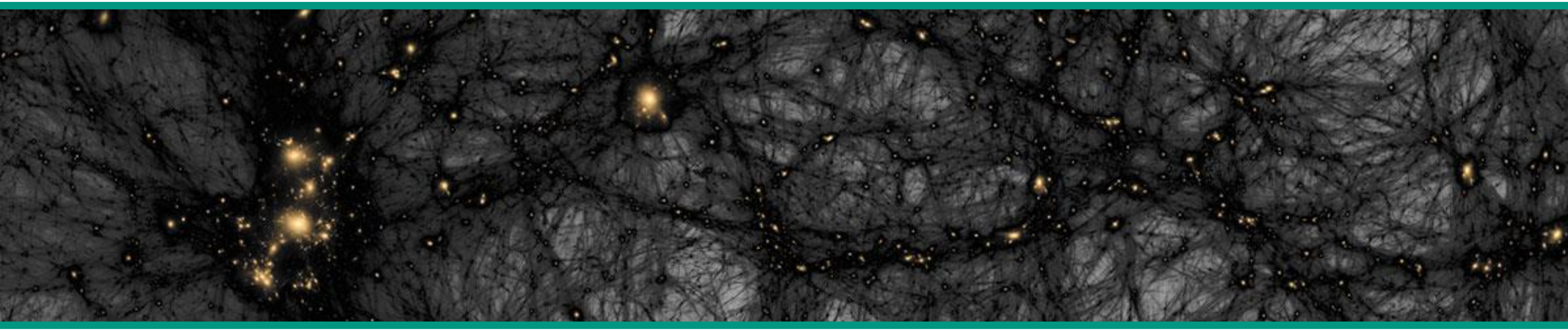
Astroparticle physics *I* – Dark Matter

Winter term 23/24 Lecture 8 Nov. 23, 2023



Recap of Lecture 7

- $\boldsymbol{UHE}$ **neutrinos: flavour oscillations studies** & **search for point sources**

  - flavour composition from decay chain $\boldsymbol{\pi \rightarrow \mu \rightarrow e}$ altered by $\boldsymbol{\nu}$ – **oscillations**

  - **background** for astrophysical neutrinos from **shower muons** & $\boldsymbol{\nu_{atm}}$

  - observatories **in–ice** ($\boldsymbol{IceCube}$) ⇔ **deep–sea** ($\boldsymbol{KM3NeT}$): techn. challenges

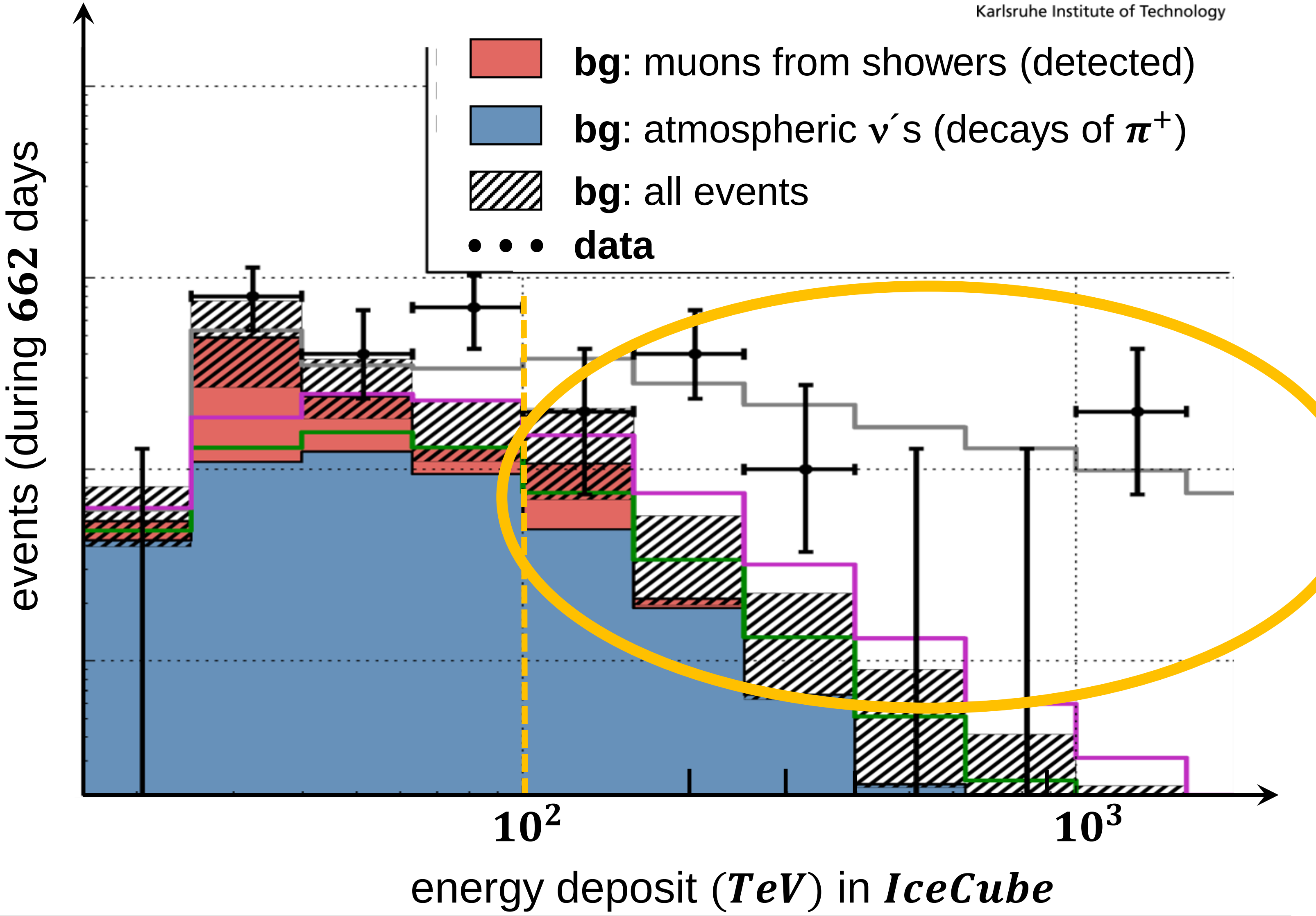
  - lower ($\boldsymbol{GeV}$ – scale) energies: study of matter–induced **oscillation effects**

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

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

$IceCube$: science harvest – 28 highest energy ν´s

- **Excess of events (2013) at highest energies**
  - $\mathbf{28}\ \boldsymbol{\nu}$ – induced events at energies $> \mathbf{100}\ \boldsymbol{TeV}$: first observation of $\boldsymbol{VHE}$ neutrinos from astrophysical sources



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

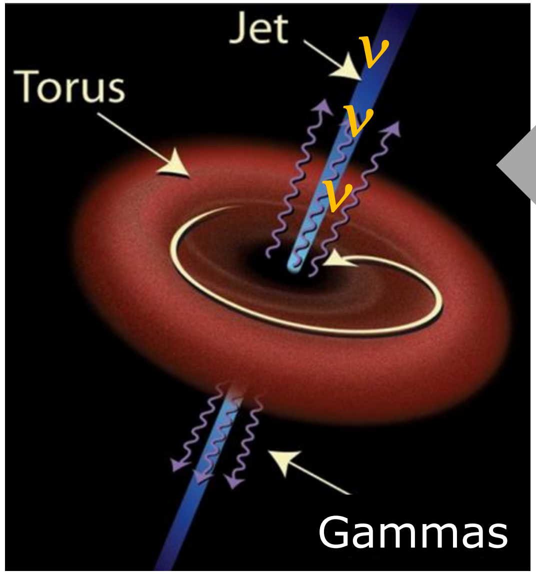
- **Gamma Ray Burst (GRBs) – VHE ν´s from a stellar collapse to black hole?**

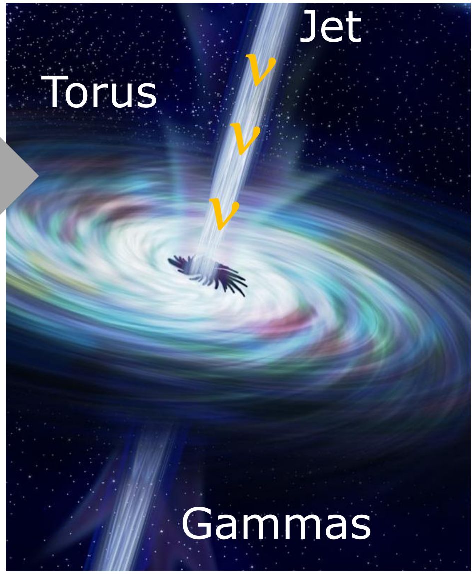
  - searching for **time coincidences** of $GRBs$ with $IceCube$ ν – signals

short GRB: merger of **2** neutron stars

formation of a black hole

long GRB: collapse of massive star





$\Delta t < 2s$

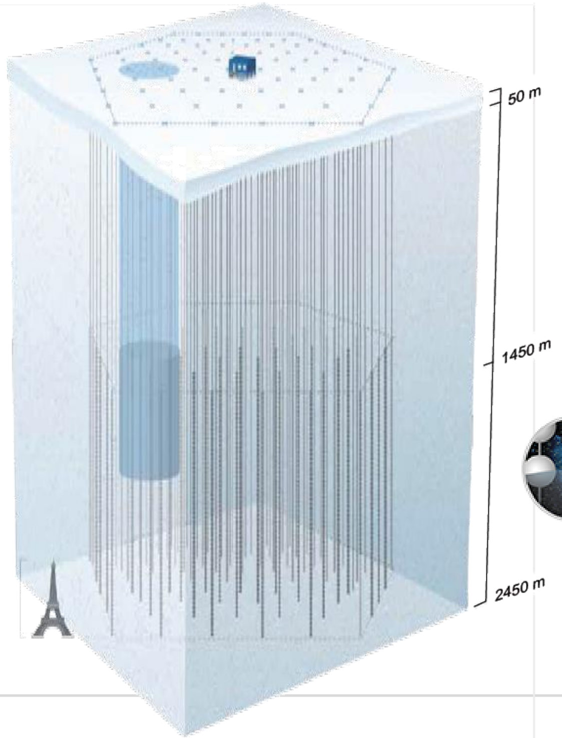
$\Delta t > 2s$

*see ATP – **2** summer term **2024**

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

- **Gamma Ray Burst (GRBs) – VHE ν´s from a stellar collapse to black hole?**
  - searching for **time coincidences** of $GRBs$ with $IceCube$ $\boldsymbol{\nu}$ – signals
  - **5** – year multimessenger–search (ν, γ) in both hemispheres

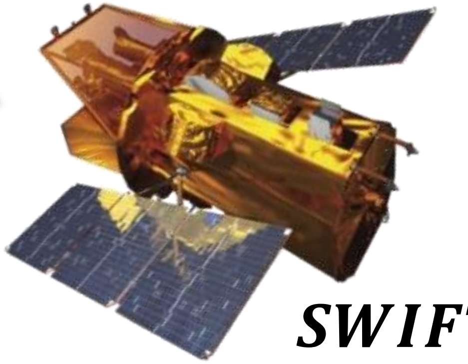
1172 $GRBs$ identified
508 northern hemisphere
664 southern hemisphere



ICECUBE SOUTH POLE NEUTRINO OBSERVATORY

γ

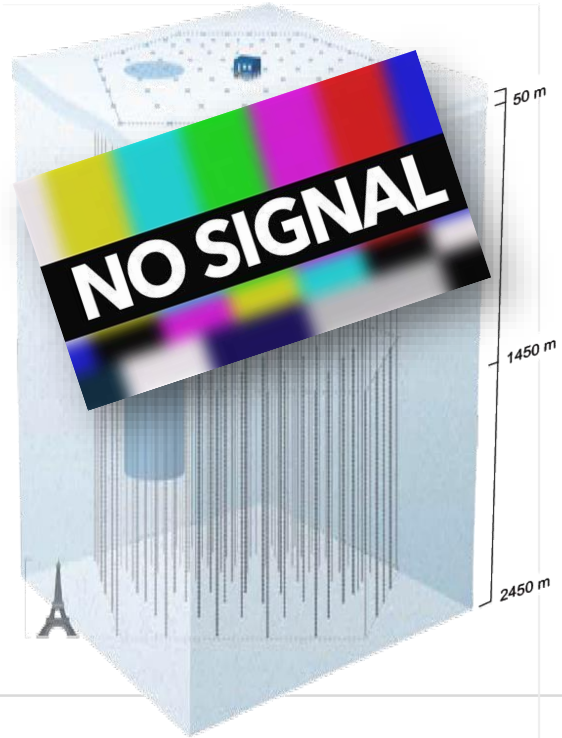
sends GRB alert to $IceCube$

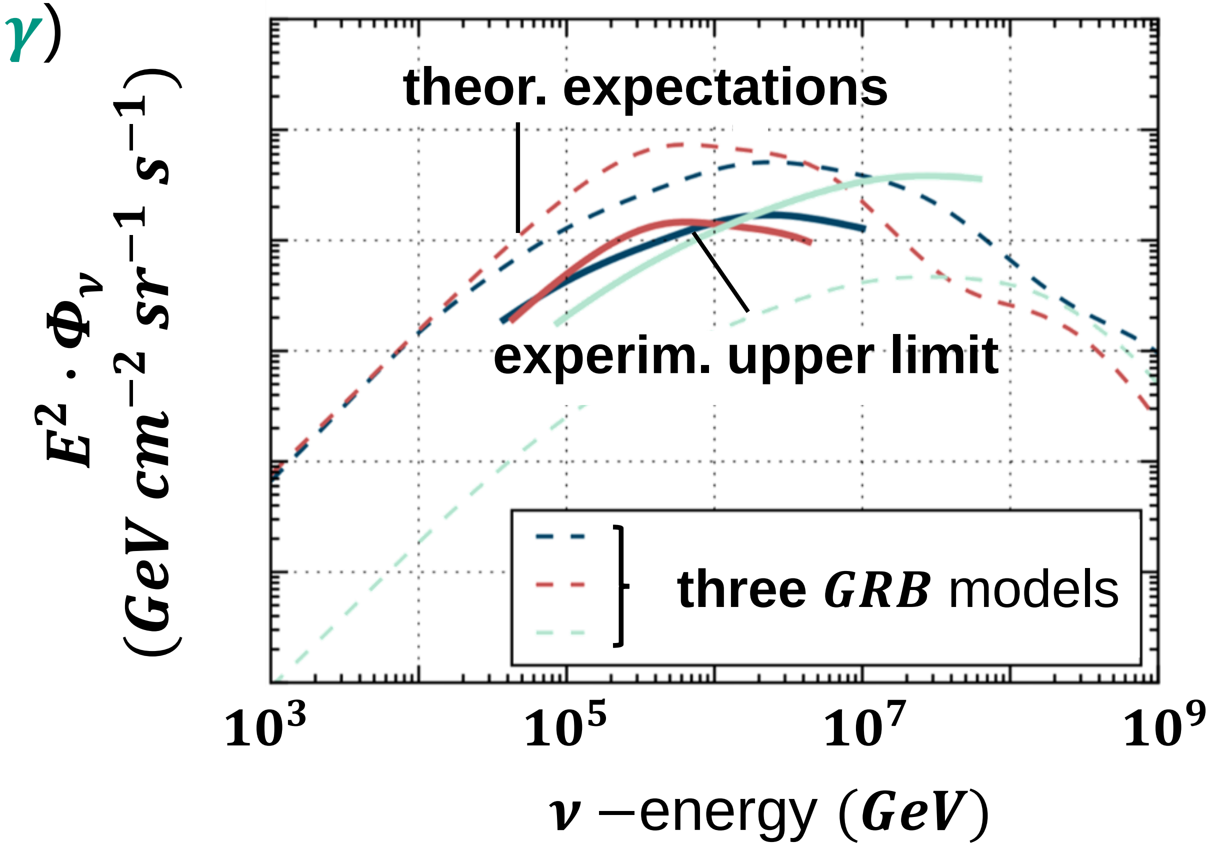


$SWIFT$

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

- Gamma Ray Burst (GRBs) – VHE ν´s from a stellar collapse to black hole?
  - $IceCube$: analysis of CC – reactions (μ – tracks) & NC – reactions (cascades)
  - 5 – year multimessenger–search (ν, γ) in both hemispheres: **0 events**





$IceCube$: a recent breakthrough for ν – astronomy

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- **Finally: a hot spot of $\boldsymbol{UHE}$ neutrinos*!**

  - observation of $\mathbf{79}$ $\boldsymbol{UHE}$ neutrinos from the direction of galaxy $\boldsymbol{M77} = \boldsymbol{NGC}\ \mathbf{1068}$ $(\boldsymbol{d} = \mathbf{47 \cdot 10^6}\ \boldsymbol{ly})$ from $\mathbf{5/2011 \ldots 5/2020}$

  - **origin**: beam dump of protons from $\boldsymbol{AGN}$ (´cocoon´, with acceleration in the corona region of the $\boldsymbol{AGN}$)

  - no $\boldsymbol{UHE}$ gammas detected (**absorption** in the massive torus of $\boldsymbol{M77}$)

  - other interpretations: chance alignment of a far more distant $\boldsymbol{UHE} - \boldsymbol{\nu}$ – 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

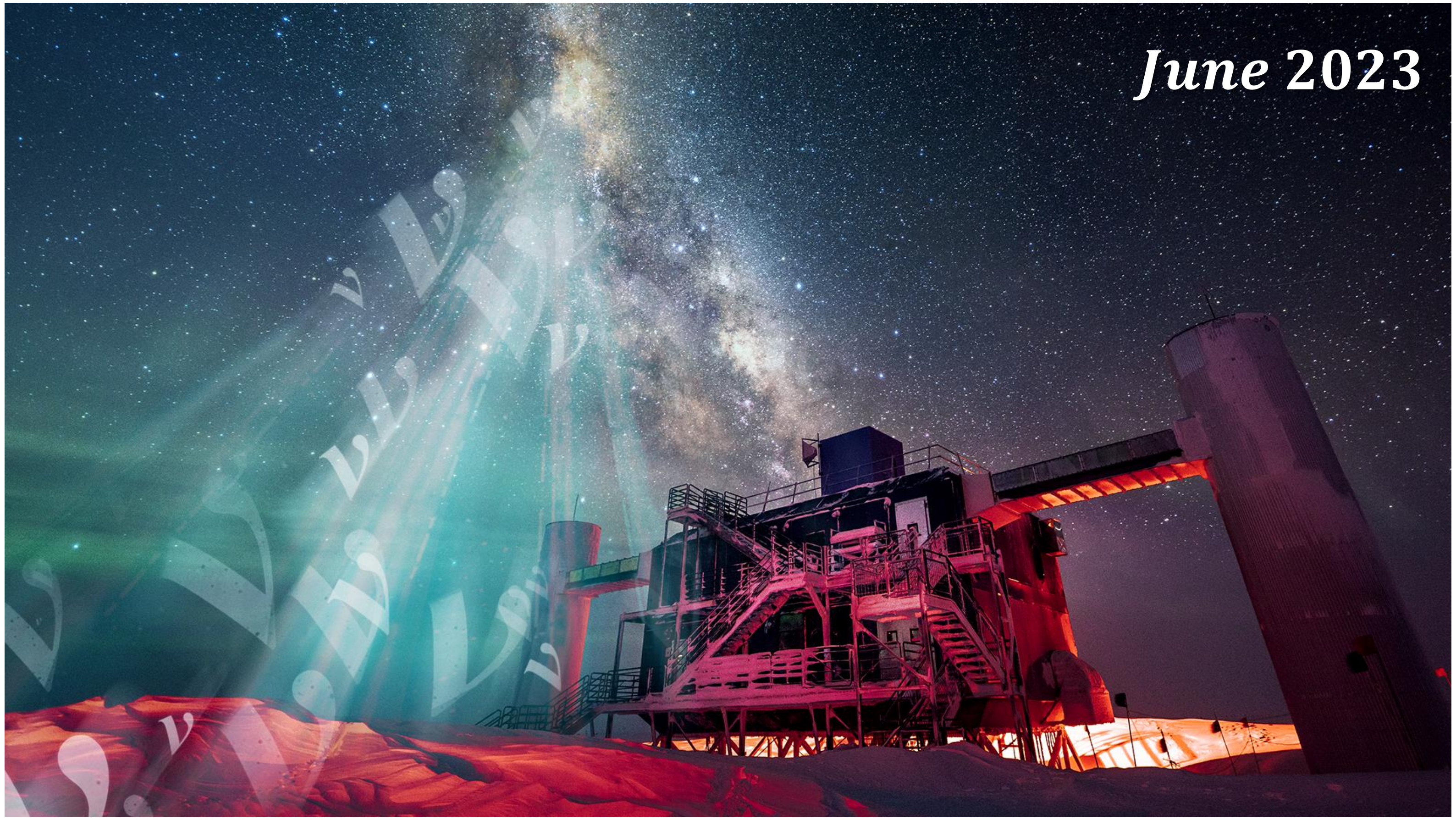
IceCube: high–energy neutrinos from our galaxy!

Karlsruhe Institute of Technology

- **Deep learning algorithms applied to 10 years of *IceCube* cascade data**

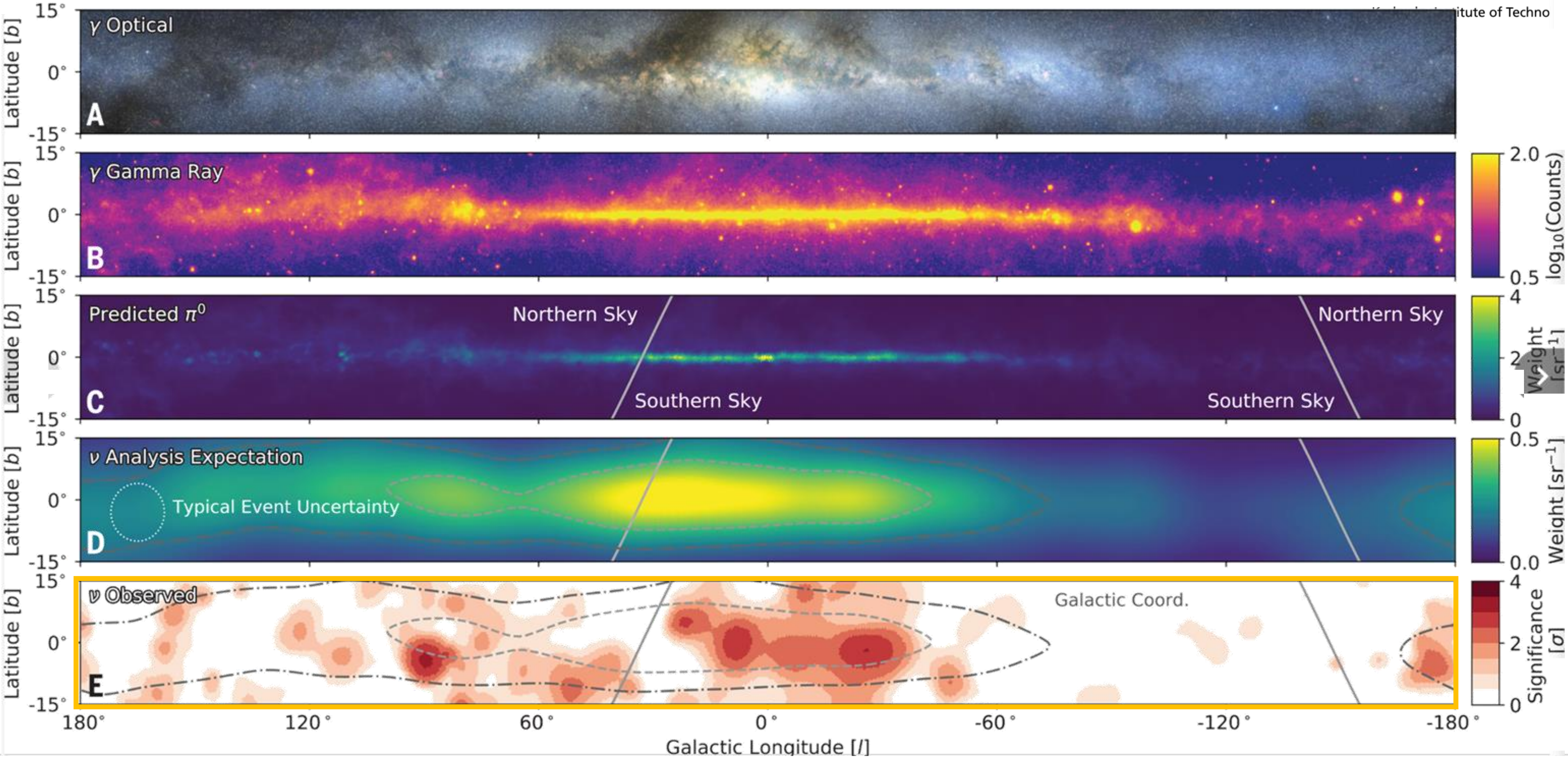
  - evidence (at $4.5\ \sigma$) for a ν – signal coming from the **galactic plane** (diffuse emission models or many unresolved sources)

  - search based on **cascade** events using deep learning techniques ($E\ >\ 500\ GeV$) & CR – models based on π^0 – decays for gammas



Observation of high-energy neutrinos from the Galactic plane | Science

$IceCube$: high−energy neutrinos from our galaxy

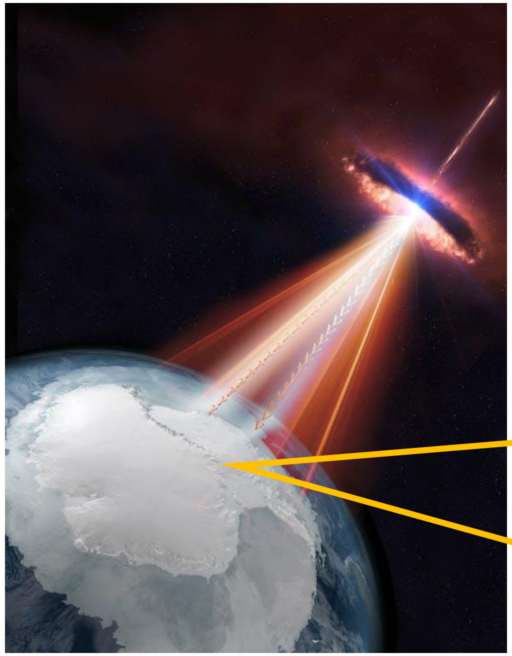


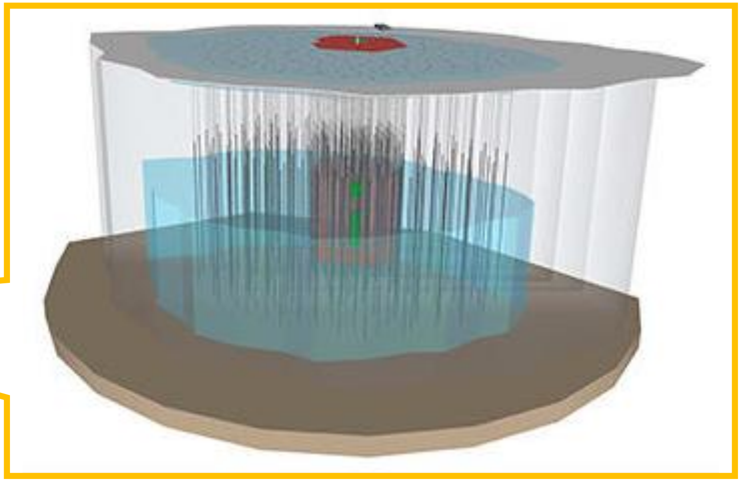
$IceCube\ Gen\ 2$: increase of the sensitive volume

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

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

ICECUBE GEN2



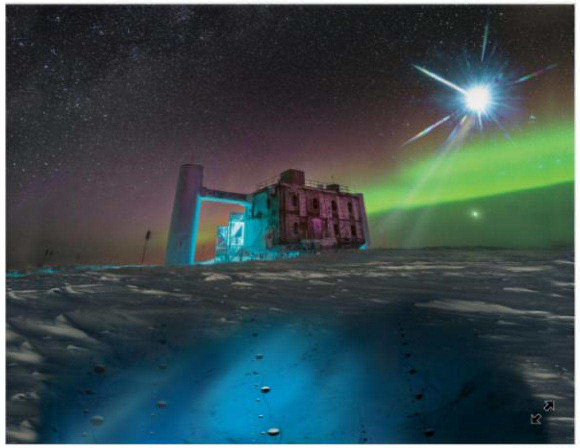


RESEARCH NEWS

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.



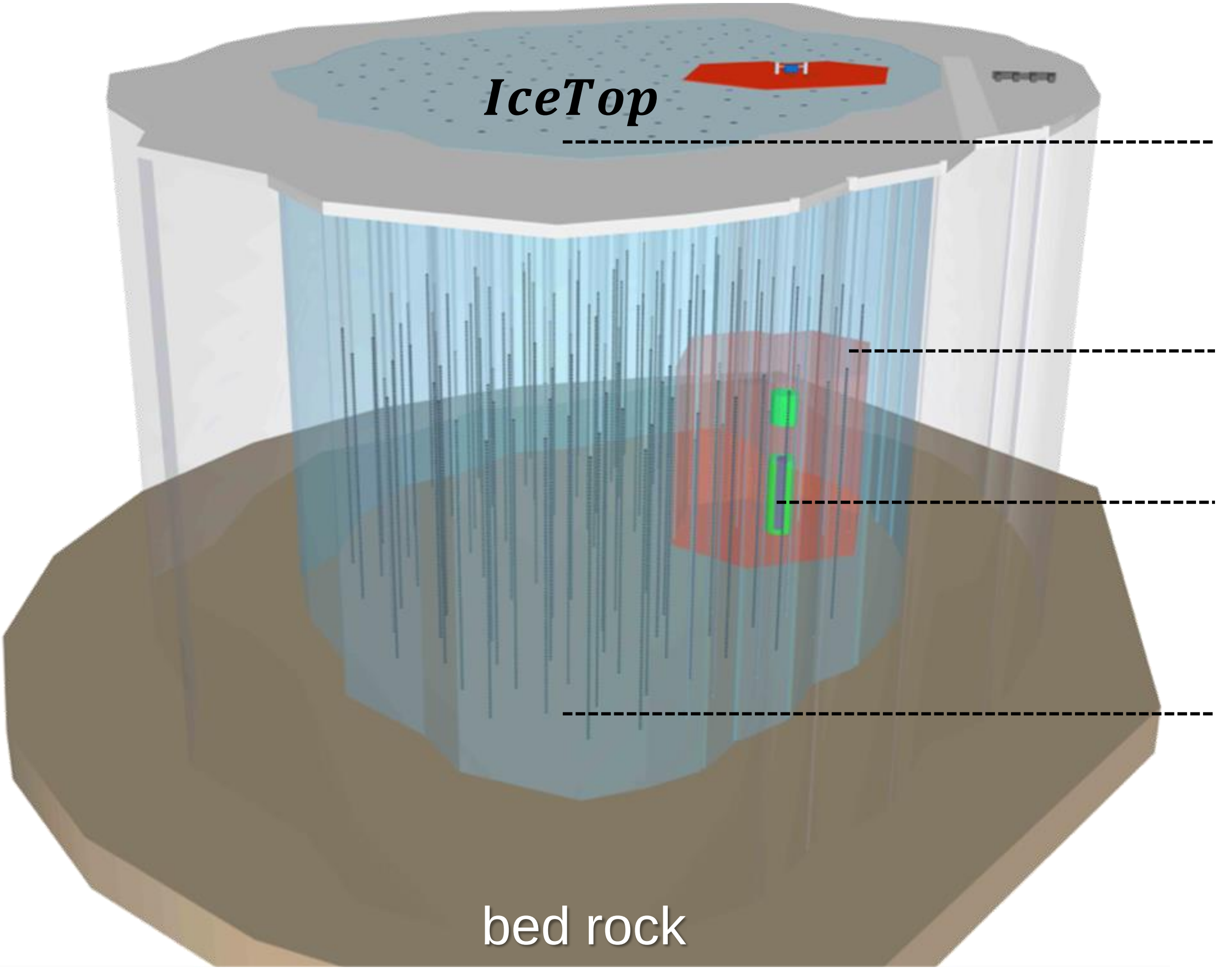
IceCube/NSF

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
- $\mathbf{8} \times$ increase in V but only factor $\times\ \mathbf{2}$ in # of $PMTs$

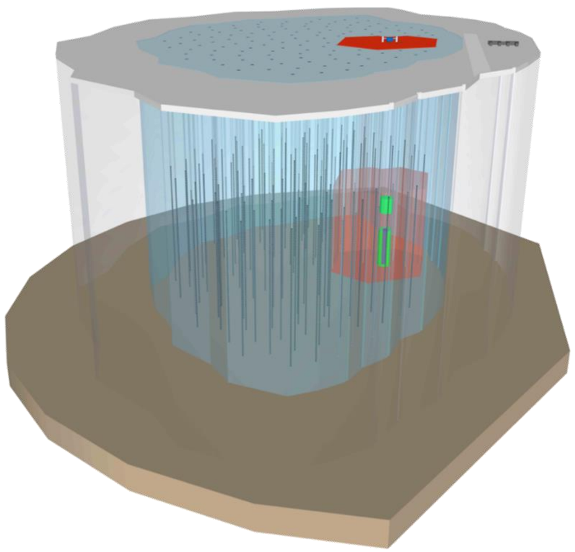
$RECAP$: design features of ν – telecopes

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

PeV – scale: IC, $KM3NeT$

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

strings: $d = 125 \dots 250\ m$

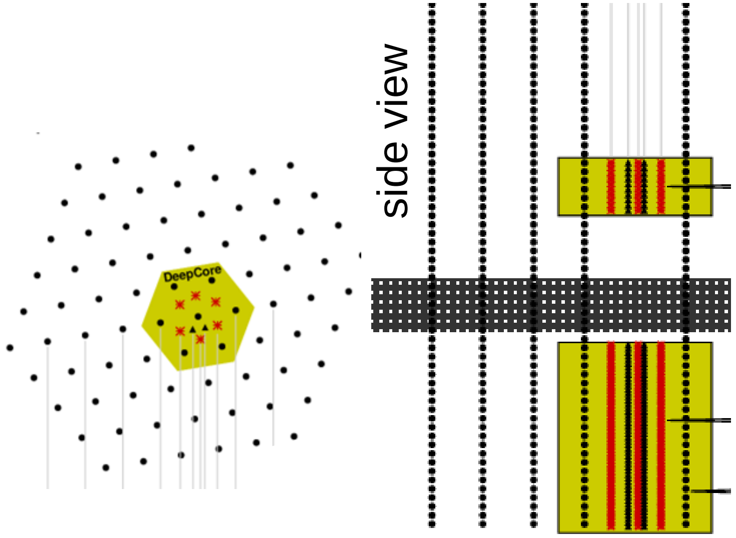


aim: $UHE - \nu$ point sources

TeV – scale: $Deep\ Core, \dots$

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

strings: $d = 42 \dots 72\ m$

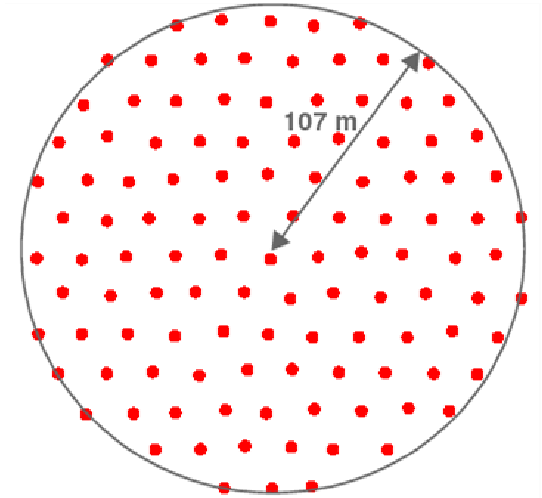


aim: search for dark matter

GeV – scale: $ORCA, PINGU$

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

strings: $d \sim 20\ m$

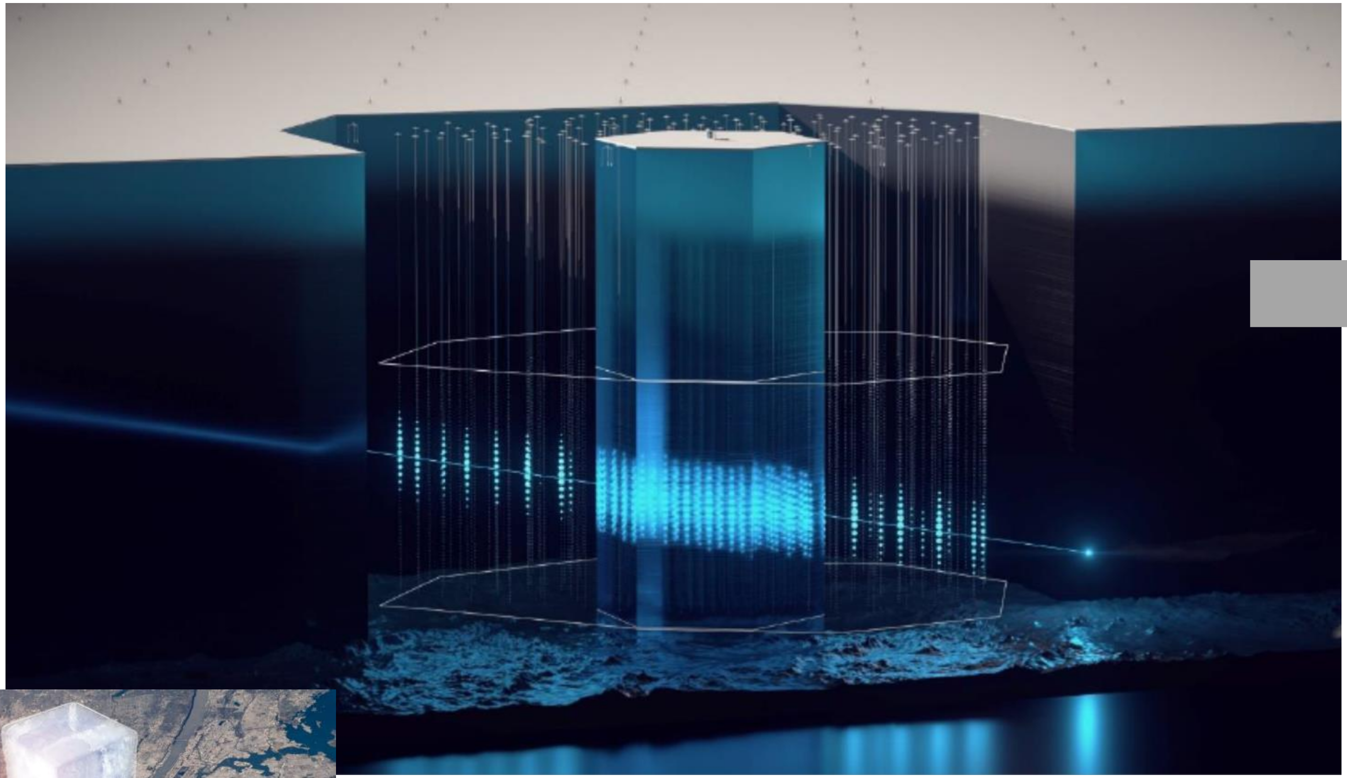


aim: ν – oscillation studies

From neutrino to Cherenkov telescopes for γ´s

Karlsruhe Institute of Technology

- Switching cosmic messengers: from UHE neutrinos to VHE gammas



ICECUBE GEN2

H.E.S.S.

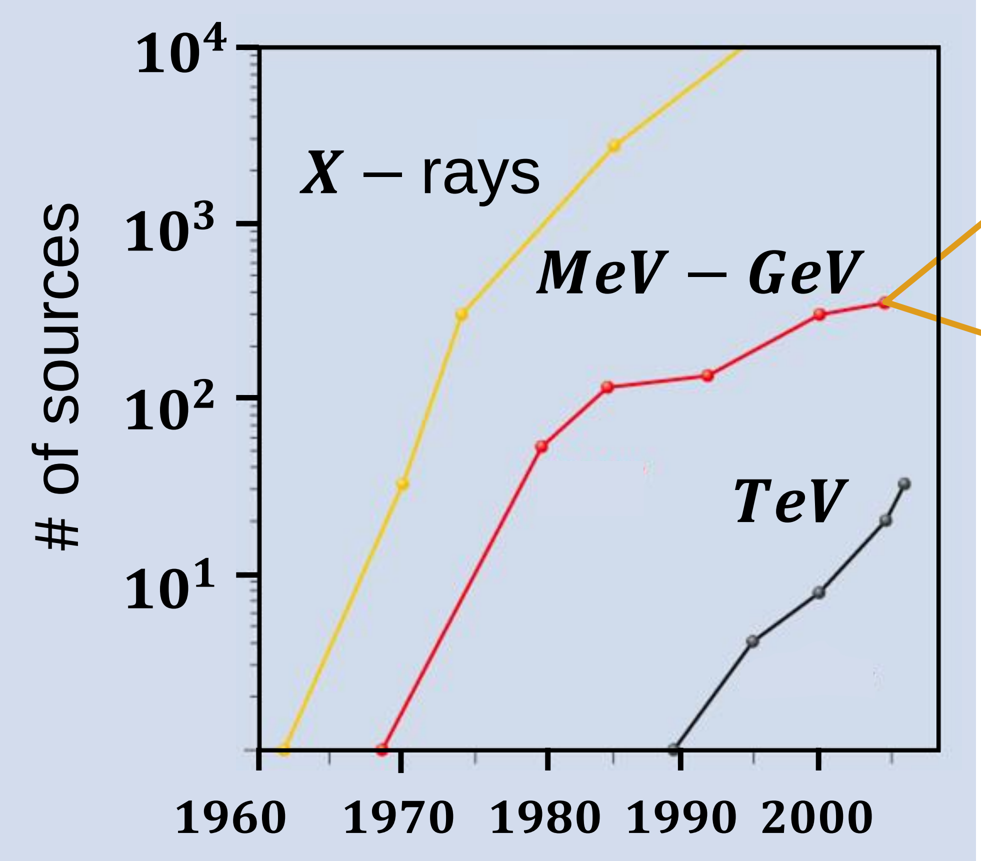
cta cherenkov telescope array

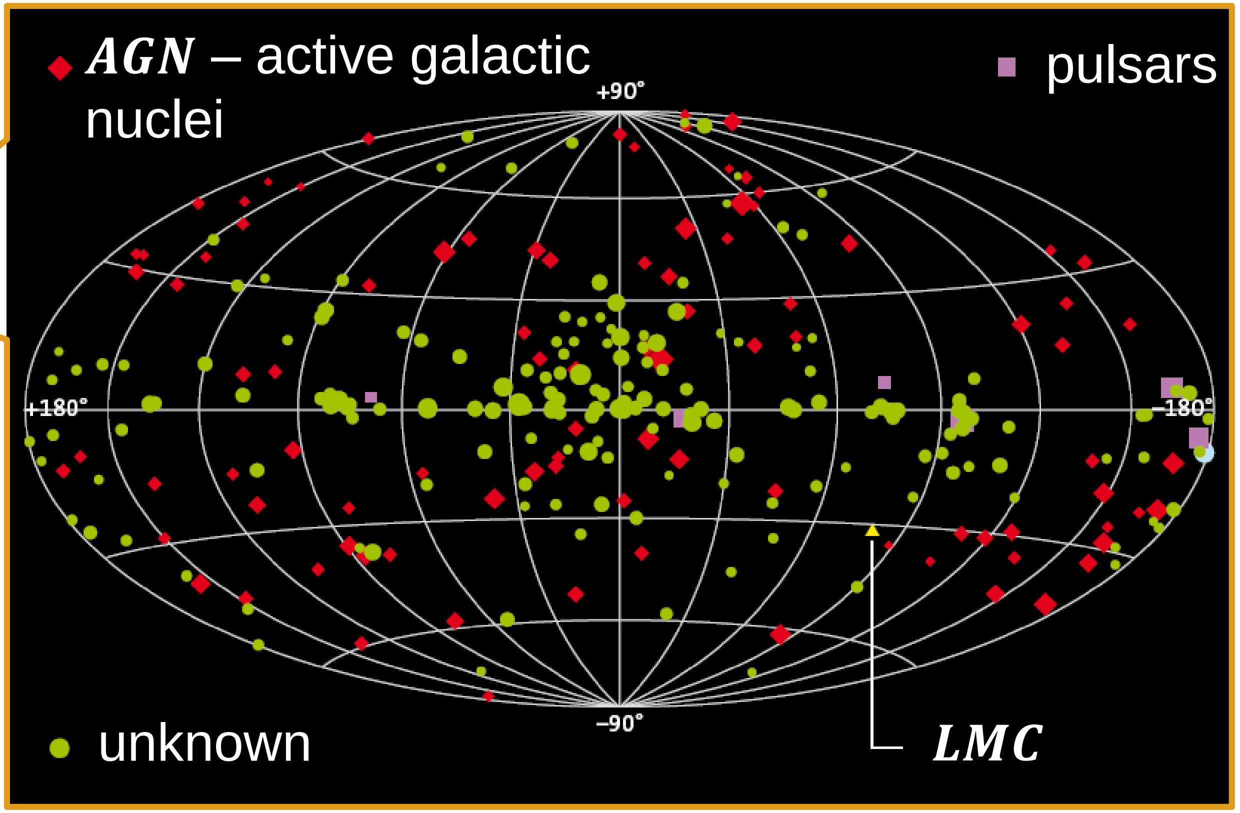
$2.1.3$ Gamma Telescopes for VHE/UHE gammas

Karlsruhe Institute of Technology

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

  - study of **non–thermal** sources: from pulsar wind nebulae to $SNRs$ & $AGNs$ ...

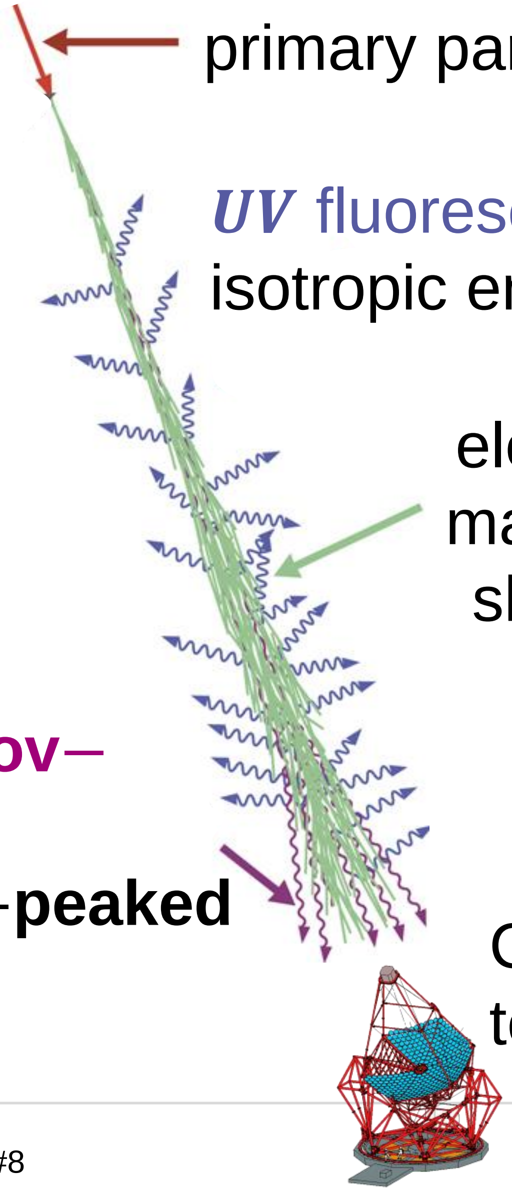


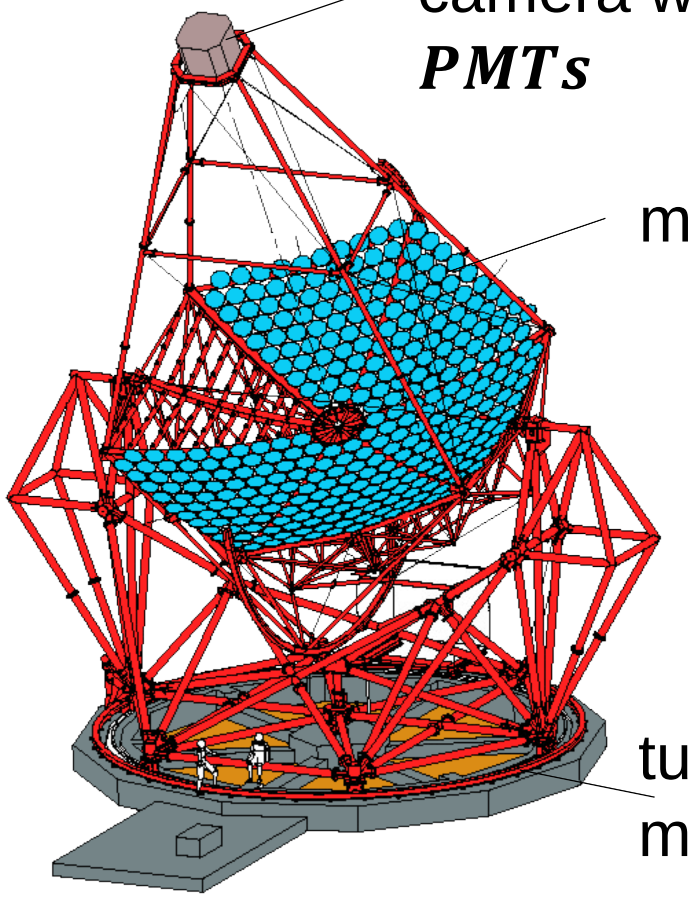


Cherenkov telescopes: working principle

- **detecting air Cherenkov light by an *I*maging *A*ir *C*herenkov *T*elescope**

  IACT



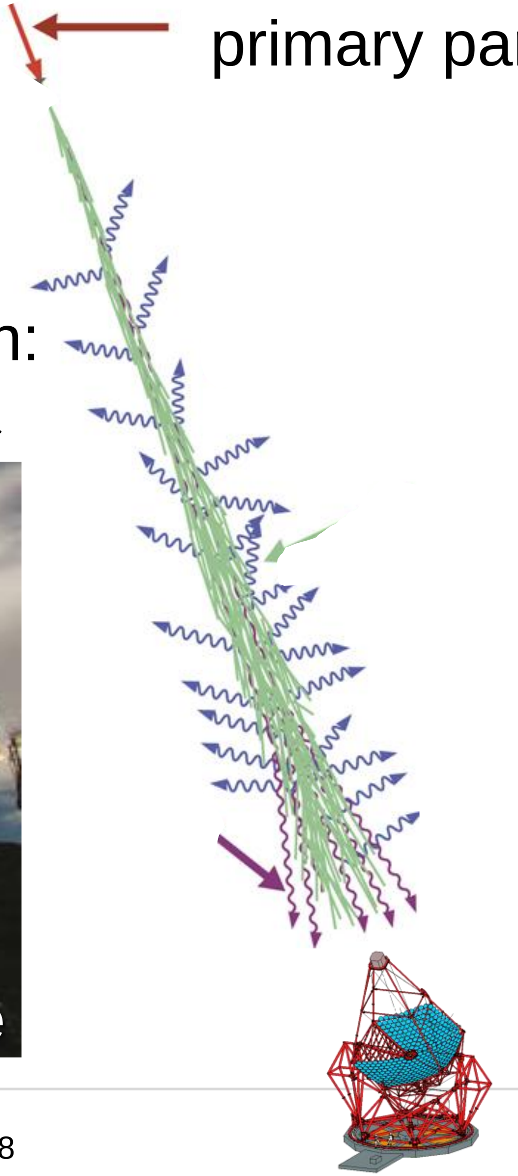


Cherenkov telescopes: working principle

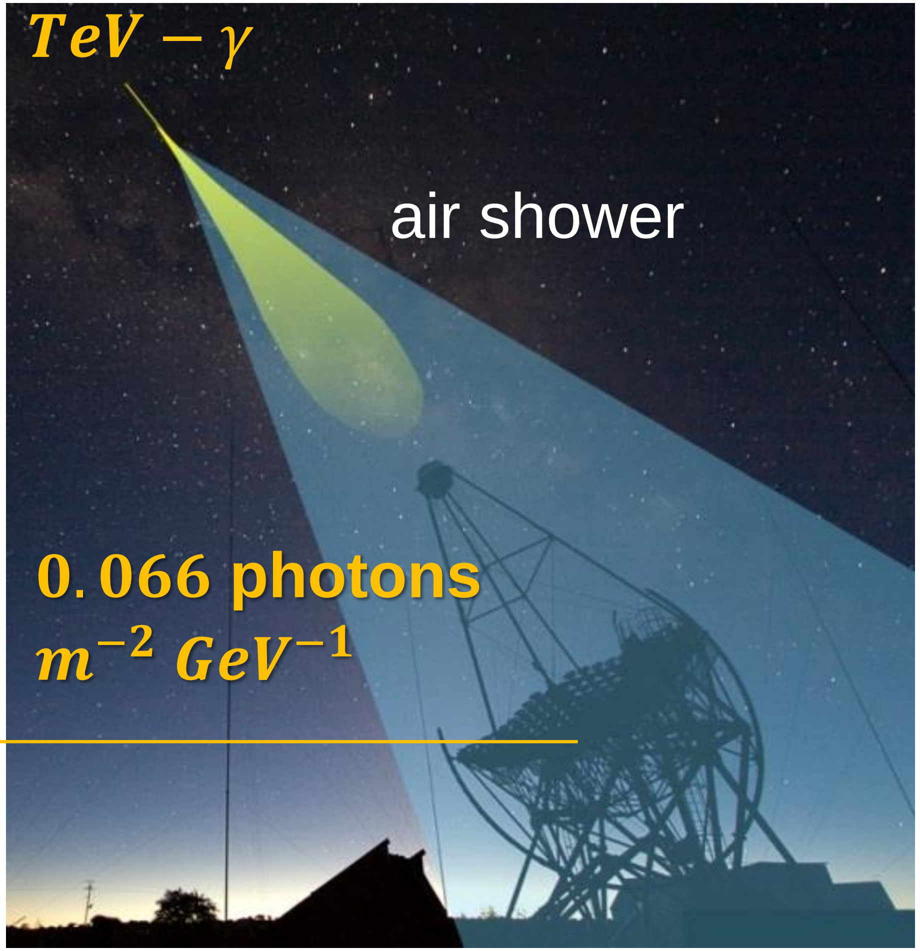
- $IACTs$ **detect the short Cherenkov pulses of $2-3\ ns$**

primary particle: high−energy gamma $GeV \ldots TeV$

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

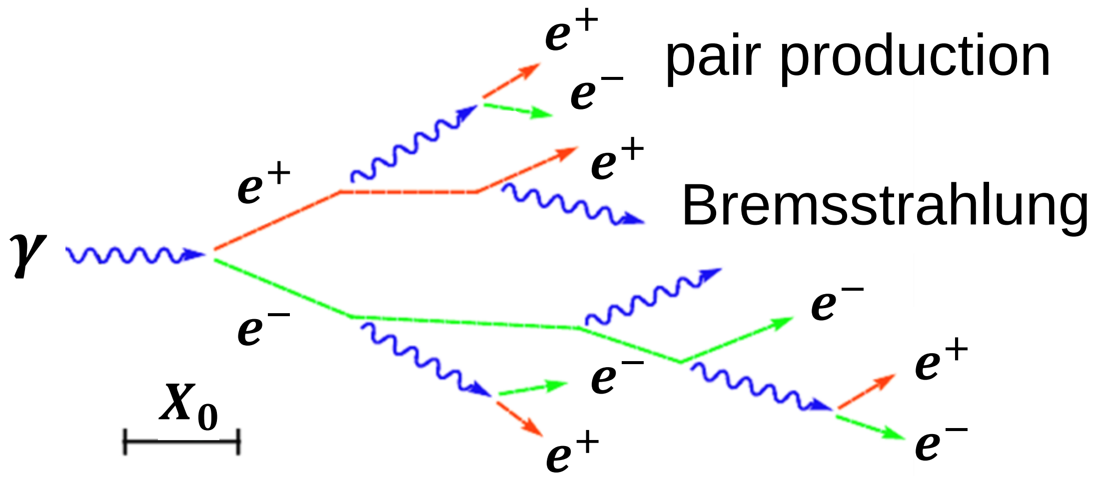


large mirror size

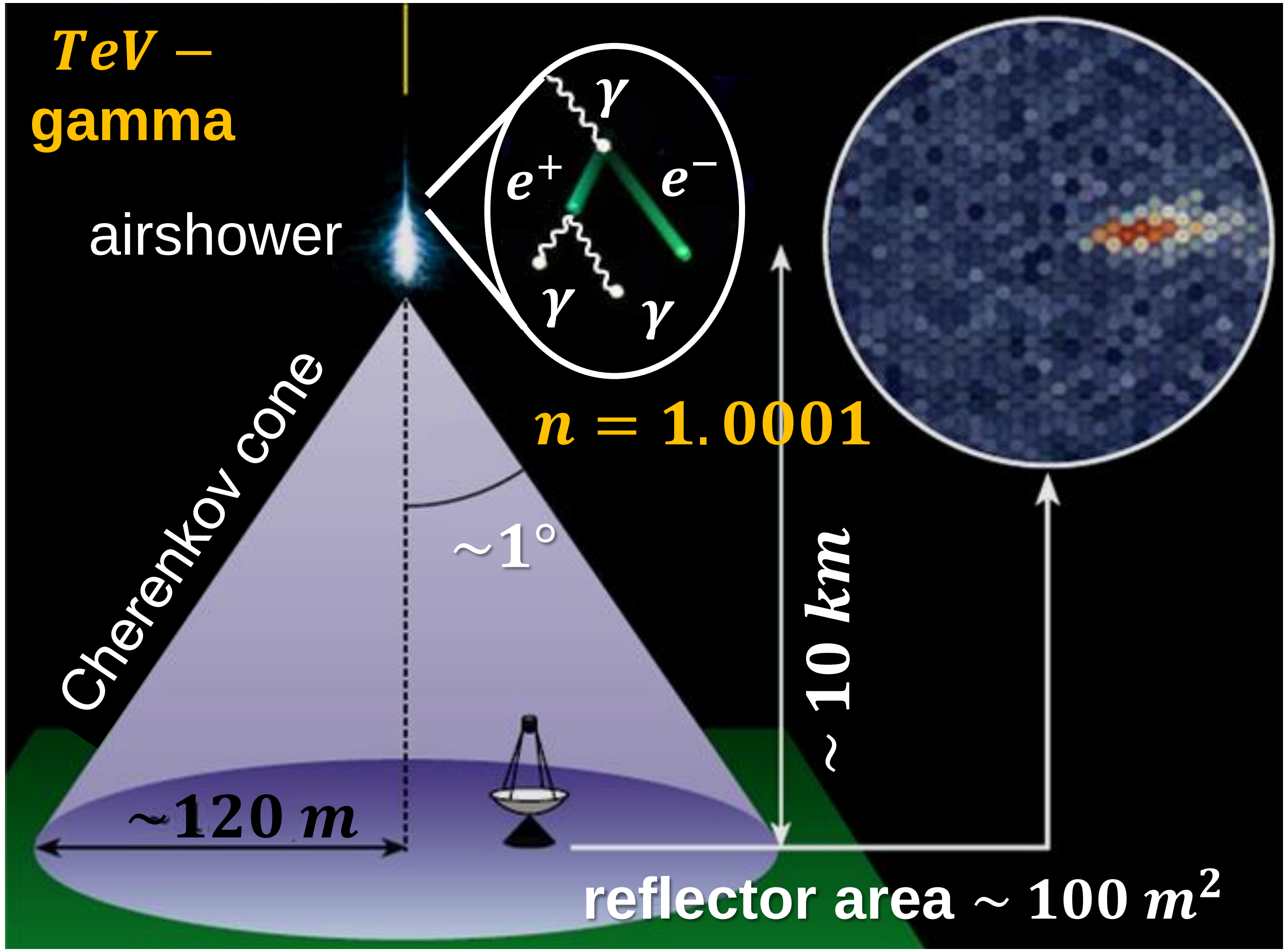


Cherenkov light from airshowers: narrow cone

- Primary gammas initiate electromagnetic cascade processes in atmosphere



- Cherenkov light produced in upper atmosphere due to relativistic e^+, e^-
- refractive index of air: $n = 1.0001$
  $\cos\Theta = 1/(n \cdot \beta)$ ⇨ angle $\Theta \approx 1°$
- surface area Cherenkov cone: $10^5\ m^2$



Detecting air Cherenkov light: challenges

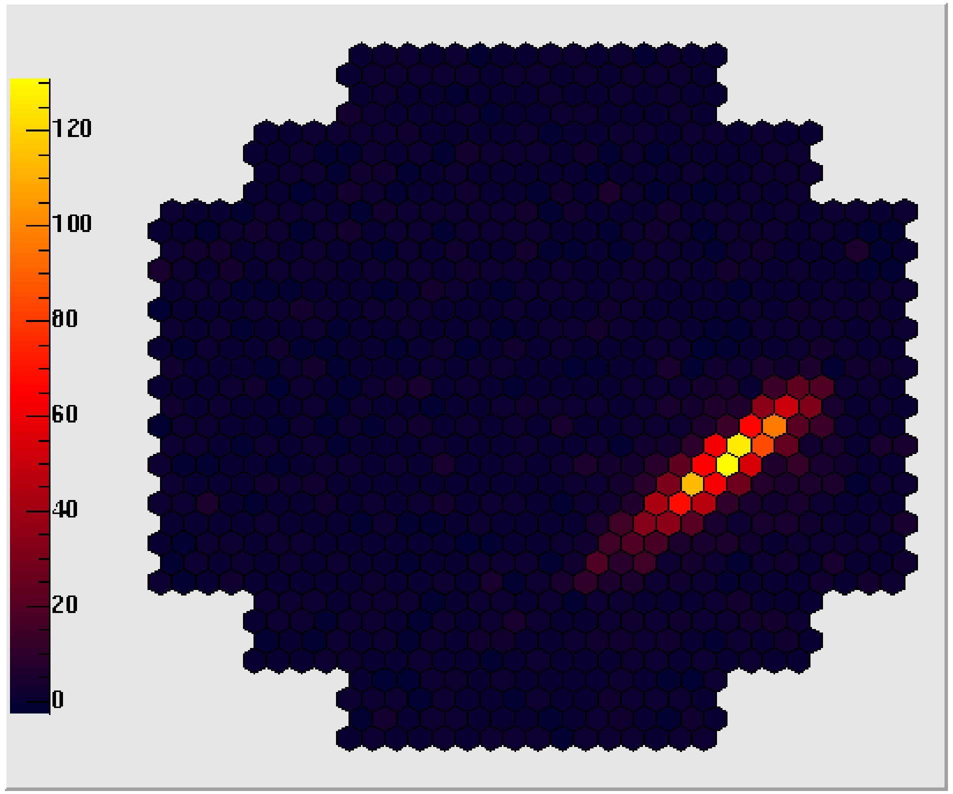
- **Main challenge: very weak light signals of TeV gamma** – $100\ photons/m^2$

- 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 $IACTs$** **for gammas in the $GeV \ldots TeV -$ range**

- reconstructing the **parameters** of the primary $TeV -$ gamma

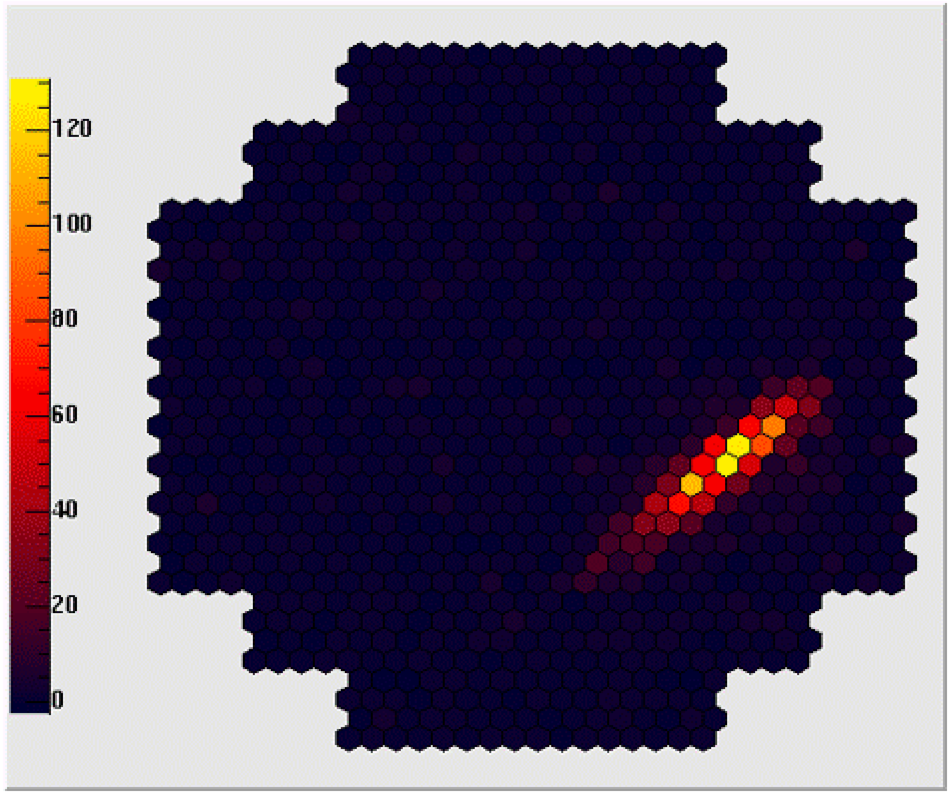
- light **intensity**: ⇨ shower **energy**

- 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: $E(\gamma) = 40\ (25)\ GeV$
  (depends on mirror–Ø, PMT – efficiency, trigger)



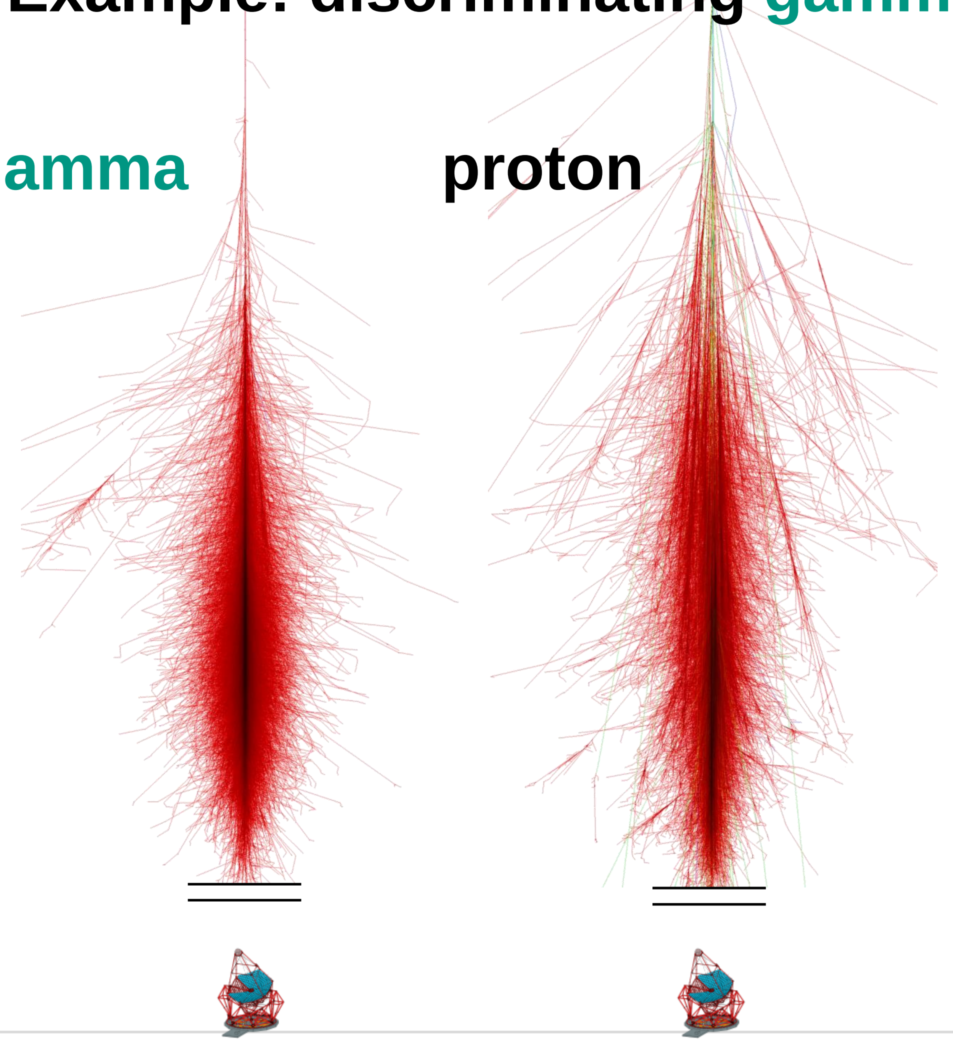
Discrimination of the primary particle type

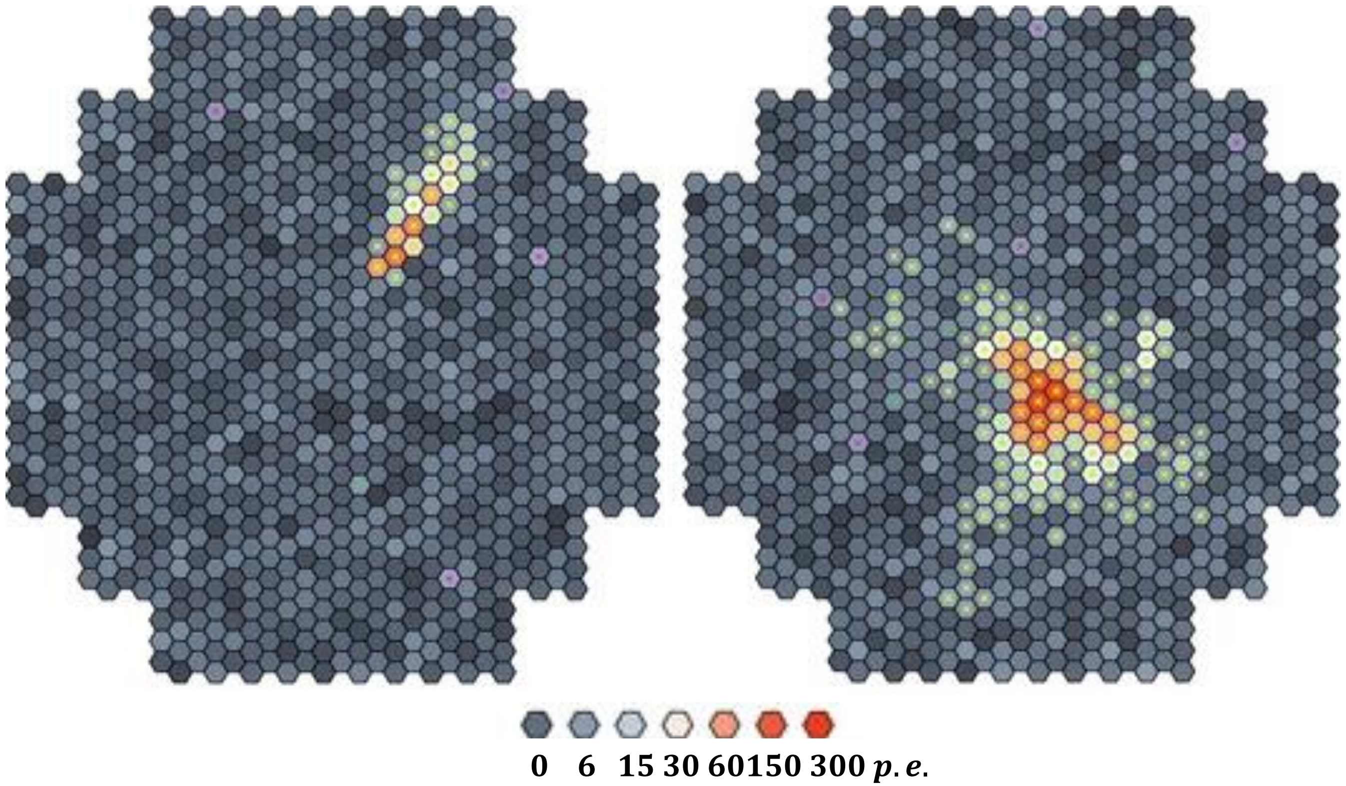
- **Example: discriminating gammas from protons via shower profile at 1 TeV**

CORSIKA

gamma

proton





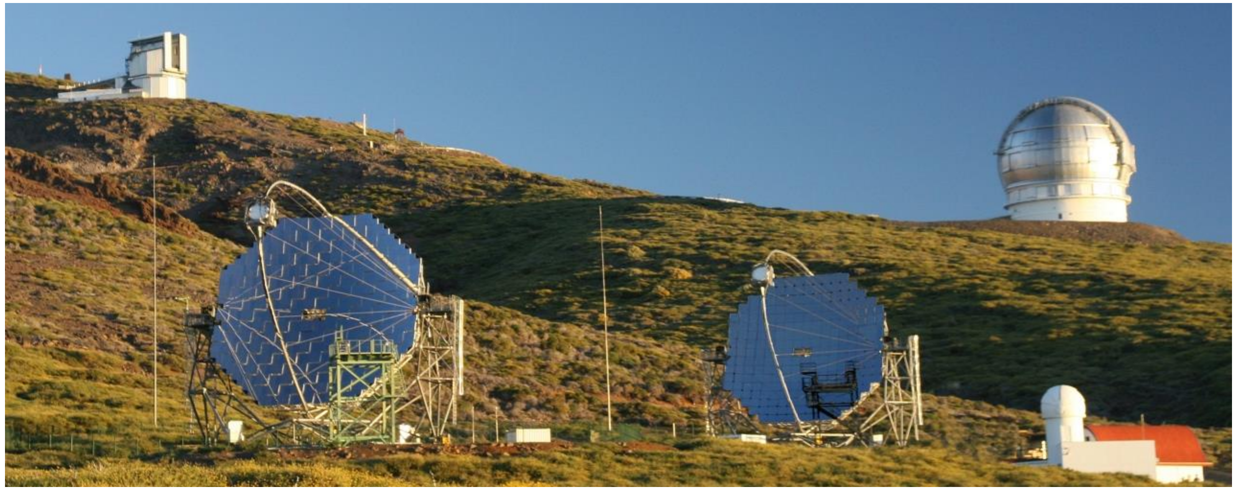
1 TeV gamma
shower image

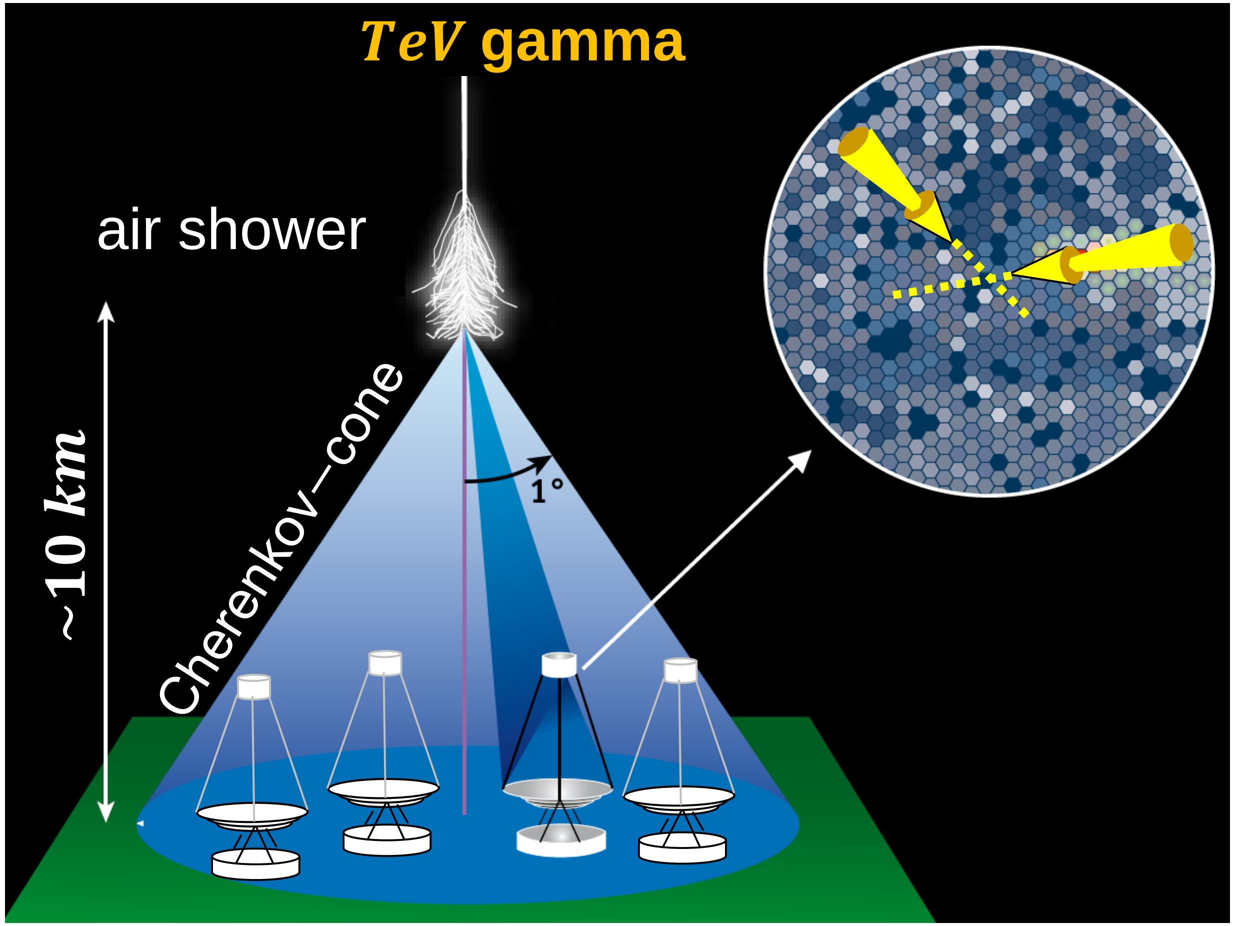
1 TeV proton
shower image

Improved sensitivity via large arrays of $IACTs$

- <u>**Stereoscopic**</u> **view of a shower by operating an array of $IACTs$**

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



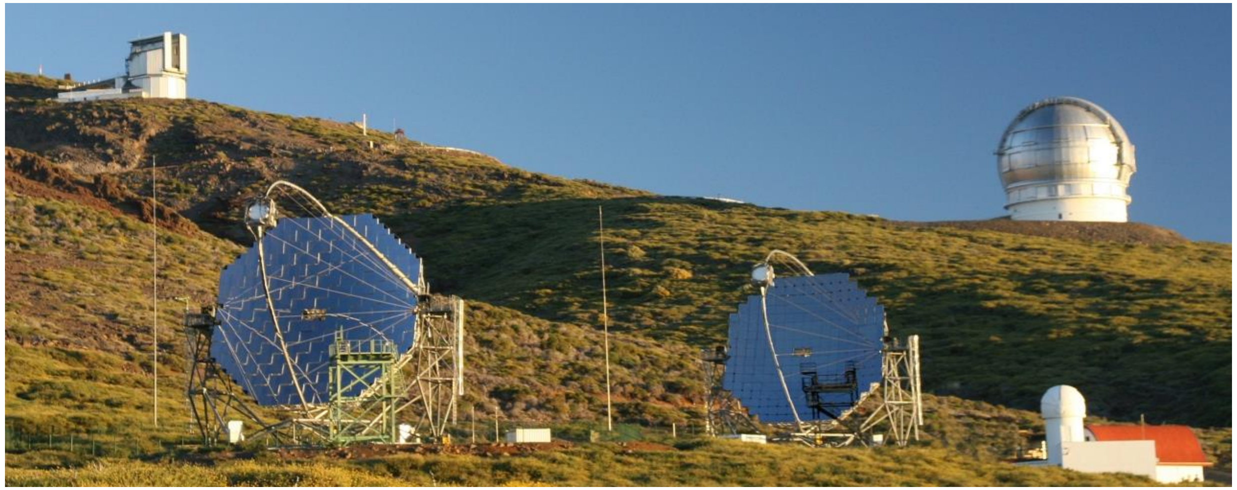


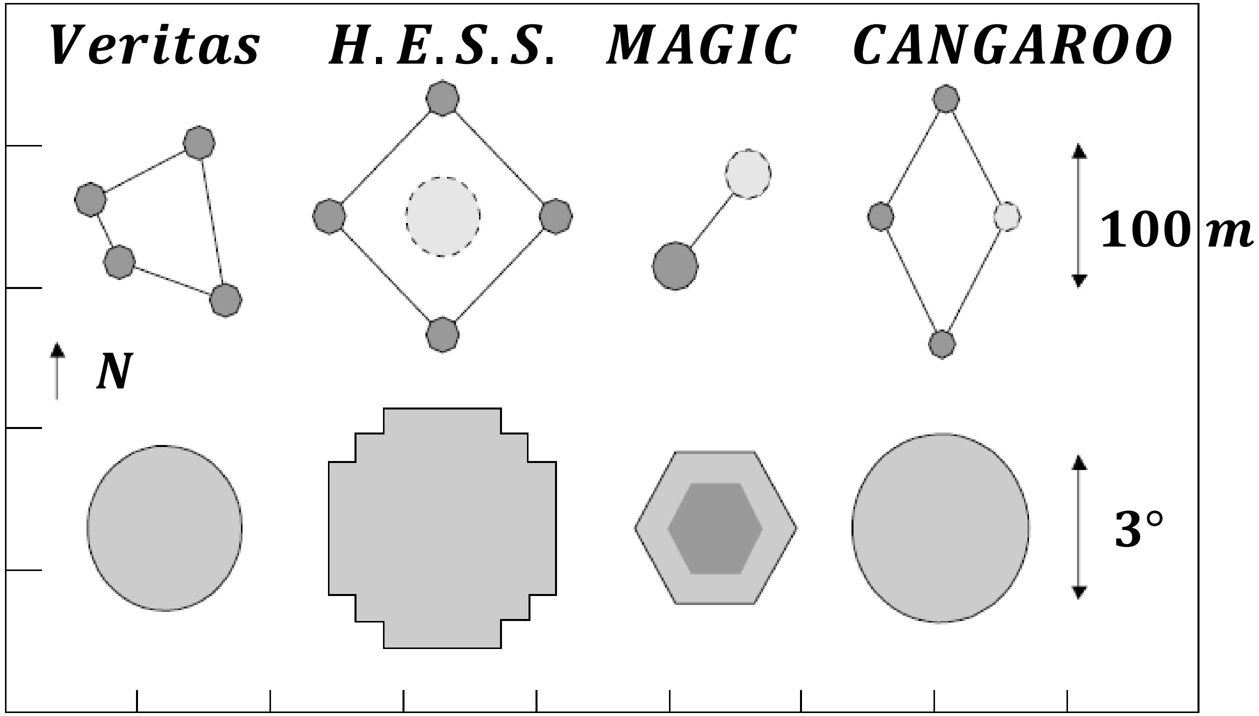
Improved sensitivity via large arrays of $IACTs$

Karlsruhe Institute of Technology

- **$3D$ view of a shower by operating an array of $IACTs$**

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



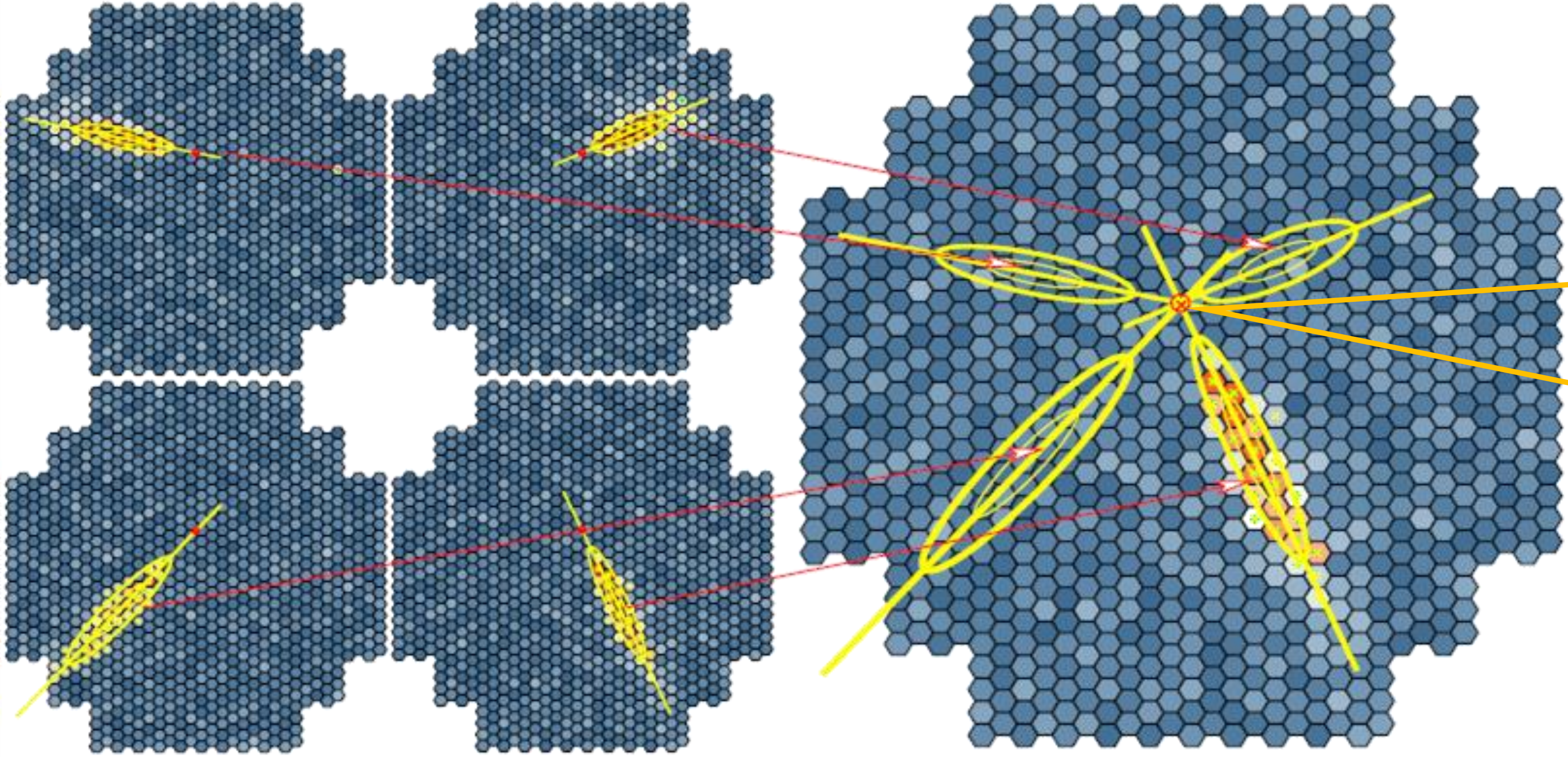


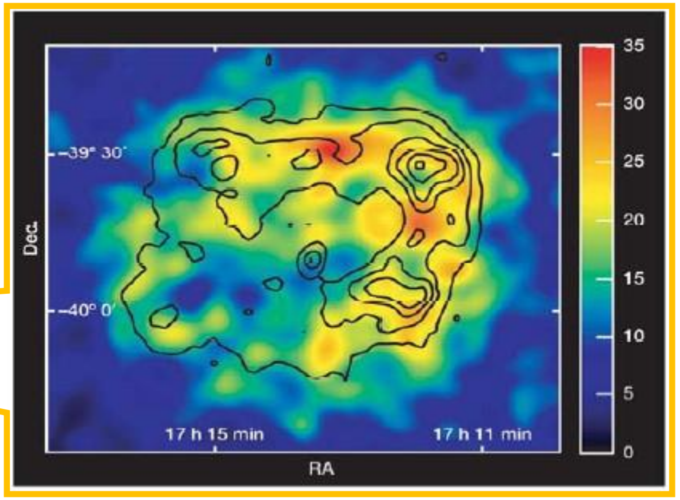
layout of large Cherenkov–telescope–arrays

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 $SNRs$, ...

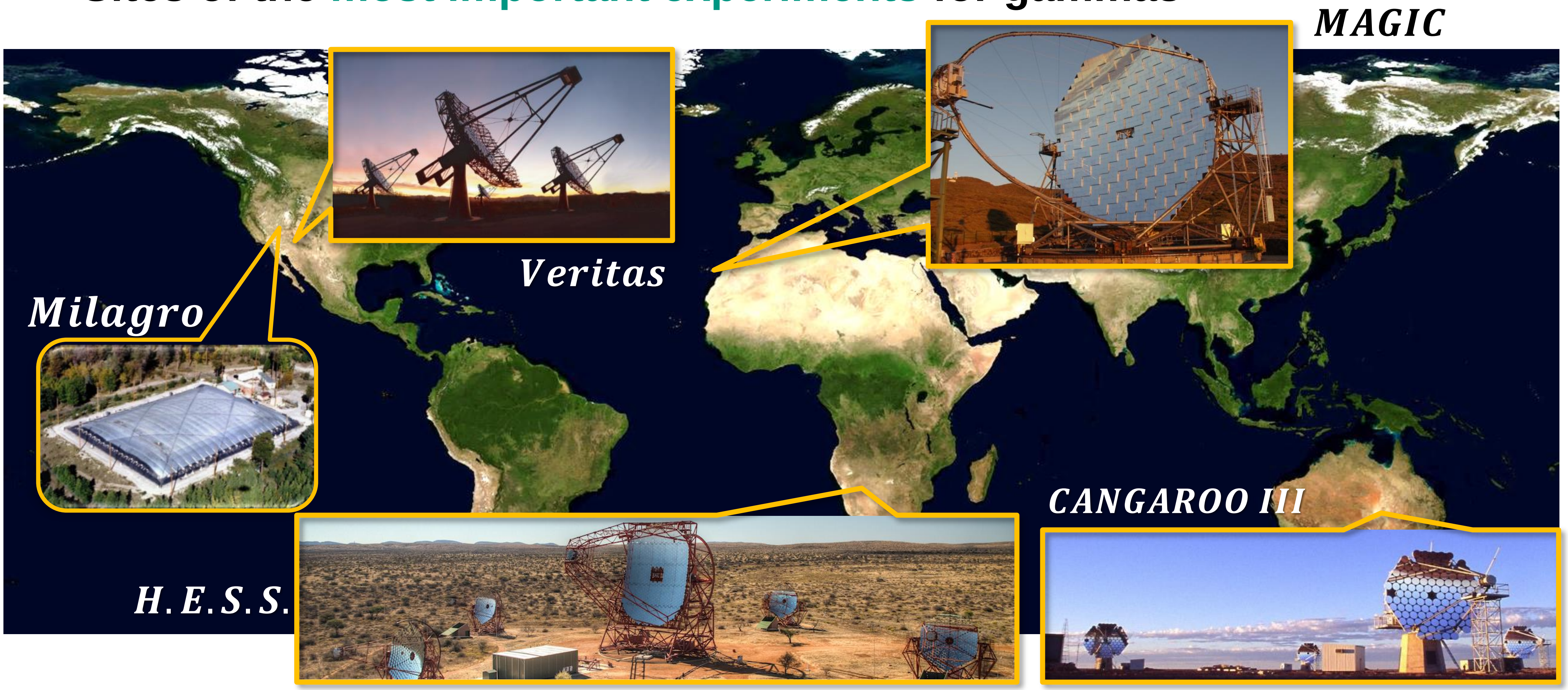




combining the information of **4** telescopes from $H.E.S.S.$

Overview of TeV gamma observatories

- Sites of the **most important experiments** for gammas



MAGIC telescopes at La Palma

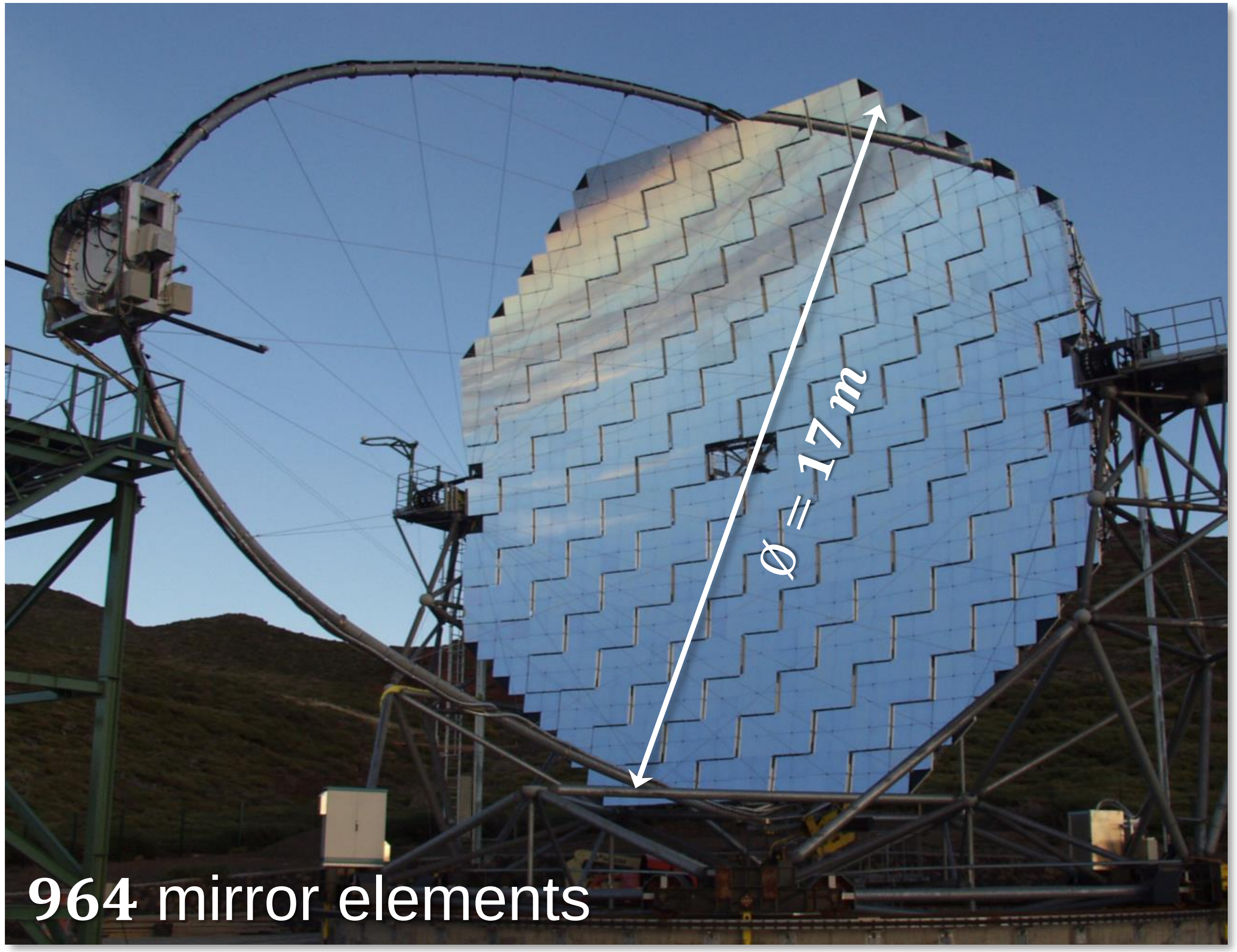
- *M*ajor *A*tmospheric *G*amma *I*maging *C*herenkov Telescope

- $\mathbf{2}$ ***IACTs*** at La Palma (Canary Islands)

- operations since $\mathbf{2009}$

- large parabolic mirror: $\emptyset = \mathbf{17}\ \boldsymbol{m}$

- mirror: $\boldsymbol{A} = \mathbf{236}\ \boldsymbol{m}^{\mathbf{2}}$, field–of–view: $\mathbf{3.6°}$



MAGIC telescopes at La Palma

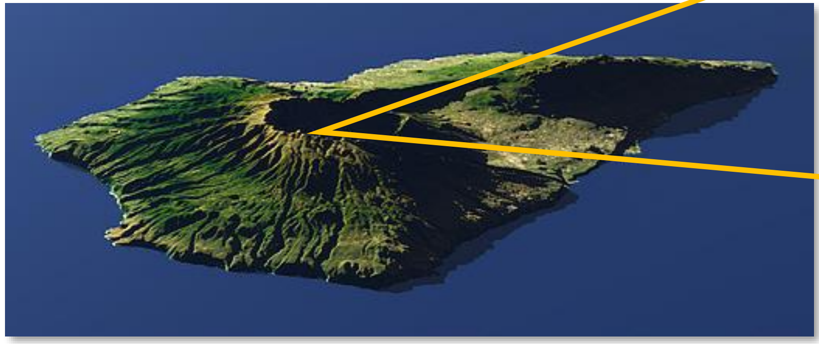
- ***M**ajor **A**tmospheric **G**amma **I**maging **C**herenkov Telescope*

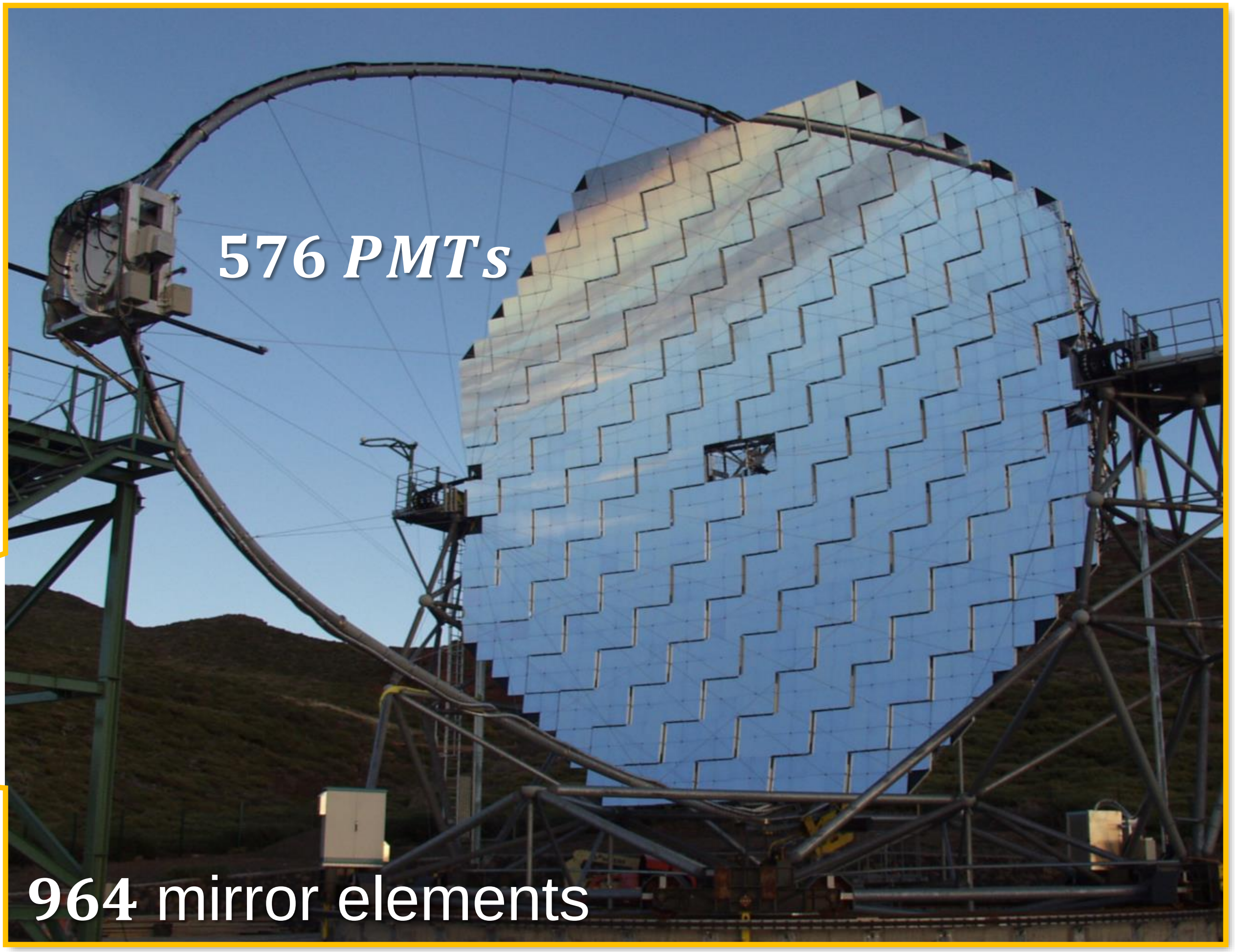
- energy range: $E = 30\ GeV \ldots 50\ TeV$

- 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





MAGIC telescopes – impact of a volcanic eruption

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

19.9.–13.12.
2021

La Palma:
volcano
Taburiente

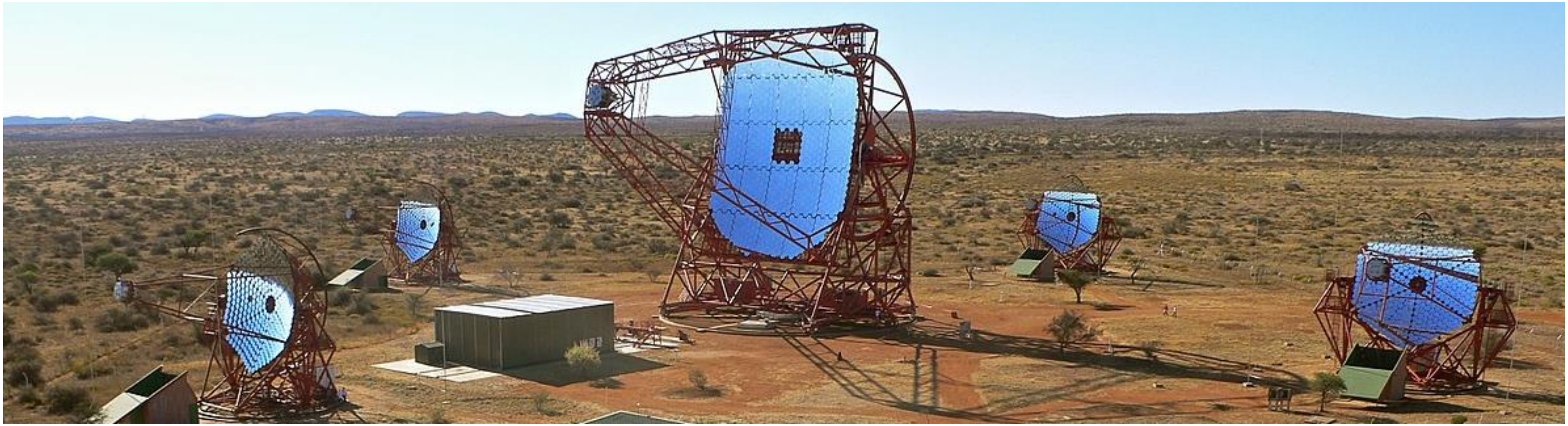
$H.E.S.S.$ observatory at Gamsberg site in Namibia

Karlsruhe Institute of Technology

- ***H**igh **E**nergy **S**tereoscopic **S**ystem in operation since* $12/2003$

- $IACTs$: 4 smaller–sized (each mirror with $\emptyset = 12\ m$) $+$ $\mathbf{1}$ large central unit

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



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

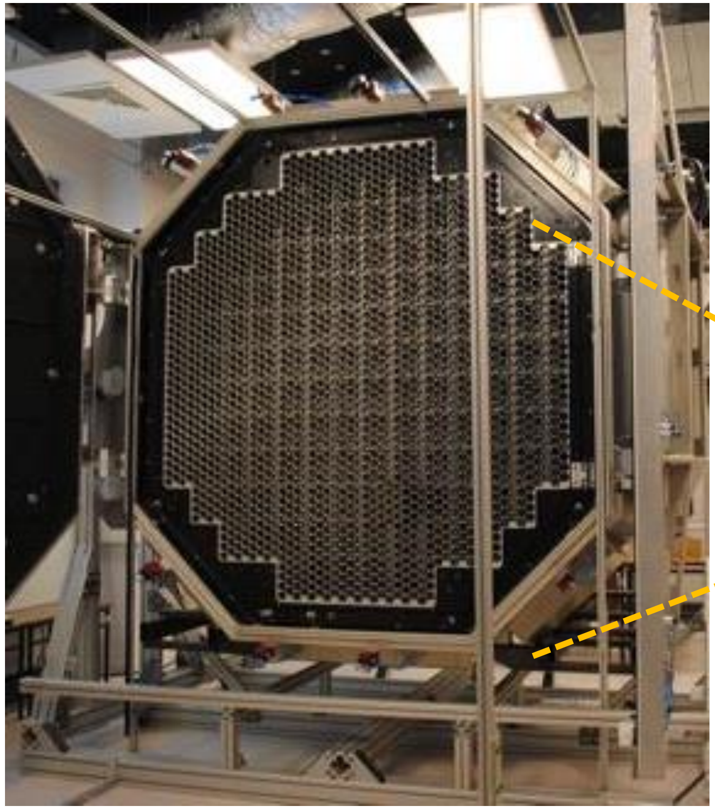
Karlsruhe Institute of Technology

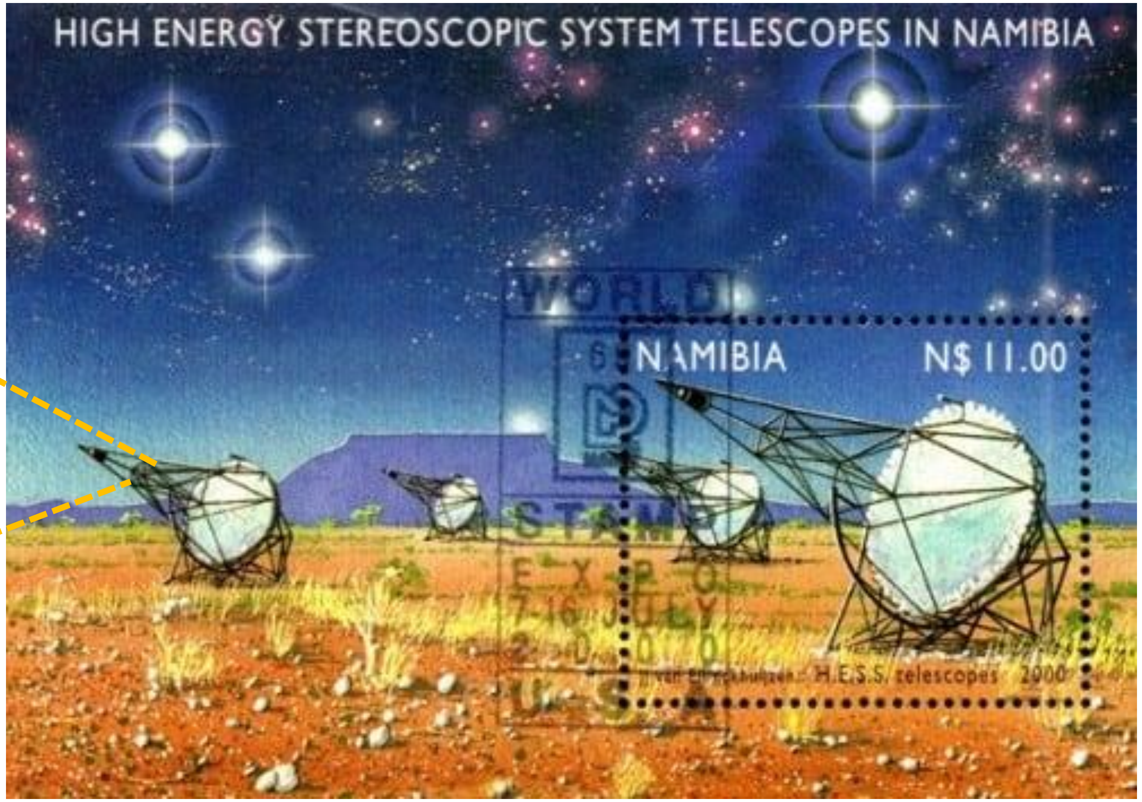
- ***H****igh* ***E****nergy* ***S****tereoscopic* ***S****ystem in operation since* $12/2003$

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

H.E.S.S.

read–out by $950\ PMTs$



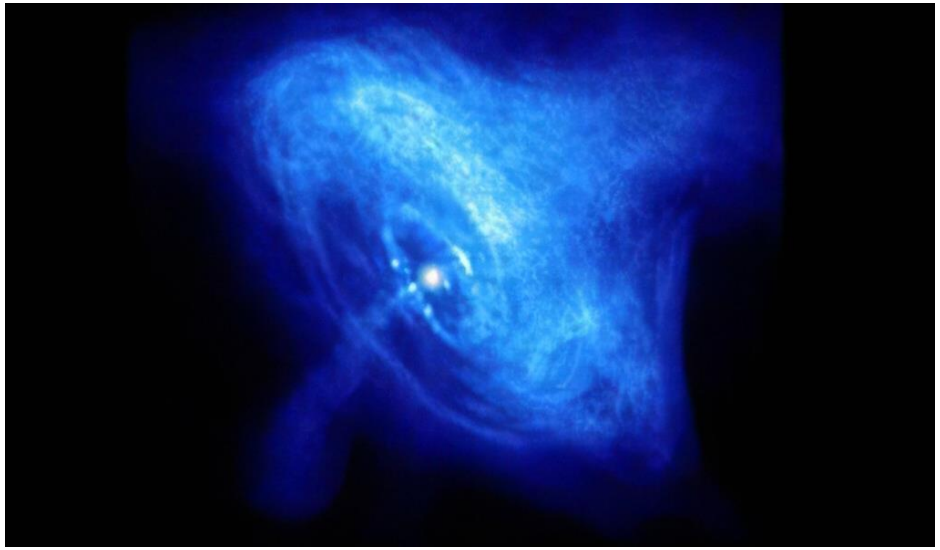


Defining the sensitivity of $IACTs$: 1 $Crab$

- **Definition: a unit for γ – astronomy – the $Crab$**

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

$$1\ Crab = 1\ event/(10^3\ m^2 \cdot h)$$



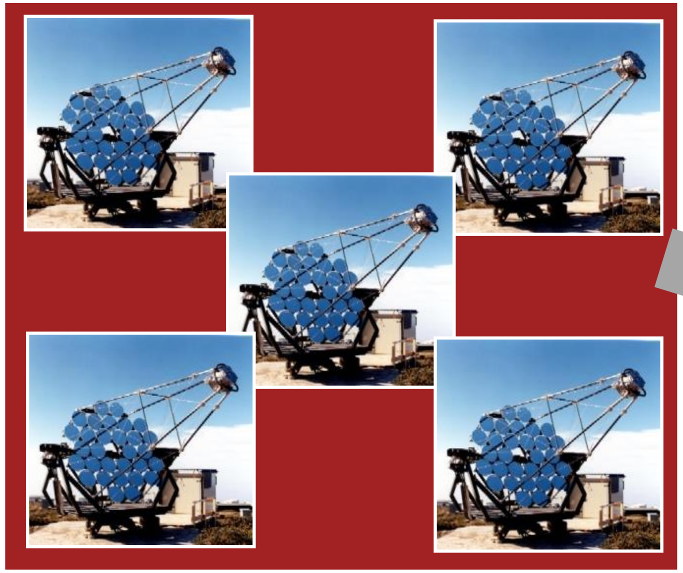
Crab nebula: brightest galactic gamma source

Improved sensitivities of $IACTs$: time to see 1 Crab

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

$Whipple$ 1989
(discovery): $50\ h$

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



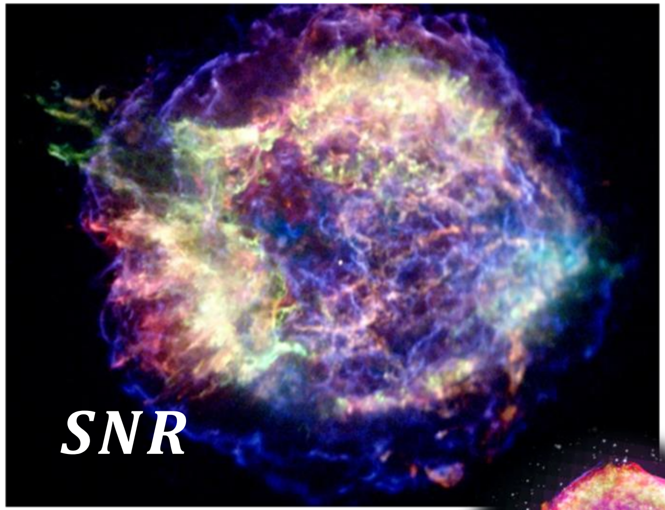
$HEGRA$ 1997:
$10\ min$

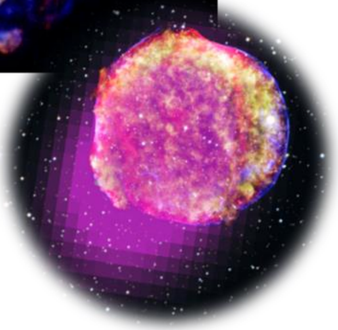
$H.E.S.S.$ 2004:
$30\ sec$

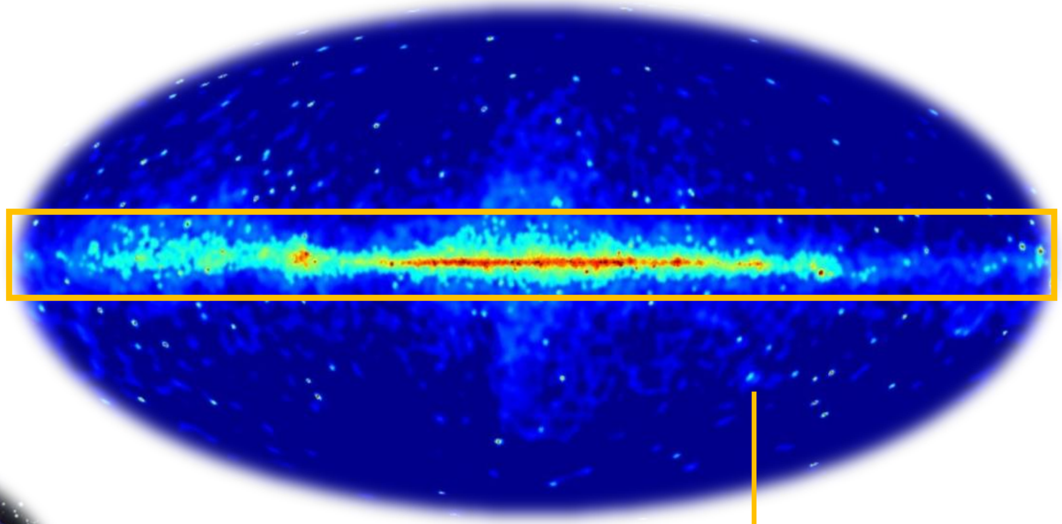
Astrophysical TeV – gamma sources

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

- galactic sources: $\boldsymbol{SN}$ shockwaves, pulsar wind–nebulae, processes in the $\boldsymbol{ISM}$*







- extra–galactic sources: $\boldsymbol{AGN}$,...

pulsar wind–nebulae

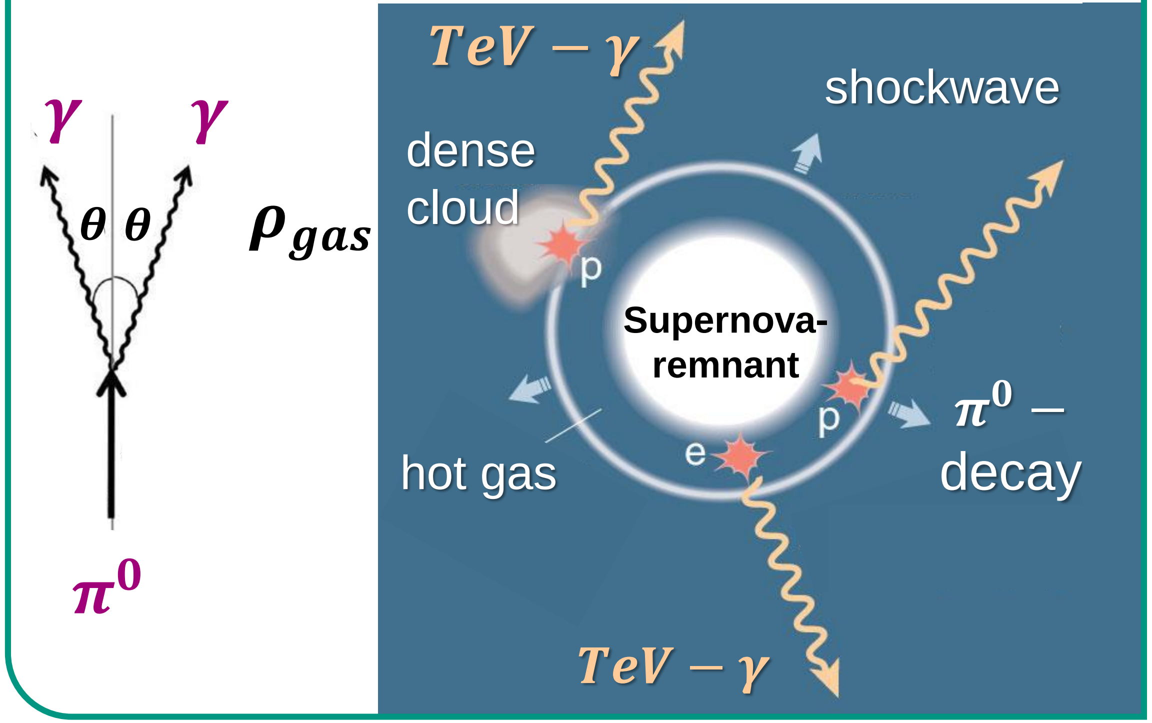
*$\boldsymbol{I}$nter$\boldsymbol{S}$tellar $\boldsymbol{M}$edium

Gamma production: hadronic or leptonic?

■ **Two basic mechanisms** to generate very high−energy gammas in an SNR

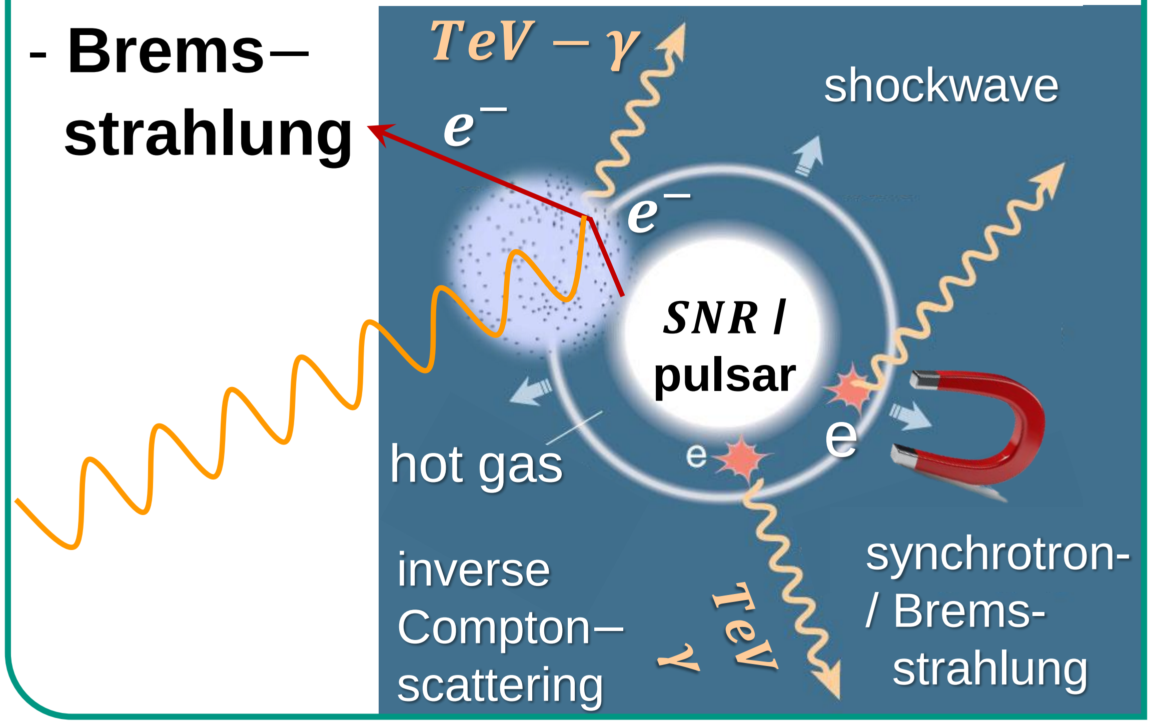
hadronic interactions

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



electron interactions

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

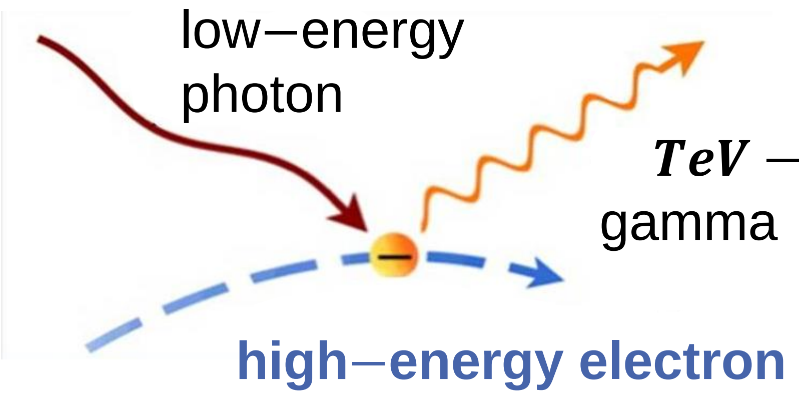


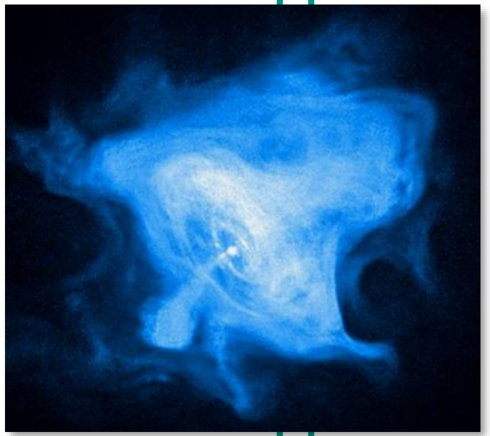
Gamma production: leptonic scenarios

■ **Pulsar wind nebulae as emitters of TeV − scale gamma radiation**

inverse Compton effect

- low−energy photon is accelerated by a **high−energy electron** (from a pulsar wind) up to TeV − energies
- highly efficient process

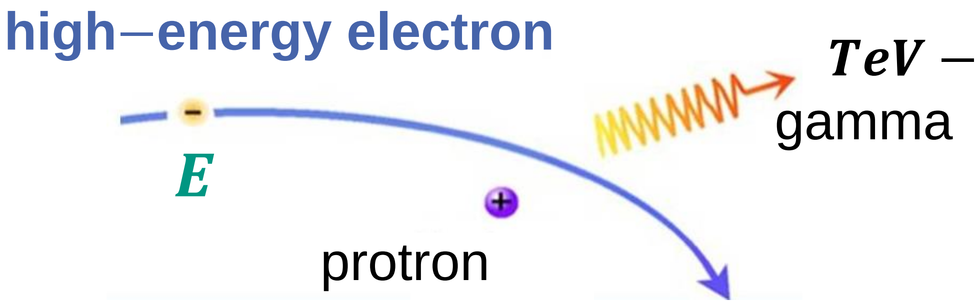




Bremsstrahlung

- **high−energy electron radiates** off an energetic gamma (GeV ... TeV range)

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



Gamma production: hadronic scenarios

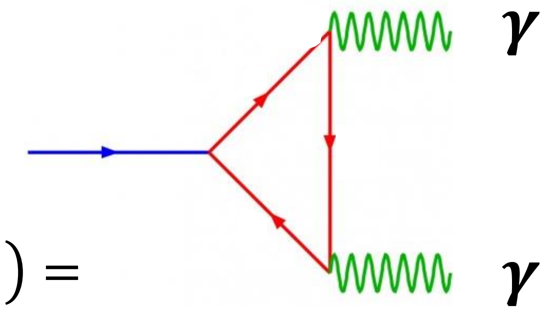
- **Shock wave of a SNR will accelerate protons to produce pions: $\pi^0 \rightarrow \gamma\gamma$**

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

neutral pions

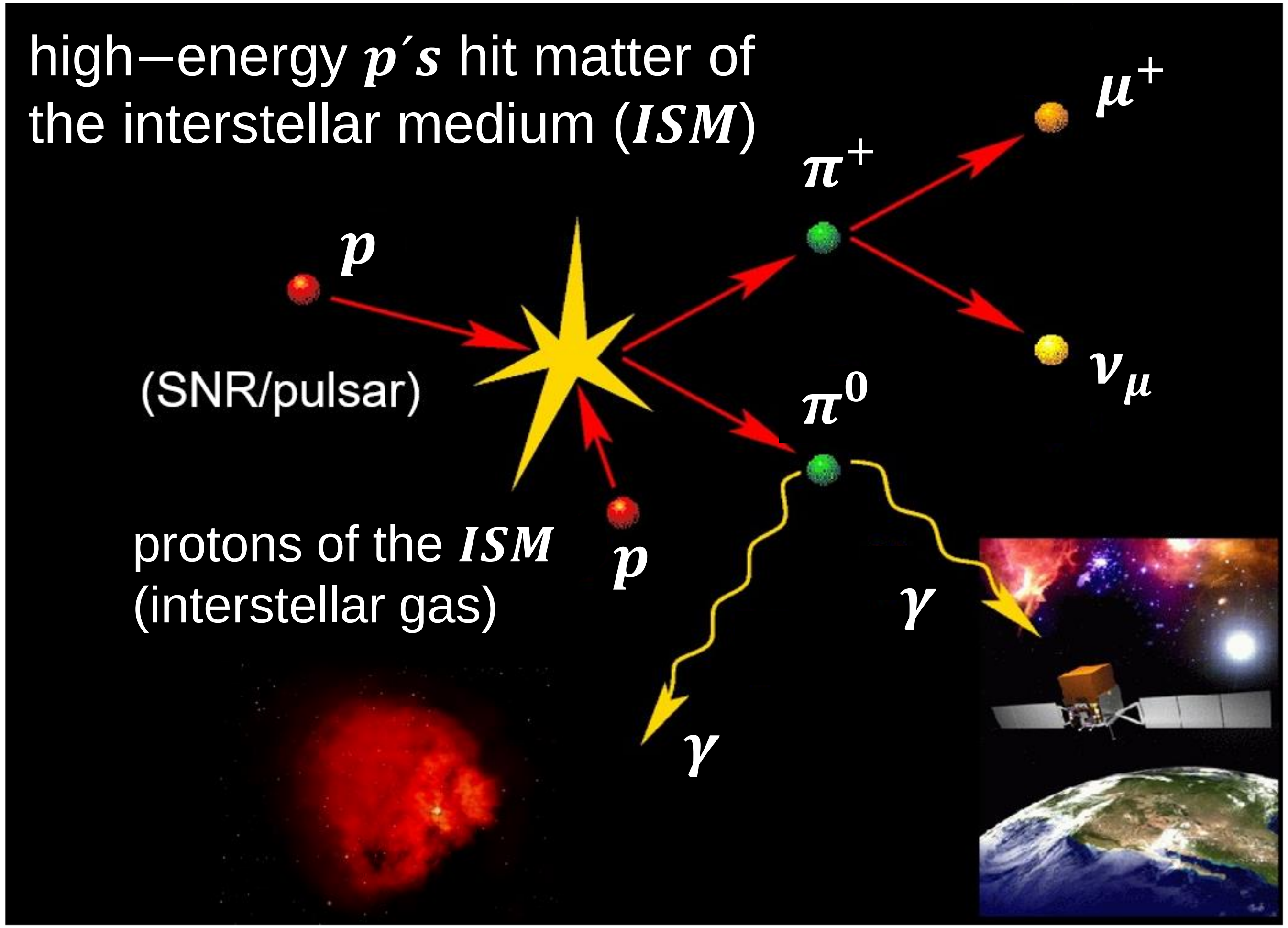
gammas from π^0 – decay:

π^0

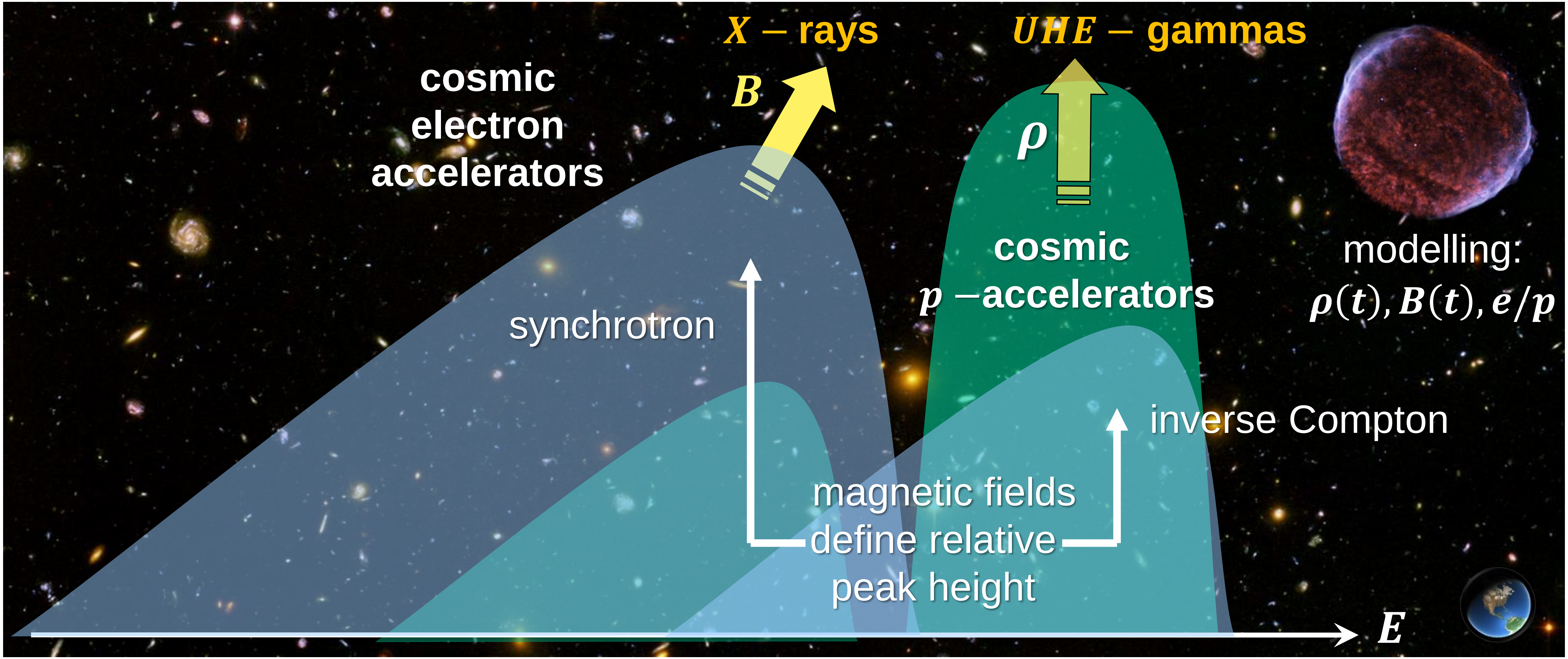


$m(\pi^0) =$ $135\ MeV$

$c.m.:$ $E_\gamma = m(\pi^0)/2$

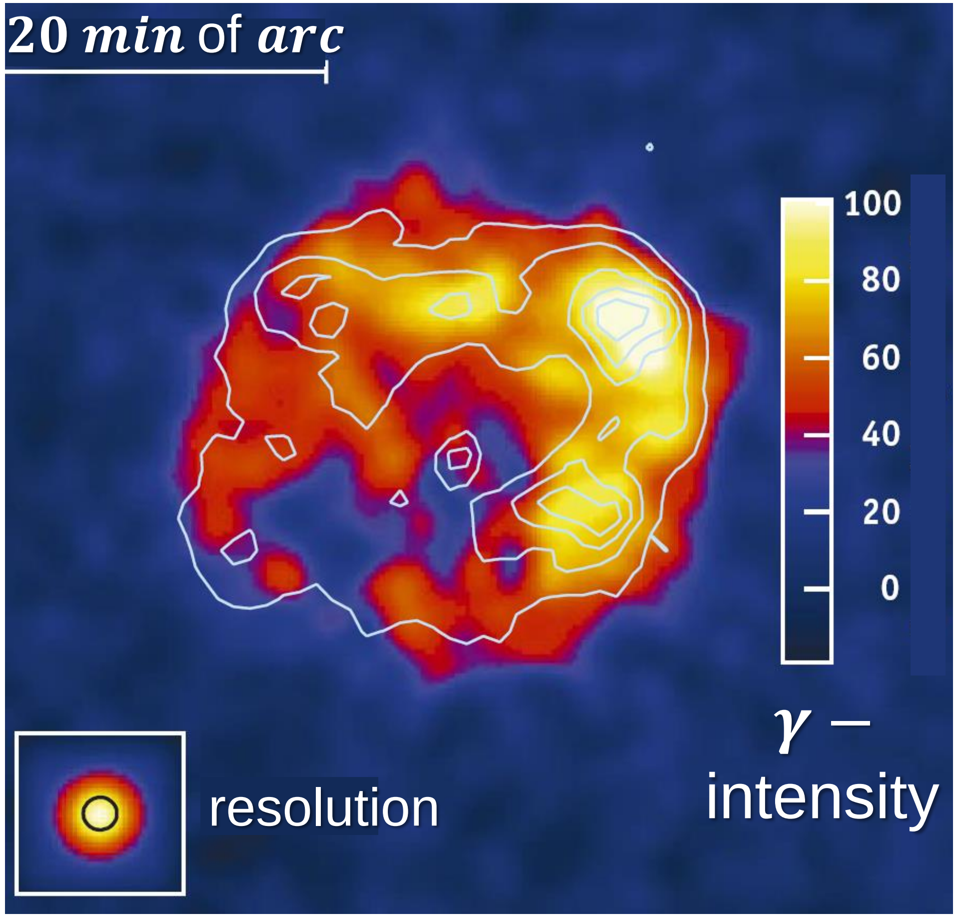


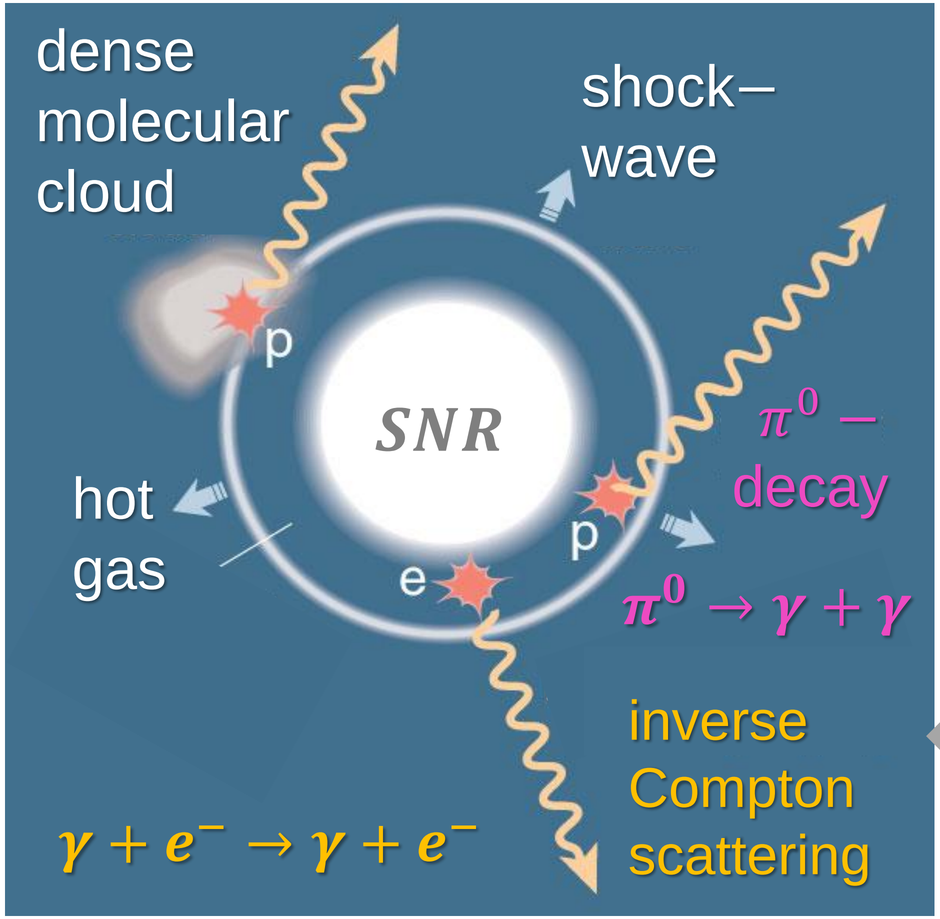
Spectral energy density of photons



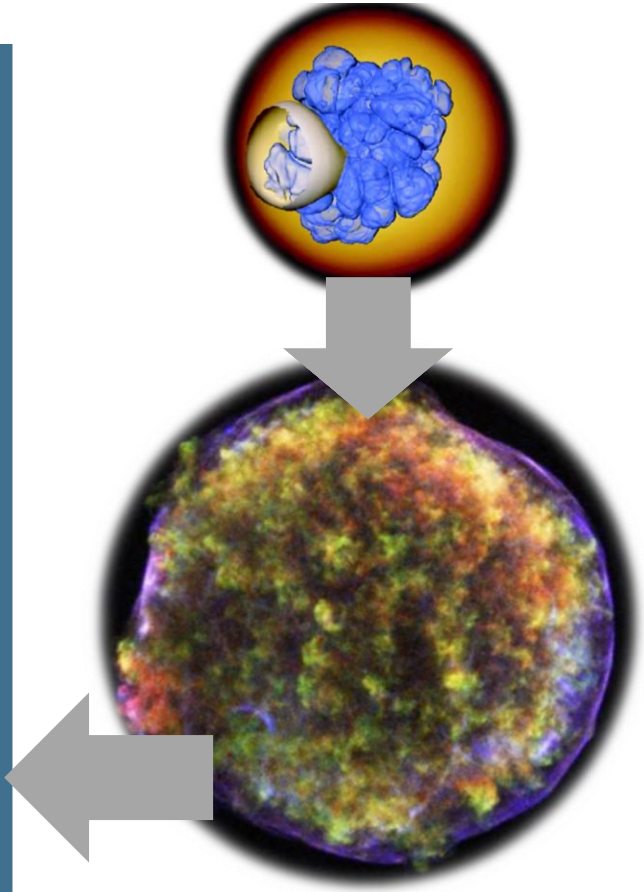
Expanding shells of supernovae ($SNRs$)

- SNR as lepton (inverse Compton) or proton ($\pi -$ decay) acclerators





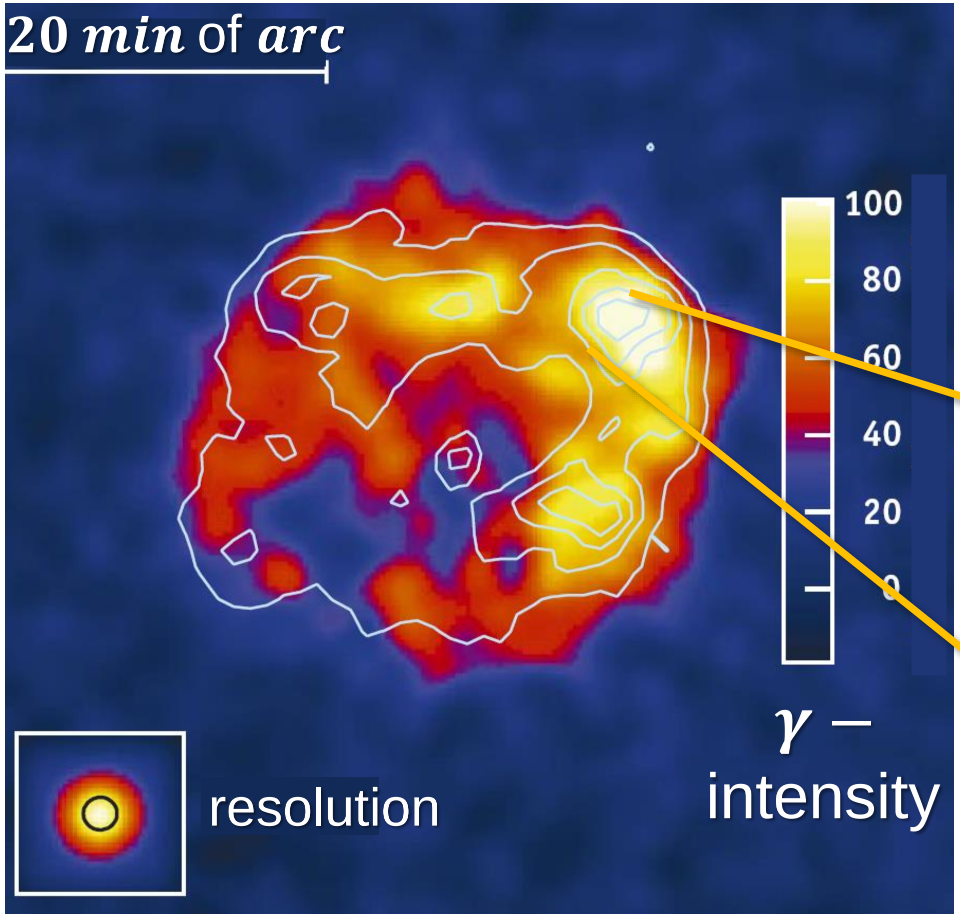
$SN - Ia$*



*see summer term 2024

Expanding SNR shells: a hadronic $TeVatron$?

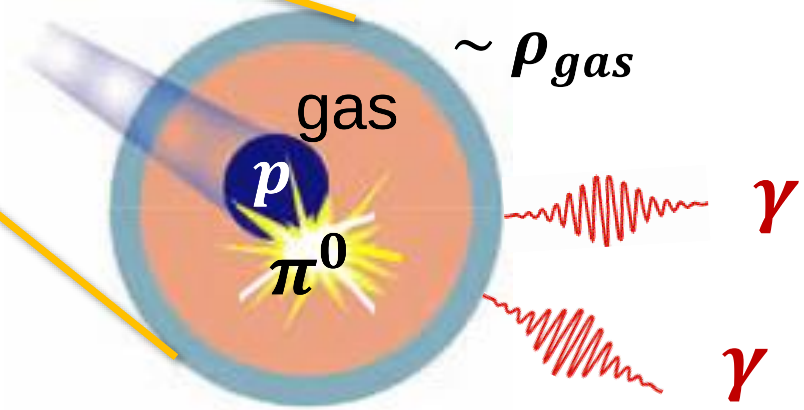
- SNR as **proton** (π – decay) **acclerator:** **interactions of $p´s$ in the hot gas**



- modelling of the extended SNR – shell $RX\ J1713.7 - 3946$ ($SN393$) at $d = 1\ kpc$

- first study of an **extended shell** of an ancient SNR in the light of TeV gammas

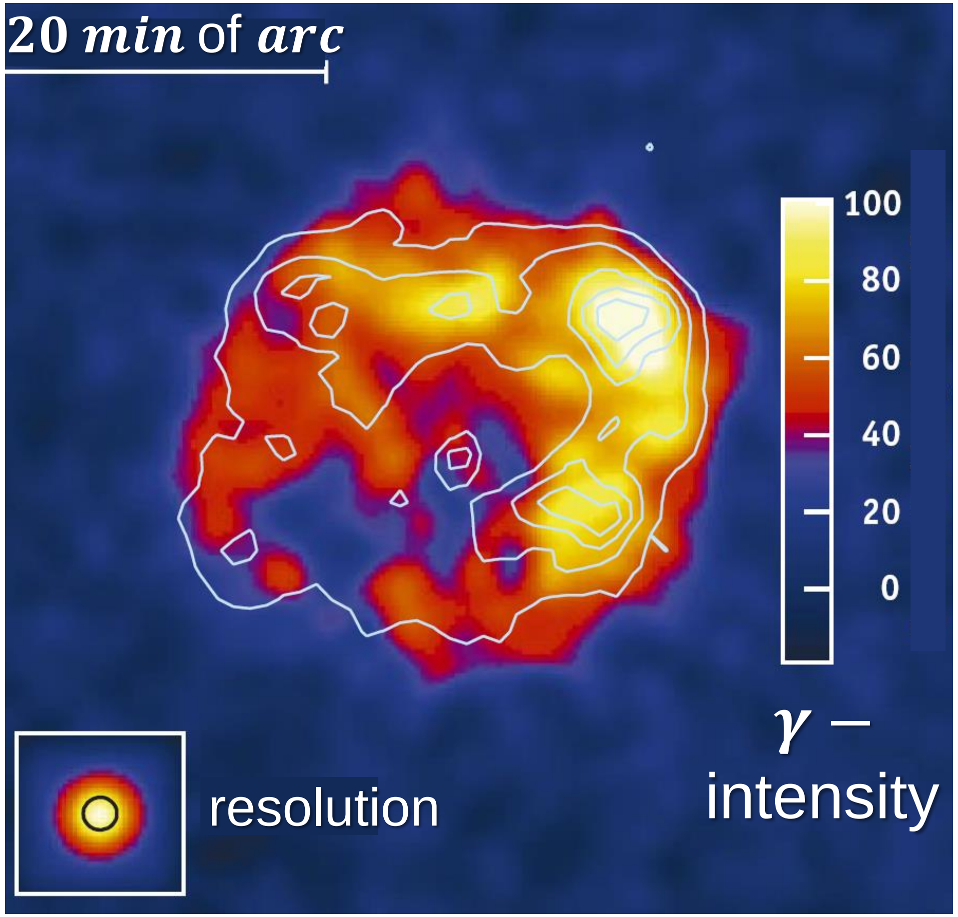
  ⇨ good agreement with X –ray contour lines

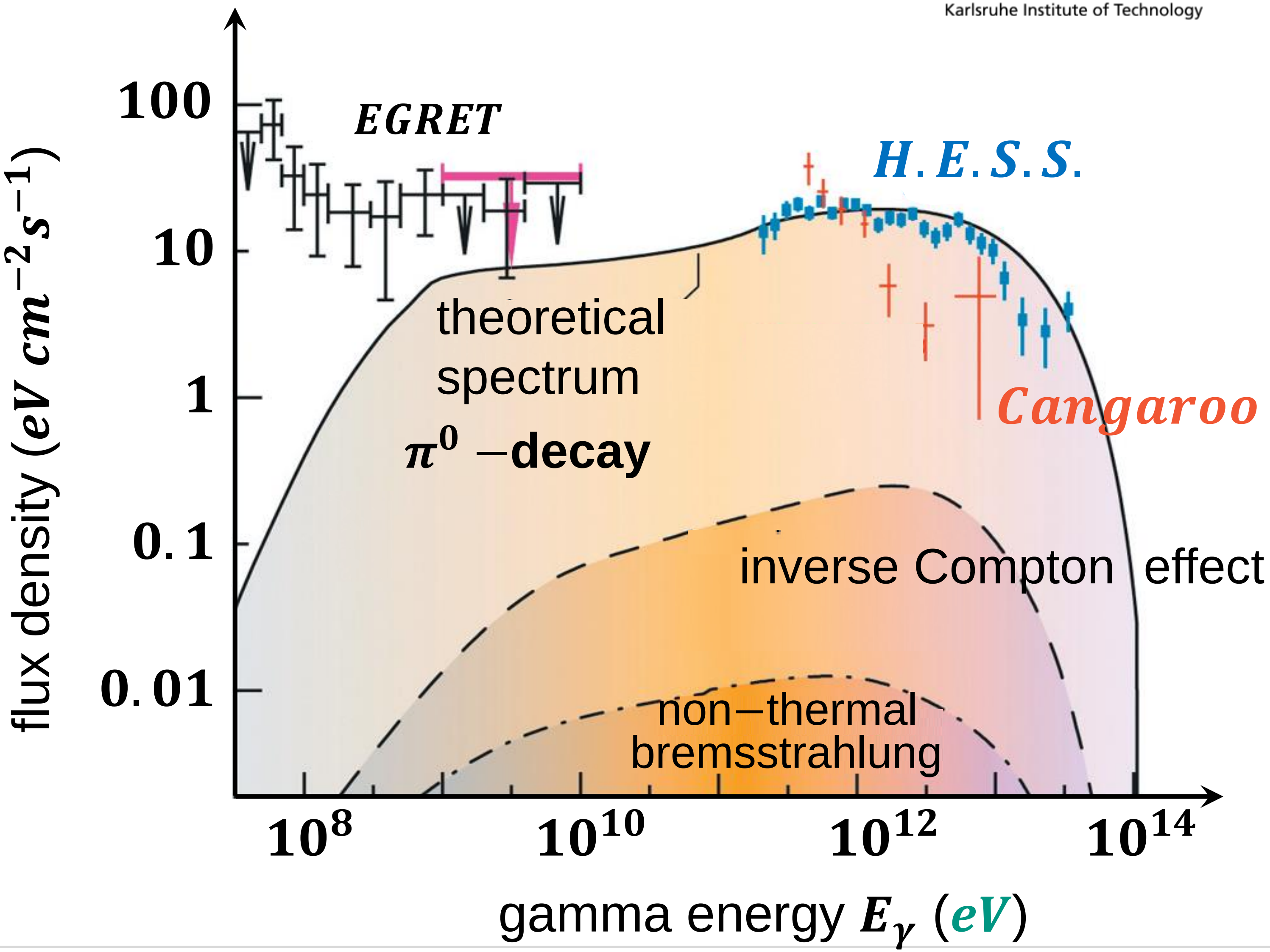


hadronic acceleration

Expanding SNR shells: a hadronic $TeVatron$

- SNR modelling: π^0 – decay



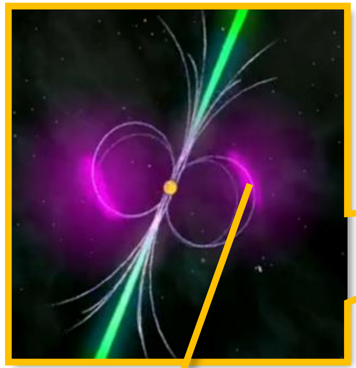


Pulsar at the center of the Crab Nebula ($SN1054$)

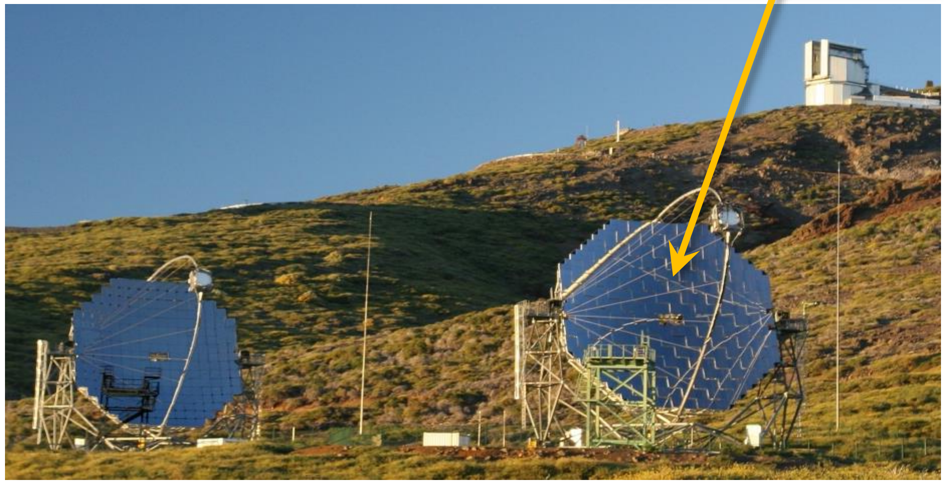
- **The ´gold standard´ for UHE gamma astronomy: gammas up to $400\ GeV$**

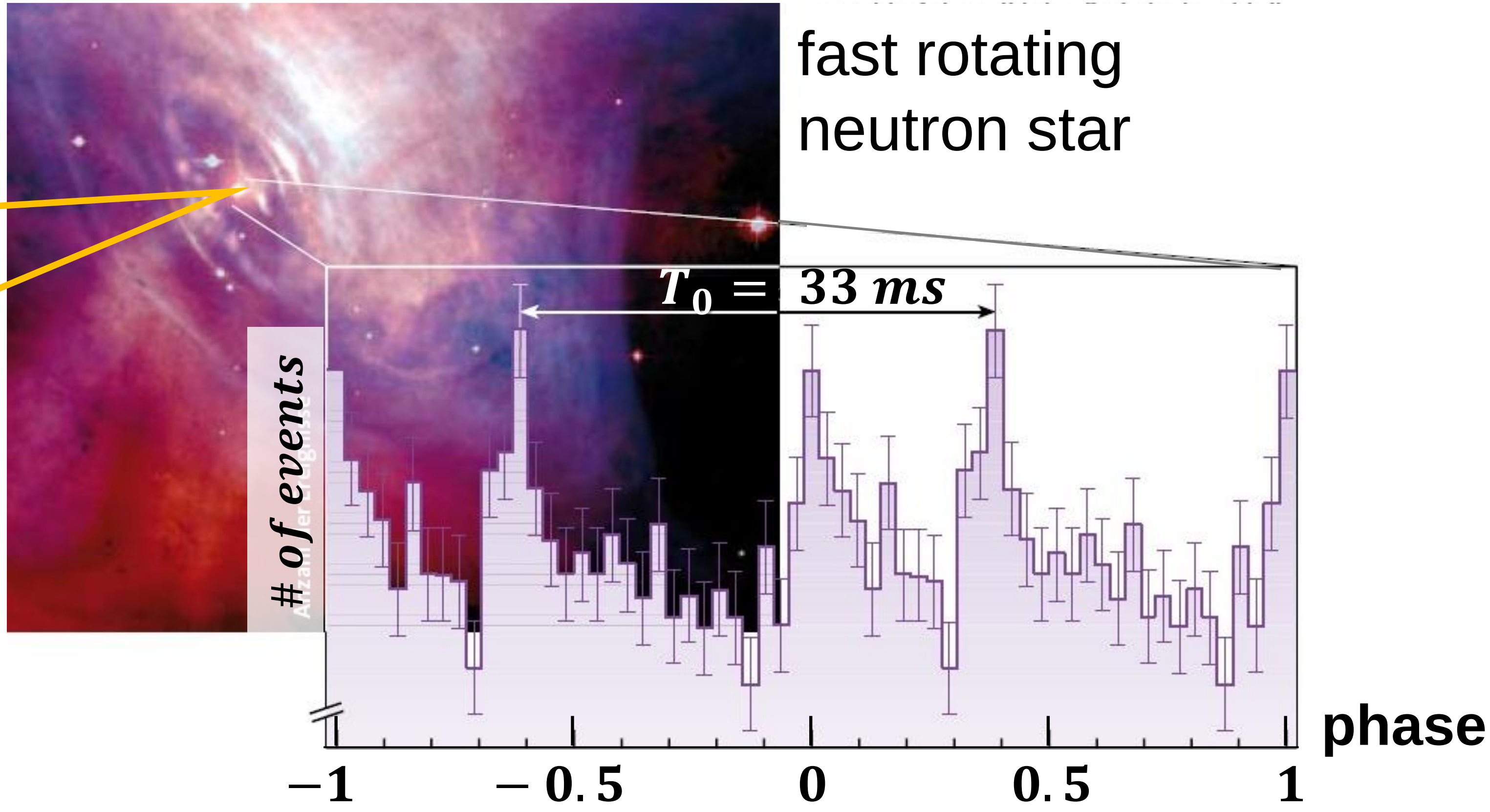
  - origin of $\gamma -$ **pulses**: from outer pulsar magnetosphere (not polar caps)

a cosmic
´light house´



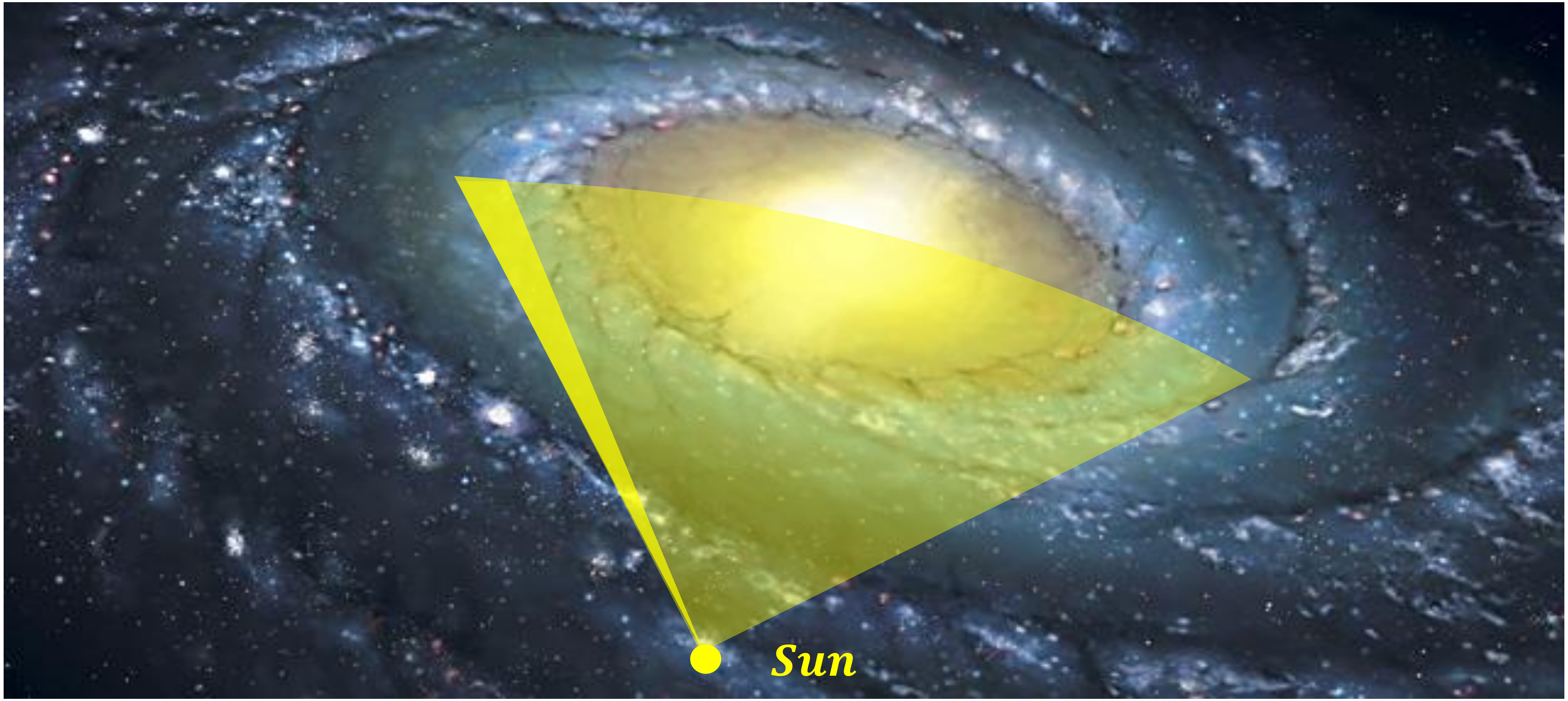
$MAGIC - II$





Scanning the galactic plane for UHE gammas

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



Scanning the galactic plane for UHE gammas

- first scan (2004) with $H.E.S.S.$ over $> 600\ h$: 15 new sources at TeV − scale