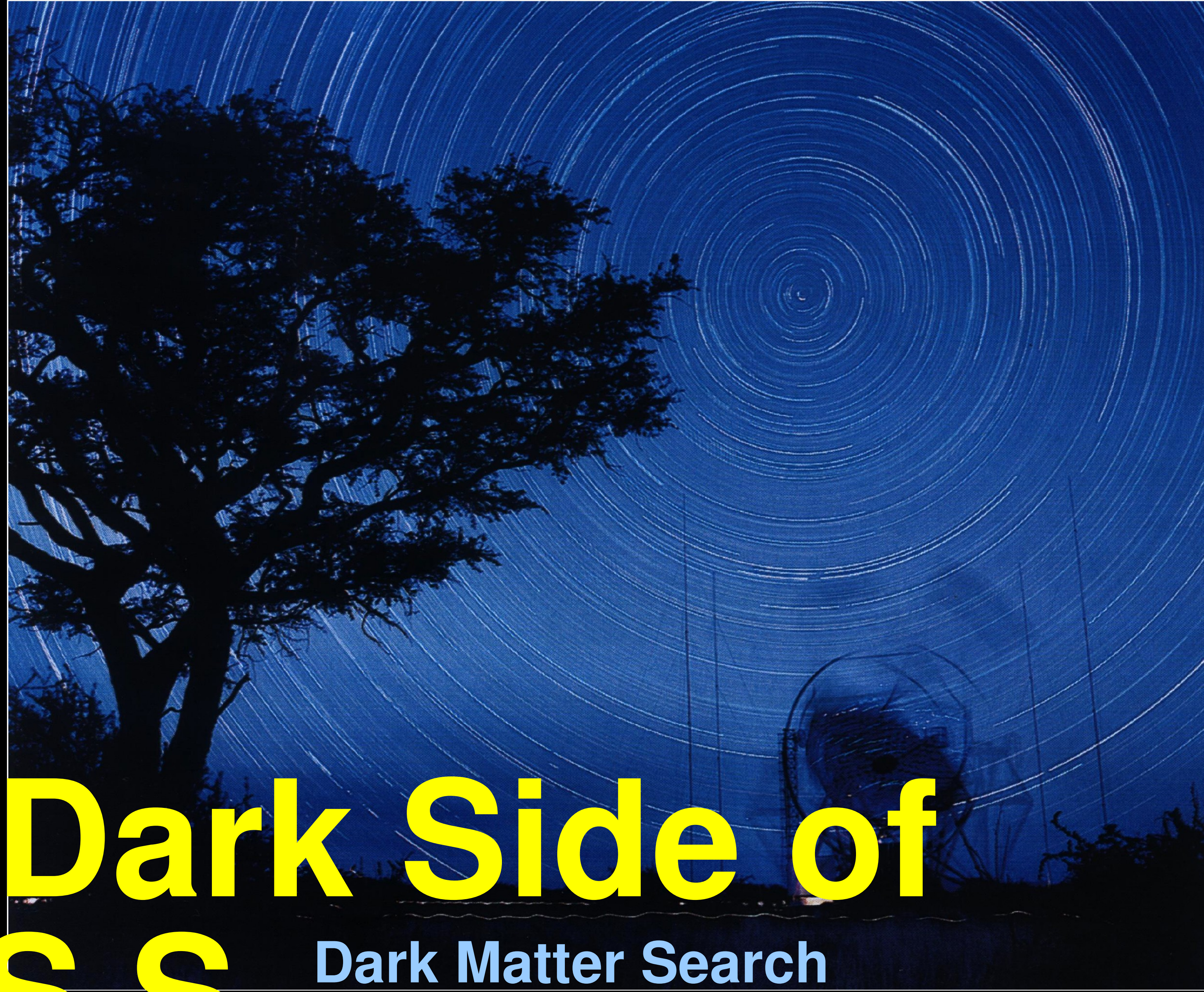


The Dark Side of H.E.S.S.

Dark Matter Search with Cherenkov Telescopes

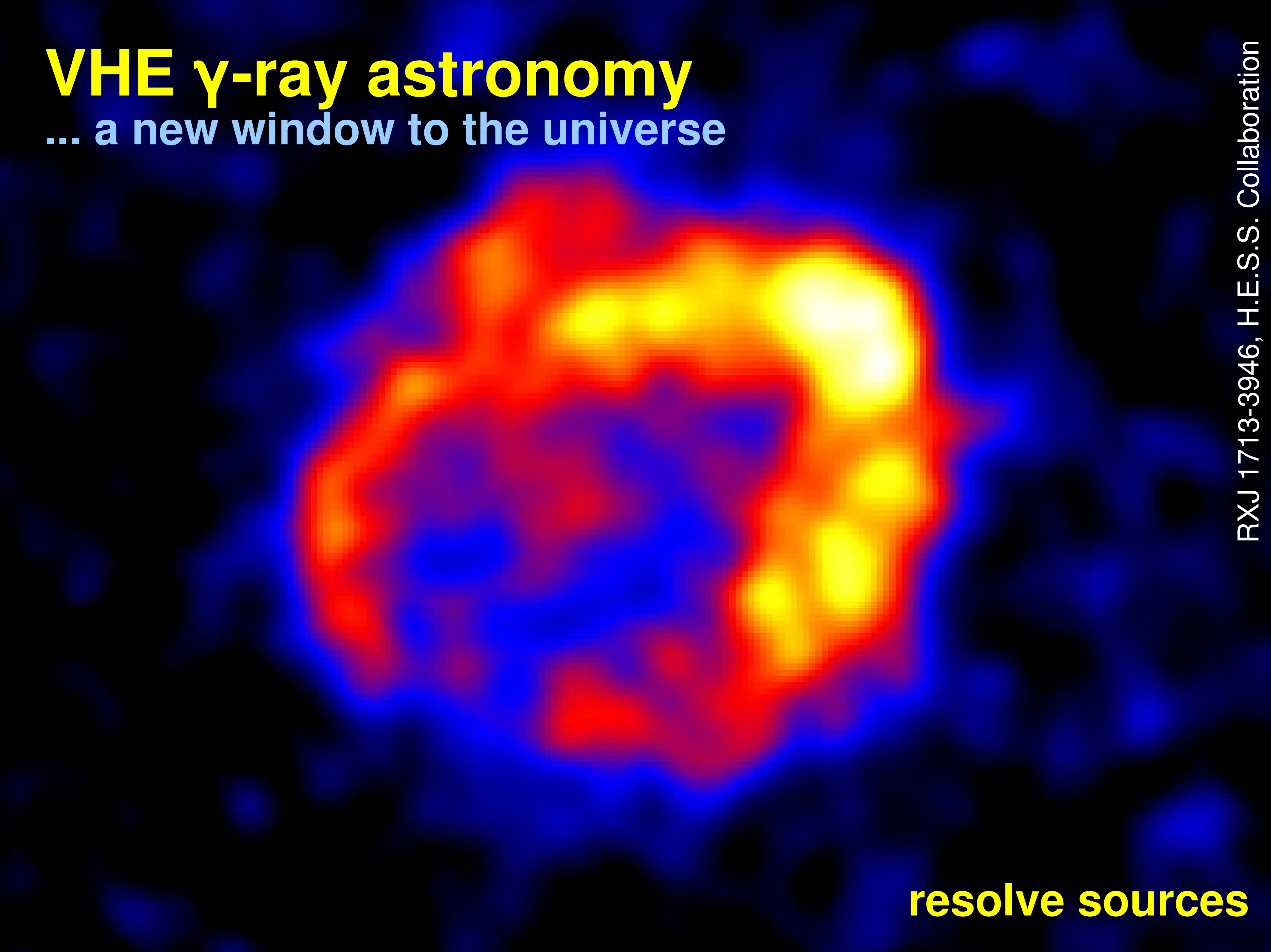
Christopher van Eldik • Max-Planck-Institut für Kernphysik • Heidelberg

VHE γ-ray astronomy

... a new window to the universe

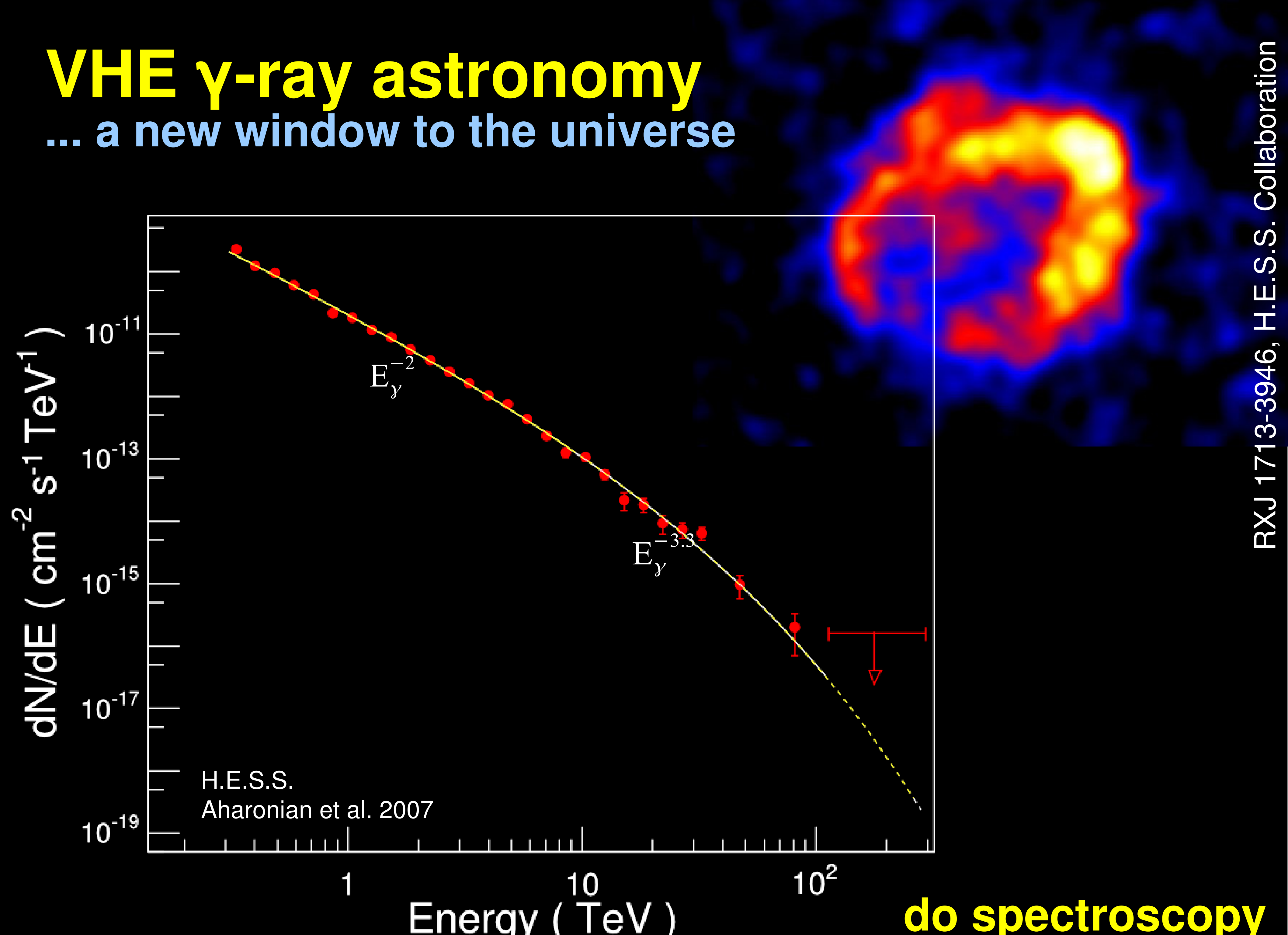
VHE γ-ray astronomy

... a new window to the universe



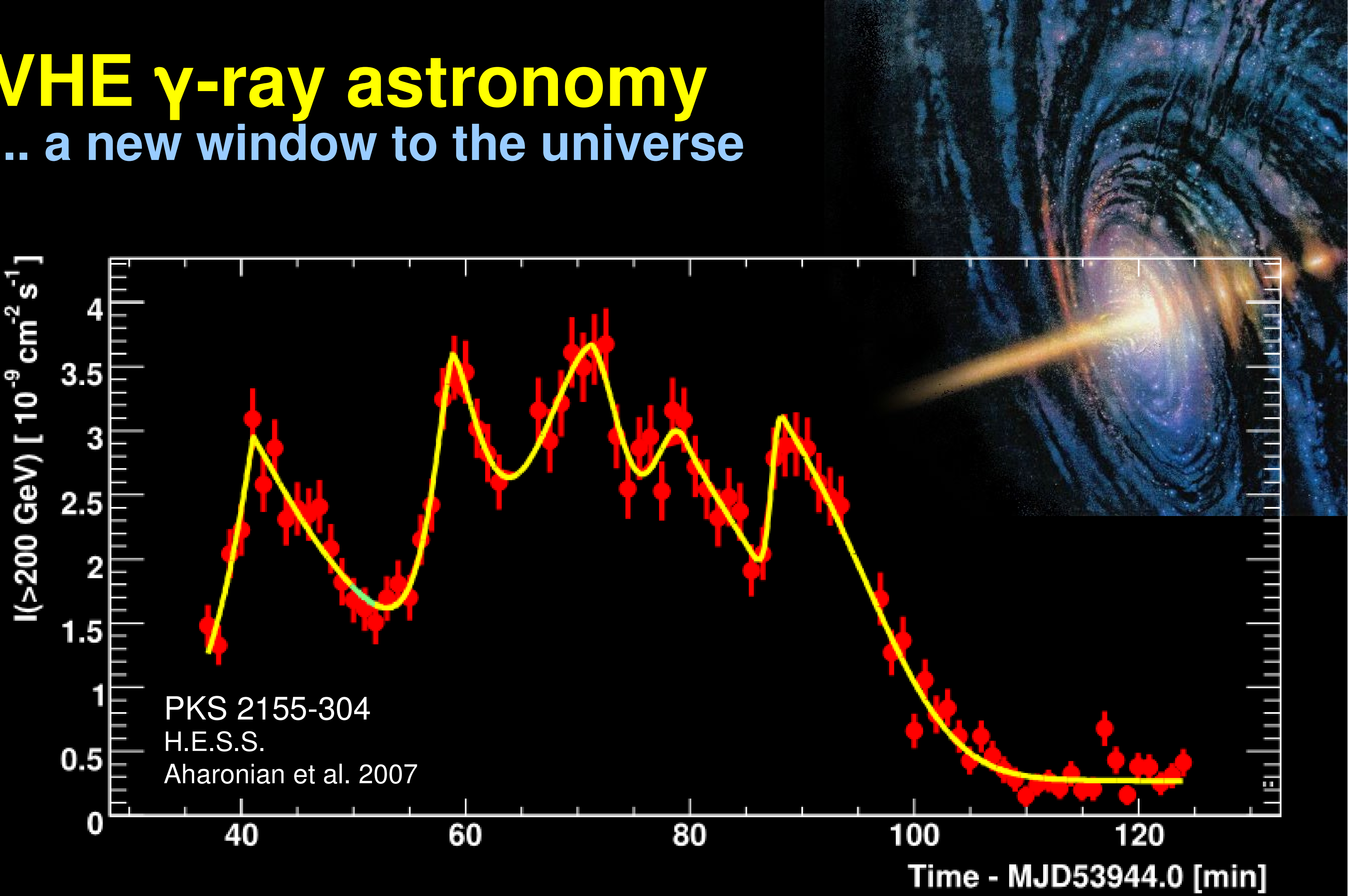
VHE γ-ray astronomy

... a new window to the universe



do spectroscopy

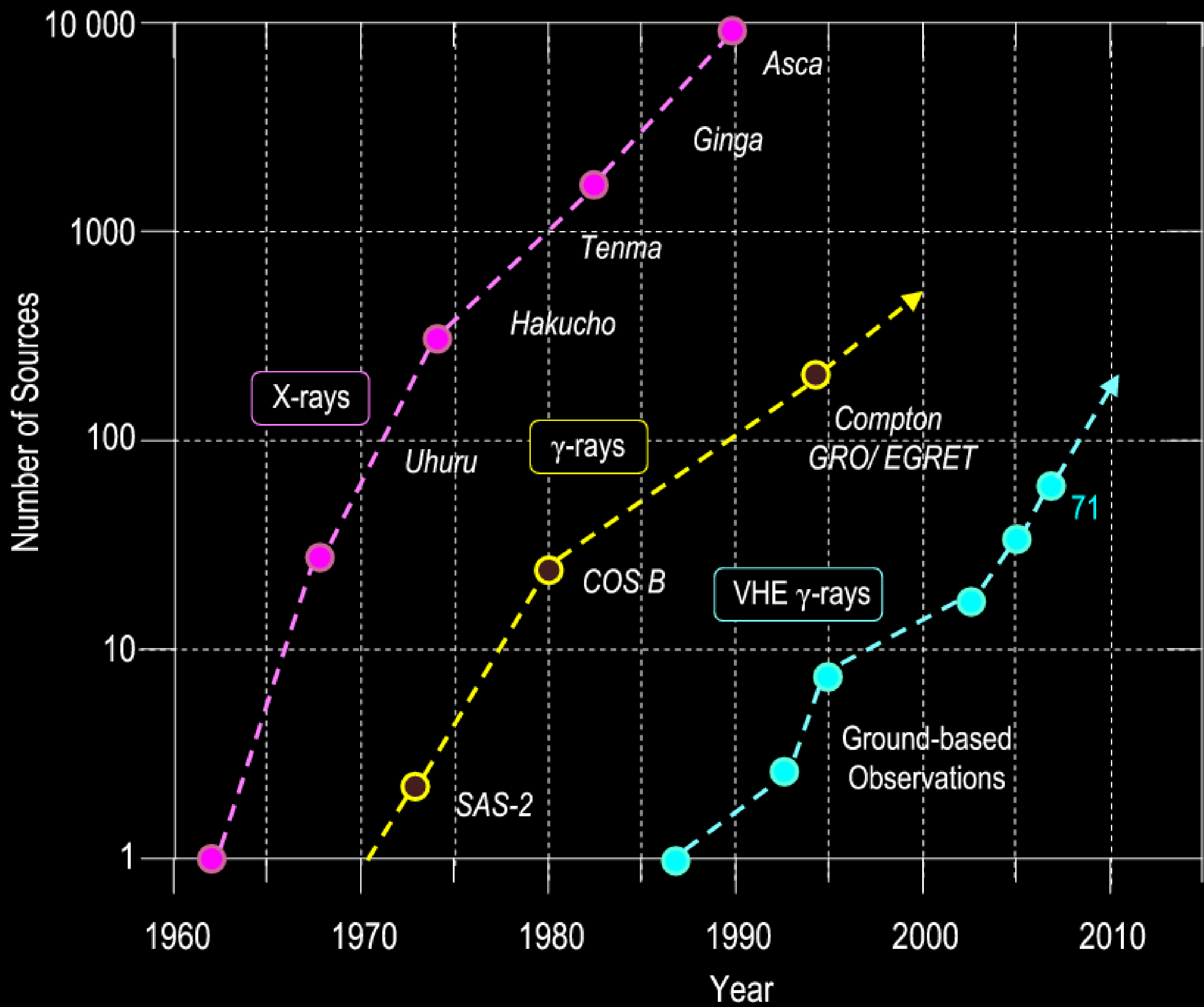
VHE γ-ray astronomy
... a new window to the universe



measure flux variability

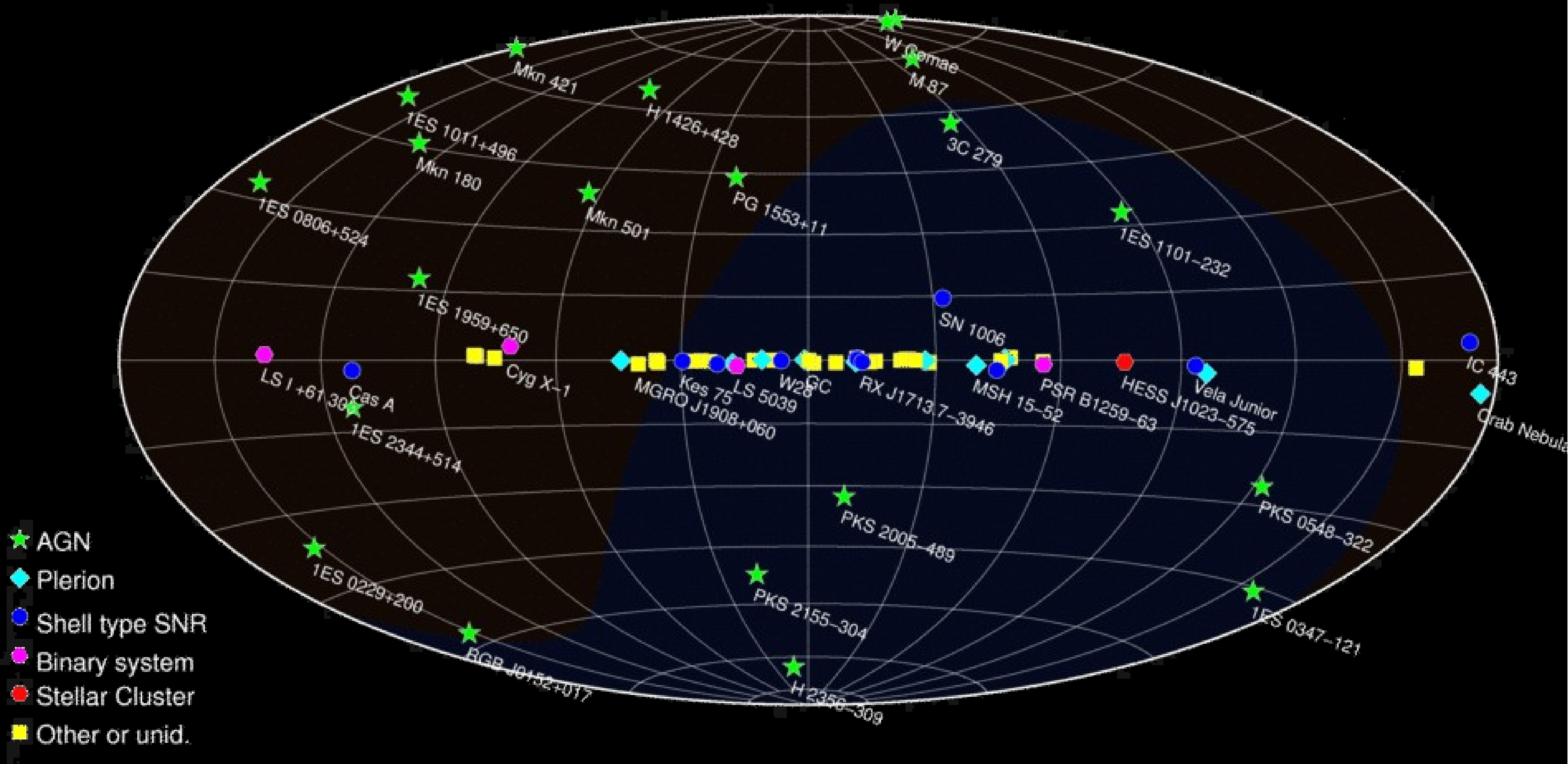
VHE γ-ray sky in 2009

... more than 75 sources known

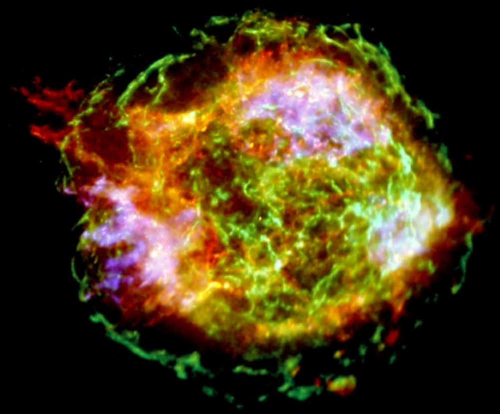


VHE γ-ray sky in 2009

... more than 75 sources known



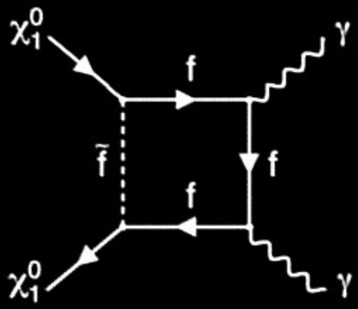
(Some) topics of VHE γ-ray astronomy



Astrophysics

- Which are the cosmic PeVatrons?
- How do they work?
- Acceleration, emission, propagation

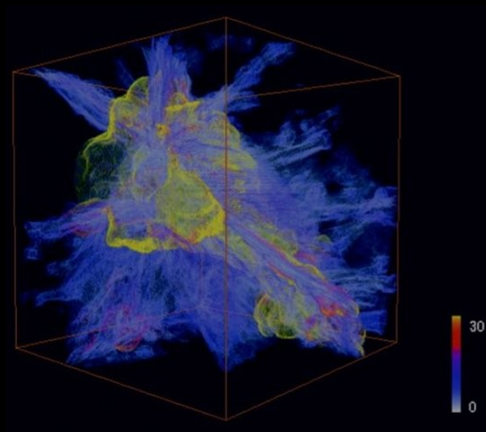
Fundamental Physics



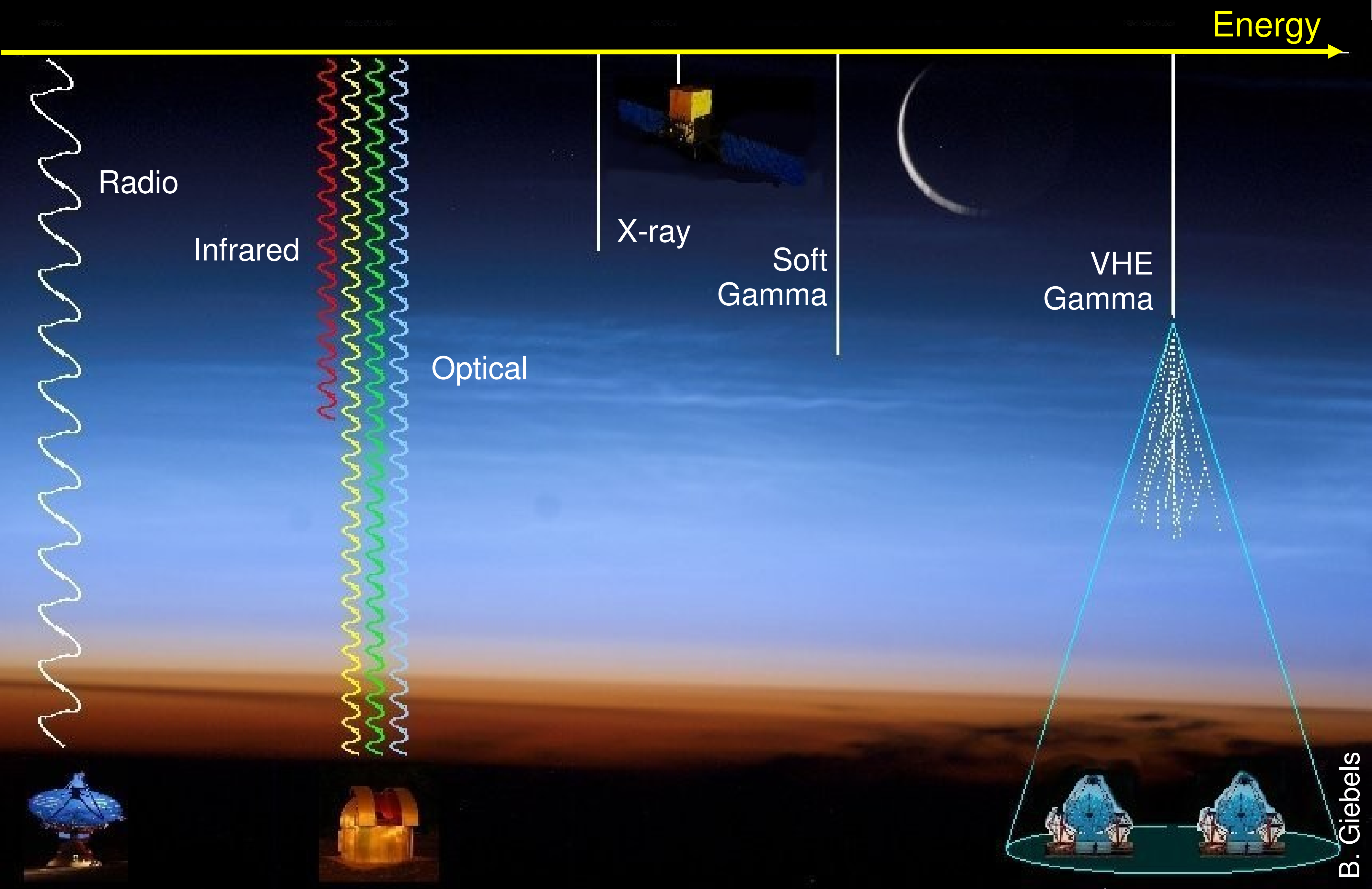
- Indirect Dark Matter searches
- Energy dependence of speed of light

Cosmology

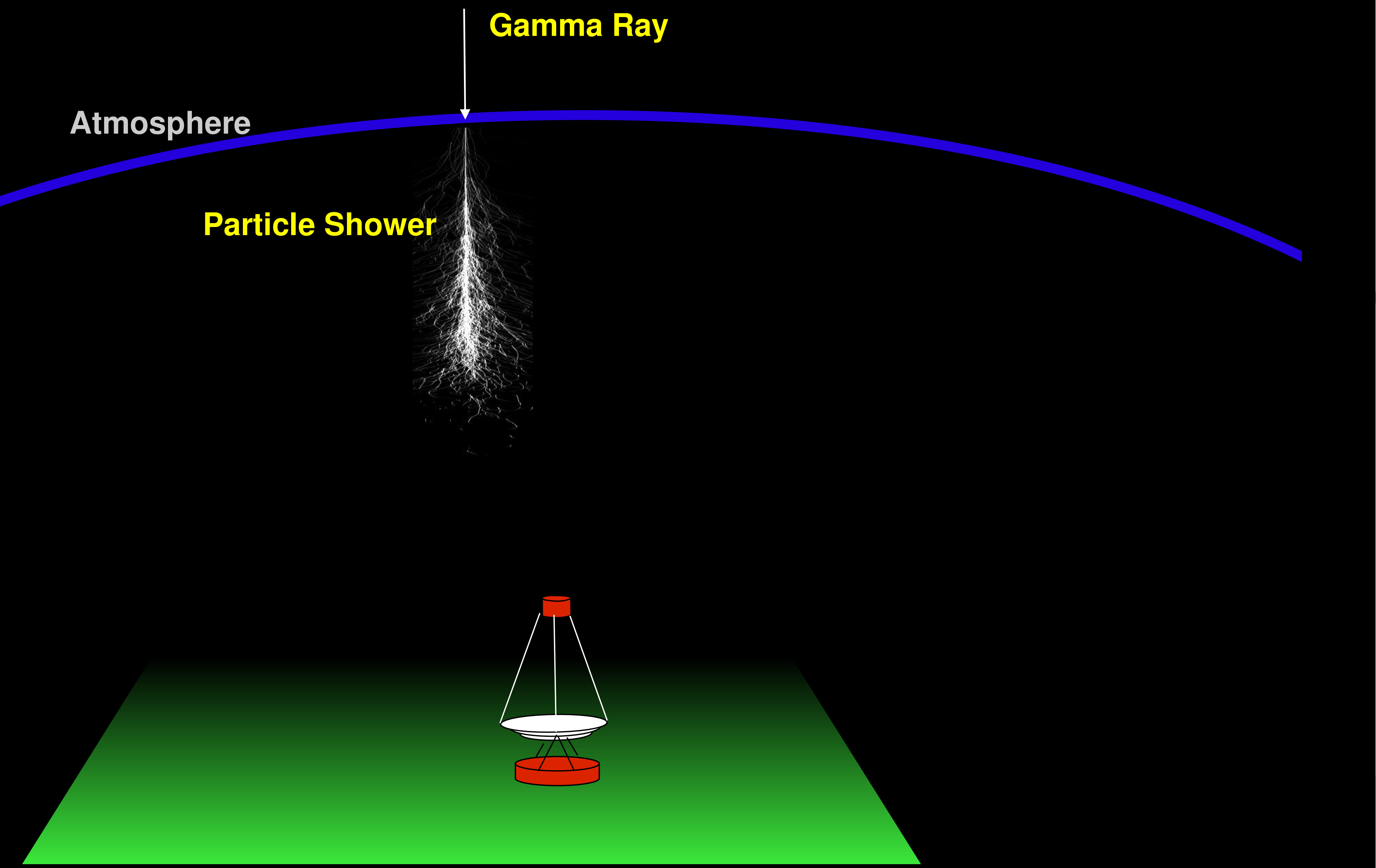
- Extragalactic Background Light
  $\rightarrow$ star formation in the early universe
- Galaxy clusters as storehouses of cosmic rays



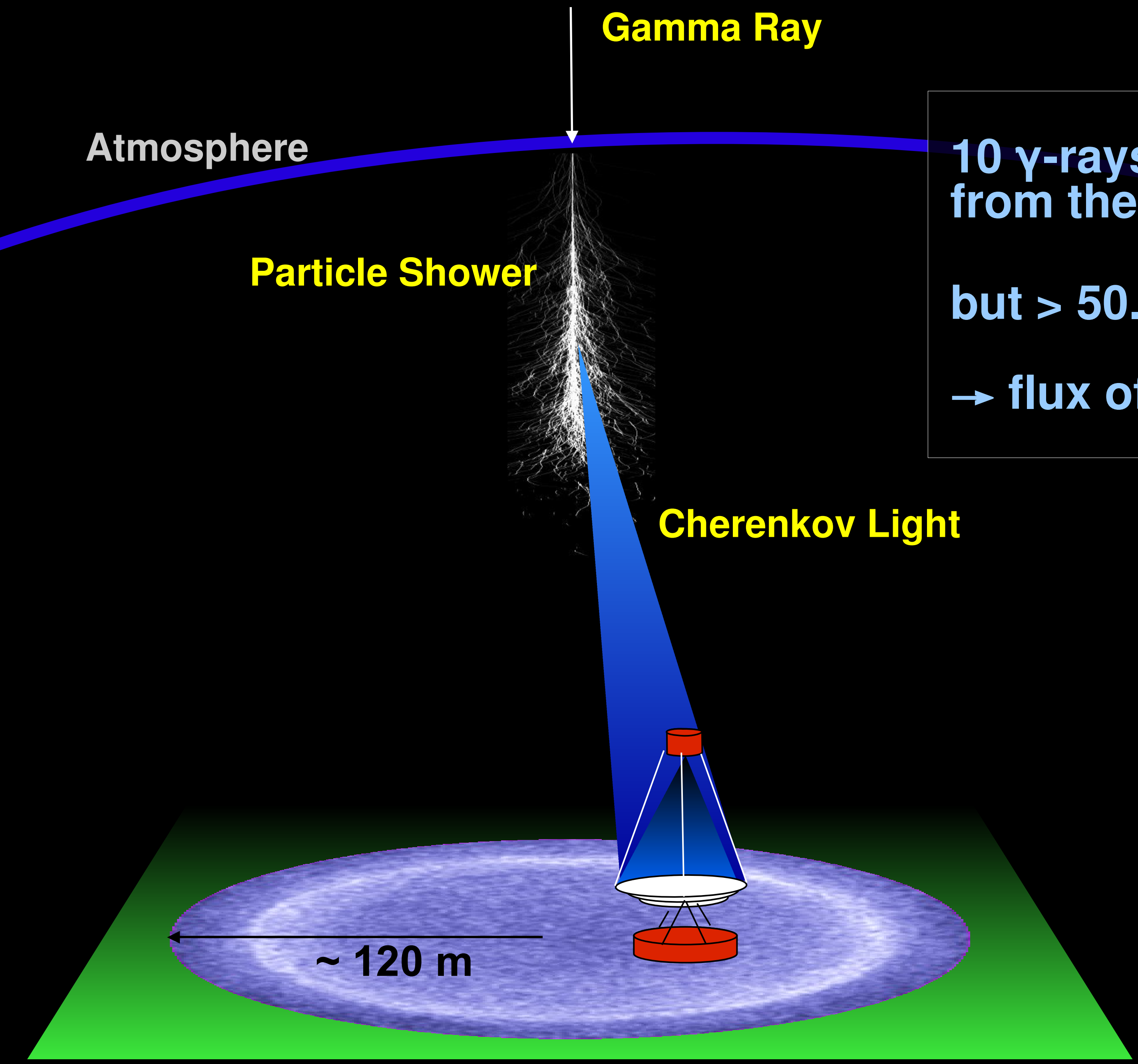
Windows for Astronomy



Detection Principle



Detection Principle

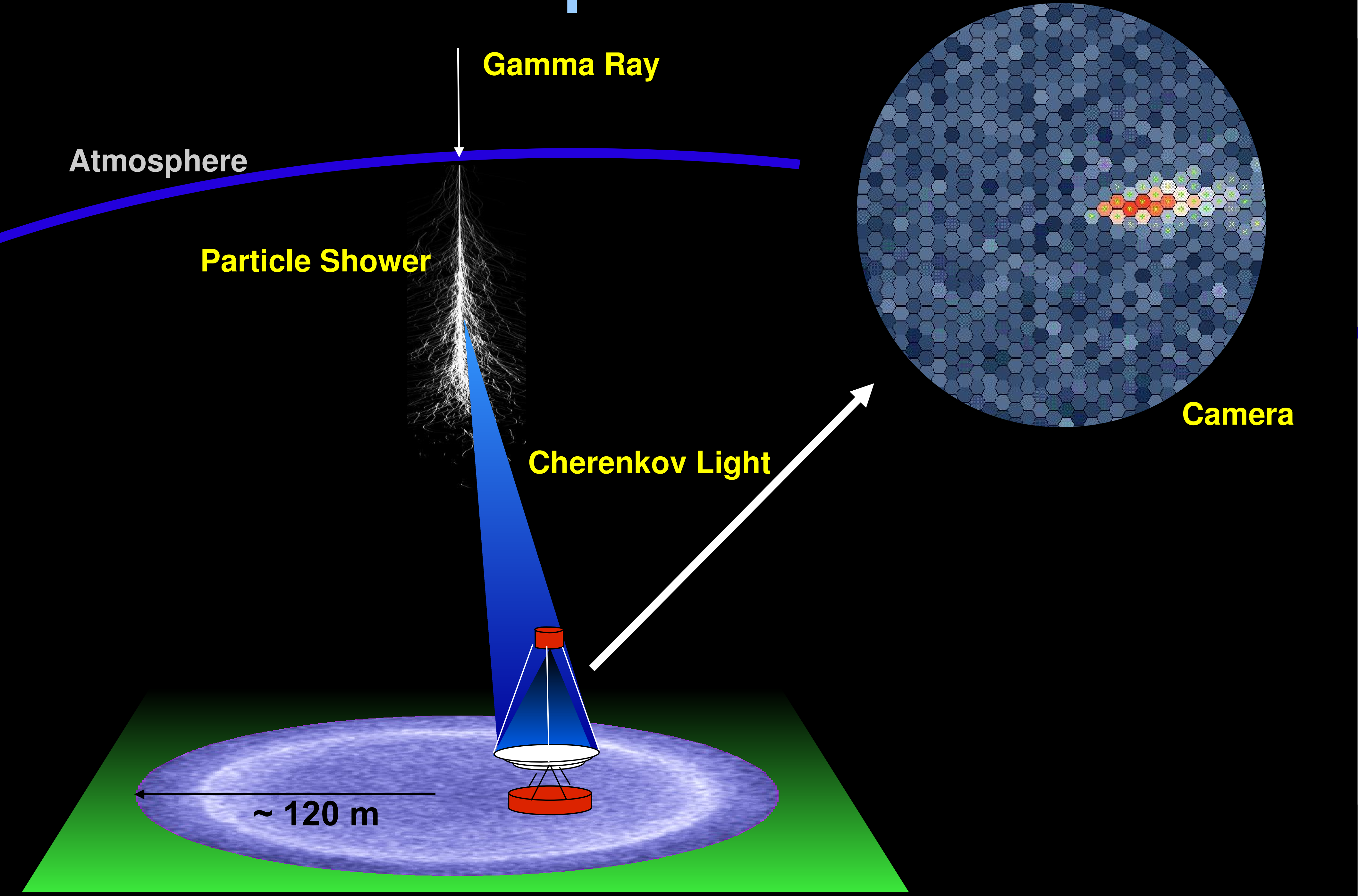


10 γ-rays / m² yr
from the Crab nebula

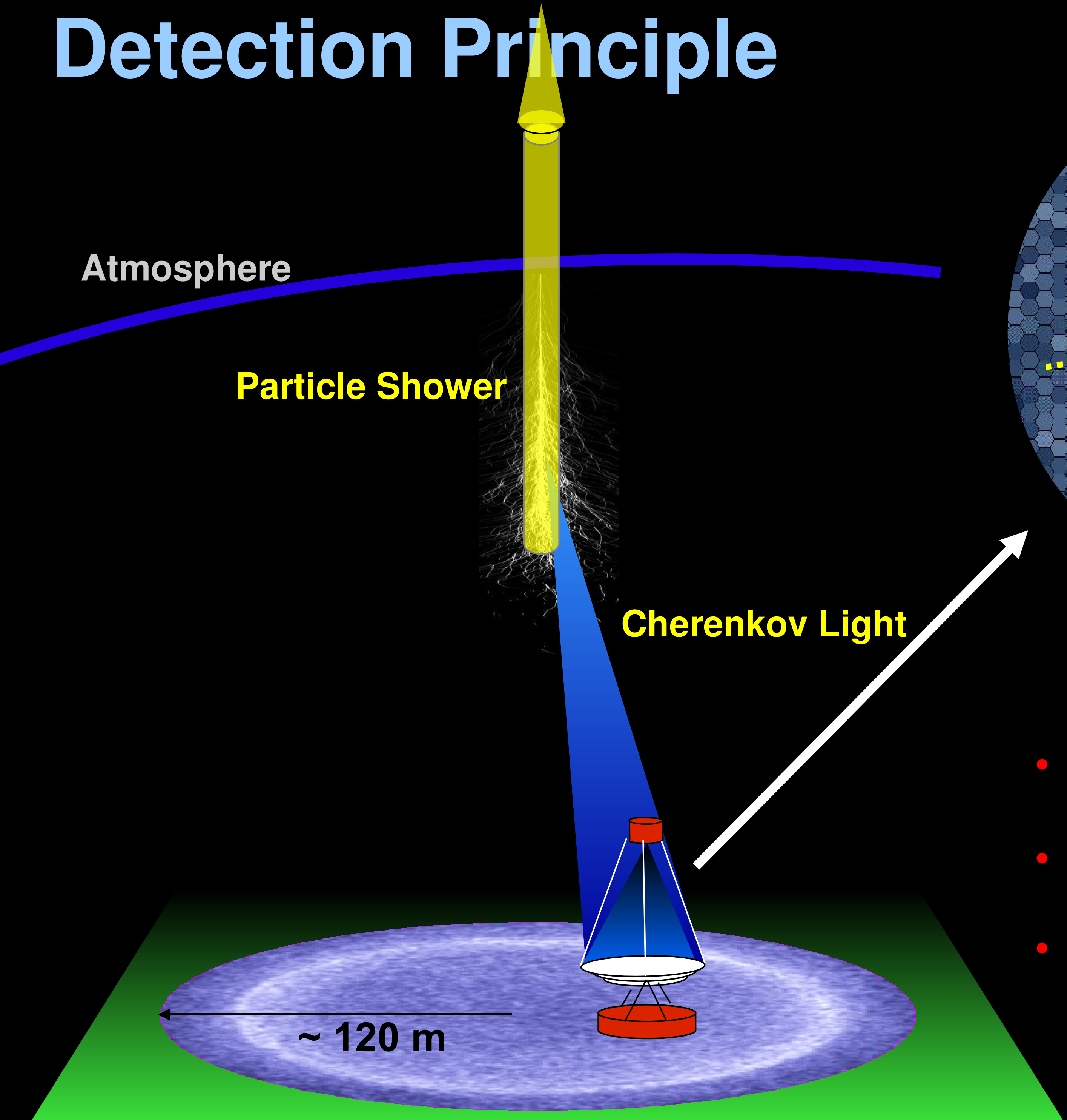
but > 50.000 m² detection area

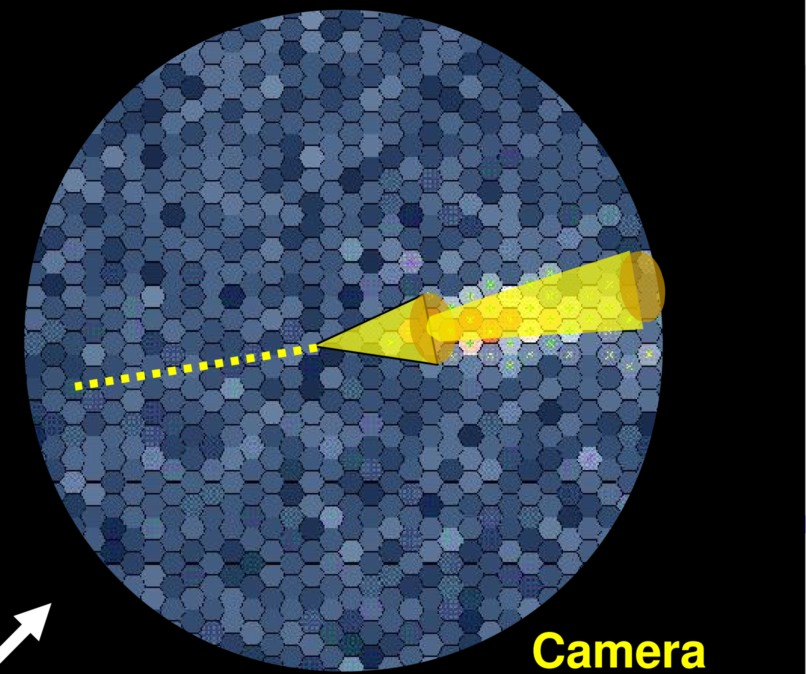
→ flux of > 1 γ-ray / min

Detection Principle



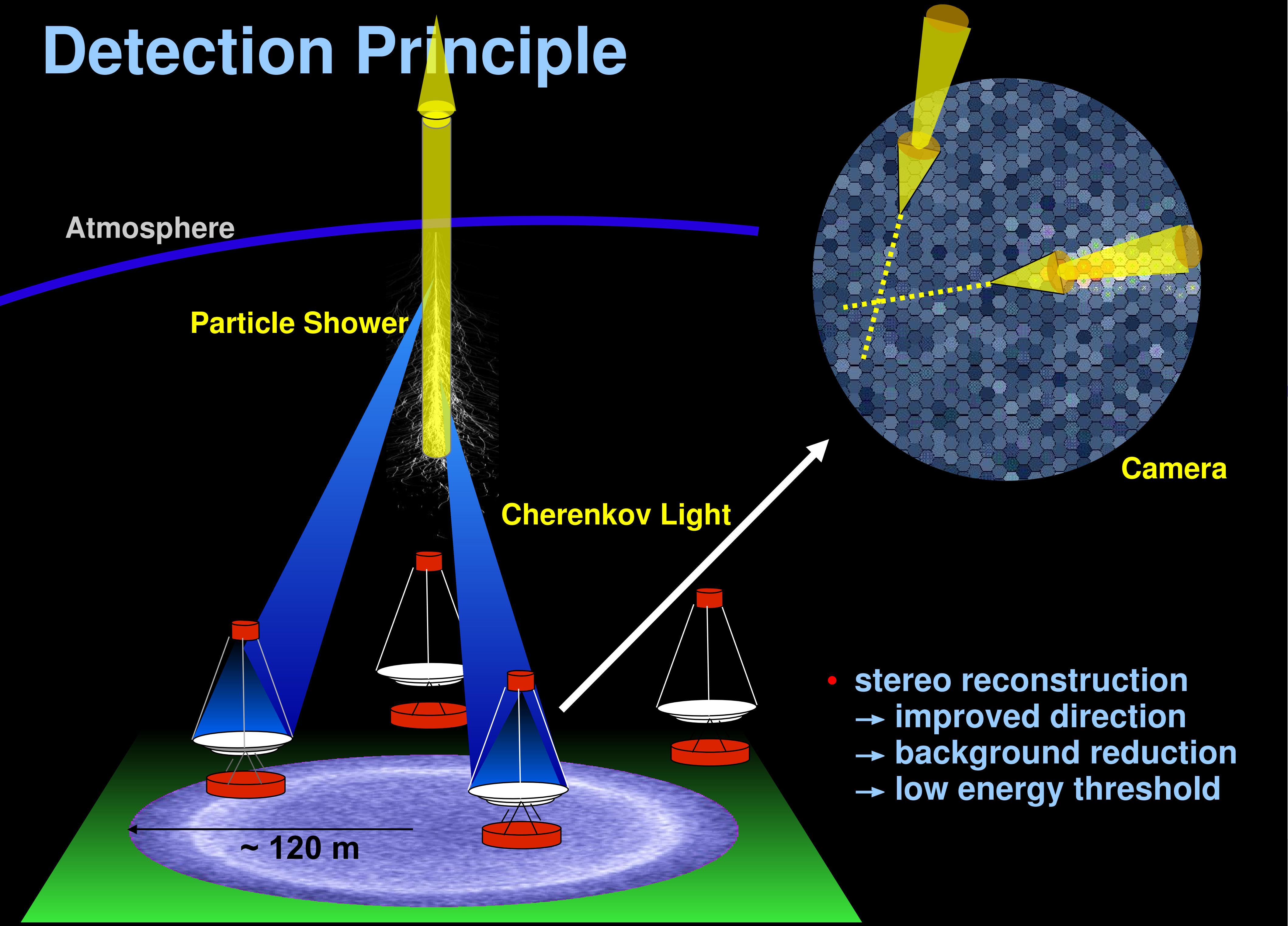
Detection Principle





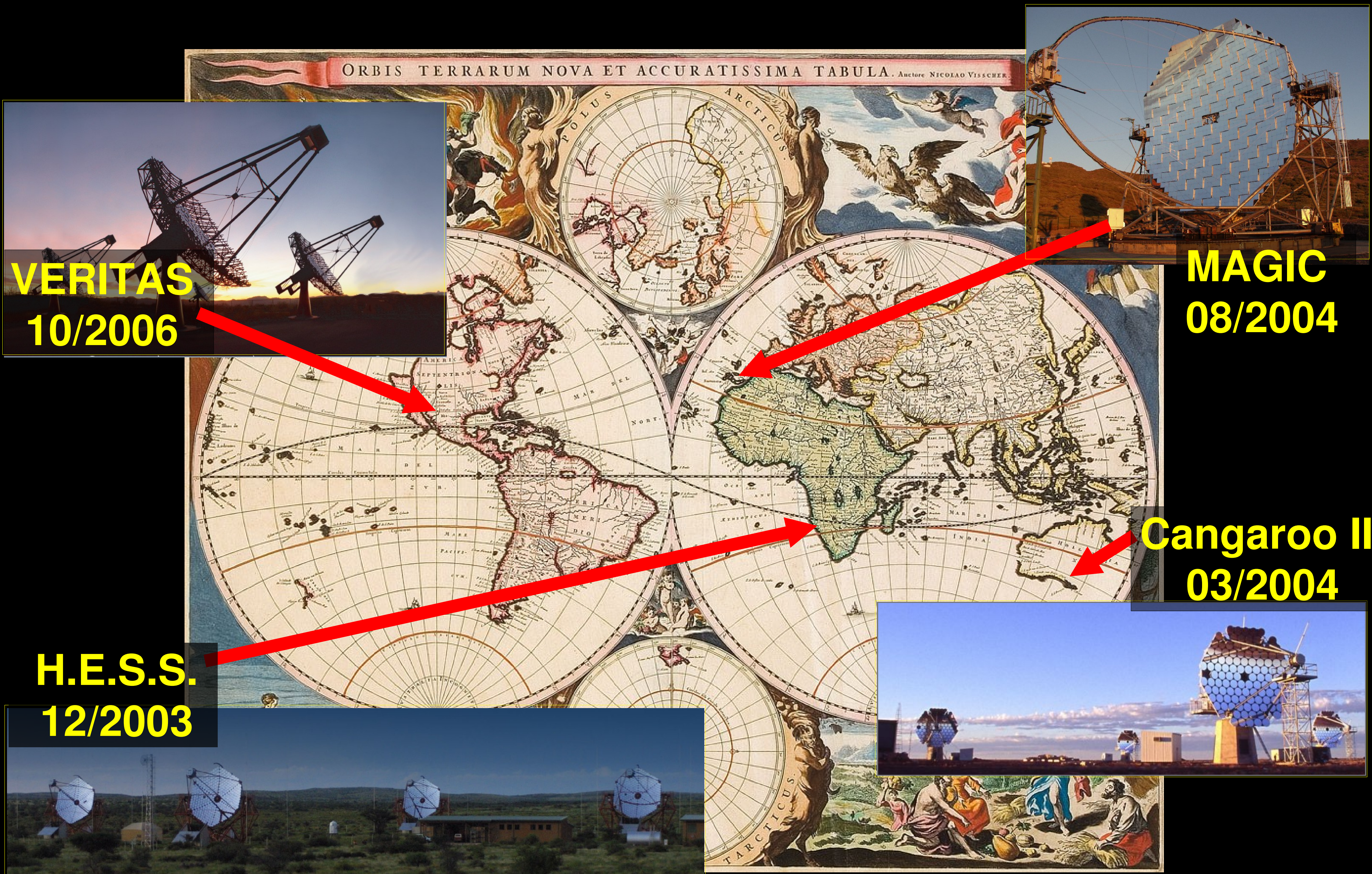
- image intensity
  → γ-ray energy
- Image form
  → background reduction
- Image orientation
  → γ-ray direction

Detection Principle



- stereo reconstruction
  → improved direction
  → background reduction
  → low energy threshold

Cherenkov Telescopes World Map



H.E.S.S. Details

MPI Kernphysik, Heidelberg
Humboldt-Univ. zu Berlin
Ruhr-Univ. Bochum
Univ. Erlangen-Nürnberg
Univ. Hamburg
LSW Heidelberg
Univ. Tübingen
Ecole Polytechnique, Palaiseau
APC Paris
Univ. Paris VI-VII
Paris Observatory, Meudon
LAPP Annecy
LAOG Grenoble
LPTA Montpellier
CEA Saclay
CESR Toulouse
Durham Univ.
Univ. Leeds
Dublin Inst. for Adv. Studies
Polish Academy of Sciences, Warsaw
Jagiellonian Univ., Cracow
Charles Univ., Prague
Yerewan Physics Inst.
Univ. Adelaide
North-West Univ., Potchefstroom
Univ. of Namibia, Windhoek

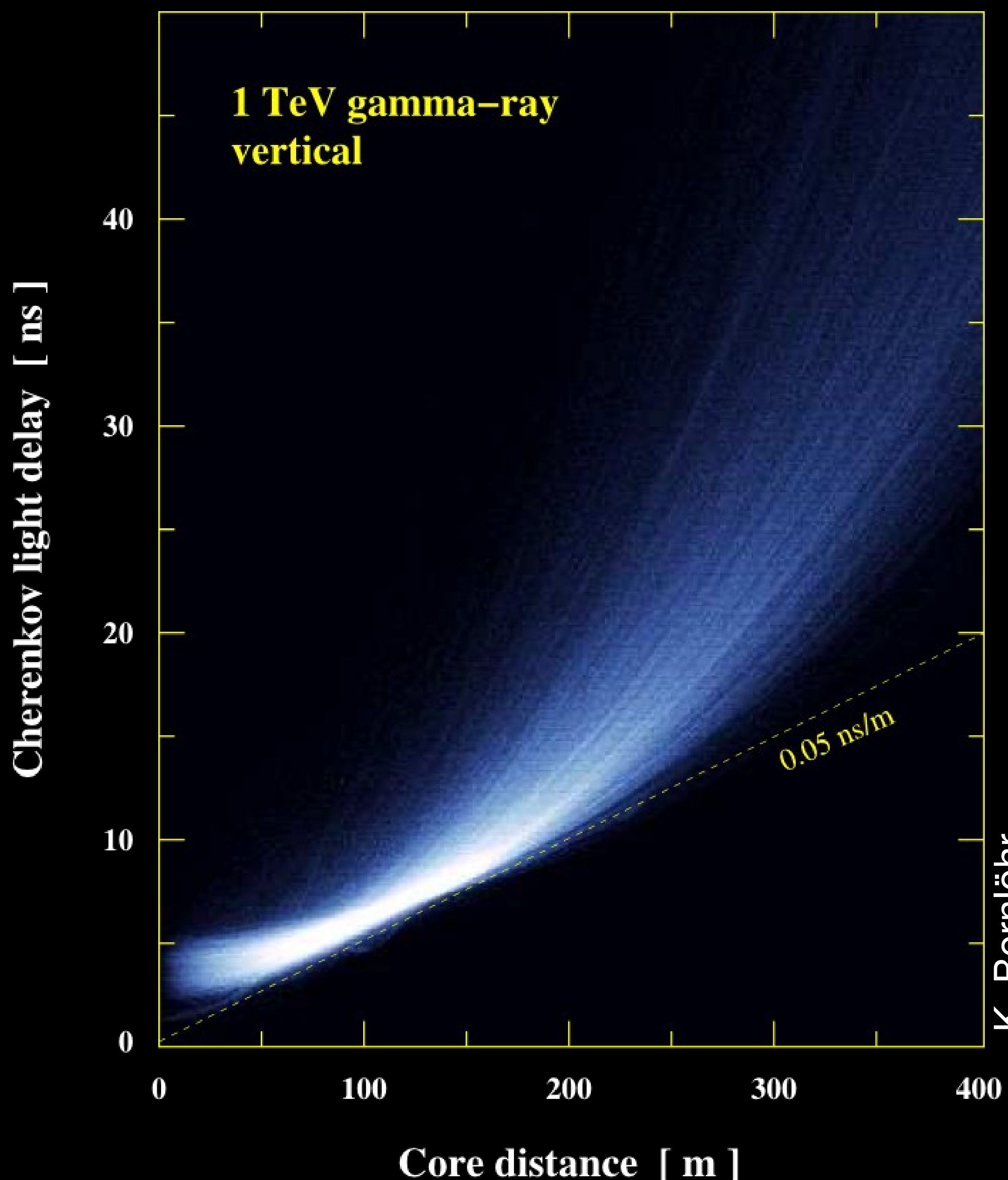
- 4 telescopes
  120 m spacing
  107 m^2 mirror surface each
- energy threshold ~100 GeV
  energy resolution < 15 %
- angular resolution ~0.1°
  pointing accuracy < 20''
- sensitivity (5σ):
  5% of Crab in 1 h
  1% of Crab in 25 h
  HEGRA: 5% of Crab in 100 h
- 1000 h of observations / year
  during moonless nights

The H.E.S.S. Cameras

- 960 pixels (0.16° per pixel)
- 5° field of view
- sensitive photomultipliers
- fast readout and trigger electronics

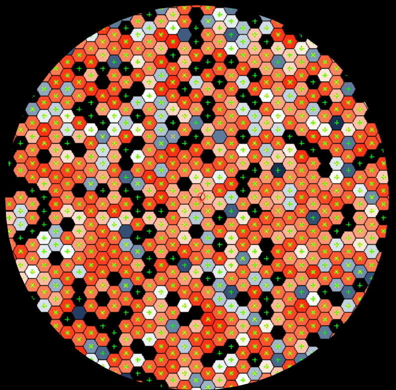
Need for short exposures

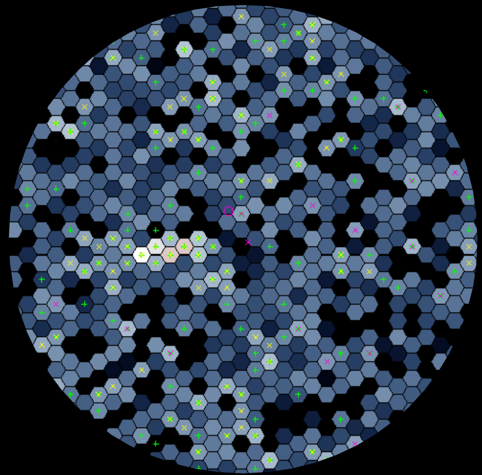
...to reduce night-sky background



K. Bernlöhr

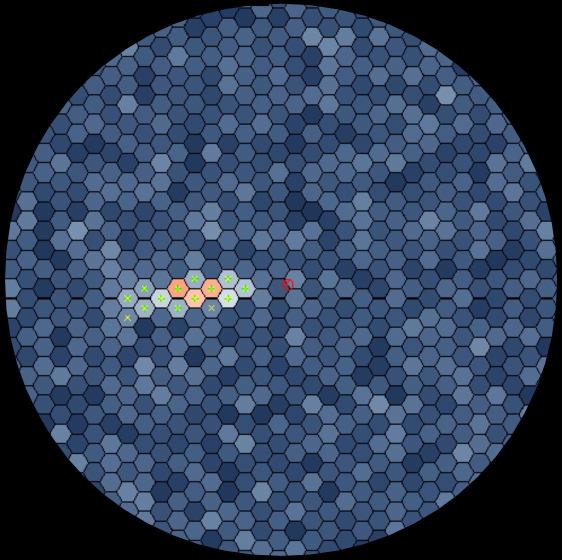
100 µs





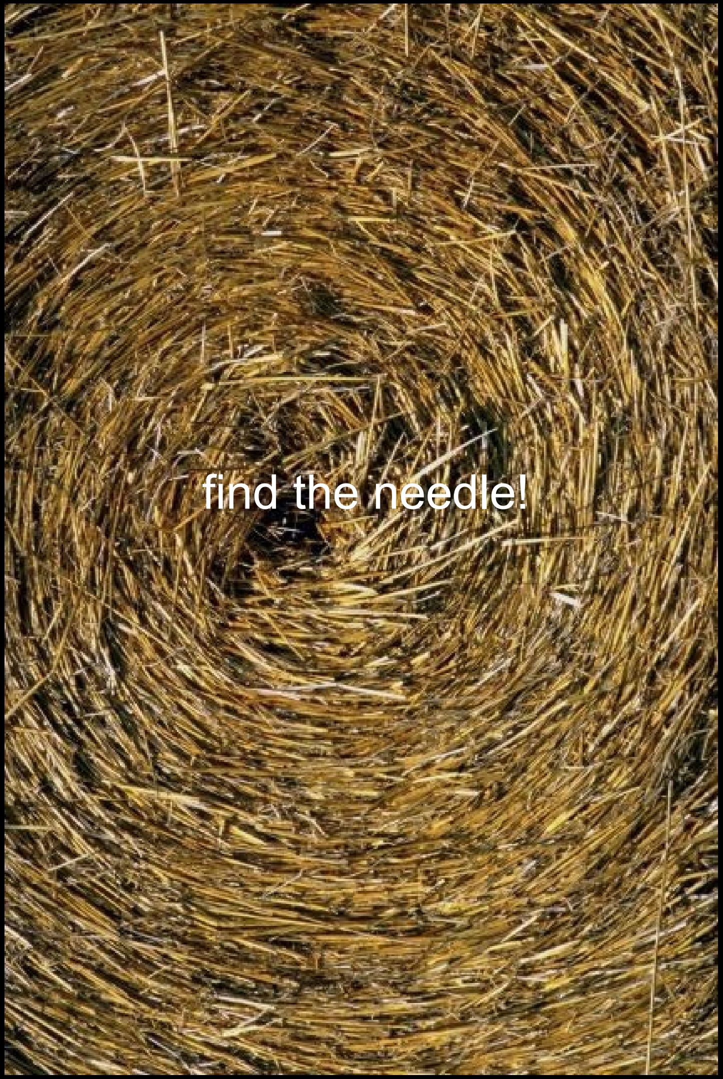
1 µs

10 ns



Background Reduction & Control

- (one of) the most critical issue for analysis
- vital for significance calculation
- vital for flux determination



2 types of background

- cosmic ray hadrons
  - produce air showers somewhat similar to gamma rays
  - about 10^4 more hadrons than gamma rays
- cosmic ray electrons
  - showers very similar to gamma rays
  - flux suppressed at TeV energies

3 stages of reduction

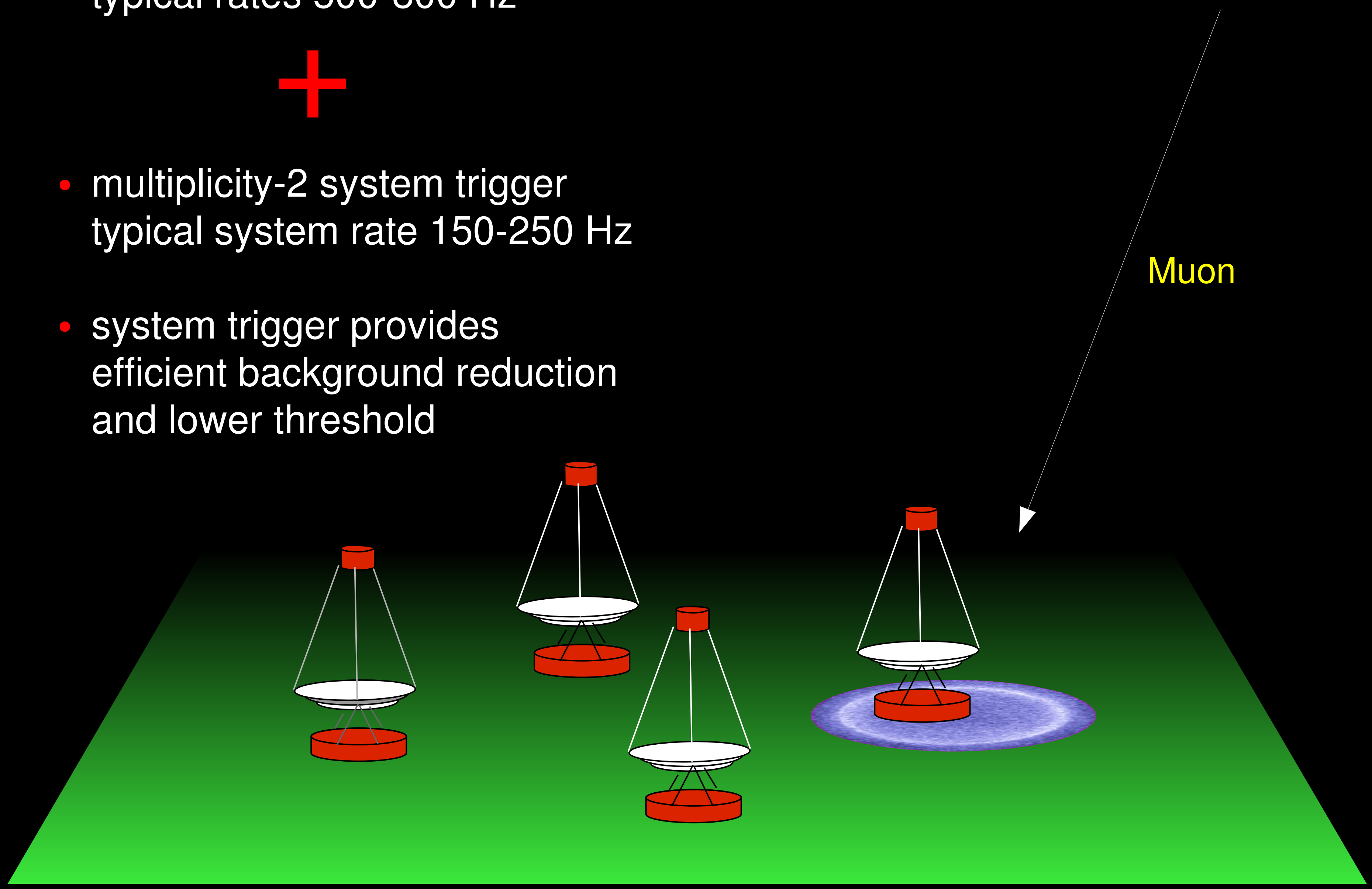
- suppression at trigger level
- reduction by image shape analysis
- subtraction by background modeling

H.E.S.S. Trigger

- 4x single telescope pixel threshold trigger
  typical rates 500-800 Hz

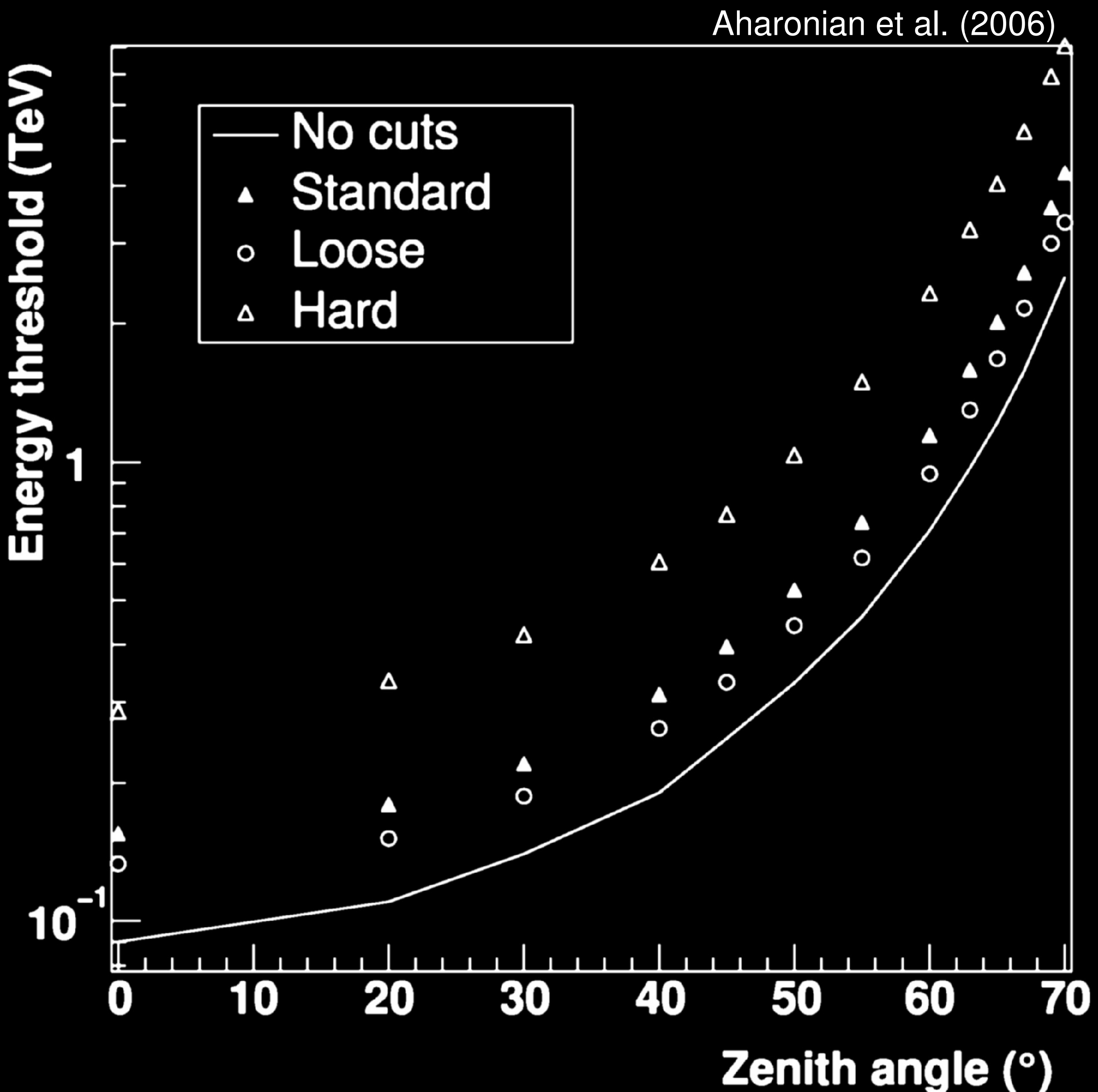
+

- multiplicity-2 system trigger
  typical system rate 150-250 Hz
- system trigger provides
  efficient background reduction
  and lower threshold



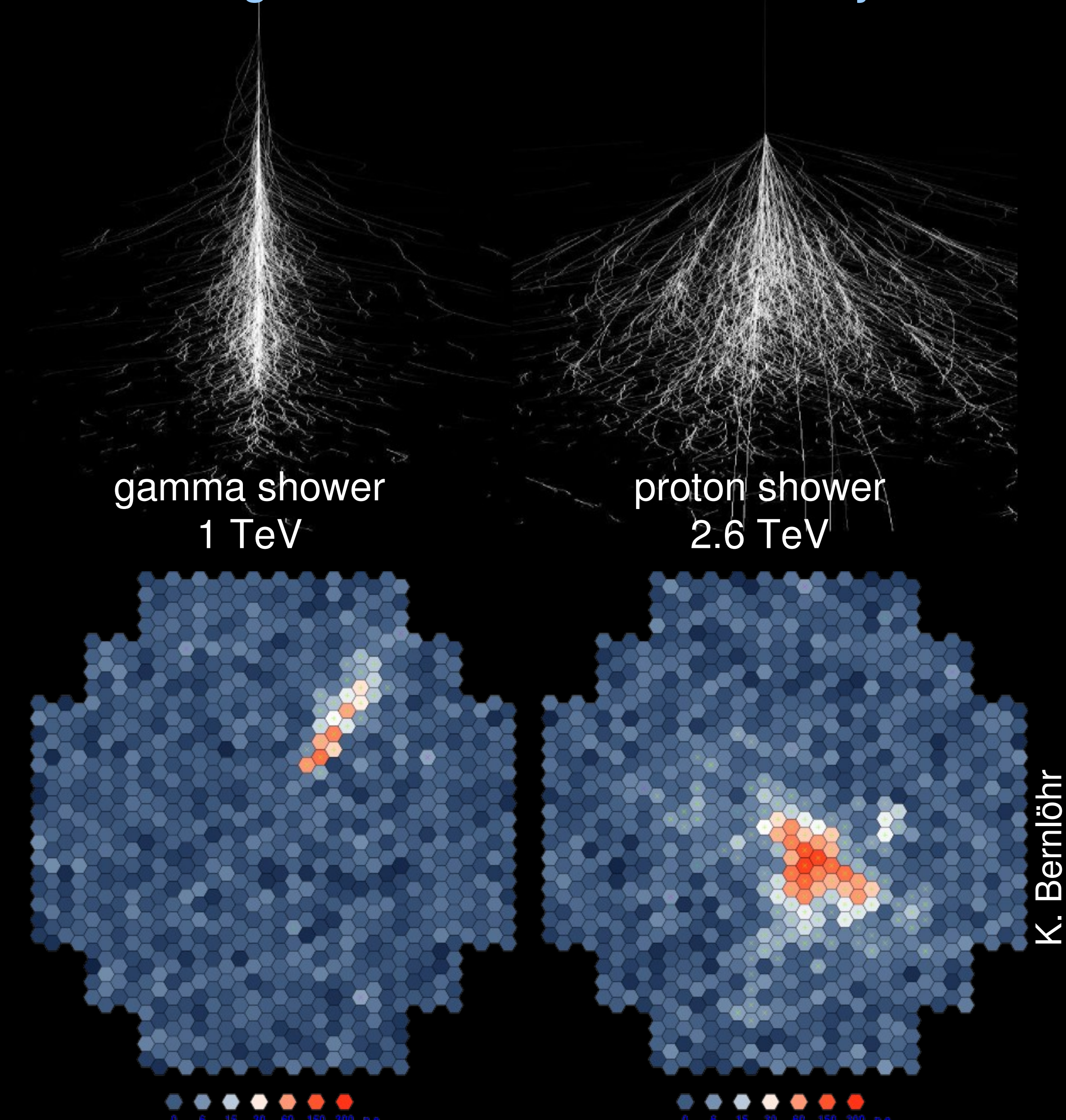
Energy Threshold

- 160 GeV @ zenith for standard cuts
- strong zenith angle dependence
- optical degradation is shifting up thresholds



Cosmic Rays...

...main background for Cherenkov astronomy



- Ratio γ/hadron ≈ 1/1000
- Cuts on image parameters → 99.9% background reduction
- Remaining S/B ~ 1..10, depending on source strength and source size

Background Modeling

- remaining background is subtracted on statistical basis:

$$N_{excess} = N_{on} - \alpha N_{off}$$

- ideally, control background is taken

  - contemporaneously
  - same position in camera
  - same sky region
  - with large event statistics
  - same image-parameter phase space

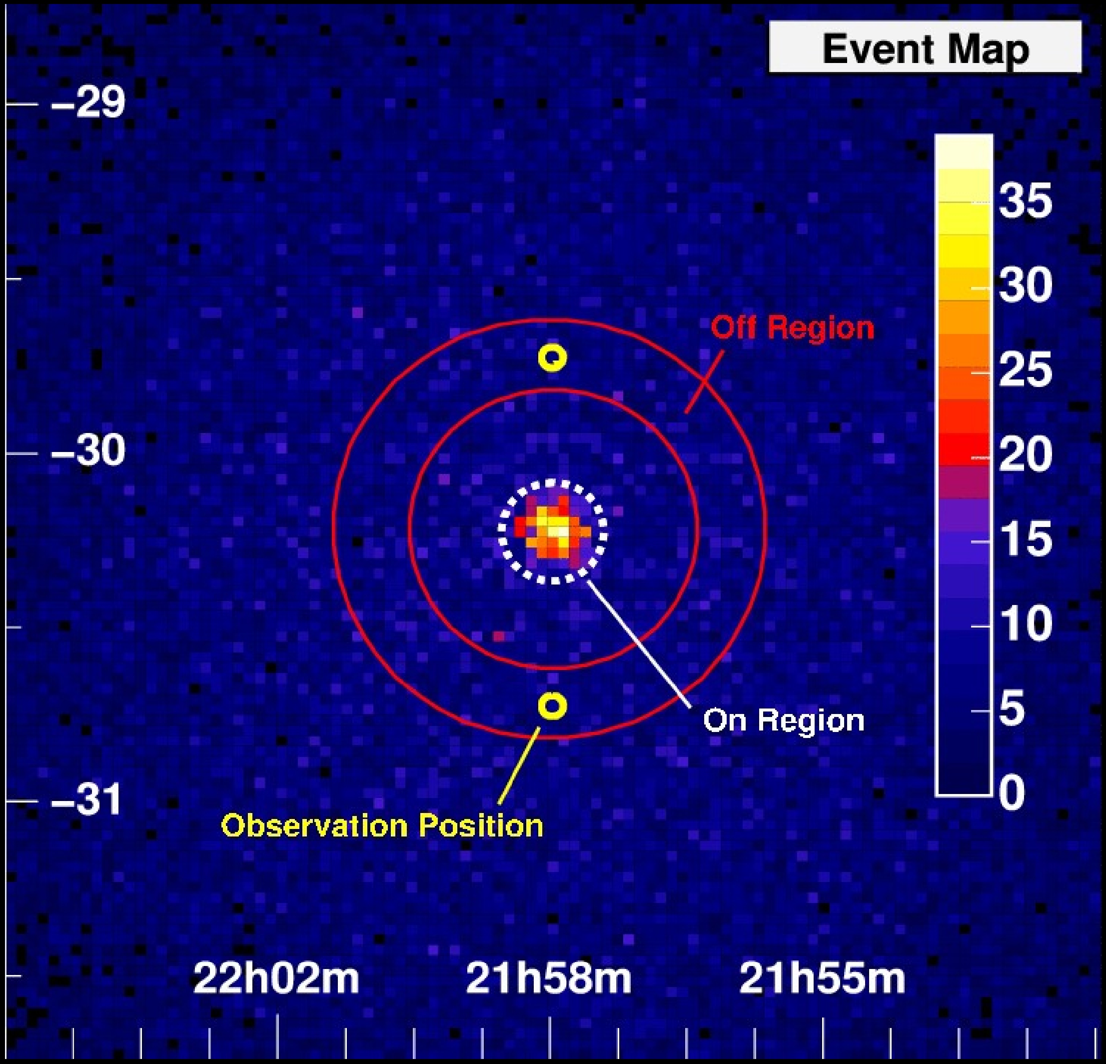
- not all criteria can be met at the same time

- favoured background model depends on type of analysis (detection, morphology, spectrum...)

Background Modeling

- Ring Background -

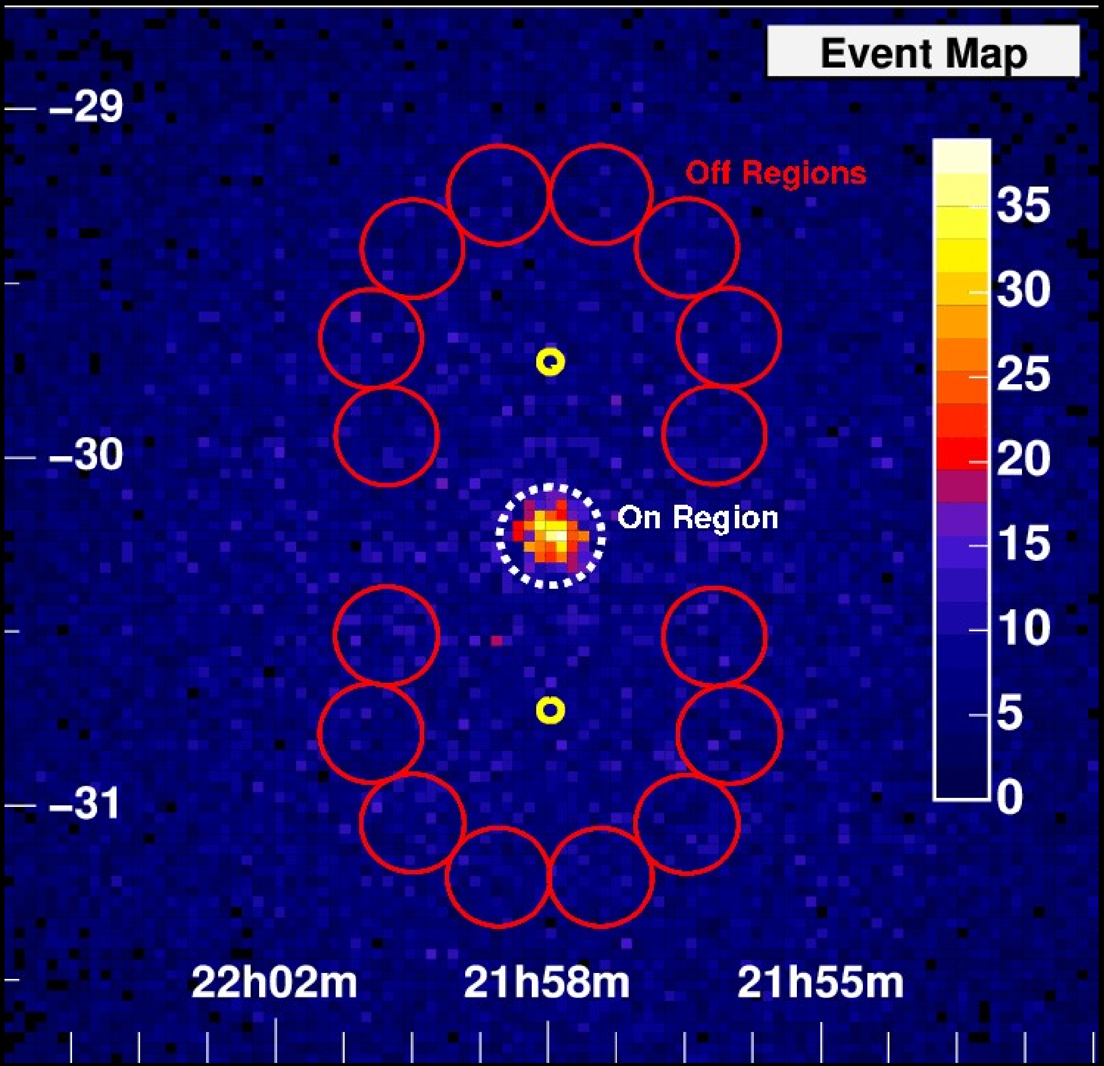
- Off-Region: ring around On-Region
- Off-Events subtracted from On-Events
  - proper area factor
  - acceptance correction
- insensitive to linear gradients in background
- applicable all over the field of view (Sky Maps, morphology)
- not very well suited for spectra due to acceptance correction



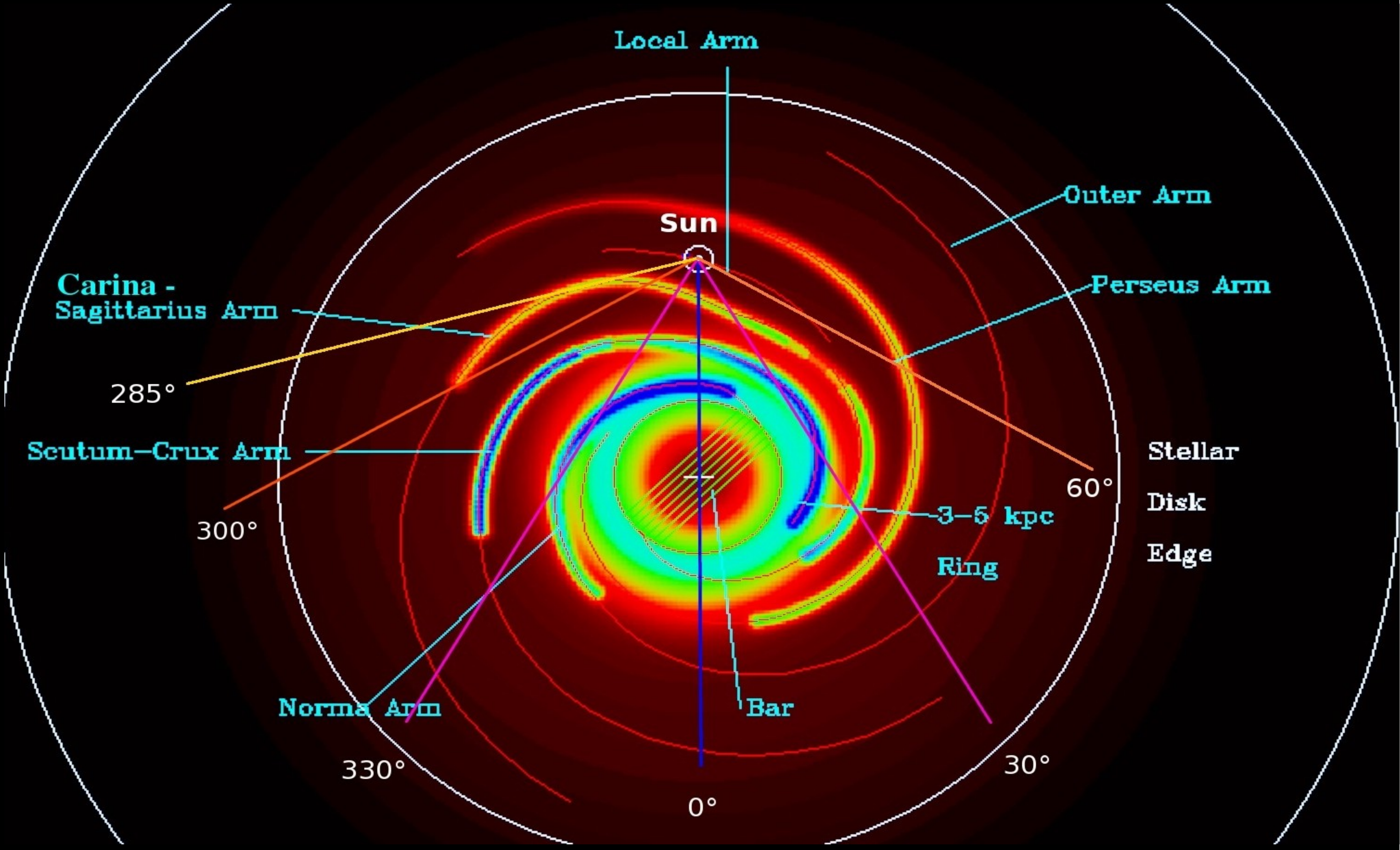
Background Modeling

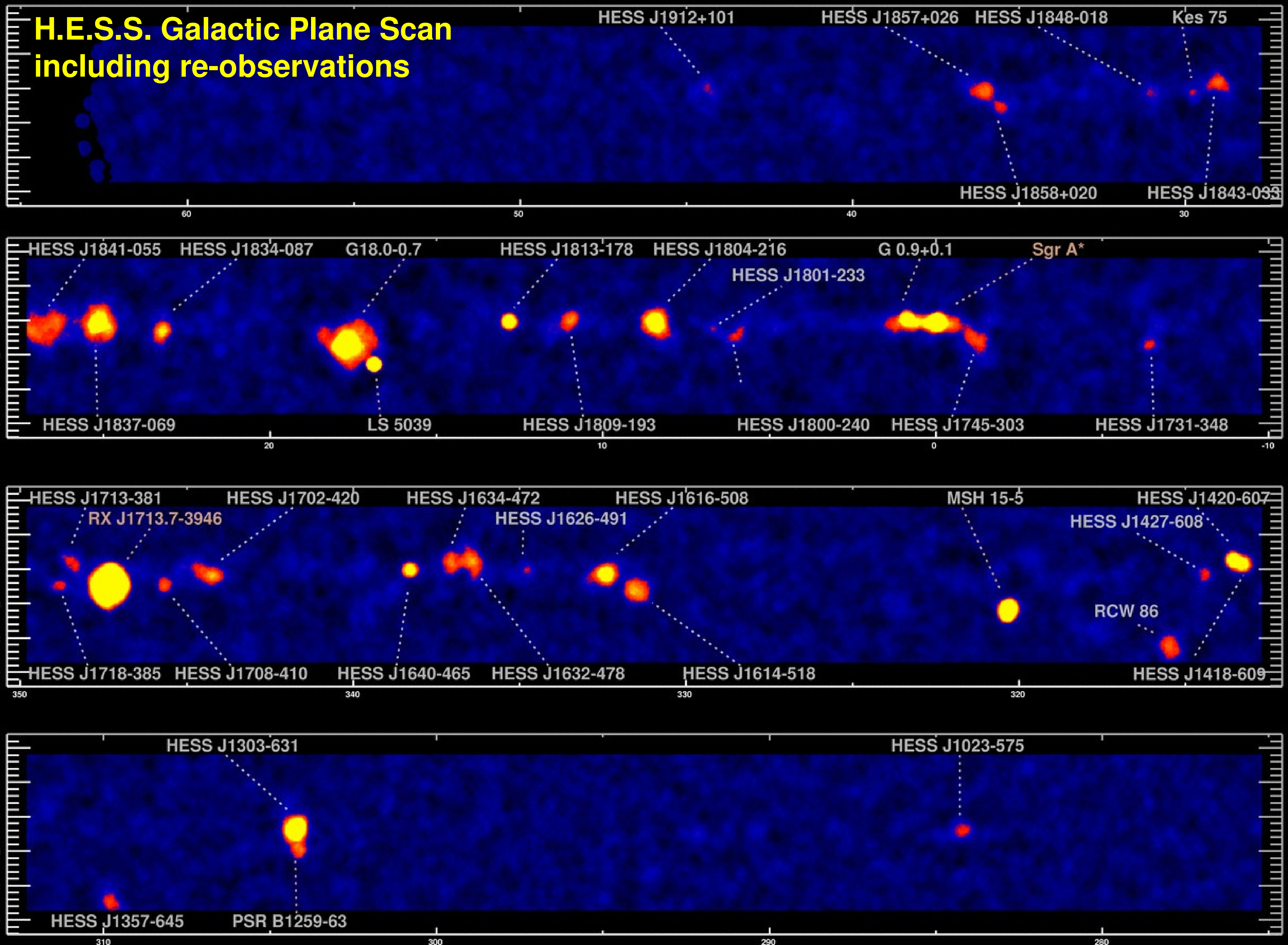
- Reflected Region Background -

- Off-Region: ring of circular regions around observation position (same distance as On-Region)
- Observation position must be outside the On-Region
- no acceptance correction needed assuming radially symmetric acceptance
- insensitive to systematics of acceptance determination
- very well suited for spectra

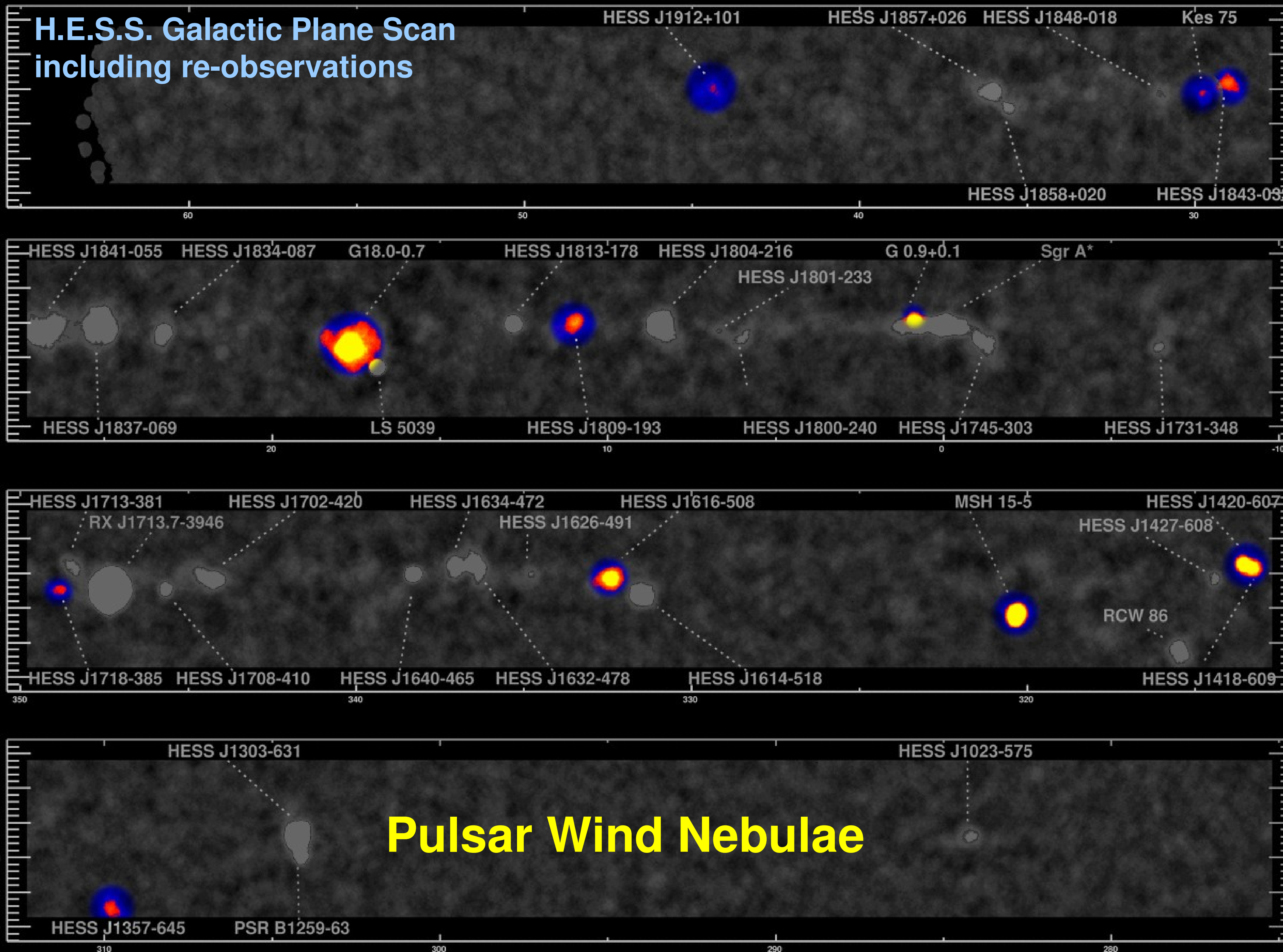


H.E.S.S. Galactic Plane Scan

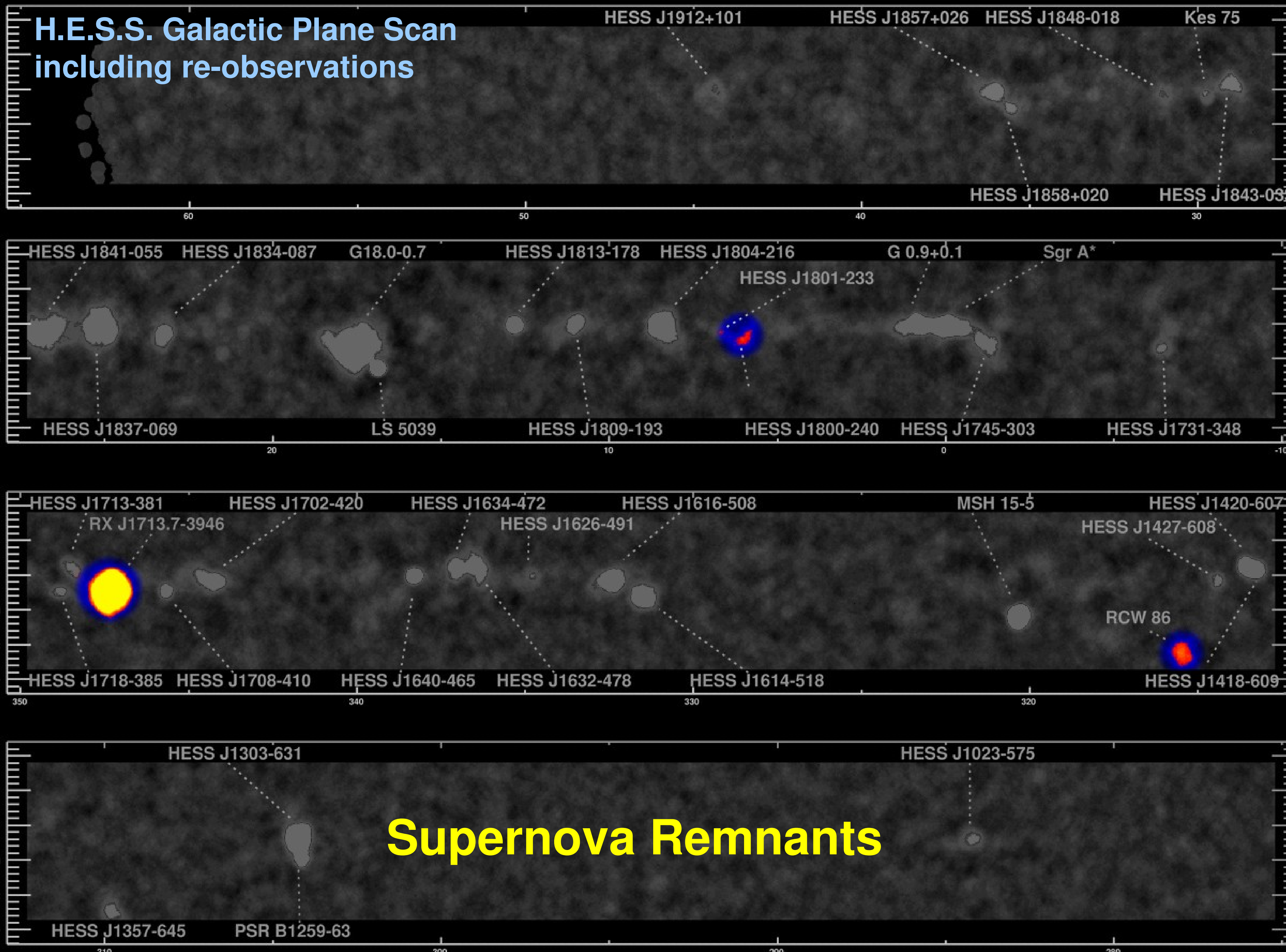




H.E.S.S. Galactic Plane Scan
including re-observations
HESS J1912+101
HESS J1857+026
HESS J1848-018
Kes 75
HESS J1858+020
HESS J1843-033
HESS J1841-055
HESS J1834-087
G18.0-0.7
HESS J1813-178
HESS J1804-216
HESS J1801-233
G 0.9+0.1
Sgr A*
HESS J1837-069
LS 5039
HESS J1809-193
HESS J1800-240
HESS J1745-303
HESS J1731-348
HESS J1713-381
RX J1713.7-3946
HESS J1702-420
HESS J1634-472
HESS J1626-491
HESS J1616-508
MSH 15-5
HESS J1420-607
HESS J1427-608
RCW 86
HESS J1718-385
HESS J1708-410
HESS J1640-465
HESS J1632-478
HESS J1614-518
HESS J1418-609
HESS J1303-631
HESS J1023-575
HESS J1357-645
PSR B1259-63



Classification from Aharonian, Buckley, Kifune and Sinnis (2008)



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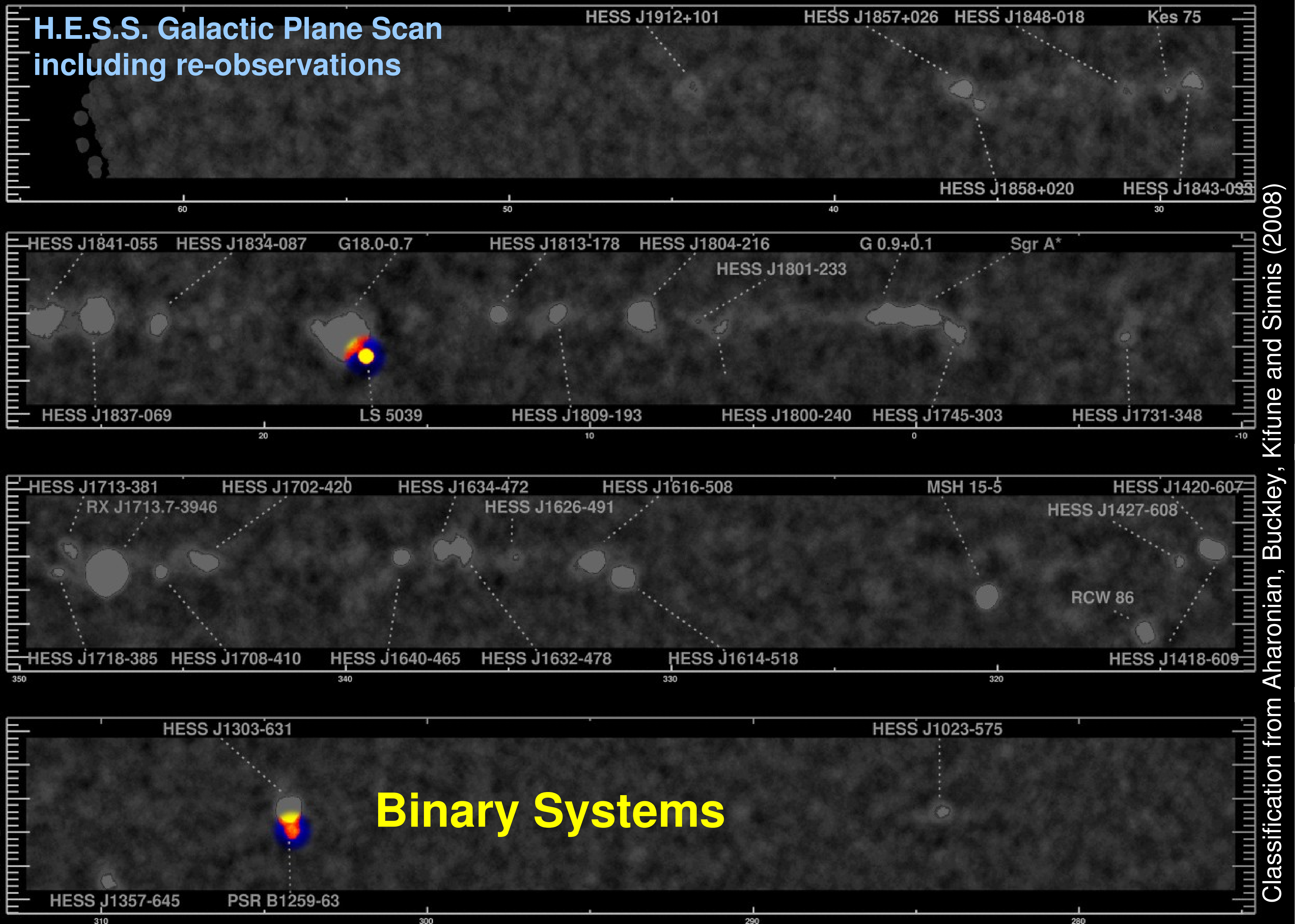

H.E.S.S. Galactic Plane Scan
including re-observations
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HESS J1857+026
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Kes 75
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HESS J1713-381
RX J1713.7-3946
HESS J1702-420
HESS J1634-472
HESS J1626-491
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MSH 15-5
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RCW 86
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HESS J1640-465
HESS J1632-478
HESS J1614-518
HESS J1418-609
HESS J1303-631
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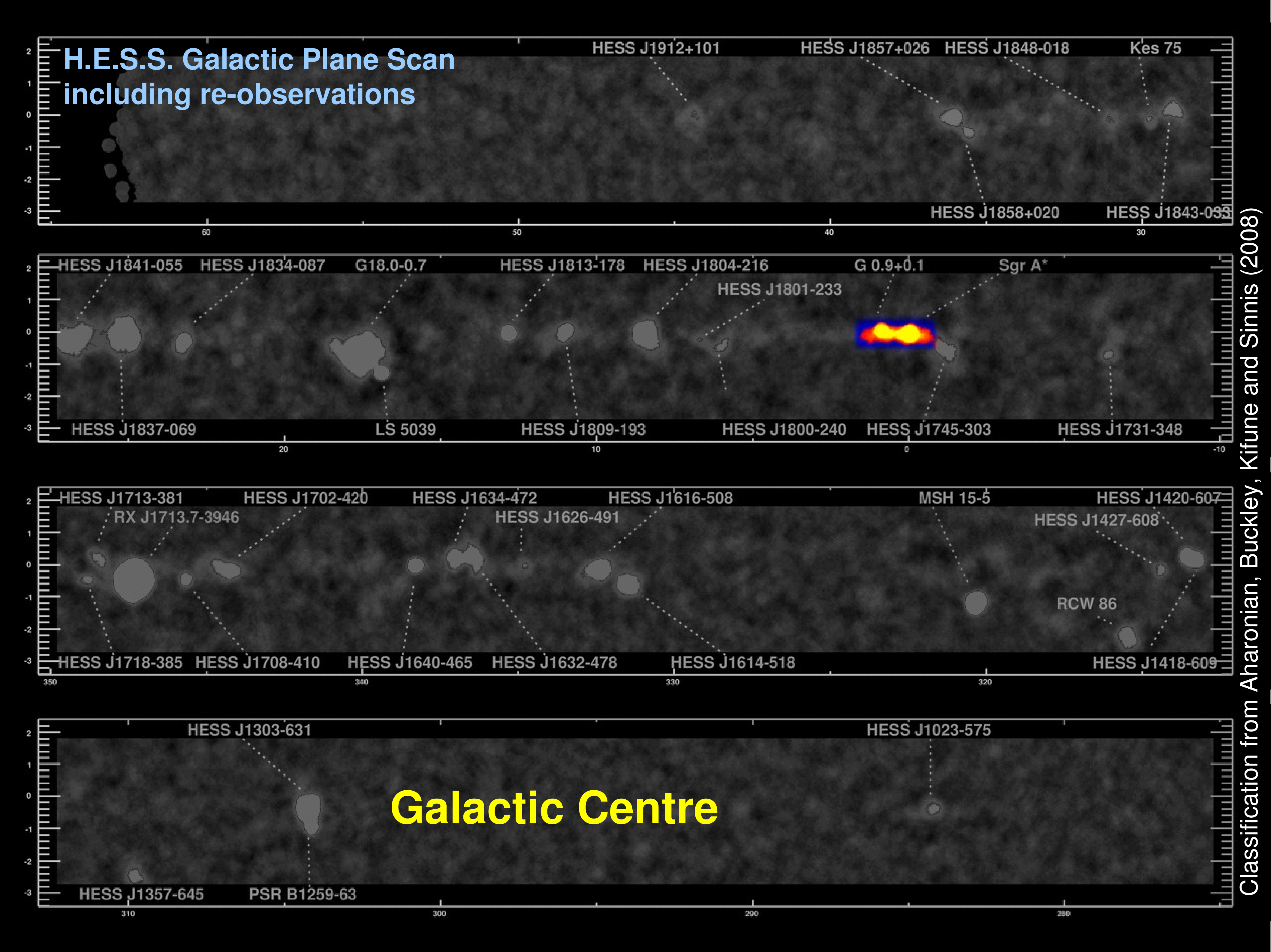
Binary Systems
HESS J1357-645
PSR B1259-63
Classification from Aharonian, Buckley, Kifune and Sinnis (2008)



H.E.S.S. Galactic Plane Scan
including re-observations
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HESS J1303-631
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Galactic Centre
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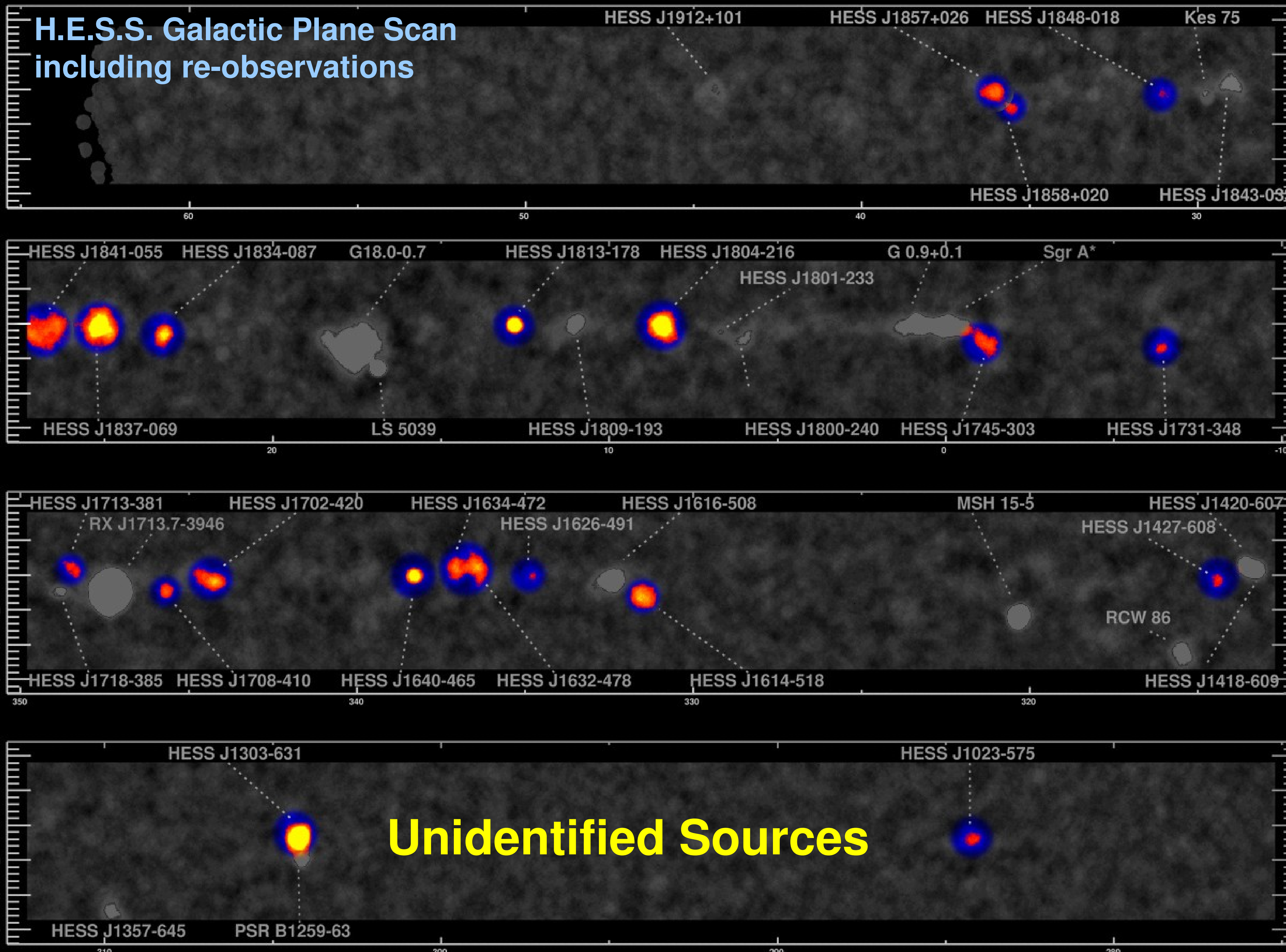
PSR B1259-63
Classification from Aharonian, Buckley, Kifune and Sinnis (2008)



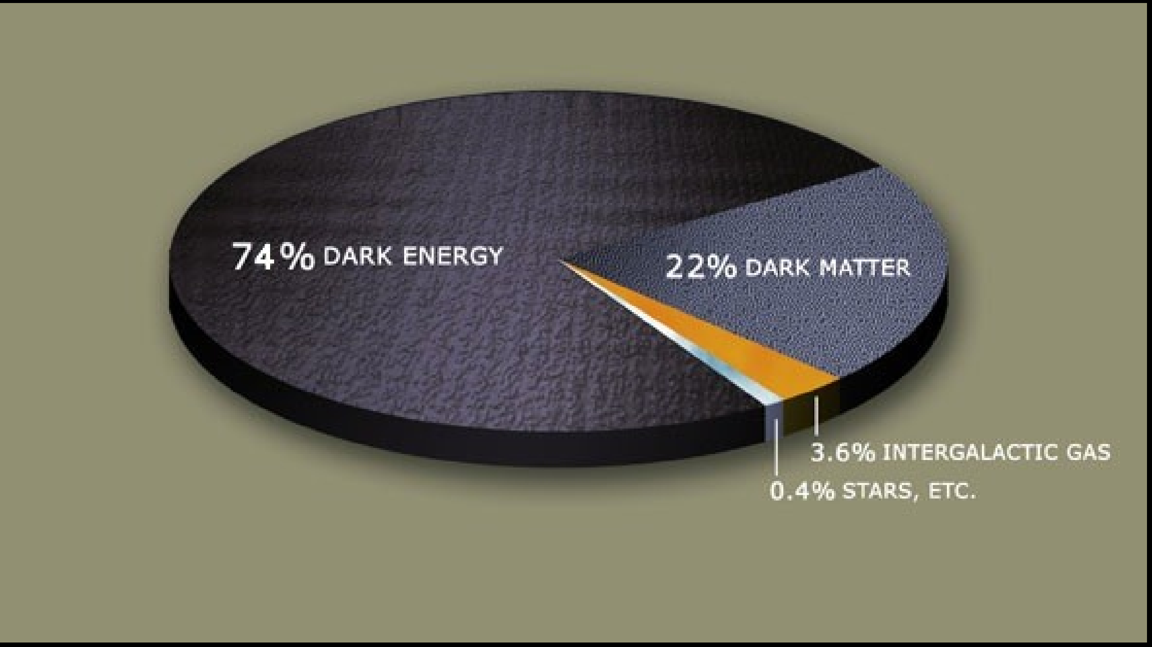
Classification from Aharonian, Buckley, Kifune and Sinnis (2008)

Indirect Dark Matter Searches

The Early Days...

- Large velocity dispersion among Coma cluster galaxies
  $\rightarrow$ Zwicky 1933

- Galactic rotation curves hard to explain with luminous matter only
  $\rightarrow$ Babcock 1939 (Andromeda)



... and 75 years later

- High-redshift supernova surveys
- Large-scale structure of the universe
- CMBR fluctuations

$\rightarrow$ ΛCDM Standard Model of Cosmology
$\rightarrow$ need CDM for structure formation

- Dark Matter accounts for
  - 22% of energy content
  - 85% of total matter

We know that we don't know, but with great precision

Particle Dark Matter

- Almost all models extensions of the SM
  $\rightarrow$ need (quasi-)stable, massive particles

Particle	Spin	Mass Scale
Axion	0	μeV - meV
Inert Higgs Doublet	0	50 GeV
Sterile Neutrino	1/2	keV
Neutralino	1/2	10 GeV – 10 TeV
Kaluza-Klein UED	1	TeV

Bergström (2009)

- Velocity-averaged annihilation cross section at the time of freeze-out ($v/c \approx 0.2 - 0.3$)

$$\langle \sigma v \rangle = 2.8 \times 10^{-26} \mathrm{cm}^3 \mathrm{s}^{-1}$$

- Galaxy today: $v/c \approx 10^{-3}$
  $\rightarrow$ significant enhancement possible, especially if bound state exists

Final states

- Too many models on the market:
  $\rightarrow$ two SM particles: e+e-, μ+μ-, τ+τ-, W+W-, bb, pp
  $\rightarrow$ >4 SM particles: 4e, 4μ, 4τ, 4π

- Branching ratios do depend on DM particle mass

- Depends on type of process:
  annihilation vs. decay
  $\rightarrow$ mainly concentrate on annihilation here

- Usually continuum spectra, but line emission possible (can be loop-suppressed)

Expected Flux

$$\Phi = \iint \begin{cases} \dfrac{1}{\tau}\dfrac{\rho_{DM}}{M_{DM}}\dfrac{dN_\gamma}{dE_\gamma} \\ \dfrac{1}{2}\dfrac{\rho_{DM}^2}{M_{DM}^2} BF \langle \sigma v \rangle \dfrac{dN_\gamma}{dE_\gamma} \end{cases} dl\, d\Omega$$

$\langle \sigma v \rangle = 2.8 \times 10^{-26}\, cm^3 s^{-1}$: cross section at freeze-out

$\rho_{DM} = 0.3\, GeV\, cm^{-3}$: local energy density

BF: boost factor (Sommerfeld, sub-structure...)

Messengers

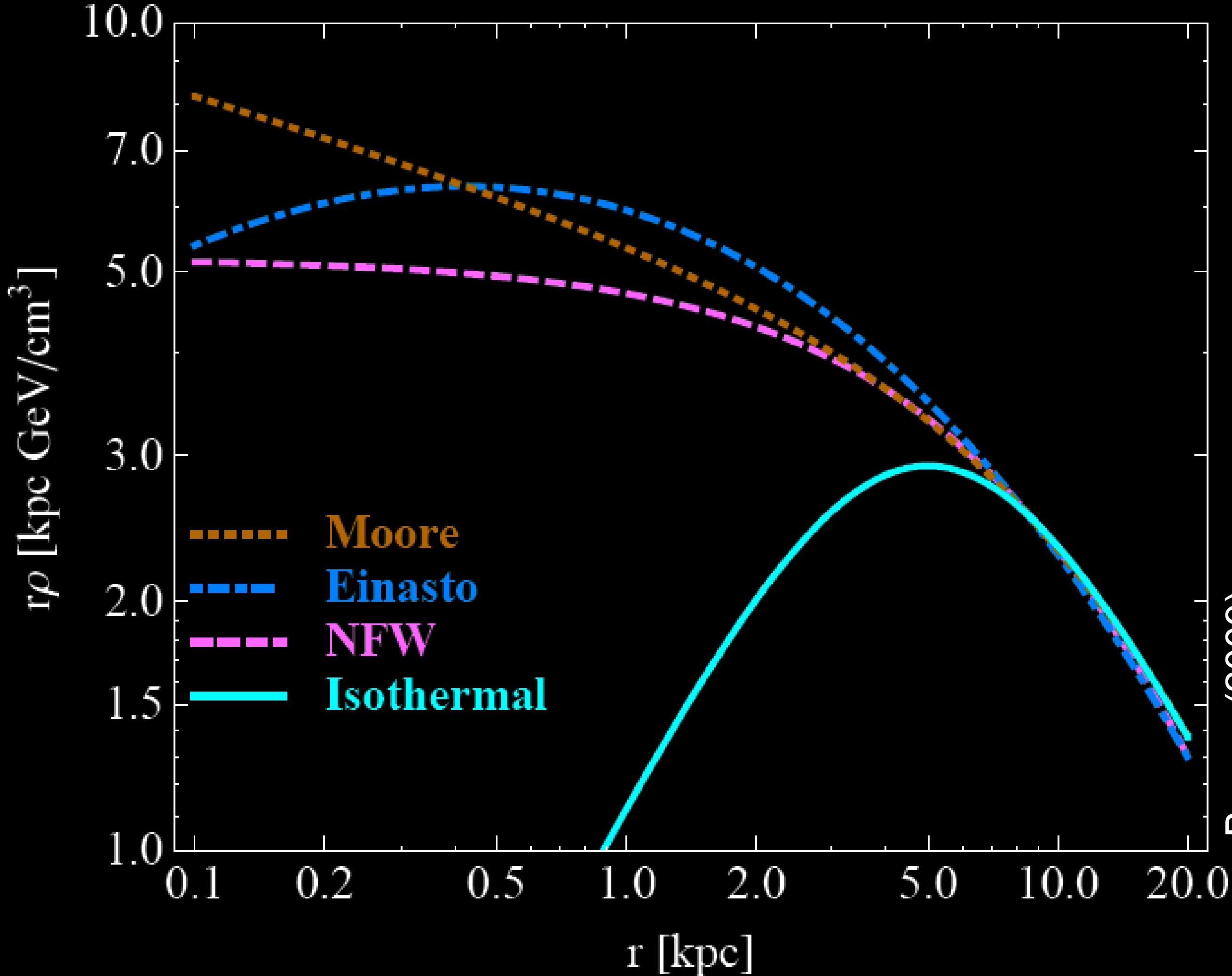
- γ-rays, neutrinos
  $\rightarrow$ sensitivity drops with 1/θ
  $\rightarrow$ observe spikes in DM profile

- electrons/positrons
  $\rightarrow$ diffusion-dominated
  $\rightarrow$ measure diffuse flux

- Diffuse γ-rays from Inverse Compton

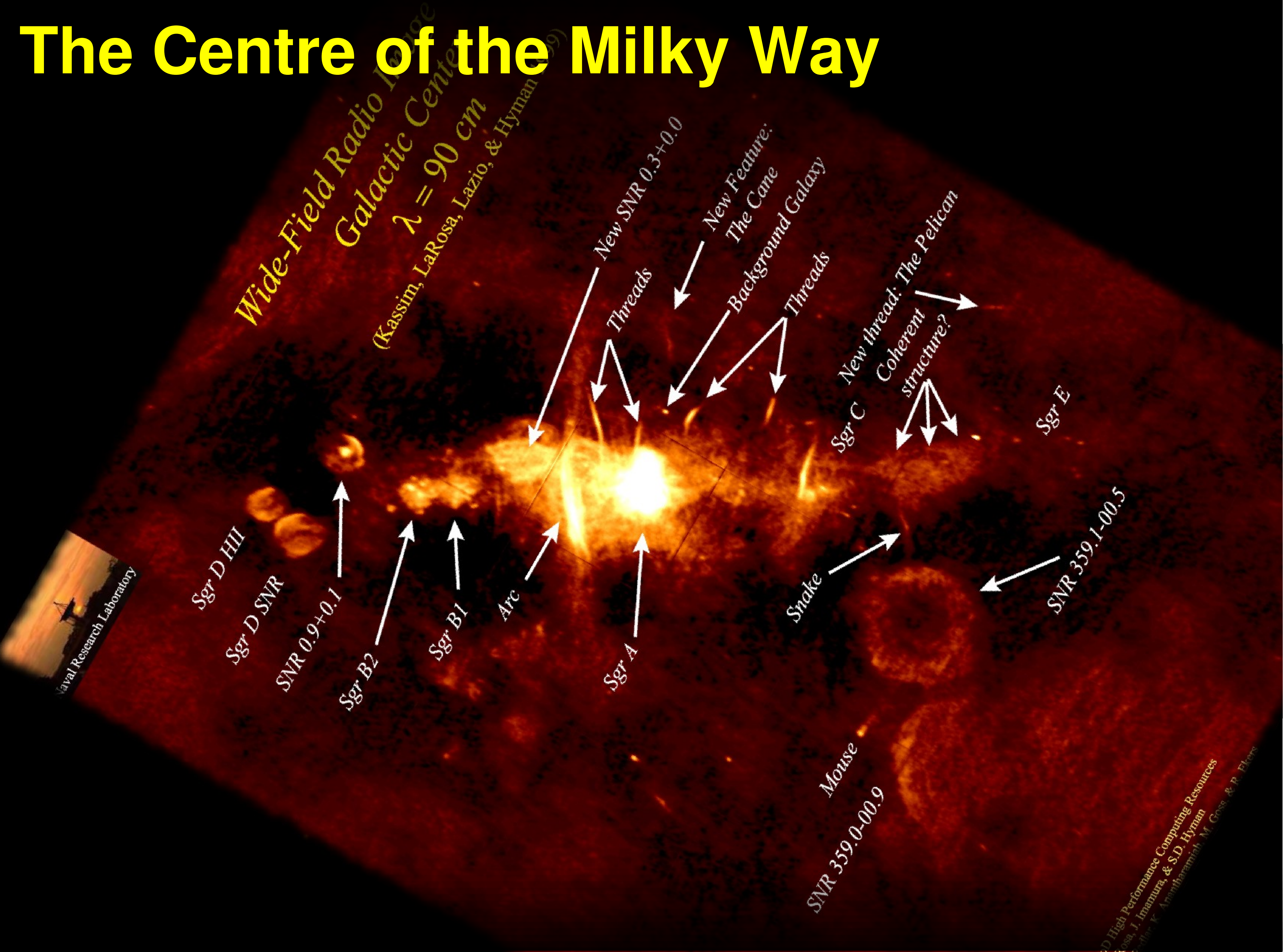
Galactic Dark Matter Distribution

- Form of DM halo critical for detection
  → e.g. large differences in density at GC, sub-structure
- More an issue for γ-rays than for electrons
- More an issue for annihilation than for decay

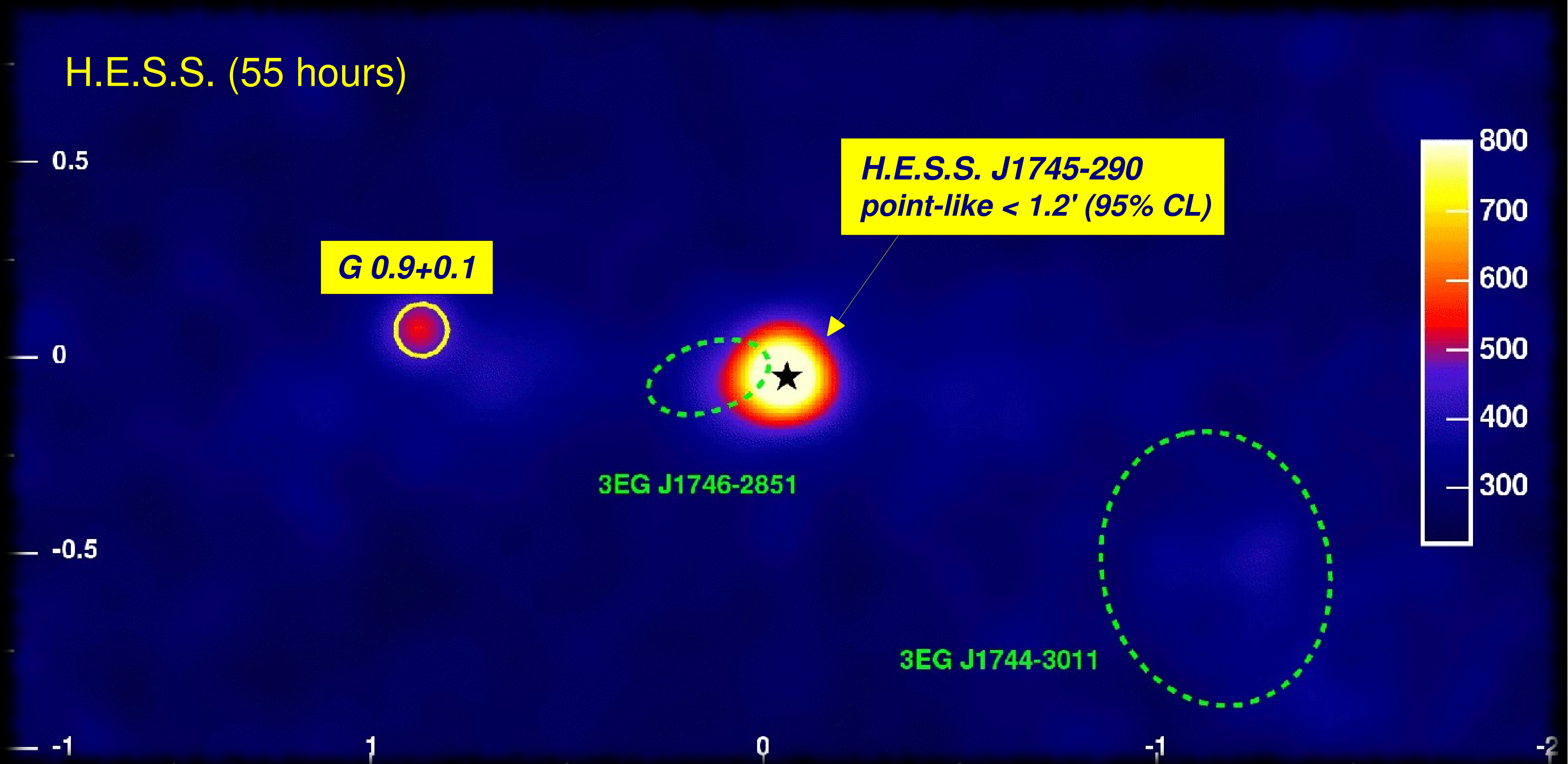


Barger (2009)

The Centre of the Milky Way

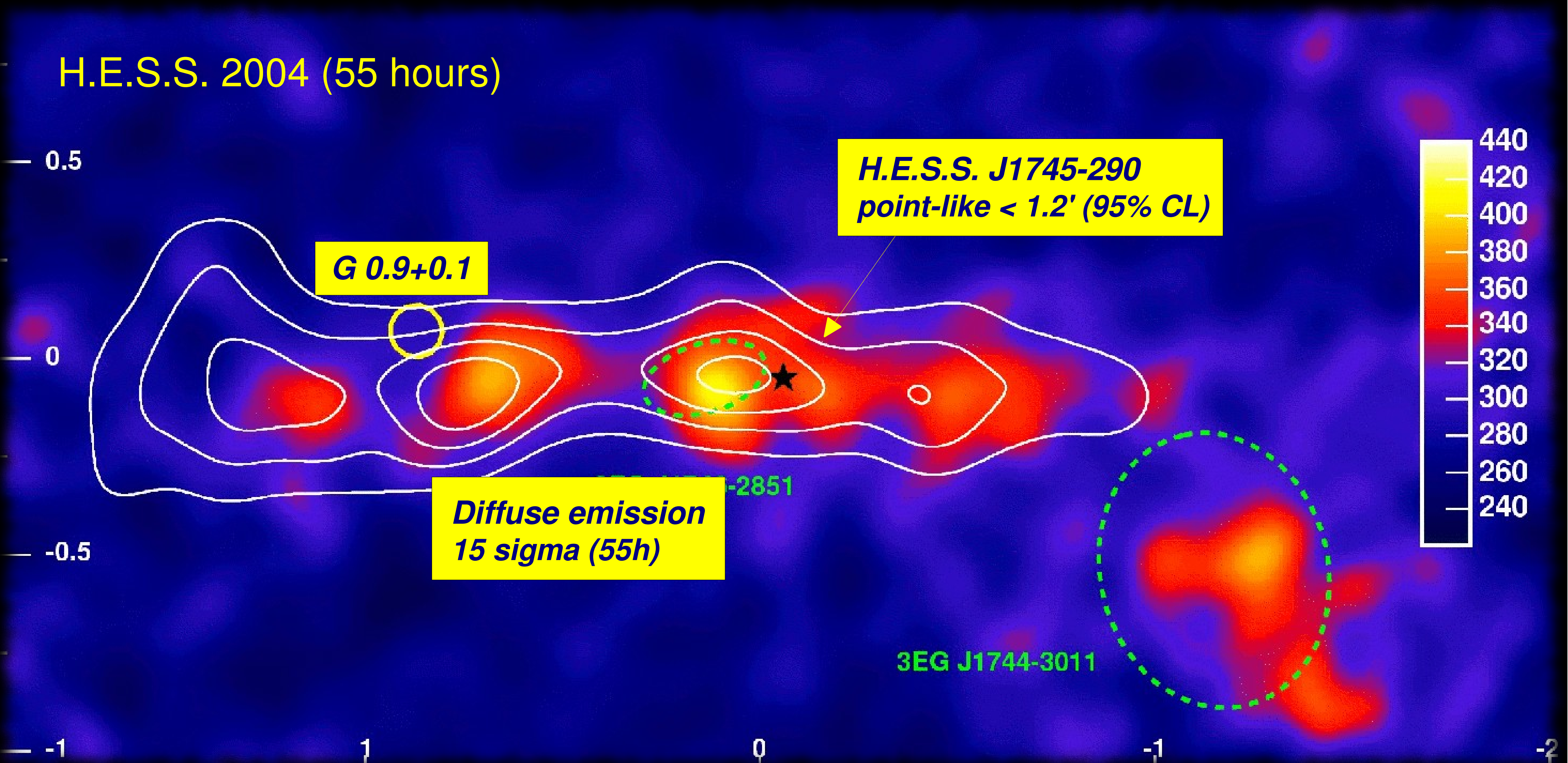


The Centre of the Milky Way



Aharonian et al. (2006)

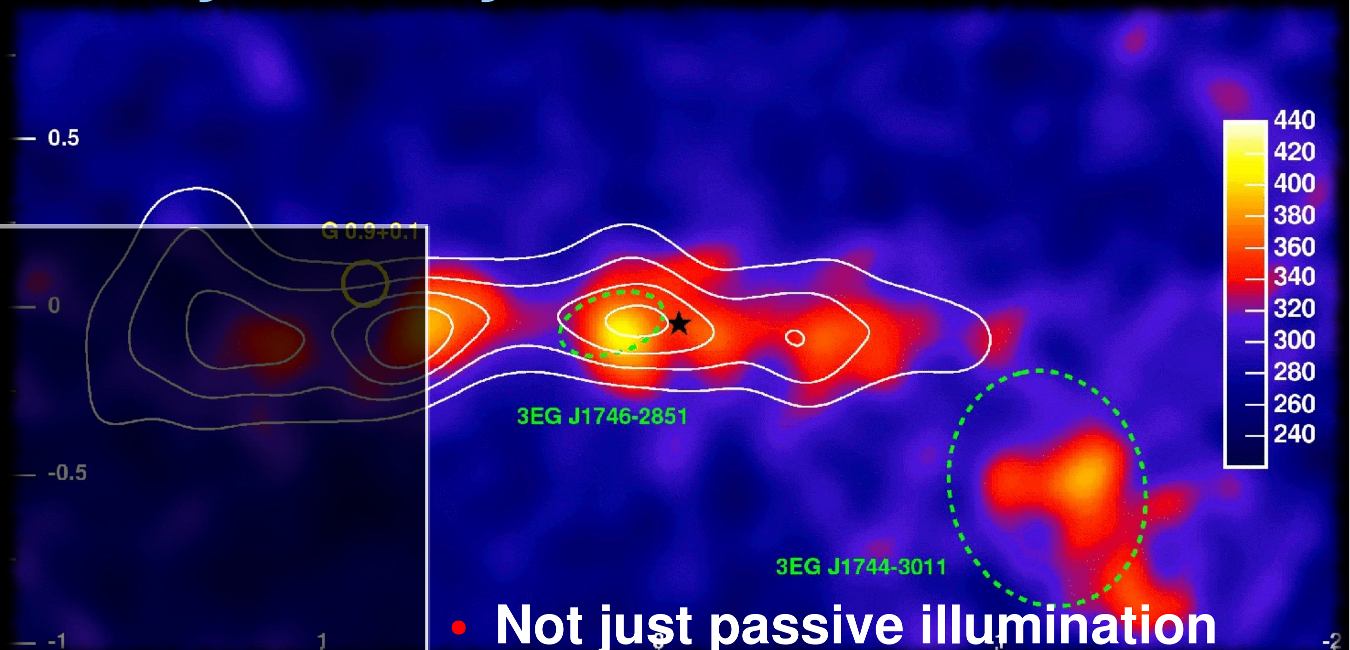
The Centre of the Milky Way

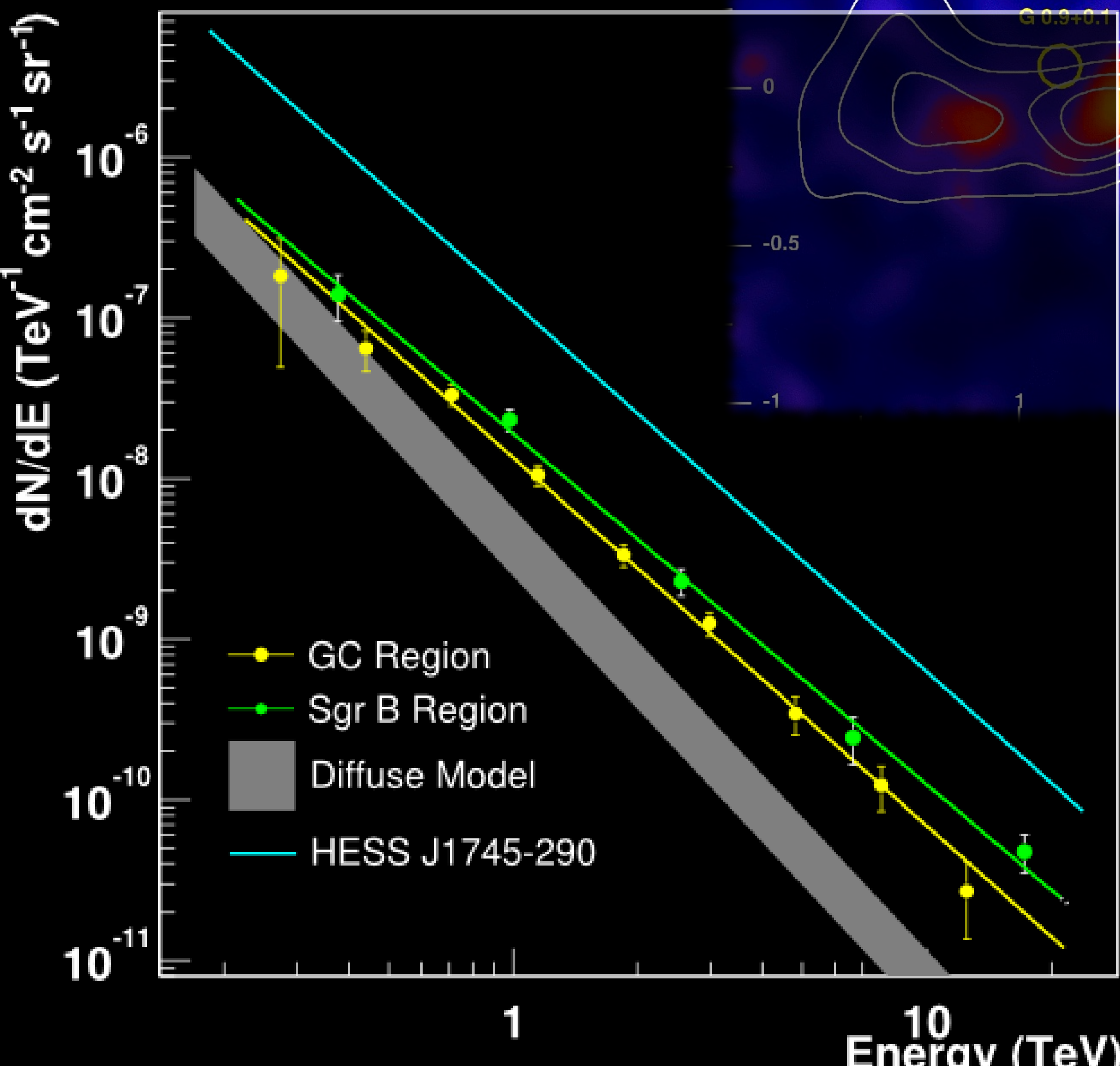


Aharonian et al. (2006)

Diffuse Emission

... enhanced cosmic ray density





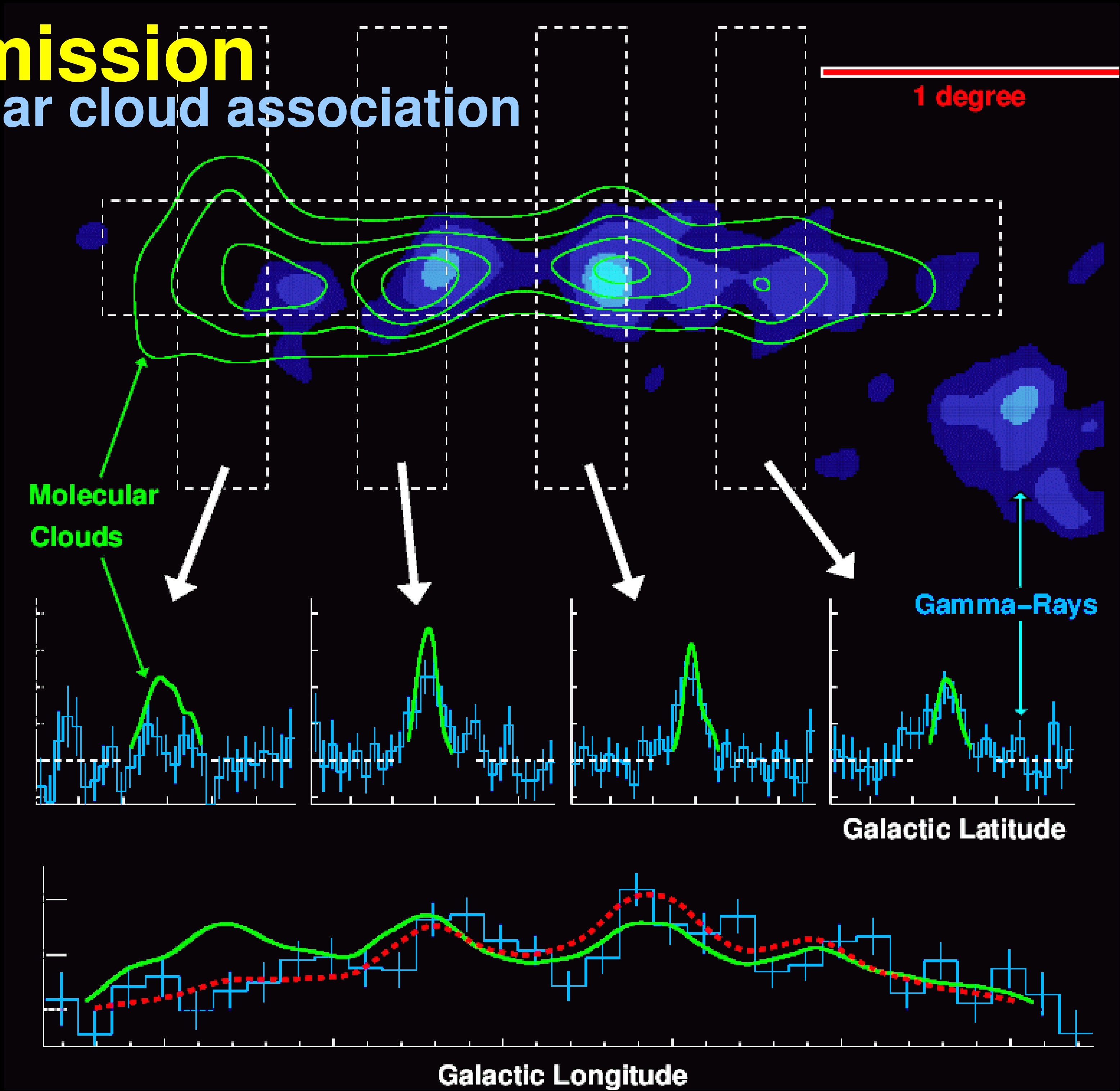
- **Not just passive illumination**
  - enhanced flux for > 1 TeV
  - photon index ~2.3
- **Similar index as HESS 1745-290**
  - everywhere in the region
- **Many sources of electrons?**
  - strong cooling: expect compact sources
  - should be strong X-ray emitters but not observed

Diffuse Emission

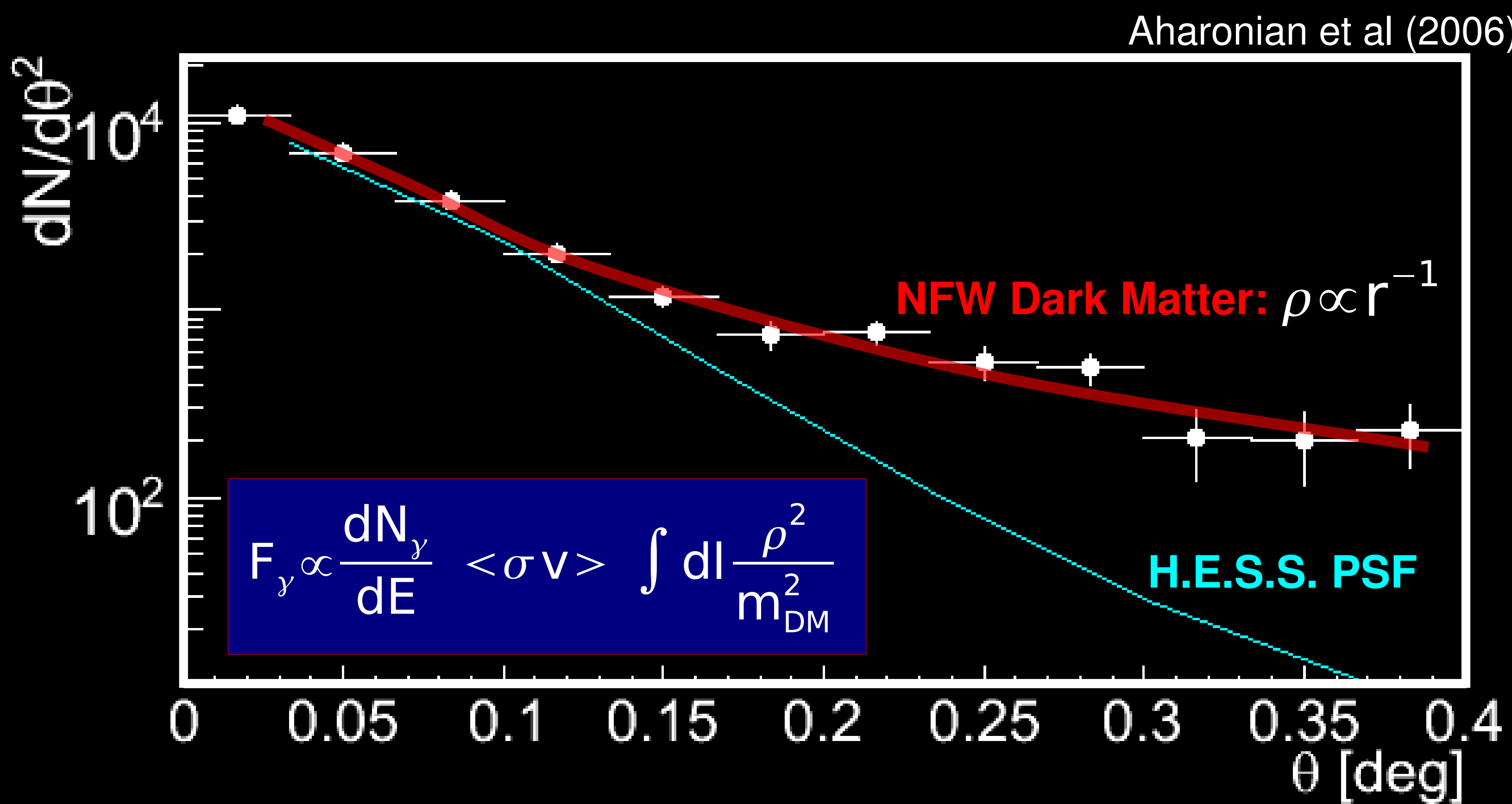
... molecular cloud association

- Lack of γ-rays for $l > 1°$
- Injection of protons at GC
- Assume $k = \sim 3\ \mathrm{kpc^2\ Myr^{-1}}$ for TeV protons

  $\rightarrow$ injection 10^4 years ago
- Fits age of Sgr A East

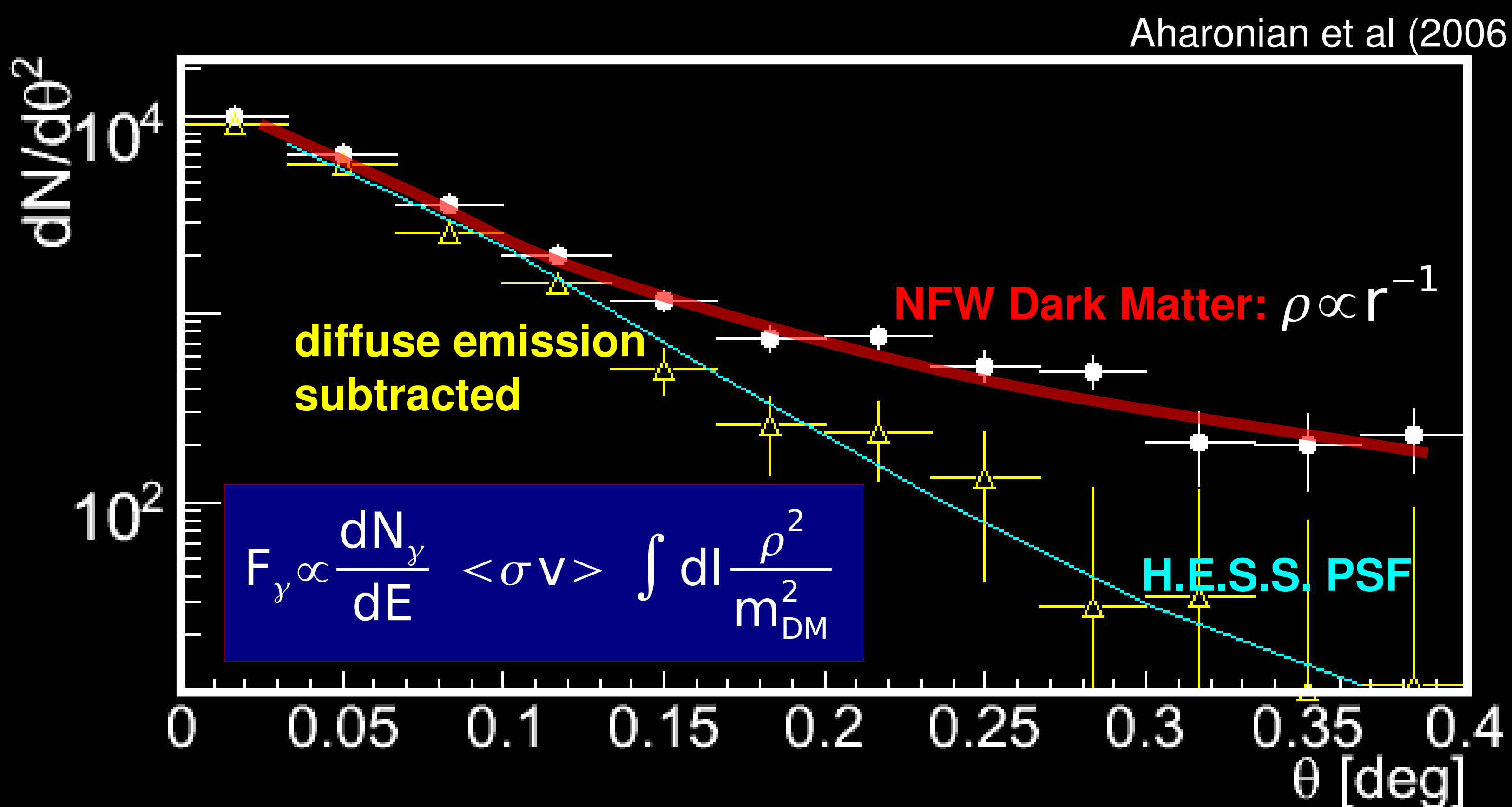


HESS J1745-290
... not much room for Dark Matter



- radial source profile fits NFW DM at first glance, but...

HESS J1745-290
... not much room for Dark Matter

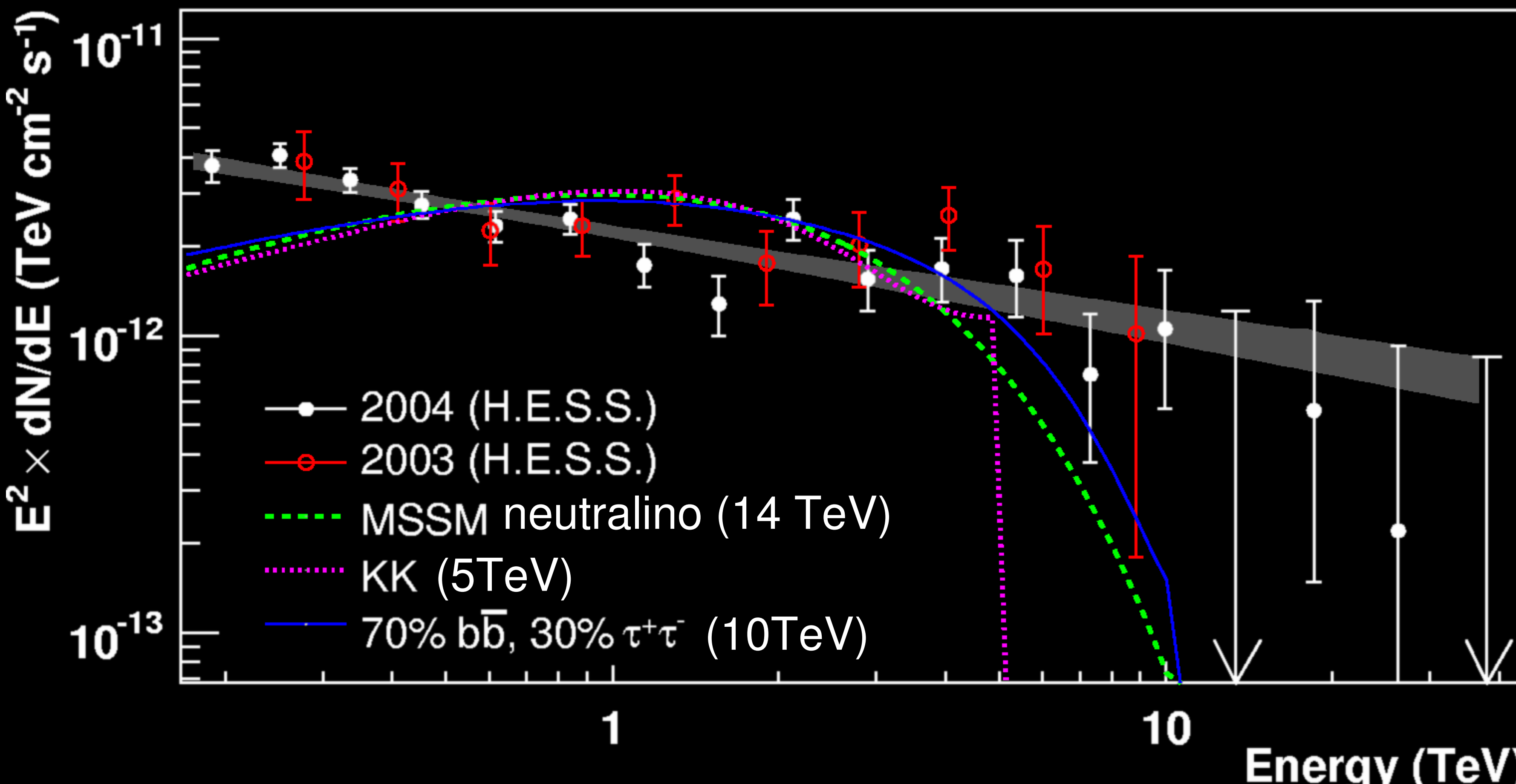


- radial source profile fits NFW DM at first glance, but...
  ... point-like after subtraction of diffuse emission
- DM density stronger peaked than $r^{-1.2}$ (99% CL)

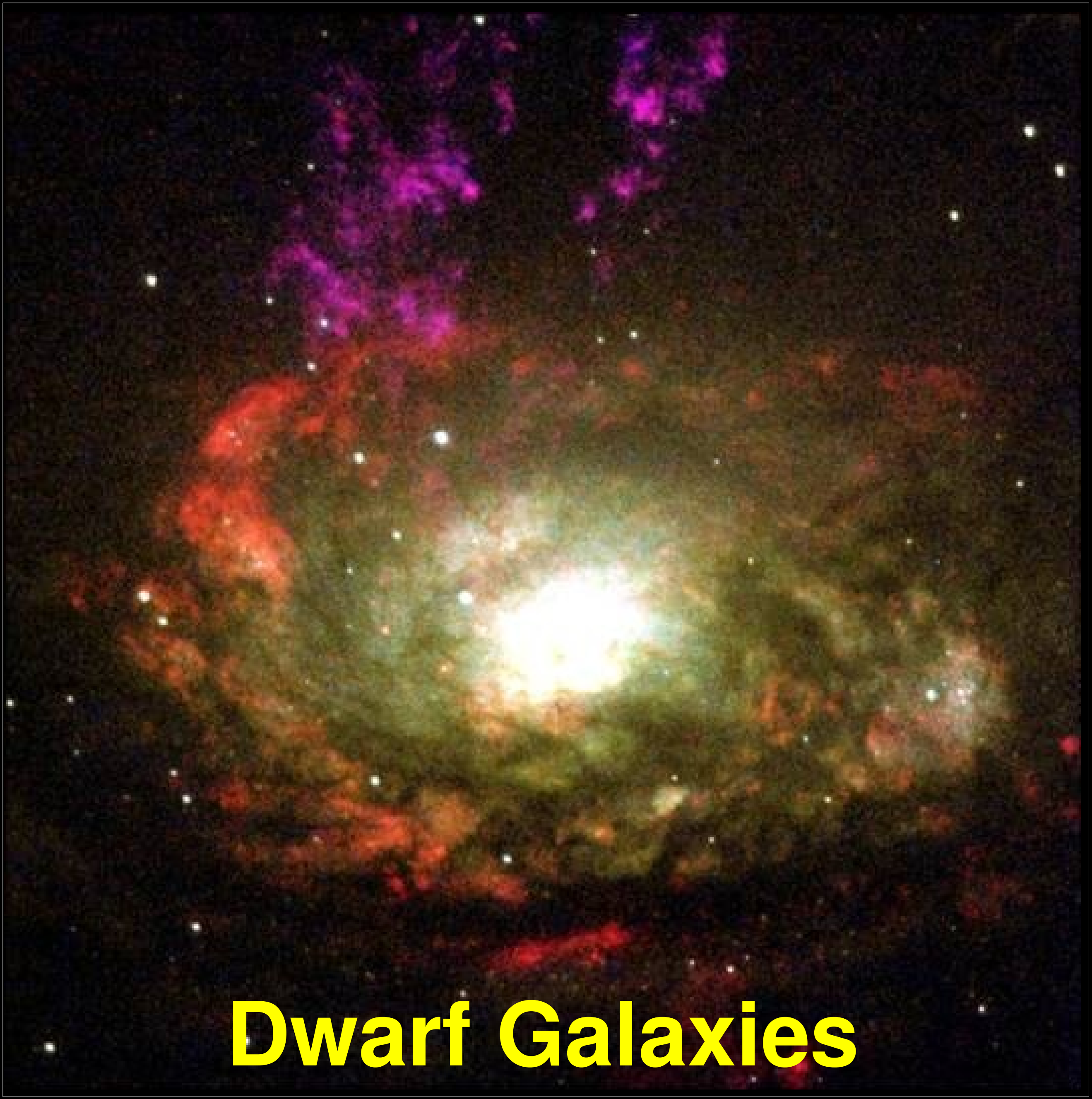
HESS J1745-290

... not much room for Dark Matter

- energy spectrum: straight powerlaw
  exponential cutoff: $E_C > 9$ TeV @ 95% CL
- curved annihilation spectra
  + "uncomfortably large" masses in MSSM
- 10% DM contribution not ruled out
  $\rightarrow$ derived limits on $<\sigma v>$ do not constrain models



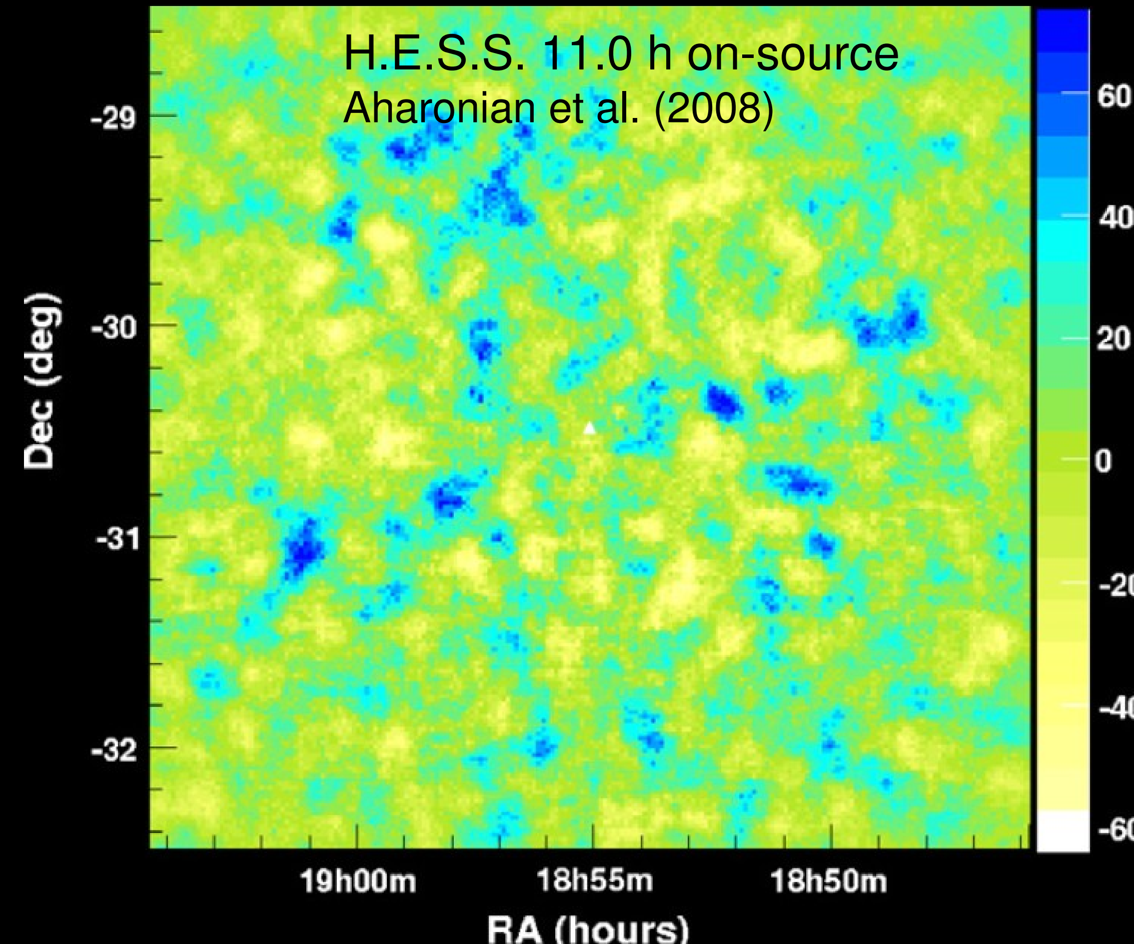
Aharonian et al. 2006

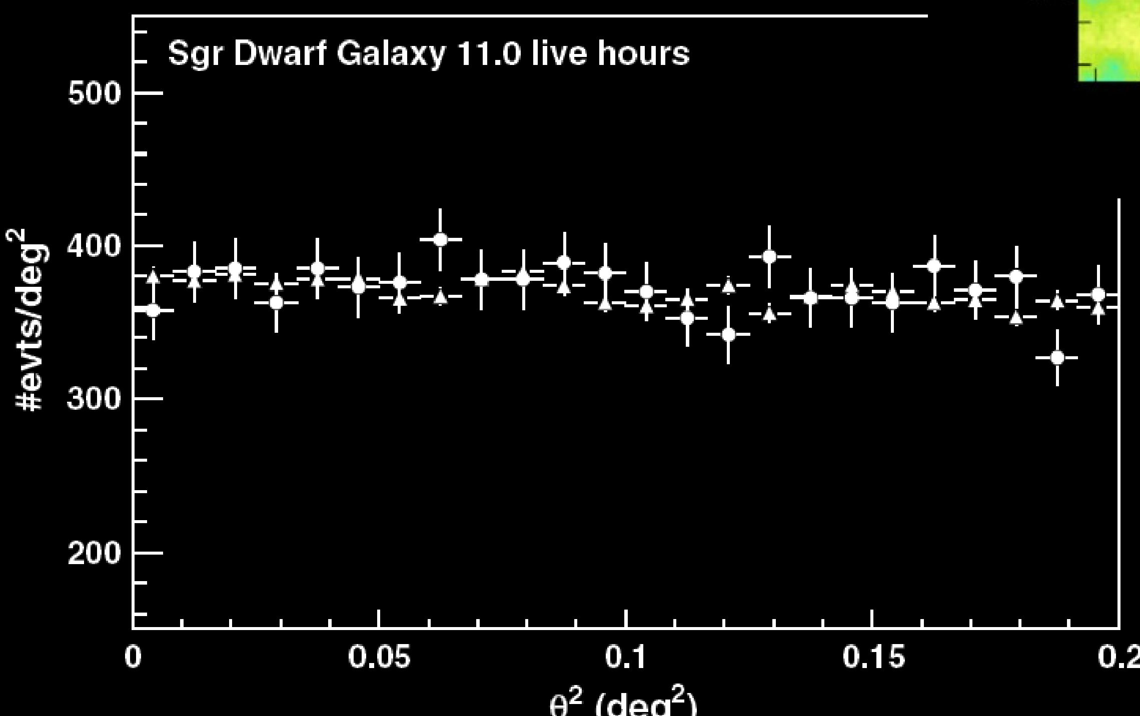


- High mass/luminosity ratio
- Most extreme DM dominated environments

Sagittarius Dwarf

- Satellite galaxy in the Local Group
- 24 kpc distance, so close-by
- Several Galactic disk crossings
  → likely disrupted w/o
  large DM content
- Galaxy core is point-like for H.E.S.S.





- No significant signal detected

  → derive flux upper limit (95% CL):

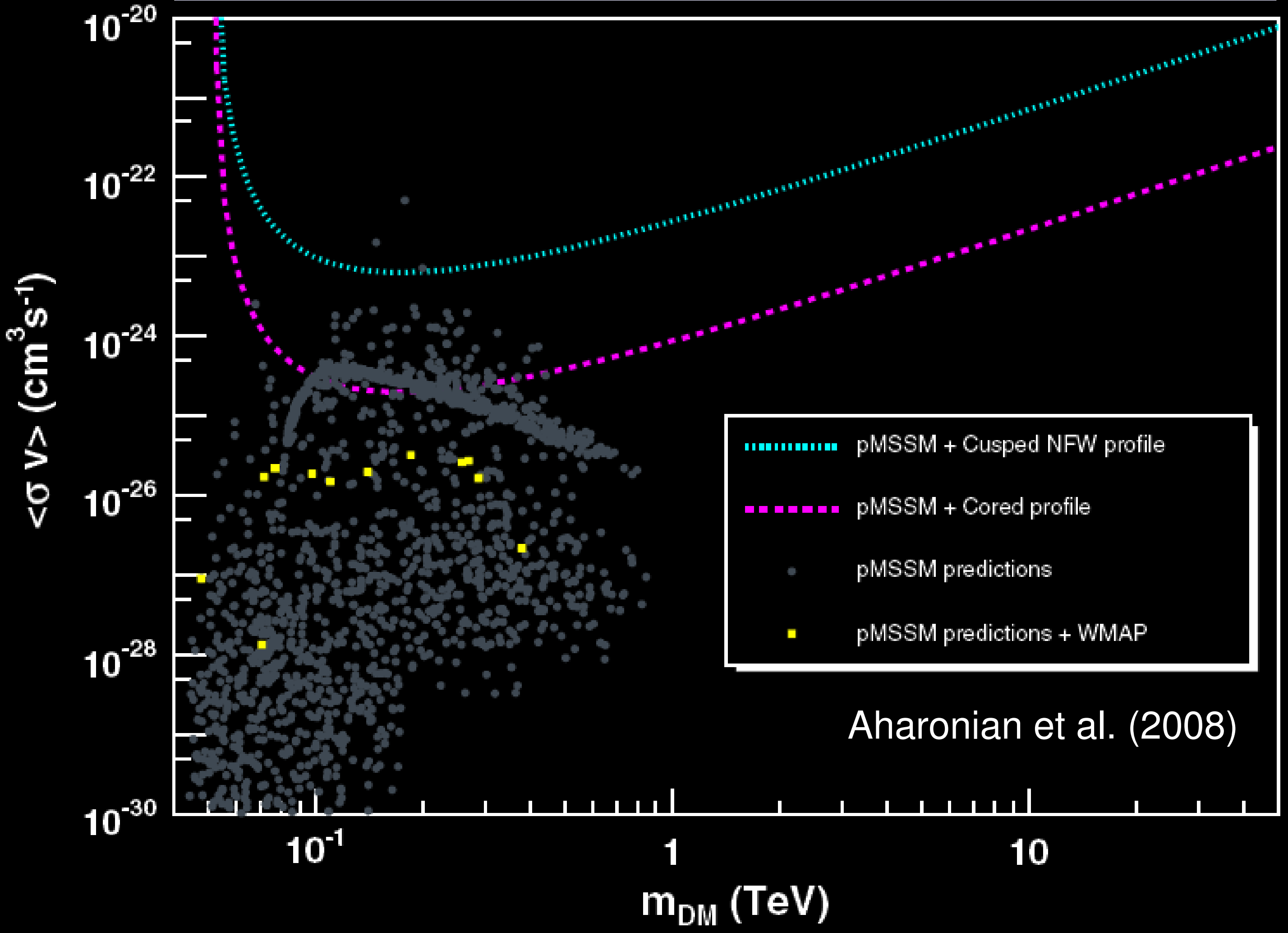
  $F(>250\,\mathrm{GeV}) < 3.6\times10^{-12}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$

  or less than 56 γ-rays...

Sagittarius Dwarf

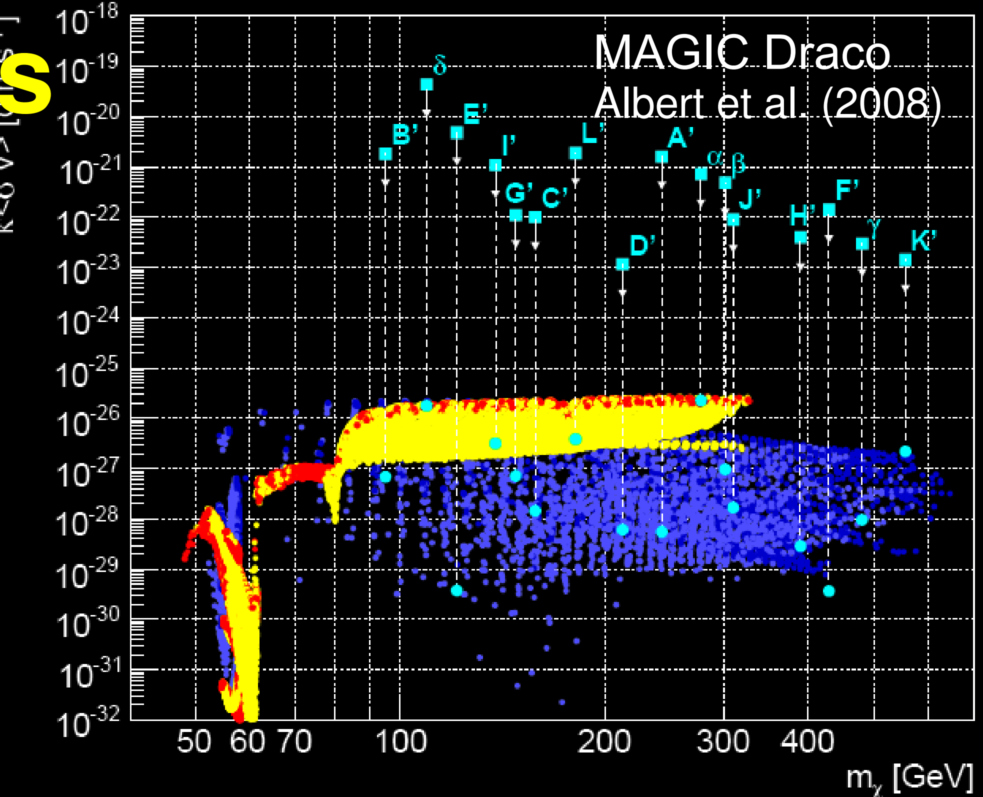
- Used both NFW and "cored" profile adjusted to object parameters
- Calculate pMSSM annihilation cross section limits
- Can constrain some models depending on core profile
- WMAP compliant models still viable

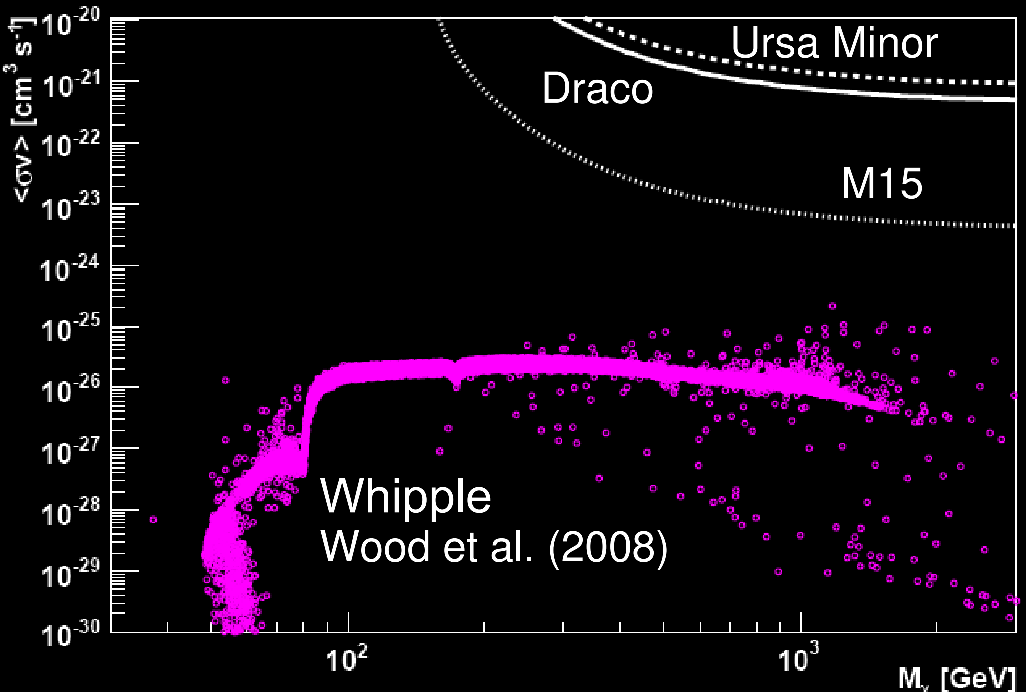
$$\langle \sigma v \rangle^{95CL} = \frac{4\pi}{T} \frac{m_{DM}^2}{J \Delta\Omega} \frac{N_\gamma^{95CL}}{\int_0^{m_{DM}} A_{eff}(E_\gamma) \frac{dN}{dE_\gamma} dE_\gamma}$$

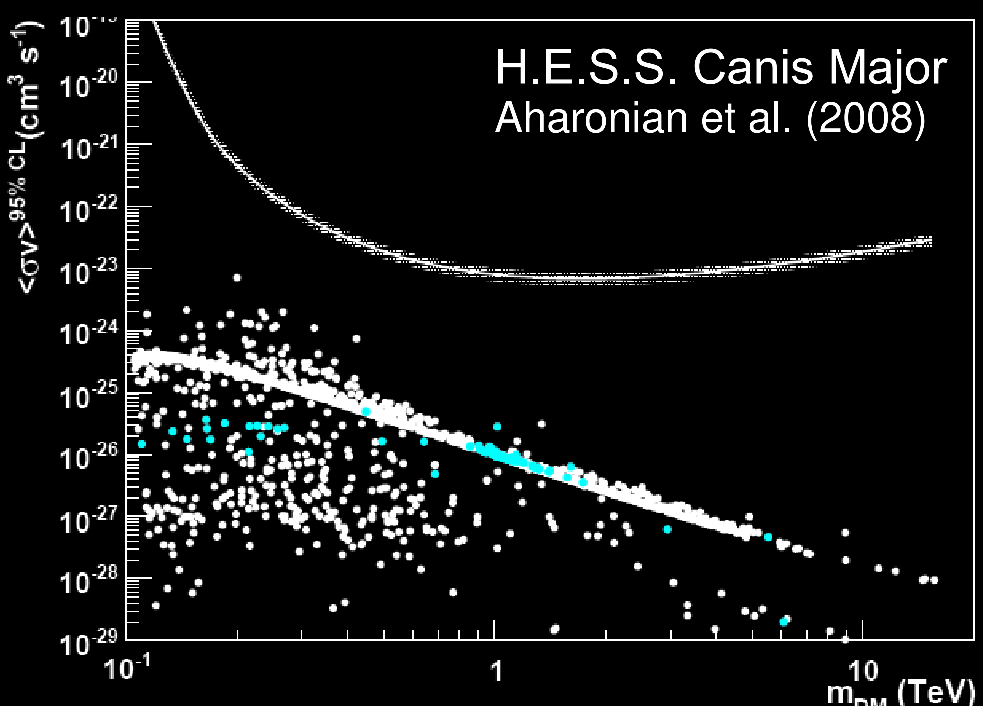


Other Dwarf Galaxies

- ULs hardly constrain models
- Large uncertainty from astrophysical parameters





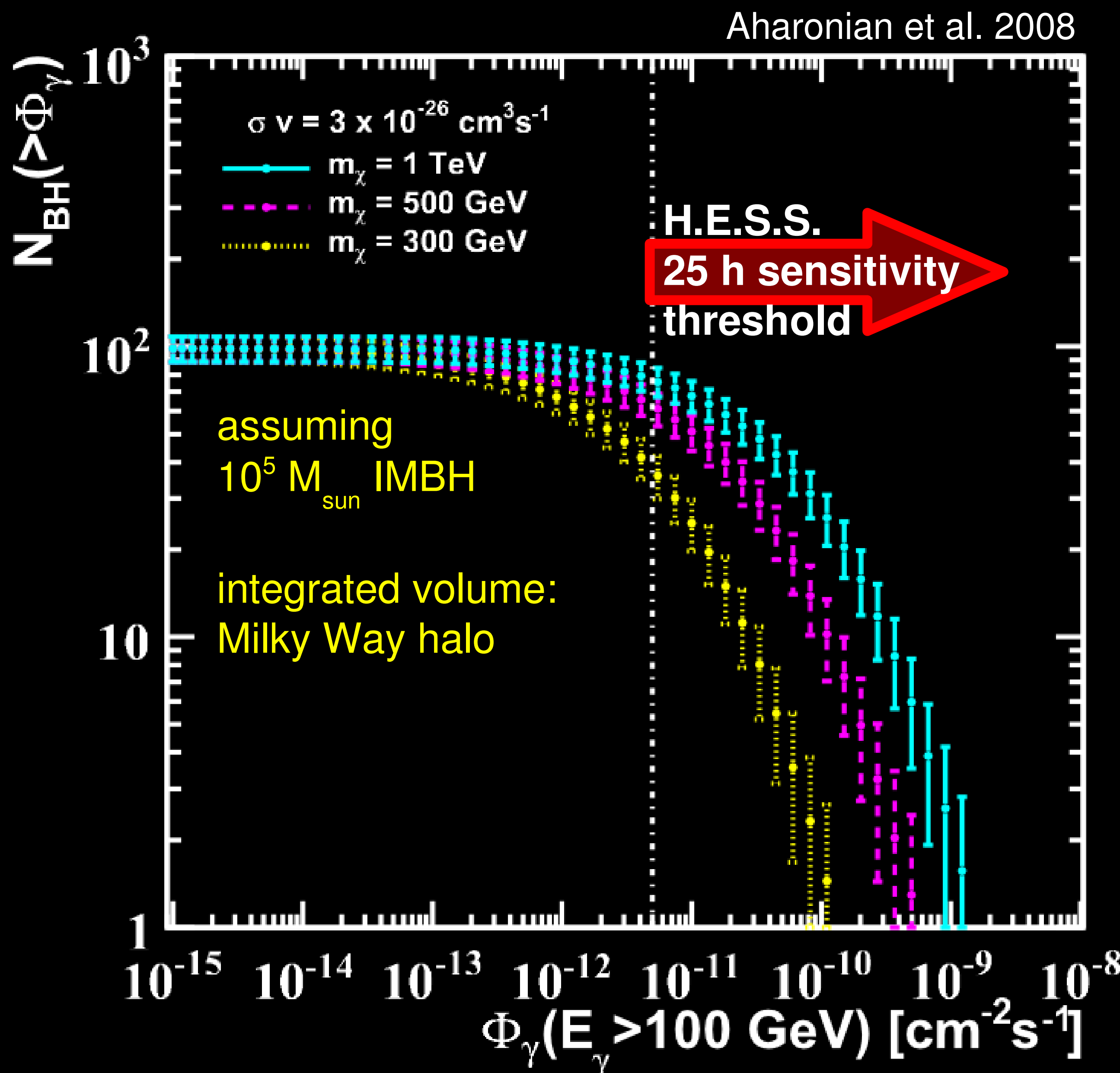


Dark Matter from IMBHs

- black holes of intermediate mass ($100\ M_{sun} < M_{BH} < 10^6\ M_{sun}$)
- may power ultra-luminous X-ray sources
- formation procedure highly debated
  but leads to formation of DM overdensities

- search in H.E.S.S. scan data for point-like sources

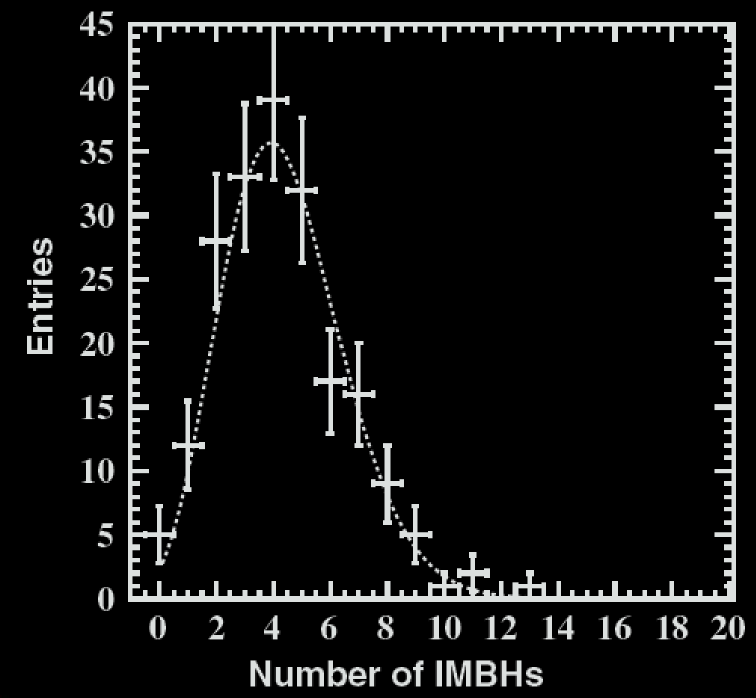
Dark Matter from IMBHs

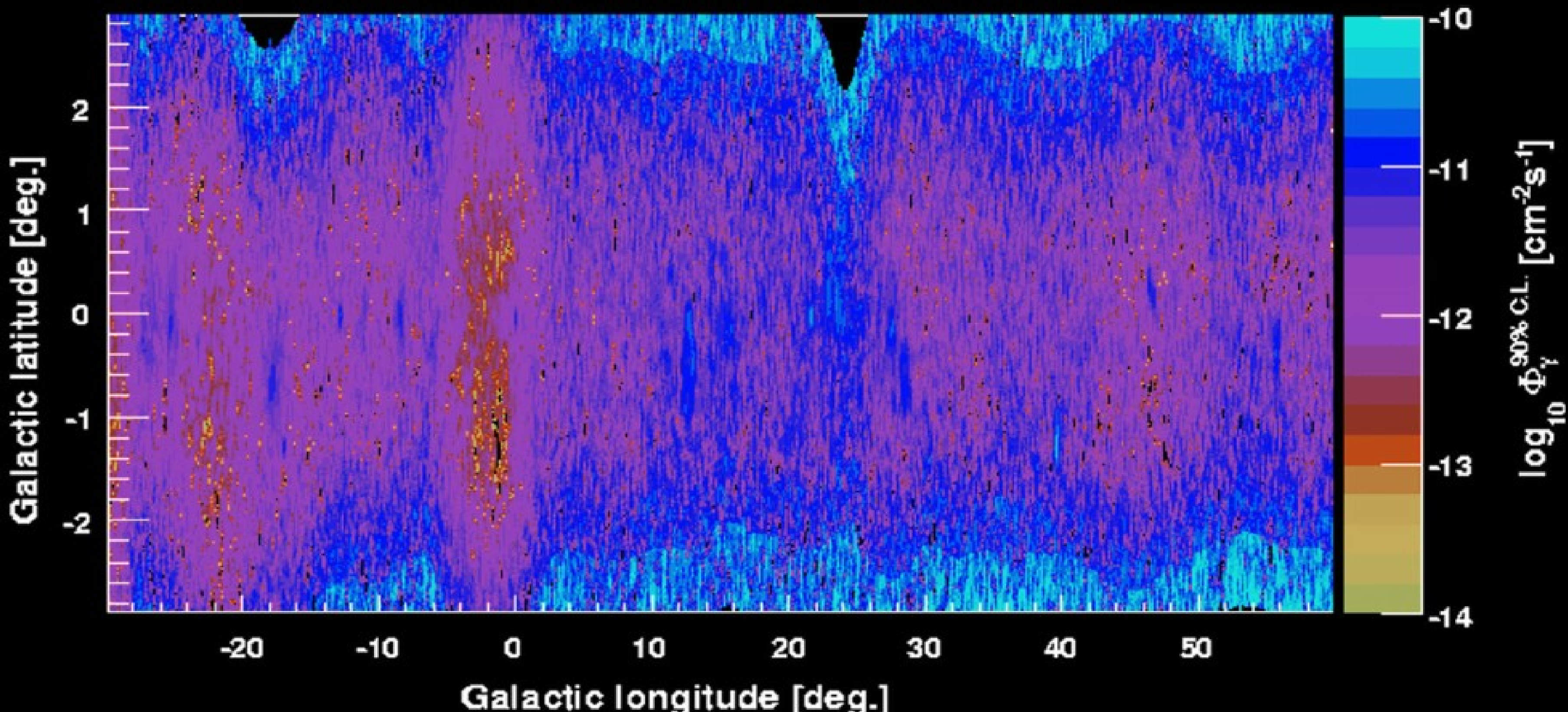


- Can calculate analytically DM profile of the "mini spike"
- expect to see DM from 50-100 IMBHs
  - for full halo coverage
  - for uniform exposure of 25 hours in each sky bin
- inner scan region
  -30° < l < 60°
  -3° < b < 3°
- expect to see 4.3 IMBHs for 400 hours of H.E.S.S. exposure
- 3 point-like sources detected
  - all compatible with being astrophysical sources
- obtain 90% limit on <σv>

Dark Matter from IMBHs

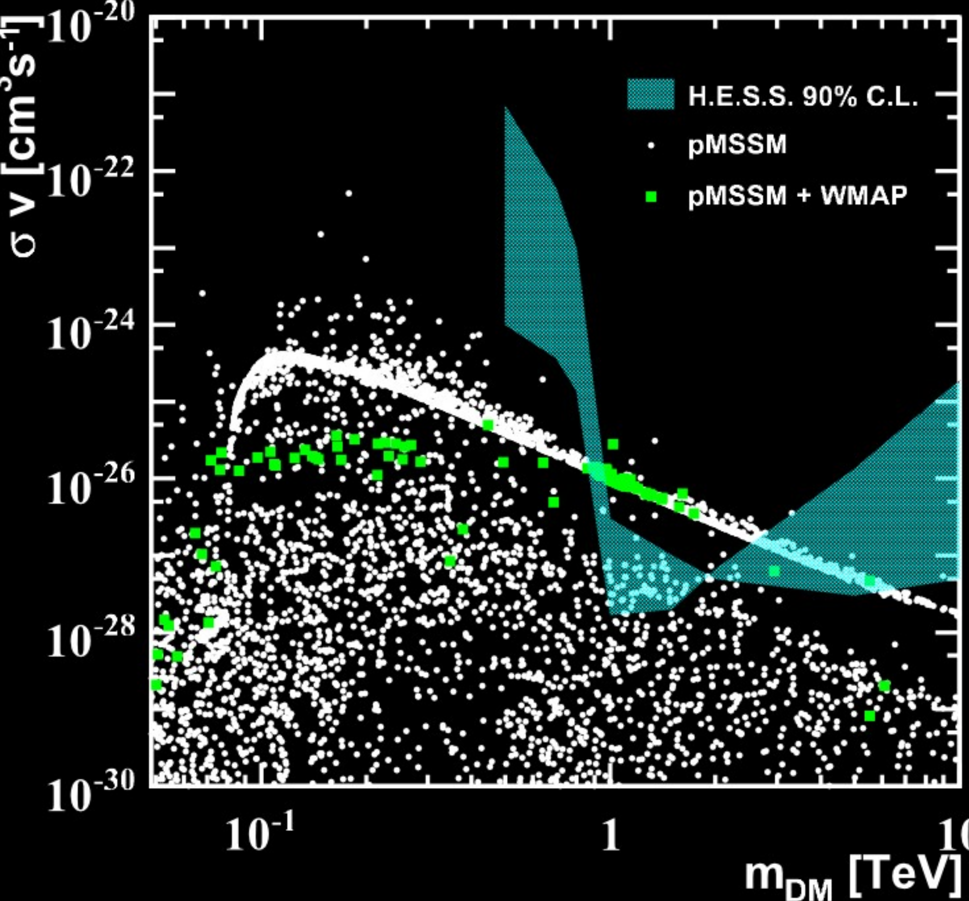
- Determine true H.E.S.S. sensitivity map of inner scan region
- Use 200 Monte-Carlo representations of Milky-Way halos
- Search for detections
  → expect to see 4.3 ± 2.3 mini spikes



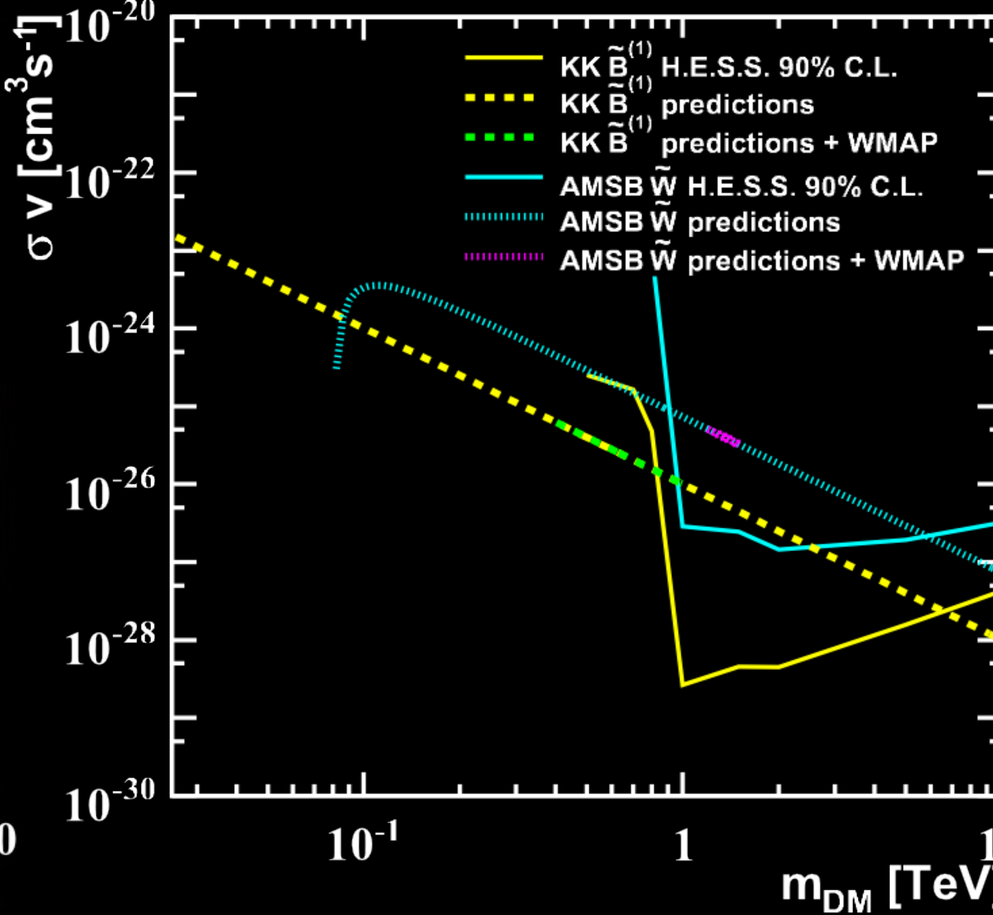


Dark Matter from IMBHs

pMSSM neutralino model

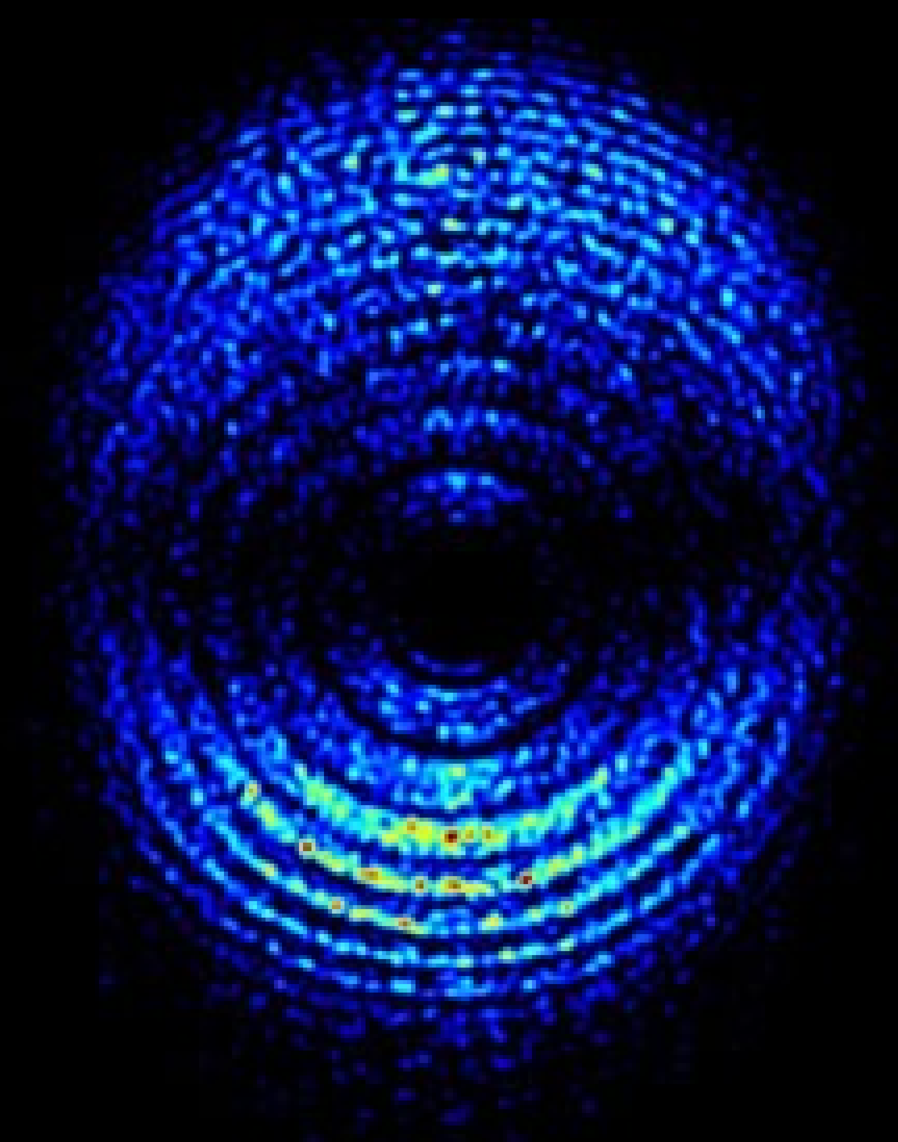


Kaluza-Klein model
AMSB model



Aharonian et al. 2008

- There is some potential to exclude single models
- But large uncertainties from IMBH formation models



Electrons and Positrons

Diffuse Electron (+positron) Spectrum

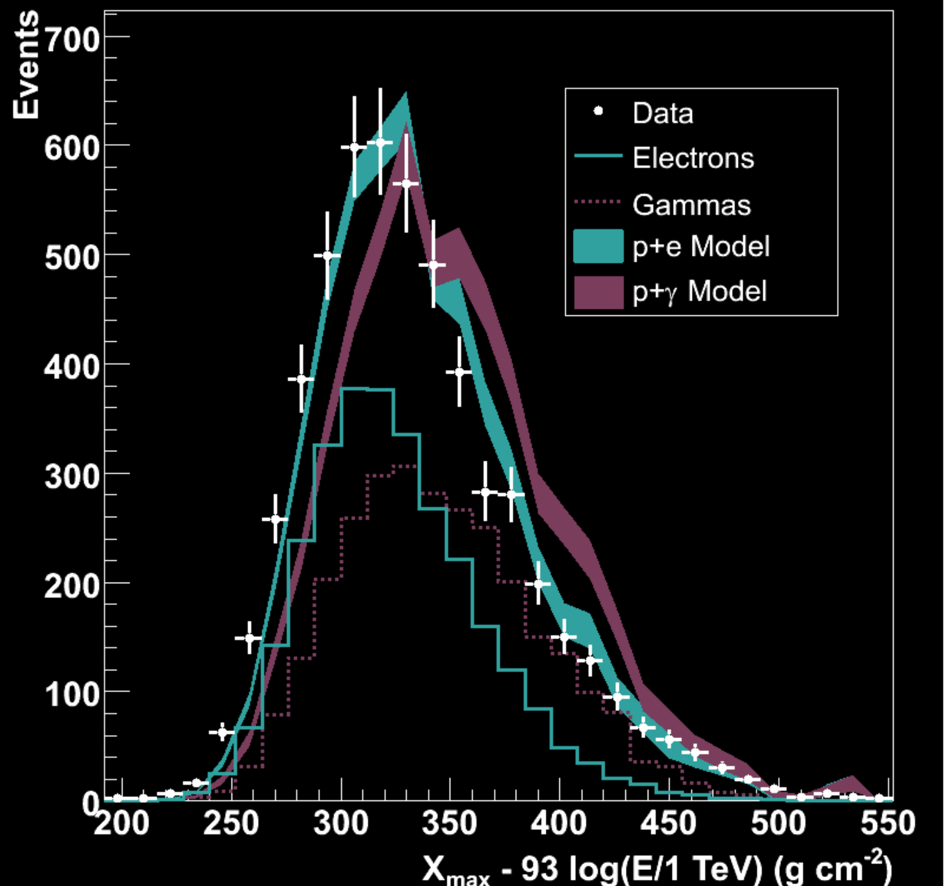
- Electrons: only small fraction of cosmic rays
- Suffer severely from synchrotron and inverse compton losses
  $\rightarrow$ TeV electrons must come from local sources
  $\rightarrow$ steep spectrum ~$E^{-3.3}$

- Balloon/satellite data available at < 1 TeV

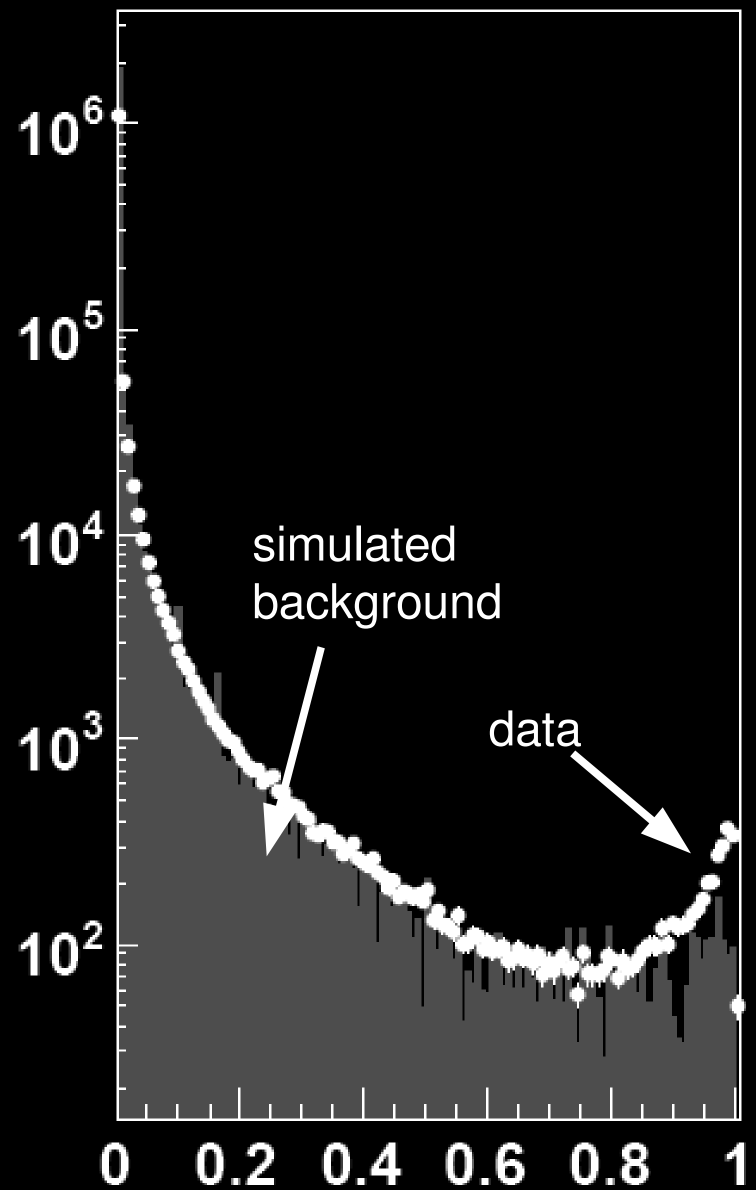
- Electron showers similar to gamma showers
- H.E.S.S. can measure at even higher energies
  $\rightarrow$ large detection area
  $\rightarrow$ but large backgrounds

- Gamma background
  $\rightarrow$ observe extragalactic fields
  $\rightarrow$ if any, at most 50% gamma contamination

- Cosmic Ray background
  $\rightarrow$ special rejection technique



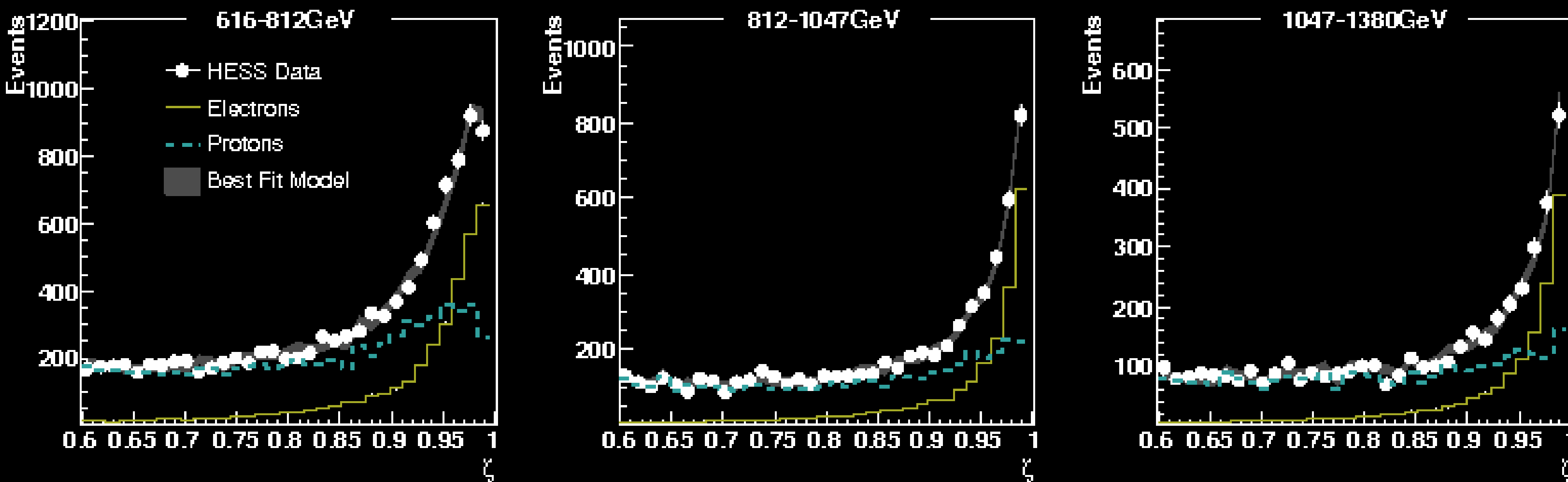
Diffuse Electron (+positron) Spectrum



- Electrons are isotropic
  $\rightarrow$ no geometric background subtraction
- Random Forest:
  train machine learning algorithm on shower image parameters
  $\rightarrow$ needs electron/hadron simulations
- For each shower, RF determines "electron likeness" parameter ζ ε [0;1]
- For $\zeta>0.9$, total background suppression is 10^{-6}
- Remaining background
  $\rightarrow$ Fit ζ-distribution with combination of electron/proton simulations
  $\rightarrow$ result depends on hadronic interaction model (Sybill/QGSJet)

Diffuse Electron (+positron) Spectrum

- One fit per energy band to derive electron spectrum



- Two analyses recently published:
  - high energies: 600 GeV – 5 TeV (hard cuts for best reconstruction)
  - low energies: 340 GeV – 700 GeV (looser cuts on intensity, 2004/2005 data only)

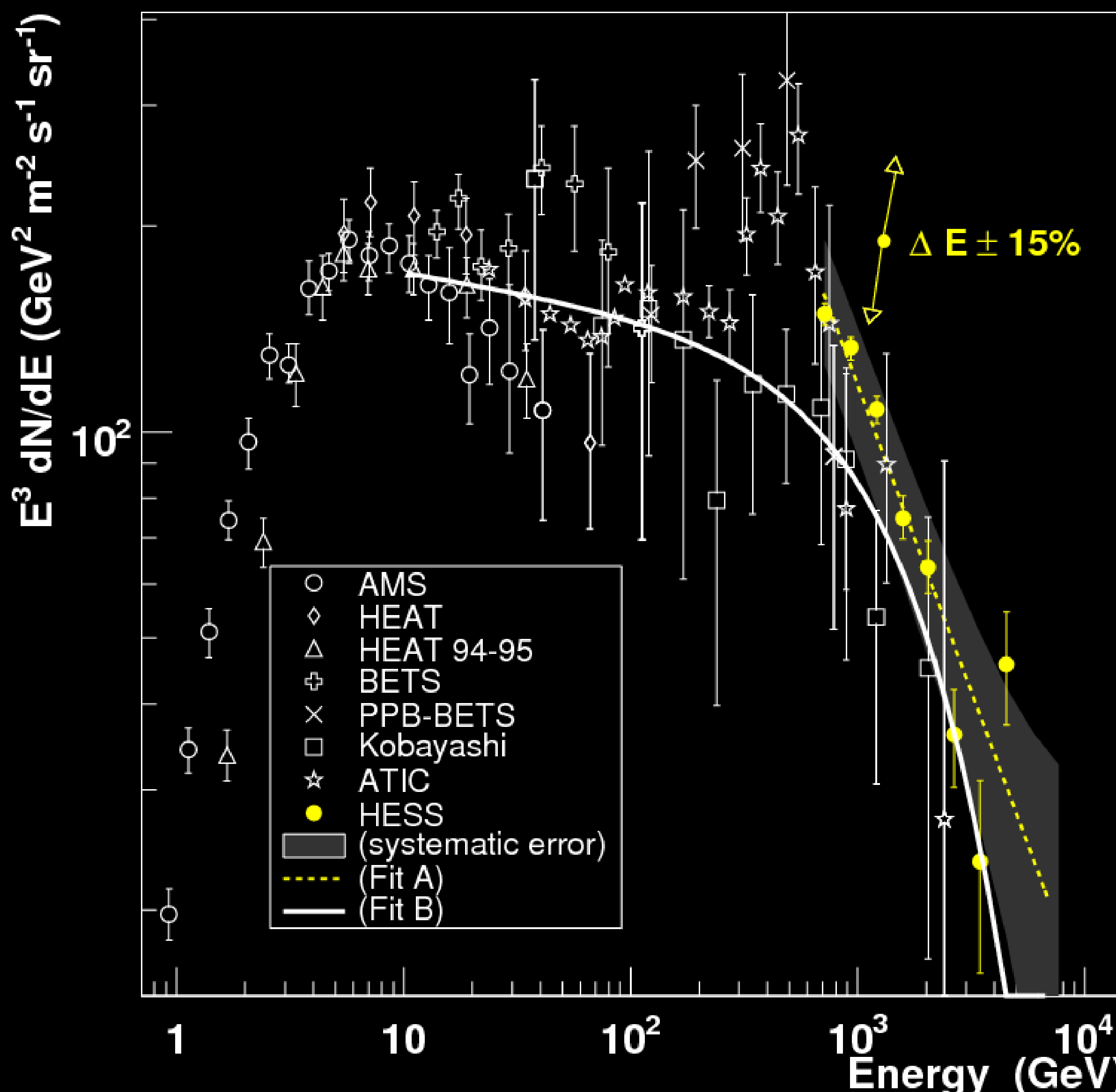
Diffuse Electron (+positron) Spectrum

- Spectral index 3.9±0.1±0.3
  → steepening compared
  to GeV energies

- After energy scale uncertainty compatible with previous measurements:
  Γ = 3.1 with cut-off at 2.1 TeV

- Existence of TeV electrons implies local electron source
  → PWN? DM?

Aharonian et al. 2008



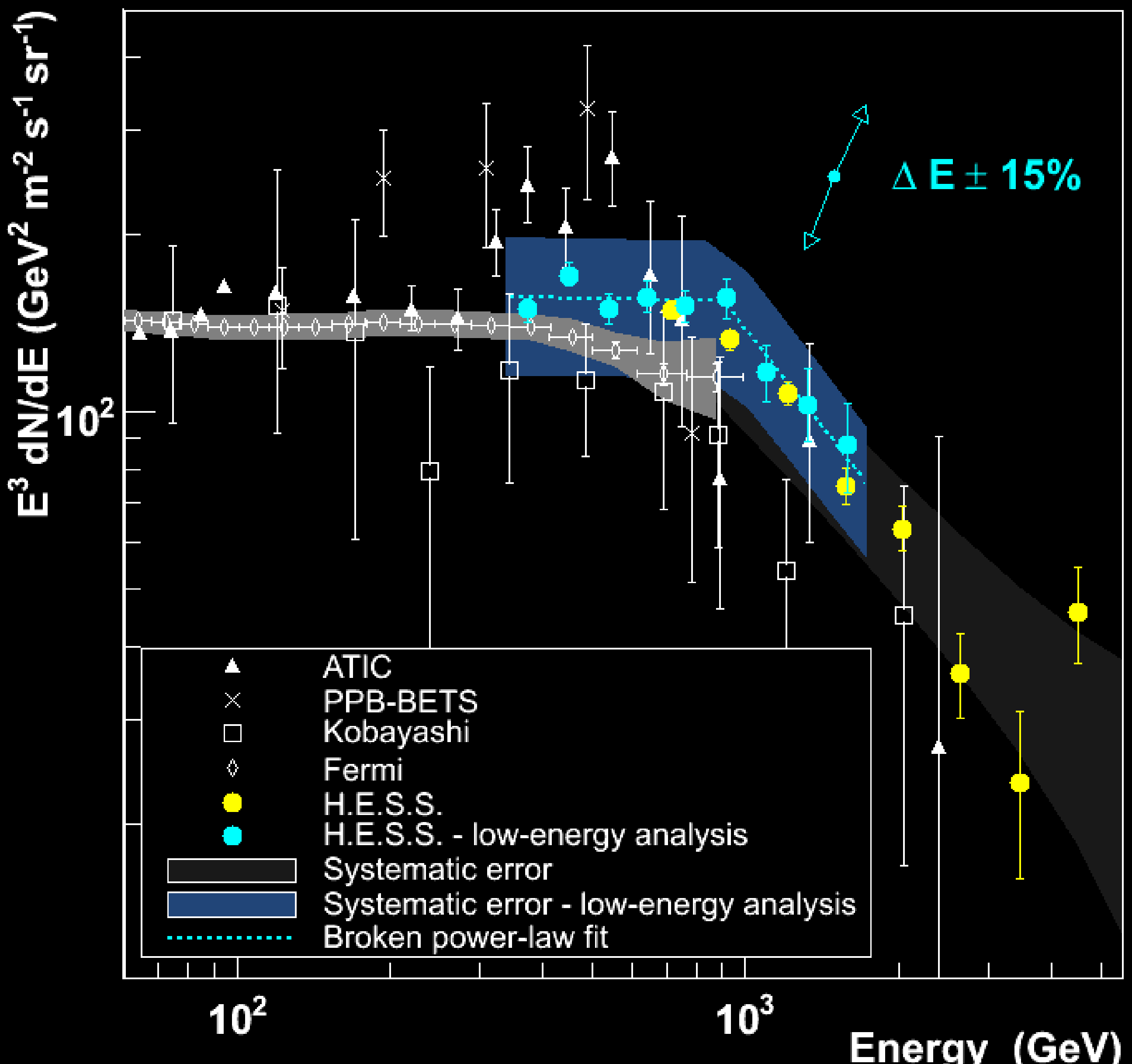
Diffuse Electron (+positron) Spectrum

- Break in spectrum:
  $\Gamma_1 = 3.0 \pm 0.1 \pm 0.3$
  $\Gamma_2 = 4.1 \pm 0.3 \pm 0.3$
  $E_B = 0.9 \pm 0.1$ TeV

- No indication of feature similar to ATIC

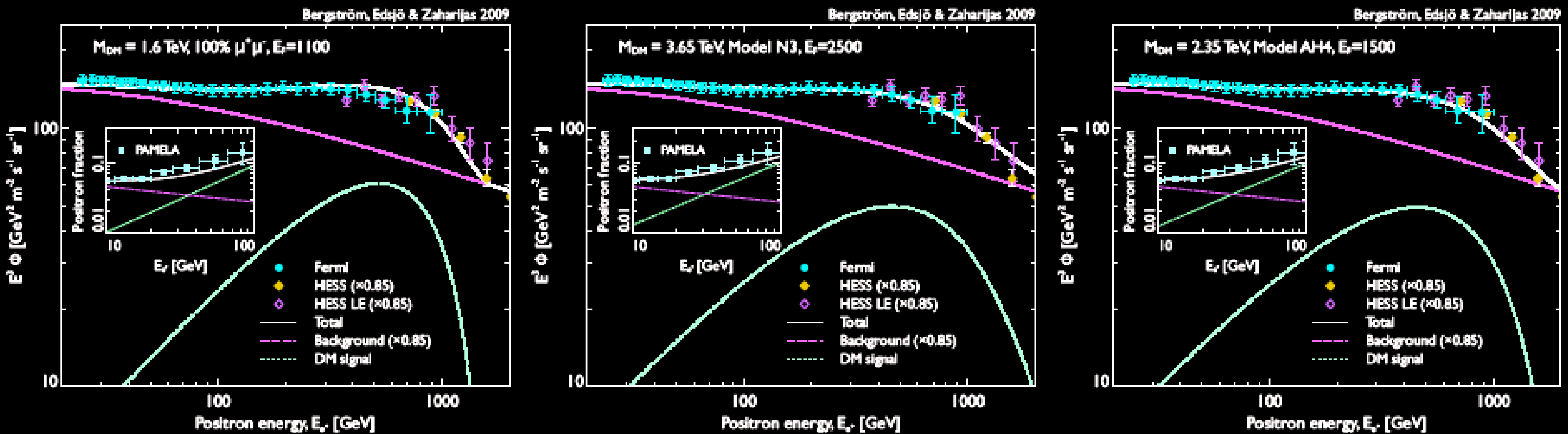
- Compatible to FERMI within energy shift uncertainty

Aharonian et al. 2009



HESS, Fermi, PAMELA Bergström, Edsjö, Zaharijas (2009)

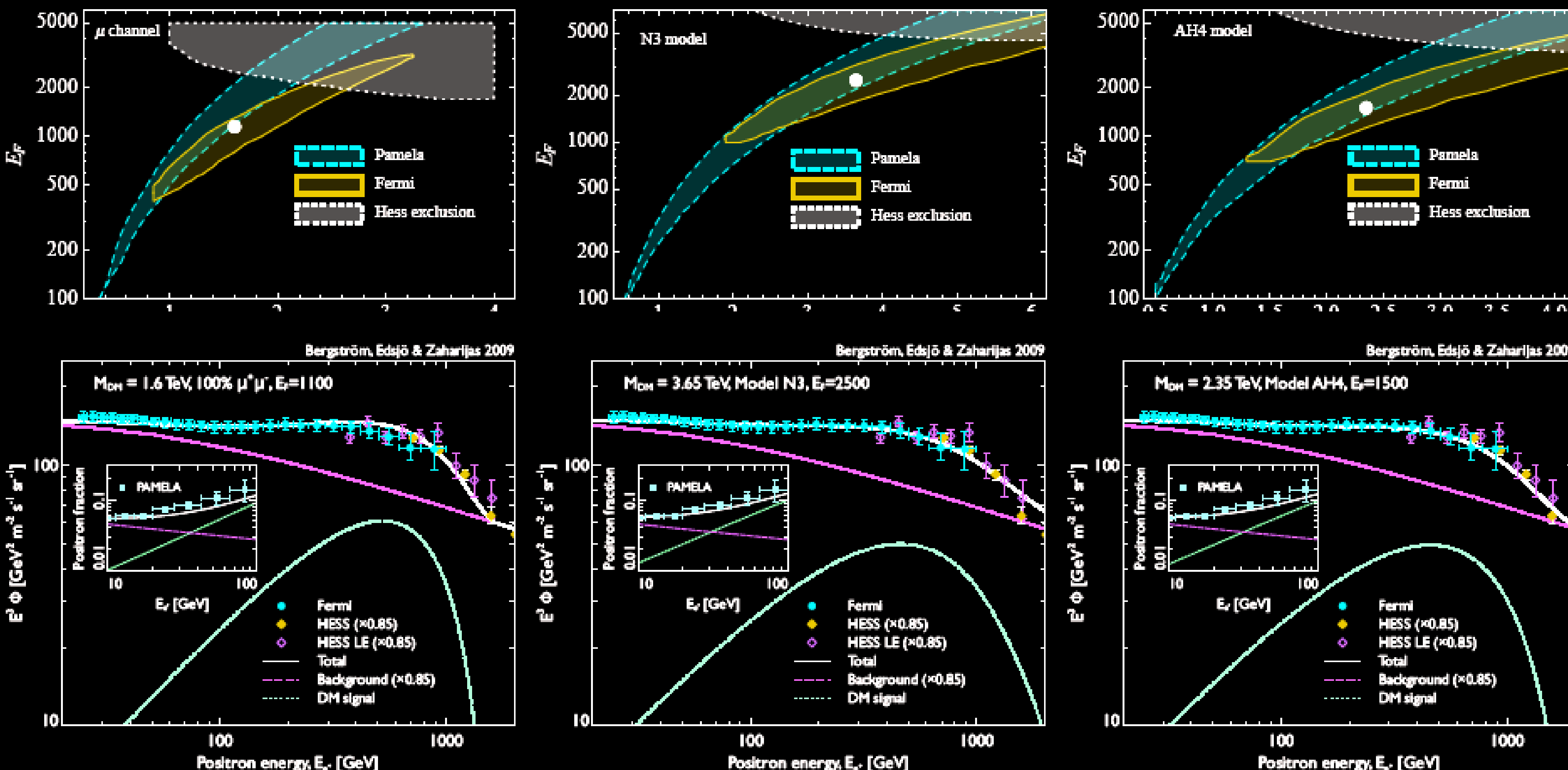
- Attempt to fit electron results with DM annihilation spectra
- Relic DM density: 0.3 GeV/cm^3
- Assume $\langle\sigma v\rangle = 3 \cdot 10^{-26}$ cm^3/s
- Isothermal Galactic halo profile
- Standard electron diffusion
- GALPROP to simulate astrophysical electron background
- Use H.E.S.S. data as upper limits



- DM DM $\rightarrow e^+e^-$ gives too hard/peaked electron spectrum
- DM DM $\rightarrow \tau^+\tau^-$ gives too soft electron spectrum

- Either direct decay into muons, or via light scalar (N3, AH4) viable
- Large boost-factors needed to explain large fluxes

HESS, Fermi, PAMELA Bergström, Edsjö, Zaharijas (2009)



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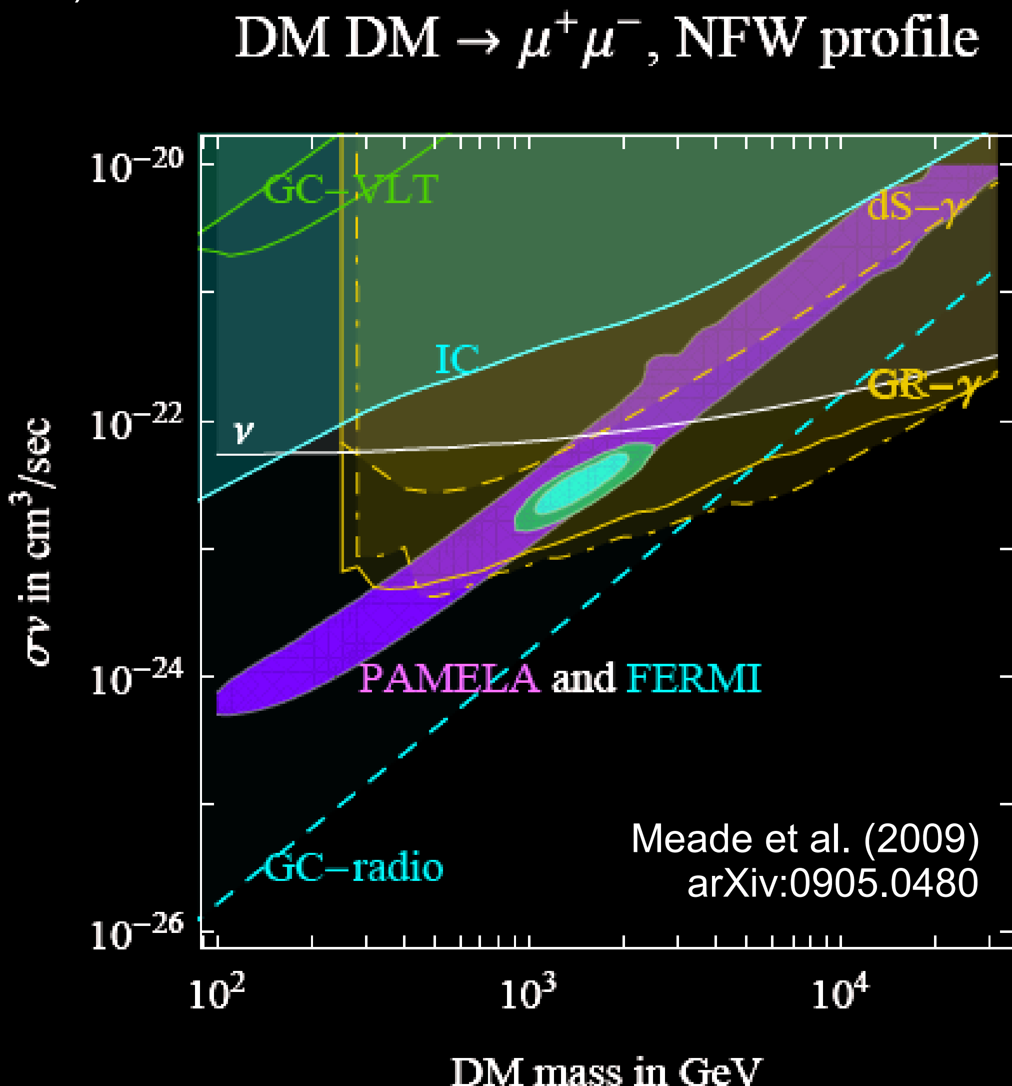
Photon and Neutrino Constraints

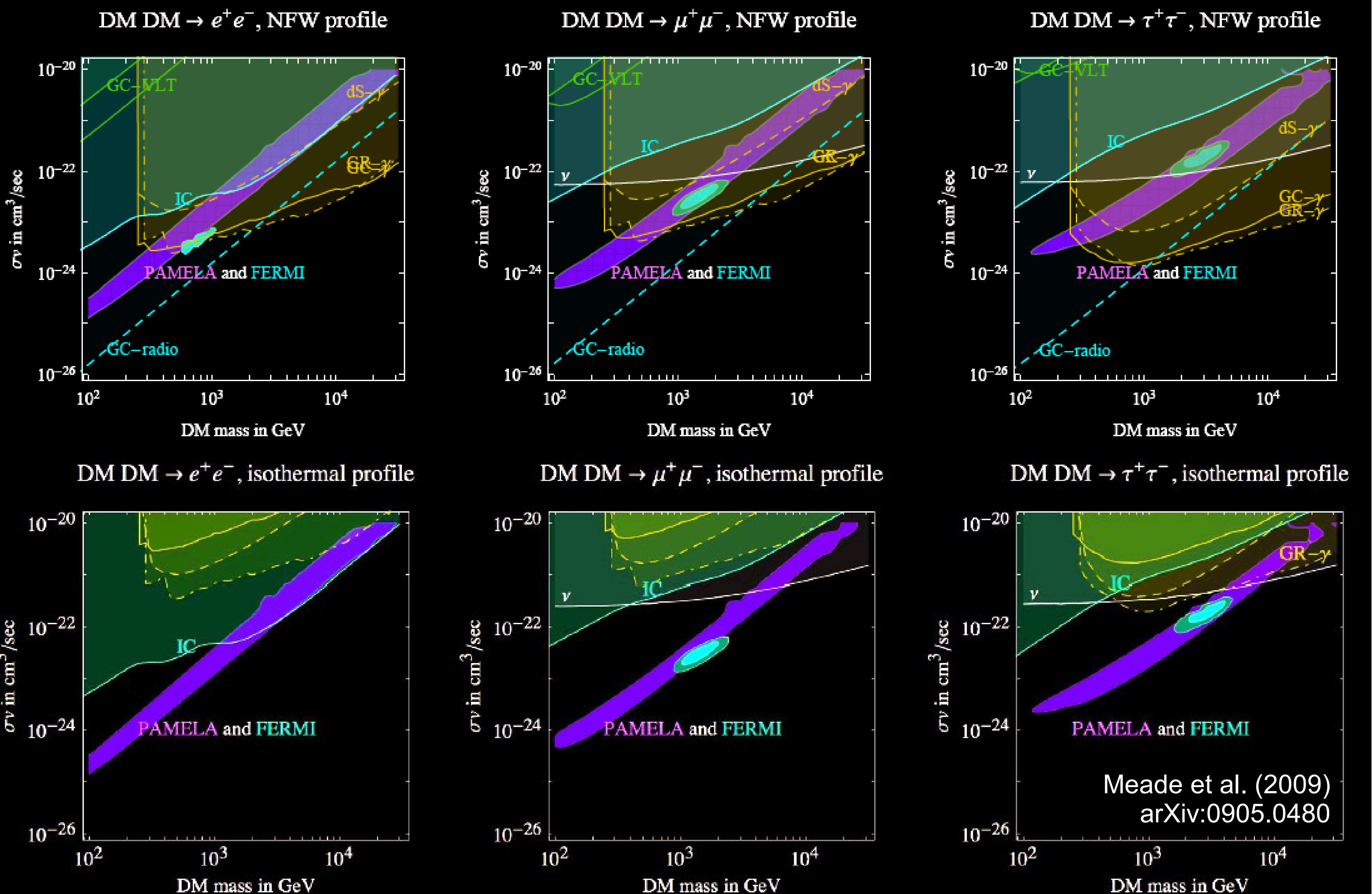
- γ-rays test constrain DM scenarios on sub-kpc scales
  → Galactic Centre
  → Galactic Centre diffuse
  → local clumps of DM (dwarf galaxies, IMBH)
  → sensitive to halo profile

- ...and on Galactic scales
  → IC photons from DM electrons
  → do not overproduce FERMI diffuse Galactic γ-ray flux

- Neutrino bounds from Super-K Galactic Centre observations
  → constraints on μ, τ final states
  → sensitive to halo profile

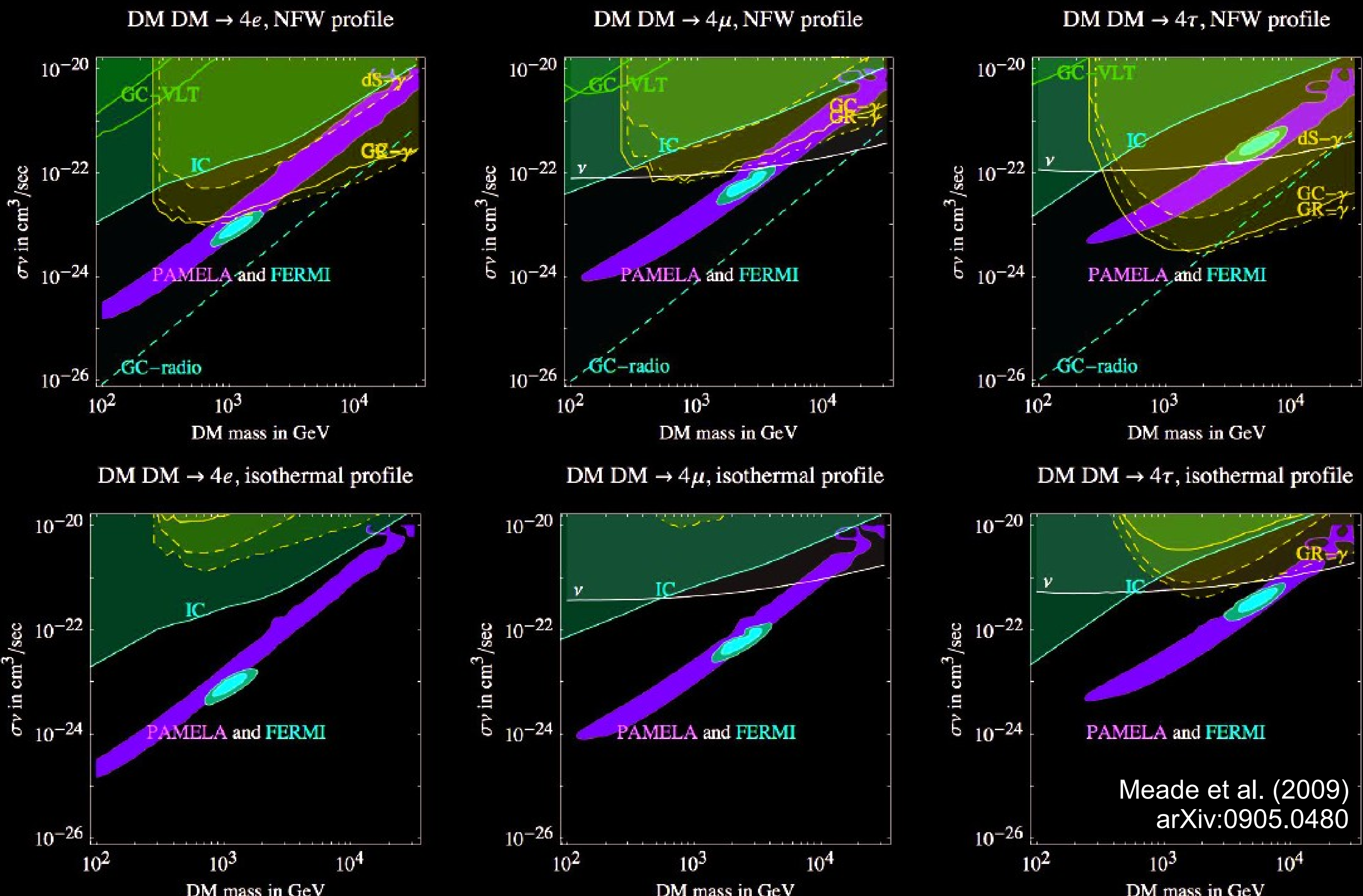


Photon and Neutrino Constraints



Meade et al. (2009)
arXiv:0905.0480

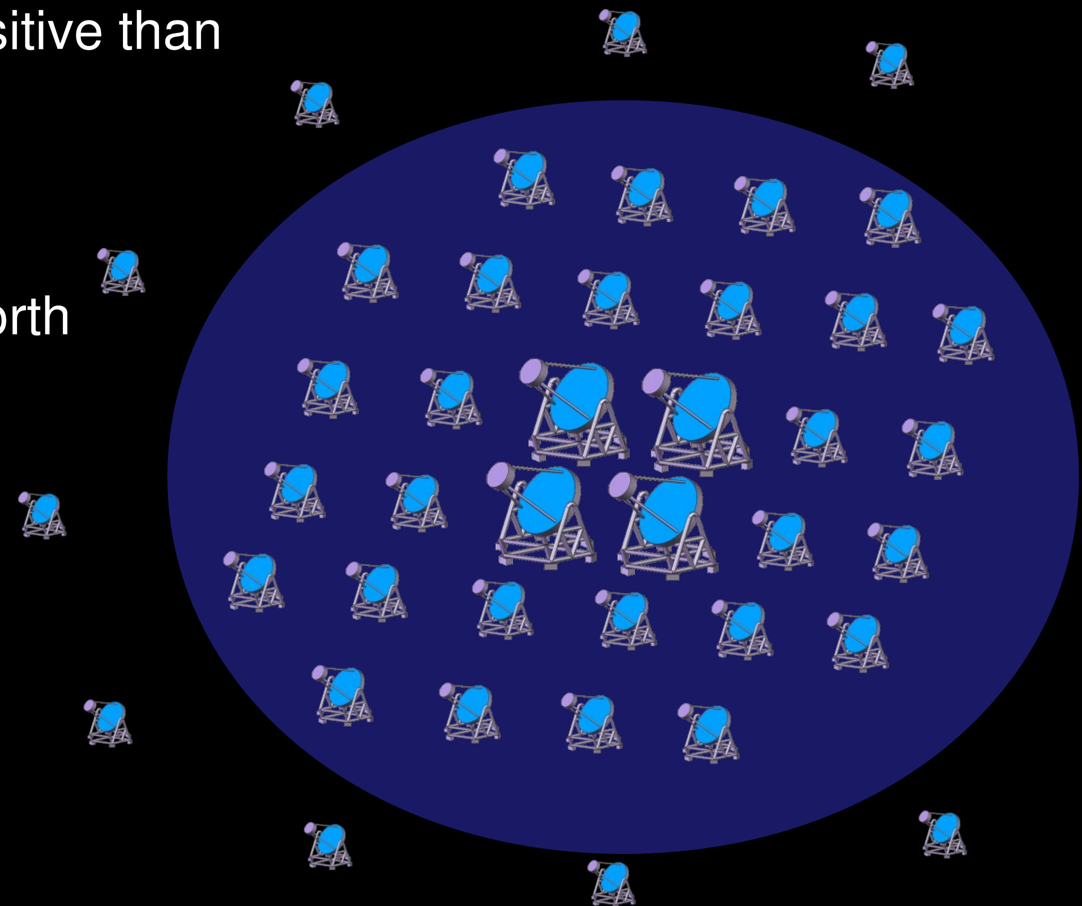
Photon and Neutrino Constraints



Meade et al. (2009)
arXiv:0905.0480

The Future: CTA

- **Concept**
  - an IACT array *observatory*
  - an order of magnitude more sensitive than HESS: 1 mCrab
  - wide energy coverage: O(10) GeV - O(100) TeV
  - possibly sites in the south and north



- **Consortium**
  - largely European
  - HESS + MAGIC + many others
  - 15 countries currently involved
- **Currently in design phase**
  - Prototype construction in 1-2 years
- **High priority in European road maps:**

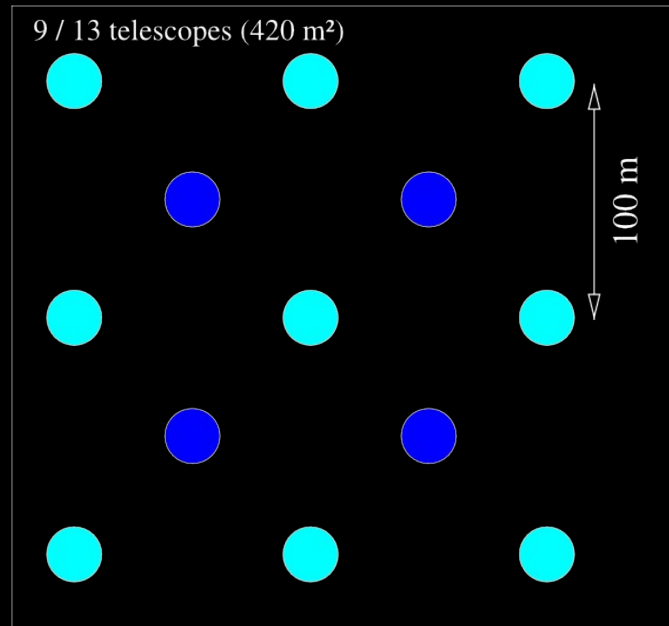
Array Simulations

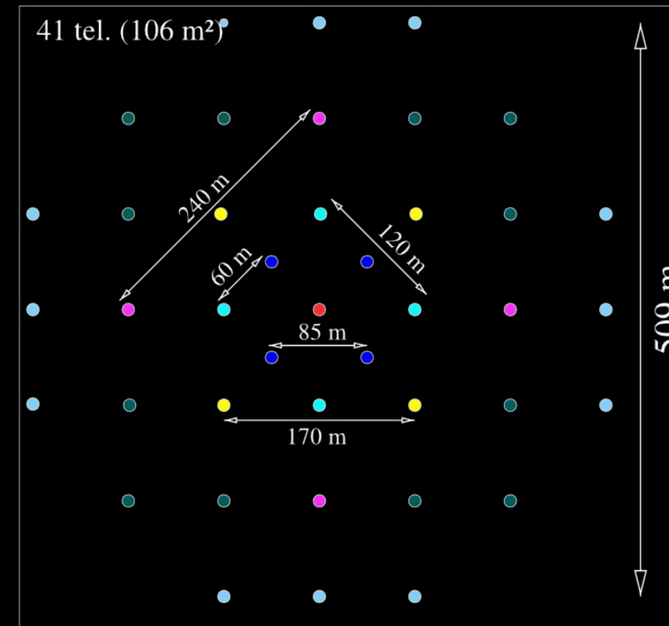
K. Bernlöhr

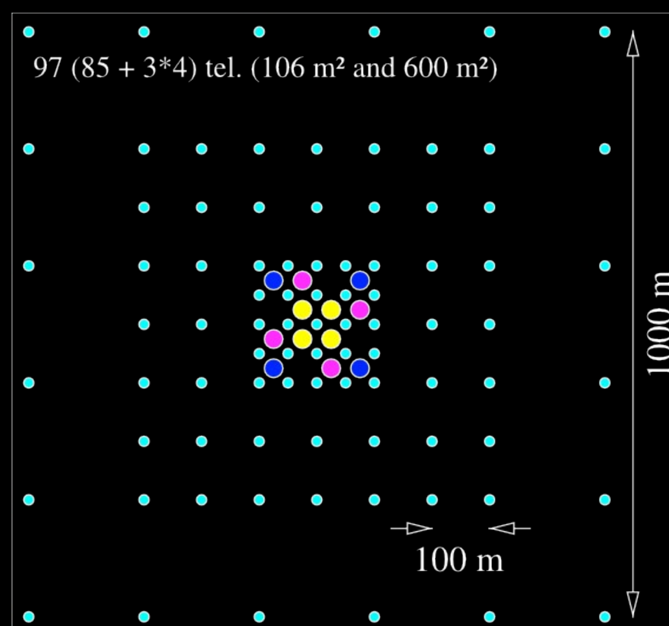
- Up to 97 telescopes
- Individual sub-arrays
- Different altitudes above sea level

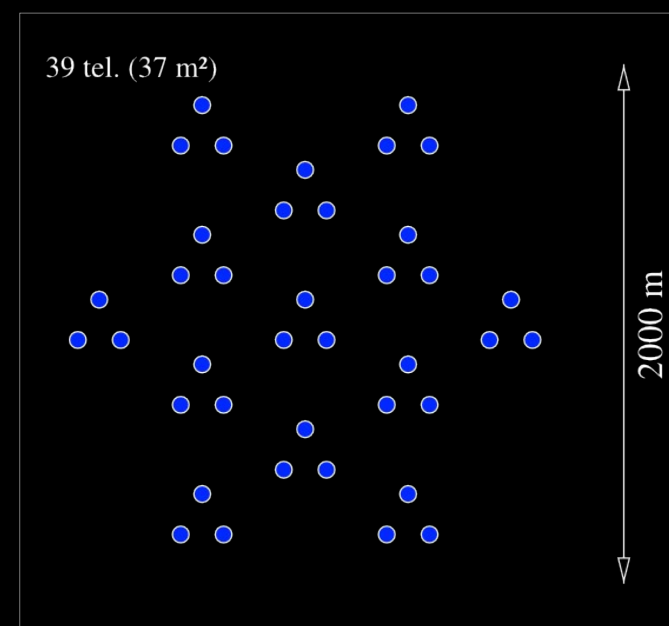
- Different pixel sizes
- Different pixel technology

- Aims:
  - Physics performance
  - Cost optimisation

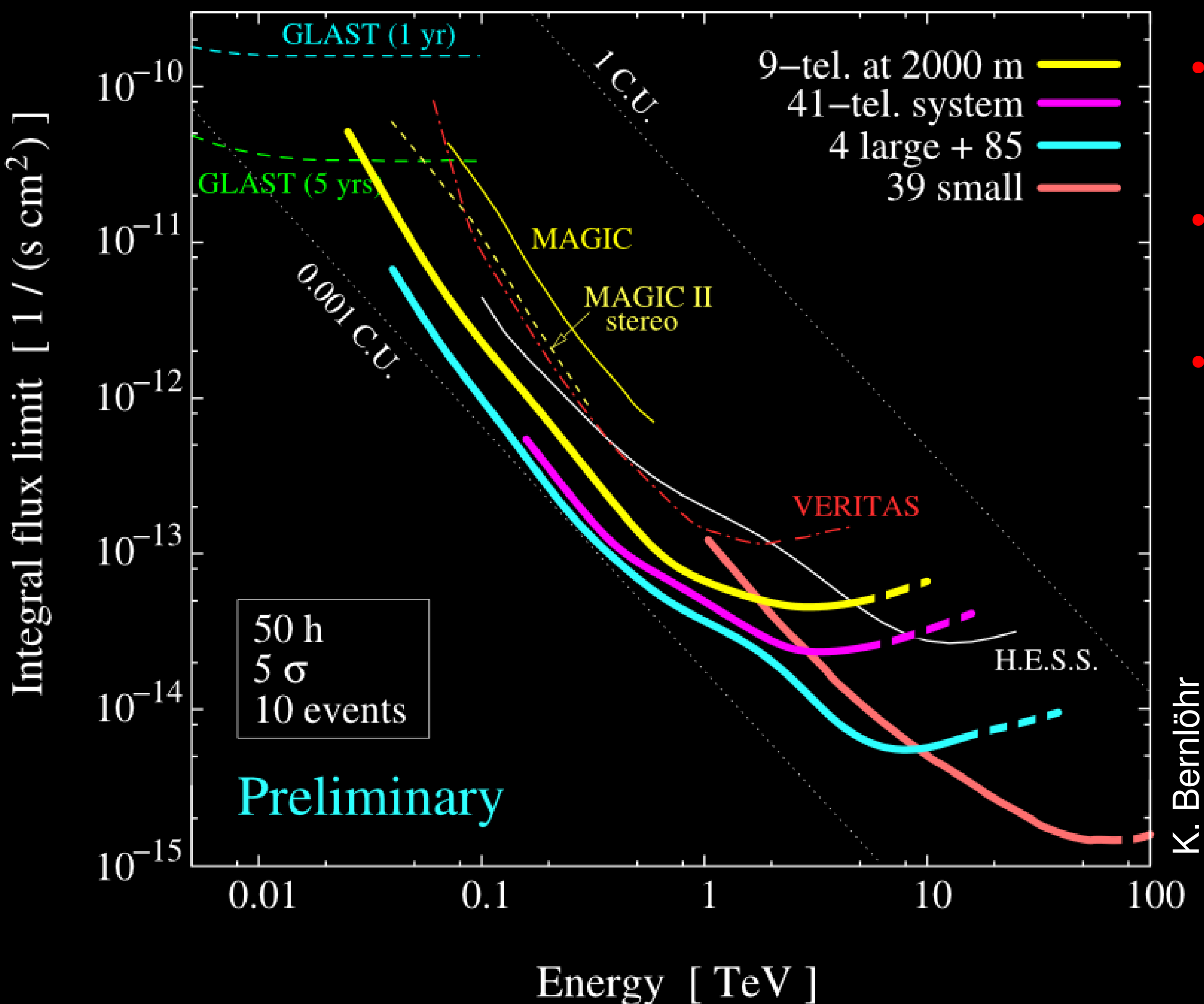






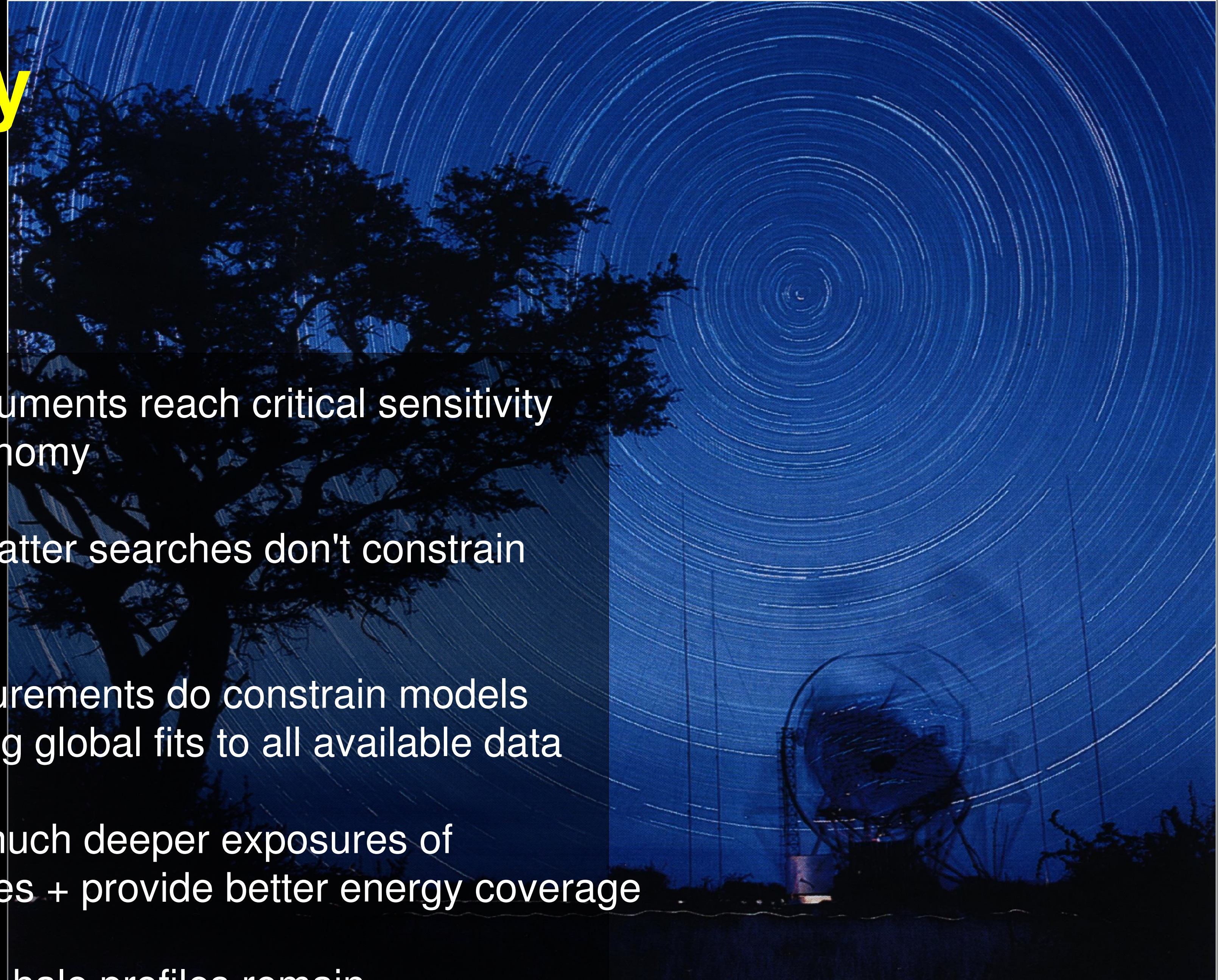


Array Simulations

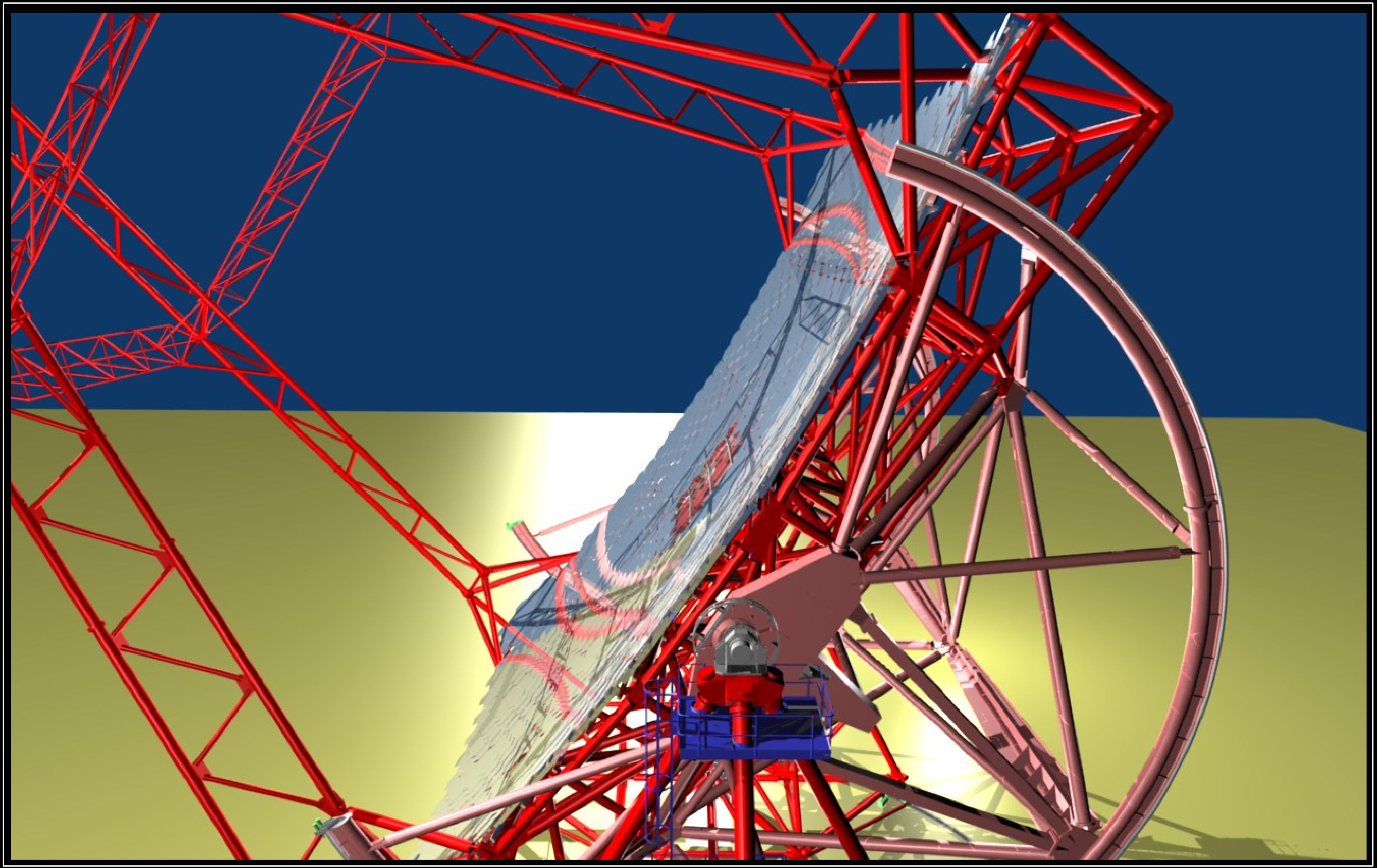


- 4+85: good all-purpose instrument
- 4 big teleskopes → low energies
- 85 small telescopes → highest energies

Summary



- VHE γ-ray instruments reach critical sensitivity to do real astronomy
- Indirect Dark Matter searches don't constrain models yet
- H.E.S.S. Measurements do constrain models when performing global fits to all available data
- CTA will offer much deeper exposures of DM overdensities + provide better energy coverage
- Uncertainties in halo profiles remain a significant problem in this field
- Will LHC detect signature of new physics?



Thank you!