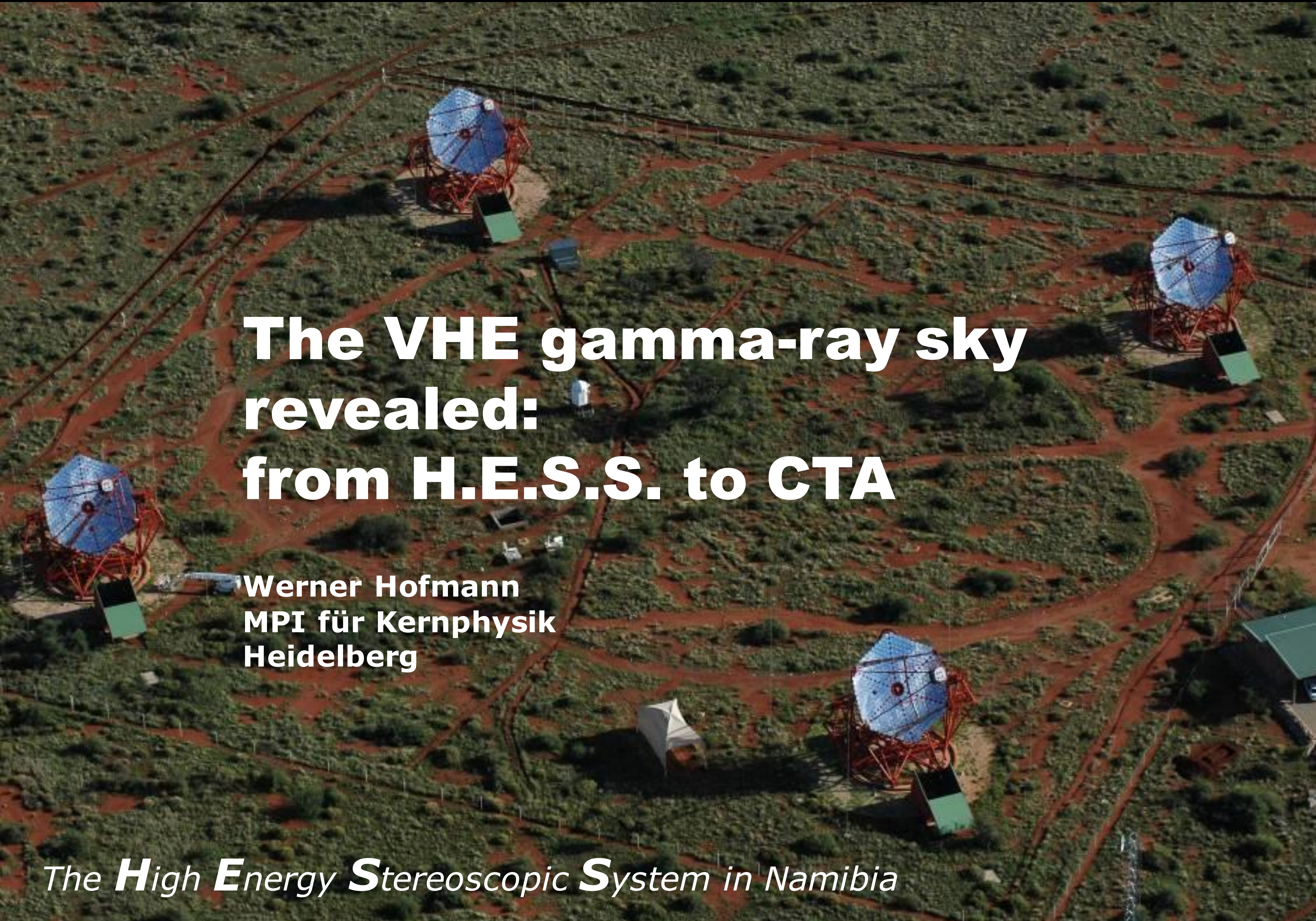
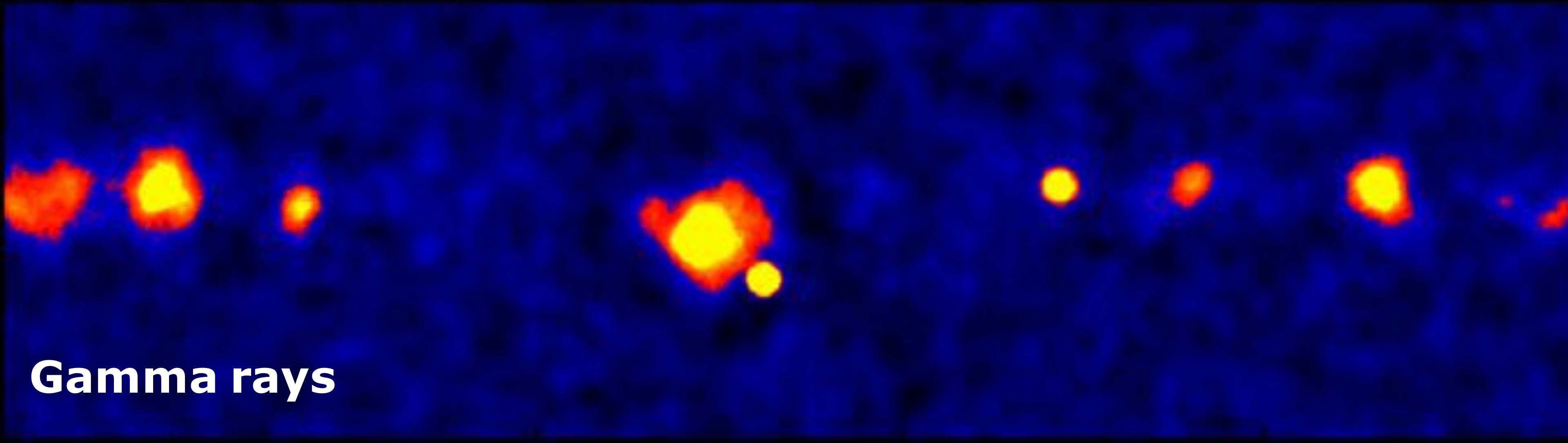


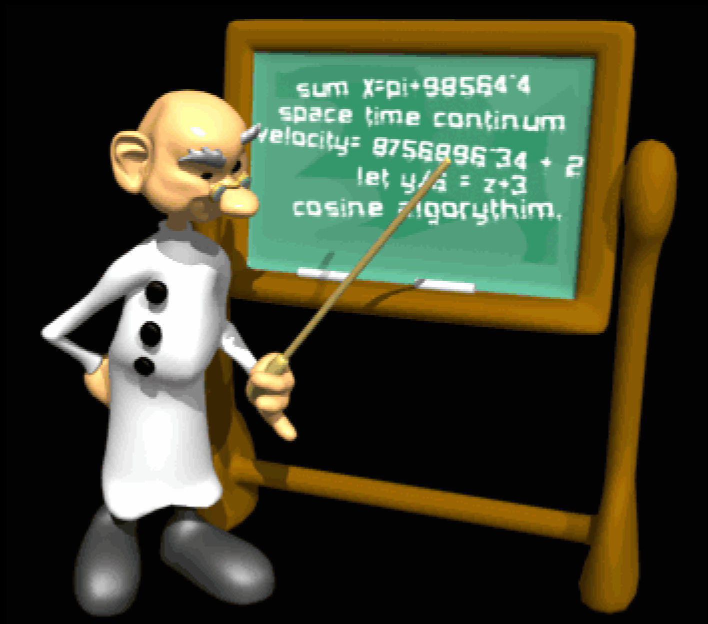
The VHE gamma-ray sky revealed: from H.E.S.S. to CTA

Werner Hofmann
MPI für Kernphysik
Heidelberg

*The **H**igh **E**nergy **S**tereoscopic **S**ystem in Namibia*

The Milky Way



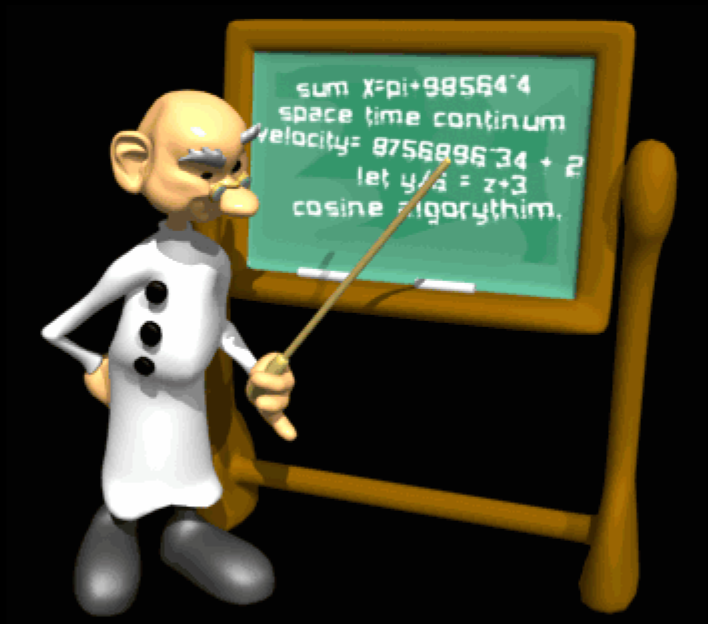


Exploring the nonthermal universe

Detecting VHE gamma rays: The H.E.S.S. telescopes

A tour of galactic particle accelerators

The next big step: CTA



Exploring the nonthermal universe

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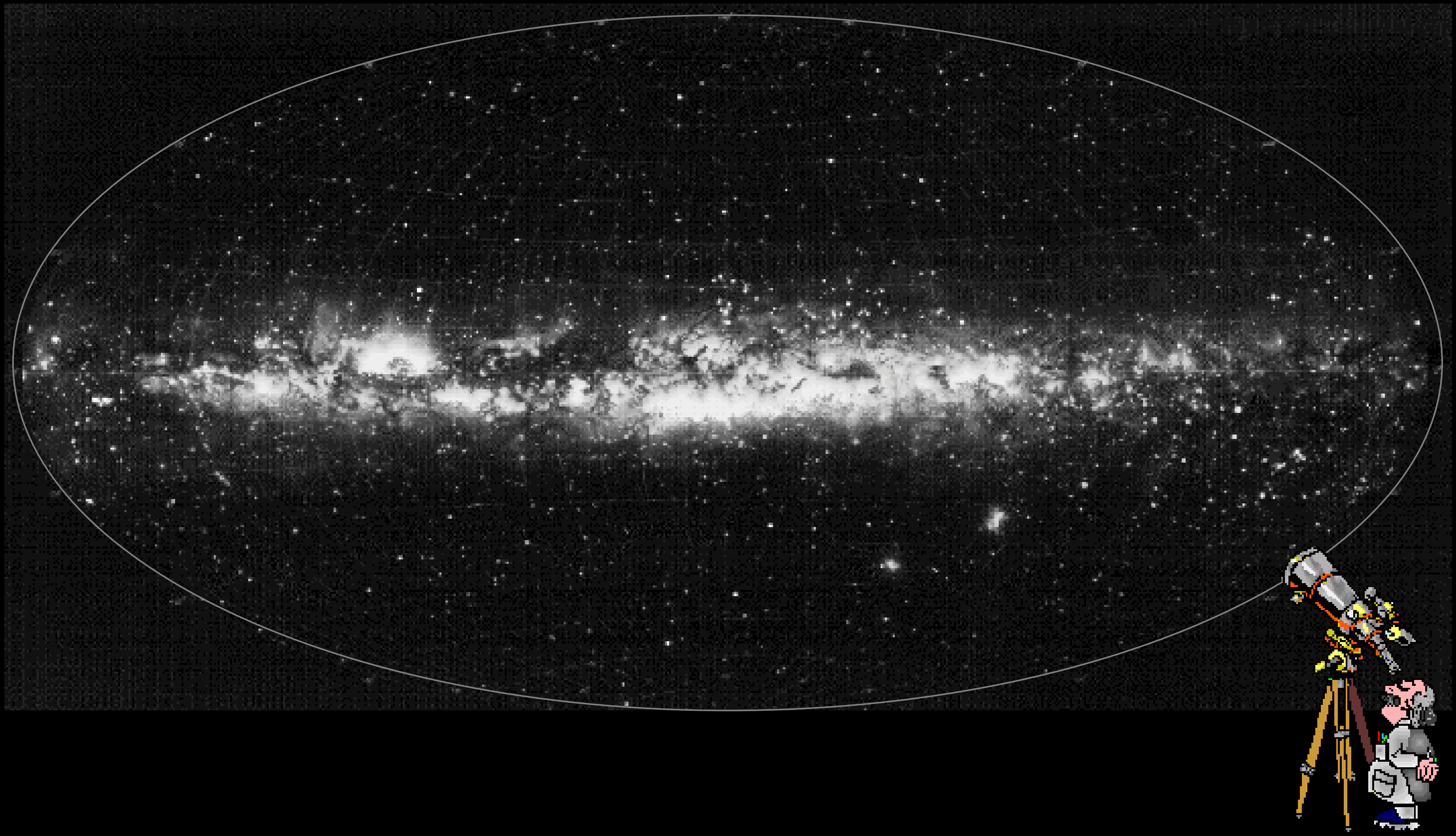
Radio Infrared **Visible Light (eV)** X-rays Gamma rays



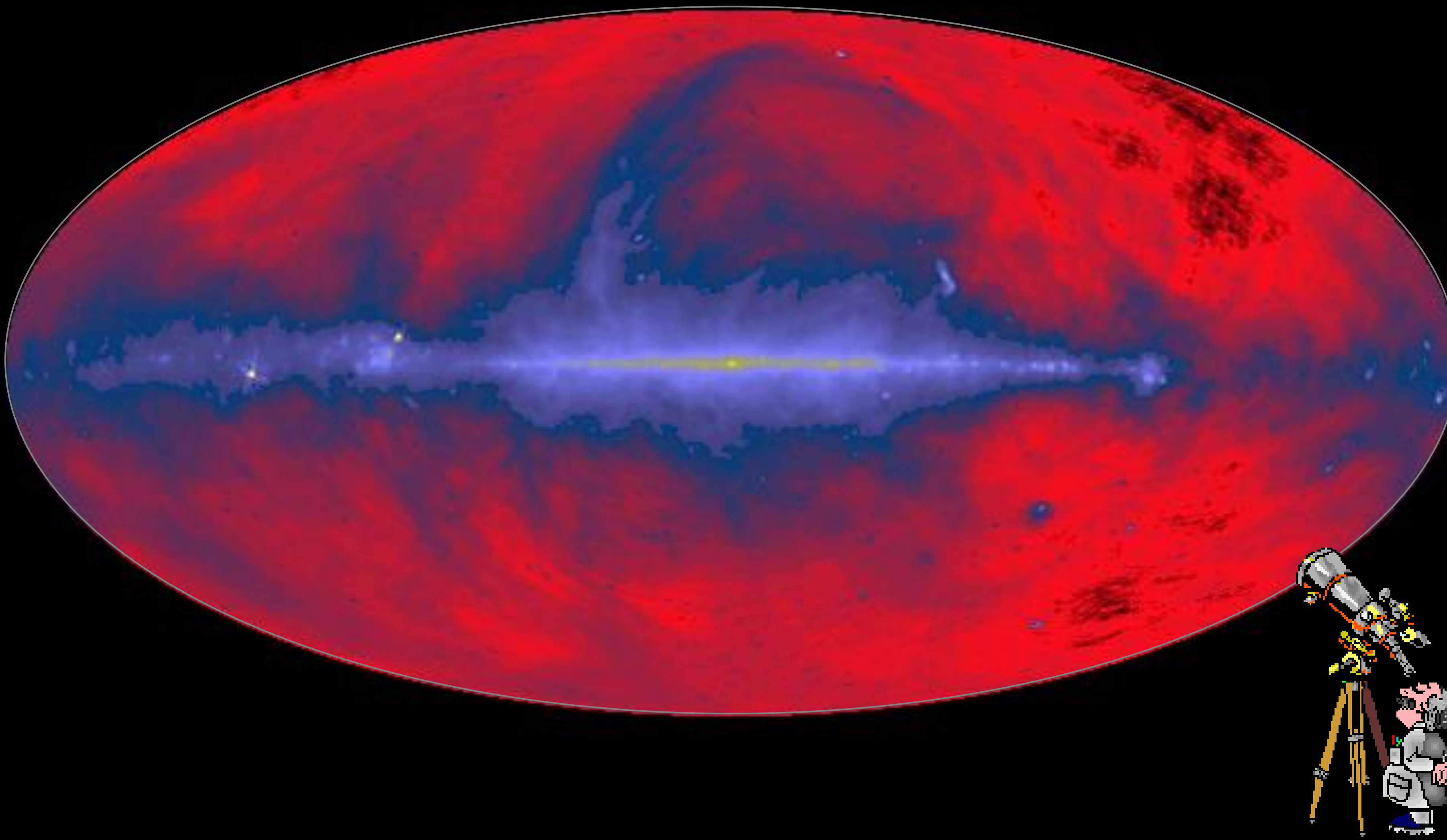
Radio
(10^{-6} eV)

Infrared

Visible Light

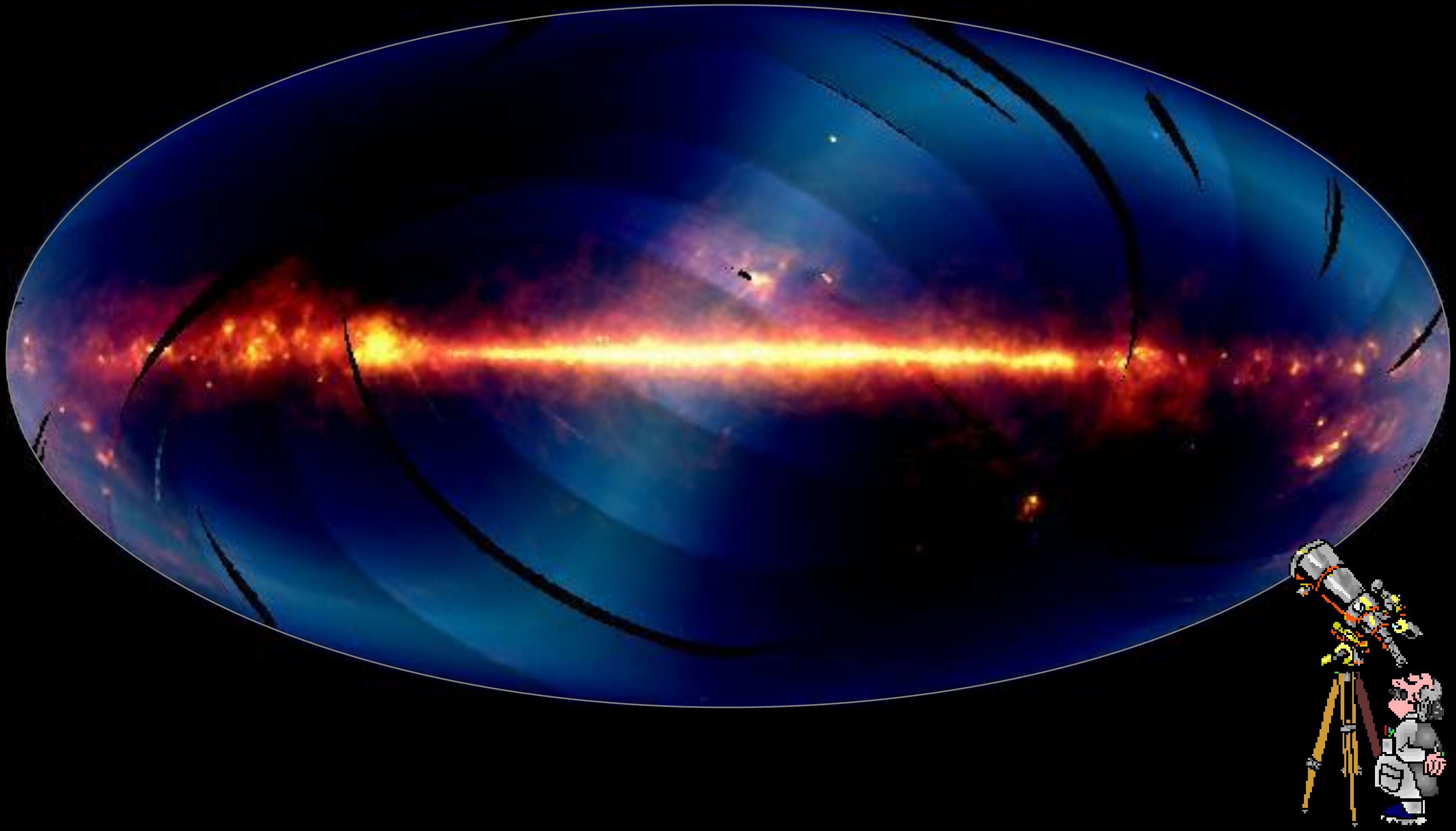
X-rays

Gamma rays



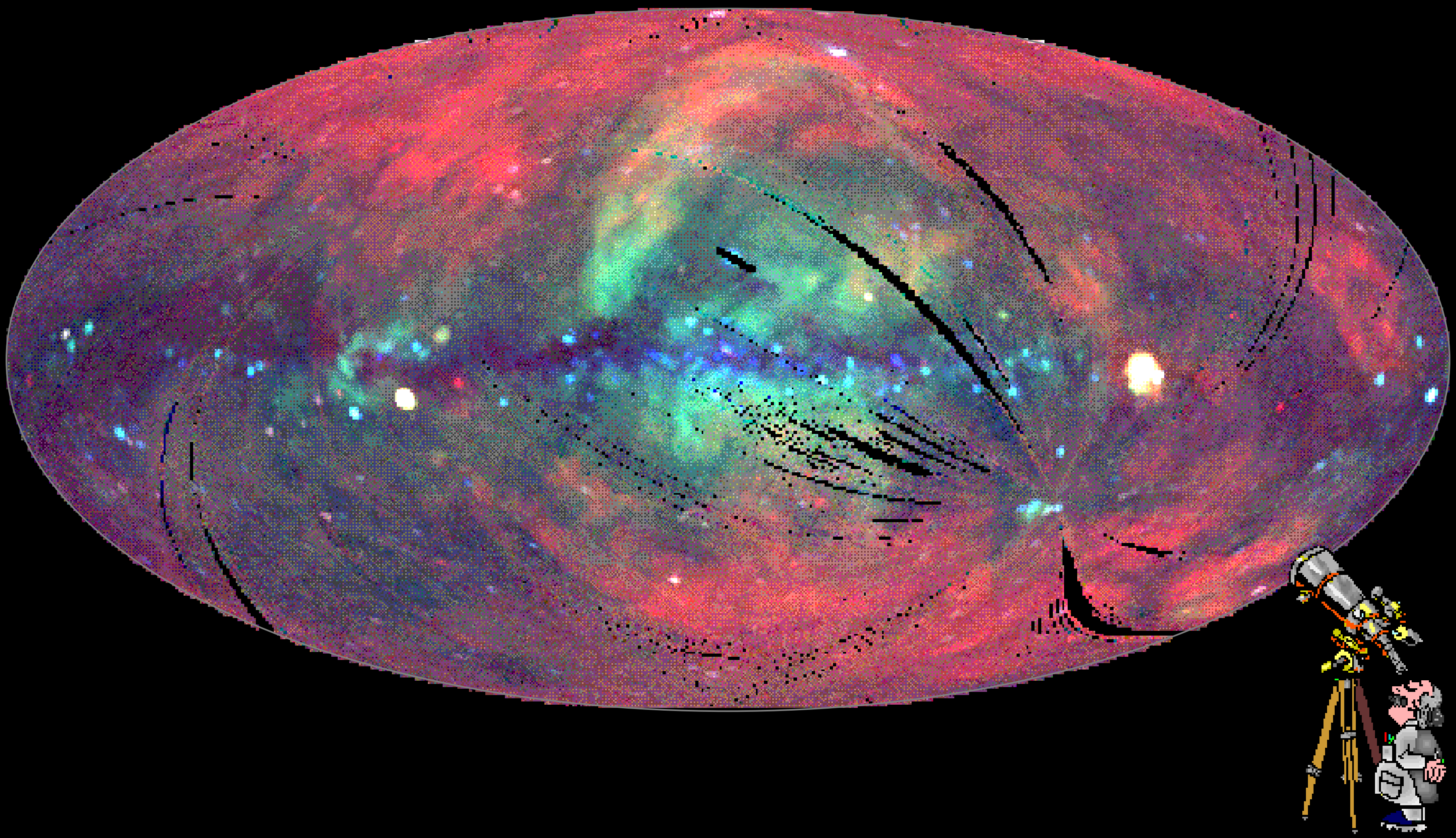
Radio Infrared Visible Light X-rays Gamma rays

(10^{-2} eV)



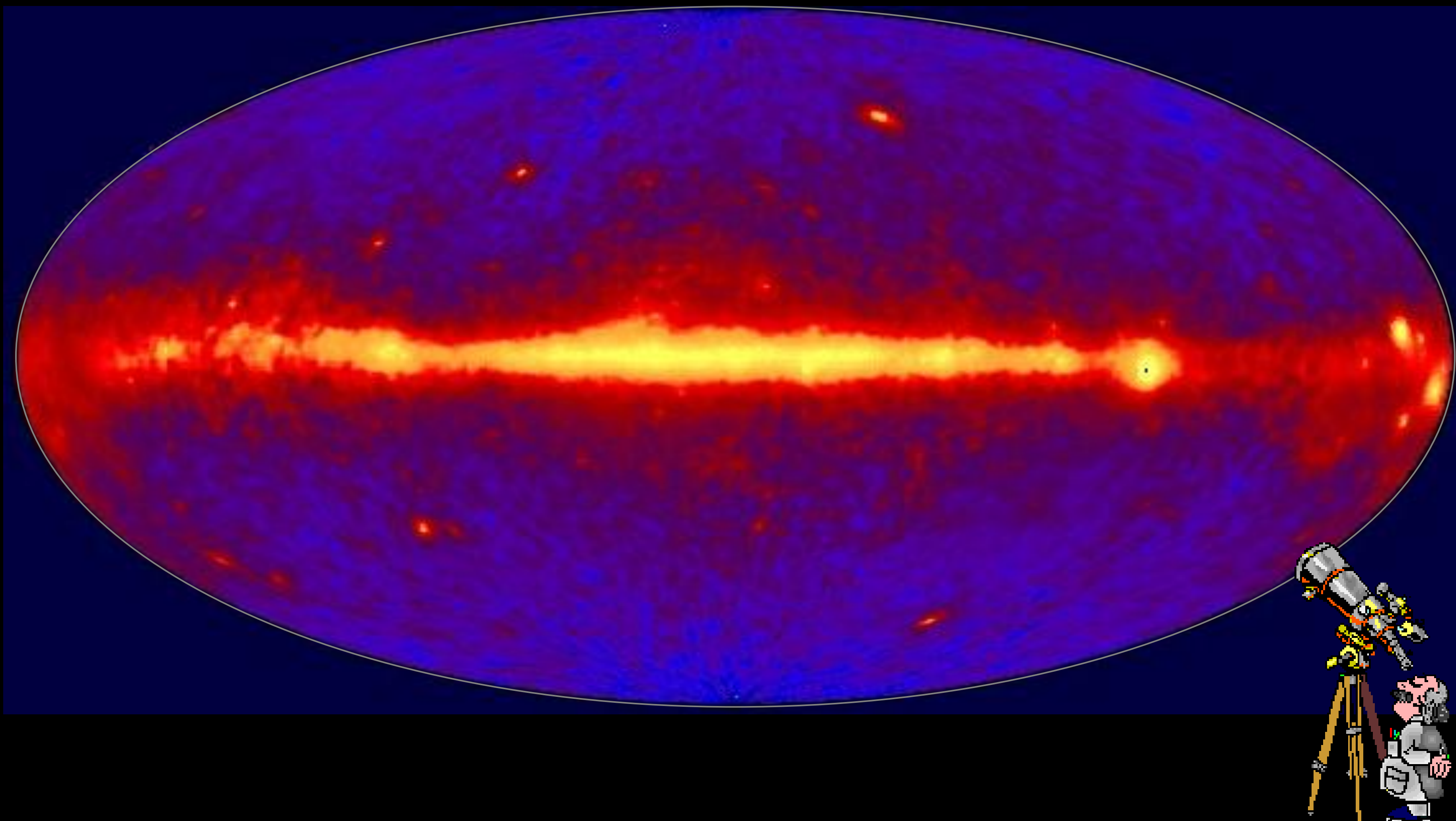
Radio Infrared Visible Light X-rays Gamma rays

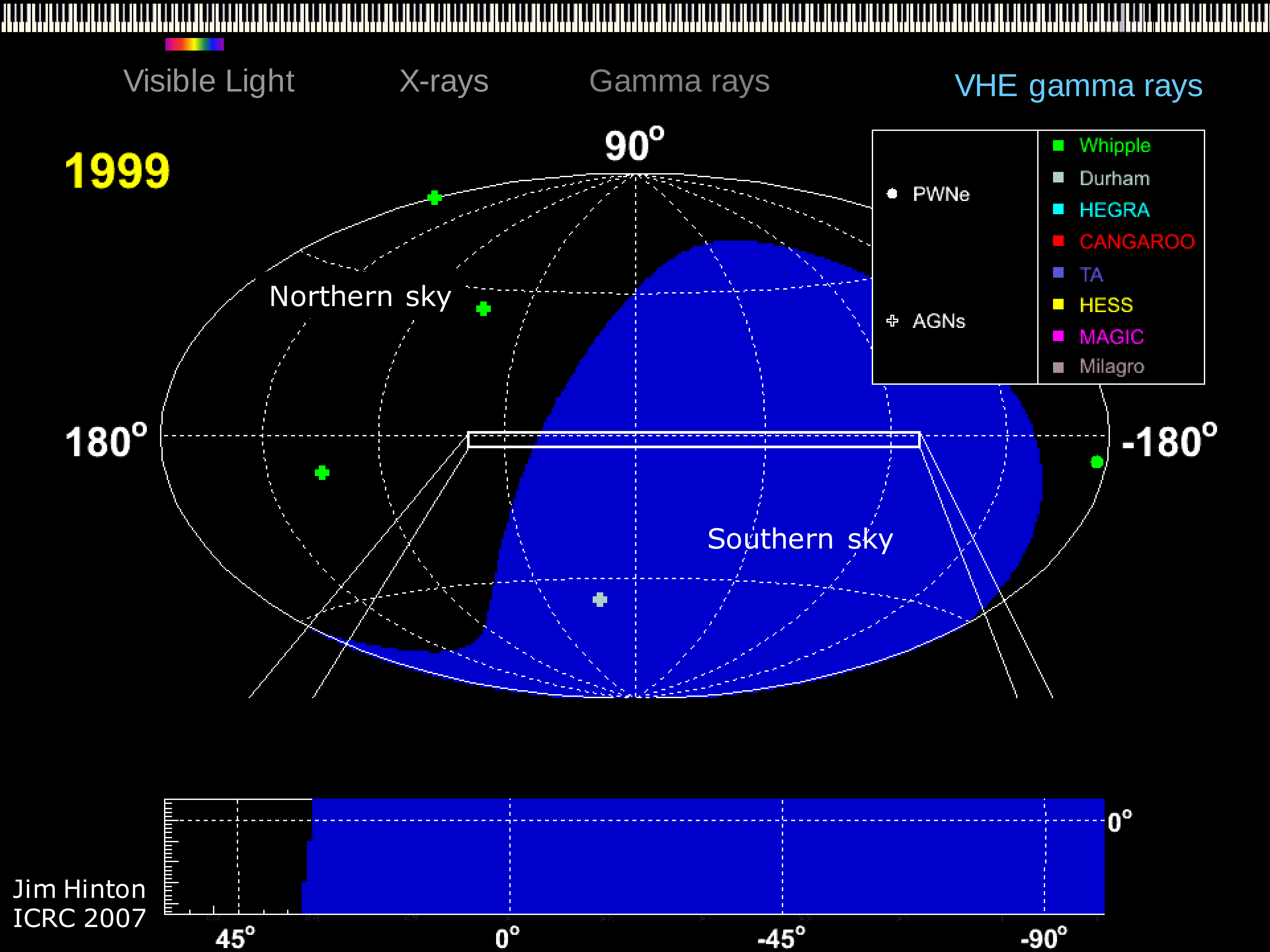
$(10^3$ eV)



Radio Infrared Visible Light X-rays VHE Gamma rays Gamma rays

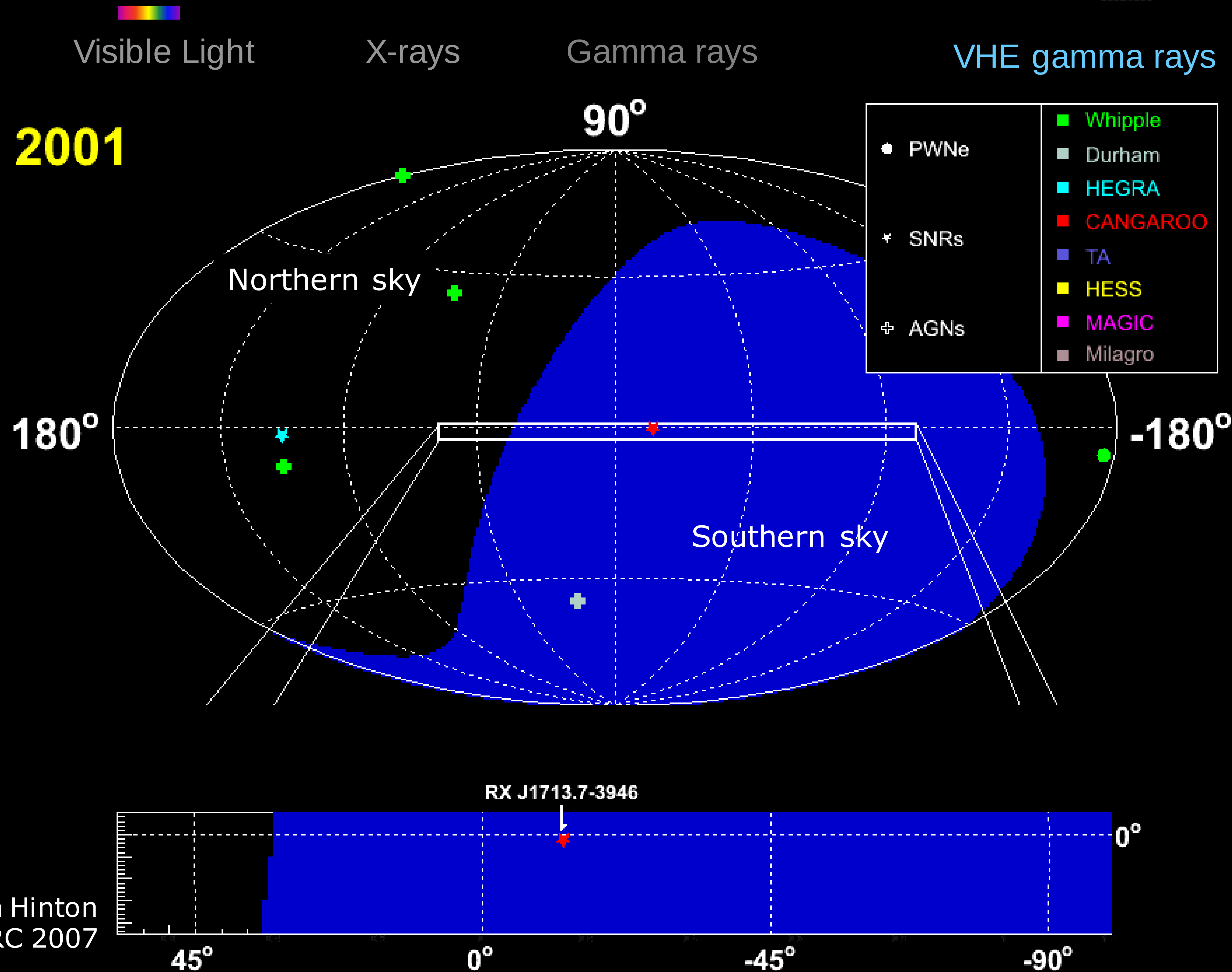
$(10^{12}\ eV)$ $(10^{8}\ eV)$





Jim Hinton
ICRC 2007

VHE gamma rays



Jim Hinton
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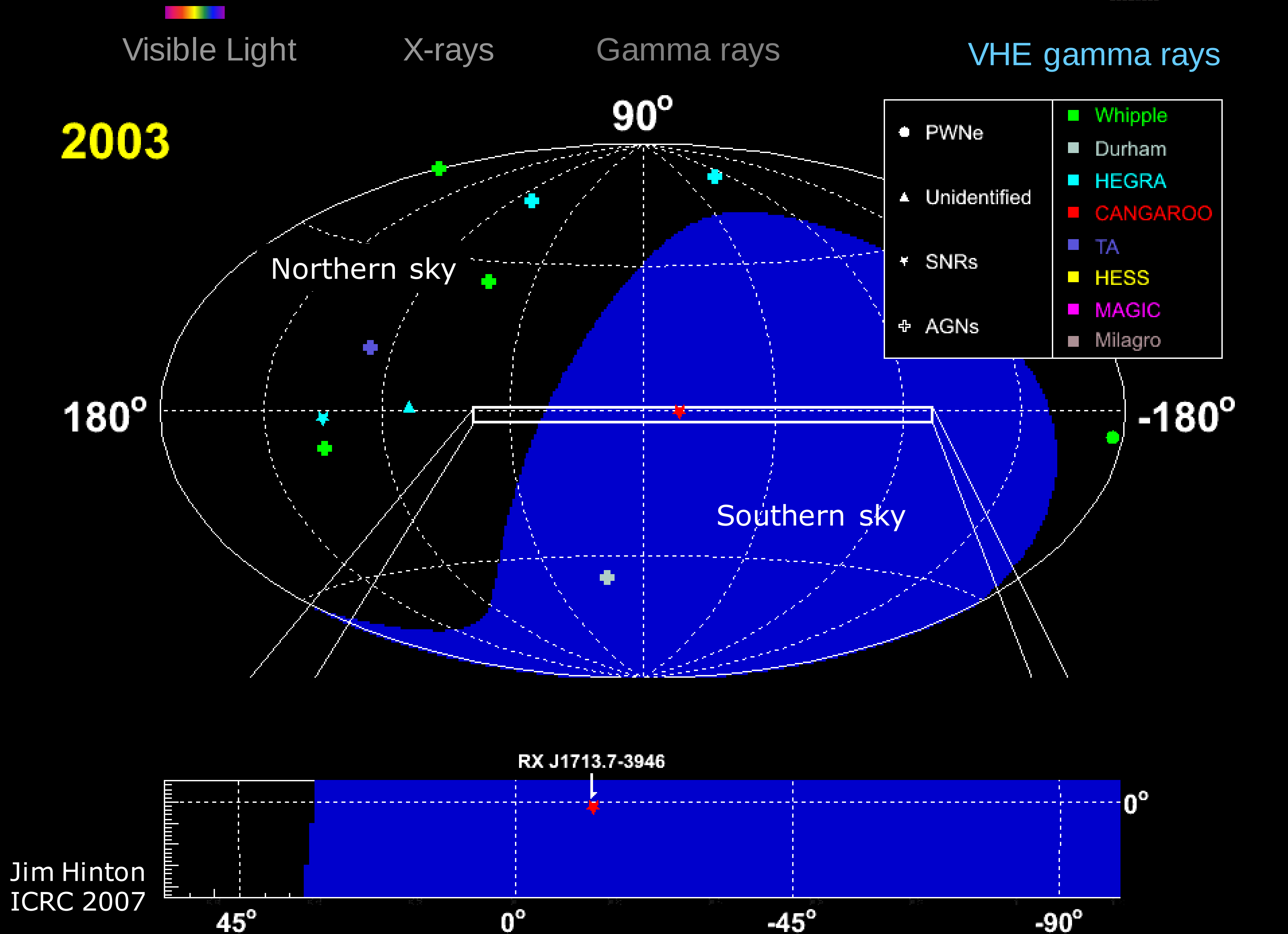
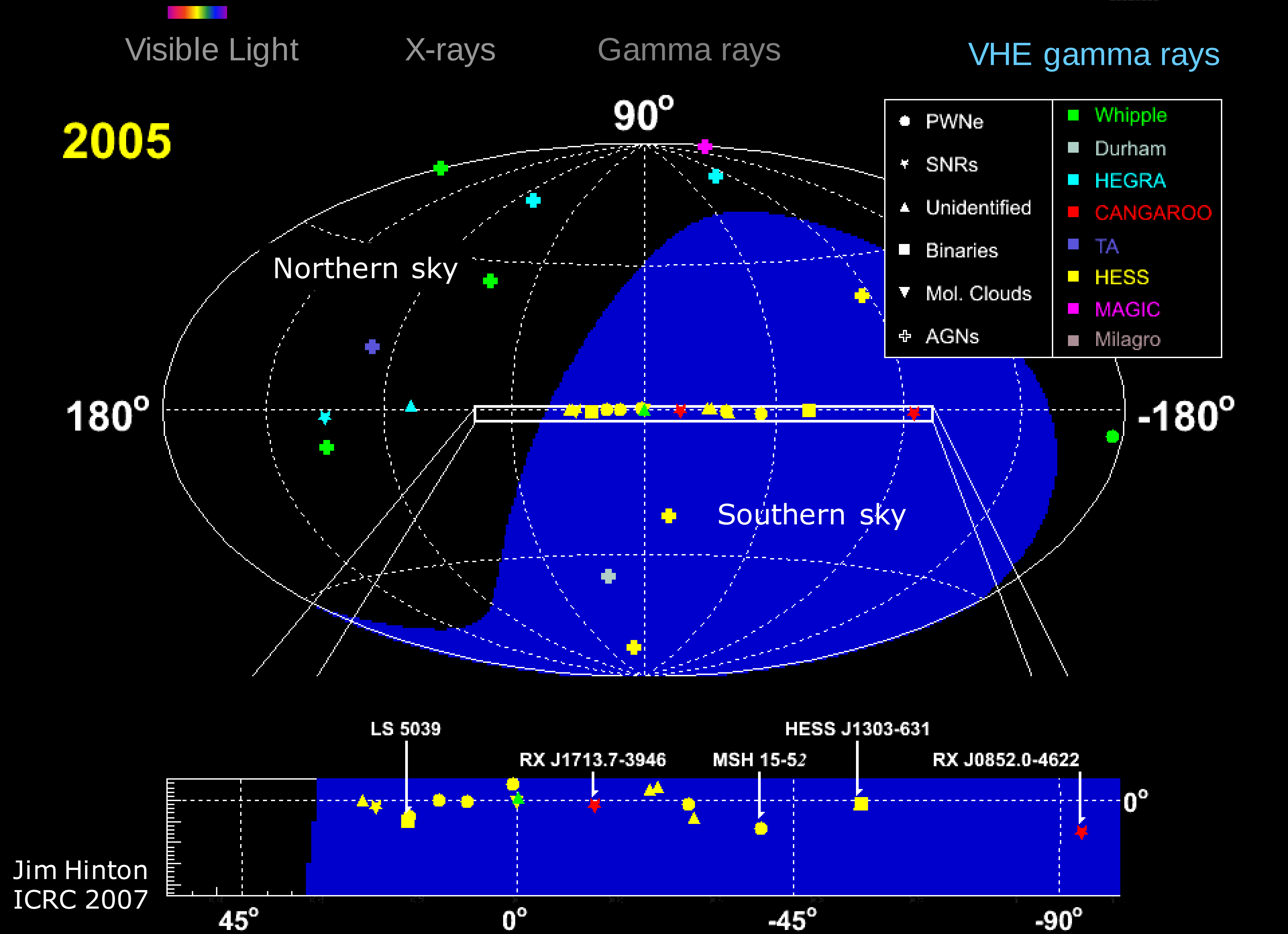

Visible Light
X-rays
Gamma rays
VHE gamma rays
2003
90°
180°
-180°
Northern sky
Southern sky
PWNe
Unidentified
SNRs
AGNs
Whipple
Durham
HEGRA
CANGAROO
TA
HESS
MAGIC
Milagro
RX J1713.7-3946
0°
45°
0°
-45°
-90°
Jim Hinton
ICRC 2007


Visible Light
X-rays
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2005
90°
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Binaries
Mol. Clouds
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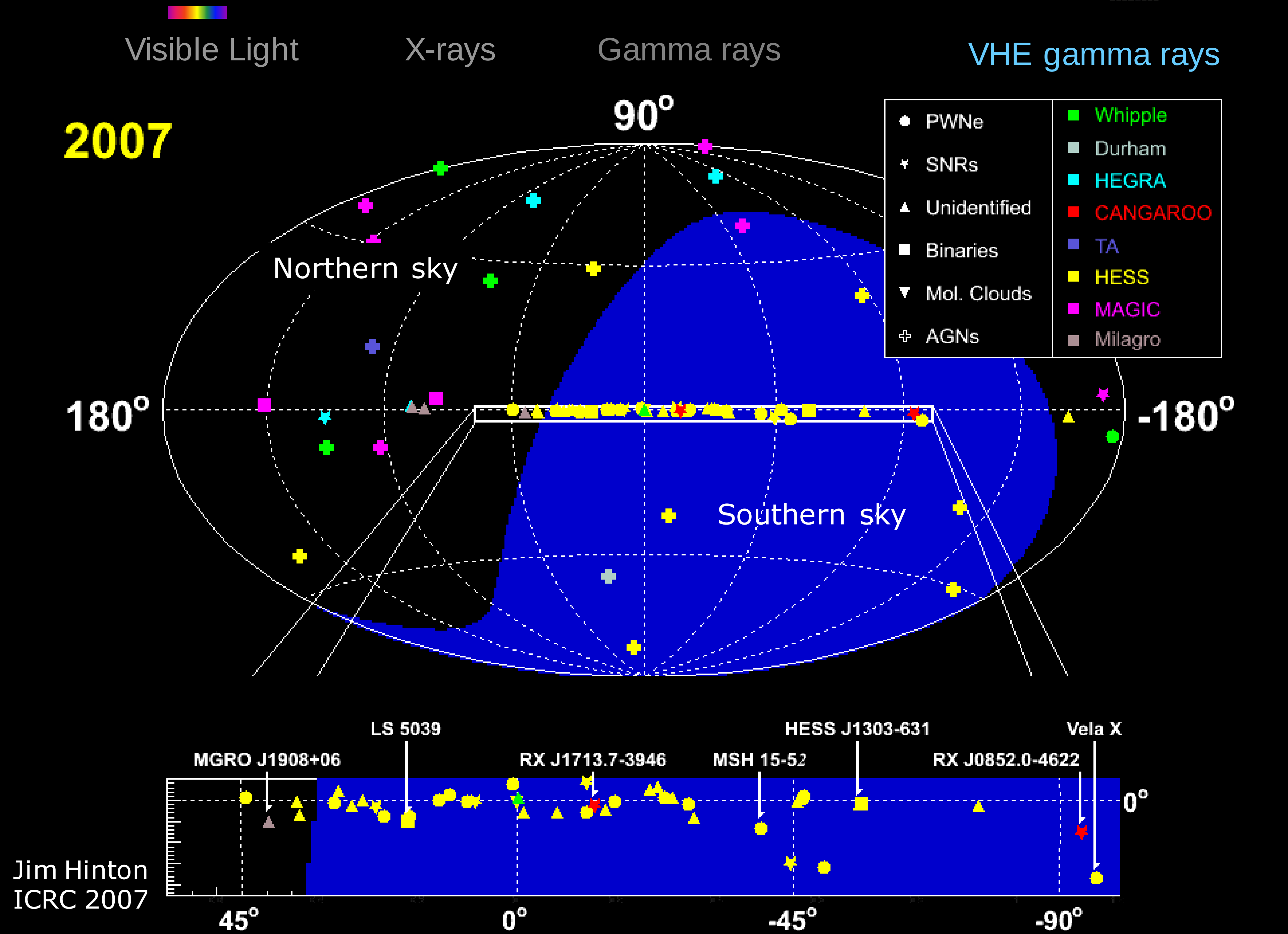
Whipple
Durham
HEGRA
CANGAROO
TA
HESS
MAGIC
Milagro
LS 5039
RX J1713.7-3946
MSH 15-52
HESS J1303-631
RX J0852.0-4622
0°
45°
0°
-45°
-90°
Jim Hinton
ICRC 2007



Visible Light
X-rays
Gamma rays
VHE gamma rays
2007
90°
180°
-180°
Northern sky
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PWNe
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Binaries
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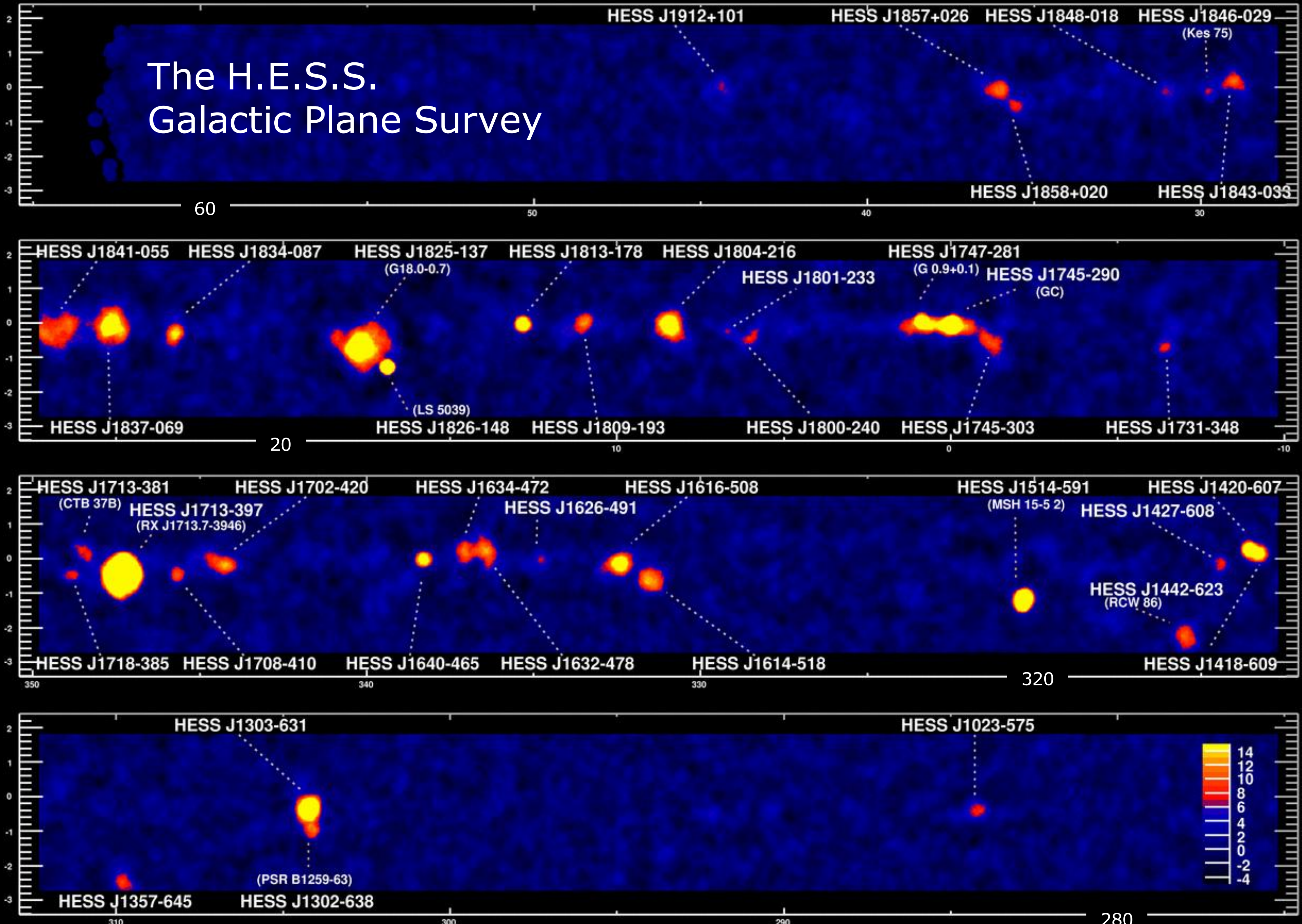
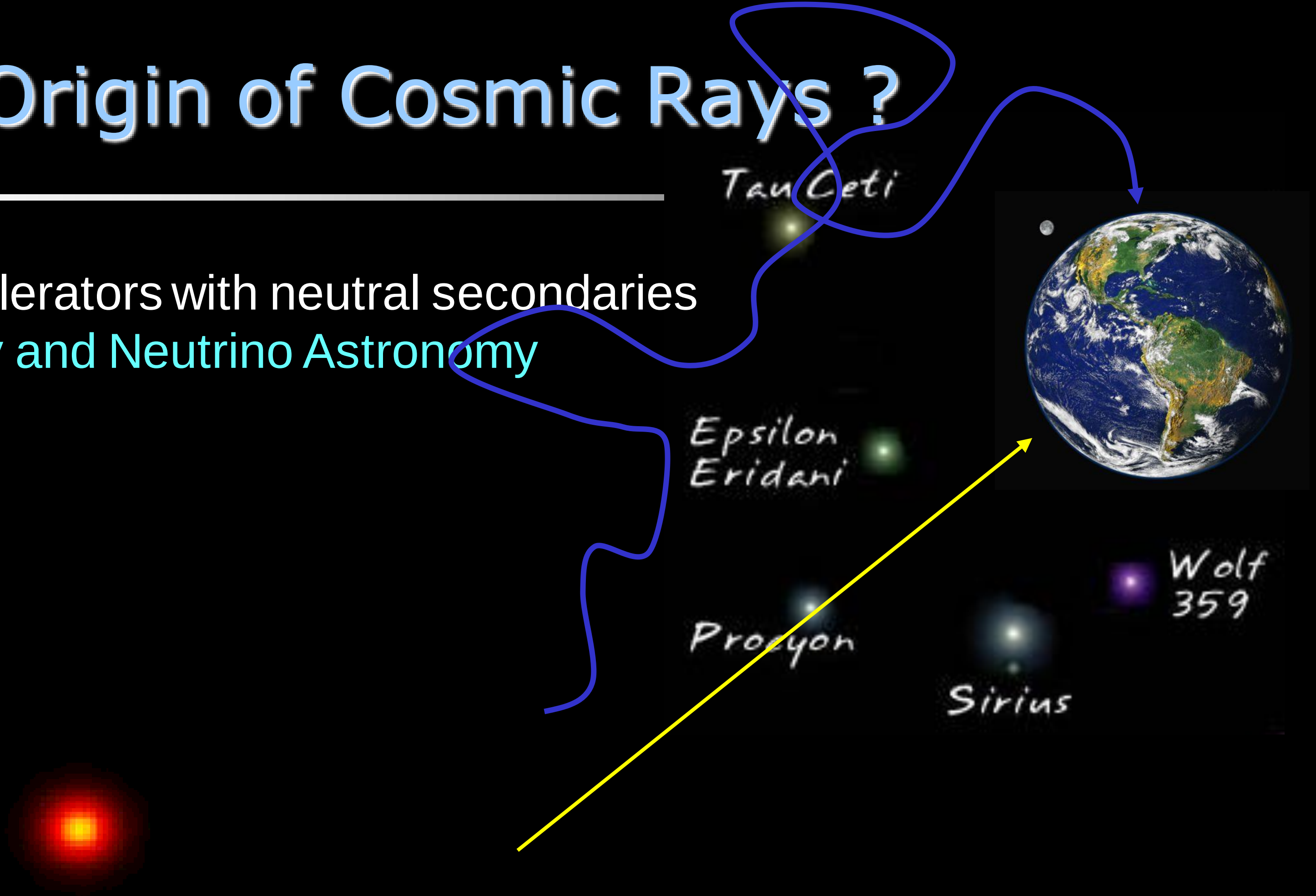
Whipple
Durham
HEGRA
CANGAROO
TA
HESS
MAGIC
Milagro
LS 5039
HESS J1303-631
Vela X
MGRO J1908+06
RX J1713.7-3946
MSH 15-52
RX J0852.0-4622
0°
45°
0°
-45°
-90°
Jim Hinton
ICRC 2007

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



⏩ Origin of Cosmic Rays ?

- ➔ Image accelerators with neutral secondaries
- ➔ Gamma-ray and Neutrino Astronomy



p + nucleus → π +X

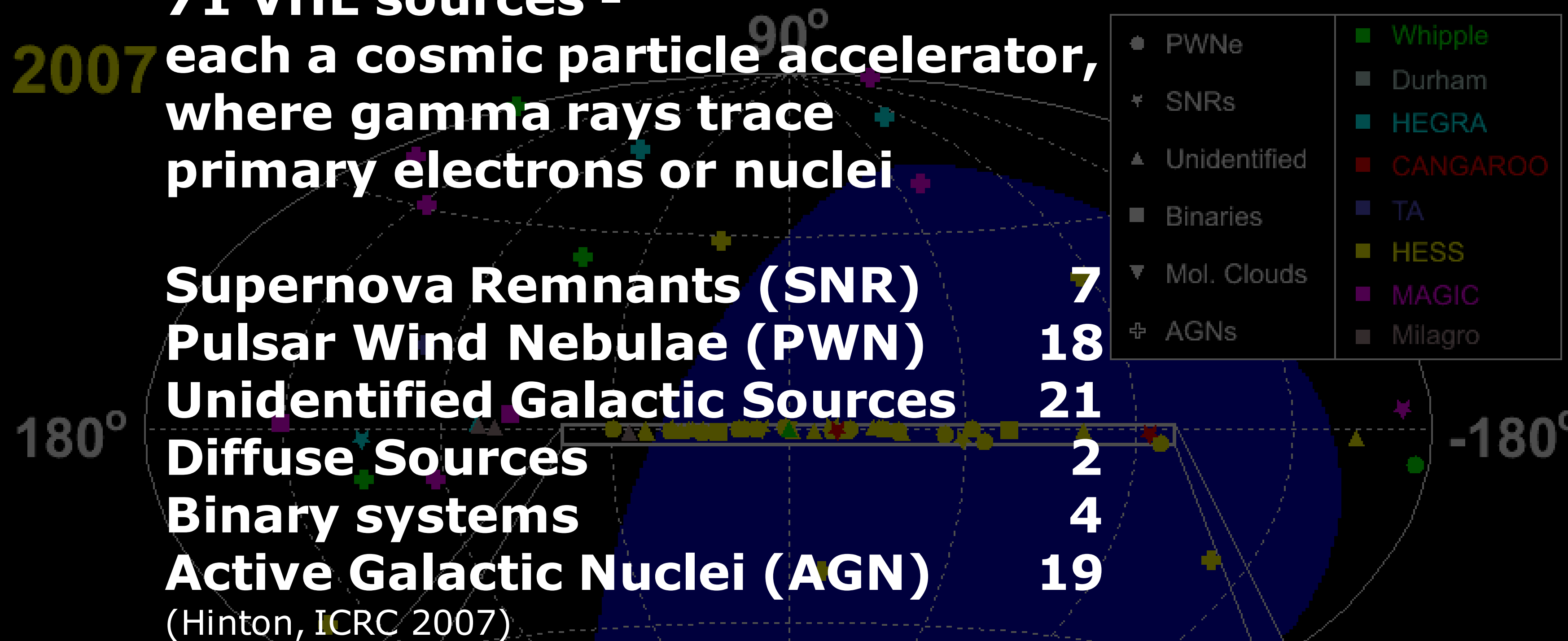
$\pi^{o} \rightarrow \gamma\gamma$

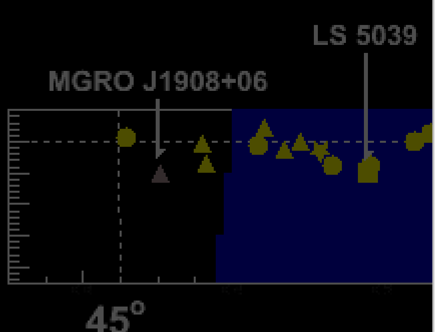
$\pi^{\pm} \rightarrow \mu^{\pm}\,\nu$

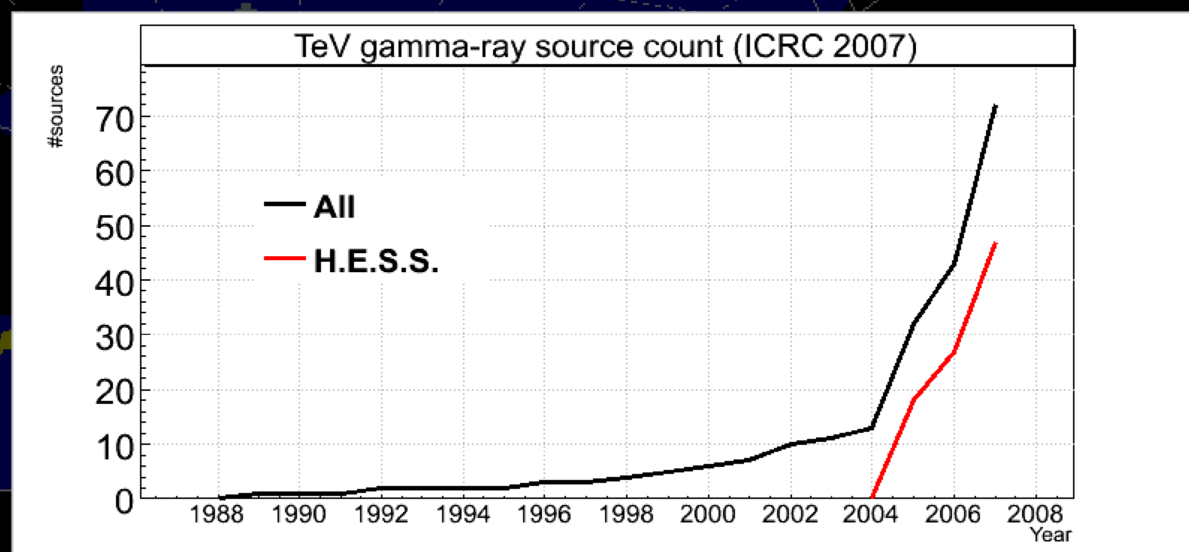
71 VHE sources -
each a cosmic particle accelerator, where gamma rays trace primary electrons or nuclei

Supernova Remnants (SNR)	**7**
Pulsar Wind Nebulae (PWN)	**18**
Unidentified Galactic Sources	**21**
Diffuse Sources	**2**
Binary systems	**4**
Active Galactic Nuclei (AGN)	**19**

(Hinton, ICRC 2007)







Jim Hinton
ICRC 2007

Exploring the nonthermal universe

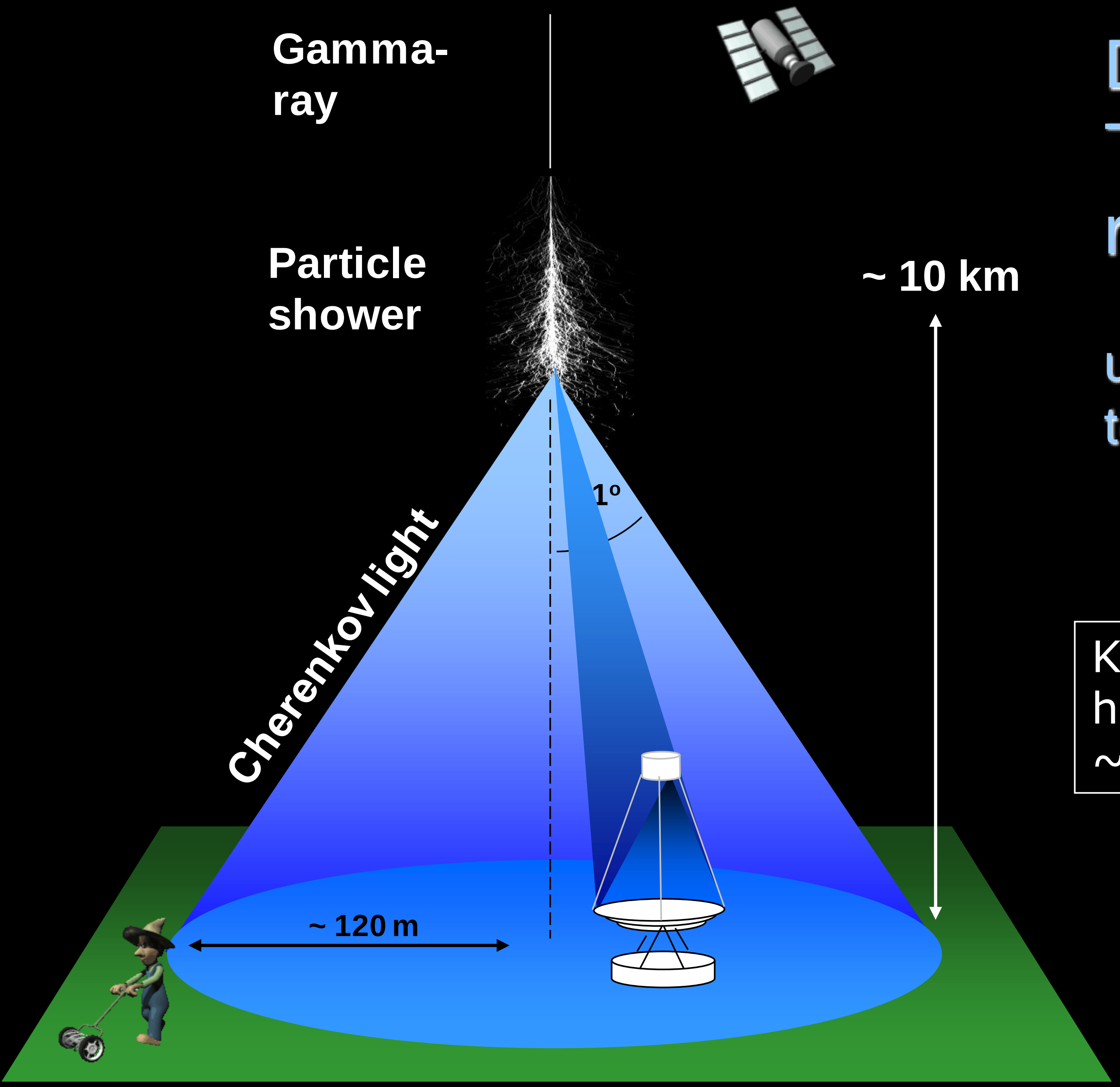
Detecting VHE gamma rays: The H.E.S.S. telescopes

A tour of galactic particle accelerators

The next big step: CTA

Detection of TeV gamma rays

using Cherenkov telescopes



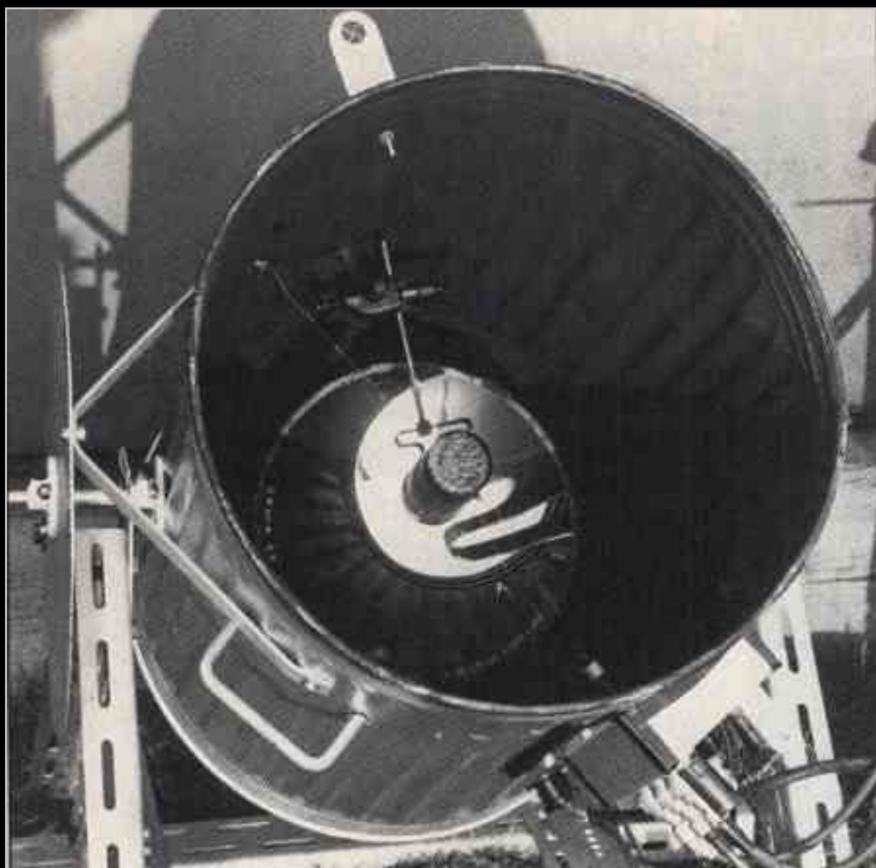
Key issue:
huge detection area
~ 10^5 m^2

Air showers
look a bit like meteors

(from Sky & Telescope)

The early days

Source:
T. Weekes



Galbraith and Jelley, 1953

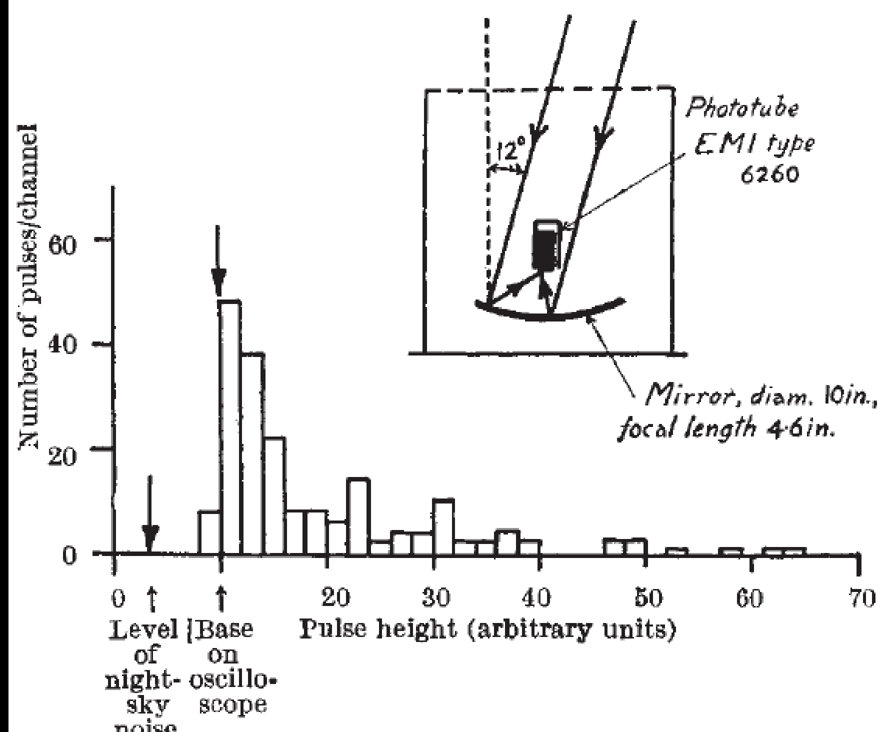
February 21, 1953 NATURE

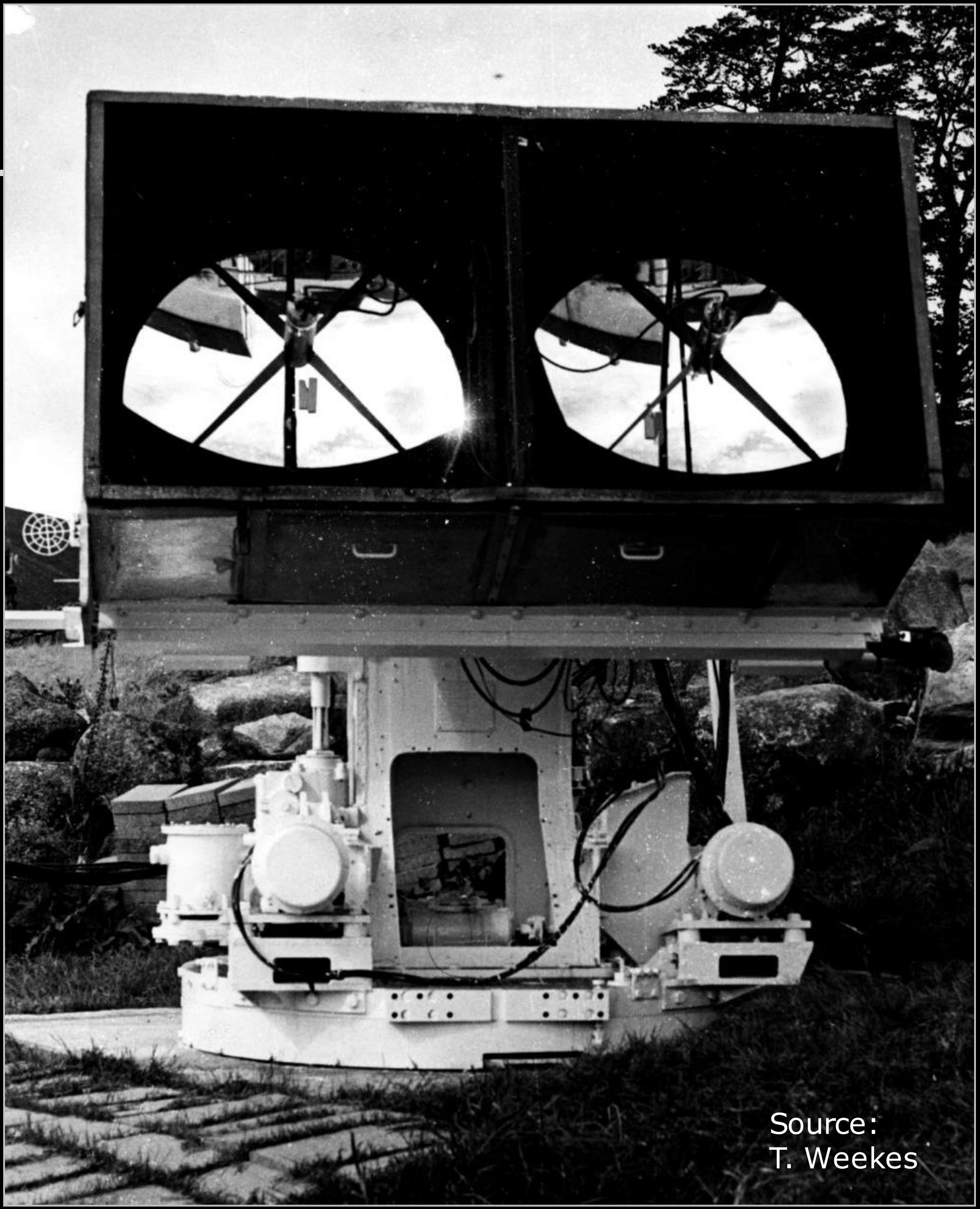
Light Pulses from the Night Sky associated with Cosmic Rays

In 1948, Blackett[1] suggested that a contribution approximately 10^{-4} of the mean light of the night-sky might be expected from Čerenkov radiation[2] produced in the atmosphere by the cosmic radiation. The purpose of this communication is to report the results of some preliminary experiments we have made using a photomultiplier, which revealed the

thank Mr. W. J. Whitehouse and Dr. E. Bretscher for their encouragement, and Dr. T. E. Cranshaw for the use of the extensive shower array.

W. Galbraith
J. V. Jelley



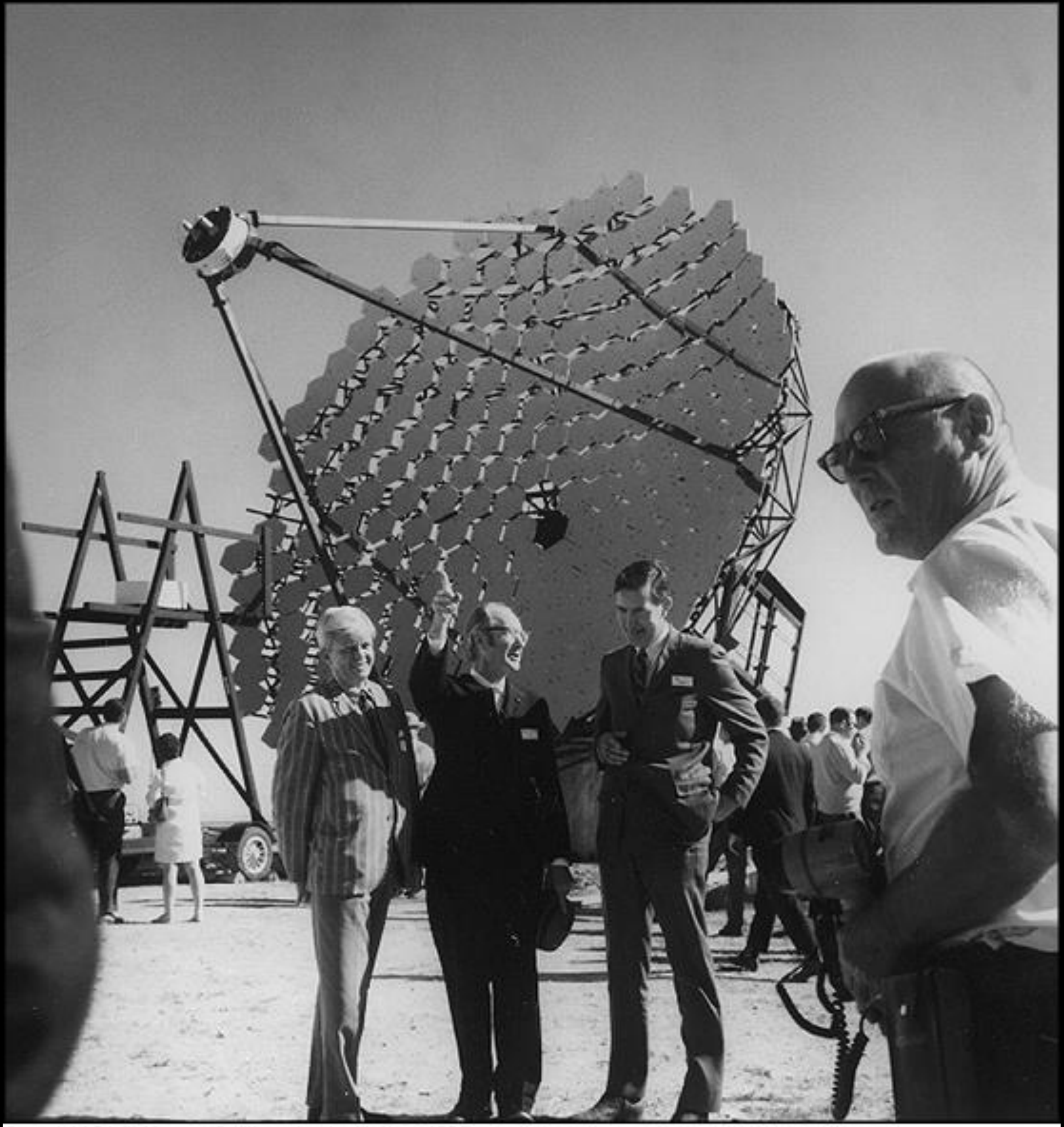


Porter & Jelley
1962

Whipple 1968

Detection of
the Crab Nebula
1989:

50 h observation
time for 5σ signal

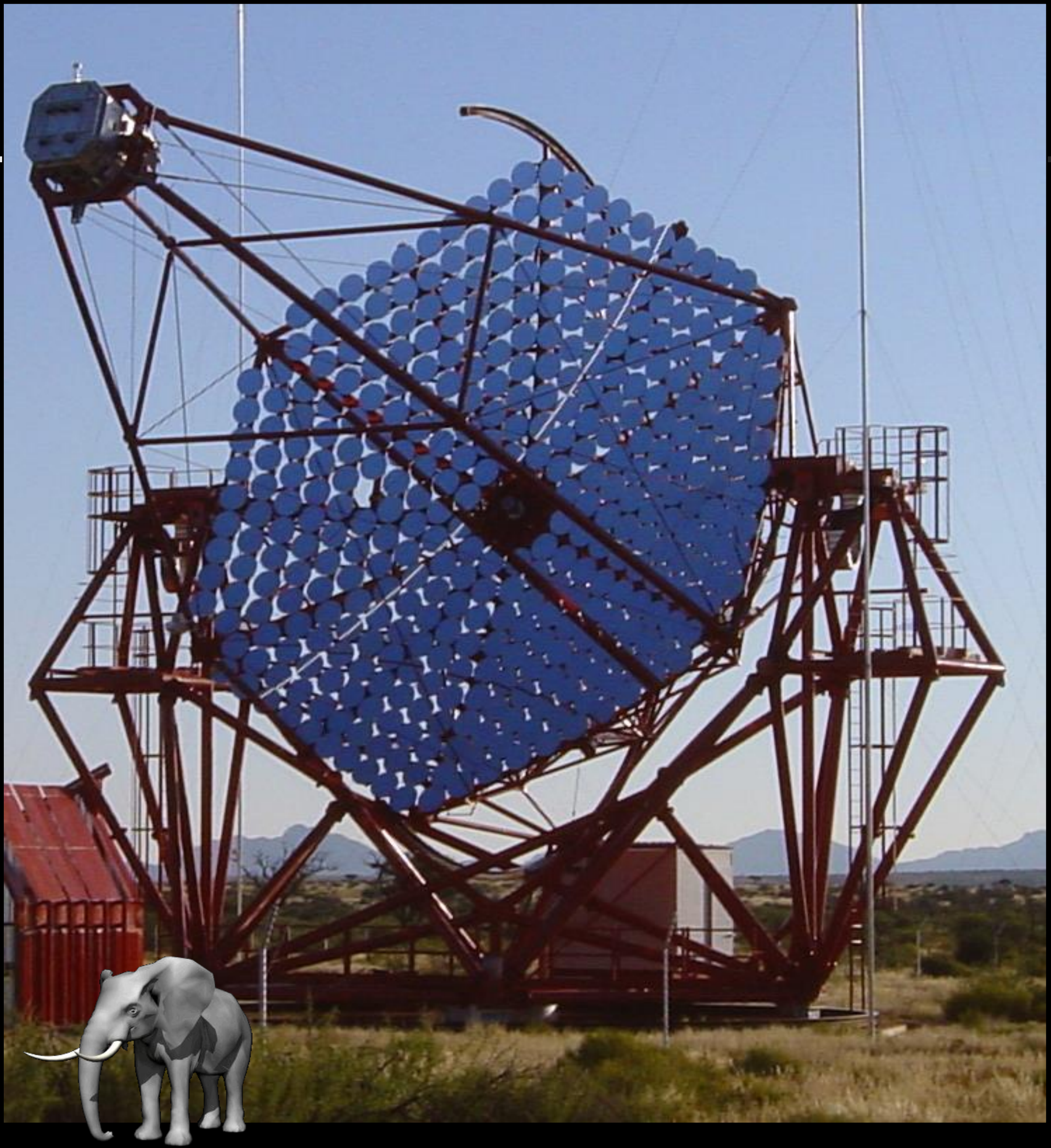


H.E.S.S.
2003

Detects Crab-like source in

30 seconds

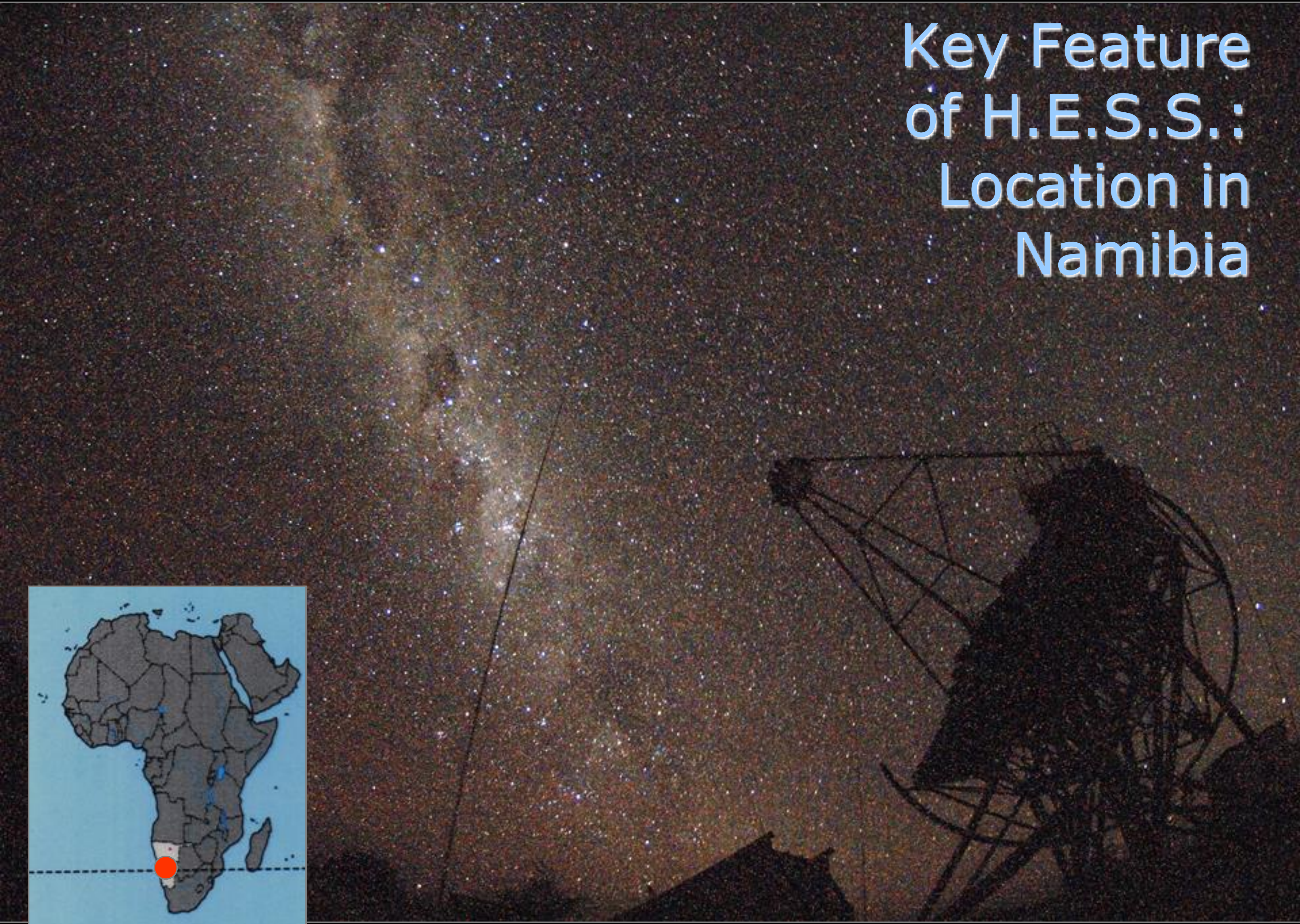
1% Crab in 25 h



MPI Kernphysik, Heidelberg
Humboldt Univ. Berlin
Ruhr-Univ. Bochum
Univ. Erlangen-Nürnberg
Univ. Hamburg
Univ. Heidelberg
Univ. Tübingen
Ecole Polytechnique, Palaiseau
APC Paris
Univ. Paris VI-VII
CEA Saclay
CESR Toulouse
LPTA Montpellier
LAOG Grenoble
Paris Observatory
LAPP Annecy
Durham Univ.
Dublin Inst. for Adv. Studies
Charles Univ., Prag
NCAC, Warsaw
Jagiellonian University, Cracow
Institute of Nuclear Physics, Cracow,
Space Research Centre, Warsaw
Yerewan Physics Inst.
North-West Univ., Potchefstroom
Univ. of Namibia, Windhoek

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

Key Feature of H.E.S.S.: Location in Namibia



Key feature: Wide field of view of 5^o

Camera:
960 pixels, 0.16^o
5^o field of view
Readout electronics in camera body
1 GHz analog memory for signal recording

The H.E.S.S. telescopes

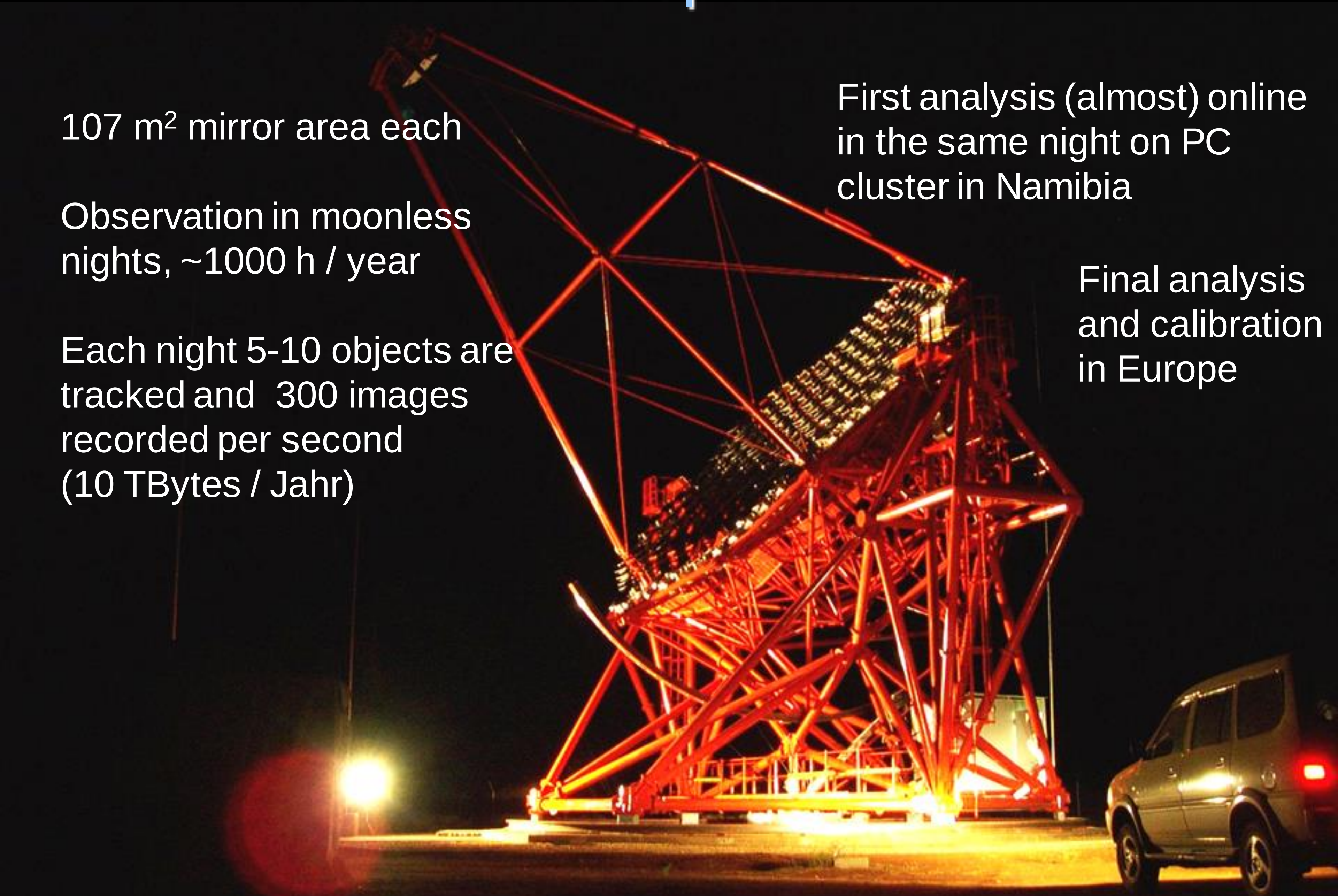
107 m² mirror area each

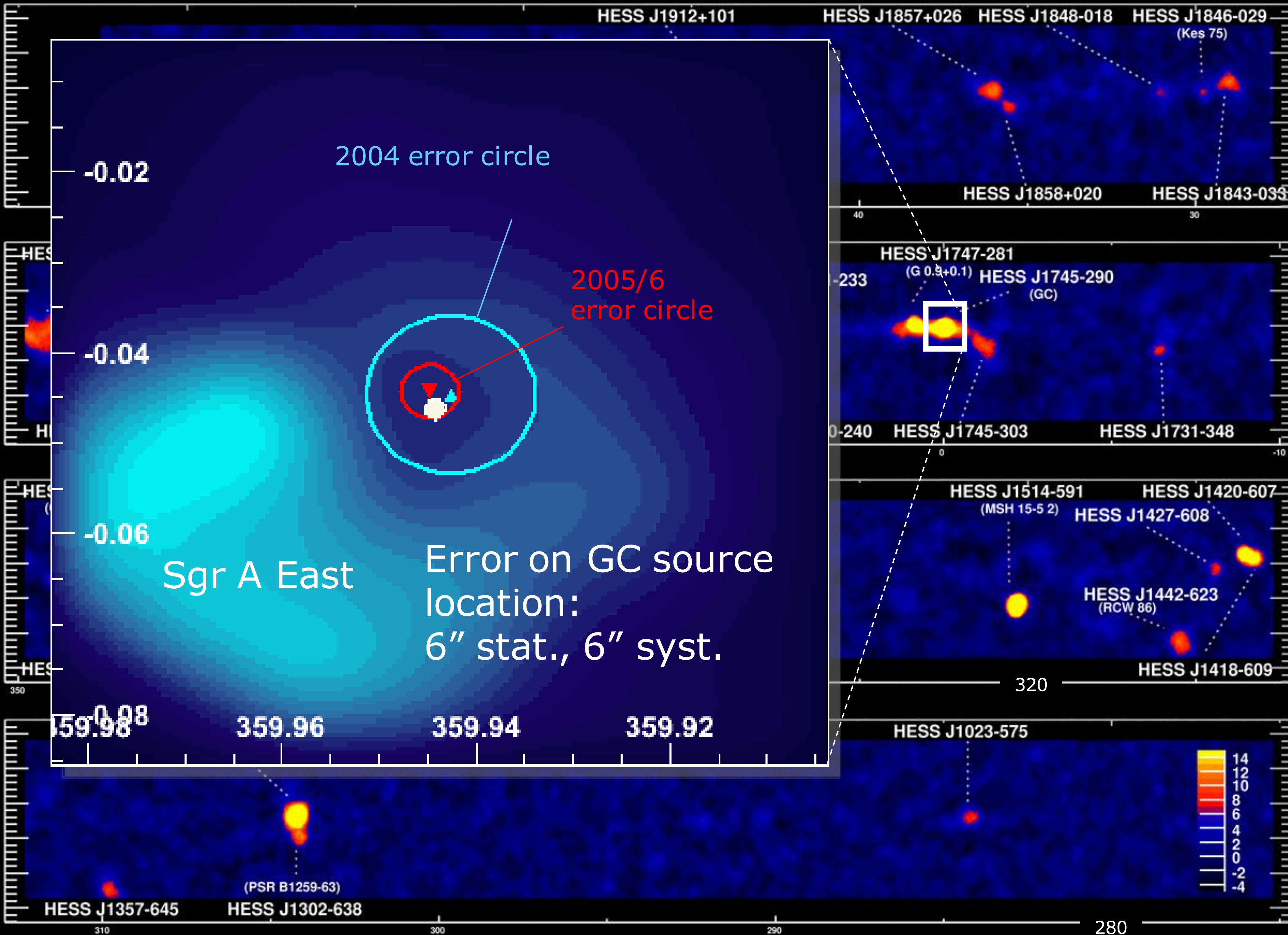
Observation in moonless nights, ~1000 h / year

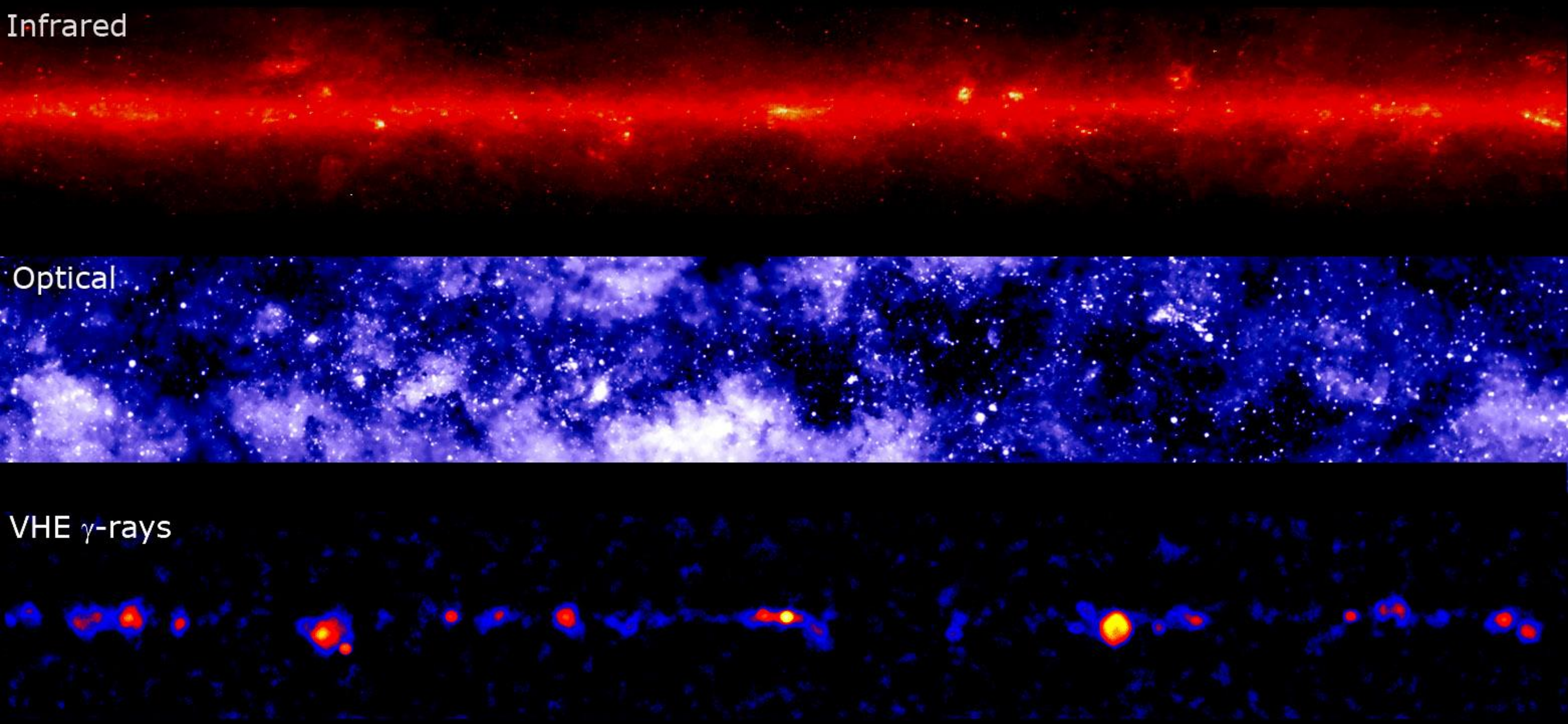
Each night 5-10 objects are tracked and 300 images recorded per second (10 TBytes / Jahr)

First analysis (almost) online in the same night on PC cluster in Namibia

Final analysis and calibration in Europe

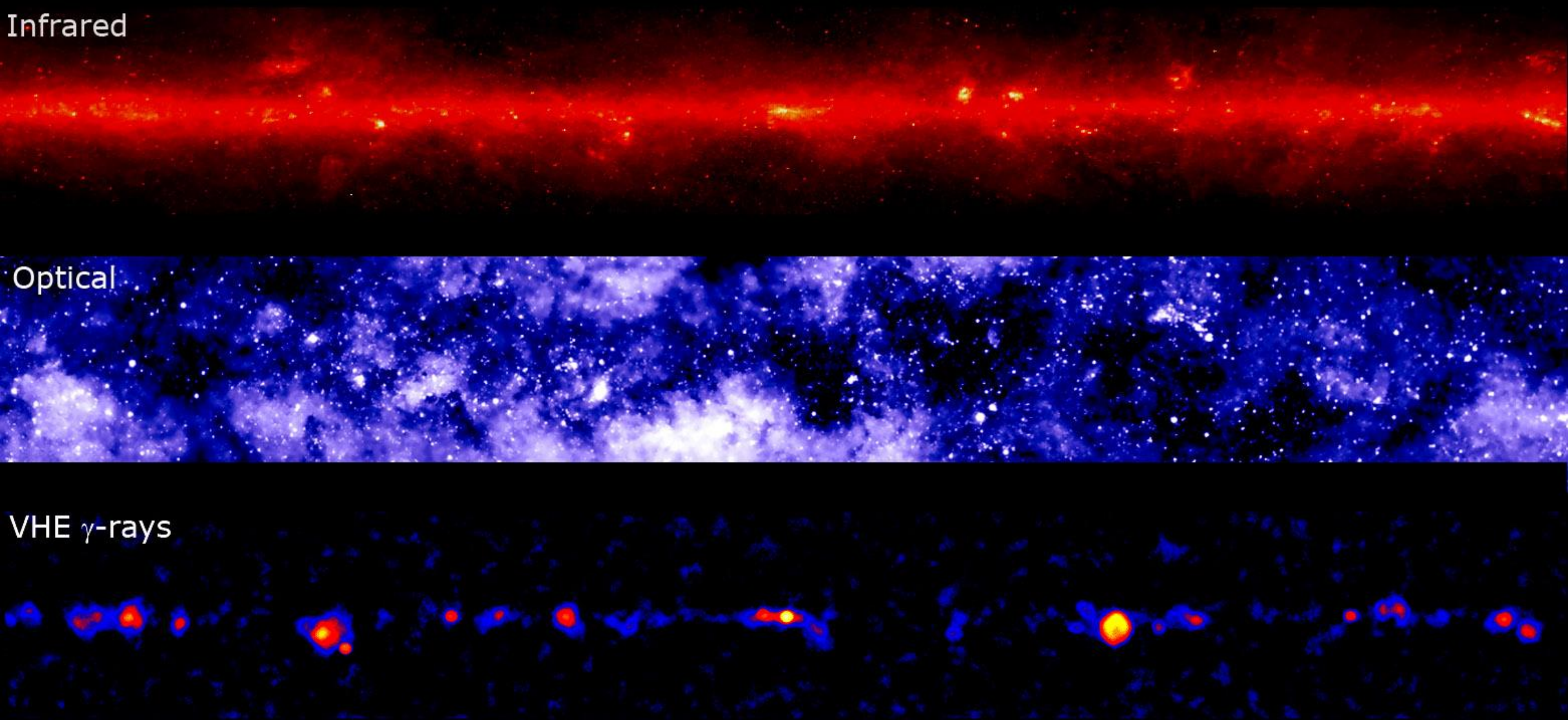



HESS J1912+101
HESS J1857+026
HESS J1848-018
HESS J1846-029
(Kes 75)
HESS J1858+020
HESS J1843-033
40
30
HESS J1747-281
(G 0.9+0.1)
HESS J1745-290
(GC)
HESS J1745-303
HESS J1731-348
0
-10
HESS J1514-591
(MSH 15-5 2)
HESS J1420-607
HESS J1427-608
HESS J1442-623
(RCW 86)
HESS J1418-609
320
HESS J1023-575
(PSR B1259-63)
HESS J1357-645
HESS J1302-638
310
300
290
280
2004 error circle
2005/6
error circle
-0.02
-0.04
-0.06
-0.08
359.96
359.94
359.92
Sgr A East
Error on GC source location:
6″ stat., 6″ syst.



A tour of galactic particle accelerators:

- Supernova remnants
- Pulsar wind nebulae
- Binaries
- "Dark sources"



A tour of galactic particle accelerators:

- Supernova remnants
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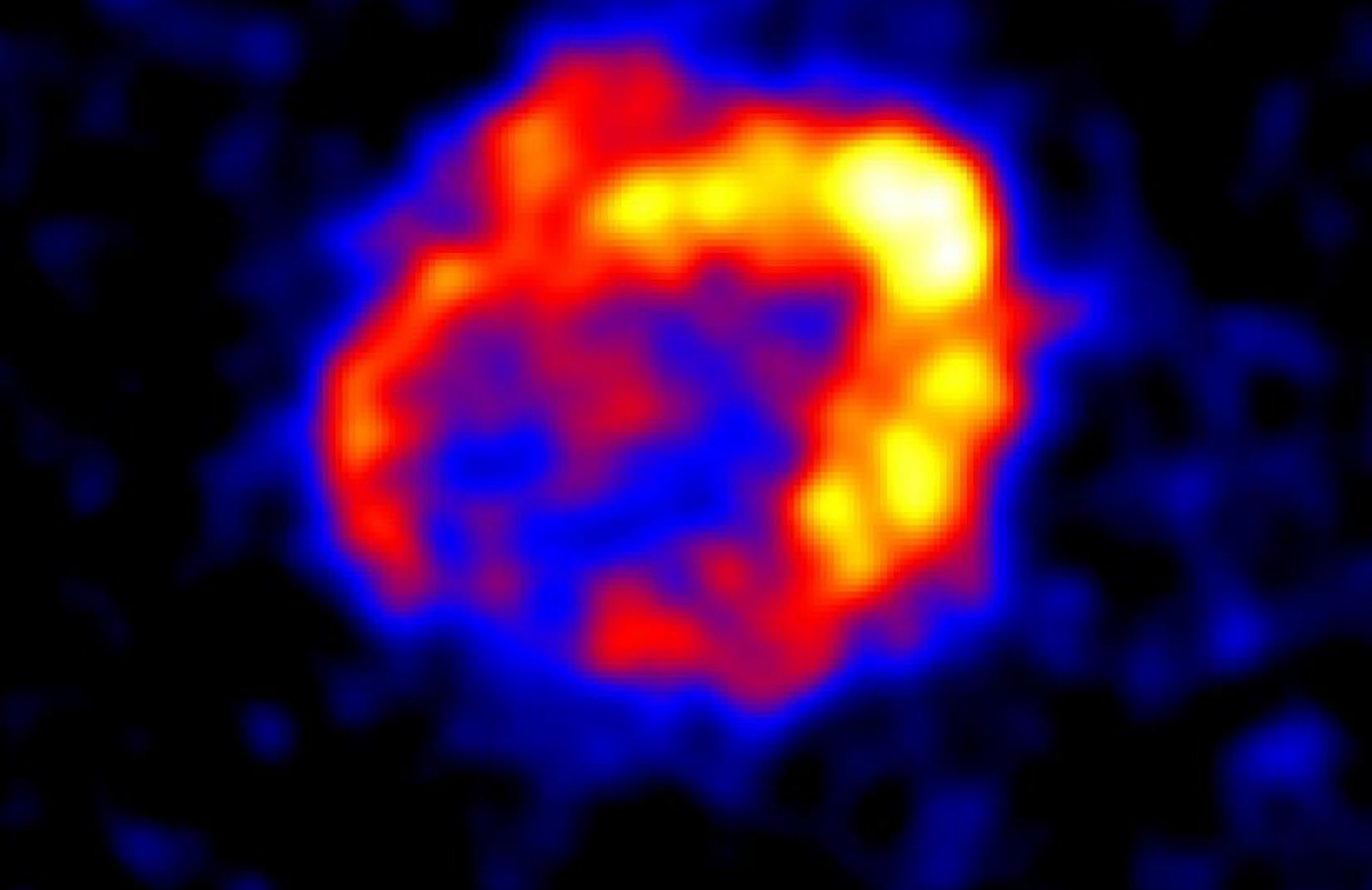
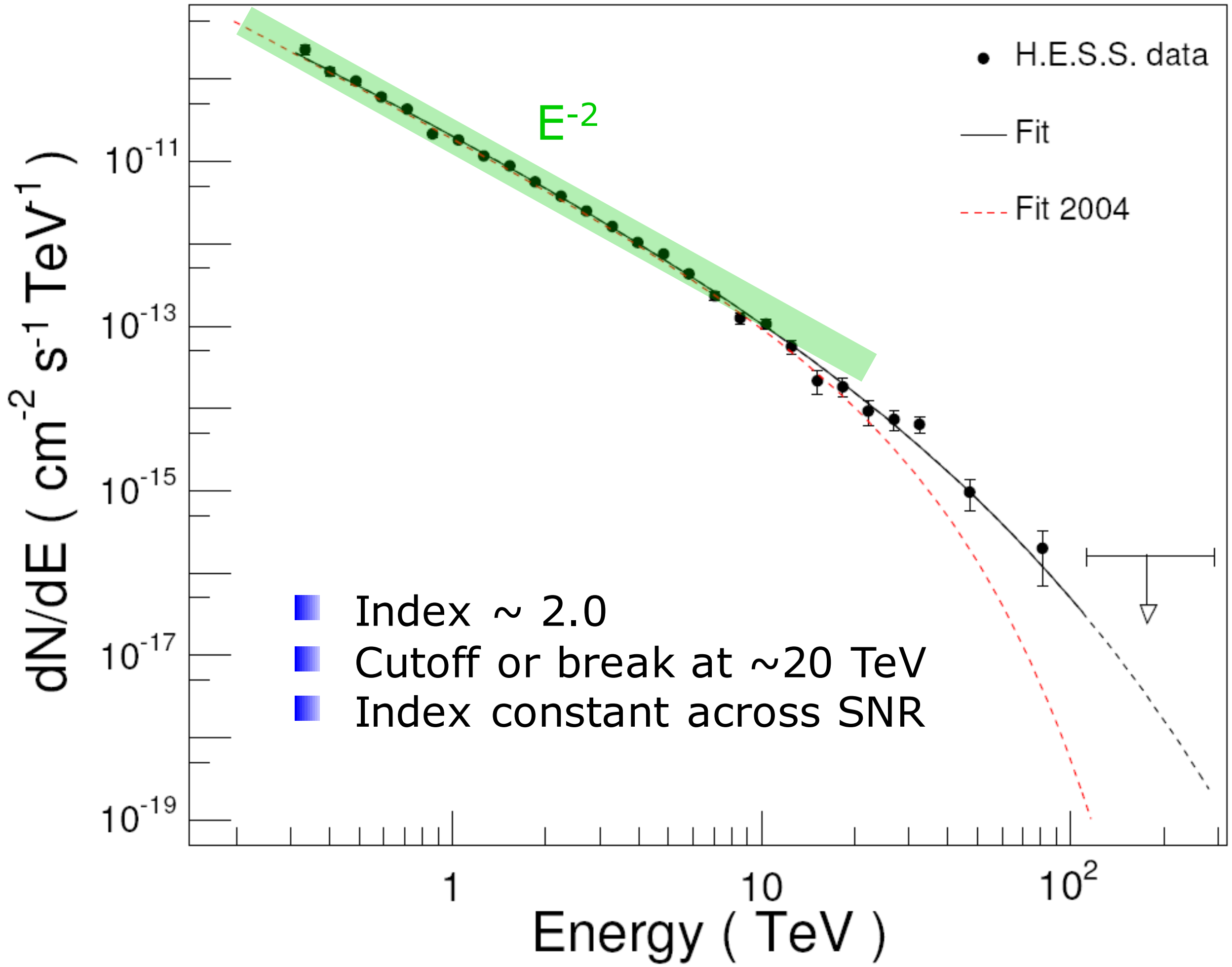
- “Dark sources”

Supernova remnant shells



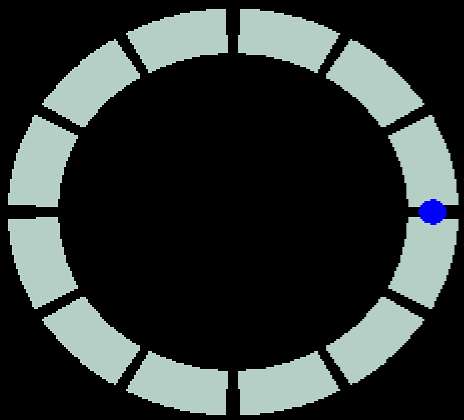
RXJ 1713.7-3946

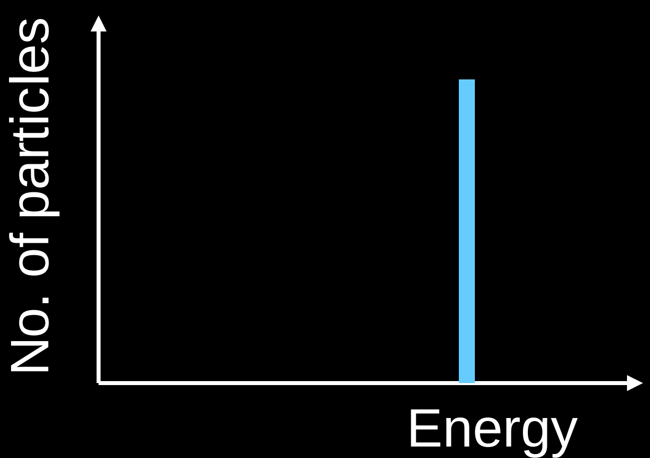
Proof that supernova shells accelerate particles to 100 TeV and beyond



How could cosmic accelerators work?

Man-made accelerators

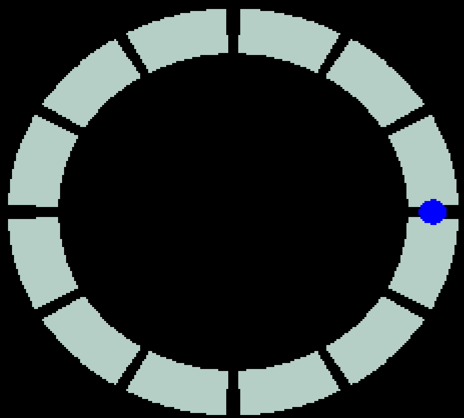


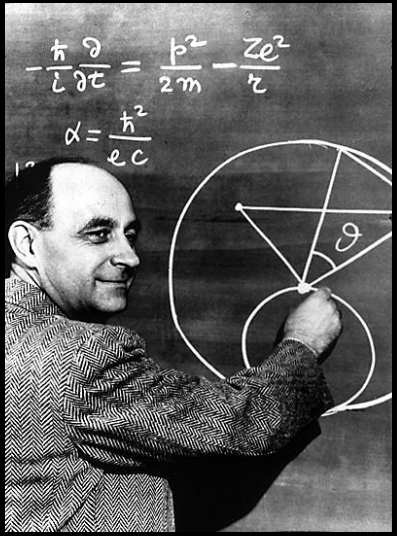


How could cosmic accelerators work?

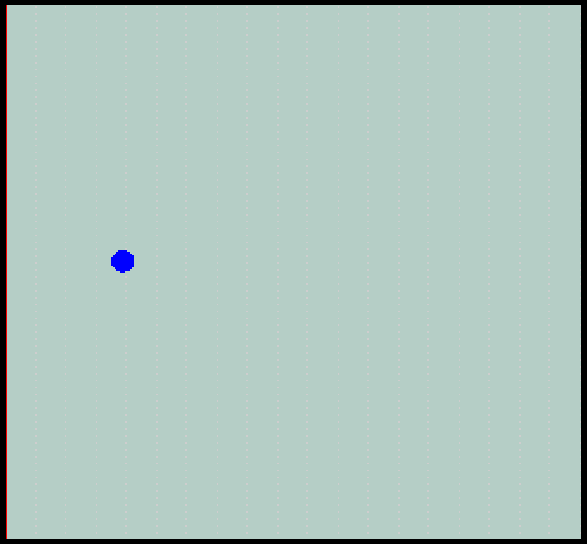
Man-made accelerators

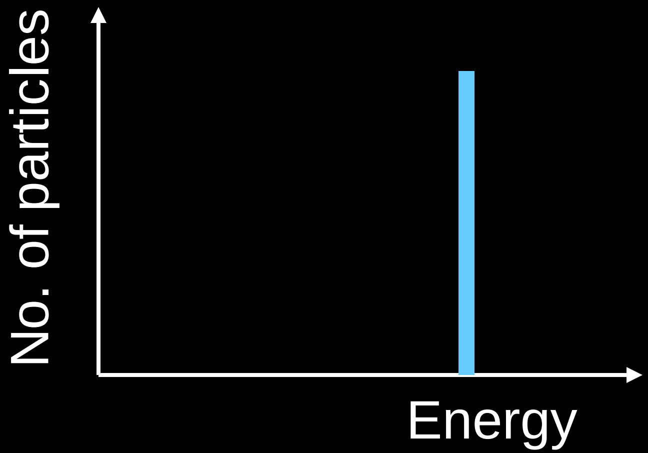
Nature's accelerators

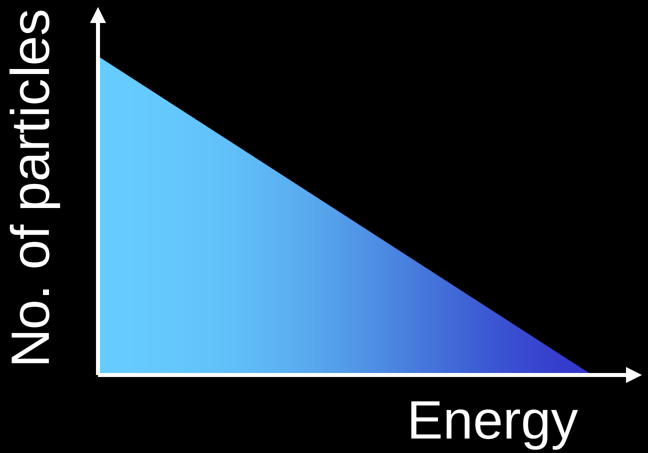




Enrico
Fermi

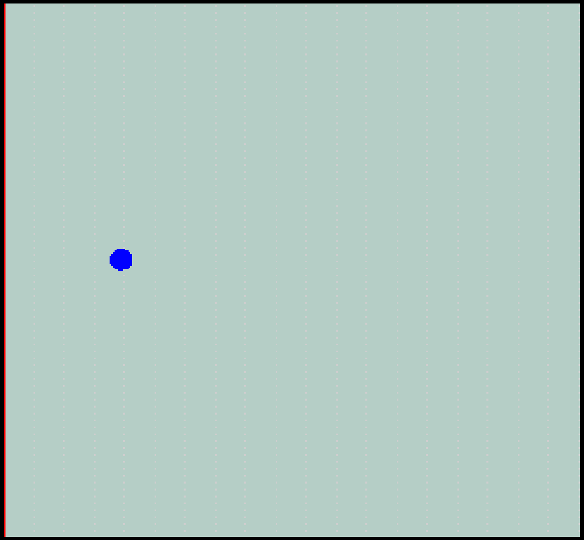






How could cosmic accelerators work?

Nature's accelerators



Energy gain / cycle $\Delta E/E \sim \beta_{shock}$

... many 100 cycles to reach TeV energies …

... takes several 100 years

Generates power law spectrum $dN/dE \sim E^{-2}$

… at some point, particle escapes …

… to be precise: $dN/dE \sim E^{-\Gamma}$, $\Gamma = (R+2)/(R-1)$

R = shock compression ratio

For strong shocks (Mach # >> 1): $R = 4 \rightarrow \Gamma = 2$

For weaker shocks: $R < 4 \rightarrow \Gamma > 2$

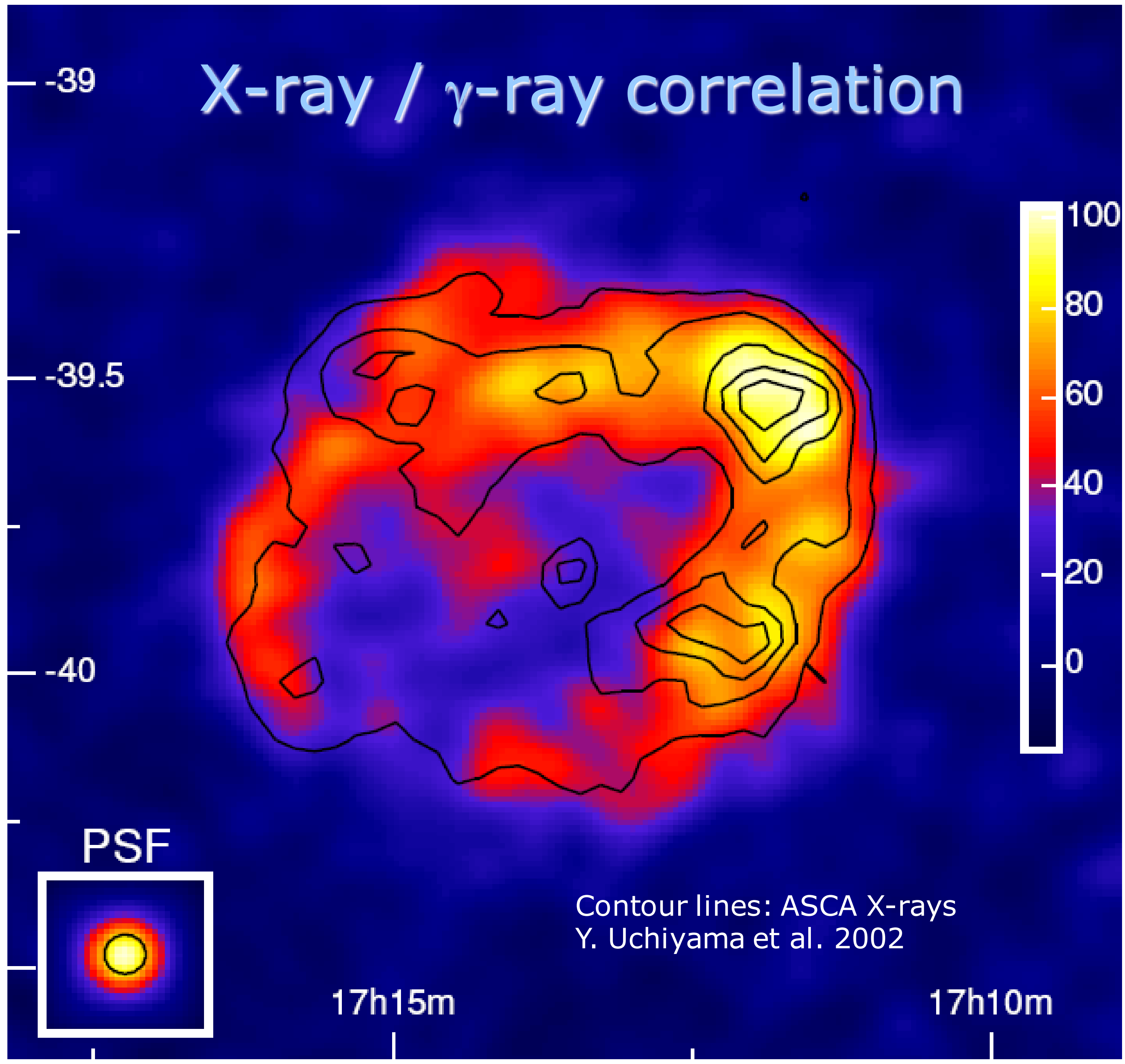
Peak energy $\sim 10^{15}$ eV

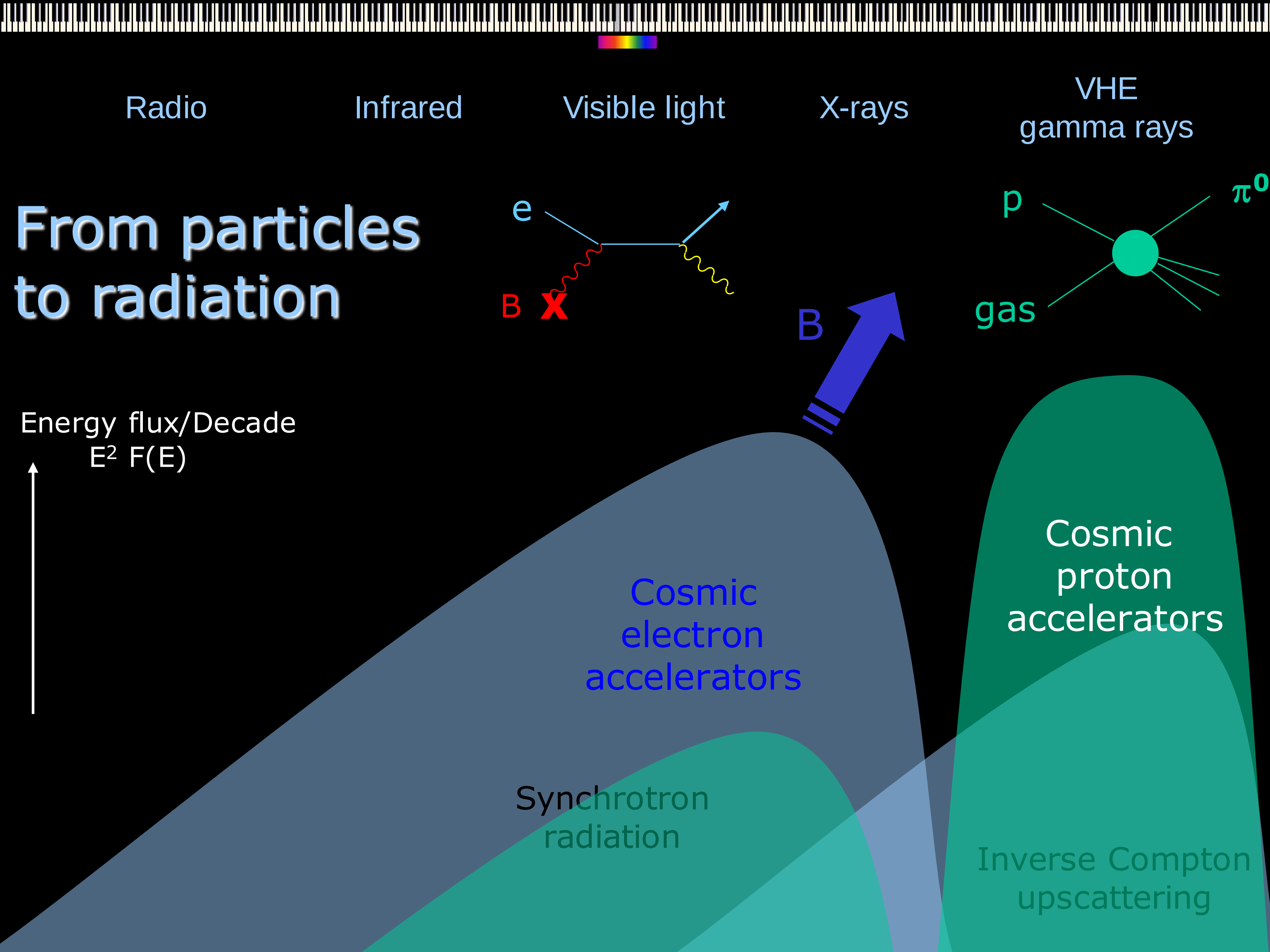
… depending on size of shock front …

Nonlinear process with efficiency ~50%!

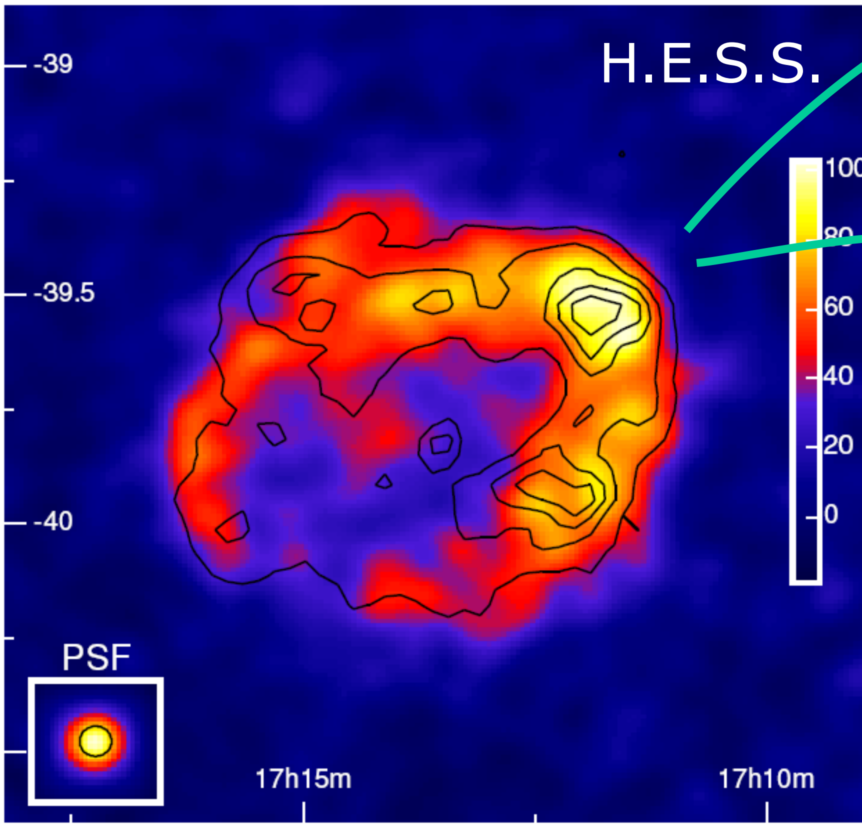
… accelerated particles generate plasma waves …

≥10% required to generate cosmic rays from supernovae


X-ray / γ-ray correlation
-39
-39.5
-40
100
80
60
40
20
0
PSF
17h15m
17h10m
Contour lines: ASCA X-rays
Y. Uchiyama et al. 2002


Radio
Infrared
Visible light
X-rays
VHE
gamma rays
From particles
to radiation
e
B
X
B
p
π^0
gas
Energy flux/Decade
E^2 F(E)
Cosmic
electron
accelerators
Cosmic
proton
accelerators
Synchrotron
radiation
Inverse Compton
upscattering

X-ray & gamma ray emission



Contour lines: ASCA X-rays
Y. Uchiyama et al. 2002

Porter et al. (2006)
Katz & Waxman (2007)
Plaga (2007)
...

electrons

X-rays ~ IC γ-rays

B ~ 10 μG

protons + 10^{-4} electrons/proton

Berezkho & Völk (2006)

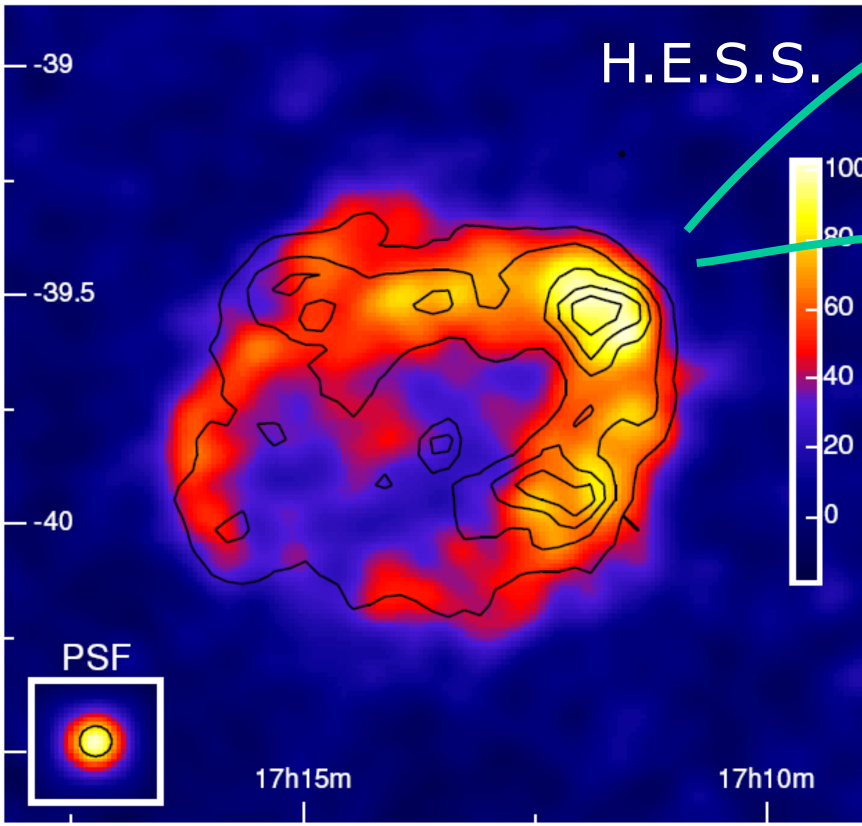
B ~ 100 μG

+ gas
$\rightarrow \pi^o \rightarrow \gamma$-rays

X-rays

X-ray & gamma ray emission

Porter et al. (2006)
Katz & Waxman (2007)
Plaga (2007)
…



Contour lines: ASCA X-rays
Y. Uchiyama et al. 2002

electrons

X-rays ~ IC γ-rays

B ~ 10 μG

protons + 10^{-4} electrons/proton

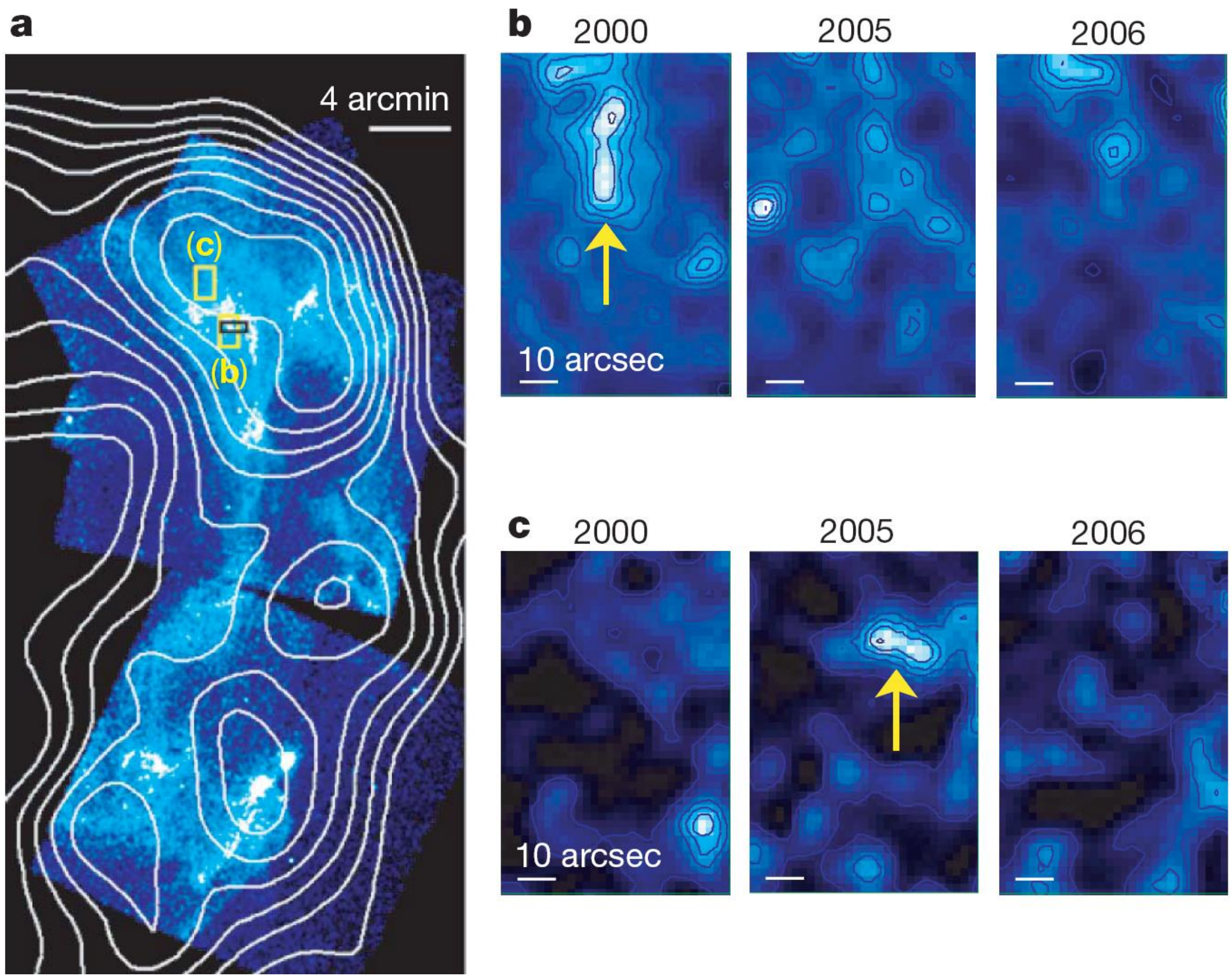
Berezkho & Völk (2006)

+ gas
$\rightarrow B^2 \sim \rho$
Lucek & Bell
MNRAS 2000

B ~ 100 μG

+ gas
$\rightarrow \pi^o \rightarrow \gamma$-rays ~ X-rays

Key issue: High B fields in SNR?



RX J1713.7
Chandra
Uchiyama et al.
Nature 449 (2007) 576

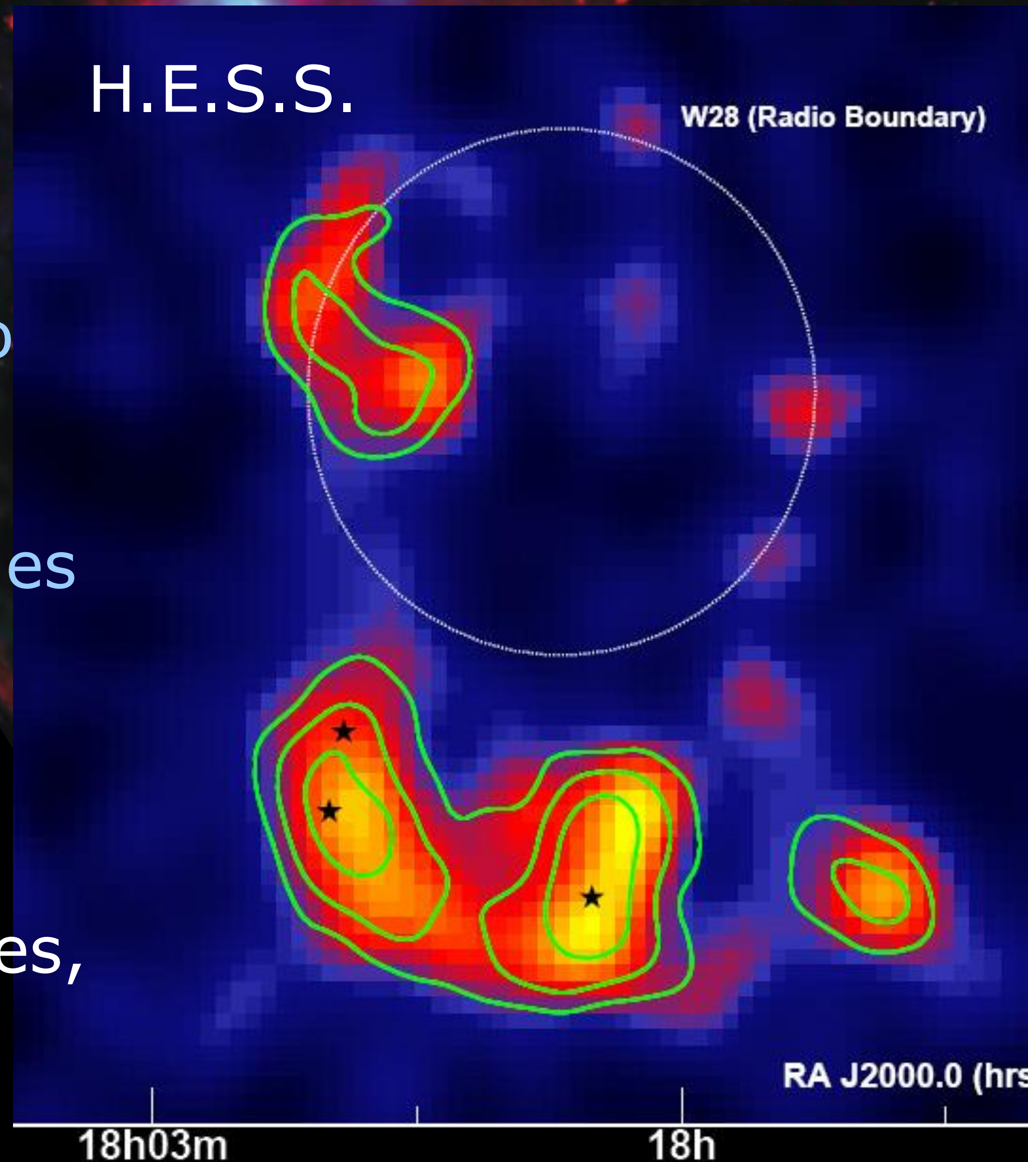
Need B > 1 mG

Old SNRs & interacting SNRs

Which fraction of SNR energy goes into cosmic-ray nuclei?

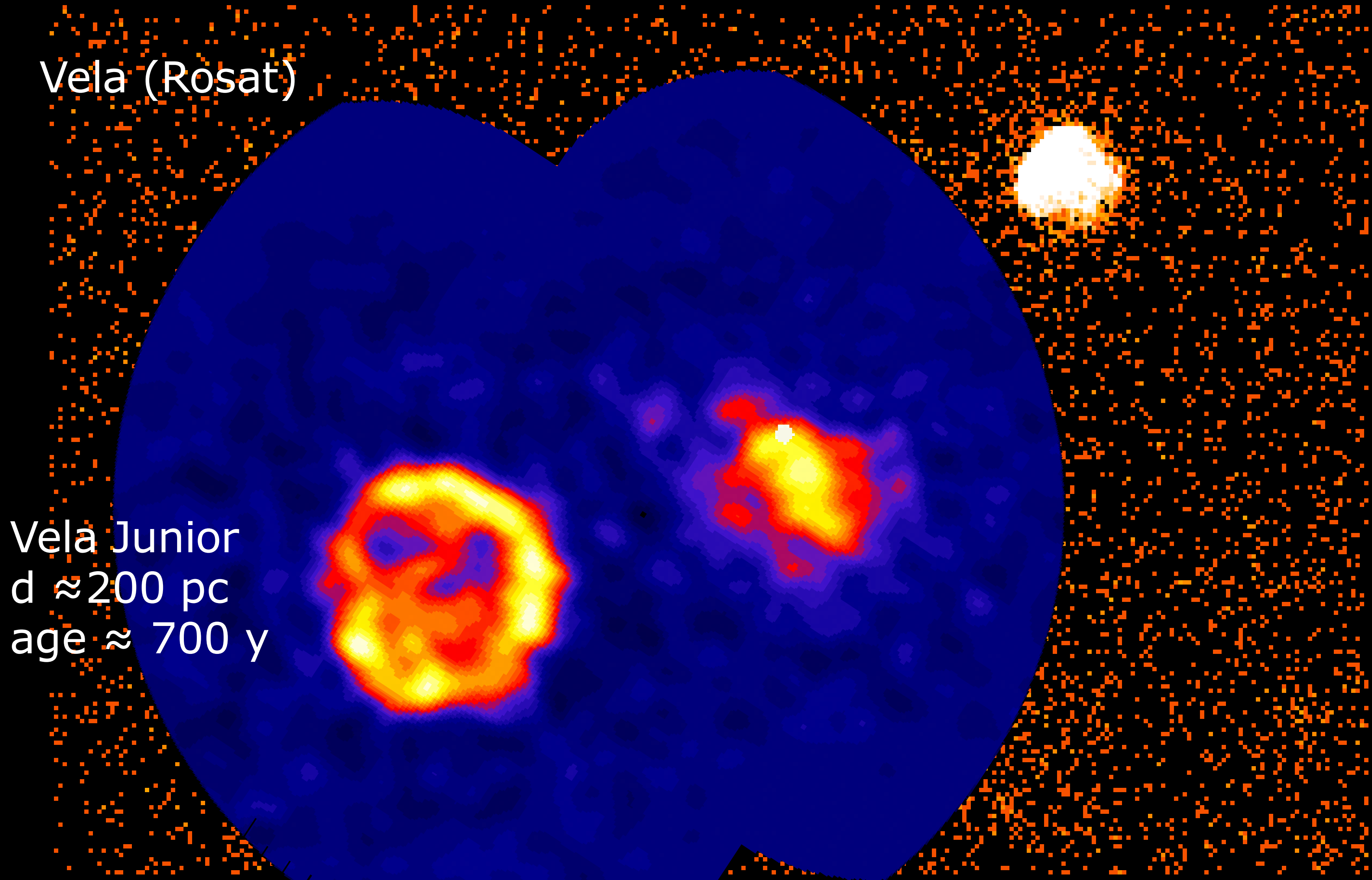
How/when are particles released/

Interacting SNR probe nature of accelerated particles, particle release, and particle propagation



l. 2006
LA
MSX 8 micron

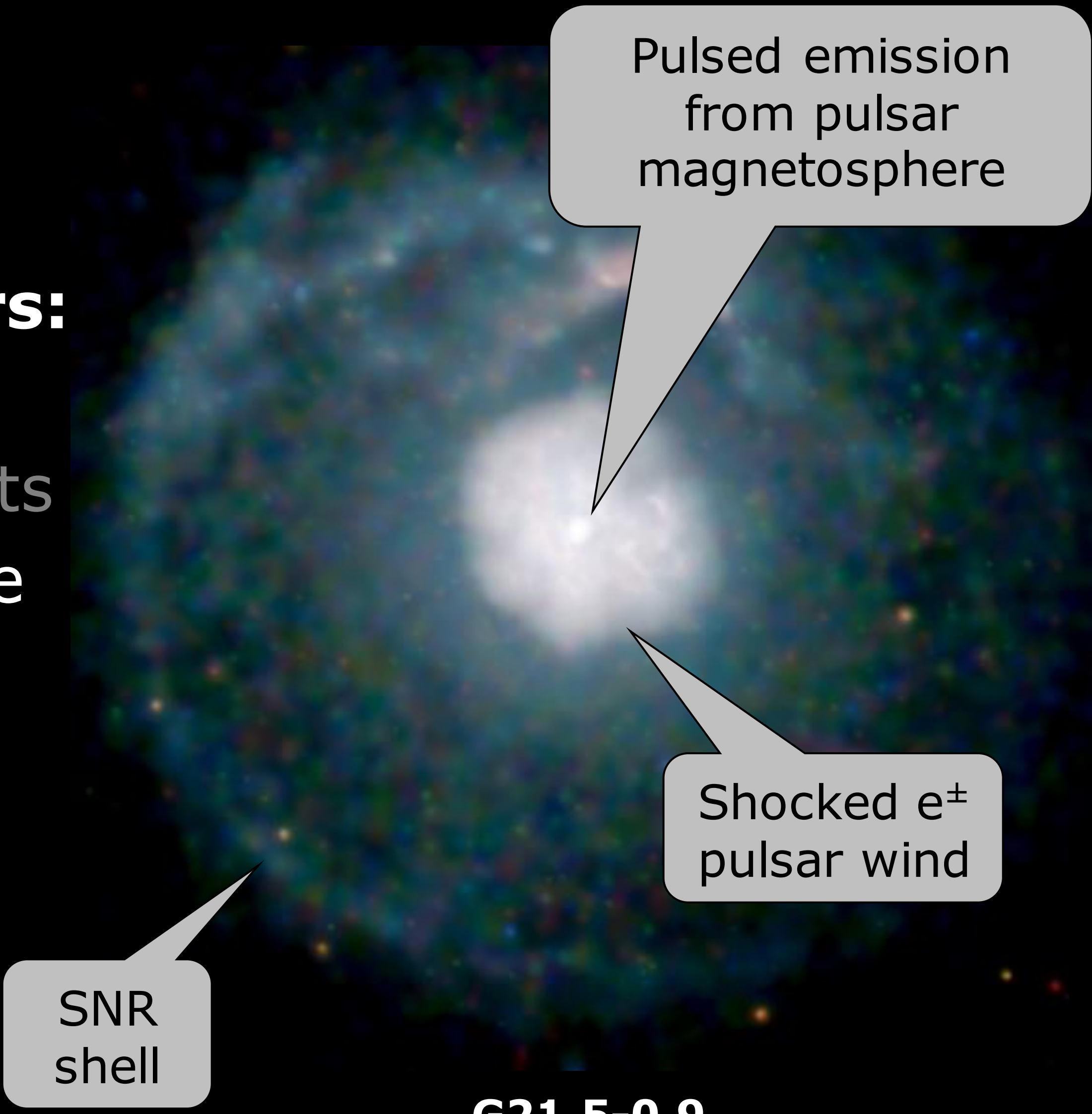
More than SNR: the Vela region



Gamma ray sources & their physics

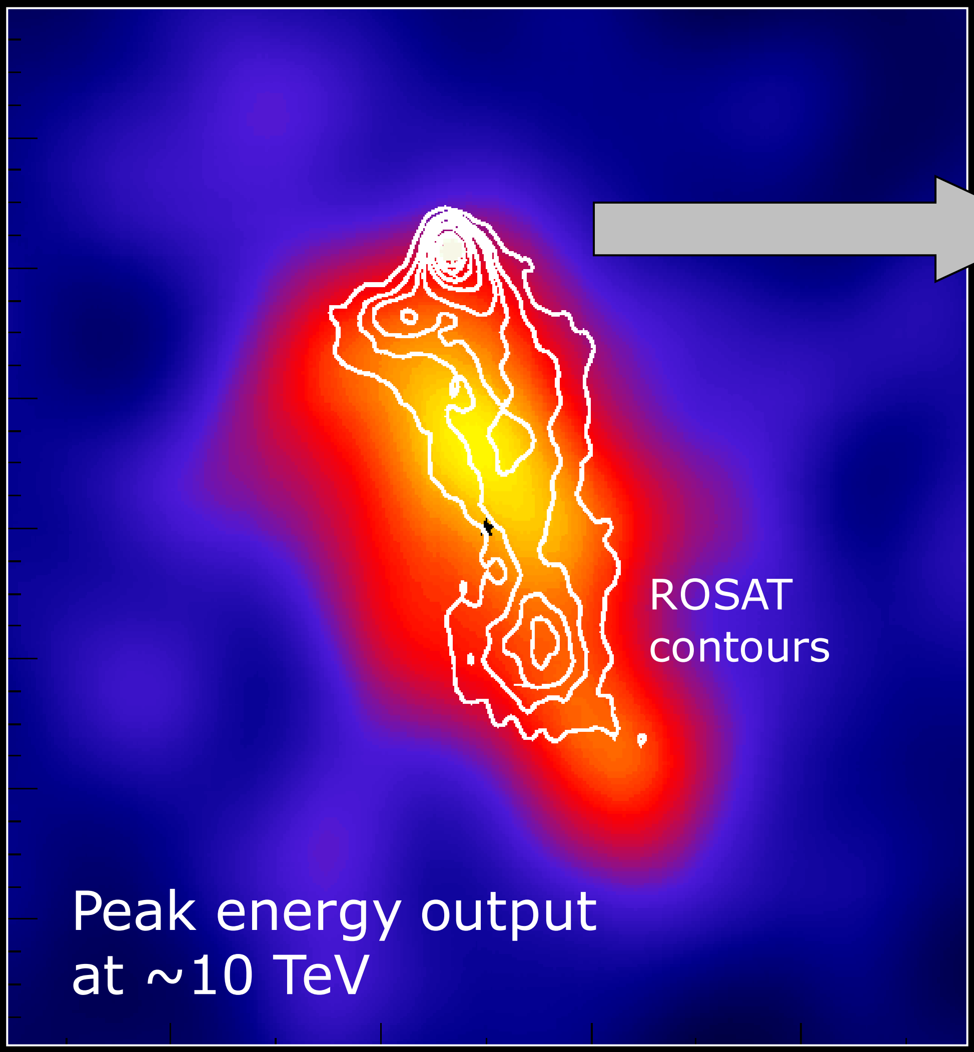
A tour of galactic particle accelerators:

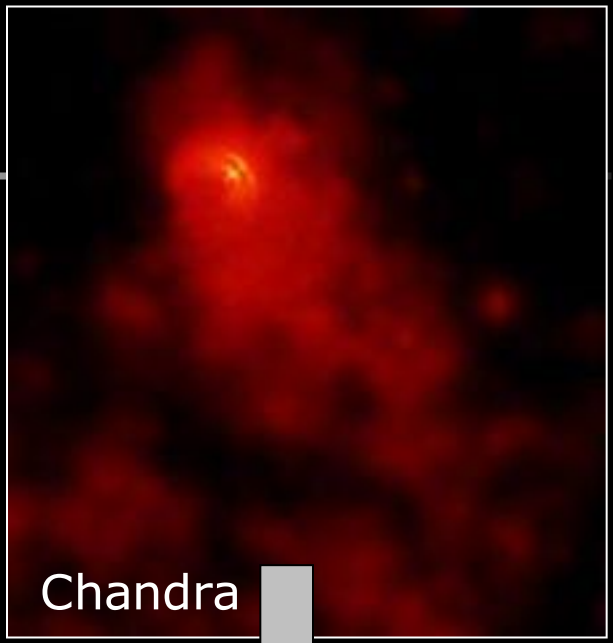
- Supernova remnants
- Pulsar wind nebulae
- Binaries
- "Dark sources"

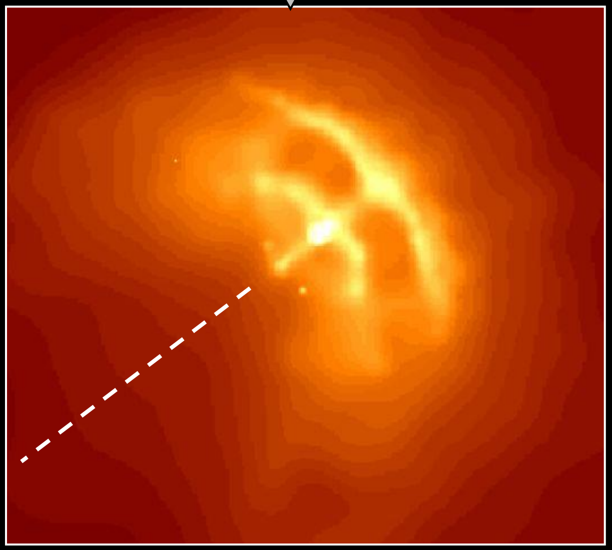


G21.5-0.9
Chandra / H.Matheson & S.Safi-Harb

Vela-X



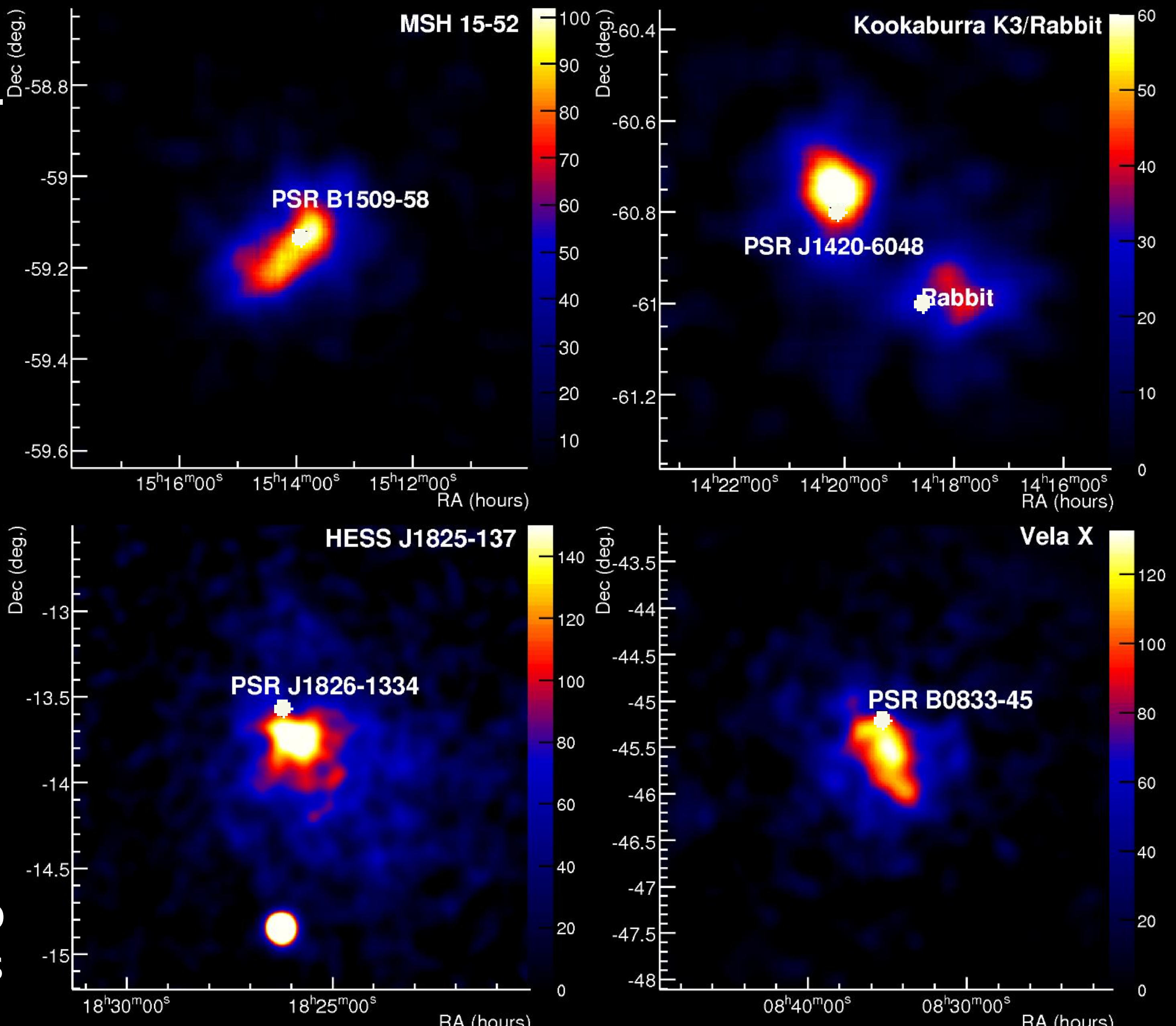




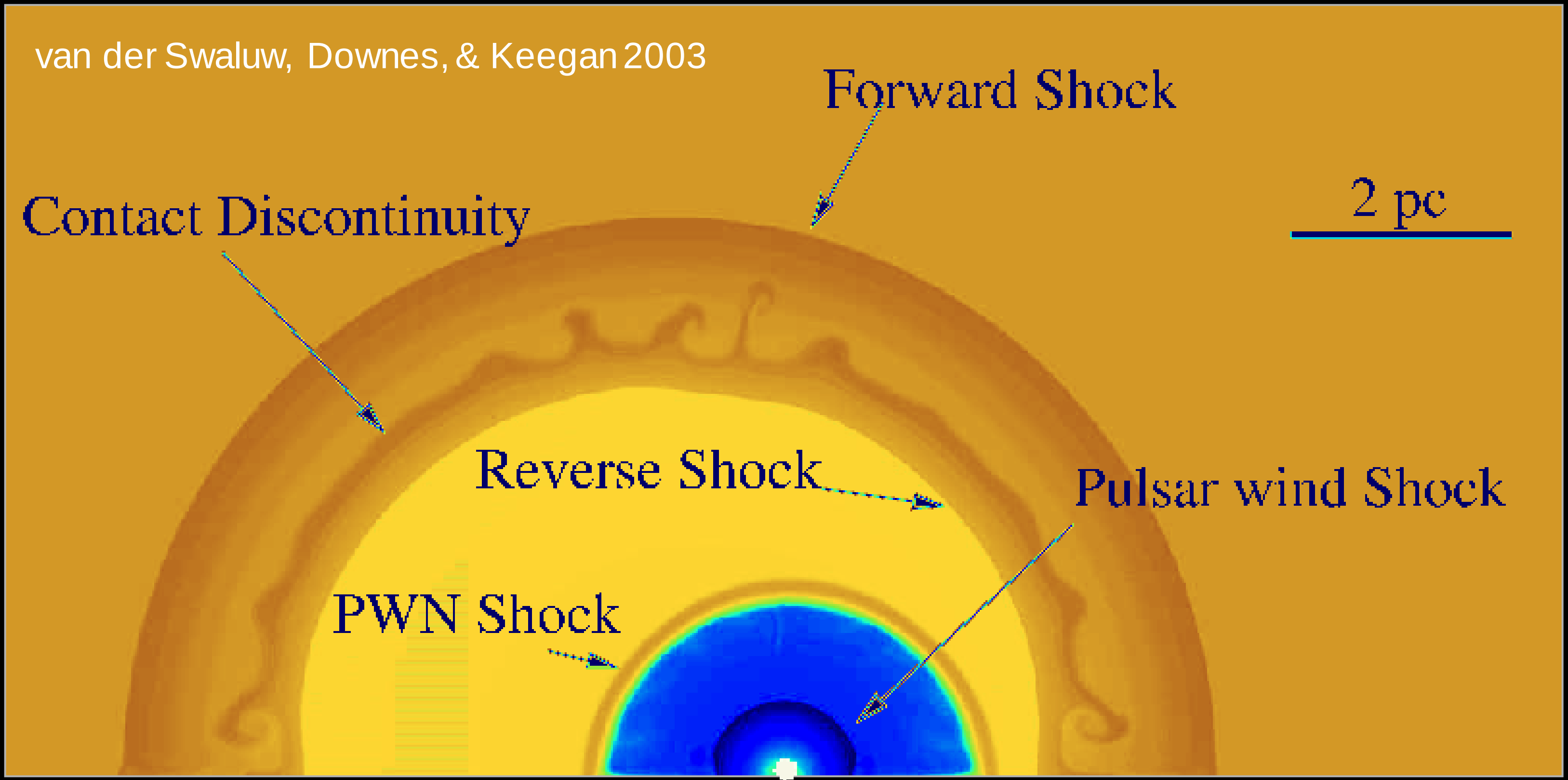
PWN

γ-ray sources are

- extended
- displaced from pulsar
- O(1%) of spin-down energy loss converted to gamma rays

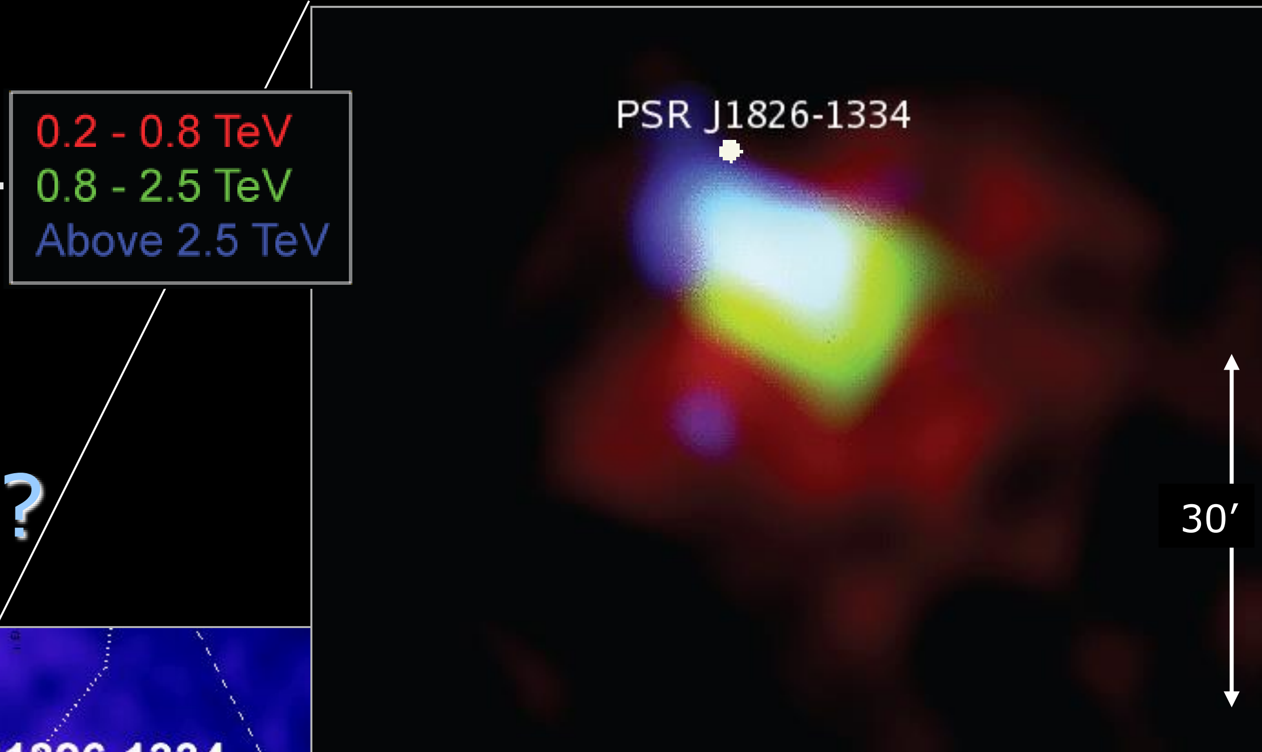


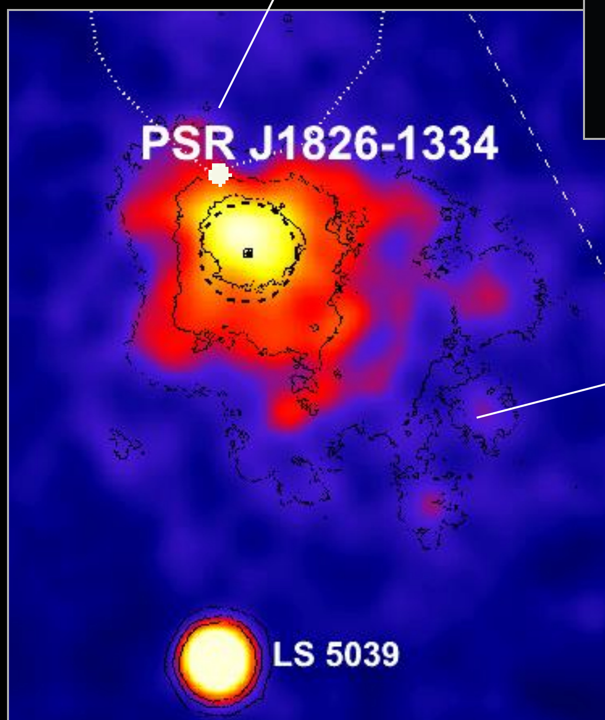
Hydrodynamics simulations: Pulsar "Kick"



Hydrodynamics simulations: Pulsar "Kick"

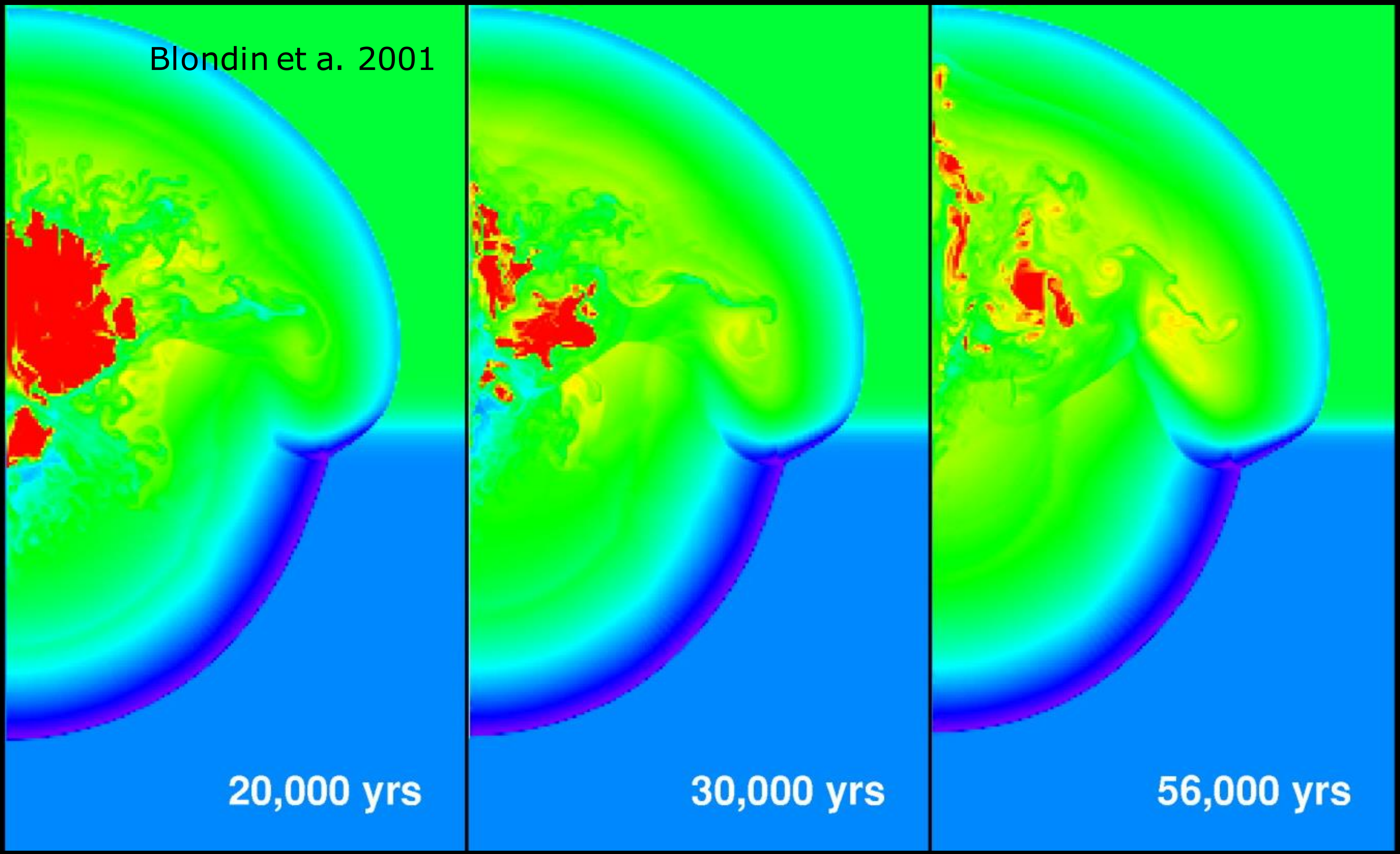
Maybe a chance coincidence ?



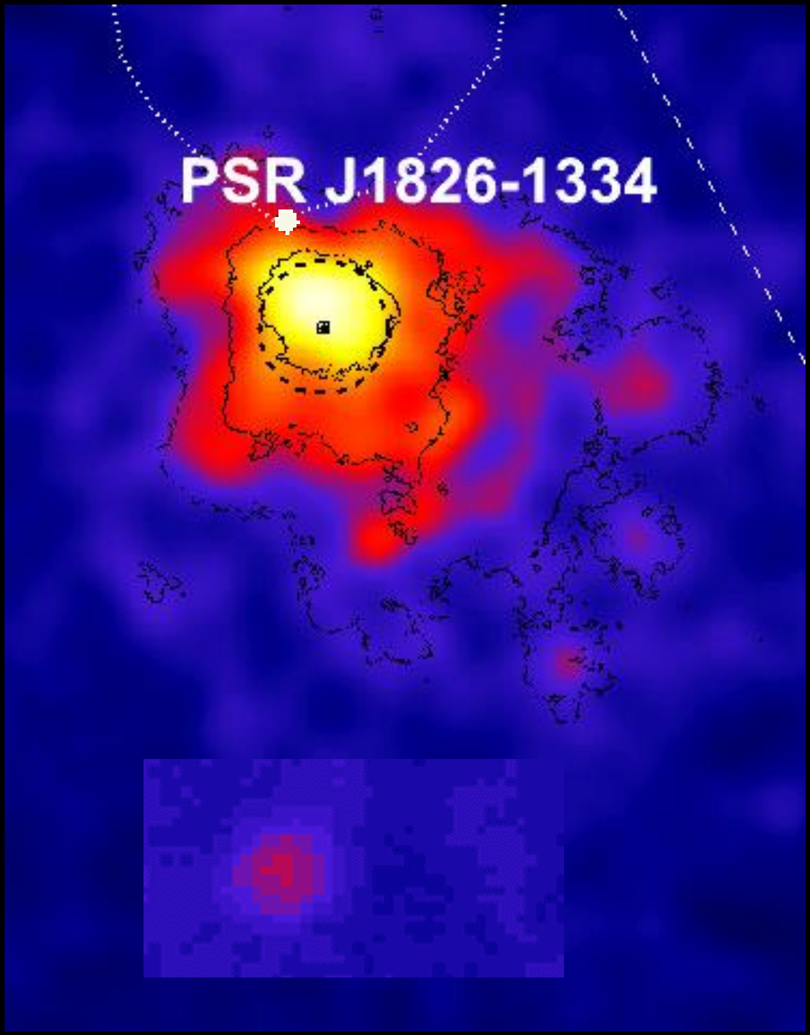


Energy-dependent morphology in HESS J1825-137

Supernova explosion in inhomogeneous medium?

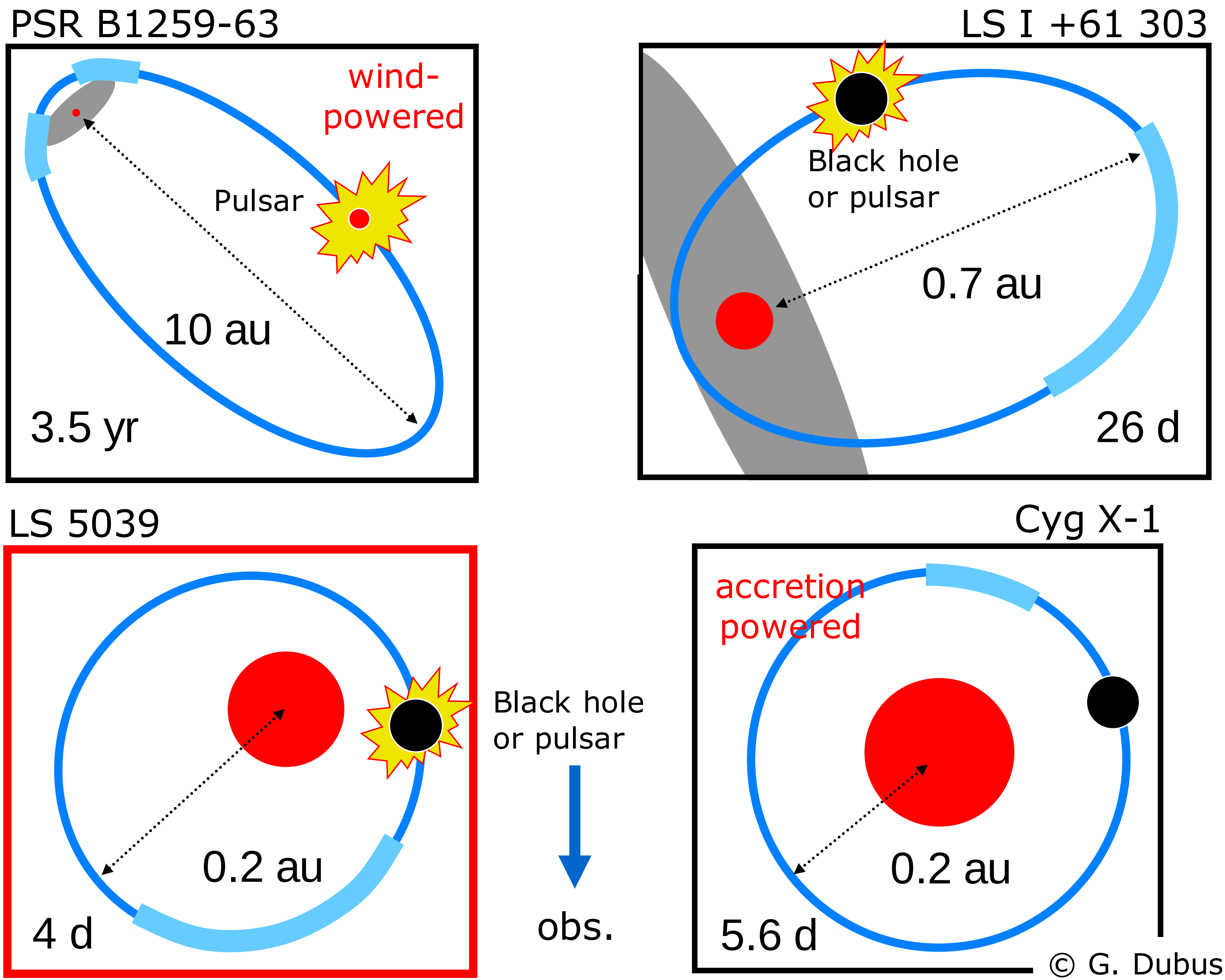


Gamma ray sources & their physics



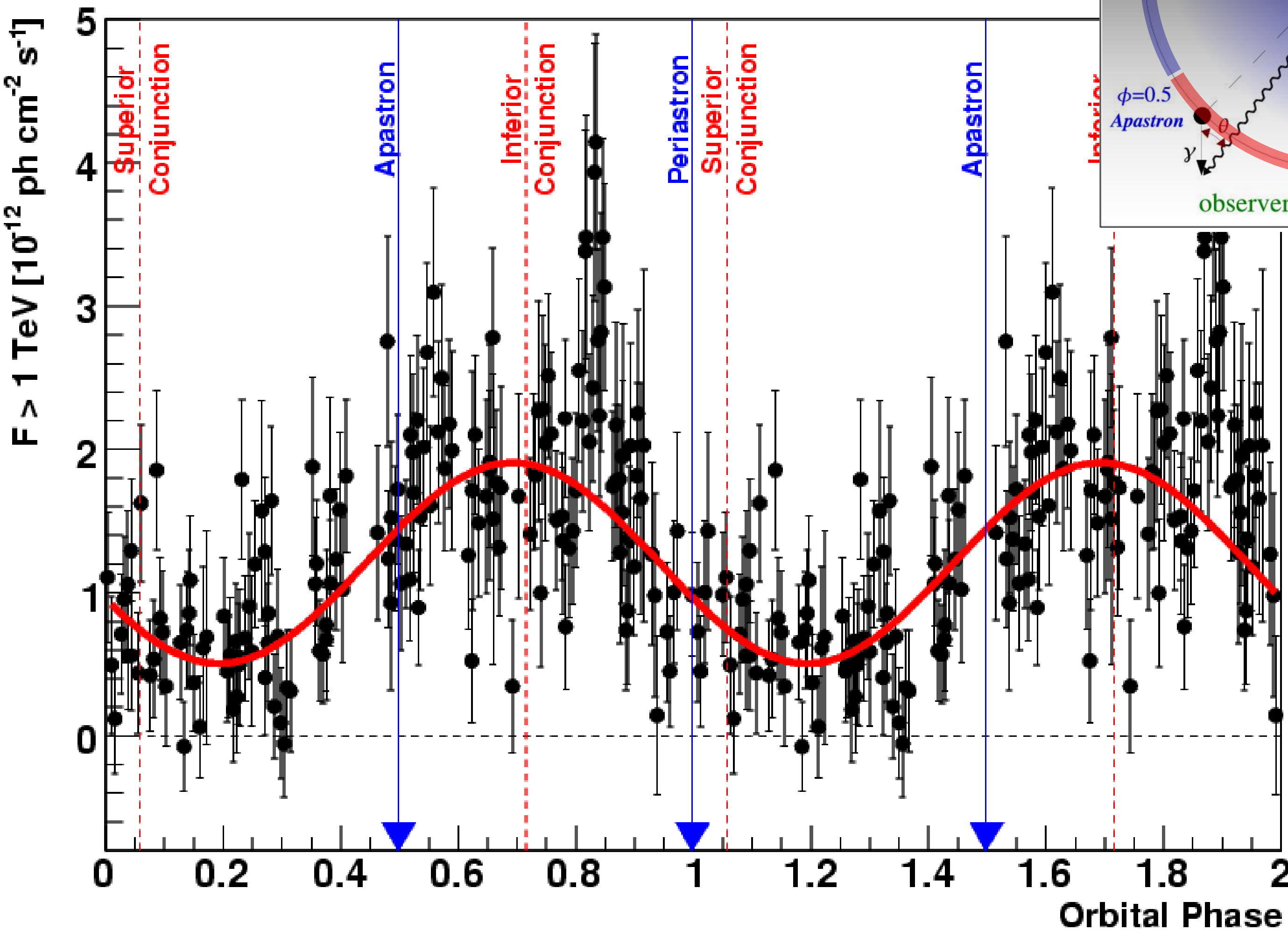
A tour of galactic particle accelerators:

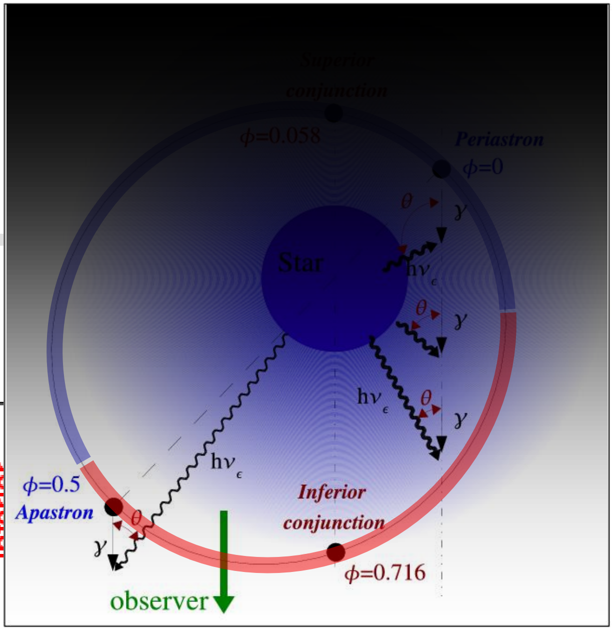
- Supernova remnants
- Pulsar wind nebulae
- Binaries
- "Dark sources"


PSR B1259-63
wind-
powered
Pulsar
10 au
3.5 yr
LS I +61 303
Black hole
or pulsar
0.7 au
26 d
LS 5039
0.2 au
4 d
Black hole
or pulsar
obs.
Cyg X-1
accretion
powered
0.2 au
5.6 d
© G. Dubus

Folded light curve

γ-Period: 3.908±0.002 days





Folded using optical period

Data repeated for 2 cycles

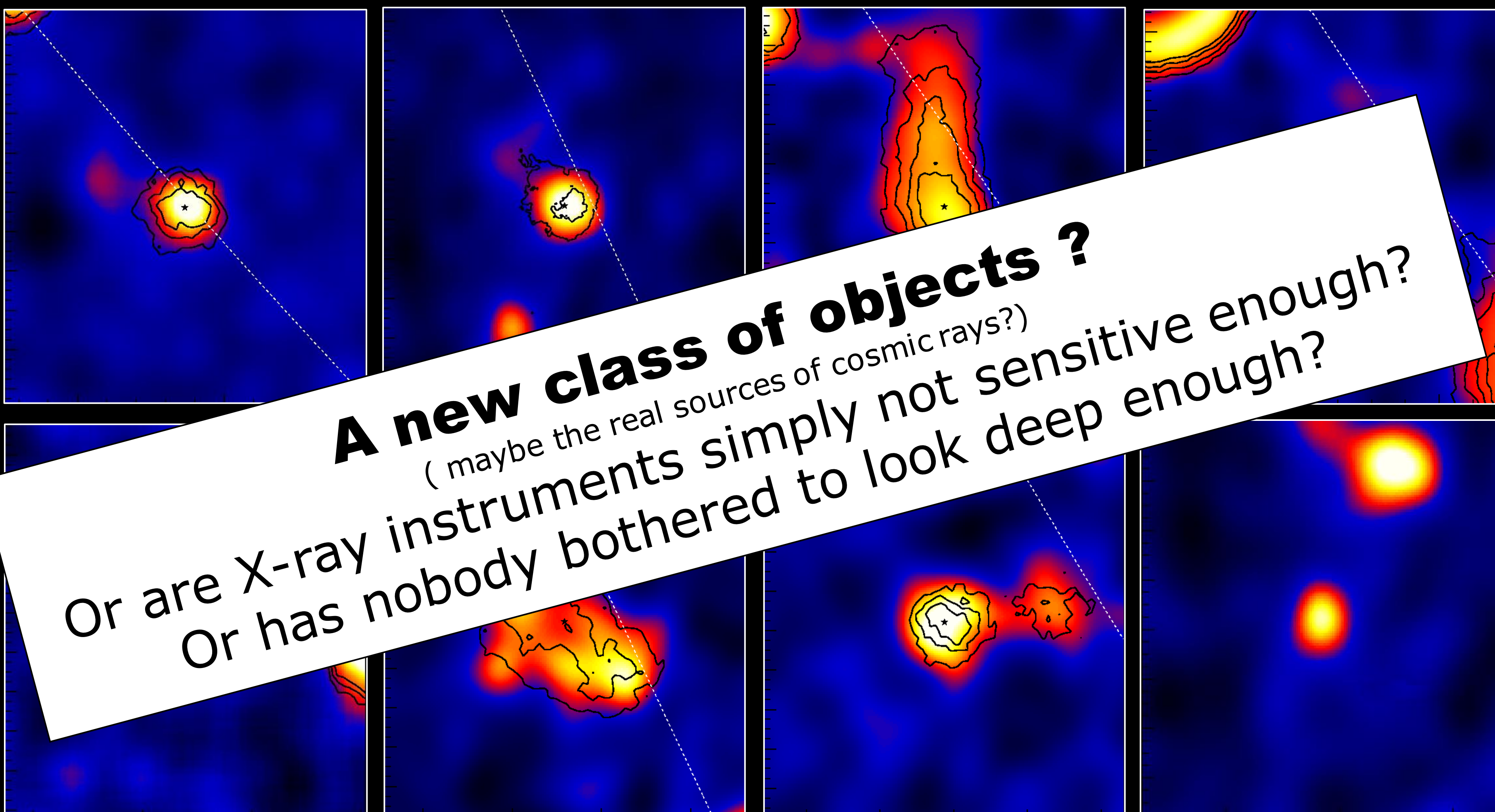
Gamma ray sources & their physics

A tour of galactic particle accelerators:

- Supernova remnants
- Pulsar wind nebulae
- Binaries
- “Dark sources”

"Dark" sources: Objects which only shine in gamma rays !

… without plausible counterparts in X-rays, radio, …



A new class of objects ?

(maybe the real sources of cosmic rays?)

Or are X-ray instruments simply not sensitive enough?

Or has nobody bothered to look deep enough?

Explanations

- Old supernova remnants (Yamazaki et al., astro-ph/0601704)
- Old PWN
- GBR remnants (Atoyan et al., astro-ph/0601704)

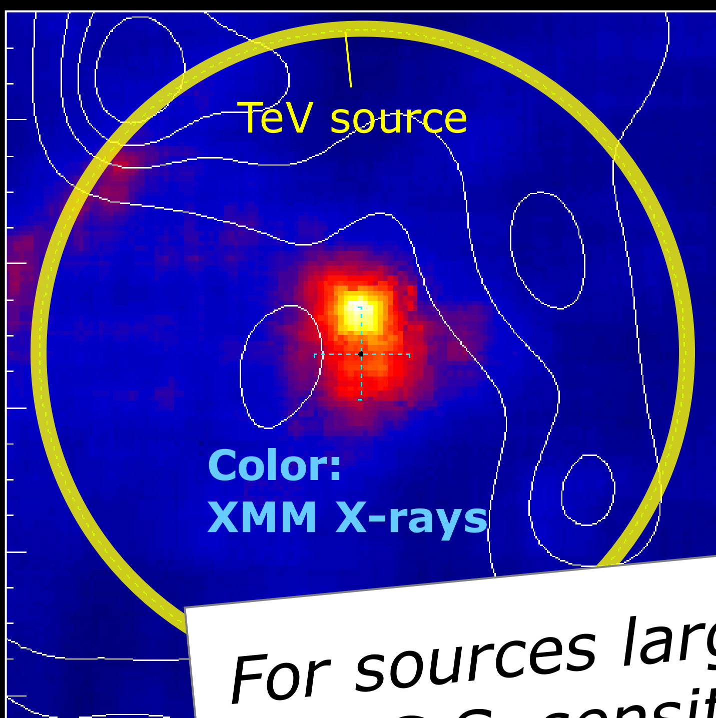
Basic idea: electrons are gone in old objects

➡ No X-rays or radio

- Stellar winds / OB assoc.
- DM halo objects / IMBHs

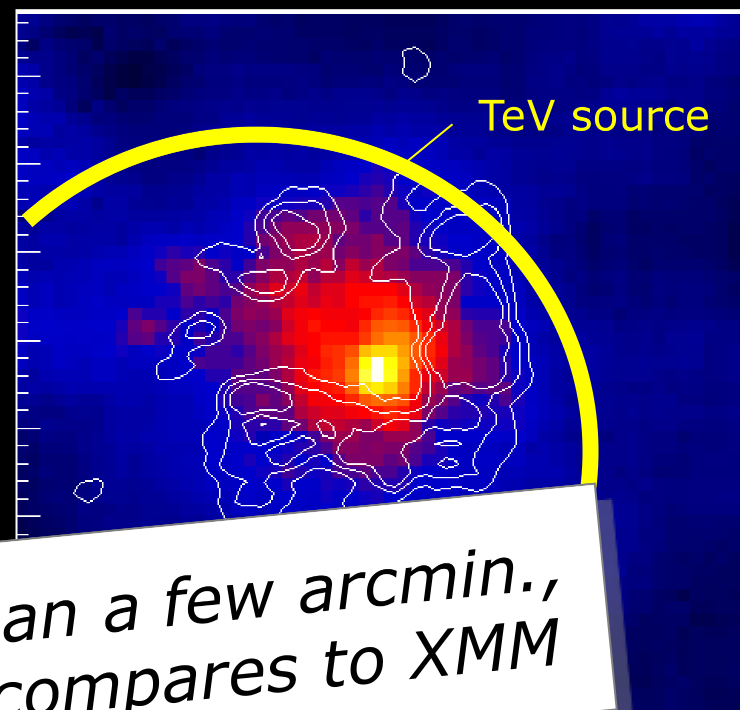
Not all remain dark…

HESS J1640-465
Funk et al., astro-ph/0701166



contours

HESS J1813-178
Funk et al., astro-ph/0611646

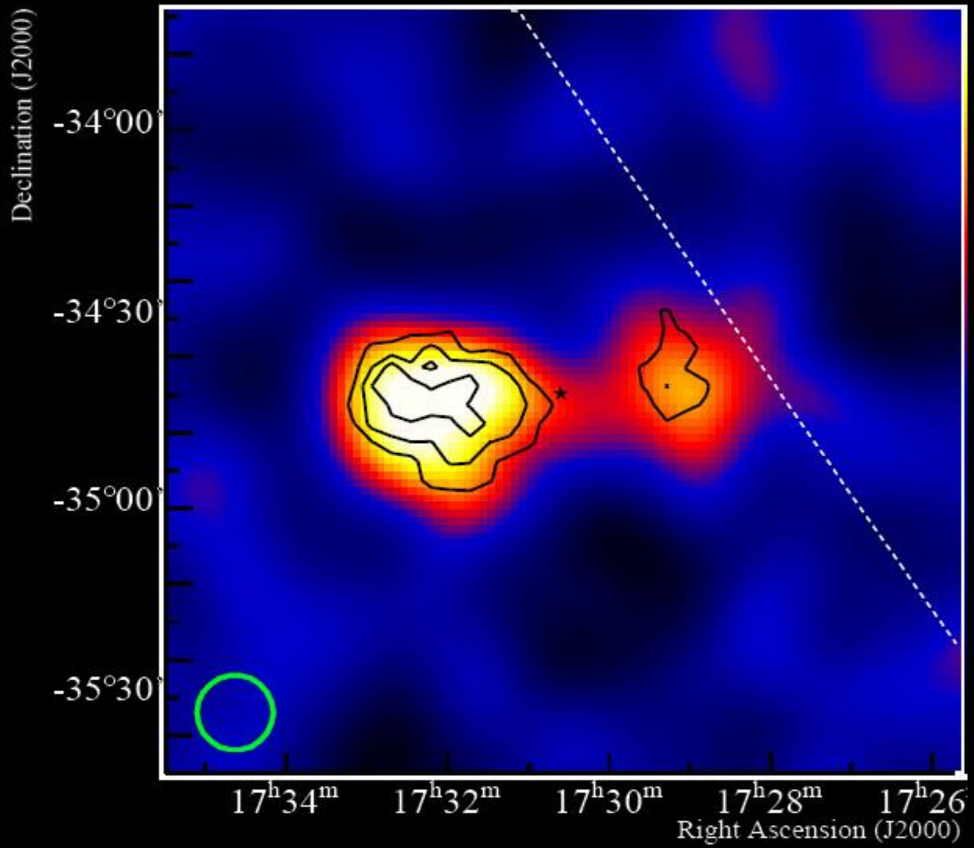


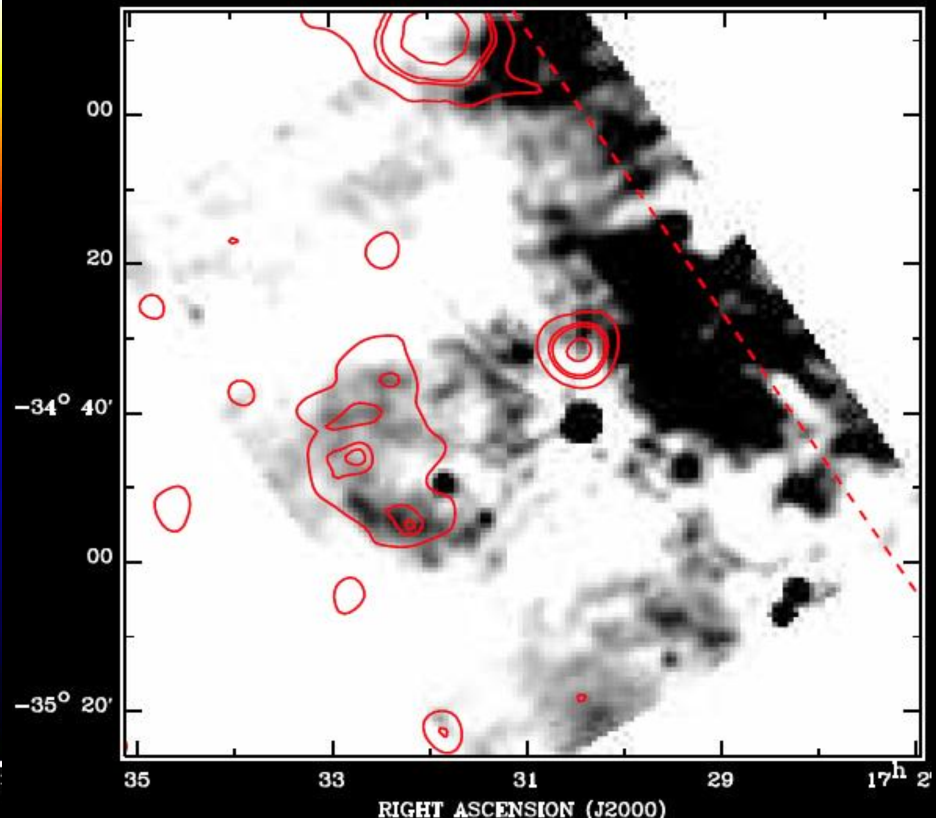
Radio shell
Helfand et al., astro-ph/0505392
Brogan et al., astro-ph/0505145

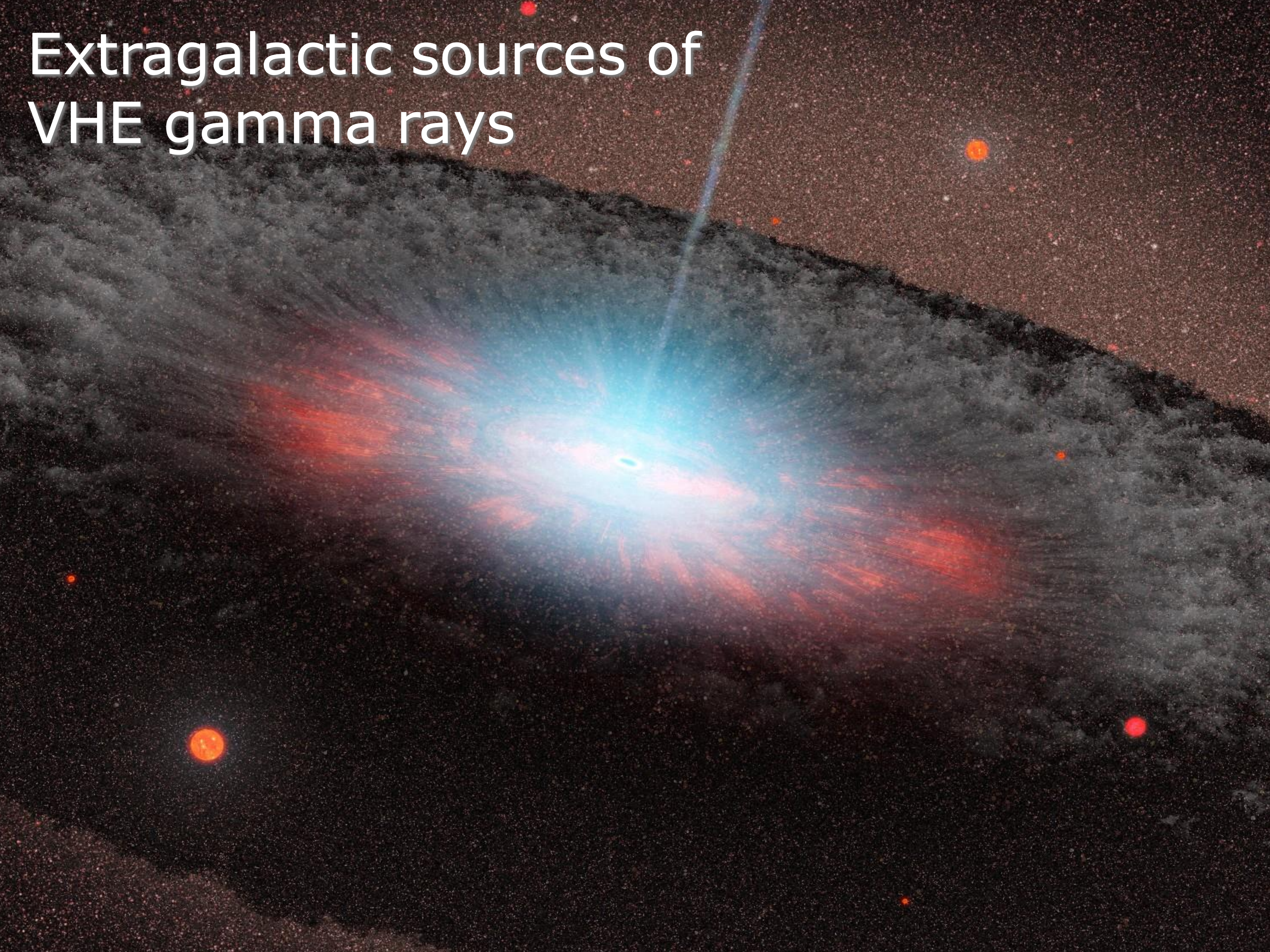
For sources larger than a few arcmin., H.E.S.S. sensitivity compares to XMM

Not all remain dark…

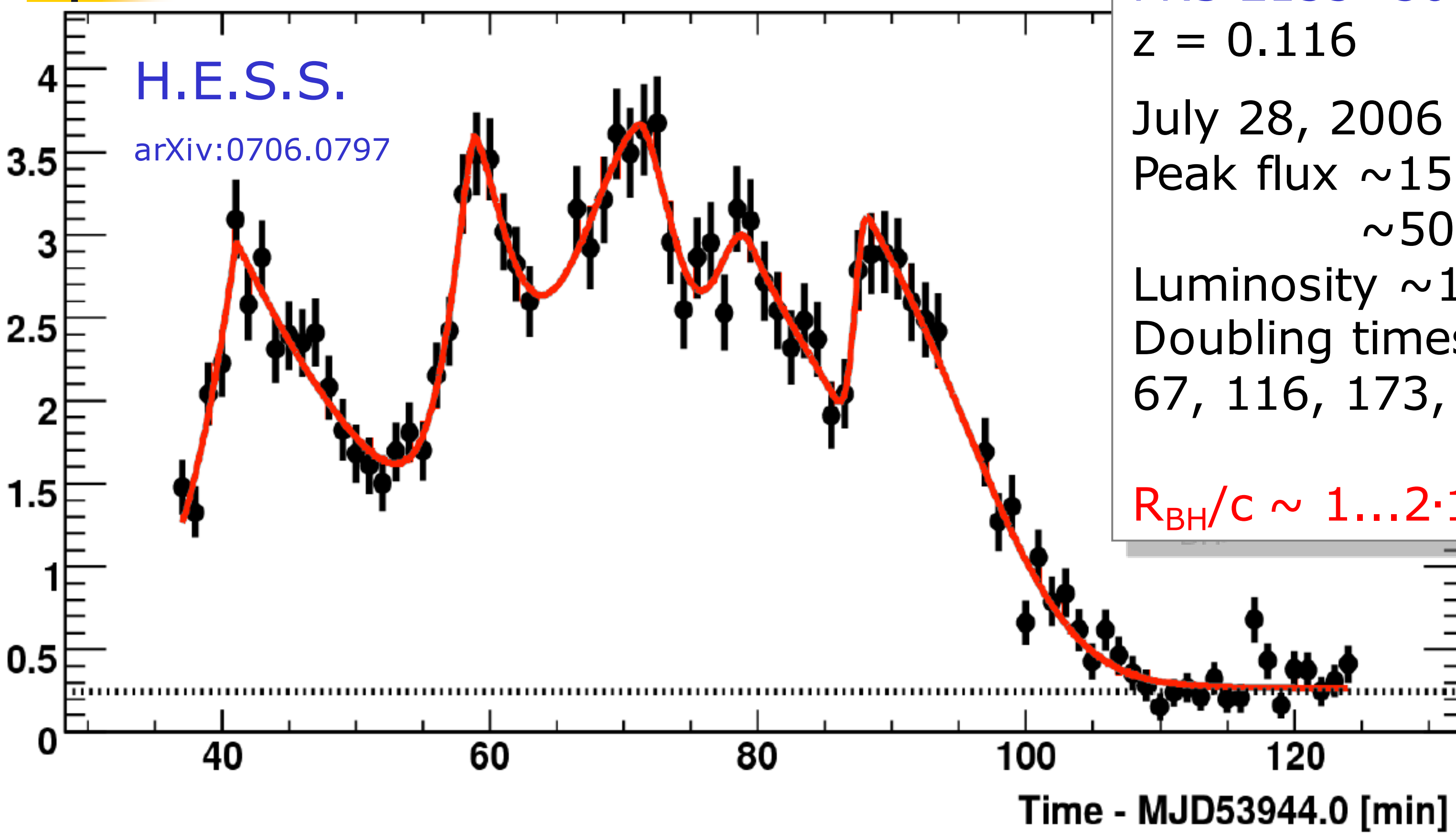
HESS J1731-347
Tian et al., arXiv:0801.3254






Extragalactic sources of
VHE gamma rays

AGN light curves



PKS 2155−304
z = 0.116

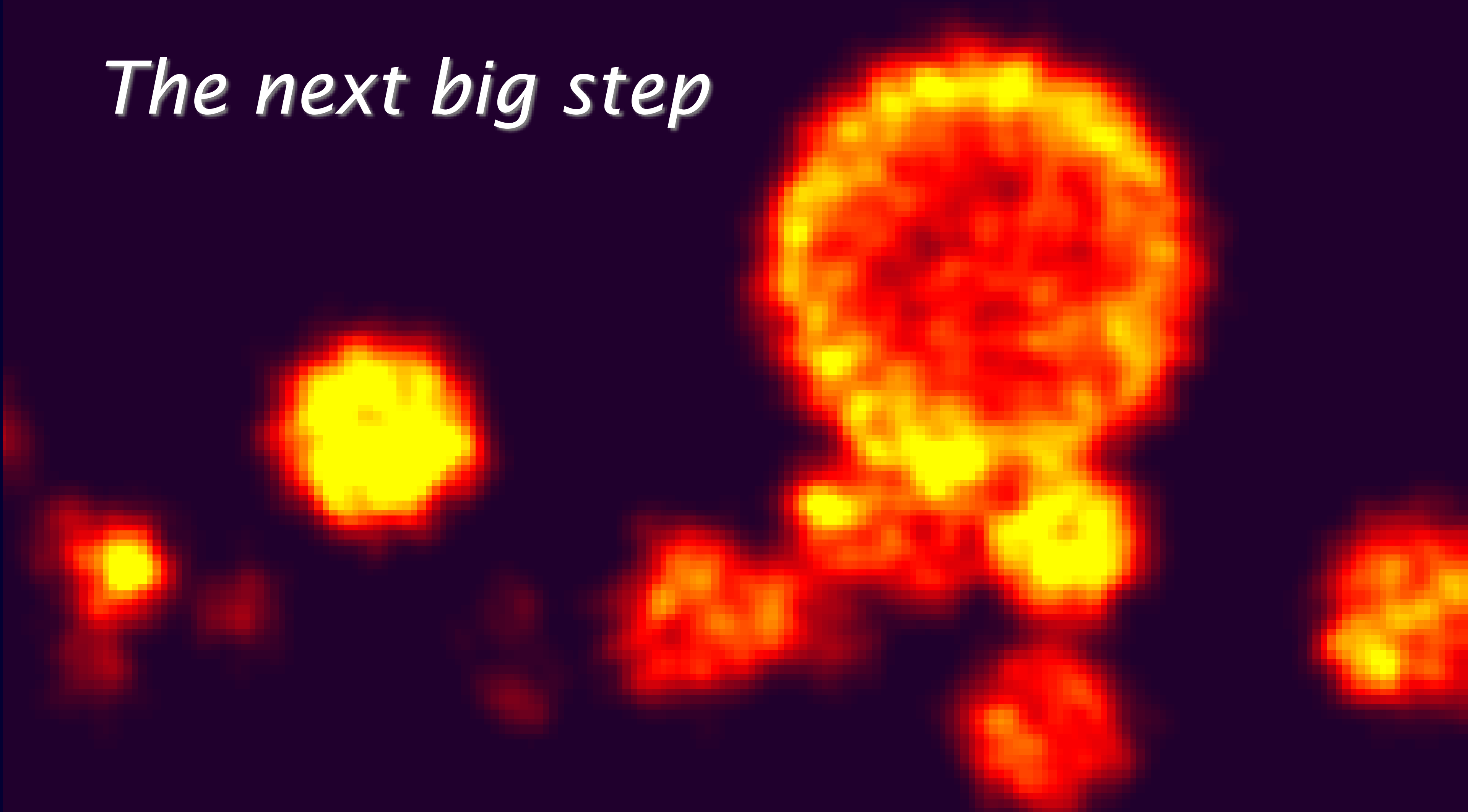
July 28, 2006
Peak flux ~15 x Crab
~50 x average
Luminosity ~10^{12} x Crab
Doubling times
67, 116, 173, 178 ±50 s

$R_{BH}/c \sim 1\ldots2 \cdot 10^4$ s

- Challenge for modelling of processes in and geometry of jets
- Search for effects of quantum gravity at the level of a few % of the Planck scale

The age of real VHE gamma ray astronomy has started

The next big step

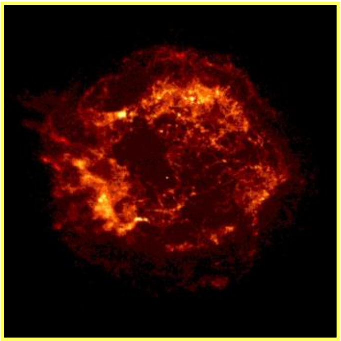


“Typical” CTA field of view

CTA – the Cherenkov Telescope Array

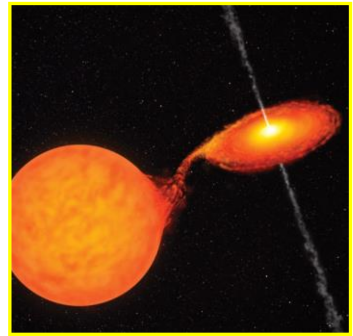
An advanced facility for ground-based gamma-ray astronomy

Scientific Objectives

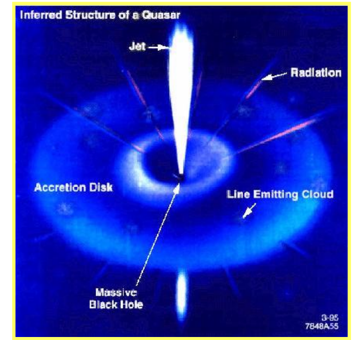


SNRs

Pulsars and PWN



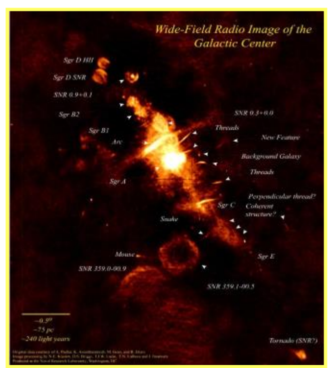
Micro quasars X-ray binaries



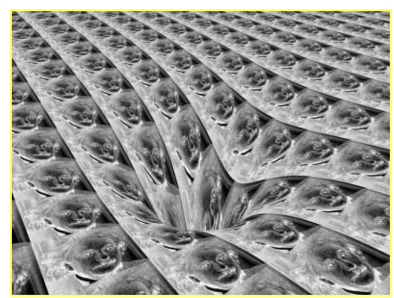
AGNs

GRBs

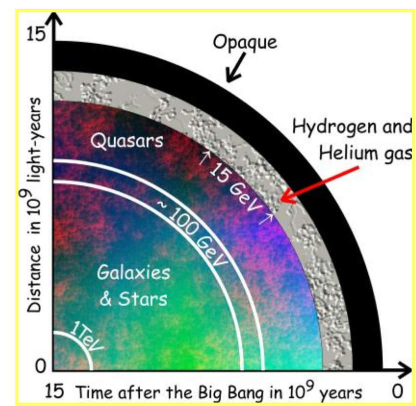
Origin of cosmic rays



Dark matter



Space-time & relativity

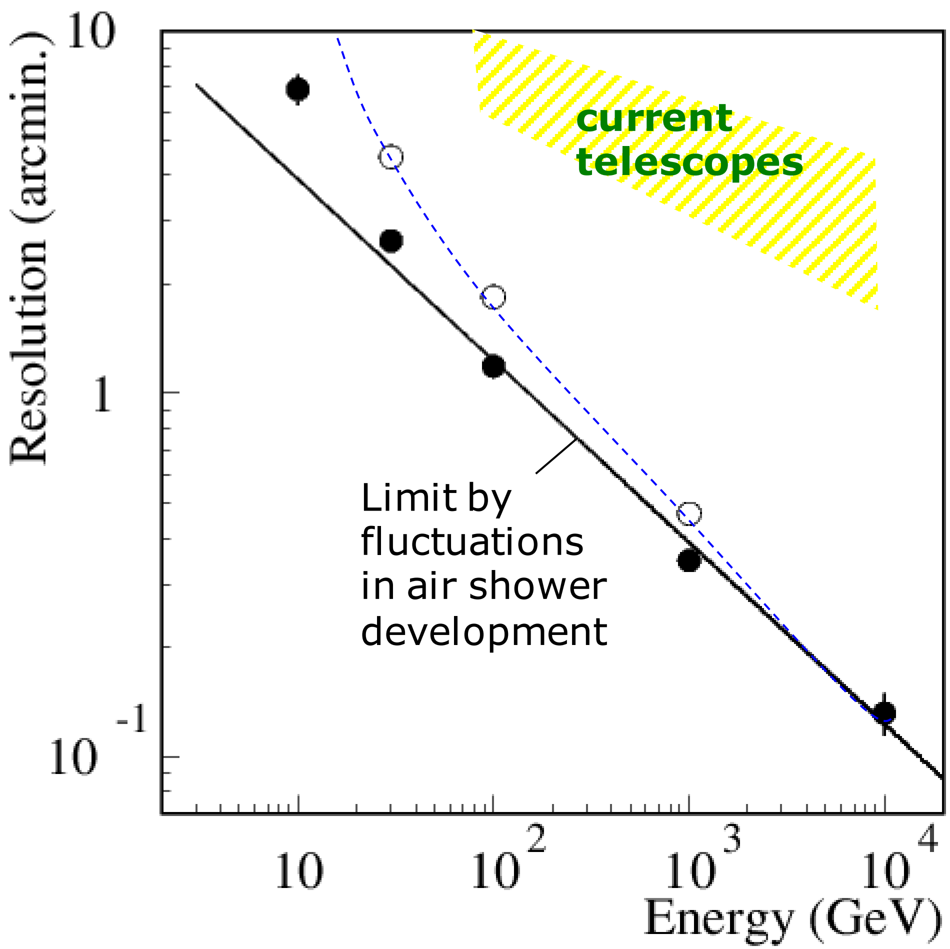


Cosmology

Wish list for CTA

- Higher sensitivity at TeV energies (x 10)
  more sources, details in extended sources
- Lower threshold (some 10 GeV)
  pulsars, distant AGN, source mechanisms
- Higher energy reach (PeV and beyond)
  cutoff region of Galactic accelerators
- Wider field of view
  extended sources, surveys
- Improved angular resolution
  structure of extended sources
- Higher detection rates
  transient phenomena

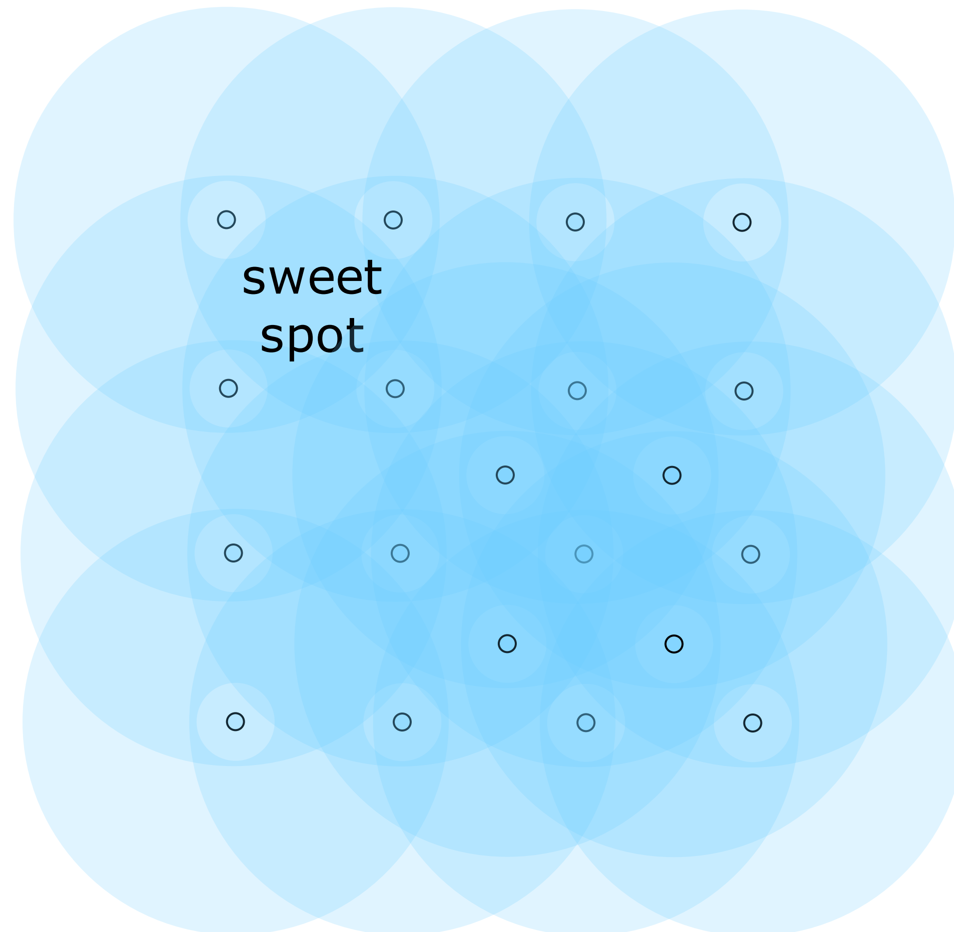
Angular resolution

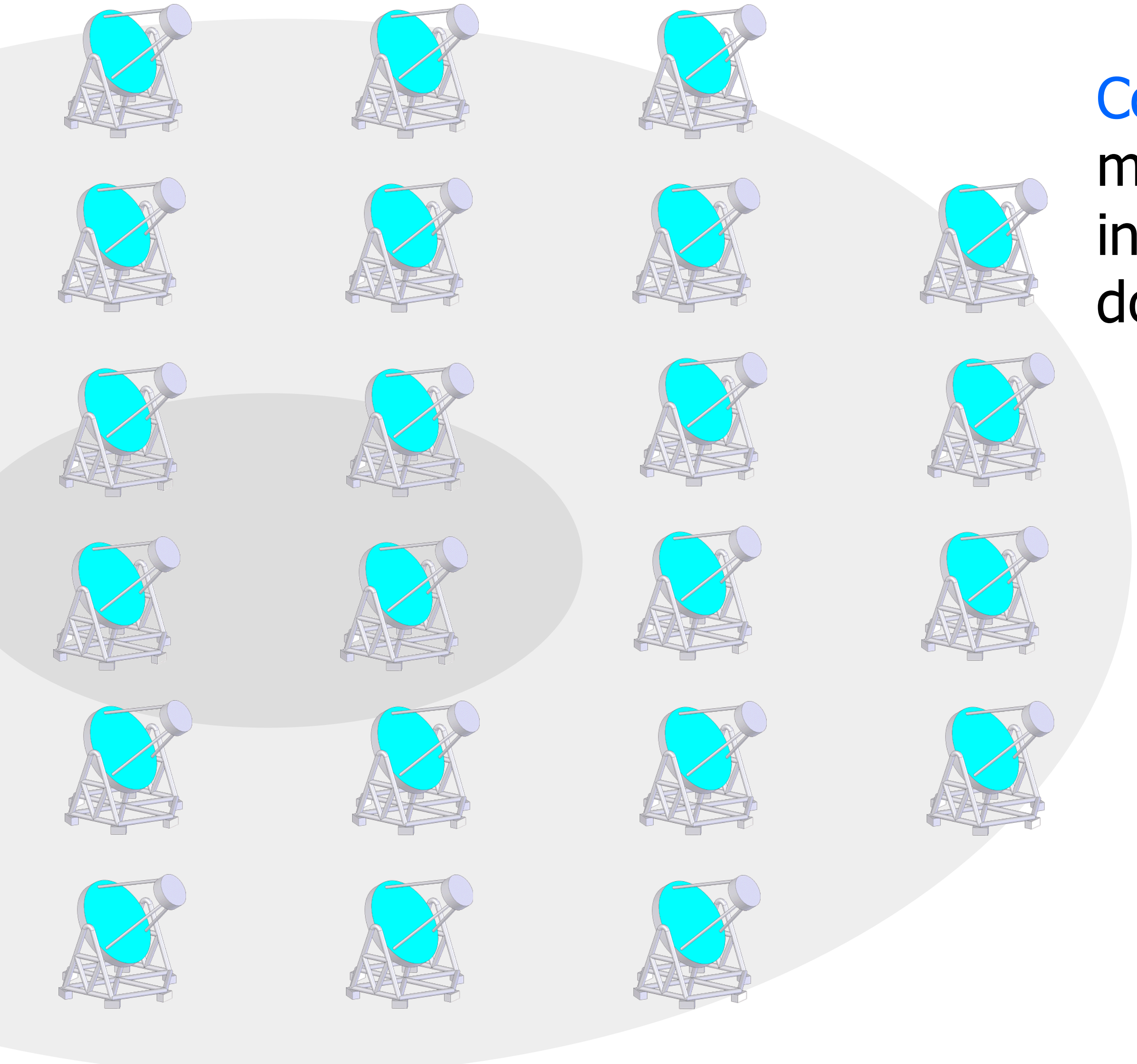


"ideal" array of telescopes measuring direction and impact point of 1% of all Cherenkov photons

Boosting sensitivity & resolution: Arrays of Cherenkov telescopes

Single telescope

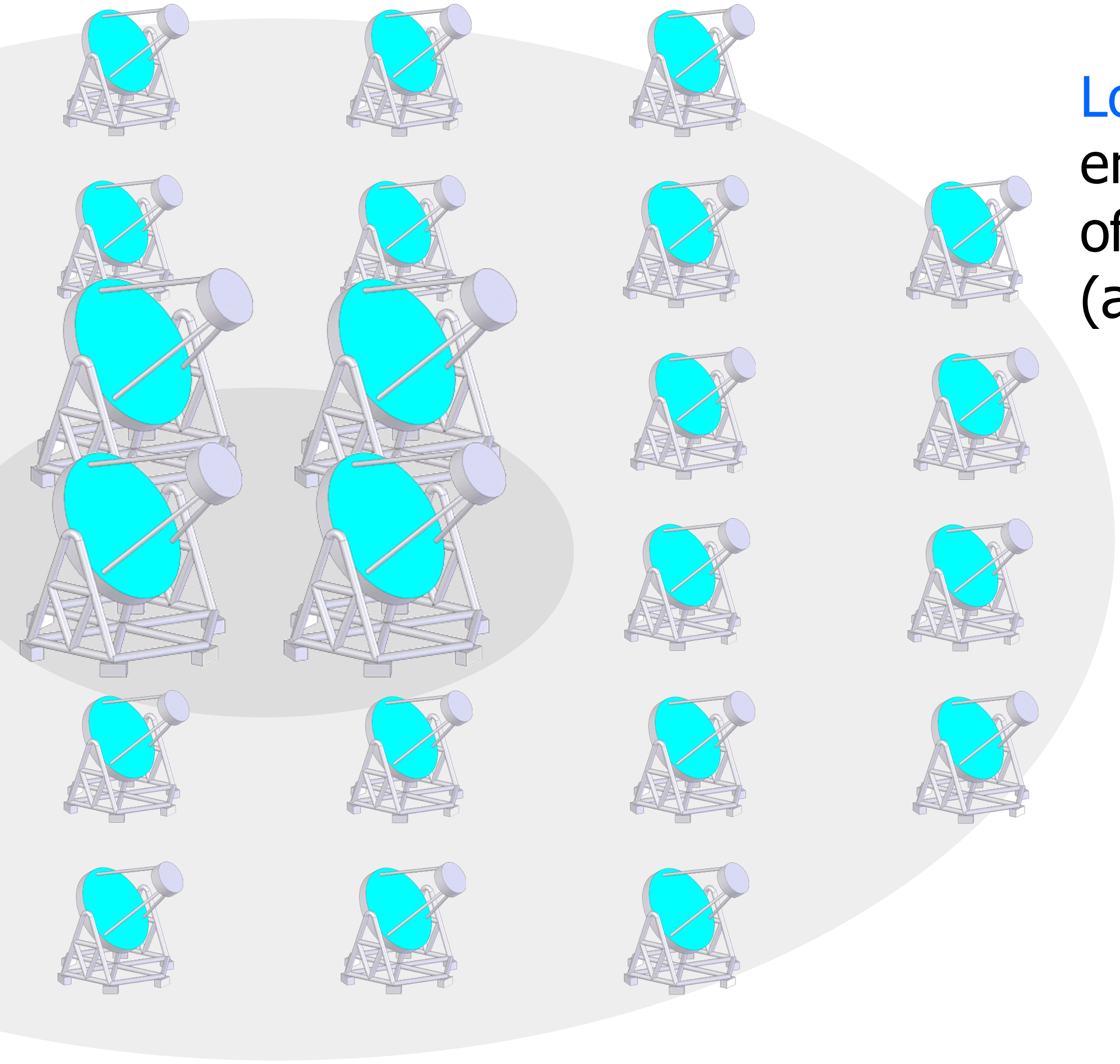




Core array:

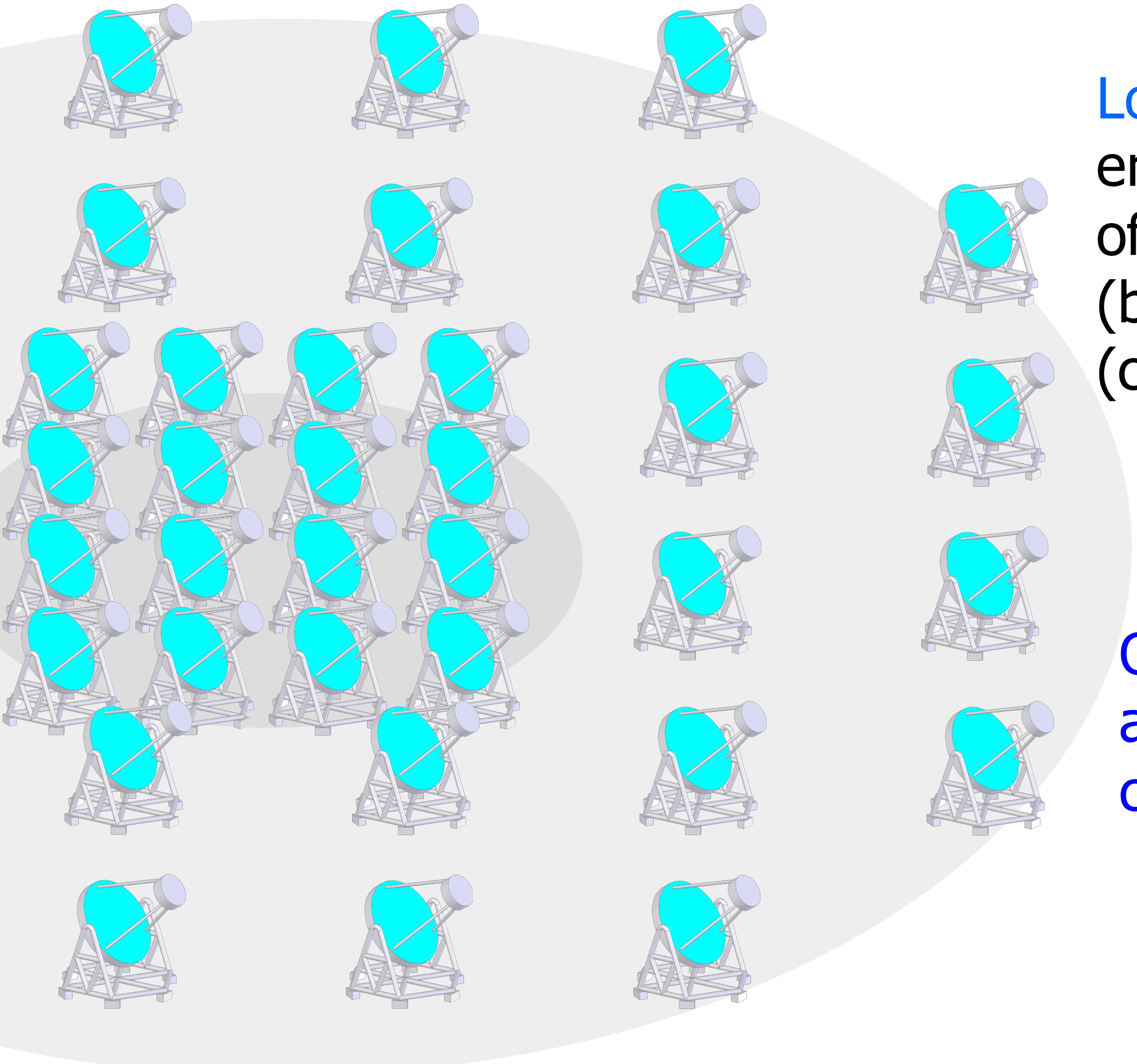
mCrab sensitivity
in the 100 GeV–10 TeV
domain

Not to scale !



Low-energy section
energy threshold
of some 10 GeV
(a) bigger dishes or

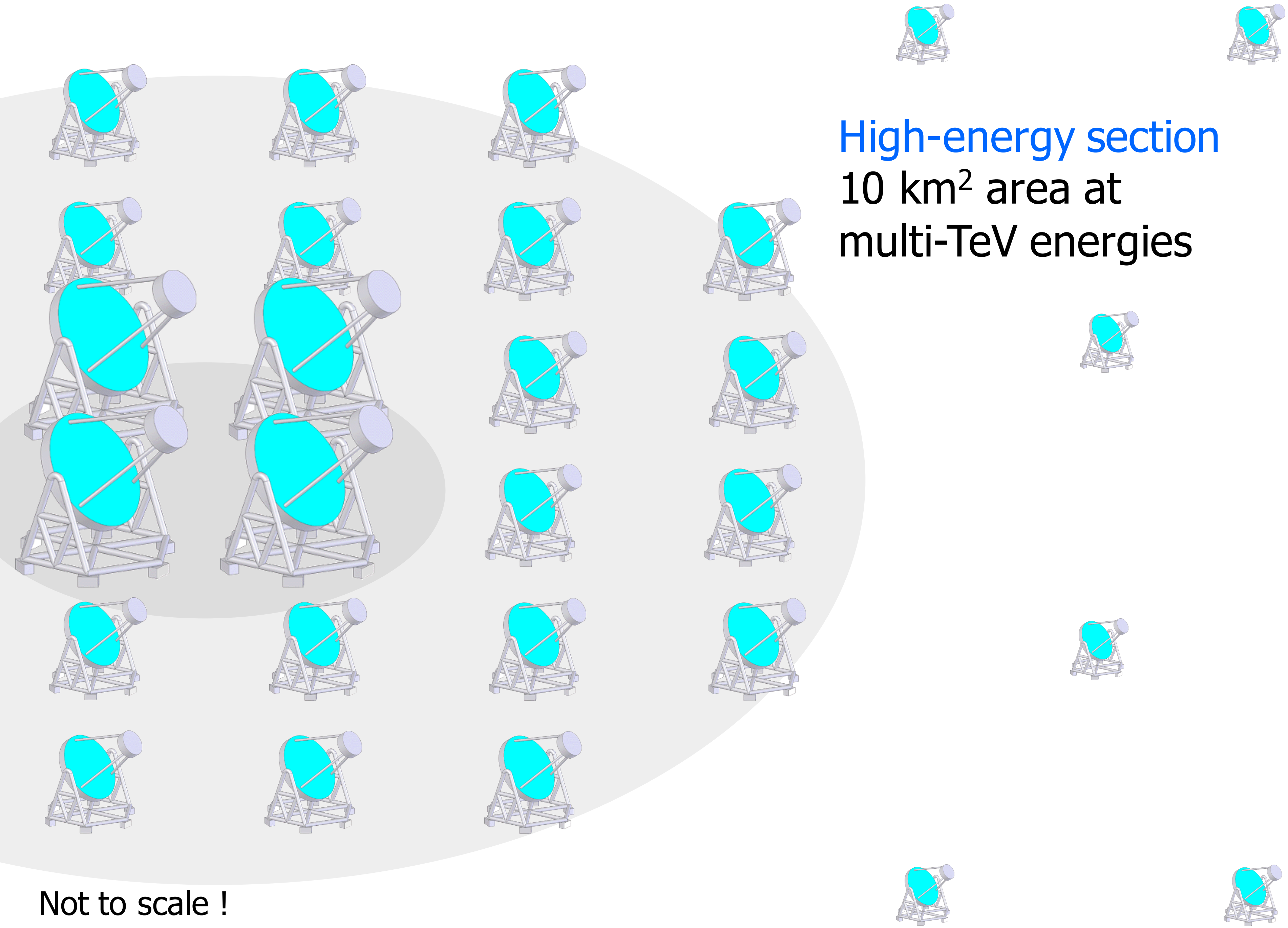
Not to scale !



Low-energy section
energy threshold
of some 10 GeV
(b) dense-pack and/or
(c) high-QE sensors

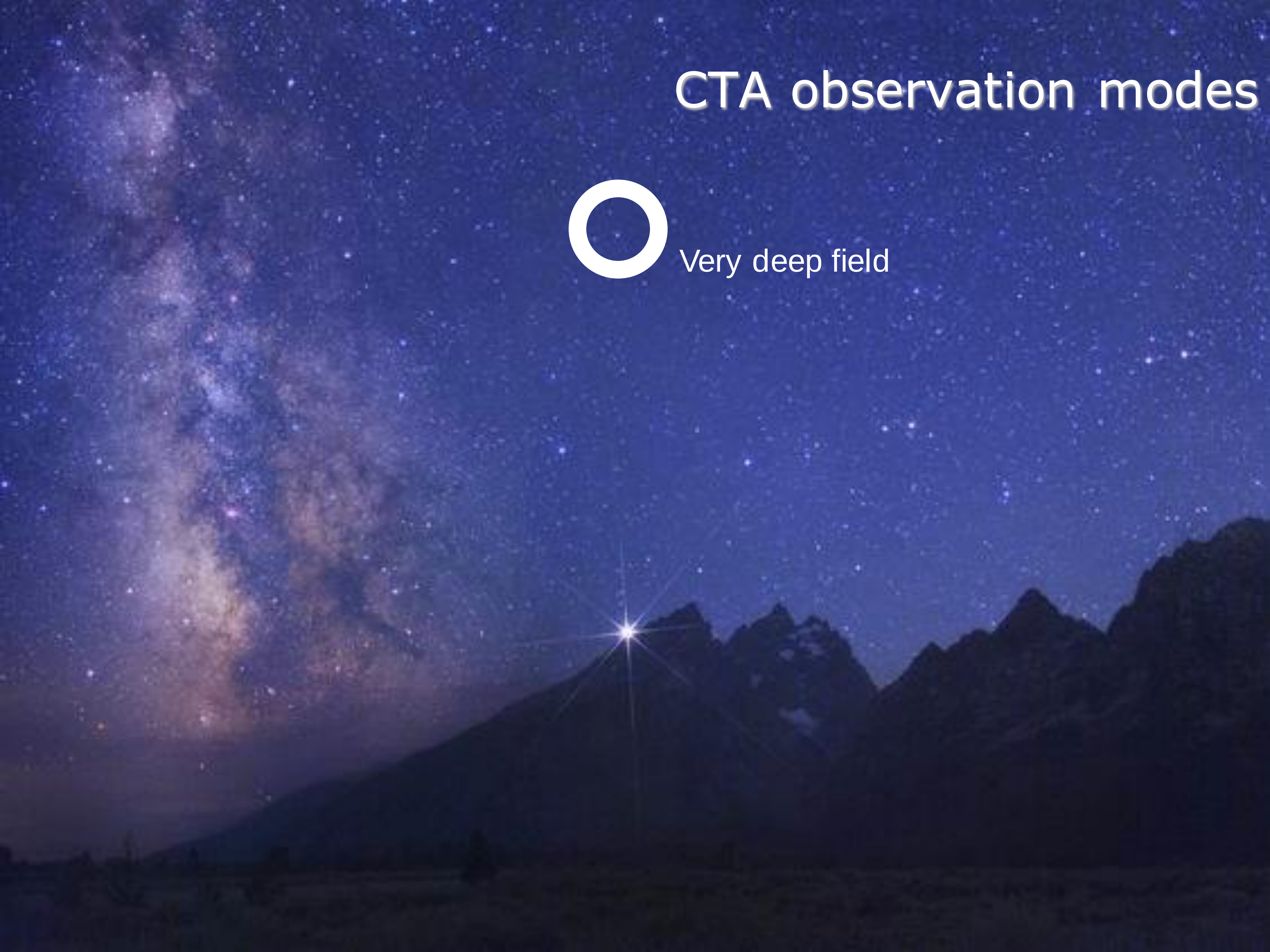
Outer telescope
array serves as
cosmic-ray veto!

Not to scale !

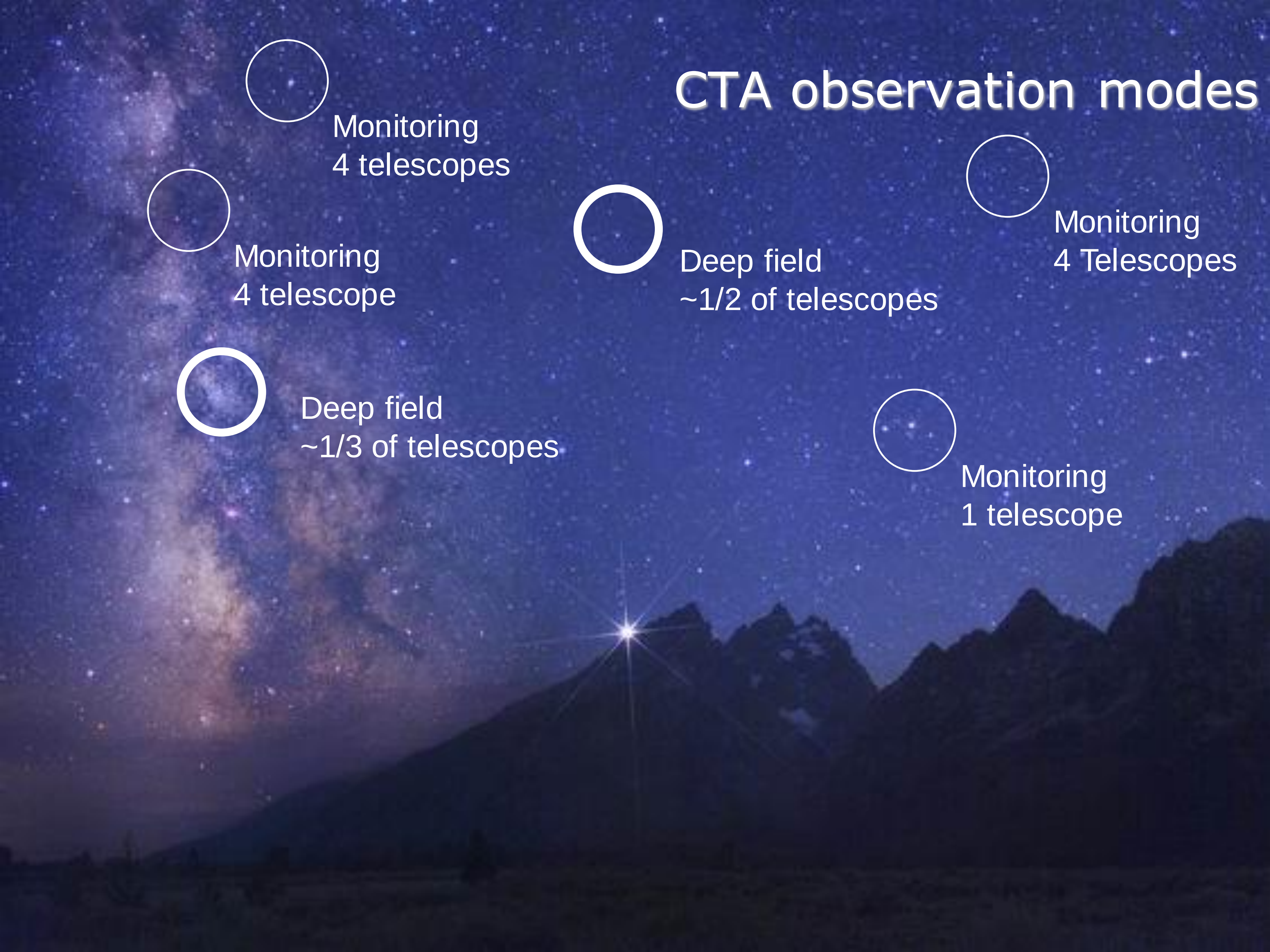

High-energy section
10 km^2 area at
multi-TeV energies
Not to scale !

CTA observation modes

CTA observation modes



CTA observation modes



CTA observation modes

Survey mode

Not to scale !

Could start building:

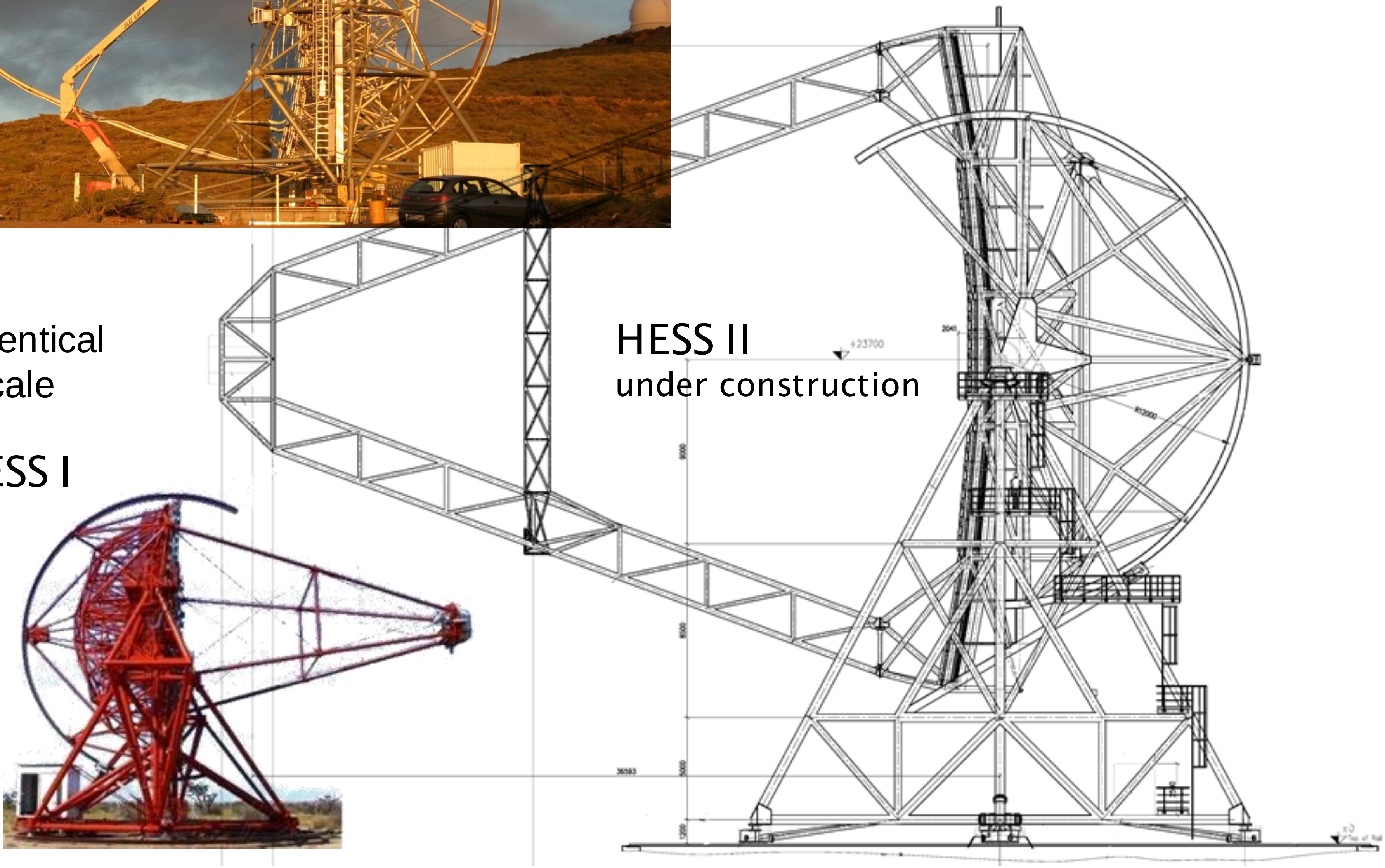
for example,
use ~100 H.E.S.S. I telescopes

plus a handful of H.E.S.S. II or MAGIC telescopes

Building blocks

identical
scale

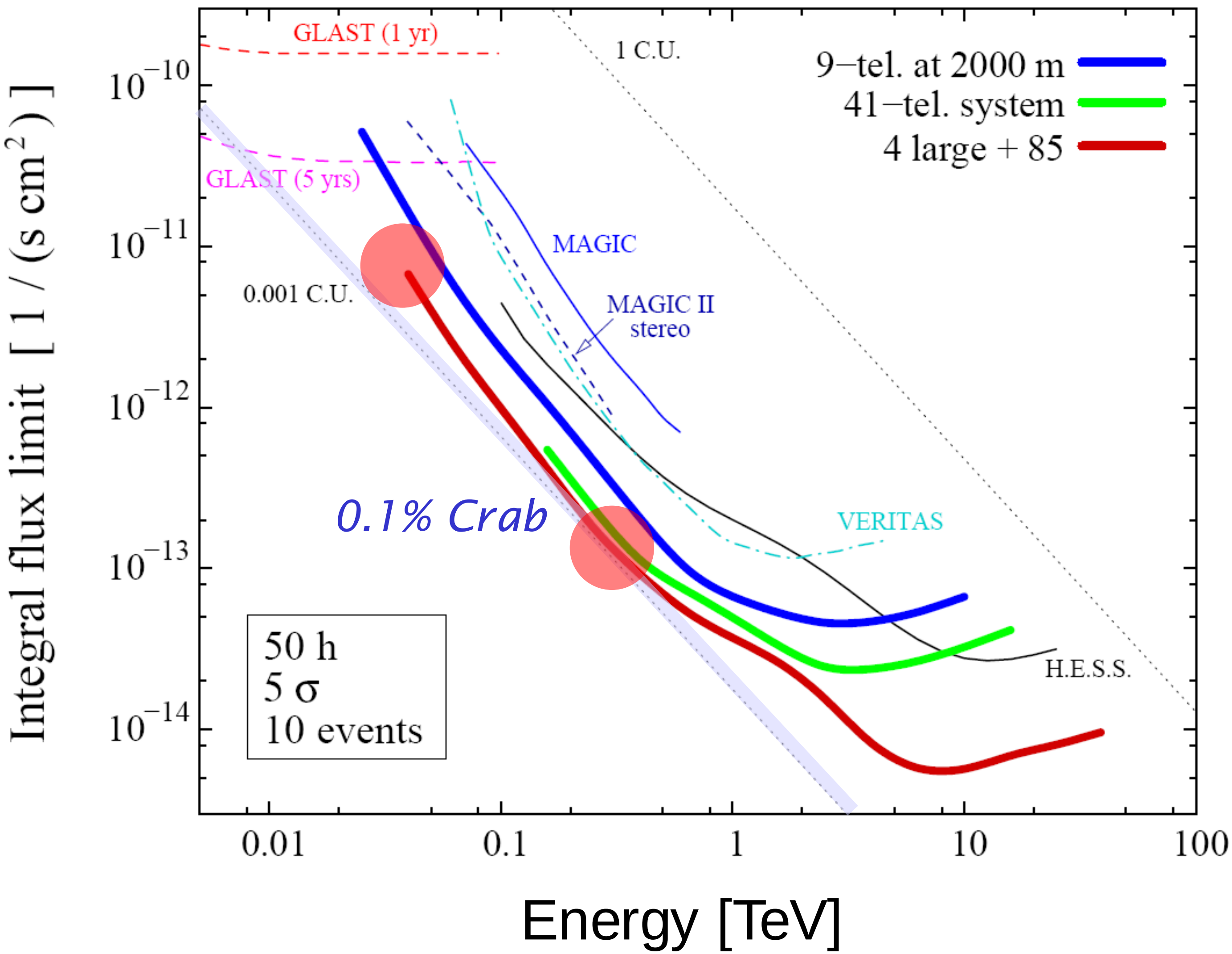
HESS II
under construction



HESS I


Truck

We know that it works

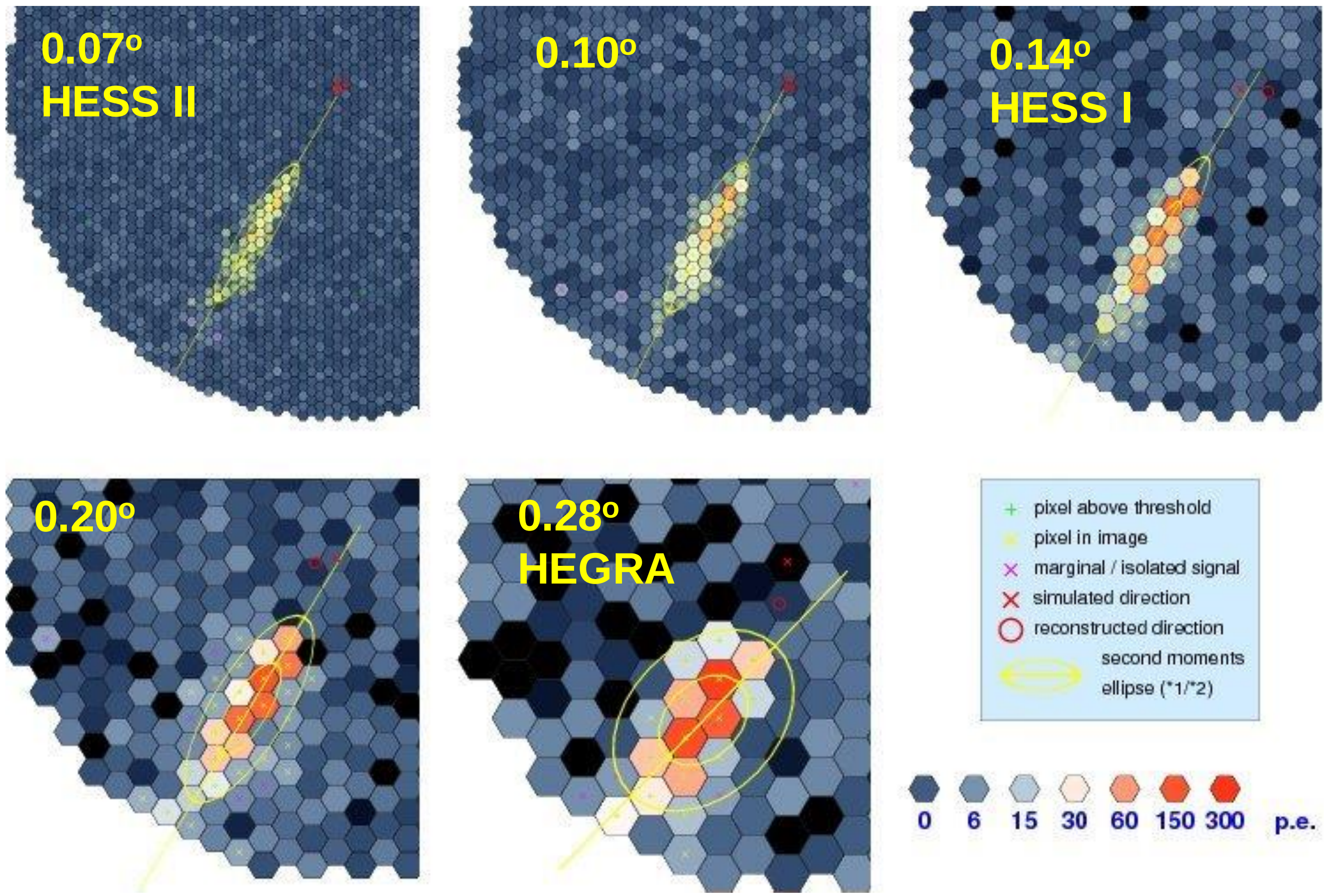


… but …

- Cost would exceed target cost by factor 1.5 to 2
  - H.E.S.S. I telescope ~1.5 M€
  - H.E.S.S. II telescope ~ 11 M€
  - MAGIC telescope ~5 M€
- Instrument reliability needs to increase by an order of magnitude (at least)
  - to provide high data quality
  - to limit operating effort
- We believe we can built even better telescopes
  - wider field of view
  - improved photo sensors
  - improved electronics
- Lacking tools to operate a user facility and to handle data
  - Observation scheduling and system control
  - Science data center and data access tools

significant effort required to optimize design

Example: Pixel size -
How much is really needed?



non-trivial: right balance

reliable,
but modest
performance and
limited comfort

too fancy,
not for daily use

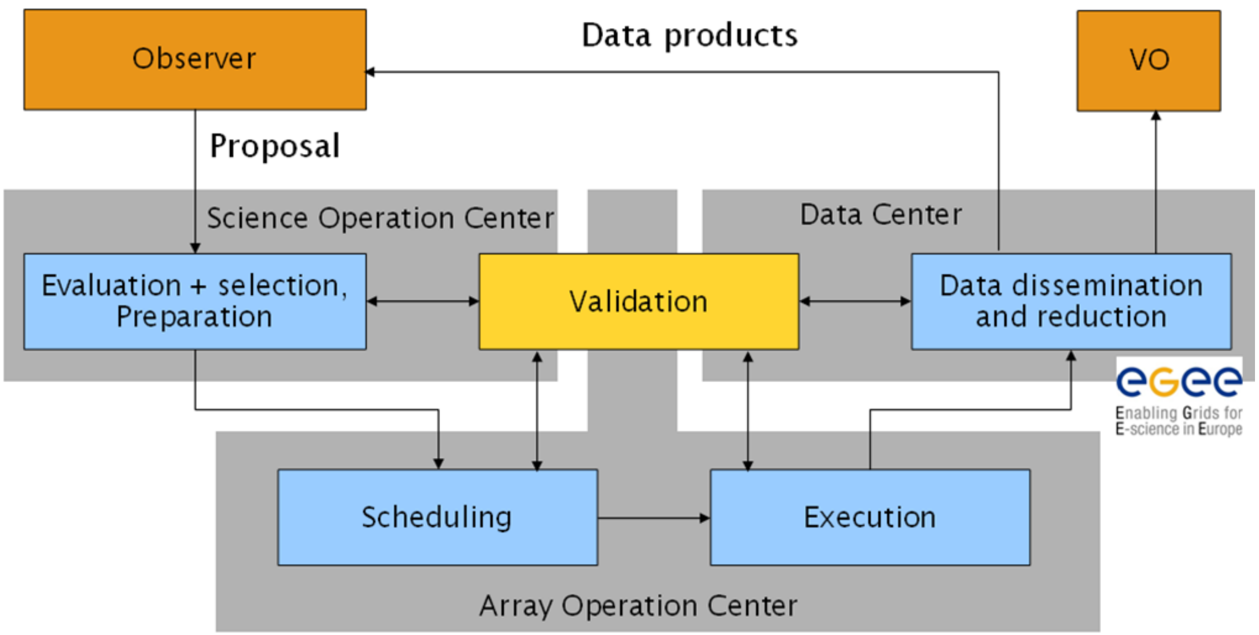
Looking
for something
like this

CTA Design Study

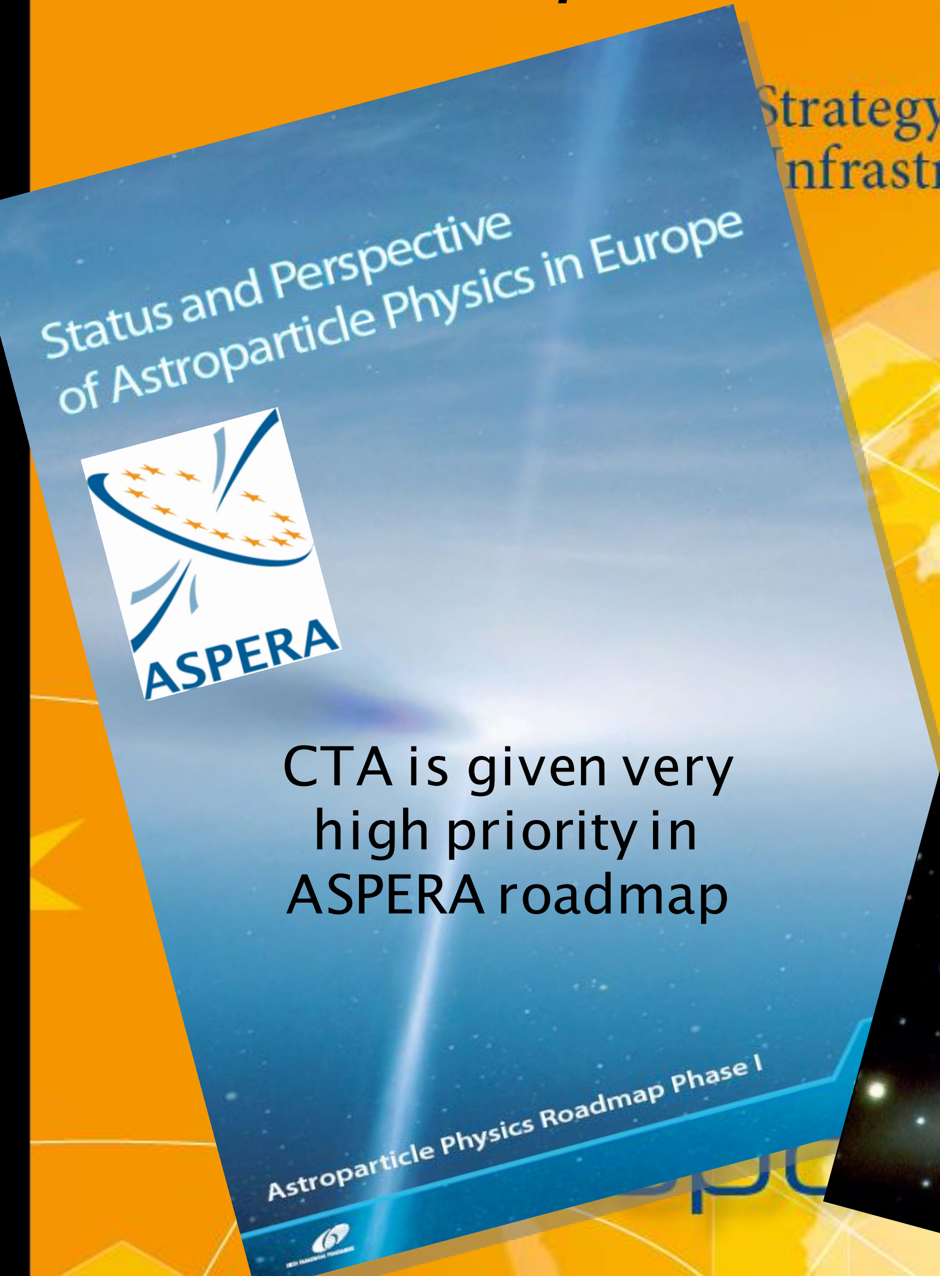
Armenia (H.E.S.S.)	Yerevan
Czech Republic (H.E.S.S.)	Prague
Germany (H.E.S.S., MAGIC, +)	HU Berlin, Bochum, DESY, Dortmund, Erlangen, Hamburg, MPI Heidelberg, U. Heidelberg, MPI Munich, Tübingen, Würzburg
Finland (MAGIC)	Turku
France (H.E.S.S.)	Annecy, Grenoble, Montpellier, LLR Palaiseau, APC Paris, Obs. Paris-Meudon, U. Paris VI-VII, CEA Saclay, Toulouse
Italy (MAGIC, +)	INFN Padova, Pavia, Pisa, Trieste, Rome, Siena, INAF Rome, Brera, Bologna, Padova, Palermo, Torino, …
Ireland (H.E.S.S., VERITAS)	DIAS Dublin, …
Japan (CANGAROO)	ICRC + Universities
Namibia (H.E.S.S.)	U. Namibia
Poland (H.E.S.S., MAGIC)	Cracow, NCAC Warsaw, U. Warsaw, Lodz
Spain (MAGIC)	IFAE, IEEC, UAB, UB Barcelona, UCM Madrid
South Africa (H.E.S.S.)	Northwest-Univ.
Switzerland (MAGIC +)	ETH Zurich, U. Zurich, Geneva, PSI
UK (H.E.S.S., VERITAS, +)	Leeds, Durham, …
more interested	Argentina, Sweden, …

The CTA facility

- expected large number of detectable objects – O(1000) – motivates operation as open observatory, with appropriate tools for data dissemination and data analysis
- expect (500+) users from astronomy, astroparticle physics, plasma physics, particle physics (DM), cosmology

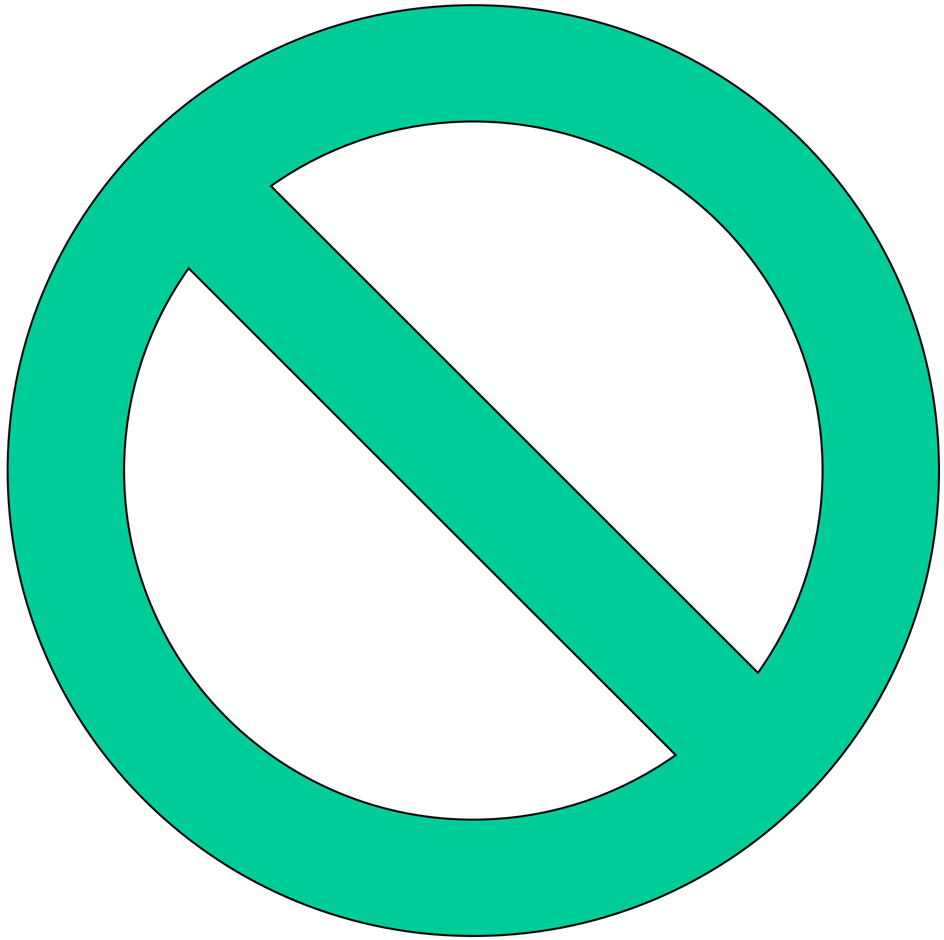


European Coordination



CTA is given very high priority in ASPERA roadmap

Strong statement expected for coming ASTRONET roadmap

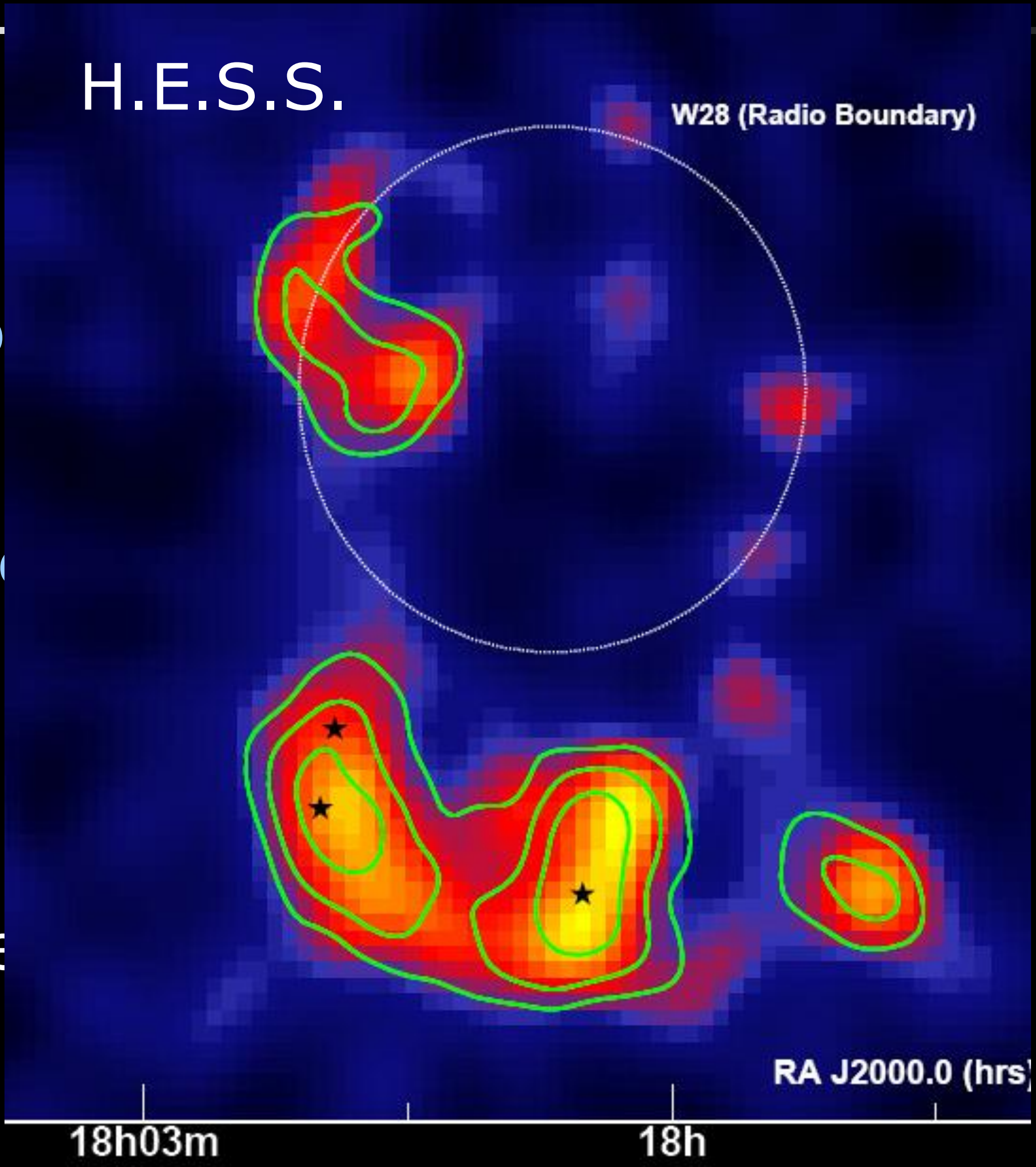


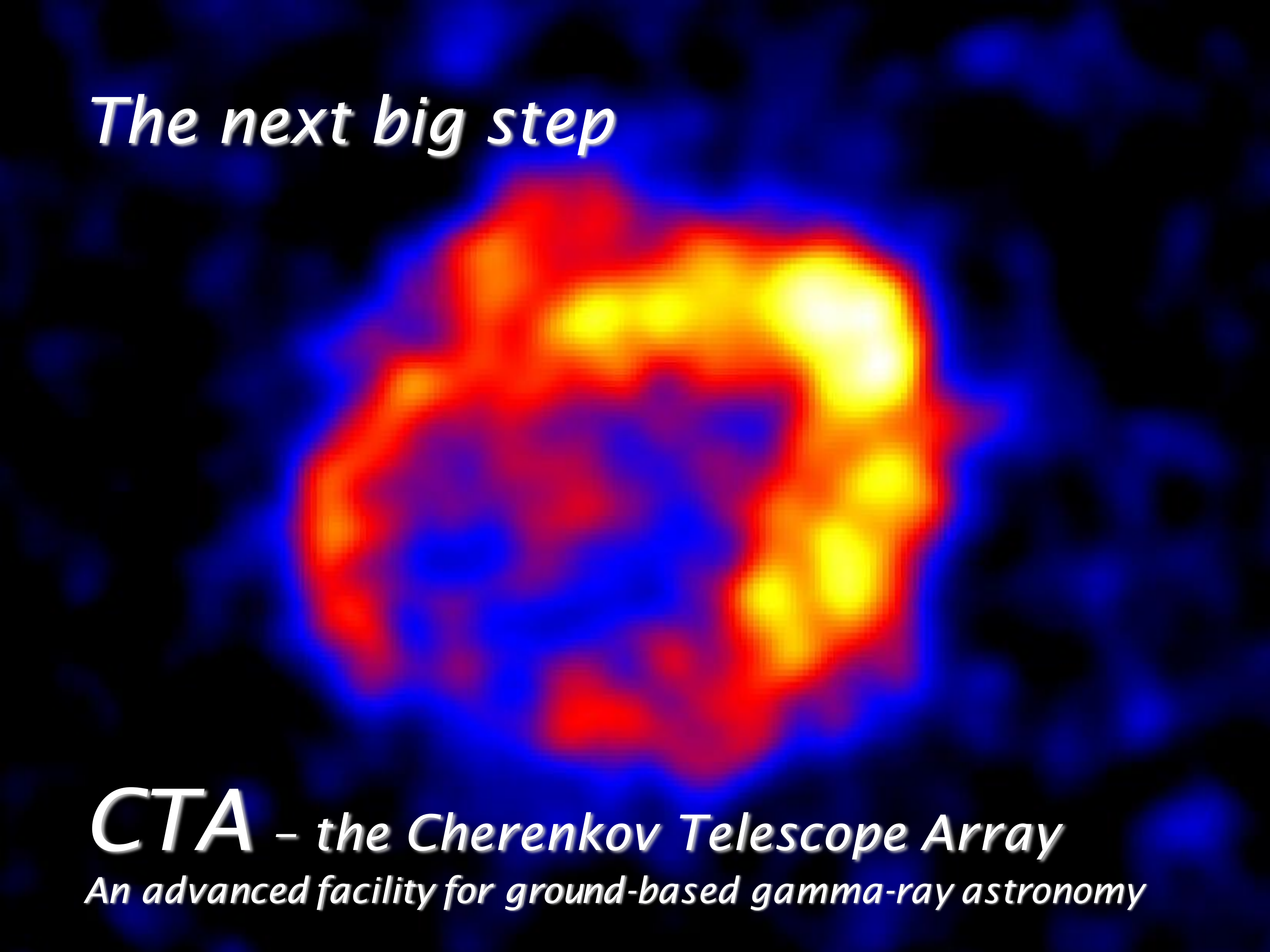
Old SNRs & interacting SNRs

Which fraction of
SNR energy goes into
cosmic-ray nuclei?

How/when are particl
released/

Interacting SNR
probe nature
of accelerated particle
particle release, and
particle propagation



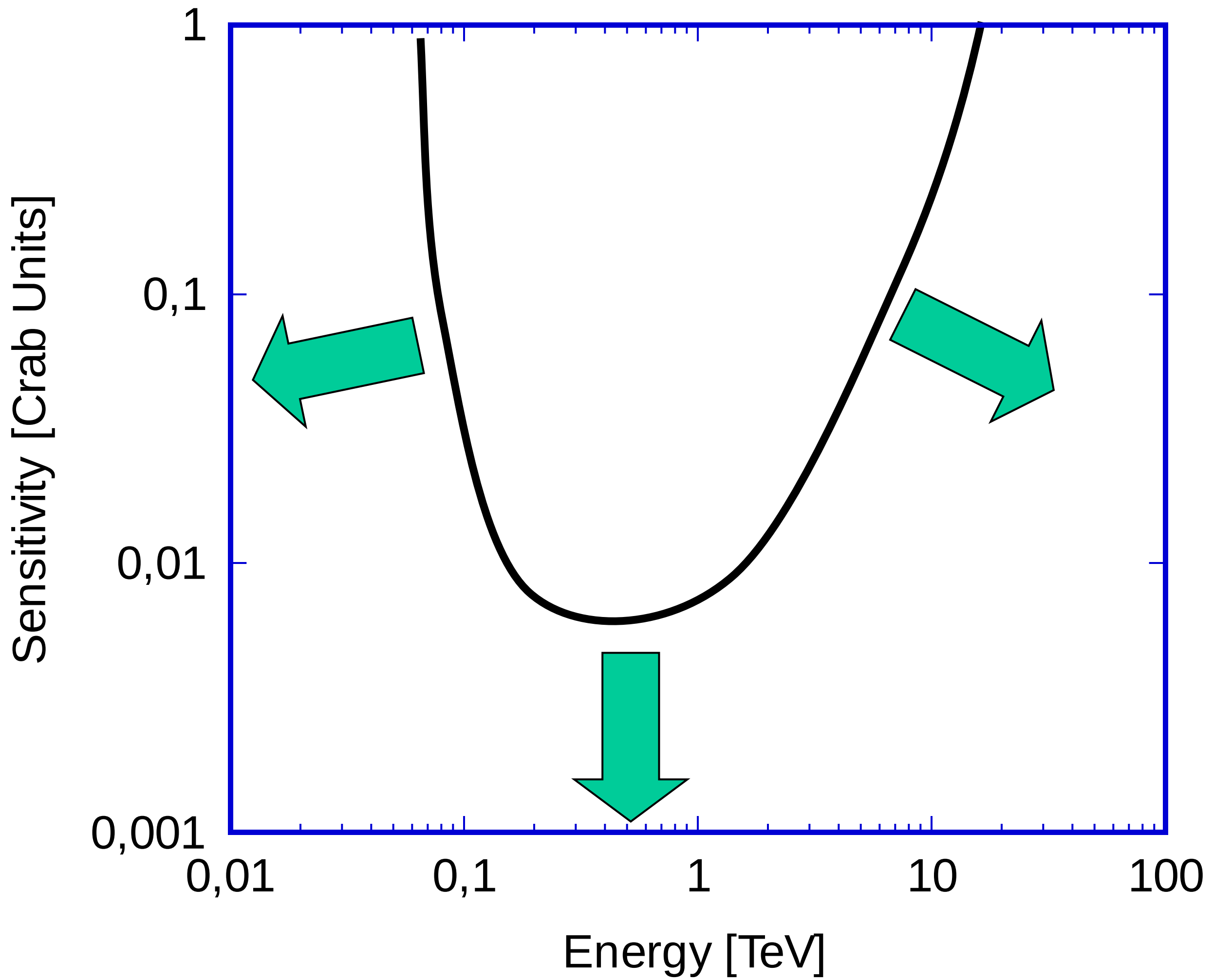


The next big step

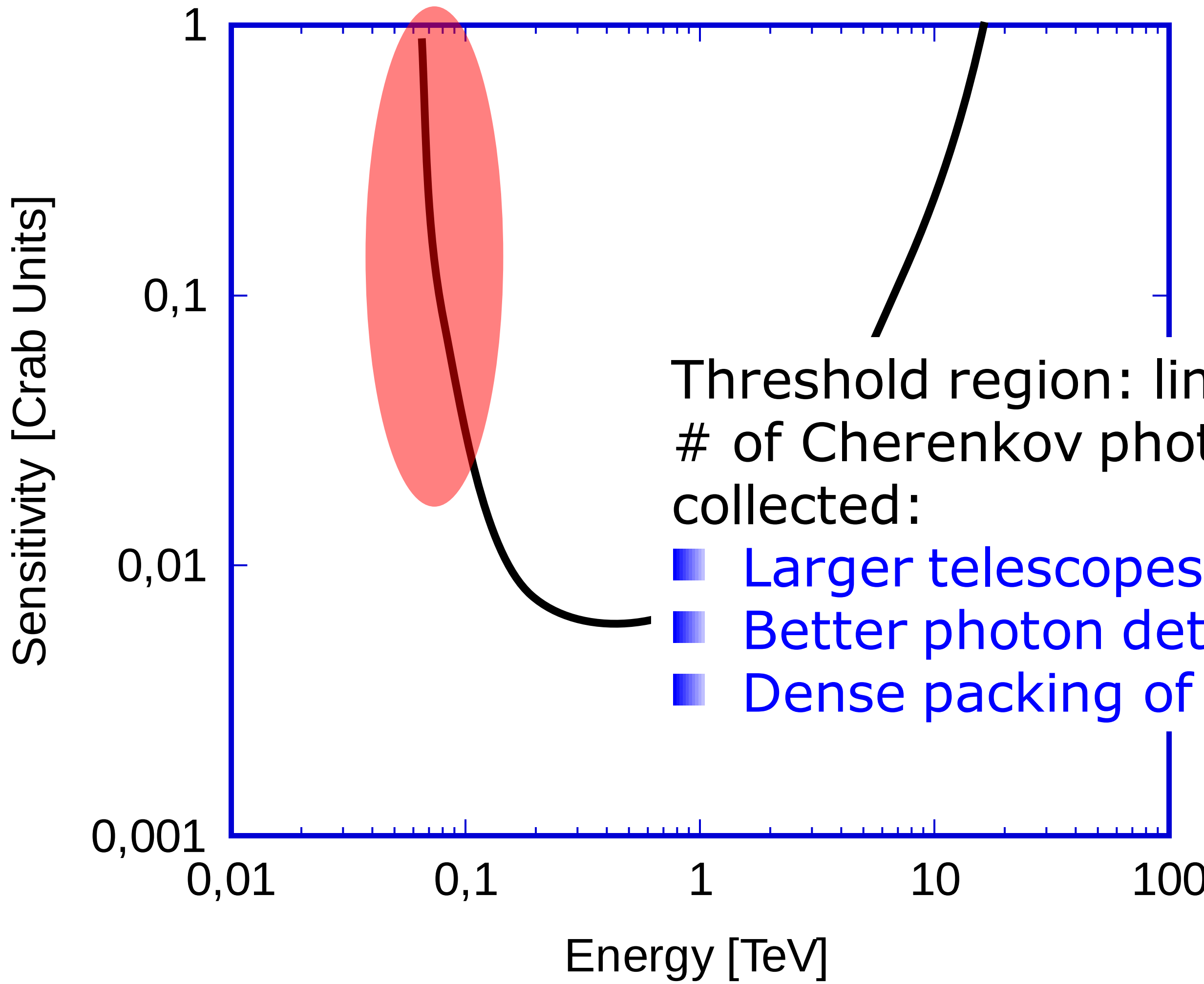
CTA – *the Cherenkov Telescope Array*

An advanced facility for ground-based gamma-ray astronomy

Instrument sensitivity



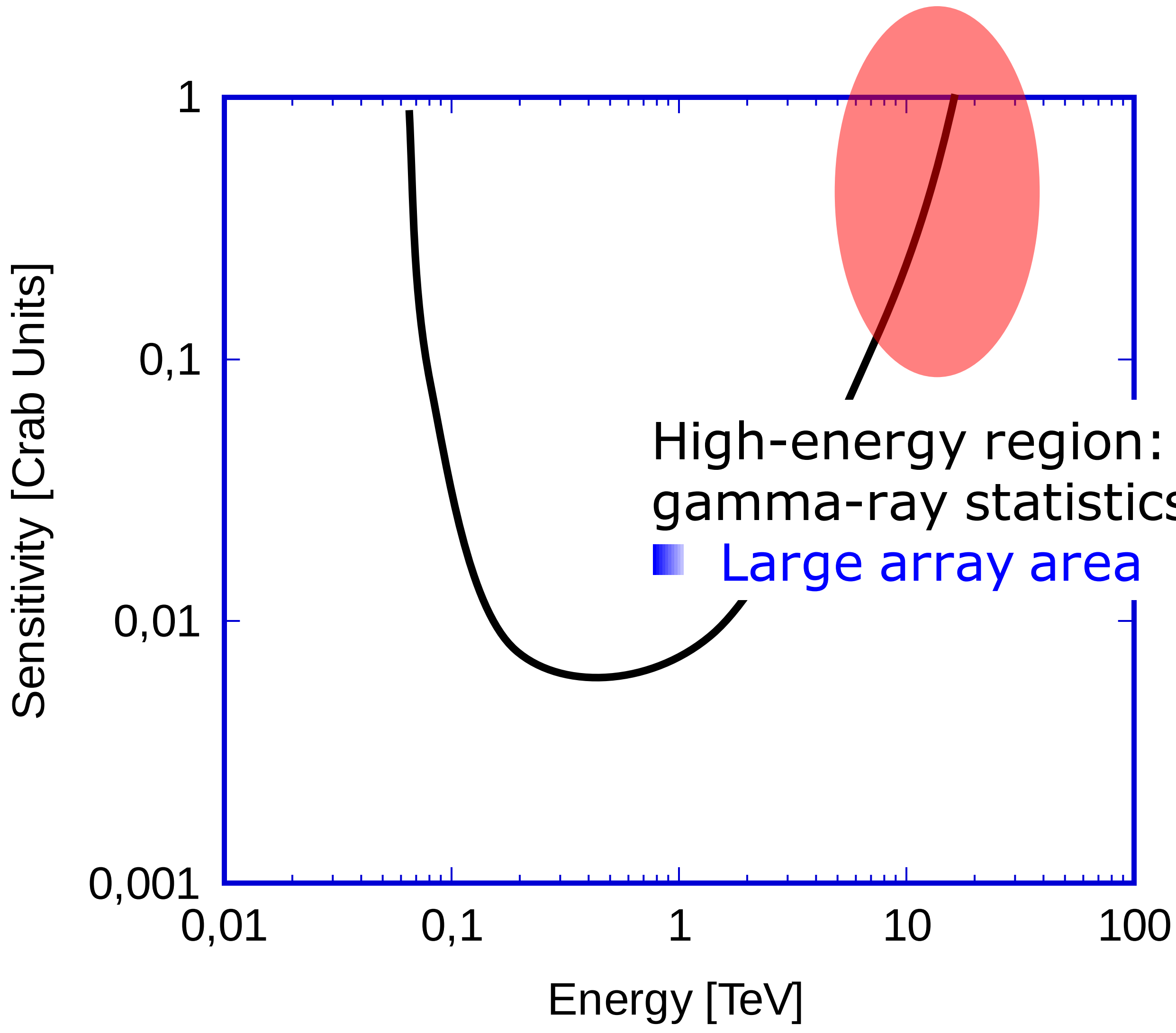
Instrument sensitivity



Threshold region: limited by # of Cherenkov photons collected:

- Larger telescopes
- Better photon detectors
- Dense packing of telescopes

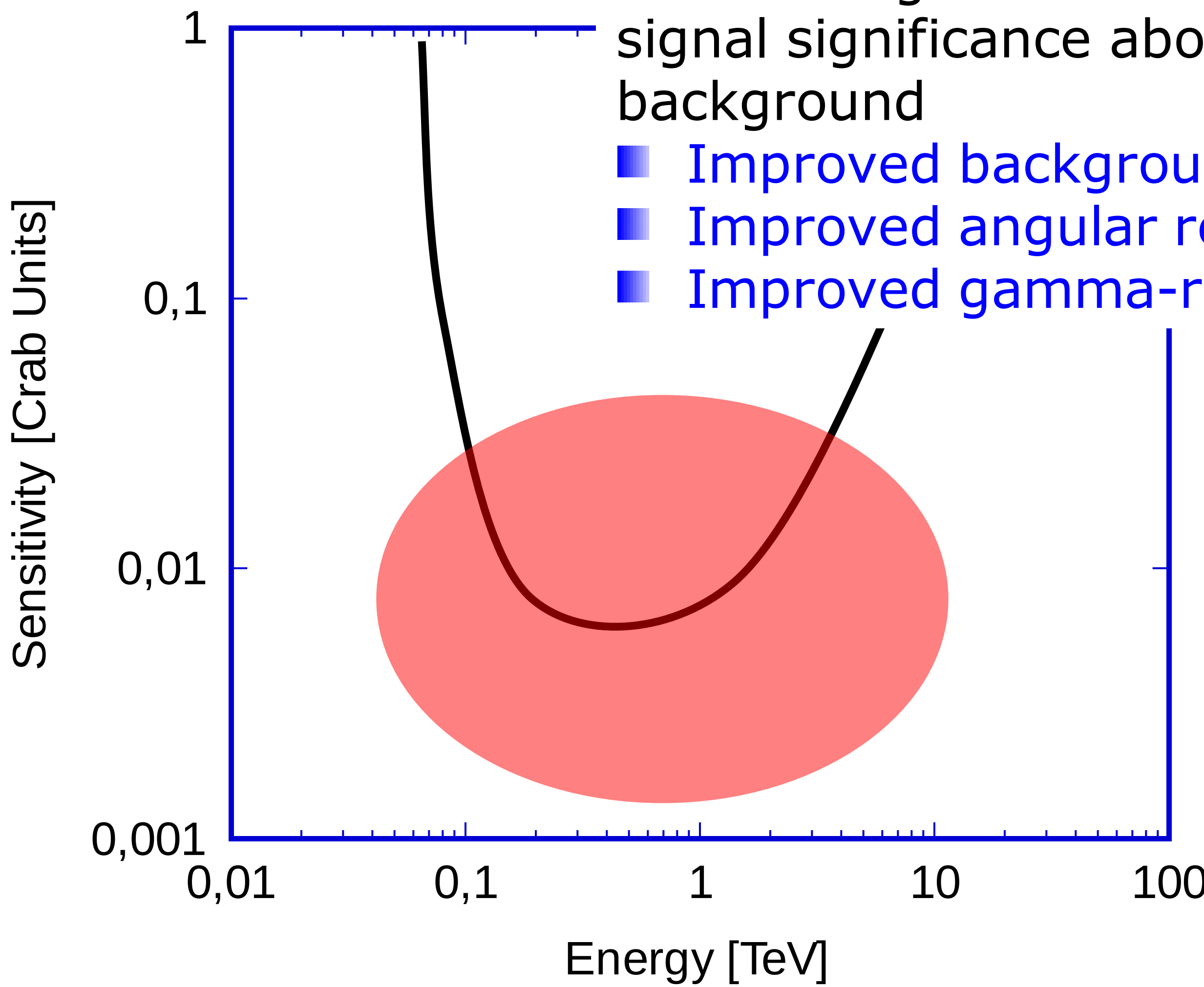
Instrument sensitivity



High-energy region: limited by gamma-ray statistics

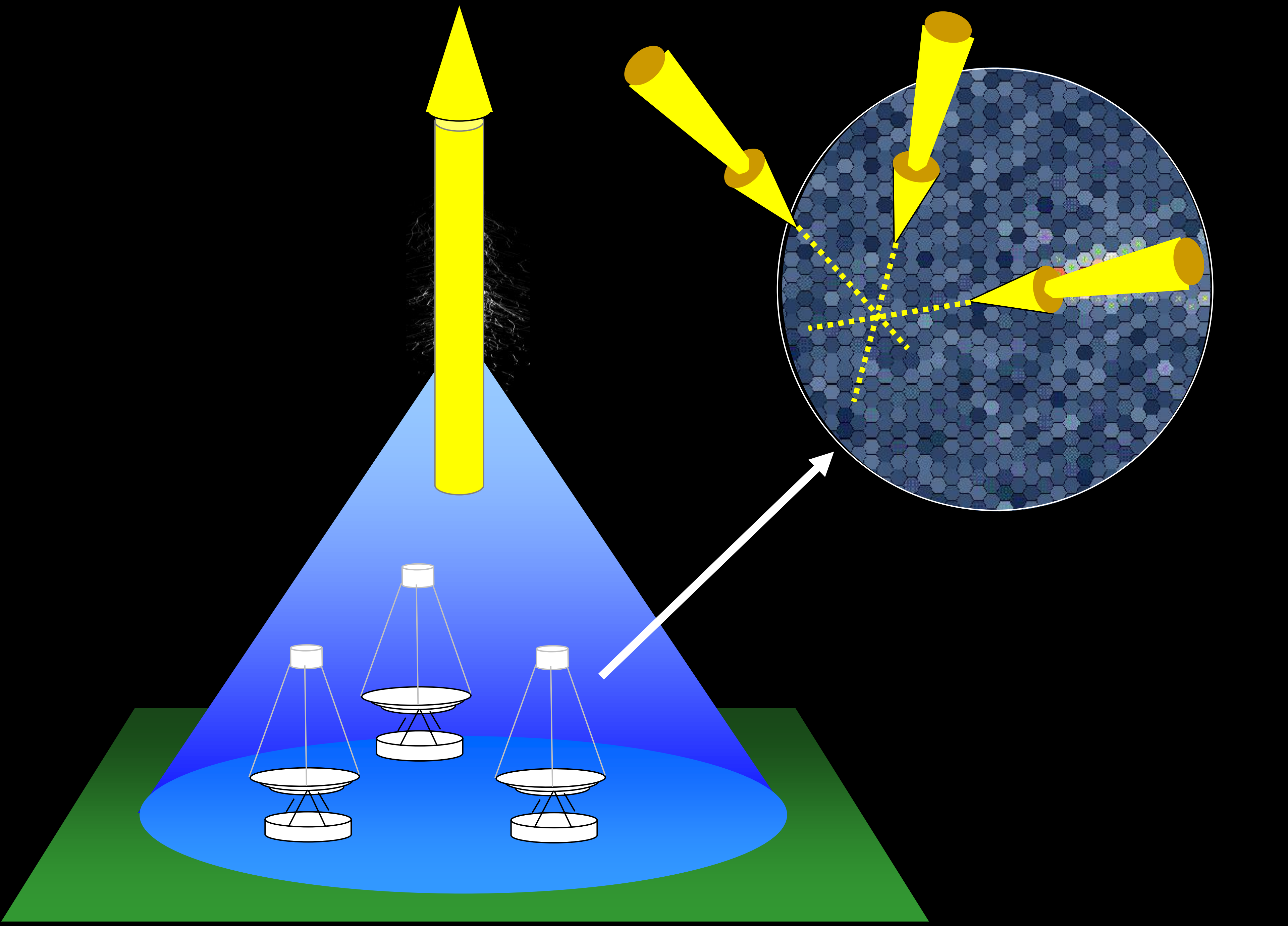
- Large array area

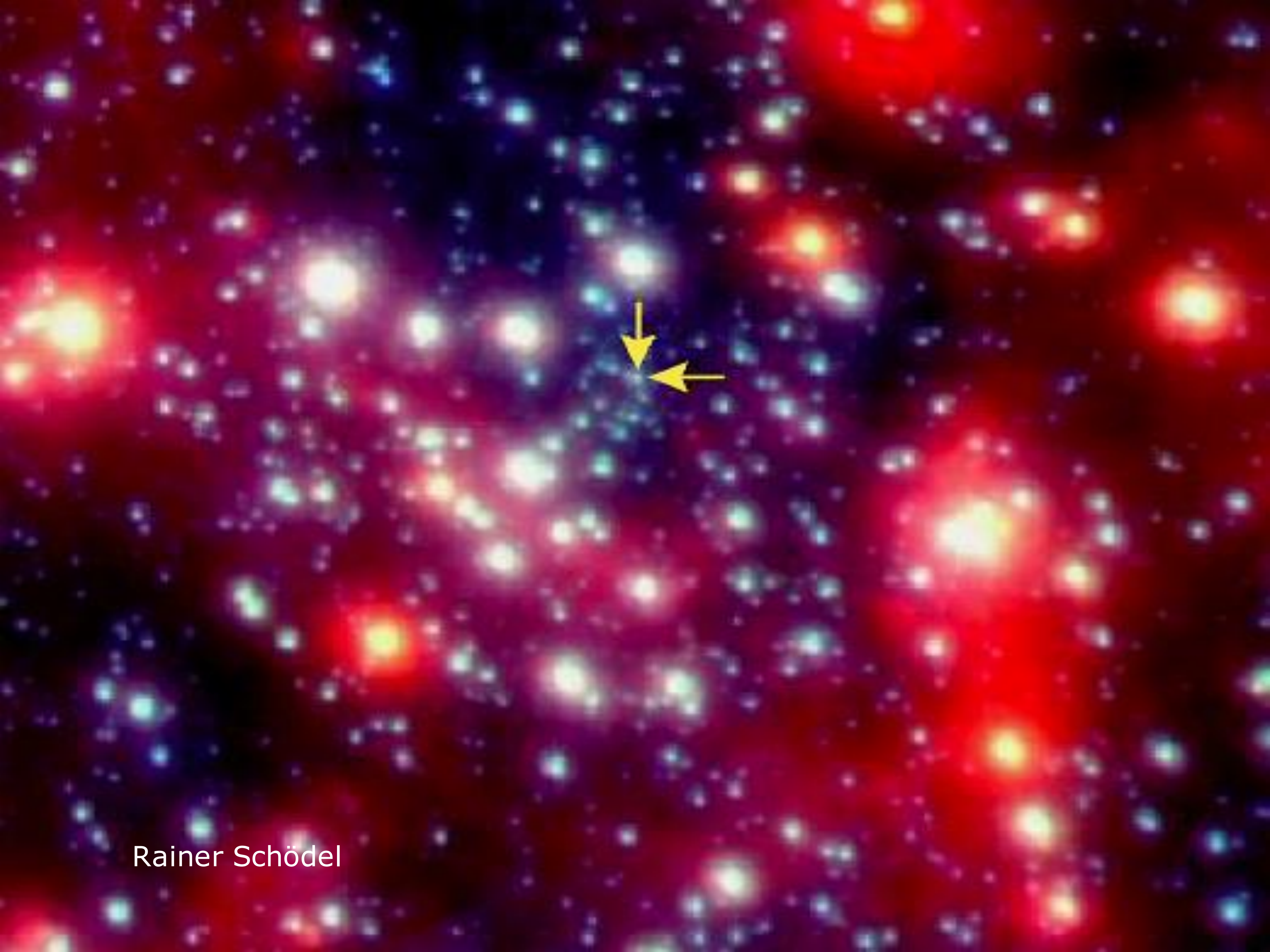
Instrument sensitivity



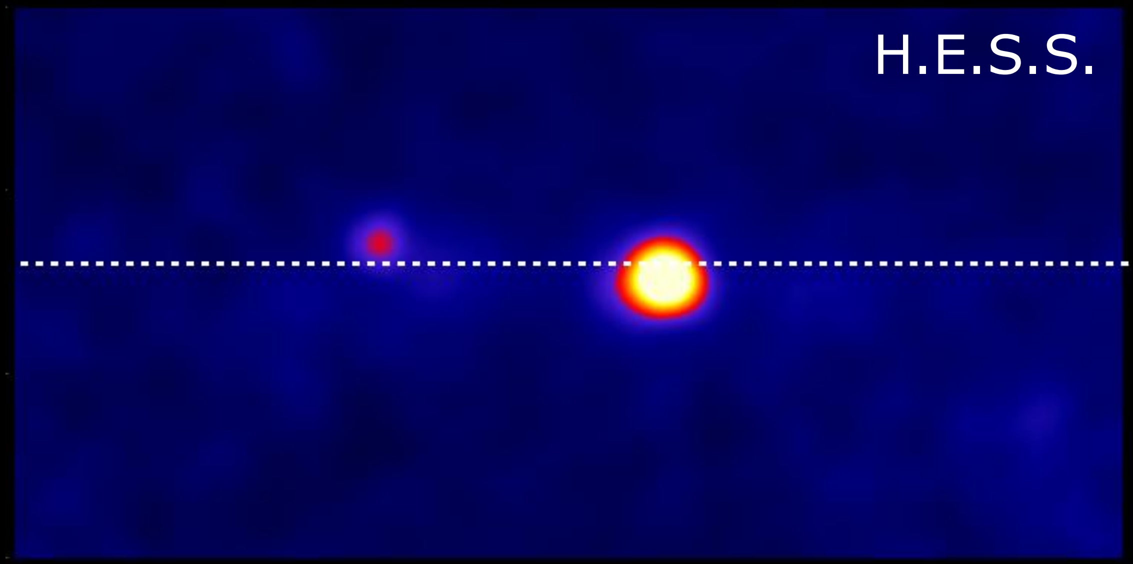
Medium region: limited by signal significance above background

- Improved background rejection
- Improved angular resolution
- Improved gamma-ray statistics



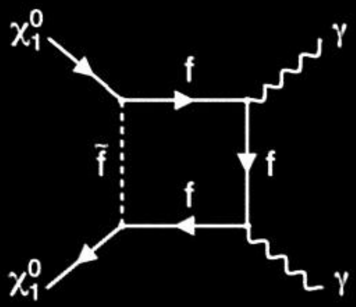

Rainer Schödel

The center of our Galaxy

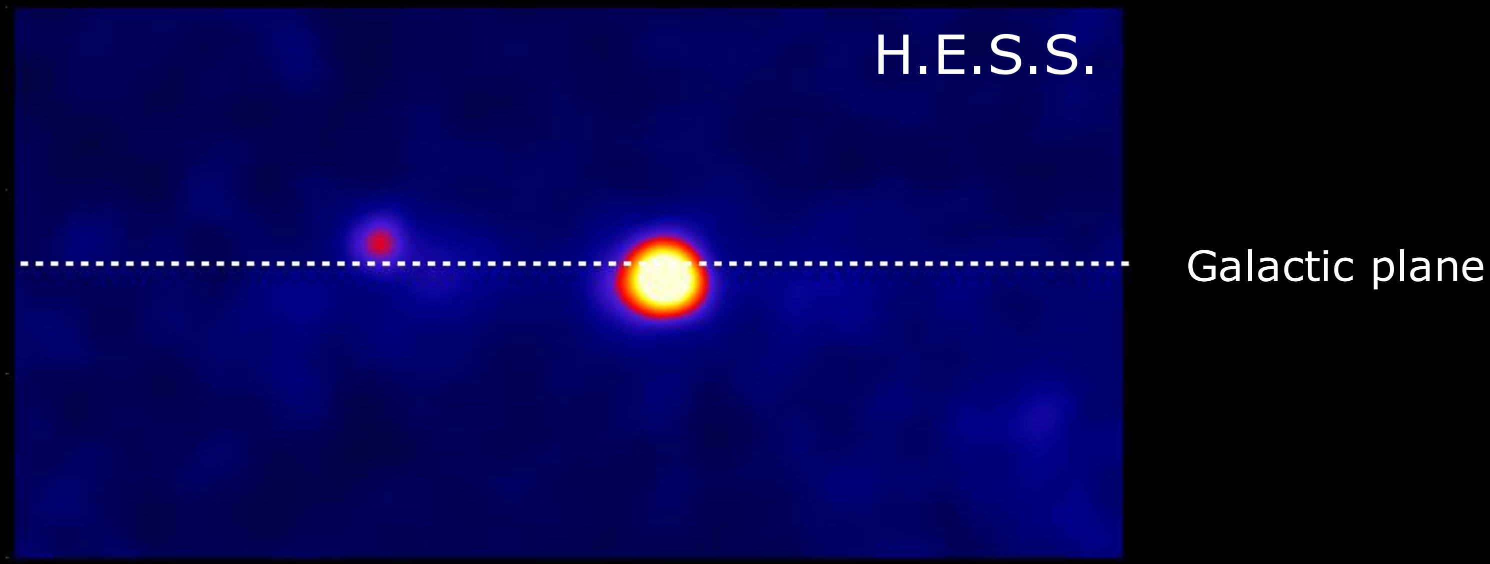


What is it: Sgr A East SRN, Sgr A* BH, DM, … ?

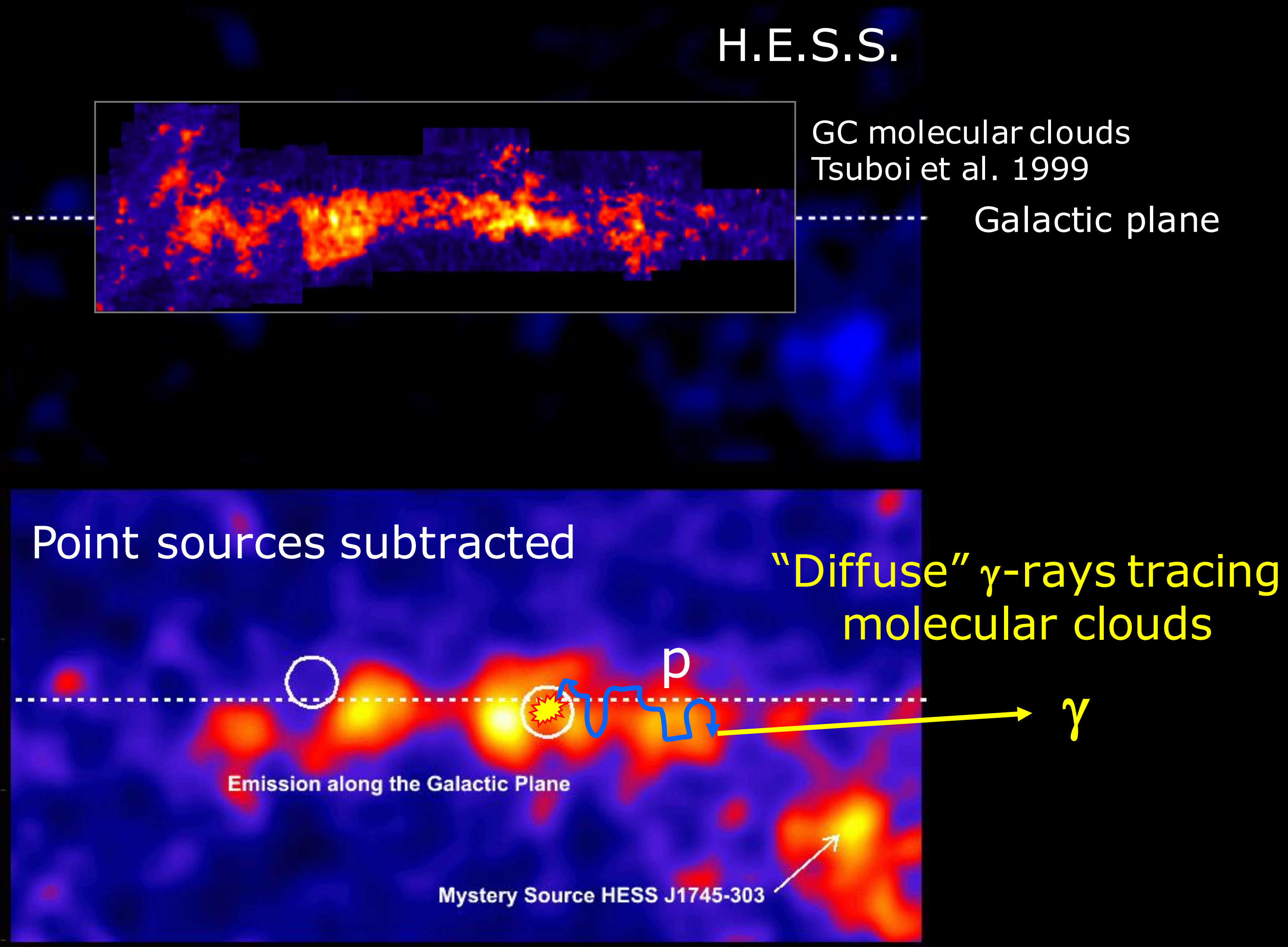
- Location
- Size / morphology
- Spectrum



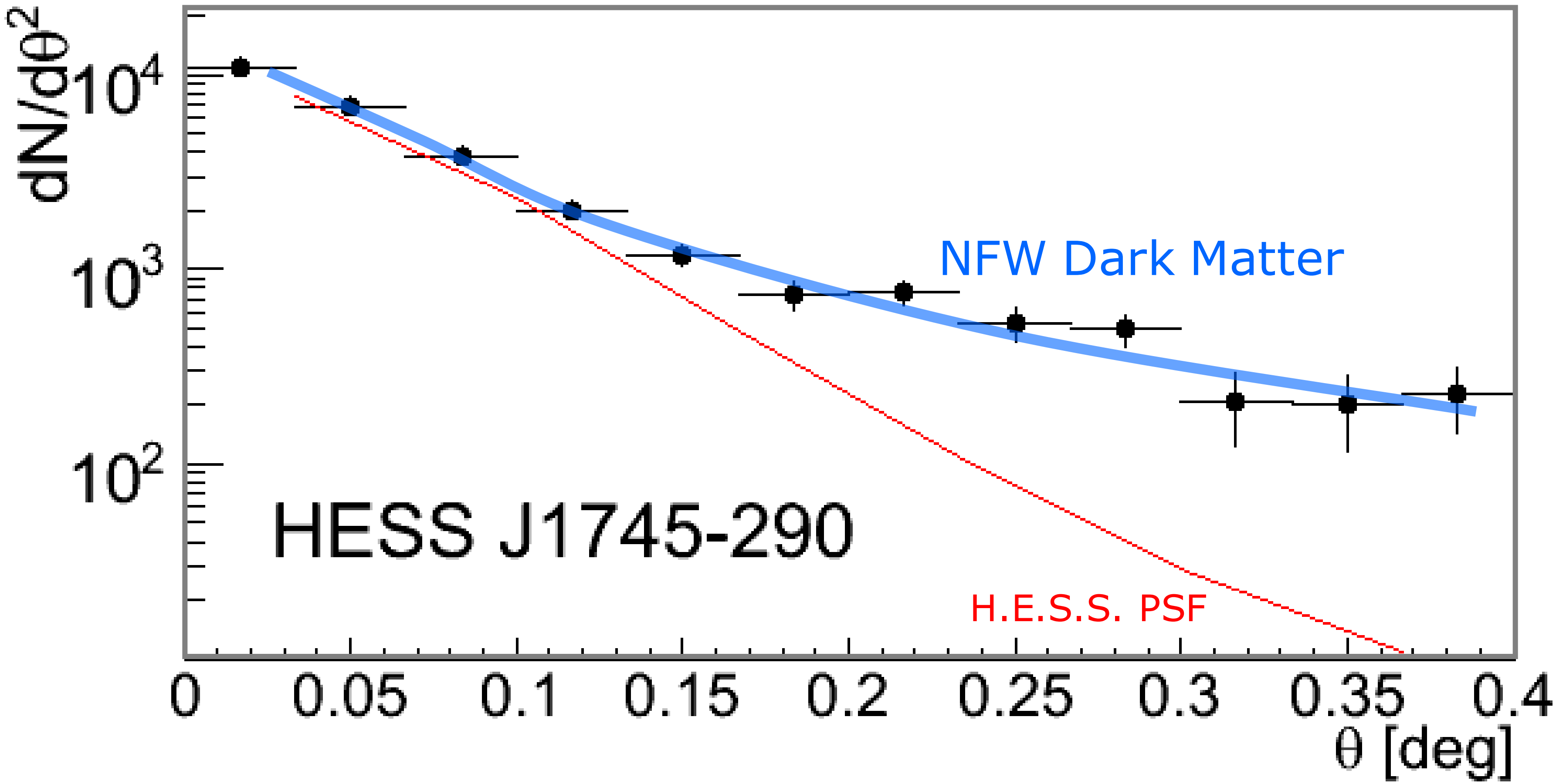
The center of our Galaxy



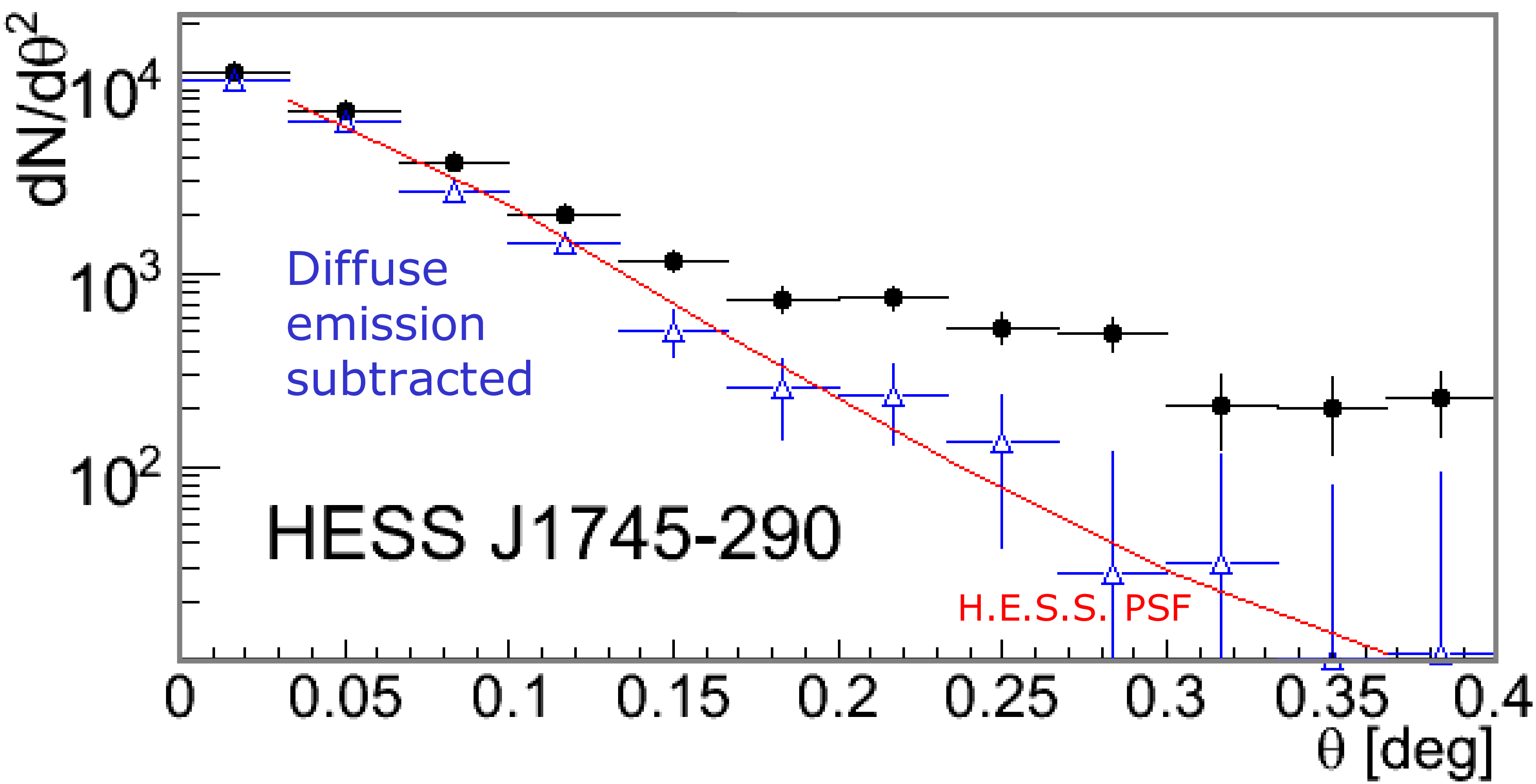
The center of our Galaxy



Is it DM? ▶ Angular distribution



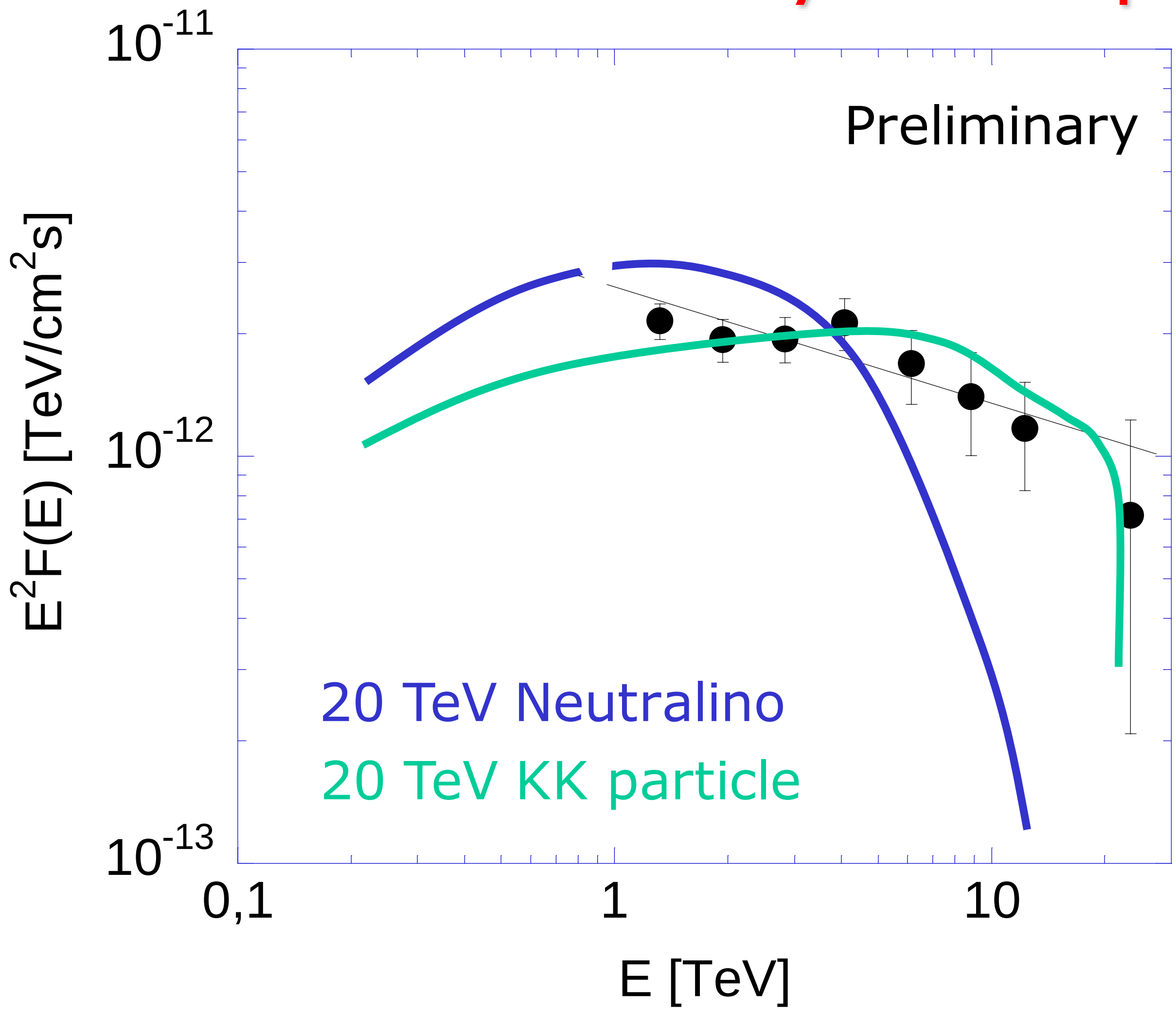
Is it DM? ▶ Angular distribution

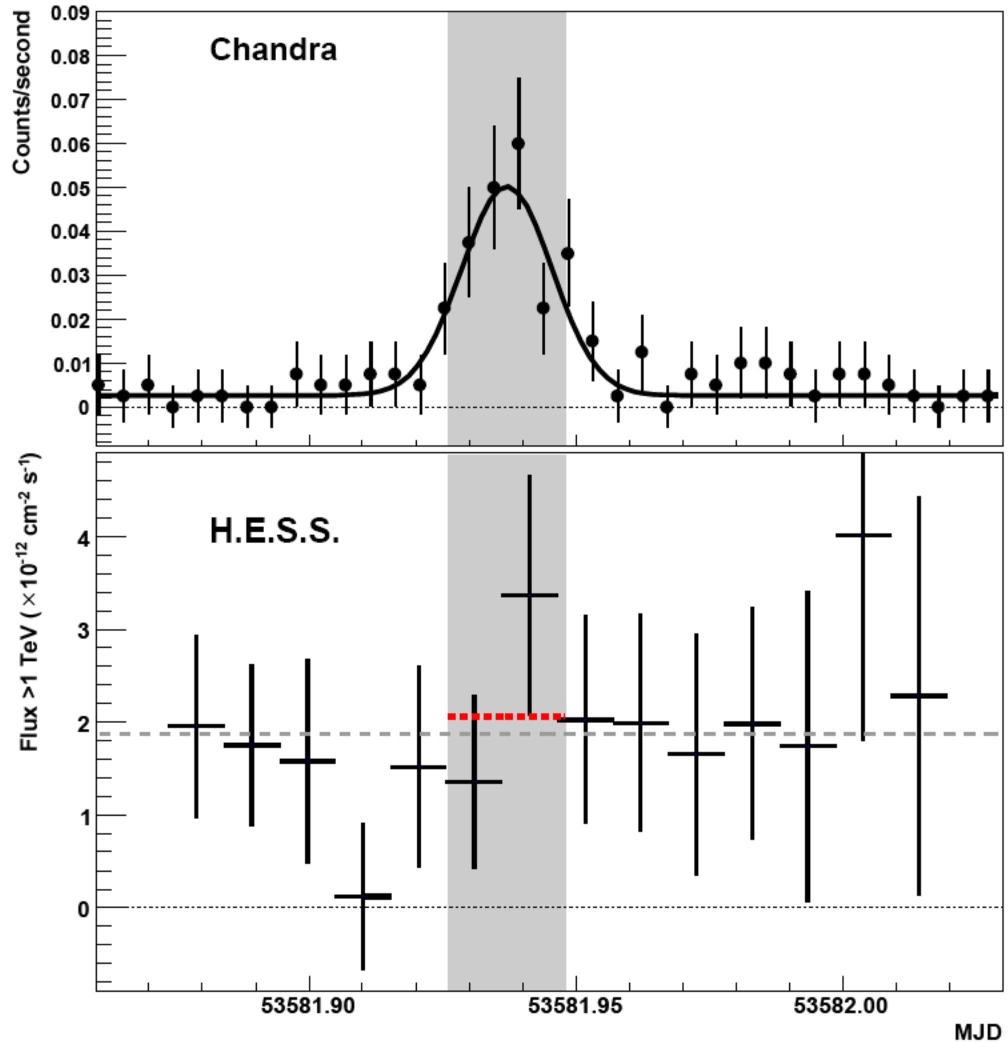


PRL, in press

Is it DM? ▶ Spectrum

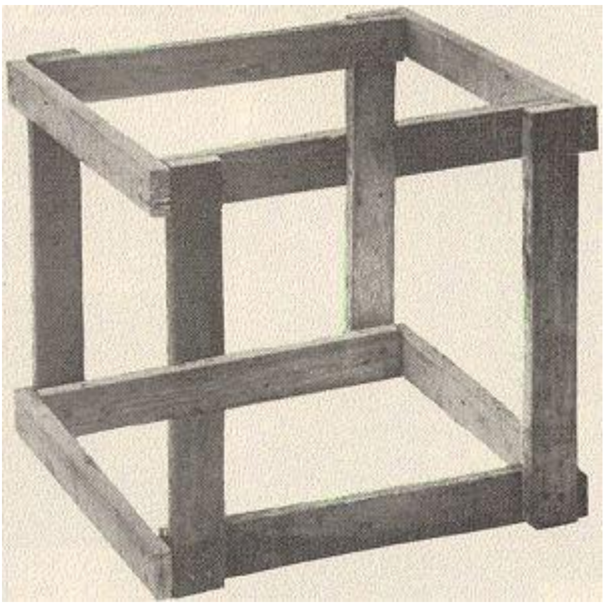
▶ "only" astrophysics!

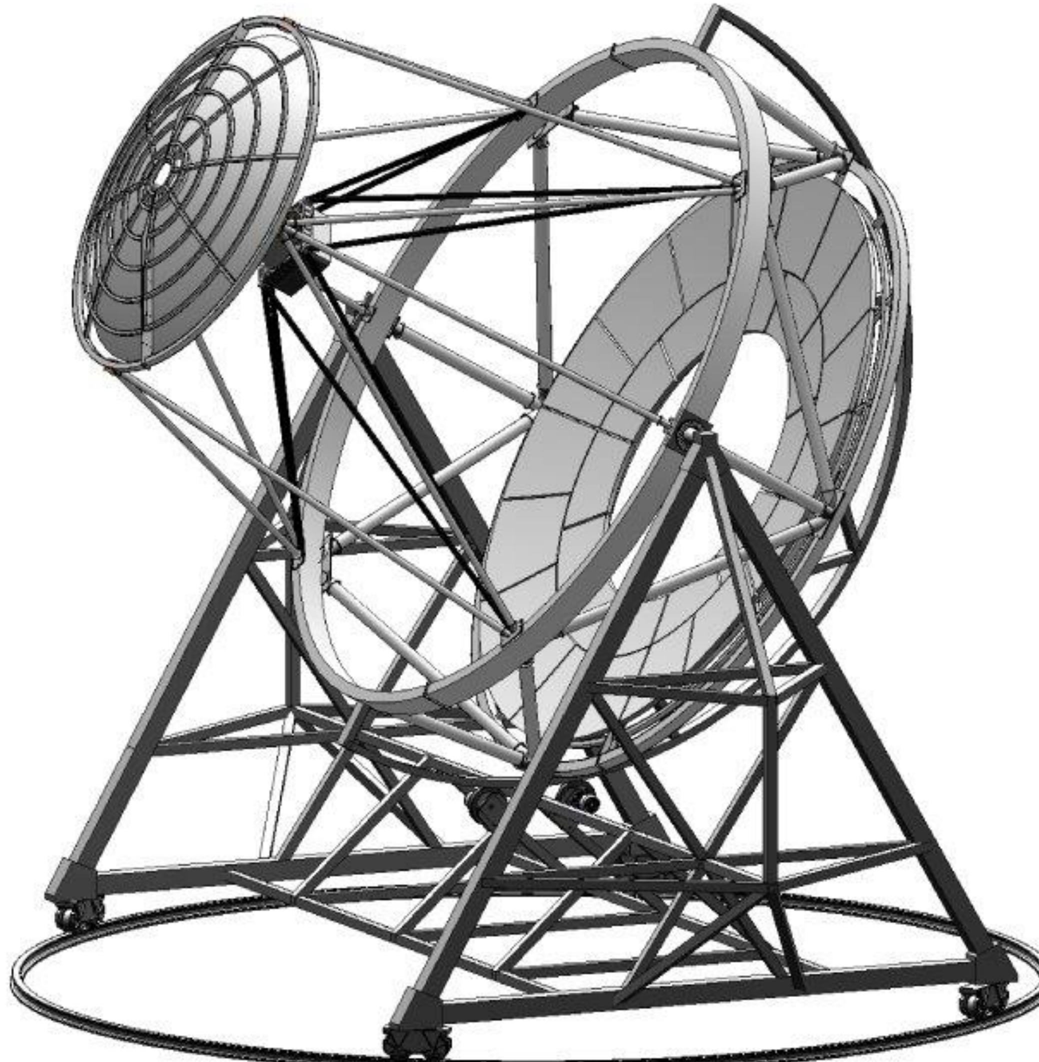




Chandra
Counts/second
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
H.E.S.S.
Flux >1 TeV (×10^{-12} cm^{-2} s^{-1})
4
3
2
1
0
53581.90
53581.95
53582.00
MJD

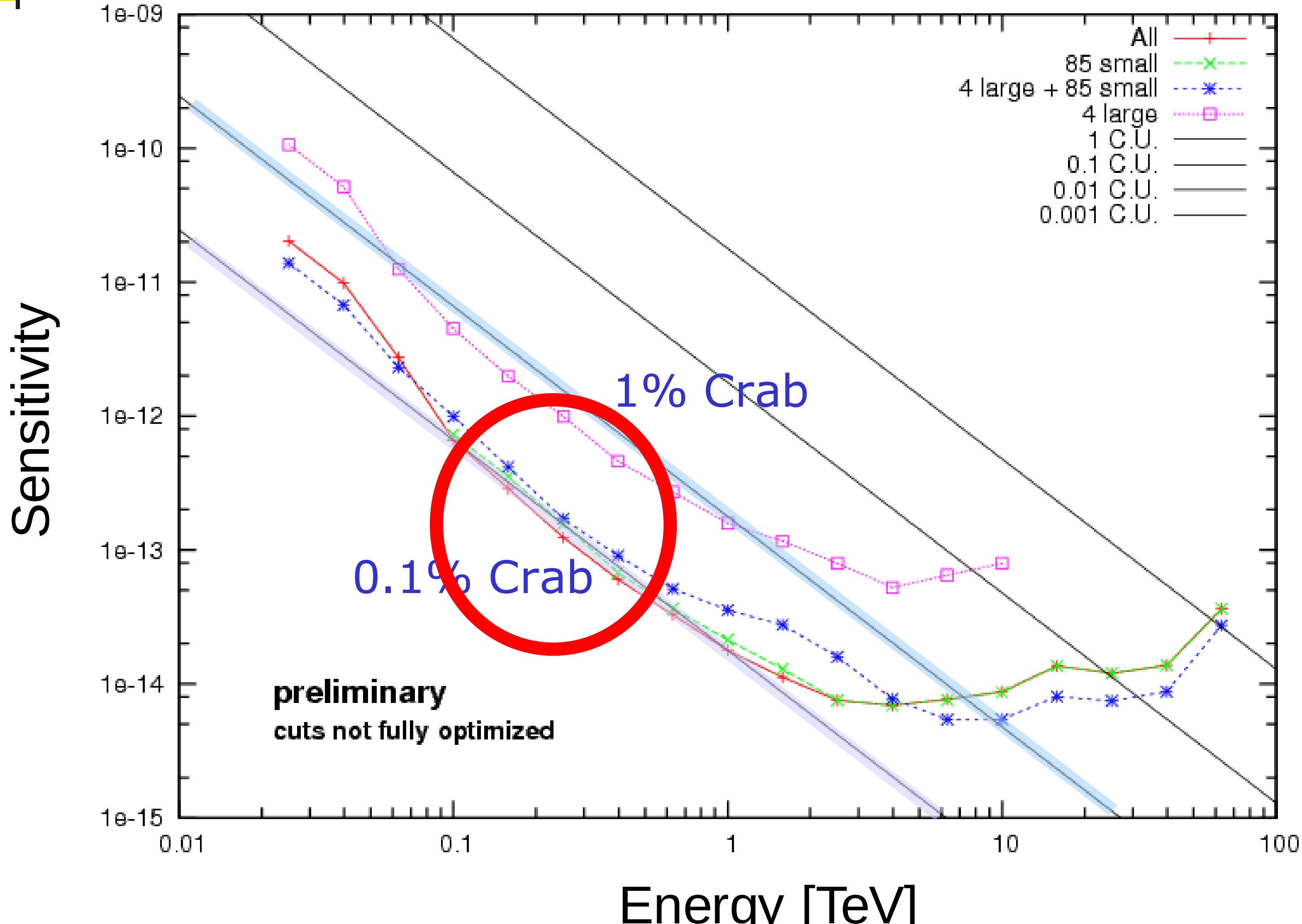
non-trivial: right balance



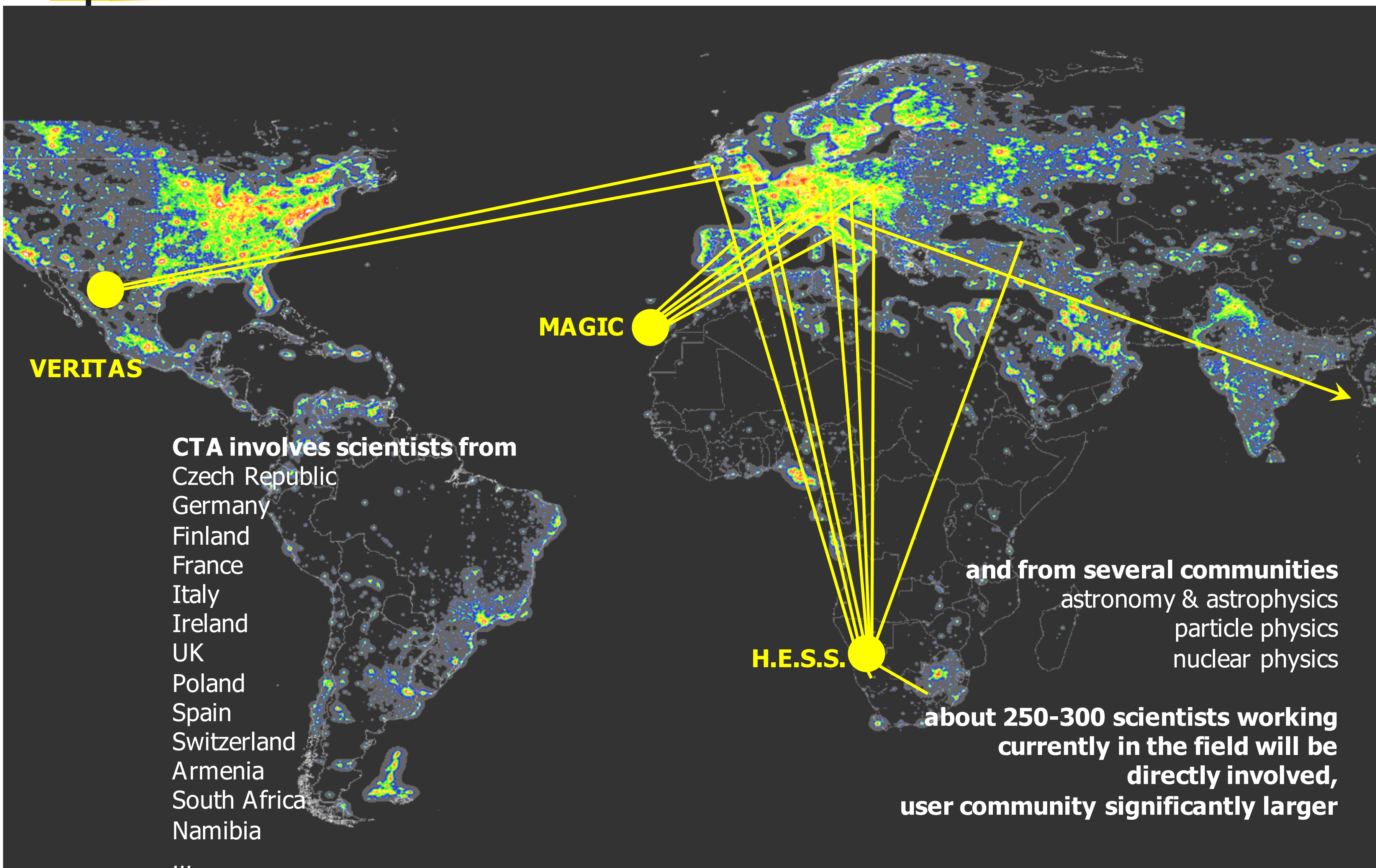


… some designs
are very powerful
but difficult to realize…

Toy array performance:
85 “small” + 4 big telescopes



An international effort

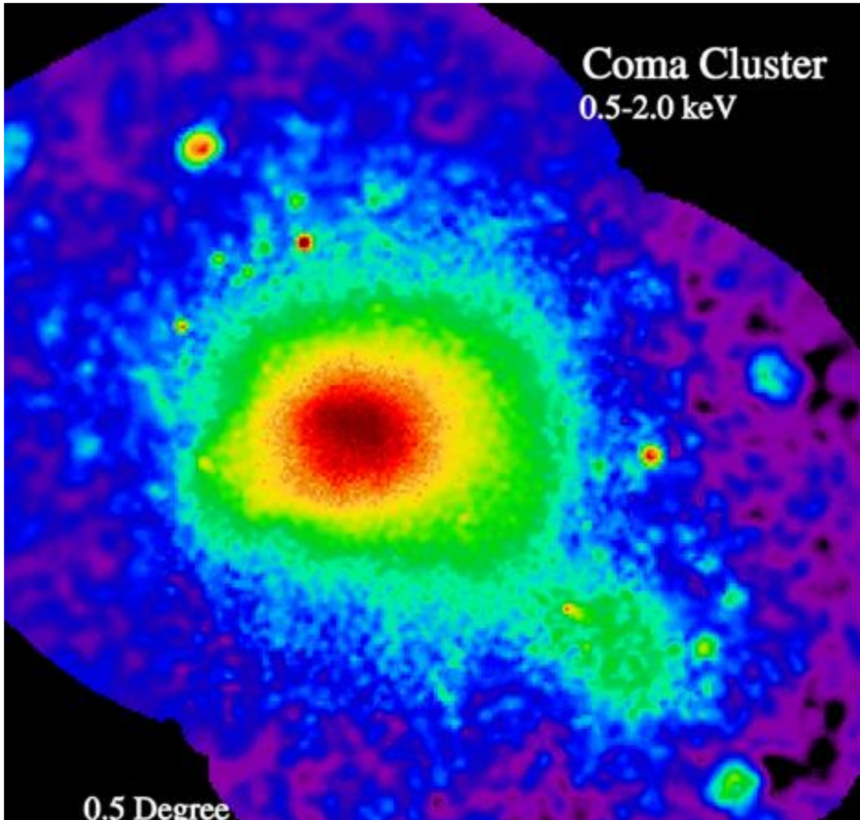


CTA involves scientists from
Czech Republic
Germany
Finland
France
Italy
Ireland
UK
Poland
Spain
Switzerland
Armenia
South Africa
Namibia
...

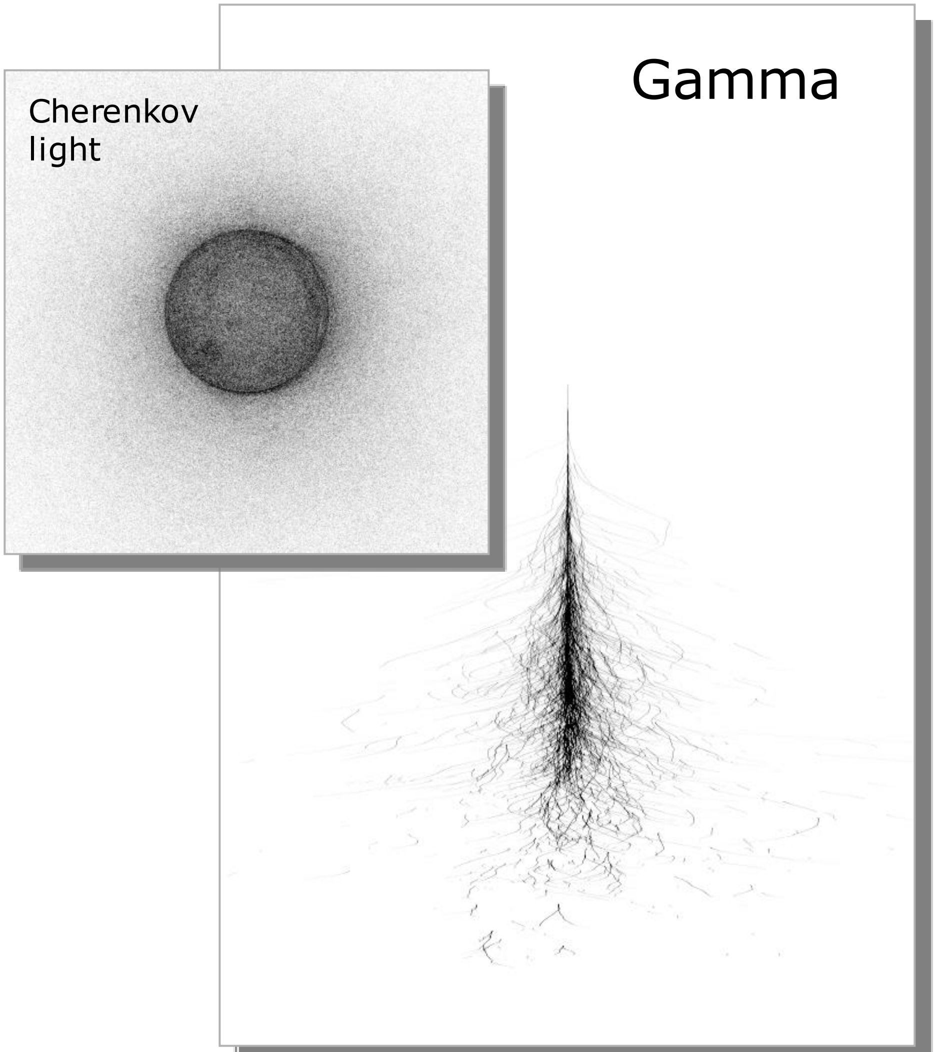
and from several communities
astronomy & astrophysics
particle physics
nuclear physics

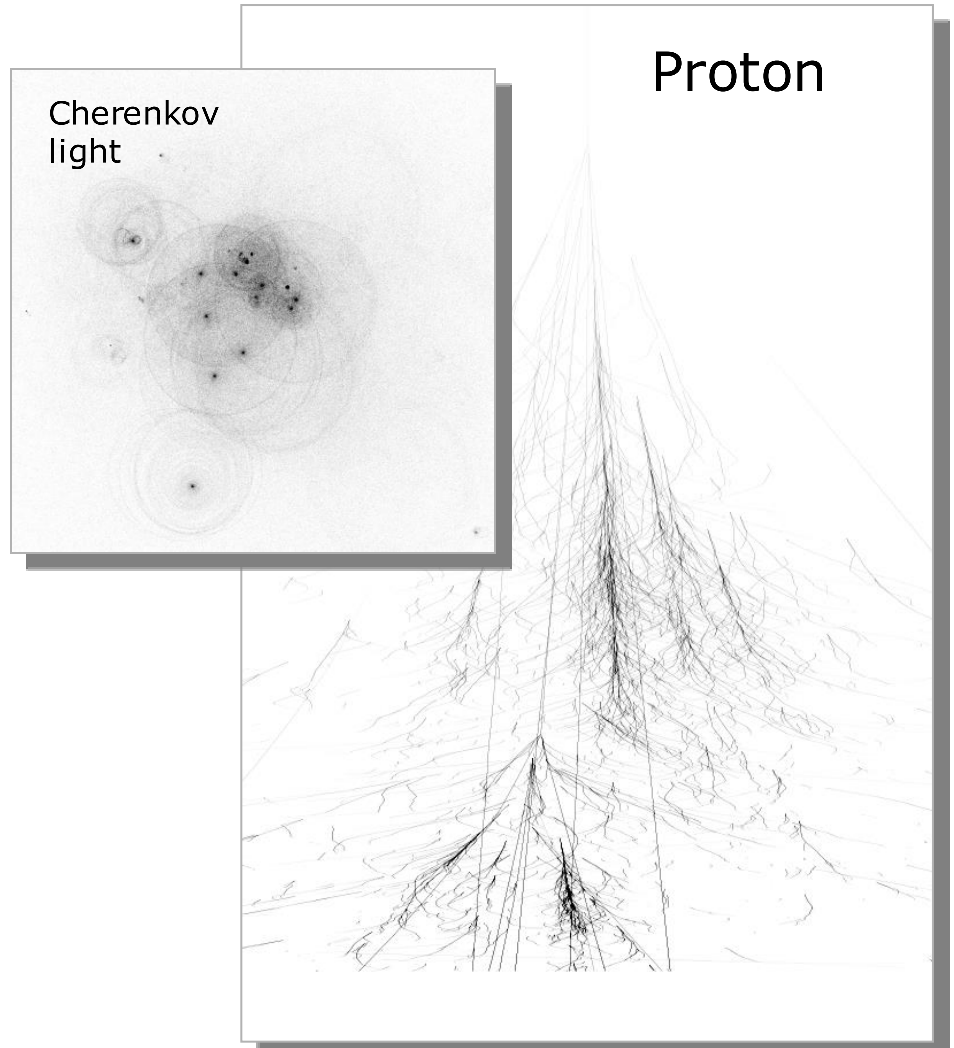
about 250-300 scientists working currently in the field will be directly involved, user community significantly larger

- Many highly interesting source types just (?) below current sensitivity
  - Starburst galaxies
  - Clusters of galaxies
  - UHECR sources
  - GRBs
  - …



Intermediate energies: cosmic ray background



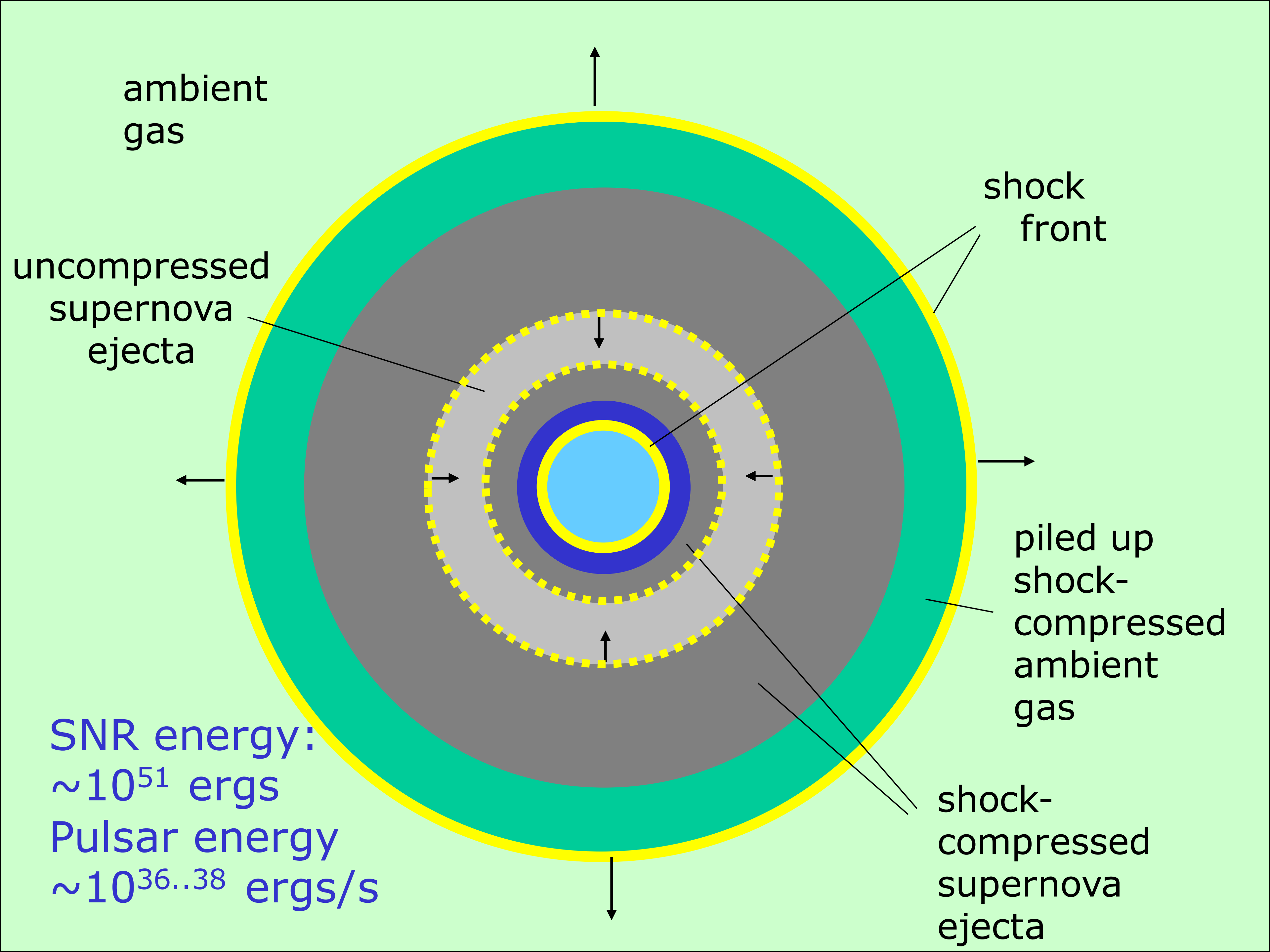


Supernova reach

The future: H.E.S.S. II

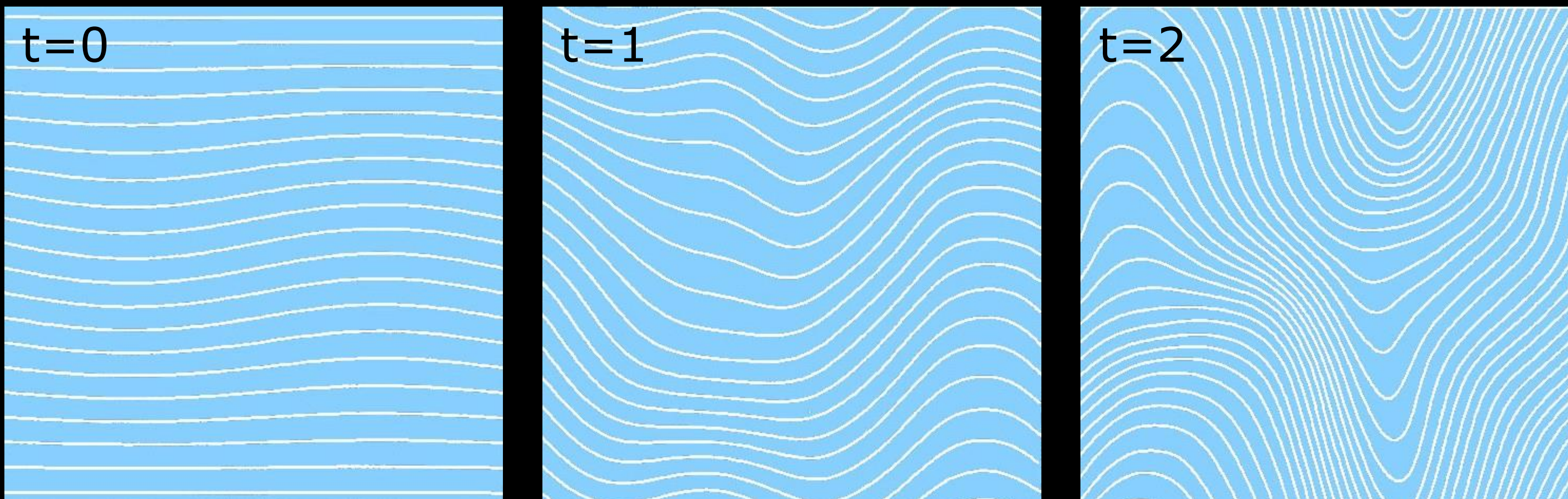
H.E.S.S. II

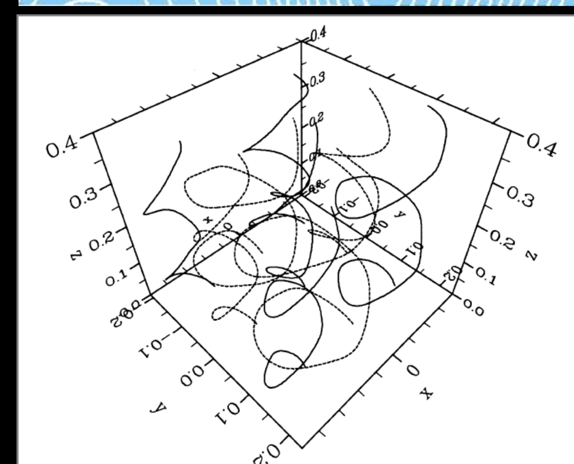
- Enhanced sensitivity above ~70 GeV in stereo mode
- Further reduction of threshold in mono mode


ambient gas
shock front
uncompressed supernova ejecta
piled up shock-compressed ambient gas
shock-compressed supernova ejecta
SNR energy: ~10^{51} ergs
Pulsar energy ~$10^{36..38}$ ergs/s

Field amplification by streaming CRs

S.G. Lucek, A.R. Bell, MNRAS 314 (2000) 65

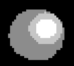
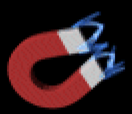




RMS B field amplified by factor up to 30

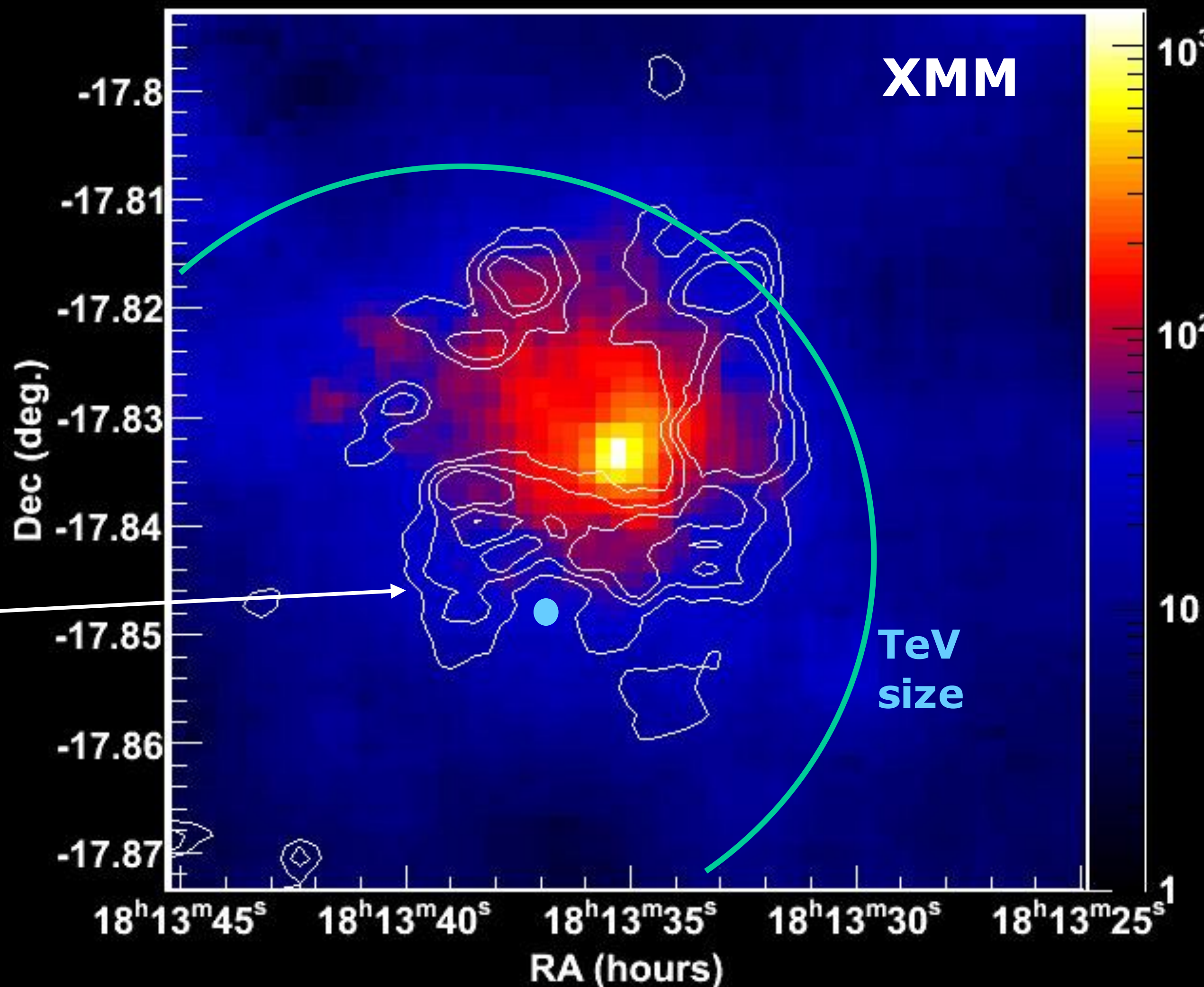
A.R. Bell, MNRAS 353 (2004) 550

Amplification factor ~ $n_{electr.}$ ~ ρ_{ion}

	X-rays	Gamma rays
Proton accelerator		
Electron Accelerator		

HESS J1813-178

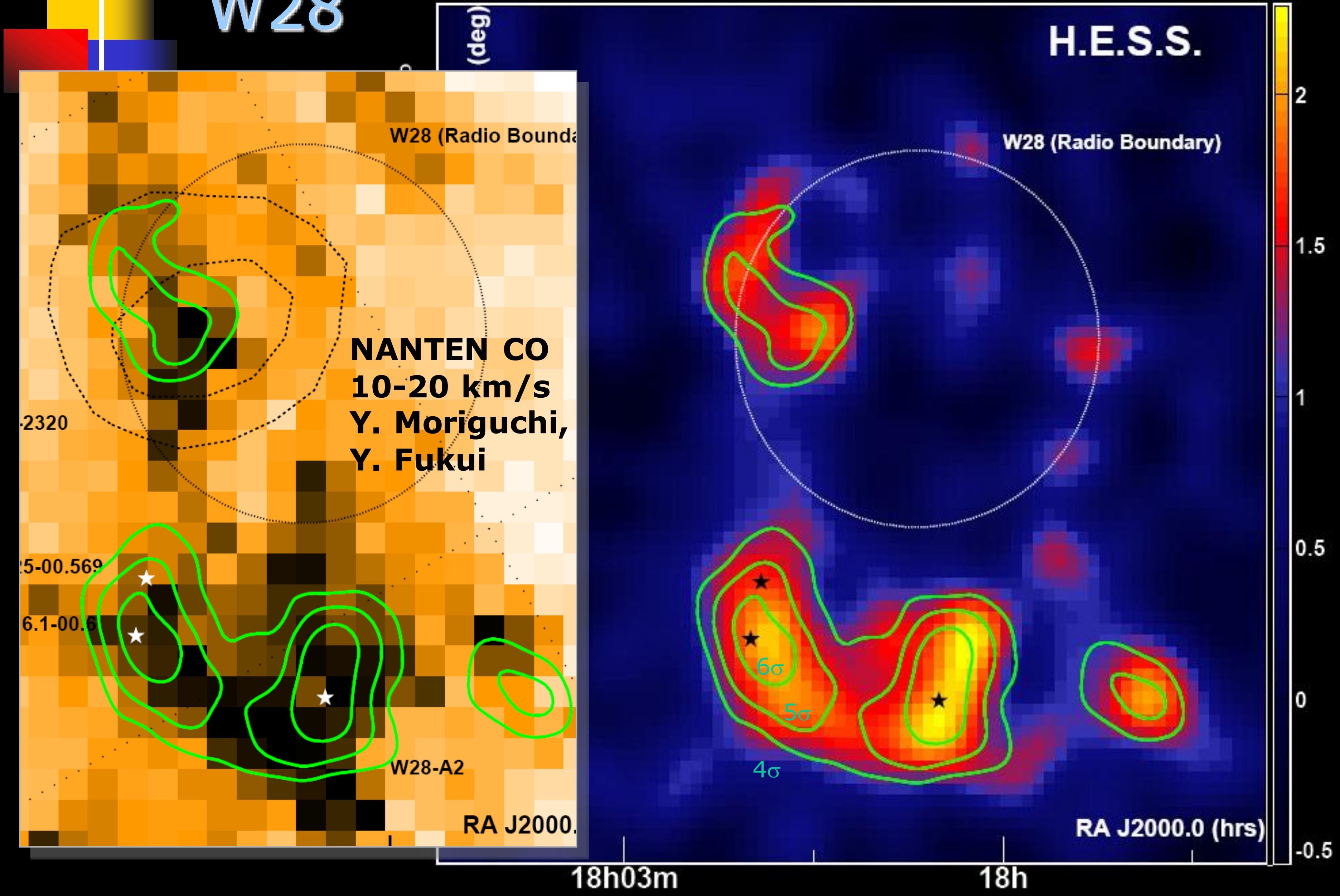
S. Funk et al., astro-ph/0611646



Radio
Supernova shell
D.J. Helfand et al.,
astro-ph/0505392
C.L. Brogan et al.,
astro-ph/0505145

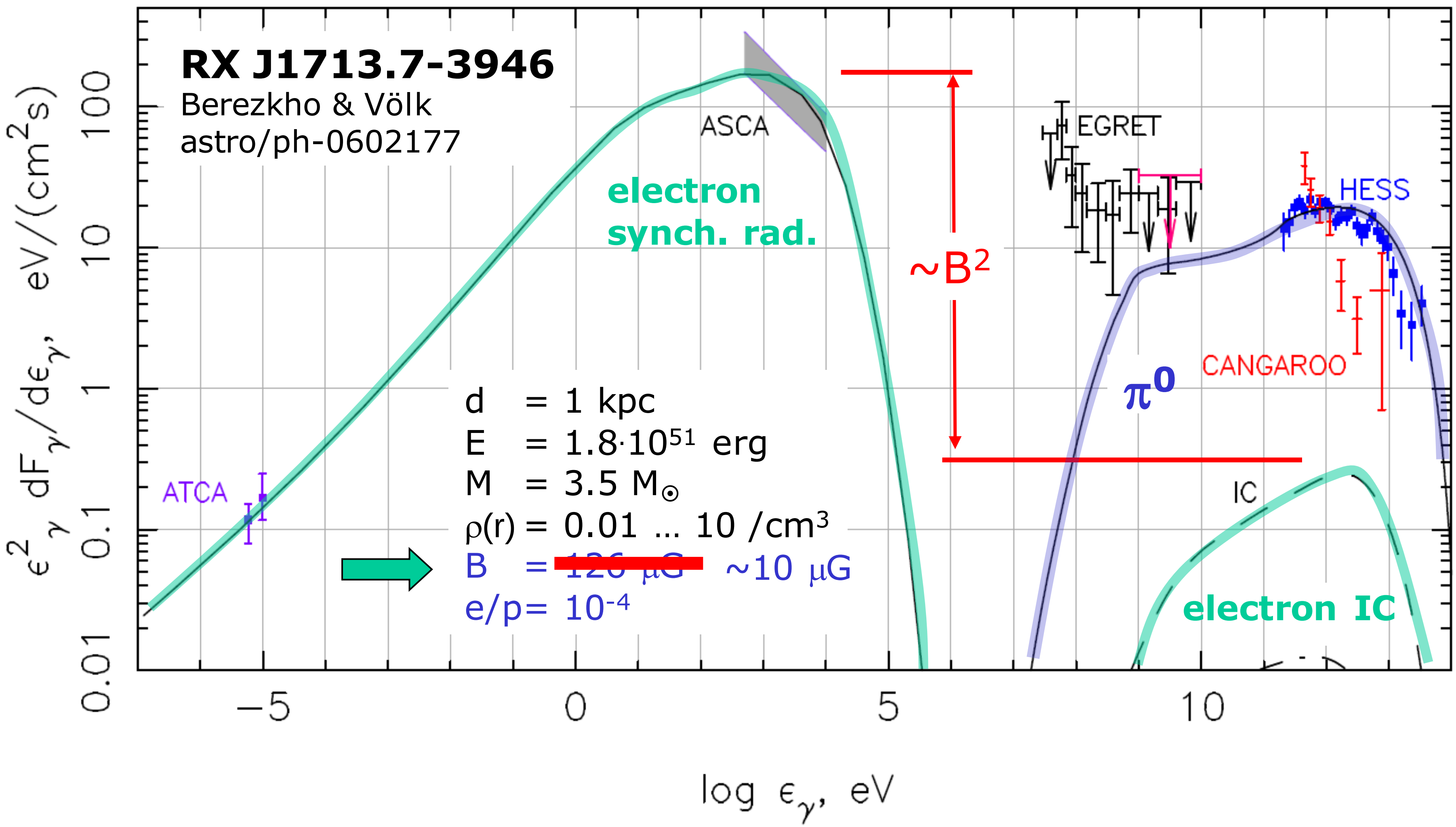
Galactic Plane Survey

W28

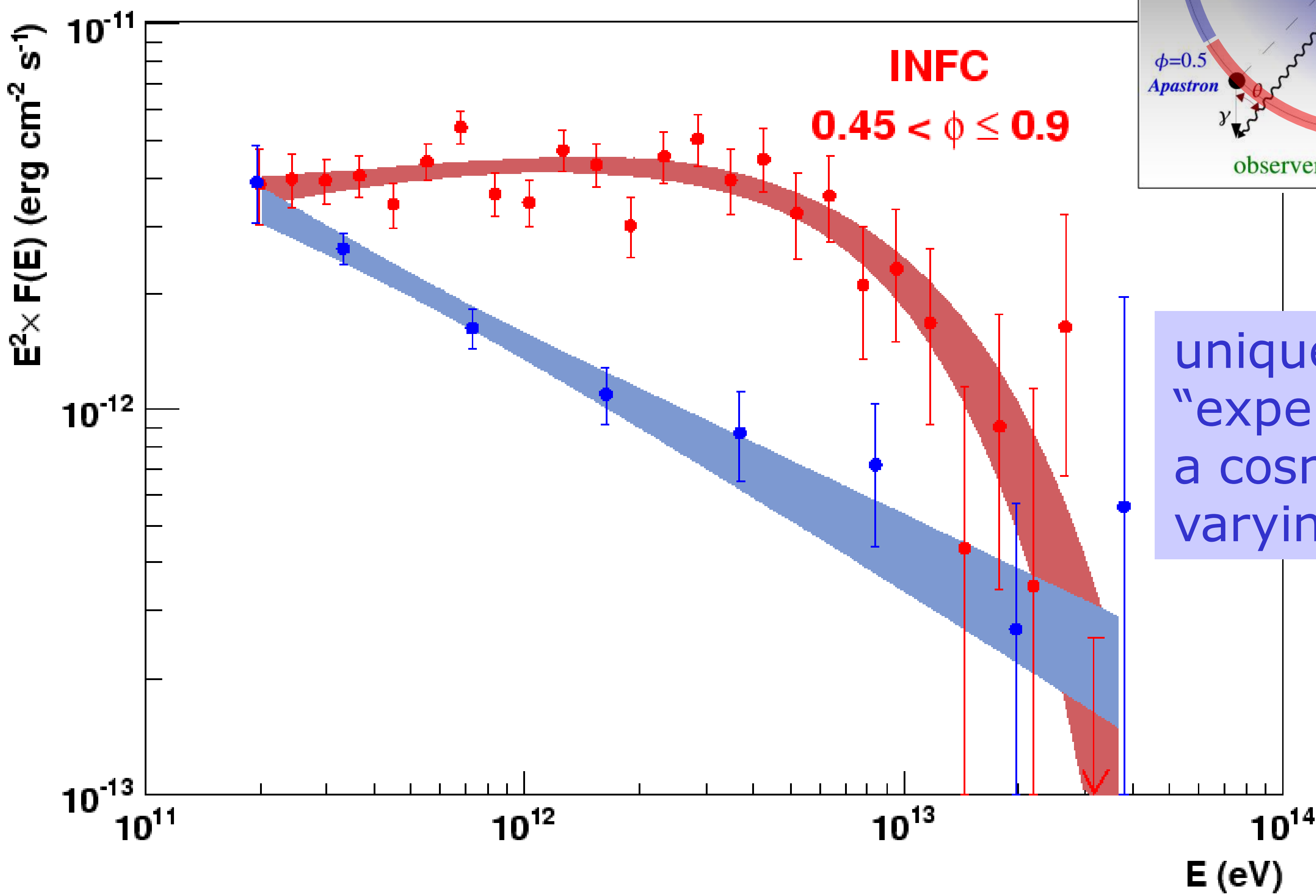


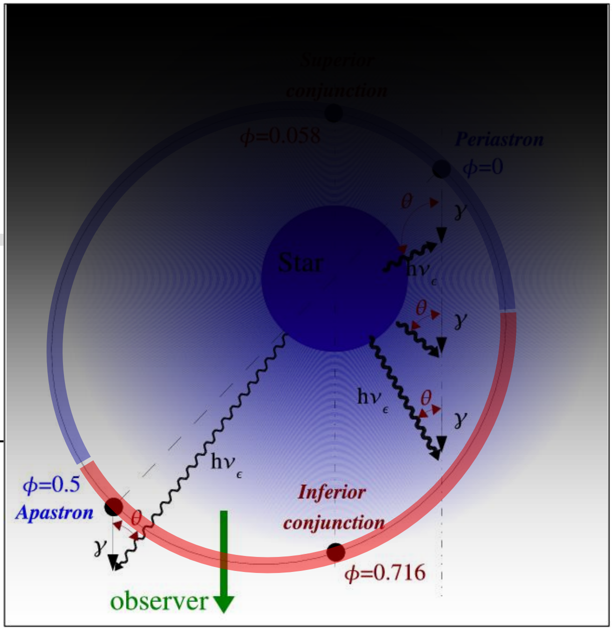
W28 (Radio Bounda
NANTEN CO
10-20 km/s
Y. Moriguchi,
Y. Fukui
-2320
25-00.569
6.1-00.6
W28-A2
RA J2000.
H.E.S.S.
(deg)
W28 (Radio Boundary)
6σ
5σ
4σ
RA J2000.0 (hrs)
18h03m
18h
2
1.5
1
0.5
0
-0.5

X-ray & gamma ray emission



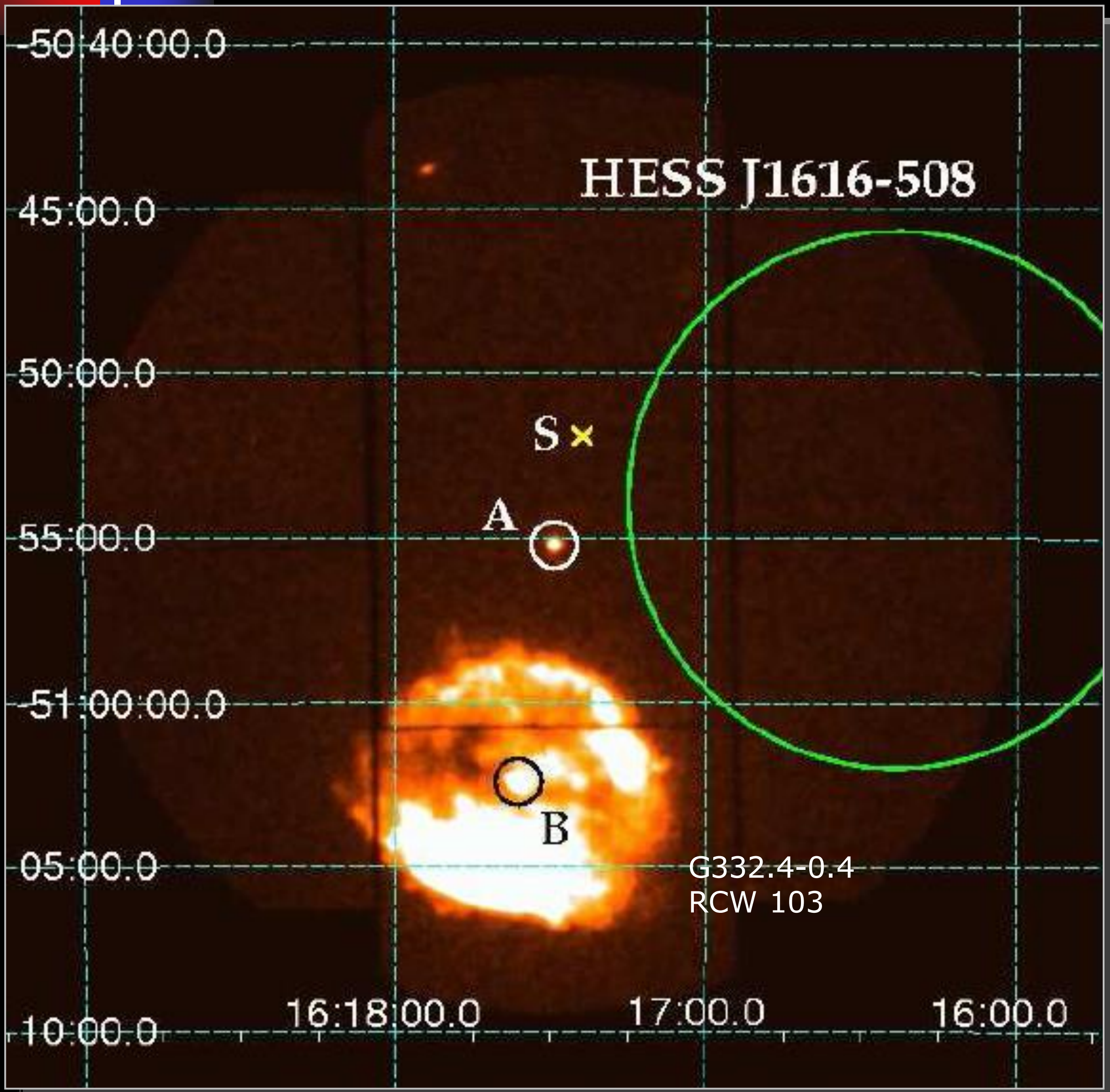
Spectral variation



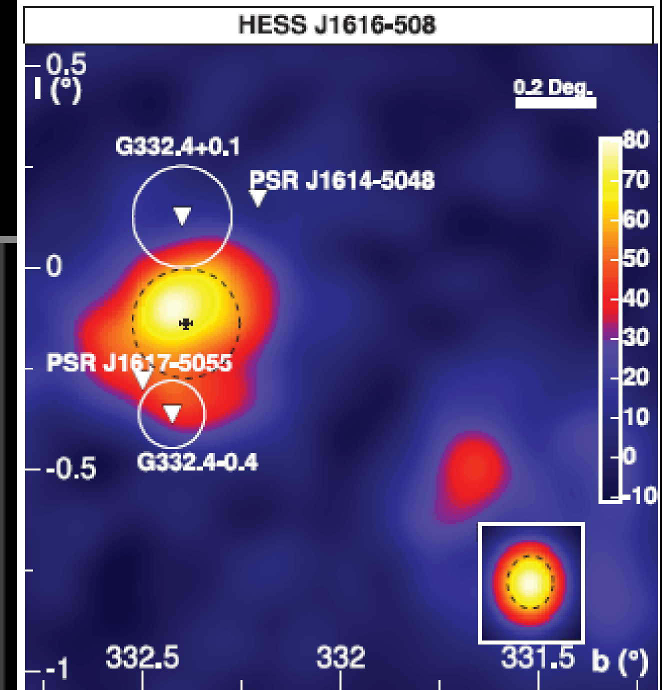


unique chance to "experiment" with a cosmic source by varying conditions

... but some do ...

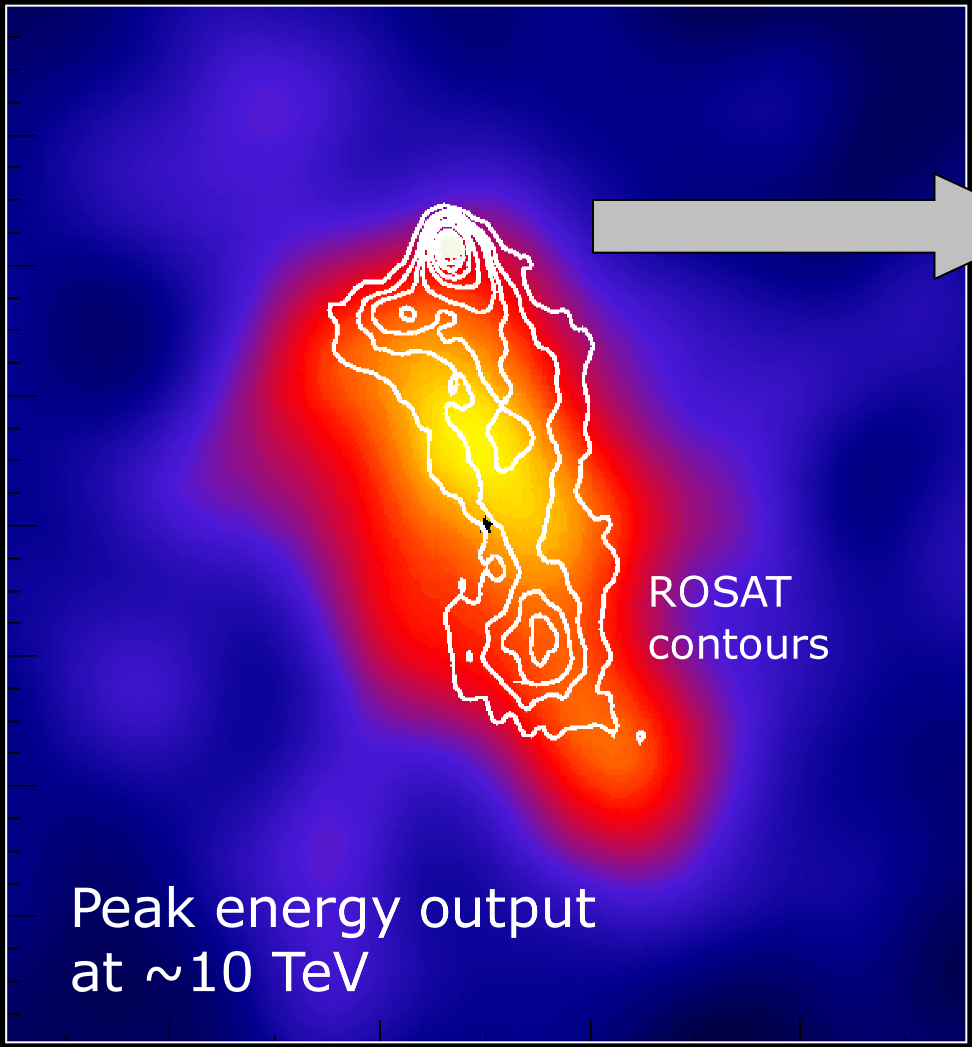


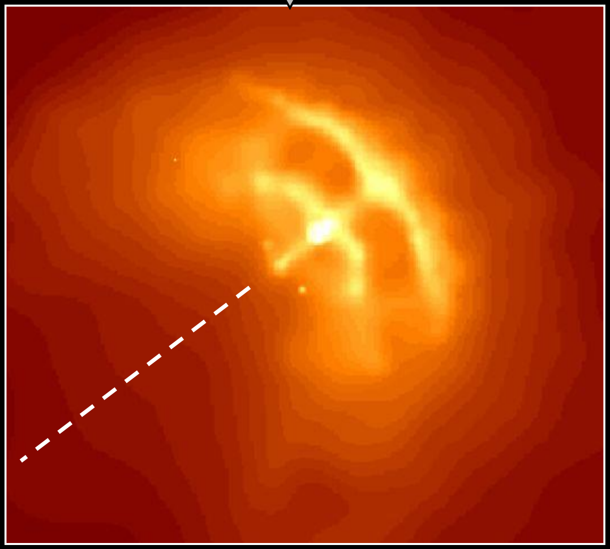
-50:40:00.0
45:00.0
50:00.0
55:00.0
-51:00:00.0
05:00.0
10:00.0
16:18:00.0
17:00.0
16:00.0
HESS J1616-508
S
A
B
G332.4-0.4
RCW 103



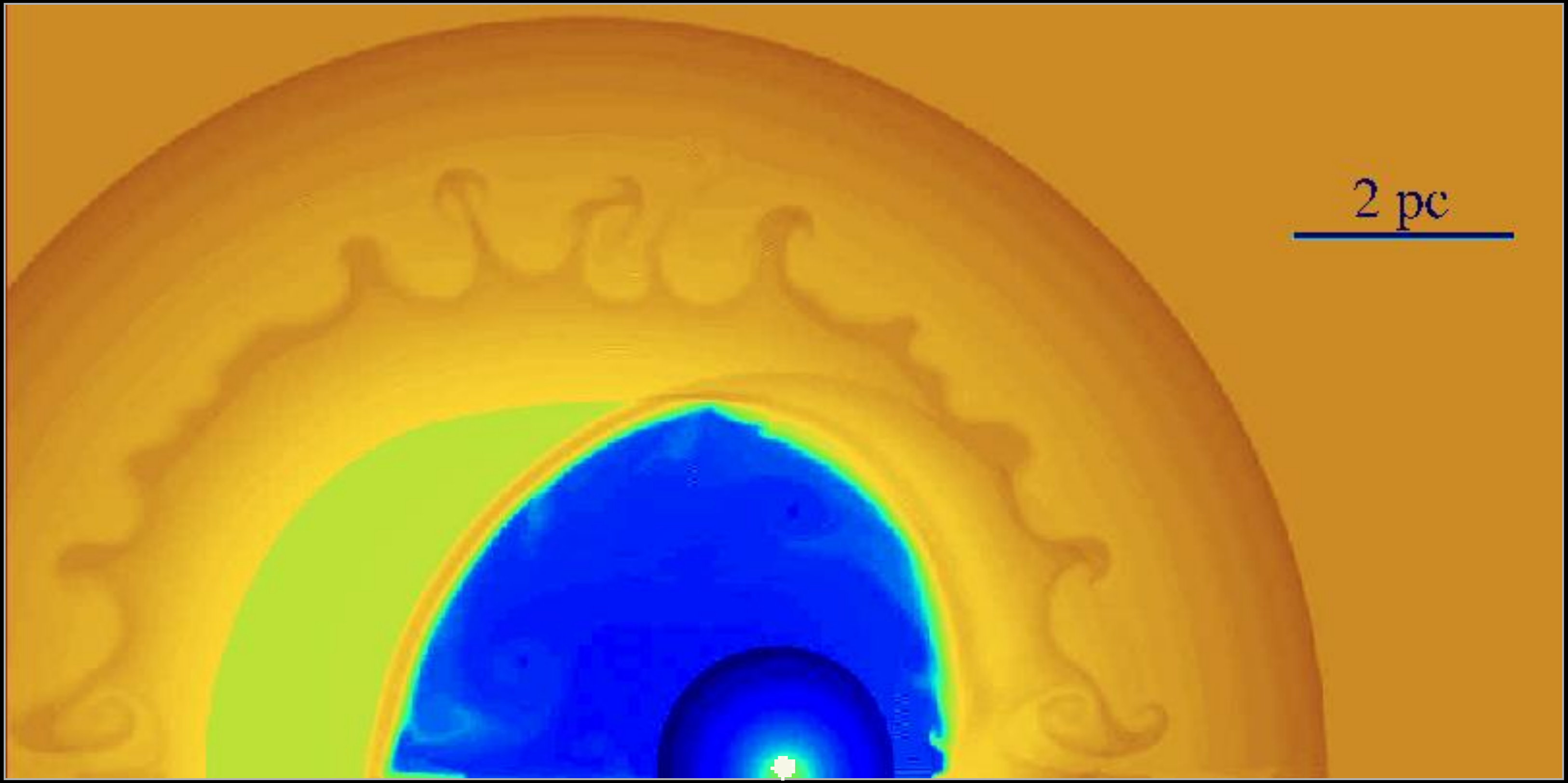
HESS J1616-508
0.5
l (°)
0
-0.5
-1
0.2 Deg.
G332.4+0.1
PSR J1614-5048
PSR J1617-5055
G332.4-0.4
80
70
60
50
40
30
20
10
0
-10
332.5
332
331.5
b (°)

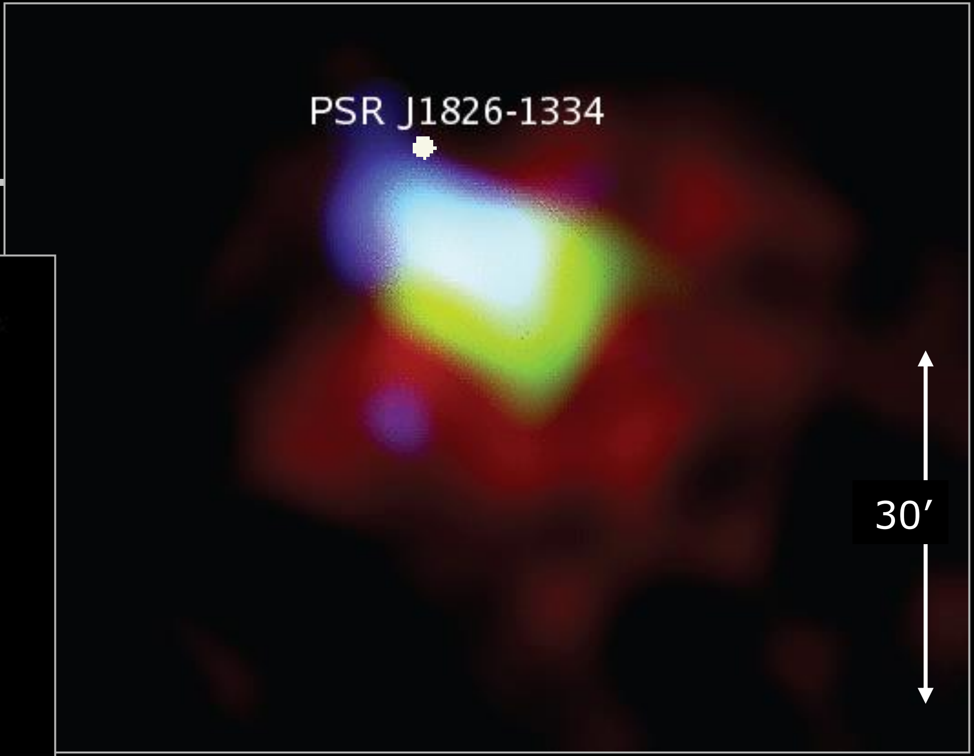
Vela-X

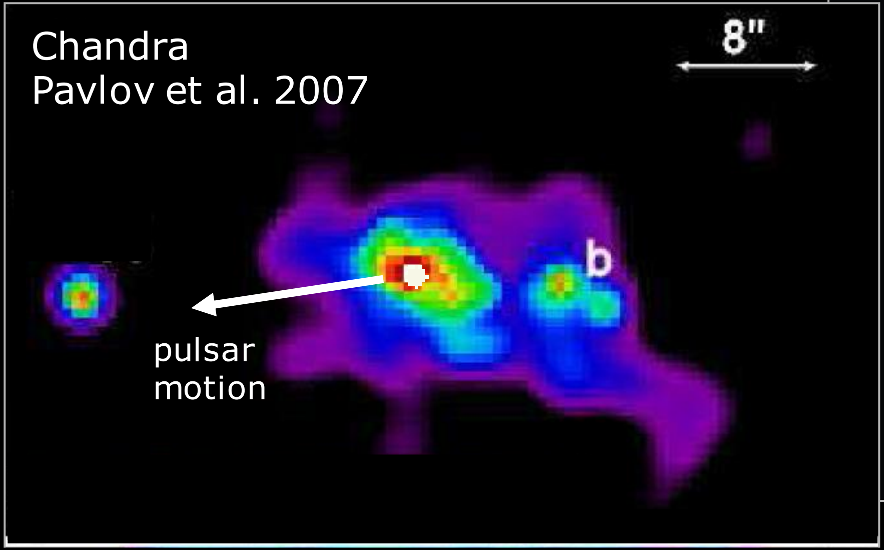




Hydrodynamics simulations: Pulsar “Kick”




PSR J1826-1334
30′


Chandra
Pavlov et al. 2007
8"
b
pulsar
motion