Results from the H.E.S.S. Telescopes

-and a look at the next generation instrument

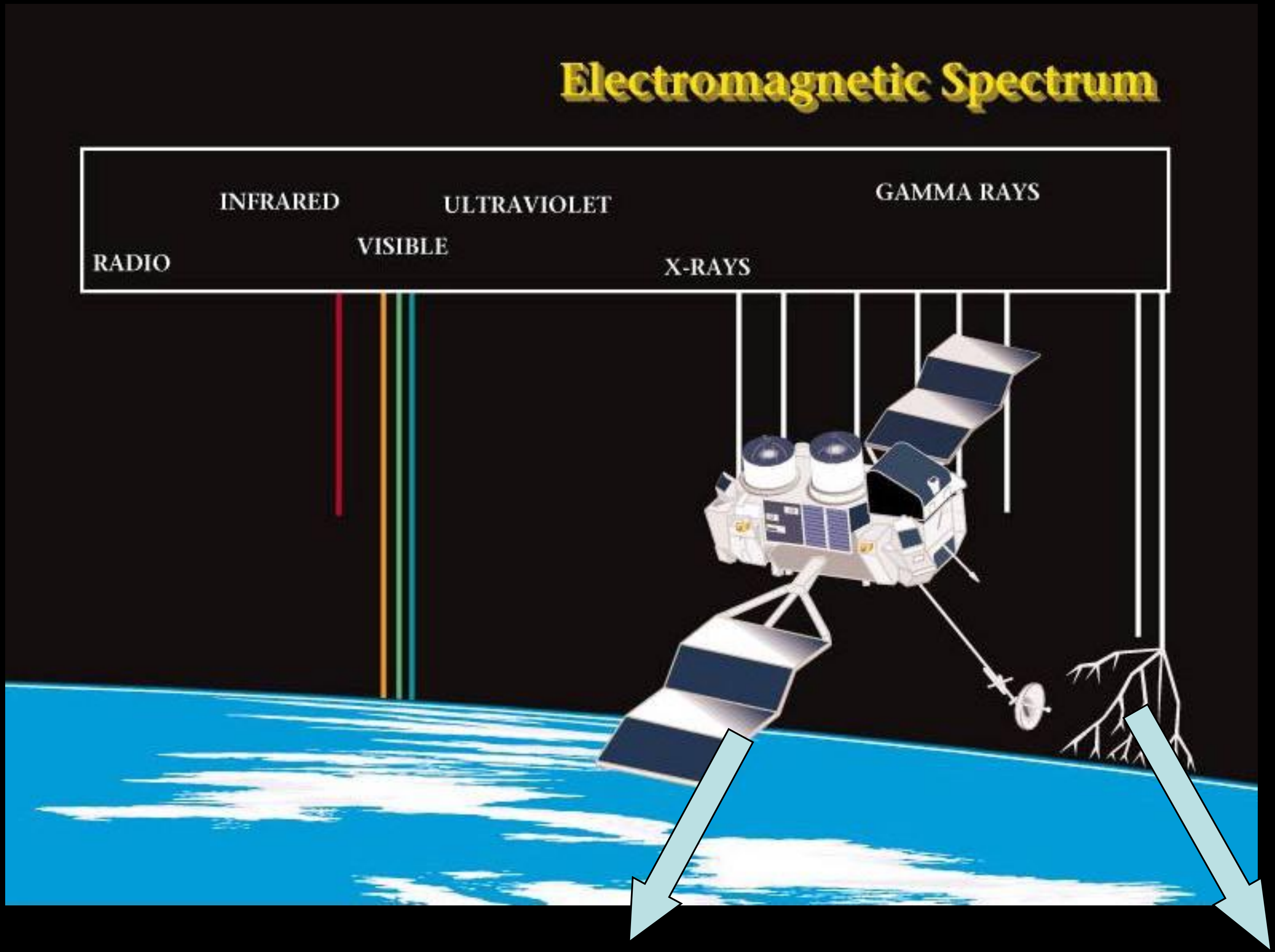
Paula Chadwick, Dept. of Physics

University of Durham

Durham University

The Plan

- Some background information
- Recent H.E.S.S. results
  - The Galactic Plane survey
  - The Galactic Ridge
  - Dark matter searches
  - Starburst Galaxies
  - The PKS2155-30 flare and quantum gravity
- CTA – the Cherenkov Telescope Array



Satellite-based:
511 keV to
around 50 GeV

Ground-based:
~20 GeV+

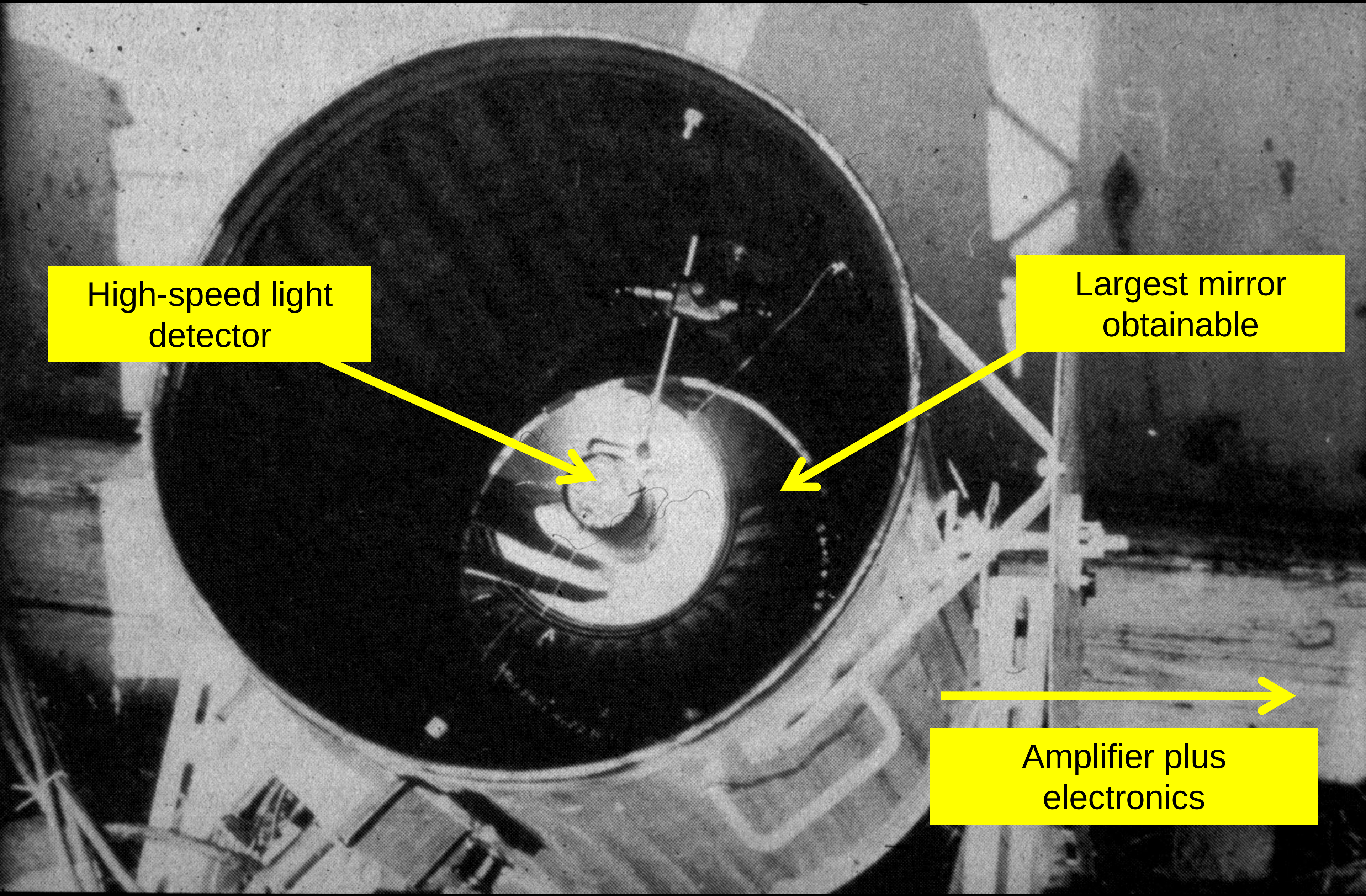
In the Beginning...

“One day in 1953, Prof Blackett was visiting Harwell....hearing of our work on Cherenkov light in water, (he) quite casually mentioned that as far back as 1948 he had shown that there should be a contribution to the light of the night sky, amounting to about 10^{-4} of the total, due to Cherenkov radiation produced in the upper atmosphere from the general flux of cosmic rays.

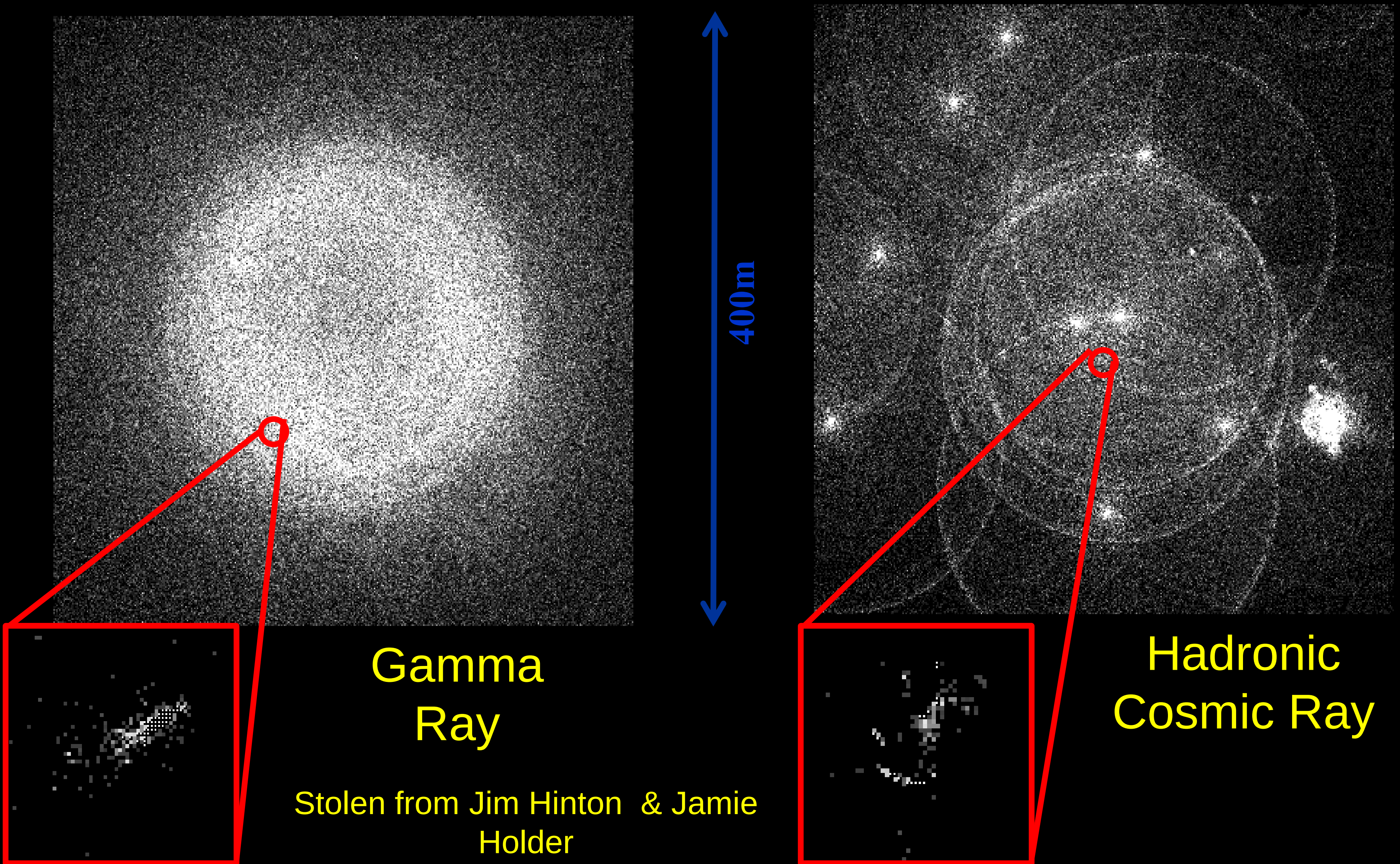
......

Blackett was only with us a few hours, and neither he nor any of us ever mentioned the possibility of pulses of Cherenkov light, from EAS. It was a few days later that it occurred to Galbraith and myself that such pulses might exist and be detectable.”

John Jelley, in ‘Very High Energy Gamma Ray Astronomy, ed. K.E. Turver, NATO ASI Proc. 199 (1986)


High-speed light detector
Largest mirror obtainable
Amplifier plus electronics

On the Ground



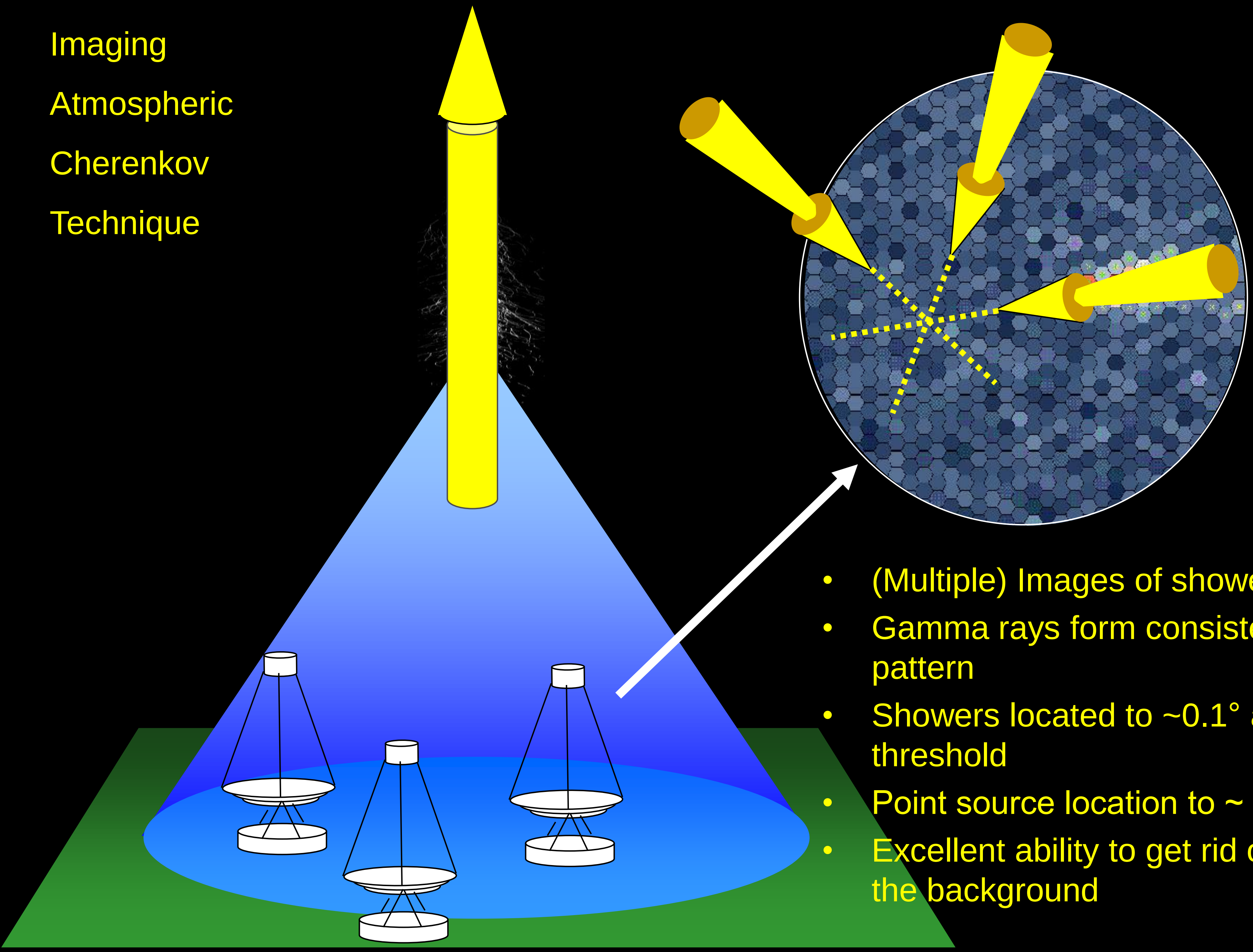
Stolen from Jim Hinton & Jamie Holder

Imaging

Atmospheric

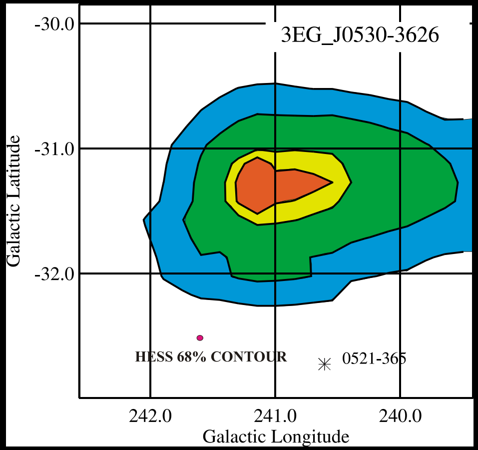
Cherenkov

Technique

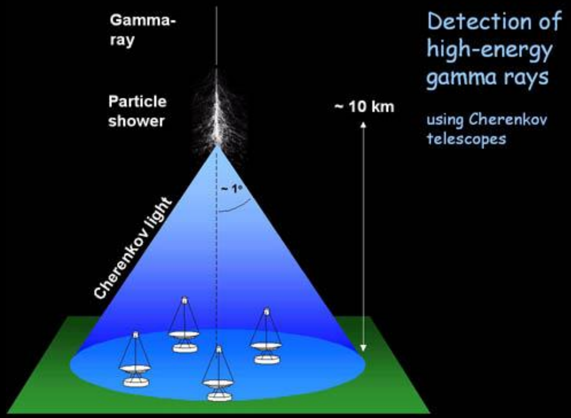


- (Multiple) Images of showers
- Gamma rays form consistent pattern
- Showers located to ~0.1° at threshold
- Point source location to ~ 30”
- Excellent ability to get rid of the background

Important features of the technique…..



Excellent source location

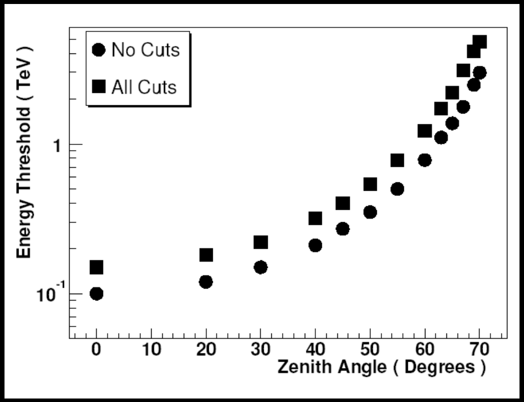


Very large effective area

Cannot observe during full moon

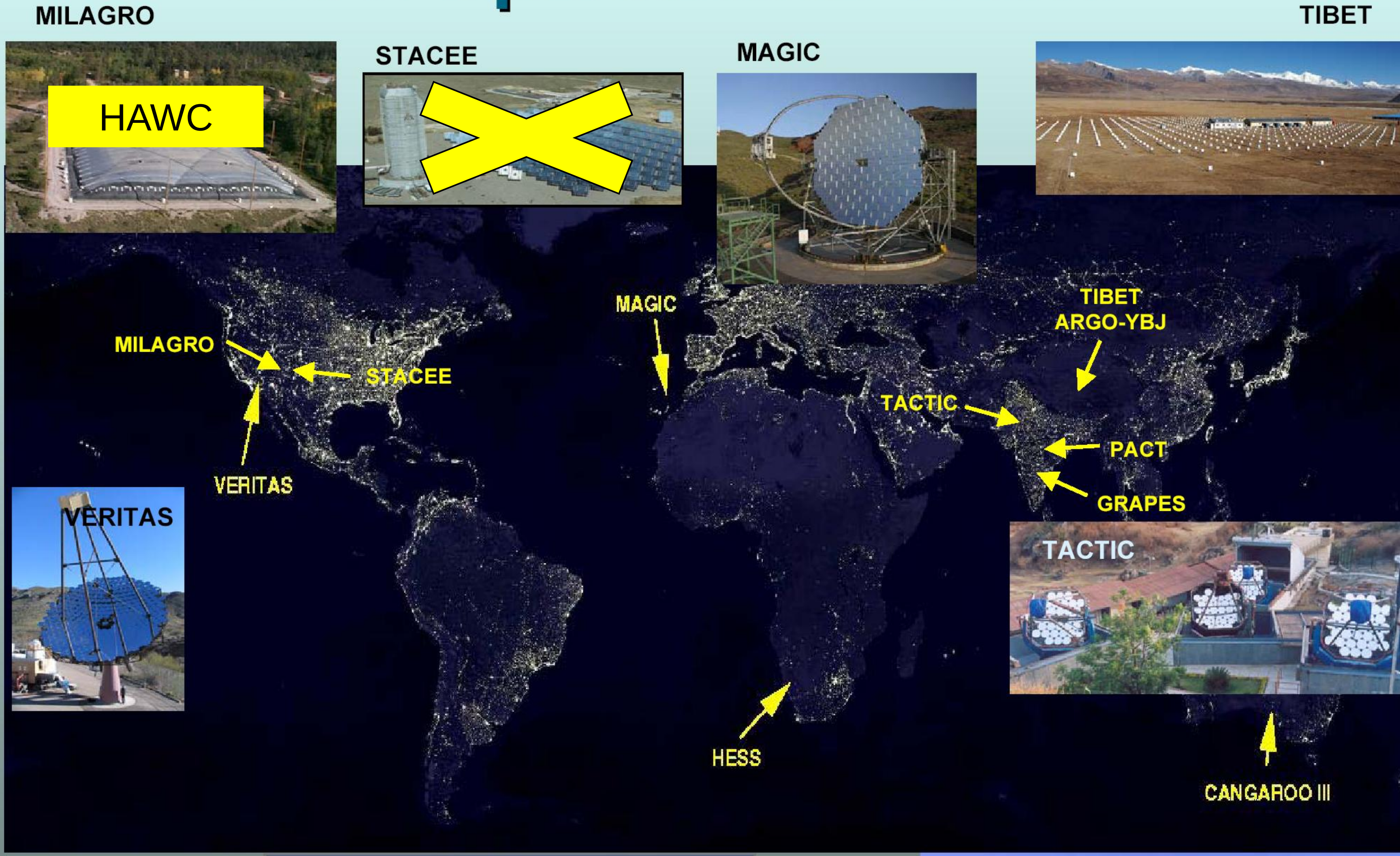
IACTs are *pointing* instruments

Clouds are bad!



Energy threshold (and collection area) increase with zenith angle.

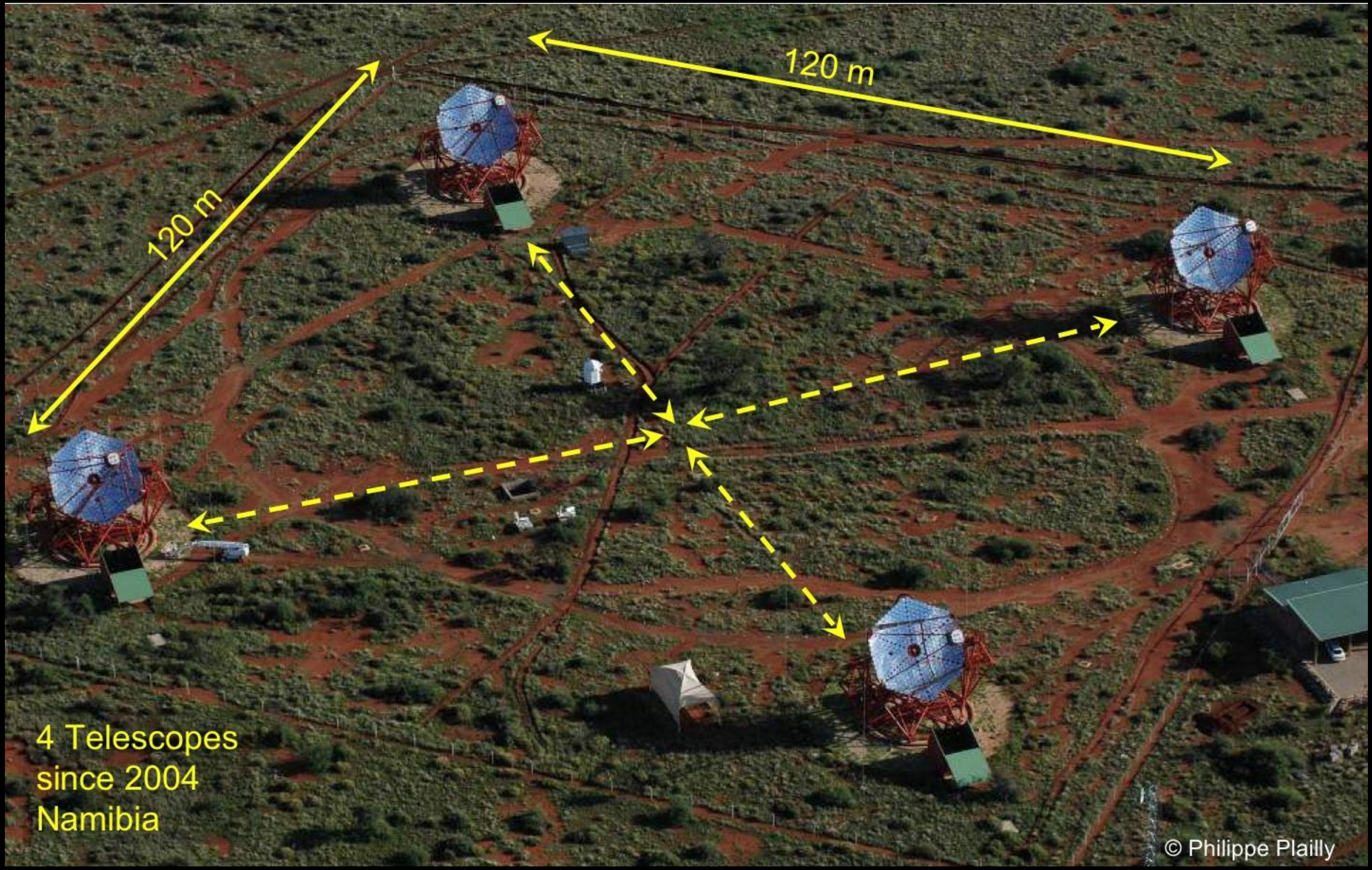
VHE Experimental World



From Rene Ong

OG 1

High Energy Stereoscopic System – H.E.S.S.



M-PIK Heidelberg; Humboldt University, Berlin; University of Hamburg; Ruhr University, Bochum; Landessternwarte Heidelberg; Tübingen University; Erlangen-Nürnberg University

LLR Ecole Polytechnique; LPNHE; APC College de France; University of Grenoble; CESR Toulouse; CEA Saclay; Observatoire de Paris-Meudon; LPTA Montpellier; LAPP Annecy

Durham University; University of Leicester

Dublin Institute for Advanced Studies

Polish Academy of Sciences (Astronomical Center & Institute of Nuclear Physics); Jagiellionian University; Nicolaus Copernicus University

Charles University, Prague

Yerevan Physics Institute, Armenia

University of Namibia

North-Western University, South Africa

University of Adelaide, Australia

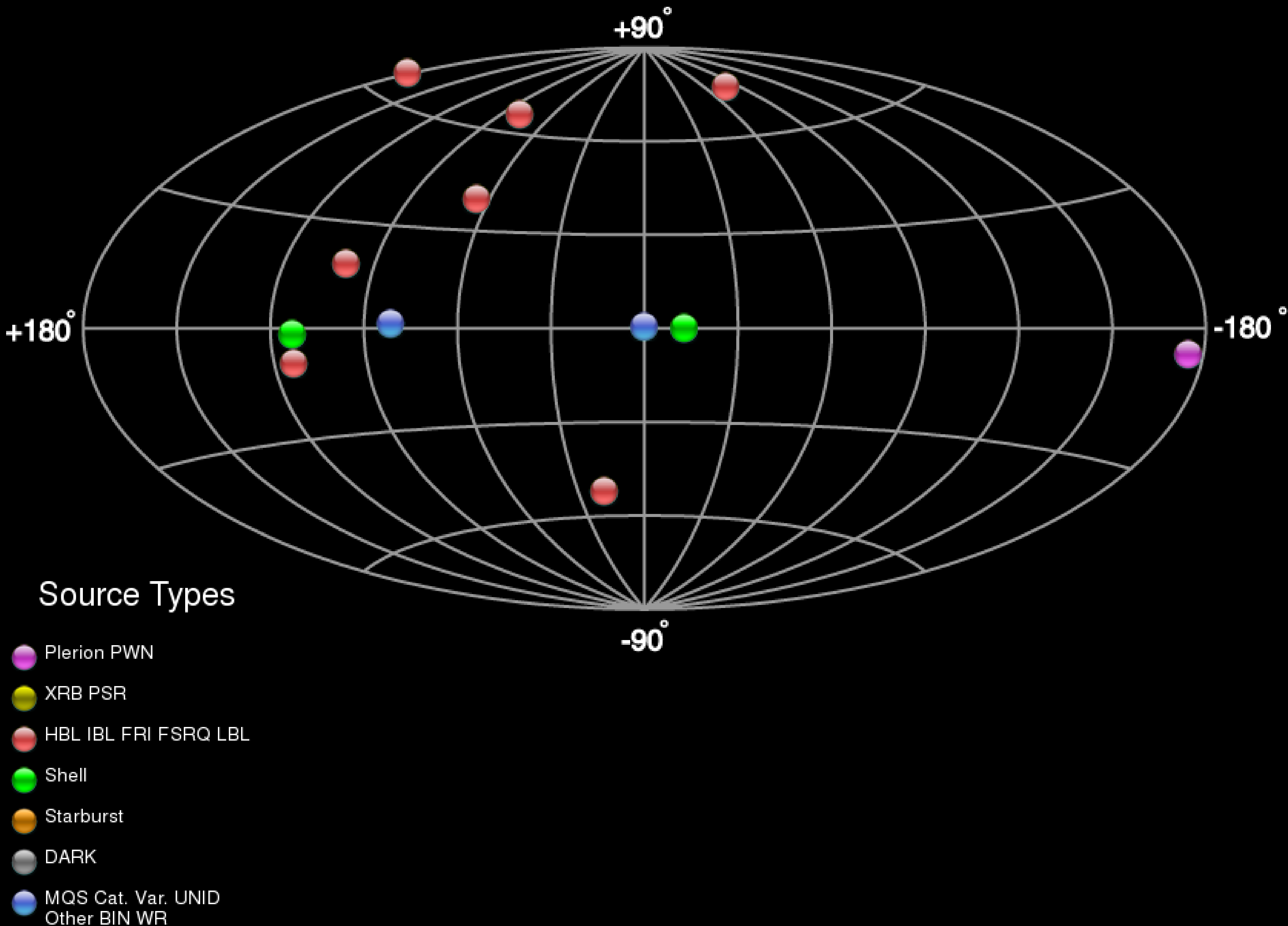
University of Innsbruck, Austria

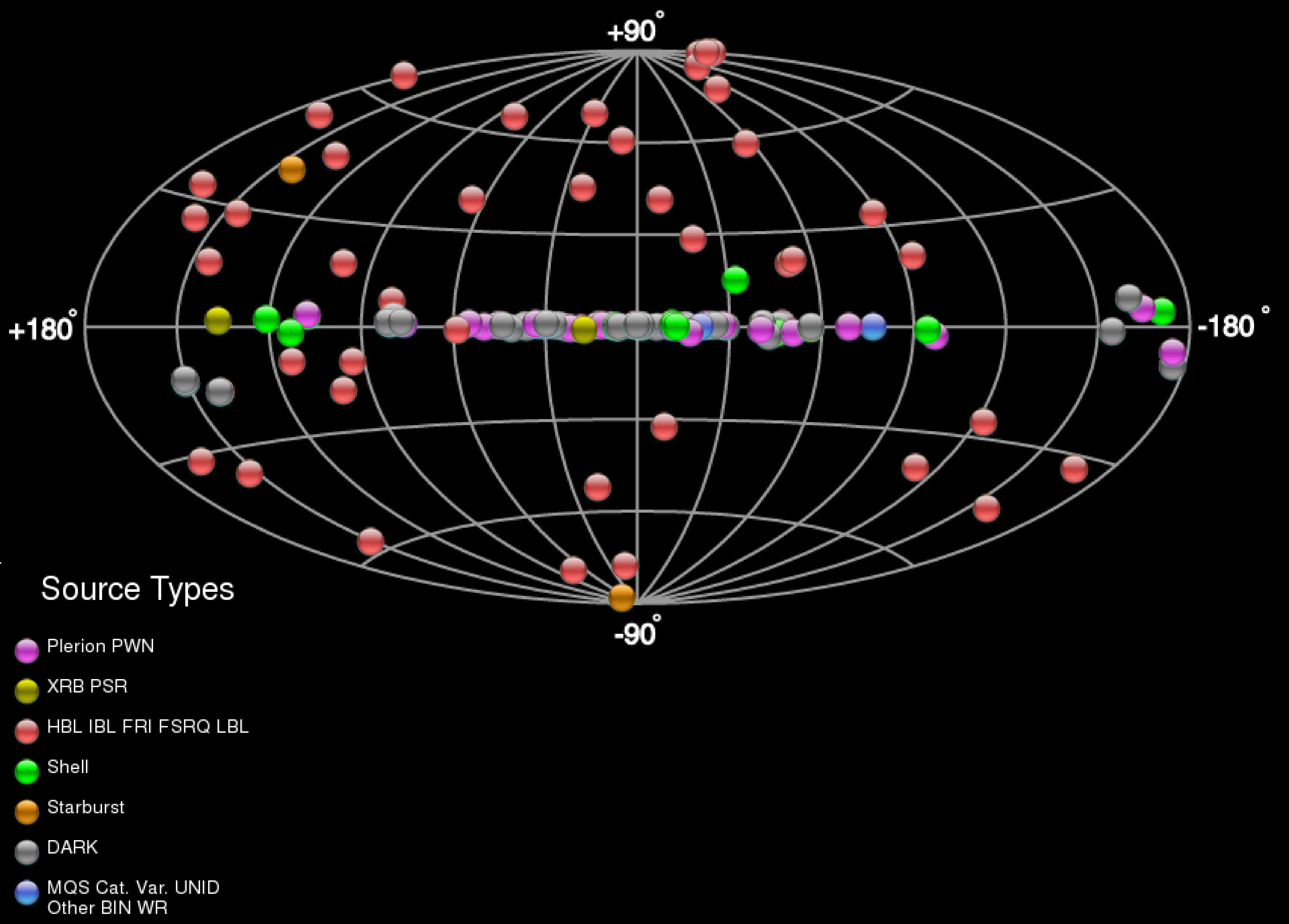
University of Stockholm, Sweden

System Parameters

- Energy Threshold 100 GeV
- Energy Resolution 15%
- Field of View ~5º
- Angular Resolution 0.05º-0.1º
- Pointing Accuracy ~10 arcsec
- Signal Rate ~55/min (Crab Like)
- Sensitivity:
  - 1 Crab in 30 sec
  - 0.01 Crab in 50h

(All at zenith)


+90°
+180°
-180°
-90°
Source Types
Plerion PWN
XRB PSR
HBL IBL FRI FSRQ LBL
Shell
Starburst
DARK
MQS Cat. Var. UNID
Other BIN WR



+90°
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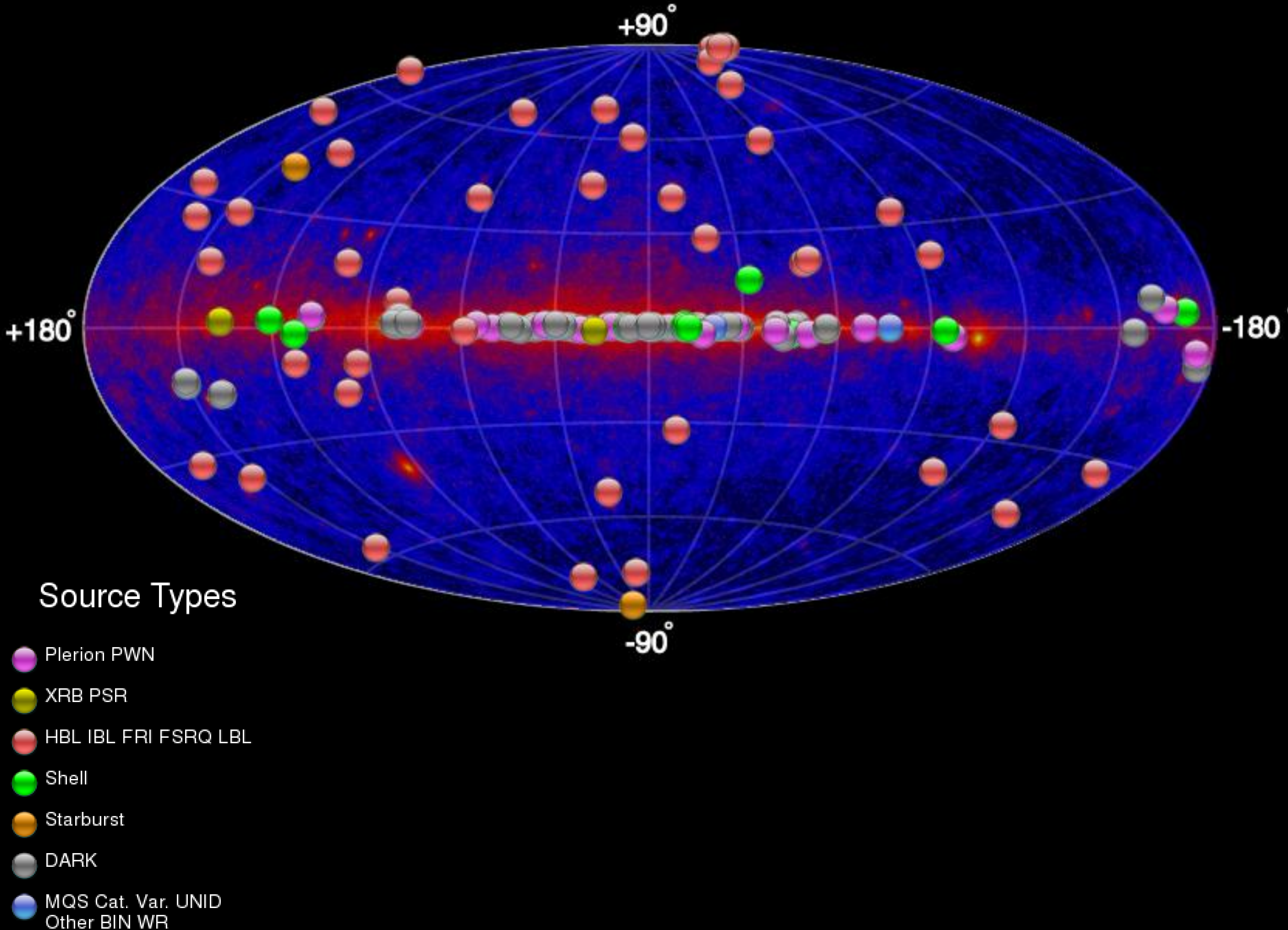

+90°
+180°
-180°
-90°
Source Types
Plerion PWN
XRB PSR
HBL IBL FRI FSRQ LBL
Shell
Starburst
DARK
MQS Cat. Var. UNID
Other BIN WR

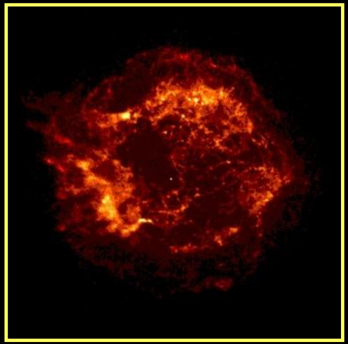
Sources by Type

Unidentified	31	HBL	29
PWN	28	IBL	4
Shell SNRs	14	LBL	4
Binaries	5	FRI	2
Clusters/WR	4	Starburst Galaxies	2
Diffuse	2	FSRQ	3
Gal. Centre	1 (!)	Seyfert 2	1?

That comes to 130 – but it is subjective, and each category has a typical uncertainty of +/- 1

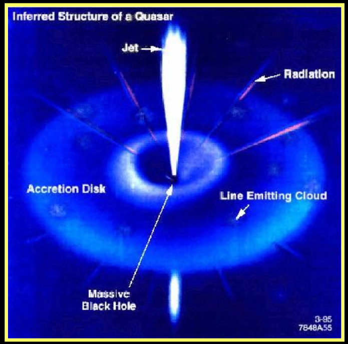
Science with VHE Gamma Rays

Origin of cosmic rays

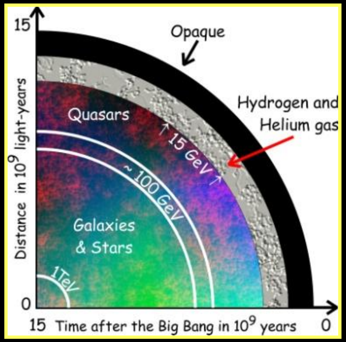


SNRs

Pulsars and PWN

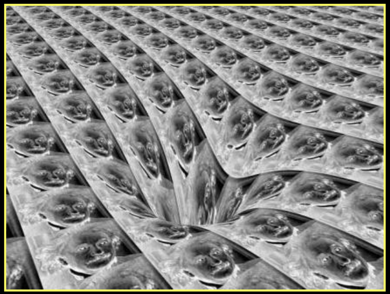


AGNs

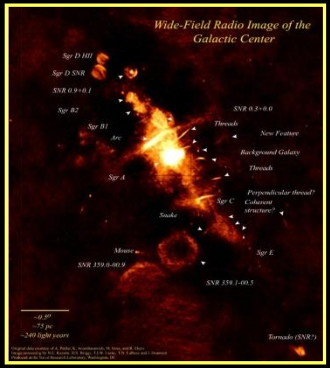


Cosmology

Space-time & relativity



Dark matter

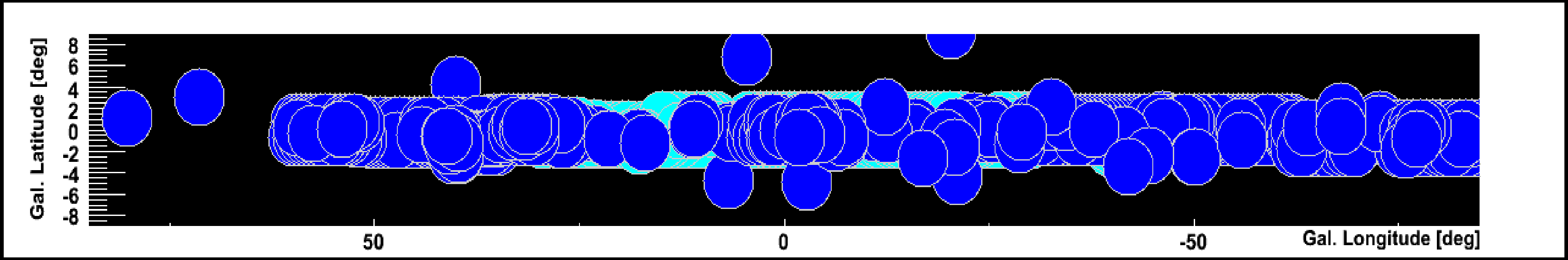


GRBs

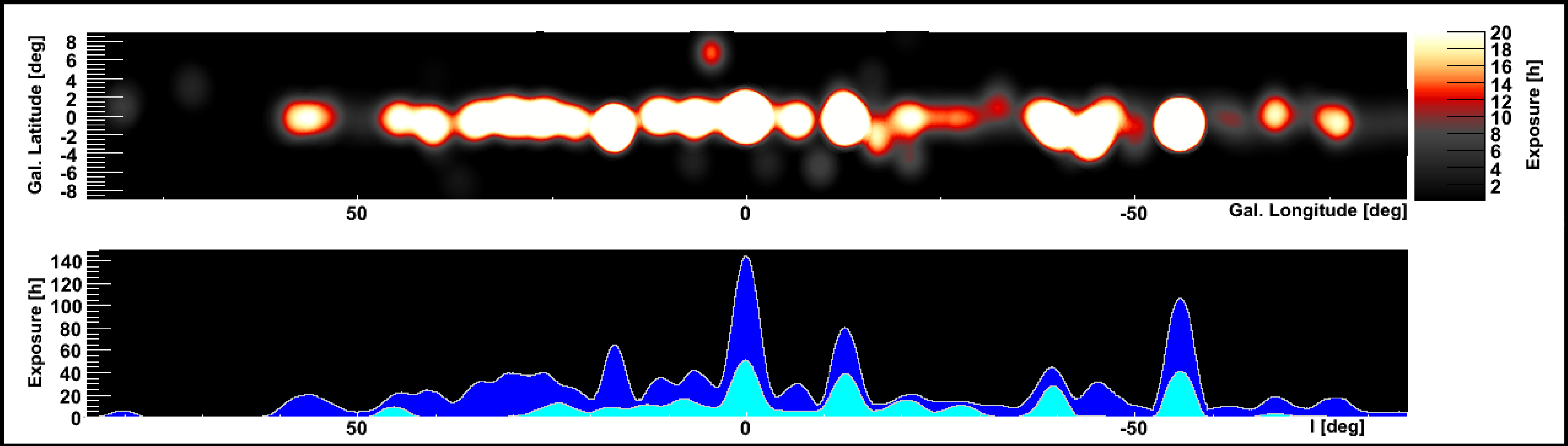
The H.E.S.S. Galactic Plane Survey

The Extended H.E.S.S. GPS

2005 - 2008

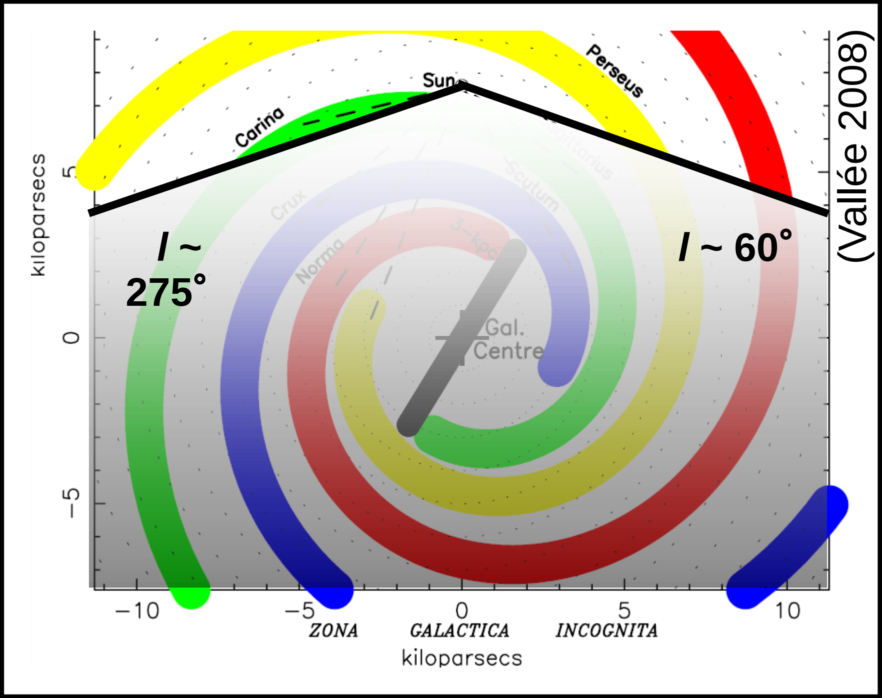


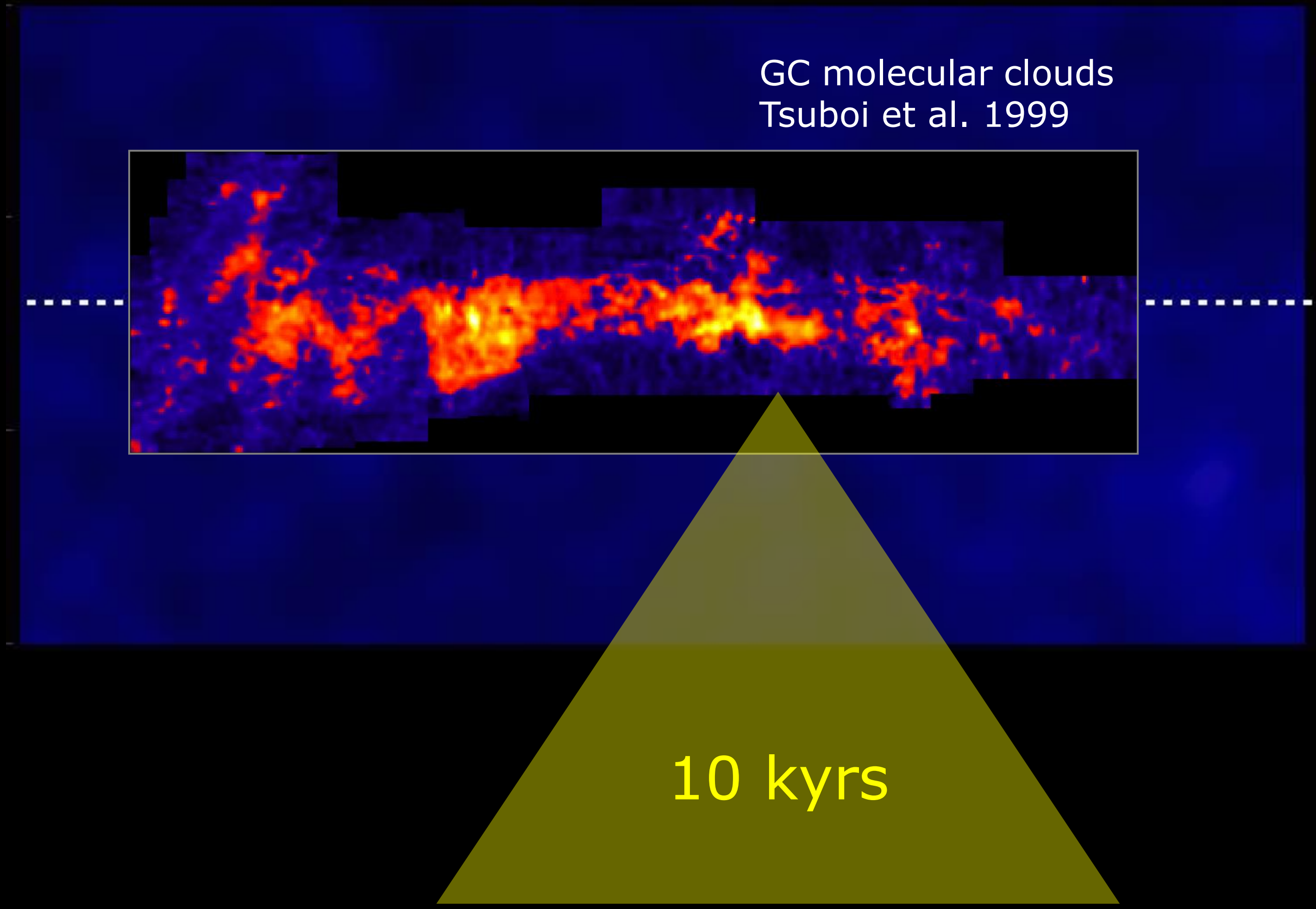
Acceptance-corrected Exposure



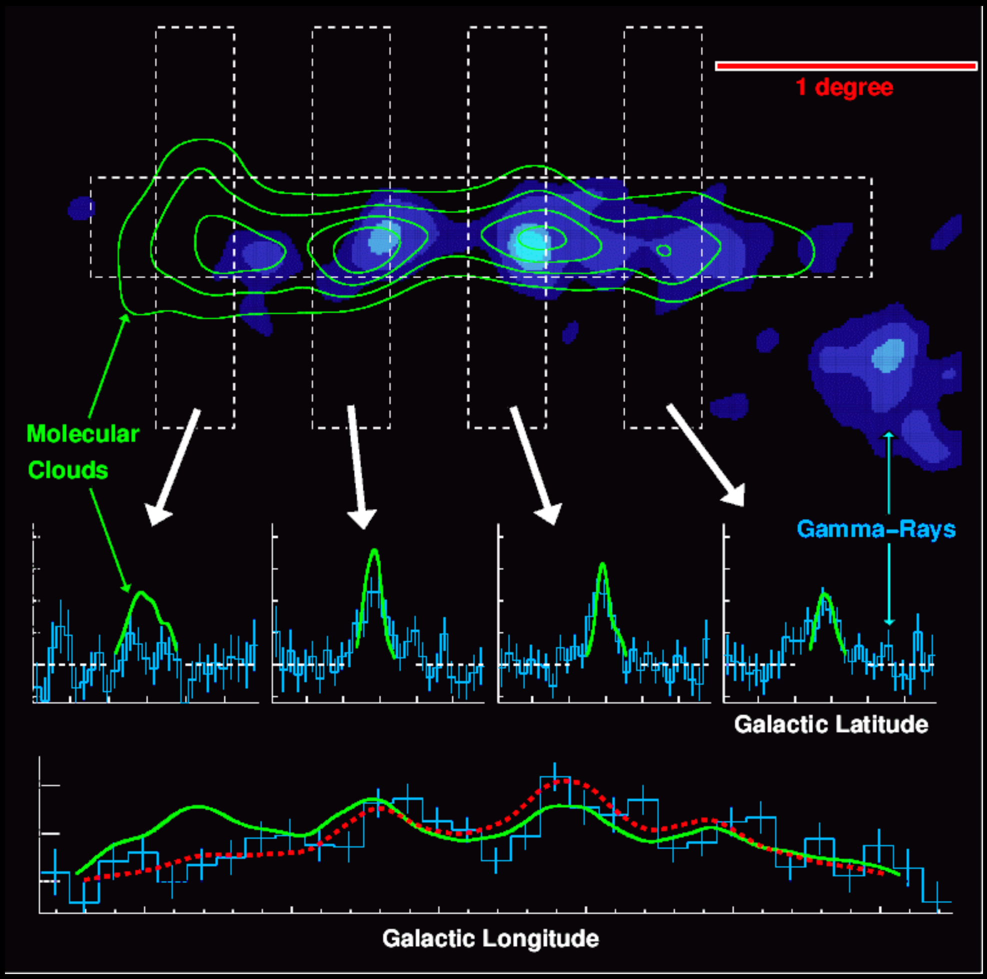
Extended H.E.S.S. GPS

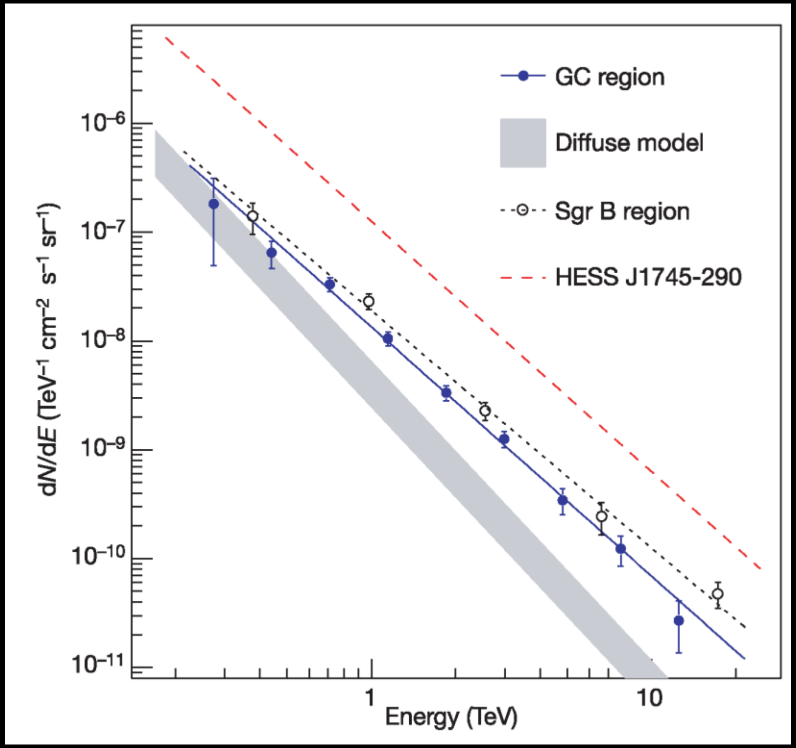
- **-85° < *l* < 60°**
- -3° < *b* < 3°
- Scan mode: **400** h
- Detected **50+ Galactic sources** of VHE gamma-rays
- ICRC 2007, DPG 2008, Gamma08




GC molecular clouds
Tsuboi et al. 1999
10 kyrs

H.E.S.S. Observations of Diffuse Emission in GC Region

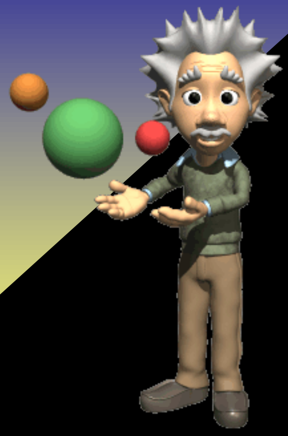




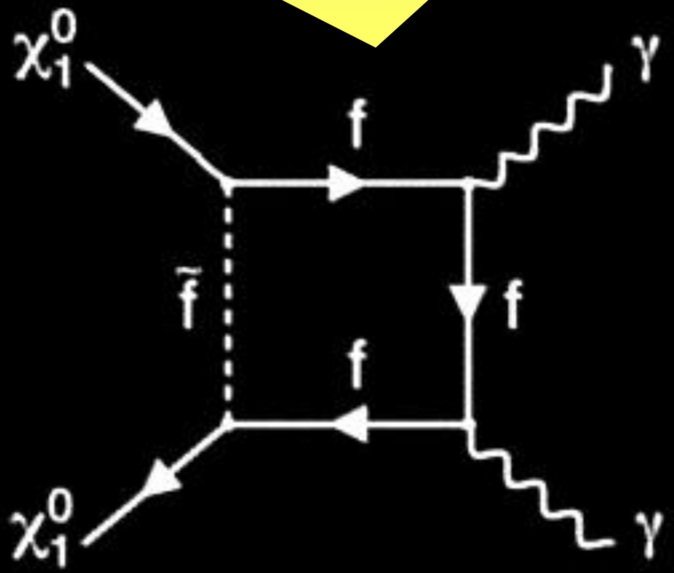
Aharonian et al., Nature, 439, 695 (2006)

Top-down: Annihilation of dark matter particles

$\chi\,\chi \rightarrow \gamma\gamma,\ \gamma Z,\ \gamma h$

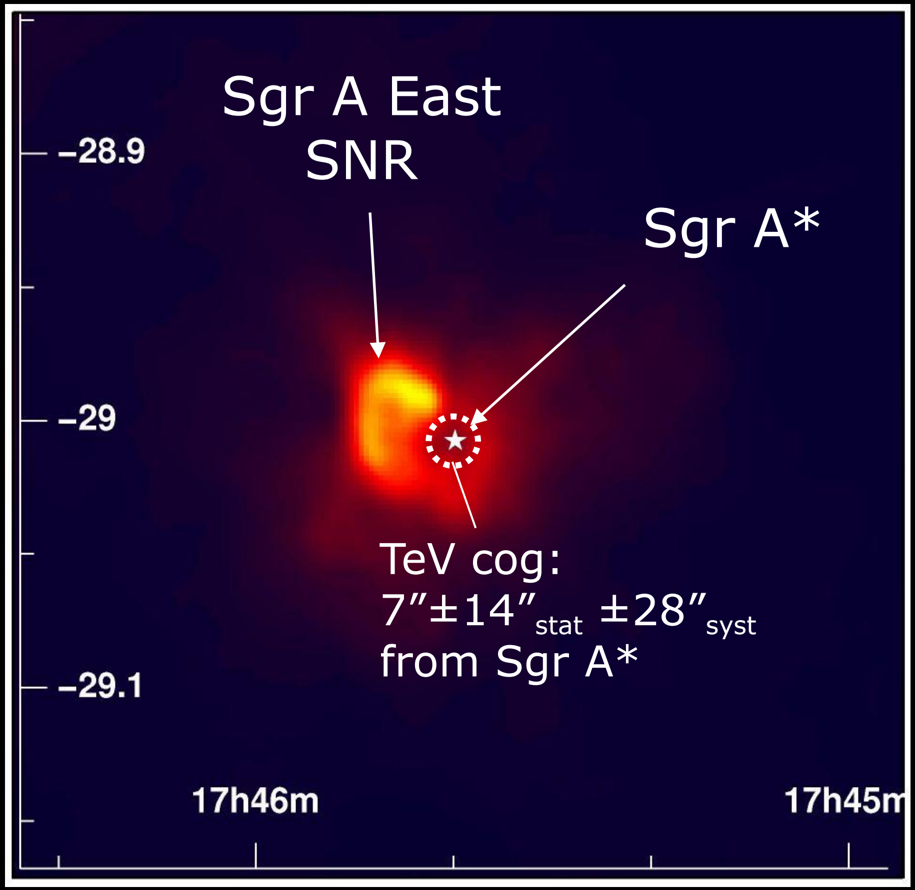


Matter distribution expected to have characteristic density profile:
$\sim r^{-1}$ (NFW)
to $r^{-1.5}$ (Moore)
sharp spike
with long tail
and characteristic energy spectrum

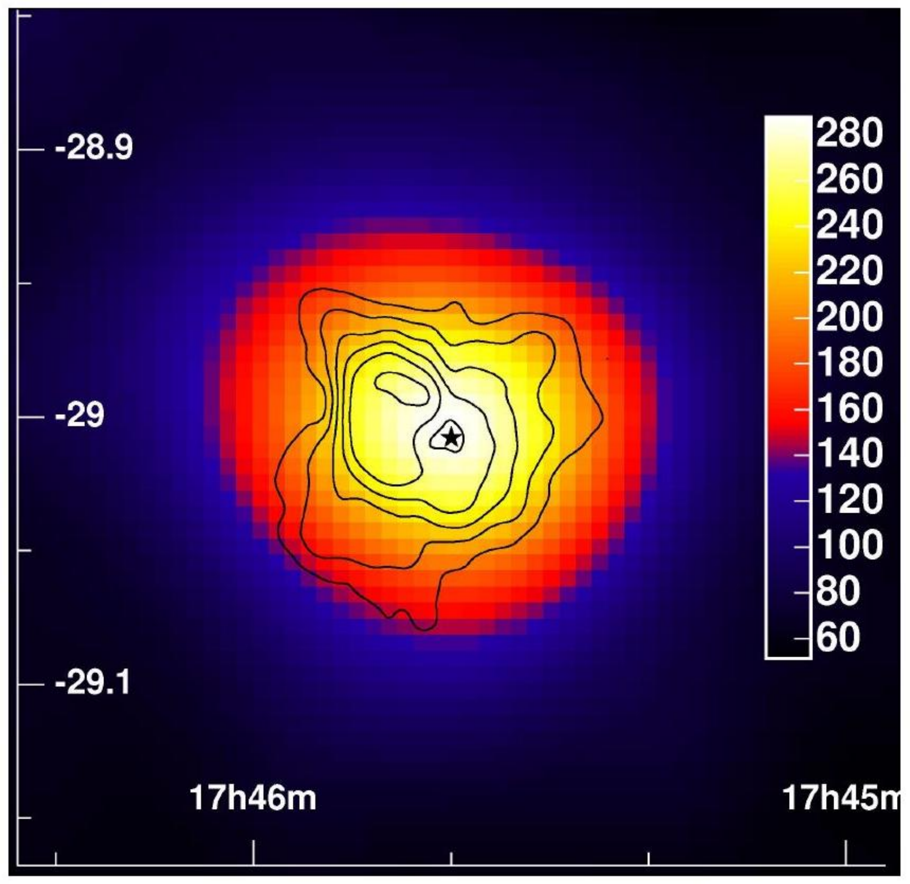


Nicked from Werner Hofmann!

Galactic Centre



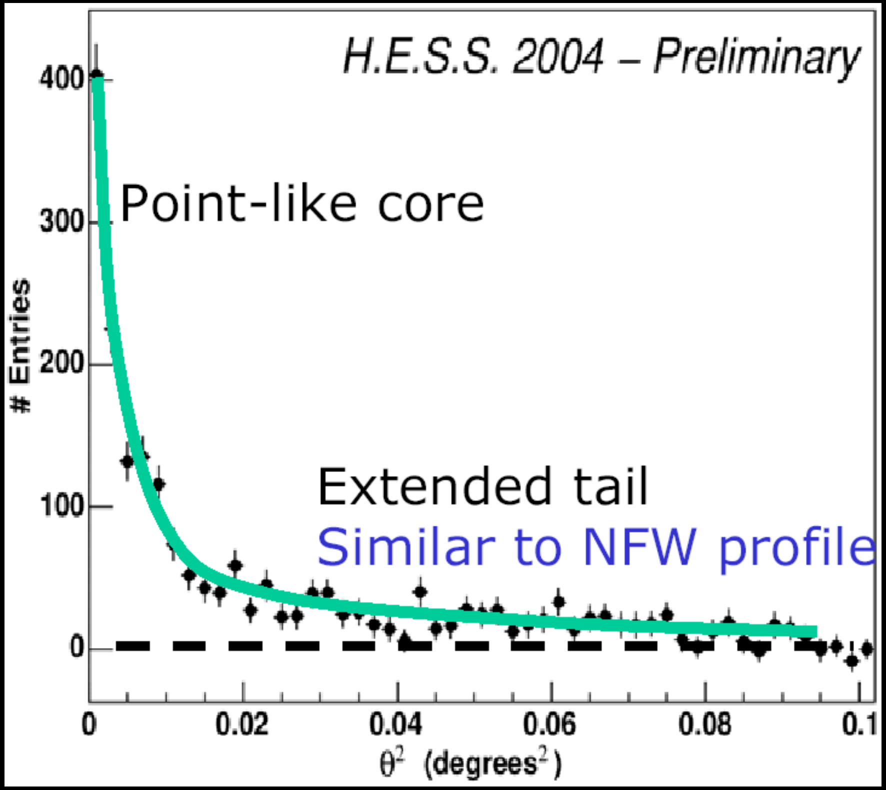
Radio



TeV H.E.S.S.

Aharonian et al., A&A, 425, 13 (2004)

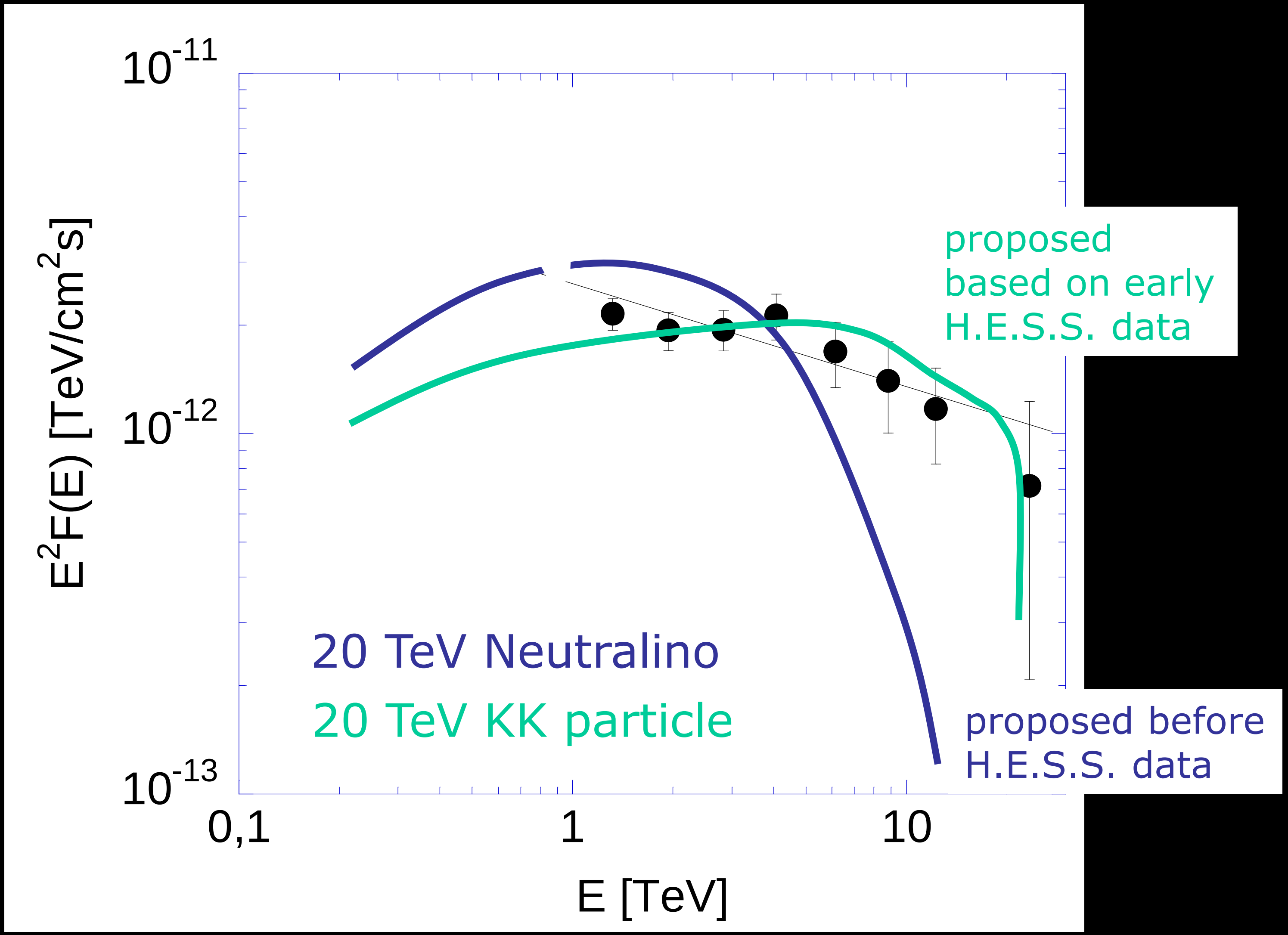
DM Annihilation – angular distribution



Angular distribution of H.E.S.S. result consistent with a point source, once diffuse BG eliminated (16% of total emission). Assume a Gaussian centred on best-fit position → lower limit to slope of distribution -1.2 (i.e. cuspy)

Aharonian et al., PhRvL, 97, 22, id 221102 (2006)

DM annihilation - spectrum

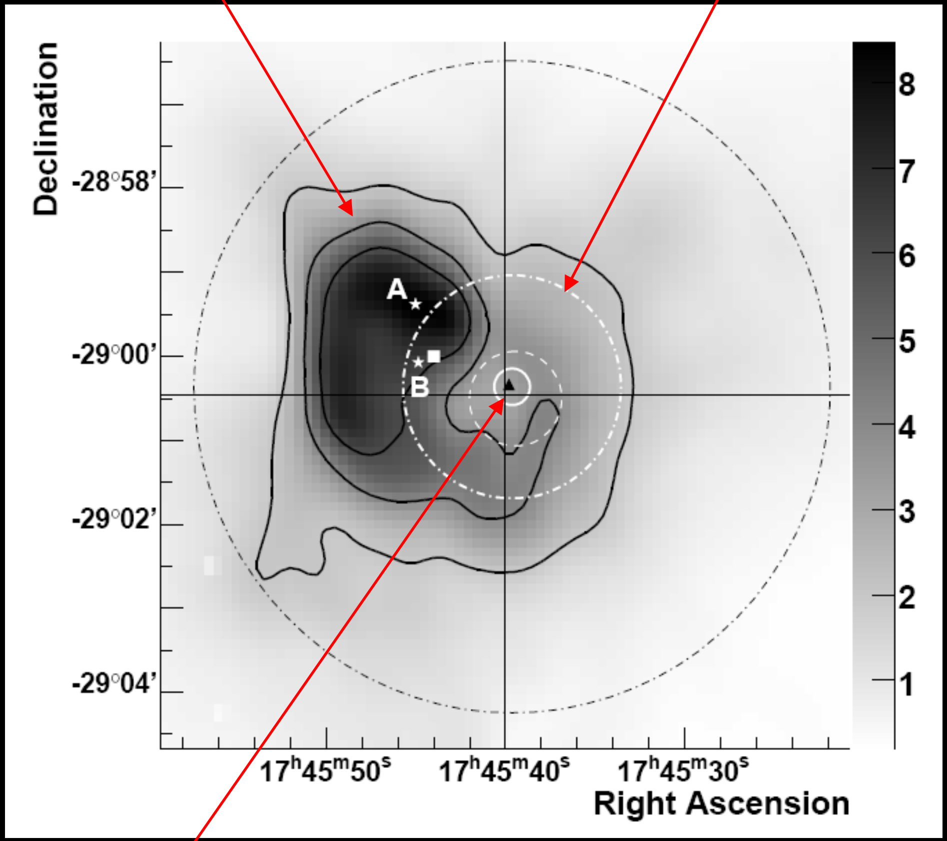


Bergström et al, Phys. Rev. Lett., 94, id. 131301 (2005)

The Position of the Galactic Centre Source

Radio contours of Sgr A East (VLA)

Previous H.E.S.S. best-fit centroid



First H.E.S.S. result was compatible with Sgr A East, Sgr A* and PWN candidate G359.95-0.04. Using paraxial optical cameras on telescopes reduced pointing errors from 20 arcsec to 6 arcsec per axis. Sgr A East looks to be ruled out as source of emission.

New H.E.S.S. best-fit centroid

Aharonian et al., *MNRAS*, Dec 2009 (astro-ph 0911.191v2)

Sgr Dwarf Spheroidal Galaxy

HST Image

Has crossed Milky Way at least 10 times without being disrupted.

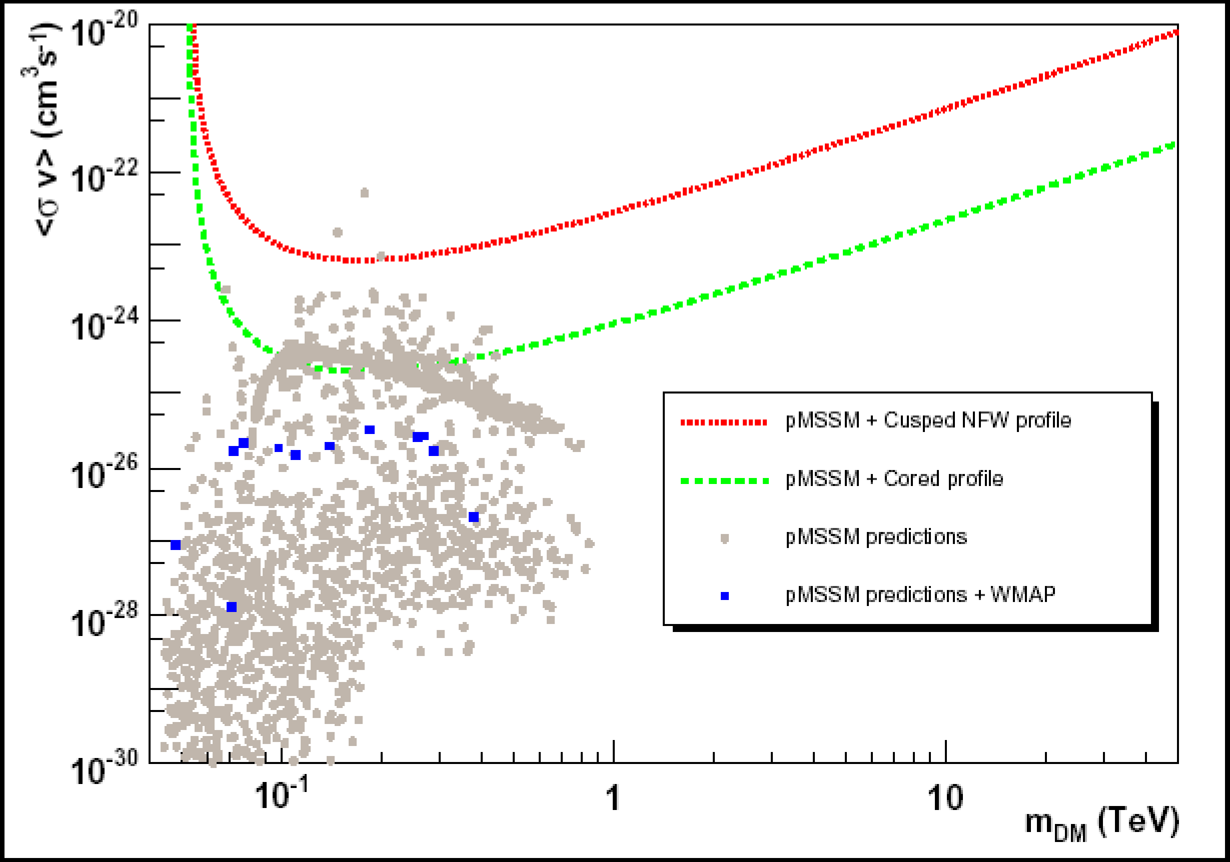
Good candidate for substantial amount of DM – not much gas, so low CR background too.

Handily, also off the Galactic Plane.

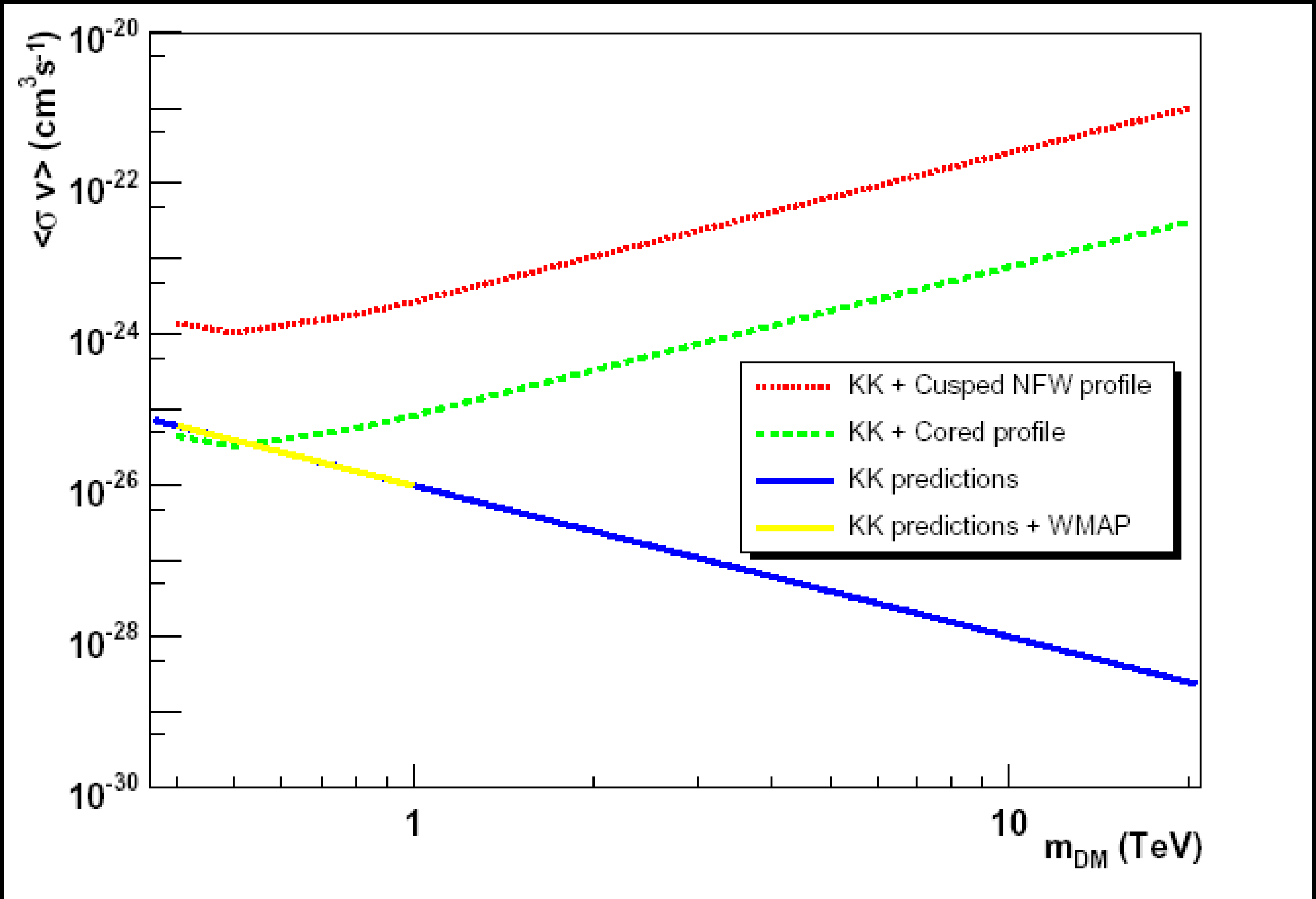
Signal is expected to come from a region ~1.5 pc, much smaller than the H.E.S.S. PSF. Profile (NFW…) doesn't matter!

H.E.S.S. Observations

June 2006, 11 hours. Upper limit E > 250 GeV: 3.6 x 10^{-12} $cm^{-2}s^{-1}$. (95% c.l.)



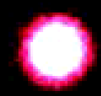
Aharonian et al., Astropart. Phys., 29, 55 (2008).

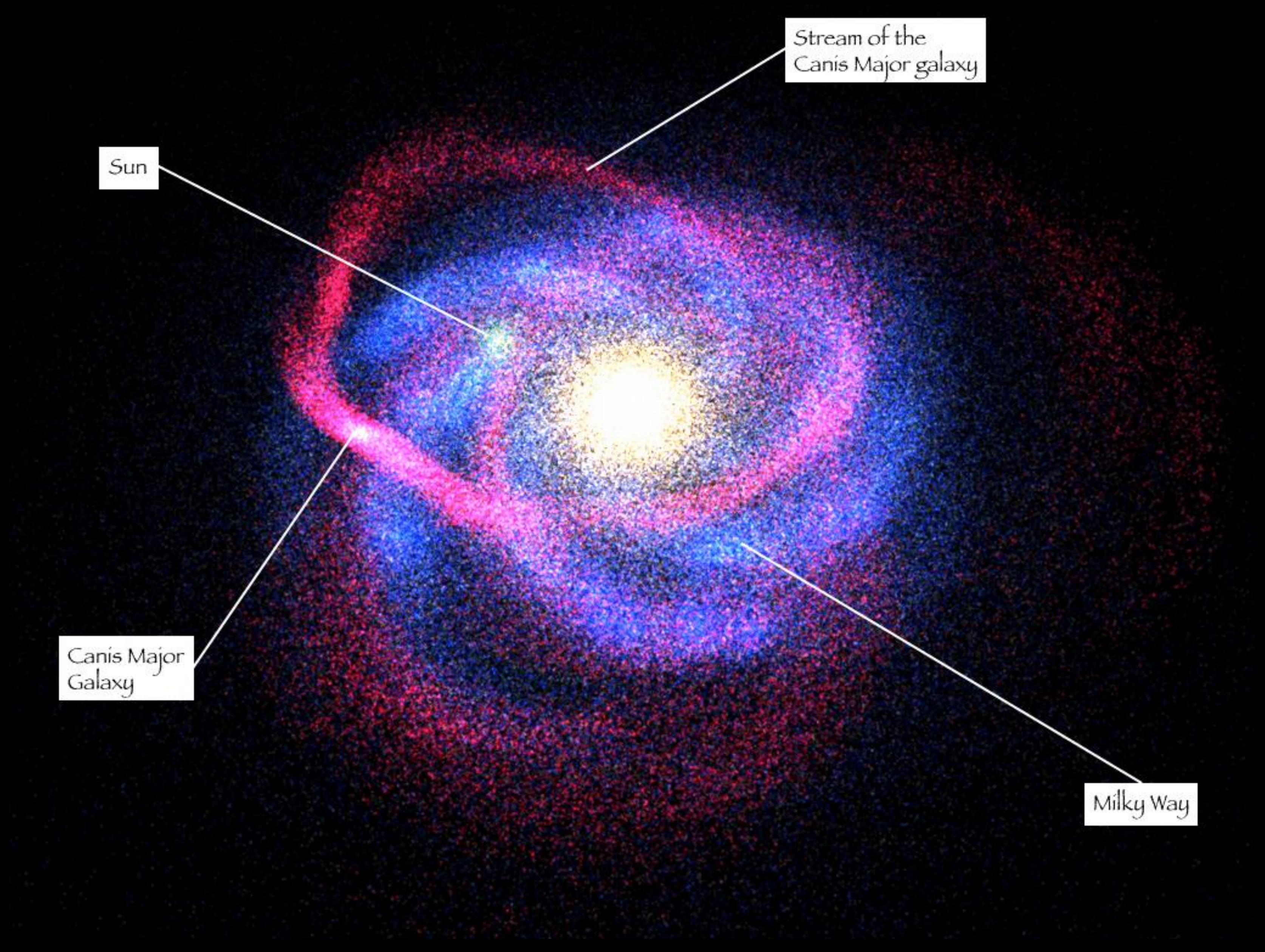


For core model, a lower limit for the $B^{(1)}$ mass of 500 GeV can be derived.

100h observation would enable the exclusion of much more pMSSM parameter space and all KK space for the core model

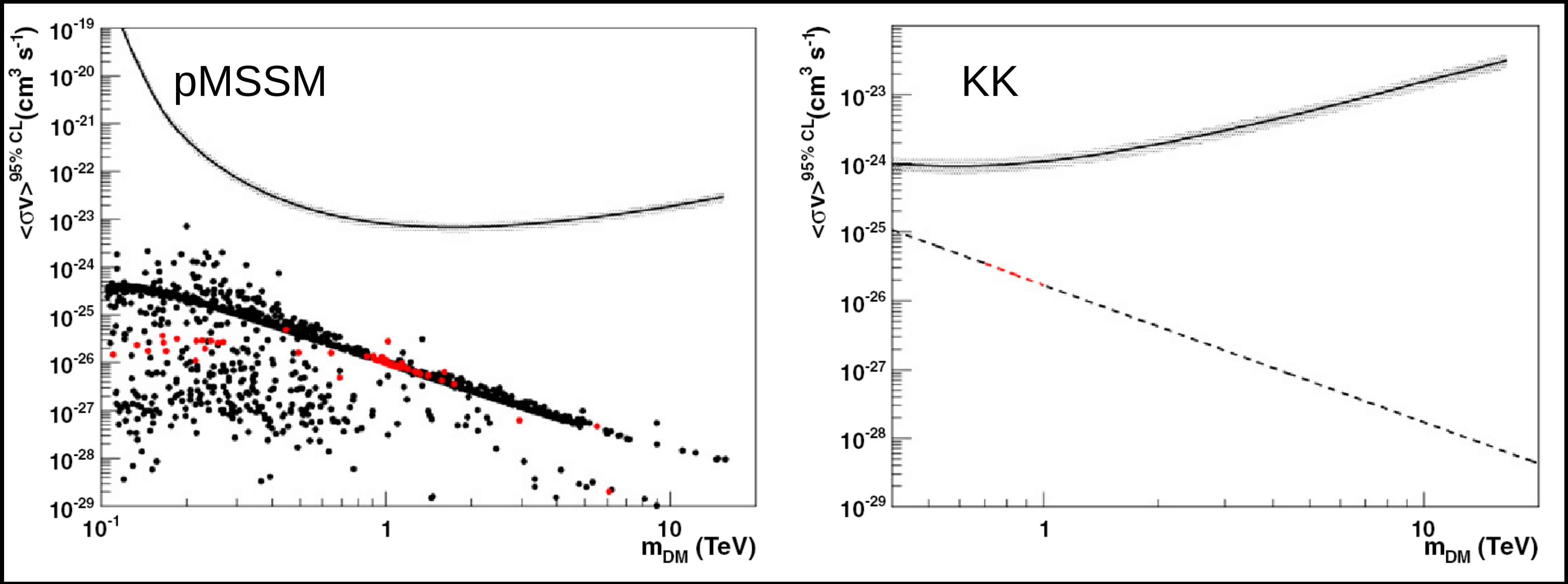
Canis Major ‘Overdensity’





From Strasbourg Observatory

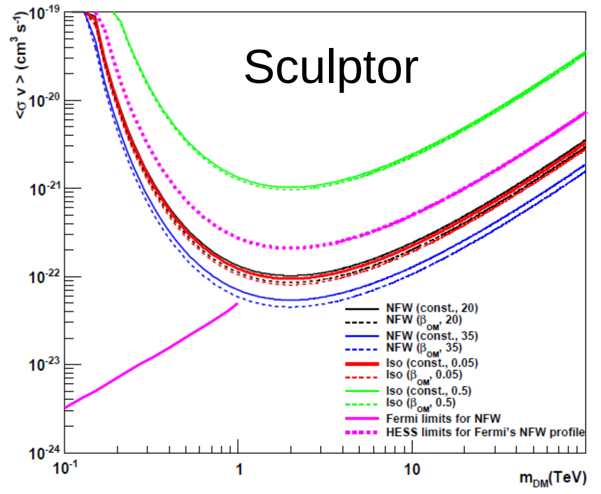
No Signal!

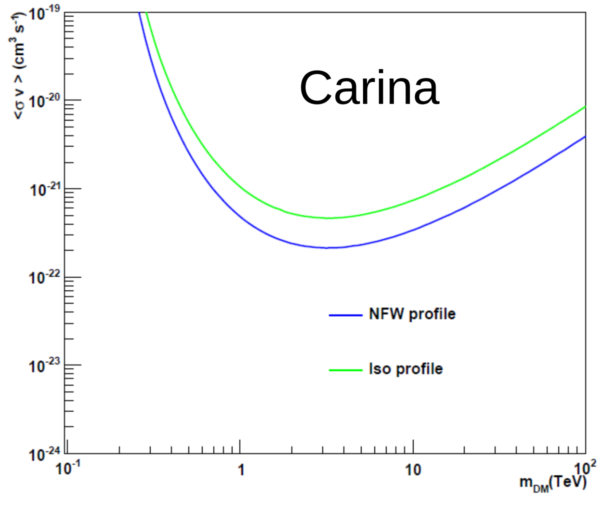


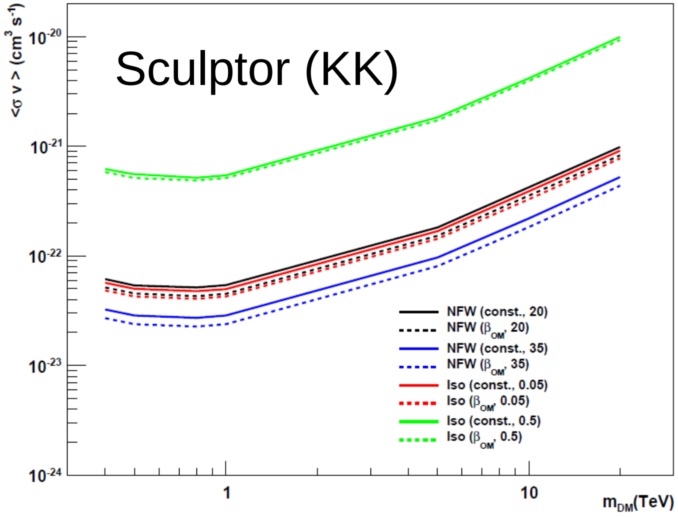
Mass of system not well known, so this is assuming mass of 3×10^8 solar masses.

Aharonian et al., Ap.J., 691, 175 (2009)

Likewise with Sculptor & Carina







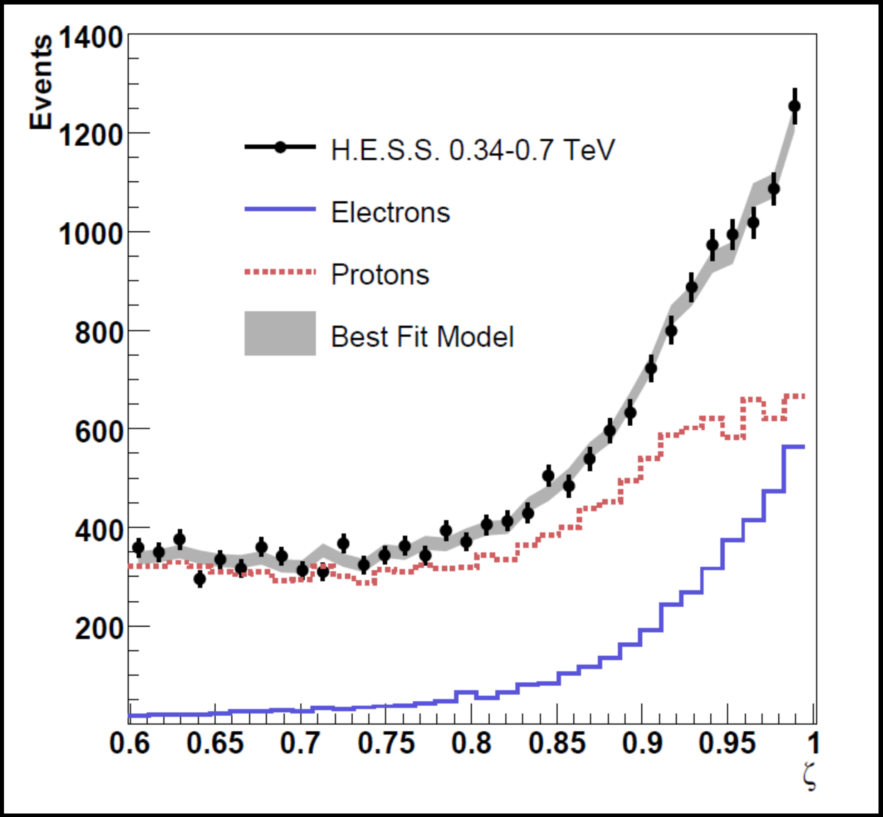
H.E.S.S. Collaboration
ArXiv:1012.5602

The Electron Spectrum

The ATIC experiment observed a peak in the electron spectrum between 300 and 800 GeV. Coupled with PAMELA excess, this has led to much speculation – e.g. dark matter, contribution from a local pulsar etc.

Measuring electron spectrum with a VHE gamma-ray experiment is tough – electrons and gamma rays both produce pure electromagnetic showers.

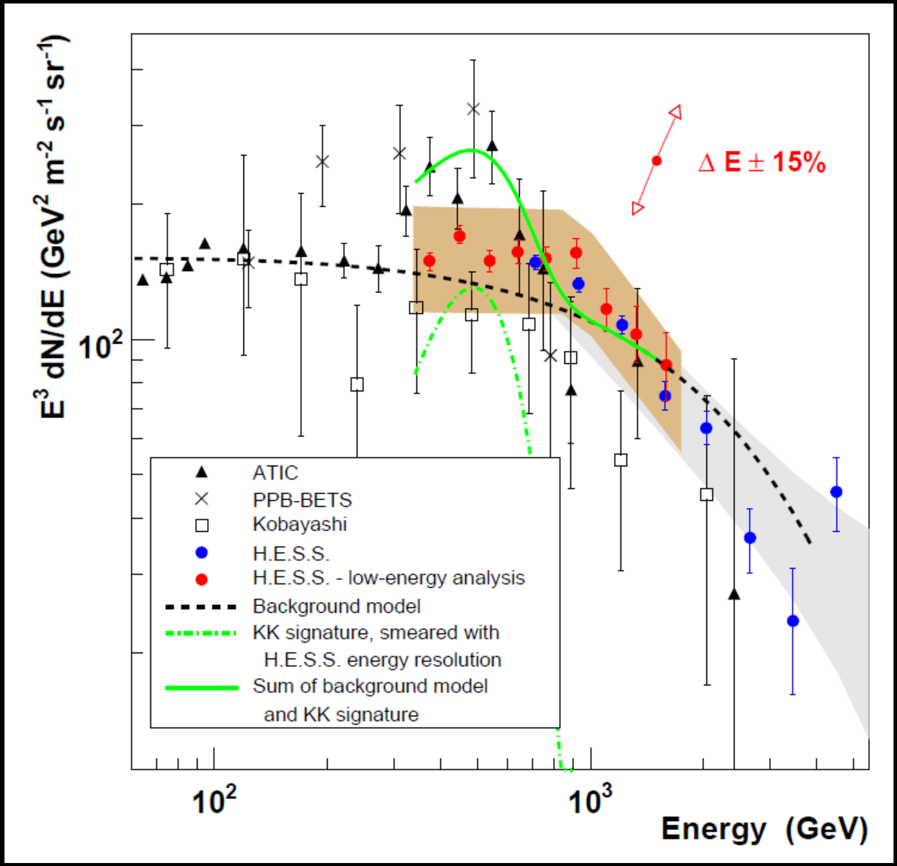
Have to use off-GP data and extensive simulations to derive an 'electron likeness' parameter, ζ.



Aharonian et al., *Astron. Astrophys*., **508**, 561 (2009)

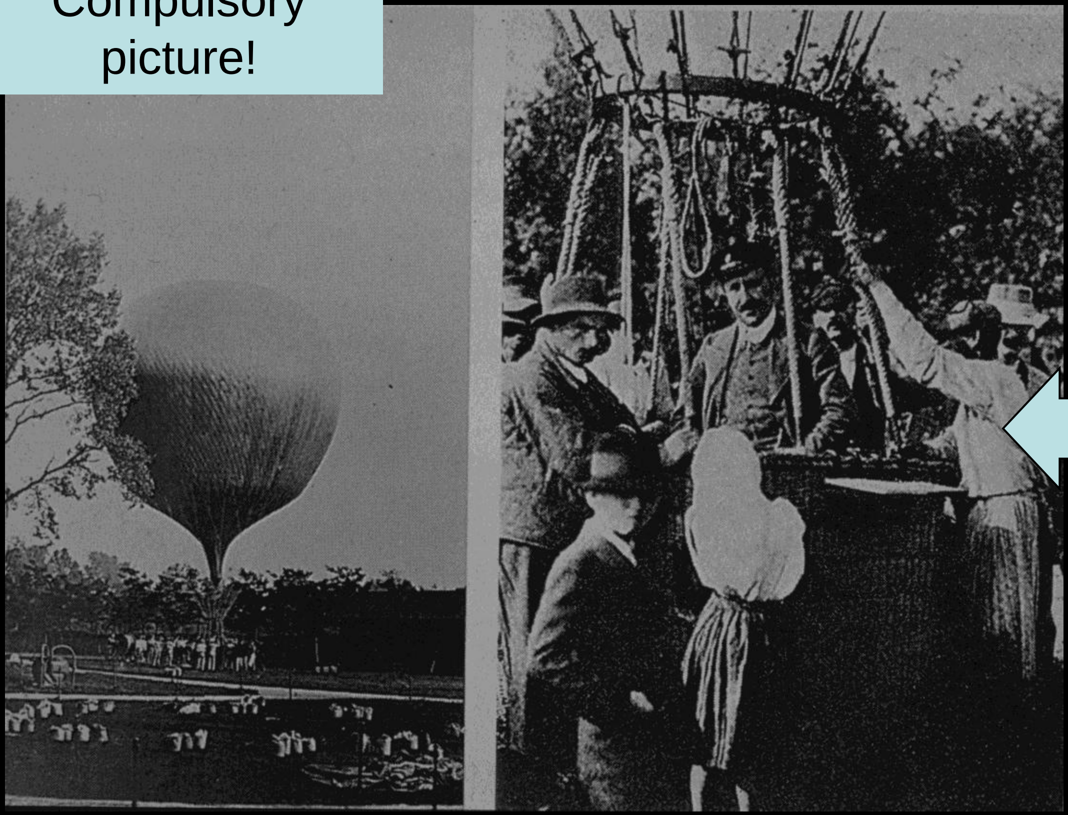
H.E.S.S. Measurements

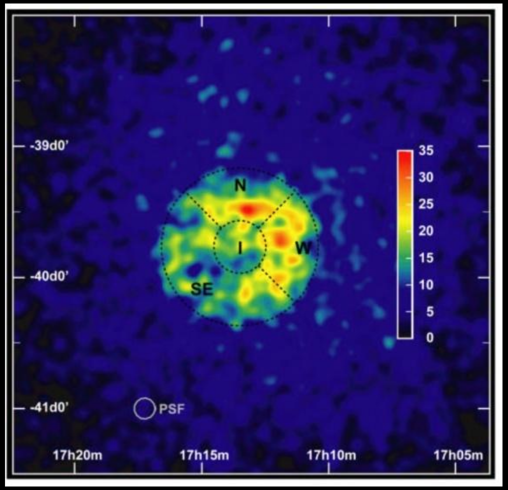
Overall electron flux is compatible with ATIC within errors, but H.E.S.S. data exclude presence of a pronounced peak in the electron spectrum, though an energy shift could be possible, so it cannot be definitively ruled out. However, it's hard to reconcile with a KK dark matter scenario.



Starburst Galaxies – why bother?

Compulsory picture!





Starburst galaxies = lots of star formation (in a small region) = lots of supernovae = lots of particle (proton) acceleration + lots of gas = lots of VHE gamma rays = confirmation of suspicions about galactic CRs (and maybe information about galaxy/star formation)

NGC 253

D = 3.9 ± 0.4 Mpc

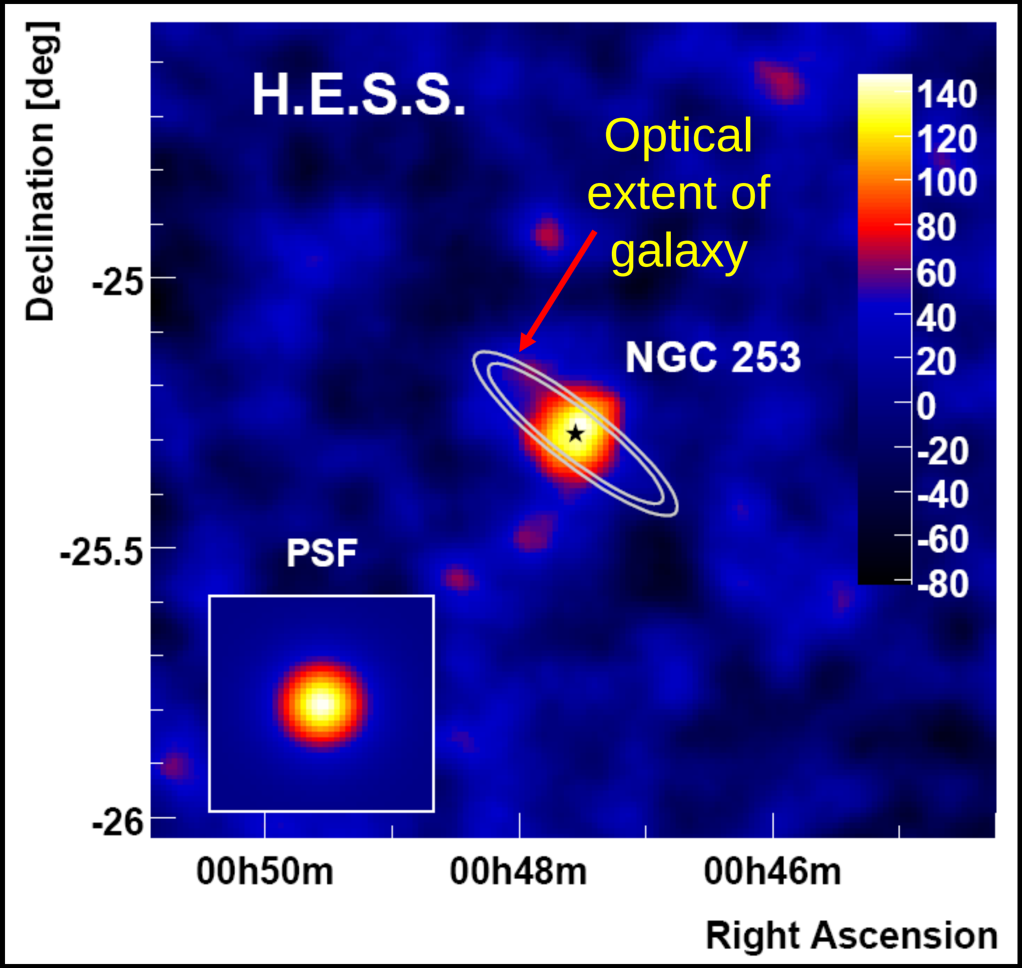
SN rate ~ 10x Milky Way in starburst region

Mean density of gas in starburst region almost 10^3 higher than MW

Radio, thermal X-rays show hot, diffuse halo consistent with galactic wind

Discovered by Caroline Herschel in 1783

H.E.S.S. Detection of NGC 253



Flux (E > 220 GeV): $5.5 \pm 1.0_{stat} \pm 2.8_{sys} \times 10^{-13}$ cm^{-2}s^{-1}

~ 0.3% Crab flux

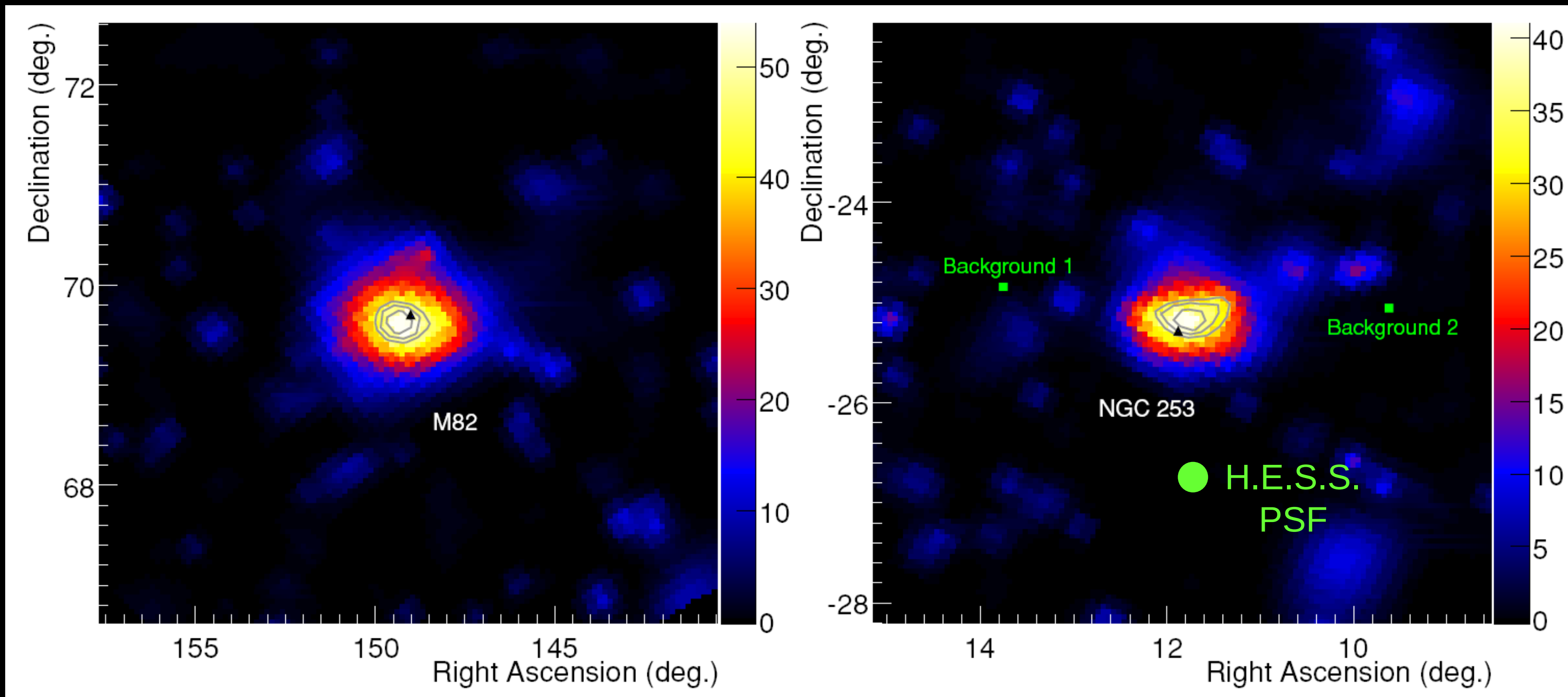
119 hours of observation

No evidence for variability

CR density in starburst region ~ 2000x that near the Solar System, and ~ 1400 times that near the GC

Acero et al., *Science*, **326**, 1080 (2009)

Fermi LAT detections of NGC253 & M82



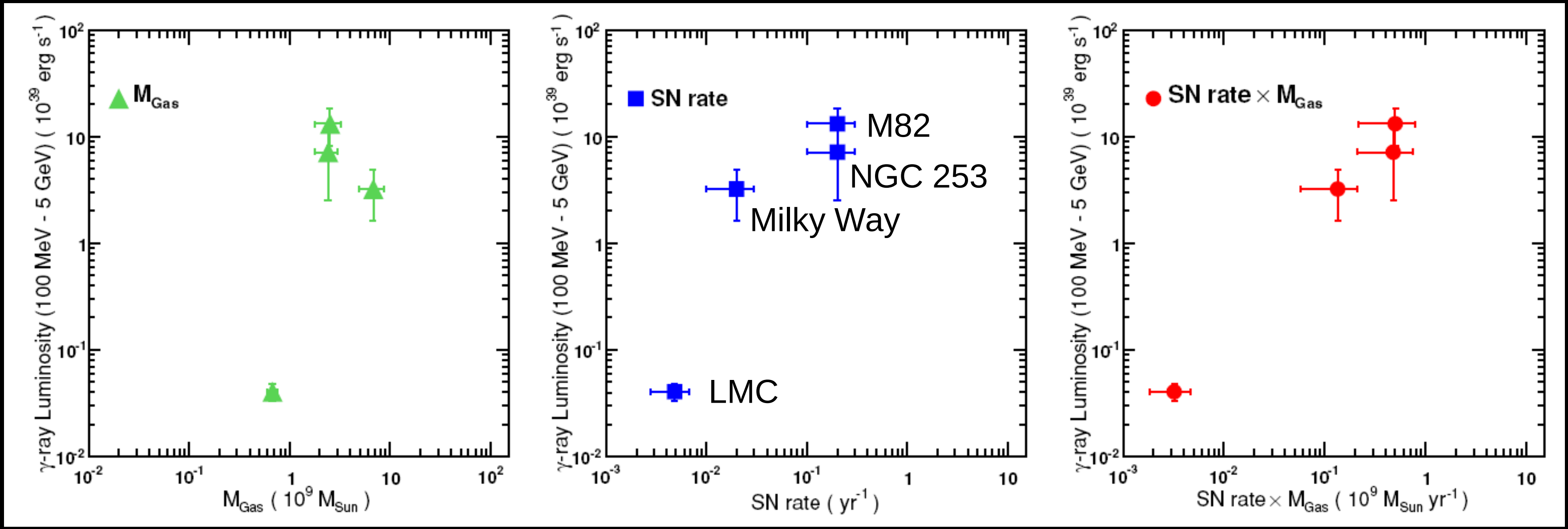
Flux (E > 100 MeV):
$1.6 \pm 0.5_{stat} \pm 0.3_{sys} \times 10^{-8}\ cm^{-2}s^{-1}$

Flux (E > 100 MeV):
$0.6 \pm 0.4_{stat} \pm 0.4_{sys} \times 10^{-8}\ cm^{-2}s^{-1}$

No evidence for variability in either object

Abdo et al., *Ap. J. Lett.*, **709**, L152 (2010)

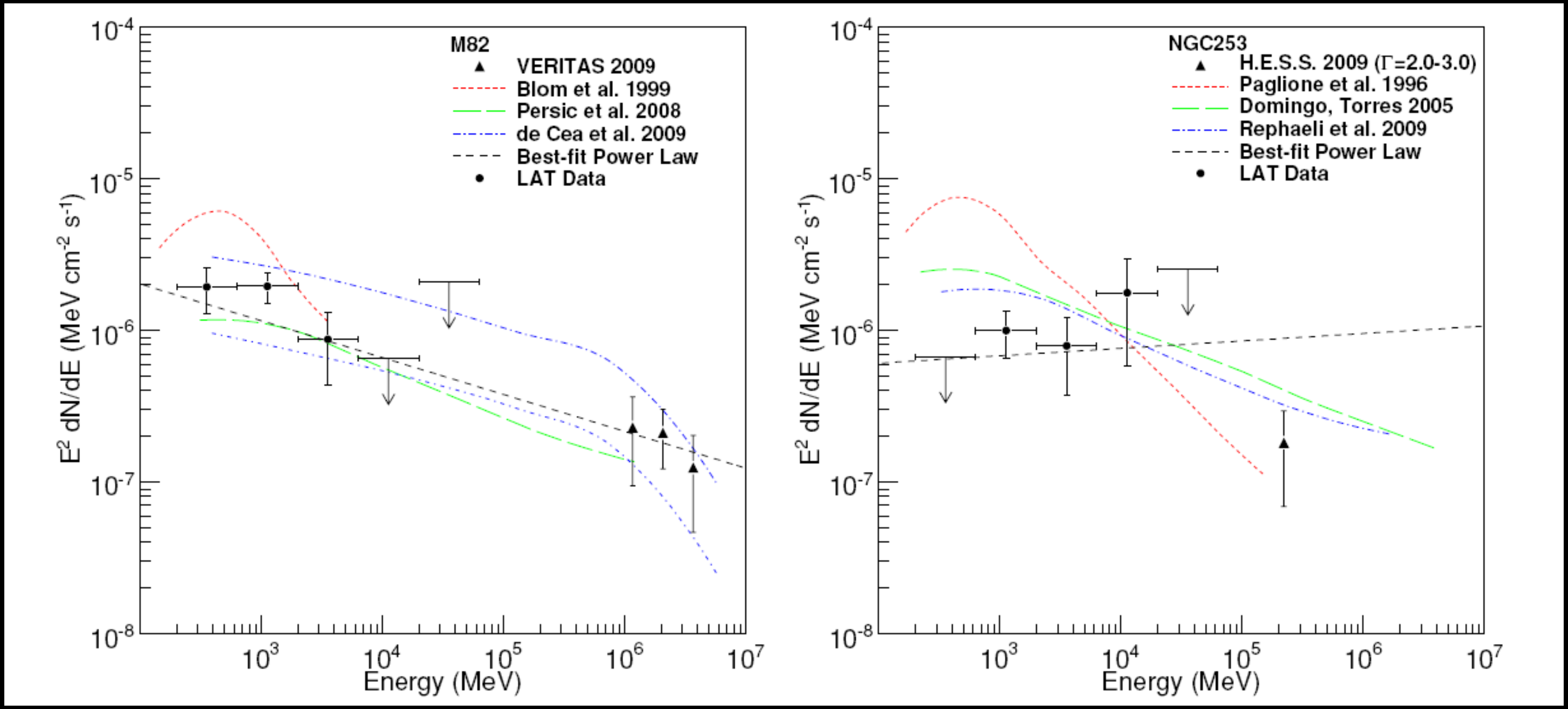
Interpretation I



Gamma-ray luminosity best correlates with SN rate *and* the mass of gas in the galaxy – perhaps not surprising.

BUT distribution of CRs is unlikely to be uniform – e.g. the GeV emission in LMC mostly comes from 30 Doradus and does not trace star formation & total gas mass.

Interpretation II

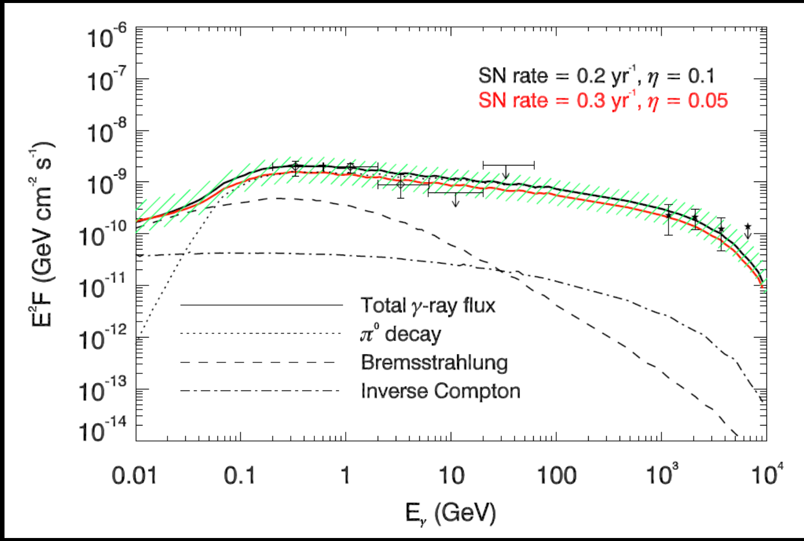


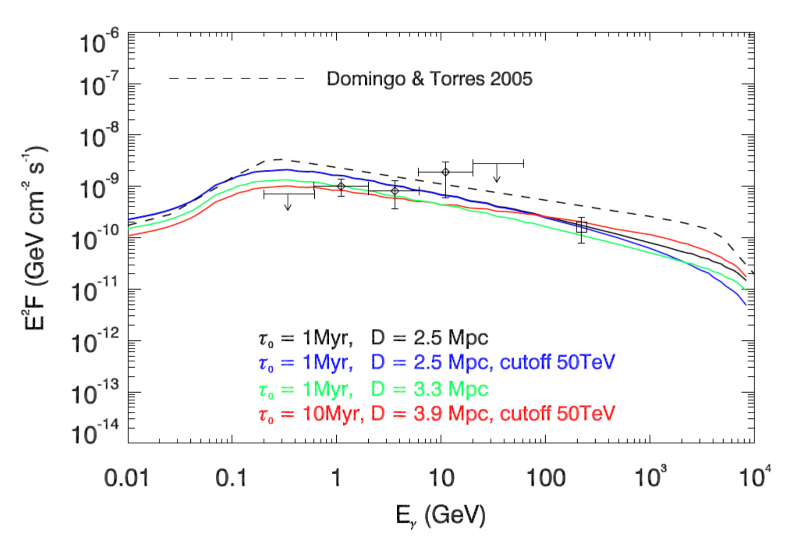
Emission models depend on many different parameters – agreement looks better for M82 than for NGC 253. In M82, the smooth power law connection between Gev & TeV emission suggests the same process produces both. Relationship less clear for NGC 253.

NGC 253 and Cosmic Rays

- 220 GeV generating protons need energy ~ 1300 GeV
- Given
  - CR energy production in equilibrium with losses from nuclear collisions;
  - Measured gas density and SN rate;
  - Production spectrum $\propto E^{-2.1}$
- Then calculate gamma ray flux to be factor of 10^2 higher than observed; suggests CRs in NGC 253 more likely to escape than expected
- NGC 253 is not a perfect CR ‘calorimeter’ – ISM does not act as a perfect ‘beam dump’
- Nevertheless, conversion efficiency of protons to gamma rays is still ~ 10x higher than in the Milky Way
- Starburst nucleus should outshine the rest of the galaxy (consistent with H.E.S.S. point source)

Interpretation III





M82

NGC 253

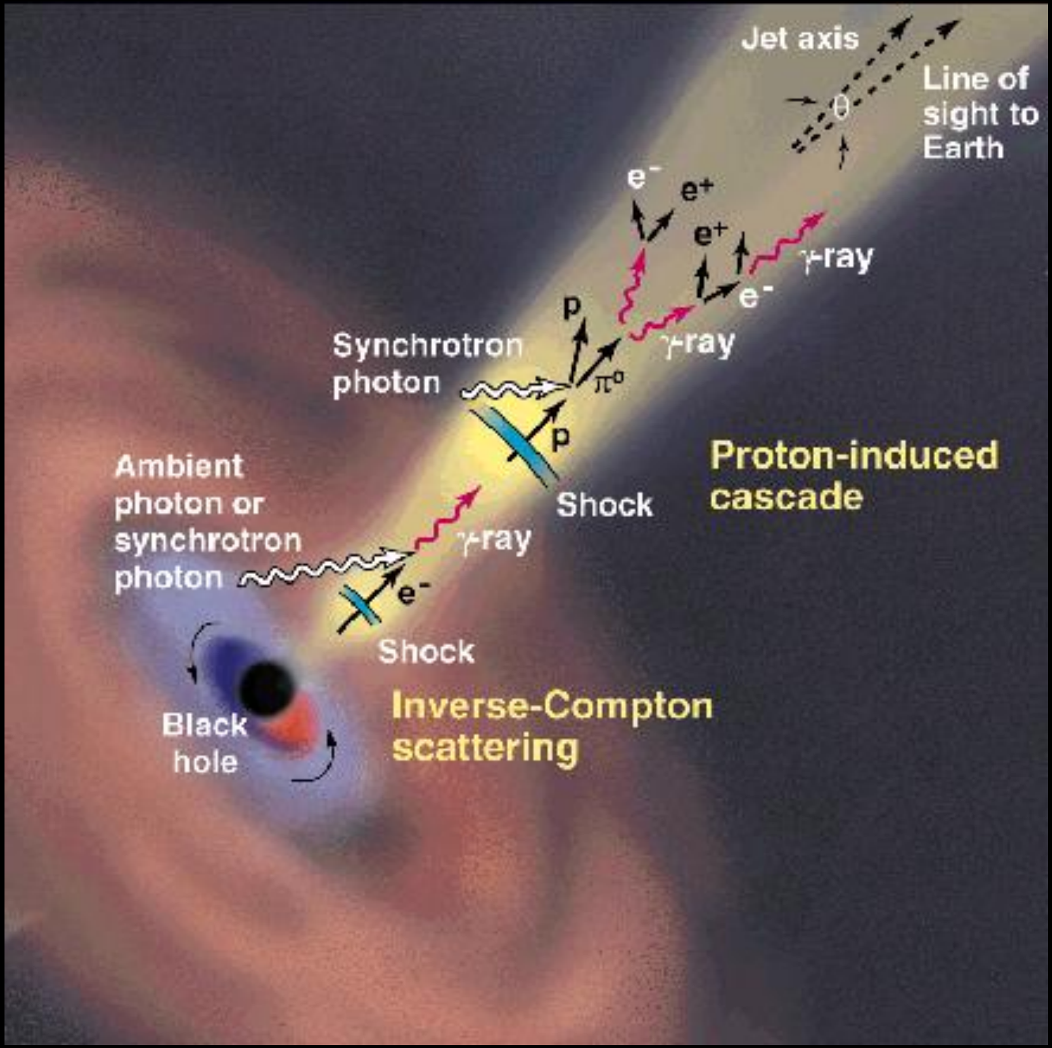
Assume protons (pion decay) gamma rays dominate

In M82: exploit uncertainties in SN explosion rate & efficiency of CR generation.

In NGC 253: exploit uncertainties in distance (2.5 Mpc has been quoted), diffusion timescales & cutoffs in the proton injection spectrum.

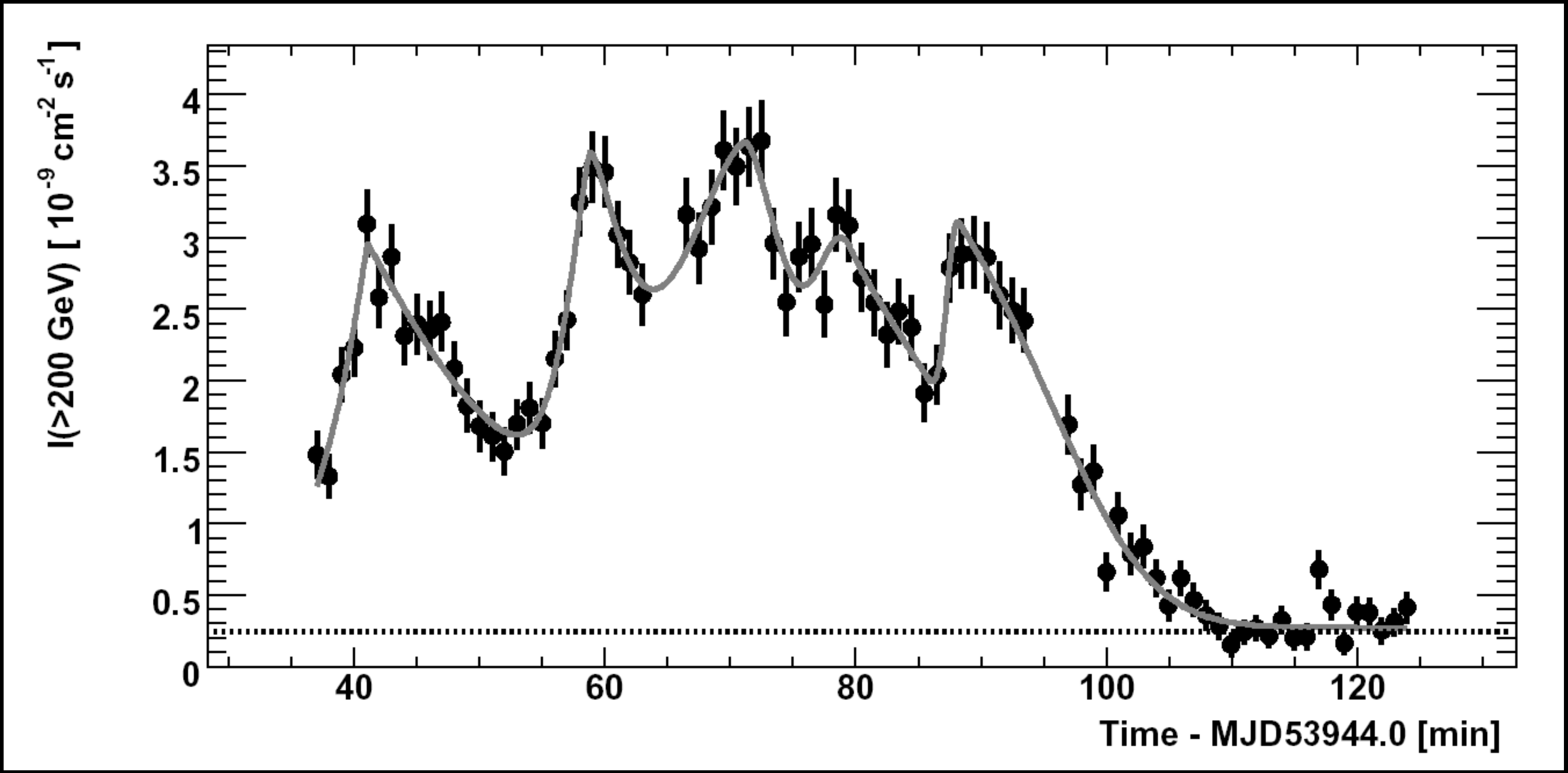
Cea del Pozo et al., 2009 Fermi Symposium (astro-ph 0912.3497v2)

Active Galactic Nuclei



The most common VHE-emitting AGN are the high-frequency peaked blazars – where we are looking almost directly down the jet.

PKS2155-304 in 2006



In late July 2006, this AGN went crazy, and produced a burst that made the object 20 times brighter than the Crab Nebula. The burst contained over 11,000 gamma rays!

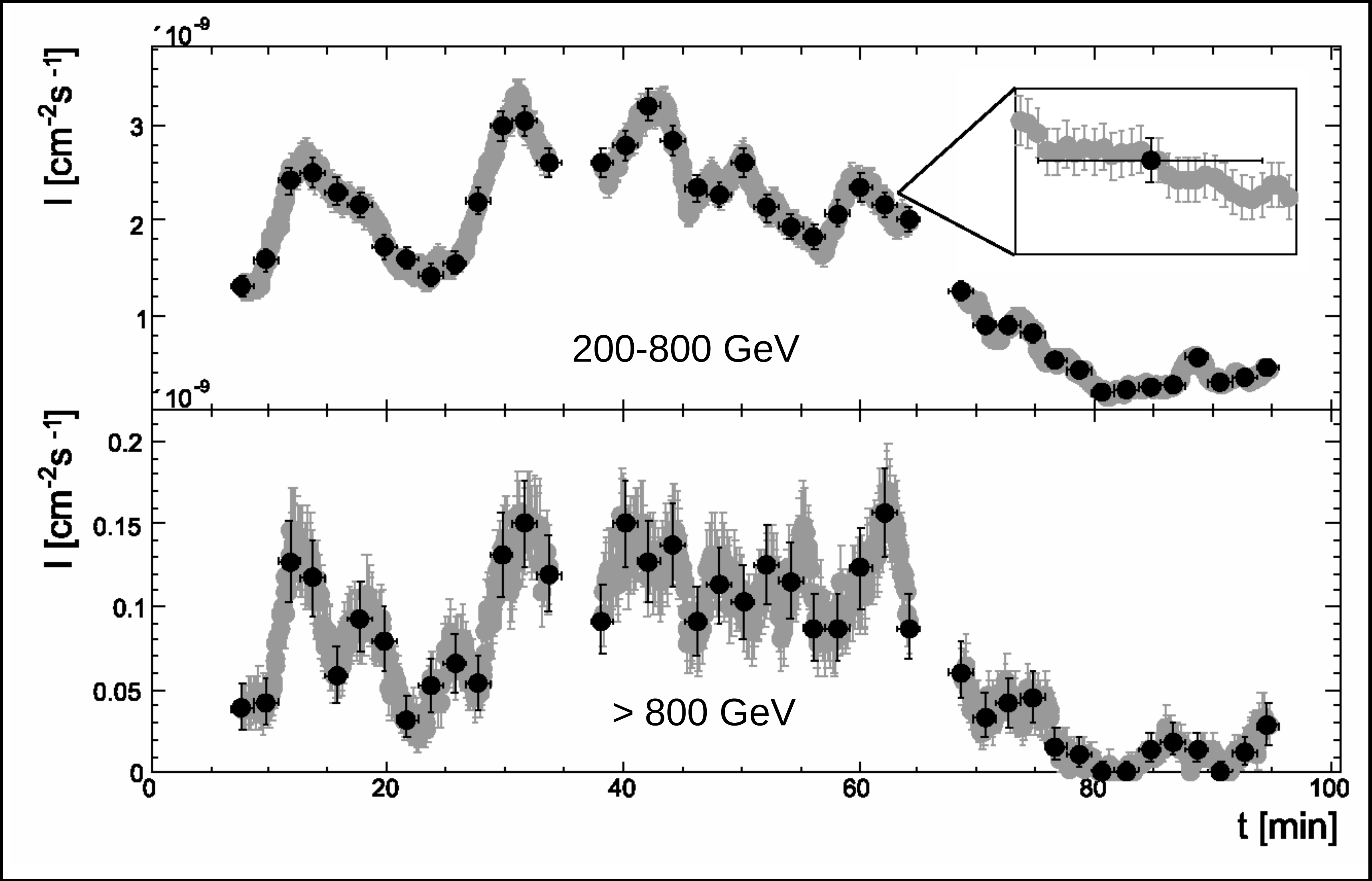
Energy Dependence of c

Broadly speaking (models vary), quantum gravity predicts an energy-dependence of the speed of light of the form:

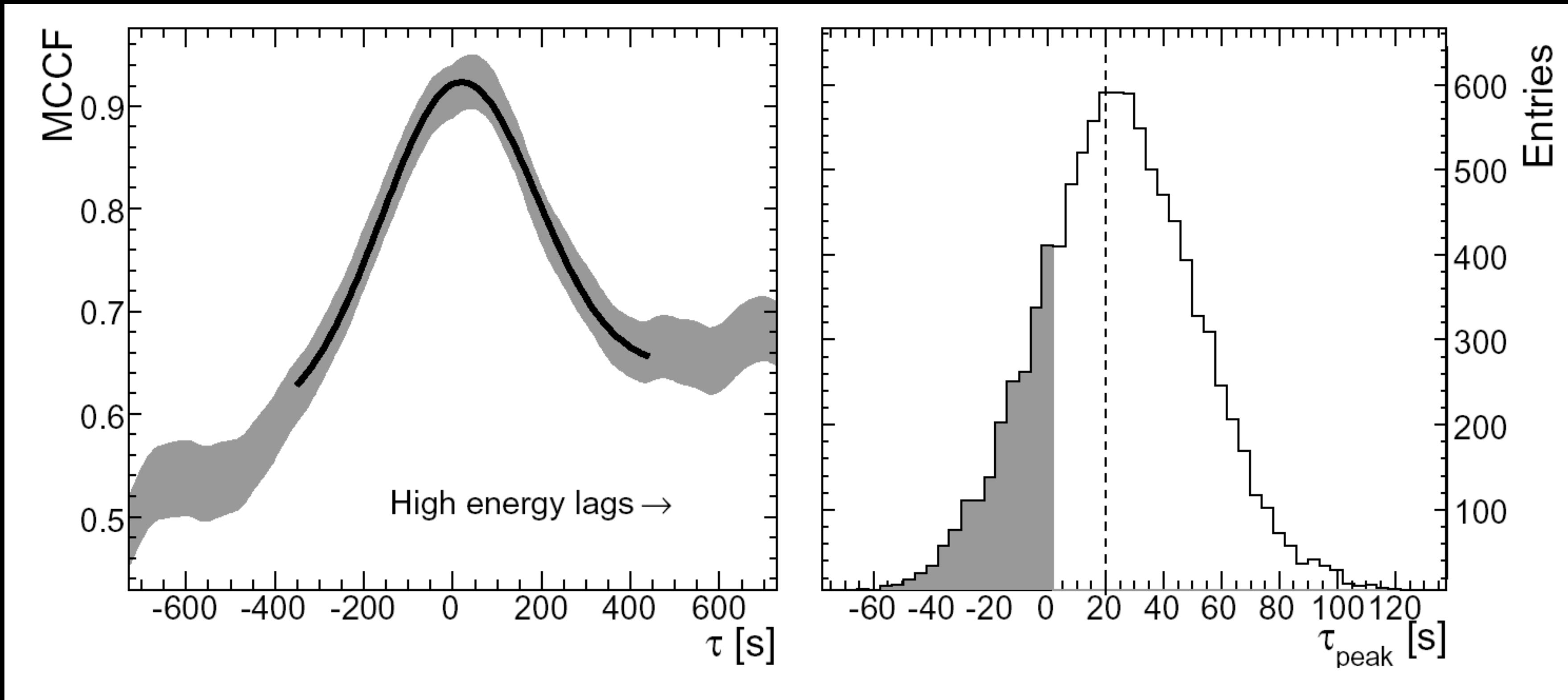
$$c' = c\left(1 + \xi \frac{E}{E_p} + \zeta \frac{E^2}{E_p^2}\right)$$

where E_p is the Planck Energy, 1.22 x 10^{19} GeV, and ξ and ζ are free parameters to be determined. The correction is expected to be very small, but Amelino-Camelia et al. (1998) suggested that these modifications can produce significant time delays with energy over cosmological distances. The absence of such energy dispersion sets limits on ξ and ζ.

We can use the massive flare from PKS2155-304 to test this.

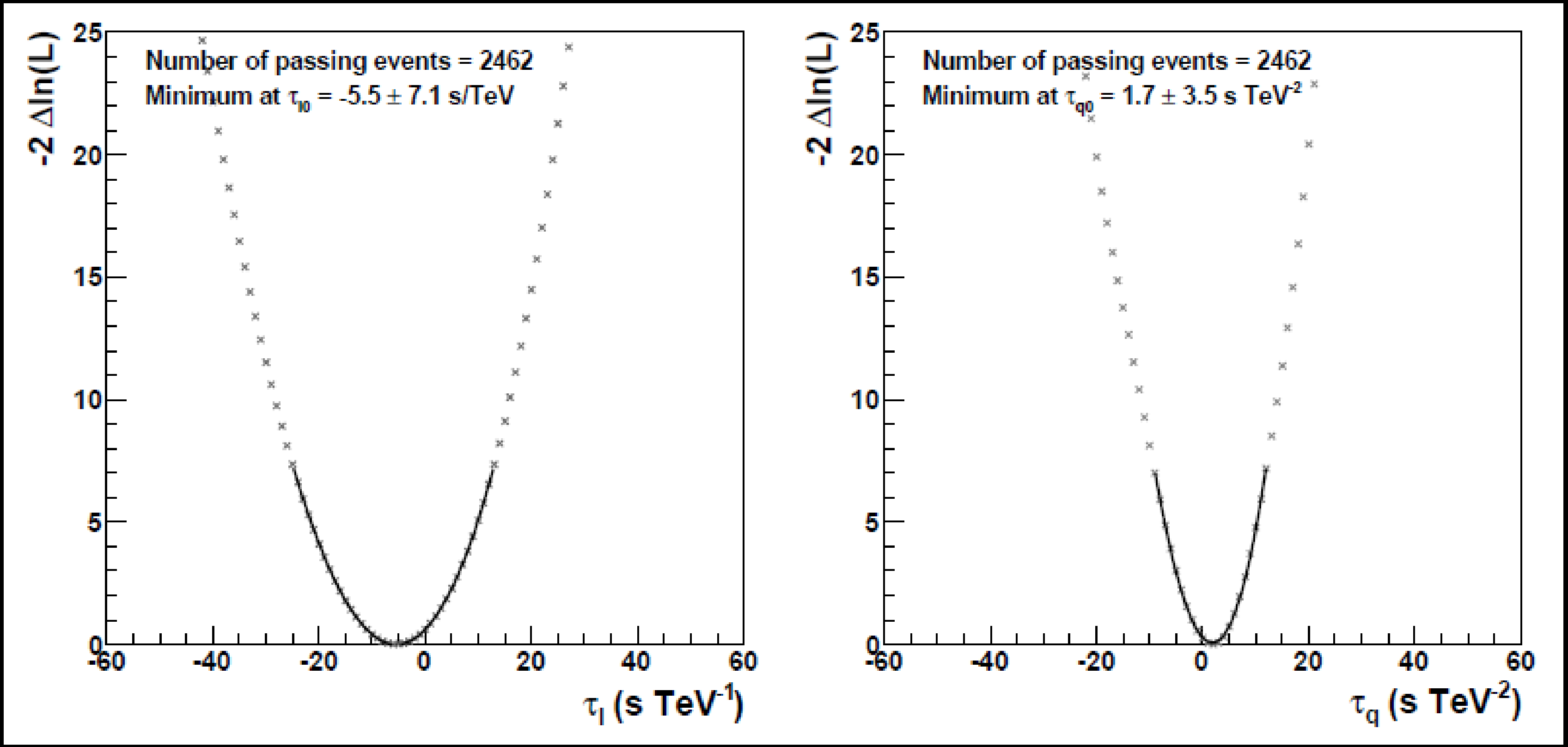


Aharonian et al., astro-ph 0810.3475v1



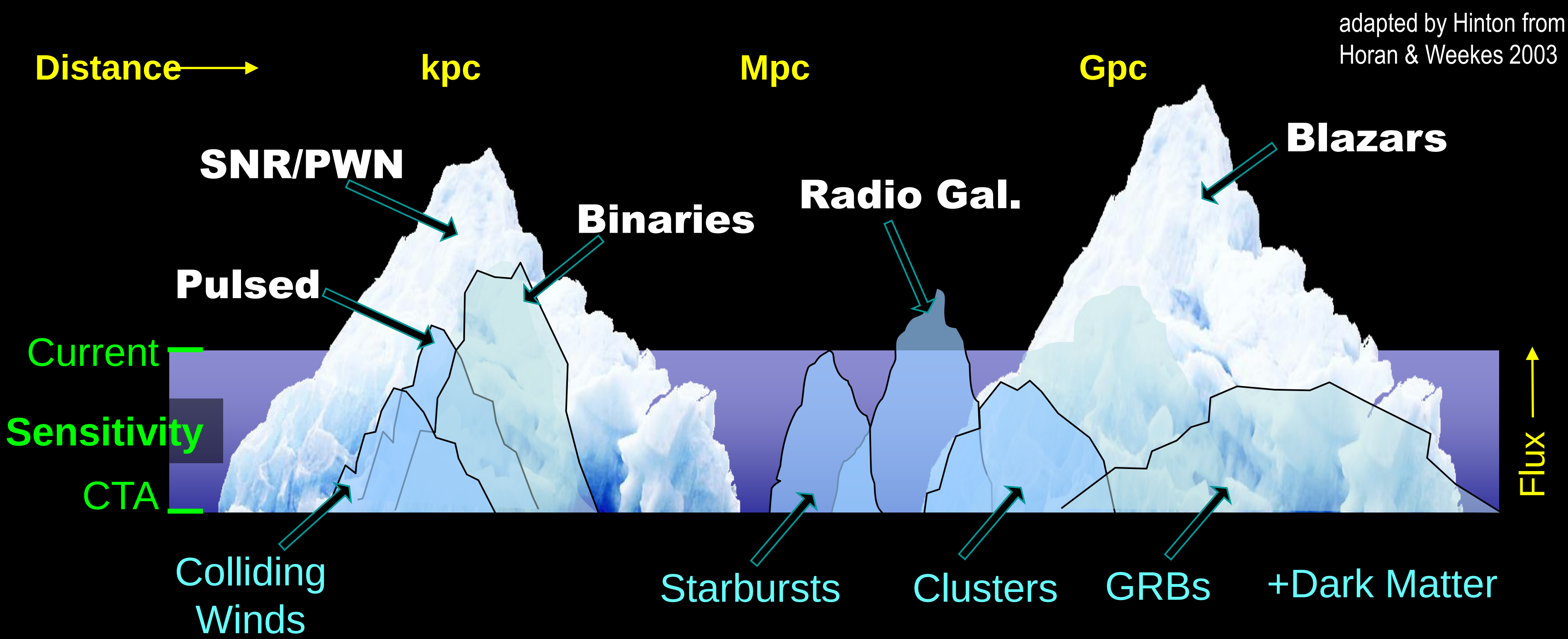
The MCCF (left) looks quite exciting, with an apparent 20s lag for higher energy. However, when you do 10,000 simulations varying the flux points of the oversampled light curve within measurement errors and create a cross-correlation peak distribution (right), you find an RMS of 28s and that simulations produce a negative delay for 21% of the time. The ‘lag’ is therefore consistent with zero.

$|\xi| < 17$ for linear dispersion & $|\zeta| < 7.3 \times 10^{19}$ for quadratic dispersion



A similar test using a more sensitive maximum likelihood approach also yields limits of $|\xi| < 5.7$ for linear dispersion & $|\zeta| < 3.6 \times 10^{16}$ for quadratic dispersion.

H.E.S.S. Collaboration ArXiv:1101.3650



- Current instruments have passed the critical sensitivity threshold and reveal a rich panorama, but this is clearly only the tip of the iceberg


So what next???

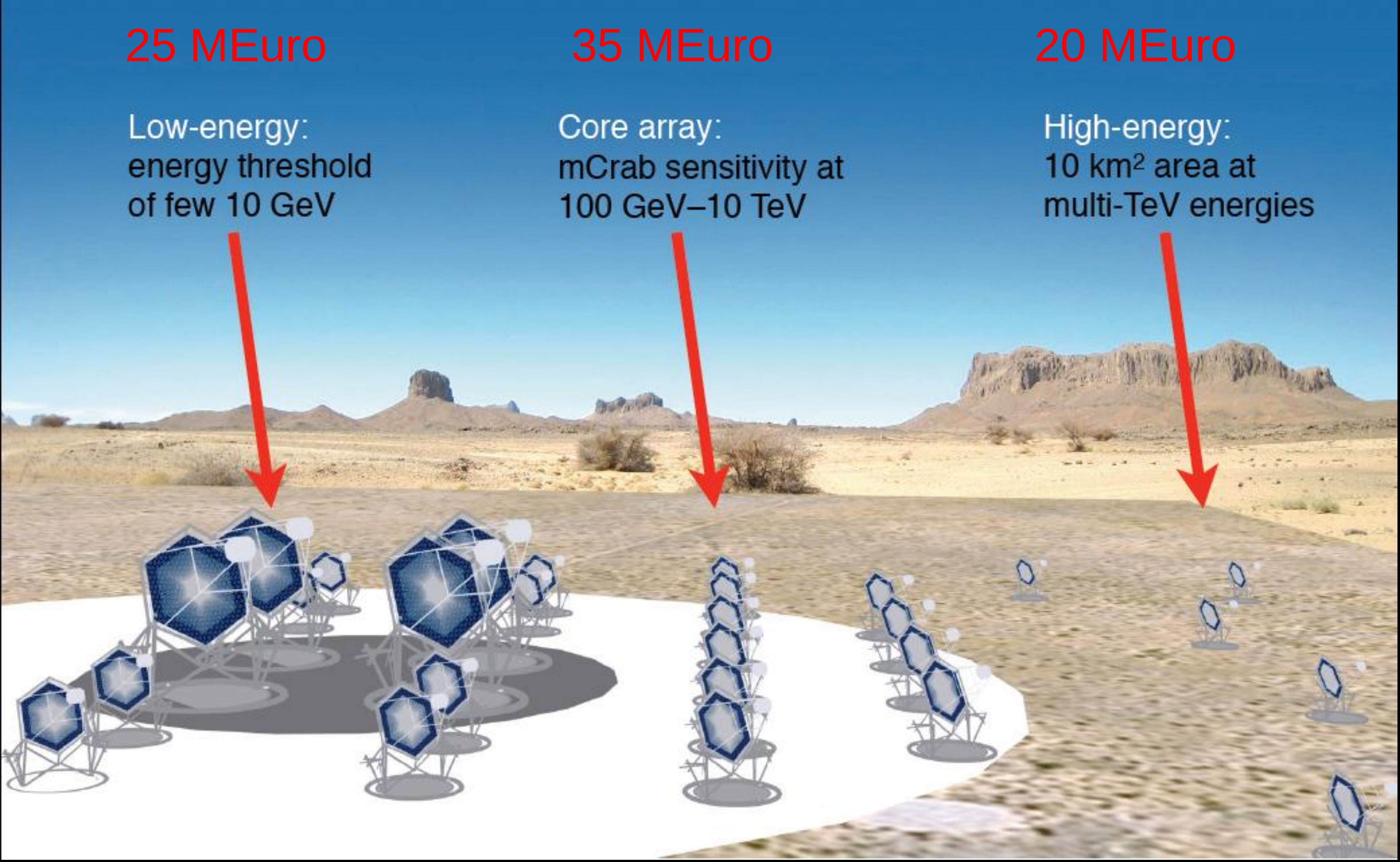
The wish list for a next generation instrument

- Better sensitivity at low energies
  - Overlap with satellite-based instruments
  - Gamma-ray bursts
  - AGNs, microquasars
- Better sensitivity at medium energies
  - Increase the ‘gamma-ray horizon’
  - Study of highly variable phenomena
- Sensitivity in the ‘unexplored’ 10s of TeV region
  - Crucial for understanding particle acceleration
- Better angular resolution
  - Reduce source confusion
  - Identification of structures e.g. in SNRs
- Wider field of view
  - Improve survey sensitivity
  - Better control of background

The CTA Consortium

- A worldwide development!
  - Argentina, Armenia, Austria, Brazil, Bulgaria, Croatia, Czech Republic, Finland, France, Germany, Greece, India, Ireland, Italy, Japan, Namibia, Netherlands, Poland, Slovenia, South Africa, Spain, Sweden, Switzerland, UK and USA
- Members from all the major ground-based instruments, plus people with satellite-based gamma-ray, X-ray, and particle physics backgrounds

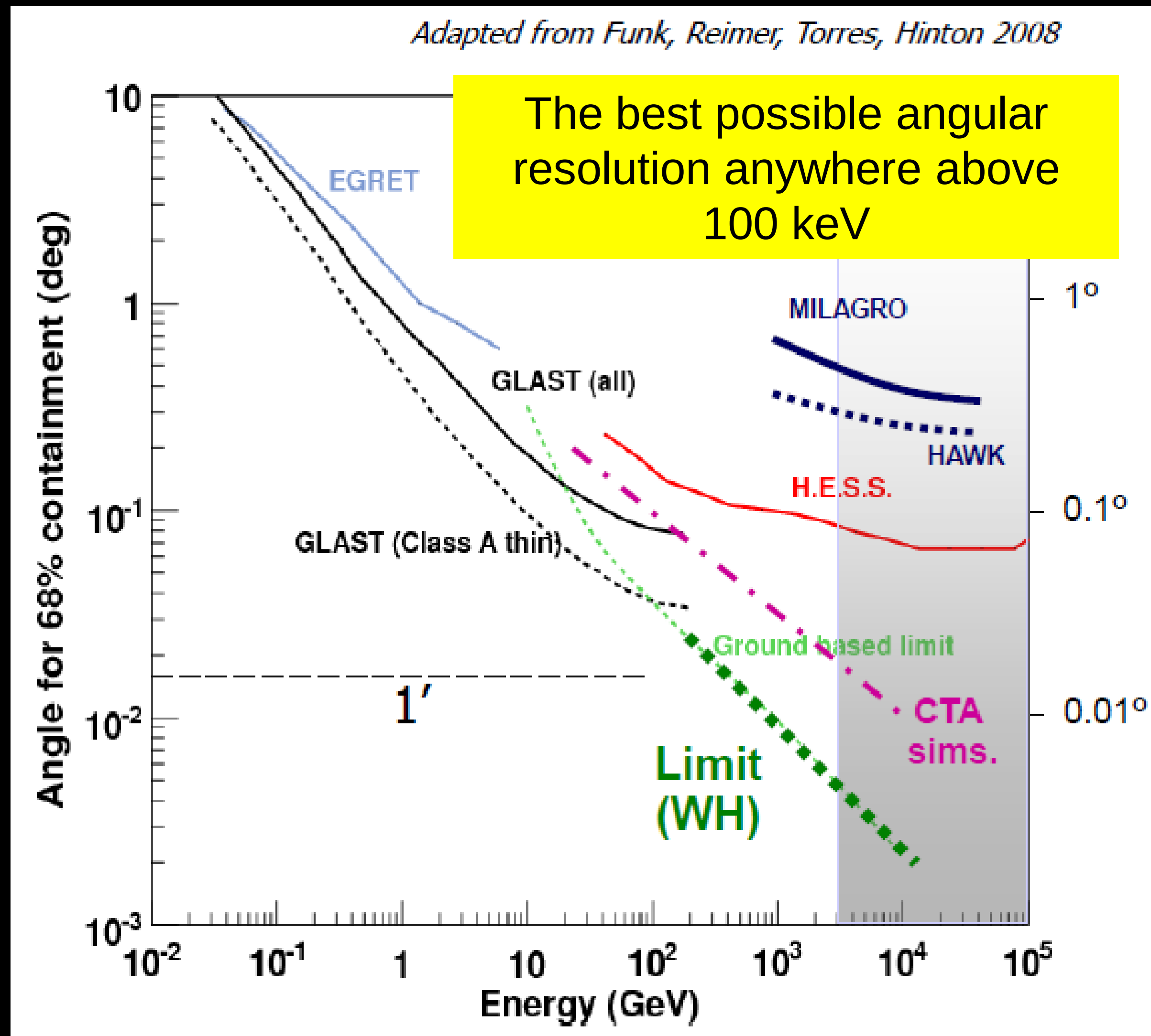
The Cherenkov Telescope Array (CTA) a ‘real’ observatory with ~ 100 telescopes in the south and ~ 50 in the north



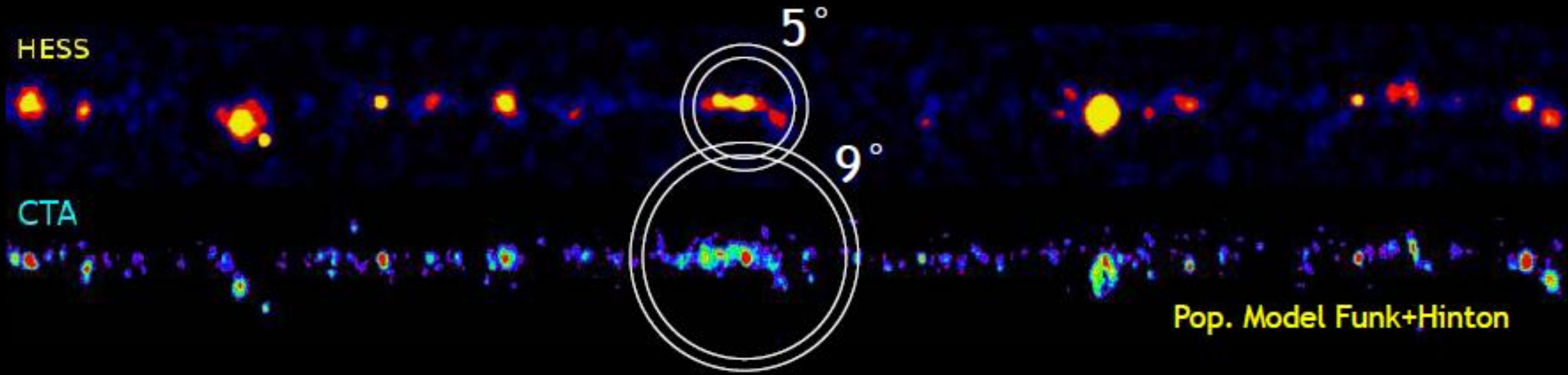
Future angular resolution

3-100 TeV

- <1 arcminute precision achievable **only** > TeV
- <1 arcminute achievable at 100 TeV with modest collection efficiency



Nicked from Jim Hinton!



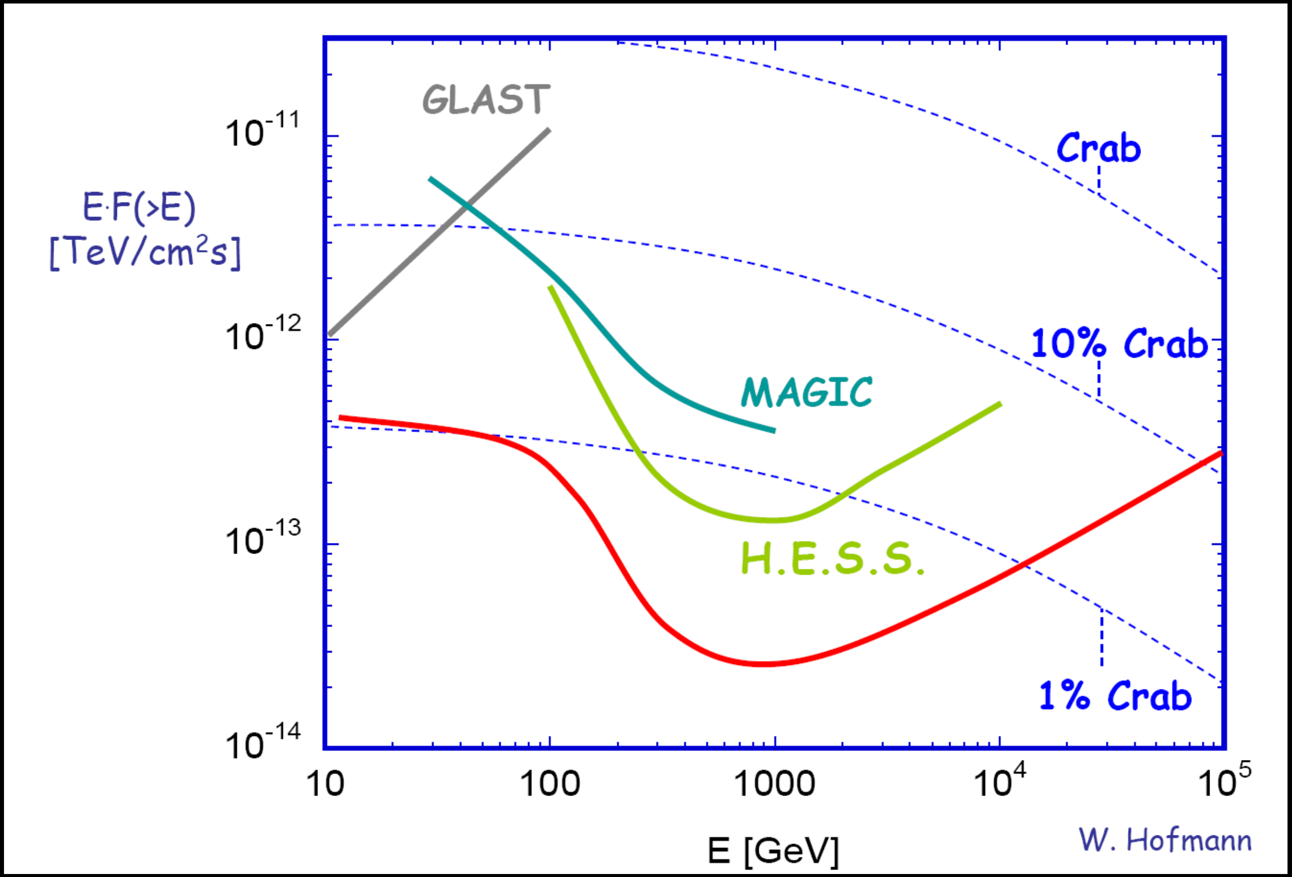
- » Typical index 2.3 – no cut-offs below ~10 TeV
  - › Many multi-TeV galactic sources
- » Confusion limit reached for current angular resolution and a factor ~3 better sensitivity
  - › A future TeV instrument must have better angular resolution
- » Wide field of view
  - › Improves survey sensitivity
  - › Improves control of background (off-plane regions in FoV)

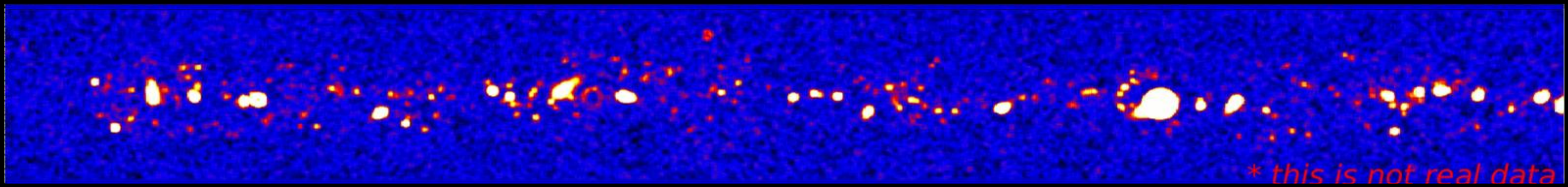
UK Involvement

- Universities of Durham, Edinburgh, Hertfordshire, Leeds, Leicester, Liverpool, Northumbria, Nottingham, Oxford, Sheffield & Southampton, and RAL
- Focussing on small-sized telescope development – structure, mirrors, camera etc.
- Also strong/leading involvement in Monte Carlo simulations, atmospheric/telescope calibration, outreach and (of course) science

There may be an advantage to a dual-mirror system for the small telescopes - could provide a wide FoV for lower camera costs

Simon Blake,
Durham University


GLAST
Crab
E·F(>E)
[TeV/cm²s]
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10% Crab
MAGIC
H.E.S.S.
1% Crab
10
100
1000
10^4
10^5
E [GeV]
W. Hofmann


* this is not real data