The cosmic high-energy frontier

A view to the next decade

HAP Meeting,
Oct. 2016
Erlangen

Christian Spiering, DESY Zeuthen

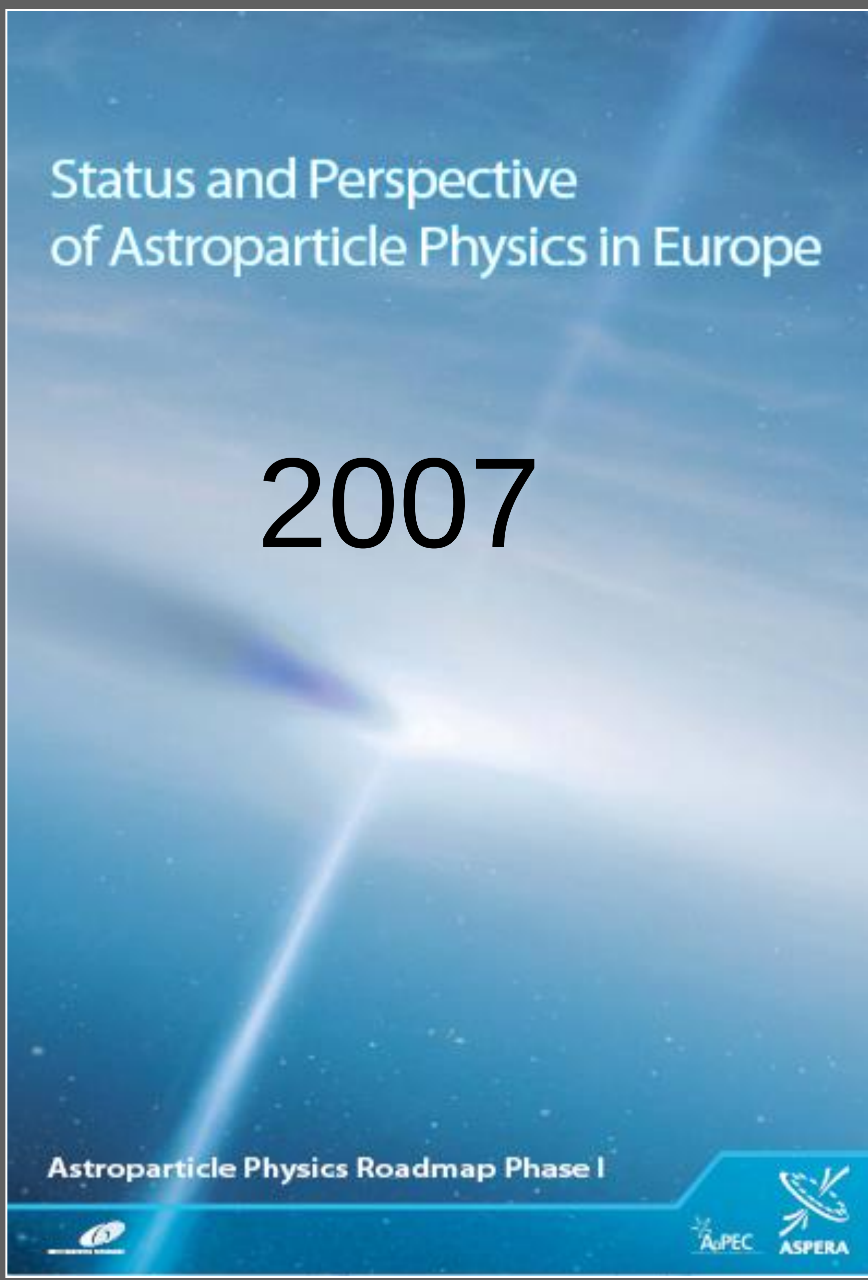
Content

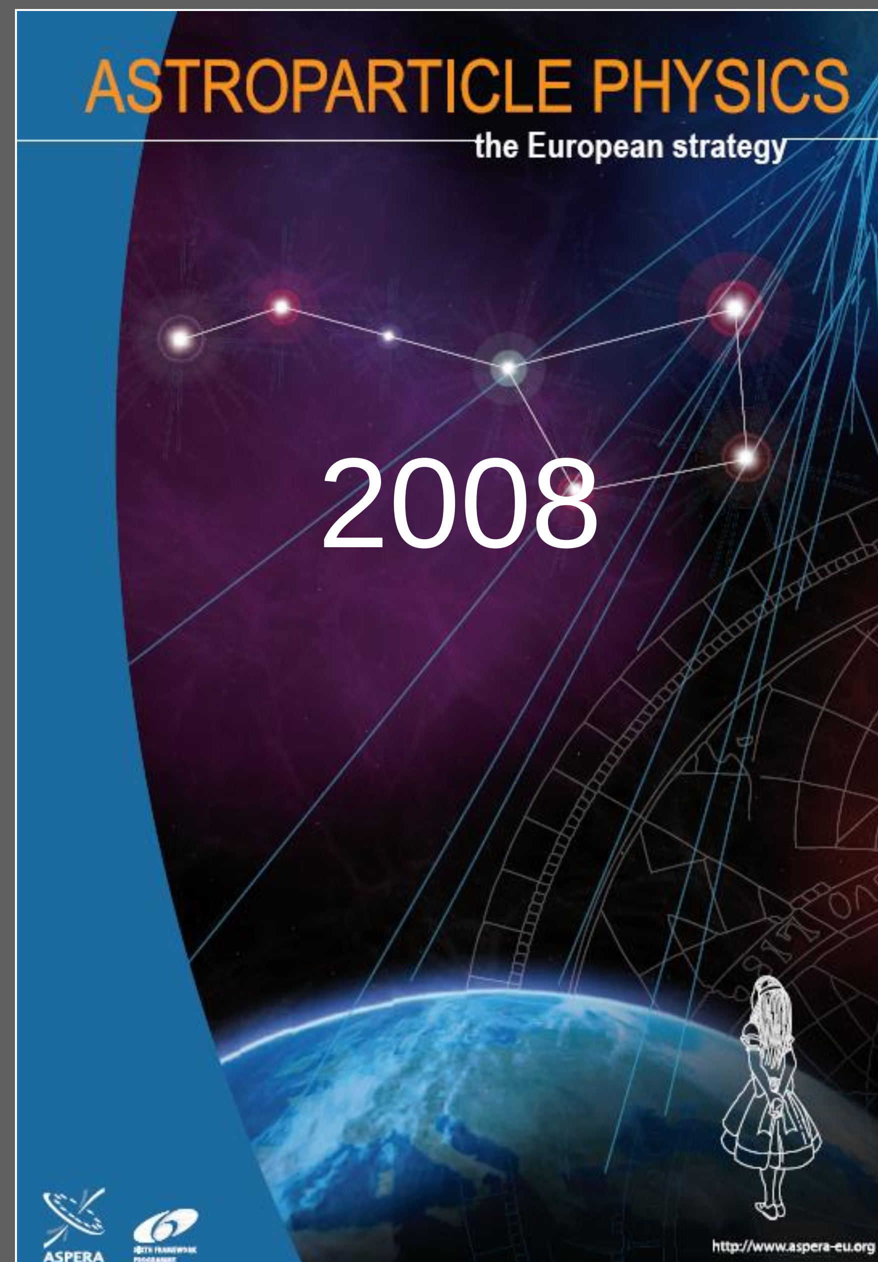
- Predicting the future: plans and reality
- EeV charged cosmic rays: approaching a turning point?
- Cosmic ray science below 10^{18} eV
- Gamma rays – a blossoming field
- HE neutrinos: window opened, landscape uncharted

PLANS AND REALITY

SOME REMARKS ON ROADMAPPING
AND THE DIFFICULTY TO PREDICT THE FUTURE

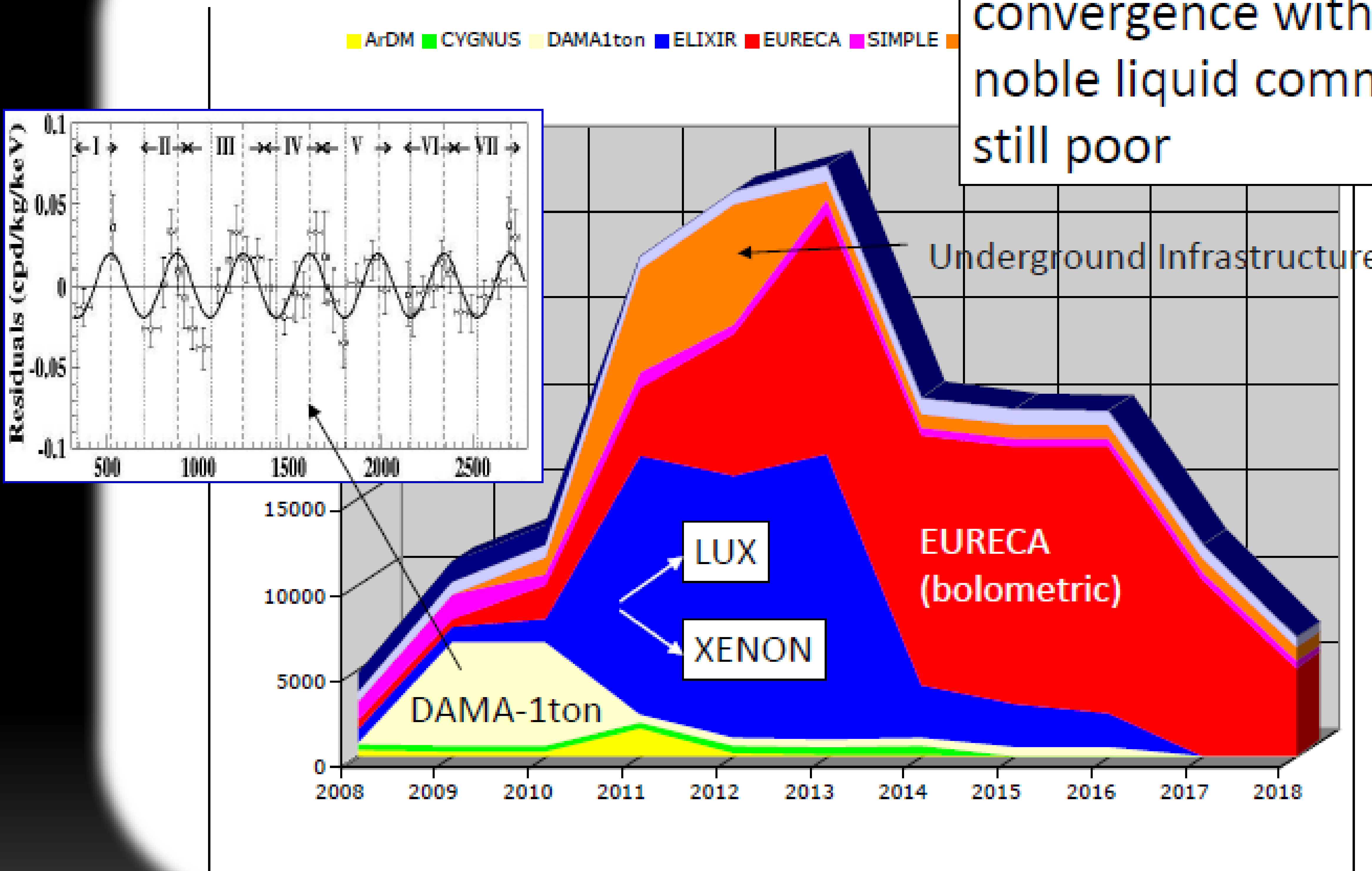
Three attempts to sketch the future …





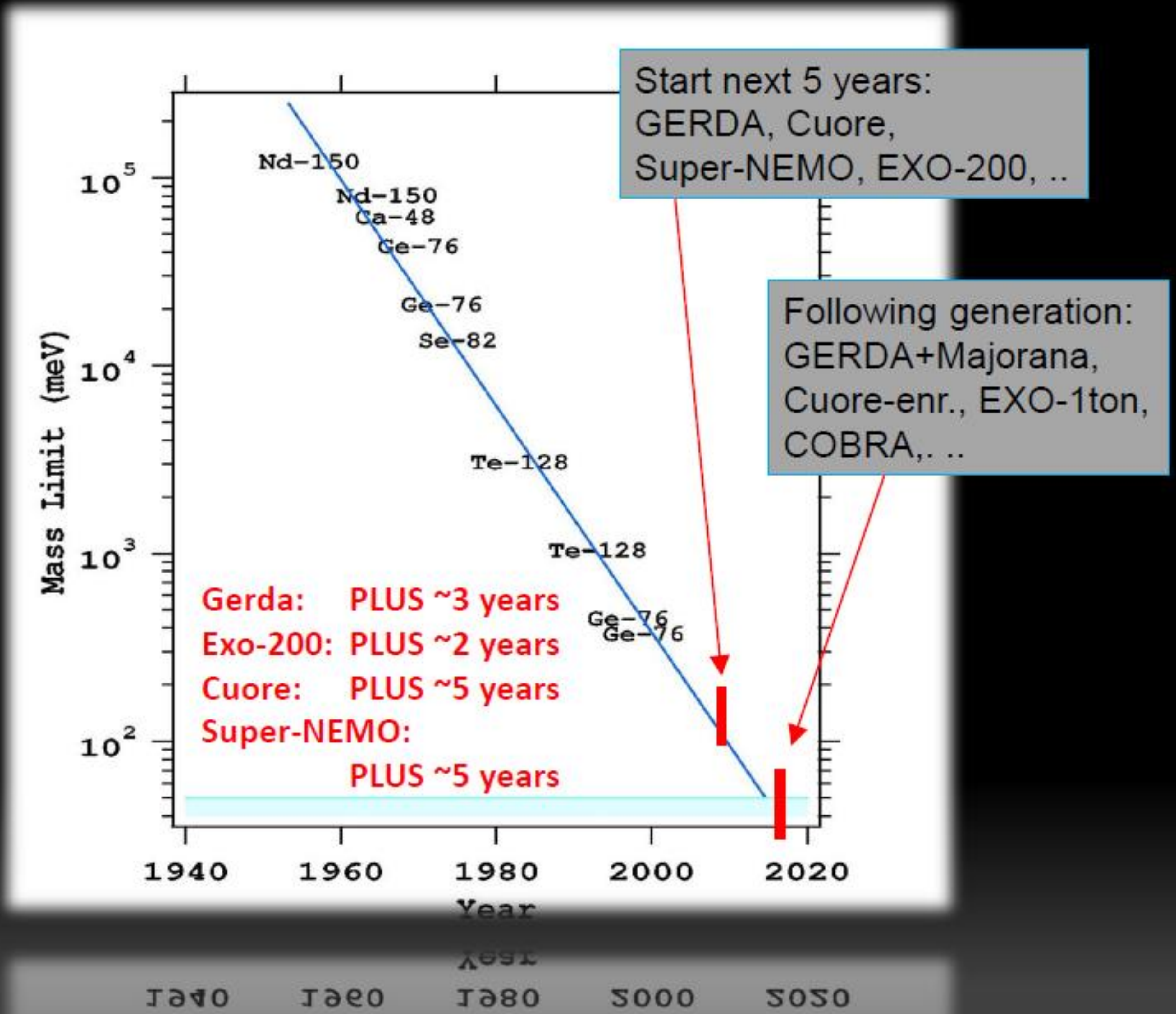
2007 Aspera WG requests European Dark Matter projects

convergence within noble liquid community still poor

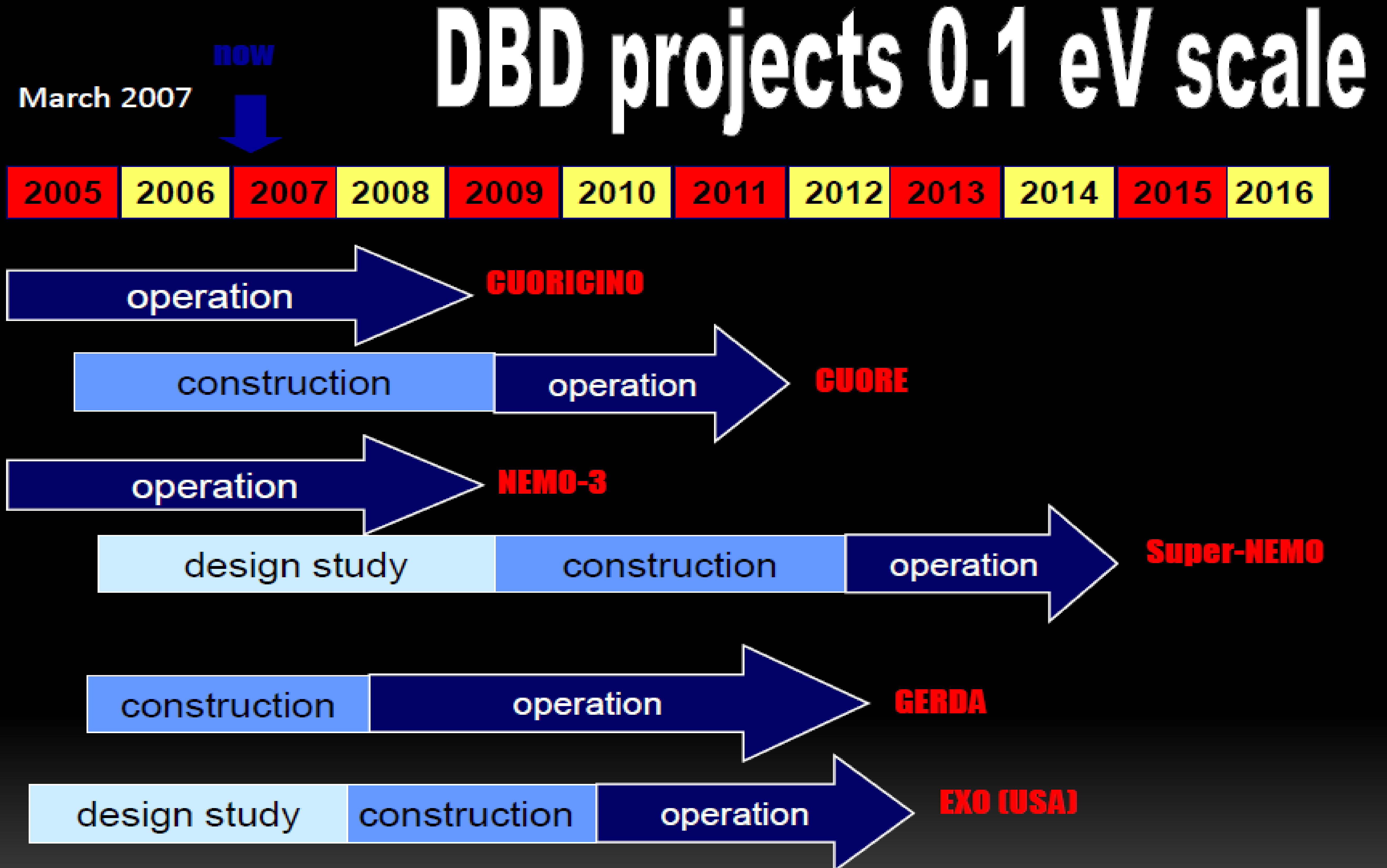


Example: ν-less double beta decay

From the 2007 roadmap (picture already somewhat older)

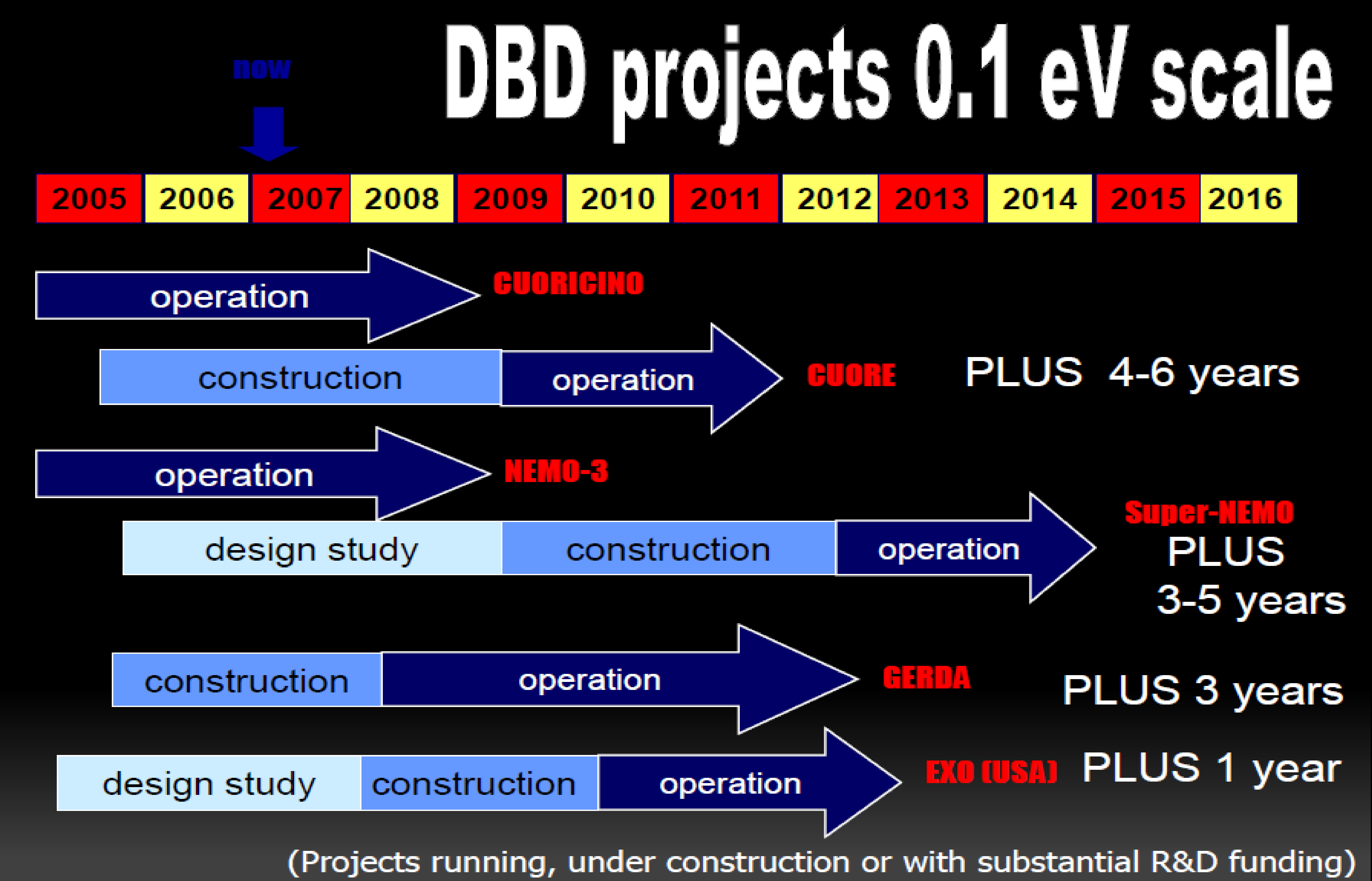


Looking back to 2007 plans from 2012



(Projects running, under construction or with substantial R&D funding)

Looking back to 2007 plans from 2012



Looking back to 2007 plans from 2012

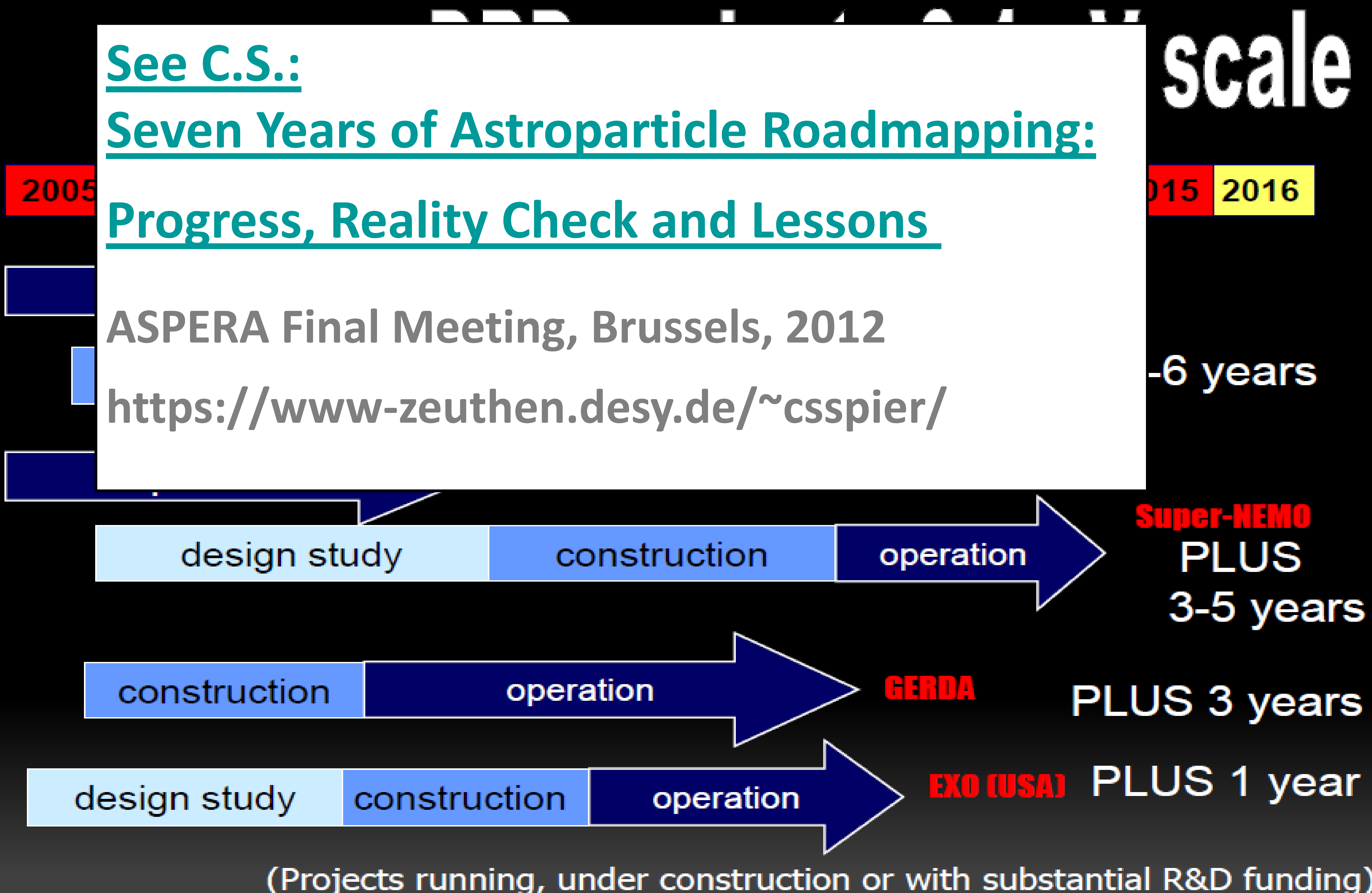
See C.S.:

Seven Years of Astroparticle Roadmapping:

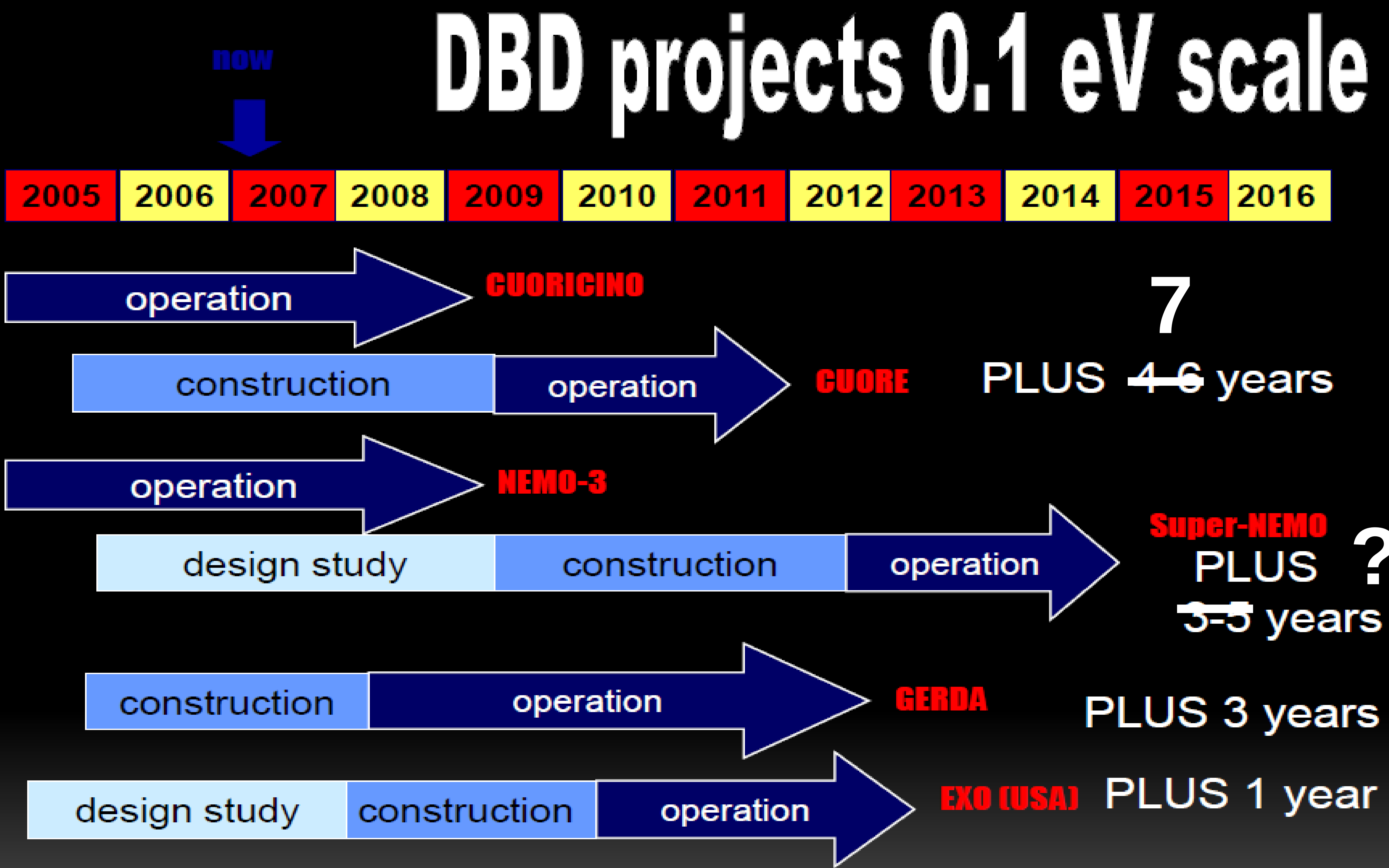
Progress, Reality Check and Lessons

ASPERA Final Meeting, Brussels, 2012

https://www-zeuthen.desy.de/~csspier/



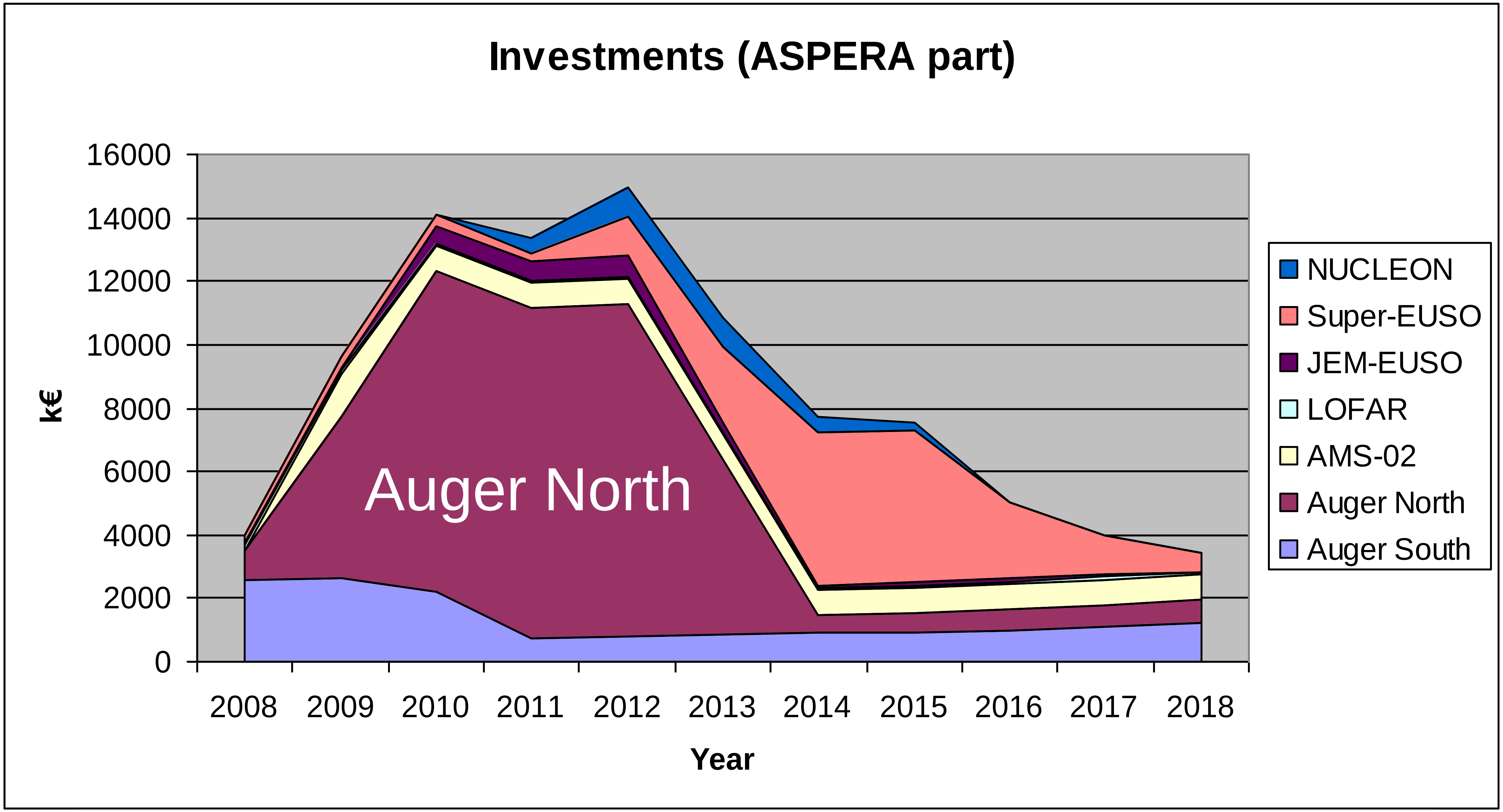
Looking back to 2007 plans from 2016



(Projects running, under construction or with substantial R&D funding)

High Energy Cosmic Rays

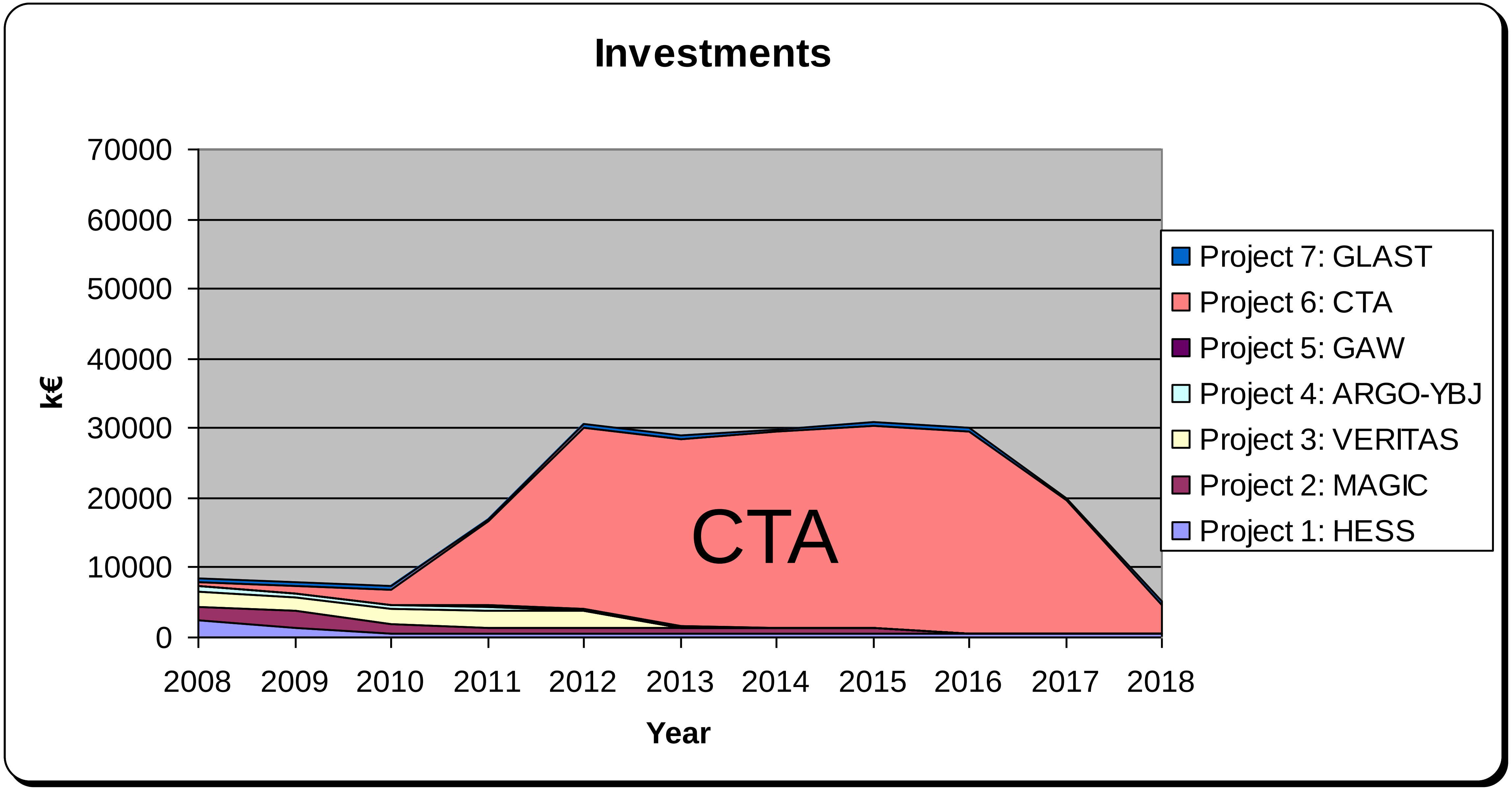
Summary: ASPERA sum 2008-2018 Clear priority: Auger North



Auger North planning at this point shifted by ~1 year compared to the figure

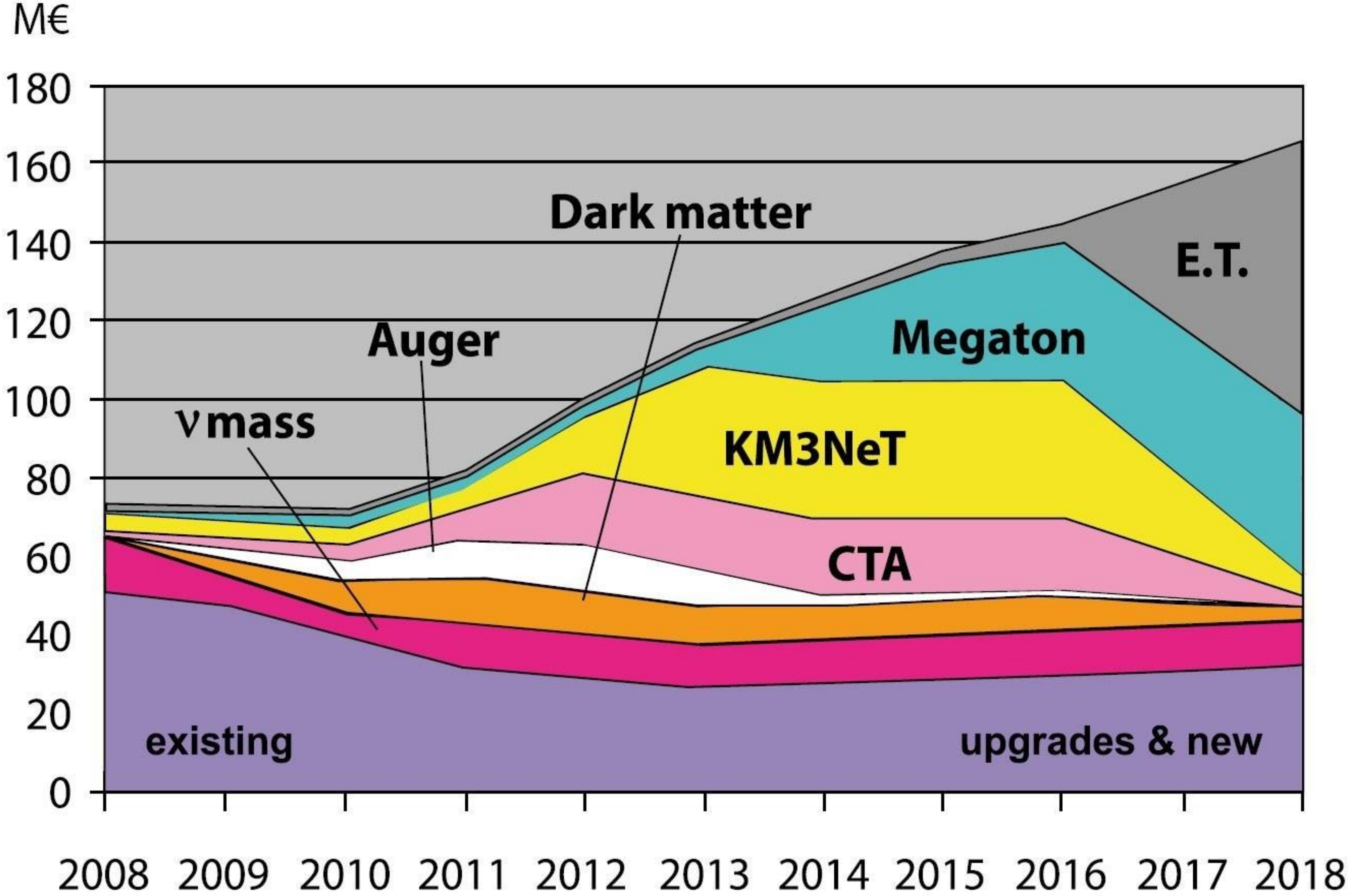
High Energy Gamma Telescopes

Clear priority: CTA



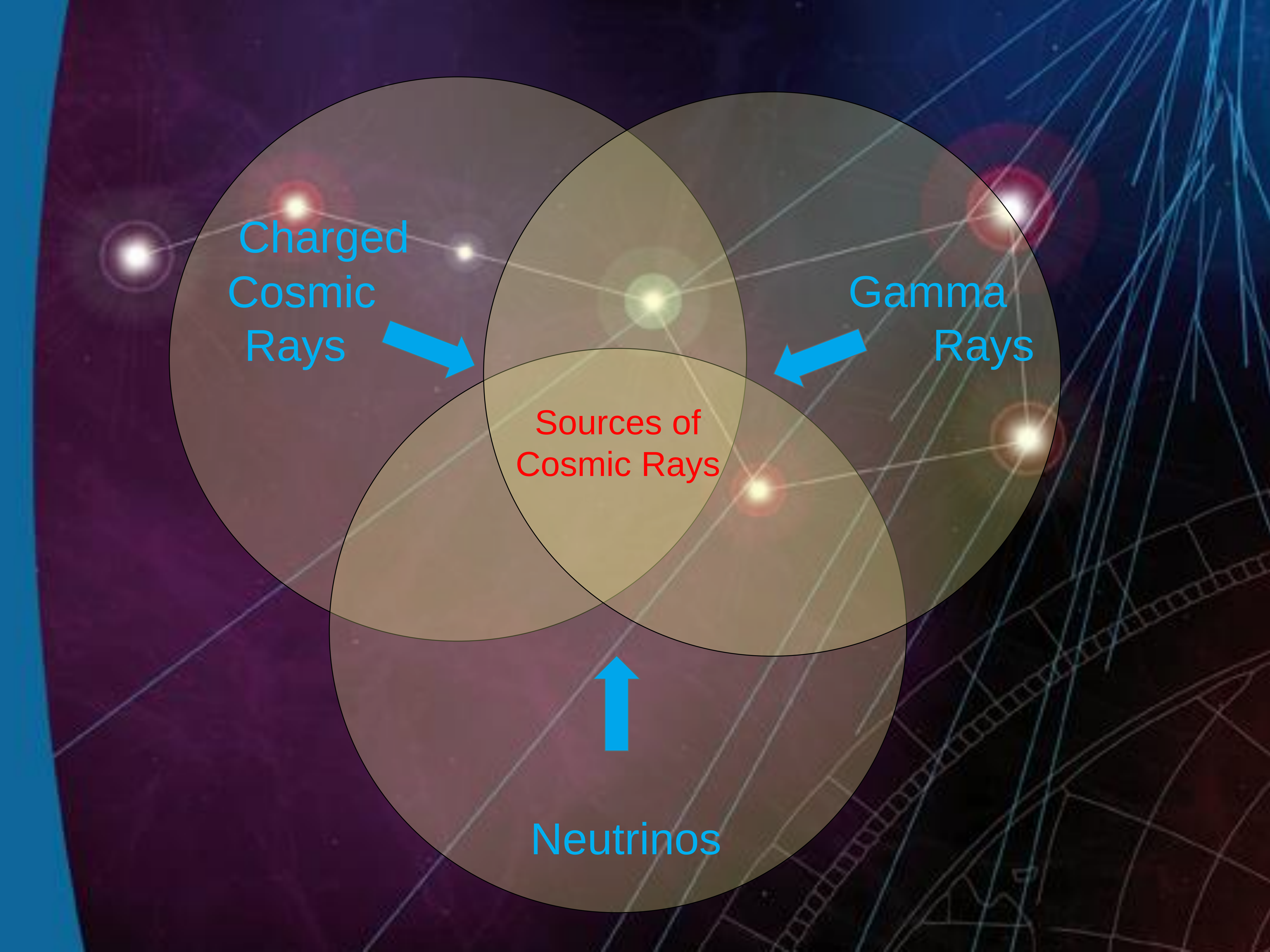
CTA planning at this point shifted by ~1 year compared to the figure

Astroparticle funding profile seen from 2008



Vorhersagen sind Glücksache, insbesondere wenn sie die Zukunft betreffen.

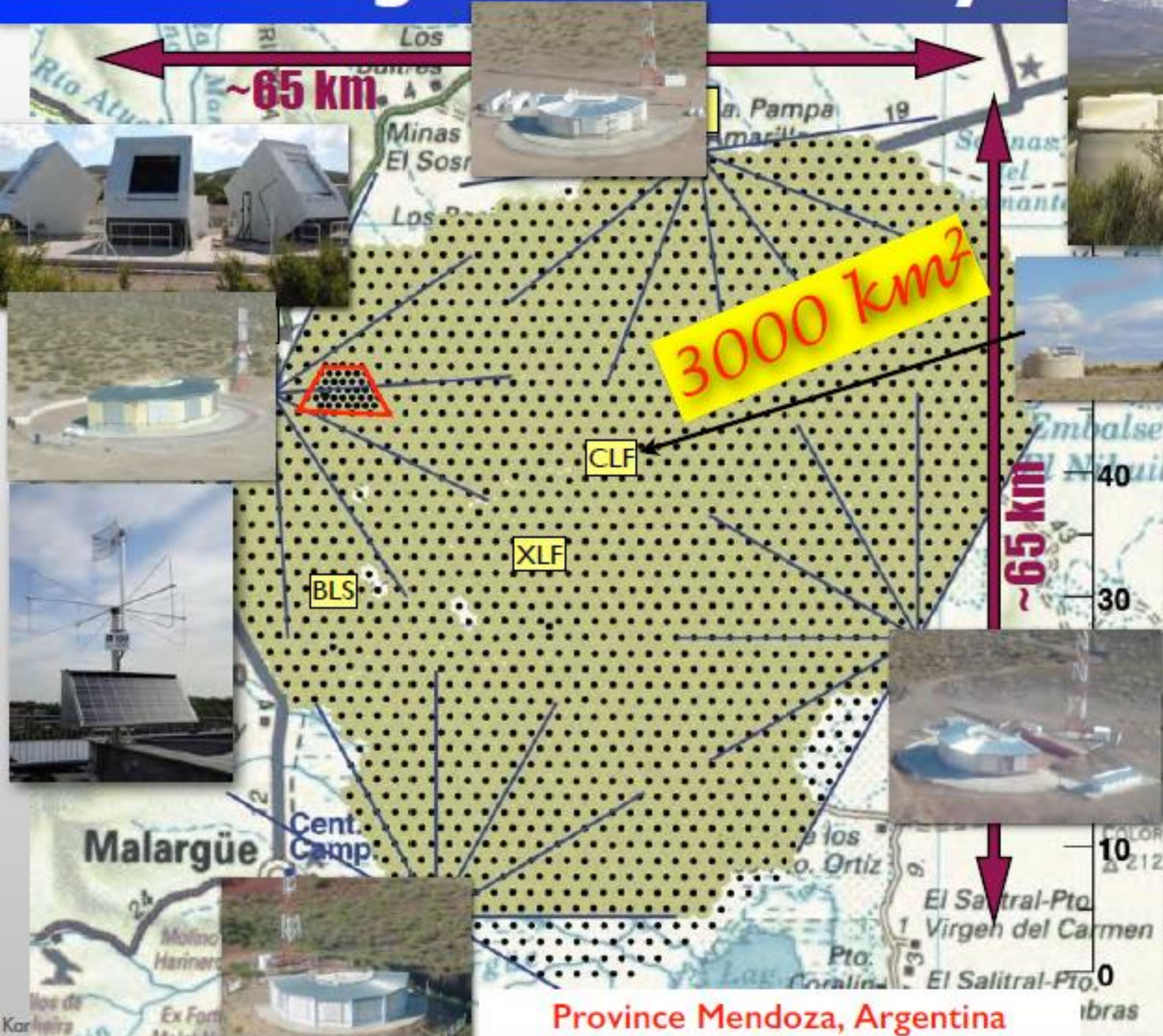
- **Es kommt (fast) immer anders als man denkt !**
- 2/3 of the changes: strong delays or even cancelation of the project
- 1/3 of the changes: new projects appear (HiSCORE/TAIGA, LHHASO, NEXT, JUNO, …) or progress as expected (IceCube, …)
- **Anyway, huge progress at many frontiers:**
  - Dark Matter sensitivity (envisage neutrino floor)
  - Neutrino oscillations (large θ_{13}, indications for NMH, δ_{CP}, DeepCore, …)
  - IceCube discovery of cosmic HE neutrinos
  - Confirmation of CR cut-off
  - Rich collection of results from gamma astronomy
  - Cosmology results (contraints on n_ν and neutrino mass, …)
  - …


Charged Cosmic Rays
Gamma Rays
Sources of Cosmic Rays
Neutrinos

EeV Cosmic Rays

Approaching a Turning Point?

Pierre Auger Observatory



1660 detector stations on 1.5 km grid

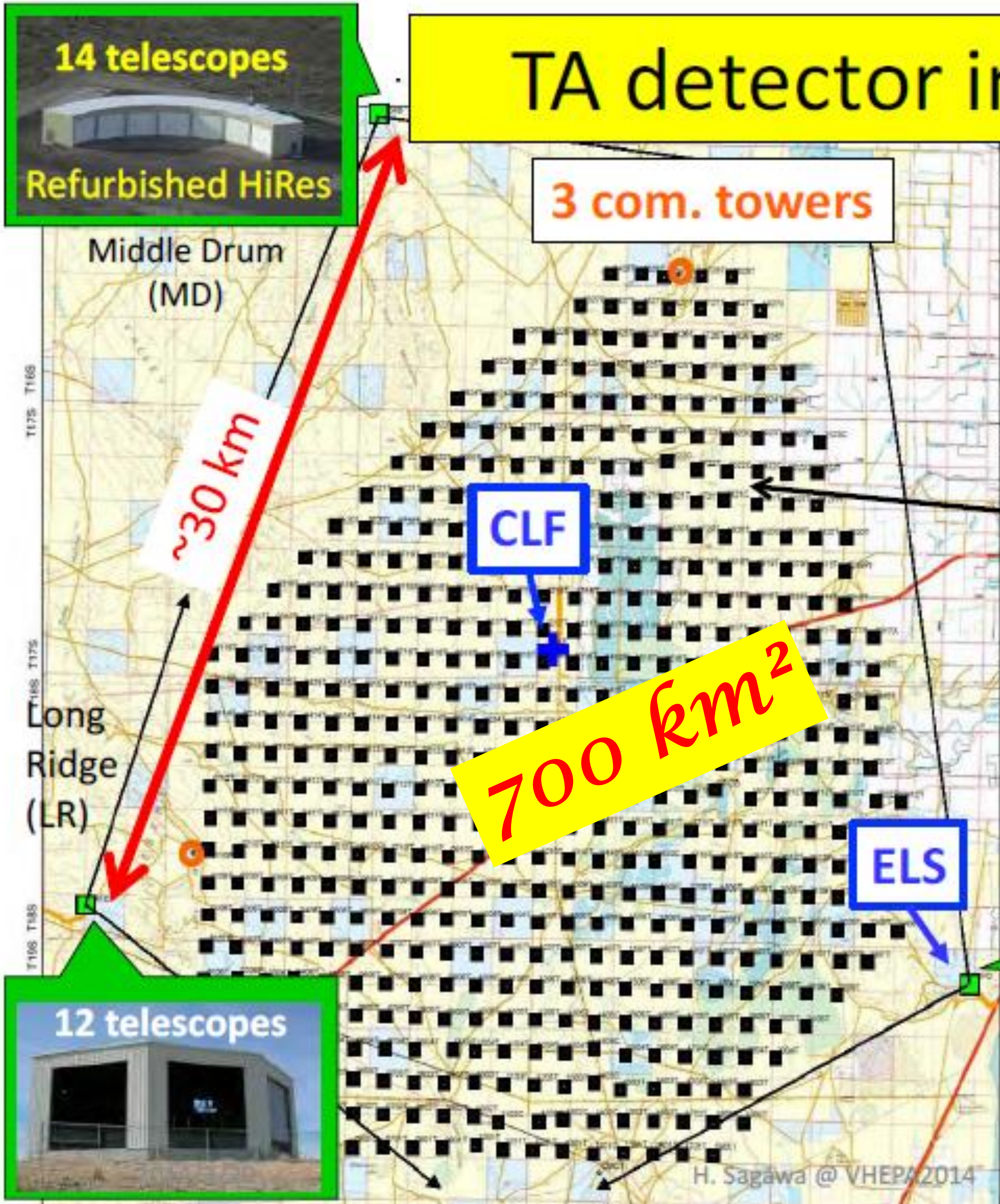
27 fluores. telescopes at periphery

130 radio antennas

Province Mendoza, Argentina

TA detector in Utah

39.3°N, 112.9°W
~1400 m a.s.l.



Surface Detector (SD)

507 plastic scintillator SDs

1.2 km spacing

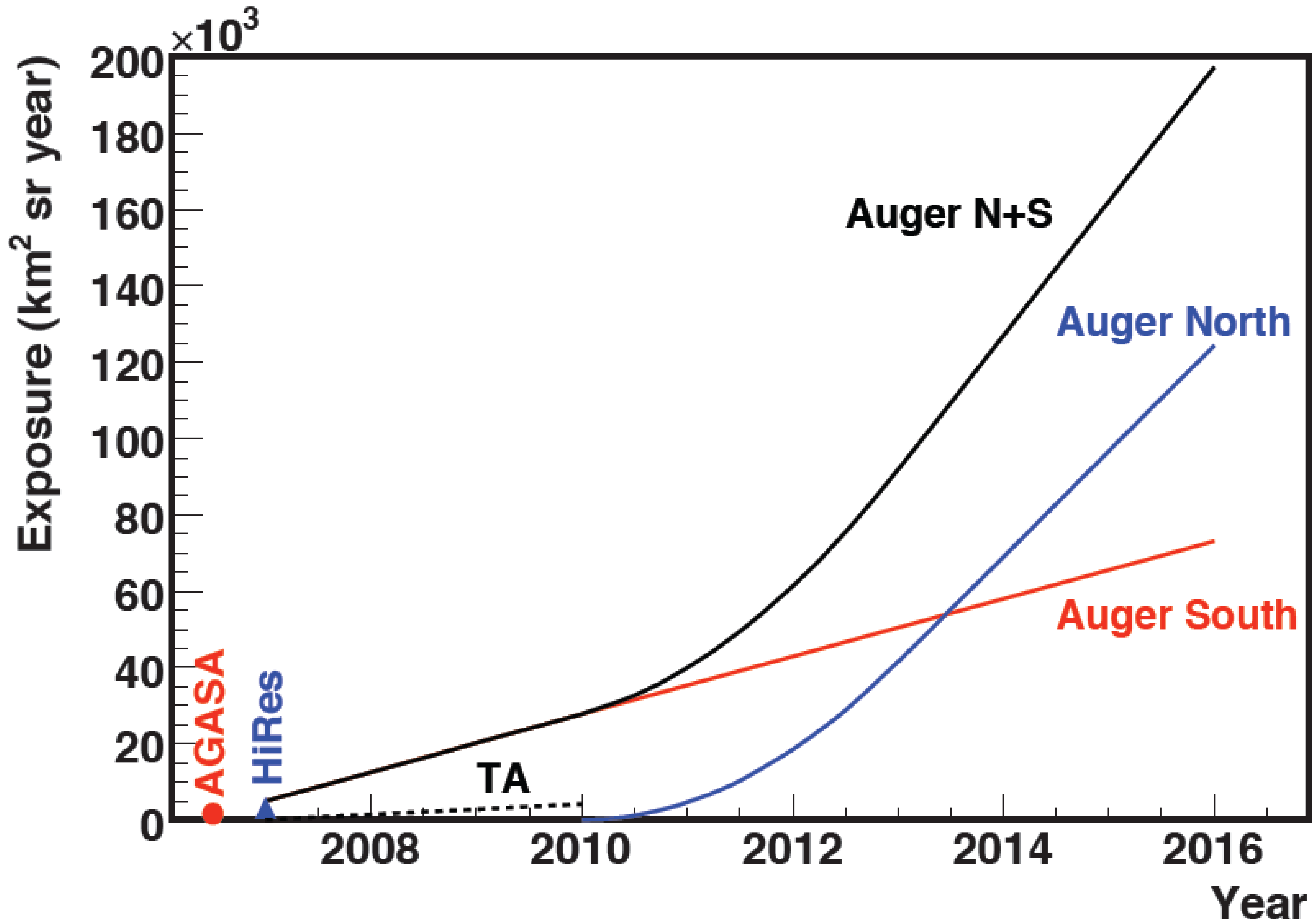
Fluorescence Detector(FD)

3 stations

38 telescopes

FD and SD: fully operational since 2008/May

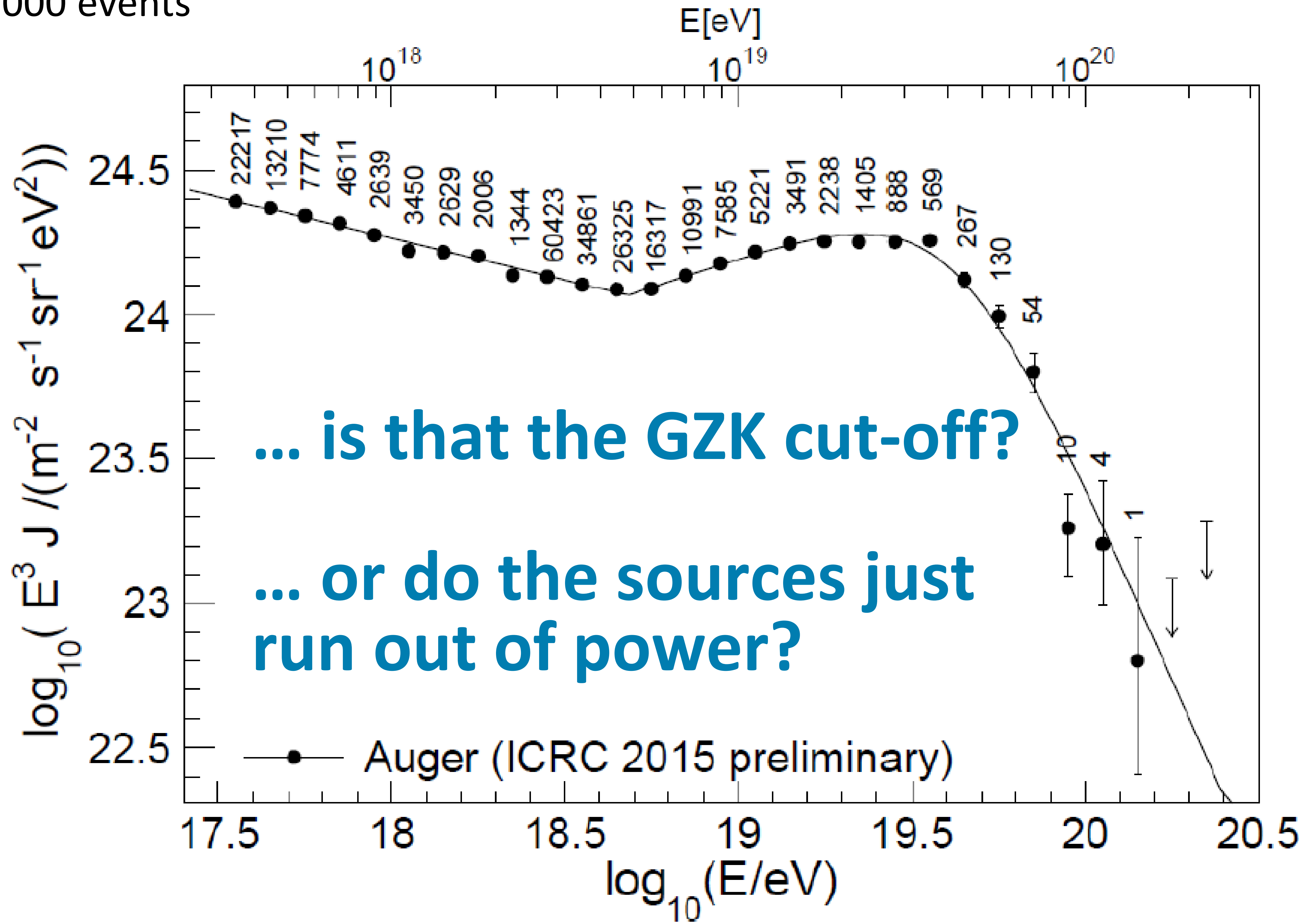
2008 projection Auger South & North



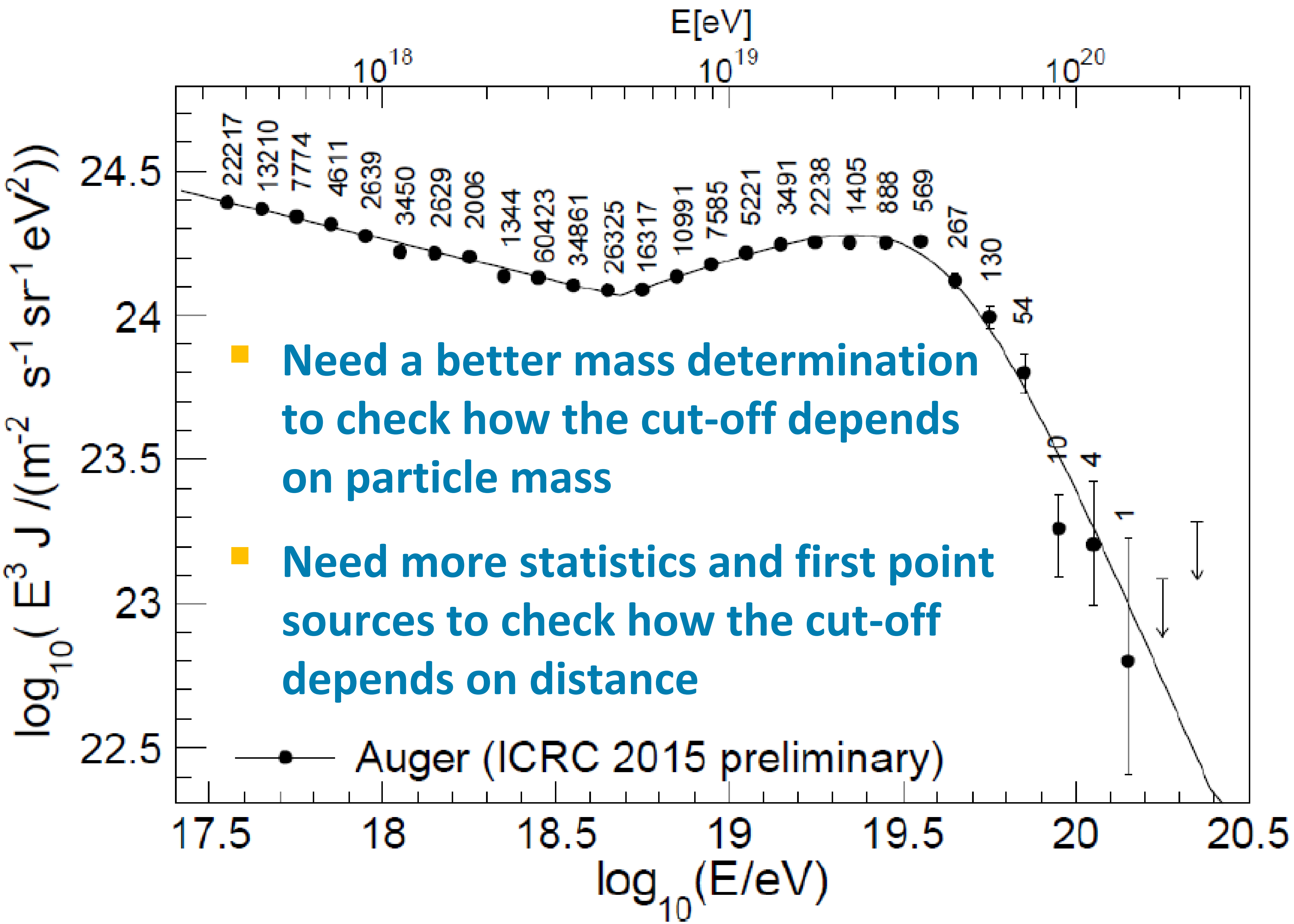
assuming construction 2009-2012

Cut-off at highest energies confirmed, but …

190 000 events



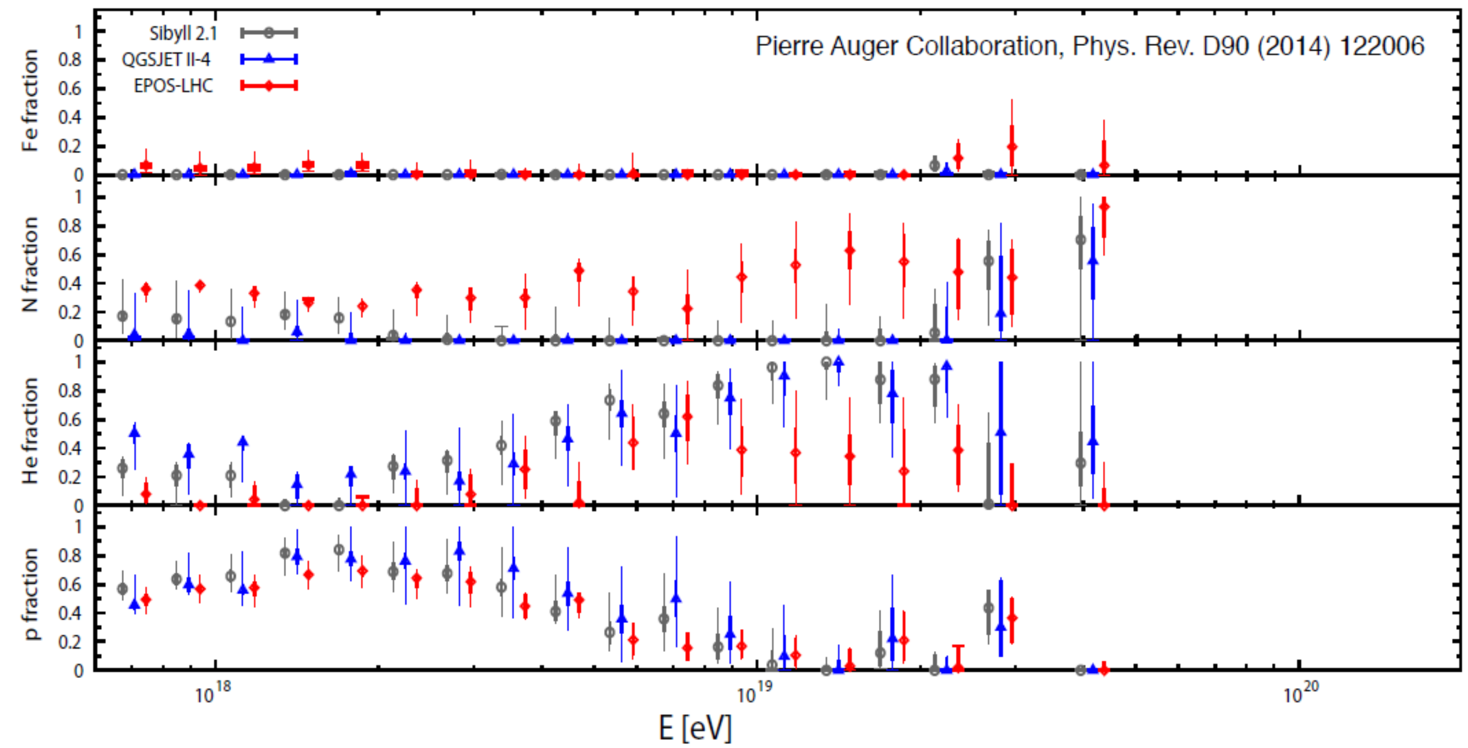
Cut-off: how to undestand its nature



- Need a better mass determination to check how the cut-off depends on particle mass
- Need more statistics and first point sources to check how the cut-off depends on distance

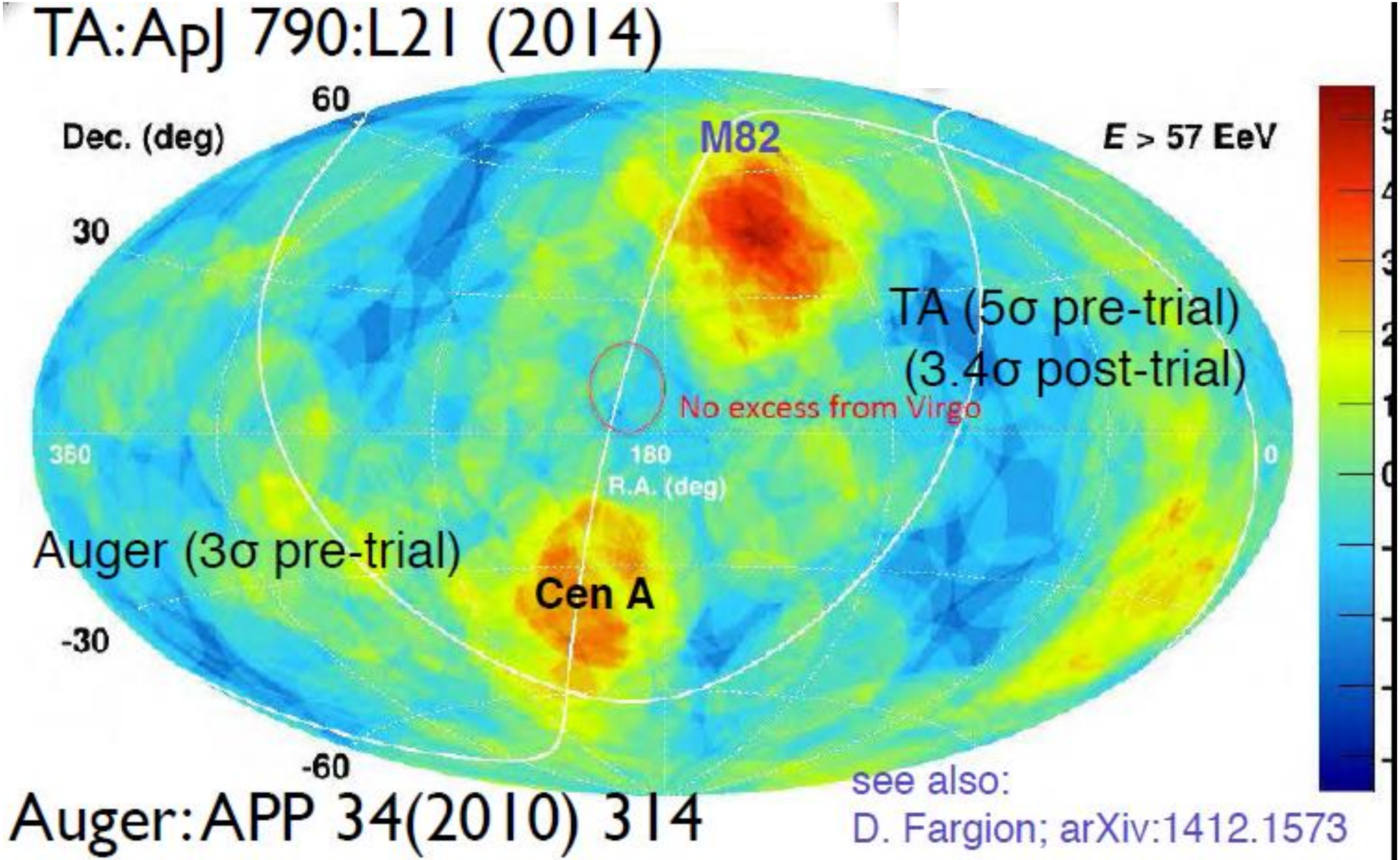
Can we do astronomy?

- Need protons - heavy nuclei are too strongly deflected in cosmic magnetic fields
- Presently derived proton contribution seems disappointingly small (~10%)
- Is that the final word? (Could well be 30% !!, See also TA!)



- **Need better mass determination + more statistics above 3× 10^{19} eV!**

Point Sources: Tantalizing hot spot at TA



Auger and TA upgrades

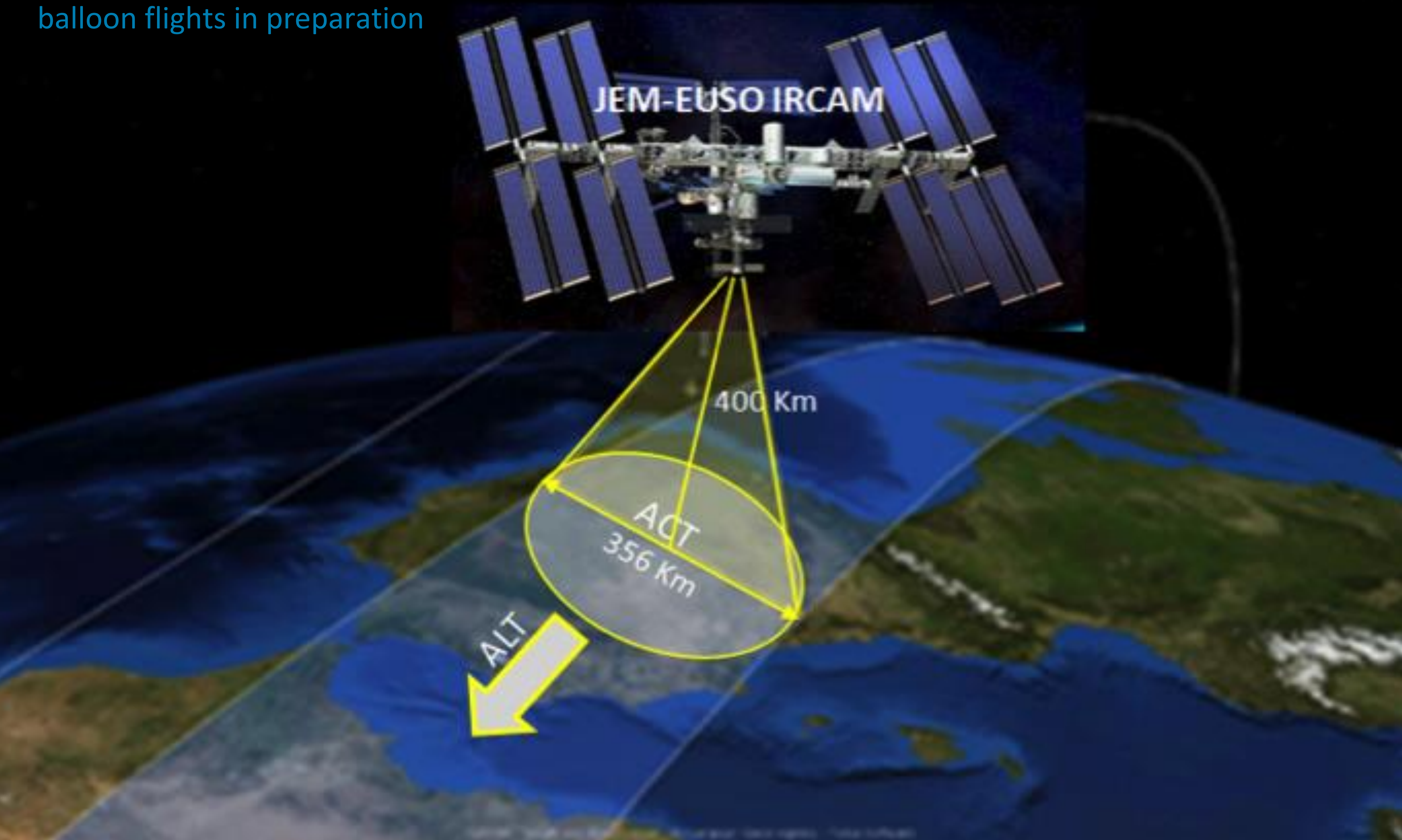
- **AugerPrime**
  - **improve measurement of mass composition !!**
  - **no area extension**
  - **upgrading water tanks with scintillators on top**
  - **raising Fluorescence Detector duty cycle by 10-15% → more hybrid events**
- **Telescope Array upgrade**
  - **more statistics for hot spot !!**
  - **increasing array from 700 km² to 2800 km² (approved in Japan April 2015)**
  - **2 new Fluorescence detectors (proposal submitted in USA)**

Ultrahigh-energy CR physics is at a turning point !

- **If proton component < 5-10%:** Next-generation detectors would fail *by definition* to identify point sources.
  That would very likely herald the end of the race towards *astronomy* with charged cosmic rays.
- **If the proton component would be much higher than the presently estimated 10%, or if even point sources could be identified, the path towards cosmic ray astronomy would be open**.
- **AugerPrime extremely important for the future of the full field**: Guidance, whether CR physics at highest energies should be continued or whether it will have reached its natural end.
- **In the most positive case, AugerPrime or TA would detect first point sources and break through a long-standing wall.**
- A larger detector could later study these sources in more detail.

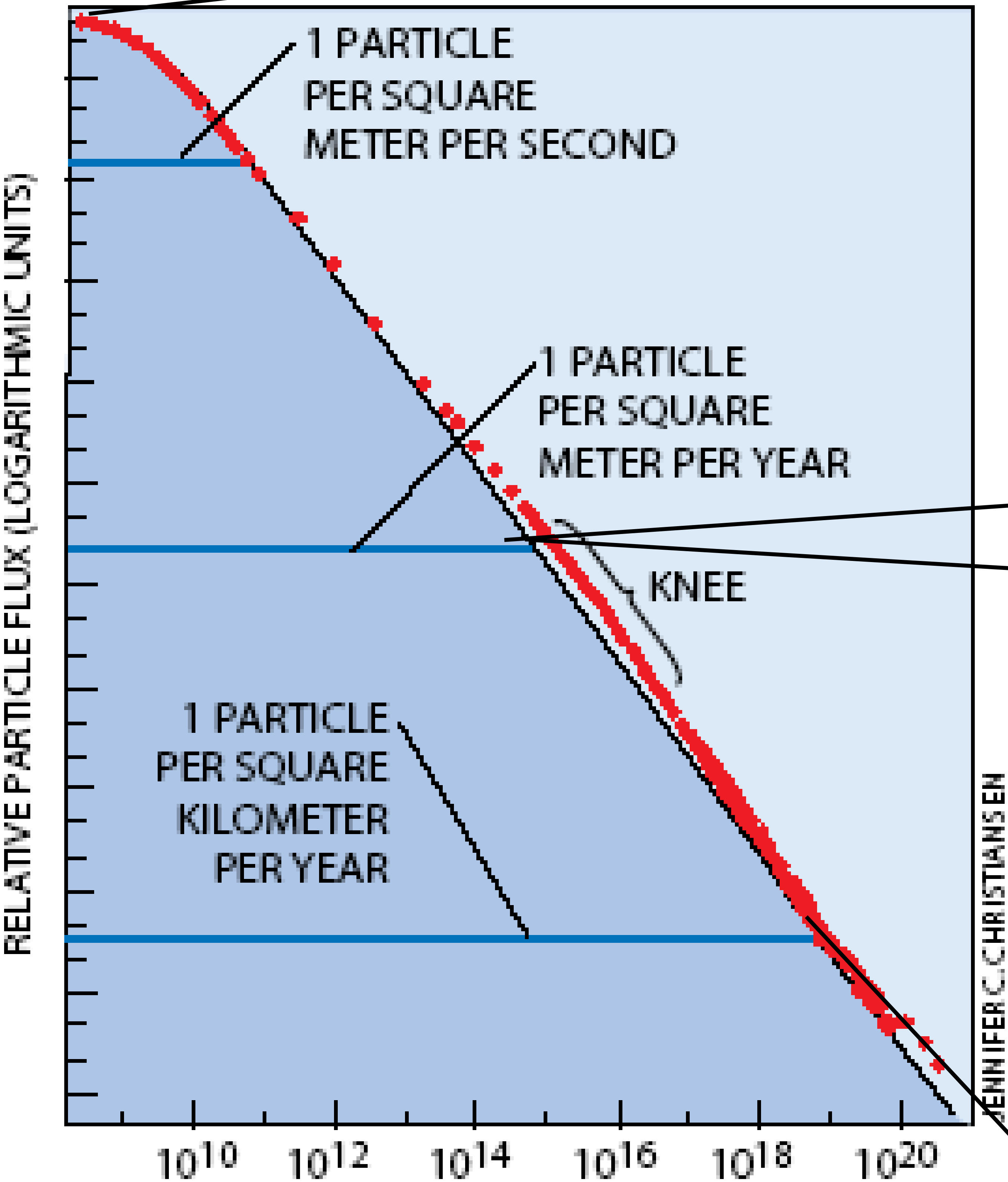
JEM-EUSO

At present: prototype tests with balloon flights in preparation



Cosmic Ray Science Below 10^{18} eV

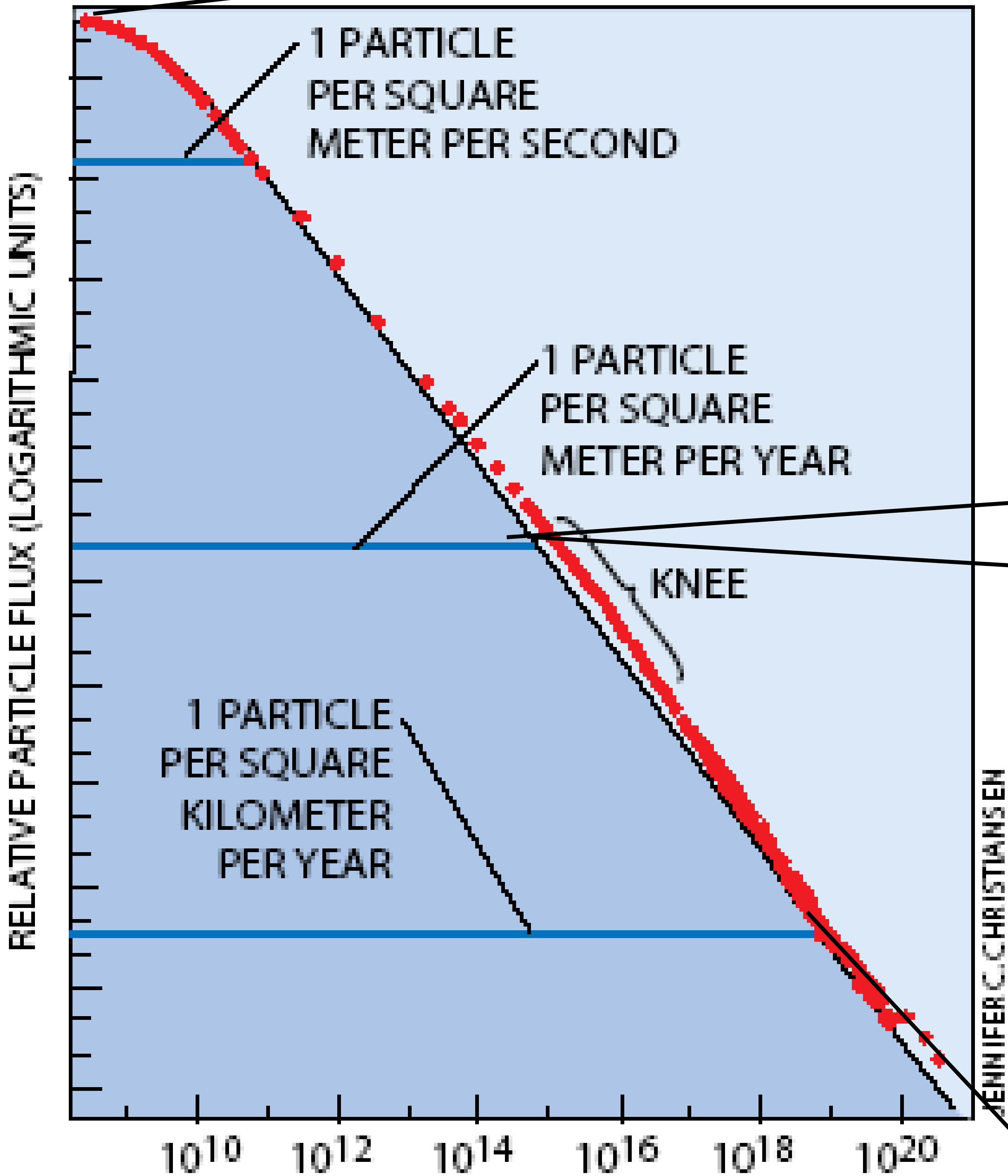
Satellites and balloons



- **Satellites (and balloons)**
  - indirect dark matter search
  - cosmic spectrum and mass composition (direct measurement)
  - Heavy (anti-) nuclei
- **Detectors:**
  - Pamela, AMS, 2015: CALET, DAMPE
- **1-10 km² air shower arrays**
  - Galactic CR, transition extragal. CR
  - understand EAS models↔ LHC
- **Detectors:**
  - (ARGO/YBJ, KASCADE-Grande), AMIGA
  - TAIGA (Siberia)
  - LHHASO (Tibet)

Radio Arrays
(LOFAR, Auger, Tunka, …)

Satellites and balloons



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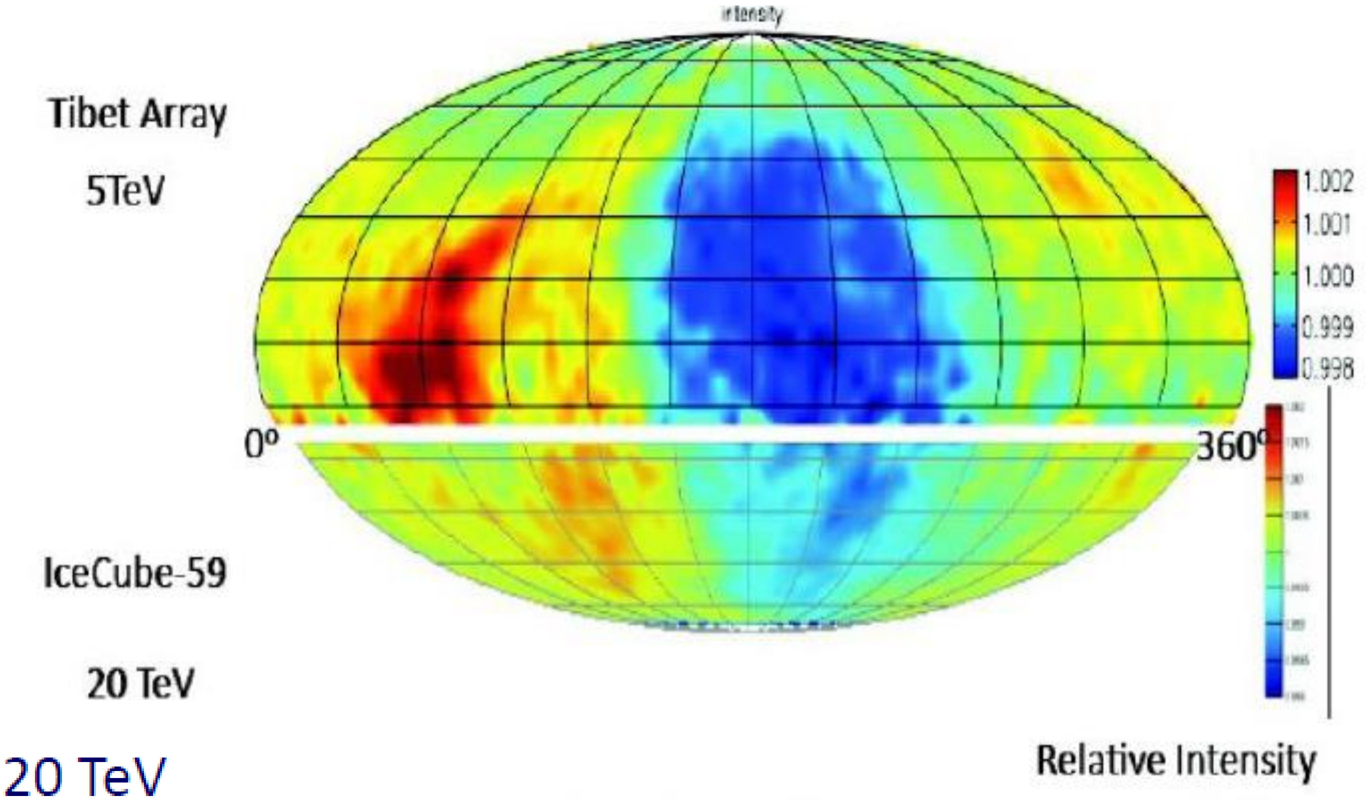
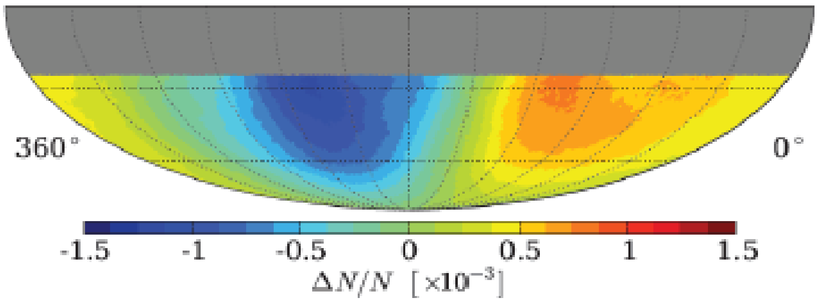
↕

Close connection to LHC community !

CR anisotropies at 5 – 5000 TeV

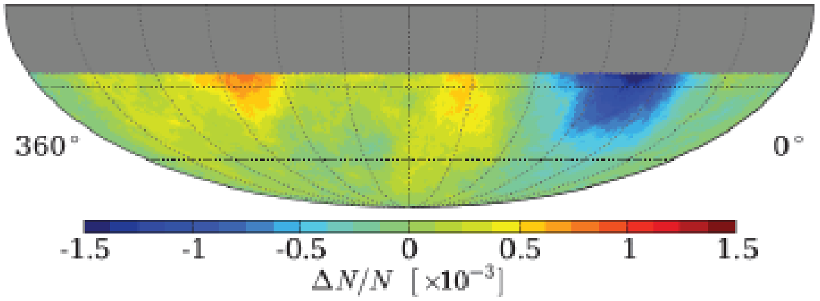
- On scales down to 3°-5°
- Origin unclear



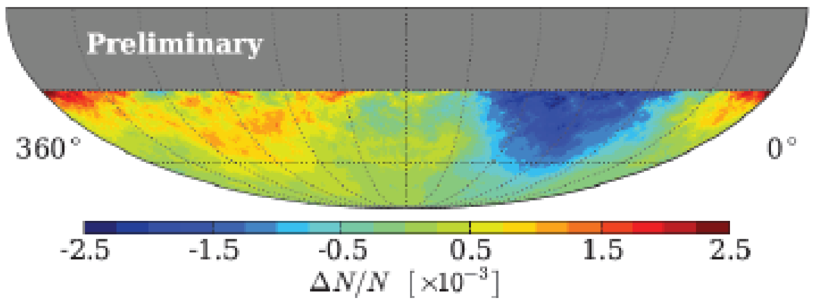


- IceCube-59: 20 TeV

Change
of polarity



- IceCube-59: 400 TeV



- IceTop-59: PeV-range

Still much to do!

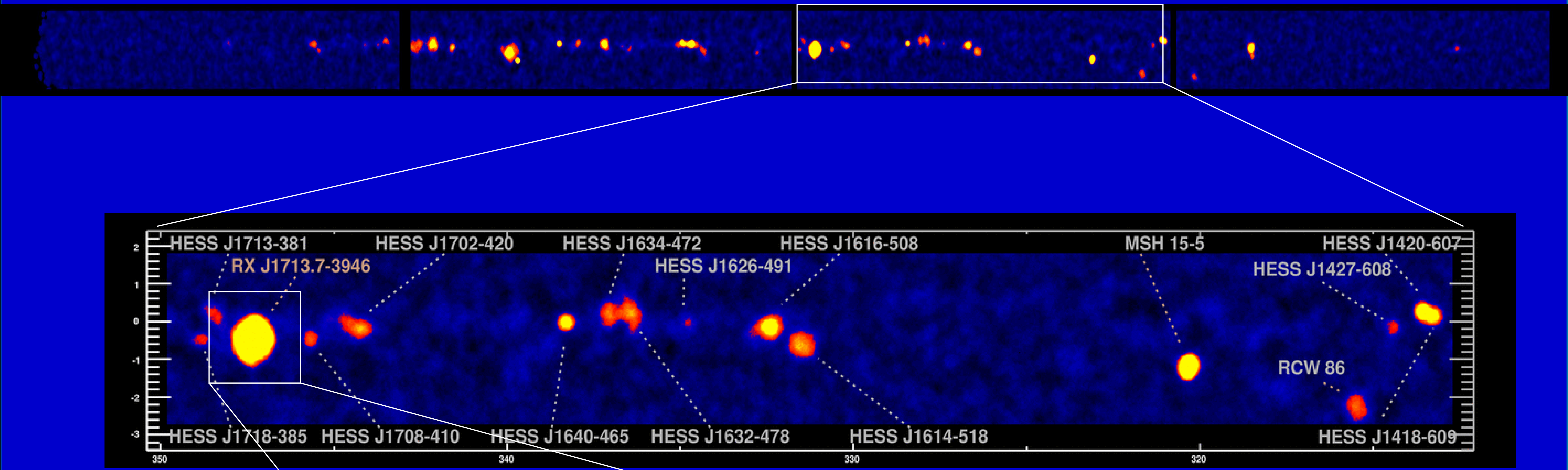
→ HAWC, LHHASO, TAIGA

GAMMA RAYS

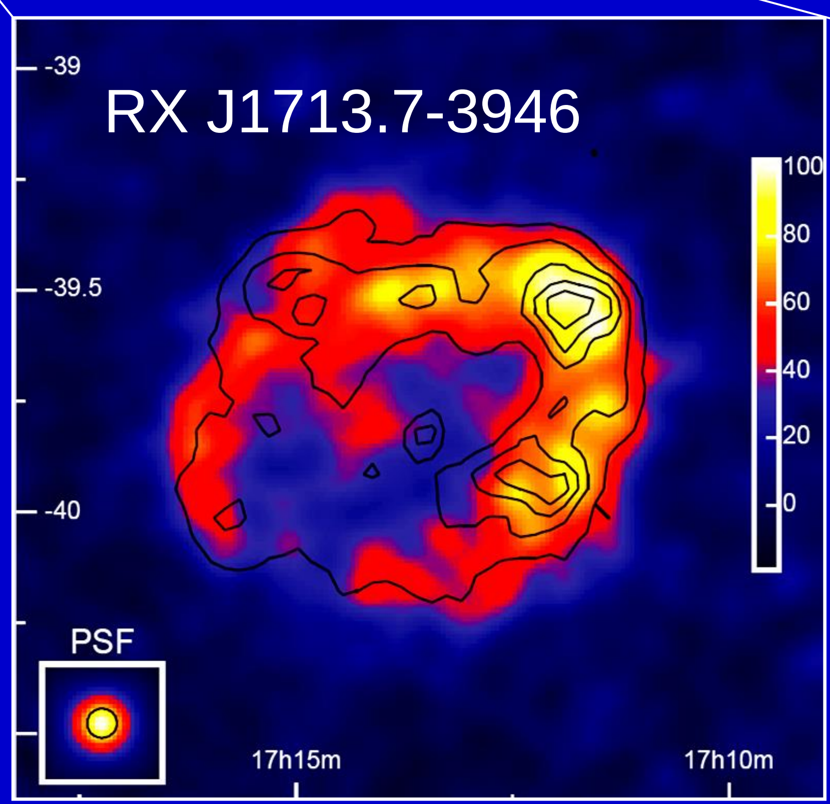
A BLOSSOMING FIELD

3rd generation Imaging Air Cherenkov telescopes

The Sky at TeV-Energies



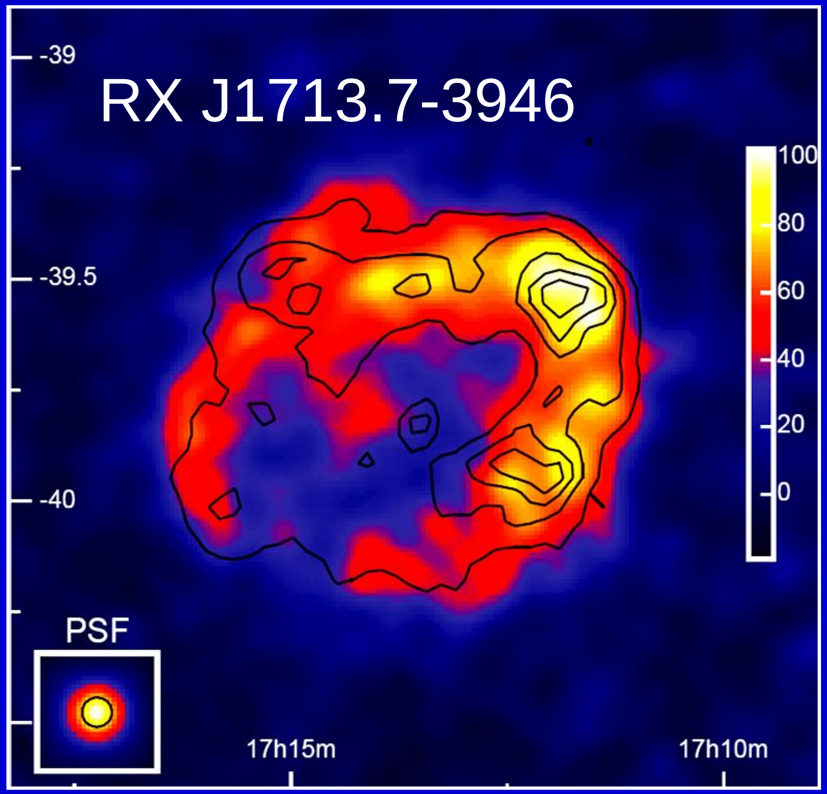
H.E.S.S.-Scan of the galactic plane



1989:	1 Source
1996:	3 Sources
2005:	80 Sources
2015:	150 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
  (even energy-dependent!)



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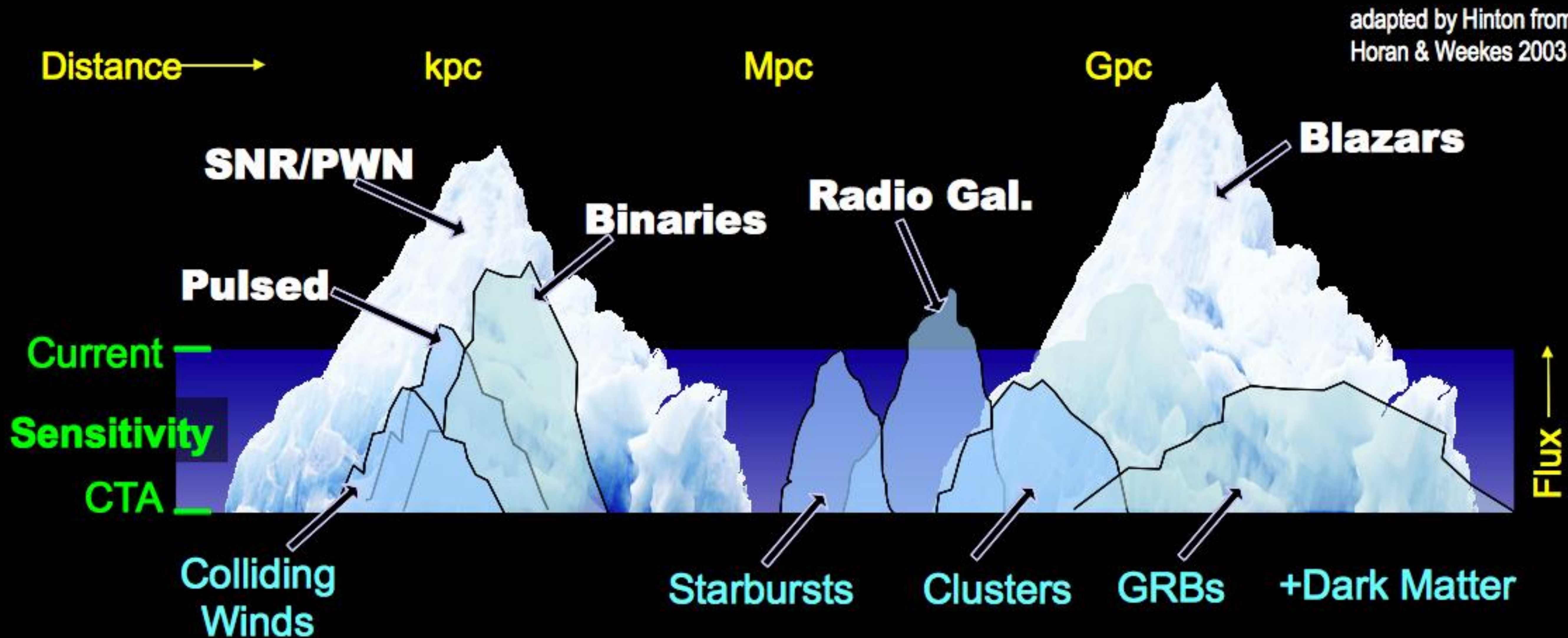
It‘s going to be like classical astronomy !

PLUS:

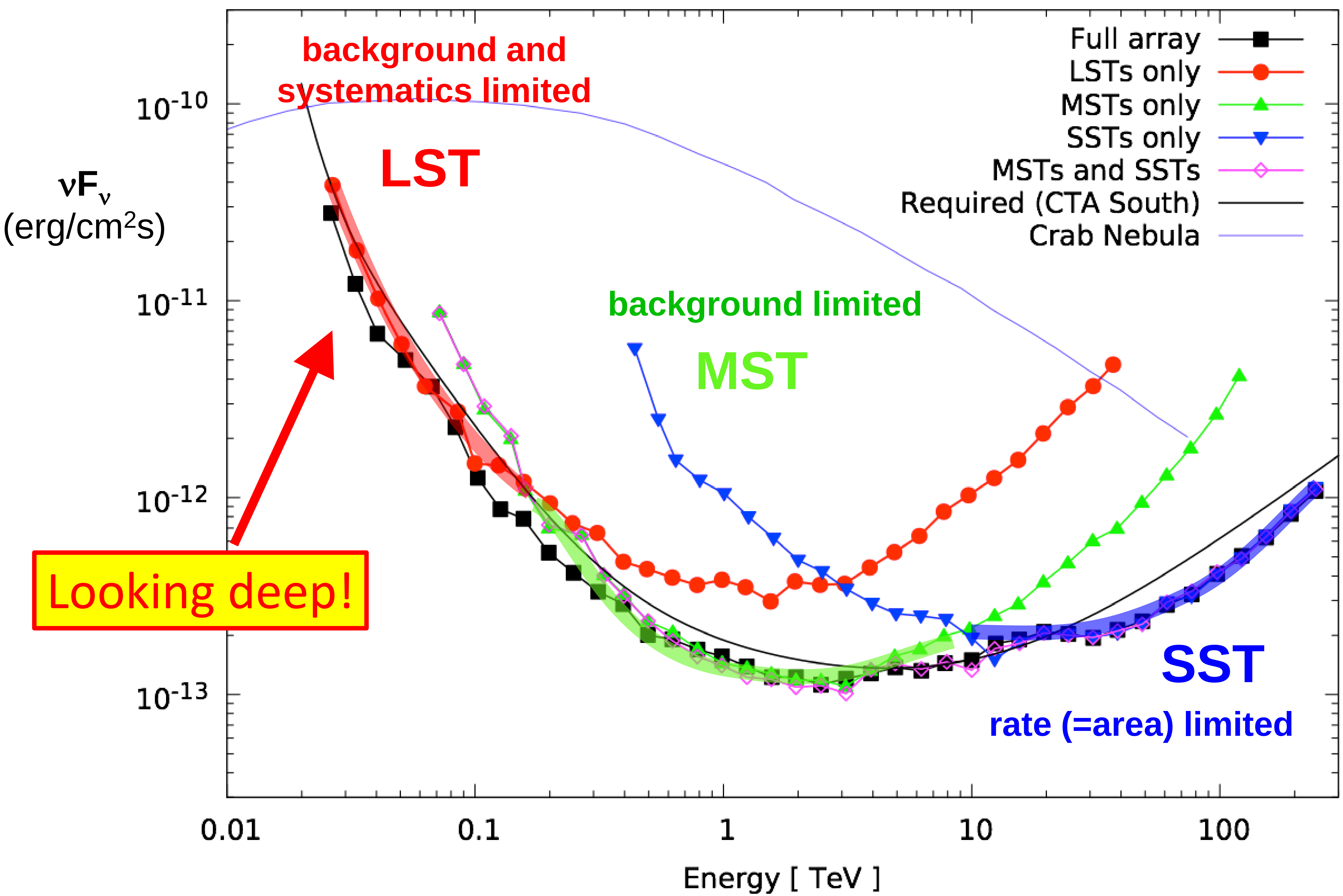
- Physics beyond the Standard Model
  - Indirect Dark Matter Search
  - Test of Lorenz Invariance
  - …
- Cosmology
  - Measurement of EBL
  - VHE Standard Candles → dark energy ?

What‘s next?



- **Current instruments have passed the critical sensitivity threshold and reveal a rich panorama, but this is clearly only the tip of the iceberg**

Sensitivity: factor 10 @ 1-10 TeV, extension to LE & HE



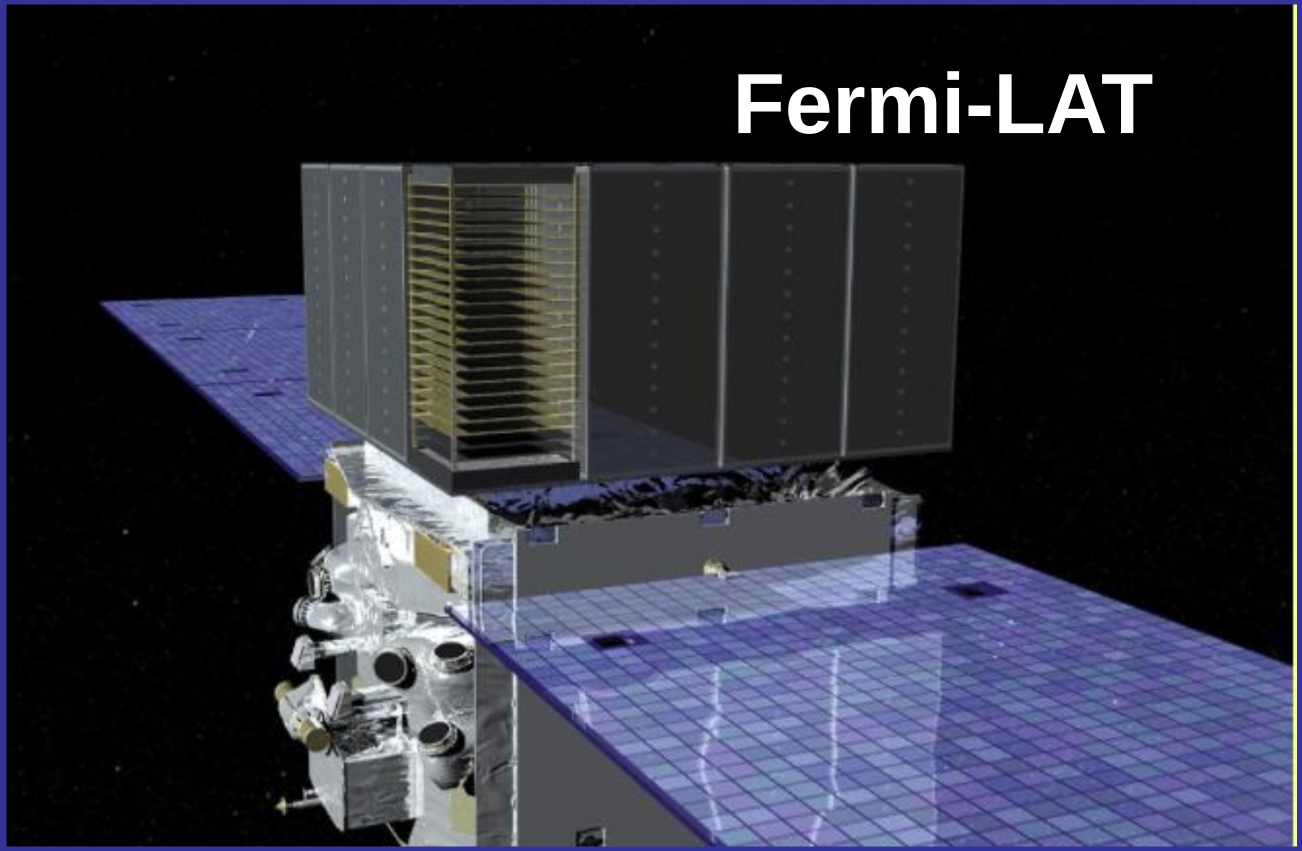
cta
cherenkov telescope array

ESFRI

- Huge improvement in all aspects
  - Factor ~10 in sensitivity,
  - Much wider energy coverage,
  - Much better resolution & field-of-view, full sky, …
- User facility / proposal-driven observatory
- €250-350M investment
  - Including everyone from H.E.S.S., MAGIC and VERITAS

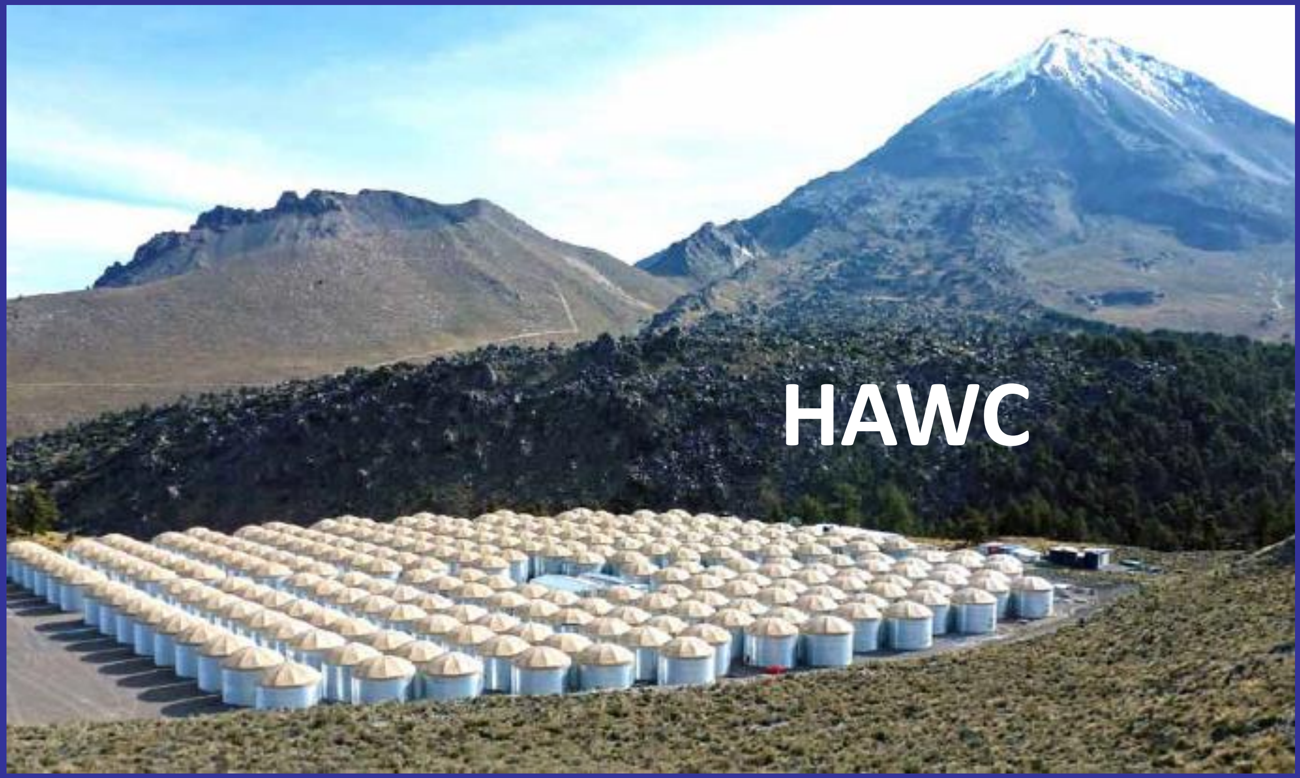
This is the future of ground based gamma-ray astronomy with Air Cherenkov Telescopes

Fermi and HAWC:



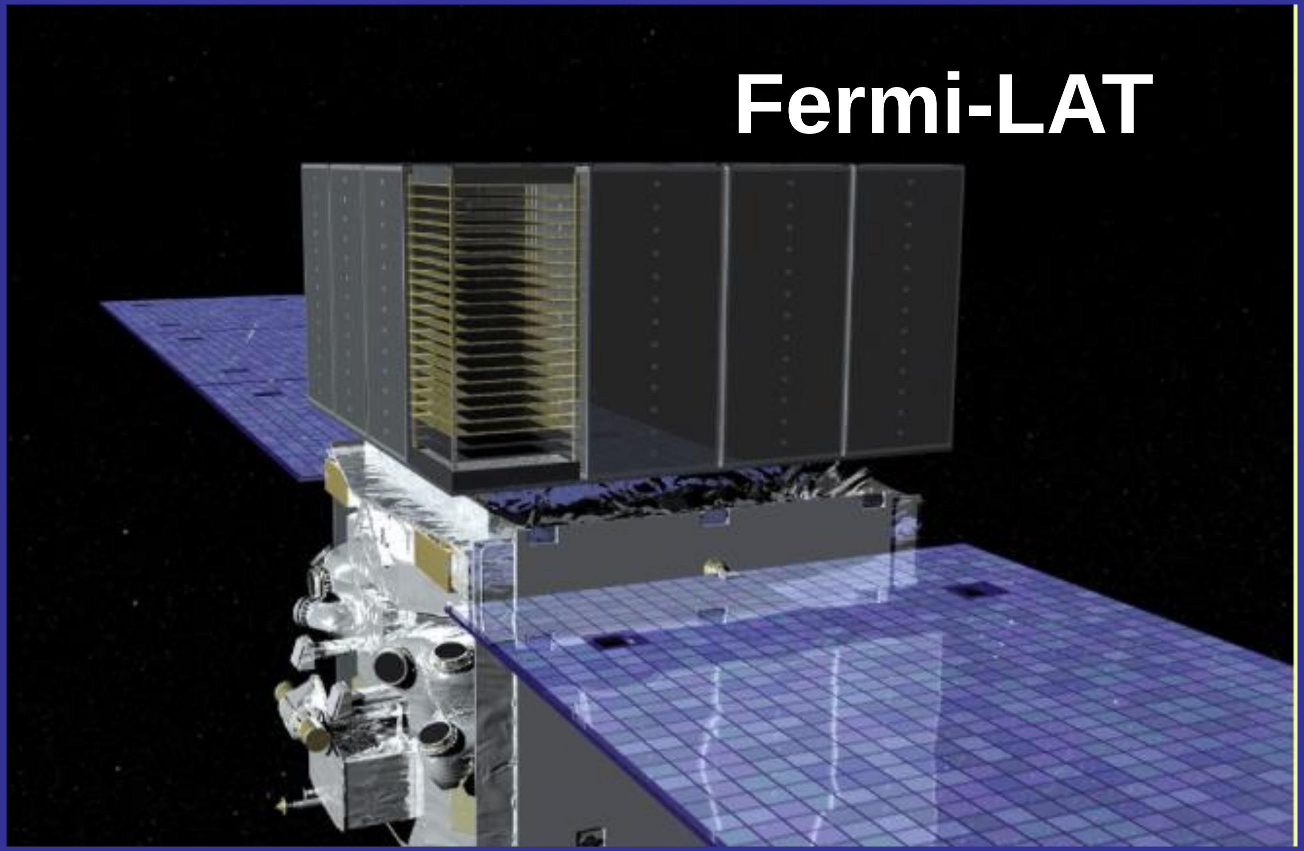
Wide angle detectors

- Best sensitivity at GeV
- **Follow-up satellite?**



- Best sensitivity around 10 TeV
- 250 water tanks, 22 000 m²
- will be upgraded with distant water tanks and a few small IACTs
- Also: HAWC South?

Fermi and HAWC:



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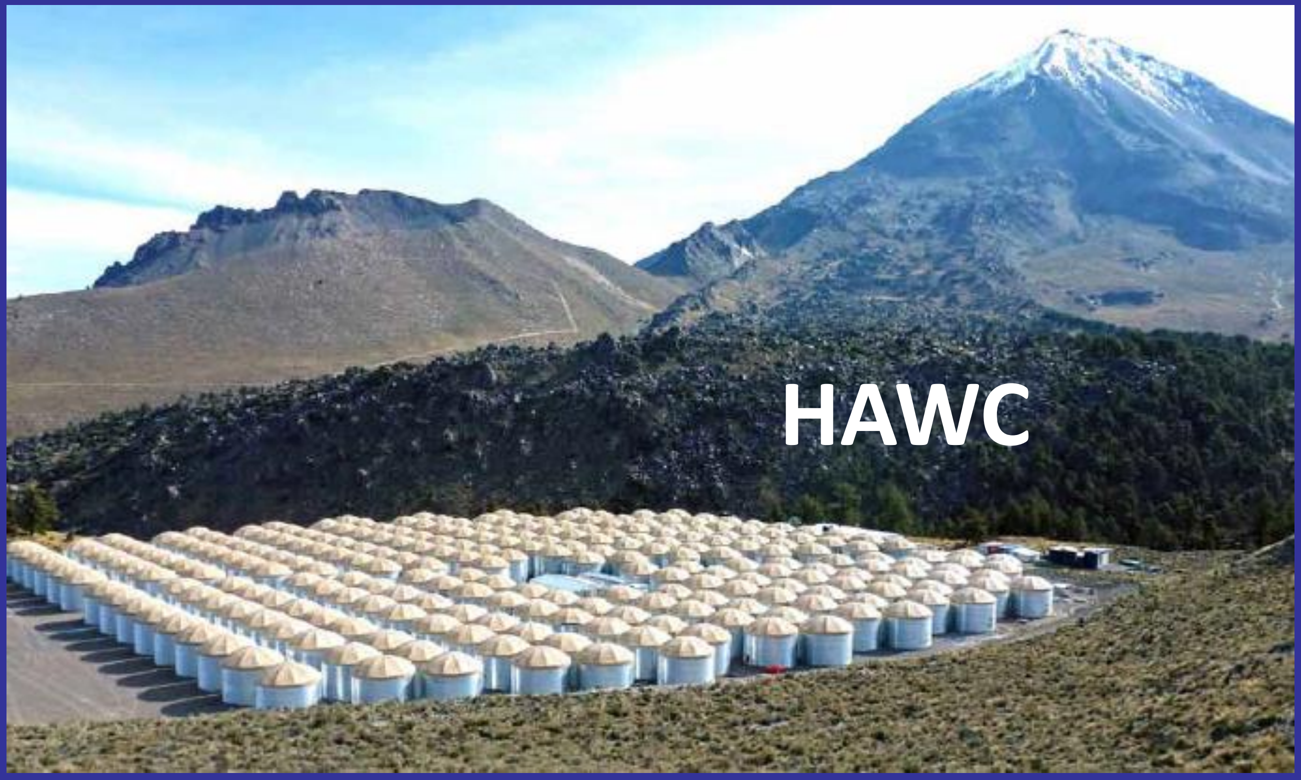
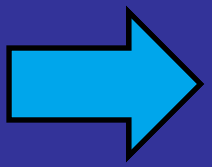
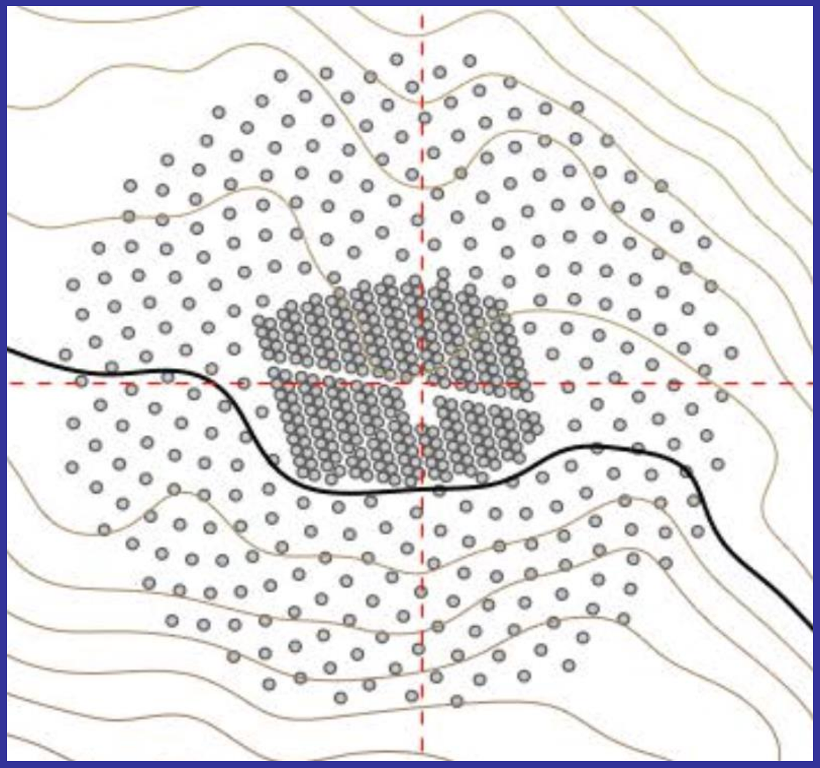
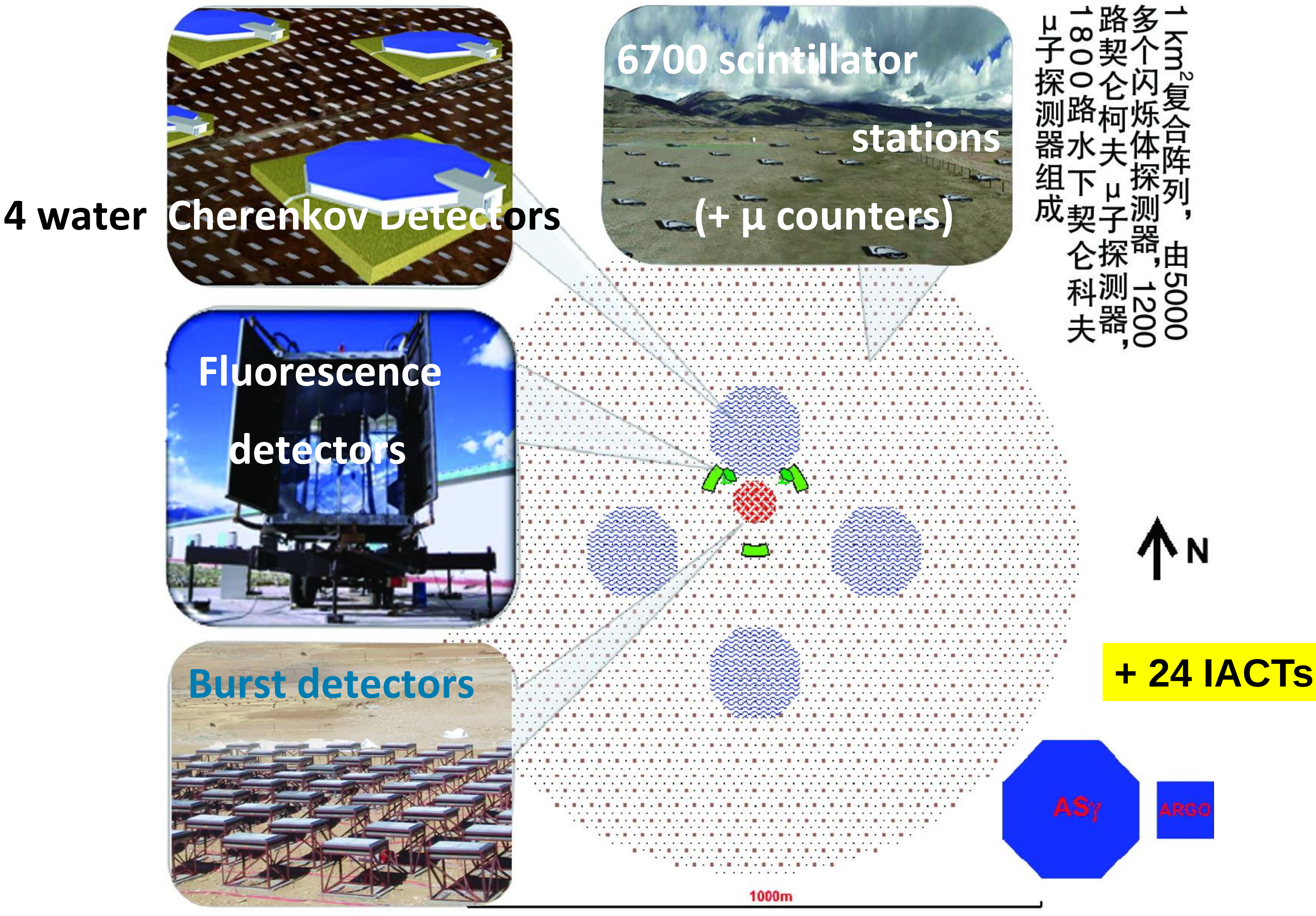






LHHASO in Tibet



TAIGA in Siberia

Combination of

wide angle timing array

few small Imaging Telescopes

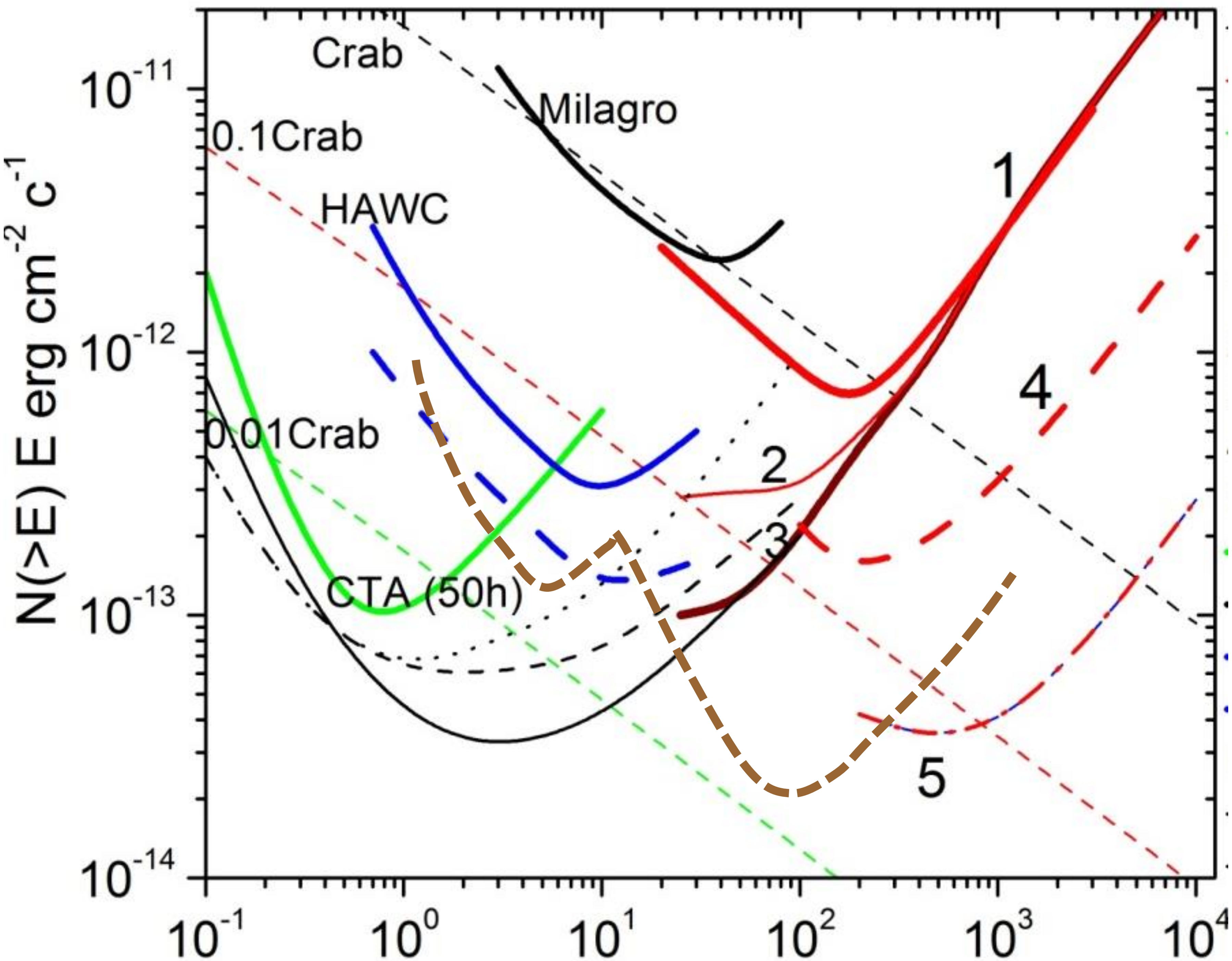
Timing array:

good γ/hadron aqt high energies, <u>cheap</u>

Imaging telescopes:

help γ/hadron separation at lower energies

LHHASO and TAIGA: find galactic Pevatrons !



TAIGA

1 – 1 km² basic design

will be completed in 2016

2 – 1 km², larger PMTs

3 – 1 km² + IACTs

4 – 10 km²

5 – 100 km²

LHAASO: Brown dashed

Approved, to be built until 2021

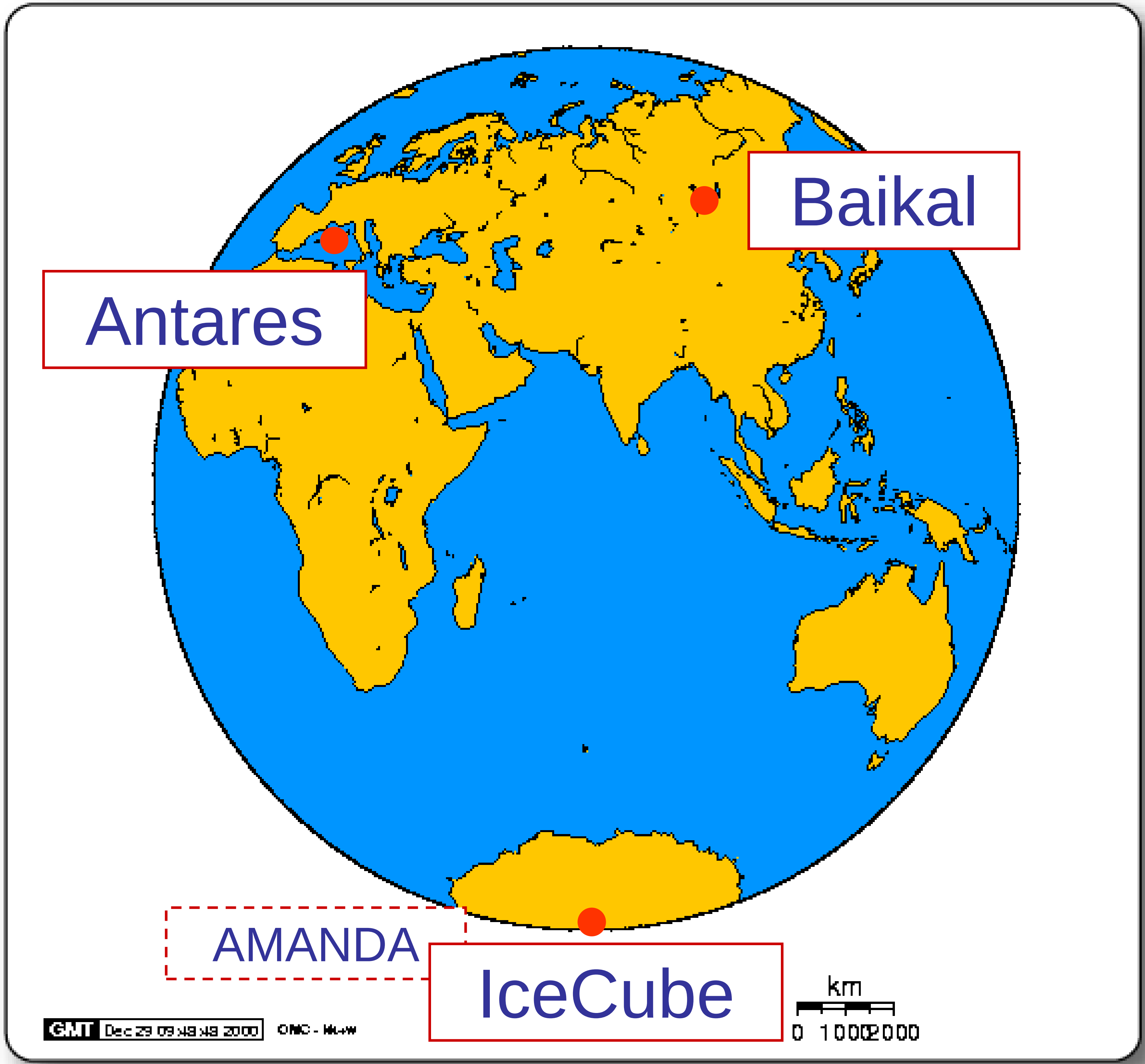
Summary on Gamma Rays

- CTA is the flagship project of gamma-ray astronomy and will likely open a new era
- MACE, small IACTs for multi-messenger programs (like FACT)?
- CTA will be flanked by wide-angle arrays like HAWC (TeV range) and LHAASO, TAIGA (reaching into PeV range)
- Fermi mission prolongated
- Follow-up of Fermi satellite is still open

HE NEUTRINO ASTRONOMY

WINDOW OPENED, LANDSCAPE UNCHARTED

The devices

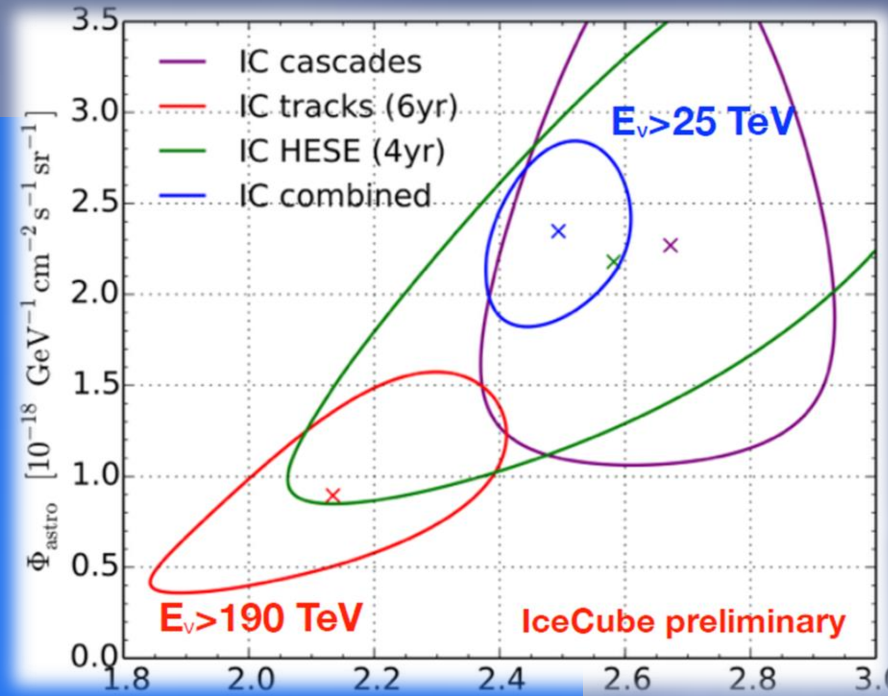


Cosmic neutrinos discovered

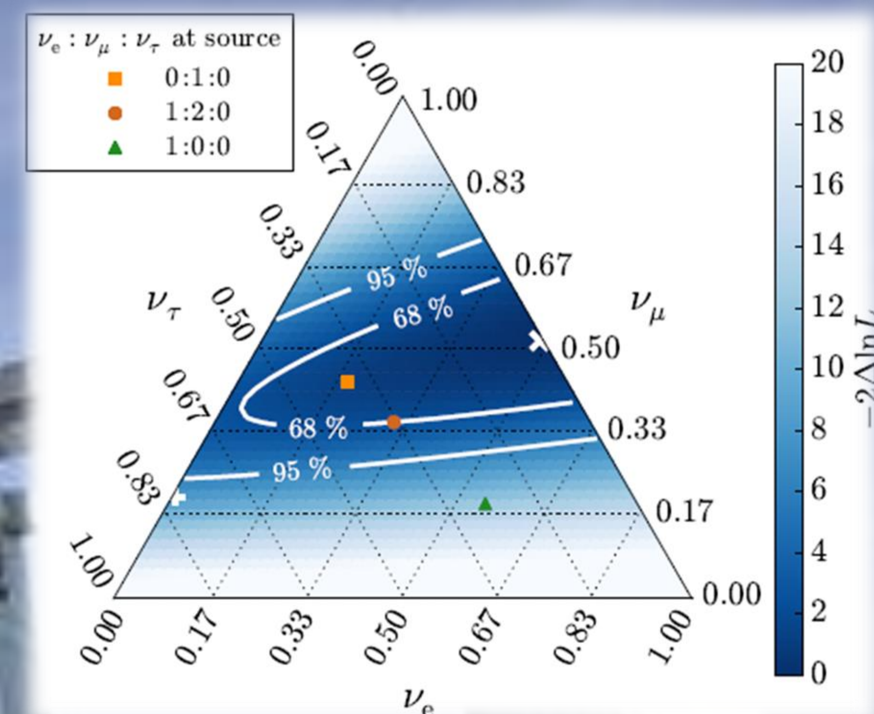
new window opened,
landscape still uncharted
(no point sources yet!)

Still Open:

- Exact Spectrum



- Flavor content (n-decay disfavored)

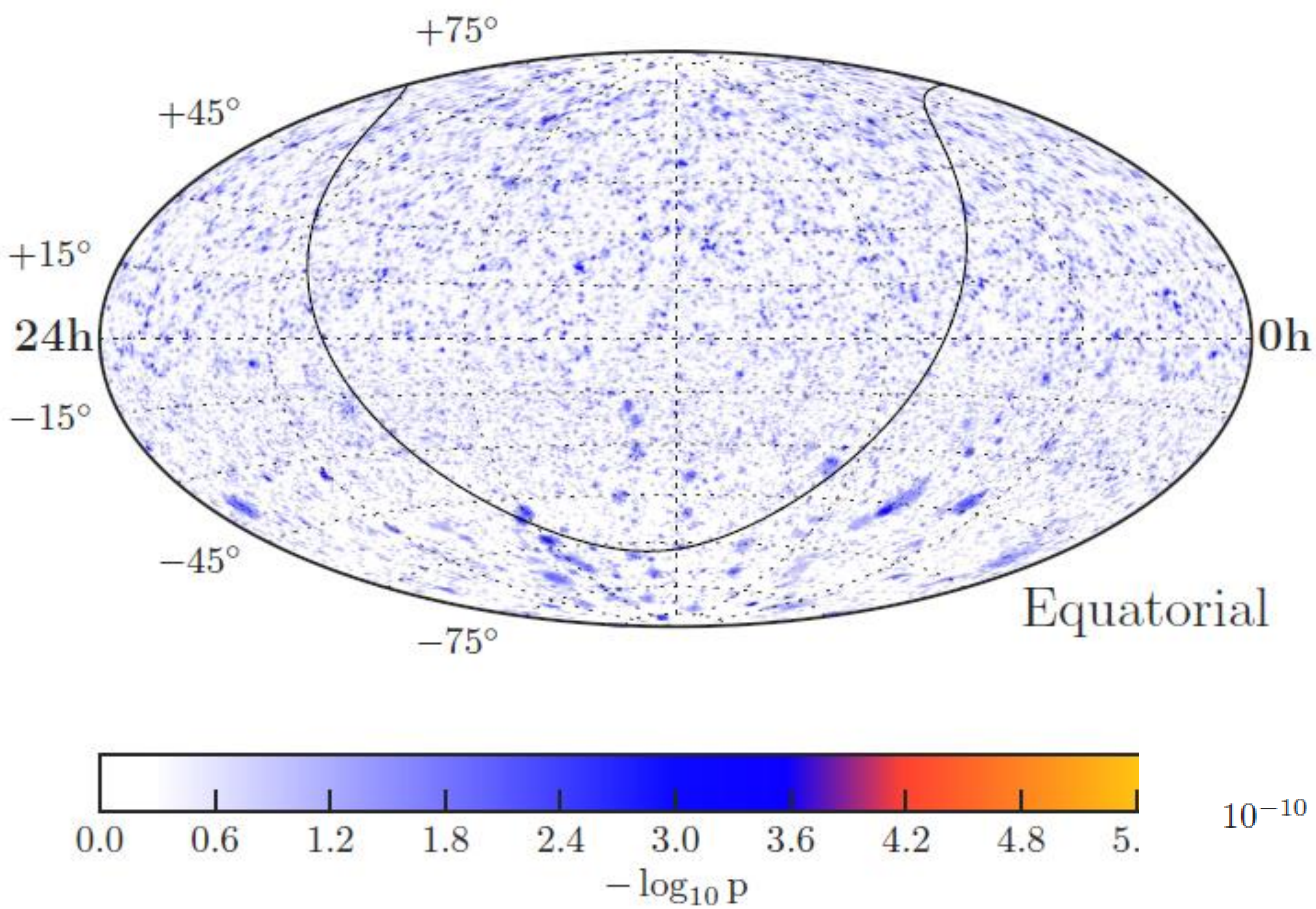


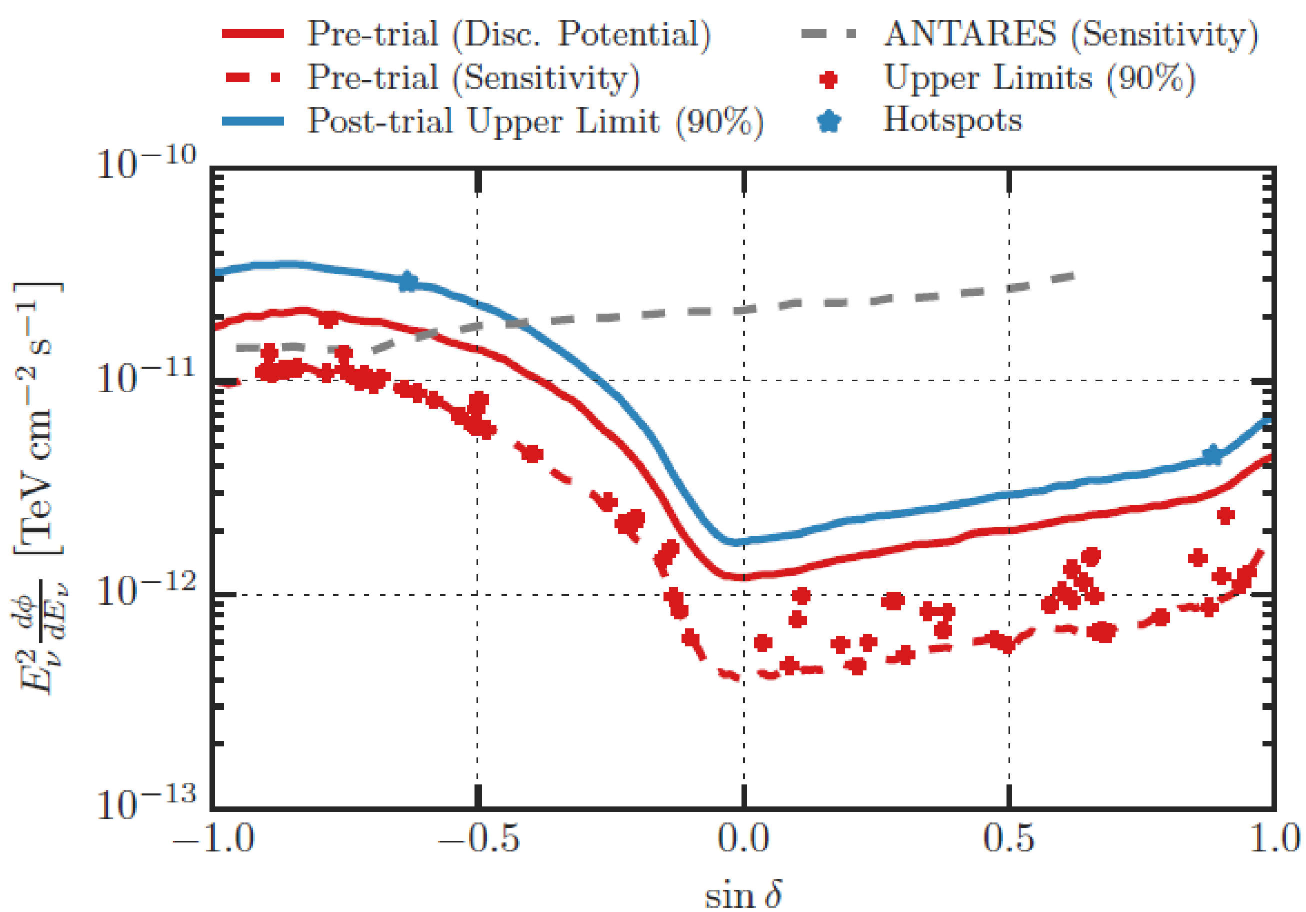
- Extragalactic? Galactic?

Individual sources?
Diffuse from CR interactions?

ALL-SKY SEARCH FOR TIME-INTEGRATED NEUTRINO EMISSION FROM ASTROPHYSICAL SOURCES WITH 7 YEARS OF ICECUBE DATA

- **arXiv:1609.04981**





- Chance to see steady point sources with IceCube becomes smaller and smaller, although certain sources/source classes seem to be in reach

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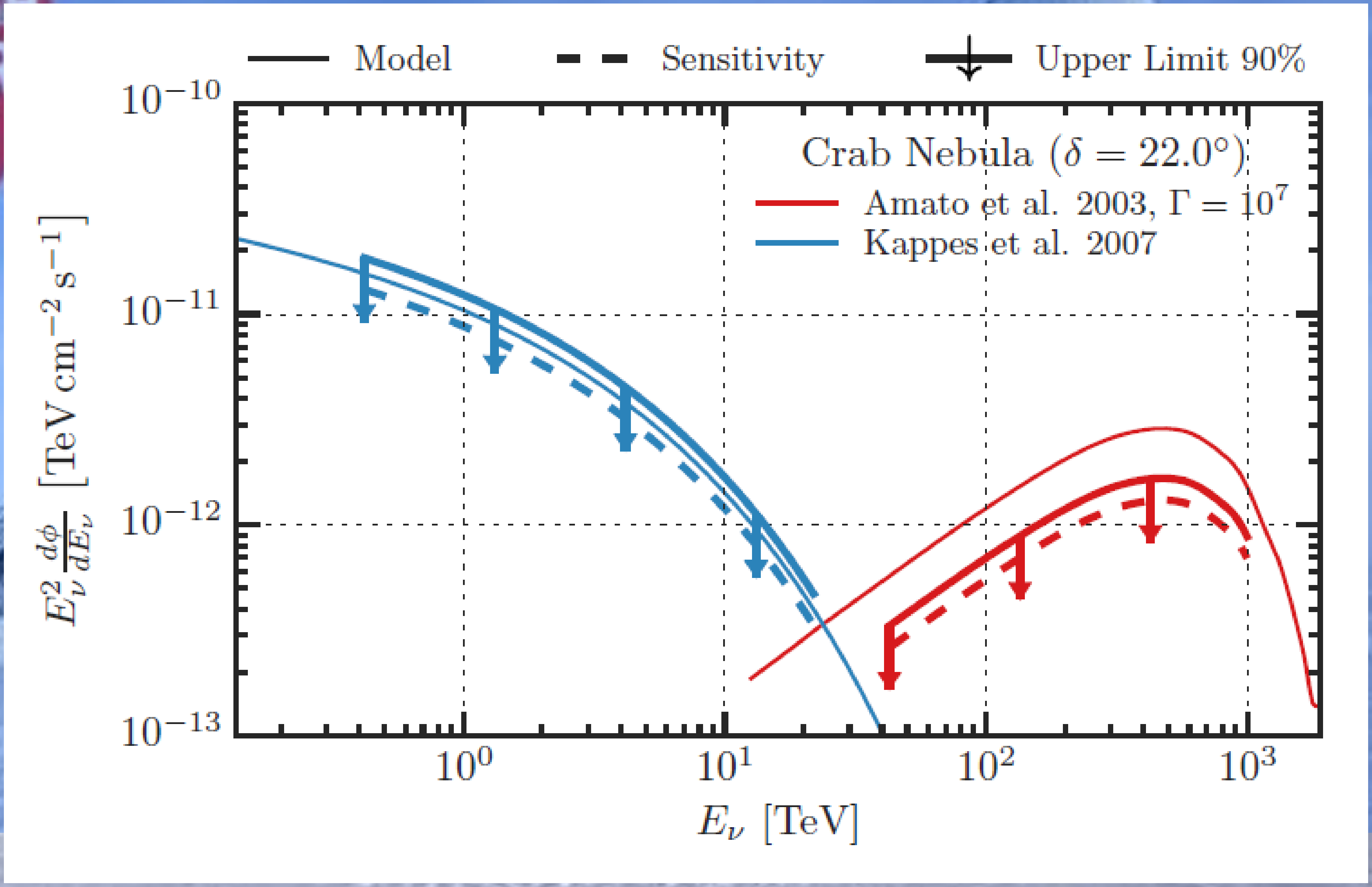

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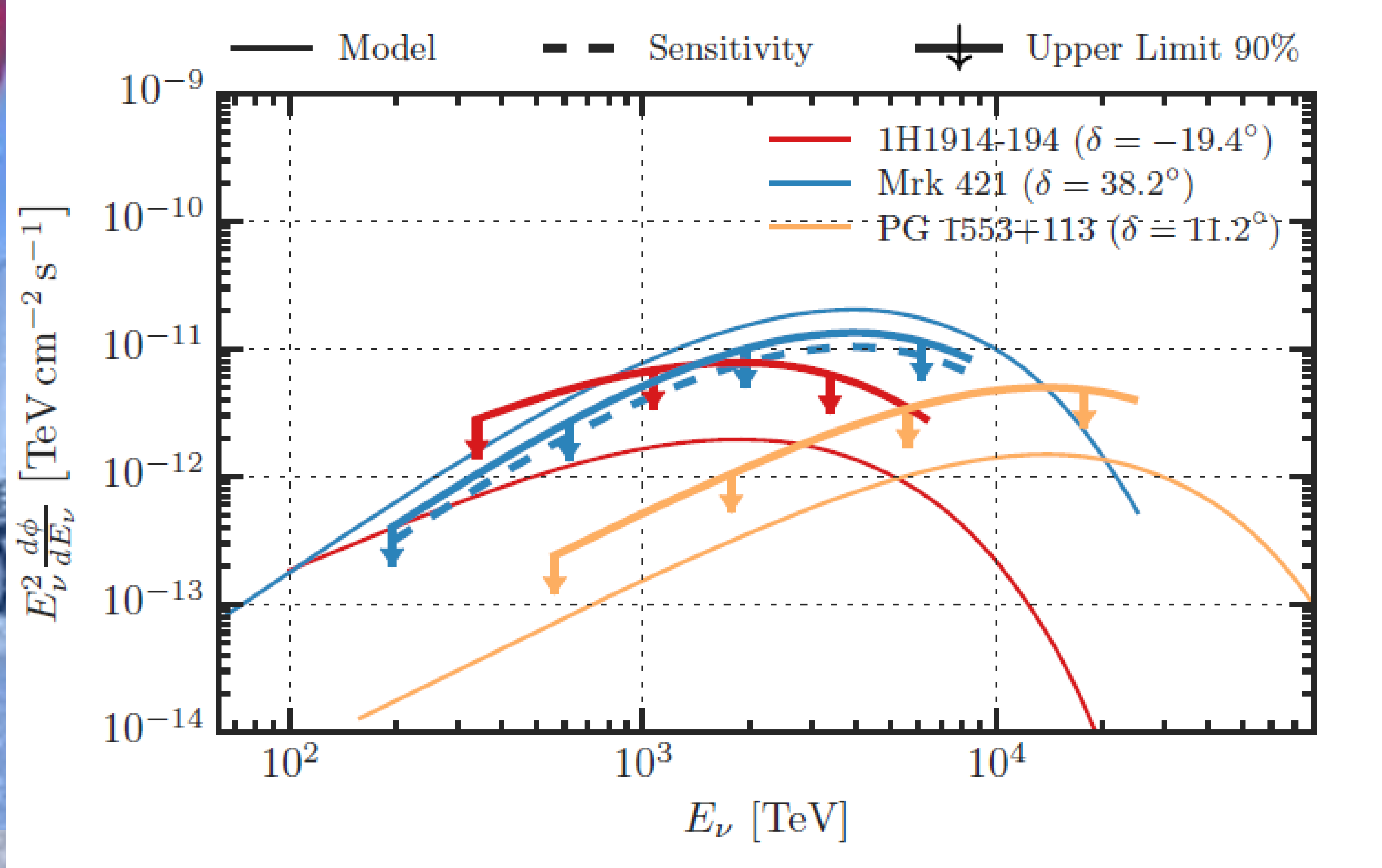


- **Chance to see steady point sources with IceCube becomes smaller and smaller, although certain sources/source classes seem to be in reach**

d

- **Focus on transient sources!**
- **Importance of multi-messenger alert programs!**

Multi-Messenger aspects

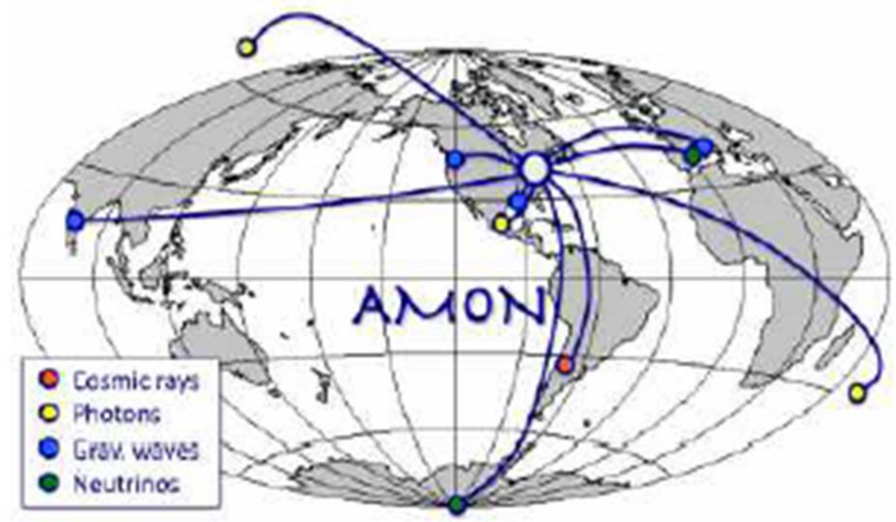
- **Rationale:**
  - Higher significance by combining several low-signficance signals
  - Getting a full picture of the source by combining information from different messengers
- Follow-up alerts: wide-angle devices trigger devices with small FoV/ higher sensitivity and/or other messengers
- Off-line, e.g. Gravitational Wave of Neutrino detectors search for correlations with signals reported from satellite or Earth-bound gamma/optical transients
- **It is highly probable that the greatest discoveries (and in any case the FULL picture) will come from multi-messenger programs.**

IceCube real-time program (Antares similar)

Individual MOU observatories:

- Swift XRT
- Palomar Transient Factory
- Magic Gamma Ray Telescope
- VERITAS
- HAWC
- HESS
- LIGO/VIRGO
- Murchison Widefield Array

Networks & public alerts:



The Astrophysical Multimessenger Oberservatory Network:
FACT, VERITAS, MASTER,
LMT, ASAS-SN, LCOGT

„The Astronomer's Telegram“

The Gamma-ray Coordinates Network

To resolve open questions, we need asap:

- More data with IceCube,
  refined analysis methods

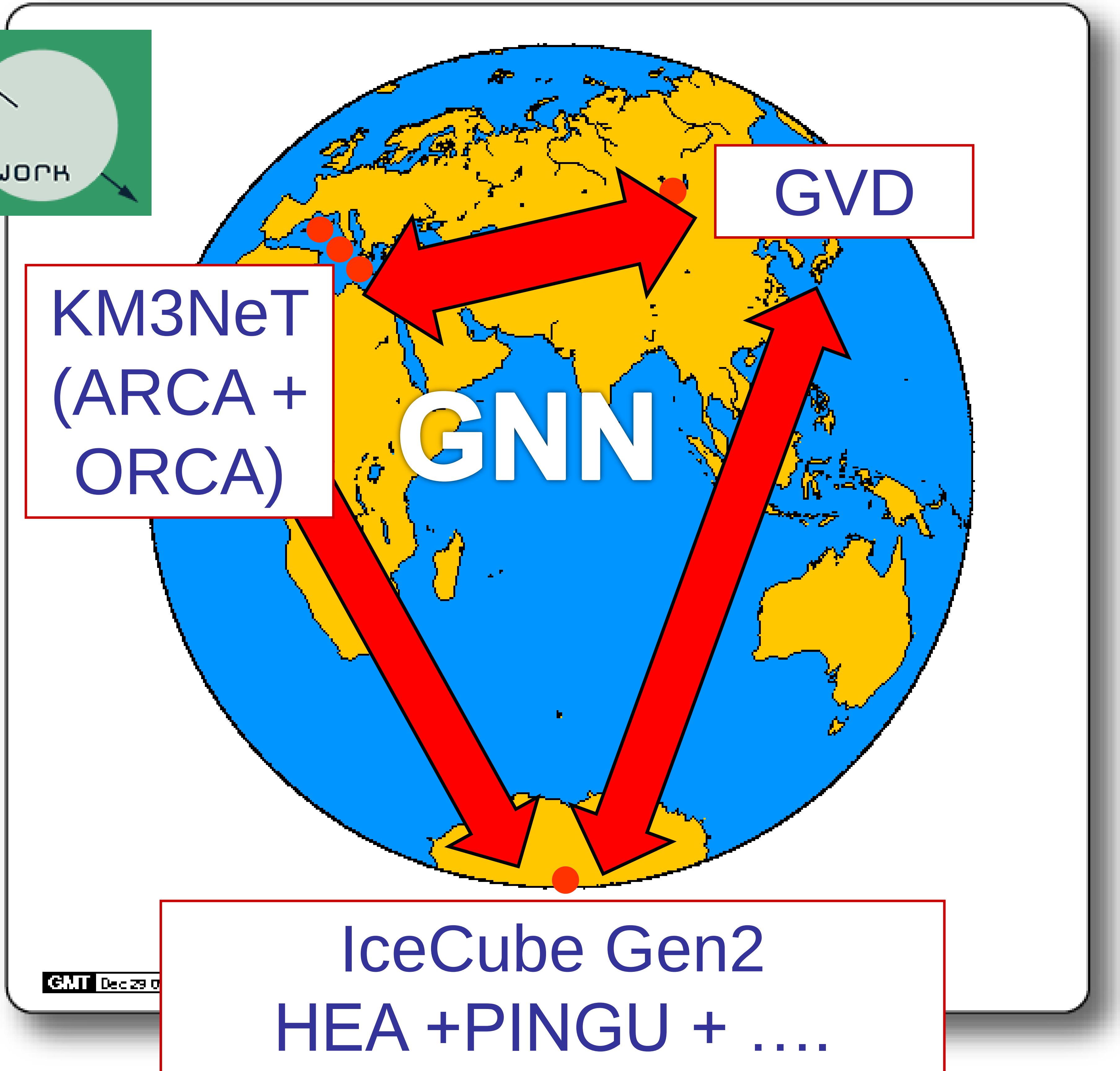
- Detectors with different systematics
- Detectors with better pointing
- Detectors on the Northern hemisphere with better TeV view to central parts of the Galaxy

} under construction !

The future of high-energy neutrino astronomy

Baikal, Mediterranean Sea, South Pole

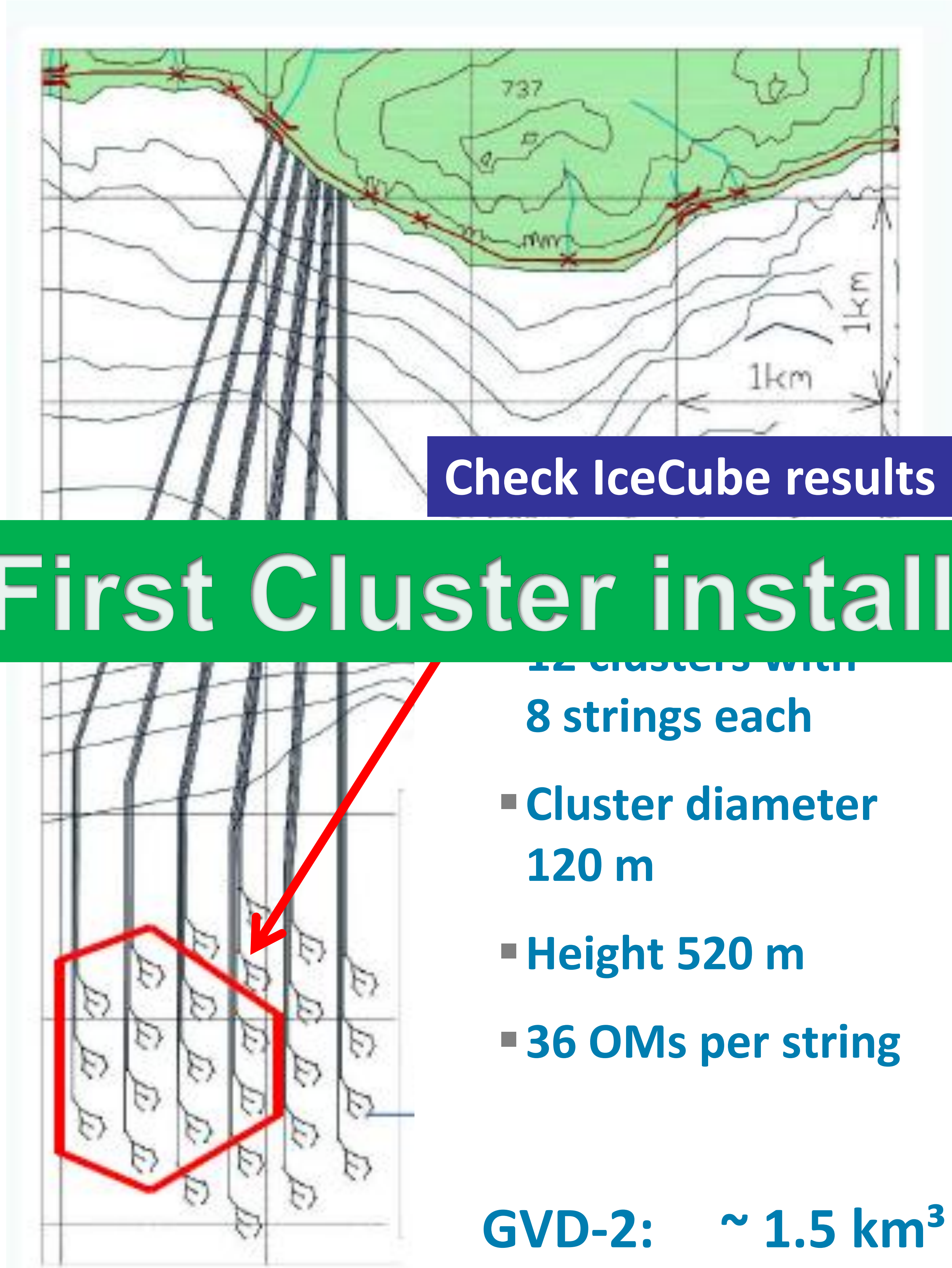
GNN
The Global Neutrino Network



GIGATON VOLUME DETECTOR

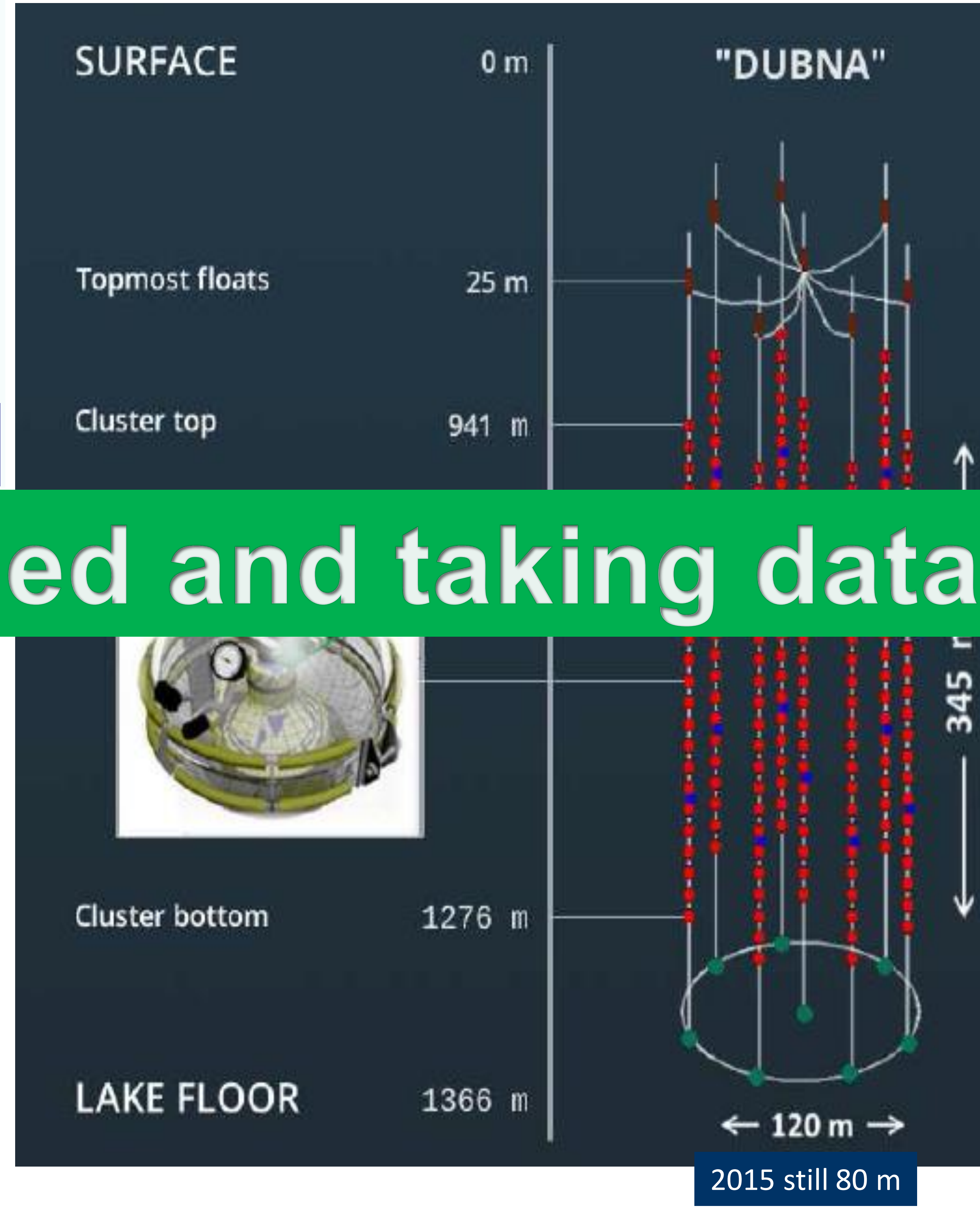
BAIKAL GVD

GVD: Phase 1 (2020) and Phase 2 (~2025)



- 12 clusters with 8 strings each
- Cluster diameter 120 m
- Height 520 m
- 36 OMs per string

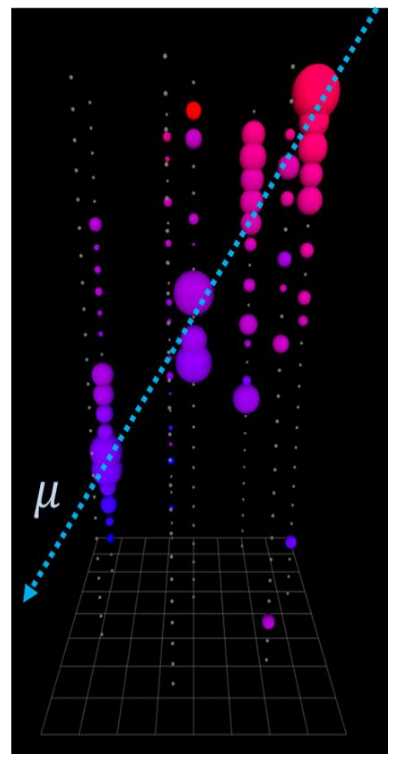
GVD-2: ~ 1.5 km^3

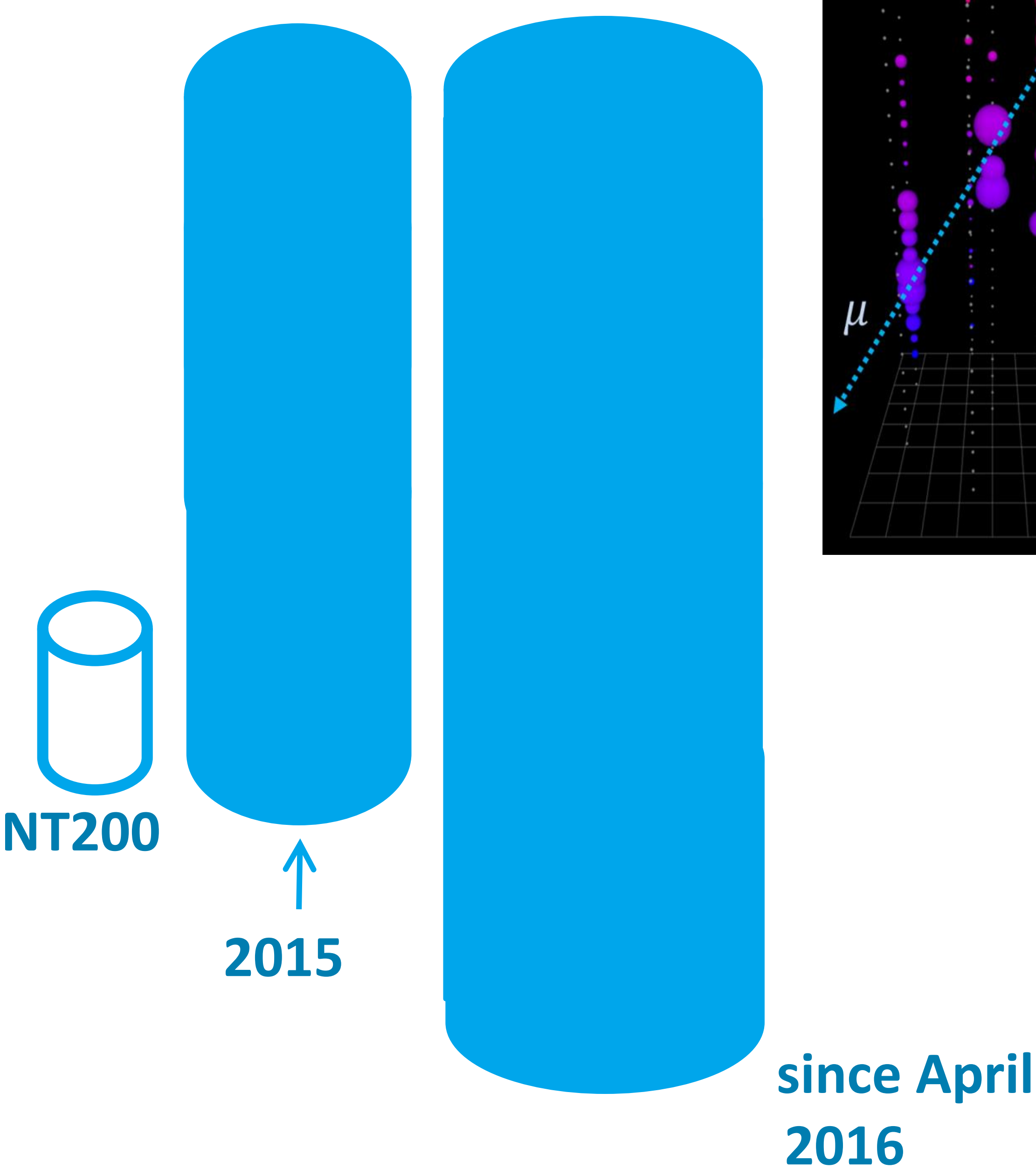


First Cluster installed and taking data

GVD: from NT200 to GVD clusters

- DUBNA cluster with 80 m diameter working since April 2015, now 120 m
- A down-going muon in the DUBNA cluster →



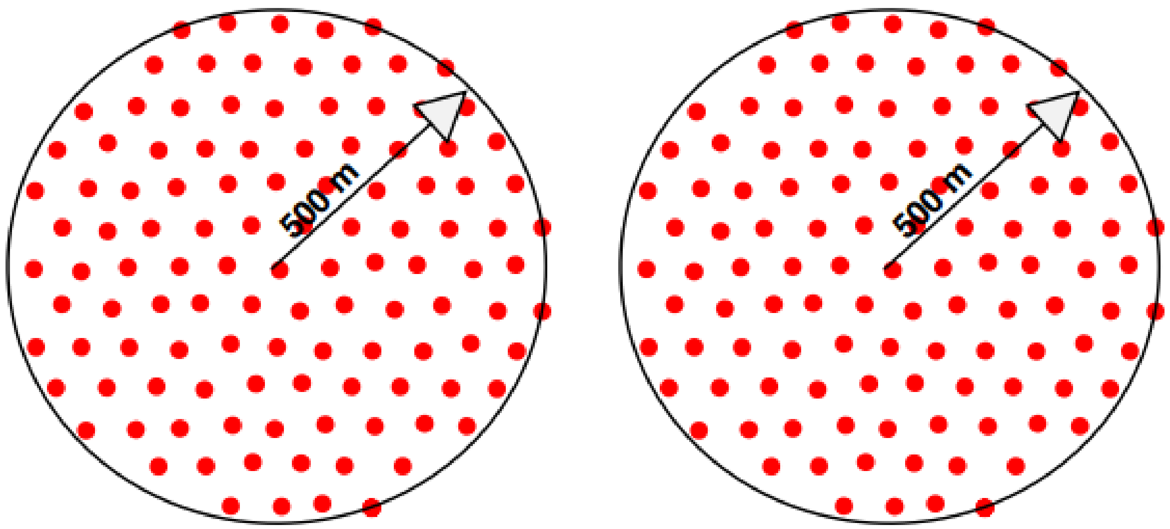


KM3NET

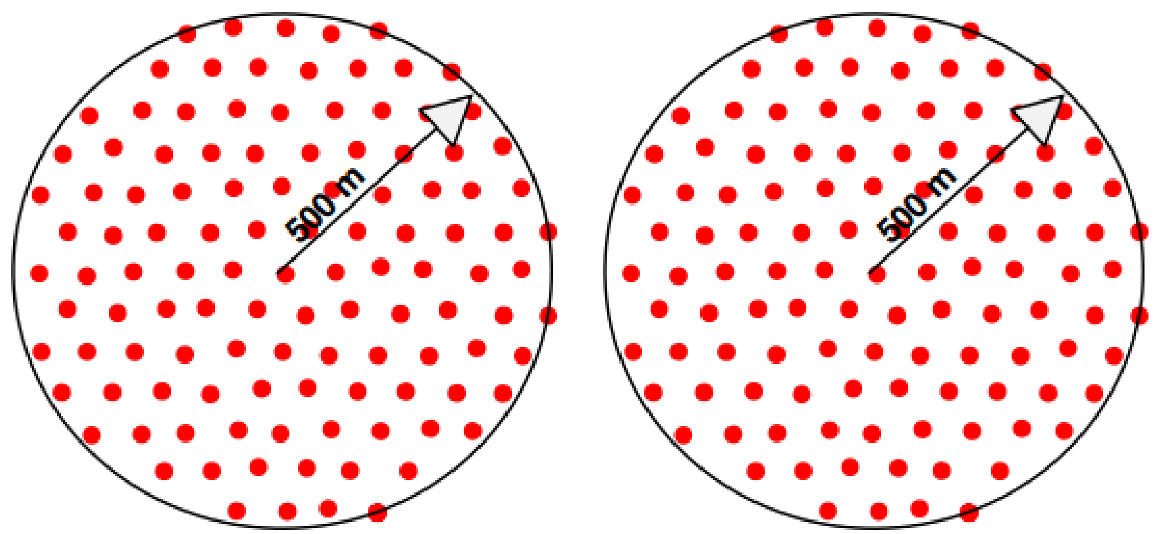
ESFRI

Original idea: 6 blocks at 3 locations: 6 x 0.6 km³

115 strings per block
18 DOMs per string
31 PMTs per DOM



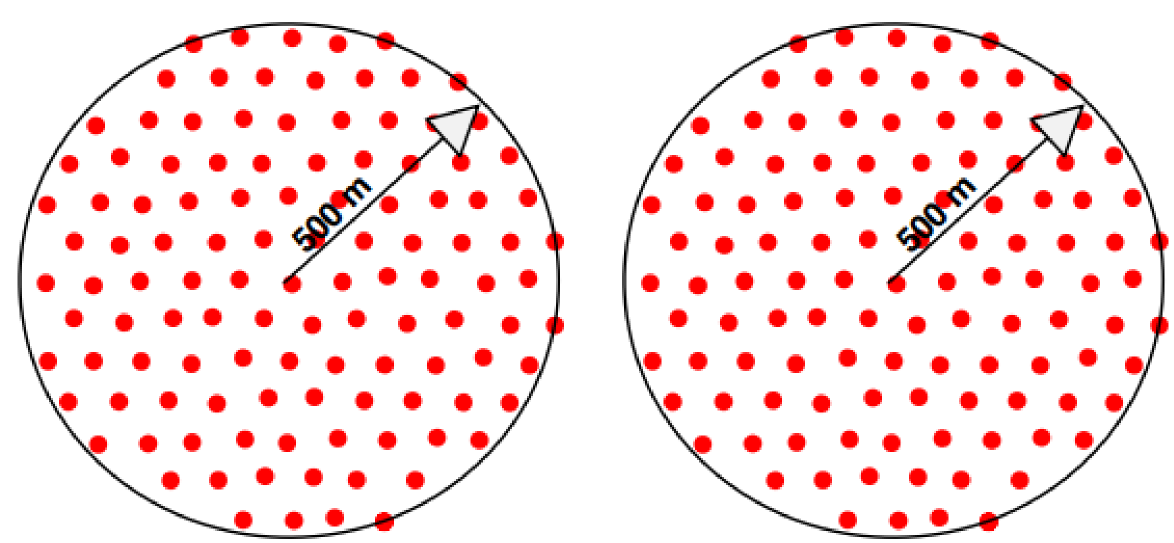
France



Italy

6 blocks are still part of „KM3NeT Phase 3“, which, however, cannot be associated yet to definite time line.

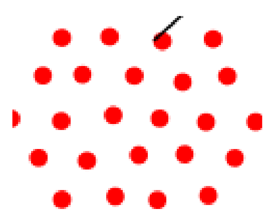
Greece



Phase 1 (2017):

France

7 strings, small spacing
- Feasibility test for ORCA

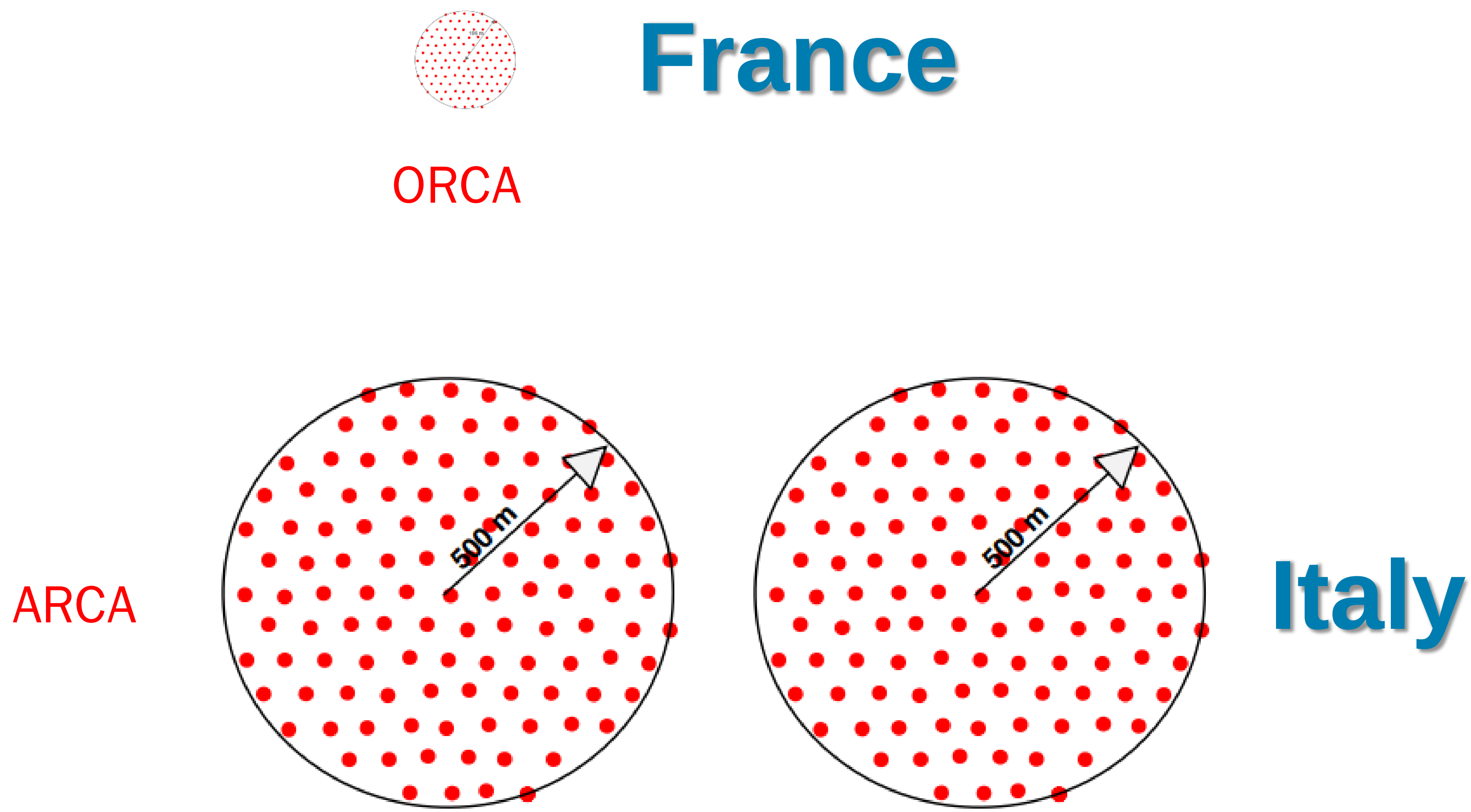


Italy

24 strings, 124 m spacing
- Demonstrate principle
- Physics on the 3-4 times Antares scale

Note: there will be, in addition, an array of 8 “NEMO towers” which run parallel but can be combined offline with data from common events in the 24 KM3NeT-strings.

Phase 2.0: ORCA and ARCA (2020?)

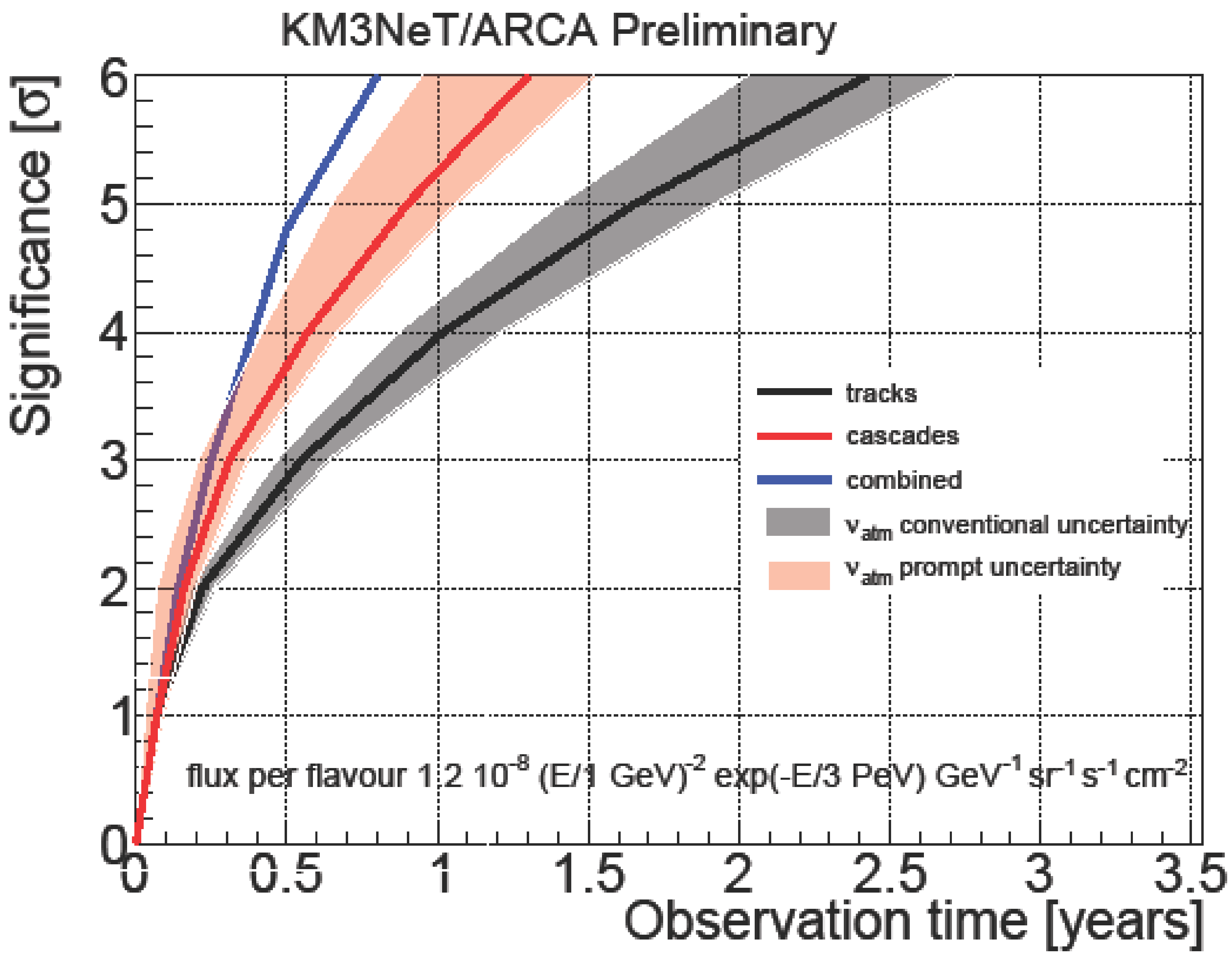


ORCA: determination of the Neutrino Mass Hierarchy (NMH)

ARCA: IceCube physics, but with better angular resolution and from the Northern hemisphere

KM3NeT 2.0: diffuse fluxes

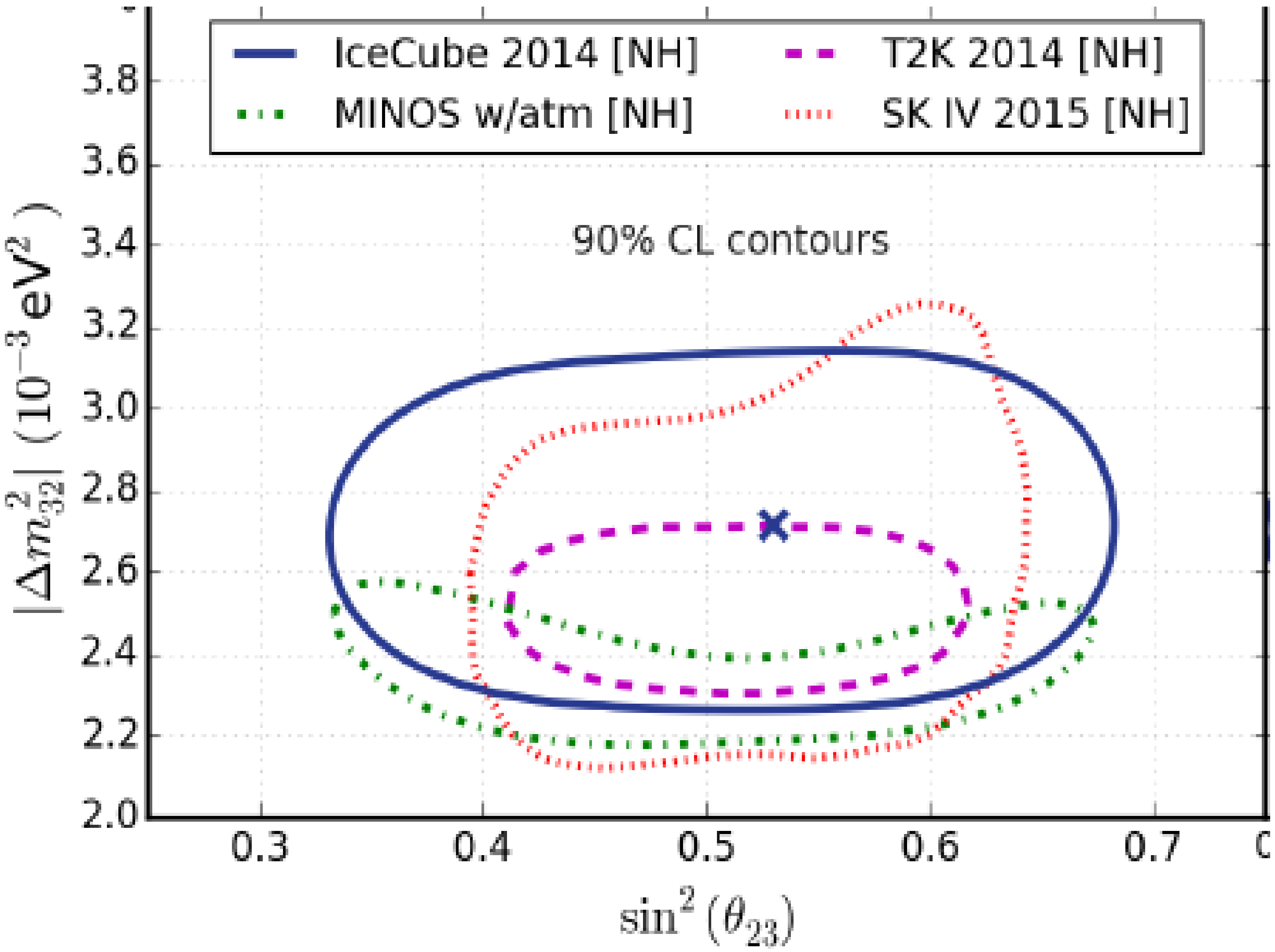
Sensitivity to IceCube HESE signal

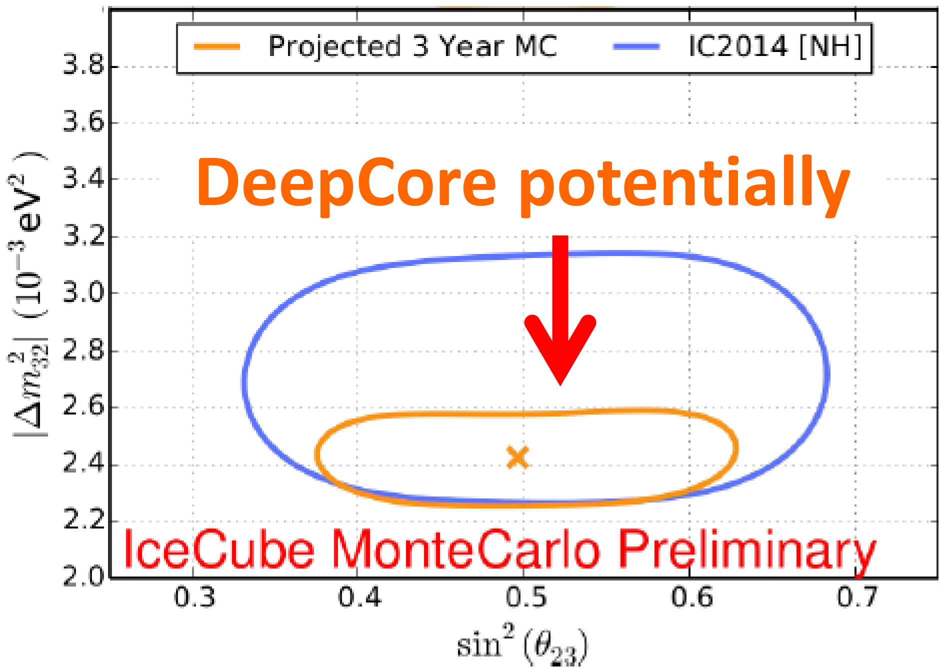


... plus first galactic sources ?

ORCA/PINGU: oscillation physics

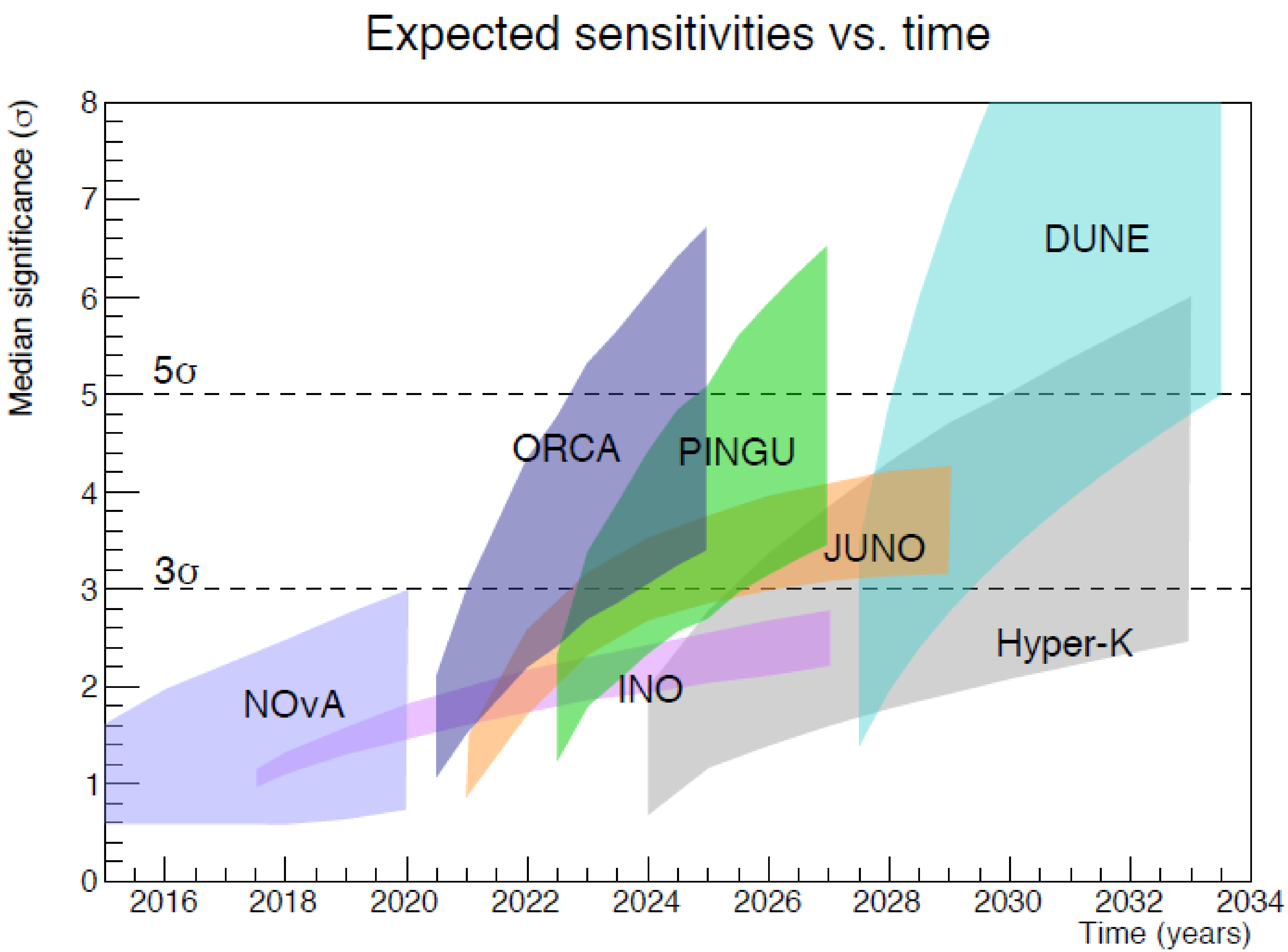
- **Deep Core has proven that neutrino telescopes in natural media can do precision neutrino physics. Threshold ~10 GeV.**





- **PINGU/ORCA:**
  precision oscillation physics. Matter effects. Need threshold ~ 3 GeV

Neutrino mass hierarchy



Time schedules have to be taken with a grain of salt!

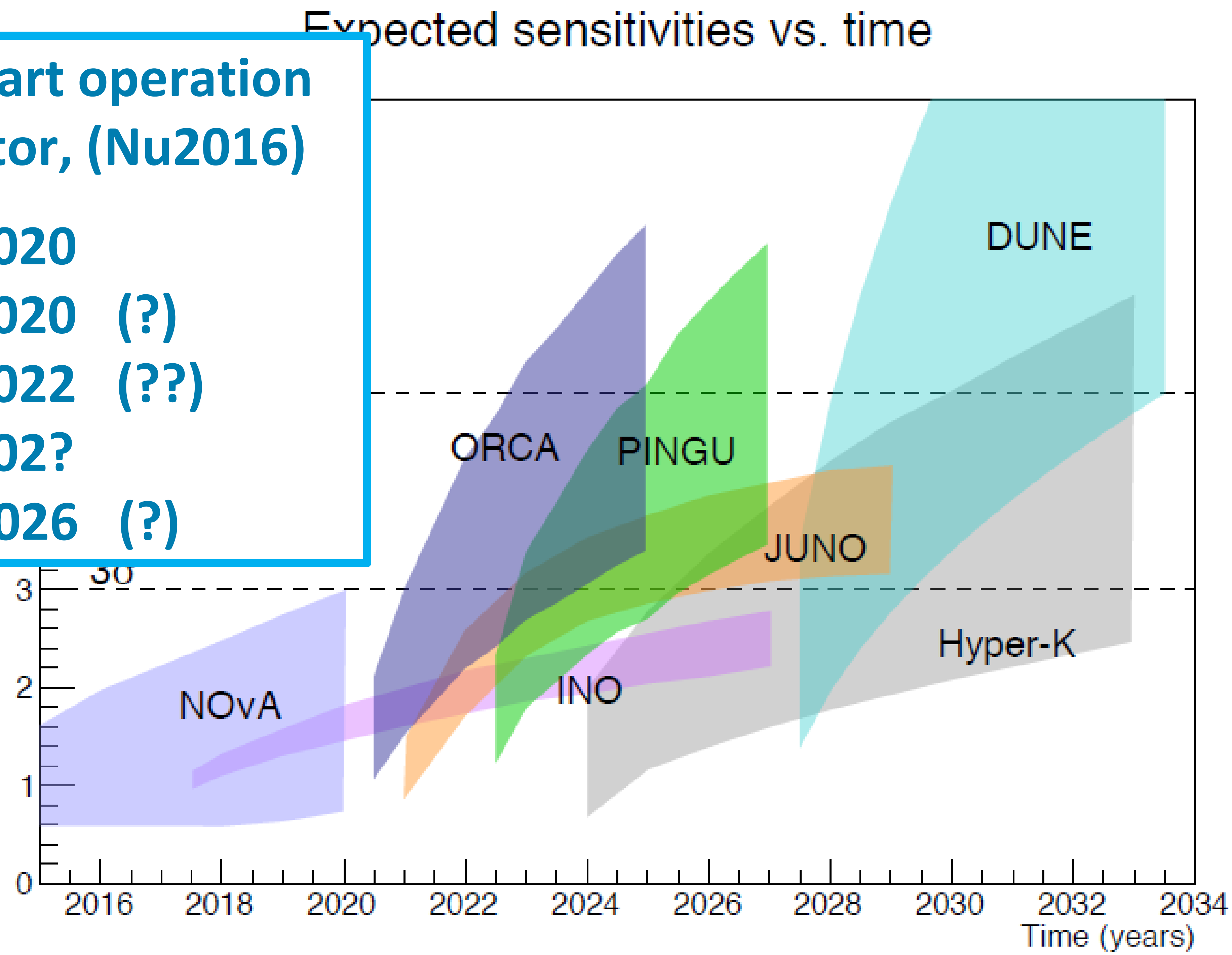
NMH sensitivity of ORCA/PINGU depends on the octant of θ_{23} (lower values for 1st octant), that of JUNO on energy resolution (lower values for 3.5%, upper for 3%), that for DUNE on the δ_{CP} value.

Compilation by p.Coyle, based on the original one of Blennow et al.

Neutrino mass hierarchy

Envisaged start operation of full detector, (Nu2016)

JUNO: 2020
ORCA: 2020 (?)
PINGU: 2022 (??)
INO: 202?
Hyper-K: 2026 (?)



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Compilation by p.Coyle, based on the original one of Blennow et al.

„Dedicated NMH experiments“

- **When JUNO, ORCA, PINGU, INO, … come into operation, the question of NMH will largely be solved**
  (much more data from NOvA, better understanding of systematics and more statistics from all experiments)
- **W.r.t. NMH, all these new experiments then may have just a „confirmation character“**
- **New focus much broader:**
  - **precision measurement of oscillation parameters**
    - **test unitarity of PSNM matrix**
    - **hints for a fourth neutrino?**
  - **Non-standard interactions?**
  - **Supernova detection,**
  - **Solar- and geo-neutrinos, proton decay, …**

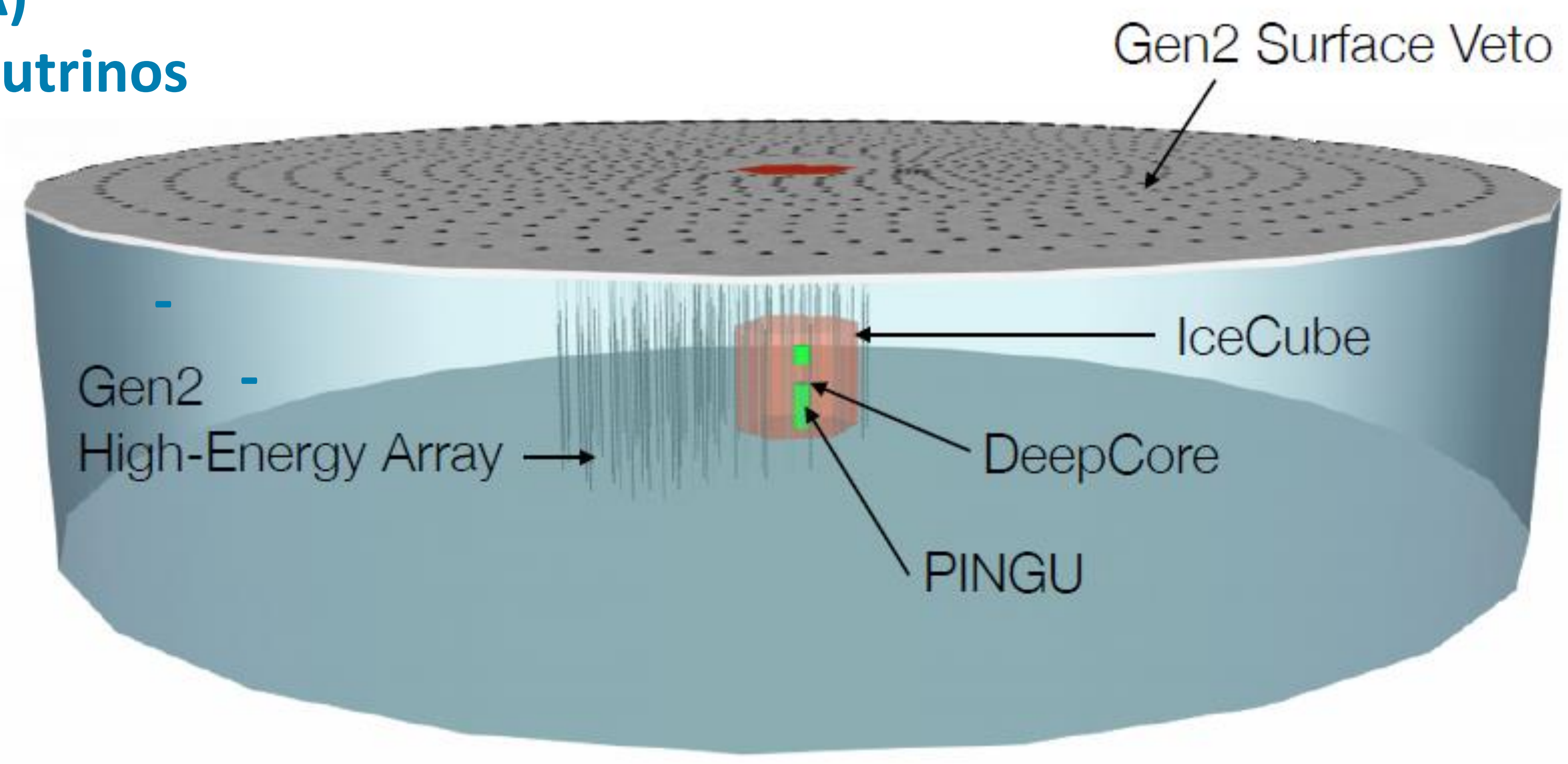
Example: PINGU and ORCA physics

- Precision measurement of θ_{23} and Δm_{32}^2 (including octant of θ_{23}) over a larger energy range than accel. experiments
- Determine (confirm) NMH with 3σ (median) after 3-4 years
- Test unitarity of PNMS matrix using appearance of ν_τ
- Search for sterile neutrinos, non-standard interactions
- Earth tomography
- Annihilation of low-mass DM in the Sun
- Detection of MeV neutrinos from SN bursts (PINGU)

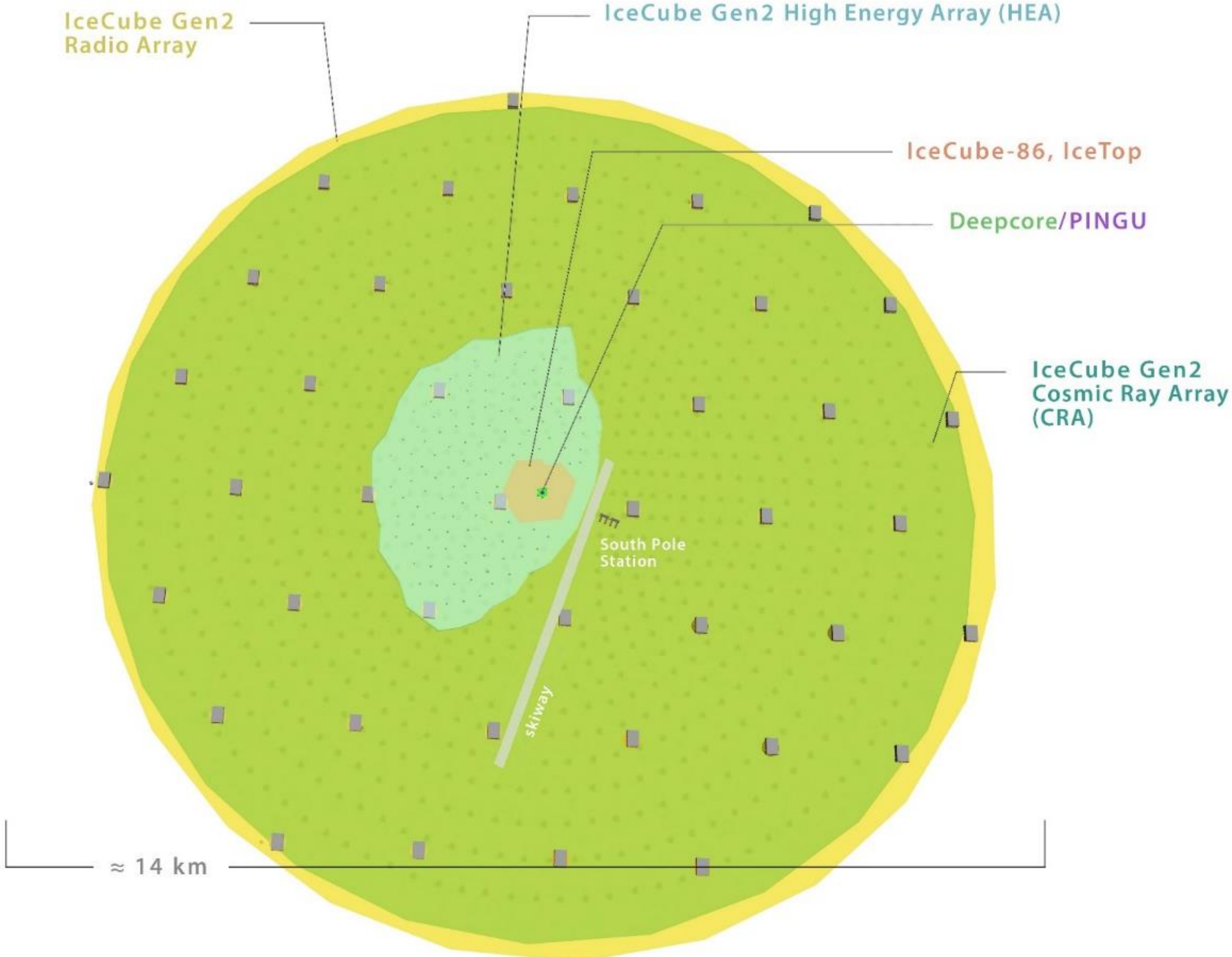
IceCube GEN2

The IceCube Gen2 facility: conceptual drawing

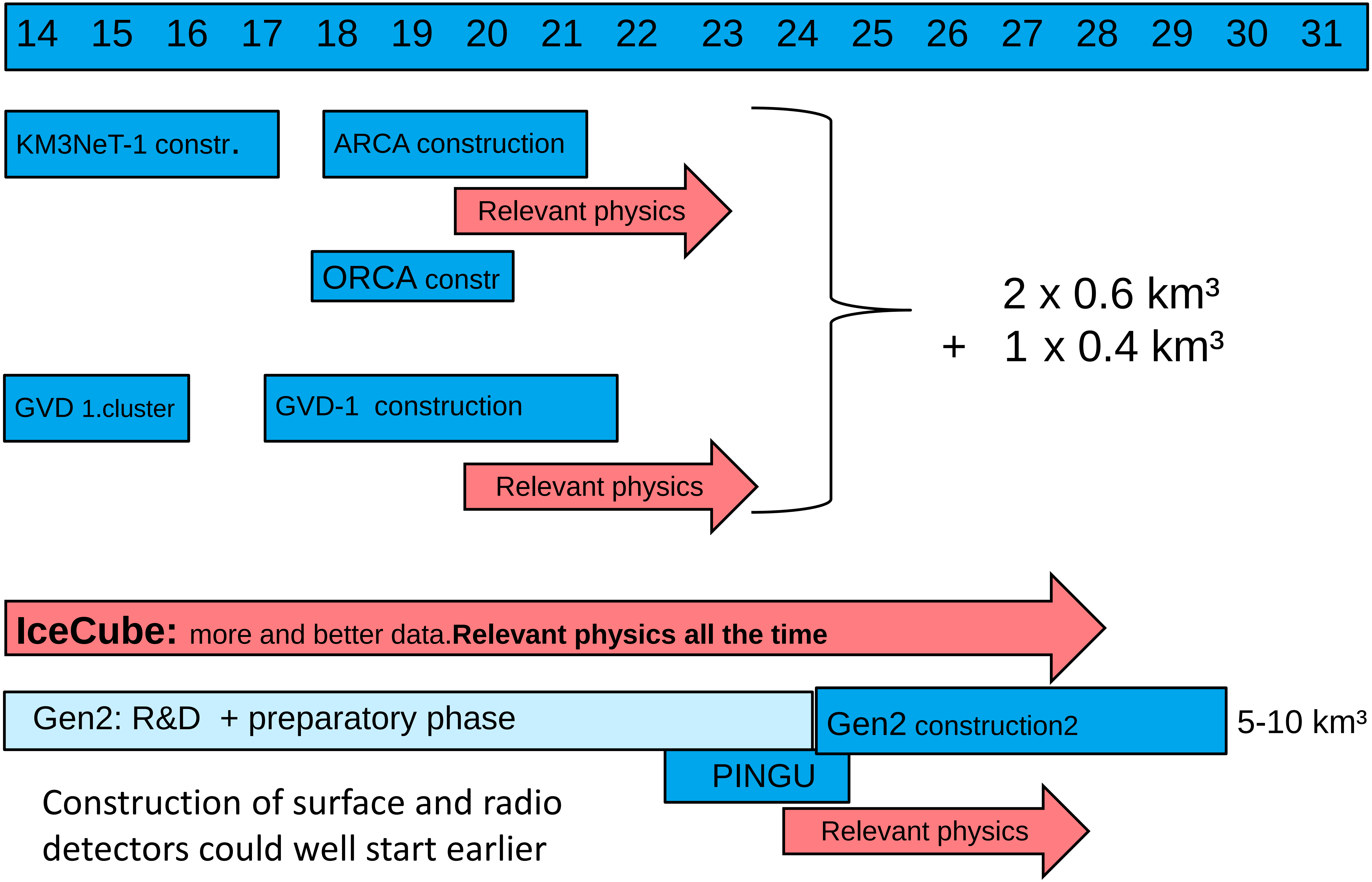
- **PINGU : low energy, mass hierarchy**
- **High Energy Array (HEA)**
  - 100 TeV- PeV scale neutrinos
- **Cosmic Ray Array -**
  veto array for HEA -
  + cosmic ray physics
- **Radio Array (RA)**
  - > 100 PeV
  - BZ (GZK) neutrinos



The IceCube Gen2 facility: conceptual drawing



Global timeline (optimist's view)



Global timeline

Complementarity

14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31

KM3NeT-1 constr.

ARCA construction

Relevant physics

ORCA constr

GVD 1.cluster

GVD-1 construction

Relevant physics

IceCube: more and better data. **Relevant physics all the time**

Gen2: R&D + preparatory phase

Gen2 construction2

5-10 km³

PINGU

Relevant physics

Construction of surface and radio detectors could well start earlier

ARCA and GVD : **North**

ARCA and GVD: **Water**

GVD: **Shallow**

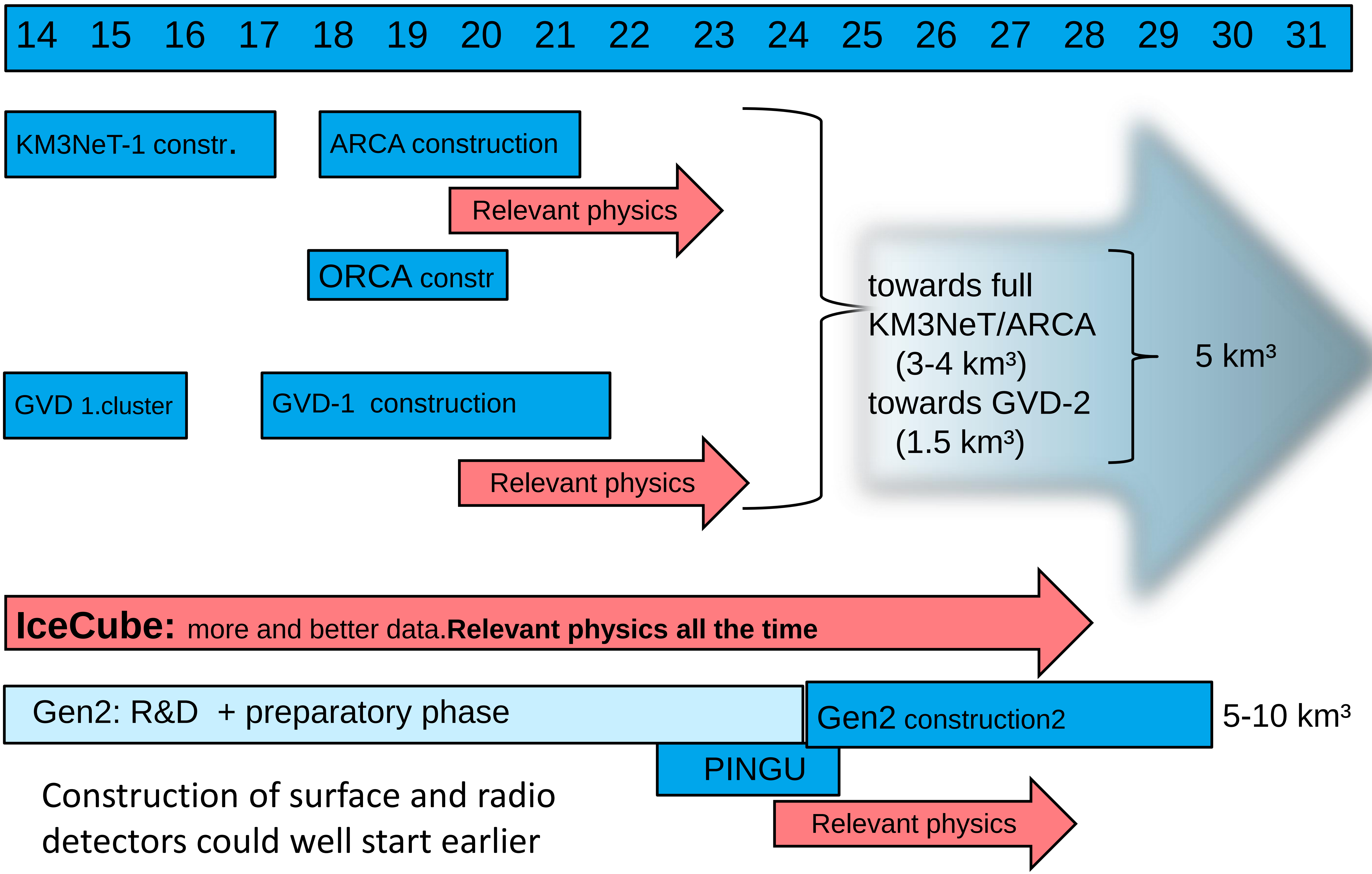
ARCA: **Deep**

GVD: **opt. to 10-30 TeV**

ARCA: **opt. to 1-10 TeV**

Gen2: **South, ice, deep, opt to 100 TeV**

Global timeline (optimist‘s view)



Summary HE neutrinos

- **Cosmic high-energy ν discovered !**
- Opened new window, but landscape not yet charted: no point sources identified up to now
- Remaining uncertainties on spectrum and flavor composition
- Individual sources: transient sources give best chance, steady sources tantalizingly close (→ ARCA/GVD).
- Need larger detectors, also with different systematics <u>and</u> at the Northern hemisphere.
- **Next logical step: ARCA + GVD_{Phase1}**
- **~2030: A Global Neutrino Observatory (KM3NeT-GVD-IceCube/Gen2) full sky with > 5 km^3**

Summary HE neutrinos

Neutrino Astronomy:
Charting the Landscape

- **~2030: A Global Neutrino Observatory (KM3NeT-GVD-IceCube/Gen2) full sky with > 5 km^3**

NEW TECHNOLOGIES

New technologies

Some of the break-throughs may come from new approaches, e.g.

- Radio detection of air showers: Tunka, Auger, …, LOFAR, SKA
- Radio detection of neutrinos: ARA, ARIANNA (Antarctica), GNO (Greenland), …
- Acoustic detection of neutrinos: along with KM3NeT
- Fluorescence detection of neutrinos (Auger, ASHRA, NTA, …)
- …

This list is clearly not complete!

- Keep supporting new approaches on a reasonable level!

THANK YOU FOR YOUR ATTENTION