Cosmic Ray and Neutrino Observatories

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Multi-messenger Astronomy

August 2017
GW170817 from Neutron Star Collision, seen by LIGO/Virgo
GRB170817 seen 1.7 seconds later by spaced-based γ-ray observatories, Fermi and Integral
then also seen in ground-based observatories: 10 hours later in optical, 20 days later in X-rays

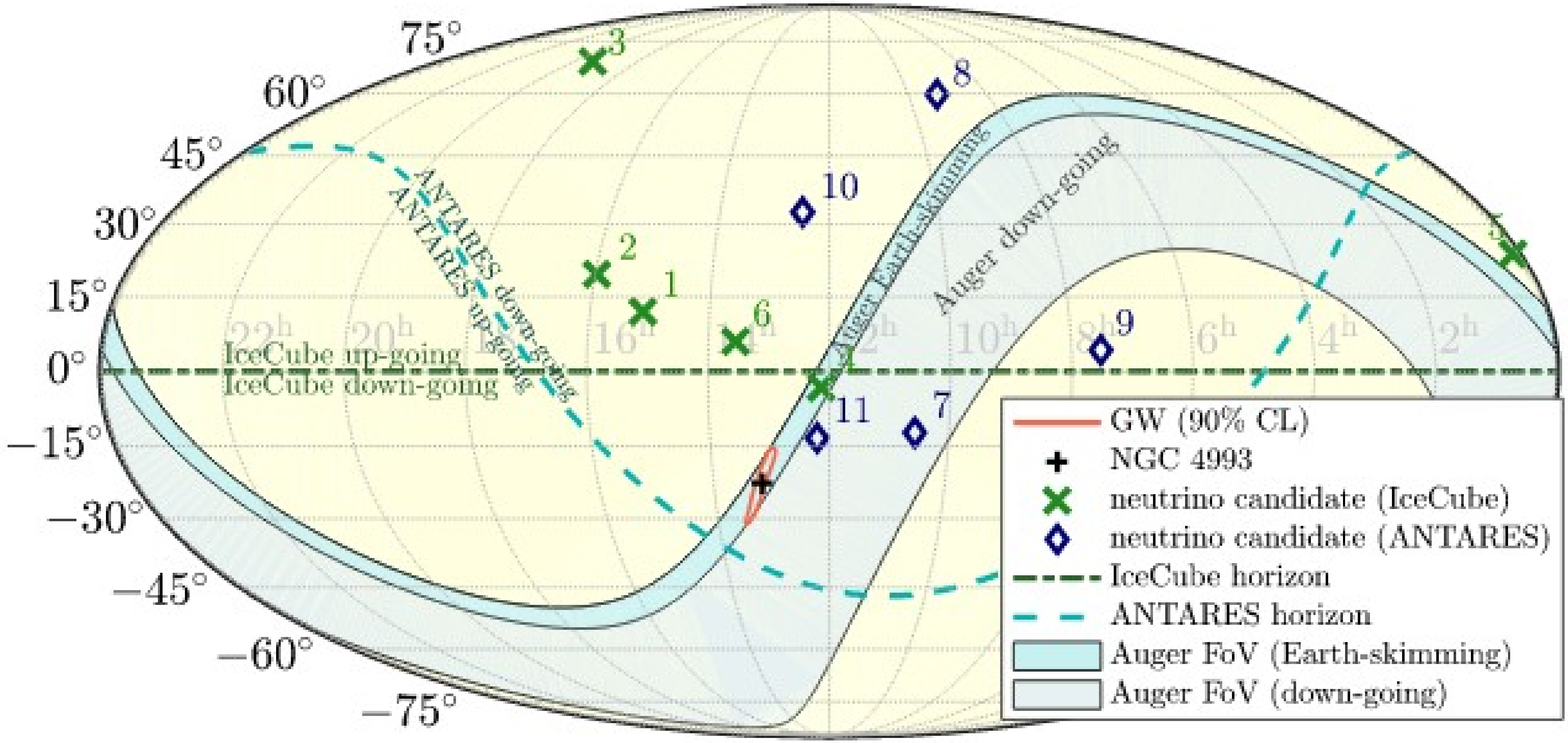
September 2017
IceCube high energy neutrino event
correlated with gammas observations at E>100 MeV (Fermi-LAT) and E>100 GeV (MAGIC)

1987A SuperNova, seen by KamiokaNDE-II, IMB, Baksan neutrino observatories
3 hours later seen by astronomers (even visible by naked eye)

SNEWS – the SuperNova Early Warning System started in 1999, automated in 2005

Outline:
High energy observatories
=> knowing the messengers
=> Lower energy observatories

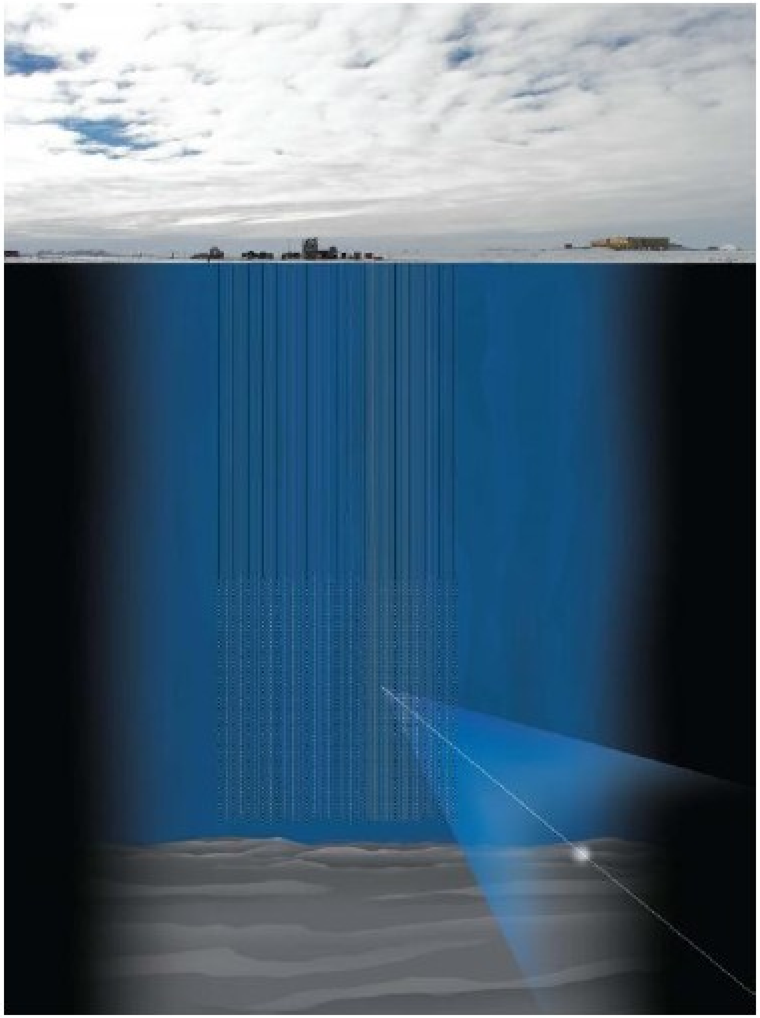
Sources and sky maps: search for neutrinos with the GWs

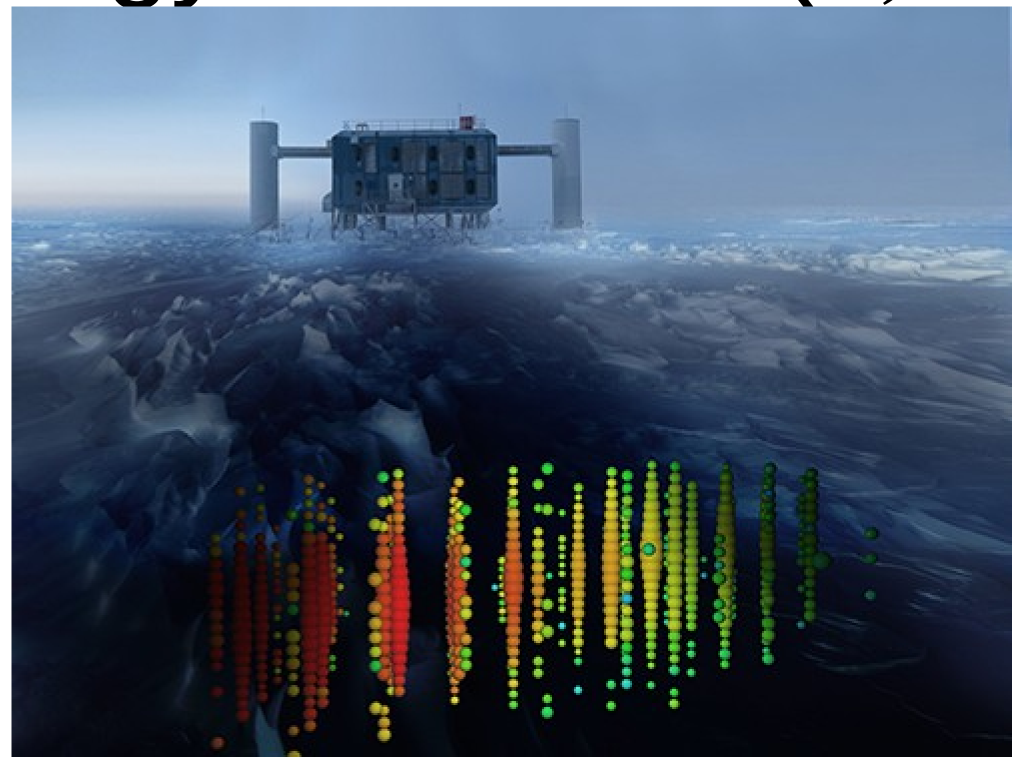


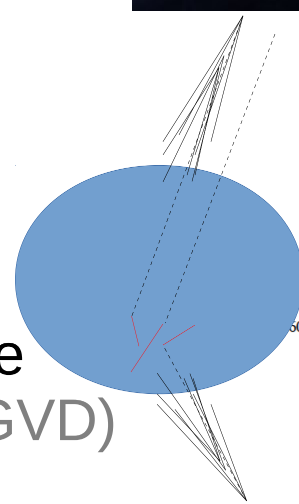
Astrophysical Journal Letters 850 (2017) L35

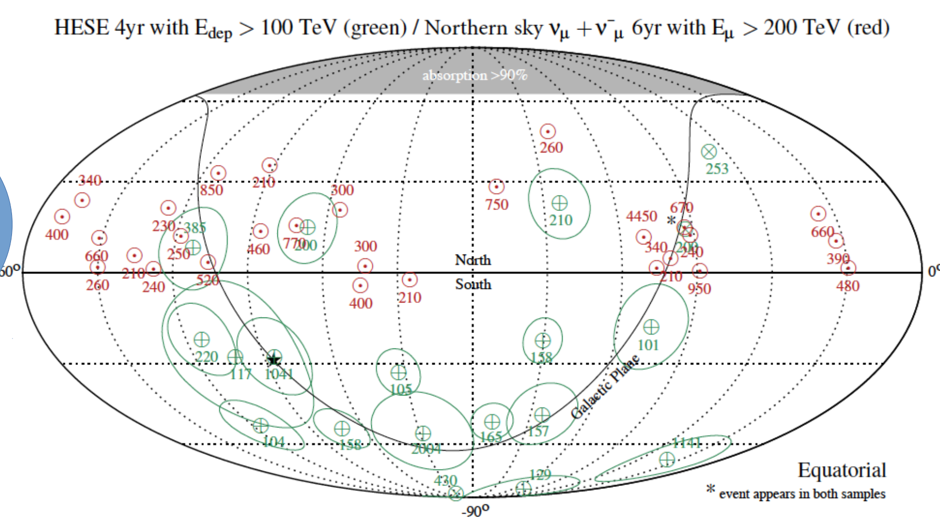
First binary neutron star merger detected in Gravitational Waves:
not seen in neutrinos, consistent with expectation for off-axis Gamma Ray Burst
>> All experiments will continue the Gravitational Waves fast follow-up programs

Catching high energy neutrinos (ν)







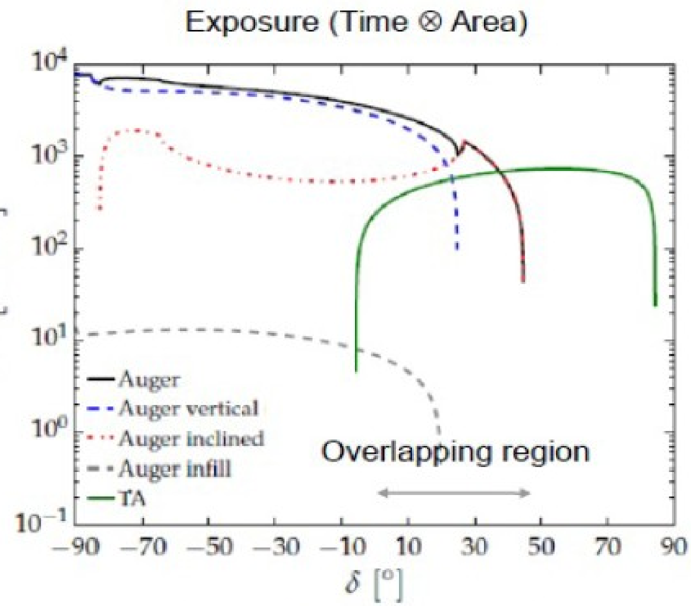


IceCube (1 km)³ in South Pole

Antares (Km3Net) + Baikal (GVD)

Auger dedicated to air-showers

Catching high energy cosmic rays



- Auger and TA are complementary

Charged Cosmic Ray observatories in both hemispheres

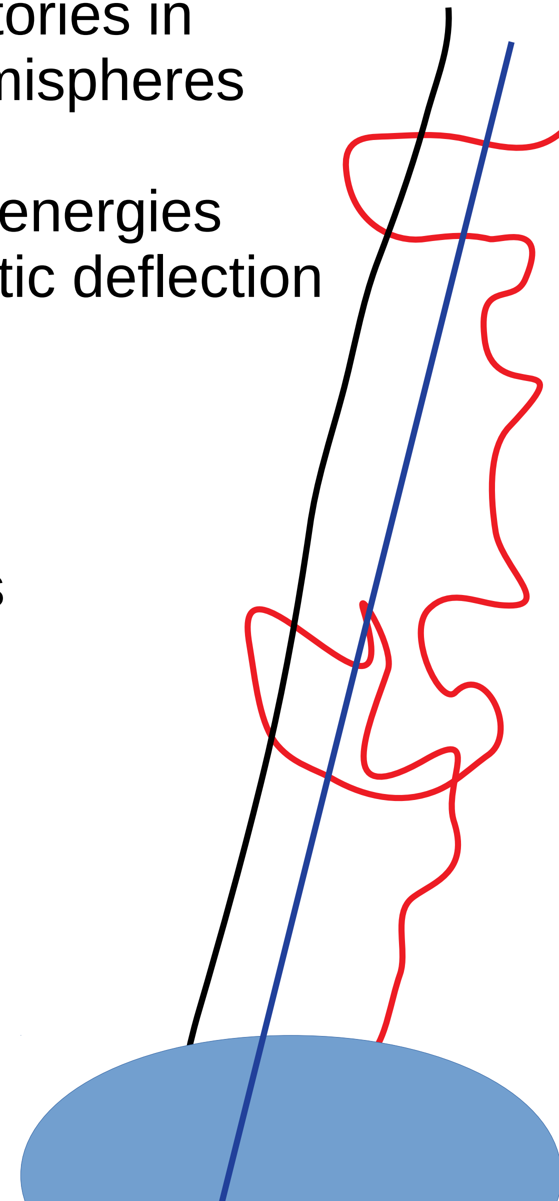
* higher energies
* magnetic deflection

$$pN \rightarrow \pi^+ \pi^- \pi^0 ...$$

$$\pi^+/\pi^- \rightarrow \mu\nu$$
$$\pi^0 \rightarrow \gamma\gamma$$

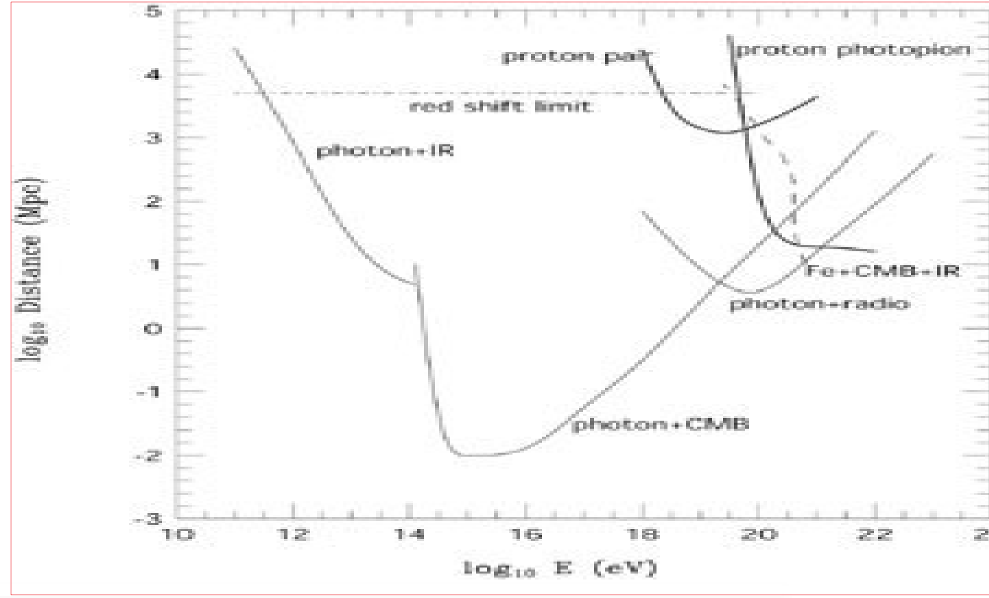
Secondary neutrinos and gammas can better point to the sources

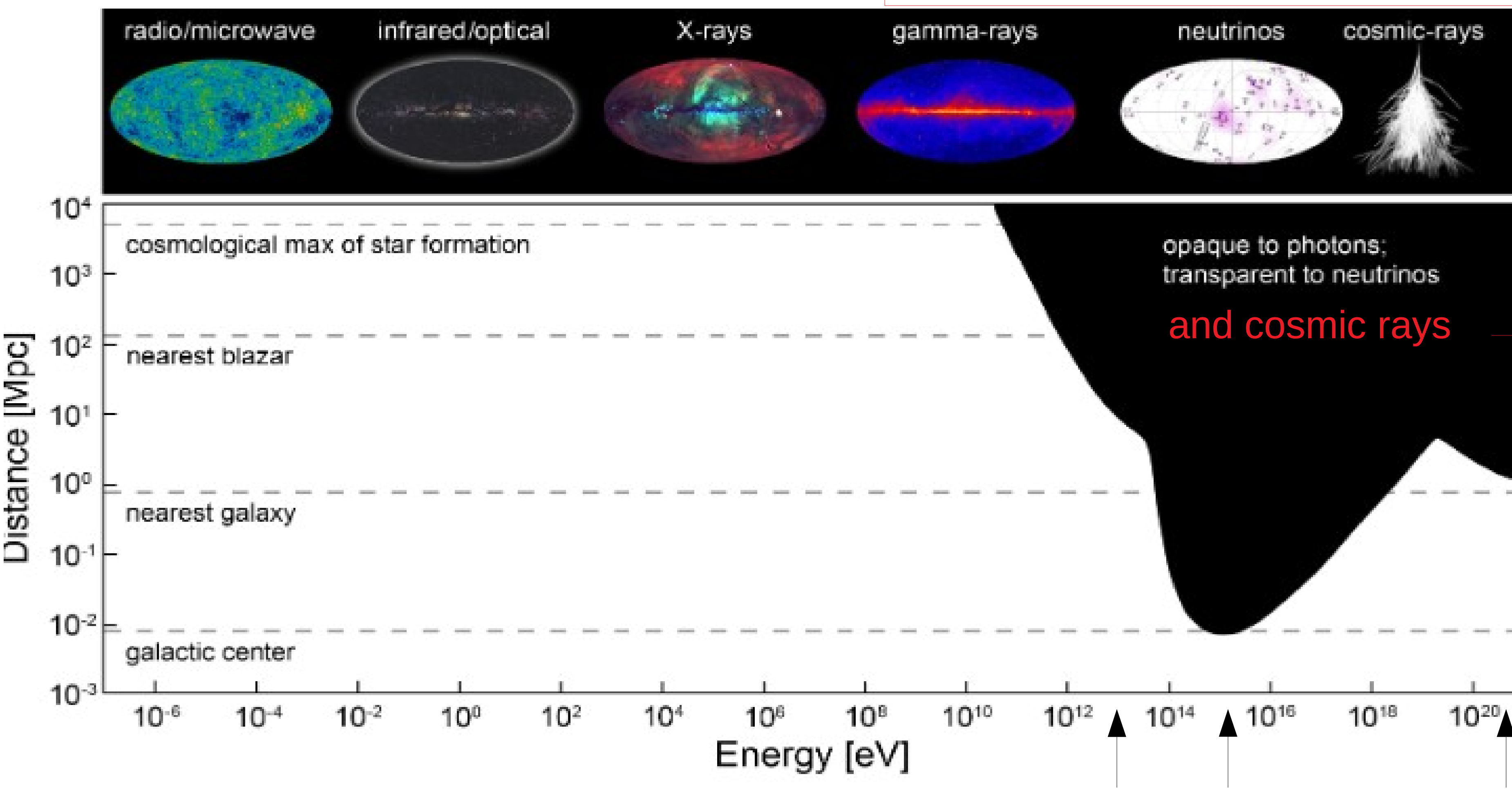
* background from charged CR
* lower energy, less transparency



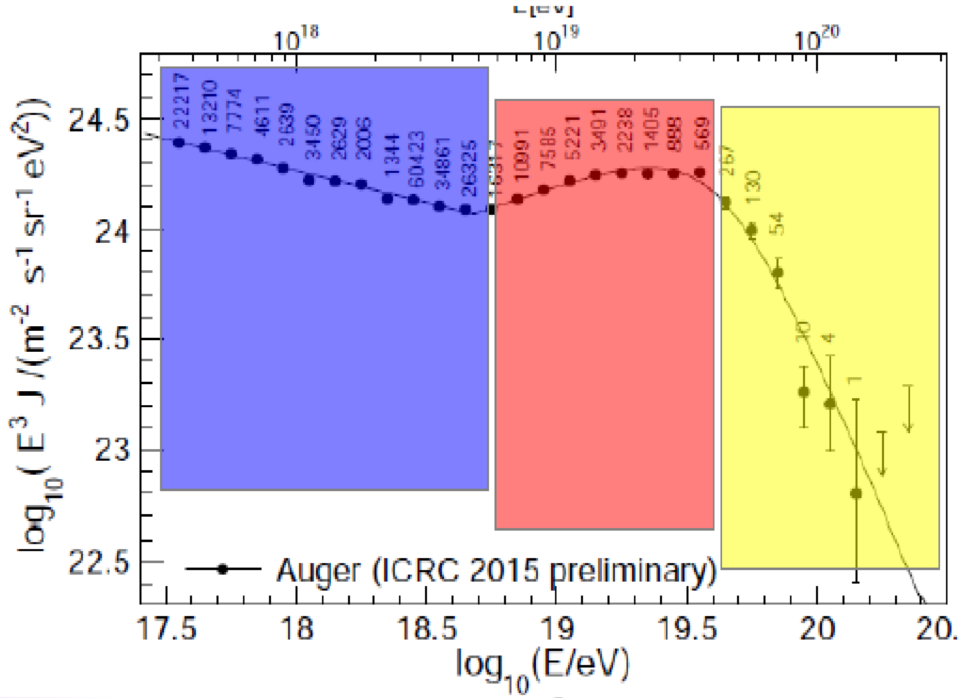
Gamma IACTs and Arrays in Northern hemisphere
CTA and LATTES proposed for Southern hemisphere
(in addition to the space-based γ telescopes)

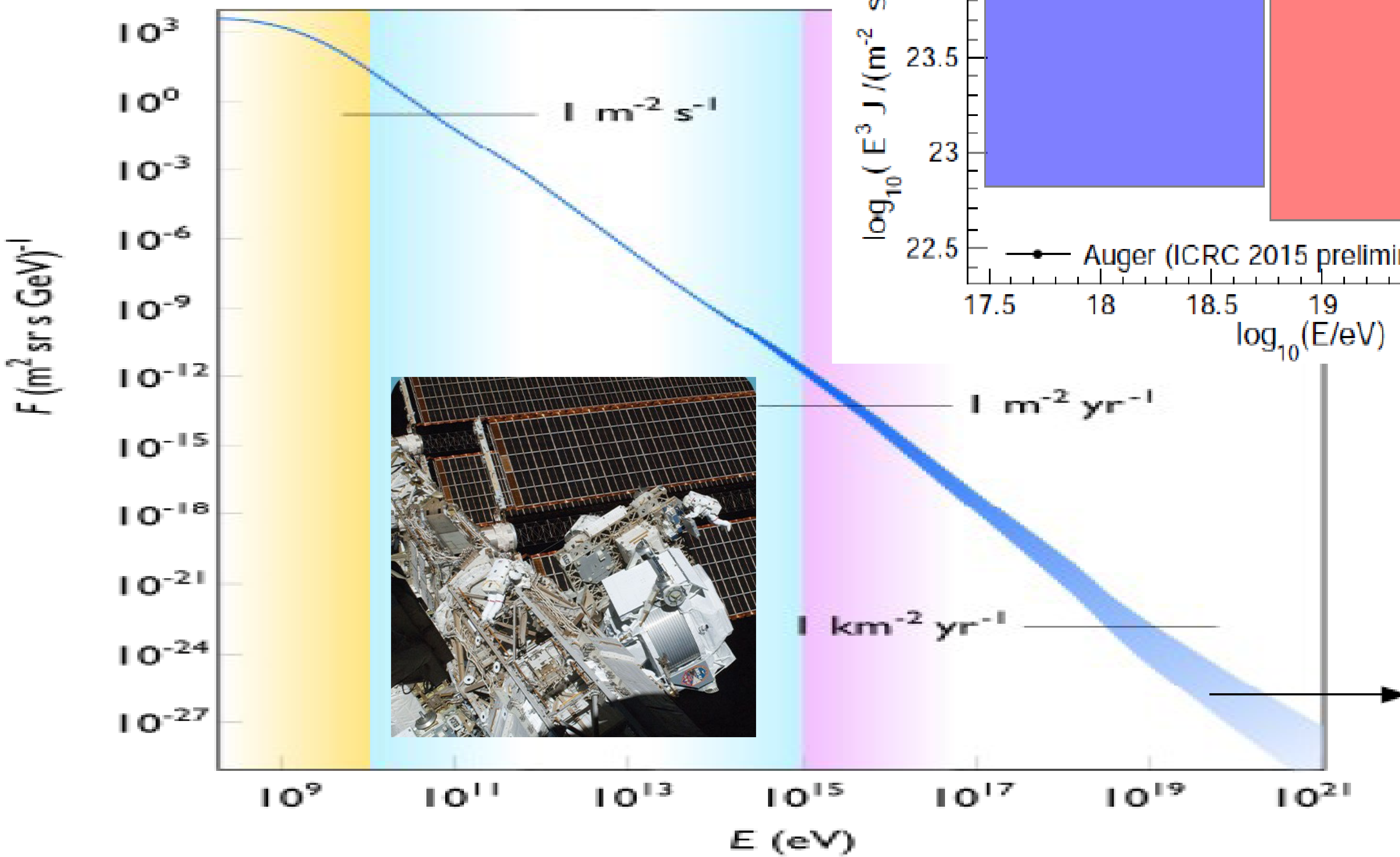
Universe Transparency





Charged particles fluxes at Earth





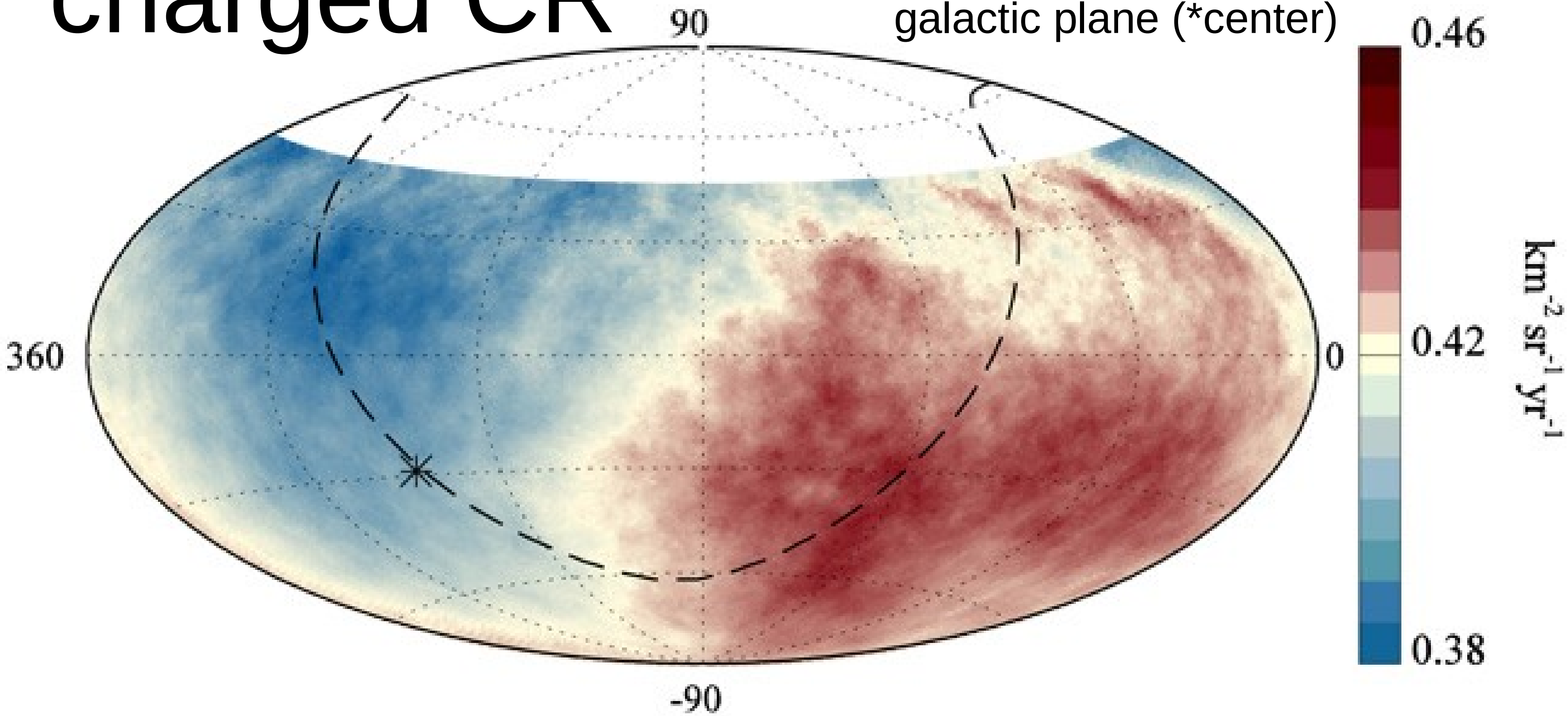
AMS installed in the ISS to identify isotopes and study propagation at lower energies
Auger needs to use the atmosphere as a calorimeter detector for very high energies

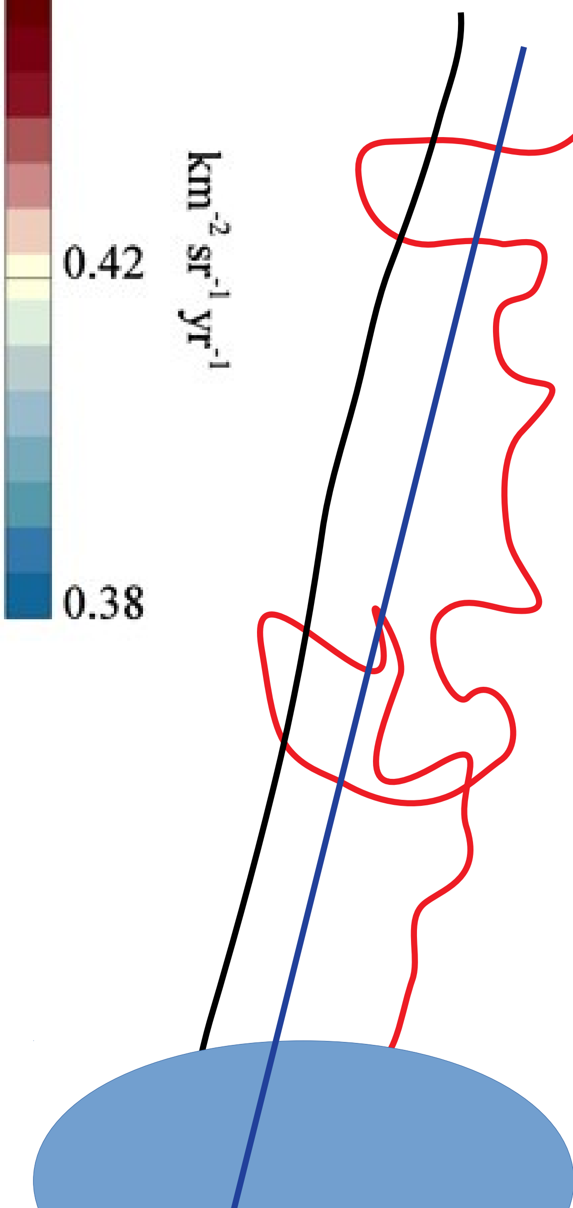
High energy sources: charged CR

$pN \rightarrow \pi^+ \pi^- \pi^0 ...$

$\pi^+/\pi^- \rightarrow \mu\nu$
$\pi^0 \rightarrow \gamma\gamma$

galactic plane (*center)





Science 357 (2017) 1266

smoothed map of very high energy charged cosmic rays

charged cosmic rays are deflected by magnetic fields but at high energy ($E > 8 \times 10^{18}$ eV) directions are less isotropic

Auger results show they do not point to the galactic plane, instead seem to follow the extra-galactic matter distribution

The Pierre Auger Observatory

1 particle / km² / century --> 30 / year

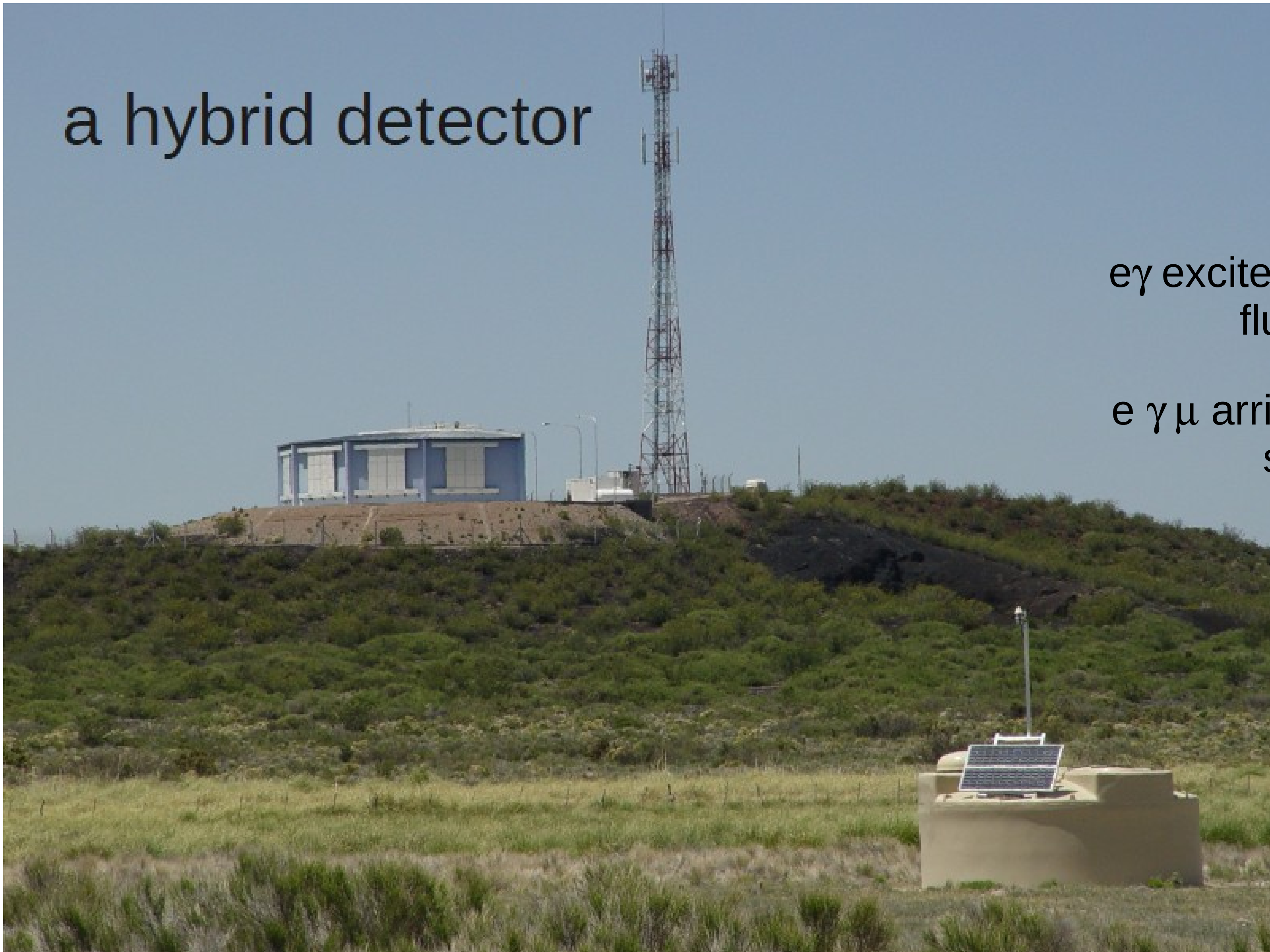
Malargüe, Mendoza, Argentina

The Pierre Auger Observatory

1 partícula/km^2/século == 30 por ano

-----------------------> Lisboa, Portugal

The Pierre Auger Observatory: fluorescence and surface detectors



$pN \to \pi \ldots$

$\pi^0 \to \gamma\gamma$

$\pi^+/\pi^- \to \mu\nu$

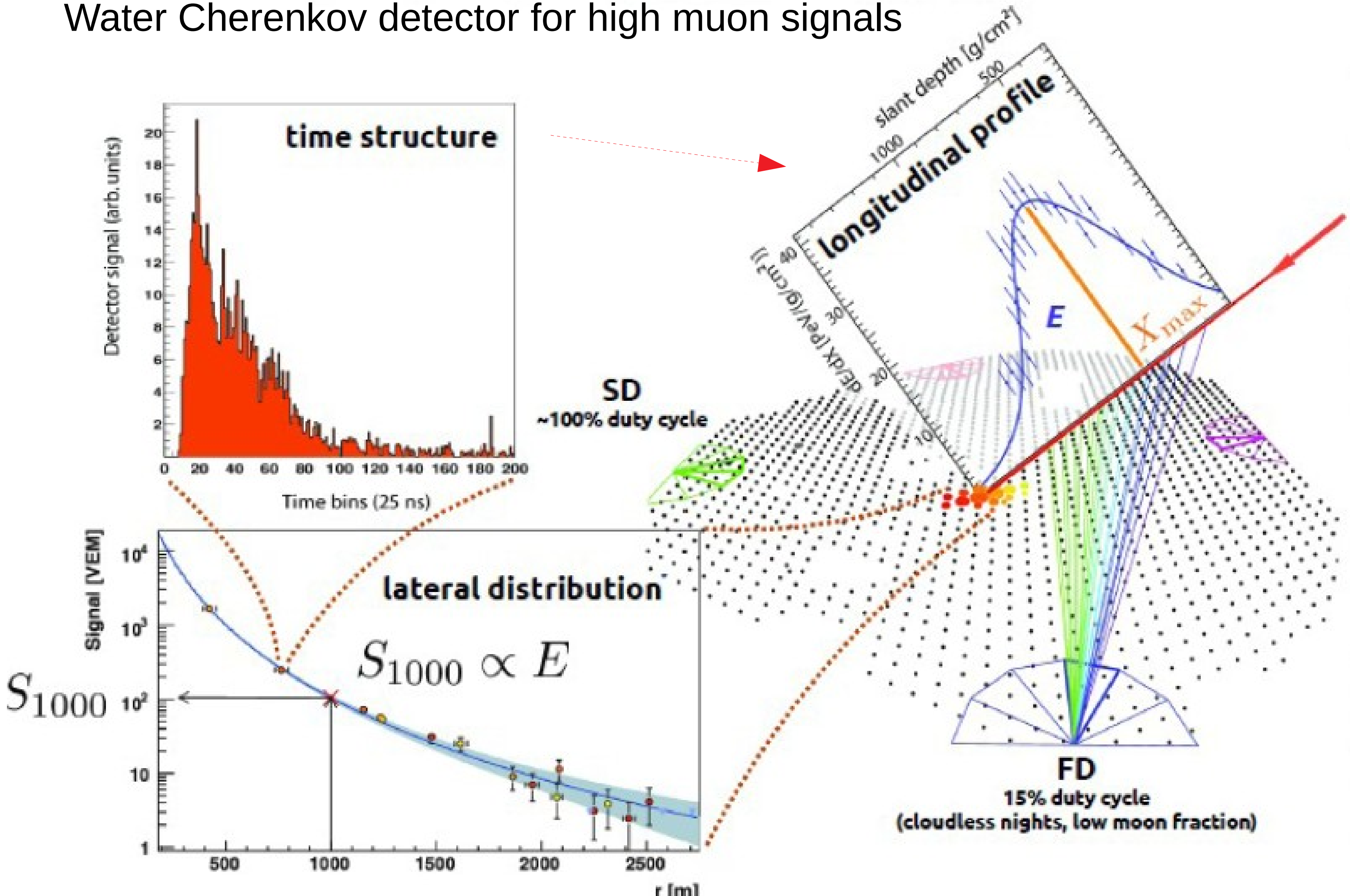
eγ excite atmosphere => fluorescence light

e γ μ arrive to ground => spread over km²

The Pierre Auger Observatory: fluorescence and surface detectors

4 x 6 (+ 1 x 3) FD stations, imaging the (em) shower development in the atmosphere
1600 SD stations w/ 1500 m (& 750 m) spacing, sampling the lateral (em/mu) distributions

Water Cherenkov detector for high muon signals



Identifying the messengers

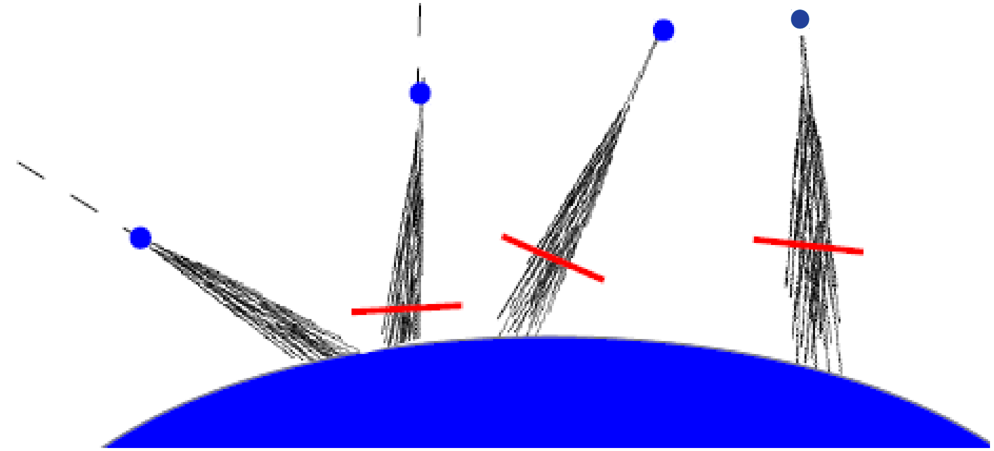
Neutrinos can cross the all atmosphere
so look for horizontal “young” showers
(ie, still close to electromagnetic X_{max})
no neutrino candidates (E_{Auger}>>$E_{IceCube}$)

Photons are electromagnetic showers
w/ less muons and closer to the ground
(but less different from usual showers)
gammas limited to <1% of the flux

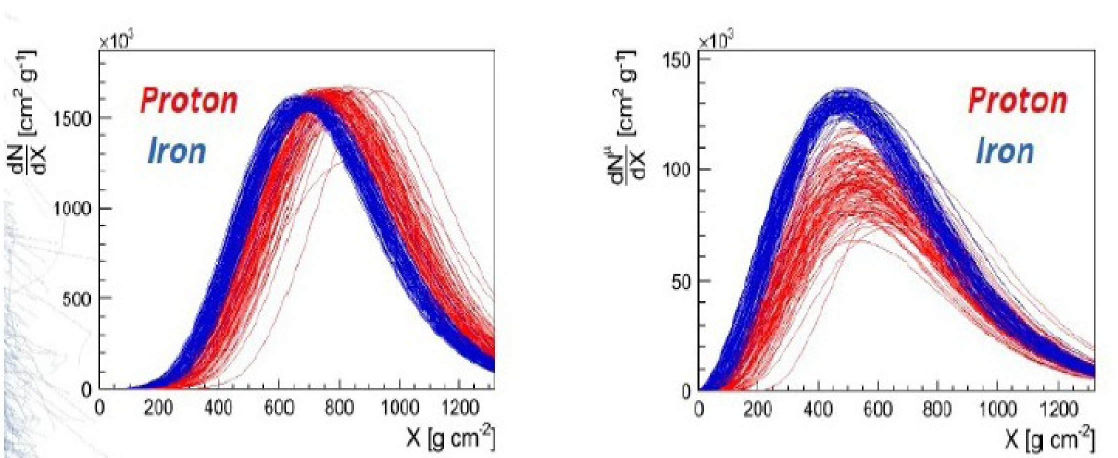
Finding no neutrals for sky maps,
=> separate iron / proton showers

1 Iron (E) ~ N x Proton (E / A)
iron showers develop *faster*
with *many more* muons
and *much less* fluctuations
(need more detailed studies)

Neutrinos? Photons? Nuclei (p – Fe)?



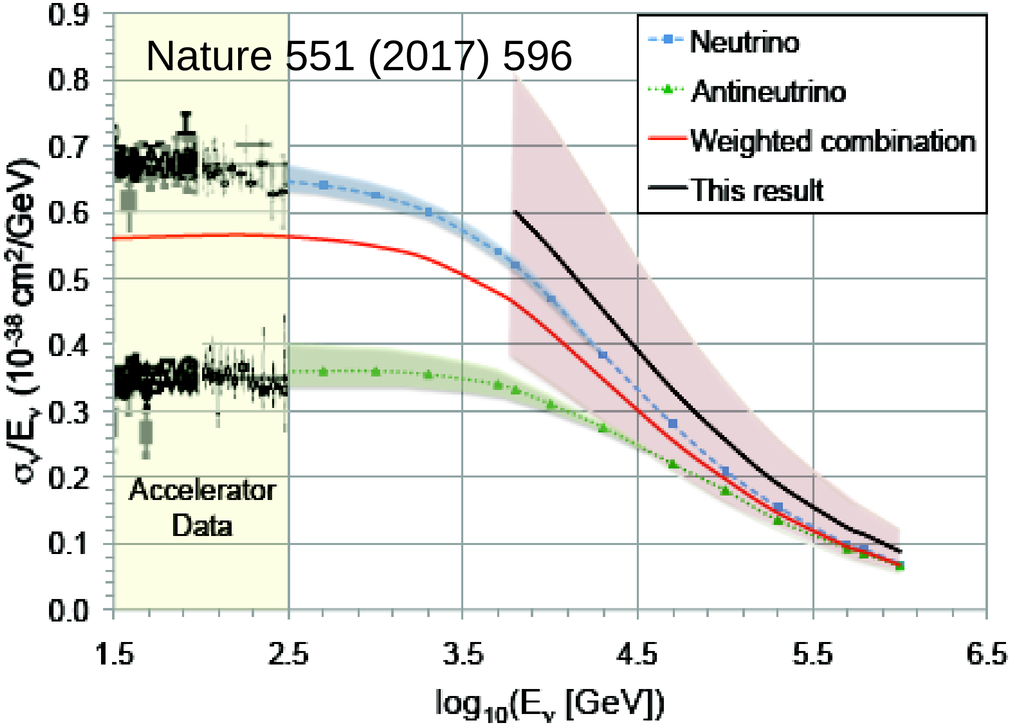
Main variables relate to
depth of shower maximum: Xmax = X1 + DX
particle content at ground: Signal = μ + e/γ



Electromagnetic shower imaged, indirectly a sum of all π° decays

Some muons arrive at ground, directly from charged π decay points

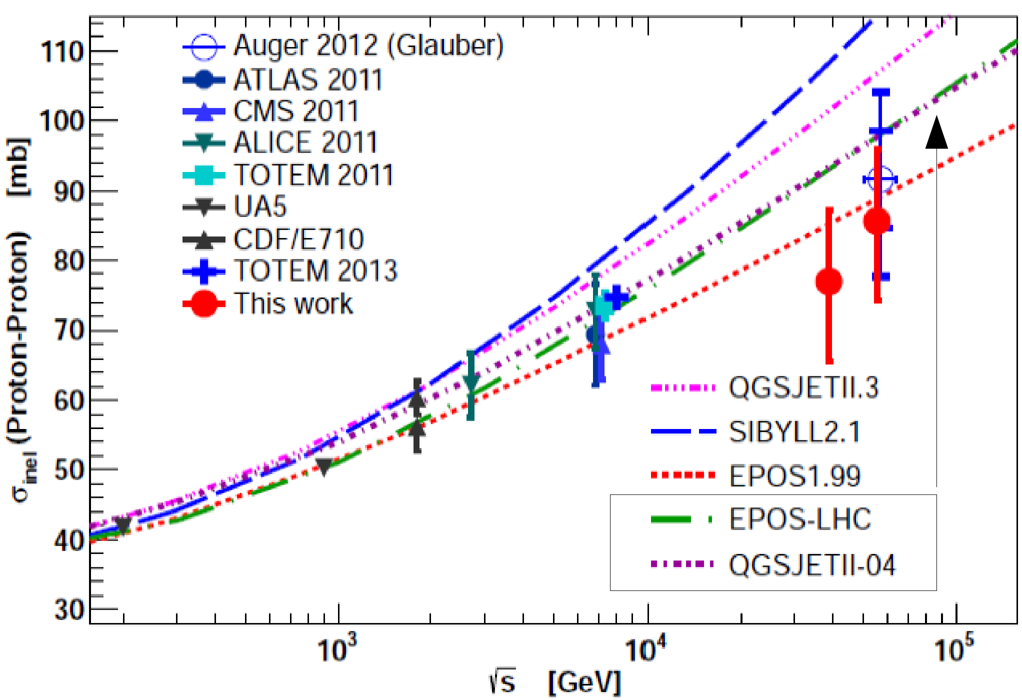
Particle physics at observatories



cross-sections, ie mean free path

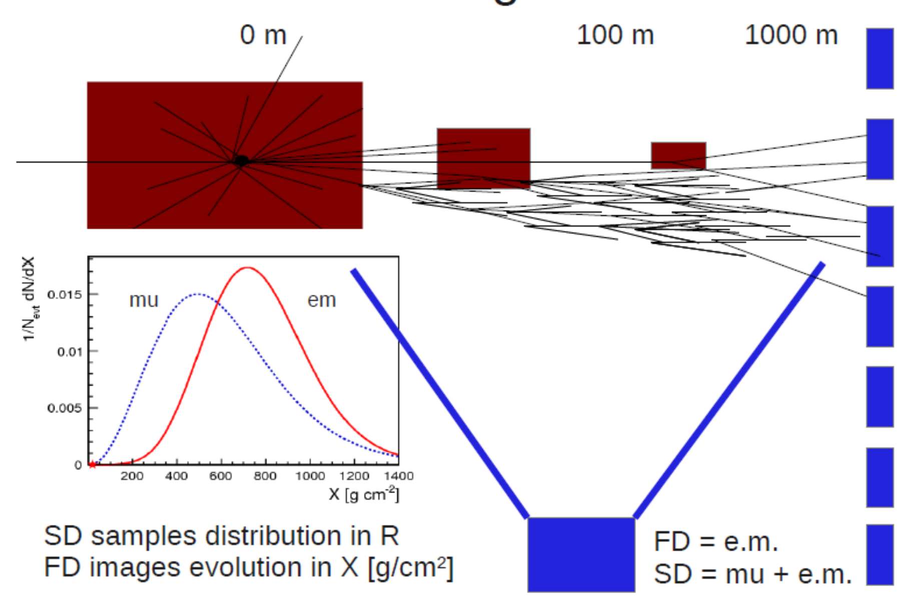
of neutrinos in the Earth and

of protons in the atmosphere

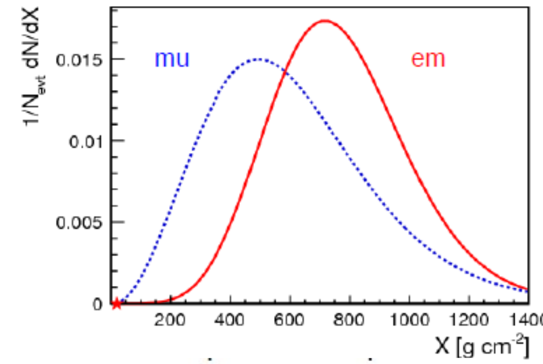


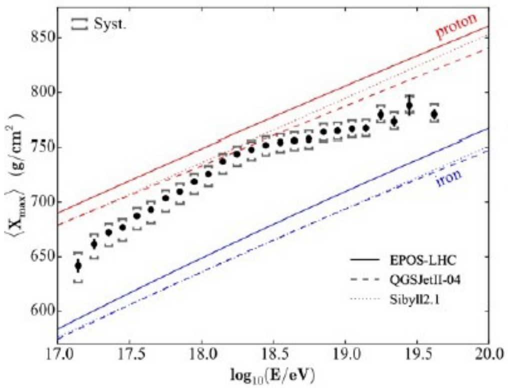
$$s = M^2 = (E_1+E_2)^2 - (P_1+P_2)^2 \sim 2\, E_1\, E_2$$

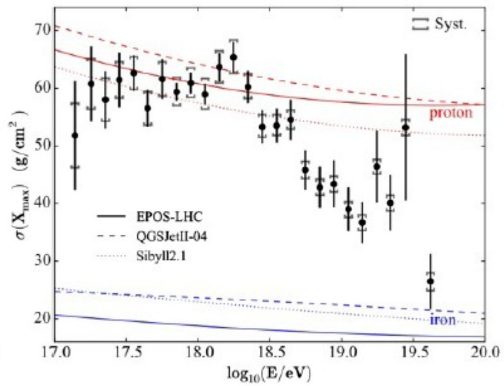
Detectors: Auger vs LHC

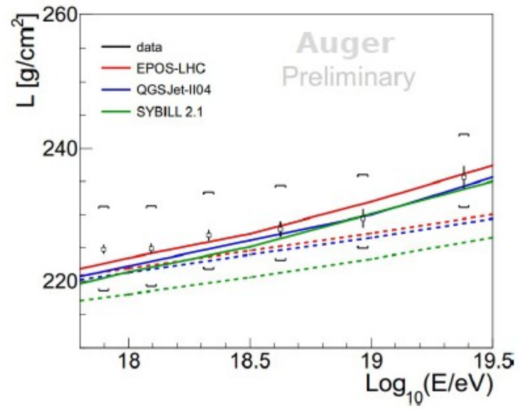


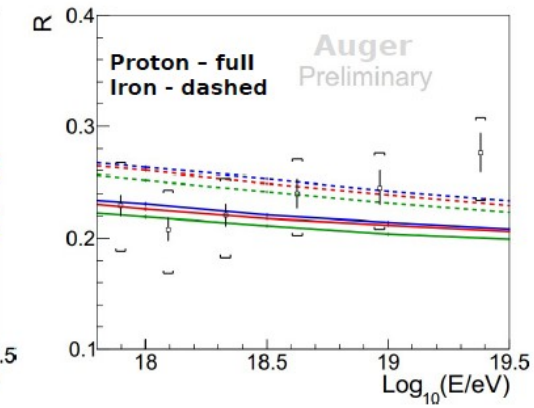
Knowing the messengers: present and future at Auger

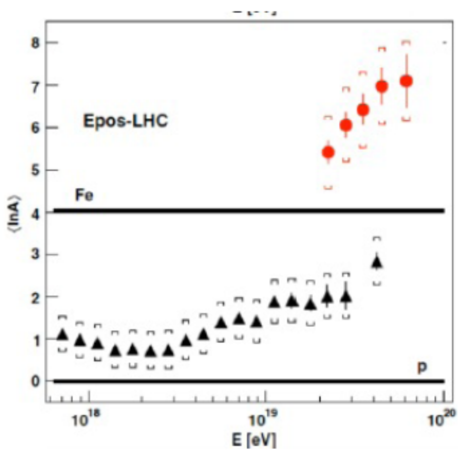


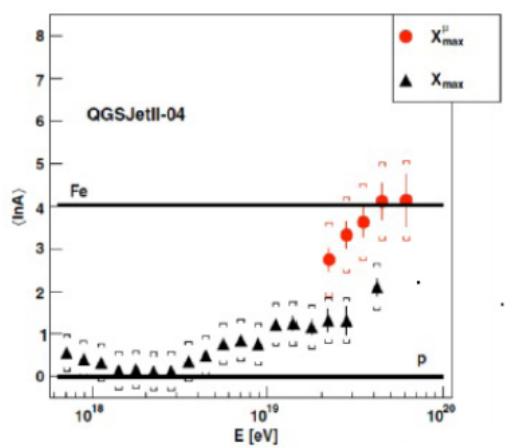


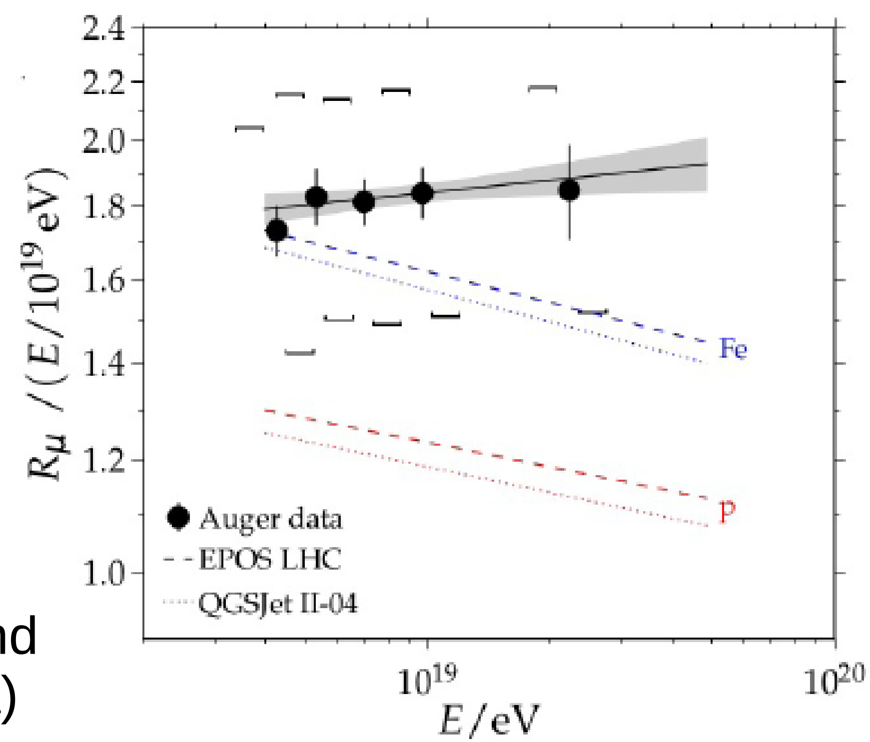












Electromagnetic component very well described
Muonic model description is inconsistent with it:

adding extra detectors to separate both at ground
(will allow more direct comparisons with TA data)

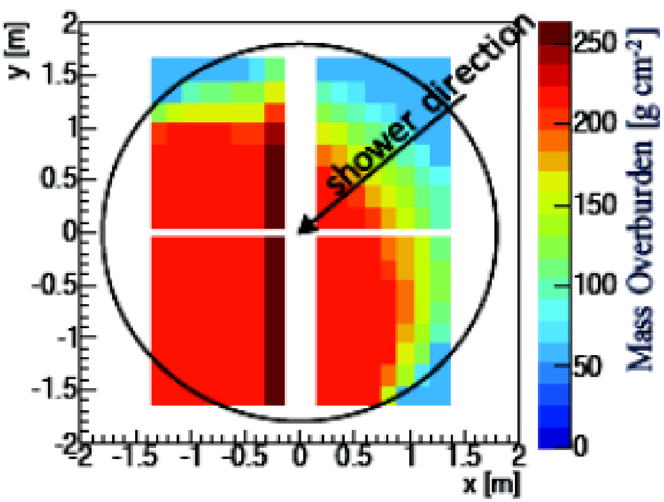
Knowing the messengers: re-connecting to the LHC

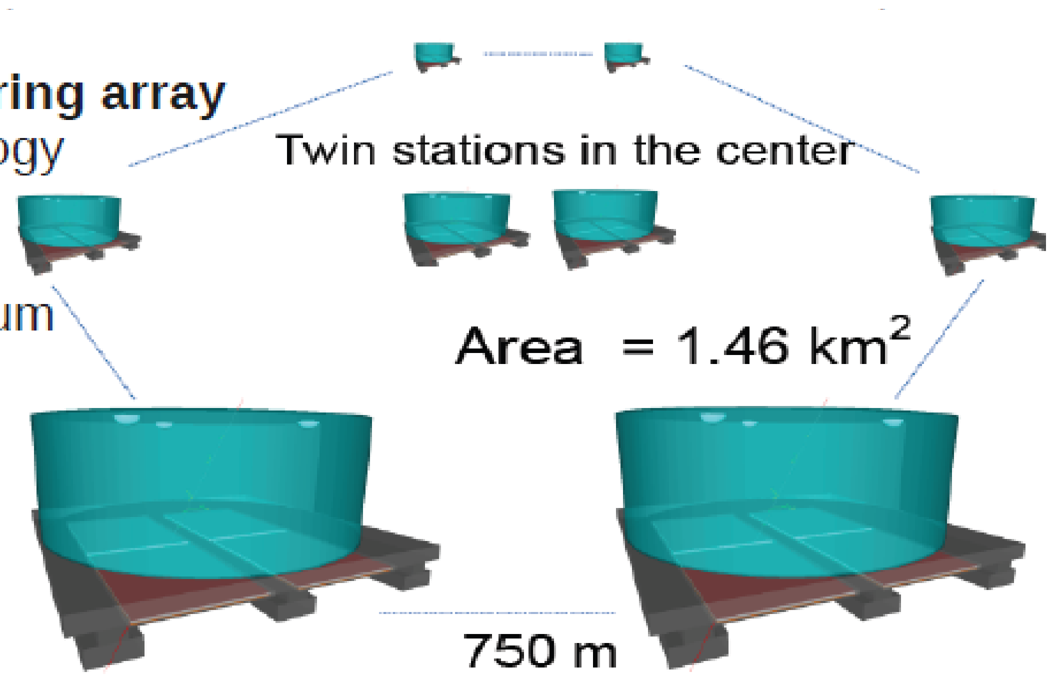
efforts to extend observatory to lower energies, with extra FD, infill SD, and muon counters

preparing MARTA engineering array
exploring LIP's RPC technology

identify single muons
measure their energy spectrum

(using 256 cells/station)





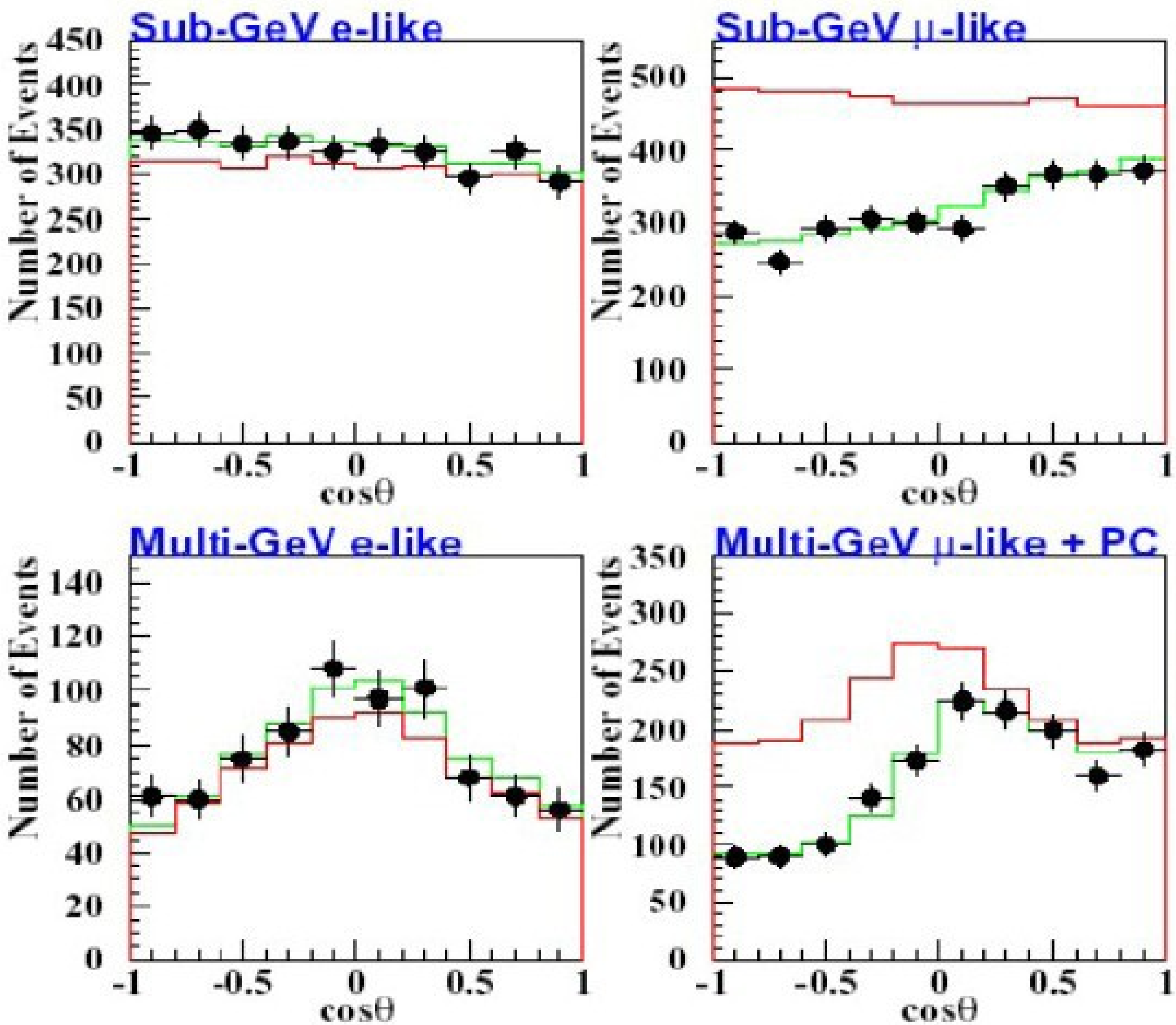
Hexagonal unitary cell (baseline design)

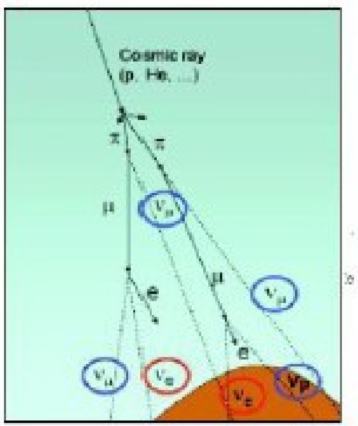
1000 events of 10^{17} eV/month

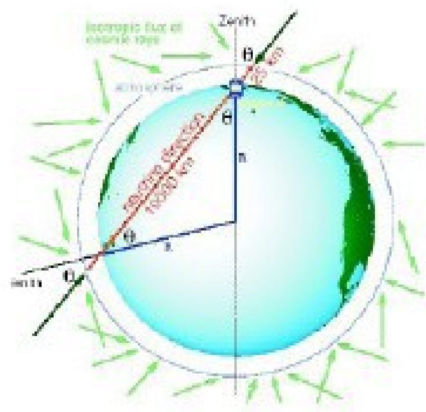
LATTES will use similar detector for γ-ray showers
but there the RPCs will be above the water tanks

(next talk on RPCs; MARTA & LATTES in two days)

Knowing the messengers (history): neutrinos in cosmic ray showers

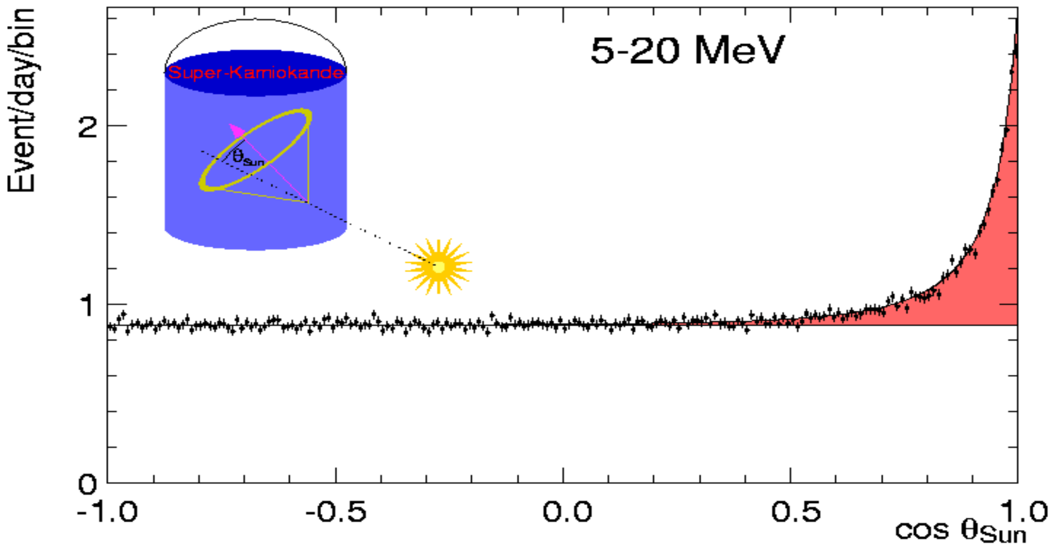


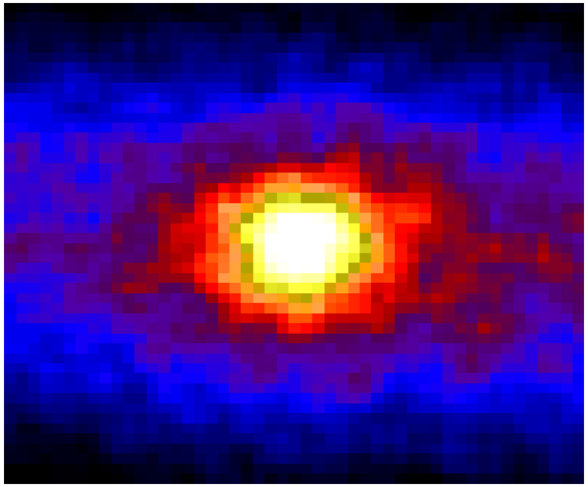




2. Lower energy observatories

Knowing the messengers (history): solar neutrino problem and solution





Direction sensitivity from electron scattering in water Cherenkov detector:
only 50% of the expected flux (recently SK measured day/night difference)

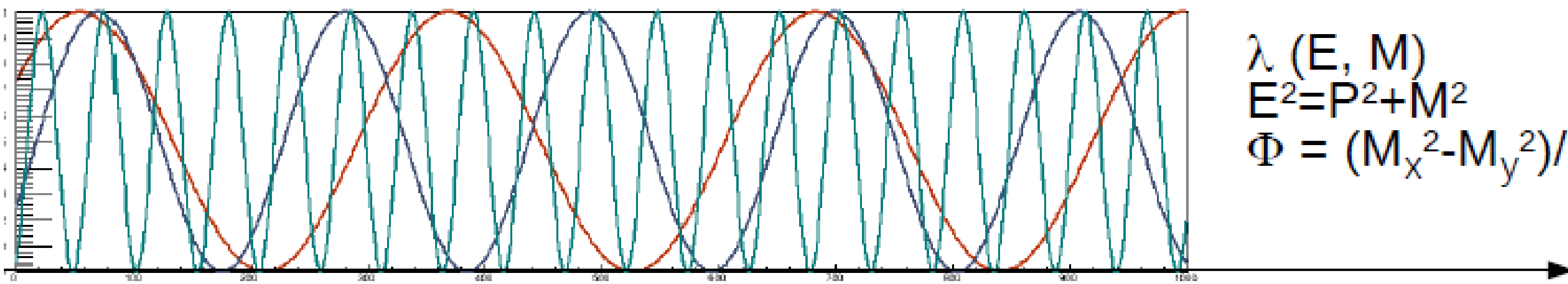
Need to separate the different neutrino types, with new interactions and detectors:
SNO measured Charged and Neutral Current interactions in (salted) heavy water

>> the total number of neutrinos (NC) is as expected in Standard Solar Model,
>> the number of electron neutrinos (CC) is just one third of the expected

Neutrinos change flavor (ν_e,ν_μ,ν_τ), oscillating from production to detection

Neutrino Oscillations: quantum mechanics of mass mixing

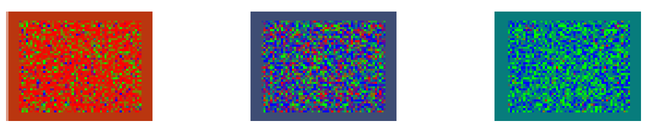
(Hands'on tomorrow)



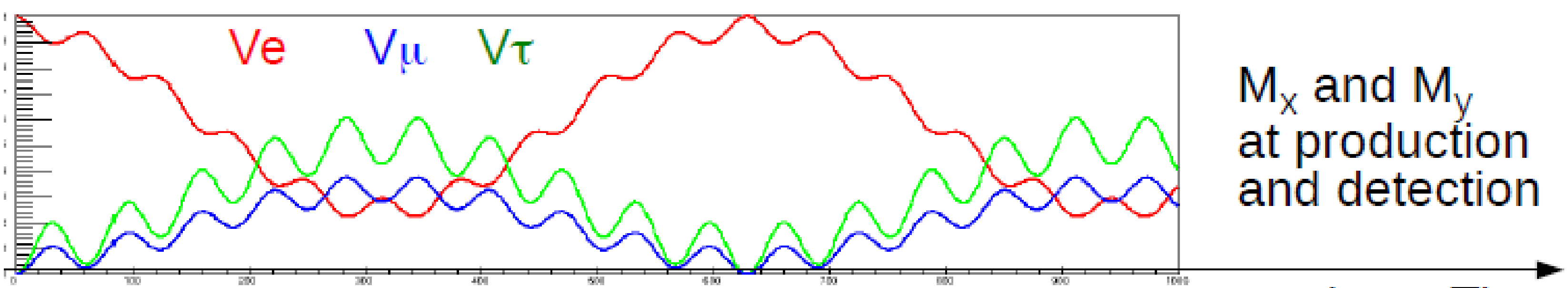
λ (E, M)
$E^2=P^2+M^2$
$\Phi = (M_x^2 - M_y^2)/E$

L = c.Time

For propagation, only energy and mass are relevant
For interaction, only the energy and flavor are relevant



Each mass has a combination of different interaction flavors
and each flavor has a combination of the different masses



M_x and M_y
at production
and detection

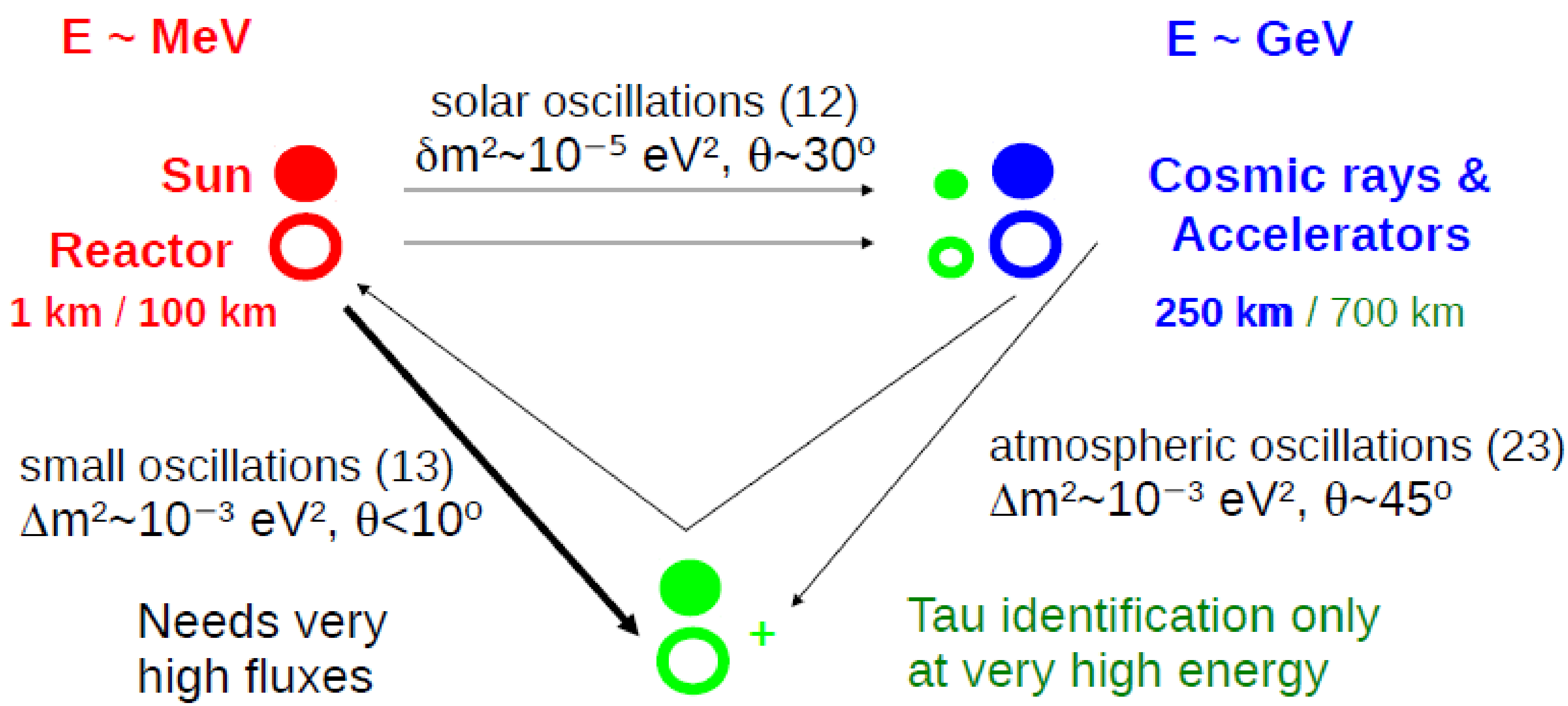
L = c.Time

(interaction in matter can be seen as inducing an effective mass)

neutrino mixing is known
neutrino mass is (still) unknown

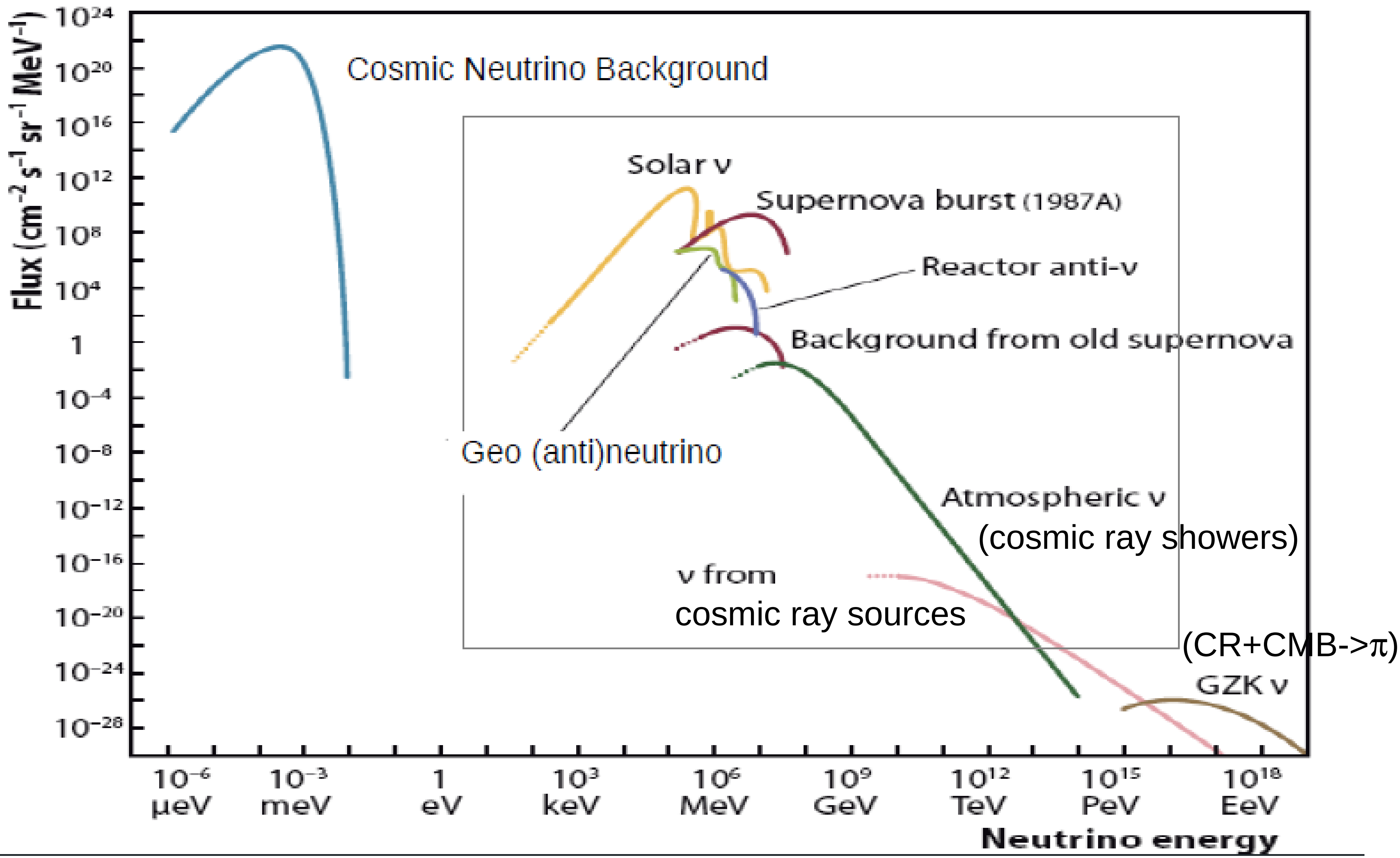
Oscillation frequencies depend of squared mass differences
Oscillation amplitudes depend on similarity of mass mixing in each flavor

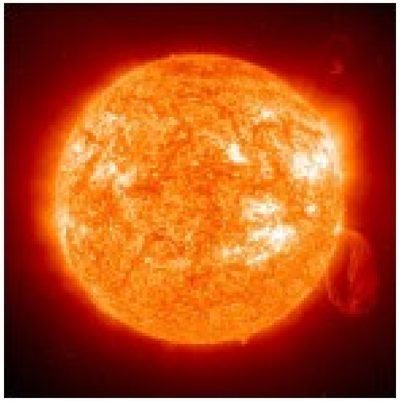
3 flavors of neutrinos (● & anti-neutrinos ○) for 3 mass values



human made beams confirmed discovery of observatories and added precision

back to neutrino observatories: HE sources, SN, Sun and Earth



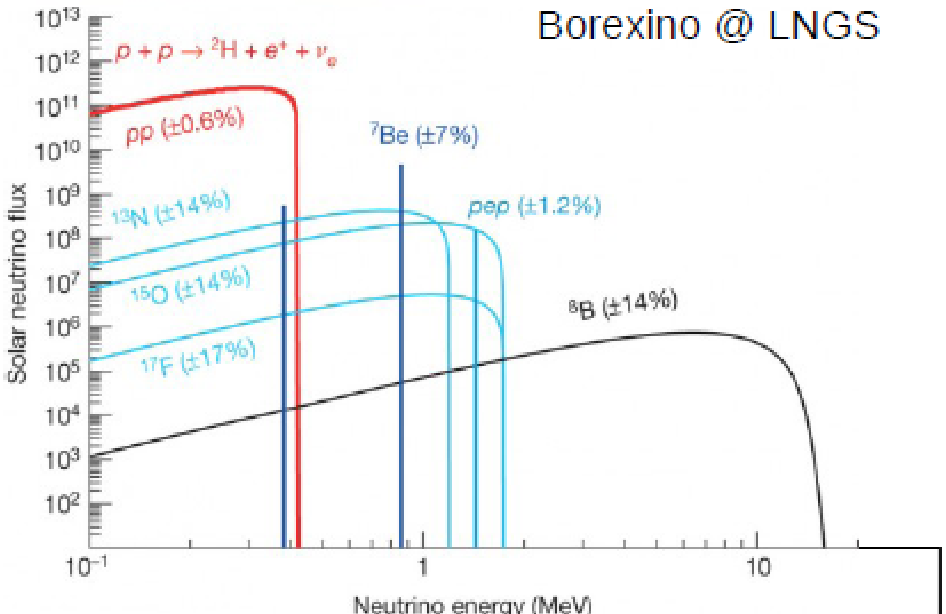


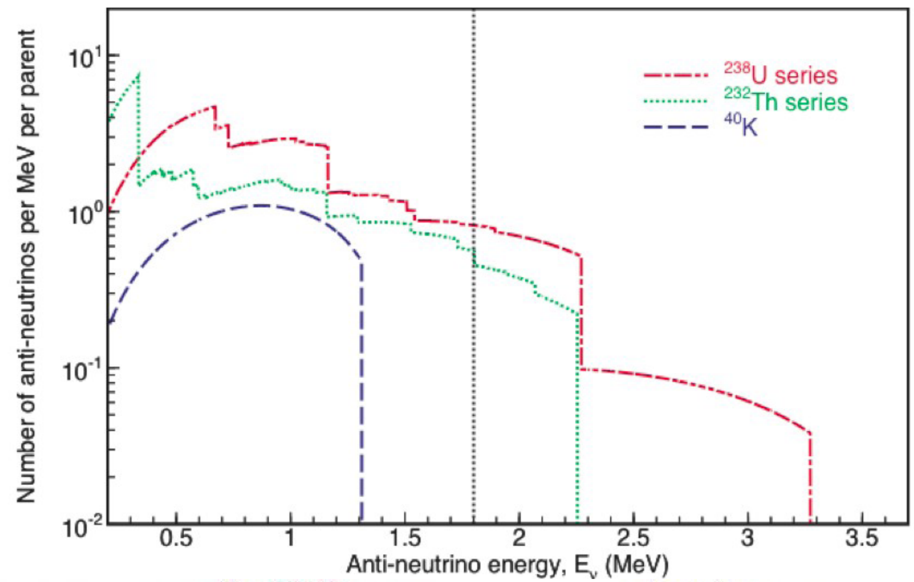
Solar ν and Geo $\bar{\nu}$

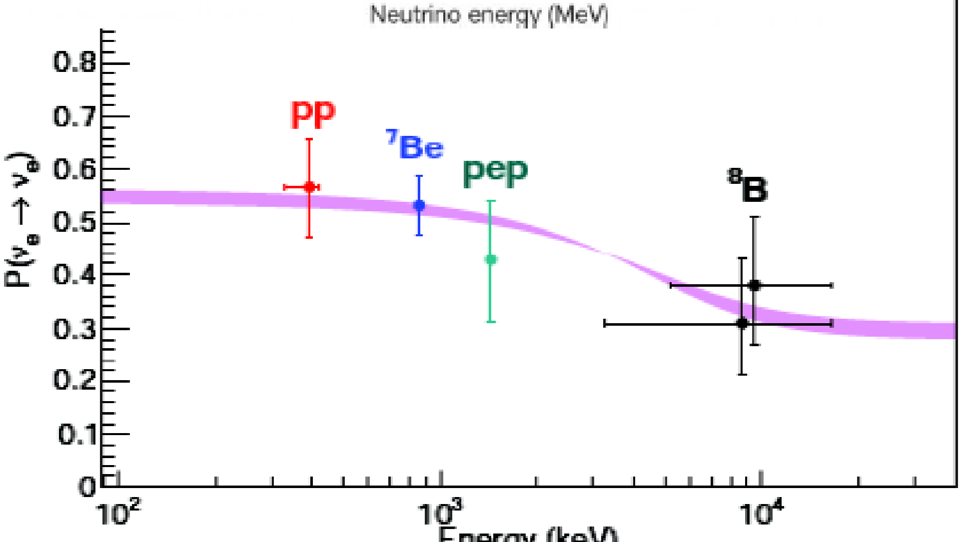
Nuclear Fusion — L~ 10^{12} /(cm².s)

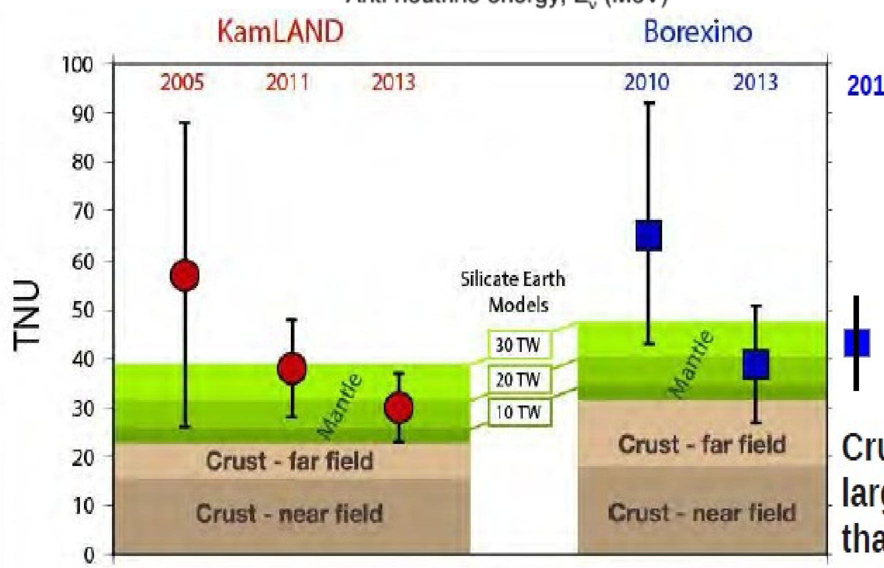
Nuclear Fission — L~ 10^{6} /(cm².s)

Borexino @ LNGS



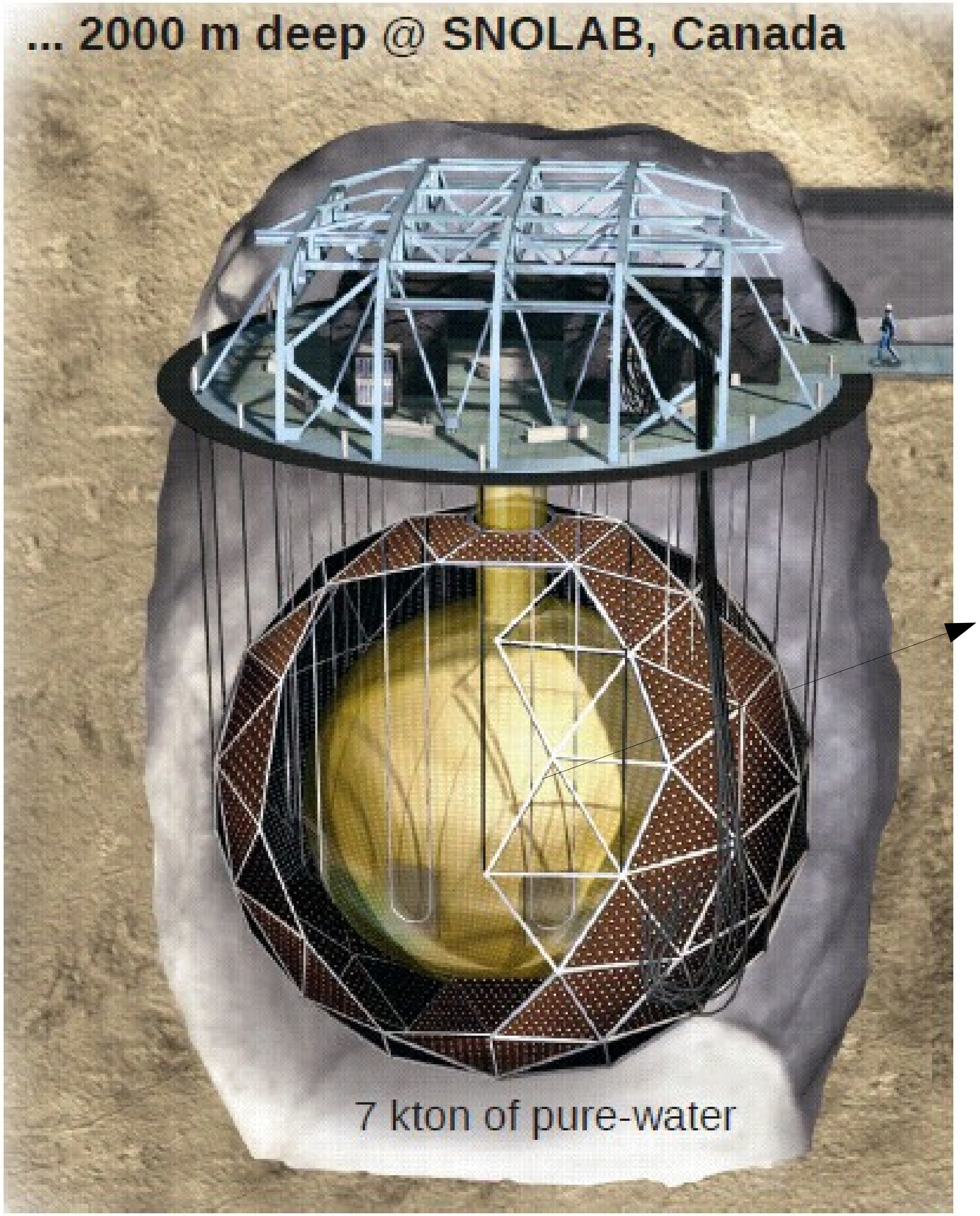






Crust flux is larger in Italy than in Japan

The SNO+ neutrino experiment



Follows / reuses hardware from
<u>Sudbury Neutrino Observatory</u>
(2015 Nobel prize for
solar neutrino oscillations)

9300 PMTs, 8.5 m away from centre

12 m diameter transparent sphere
holding 750 ton of active medium:

heavy water -> liquid scintillator

make lower energy events visible

loaded with 1.3 tons of ^{130}Te

Still an observatory but now focusing on neutrino mass!

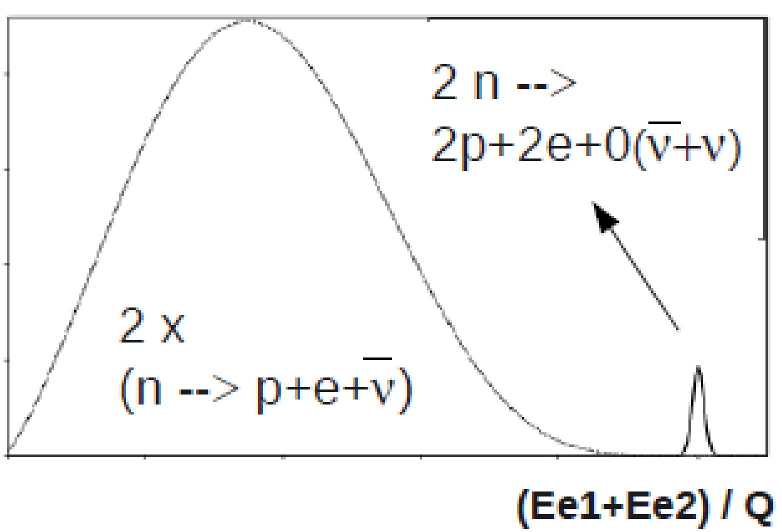
Neutrino mass origin neutrinoless double beta decays ??

Oscillations => neutrinos have mass / Beta decays => it is very, very small

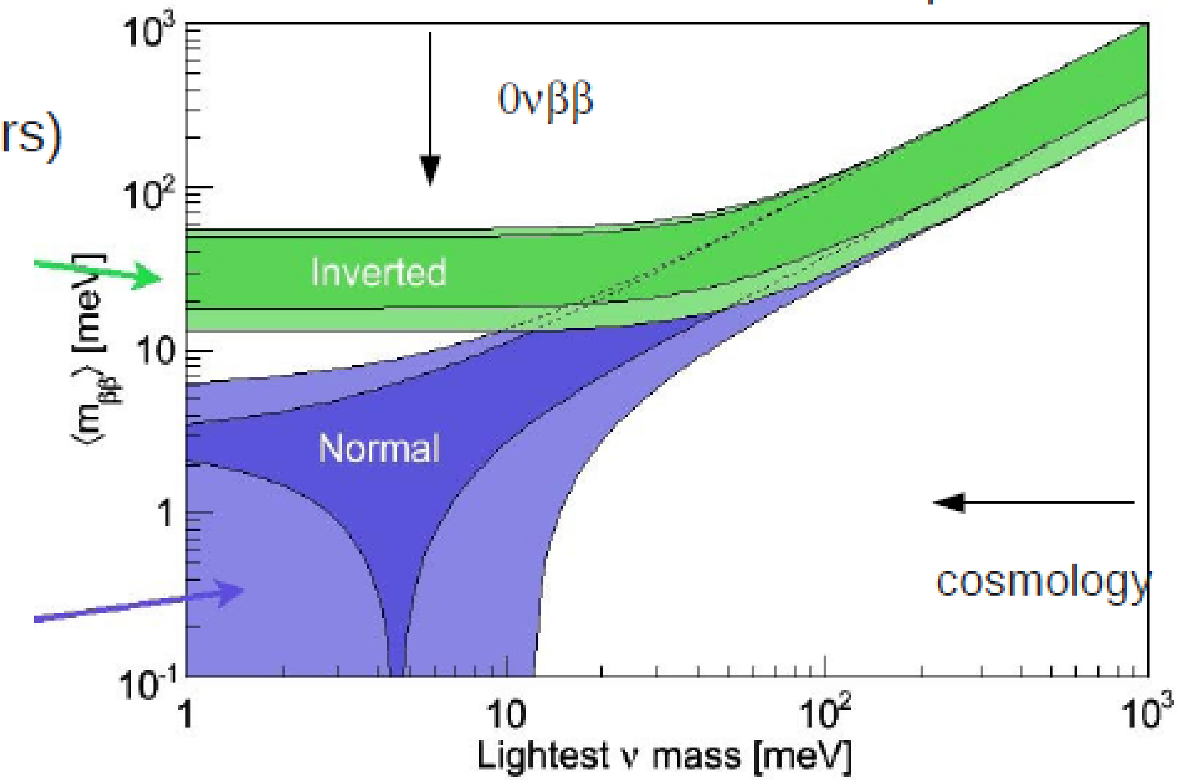
A different mechanism for mass? Are neutrinos Majorana particles?

A few isotopes have $2\nu\beta\beta$, if $\nu=\bar{\nu}$ also $0\nu\beta\beta$

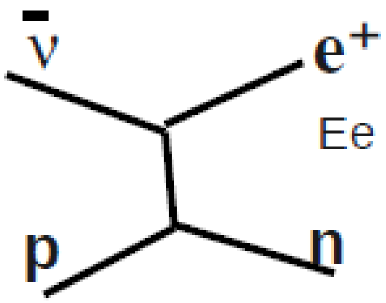
Very rare process (T1/2~ 10^{20} yrs)



mass bands from neutrino oscillation parameters



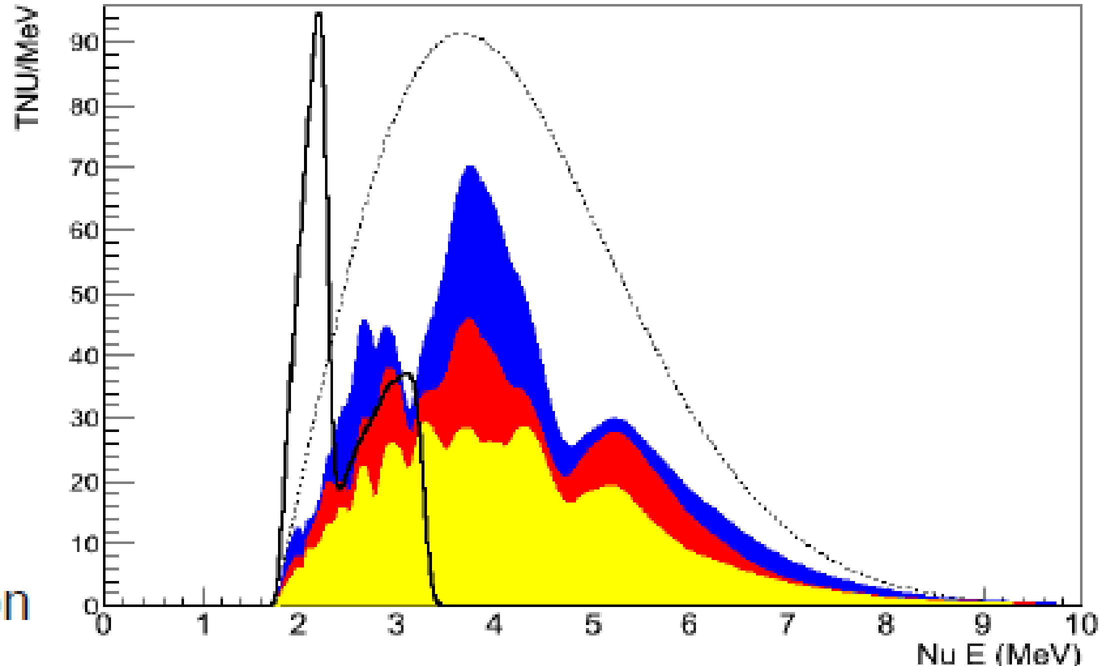
Particle, geophysics and astrophysics with anti-neutrinos



Ee = Eν + 0.8 MeV

200 μs delay, 2.2 MeV γ

* tagging of a delayed coincidence
* identification of gamma and positron
* reduction of neutron backgrounds
* and again the energy resolution



~ 100 ν / year from reactors
Oscillation signals @ 250 km, 350 km

~ 20 / year from U/Th in the Earth
measured only in Japan and Italy,
disentangle crust / mantle in global analysis

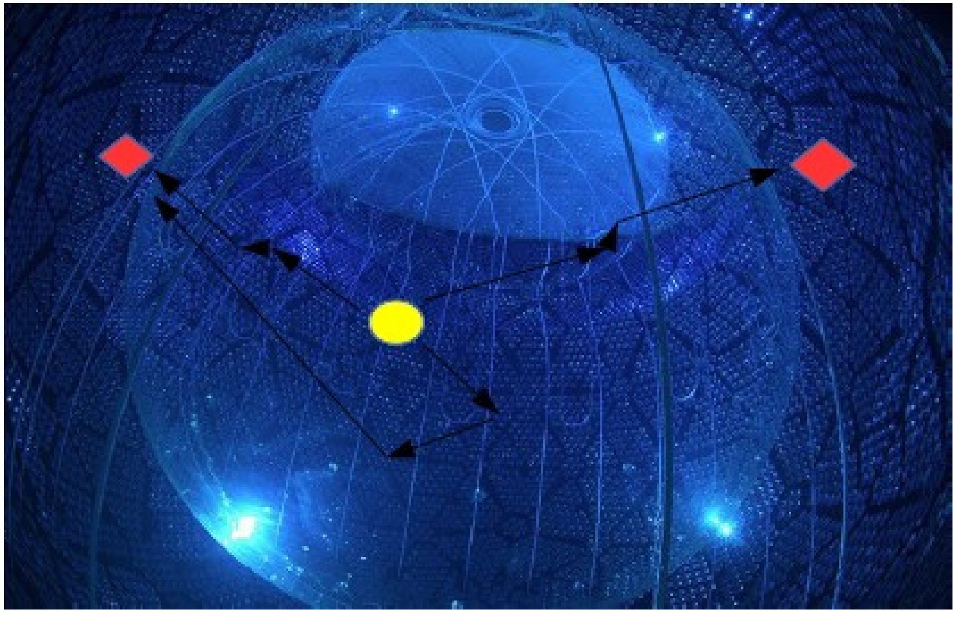
~ several / day in pre-supernova phases
monitor rate changes in an automated way

~ many ν / minute in a supernova explosion
neutrinos arrive 3 hours before light: SNEWS!

In addition to the 0νββ search
SNO+ is also an Observatory!

Currently in commissioning phase
not favorable for anti-nu detection
but could already catch a SuperNova

Present SNO+ and near future



2017-2018
Taking data with water filled detector

PMT / optical detector calibration,
external background measurements,
exercise data taking and analysis methods

(talk on wedesday about data analysis in SNO+)

2018: Fill detector with pure scintillator

scintillator optical properties and lower energy backgrounds,
start of the low energy non-$\beta\beta$ physics measurements

2019 – 2024: Tellurium loaded scintillator for $\beta\beta$ analysis
If $0\nu\beta\beta$ is found
>> proves that neutrinos are Majorana particles,
>> shows that the neutrino mass hierarchy is inverted,
>> places an upper bound on the absolute mass scales
>> would first need to confirm the results with different isotopes

Outlook

Multi-messenger astronomy is speeding up

Knowing the messengers is key for astrophysics analysis

Particle physics at observatories extends accelerator measurements

* first by providing the first beams and evidence for e^+, μ, π, ...

* later providing intense neutrino beams traveling large distances
  and allowing the discovery of neutrino oscillation, mixing and mass

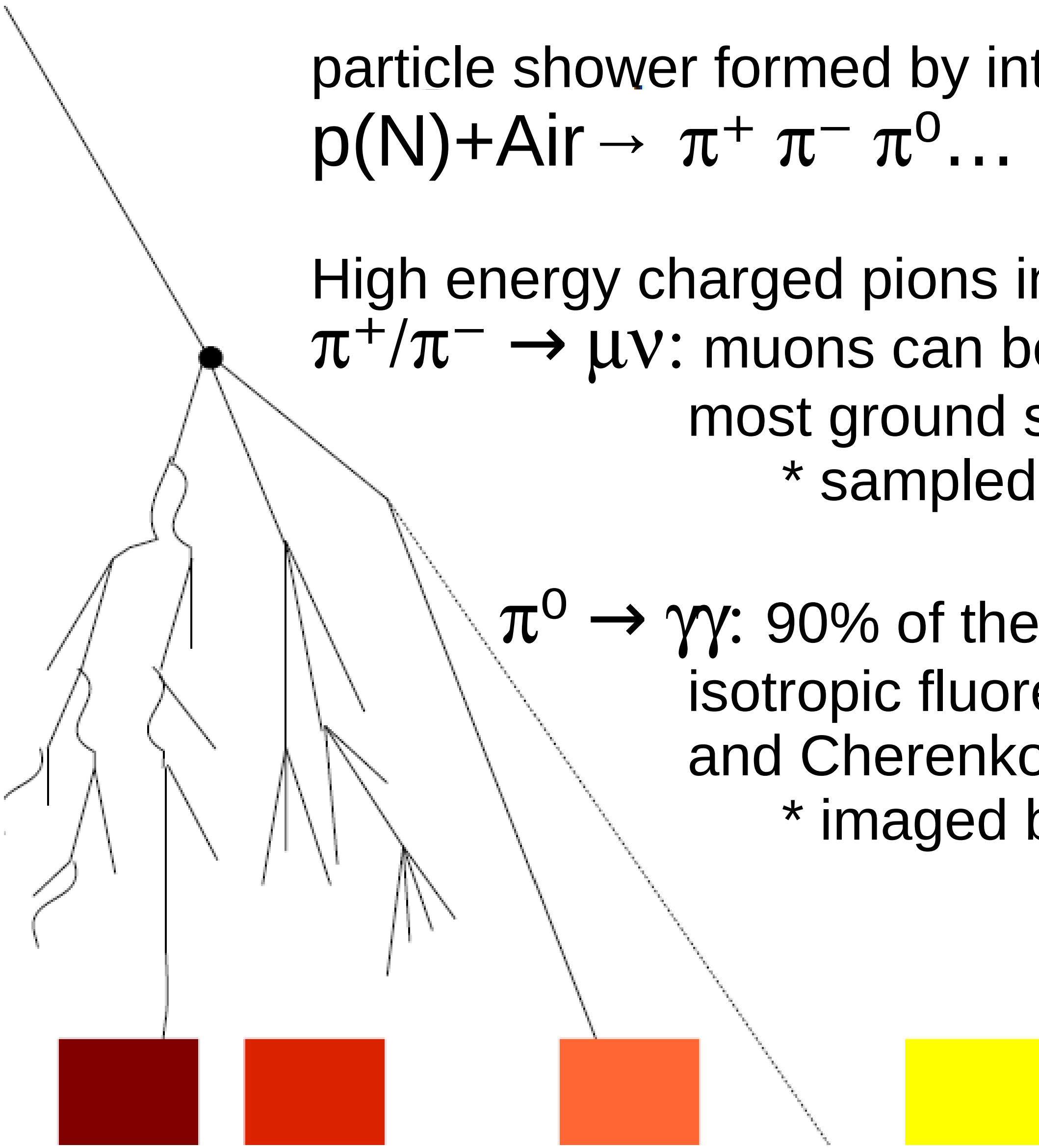
* now by providing particle interaction properties at higher energies

Many open questions remain to be answered

* from the sources of the highest energy cosmic rays
  to the most fundamental properties of neutrinos

thank you for your attention!

Cosmic ray showers detection techniques



particle shower formed by interaction in atmosphere nuclei

$p(N)+Air \rightarrow \pi^{+}\ \pi^{-}\ \pi^{0}\ldots$

High energy charged pions interact feeding the shower

$\pi^{+}/\pi^{-} \rightarrow \mu\nu$: muons can be detected at ground

most ground signal from electrons

* sampled by detector ground arrays

$\pi^{0} \rightarrow \gamma\gamma$: 90% of the energy in electromagnetic shower

isotropic fluorescence light from excited N2

and Cherenkov light in shower's direction

* imaged by telescopes in clear nights

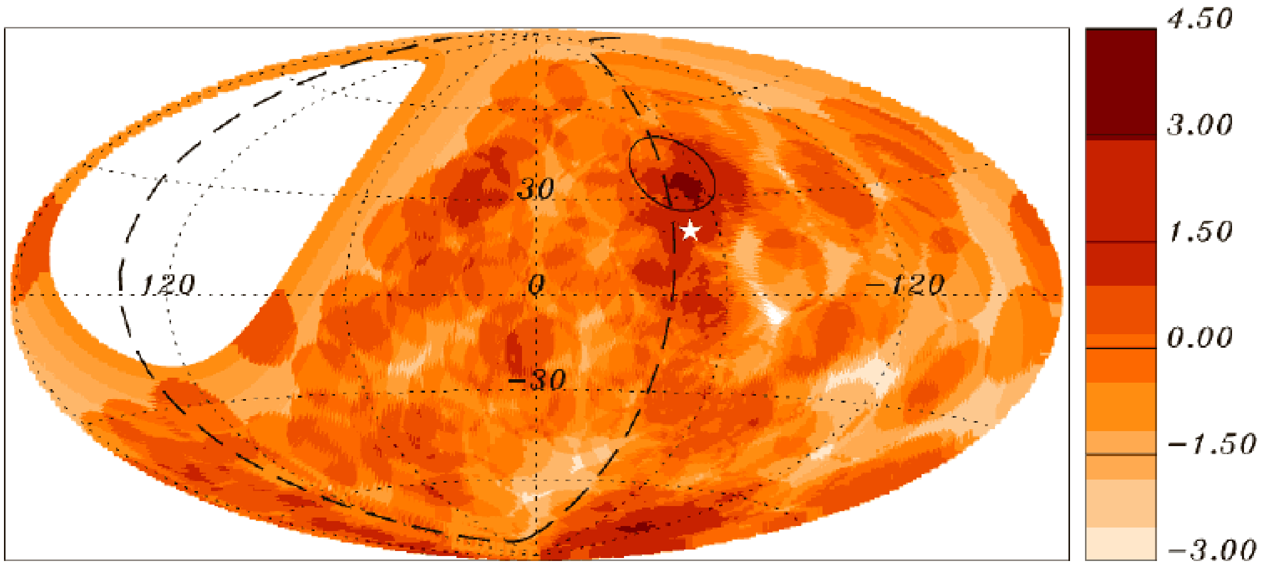
Ground sampling proposed by Pierre Auger

Sources and the sky maps

Protons/Nuclei + Matter == > Pions

$\pi^0 \rightarrow \gamma\gamma$

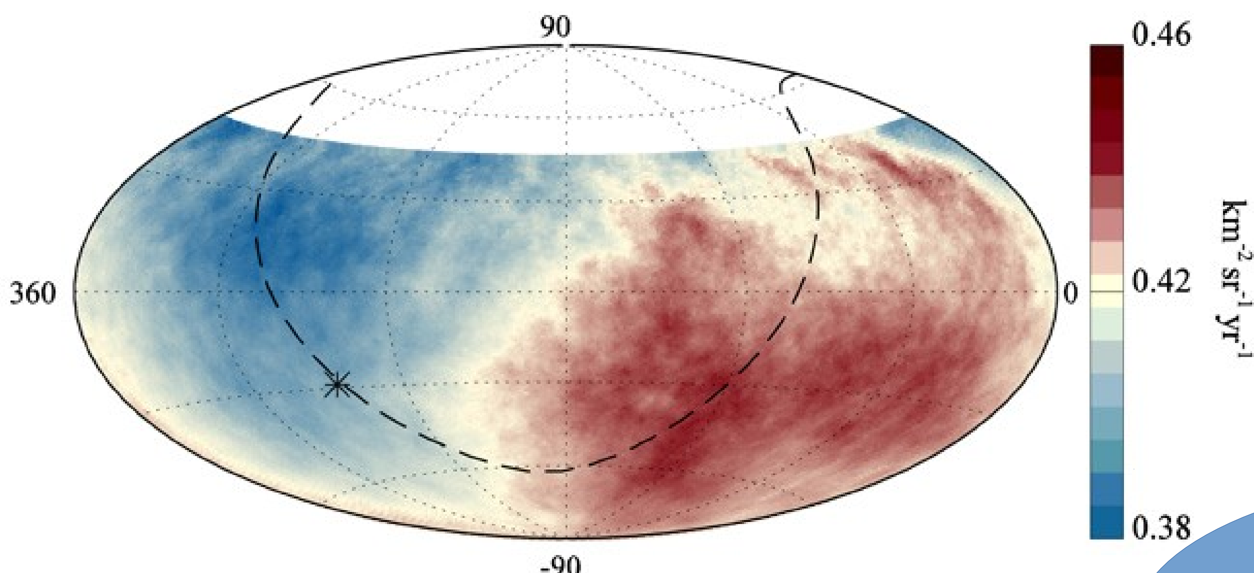
$\pi^- \rightarrow \mu\nu$

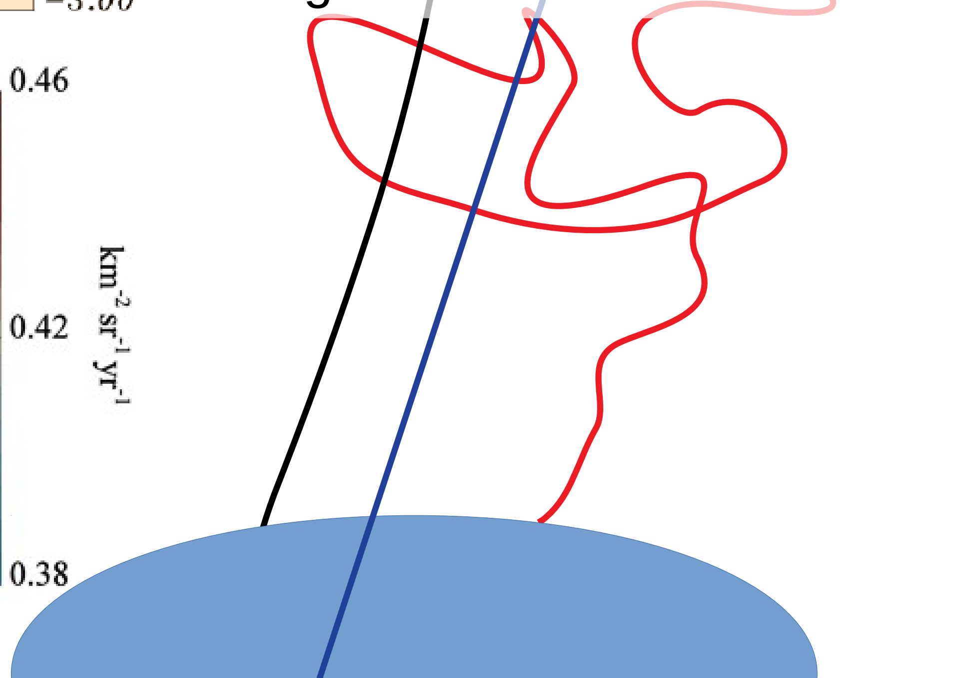


At high energy charged particle directions become less isotropic

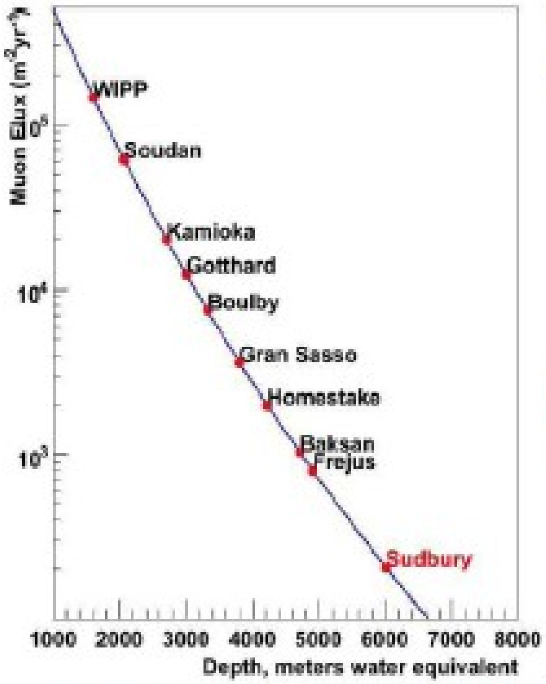
Auger results show they do not point back to the galactic plane,

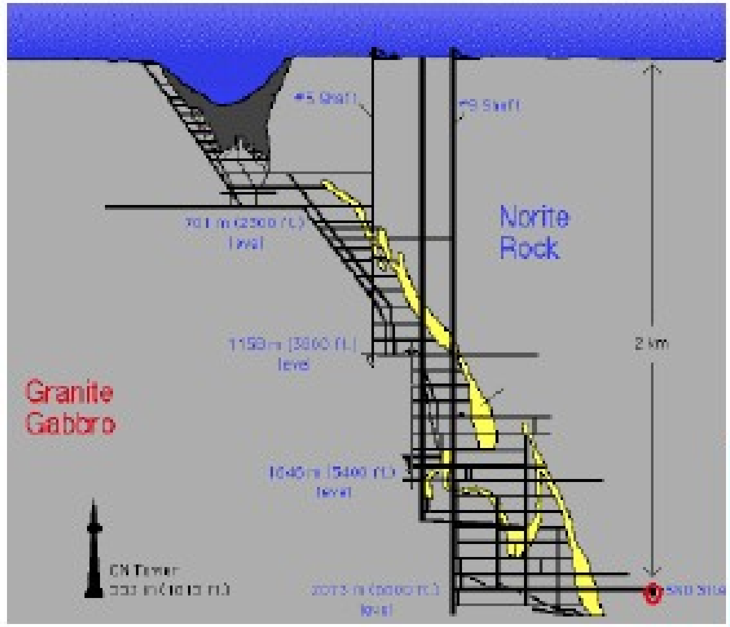
instead they seem to follow the extra-galactic matter distribution





SNOLAB: a deep and clean underground laboratory





50×10^6 less muons at -2000 m!
100 / day in 20m x 20m hall

Scintillator and tellurium are stored in the clean lab underground for a few years

Measuring and constraining cosmogenic backgrounds