Experimental Astroparticle 2

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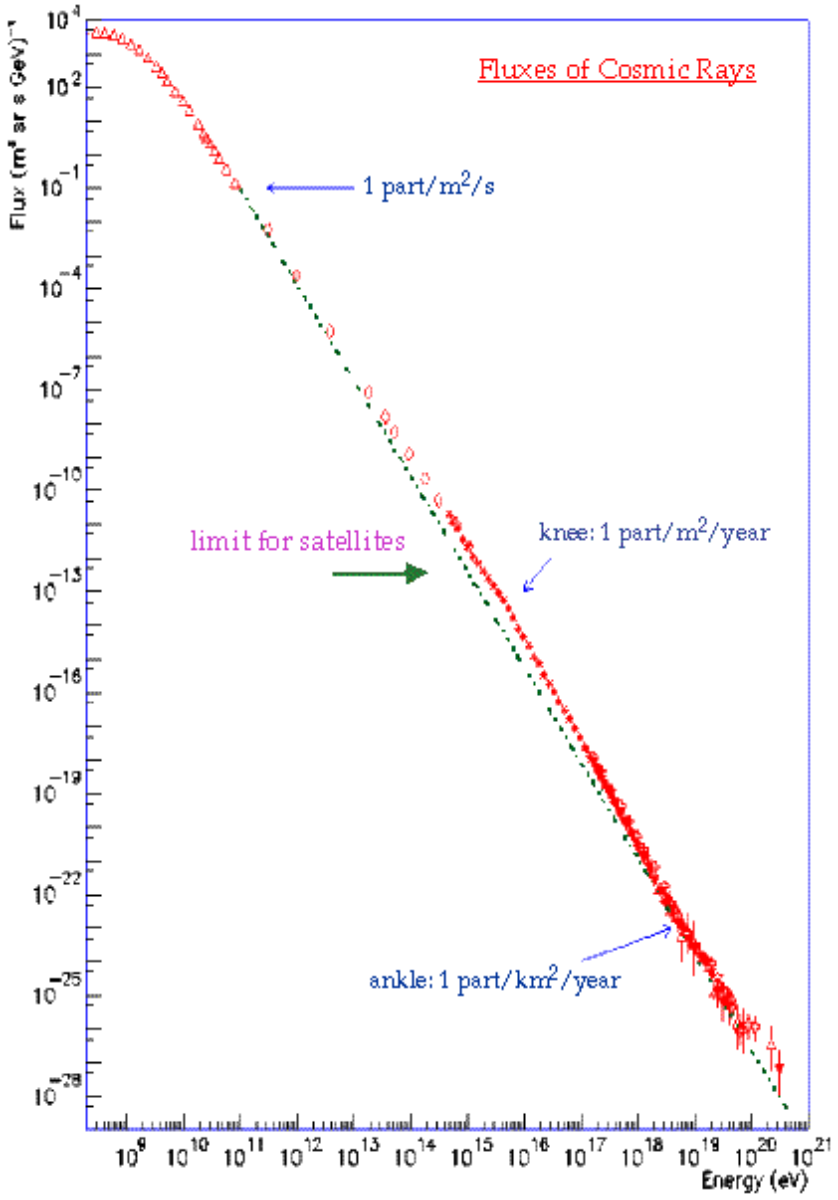
Subatech

Xe

XENON

Dark Matter Project

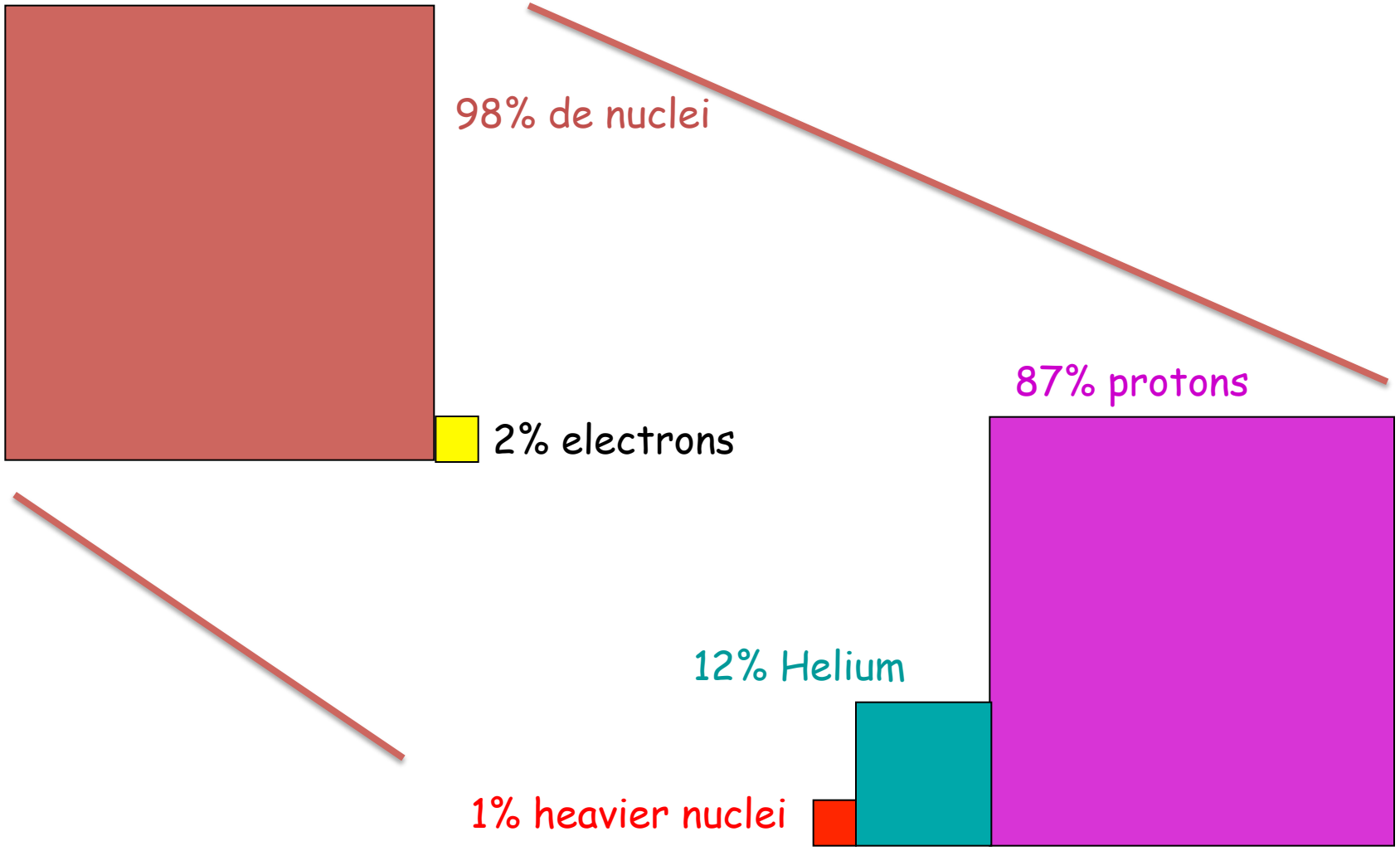
The "all" paticle sectrum



$$\frac{dI}{dE} \propto E^{-\gamma} \quad ou \quad I(>E) \propto E^{-(\gamma-1)}$$

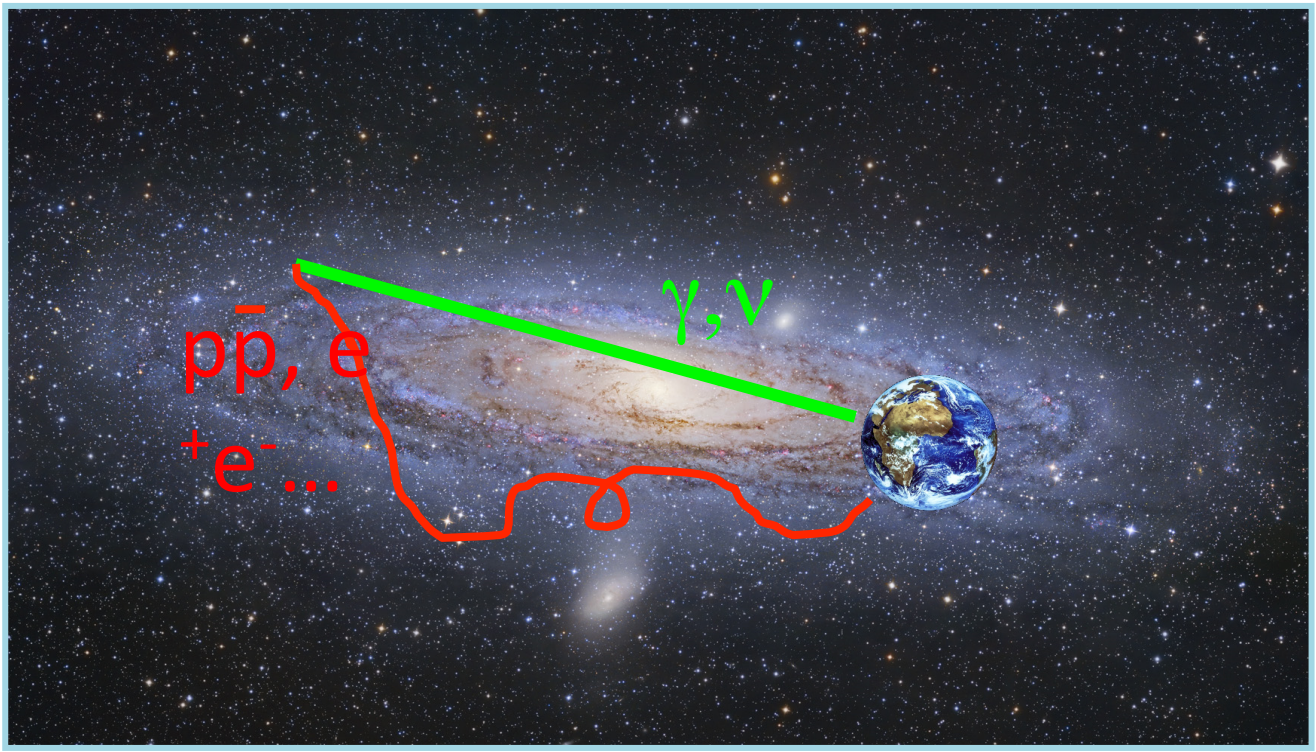
- Regular spectrum over 12 decades in energy, and 32 decades in flux !!!
- Small break near 3×10^{15}eV : the "knee"
- An other one near 10^{18}eV : the "ankle"
- Spectrum badly known at the two extremities
  - Geomagnetic "shield" + Solar modulation
  - Extreme rareness…

Composition

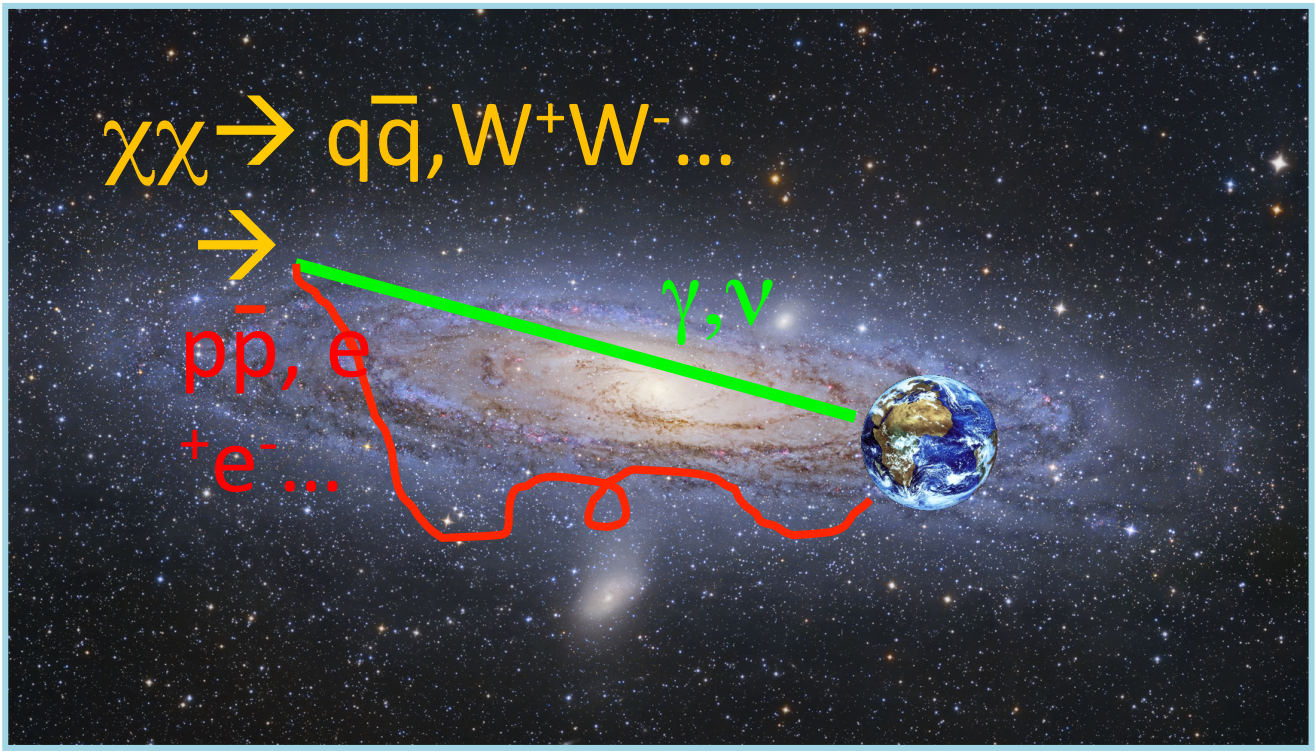


Flux : 4 RC/cm^2/s $\Rightarrow$ 1 kg/year << 40 000 ton/year (meteorites)

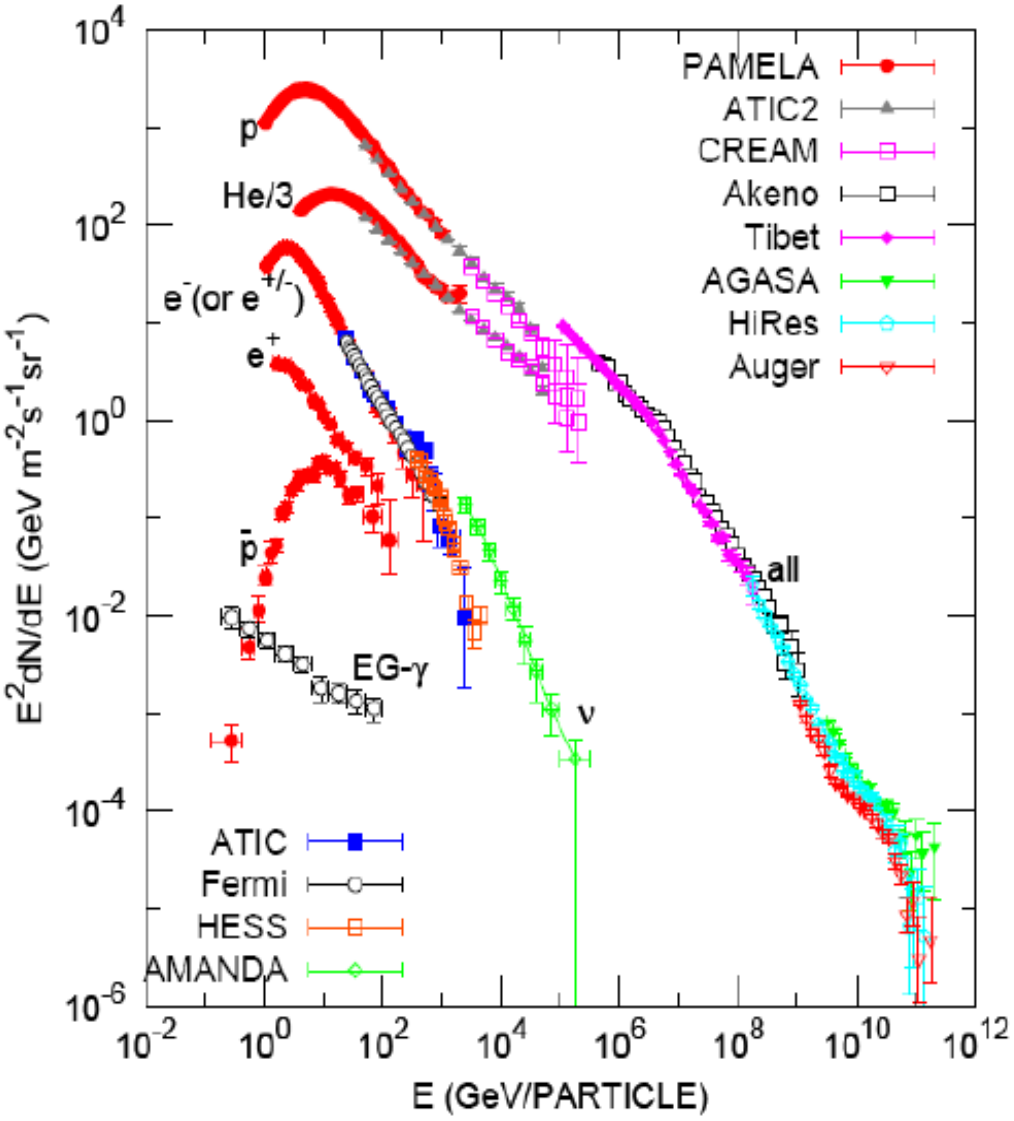
Propagation



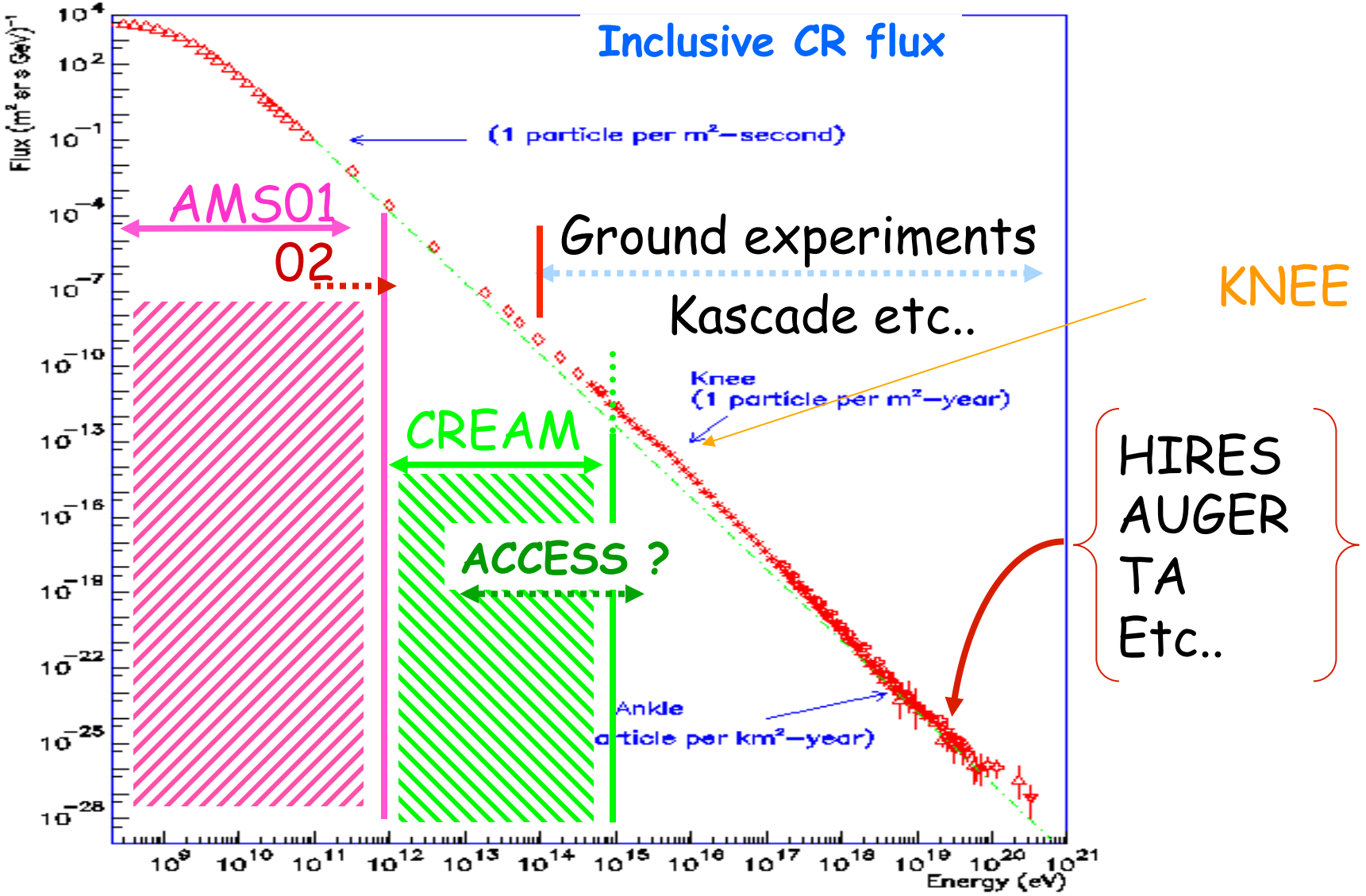
Propagation



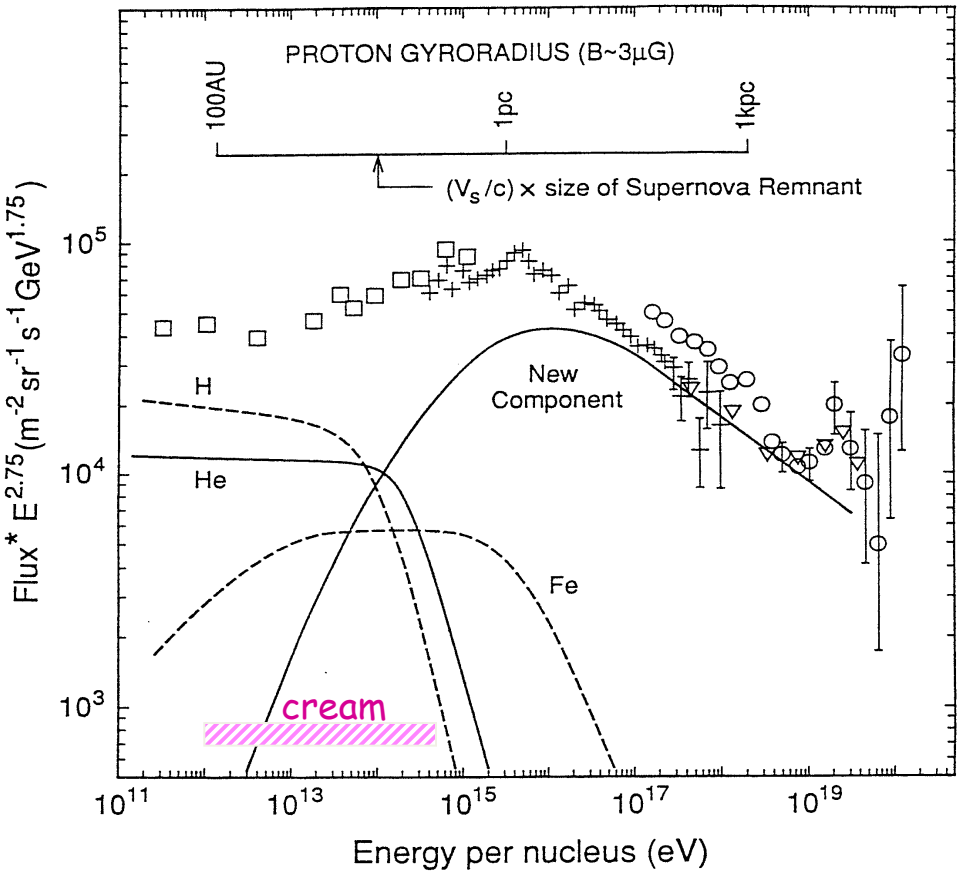
Composition



Experimental context



The knee

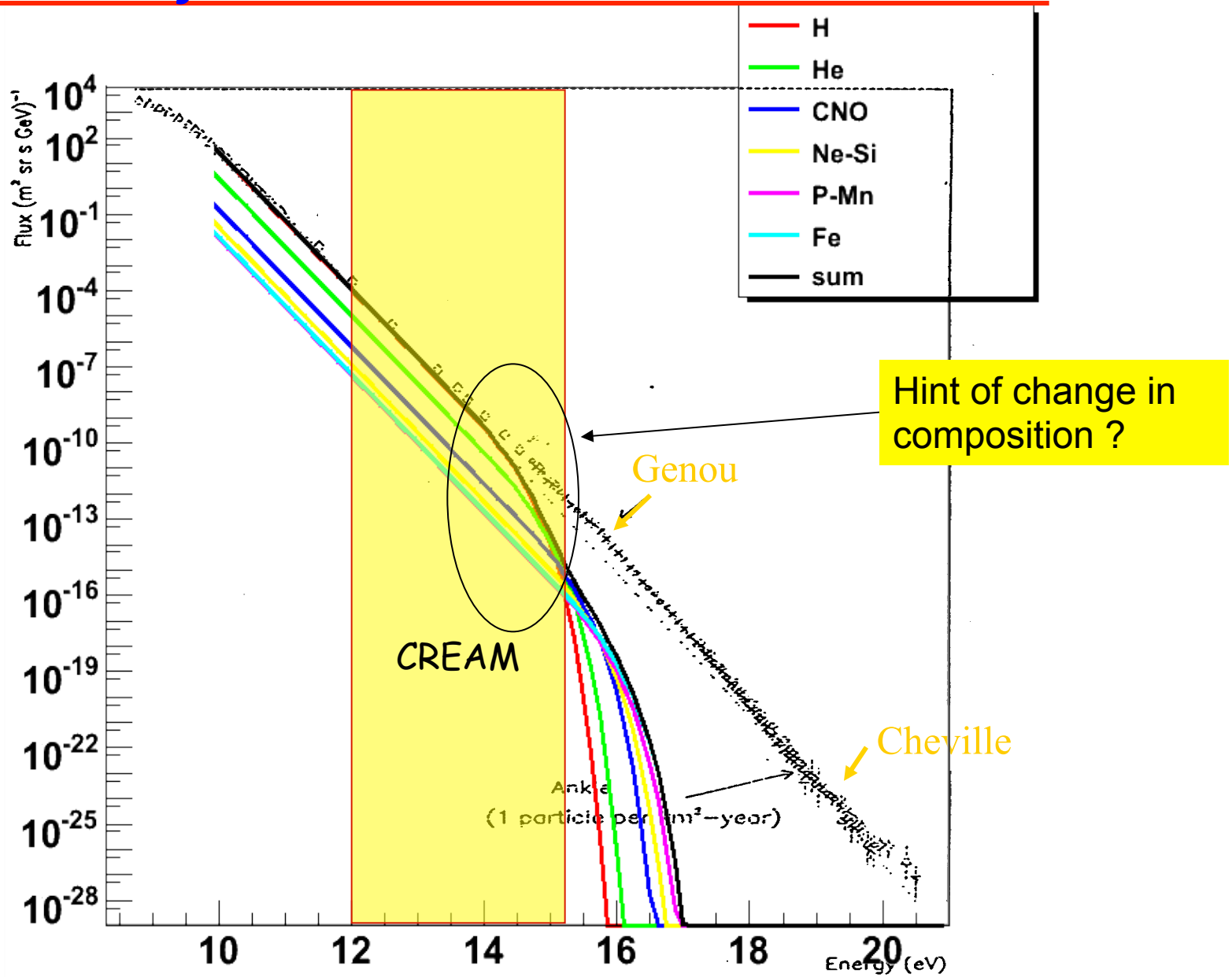


- Is the knee due to:
  - Acceleration mechanisms or to changes :
  - in propagation?
  - in CR sources?
  - in interaction properties (threshold) ?

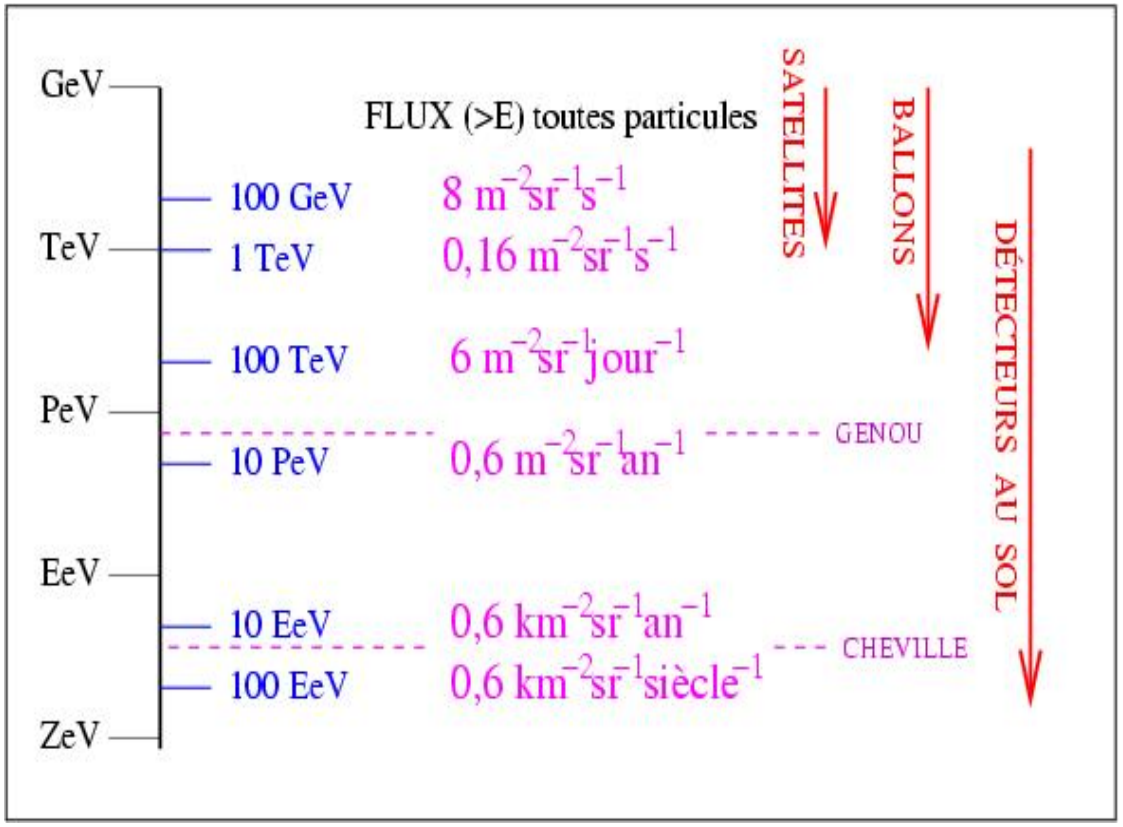
⇨ A diffuse SNR shock acceleration with E_{max} implies a change in composition around ~10^{14} eV.

SNR energy limit: $E_{max} \sim Z \cdot 10^{14}$ eV

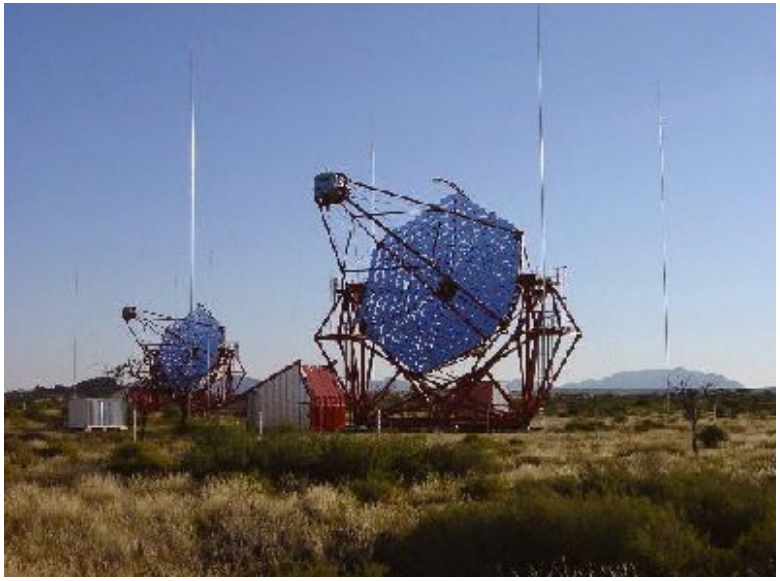
Composition of the knee



What type of detector ?



The atmosphere as a detector



H.E.S.S.

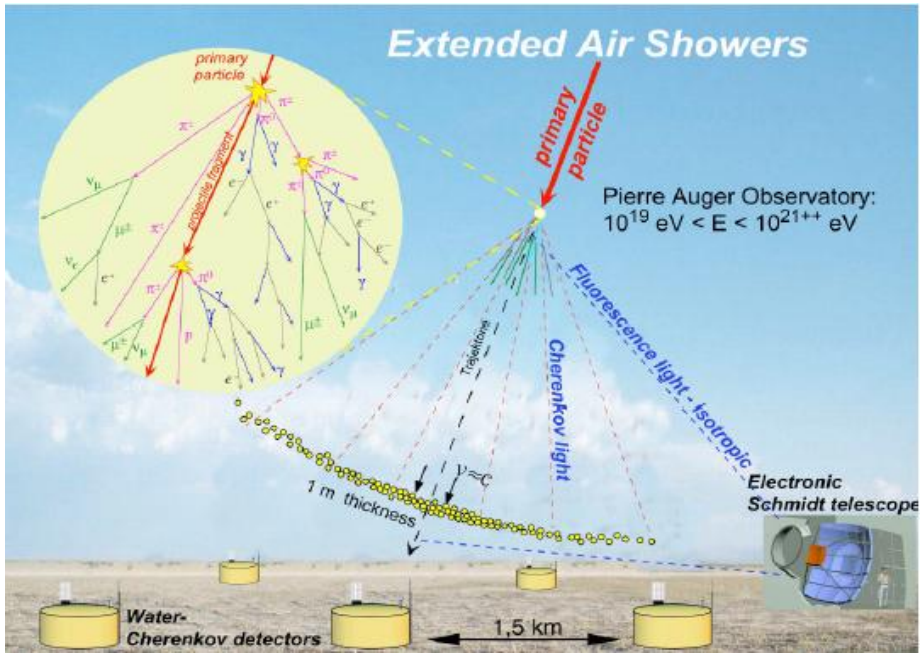
γ

Pierre Auger Observatory

proton

Temploral aspect

- During the shower development, a thin layer of charged particle move to the ground
- A bit “curved”
- ~10m thick



Observables from the ground

- Only secondary particles of the shower reaches the ground
- Depending on the energy and the altitude:
  - Few residuals hadrons, because hadronic components quickly absorbed
  - $e^{\pm}$: the most numerous at the maximun of the shower
  - $\mu^{\pm}$: reach (almost) always the grounds, very penetrating up to underground !
  - Secondary γ detected after $e^{+}e^{-}$ conversion (Chrenkov effect in water)

- Photons emitted along the development of the shower (Cherenkov or fluorescence)

  → 3D calorimetric information

- Radio emission from the particles

Electromagnetic / hadronic Showers

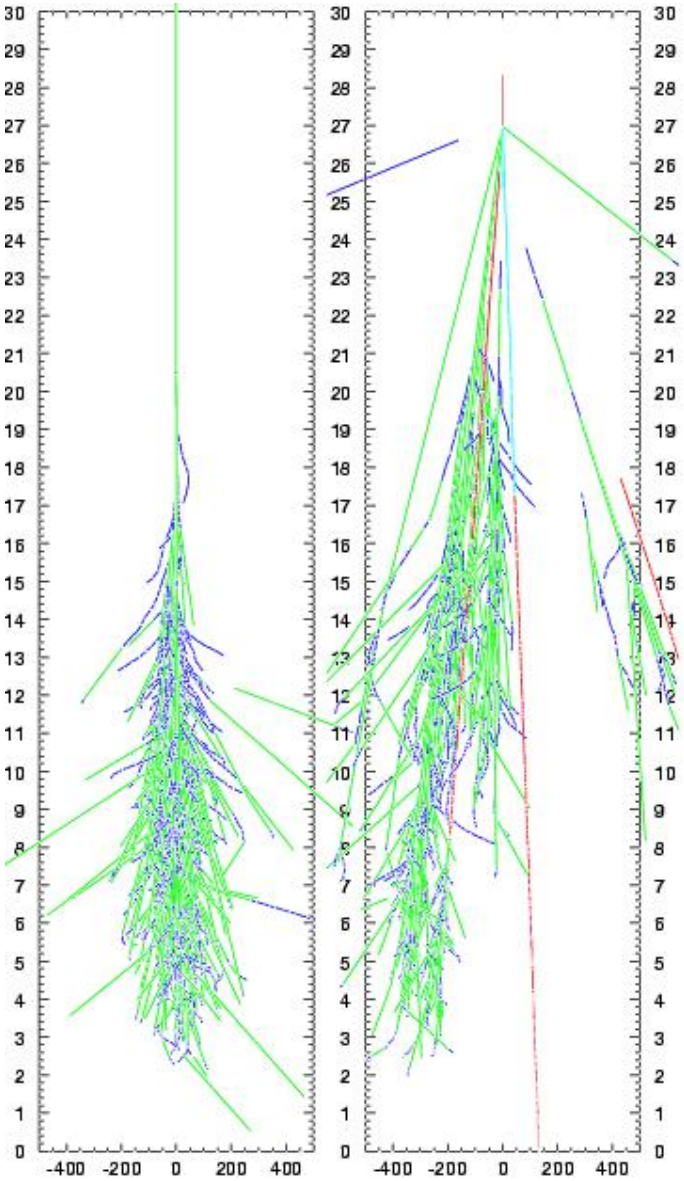
Shower from γ of 300 GeV

Symmetry of revolution

Small transverse momentum

Few muons

Mainly e^+e^- and γ



Shower from proton of 300 GeV

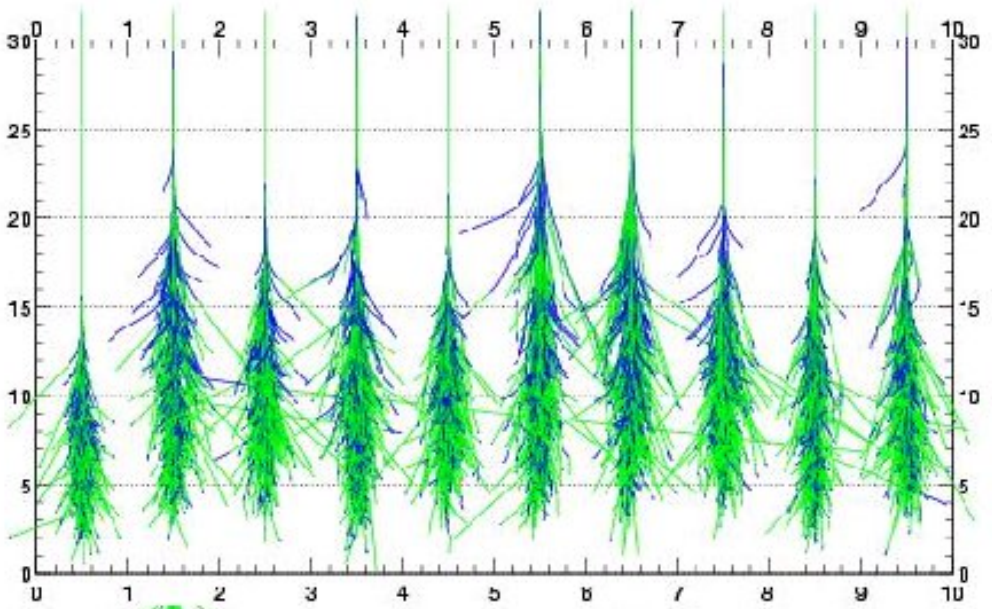
Big transverse momentum

Presence of muons

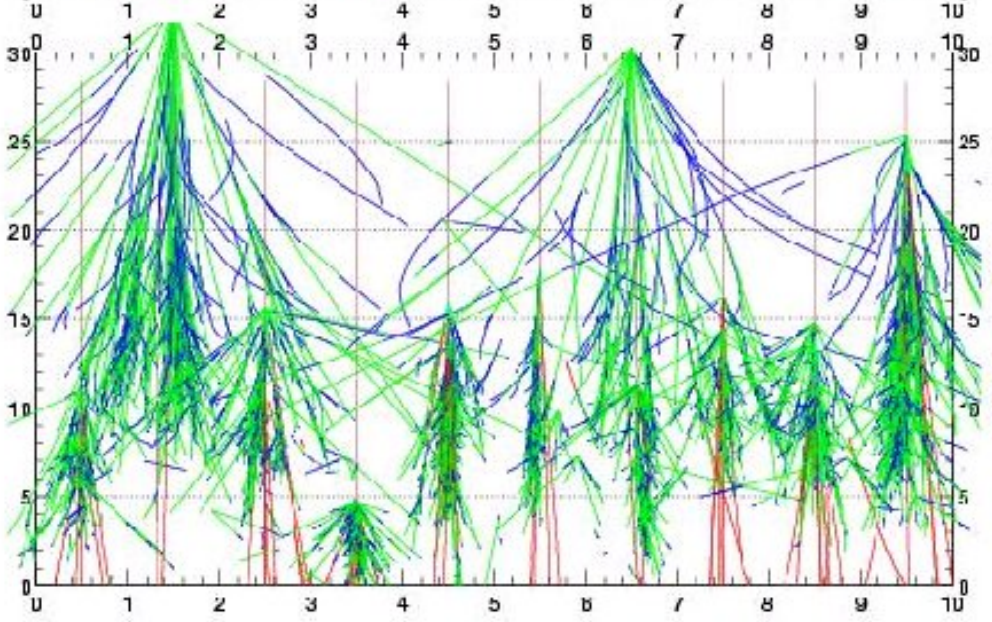
Possibility of sub-electromagnetic showers

Electromagnetic / hadronic Showers

10 γ of
300 GeV



10 protons
of
300 GeV



The atmosphere as a detector

- Gamma-ray astronomy > 100 GeV
  - Cherenkov experiments (HESS, MAGIC, CANGAROO, VERITAS)
  - Wide field of view experiments (MILAGRO, TIBET-ARGO)

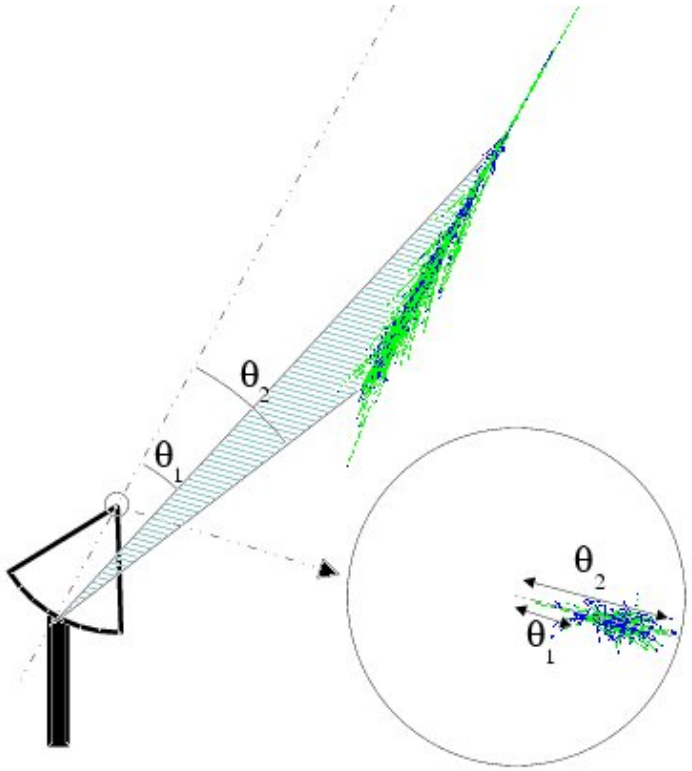
- Ultra High Energy Cosmic Ray Experiment
  - An hybride detector (Pierre Auger Observatory)

The atmosphere as a detector

- Atmospheric Cherenkov telescope
  - Limited field of view (5° for H.E.S.S.)
    - Follow the travel of the source in the sky
  - Can work only during night time, no moon and good weather
  - High discrimination power between gamma and hadron

- Surface detectors (secondary particles on the ground)
  - Large field of view (~ 1 sr)
  - High working time
  - Low discrimination

Atmospheric Cherenkov telescope



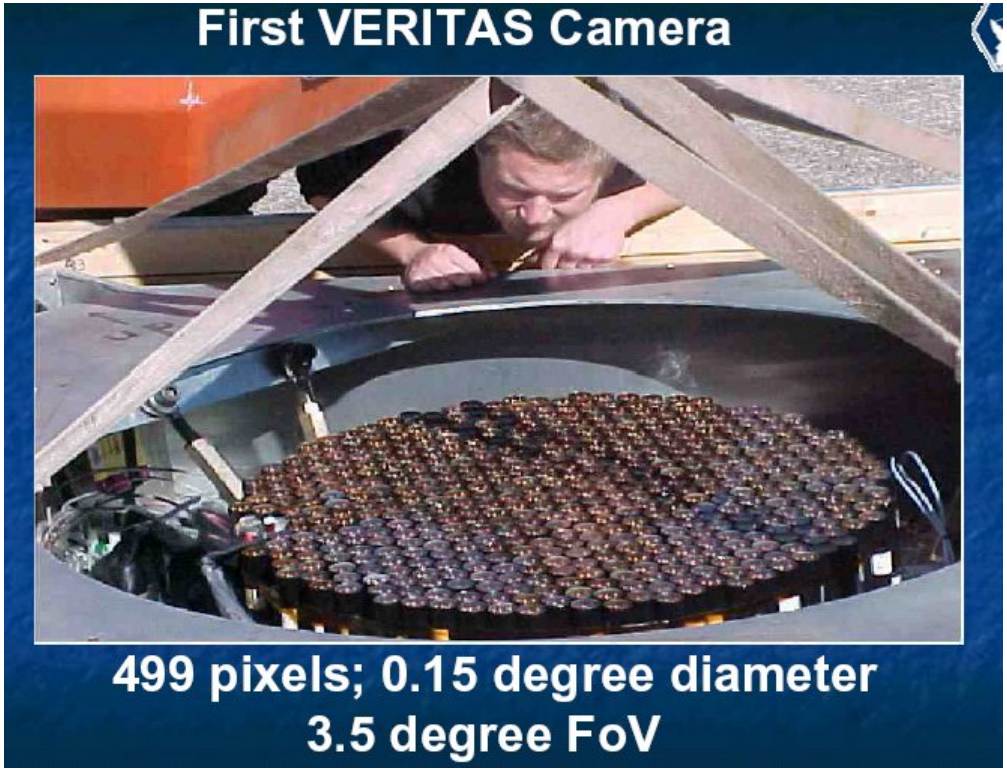
Cherenkov telescopes

MAGIC 2 :
2 telescopes
Ø 17m (3.5˚)
E > 60 GeV

Veritas :
4 telescopes
Ø 12m (3.5˚)
E > 85 GeV

H.E.S.S. 2 :
4 telescopes +1
Ø 13m (5˚) + Ø 28m
E > 20 GeV

Camera properties



VERITAS

MAGIC

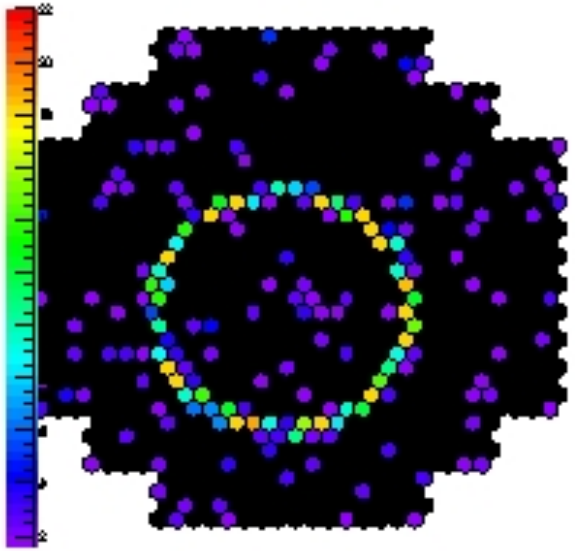
Muons for monitoring the detector

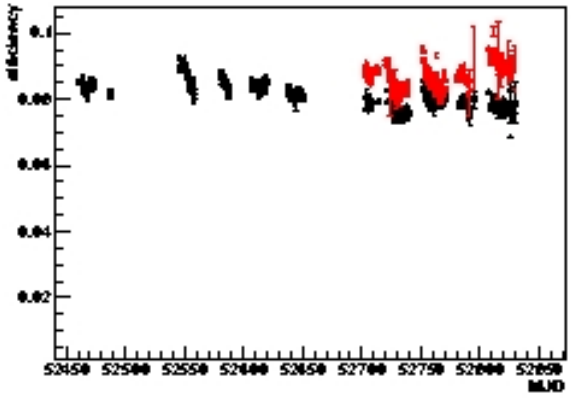
- Muons falling on the miroir of a telescope create an annulus, its equation is perfectly known

- Comparaison with real signal gives the global efficiency including :

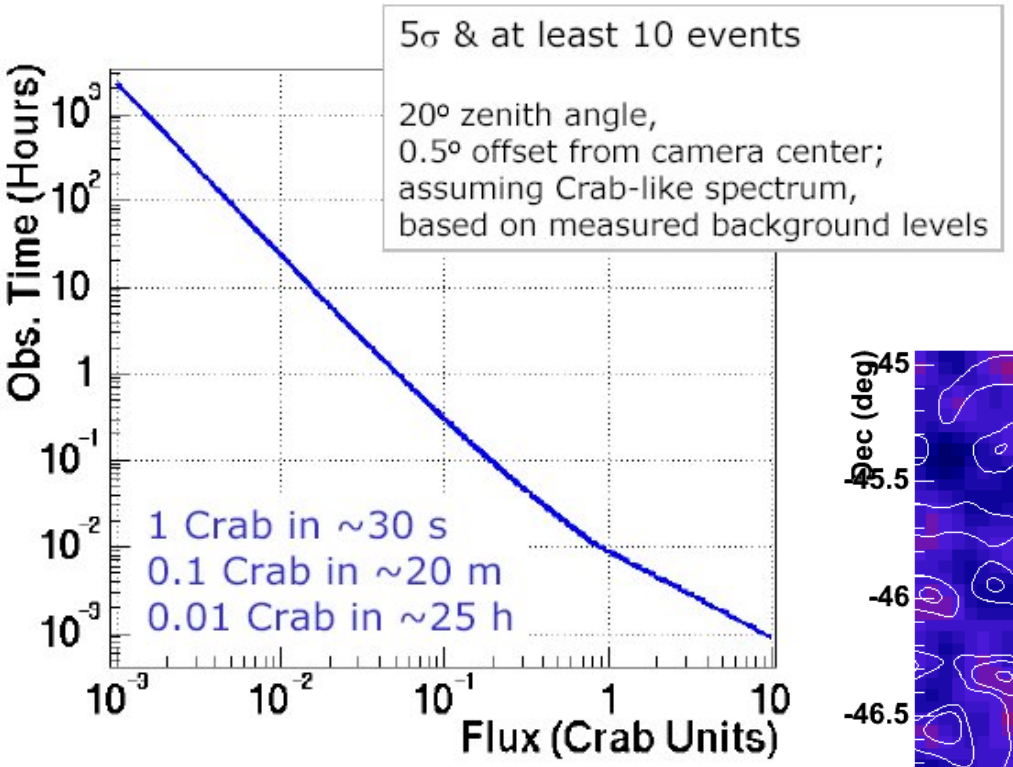
- absorption in the atmosphere
- Reflectivity of miroirs
- Quantum efficiencies of PMTs

- The evolution of the detector as function of the time is automatically taken into account in the analysis.

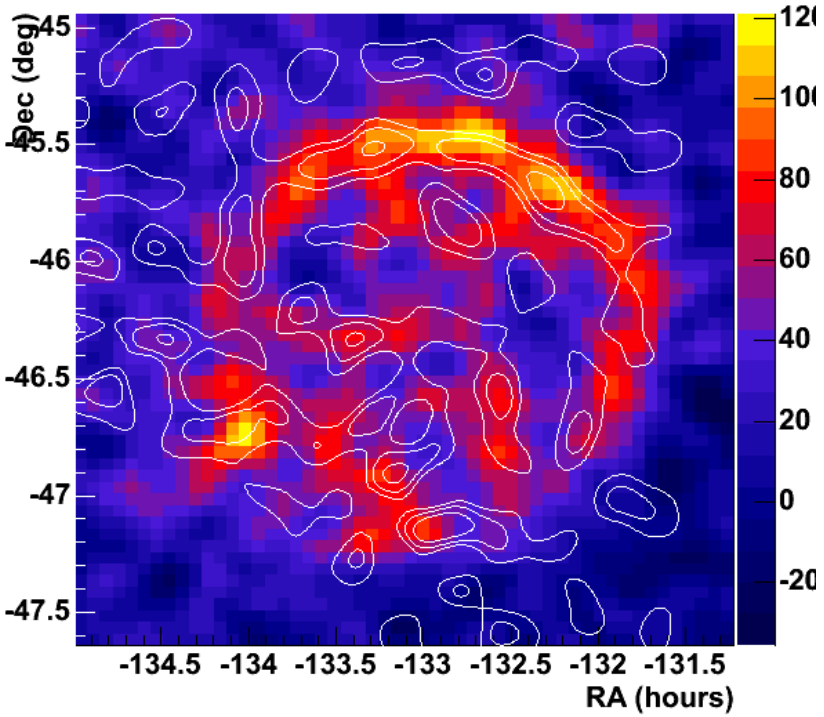




Sensitivity to gamma sources



Large sources:
Vela Junior
(diameter 2°)

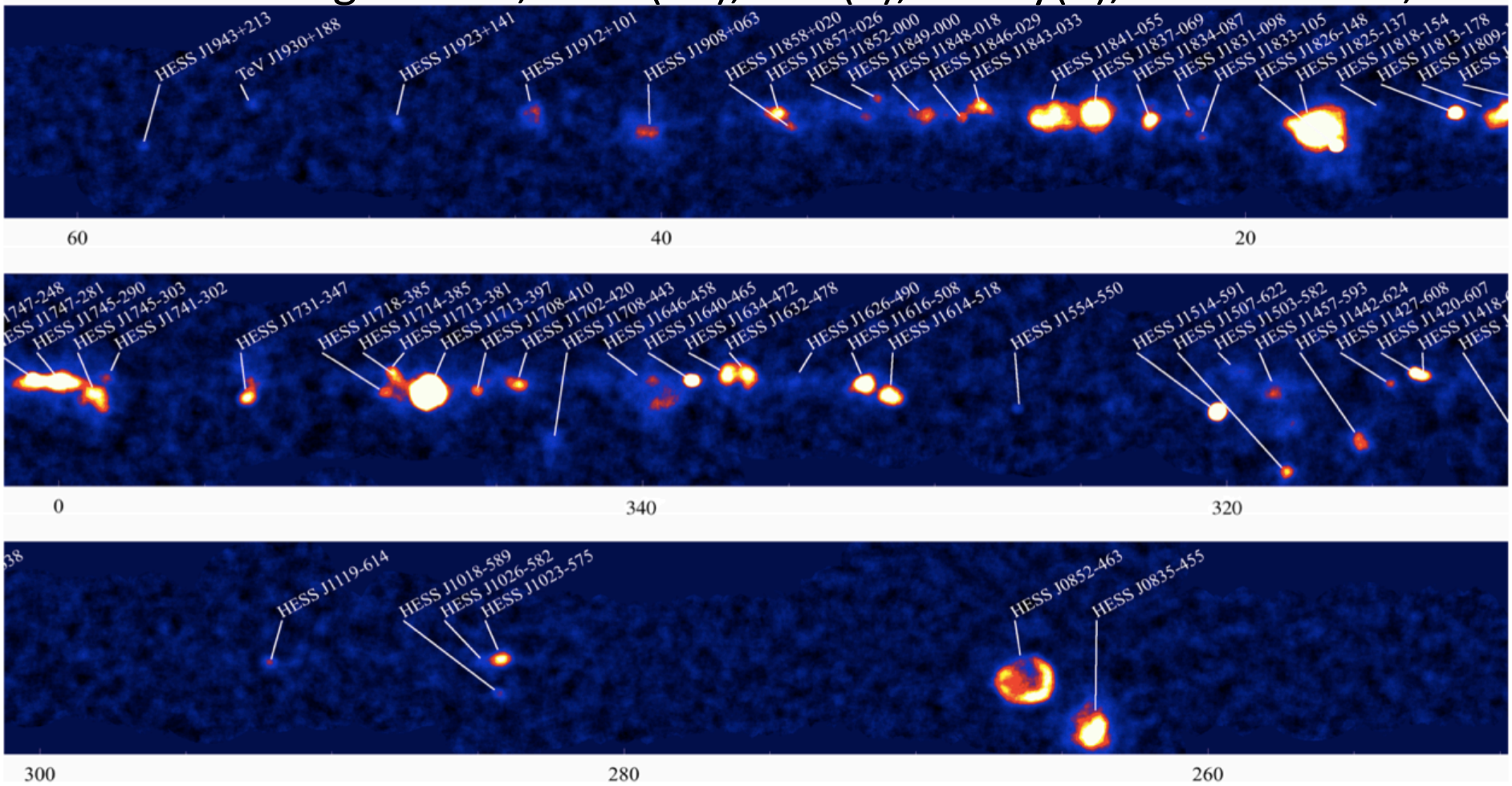


- > 100 sources in 2012
- 6 in 2006

H.E.S.S. Galactic Plan Survey

- Inner part of the Galaxy, 1400 h of data + dedicated pointing on 56 sources

→ Molecular gaz scale, PWN(29), SNR(9), binary(3), Dark sources,…



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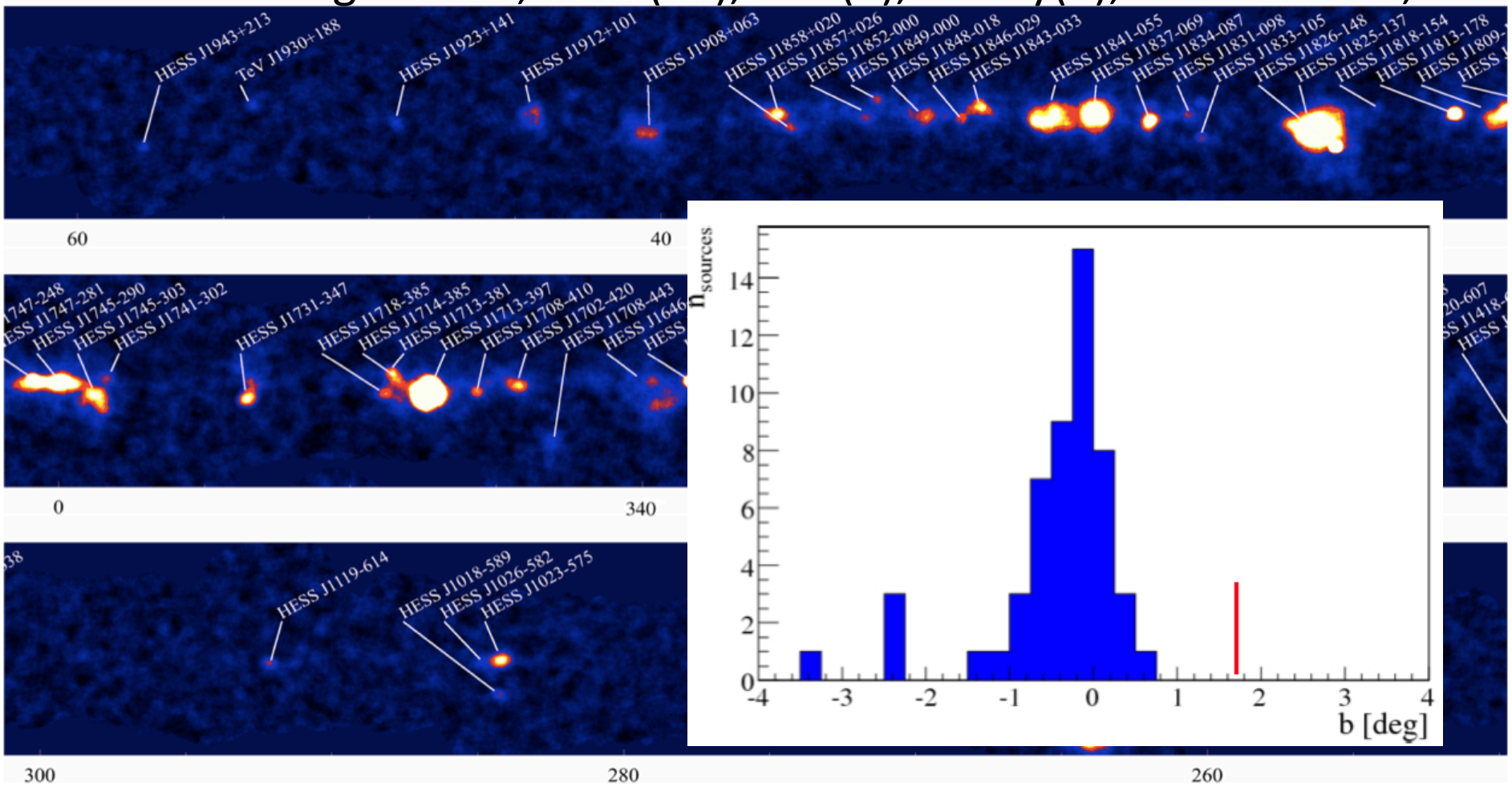


The Galactic Center

In principle the best option :

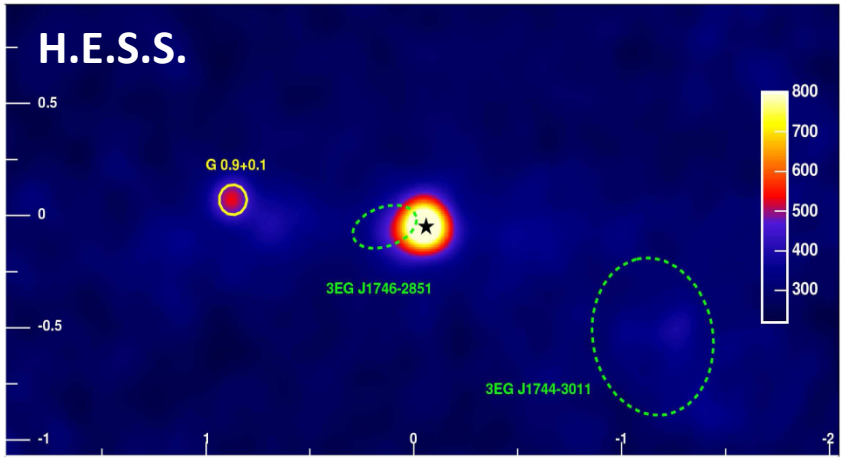
- Very near, and high DM concentration expected

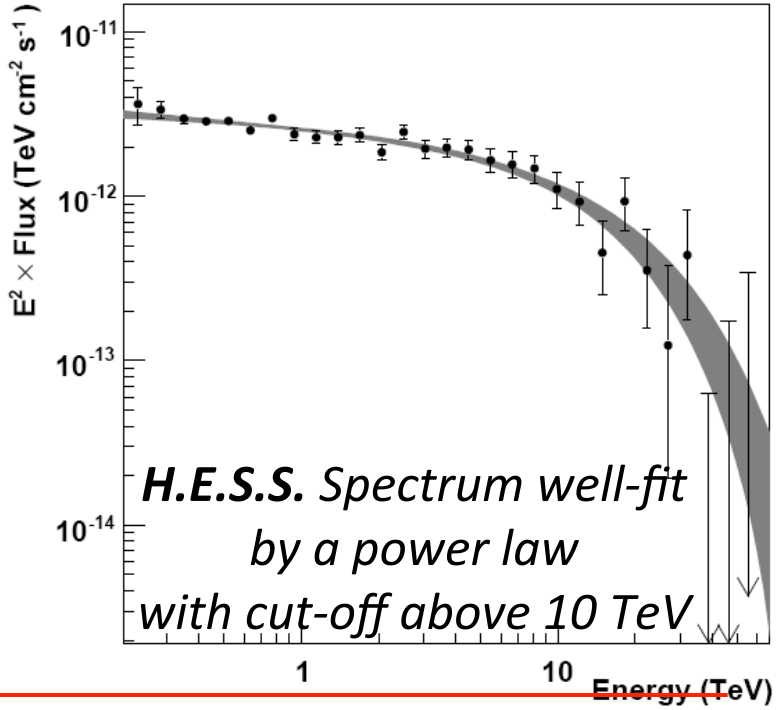
  → Flux should be high.

- HESS and MAGIC reported a point-like source

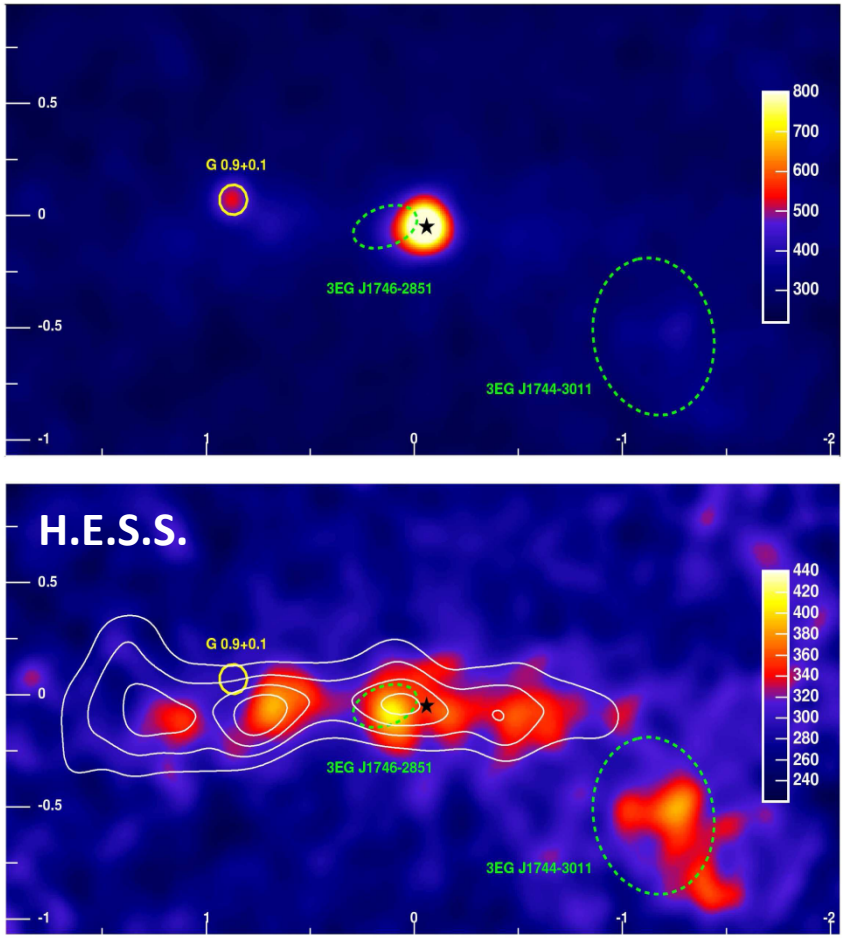
a very massive neutralino, not compatible with WMAP cosmology.

Aharonian et al. (H.E.S.S., 2004) P.R.L., 97221102 / A&A 503 (2009)
Albert et al. (MAGIC, 2005) A.J., 638





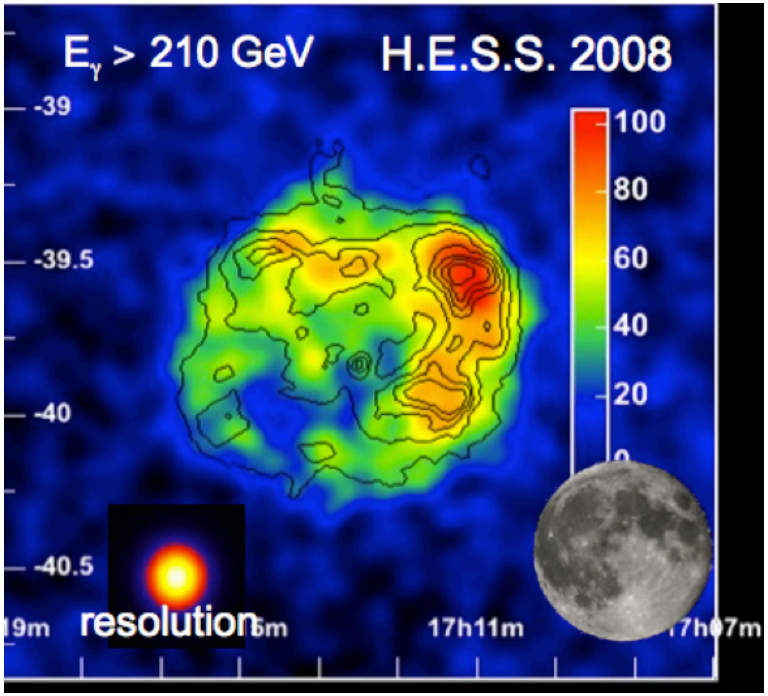
The Galactic Center



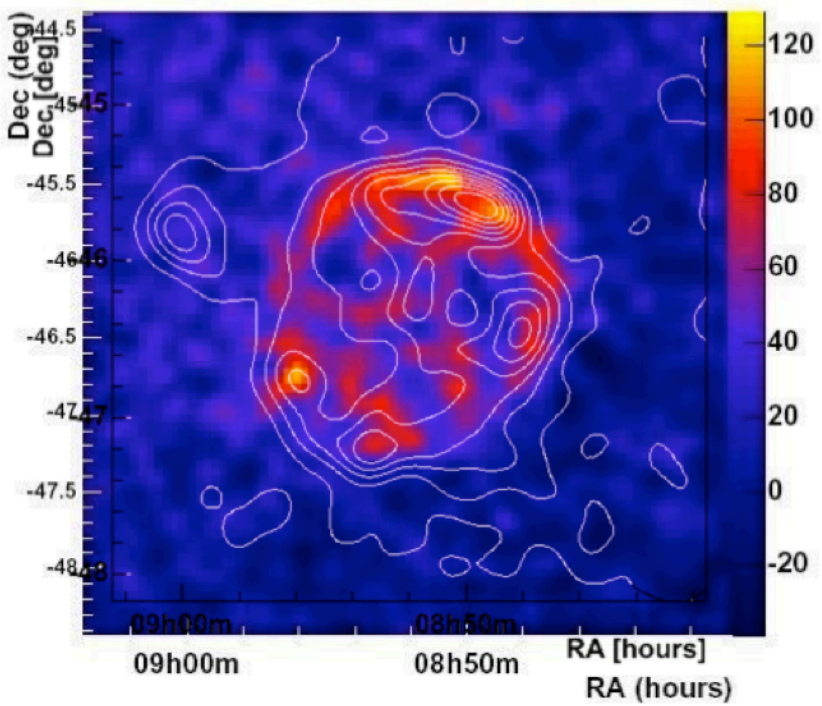
Later on an extended emission was discovered,
but associated to the galactic plane and molecular clouds.

Aharonian et al. (H.E.S.S., 2006), Nature 439

Supernovae remanent



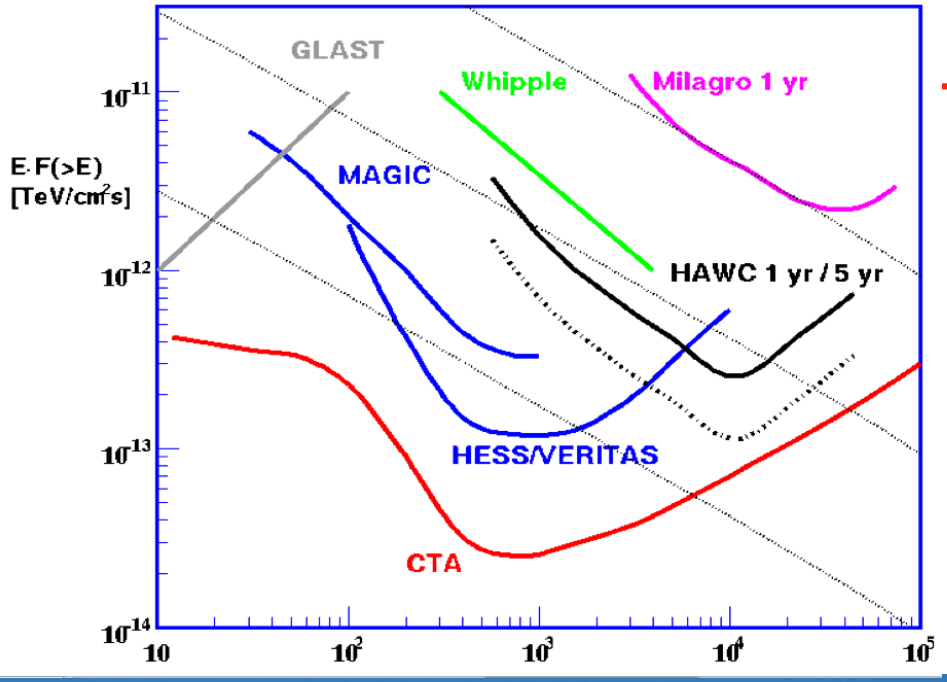
RX J1713.7-3946

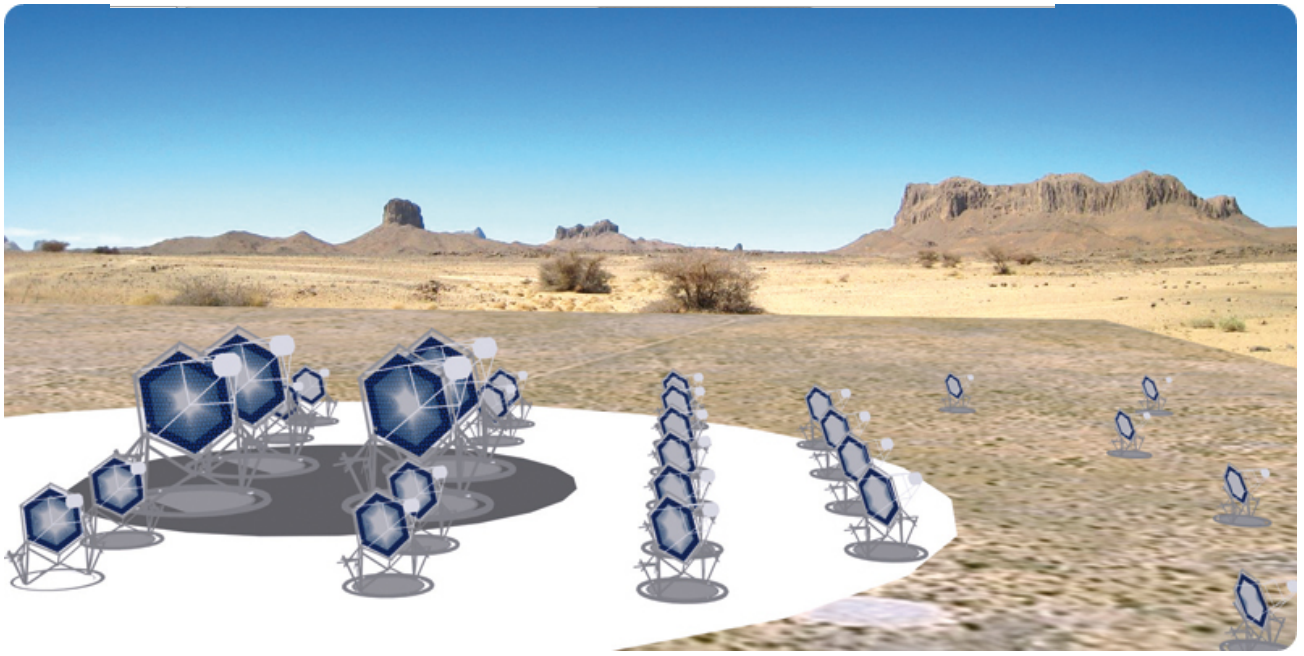


RX J0852.0-4622

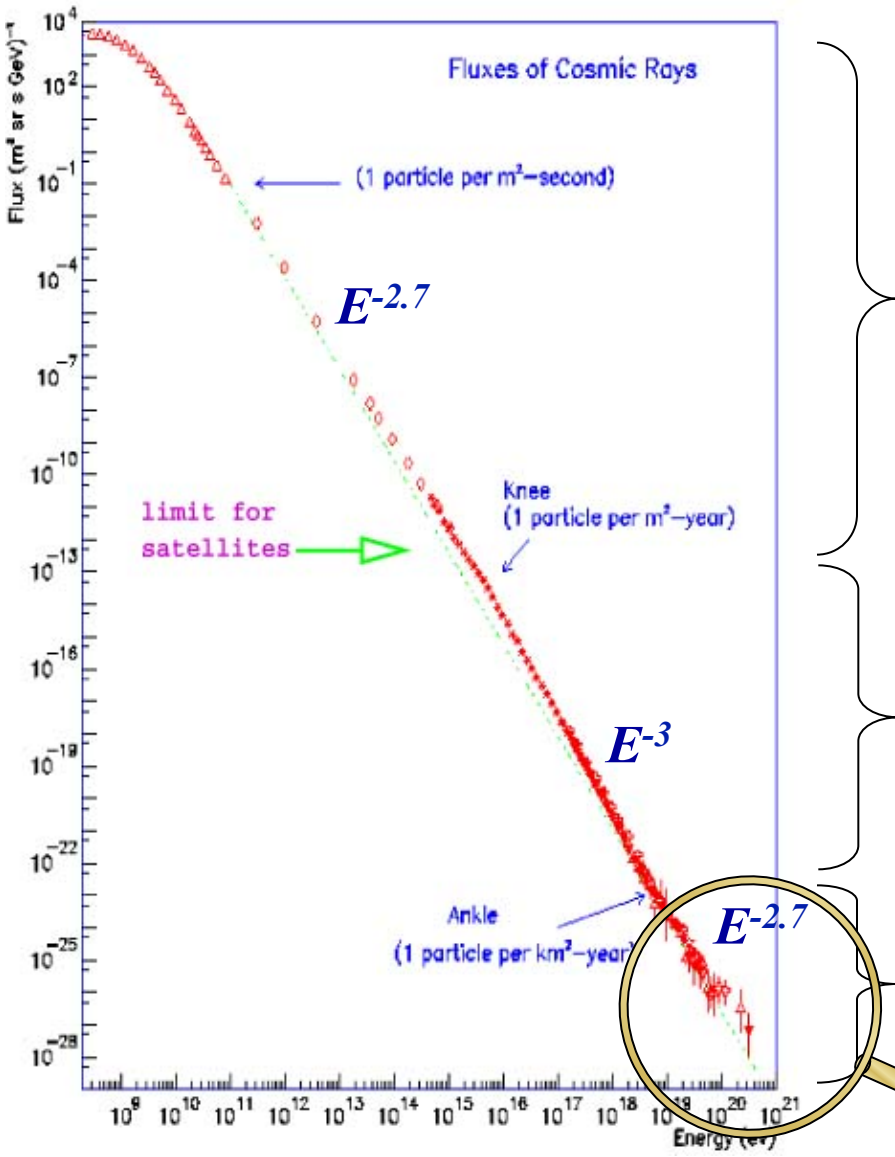
- Stricking correlation between X-ray and γ-ray emission
- SNRs are proved to accelerated particules up to 100 TeV
- Type of particle unknown

Future


GLAST
Whipple
Milagro 1 yr
MAGIC
HAWC 1 yr / 5 yr
HESS/VERITAS
CTA
E·F(>E)
[TeV/cm²s]
10⁻¹¹
10⁻¹²
10⁻¹³
10⁻¹⁴
10
10²
10³
10⁴
10⁵



The Ankle



Galactic CR :
Supernovae, MIS,
but no source pointing!

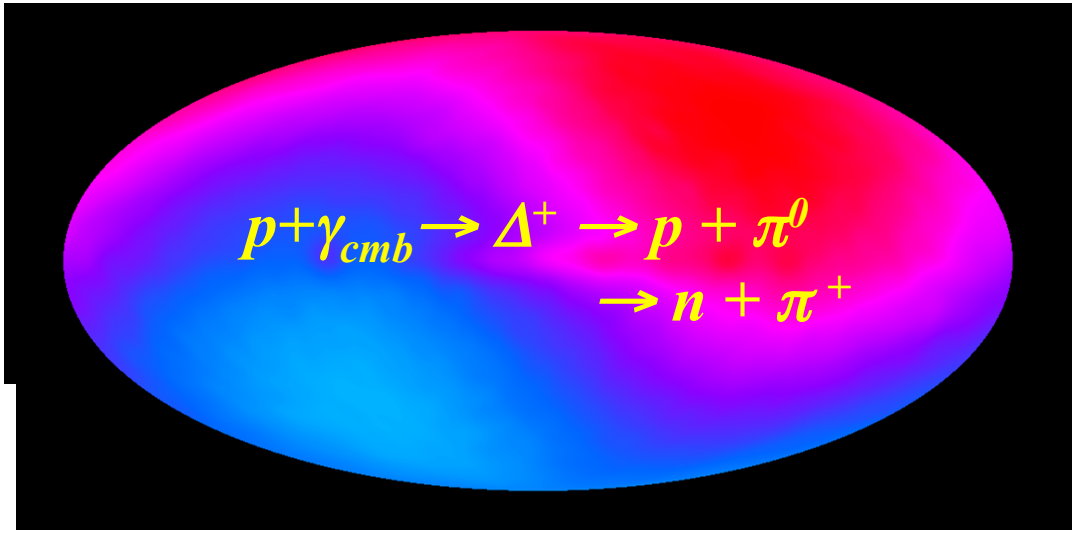
Galactic ?
SuperNovae? Superbubles?
reacceleration?
Heavier nuclei → protons ?

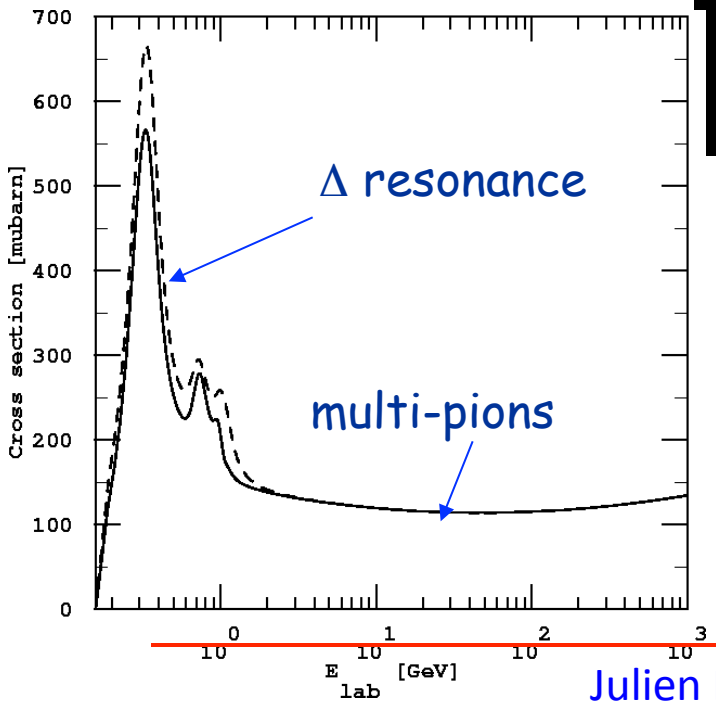
Extragalactic ?
source ?, composition ?

UHECR, terra incognita

GZK Cutoff

An extrem case of relativistic kinematics !!!

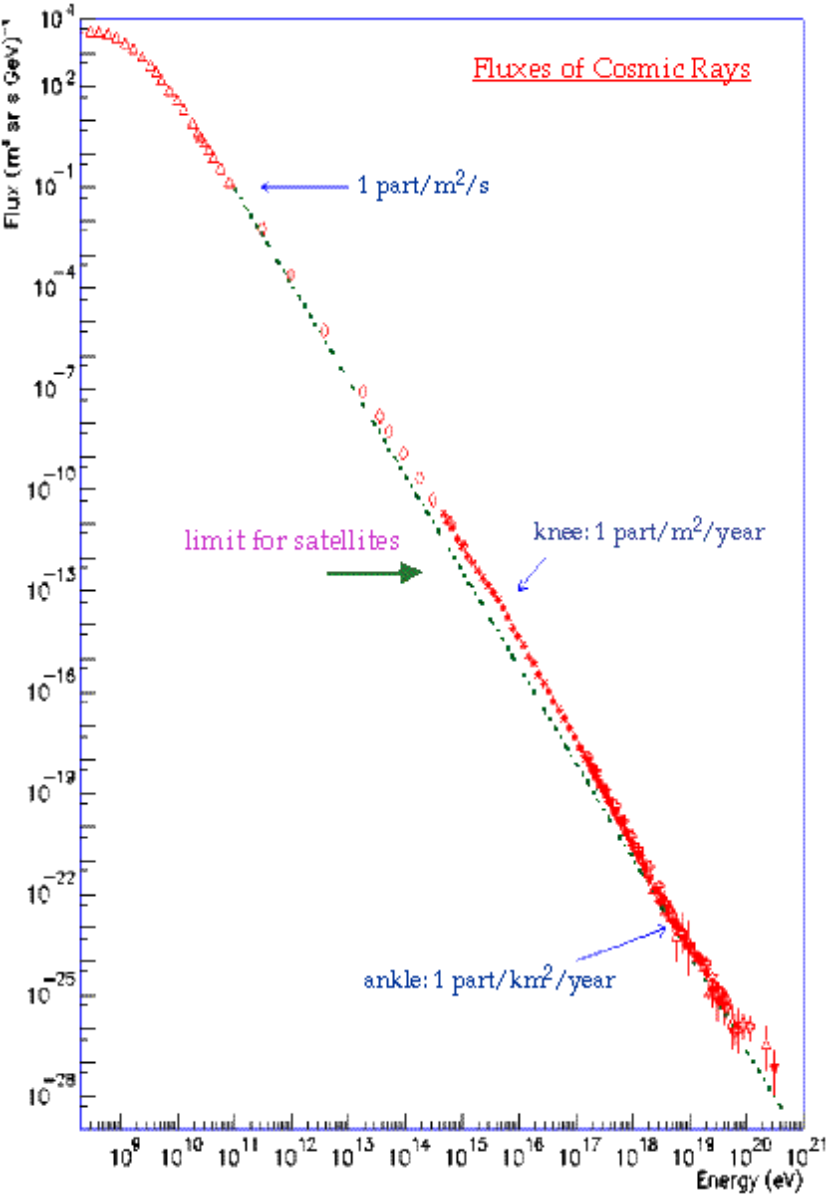


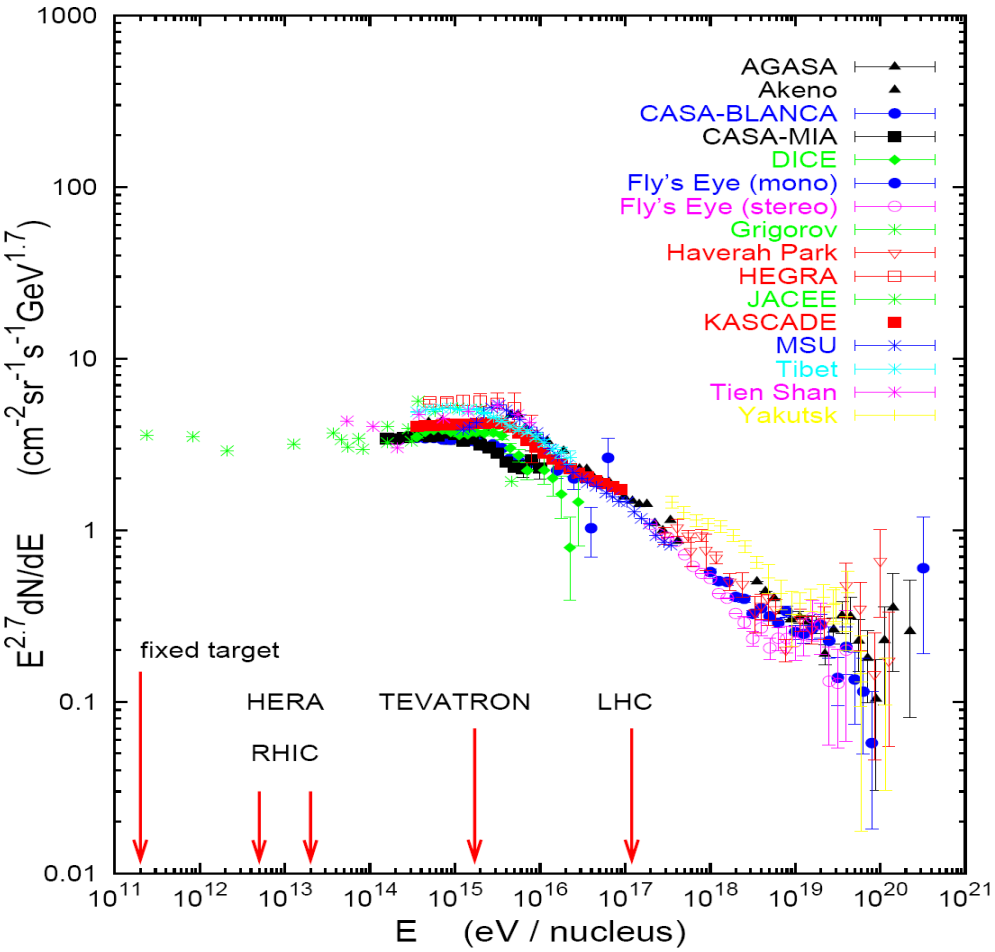


GZK "cutoff"

Greisen '66, Zatsepin & Kuzmin '66

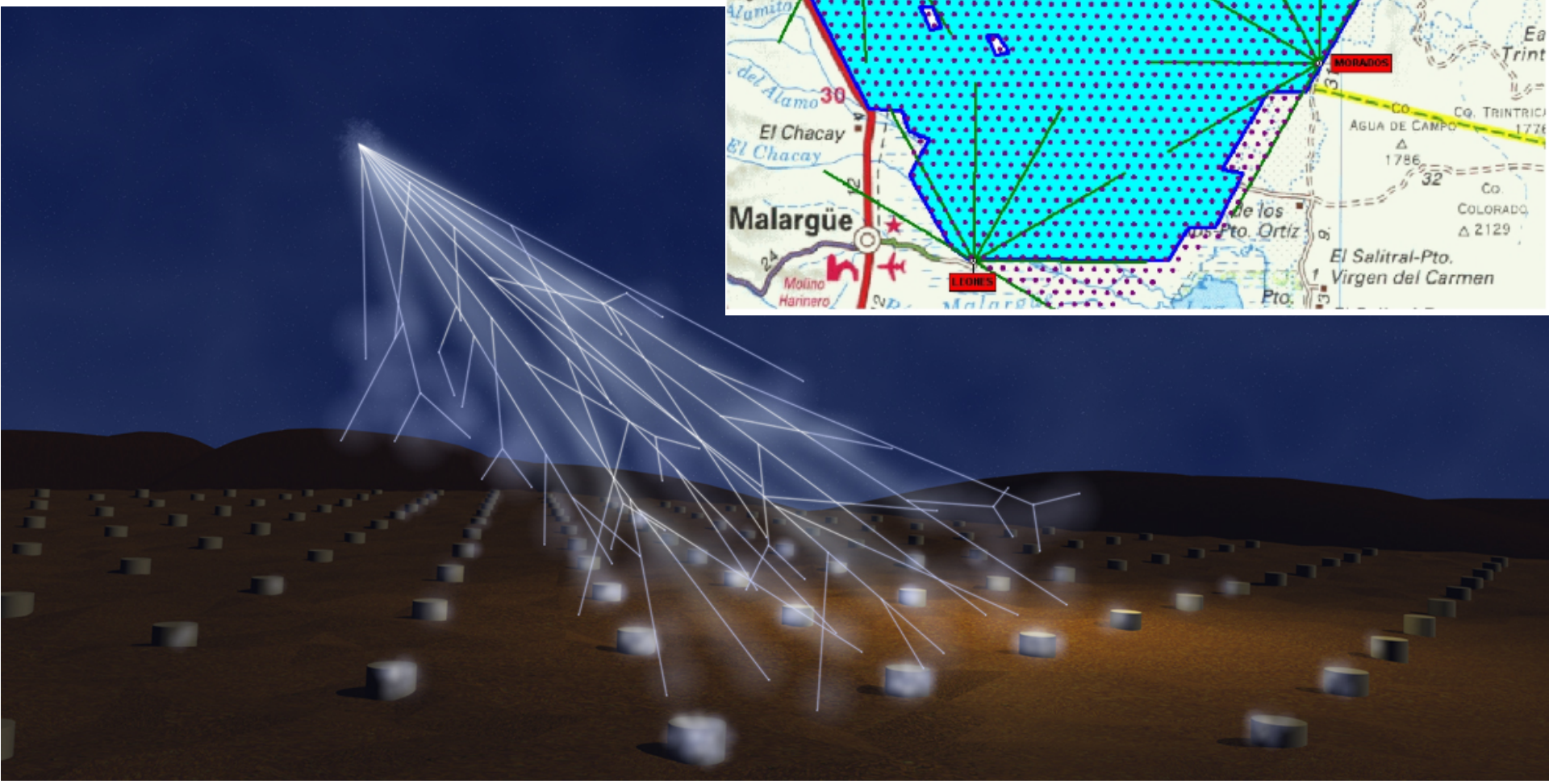
The "all" paticle sectrum



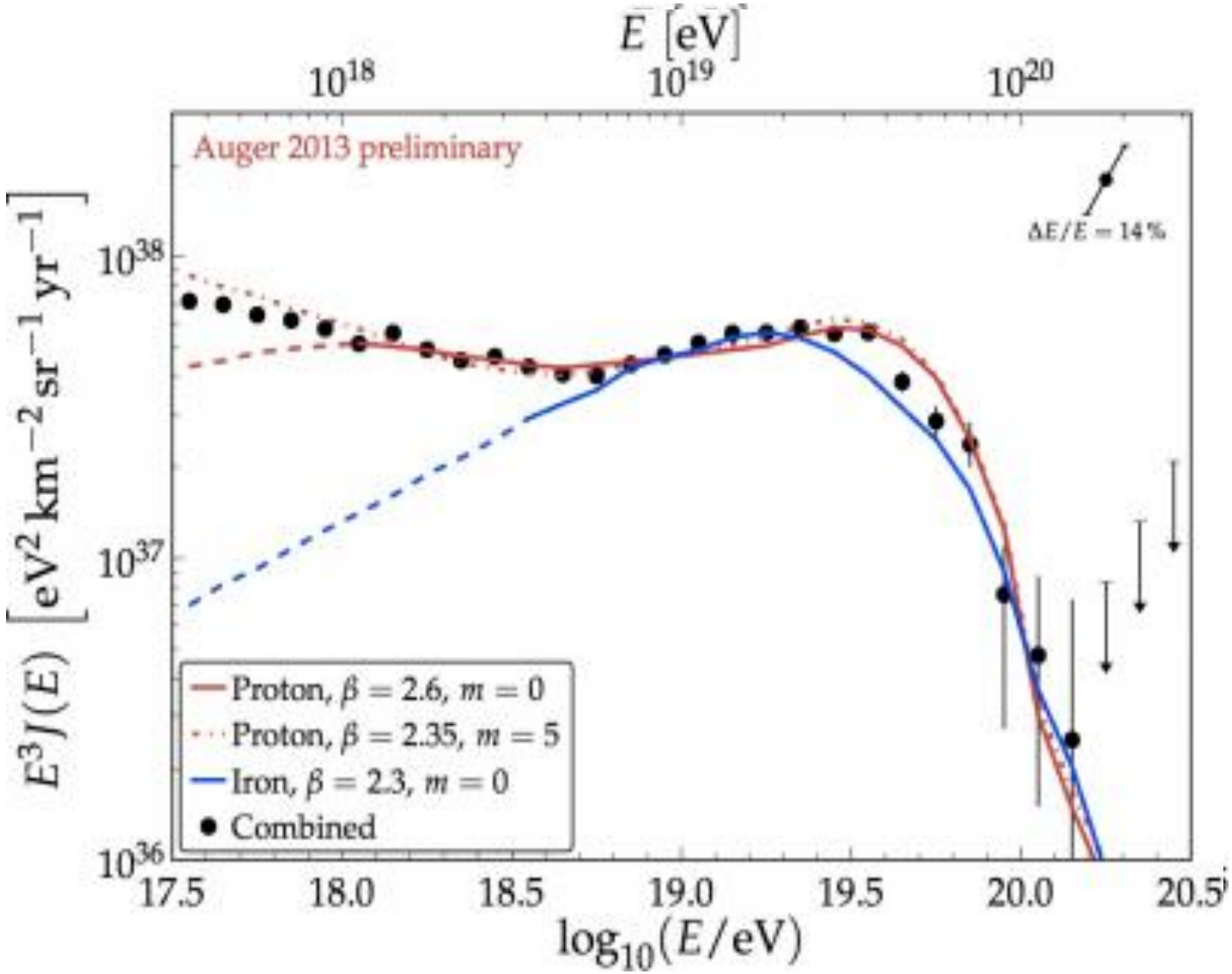


Pierre Auger Observatory

3000m^2 / 1600 tanks

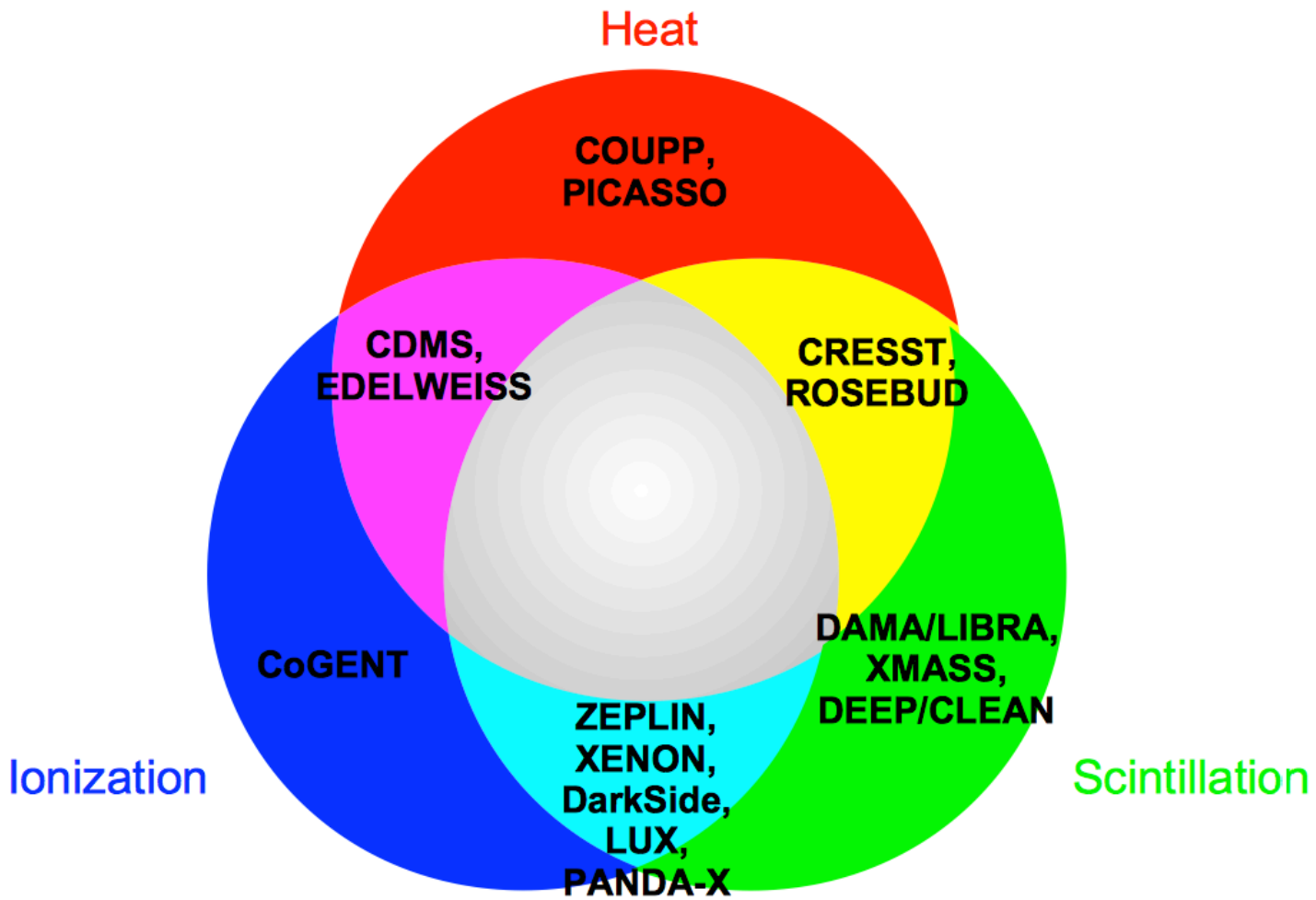


GZK Cutoff


E [eV]
10^18
10^19
10^20
Auger 2013 preliminary
ΔE/E = 14%
10^38
10^37
10^36
E^3 J(E) [eV^2 km^-2 sr^-1 yr^-1]
Proton, β = 2.6, m = 0
Proton, β = 2.35, m = 5
Iron, β = 2.3, m = 0
Combined
17.5
18.0
18.5
19.0
19.5
20.0
20.5
log10(E/eV)

Direct Dark Matter Detection techniques

Various targets are used (Ge, Xe, Ar, Ne, . . .)
Energy recoil is transferred to three possible phenomena: **scintillation**, **ionization**, **heat**
One (or two) among these three signals are used for particle detection.



Direct detection with xenon

The XENON Dark Matter Program

XENON10

Achieved (2007)

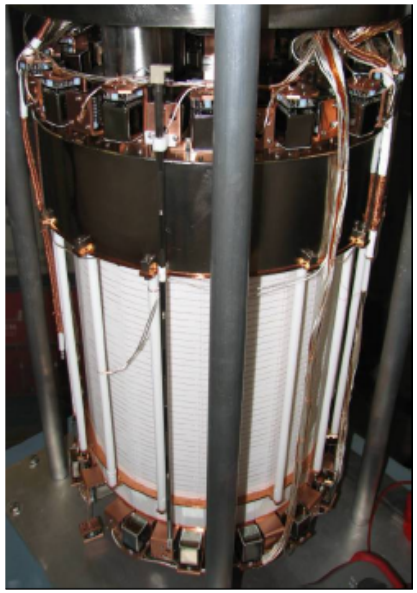
σ_{SI} = 8.8 · 10^{-44} cm^2 @ 100 GeV/c^2

Phys.Rev.Lett. 100 (2008) 021303

Light DM:

σ_{SI} = 7 · 10^{-42} cm^2 @ 7 GeV/c^2

Phys.Rev.Lett. 107 (2011) 051301



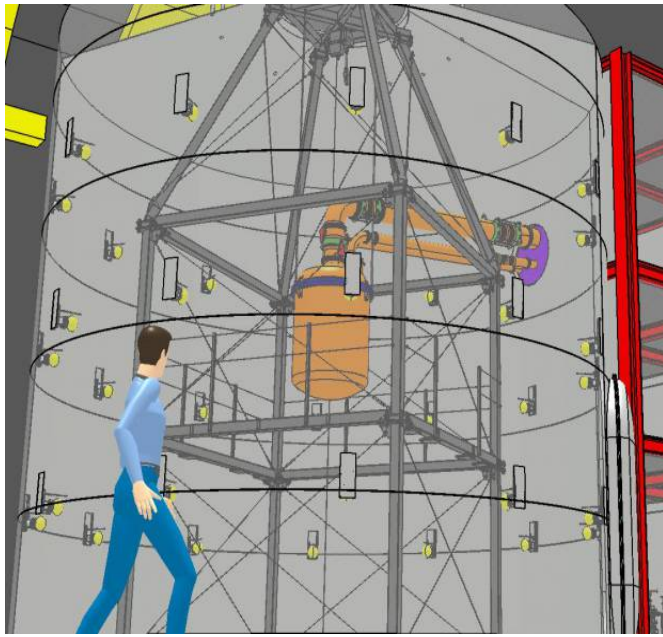
XENON100

Achieved (2012)

σ_{SI} = 2.0 · 10^{-45} cm^2 @ 55 GeV/c^2

E. Aprile et al. (XENON100),
Phys. Rev. Lett. 109 (2012)
arXiv:1207.5988

In operation since 2009



XENON1T

Projected (2017)

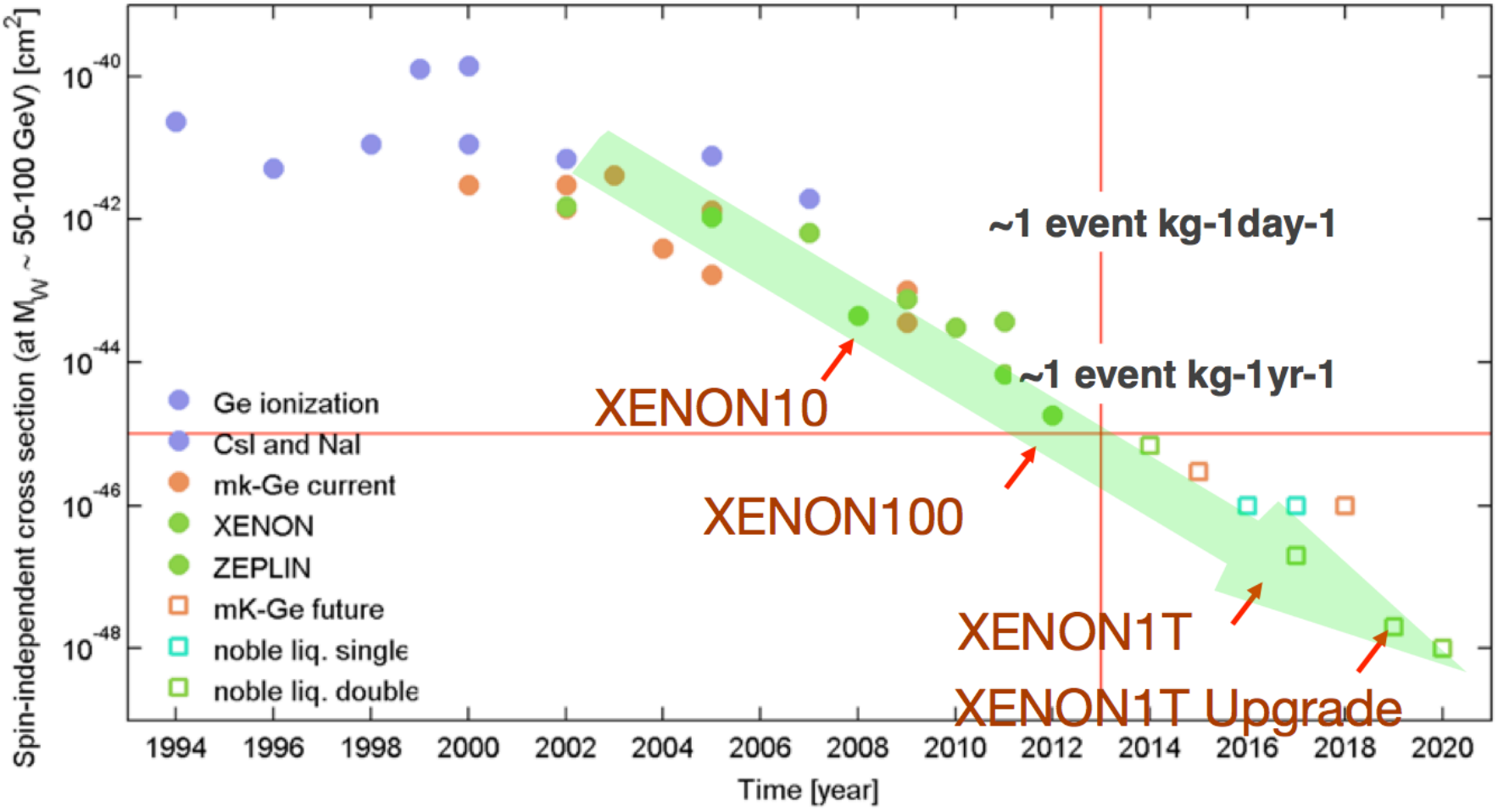
σ_{SI} = ~ 10^{-47} cm^2

Construction started in 2013

Upgrade : XENONnT

σ_{SI} = ~ 10^{-48} cm^2

Direct detection : progress over time



Background Suppression

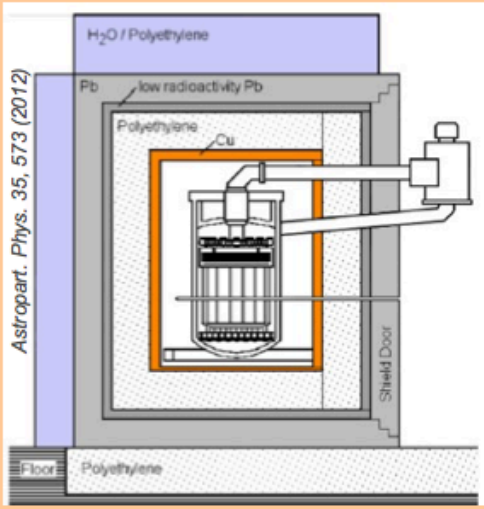
A Avoid Backgrounds

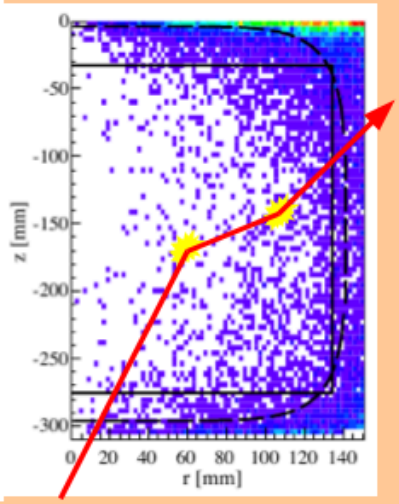
Use of radiopure materials

Shielding

deep underground location
large shield (Pb, water, poly)
active veto (μ, γ coincidence)

self Shielding → fiducialization





B Use knowledge about expected WIMP signal

WIMPs interact only once

→ single scatter selection
require some position resolution

WIMPs interact with target nuclei

→ nuclear recoils
exploit different dE/dx from signal and background

Scintillation Pulse Shape

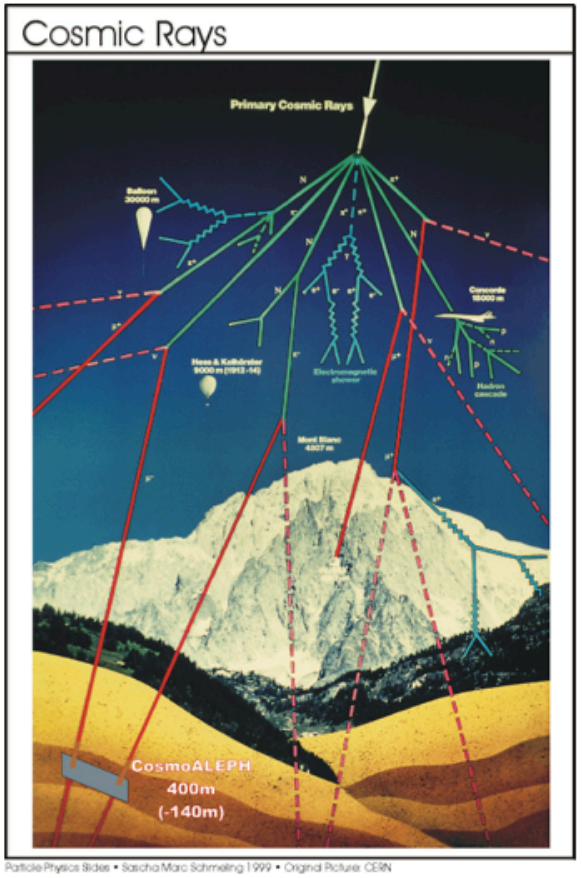
Signal Quenching

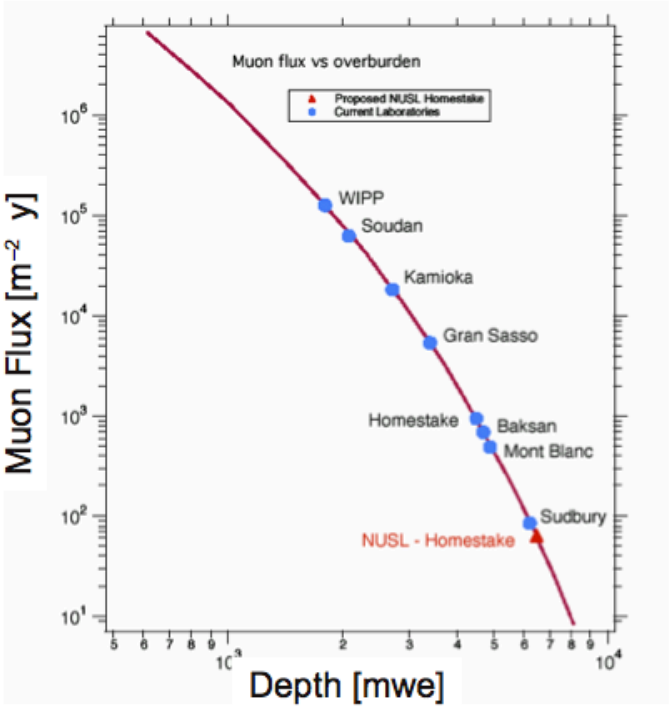
Cosmic Rays

Cosmic rays and secondary/tertiary particles which they create in reactions can be reduced by going to underground laboratories

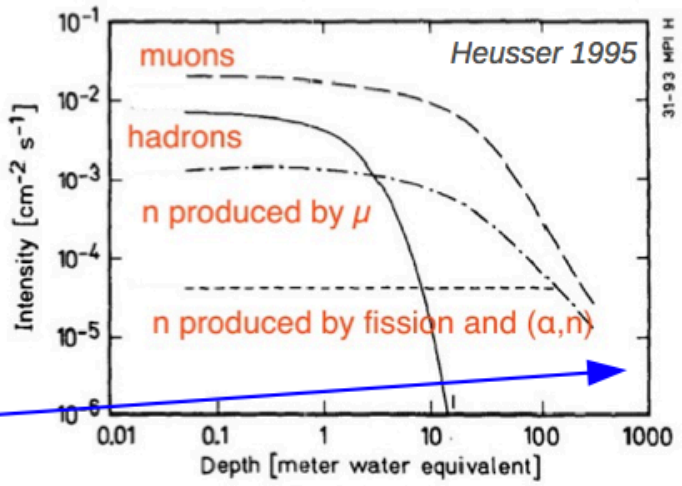
The hadronic component (n, p) is already reduced significantly after a few meters rock

Shielding thickness (rock, soil) given in „meter-water-equivalent“ (mwe) to allow for comparison between different laboratories

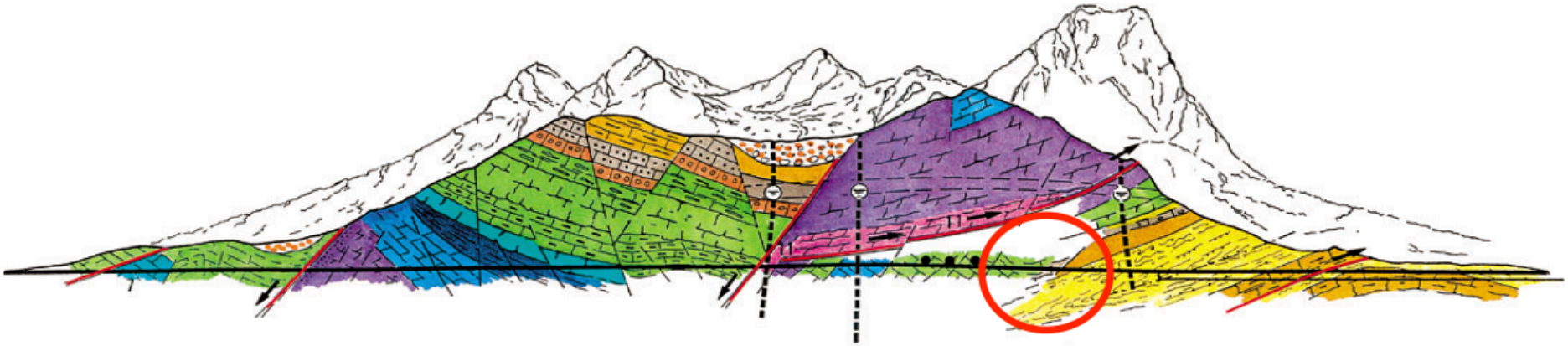


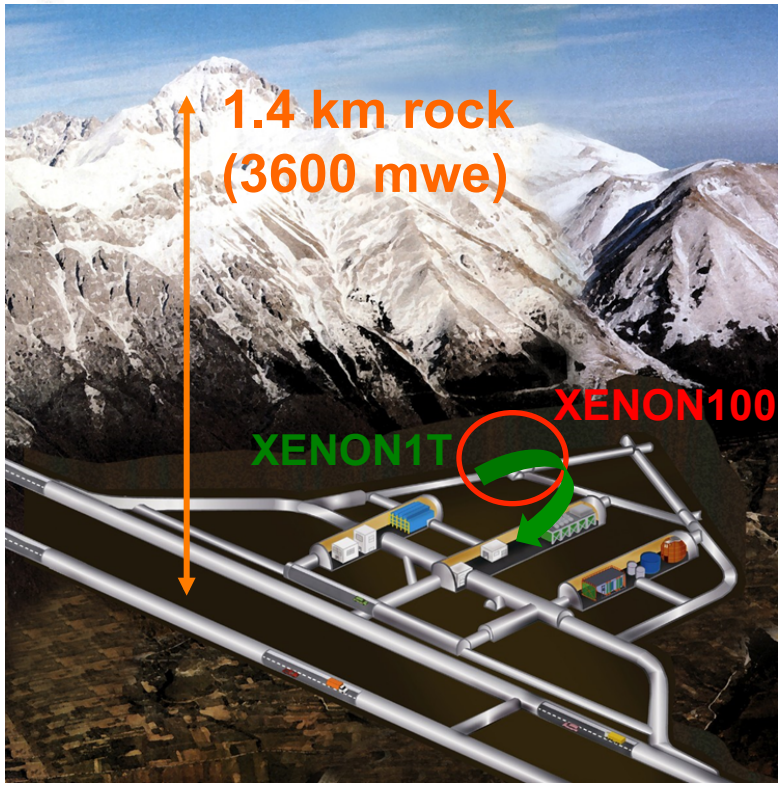


in deep laboratories, only muons remain which cause e/m showers and also generate neutrons

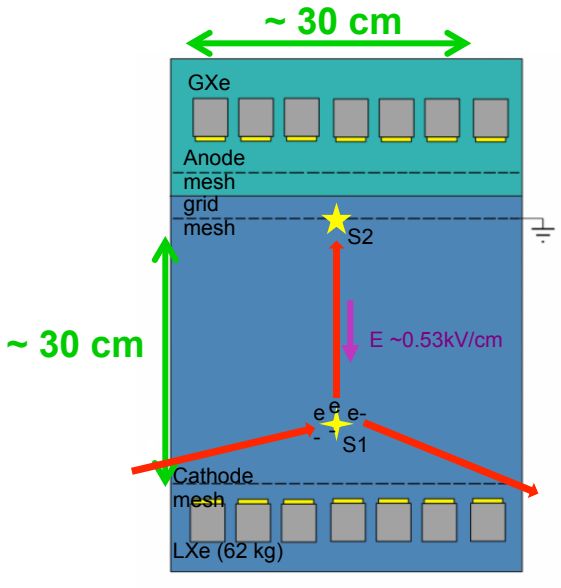


Location of the XENON experiment

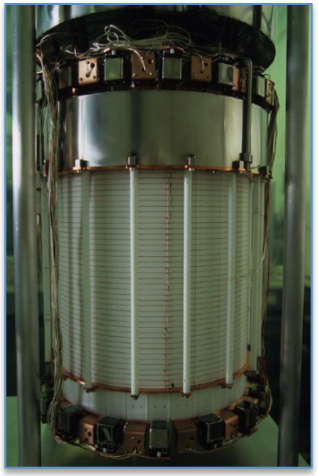


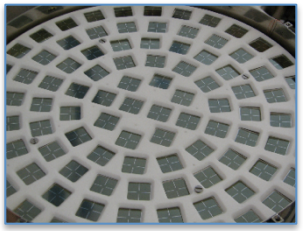


Two phase XENON TPC principle

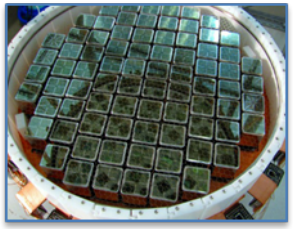


E. Aprile et al. (XENON100), Astropart. Phys. 35, 573-590 (2012)

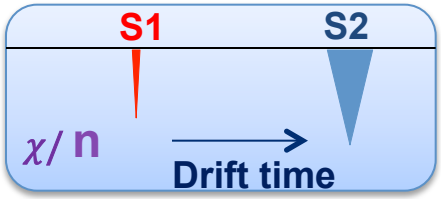




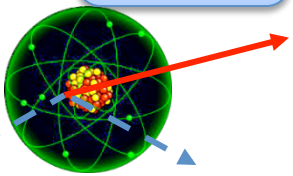
Top array
98 PMTs



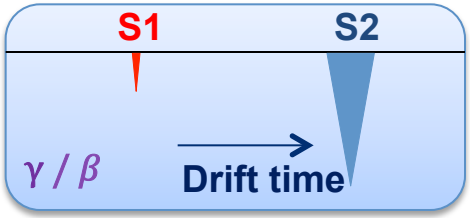
Bottom
array
80 PMTs



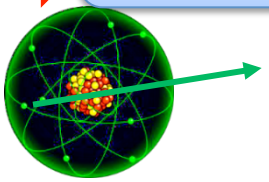
Nuclear Recoil



- **Materials selected for low radioactivity**
- **Scintillation (S1) and Charge (S2) Signals**
  - ER / NR discrimination
- **3D Reconstruction for fiducialization:**
  - **(XY)** – Top PMTs hit pattern (± 3 mm)
  - **(Z)** – Drift time (± 0.3 mm)
- **Multiple scattering rejection**



Electronic Recoil

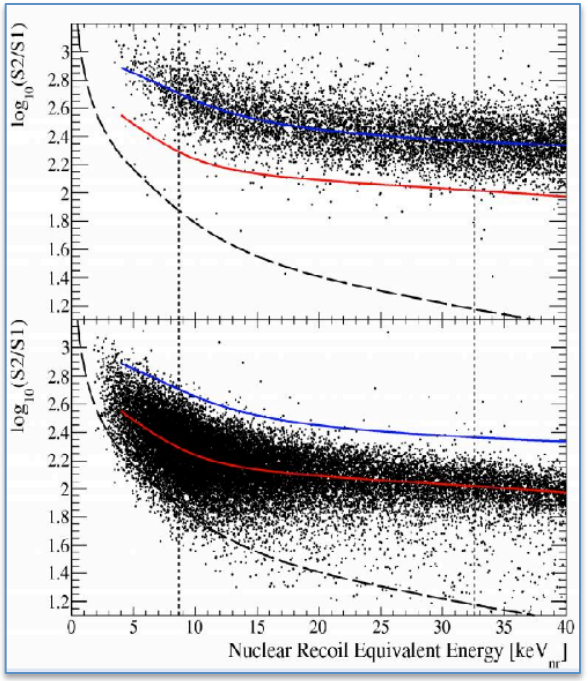


Background expectation

E. Aprile et al. (XENON100), arXiv:1207.3458

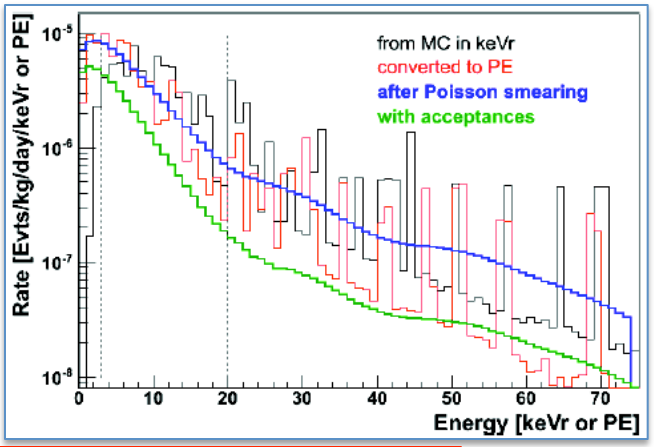
Electronic recoil background:

- Electronic recoil estimation done with ^{60}CO and ^{232}Th Data collected all the time for a total of 40 effective days
- 35 times more statistics than in data used for Dark Matter search
- Expected events in a benchmark region : **0.79±0.16**



Neutron recoil background:

- Calibration done with ^{241}AmBe exposure
  Two exposure campaigns:
  one at beginning and one at the end of run
- Nuclear recoil estimation done with Geant4 simulation
- Expected events in a benchmark region : $\mathbf{0.17^{+0.12}_{-0.07}}$



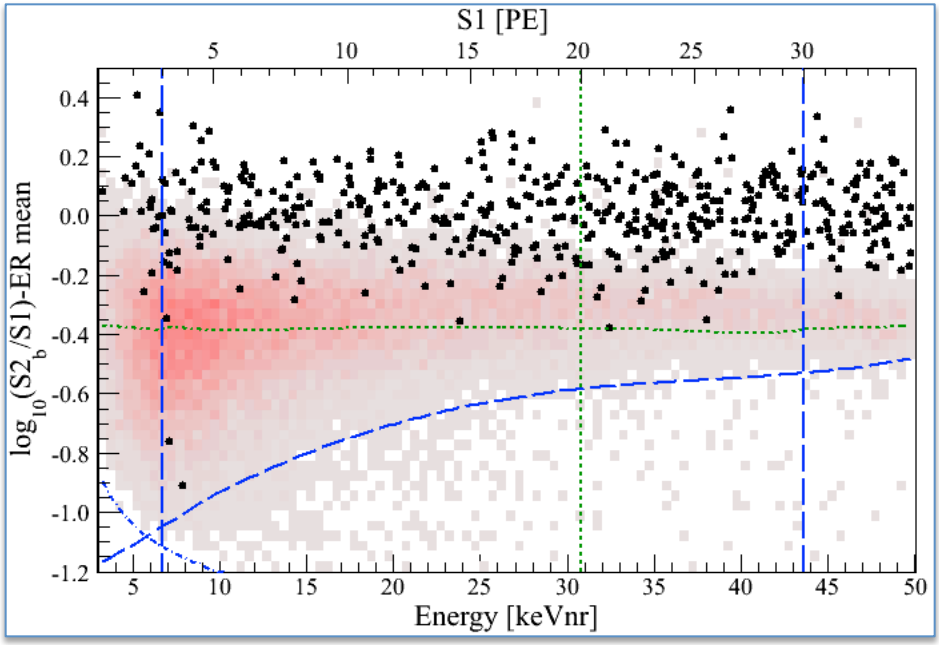
Total background:

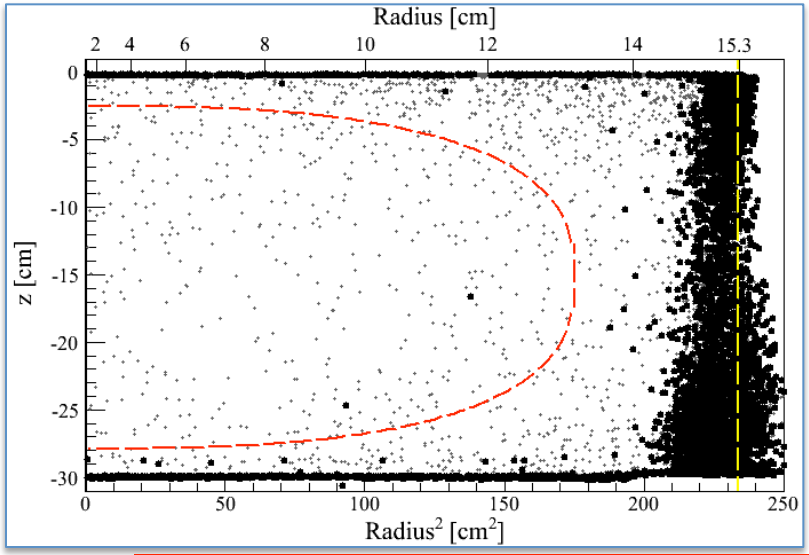
- In the benchmark region we expect in **total**
  1.0±0.2 events

E. Aprile et al. (XENON100), Phys. Rev. Lett. 109, 181301 (2012)

Blind analysis

- XENON100 did a blind analysis
- Event discrimination by S2/S1 separation
- Defined WIMP searching region:
  - S1 with benchmark region (3 - 30 pe)
  - S2 threshold cut (S2 > 150 pe)
  - 99.75 % ER rejection line

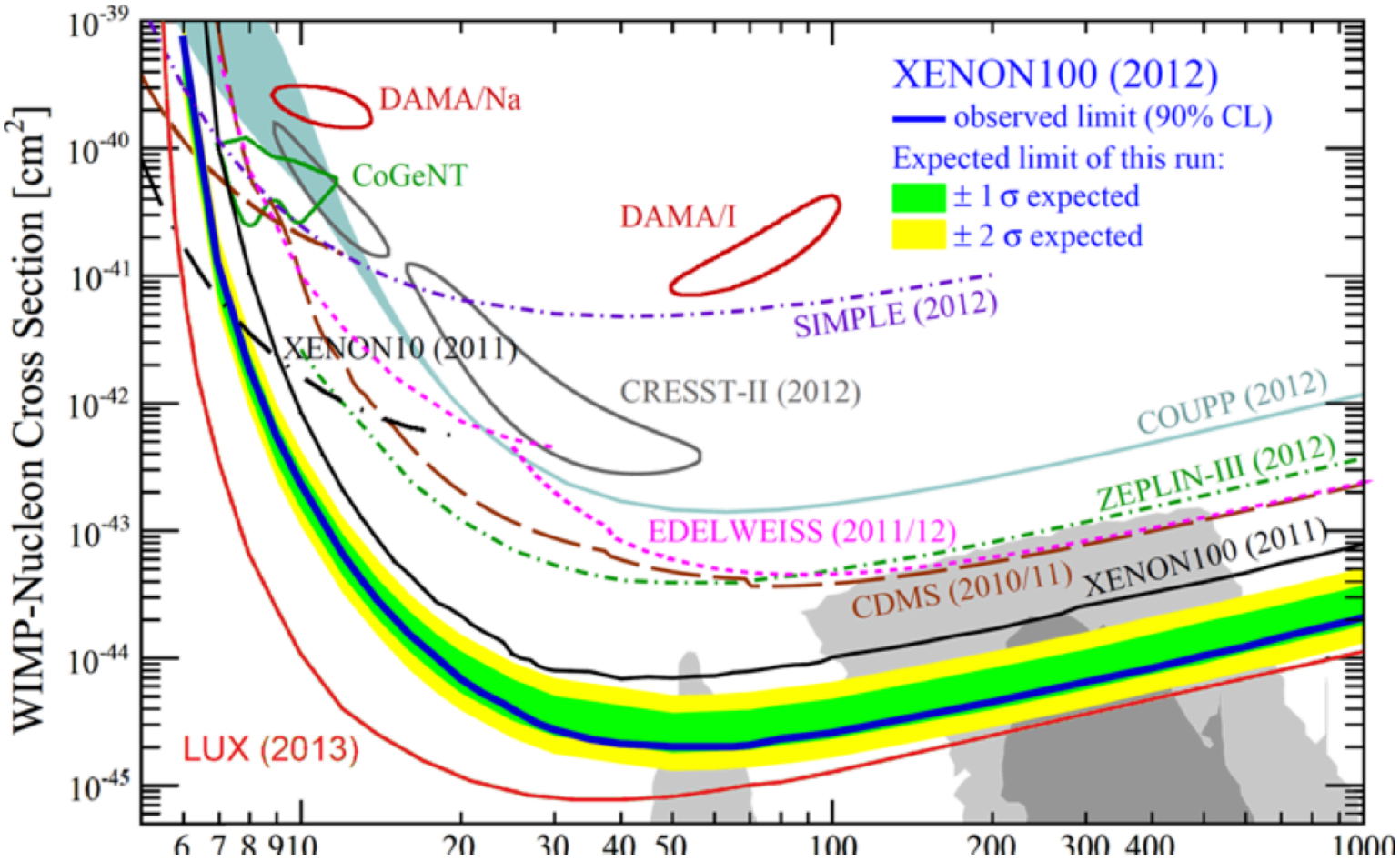




- Event rejection by defining a 34kg super-ellipse
- Double scatters excluded

Probability that 2 events fluctuate over the background expectation is 26.4%

Dark Matter Spin independent limits



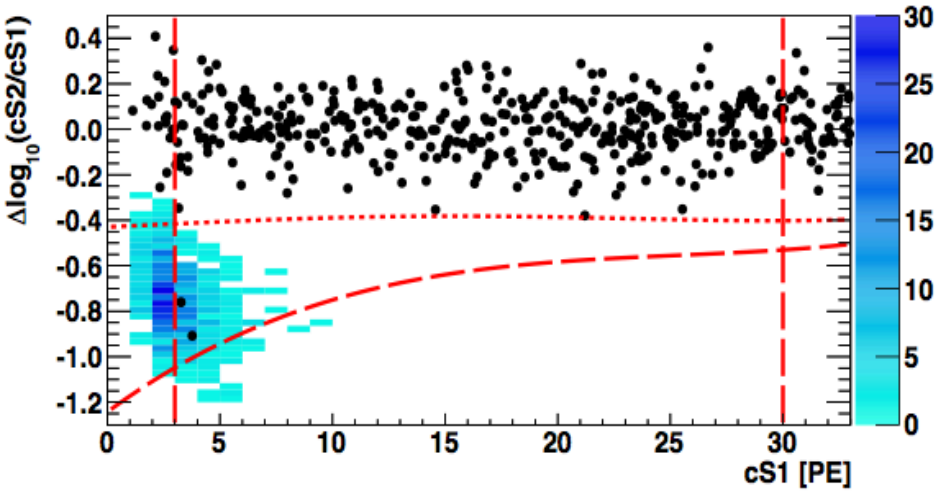
XENON100:
2×10^{-45}cm^2
@50GeV
Blinded Analysis

LUX:
7.6×10^{-46}cm^2
@33GeV

XENON100 Collaboration, Phys. Rev. Lett. 109, 181301 (2012)
LUX Collaboration, Phys. Rev. Lett. 112, 091303 (2014)

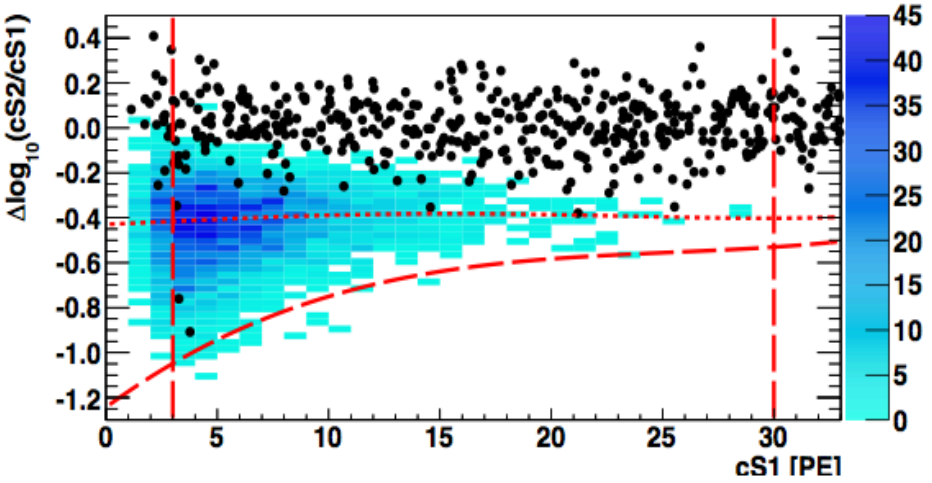
How signal look like in XENON100's data ?

WIMP with m_W = 8 GeV



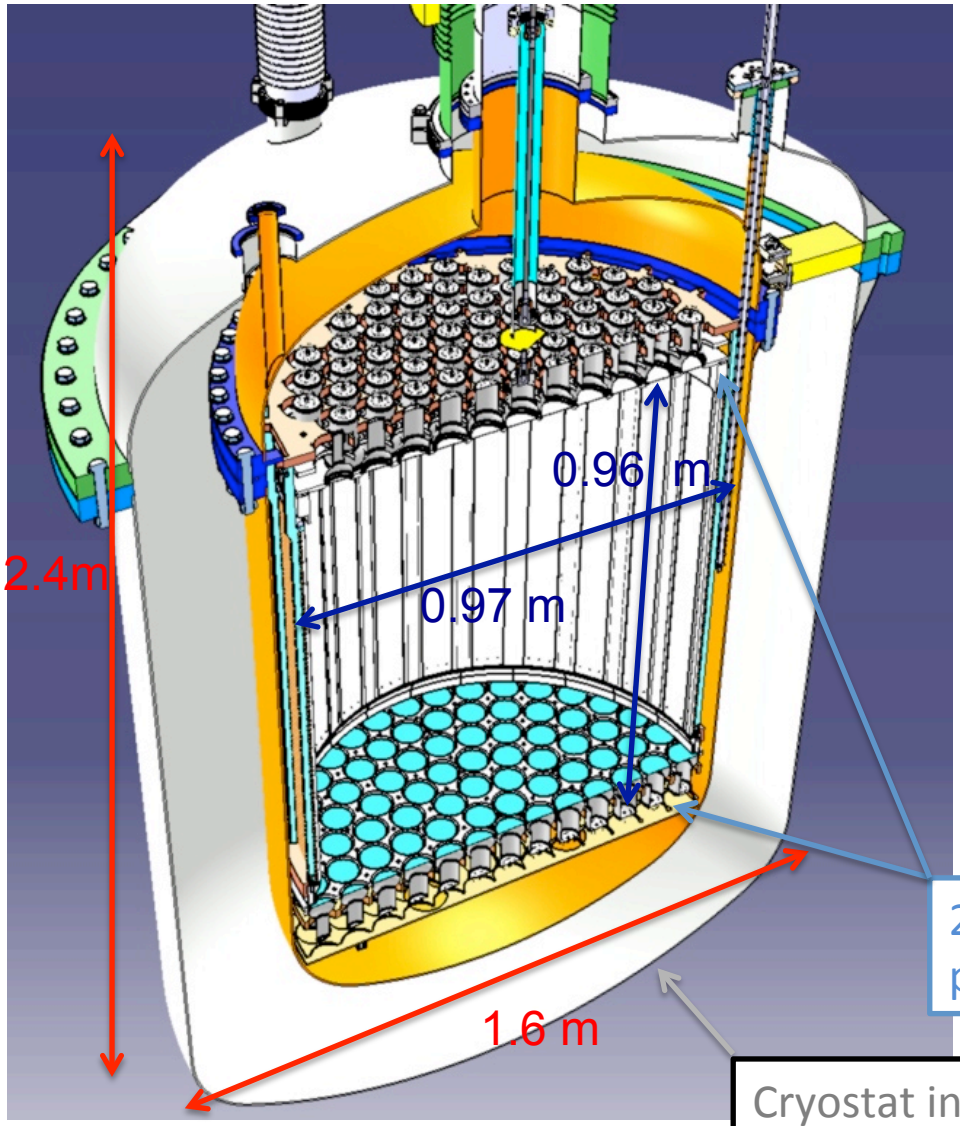
WIMP-nucleon cross section : 3 x 10^{-41} cm^2

WIMP with m_W = 25 GeV



WIMP-nucleon cross section : 1.6 x 10^{-40} cm^2

XENON1T : the detector



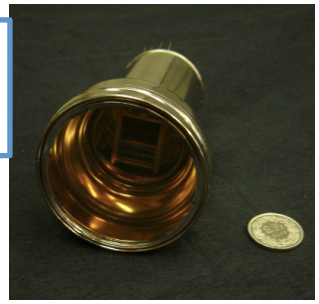
• In total 3.5 ton of LXe: 2 ton active inside the TPC, part of the outside LXe used as an active veto. Fiducial volume: > 1 ton

• 100x lower background (≈10 cm self shielding + low radioactivity components): background goal: ~ 1 ev in 2 years

• improved Light Collection Efficiency: better PTFE reflector coverage, electrode transparency

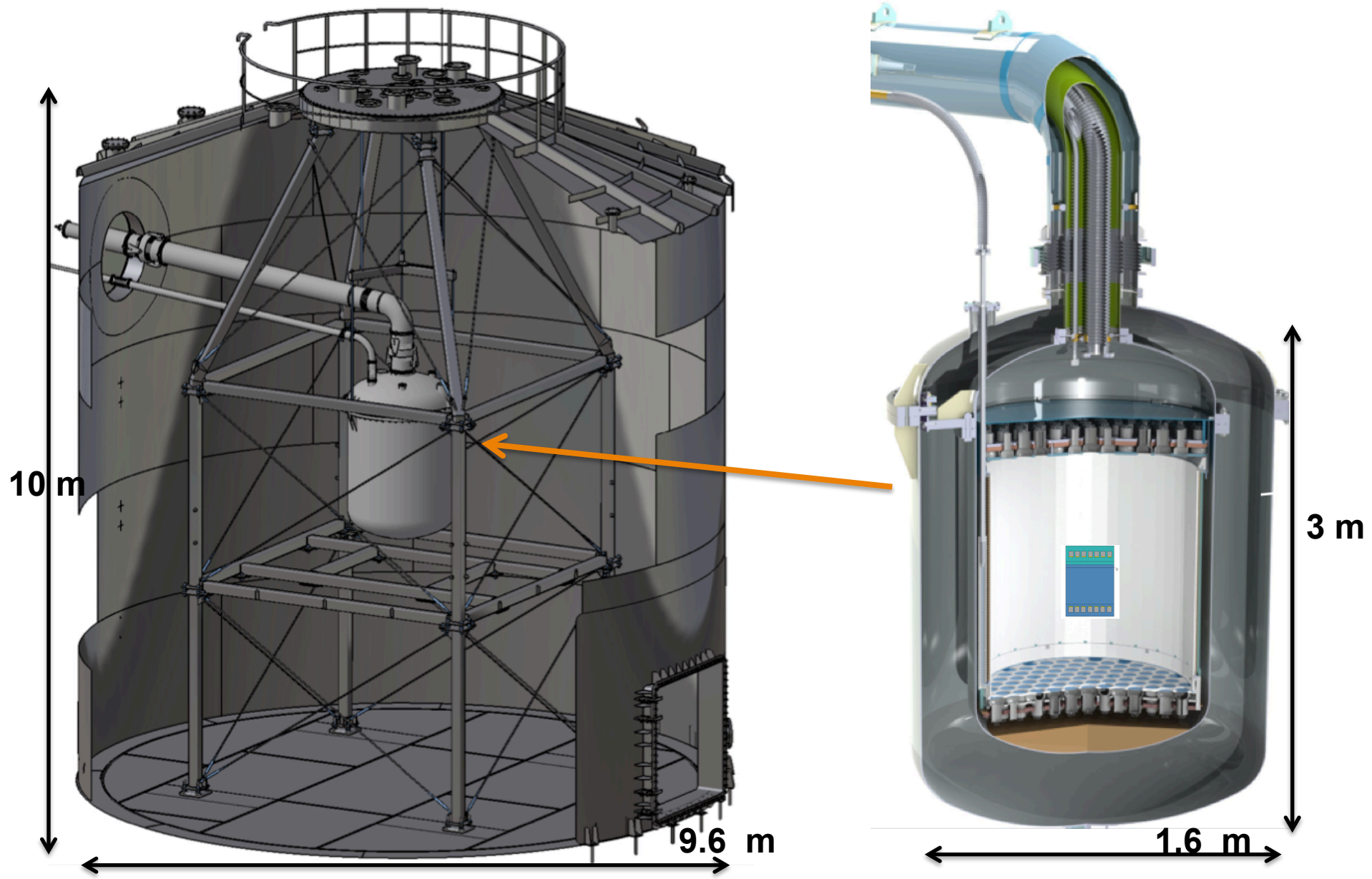
• 1m drift in the TPC: nominal Ed=500V/cm; HV = 50 kV

248 Low radioactivity photon detectors

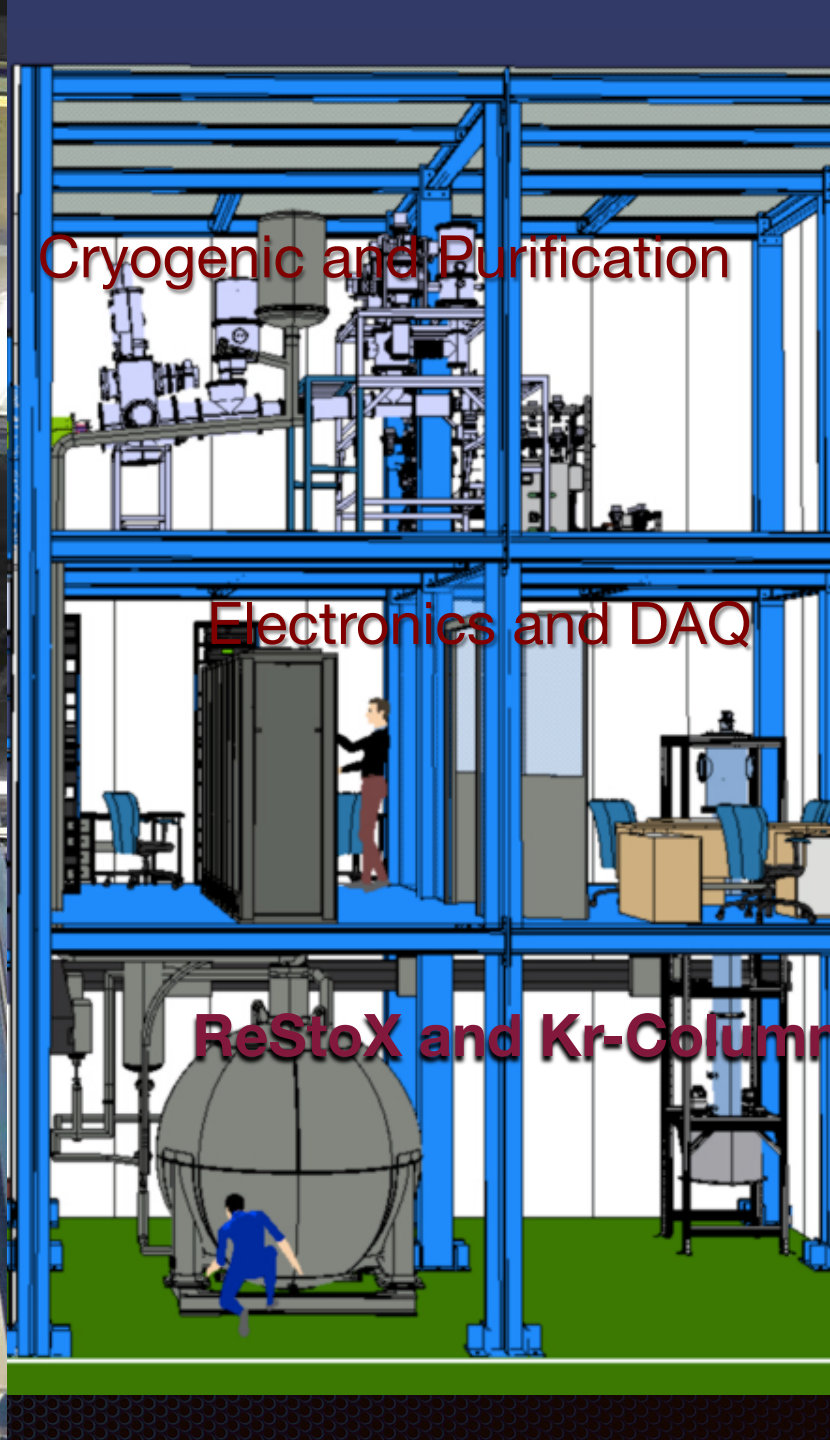


Cryostat in low radioactivity stainless steel

XENON1T in construction




Xe
XENON
Matter Project
XENON1
enlightening the

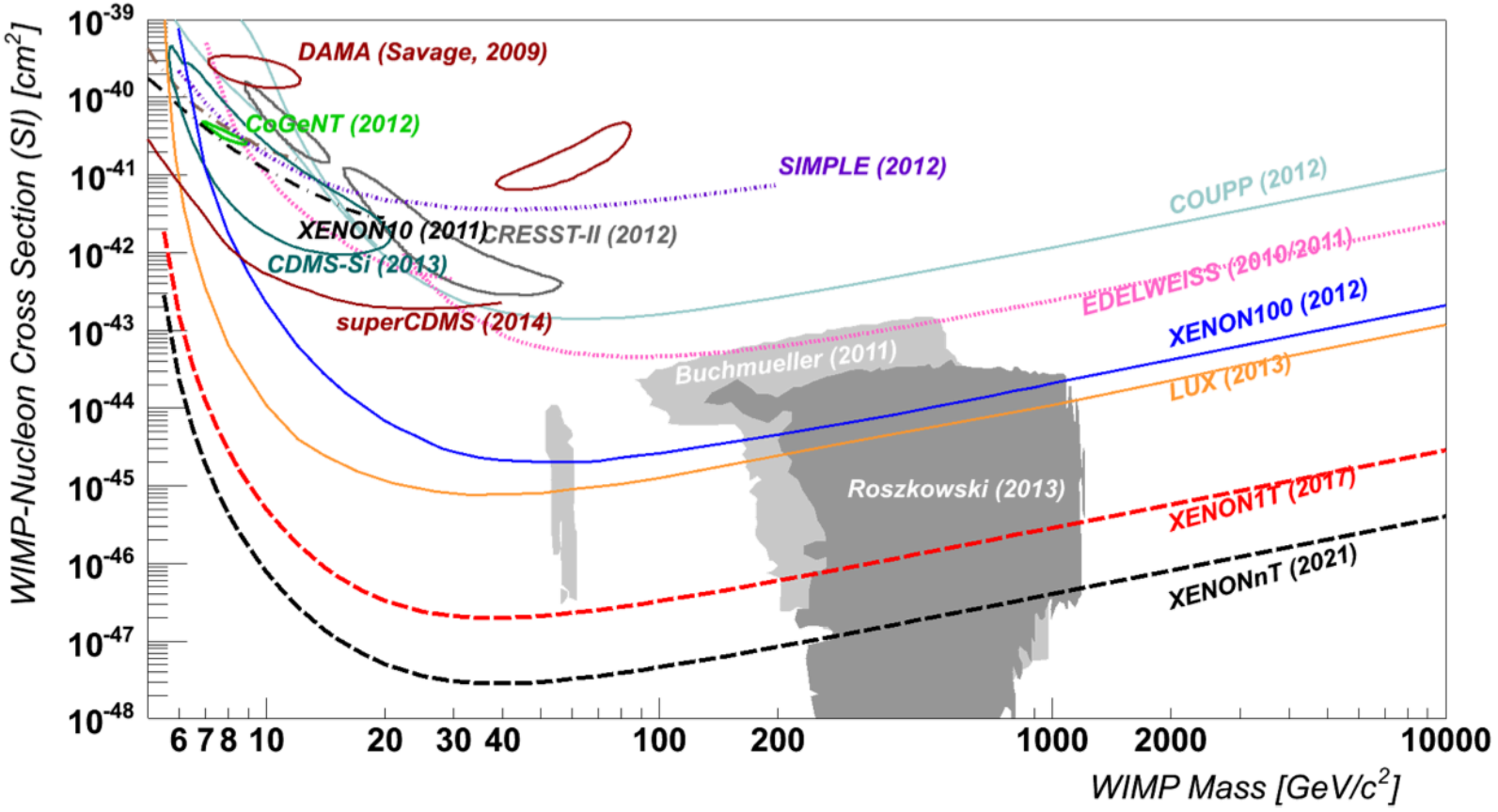

Cryogenic and Purification
Electronics and DAQ
ReStoX and Kr-Column

XENONnT : limits

No WIMP Dark Matter found yet

(apart several hints at low masses not supported by other experiments)

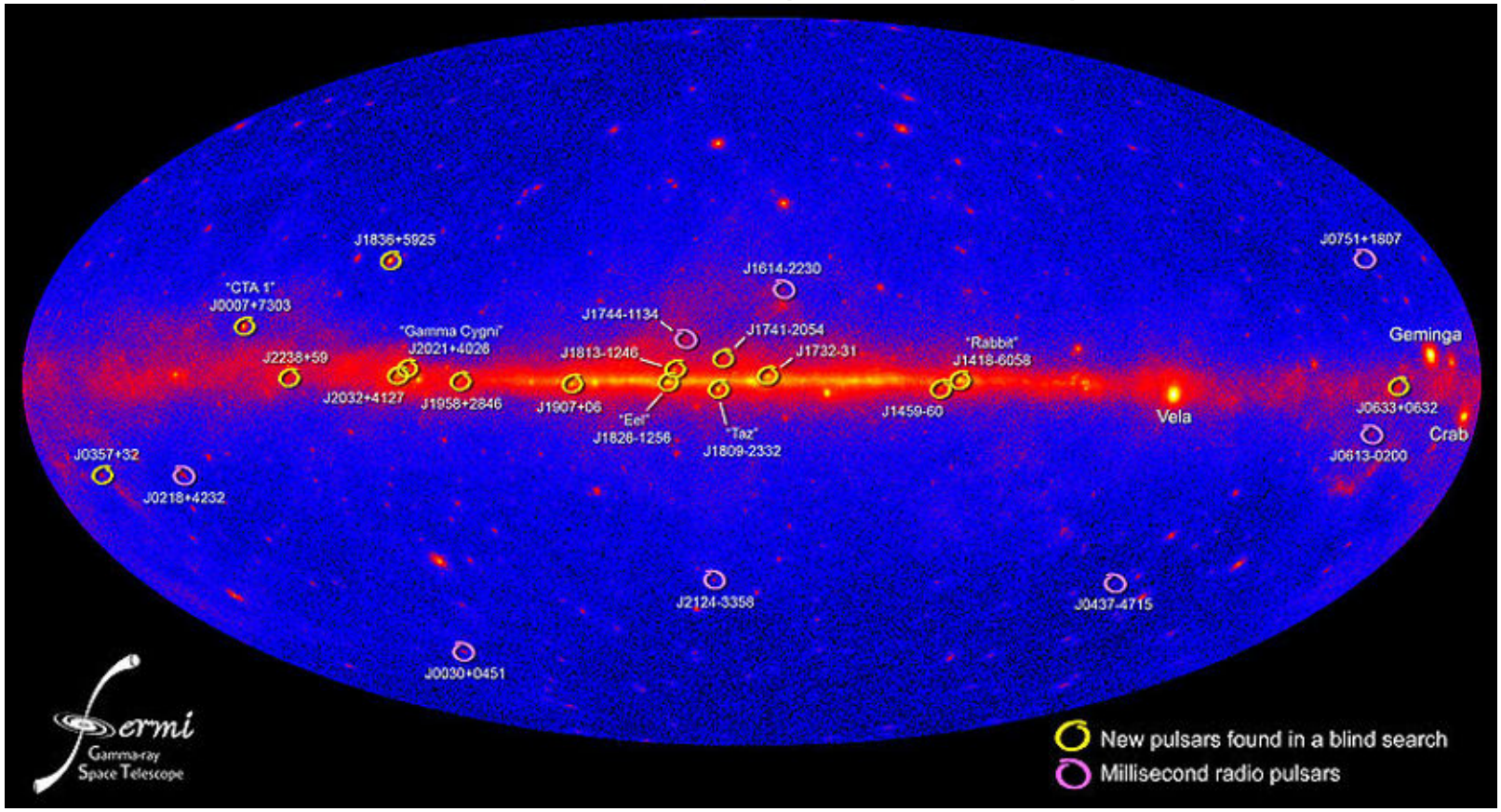
Increase the fiducial volume by building a bigger TPC and cryostat



XENON10 → XENON100 → **XENON1T** → XENONnT

Our galaxy

High Energy Sky
Gamma rays (>100 MeV)



The gamma emission is due to collision between cosmic rays (atoms and relativistic particles) and interstellar clouds, to bremsstrahlung and inverse Compton process