COSMIC RADIATION

- **Observing the sky with different messengers**

  - *Charged Particles, Photons, Neutrinos, Gravitational Waves*

  Great extension of our power to study the Universe

  Hunting for new physics & observing the sky

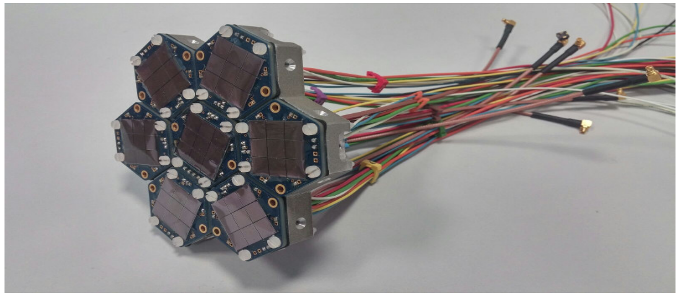
- **Scientific Motivations**
  - Investigate ”extreme environments” as laboratories to test the fundamental laws of Nature
  - Study some of the most fascinating objects and events in Nature: Neutron stars, e.g. Pulsars, Black Holes, …
  - Finding the counterparts of the Gravitational Wave emitters
  - Dark Matter: discovered by astronomical means, can be investigated with the tools of astroparticle physics
  - Primordial anti-matter : never seen so far....

- **Outlook**
  - Gamma astronomy, from space and from the ground
  - Atmospheric and cosmic neutrinos
  - Solar neutrinos, supernova neutrinos, geo-neutrinos
  - Precision measurements of cosmic rays from space
  - Cosmic rays at the highest energy (E ~10^{19} eV)

- **Enrico Fermi:** nuclear physics, accelerators & cosmic rays
- **Edoardo Amaldi:** founder of CERN & pioneer of CR and GW search

WHERE CAN INFN MAKE THE DIFFERENCE?

Solid theoretical & experimental background



- Know-how in detectors

- Sensors
- Electronics
- Software

- New technologies

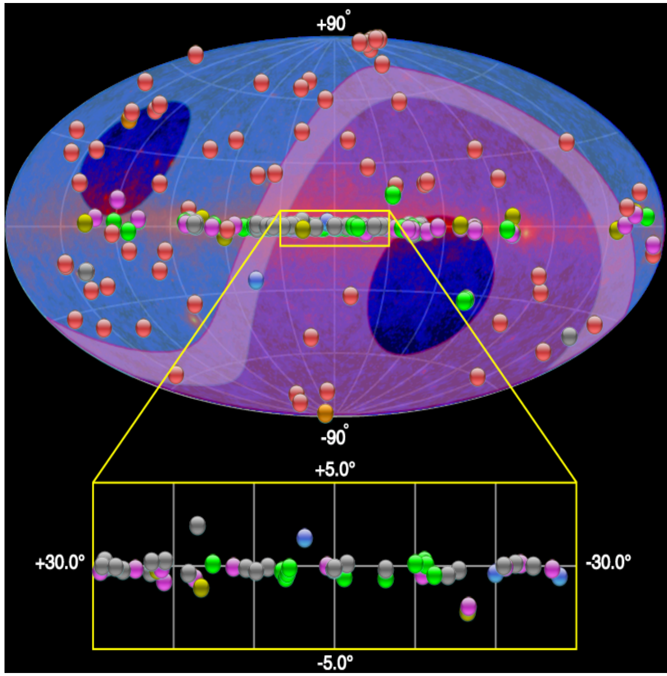
- New detectors for satellites (advanced calorimeters, new trackers, magnets…)
- NUV SiPM for Cherenkov telescopes
- High-depth undersea technologies
- Emphasis on the interaction with industries

PHOTONS

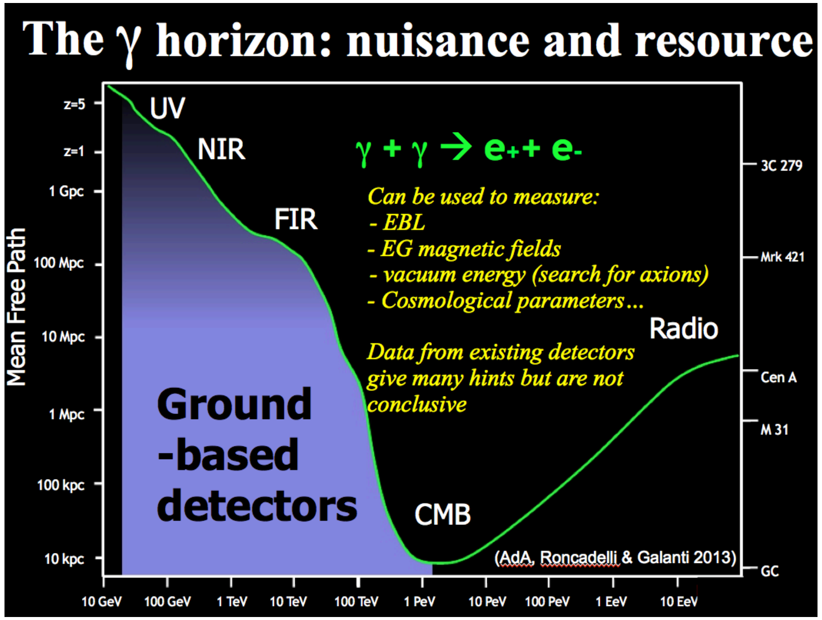
DETECTION OF HIGH ENERGY PHOTONS

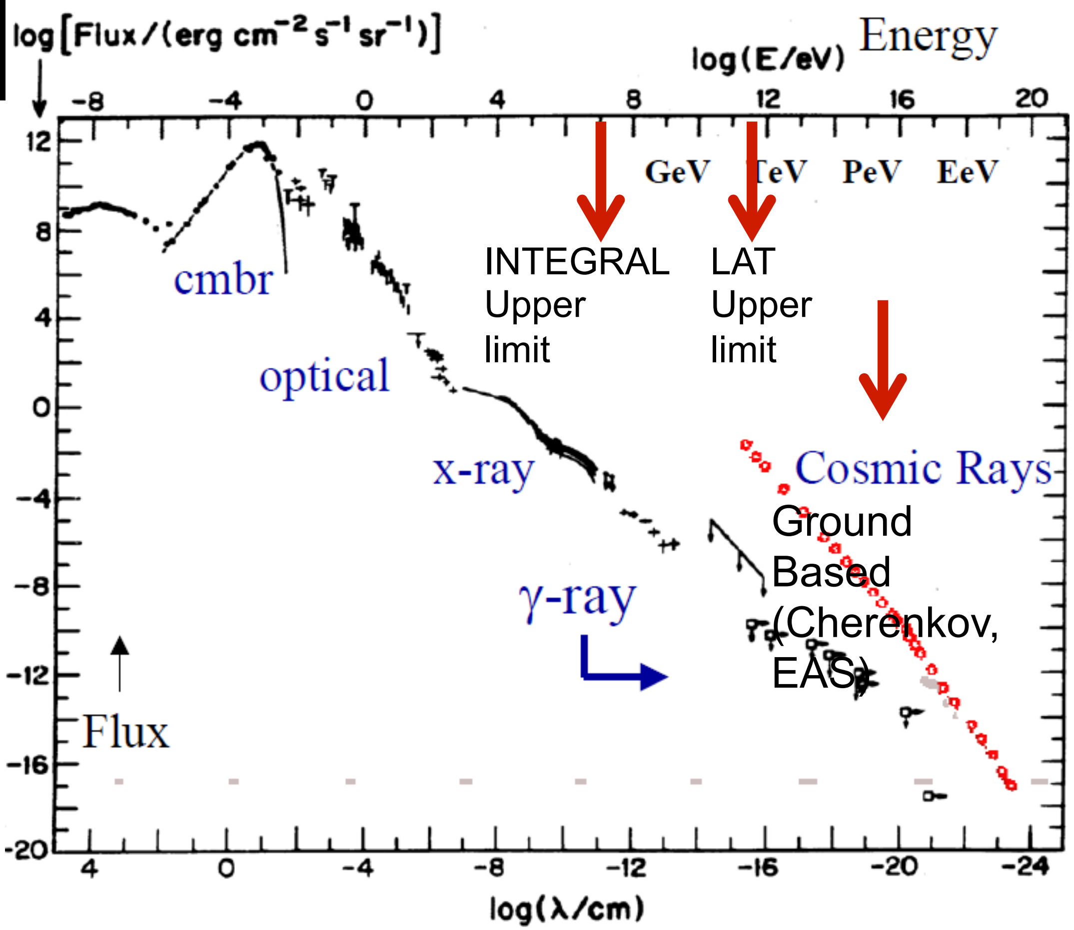
- Has been crucial during the last 20 years as the main tool to identify sources of cosmic rays and regions of extreme physics in the Universe

- Is and will be a very important tool for:
  - Multimessenger HE astrophysics
  - Probing nuclear mechanisms
  - Cosmology
  - Search for new particles (including DM)



- INFN is doing well with present detectors:
  - Fermi, DAMPE, MAGIC, …


The γ horizon: nuisance and resource
Mean Free Path
z=5
z=1
1 Gpc
100 Mpc
10 Mpc
1 Mpc
100 kpc
10 kpc
UV
NIR
FIR
Radio
CMB
γ + γ → e+ + e-
Can be used to measure:
- EBL
- EG magnetic fields
- vacuum energy (search for axions)
- Cosmological parameters…
Data from existing detectors give many hints but are not conclusive
Ground -based detectors
(AdA, Roncadelli & Galanti 2013)
3C 279
Mrk 421
Cen A
M 31
GC
10 GeV
100 GeV
1 TeV
10 TeV
100 TeV
1 PeV
10 PeV
100 PeV
1 EeV
10 EeV


log[Flux/(erg cm^-2 s^-1 sr^-1)]
log(E/eV)
Energy
-8
-4
0
4
8
12
16
20
GeV
TeV
PeV
EeV
INTEGRAL Upper limit
LAT Upper limit
cmbr
optical
x-ray
γ-ray
Cosmic Rays
Ground Based (Cherenkov, EAS)
Flux
12
8
4
0
-4
-8
-12
-16
-20
4
0
-4
-8
-12
-16
-20
-24
log(λ/cm)

MANY OPEN PROBLEMS AND POSSIBLE SOLUTIONS

- **The classics of (very) high energies:**
  - Behaviour near high-density regions
    - Even more interesting when/if GW astrophysics and/or ν astrophysics will be at work
  - Indirect detection of WIMPs
  - Structure of spacetime
  - Studies of photon propagation:
    - Cosmology
    - Energy of the vacuum (ALPs, etc.)

- **But lower energies can be essential:**
  - Tensions between observations at the scales of galactic cores and satellite halos vs. ΛCDM predictions
    - WDM after all?
  - e^+e^- annihilation (0.5 MeV). Large emission from GC still to be clarified
  - Lines from radioactive isotopes ^{26}Al, 1.8 MeV; ^{7}Be, 0.47MeV; ^{44}Ti , up to 1.157 MeV; ^{60}Fe, up to 1.33MeV. Can change our ideas on how nuclei are made in stars
  - Claims of observations by Chandra, & XMM of X-ray lines (few keV); could be signatures of decay of light "sterile" particles on cosmological time scales

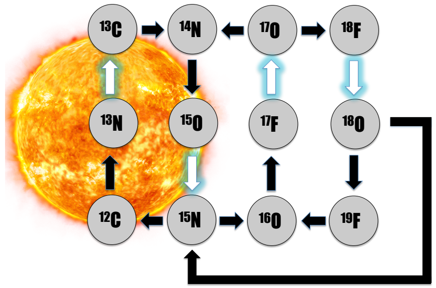
THE EXPERIMENTAL SITUATION IN THE MEDIUM AND LONG TERM IS RATHER CLEAR

- **keV region**: ATHENA or similar X-ray experiments. Gamma-burst monitor(s) (CALET, Fermi, …) can help for nuclear astrophysics & DM search. Polarimeters.
- **MeV region**: crucial for nuclear astrophysics and badly known needs satellites as COMPTEL (1990). New missions (e-ASTROGAM, COMPAIR ?) 100 times more sensitive could profit of INFN know-how in Si trackers (2025+)
- **GeV region**: Fermi cannot be reasonably improved with present technologies: try to keep it in space till 2028. INFN experience in smaller missions (AGILE, now DAMPE). New large space missions should be programmed for the post-Fermi era (HERD?)
- **sub-TeV and TeV regions**: CTA (2021-2050?) has no rivals in this essential region for fundamental physics and astrophysics; INFN has a clear role. HAWC and LHAASO (and possibly a southern EAS detector) can contribute with their large FoV to the high-end (several TeV) region
- **PeV region**: Only few sources could be visible in the North and less than a dozen in the South, all galactic. Experiments as HAWC+ (upgrade of HAWC, 2016?), LHAASO (phase 1 in 2018?), TAIGA/HiSCORE provide a serendipitous coverage of the Northern sky. A large FoV experiment in the South, possibly starting at ~100 GeV, is highly desirable (LATTES?)

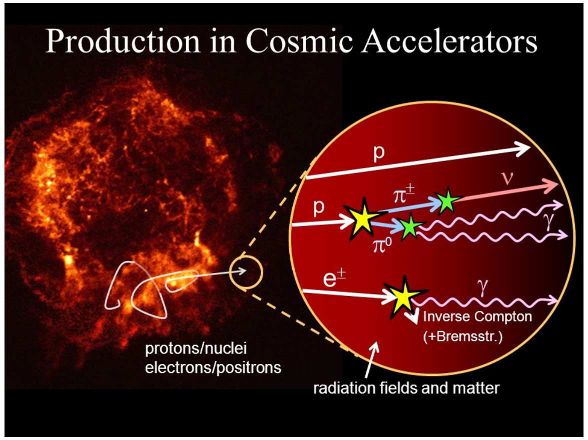
NEUTRINOS

WHY NEUTRINO ASTRONOMY?

To study cosmic reactors: e.g., the CNO cycle of the Sun



To study cosmic accelerator: e.g., SNRs, AGNs, GRBs, …



LOW ENERGY NEUTRINOS

Solar neutrinos

- neutrinos from all pp reactions measured, but CNO
  - important for solar metallicity and very challenging
  - What now: Borexino. What next: Juno, Argo, …

Supernova neutrinos

- from SN1987 explosion ~20 neutrinos detected within 10 sec
  - What now: LVD. What next: Juno, HyperK, ARGO …

HIGH ENERGY NEUTRINOS

To shed light on the role of hadronic processes in the cosmos. Several candidate sources

- Extragalactic: AGN, GRB, starburst galaxies…
- Galactic: SNRs, Galactic Center and nearby region, diffuse fluxes, …
- DM, …

HIGH NEUTRINO ASTRONOMY

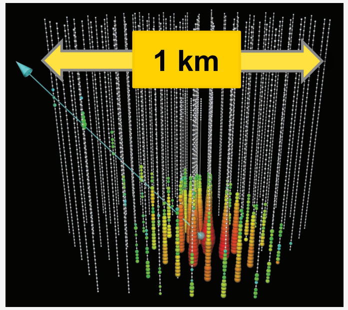
RESEARCH ARTICLE SUMMARY

SCIENCE VOL 342 22 NOVEMBER 2013

Evidence for High-Energy Extraterrestrial Neutrinos at the IceCube Detector

READ THE FULL ARTICLE ONLINE
http://dx.doi.org/10.1126/science.1242856

Cite this article as IceCube Collaboration, *Science* **342**, 1242856 (2013).
DOI: 10.1126/science.1242856



A 250 TeV neutrino interaction in IceCube.

Results from IceCube and open questions

- flux observed at 6.5σ (4 year data)

energy spectral index

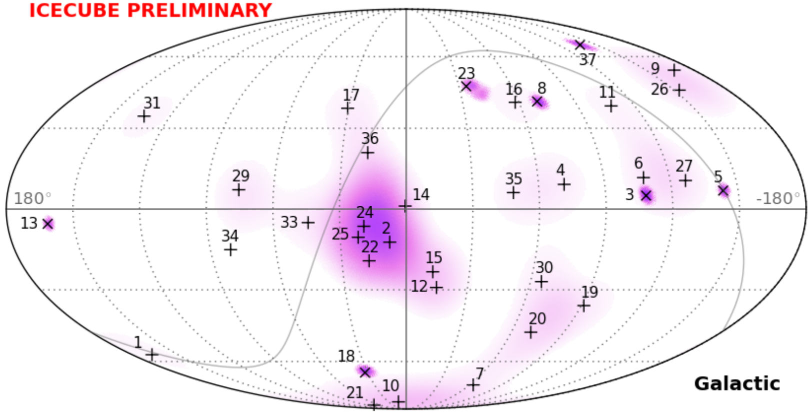
- softer than E^{-2}?, HE cut-off?, Glashow resonance?

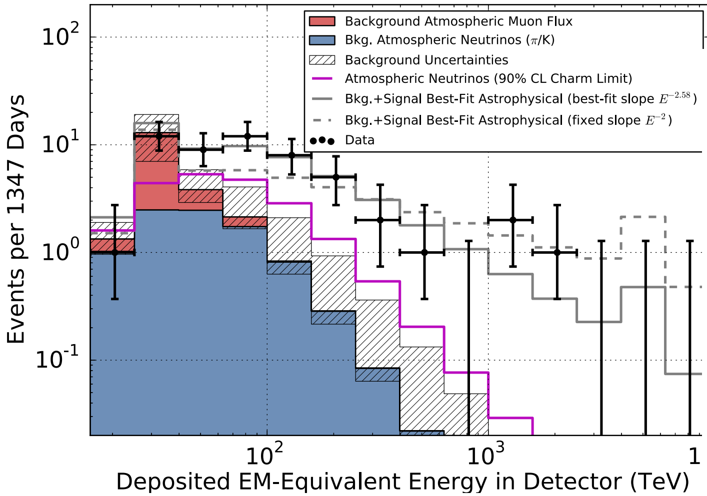
angular distribution

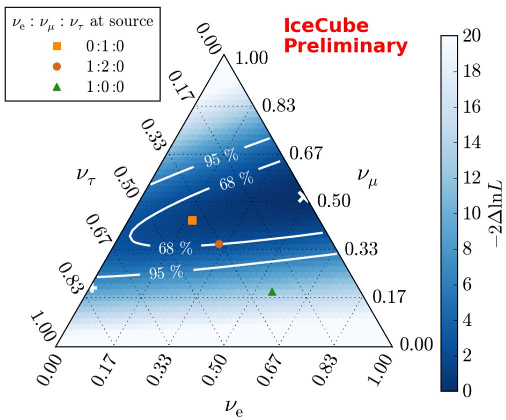
- localized excess not statistically significant

flavour composition

- compatible with 1:2:0 at source, tau signal?







HIGH NEUTRINO ASTRONOMY

Galactic versus extra-galactic contribution in IceCube data

- quasi isotropic dominant component at high energy (E>100TeV) suggest extragalactic origin
- some hints for a galactic contribution at lower energy, but can be probed only marginally with IceCube

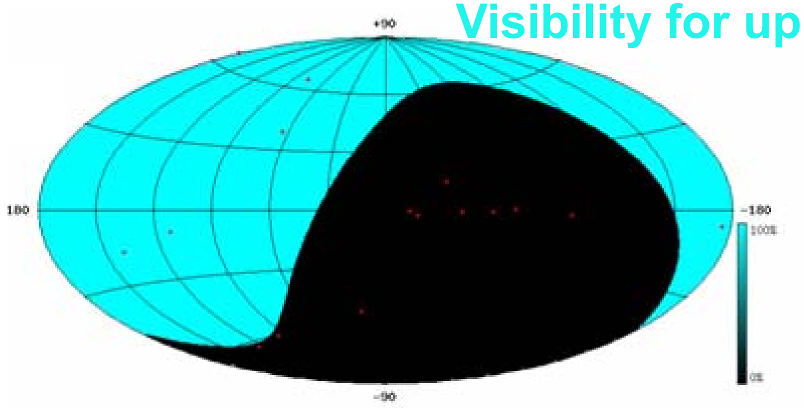
ICECUBE IS DOING GREAT PHYSICS, BUT WE NEED TO DO MORE AND BETTER

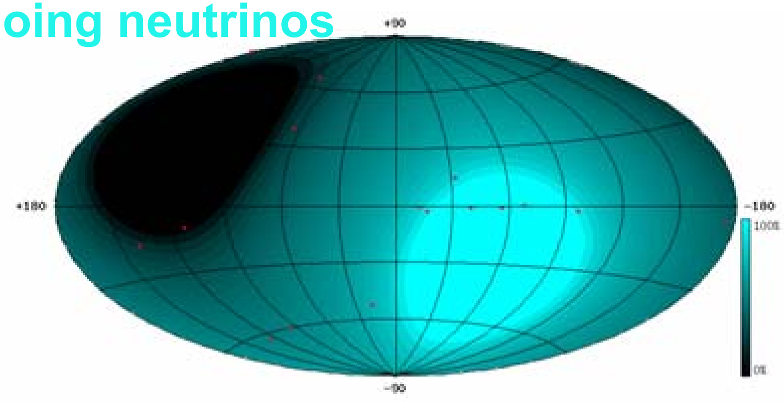
"Complete coverage of the sky, which is important given the exploratory nature of these experiments, thus requires two detectors located in opposite Earth hemispheres" - HENAP Report to PaNAGIC, July 2002

SOUTH POLE

MEDITERRANEAN SEA

Visibility for up-going neutrinos





A STAGED PATH TOWARDS THE KM3 TELESCOPE IN THE MEDITERRANEAN SEA

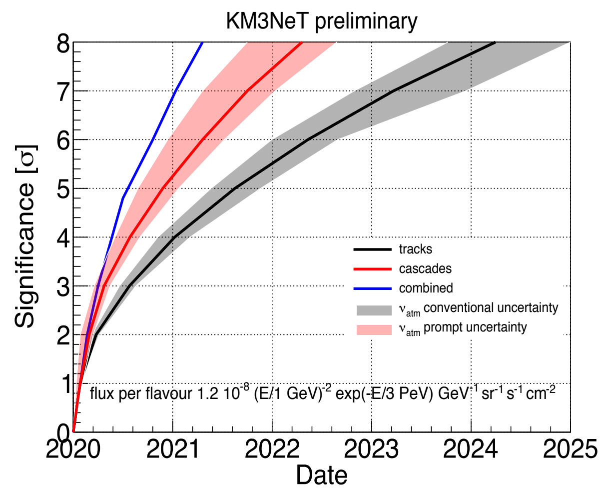
- **ANTARES - running, 1% km^3 (2500 m undersea off-shore Toulon, Fr)**
  - limits on origin IceCube flux and strong limits on DM in Sun and GC
  - broad multimessanger program, e.g. limit on neutrino flux from GW

> **High-energy Neutrino follow-up search of Gravitational Wave Event GW150914 with ANTARES and IceCube**
> The Antares, IceCube, Ligo and Virgo collaborations

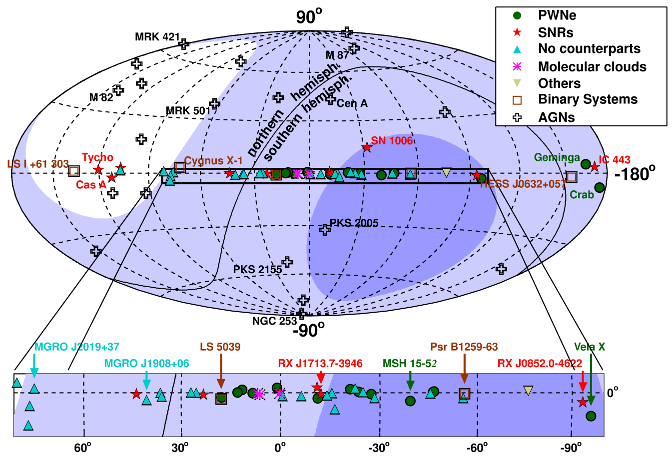
- **Phase1 of KM3NeT - in construction, 10% km^3 (3500 m undersea off-shore Capo Passero)**
- **WHAT NEXT => KM3NeT, 1 km^3**
- **KM3NET aims at the discovery and subsequent observation of high neutrino sources in the Universe (ARCA – Capo Passero, Italy)**
  - measure *IceCube flux* at 5σ in less than one year
  - observe the neutrino sky with larger field of view

Angular resolution allows source identification and pointing,

<u>0.1° for tracks and 2° for showers to be compared with1° and 10°-15° in IceCube respectively</u>



KM3NeT will survey our Galaxy including the Galactic Center which are sites of new unknown phenomena observed in HE gamma emission such as Fermi Bubbles, Galactic Ridge, …



- will detect the most intense galactic gamma sources (RX1713, VelaX, …) at 3s level in the hypothesis of hadronic emission

- will contribute, with IceCube, to a multimessanger survey of the Universe

KM3NeT also aims at determining the neutrino mass hierarchy with a much denser telescope, ORCA, built with the same technology (and to be deployed off-shore Toulon, France)

  - measure at 3σ in about 3 years => see Neutrino Working Group

The investigation of neutrino properties and of neutrino astronomy begun late fifties and now are on full bloom. What next is the high energy neutrino frontier. Km3NeT is ready to take the challenge with the construction of a km^3 telescope in the Mediterranean sea.

CHARGED COSMIC RAYS

CHARGED CR

Experimental observables

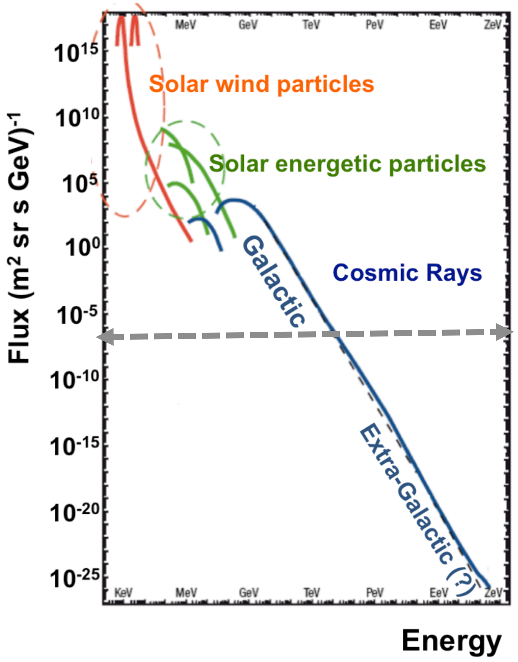
- Energy Spectrum
- Particle ID / Composition
- Arrival direction

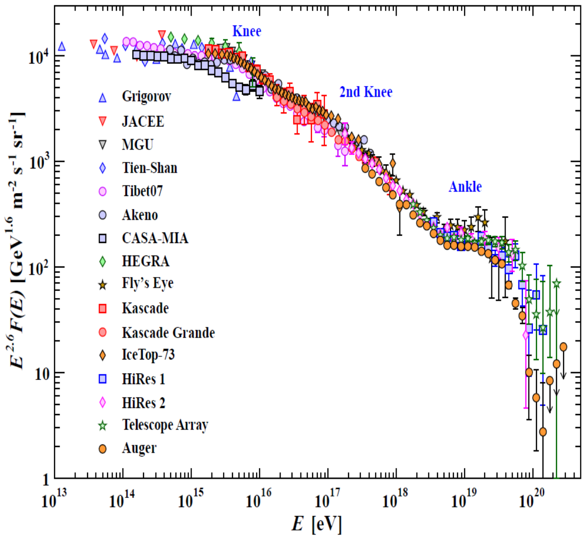
all we can gather is embedded in these three observables.

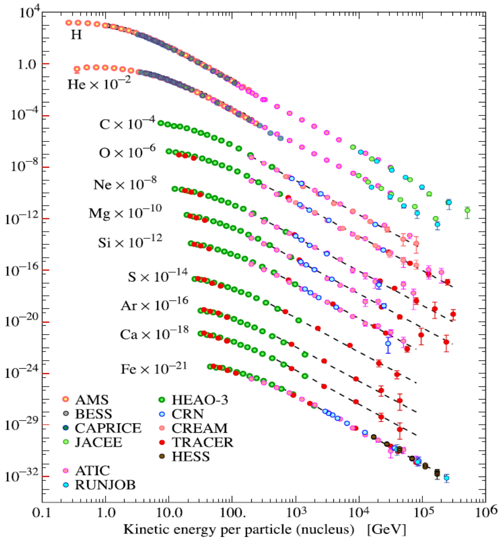
Science cases

- Earth/Sun/ Space weather
- Particle acceleration mechanisms
- Astrophysical sources
- Galactic and inter-galactic media
- High energy hadronic interactions
- Indirect detection of new particles
- Cosmology

a complementary view deeply related to other messengers: γ, ν and GW.







Fluxes extend over 14 decades in energy → > 30 decades in flux intensity.

→ Direct measurements in space

→ Indirect measurements on ground

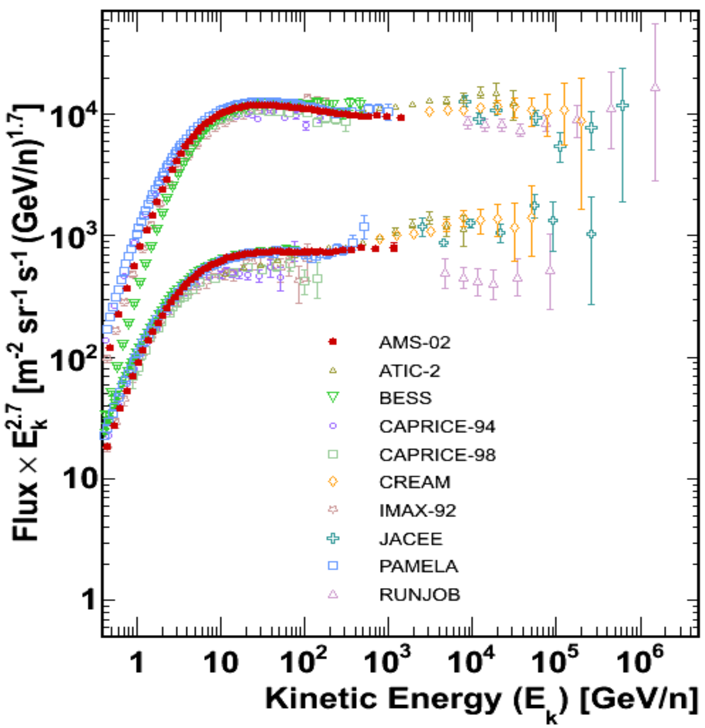
DIRECT DETECTION

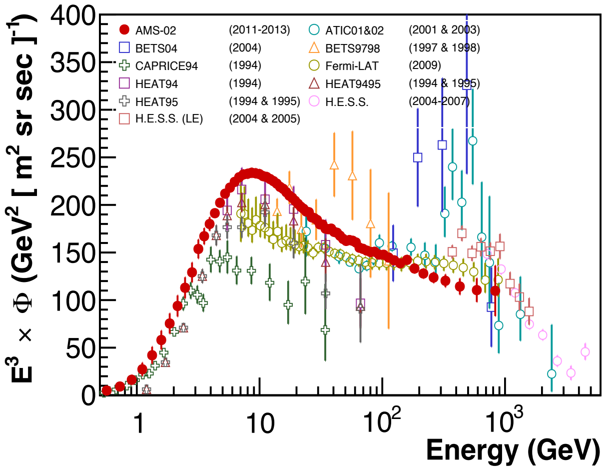
In the last 5 years with **PAMELA** and **AMS**, entered a new era of precision. Important breakthroughs:

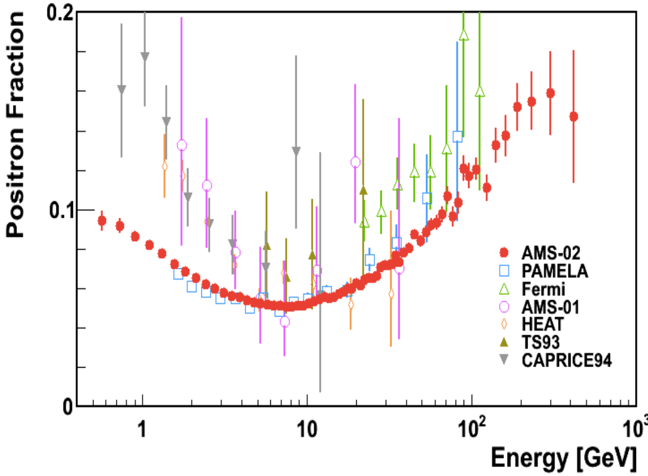
- ✓ Spectral features (p, He hardening at 200 GeV)
- ✓ Electrons, positrons and anti-protons fluxes
- ✓ Physics of the interaction Earth-Sun

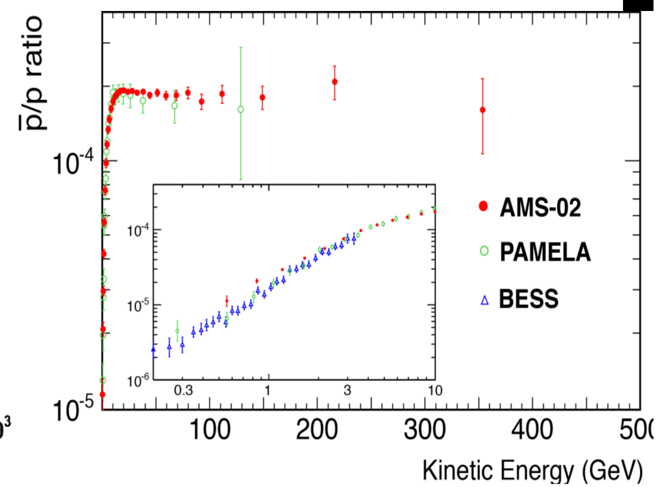
New precious information on the interstellar medium and to identify astrophysical sources. Important limits on WIMP DM models.

CALET, **DAMPE**, ISS-CREAM will soon provide more precise measurements in the multi-TeV regime.









INDIRECT DETECTION

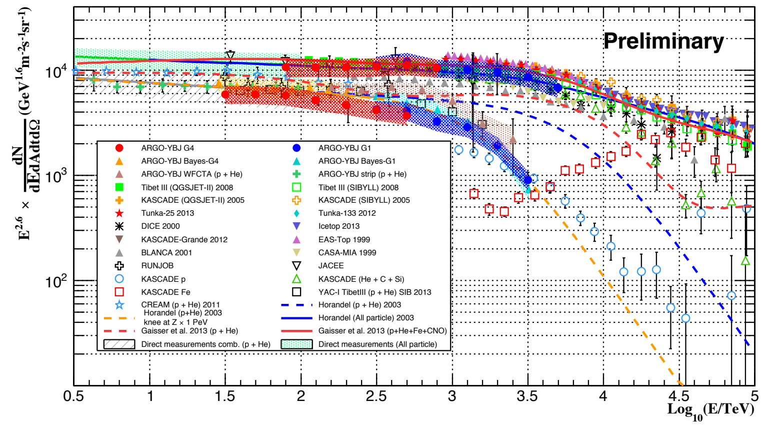
A rich experimental activity: **Argo-YBJ**, Kascade, Kascade-Grande, Tunka, IceTop, **Auger**, TA.
Important results:

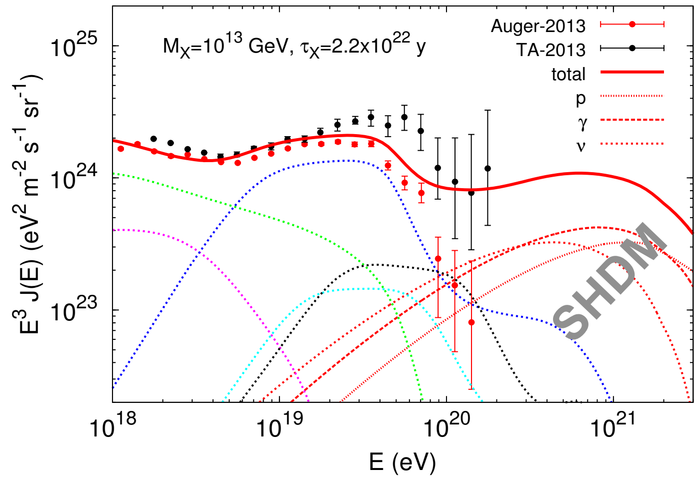
- ✓ Spectral features: break at 3×10^6 GeV, hardening at 4×10^9 GeV, suppression at the highest energies $E \sim 10^{11}$ GeV
- ✓ Composition: transition light-heavy at 3×10^6 GeV, at $E > 10^9$ GeV light (TA) or heavy (Auger)
- ✓ Anisotropy: 10^{-3} at 100 TeV, hints of correlation with sources at $E > 5 \times 10^{10}$ GeV (Astronomy?).

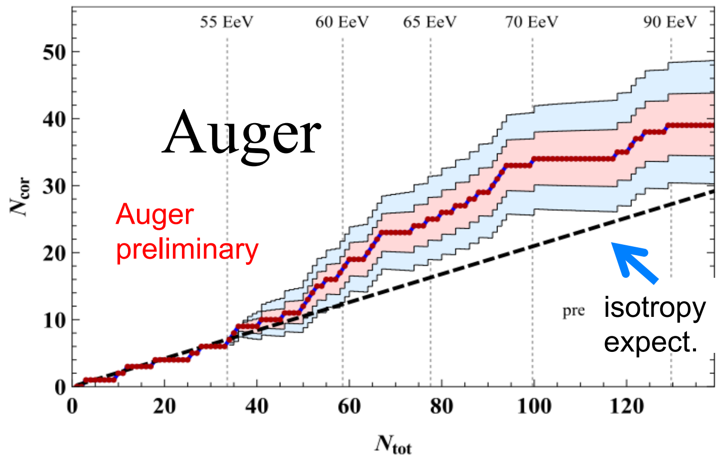
Important information on: galactic and extra-galactic sources, galactic and intergalactic medium, cosmological evolution, new physics at the highest energies ($>10^{10}$ GeV).

A key problem of the indirect measurement is the determination of the chemical composition of the primary particles.

- ✓ Shower simulations, hadronic cross sections at $\sqrt{s} \approx 10^2$ TeV (TOTEM, Castor, LHCf, …)







FUTURE DIRECTIONS

Direct measurements

The next challenge will be to extend direct measurements up to 1000 TeV with the same level of accuracy reached so far.

- ✓ New "ideas" on Calorimetry : increase acceptance, good resolution with reasonable size/weight (e.g. Calocube).
- ✓ Gain one energy decade in anti-matter detection: warm superconducting magnets, μm tracking on large surface with low-consumption electronics

Opportunities are around the corner: e.g. China space programs (HERD)

Indirect measurements:

Next challenges: better determination of chemical composition and higher exposures with, at the highest energies, a full sky coverage (north/south observations)

- ✓ LHAASO – Cosmic rays in the region of the transition galactic extra-galactic.
- ✓ Auger Prime – Muon content to better address composition at the highest energies.
- ✓ Ground based detection of ultra high energy cosmic rays with full sky coverage.
- ✓ Space based detection of ultra high energy cosmic rays (EUSO concept).

Not only CR:

- ✓ p-He cross section measurements → pbar production in ISM (LHCB-SMOG? COMPASS?)
- ✓ particle production in atmospheric showers → TOTEM, LHCF.....SAS?

THE END

CONCLUSIONS

- Universe is the ultimate laboratory and the study of its messengers is a field of research rich and complex, that spans from fundamental physics to high energy astrophysics.

- Cosmic radiation always involves multi-purpose experiments that can address different problems with a huge discovery potential.

- There are several important opportunities worldwide, both in terms of international collaborations and funding, that can be caught by INFN (i.e. China programs for space and on-ground detection of cosmic radiation).

- All lines of research discussed here are of considerable interest and should be developed by INFN. Selecting priorities is not an easy task, but the science is in any case of the highest interest.

A Thousand Invisible Cords Binding Astronomy and High-Energy Physics
R.Kolb, Rept.Prog.Phys.70,1583 (2007)

CHOOSE YOUR FAVOURITE NOBEL PRIZE

The Nobel Prize in Physics 2002

Raymond Davis Jr.
Prize share: 1/4

Masatoshi Koshiba
Prize share: 1/4

Riccardo Giacconi
Prize share: 1/2

The Nobel Prize in Physics 2006

Photo: P. Izzo
John C. Mather
Prize share: 1/2

Photo: J. Bauer
George F. Smoot
Prize share: 1/2

The Nobel Prize in Physics 2011

Photo: U. Montan
Saul Perlmutter
Prize share: 1/2

Photo: U. Montan
Brian P. Schmidt
Prize share: 1/4

Photo: U. Montan
Adam G. Riess
Prize share: 1/4

The Nobel Prize in Physics 2015

Photo: A. Mahmoud
Takaaki Kajita
Prize share: 1/2

Photo: A. Mahmoud
Arthur B. McDonald
Prize share: 1/2

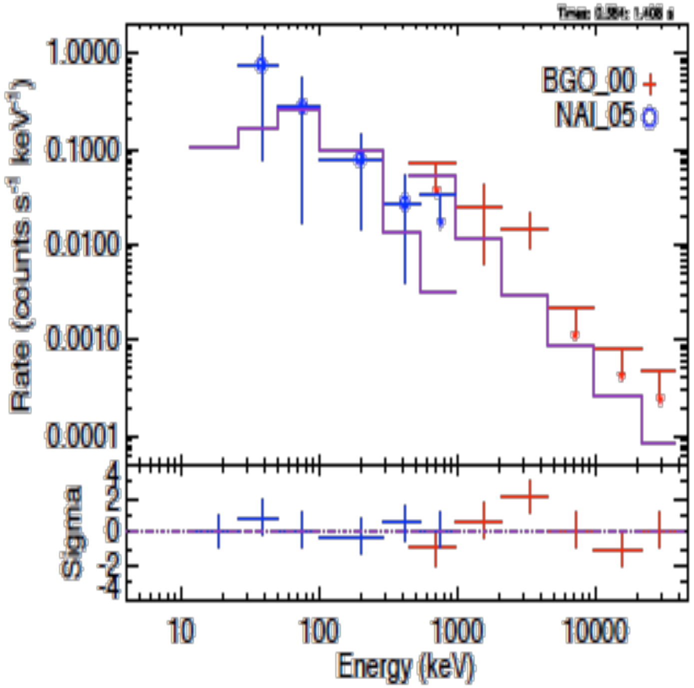
?
Gravitational Waves

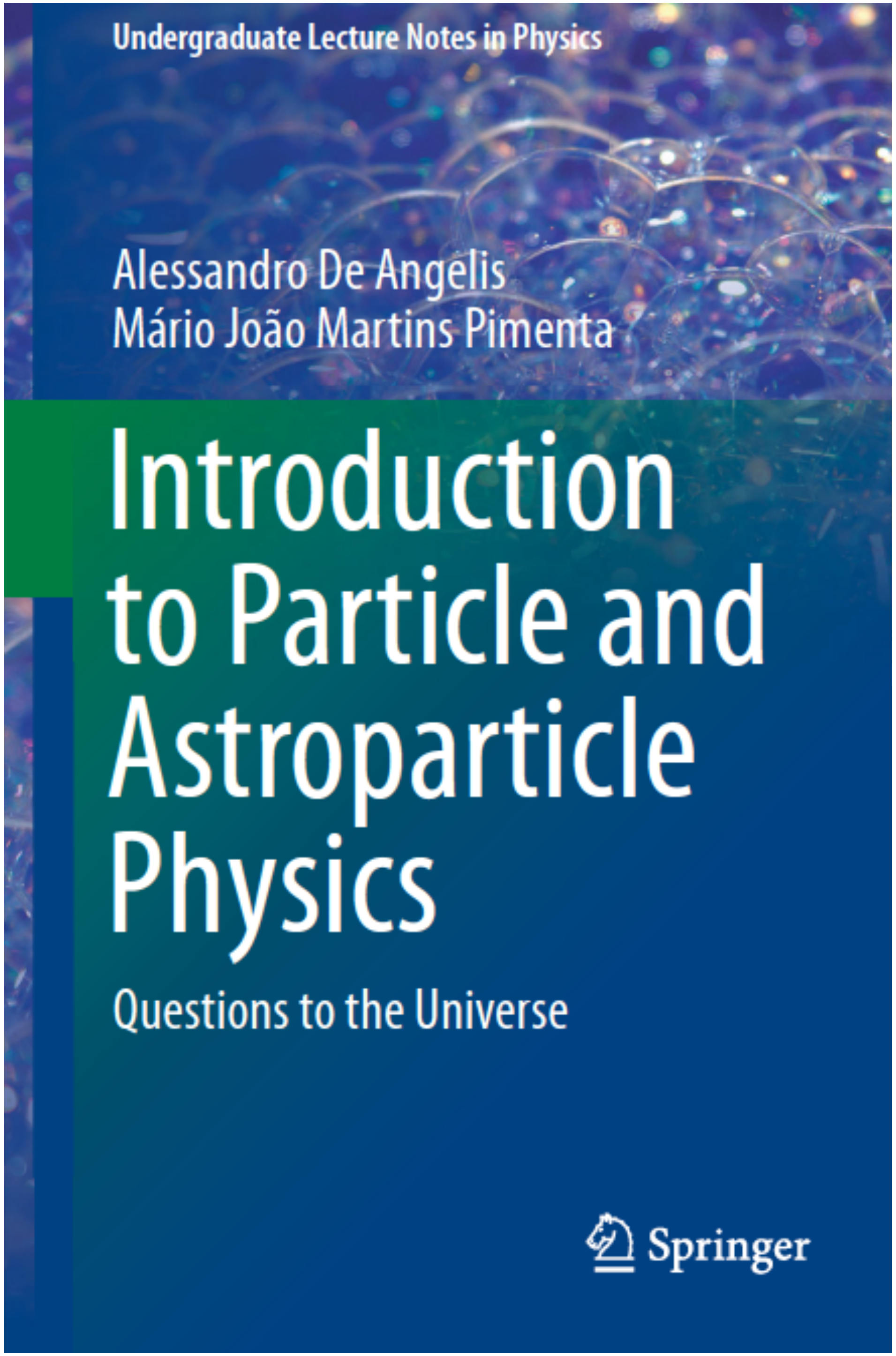
A POSSIBLE COINCIDENCE SEEN BY FERMI GBM?

GBM observations at the time of the LIGO event GW150914 reveal the presence of a weak transient source above 50 keV (peak ~ 1 MeV), 0.4 s after the GW event was detected, with a false alarm probability of 0.0022.

Detector response is not optimal.

If the GBM transient is associated with GW150914, this electromagnetic signal from a stellar mass black hole binary merger is unexpected.

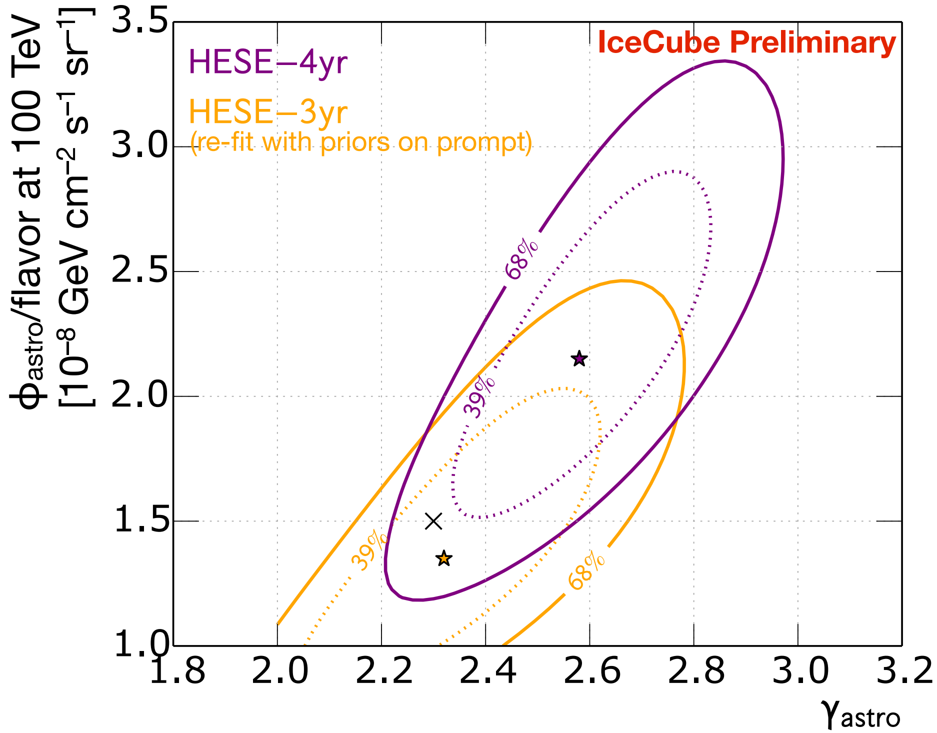



Undergraduate Lecture Notes in Physics
Alessandro De Angelis
Mário João Martins Pimenta
Introduction to Particle and Astroparticle Physics
Questions to the Universe
Springer

BACKUP NEUTRINI

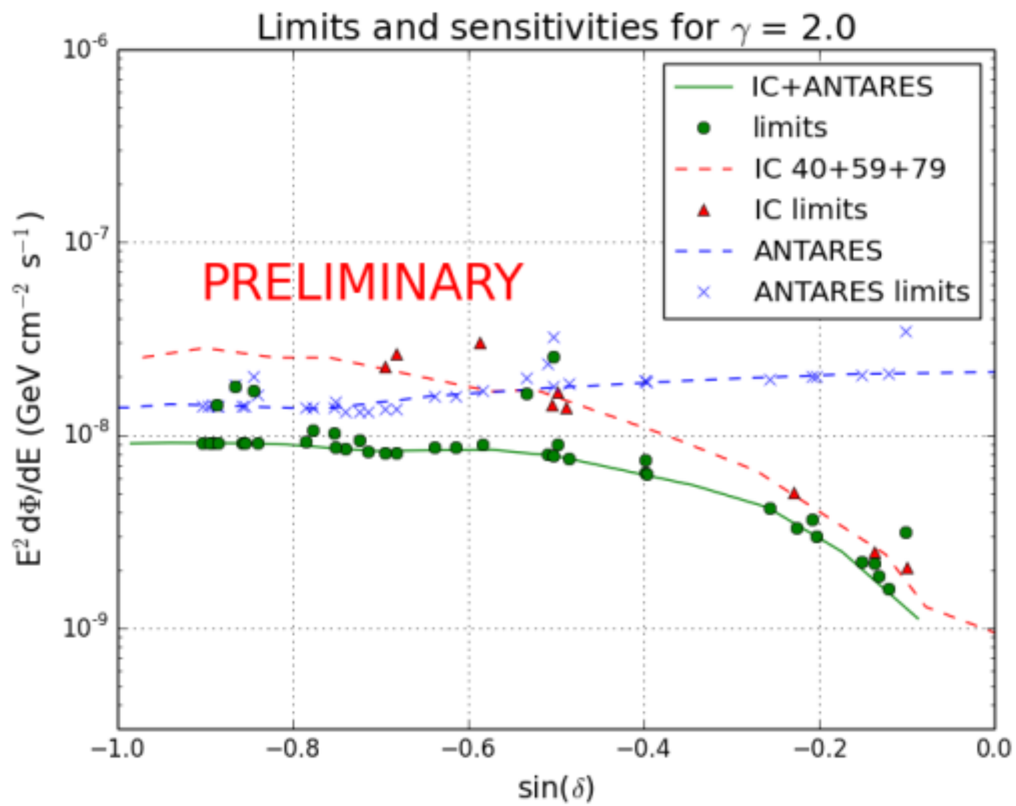
SPECTRAL INDEX OF COSMIC FLUX

- Now 53(+1) events observed
  - $9.0^{+8.0}_{-2.2}$ atm. neutrinos
  - 12.6±5.1 atm. muons
- Substantial (but not significant) shift in best fit spectral index
  - Beware statistical fluctuations!

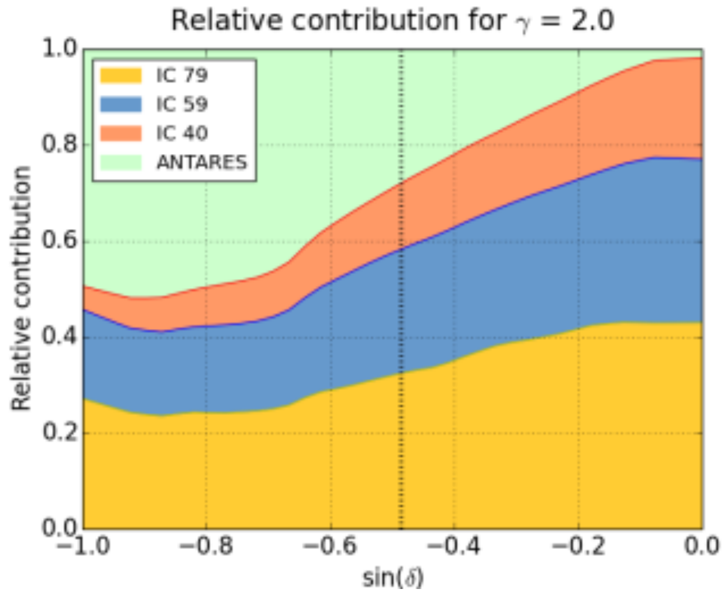


ANTARES-ICECUBE POINT-LIKE SEARCH

Point-source analysis using the ANTARES 2007-2012 and the IC40, IC59, and IC79 samples for the Southern Hemisphere



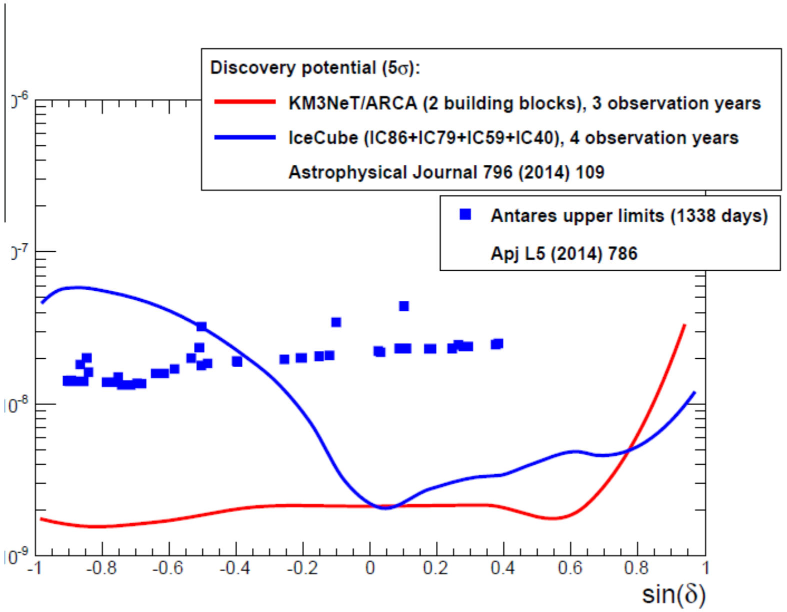
Barrios-Martì ICRC2015



Combined 90% CL sensitivities (green line) and limits (points) for an E^{-2} source spectrum. Blue (Red) curves/points indicate ANTARES (*IceCube*) sensitivities/ limits

DISCOVERY POTENTIAL FOR E^{-2} POINT LIKE SOURCES

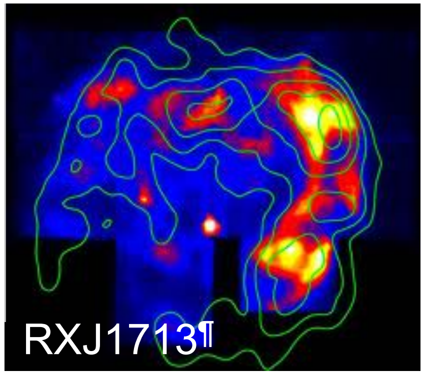
ARCA discovery potential for point-like sources better than or comparable with IceCube over almost whole sky already

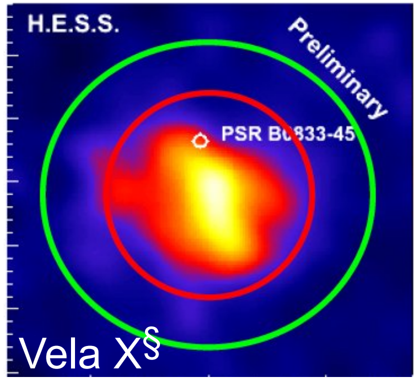


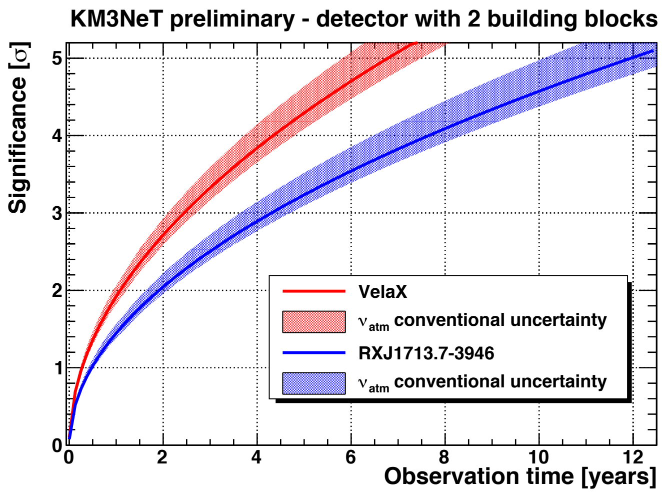
Futher improvement expected with inclusion of energy dependence and development of new analysis

SENSITIVITY TO GALACTIC SOURCES

- HE gamma emission observed by HESS in SNRs
- Neutrino spectra predicted using gamma spectra
  - ¶ S.R. Kelner, *et al.*, PRD 74 (2006) 034018
  - § F.L. Villante and F. Vissani, PRD 78 (2008) 103007
- Hypotheses: 100% hadronic emission and transparent source





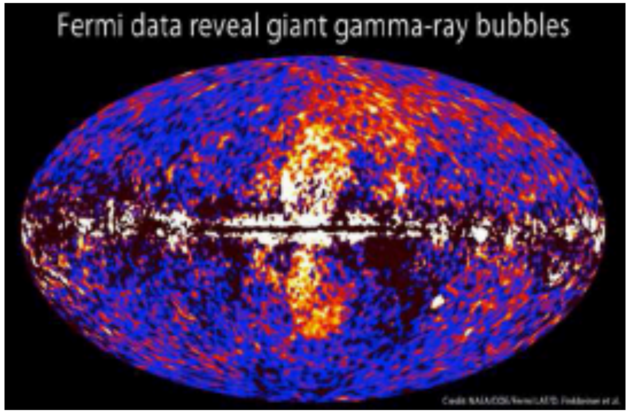


Vela X: 3σ in about 2 years
RXJ1713: 3σ in about 4 years

FERMI BUBBLES

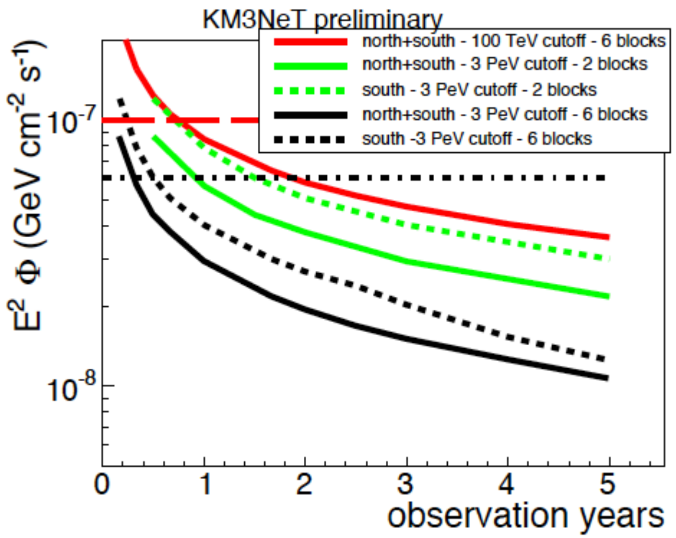
See last spectra from Fermi

Two huge extended regions above/below the Galactic Centre



Fermi detected hard gamma emission (E^{-2}) up to hundreds of GeV

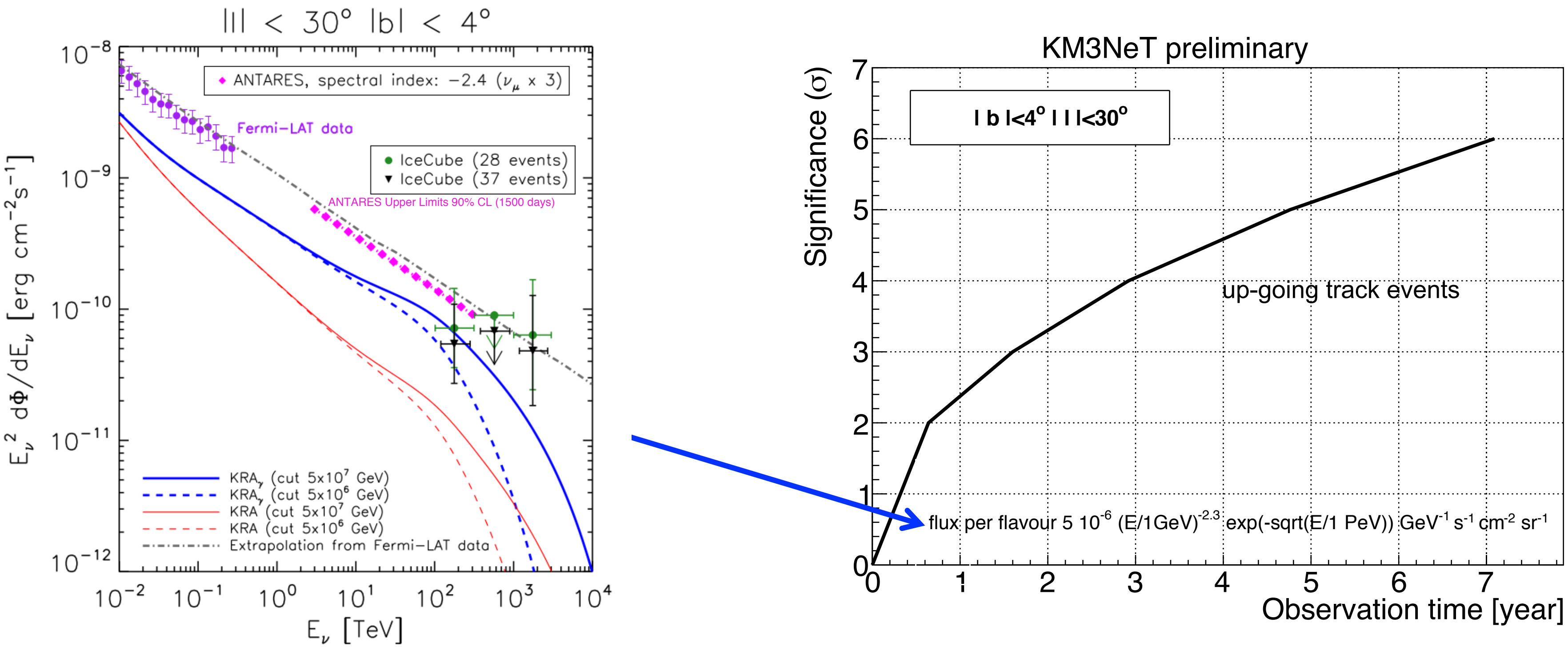
In case of hadronic emission neutrino flux expected, but detectable by neutrino telescopes only if $E_{cut\text{-}off}$ >100 TeV



Results for 6 blocks published in Adrian Martinez et al Astroparticle Phys. 42 (2013)

DIFFUSE FLUX FROM THE GALACTIC PLANE

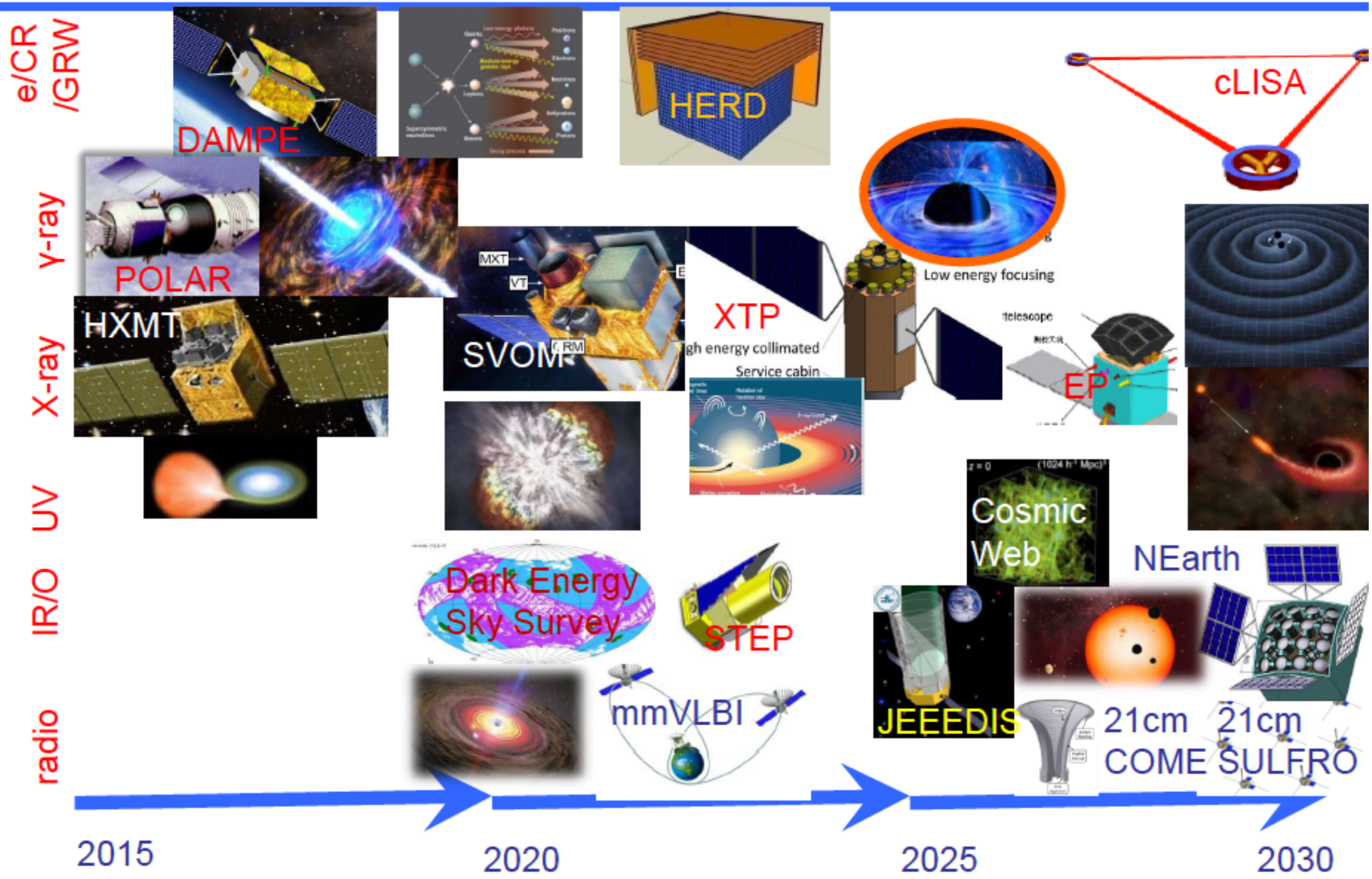
ARCA performance to a flux from a region of the Galactic Plane near the Galactic Center. Evaluation of the neutrino flux based on a radially-dependent cosmic-ray transport properties (D. Gaggero et al. 2015)

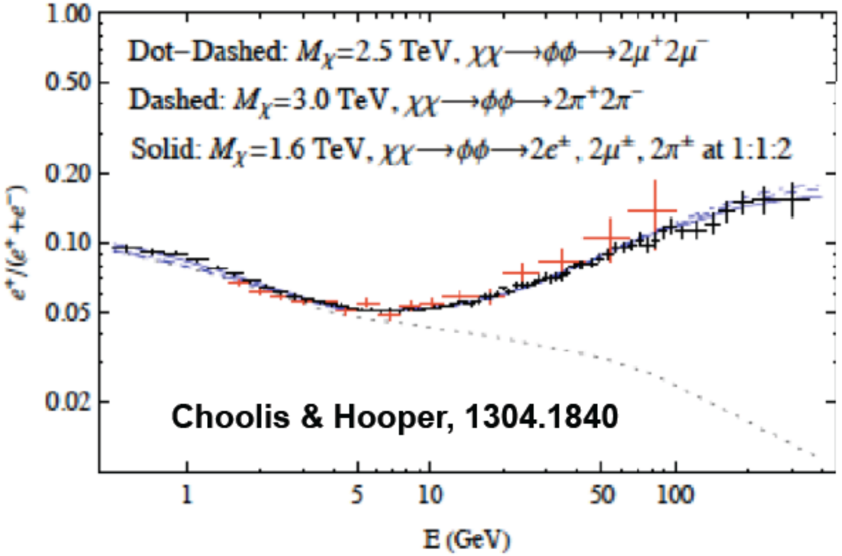


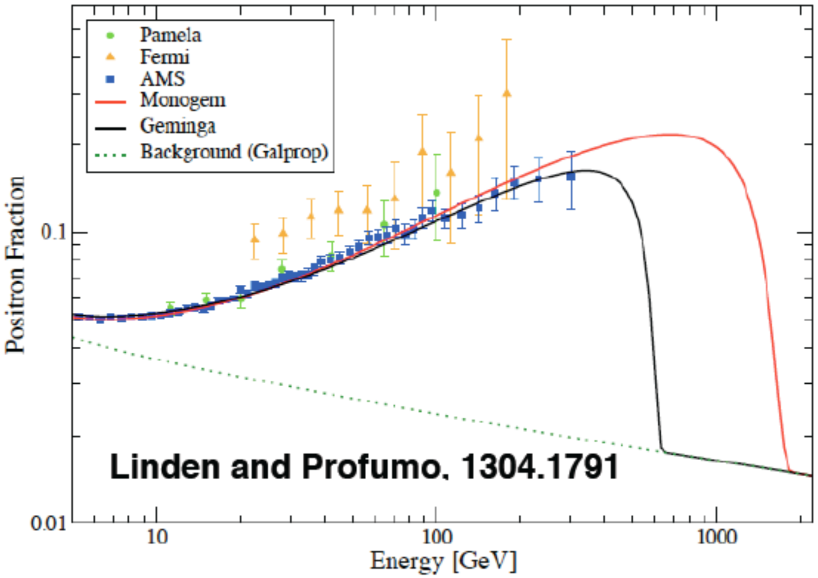
Discovery at 5σ significance (50% probability) in about 5 years

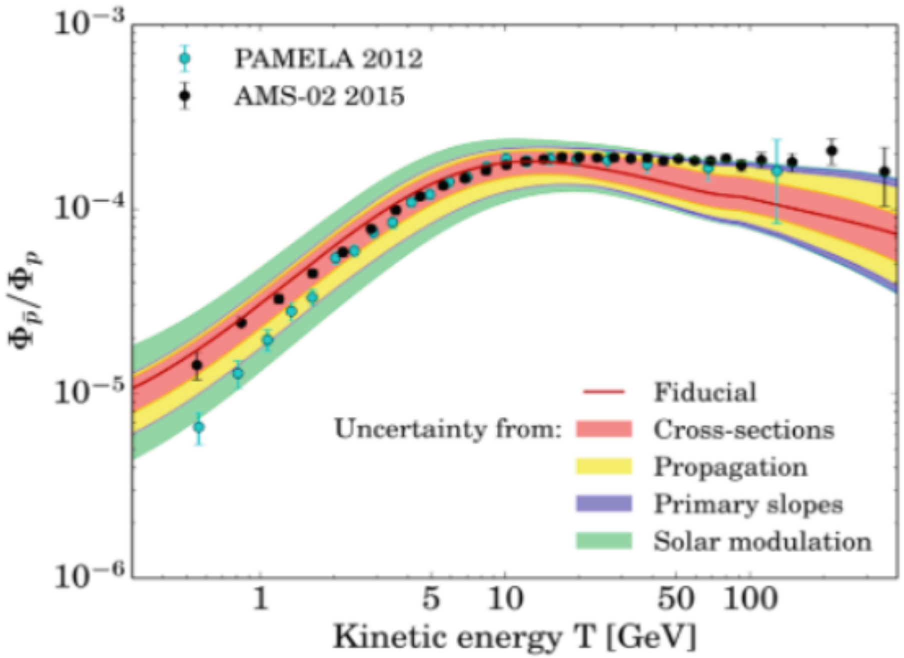
BACKUP CR

China's Future Space Astronomy Missions



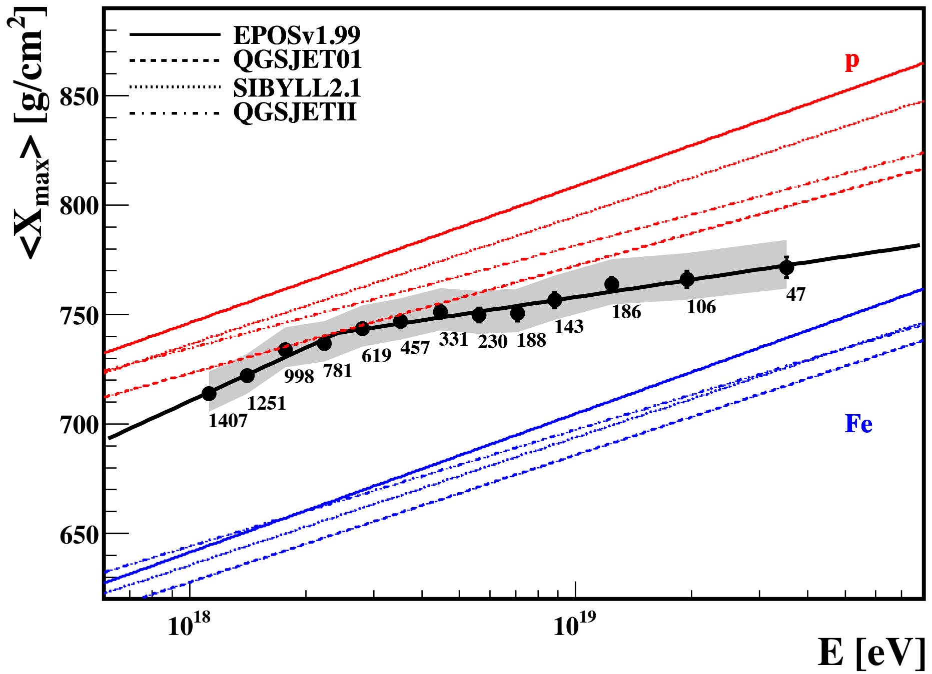


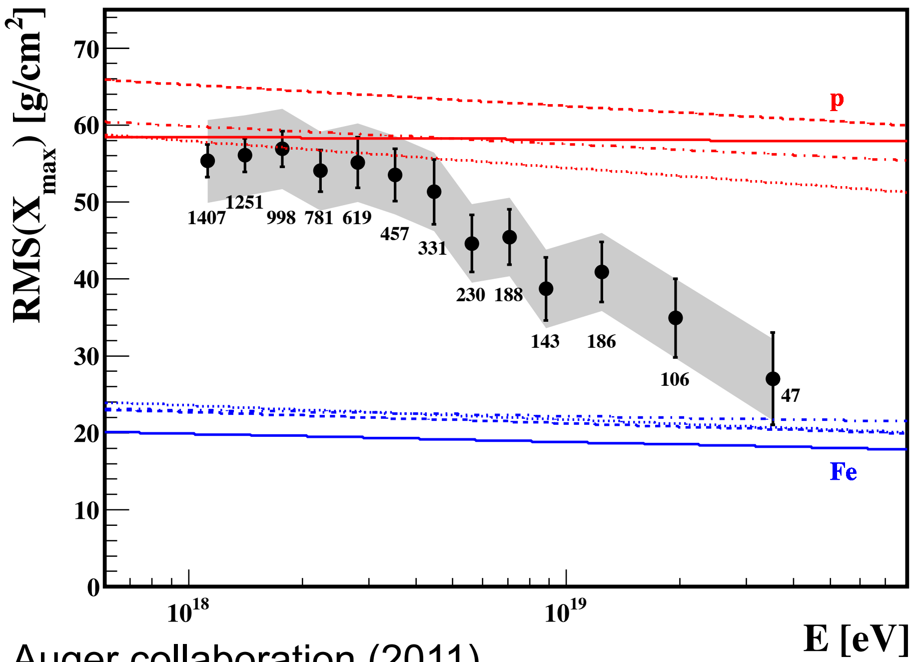




G. Giesen et al. arxiv:1504.04276

Auger chemical composition



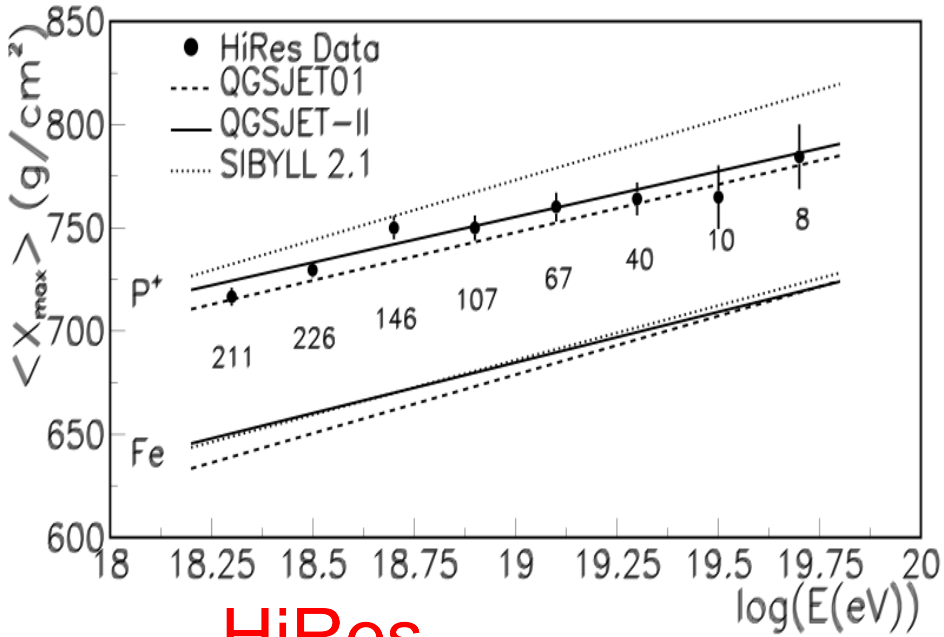


Auger collaboration (2011)

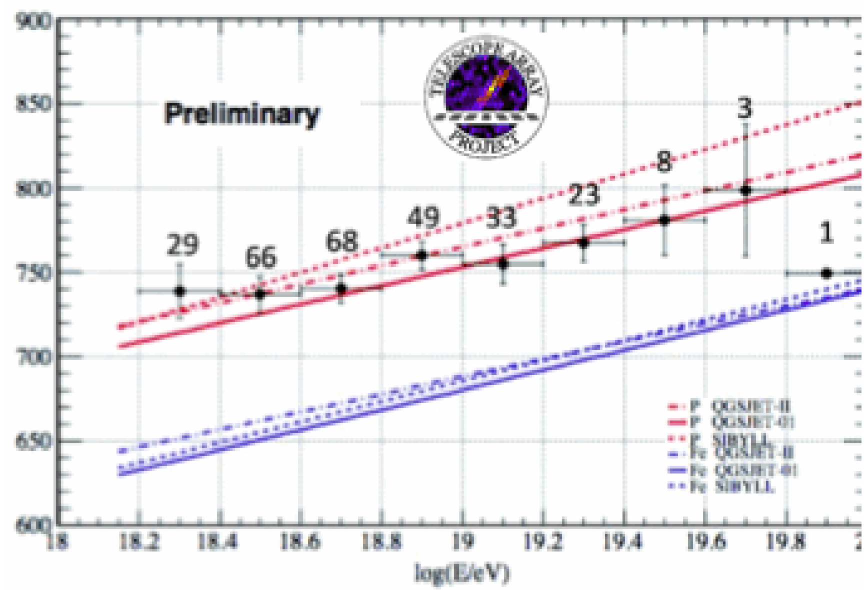
The Auger observations on chemical composition show the tendency for a nuclei dominated flux at the highest energies.

HiRes & Telescope Array – Chemical Composition

HiReS and Telescope Array observe a proton dominated spectrum at all energies, starting from 10^{18} eV up to the highest energies.



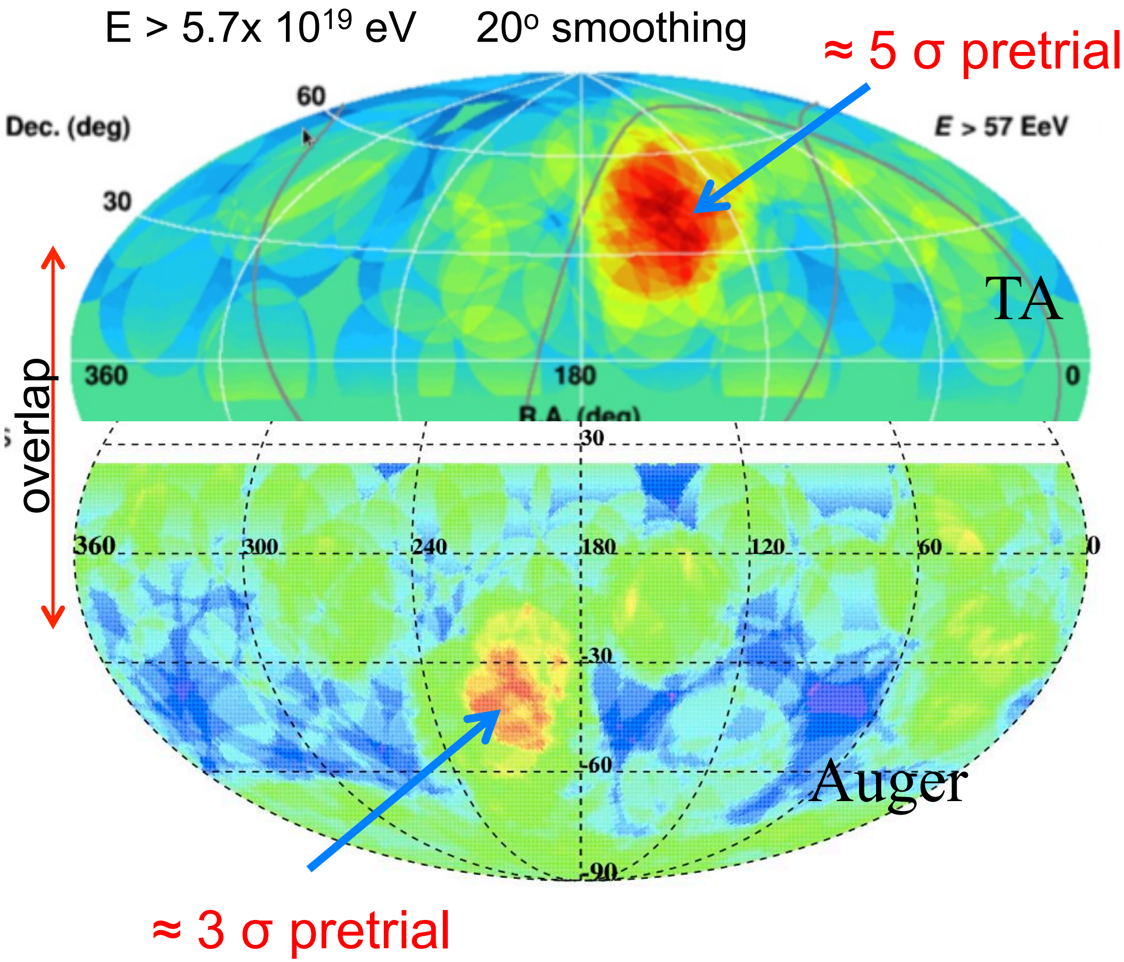
HiRes



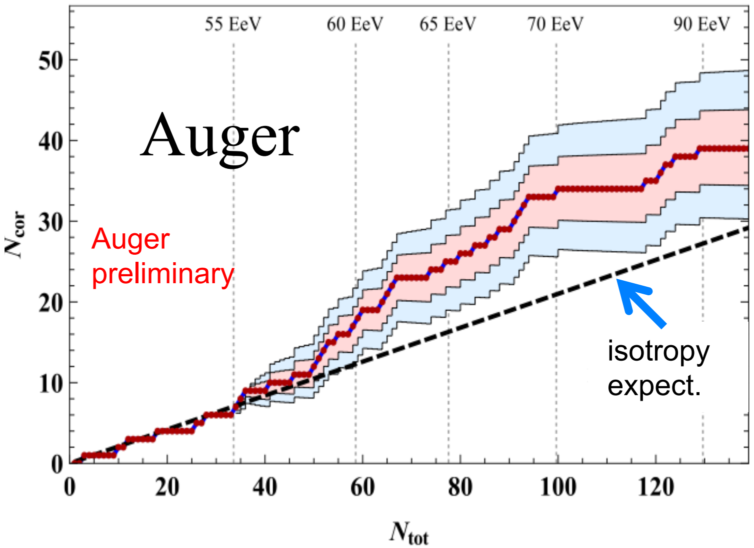
TA

Hints of CR astronomy?

Evidence of Cosmic Rays anisotropy above 57 EeV in both northern and southern hemispheres. The signal is statistically limited. Hopefully it will be clear in a few years.

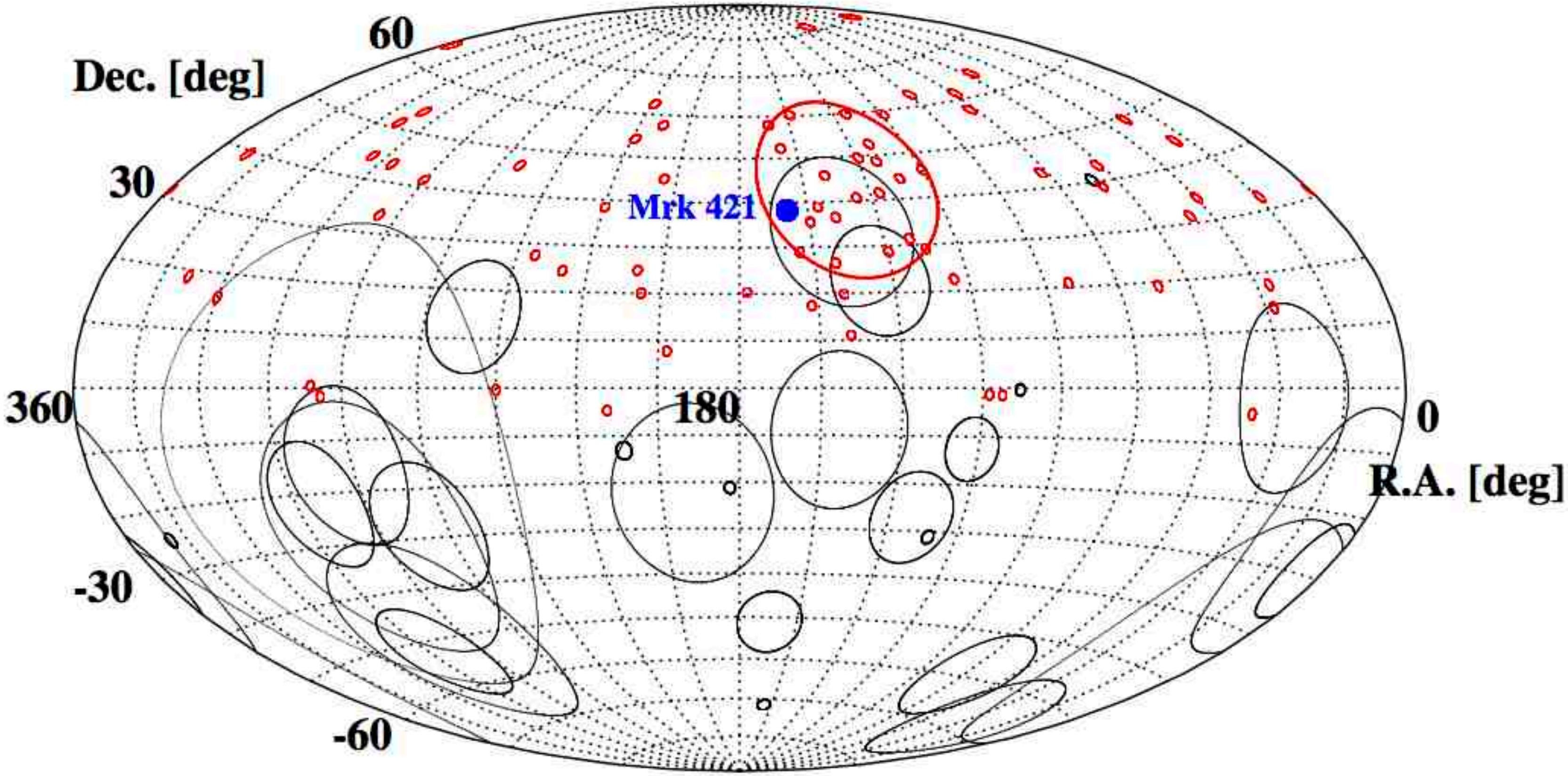


# of events correlating with AGN, ordered in energy (integral plot)



4 neutrino events out of 28 in IC are detected from the northern hemisphere.

Two neutrino events out of four in the northern hemisphere fall in the region of the TA excess and seem to correlate with Mrk 421.



Fang, Fujii, Linden, Olinto (2014)

The chance coincidence of the IC events with the TA hot spot can be rejected at 2 σ level. This tenuous correlation is based on the extremely small statistics of both TA and IC and should be taken just as an indication that needs to be confirmed by higher statistics.