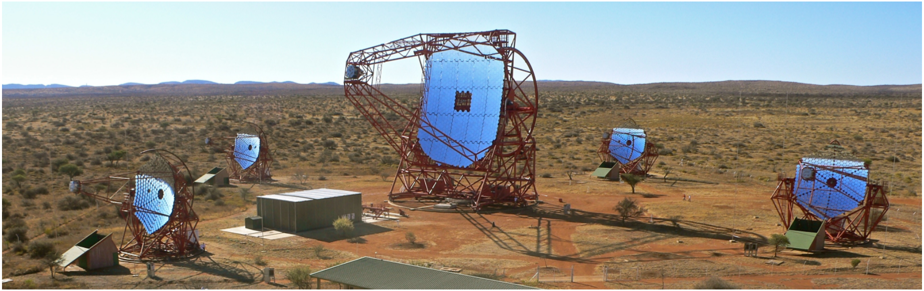
Experimental study of VHE gamma emission with IACTs.



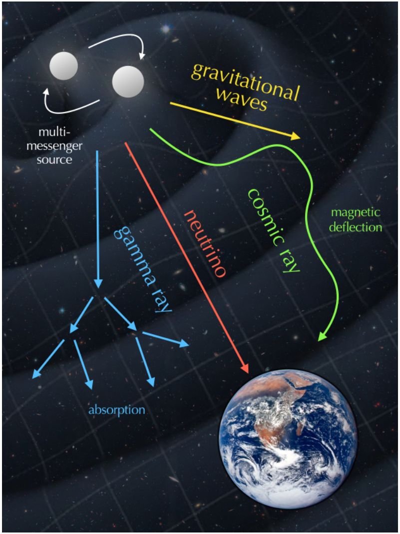
D. Kostunin

SAI seminar, Moscow 2019

HELMHOLTZ | GEMEINSCHAFT

DESY.

Multimessenger astronomy



Hadronic reactions

$pp \to \pi^0 \ldots \to \gamma\gamma \ldots$

$pp \to \pi^{\pm} \ldots \to \mu\nu \ldots \to e\nu_e\nu_\mu\nu_\mu \ldots$

Photo-hadronic reactions

$p\gamma \to \Delta^+ \to p\pi^0 \to p\gamma\gamma$

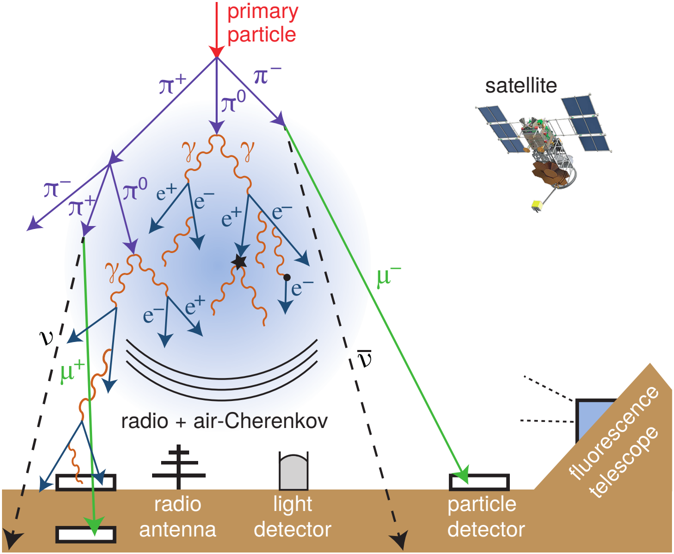
$p\gamma \to \Delta^+ \to n\pi^+ \to n\mu\nu_\mu \to ne\nu_e\nu_\mu\nu_\mu$

ν(1 PeV) $\leftrightarrow$ (20 PeV) $\leftrightarrow$ γ(2 PeV)

Gamma-production processes

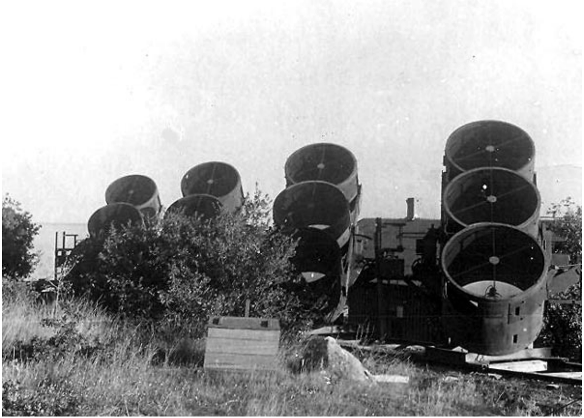
- Synchrotron
- Inverse compton
- Hadronic

Air showers



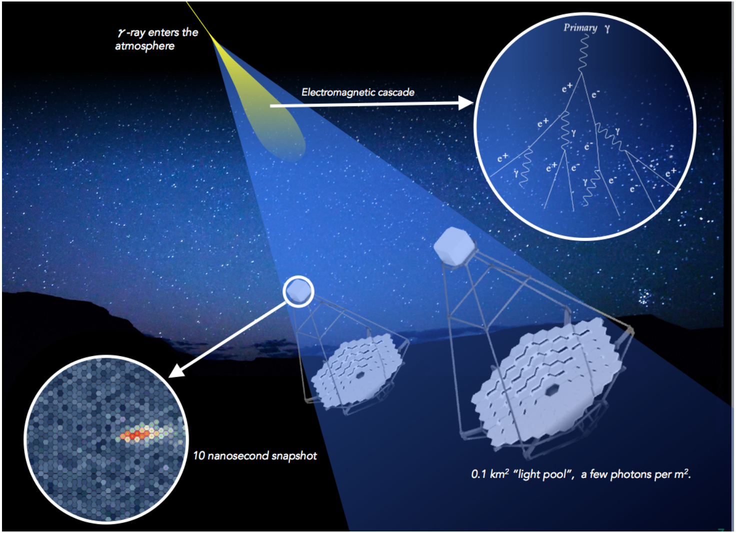
primary particle
π+
π0
π−
satellite
γ
γ
π−
π+
π0
e+
e−
e+
e−
γ
e−
e+
e−
μ−
ν
ν̄
μ+
radio + air-Cherenkov
fluorescence telescope
radio antenna
light detector
particle detector

First experiments with air-shower Cherenkov

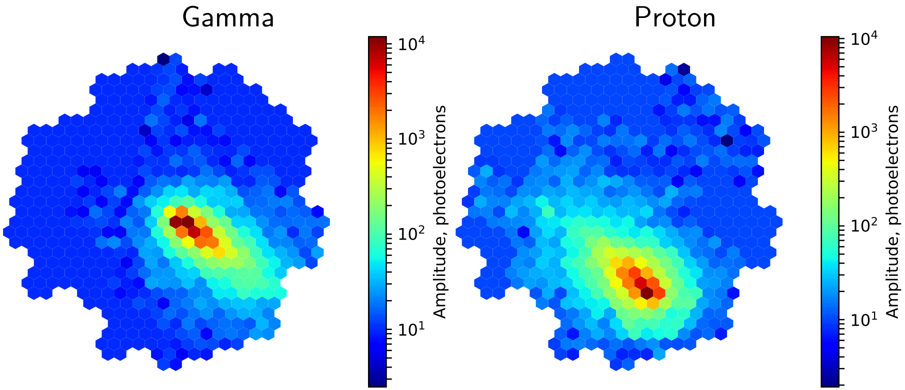


Left: Experiment by Galbraith & Jelley (discovery of air-Cherenkov light in 1952)
Right: First telescope by Chudakov & Zatsepin in Crimea (1959-1964)

Principle of IACT detection

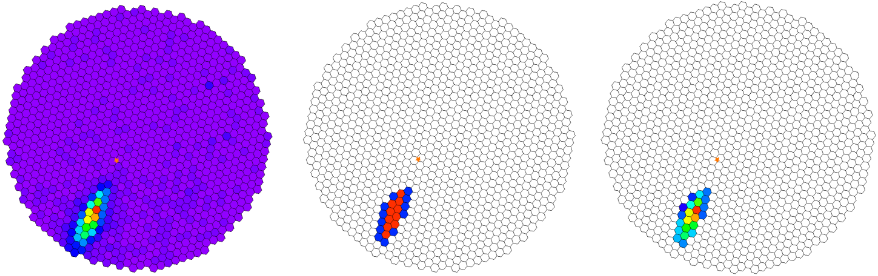


Event reconstruction



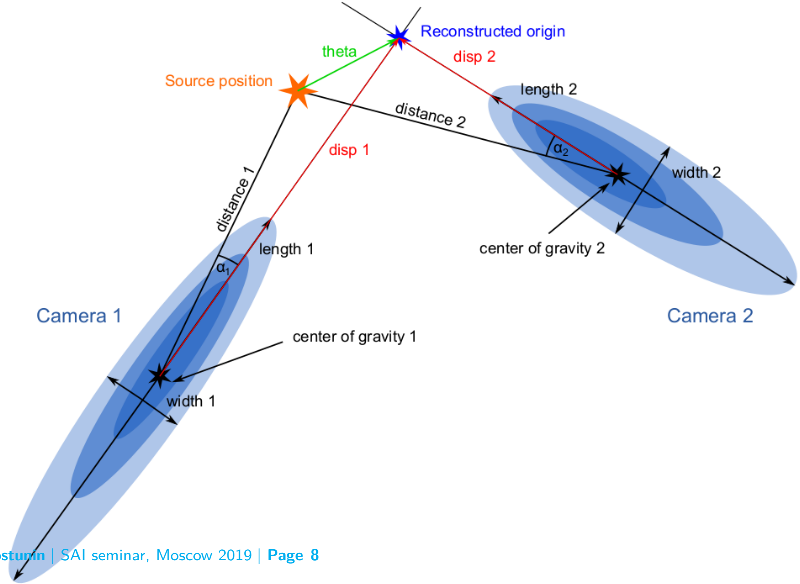
- Image cleaning
- Fitting of Hillas parameters
- Cuts/MWA/Templates/etc for gamma/hadron separation

Image cleaning

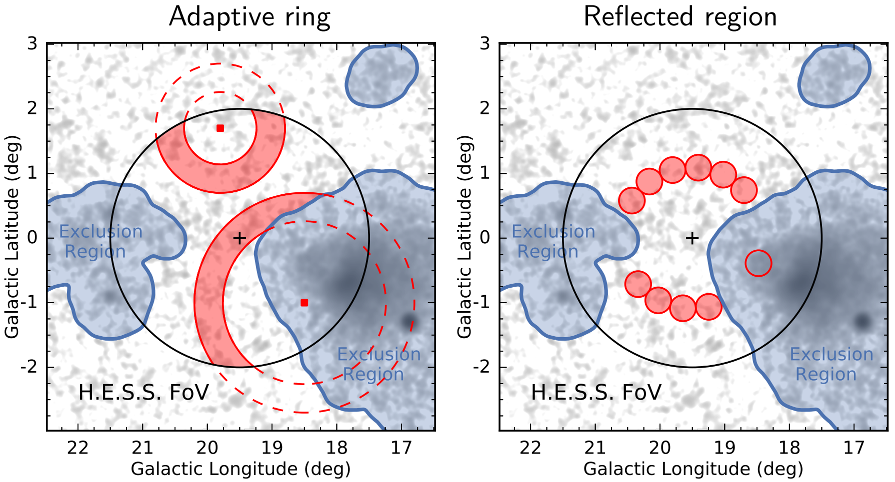


calibrated image | core and boundary | cleaned image

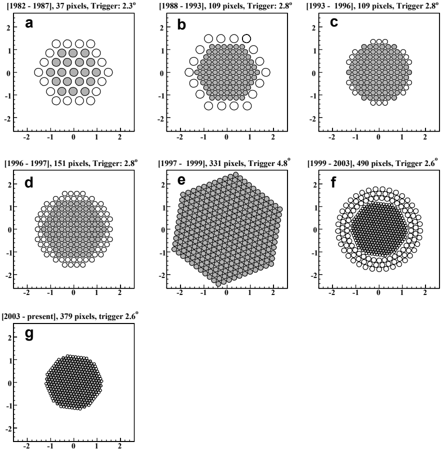
Direction reconstruction



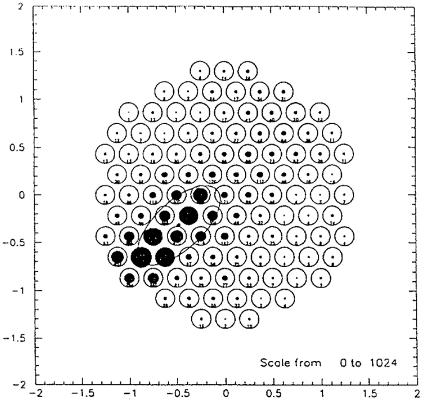
Background estimation

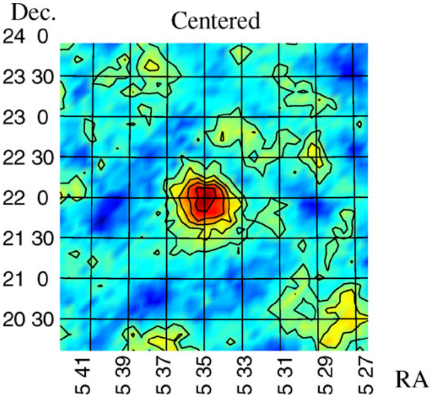


Whipple Telescope



Discovery of Crab in TeV (1989)





Very Energetic Radiation Imaging Telescope Array System (VERITAS)

4 telescopes with 12-m reflectors

$31°40'30''$ N $110°57'07''$ W, 1268 m a.s.l.

Arisona, USA

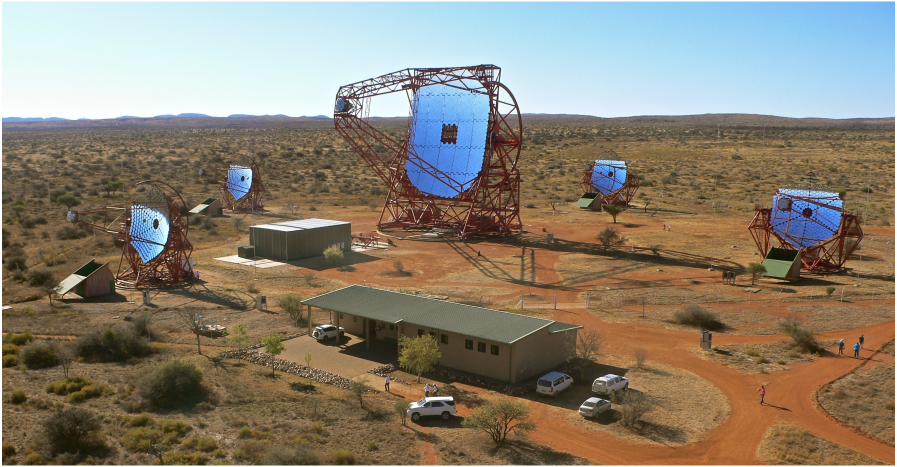
Major Atmospheric Gamma Imaging Cherenkov Telescopes (MAGIC)

2 telescopes with 17-m reflectors

$28°45'43''$ N $17°53'24''$W, 2200 m a.s.l.

La Palma (Canarian islands, Spain)

High Energy Stereoscopic System (H.E.S.S.)

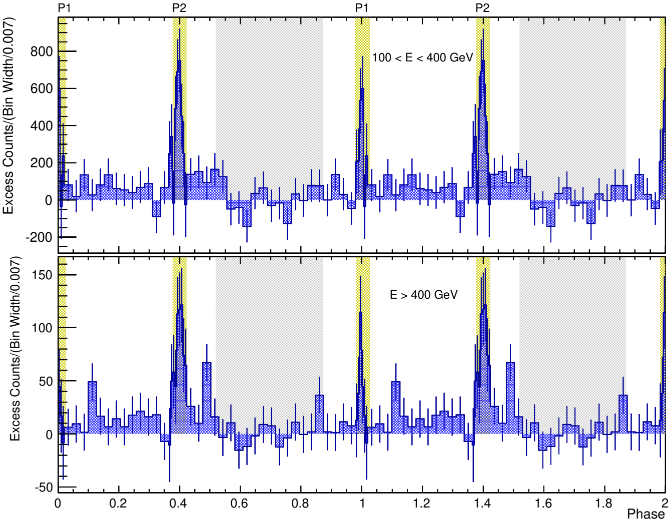


4 telescopes with 12-m reflectors

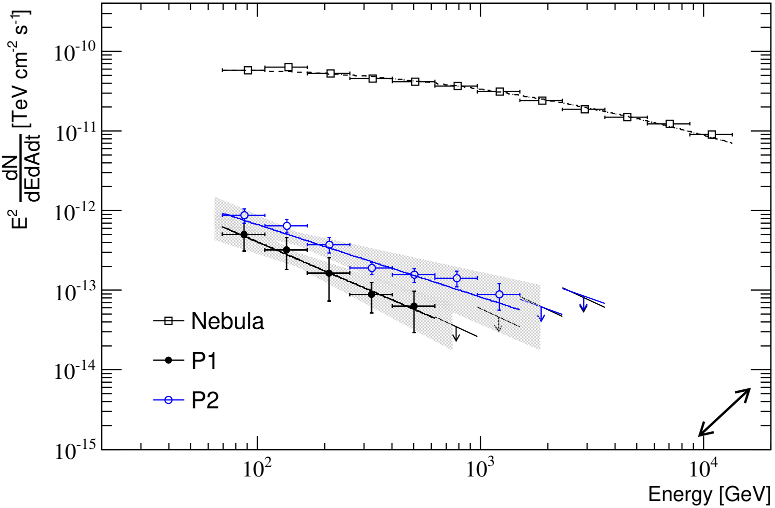
1 telescopes with 28-m reflector

$23°16'17''$ S $16°30'00''$ E, 1800 m a.s.l, Namibia

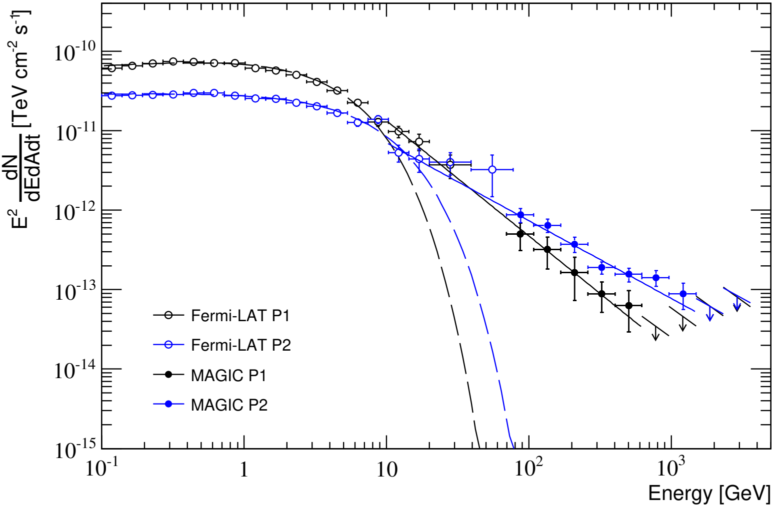
Crab pulsation with MAGIC



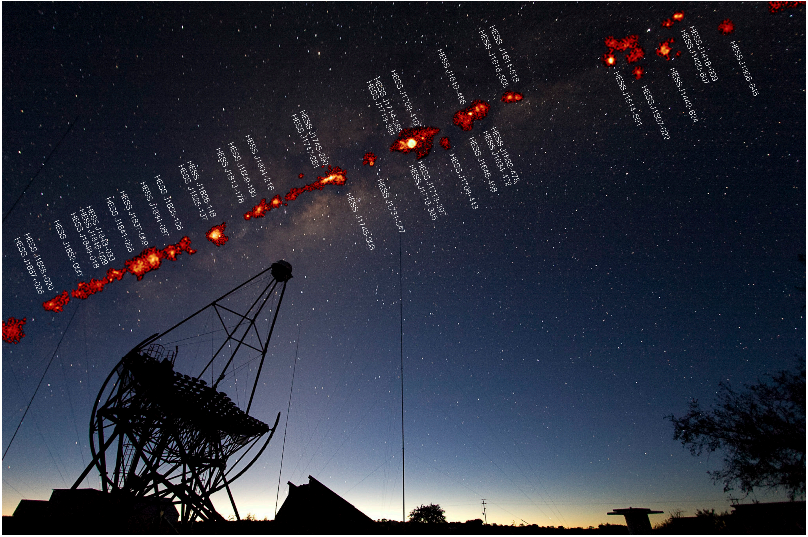
Crab pulsation with MAGIC



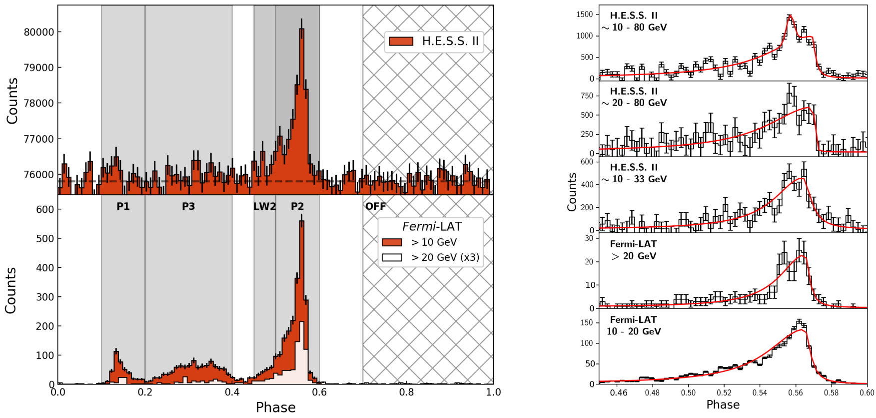
Crab pulsation with MAGIC



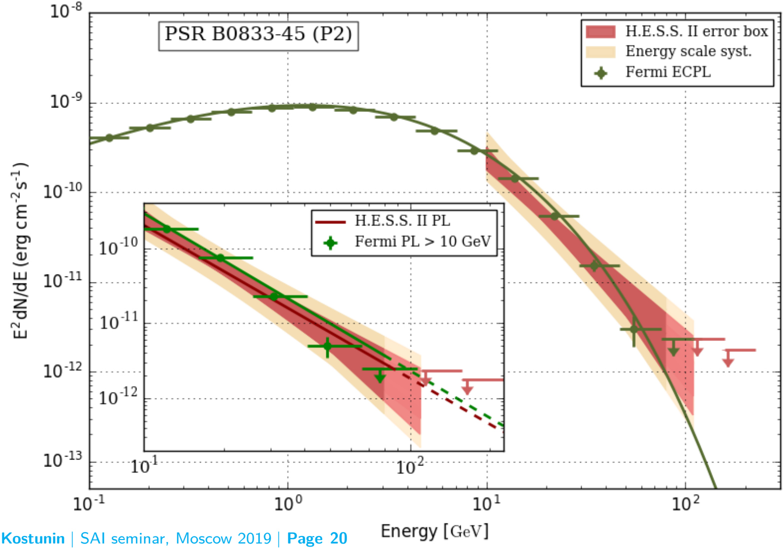
Galaxy seen by H.E.S.S.



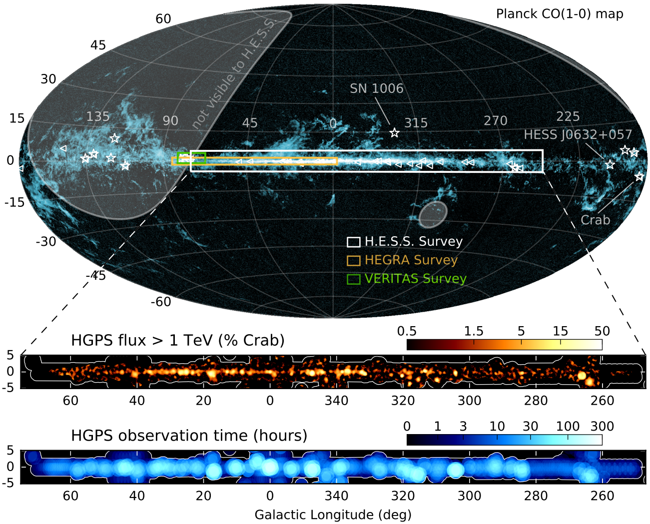
Vela pulsation with H.E.S.S



Vela pulsation with H.E.S.S

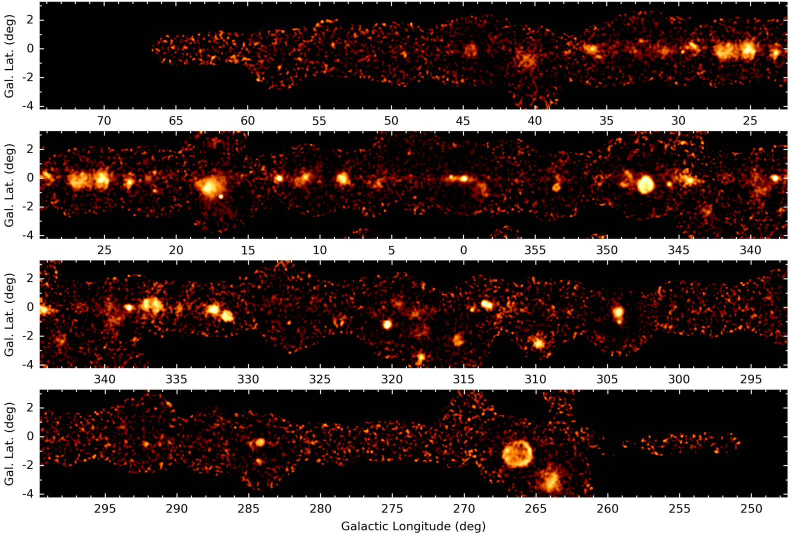


H.E.S.S. Galactic Plane Survey (HGPS)

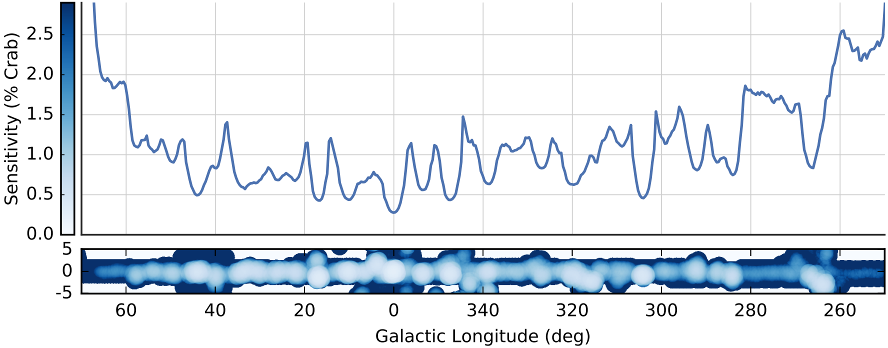


https://www.mpi-hd.mpg.de/hfm/HESS/hgps/

H.E.S.S. Galactic Plane Survey (HGPS)



HGPS sensitivity



PWN identification

- Morphology
- Position
- Containment
- Counterparts

PWN quantities

From 2D Gaussian fit

- Source position
- Source extension (σ)

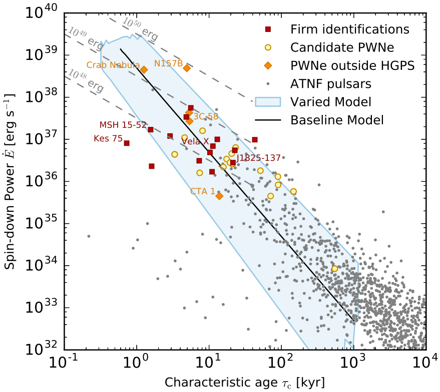
From power-law fit of spectrum $\phi_0 \times (E/E_0)^{-\Gamma}$

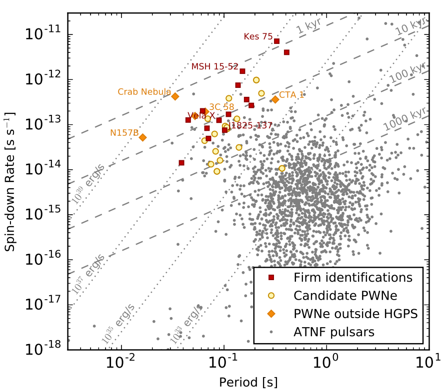
- Integral flux > 1 TeV
- Spectral index Γ

The luminosity is estimated as

$$L_{1-10\,\mathrm{TeV}} = 1.92 \times 10^{44} \frac{I_{>1\,\mathrm{TeV}}}{\mathrm{cm}^{-2}\mathrm{s}^{-1}} \frac{\Gamma - 1}{\Gamma - 2} \left(1 - 10^{2-\Gamma}\right) \left(\frac{d}{\mathrm{kpc}}\right)^2 \,\mathrm{erg\,s}^{-1},$$

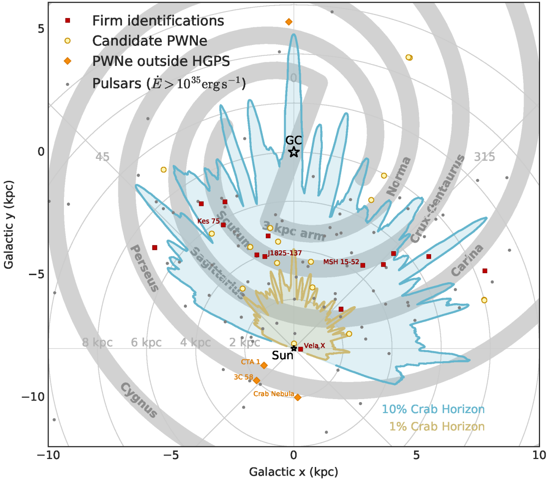
Power and age of PWN pulsars

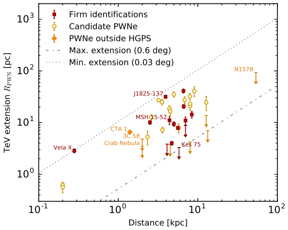


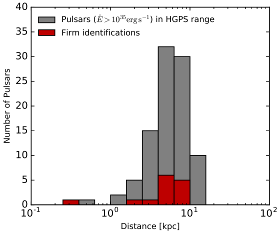


Candidate PWNs are older that established ones $\Rightarrow$
have no detectable X-ray conterparts

HGPS sensitivity & identified PWN





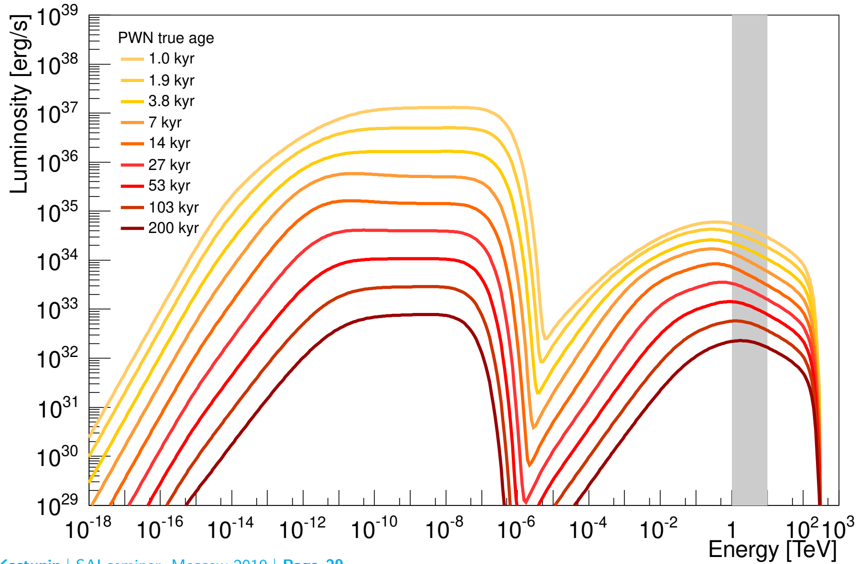


H.E.S.S. angular resolution $\approx 0.03°$, FOV $\approx 5°$

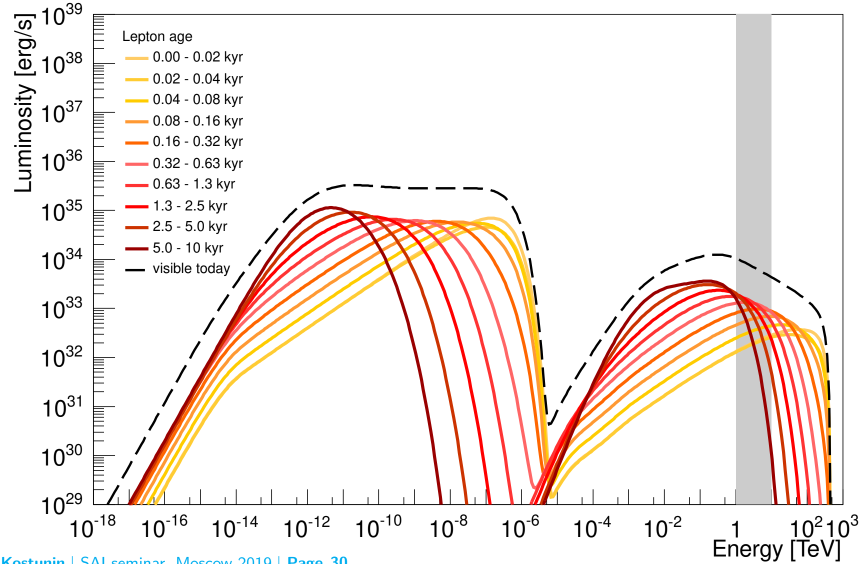
Modeling

Parameter description			Parameter values	
			baseline model	varied model
Braking index	n		3.0	2.5 . . . 3.5
Initial spin-down power	$\dot{E}_0$	$(10^{39}\,\mathrm{erg\,s^{-1}})$	2.0	1.0 . . . 4.0
Initial spin-down timescale	τ_0	$(\,\mathrm{kyr})$	0.5	0.32 . . . 0.77
Initial magn. field strength	B_0	(μG)	200	110 . . . 270
Reverse shock interaction timescale	t_{rs}	$(\,\mathrm{kyr})$	4.0	4.0 . . . 8.0
PWN radius at $t = 3\,\mathrm{kyr}$	R_3	(pc)	6.0	3.0 . . . 12.0
Adopted const. ISM magn. field strength	B_{ISM}	(μG)	3.0	3.0
Lepton conversion efficiency	η		1.0	1.0
Index of magn. field evolution	α		0.6	0.6
Index of lepton injection spectrum	β		2.0	1.75 . . . 2.25
Lower bound of lepton energy distribution	E_{min}	(TeV)	0.03	0.03
Upper bound of lepton energy distribution	E_{max}	(TeV)	300	300

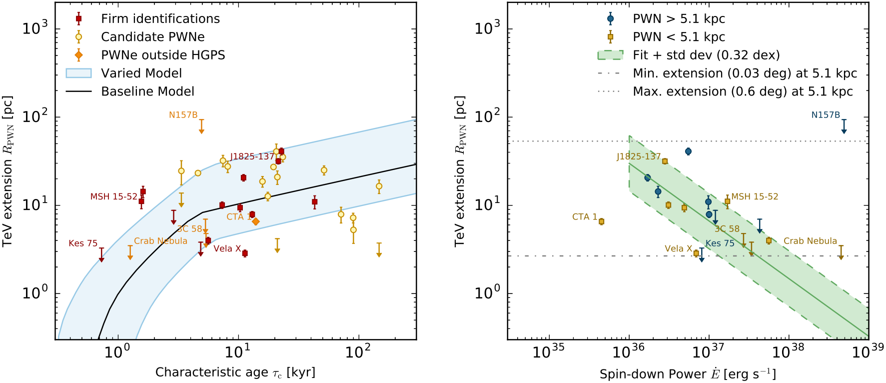
PWN evolution



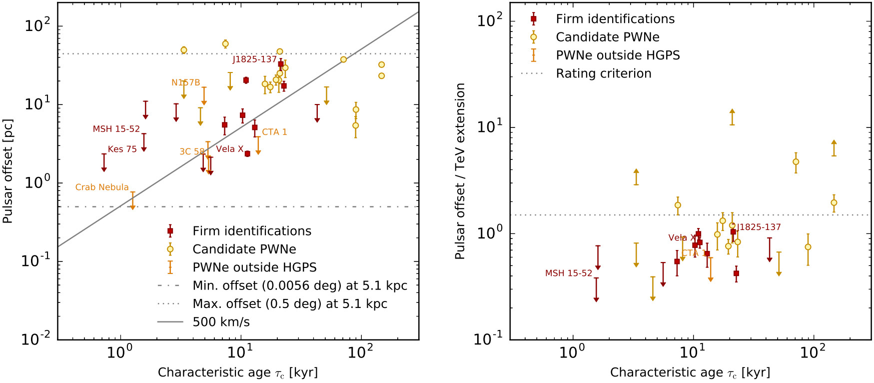
PWN composition (10 kyr age)



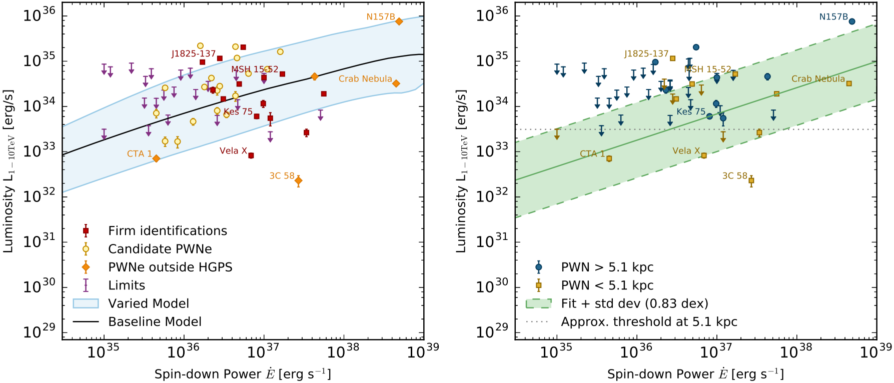
PWN extension



PWN-TeV offset & containment

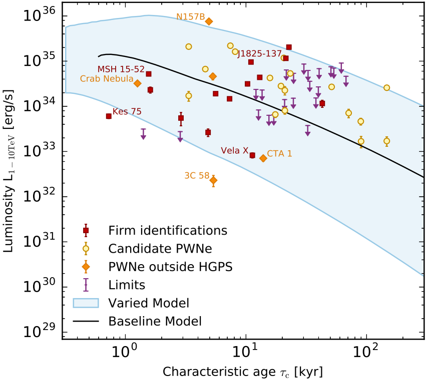


Luminosity

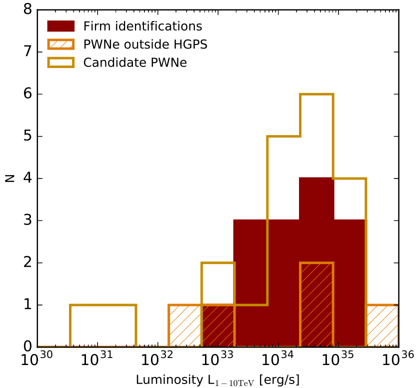


Luminosity L 1−10TeV [erg/s]
Spin-down Power Ė [erg s−1]
N157B
J1825-137
MSH 15-52
Crab Nebula
Kes 75
CTA 1
Vela X
3C 58
Firm identifications
Candidate PWNe
PWNe outside HGPS
Limits
Varied Model
Baseline Model
PWN > 5.1 kpc
PWN < 5.1 kpc
Fit + std dev (0.83 dex)
Approx. threshold at 5.1 kpc

Luminosity

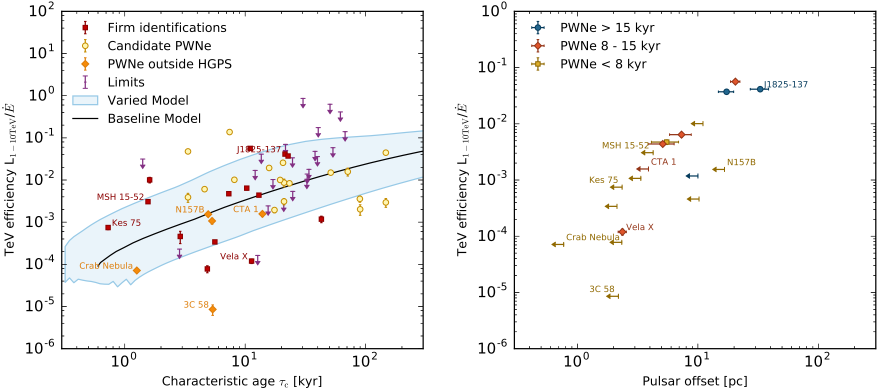


N157B
J1825-137
MSH 15-52
Crab Nebula
Kes 75
Vela X
CTA 1
3C 58
Firm identifications
Candidate PWNe
PWNe outside HGPS
Limits
Varied Model
Baseline Model
Luminosity $L_{1-10\mathrm{TeV}}$ [erg/s]
Characteristic age τ_c [kyr]

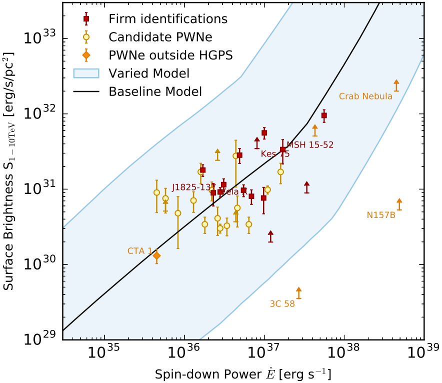


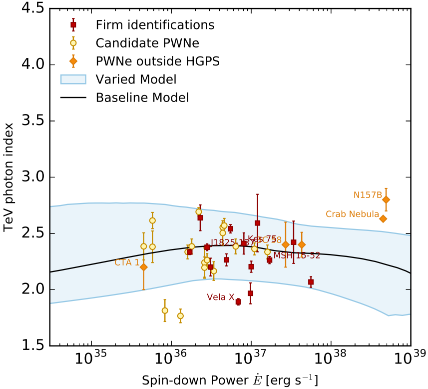
Firm identifications
PWNe outside HGPS
Candidate PWNe
N
Luminosity $L_{1-10\mathrm{TeV}}$ [erg/s]

TeV efficiency

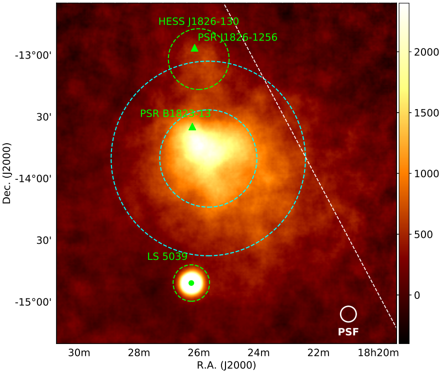


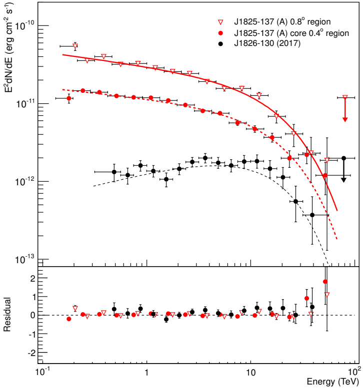
Surface brightness & photon index





HESS J1825-137

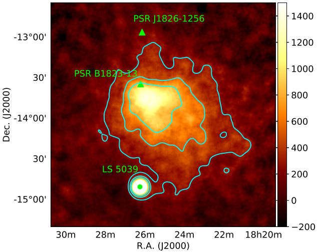


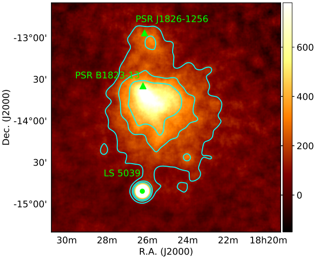


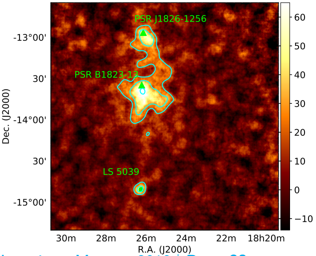
doi:10.1051/0004-6361/201834335

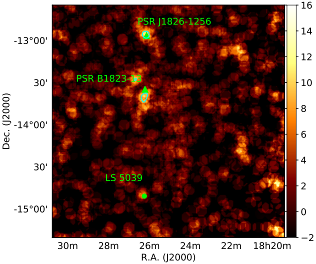
Excess count maps

Enegy bins: $E < 1$ TeV, $1 < E < 10$ TeV, $E > 10$ TeV, $E > 32$ TeV

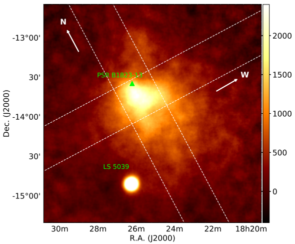


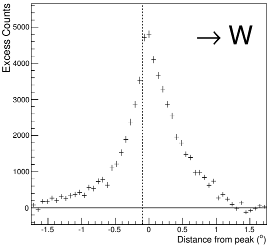


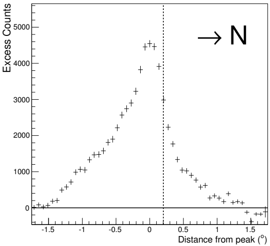


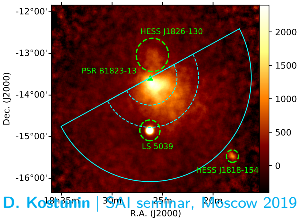


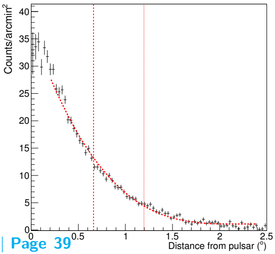
Nebula extent

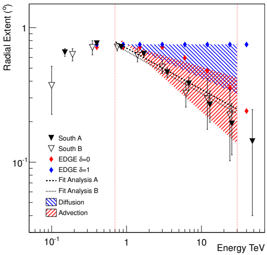






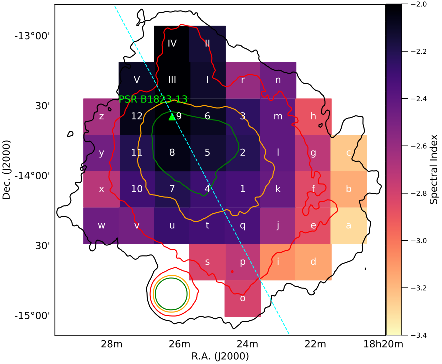


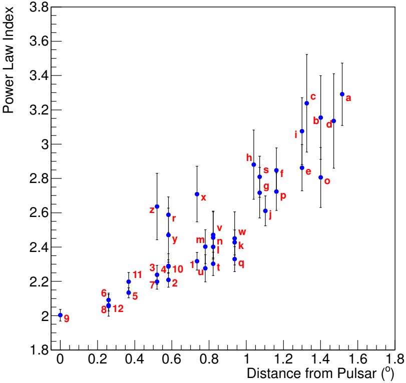




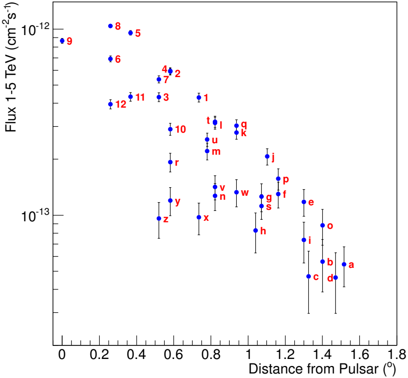
Emission index

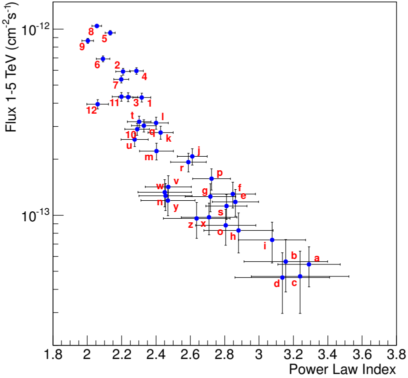
Independent spectral analysis for 38 boxes $0.26° \times 0.26°$



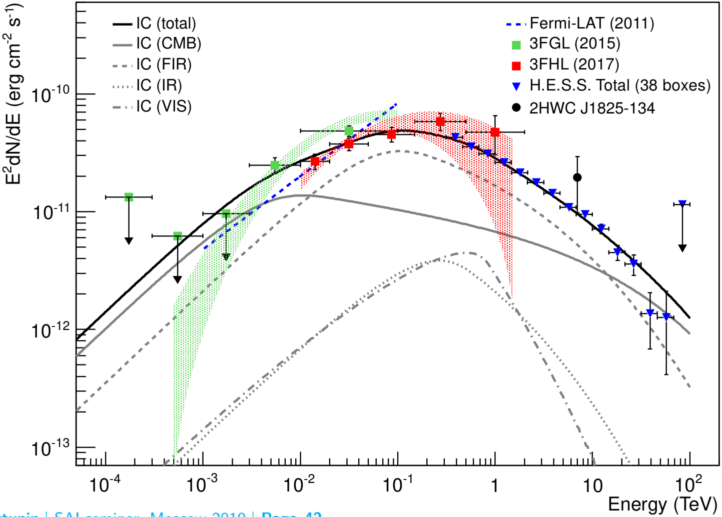


Flux analysis





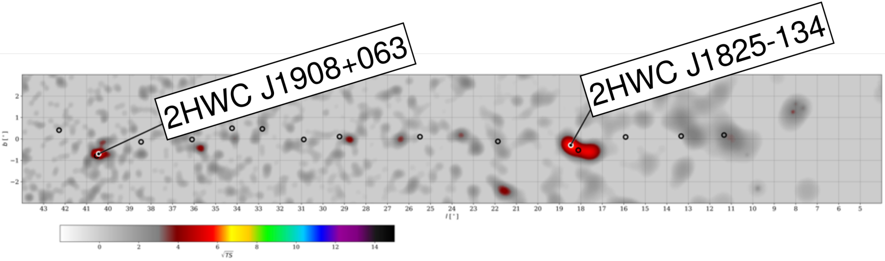
Total nebula spectrum



Another interesting example: J1908+063

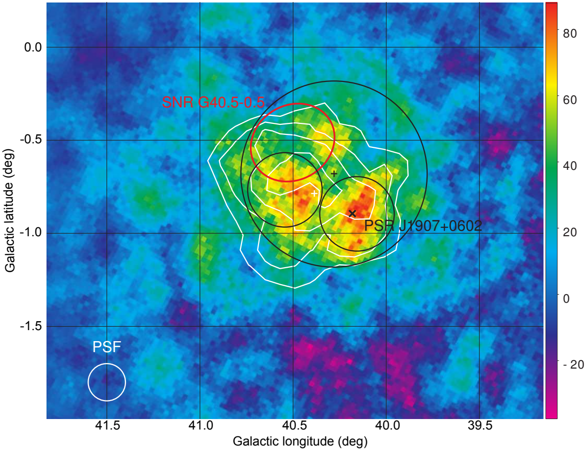
First detection with IACTs by H.E.S.S. in 2008

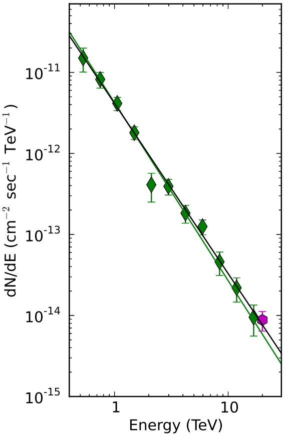
- One of two HAWC sources with E>100 TeV
- (Second) Best p-value (0.32%) for IceCube point search
- association of SNR with PSR / PWN hypotethis ?



On TeVPa2018 HAWC collaboration has presented
gamma detection with $E > 100$ TeV
associated with 2HWC J1908+063 and HESS J1908+063

VERITAS observation (2014)





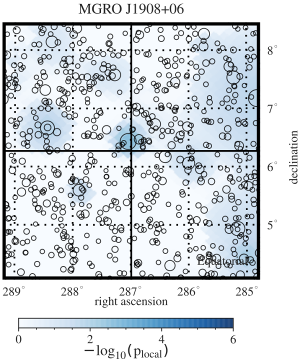
doi:10.1088/0004-637X/787/2/166

HGPS paper

“A plausible cause for these discrepancies is that this is a large source likely composed of multiple components, where results are expected to be sensitive to the morphology assumptions and to details in background modeling techniques, in particular, if those tend to absorb large-scale features.”

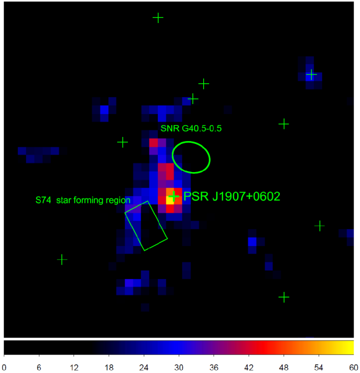
Neutrino point-like search

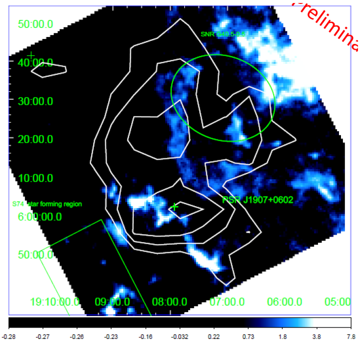
Telescope	# cand.	Flux upper limit (10^{-9} GeV cm^{-2} s^{-1})	TS	Ref.
ANTARES	-	12.2	-	1706.01857
IceCube	-	0.762	4.7933	1811.07979
GVD	0 (casc.)	-	-	internal forum



Fermi-LAT results by Jian Li @ TeVPA2018

Fermi-LAT analysis of off-peak emission



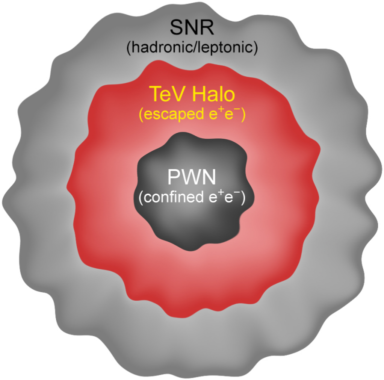


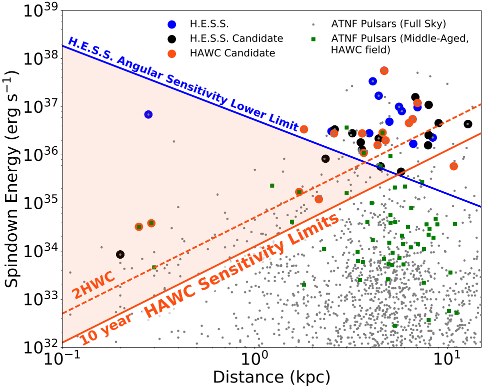
https://indico.desy.de/indico/event/18204/session/10/contribution/137
CO maps (blue) are from Milky Way Imaging Scroll Painting (proprietary)
White contours are from VERITAS map

?

TeV halos

Old pulsars ($\tau_c > 100$ kyr) produce $O(1^\circ)$ TeV emission: Geminga $\tau_c = 342$ kyr
$\Rightarrow$ hard to detect with IACT: narrow-FoV, complicated background estimation

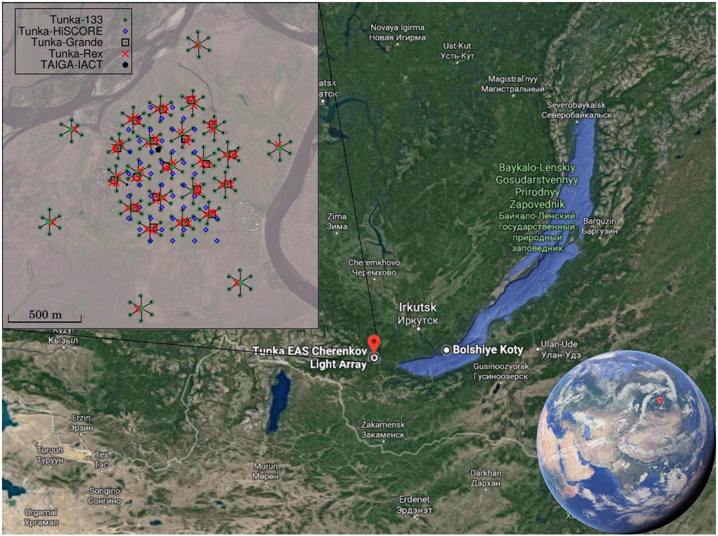




- Cross-check of HAWC UNID sources and MAGIC/H.E.S.S. reconst.
- Improving background estimation for IACT
- Non-imaging detectors for investigation of TeV halos

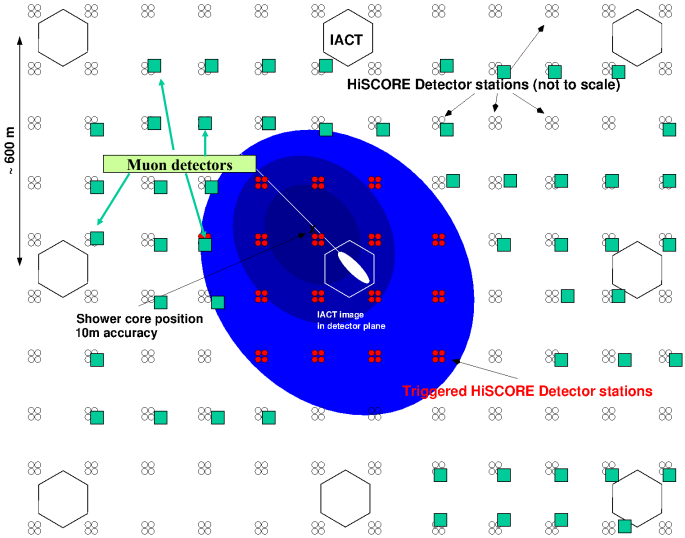
Tunka Advanced Instrument for cosmic rays and Gamma Astronomy (TAIGA)

Location



Tunka-133
Tunka-HiSCORE
Tunka-Grande
Tunka-Rex
TAIGA-IACT
500 m
Novaya Igirma
Новая Игирма
Ust-Kut
Усть-Кут
Magistral'nyy
Магистральный
Severobaykalsk
Северобайкальск
Baykalo-Lenskiy Gosudarstvennyy Prirodnyy Zapovednik
Байкало-Ленский государственный природный заповедник
Barguzin
Баргузин
Zima
Зима
Cheremkhovo
Черемхово
Irkutsk
Иркутск
Tunka EAS Cherenkov Light Array
Bolshiye Koty
Ulan-Ude
Улан-Удэ
Gusinoozyorsk
Гусиноозерск
Kyzyl
Кызыл
Erzin
Эрзин
Turuun
Туруун
Tes
Тэс
Songino
Сонгино
Urgamal
Ургамал
Murun
Мөрөн
Zakamensk
Закаменск
Darkhan
Дархан
Erdenet
Эрдэнэт

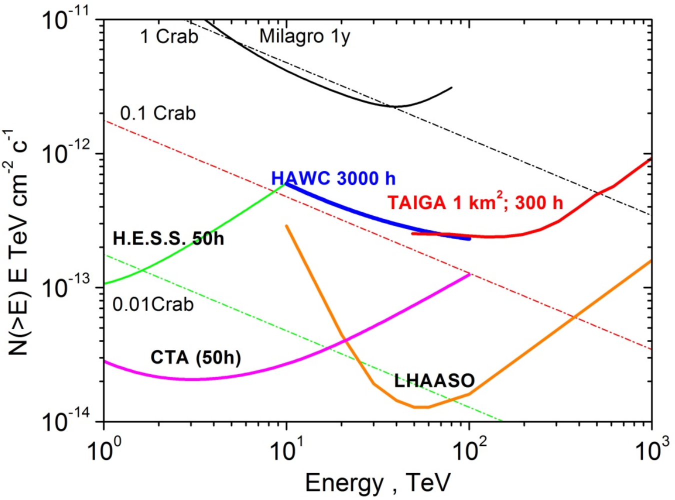
TAGA concept



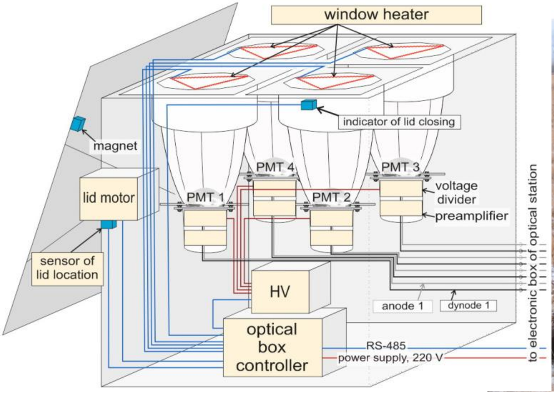
TAIGA objectives

- search for galactic sources of gamma-quanta with energies higher then 20 TeV
- studies of gamma-radiation fluxes from known sources in the energy range of higher than 20 TeV at the recorded level of sensitivity
- studies of high energy part of gamma radiation spectrum from the most bright blazars with aim to study gamma-quanta absorption on intergalactic background radiation (infrared and microwave) and search for axion-photon transitions
- search for possible violations of Lorenz-invariance and axion-photon transitions which in new approach to search of dark matter in the Universe

TAIGA sensitivity



TAIGA-HiSCORE design



Each station is equipped with four PMTs inside Winston cones

TAIGA-HiSCORE design

Each station is tilted towards galaxy/Crab nebula to increase the exposure

TAIGA-IACT design

HEGRA-like telescope with the following properties:

Camera

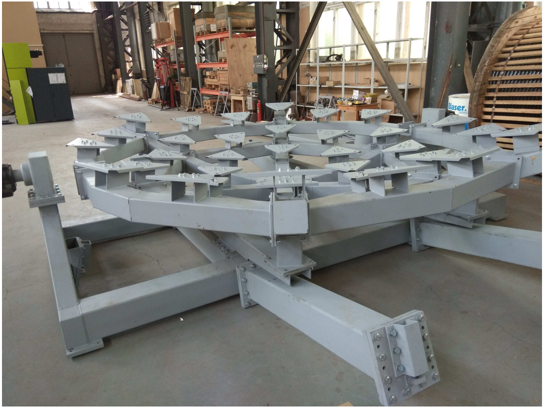
- 547 hexagonal-shaped pixels
- PMT XP1911 with size of 3/4" (19 mm) + Winston cone
- FOV of single pixel: 0.36°
- Full FOV: 9.72°

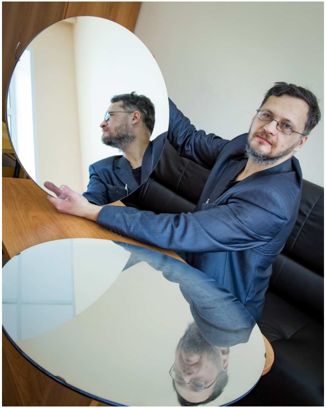
Mirror

- Davies-Cotton design
- Focal length: 4750 mm
- 34 spherical mirror segments
- Diameter of each segment: 60 cm
- Diameter of the mirror: 4.3 m

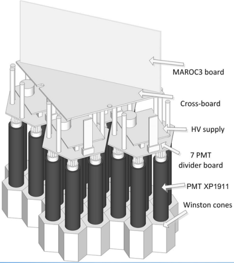
Mechanics and mirror production

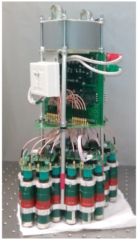
Workshop at LNP JINR, Dubna



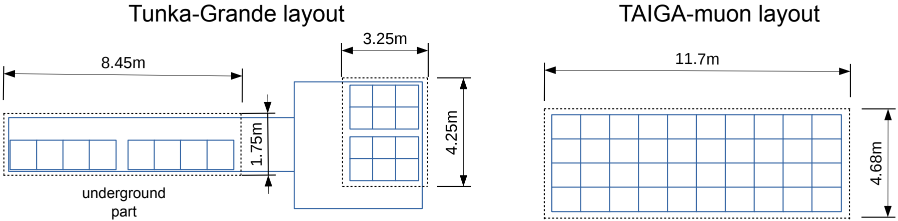


Camera design and installation





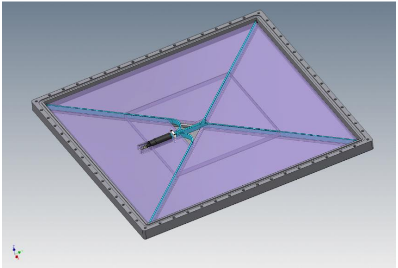
TAIGA-muon concept

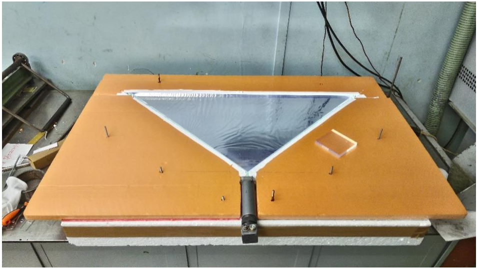


- HiSCORE is not able to perform γ/h separation alone
- Tunka-Grande features small number underground muon detectors with relative high threshold

$\Rightarrow$ Dense cluster of muon detectors with lower threshold will be deployed in central area of HiSCORE

TAIGA-muon design and status





- Counter dimension 1×1 m^2
- Inexpensive, industrially produced plastic scintillator based on polystyrene with thickness 10-20 mm is used
- PMT with 25-46 mm photocathode will be is used for photon detection
- First cluster will be installed this autumn

Joint operation of HiSCORE + IACT

- IACT in monoscopic mode is not able to resolve shower axis
- HiSCORE is not able to separate γ/h on event level

$\Rightarrow$ Combined analysis taking shower axis and core from HiSCORE

- Joint events with low energy are selected from source direction
- Axis, core and energy is taken from HiSCORE
- Quality cuts based on CORSIKA simulations are applied to IACT reconstruction

- First observation period was about 20 h long (Crab + Mrk-421)
- About 15k joint events were recorded
- Gamma candidates are selected and under analysis

Conclusion

- VHE gamma astronomy is a young interdisciplinary (astronomy$\times$astroparticle) field
- The phenomenon is studied with imaging as well as with non-imaging instruments

- The population of VHE sources are being studied, and the MWL/MM conterparts are crutial for understanding the emission processes
- New techniques for studying of extended sources are required

- Future instruments (TAIGA, LHAASO, CTA) will increase the sensitivity and statistics on the both edges of VHE/UHE gamma spectrum