite-borne

shortcomings? modest angular resolution < 1 GeV (few deg) reasonable photon statistics
good angular resolution: >10 GeV (0.1 deg) very limited photon statistics
compromise around 1 GeV - sensitivity approaches 10^{-13}erg/cm^{2}s

improvements?

low energies: better PSF below 1 GeV - possible but not better than 1 deg

high energies: increase of the detection area - possible but $A_{eff} \ll 10m^2$



Knödlseder (2016)

future? many uncertainties

below 100 MeV:

ASTROGAM approach - feasible
almost unexplored territory
exciting (new) science

0.1 -10 GeV: a a few m^2 telescope ?

above 10 GeV - large aperture IACT ?

GeV

TeV gamma-ray astronomy - *a success story*

over last 2 decades the field has bee revolutionised

> 250 G & EXG sources and 10+ source populations

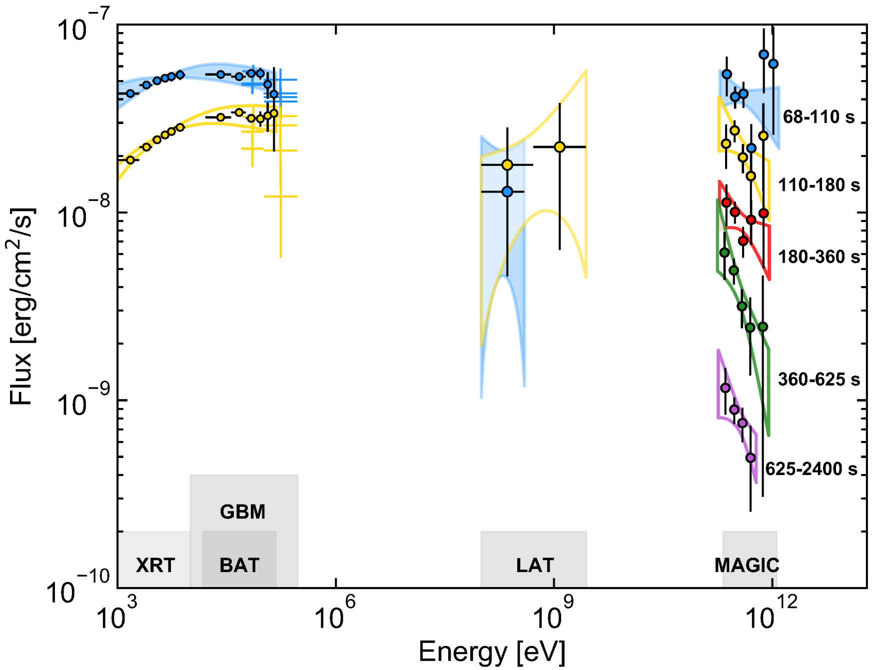
SNRs, PWNe, Stellar Clusters, GMCs, Pulsars, Binary Systems,
Galactic Center, Starburst Galaxies, AGN, Radiogalaxies, GRB afterglows

the potential of the current IACTs close to saturation, nevertheless over last two years new discoveries, e.g. VHE GRB afterglows, resolution kpc-jet of Cen A in TeV gamma-rays

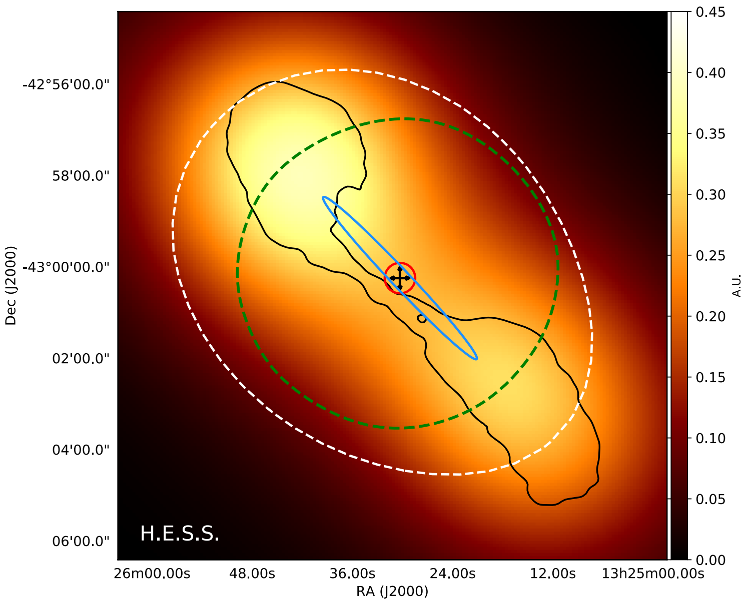
well established detection technique and clear guideline for the future

- curent IACT arrays: HESS/Magic/VERITAS
- future - CTA; Northern CTA started

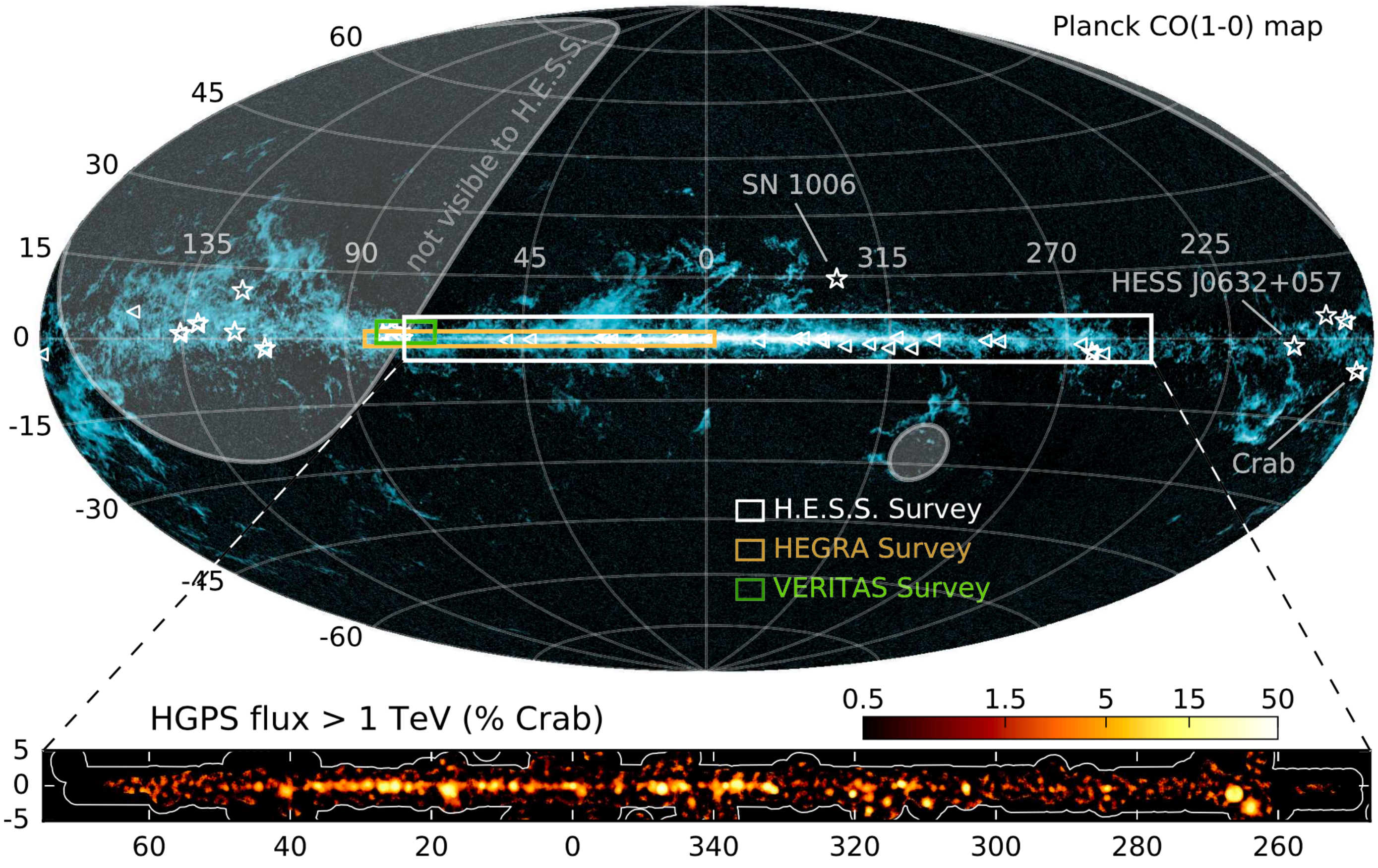
Recent results obtained with IACT arrays



resolving the decay of early GRB 190114 afterglow on min timescales by Magic



resolving kpc scale jet in Cen A by H.E.S.S. on a few arcmin scales



Planck CO(1-0) map
not visible to H.E.S.S.
SN 1006
HESS J0632+057
Crab
H.E.S.S. Survey
HEGRA Survey
VERITAS Survey
60
45
30
15
0
-15
-30
-45
-60
135
90
45
0
315
270
225
HGPS flux > 1 TeV (% Crab)
0.5
1.5
5
15
50
5
0
-5
60
40
20
0
340
320
300
280
260

Major topics

- origin of Galactic and Extragalactic Cosmic Rays

- physics and astrophysics of relativistic outflows (jets and winds)

- high energy processes at extreme conditions (e.g. close to BHs)

- cosmological issues - Dark Matter, Large Scale Structures., etc.

. . .

IACT arrays - high performance and great potential

- huge detection areas, potentially >> 1 km; photon statistics !
- good (~10 to 20%) energy resolution and
- good angular resolution: potentially down to 1-2 arcmin
- relatively large FoV (5 to 10 degree)

=> spectrometry, morphology, timing, surveys

- sensitivity for point-like sources: potentially down to 10^{-14} erg/cm^{2}s (impressive by standards of modern astronomical instruments!)

- energy coverage from 10 GeV to 100 TeV (4 decades!)

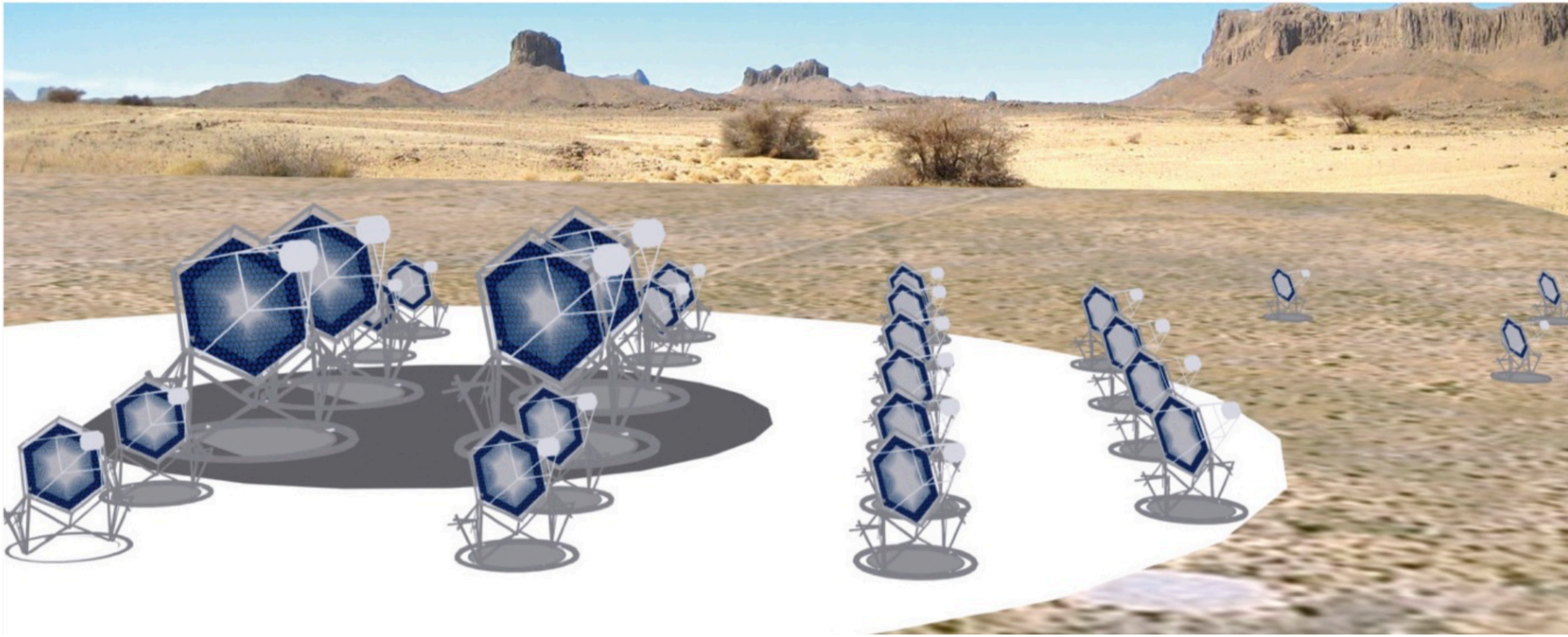
multi-functional tools:

✓ extended sources: from SNRs to Clusters of Galaxies

✓ transient phenomena μQSOs, AGN, GRBs, ...

Galactic Astronomy | Extragalactic Astronomy | Observational Cosmology

CTA - Cherenkov Telescope Array - natural successor of the current IACT arrays: quantity => quality



Beyond CTA

1. Substantial improvement of sensitivity at TeV energies?

only through *brute-force-approach* - by dramatic increase of number of telescopes N:

(i) intrinsic limit on PSF ~ 1-2 arcmin plus

(ii) operation in background dominated regime => $F_{min} \propto N^{-1/2}$

2. IACTs for GeV astronomy ?
   reduction of the threshold down to 10 GeV - feasible
   down to 1 GeV ? - in principle, yes, although very difficult

~1 GeV threshold IACT(s) - enormous scientific reward

10^{-8} erg/cm^{2}s fluxes plus $\geq 10^4$m^2 collection area =>
detection of strong GeV sources just for 1 sec

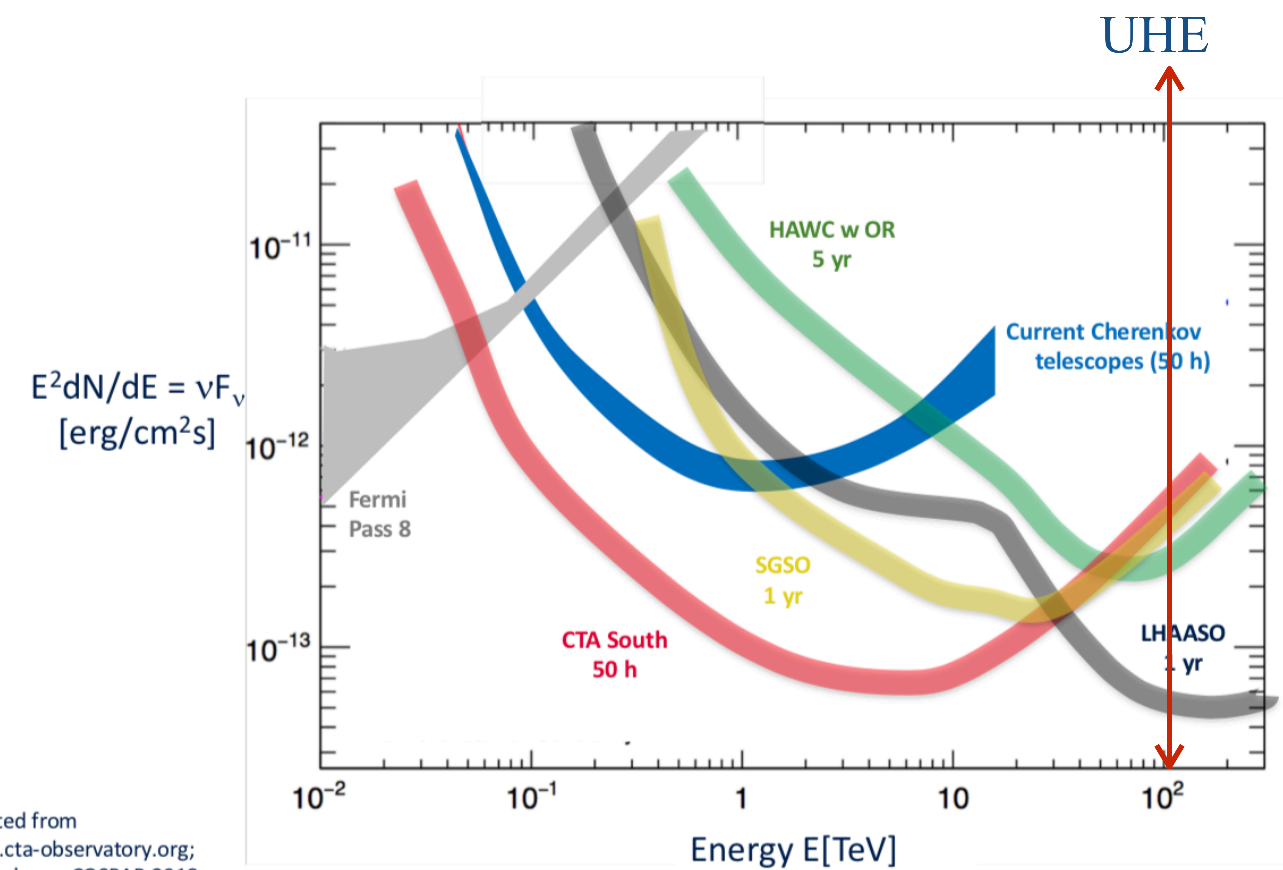
timing explorer for study of Pulsars, AGN, binaries, transients or solitary events (GRBs..)

3. Complementary to CTA: LAAASO's WCDA (completed!) and SWGO

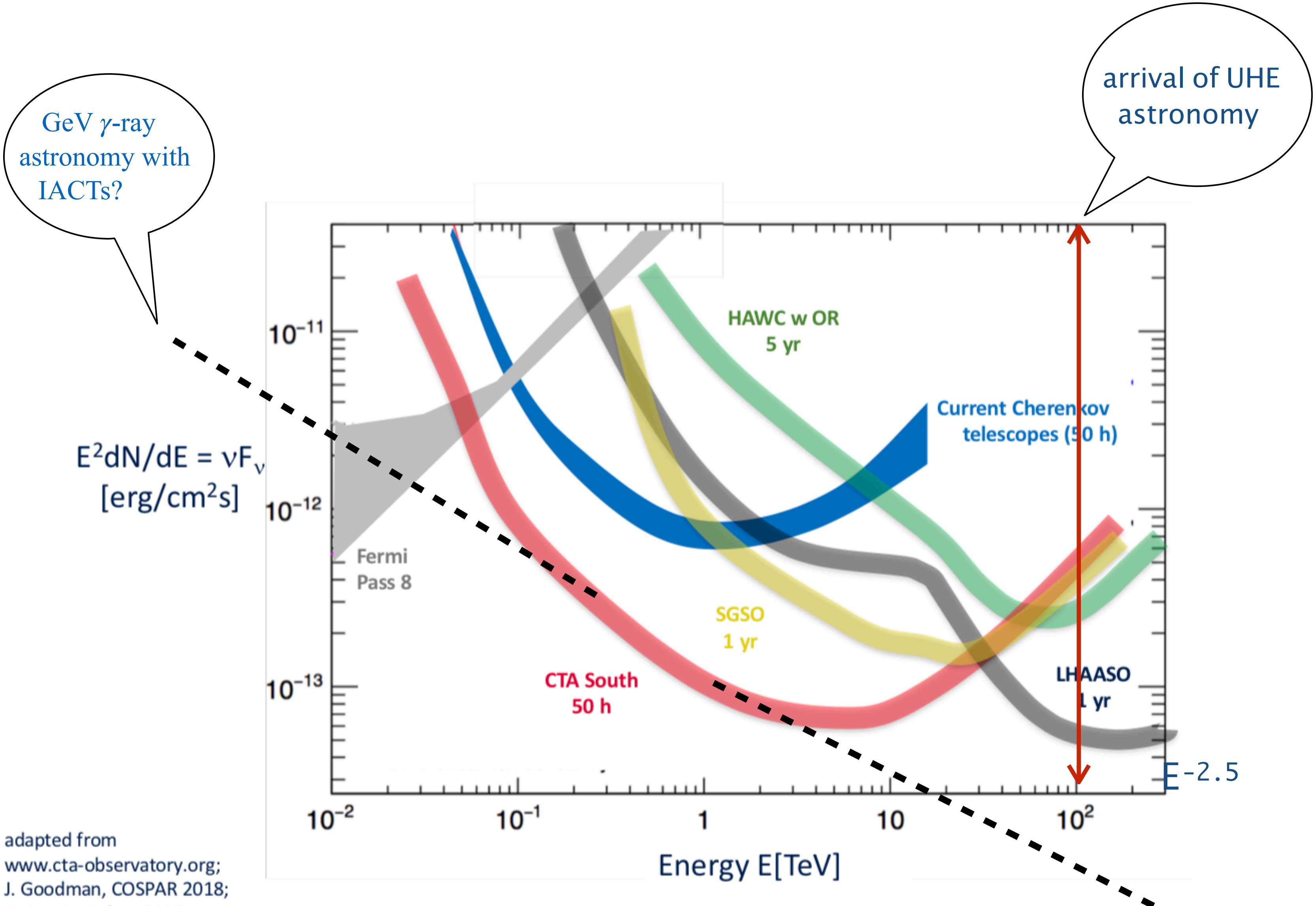
success of HAWC guaranties that WCDA and SWGO will complement CTA in Northern and Southern Hemispheres for surveys of the transient sky, dealing with very large structures, etc.

A GeV Cherenkov telescope?

arrival of UHE gamma-ray astronomy!



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



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VHE astronomy versus UHE astronomy

major factors for the success of VHE astronomy?

several factors… but basically thanks to the combination of two:

- great potential of the stereoscopic IACT technique
  predicted … although recognised with significant delay

- effective acceleration of multi-TeV particles on all astronomical scales coupled with favorable conditions for production of gamma-rays

detection of hundreds TeV-emitters sources representing more than 10 galactic and extragalactic source populations was a big surprise

Do we expect similar success in UHE domain?

detection techniques

1. IACTs: same approach as in TeV band but dramatically increased detection area

CTA: ~100 times larger collection area compared to HESS/Magic/VERITAS
also, dedicated multi-TeV IACT arrays in Norther Hemisphere?

(2) LHAASO, SWGO, HiSCORE

LHAASO is almost completed !

jump from the 1st generation (Tibet, HAWK) to 3rd generation

TAIGA-HiSCORE - multi-PeV detector

should we expect similar success in UHE domain?

Sources?

- *effective acceleration of electrons and protons to PeV energies?*

not trivial but possible for galactic sources SNRs, PWNe, Young Stars
easier for extragalactic objects but limited by Local Universe

- *effective gamma-ray production?*

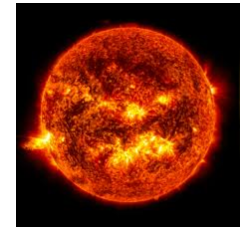
not always - fast escape of PeV particles, $t_{esc} \sim l/c << t_{cool}$
ballistic motion with non-trivial implications for radiation

Detections of > 100 TeV gamma-rays?

one of the highlights of gamma-ray astronomy over the last two years:
reports on >100 TeV γ-rays from Crab, J1825, J1908, …
by Tibet and HAWC - reliable but marginal detections

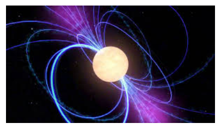
great expectations from LHAASO - stay tuned…

TeVatrons (!) and PeVatrons (?)



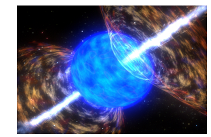
nonthermal processes in Universe proceed everywhere and on all astronomical scales:

Pulsars

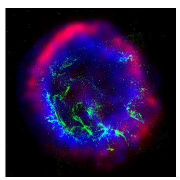


Binary Pulsars
Microquasars

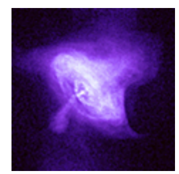
γ-ray Bursts



Supernova Remnants

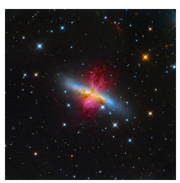


Pulsar Wind Nebulae

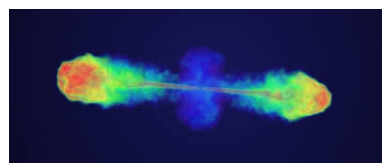


Massive Stars

Galaxies
Starburst Galaxies

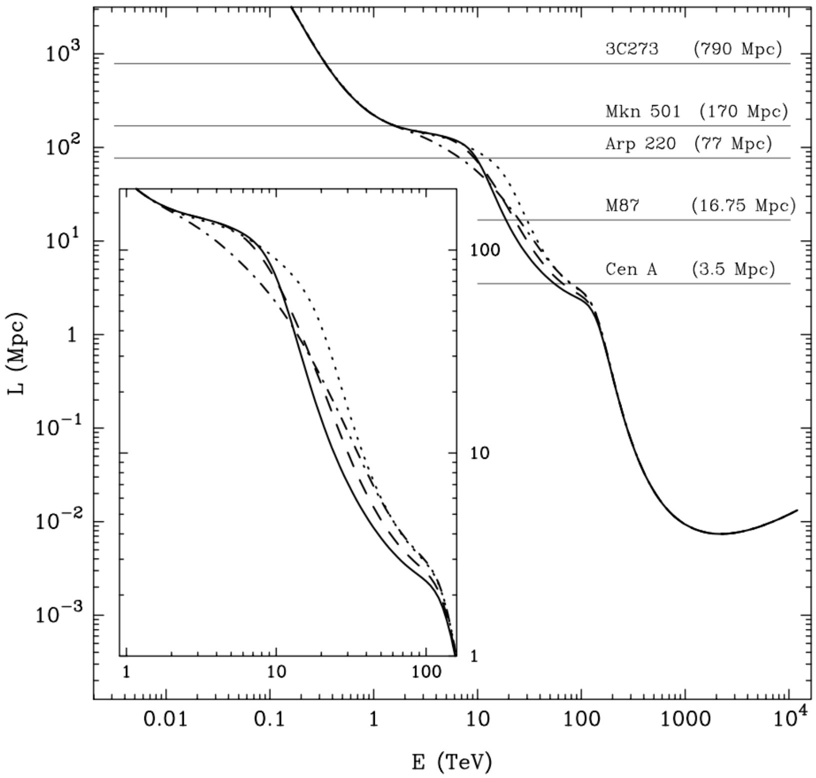


AGN Jets



GalaxyClusters

mean free path of gamma-rays in EBL+CMB



extragalactic sources at multi-TeV and UHE energies

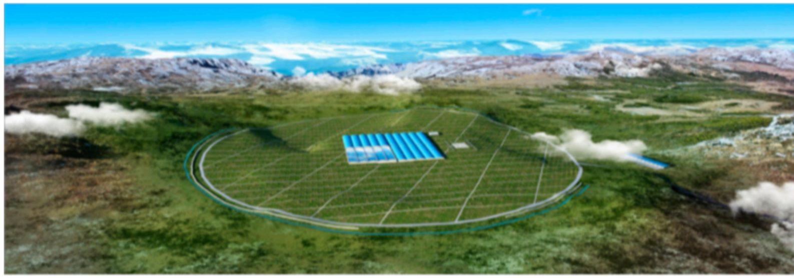
>10 TeV

- nearby blazers, Mkn 501,421,
- radiogalaxy M87,
- powerful SBGs like Arp220
- Clusters of Galaxies Coma, Perseus

E>100 TeV

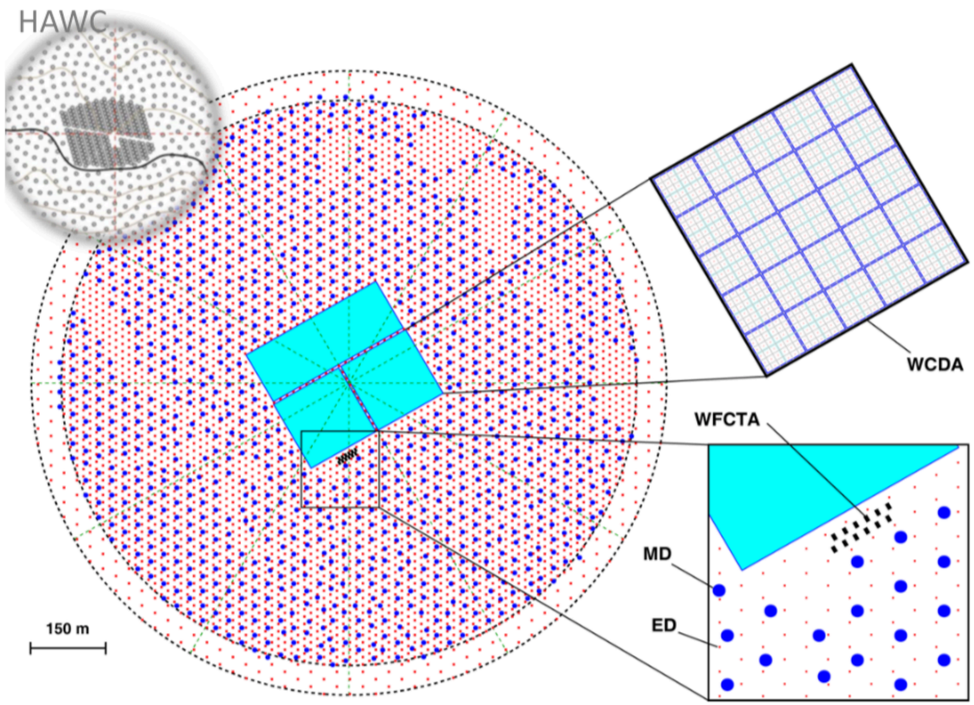
- starburst galaxies M82, NGC 253
- nearby radiogalaxy Can A
- Wind (100kpc) Halo
- Fermi Bubbles

$E_\gamma \sim 10$ TeV : $d \sim 100$ Mpc $E_\gamma \sim 100$ TeV : $d \sim 3$ Mpc $E_\gamma \sim 1 - 10$ PeV : $d \sim 10$ kpc



LHAASO

Sichuan, China, 4410 m asl



5195 Scintillators
- 1 m^2 each
- 15 m spacing

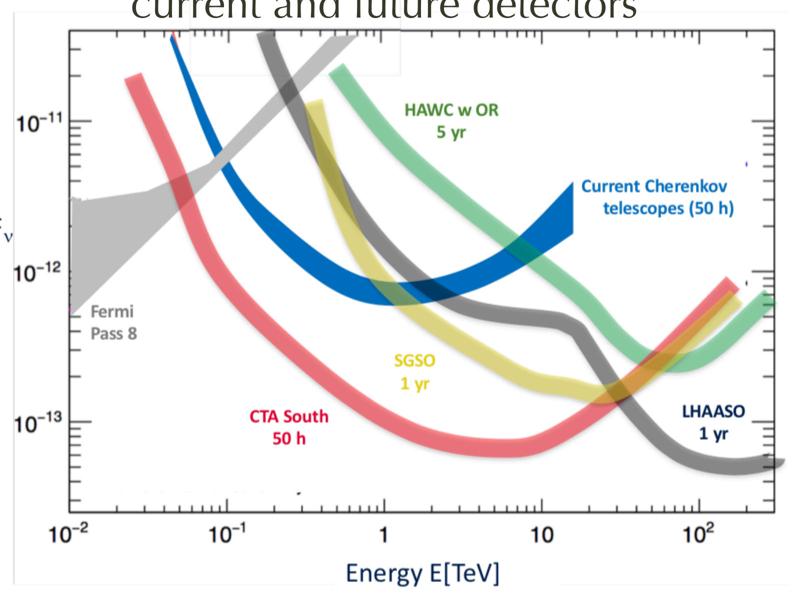
1171 Muon Detectors
- 36 m^2 each
- 30 m spacing

3000 Water Cherenkov Cells
- 25 m^2 each

12 Wide Field Cherenkov Telescopes

LHAASO - a PeVatron hunter

current and future detectors



adapted from
www.cta-observatory.org;
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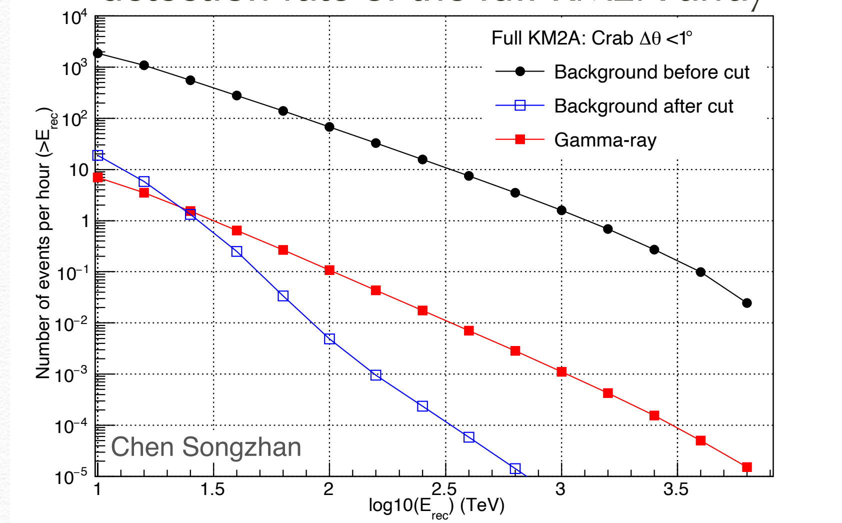
detection rate of the full KM2A array



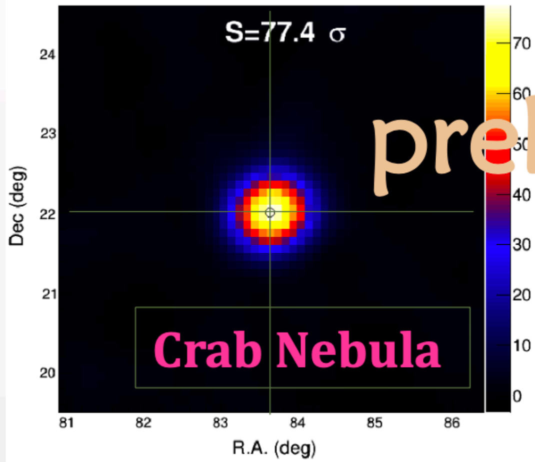
KM2A - PSF: 25′ at 20 TeV, 12′ at 100 TeV
KM2A - energy resolution better than 20%

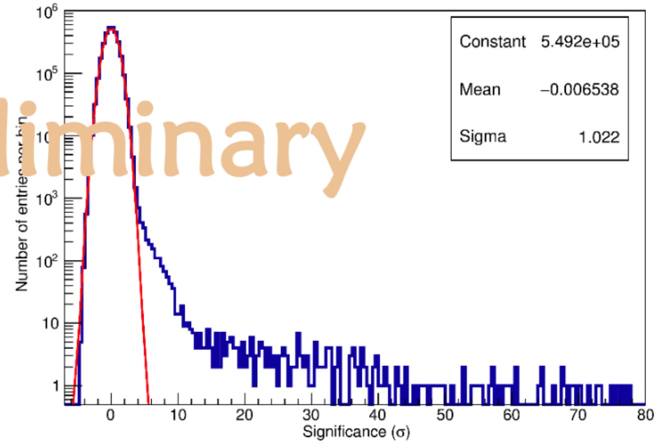
background-free detection of extended 1deg sources of >100 TeV gamma-rays of strength 0.1 Crab by KM2A with a rate 1 ph/100 h

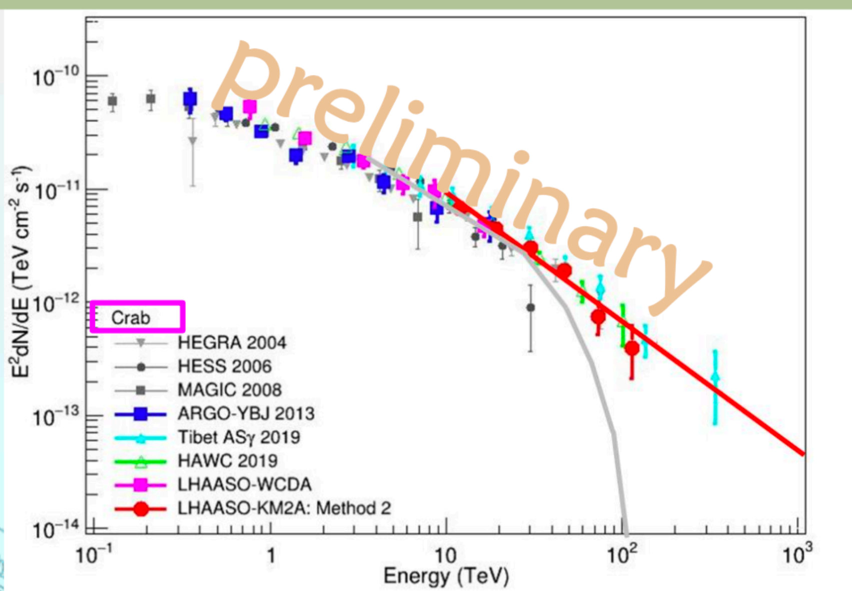
ideal to study diffuse gamma-ray emission of the galactic disk, Fermi Bubbles

Standard Candle for WCDA & KM2A

- **Up to March 2020**
- **Crab 77 σ (E>1 TeV) by WCDA-1**
- **Pointing error <0.1°**







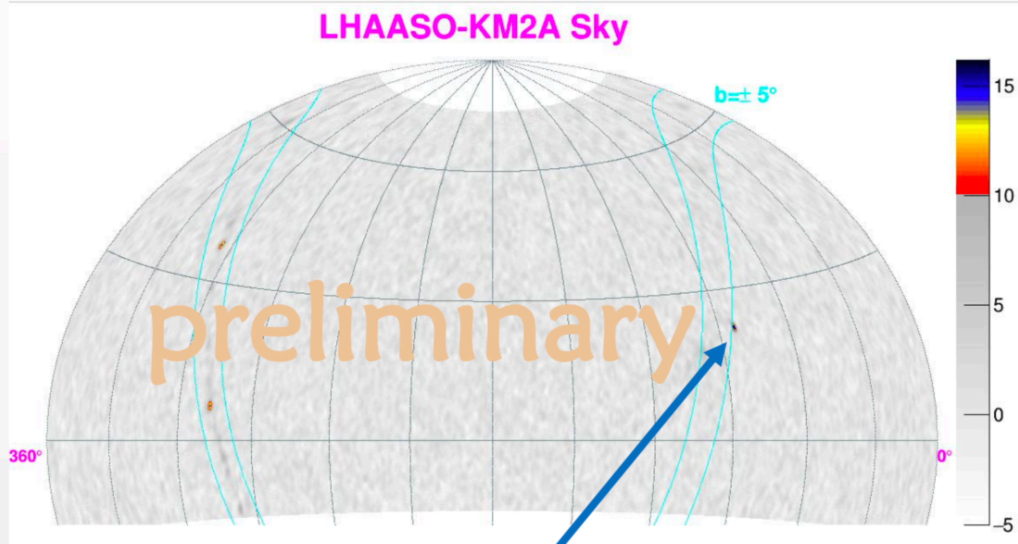
- Not only for the Crab Nebula
- All sources have clear power law spectra in UHE region
- no indication of cut-off
- Posting challenges to models with limits of accelerating power of galactic sources

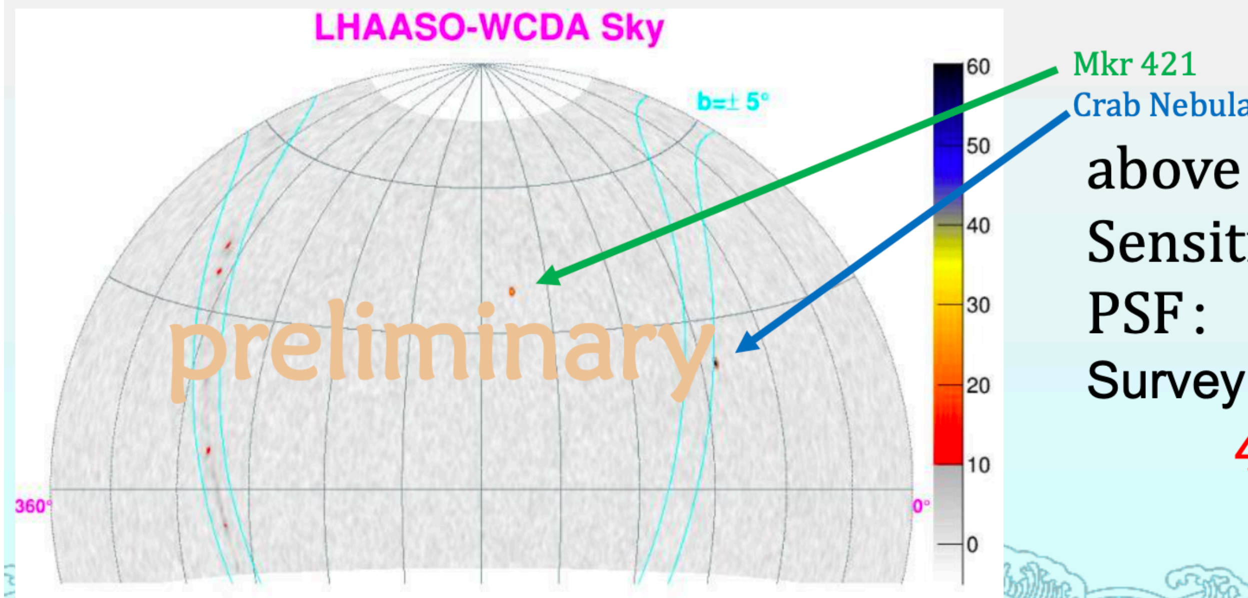
Zhen Cao

LHAASO: Full of PeVatrons in MW

LHAASO
高海拔宇宙线观测站

Below 10TeV by WCDA-1
Sensitivity: **60** mC.U.
PSF： **0.26°**
Survey for 300 days：
6 sources >10σ





above **100TeV** by KM2A-1/2
Sensitivity: **0.1 C.U.**
PSF： **0.26°**
Survey for 259 days：
4 sources >10σ

Zhen Cao

Summary

MeV Astronomy: great science; well justified and feasible proposals.
But it is not clear whether these projects could be realised (converted to Space Missions) in the near future

GeV Astronomy - great achievements. To continue success (beyond Fermi LAT) a new GeV significantly larger (effective area $\approx 10\text{m}^2$) space-borne gamma-ray space telescope is needed

TeV Astronomy - great achievements. CTA - right choice for future - feasible, but should move towards realisation faster.
WCDA and SWGO - complementary to CTA detectors

PeV Astronomy - LHAASO - "detector from future operating now" ; promises discoveries in several topical areas of Astrophysics and Astroparticle Physics.
It is likely that 2020s will be years of LHAASO