The onset of astroparticle physics (multi messenger astronomy), especially in France: a tribute to Stavros, a scientist, a philosopher,

History of Particle Astrophysics

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

Michel Spiro

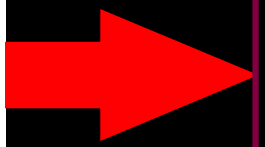
President of IUPAP

WHAT IS PARTICLE ASTROPHYSICS

from Nathalie Palanque

Big Bang Nucleosynthesis
Cosmic Microwave Background
Supernovae and cosmology (R. Pain)
Clustering of Galaxies (BAO…)
Dark matter (Fritz Zwicky and Vera Rubin), dark energy

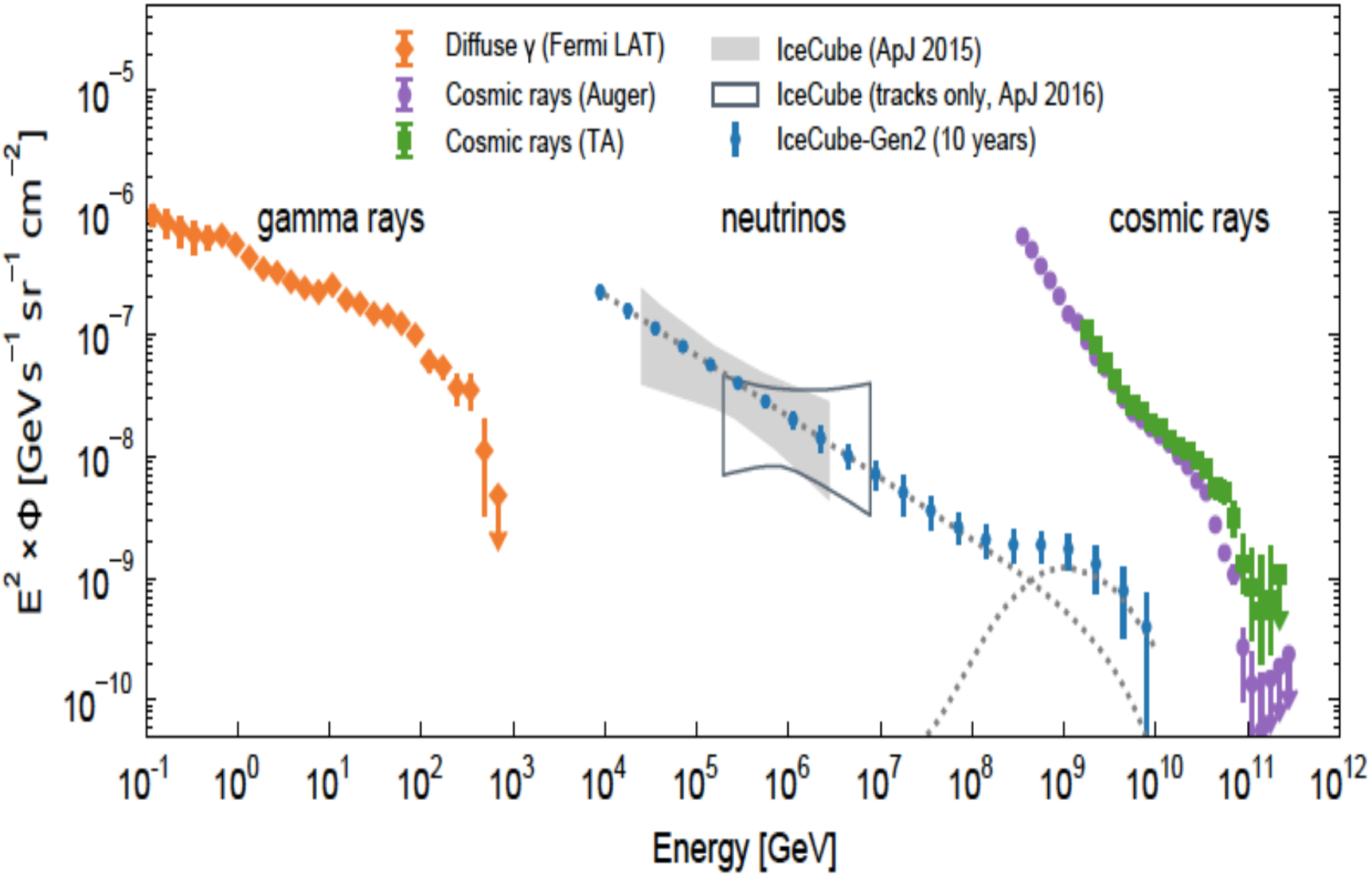
2) Neutrino Physics and Proton Decay
Neutrino cosmology (Nathalie Palanque)
Neutrinos and star evolution: **Solar neutrinos**, **Supernova 1987**
Non accelerator Neutrino physics (mass, oscillations, nature:
Dirac, Majorana, sterile)
Proton decay.



With a Zoom on France

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

Science: Resolving the mysteries of the UHE Universe



Motivations

- Spectra, composition and origins of cosmic rays (super/hypernovae, Active Galactic Nuclei, coalescence..)

- Discover new particles

- 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

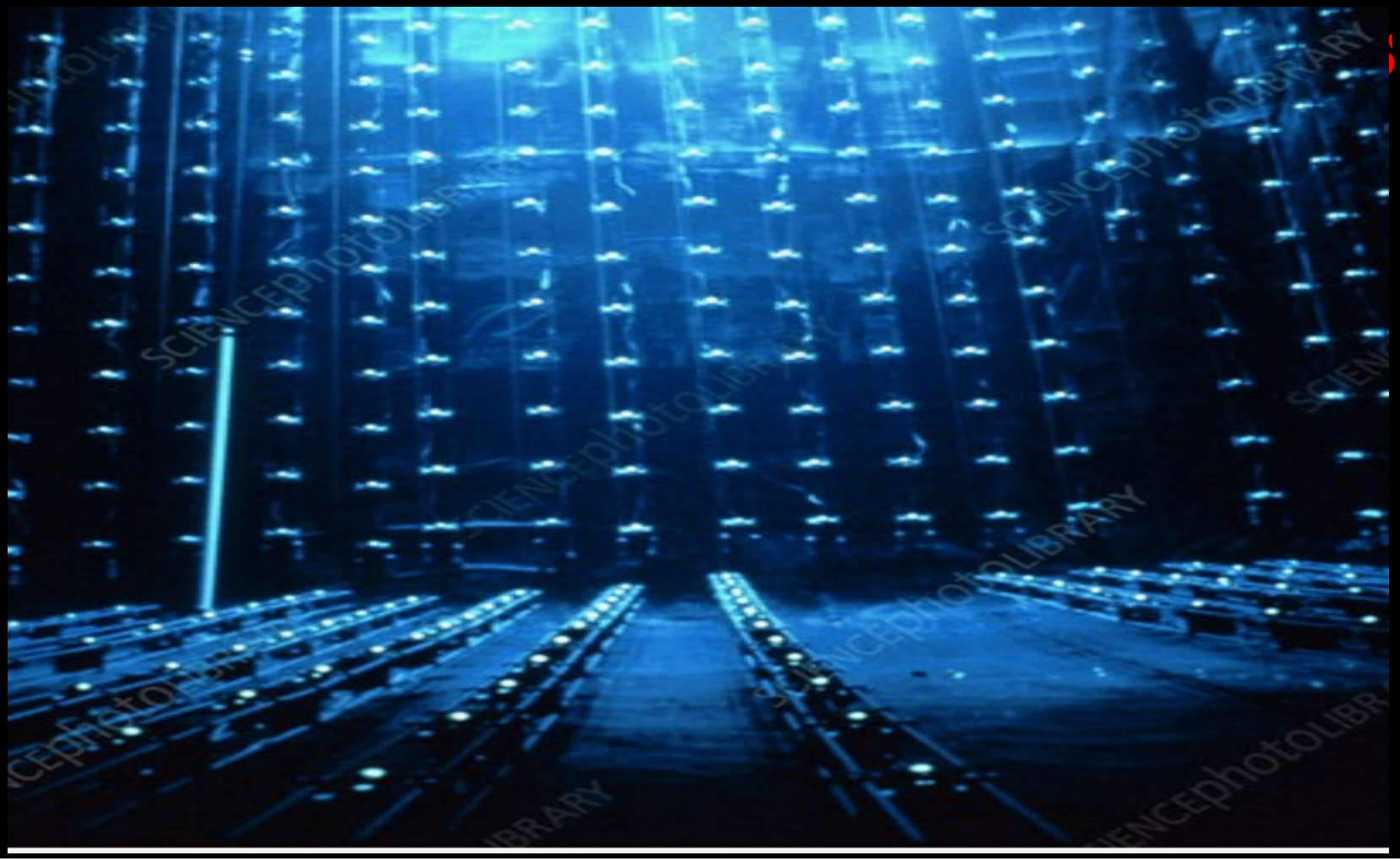
- Resurrected in the 80's with underground searches for proton decay(10^{30} years expectation) detectors and three anomalies: solar neutrino deficit (Chlorine experiment), Cygnus X3 anomaly, ultra high energy cosmic ray anomaly (events beyond the Greisen, Zatsepine, Kouznine GZK cut-off observed by AGASA EAS)

Early times: Louis Leprince Ringuet and M. Lhéritier

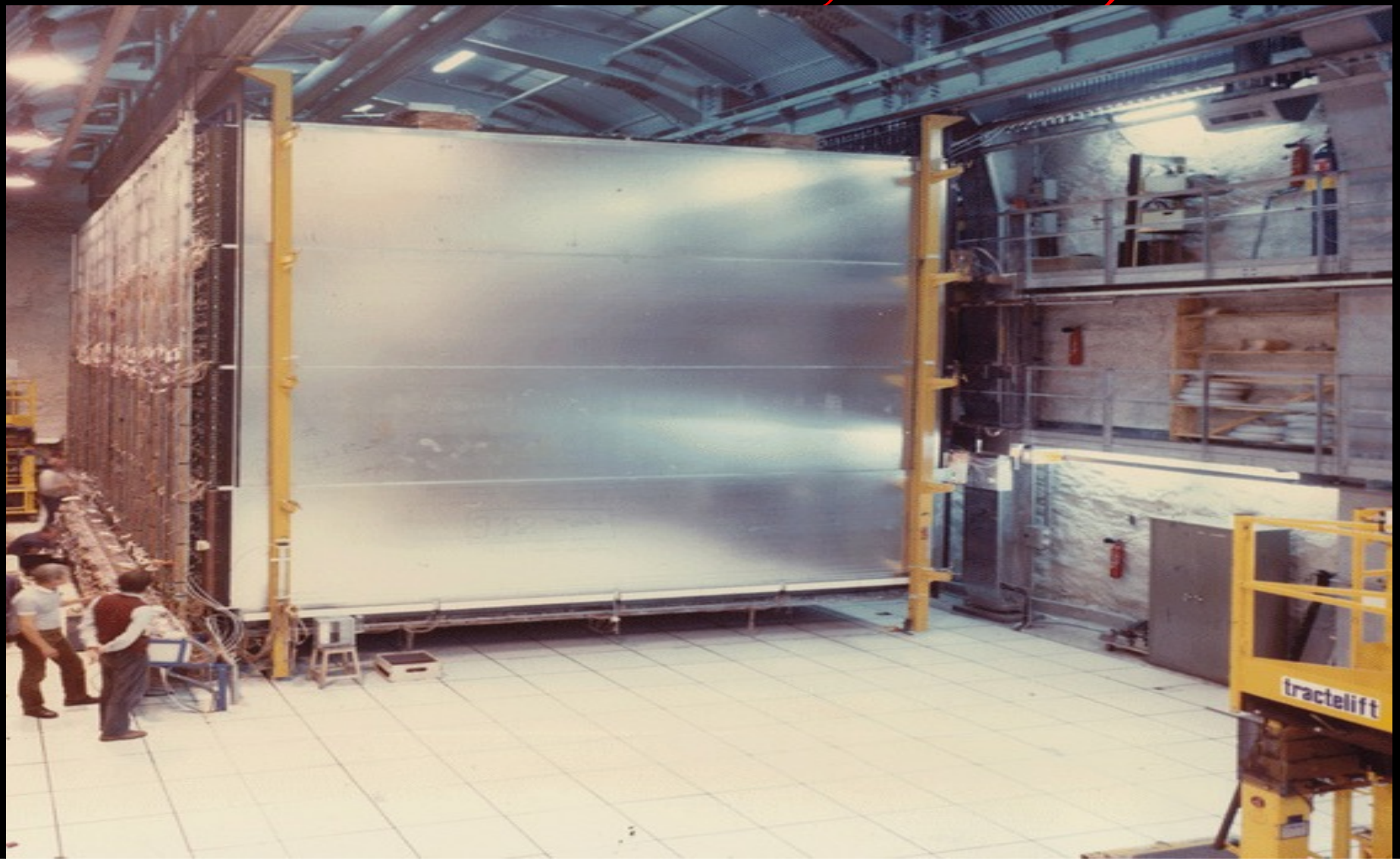
1944: 10 000 pictures Wilson Cloud Chamber
Largentière- La Bessée
First evidence for a new particle which turned to be the K meson

Proton lifetime experiments

IMB 1981 (Sulak..), Kamiokande (1983, Koshiba, and Totsuka…): also



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



Three important results in 1985
1. solar neutrinos deficit enigma

Homestake mine
Ray Davis

Expected Solar Neutrino Spectrum , flux measured by Homestake, three times less than expected (J. Bahcall, debate with S. Turck-Chièze))

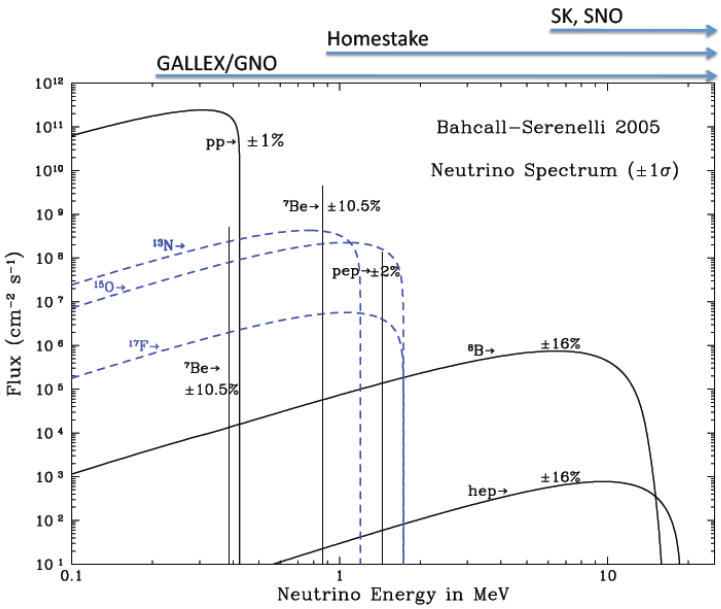
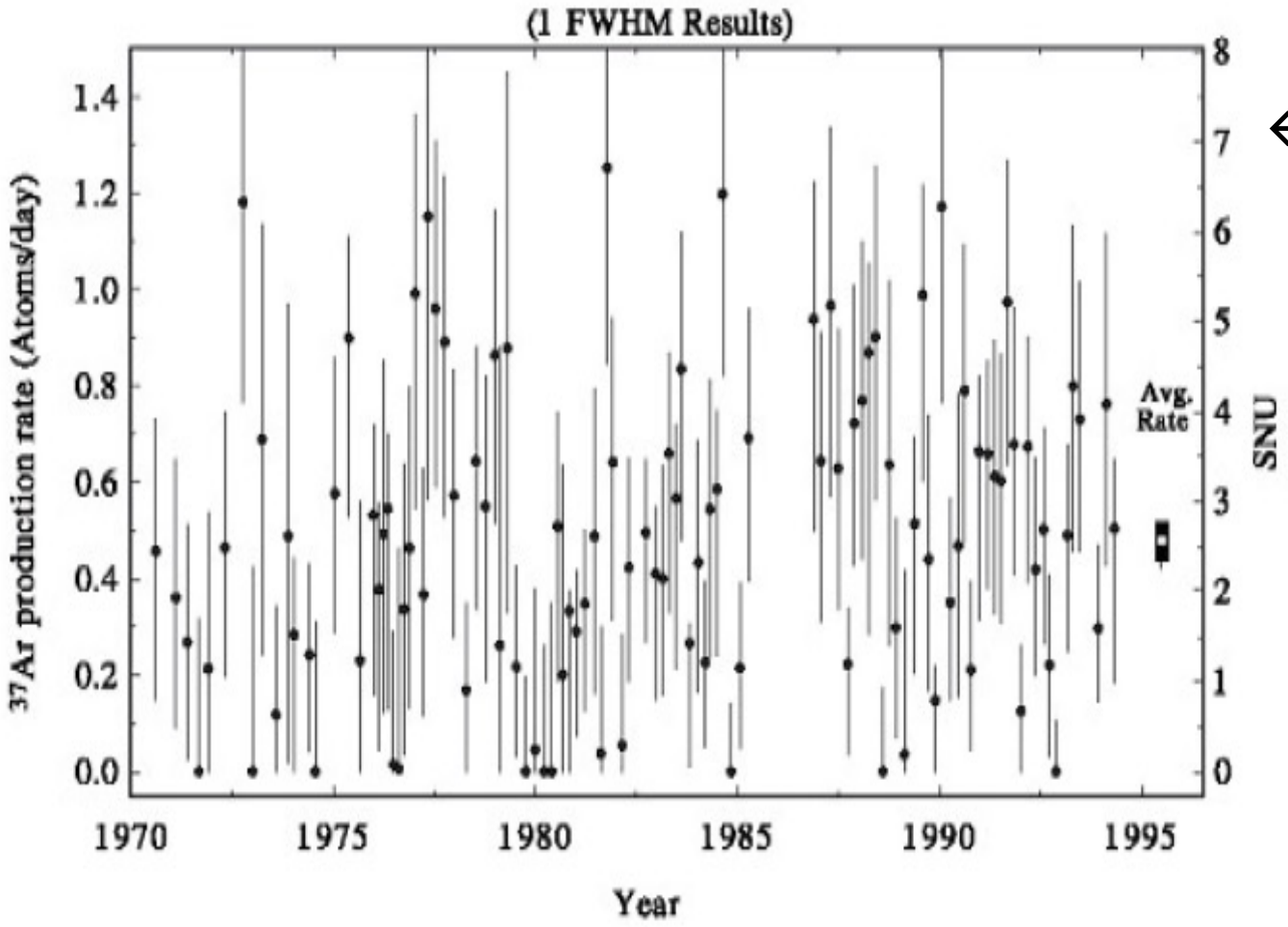


Figure 1: Neutrino fluxes (with percentage uncertainties) as predicted by the Bahcall-Serenelli



←Expected

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 (Sylvaine Turck-Chieze vs Bahca
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

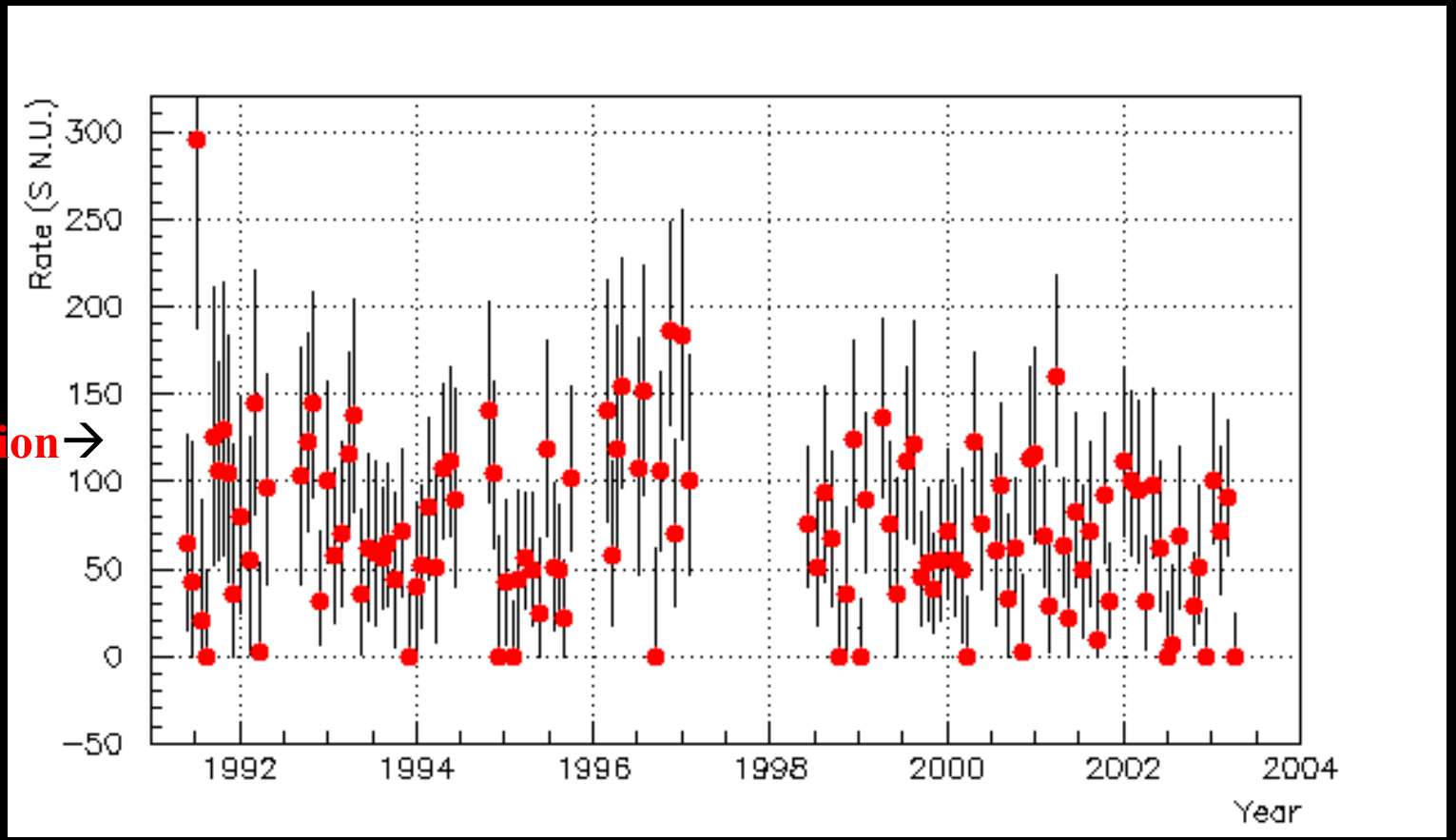
pp + pep	73 SNU	(55 %)
^{7}Be	35 SNU	(27 %)
CNO	8 SNU	(8 %)
^{8}B	13 SNU	(10 %)

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)

expectation→



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

Zeitschrift für Physik C Particles and Fields

Matter Effects for Solar Neutrino Oscillations

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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]:

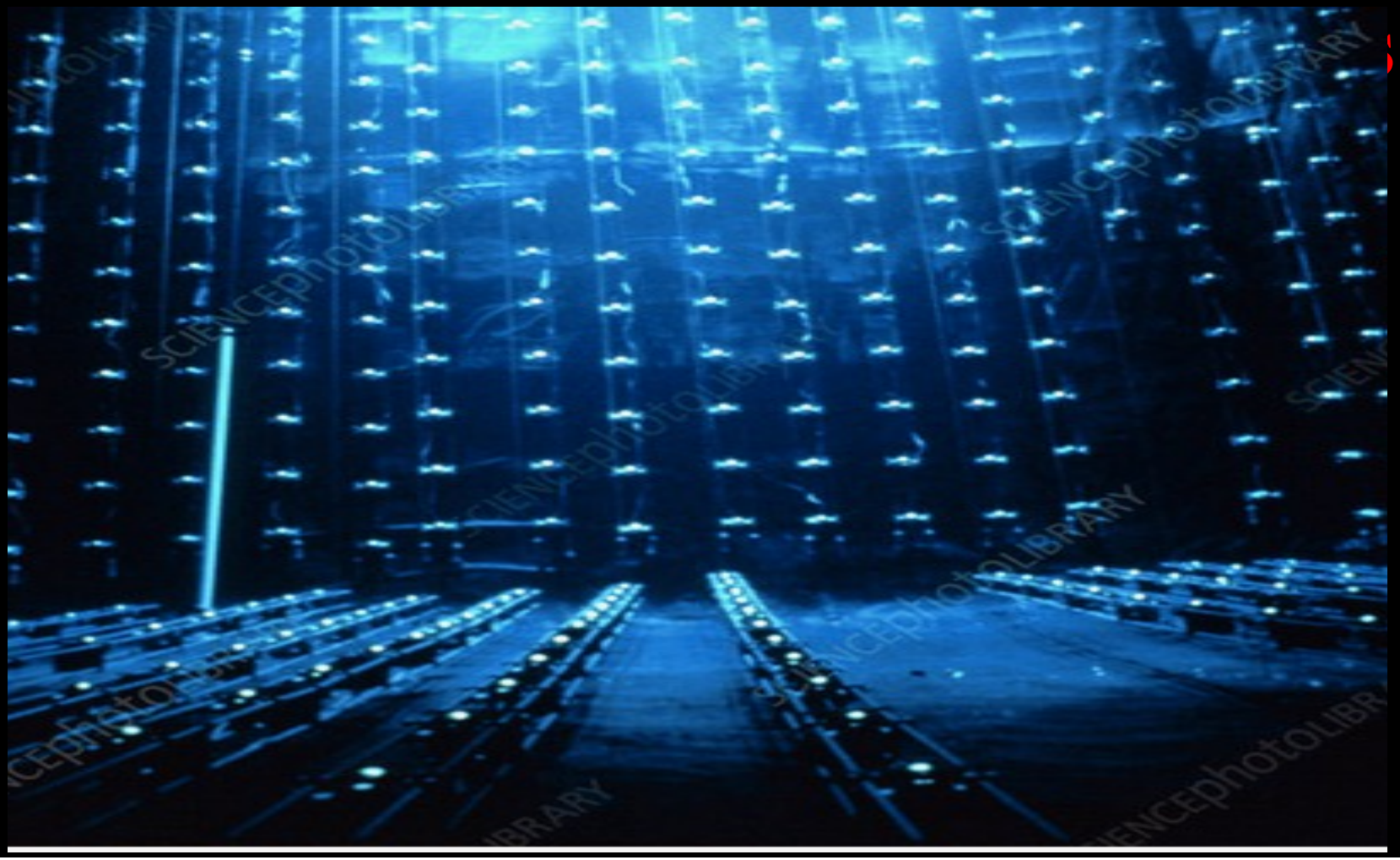
$$d\varphi_m/dt = k(x) = \sqrt{2}\cdot G\cdot N(x)$$

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

Proton lifetime experiments

IMB 1981 (Sulak..), Kamiokande (1983, Koshiba and Totsuka…): also



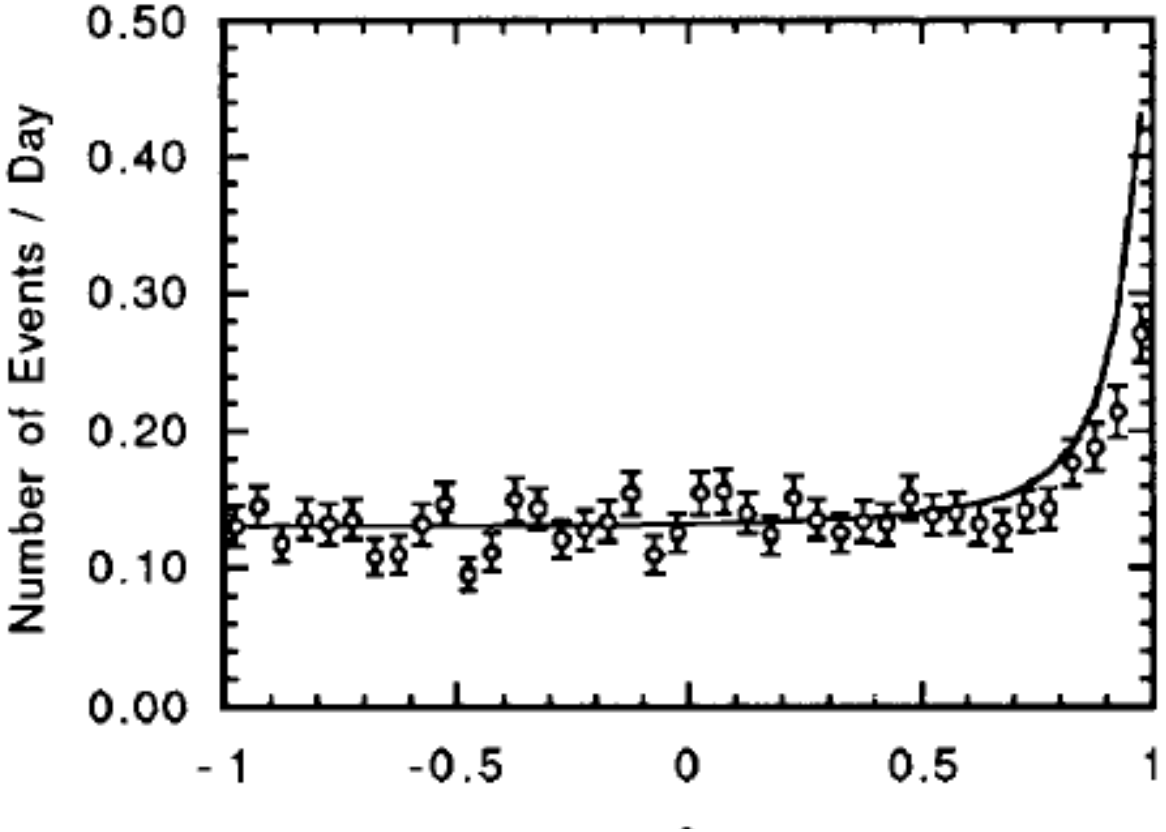
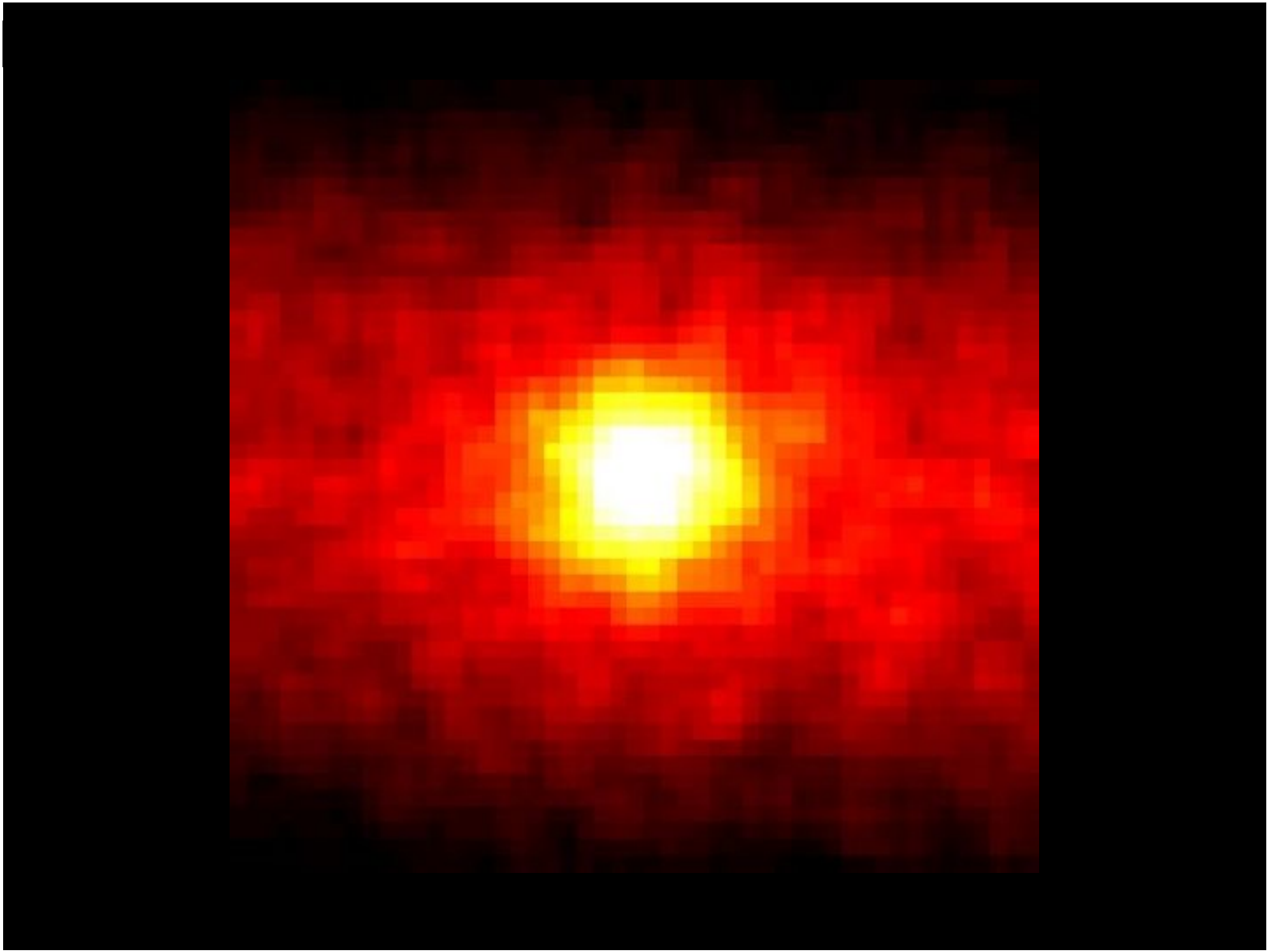


Figure 2: Angular distribution of events with respect to the Sun, Kamiokande [29].



SN 1987 a
Neutrino detection
Neutrino image of SN 1987 a

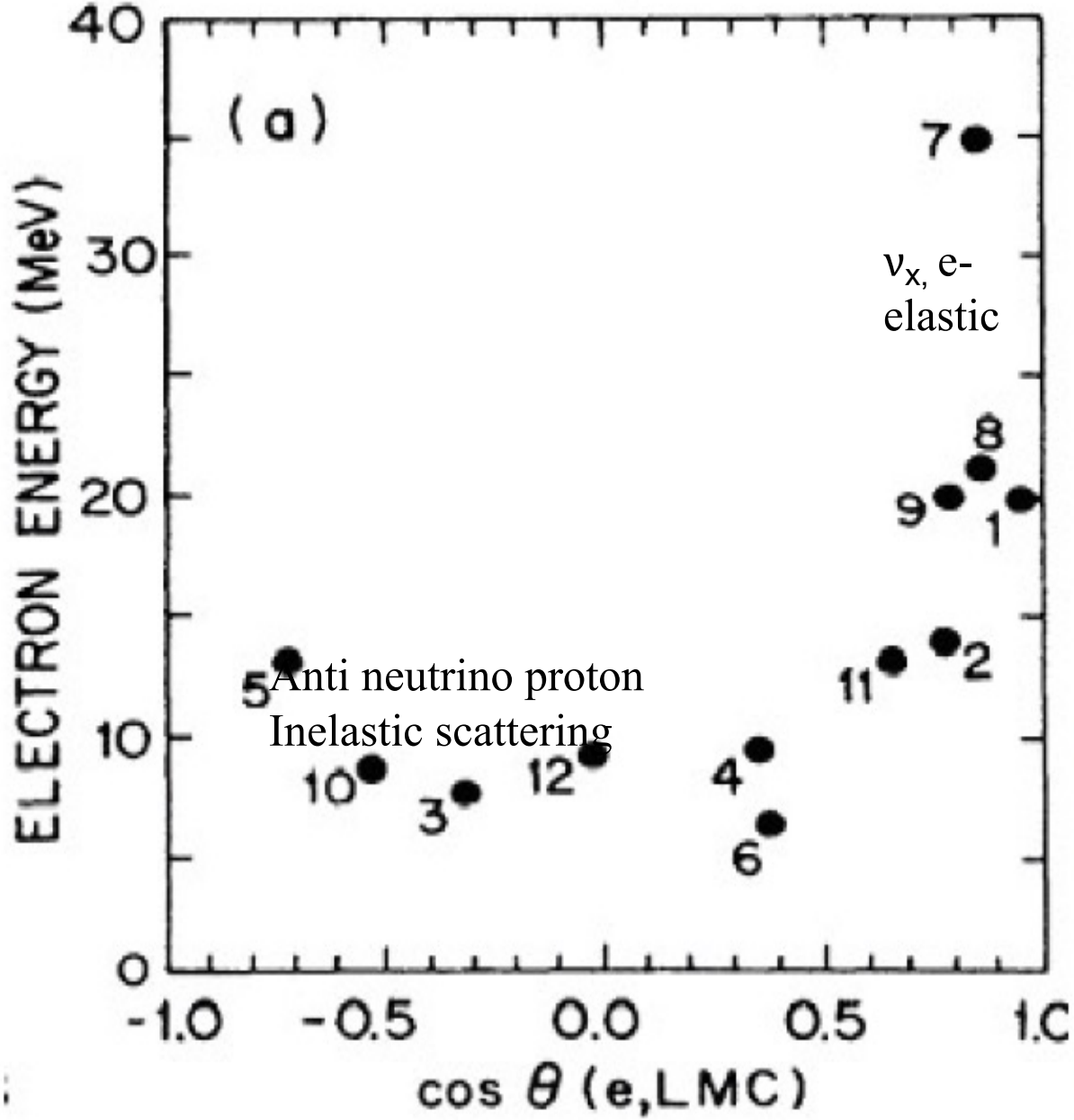
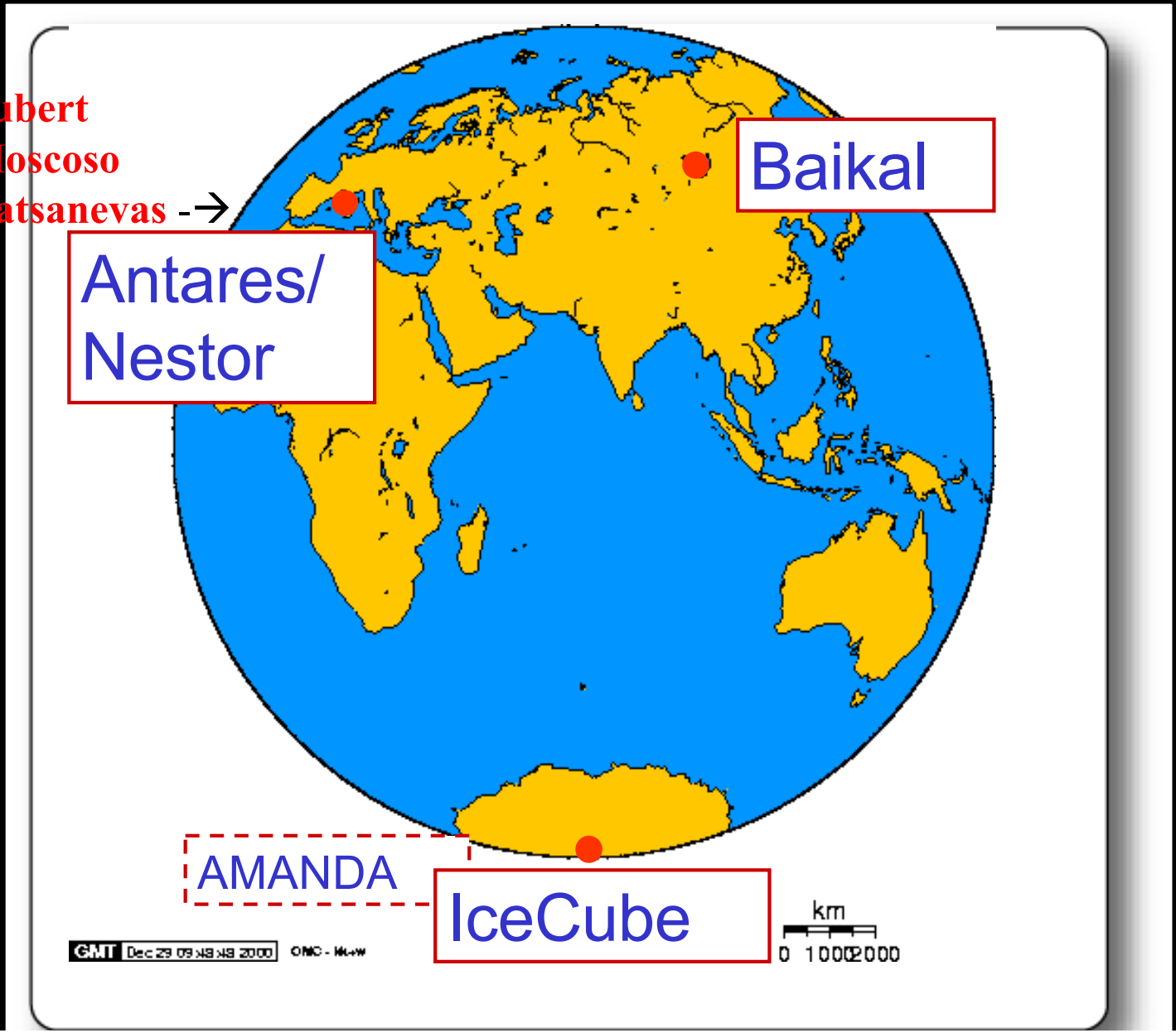


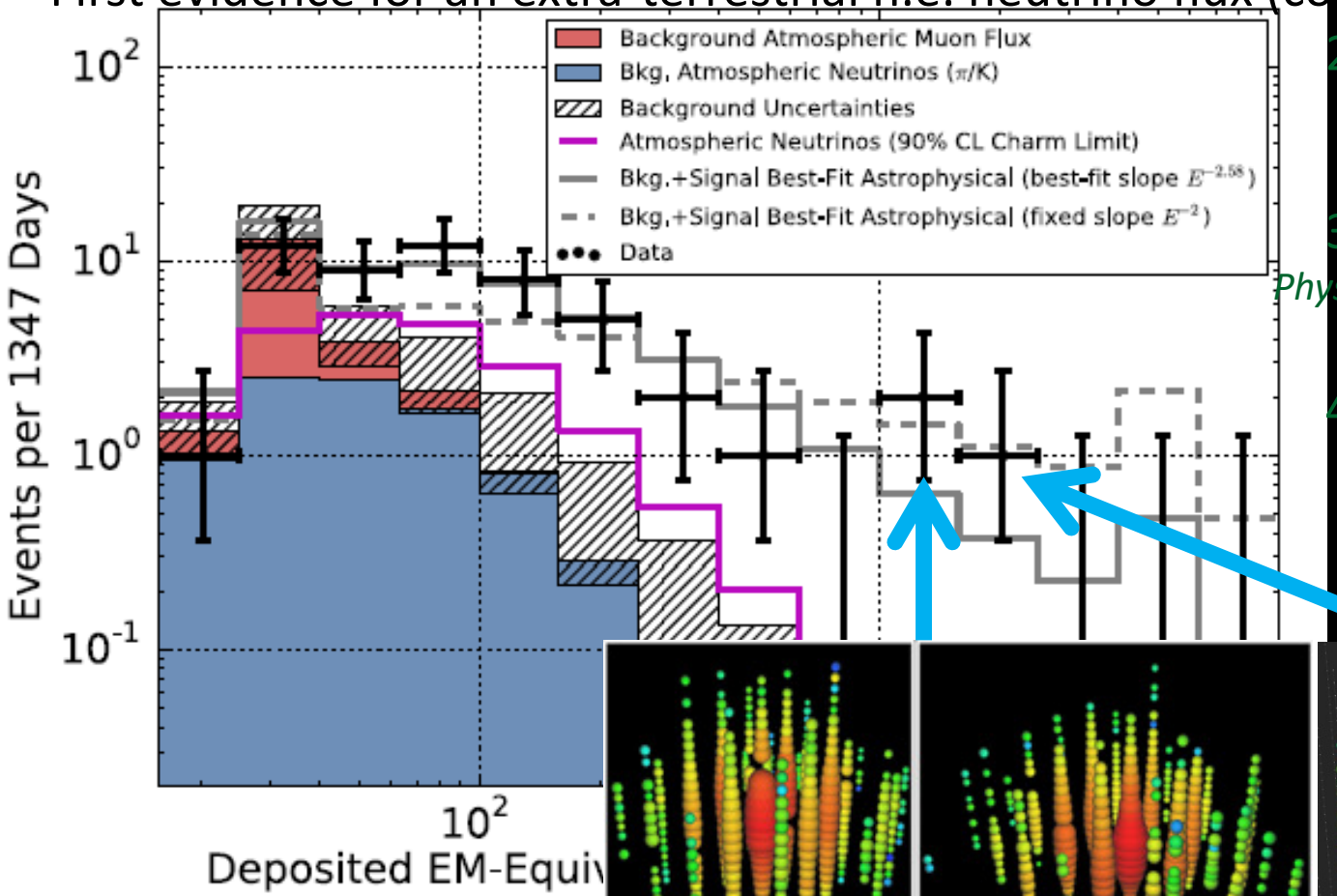
Fig. 4 Scatter plot of the detected electron energy and the cosine of the angle between the measured electron direction and the direction of the Large Magellanic Cloud. The number on each entry is the time-sequential event number. The direction of the positron from an anti-neutrino reaction has very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

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

Jj Aubert
L. Moscoso
S. Katsanevas -→



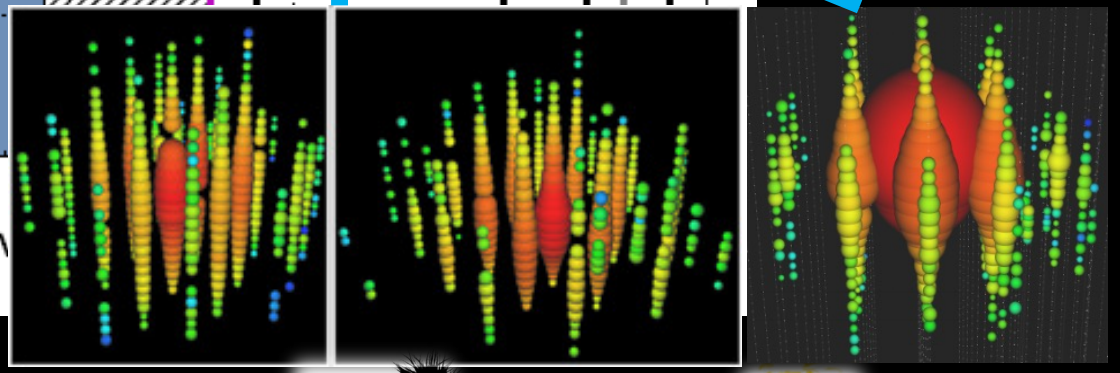
First evidence for an extra-terrestrial h.e. neutrino flux (co



2 yrs data, 28 evts 4.1σ
Science 342 (2013)

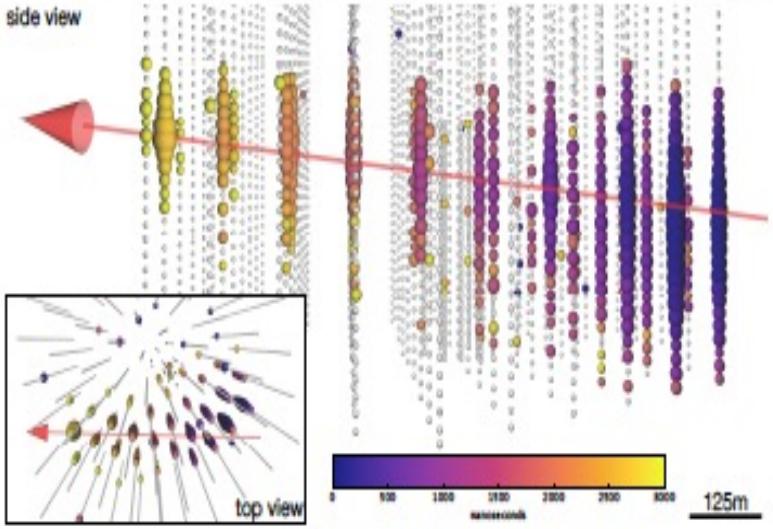
3 yrs data, 37 evts 5.9σ
Phys.Rev.Lett. 113:101101 (2014)

4 yrs data, 54 evts ~ **7σ**

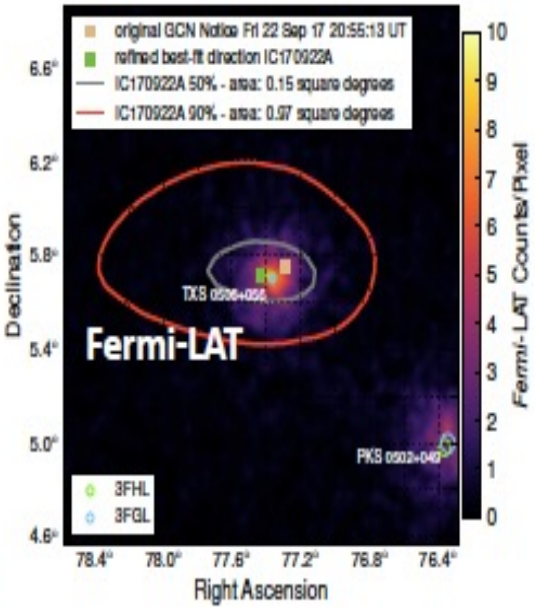


indication for point source

A high energy neutrino in coincidence with a flaring blazar



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



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

Science 13 Jul 2018: Vol. 361, Issue 6398

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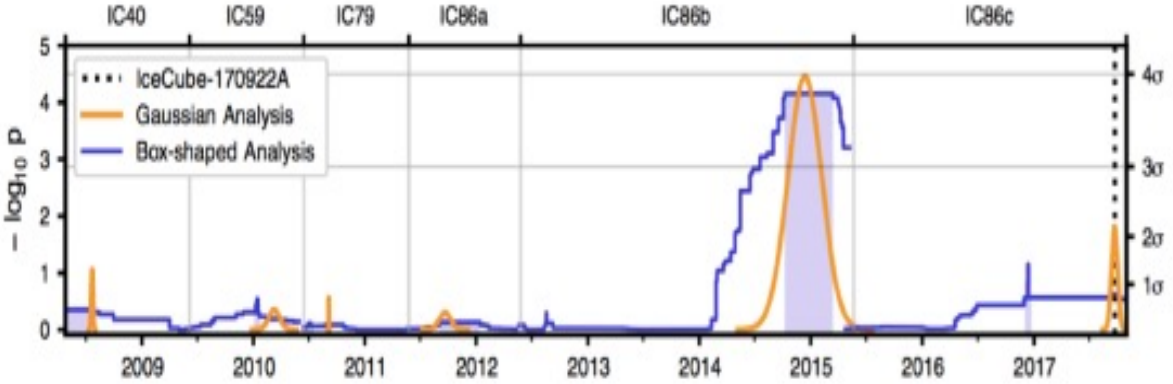
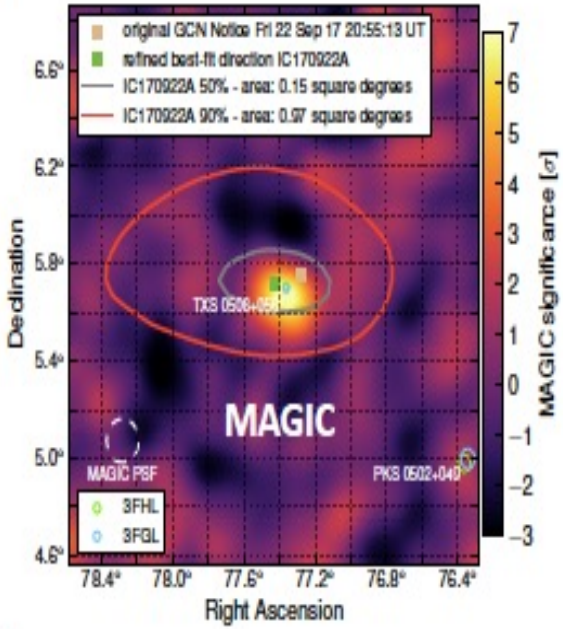


Excess of neutrinos observed between September 2014 and March 2015

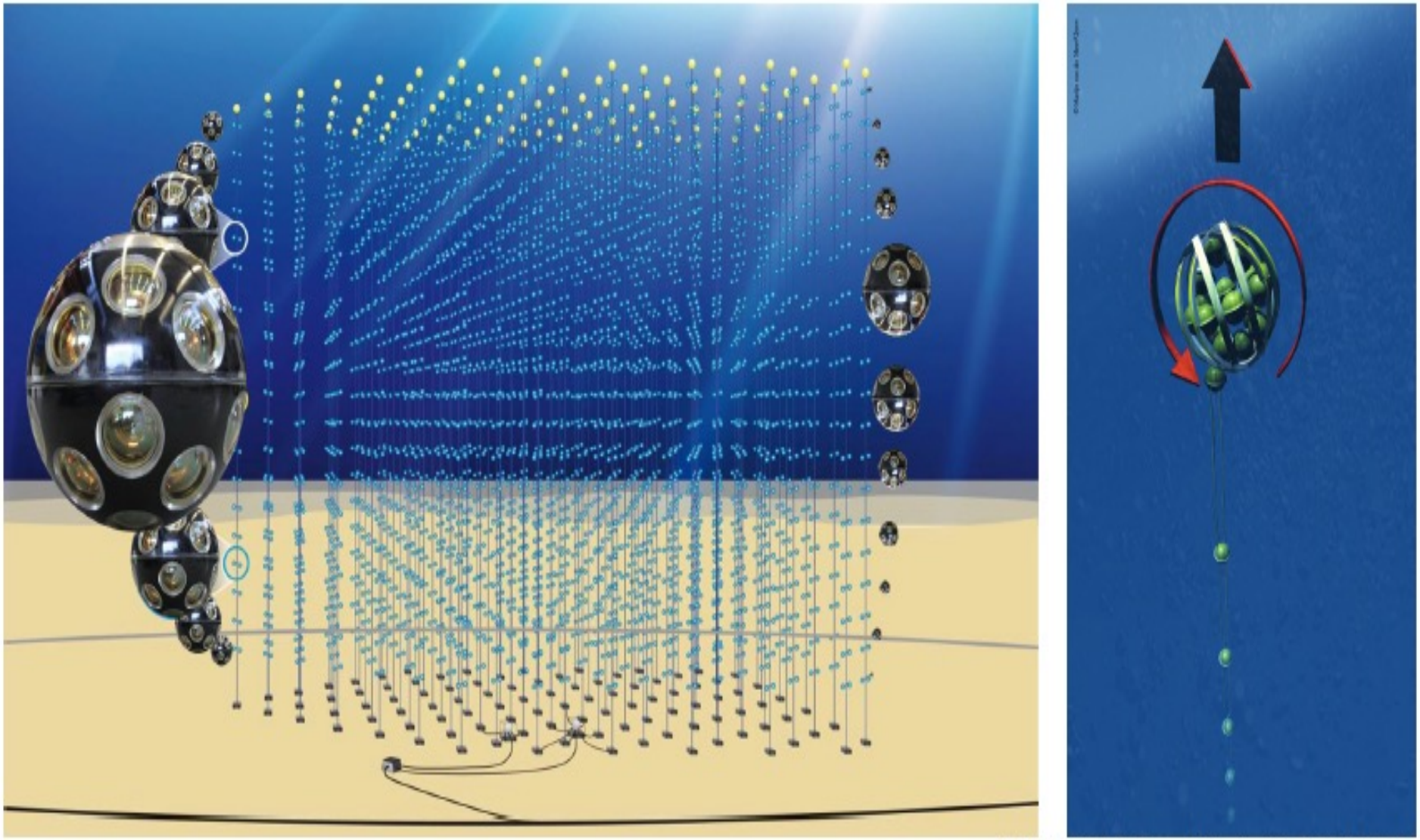
Background only hypothesis rejected at 3.5σ



21

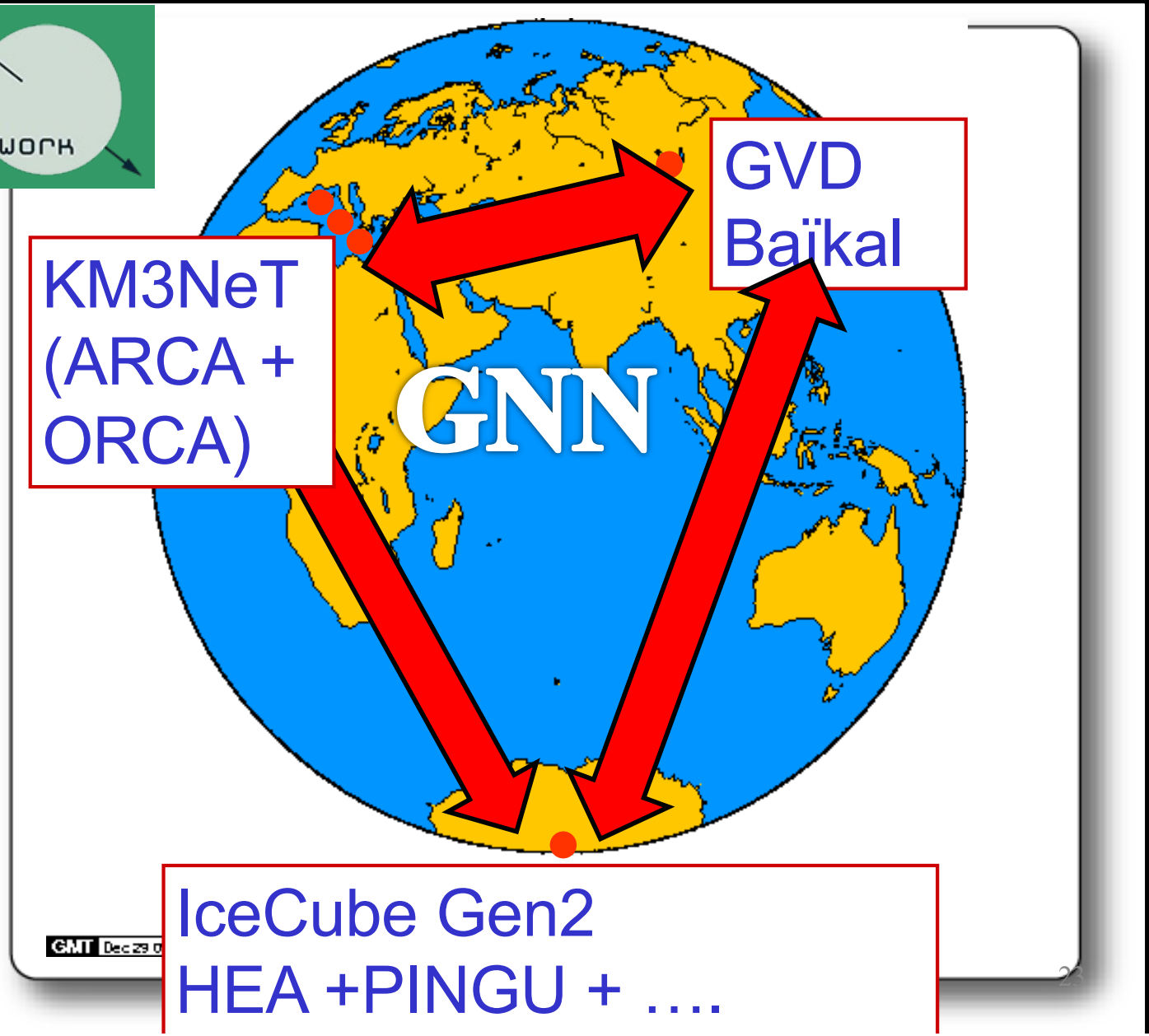
KM3NeT

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

GNN
The Global Neutrino Network



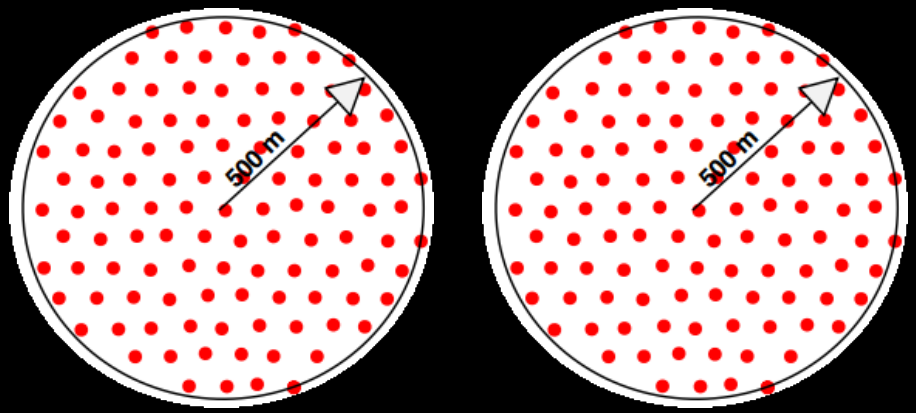
Phase 2.0: ORCA and ARCA

(2022 well advanced)

France

ORCA

ARCA



Italy

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)

Three important results in 1985
2. Cygnus X3

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

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

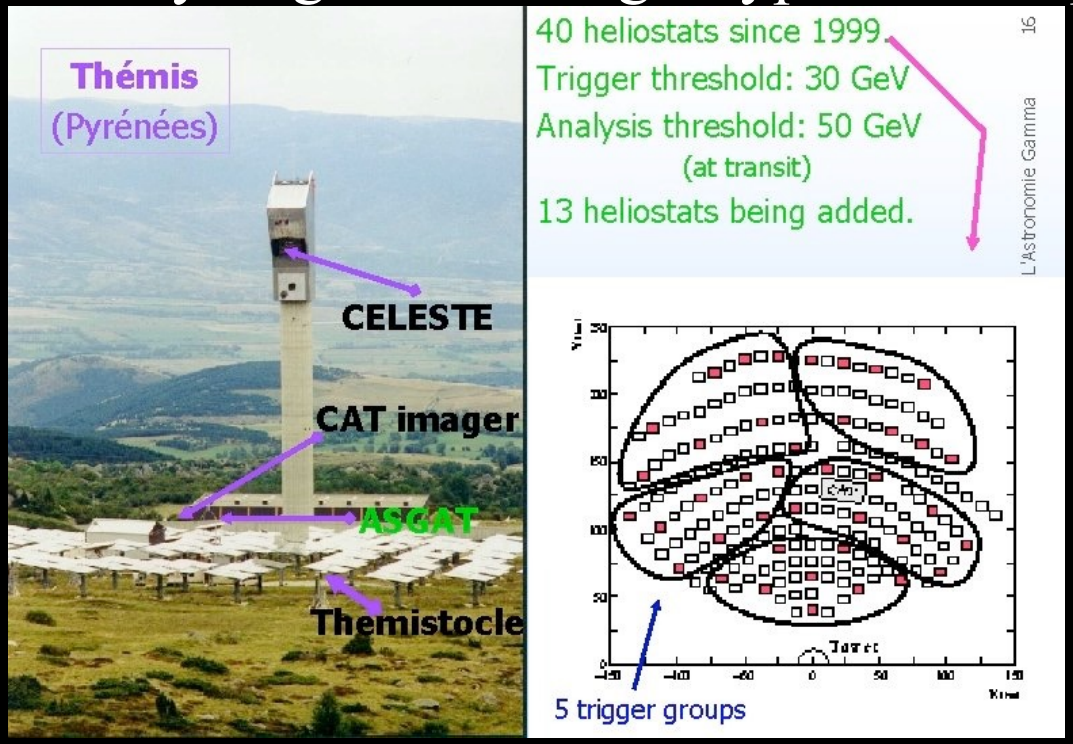
Themistocle and ASGAT: sampling techniques: many parabola with photomultipliers at the focus

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

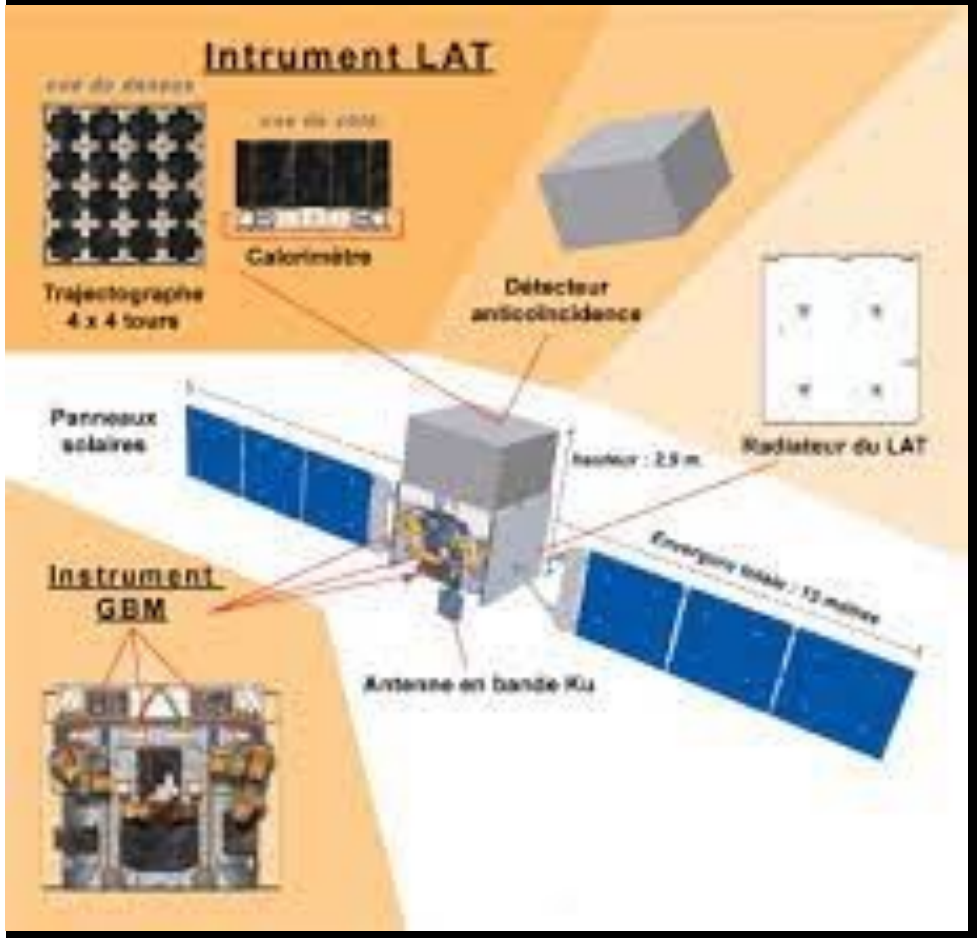
3rd generation will use many large CAT imager type mirrors plus focal plane imagers:

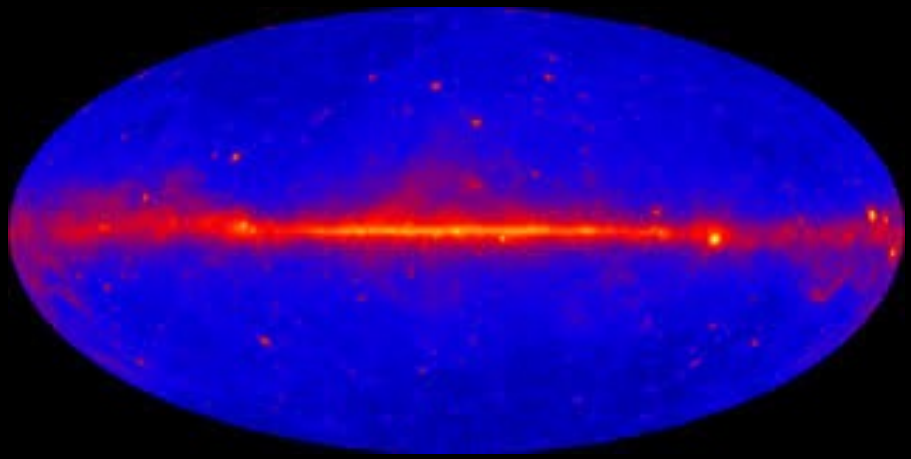
HESS



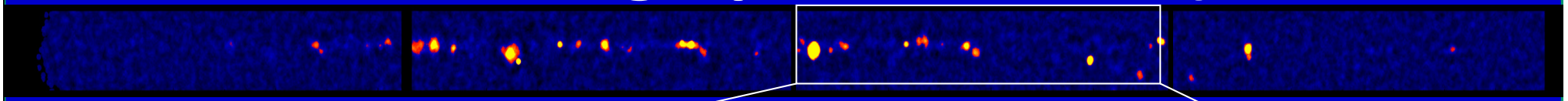
3rd generation Imaging Air Cherenkov telescopes

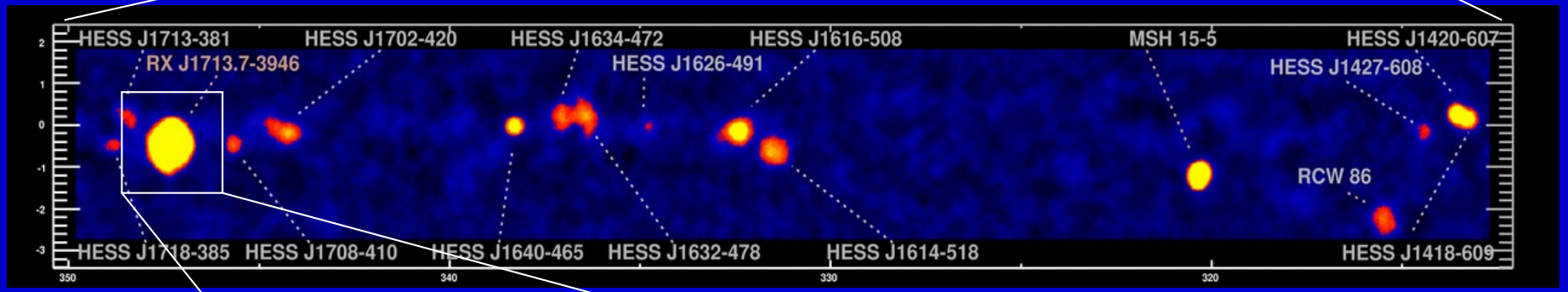
Reference map (20 MeV to 300 GeV) FERMI SATELLITE (strong French contribution, P. Fleury, I. Grenier…), LAT instrument CMS/LHC inspired, 6000 sources>50 MeV





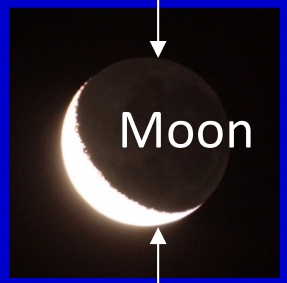
The Sky at TeV-Energies (Fermi satellite covering up to 300 GeV)

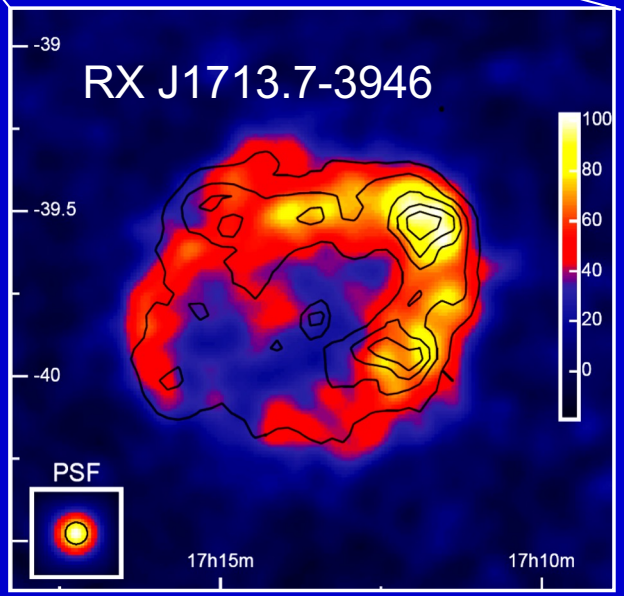




H.E.S.S.-Scan of the galactic plane

0.5°

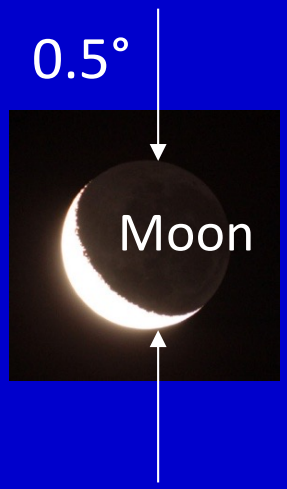


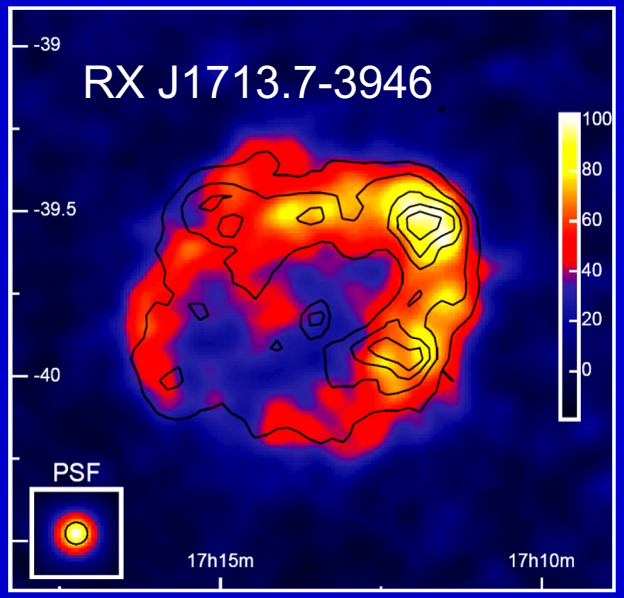


1989:	1 Source
1996:	3 Sources
2005:	80 Sources
2015:	150 Sources

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!)





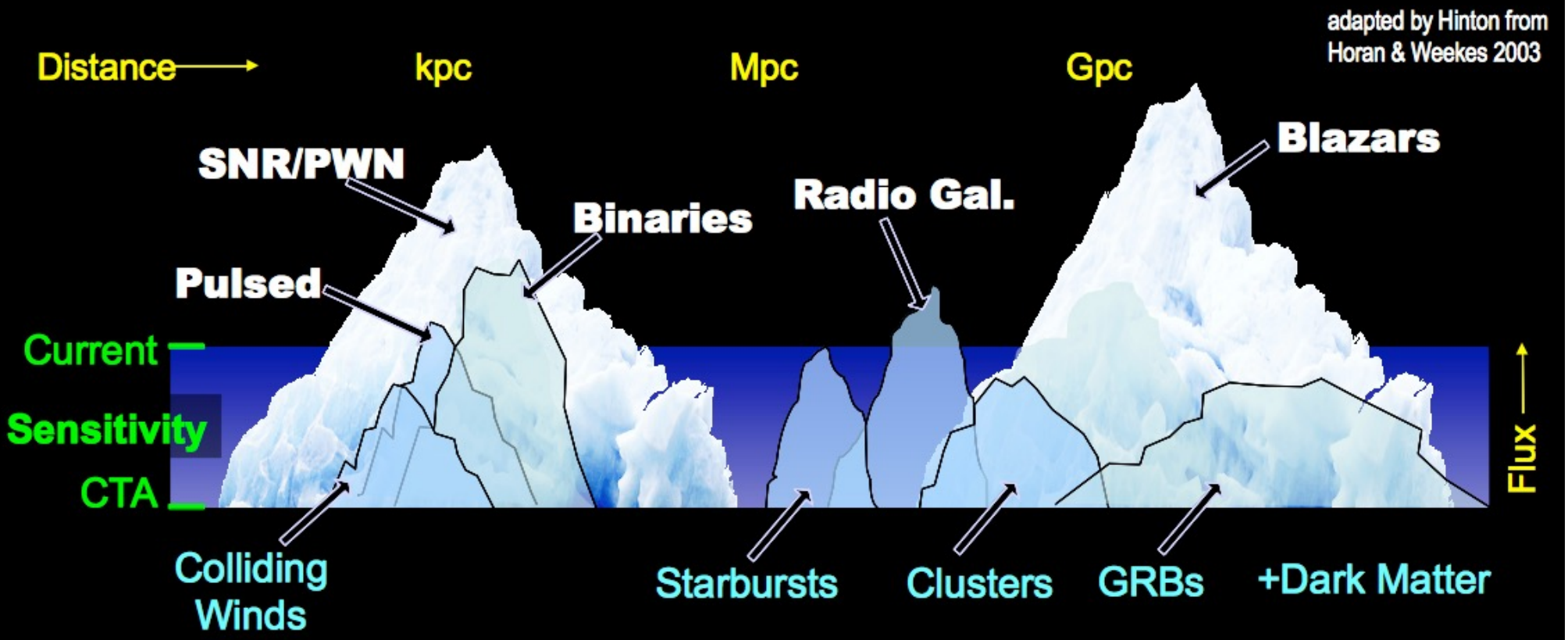
1989: 1 Source
1996: 3 Sources
2005: 80 Sources
2015: **150 Sources**

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

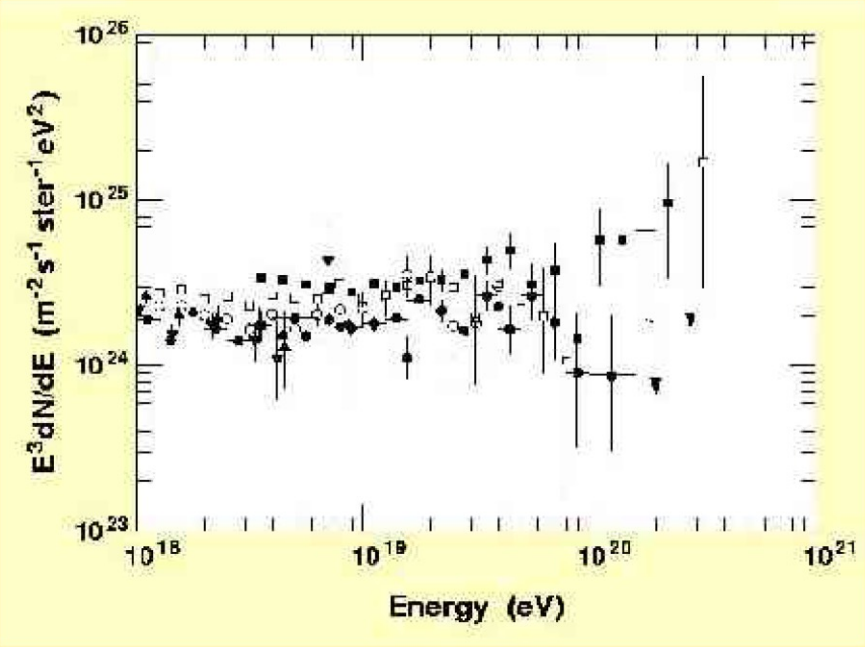
CTA after HESS will open a new era in gamma-ray astronomy

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 debated

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

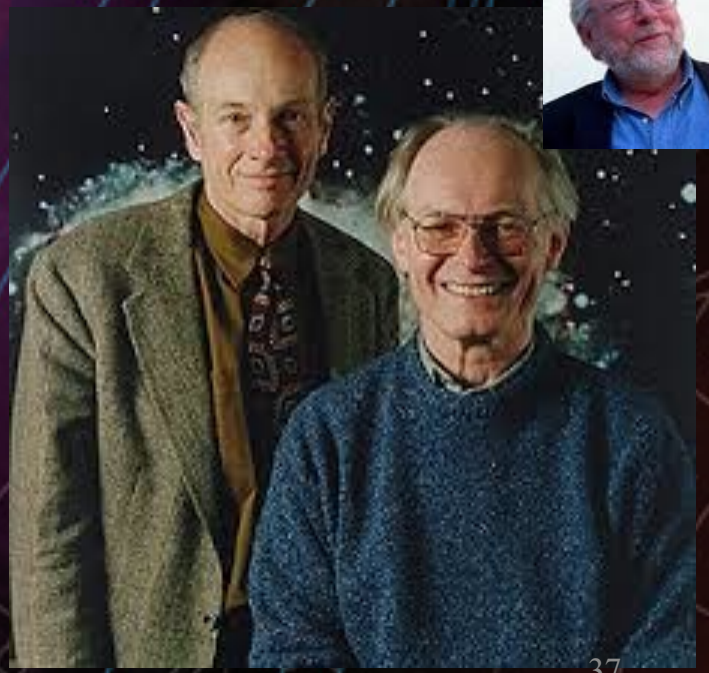
Experimental data: The spectra measured by several experiments have absolute normalization different by 40%. Note that the differential flux is multiplied by E^3 to emphasize the shape of the spectrum. The results are obtained with the same hadronic interaction model.



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

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

1989



Pierre Auger Observatory

~65 km

3000 km²

~65 km

CLF

XLF

BLS

Malargüe

Cent. Camp

40

30

10

0

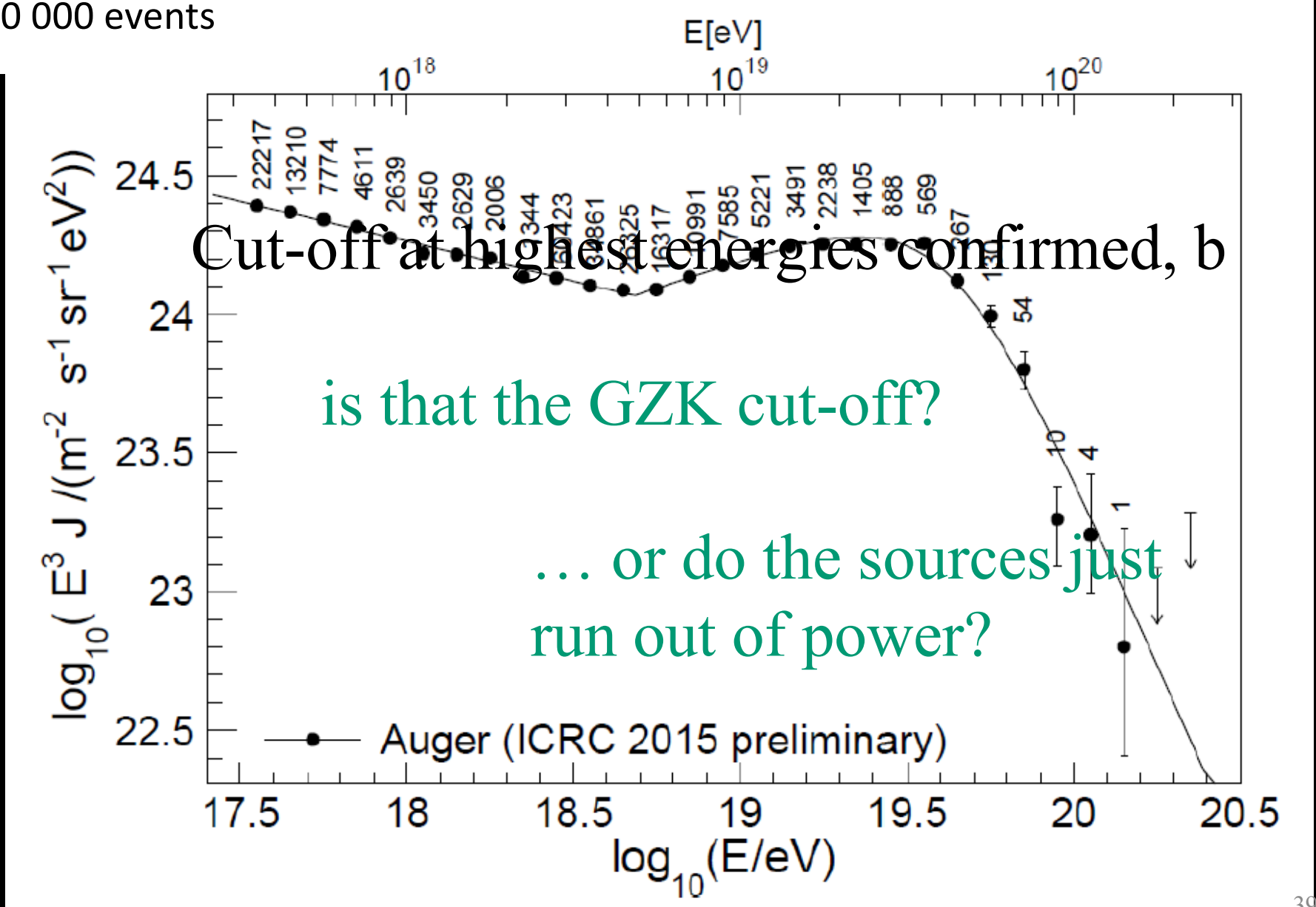
1660 detector stations on 1.5 km grid

27 fluores. telescopes at periphery

130 radio antennas

Province Mendoza, Argentina

190 000 events



Cut-off at highest energies confirmed, b

is that the GZK cut-off?

… or do the sources just run out of power?

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 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.

Evidence for Dark Matter or not from positron Cosmic Ray Spectrum in AMS

Samuel Ting vs Sylvie Rosier

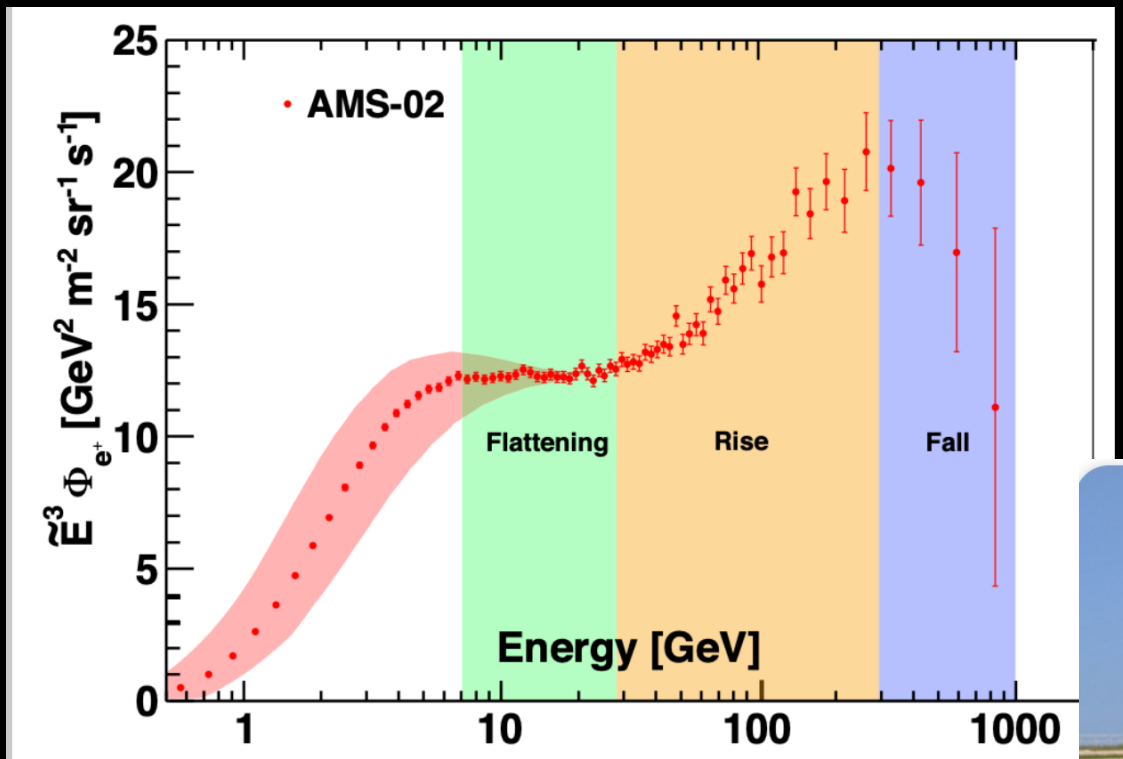


Figure 1. For display purposes, the positron flux, Φ_{e^+} is traditionally presented scaled by $\tilde{E}^3$. The resulting AMS positron spectrum, $\tilde{E}^3\ \Phi_{e^+}$, (red data points) is shown as a function of energy. $\tilde{E}$ is the spectrally weighted mean energy for a flux proportional to E^{-3}. The time variation of the flux at low energies due to solar modulation is indicated by the red band. To guide the eye, the vertical color bands indicate the energy ranges corresponding to changing behavior of the spectrum: flattening, rising, and falling spectrum.

Sylvie Rosier-Lees 1961–2022 – ...

Consulter

ANTIMATTER

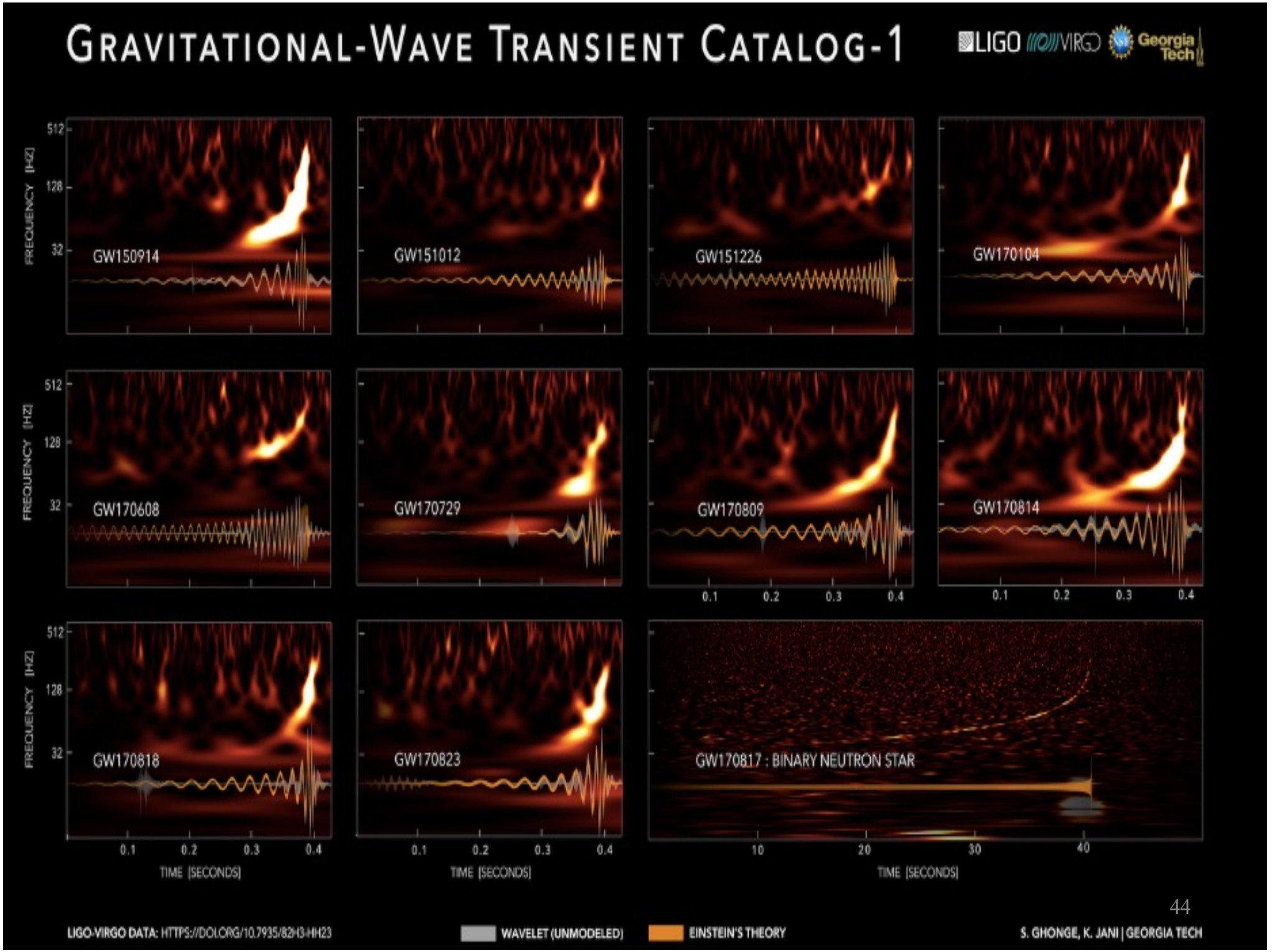
Originally AMS was to search for antimatter in the Universe (anti He, anti C)

So far only limits

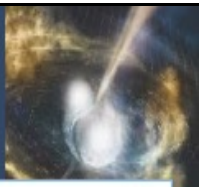
But there might be other surprises with antimatter: look for gravitational mass of antihydrogen atoms at CERN

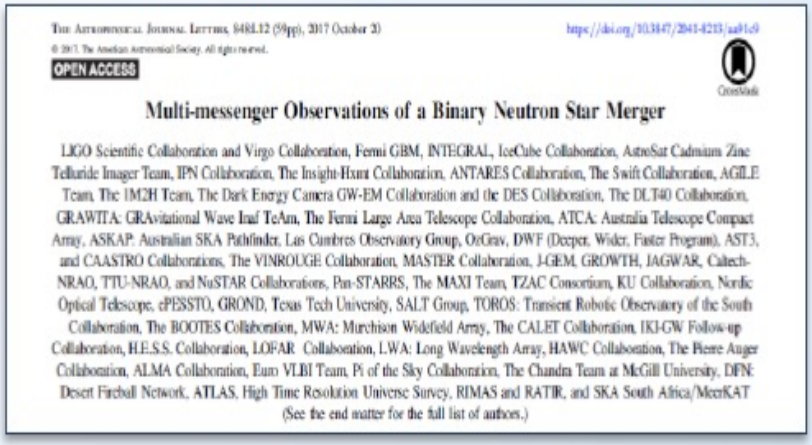
VIRGO project initiated in France by A. Brillet. Project accepted after the P. Fleury review panel examination (1990)

S. K. Katsanevas EGO Director 2018 - 2022


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

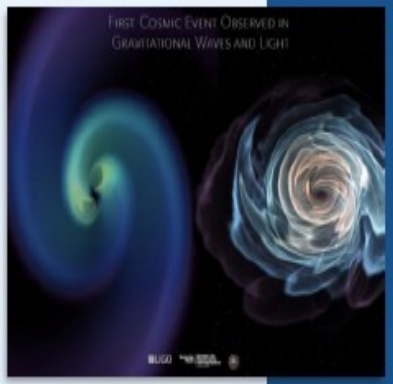
LIGO Scientific Collaboration and Virgo Collaboration, Fermi GBM, INTEGRAL, IceCube Collaboration, AstroSat Cadmium Zinc Telluride Imager Team, IPN Collaboration, The Insight-Hxmt Collaboration, ANTARES Collaboration, The Swift Collaboration, AGILE Team, The 1M2H Team, The Dark Energy Camera GW-EM Collaboration 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.)

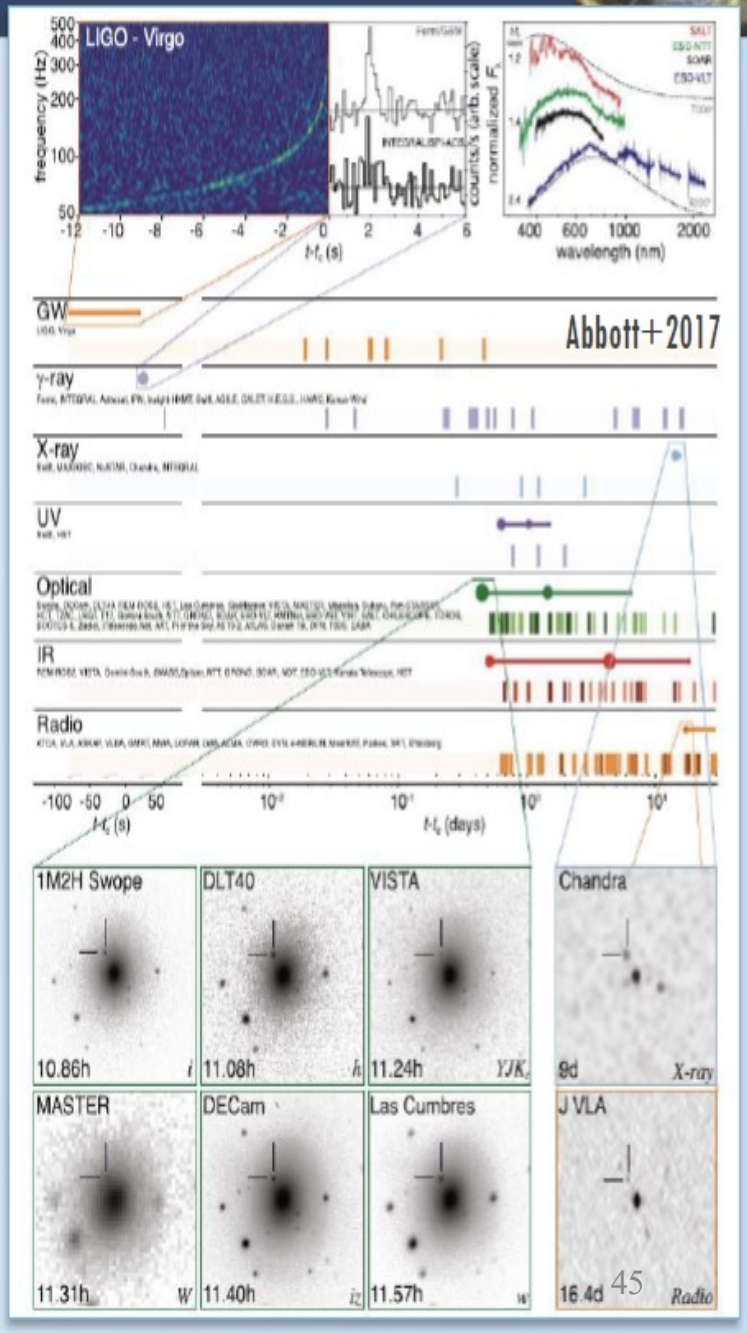
50 teams
>3600 authors

~20 orders of magnitude in wavelength

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



Credit: LIGO-Virgo



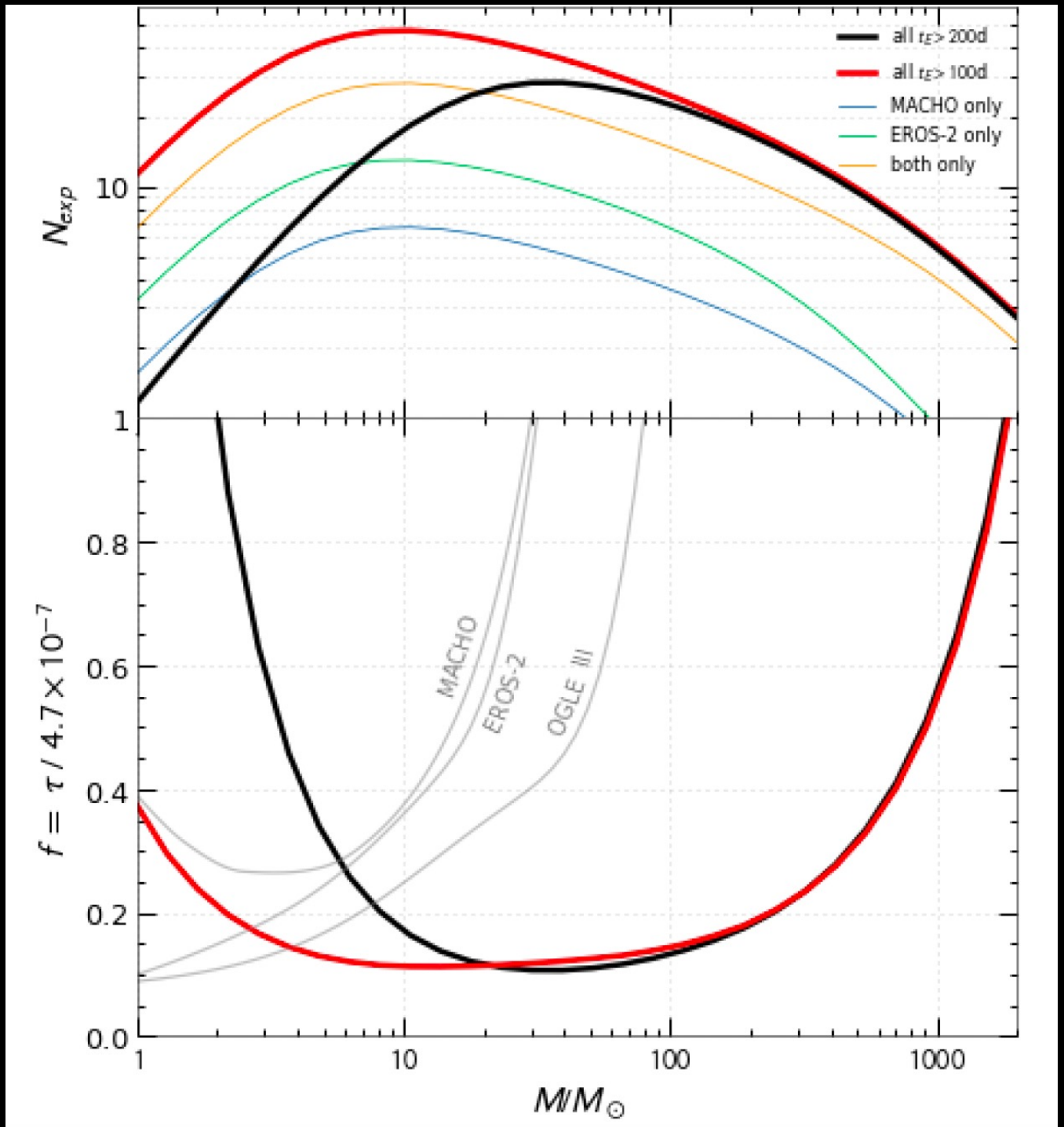
Black holes as dark matter?

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?

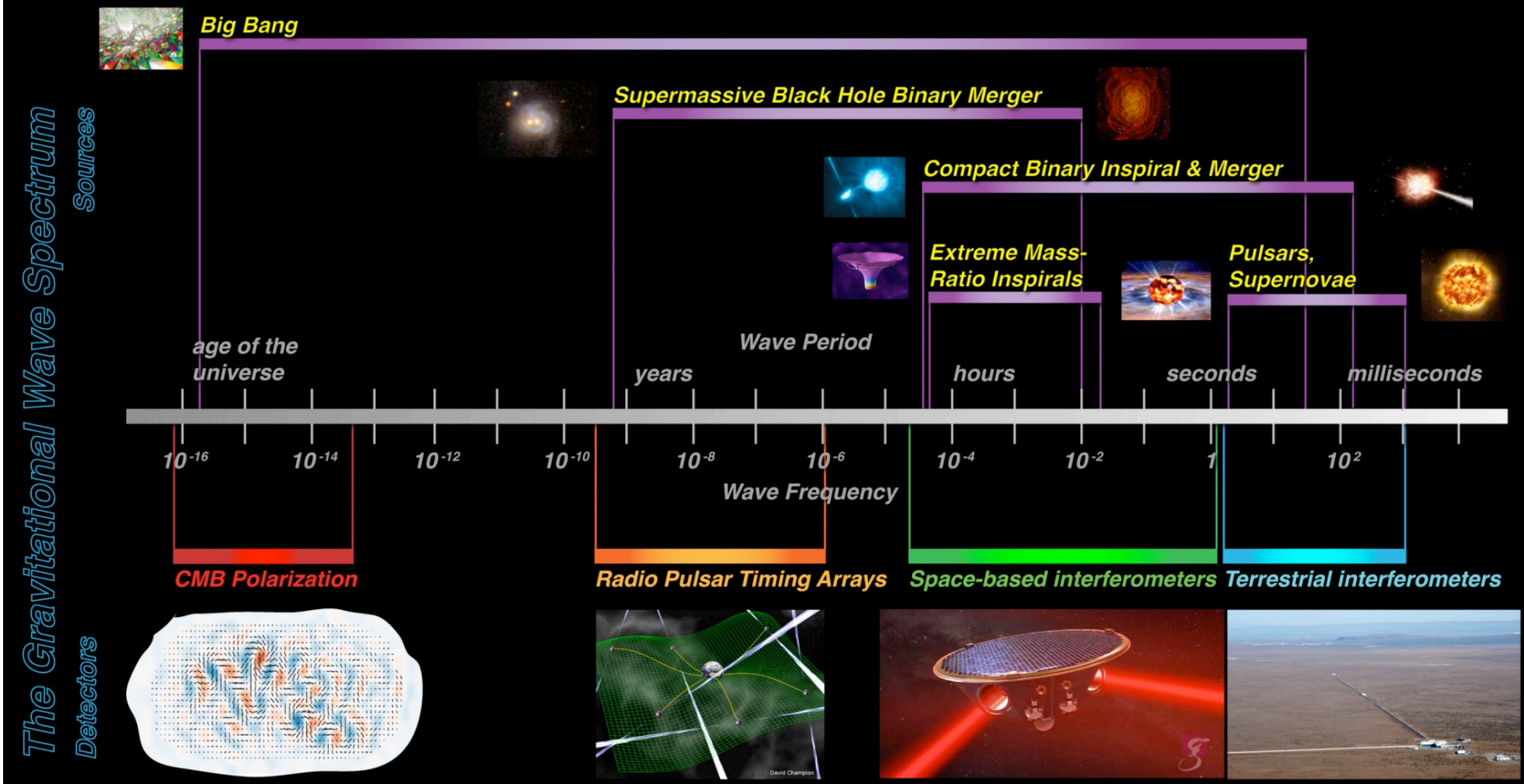
Very recently the EROS collaboration, combining its data with MACHO, has shown that the dark matter in the halo of our galaxy cannot be made of compact objects of masses between 10^{-6} and 10^{3} solar masses

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
0.8
0.6
0.4
0.2
0.0
$f = \tau / 4.7 \times 10^{-7}$
MACHO
EROS-2
OGLE III
1
10
100
1000
$M/M_\odot$

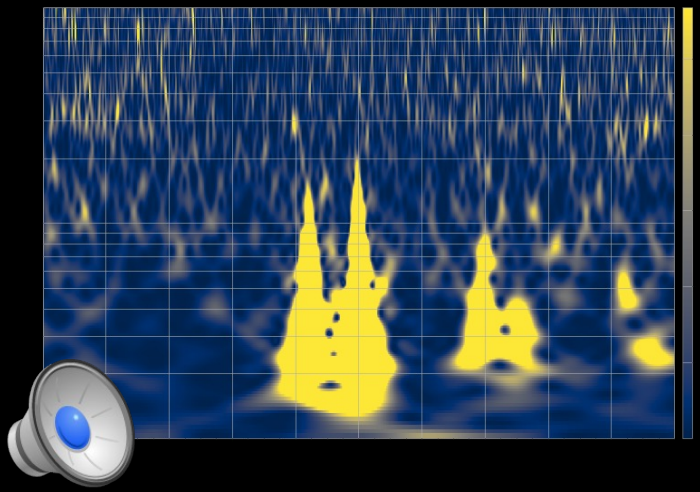
Gravitational Waves « Frequency Domain » Analysis



Discovering (direct or indirect) the stochastic GW from inflation would be a major discovery

Inclusion for augmenting humanities perception capabilities from Multi-Messenger to Multi-sensorial (radiation and vibration)

- From multi-messenger to multisensorial apprehension of reality
- Not only increasing inclusion . Also increasing the researchers discrimination power of signal over background through the use of sound.



Editorials

nature

Sounds of the stars: how scientists are listening in on space

In astronomy, the use of sound instead of light is breaking down barriers to participation and providing insight into the Universe.

conveyed details of the physics of these stellar explosions. When, in early 2020, the pandemic meant she was unable to get to a 3D printer, she shifted to working on sonification.

In August, NASA tweeted about the sound of the black hole at the centre of the Perseus galaxy cluster; the attached file has since been played more than 17 million times. In the same month, Arcand and others converted some of the first images from the James Webb Space Telescope into sound. They worked under the guidance of people who are blind and visually impaired to map the intensity and colours of light in the headline-grabbing pictures into audio.

These maps are grounded in technical accuracy. The sonification of an image of gas and dust in a distant nebula, for instance, uses loud high-frequency sounds to represent

Editorial

https://doi.org/10.1038/s41550-022-01848-z

Hearing is believing

Check for updates

For blind and visually impaired astronomers, sonification of data creates opportunities for research and outreach. But for everyone, this Focus issue lays out the benefits of complementing vision-based data analysis tools with data sonification.

accessibility. In their Q&A, Jake Noel-Storr and Michelle Willebrands interview four blind or visually impaired researchers working in astronomy research, education and outreach: Nicolas Bonne, Cheryl Fogle-Hatch, Garry Foran and Enrique Perez Montero. These days very few astronomers travel to observatories, yet the image of an astronomer as someone gazing into a telescope persists. This

from perception to experience. The authors consider the main motivations for their community: what can be learned from the sound experience; where are they heading in terms of improved or new tools; and how to evaluate the usefulness, usability and desirability? Within this broader context, astronomers can develop accessible, well-designed and multi-purpose tools that can be assessed

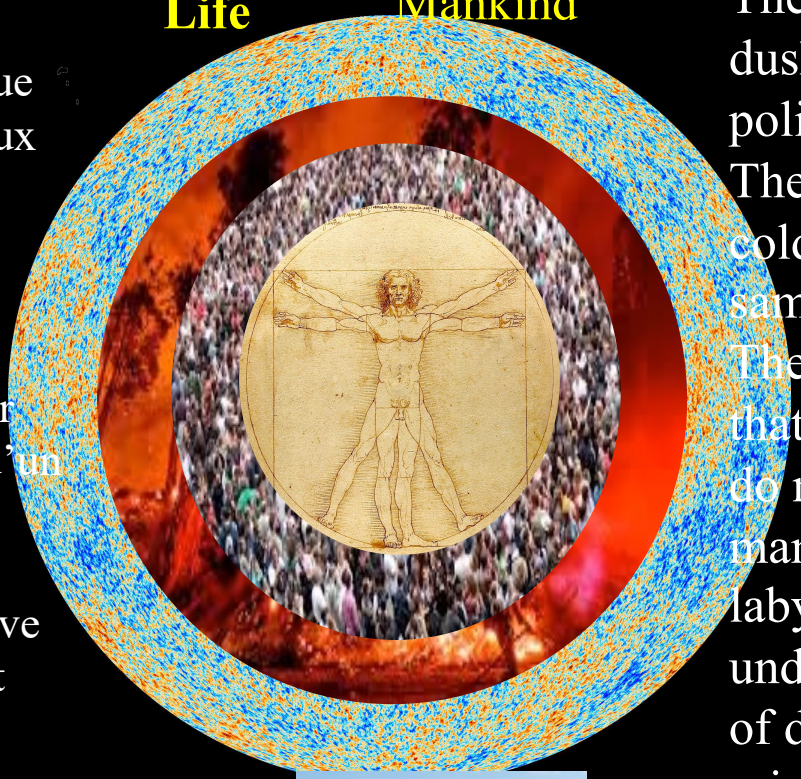
Recent Nature Editorial, and NAture Astronmy published 6 articles on sonification 18 Nov.

Stressing the pioinnering role of WAnd Diaz-MErced

Conclusion the 4 cosmos

Universe Earth Planet

Life Mankind



Les translucides mains du Juif polissent Dans la pénombre le dur cristal et
Le soir qui se meurt n ‘est que froid et peur. (Chaque soir aux autres soirs ressemble.)
Les mains et l’espace de jacinthes,
Qui pâlissent aux confins du ghetto, N’existent guère pour l’homme paisible Qui rêve d’un diaphane labyrinthe.
La gloire ne le trouble point, vague Reflet d’un rêve au rêve d’un miroir, Ni les tendres et craintives amours. Libre du mythe et de la métaphore II polit le cristal : carte infinie
De Celui qui est toutes ses étoiles. Jorge Luis Borges, *Spinoza*, 1964

The Jew's hands, translucent in the dusk,
polish the lenses time and again.
The dying afternoon is fear, is cold, and all afternoons are the same.
The hands and the hyacinth-blue air that whitens at the Ghetto edges do not quite exist for this silent man who conjures up a clear labyrinth—
undisturbed by fame, that reflection of dreams in the dream of another mirror, nor by maidens' timid love.
Free of metaphor and myth, he grinds
a stubborn crystal: the infinite map of the One who is all His

Que le monde soit cosmos fut une des décisions constitutives de notre histoire intellectuelle
H. Blumenberg