Facilities for Extreme Particles and Photons

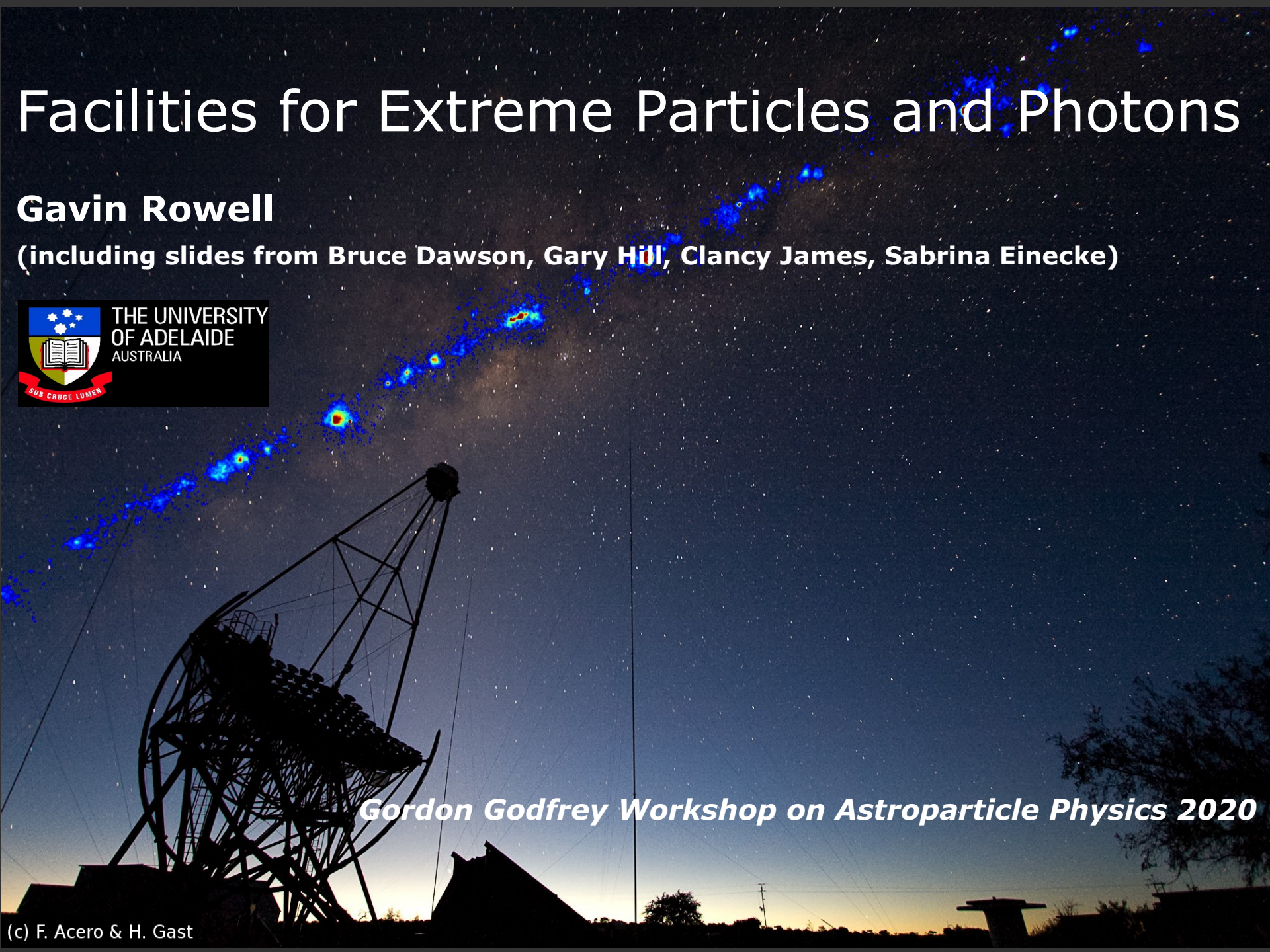
Gavin Rowell

(including slides from Bruce Dawson, Gary Hill, Clancy James, Sabrina Einecke)

THE UNIVERSITY OF ADELAIDE AUSTRALIA

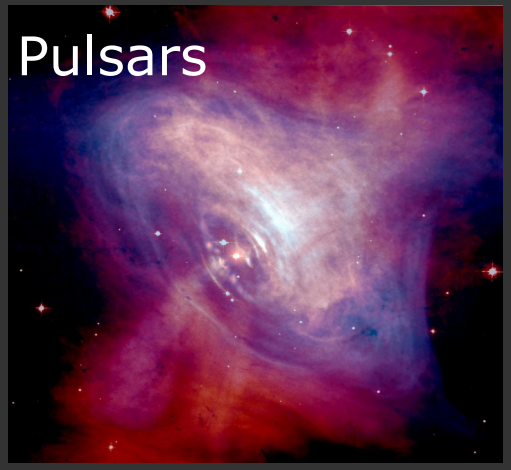
SUB CRUCE LUMEN

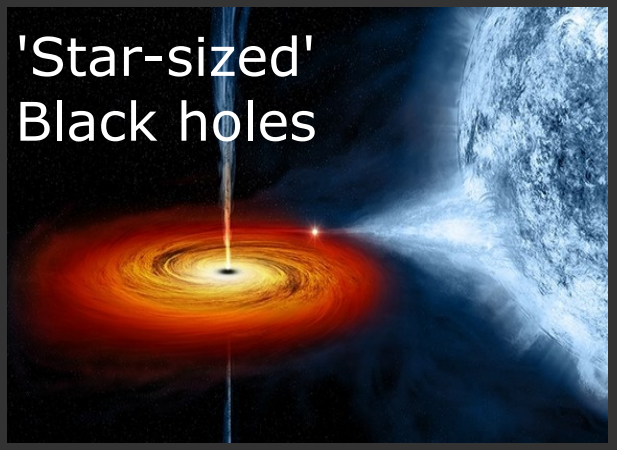
Gordon Godfrey Workshop on Astroparticle Physics 2020

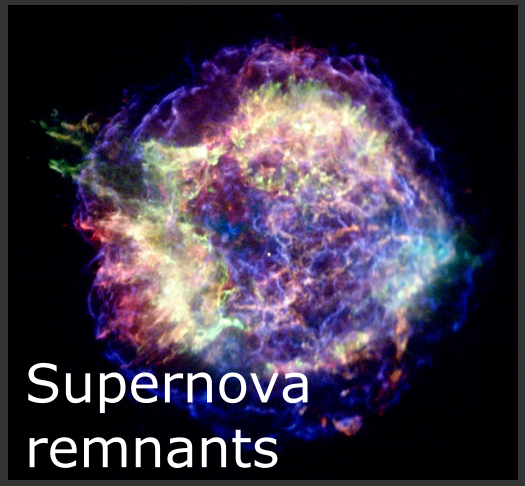


(c) F. Acero & H. Gast

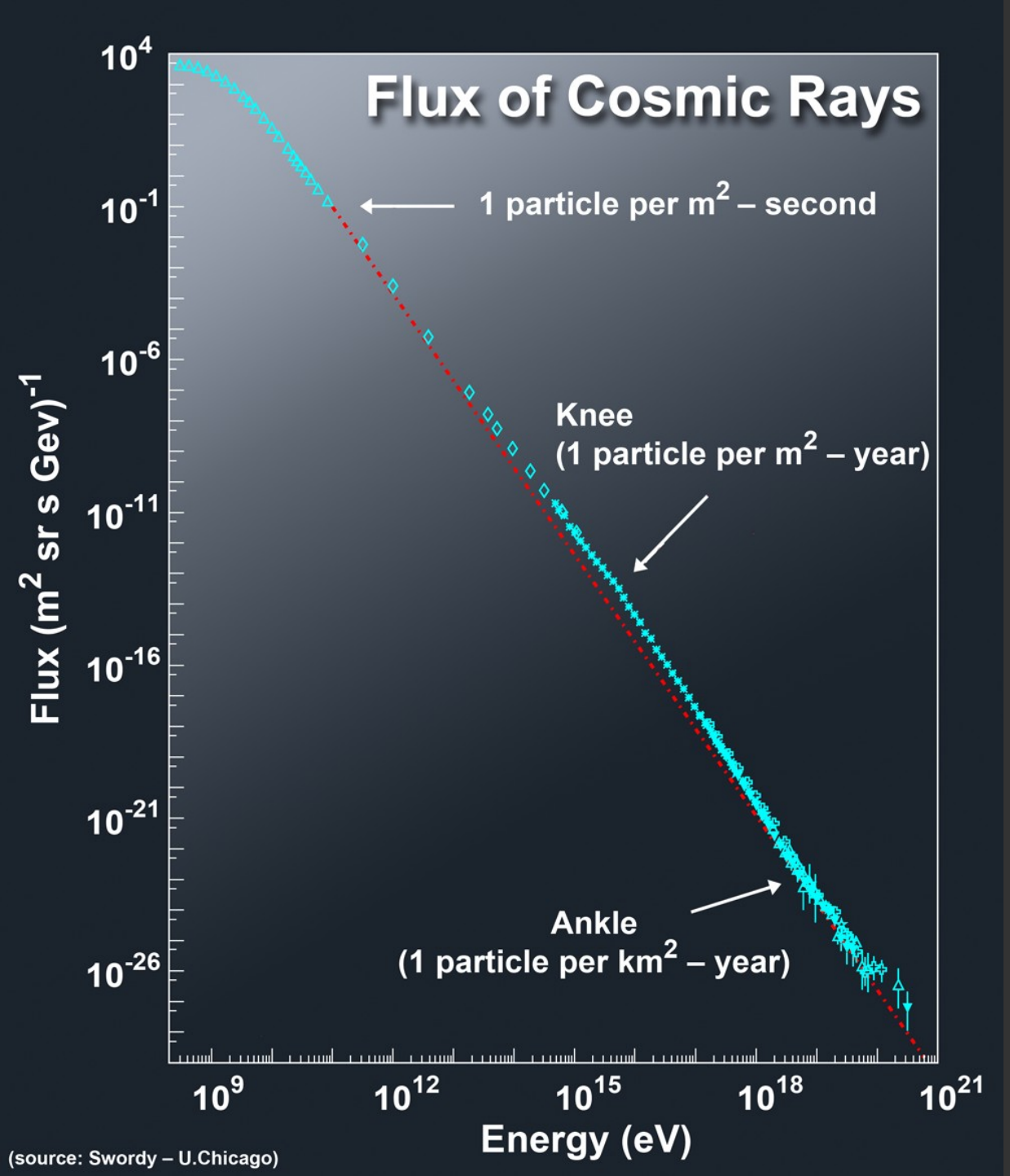
Some (inferred) Cosmic-Ray and Electron Accelerators







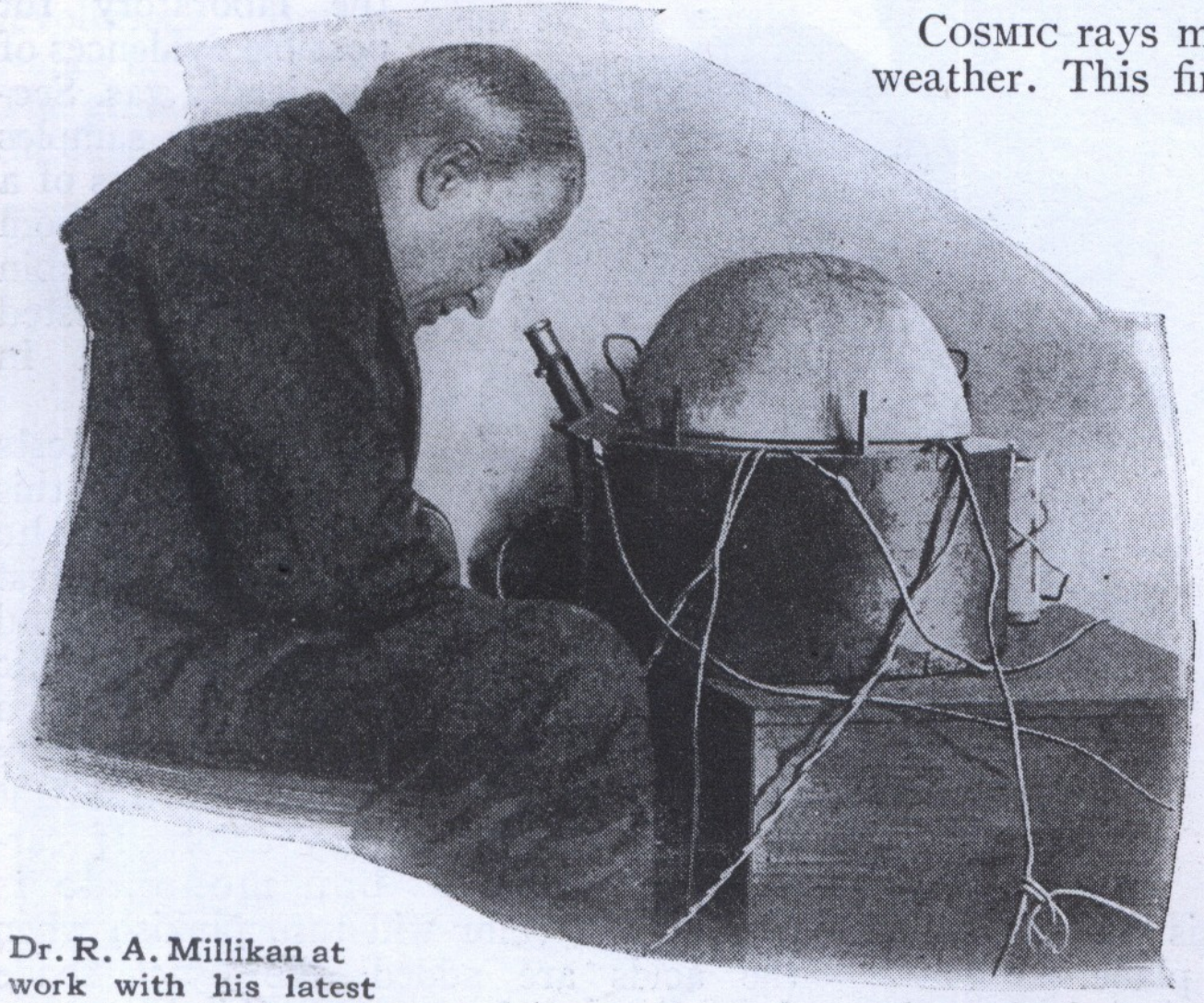
So...where is the evidence?



CRs discovered by Victor Hess: 1912 Balloon Flights

CR origin is still not clear, but we have clues!

COSMIC RAYS MAY FORECAST WEATHER



Dr. R. A. Millikan at work with his latest electroscope, with which he is studying the cosmic rays. He believes these mysterious rays may be used in making reliable forecasts of the weather.

Cosmic rays may help to prophesy the weather. This first practical use for the mysterious radiations from outer space was recently announced by Dr. R. A. Millikan, Calif. Institute of Technology physicist.

The "cosmic rays" are more penetrating than radium or X-rays, but it is not known whether they affect human beings.

Dr. Millikan, who discovered the source of the rays (P. S. M., July, '28, p. 13), has measured their strength with his new electroscope, and is able to determine high-altitude atmospheric conditions.

Why study cosmic-rays (CRs) and electrons?

- Energy density of galactic CRs similar to that in starlight, magnetic fields, and gas kinetic energy

  → these energy densities are all tightly connected.

  → CRs carry energy throughout galaxies

  → CRs intimately linked to evolution of stars and galaxies

- CRs are a signpost of massive stellar evolution

  – death (supernova remnants)

  – life (winds from massive stars)

  – birth (perhaps) signalling onset of fusion/stellar winds

  – catalyst for astro-chemistry → life!

- Where do magnetic fields come? Are they important?

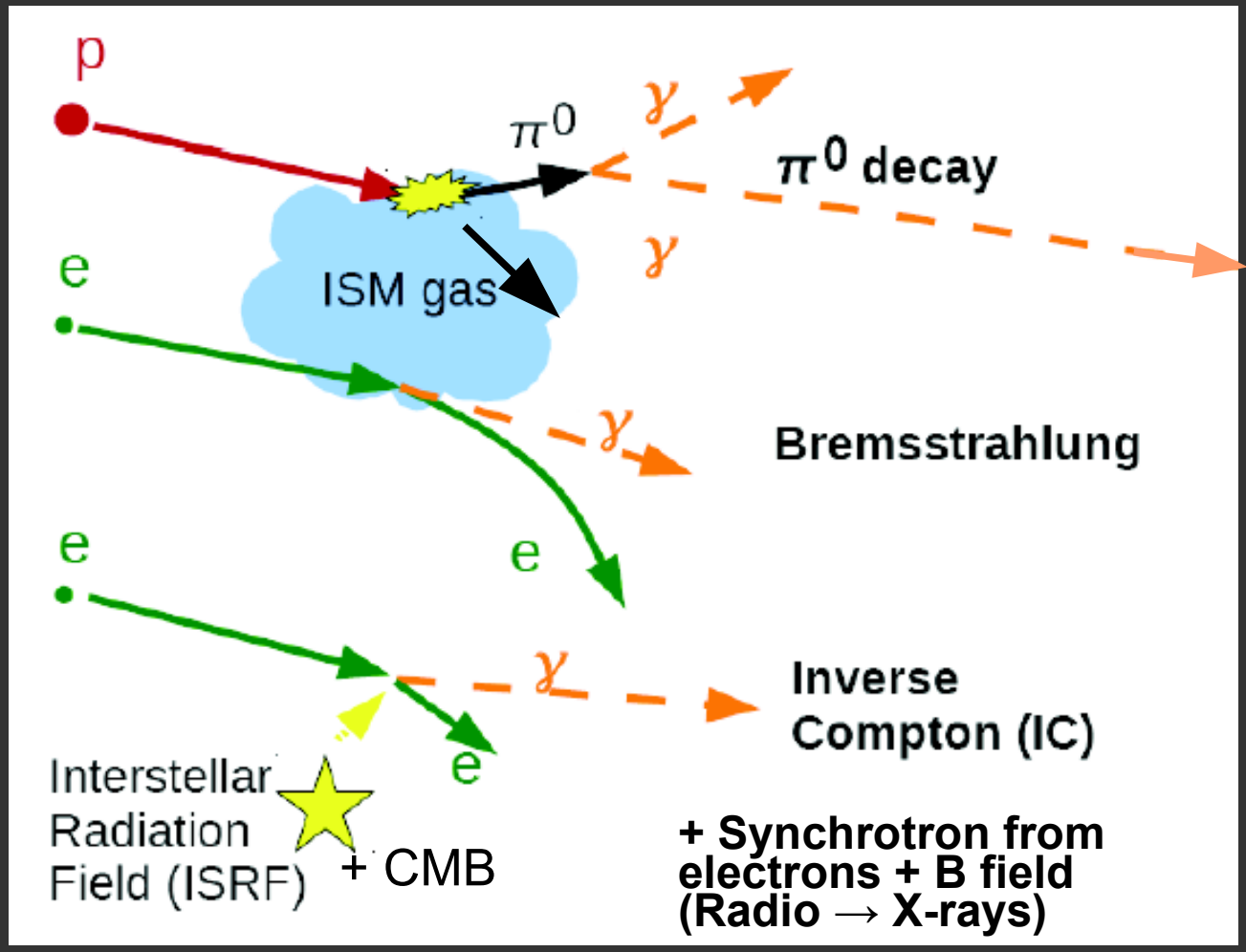
  – Magnetic fields can greatly inflence star formation!

  – CRs can create magnetic fields - they ionise atoms

- CRs and electrons trace outflows and jets

  – jets, pulsar winds, accretion, active Galaxies, GRBs, merger events.....

Gamma Rays from multi-TeV particles



"ISM" gas
Interstellar Medium

→ molecular + atomic + ionised gas in the Milky Way

Protons: Gamma-rays and gas targets are generally spatially correlated
(need to map atomic and molecular ISM → mm radio astronomy)

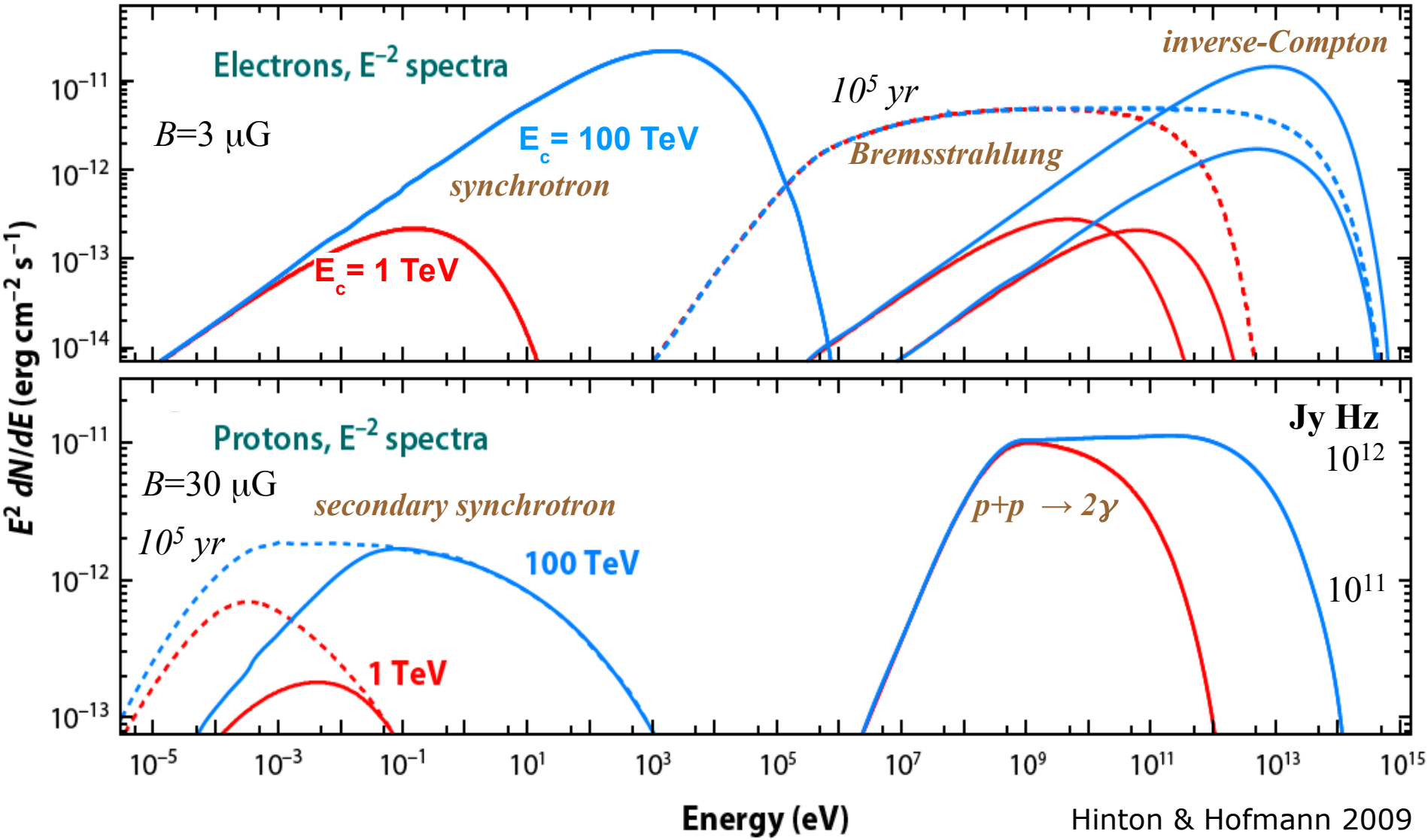
Electrons: Gamma-ray (IC) + non-thermal X-ray, radio emission (synchrotron)
highly coupled

Non-Thermal Photon Energy-fluxes (hypothetical particle accelerator)

Particle Spectrum

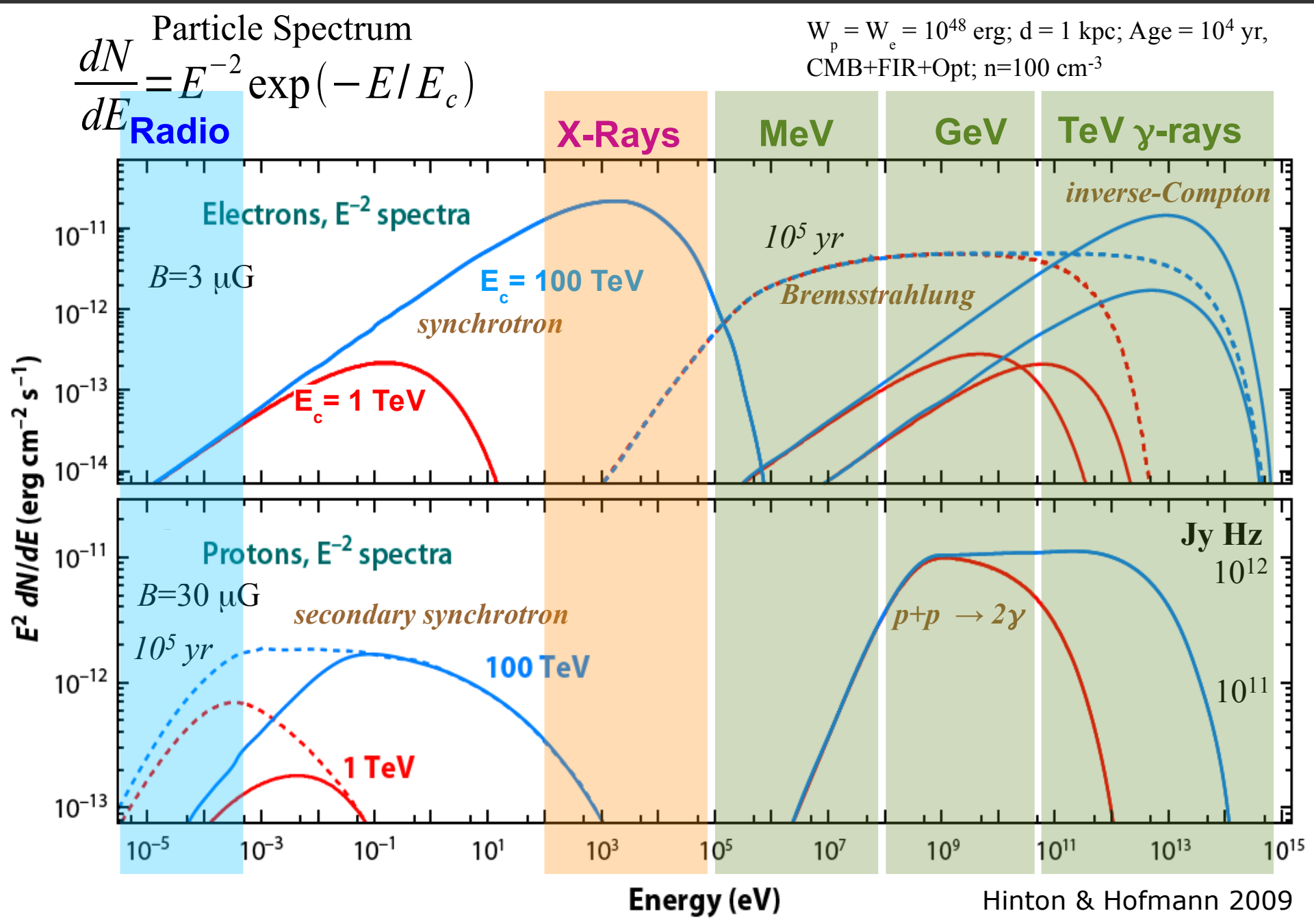
$$\frac{dN}{dE} = E^{-2}\exp(-E/E_c)$$

$W_p = W_e = 10^{48}$ erg; d = 1 kpc; Age = 10^4 yr, CMB+FIR+Opt; n=100 cm^{-3}



Hinton & Hofmann 2009

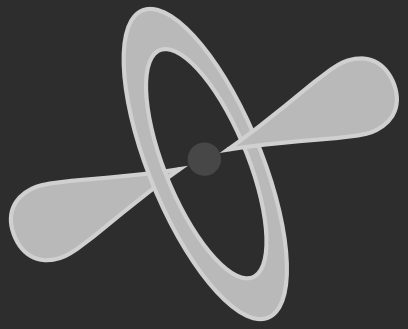
Non-Thermal Photon Energy-fluxes (hypothetical particle accelerator)



Hinton & Hofmann 2009

Multi-Messenger Astronomy

COSMIC OBJECTS
(E.G. ACTIVE GALACTIC NUCLEI)



COSMIC RAYS

PHOTONS / GAMMA RAYS

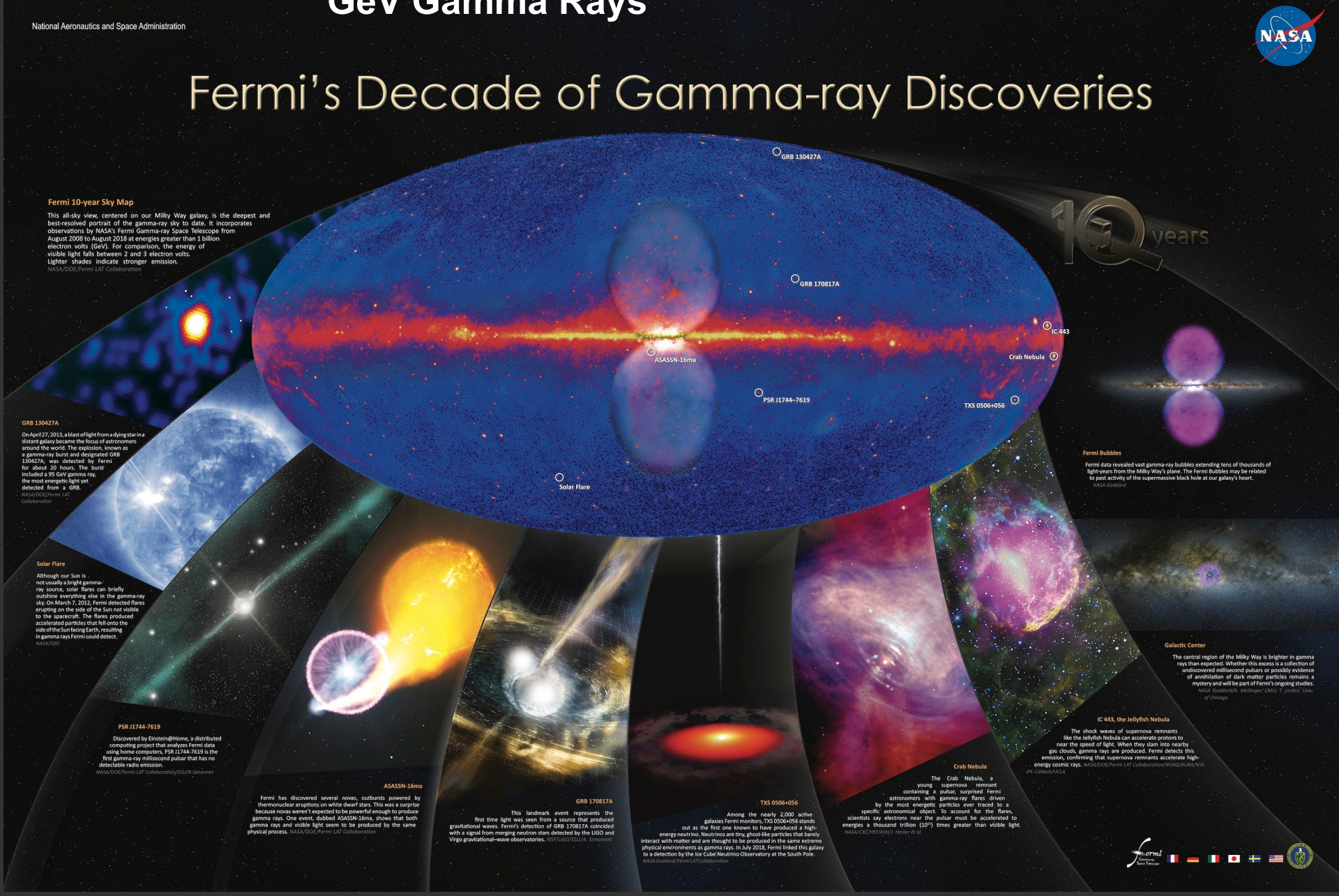
NEUTRINOS

GRAVITATIONAL WAVES

GROUND- AND SPACE-BASED
TELESCOPES

GeV Gamma Rays

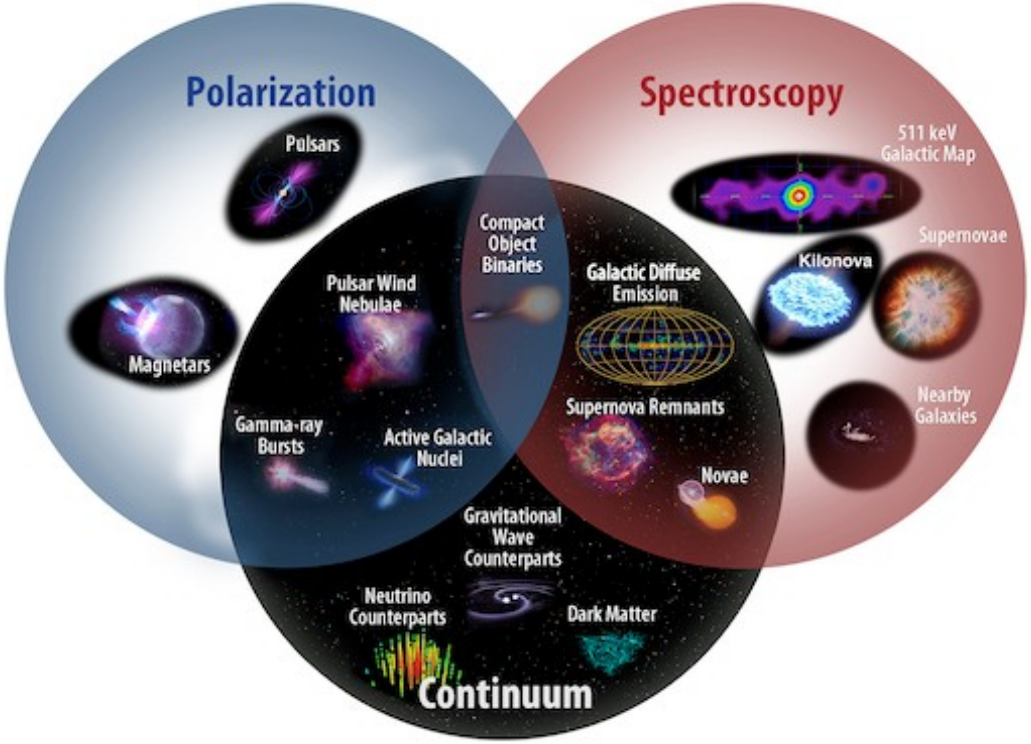
National Aeronautics and Space Administration

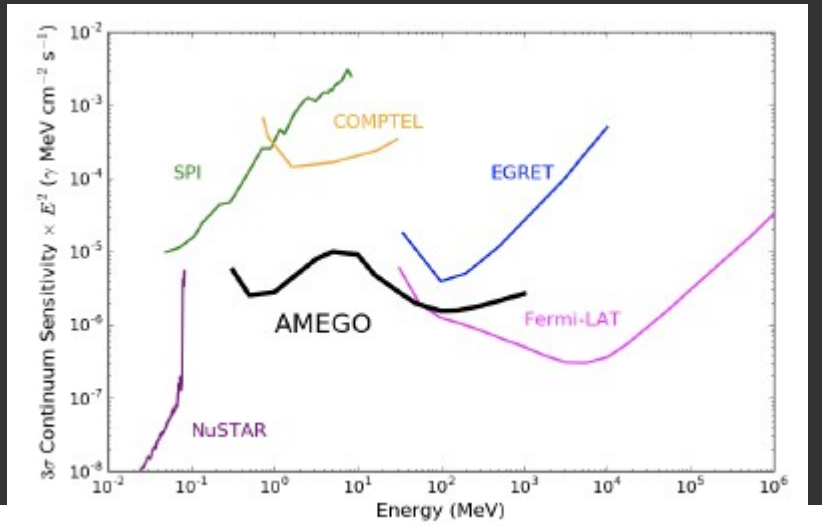


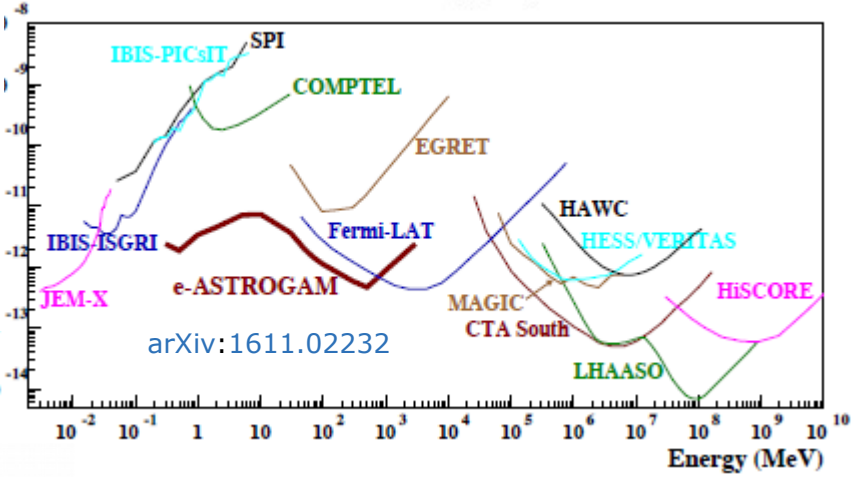
11 June 2018

https://www.nasa.gov/feature/goddard/2018/nasa-s-fermi-satellite-celebrates-10-years-of-discoveries

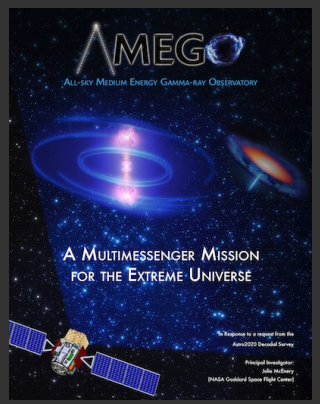
MeV Gamma Rays

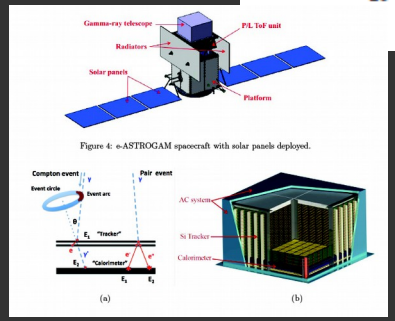


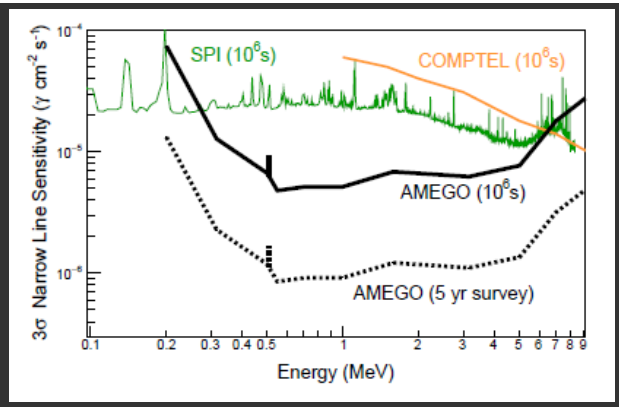




arXiv:1611.02232







AMEGO & e-ASTROGAM

https://asd.gsfc.nasa.gov/amego/index.html

Gamma-rays (GeV to >TeV Energies)

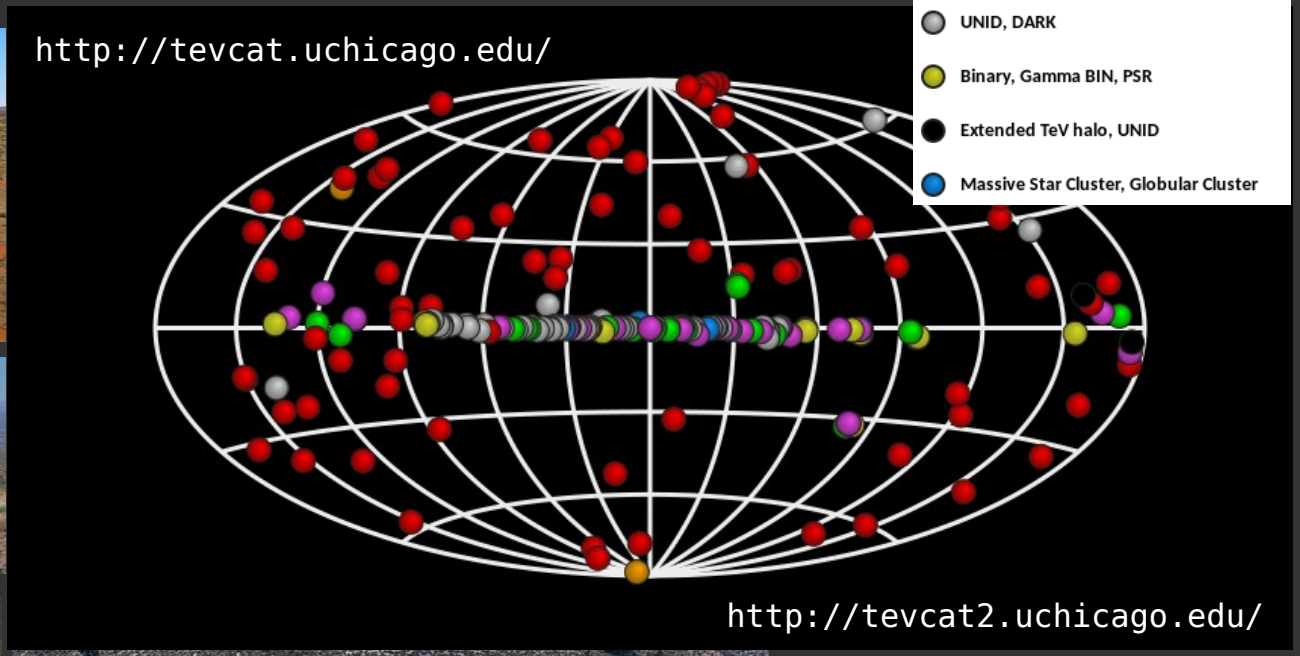
- **Gamma rays: Highly effective tracer of particle acceleration**
- **Many TeV gamma-ray source types + astro/particle physics impact**
  - *Supernova remnants*
  - *Pulsars & pulsar-wind nebulae & their halos*
  - *Compact binaries, stellar black holes*
  - *Gamma-ray bursts (hypernovae & compact mergers)*
  - *Galactic centre region*
  - *Massive stellar clusters and star formation regions*
  - *PeVatrons → our galaxy's extreme accelerators*
  - *Relativistic outflows; stellar winds; wind interactions*
  - *Formation of molecular gas; ISM; magnetic fields*
  - *Unidentified & Dark TeV sources*
  - *Active Galaxy Cores; super-massive black holes*
  - *Star-burst galaxies*
  - *Globular clusters (millisecond pulsars and/or X-ray binaries?)*
  - *Extragalactic IR background constraints → cosmology*
  - *Indirect dark matter search, quantum gravity, axions, beyond SM physics*
  - *Cosmic ray electrons*

(see talks F. Aharonian, A. Taylor, S. Celli, M. Krumholz, M. White...)

Gamma-rays (~30 GeV to ~500TeV)

Ground-based detection of Cherenkov emission

High impact > 20 Nature, Science, PRL papers since 2004

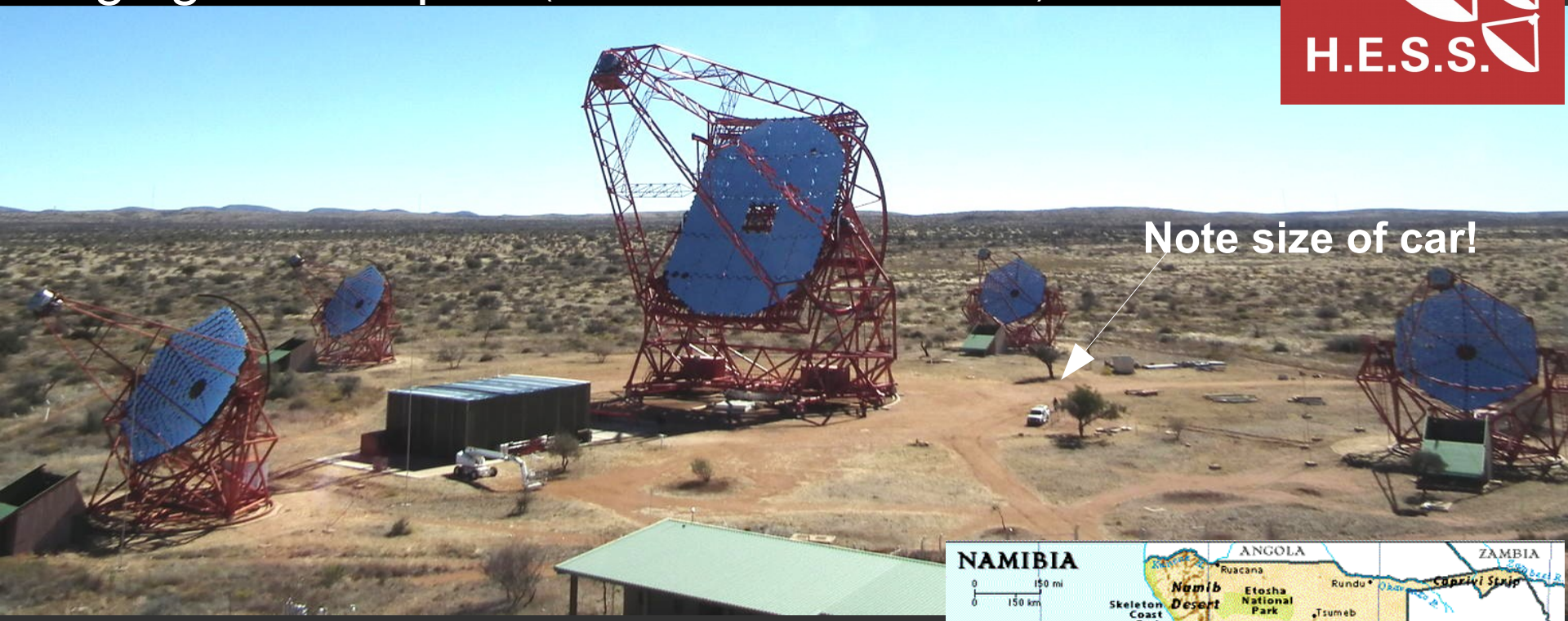


Great success with HESS, VERITAS, MAGIC, HAWC, building on previous generations (Whipple, HEGRA, CAT, MILAGRO.…)

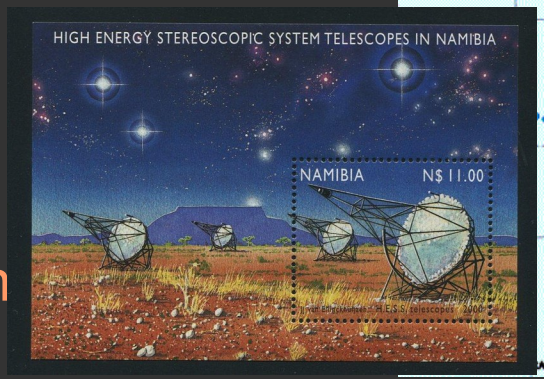
Continued operations of HESS/VERITAS/MAGIC/HAWC towards 2025..

Next generation → CTA, LHAASO, SGSO…..

H.E.S.S. 4x12m + 1x28m diam. Cherenkov Imaging Telescopes (22° S 1800m a.s.l. Namibia)



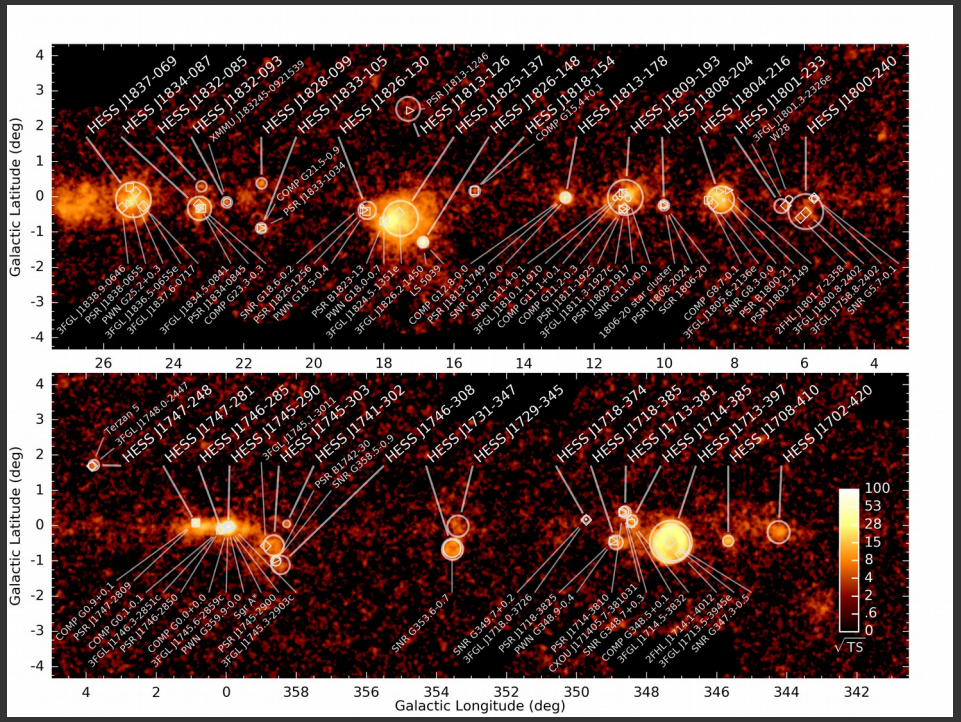
- 0.02 to ~ 20 TeV coverage
- HESS-II ~0.02 to 1 TeV
- Field of view 3 to 5°
- Angular res. ~3 to 6 arcmin

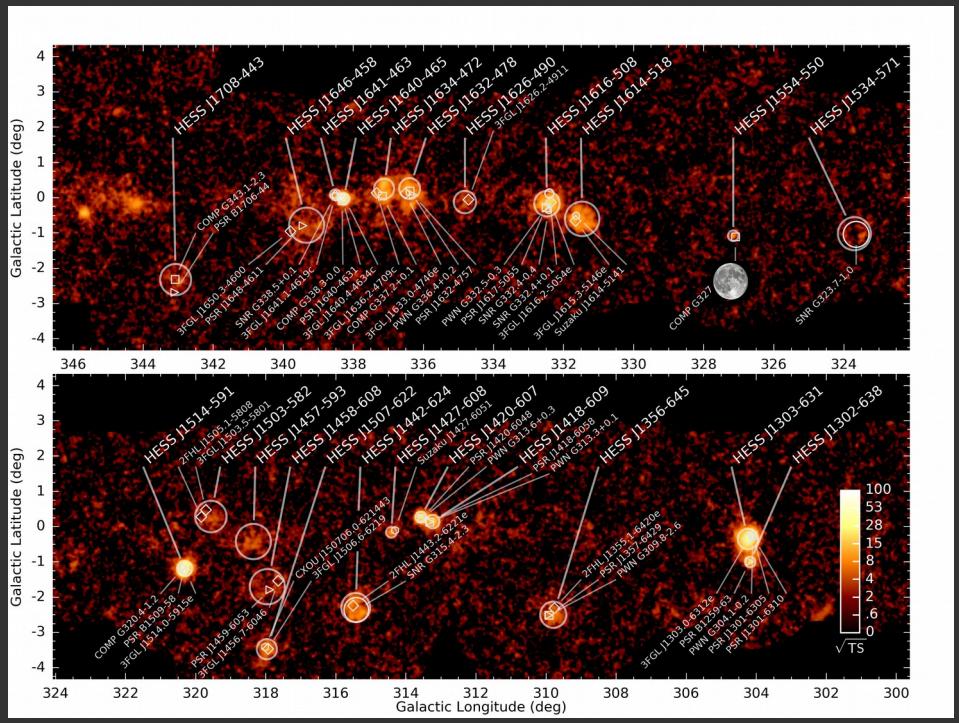


Funded to 2022; Considering extension to 2025+

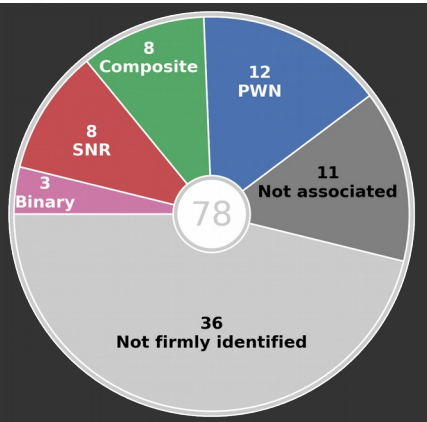
The H.E.S.S. Galactic Plane Survey (2018)

HGPS - The Southern Milky Way in TeV Gamma-Rays





- Over 70 sources of Galactic TeV gamma-rays (>50% unidentified)
- Log N vs. log S studies for the first time
- Three new TeV shells → gamma-ray bright supernova remnants?
- TeV source assoc. massive stellar cluster/LBV star/magnetar



Further info & data download https://www.mpi-hd.mpg.de/hfm/HESS/hgps/

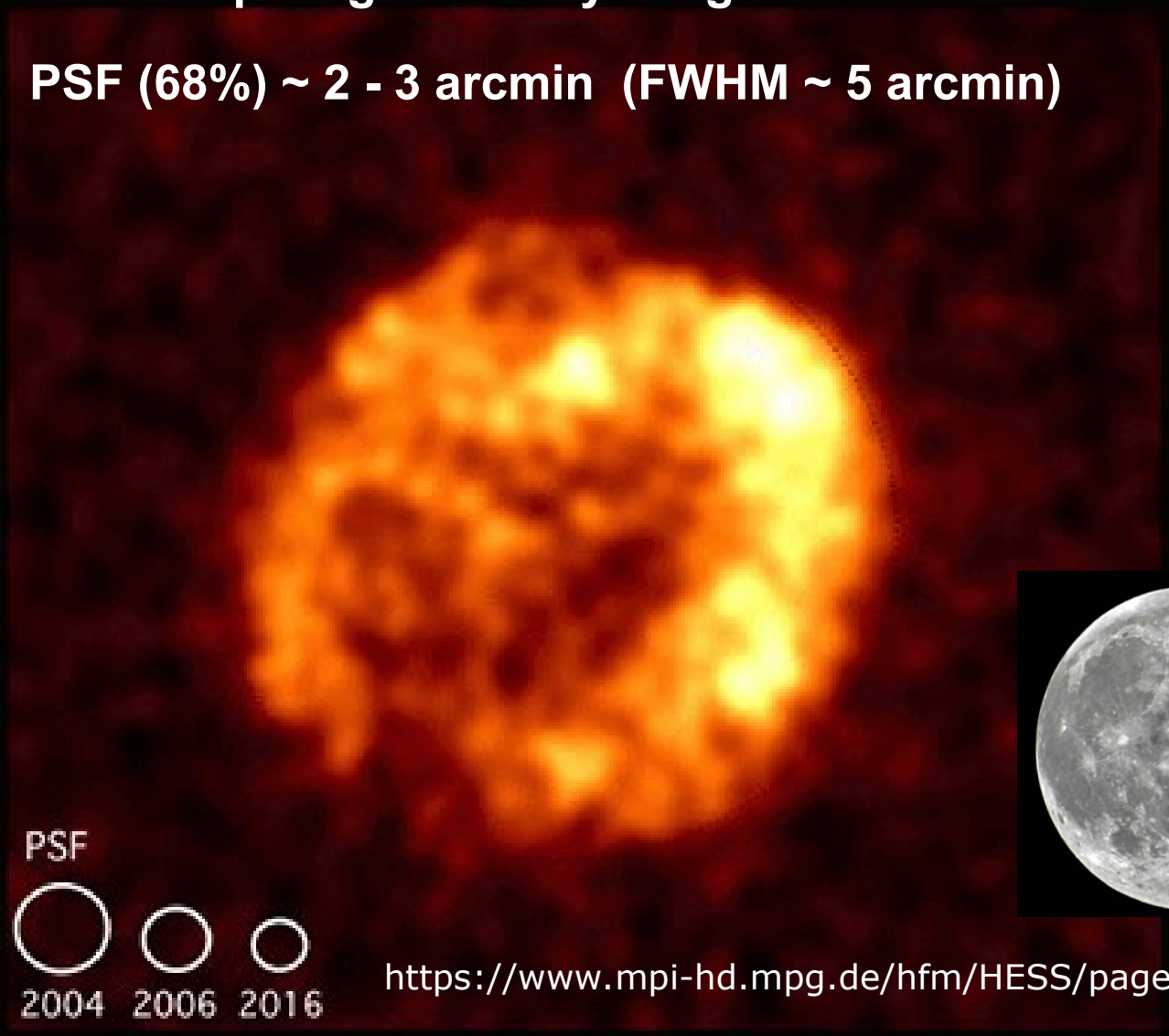
H.E.S.S. RX J1713.7-3946

~1600 yr old supernova remant

The sharpest gamma-ray image so far!

PSF (68%) ~ 2 - 3 arcmin (FWHM ~ 5 arcmin)

HESS 2018



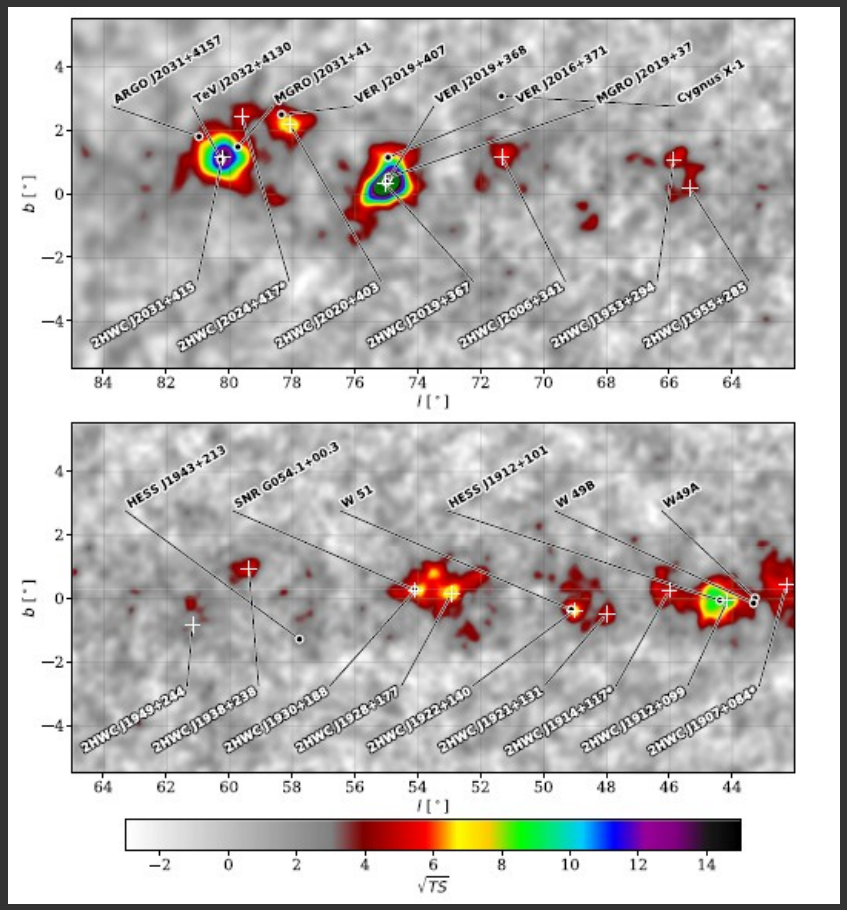
Year	2016
Live-time	164h
Energy	> 0.25 TeV
PSF (R_{68})	2.9 arcmin
γ's	31,000

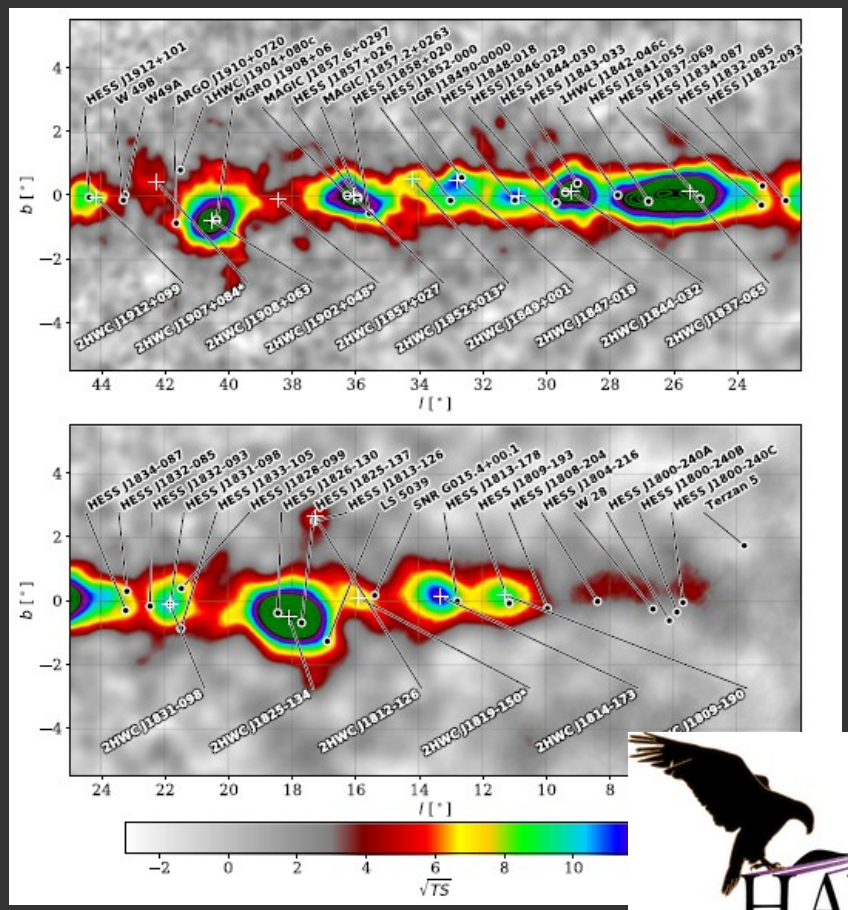
https://www.mpi-hd.mpg.de/hfm/HESS/pages/home/som/2016/09/

HAWC Galactic Plane Survey (2HWC)

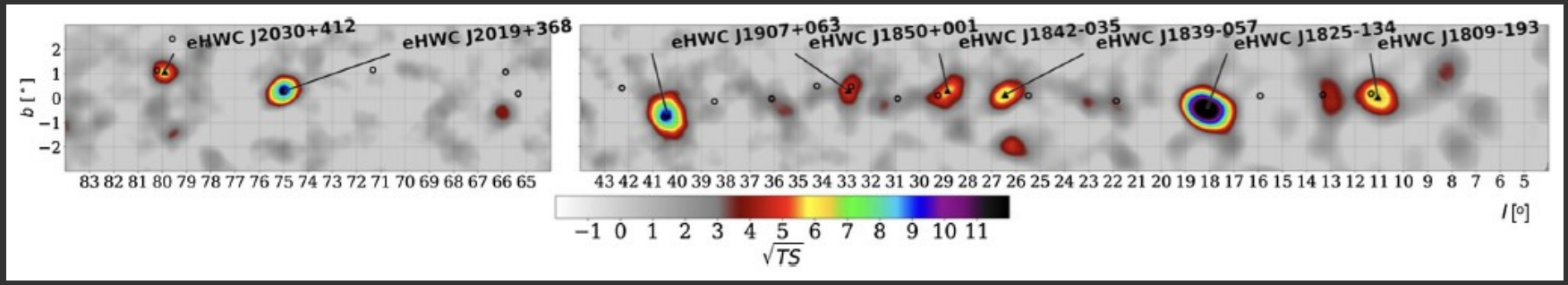
→ 39 sources (17 new sources)

Abeysekara et al. (HAWC) 2017,2020

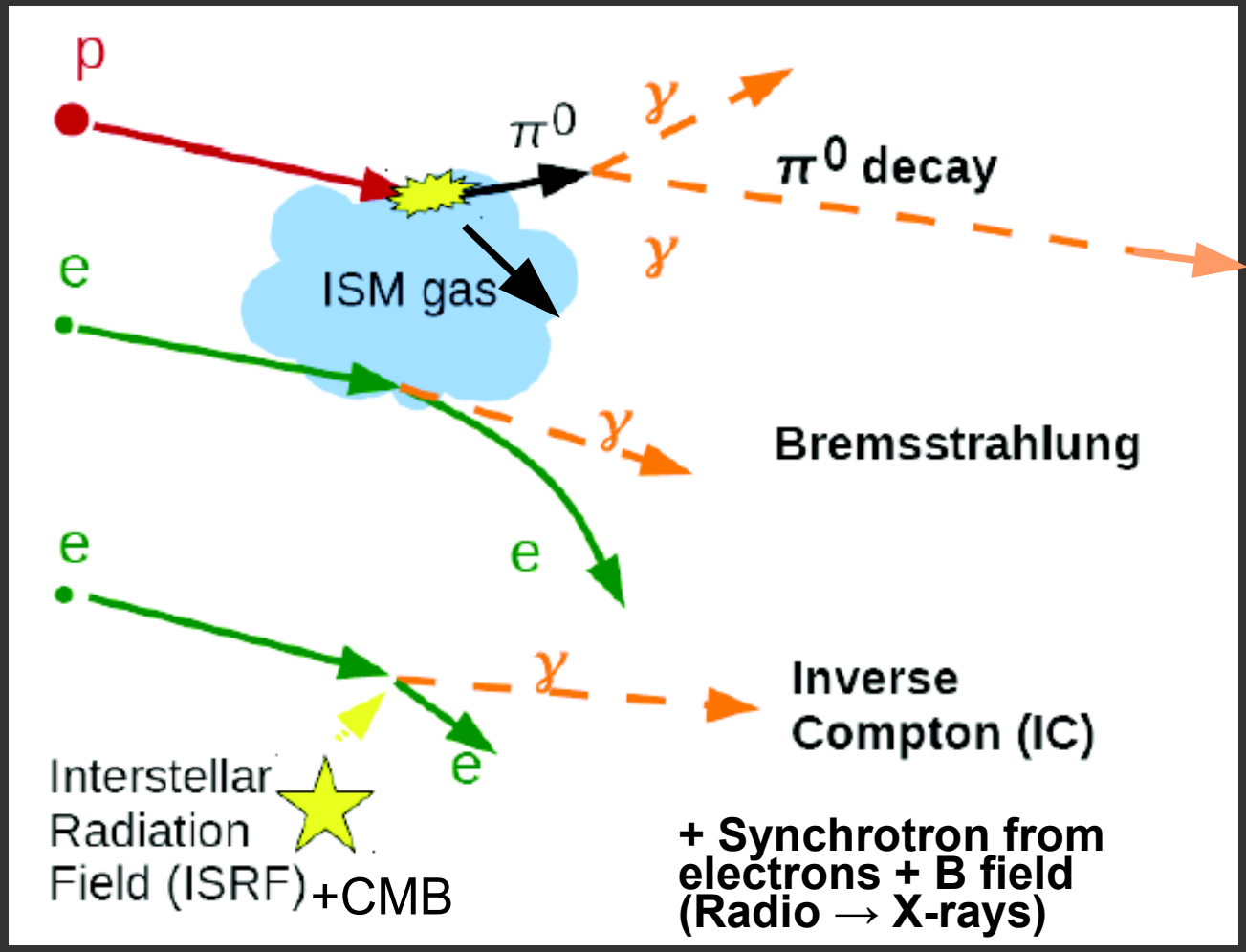




Sources >56 TeV → PeVatrons



Gamma Rays from multi-TeV particles



"ISM" gas
Interstellar Medium

→ molecular + atomic + ionised gas in the Milky Way

Protons: Gamma-rays and gas targets are generally spatially correlated
(need to map atomic and molecular ISM → mm radio astronomy)

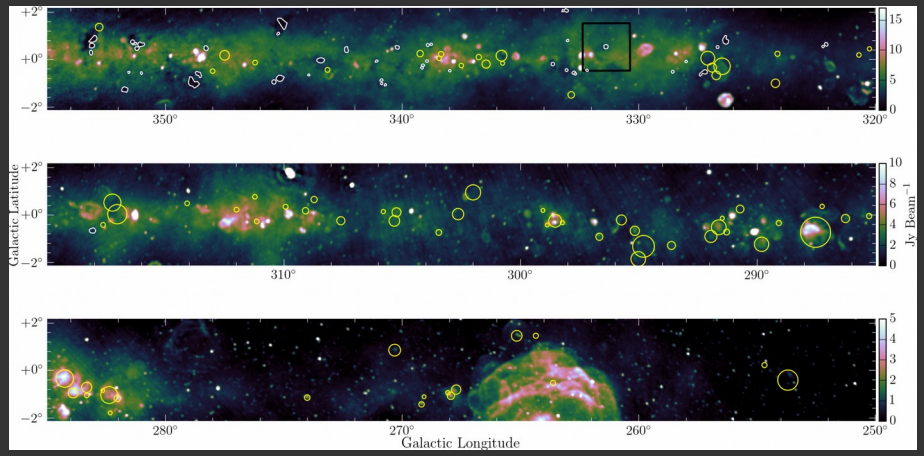
Electrons: Gamma-ray (IC) + non-thermal radio to X-ray synchrotron

Synergies with Radio Continuum Surveys

- Radio synchrotron & TeV gamma-ray (esp. hadronic) are often 'relics' of earlier particle acceleration.

- Dark TeV Sources:
  → Old/evolved SNRs & PWNe?
  → Missing Supernova remnants?

ASKAP – EMU, POSSUM, SCORPIO
MWA – GLEAM
→ towards the SKA

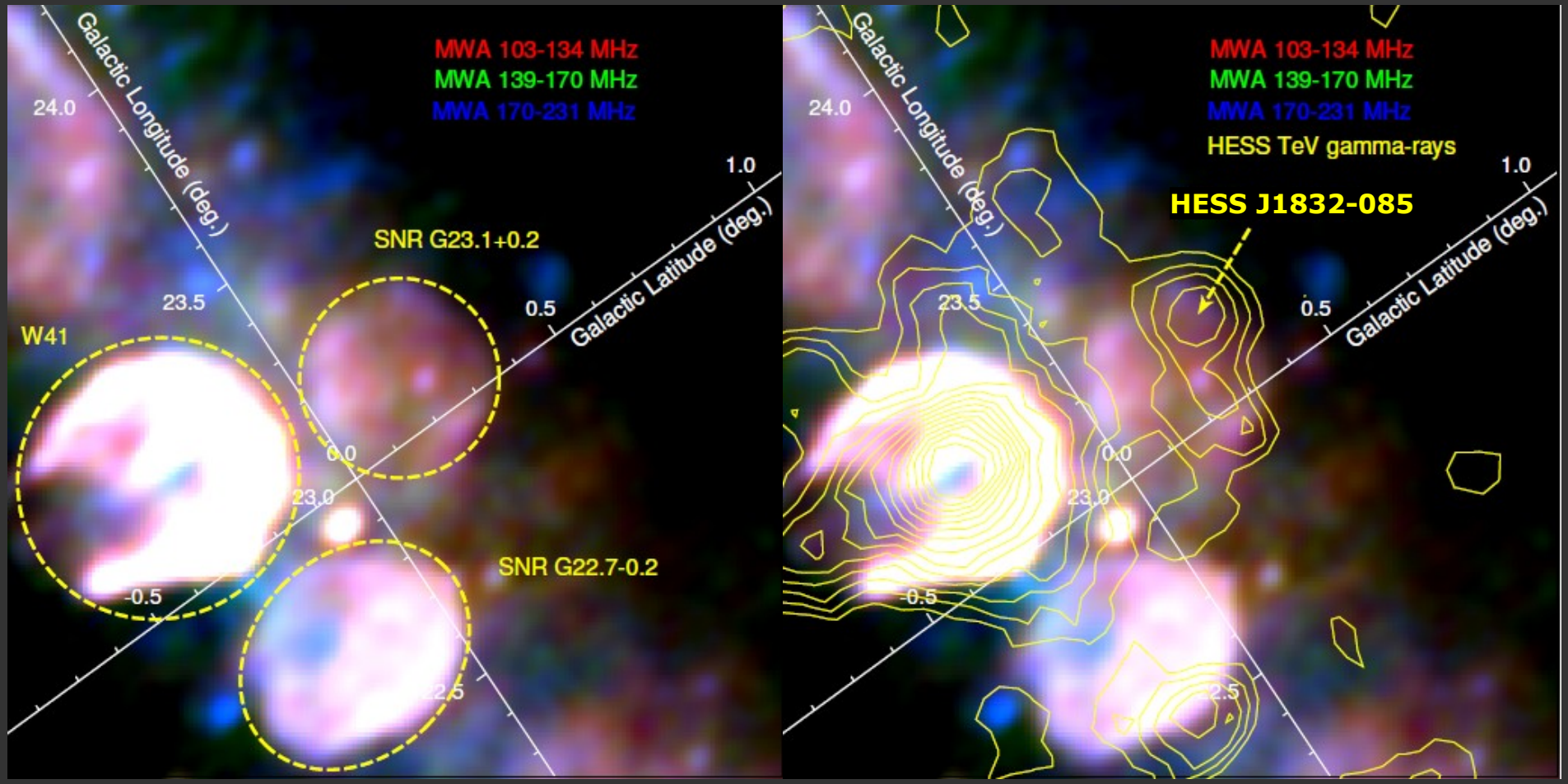


MWA GLEAM 88 MHz (MWA 2016)

ASKAP EMU
Evolutionary Map of the Universe

POSSUM
POLARISATION SKY SURVEY OF THE UNIVERSE'S MAGNETISM

GLEAM



- MWA SNR candidate G23.11+0.18; Also seen with VLA THOR (Anderson et al 2017)
- Overlaps unidentified TeV gamma-ray source HESSJ1832-085
- No X-ray emission → old-ish (>~10kyr) SNR?

Maxted etal. 2019

Synergies with interstellar gas surveys

www.atnf.csiro.au/research/HI/sgps

HI (atomic H), OH, CS

CO

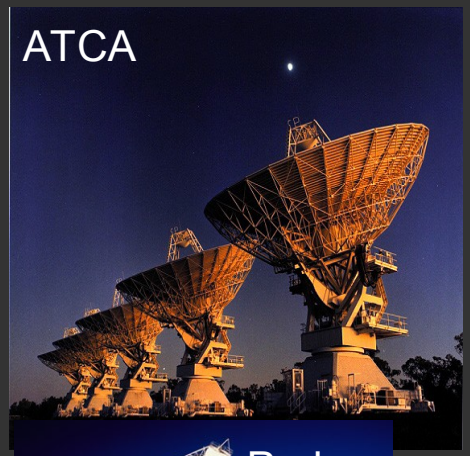
CO, NH_3, CS, SiO...

Gas density

~$10^{1\text{ to }4}$ cm^{-3}

~10^{3} cm^{-3}

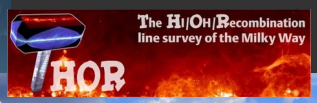
>$10^{3\text{ to }4}$ cm^{-3}



NANTEN
Submillimeter Observatory
なんてん電波天文台

国立天文台
NAOJ
National Astronomical Observatory of Japan

CSIRO

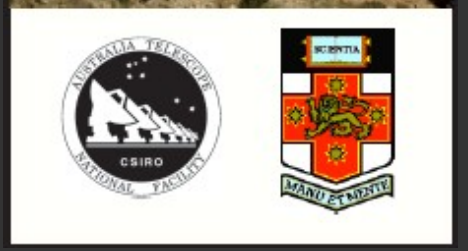


GASKAP

THz (Antarctica & High-alt)
[CI] + [CII]

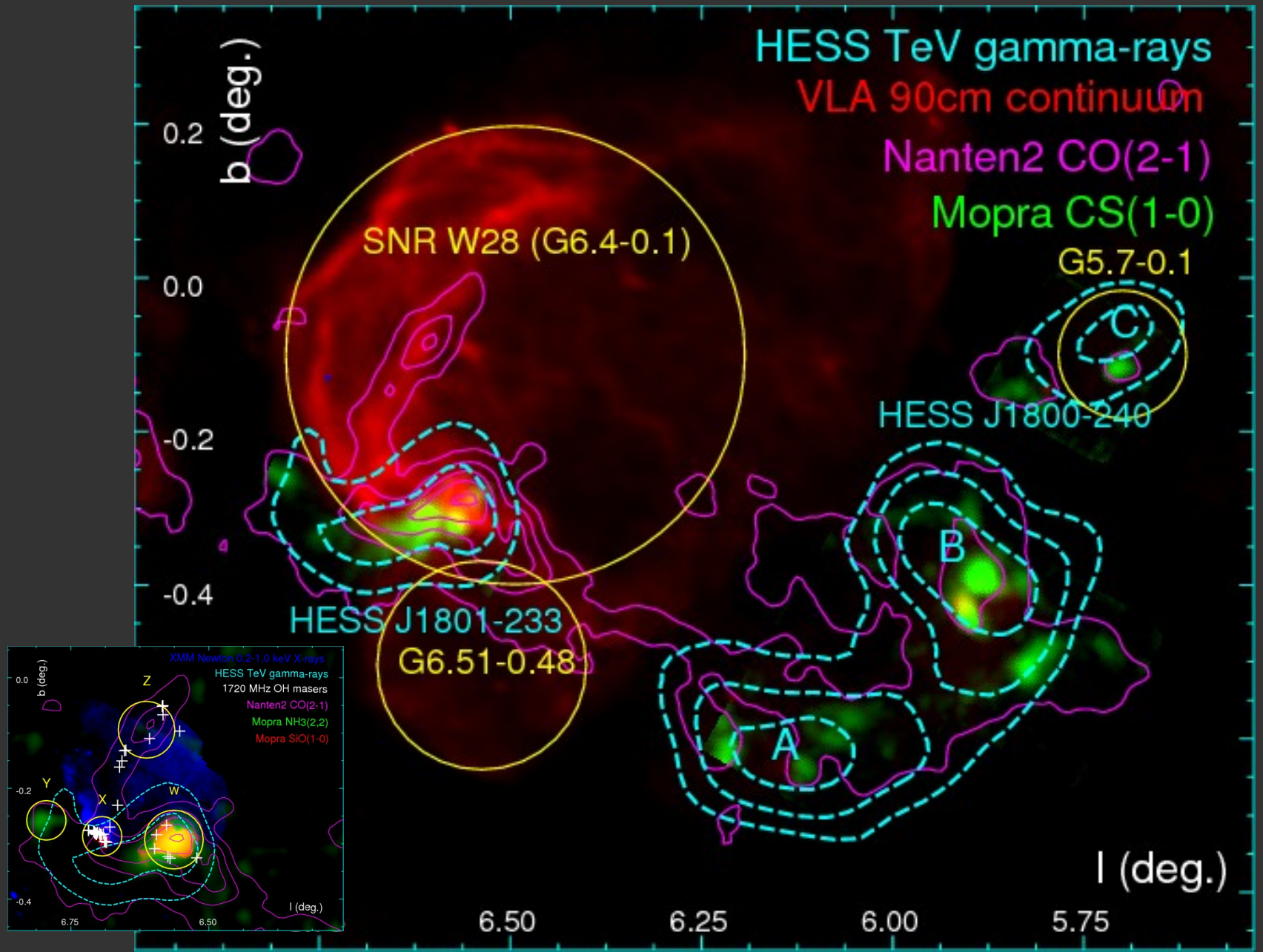
Mopra Telescope

CSIRO



Mature SNR W28 – Radio to TeV

HESS 2008, Niicholas etal 2011, 2012, Maxted etal 2016, 2017



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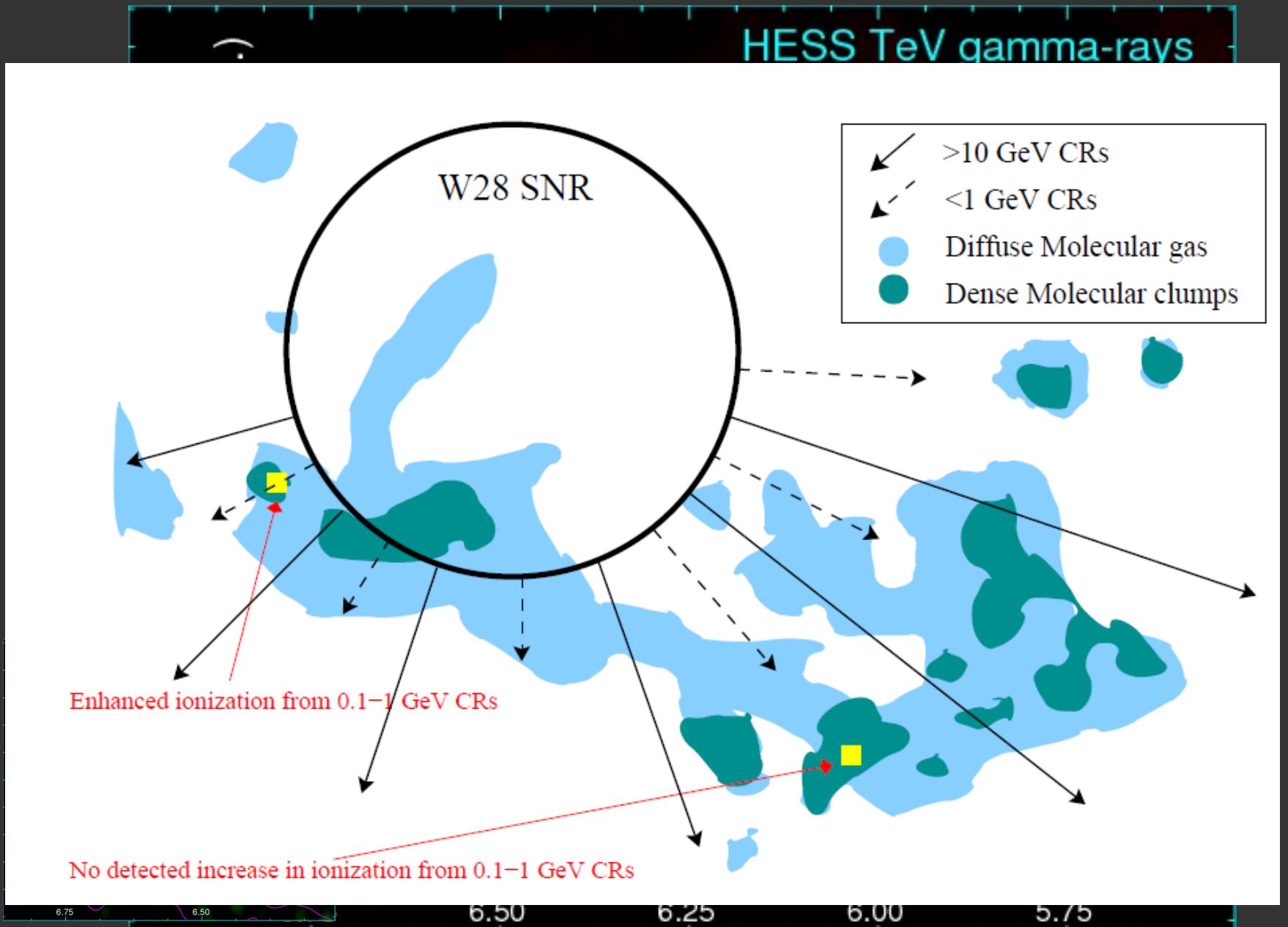
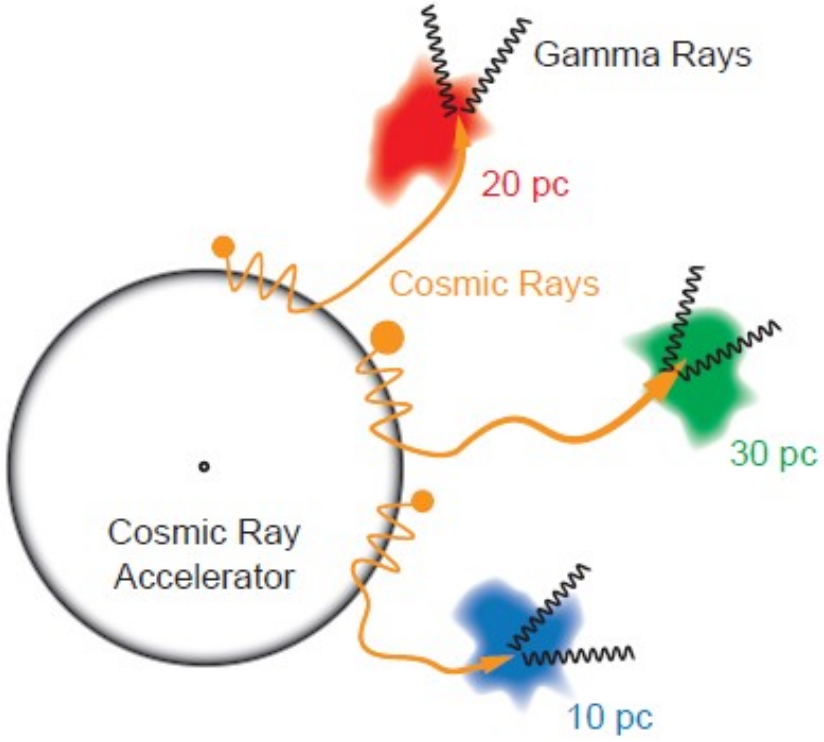
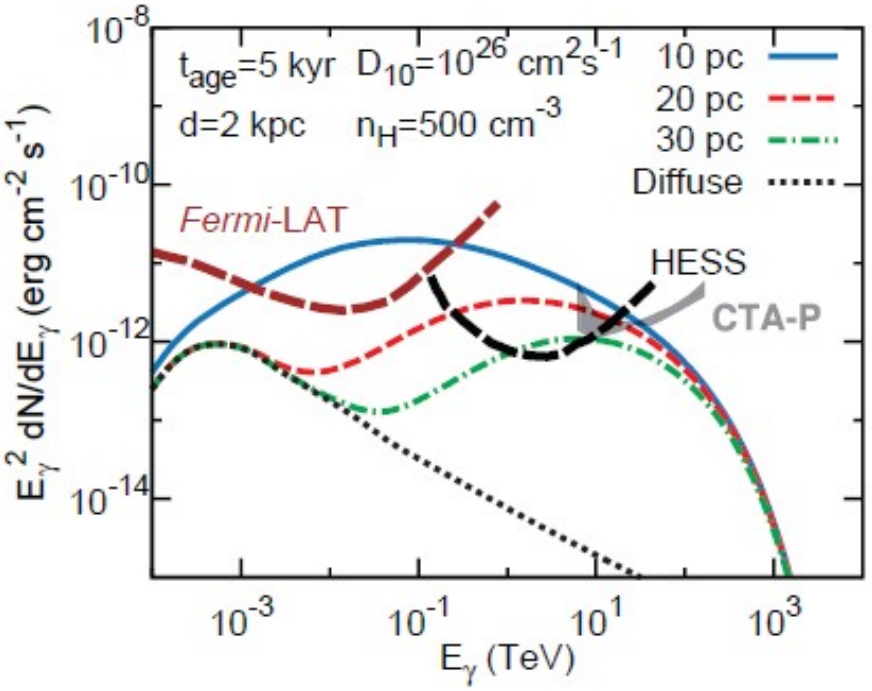


Gamma-ray spectra from local and escaped cosmic-rays

Flux sensitivity (150 hr) for 3 CTA Pathfinder Small Sized Telescopes (CTA-P) at CTA-South site (Chile)

Graphic from F. Voisin; S. Einecke





- Cosmic ray diffusion modeling from accelerator to target clouds (e.g. Aharonian& Atoyan 1996, Voisin 2016)

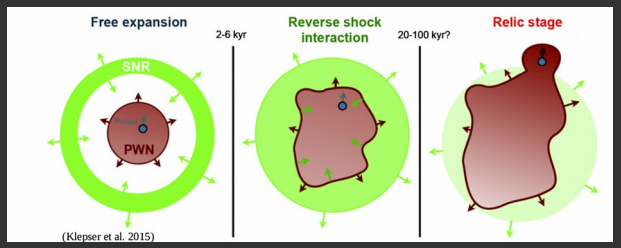
$$f(E,R,t) \approx \frac{N_0\,E^{-\alpha}}{\pi^{3/2}\,R_{\rm dif}^3}\,\exp\left(-\frac{(\alpha-1)t}{\tau_{\rm pp}}-\frac{R^2}{R_{\rm dif}^2}\right)$$

$$\frac{\partial n}{\partial t} = -\nabla\left(D\left(\mathbf{r},\gamma\right).\nabla n\right) + \frac{\partial}{\partial\gamma}\left(\dot{\gamma}n\right) + S\left(\gamma,\mathbf{r},t\right)$$

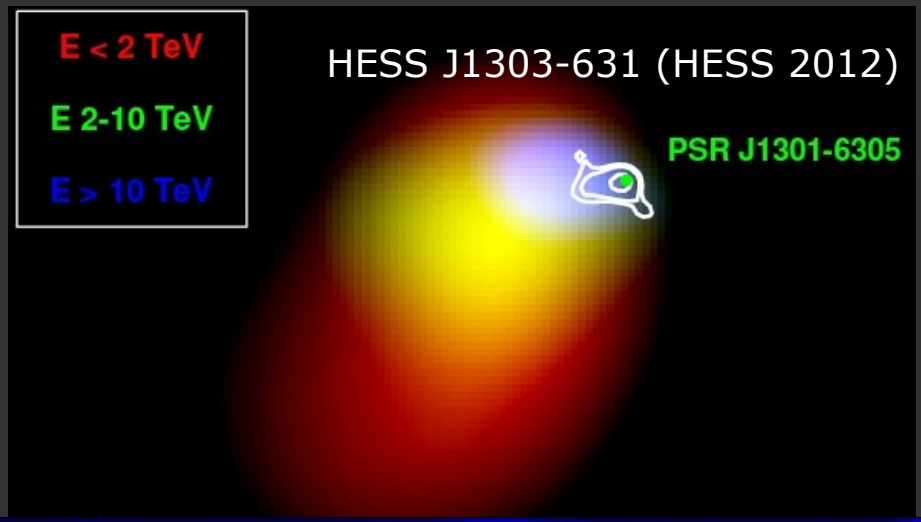
→ Perfect way to search for PeVatrons, the Milky Way's extreme cosmic Ray accelerators to > 10^{15} eV (HESS/eROSITA/ASKAP/MWA linkages)

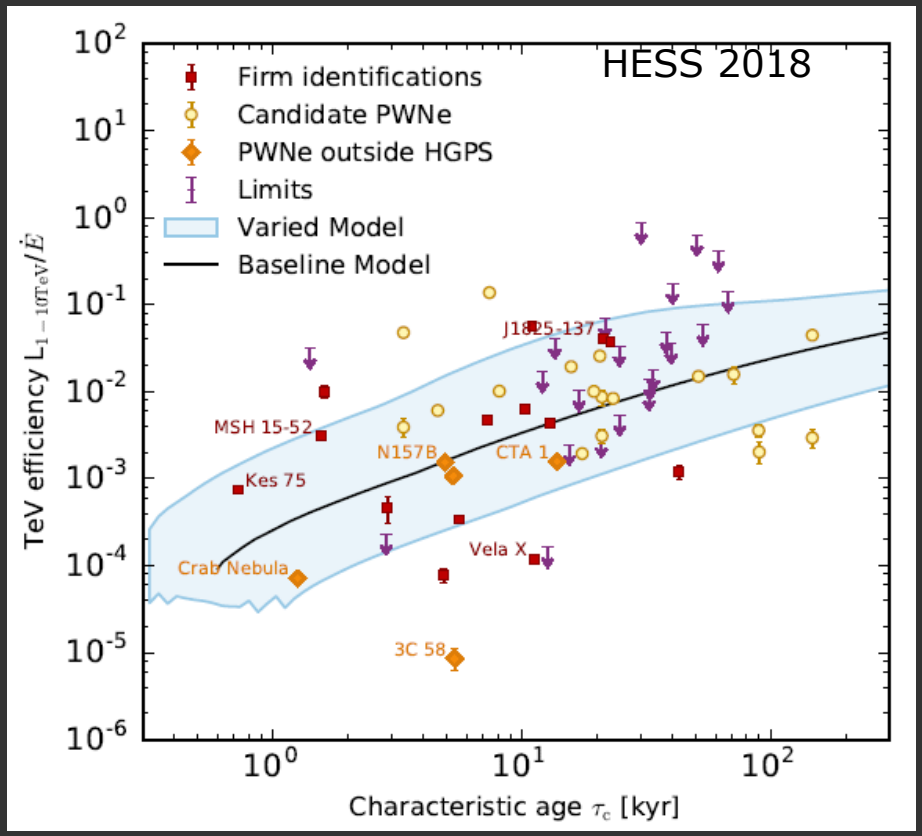
TeV Pulsar Wind Nebulae (PWN)

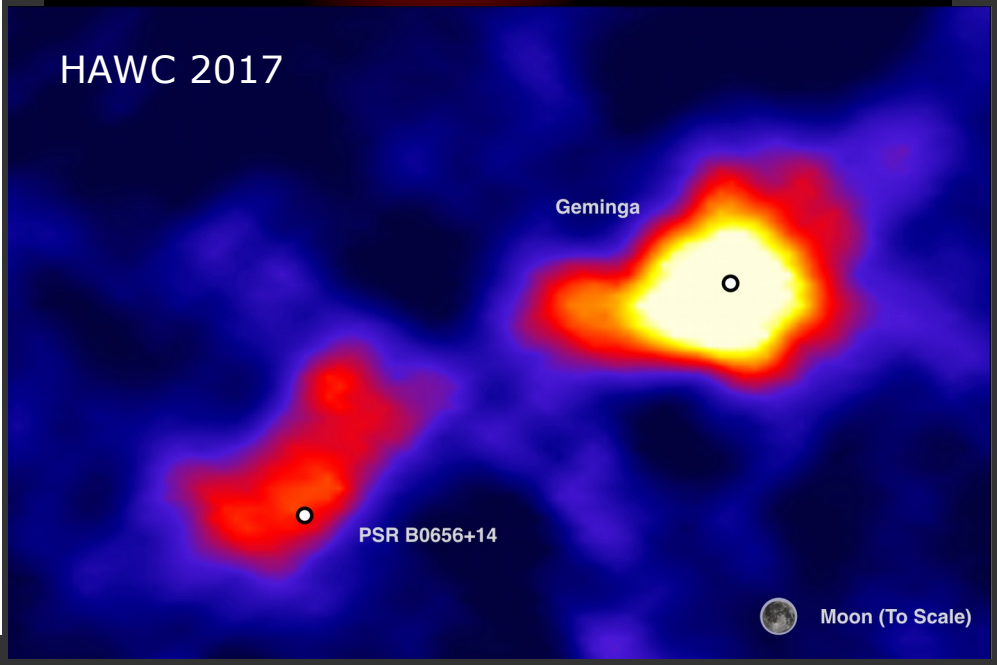
- Most populous Galactic TeV class
- Old PWNe as UnID TeV sources
  (e.g. Aharonian etal 1997, Kargaltsev etal 2013)
- ISM influence on development
- TeV efficiency increases with time
- TeV halos (relic electrons)



Reynolds (2017)



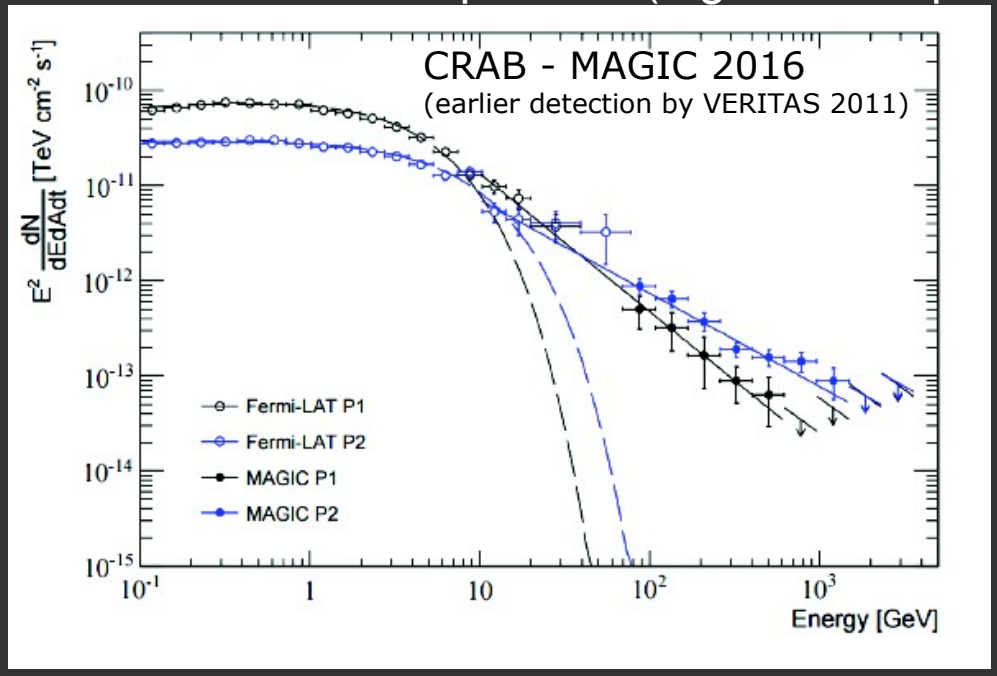


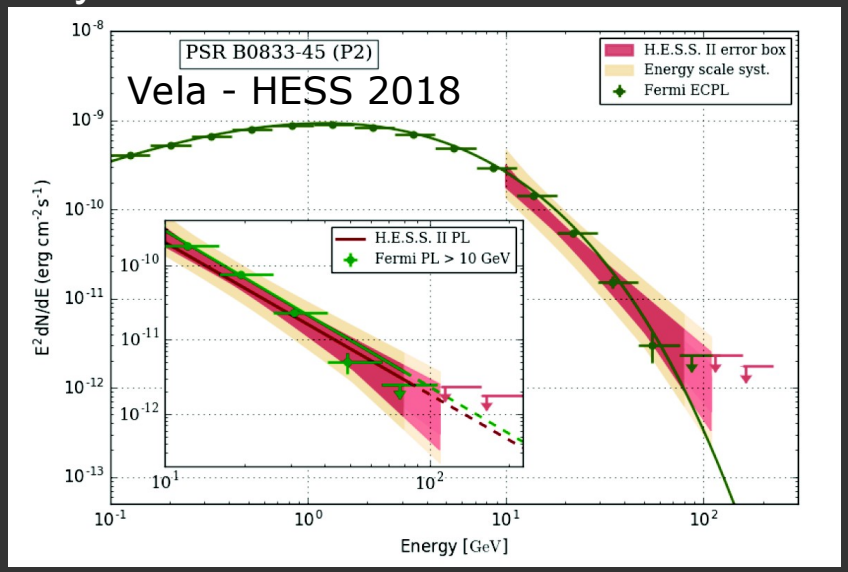


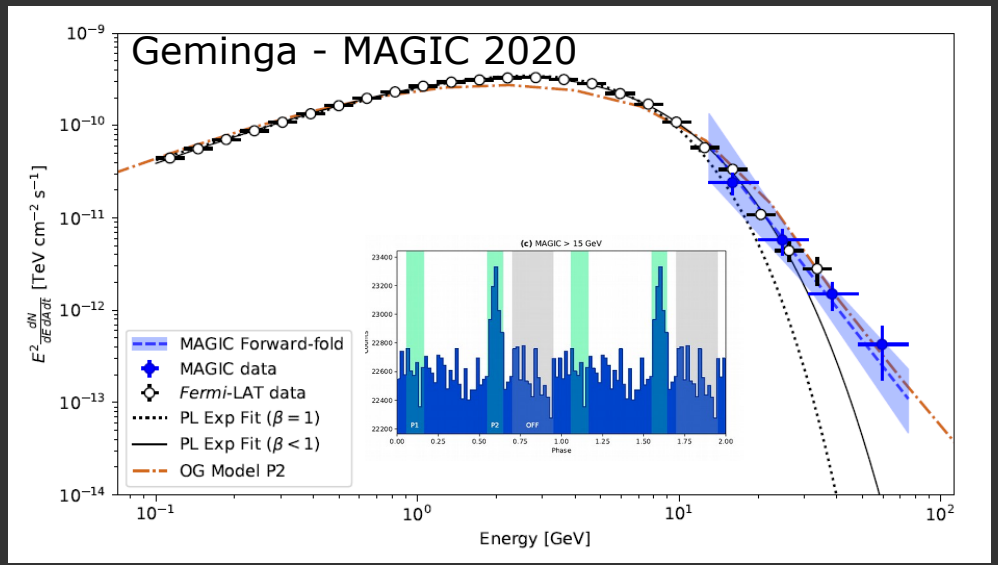
TeV Pulsars > 50 GeV – Now there are four!

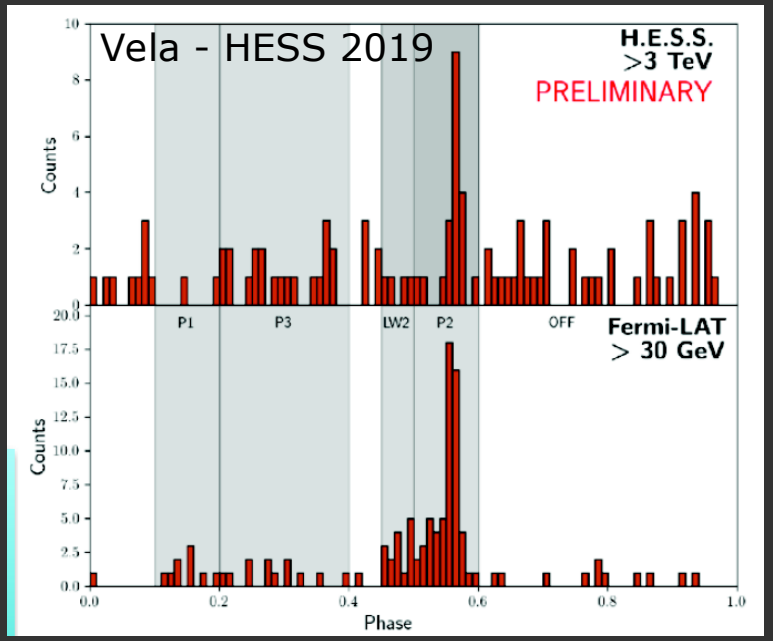
– Crab, Vela, PSR B1706-44, Geminga (brightest pulsars in Fermi-LAT 2PC)

→ New electron components (e.g. inv-Compton) beyond curvature radiation...









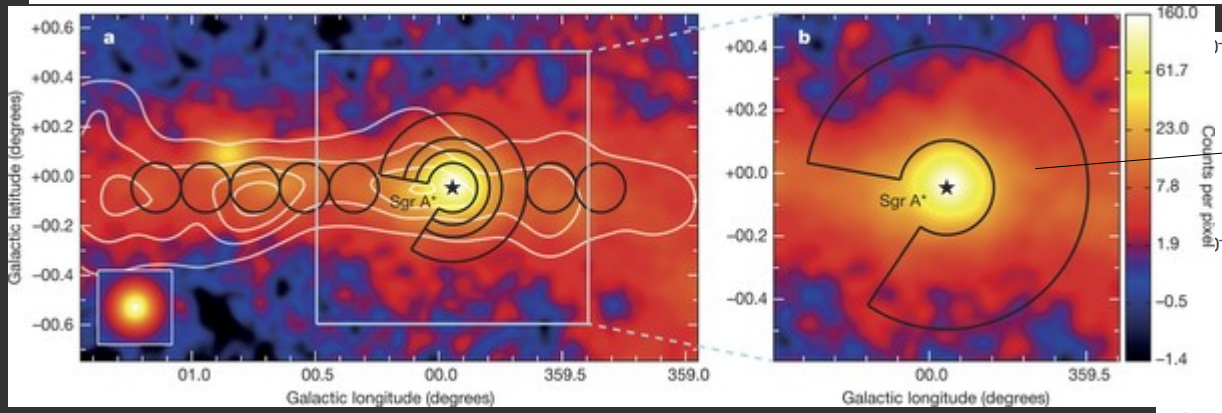
LETTER

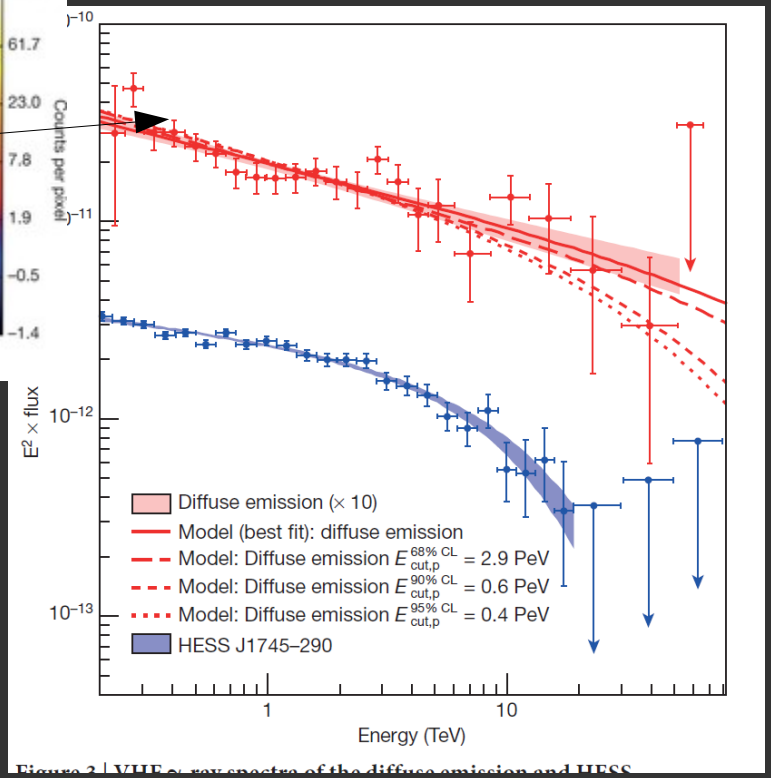
doi:10.1038/nature17147

Acceleration of petaelectronvolt protons in the Galactic Centre

HESS Collaboration*

H.E.S.S.





- Hard spectrum from diffuse region 70pc
- Cutoff ~ PeV energies
- Continous CR injector over ~few1000yr

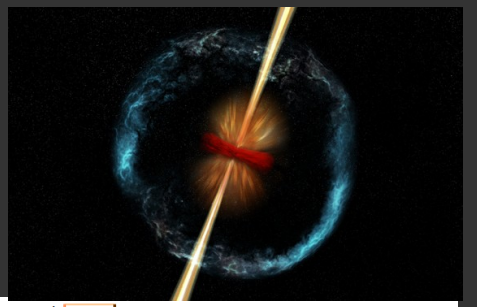
→ Central BH most likely accelerator

→ Could explain galactic CRs >0.1 PeV if BH more active in past.

(SNRs may still contribute some PeV CRs)

TeV Gamma Ray Bursts : A New Era Begins

(MAGIC 2019, HESS 2019)



First time detection of a GRB at sub-TeV energies; MAGIC detects the GRB 190114C

ATel #12390; ***Razmik Mirzoyan on behalf of the MAGIC Collaboration***
*on **15 Jan 2019; 01:03 UT***
Credential Certification: Razmik Mirzoyan (Razmik.Mirzoyan@mpp.mpg.de)

Subjects: Gamma Ray, >GeV, TeV, VHE, Request for Observations, Gamma-Ray Burst

Referred to by ATel #: 12395, 12475

Tweet

The MAGIC telescopes performed a rapid follow-up observation of GRB 190114C (Gropp et al., GCN 23688; Tyurina et al., GCN 23690, de Ugarte Postigo et al., GCN 23692, Lipunov et al. GCN 23693, Selsing et al. GCN 23695). This observation was triggered by the Swift-BAT alert; we started observing at about 50s after Swift T0: 20:57:03.19. The MAGIC real-time analysis shows a significance >20 sigma in the first 20 min of observations (starting at T0+50s) for energies >300GeV. The relatively high detection threshold is due to the large zenith angle of observations (>60 degrees) and the presence of partial Moon. Given the brightness of the event, MAGIC will continue the observation of GRB 190114C until it is observable tonight and also in the next days. We strongly encourage follow-up observations by other instruments. The MAGIC contact persons for these observations are R. Mirzoyan (Razmik.Mirzoyan@mpp.mpg.de) and K. Noda (nodak@icrr.u-tokyo.ac.jp). MAGIC is a system of two 17m-diameter Imaging Atmospheric Cherenkov Telescopes located at the Observatory Roque de los Muchachos on the Canary island La Palma, Spain, and designed to perform gamma-ray astronomy in the energy range from 50 GeV to greater than 50 TeV.

[Previous | Next | ADS]

GRB190829A: Detection of VHE gamma-ray emission with H.E.S.S.

ATel #13052; ***M. de Naurois (H. E.S. S. Collaboration)***
*on **30 Aug 2019; 07:12 UT***
Credential Certification: Fabian SchÃ¼ssler (fabian.schussler@cea.fr)

Subjects: Gamma Ray, >GeV, TeV, VHE, Gamma-Ray Burst

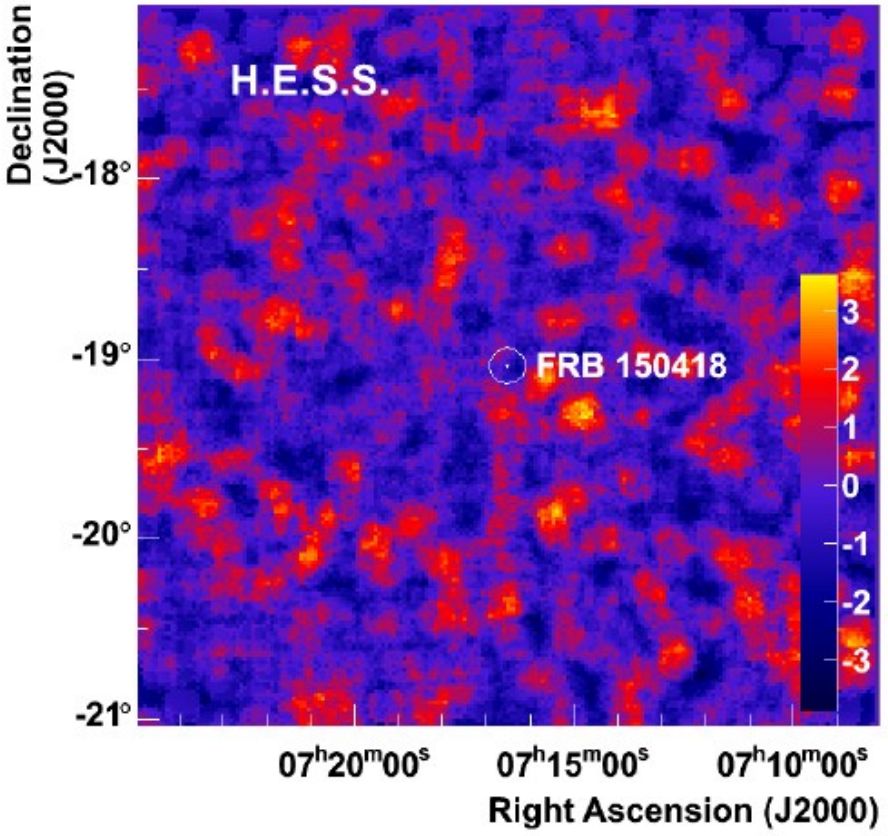
Tweet

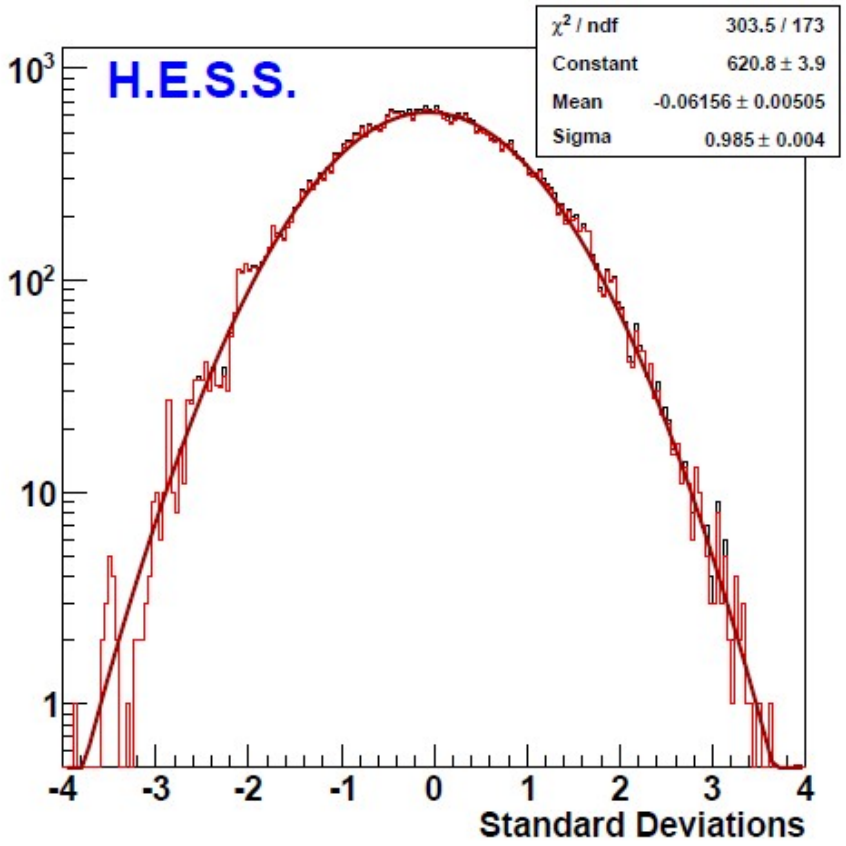
The H.E.S.S. array of imaging atmospheric Cherenkov telescopes was used to carry out follow-up observations of the afterglow of GRB 190829A (Dichiara et al., GCN 25552). At a redshift of z = 0.0785 +/- 0.005 (A.F. Valeev et al., GCN 25565) this is one of the nearest GRBs detected to date. H.E.S.S. Observations started July 30 at 00:16 UTC (i.e. T0 + 4h20), lasted until 3h50 UTC and were taken under good conditions. A preliminary onsite analysis of the obtained data shows a >5sigma gamma-ray excess compatible with the direction of GRB190829A. Further analyses of the data are on-going and further H.E.S.S. observations are planned. We strongly encourage follow-up at all wavelengths. H.E.S.S. is an array of five imaging atmospheric Cherenkov telescopes for the detection of very-high-energy gamma-ray sources and is located in the Khomas Highlands in Namibia. It was constructed and is operated by researchers from Armenia, Australia, Austria, France, Germany, Ireland, Japan, the Netherlands, Poland, South Africa, Sweden, UK, and the host country, Namibia. For more details see https://www.mpi-hd.mpg.de/hfm/HESS/

- Three TeV GRBs (LongGRBs) GRB180720B, GRB190114C, GRB1900829A
  z=0.653 0.424 0.079
- Two Nature papers so far.
- GRB190114C seen at >300 GeV at low elevation during moonlight!
  > 1000's photons > 50 GeV → gamma-ray spectra on sub-minute timescales
- Rapid radio follow-up planned (HESS+ATCA; Anderson etal)
  → polarisation; B-field; CSM; reverse/forward shock

HESS Follow-up of FRB 150418 (T+14.5hr)

- Triggered via email from the Parkes SUPERB team





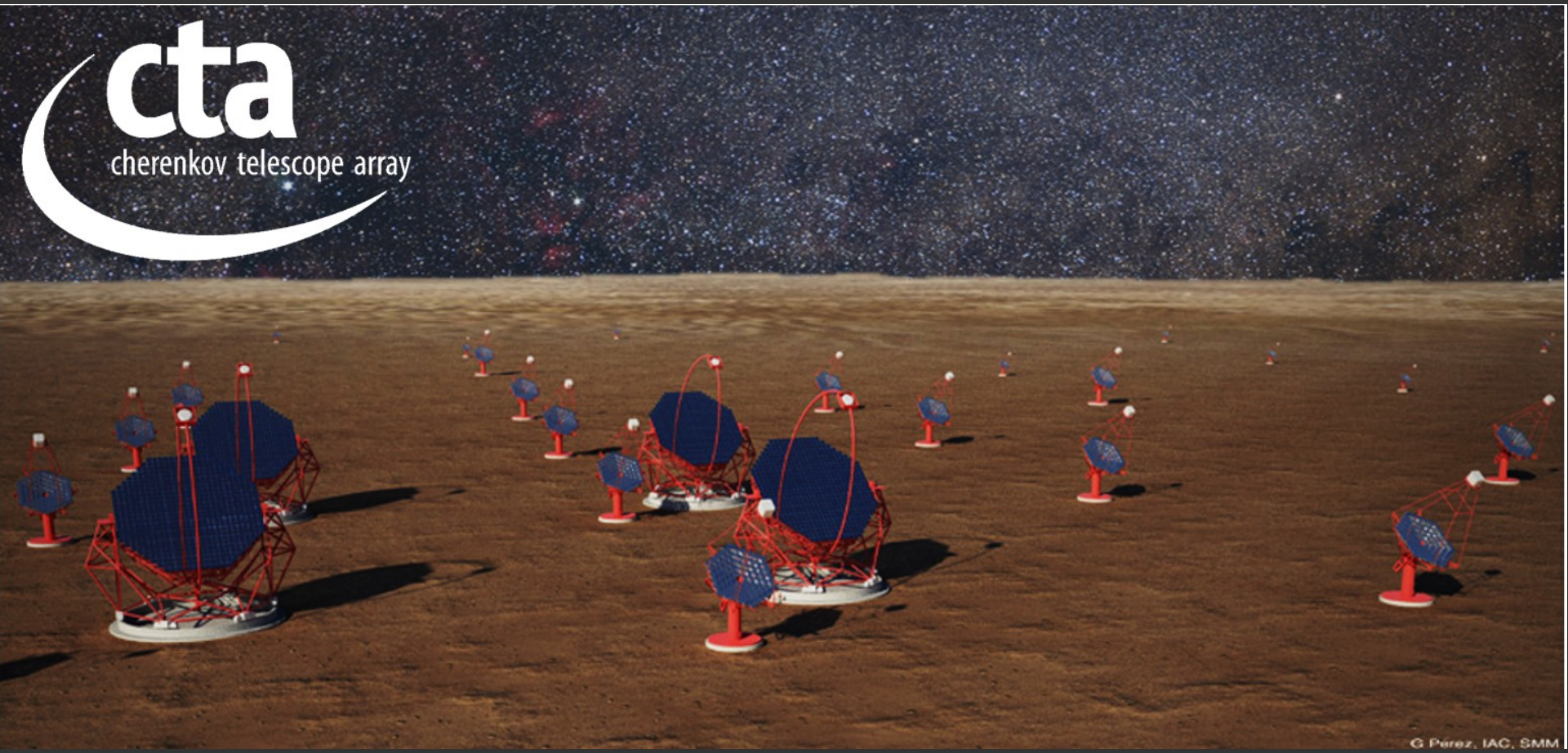
- TeV upper limit only (HESS+SUPERB A&A 2016)
- Also FRB150215 T+9days (Petroff etal MNRAS 2017)

→ Faster response needed: auto alerts & auto slewing ala GRBs

- Now receiving VOEvents from UTMOST FRB190806 (T+5hr)
- Auto-slewing with HESS → on-target in < few mins.

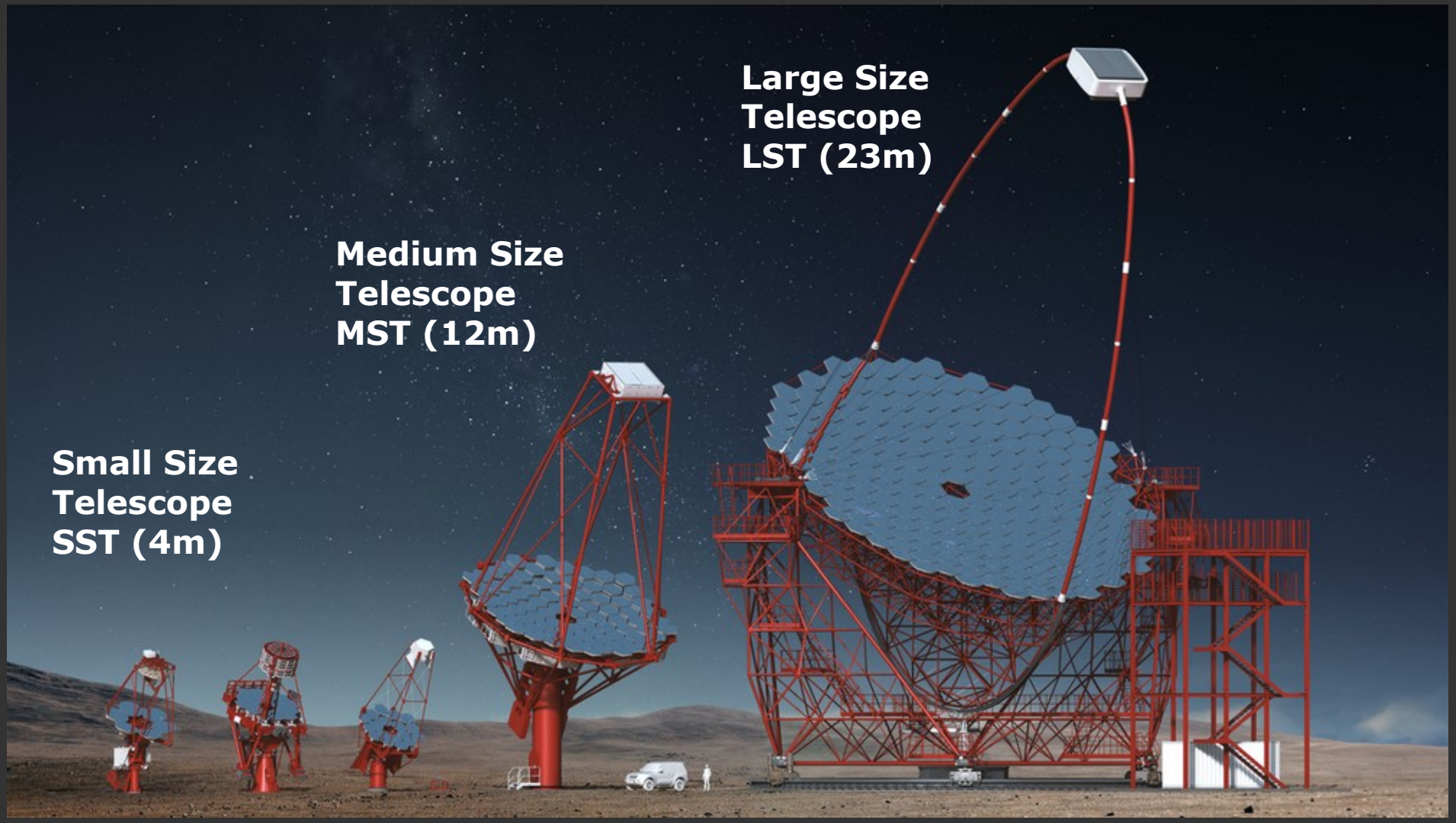
The Cherenkov Telescope Array : Next Generation TeV Gamma-Ray Observatory

https://www.cta-observatory.org/



>10 x better than HESS
Now under construction! Two sites (North ~10 tels & South ~ 75 tels) Phase I
> Full operation by 2026/7
> 30 countries involved; Australia (Adelaide, Sydney, WSU, UNSW, Monash, ANU)

CTA's Telescopes....



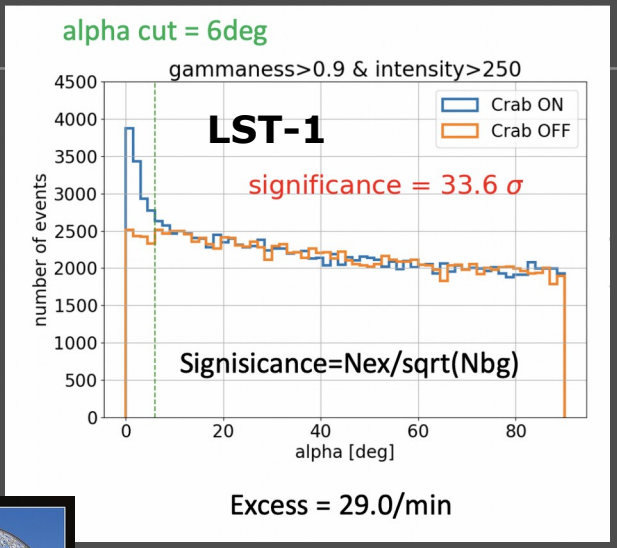
CTA Sites

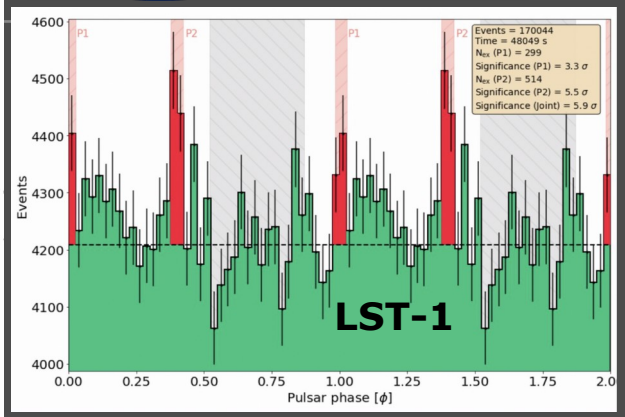
Zeuthen
DESY
CTA Science Data
Management Centre
CTA-North
Spain
La Palma
CTA HQ
Bologna
INAF
northern hemisphere
southern hemisphere
CTA-South
Chile
Paranal
La Palma Map: ©2015 Google, Inst. Geogr. Nacional
Paranal Map: ©2015 Google
Array Sites
Headquarters
Science Data Management Centre

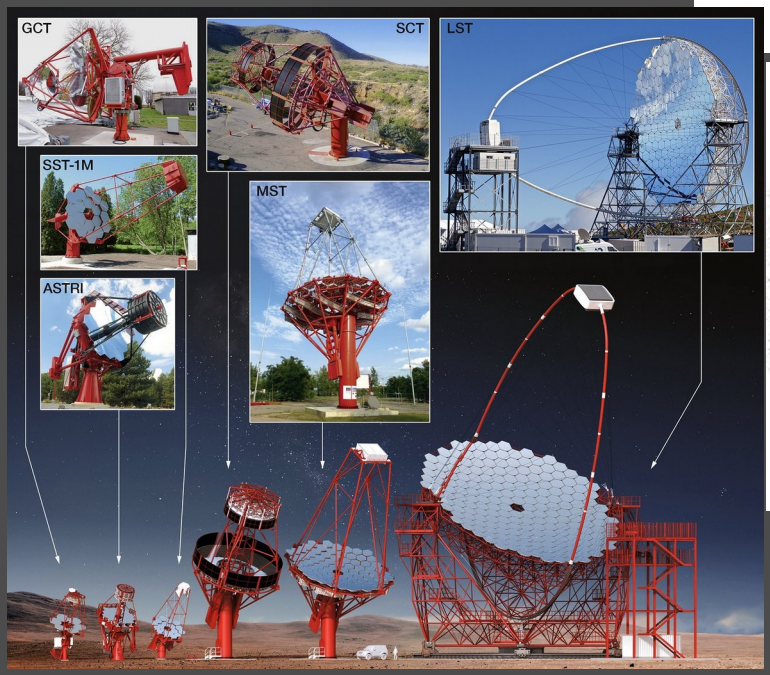
CTA's First Telescopes – They Work!

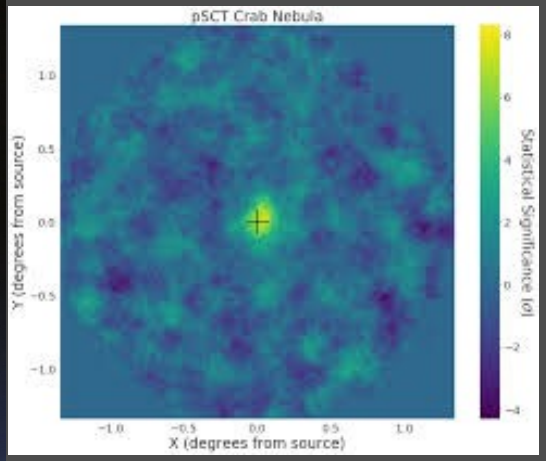
ie. real Cherenkov images; Detection of the Crab nebula, Crab pulsar and some AGN

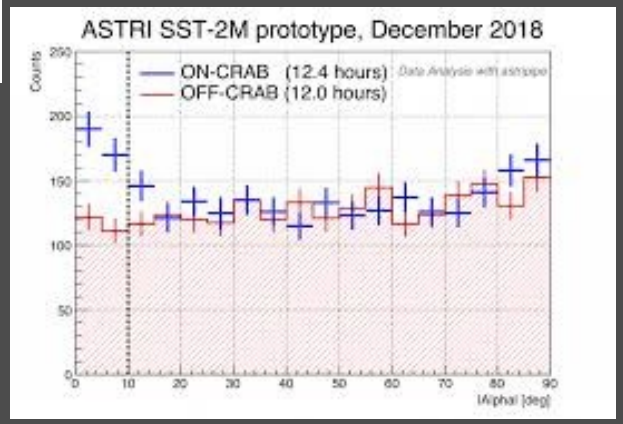
cherenkov telescope array

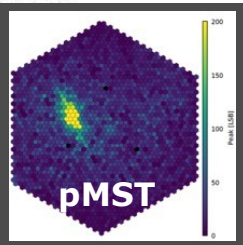


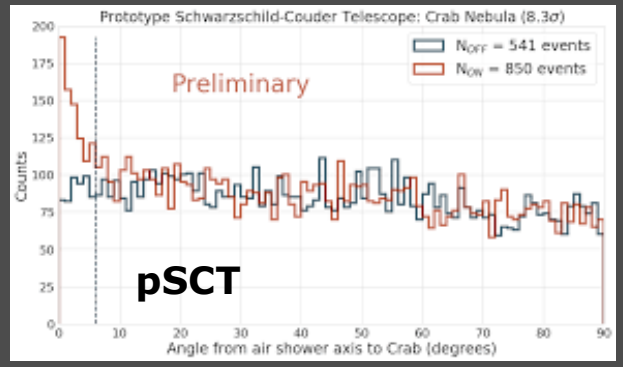








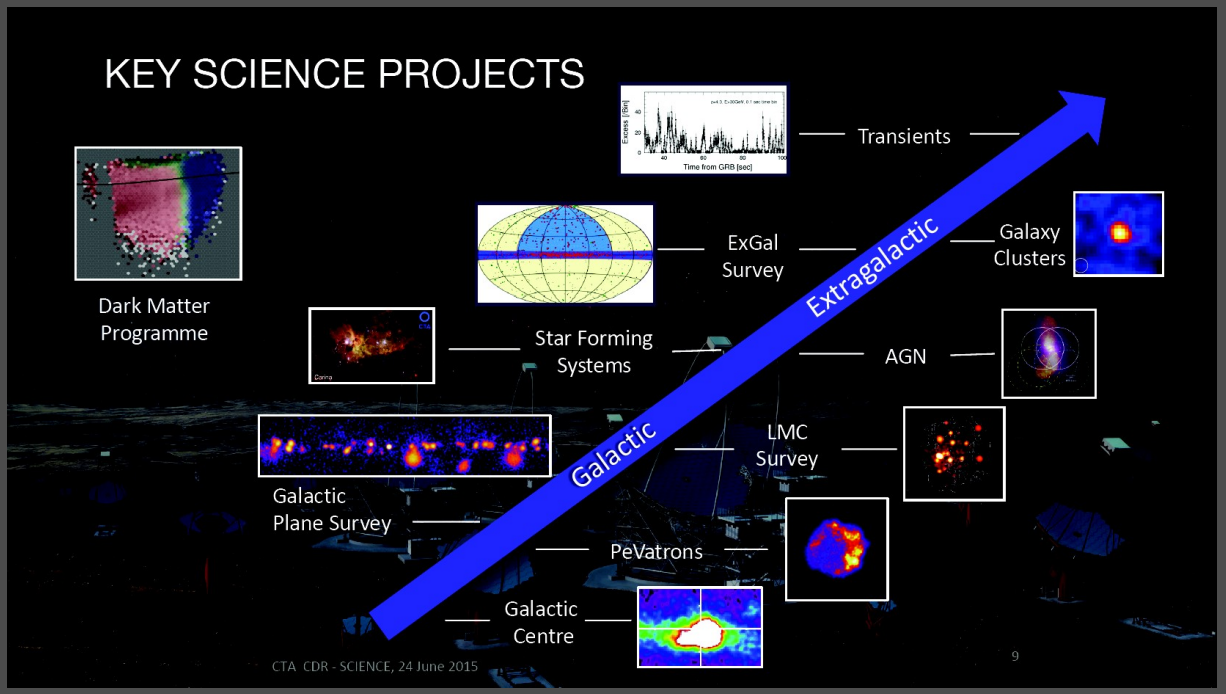


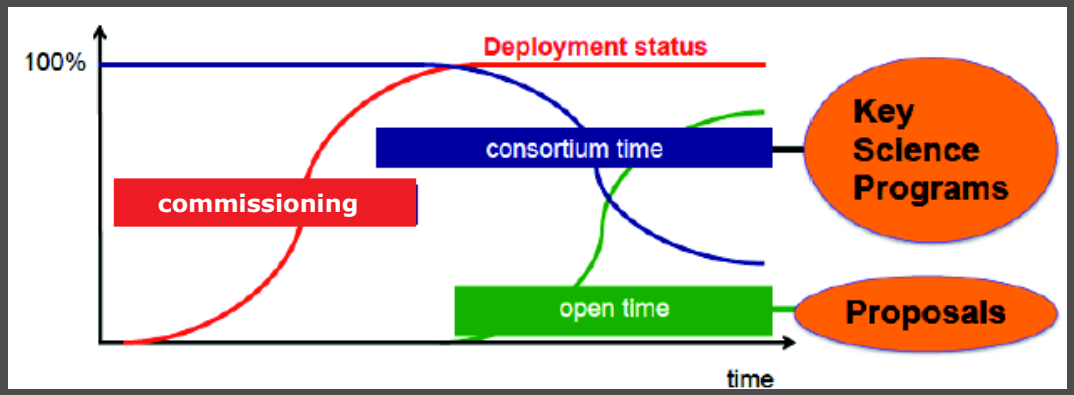


CTA's Science

Key Science Projects: ~40% of observing time in first 10 yrs devoted to major projects.

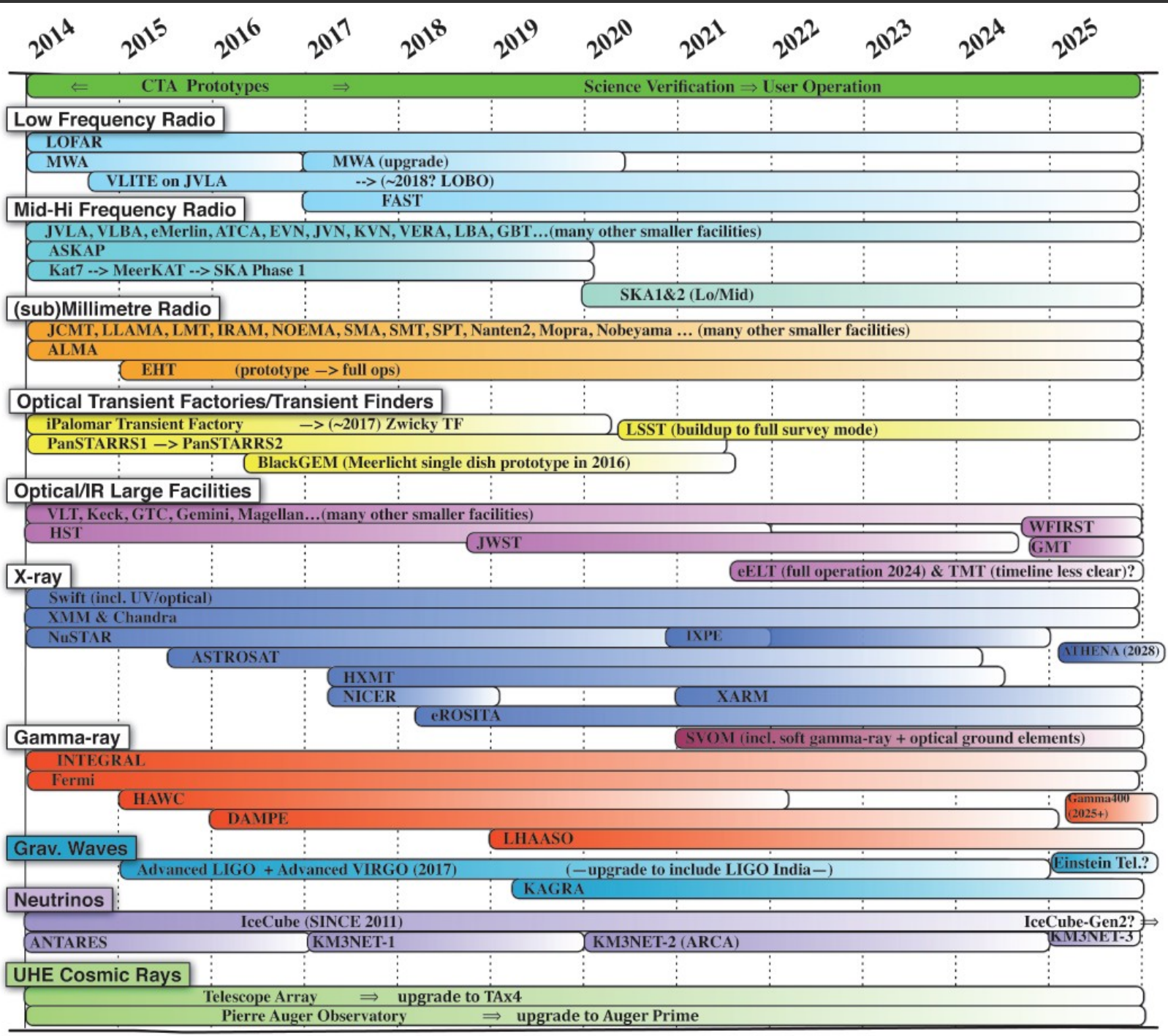
https://www.worldscientific.com/worldscibooks/10.1142/10986





Signficant multi-wavelength support needed.

e.g optical/radio coverage > 500 hr/yr


2014
2015
2016
2017
2018
2019
2020
2021
2022
2023
2024
2025
⇐ CTA Prototypes ⇒ Science Verification ⇒ User Operation
Low Frequency Radio
LOFAR
MWA
MWA (upgrade)
VLITE on JVLA
--> (~2018? LOBO)
FAST
Mid-Hi Frequency Radio
JVLA, VLBA, eMerlin, ATCA, EVN, JVN, KVN, VERA, LBA, GBT…(many other smaller facilities)
ASKAP
Kat7 --> MeerKAT --> SKA Phase 1
SKA1&2 (Lo/Mid)
(sub)Millimetre Radio
JCMT, LLAMA, LMT, IRAM, NOEMA, SMA, SMT, SPT, Nanten2, Mopra, Nobeyama … (many other smaller facilities)
ALMA
EHT (prototype —> full ops)
Optical Transient Factories/Transient Finders
iPalomar Transient Factory —> (~2017) Zwicky TF
LSST (buildup to full survey mode)
PanSTARRS1 —> PanSTARRS2
BlackGEM (Meerlicht single dish prototype in 2016)
Optical/IR Large Facilities
VLT, Keck, GTC, Gemini, Magellan…(many other smaller facilities)
HST
WFIRST
JWST
GMT
eELT (full operation 2024) & TMT (timeline less clear)?
X-ray
Swift (incl. UV/optical)
XMM & Chandra
NuSTAR
IXPE
ATHENA (2028)
ASTROSAT
HXMT
NICER
XARM
eROSITA
Gamma-ray
SVOM (incl. soft gamma-ray + optical ground elements)
INTEGRAL
Fermi
HAWC
Gamma400 (2025+)
DAMPE
LHAASO
Grav. Waves
Einstein Tel.?
Advanced LIGO + Advanced VIRGO (2017)
(—upgrade to include LIGO India—)
KAGRA
Neutrinos
IceCube (SINCE 2011)
IceCube-Gen2? ⇒
ANTARES
KM3NET-1
KM3NET-2 (ARCA)
KM3NET-3
UHE Cosmic Rays
Telescope Array ⇒ upgrade to TAx4
Pierre Auger Observatory ⇒ upgrade to Auger Prime

CTAO-SKAO MoU (29 January 2020)

https://www.cta-observatory.org/ctao-signs-cooperation-agreement-with-the-skao/

The CTAO Signs Cooperation Agreement with the Square Kilometre Array Organisation - Cherenkov Telescope Array

29 January 2020 – The Cherenkov Telescope Array Observatory (CTAO) and the Square Kilometre Array Organisation (SKAO) will engage in closer collaboration under a new agreement signed by the two research infrastructures. The Memorandum of Understanding (MOU) will facilitate greater sharing of knowledge and expertise in areas including engineering, science, technology and administration.

The CTAO and SKAO are both large international collaborations and have several member countries in common, including many European countries but also astronomy organisations in Australia and South Africa. Like CTA, which will have two arrays of telescopes on different continents observing gamma rays, one in Chile and one on La Palma in the Canary Islands (Spain), the SKA will also have radio telescopes in Australia and South Africa. The two observatories are due to begin delivering science within just a few years of each other.

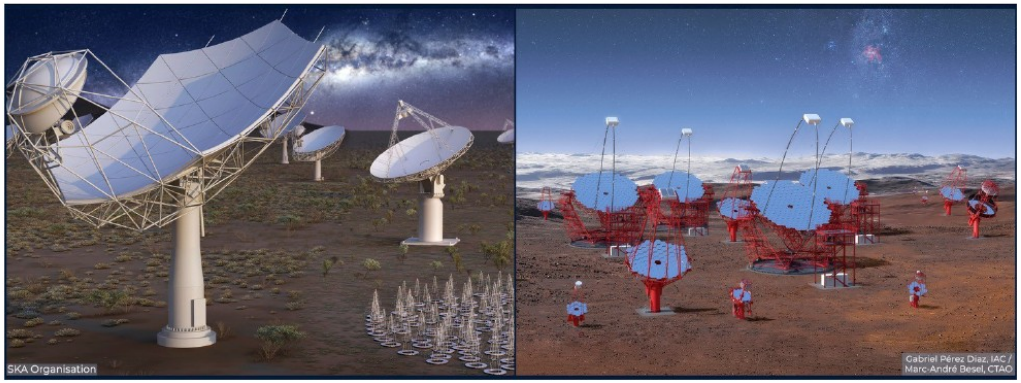
Both have also begun transitions on the governance front; the CTAO is becoming a European Research Infrastructure Consortium (ERIC), while the SKA is becoming an intergovernmental organisation or IGO.

"In this age of multi-messenger astronomy, building alliances with observatories across the spectrum is critical to achieving our common missions to expand our view and understanding of the Universe," says Federico Ferrini, CTAO Managing Director. "The CTAO-SKAO partnership was an obvious fit due to our vast similarities, and we are looking forward to the collaboration."

"Both the SKA and CTA are pushing the boundaries of what's possible technically, scientifically and logistically, and some of the challenges that brings are common to both projects," says Simon Berry, Director of Strategy for the SKA. "This MOU formalises our relationship, so we can keep learning from each other's experiences and share expertise for the benefit of both observatories."

While the respective telescopes will observe opposite ends of the electromagnetic spectrum, there are exciting areas of scientific synergy between them. Both radio and gamma rays are a probe of the violent and variable Universe, including the study of active galactic nuclei, transient events such as gamma-ray bursts and fast radio bursts, accretion into compact objects and gravitational wave counterparts.

As the world's largest radio telescope, SKA is one of several next-generation facilities targeting cosmic sources by detecting other wavelengths or messengers (such as neutrinos or gravitational waves) that will be complementary to CTA. Coordinated observations between such facilities can give a more complete picture of astronomical sources and phenomena, resulting in greatly enhanced scientific discoveries.

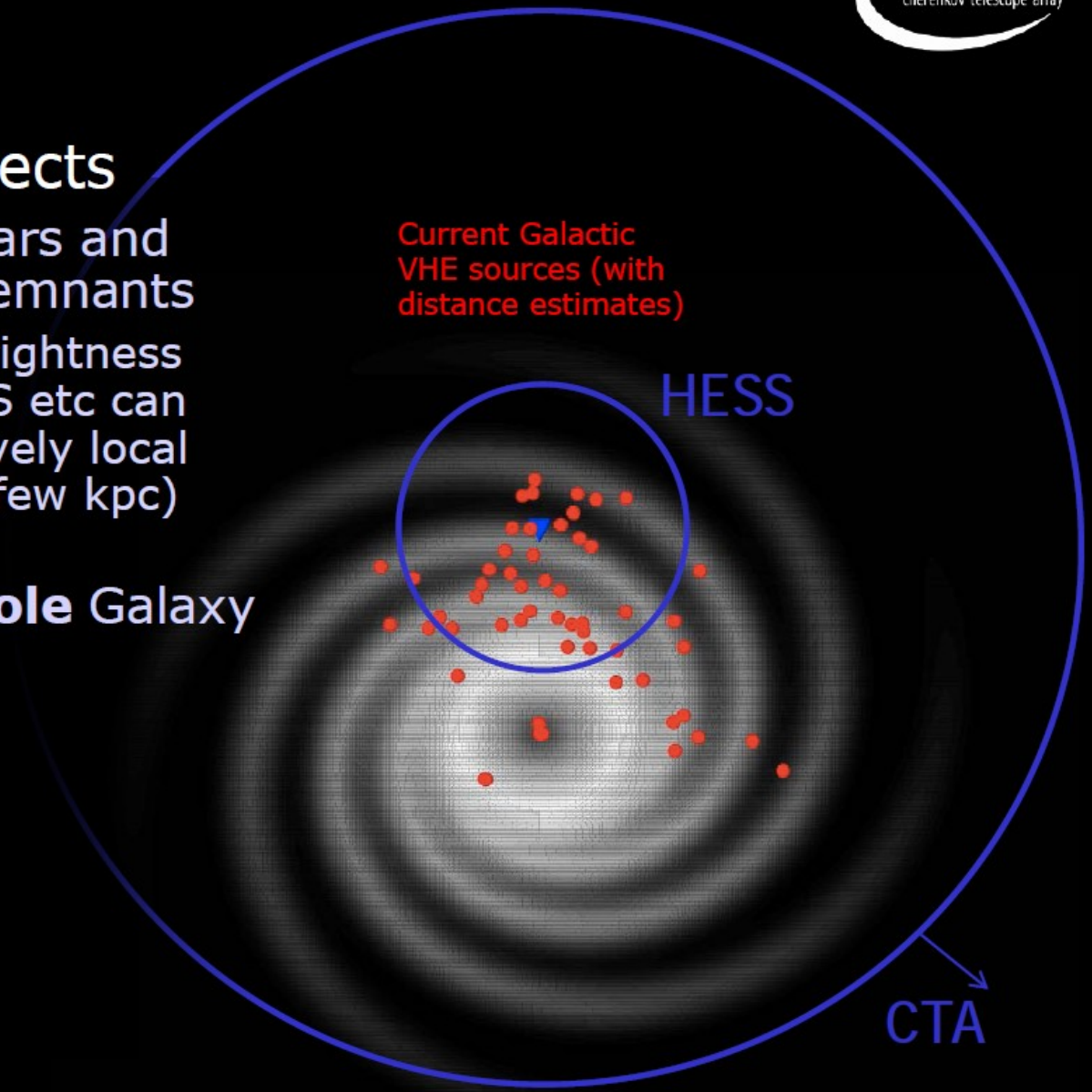


Science 'white paper' under discussion.

Similar discussions with other future observatories, e.g. Athena (X-rays).

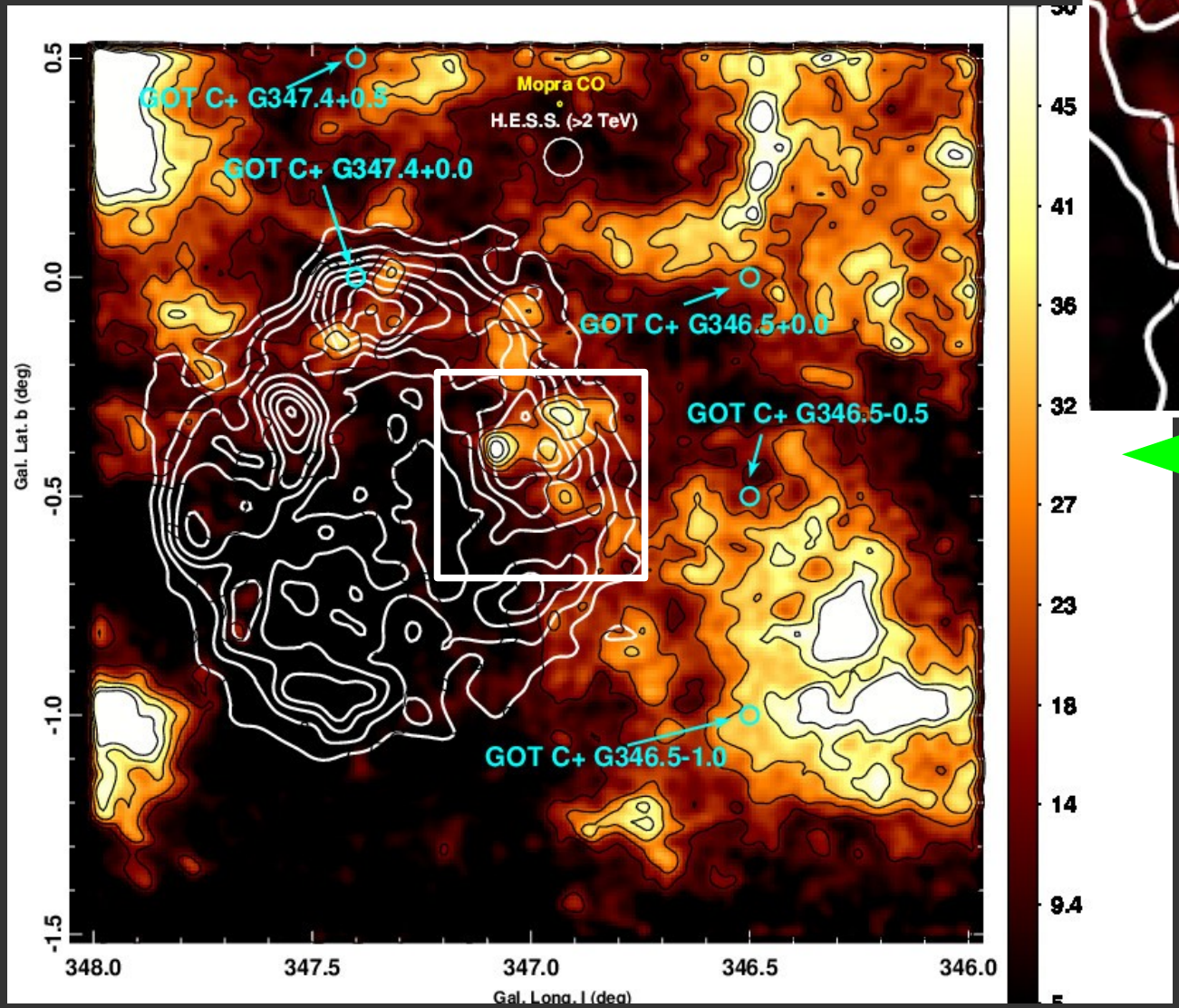
CTA Galactic Science

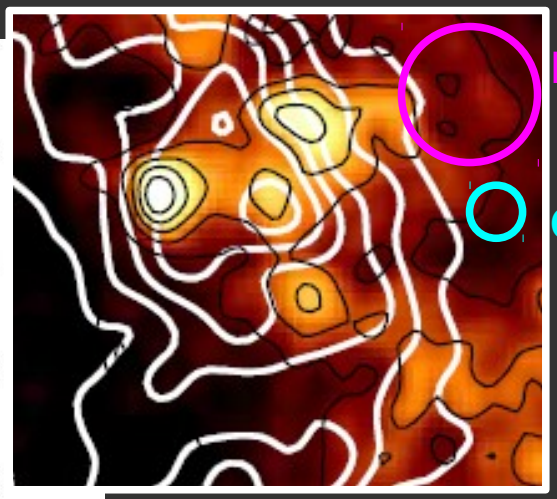
- e.g. Galactic objects
  - Newly born pulsars and the supernova remnants
    - have typical brightness such that HESS etc can see only relatively local (typically at a few kpc) objects
  - CTA will see **whole** Galaxy
- Survey speed ~300×HESS



Young SNR RXJ1713 TeV and ISM on Parsec Scales!

Mopra CO(1-0) Image + HESS > 2 TeV contours



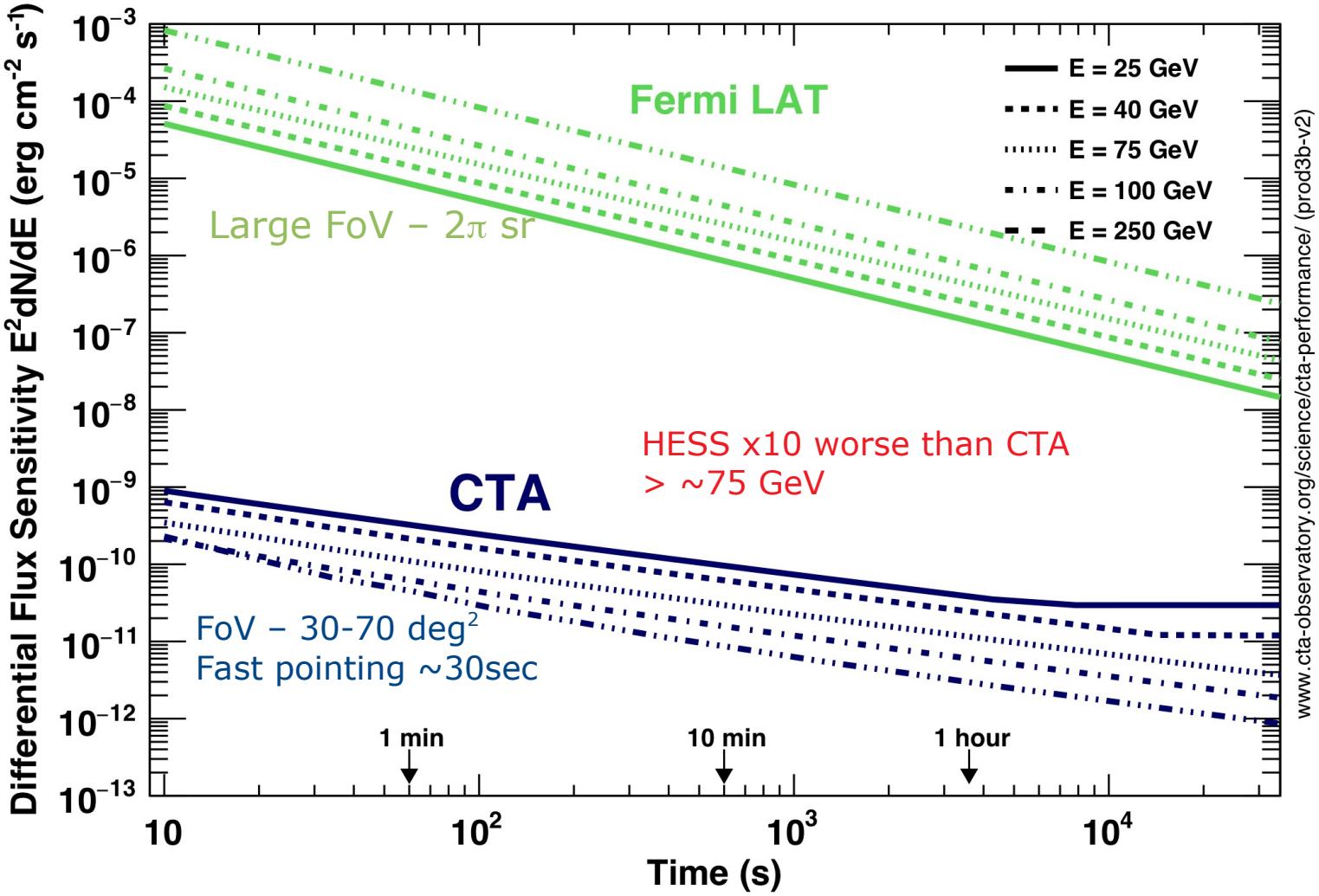


7 pc

CTA will finally be able to probe diffusion properties of hadronic cosmic rays

Transients & Variable Sources: CTA Sensitivity vs. Time

(CTA Collab 2019)



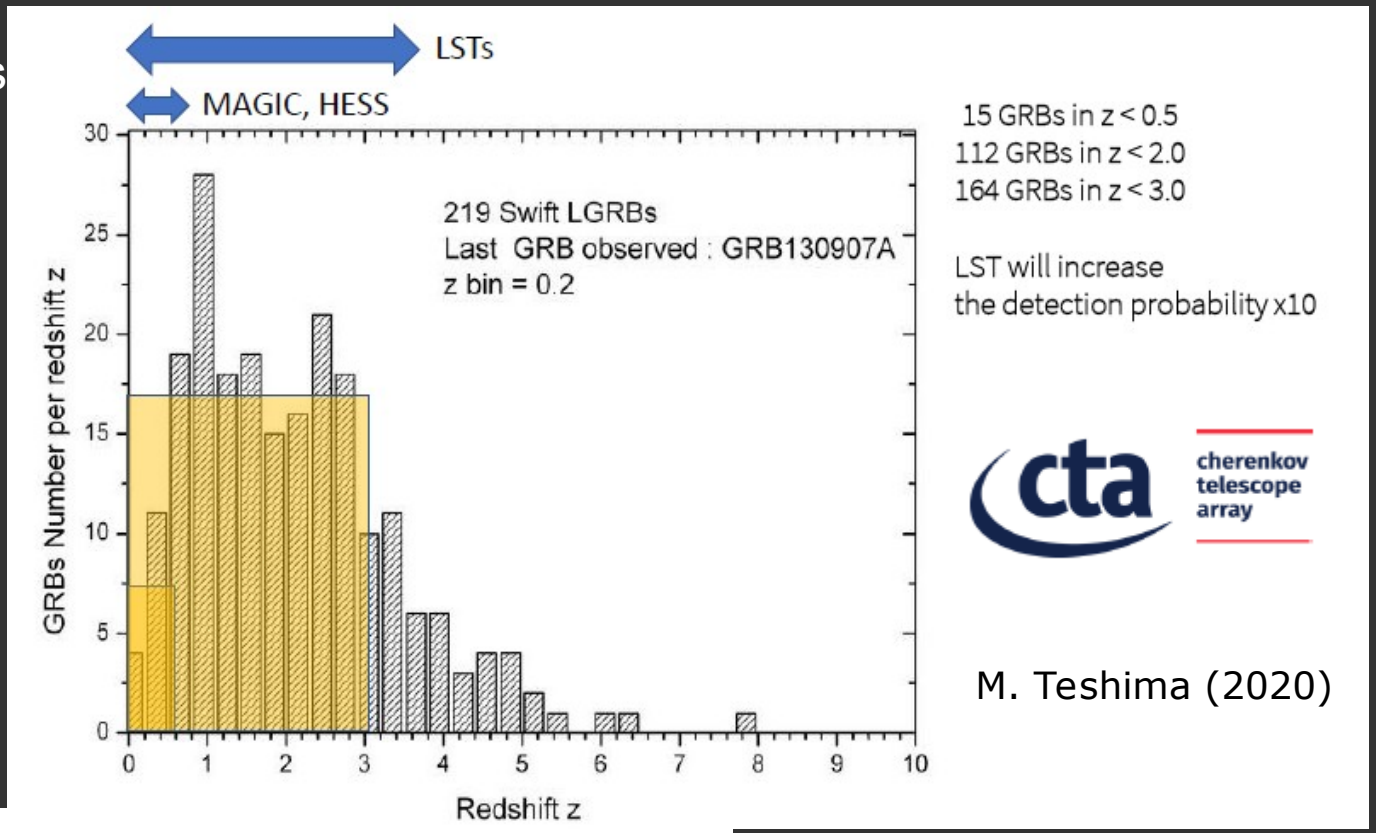
CTA >10,000 times more sensitive than Fermi-LAT in multi-GeV range

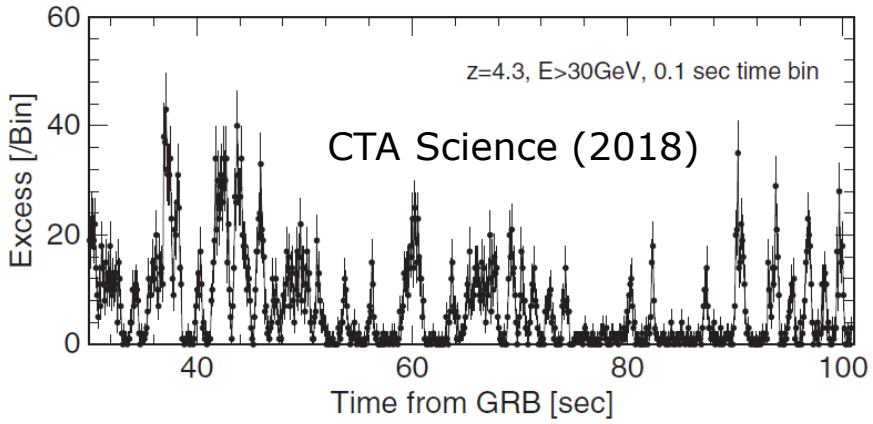
→ GRBs, AGN, giant pulses, FRBs, GW, SGR bursts.....

CTA's Prospects for TeV GRBs

CTA will reach GRBs out to z ~4

Light curves and seconds resolution and spectra within a minute!





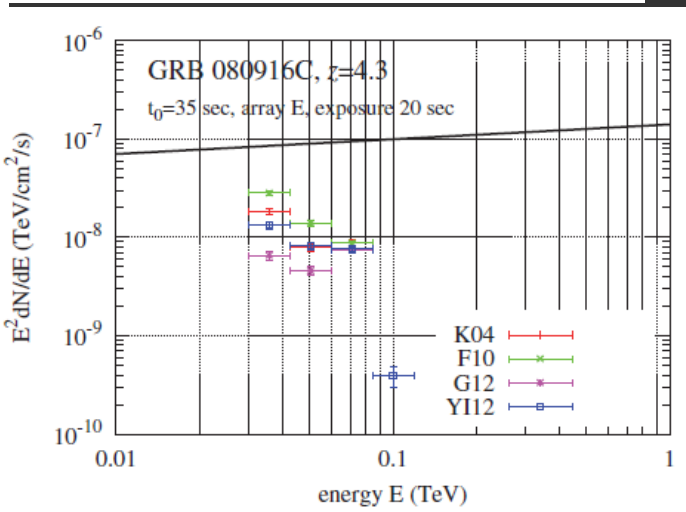
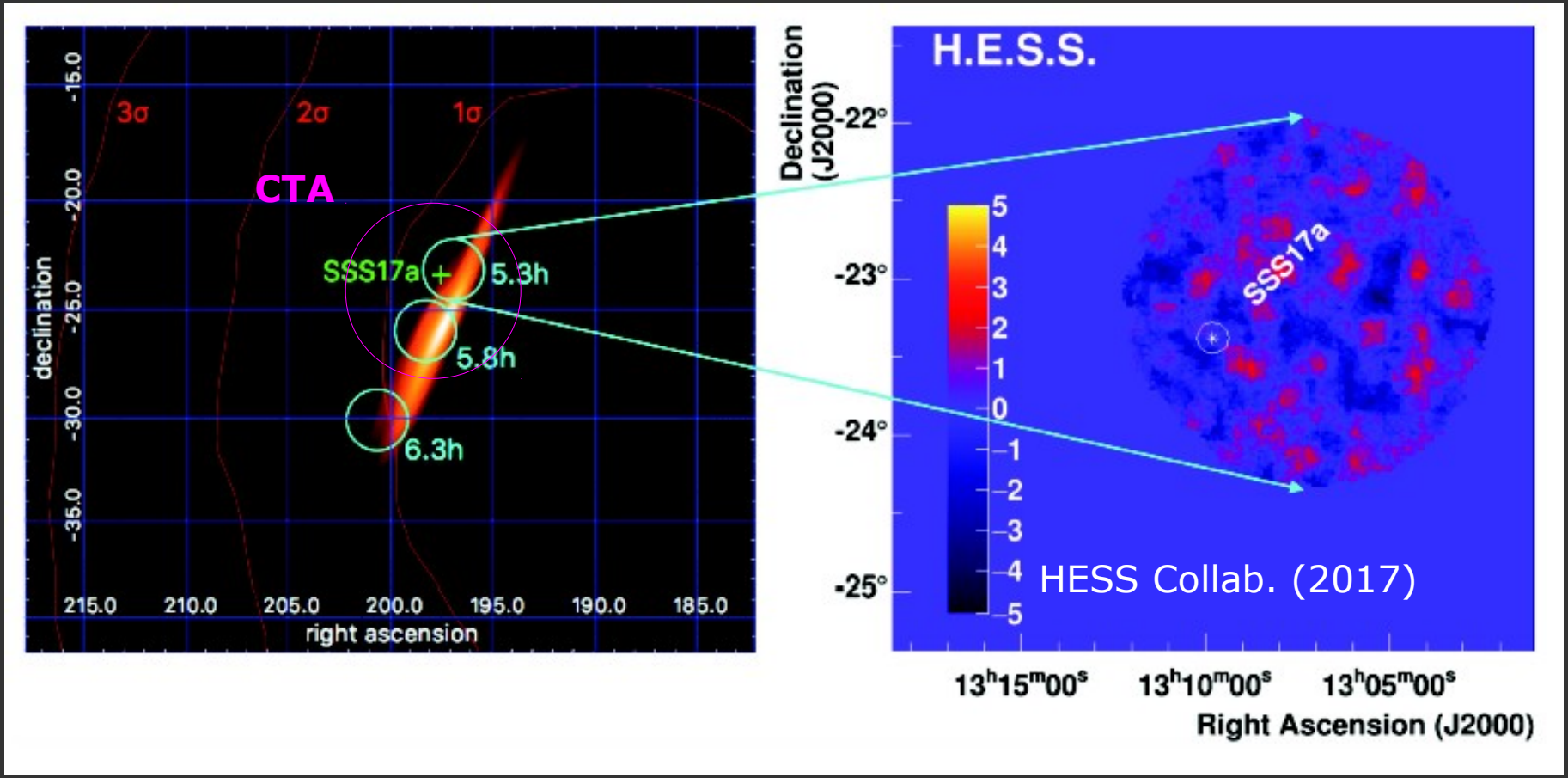


Figure 1.6: Simulated CTA GRB light curve, based on the Fermi-LAT-detected GRB 080916C at $z = 4.3$. See Figure 9.1 for more details.

GW170817 (ns-ns) – HESS Follow-up

- 5.3h after GW event (first pointed telescope on target!)

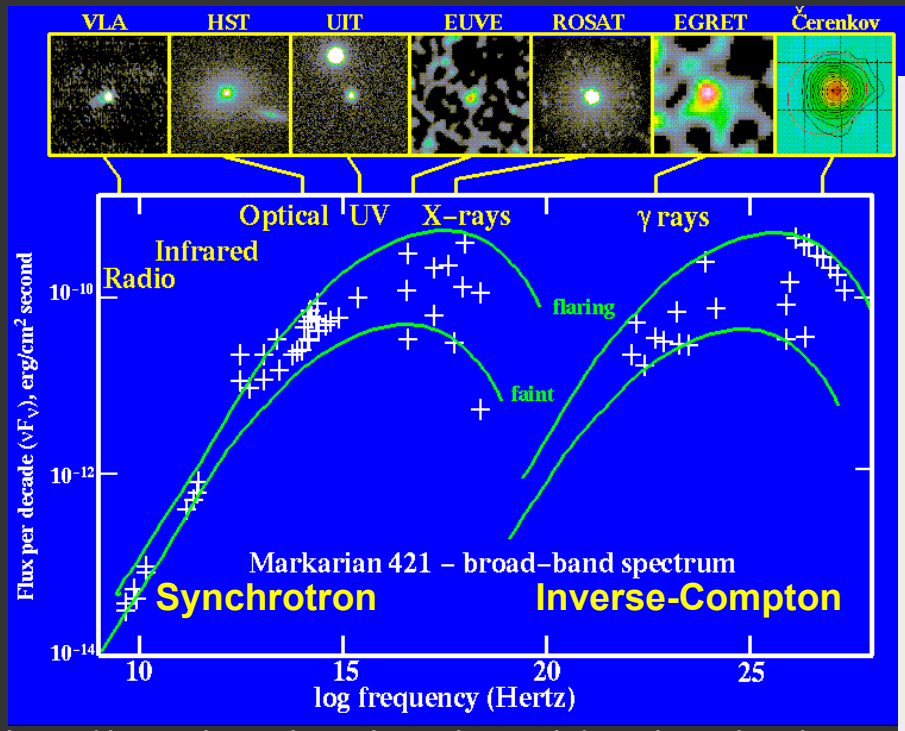


FoV FWHM: HESS ~3.0 deg

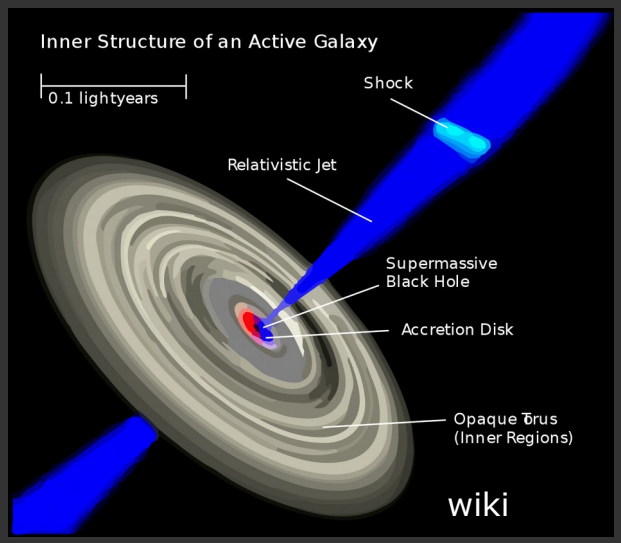
CTA 5.0 ~ 7.0 deg

- TeV upper limit only.
- EM counterparts in radio, optical, X-ray

AGN Blazars : Radio to TeV



http://vega.bac.pku.edu.cn/~wuxb/agn/text.html



TeVCat v2 Extragalactic Sources (z <~ 1)

http://tevcat2.uchicago.edu/

RegExp Search | × XGal | Filter by Observer | AND | AND | Sync To Map | Filter Selected | Reset | Table Columns

Name	RA	Dec	Type Tags	Distance	Catalog	Seen By?
S3 0218+35	02 21 05.5	+35 56 14	XGal,AGN,Blzr,F...	z=0.954	Default Catalog	MAGIC
3C 279	12 56 11.1	-05 47 22	XGal,AGN,Blzr,F...	z=0.5362	Default Catalog	MAGIC
PG 1553+113	15 55 44.7	+11 11 41	XGal,AGN,Blzr,B...	z=0.5	Default Catalog	VERITAS,MAGIC,...
1ES 0033+595	00 35 16.8	+59 47 24.0	XGal,AGN,Blzr,B...	z=0.467	Default Catalog	MAGIC
1ES 0647+250	06 50 46.5	+25 03 00	XGal,AGN,Blzr,B...	z=0.45	Newly Announced	VERITAS,MAGIC
4C +21.35	12 24 54.4	+21 22 46	XGal,AGN,Blzr,F...	z=0.432	Default Catalog	VERITAS,MAGIC
PKS 1510-089	15 12 52.2	-09 06 21.6	XGal,AGN,Blzr,F...	z=0.361	Default Catalog	MAGIC,H.E.S.S.
PKS 0447-439	04 49 28.2	-43 50 12	XGal,AGN,Blzr,B...	z=0.343	Default Catalog	H.E.S.S.
3C 66A	02 22 41.6	+43 02 35.5	XGal,AGN,Blzr,B...	z=0.34	Default Catalog	Crimea,VERITAS
1ES 0502+675	05 07 56.2	+67 37 24	XGal,AGN,Blzr,B...	z=0.340	Newly Announced	VERITAS
OT 081	17 51 32.82	+09 39 00.73	XGal,Blzr,BLLac,...	z=0.322	Newly Announced	MAGIC
S5 0716+714	07 21 53.4	+71 20 36	XGal,AGN,Blzr,B...	z=0.31	Default Catalog	MAGIC
1ES 0414+009	04 16 52.96	+01 05 20.4	XGal,AGN,Blzr,B...	z=0.287	Default Catalog	VERITAS,H.E.S.S.
PKS 0301-243	03 03 23.49	-24 07 35.86	XGal,AGN,Blzr,B...	z=0.2657	Default Catalog	H.E.S.S.
S2 0109+22	01 12 05.8	+22 44 39	XGal,AGN,Blzr,IBL	z=0.265	Newly Announced	MAGIC
1RXS J023832.6-311658	02 38 32.5	-31 16 58	XGal,Blzr,BLLac,...	z=0.232	Newly Announced	H.E.S.S.
MS 1221.8+2452	12 24 24.2	+24 36 24	XGal,AGN,Blzr,B...	z=0.218	Newly Announced	MAGIC
1ES 1011+496	10 15 04.1	+49 26 01	XGal,AGN,Blzr,B...	z=0.212	Default Catalog	VERITAS,MAGIC
RBS 0723	08 47 12.9	+11 33 50	XGal,AGN,Blzr,B...	z=0.198	Newly Announced	MAGIC
RBS 0413	03 19 47	+18 45 42	XGal,AGN,Blzr,B...	z=0.19	Default Catalog	VERITAS
PKS 0736+017	07 39 18.0	+01 37 05	XGal,Blzr,FSRQ	z=0.18941	Newly Announced	H.E.S.S.
1ES 0347-121	03 49 23.0	-11 58 38	XGal,AGN,Blzr,B...	z=0.188	Default Catalog	H.E.S.S.
1ES 1101-232	11 03 36.5	-23 29 45	XGal,AGN,Blzr,B...	z=0.186	Default Catalog	H.E.S.S.

Sources Listed: 74

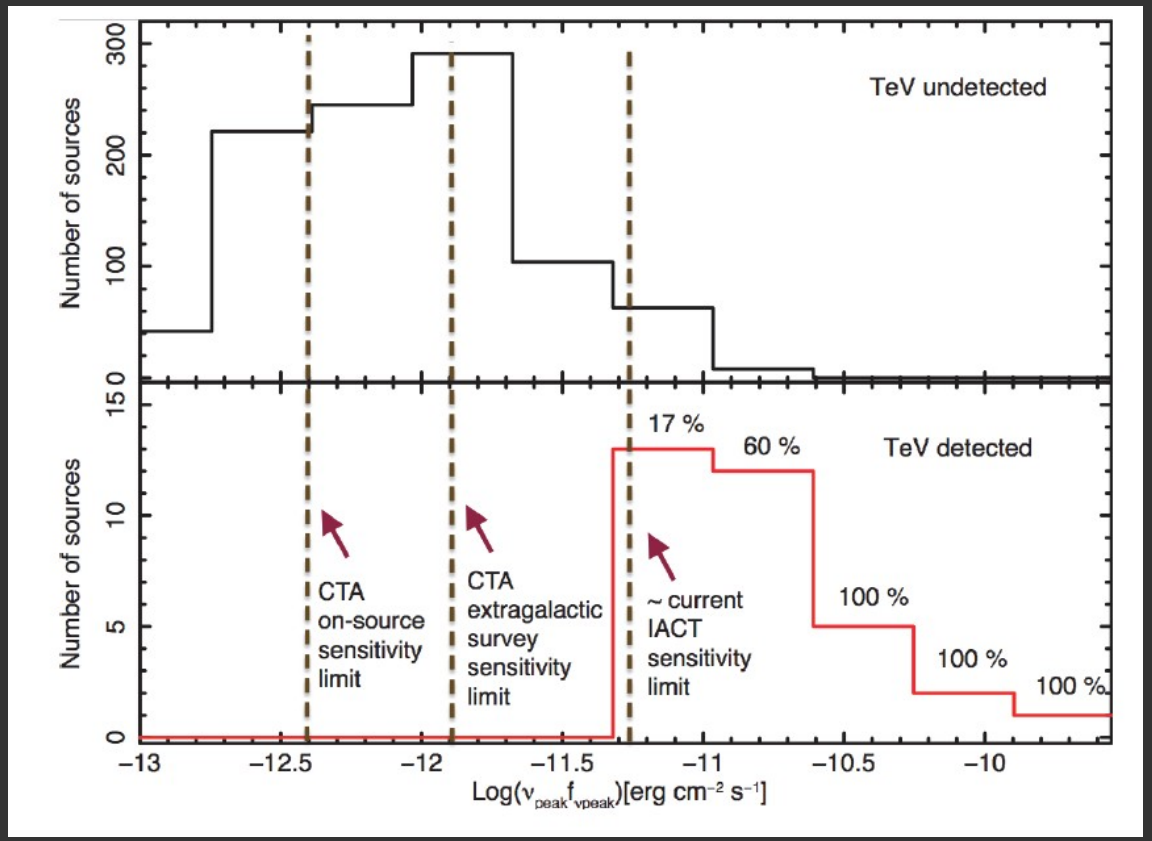
CTA's Prospects for AGN

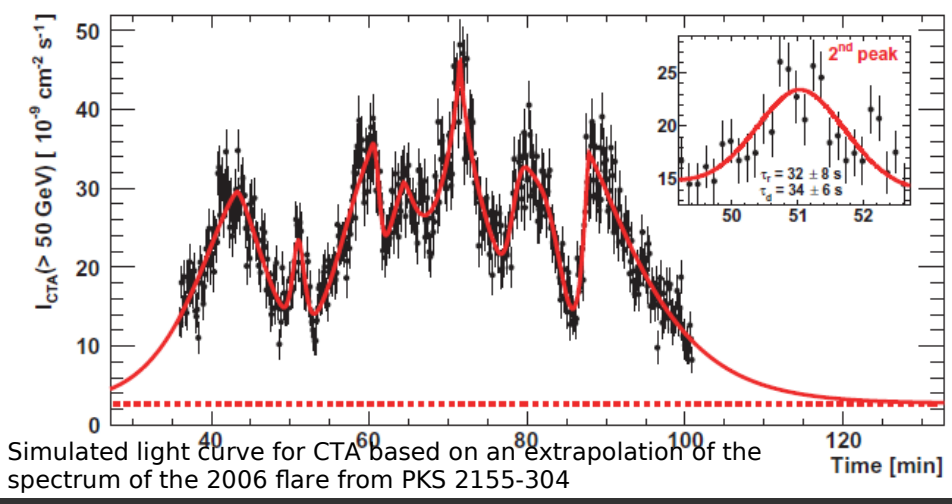
CTA will detect many 100s of AGN to z~2

FoV up to 10 degrees → several AGN in FoV at same time.

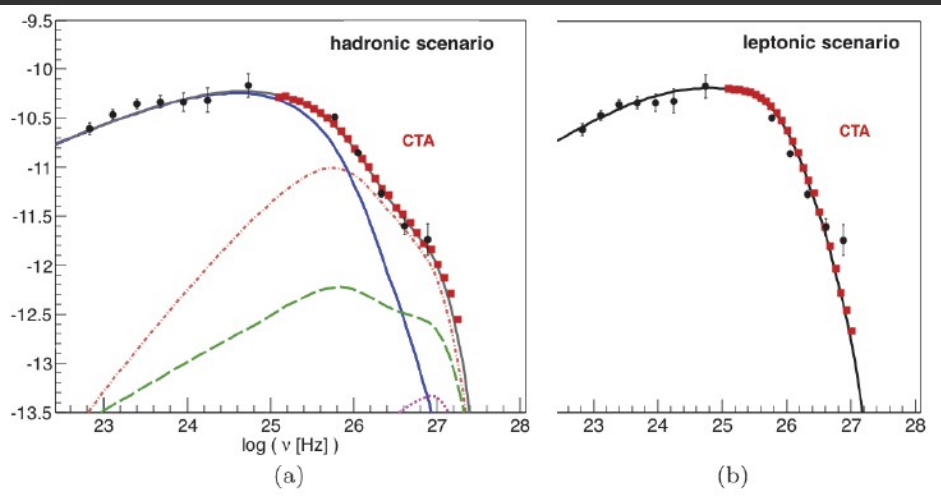
Light curve details down to sub-minutes.

Spectral resolution to reveal sub-components:
- Hadronic (synchrotron from protons, muons, + secondaries)
- Leptonic (SSC)



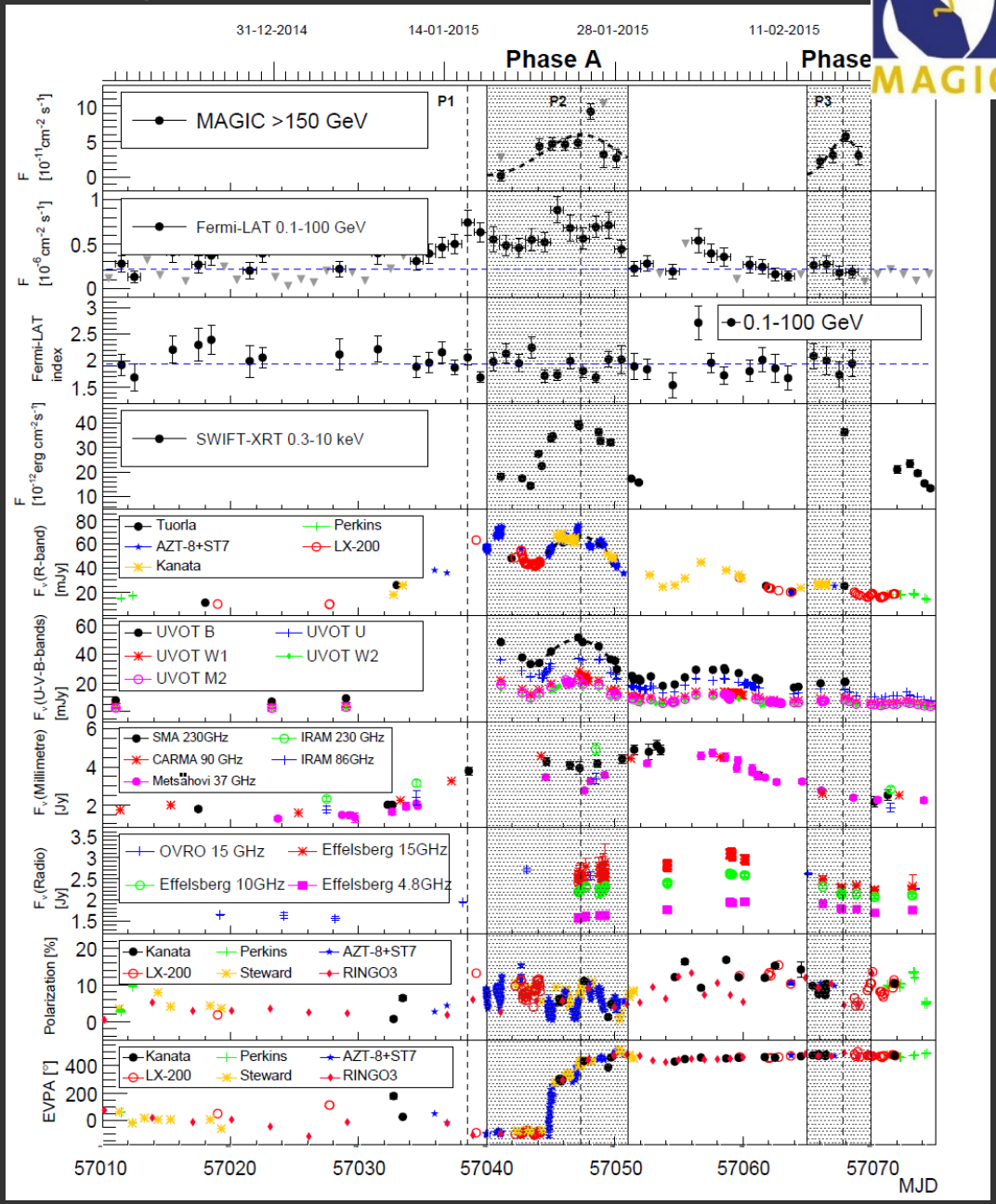


Simulated light curve for CTA based on an extrapolation of the spectrum of the 2006 flare from PKS 2155-304



AGN Flares : Many Synergies!

MWL light-curve (MAGIC 2018)



BL-Lac S5 0716+714

- AGN flare radio to TeV.
- Polarisation angle swing looks very interesting!
- CTA is considering its own on-site 1m class telescopes

1. Limiting magnitude 20 for photometry
2. Limiting magnitude 17 for polarimetry
3. Polarimetric accuracy 0.5 to 1%
4. 5'x5' Field of View (FoV)
5. Intranight cadence
6. Fast (< 2 arc-min) re-pointing

- 2m class telescope access via MoUs etc.

<u>Australia:</u>

Unique longitude coverage in S hemisphere (optical/radio)

H.E.S.S. and ATOM detect a high flux state in the blazar PKS 1510-089

ATel #12965; ***Mathieu de Naurois for the H. E.S. S. Collaboration***
*on **30 Jul 2019; 12:04 UT***
Credential Certification: Michael Zacharias (mz@tp4.rub.de)

Subjects: VHE, Request for Observations, AGN, Blazar, Quasar

Tweet

The High Energy Stereoscopic System (H.E.S.S.) conducted observations on the flat spectrum radio quasar PKS 1510-089 (z=0.361) last night (July 29, 2019) as part of its regular monitoring campaign on this source. While this source usually cannot be detected within a single night at very-high-energy gamma-rays (E>100GeV), during observations last night an exceptional high state was detected with a preliminary flux exceeding 10^-10 ph/cm^2/s (E>100GeV) or about 25% of the flux of the Crab Nebula above the same energy threshold. The observations were conducted under favorable conditions and lasted for 3h50.

A VHE gamma-ray flux like this has only been seen once before, namely in 2016 (ATel #9102, #9105). In that instance the flare lasted for only 2 nights, and therefore follow-up observations are strongly encouraged.

The Automatic Telescope for Optical Monitoring (ATOM) measured an optical B-band flux of 13.9 at MJD 58693.80. PKS 1510-089 went on to exhibit strong variability on timescales below 10 minutes -- including a drop of 0.2 magnitudes over less than 30 minutes.

H.E.S.S. is an array of five imaging atmospheric Cherenkov telescopes for the detection of very-high-energy gamma-ray sources and is located in the Khomas Highlands in Namibia. It was constructed and is operated by researchers from Armenia, Australia, Austria, France, Germany, Ireland, Japan, the Netherlands, Poland, South Africa, Sweden, UK, and the host country, Namibia.

Flat Spectrum Radio Quasar PKS1510-089 (z=0.361)

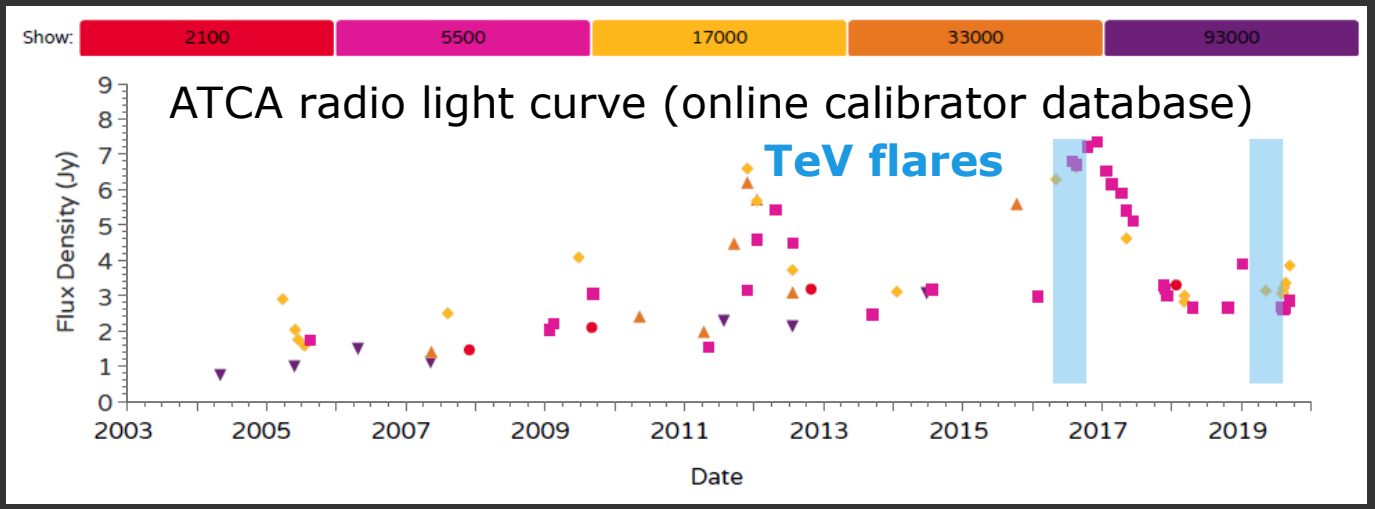
- TeV/optical flare again in July 2019

- Previous TeV flare late 2016 with lag for ATCA radio (2-20 GHz) high state

→ waiting for another ATCA rise?

- mm-VLBI (Boston) obs > 40 GHz
  Probe initial jet outflows

→ mm-VLBI very important!
Australia (LBA ~20 GHz max)



Fast Transients : The Way Forward?

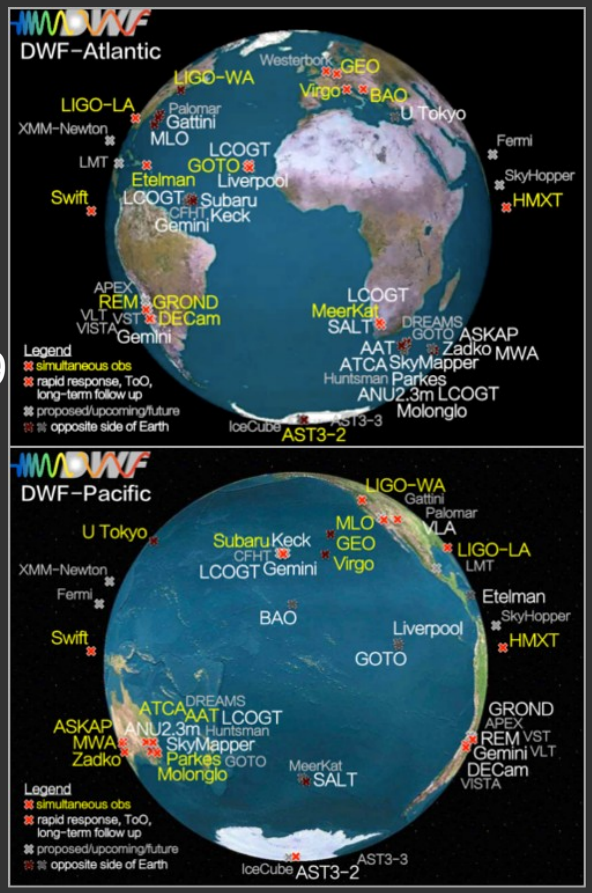
- Many transients (FRBs, GRBs, SGRs, GW etc.) < minute/seconds duration
- Fastest follow-up ~ 1 minute (fully robotic).
  → too slow for follow-ups of FRBs, magnetar bursts etc..
  → gamma, X-ray, optical FRB signals may even precede radio..

→ Contemporaneous/shadowing campaigns (e.g. DeeperWiderFaster)
→ Slaved telescopes
(e.g. 1m optical telescope at CTA sites.)

– DeeperWiderFaster 2019, 2020…..
MeerKAT, HESS, DeCAM, SPT, Auger, IceCube..

– MeerKAT+HESS shadow FRB171019 Sept/Oct 2019

→ "Practise" for the CTA era
HESS+ASKAP shadowing (AGN, FRBs...)



Cherenkov Telescope Ring (CTR)

Rohde etal 2017, Ruhe etal 2019
+ Einecke, Rowell, Lee….

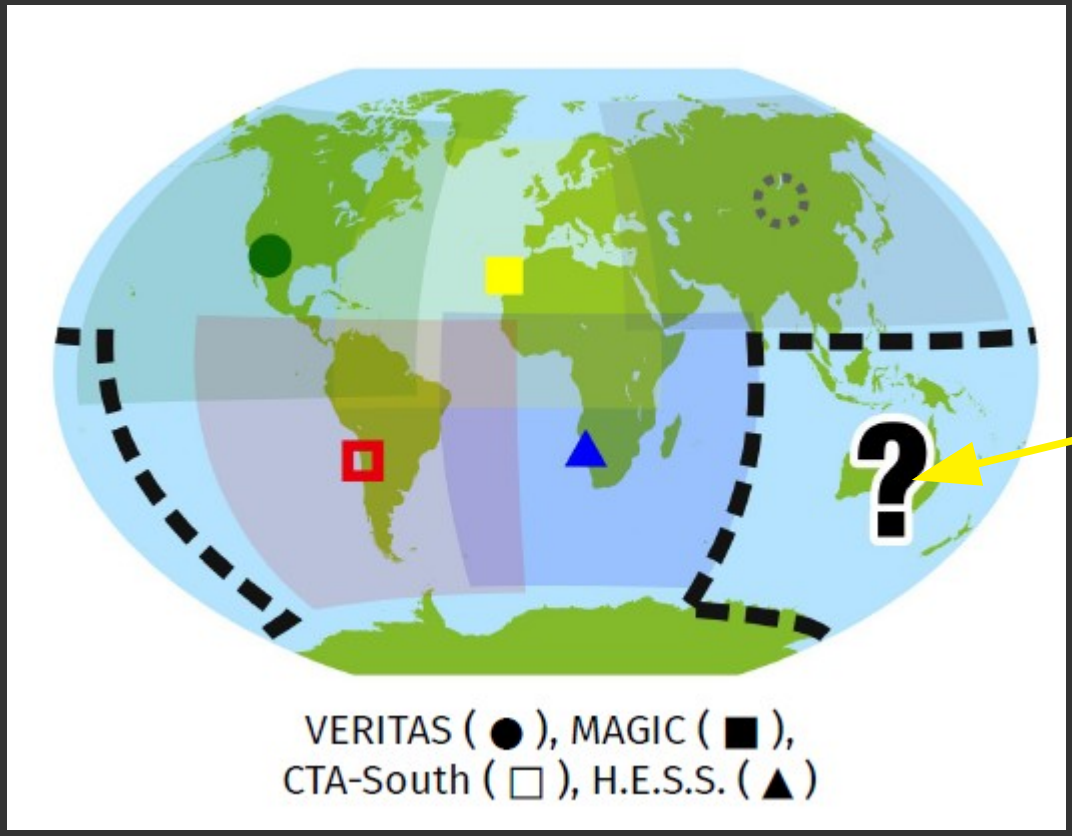
- Worldwide network of Cherenkov telescopes

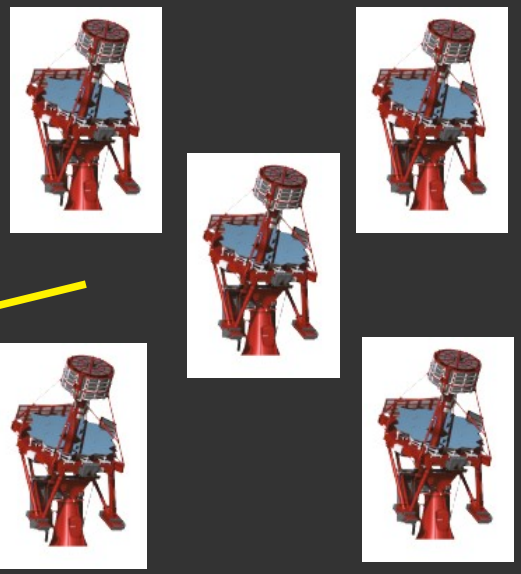
→ need to provide >=1 km^2 instantaneous collection area

For transients and variable TeV sources:

Rapid follow-up, discovery and monitoring

- Missing coverage in Australia! (& E-Asia)

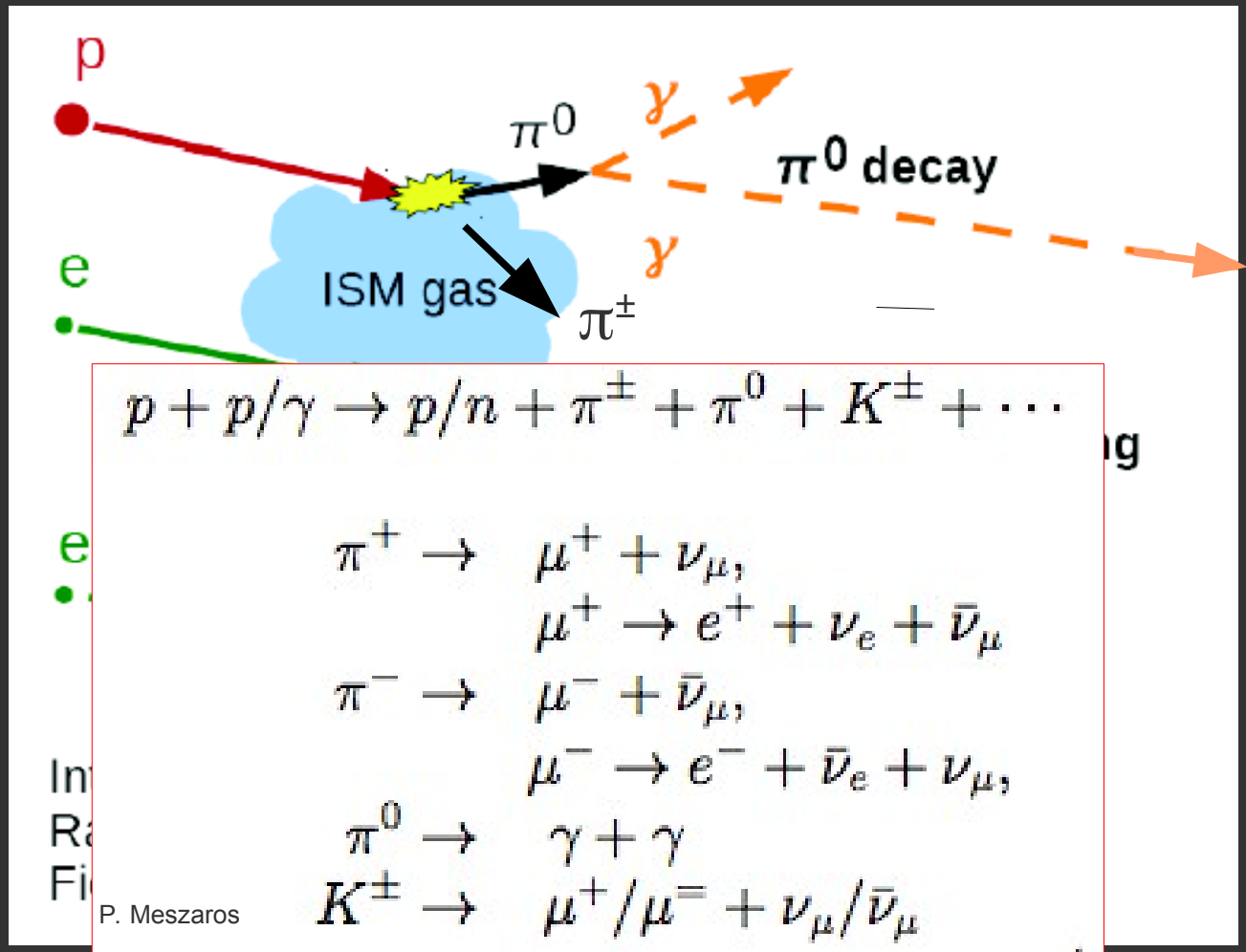




Small array of CTA-type SSTs or MSTs?

→ fully robotic!

Neutrinos from multi-TeV protons



For p+p → neutrinos, gamma-rays and gas targets spatially correlated
(need to map atomic and molecular ISM → mm radio astronomy)

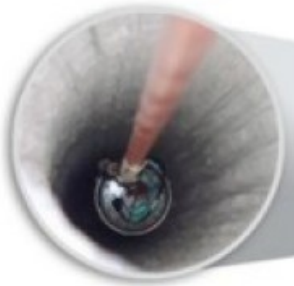
For p+γ → neutrinos and photon targets (e.g. in AGN cores) spatially correlated

IceCube
South Pole Neutrino Observatory

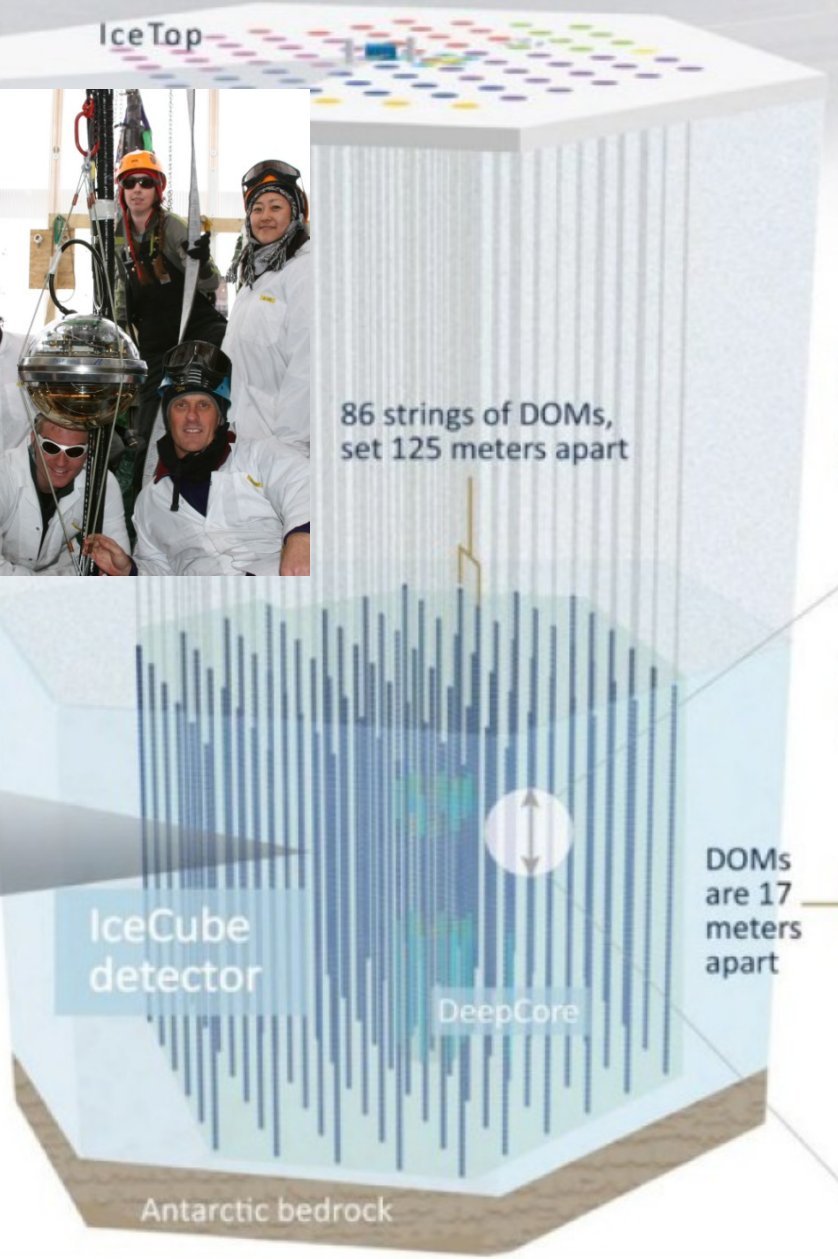
Cubic kilometre neutrino detector at the South Pole
(Initial upgrade funded → Gen II planned)

IceCube Laboratory
Data is collected here and sent by satellite to the data warehouse at UW–Madison

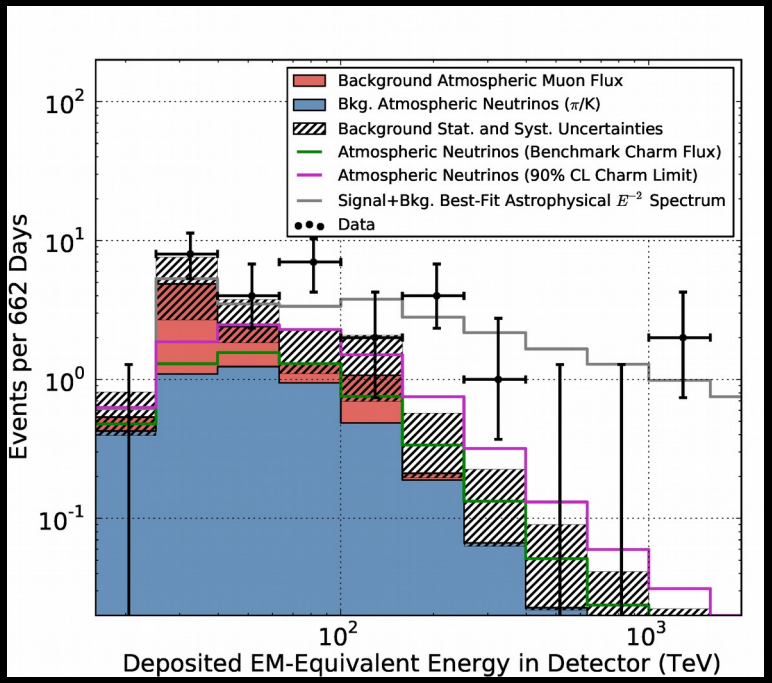
Amundsen–Scott South Pole Station, Antarctica
A National Science Foundation-managed research facility

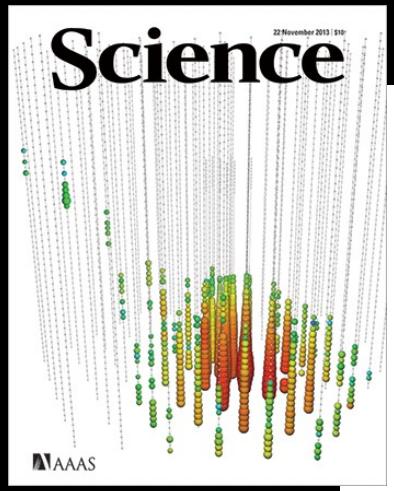


Digital Optical Module (DOM)
5,160 DOMs deployed in the ice



Courtesy: Gary Hill





RESEARCH ARTICLE

NEUTRINO ASTROPHYSICS

Neutrino emission from the direction of the blazar TXS 0506+056 prior to the IceCube-170922A alert

IceCube Collaboration*†

A high-energy neutrino event detected by IceCube on 22 September 2017 was coincident in direction and time with a gamma-ray flare from the blazar TXS 0506+056. Prompted by this association, we investigated 9.5 years of IceCube neutrino observations to search for excess emission at the position of the blazar. We found an excess of high-energy neutrino events, with respect to atmospheric backgrounds, at that position between September 2014 and March 2015. Allowing for time-variable flux, this constitutes 3.5σ evidence for neutrino emission from the direction of TXS 0506+056, independent of and prior to the 2017 flaring episode. This suggests that blazars are identifiable sources of the high-energy astrophysical neutrino flux.

RESEARCH ARTICLE

NEUTRINO ASTROPHYSICS

Multimessenger observations of a flaring blazar coincident with high-energy neutrino IceCube-170922A

The IceCube Collaboration, *Fermi*-LAT, MAGIC, *AGILE*, ASAS-SN, HAWC, H.E.S.S, *INTEGRAL*, Kanata, Kiso, Kapteyn, Liverpool Telescope, Subaru, *Swift/NuSTAR*, VERITAS, and VLA/17B-403 teams*†

Previous detections of individual astrophysical sources of neutrinos are limited to the Sun and the supernova 1987A, whereas the origins of the diffuse flux of high-energy cosmic neutrinos remain unidentified. On 22 September 2017, we detected a high-energy neutrino, IceCube-170922A, with an energy of ~290 tera–electronvolts. Its arrival direction was consistent with the location of a known γ-ray blazar, TXS 0506+056, observed to be in a flaring state. An extensive multiwavelength campaign followed, ranging from radio frequencies to γ-rays. These observations characterize the variability and energetics of the blazar and include the detection of TXS 0506+056 in very-high-energy γ-rays. This observation of a neutrino in spatial coincidence with a γ-ray–emitting blazar during an active phase suggests that blazars may be a source of high-energy neutrinos.

First astrophysical neutrino detection besides Sun and SN1987a.

First identified high-energy neutrino source! (~1 Gpc distant). A site of PeV cosmic rays.

Neutrino Event (IceCube EHE 170922A)

- TeV flare (5σ) from MAGIC
ATel #10817

First-time detection of VHE gamma rays by MAGIC from a direction consistent with the recent EHE neutrino event IceCube-170922A

ATel #10817; ***Razmik Mirzoyan for the MAGIC Collaboration***
on ***4 Oct 2017; 17:17 UT***
Credential Certification: Razmik Mirzoyan (Razmik.Mirzoyan@mpp.mpg.de)

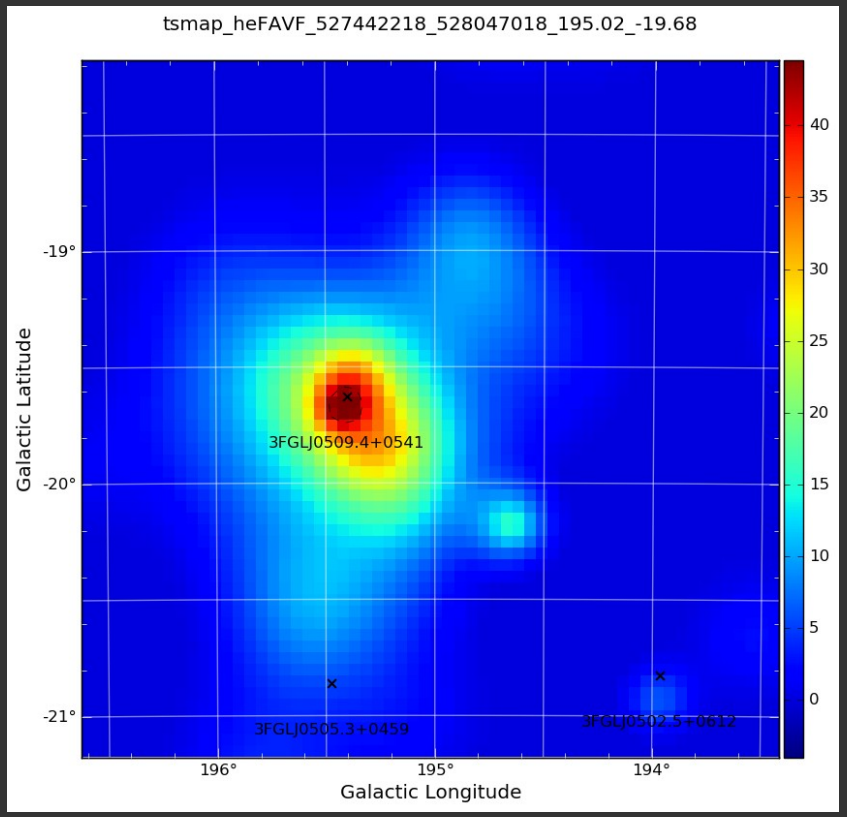
Subjects: Optical, Gamma Ray, >GeV, TeV, VHE, UHE, Neutrinos, AGN, Blazar

Referred to by ATel #: 10830, 10833, 10838, 10840, 10844, 10845, 10942

Tweet | Recommend 448

After the IceCube neutrino event EHE 170922A detected on 22/09/2017 (GCN circular #21916), Fermi-LAT measured enhanced gamma-ray emission from the blazar TXS 0506+056 (05 09 25.96370, +05 41 35.3279 (J2000), [Lani et al., Astron. J., 139, 1695-1712 (2010)]), located 6 arcmin from the EHE 170922A estimated direction (ATel #10791). MAGIC observed this source under good weather conditions and a 5 sigma detection above 100 GeV was achieved after 12 h of observations from September 28th till October 3rd. This is the first time that VHE gamma rays are measured from a direction consistent with a detected neutrino event. Several follow up observations from other observatories have been reported in ATels: #10773, #10787, #10791, #10792, #10794, #10799, #10801, GCN: #21941, #21930, #21924, #21923, #21917, #21916. The MAGIC contact persons for these observations are R. Mirzoyan (Razmik.Mirzoyan@mpp.mpg.de) E. Bernardini (elisa.bernardini@desy.de), K.Satalecka (konstancja.satalecka@desy.de). MAGIC is a system of two 17m-diameter Imaging Atmospheric Cherenkov Telescopes located at the Observatory Roque de los Muchachos on the Canary island La Palma, Spain, and designed to perform gamma-ray astronomy in the energy range from 50 GeV to greater than 50 TeV.

- GeV flare from Fermi-LAT
ATel #10791
(0.8-300 GeV TS map)



→ Linked to AGN TXS 0506+056
→ Six-month-long cluster of neutrinos 2015/15 at 3.5 sigma

KM3NeT: ARCA + ORCA

ARCA

Astrophysical Research with Cosmics in the Abyss

- E_ν 1 TeV -10 PeV
- 1.2 km^3, 3.5 km deep off Sicily
- Astrophysical neutrino source
- Completion: 2027

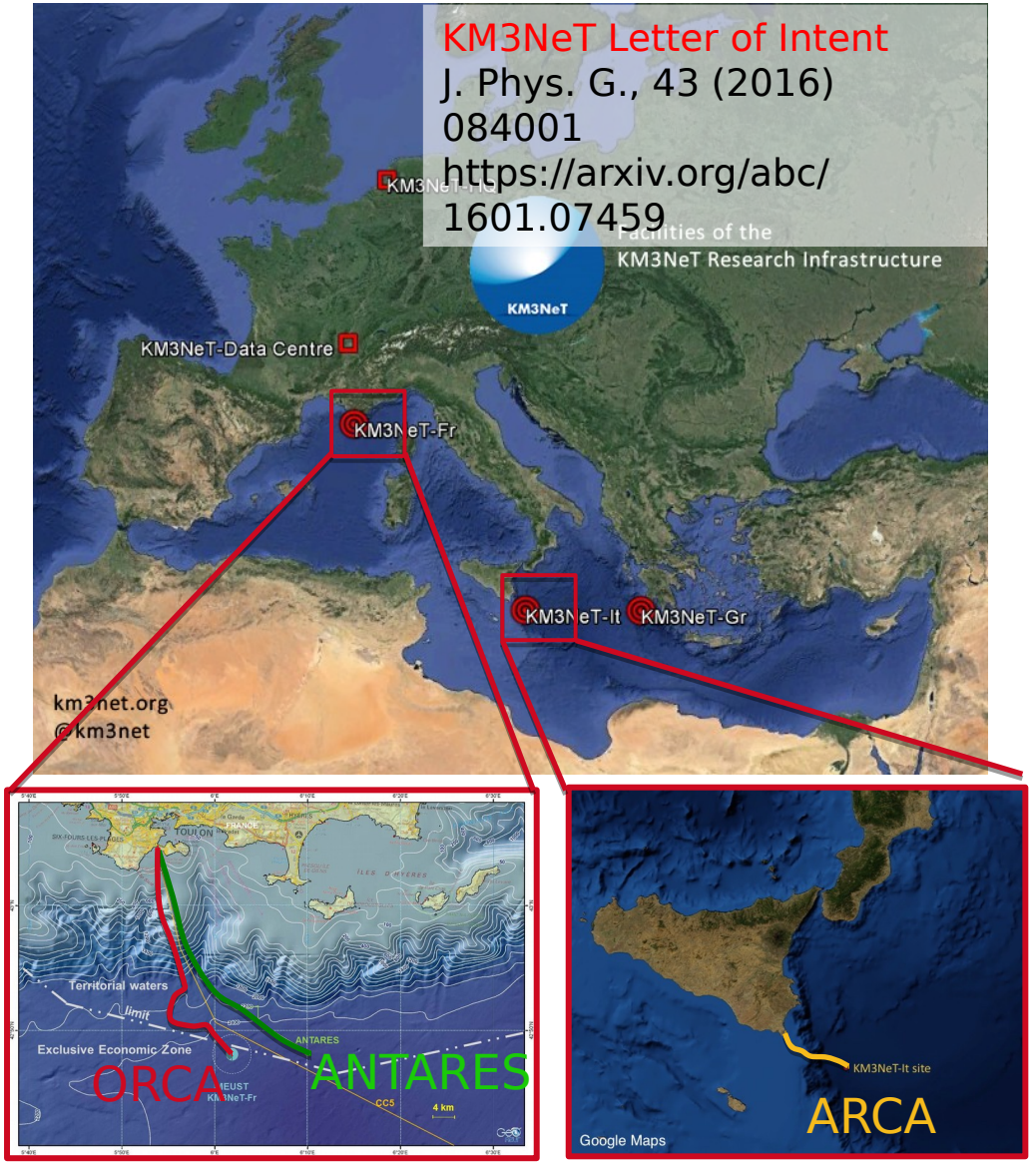
ORCA

Oscillation Research with Cosmics in the Abyss

- E_ν 1 GeV - 100 GeV
- 2.5 km deep off Toulon (O~4x10^6 m^3)
- Target neutrino mass hierarchy
- Completion: 2026

Northern Hemisphere

- Views same sky as Australian instruments

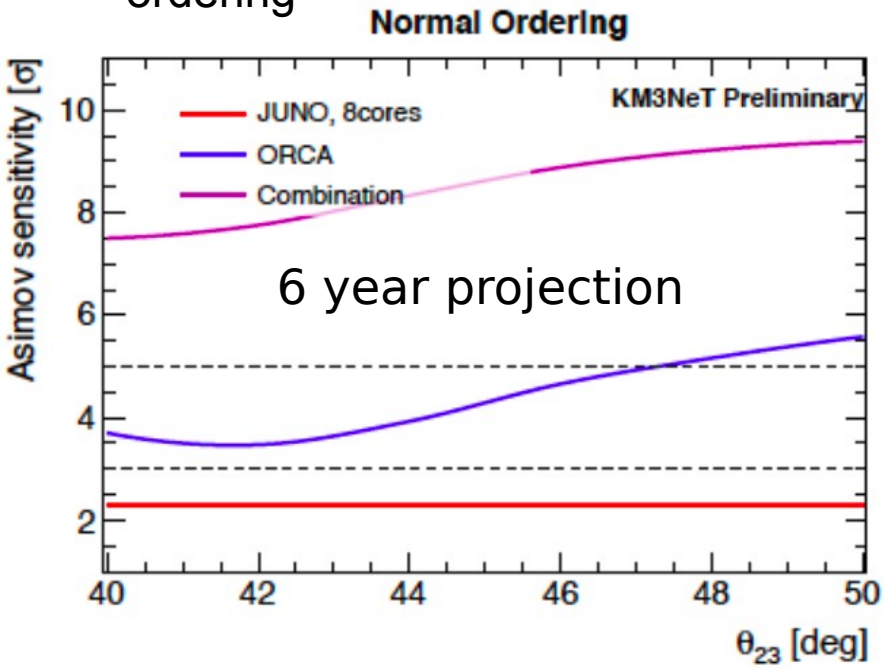


Performance

Multi-PMT optical module

ORCA

- 3 years (2029): 2.5-5 sigma detection of normal mass ordering

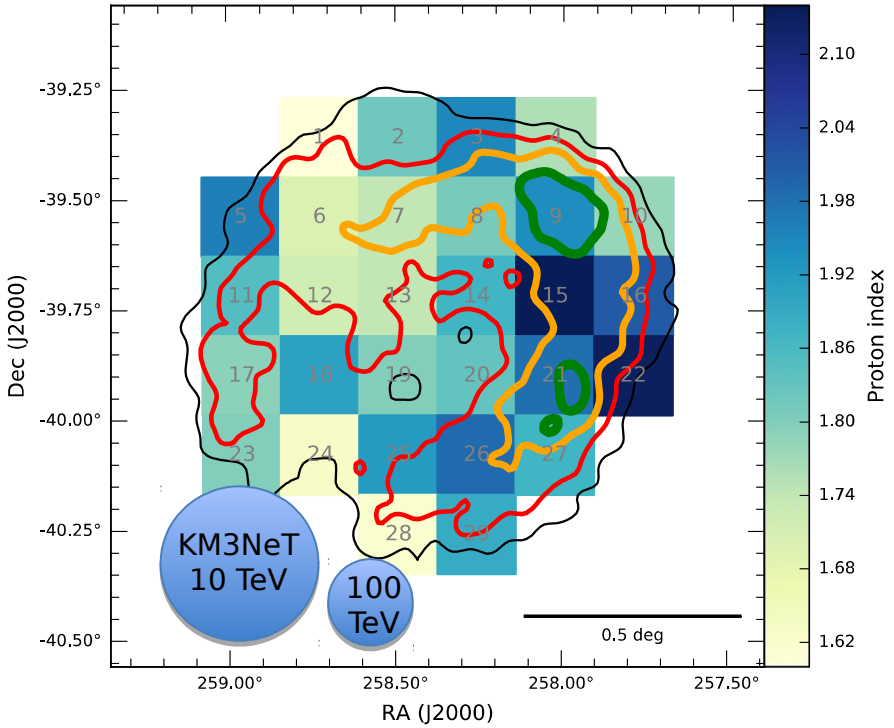


- Complementary to e.g. Juno
- Sensitivity to BSM neutrino physics

ARCA

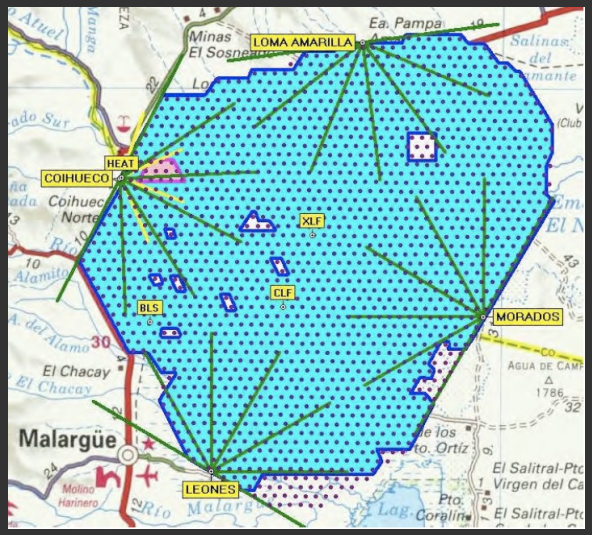
- Angular resolution @ 100 TeV:
- 0.1º muons, ~1.8º cascades

RX J1713: H.E.S.S. Collaboration, A&A, Volume 612, id.A6



Pierre Auger Observatory

(particle + fluorescence cosmic ray detectors)

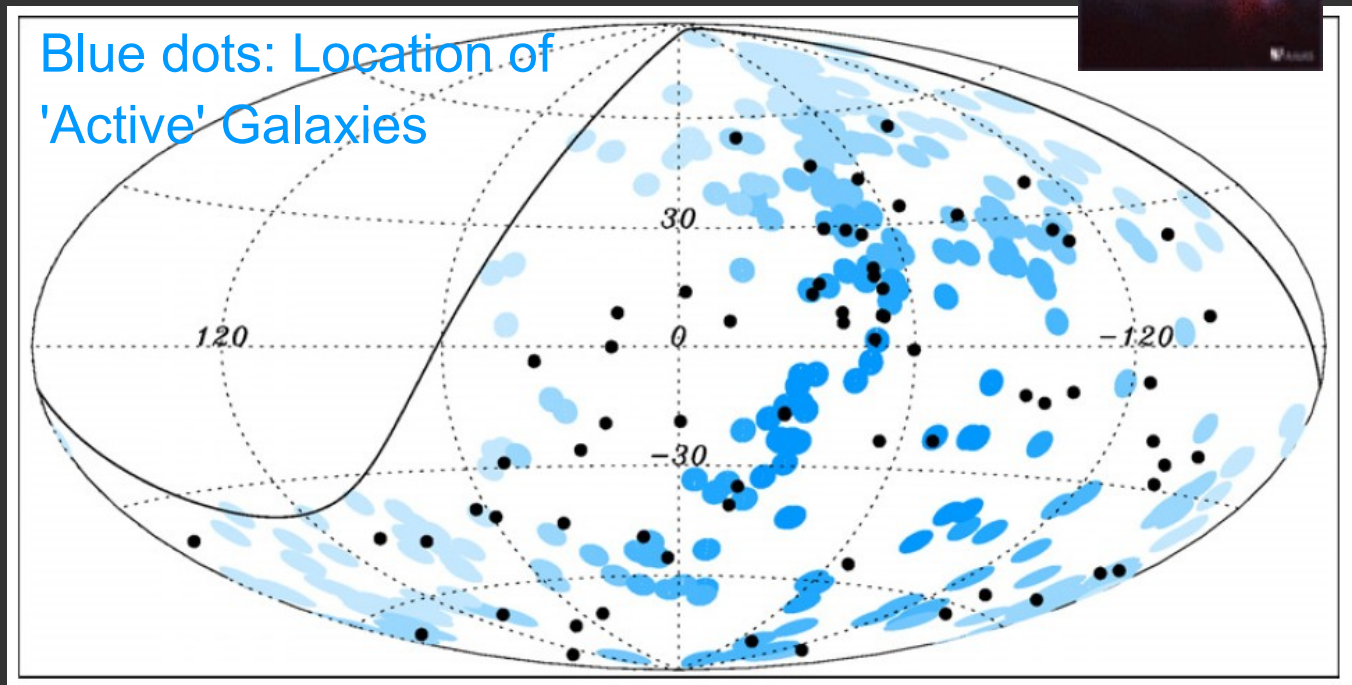


PIERRE AUGER OBSERVATORY

Arrival Directions of Cosmic-Rays
E > 55 EeV
(black dots)

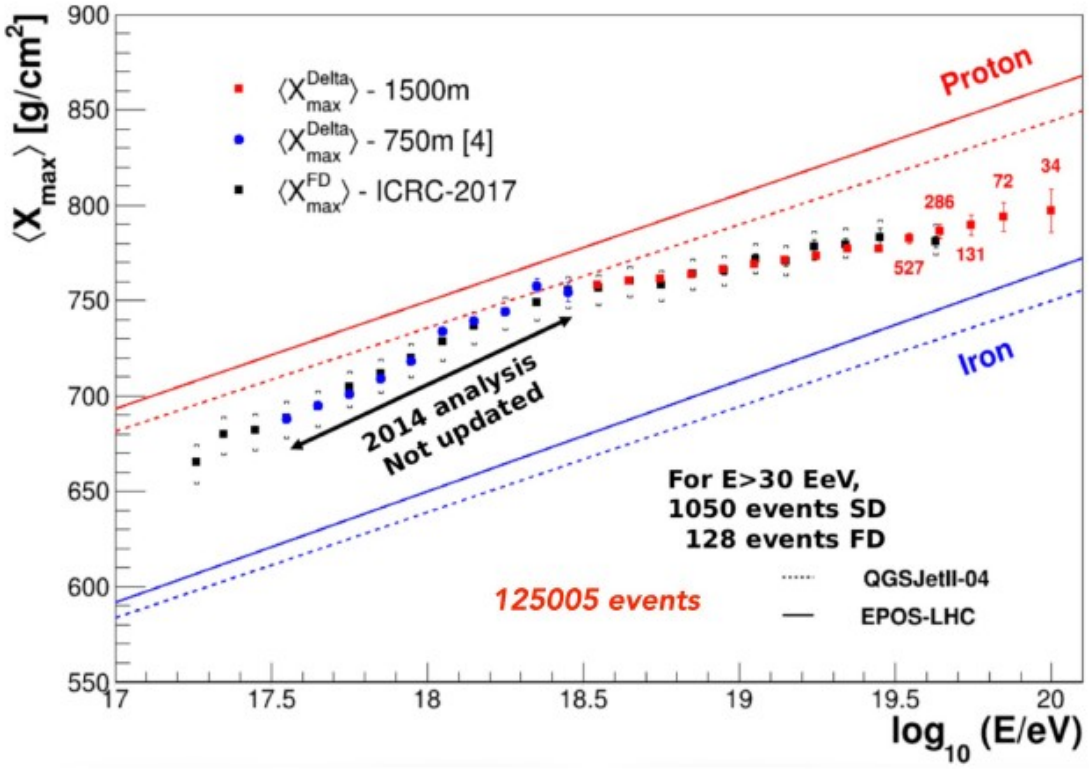
- Origin of EHE CRs
- CR mass composition
- Hadron physics >LHC energies

Upgrade underway



CR Composition (protons up to iron)

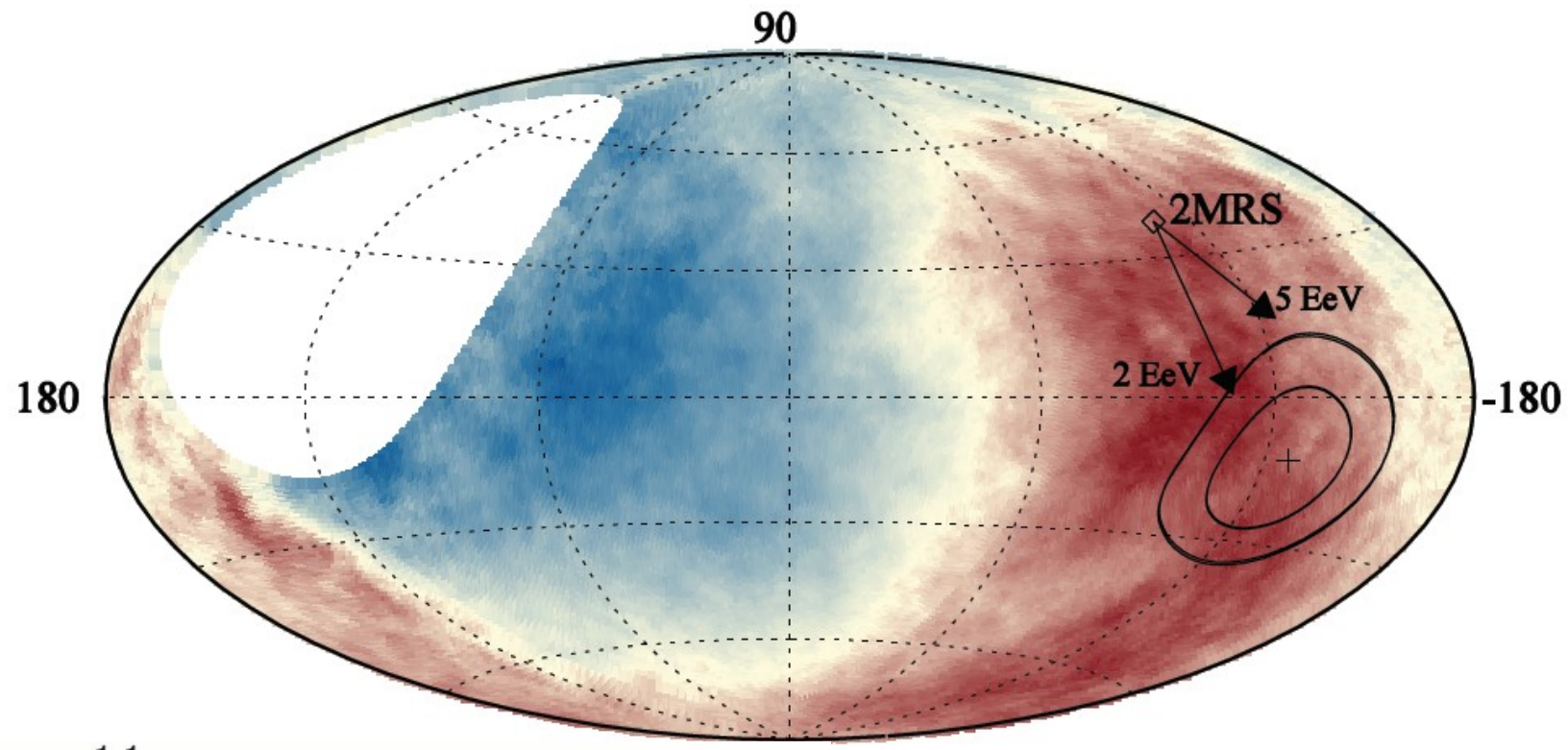
Mean Xmax from Auger's surface detector

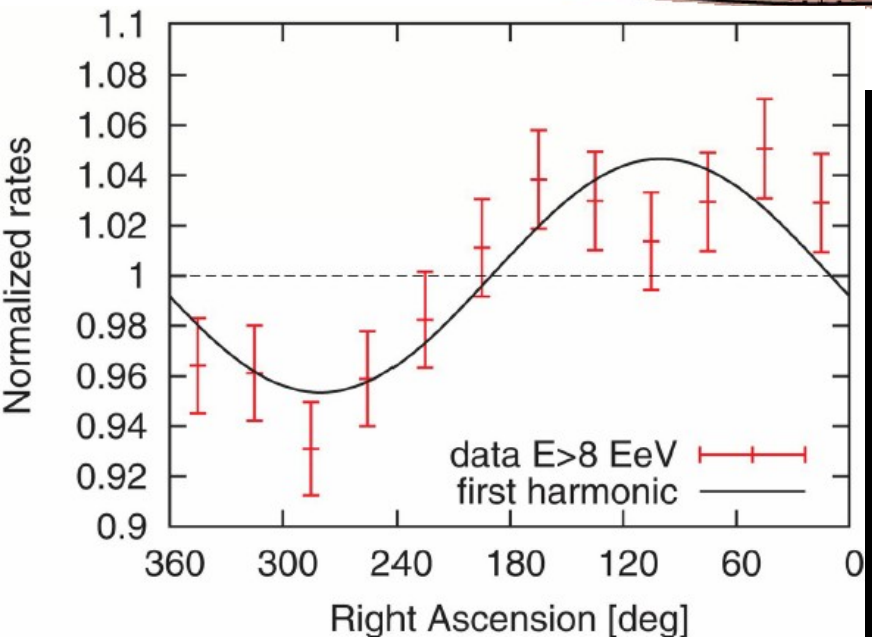


$\log_{10}$(E/eV)	SD
18.5-18.6	45872
18.6-18.7	27783
18.7-18.8	17011
18.8-18.9	11631
18.9-19.0	7960
19.0-19.1	5489
19.1-19.2	3582
19.2-19.3	2290
19.3-19.4	1473
19.4-19.5	864
19.5-19.6	527
19.6-19.7	286
19.7-19.8	131
19.8-19.9	72
>19.9	34
Total	125005

Prima ry mass not constant with energy, in agreement with more direct fluorescence measurer nents

J. Todero Peixoto [Auger Collaboration], ICRC 2019 arXiv:1909.09073





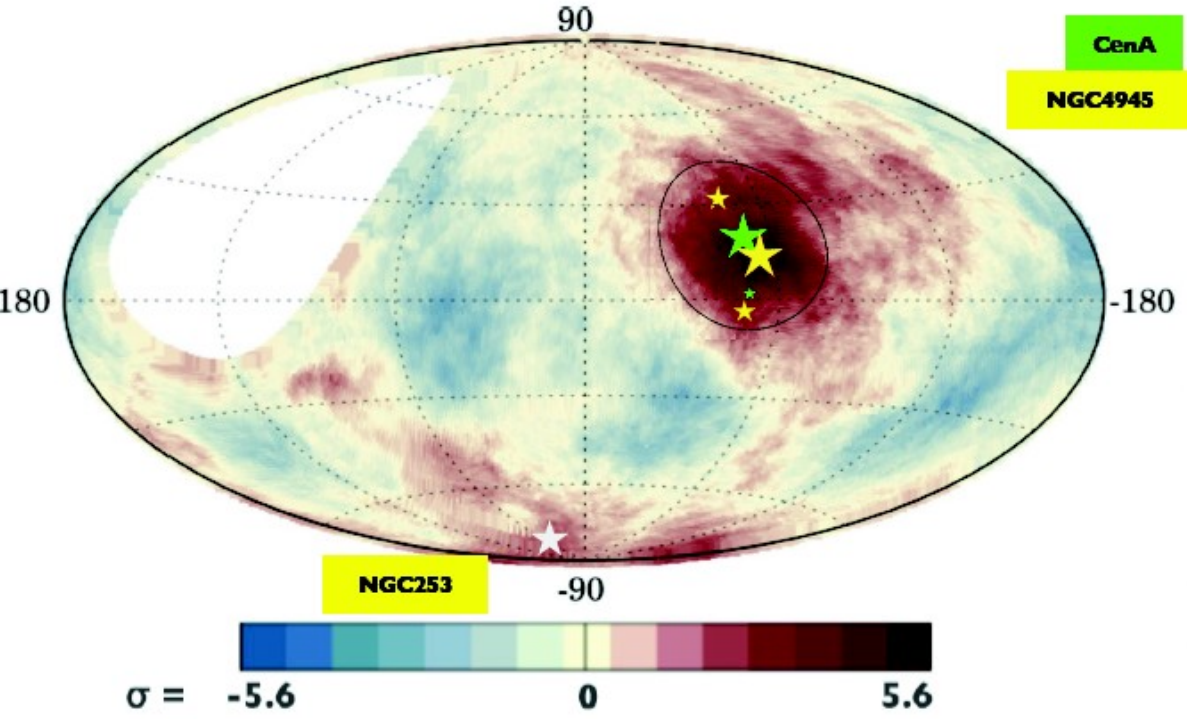
Cosmic rays above 8 x 10^{18} eV:
6% dipole anisotropy, consistent with 2MRS (local extra-galactic matter density), 120 degrees away from galactic centre

Science 357 1266 (2017)

The **arrival directions** of the highest energy cosmic rays

Total SD events with E>32 EeV : 2157

Total exposure 101,400 km² sr yr



Blind search

Scan ranges:

32 EeV ≤ Eth ≤ 80 EeV (1 EeV steps)

1° ≤ ψ ≤ 30° (1° steps)

Most significant excess for E>38 EeV
(α=202⁰, δ= -45⁰) ~2⁰ from CenA

Centaurus A

3.9 σ effect (post-trial)
for E>37 EeV, 28⁰ window

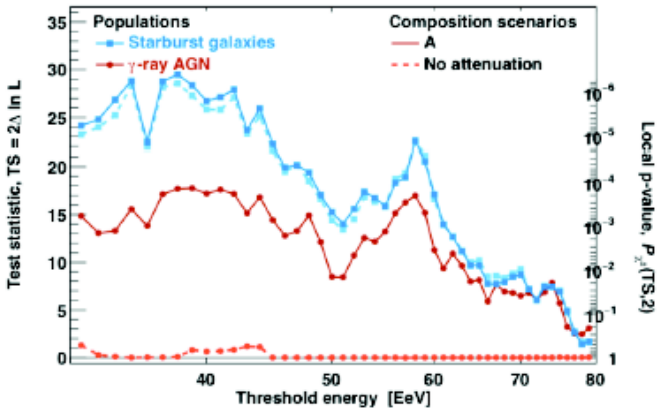
The **arrival directions** of the highest energy cosmic rays

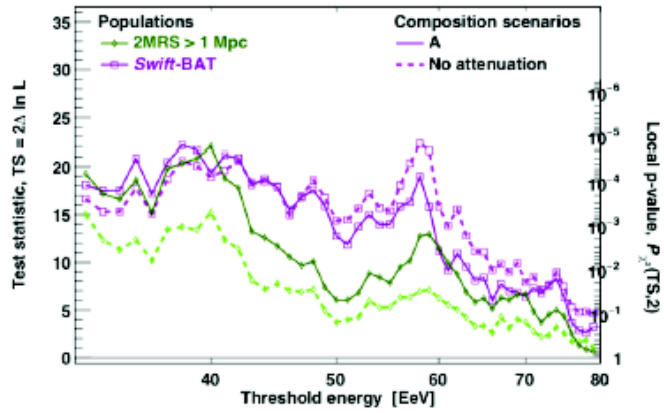
γ AGNs
- 3FHL catalog < 250 Mpc
- 33 sources (CenA, Fornax A, M87…)
- Flux proxy **ϕ**(>10 GeV)

Starburst Galaxies
- 32 sources (Circinus, M82, M83,…)
- <250 Mpc
- Flux proxy **ϕ**(>1.4 GHz), > 0.3 Jy

Swift-BAT
- >300 radio loud and quiet sources
- <250 Mpc
- **ϕ**>13.4 10^{-12} erg cm^{-2} s^{-1}

2MRS
- ~10^4 sources with D>1 Mpc
- <250 Mpc
- Flux proxy **ϕ**(14-195 keV)





Likelihood analysis $TS = 2Log\,[L(\psi, f_{anis})/L(f_{anis} = 0)]$

Catalog	$E_{\rm th}$	TS	Local p-value	post-trial	$f_{\rm aniso}$	θ
Starburst	38 EeV	29.5	4×10^{-7}	4.5 σ	11^{+5}_{-4}%	15^{+5}_{-4}°
γ−AGN	39 EeV	17.8	1×10^{-4}	3.1 σ	6^{+4}_{-3}%	14^{+6}_{-4}°
Swift-BAT	38 EeV	22.2	2×10^{-5}	3.6 σ	8^{+4}_{-3}%	15^{+6}_{-4}°
2MRS	40 EeV	22.0	2×10^{-5}	3.6 σ	19^{+10}_{-7}%	15^{+7}_{-4}°

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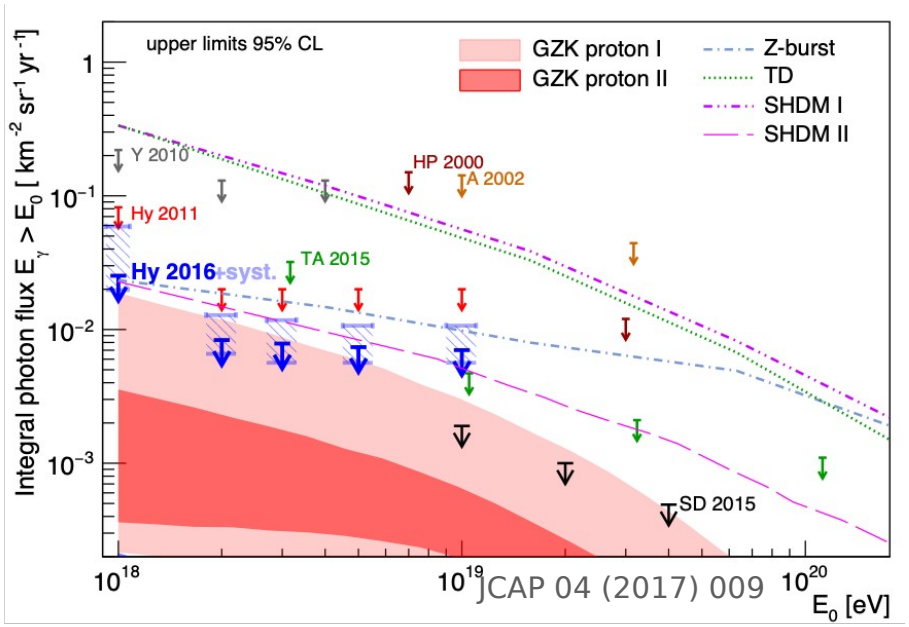
Other physics from Auger

- Photon searches 10^{17} - 10^{20} eV
  (strong limits on super-heavy dark matter)
- UHE transients; photons, neutrinos (GWs, GRBs, etc)
- Neutrinos (ultra-high energy)
- Testing Lorentz invariance violation
  (in air showers, and in propagation of CR)
- Standard model at extreme energies (e.g. deficit of muons in air shower models.
- Correlations with IceCube/ANTARES
- Beyond SM (e.g. monopoles, ANITA-type upward events)



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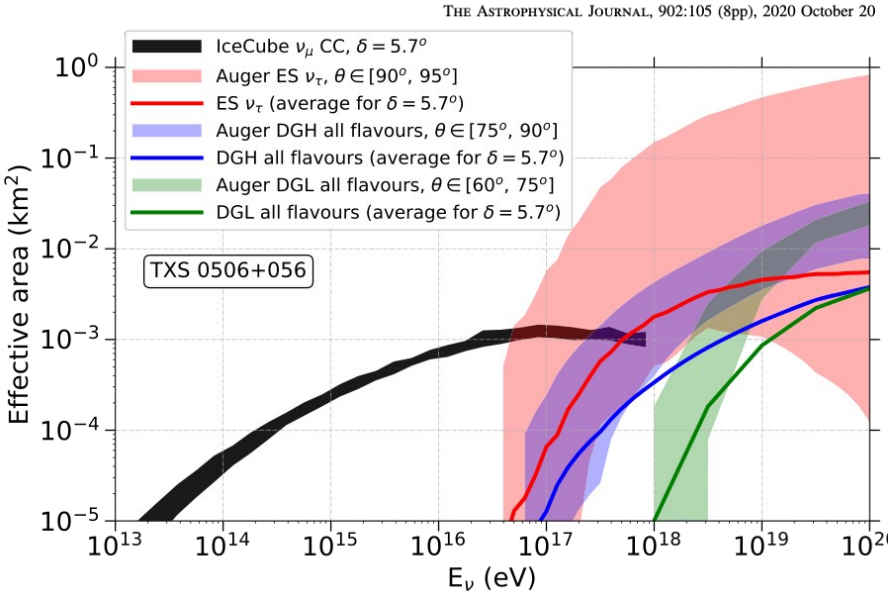

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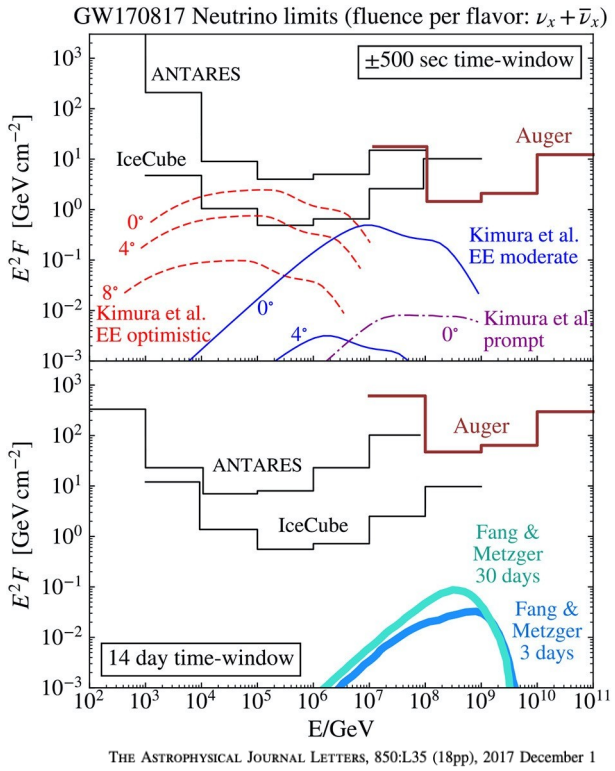
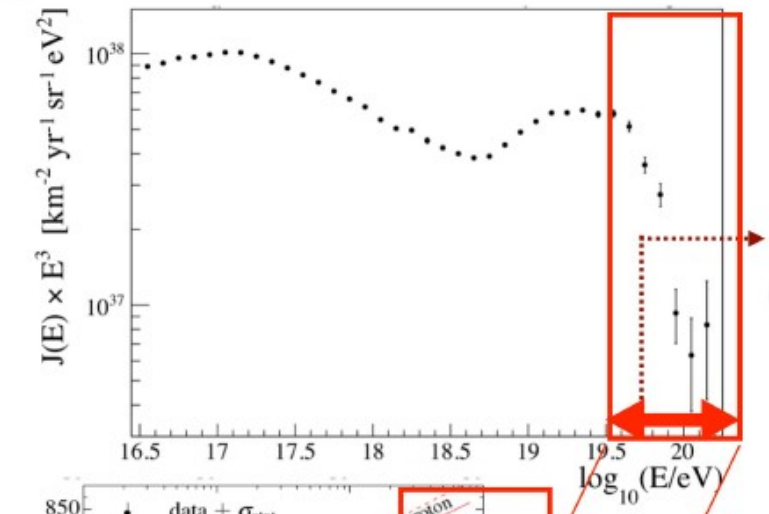


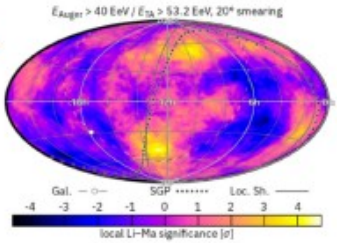
The Astrophysical Journal Letters, 850:L35 (18pp), 2017 December 1

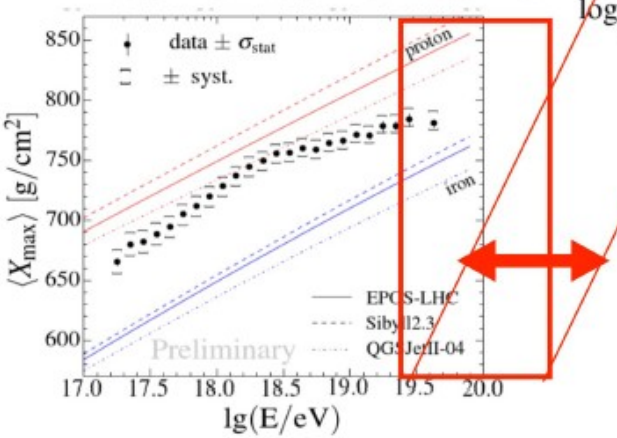
AugerPrime - science case for the upgrade

- Study the highest energy cosmic rays (spectral suppression region) with mass composition information
- Select light primaries for charged particle astronomy
- Provide better estimates of the UHE neutrino and photon fluxes. Establish potential for future experiments.
- Better measure shower components, study hadronic physics, search for non-standard phys ics

Auger operations extended to beyond 2025



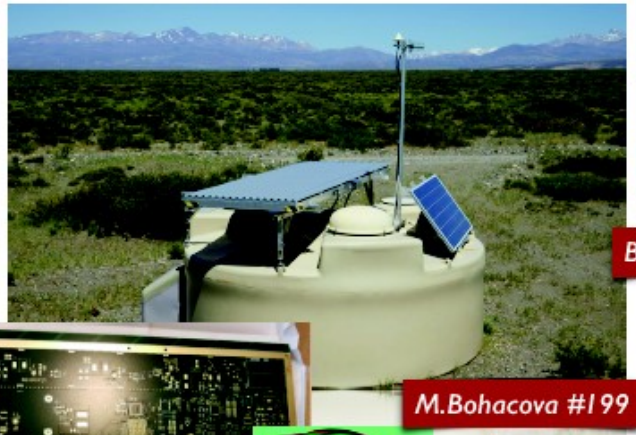


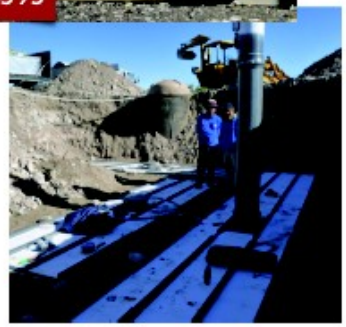


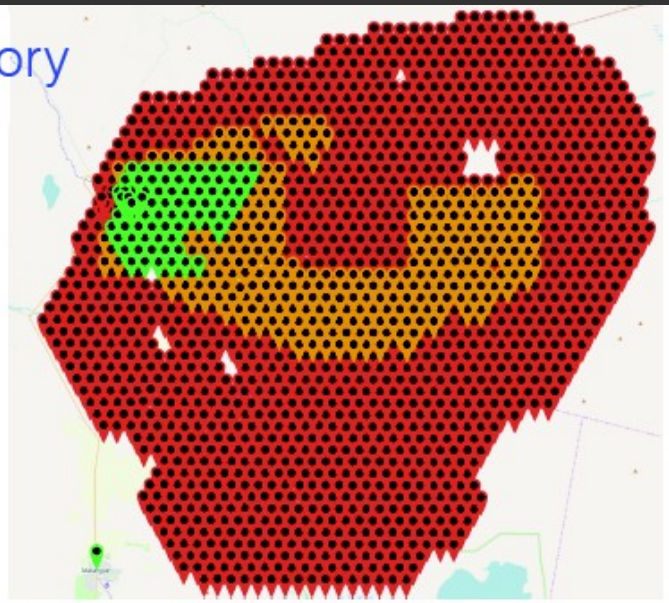
So far, event by event mass estimates limited to 13% FD duty cycle

Auger Prime - a major upgrade of the Observatory

a large exposure detector with composition sensitivity above ~4 10^{19} eV







- **12 upgraded stations (Engineering Array)** since 2016 with new electronics, higher sampling, large dynamic range
- the SSD preproduction array: **80 stations** (since March 2019)
- 356 SSD stations already deployed
- Underground Muon detector
- the largest radio detector (3000 km^2)

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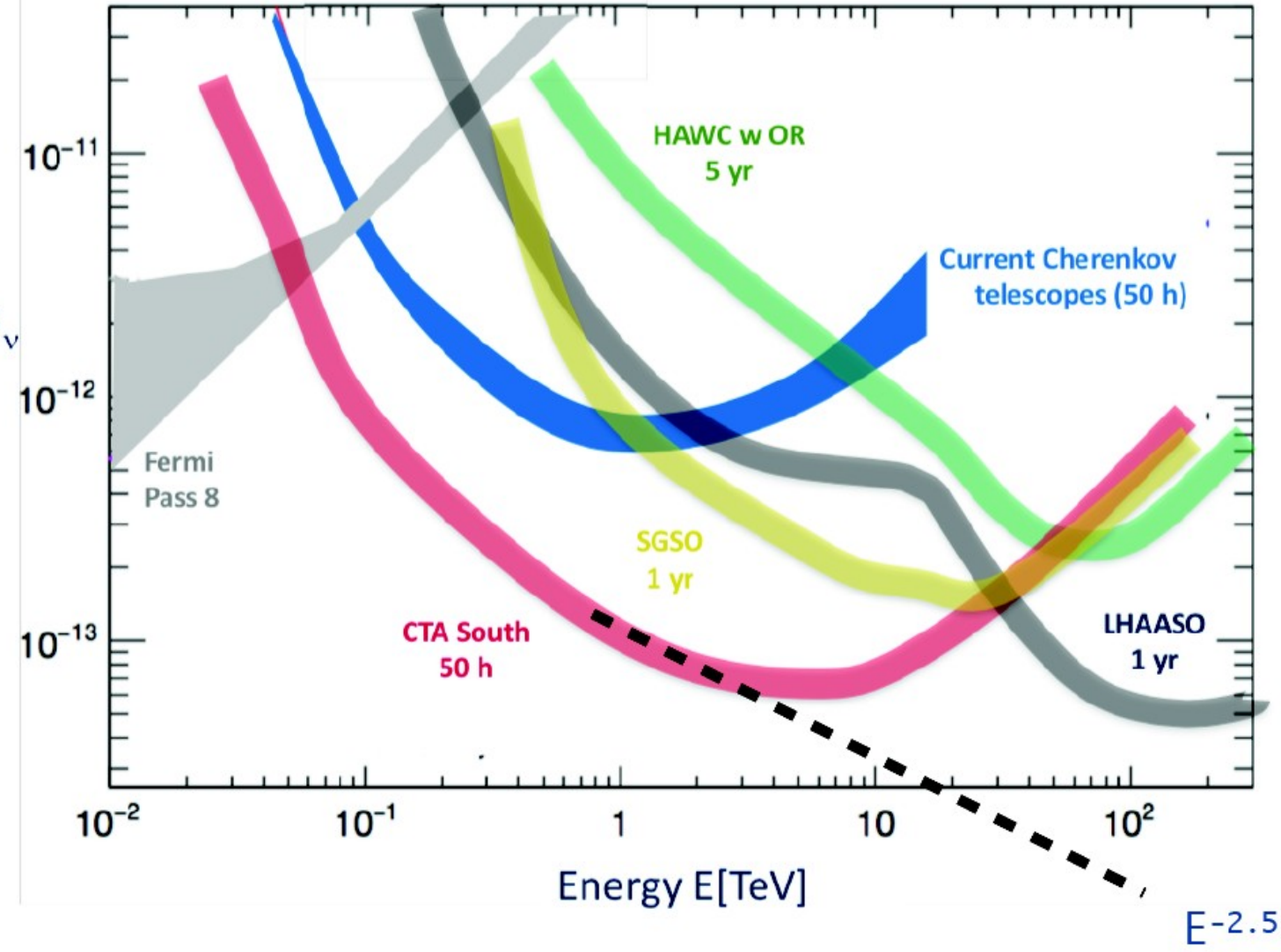
We are certainly seeing just the tip of the iceberg…..
credit: S. Saffi



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

Slide from : F. Aharonian

HESS+ASKAP shadowing

Common sky for HESS+ASKAP up to 2hrs for many southerly AGN (e.g. Fermi-LAT 3FHL)

HESS & ASKAP have v.similar fields of view 20 to 30 deg^2

→ Perfect opportunity for joint gamma/radio searches for FRBs and other transients.

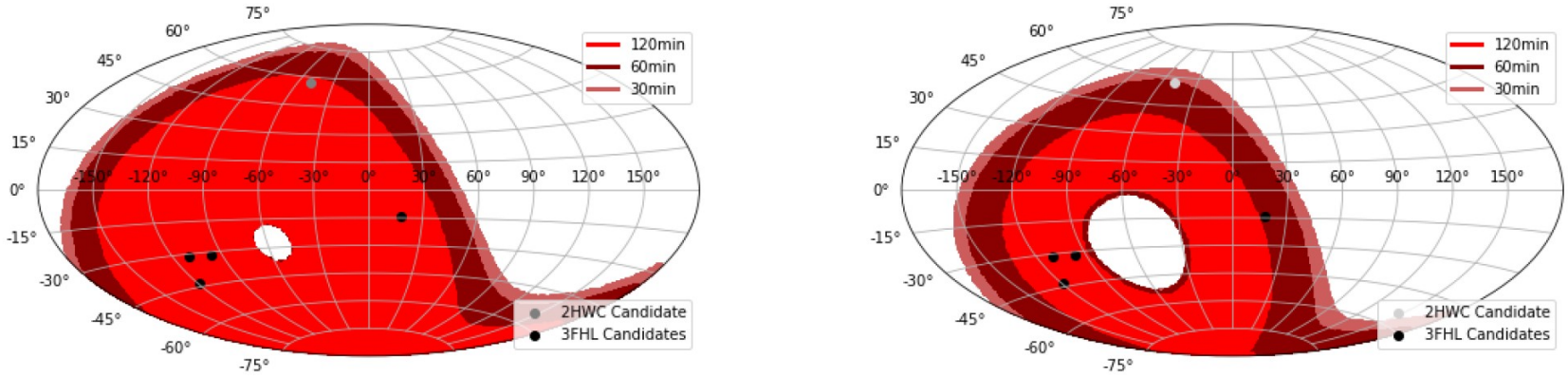


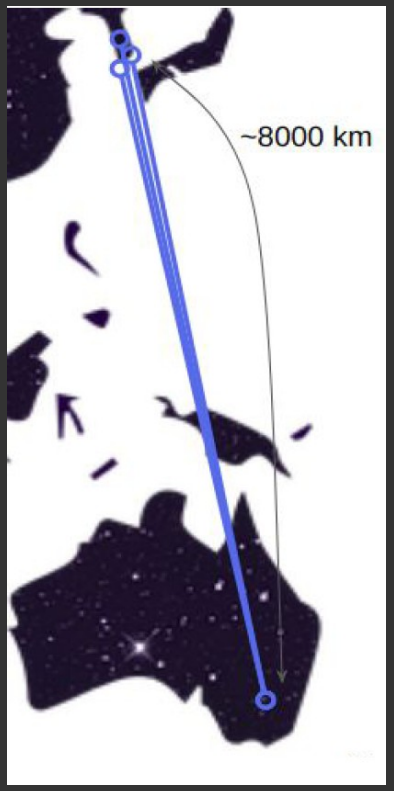
Figure 1: Common sky (Galactic coordinates - **southern sky to the left**) between ASKAP and HESS, overlaid with potential candidates from the third *Fermi*-LAT catalog of high-energy sources (3FHL, [6]) and the first HAWC catalog (2HWC, [7]). The common sky (red) is defined as positions visible for ASKAP at zenith angles below 75° and at the same time visible for HESS at zenith angles below 55° (left) and below 30° (right) between 19:00 and 02:30 UTC. The minimal common observation duration is indicated by the different shades of red.

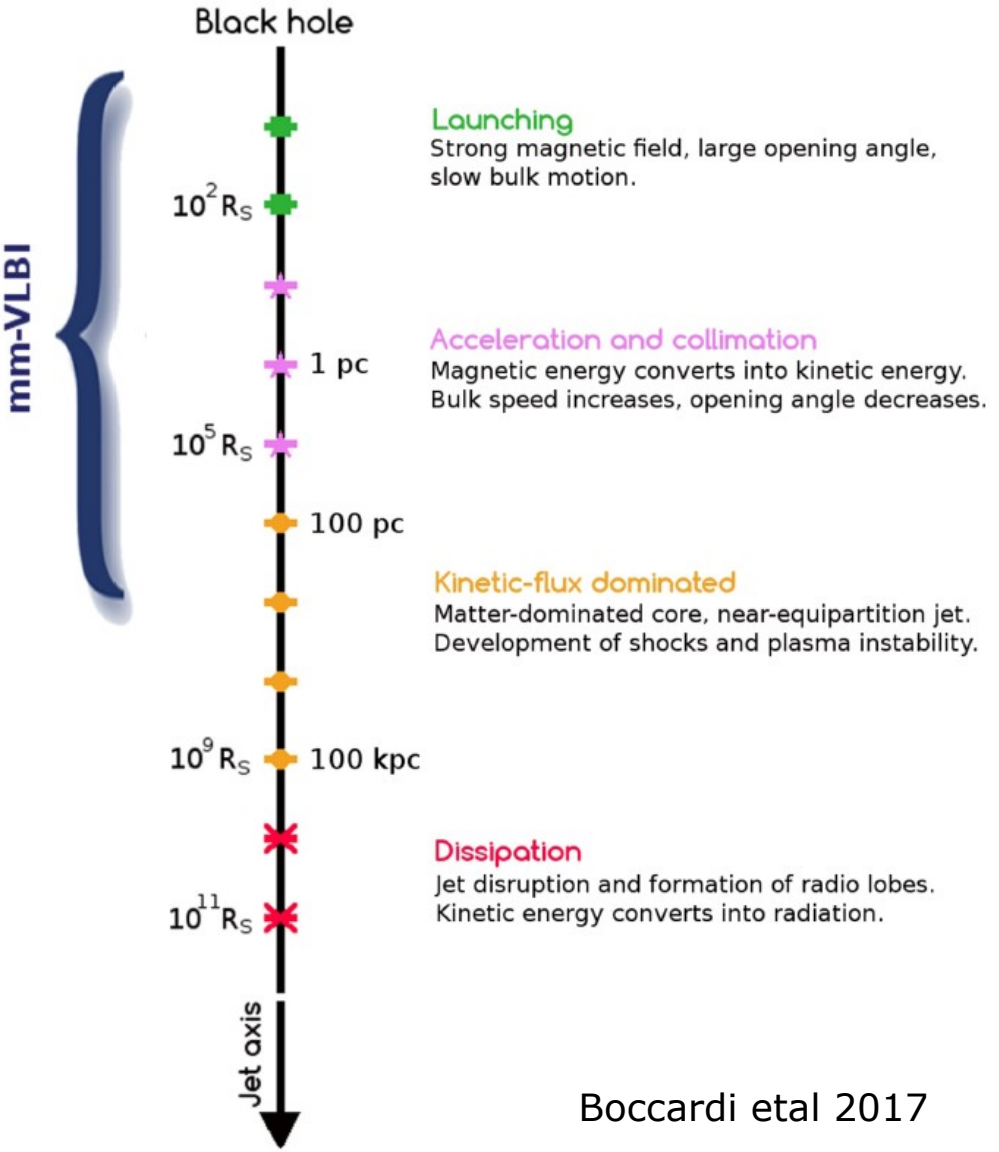
Mopra upgrade for mm-VLBI

- ARC Linkage Project ~~2019~~ 2020: UNSW (CI M. Cunningham), KASI, CSIRO, WSU, Adelaide, UTas, UWA….

KASI – Korean Astronomy and Space Science Inst.

- New VLBI backend
→ Probe AGN jets down to their base
→ Distance indicators for AGN..
→ EventHorizonTelescope at 3mm
→ Further mm mapping for CTA
→ Trigger on TeV flares (HESS/CTA)





Boccardi etal 2017