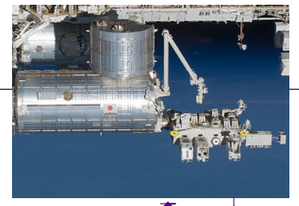
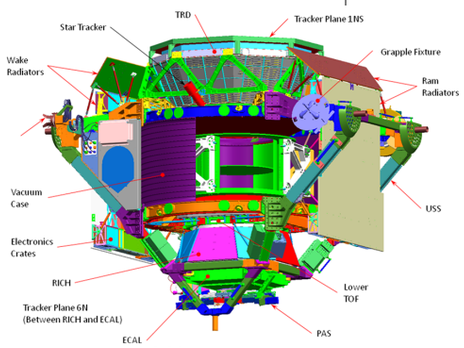
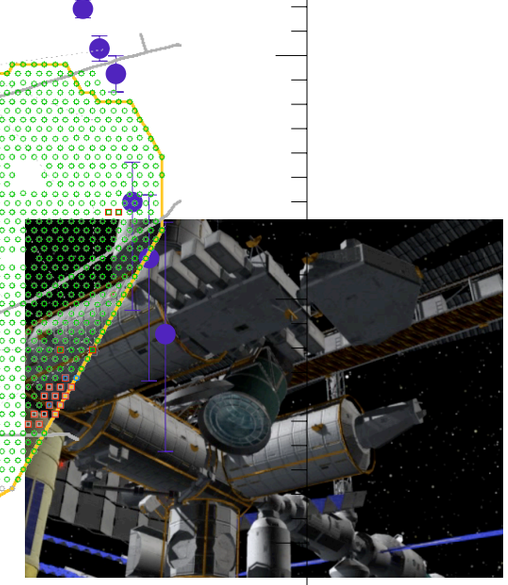
Cosmic-rays : tour of the recent observations and perspectives







Cosmic-rays a major player in high-energy astrophysics

Galactic cosmic-rays and Galactic ecology :

❖ Cosmic-rays are one of the most important components of the Galaxy, they play a role in the most significant processes

➡Energy density similar to that of starlight and magnetic fields

❖ Cosmic-rays :

➡ Regulate the equilibrium between the different phases of the ISM (very hot, hot, cold, atomic, molecular)
➡ Control the ionization of the ISM
➡ Generate turbulent fields
➡ Control astrochemical processes
➡ Responsible for light nuclei nucleosynthesis

But their origin is still unknown !!!

Ultra-high-energy cosmic-rays :
➡

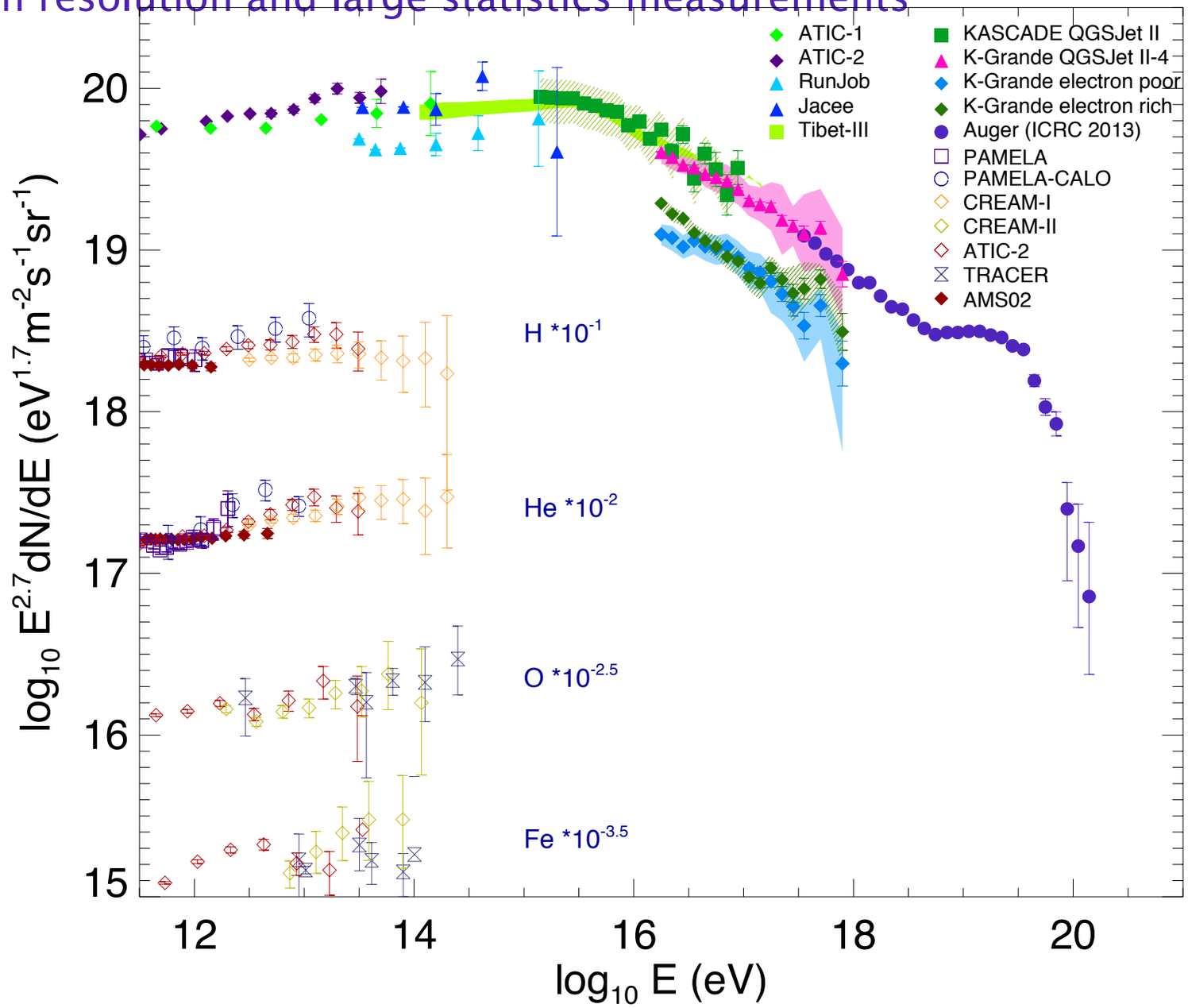
❖ Simply the most energetic particles we receive from the cosmos

➡How are they accelerated?
➡What is their sources?

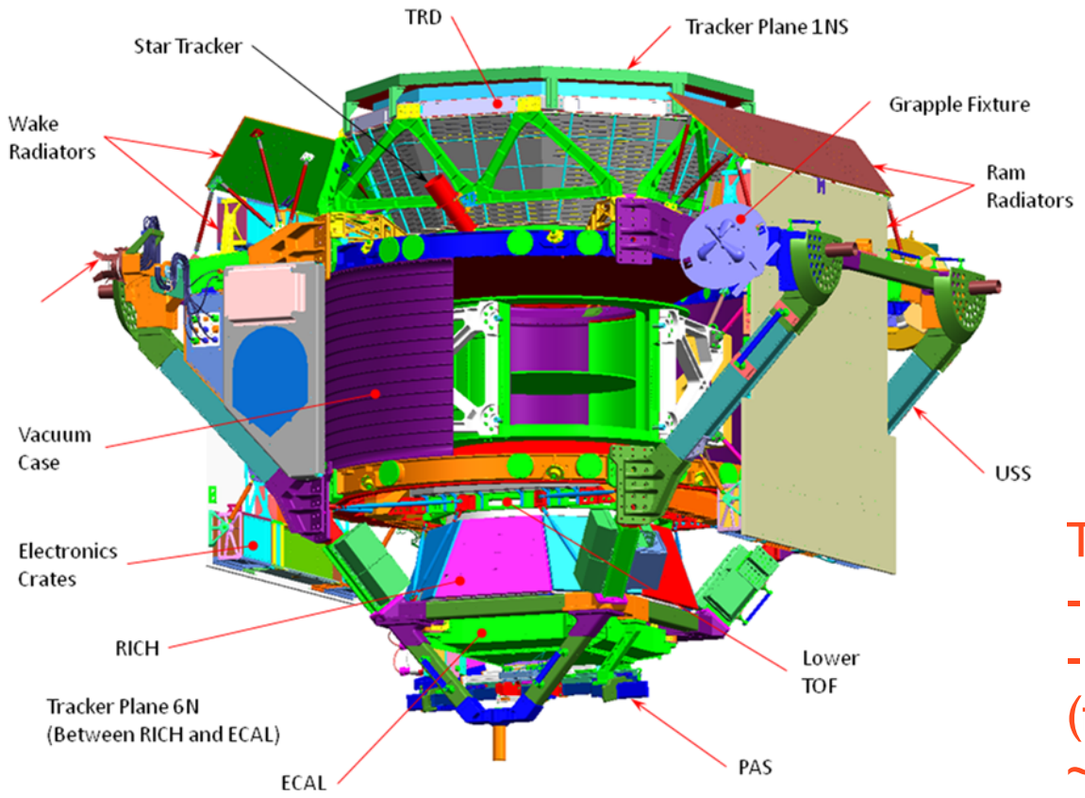
Cosmic-rays a major player in high-energy astrophysics

❖ To understand cosmic-ray one needs to measure the cosmic-ray spectrum, composition and arrival directions
The cosmic-ray spectrum cover a huge range in energy and flux :

❖ Many different experiments and detection techniques are needed to cover the full extend of the cosmic-ray with high resolution and large statistics measurements



AMS02 : the most advanced cosmic-ray detector ever sent to space



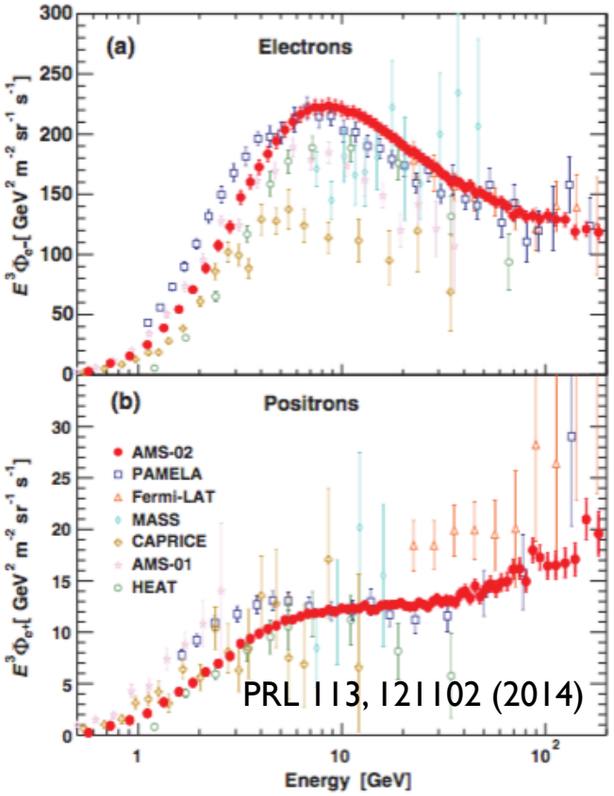
- 1998 AMS01 flight in the space shuttle
- AMS program on hold after Columbia's crash in 2003
- AMS back in Nasa's program in 2010
- AMS02 installed on the ISS in May 2011

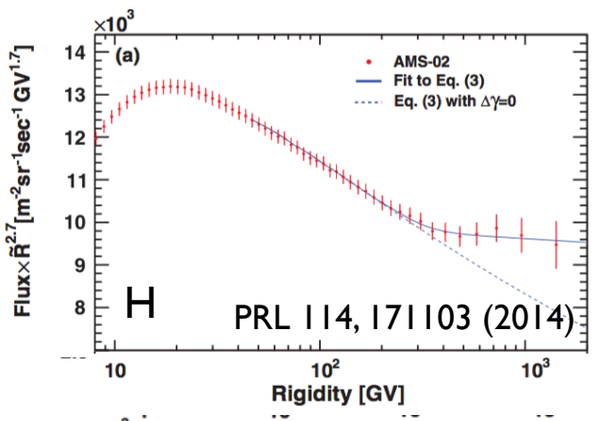
Two french groups involved :
- LAPP (ECAL)
- LPSC (RICH)

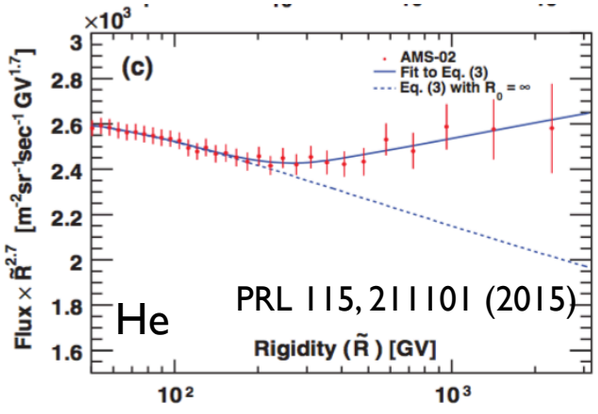
(former involvement of the LPTA Montpellier (GPS))
~ 12 members of the French collaboration signing the publications

- ~ 40 millions triggers per day -> 16 billions per year
- 39 TB of data per year
- 60 billions events collected so far
- High statistics and high resolution measurement of CR nuclei and e
$^{+}e^{-}$ from ~1 GV to ~2 TV
- publication of the first results started in 2013

AMS02 : first physics results





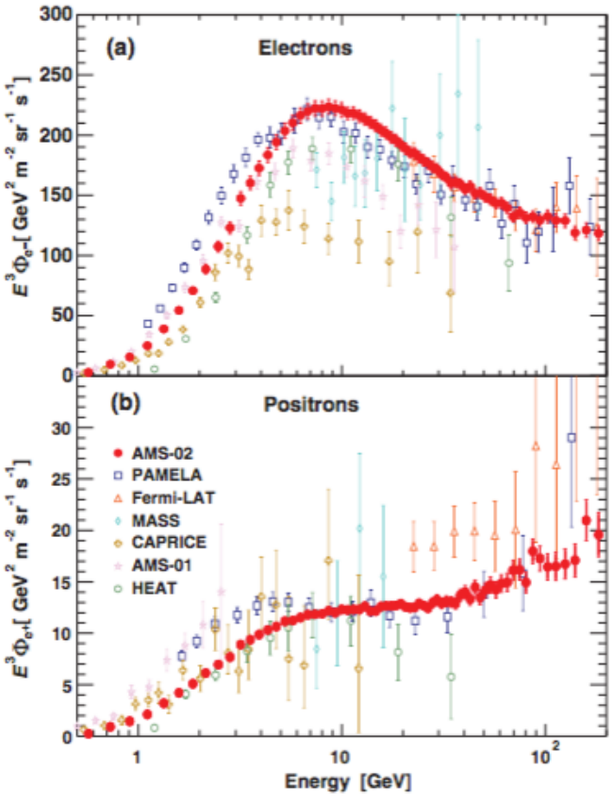


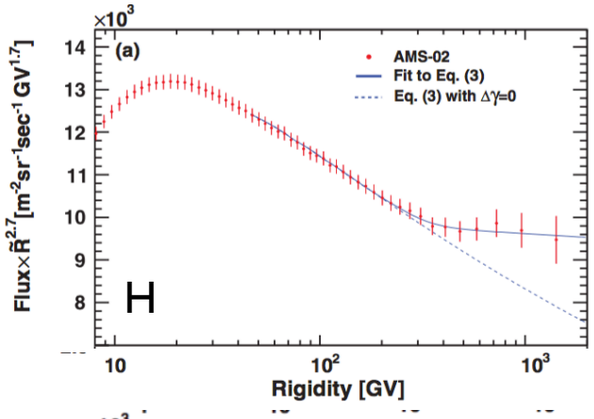
Measurements of the flux and spectrum of e^+ and e^-
first strong evidence for a significantly harder spectrum for positrons at high energy
--> already strong constrains on astrophysical (local source(s)) and dark matter scenarios
--> of course statistics will improve

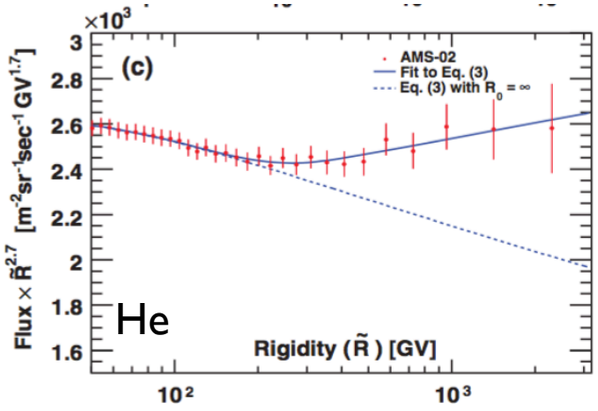
Measurements of the flux of H and He CRs
- confirmation of the presence of a spectral hardening around ~200 GV (already claimed by PAMELA but measured by AMS02 with a higher resolution and statistics)
- difference of the spectral shape of H and He
---> very intriguing result, constraining for astrophysical models !
---> a lot of theoretical/phenomenological efforts dedicated to understand these features (acceleration, propagation, local sources)

Strong implications and impact of the french teams in these analyses
(LAPP --> e^+e^- , proton/antiproton, LPSC -->nuclei)

AMS02 : more to come







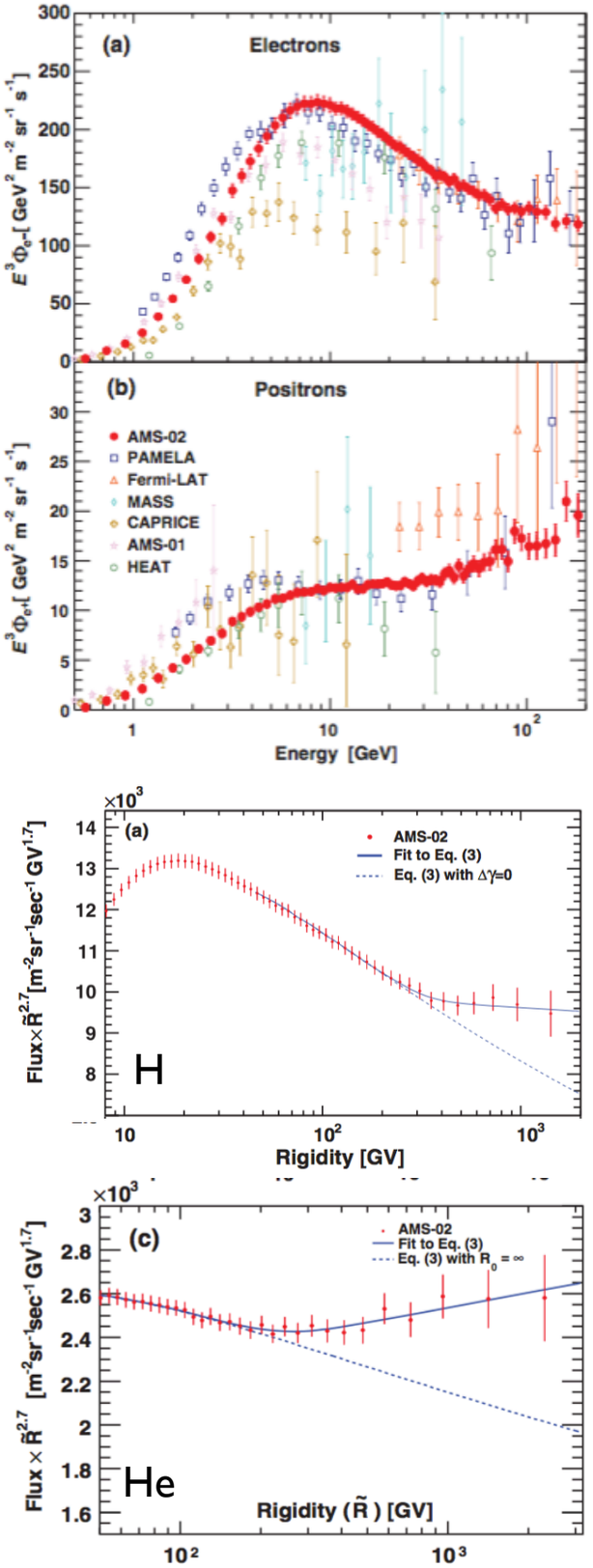
Other new analyses expected to be released soon (some results were hinted at the conference "AMS days at CERN"):

- Li
- C,O
- B/C (secondary to primary ratio)
- heavier nuclei
- isotopic ratios

--> do heavier nuclei present the same hardening as H and He?

--> high resolution measurements of secondary nuclei at high energy important to constrain astrophysical scenarios

AMS02 : theoretical/phenomenological aspects



AMS02 result have been long expected by the community, the first results triggered a huge interest

--> a large community of theoreticians and phenomenologist in France interested in AMS measurements

--> significant contribution of teams from Grenoble and Annecy (inside or very close to the AMS collaboration) to the interpretation of the first AMS02 data

Very interesting papers published in the past two years :

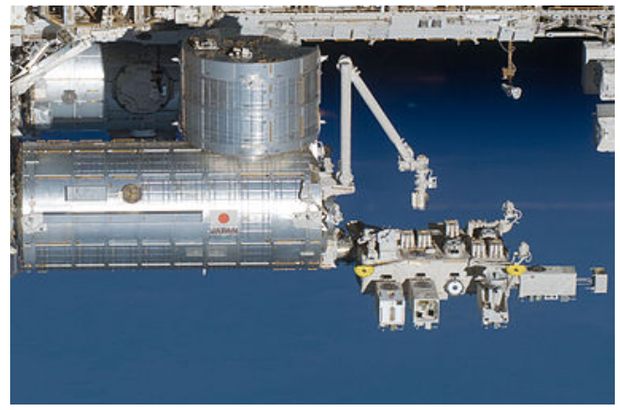
- constrains on astrophysical and dark matter scenario from e^+e^-
- interpretation of the features in the spectra of H and He (in terms of the CR propagation or the presence of a local source)

More to come on solar modulation and the interpretation of the forthcoming primary/secondary ratios

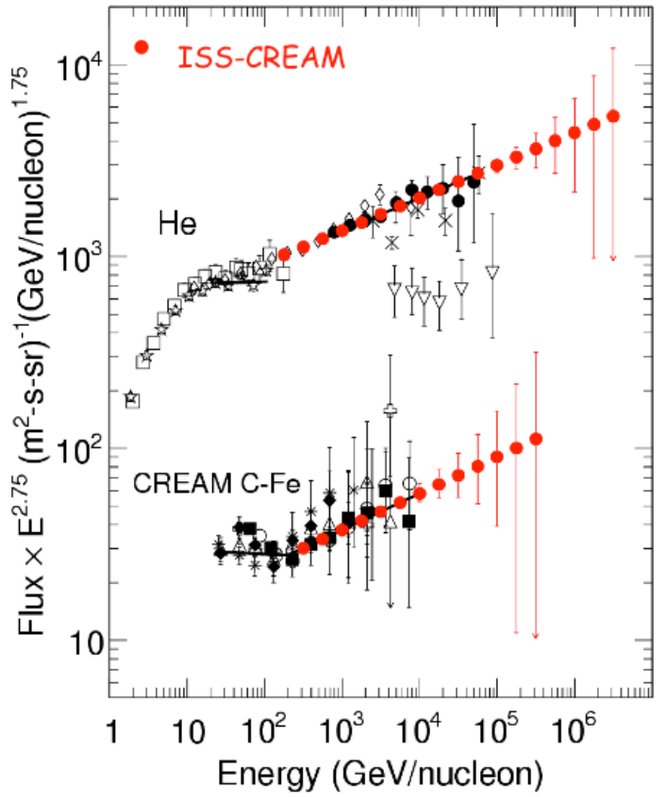
Strong involvement of the French groups/labs in all the different aspects of AMS02 (instrument, analyses, interpretation)

From CREAM to ISS-CREAM

The CREAM ballon experiment measured the flux of cosmic-ray nuclei above ~ 1 TeV from 2004 to 2010 (6 flights)
- LPSC joined to CREAM experiment as the AMS program in 2005 was on hold
- Conception of the Cherenkov Imager CHERCAM
- Participation to the data analysis and interpretation (B/C ratio)



The CREAM detector will be sent to the ISS in 2017
- 3 years of observations ---> much larger statistics above 1 TeV
---> possibility to reach energies relatively close the knee (very important perspective of a better cross calibration with indirect measurements)
---> measurement of primary cosmic-ray spectra and secondary/primary ratios with unprecedented statistics in this energy range
---> extremely interesting to constrain astrophysical scenarios and CR propagation



The LPSC group proposes to continue the CREAM program with a participation to ISS-CREAM
- instrumental contribution already delivered
- very strong science case complementary to that of AMS02

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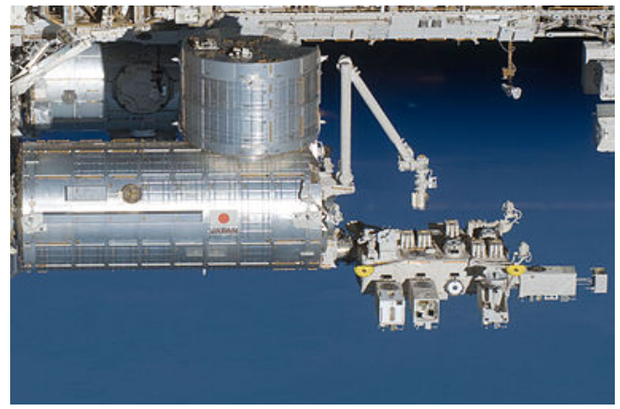
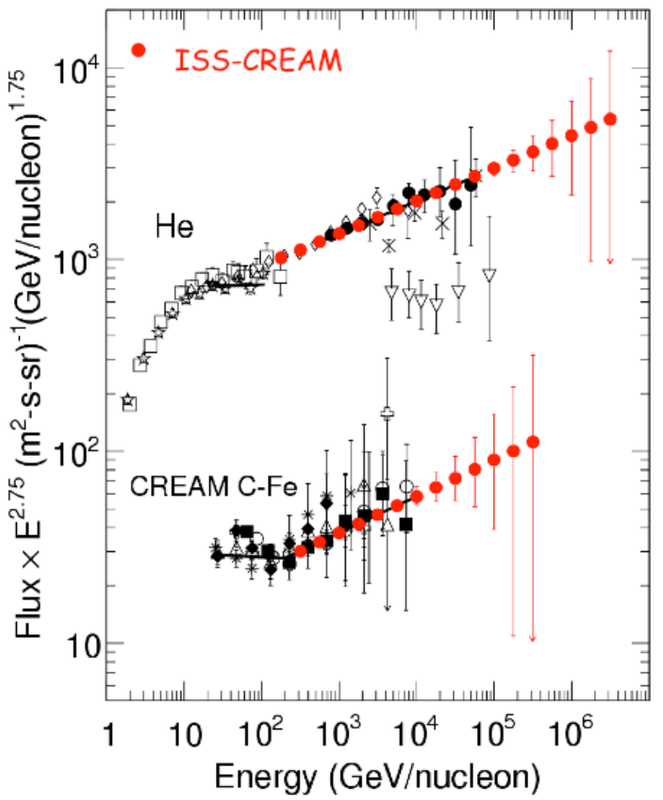
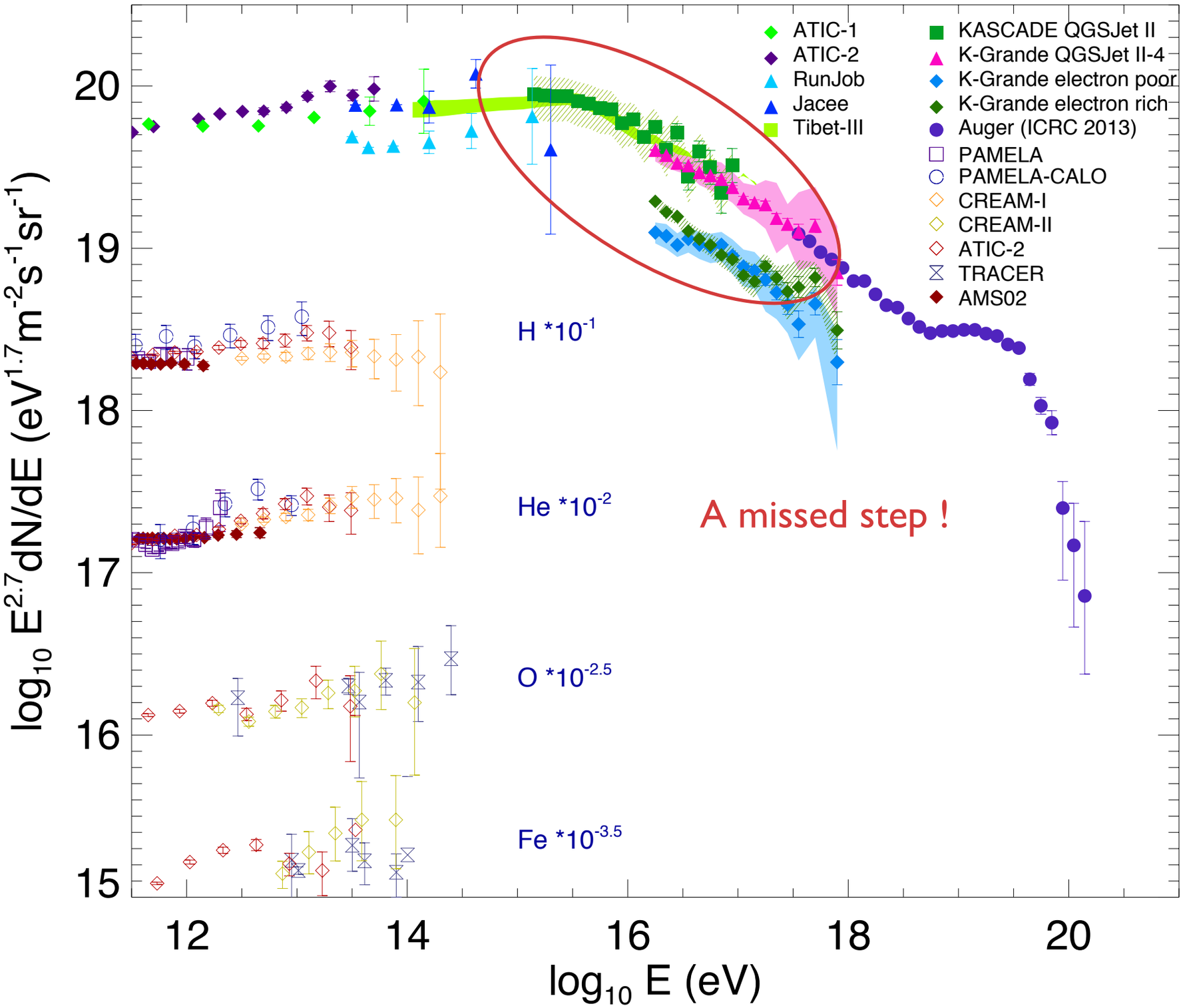
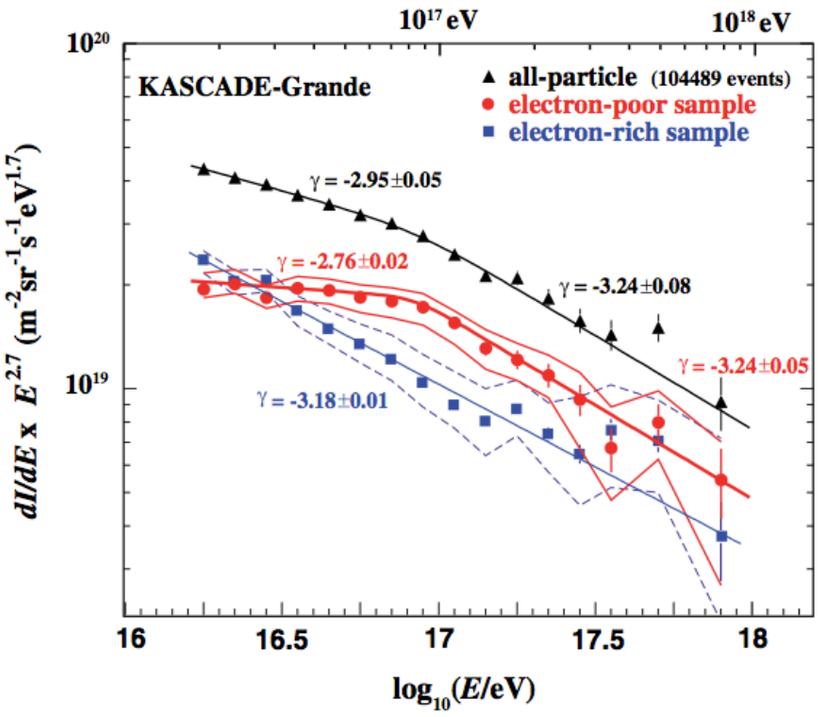




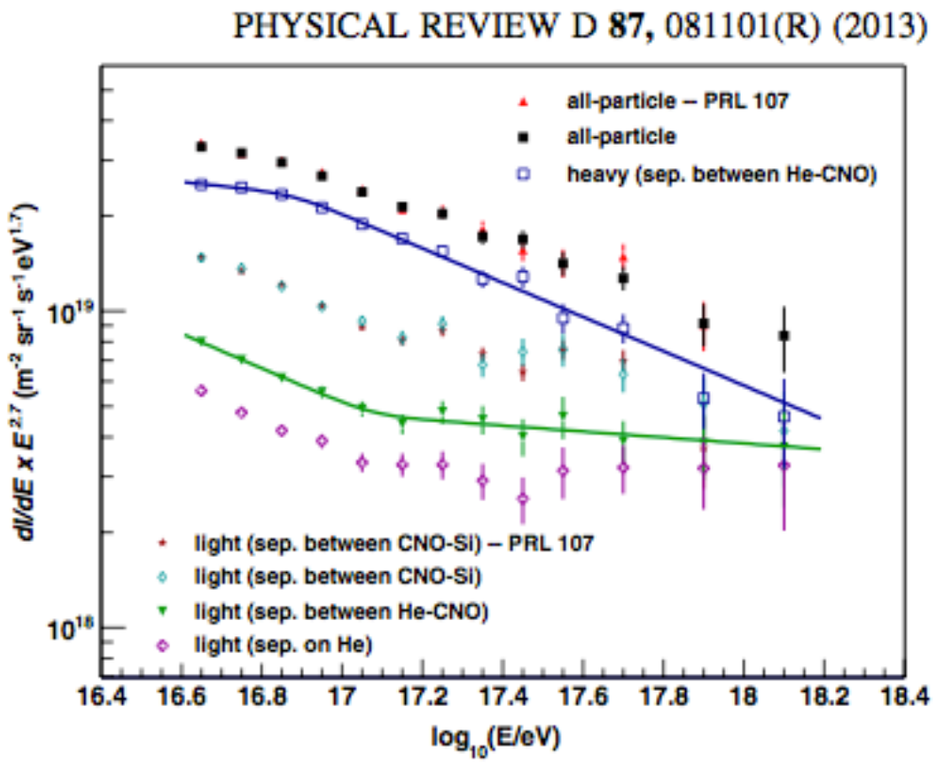
The knee region and beyond



Kascade-Grande : Heavy knee and light ankle



KG collab, Phys. Rev. Lett., 2011



- Significant break of the heavy component (supposed to be Si+Fe) spectrum seen for all hadronic models
- Moderate change of spectral index ~0.5 in all cases
- The heavy component does not seem to disappear immediately after its knee
(smooth knee rather than sharp)
- The heavy component still seems to be significantly there at 10^{18} eV in all case
- The hadronic model dependence is mostly found in the relative abundance of the heavy component
(not in the existence or the sharpness of the break)

- A similar analysis showed evidence for an "ankle" in the light component
- The spectral index before the "light ankle" is compatible with the post knee spectral index of the heavy component
- Likely explanation : an extragalactic light component is starting to emerge on top of the light galactic component ==> smooth knee for the light component too ==> post knee protons at ~10^{17} eV (?)
- Cross check with other hadronic models ==> the result seems to be confirmed

Constraining for the transition from Galactic to Extragalactic cosmic-rays
Constraining for Galactic sources ---> "more than pevatrons" needed

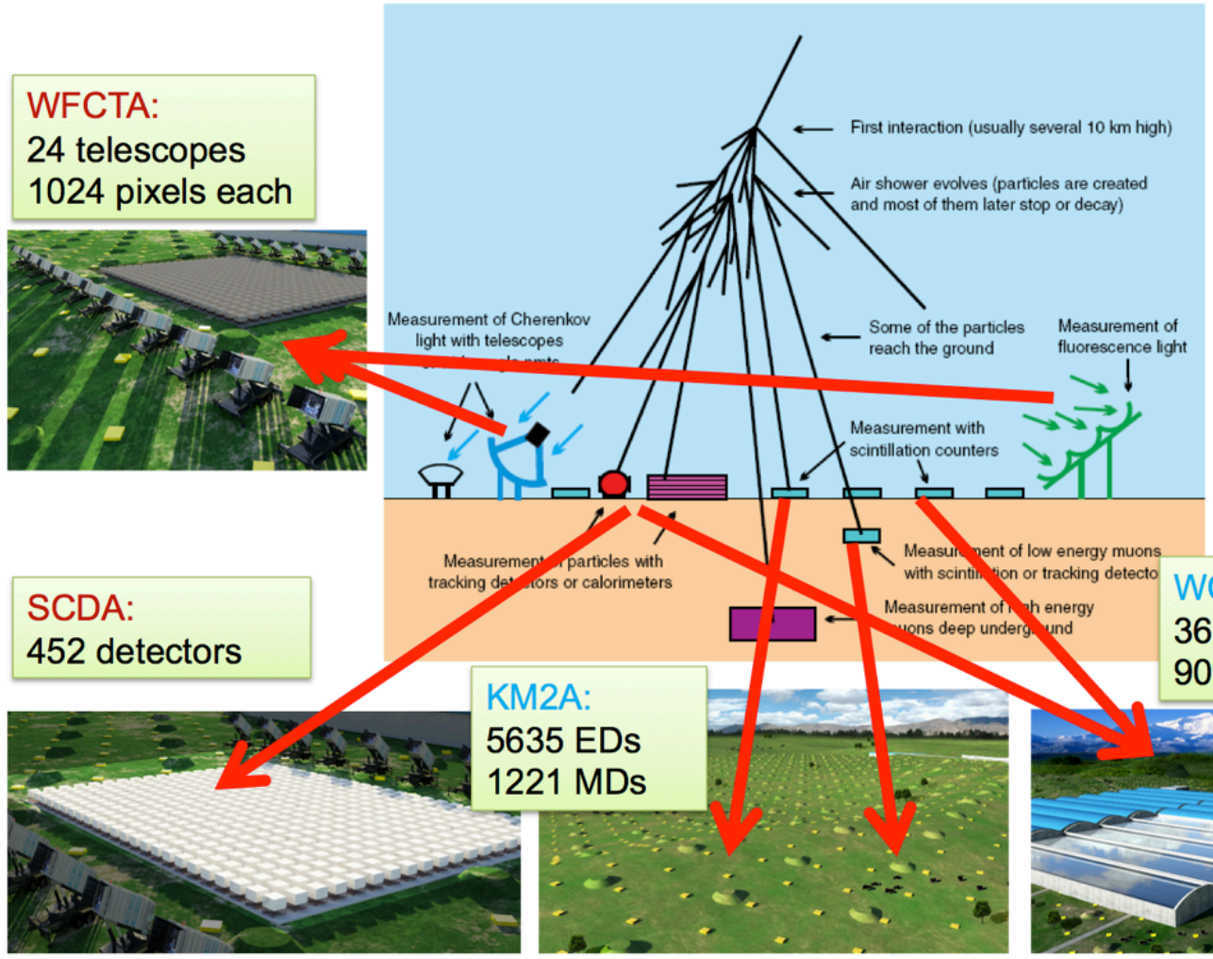
The future in the knee region : LHAASO

Hybrid (multidetector) VHE cosmic-ray and gamma-ray observatory to be installed in the Sichuan province
4400 m a.s.l
High altitude + multidetector :

- ✳ very low energy threshold (30 TeV) ---> good overlap with direct measurements
- ✳ high resolution measurements of air showers

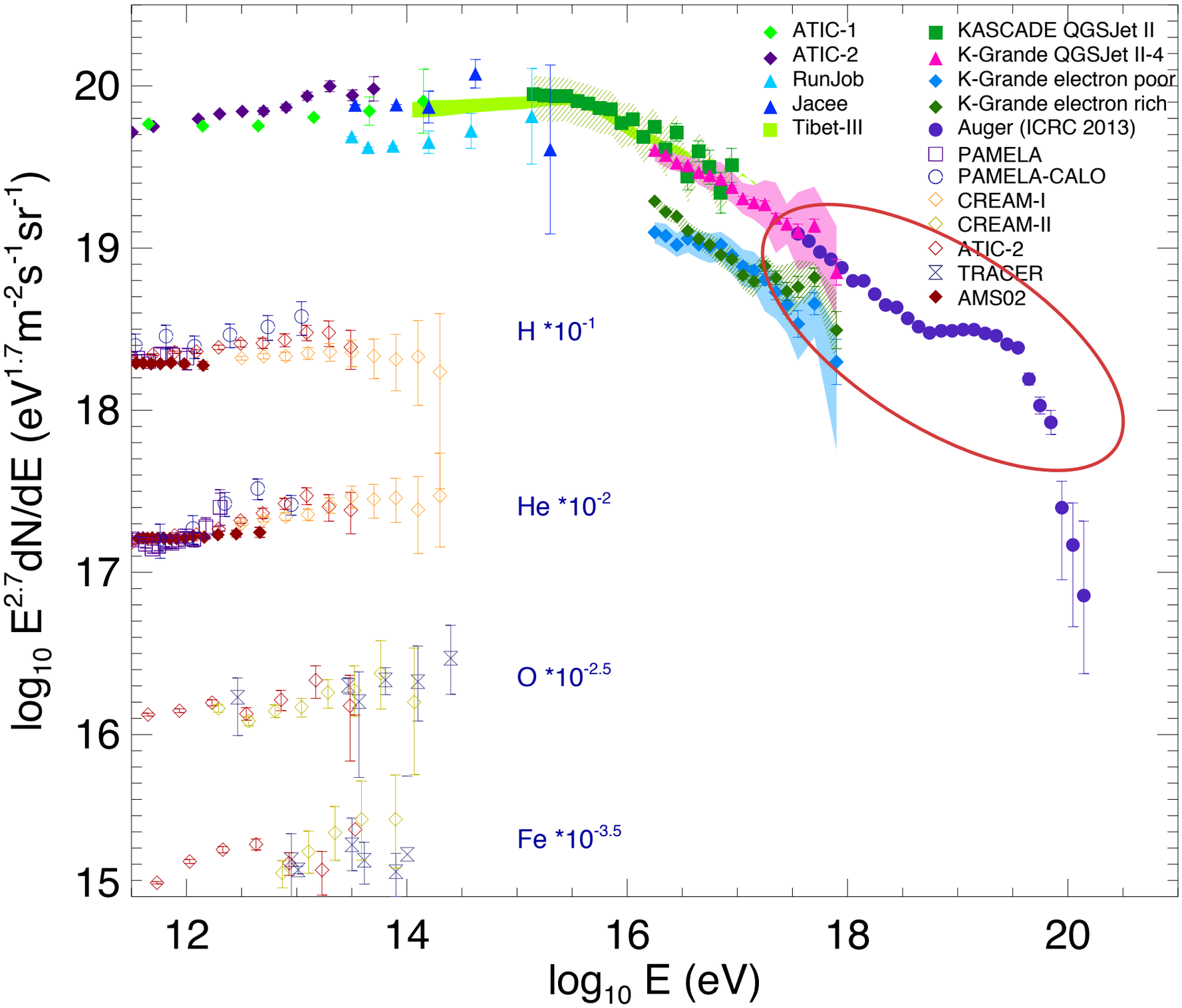
particle content ---> sensitivity to the cosmic-ray mass

✳ MILAGRO-like gamma-ray detector (complementary to CTA above 30 TeV) ---> useful to search (multi-) Pevatrons



- Instrument almost completely funded by China
- To be deployed relatively soon (1/4 of the instrument should be deployed within the next two years)
- France already has a foot in the LHAASO collaboration :
  - ✳ Part of the IPNO Auger team involved
  - ✳ A front end board for the Cherenkov telescopes has been delivered by IPNO and the Omega platform
  - ✳ Student exchange program between France and China
  - ➡ interesting science case, probably worth considering if a critical mass can emerge in the French community

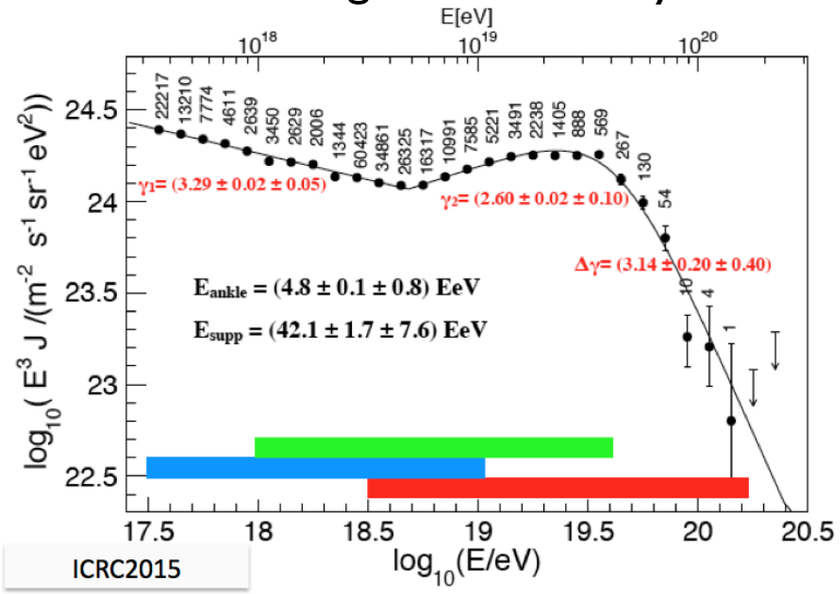
The ultra-high energies



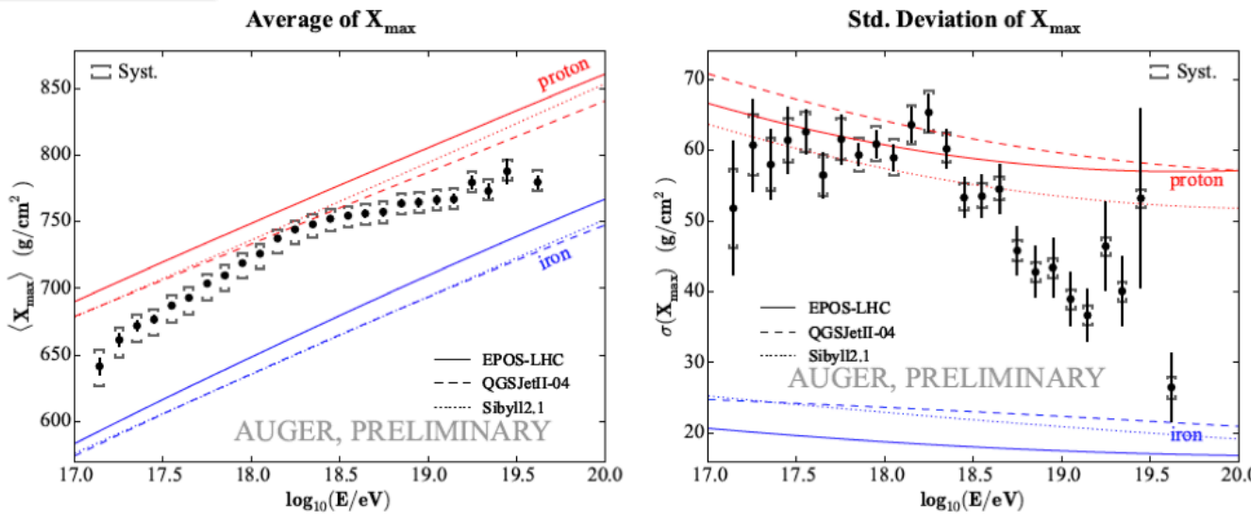
Auger the largest cosmic-ray observatory in the world

The Pierre Auger observatory has been measuring the cosmic-ray spectrum, composition and arrival directions for more than 10 years.

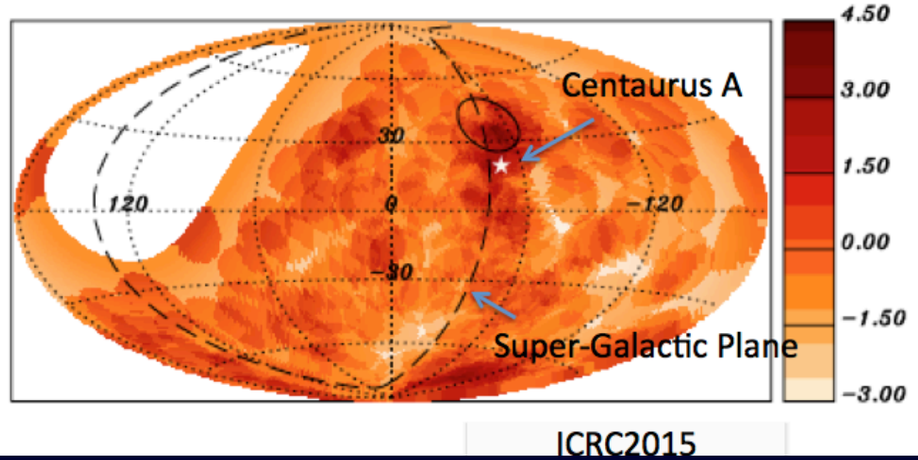
Very strong involvement of the French community (on all the aspects of the experiment), more than 30 French collaborators signing the publications at the peak of the involvement



Spectrum measured on three orders of magnitude in energy
(thanks to the recent low energy upgrade)
--> ankle and high energy suppression



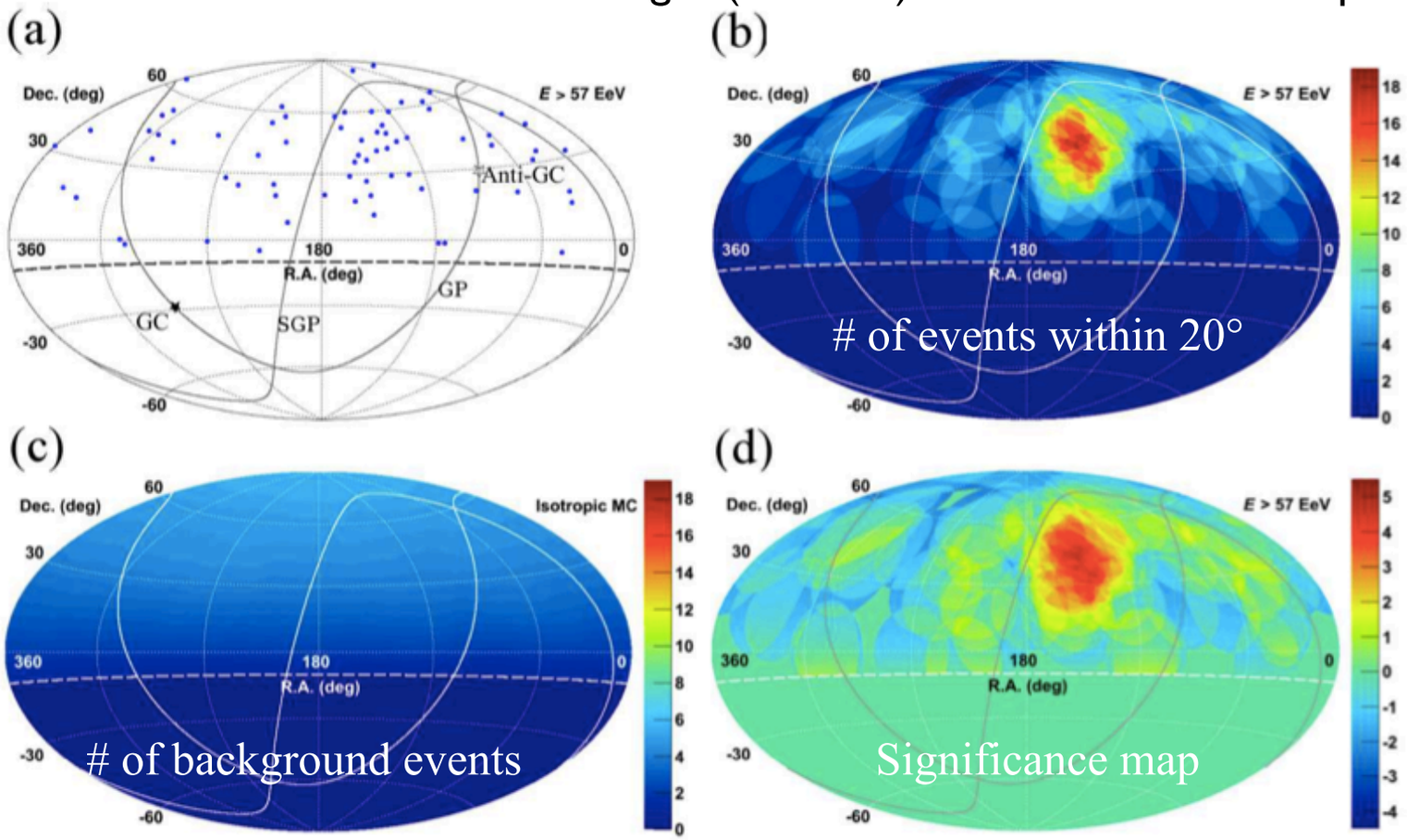
Composition estimated by measuring the maximum of air shower development and its spread
--> significant lightening below the ankle
--> significant increase of the cosmic-ray mass above the ankle
--> most likely explanation : the cosmic accelerators cannot accelerate protons to the highest energies, heavier nuclei can make it due to their higher charge



Small scale anisotropies at high energy :
No strong deviation to isotropy at best a warm spot (<3 sigmas) in the Centaurus region on an angular scale of the order of 15-20 degrees

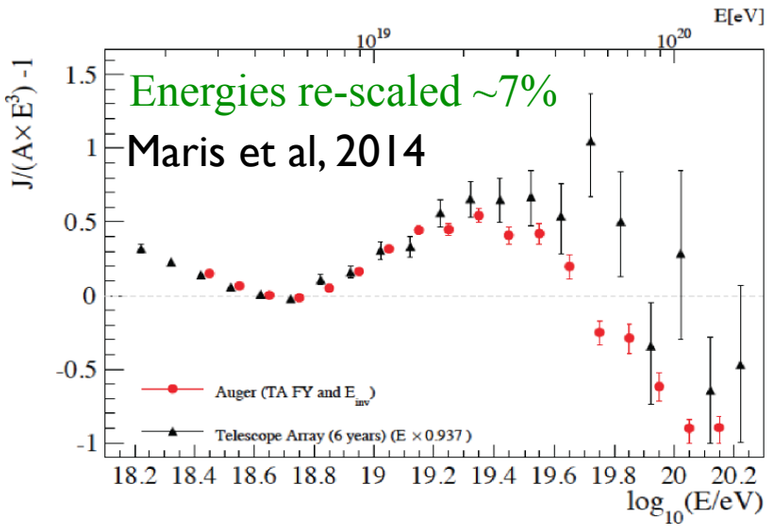
Anisotropies : a hope from the North

TA a smaller version of Auger (700 km^2) in the northern hemisphere claims a significant anisotropy signal



Abbasi et al., ApJ Letters, 2014

Cluster of events, angular scale ~ 20 deg
3.4 sigmas (once penalized)
surprising at first sight :
TA is smaller than Auger and started its operations later (~66000 km^2.sr.yr vs 7250) !
First real source(s) or instrumental effect?
Not located in a portion of the sky Auger can observe



Also some differences in the spectrum at the highest energies (even after rescaling to a common normalization at the ankle) not quantified and not explained yet !
Joint analyses between Auger and TA very useful to understand difference between the two experiments
TA to be extended to the size of Auger in the next few years

Short term future of Auger : “Auger prime”

The Auger collaboration proposes a significant upgrade of their detectors for the period 2018-2024 of data taking :

- improved electronics for the surface detector faster ADCs
- larger dynamic-range PMTs (useful to avoid detector saturation)
- scintillator detectors on top of the water tanks

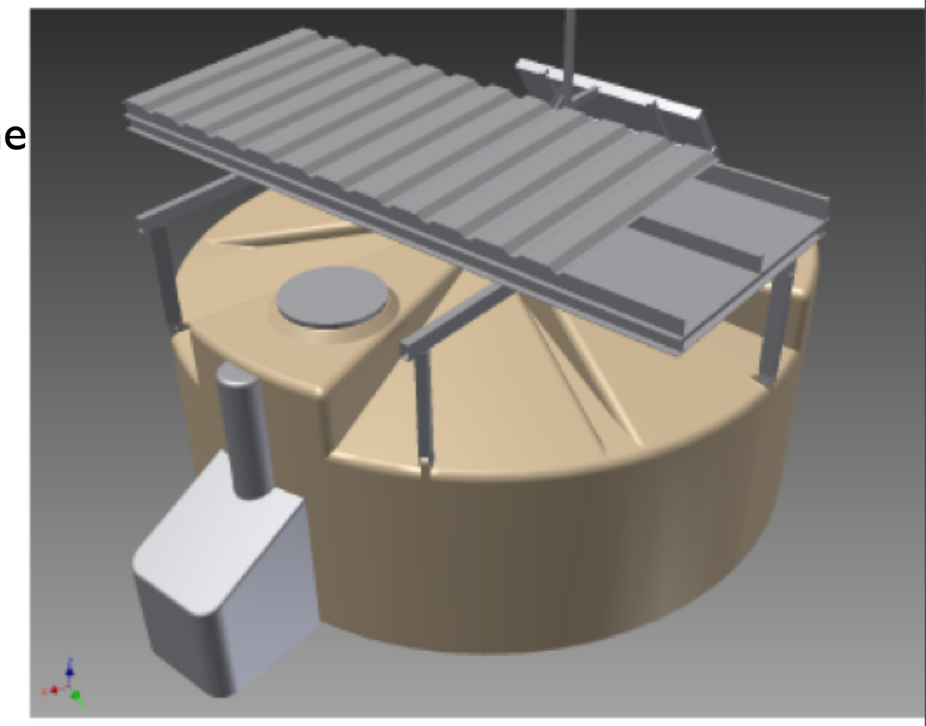
---> better separation of the muonic and electromagnetic components for the surface detector

---> better constrain of the muon content of air showers

---> better constrains on the composition for the surface detector

---> hope to better constrain/isolate the light component of UHECRs

---> improved sensitivity to photons and neutrinos

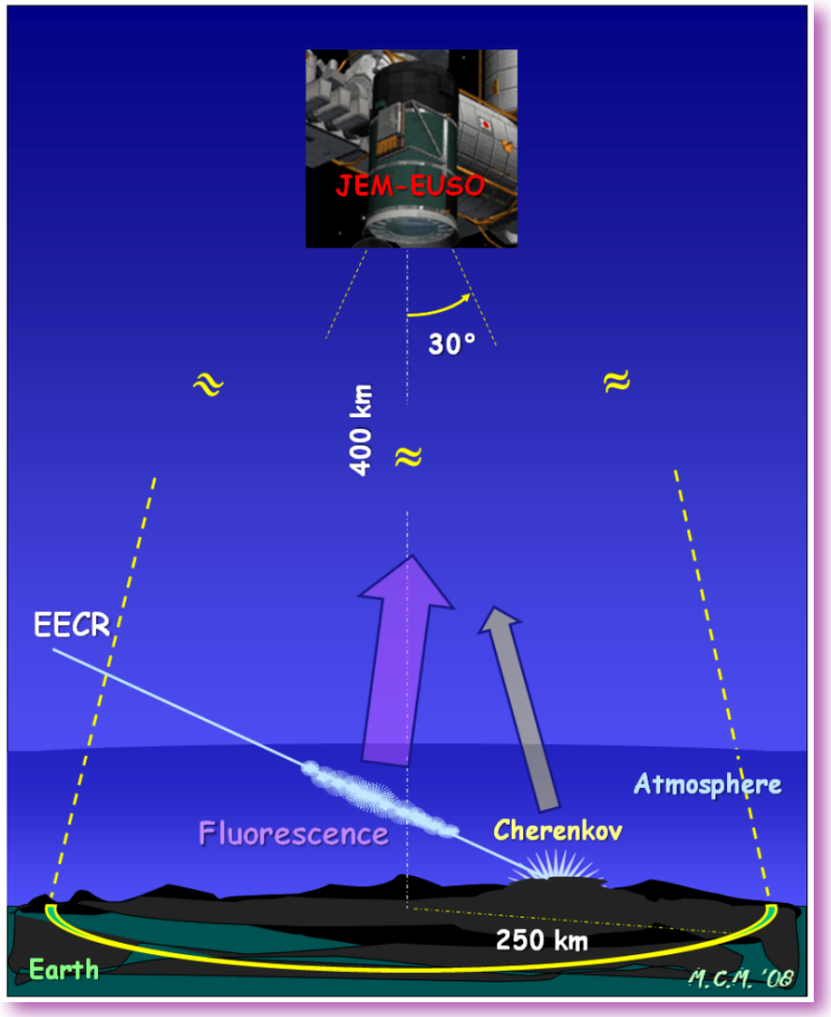


- increase of the FD duty cycle by 50% (by operating in brighter background sky conditions, switch the photodetectors to lower gains)

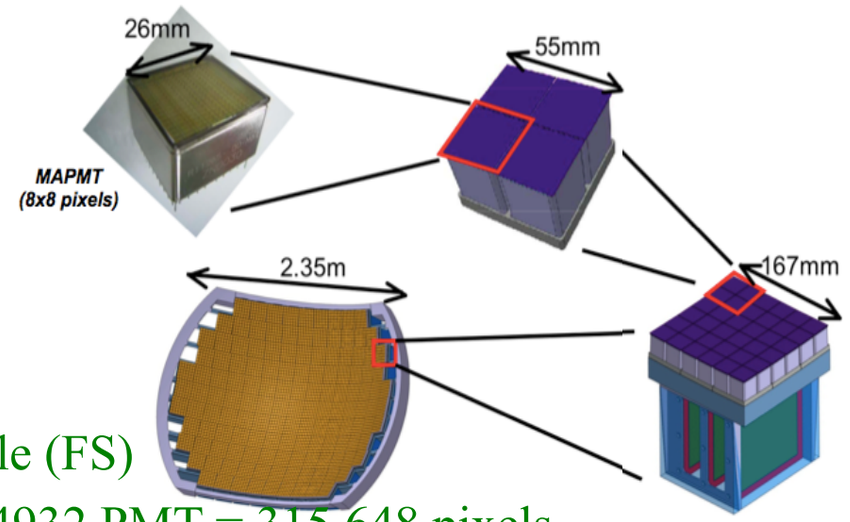
---> increase of the hybrid events statistics

Longer term future of UHECR observations : JEM-EUSO

Current statistics at UHE only give hints for the presence of anisotropies
--> these anisotropies are crucial to better constrain UHE origin, a significant increase of the statistics will be needed.
A milestone would be to approach exposures of the order of 10^6 km^2.sr.yr
If TA hotspot is real, one of the lessons is that full sky coverage is crucial
Detection from space is currently the only credible possibility to obtain both a significant increase of statistics and full sky coverage



The idea is to observe air showers from space :
- Telescope with 30 deg opening angle observing the earth from the ISS (400 km altitude)
---> huge area covered on the ground
---> drawback of the fluorescence technique ~19% duty cycle
---> still annual exposure ~10 times that of Auger above ~5.10^{19} eV in nadir mode
- need for a large Fresnel lens (2.5 m) to focus the faint shower fluorescence light on finely pixelized



Surface focale (FS)
137 PDM = 4932 PMT = 315 648 pixels

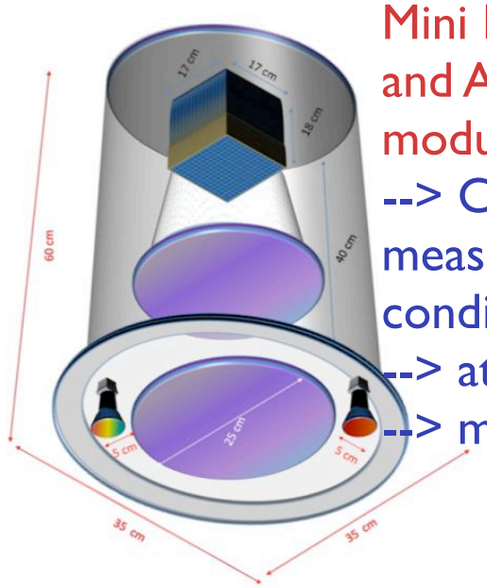
JEM-EUSO pathfinders

Several prototypes have been built or are planed to serve as proof of concept and prototypes for JEM-EUSO :

EUSO balloon (CNES) :
a one night flight in northern Canada in August 2014
--> small lens (1 m^2) and a single PDM in the focal plane
--> sky background measurements and successful measurement and reconstruction of laser shots but no autonomous trigger

EUSO Super Pressure Balloon:
Improved version of EUSO-balloon with an autonomous trigger
-->~ one month long flight expected
--> to be launched in March 2017 from New Zeland
--> the main goal is to detect for the first time UHECR showers from near space altitudes
--> atmospheric phenomena
--> UV background above the ocean

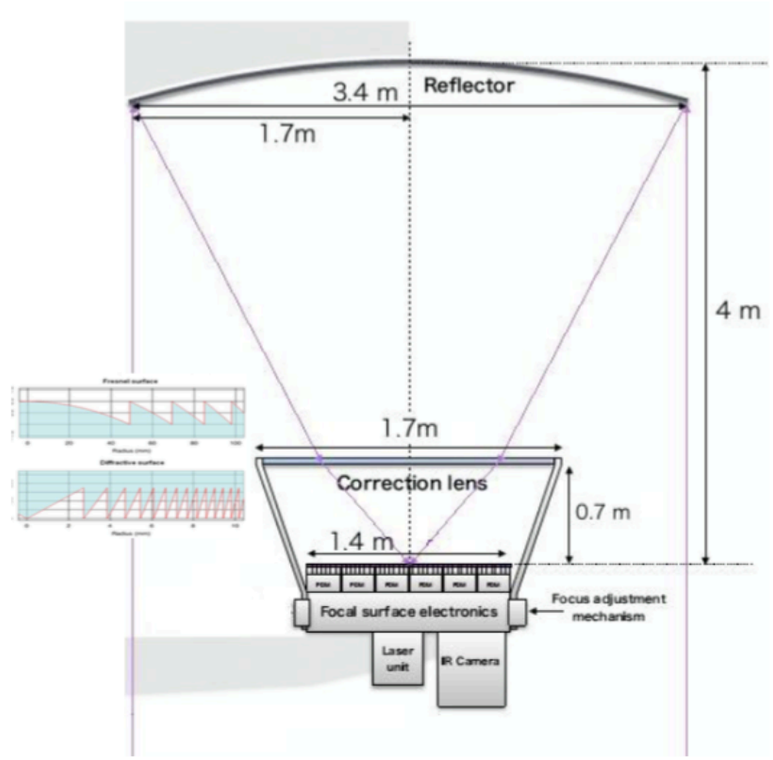
TA-EUSO :
~Same optics as EUSO-ballon installed and operating on the TA site
--> detection of real air showers with an autonomous trigger
--> validation of the JEM-EUSO trigger strategy



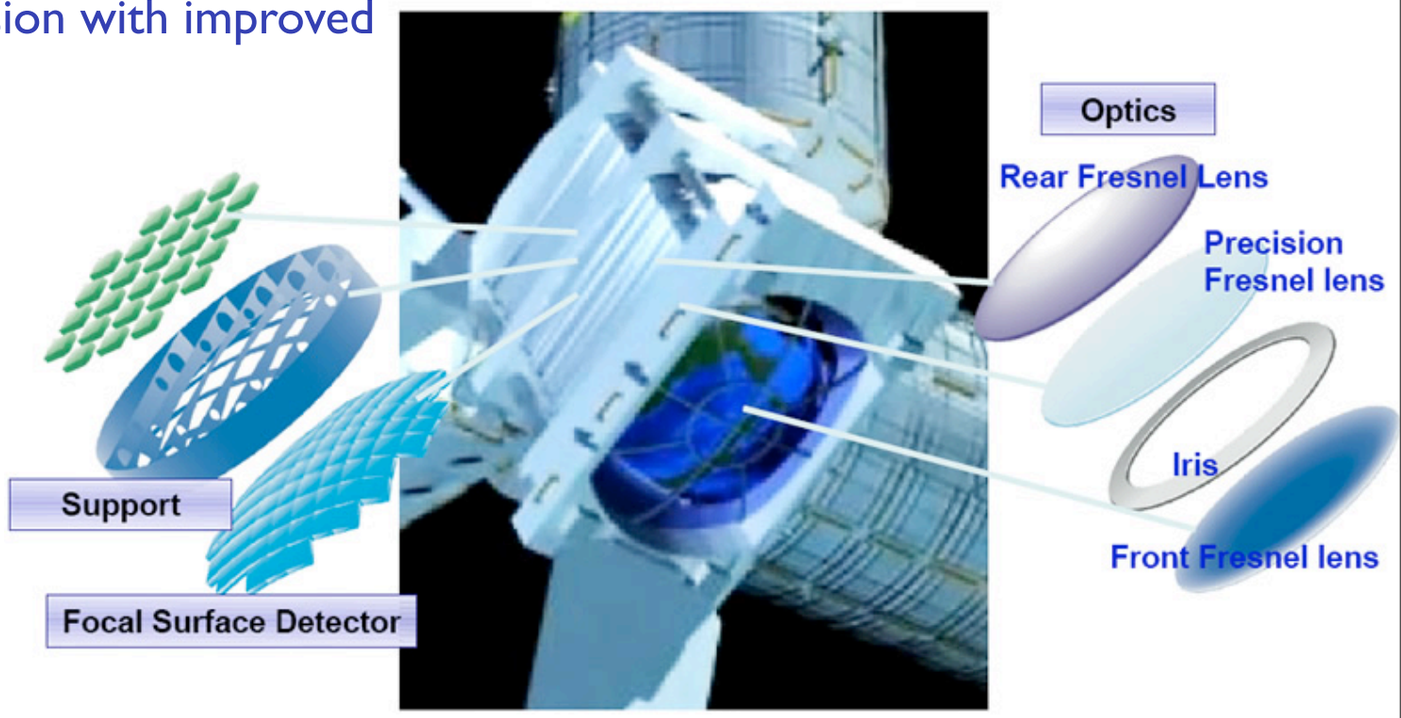
Mini EUSO : accepted by ROSCOSMOS and ASI to be installed on the Russian module of the ISS in 2017:
--> Complete background measurements from space in the same conditions as the full mission
--> atmospheric phenomena
--> meteorites

The future of JEM-EUSO

Klypve-EUSO (AKA K-EUSO) concrete effort toward a full JEM-EUSO mission :
--> accepted by ROSCOMOS
--> to be installed on the ISS (2019)
--> annual exposure expected to be similar to that of Auger
--> first UHECR large exposure full sky coverage experiment



Full JEM-EUSO mission :
- Launch expected > 2020
- relevance depends on the extension of the ISS program
- the alternative solution is to propose a free flyer mission with improved performances
---> Proposal ESA M5
---> Proposal NASA MidEx



French contribution

To JEM-EUSO : major actor of the international collaboration
--> PI and project manager of EUSO-balloon (CNES)
--> Calibration and integration of the photodetection modules
--> Front-end electronics : ASICs
--> Science case

UHECR phenomenology/theory
--> Strong involvement of the French community
--> Propagation
--> Multimessenger studies
--> Acceleration
--> Source models
--> Anisotropy modeling
--> part of this community is close or even part of ongoing and planed experiments

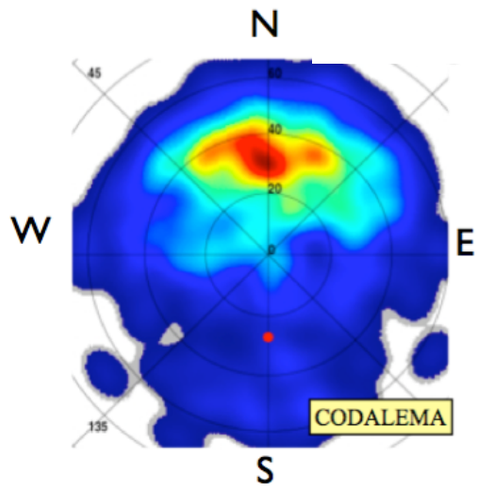
Radio detection of VHE and UHE cosmic-rays

For ~ a decade a lot of experimental efforts have been dedicated to the radio detection of VHE and UHE air showers :
CODALEMA (I, II, III), LOPES, RAuger (1, 2), AERA, TREND, EASIER, LOFAR, TUNKA-REX (complete review by Tim Huege, 2016)

Many important progresses have been made regarding the radio signal (20-200 MHz) produced during the development of air shower and its relation to the primary cosmic-ray characteristics :

✦ The radio signal is mainly due to the geomagnetic effect (CODALEMA, hints from Haverah Park in the 70s)

✦ Subdominant but measurable effect of the charge excess (CODALEMA)



✦ Correlation between the energy radiated in radio and the primary energy (AERA)
--> perspective of a calorimetric measurement of the energy

✦ Relation between the lateral distribution of the radio signal and X_{max} (LOPES, LOFAR) so far based on simulations but can be probed experimentally by AERA (ongoing)
--> 100% duty cycle X_{max} measurements

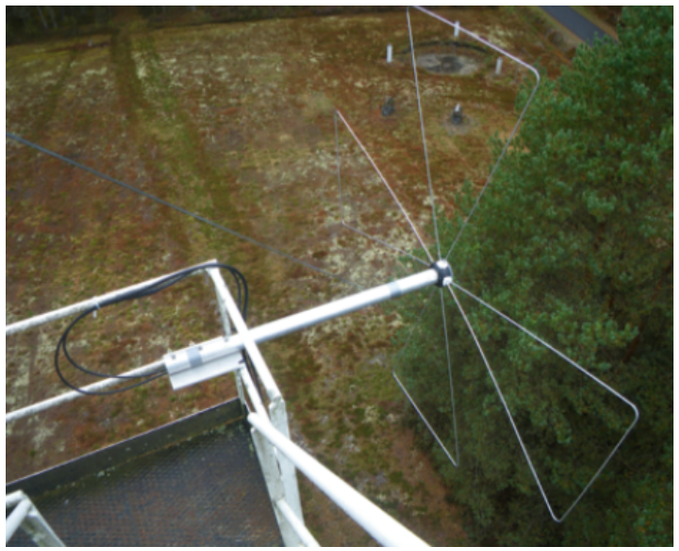
✦ Main drawback : vertical/low inclination radio showers have very steep lateral profile
--> not very promising for a cosmic-ray observatory fully based on radio (see Huege, 2016)

✦ New promising direction : use a lower frequency radio signal of different origin, "the sudden death radio pulse"
--> the electric field originates from the absorption of the charge excess as the shower core hits the ground
--> it can be shown that the electric field decreased as 1/d rather than exponentially for the geomagnetic signal
--> coherent between ~100 kHz to a few MHz (typical size of the emission region : lateral extension of the shower core at ground
--> signal clearly expected from simulation

Radio detection of VHE and UHE cosmic-rays

✦ New promising direction : use a lower frequency radio signal of different origin, "the sudden death radio pulse"
--> the electric field originates from the absorption of the charge excess as the shower core hits the ground
--> it can be shown that the electric field decreased as 1/d rather than exponentially for the geomagnetic signal
--> coherent between ~100 kHz to a few MHz (typical size of the emission region : lateral extension of the shower core at ground
--> signal clearly expected from simulation

✦ The Subatech have built the EXTASIS experiment (low frequency antennas)
--> Project currently in the R&D phase
--> Will work in parallel with CODALEMA III
--> A milestone already reached with the realization of low noise amplifier which reduced drastically the ambient background
--> measurements will take place until 2019 (funded by region Pays de Loire with a small contribution of IN2P3)



The multimessenger nature of cosmic-ray physics

- Accurate measurements of the cosmic-ray spectrum, composition, anisotropies are key to solve the puzzle
- A complete understanding however requires a multimessenger approach

CARPEAUX Jean-Baptiste (1827-1875) :
« Les Quatre parties du monde soutenant la sphère céleste »

- Cosmic-rays
- Photons
- Neutrinos
- Gravitational waves

- Photons :
  - ✦ constrains on the possible SNR/cosmic-ray connexion (CTA)
  - ✦ searches for (multi-)Pevatrons (CTA, LHAASO)

- Neutrinos :
  - ✦ what is IceCube flux telling about Galactic cosmic-ray, about extragalactic cosmic-rays?
  - ✦ first point sources highly expected and so is KM3Net !
  - ✦ best way to reveal powerful protons accelerators ($E>10^{20}$ eV) beyond the GZK horizon !

- Gravitational waves
  - ✦ the first observation already revealed something fantastic and unexpected
  - ✦ what will come next? What is it going to tell us about high-energy astrophysics?

PNHE : connecting people

The PNHE (formerly GDR PCHE) significantly contributed to initiate synergies and create strong bounds among the French high-energy astrophysics community

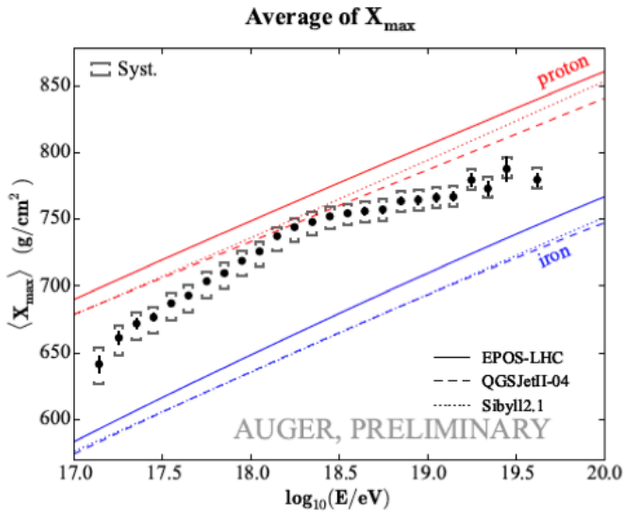
--> contribution to the organization and funding of workshop, schools and conferences

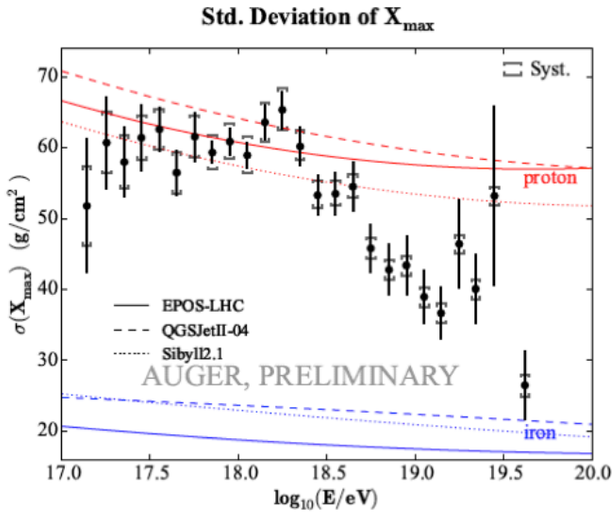
--> catalyzer for collaboration between different communities

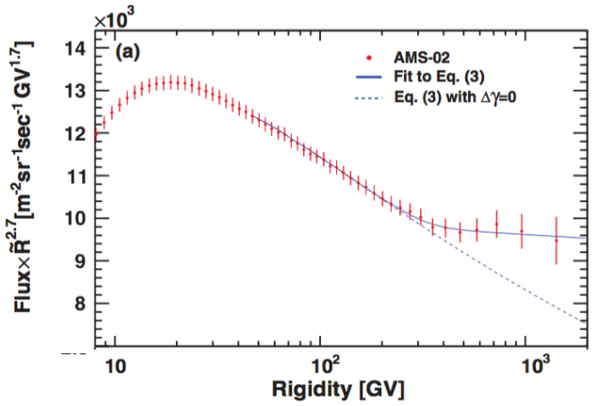
--> catalyzer for the multi-messenger high-energy astrophysics

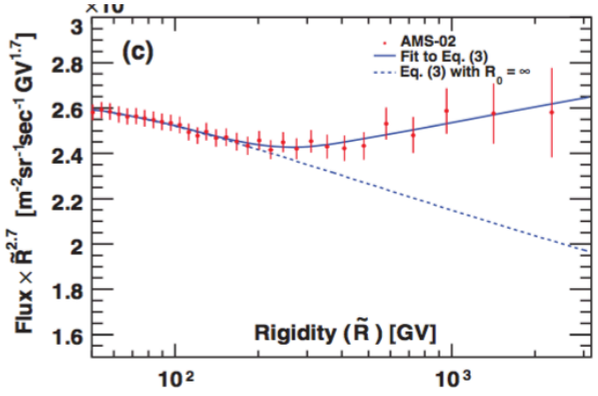
école de Goutelas (2003)
"rayons cosmiques"

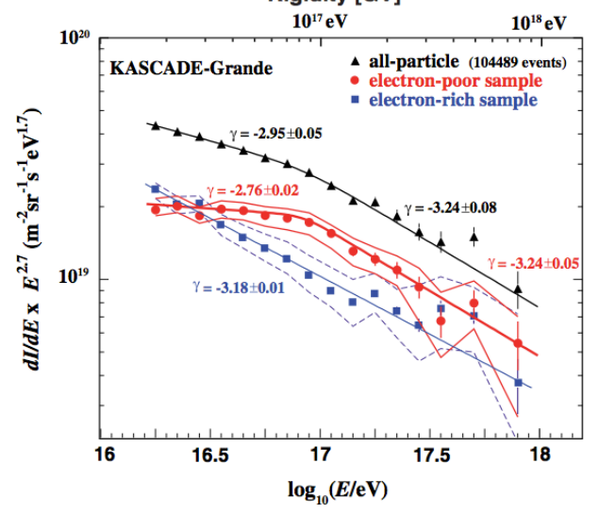
Take home message

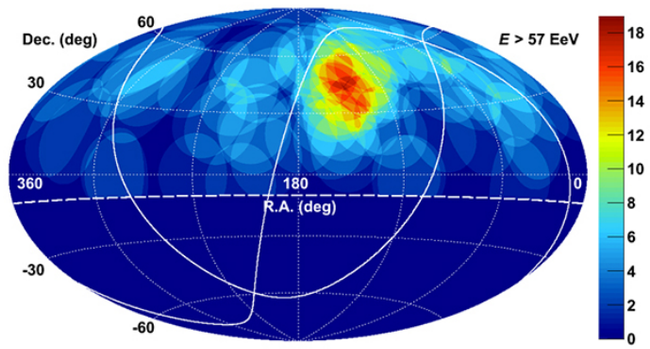












- Many new high quality observations constraining for cosmic-ray origin in the last few years
- The French community played a significant role in this process
- Strong cosmic-ray community in France, with a coherent implication in the different experiments and thematics

The origin of cosmic-rays is still a complicated (fascinating) puzzle but we are slowly improving at assembling the pieces