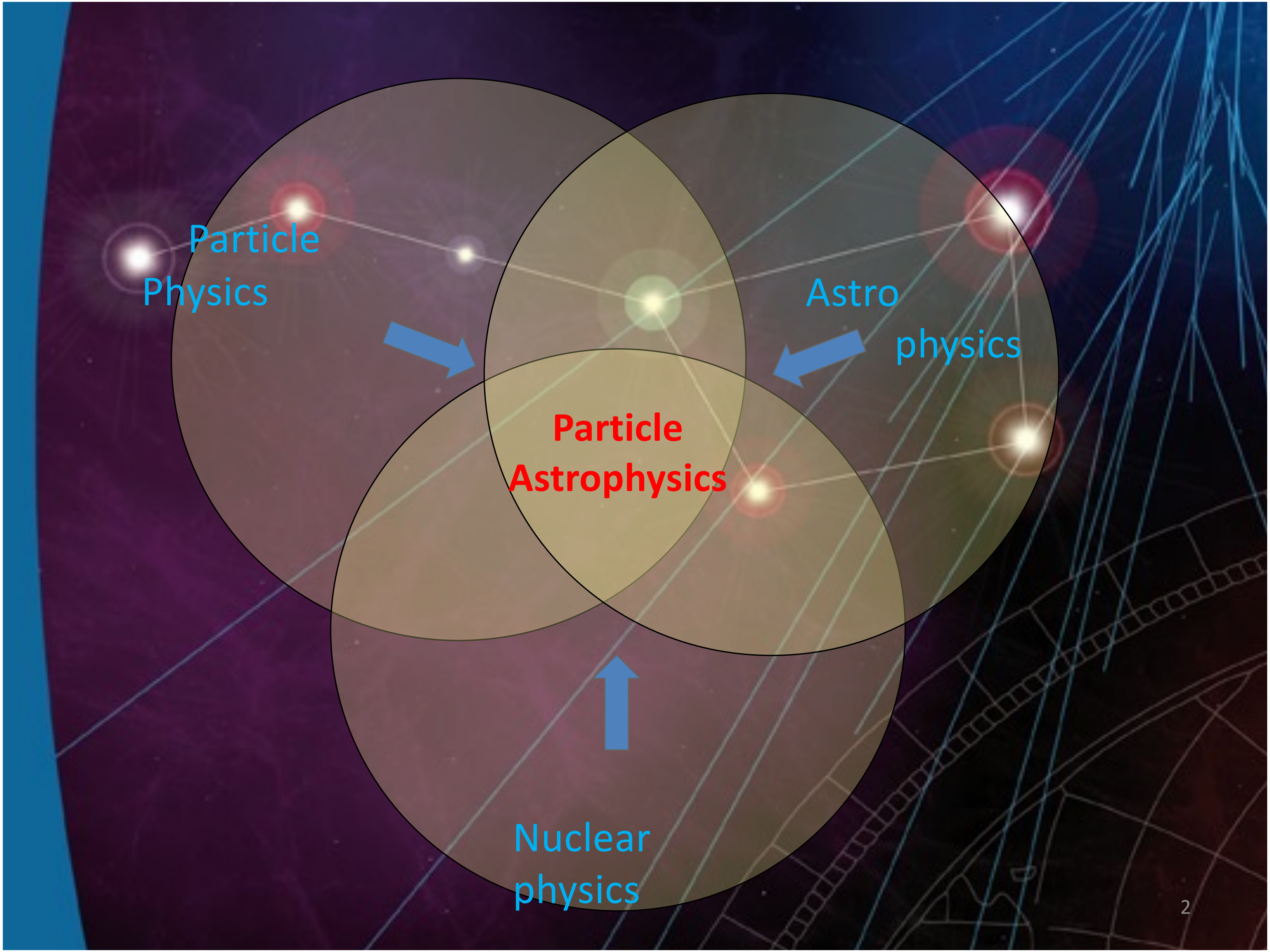
History of Particle Astrophysics

Multi messenger astronomy, past and present with a view to the Future

Michel Spiro
President of IUPAP


Particle
Physics
Astro
physics
Particle
Astrophysics
Nuclear
physics

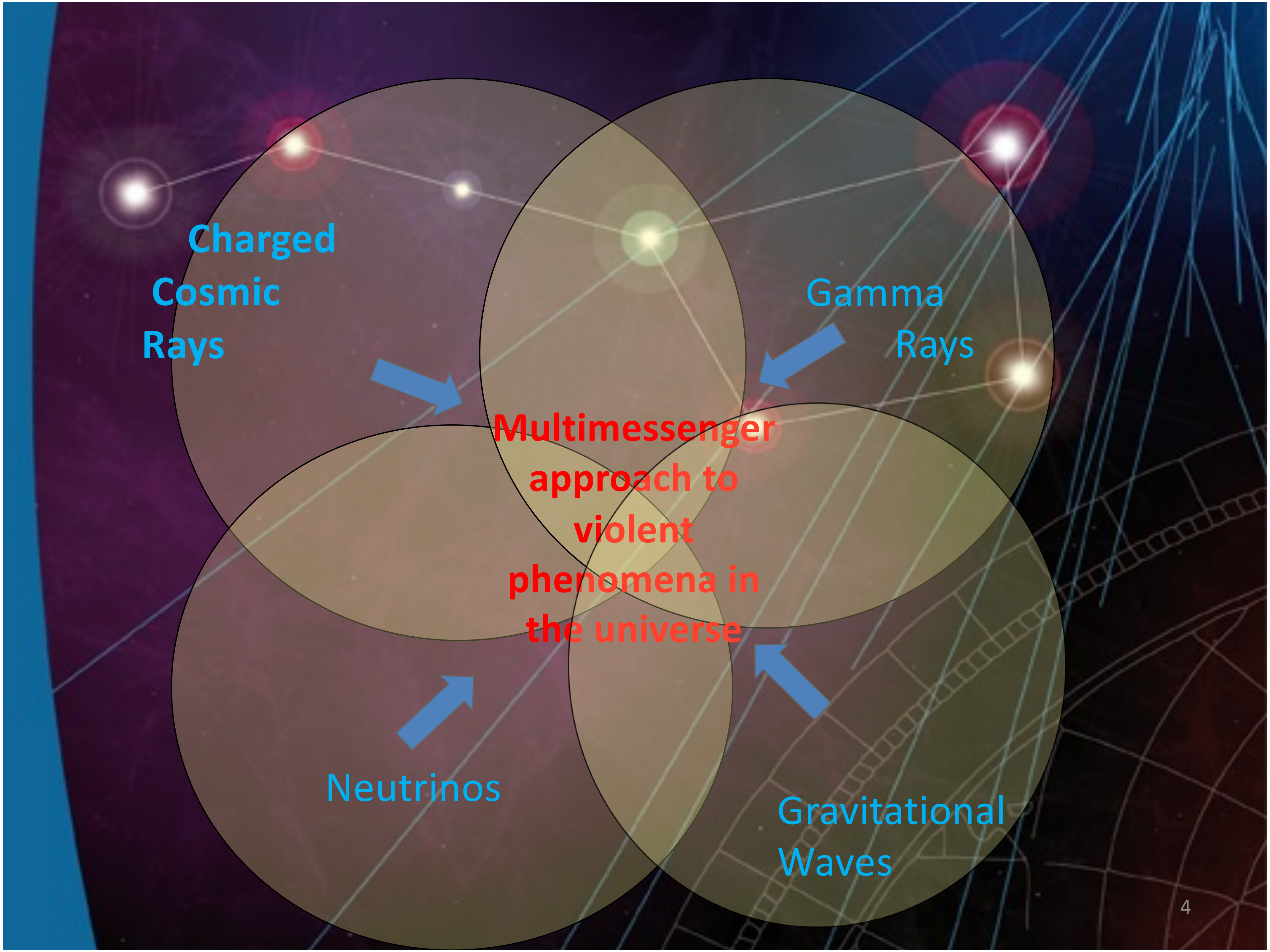
WHAT IS PARTICLE ASTROPHYSICS

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

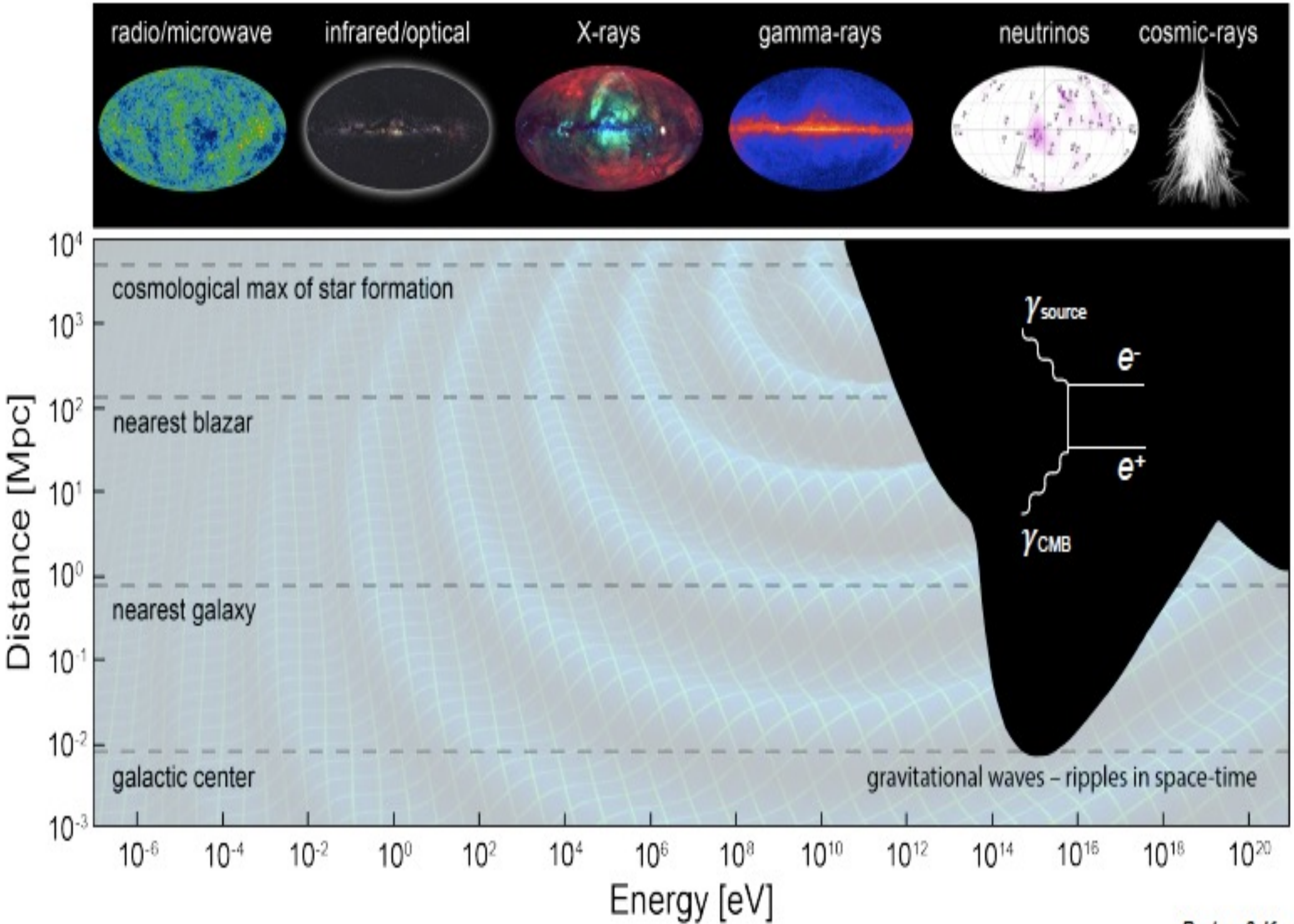
2) Neutrino Physics and Proton Decay
   Neutrino cosmology
   Neutrinos and star evolution: **Solar neutrinos**, **Supernova 1987**
   Non accelerator Neutrino physics (mass, oscillations, nature:
      Dirac, Majorana, sterile)
   Proton decay.

3) High energy astrophysics (multimessenger approach)
   high Energy Neutrinos (Moisej Markov)
   high energy Gamma rays (Alexander Chudakov)
   high enregy cosmic rays (Pierre Auger)
   Gravitational waves (Albert Einstein)
   coupled to astronomy from infra red to X-rays

With a Zoom on France


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

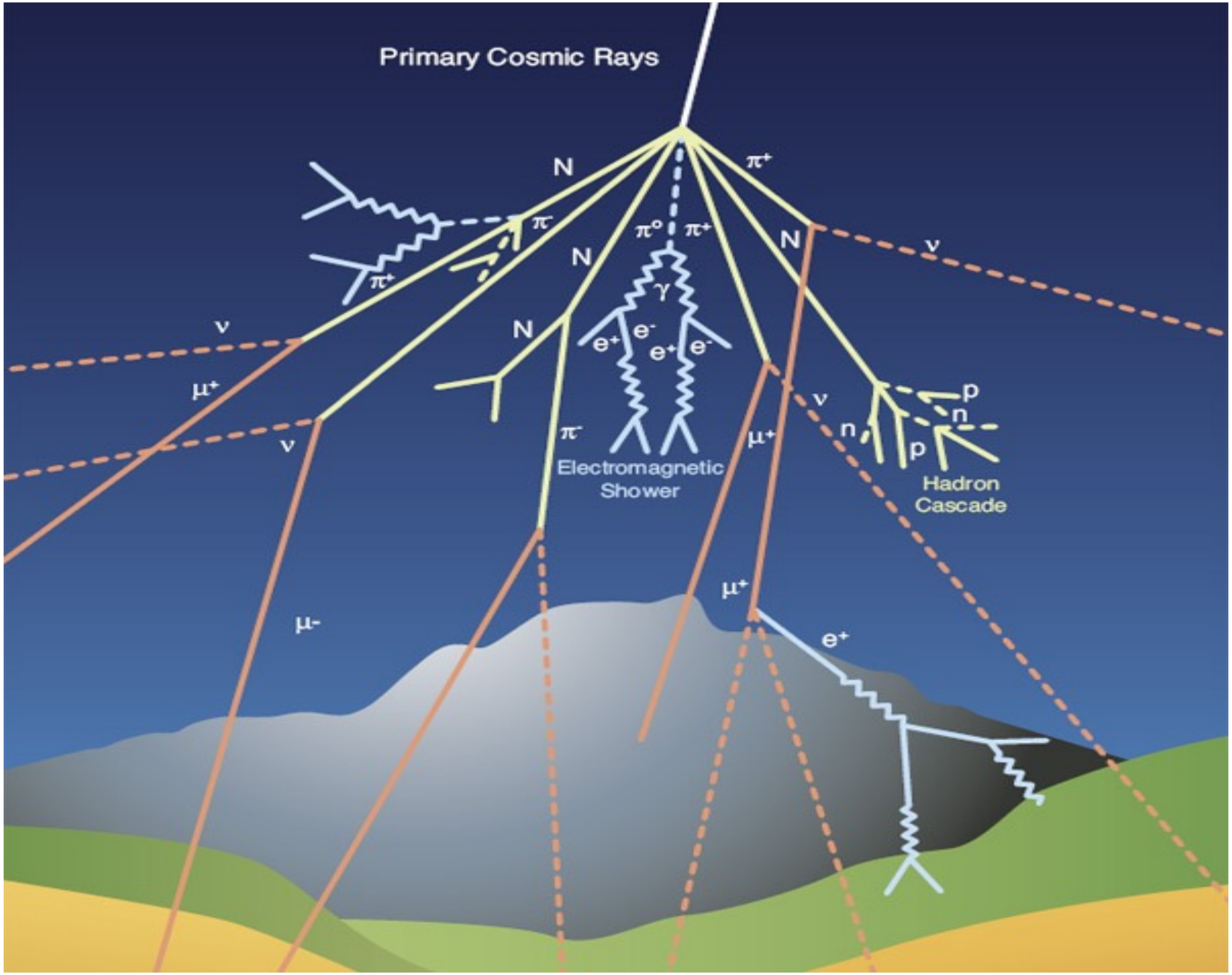
A multitude of cosmic messengers from from low to high energies



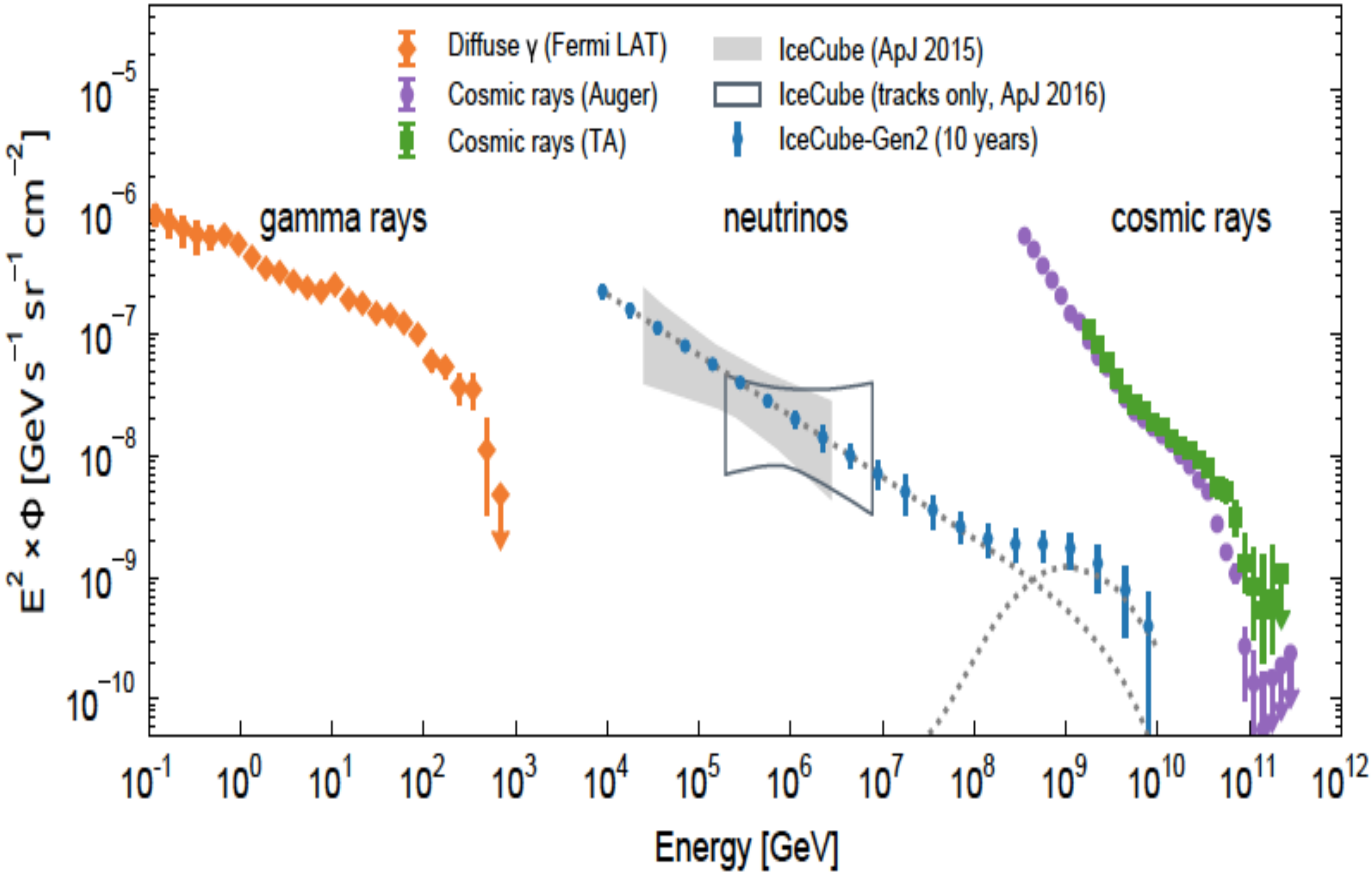
Bartos & Kowalski, IOP 2017

Primary cosmic ray showers:

detectors are on ground, on mountains, on balloons or in space, deep underwater



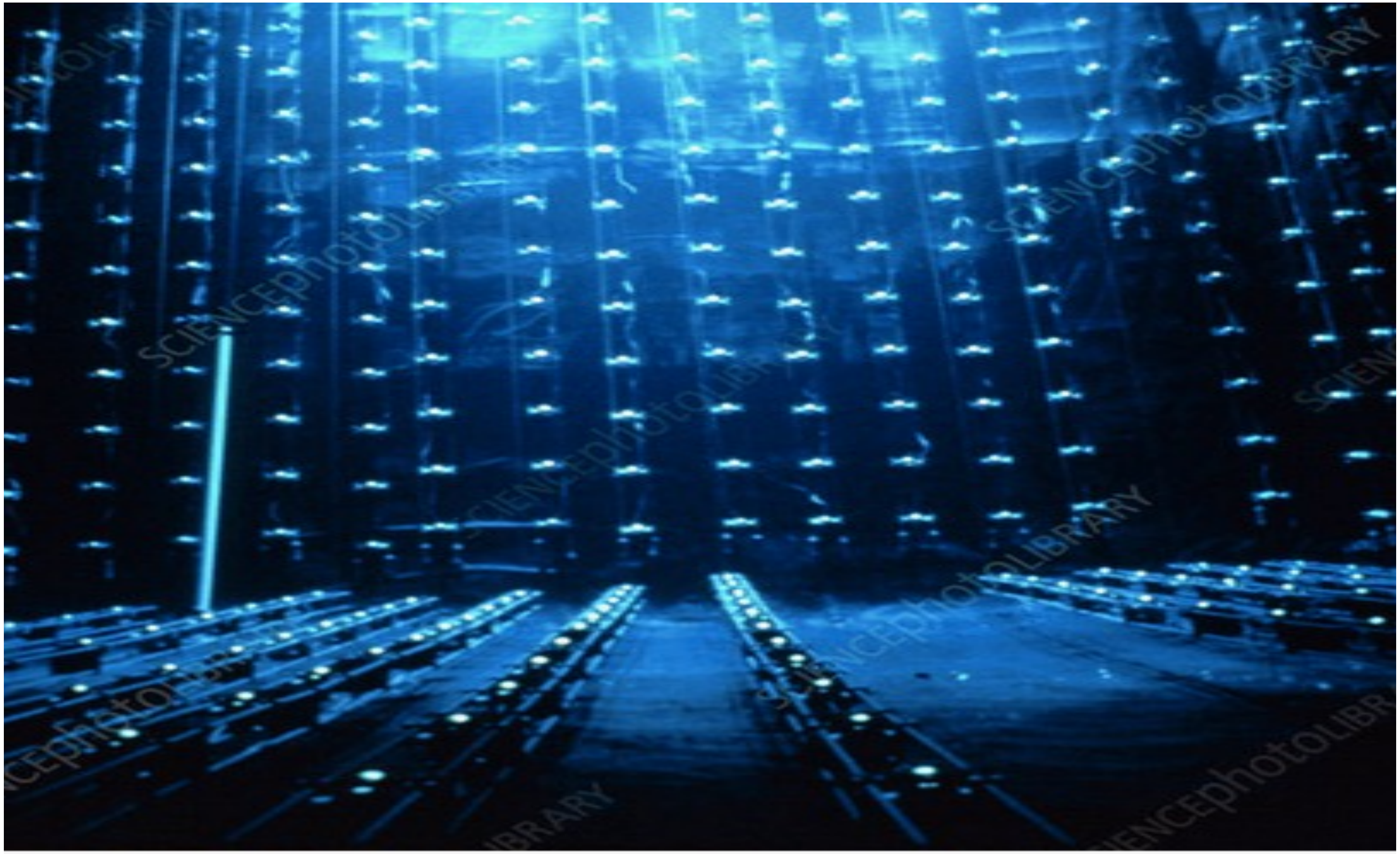
Science: Resolving the mysteries of the UHE Universe



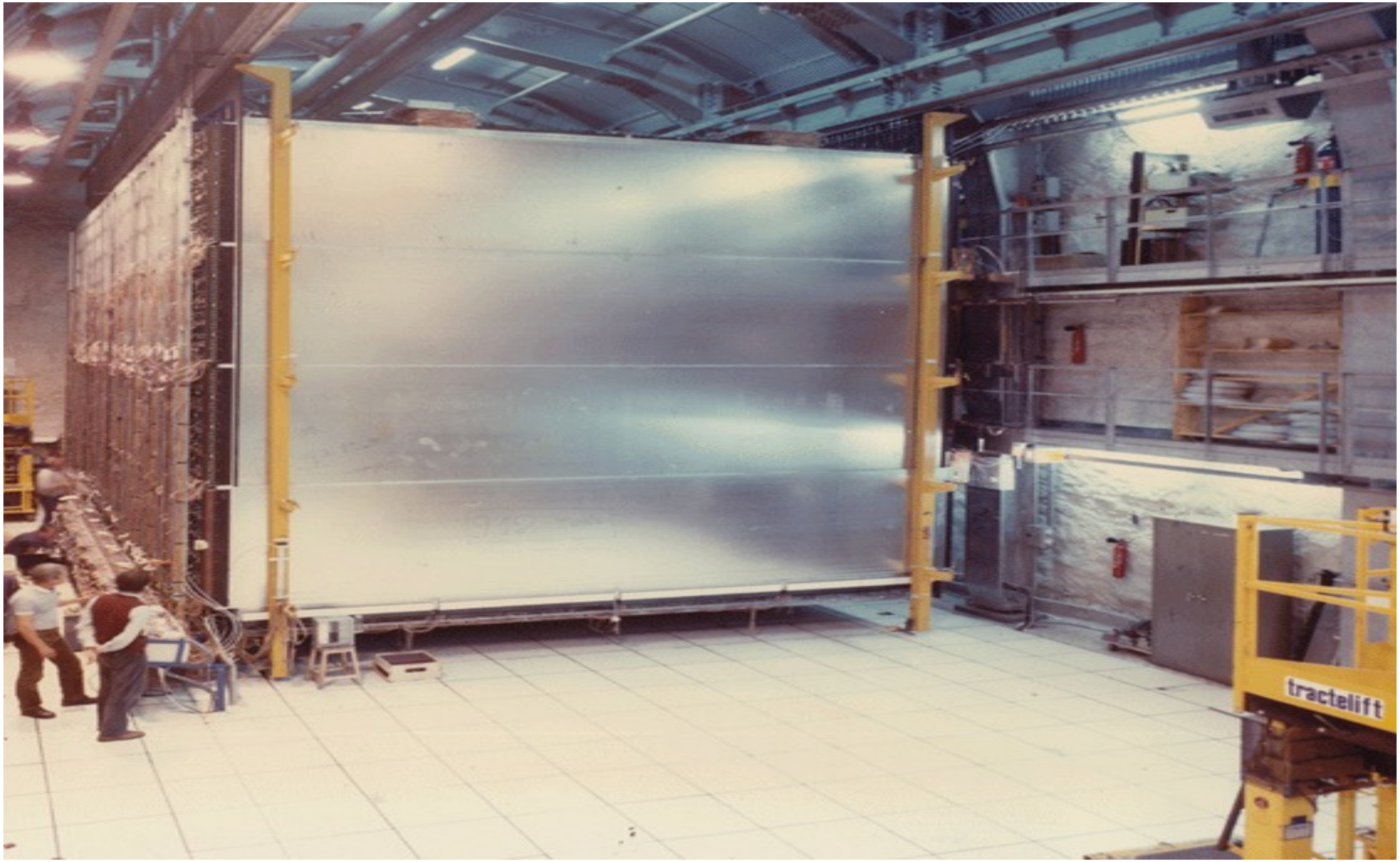
Motivations

- Spectra, composition and origins of cosmic rays (super/hypernovae, Active Galactic Nuclei, coalescence..)
- Learn about acceleration mechanisms in the Universe (jets)
- Search for new physics beyond the reach of accelerators
- Indirect detection of dark matter particles, through their annihilation into gamma rays or neutrinos, or in the form of dark matter black holes detected recently through their gravitational coalescence
- Started in the 80's with underground searches for proton decay(10^{30} years expectation) detectors and three anomalies: ultra high energy cosmic ray anomaly (events beyond the Greisen, Zatsepine, Kouznine GZK cut-off observed by AGASA EAS), Cygnus X3 anomaly, solar neutrino deficit (Chlorine experiment) and

Proton lifetime experiments IMB 1981 (Sulak..), Kamiokande (1983, Koshiba…): also good muon and neutrino detectors

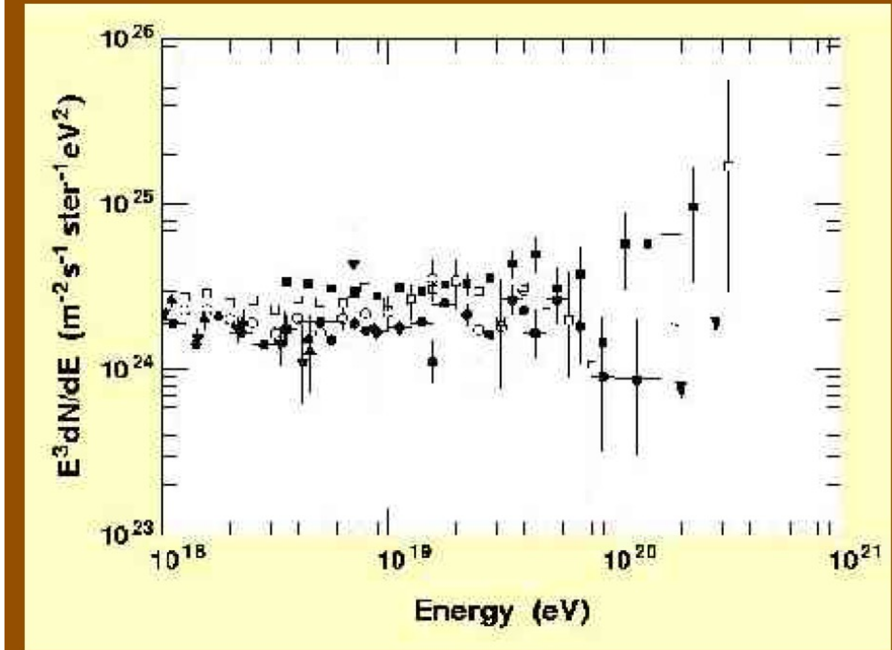


Expérience durée de vie du proton LSM 1983 (Rousset, Barloutaud, Julian..)



Three important results in 1985
1. Cosmic Rays above the GZK cut-off

Experimental data: The spectra measured by several experiments have absolute normalization different by 40%. Note that the differential flux is multiplied by E^3 to emphasize the shape of the spectrum. The results are obtained with the same hadronic interaction model.

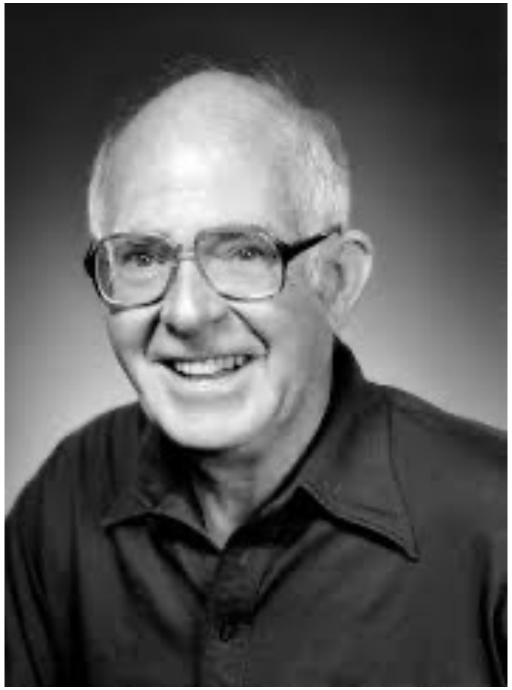


The AGASA and HiRes experiments have the highest current statistics around the GZK cut-off. AGASA shows no cut-off, while HiRes does.

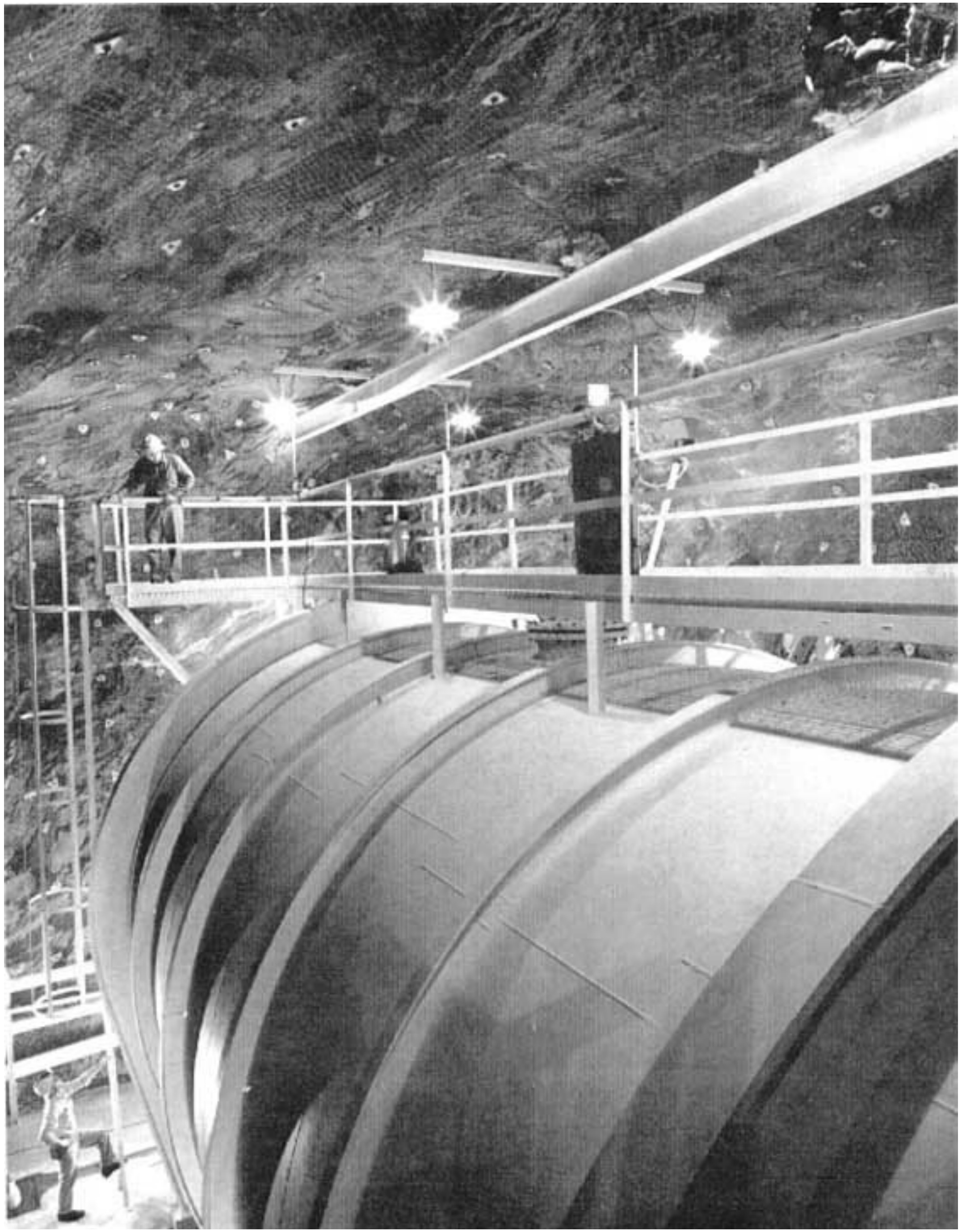
Two important results in 1985
2. Cygnus X3

- The Soudan 1 proton decay experiment has obtained additional evidence for underground muons associated with the x-ray pulsar Cygnus X-3. We report the preliminary analysis of data recorded during the October 1985 radio outburst of Cygnus X-3, which show a significant excess of muons for a narrow range of Cygnus X-3 pulsar phases.
- Trevor Weekes: After decades of fruitless search, astronomers have found a source (Cygnus X3) of high energy charged particles and TeV gamma rays bombarding the earth
- Finally this turned out to be wrong *(G. Chardin anticipated)* , but one source of TeV gamma rays was discovered by Whipple (the crab nebula supernova remnant), which is by now the reference (brightest) source in this energy range

3. The solar neutrinos deficit enigma



Ray Davis
Homestake mine
600t C_2Cl_4



Expected Solar Neutrino Spectrum (J. Bahcall)

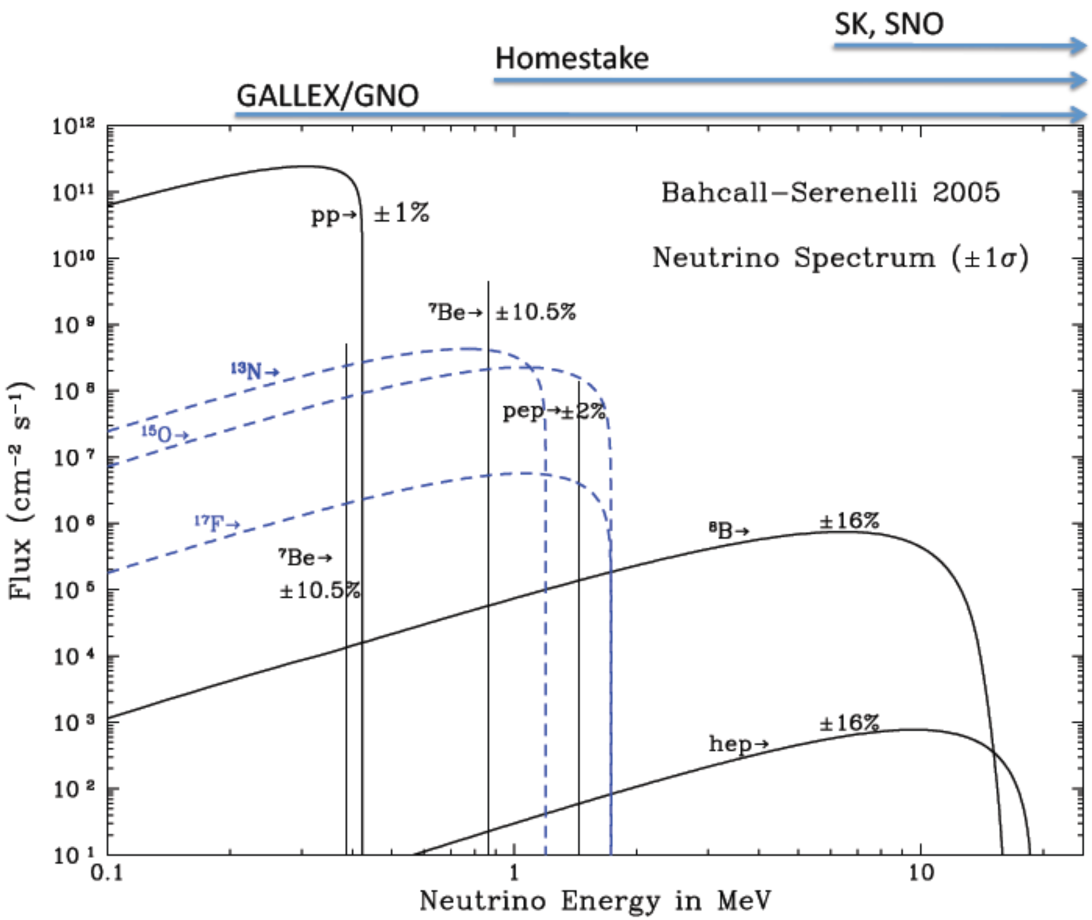


Figure 1: Neutrino fluxes (with percentage uncertainties) as predicted by the Bahcall-Serenelli

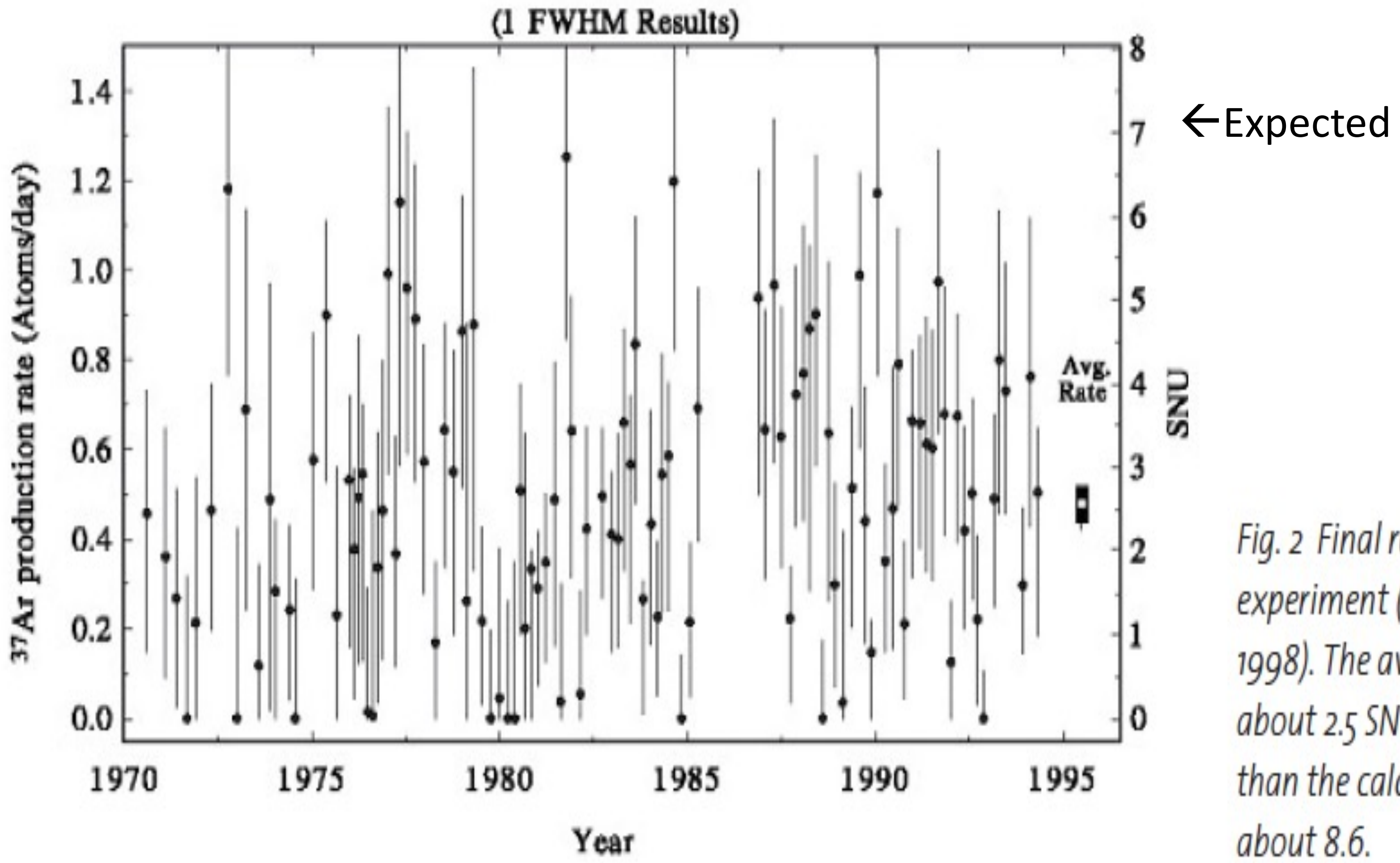


Fig. 2 Final results of Davis experiment (Cleveland et al. 1998). The average rate of about 2.5 SNU is much lower than the calculated rate of about 8.6.

Is he signal coming from solar neutrinos?
Is the detector fully efficient?
Is the discrepancy due to solar modeling (Turck-Chieze vs Bahcall) or to new neutrino properties.

GALLEX (Italy, Germany, France..)
in Gran Sasso 100t $GaCl_3$

Reaction

$^{71}Ga(\nu_e,e)^{71}Ge$ (E_{thr} = 233 keV)
EC τ = **16.5** d
^{71}Ga

Source of the signal

pp + pep	73 SNU	(55 %)
^{7}Be	35 SNU	(27 %)
CNO	8 SNU	(8 %)
^{8}B	13 SNU	(10 %)
Tot	129 SNU $^{+9}_{-7}$ 1σ	

Expected Signal (SSM)

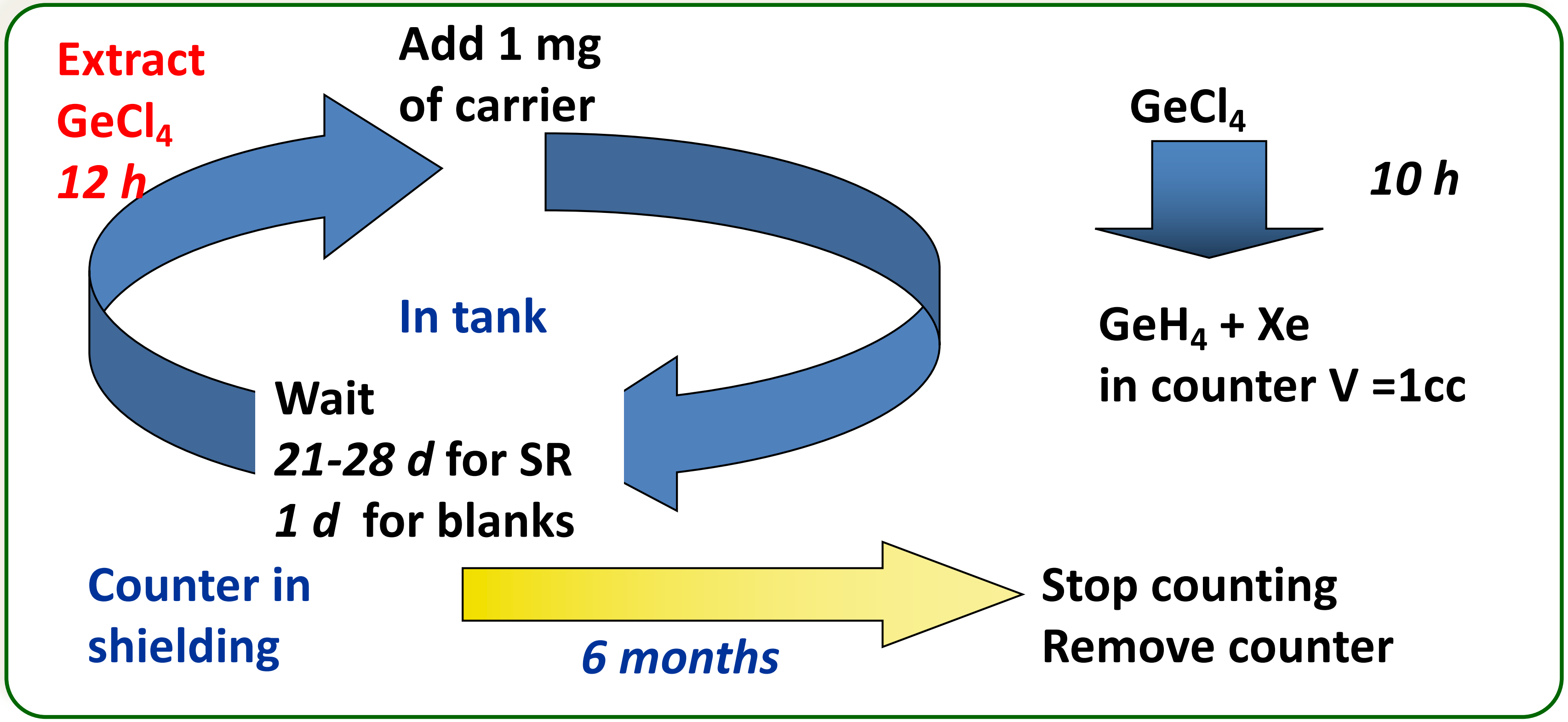
1.2 ν int. per day, but due to decay during exposure + ineff., 9 ^{71}Ge decay detected per extraction
(28 days exposure)

Extraction

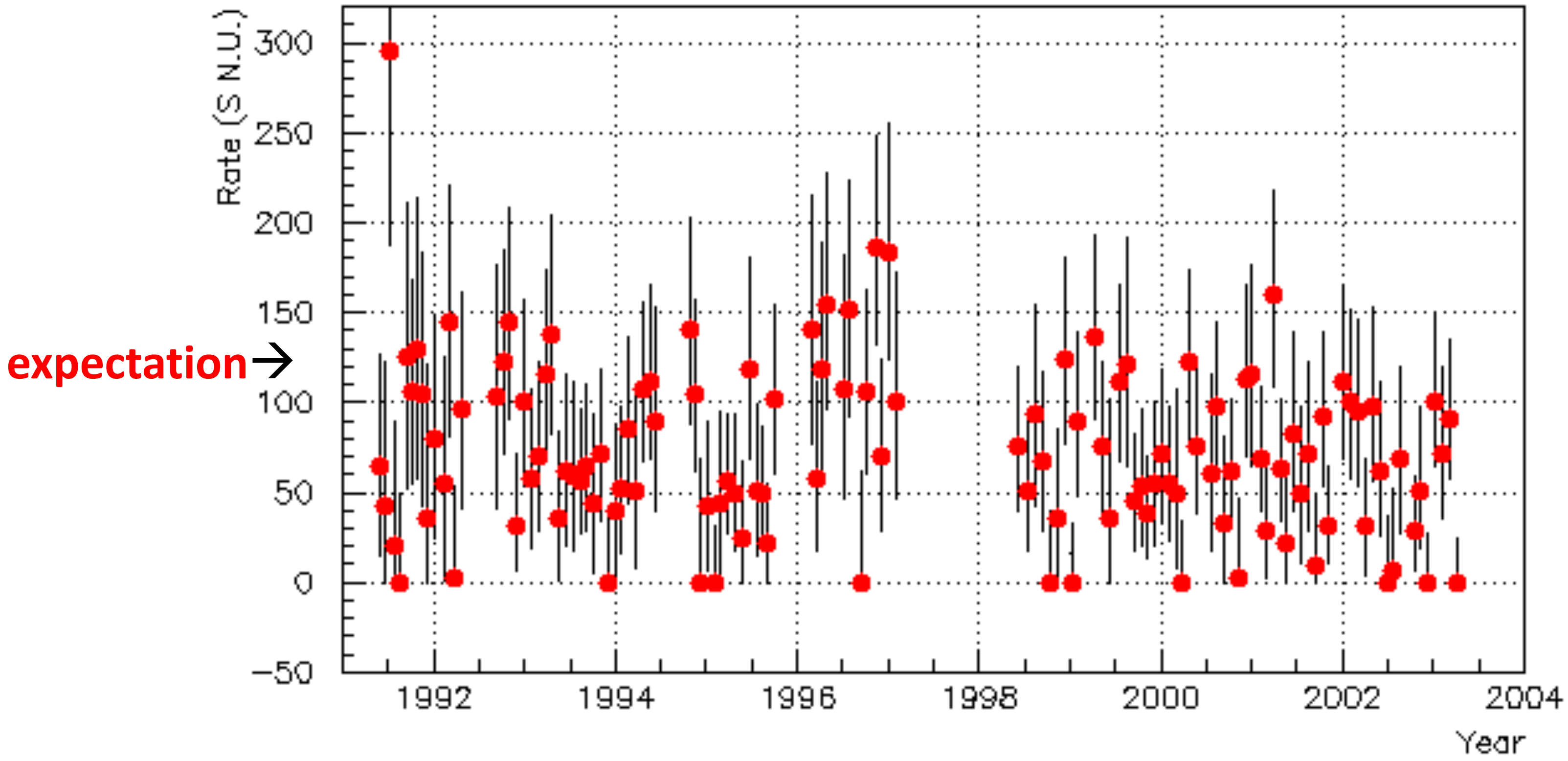
$GeCl_4$ volatile in acidic soluion
dans 100 t of $GaCl_3$ in sol. Flux d'Azote

Operation

See f.i. PL B490(2000)16
PL B314(1993)445



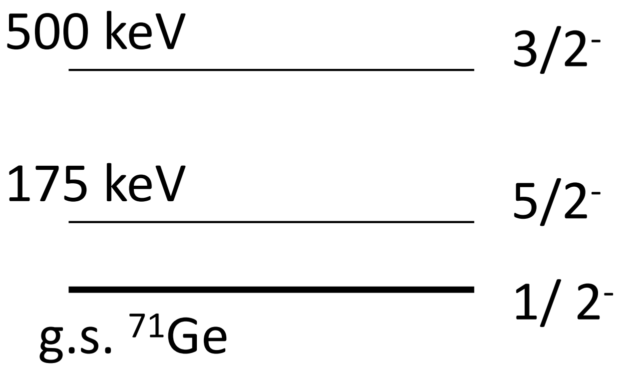
GALLEX - GNO
Davis plot



GALLEX
65 solar runs

GNO (Russia)
58 solar runs

^{51}Cr Source



Strength	63.4 PBq	69.1 PBq
R (meas/expt)	1.01 ±11.5%	0.84 ±11.5%

0.93 ± 0.08 [0.91 ± 0.08]

Energy (keV)	^{51}Cr	^{7}Be
862	-	90%
751	80.6%	-
746	9.5%	-
431	8.8%	-
426	1.1%	-
384	-	10%

Z. Phys. C - Particles and Fields 32, 499-511 (1986)

Zeitschrift für Physik C Particles and Fields

Matter Effects for Solar Neutrino Oscillations

J. Bouchez[1], M. Cribier[1], W. Hampel[2], J. Rich[1], M. Spiro[1], D. Vignaud[1]

[1] DPhPE, CEN Saclay, F-91191 Gif-sur-Yvette, France
[2] Max Planck Institut für Kernphysik, D-6900 Heidelberg, Federal Republic of Germany

Received 7 May 1986; in revised form 16 June 1986

Abstract. Possible solar neutrino oscillations are reviewed in the two-neutrino case taking into account the effect of coherent forward scattering when neutrinos travel through the sun and earth. As recently pointed out by Mikheyev and Smirnov this effect can induce a large suppression of the solar ν_e flux for values of Δm^2 around $10^{-4}-10^{-8}\,\mathrm{eV}^2$ even for small values of the mixing angle. It also may cause substantial modifications of the solar neutrino spectrum shape. All this may be used for determining Δm^2 and $\sin^2 2\theta$ in a large domain from the experimental results of the chlorine, gallium, indium and heavy water detectors.

1. Introduction

As was first suggested by Pontecorvo [1], if neutrinos are massive and if there is nonconservation of the lepton family number, the mass eigenstates ν_1 and ν_2 (of masses m_1 and m_2) may differ from ν_e and ν_μ, leading to operative only for ν_e. For neutrinos the phase mismatch φ_m obeys [5]:

$$d\varphi_m/dt = k(x) = \sqrt{2}\cdot G\cdot N(x)$$

where $x = ct$ and where $N(x)$ is the electron density in cm^{-3} and G is the Fermi coupling constant. The net effect of this new phase is that the propagation eigenstates in matter are no longer the mass eigenstates ν_1 and ν_2, therefore oscillation parameters in matter differ from those in vacuum. This formalism was extended to three neutrino oscillations by Barger et al. [6]. More recently Mikheyev and Smirnov [7] showed that the difference might introduce dramatic effects for solar neutrinos, which may lead to a very strong suppression of the ν_e flux measured on earth, even if the vacuum mixing angle is small.

In this paper we develop the formalism of two-neutrino oscillations in matter in a way exhibiting the possible approximations and their limits. We then apply it to the solar neutrino case and demonstrate the

Moisej Markov

1960

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

Fred Reines

1965

Detection of (reactor) antineutrinos with liquid scintillator

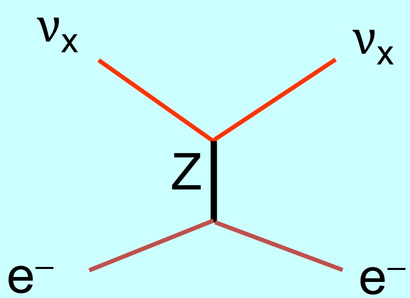
Are the neutrinos really coming from the sun ?

Water Cerenkov neutrino detector: Kamiokande

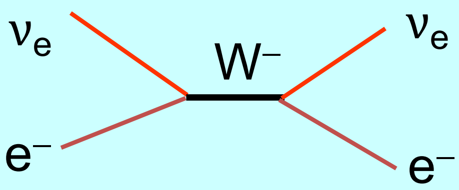
$$\upsilon + e \longrightarrow \upsilon + e^-$$

high energy (compared to rest mass)

- produces cerenkov radiation when traveling in water **(can get direction of neutrinos)**



neutral current (NC)



charged current (CC)

Masatoshi Koshiba

SN 1987a
Neutrino detection

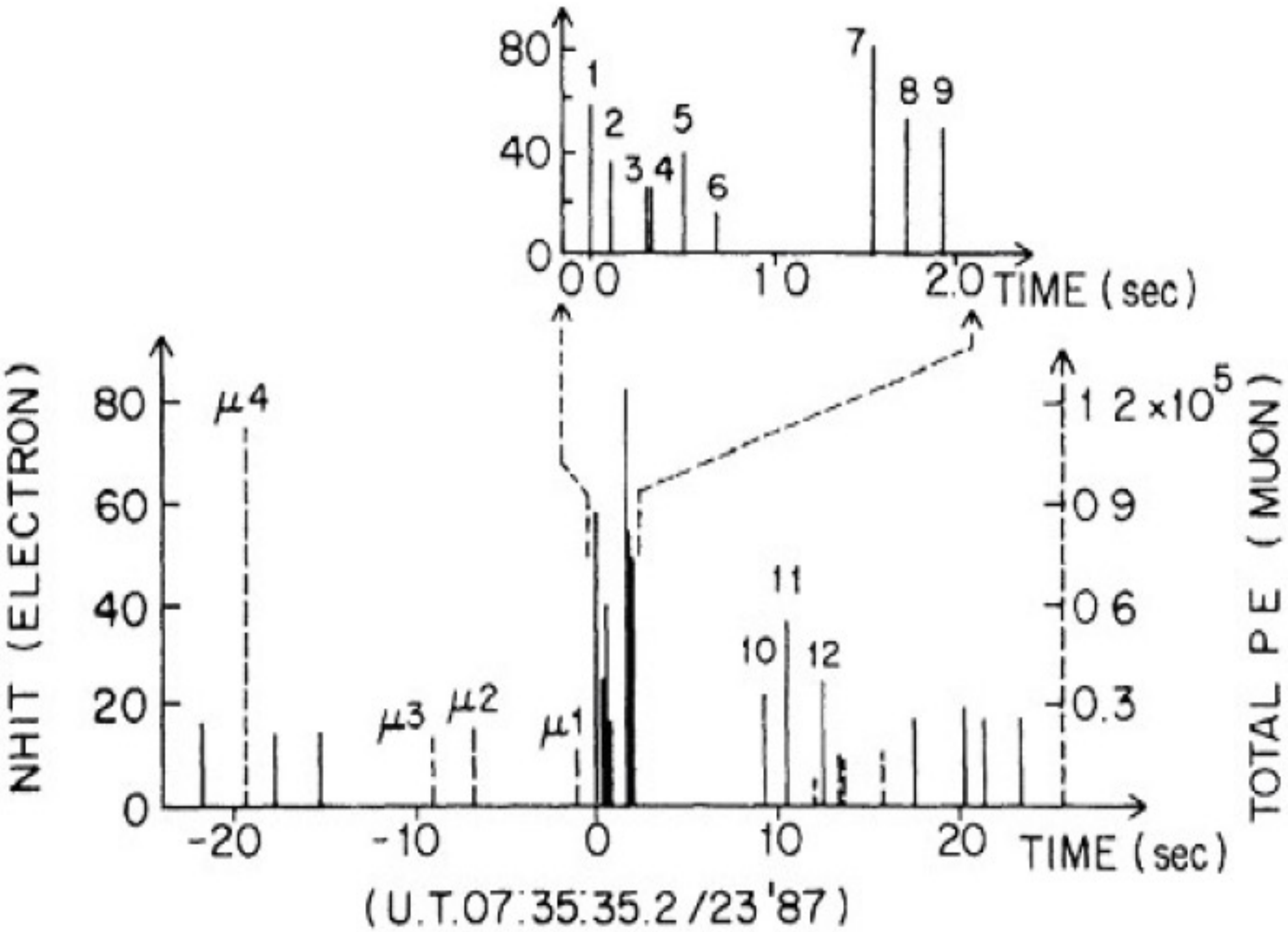


Fig. 5 Each vertical line represents the relative energy of a muon (dashed lines) or of an electron (solid lines). Events μ1 - μ4 are muon events preceeding the electron bursts at time 0. The background events with NHIT<20 are largely due to decay of ^{214}Bi, a decay product of ^{222}Rn. From Hirata et al. 1988.

SN 1987 a
Neutrino detection
Neutrino image of SN 1987 a

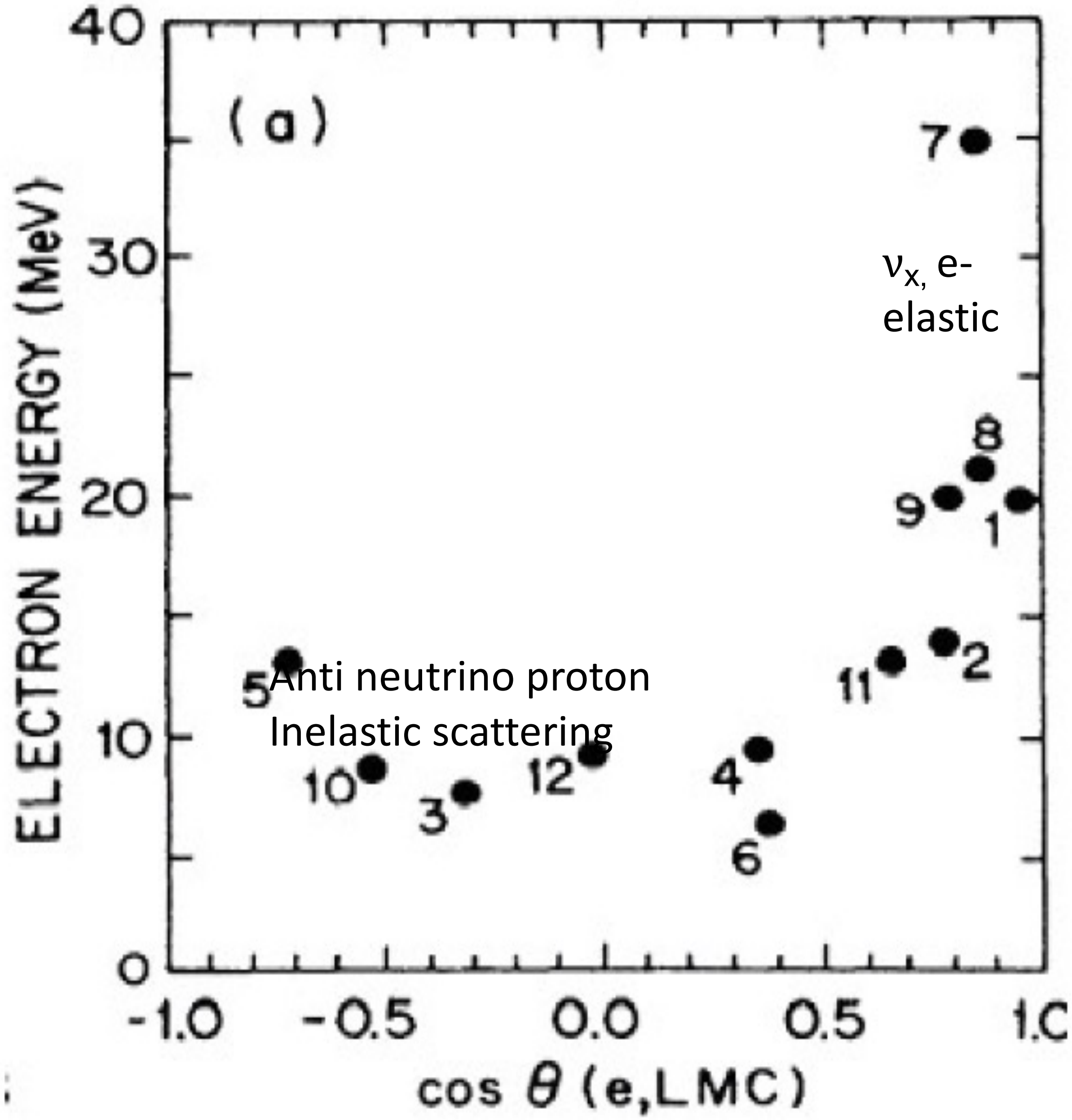


Fig. 4 Scatter plot of the detected electron energy and the cosine of the angle between the measured electron direction and the direction of the Large Magellanic Cloud. The number on each entry is the time-sequential event number. The direction of the positron from an anti-neutrino reaction has very small correlation with the direction of the neutrino. From Hirata et al. 1987.

Solar neutrino detection

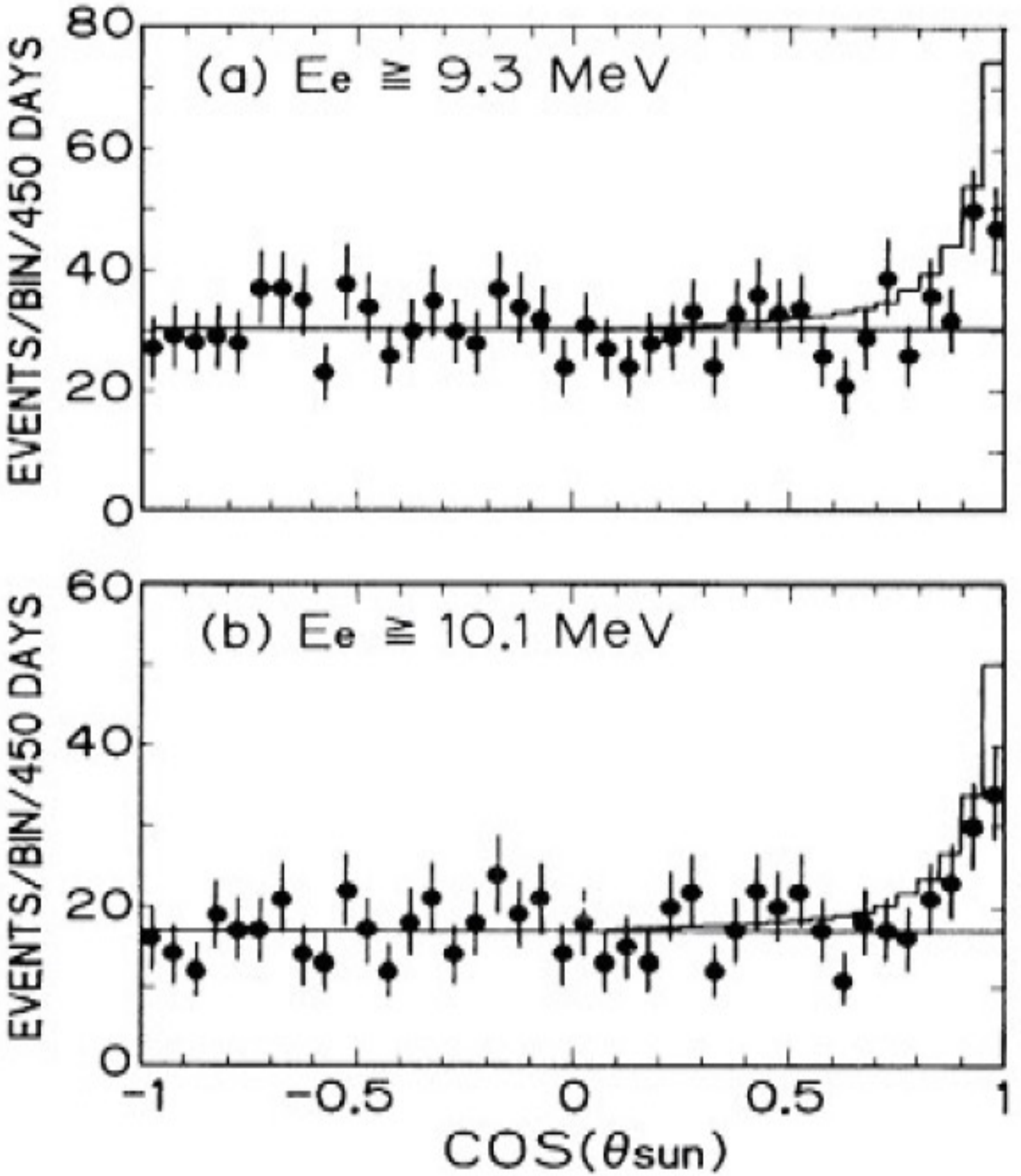
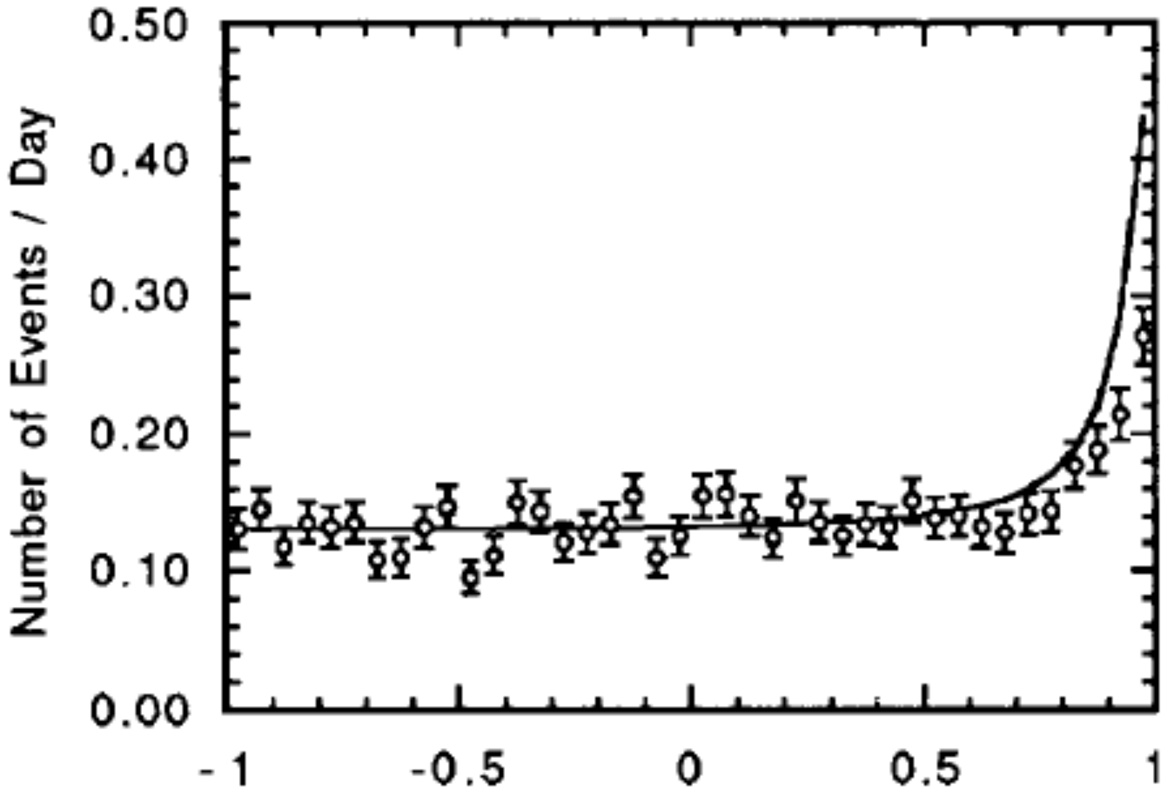


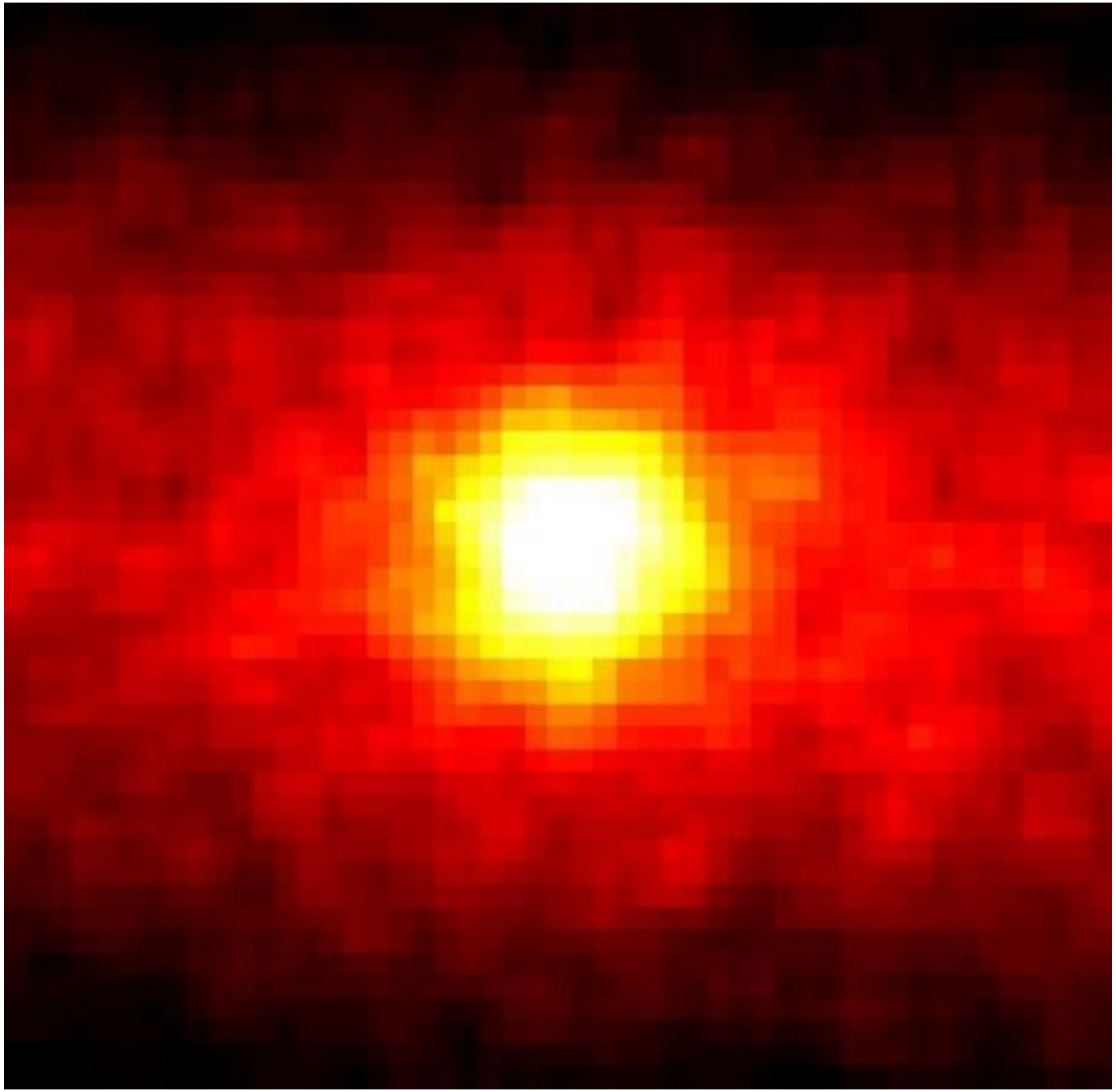
Fig. 3 The angular distribution of electron neutrinos measured by the Kamiokande collaboration. Data are shown for two different cuts on the electron energy. The histogram shows the calculated distribution from a solar model. Notice the deficit, confirming Davis result. The direction towards the sun corresponds to cos(θsun) = 1. (Hirata et al. 1989).



v

Figure 2: Angular distribution of events with respect to the Sun, Kamiokande [29].

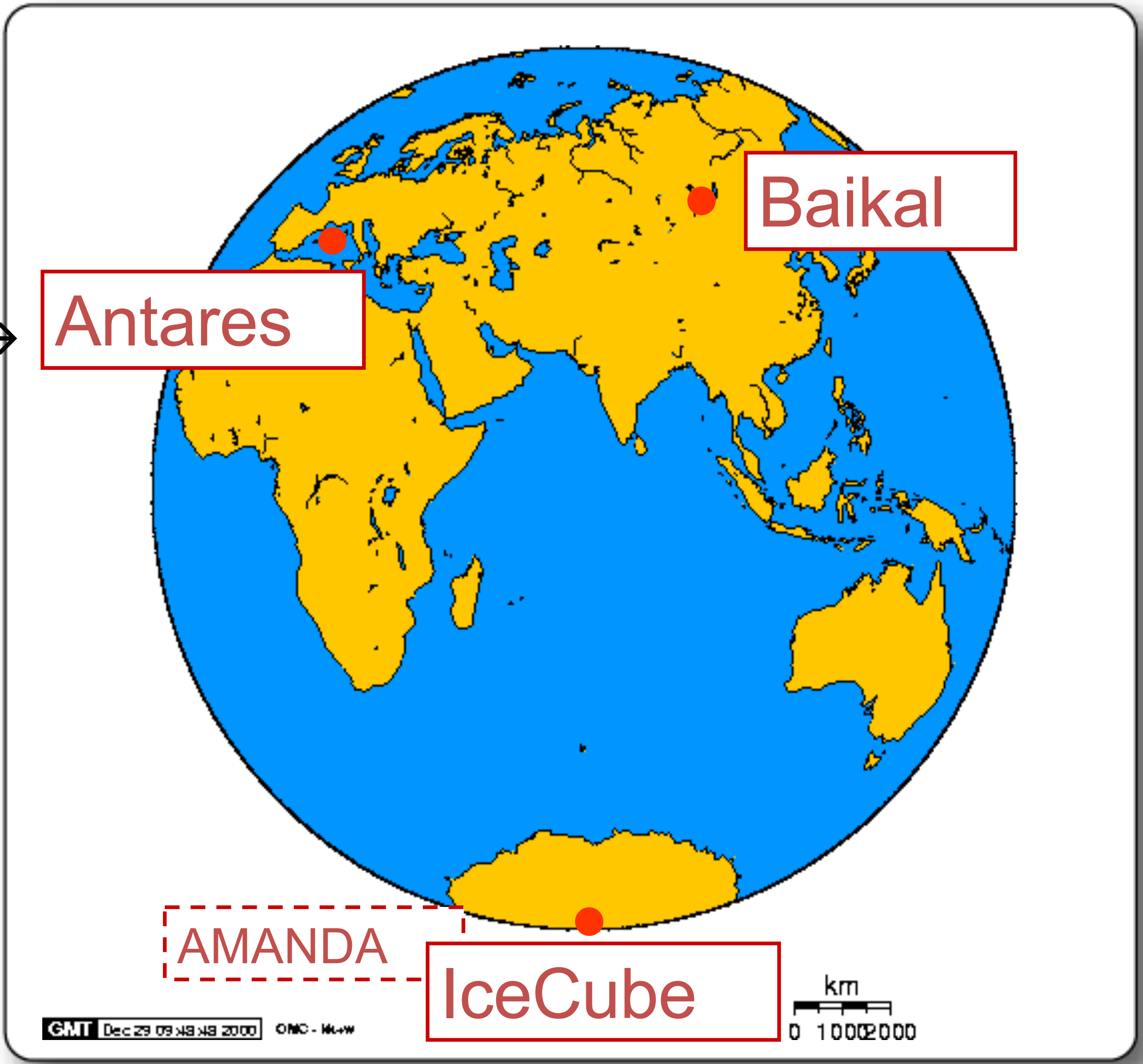
Astronomy Picture of the Day June 5, 1998



Neutrino image of the sun by Kamiokande – first step in neutrino astronomy

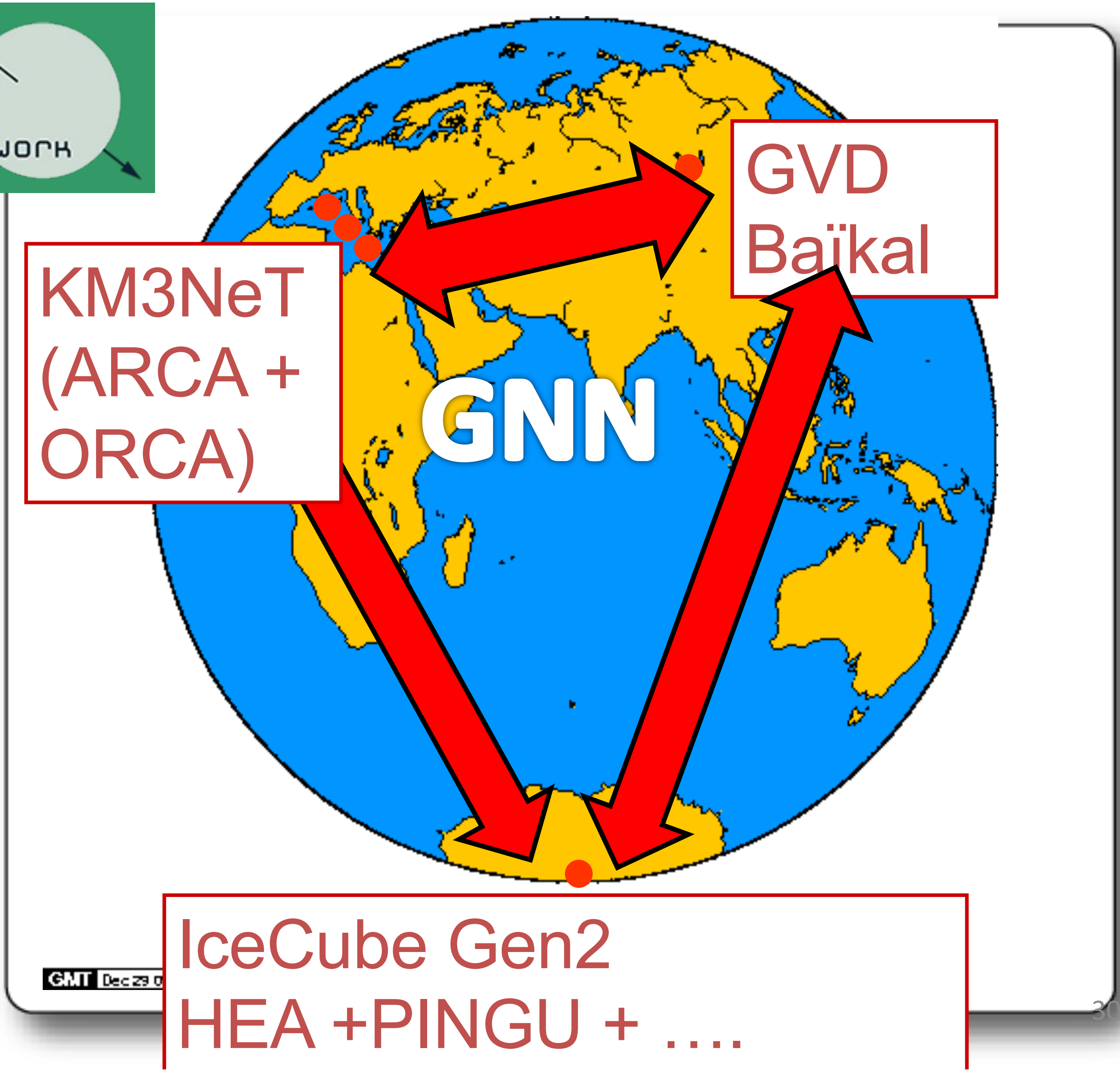
High energy neutrino detectors: neutrinos come from below and interact in the rock or in water/ice

Jj Aubert -→

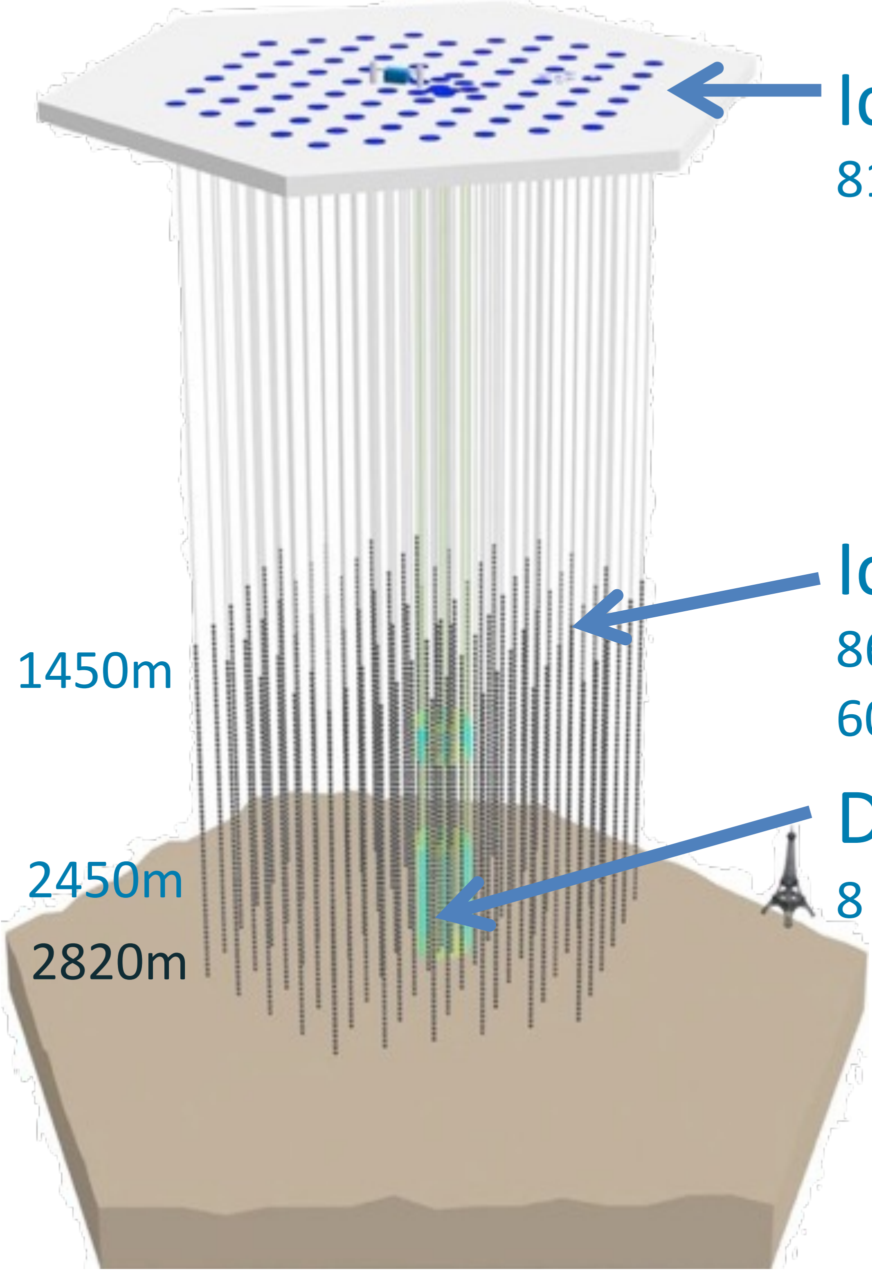


Baikal, Mediterranean Sea, South Pole

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

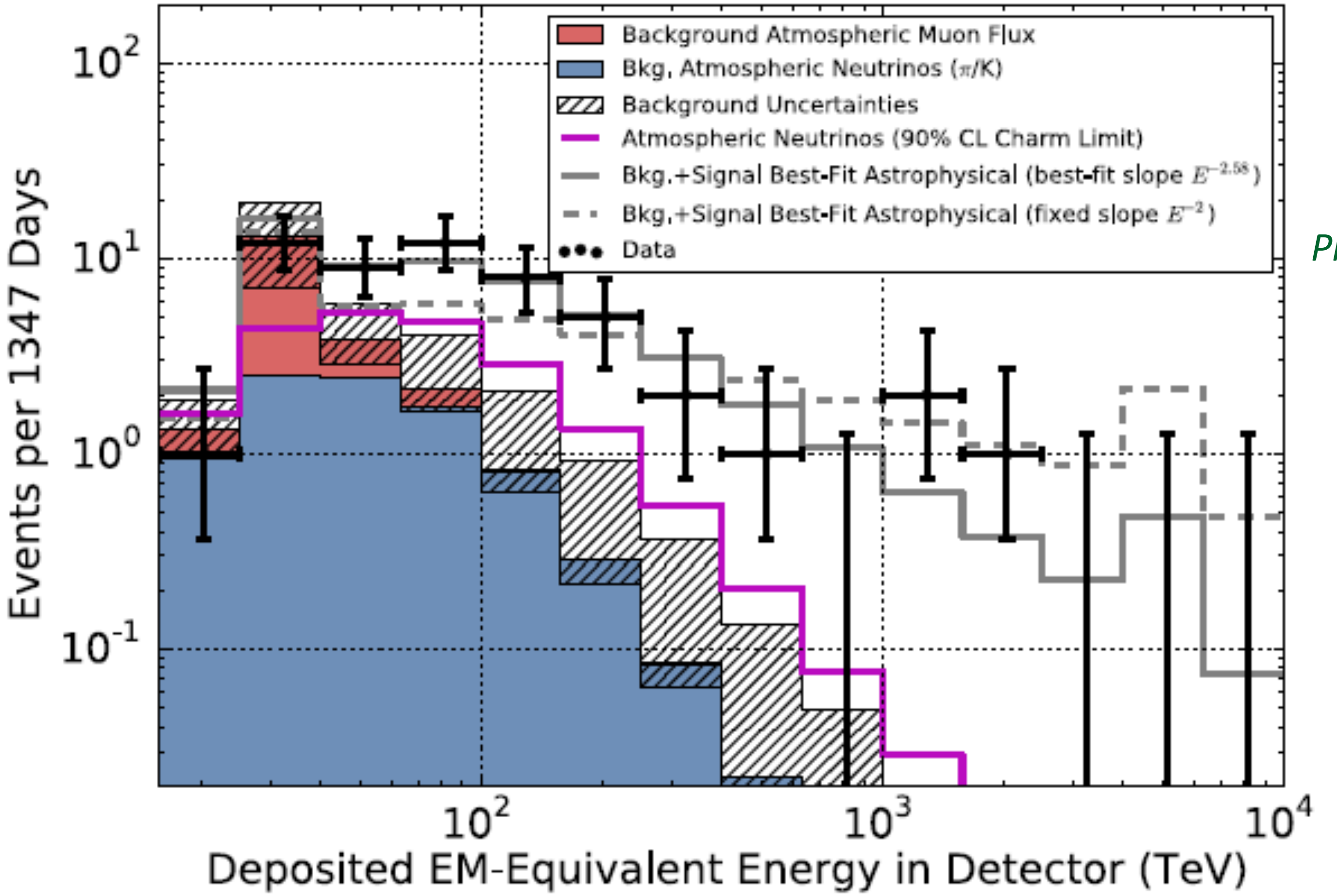
DeepCore

8 closely spaced strings

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

Follow-up Analysis: HESE (High Energy Starting Event)

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



2 yrs data, 28 evts 4.1σ

Science 342 (2013)

3 yrs data, 37 evts 5.9σ

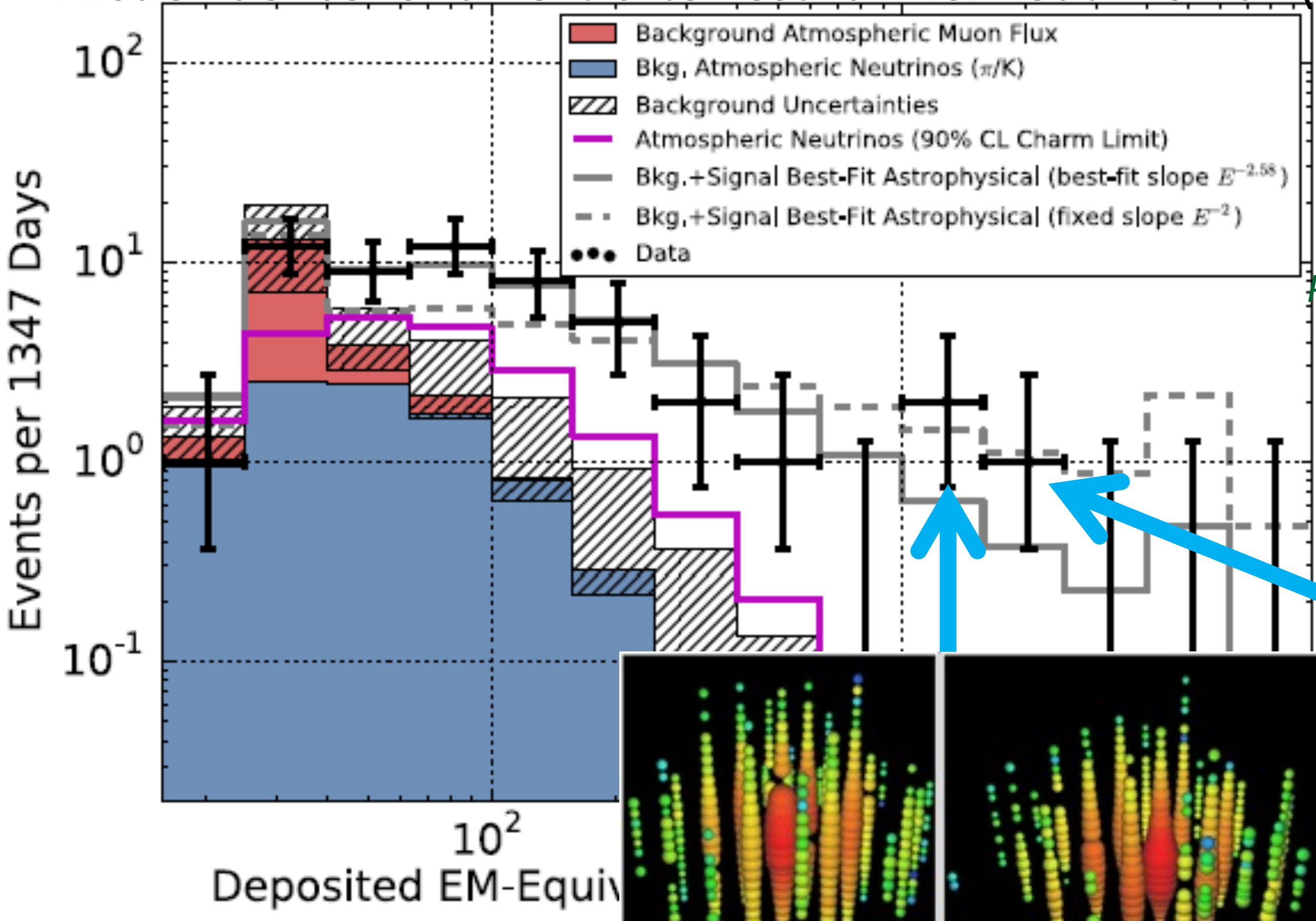
Phys.Rev.Lett. 113:101101 (2014)

4 yrs data, 54 evts ~ 7σ

Threshold ~ 30 TeV

Follow-up Analysis: HESE (High Energy Starting Event)

First evidence for an extra-terrestrial h.e. neutrino flux (confirmed recently by Baïkal)



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Science 342 (2013)

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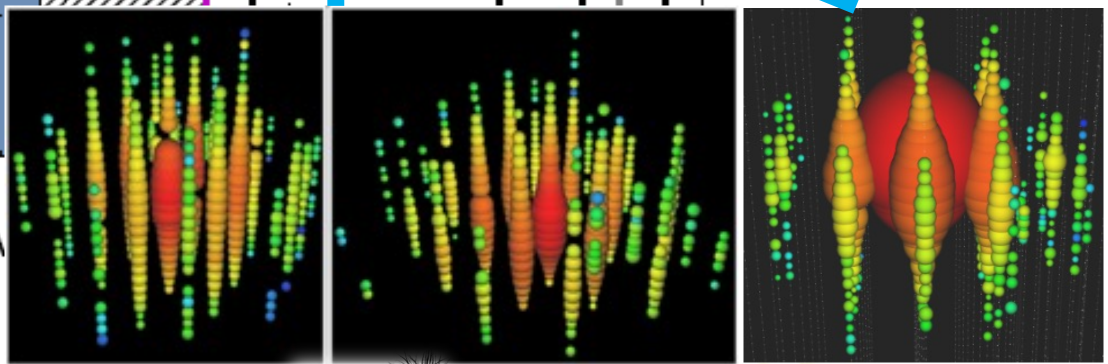
4 yrs data, 54 evts ~ **7σ**



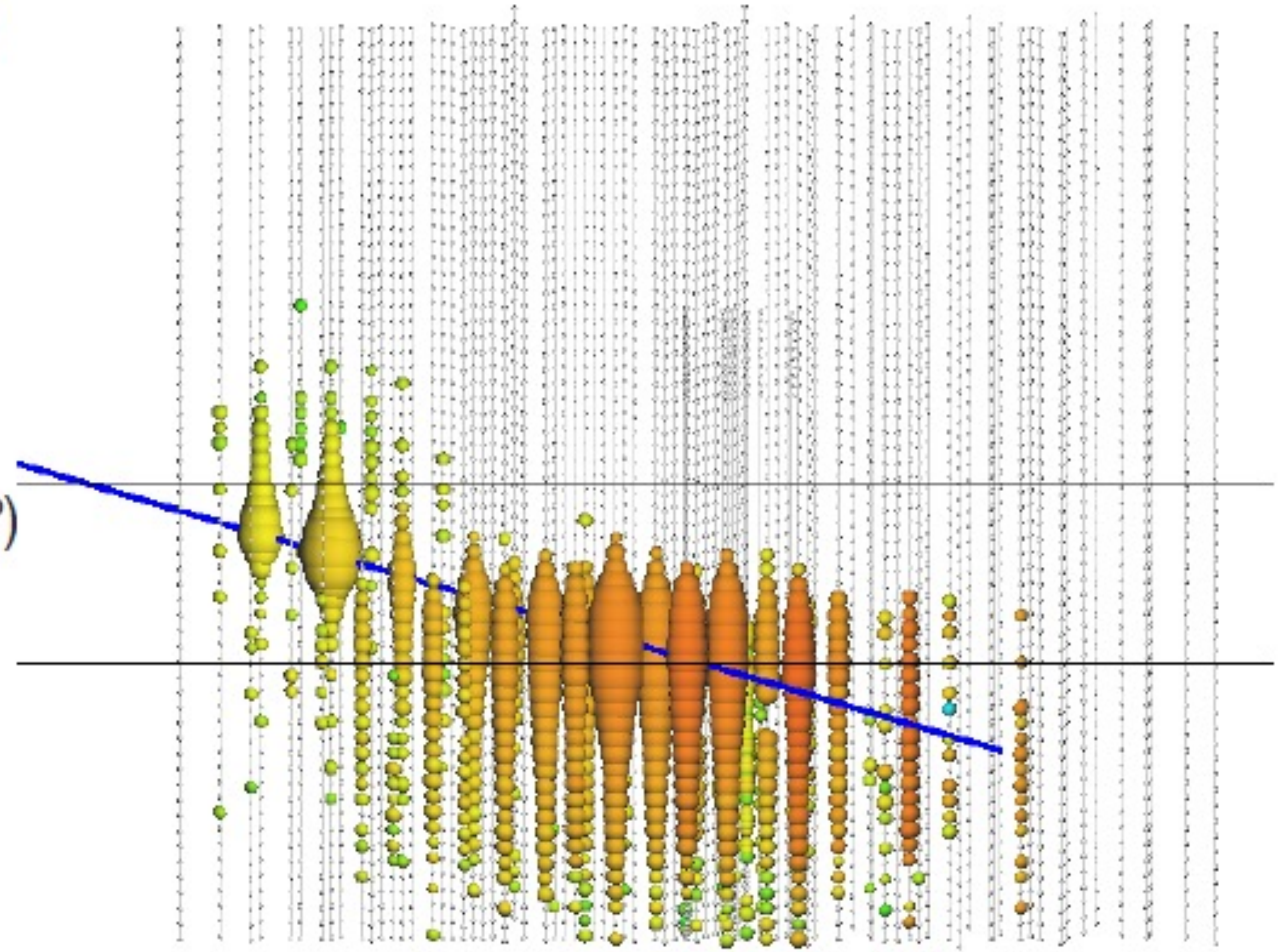
"Bert"
1.04 PeV
Aug. 2011

"Ernie"
1.14 PeV
Jan. 2012

"Big Bird"
2 PeV
Dec. 2012

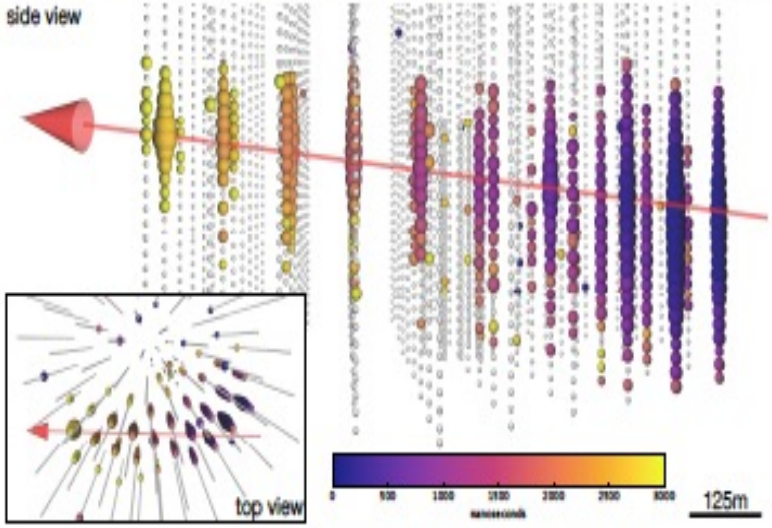
2.6 PeV !

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



indication for point source

A high energy neutrino in coincidence with a flaring blazar



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

Science 13 Jul 2018: Vol. 361, Issue 6398

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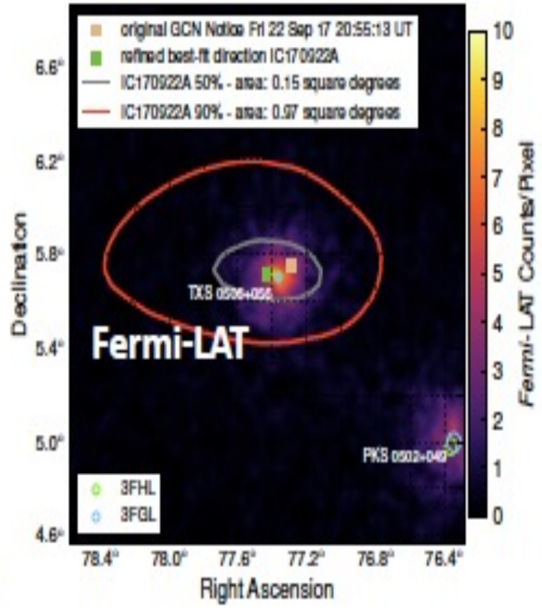
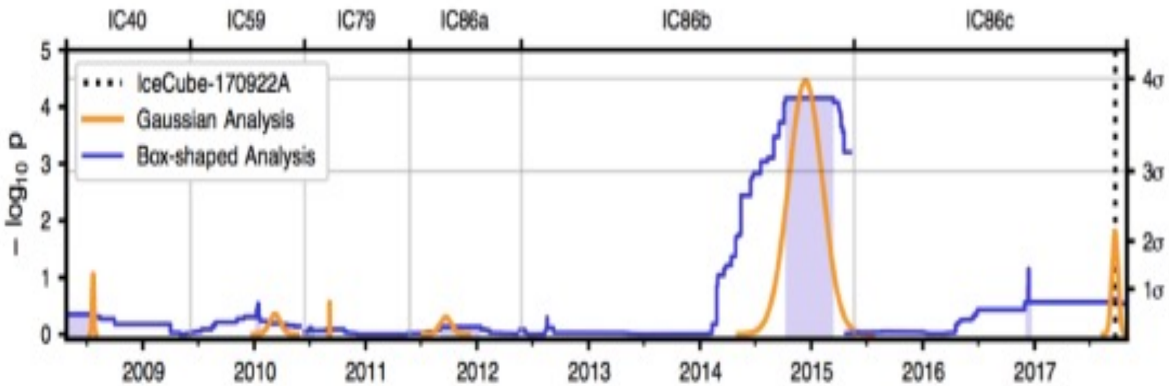
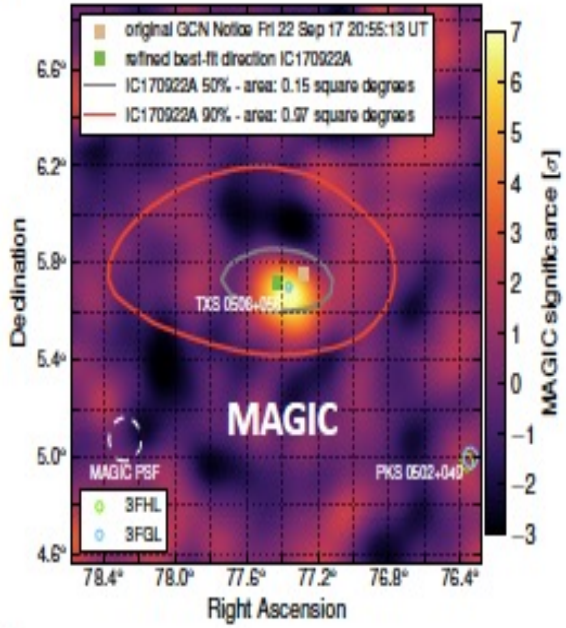


Blazar redshift 0.3365 +/0.0010 (Paiano *et al.*)



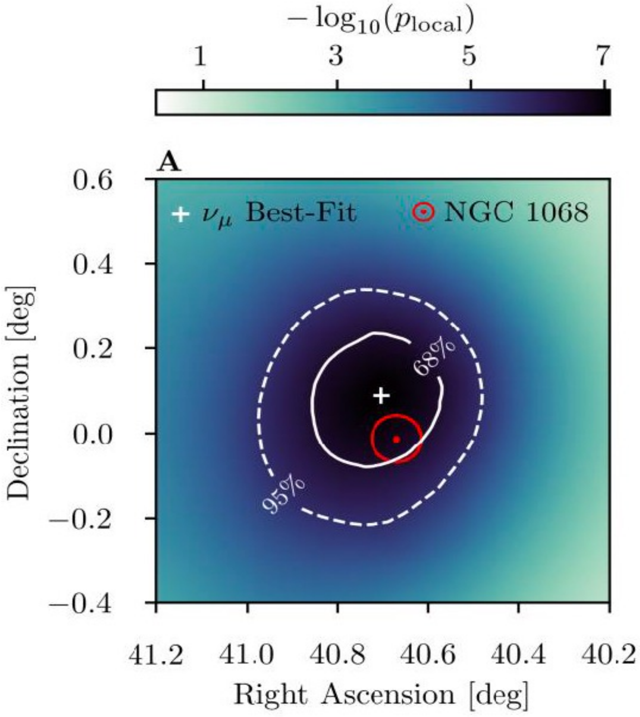


Excess of neutrinos observed between September 2014 and March 2015

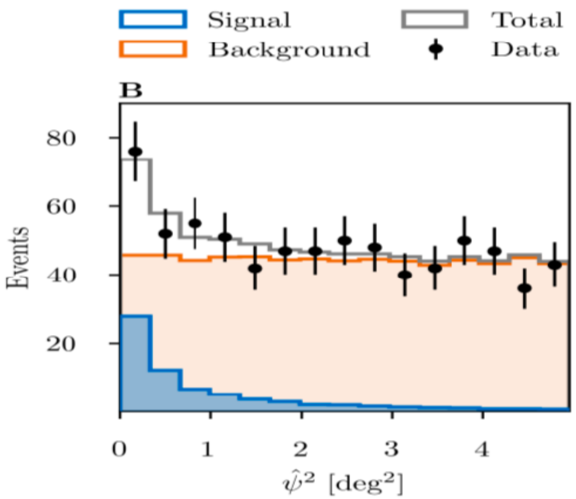
Background only hypothesis rejected at 3.5σ

Second event: Evidence for neutrino emission from the nearby active galaxy NGC 1068 at 4.2σ

expectations. An excess of 79 (+22,-20) neutrinos associated with NGC 1068 was found, with the mentioned significance of 4.2σ (corrected for all possible trials).



The sky region around the most significant spot in the Northern Hemisphere and NGC 1068. The plot shows a fine scan of the region around the hottest spot. The spot itself is marked by a yellow cross, the red circle shows the position and size of NGC 1068. In addition, the solid and dashed contours show the 68% and 95% confidence regions of the hot spot localization.

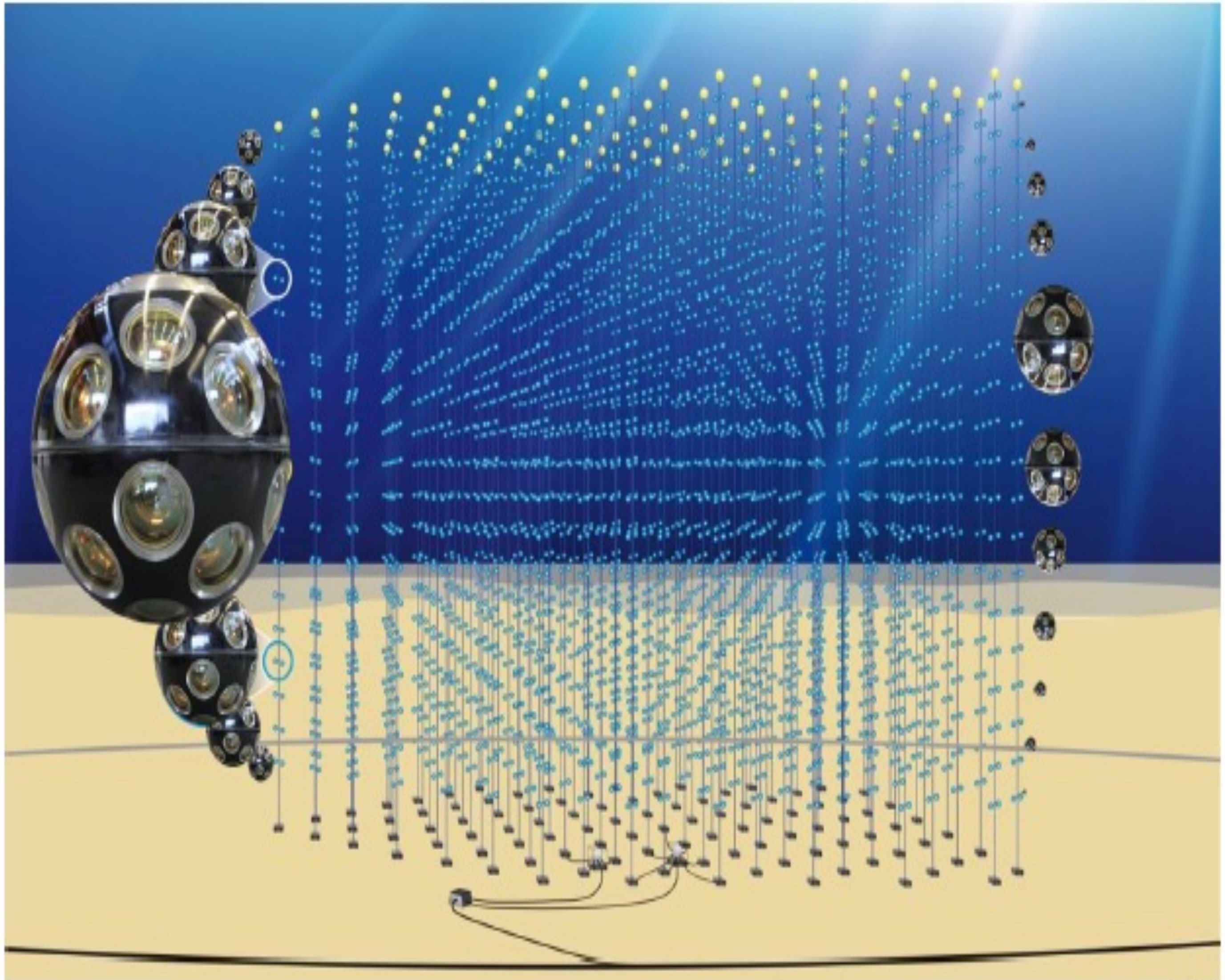


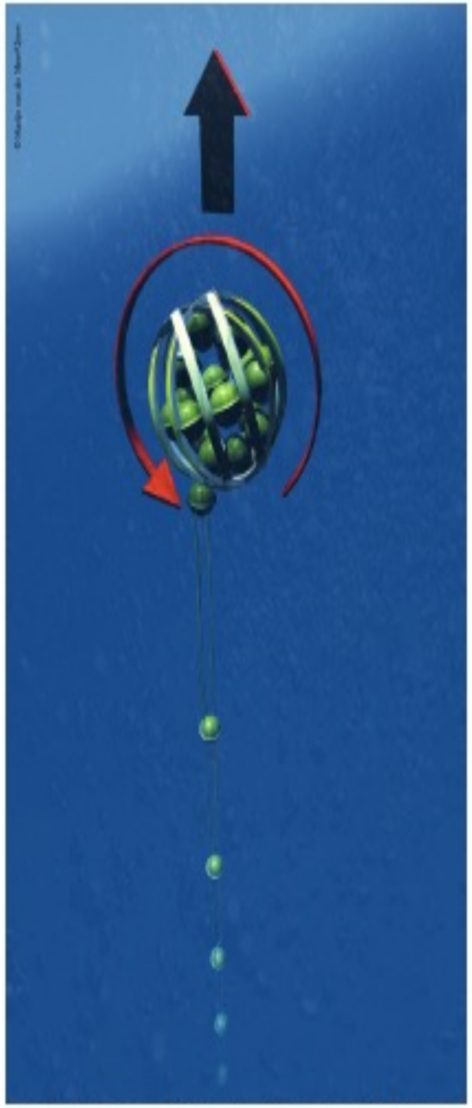
Distribution of the squared angular distance between NGC 1068 and the reconstructed event direction. From Monte Carlo one estimates the background (orange) and the signal (blue) assuming the best-fit spectrum at the position of NGC 1068. The superposition of both components is shown in gray and provides an excellent match to the data (black). Note that this representation of the result neglects all the information on the energy and angular uncertainty of the events that is used in the unbinned maximum likelihood approach.

This result is interpreted as direct evidence of TeV neutrino emission from NGC 1068. The inferred flux exceeds the potential TeV gamma-ray flux by at least one order of magnitude, as shown in the next figure, i.e. the source is obscured in gamma rays.

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.

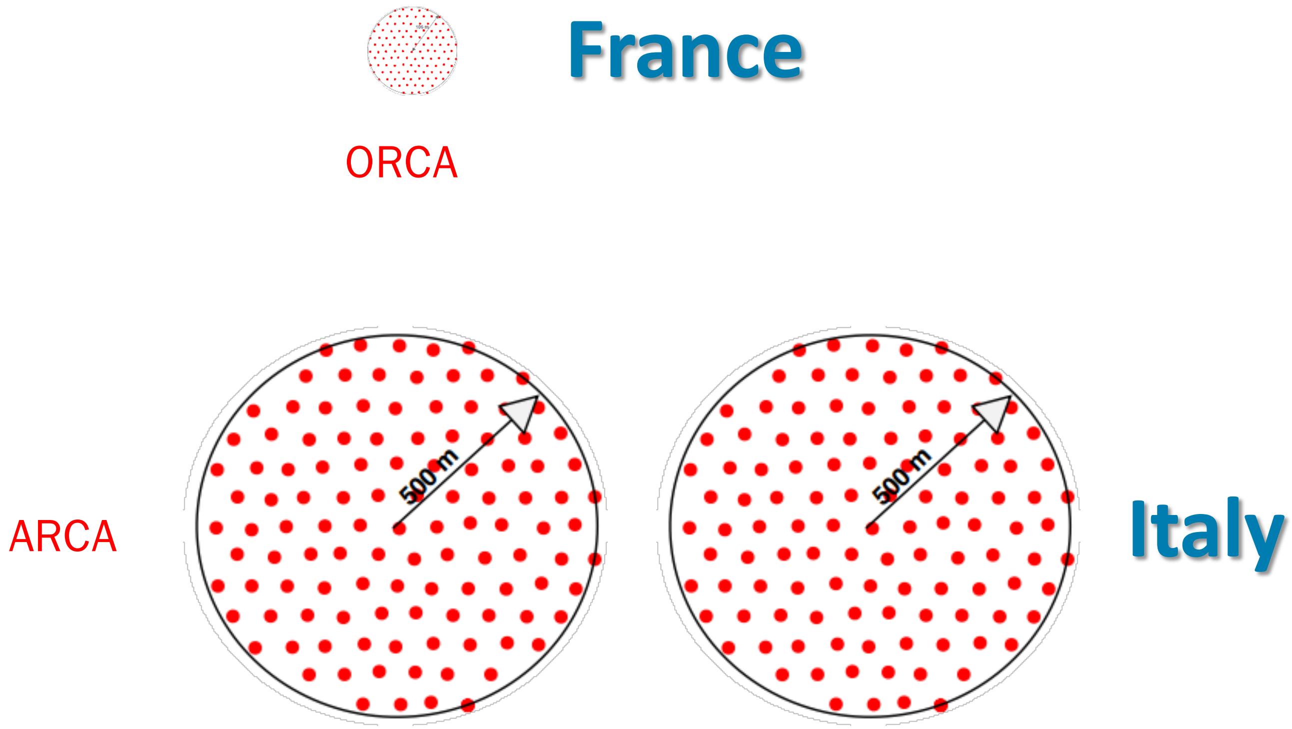




KM3NeT 2.0 Letter of Intent, arXiv:1601.07459

Phase 2.0: ORCA and ARCA

(2022 well advanced)



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:
  two point sources identified(3 and 4.2 sigmas) up to now
- Remaining uncertainties on spectrum and flavor composition
- First point sources seen. Many Point sources in reach!
- Need larger detectors, also with different systematics and at the Northern hemisphere.
- Next logical step: ARCA + GVD Baïkal$_{\text{Phase1}}$
- Next logical step on NMH: ORCA (then PINGU)
- ~2028: A Global Neutrino Observatory (KM3NeT-GVD-IceCube-Gen2,) full sky with > 5 km^3
- Indirect search for dark matter (heavy particles trapped in the sun or in the center of the earth)

Alexander Chudakov

1965

First search for gamma-ray showers in the atmosphere

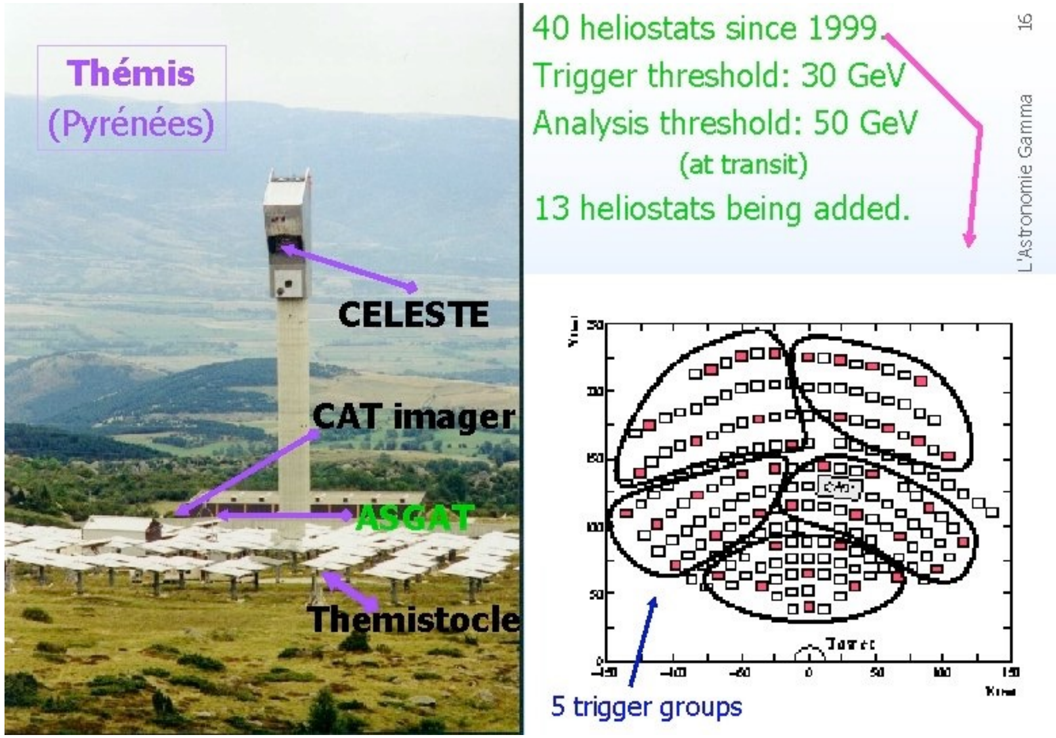
Trevor Weekes

1985 Whipple

Imaging Atmospheric Cerenkov Telescope: Crab Nebula discoverer

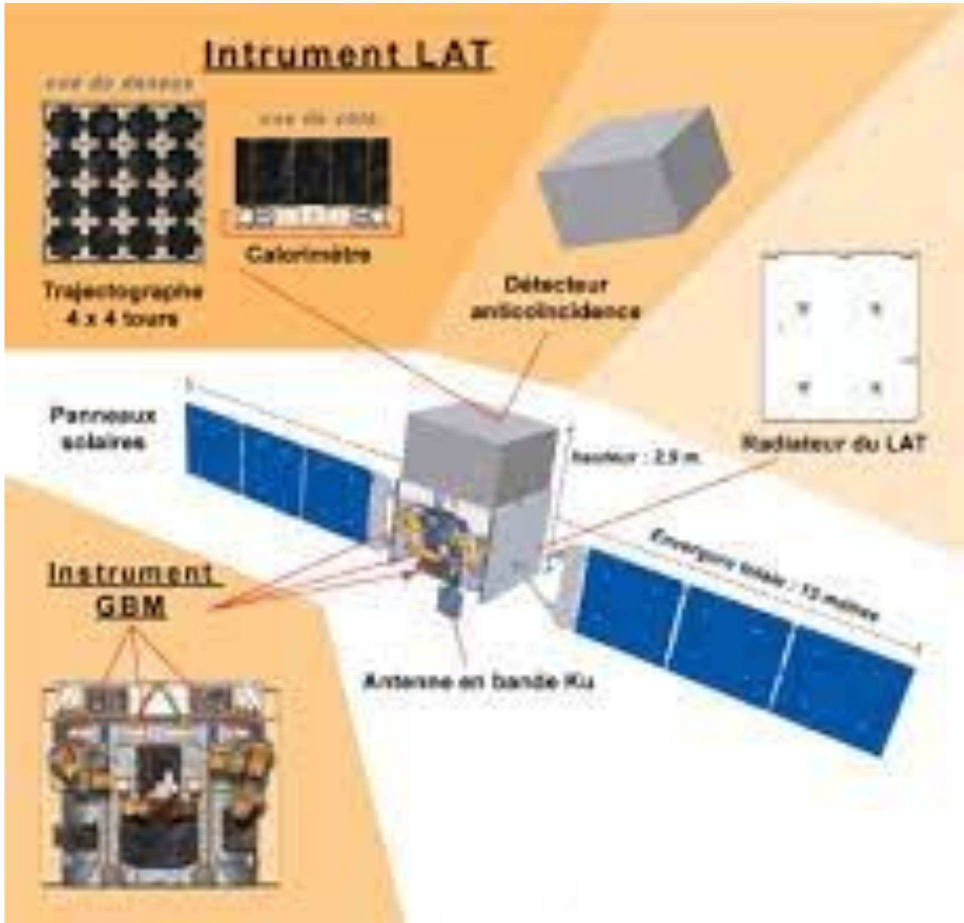
ASGAT 1988 , Themistocle 1988 CAT 1996, CELESTE 1997 → 2004: La France, pionnière en astro gamma: P. Goret, G. Fontaine, B. Desgranges, E. Paré, P. Fleury, M. Urban, M. Rivoal, C. Guesquière

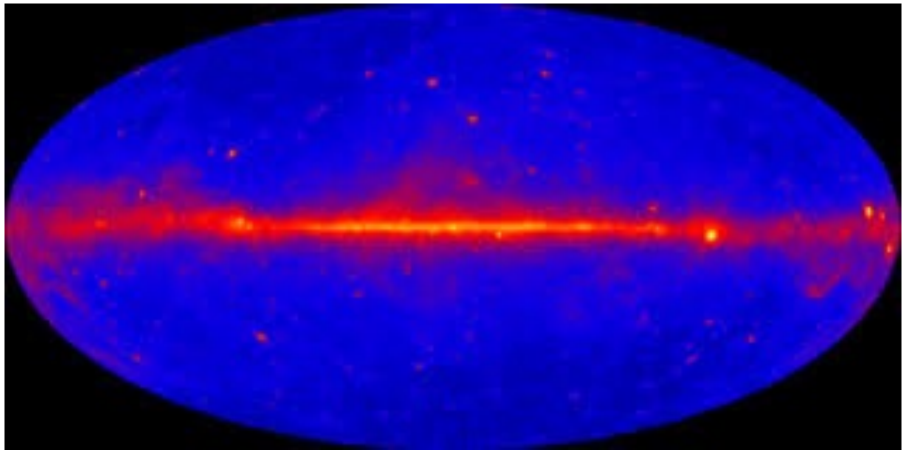
Themistocle and ASGAT: sampling techniques: many parabola with photomultipliers at the focus
CAT: imaging technique→ one large mirror with many photomultipliers at the focal plane to image the shower
CELESTE uses the full (40 heliostats) solar plant to focus the light at the top of the tower→ low threshold
3rd generation will use many large CAT imager type mirrors plus focal plane imagers



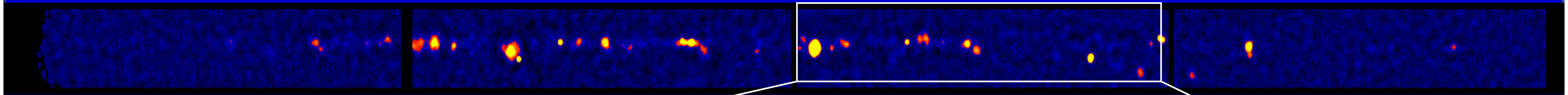
3rd generation Imaging Air Cherenkov telescopes

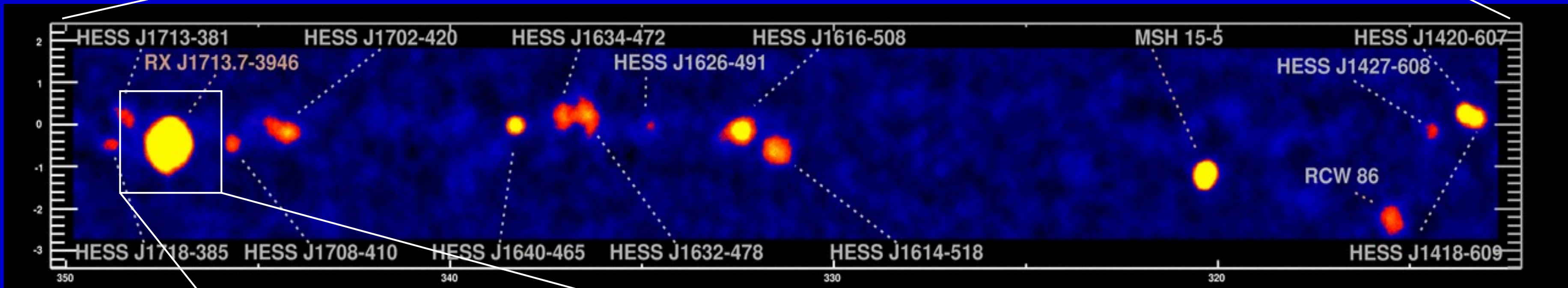
Reference map (20 MeV to 300 GeV) FERMI SATELLITE (strong French contribution), LAT instrument CMS/LHC inspired, 6000 sources > 50 MeV



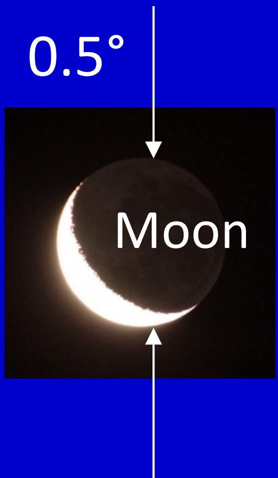


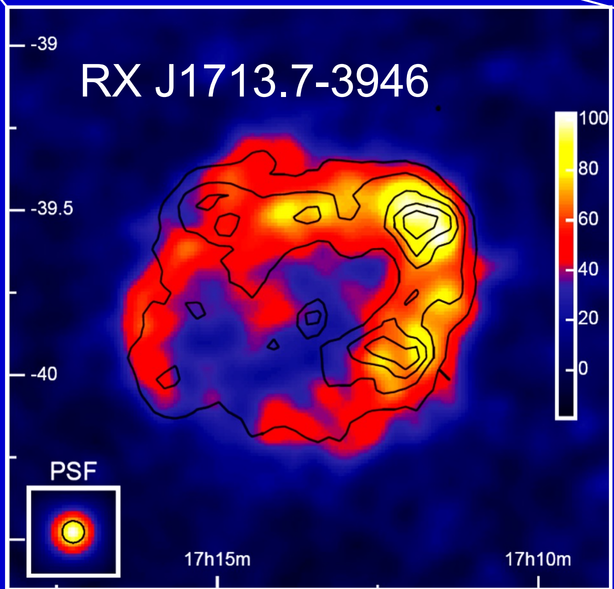
The Sky at TeV-Energies (Fermi satellite covering up to 300 GeV)





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

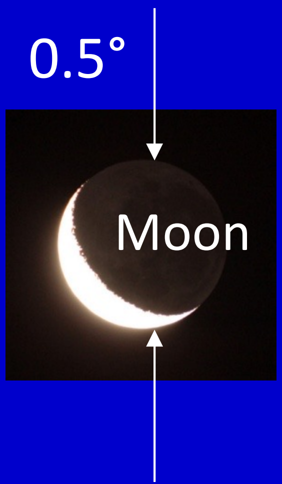


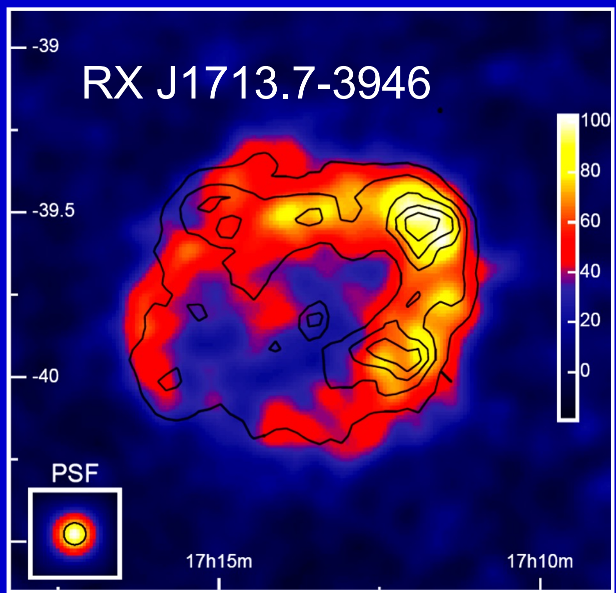


1989: 1 Source
1996: 3 Sources
2005: 80 Sources
2015: 150 Sources

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!)





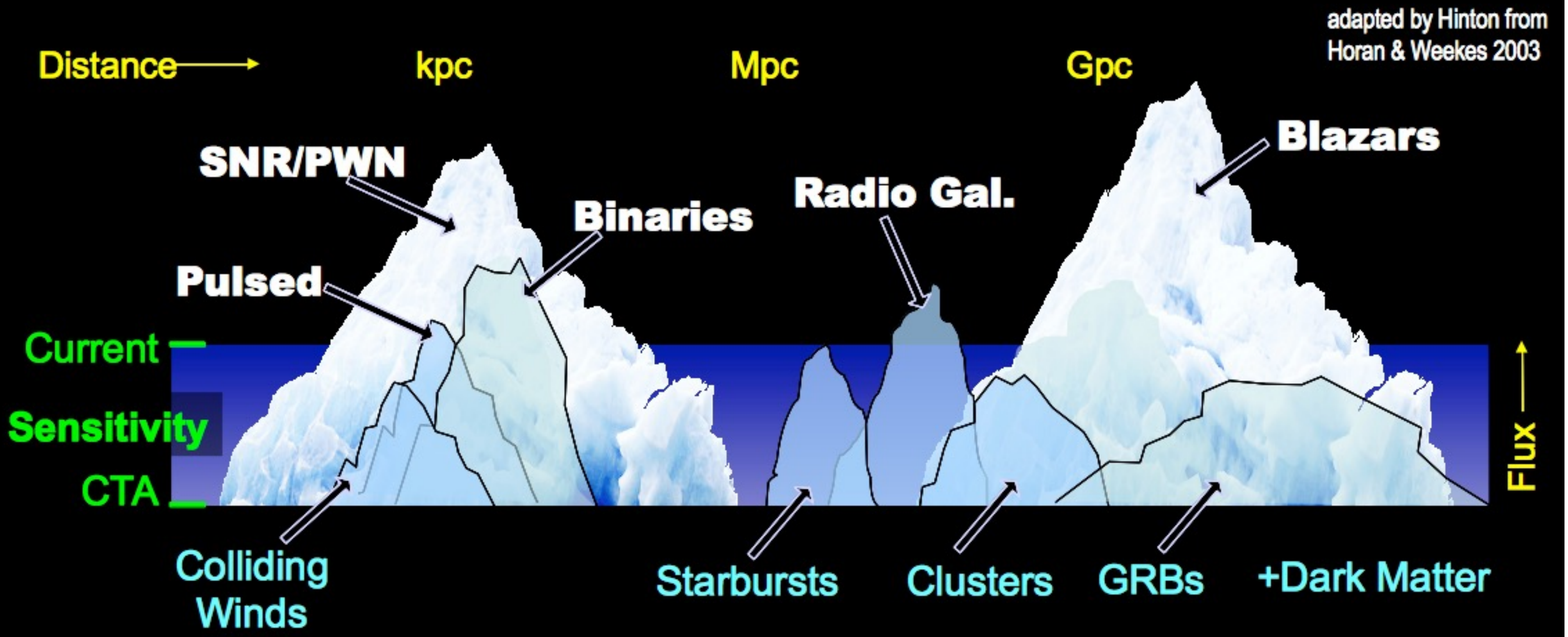
1989:	1 Source
1996:	3 Sources
2005:	80 Sources
2015:	**150 Sources**

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 Light
  - Indirect search for dark matter
  - 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

Viktor Hess

1912

Detection of cosmic rays

Pierre Auger

1939

Detection of cosmic air showers

James Cronin
Alan Watson
Murat Boratav
(avec Antoine
Letessier!)

1989


Pierre Auger Observatory

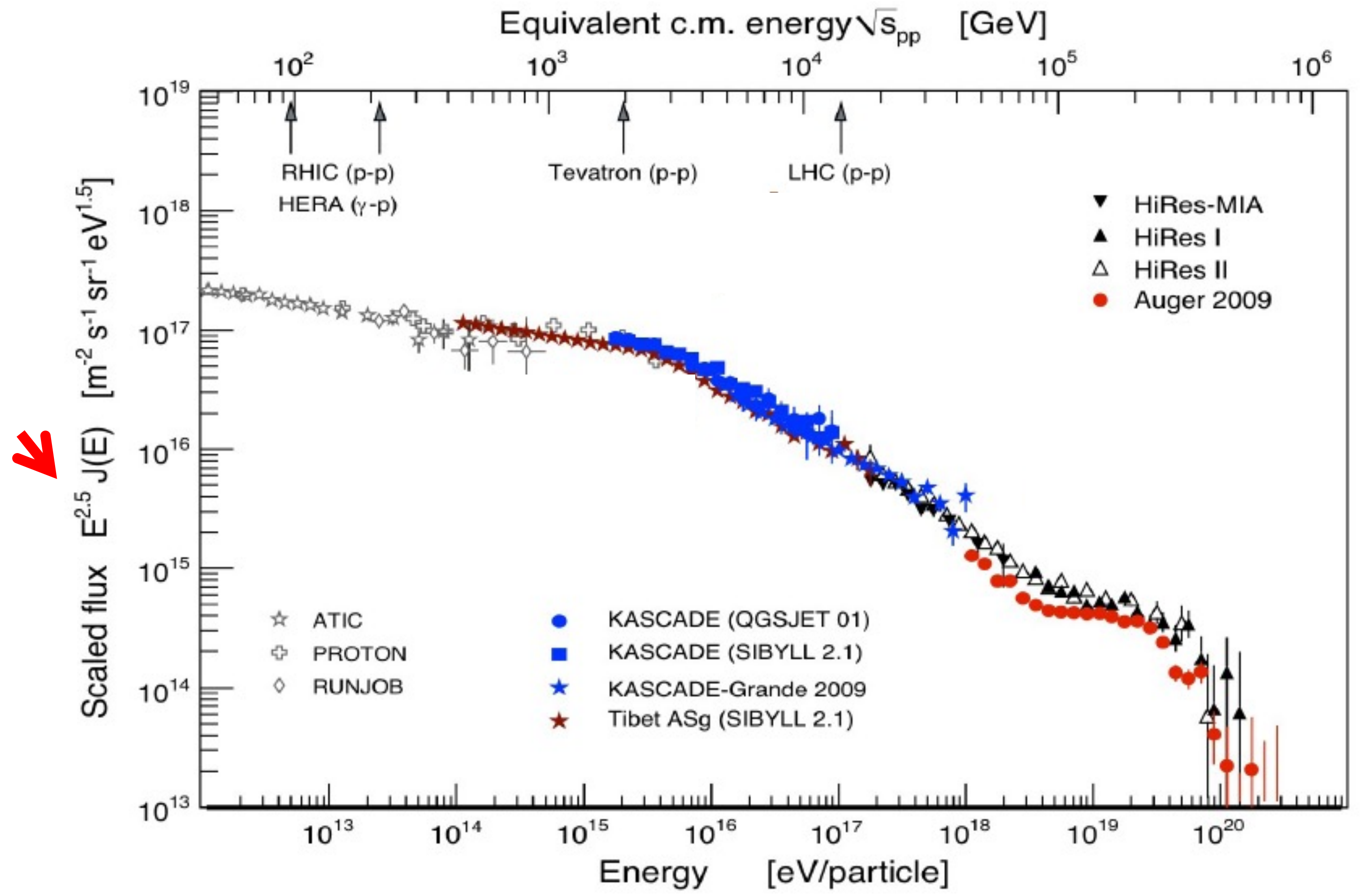
1660 detector stations on 1.5 km grid

27 fluores. telescopes at periphery

130 radio antennas

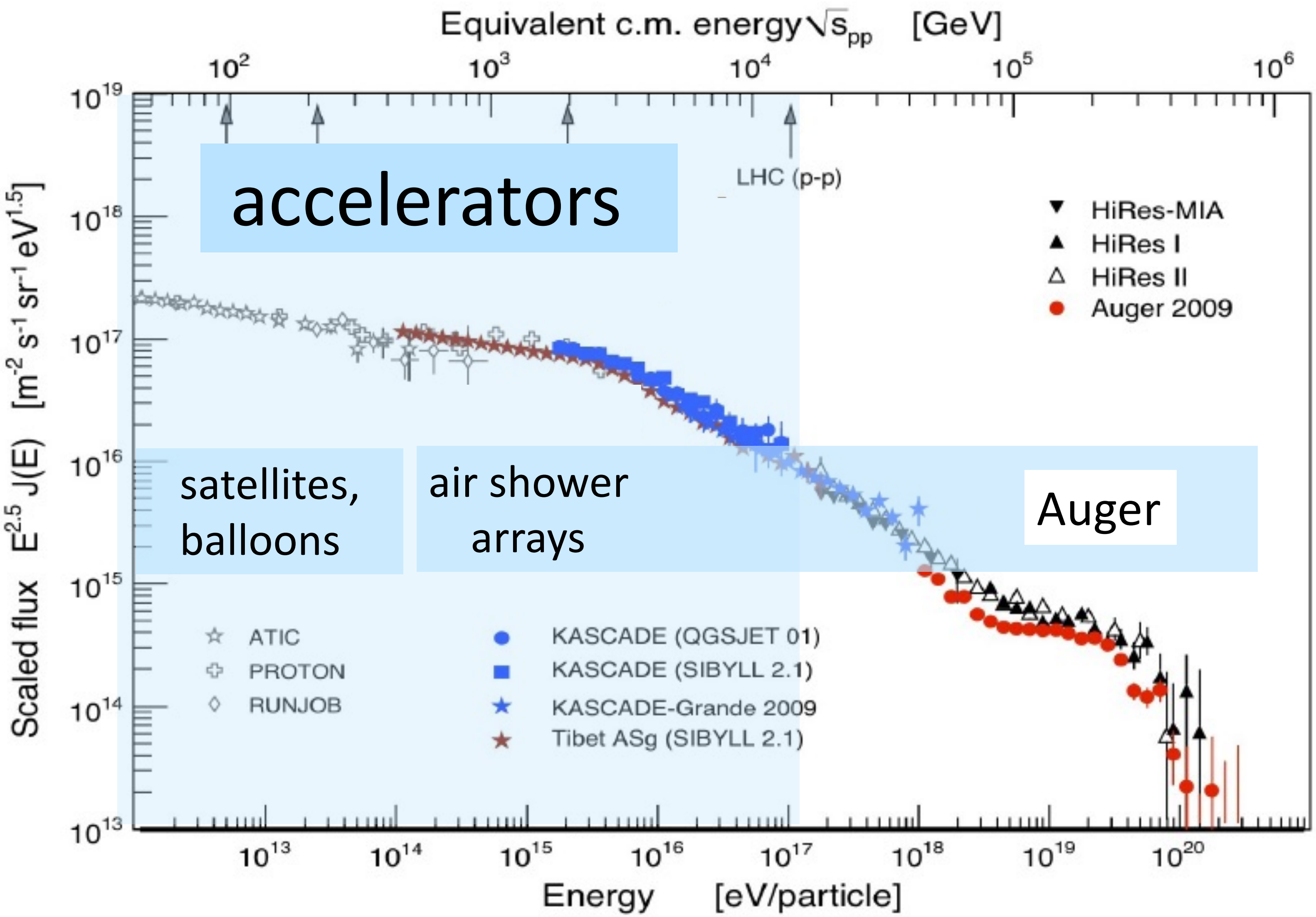
Province Mendoza, Argentina

Spectrum of Cosmic Rays



R. Engel (KIT)

Spectrum of Cosmic Rays



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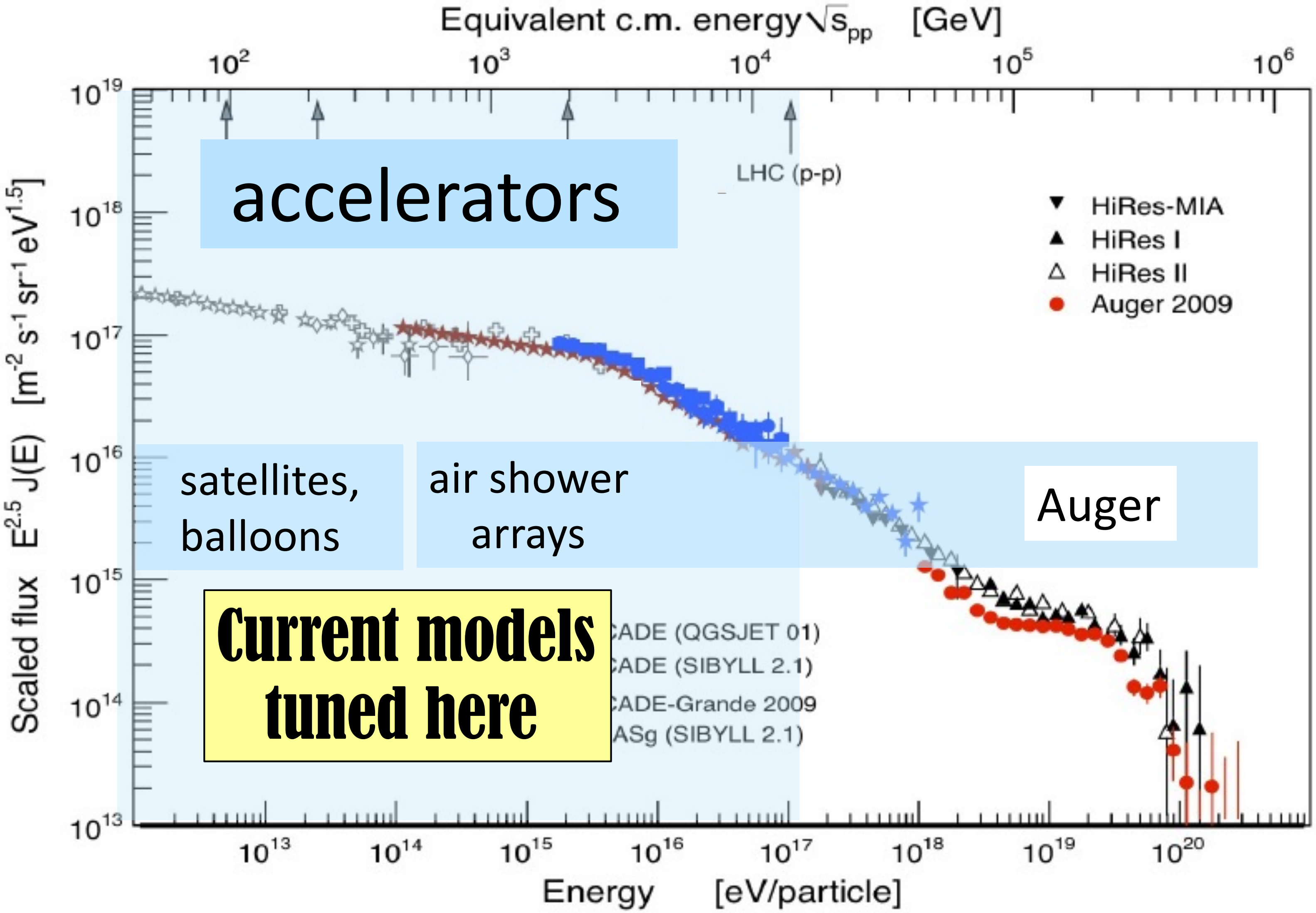
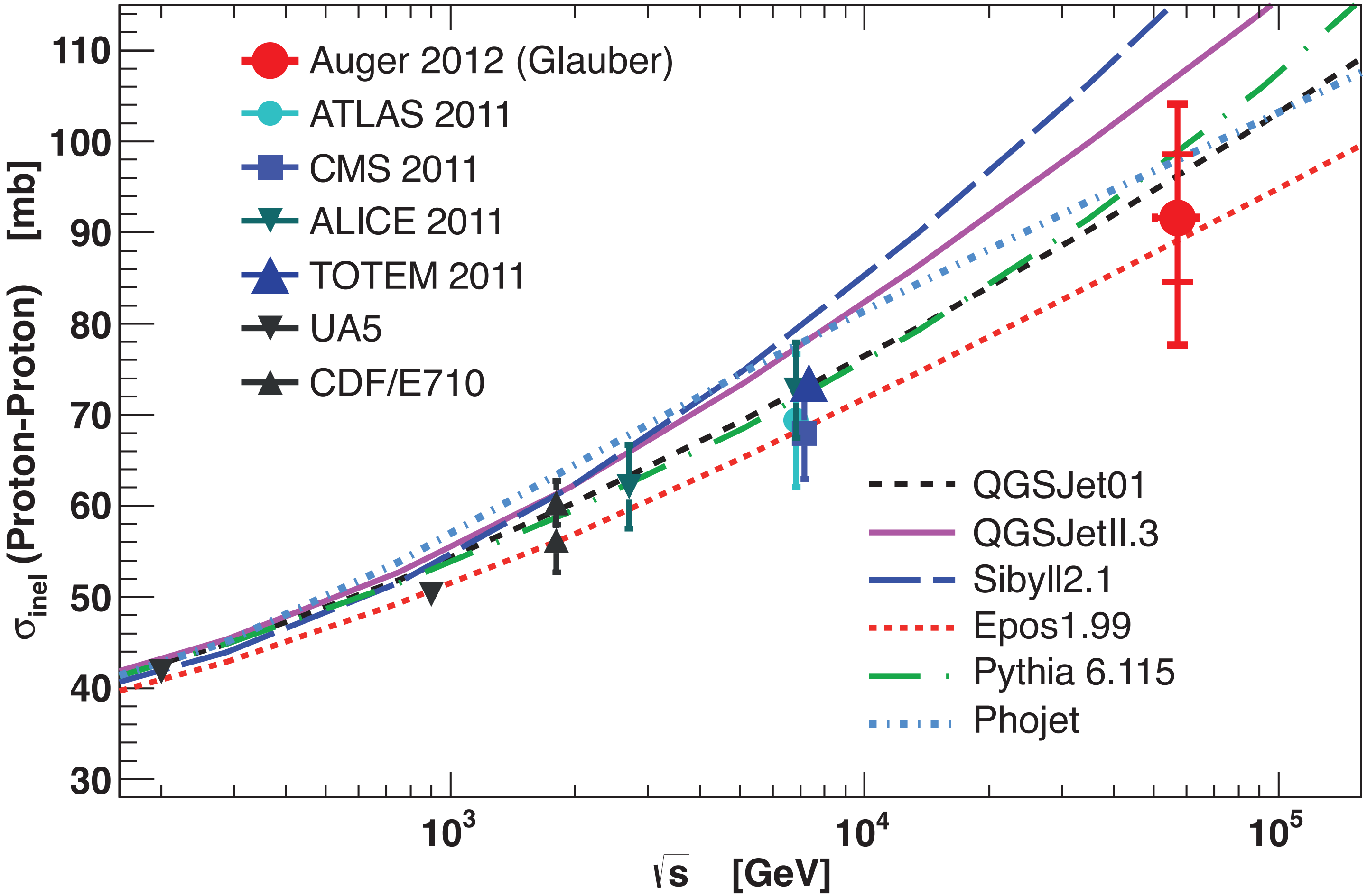
Spectrum of Cosmic Rays



R. Engel (KIT)

Cosmic Rays and LHC

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



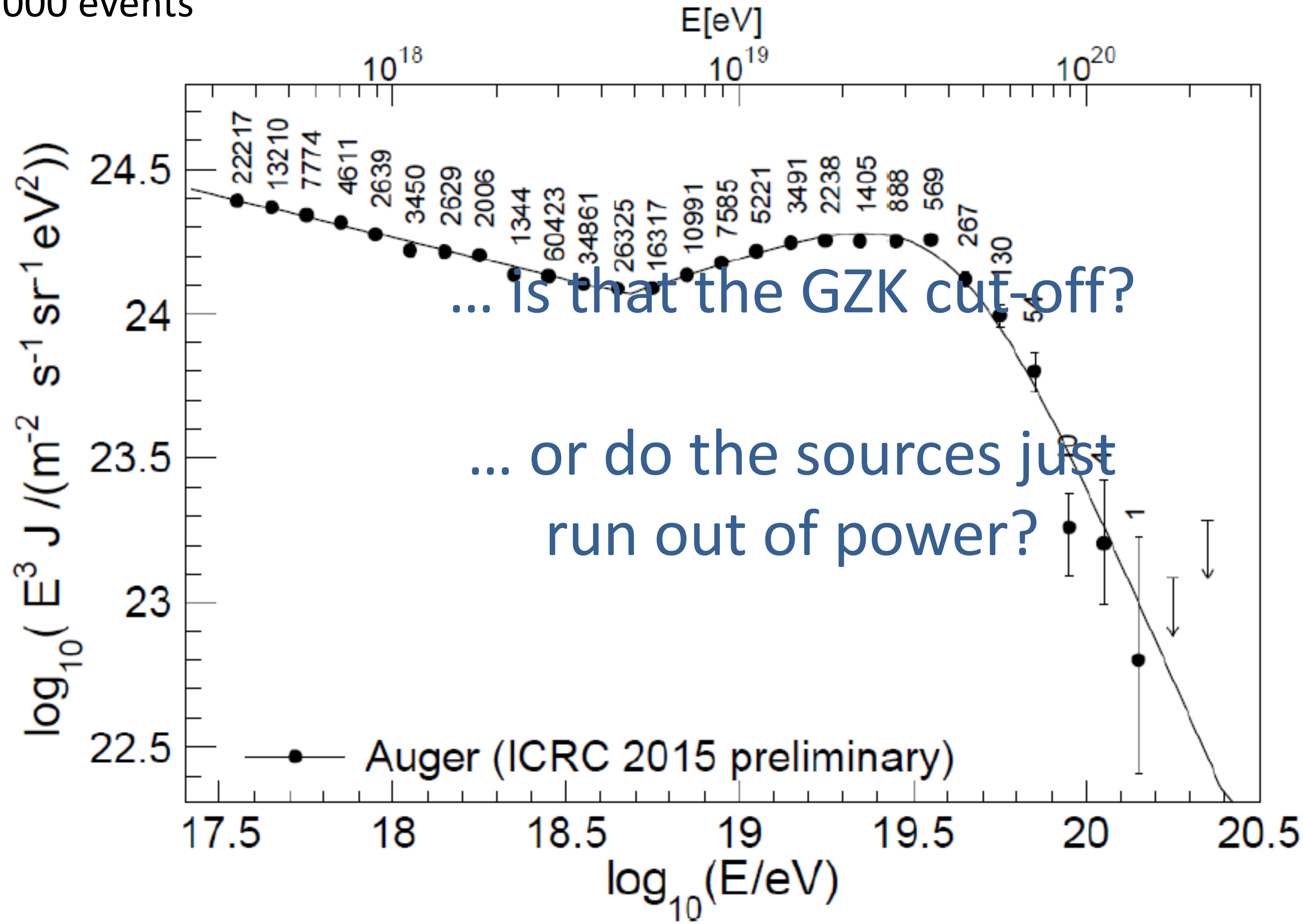
- Compare to QCD and Glauber model, tuning EAS simulations

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 muon excess in HE CR showers
- NA61/SHINE (SPS Heavy Ion and Neutrino Experiment):
  important input data for cosmic ray and neutrino experiments.

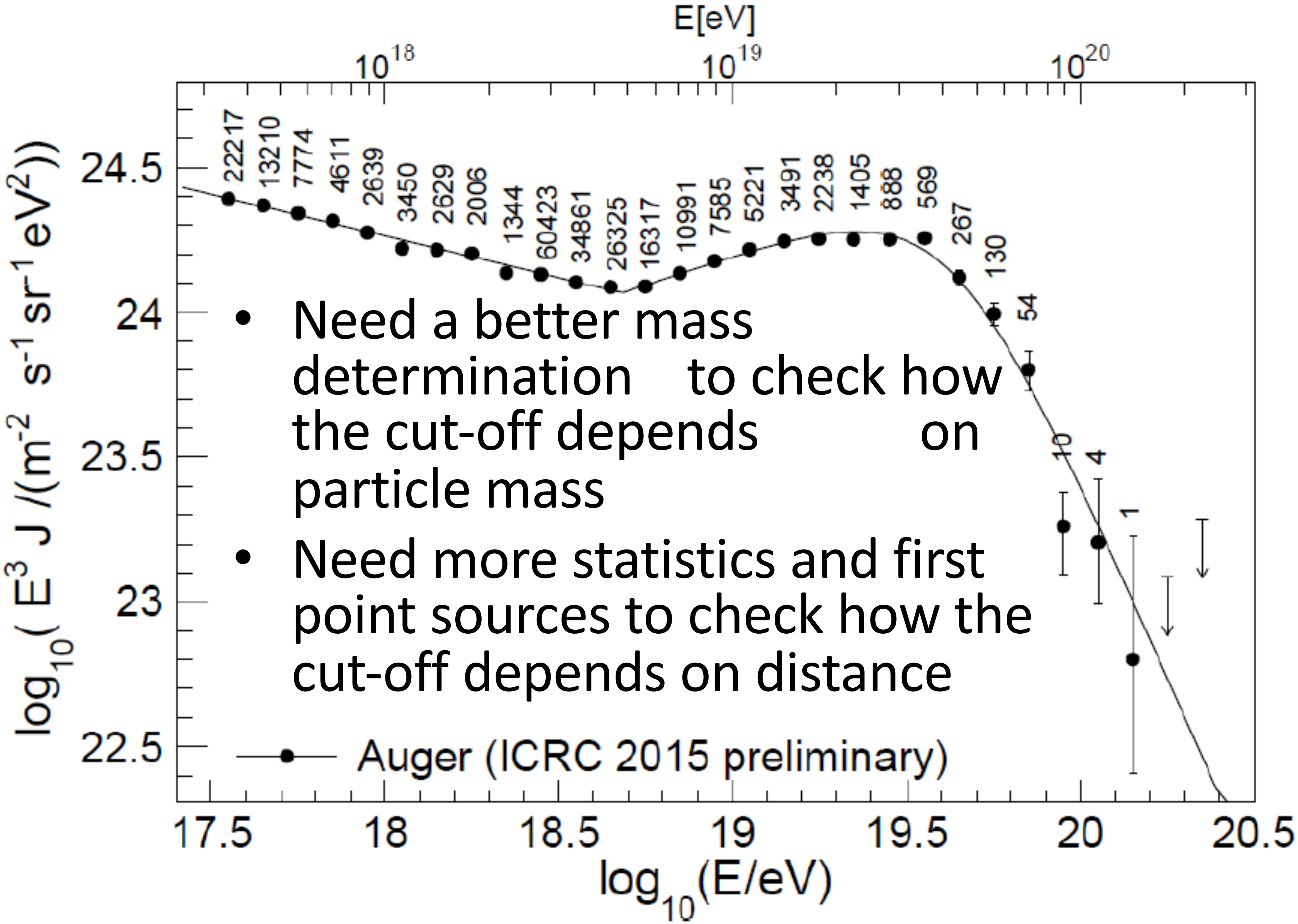
Cut-off at highest energies confirmed, but …

190 000 events



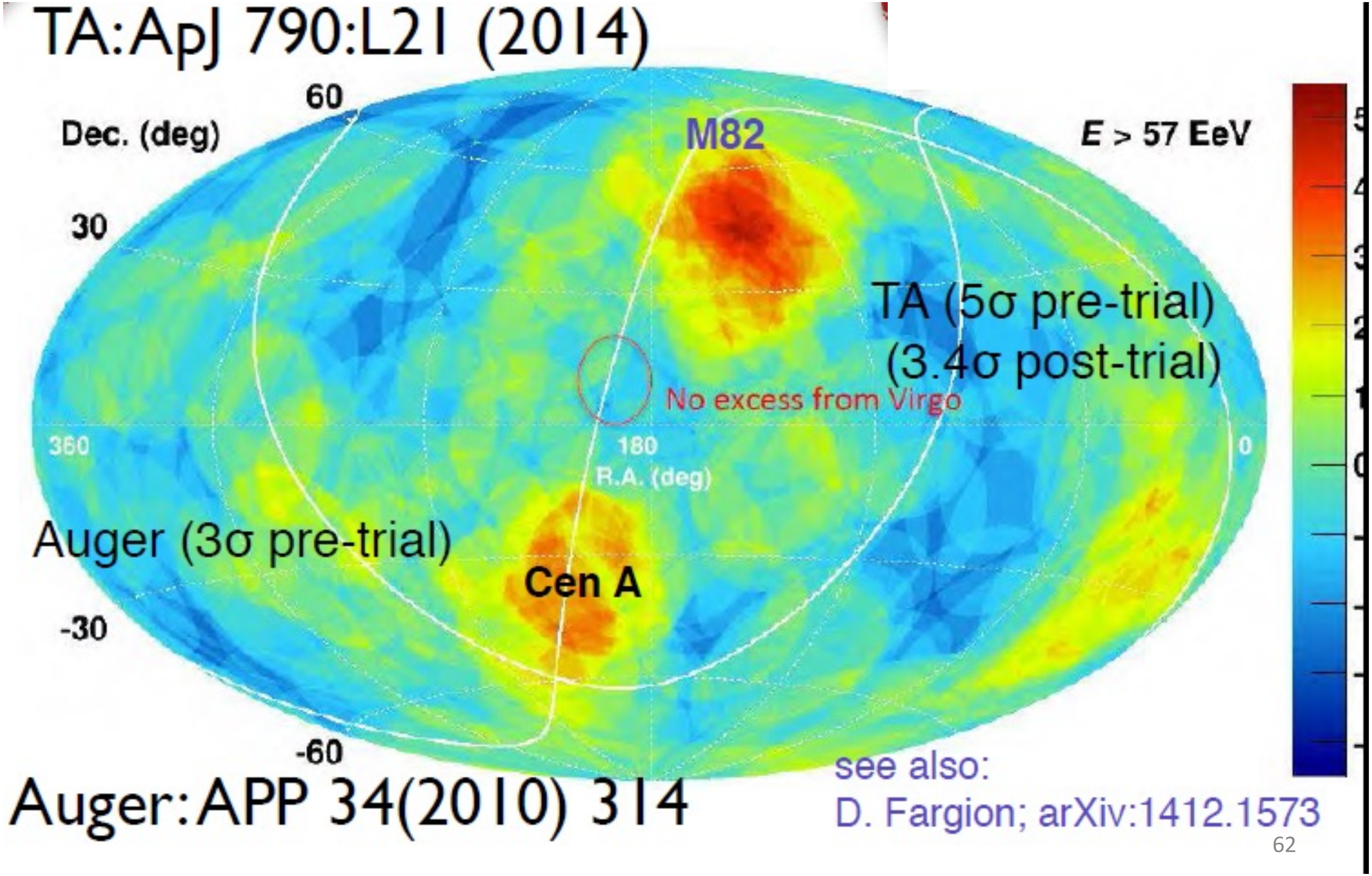
… is that the GZK cut-off?

… 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

Point Sources: Tantalizing hot spot at TA



What after results with upgraded arrays?

- Ultrahigh-energy cosmic ray physics is at a turning point
- Ultrahigh-energy cut-off has been clearly confirmed, but nature unclear (composition near the cut-off is key!)
- No point sources, but hot spot TA + “warm” spot Auger
- Origin of the muon excess at high energies not understood
- 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 km^2 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.

Albert Einstein

1916

Prediction of gravitational waves

Joseph Weber

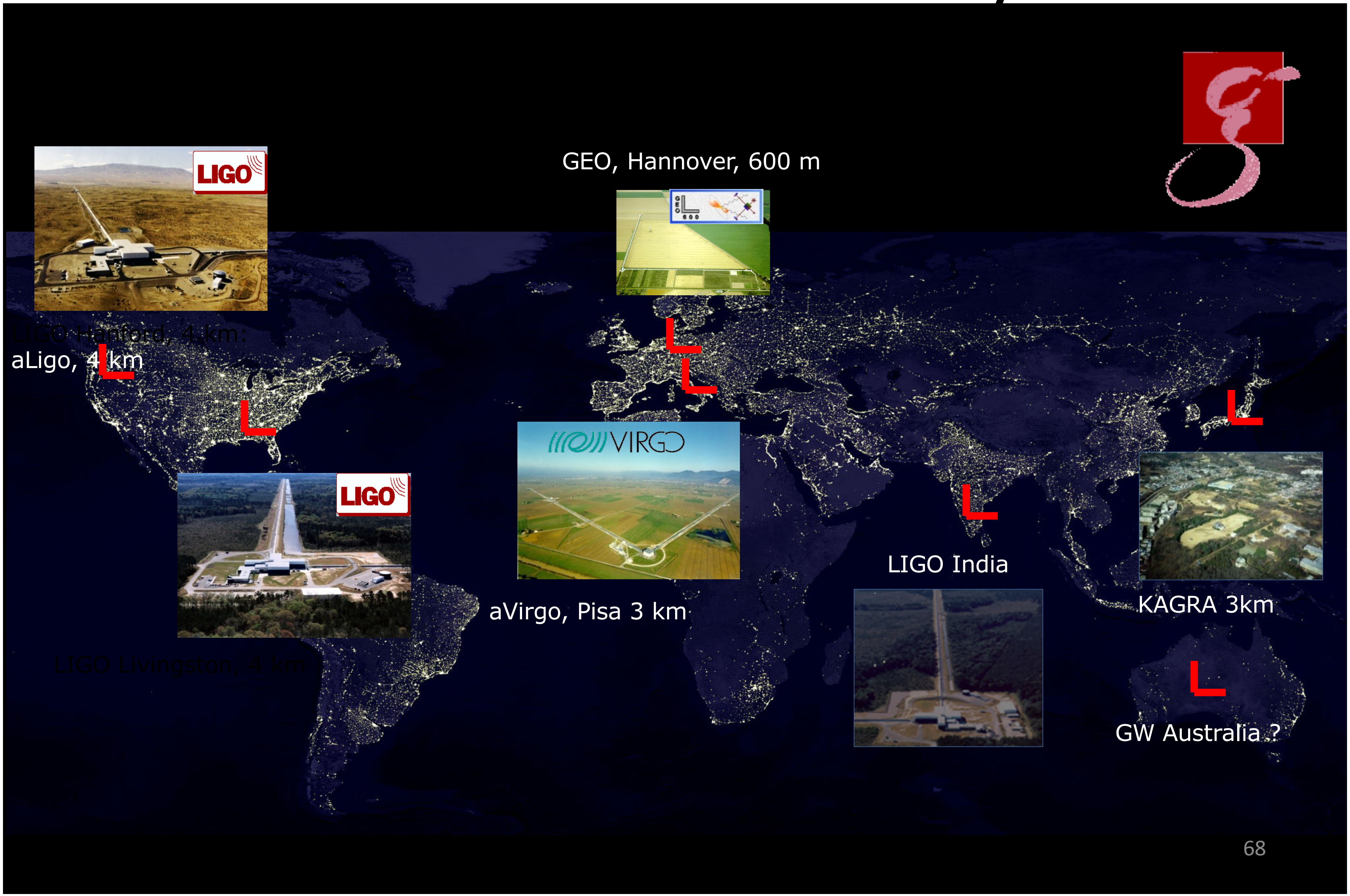
1958

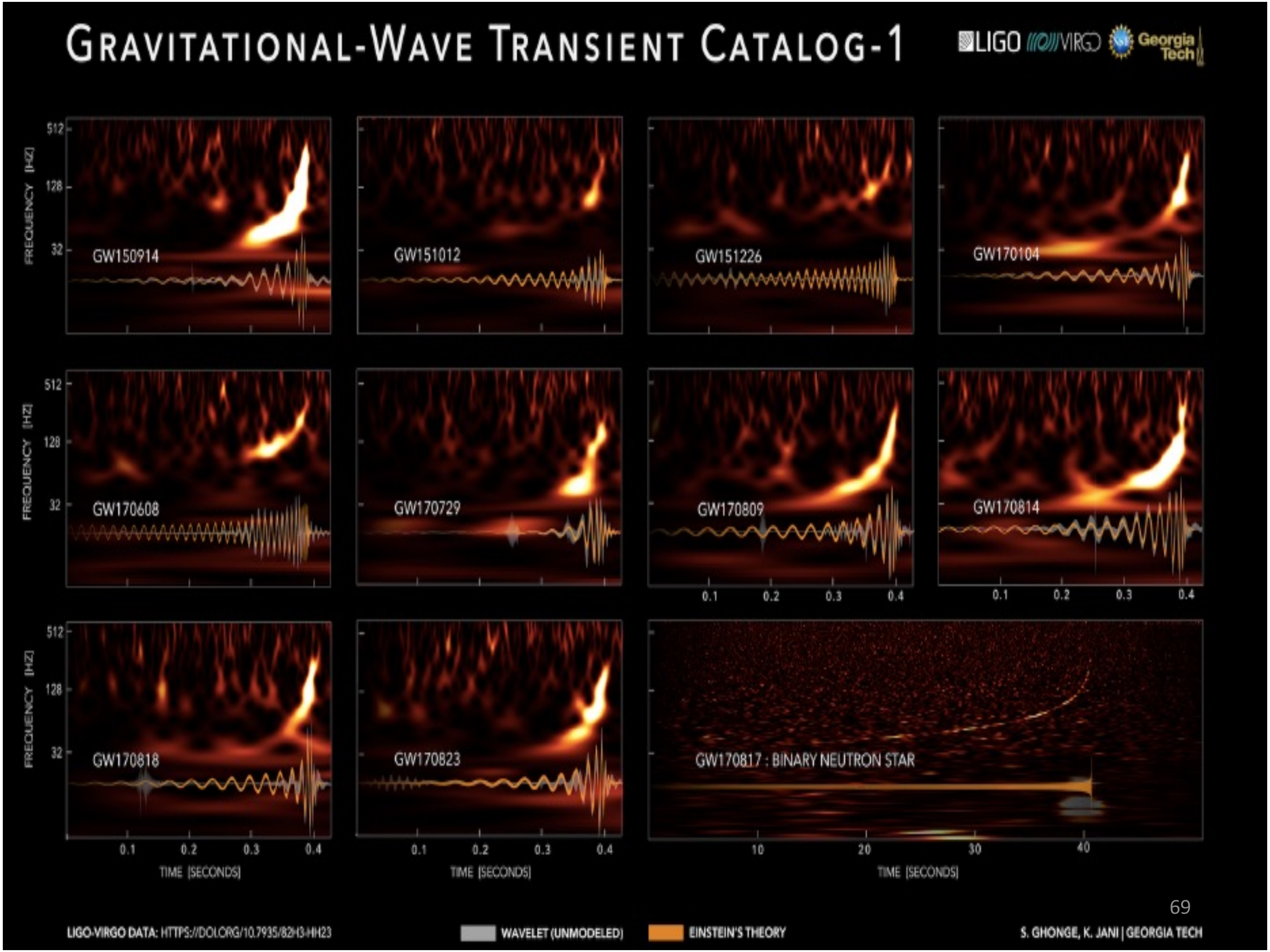
Search for GW with a bar cylinder

Rapport du comité présidé par Patrick Fleury en 1990

The current GW network of interferometers:
A model of collaboration

The GW network in 4-5 years





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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OPEN ACCESS

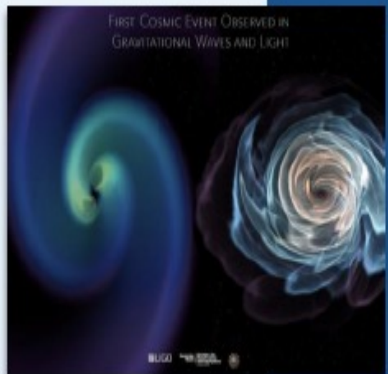
Multi-messenger Observations of a Binary Neutron Star Merger

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.)

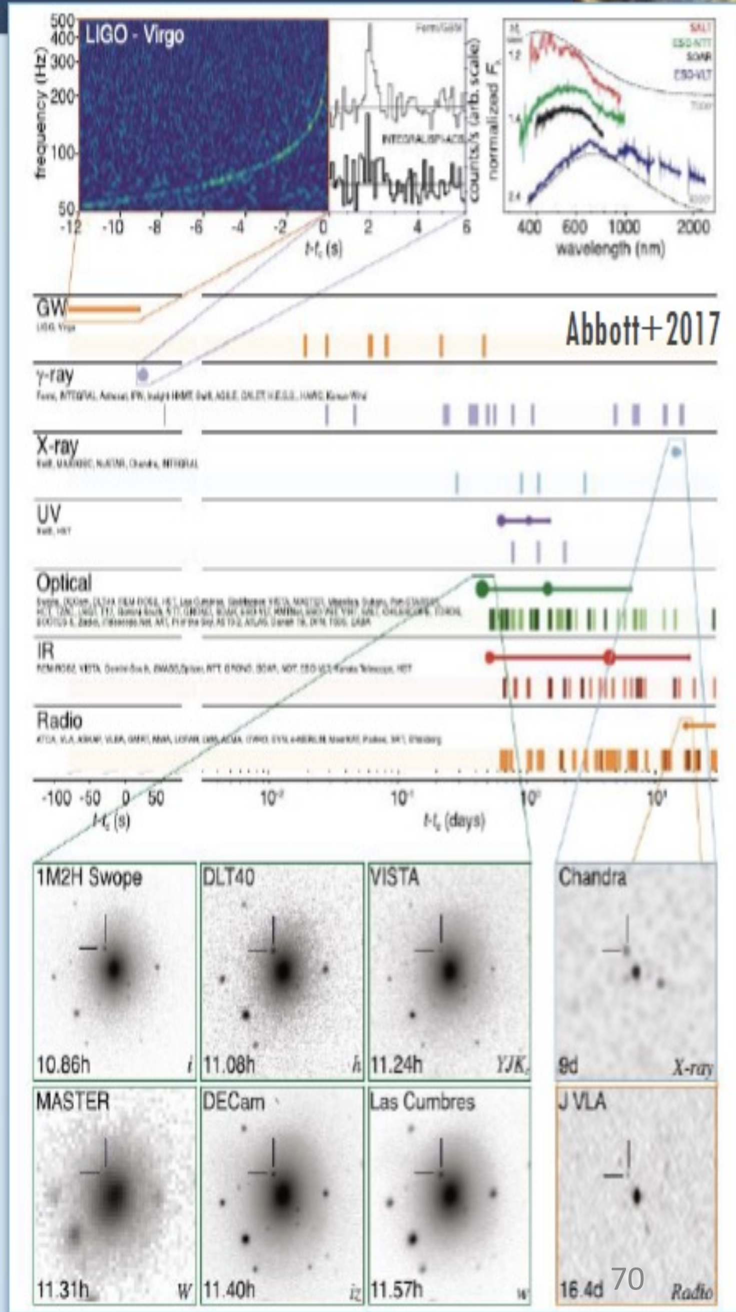
50 teams
>3600 authors

~20 orders of magnitude in wavelength

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

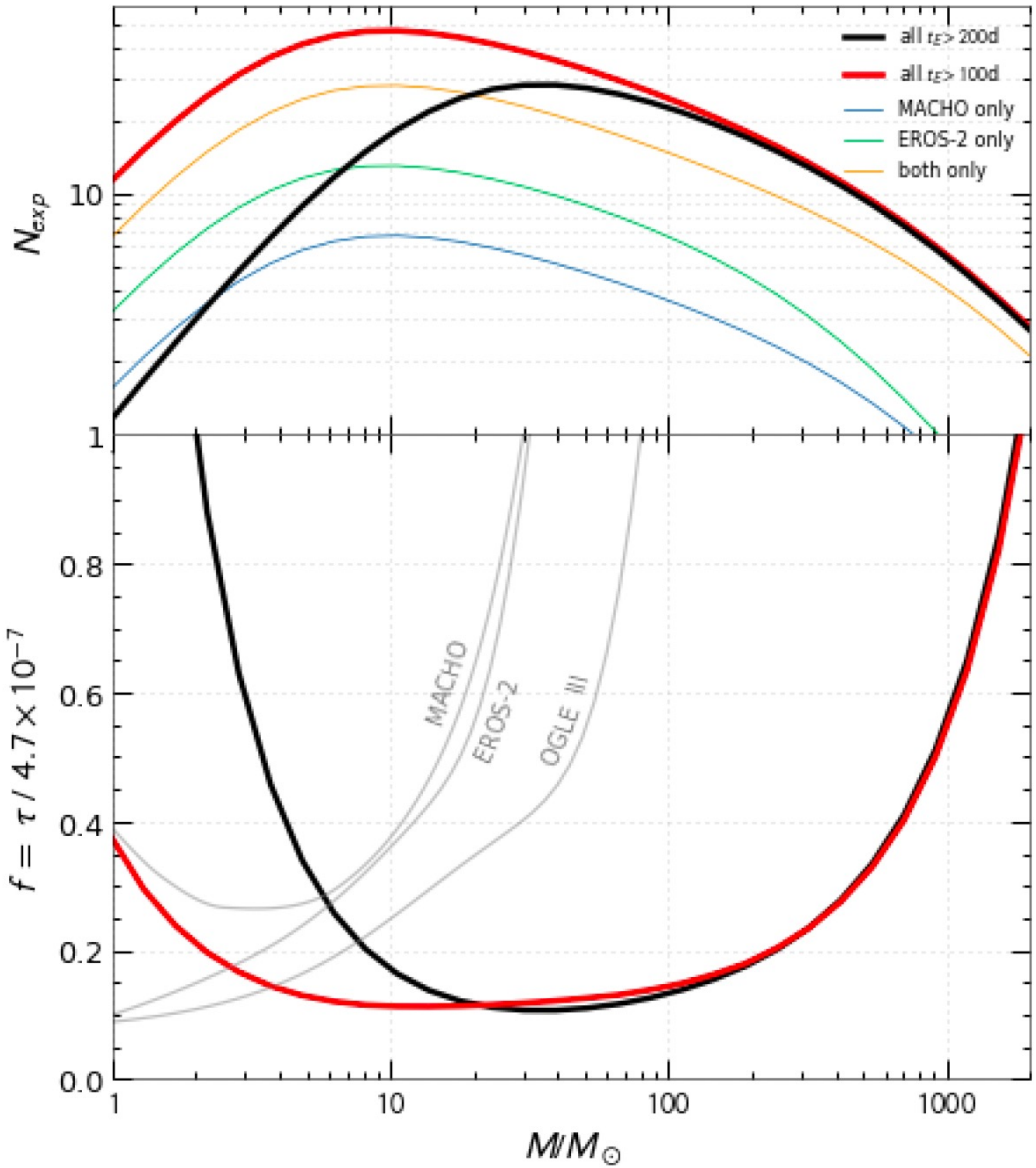


Credit: LIGO-Virgo

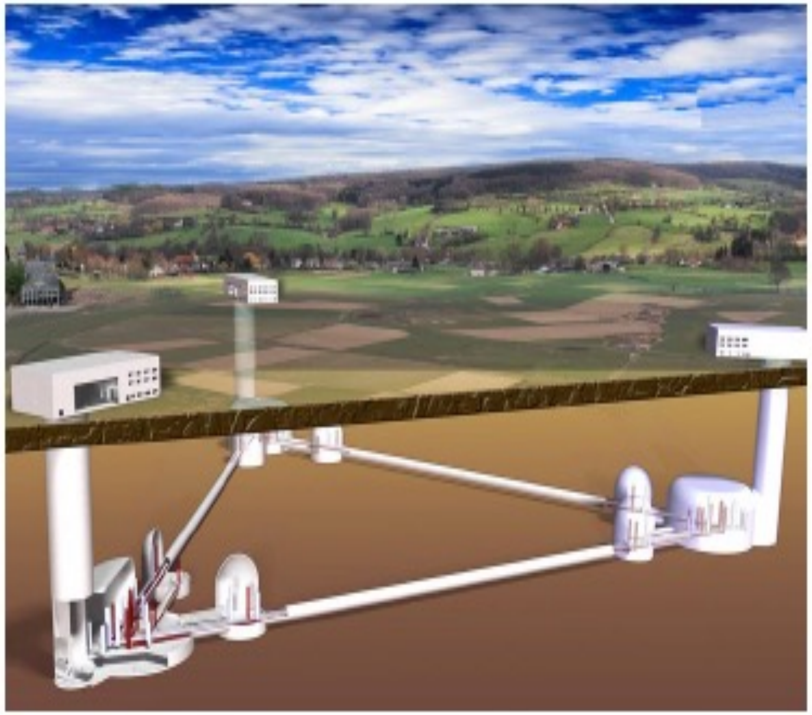


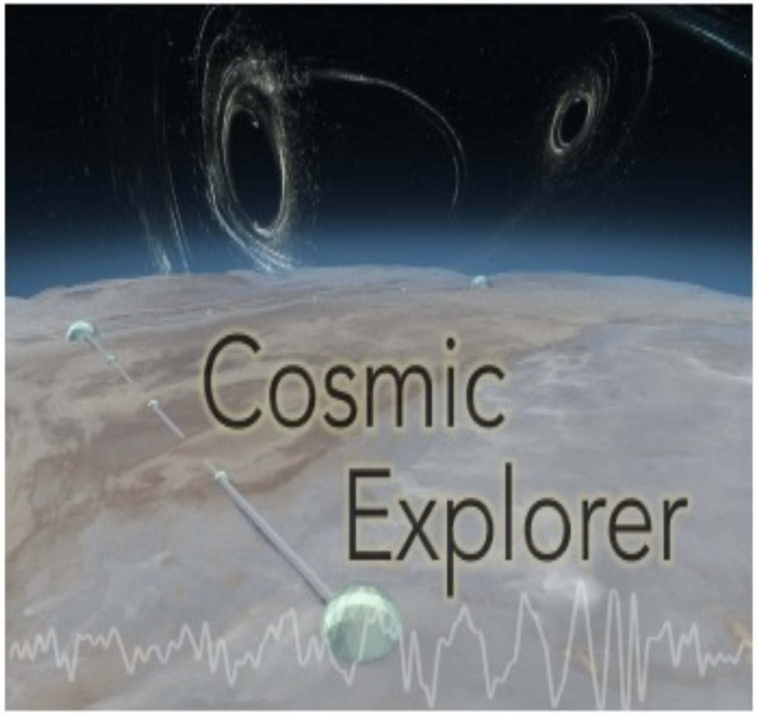
Black holes as dark matter?

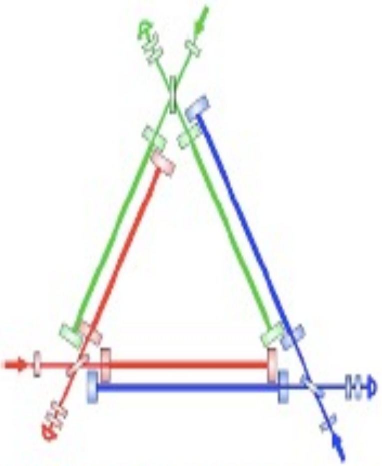
- Most events seen by LIGO/VIRGO are coalescence of few tens of solar masses black holes (excellent laboratory to test General Relativity)! Could these black holes be the dark matter in the universe?
- Very recently the EROS collaboration, combining its data with MACHO, has shown that the dark matter in the halo of our galaxy cannot be made of compact objects of masses between 10^{-6} and 10^{3} solar masses
- This is based on observations of millions of stars in the LMC, looking (during 10 years) at the occurrence of alignments between us, a dark compact object in the halo of our galaxy and a star in the LMC.
    - » Thèse 2021: Tristan Blaineau, directeur de thèse: Marc Moniez


all t_E> 200d
all t_E> 100d
MACHO only
EROS-2 only
both only
N_{exp}
10
1
$f = \tau / 4.7 \times 10^{-7}$
0.8
0.6
0.4
0.2
0.0
MACHO
EROS-2
OGLE III
1
10
100
1000
$M/M_\odot$

Gravitational Waves: 3rd generation interferometers





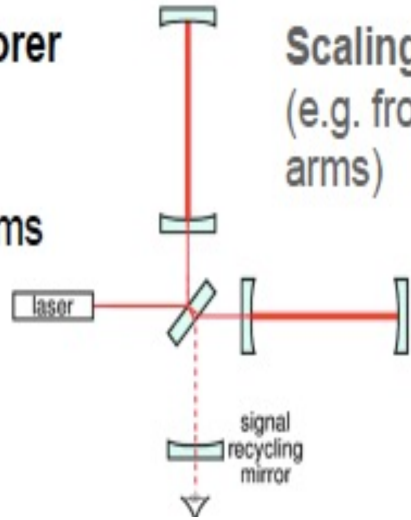


Einstein Telescope
(EU lead)

- 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)

The Dawn of Multimessenger Astronomy

Recent highlights

Highlight #1: First merger of two Neutron-stars

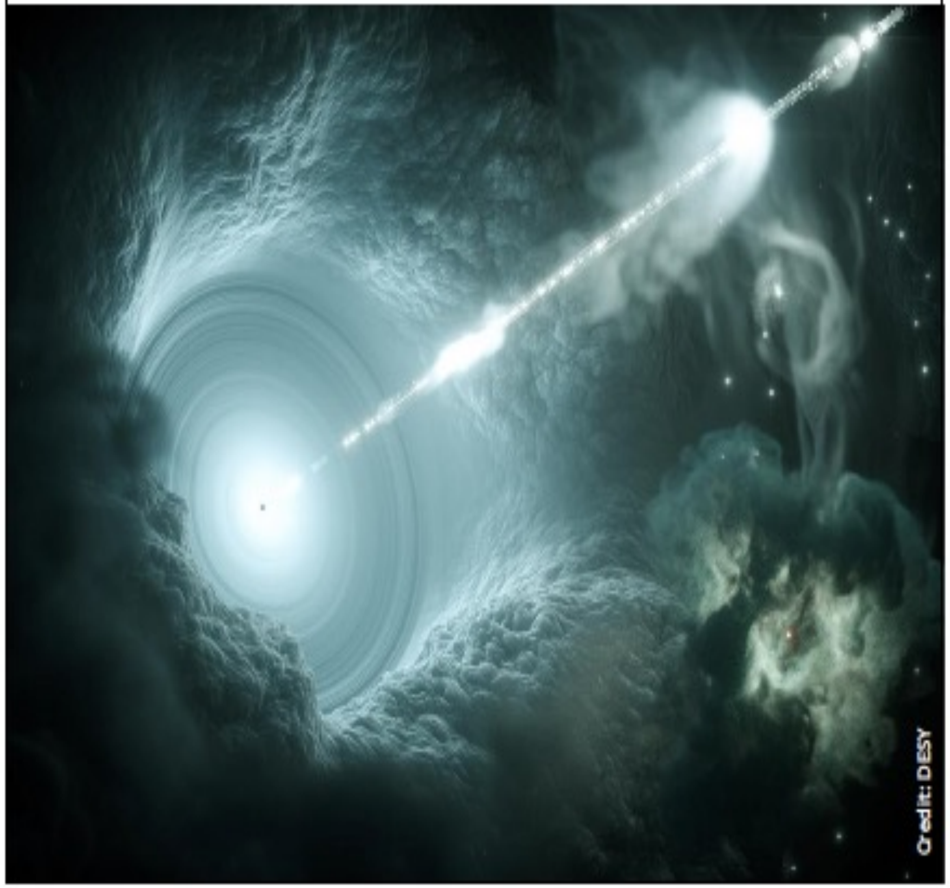
How: Gravitational waves + optical + X-rays

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)



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, hypernovae 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)
- This is a new astronomy: the astronomy of the most violent phenomena in the Universe today!!

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
- Guided by curiosity: serendipity plays a role

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 2022/2023

- Long term curiosity driven sciences, source of knowledge, of disruptive discoveies and of applications for future generations (astroparticle physics is an example). Re-enchant our world.
- IUPAP (International Union of Pure and Applied Physics) has taken the lead of this 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 by thr UN General Assembly happened on December 2nd 2021! The Year will extend over 2022 and 2023

END