The Quest for the Origin of Cosmic Rays

Werner Hofmann
MPI für Kernphysik
Heidelberg

Sagittarius
Region

Hubble
Space
Telescope


Galaxy M 51
T. & M. Hallas

Cone Nebula
ACS NASA


Eagle Nebula
T.A. Rector &
B.A. Wolpa
NOAO

Cosmic rays

Discovery:
Victor Hess 1912
(Nobel Prize 1932)

A detective story in science

The case:
A 90-year mystery –
the origin of Cosmic Rays

The suspects:
Black holes & exploding stars

The evidence:
Blue flashes from space -
Astrophysics with Cherenkov telescopes

The judgement

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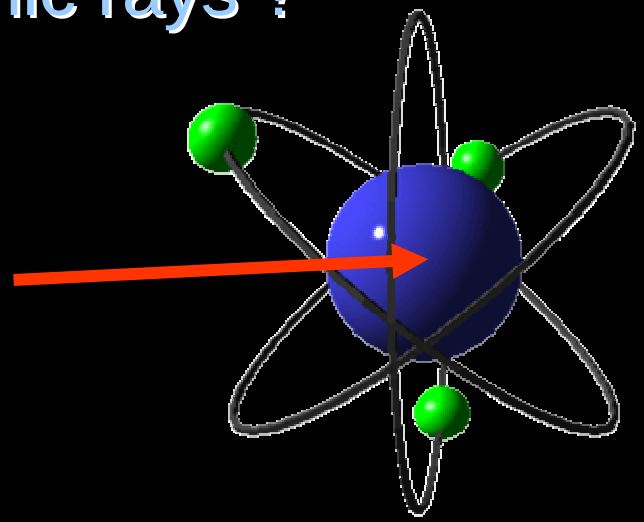
What do we know about cosmic rays ?

- They consist mostly of atomic nuclei, like those found in the sun



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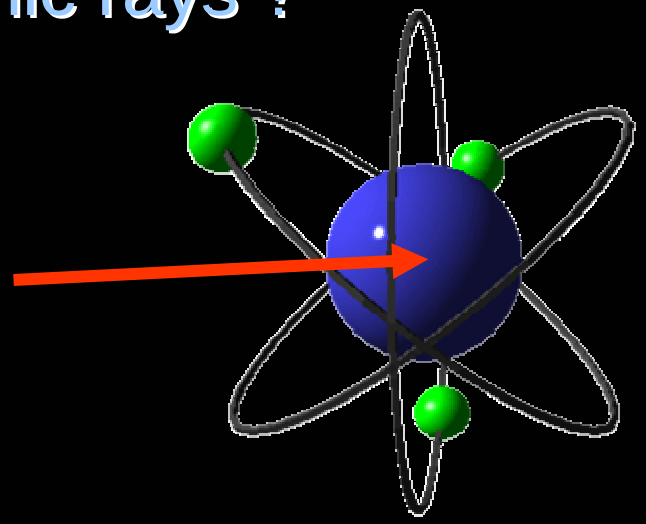
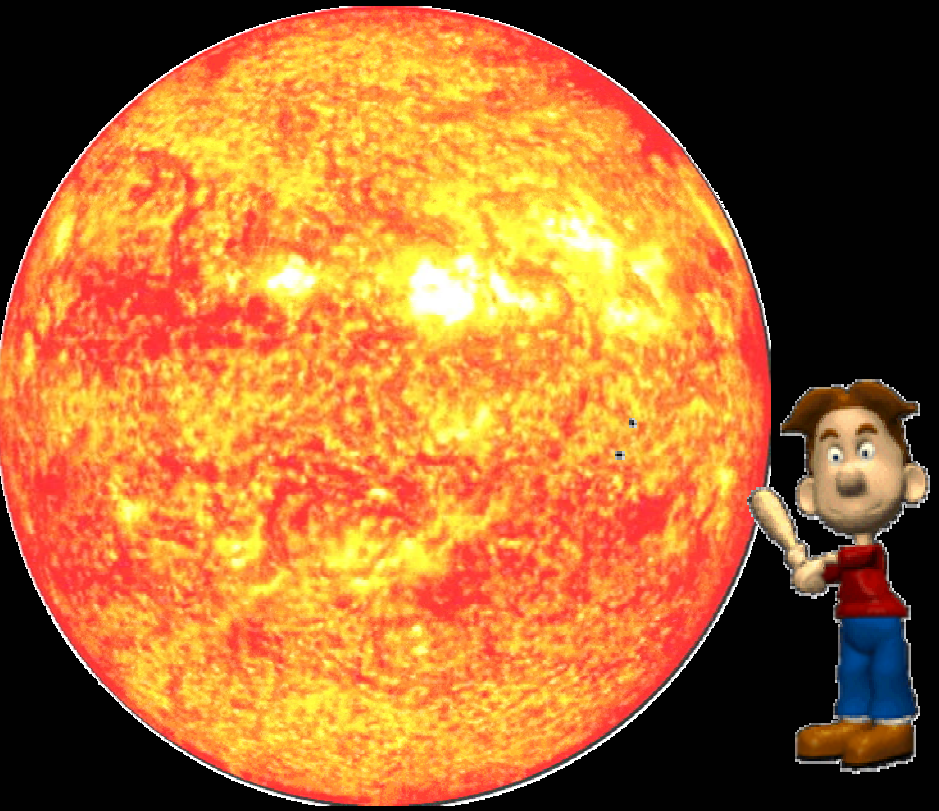




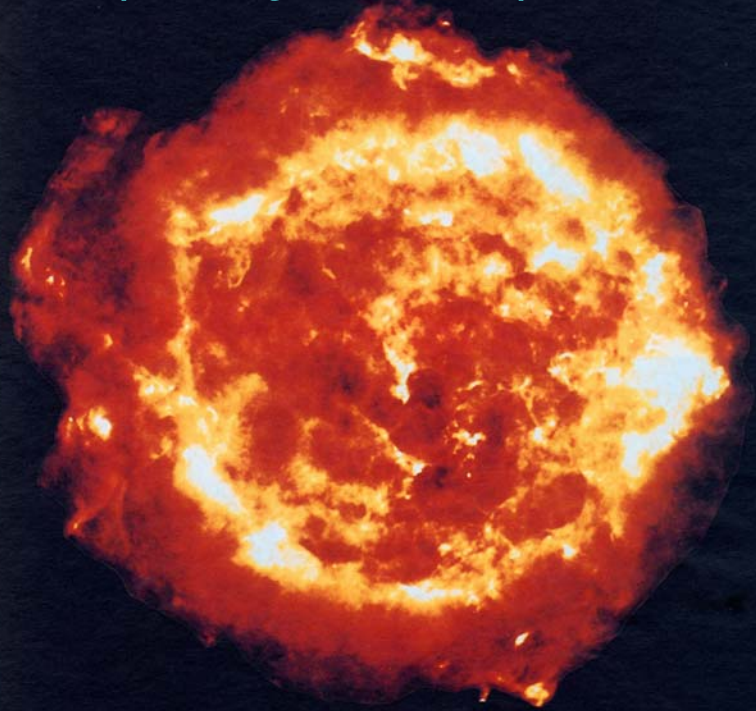
- They cover a wide spectrum of energies; the highest energies are 100000000 times higher than those of the largest man-made accelerator
- They cover the whole sky more or less uniformly ... they come from everywhere

Why do we care ?

The sources of cosmic rays must be some of the most interesting and most violent objects in the Universe

ICRR
Institute for Cosmic Ray Research

Exploding stars: Supernovae



Giant Black Holes at the Cores of Galaxies

Why do we care ?

Cosmic rays are
“responsible” for th
evolution of specie

ICRR

Institute for Cosmic Ray Research

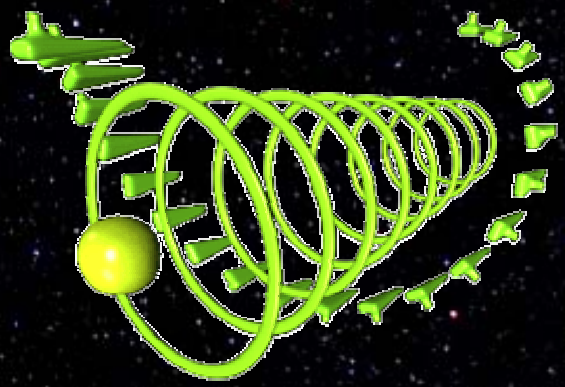
Why do we care ?

Cosmic rays are “responsible” for the evolution of species

ICRR

Institute for Cosmic Ray Research

Why is it so difficult to spot the origins of Cosmic Rays ?



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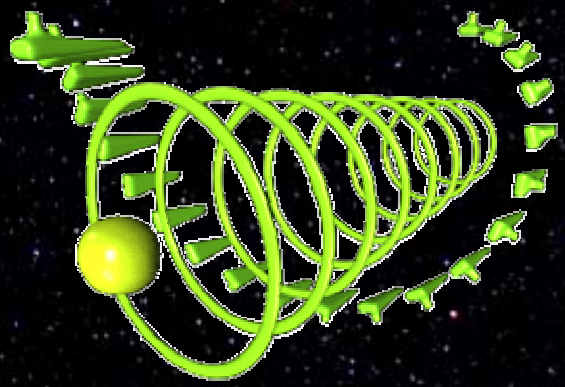
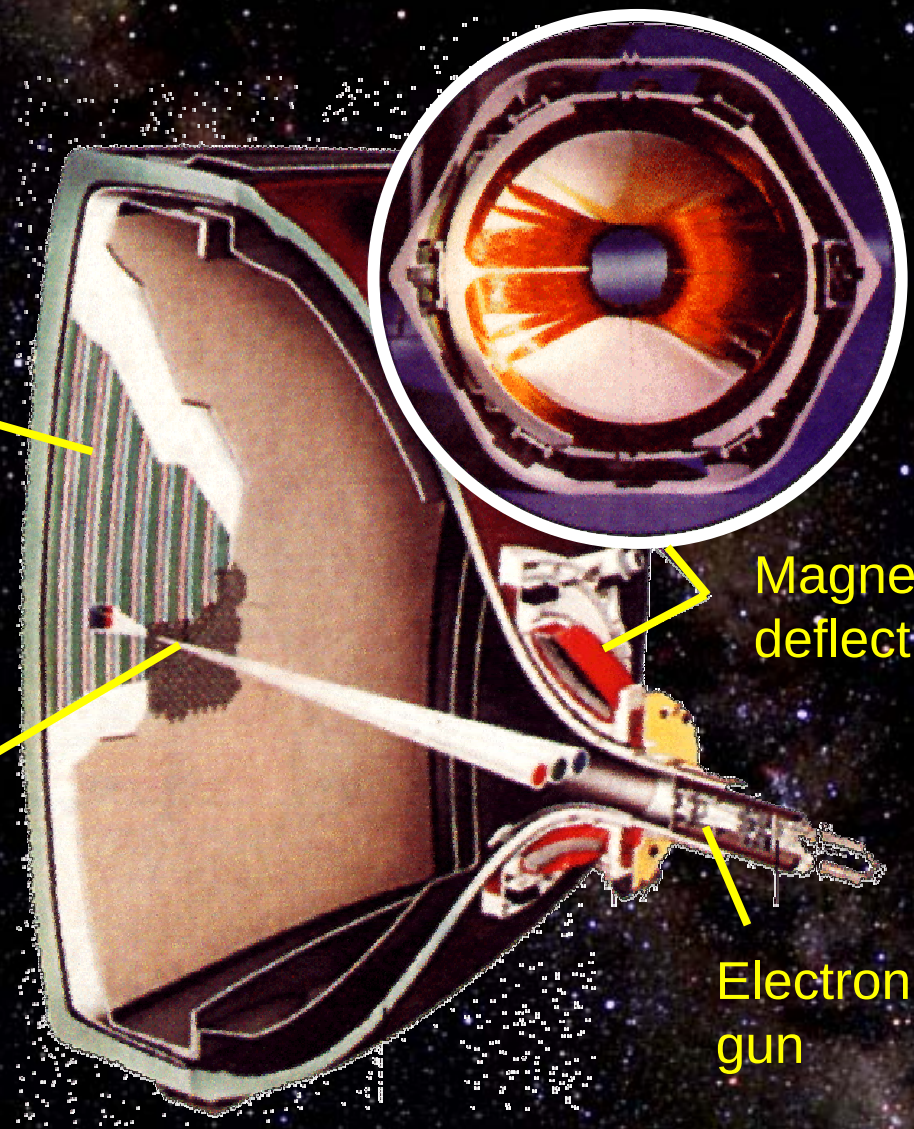


Magnetic fields bent particle tracks !



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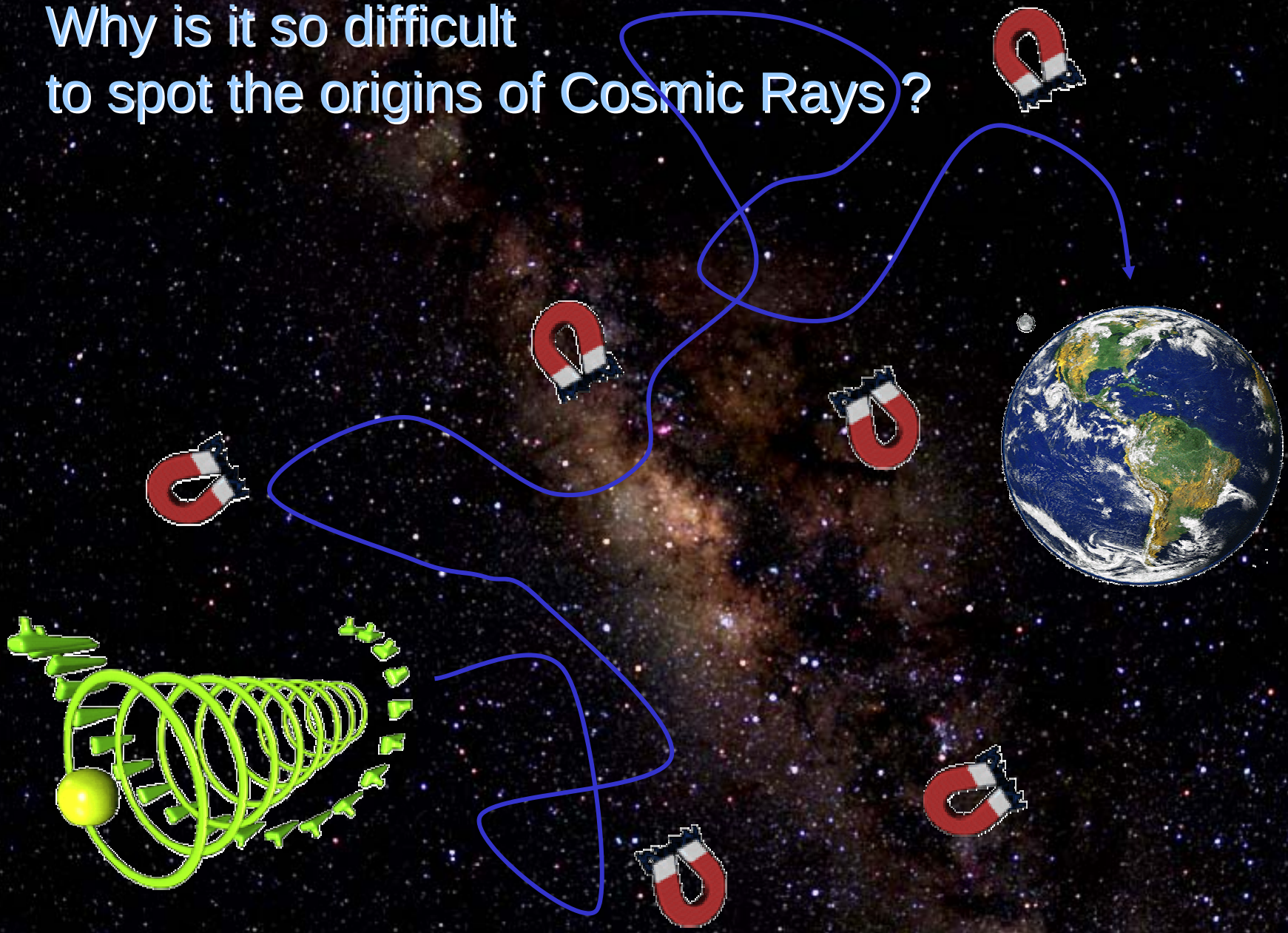

Think!

What objects could be cosmic accelerators ?

Are there other ways to find them ?

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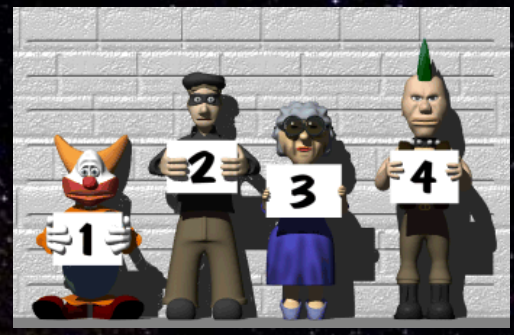

The suspects:
Black holes & exploding stars

The evidence:
Blue flashes from space -
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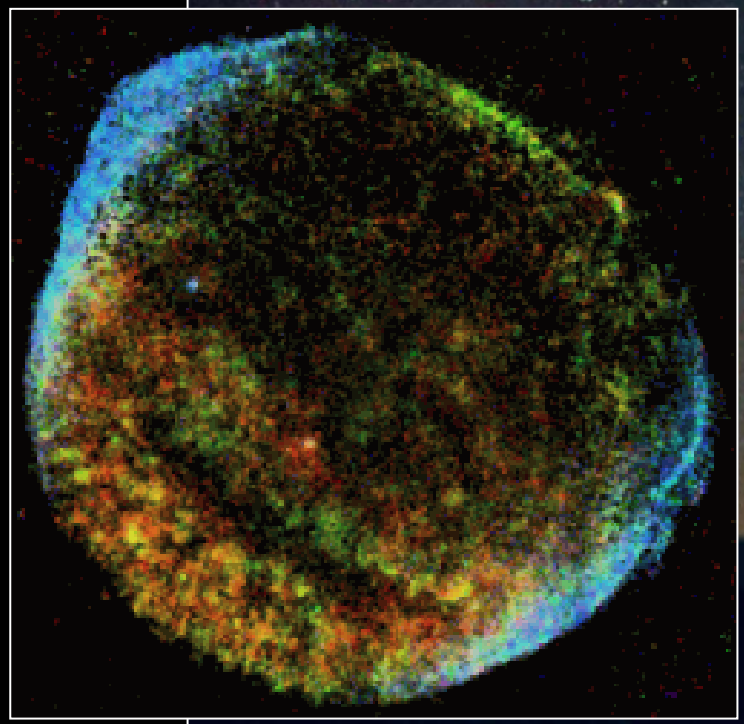
The judgement

Supernova 1006

T. Tezel

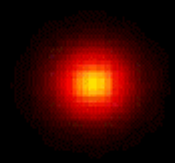
50 light years
0.5° diameter



以後七月以前、客星入羽林中
1006 一條院寛弘三年四月一
日、癸酉、夜以降騎官中有大客星、如熒惑、光明動耀、
連夜正見南方、或云、騎陣將軍星變本體增光歟
1054 後冷
泉院天喜二年四月中旬以後丑時、客星出觜參度、見東
方、孛天關星、大如歲星、二條院永萬二年四月廿二日、

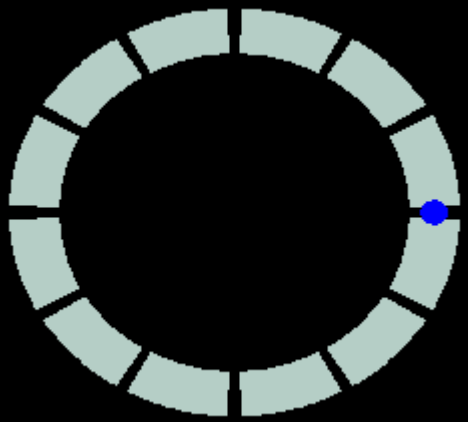
from Meigetsuki

Galactic accelerators: Supernovae ?



How might such cosmic accelerators work?

Man-made accelerators



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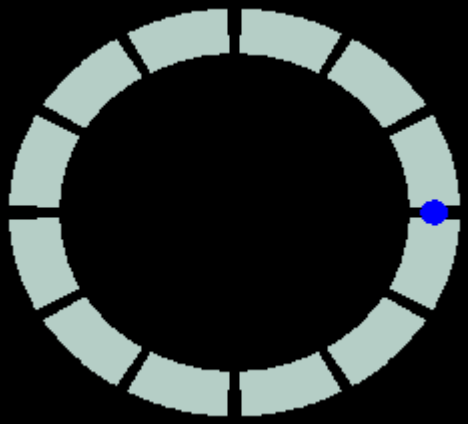

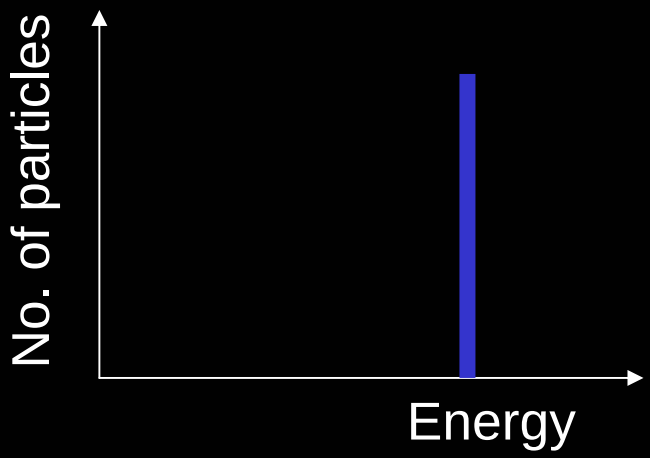

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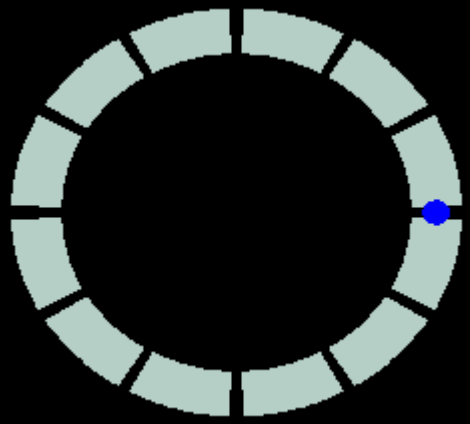
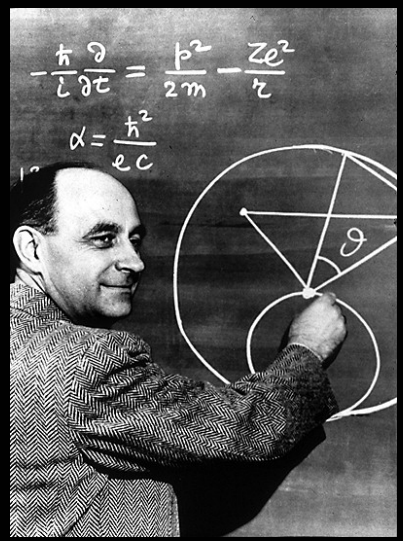
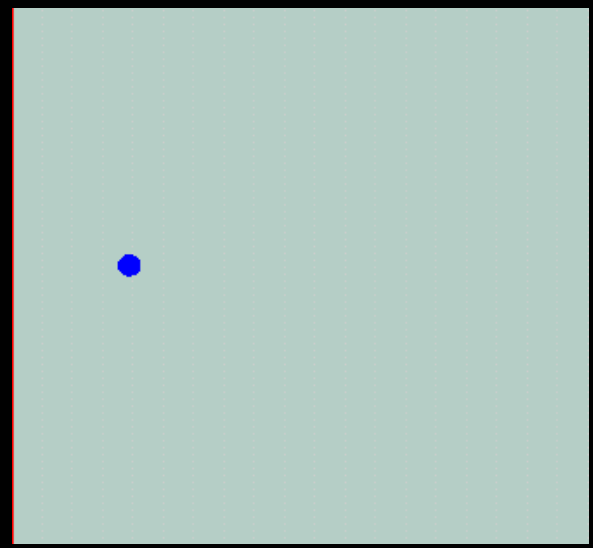
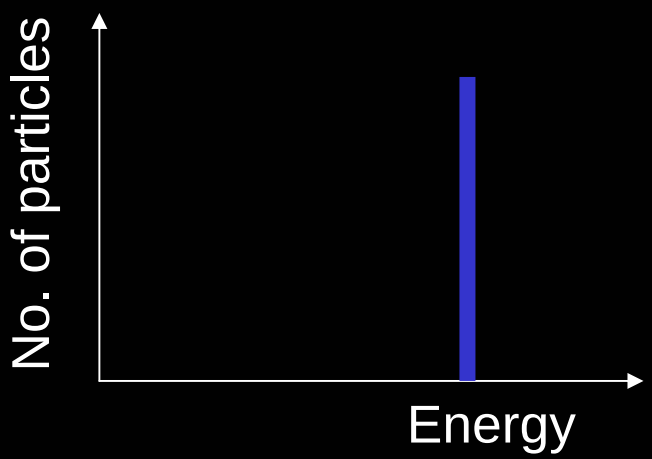


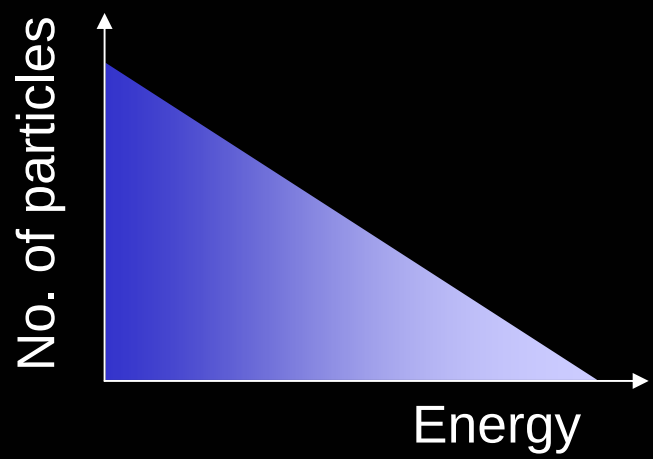


Enrico Fermi

Nature's accelerators







A detective story in science

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but is this really tru
can we observe it ?

The suspects:
Black holes & exploding stars

The evidence:
Blue flashes from space -
Astrophysics with Cherenkov telescopes

The judgement

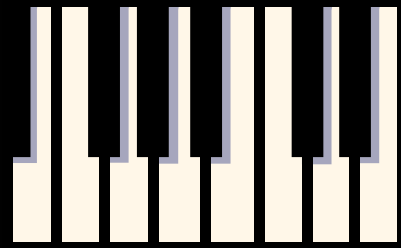
Galactic accelerators: Supernovae ?

- ➔ Image the source using neutral particles
- ➔ Astronomy with gammas and neutrinos

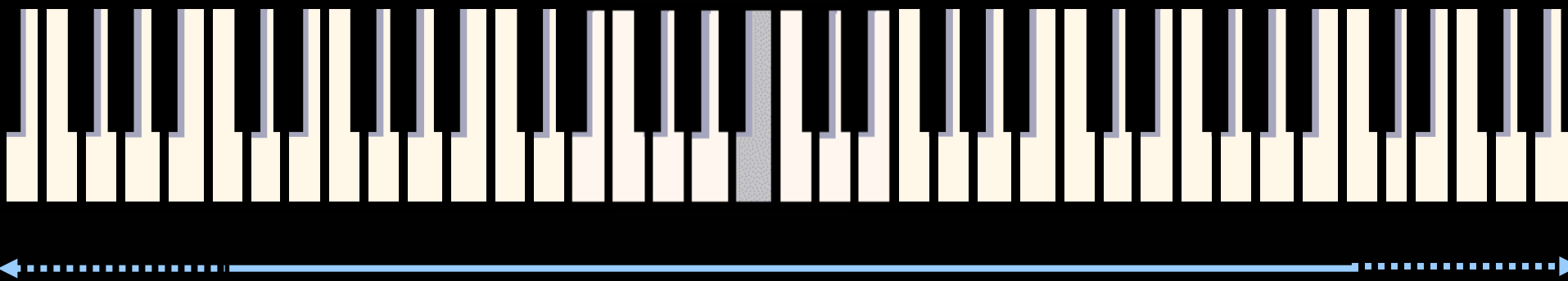
The spectrum of electromagnetic radiation: from radio waves to gamma rays

long **short**
wavelengths

Visible light encompasses
one octave in wavelength



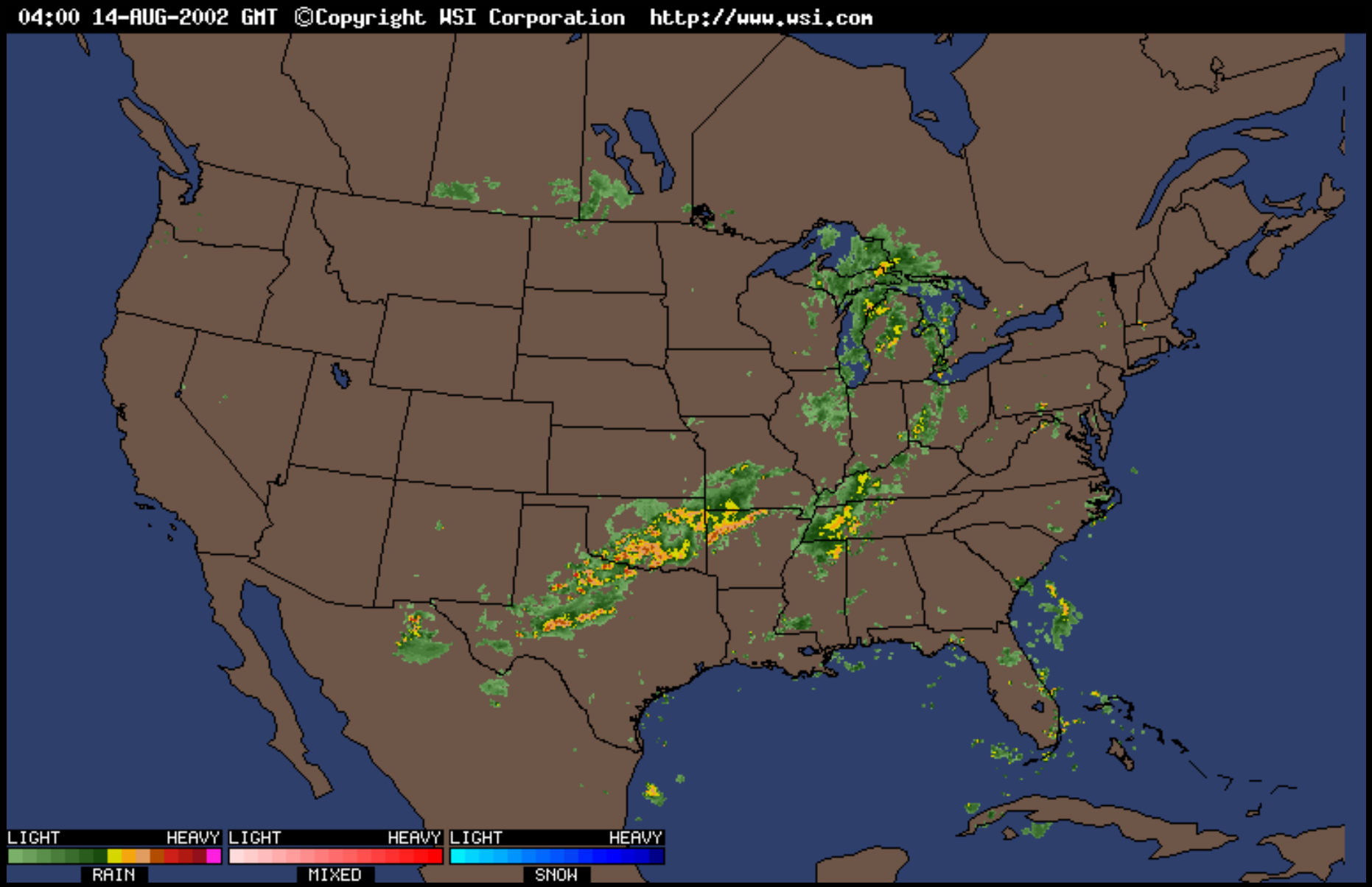
… but the spectrum of electromagnetic radiation
from space extends over more than 70 octaves …



... which means that Nature is playing a 15 m long piano …

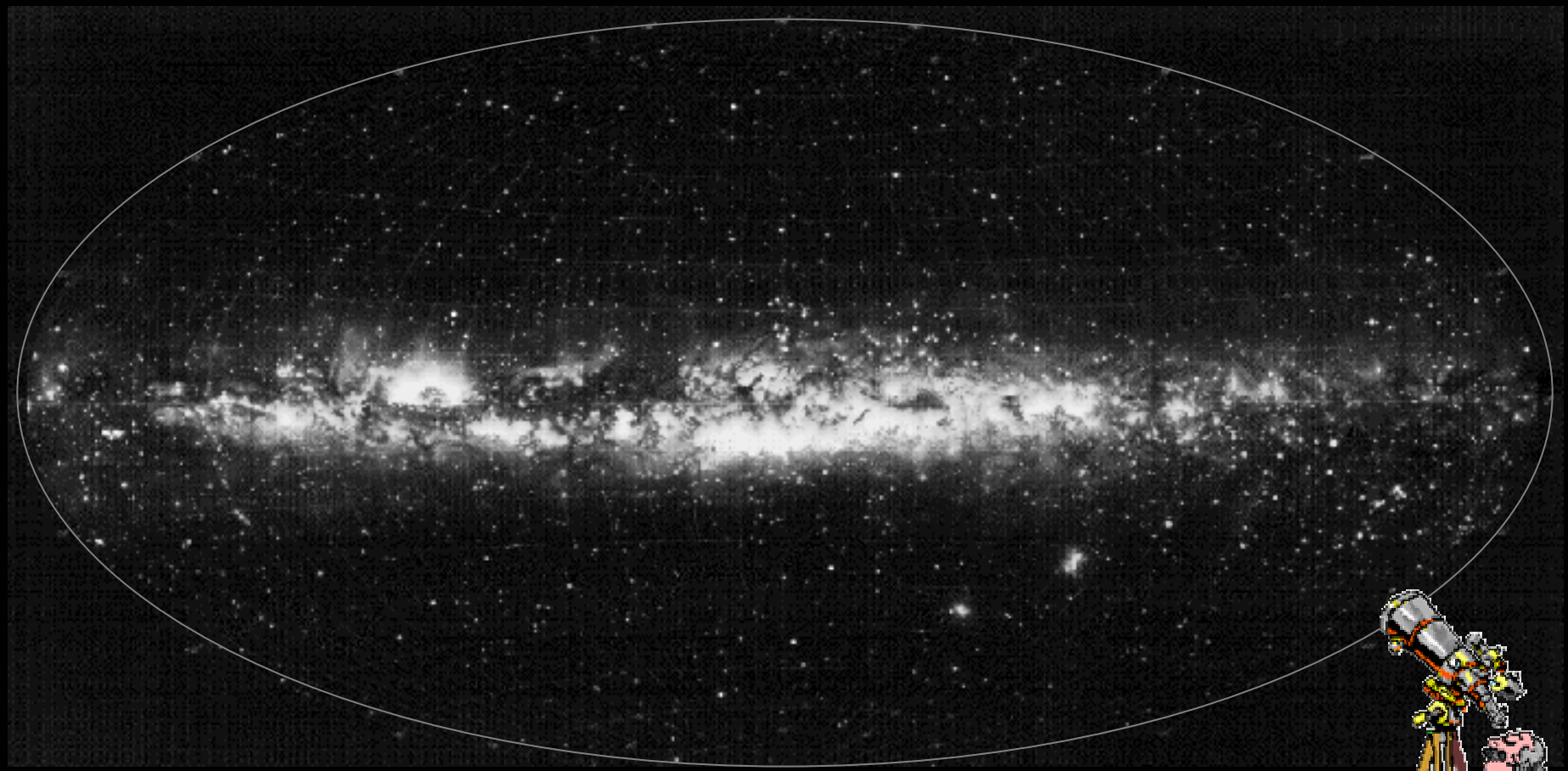
Infrared images

Radio waves


04:00 14-AUG-2002 GMT ©Copyright WSI Corporation http://www.wsi.com
LIGHT HEAVY
RAIN
LIGHT HEAVY
MIXED
LIGHT HEAVY
SNOW

X-ray images

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



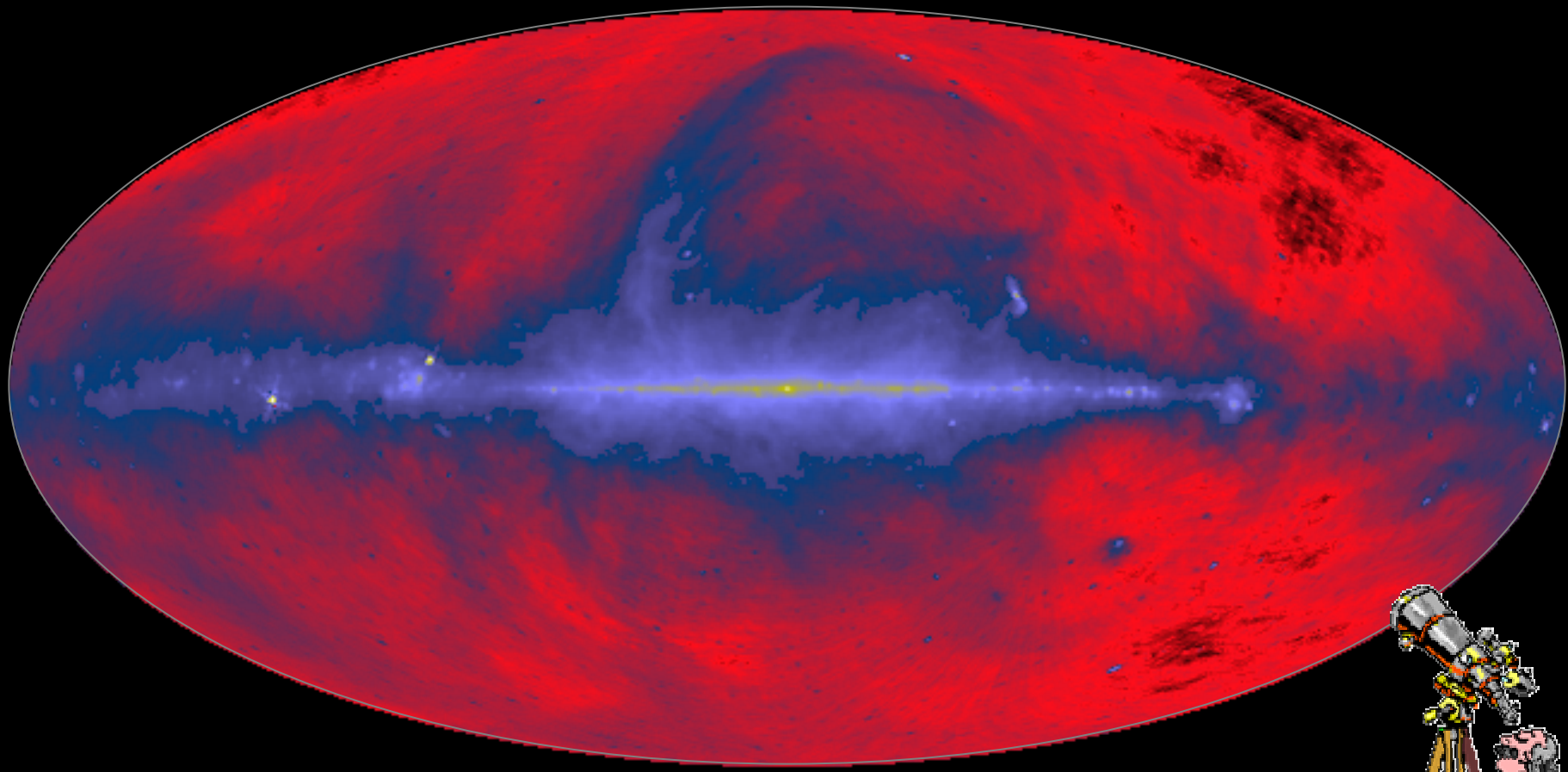
Radio (10^{-6} eV)

Infrared

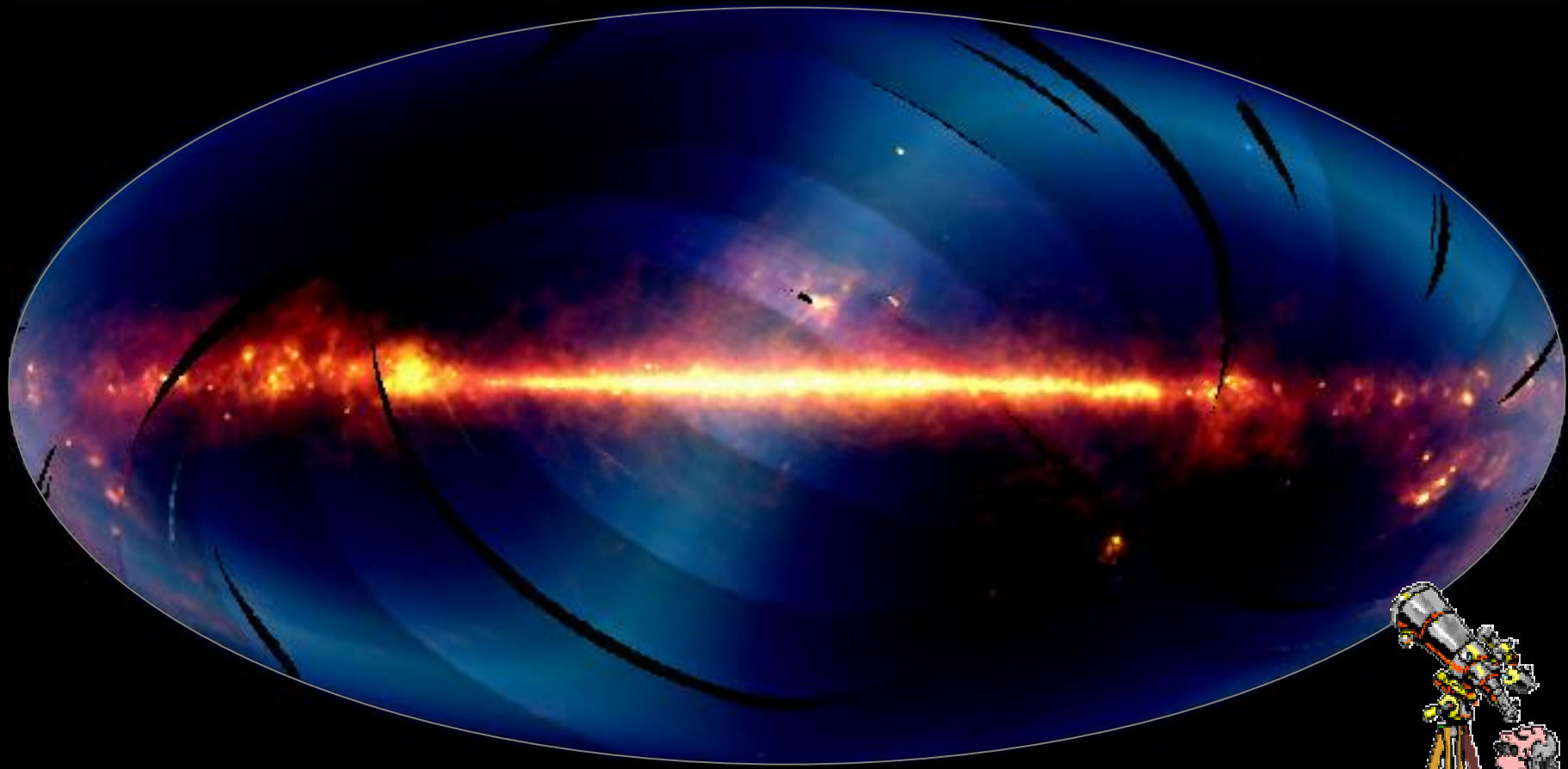
Visible Light

X-rays

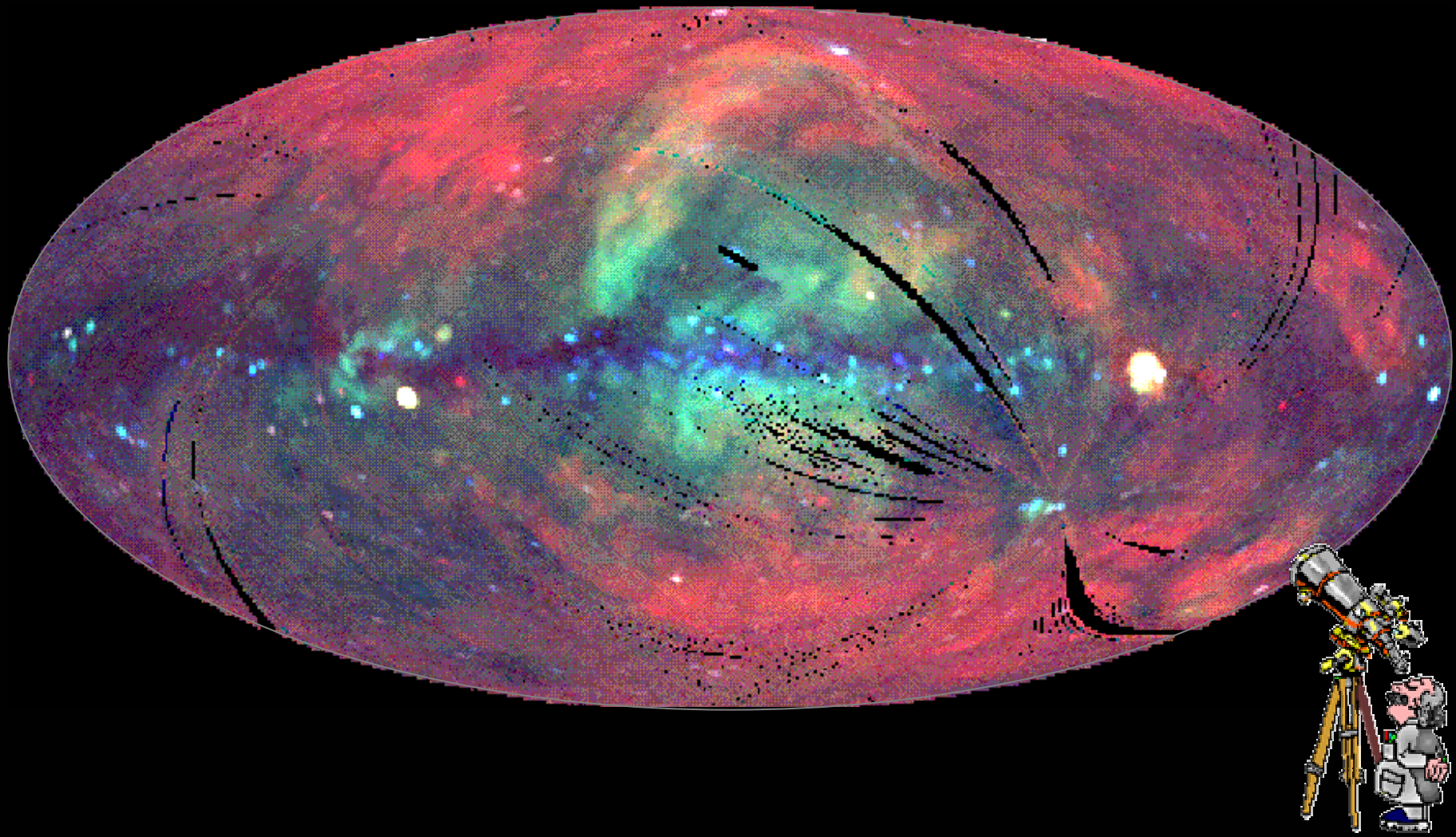
Gamma rays



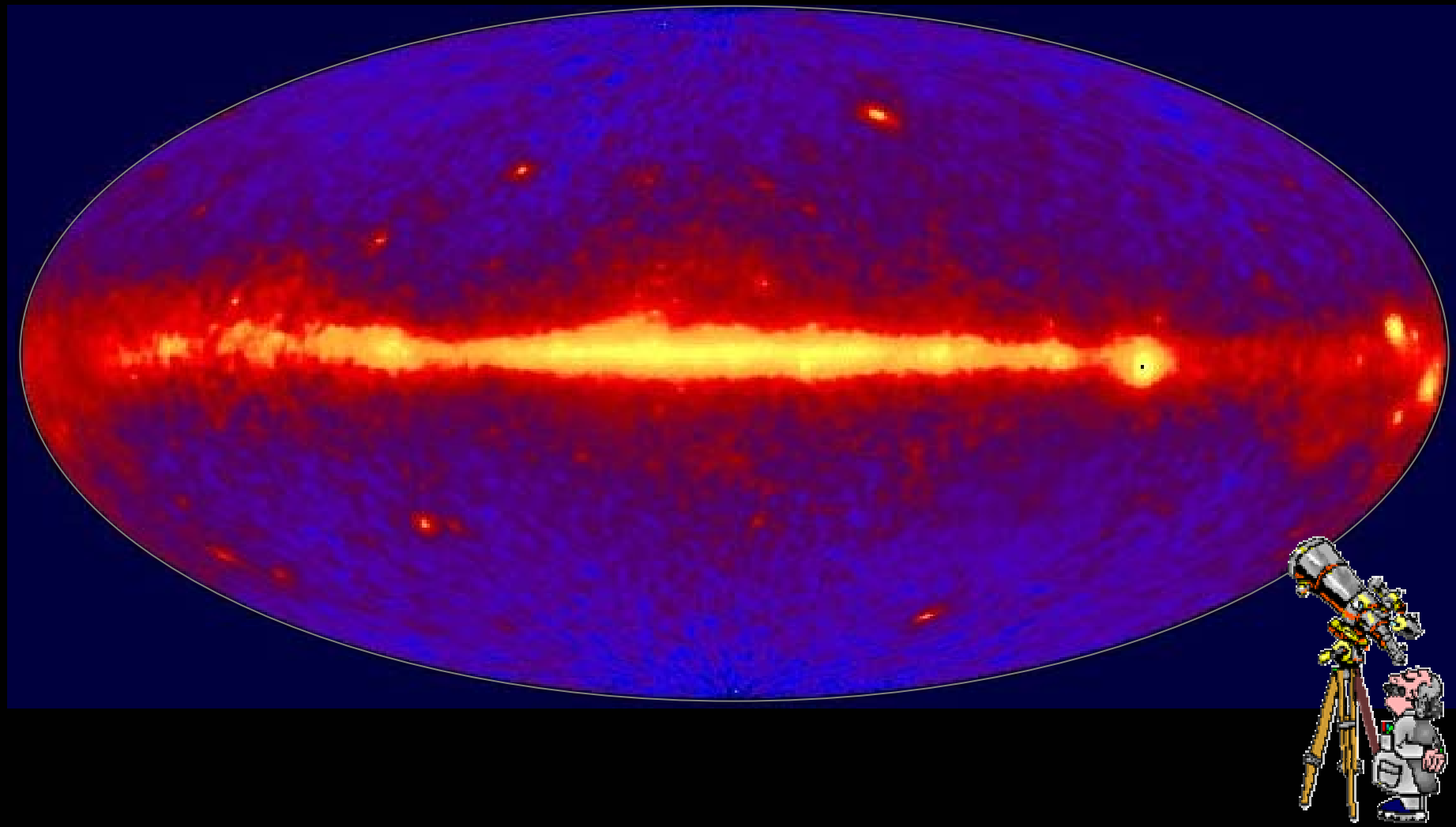
Radio | Infrared (10^{-2} eV) | Visible Light | X-rays | Gamma rays



Radio Infrared Visible Light **X-rays** (10^3 eV) Gamma rays



Radio Infrared Visible Light X-rays Gamma rays (10^9 eV)

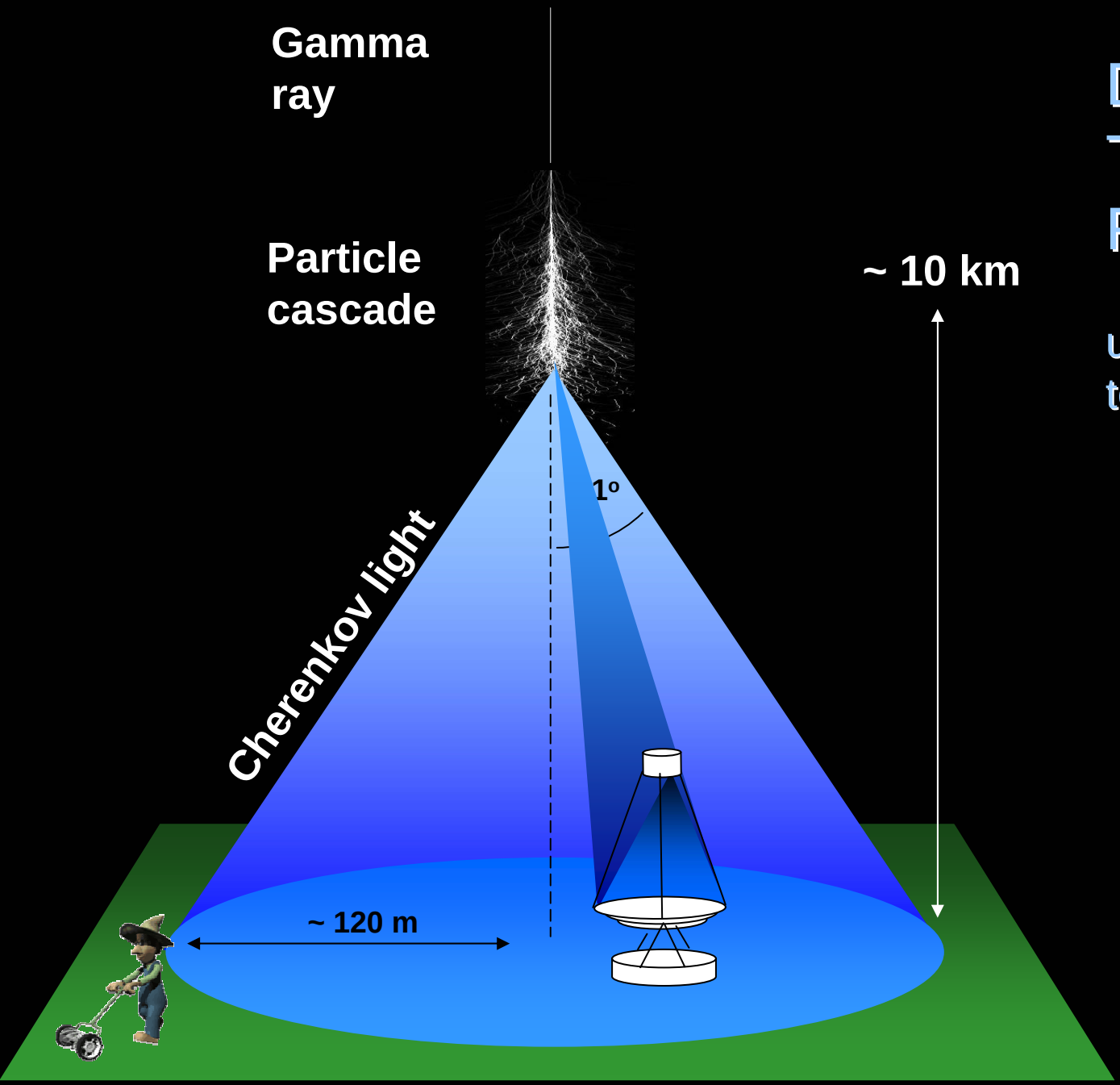


Gamma
(TeV = 10^{12} eV)

TeV Gamma rays
from the Crab Nebula
Whipple Cherenkov Telescope
1989

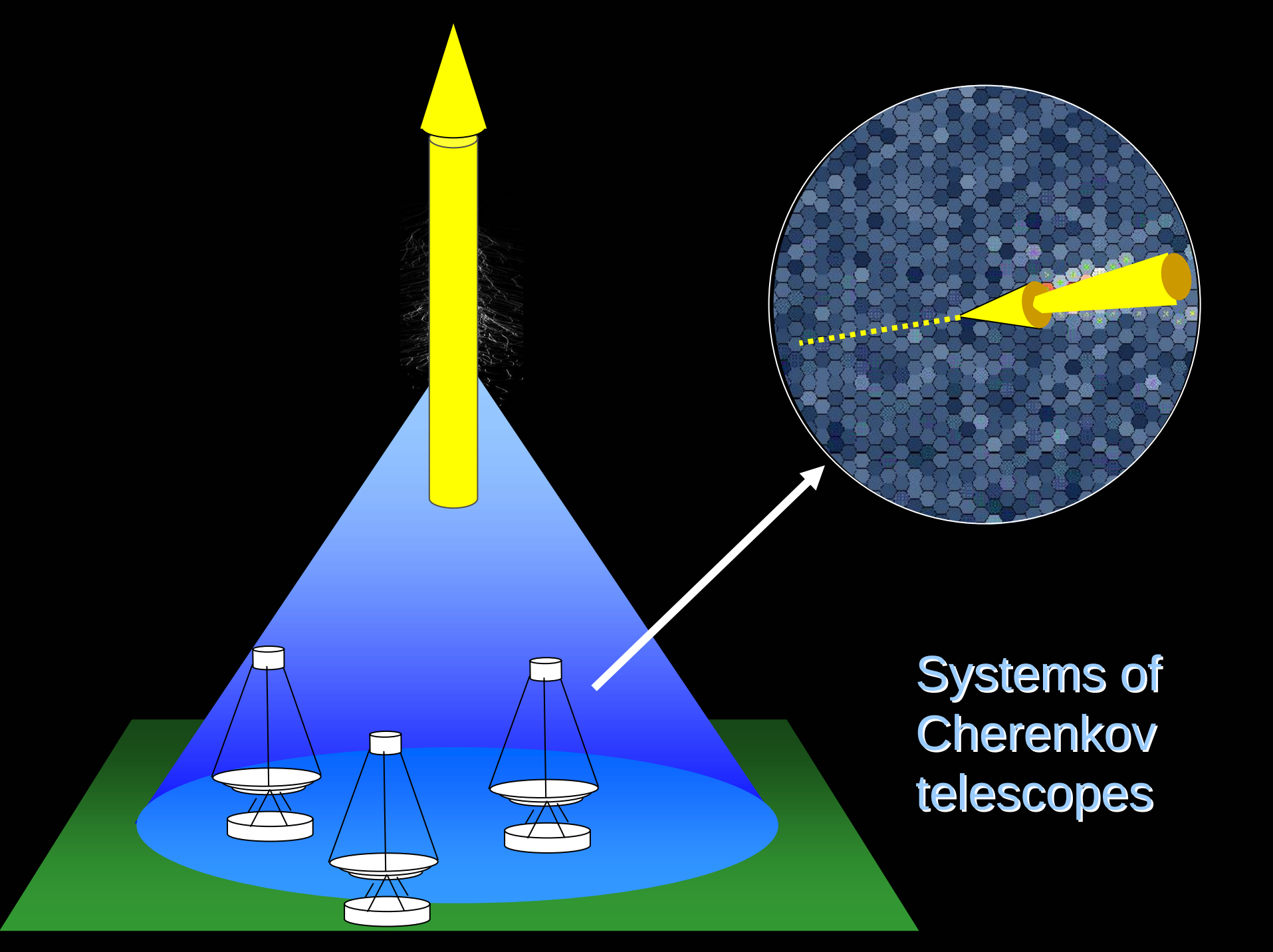
Detection of TeV Gamma Rays

using Cherenkov telescopes



Cherenkov light

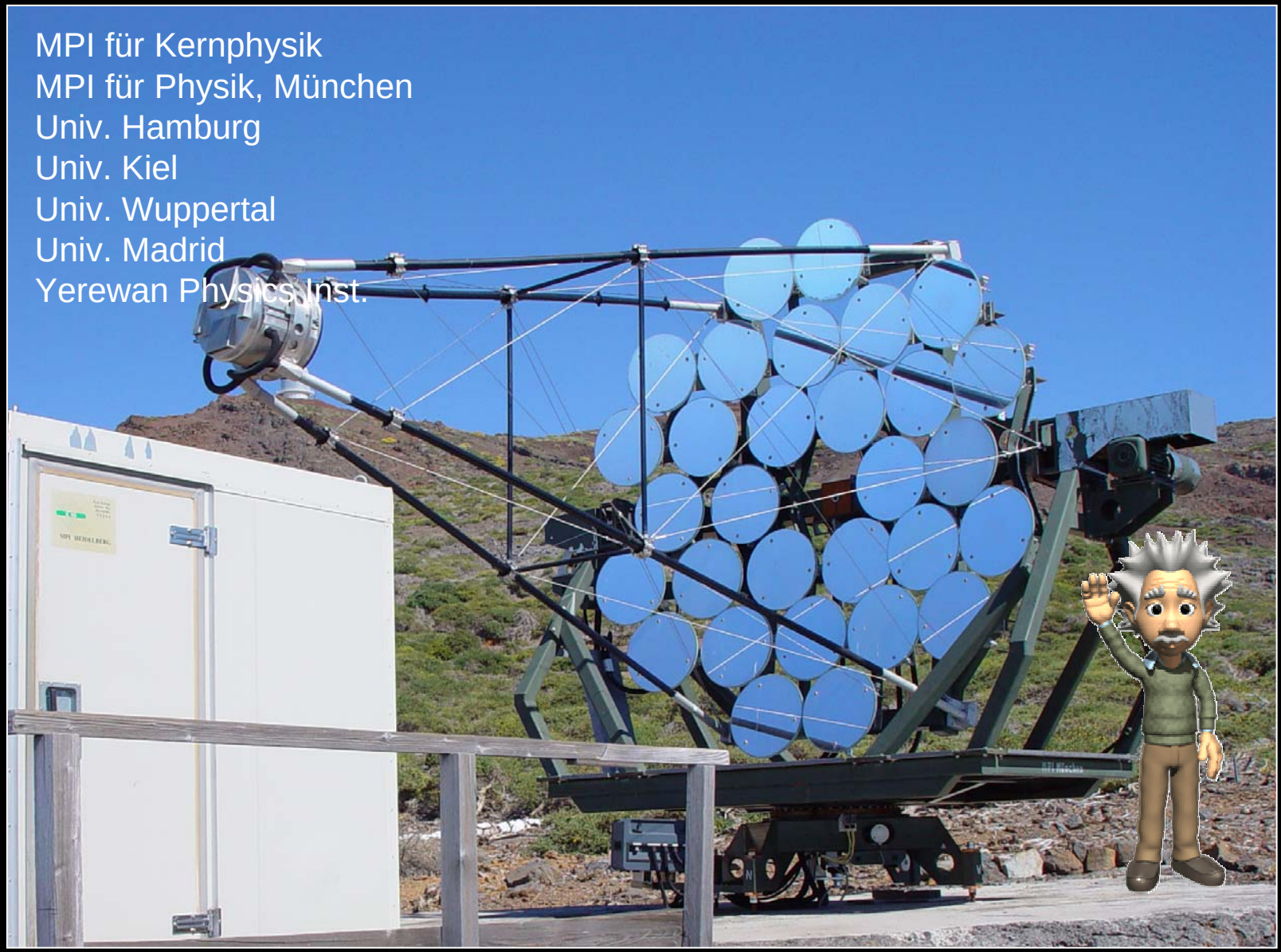
is the equivalent of the sonic boom


Systems of
Cherenkov
telescopes

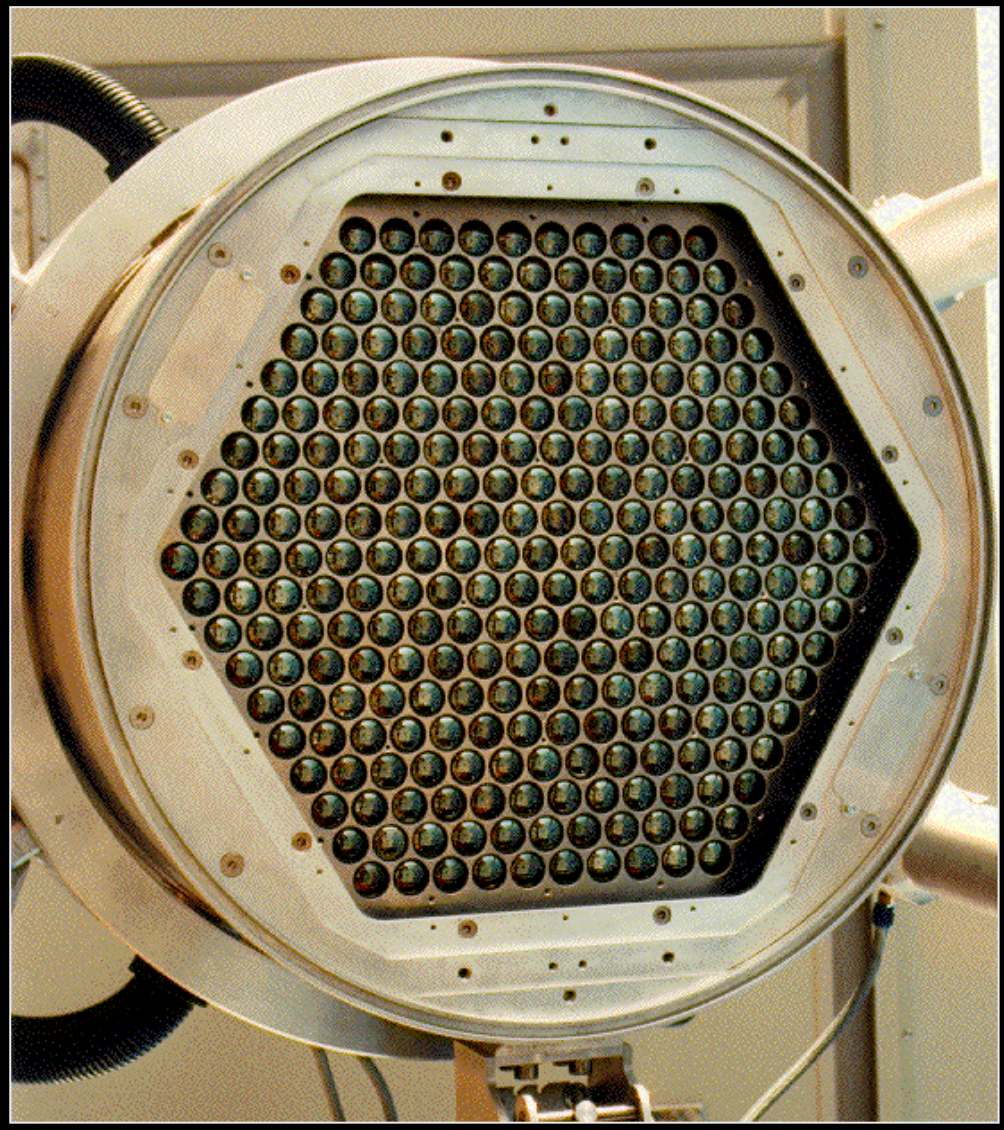
Air showers look a bit like meteors

(from Sky & Telescope)

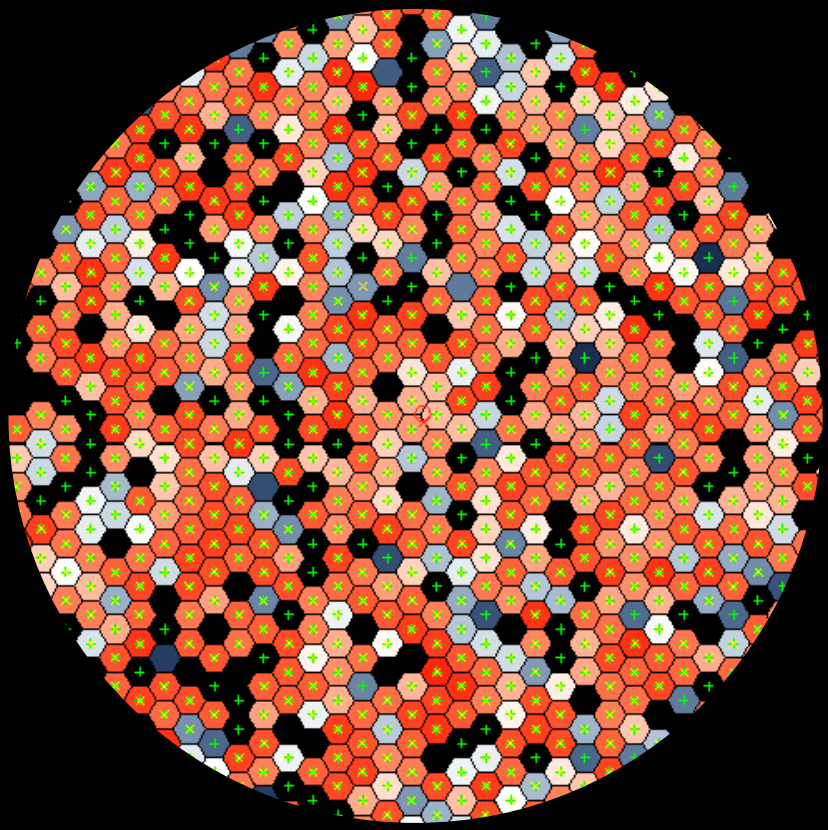
The HEGRA Teleskopes on La Palma



The HEGRA Cameras



Key feature of camera: speed !



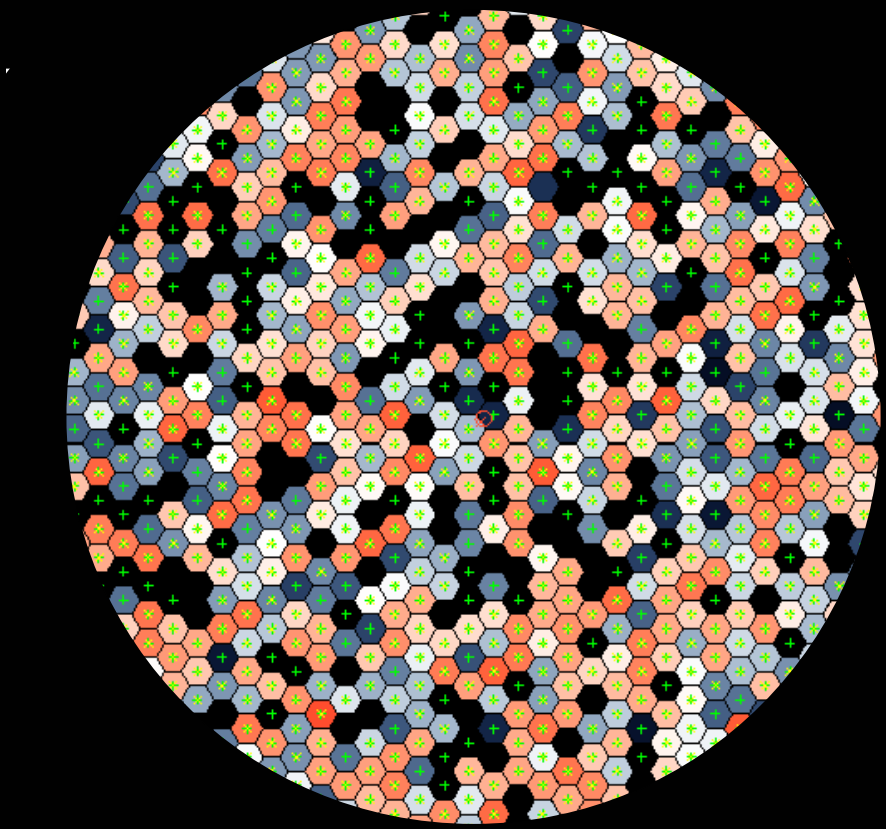
1/10000
(100 μs)

1/100000
(10 μs)

1/1000000
(1 μs)

1/10000000
(100 ns)

1/100000000
(10 ns)



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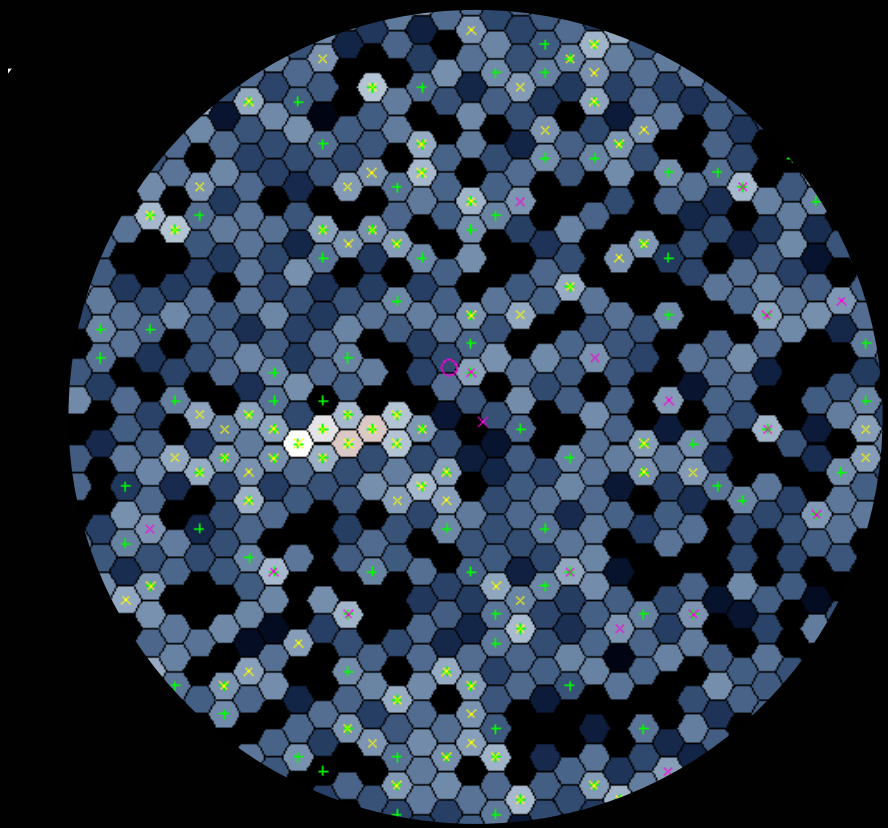

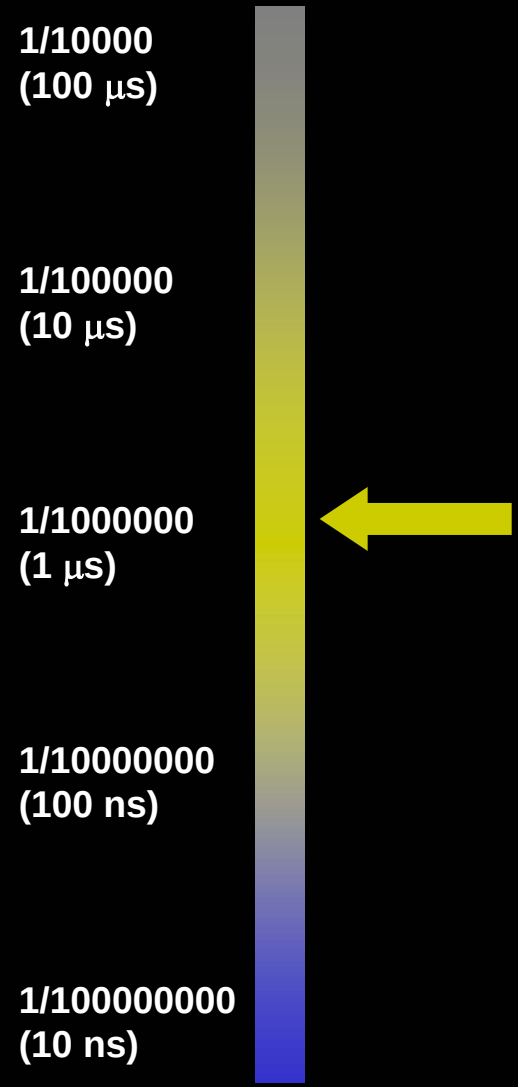
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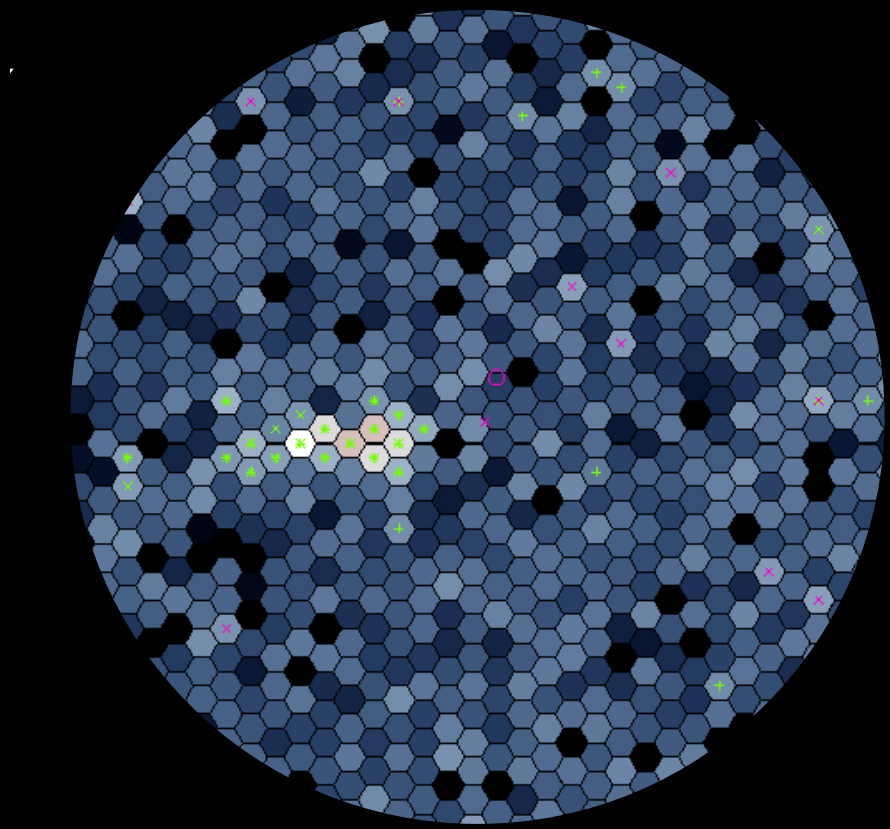

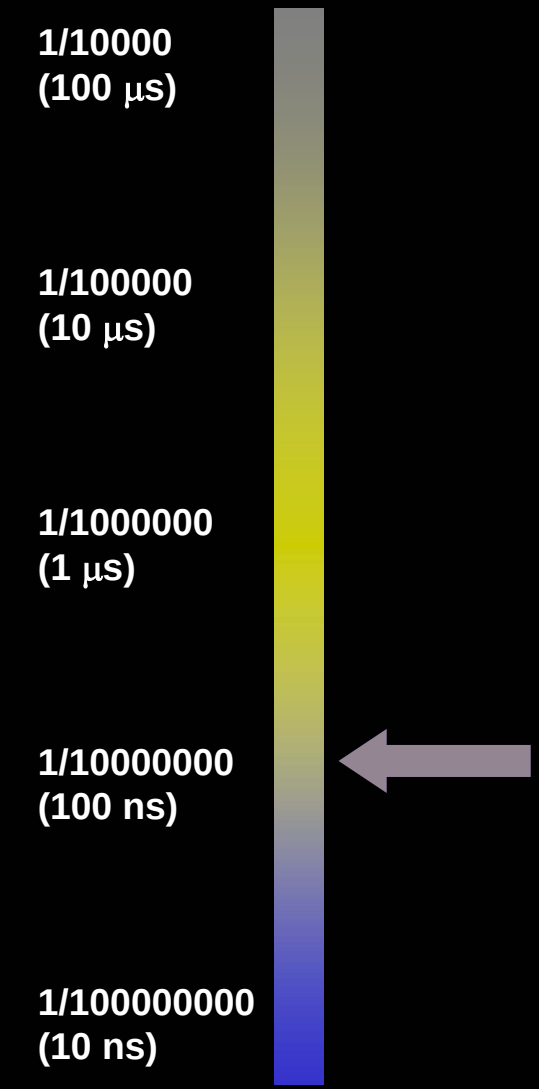
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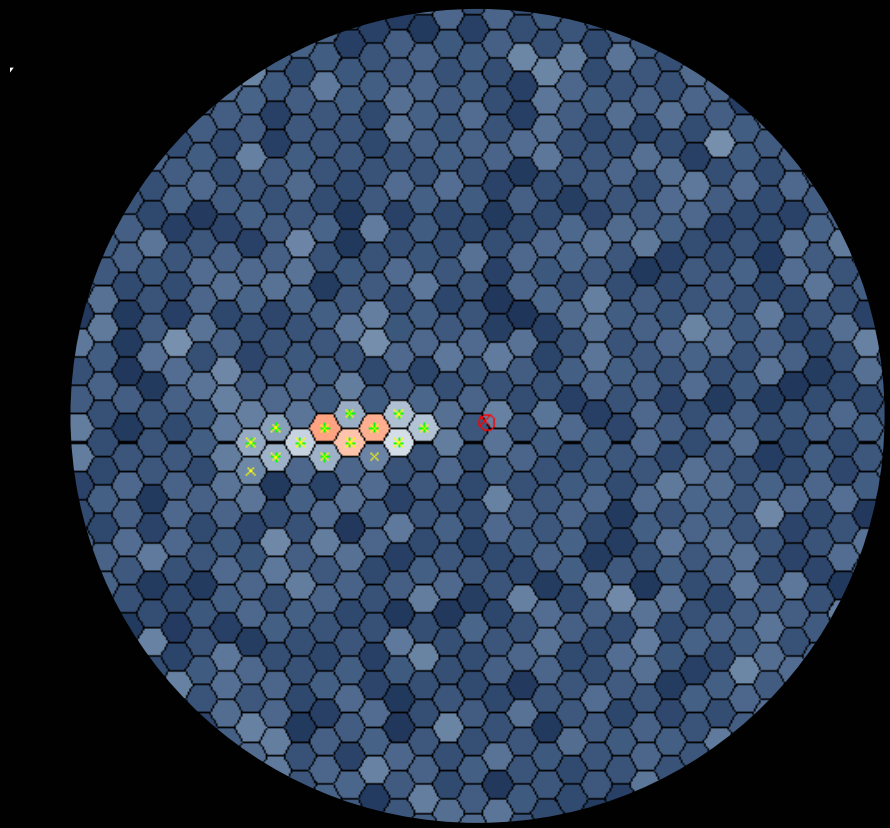


1/10000
(100 μs)

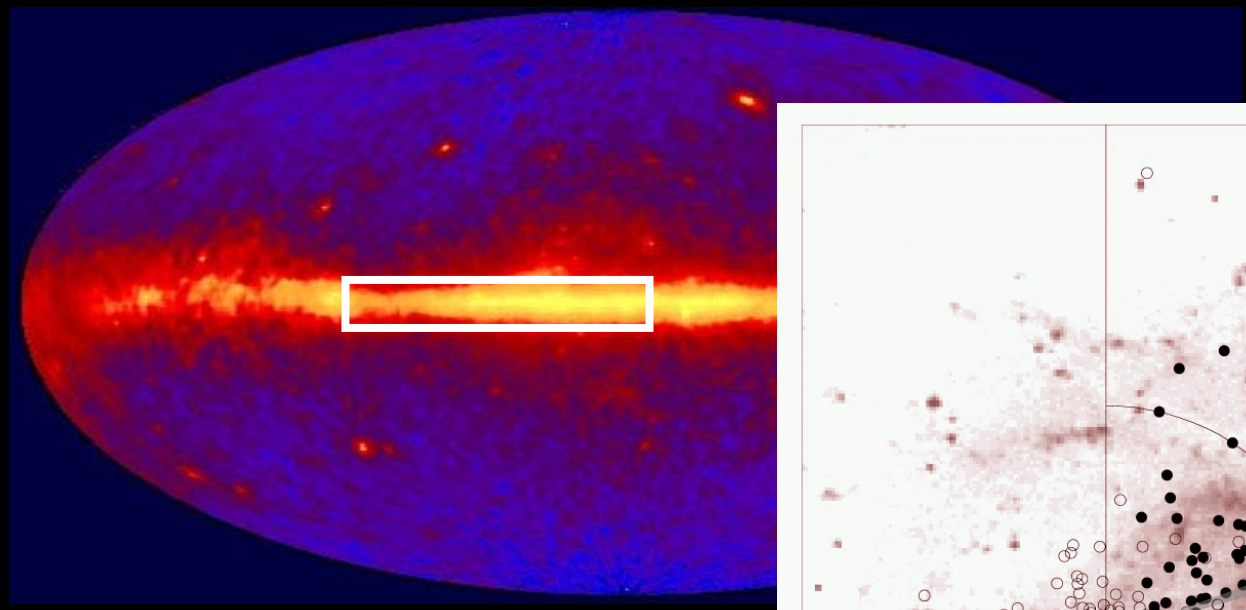
1/100000
(10 μs)

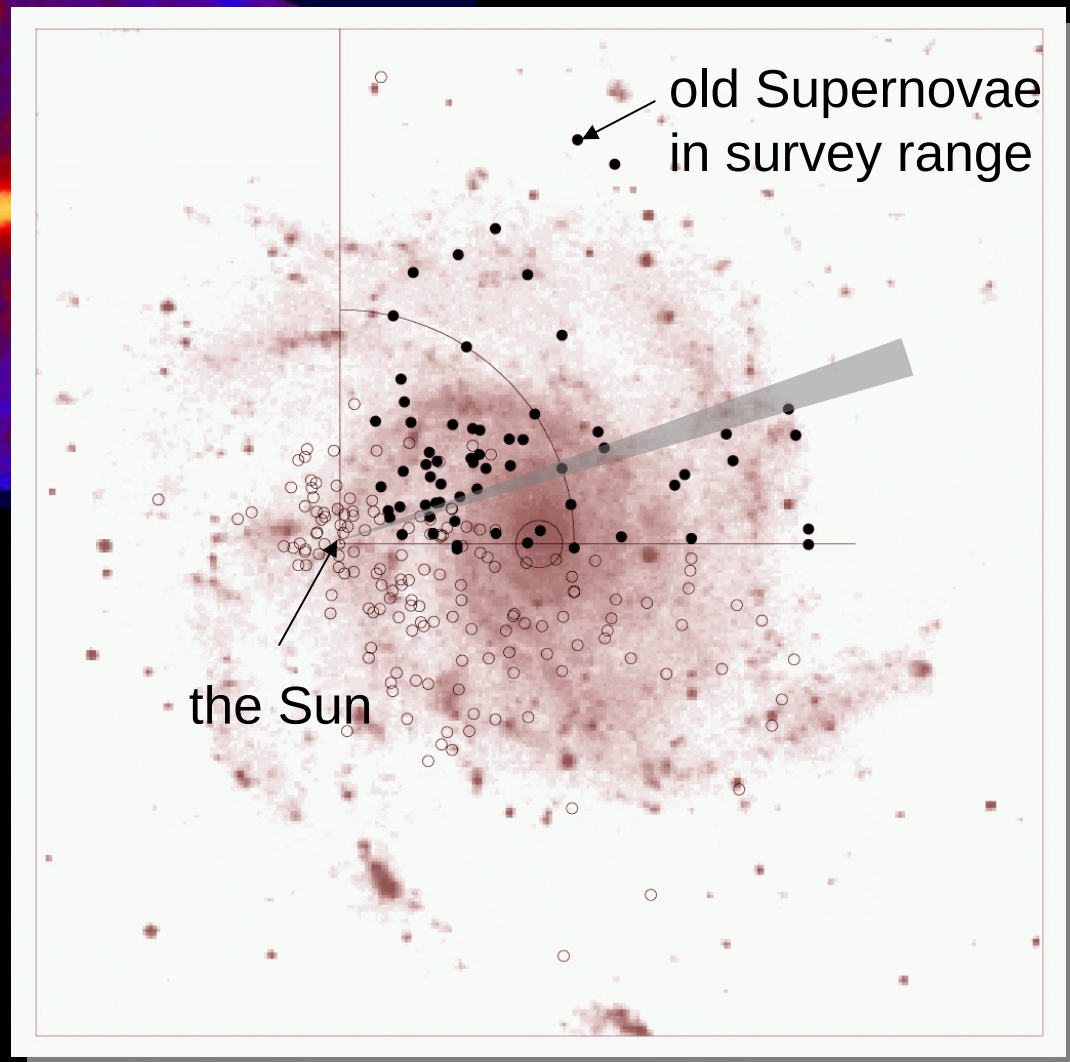
1/1000000
(1 μs)

1/10000000
(100 ns)

1/100000000
(10 ns)

Very high energy gamma rays from Supernovae ?
The HEGRA Galactic plane survey



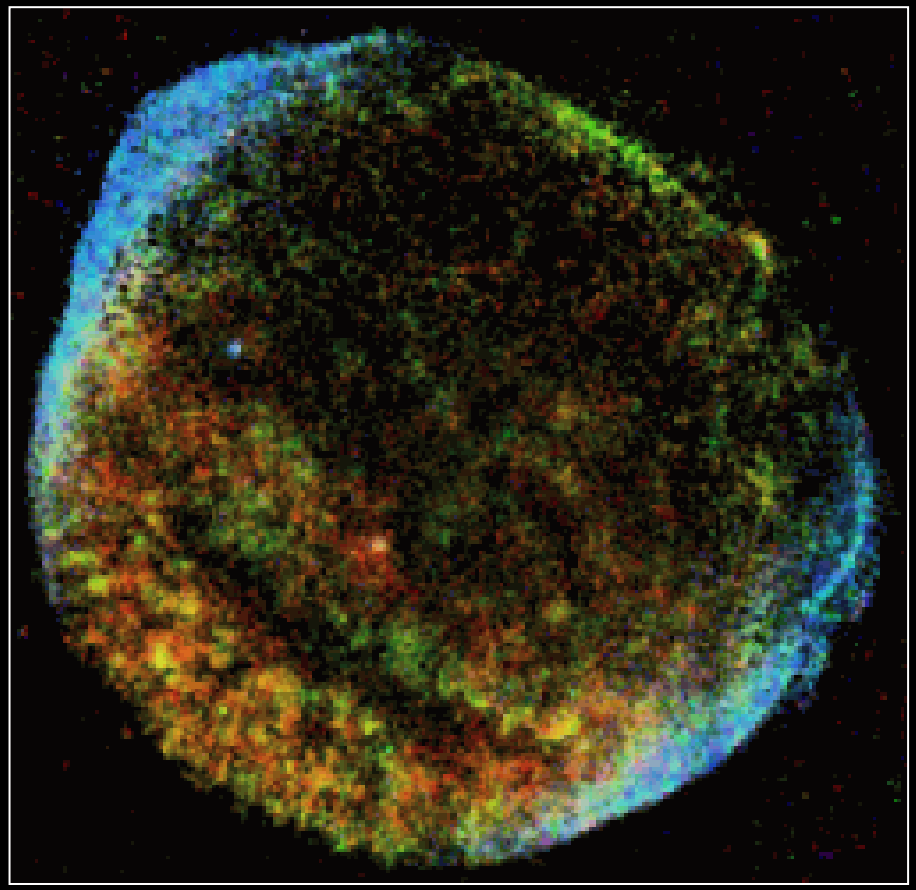


- 60 Supernovae investigated
- No gamma signal found
- Sensitivity should have been (just) sufficient

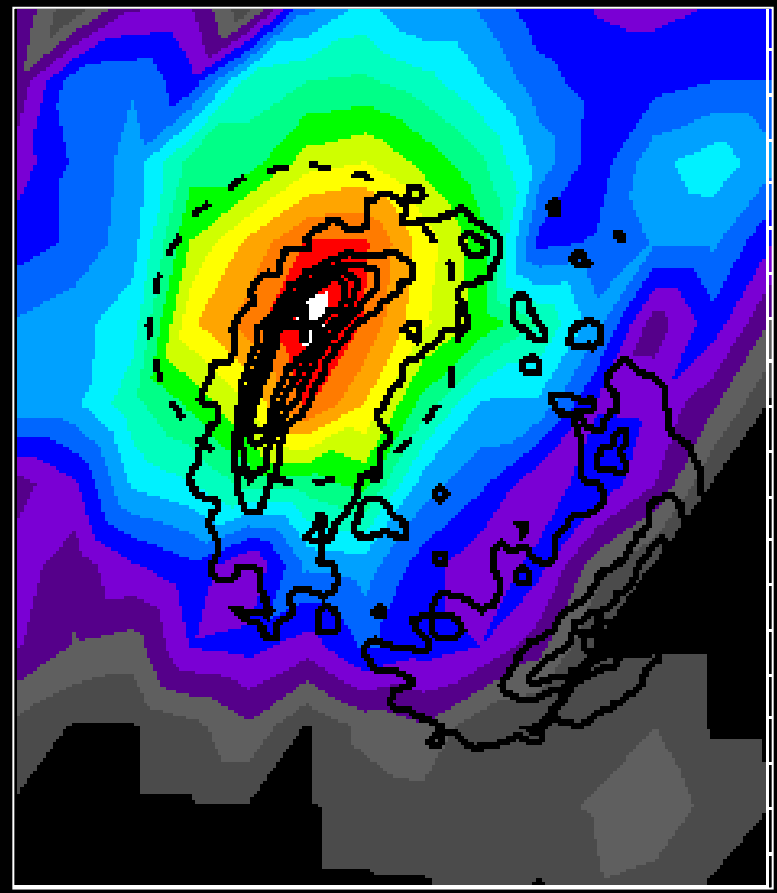
The CANGAROO telescopes (Japan & Australia)

For a long time,
the most powerful
instrument watching
southern skies

Supernova 1006



X-ray image
(ROSAT)



VHE gamma-ray image
(CANGAROO 1997)

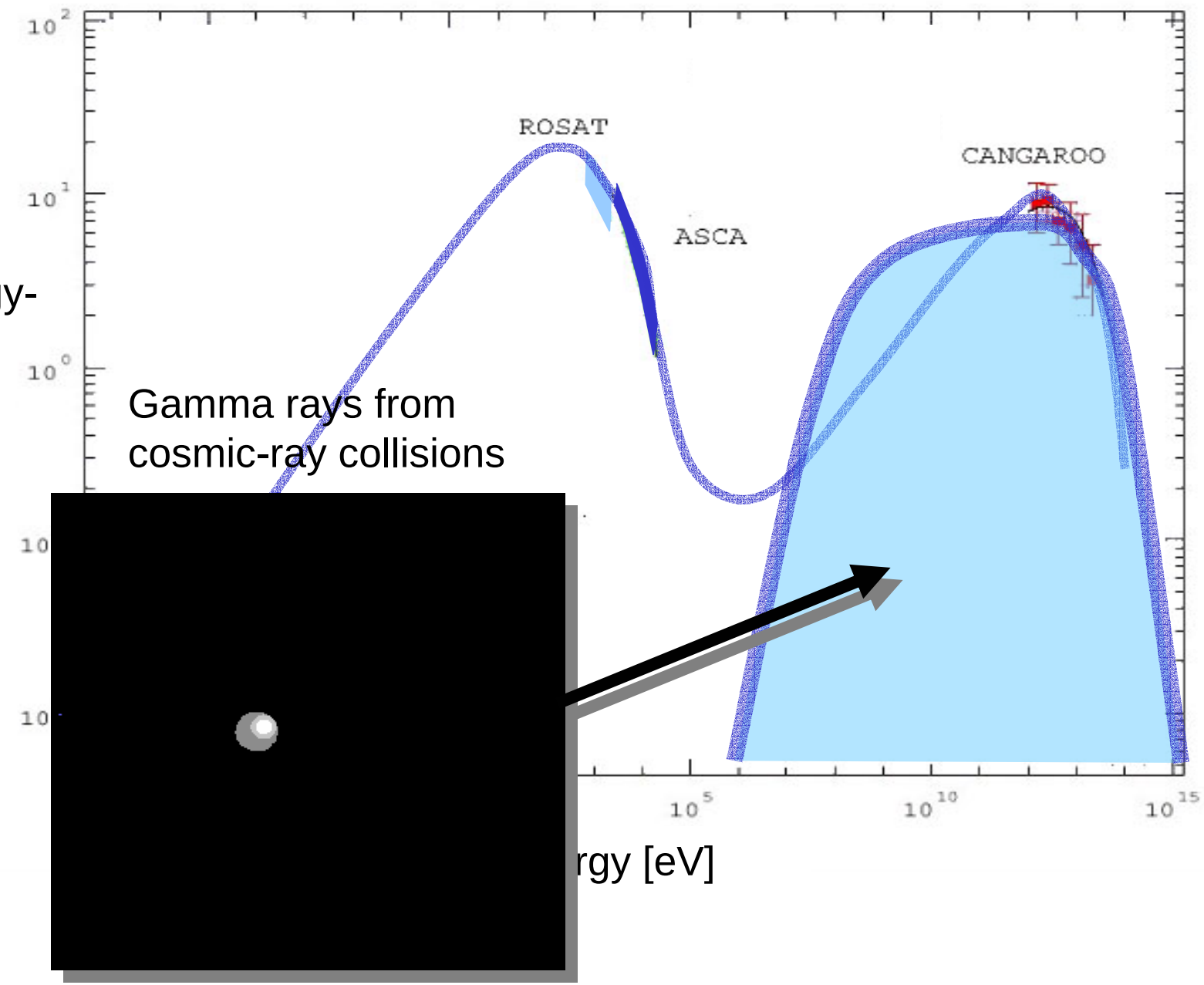
Chandra
(X-rays)

Rosat (X-rays)

ASCA
(hard X-rays)

CANGAROO
(gamma rays)

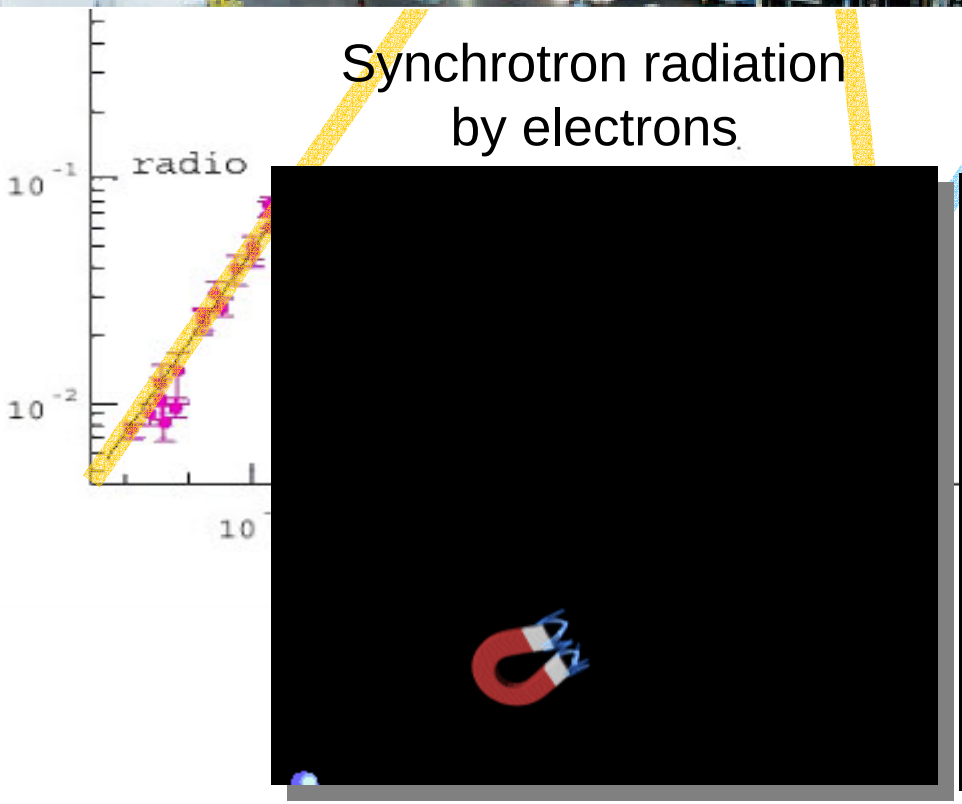
Energy-flux

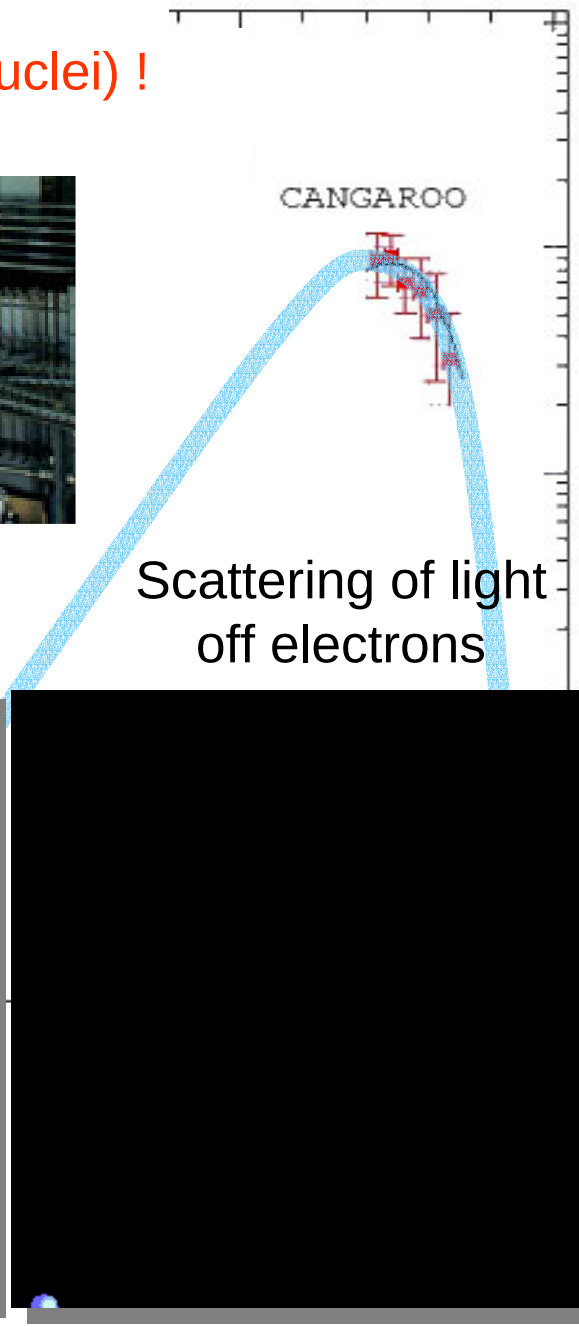

ROSAT
ASCA
CANGAROO
Gamma rays from cosmic-ray collisions
rgy [eV]

This supernova is clearly a cosmic accelerator!

But it seems to accelerate electrons (rather than nuclei) !

Have we found the wrong accelerator ???

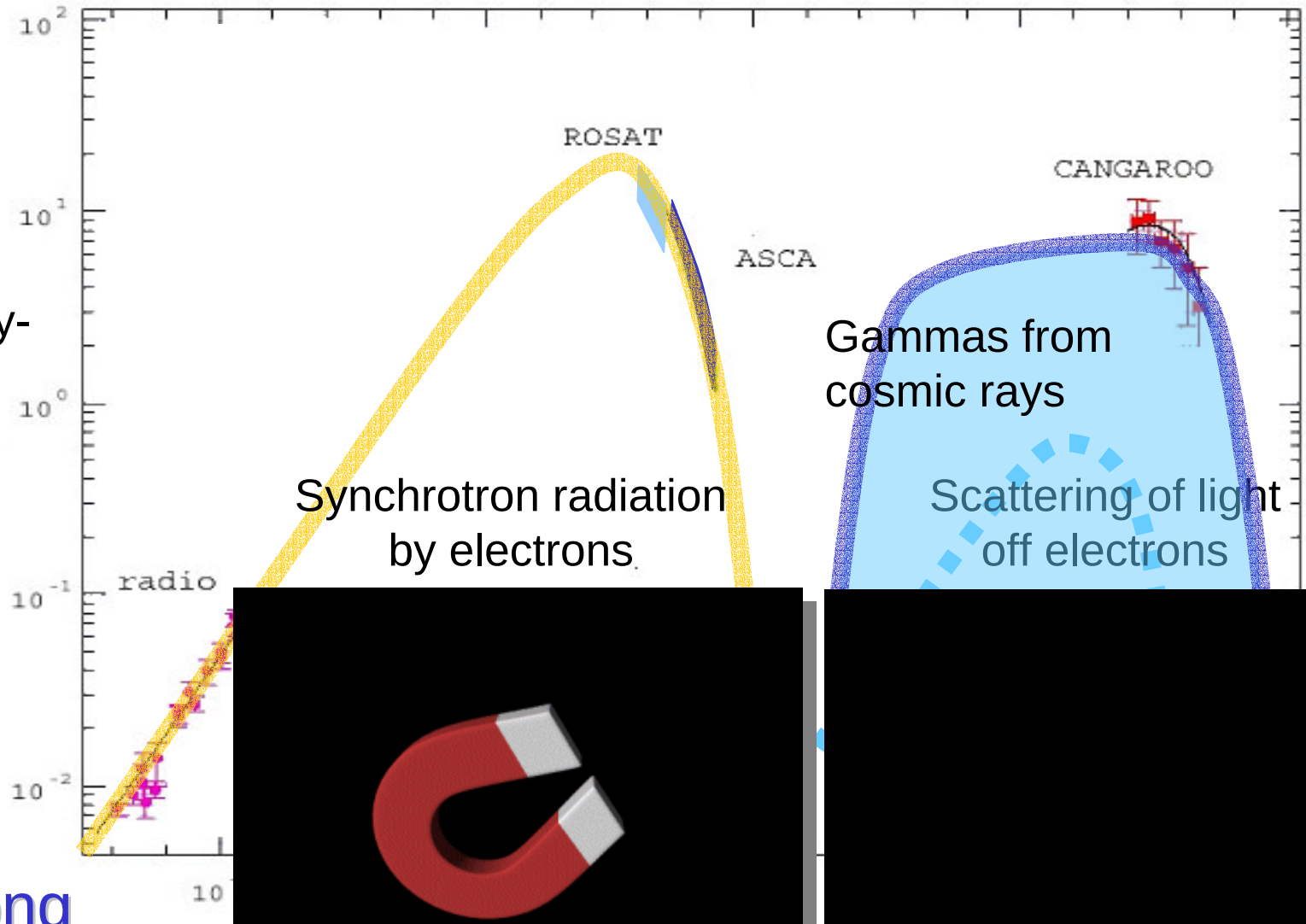




Synchrotron radiation
by electrons

Scattering of light
off electrons

Energy-flux



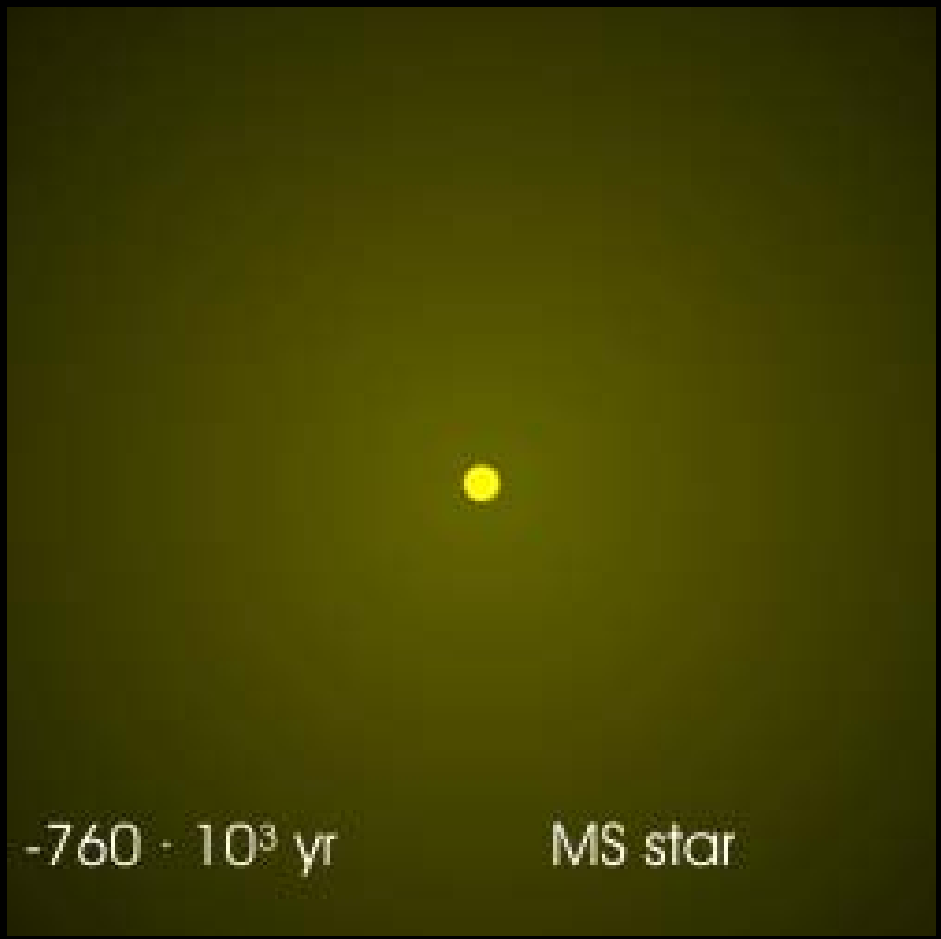
Gammas from cosmic rays

Synchrotron radiation by electrons

Scattering of light off electrons

Strong magnetic field

1999: Supernova Cassiopeia A detected with HEGRA (232 h exposure)



Type II SN
(Animation: G. Pühlhofer)

Again, a double-humped spectrum ...
Equal amounts of energy in X-rays and high energy gamma rays ...
but ... this object should have a very high magnetic field!

The acceleration of cosmic-ray protons in the supernova remnant RX J1713.7–3946

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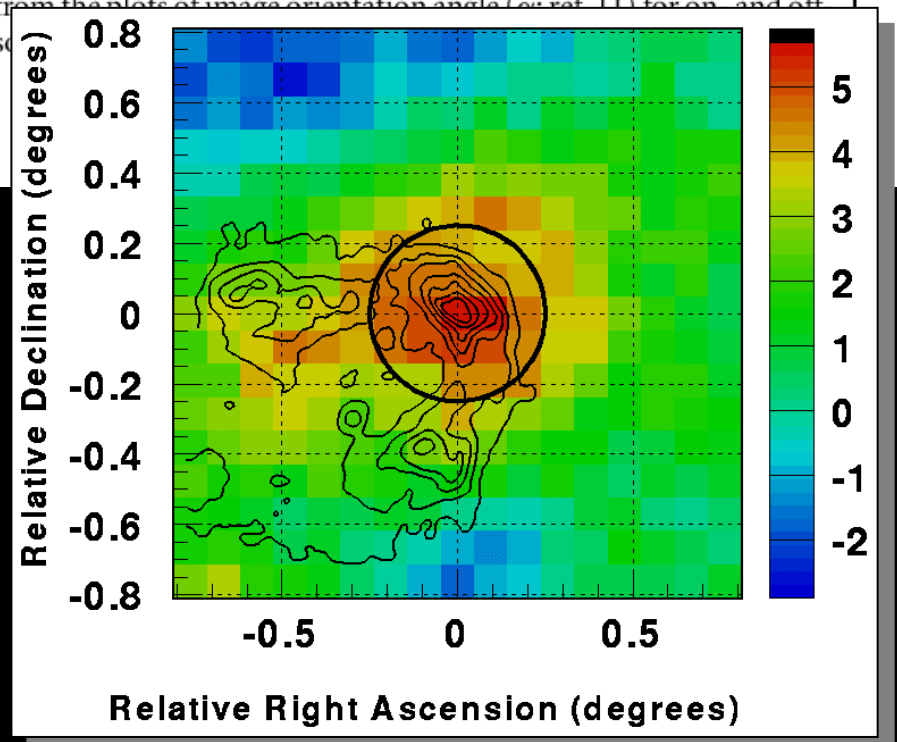
molecular cloud complex[10].

The CANGAROO air Cerenkov telescope, which is intended to detect very high energy γ-rays, is located near Woomera, South Australia. The 3.8-m telescope[9], which operated from 1994 to 1998, was replaced in 2000 by a 10-m reflector with a 552-pixel camera of 0.115° square photomultiplier pixels. Observations of RX J1713.7–3946 were carried out 23–26 July and 19–27 August 2000, and 20 May–26 June 2001 with the 10-m telescope. After selecting data taken at high elevation angles (>60°) in good weather conditions, a total of 2,332 min on-source and 1,789 min off-source data remained for further analysis.

The differential fluxes of γ-rays from RX J1713.7–3946 are plotted in Fig. 1. The number of excess events was determined from the plots of image orientation angle (cf. ref. 11) for on- and off-



RX J1713.7-3946
CANGAROO 2000/02

A detective story in science

The case:
A 90-year mystery –
the origin of Cosmic Rays

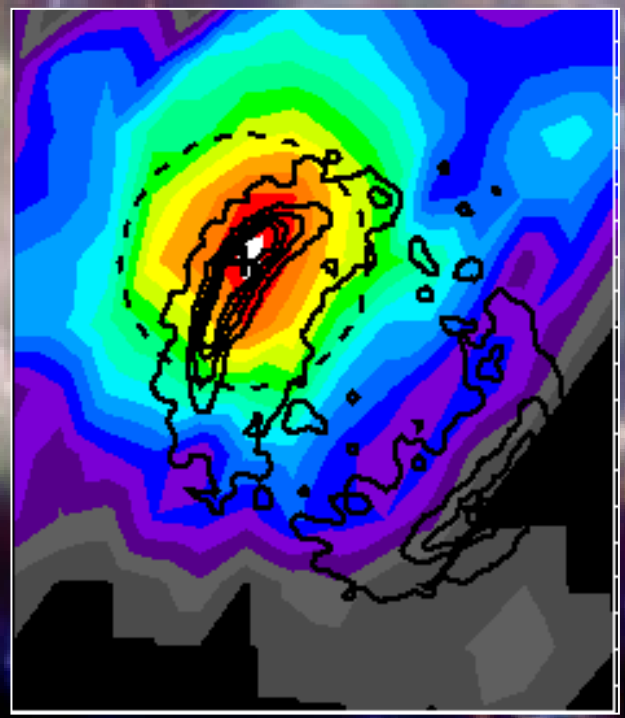
The suspects:
Black holes & exploding stars

The evidence:
Blue flashes fro
Astroph
telescope

The judgement

No question,
Supernovae are cosmic accelerators !
But are they THE sources of cosmic rays ?

- Compare in detail the distribution of X-rays and gamma rays
- Understand the magnetic fields
- Find more objects



Built better instruments

CANGAROO III

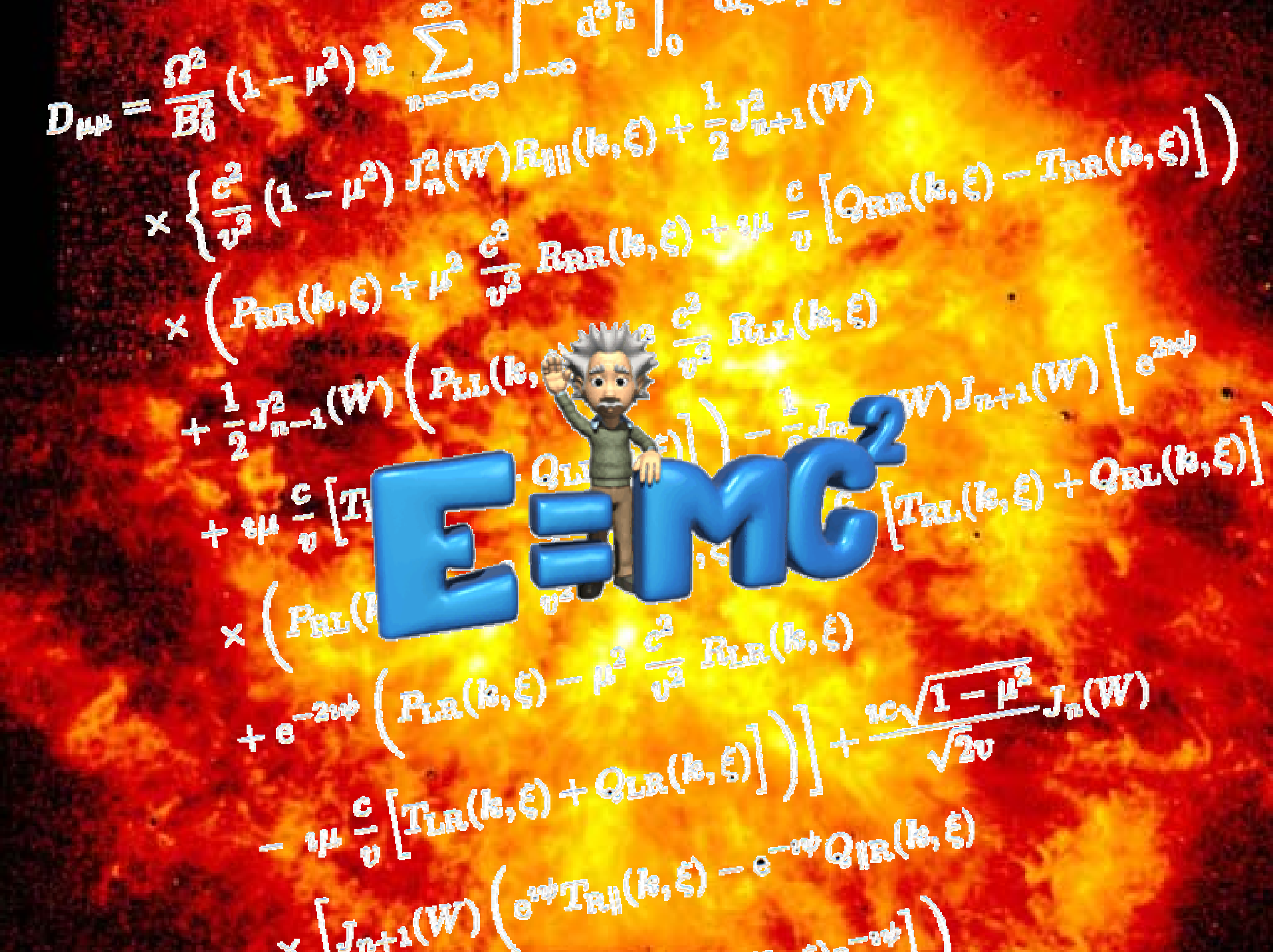
The H.E.S.S. Project
High Energy Stereoscopic System

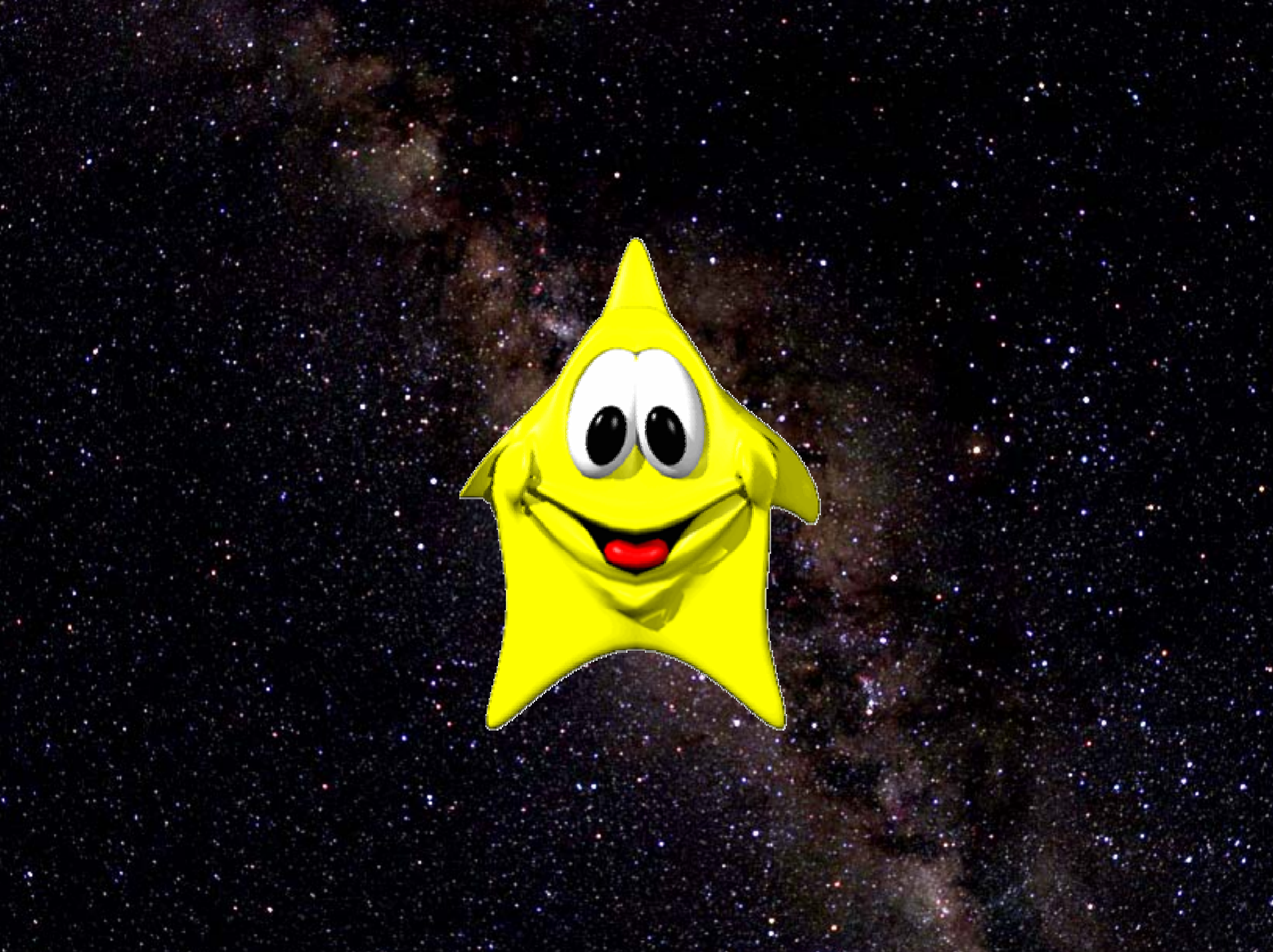
Progress

First detection of Crab Nebula
Whipple 1989: 50 h Observation time

HEGRA 1997:
15 min

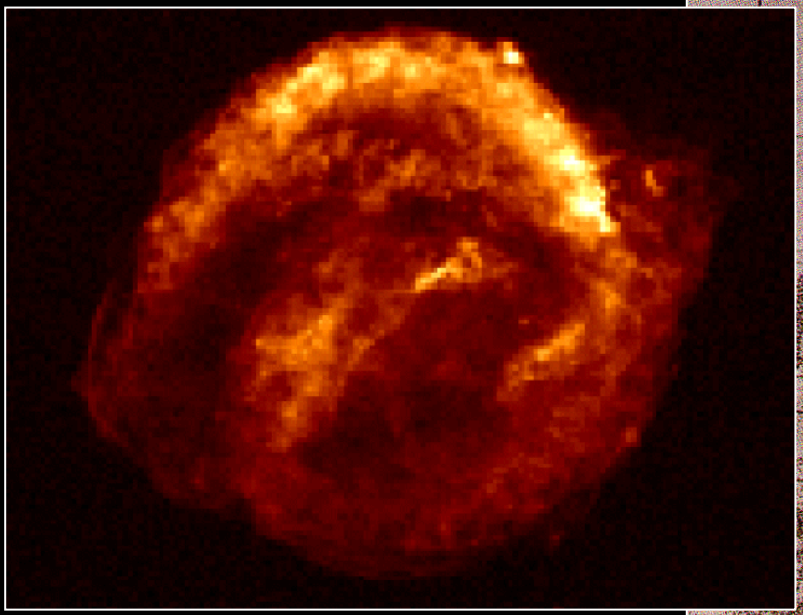
The new instruments:
30 sec

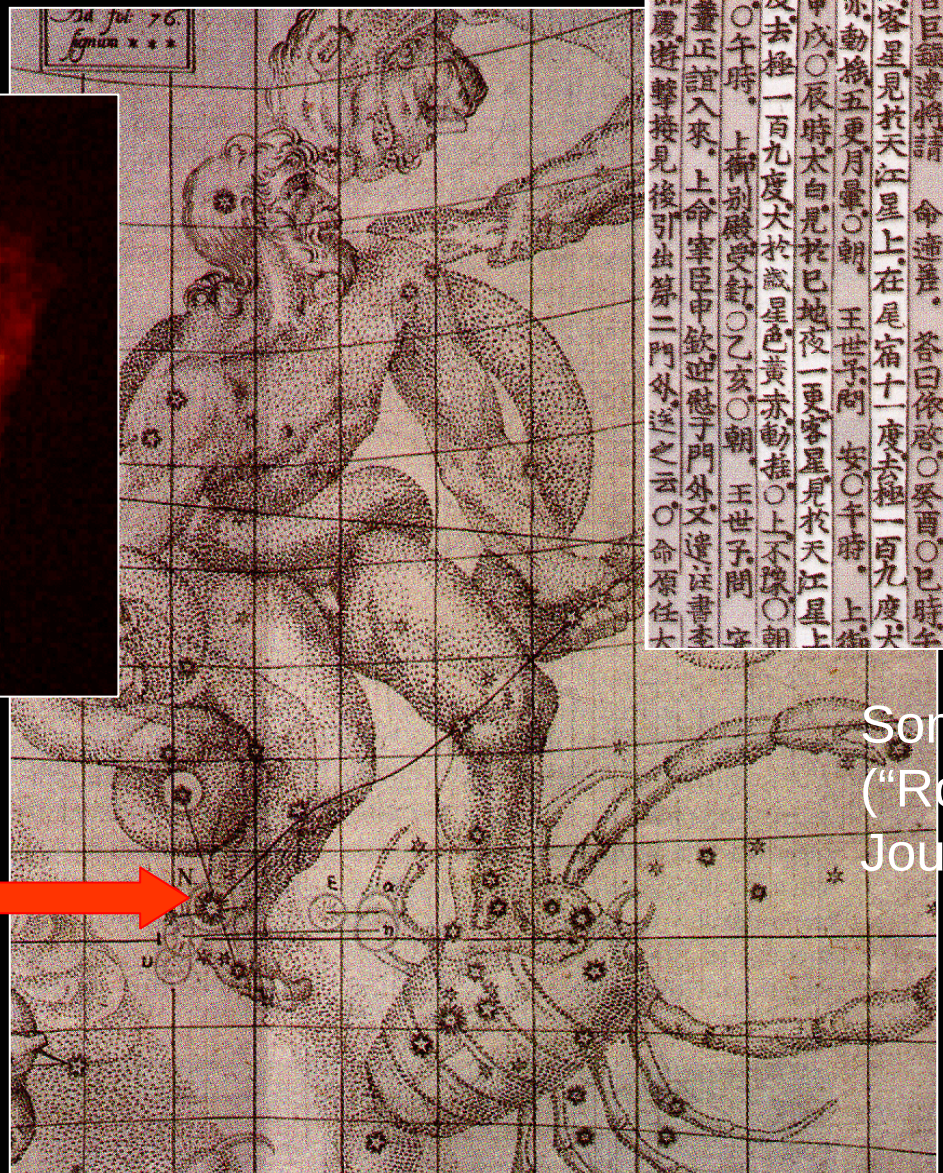

E=MC²



International Cosmic Ray Conference

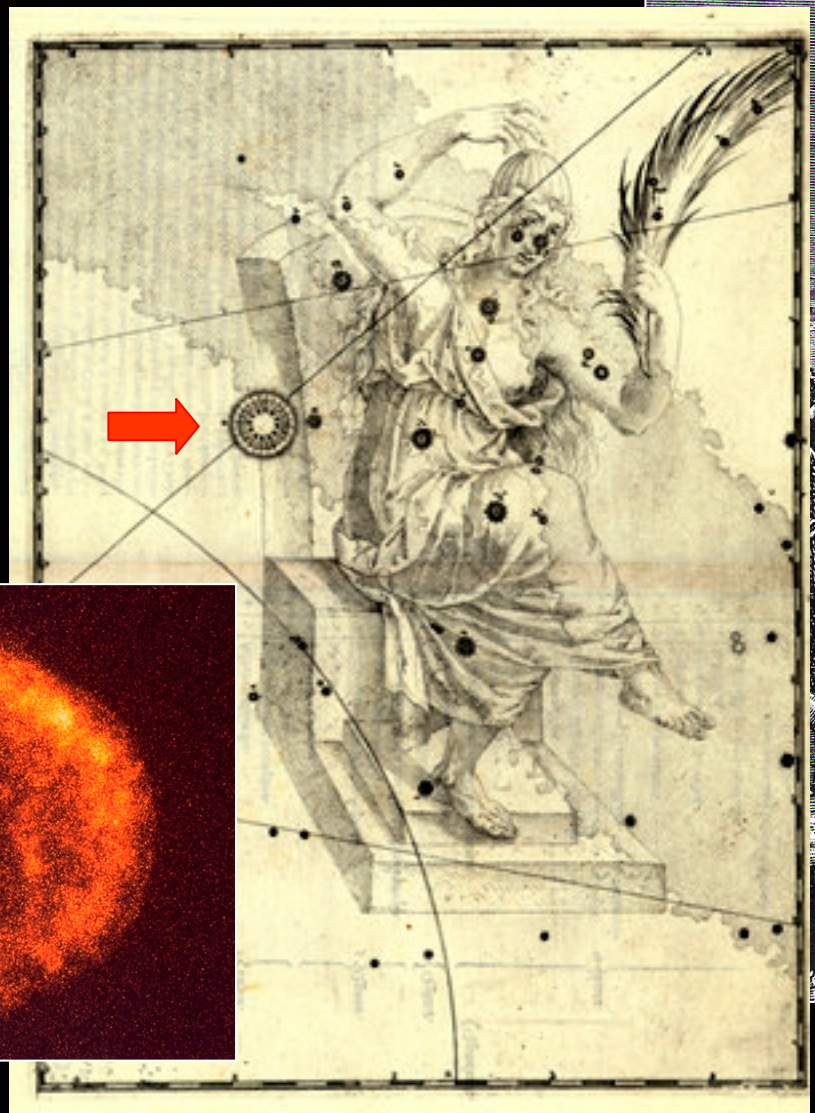
1604: Kepler's Supernova

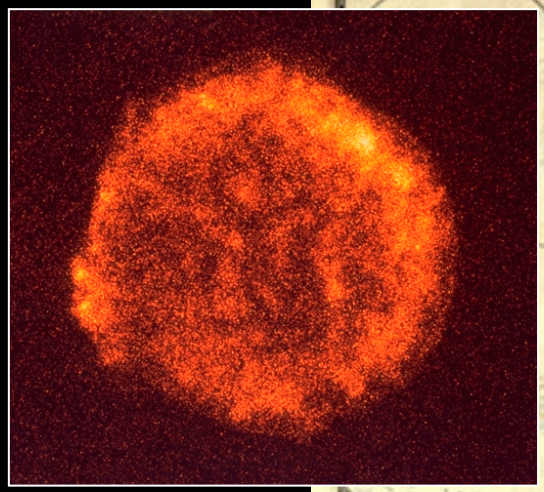




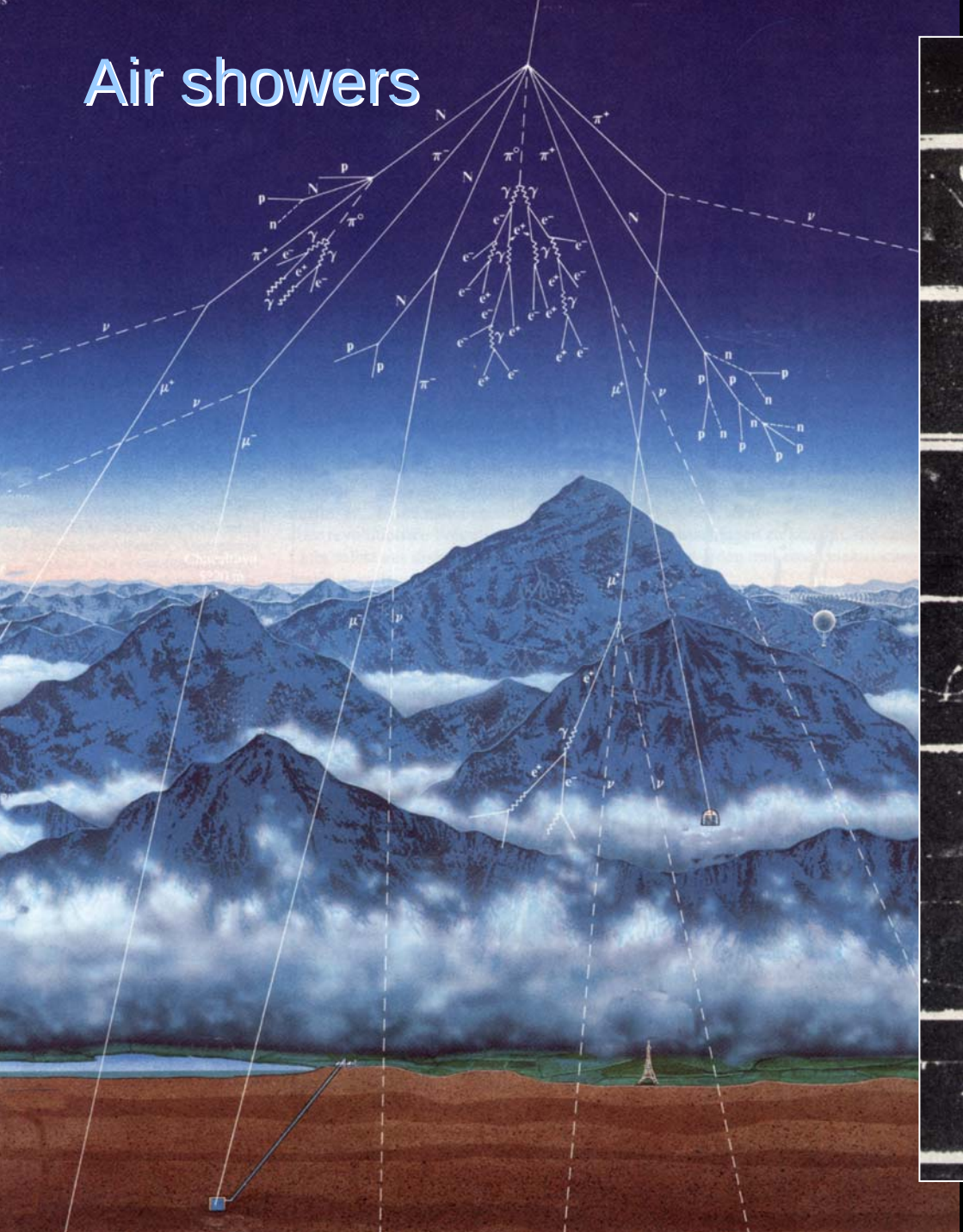
Sonjo Sillok ("Royal Korean Journal")

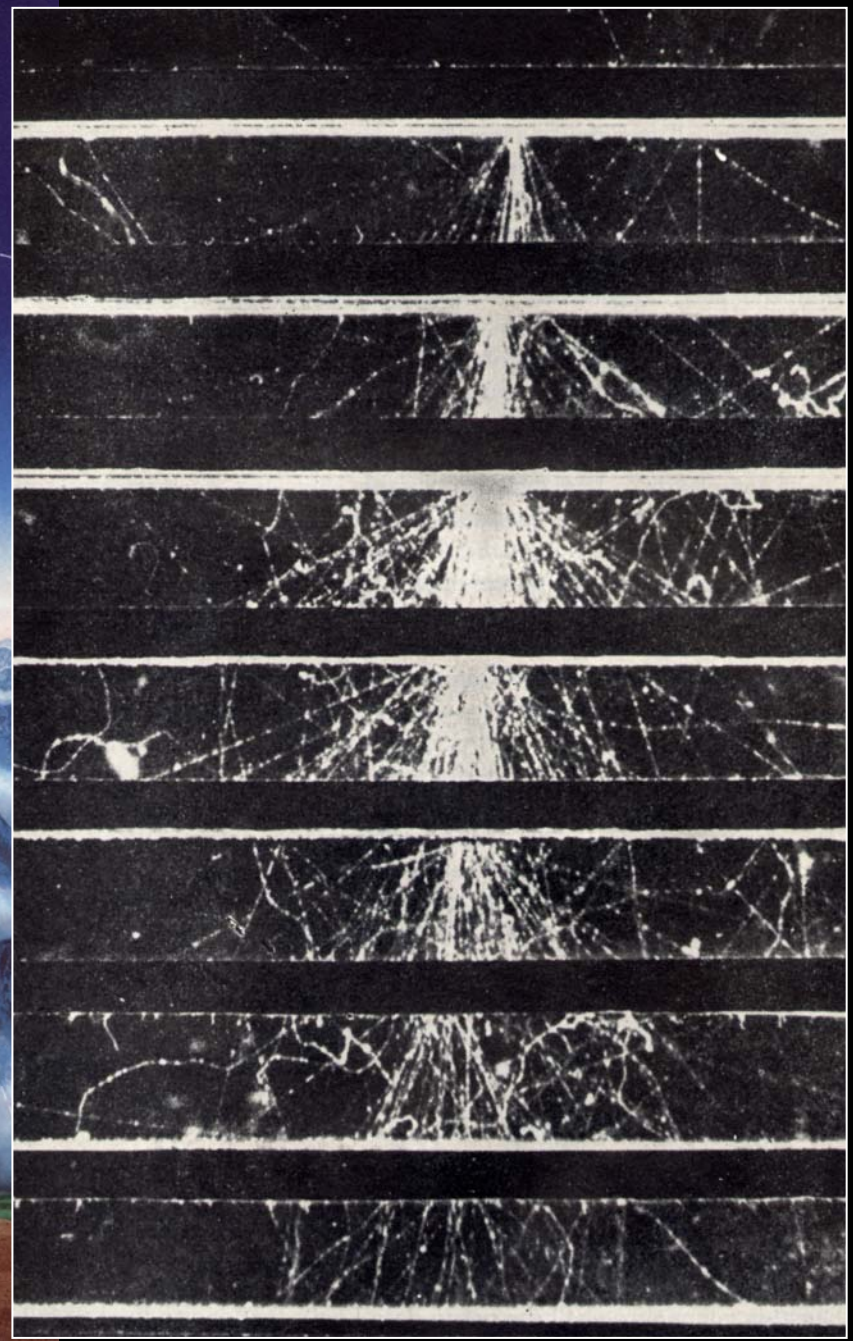
1572: Tycho's supernova





Air showers





The flux of Cosmic Rays

- Energy scales
- Flux scales
- Composition: mostly atomic nuclei