Teilchenteleskope in der Physik

Astronomie bei sehr hohen Energien - Gammastrahlungsastronomie

Gernot Maier

Inhalt

> Astronomie
  - Einführung
  - Höchste Energien - Gammastrahlung

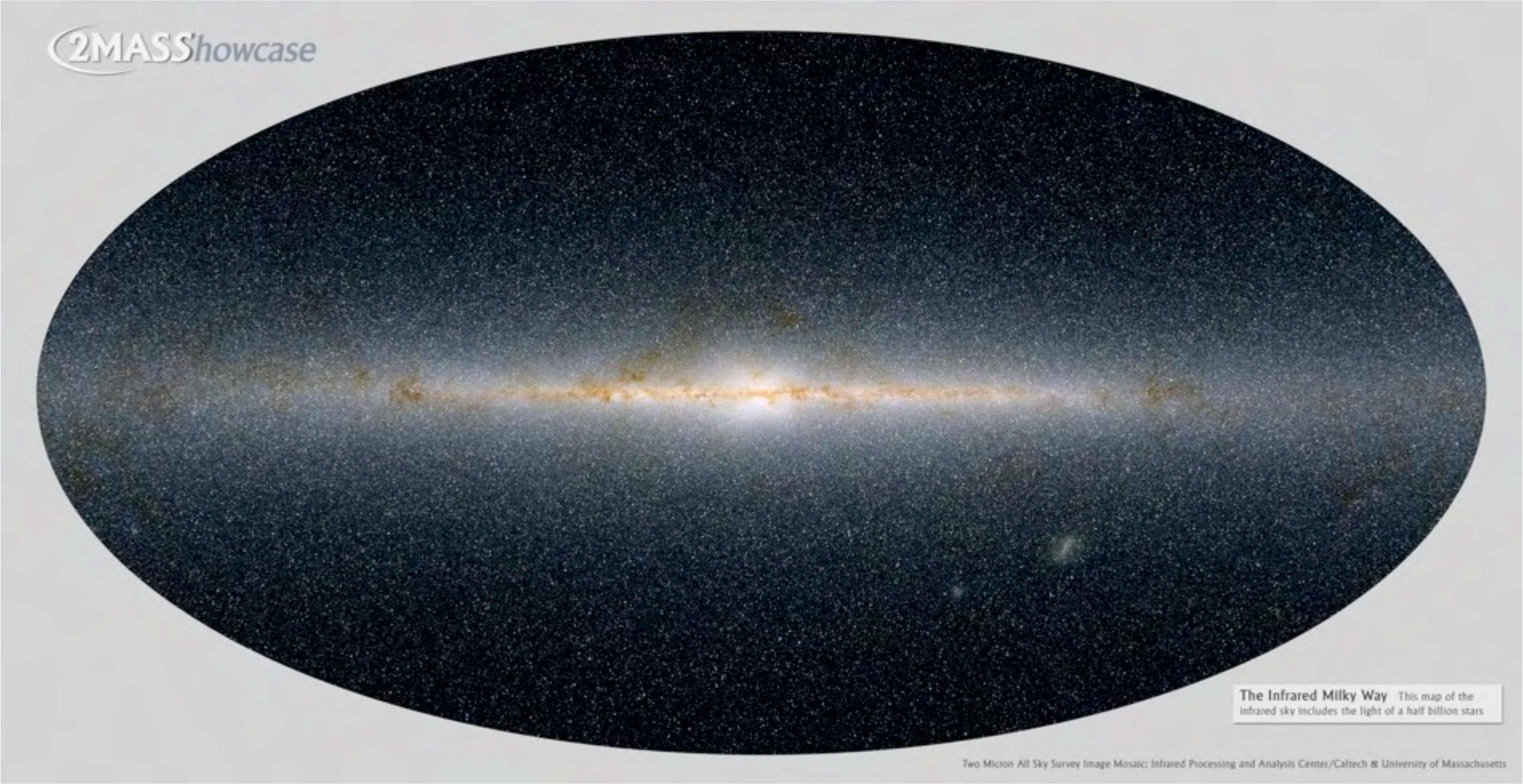
> Kosmische Teilchenbeschleuniger
  - Explodierende Sterne (Supernovae)
  - Doppelsternsysteme
  - Supermassive schwarze Löcher

> Teleskope zur Messung hochenergetischer Gammastrahlung
  - HESS, MAGIC, VERITAS
  - Fermi - LAT
  - CTA, AGIS

> Ausblick

Die Milchstrasse

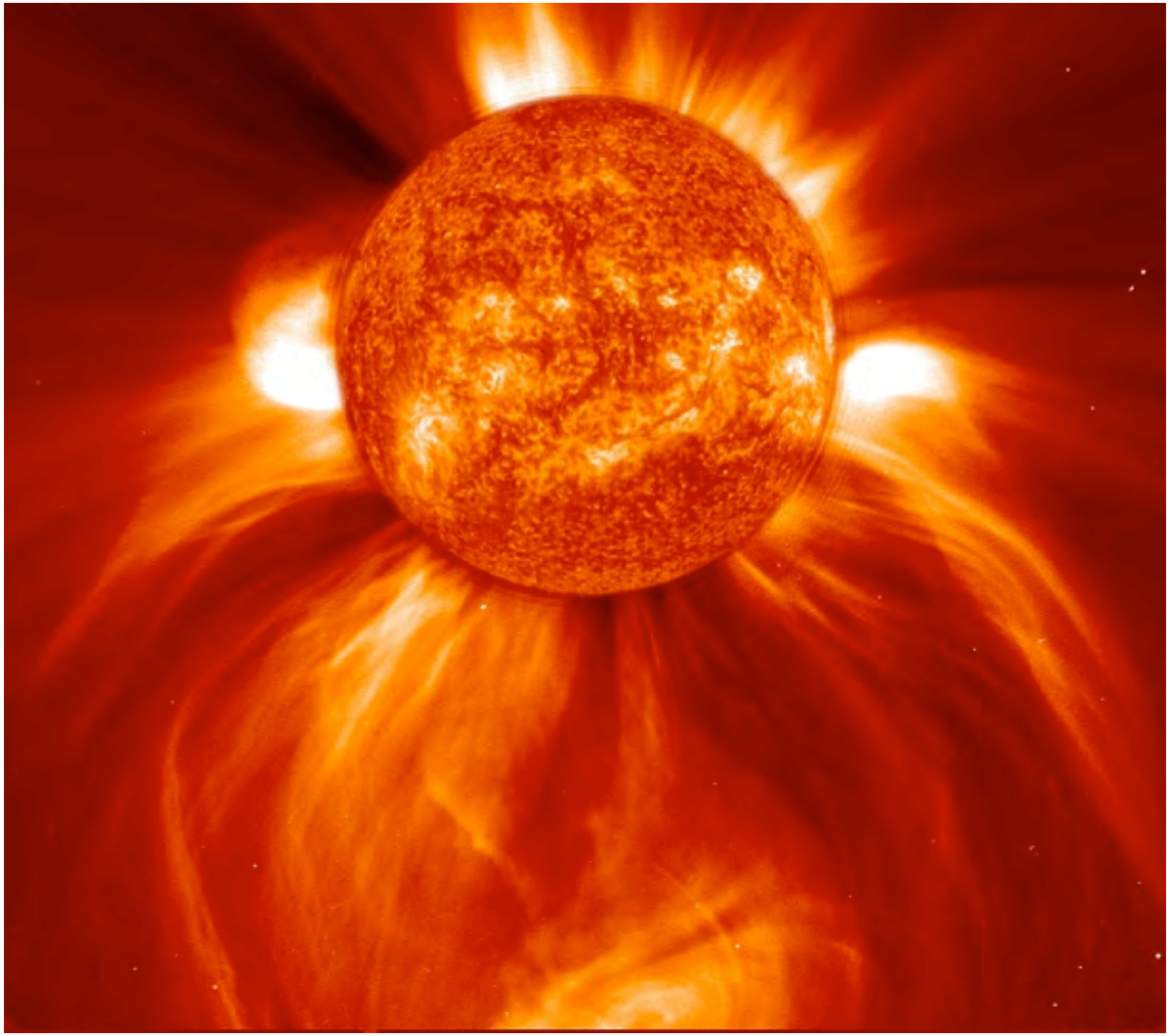
500 Millionen Sterne



100 000 Lichtjahre = 900 000 000 000 000 000 km = 9×10^{17} km

Die Sonne

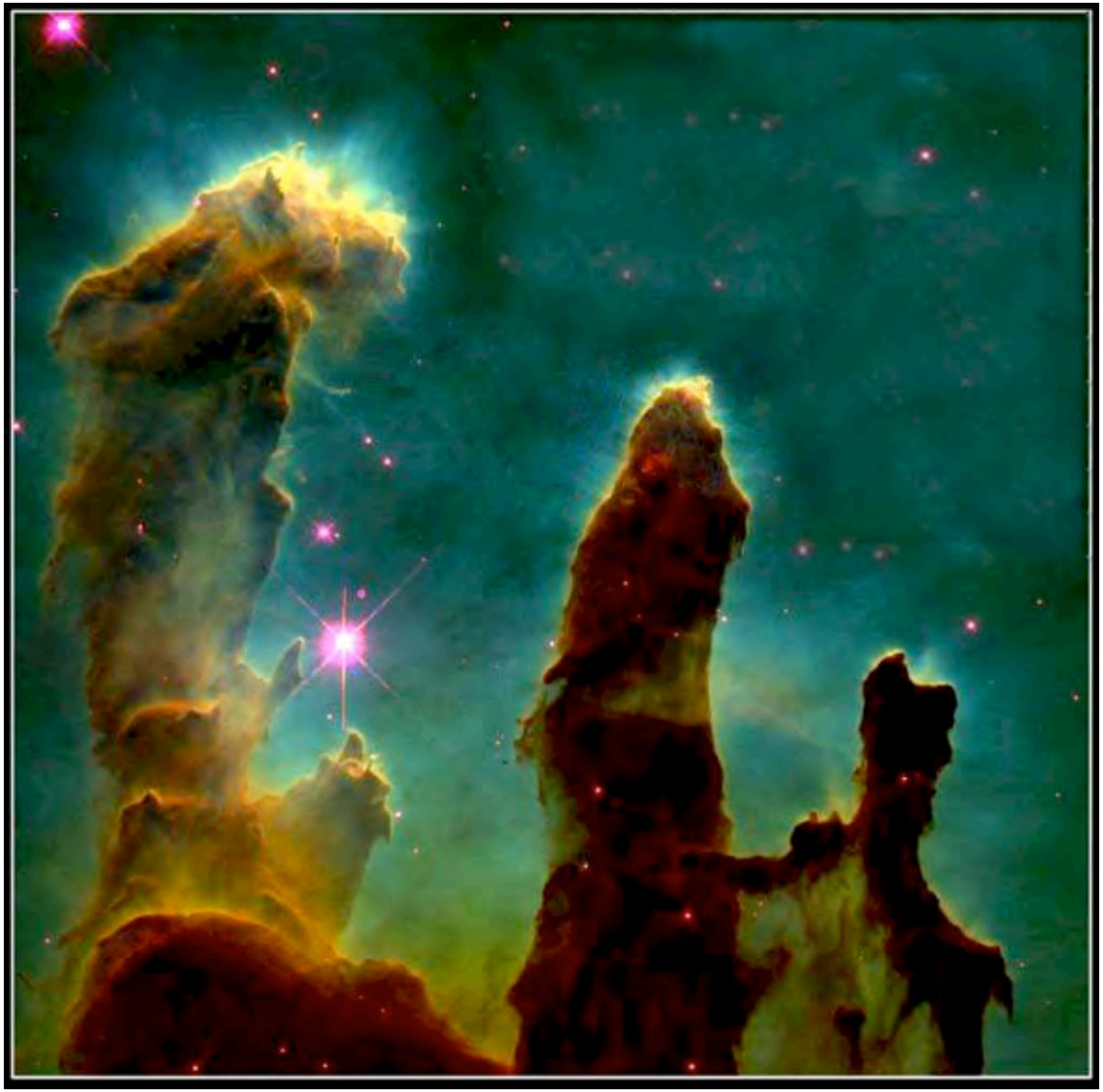
Die Sonne



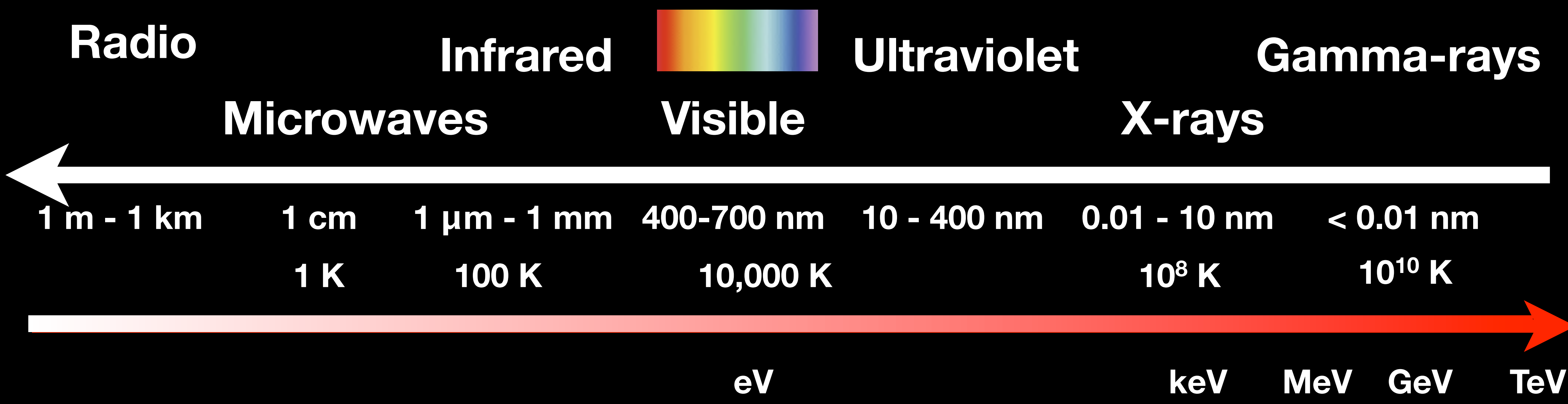
Galaxien

Galaxien - Kollisionen

Nicht nur Sterne - Gas und Staub



Photons


Radio
Infrared
Ultraviolet
Gamma-rays
Microwaves
Visible
X-rays
1 m - 1 km
1 cm
1 μm - 1 mm
400-700 nm
10 - 400 nm
0.01 - 10 nm
< 0.01 nm
1 K
100 K
10,000 K
10^8 K
10^{10} K
eV
keV
MeV
GeV
TeV

Photons

Radio | Microwaves | Infrared | Visible | Ultraviolet | X-rays | Gamma-rays

Radio	Microwaves	Infrared	Visible	Ultraviolet	X-rays	Gamma-rays
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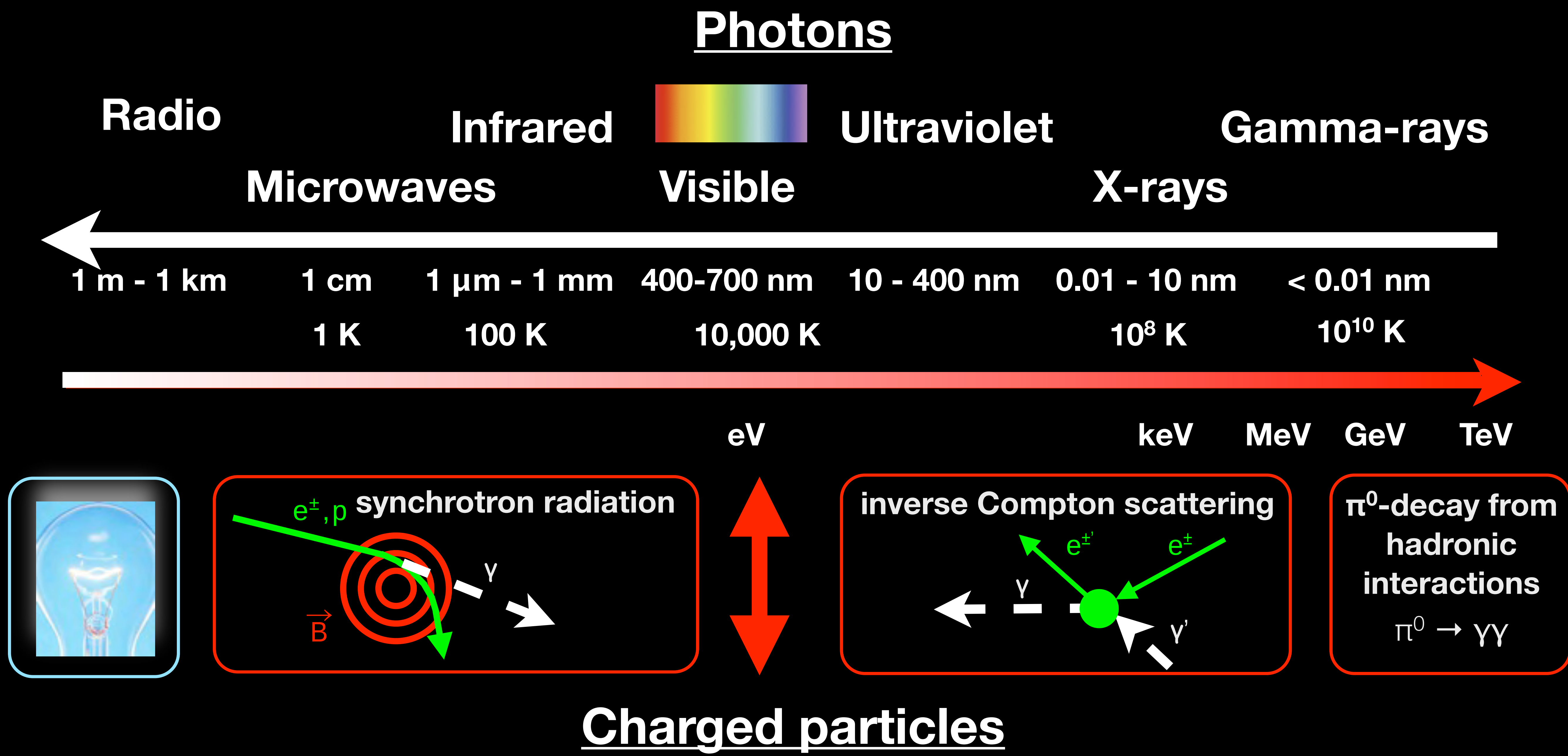
eV keV MeV GeV TeV



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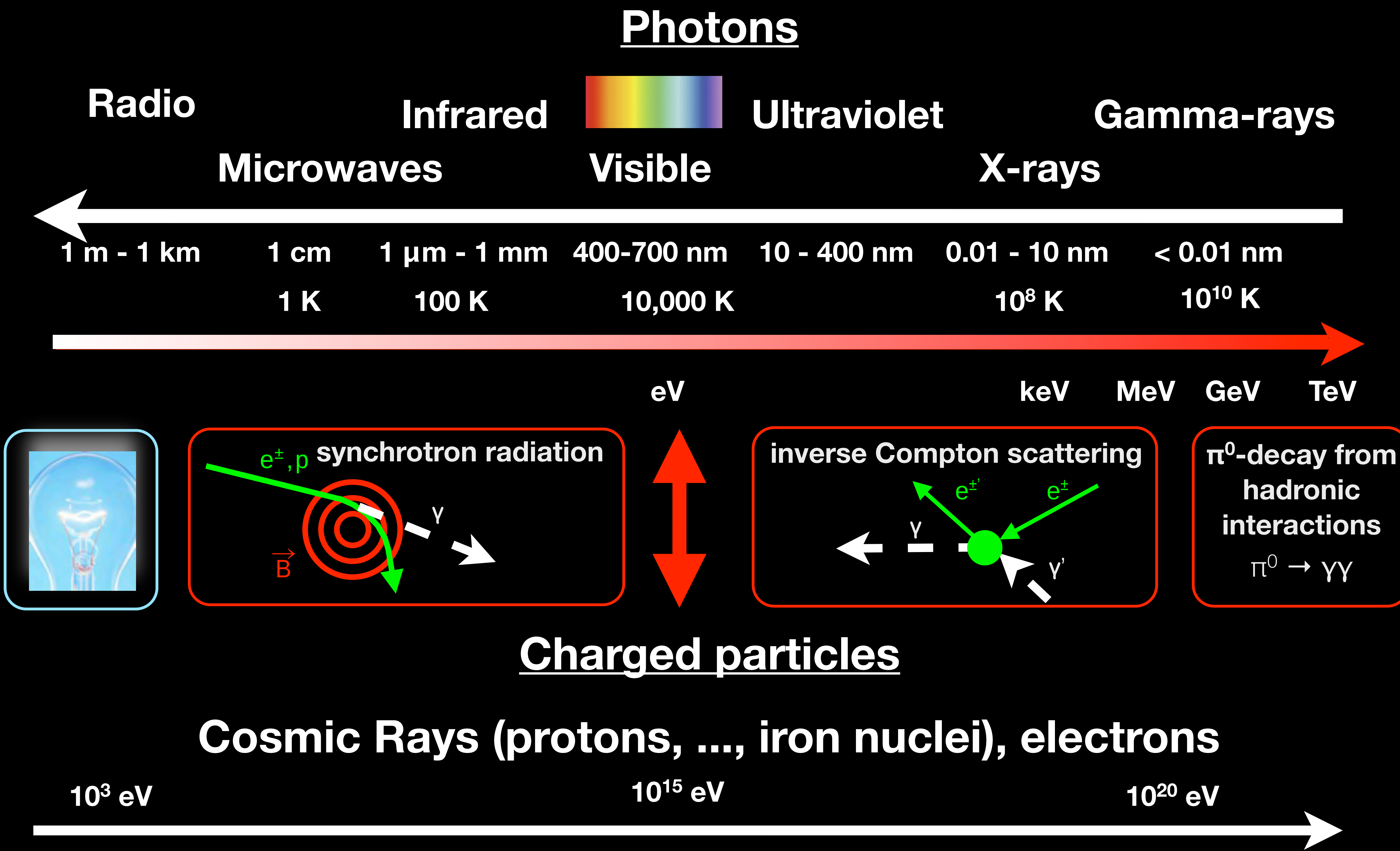
TeV
$e^{\pm}$, p
synchrotron radiation
γ
$\vec{B}$
inverse Compton scattering
$e^{\pm'}$
$e^{\pm}$
γ
γ'
π^0-decay from hadronic interactions
$\pi^0 \rightarrow \gamma\gamma$
Charged particles



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π^0-decay from hadronic interactions
$\pi^0 \rightarrow \gamma\gamma$
Charged particles
Cosmic Rays (protons, ..., iron nuclei), electrons
10^3 eV
10^{15} eV
10^{20} eV

Photons

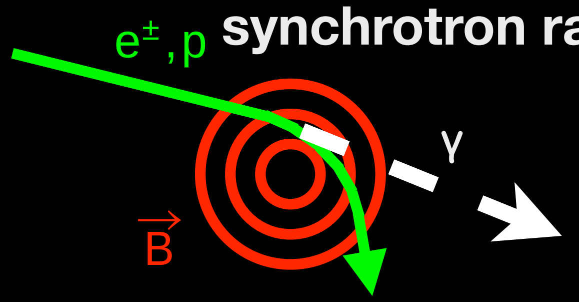
Radio | Microwaves | Infrared | Visible | Ultraviolet | X-rays | Gamma-rays

1 m - 1 km | 1 cm | 1 µm - 1 mm | 400-700 nm | 10 - 400 nm | 0.01 - 10 nm | < 0.01 nm

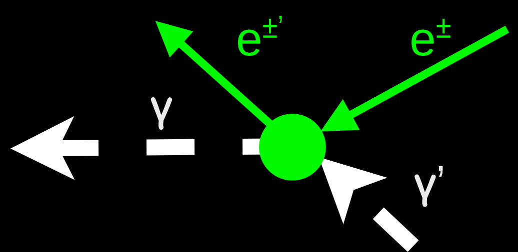
1 K | 100 K | 10,000 K | 10^8 K | 10^{10} K

eV | keV | MeV | GeV | TeV

synchrotron radiation



inverse Compton scattering



π^0-decay from hadronic interactions

$\pi^0 \rightarrow \gamma\gamma$

Charged particles

Cosmic Rays (protons, ..., iron nuclei), electrons

10^3 eV | 10^{15} eV | 10^{20} eV

Neutrinos

Gravitational waves

Multi-wavelength Astronomy

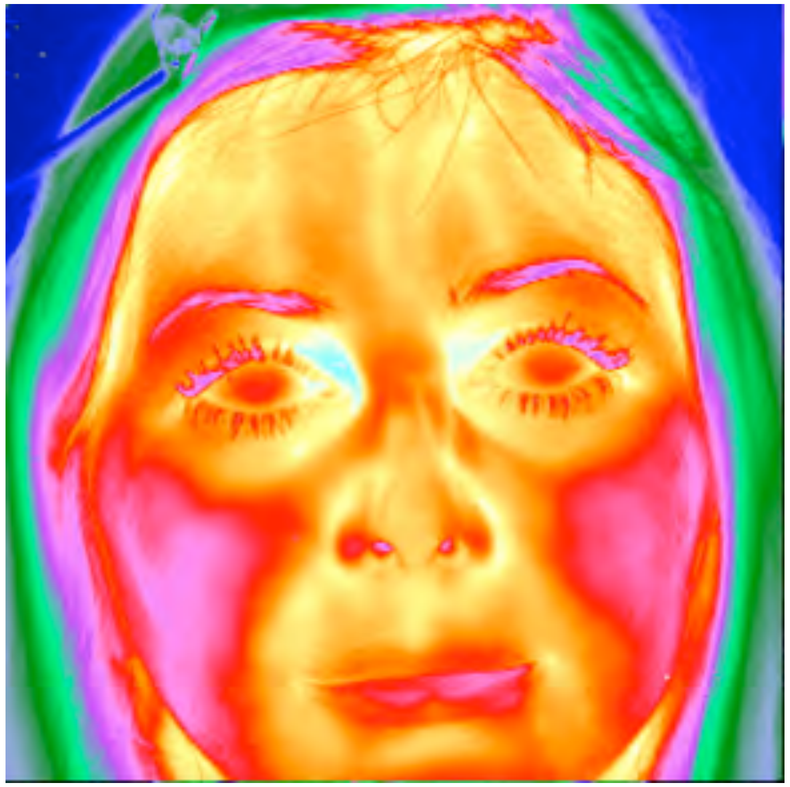
optical

Multi-wavelength Astronomy

optical

x-ray

Multi-wavelength Astronomy

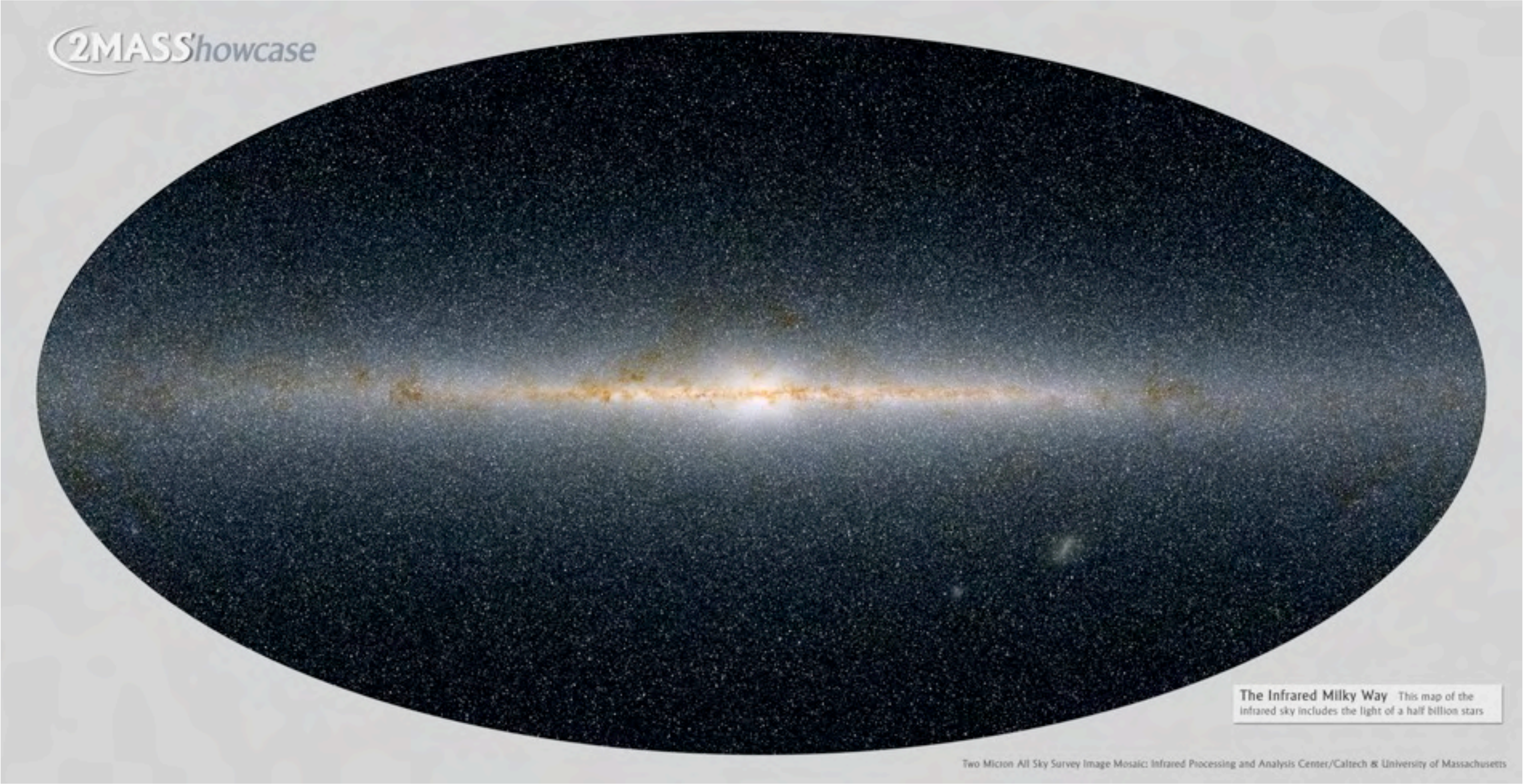


infrared

optical

x-ray

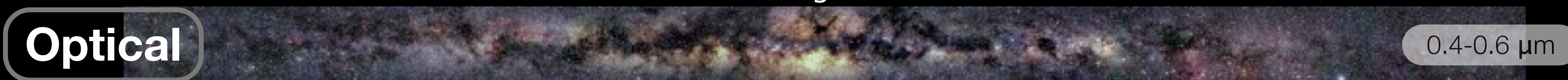
Die Milchstrasse



Die Milchstrasse

The Milky Way

star light



NASA, mwmw.gsfc.nasa.gov

The Milky Way

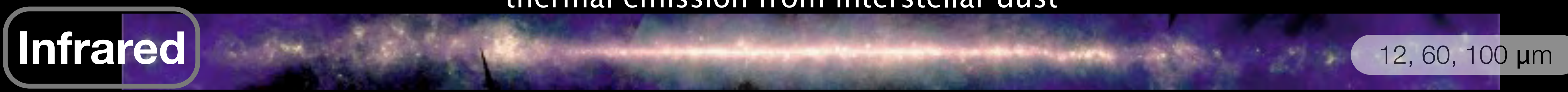
thermal emission from interstellar dust

star light

NASA, mwmw.gsfc.nasa.gov

The Milky Way

thermal emission from interstellar dust



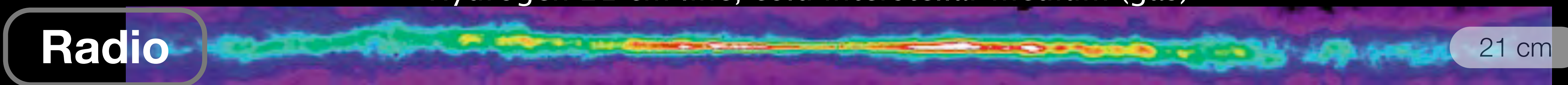
star light

very hot, shocked gas

NASA, mwmw.gsfc.nasa.gov

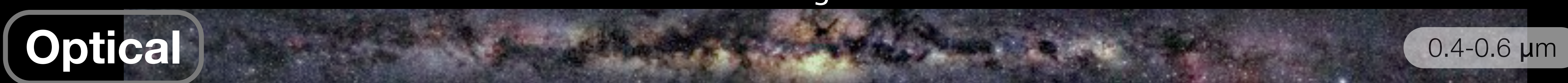
The Milky Way

Hydrogen 21 cm line, cold interstellar medium (gas)



thermal emission from interstellar dust

star light



very hot, shocked gas

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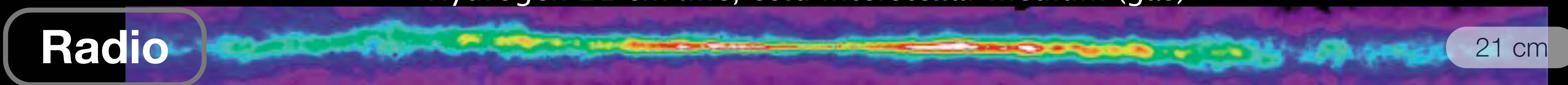
The Milky Way

synchrotron emission from HE electrons moving through interstellar magnetic fields

Hydrogen 21 cm line, cold interstellar medium (gas)



thermal emission from interstellar dust

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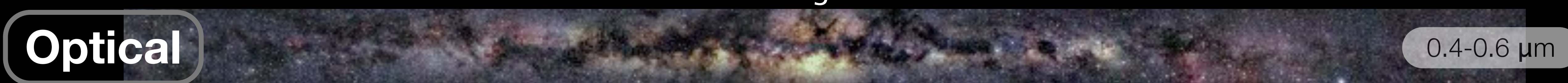
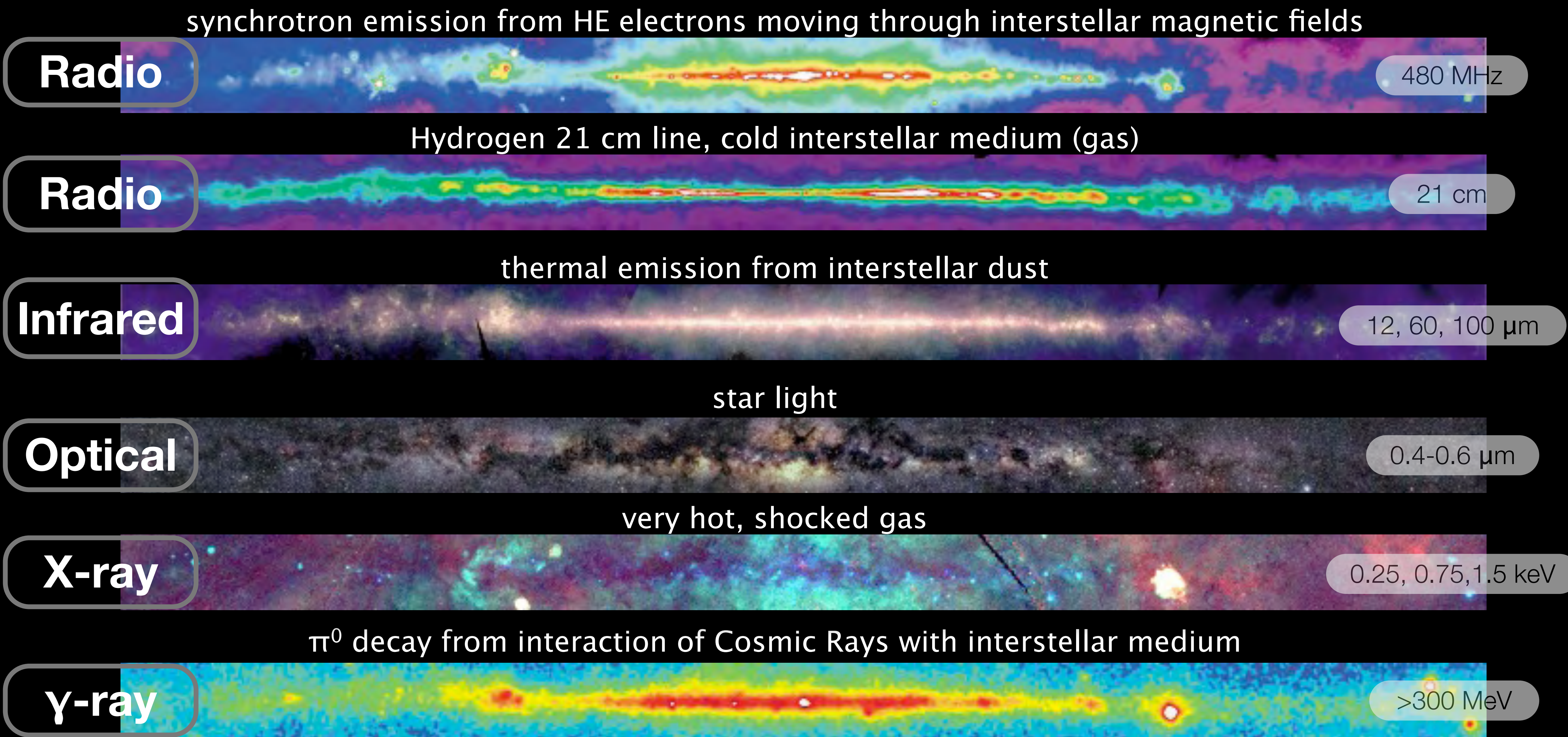


very hot, shocked gas

NASA, mwmw.gsfc.nasa.gov

The Milky Way



NASA, mwmw.gsfc.nasa.gov

The Milky Way

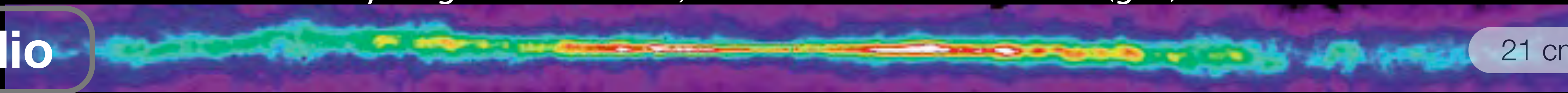
synchrotron emission from HE electrons moving through interstellar magnetic fields

Radio

480 MHz

Hydrogen 21 cm line, cold interstellar medium (gas)

Radio



21 cm

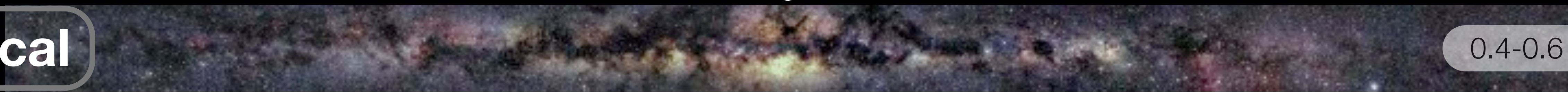
thermal emission from interstellar dust

Infrared

12, 60, 100 µm

star light

Optical



0.4-0.6 µm

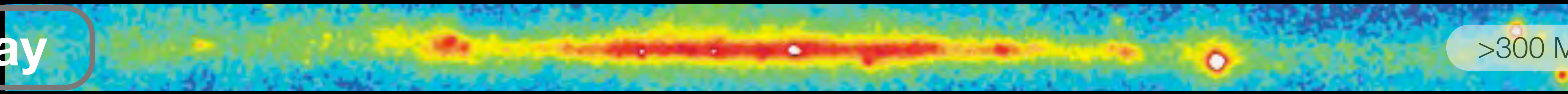
very hot, shocked gas

X-ray

0.25, 0.75,1.5 keV

π^0 decay from interaction of Cosmic Rays with interstellar medium

γ-ray



>300 MeV

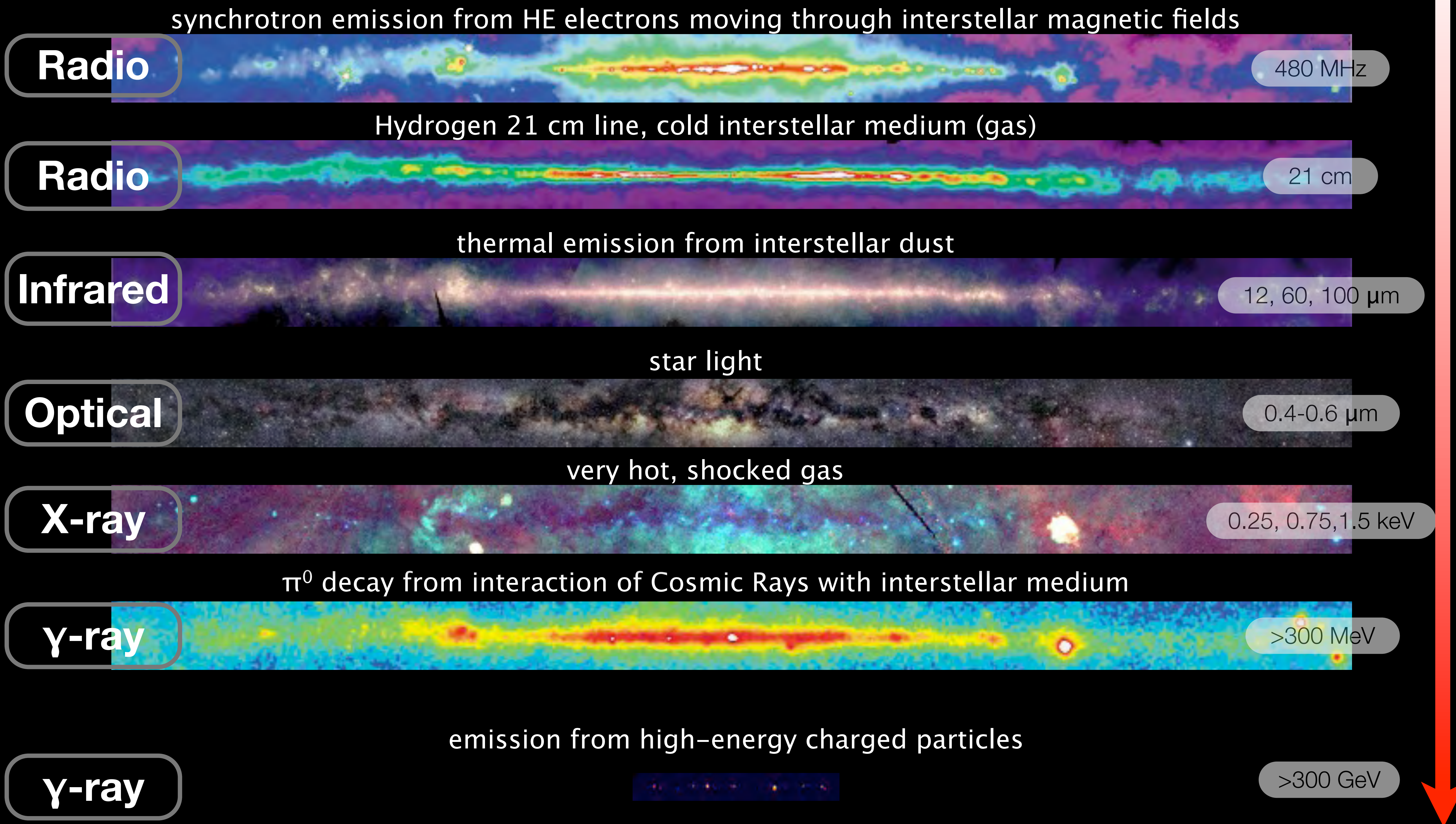
emission from high-energy charged particles

γ-ray

>300 GeV

NASA, mwmw.gsfc.nasa.gov

The Milky Way

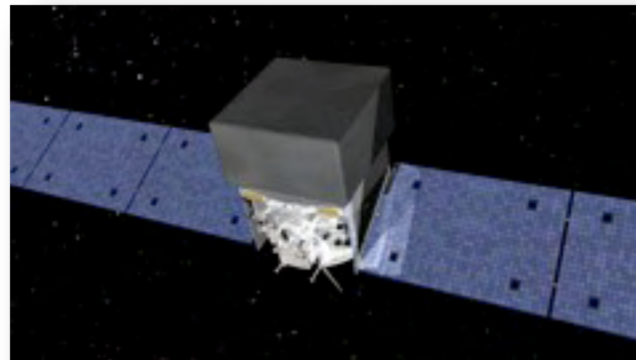


NASA, mwmw.gsfc.nasa.gov

Instruments

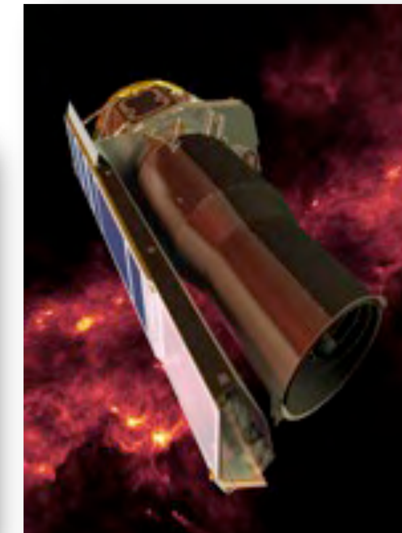
Arecibo (Radio)

Fermi (Gamma-rays)



Suzaku (X-rays)

Spitzer (IR)



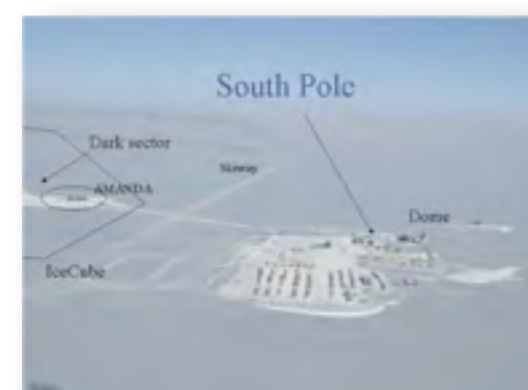
VLT (Optical)

VERITAS (Gamma-rays)

Auger (Cosmic Rays)

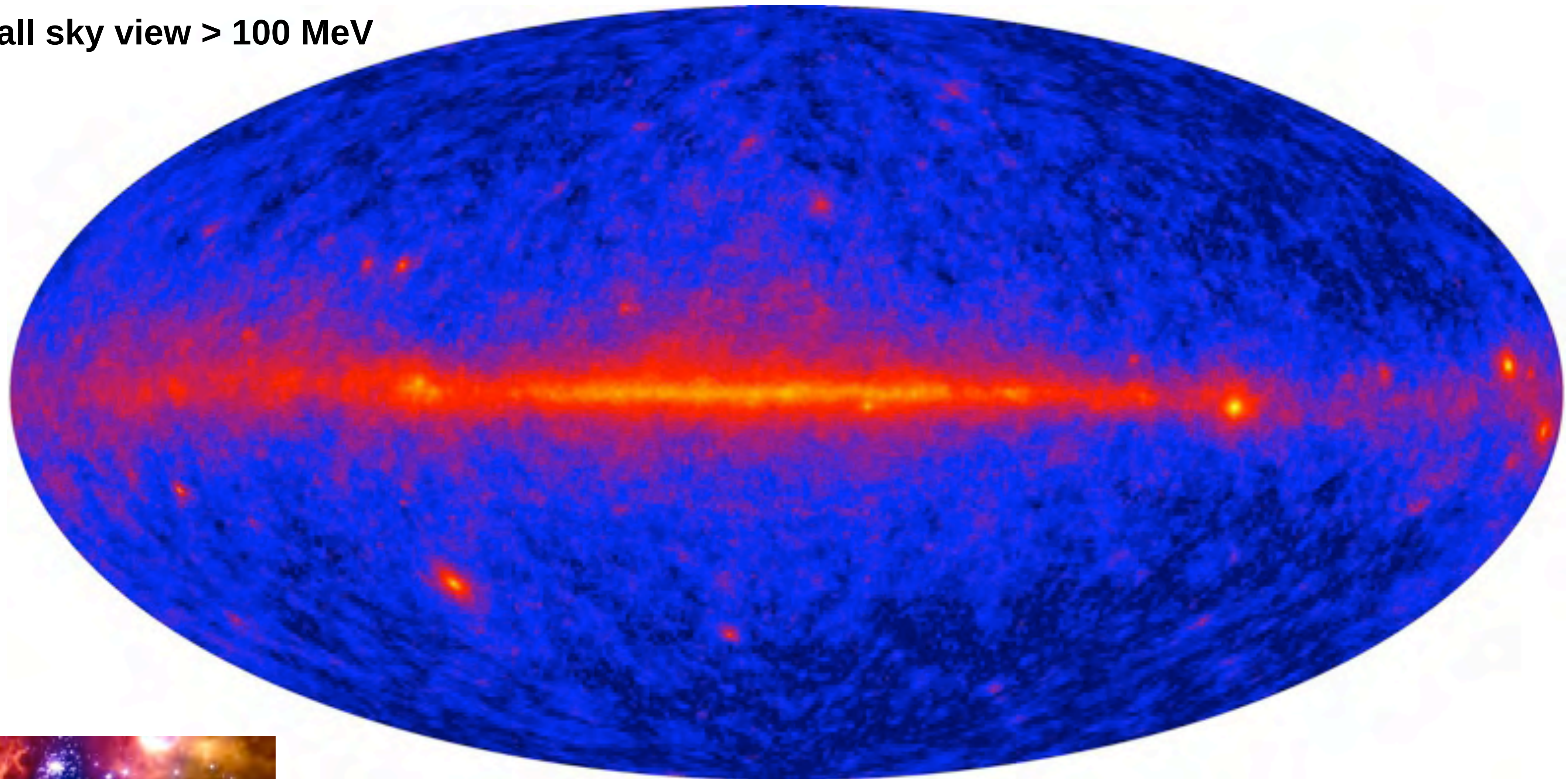
LIGO (Gravitational waves)

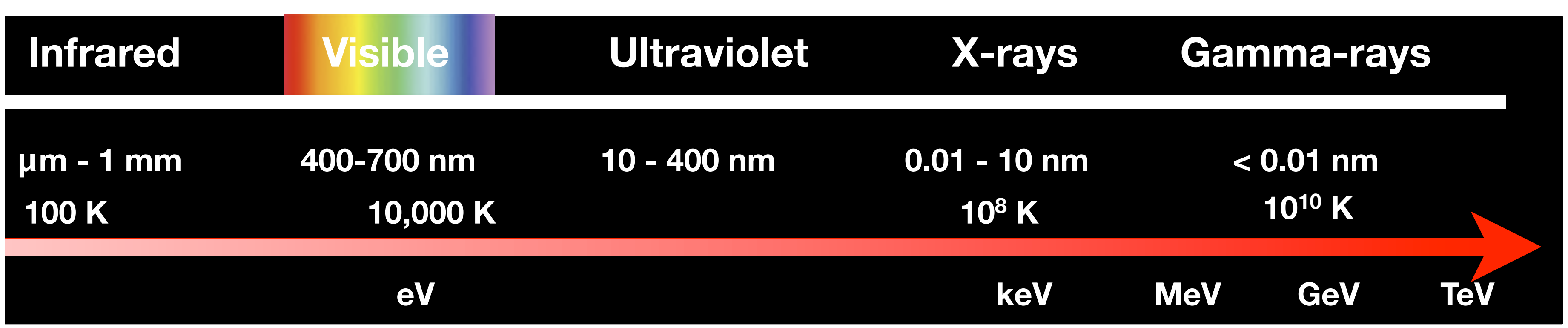
IceCube (Neutrinos)



The non-thermal Universe

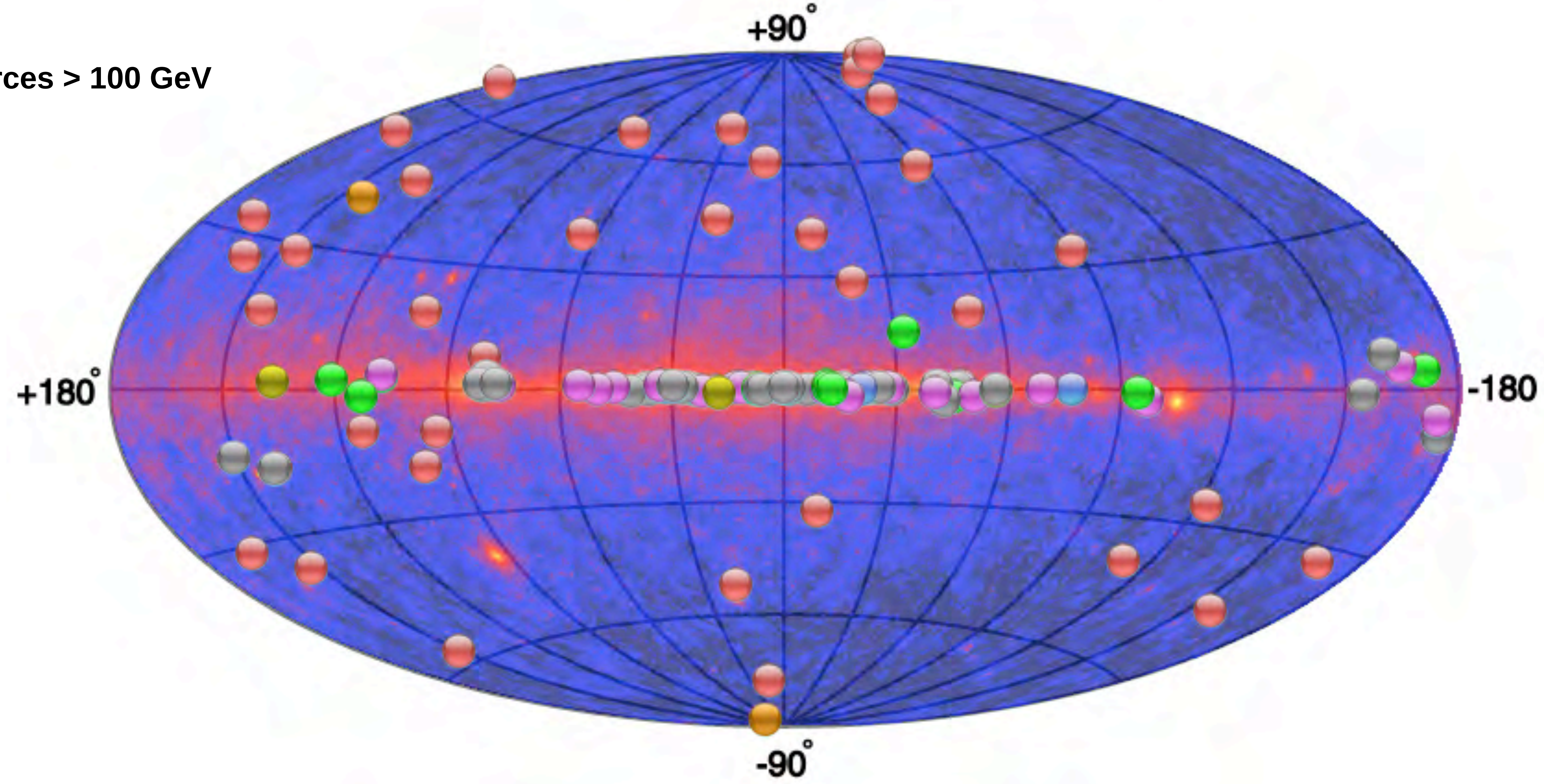
Fermi LAT all sky view > 100 MeV





The non-thermal Universe

sources > 100 GeV



The non-thermal Universe

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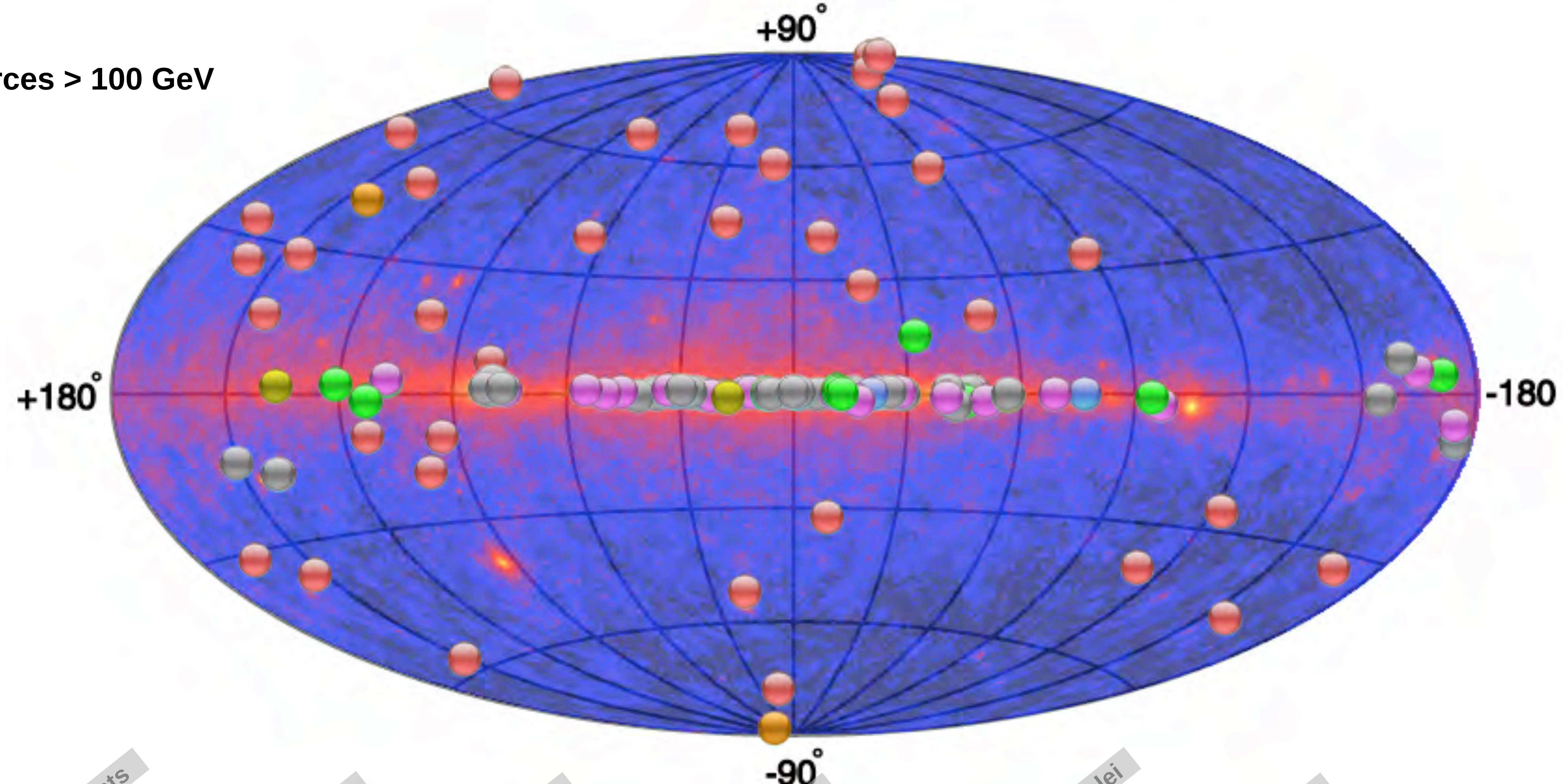
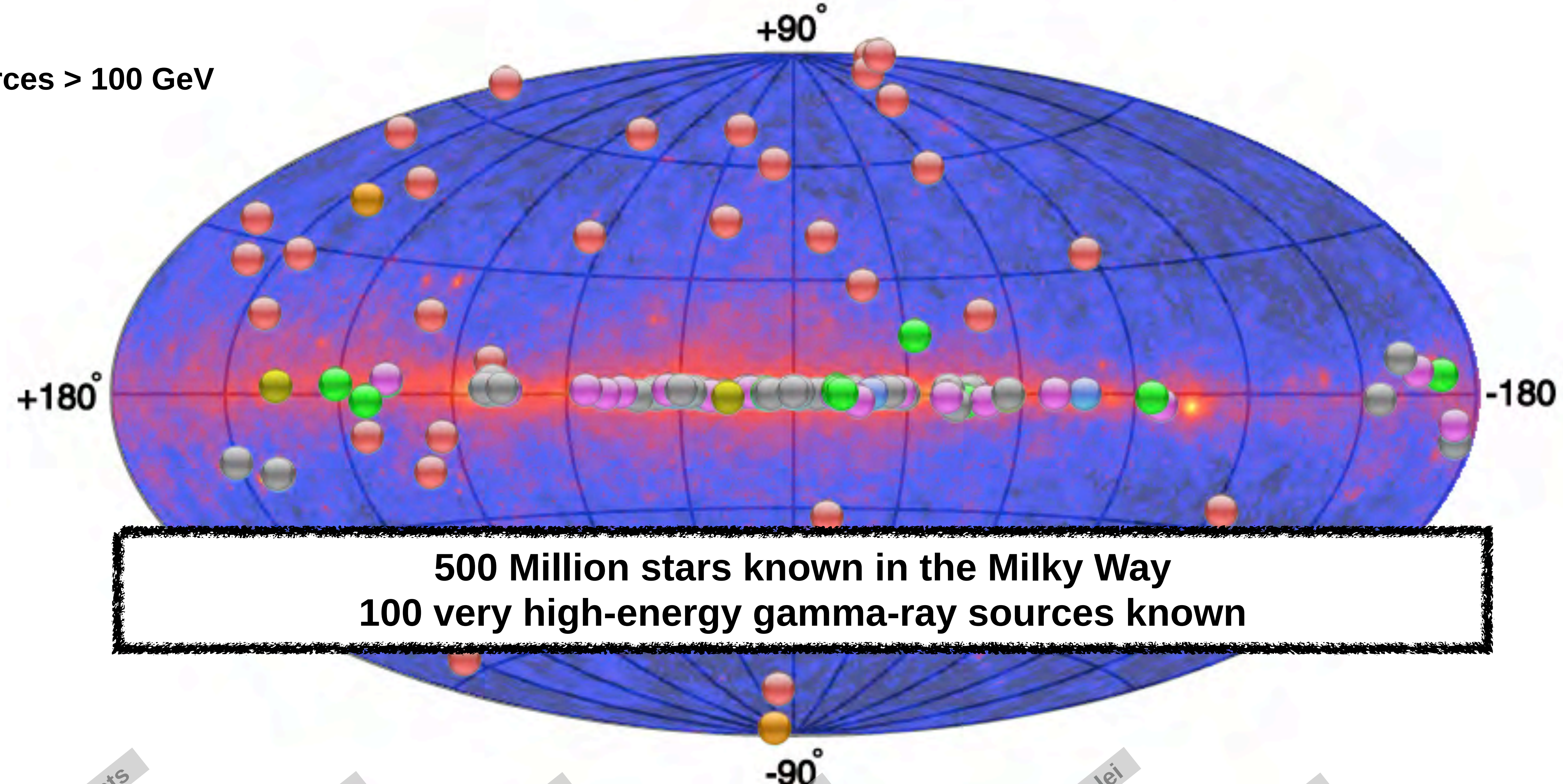


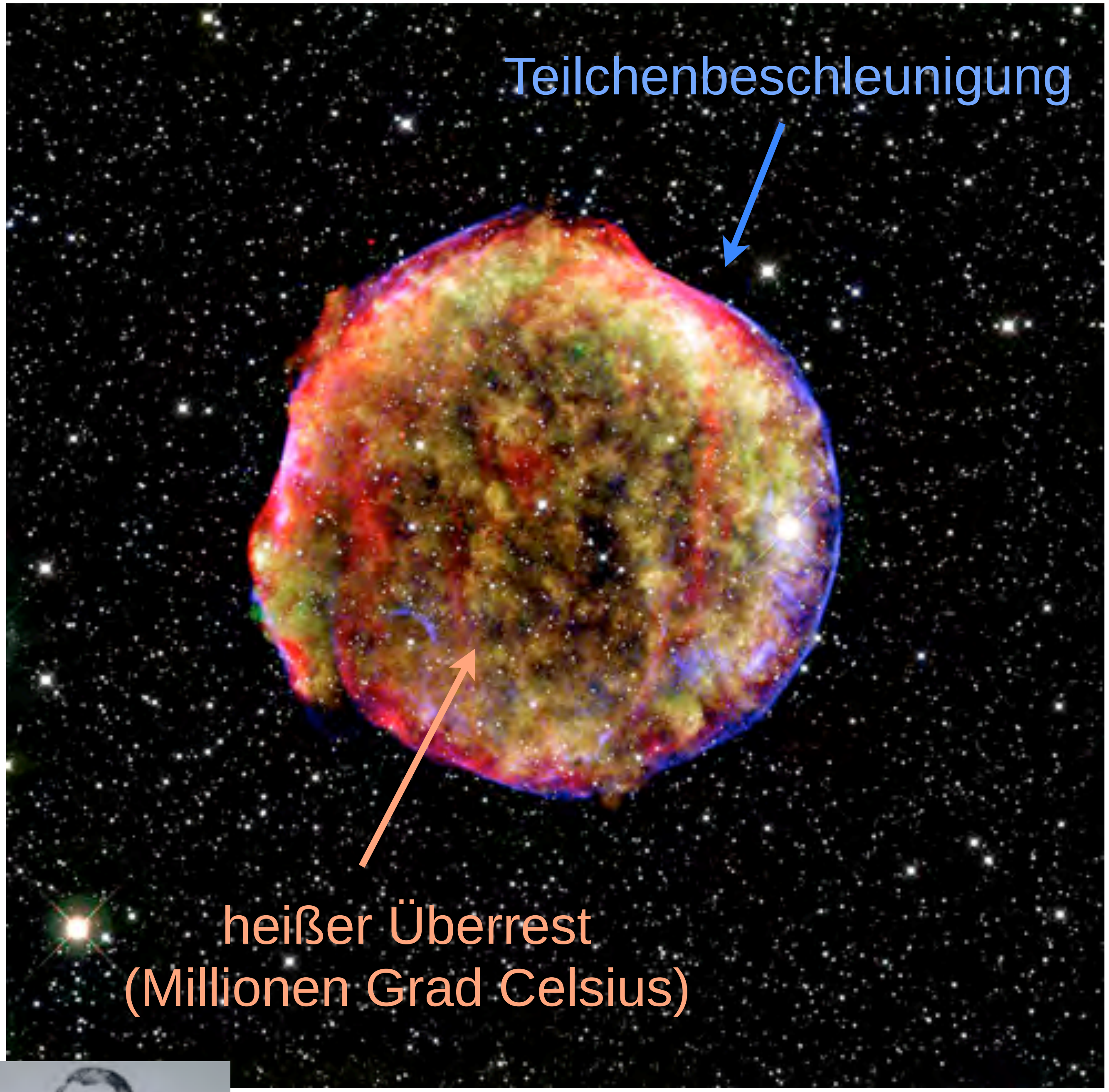
The non-thermal Universe

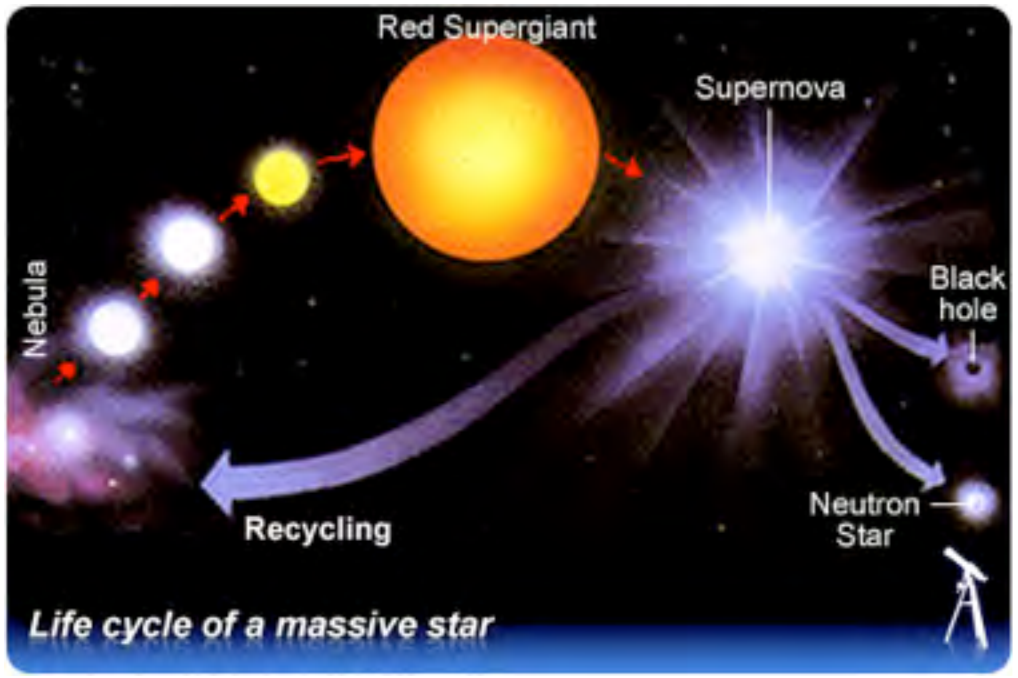
sources > 100 GeV



500 Million stars known in the Milky Way
100 very high-energy gamma-ray sources known

Quellen von Gammastrahlung - Explodierende Sterne



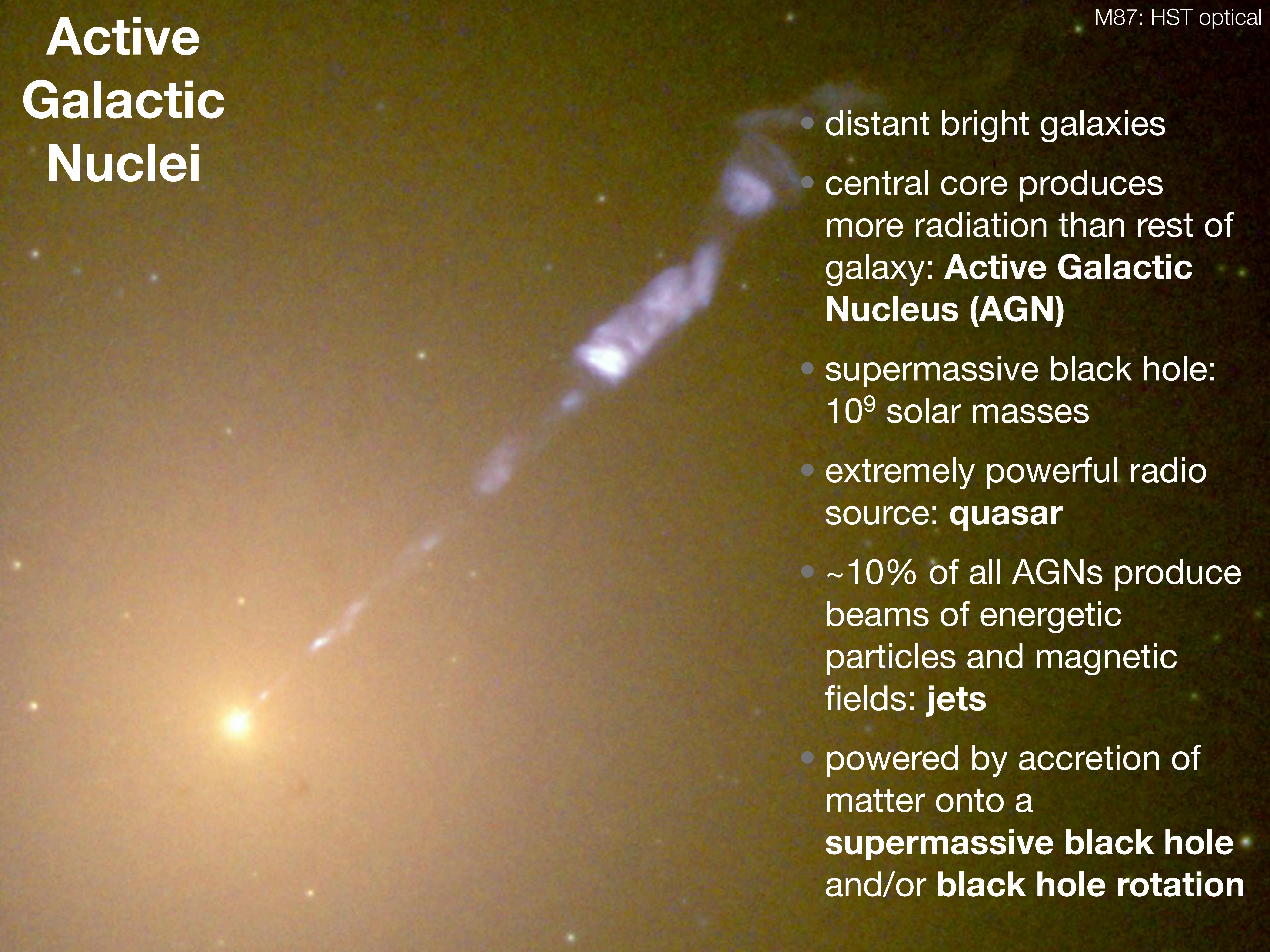


Tycho's Supernova (1572)

Massive Sterne explodieren am Ende ihres 'Lebens'

Wahrscheinlich die Quellen der kosmischen Strahlung

Active Galactic Nuclei



M87: HST optical

- distant bright galaxies
- central core produces more radiation than rest of galaxy: **Active Galactic Nucleus (AGN)**
- supermassive black hole: 10^9 solar masses
- extremely powerful radio source: **quasar**
- ~10% of all AGNs produce beams of energetic particles and magnetic fields: **jets**
- powered by accretion of matter onto a **supermassive black hole** and/or **black hole rotation**

Active Galactic Nuclei

M87: HST optical

blue light: synchrotron radiation from HE electrons

jet: relativistic, hot, magnetized plasma

thousands of light years

hot spots: shocked jet plasma

core and accretion disk

- distant bright galaxies
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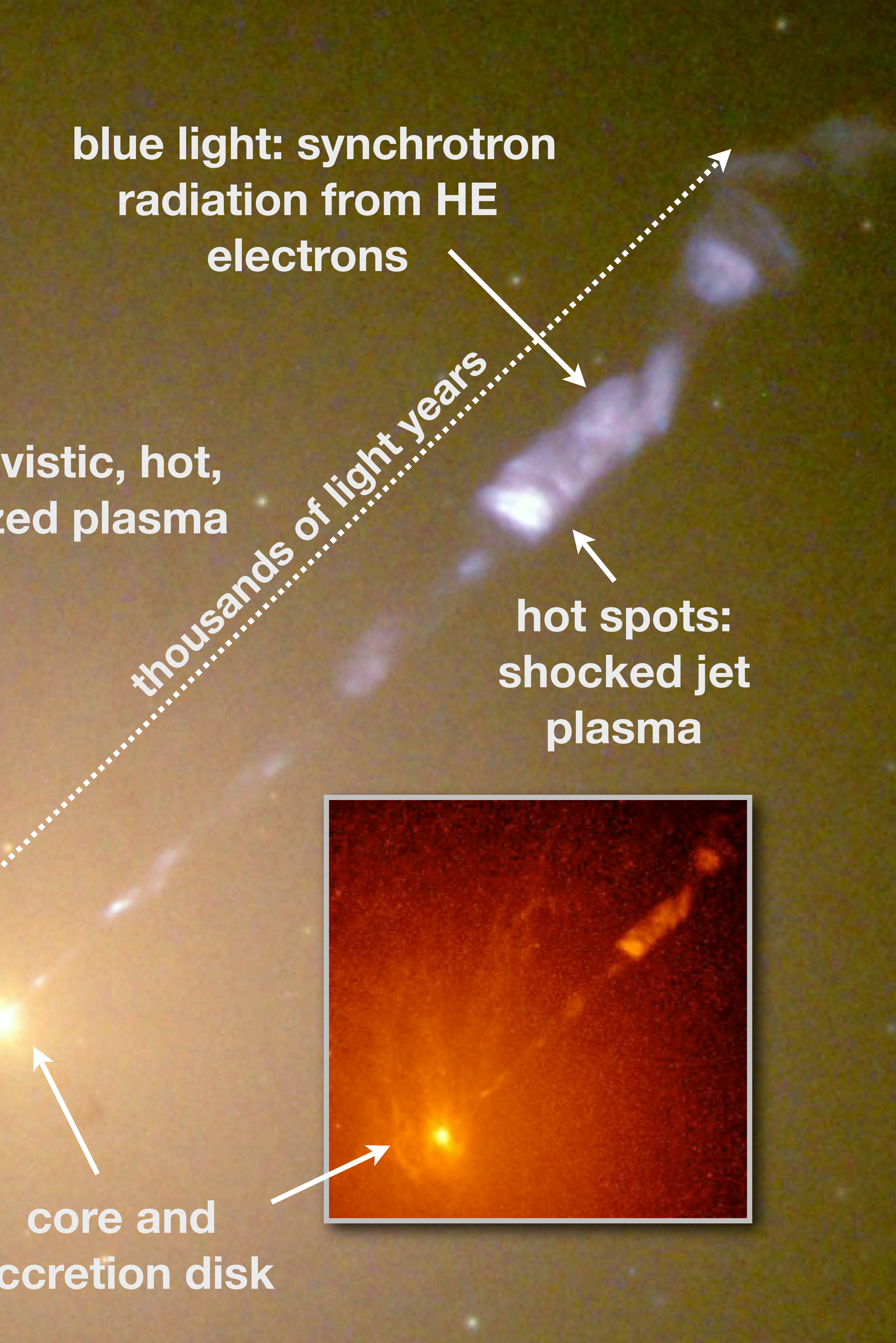
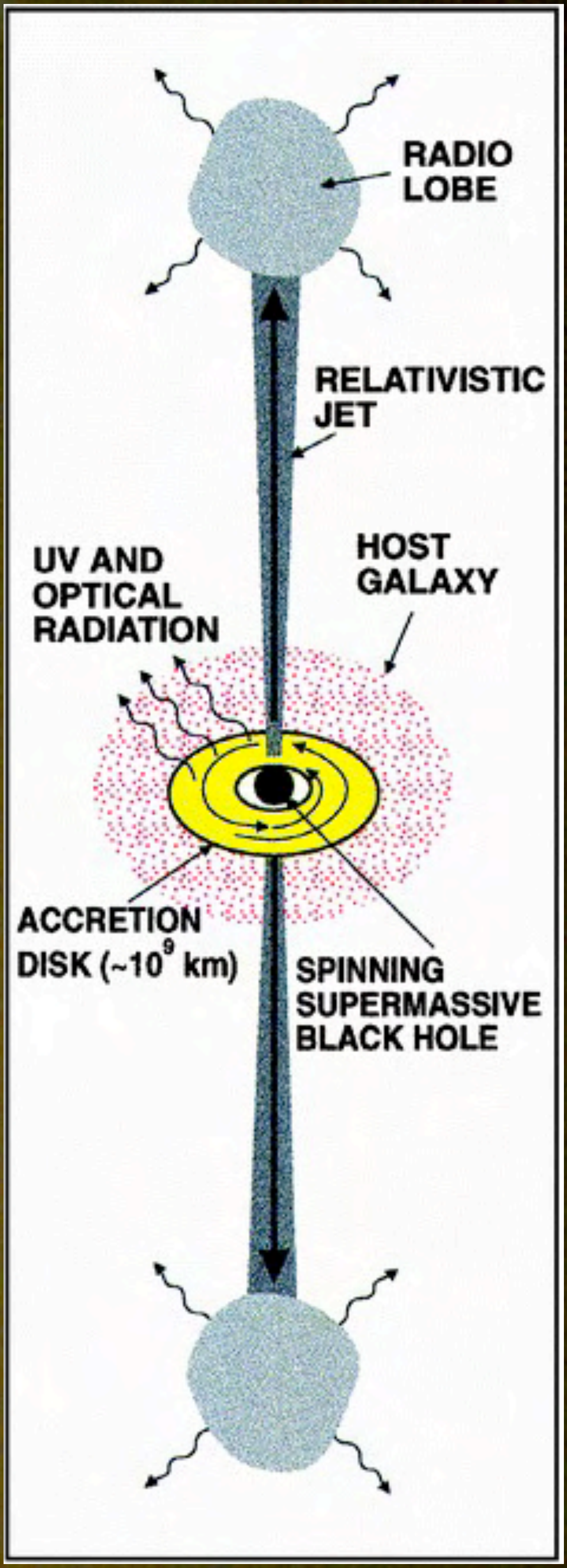
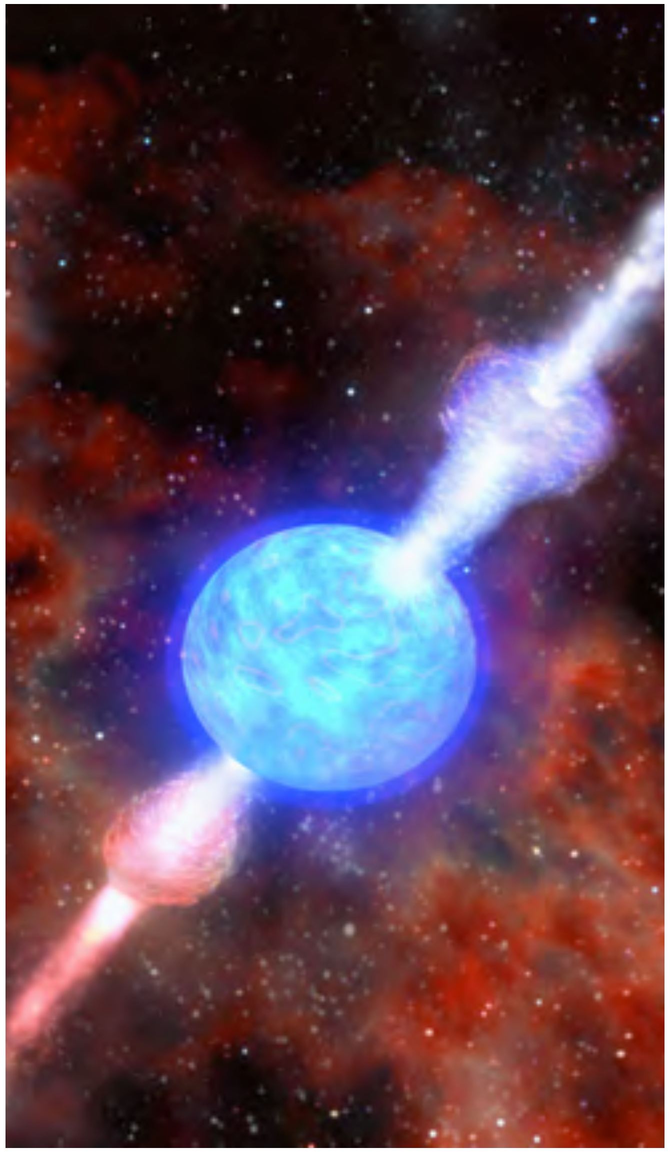




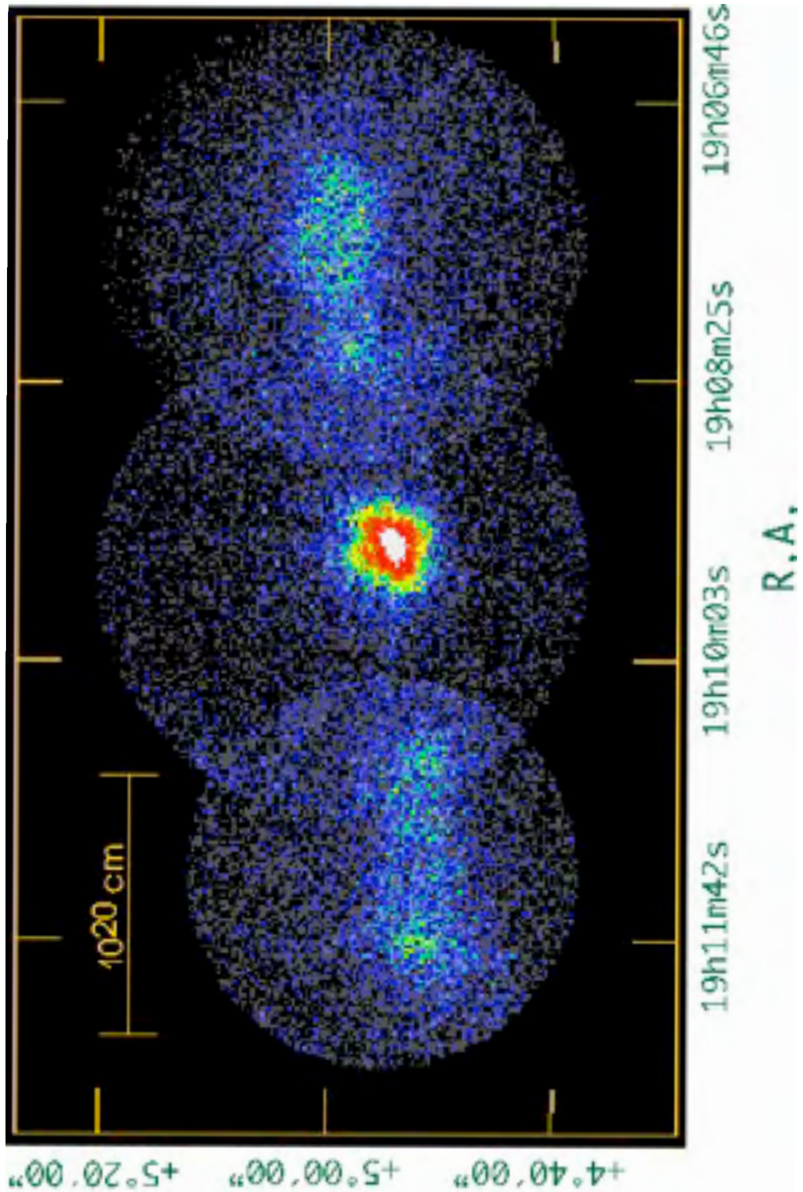
Schwarze Löcher und Jets

Gamma Ray Bursts
(hypernovae)



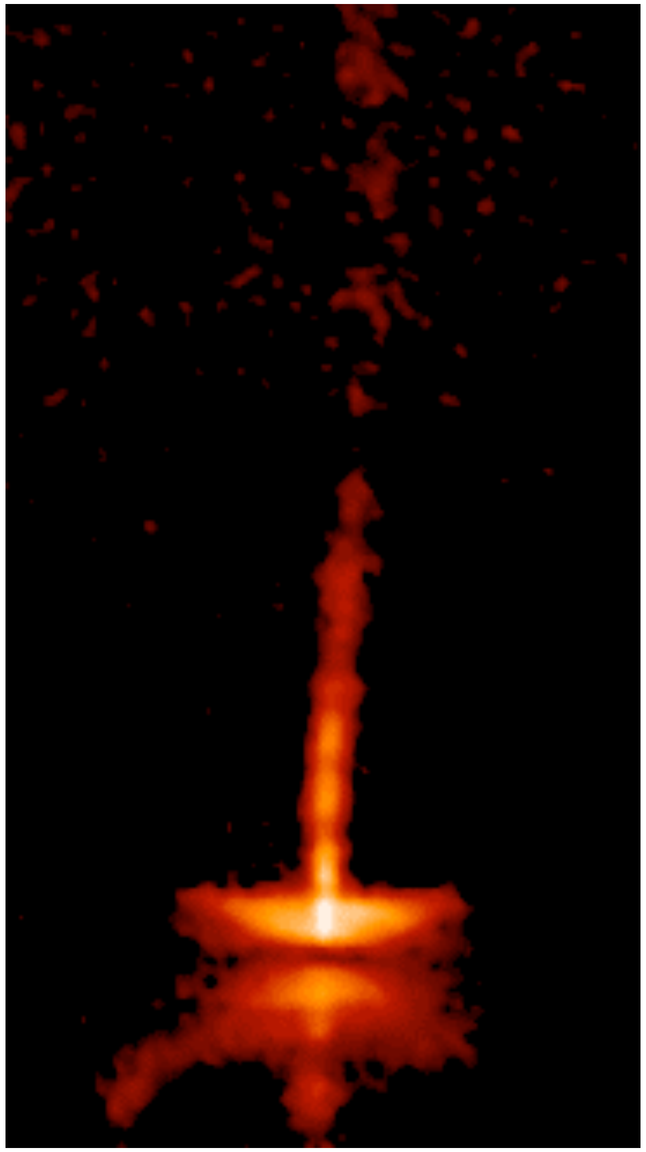
long GRBs
collapse of massive, rapidly rotating stars

Microquasars
(X-ray binaries)



SS 433
(2-10 keV)

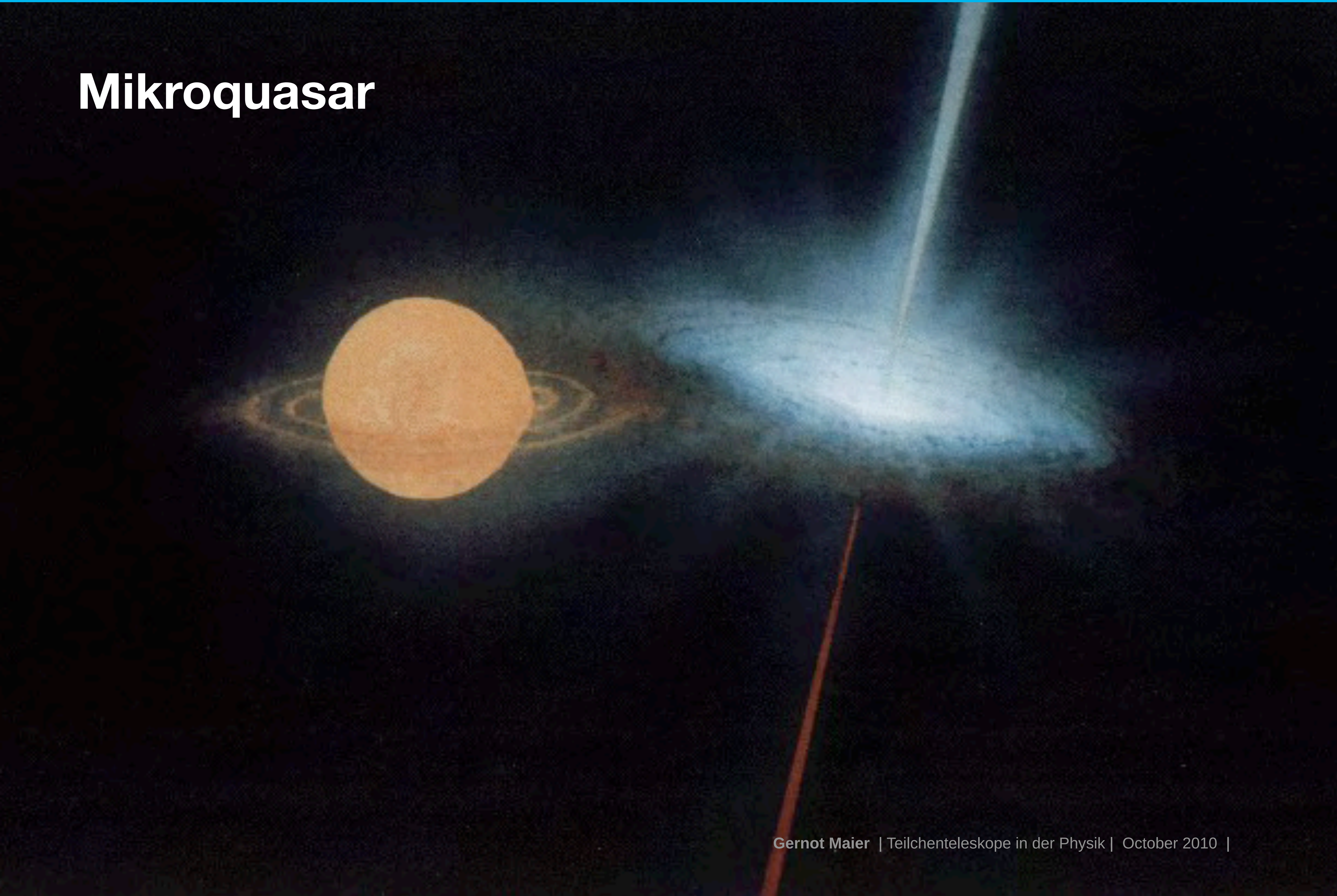
Young Stars
(Herbig-Haro Objects)



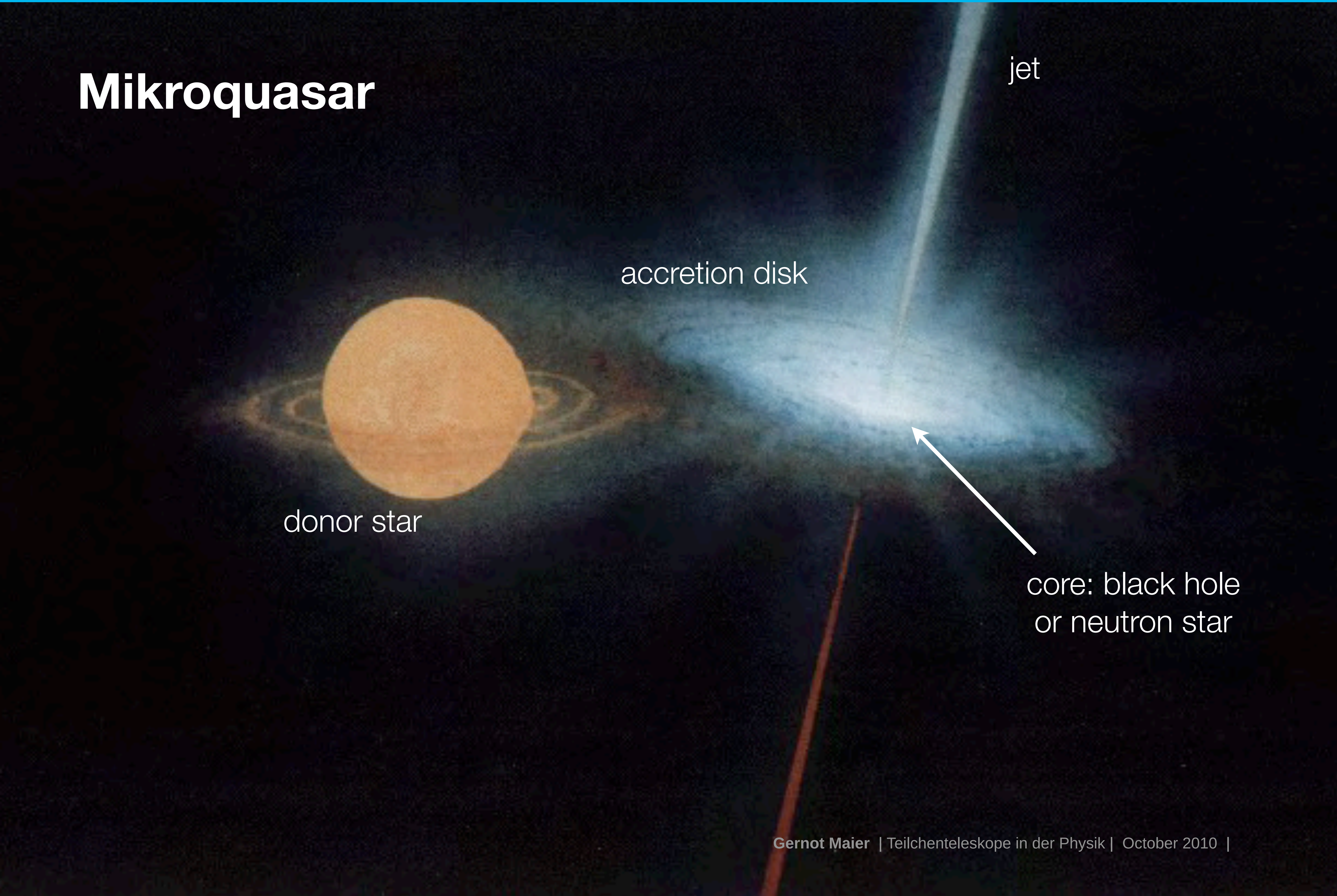
HH30:
1995 - 2000

Quellen von Gammastrahlung - Doppelsternsysteme

Mikroquasar

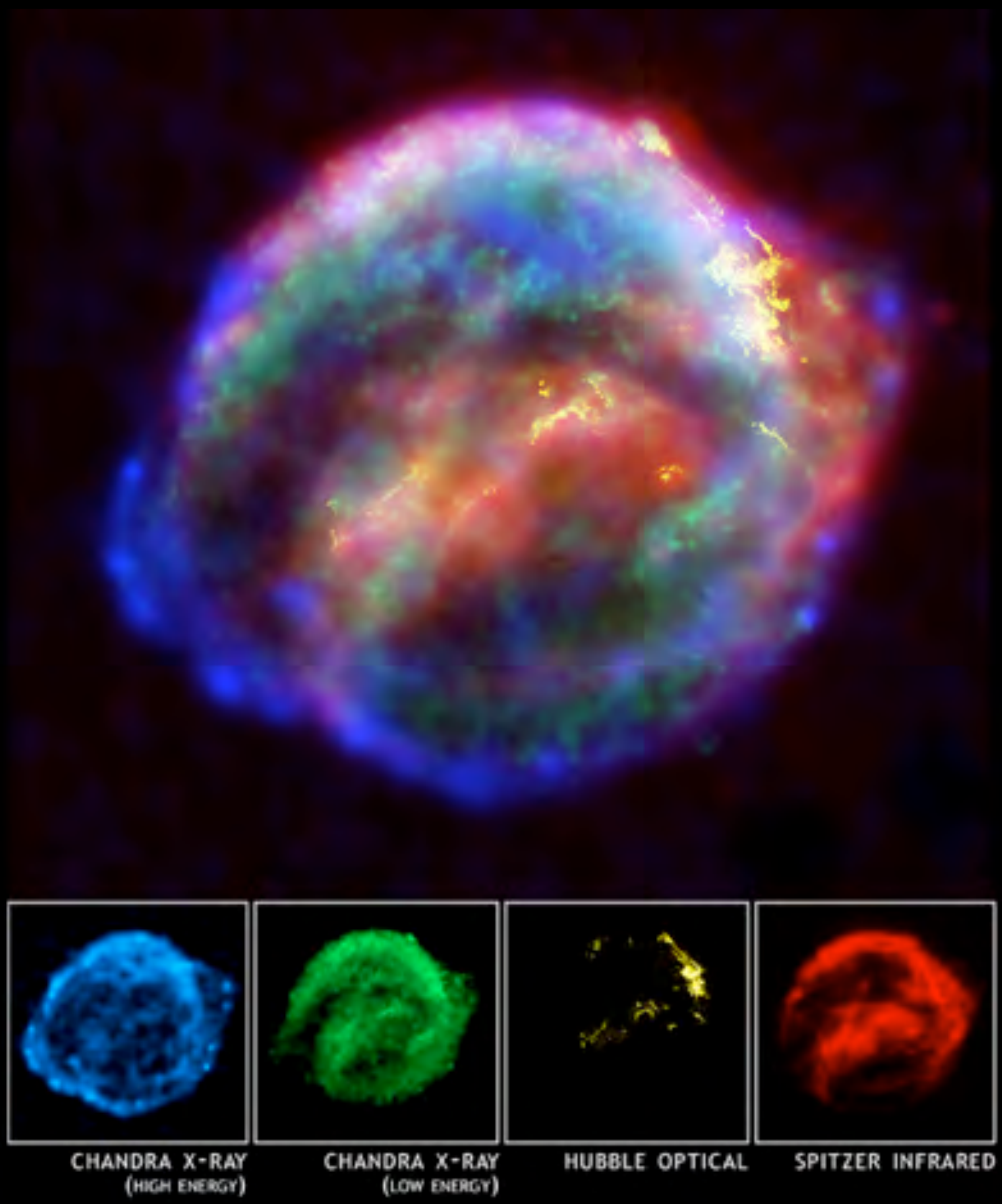


Quellen von Gammastrahlung - Doppelsternsysteme



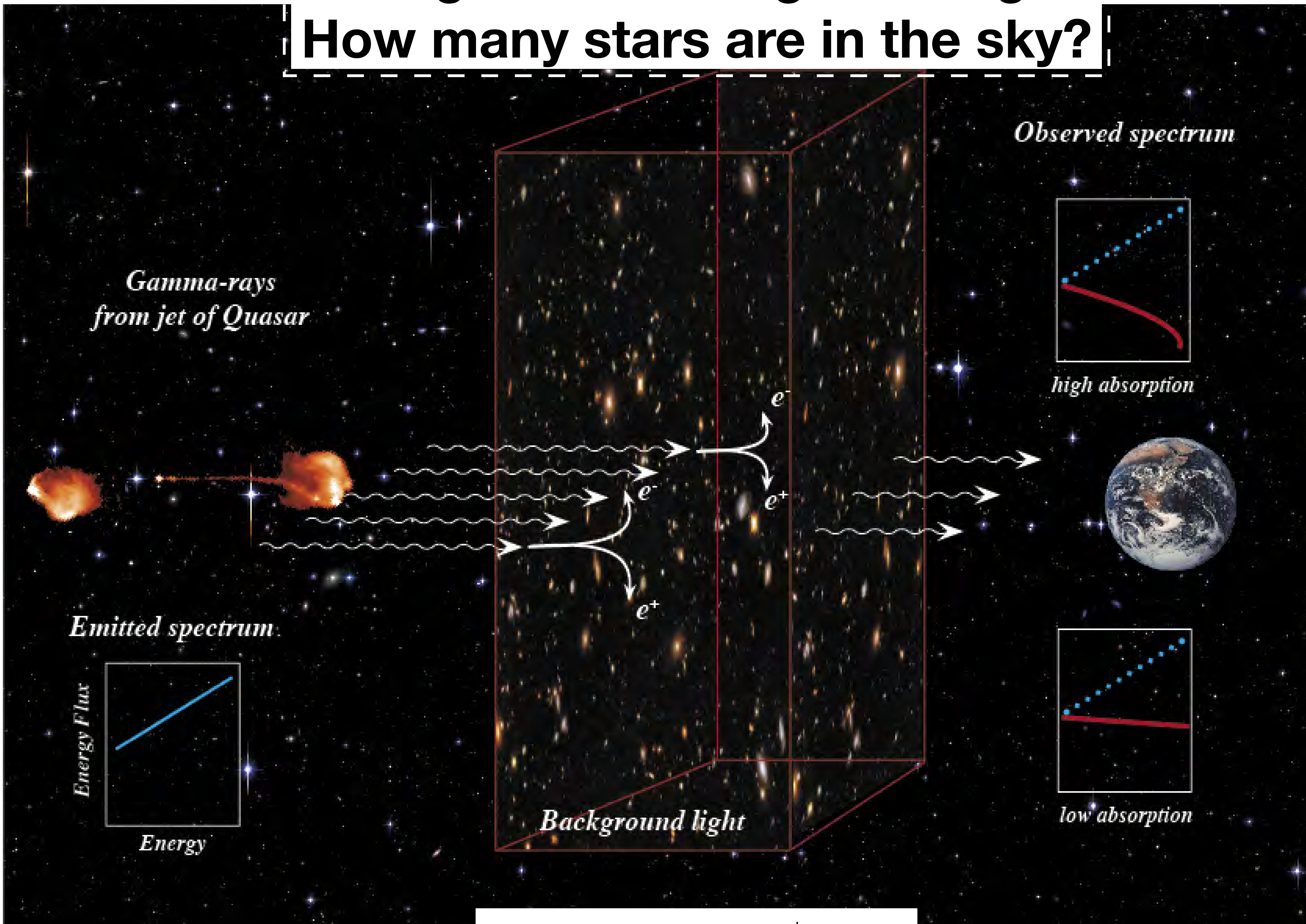
Charged Particle Acceleration - Shocks in the Universe

kitchen sink



Kepler's Supernova

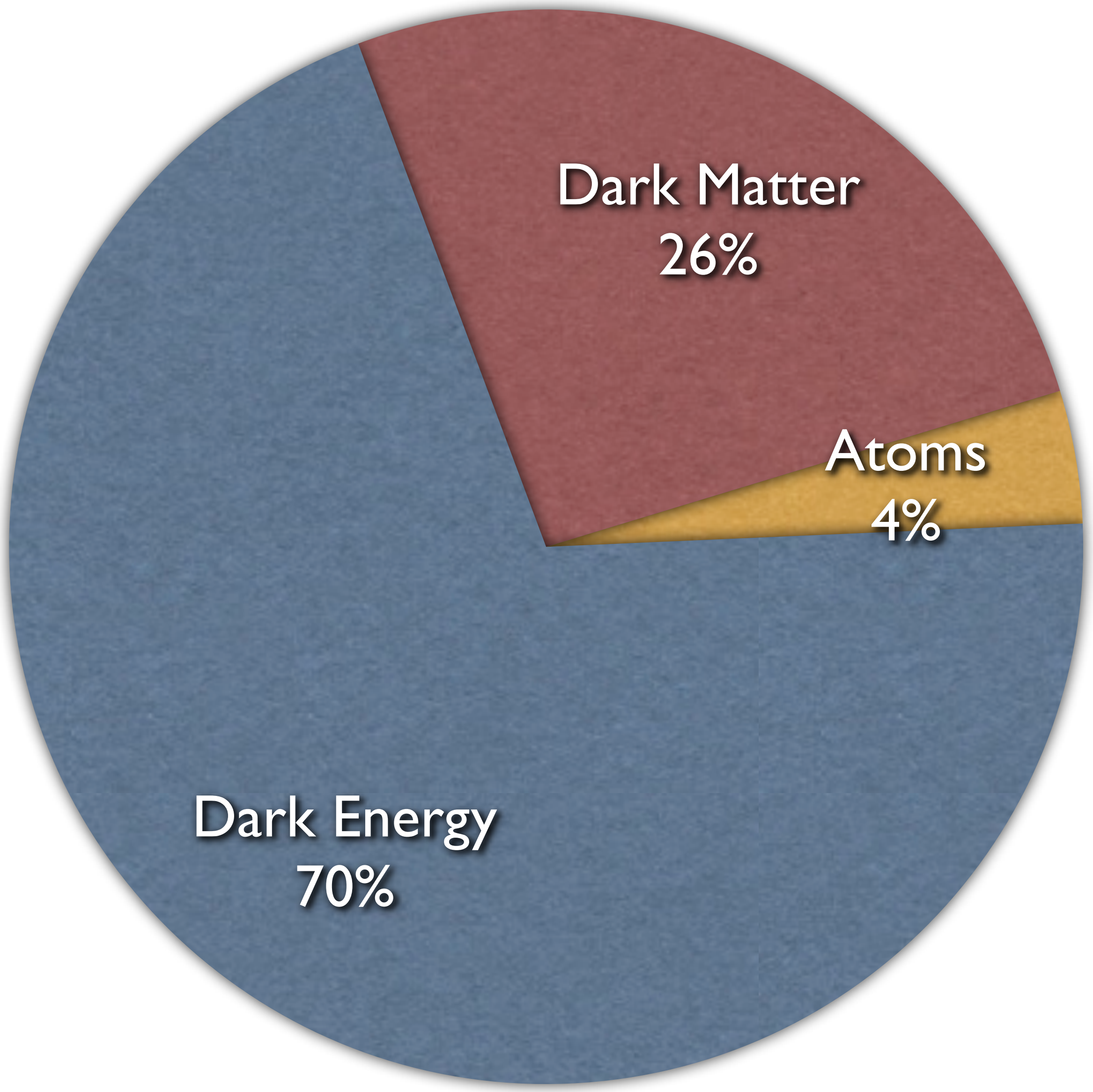
Extragalactic background light: How many stars are in the sky?

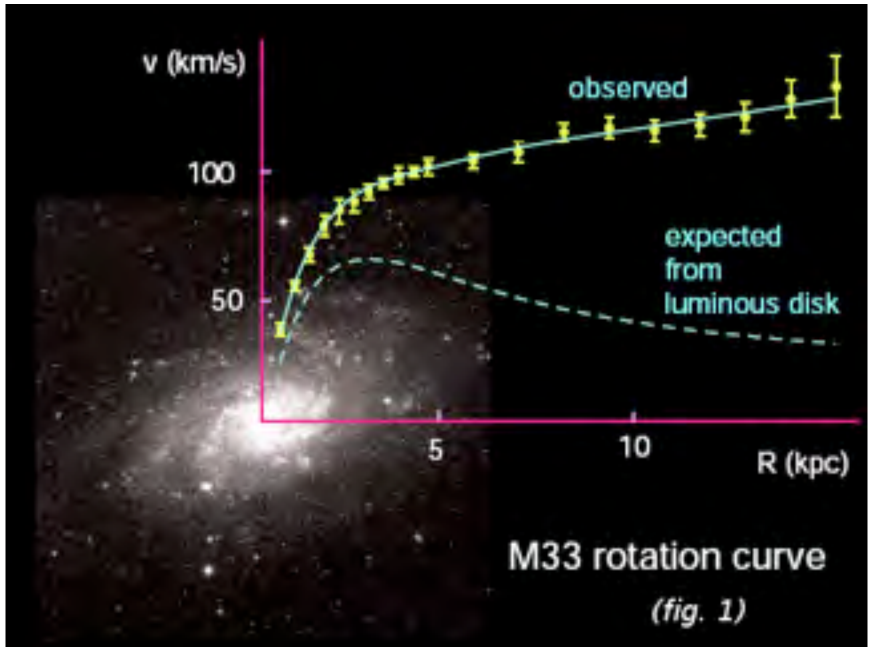


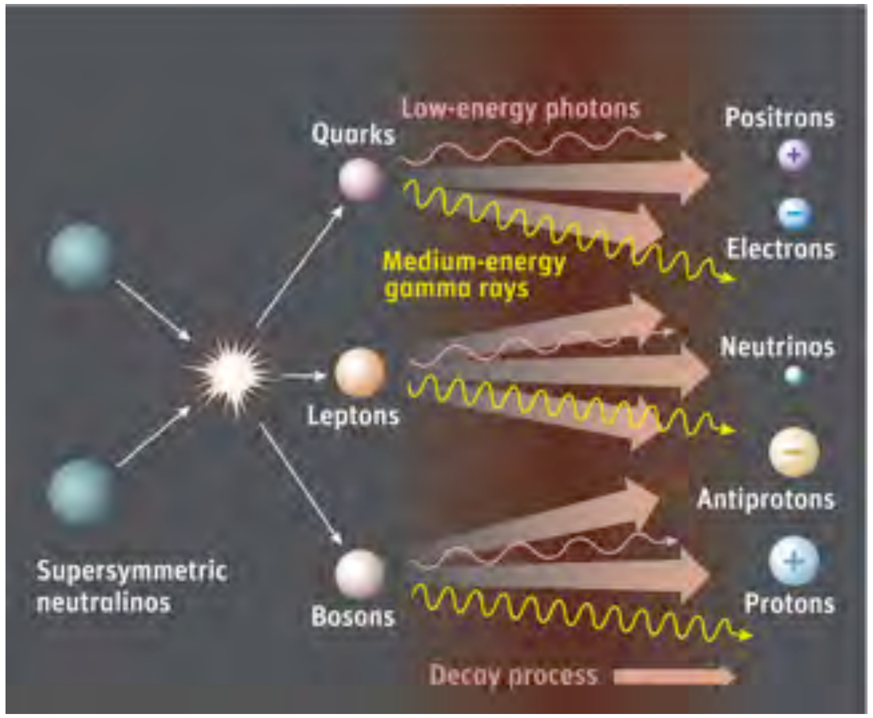
$\gamma_{\mathrm{TeV}} + \gamma_{\mathrm{star}} \rightarrow e^{+}e^{-}$

Dark Matter

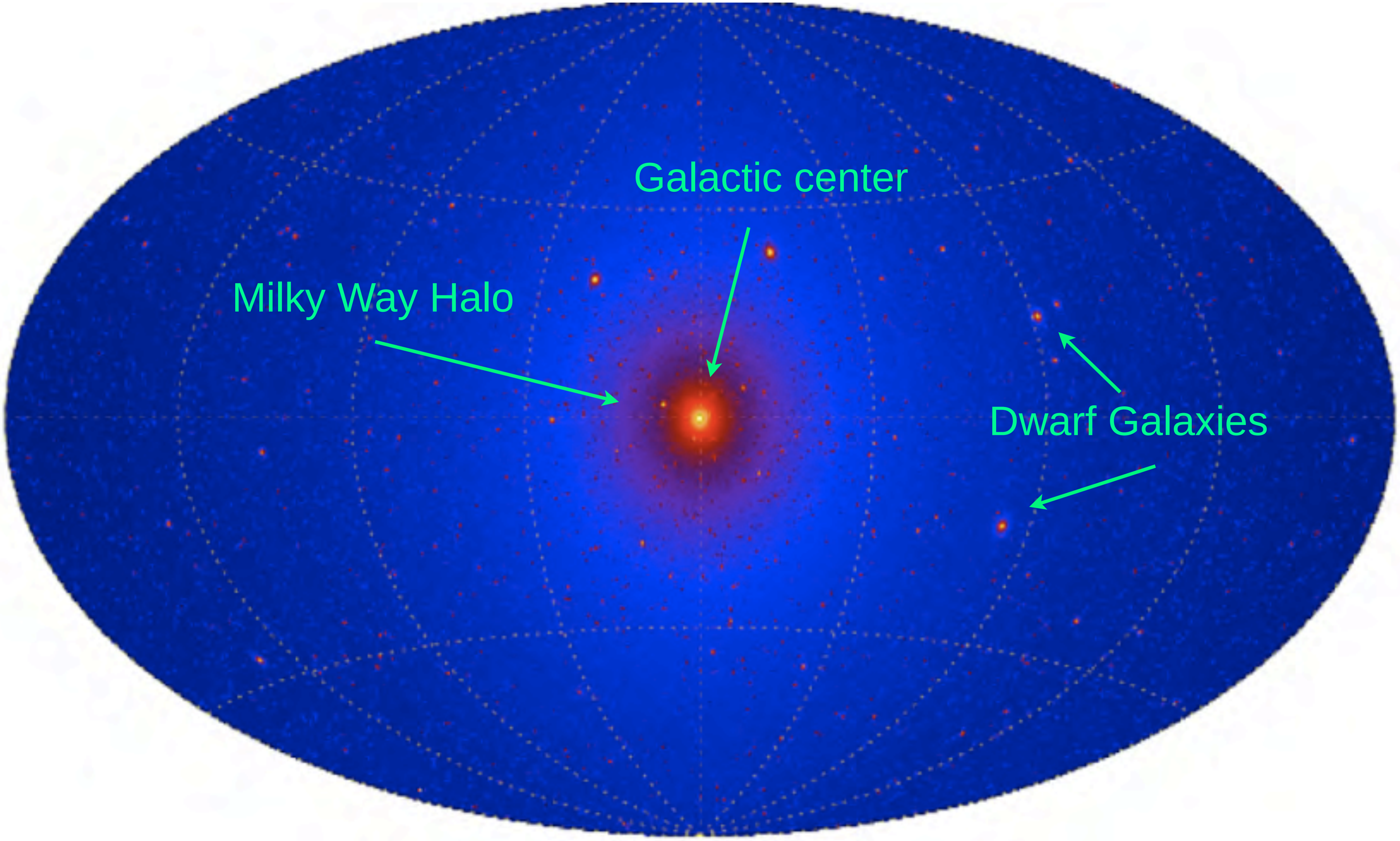
Wir kennen nur 4% unseres Universums...



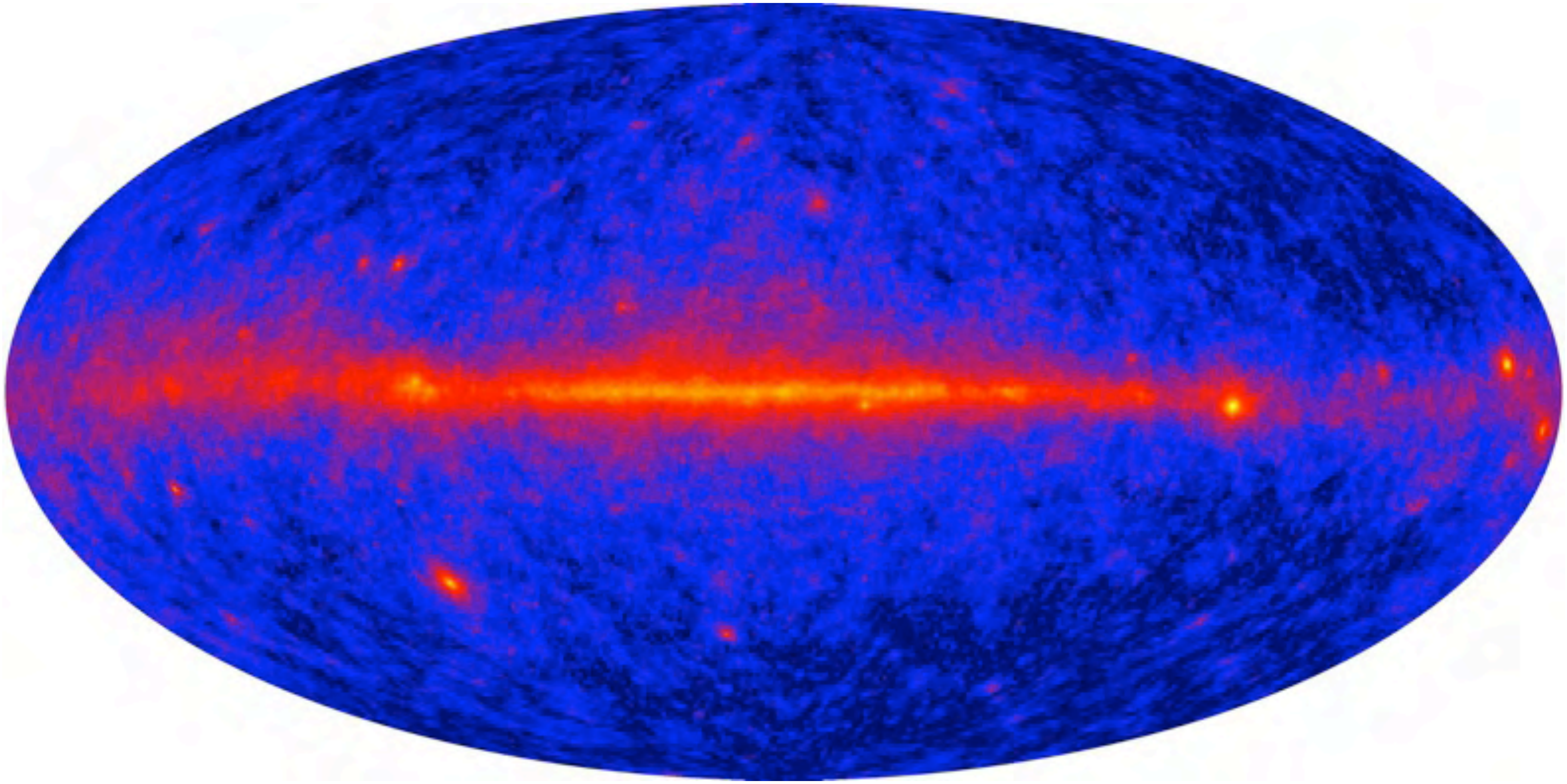




Dark Matter

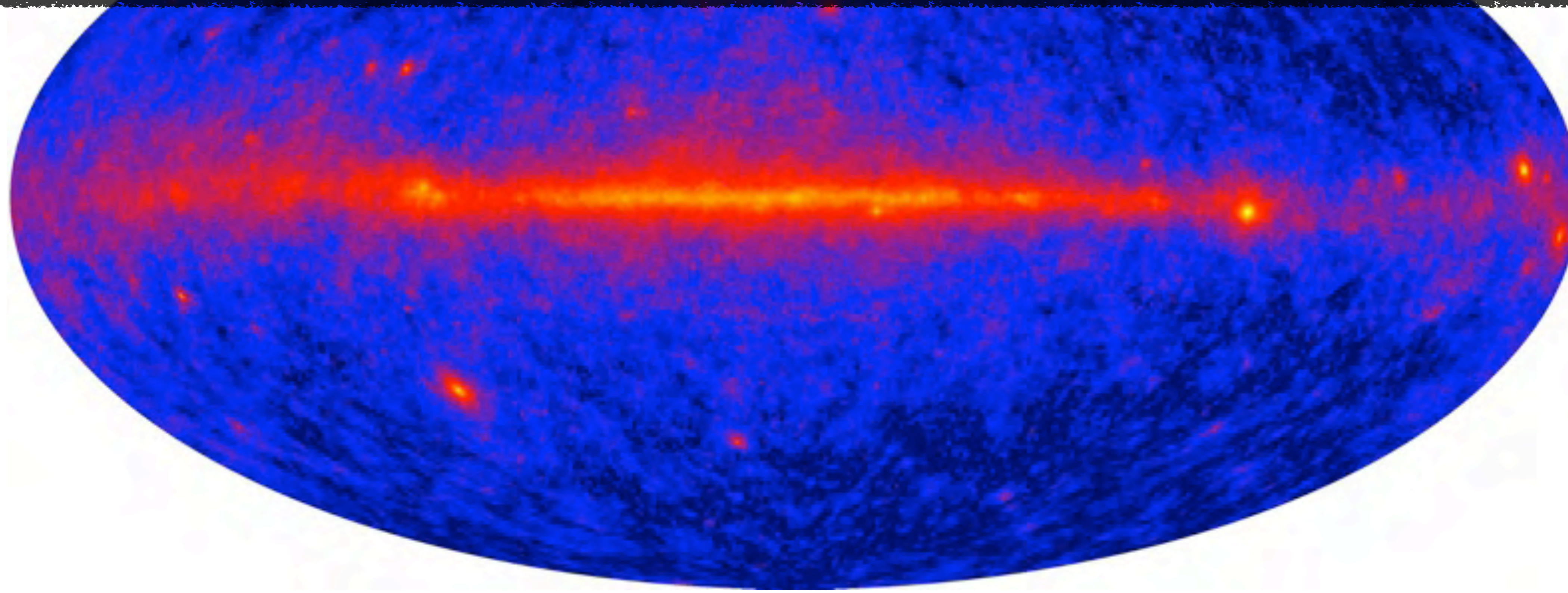


The non-thermal Universe - the big questions



The non-thermal Universe - the big questions

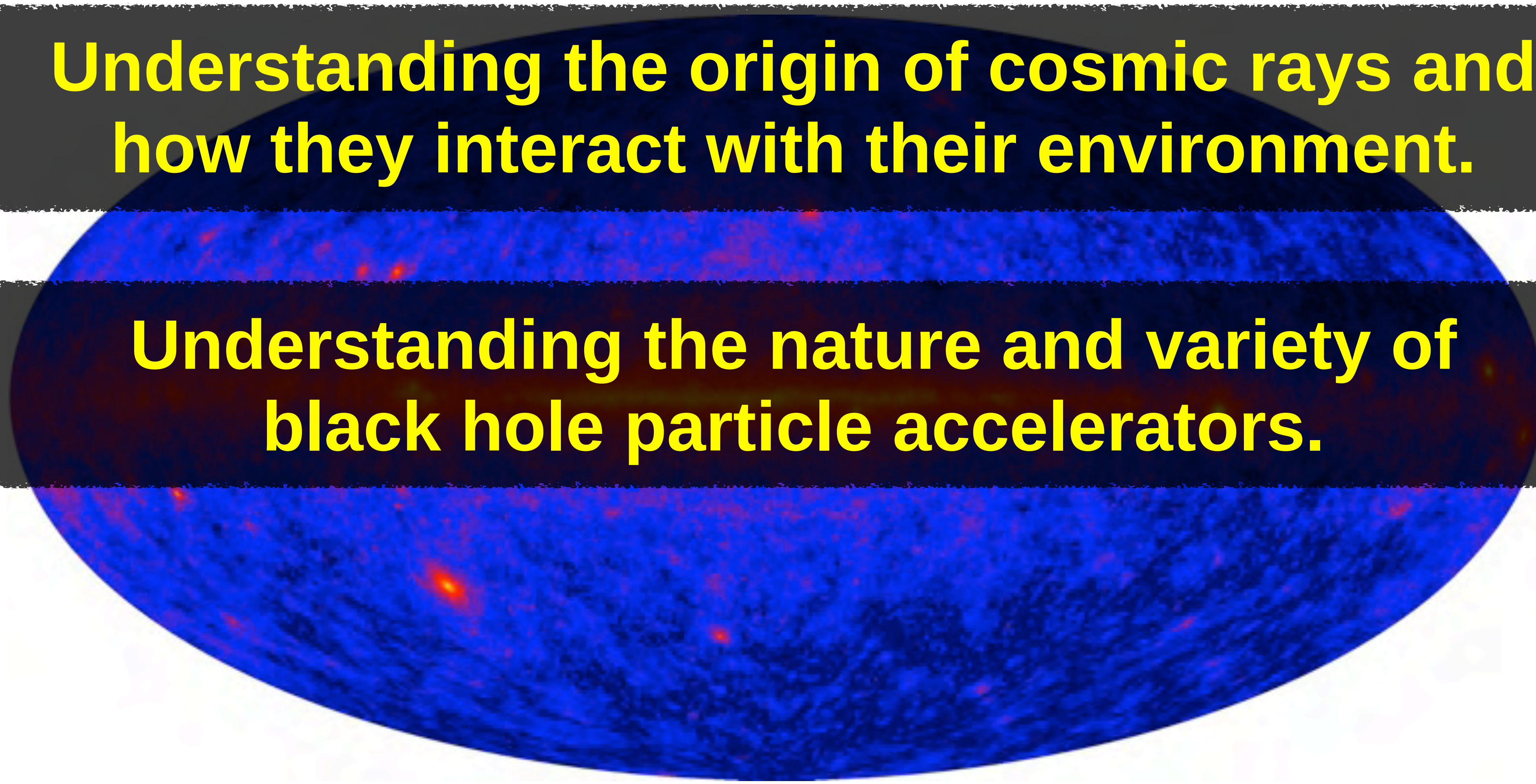
Understanding the origin of cosmic rays and how they interact with their environment.



The non-thermal Universe - the big questions

Understanding the origin of cosmic rays and how they interact with their environment.

Understanding the nature and variety of black hole particle accelerators.



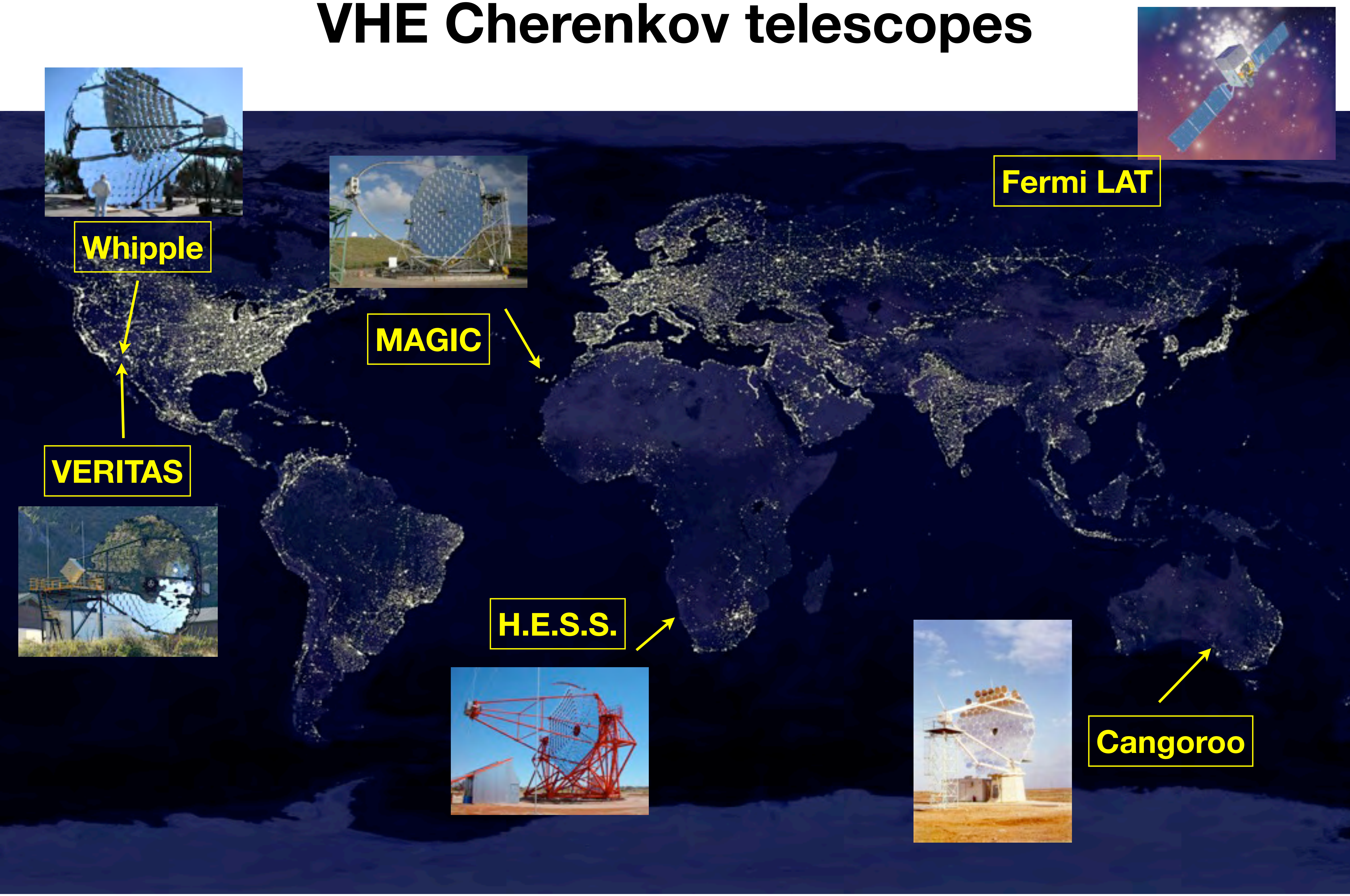
The non-thermal Universe - the big questions

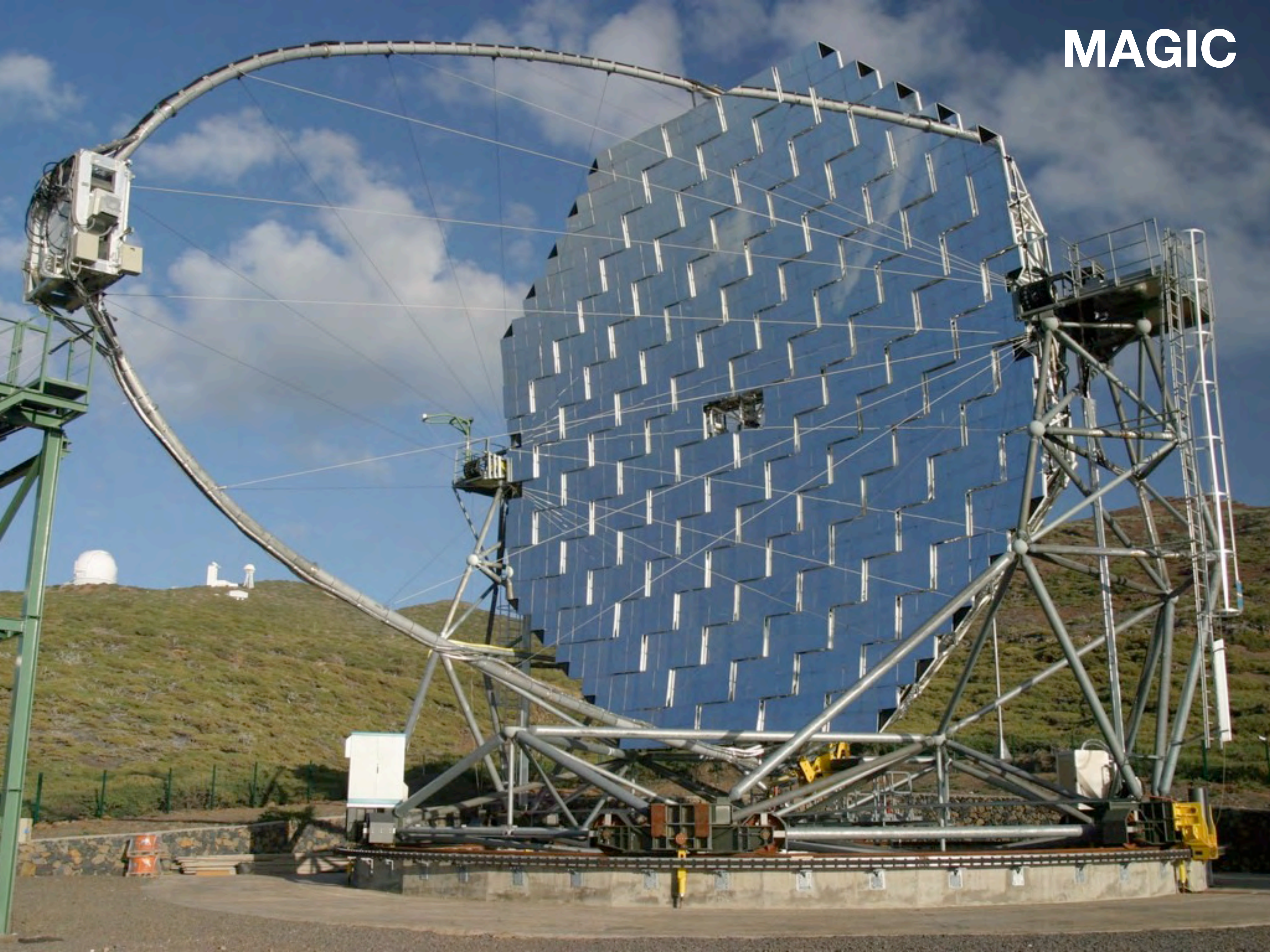
Understanding the origin of cosmic rays and how they interact with their environment.

Understanding the nature and variety of black hole particle accelerators.

What is the nature of dark-matter particles?

VHE Cherenkov telescopes




MAGIC

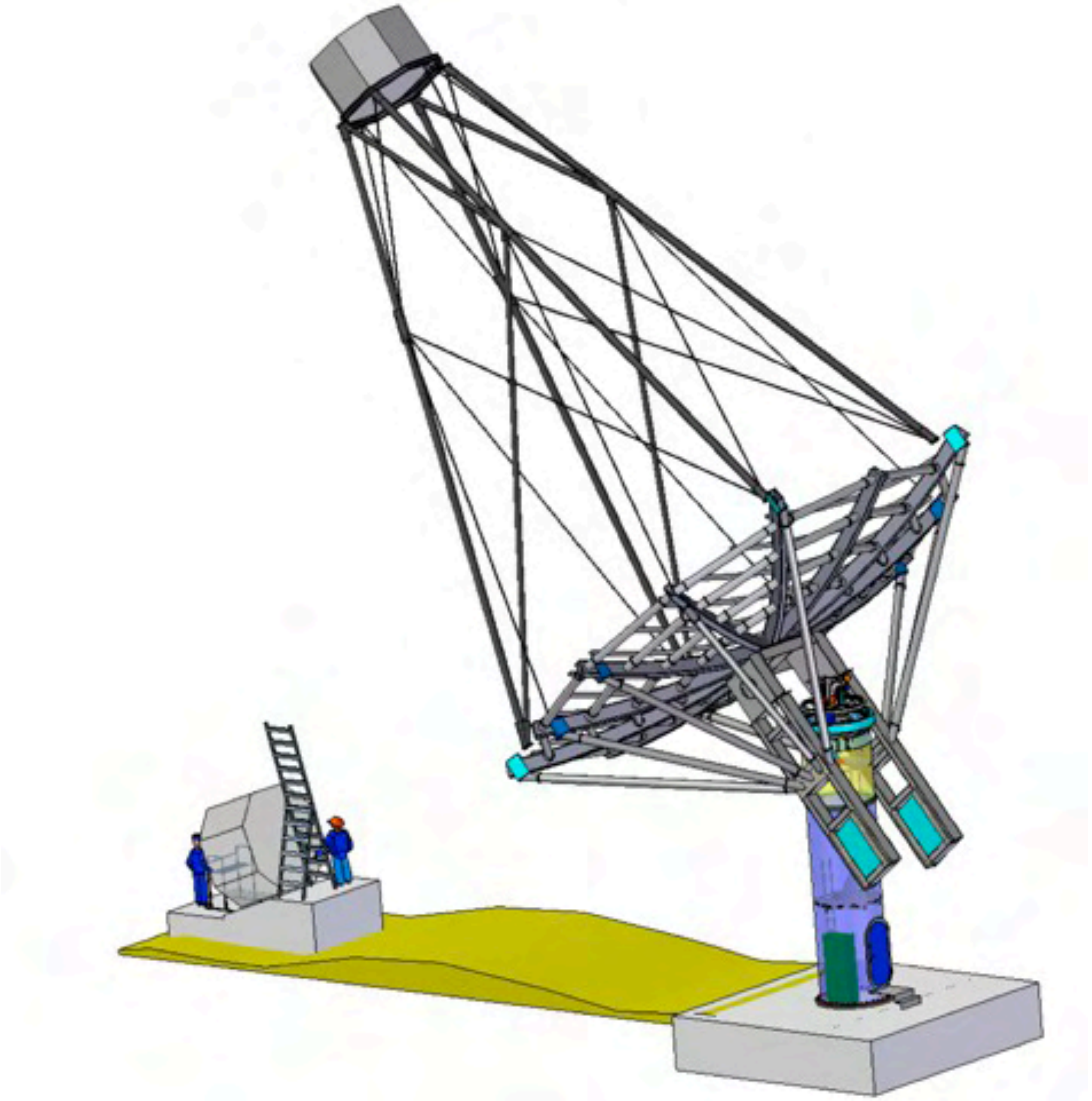

VERITAS
VERITAS


H.E.S.S.

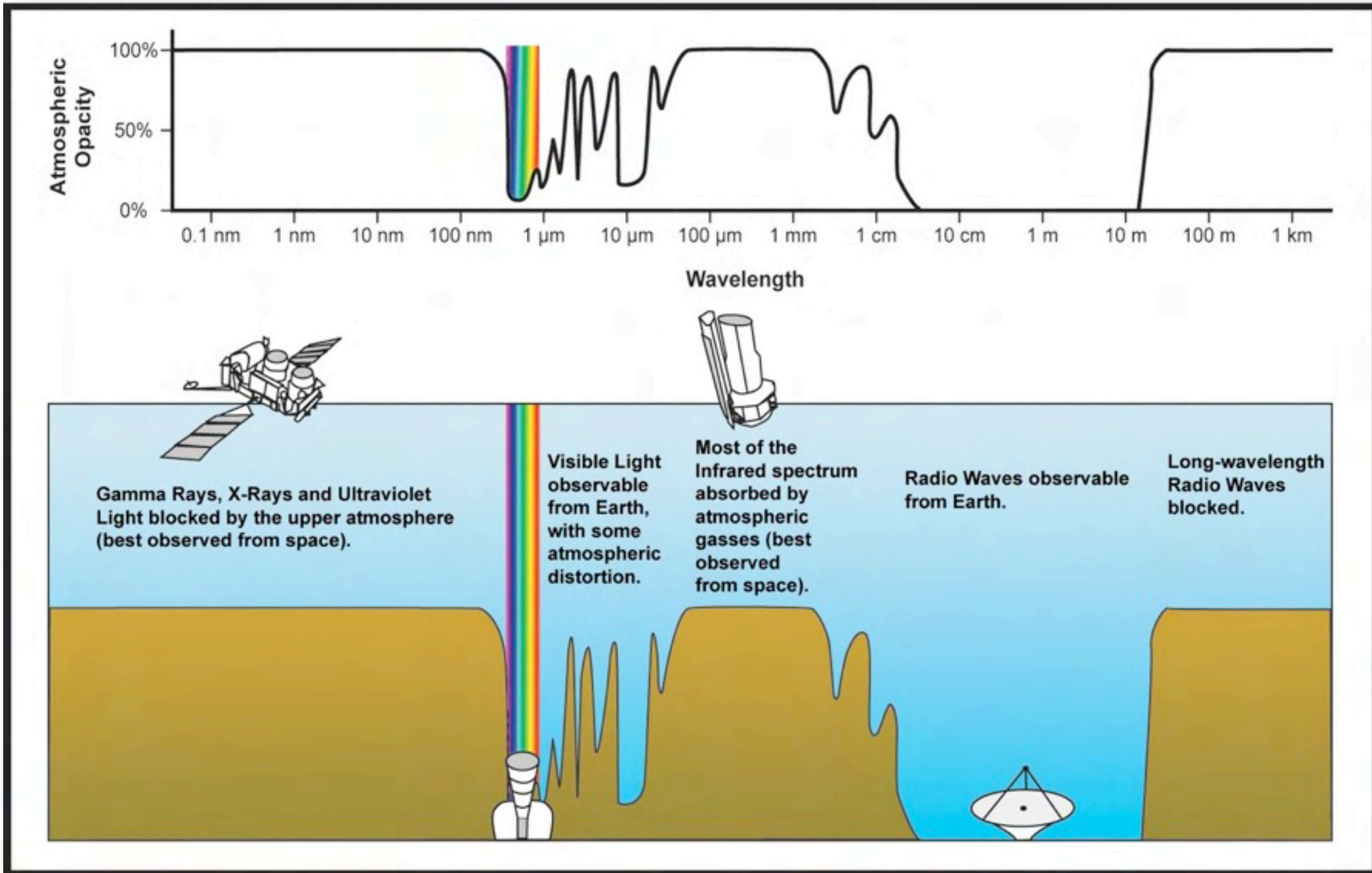
October 1968

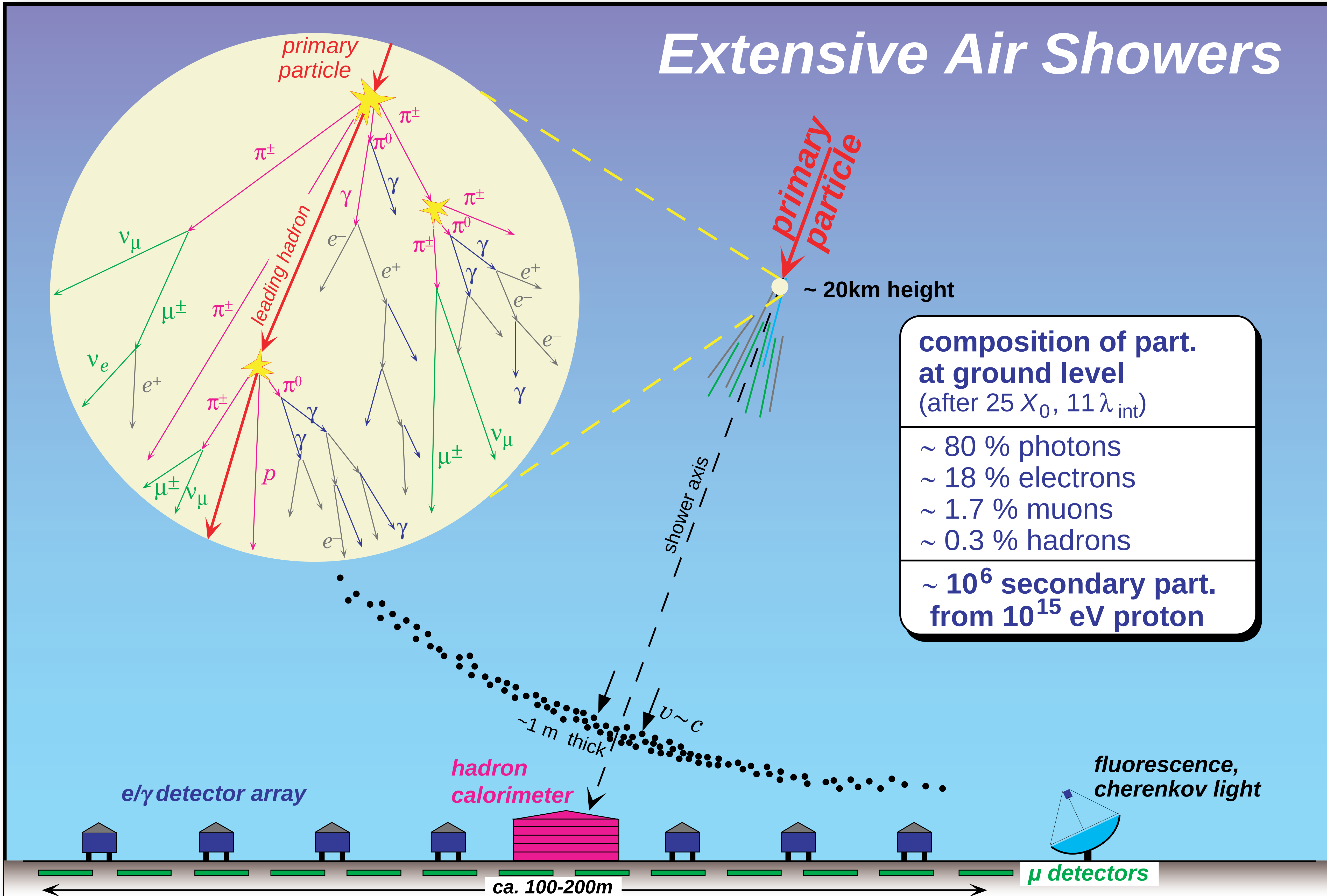
First detection: 1989

A CTA telescope



Atmospheric Opacity



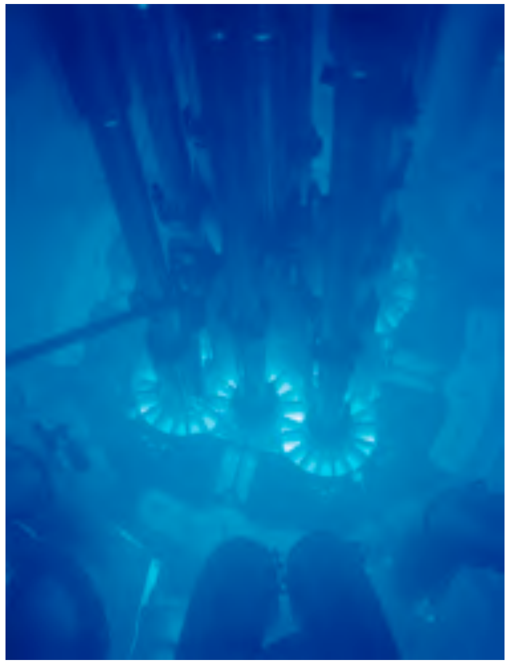


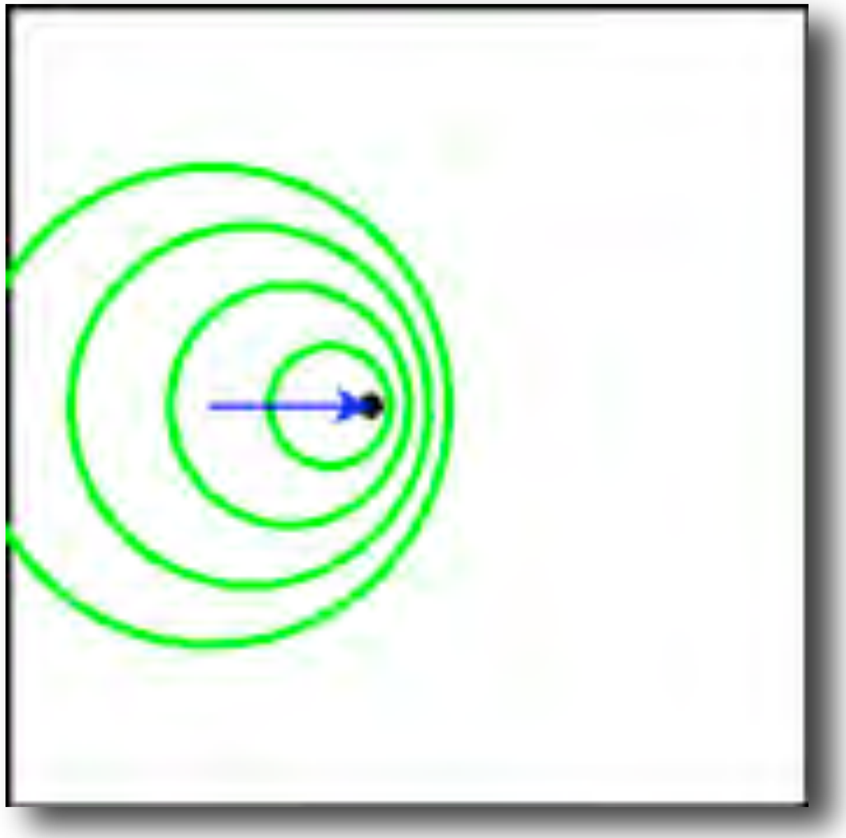
Extensive Air Showers
primary particle
leading hadron
π±
π0
γ
e−
e+
μ±
νμ
νe
p
primary particle
~ 20km height
shower axis
composition of part. at ground level
(after 25 X_0, 11 λ_{int})
~ 80 % photons
~ 18 % electrons
~ 1.7 % muons
~ 0.3 % hadrons
~ 10^6 secondary part. from 10^{15} eV proton
~1 m thick
$v \sim c$
hadron calorimeter
e/γ detector array
fluorescence, cherenkov light
μ detectors
ca. 100-200m

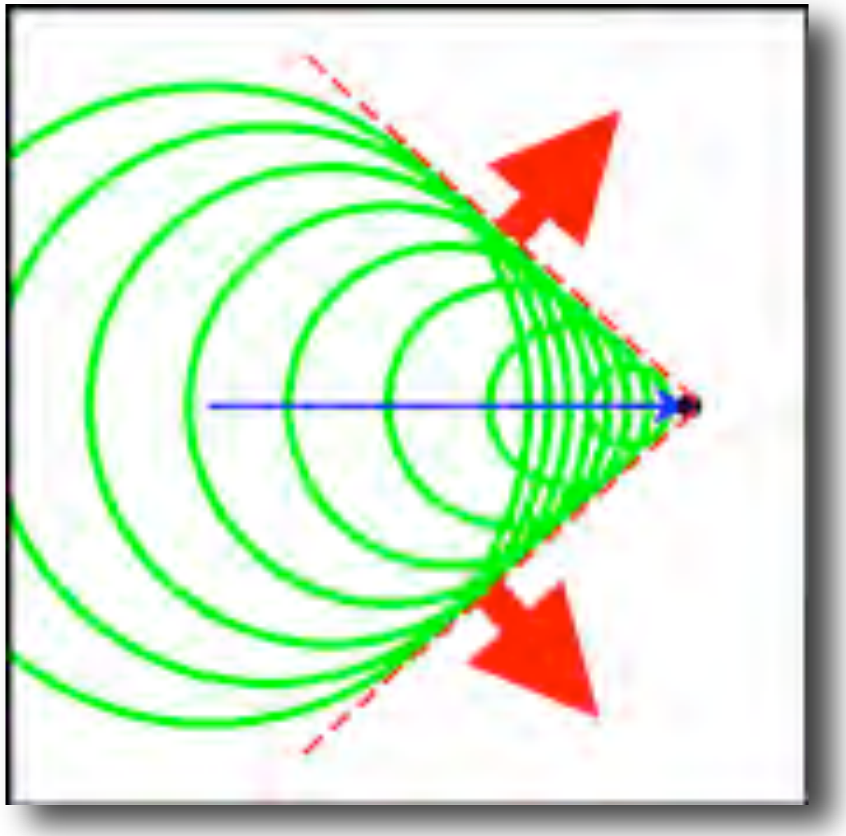
Cherenkov light

emitted when velocity of charged particle exceeds local speed of light

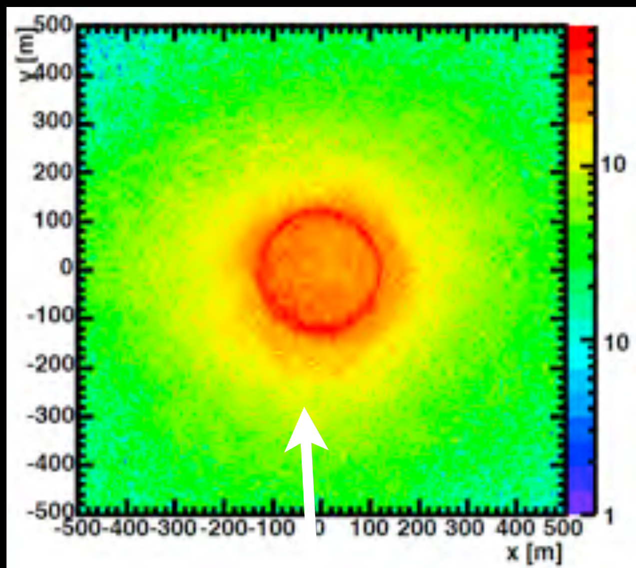
Pavel Alekseyevich Cherenkov
(Nobel 1958)

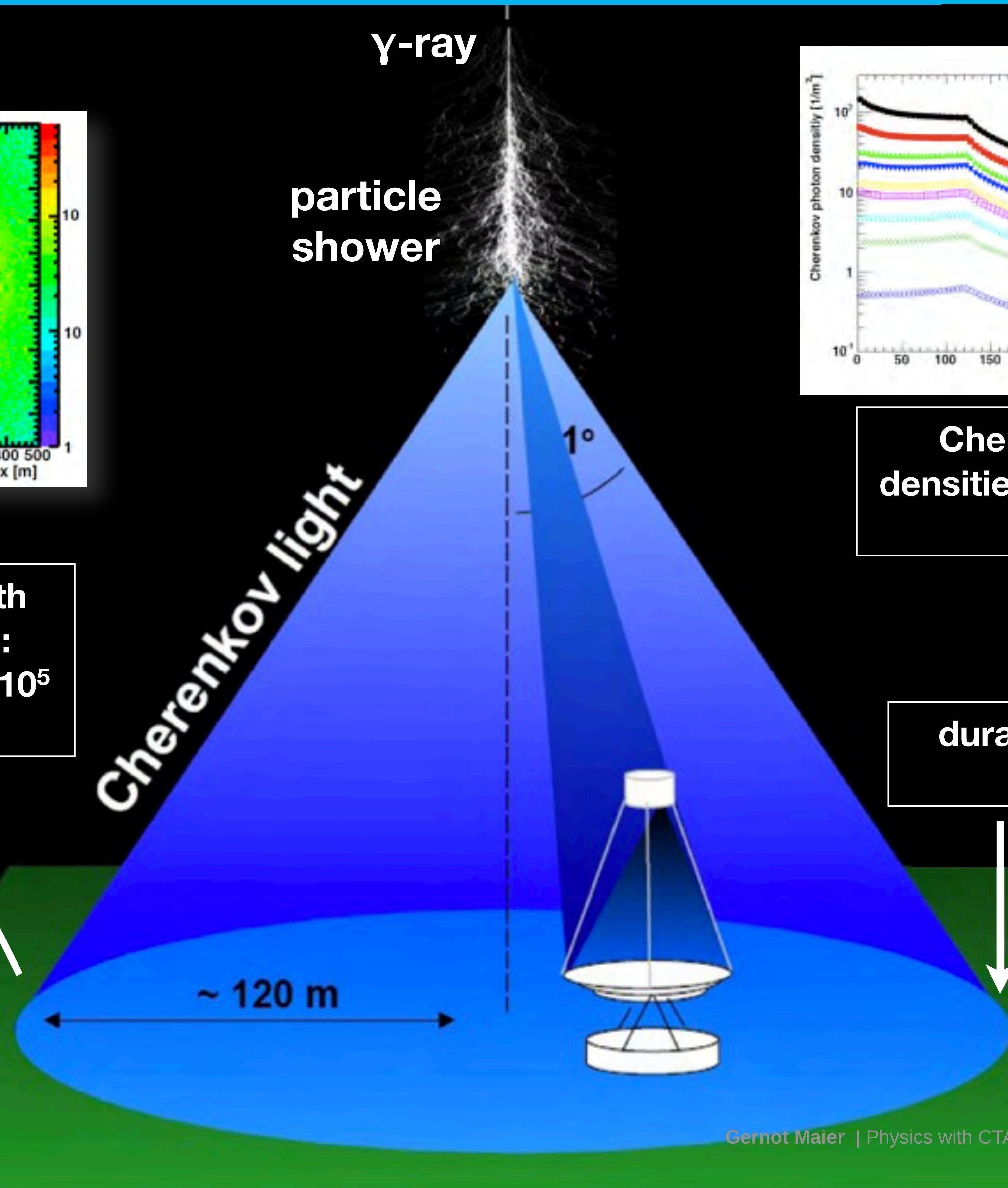


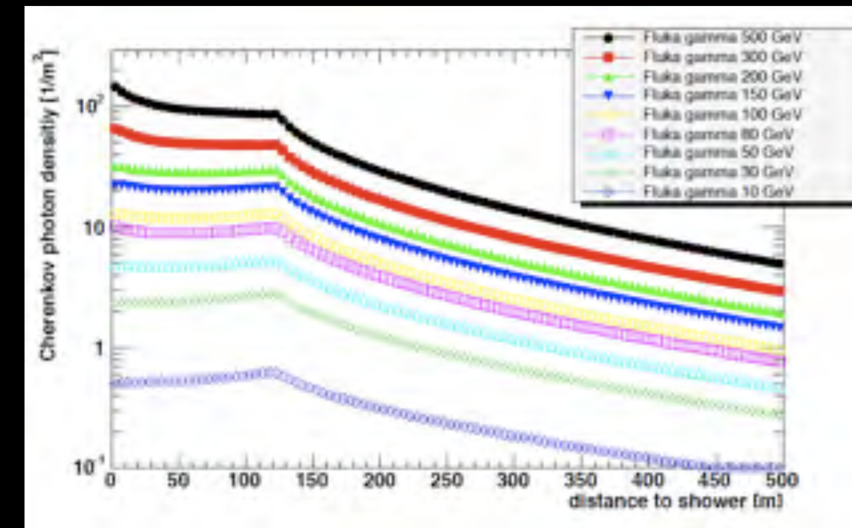




Detection of high-energy γ-rays







Cherenkov photon densities on ground level: 1-10^5 γ/m^2

'flat' light pool with radius of ~120 m: detection areas of 10^5 to 10^6 m^2

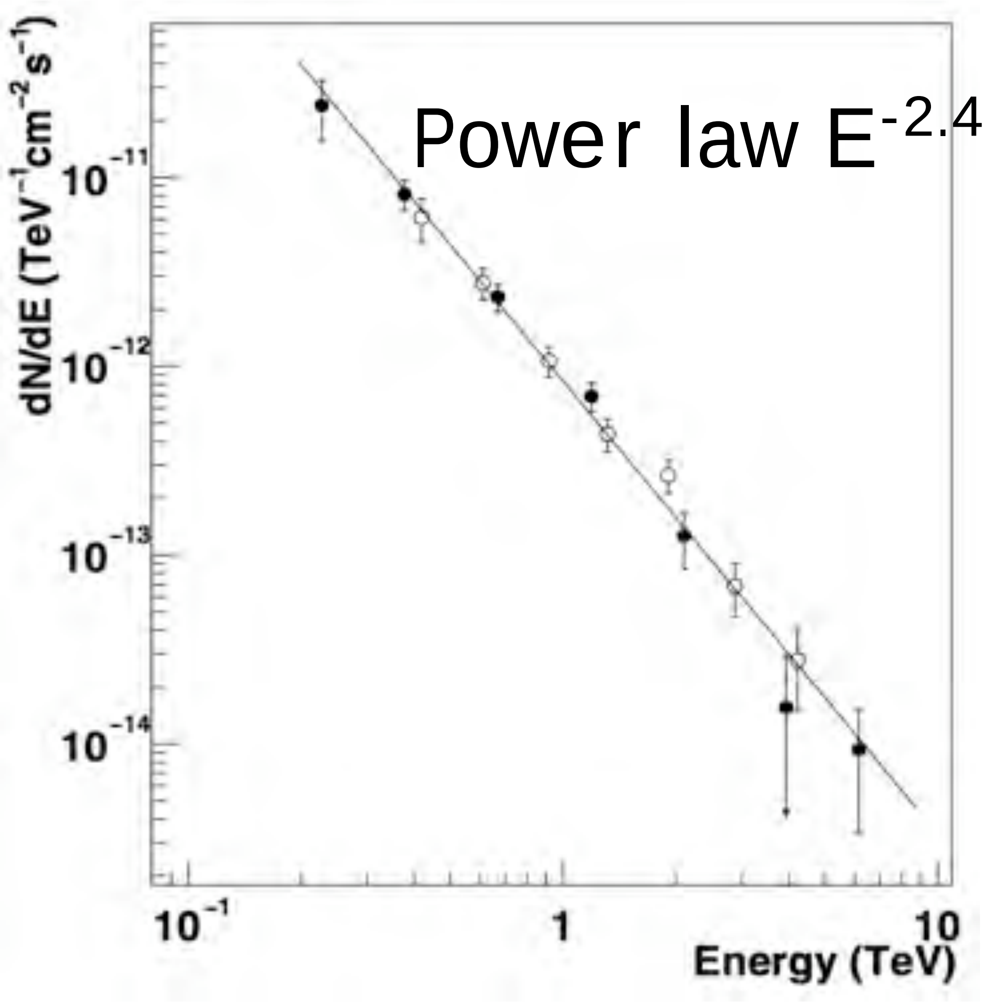
duration of Cherenkov flash: ~ns

Fluxes

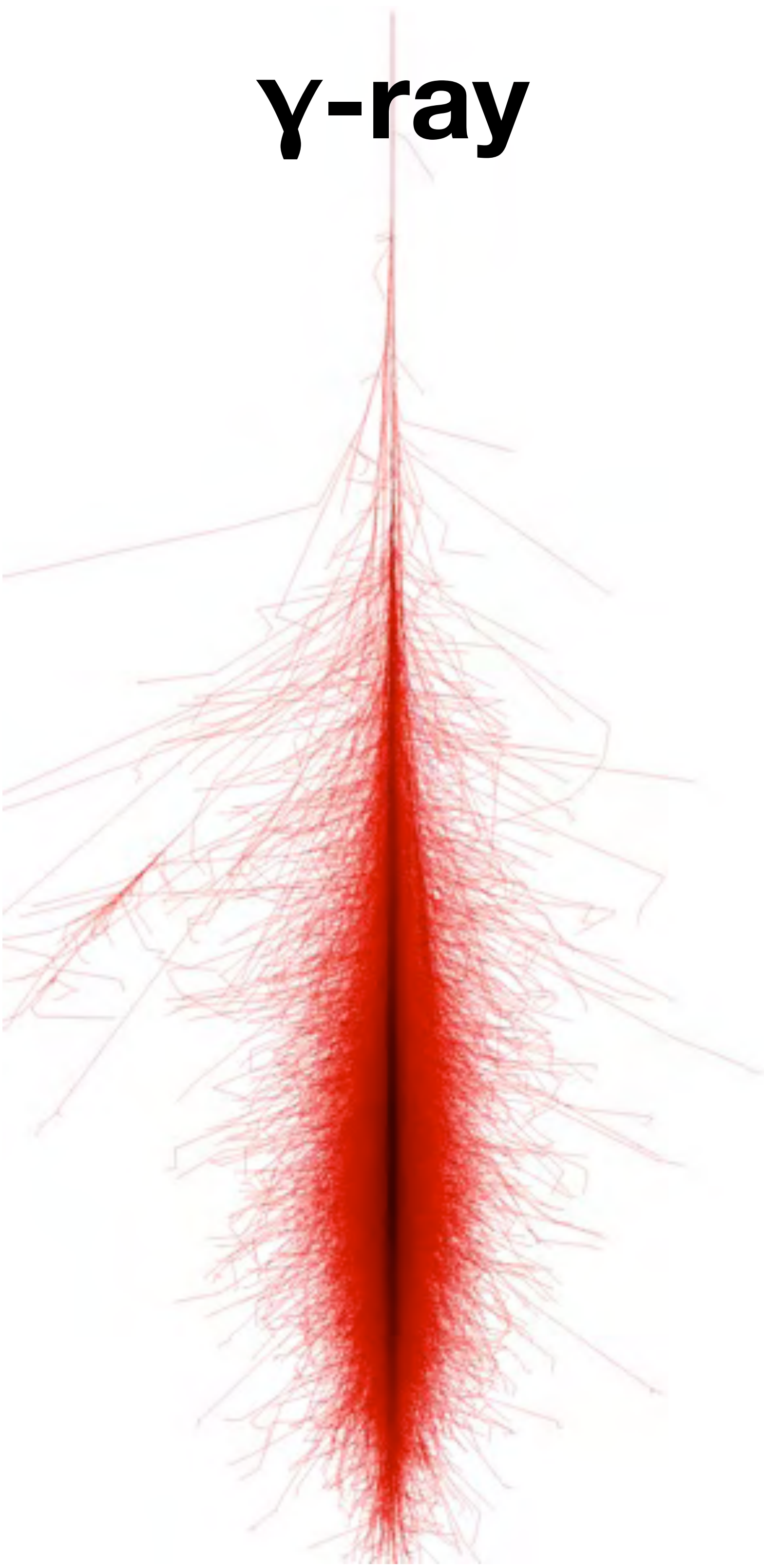
> flux of strongest γ-ray source (Crab Nebula): ~10^{-7} γ's/m^2/s

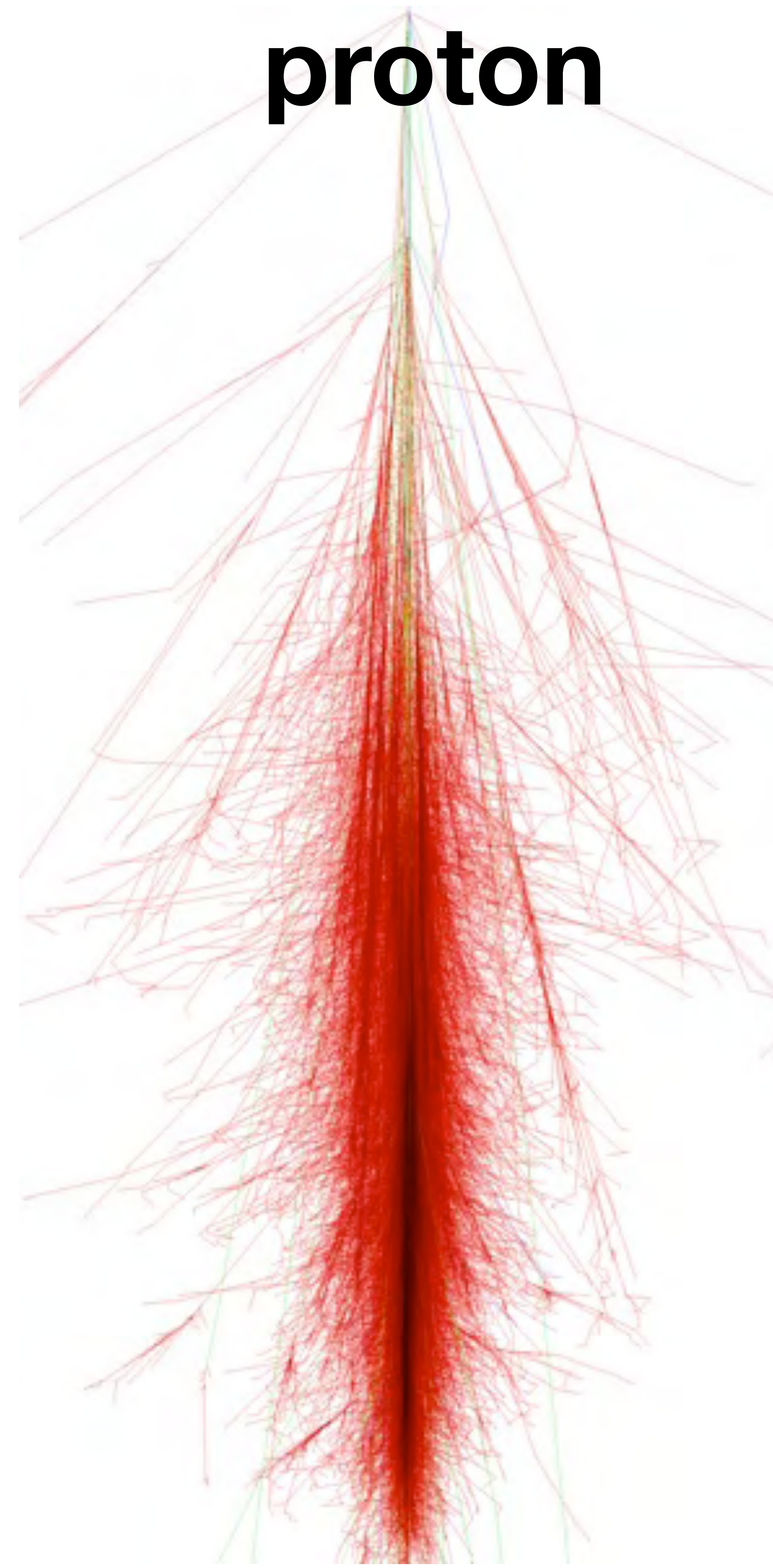
> satellite with detection area of 1-5 m^2: ~15 γ's / year

> imaging atmospheric Cherenkov telescopes:
> detection area >10^5 m^2: 50 γ's/h



Background

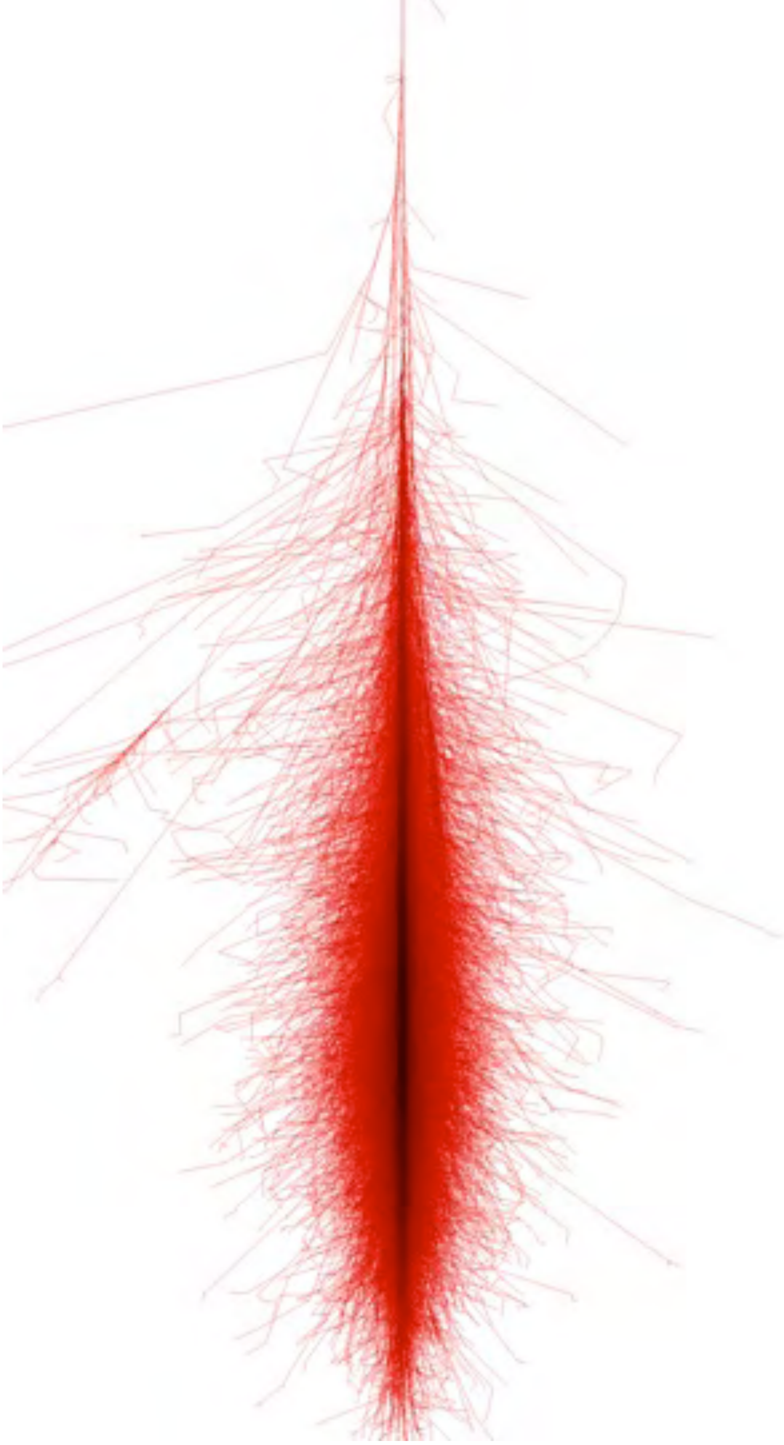




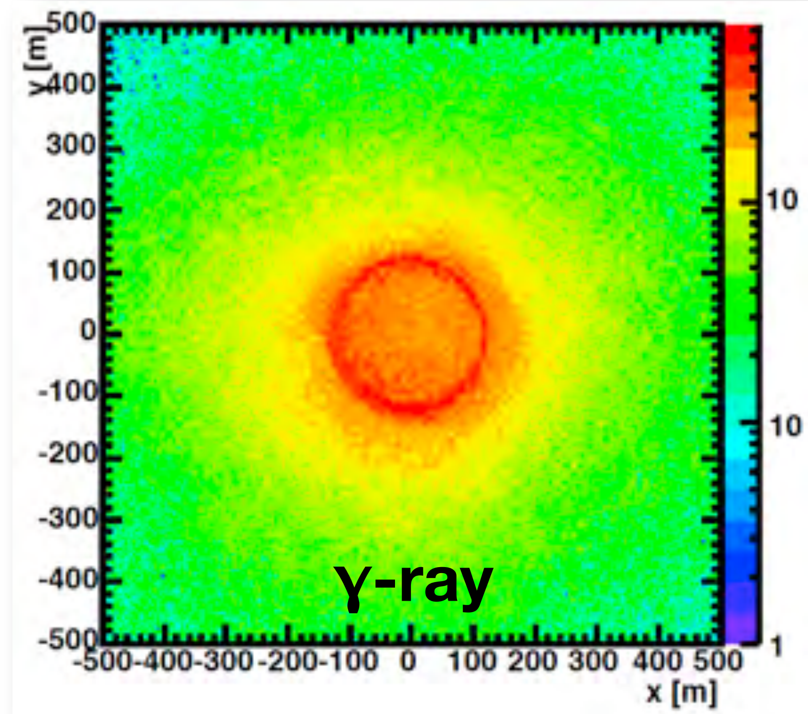
Cosmic Ray flux typically 10^3-10^4 larger than γ-ray flux

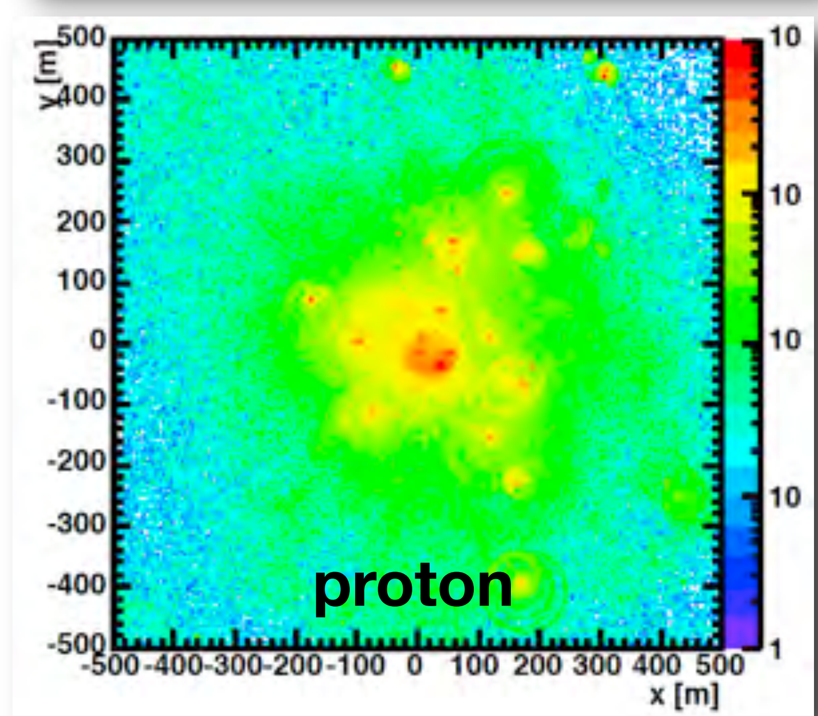
Background

γ-ray

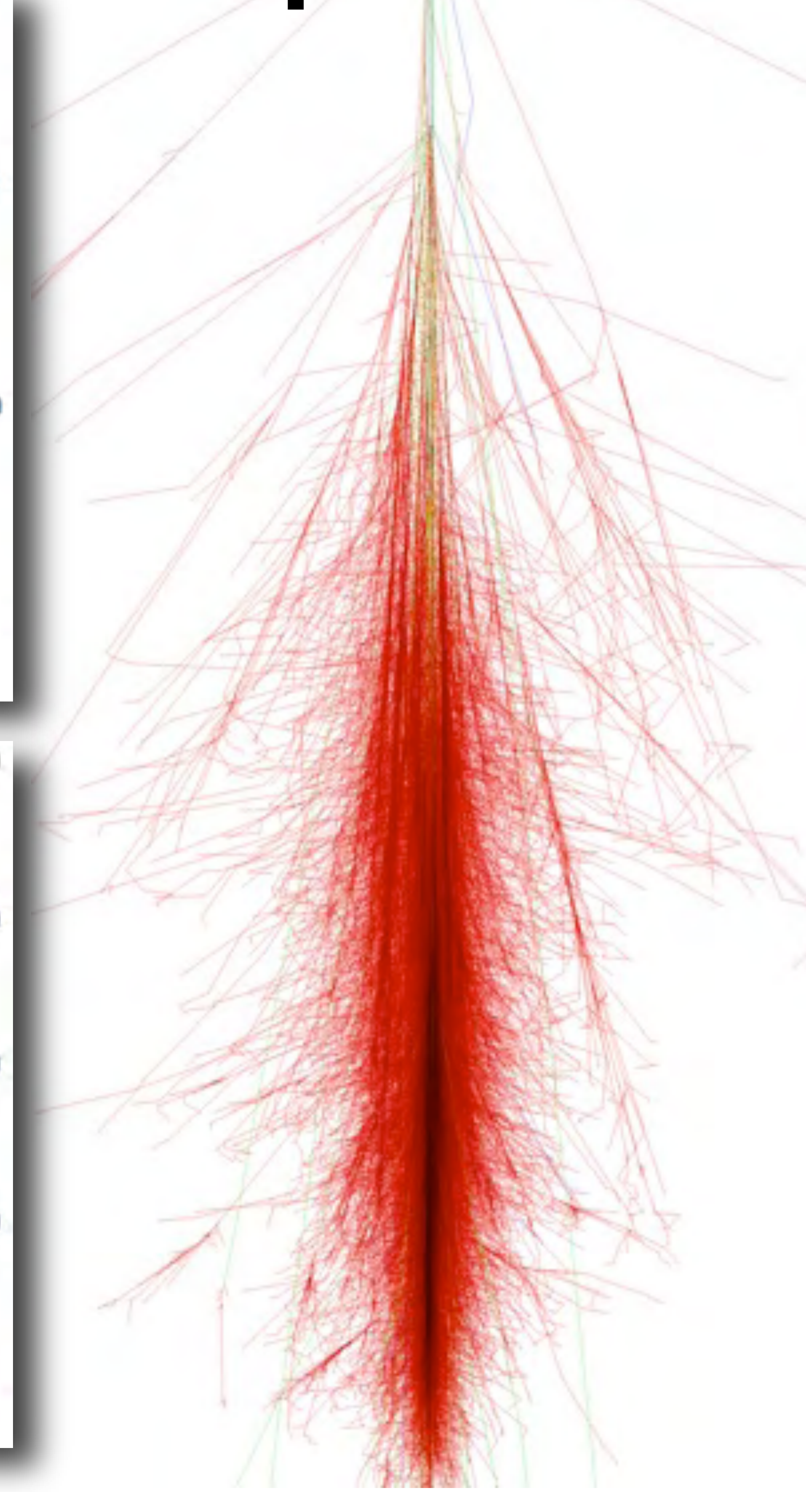


Cherenkov photons on ground

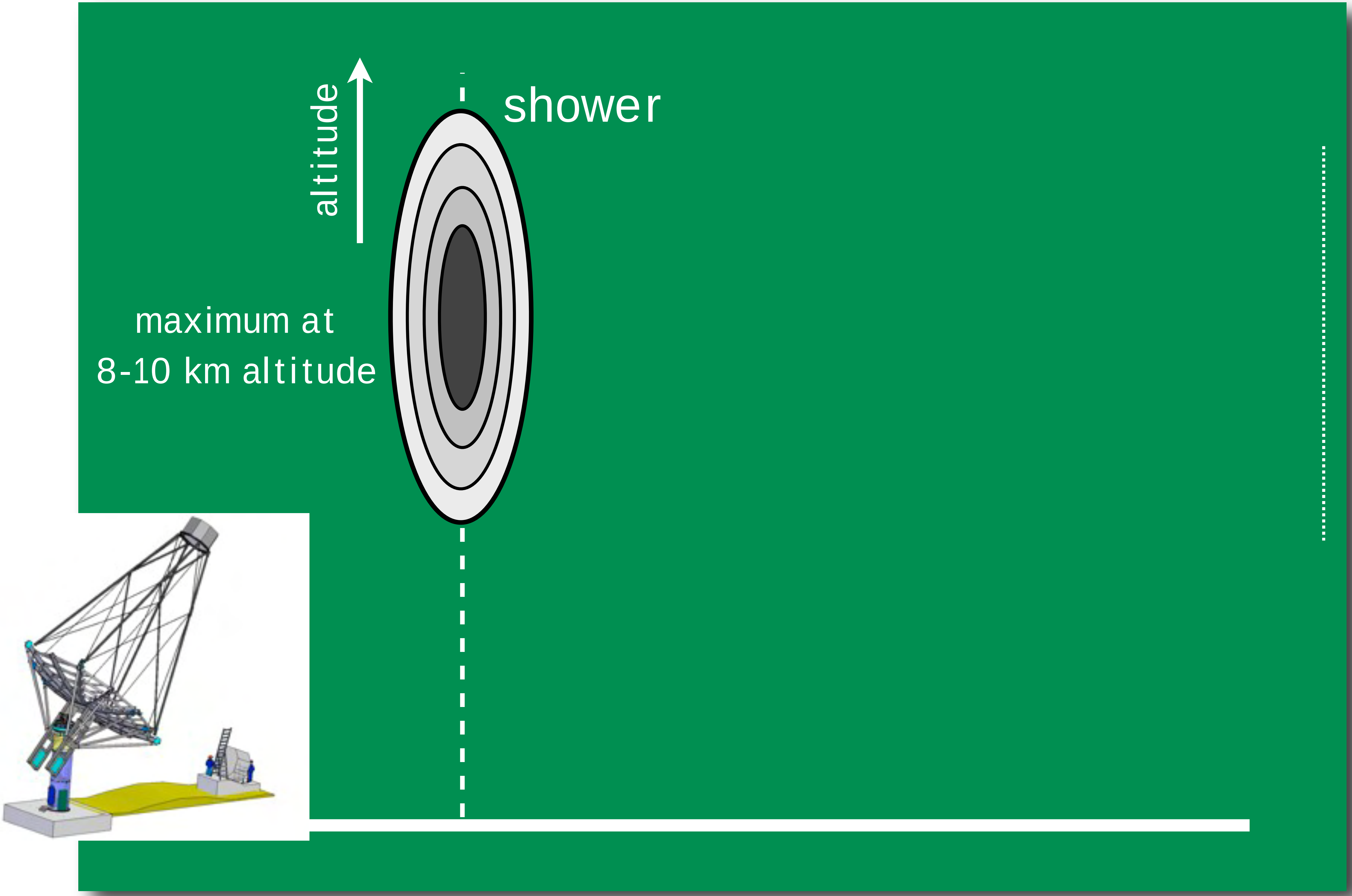




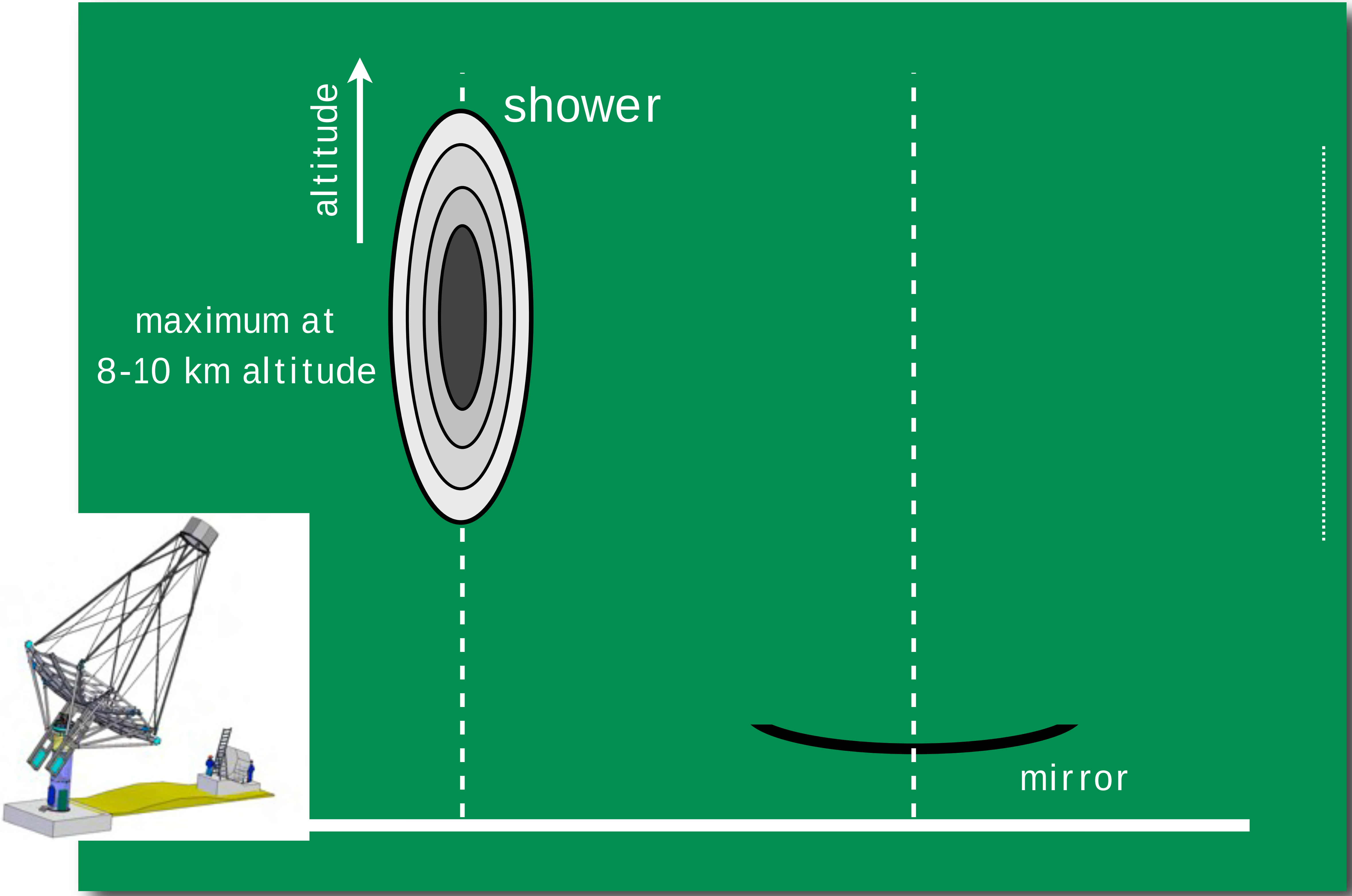
proton



Cosmic Ray flux typically 10^3-10^4 larger than γ-ray flux



Cherenkov flash is a few nanoseconds long



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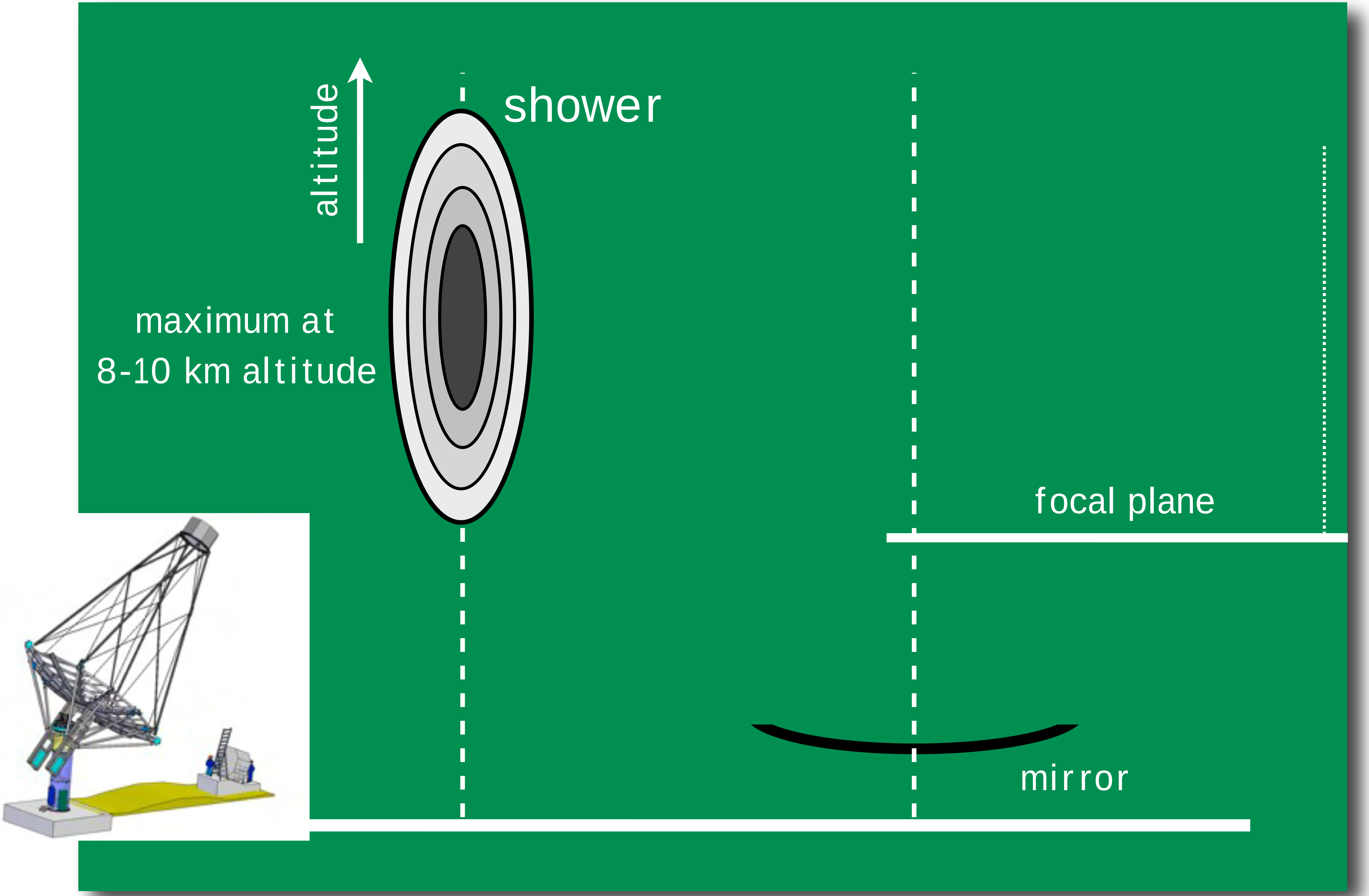

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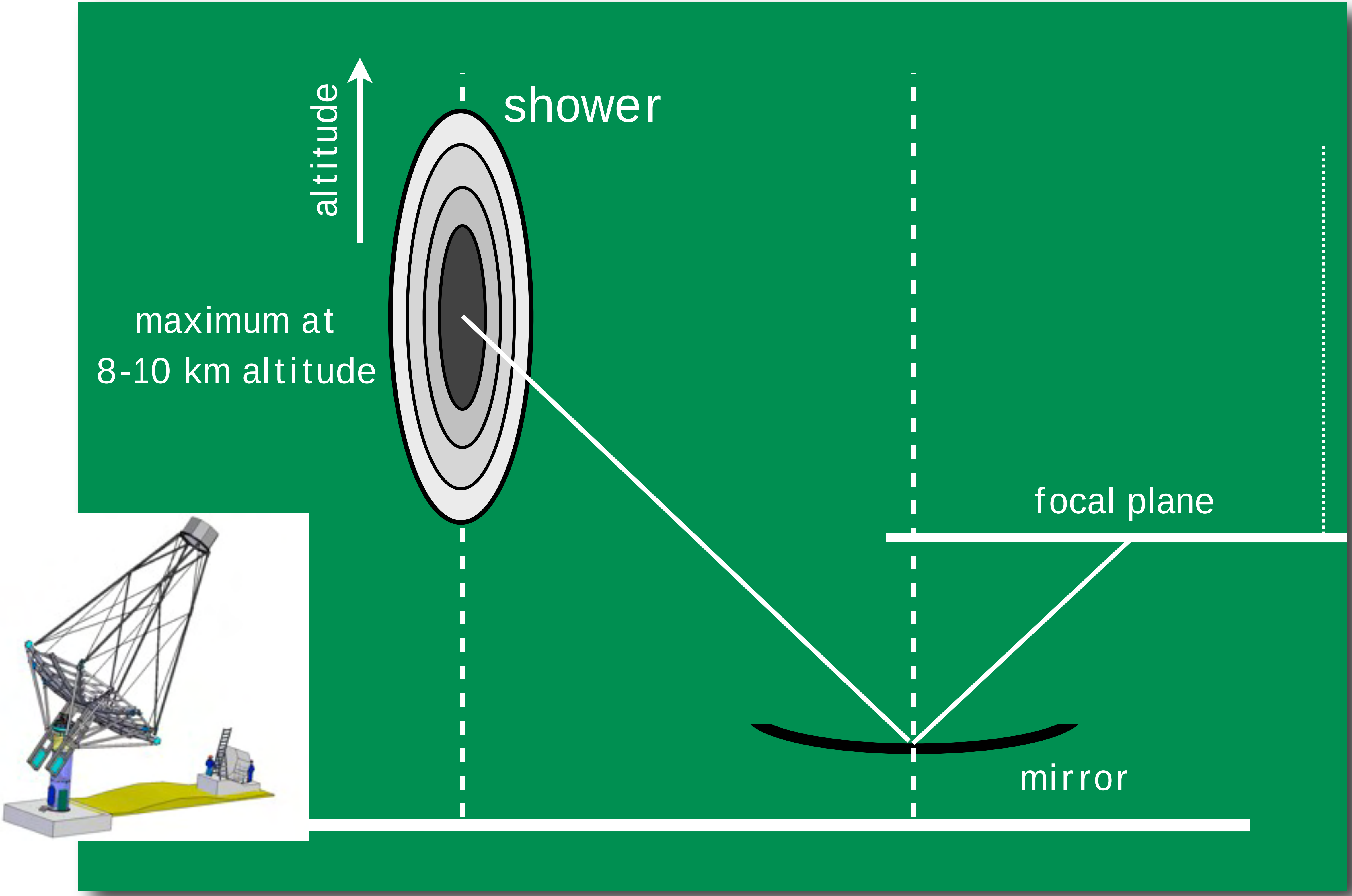

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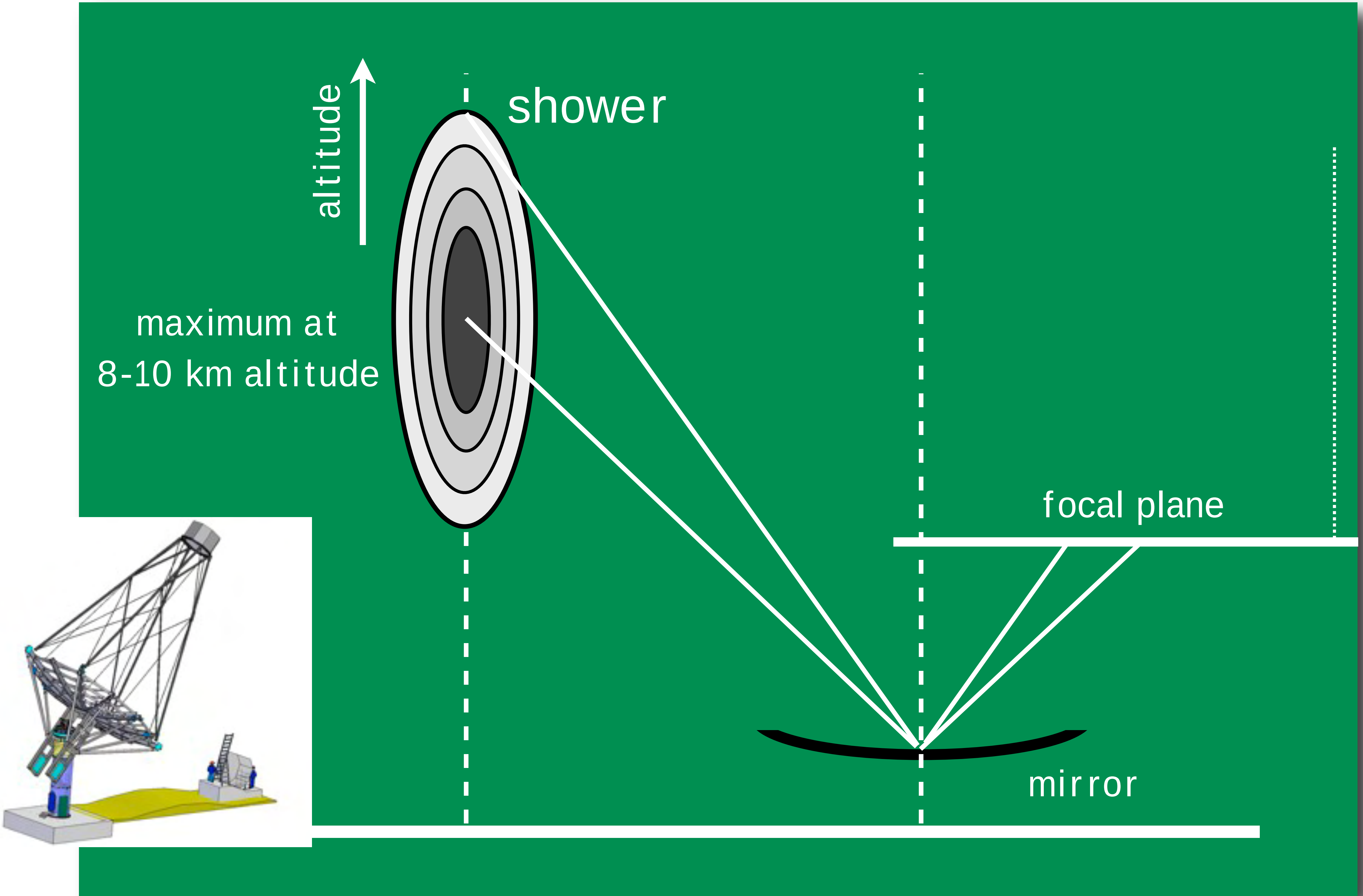

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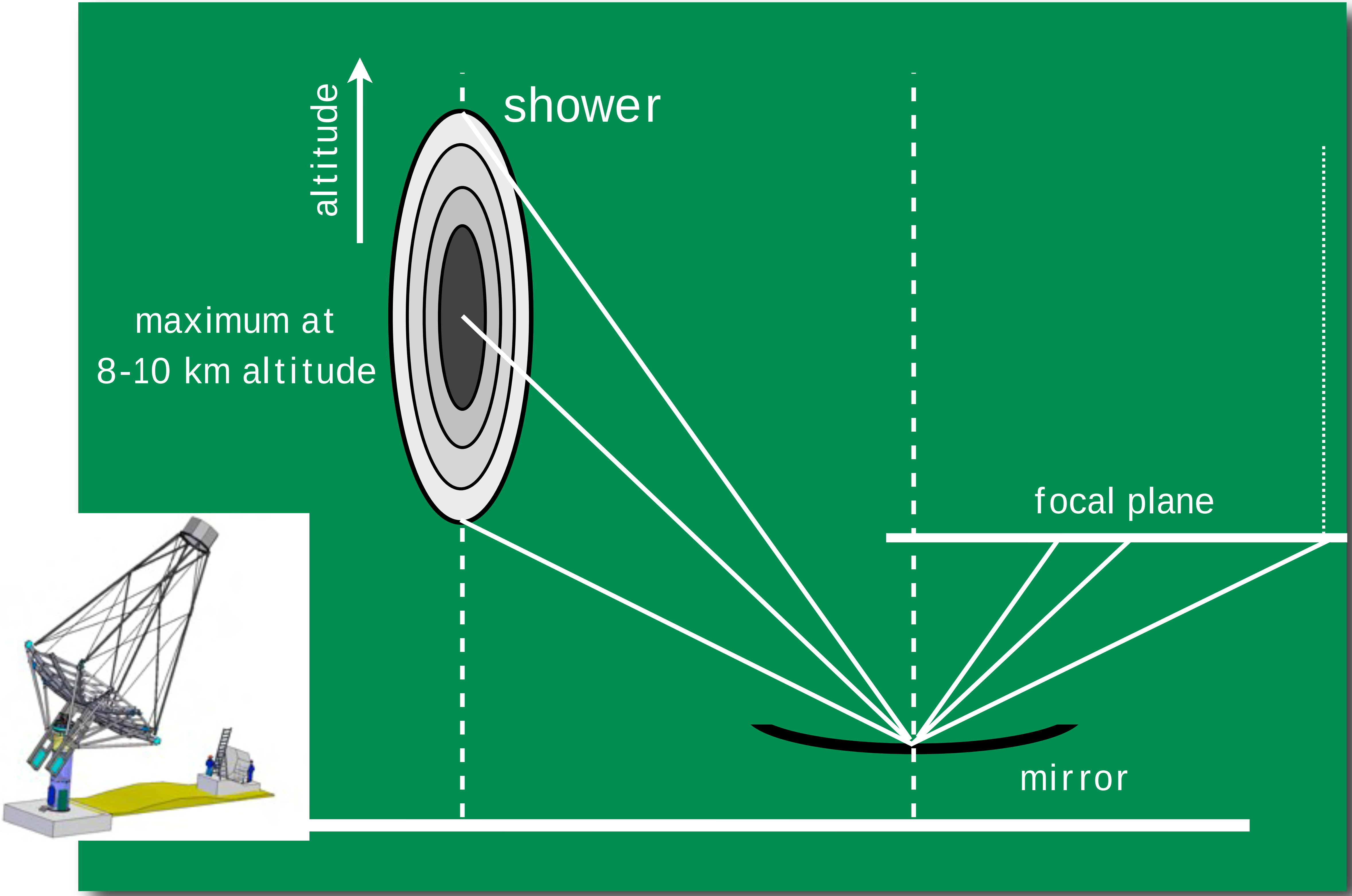

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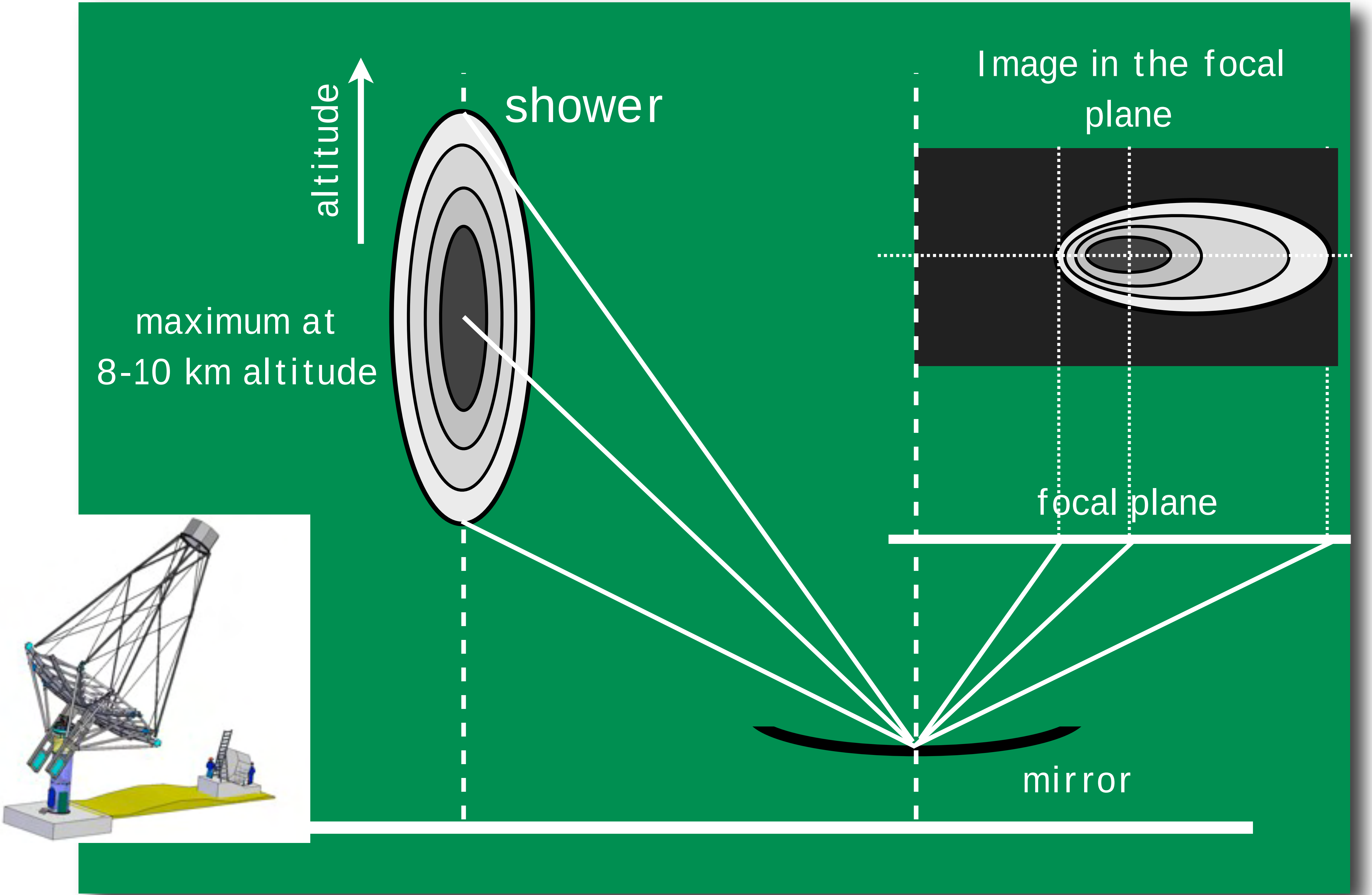
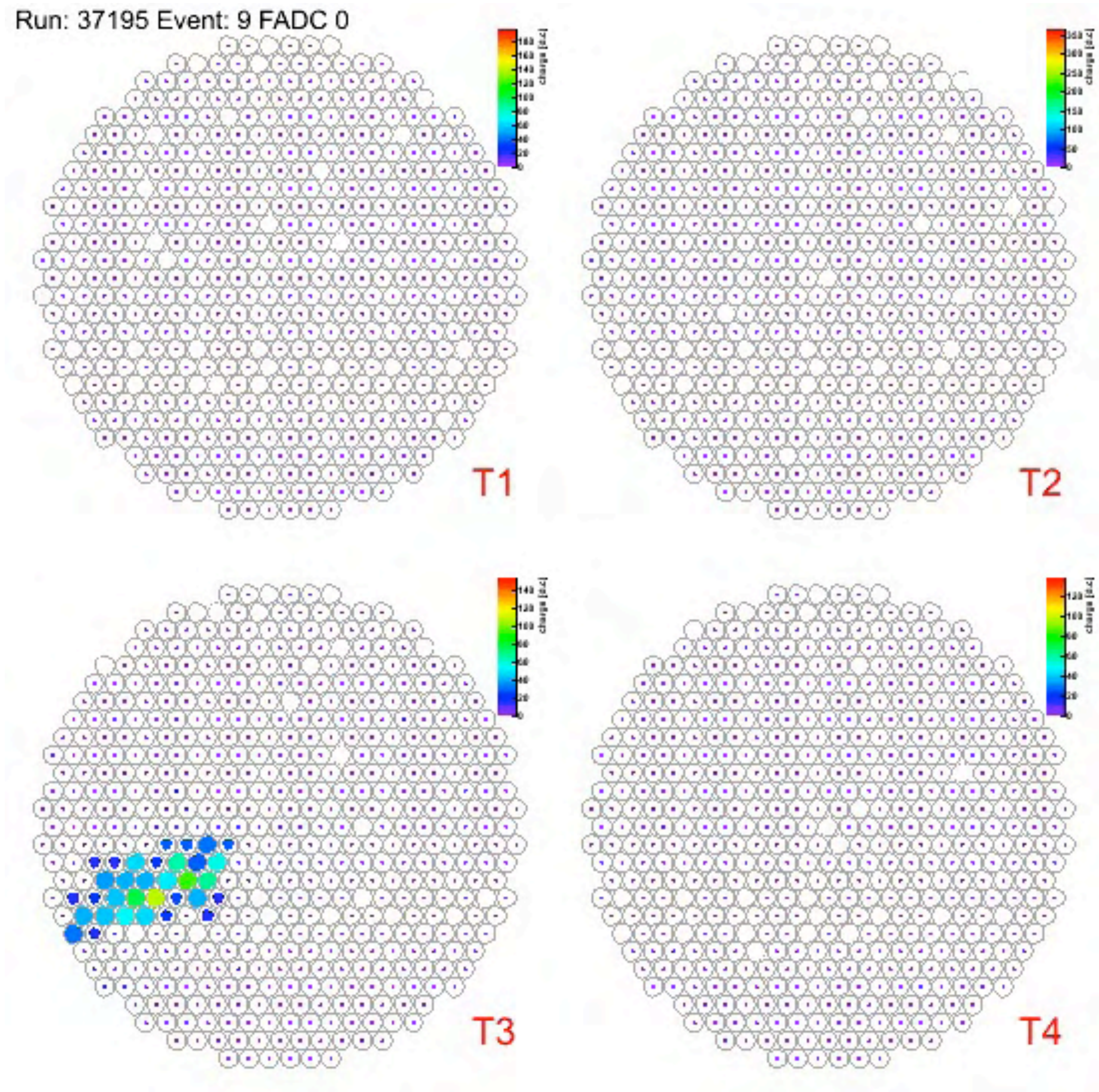


Cherenkov flash is a few nanoseconds long

gamma-rays measured by VERITAS

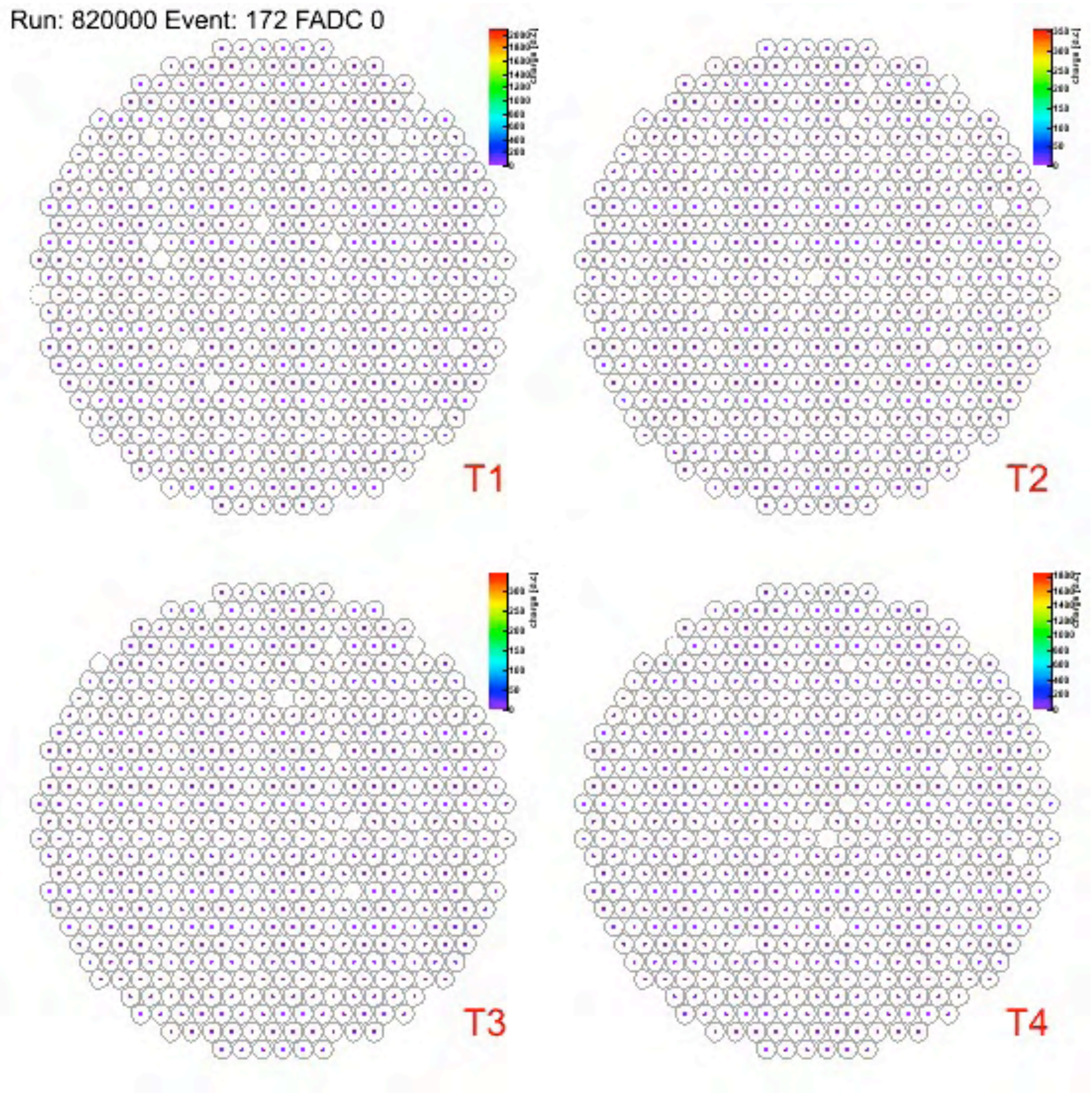
(observation of the Crab Nebula)



(each frame 2 ns long)

gamma-rays ‘measured’ by VERITAS

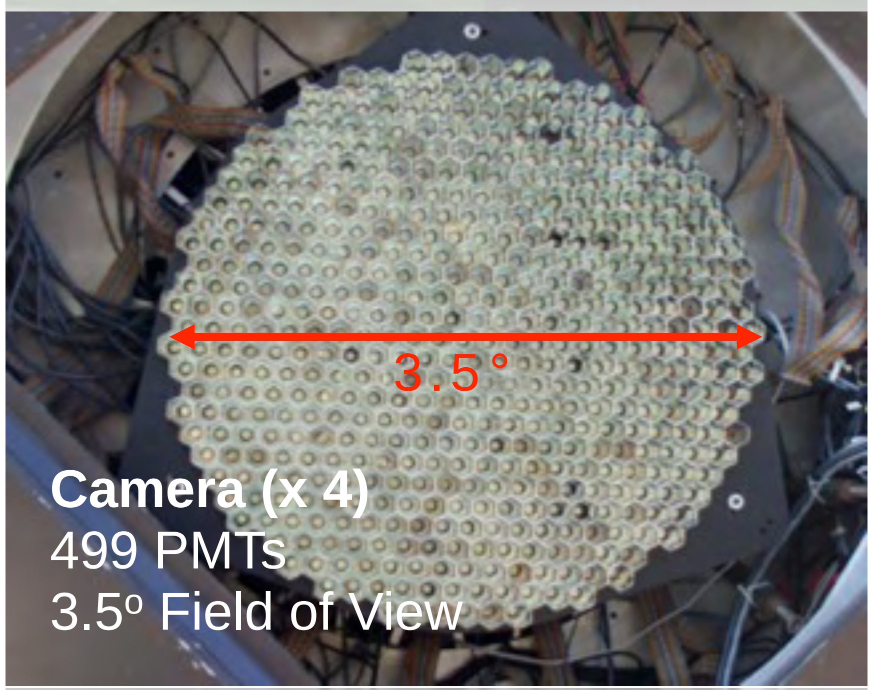
Monte Carlo Simulation



(each frame 2 ns long)

VERITAS - Technical Details

Telescope (x 4)
12 m diameter Davies-Cotton
f 1.0, 110 m^2 mirror area



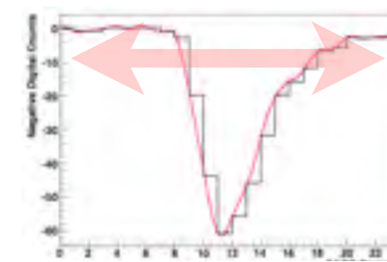
Camera (x 4)
499 PMTs
3.5° Field of View

Mirror Facets (x 350)
Reflectivity ~88%
(recoated every 2 y)

Light concentrators

PMT (x 499)

Electronics
500 MSPS FADC
CFD trigger,
3 adjacent pixel and 2/4
telescope coincidence
~10% dead time; ~300 Hz



FADC SAMPLES

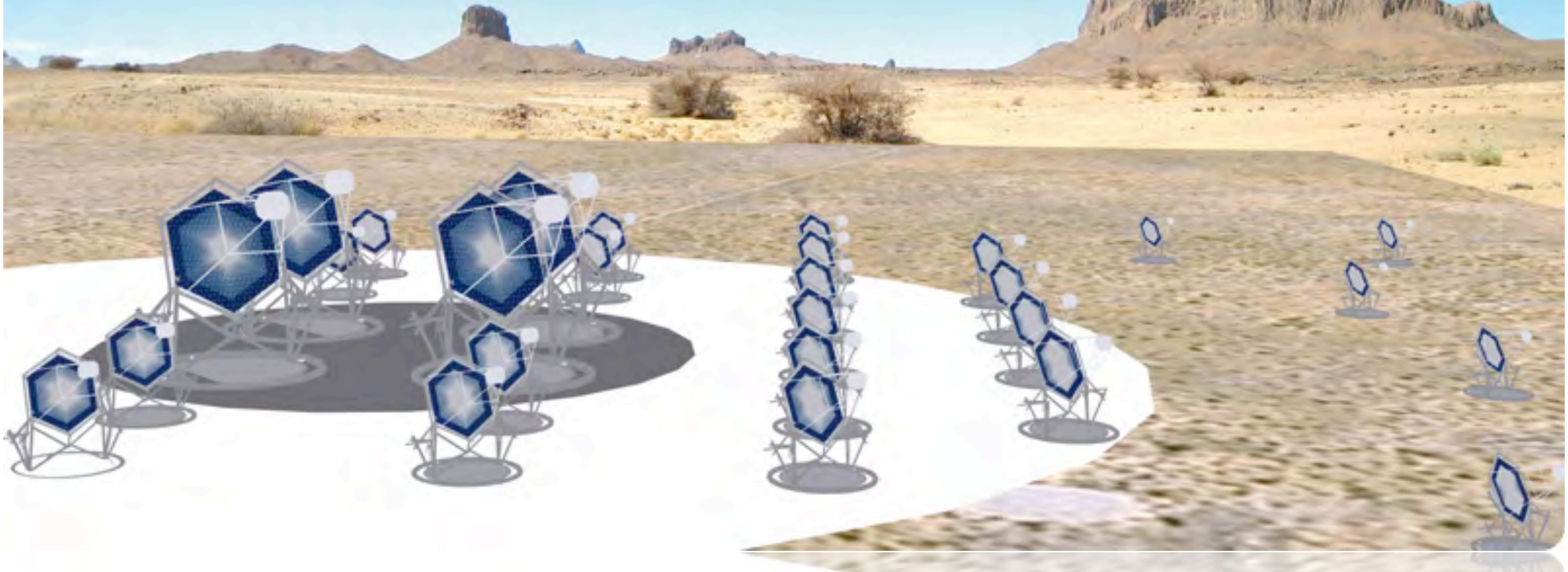
Alt-Az Mount
speed 1°/s

Pointing Monitor
<30” accuracy

Calibration
laser+LED flasher

The Cherenkov Telescope Array

CTA Consortium:
- >22 countries (big: D, F, US)
- >600 scientists
- €180 M (invest)
- first science data 2014



north and south array - full sky coverage

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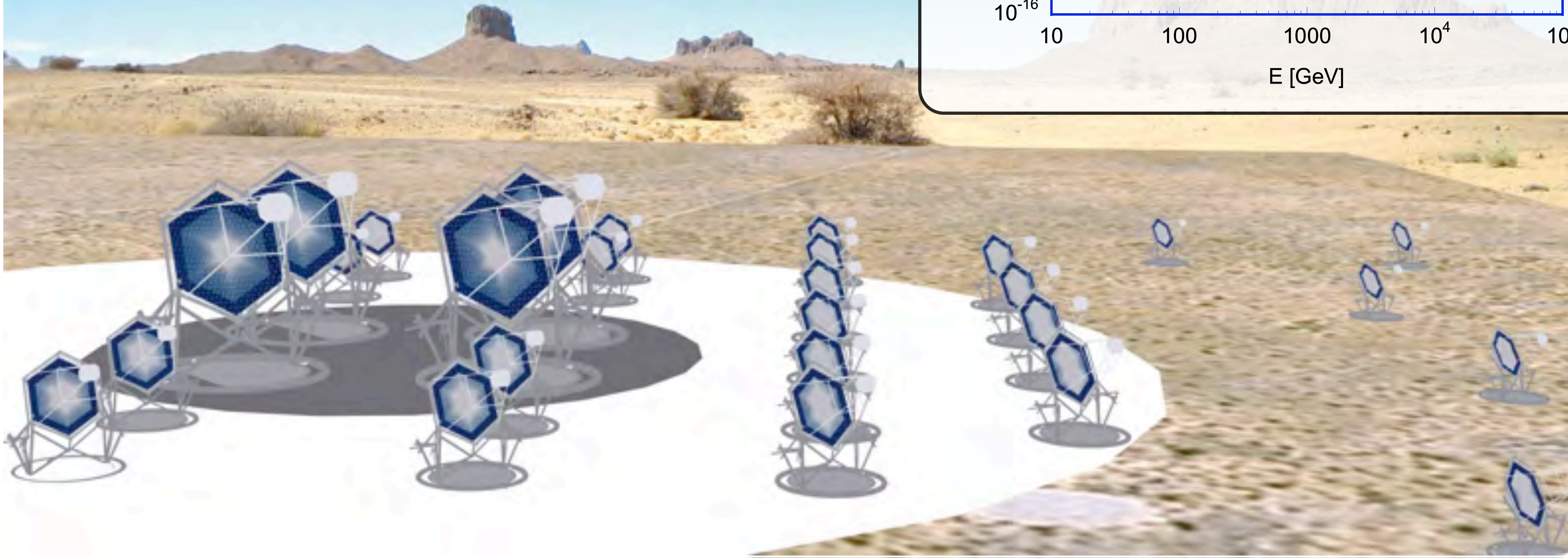

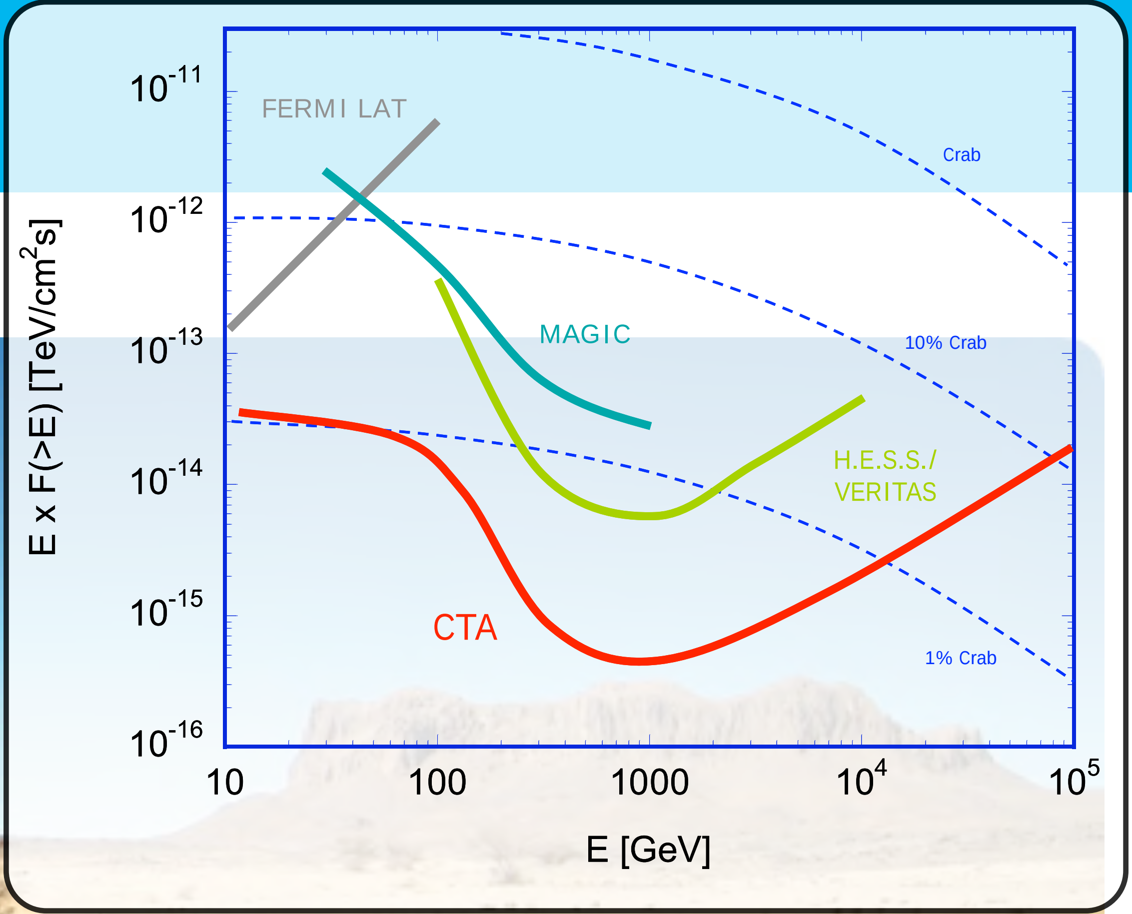

north and south array - full sky coverage