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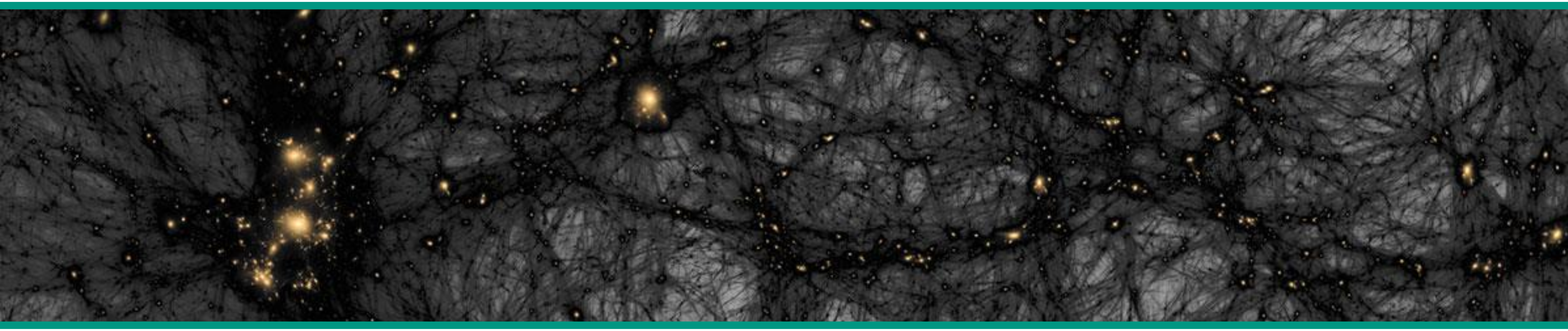
Astroparticle physics I – Dark Matter

WS22/23 Lecture 8 Nov. 24, 2022



Recap of Lecture 7

■ UHE neutrinos: flavour oscillations studies & search for point sources

- flavour composition from decay chain $\pi \rightarrow \mu \rightarrow e$ altered by $\nu -$ oscillations

- background for astrophysical neutrinos from shower muons & ν_{atm}

- observatories in-ice (Ice-Cube) ⇔ deep-sea (KM3NeT): technolog. challenges

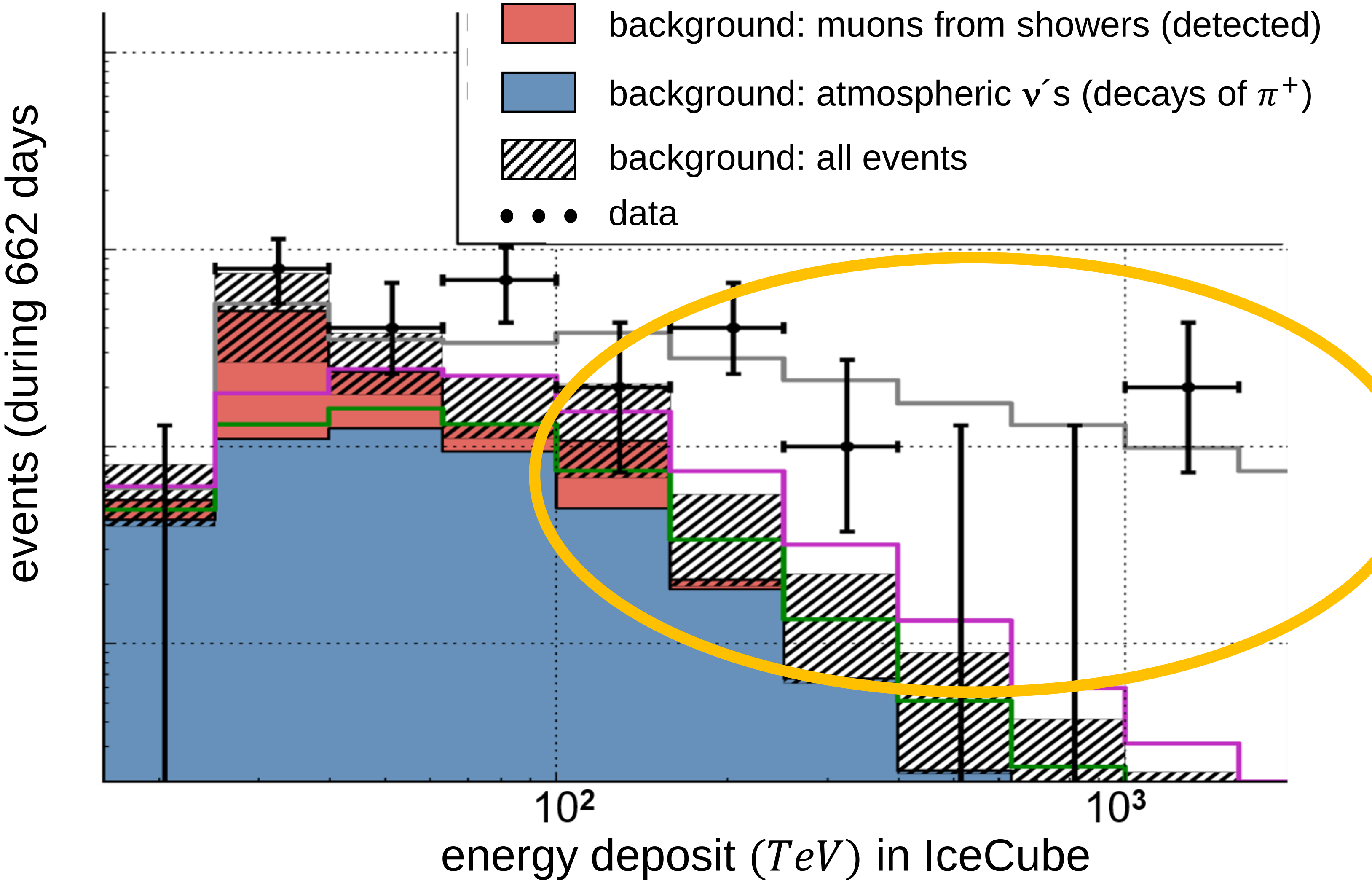
- lower (GeV –scale) energies: study of matter-induced oscillation effects

- IceCube (astrophysical) excess events at UHE energies $E > 10^{14}\ eV$

- identification of first source(s) via muon tracks (Cherenkov cone)

IceCube: science harvest – 28 highest energy ν´s

- **Excess of events at the highest energies**
  - 28 ν-induced events at energies $> 100\ TeV$: first observation of VHE neutrinos from astrophysical sources



Search for astrophysical ν´s: GRBs* as sources?

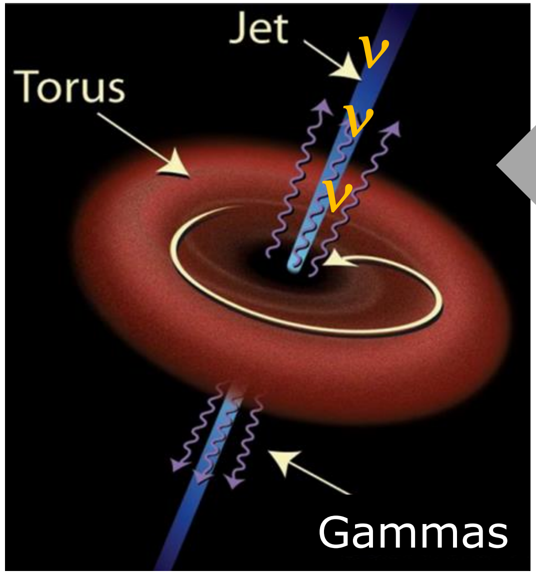
- **Gamma Ray Bursts (GRBs) – VHE ν´s from a stellar collapse to black hole?**

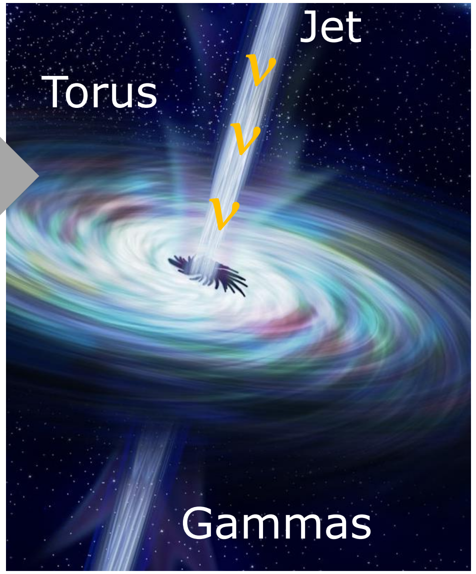
  - searching for **time coincidences** of GRBs with IceCube ν-signals

short GRB: merger of 2 neutron-stars

formation of a black hole

long GRB: collapse of massive star





$\Delta t < 2s$

$\Delta t > 2s$

*see ATP-2 summer term 2023

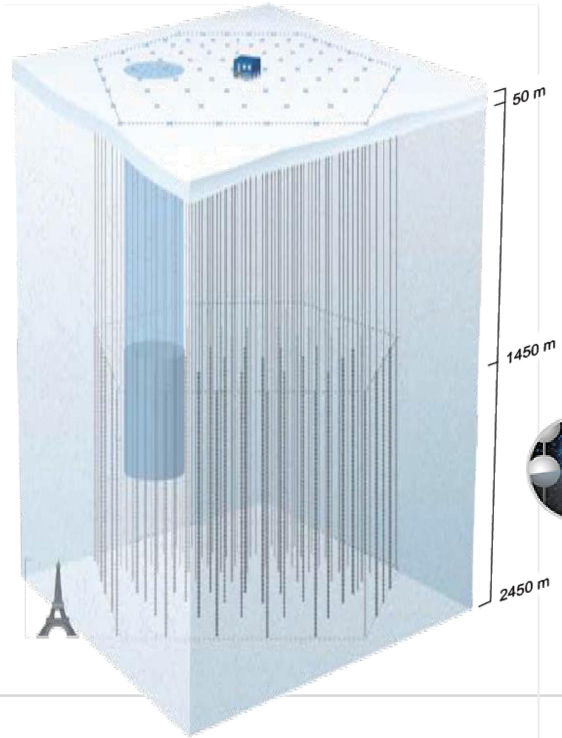
Search for astrophysical ν´s: GRBs as sources?

- **Gamma Ray Bursts (GRBs) – VHE ν´s from a stellar collapse to black hole?**

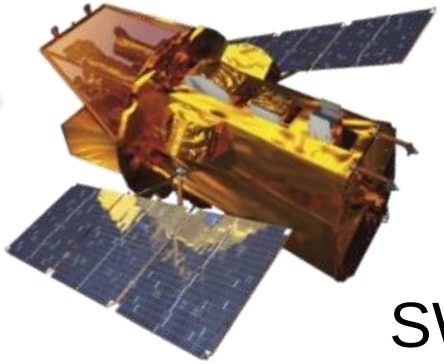
  - signal: time coincidences of GRBs with IceCube ν-signals

  - 5-year-multimessenger-search (ν,γ) in both hemispheres

1172 GRBs identified
508 northern hemisphere
664 southern hemisphere



γ



SWIFT

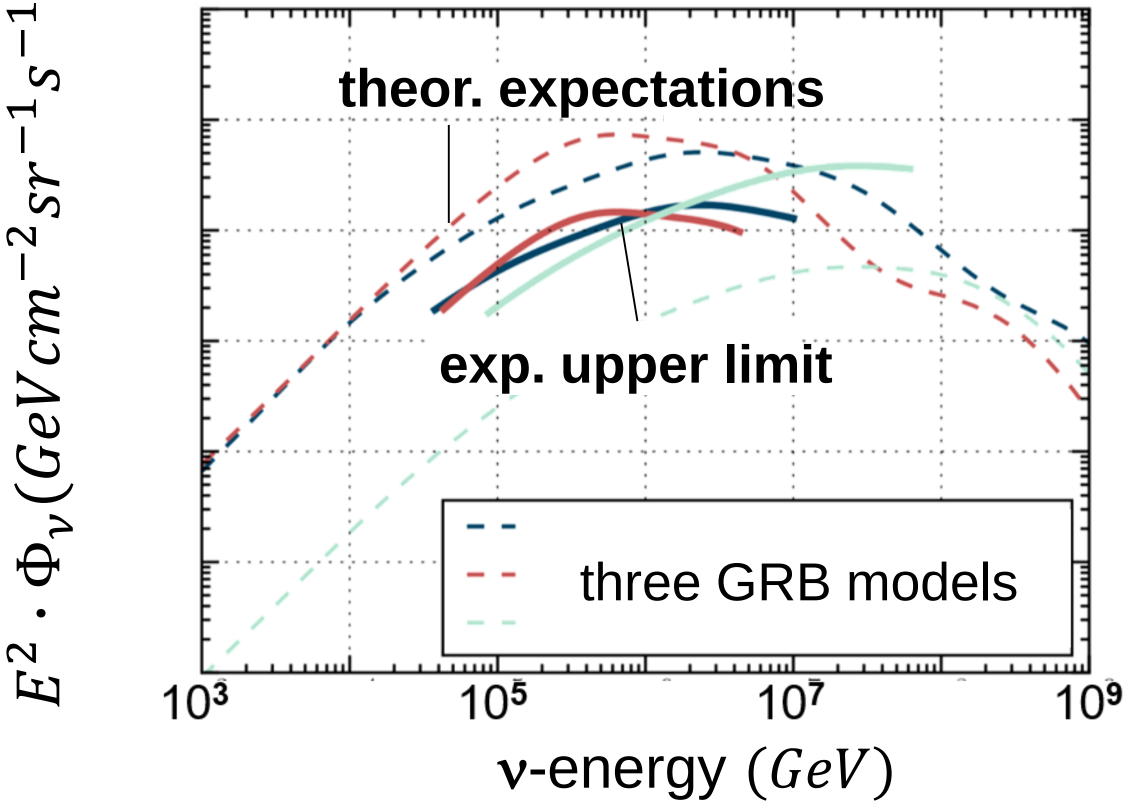
sends GRB alert to IceCUbe

ICECUBE SOUTH POLE NEUTRINO OBSERVATORY

Search for astrophysical ν´s: GRBs as sources?

- **Gamma Ray Bursts (GRBs) – VHE ν´s from a stellar collapse to black hole?**

  - IceCube: analysis of CC-reactions (μ –tracks) & NC-reactions (cascade)
  - 5-year-multimessenger-search (ν,γ) in both hemispheres: 0 events



IceCube: a recent breakthrough for ν-astronomy

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- **A hot spot of UHE neutrinos*!**

  - observation of 79 UHE neutrinos from a direction of galaxy M77 = NGC 1068 $(d = 47 \cdot 10^6\ ly)$ from 5/2011…5/2020

  - origin: beam dump of protons from AGN (´cocoon´, with acceleration in the corona region of the AGN)

  - no UHE gammas detected (absorption in the massive torus of M77)

  - other interpretations: chance alignment of a far more distant UHE-ν-source,…

physicsworld

IceCube detects high-energy neutrinos from an active galactic nucleus

08 Nov 2022

Particle accelerator: IceCube has detected 79 high-energy neutrinos from the Messier 77 galaxy, which appears in this image from the Hubble Space Telescope. (Courtesy: NASA/ESA/A van der Hoeven)

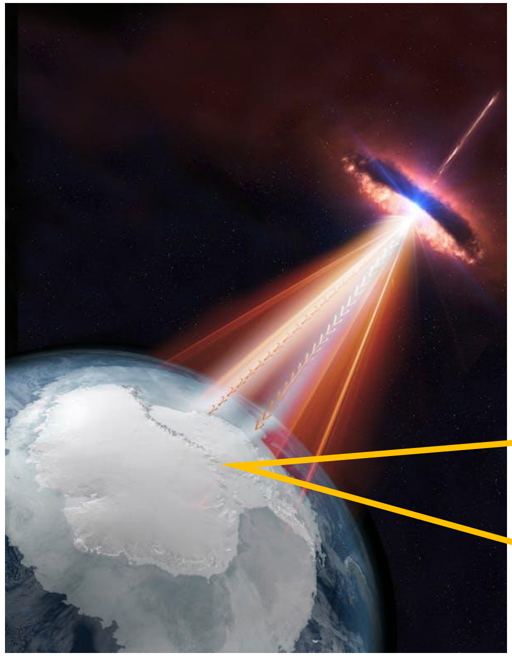
High-energy neutrinos from the active galactic nucleus (AGN) at the heart of the Messier 77 galaxy have been detected by the IceCube neutrino observatory. Also known as NGC 1068, the galaxy is harbours a supermassive black hole and the observations open a window into the violent processes that are believed to create cosmic rays.

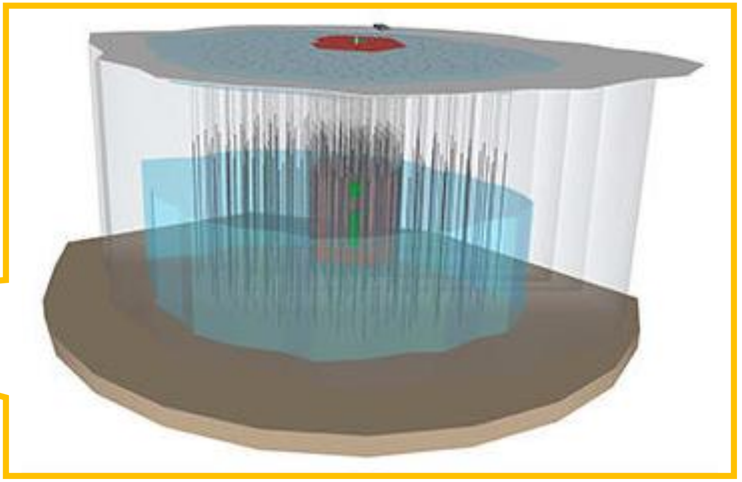
* Evidence for neutrino emission from the nearby active galaxy NGC 1068 | Science

IceCube Gen 2: increase of the sensitive volume

- **We need more hot spots of UHE neutrinos!**

- observation of many more UHE neutrinos & other sources will require a much larger ν-telescope: **IceCube Gen 2**!



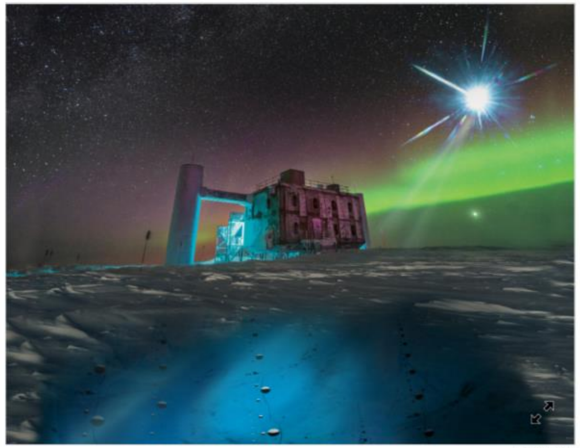


RESEARCH NEWS

Neutrino Astronomy Enters a New Era

November 3, 2022 • *Physics* 15, 171

Using the IceCube Neutrino Observatory in Antarctica, researchers have found significant evidence of a cosmic source of high-energy neutrinos.



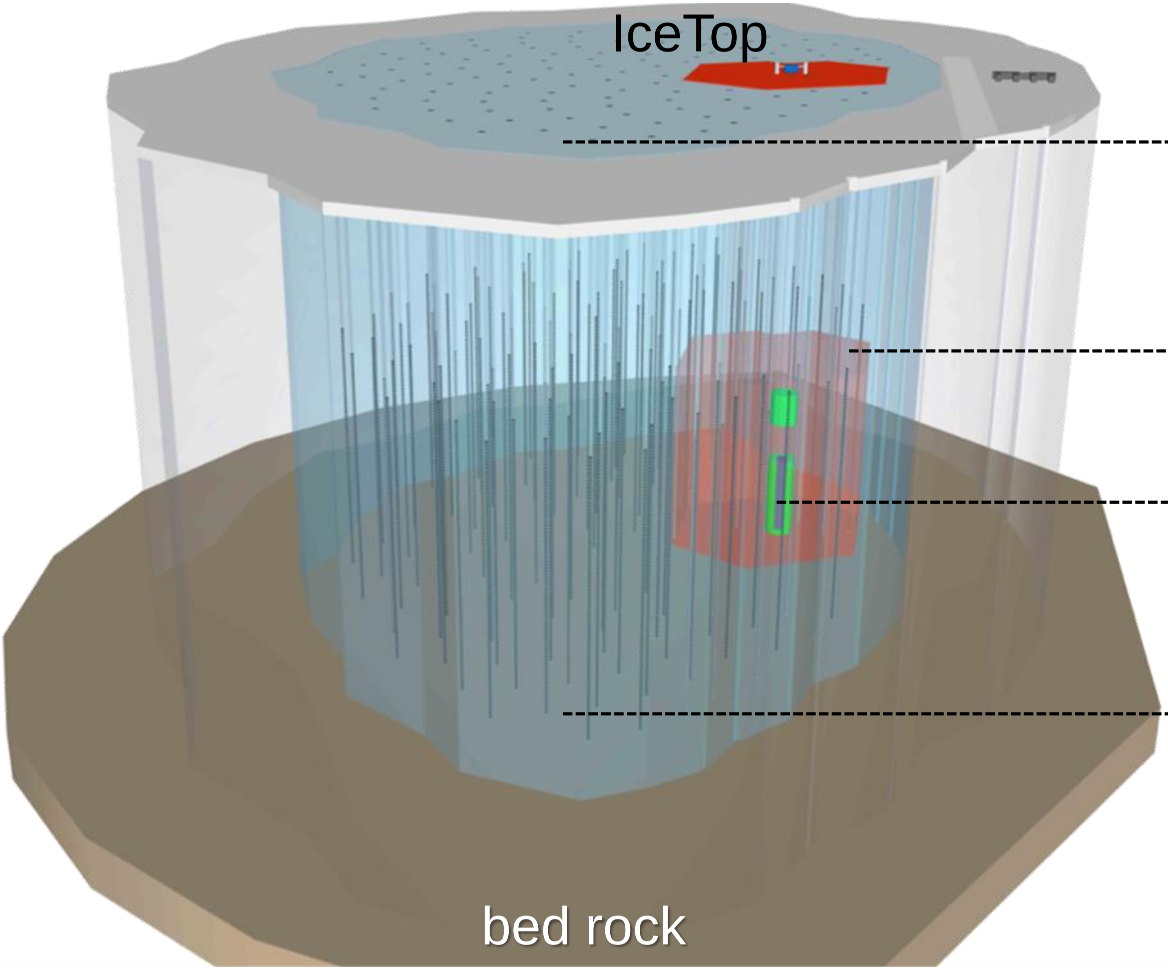
IceCube/NSF

An artist's representation of a cosmic neutrino source shining above the IceCube Observatory at the South Pole. Beneath the ice are photodetectors that pick up the neutrino signals.

Don your binoculars for a night of star gazing and you might be able to spot the seemingly innocuous spiral galaxy Messier 77 (M77), a bright but dusty mass of stars that sits 47 million light-years from Earth. Hidden under this dust is a supermassive black hole that is powering intense radiation from the surrounding gas. Now the IceCube Collaboration reports that they have found evidence that this galaxy is also a source of high-energy cosmic neutrinos [1]. Collaboration members say that the finding paves the way to using cosmic neutrinos for astrophysical measurements that could help solve the origin of cosmic rays, the Universe's highest-energy particles, and help solve mysteries about cosmic rays and dark matter.

IceCube Gen 2 – a $multi - km^3$ observatory

- **Enlarging the IceCube sensitive volume by a factor of 8 until ~2033**



planned extension of IceTop surface detector array: a larger veto against atmospheric muons / charged particles: better statistics for CR-physics

existing instrumented PMT-volume $V = 1\ km^3$

existing *Deep Core* area

planned Gen 2 array with $V = multi - km^3$
- increase distance d of PMTs to $d > 250\ m$ possible due to excellent optical quality of deep antarctic ice
- $8 \times$ increase in V but only factor × 2 in # of PMTs

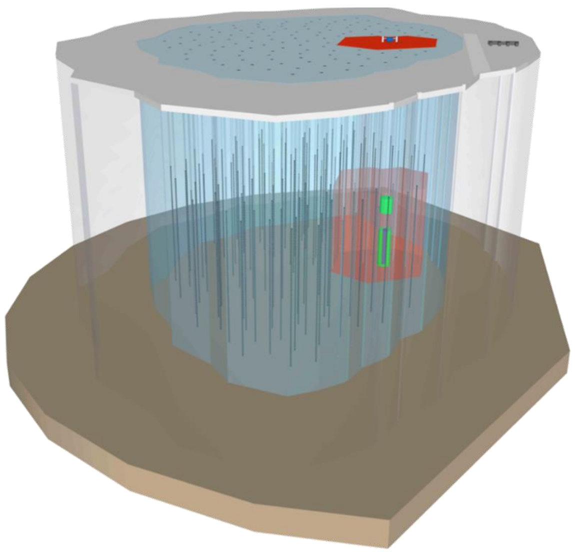
RECAP: Design features of ν-telecopes

- **Optimizing detection efficiency for different energy scales: $GeV - TeV - PeV$**

PeV-scale: IC, KM3NeT,…

volume $V: 1 \dots 10\ km^3$

PMT-strings d: $\mathbf{125 - 250\ m}$

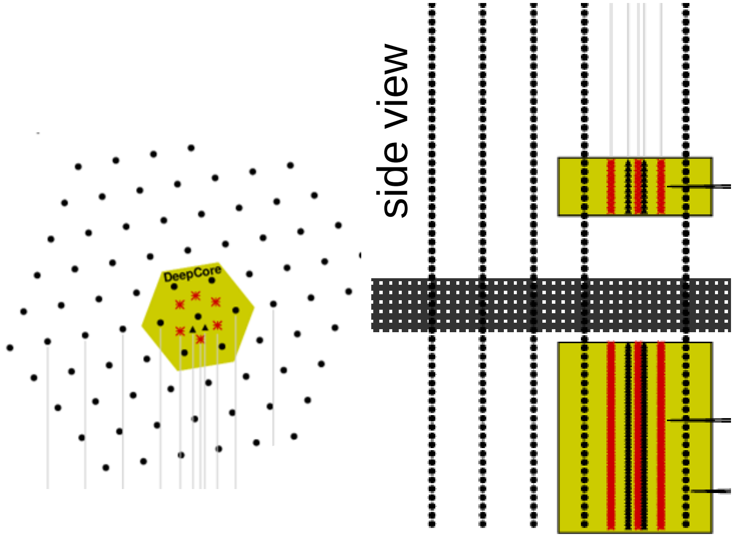


aim: UHE-ν-point sources

TeV-scale: Deep Core,…

$\emptyset = 125\ m,\ h = 300\ m$

PMT-strings $\boldsymbol{d}$: $\mathbf{42 - 72\ m}$

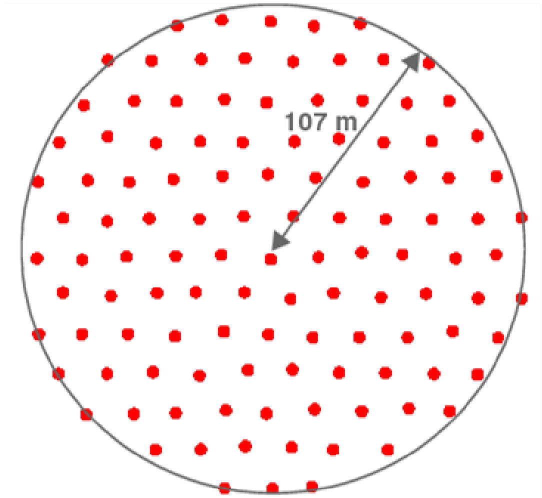


aim: search for dark matter

GeV-scale: ORCA, PINGU

$\emptyset = 100\ m, h = 150 - 300\ m$

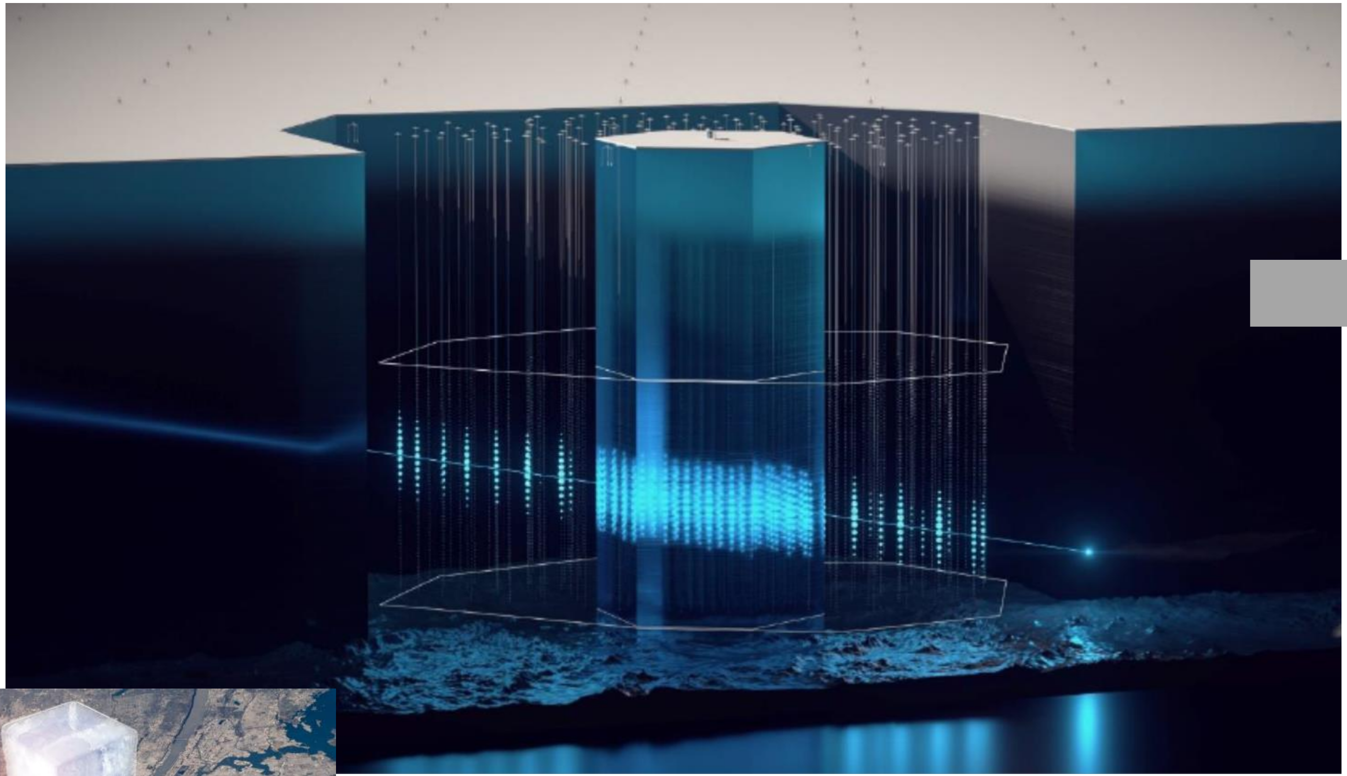
PMT-strings $\boldsymbol{d}$: $\sim\mathbf{20\ m}$



aim: ν-oscillation studies

From neutrino to Cherenkov telescopes for γ´s

- Switching messengers: from UHE neutrinos to VHE gammas



ICECUBE GEN2

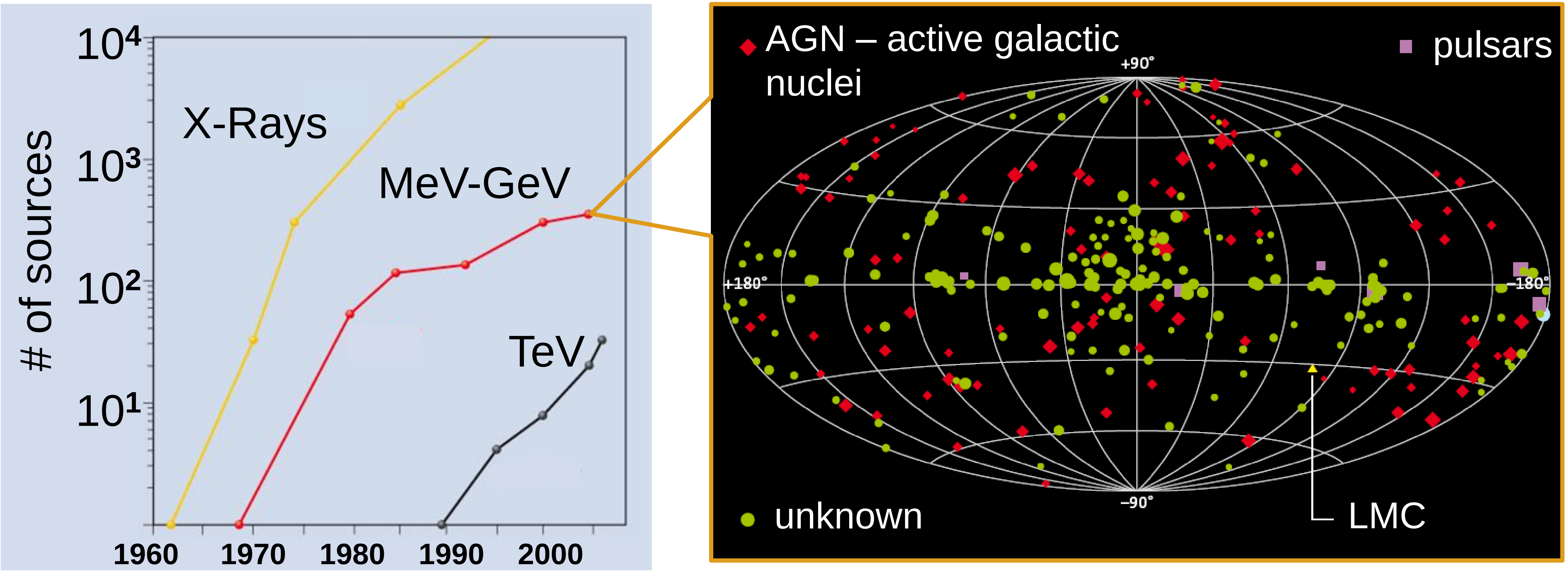
H.E.S.S.

cta cherenkov telescope array

2.1.3 Gamma Telescopes for VHE/UHE gammas

- **Gamma Astronomy at the TeV-scale: a new window to the hidden universe**

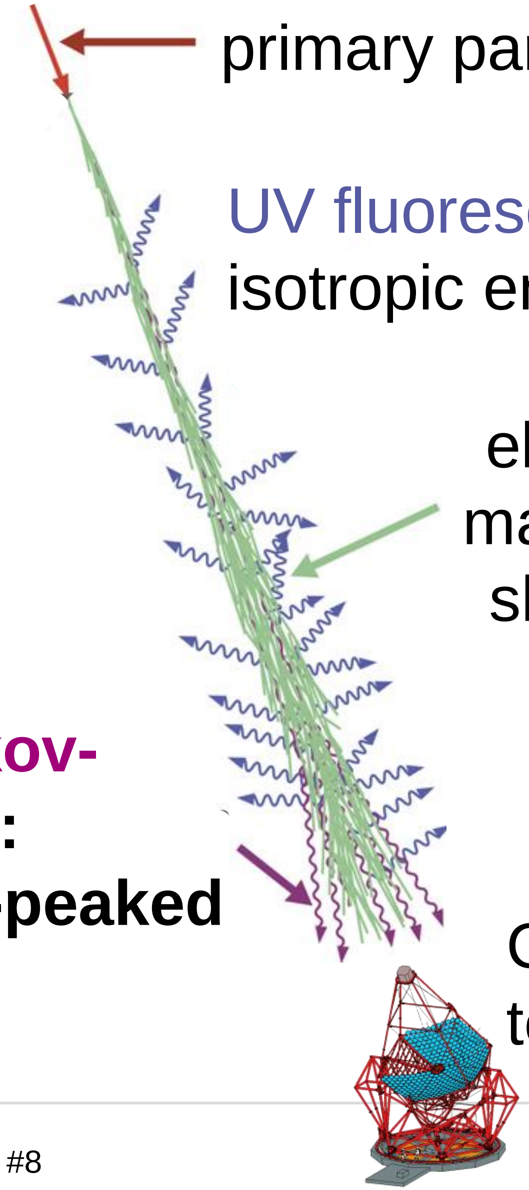
  - study of non-thermal sources: from pulsar wind nebulae to SNRs & AGNs…



Cherenkov telescopes: working principle

- **Detecting air Cherenkov light by an Imaging Air Cherenkov Telescope**

IACT



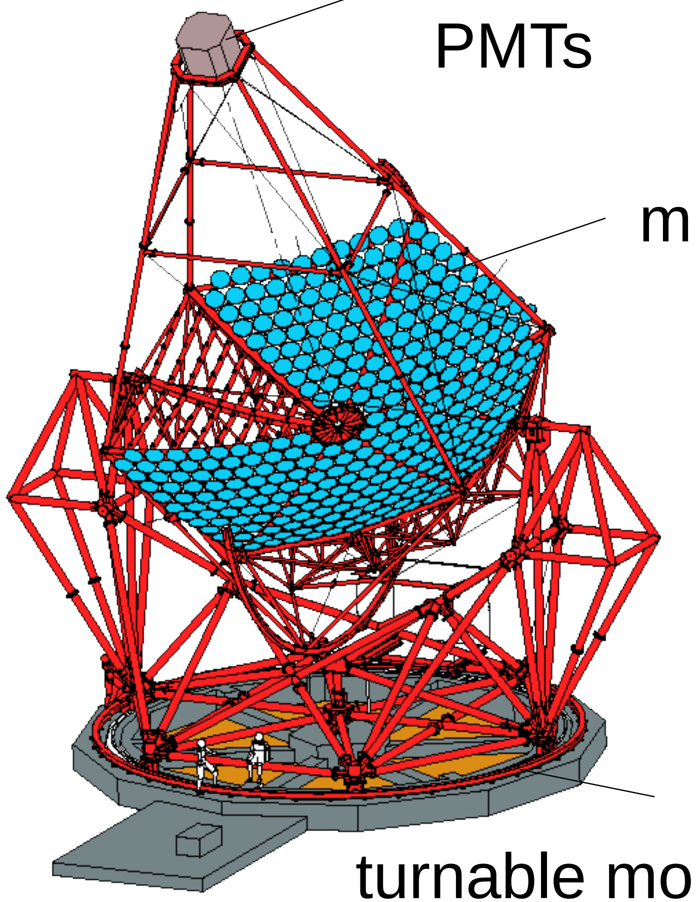
primary particle: high-energy gamma $GeV \dots TeV$

UV fluorescence
isotropic emission

electro-magnetic shower

Cherenkov-photons: forward-peaked emission

Cherenkov-telescope



camera with PMTs

mirror

turnable mounting

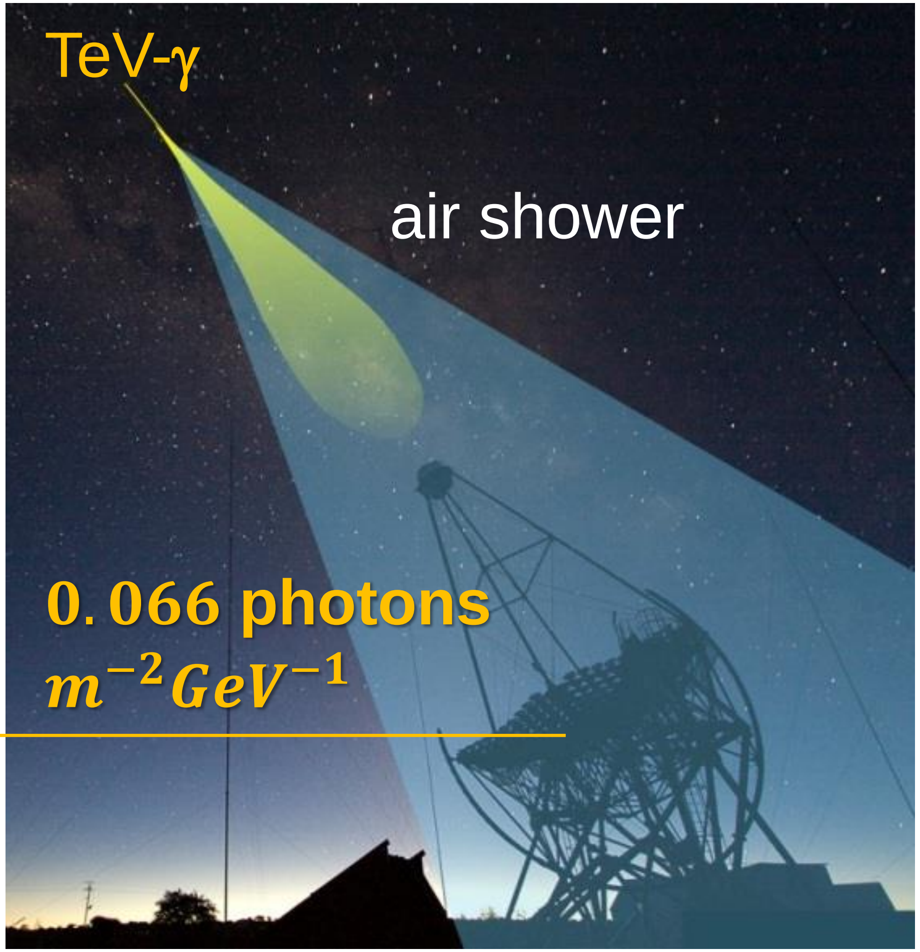
Cherenkov telescopes: working principle

- **IACTs detect the short Cherenkov pulses of 2-3 ns**

- after $10\ km$ transmission: wavelength $\boldsymbol{\lambda > 300\ nm}$

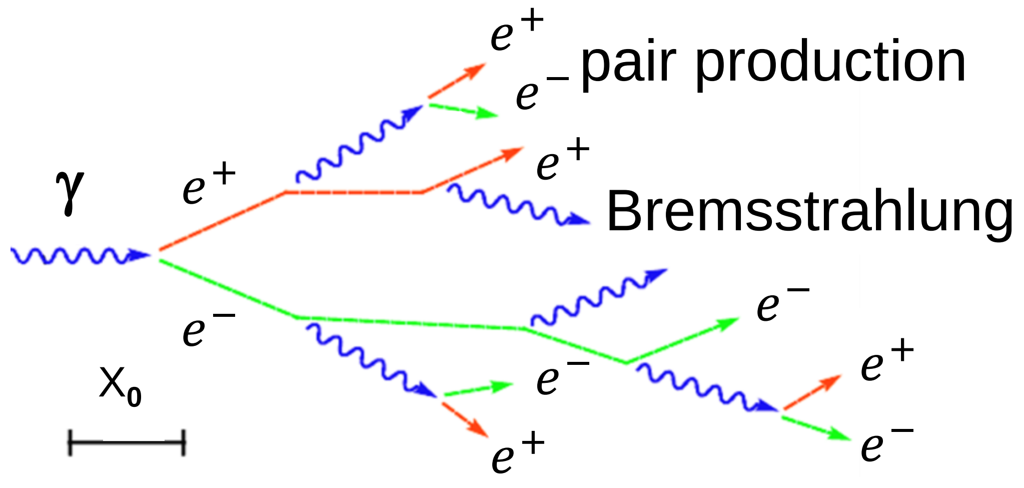
primary particle: high-energy gamma $\boldsymbol{GeV \ldots TeV}$

large mirror size



Cherenkov light from airshowers: narrow cone

- **Primary gammas initiate electromagnetic cascade processes in atmosphere**

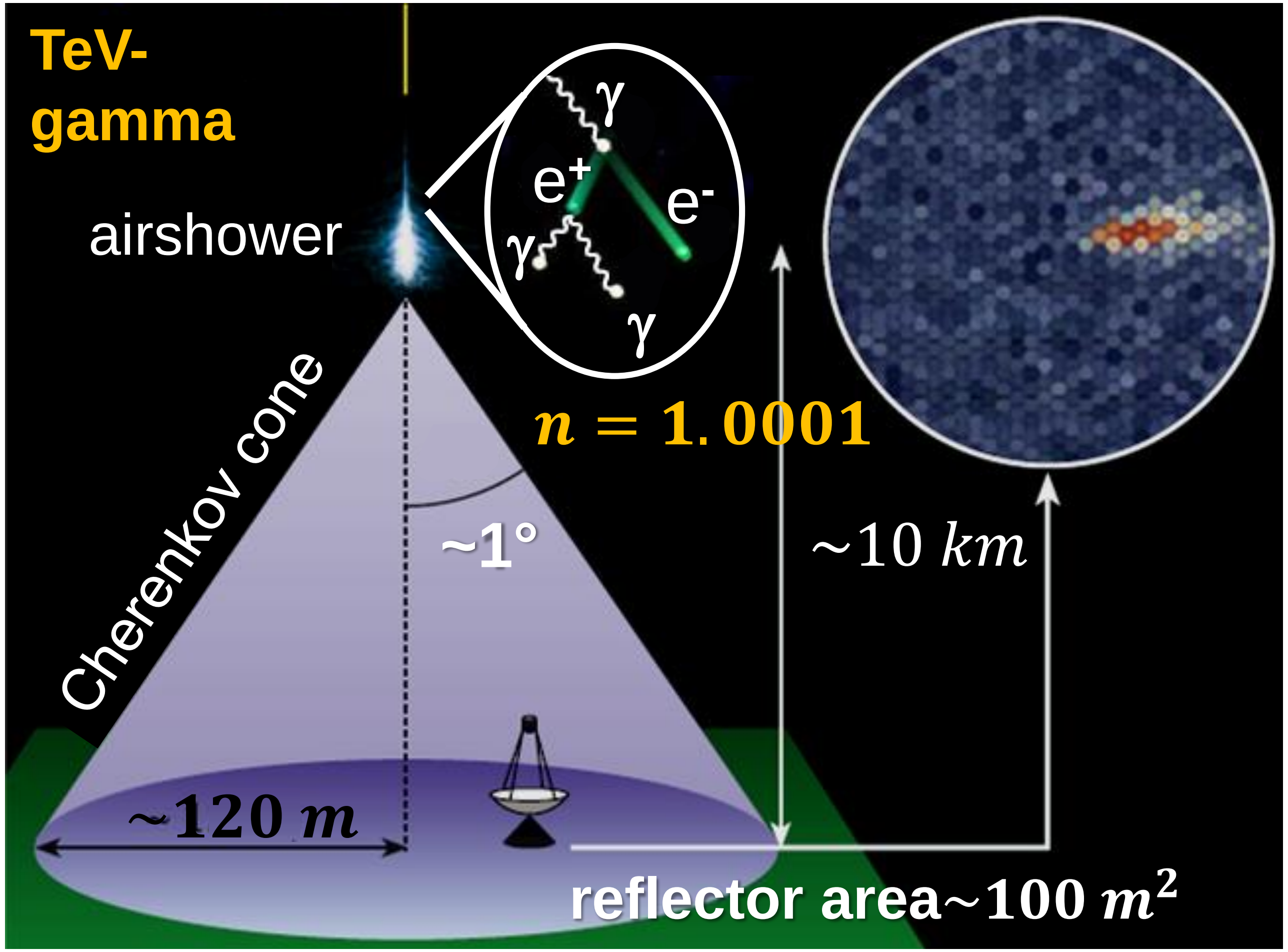


- Cherenkov light produced in upper atmosphere by relativistic e^+, e^-

- refractive index of air: $n = 1.0001$

$\cos\Theta = 1/(n \cdot \beta) \Rightarrow$ **opening angle $\Theta \approx 1°$**

- surface area Cherenkov cone: $10^5 m^2$



Detecting air Cherenkov light: challenges

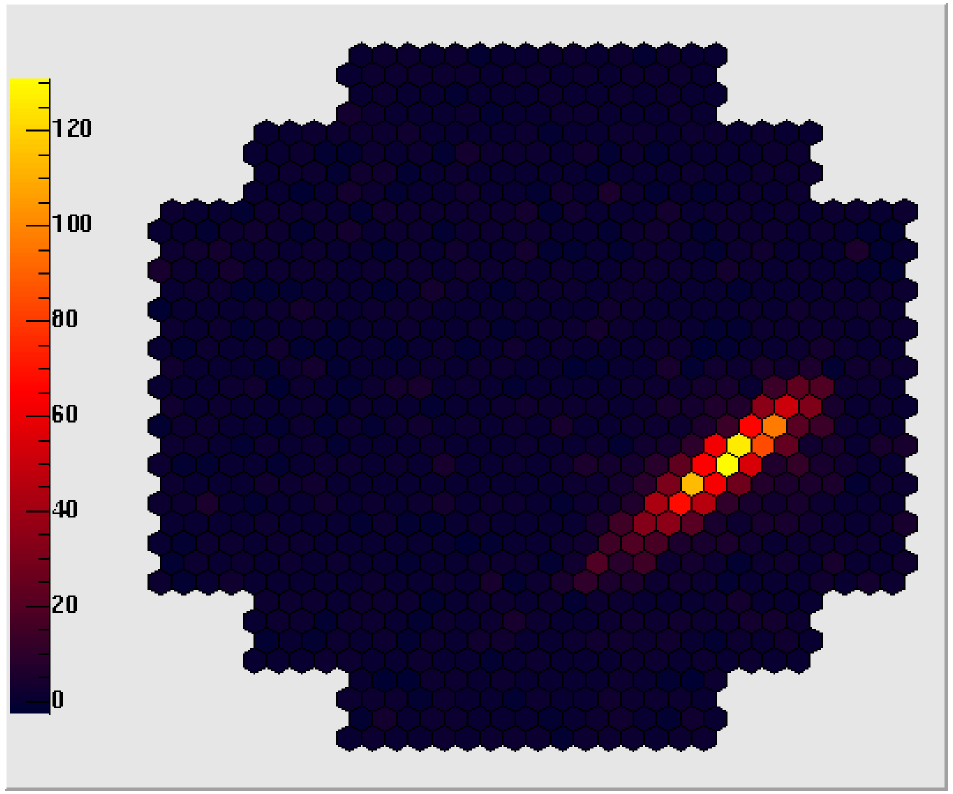
- **Main challenge: very weak light signals of TeV gamma -** $100\ photons/m^2$

- further challenges for VHE gamma astronomy with IACTs:

- very small gamma fluxes at TeV scale

- discrimination against large flux of CRs: use lateral distribution of shower image & pulse duration

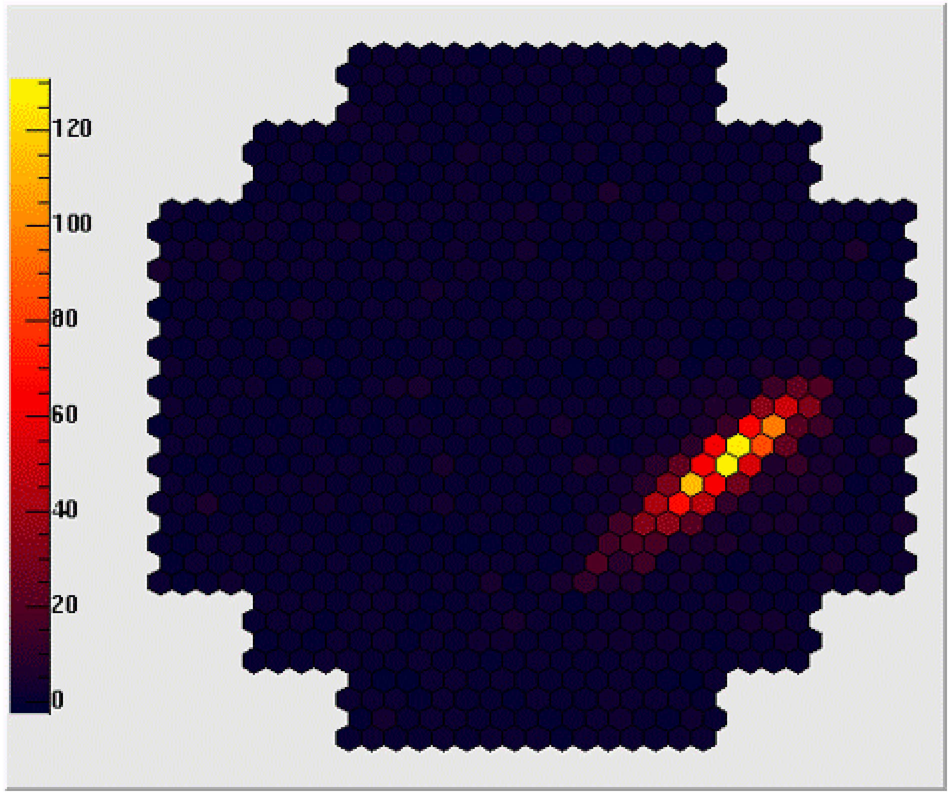
- p, He, Fe: diffuse lateral distributions



Detecting air Cherenkov light: challenges

- **Observables & properties of an IACT for gammas in the GeV…TeV-range**

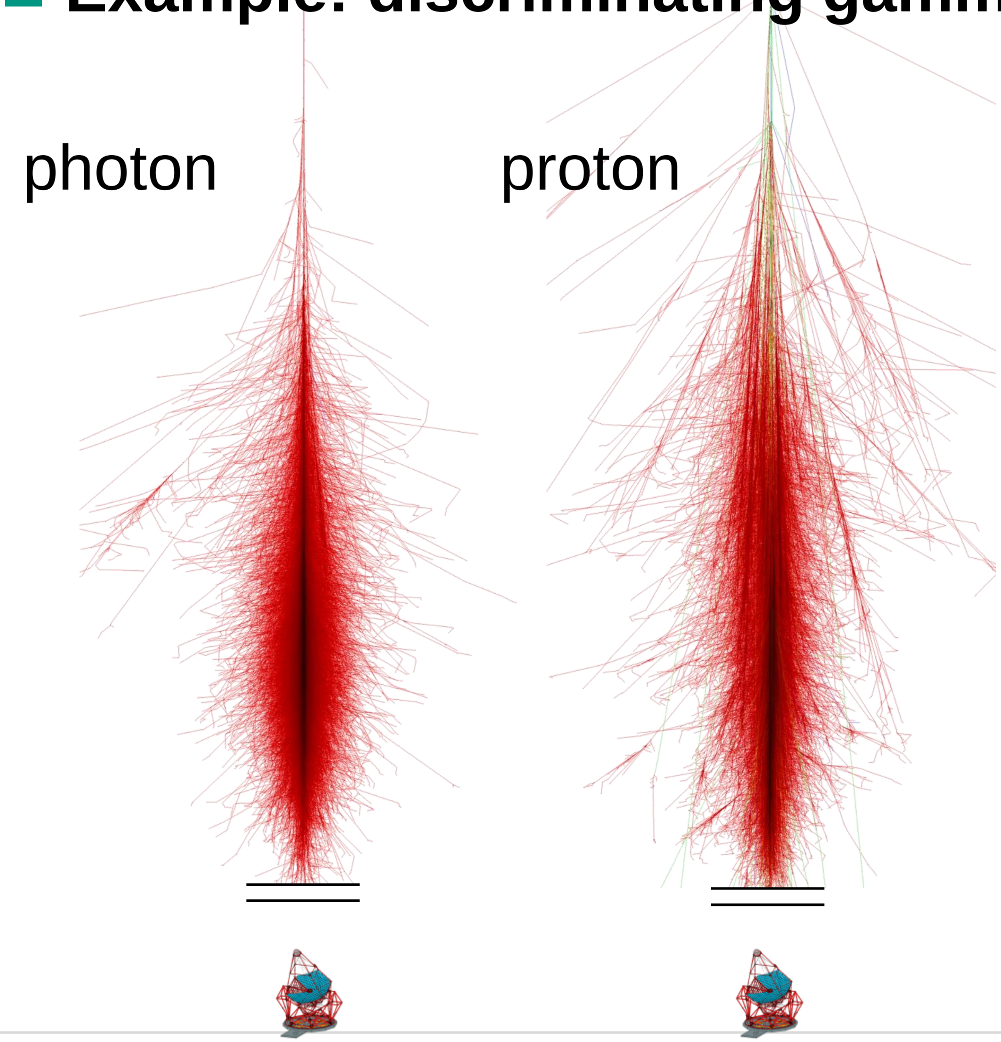
  - reconstructing the parameters of the primary TeV-gamma
  - light intensity: ⇨ shower energy
  - light orientation: ⇨ shower arrival direction
  - light profile: ⇨ primary particle type
  - angular resolution: $\Delta\theta \sim 0.1°$
    (depends on # of PMTs, # of telescopes)
  - energy threshold: $\boldsymbol{E(\gamma) = 40\ (25)\ GeV}$
    (depends on mirror-Ø, PMT-efficiency, trigger)

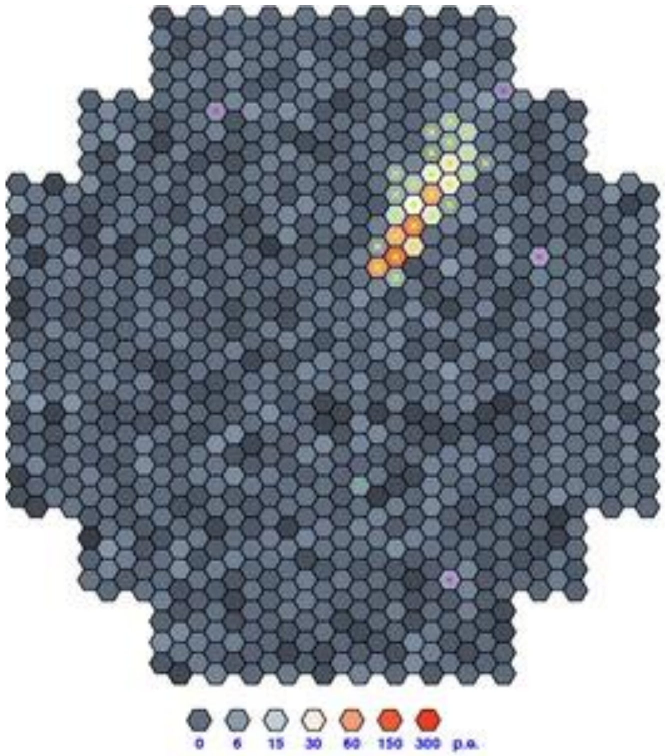


Detecting air Cherenkov light: challenges

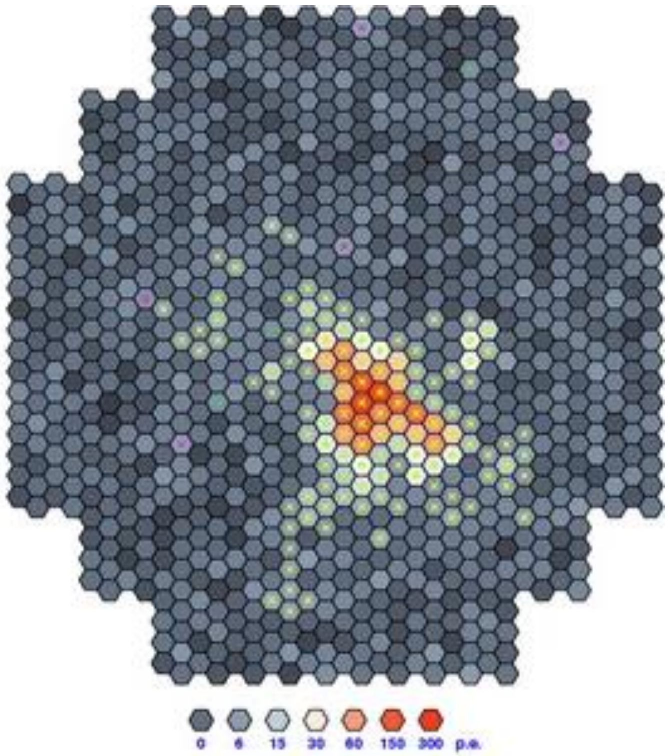
- **Example: discriminating gammas from protons via shower profile at $1\ TeV$**

C O R S I K A





$1\ TeV$ **photon** shower image

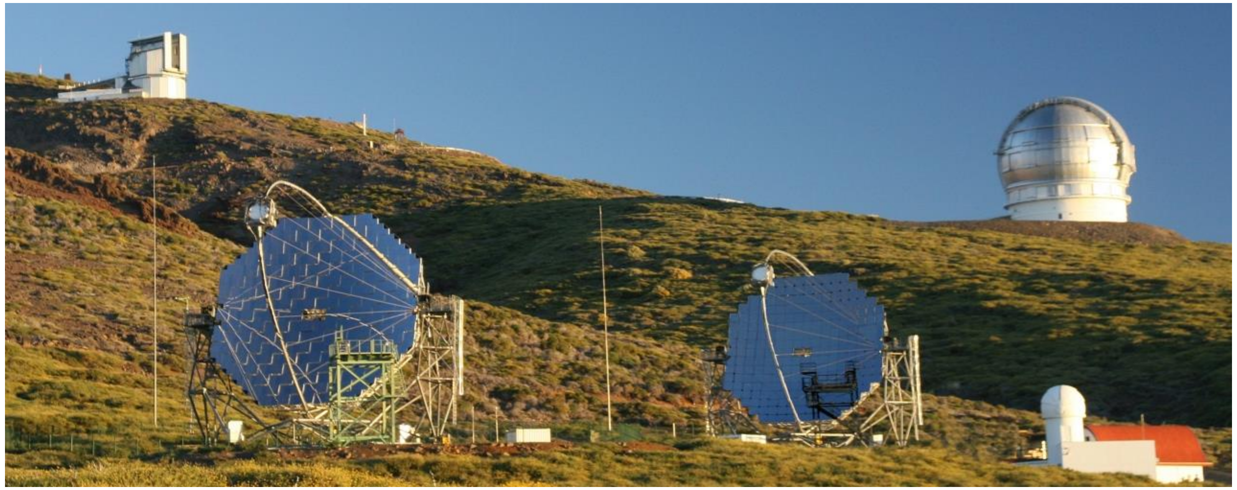


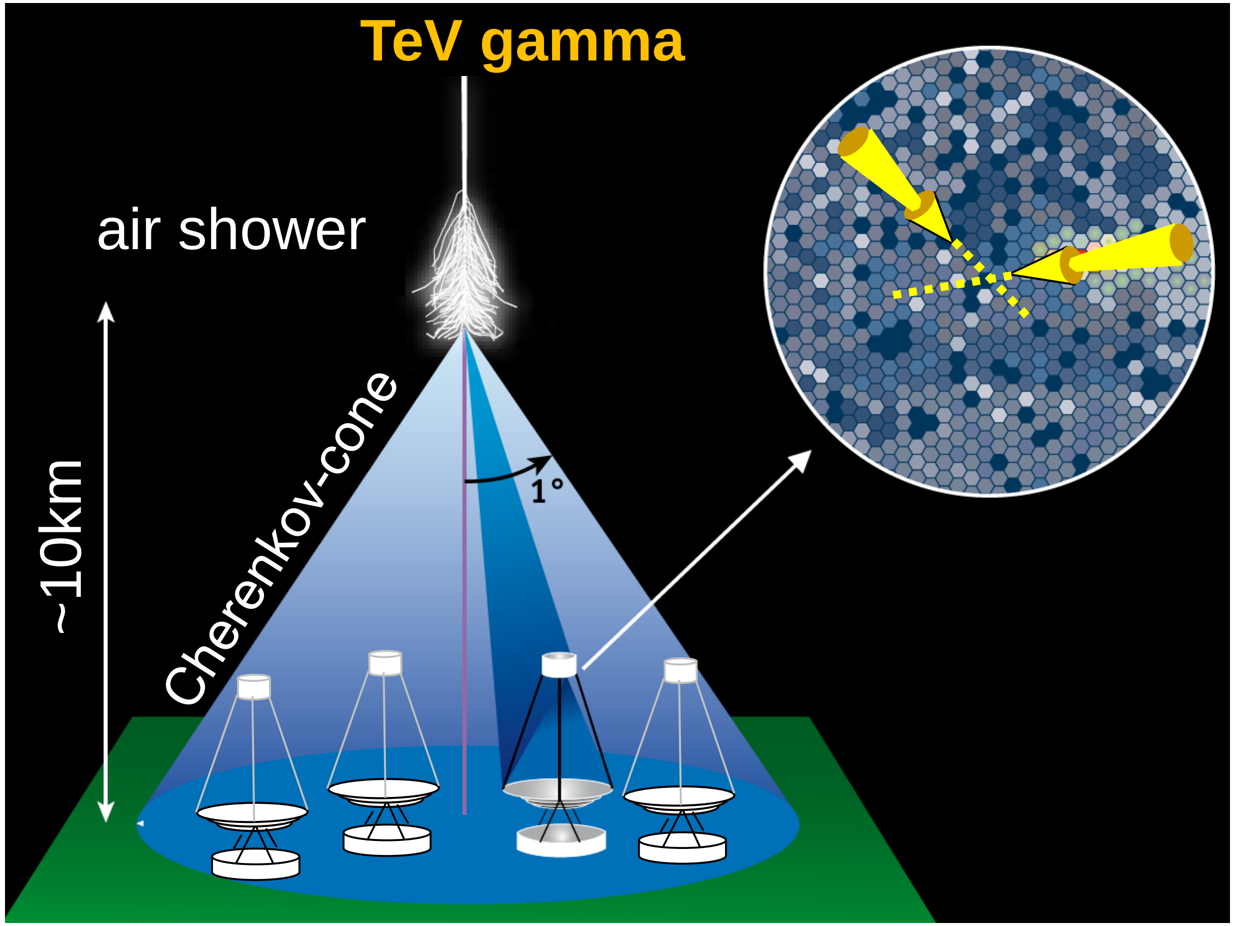
$1\ TeV$ **proton** shower image

Improved sensitivity via large arrays of IACTs

- **<u>Stereoscopic</u> view of a shower by setting up many IACTs**

  - improved sensitivity to
    - low gamma fluxes
    - arrival direction
    - energy estimate
  - improved particle discrimination

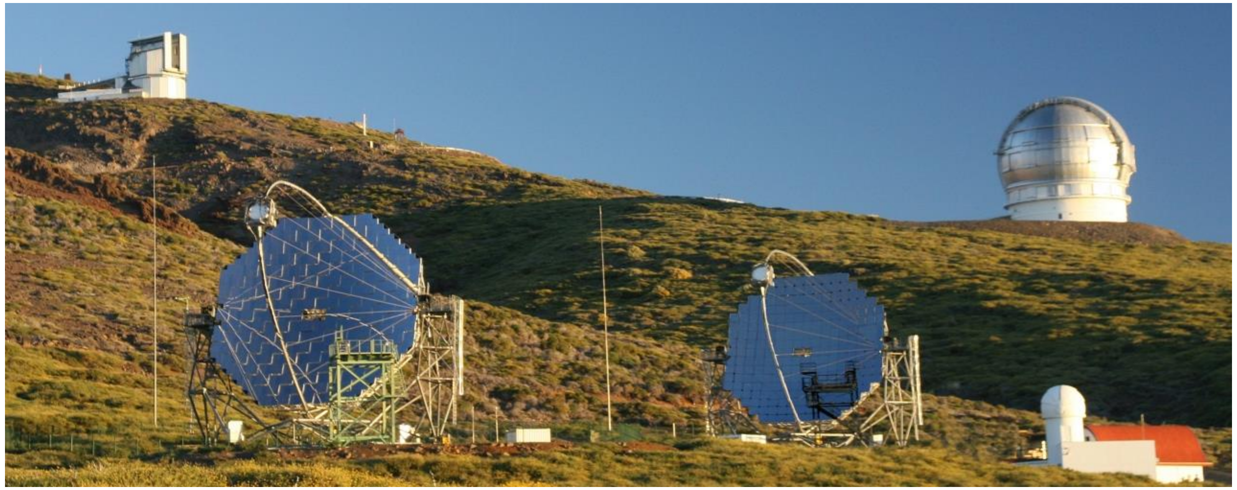


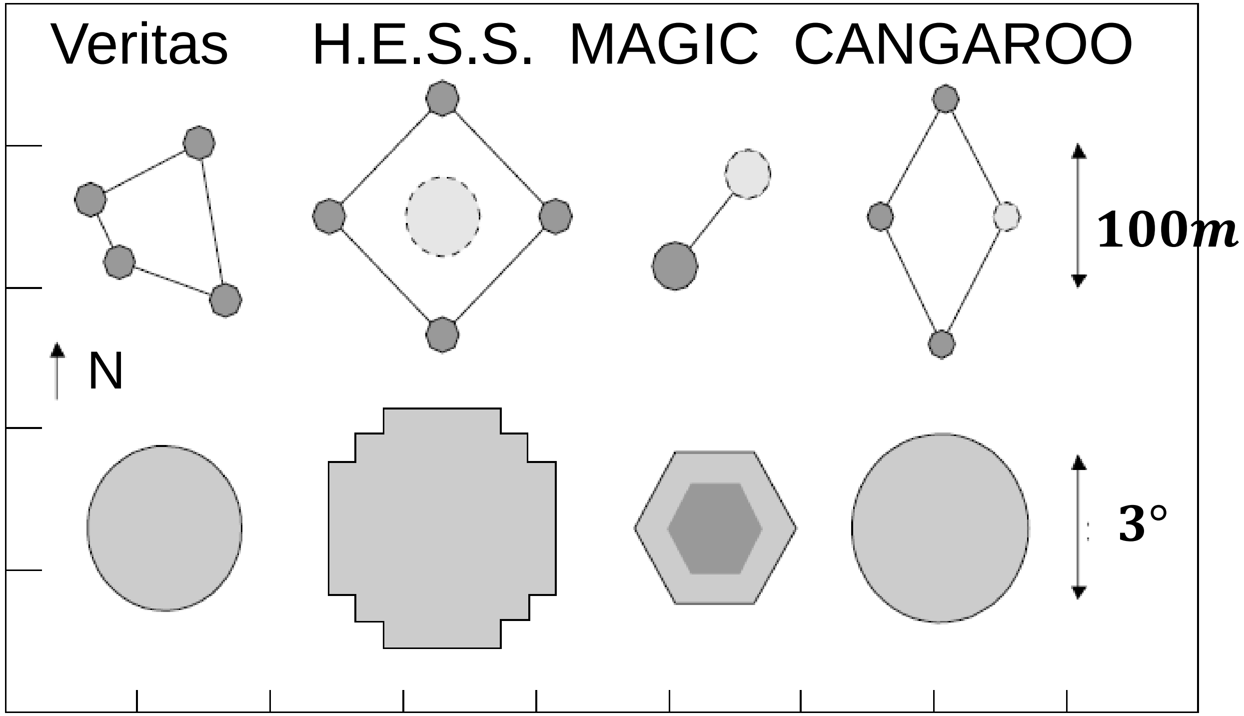


Improved sensitivity via large arrays of IACTs

- **3D view of a shower by setting up many IACTs**

  - improved sensitivity to
    - low gamma fluxes
    - arrival direction
    - energy estimate
  - improved particle discrimination

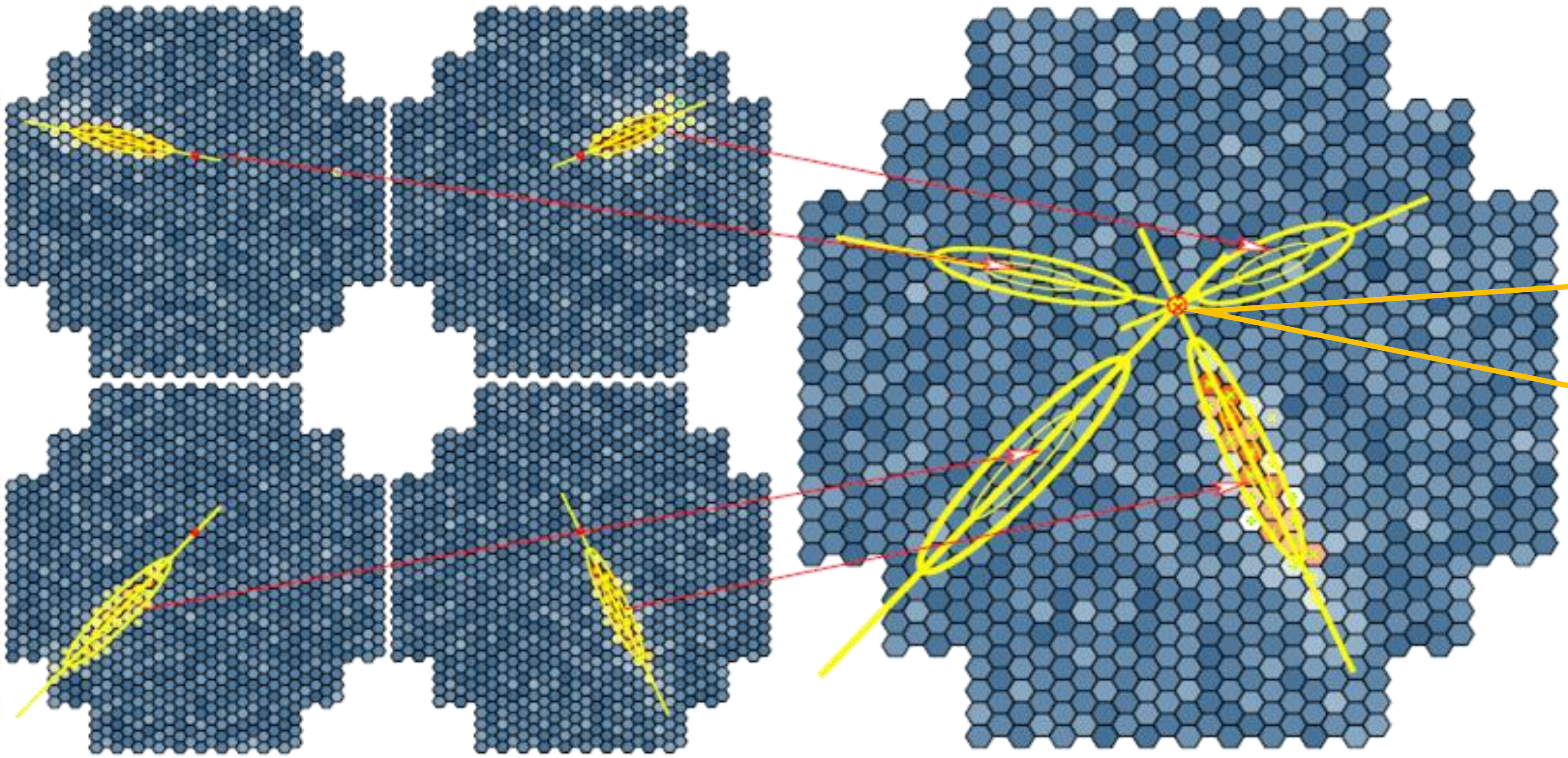


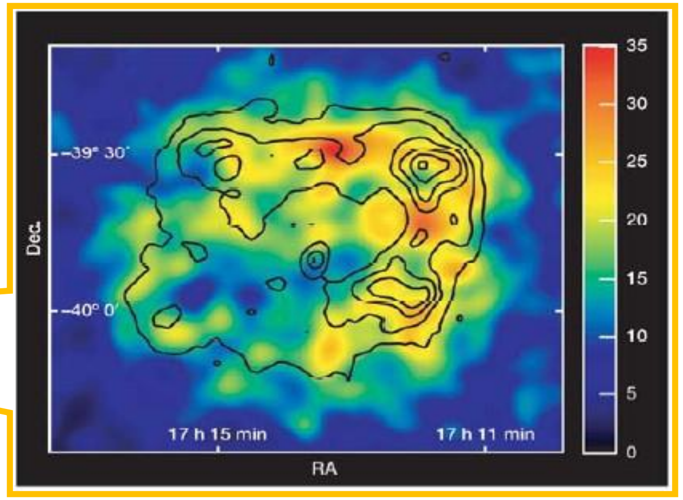


layout of large Cherenkov-telescope-arrays

Arrays of IACTs: example H.E.S.S.

- **Combining 4 IACTs in the H.E.S.S. experiment: 3D reconstruction of tracks**
  - improved angular resolution at the TeV-scale: images of shells of SNRs,…





combining the information of 4 telescopes from H.E.S.S.

Overview of TeV gamma observatories

- Sites of the most important experiments for gammas

MAGIC telescopes at La Palma

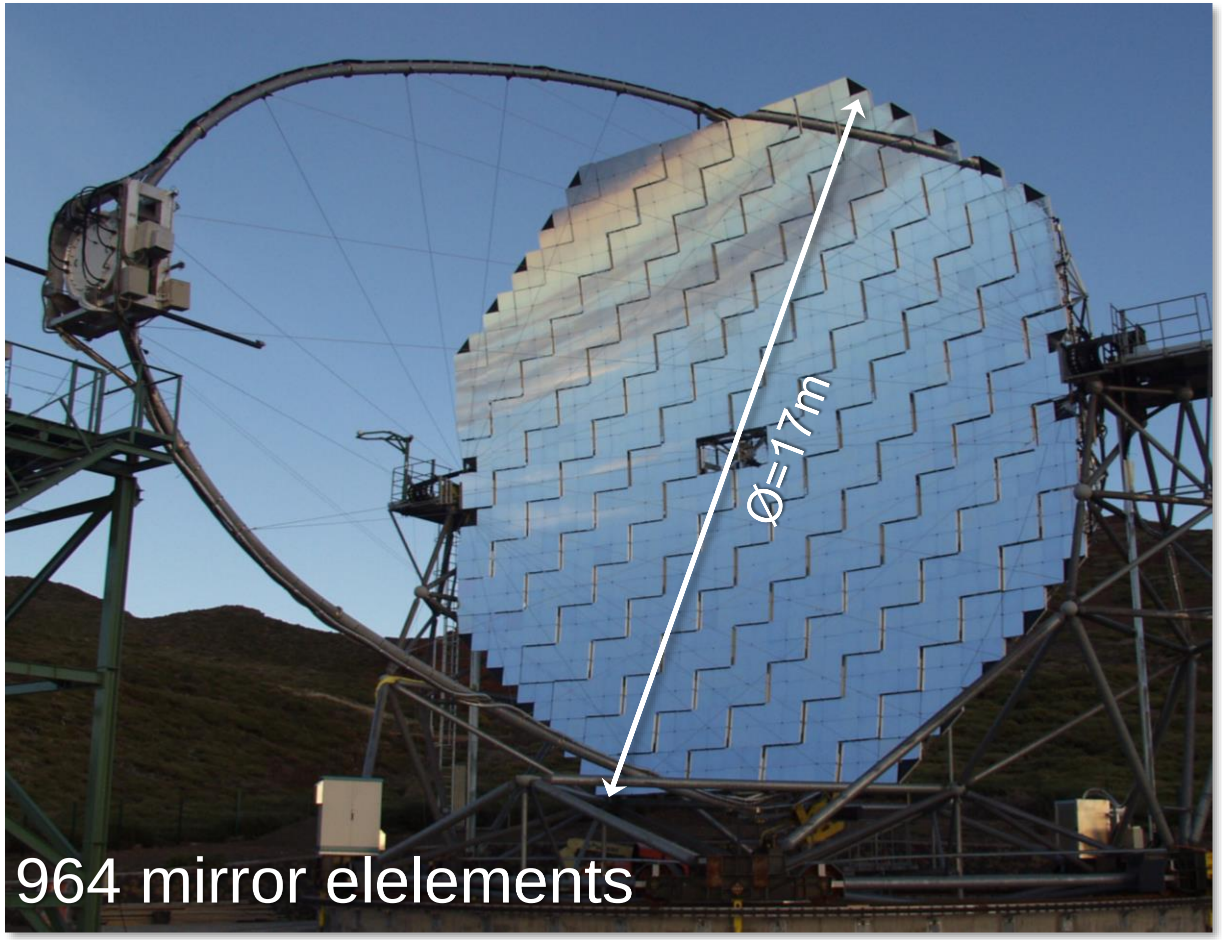
- **M**ajor **A**tmospheric **G**amma **I**maging **C**herenkov Telescope

- **2 IACTs** at La Palma (Canary Islands)

- operations since 2009

- large parabolic mirror: $\emptyset = 17\,m$

- mirror: $A = 236\,m^2$, field-of-view: 3.6°



MAGIC telescopes at La Palma

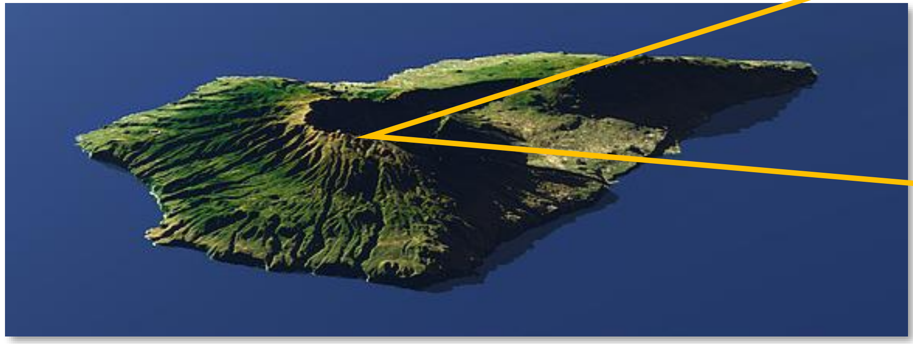
- Major Atmospheric Gamma Imaging Cherenkov Telescope

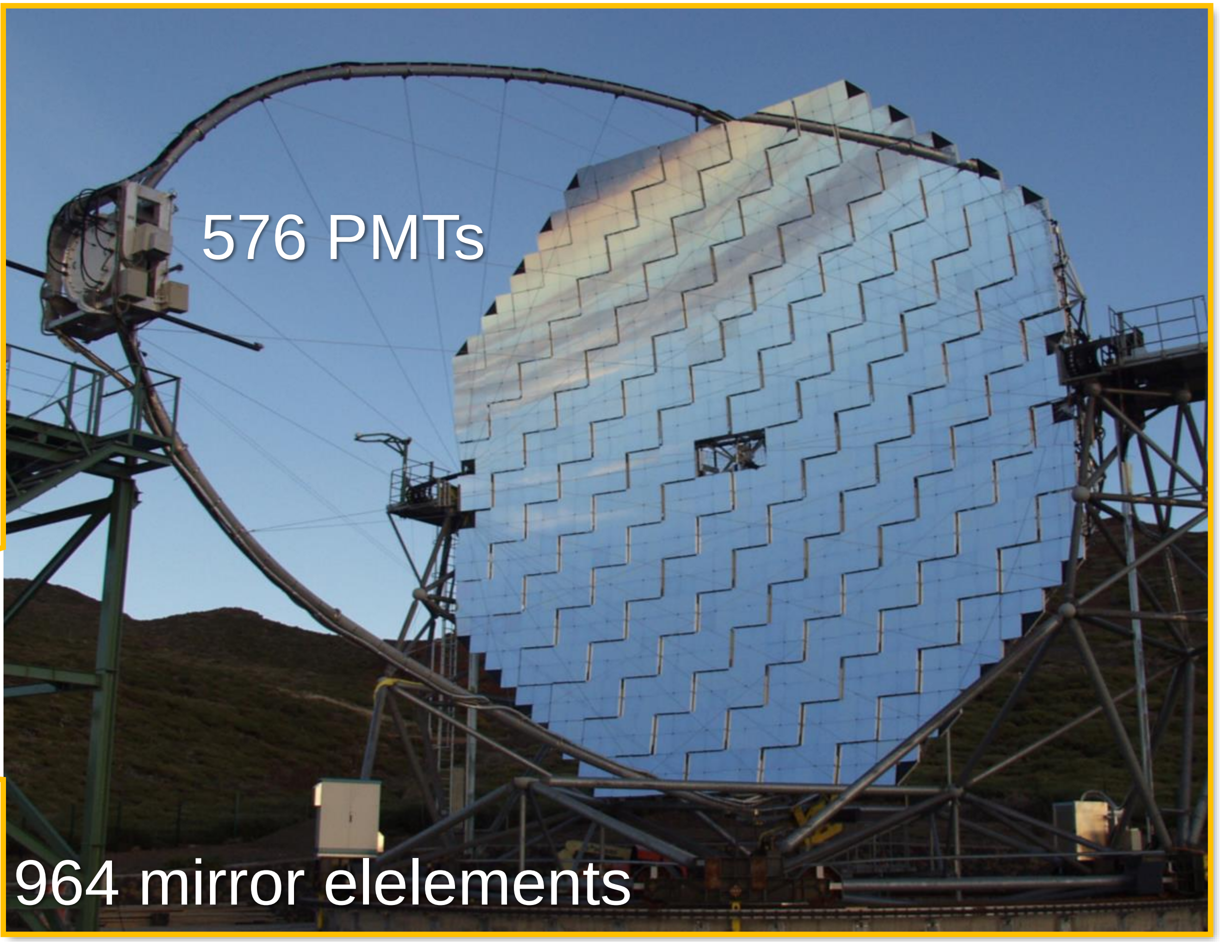
- energy range: $E = 30\ GeV \dots 50\ TeV$

- construction based on carbon-fibres:
  lightweight construction - $M = 64\ t$

- fast positioning: $\Delta t \sim 50\ s$
  very important in case of GRBs

La Palma
volcano
Taburiente





MAGIC telescopes at La Palma

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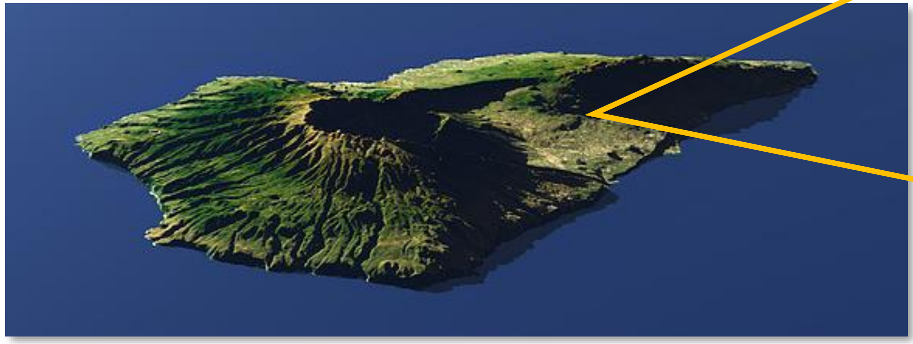
- MAGIC observations stopped due to **volcanic ash** over several months

19.9.-13.12.
2021

La Palma
volcano
Taburiente

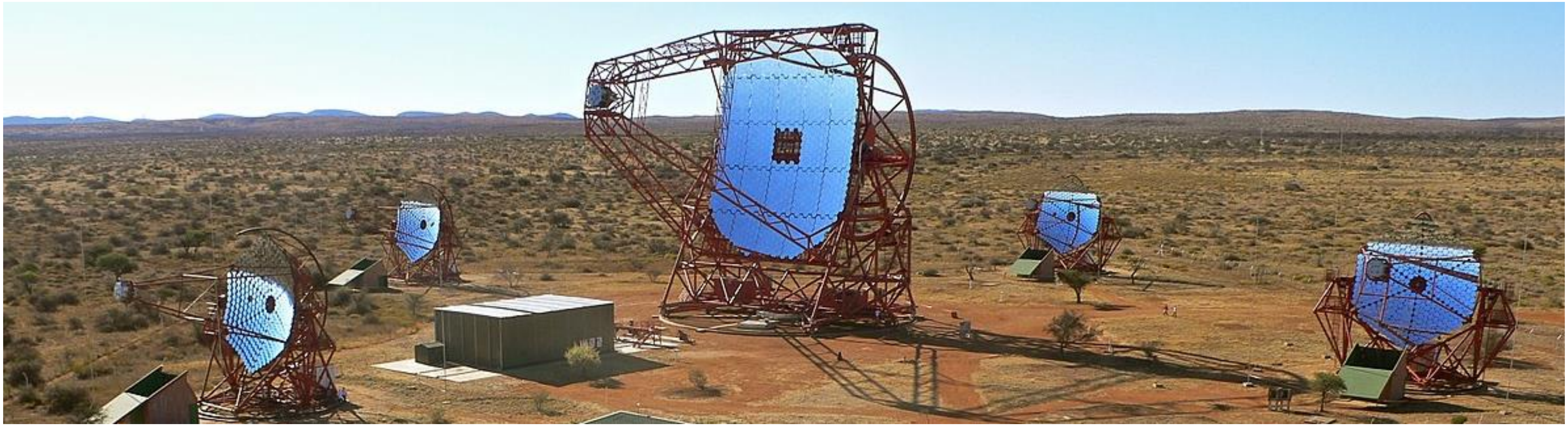


H.E.S.S. observatory at Gamsberg in Namibia

- **High Energy Stereoscopic System in operation since 12/2003**

\- **IACTs**: 4 smaller-sized - each mirror with $\emptyset = 12\ m$, 1 large IACT

\- energy range: $E = 30\ GeV \ldots 100\ TeV$



H.E.S.S. observatory at Gamsberg in Namibia

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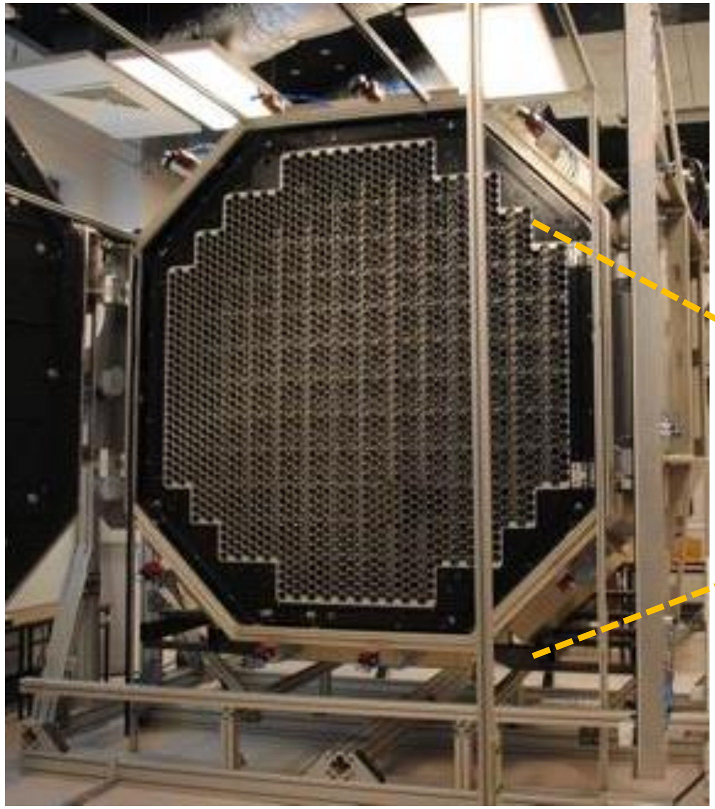
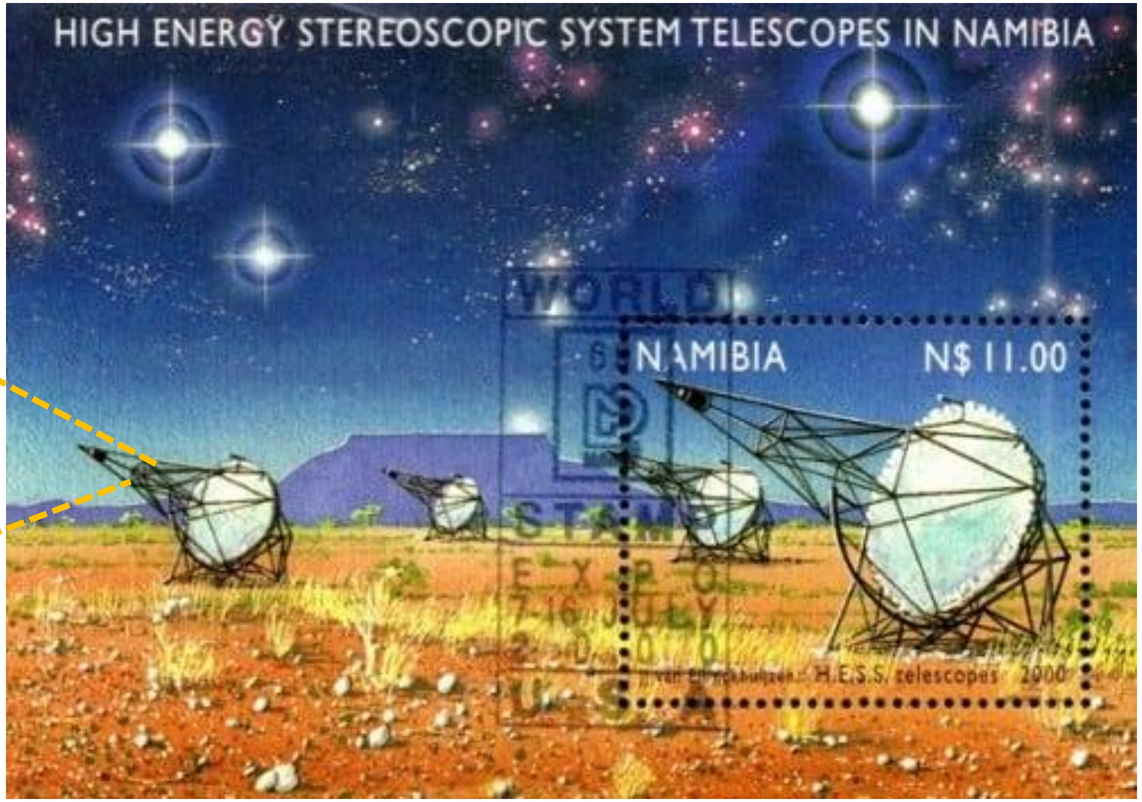
- **High Energy Stereoscopic System in operation since 12/2003**

\- large IACT: mirror $\emptyset = 28\,m$ area: $a = 107\,m^2$ focal lenght: $f = 15\,m$

H.E.S.S.

read-out by
950 PMTs





Defining sensitivities of IACTs: 1 Crab

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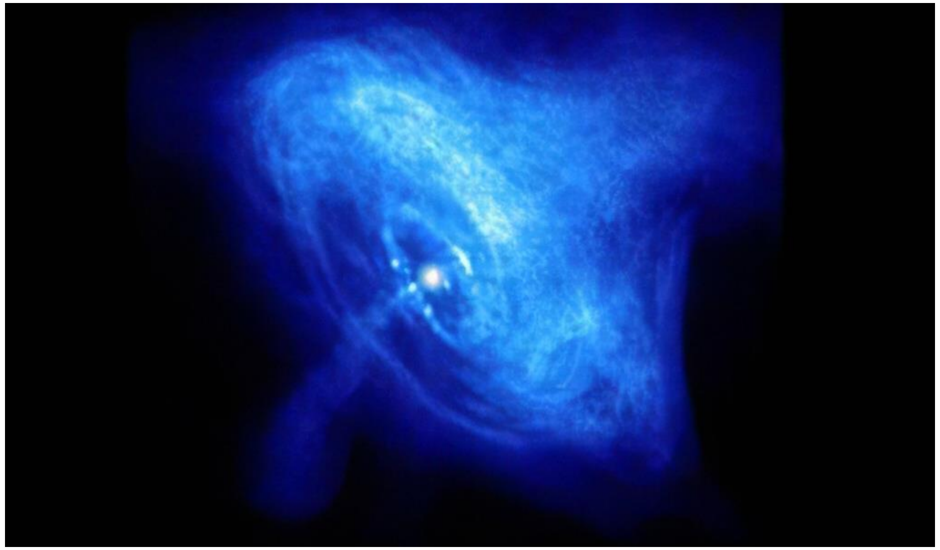
- **Definit a unit for gamma astronomy: the Crab**

  - **unit** for gamma flux from astrophysical sources with $E(\gamma) > 1\,TeV$:

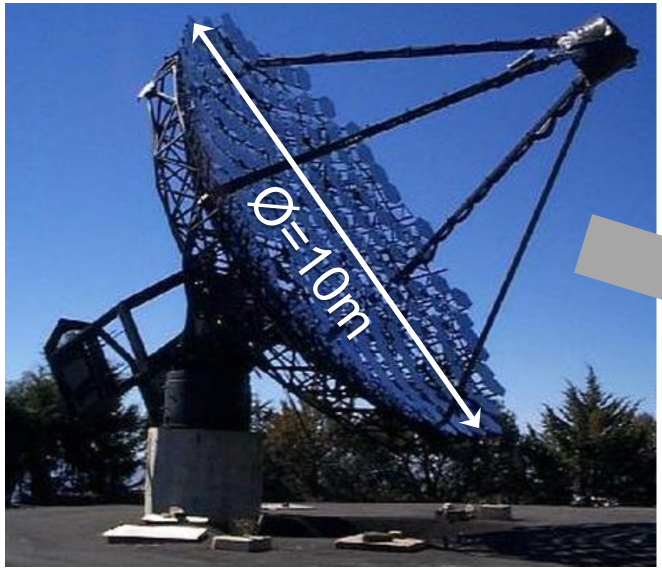
$$\mathbf{1\,Crab = 1\,event/10^3 m^2 \cdot h}$$



Crab nebula:
brightest galactic
gamma source

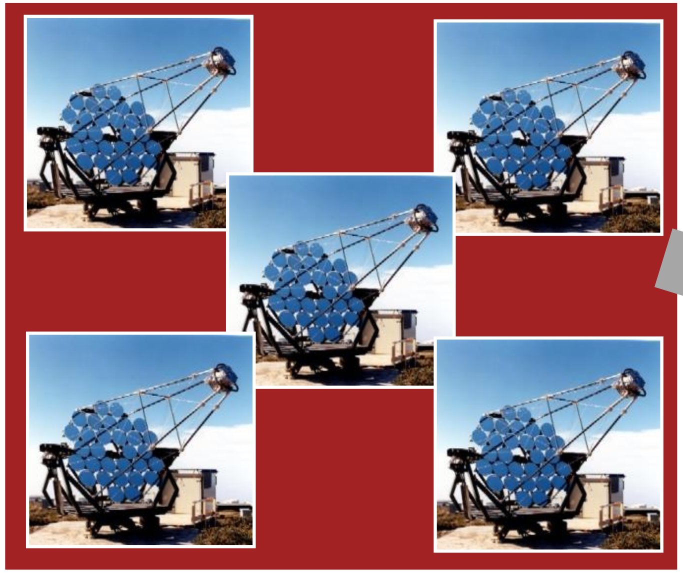
Improving sensitivities of IACTs: time to see Crab

- **Larger mirrors & better light detection (PMTs)**



Whipple 1989
(discovery): 50 h

5 telescopes of
each $A = 8.5\,m^2$



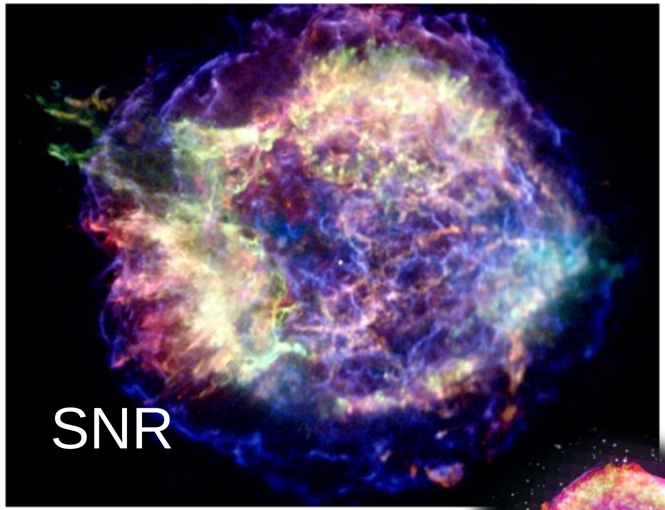
HEGRA 1997:
10 min

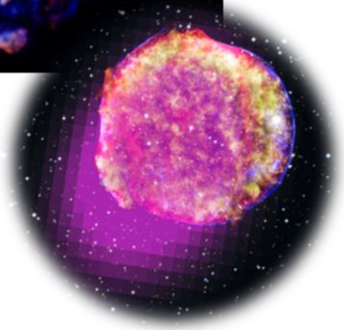
H.E.S.S. 2004:
30 sec

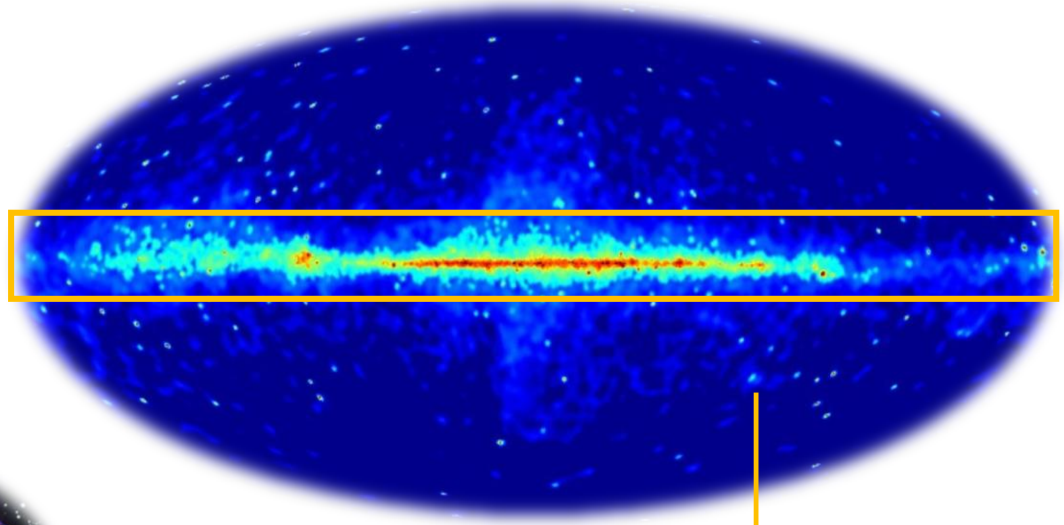
Astrophysical TeV- gamma sources

- **How & where are high-energy TeV gammas being created?**

  - galactic sources: SN shockwaves, pulsar wind nebulae, processes in the ISM*







- extra-galactic sources: AGN,…

pulsar wind-nebulae

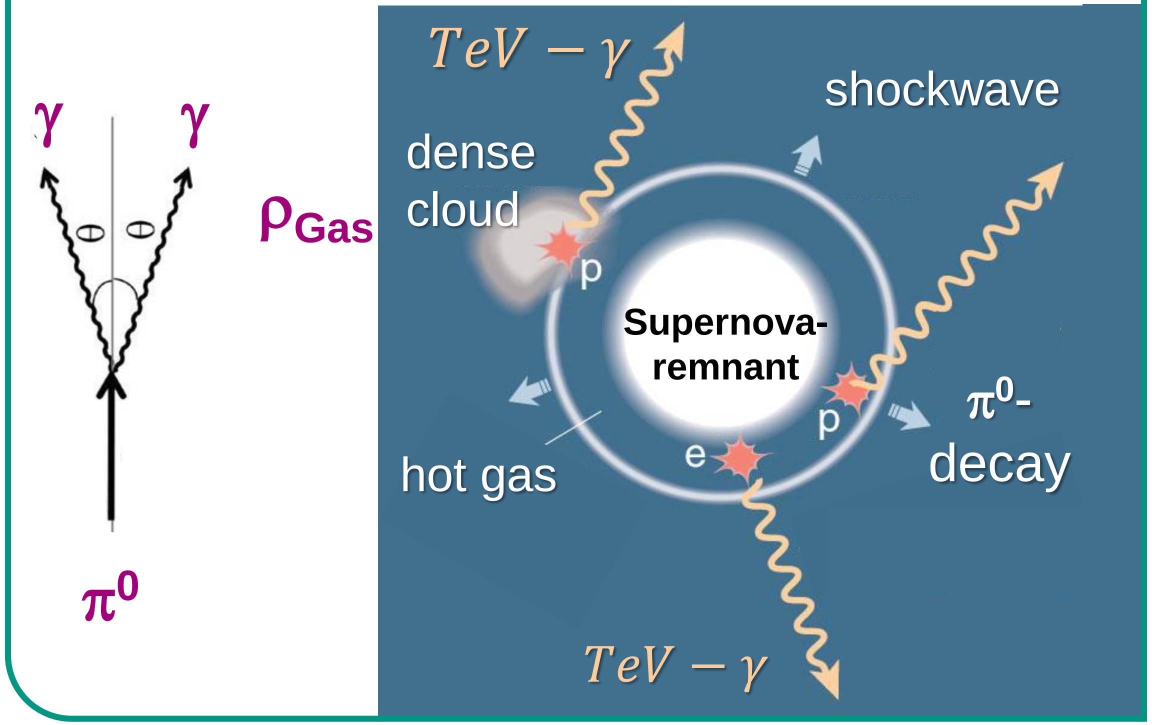
*interstellar medium

Gamma production: hadronic or leptonic?

- **Two basic mechanisms to generate very high-energy gammas in a SNR**

hadron-interactions

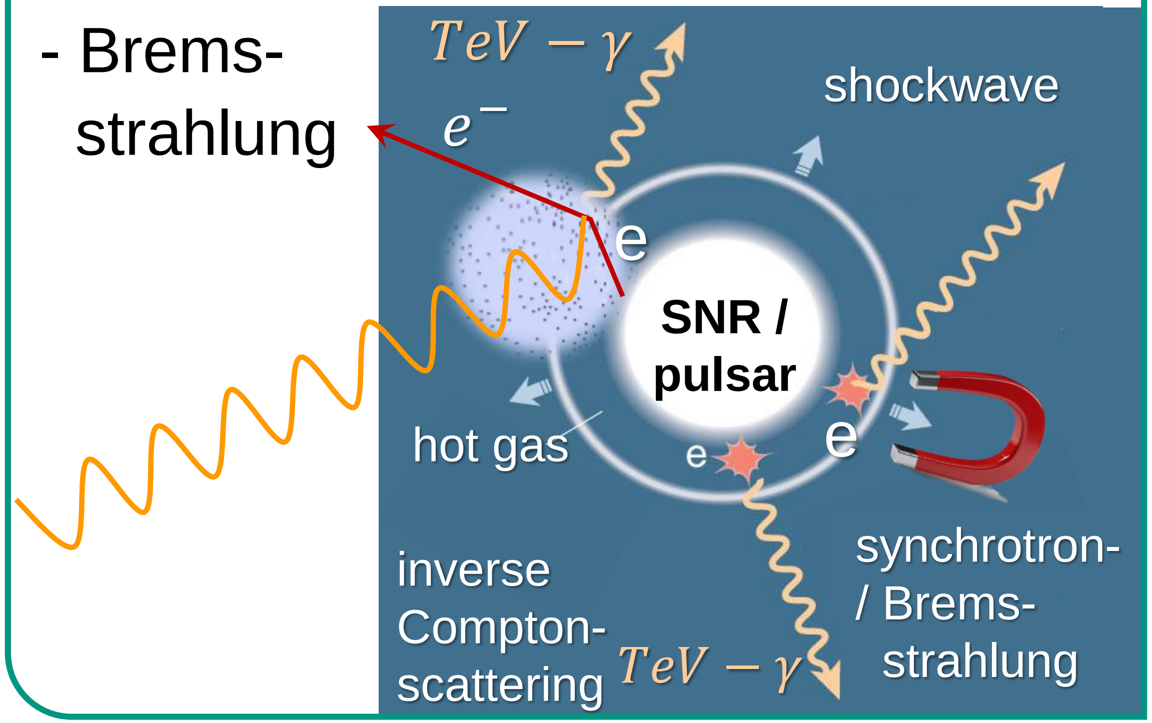
- **decay neutral pions**: $\pi^0 \rightarrow \gamma + \gamma$



electron-interactions

- **inverse Compton**: $\gamma + e^- \rightarrow \gamma + e^-$

- Brems-strahlung

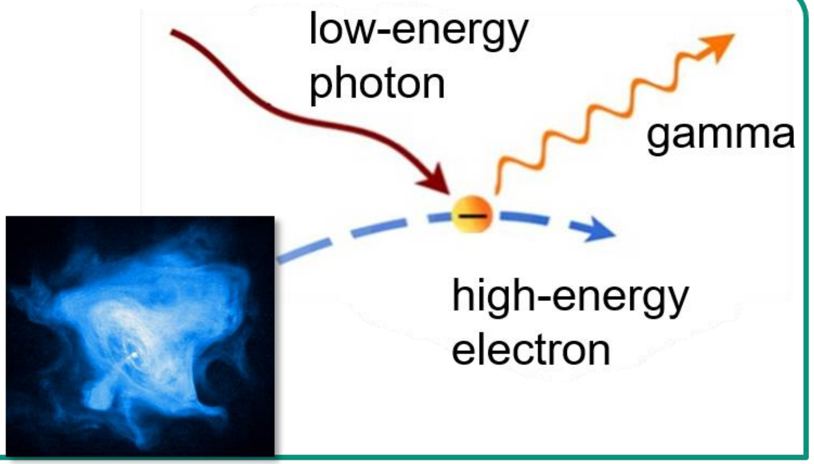


Gamma production: leptonic scenarios

- **Pulsar wind nebulae as emitters of TeV –scale gamma radiation**

inverse Compton effect

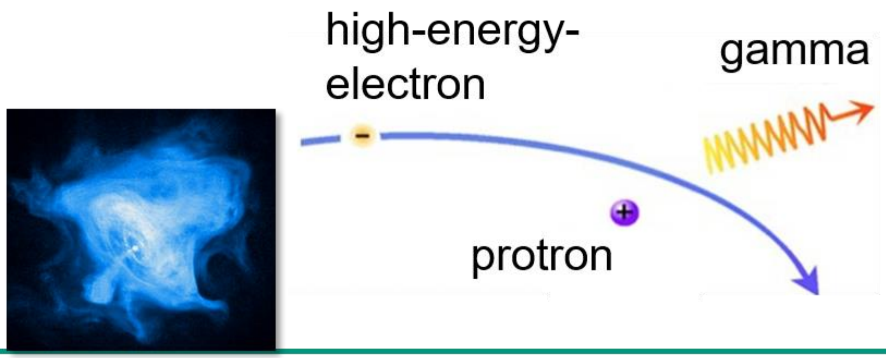
- low-energy photon is acclerated by a high-energy electron from a SNR/pulsar
- efficient acceleration to TeV-energies



bremsstrahlung

- high-energy electron radiates off gamma rays (GeV-TeV-energies)

$$\left(\frac{dE}{dX}\right)_{brems} = \frac{4\cdot\alpha^3\cdot N_0}{m^2}\cdot\frac{Z^2}{A}\cdot\ln\left(\frac{183}{Z^{1/3}}\right)\cdot E$$



Gamma production: hadronic scenarios

Karlsruhe Institute of Technology

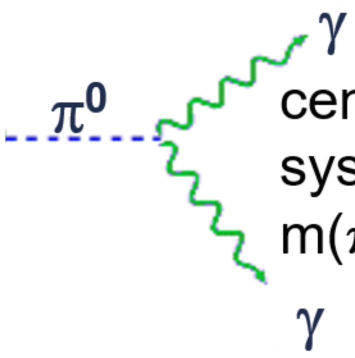
- **Shock wave of SNR accelerates protons to produce $\pi^0 \rightarrow \gamma\gamma$**

- proton-proton collisions:
  generation of pions
  (charged, neutral)

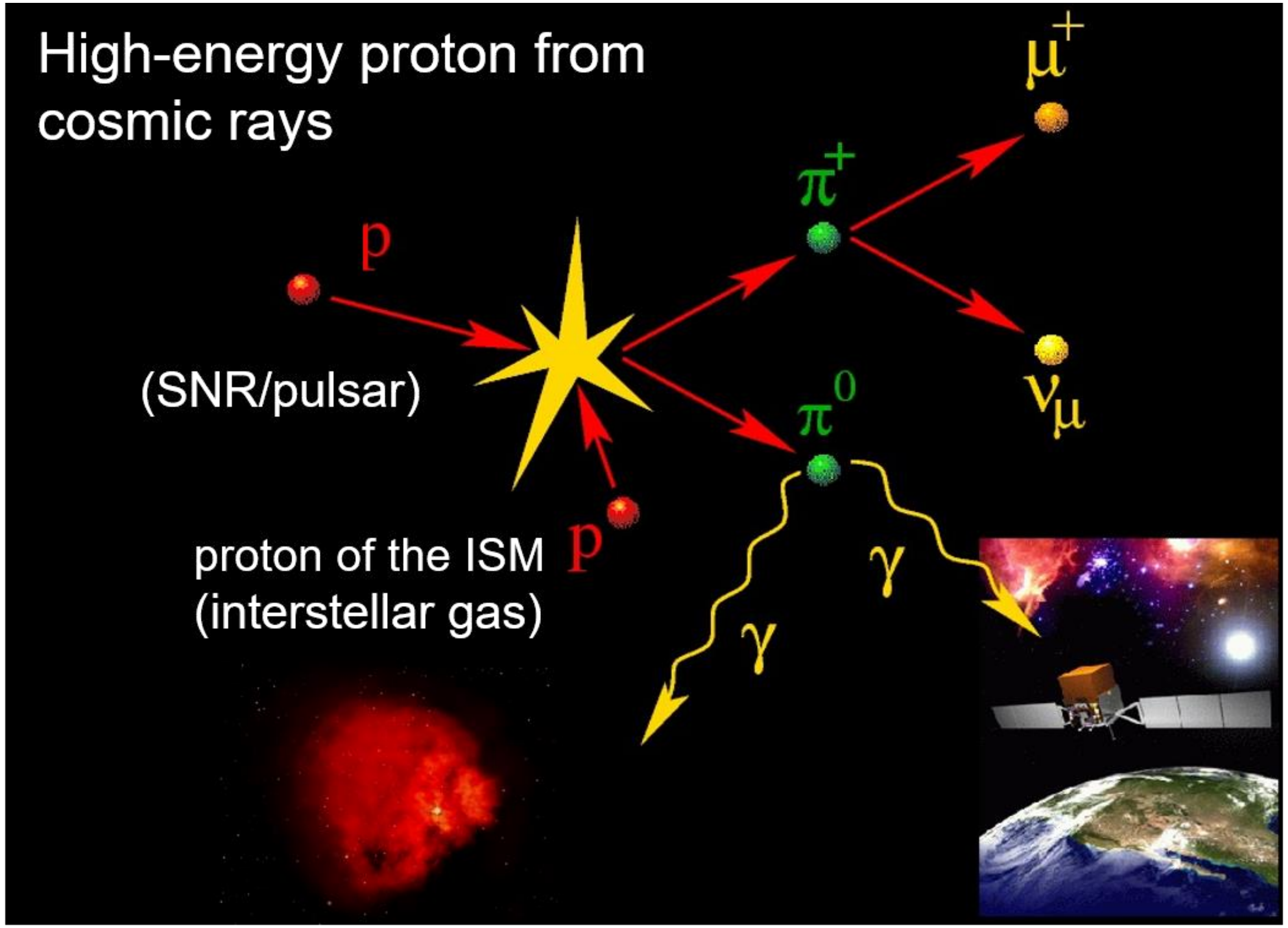
pion decay

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

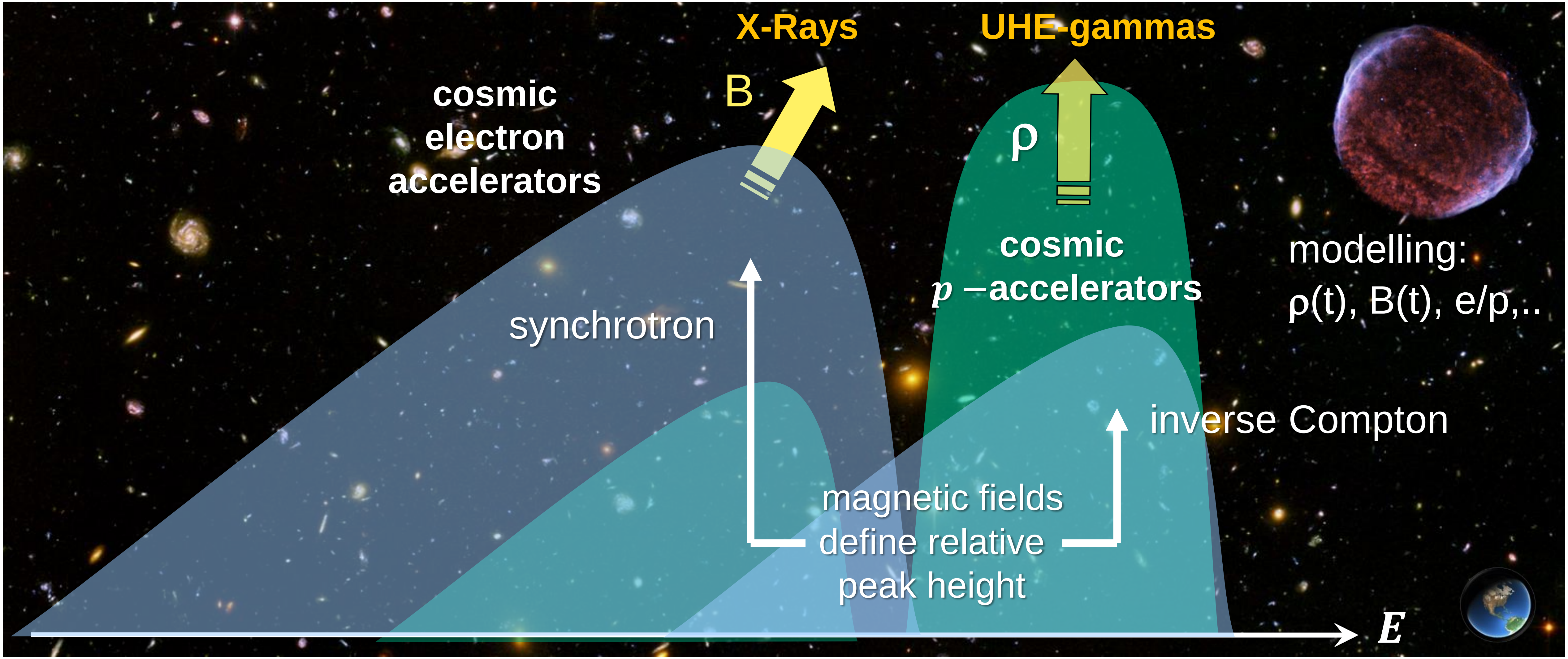
gammas from π^0-decay:



centre-of-mass system:
$m(\pi^0) = 135$ MeV

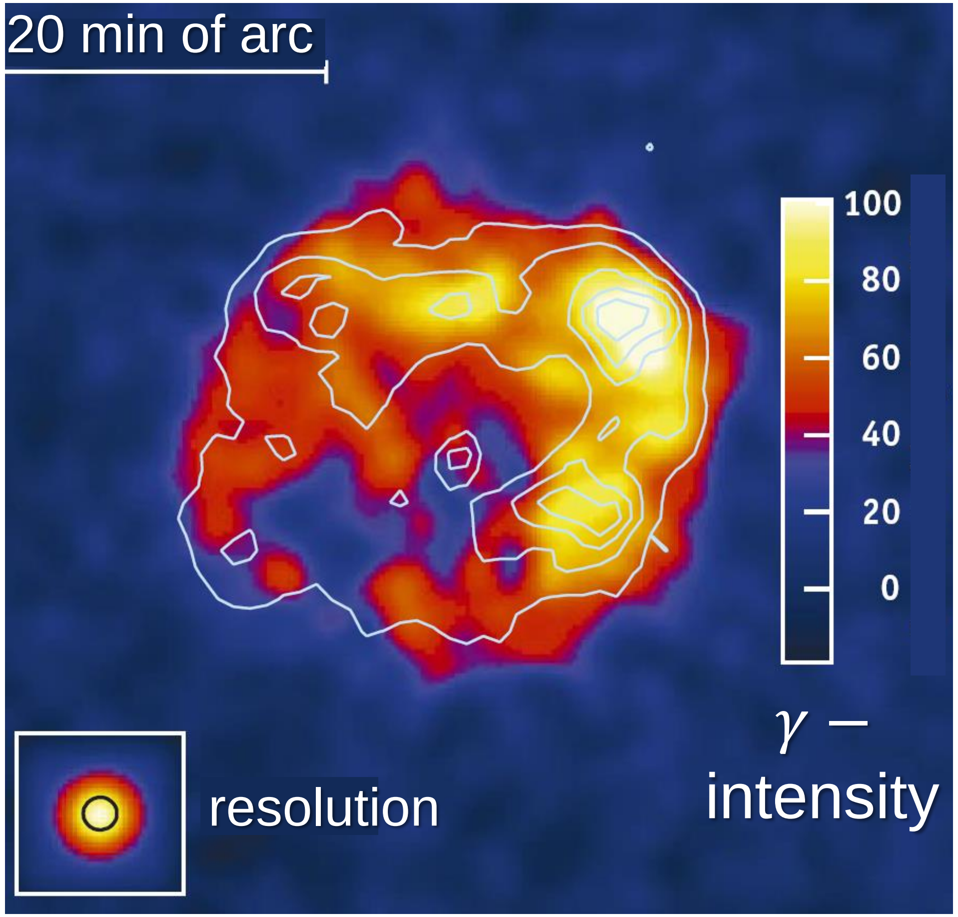


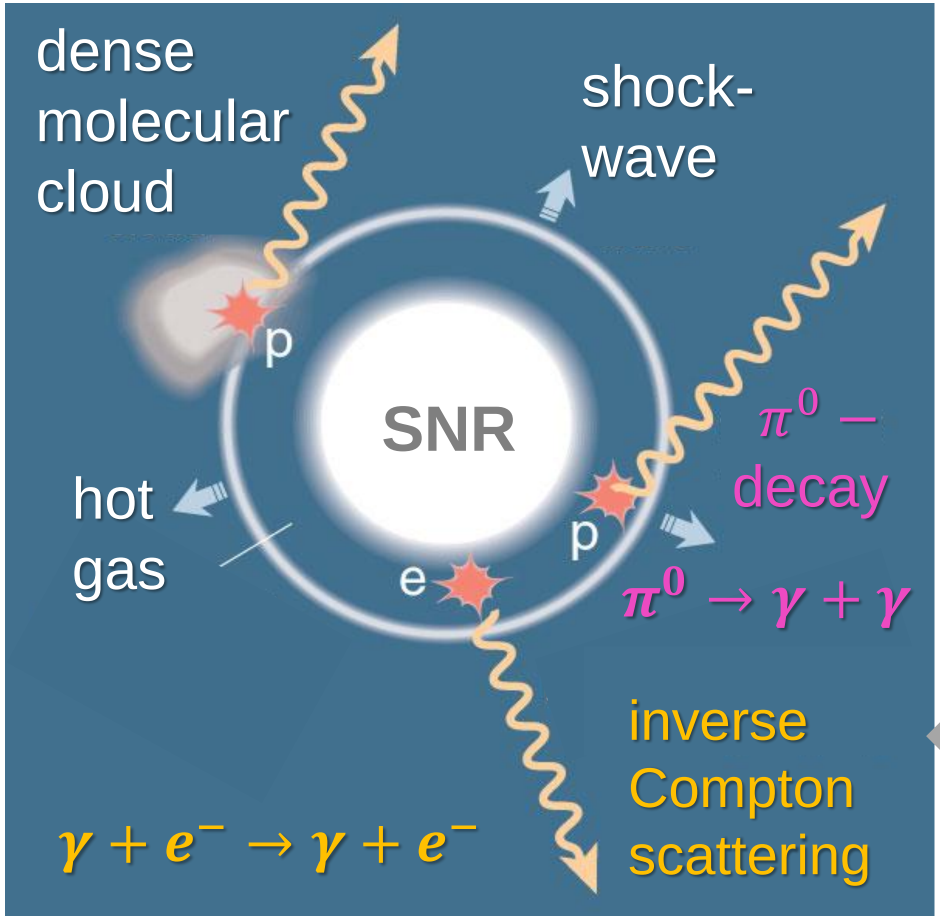
Spectral energy density of photons



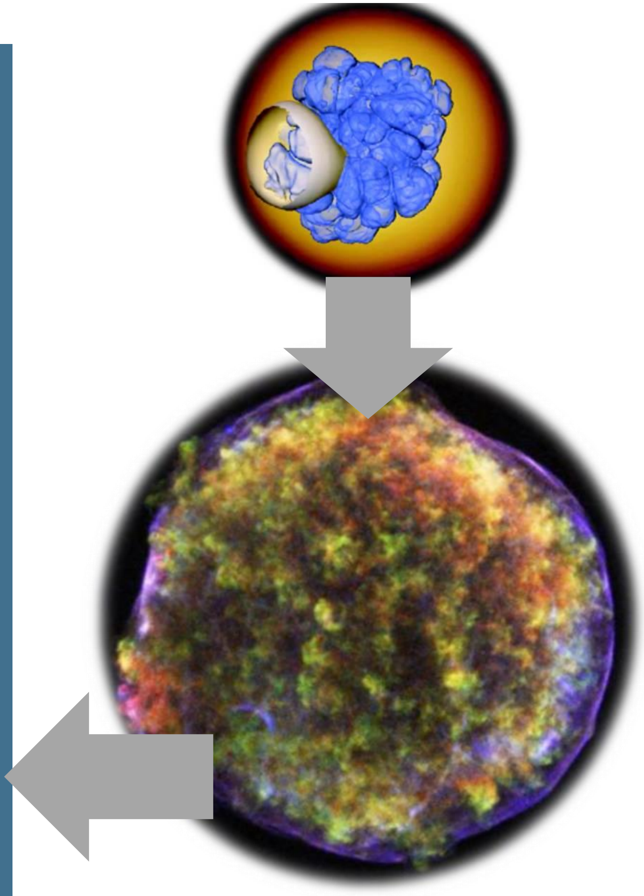
Expanding shells of supernovae (SNRs)

- SNR as lepton (inverse Compton) or proton (π −decay) acclerators





SN-1a*

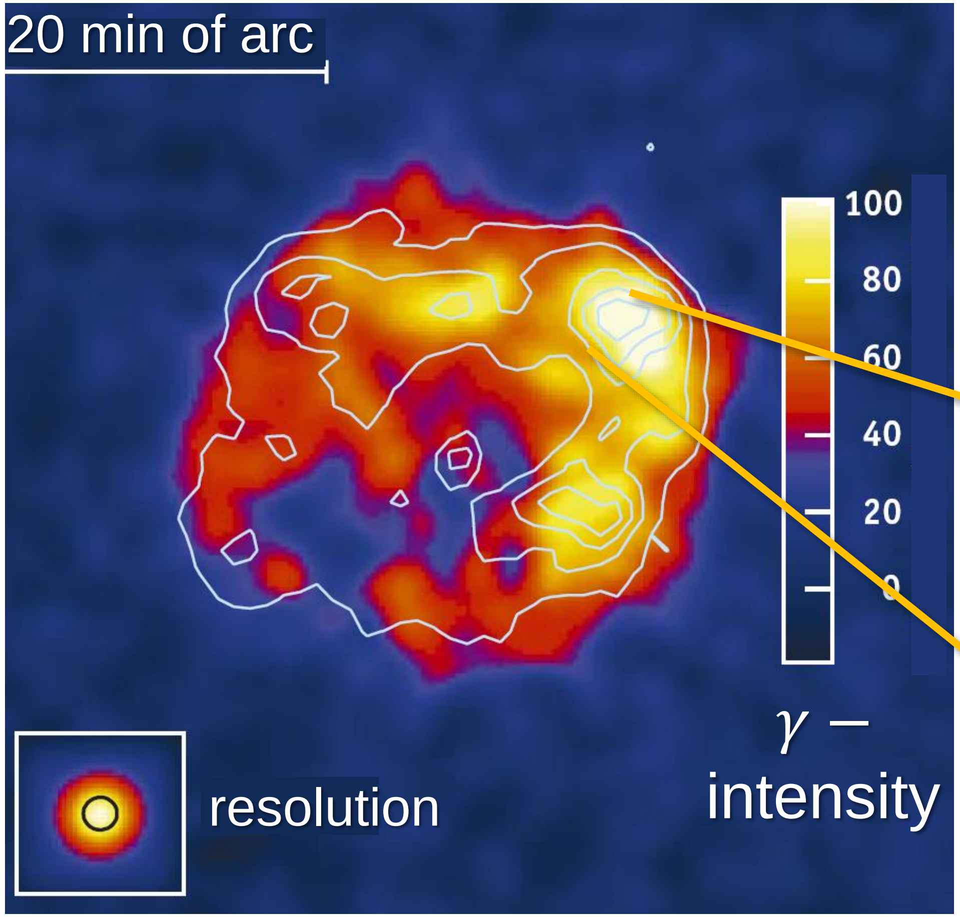


*see summer term 2023

Expanding SNR shells: a hadronic TeVatron?

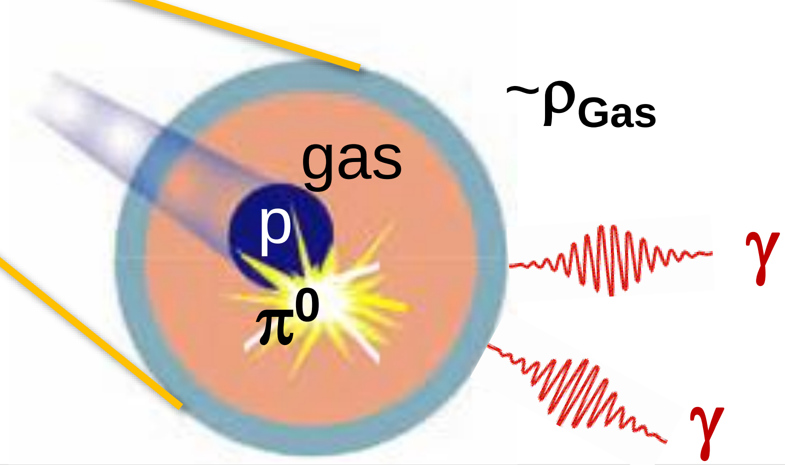
Karlsruhe Institute of Technology

- **SNR as proton (π –decay) acclerator: interactions of $p´s$ in hot gas**



- modelling of the extended SNR-shell RX J1713.7-3946 (SN393) in $d = 1\ kpc$
- first study of an **extended shell** of an ancient SN in the light of TeV Gammas

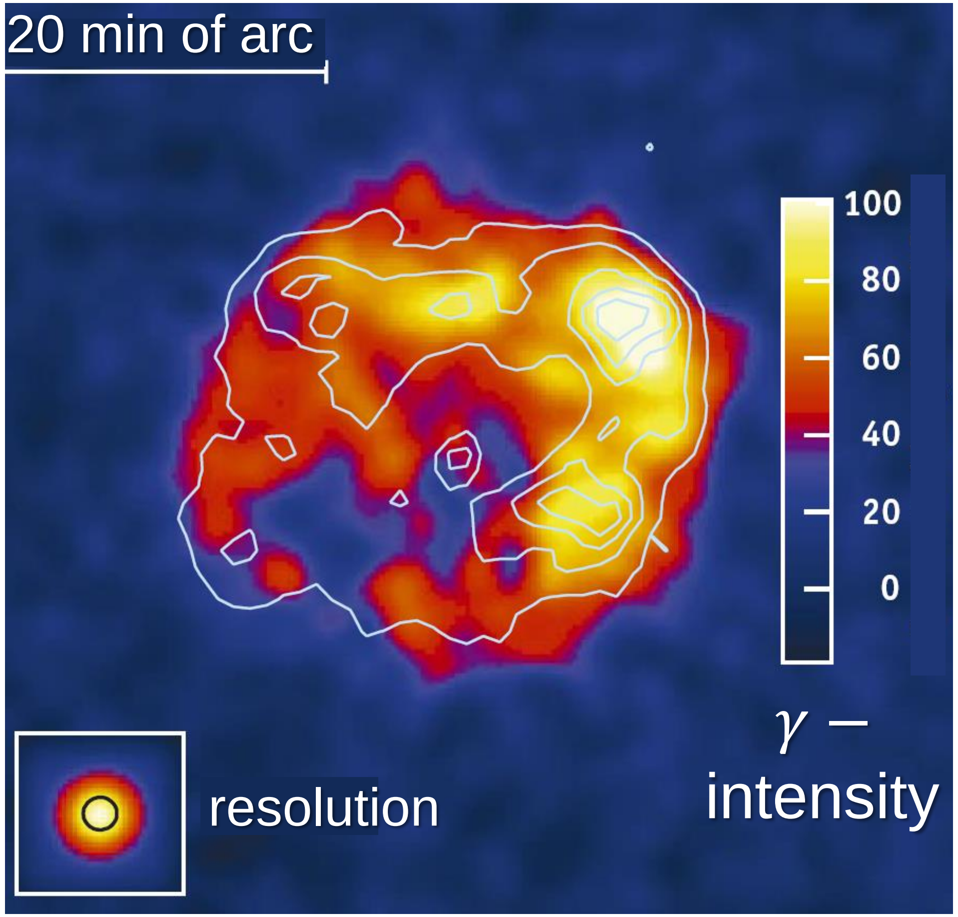
⇨ good agreement with X-ray contour lines

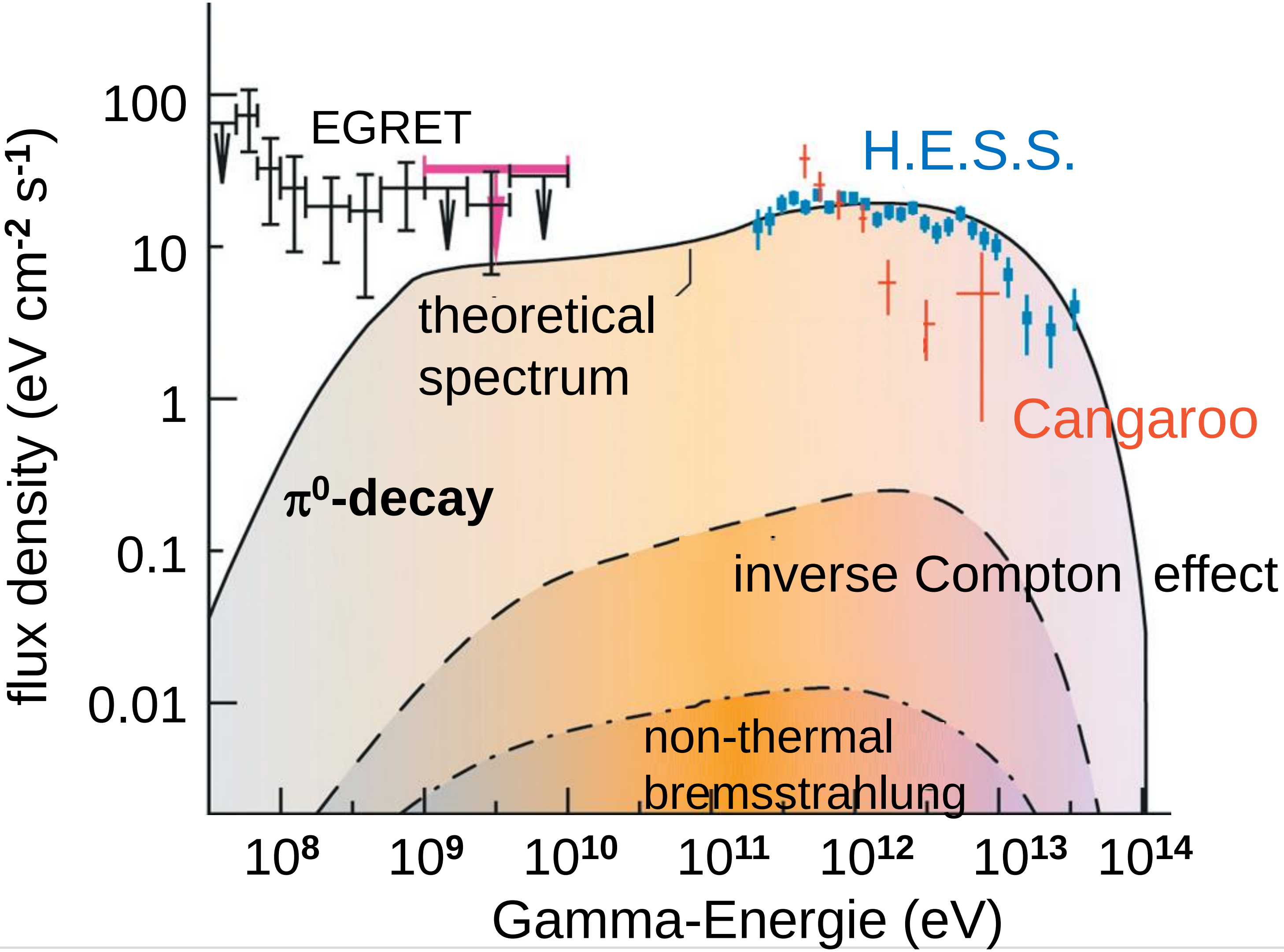


hadronic acceleration

Expanding SNR shells: a hadronic TeVatron

- **SNR modelling: π^0 – decay**

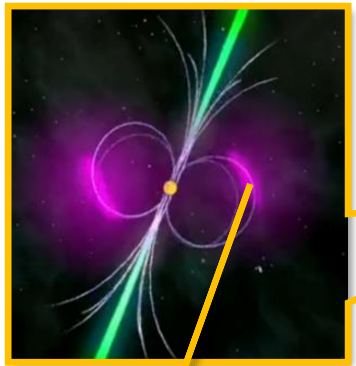




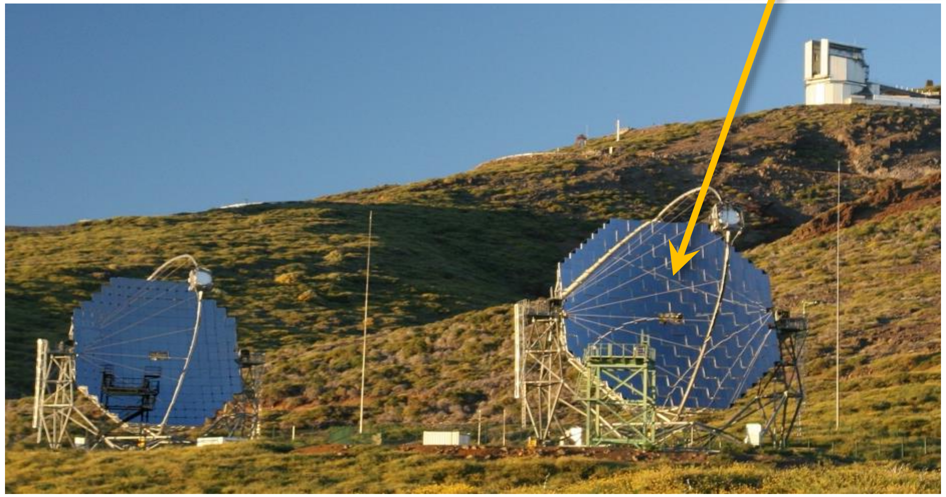
Pulsar at the center of the Crab Nebula (SN1054)

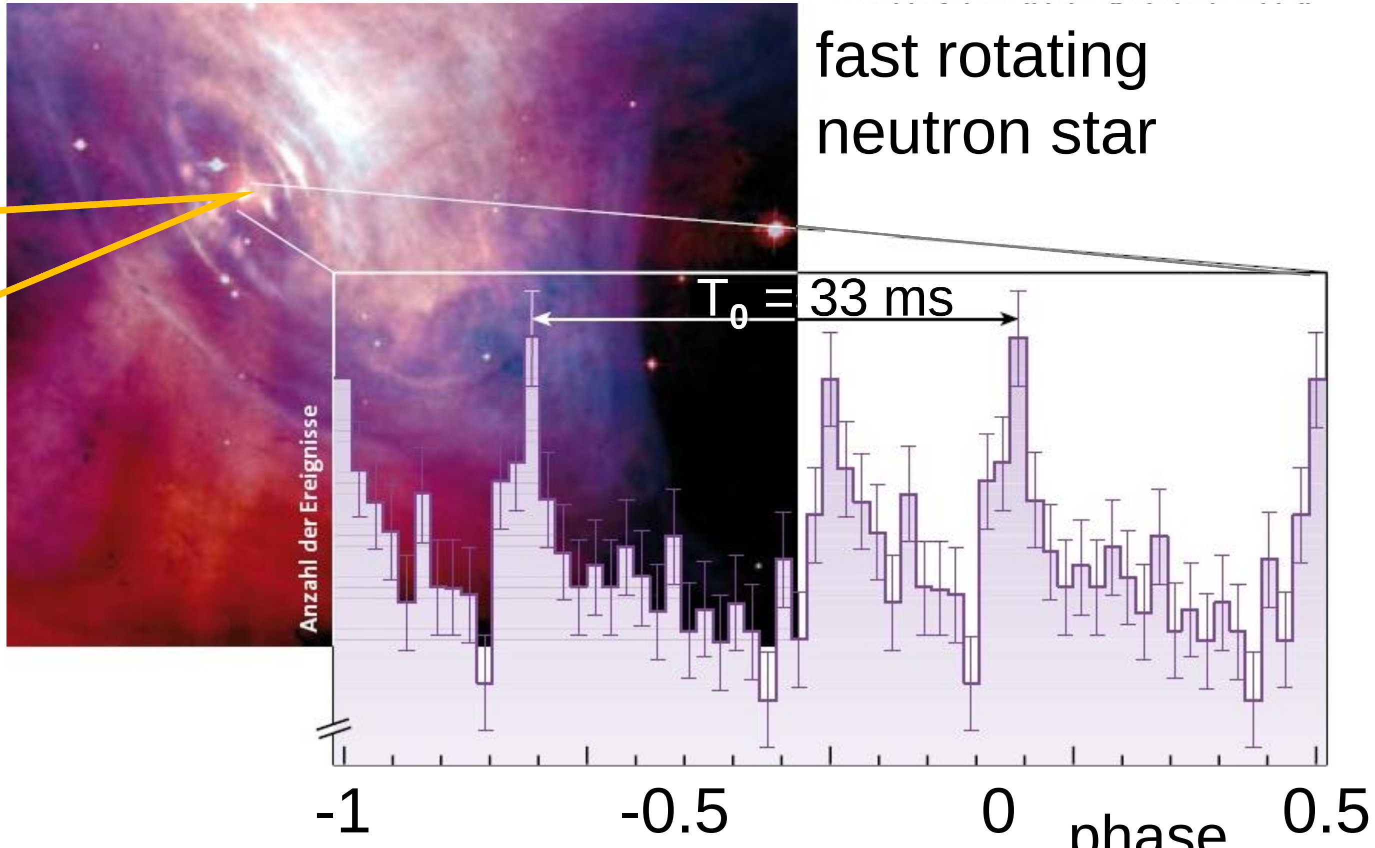
- **The ´gold standard´ for UHE gamma astronomy: gammas up to 400 GeV**
  - origin of γ – pulses: not from polar caps, but from outer pulsar magnetorsphere

a cosmic
´light house´



MAGIC-II

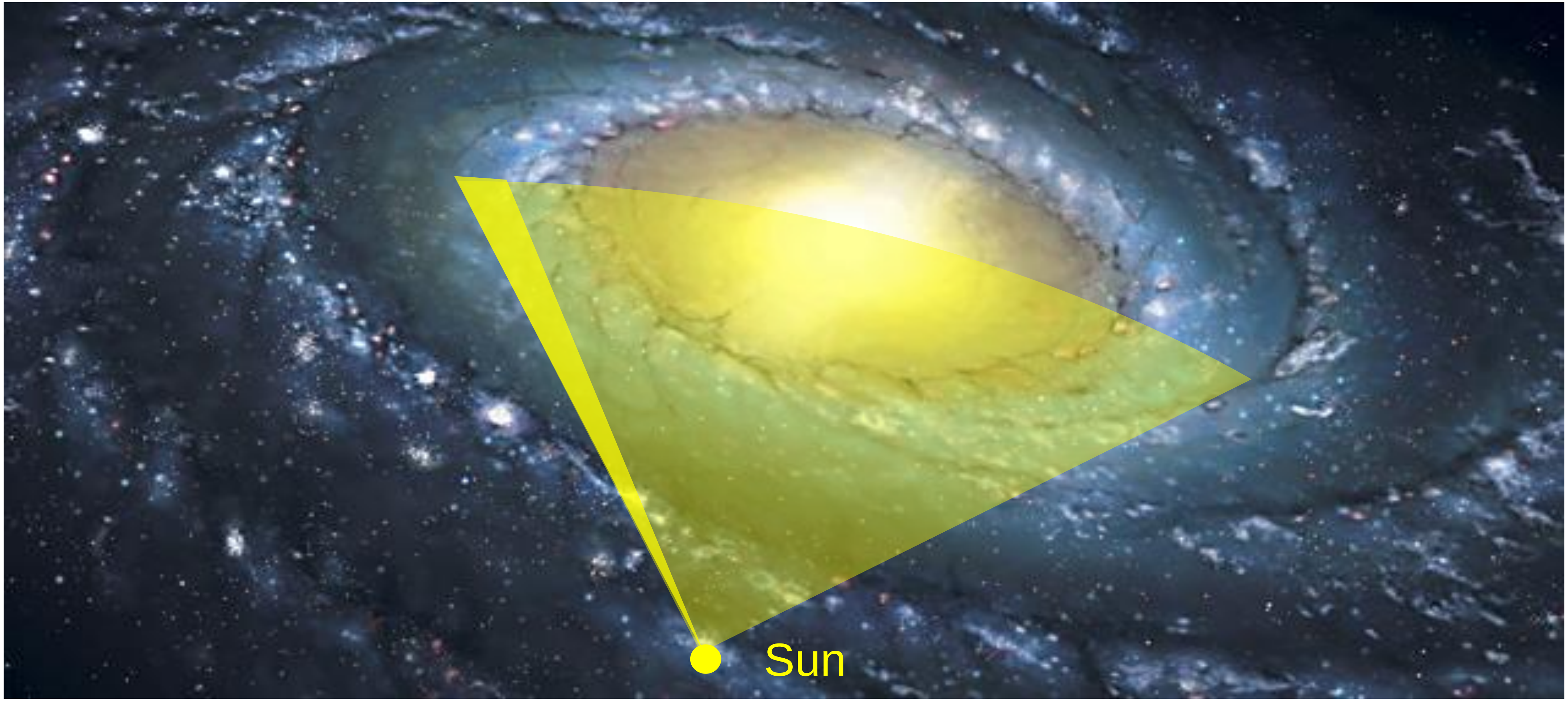




fast rotating
neutron star

Scanning the galactic plane for UHE gammas

- 2004: first scan with H.E.S.S. over > 600 h – 15 new sources at TeV – scale



Scanning the galactic plane for UHE gammas

- **2004: first scan with H.E.S.S. over > 600 h – 15 new sources at TeV – scale**