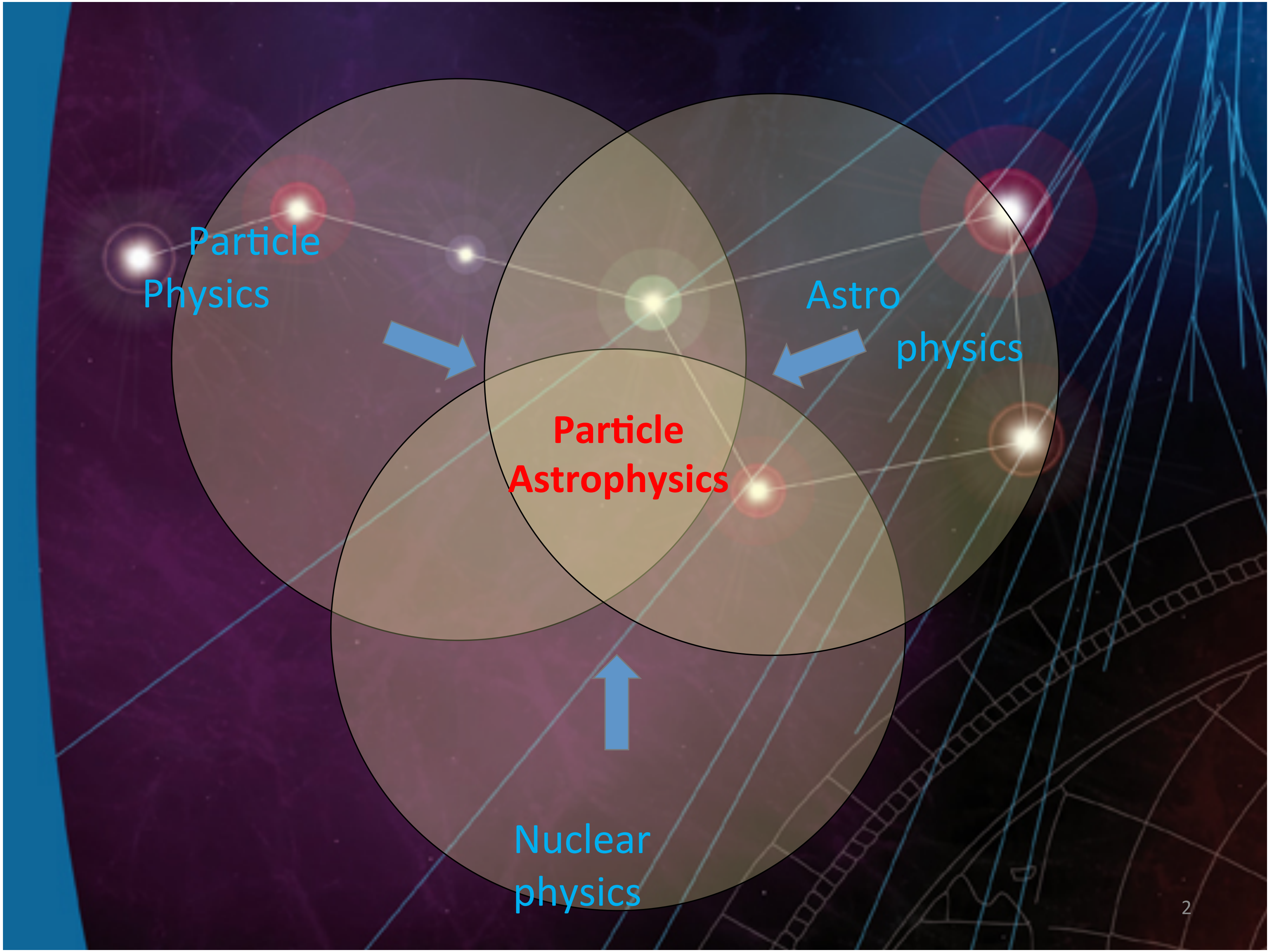
Future of Particle Astrophysics,

Michel Spiro
President of IUPAP
Malargue November 15th, 2019
20 years Auger Symposium
(with the help of Christian Spiering)


Particle
Physics
Astro
physics
Particle
Astrophysics
Nuclear
physics

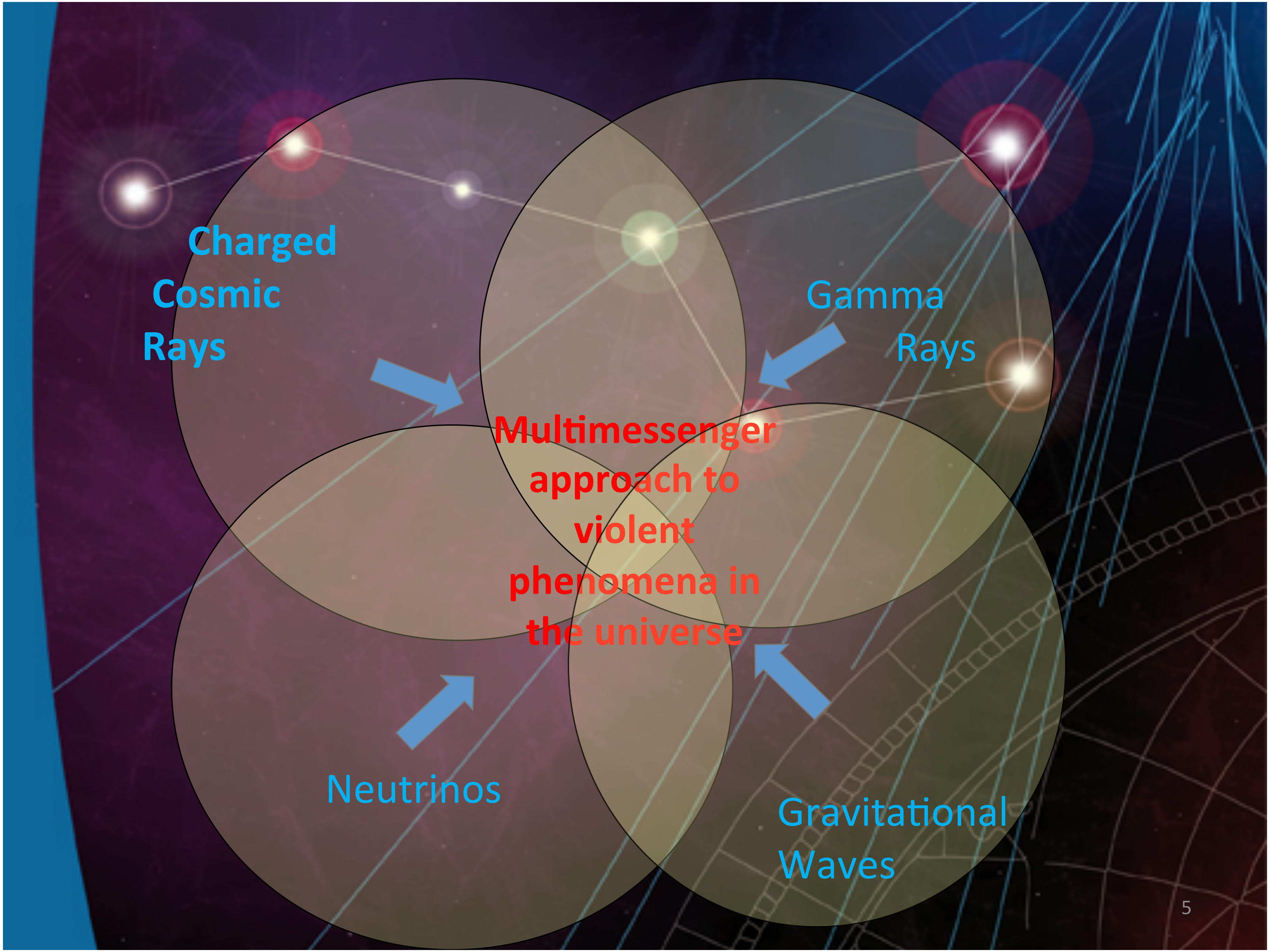
WHAT IS PARTICLE ASTROPHYSICS

1) Observational Cosmology
   Big Bang Nucleosynthesis
   Cosmic Microwave Background
   Supernovae and cosmology
   Clustering of Galaxies (BAO…)
   Dark matter, dark energy

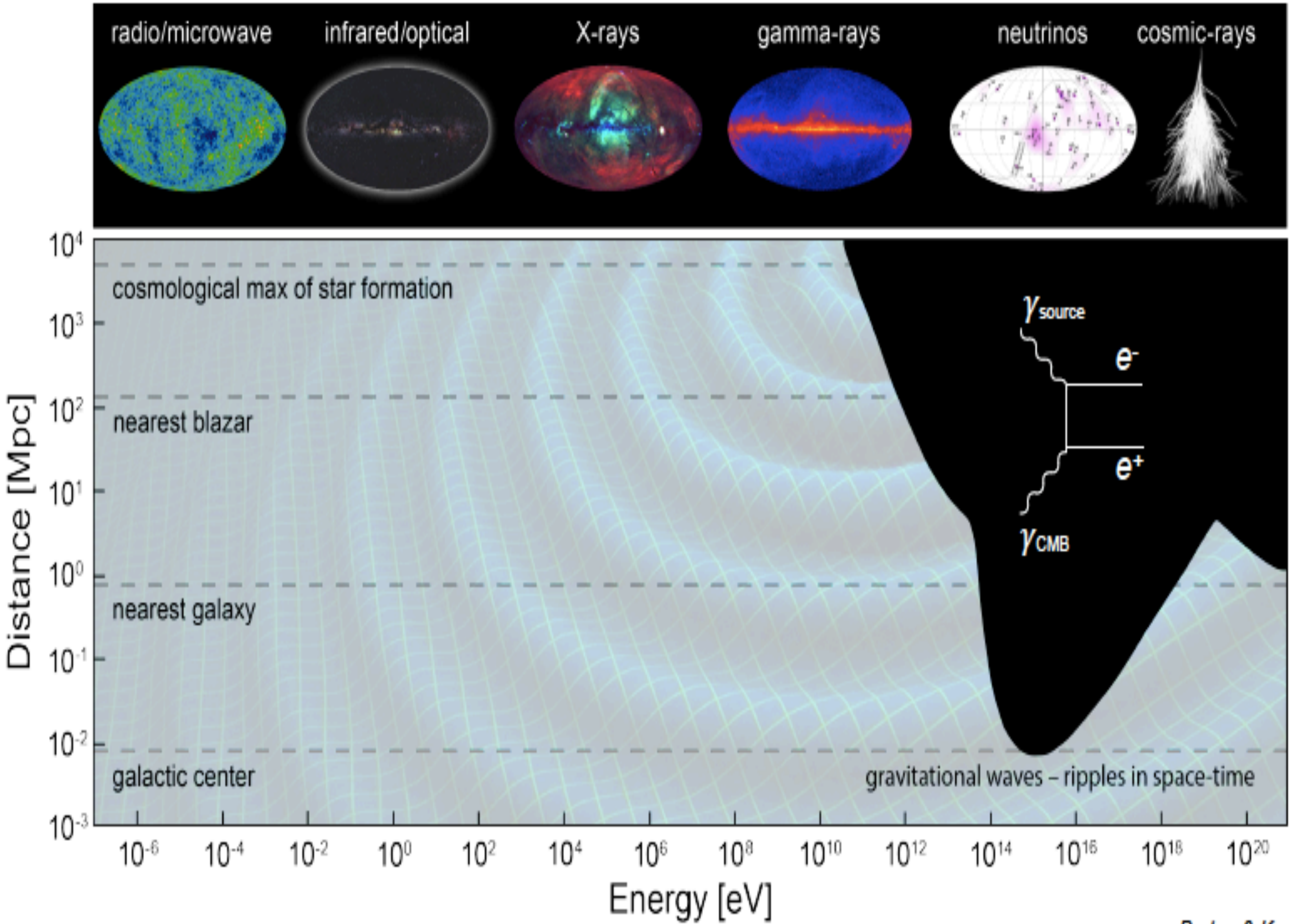
2) Neutrinos and Proton Decay
   Neutrino cosmology
   Neutrinos and star evolution: Supernovae
   Non accelerator Neutrino physics (mass, oscillations, nature: Dirac, Majorana, sterile)
   Proton decay.

1) **High energy astrophysics (multimessenger approach)**
   cosmic rays
   Gamma rays
   Neutrinos
   Gravitational waves

Future of Multi Messengers Astronomy

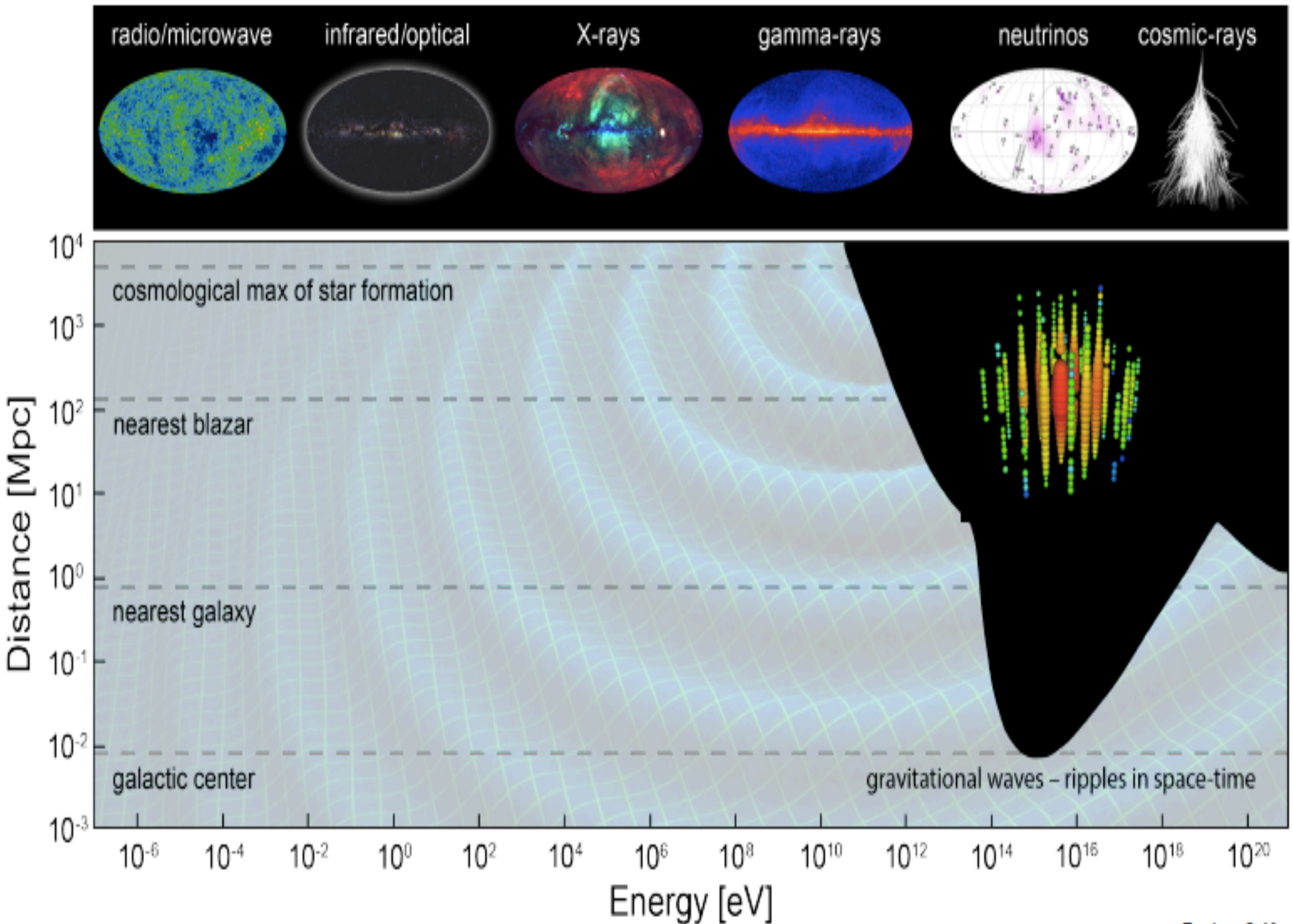

Charged
Cosmic
Rays
Gamma
Rays
Multimessenger
approach to
violent
phenomena in
the universe
Neutrinos
Gravitational
Waves

A multitude of cosmic messengers from from low to high energies



Bartos & Kowalski, IOP 2017

A multitude of cosmic messengers from from low to high energies



Bartos & Kowalski, IOP 2017

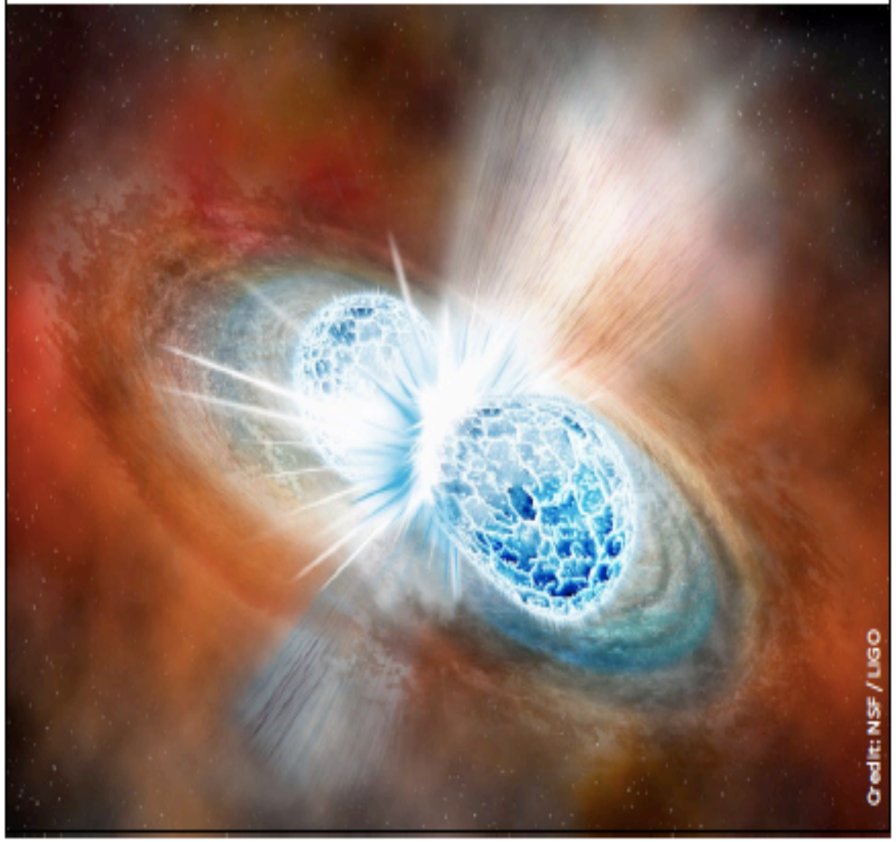
The Dawn of Multimessenger Astronomy

Recent highlights

Highlight #1: First merger of two Neutron-stars

How: Gravitational waves + optical + X-rays

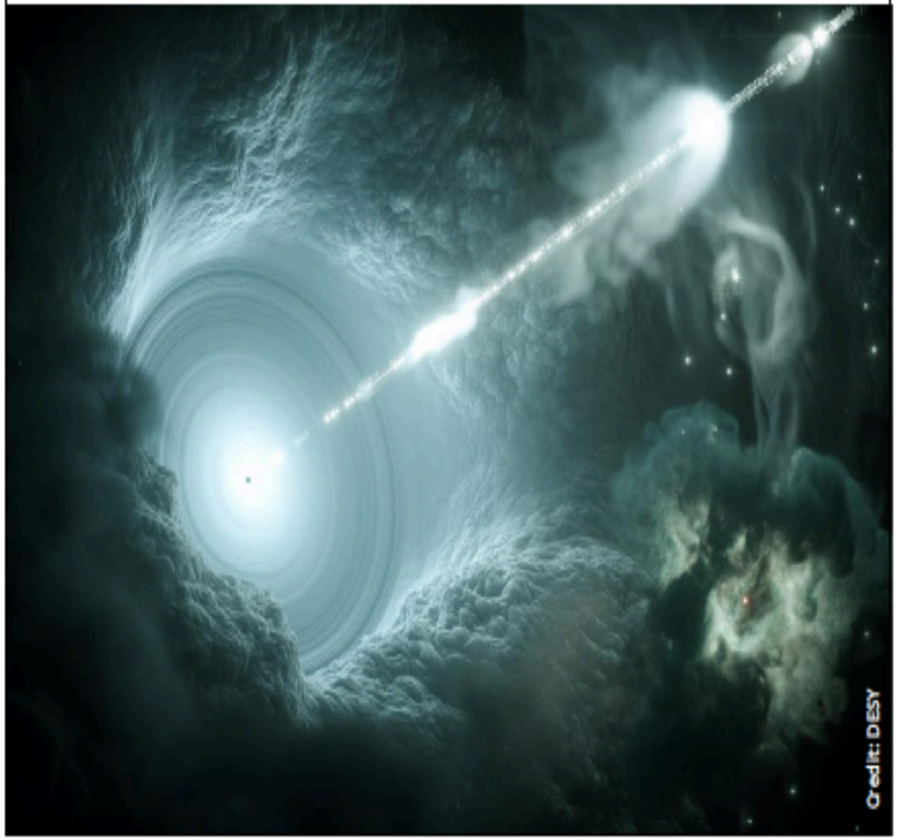
Where: Nature 551 (2017), Science 358 (2017), Astrophys.J. 848 (2017), MNRAS 481 (2018)



Highlight #2: First source of high energy neutrinos

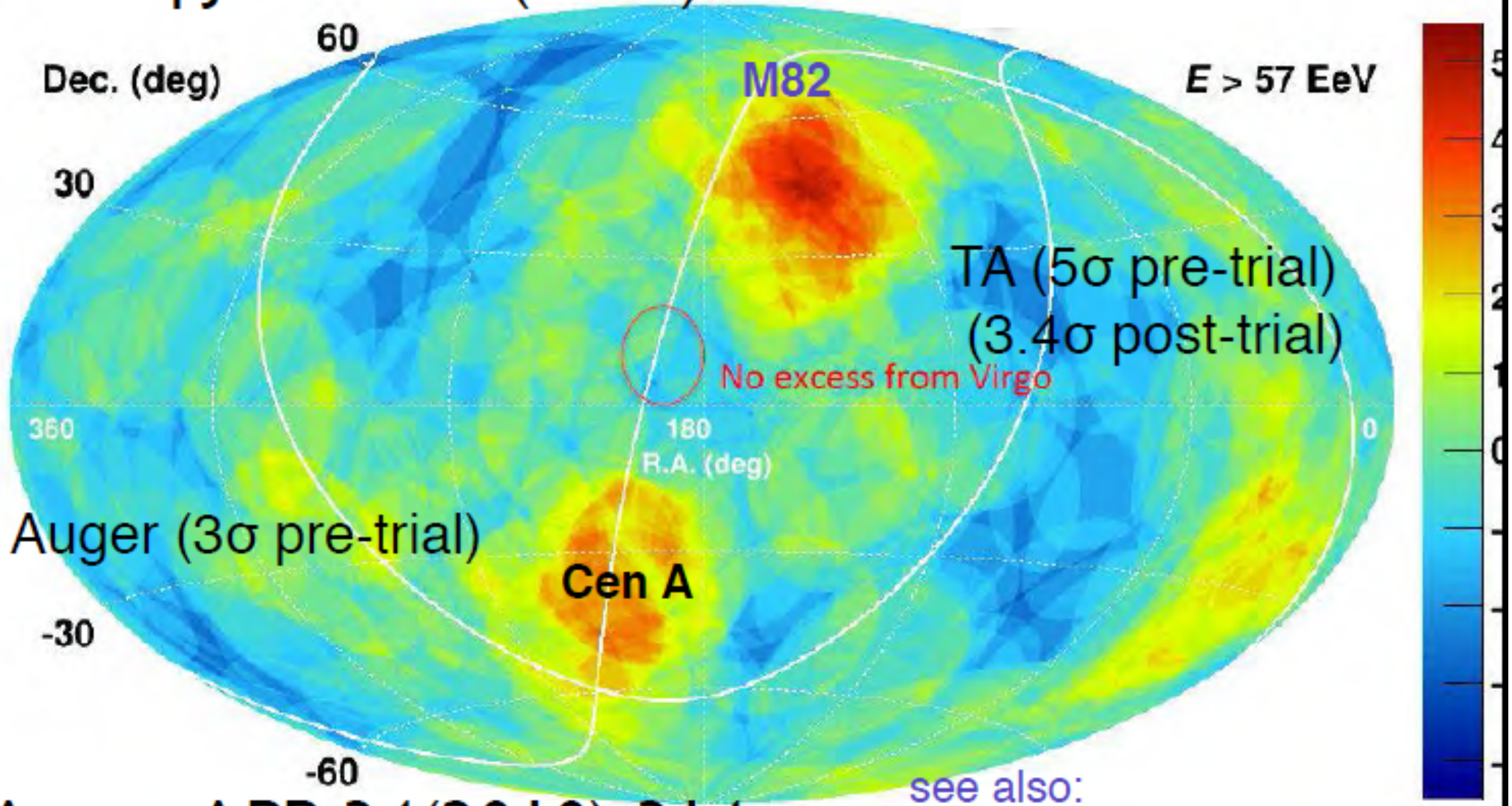
How: Neutrinos + gamma-rays

Where: Science 361 (2018), Astrophys.J.Lett. 863 (2018)



EVEN EARLIER: Point Sources: Tantalizing hot spot at TA

TA: ApJ 790:L21 (2014)



Auger: APP 34(2010) 314

see also:
D. Fargion; arXiv:1412.1573

Viktor Hess

1912

Detection of cosmic rays

Pierre Auger

1939

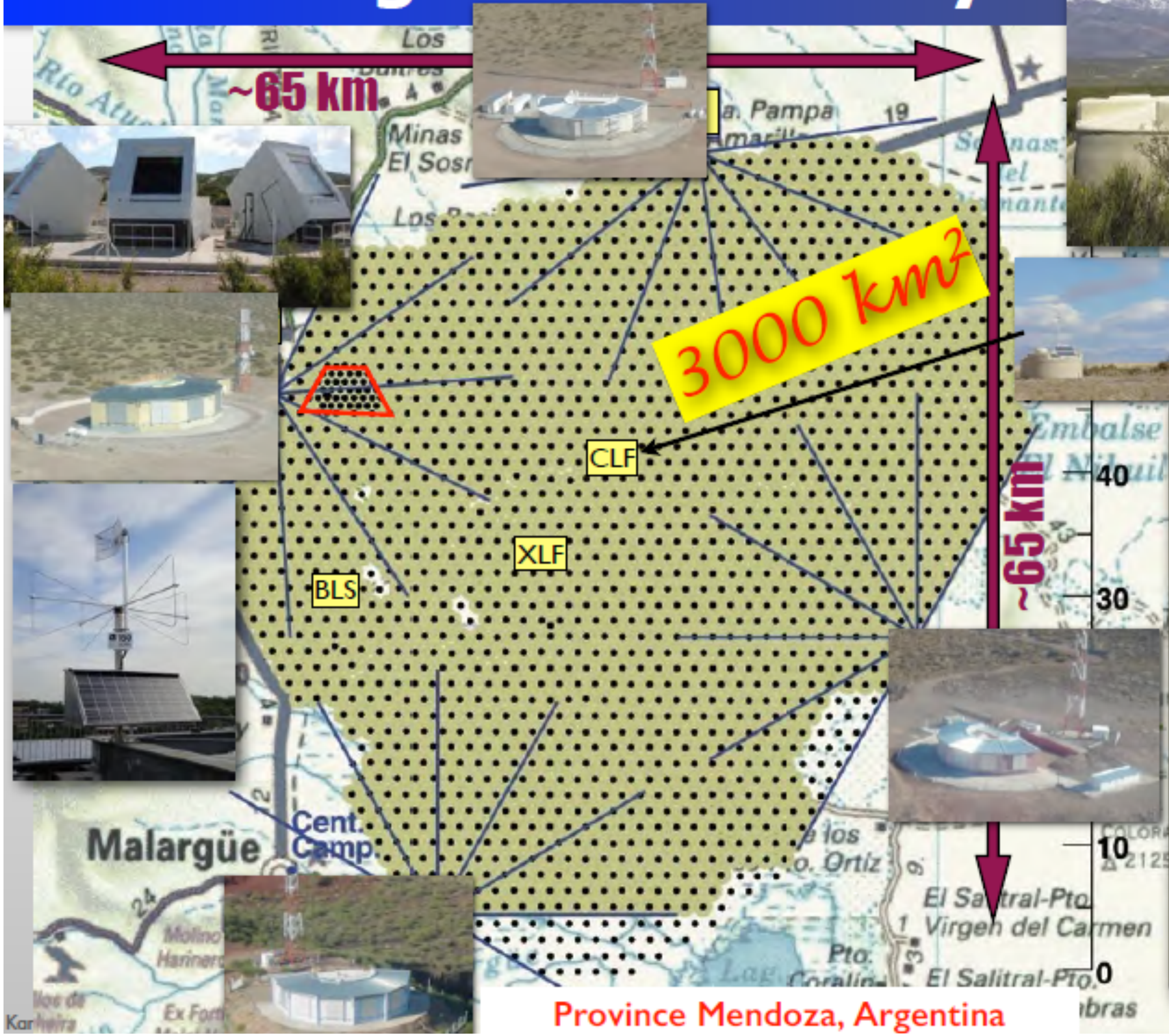
Detection of cosmic air showers

James Cronin
Alan Watson

1989

Detection of cosmic highest energy air showers

Pierre Auger Observatory

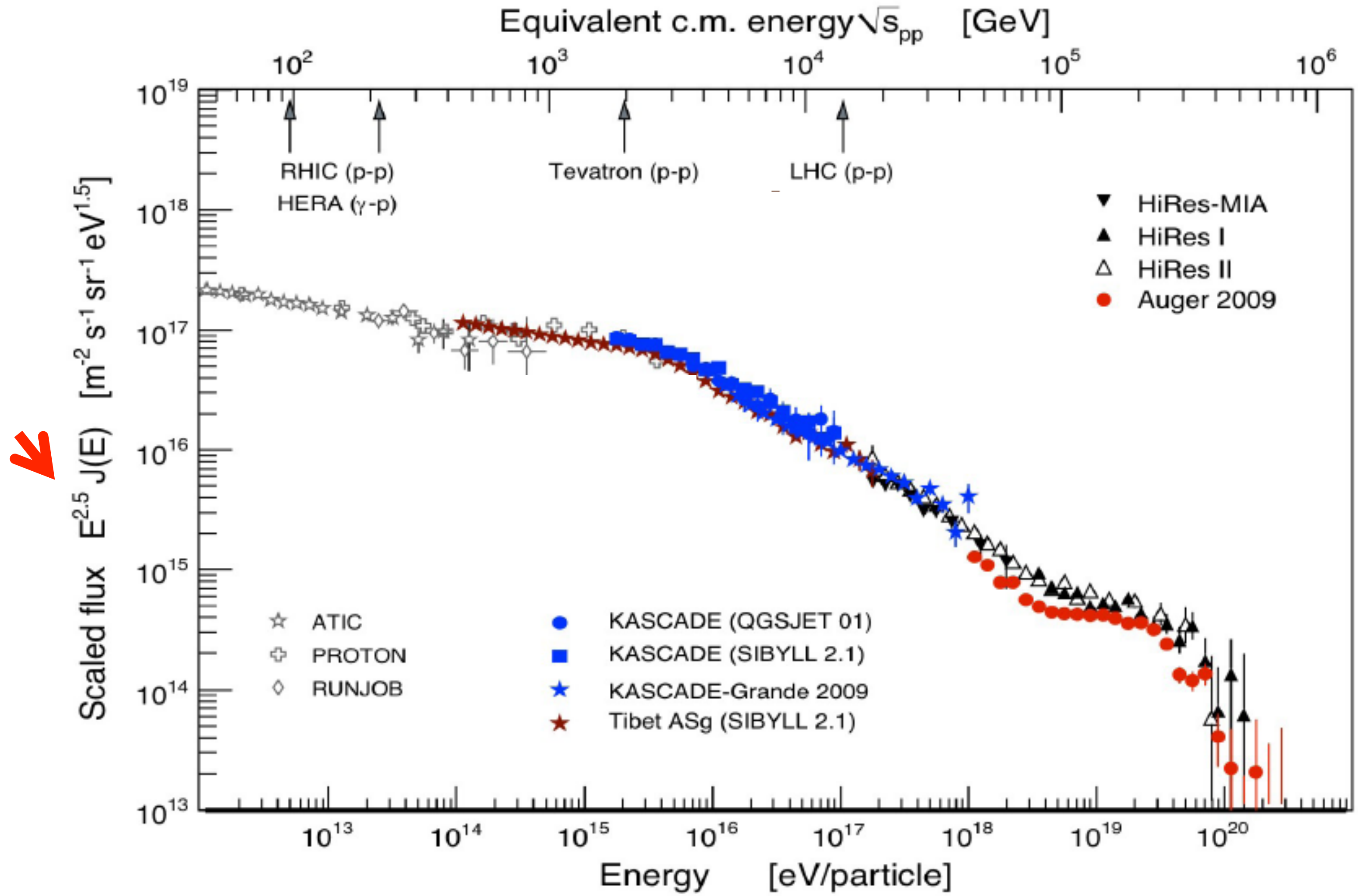


1660 detector stations on 1.5 km grid

27 fluores. telescopes at periphery

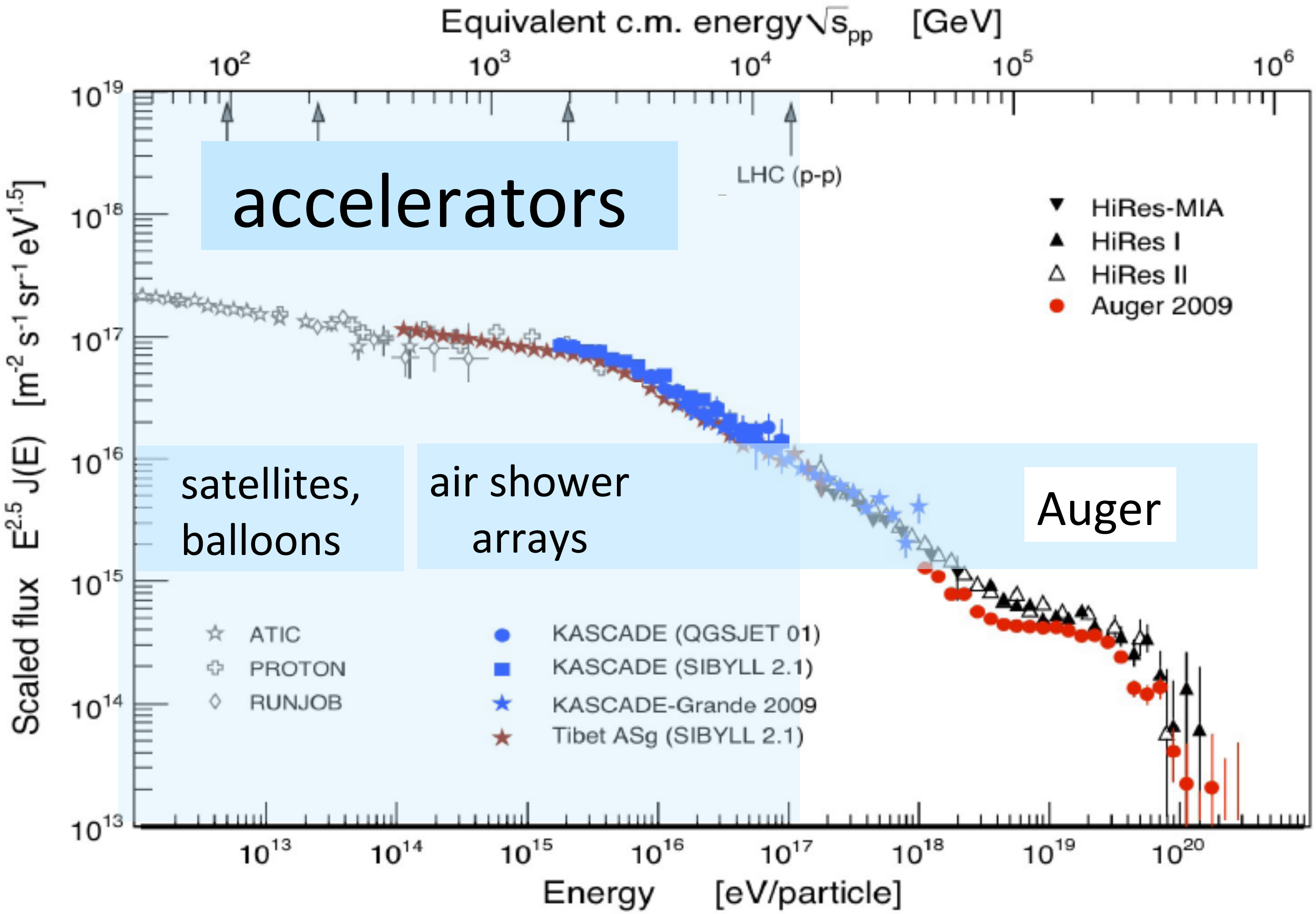
130 radio antennas

Spectrum of Cosmic Rays



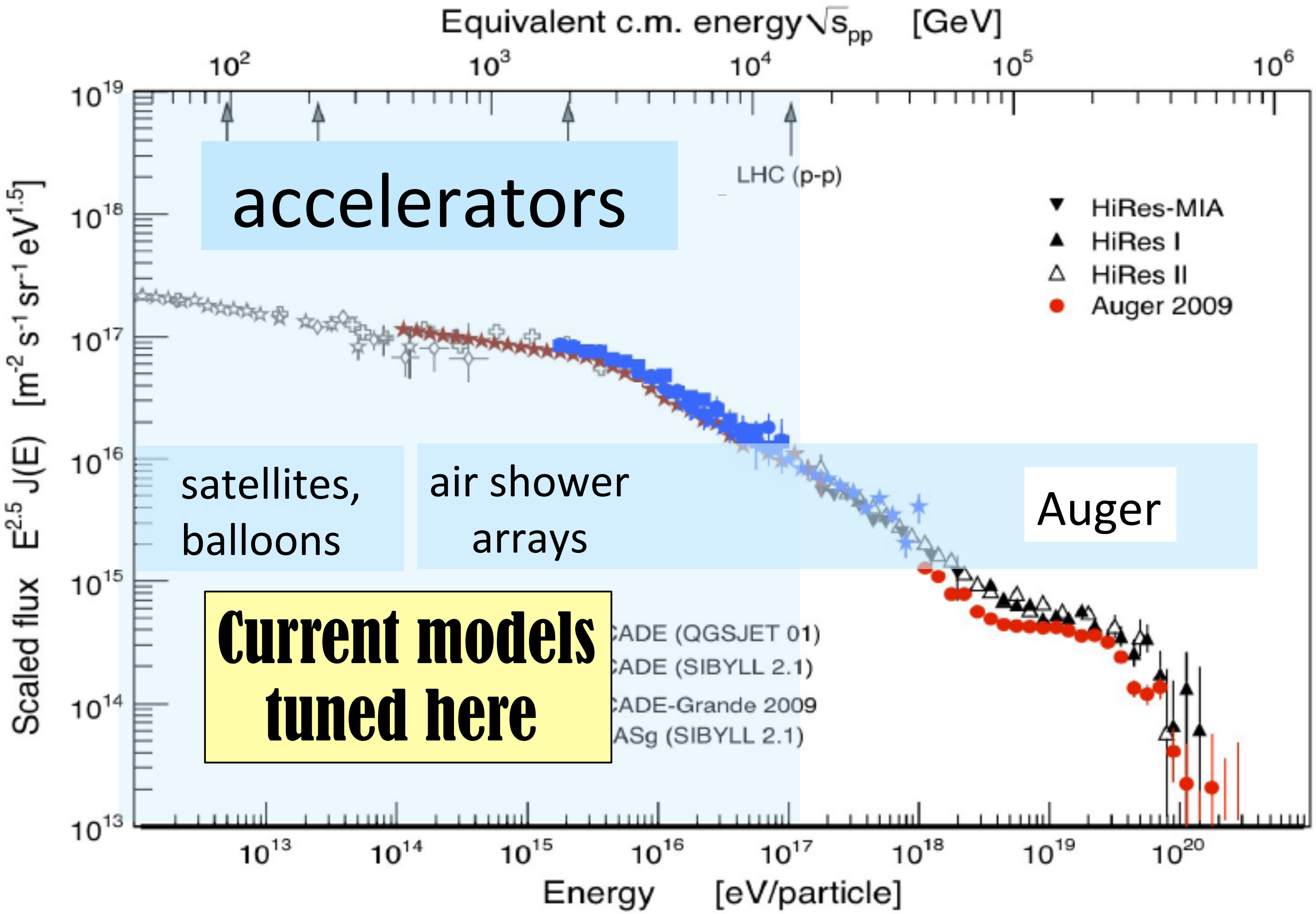
R. Engel (KIT)

Spectrum of Cosmic Rays



R. Engel (KIT)

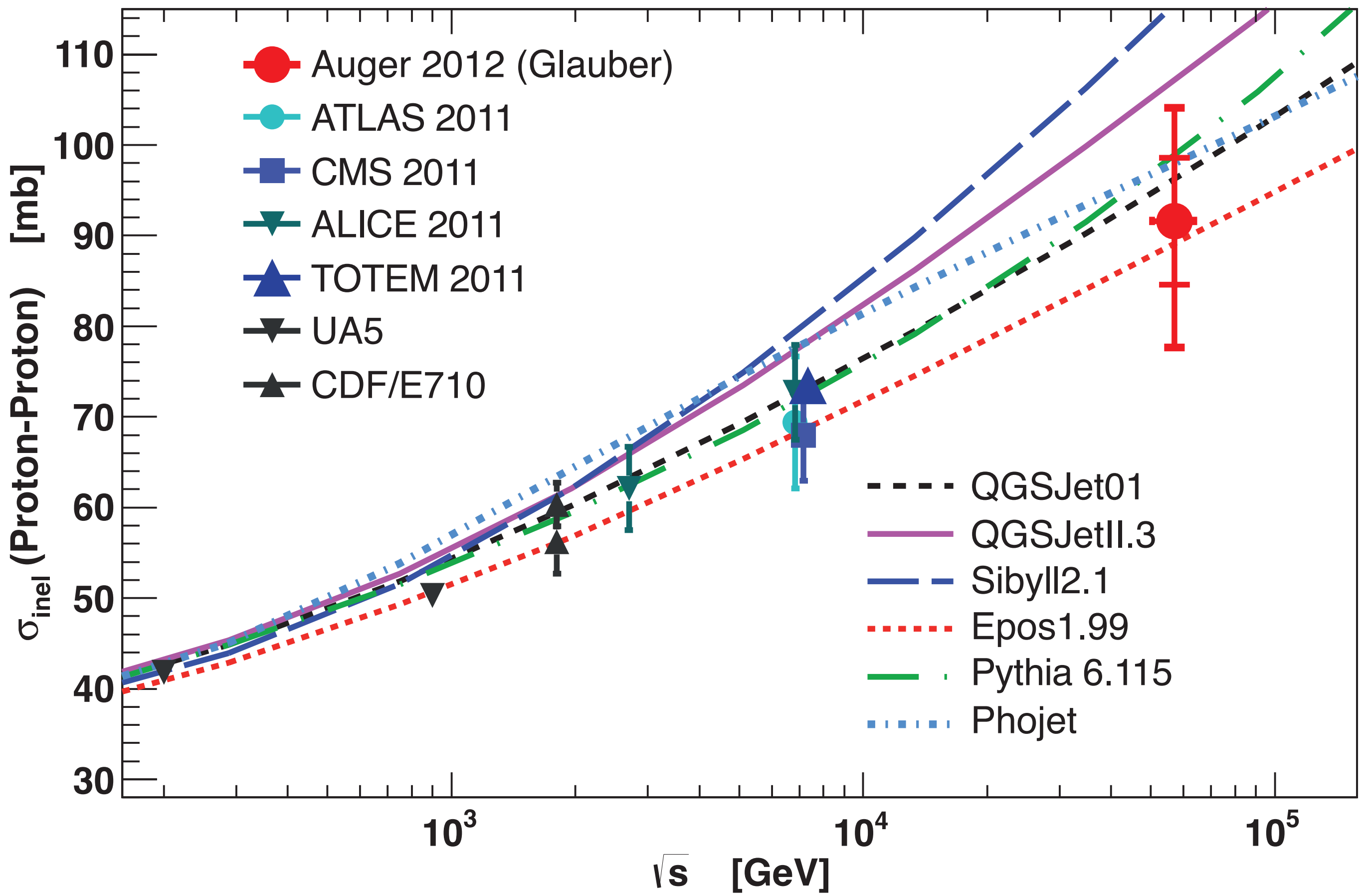
Spectrum of Cosmic Rays



R. Engel (KIT)

Cosmic Rays and LHC

pp inel. cross section at sqrt(s)=57 TeV



- Compare to QCD and Glauber model, tuning EAS simulations

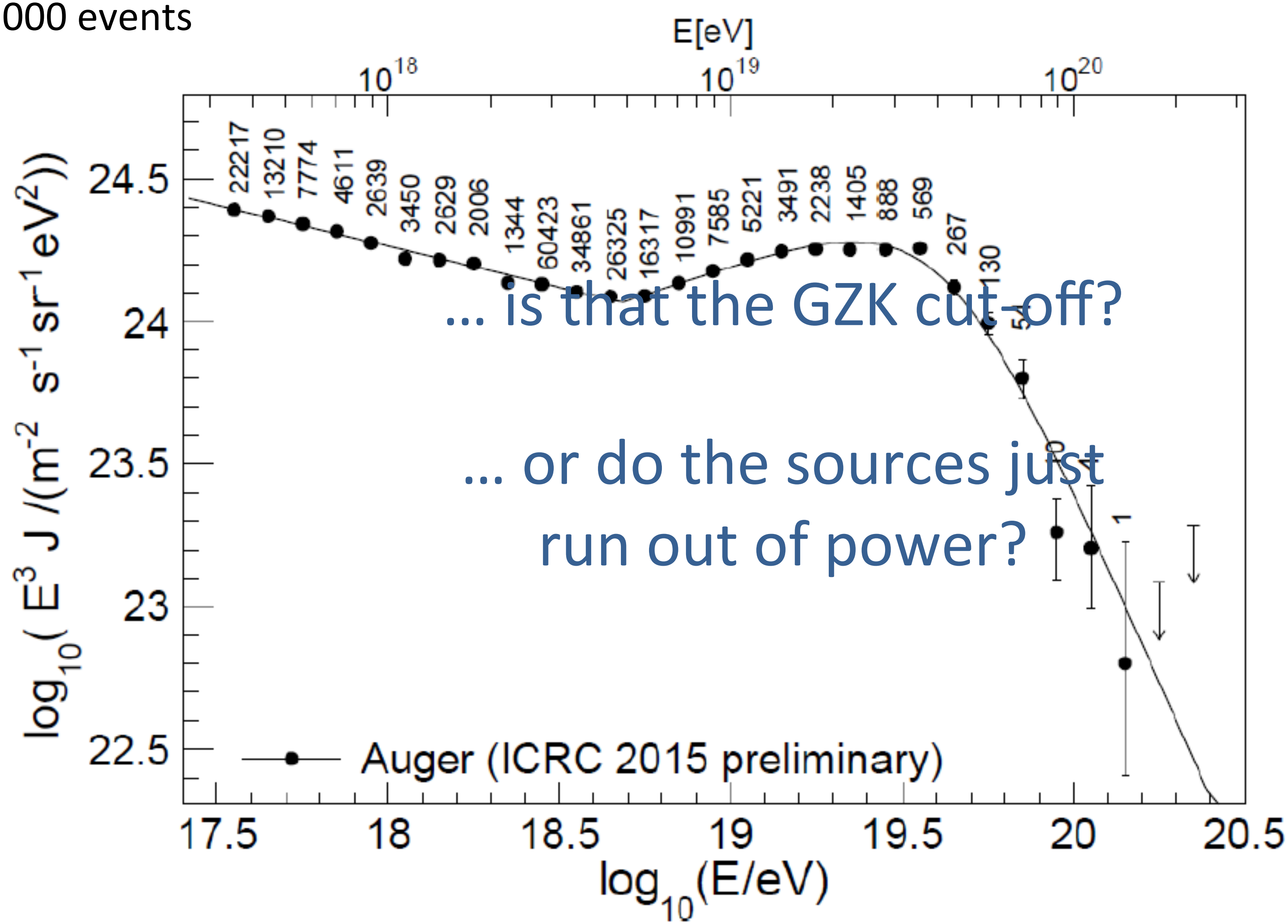
Cosmic Rays and LHC

- Cooperation of particle- and CR-physicists has been intensified over the last years.
- Extremely useful for understanding CR nature
- Accelerator data helped improving shower models.
  Tools of CR community will also help better understanding HE particle interactions: models sometimes better than HEP models
- Need common approach to understand muons in CR showers

- NA61/SHINE (SPS Heavy Ion and Neutrino Experiment):
  important input data for cosmic ray and neutrino experiments.

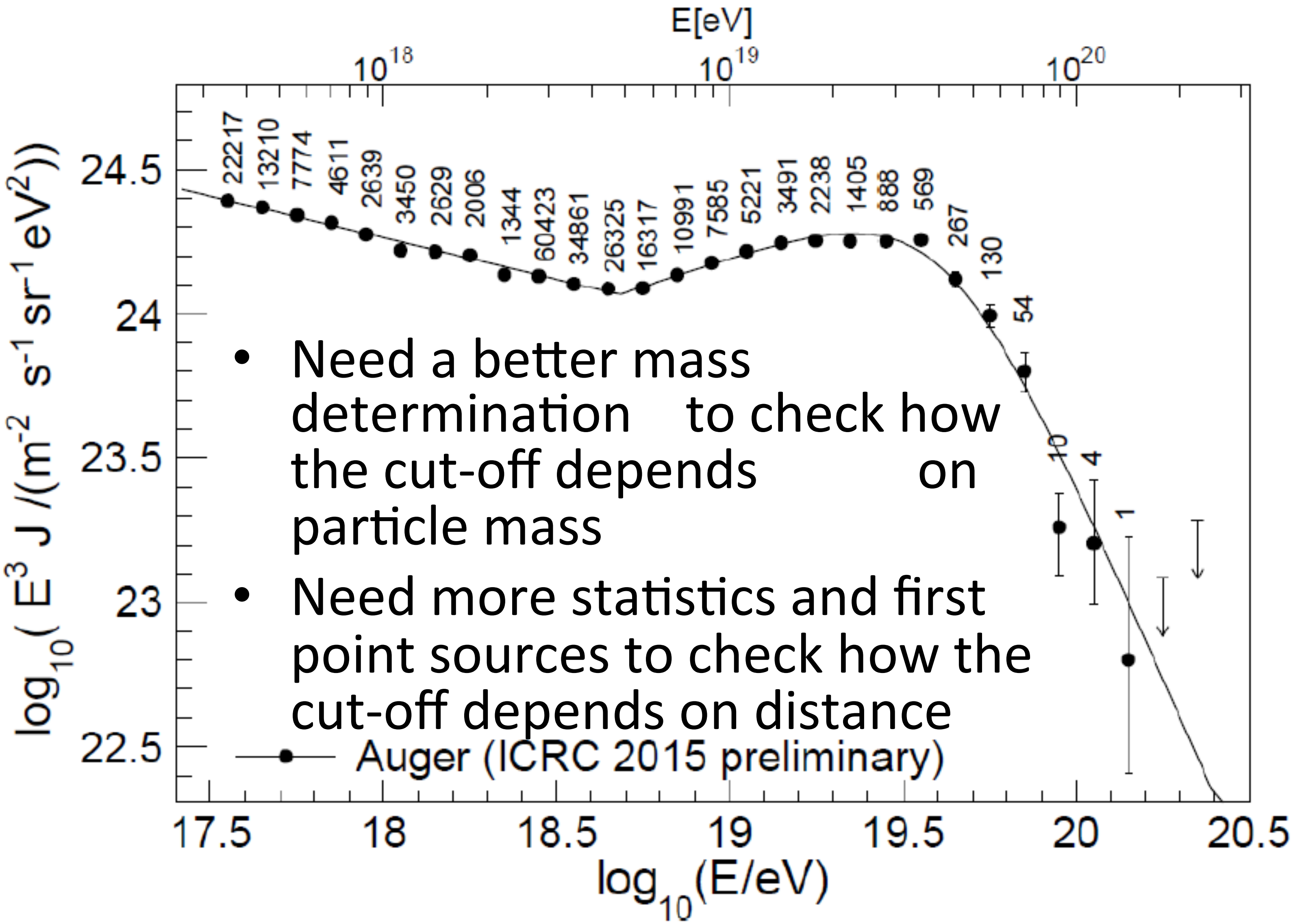
Cut-off at highest energies confirmed, but …

190 000 events



… is that the GZK cut-off?

… or do the sources just run out of power?



- 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

What after results with upgraded arrays?

- Ultrahigh-energy cosmic ray physics is at a turning point
- High-energy cut-off has been clearly confirmed, but nature unclear
- No point sources, but hot spot TA + “warm” spot Auger
- Origin of the muon excess at high energies not undersstood
- Detection and study of point sources was one of the two primary goals of Auger/TA. Would also be the primary motivation for any future EeV CR experiment – ground based arrays of the 30 000 – 90 000 km² class or the space based JEM-EUSO.
- Key to move ahead in both directions: more precise mass assignment of individual events and the separation of a proton event sample which is minimally polluted by heavier nuclei.

Alexander Chudakov

1965

First search for gamma-ray showers in the atmosphere

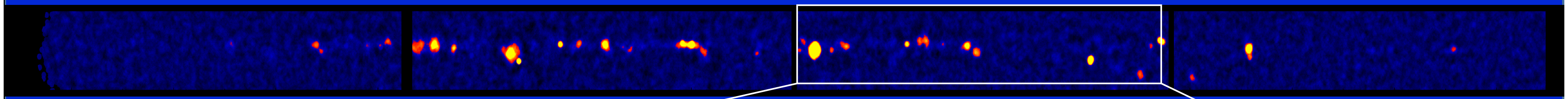
Trevor Weekes

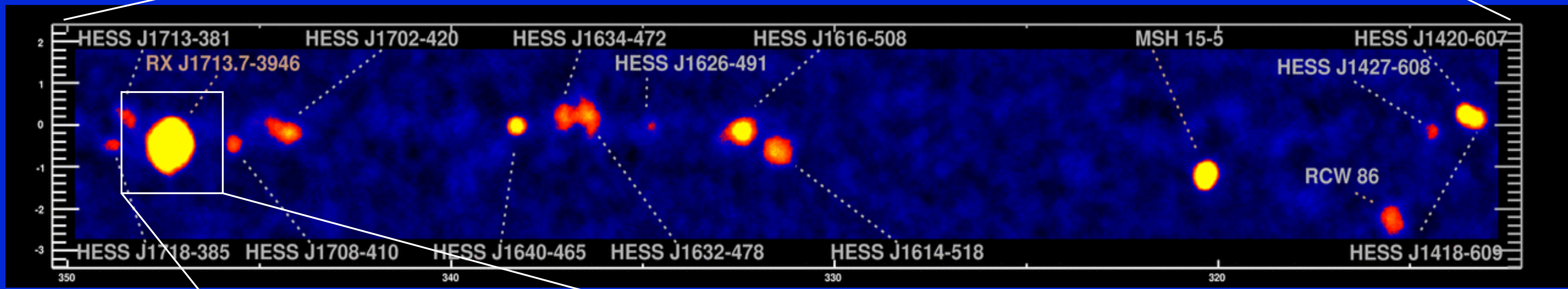
1989

Detection of the Crab nebula as TeV gamma-ray source
(WHIPPLE Telescope/Arizona)

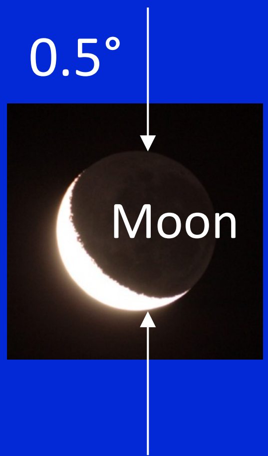
3rd generation Imaging Air Cherenkov telescopes

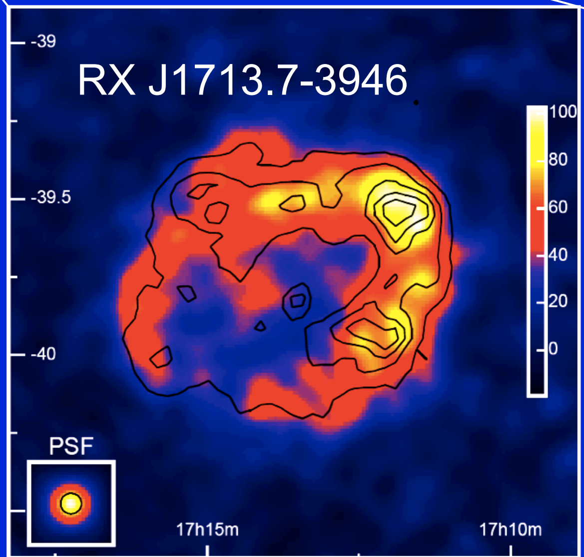
The Sky at TeV-Energies





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



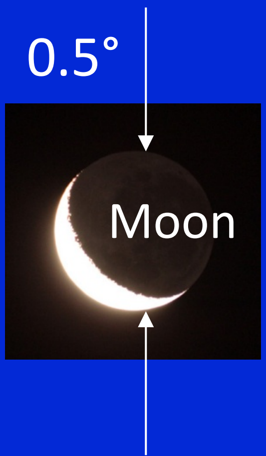


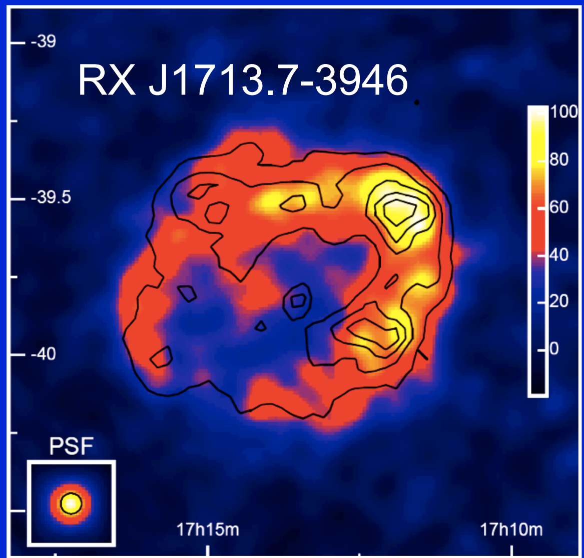
1989:	1 Source
1996:	3 Sources
2005:	80 Sources
2015:	150 Sources

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!)

0.5°





1989:	1 Source
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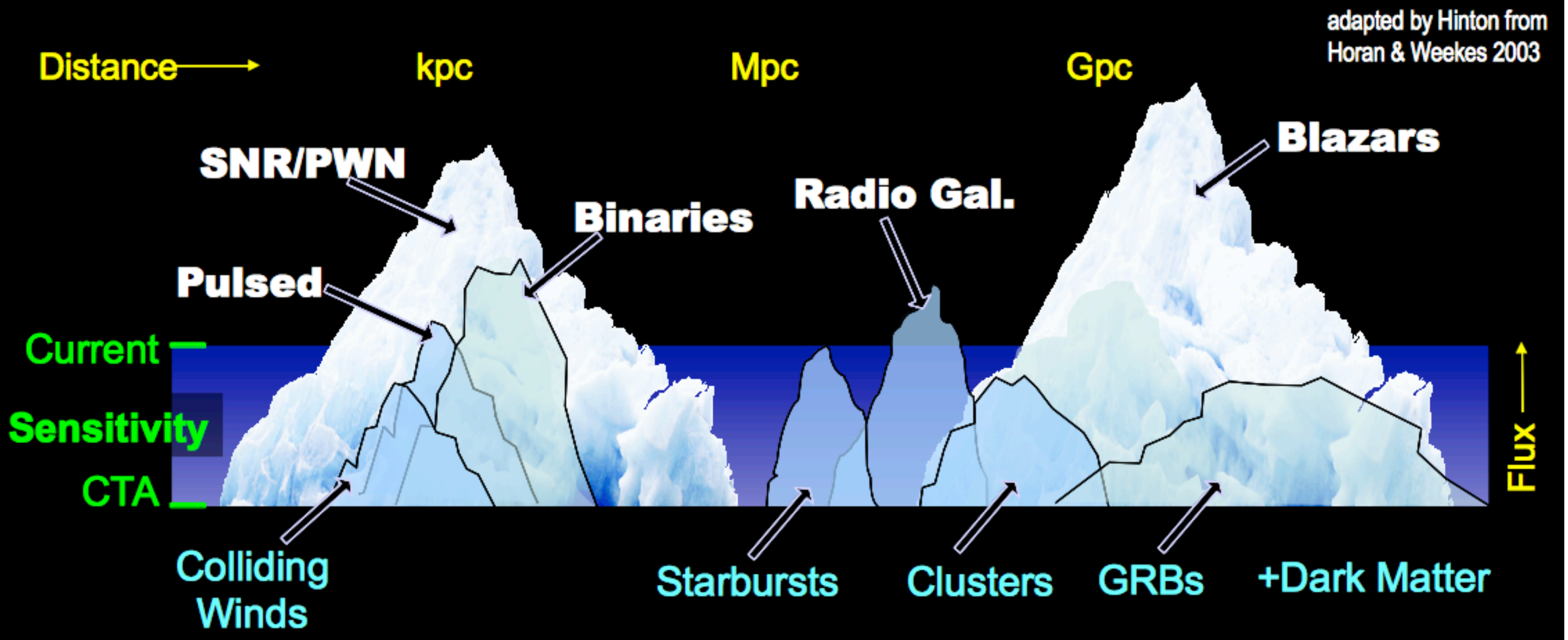
It‘s going to be like classical astronomy !

PLUS:

- Physics beyond the Standard Model
  - Indirect Dark Matter Search
  - Test of Lorenz Invariance
  - …
- Cosmology
  - Measurement of Extragalactic Background ightL
  - 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**

cta
cherenkov telescope array

Summary on Gamma Rays

- CTA will open a new era in gamma-ray astronomy
- It will be flanked by wide-angle arrays like HAWC (TeV range), SWGO? and LHAASO, TAIGA (reaching into PeV range)
- Follow-up of Fermi satellite is still open

Moisej Markov

1960

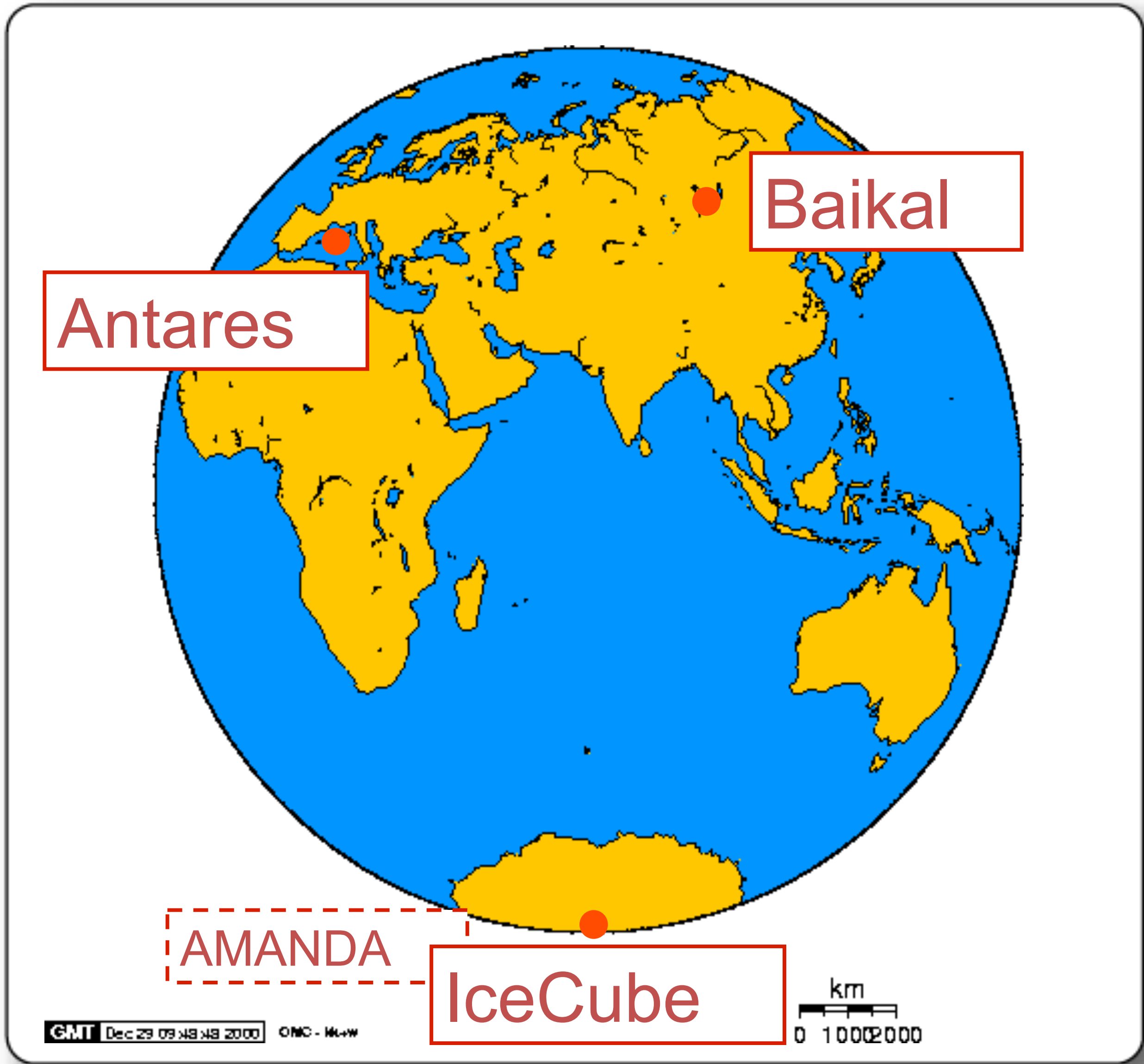
Proposal to detect C-light from charged particles in open water

Fred Reines

1965

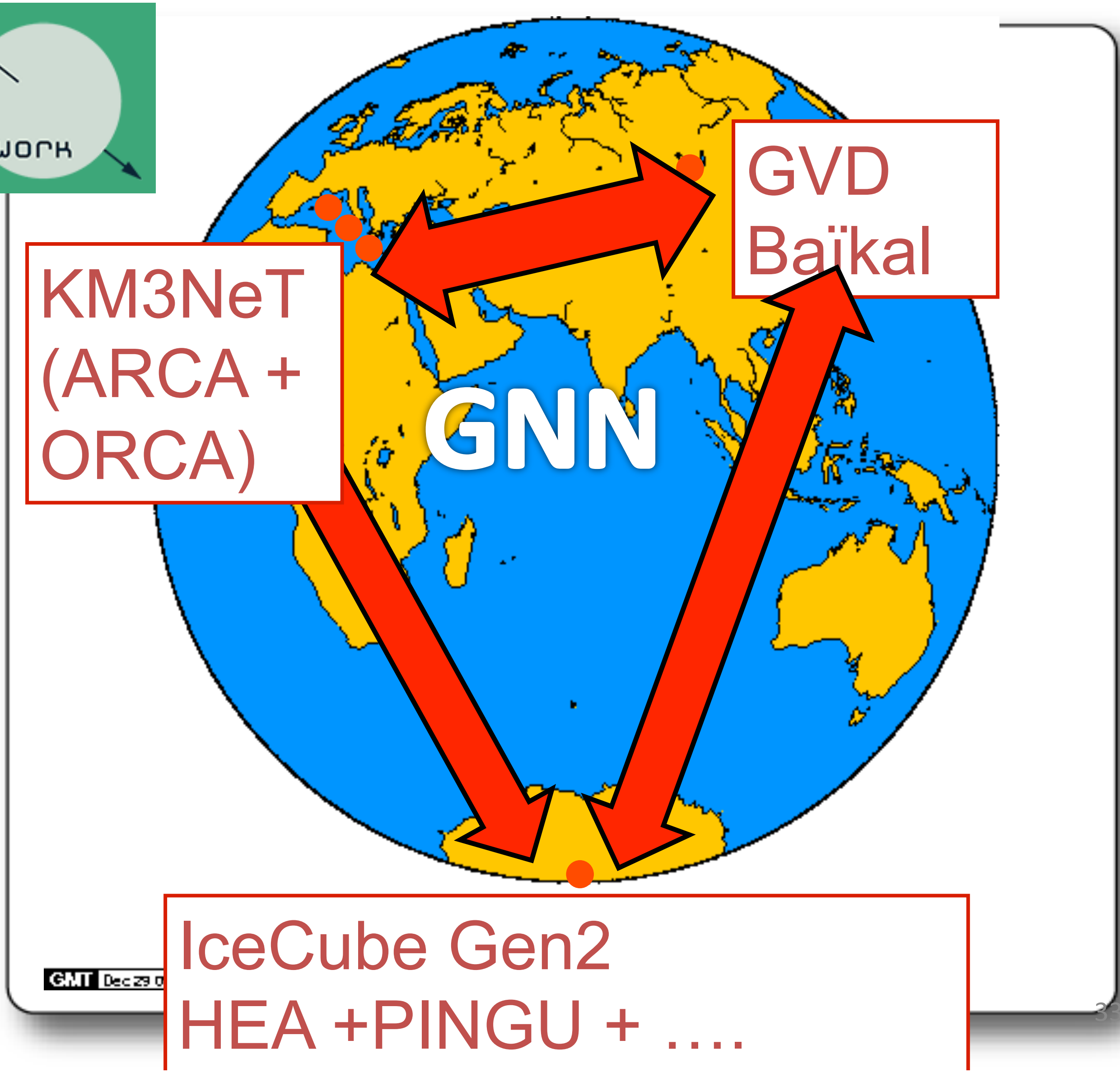
Atmospheric neutrinos in South Africa and India

The devices

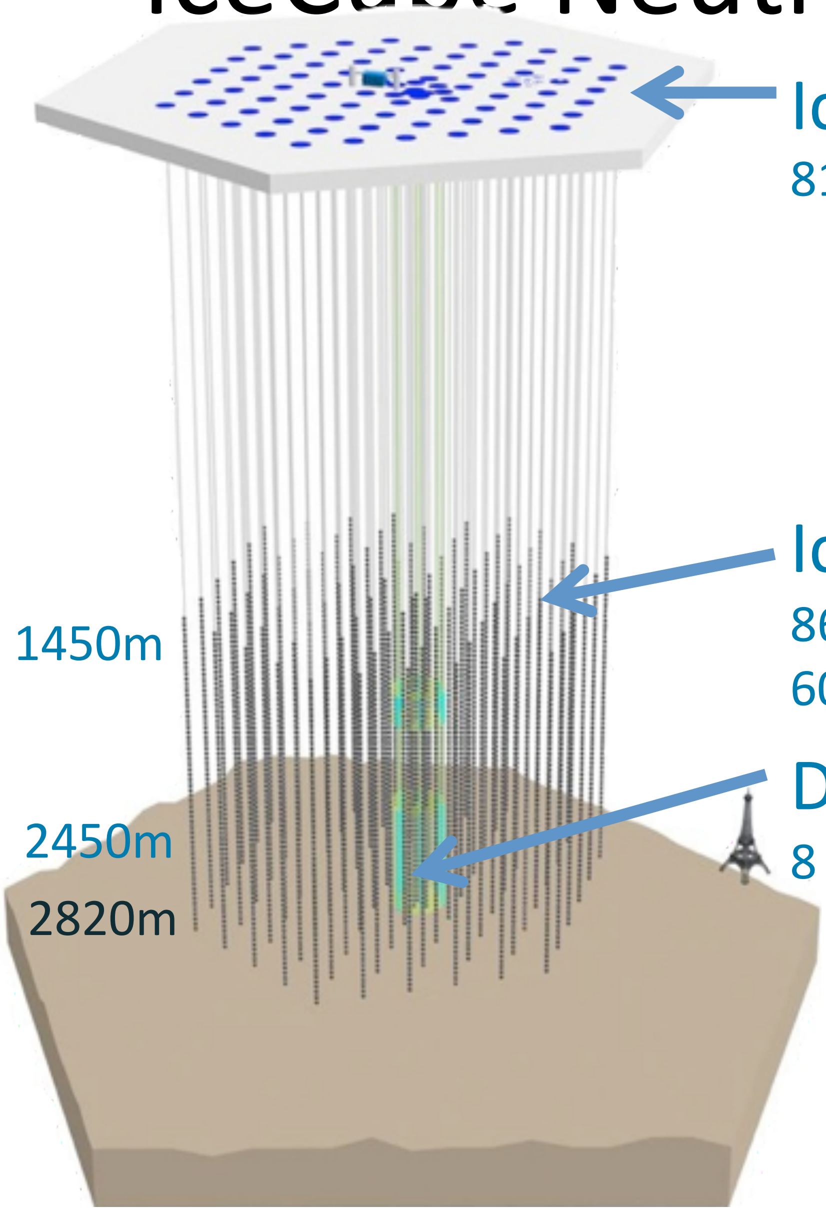


Baikal, Mediterranean Sea, South Pole

GNN
The Global Neutrino Network



IceCube Neutrino Observatory



IceTop air shower detector

81 pairs of water Cherenkov tanks

IceCube

86 strings including 8 Deep Core strings

60 PMT per string

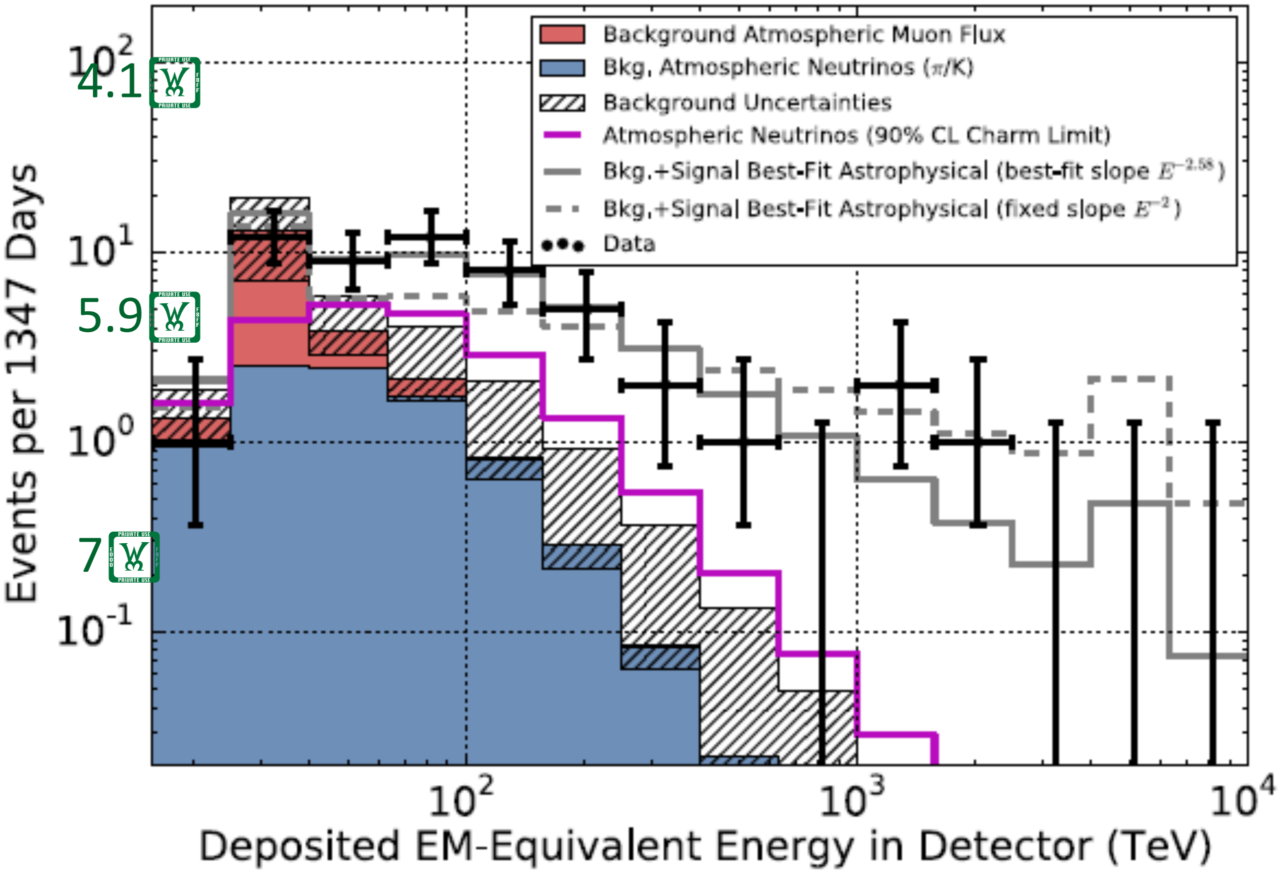
DeepCore

8 closely spaced strings

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

Follow-up Analysis: HESE (High Energy Starting

First evidence for an extra-terrestrial h.e. neutrino flux



2 yrs data, 28 evts

Science 342 (2013)

3 yrs data, 37 evts

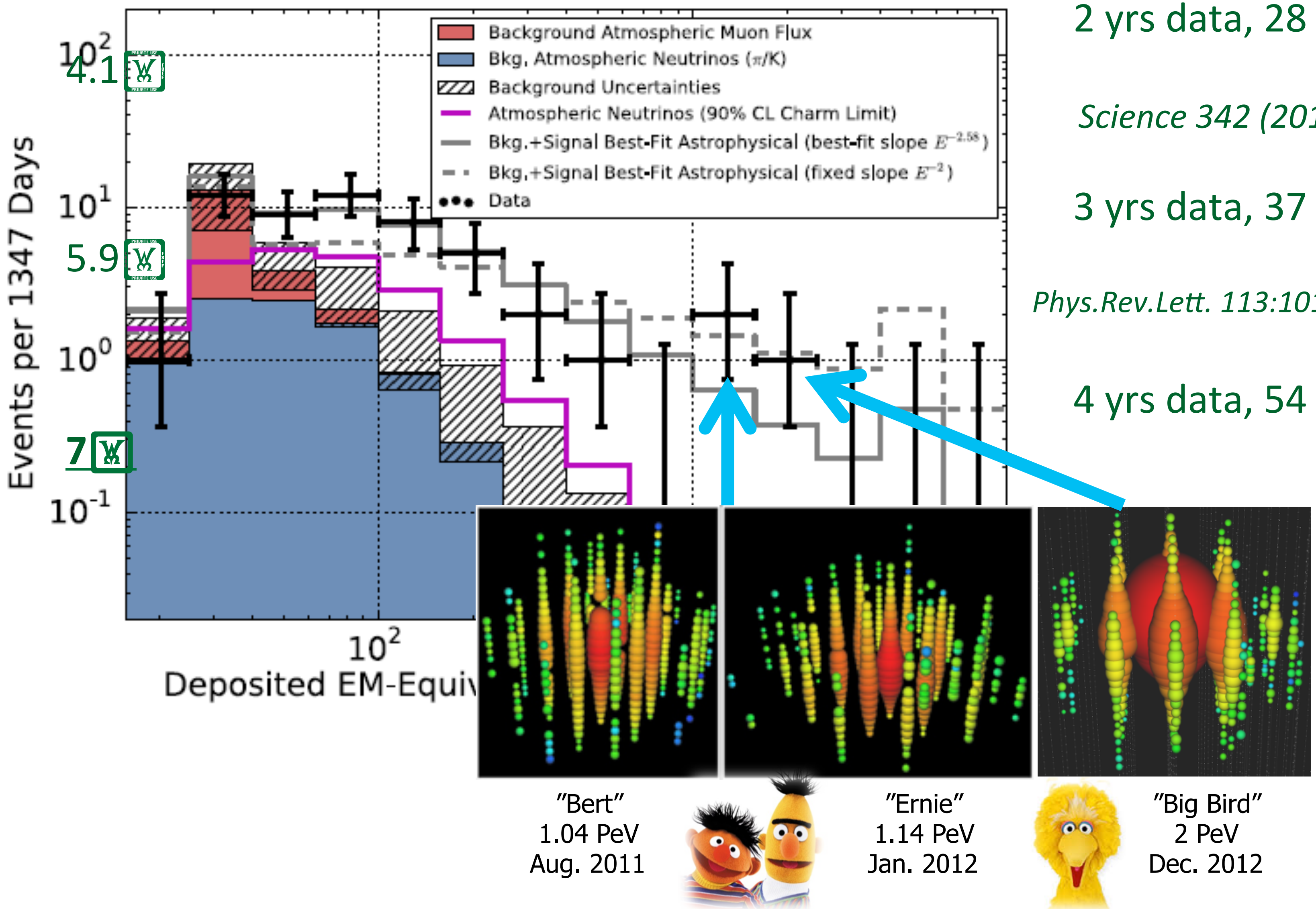
Phys.Rev.Lett. 113:101101 (2014)

4 yrs data, 54 evts ~

Threshold ~ 30 TeV

Follow-up Analysis: HESE (High Energy Starting

First evidence for an extra-terrestrial h.e. neutrino flux



2 yrs data, 28 evts

Science 342 (2013)

3 yrs data, 37 evts

Phys.Rev.Lett. 113:101101 (2014)

4 yrs data, 54 evts ~

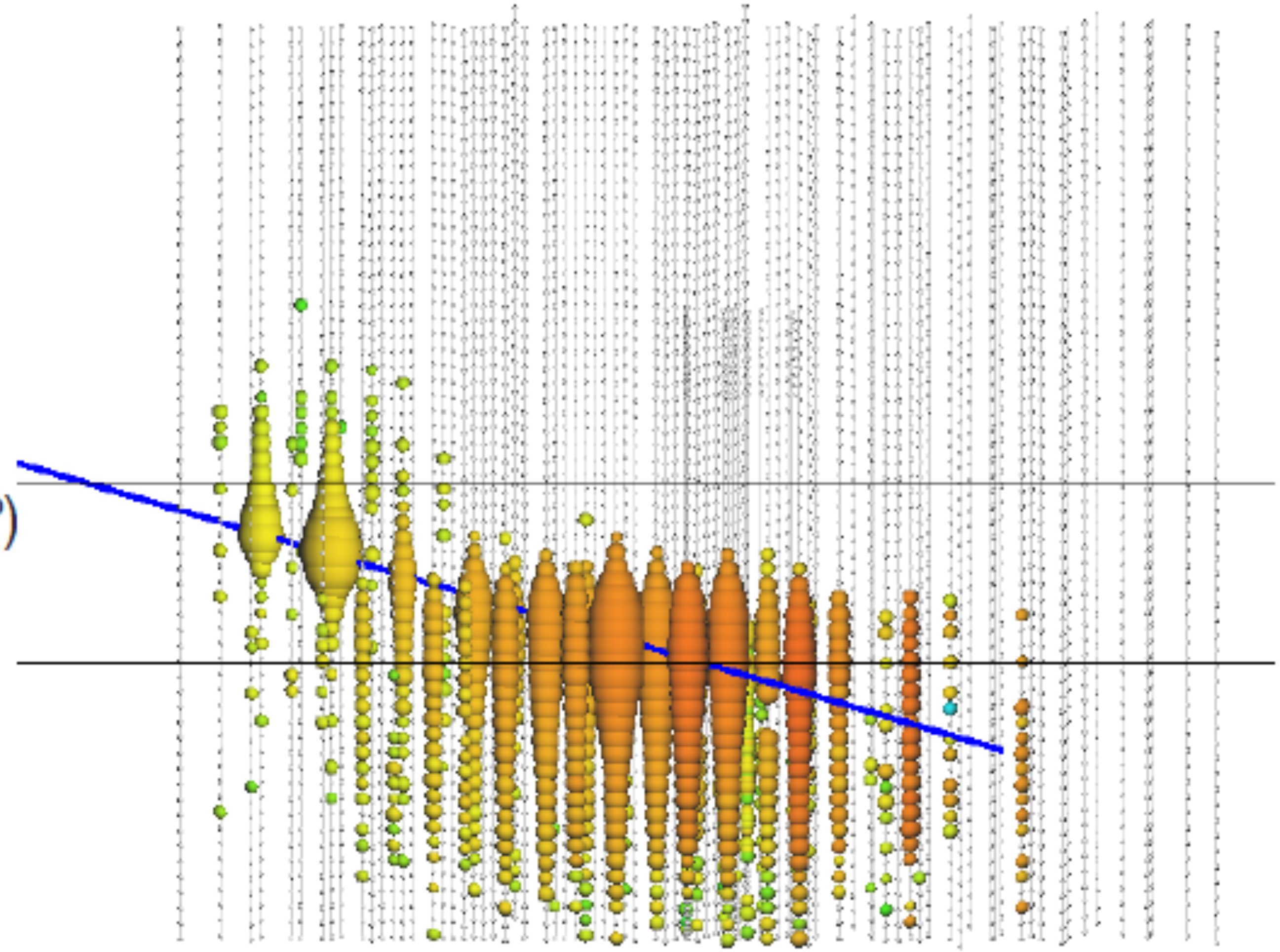
"Bert"
1.04 PeV
Aug. 2011

"Ernie"
1.14 PeV
Jan. 2012

"Big Bird"
2 PeV
Dec. 2012

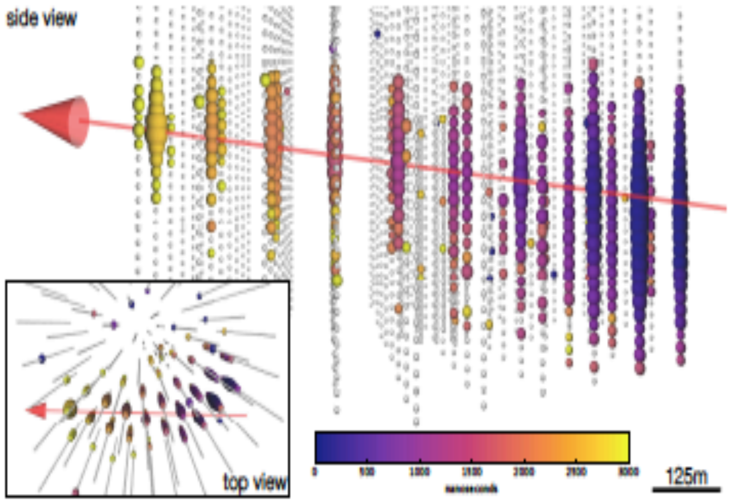
2.6 PeV !

- Reconstructed with 2.6±0.3 PeV *deposited* energy
  - Lower limit on neutrino energy
- Up-going muon neutrino (decl. 11.5°)
  - June 11, 2014



2 indications for point sources

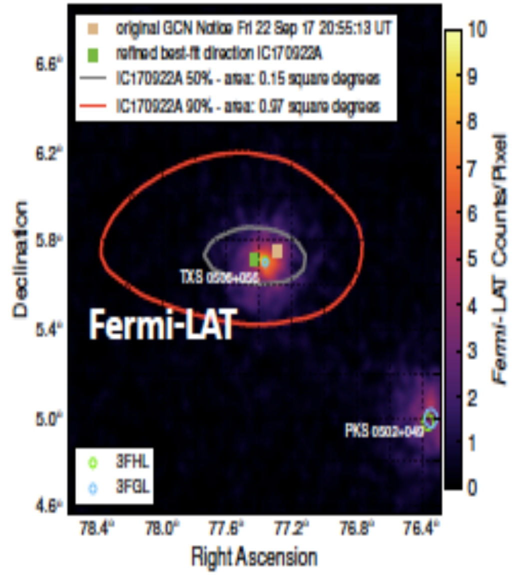
A high energy neutrino in coincidence with a flaring blazar



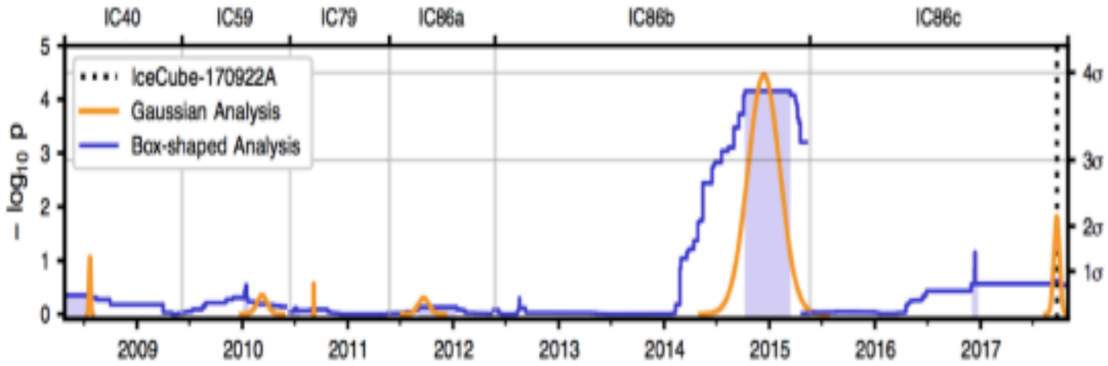
Science 13 Jul 2018: Vol. 361, Issue 6398

Science 13 Jul 2018: Vol. 361, Issue 6398

Correlation of IC170922A with TXS 0506+056 preferred to chance at 3σ level

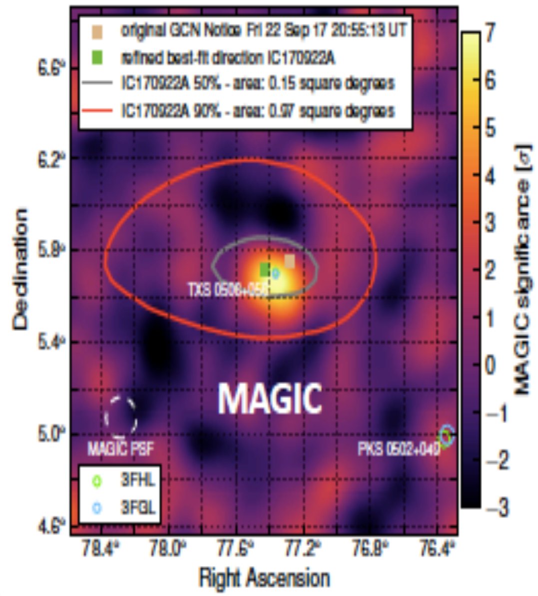


Blazar redshift 0.3365 +/0.0010 (Paiano *et al.*)



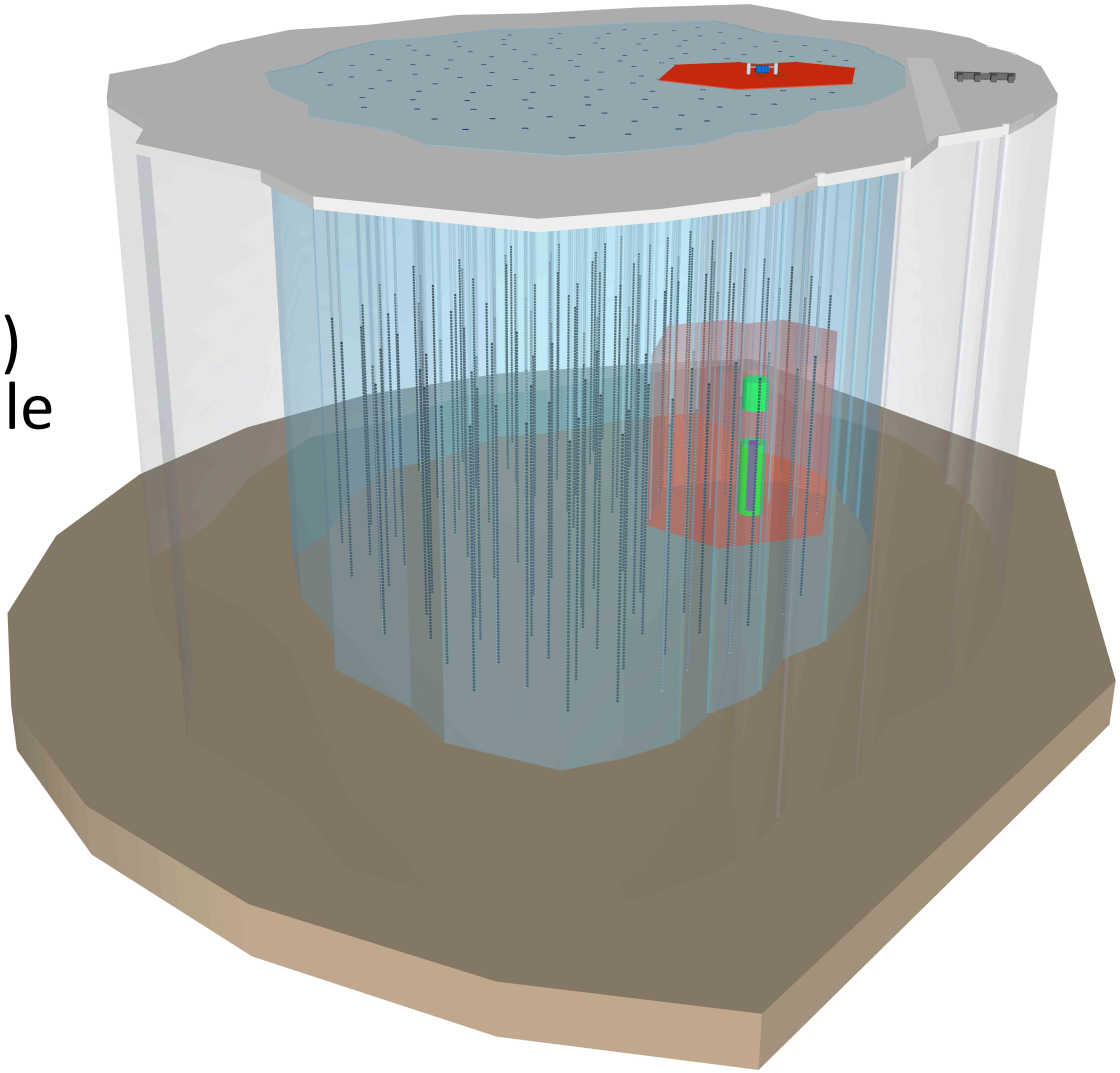
Excess of neutrinos observed between September 2014 and March 2015

Background only hypothesis rejected at 3.5σ



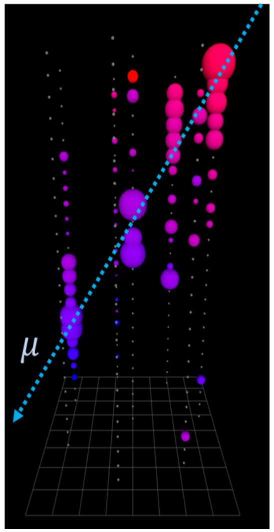
The IceCube Gen2 facility: conceptual drawing

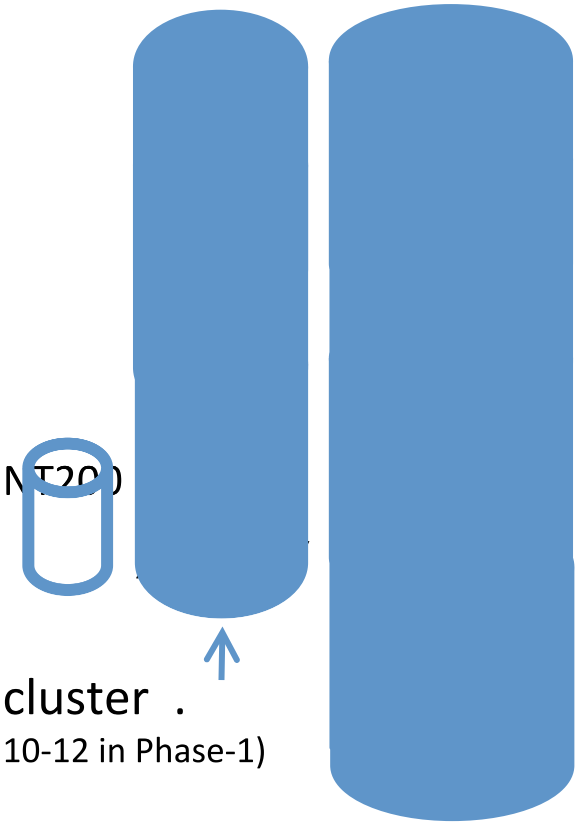
- PINGU : low energy, mass hierarchy
- High Energy Array (HEA)
  - 100 TeV- PeV scale neutrinos
- Cosmic Ray Array (CRA)
  - veto array for HEA
  - cosmic ray physics
- Radio Array (RA)
  - > 100 PeV
  - BZ (GZK) neutrinos

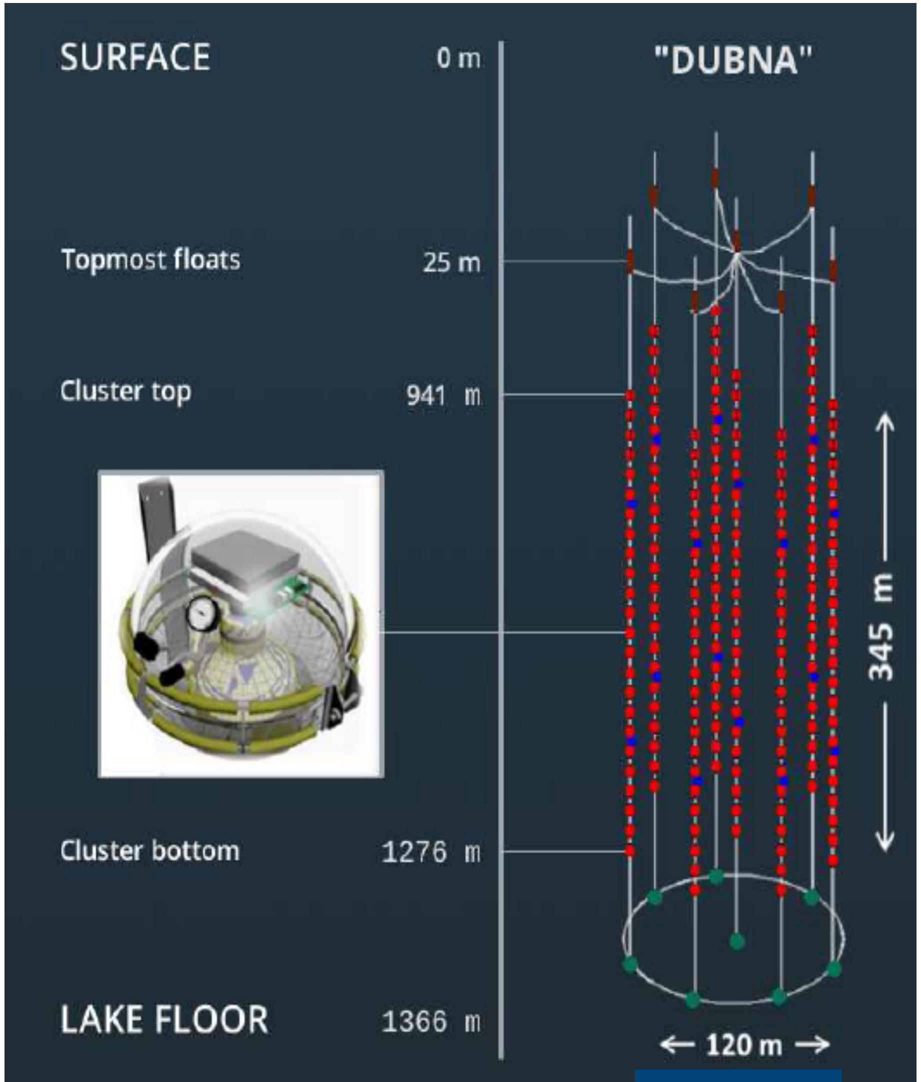


GVD: from NT200 to GVD clusters

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



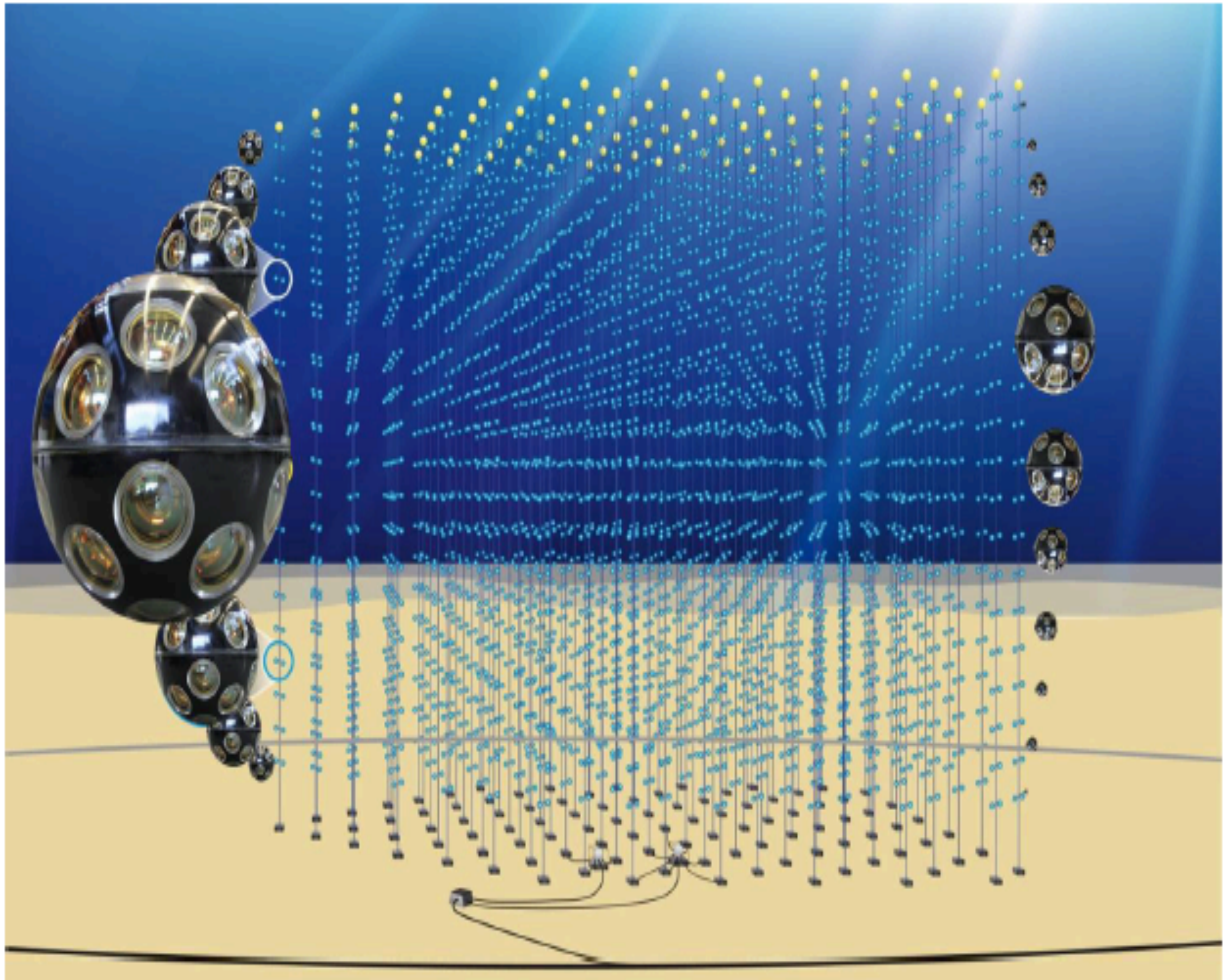


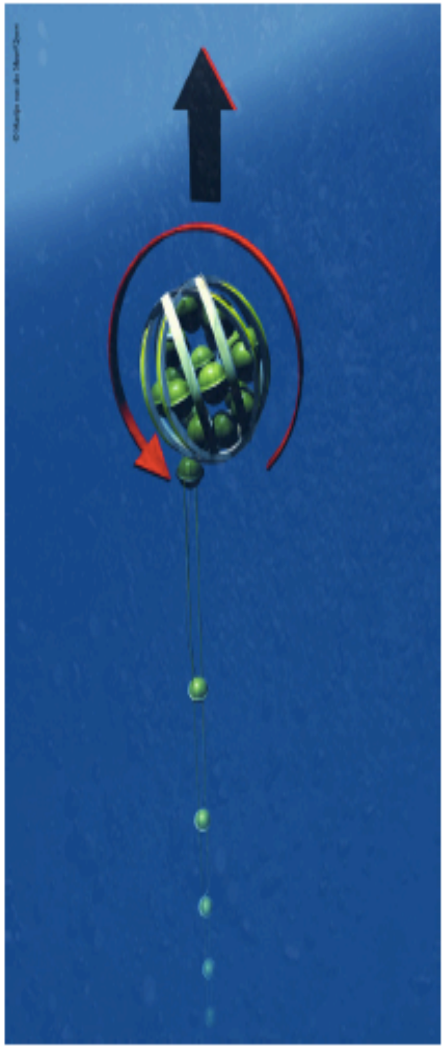


2015 still 80 m

KM3NeT

KM3NeT consists of “blocks” of 115 strings with 18 Digital Optical Modules. Two blocks for high energy (ARCA) and one for low energy (ORCA) under construction. Superb angular resolution and complementary hemisphere to IceCube.

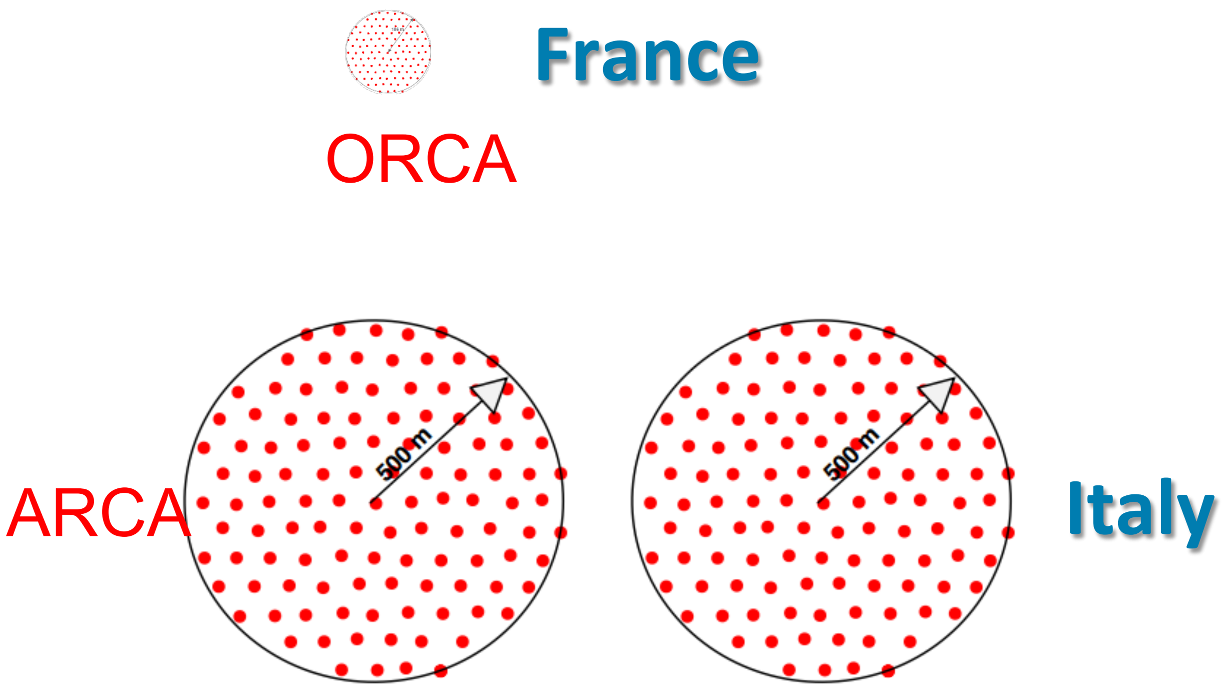




KM3NeT 2.0 Letter of Intent, arXiv:1601.07459

Phase 2.0: ORCA and ARCA

(2020?)



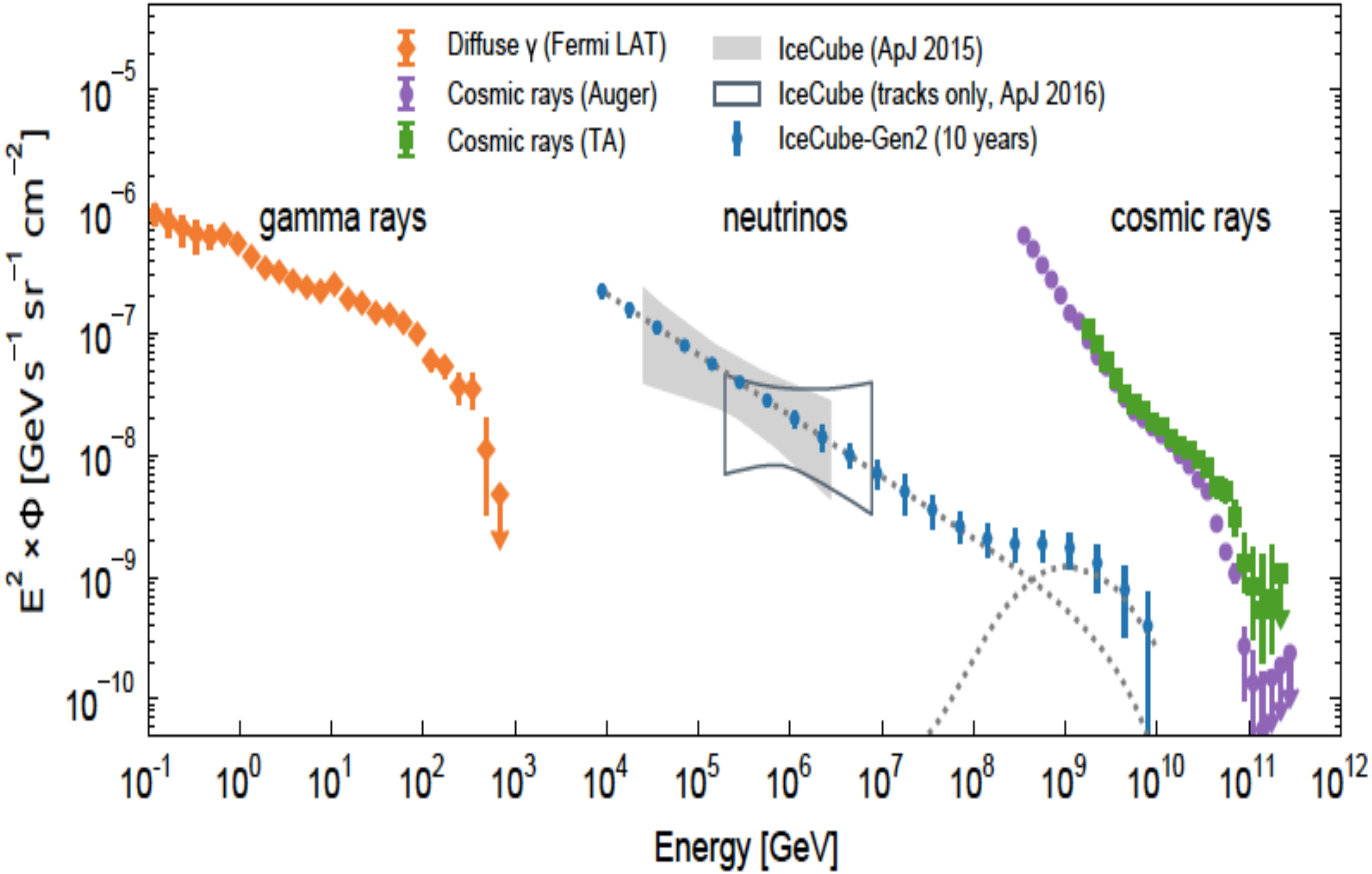
ORCA: determination of the Neutrino Mass Hierarchy (NMH)

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

Conclusions HE neutrinos

- Cosmic high-energy neutrinos discovered !
- Opened new window, but landscape not yet charted:
  one point source identified(3 sigmas) up to now
- Remaining uncertainties on spectrum and flavor composition
- First point source(s) seen. Many Point sources in reach!
- Need larger detectors, also with different systematics and at the Northern hemisphere.
- Next logical step: ARCA + GVD_{Phase1}
- Next logical step on NMH: ORCA (then PINGU)
- ~2028: A Global Neutrino Observatory (KM3NeT-GVD-IceCube-Gen2,) full sky with > 5 km^3

Science: Resolving the mysteries of the UHE Universe



Albert Einstein

1916

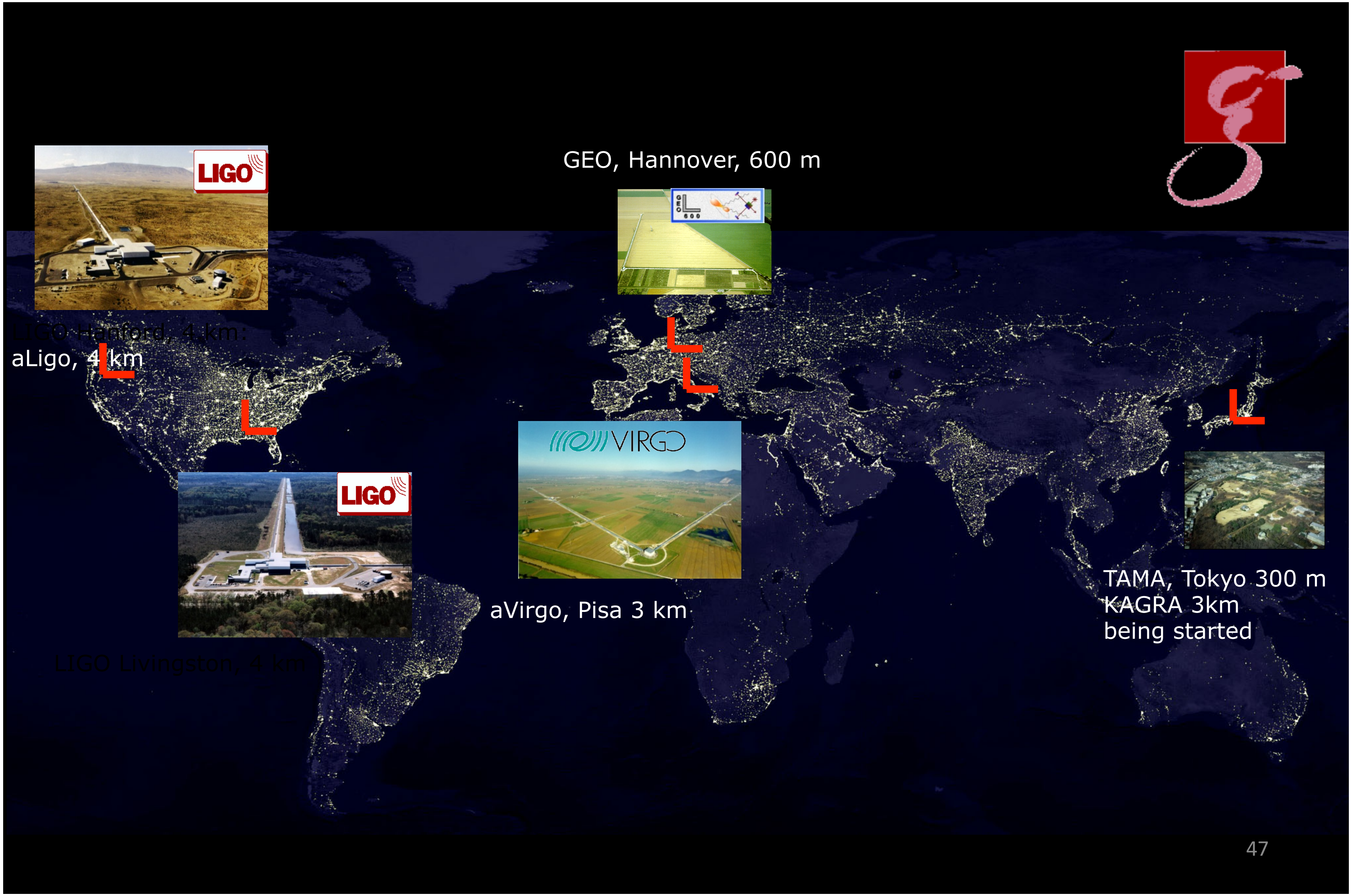
Prediction of gravitational waves

Joseph Weber

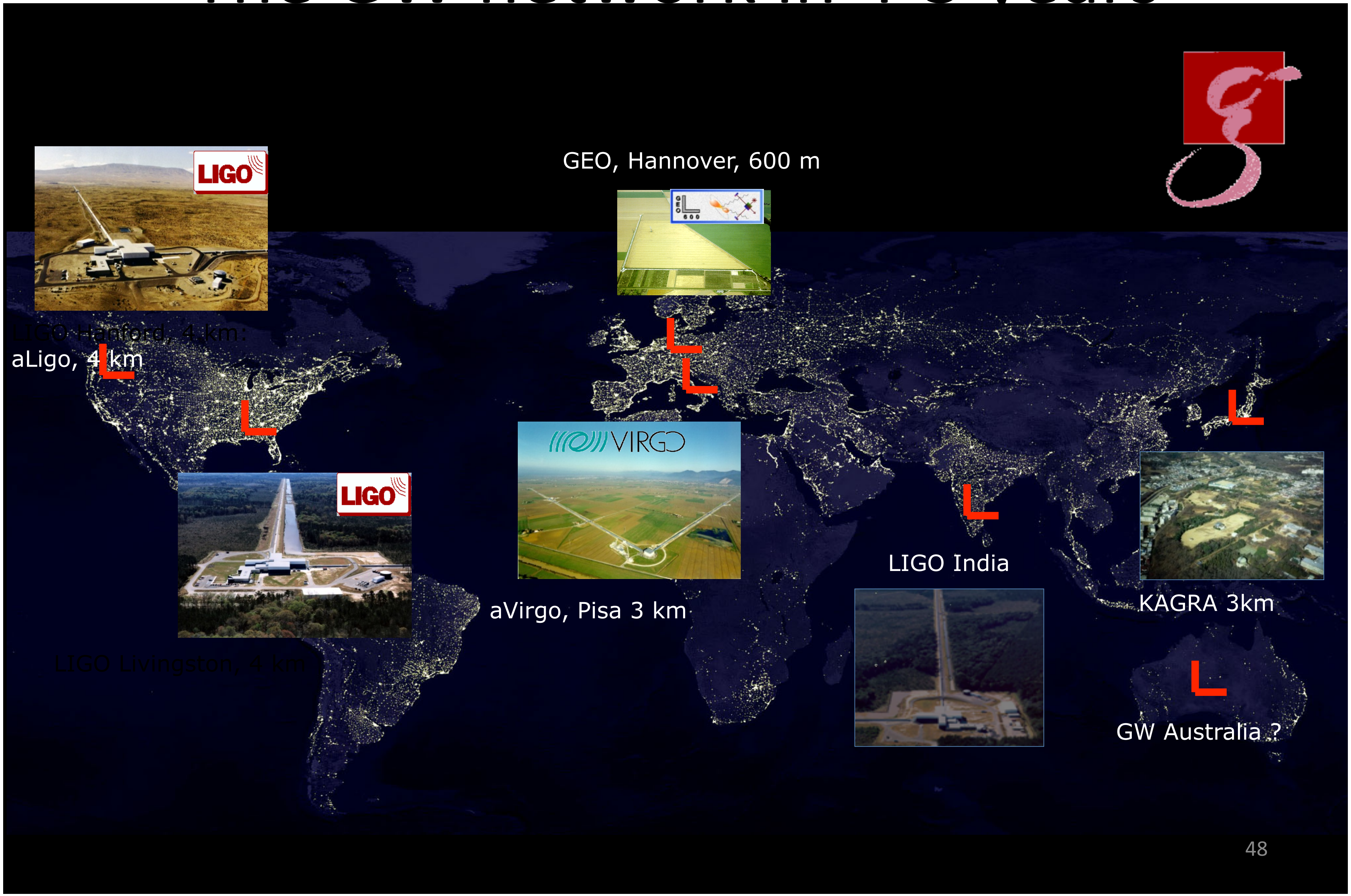
1958

Search for GW with a bar cylinder

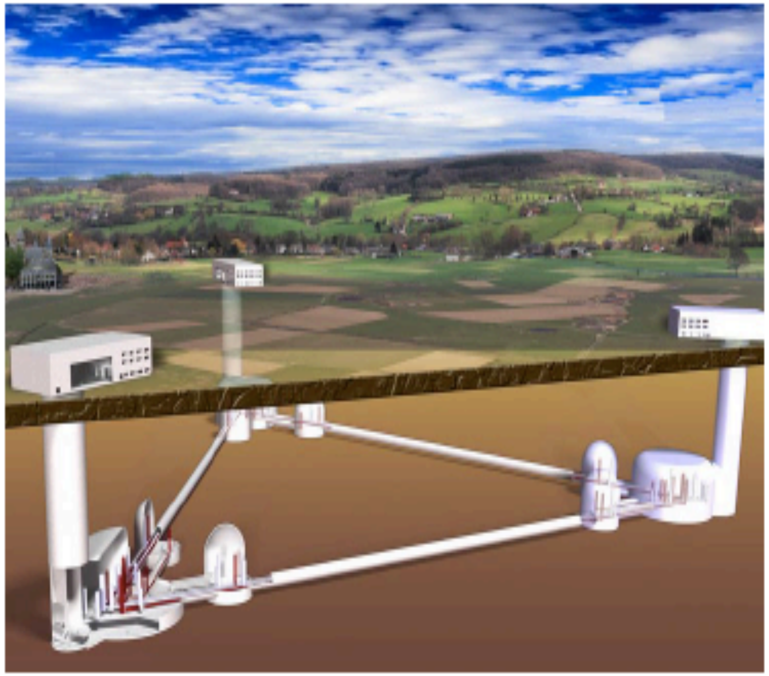
The current GW network of interferometers

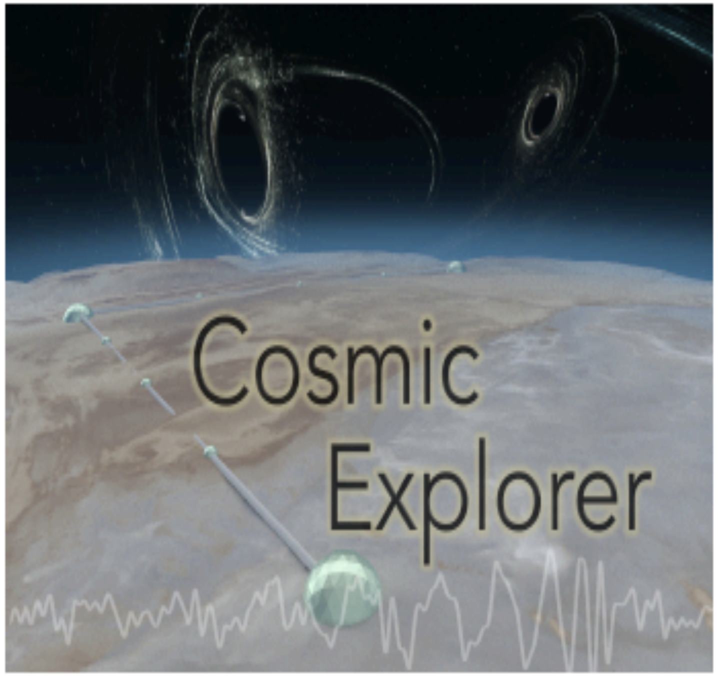


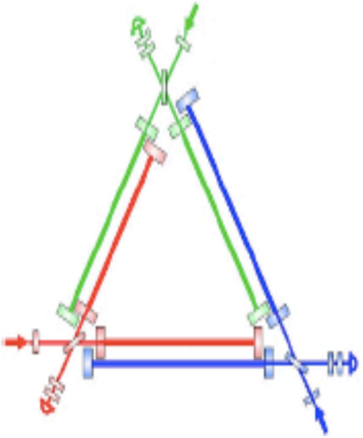
The GW network in 4-5 years



Gravitational Waves: 3rd generation interferometers





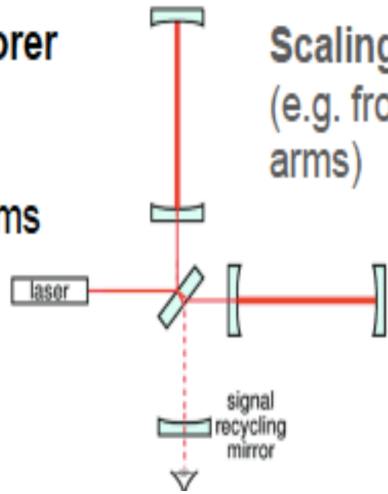


Einstein Telescope (EU lead)

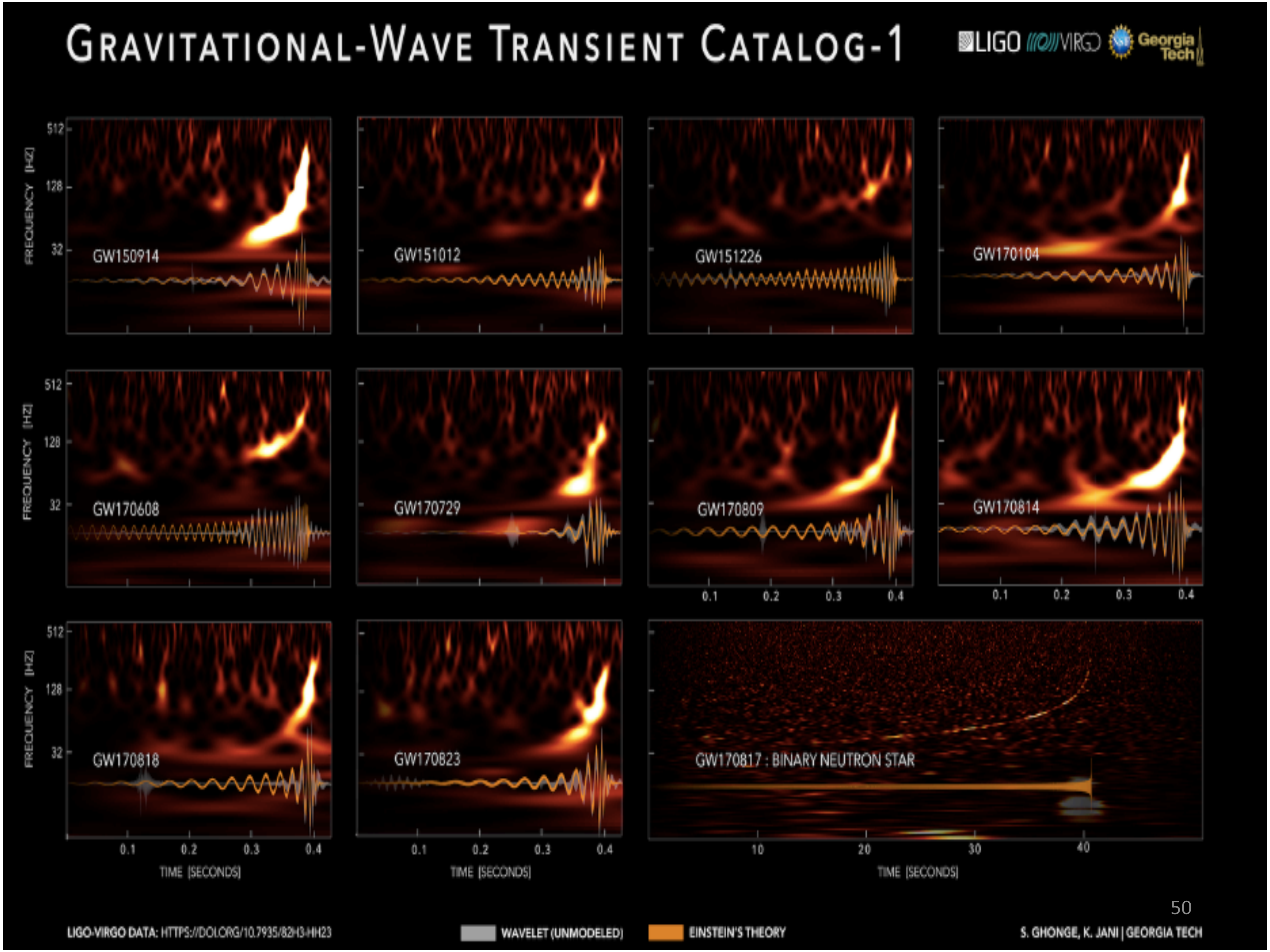
- 3 x 10 km arms
- underground
- cryo technology

Cosmic Explorer (US lead)

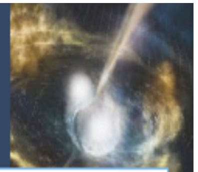
- 2 x 40 km arms
- on ground

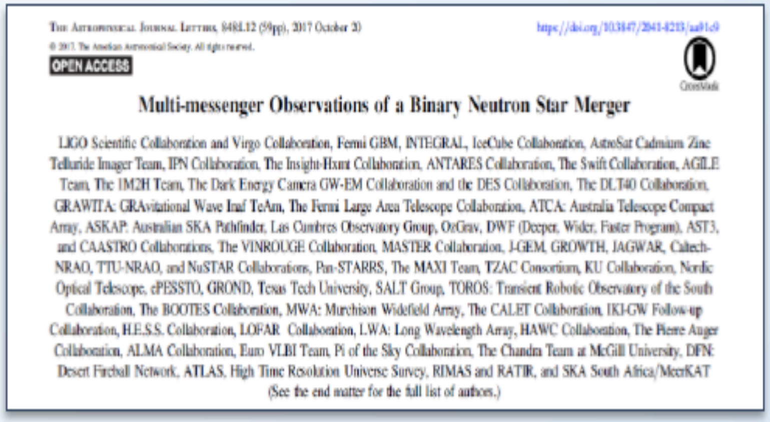


Scaling of project size: ~10
(e.g. from current 4 to ~40 km arms)


GRAVITATIONAL-WAVE TRANSIENT CATALOG-1
LIGO VIRGO
Georgia Tech
FREQUENCY [HZ]
512
128
32
GW150914
GW151012
GW151226
GW170104
GW170608
GW170729
GW170809
GW170814
GW170818
GW170823
GW170817 : BINARY NEUTRON STAR
0.1
0.2
0.3
0.4
10
20
30
40
TIME [SECONDS]
LIGO-VIRGO DATA: HTTPS://DOI.ORG/10.7935/82H3-HH23
WAVELET (UNMODELED)
EINSTEIN'S THEORY
S. GHONGE, K. JANI | GEORGIA TECH

The first Multi-Messenger paper!




The Astrophysical Journal Letters, 848:L12 (59pp), 2017 October 20
https://doi.org/10.3847/2041-8213/aa91c9
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Multi-messenger Observations of a Binary Neutron Star Merger

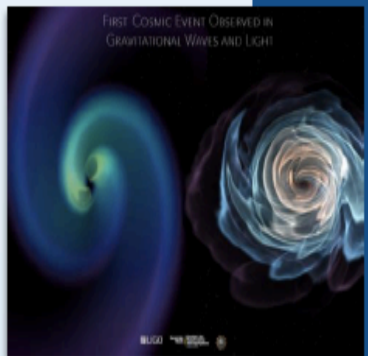
LIGO Scientific Collaboration and Virgo Collaboration, Fermi GBM, INTEGRAL, IceCube Collaboration, AstroSat Cadmium Zinc Telluride Imager Team, IPN Collaboration, The Insight-Hxmt Collaboration, ANTARES Collaboration, The Swift Collaboration, AGILE Team, The 1M2H Team, The Dark Energy Camera GW-EM Collaboration and the DES Collaboration, The DLT40 Collaboration, GRAWITA: GRAvitational Wave Inaf TeAm, The Fermi Large Area Telescope Collaboration, ATCA: Australia Telescope Compact Array, ASKAP: Australian SKA Pathfinder, Las Cumbres Observatory Group, OzGrav, DWF (Deeper, Wider, Faster Program), AST3, and CAASTRO Collaborations, The VINROUGE Collaboration, MASTER Collaboration, J-GEM, GROWTH, JAGWAR, Caltech-NRAO, TTU-NRAO, and NuSTAR Collaborations, Pan-STARRS, The MAXI Team, TZAC Consortium, KU Collaboration, Nordic Optical Telescope, ePESSTO, GROND, Texas Tech University, SALT Group, TOROS: Transient Robotic Observatory of the South Collaboration, The BOOTES Collaboration, MWA: Murchison Widefield Array, The CALET Collaboration, IKI-GW Follow-up Collaboration, H.E.S.S. Collaboration, LOFAR Collaboration, LWA: Long Wavelength Array, HAWC Collaboration, The Pierre Auger Collaboration, ALMA Collaboration, Euro VLBI Team, Pi of the Sky Collaboration, The Chandra Team at McGill University, DFN: Desert Fireball Network, ATLAS, High Time Resolution Universe Survey, RIMAS and RATIR, and SKA South Africa/MeerKAT

(See the end matter for the full list of authors.)

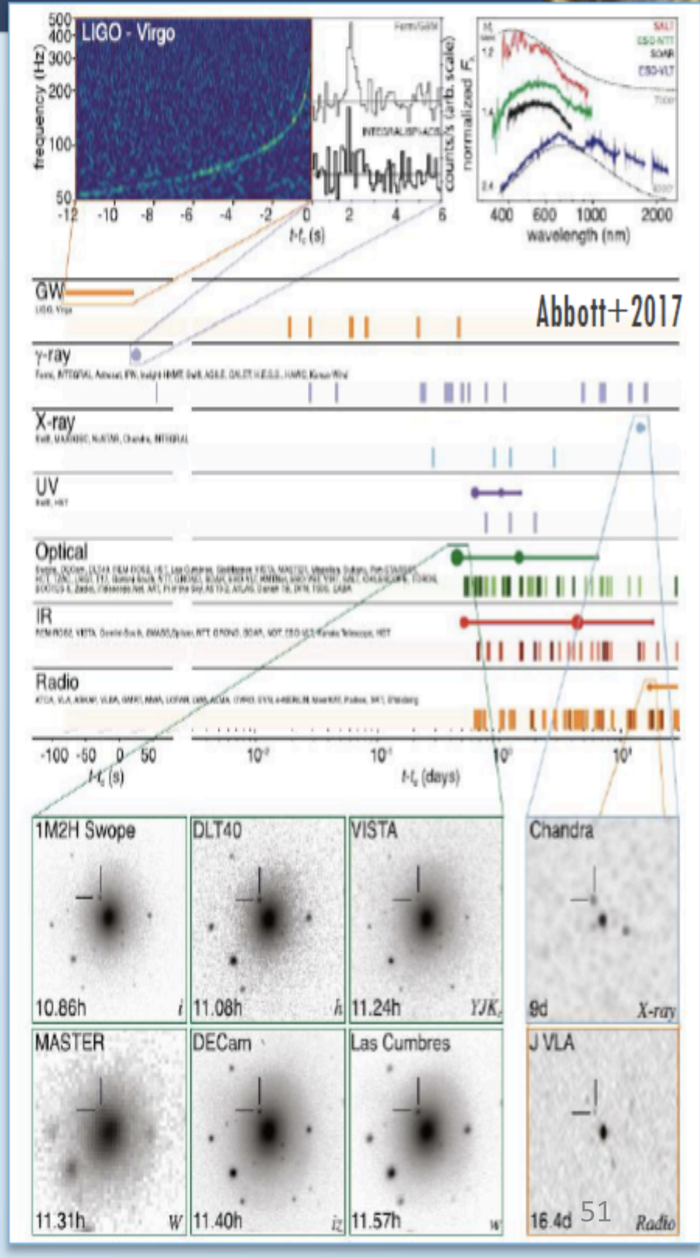
50 teams
>3600 authors

~20 orders of magnitude in wavelength

Including **VHE** and **neutrino** follow-up



Credit: LIGO-Virgo



High and ultra high energy multi-messenger astronomy

- Gamma ray astronomy paved the way, gives the reference map of the high energy sky (Thousands of sources): CTA next very large infrastructure
- Strong evidence for extraterrestrial TeV to PeV neutrinos. Probably pointing to a new class of blazars (mergers?).
- Cut-off of the cosmic ray high energy spectrum seen: composition (p or Fe) and muon production near the cut-off debated. Origin unknown.
- Gravitational waves is entering the game and open new questions: origin of 30 solar masses black holes, gamma ray bursts and neutron stars collapses…
- Multi messenger approach crucial, including gravitational waves and conventional astronomy (open data policy, virtual observatories including these new messengers will help)

General conclusions on Open Data Policy taken from gravitational waves antennas remarkable practices

- Ground gravitational antennas: bottom-up approach, science driven data policy
- General considerations: avoid false discoveries (largely quoted and contributing to the h-index!!!!), give proper credit by quoting properly the used data release (collaboration), resources have to be planned from the very beginning with funding agencies
- Works now also quite well with GNN (Global Neutrino Network observatory)

Open Data policy (5 tempos) for high energy multimessenger astronomy (extra resources needed)

- Data validation (Collaboration)
- First data releases for joint analysis (Collaborations)
  - For combinations and mutual cross-checks
  - For complementary approaches
- Open trigger on or off line (for collaborations on multi-messenger astronomy)
- Data in open access for the community (get the collaboration and the community prepared, virtual observatory model, central office and help-desk for data and codes?)
- Data preservation and legacy

Access and Data Policy

- There is always competition (e.g. for funding opportunities, fame, …) but there must be also consensus on sharing of data, know-how, …
- MoU (bottom-up initiated and science driven) signed by funding agencies, with attached resources, could be an adequate tool

Features of Particle astrophysics

- Collaborative
- Innovative (creating new instruments)
- Stimulating
- “coopetition”
- Search for Unity (explanations, class of objects, laws) within Diversity (objects in the sky): observational cosmology is a success in that direction

A fascinating field

- Bold
- Inclusive and participative (developing countries, gender balance,young people, local community)
- Interdisciplinary
- Incredible locations and instruments
- Rich in discoveries
- Sometimes disruptive

International Year of Basic Sciences for Sustainable Development in 2022

- IUPAP (International Union of Pure and Applied Physics) is taking the lead for the proclamation of an International Year of Basic Sciences for Sustainable Development)
- It was recommended by the UNESCO Executive Board and soon by the UNESCO General Conference. The proclamation should be by the UN end of 2020
- We are looking forward Argentina organizing an event, maybe on Multimessenger Astronomy and Sustainable Development.

END