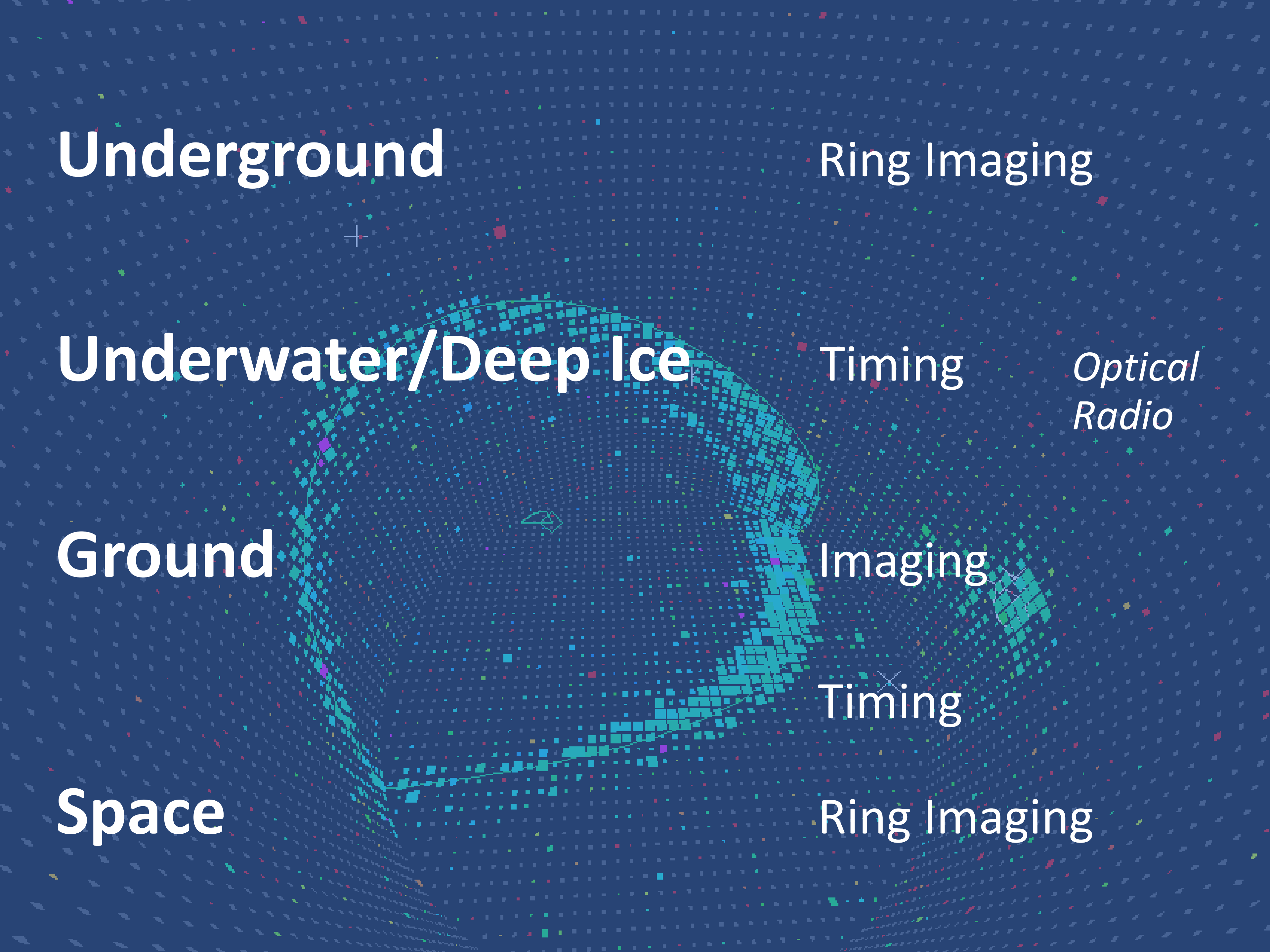
Cherenkov Detectors in Astroparticle Physics

Christian Spiering

RICH 2022, Edinburgh

C. Spiering, RICH 1995
Cherenkov imaging and timing techniques in astroparticle physics

Talk with some historical context


Underground
Ring Imaging
Underwater/Deep Ice
Timing
Optical
Radio
Ground
Imaging
Timing
Space
Ring Imaging

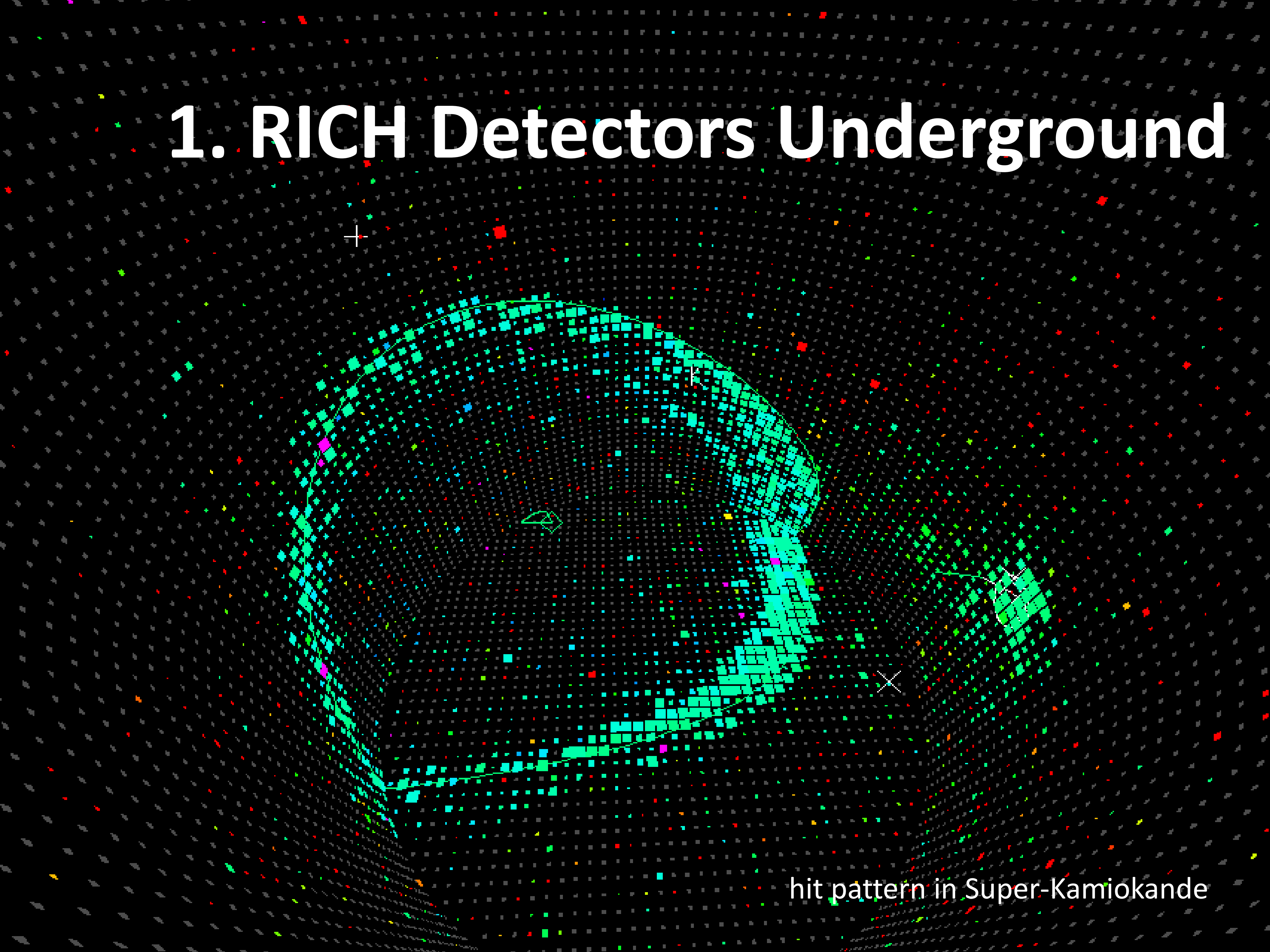
Underground — Ring Imaging

Underwater/Deep Ice — Timing — *Optical* / ~~*Radio*~~

Ground — Imaging / Timing

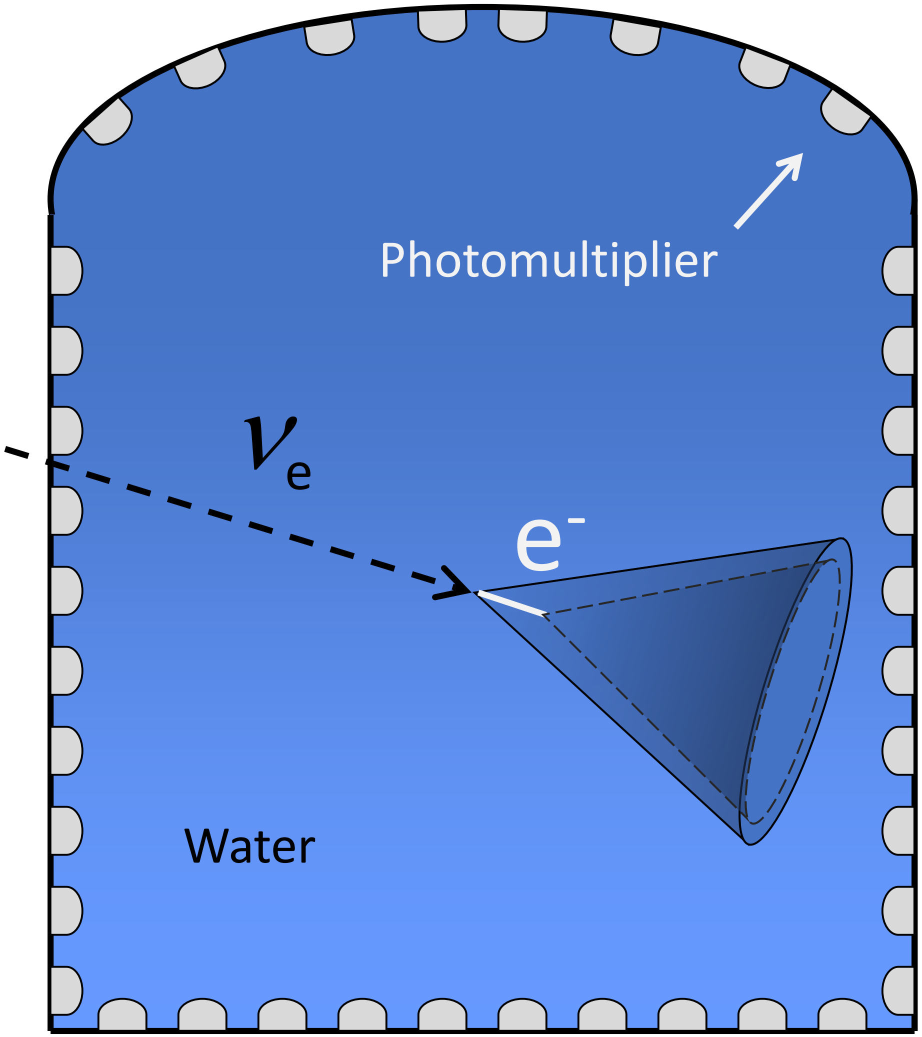
~~**Space**~~ — ~~Ring Imaging~~

1. RICH Detectors Underground

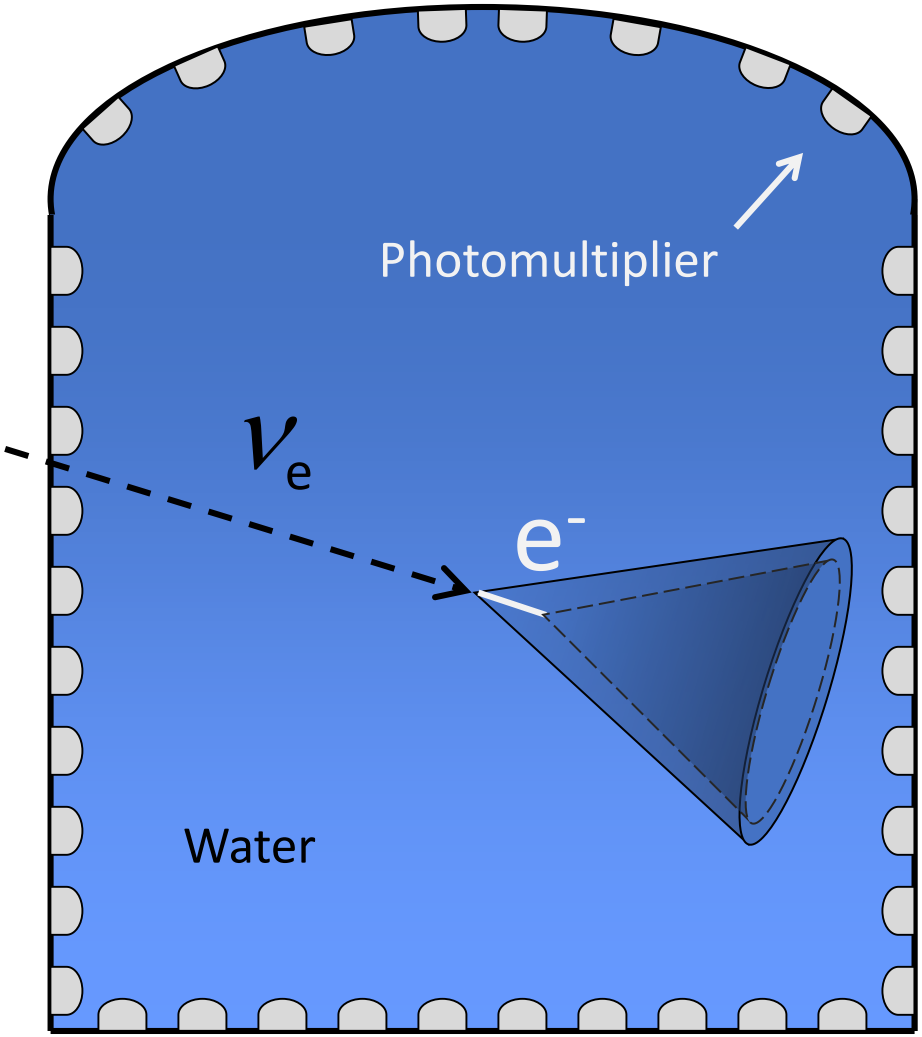


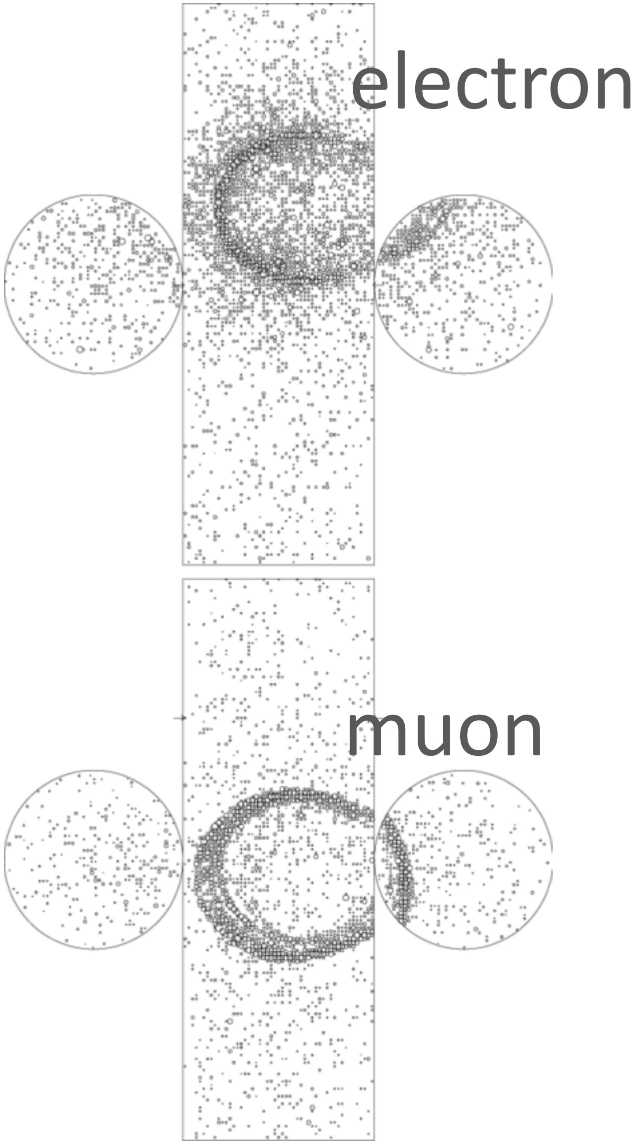
hit pattern in Super-Kamiokande

RICH Detectors Underground: Principle

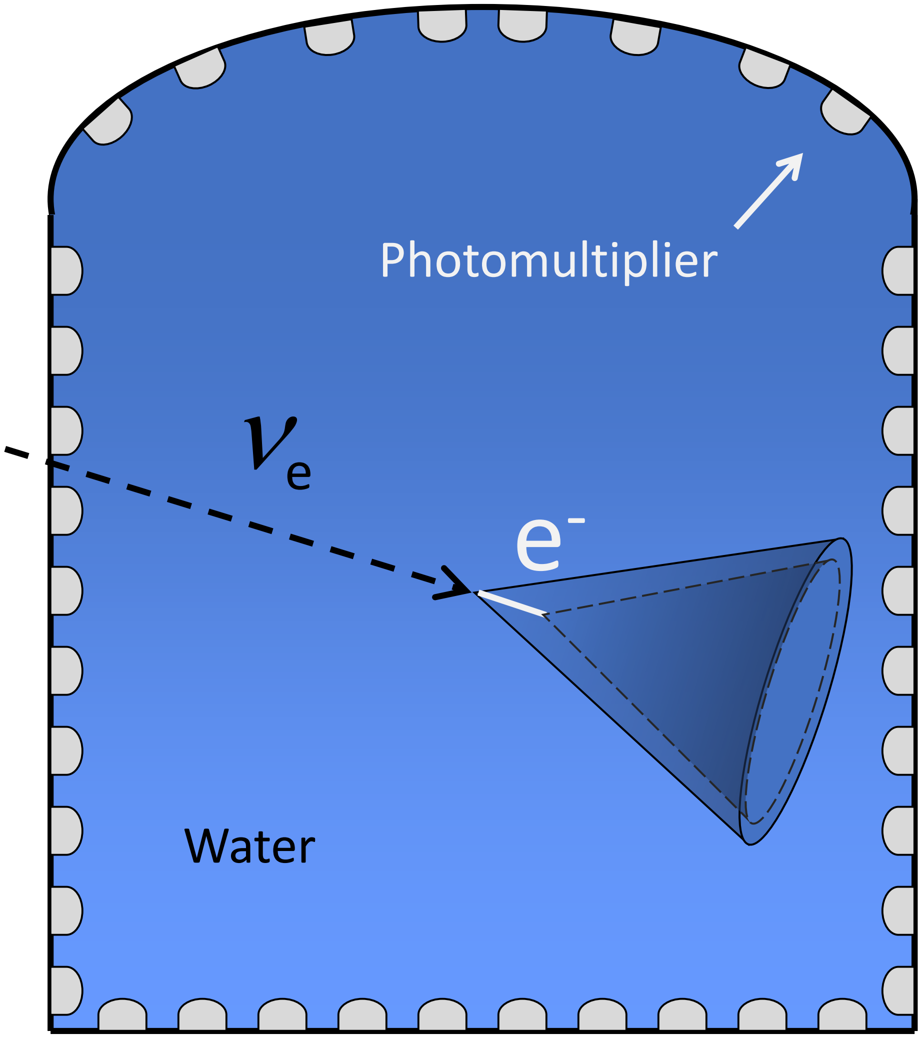


RICH Detectors Underground: Principle





RICH Detectors Underground: $\leq$ 1995



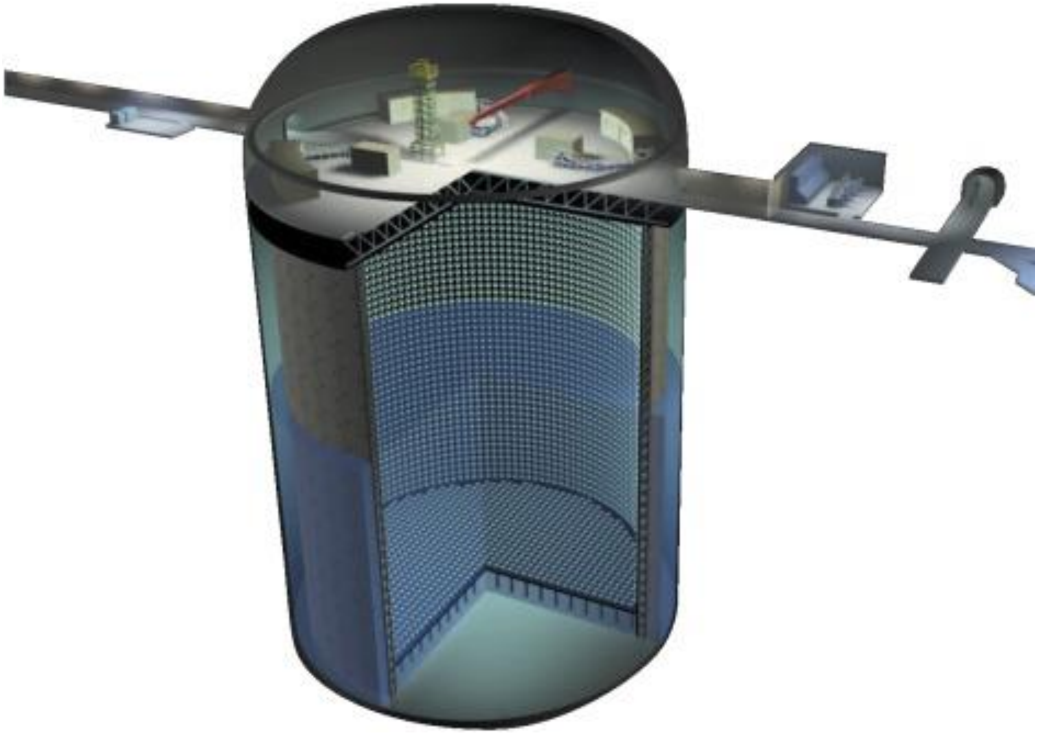
- **Kamiokande**
  - Japan
  - **3 kt H_2O**
  - 1000 PMTs
  - 1983 – 1995

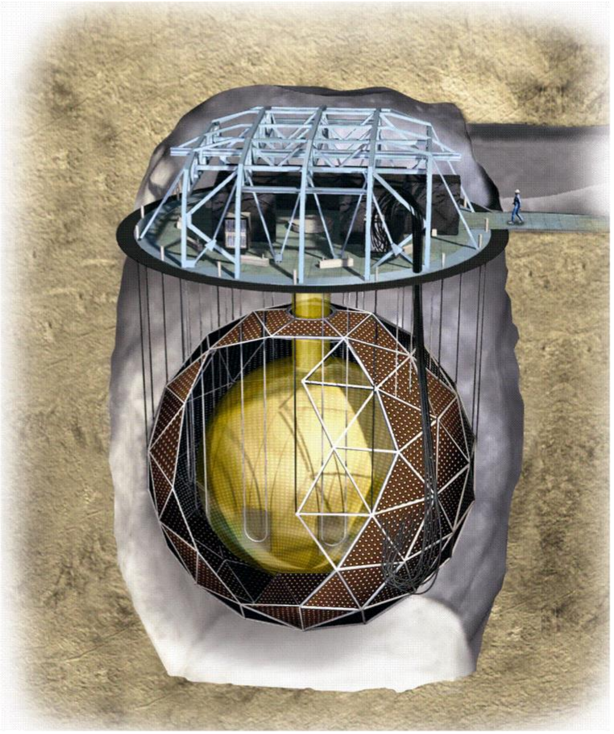
  - **SN 1987A – 12 events**
  - **Solar B^8 neutrinos**

- **IMB**
  - USA
  - **9 kt H_2O**
  - 2048 PMTs
  - 1982 – 1991

  - **SN1987A – 8 events**

RICH Detectors Underground: >1995





Super-Kamiokande

- Japan
- **50 kt H_2O**
- 11,000 20“ PMTs
- since 1996

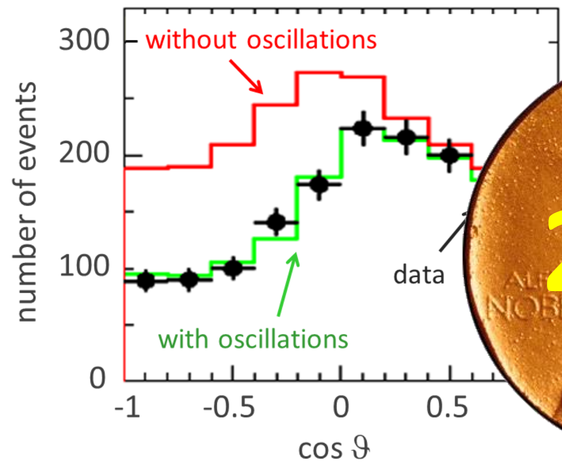
SNO D_2O

- Canada
- **1 kt D_2O**
- 9,438 10“ PMTs
- 1999 – 2006

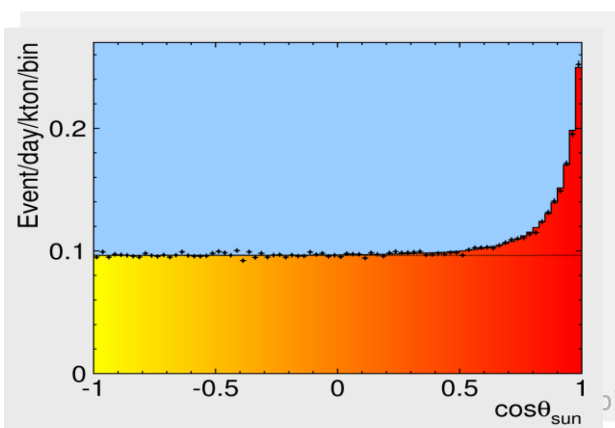
RICH Detectors Underground: Results

Super-Kamiokande

- oscillations atmospheric ν

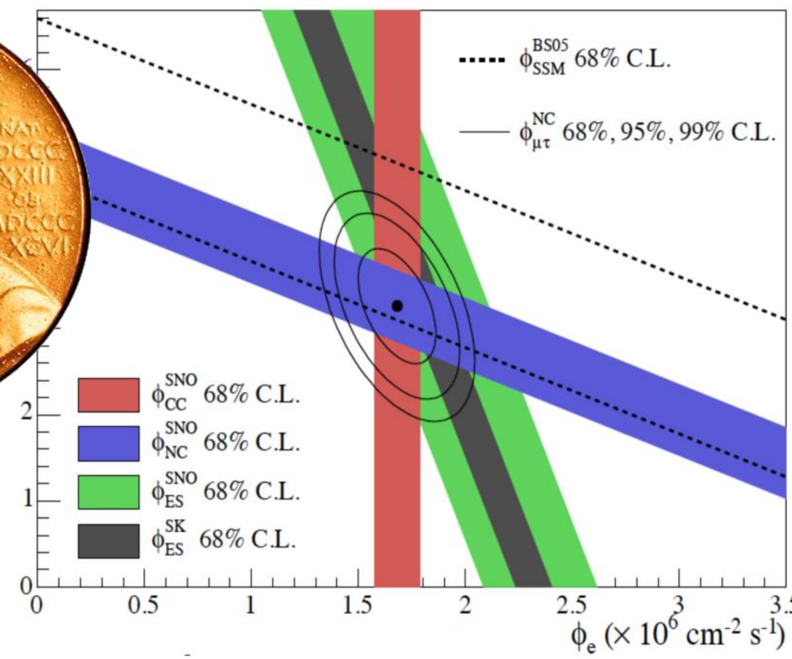


- precision flux solar ^8B



SNO D_2O

- oscillations solar ν: final proof

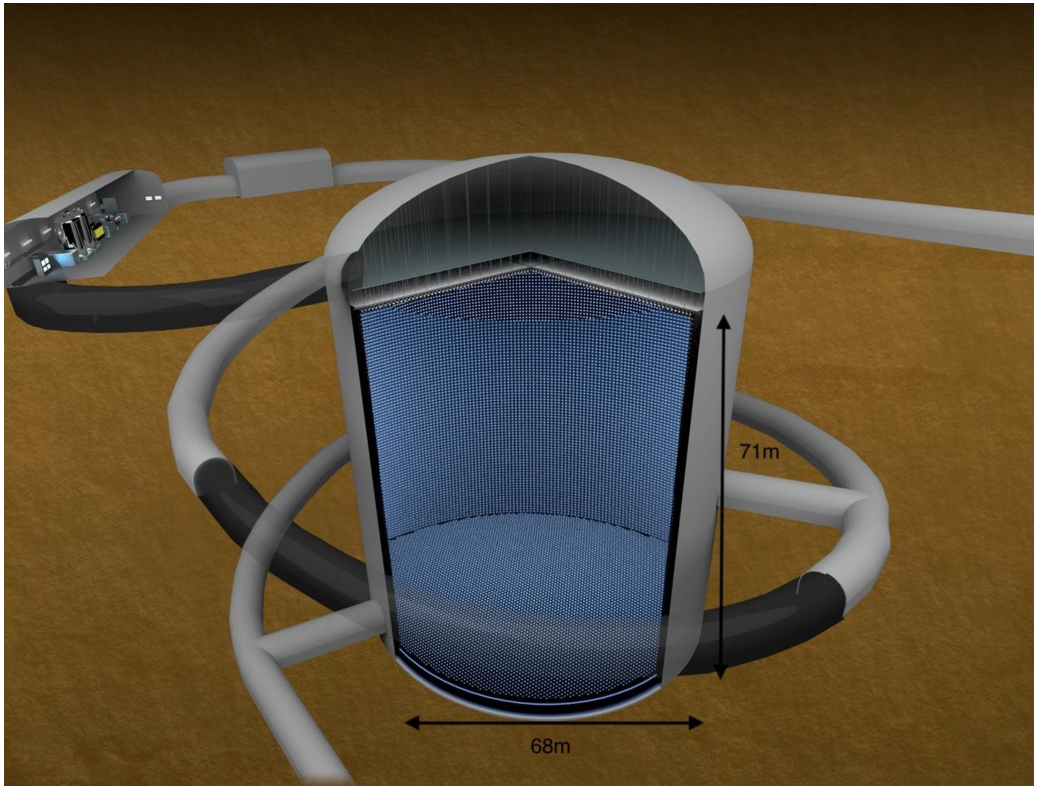


The Future: Hyper-Kamiokande

- Japan
- **260 ktons H_2O**
- 40,000 20“ PMTs (QE: 2×SK)
- Start data taking 2027

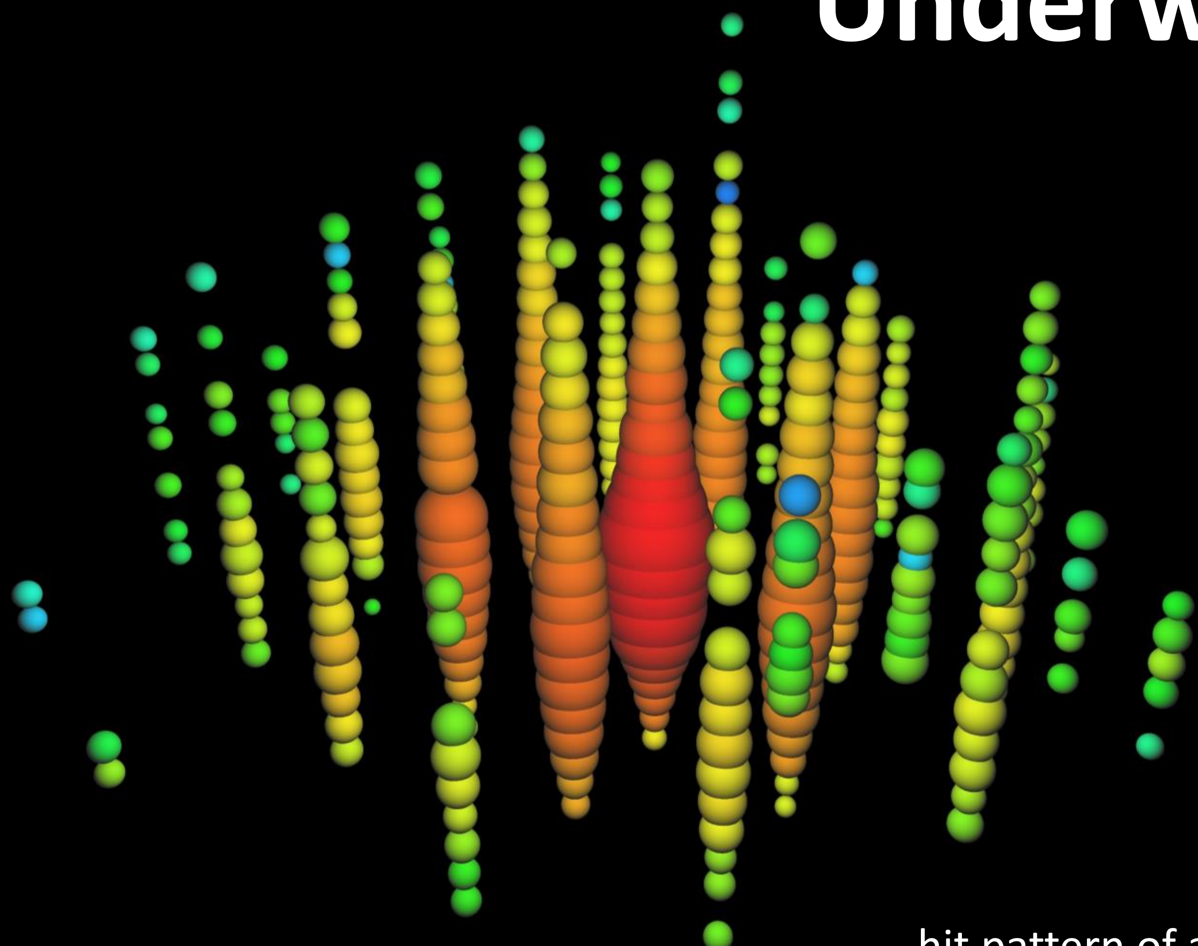
See talk of J.E.Kisiel

- Study of CP violation in leptonic sector
- Neutrino mixing parameters
- Proton decay
- Supernova neutrinos
- Dark matter
- …



2. Timing Detectors

Underwater/ice



hit pattern of a PeV event in IceCube

Underwater Detectors: Science goals

- Main purpose:

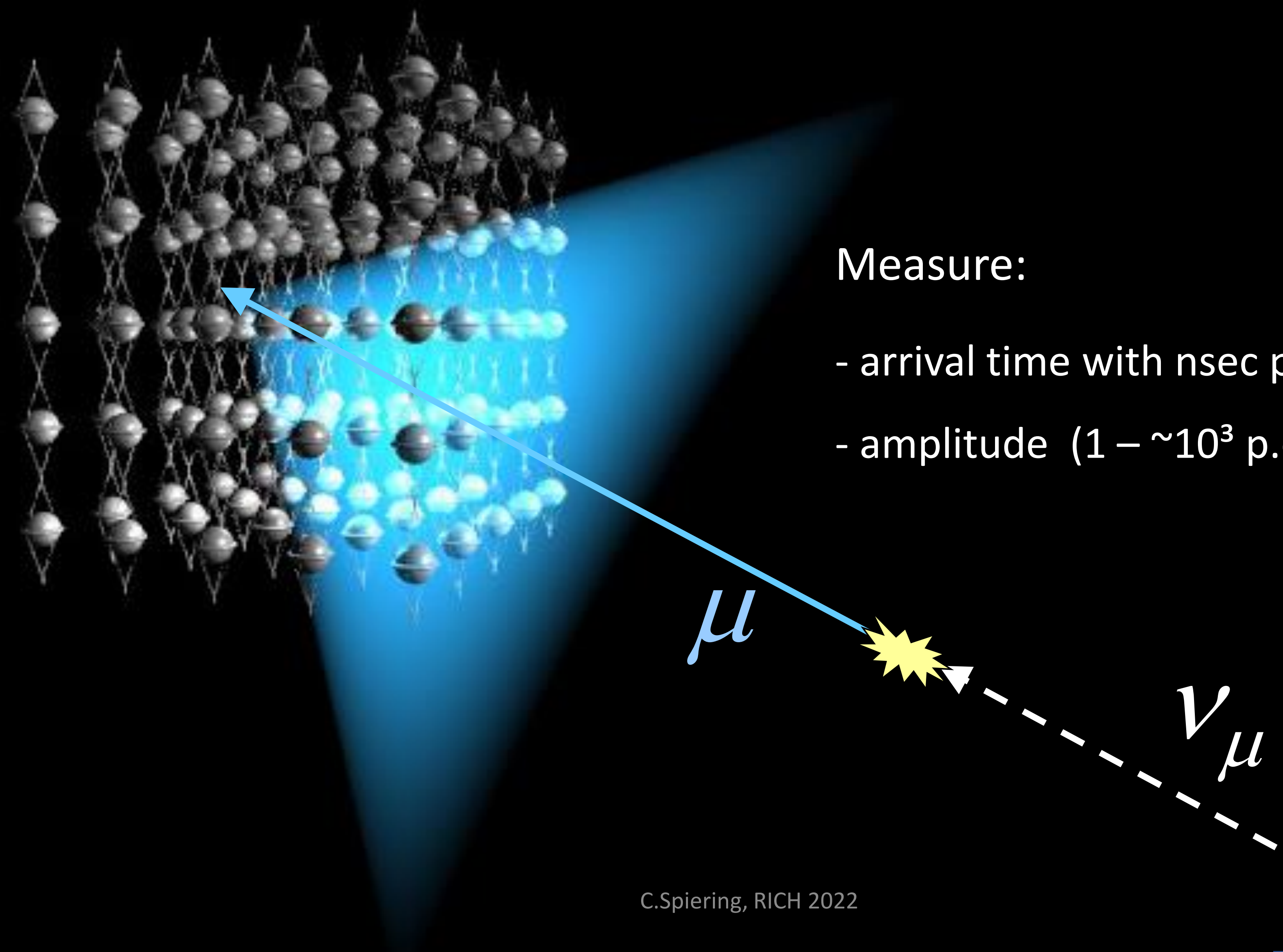
  Neutrinos from cosmic accelerators. What are the sources of cosmic rays?

  - 1 TeV- 100 PeV

  Fluxes ~ $E^{-2 \ldots 2.5}$ → need detectors on km³ scale or larger
  → open water or ice

- Oscillations of atmospheric neutrinos
  - few GeV – 20 GeV
- HE neutrino cross section, Earth tomography (using atmospheric neutrinos)
  - > 10 TeV
- Physics Beyond Standard Model, Dark Matter, Magnetic Monopoles, …
  - 100 GeV – PeV region
- Environmental science

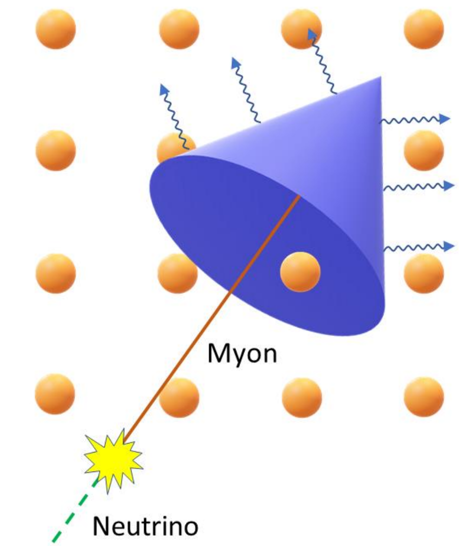
Underwater Detectors: Tracks



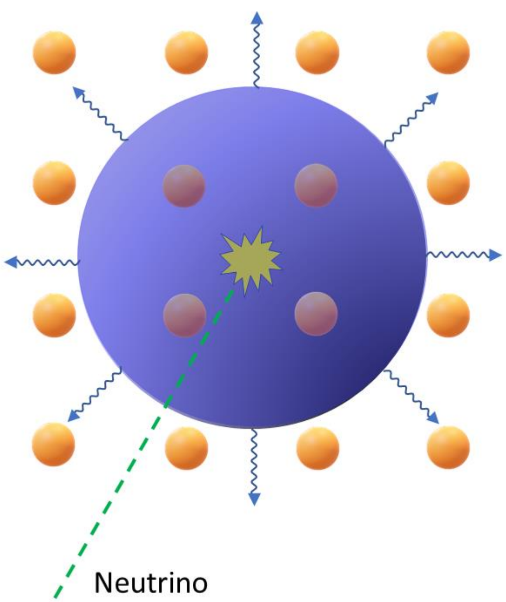
Measure:

- arrival time with nsec precision
- amplitude (1 – ~10^3 p.e.)

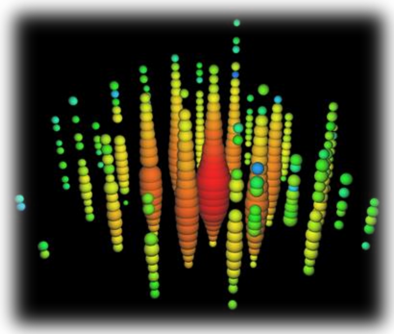
Underwater Detectors: Tracks & Cascades



- Excellent angular resolution
  - IceCube ~ 0.4°, KM3NeT ~ 0.1° at 100 TeV
- Energy determination: order of magnitude



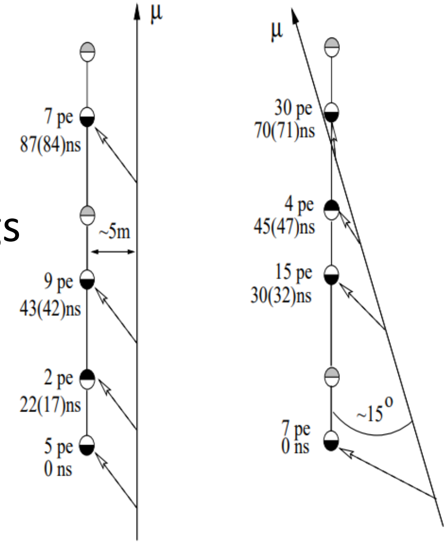
- Bad/moderate angular resolution
  - IceCube ~ 10°, KM3NeT ~ 2°
- Energy determination: ~ 10%



First generation detectors

- Baikal-NT200

The first 2 ν candidates
(36 PMT @ 3 half-strings
1993/1994)



196 hybrid 37cm PMTs „QUASAR“
0.0001 km³
1993 – 1998 – 2015

first data – completion – termination

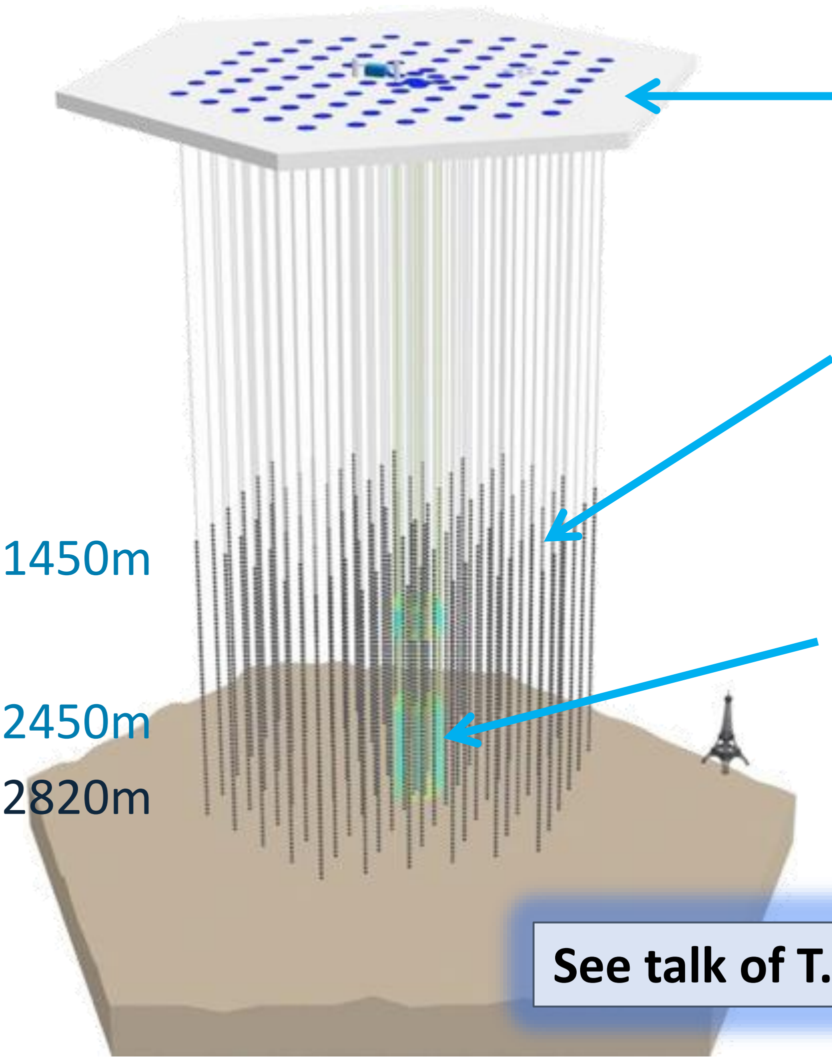
- AMANDA (South Pole)

677 8“- PMTs Hamamatsu
0.015 km³
1996 – 2000 – 2009

- ANTARES (Mediterranean)

885 10“- PMTs Hamamatsu
0.010 km³
2006 – 2008 – 2021

The IceCube Neutrino Observatory



IceTop air shower detector

81 pairs of water Cherenkov tanks

IceCube

86 strings including 8 Deep Core strings
60 10“ PMT per string

DeepCore

8 closely spaced HQE 10“ strings

See talk of T. Yuan

- ~220 ν/day
- Threshold
  - IceCube ~ 100 GeV
  - DeepCore ~10 GeV

The IceCube Neutrino Observatory

Main results:

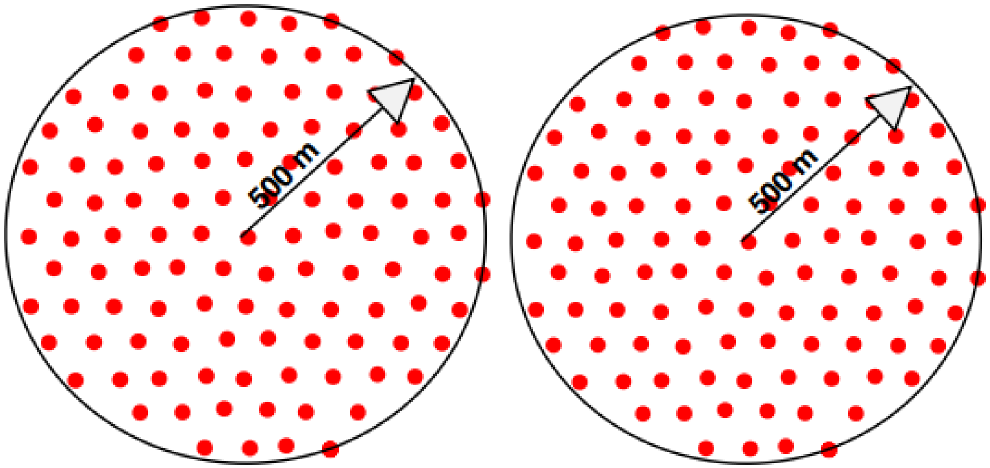
See talk of T. Yuan

- ***Breakthrough 2013***:
  Diffuse flux of extraterrestrial neutrinos

- First evidences for cosmic neutrino point sources
- Strong constraints on neutrino oscillations
- Neutrino cross section at > 10 TeV
- Record limits on DM, magnetic monopoles and other BSM phenomena

KM3NeT

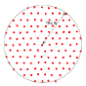
- KM3NeT-ARCA: High-Energy Neutrino Astronomy



Italy
100 km from Sicily
2×0.6 km³

- KM3NeT-ORCA: Precision Neutrino Oscillations

Each block has 115 strings ("Detection Units", DUs), each with 18 Digital Optical Modules



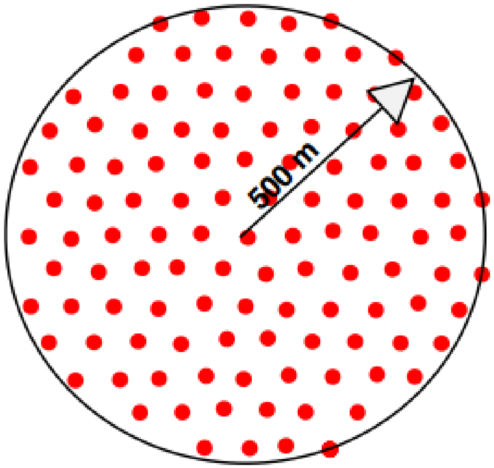
Diameter 220 m

France
40 km from Toulon
0.006 km³ (6 Mtons)

KM3NeT

See talk of E. Dragopoulou

- KM3NeT-ARCA: High-Energy Neutrino Astronomy



July 2022
19 DUs deployed

- KM3NeT-ORCA: Precision Neutrino Oscillations

See poster of J. De Athayde Marcondes Andre

Diameter 220 m

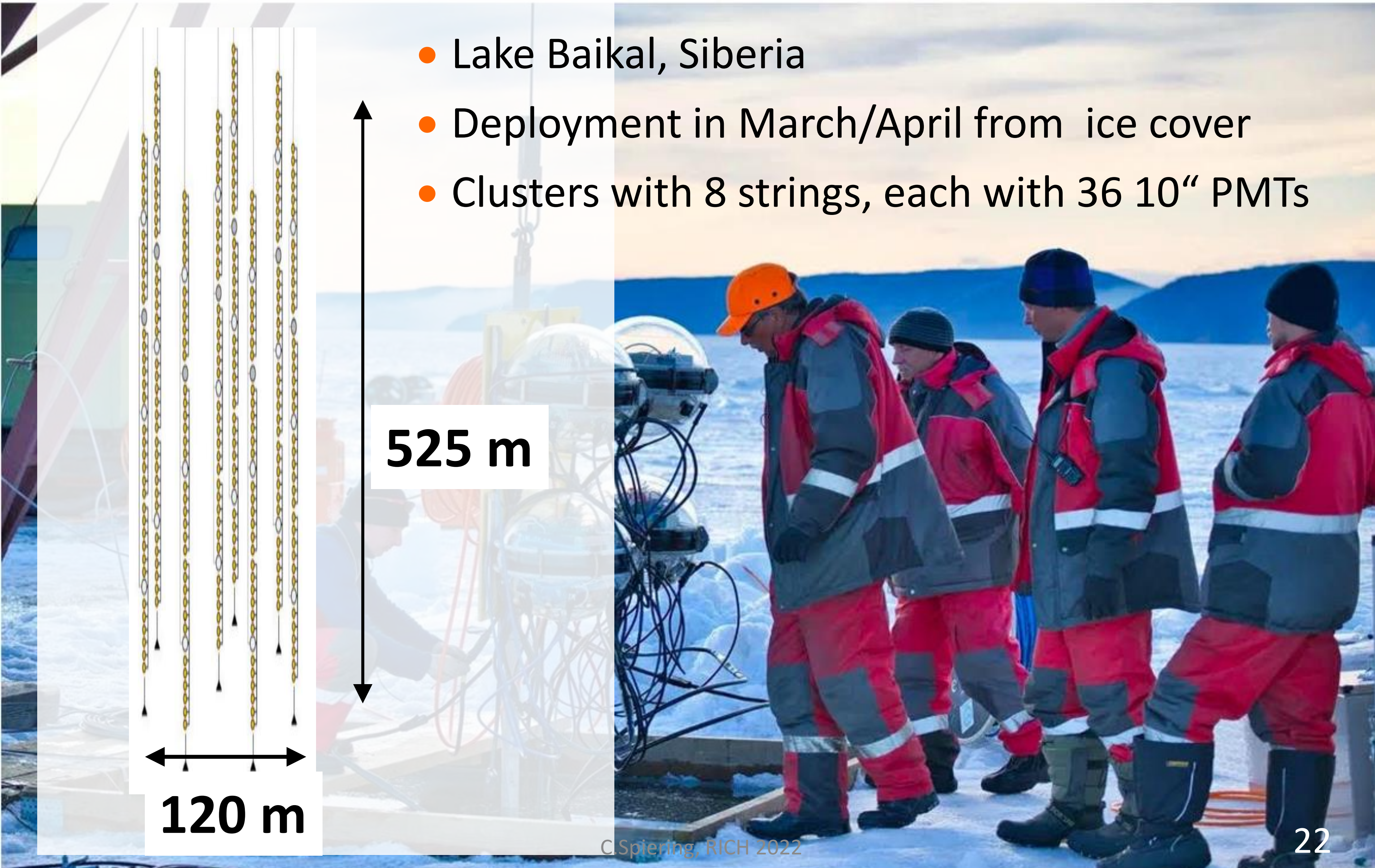
July 2022
10 DUs deployed

The KM3NeT Digital Optical Module

- 31 3-inch PMTs in 17-inch glass sphere (cathode area ~3x10-inch PMTs)
- Advantages:
  - Increased photocathode area
  - 1-vs-2 photo-electron separation
  - Directionality
  - Cost / photocathode area
  - Minimal number of feed-throughs per photoathode area → reduced risk

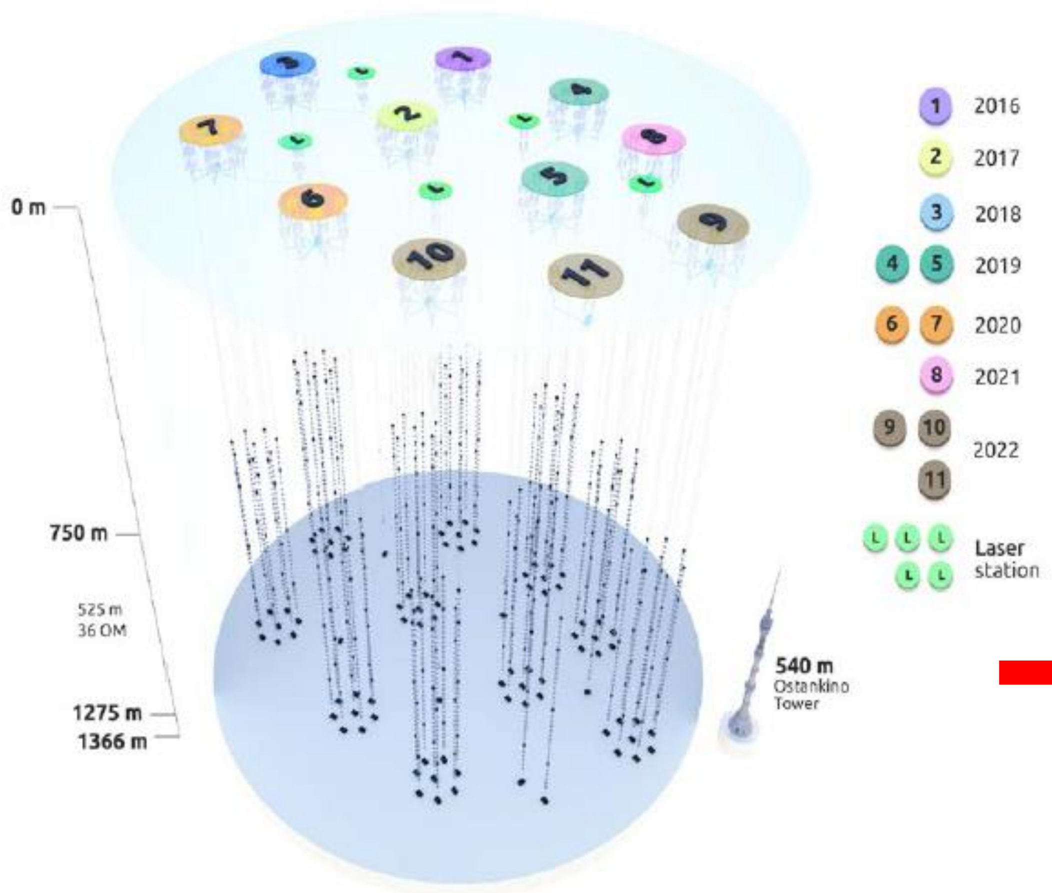
Baikal-GVD (Gigaton Volume Detector)

- Lake Baikal, Siberia
- Deployment in March/April from ice cover
- Clusters with 8 strings, each with 36 10“ PMTs



Baikal-GVD

Status 2022: 10 clusters, 5 laser stations, experimental strings

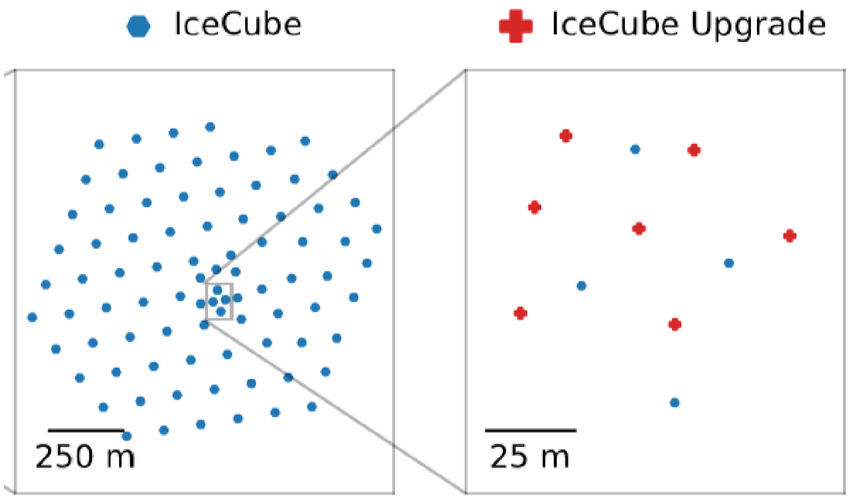


Deployment schedule

Year	Number of clusters	Number of OMs
2016	1	288
2017	2	576
2018	3	864
2019	5	1440
2020	7	2016
2021	8	2304
2022	10	2880
2023	12	3456
2024	14	4032
2025	16	4608
2026	18	5184

First clear cosmic neutrino candidates identified

IceCube-Gen2: towards the 10-km^3 scale



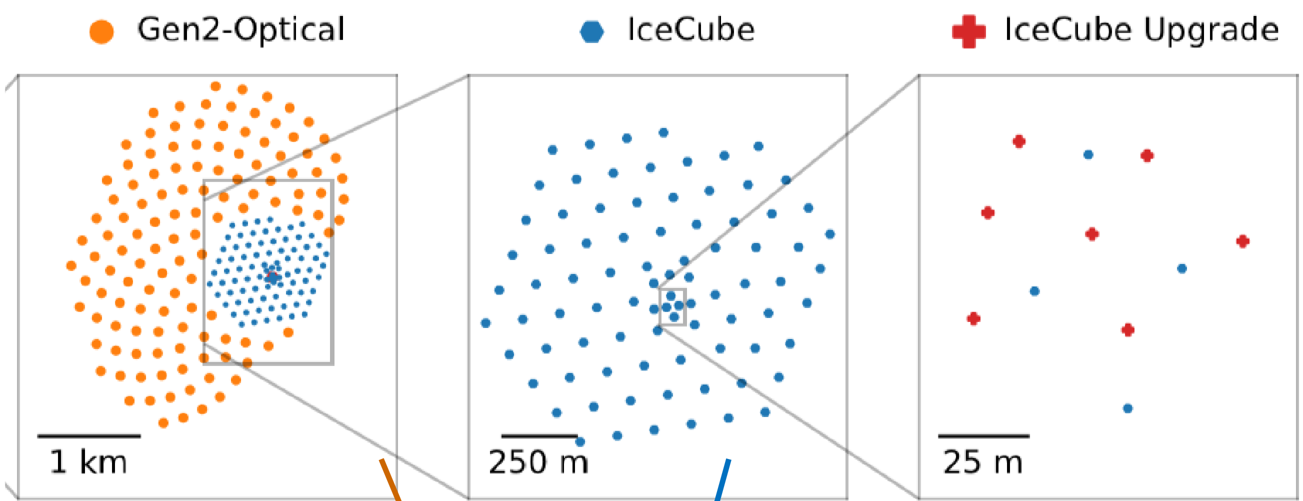
1 TeV – 5 PeV

improves DeepCore performance at < 10 GeV

also: detailed ice studies

to be deployed 2025/26

IceCube-Gen2: towards the 10-km^3 scale



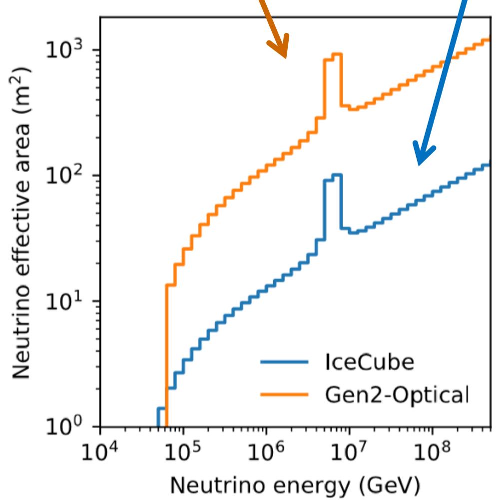
10 TeV – 50 PeV

1 TeV – 5 PeV

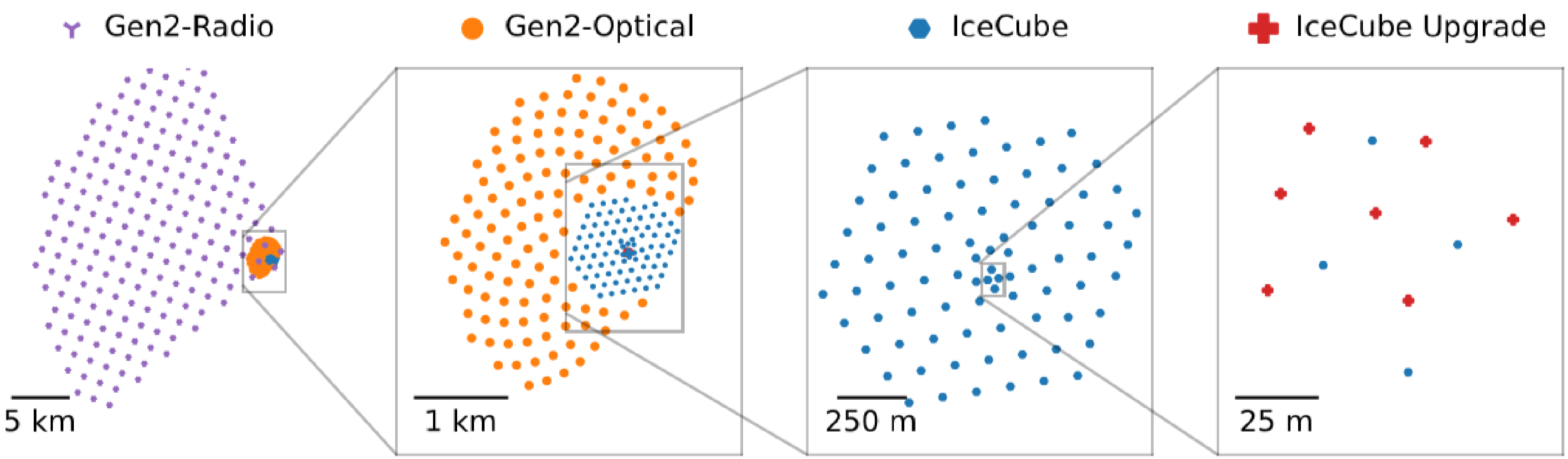
improves DeepCore performance at < 10 GeV

Neutrino effective area:

Gen2 -Optical vs. IceCube



IceCube-Gen2: towards the 10-km³ scale



10 PeV to >10 EeV

10 TeV – 50 PeV

1 TeV – 5 PeV

improves DeepCore performance at < 10 GeV

- Radio emission from extremely energetic particle cascades
- at wavelengths >> cascade diameter (20-30 cm) → coherent emission!
- scales with E^2 → optimal for energies > 10-50 PeV
- absorption length in ice ~ 500 m (optically: ~ 100 m) → allows large spacing
- **First large-scale implementation: RNO-G (Radio Neutrino Observatory Greenland)**

Gen2 sensor developments

Multi-PMT optical module (mDOM)

- 24 × 3” PMTs (Hamamatsu 12199-02)
- Based on KM3NeT design
- R&D and production by German groups

“D-Egg”

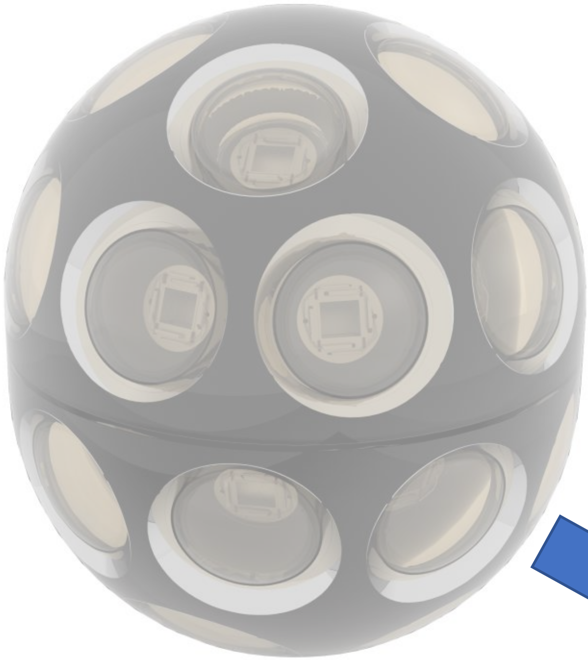
- Two 8” PMTs
- R&D and production by Japanese groups

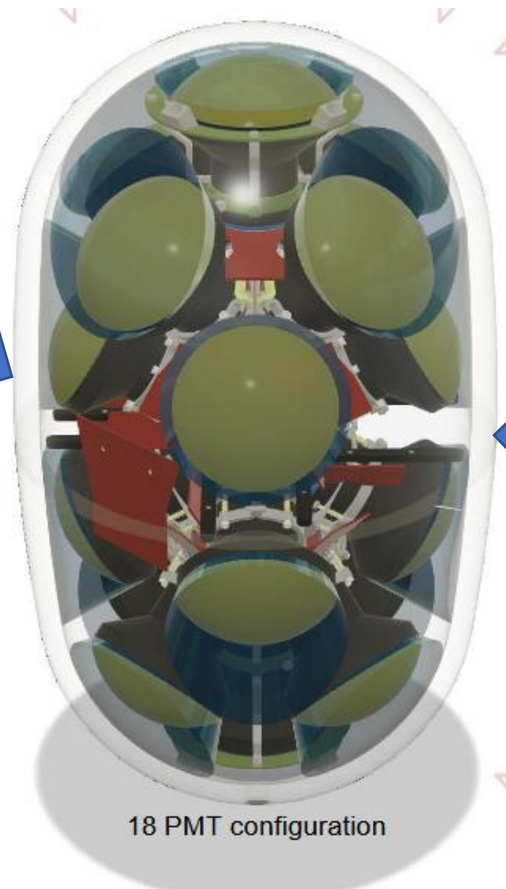
Further light sensor technologies under study

Gen2 sensor developments

e.g. the „LOM“

Small diameter → reduced drilling cost



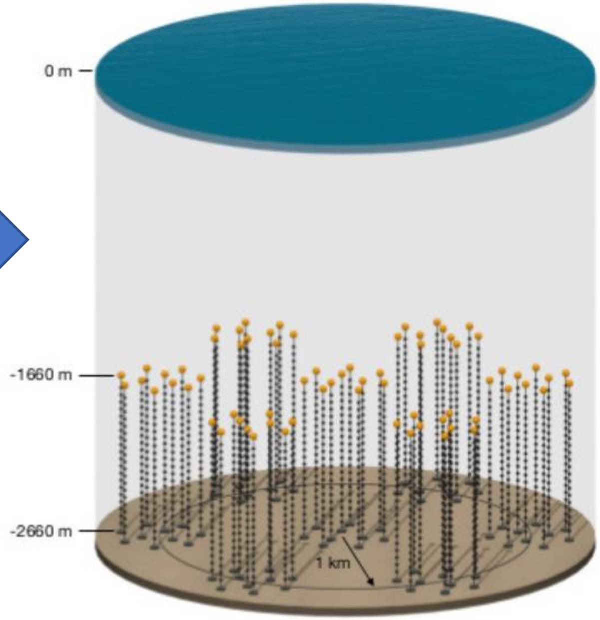


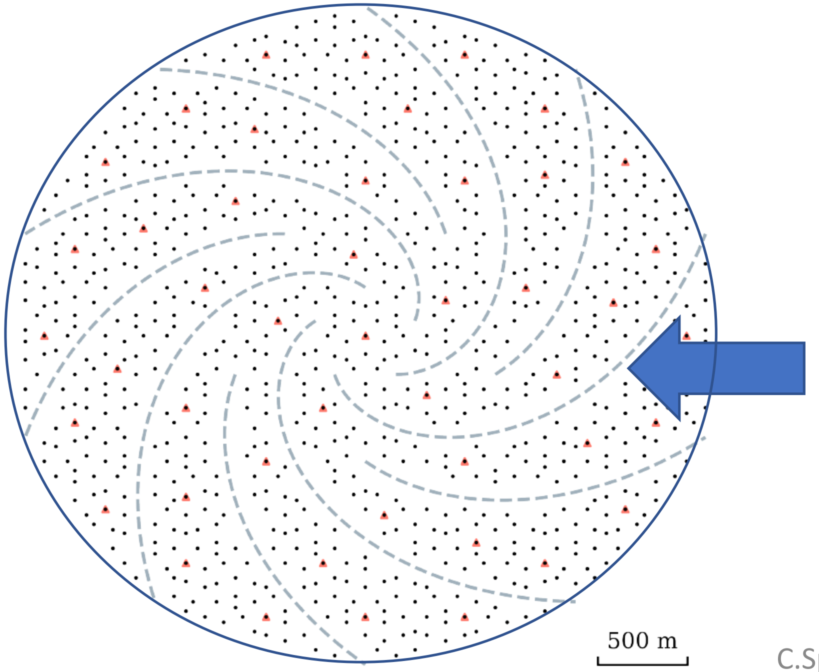
Further light sensor technologies under study

Two Newcomers:

P-ONE (Pacific Ocean Neutrino Explorer)

- Multi-cluster neutrino telescope to be deployed at the West Coast of Canada, using the infrastructure of the Ocean Networks ONC.
- Prototype phase



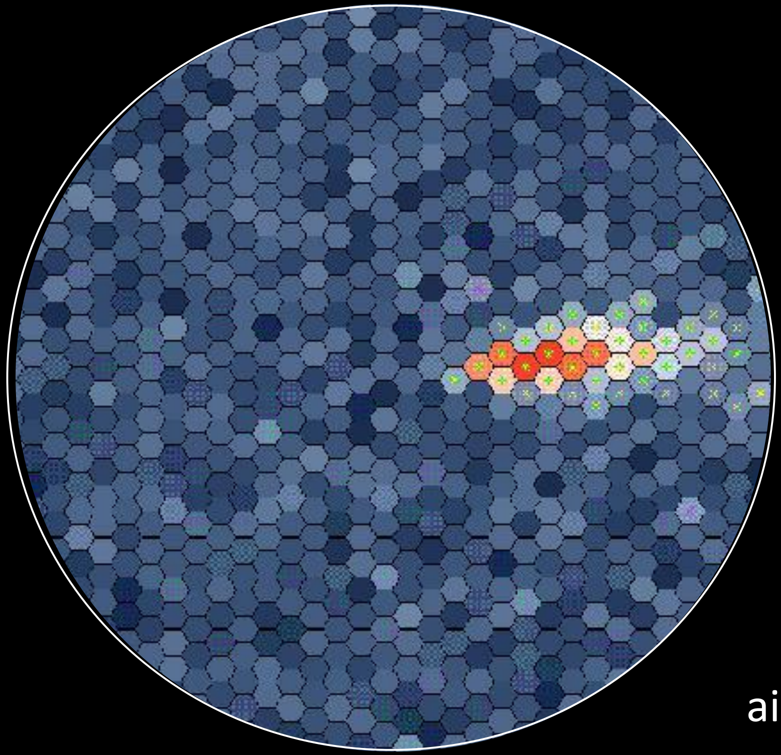


TRIDENT

- Plans for a 7.5 km³ Neutrino Telescope in the South-China Sea
- First results from an exploratory ship cruise
- No local infrastructure, moderate water quality!

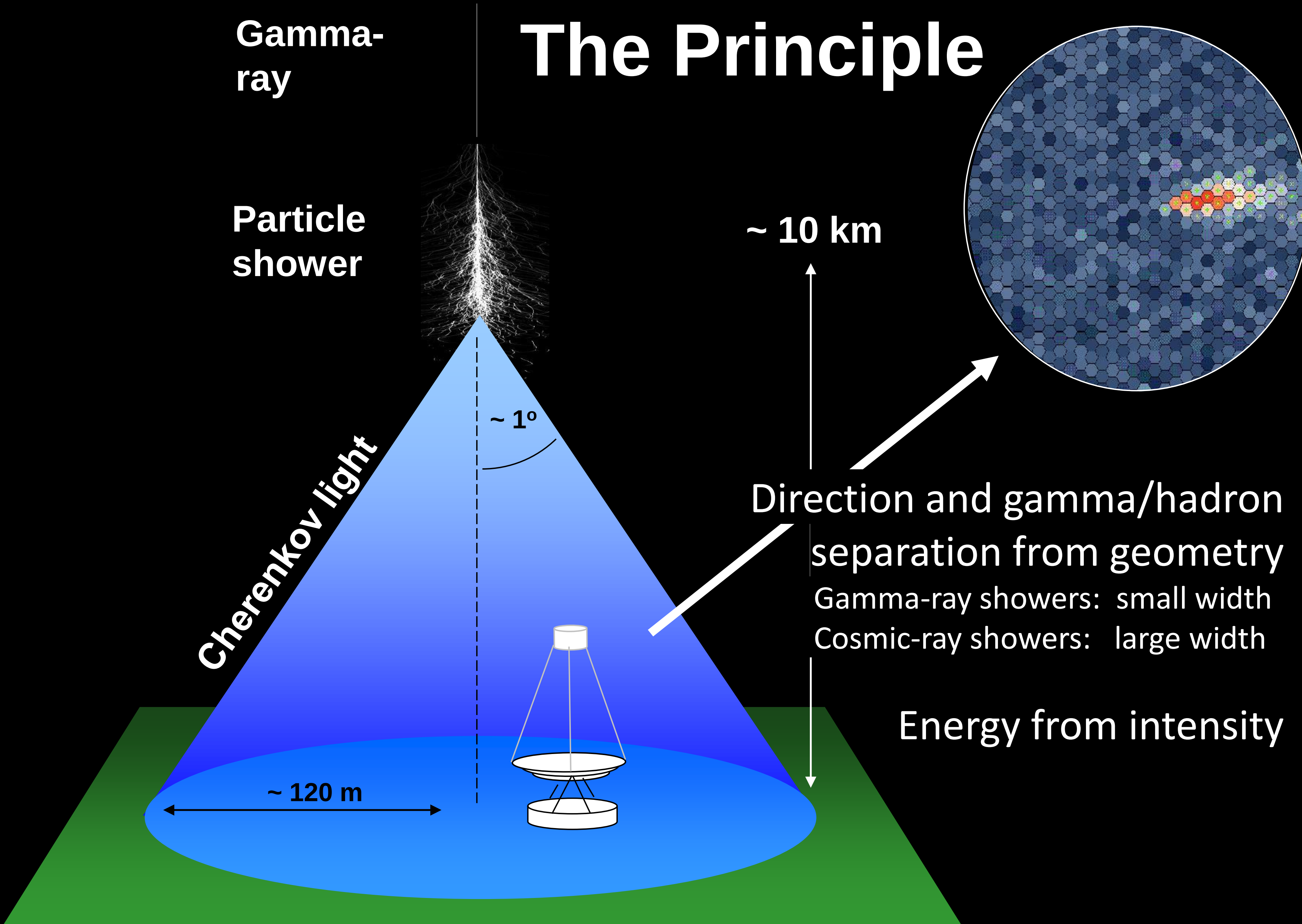
3. Imaging Atmospheric Cherenkov Detectors

(IACTs)

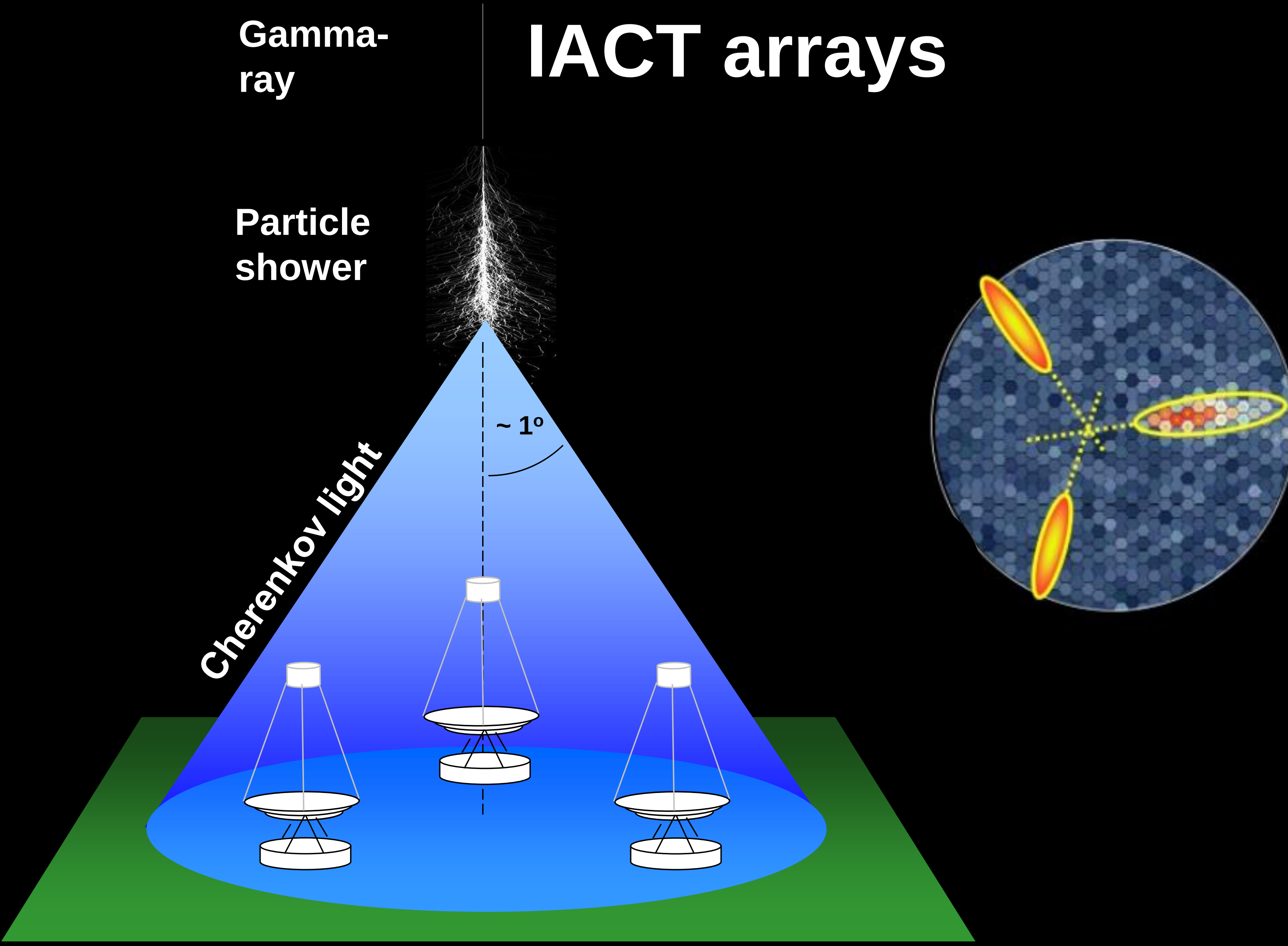


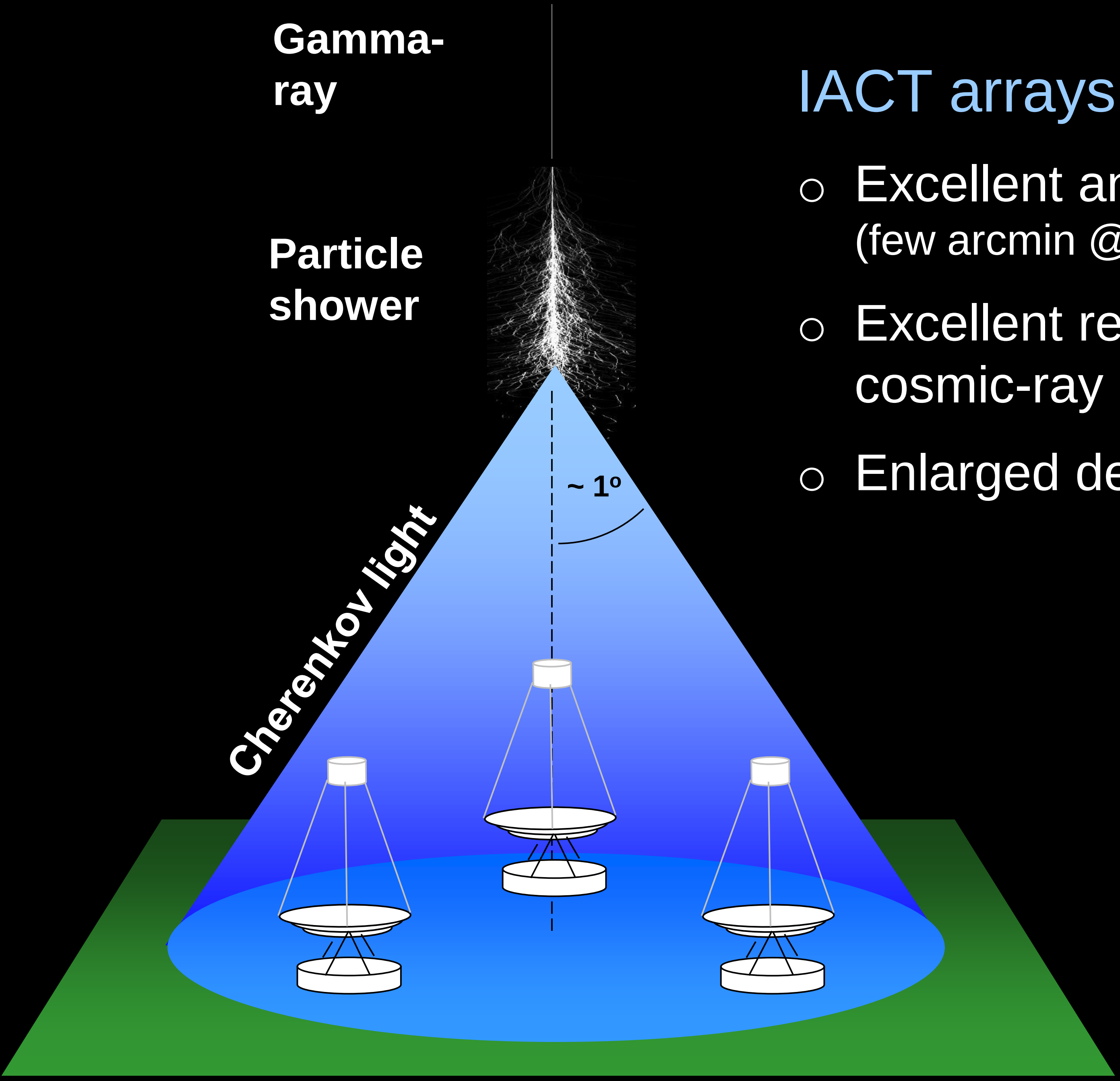
air shower image in an IACT camera

The Principle



IACT arrays





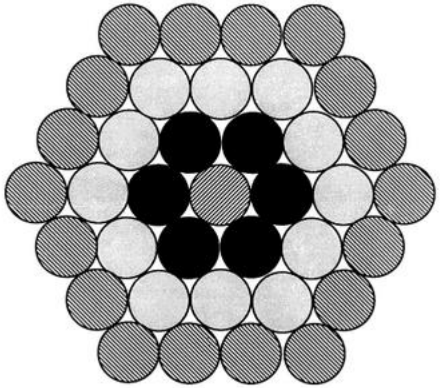
IACT arrays provide

- Excellent angular resolution
  (few arcmin @ TeV energies)
- Excellent rejection of cosmic-ray background
- Enlarged detection area

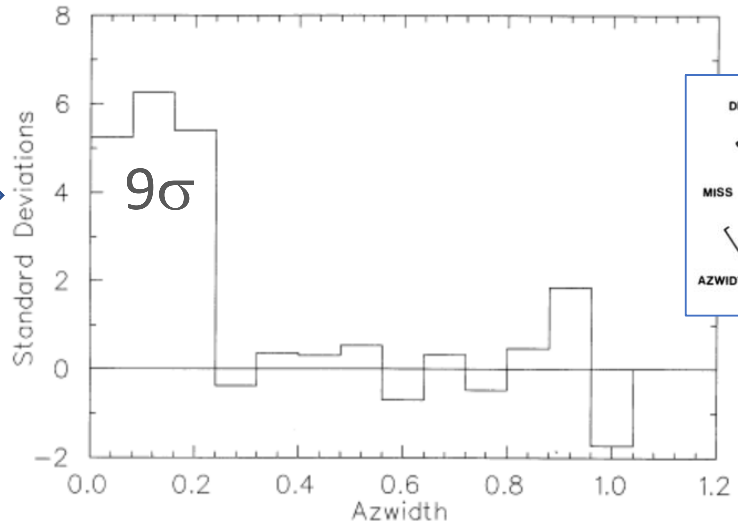
The pioneer: Whipple (Arizona)

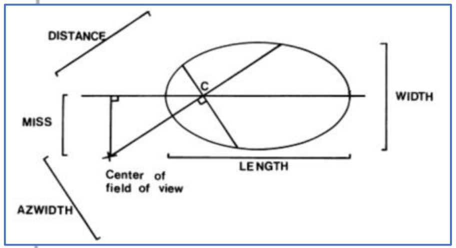
10 m reflector

37-pixel camera



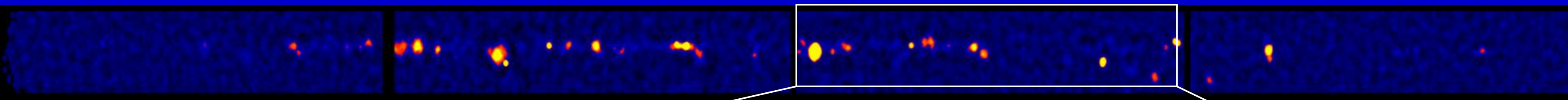
- Crab Nebula 1989
- 1992 Active Galaxy Mk 421
- 1996 Active Galaxy Mk 501

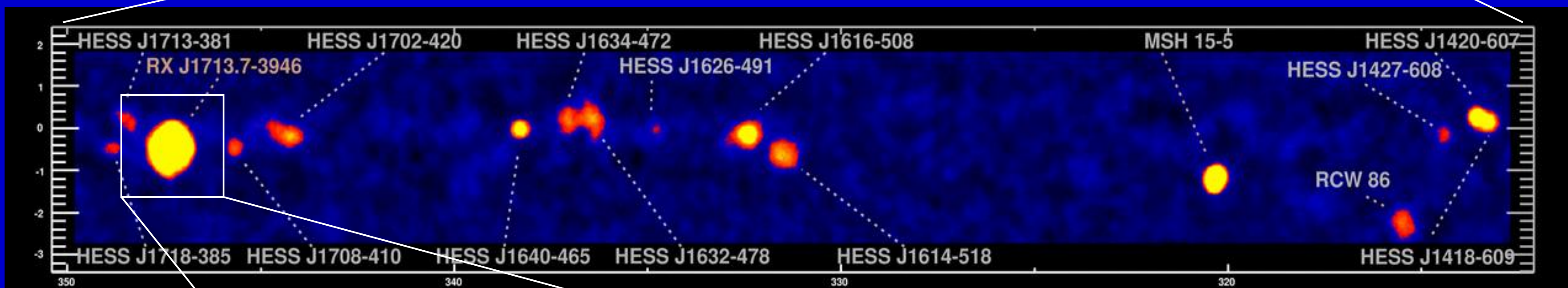




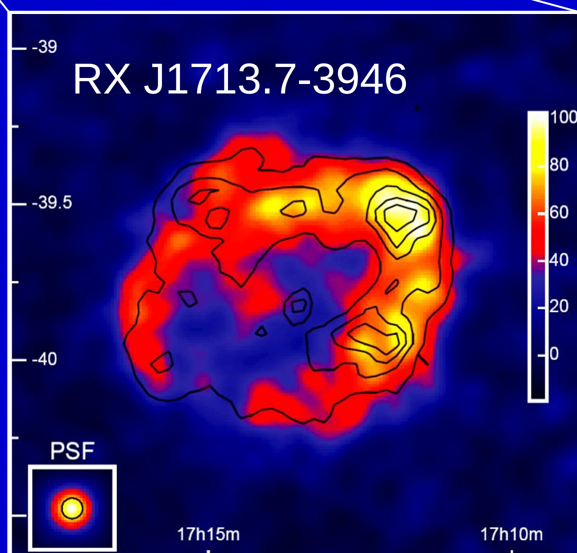
Present IACT Arrays

The Sky at TeV-Energies





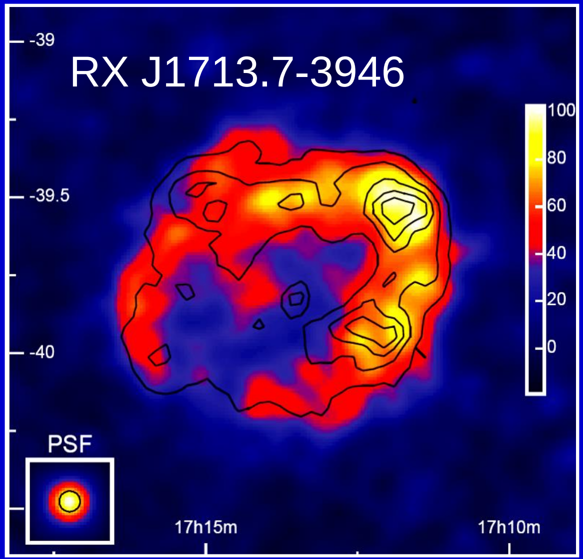
first H.E.S.S.-Scan of the galactic plane
2005



1989:	1 Source
1996:	3 Sources
2005:	80 Sources
2015:	150 Sources
2022:	>200 Sources

It's going to be like classical astronomy !

- Periodicities/Variability: from ms to years
- Energy-coverage: over several decades
- Source position: on the arc-second level
- Morphology : few arc-min level (including energy-dependence!)



1989:	1 Source
1996:	3 Sources
2005:	80 Sources
2015:	150 Sources
2022:	>200 Sources

The future: CTA (Cherenkov Telescope Array)

Two sites: CTA North: La Palma CTA-South: Chile

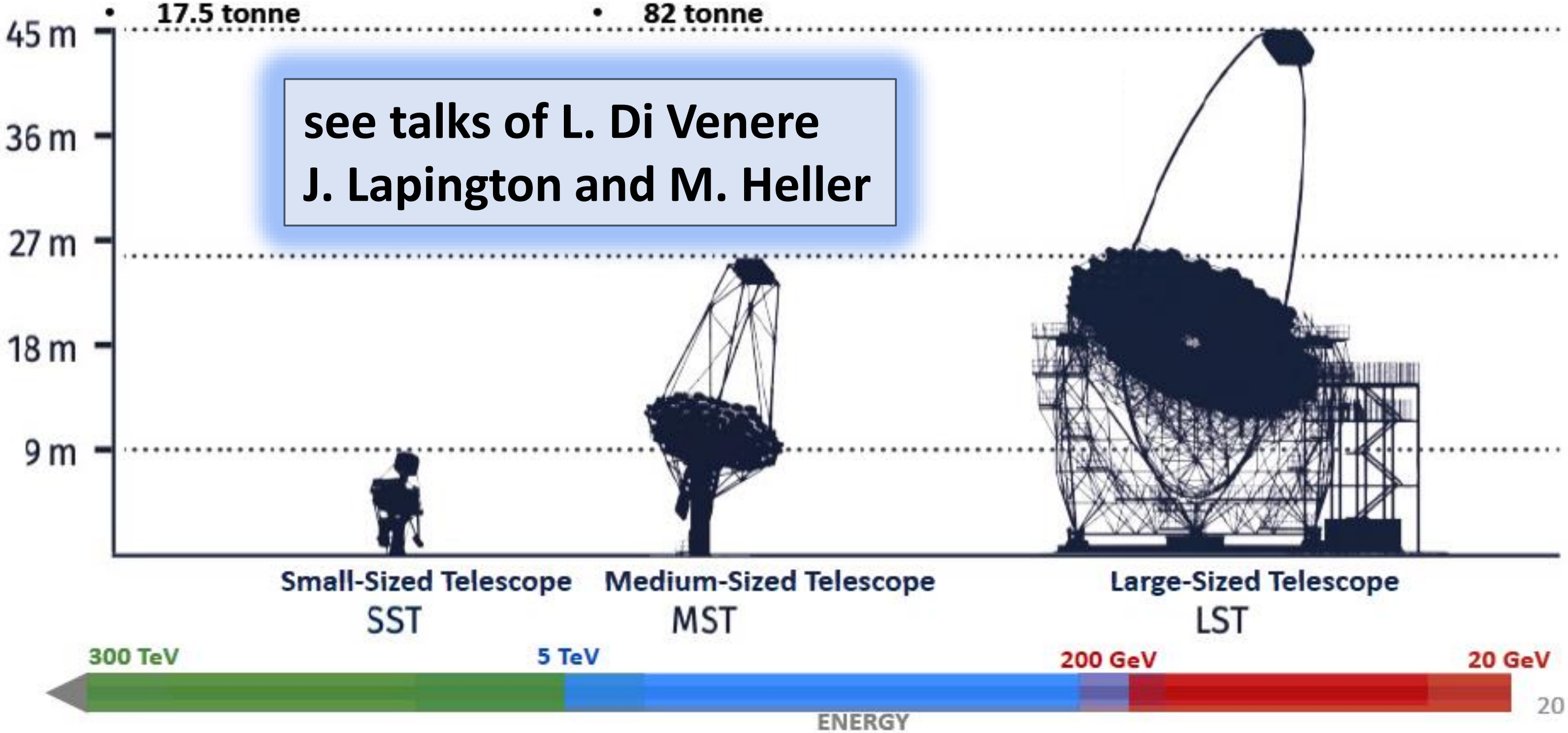
Three telescope types:

- 2-mirror Schwarzschild-Couder optical design
- 4.3 m ∅ primary reflective surface
- SiPM camera: 2048 pixels (0.16 °)
- 8.8° FoV
- 17.5 tonne

- Davies-Cotton optical design
- 12 m ∅ reflective surface
- PMT camera – 2 designs:
  - NectarCam: 1855 pixels
  - FlashCam: 1764 pixels
- ~7° FoV
- 82 tonne

- Parabolic optical design
- 23 m ∅ reflective surface
- PMT camera: 1855 pixels (0.1°)
- 4.3° FoV
- 100 tonne

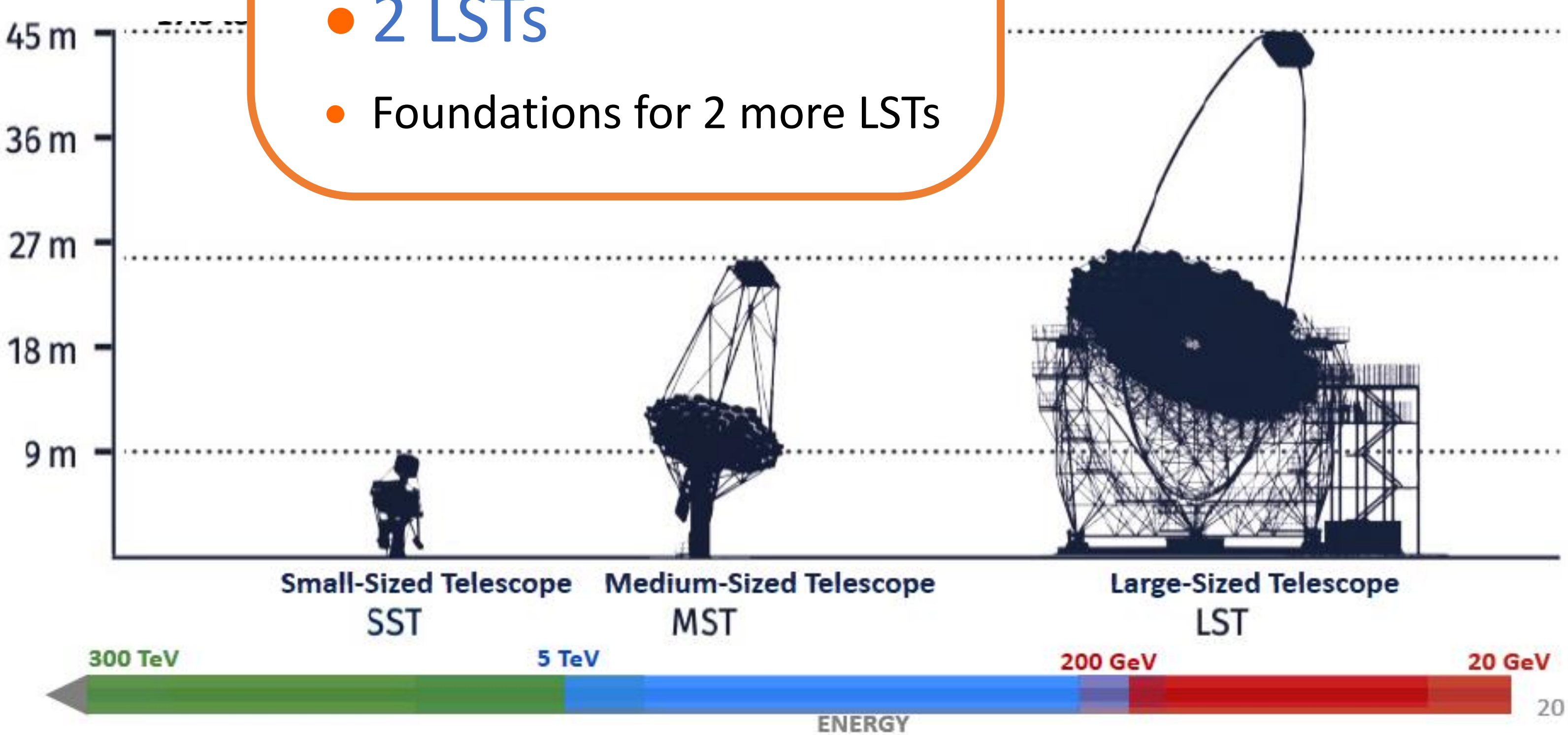
see talks of L. Di Venere J. Lapington and M. Heller



The future: CTA (Cherenkov Telescope Array)

CTA South

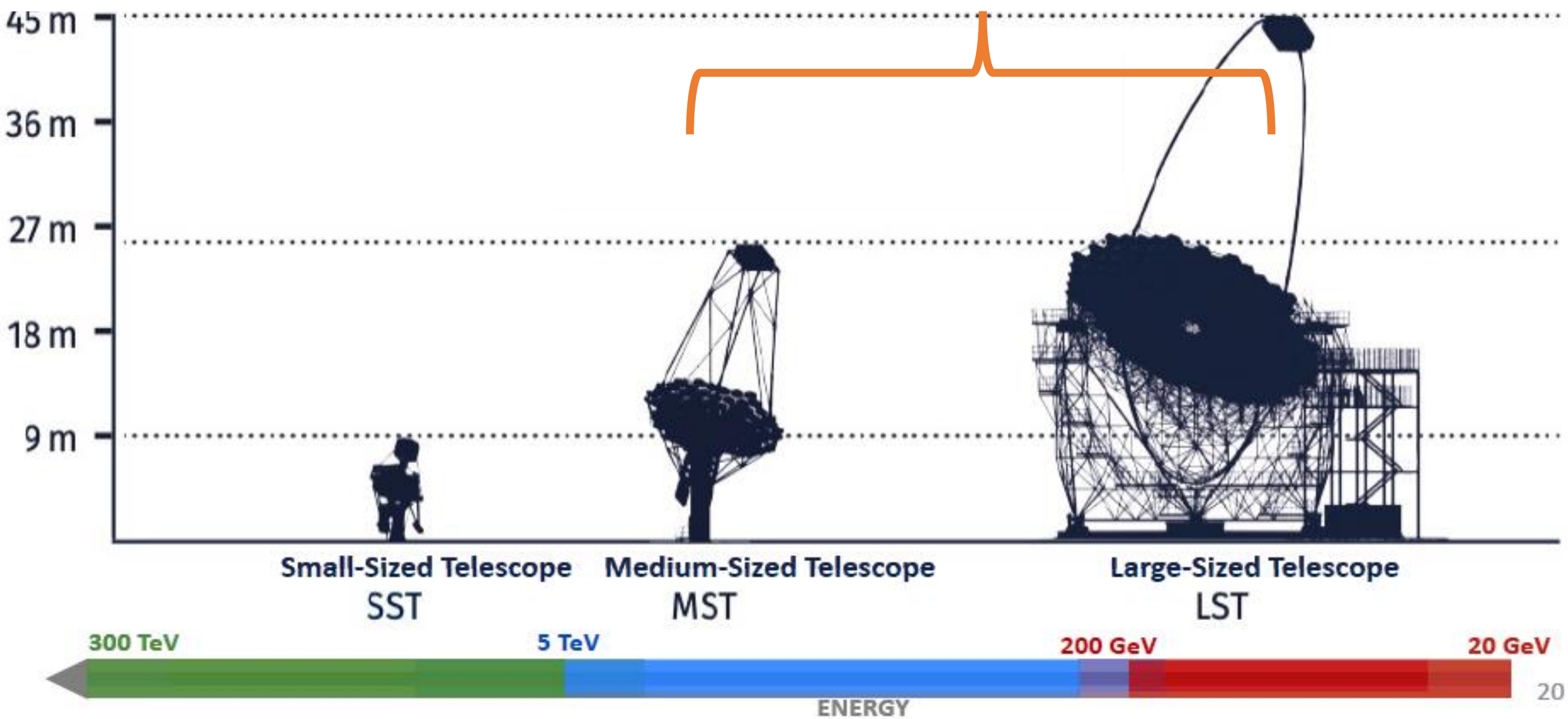
- 14 MSTs
- 42 SSTs
- 2 LSTs
- Foundations for 2 more LSTs



The future: CTA (Cherenkov Telescope Array)

CTA North

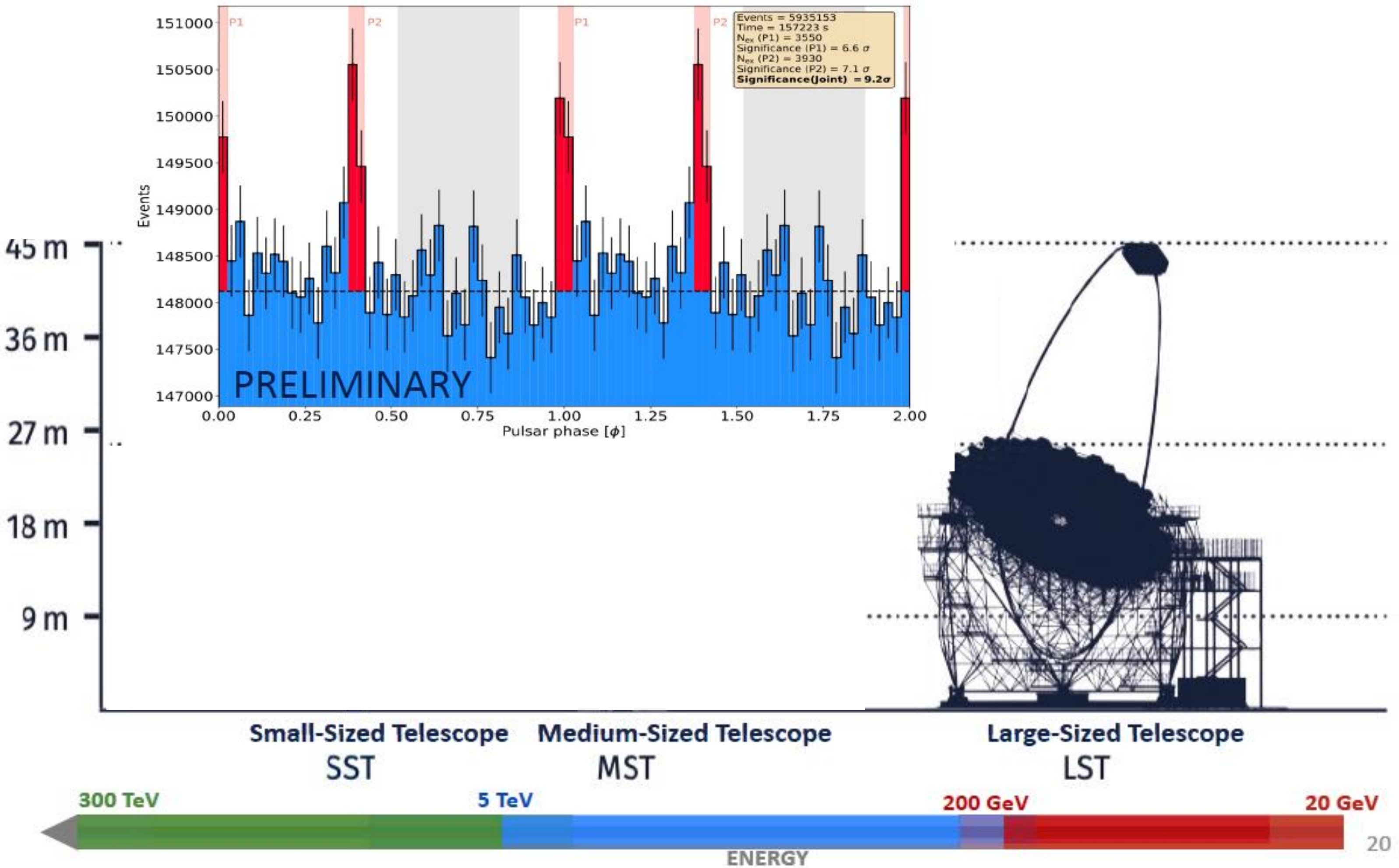
- 4 LSTs
- 9 MSTs
- Optimized for low energies



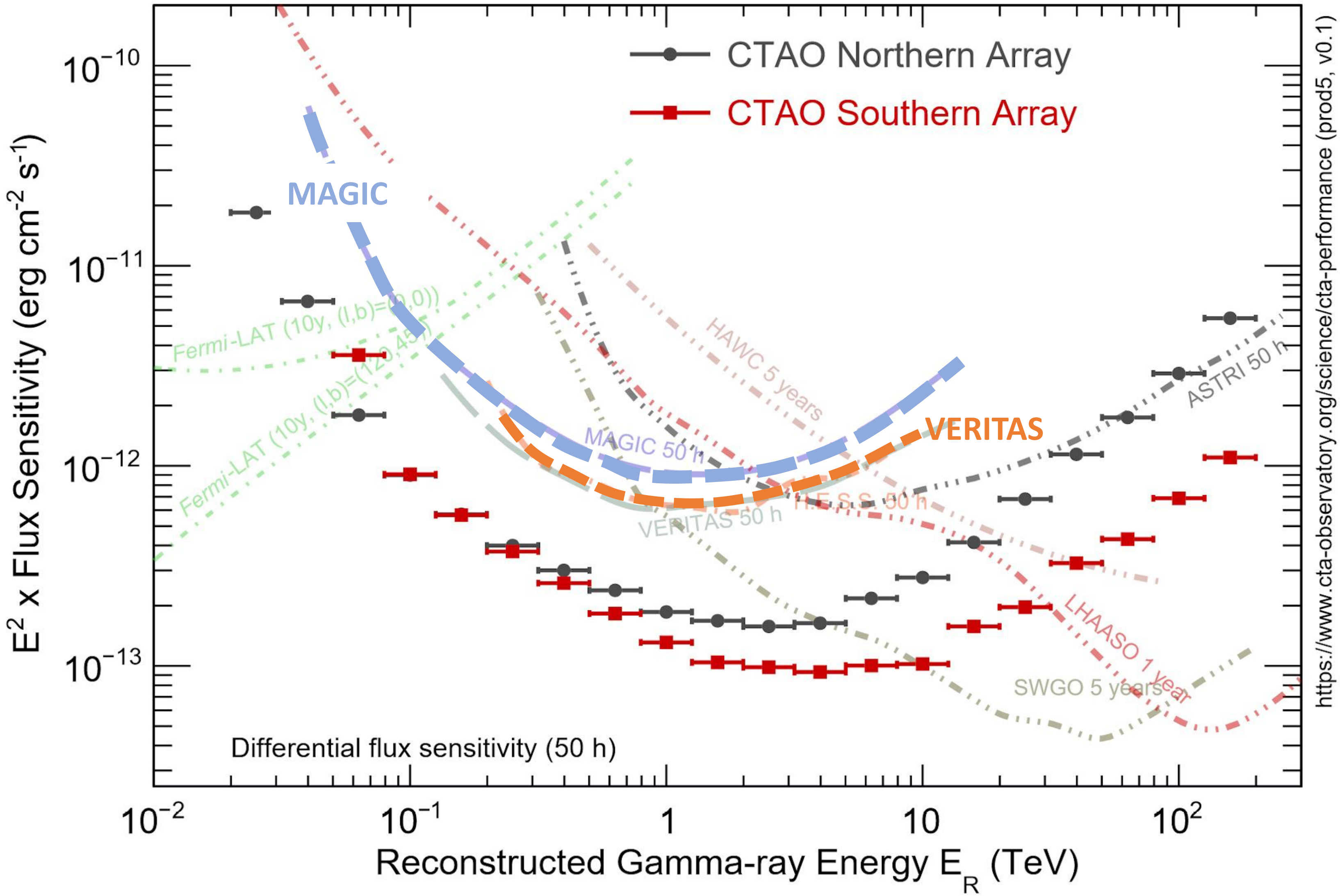
The future: CTA (Cherenkov Telescope Array)

LST 01 already delivering science

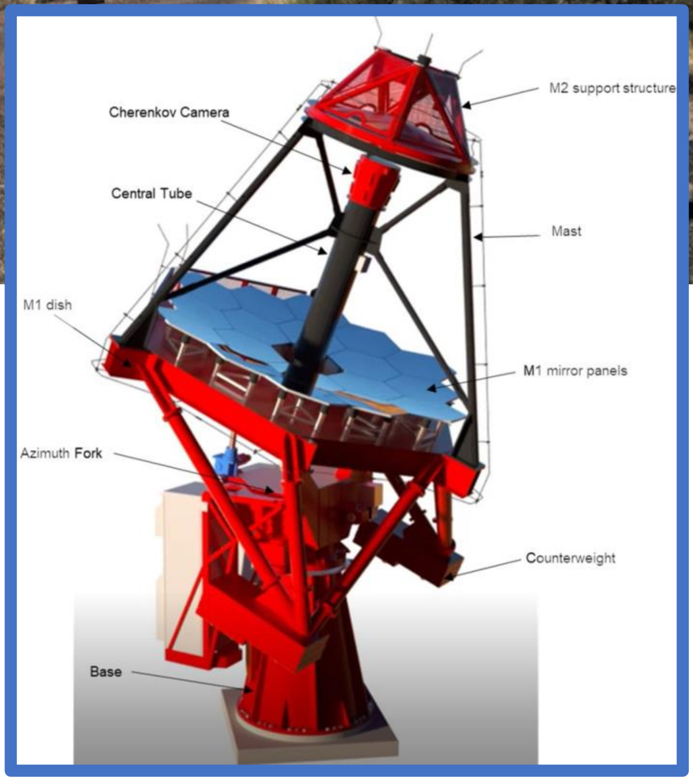
Pulsar: energy threshold ~50 GeV



CTA: A huge leap in sensitivity



ASTRI a Mini-Array of Cherenkov telescopes, Tenerife

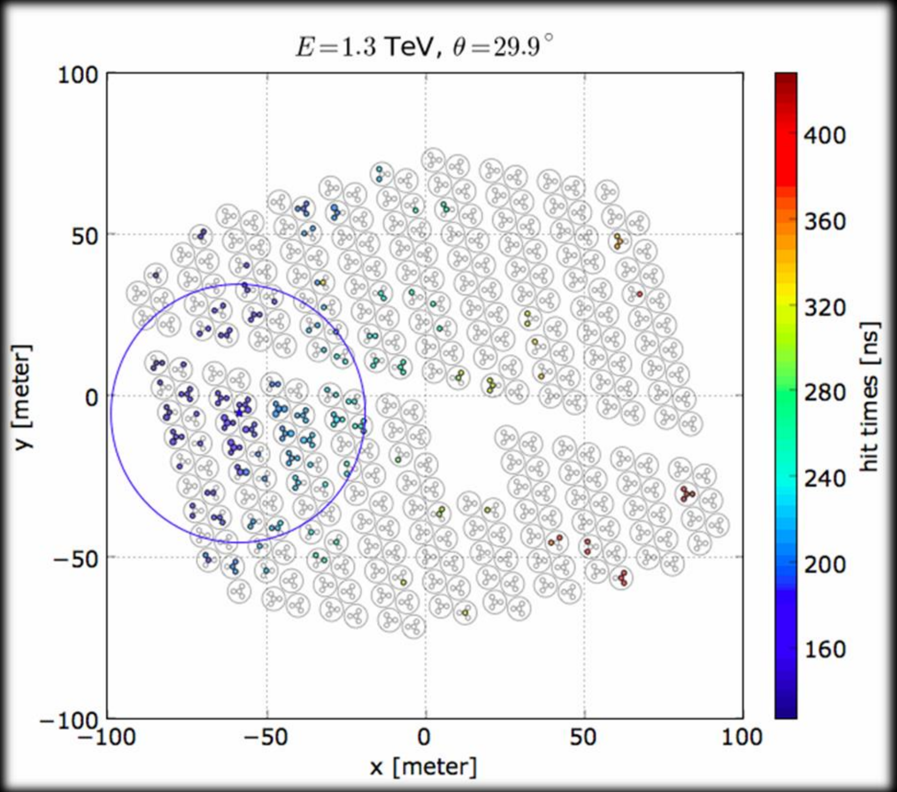


9 Schwarzschild-Couder IACTs, to be installed at the Observatorio del Teide in Tenerife.

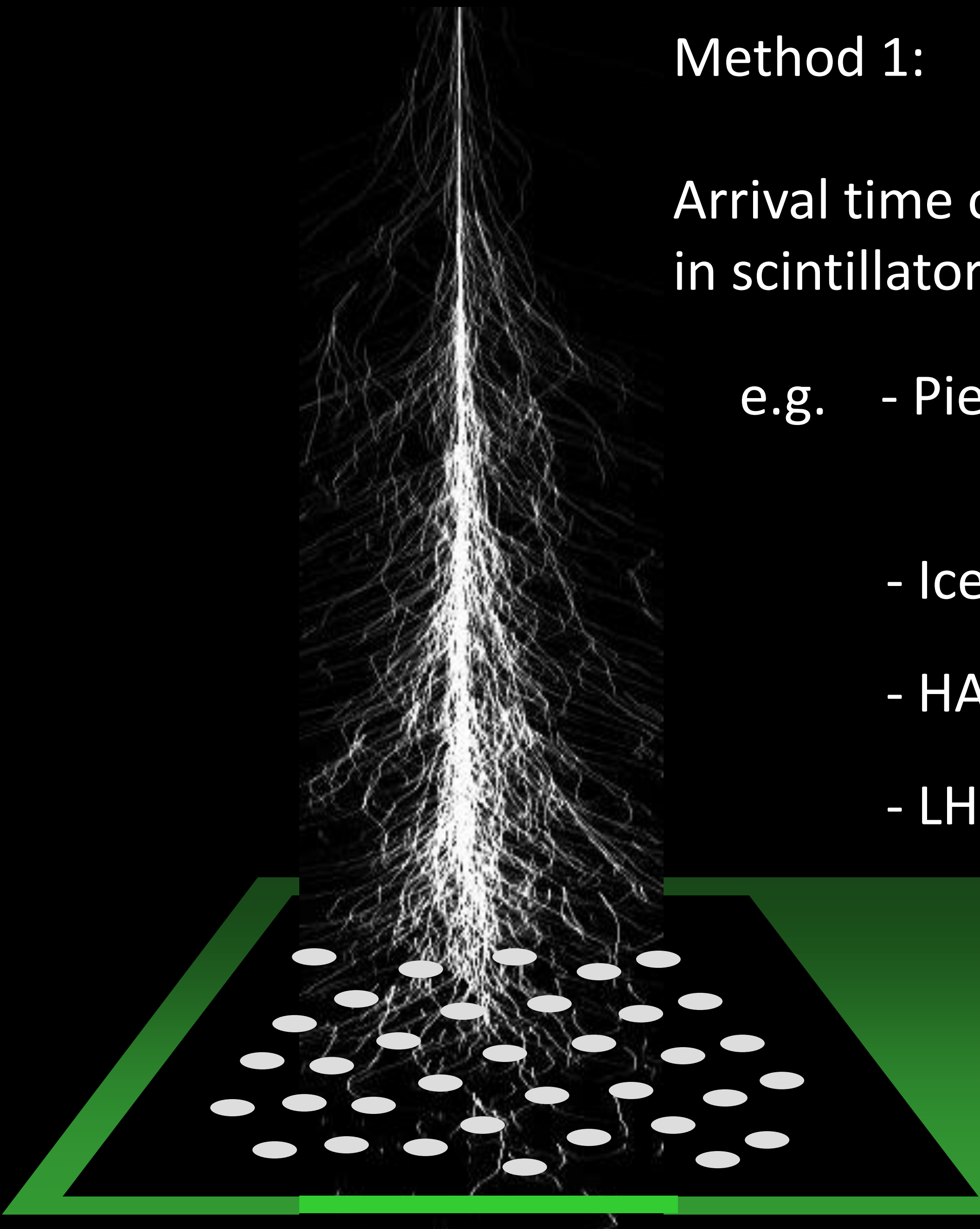
A “child of CTA prototype phase for SMTs”

See talk of S. Scuderi

4. Timing and Hybrid Detectors for Air Showers



hit pattern of a 1.3 TeV γ-ray air shower in the HAWC array



Method 1:

Arrival time of shower particles on ground in scintillators or water tanks

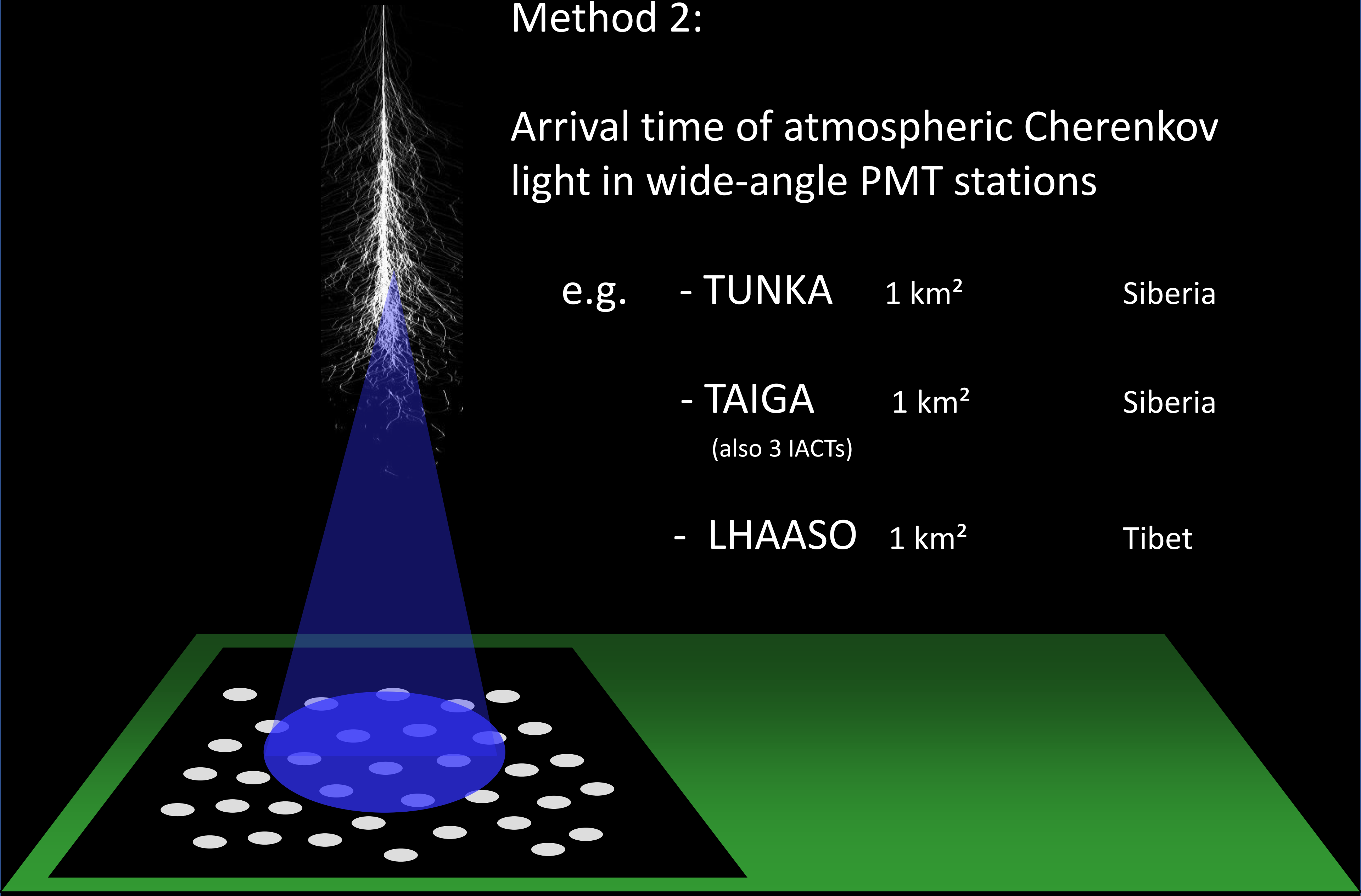
e.g.

- Pierre Auger Observatory	3000 km²	Chile
- IceTop	1 km²	South Pole
- HAWC	0.02 km²	Mexico
- LHAASO	~1 km²	Tibet

Method 2:

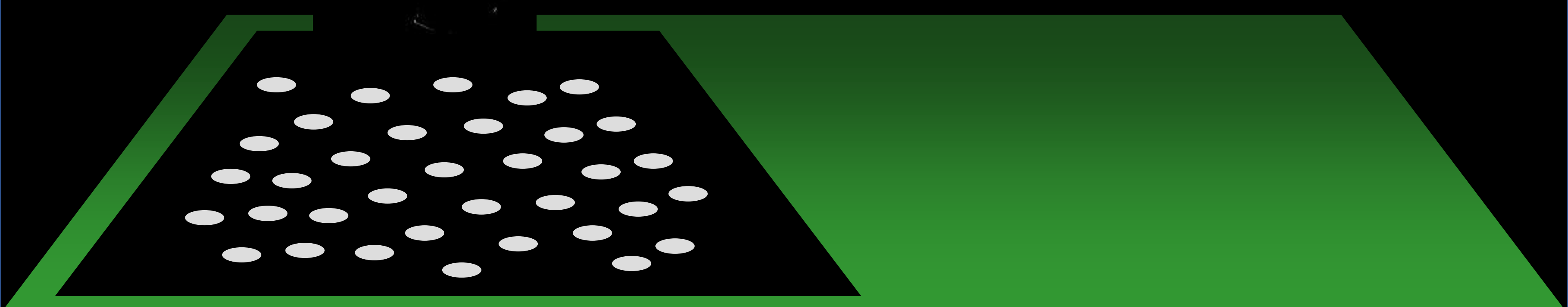
Arrival time of atmospheric Cherenkov light in wide-angle PMT stations

e.g.	- TUNKA	1 km²	Siberia
	- TAIGA (also 3 IACTs)	1 km²	Siberia
	- LHAASO	1 km²	Tibet



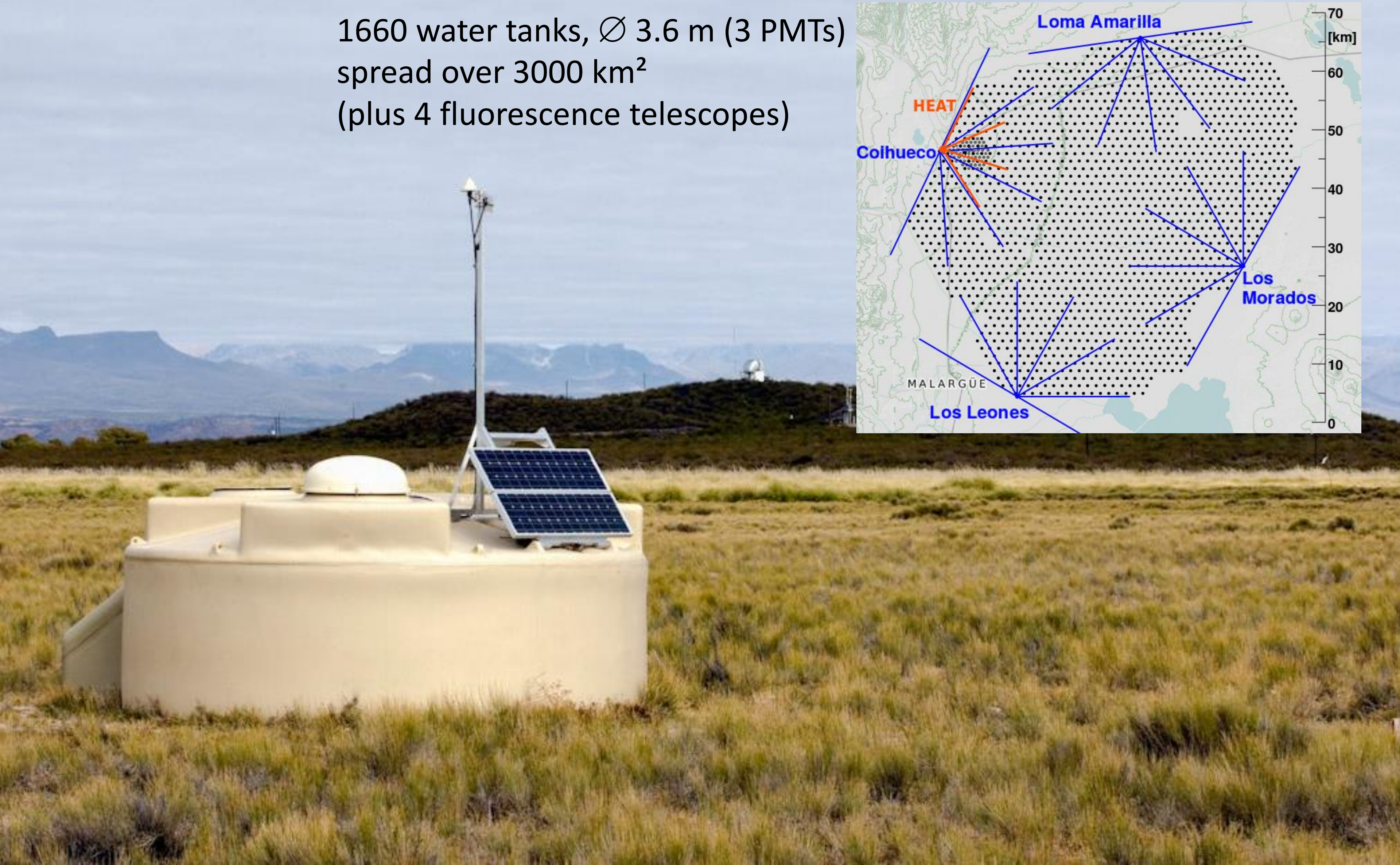
Compared to IACTs

+ larger field of view
+ higher duty cycle for water tank detection
– inferior angular resolution
– inferior sensitivity to transient events

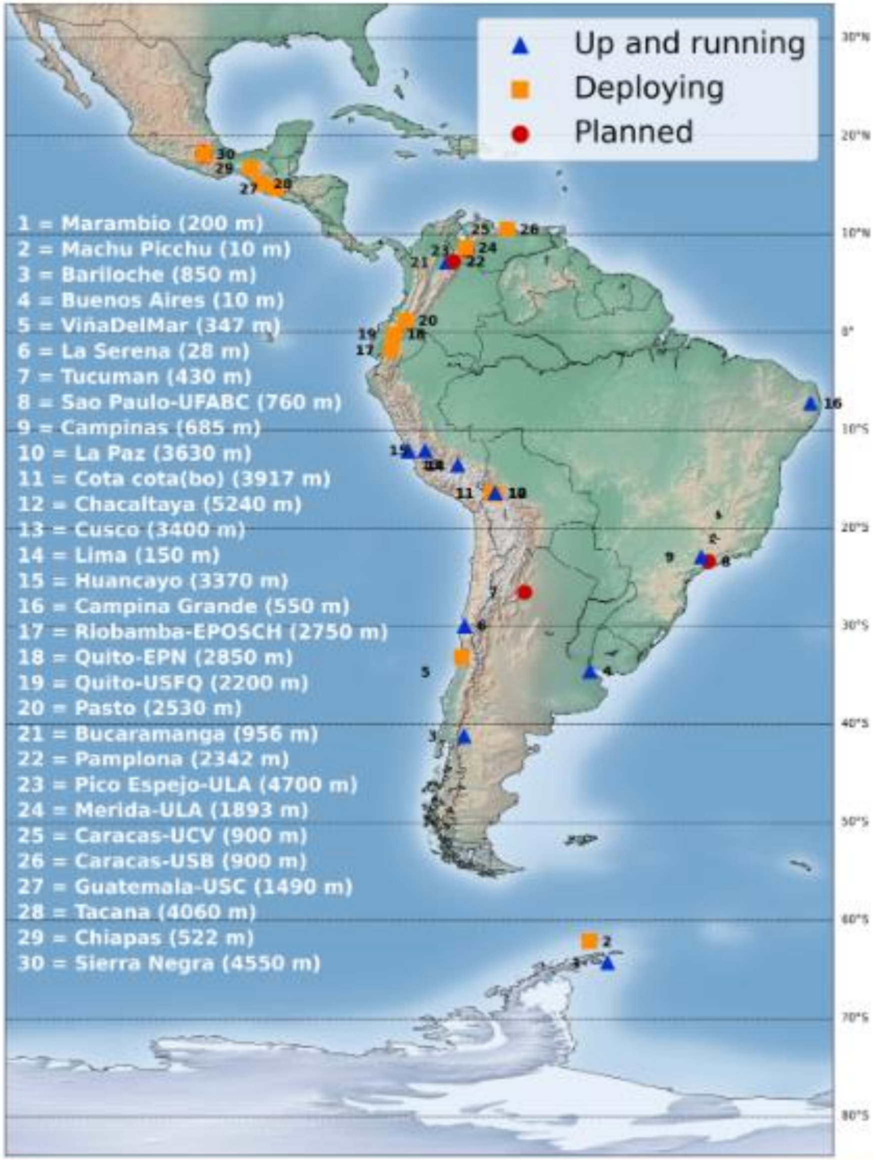


Pierre Auger Observatory

1660 water tanks, ∅ 3.6 m (3 PMTs)
spread over 3000 km²
(plus 4 fluorescence telescopes)



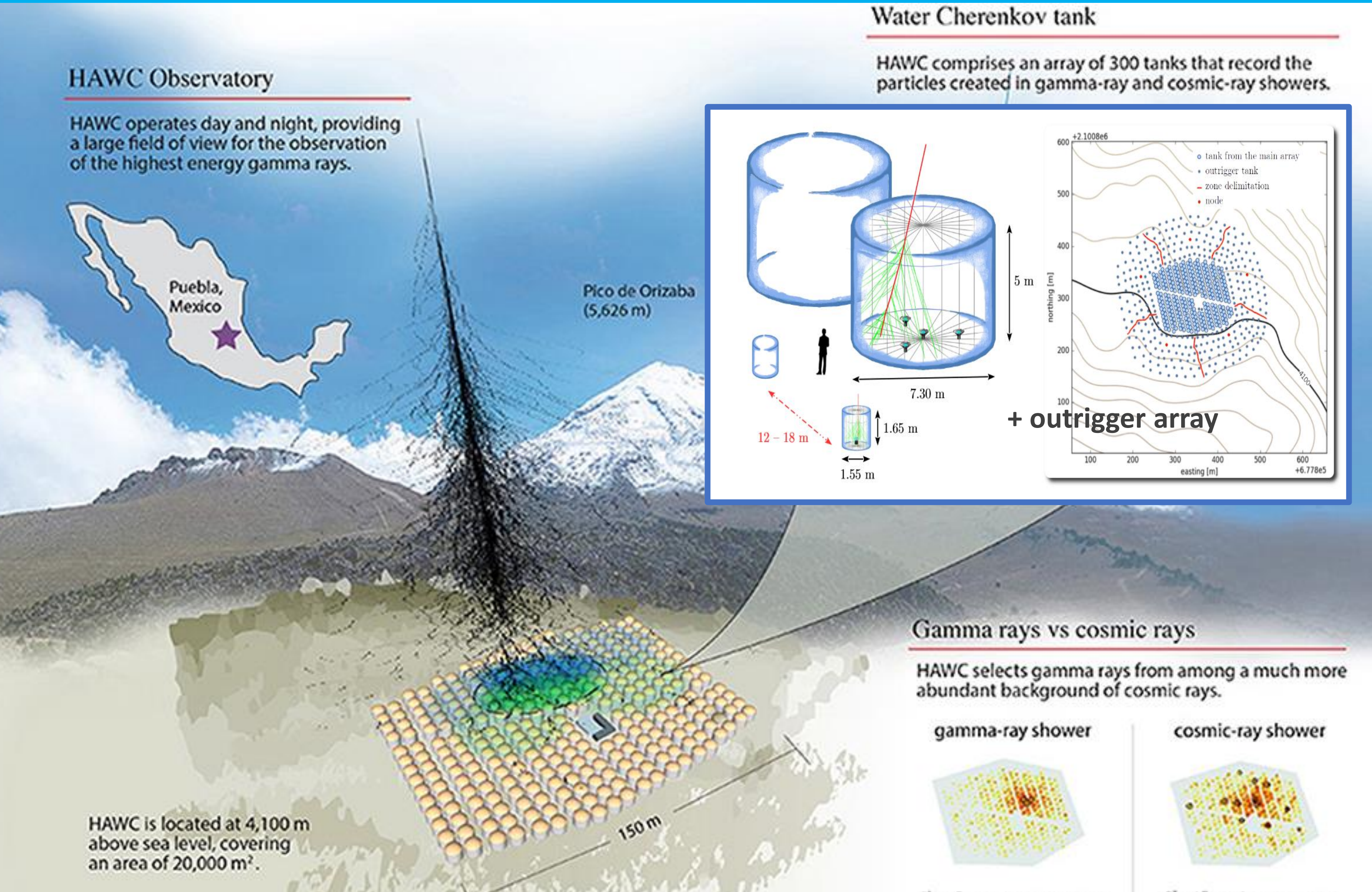
The Latin American Giant Observatory (LAGO) Project



A very long baseline "array" of water Cherenkov detectors

See posters of T. Torres and I. Sidelnik

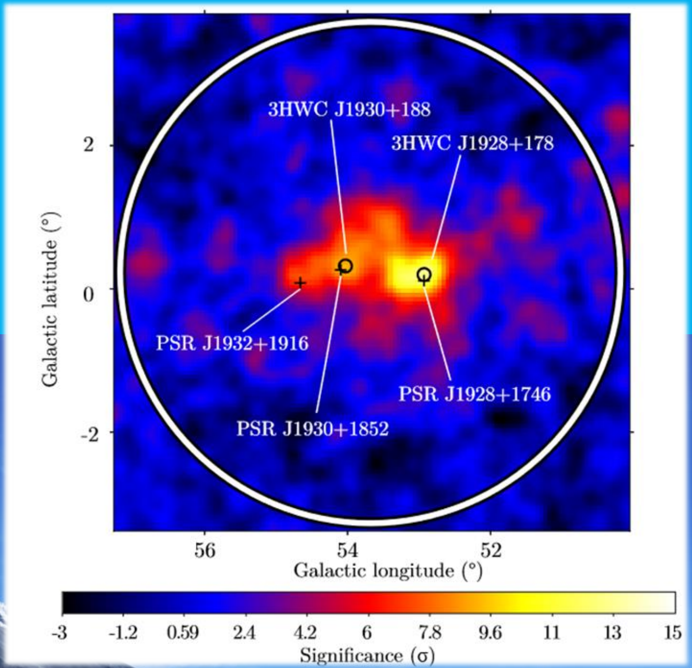
HAWC


Water Cherenkov tank
HAWC comprises an array of 300 tanks that record the particles created in gamma-ray and cosmic-ray showers.
HAWC Observatory
HAWC operates day and night, providing a large field of view for the observation of the highest energy gamma rays.
Puebla, Mexico
Pico de Orizaba (5,626 m)
5 m
7.30 m
12 – 18 m
1.65 m
1.55 m
tank from the main array
outrigger tank
zone delimitation
node
northing [m]
easting [m]
+ outrigger array
Gamma rays vs cosmic rays
HAWC selects gamma rays from among a much more abundant background of cosmic rays.
gamma-ray shower
cosmic-ray shower
150 m
HAWC is located at 4,100 m above sea level, covering an area of 20,000 m².

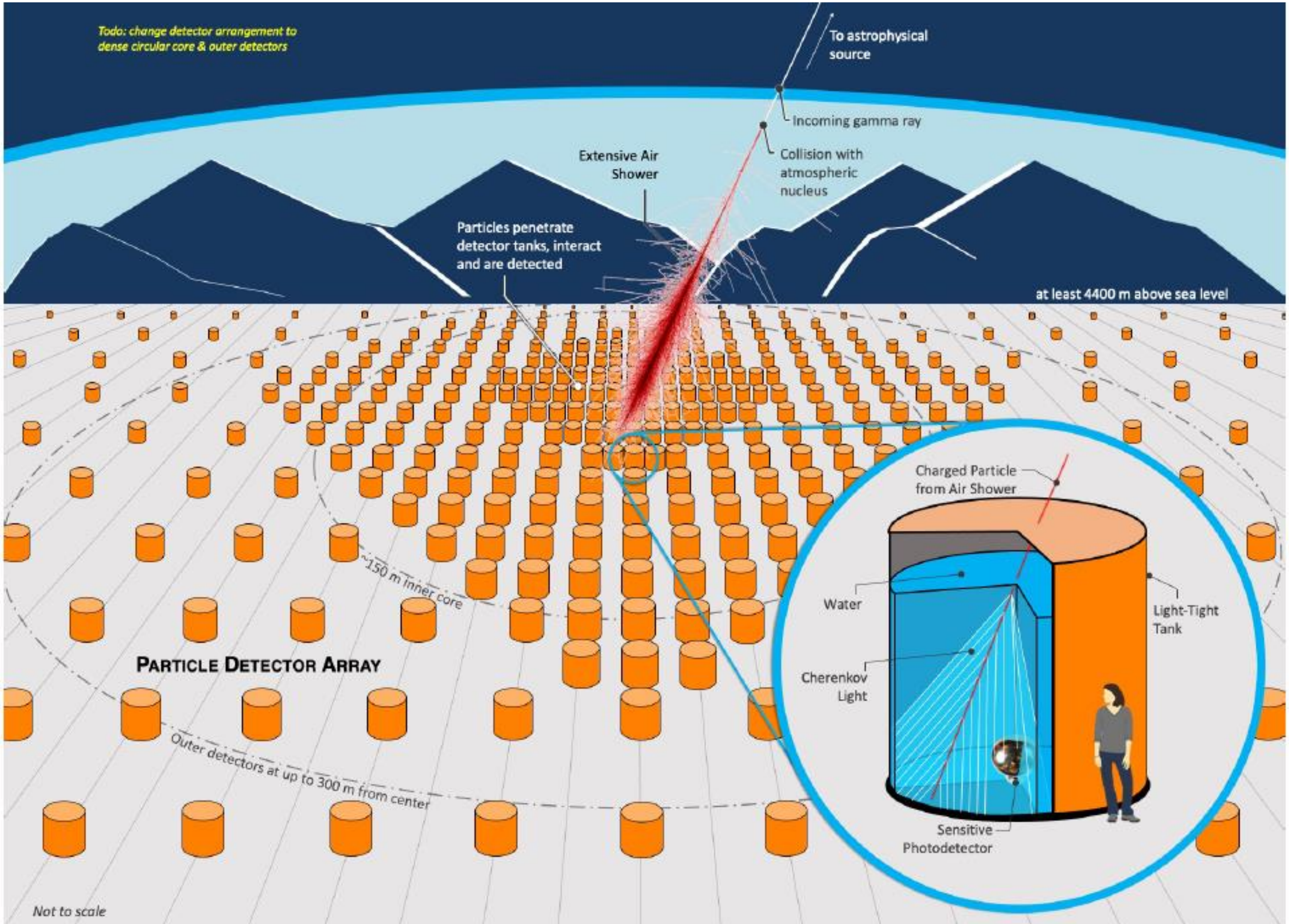
HAWC

Gamma ray source 3HWC J1928 discovered by HAWC, coincident with the Pulsar PSR J1928+1746

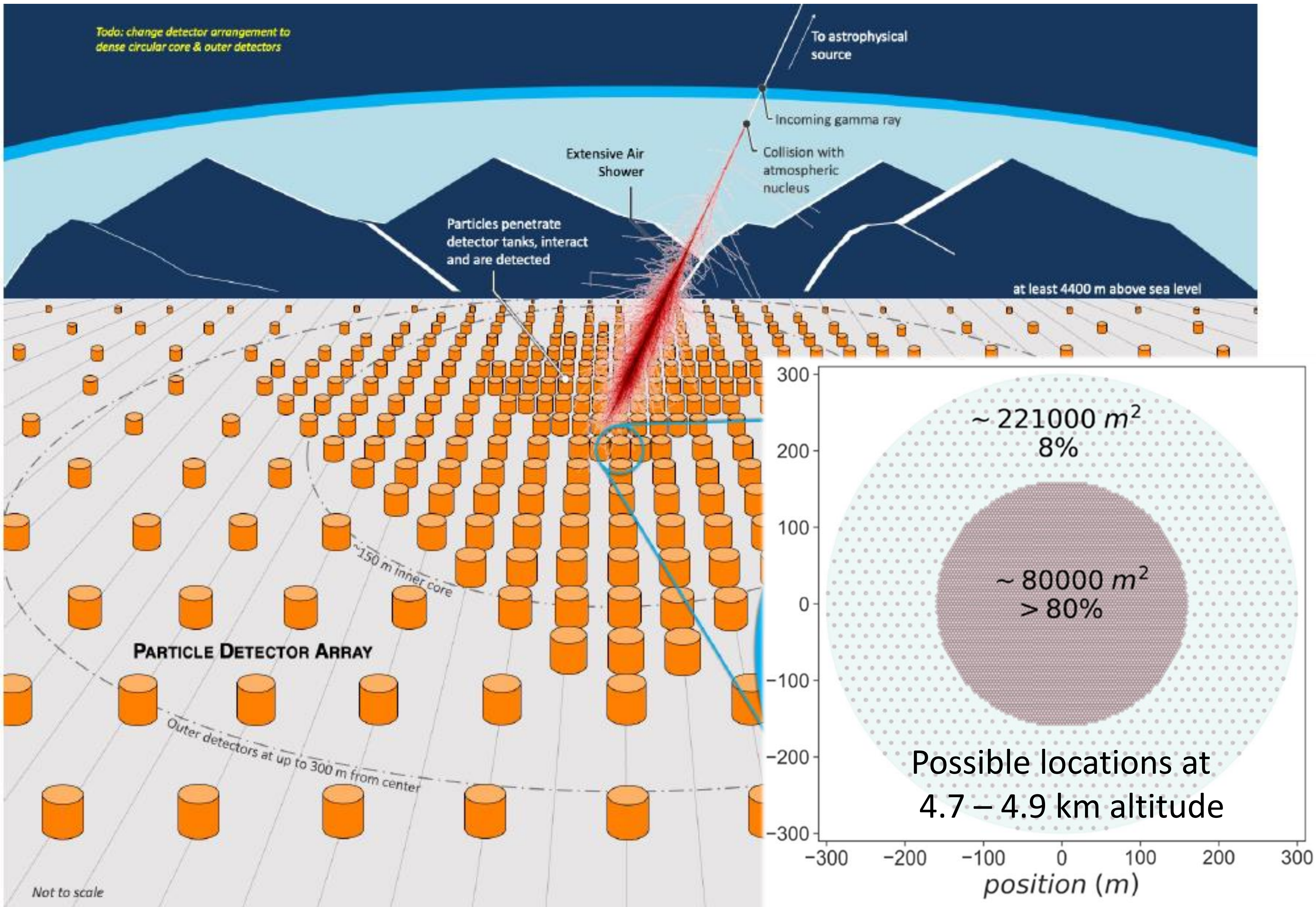
A.Jardin-Blicq et al. ICRC 2021



SWGO: A future „HAWC in the South“



SWGO: A future „HAWC in the South“



TAIGA in Siberia

See poster of E. Kravchenko

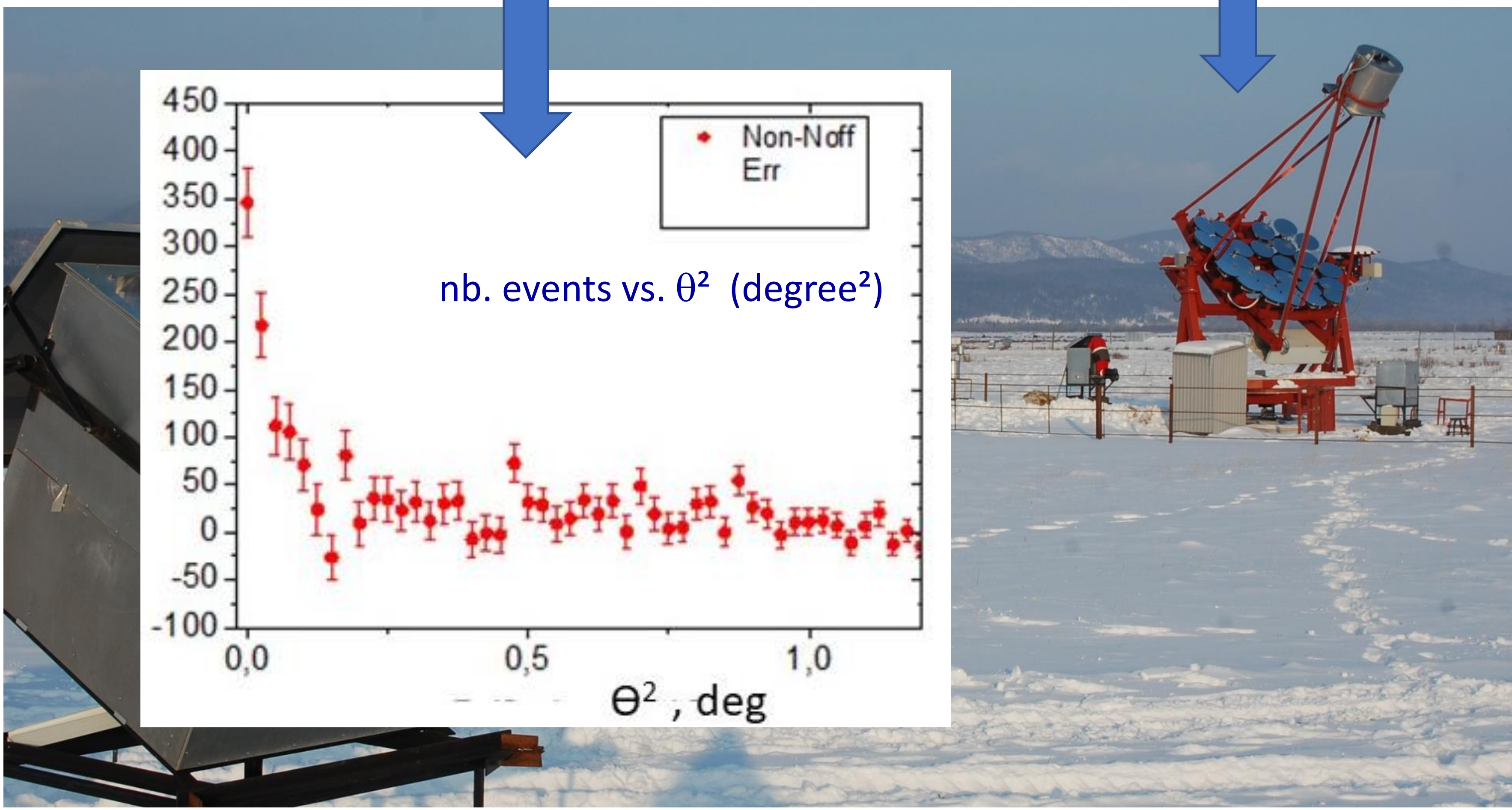
Combination of

120 wide angle timing detectors — **3 small Imaging Telescopes**

TAIGA in Siberia

The Crab Nebula recorded with the IACTs (12.6 σ)

3 small Imaging Telescopes



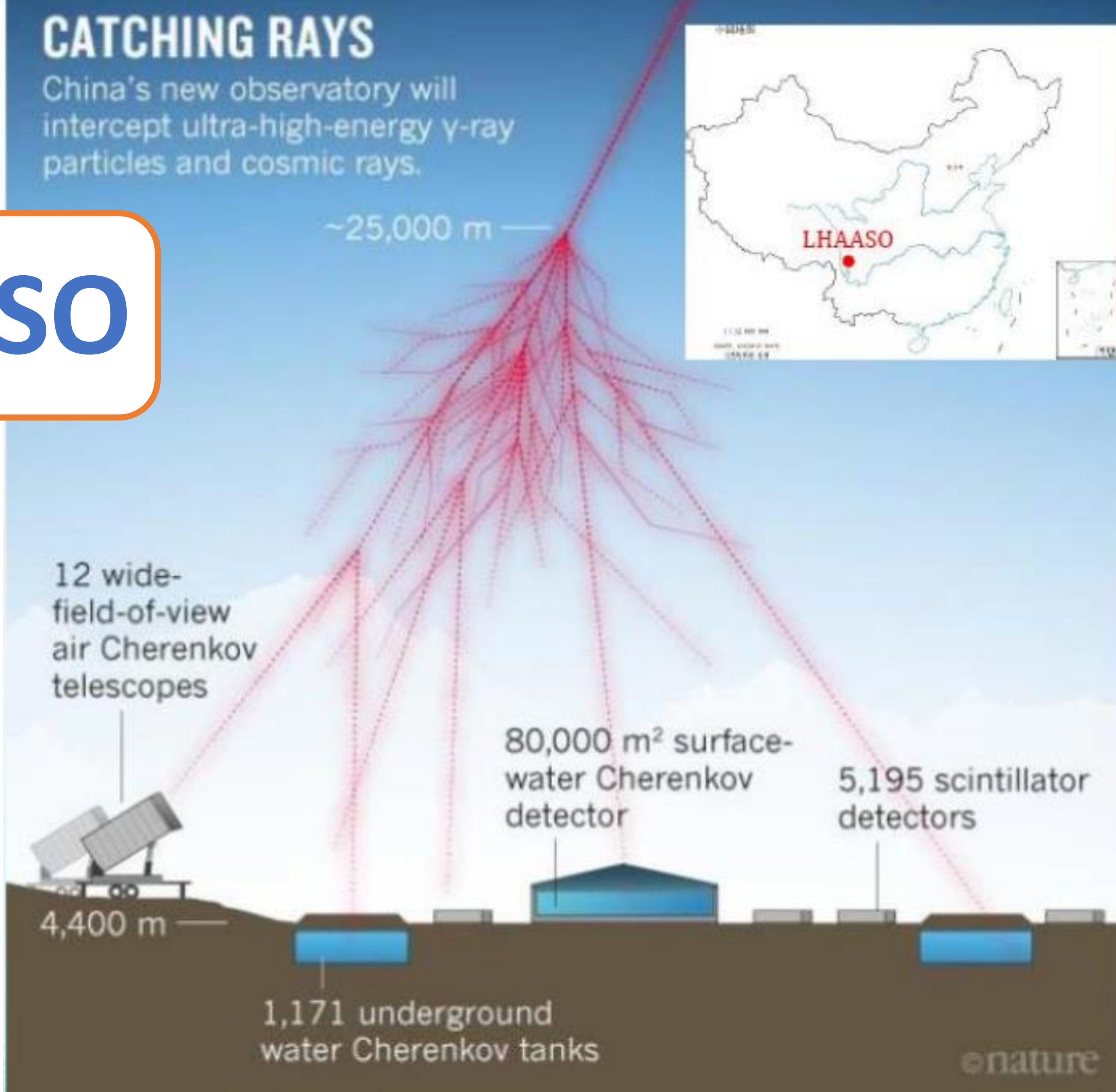
TAIGA in Siberia

Method was pioneered in the early 1990
with the AIROBICC array in La Palma
(Eckard Lorenz, Albrecht Karle)

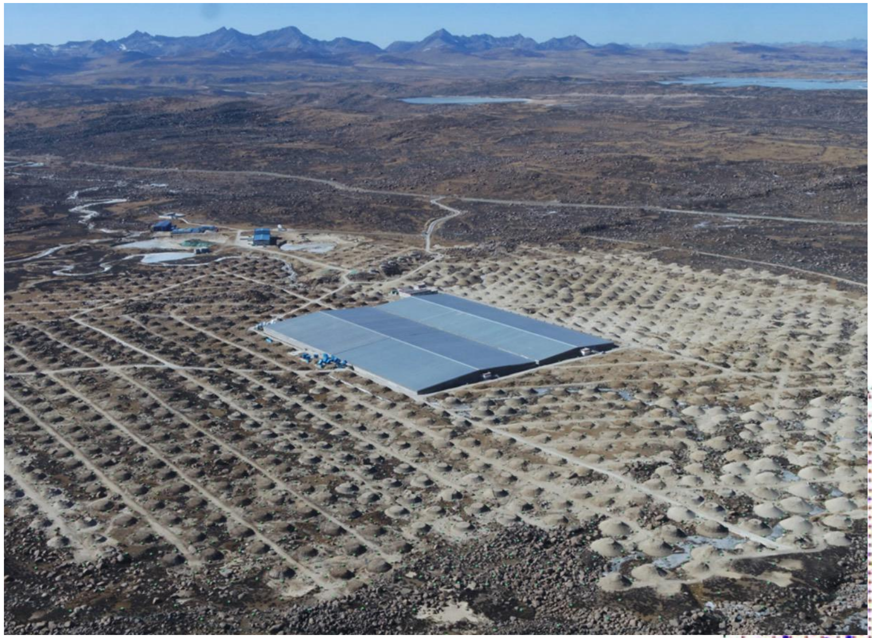
But: problems with gamma/hadron discriminations

LHAASO
高海拔宇宙线观测站

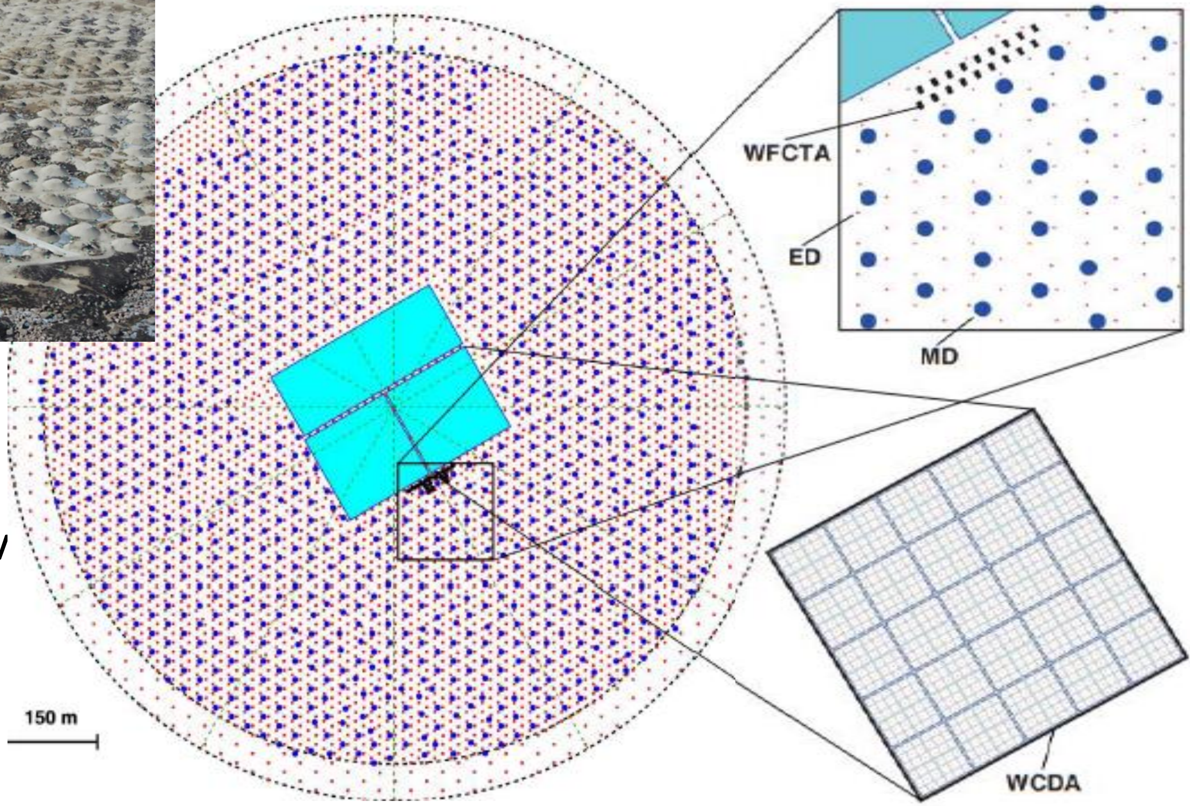
LHAASO



LHAASO



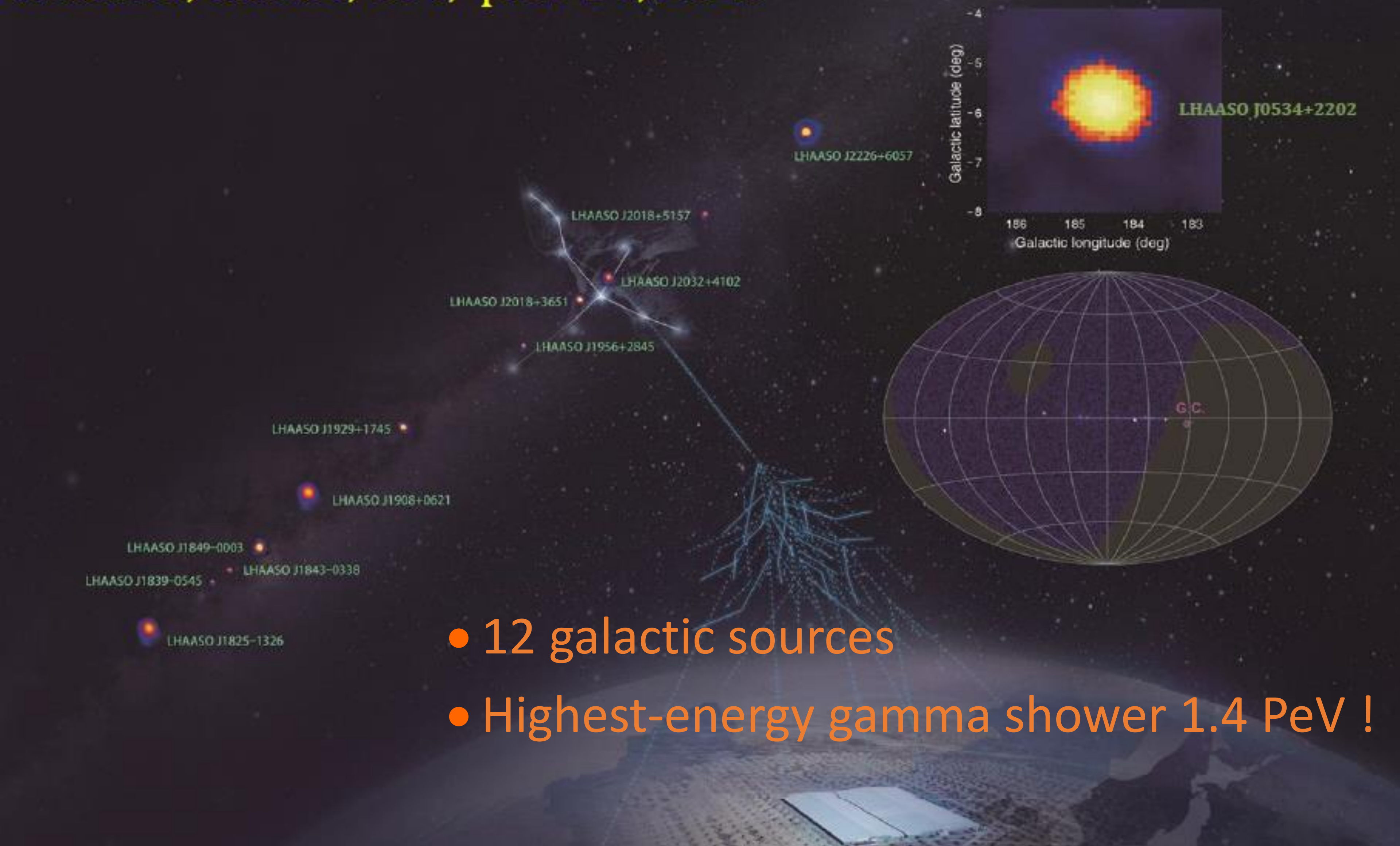
- WDCA – compact **W**ater **C**herenkov **D**etector **A**rray (78,000 m²)
- ED – **E**lectromagnetic-particle **D**etectors (~5500 1m² scintillators)



- MD – **M**uon Detectors (1146 underground water Cherenkov tanks à 36 m²)
- WFCTA – **W**ide-**F**ield-of-View **C**herenkov **T**elescope **A**rray

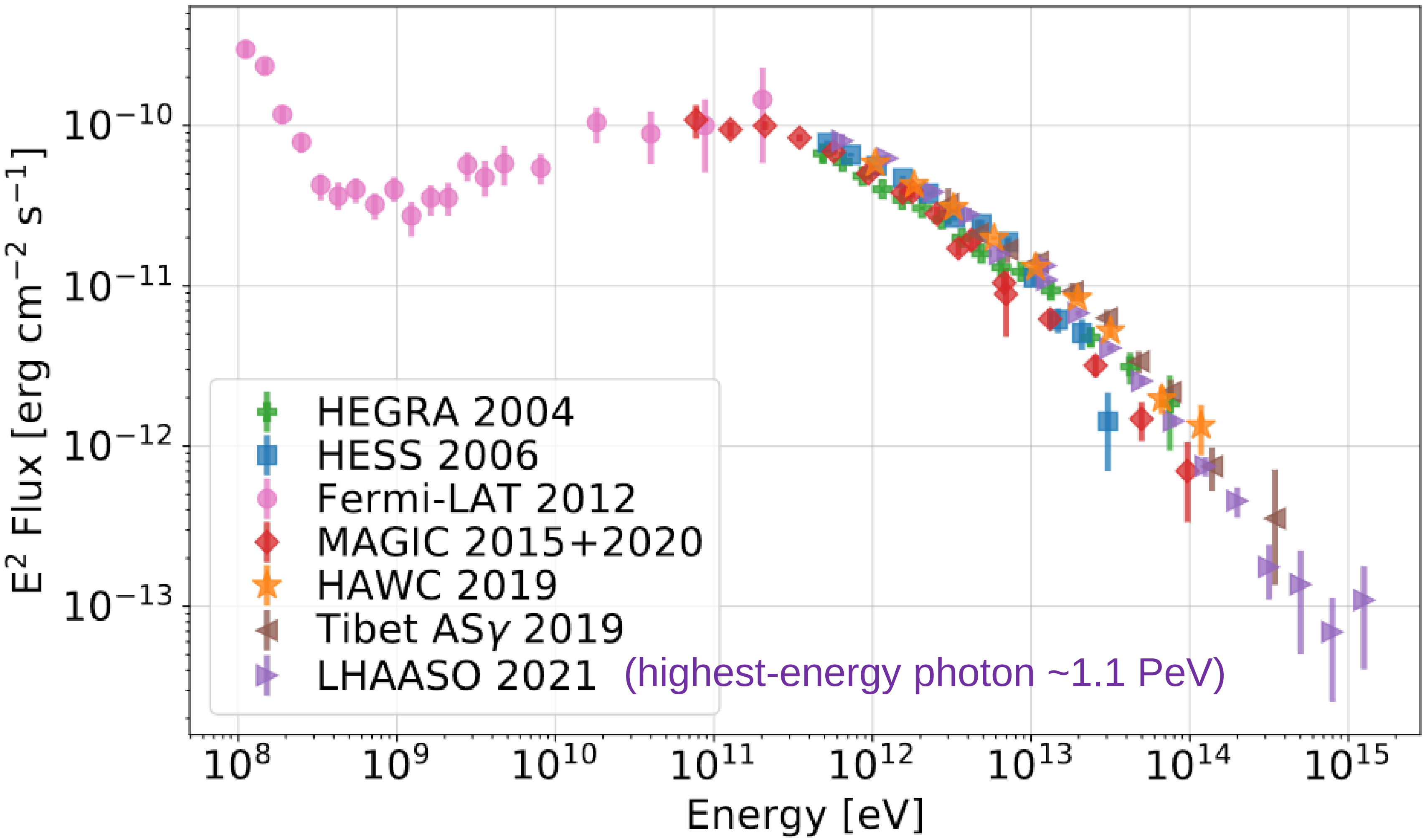
LHAASO Results (with ½ of the Array)

LHAASO, Nature, 594, p.33-36, 2021

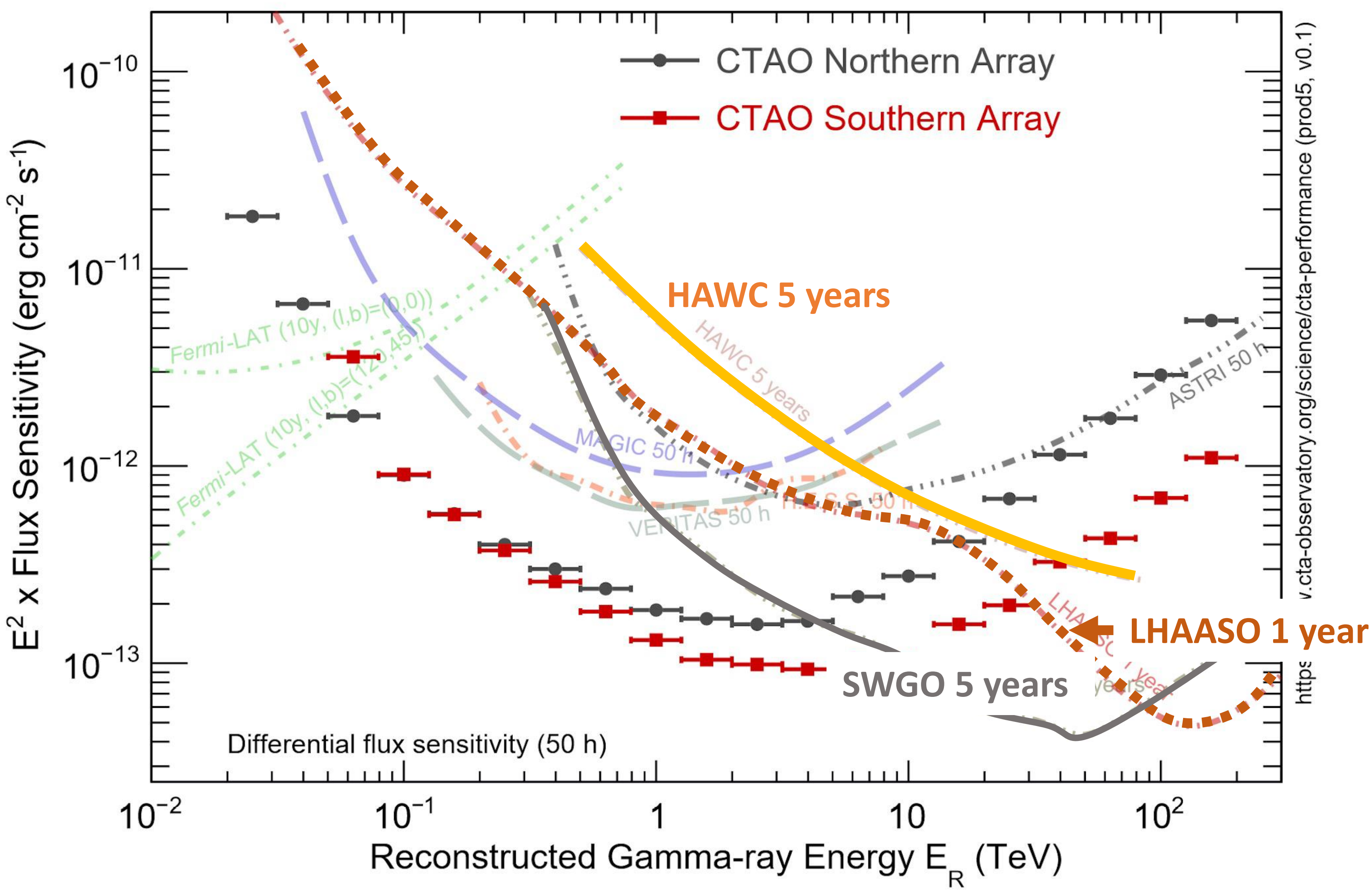


- 12 galactic sources
- Highest-energy gamma shower 1.4 PeV !

The Crab Nebula after LHAASO 2021



Gamma-Ray Telescopes: a Synopsis



Summary

- Cherenkov techniques are essential tools of astroparticle physics
- Enormous progress and several breakthrough results during the last 25 years
  - Two to three orders of magnitude in sensitivity
  - Factor 100 increase in number of TeV gamma-ray sources
  - First TeV neutrino sources
- This is mainly due to
  - Size
  - Technology
  - Analysis methods
  - Site
  - Combination of different detection methods
- Venue of progress being continued with projects like
  - Hyper-Kamiokande
  - KM3NeT, IceCube-Gen2
  - CTA
  - …

Thank you
for your attention

The Venues 1995

Detector location	Detection Medium	Detectors
Underground	purified water heavy water	Kamiokande
Underwater	natural waters	Baikal-NT200 under constr.
Deep Ice	Antarctic ice	AMANDA under construction
Ground	atmosphere	IACTs: Whipple, HEGRA CAT, CANGAROO timing: hybrid:

The Venues 2022

Detector location	**Detection Medium**	**Detectors**
Underground	purified water heavy water	Super-Kamiokande SNO
Underwater	natural waters	Baikal-GVD, ANTARES, KM3NeT
Deep Ice	Antarctic/Arctic ice	IceCube, R-GNO
Ground	atmosphere water/ice tanks atm., water tanks	IACTs*:* H.E.S.S., VERITAS, MAGIC timing: HAWC, IceTop hybrid: Auger, LHAASO, TAIGA, NEVOD

Requirements and Devices

$$\frac{dN_\gamma}{dx} = 2\pi\alpha\left(1 - \frac{1}{\beta^2 n^2}\right)\cdot\left(\frac{1}{\lambda_{\min}} - \frac{1}{\lambda_{\max}}\right)$$

$$\overset{\beta=1}{\approx} \begin{cases} 7.6\times 10^4/\mathrm{m} & \text{in water/ice} \\ 15/\mathrm{m} & \text{in air (8 km)} \end{cases} \quad \text{for} \quad 300\,\mathrm{nm} \le \lambda \le 600\,\mathrm{nm}$$

- Single-photon detection
- Timing at nanosecond level
- Synchronisation of large arrays with nanosecond precision

- Photomultipliers (PMTs)
- SiPMs
- Radio antennas
  (coherent emission from particle showers in the range λ ~ 10 cm)

The future: CTA (Cherenkov Telescope Array)