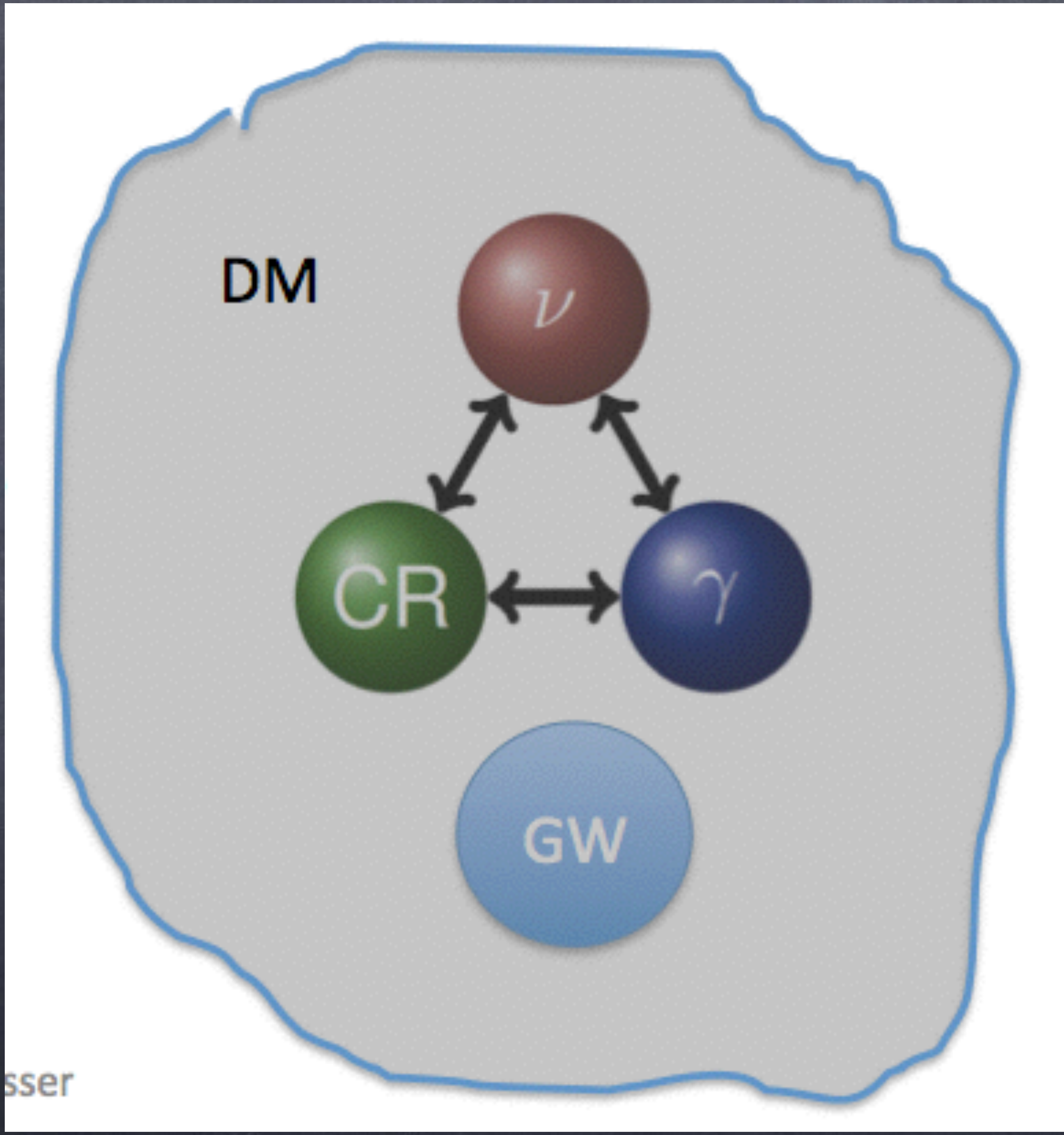
Introduction Astroparticules, neutrinos, ~~cosmologie~~

Damien Dornic (CPPM)

Astroparticles: multi-messager

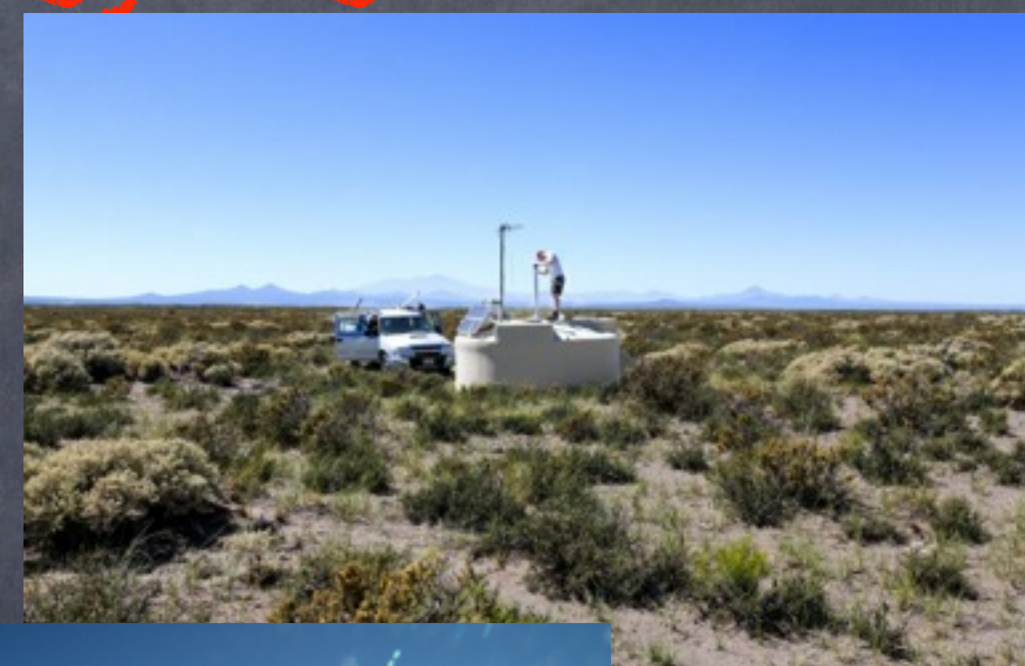


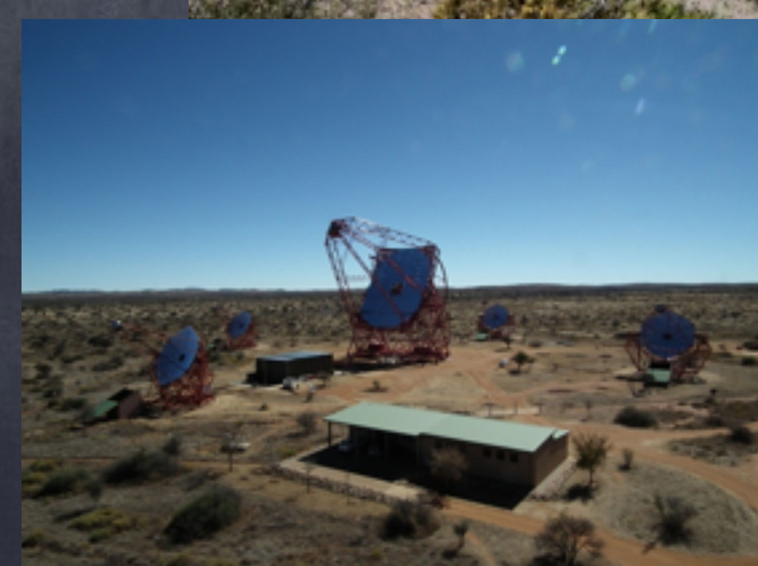
Why I have decided to work in the astroparticles field

It is really an aventure !!!

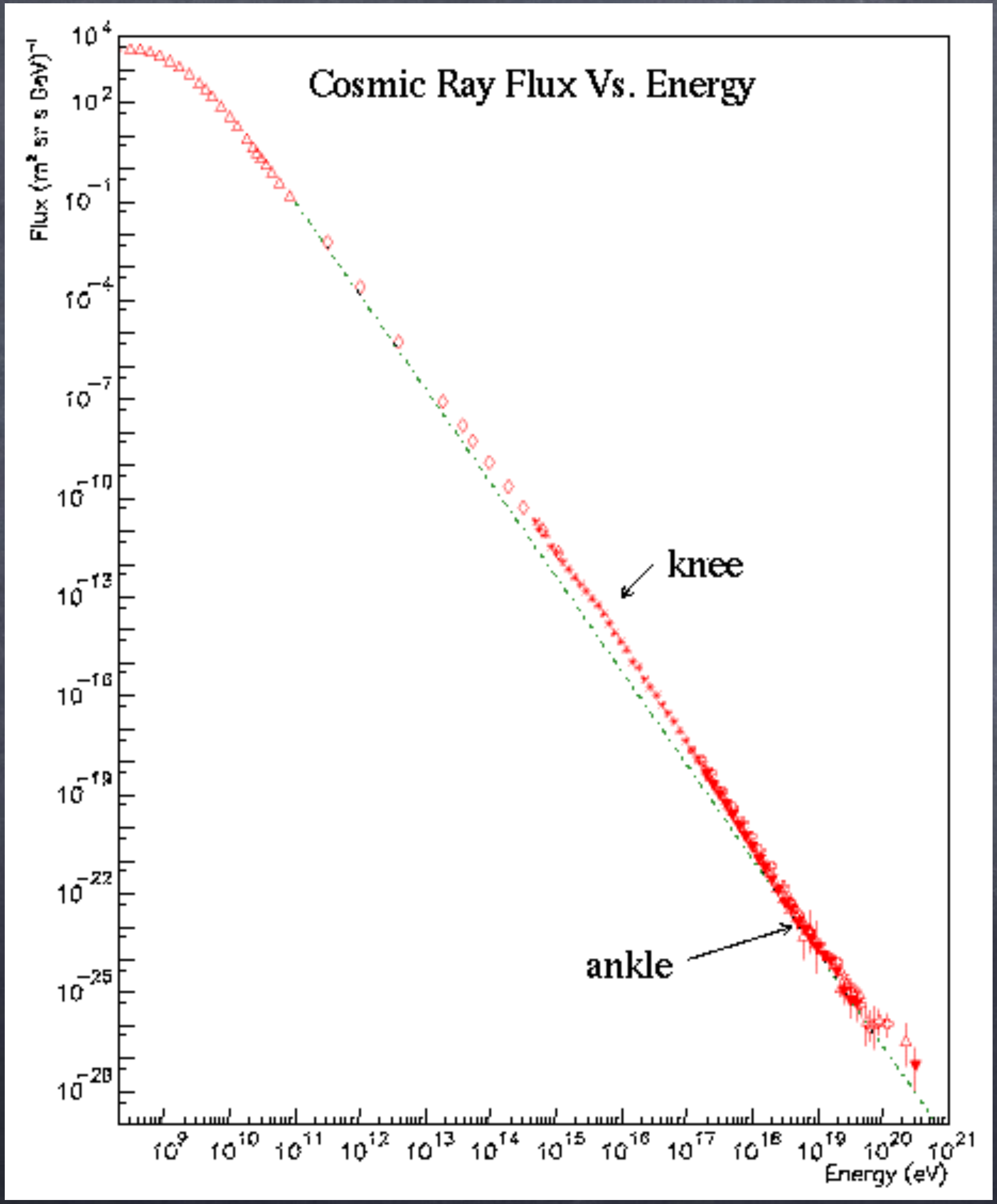
Center of different thematics

(particle, astrophysics, cosmology, engineers...)



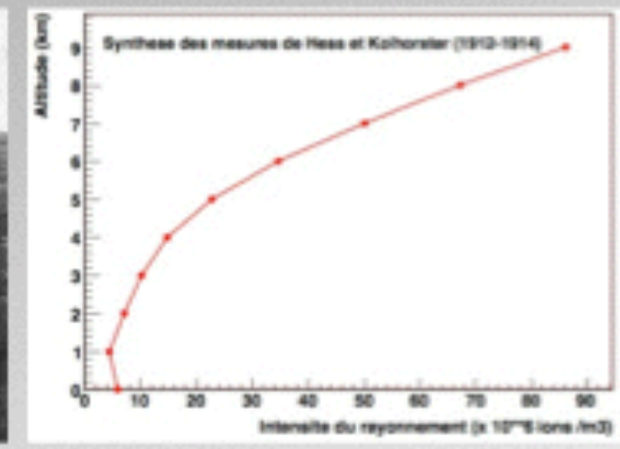


Rayons cosmiques

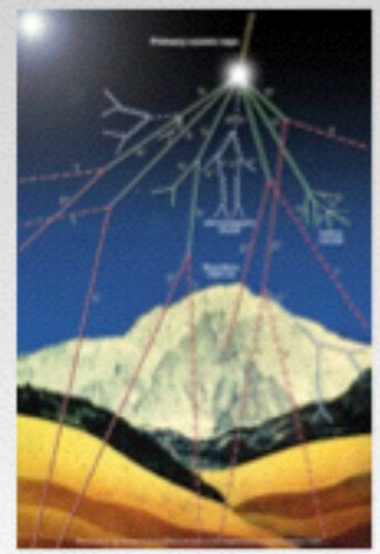


Rayons cosmiques

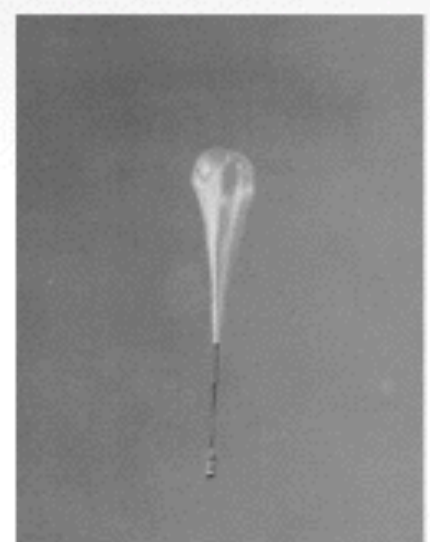
1912 — Viktor HESS découvre les rayons cosmiques à l'aide de plusieurs vols en ballon sur lesquels il embarque un électroscope



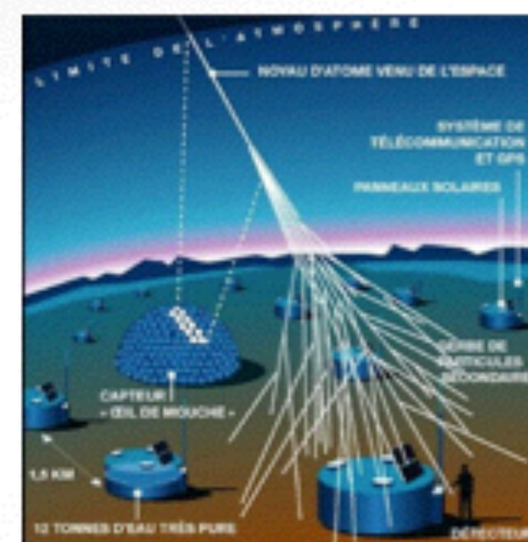
1938 — A l'aide de compteurs Geiger-Muller, Pierre Auger découvre les gerbes atmosphériques, issues de l'interaction du rayonnement cosmique primaire avec l'atmosphère



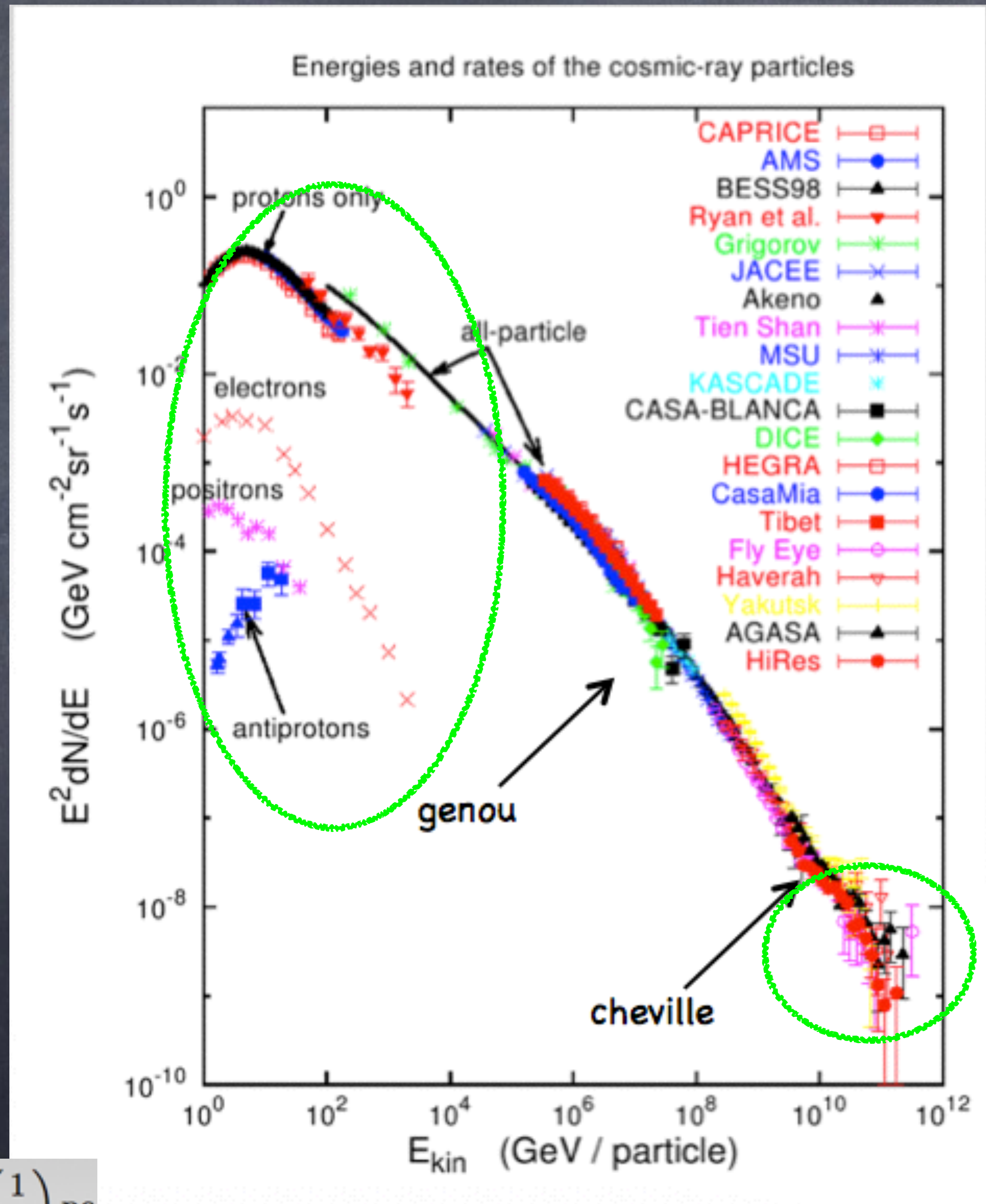
1950 — Identification des rayons cosmiques primaires, par l'envoi d'émulsion nucléaires à très haute altitude.



≥ 1950 — Etude du spectre, de la composition, et de l'anisotropie du rayonnement cosmique à l'aide d'immenses réseaux de détecteurs + satellites + ballons

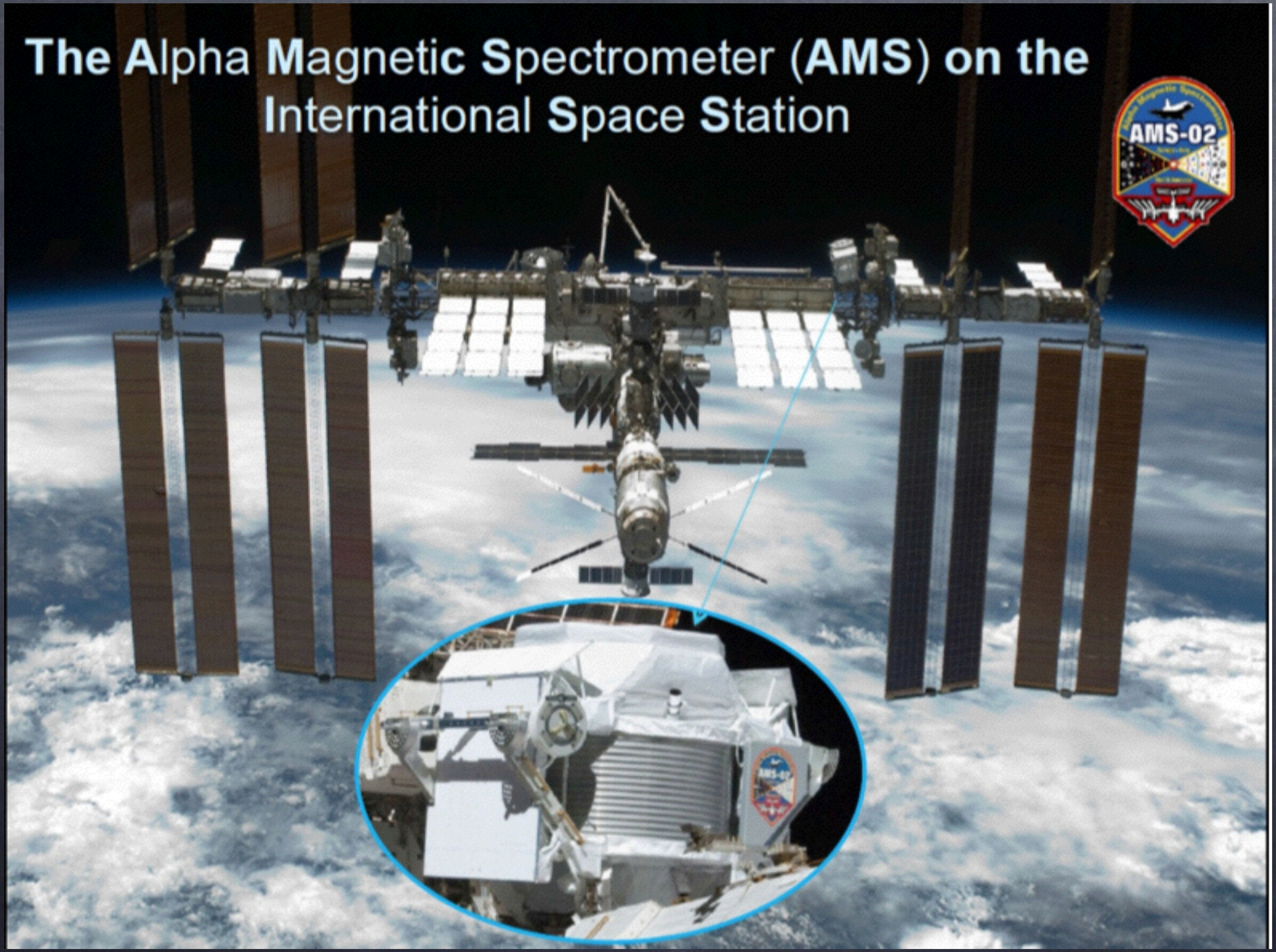


Rayons cosmiques

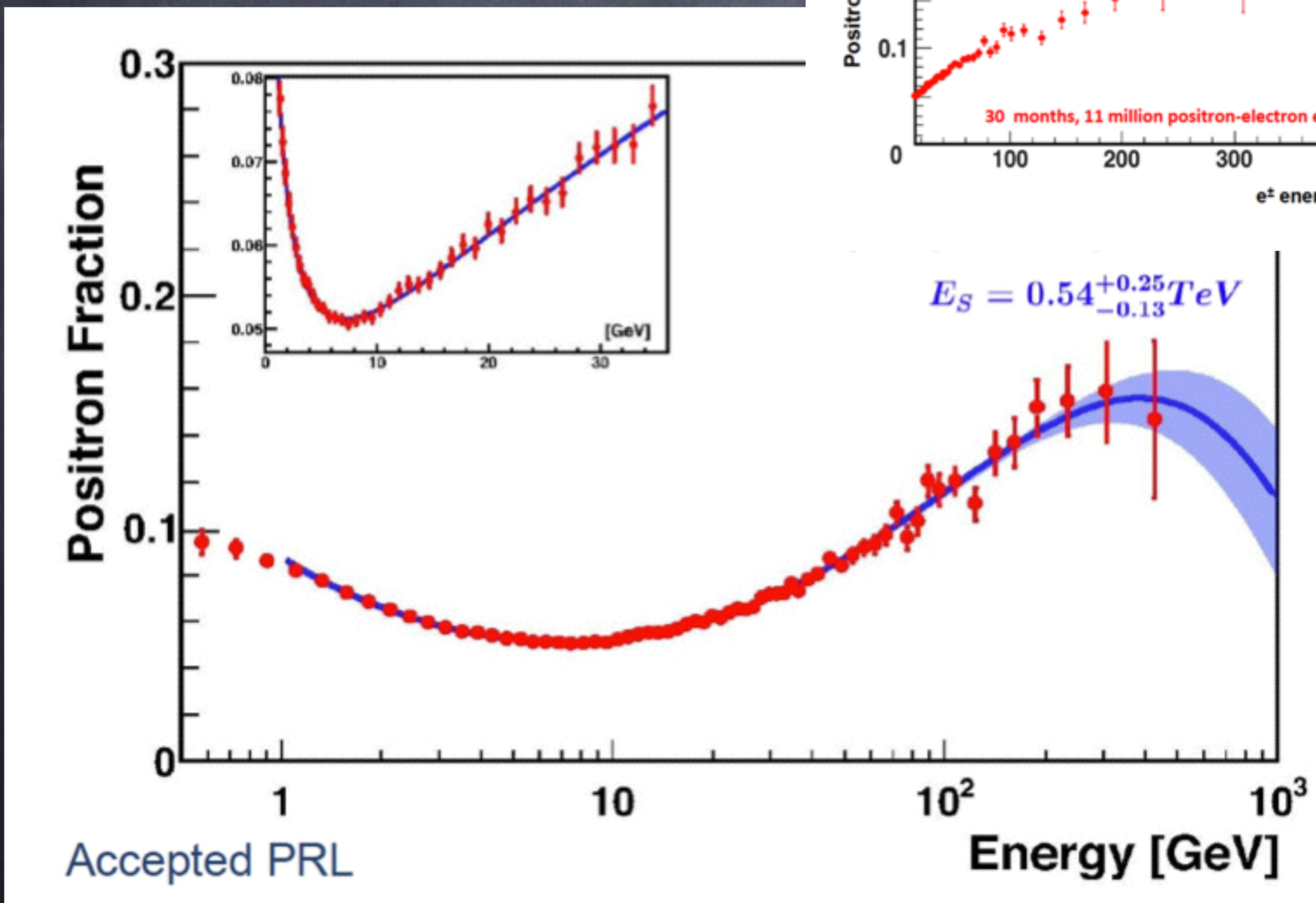


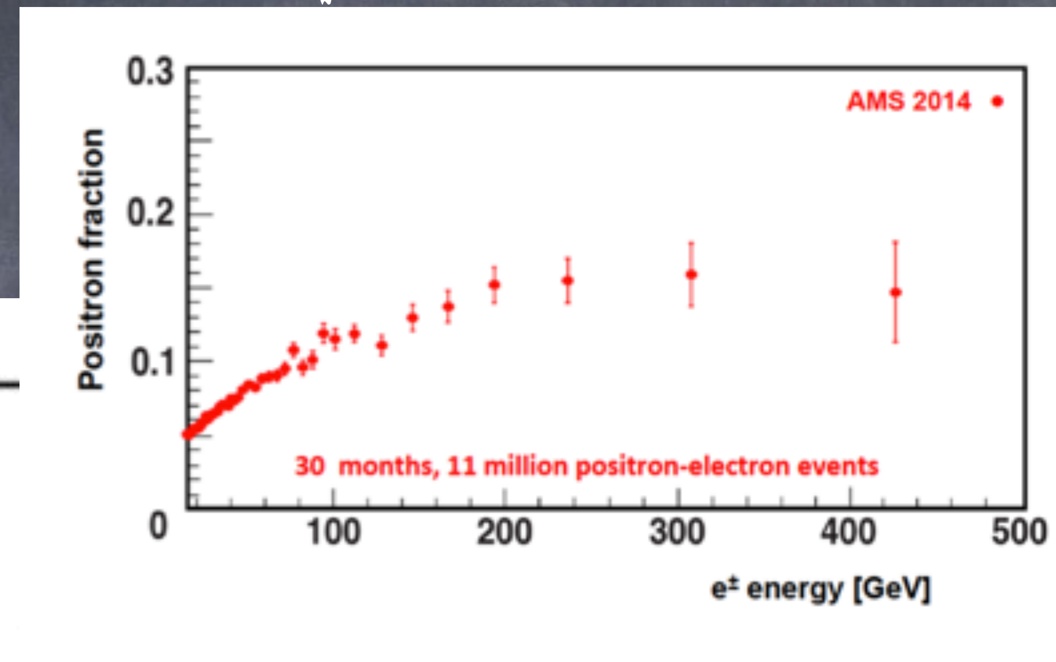
$$R \approx 50 \times \left(\frac{E}{10^{17}\,eV}\right) \times \left(\frac{1\mu G}{B}\right) \times \left(\frac{1}{Z}\right) pc$$

Rayons cosmiques: AMS



Rayons cosmiques: AMS





?

ratio e+/e- : AMS

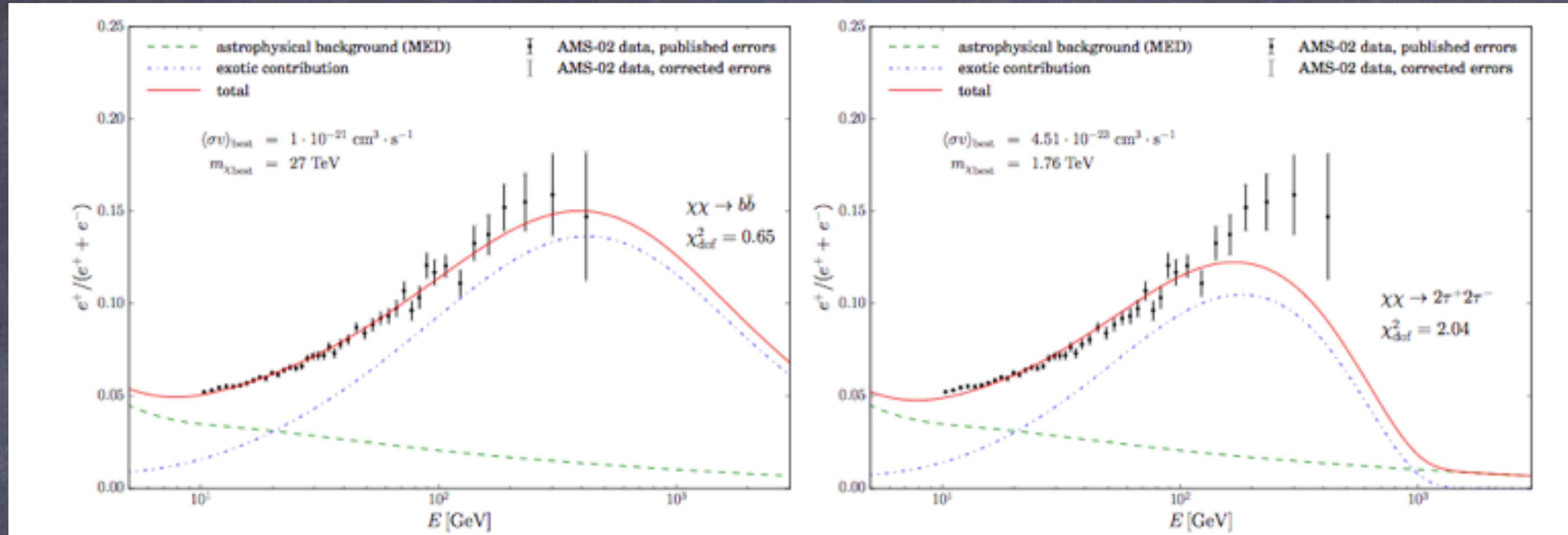
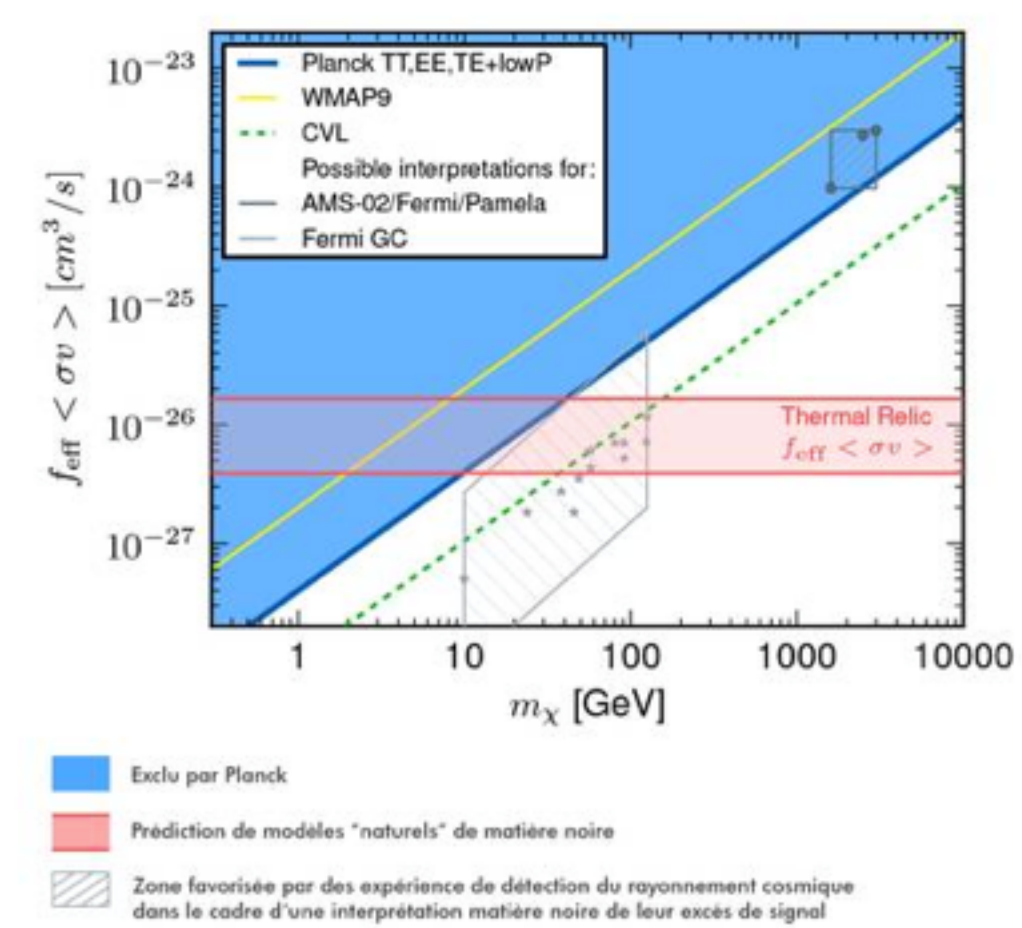
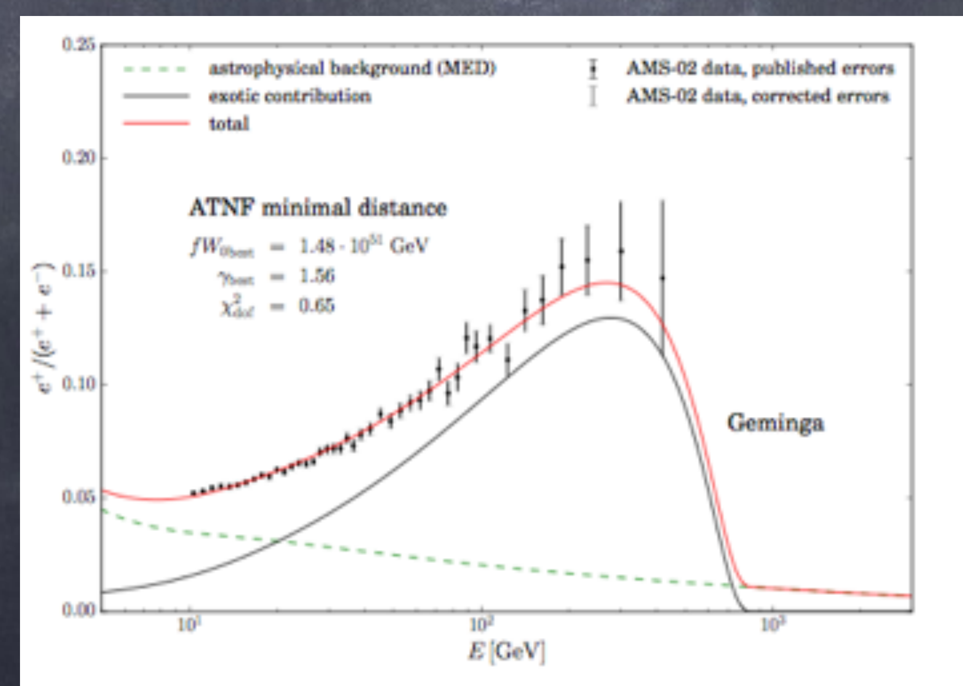
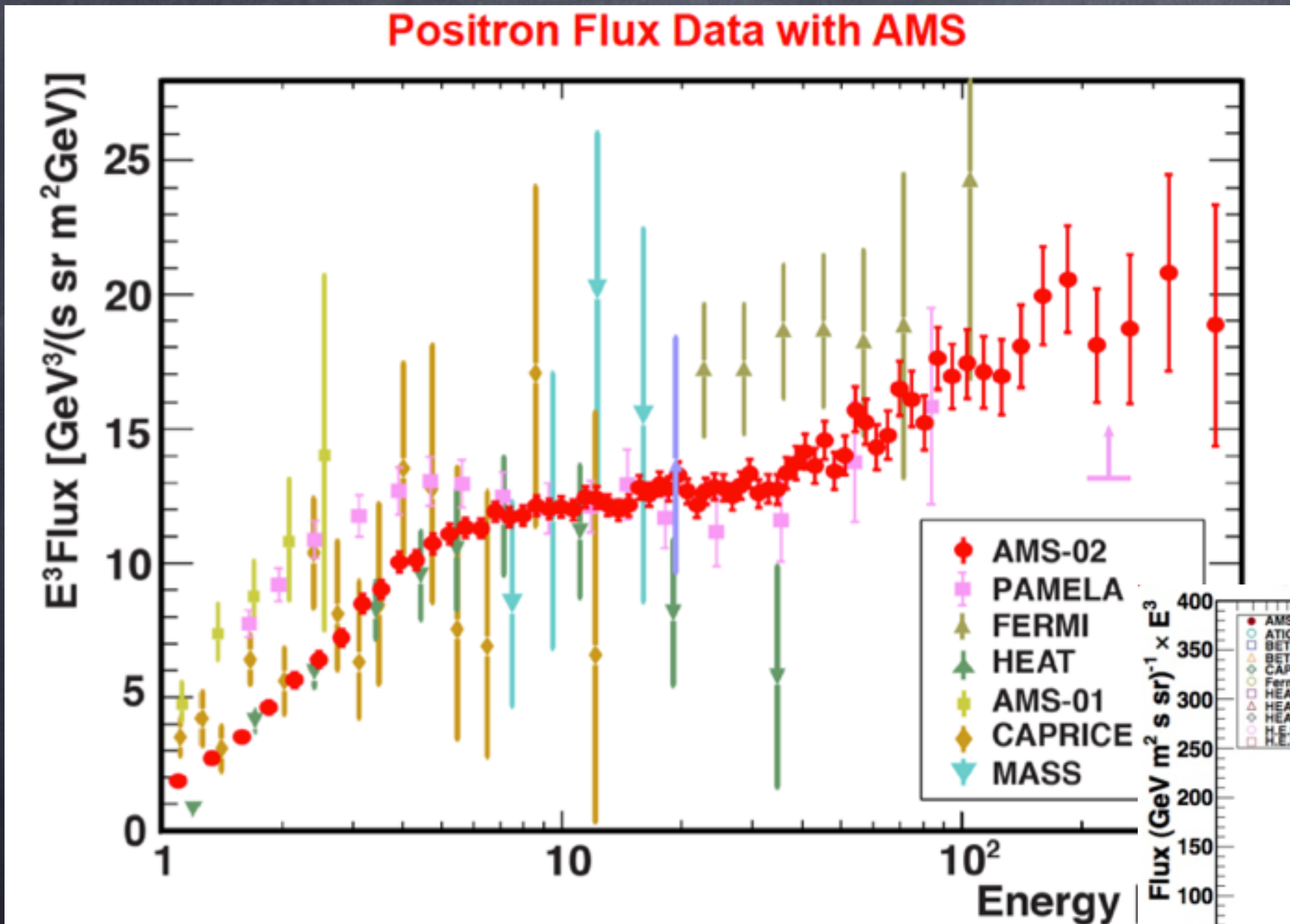


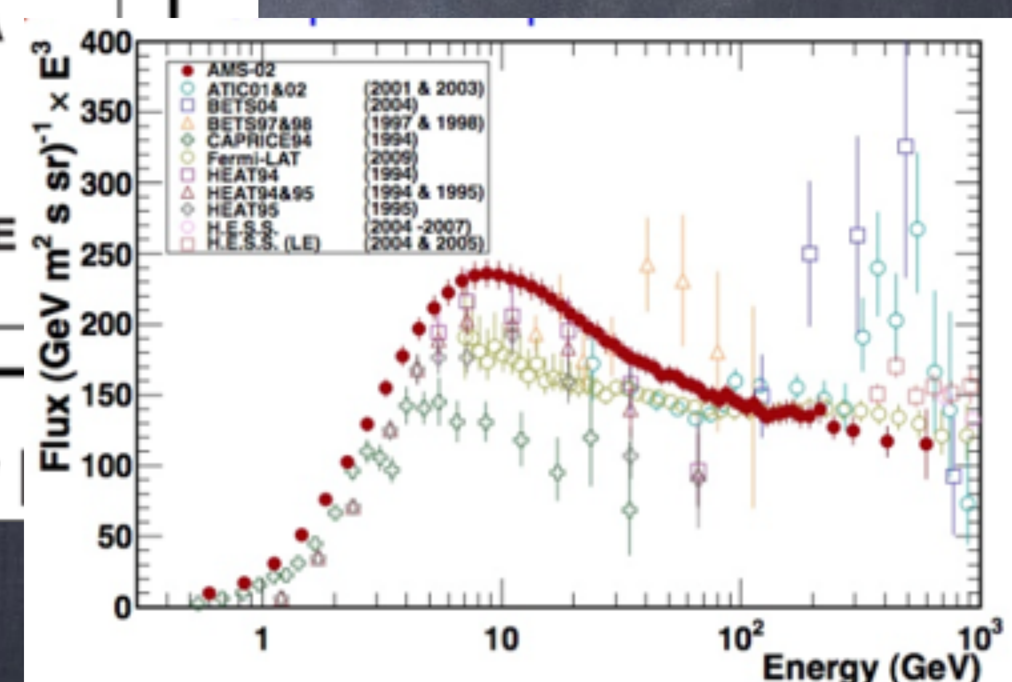
Fig. 2. Positron fraction as a function of the positron energy corresponding to the best fit value of $\langle\sigma v\rangle$ and DM mass m_χ for $b\bar{b}$ (left) and 4τ annihilation channels (right), compared with AMS data (Accardo et al. 2014). The propagation parameters correspond to the MED model. The ... al. 2014) is used to derive the χ^2.





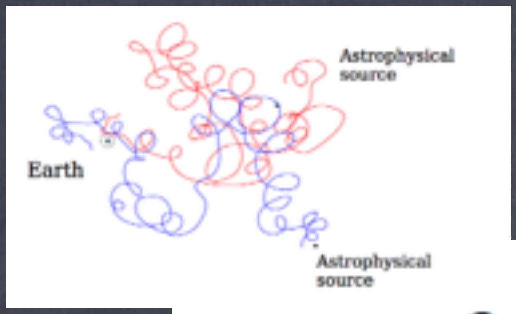
Rayons cosmiques: AMS

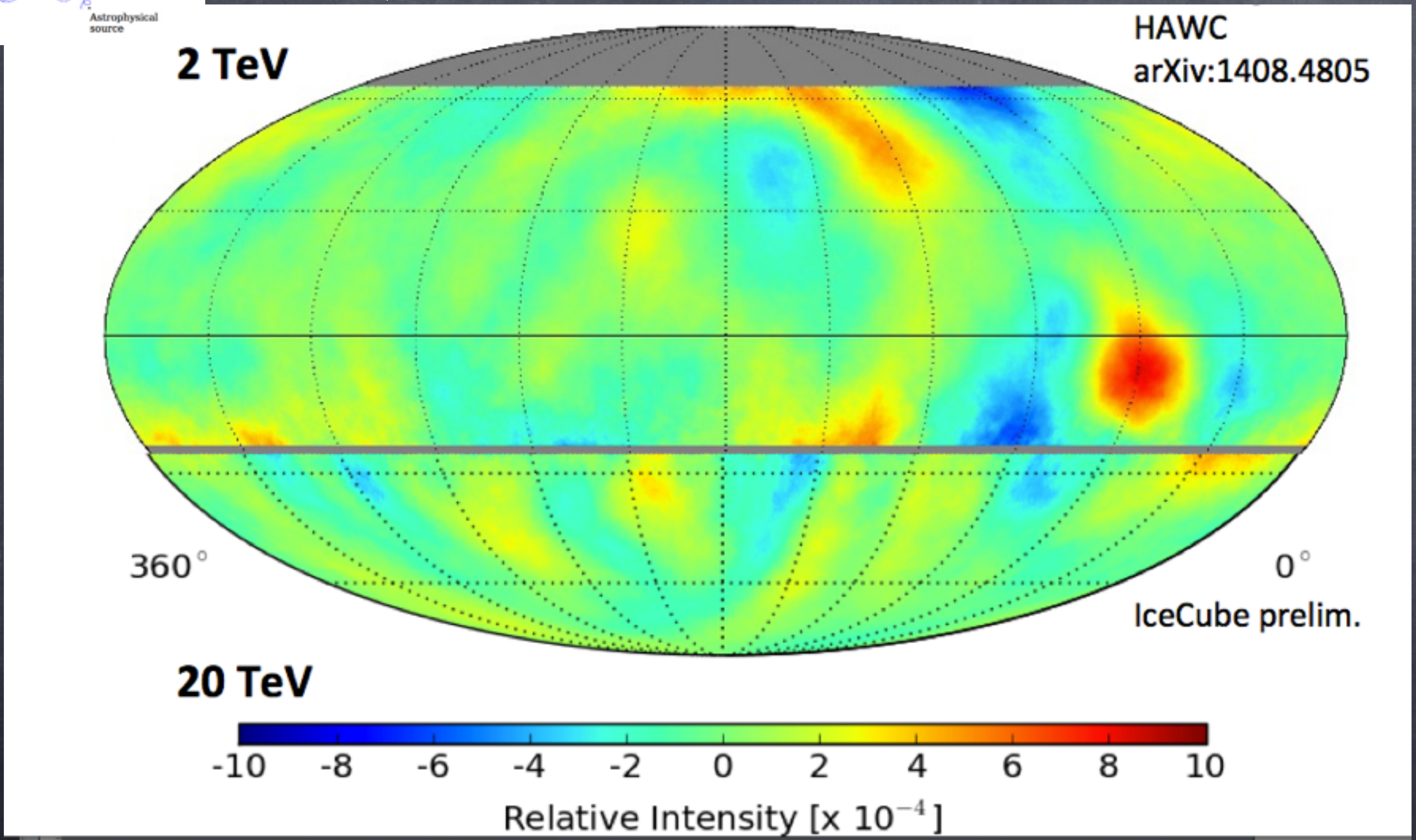




Unexpected features in the positron spectrum

Rayons cosmiques



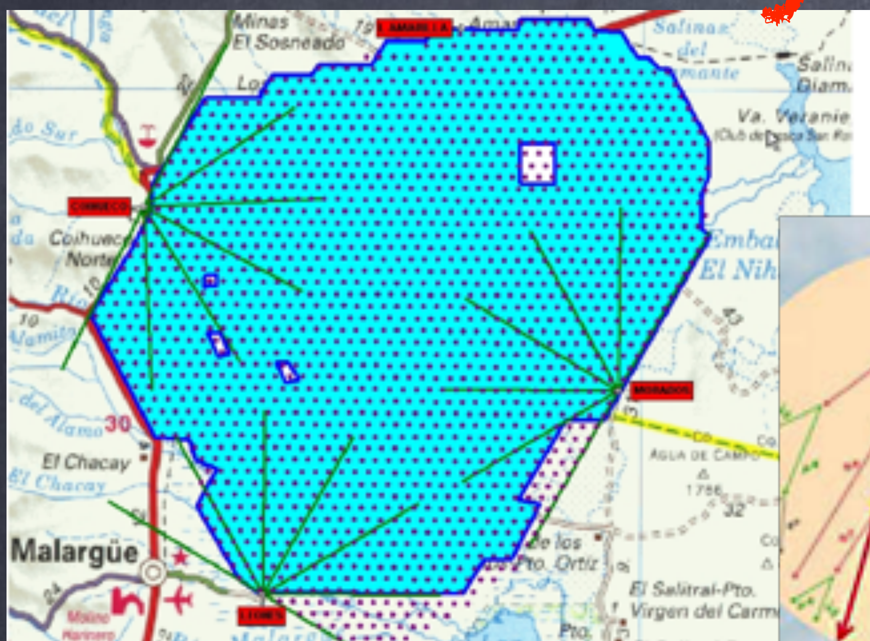


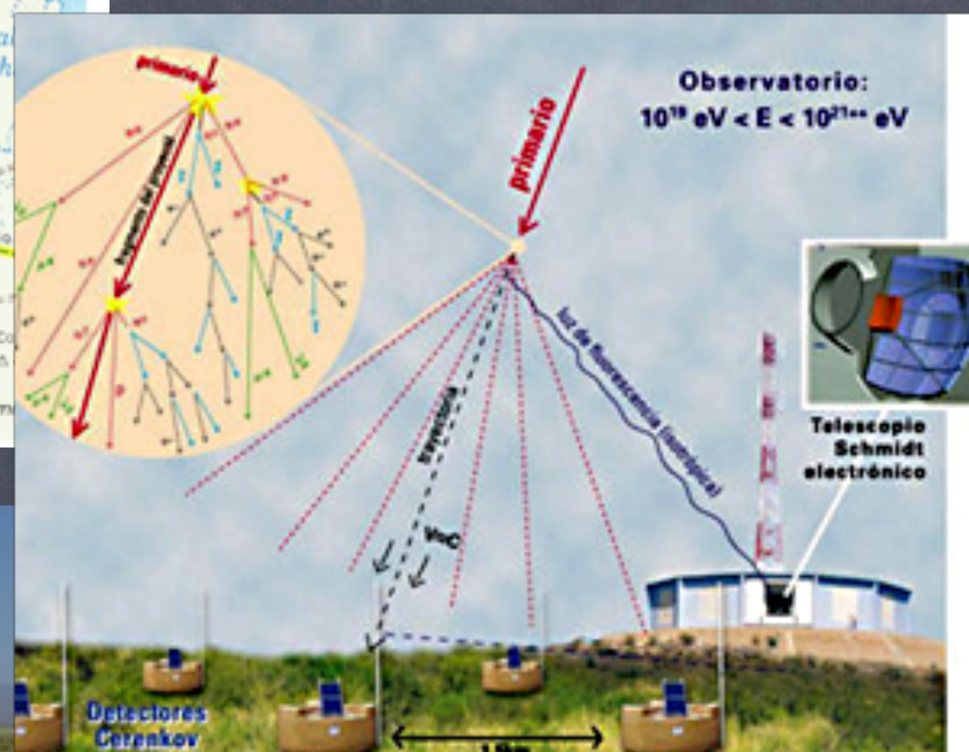
Anisotropy in the CR distribution

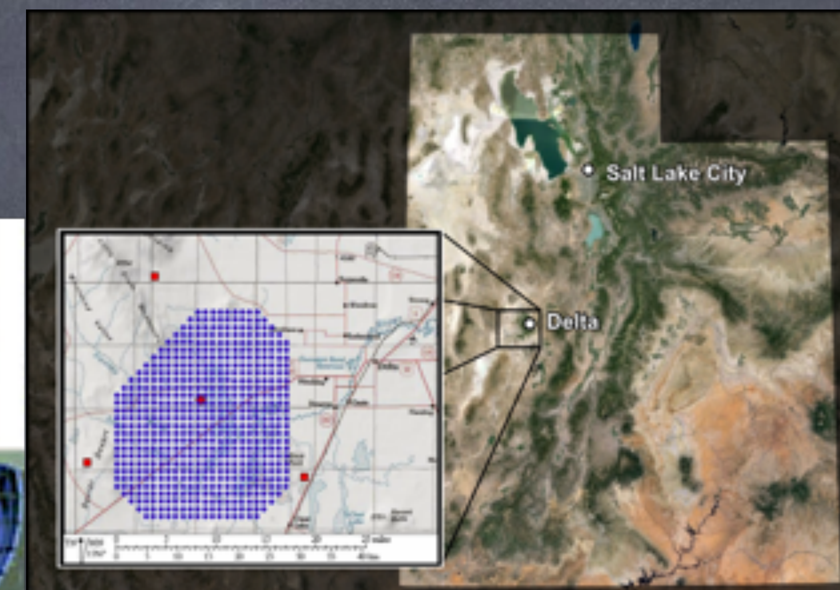
Rayons cosmiques: UHE

Pierre Auger Observatory

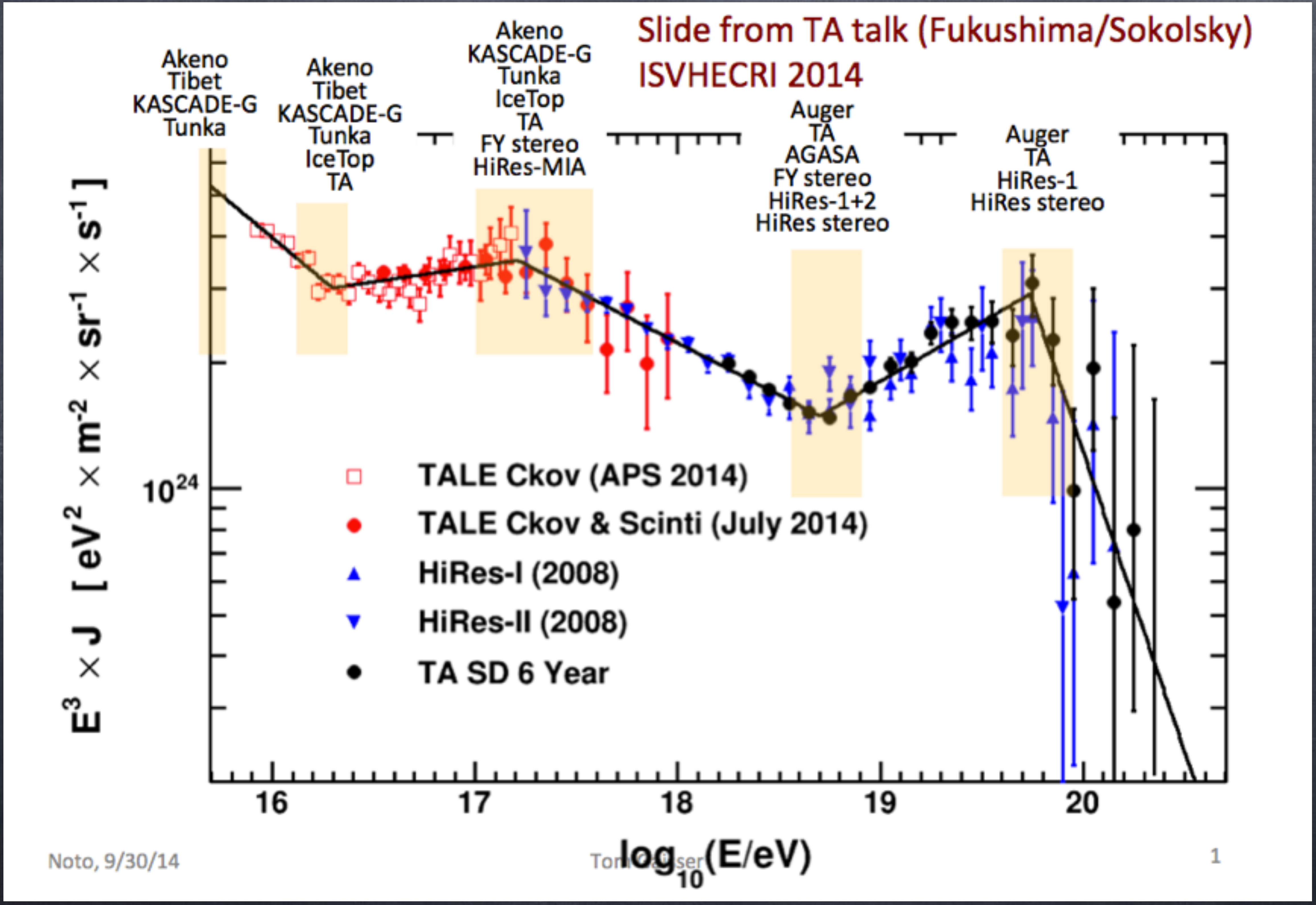
Telescope Array







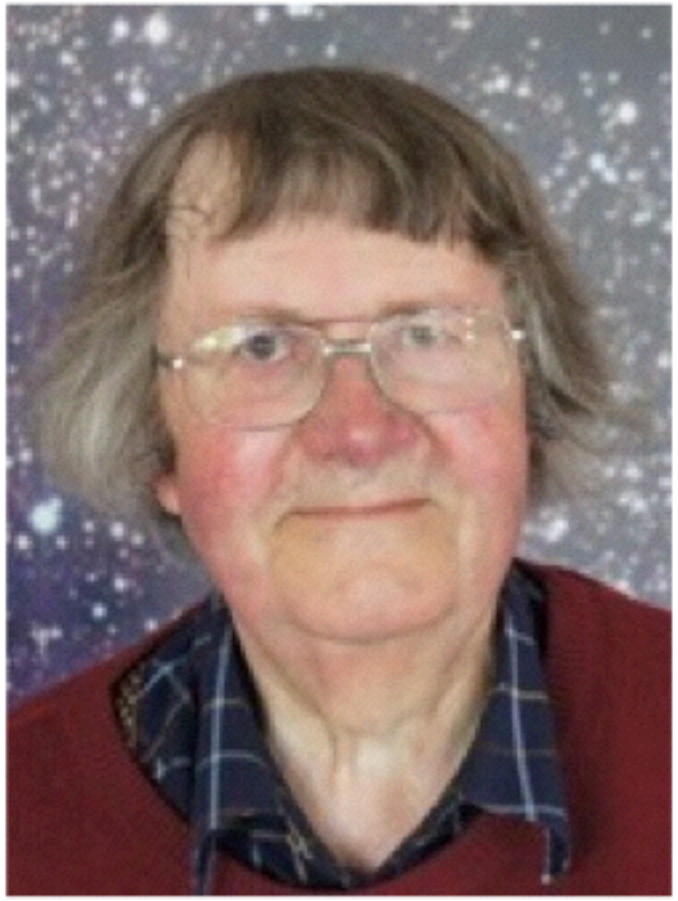
Rayons cosmiques: UHE



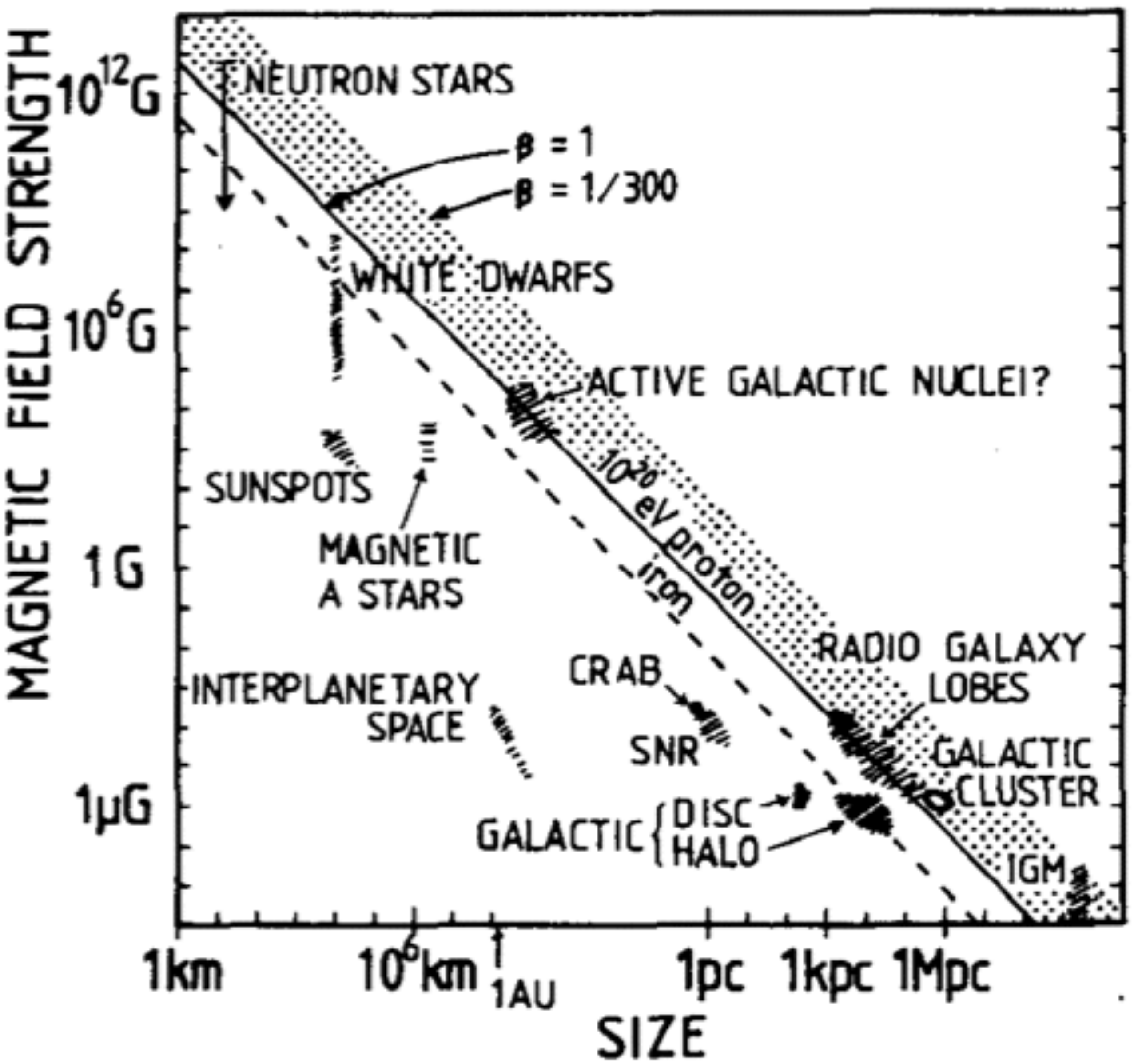
Rayons cosmiques: UHE

$$p + \gamma_{CMB} \rightarrow N + \pi + ...$$

Rayons cosmiques: UHE

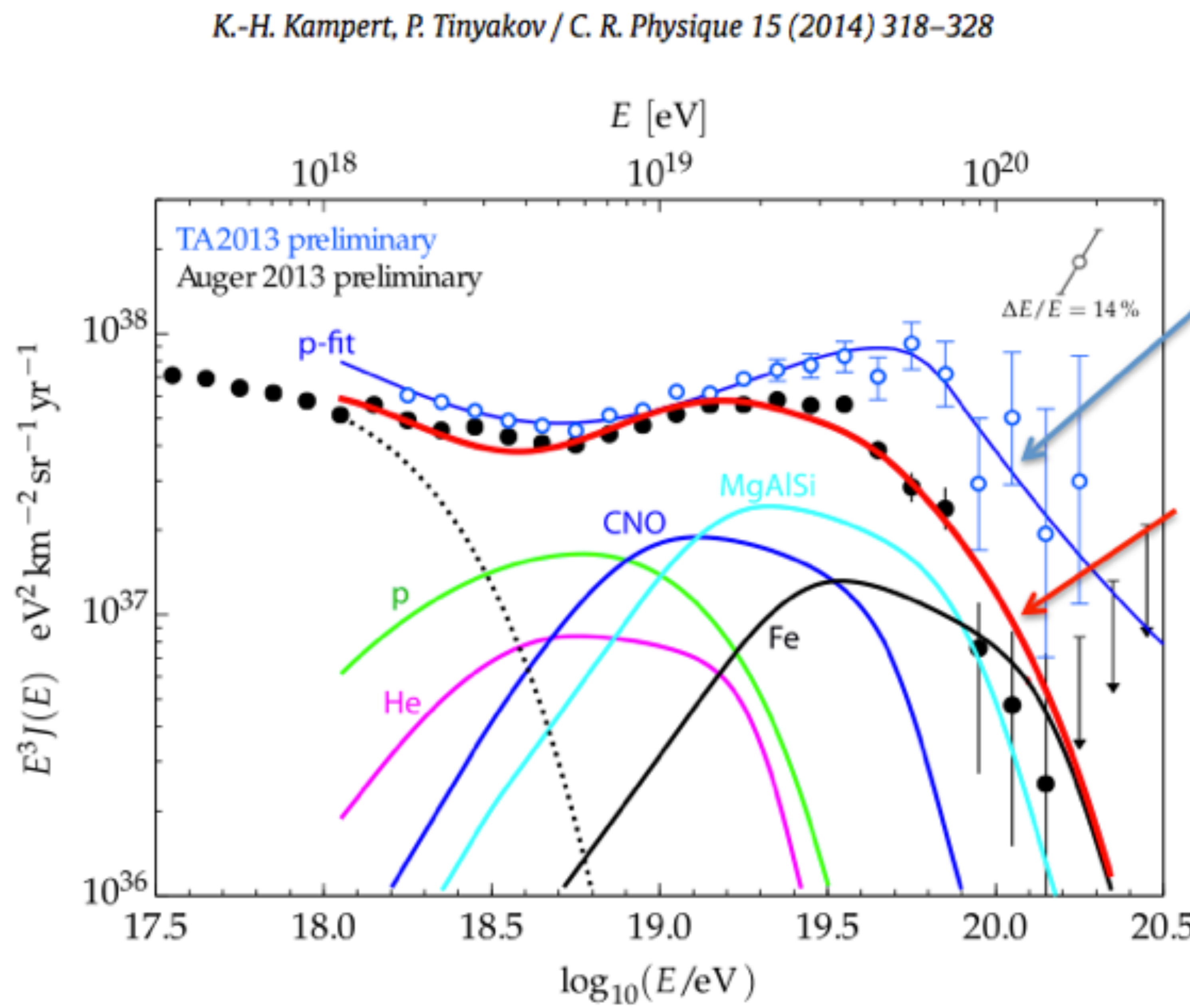


Hillas



$$E_{max} = \beta Z e \times B \times R.$$

Rayons cosmiques: UHE



The UHECR dilemma:

Protons + GZK cutoff

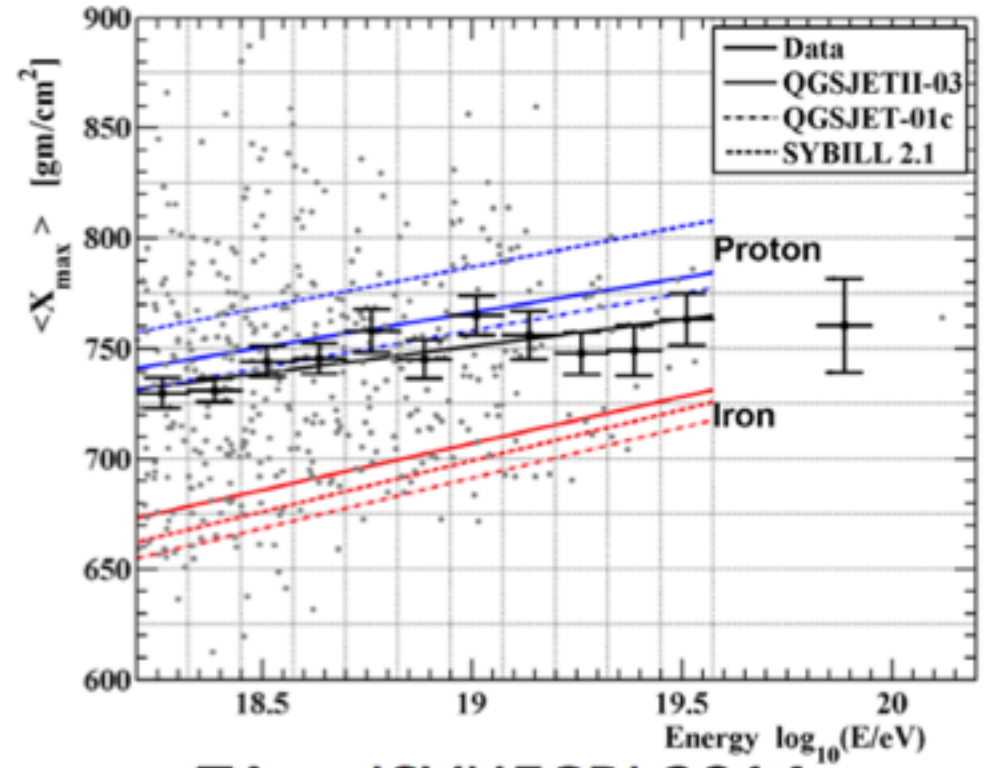
or

Mixed composition with E_{max} at sources

(Model of Aloisio, Berezinsky, Blasi, arXiv:1312.7459)

Rayons cosmiques: UHE

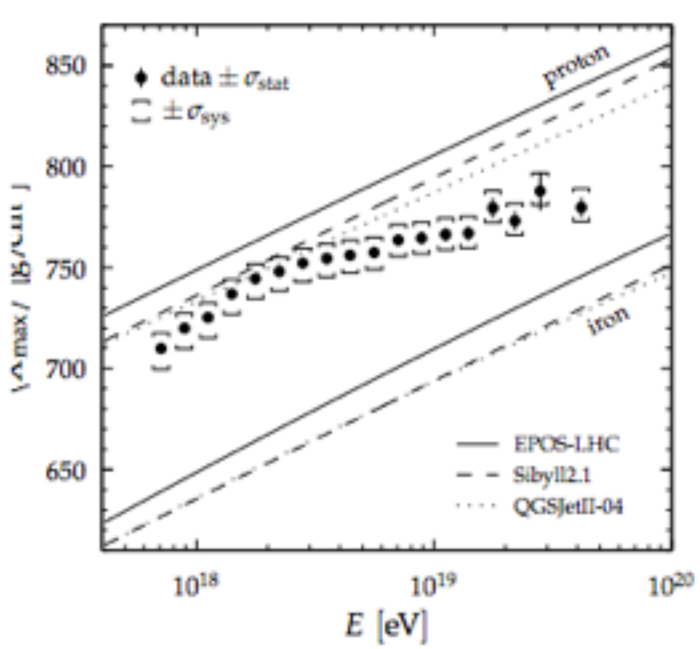
Are Auger and TA consistent?

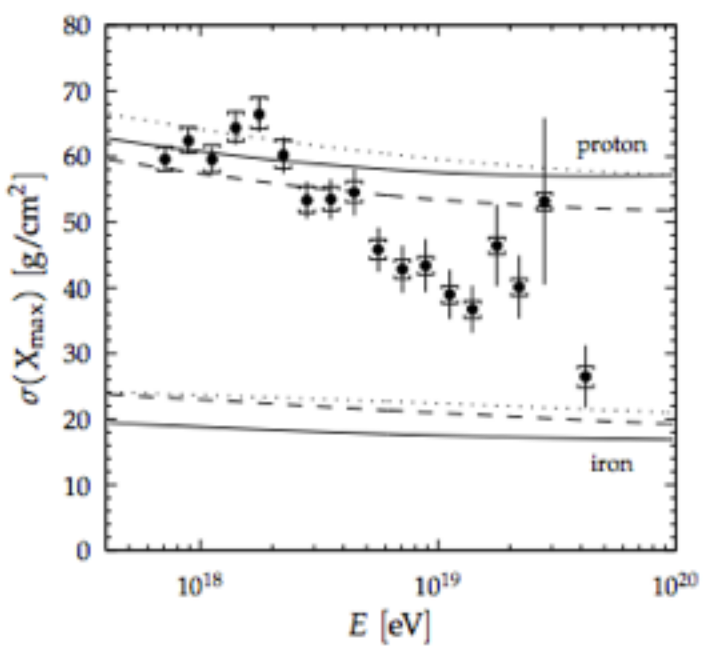


Auger Collaboration: mixed composition
arXiv:1409.4809

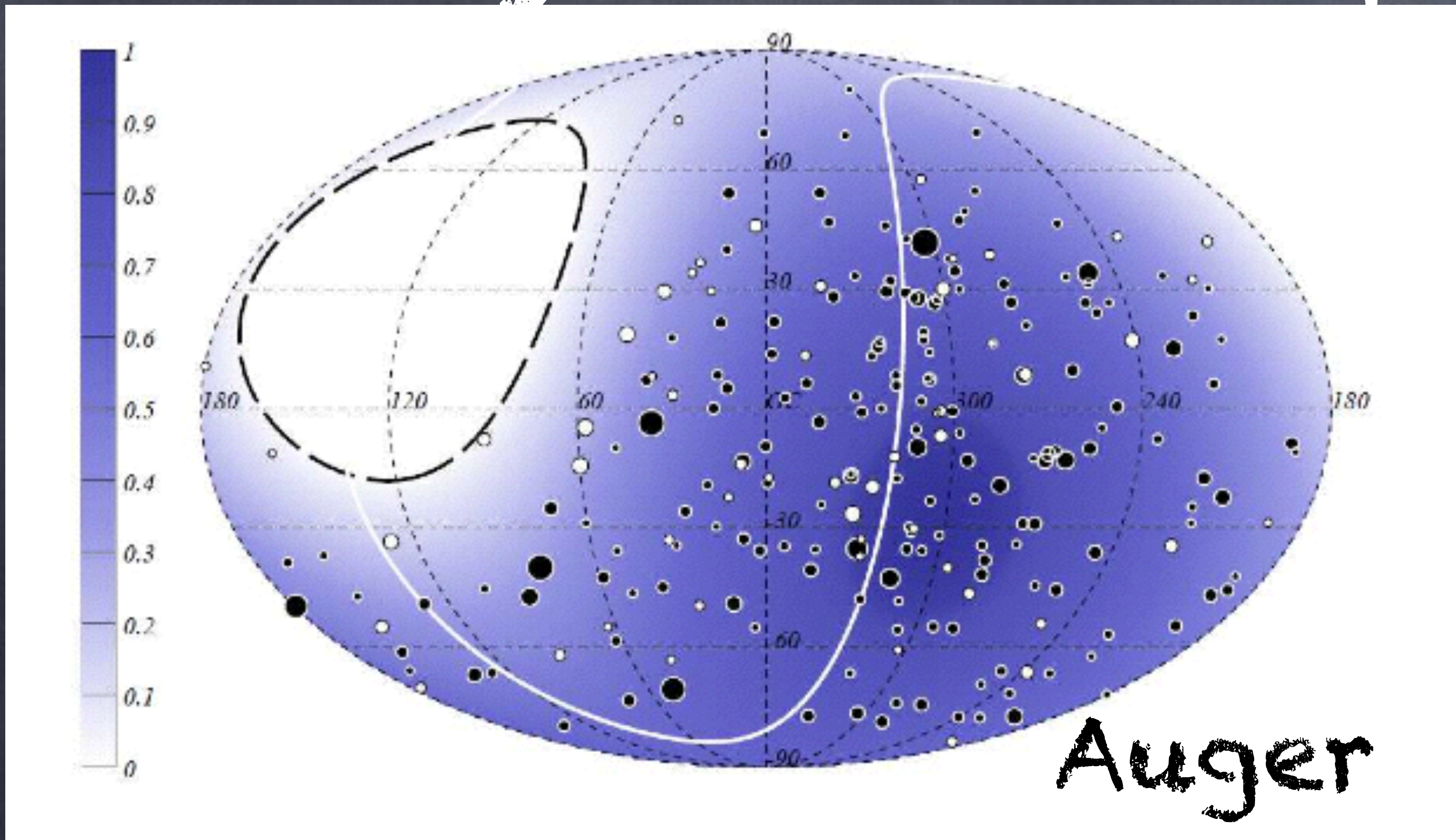
TA at ISVHECRI 2014

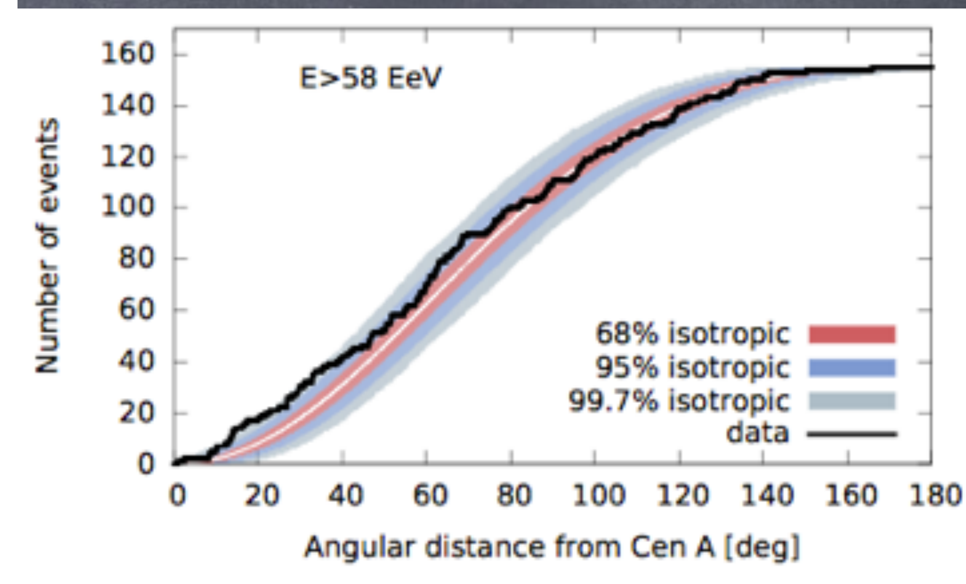
Results are consistent with proton at all energies and inconsistent with iron.





Rayons cosmiques: UHE

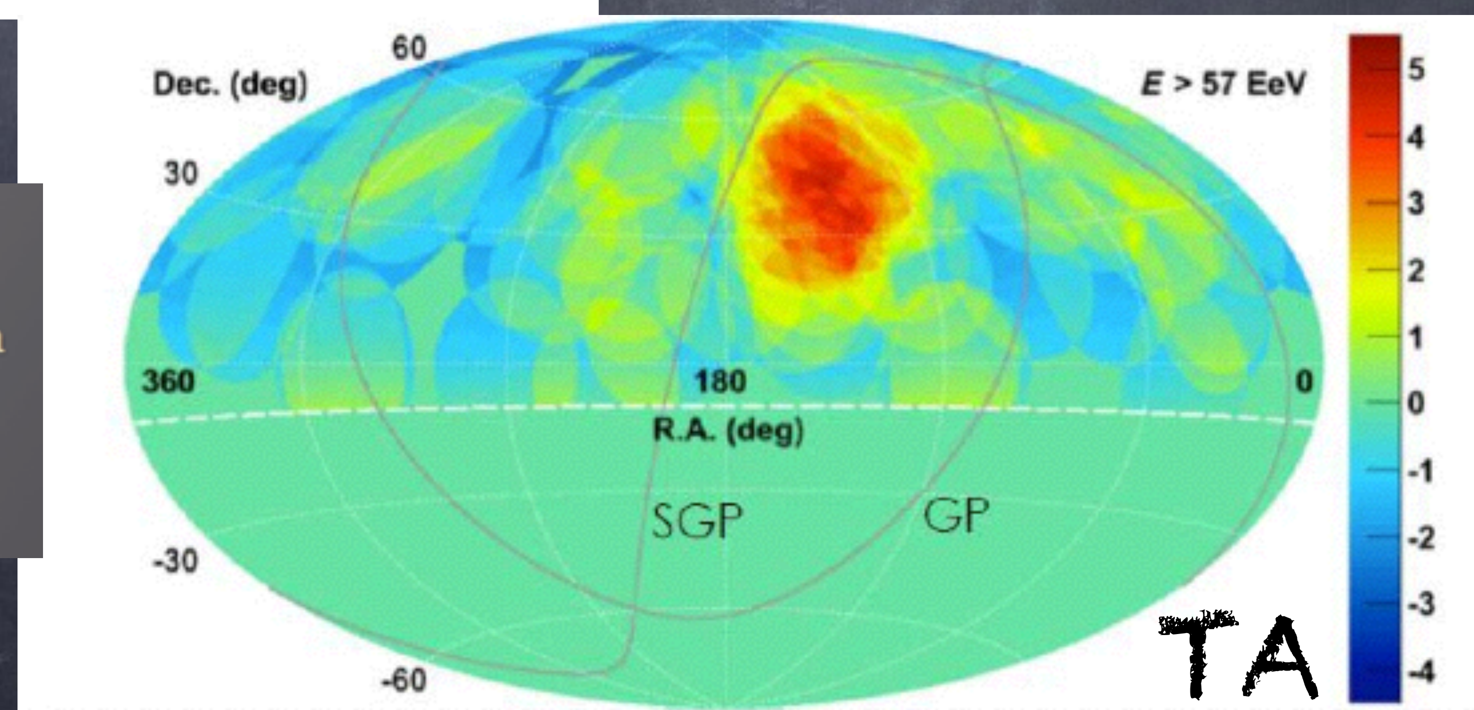




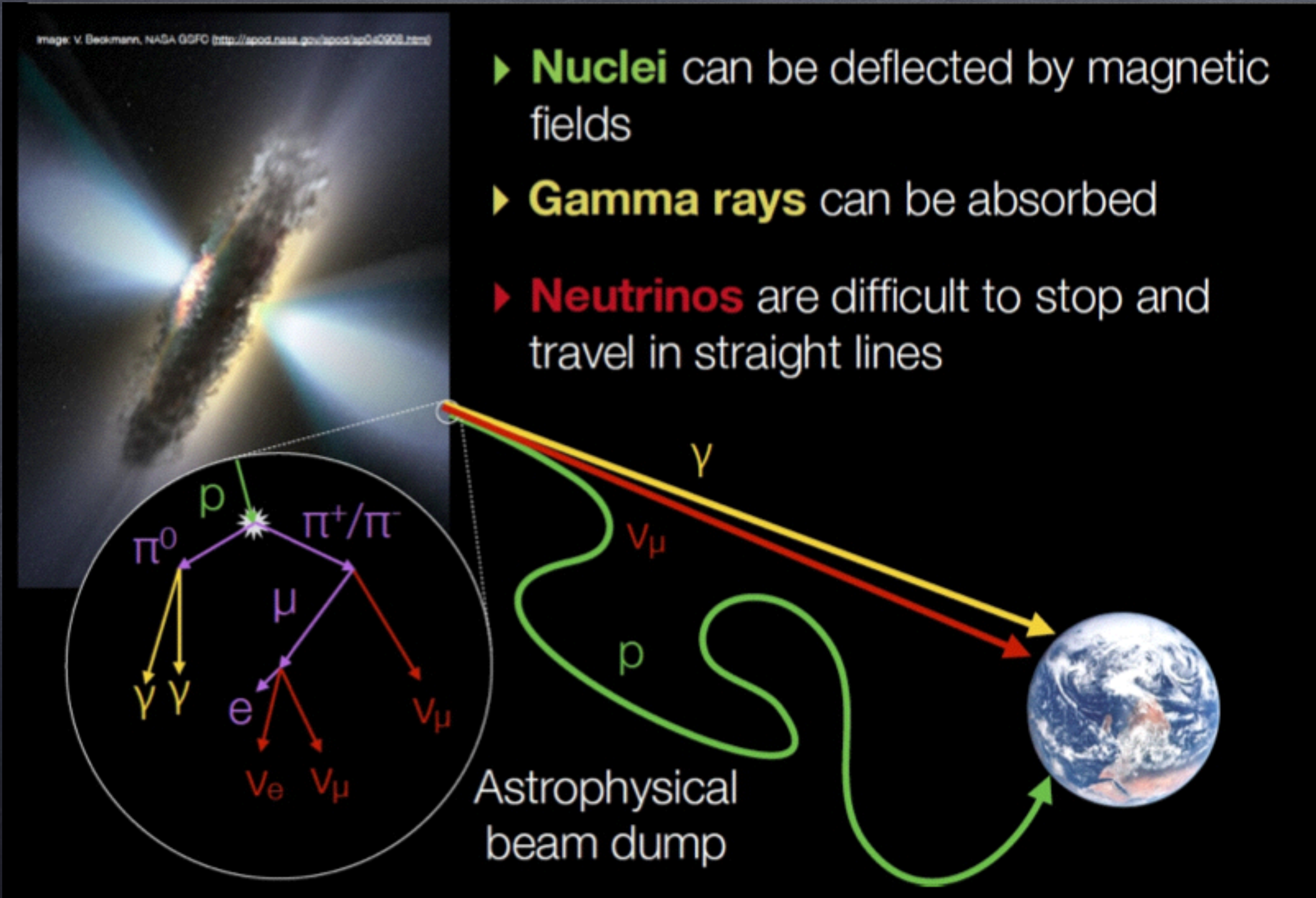
231 events 2004-14

The TA Hotspot, Update

- 72 events (5 years) + 15 events (6th year) total with $E > 57$ EeV
- 19 events (5 years) + 4 events (6th year) in hotspot
- 5.1σ Li-Ma significance goes to 5.55σ



Indirect CR detection

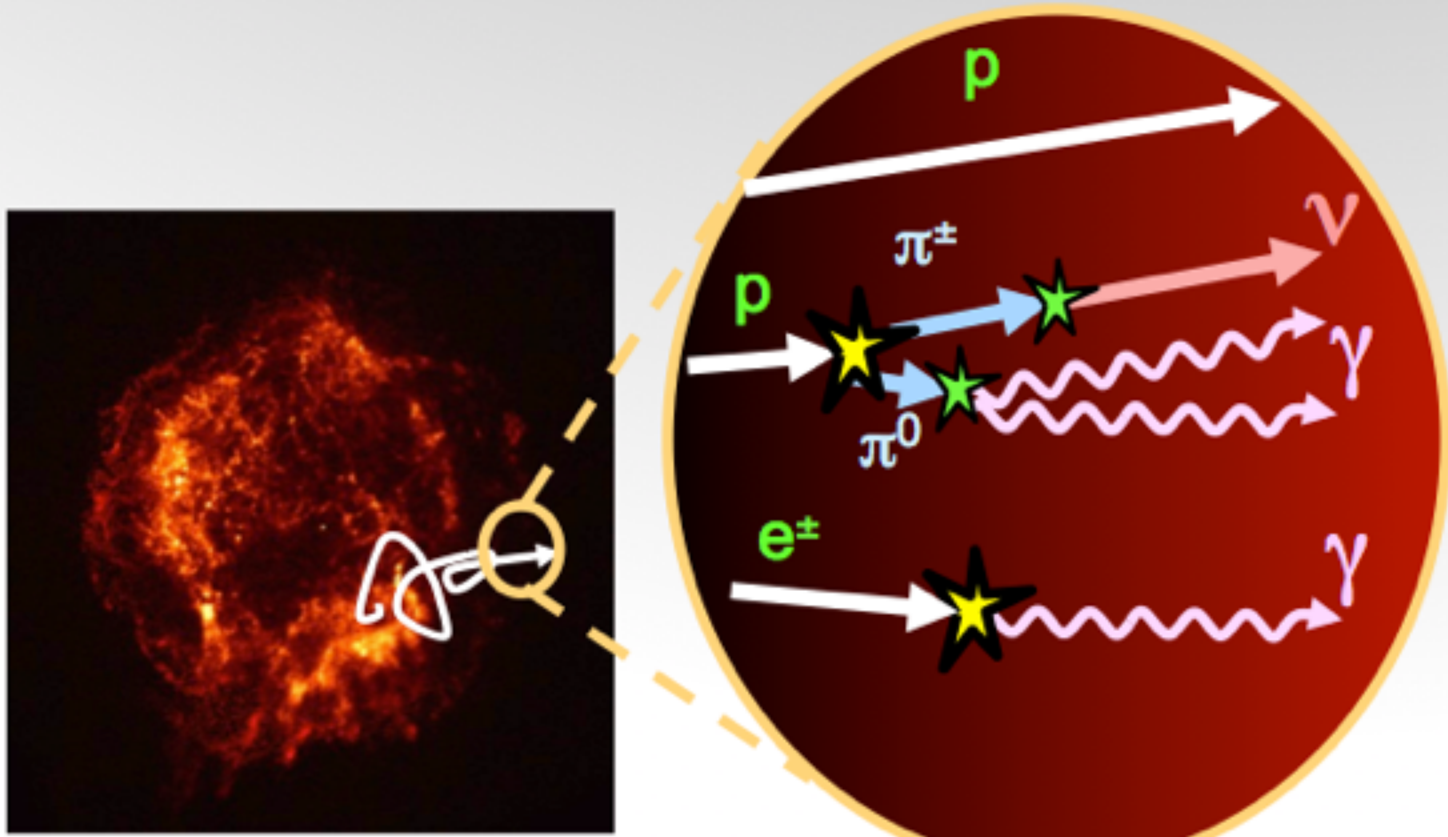


Astronomy VHE 9

Observation des photons gamma (100 MeV ≤ E ≤ 100 TeV) d'origine cosmique.

Qui dit gamma dit accélération de particules chargées: sonde les processus d'accélération des particules au sein des phénomènes les plus violents de l'Univers

Très bon moyen de débusquer les sources de rayonnement cosmique: les gammas se propagent en ligne droite depuis leur lieu de production



- Production hadronique (protons de haute énergie):

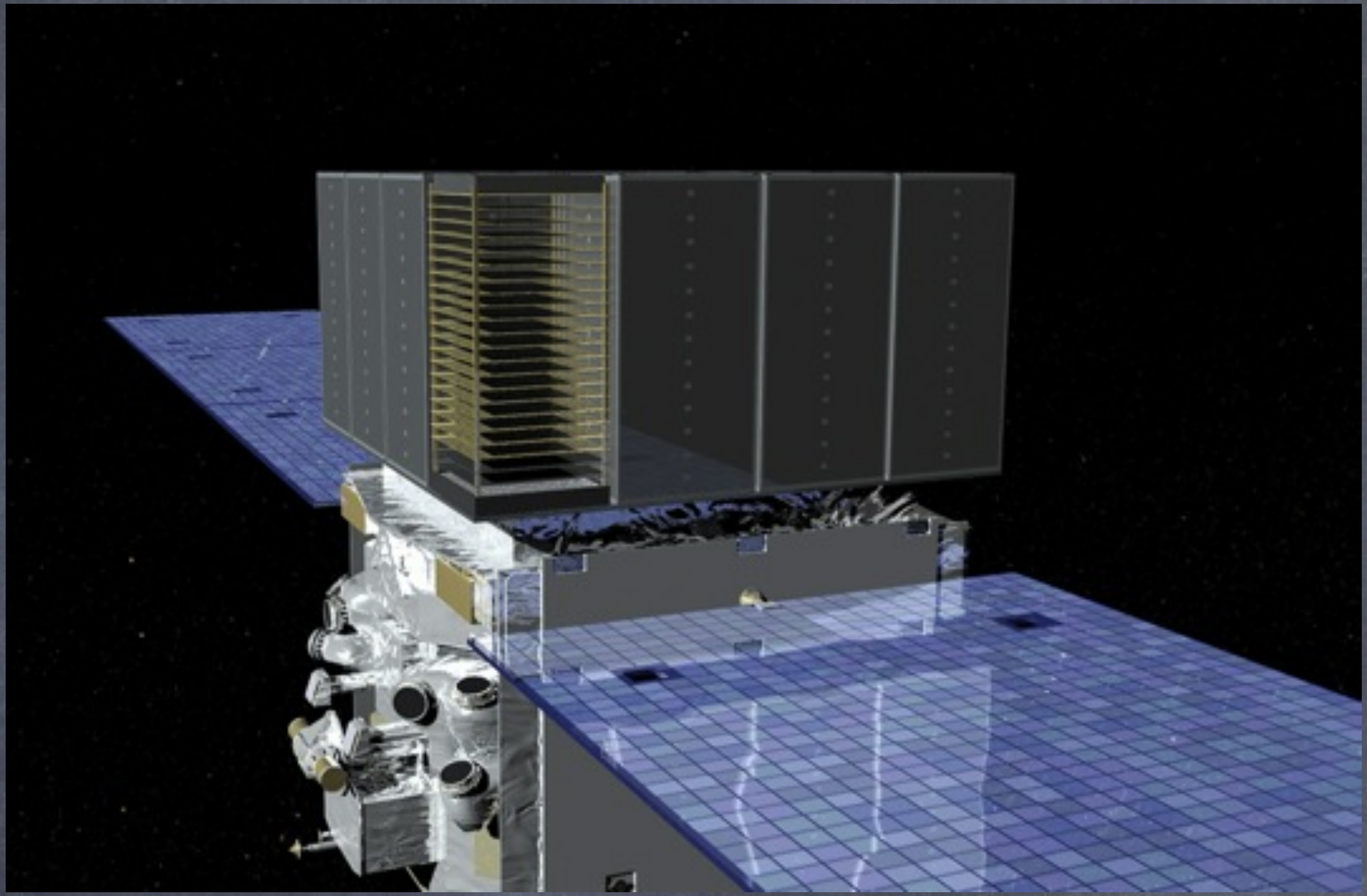
$$p^+ + X \to \pi^0 + Y \to 2\gamma$$

- Production leptonique (électrons de haute énergie)
  → Rayonnement synchrotron
  → Bremsstrahlung
  → Diffusion compton-inverse

$$e^- + \gamma_{\mathrm{CMB}} \to e^- + \gamma_{\mathrm{TeV}}$$

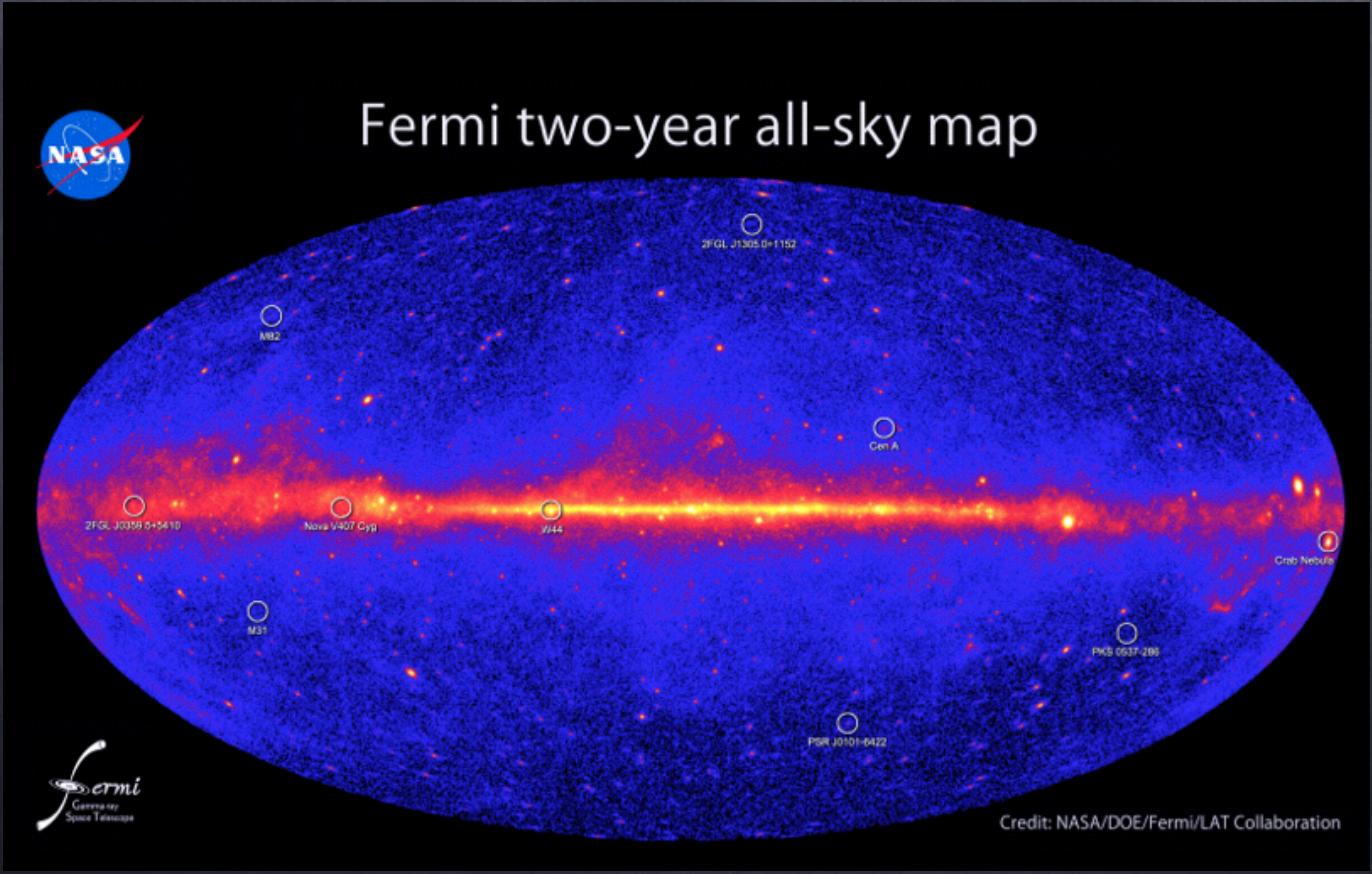
Astronomy UHE 9

Fermi

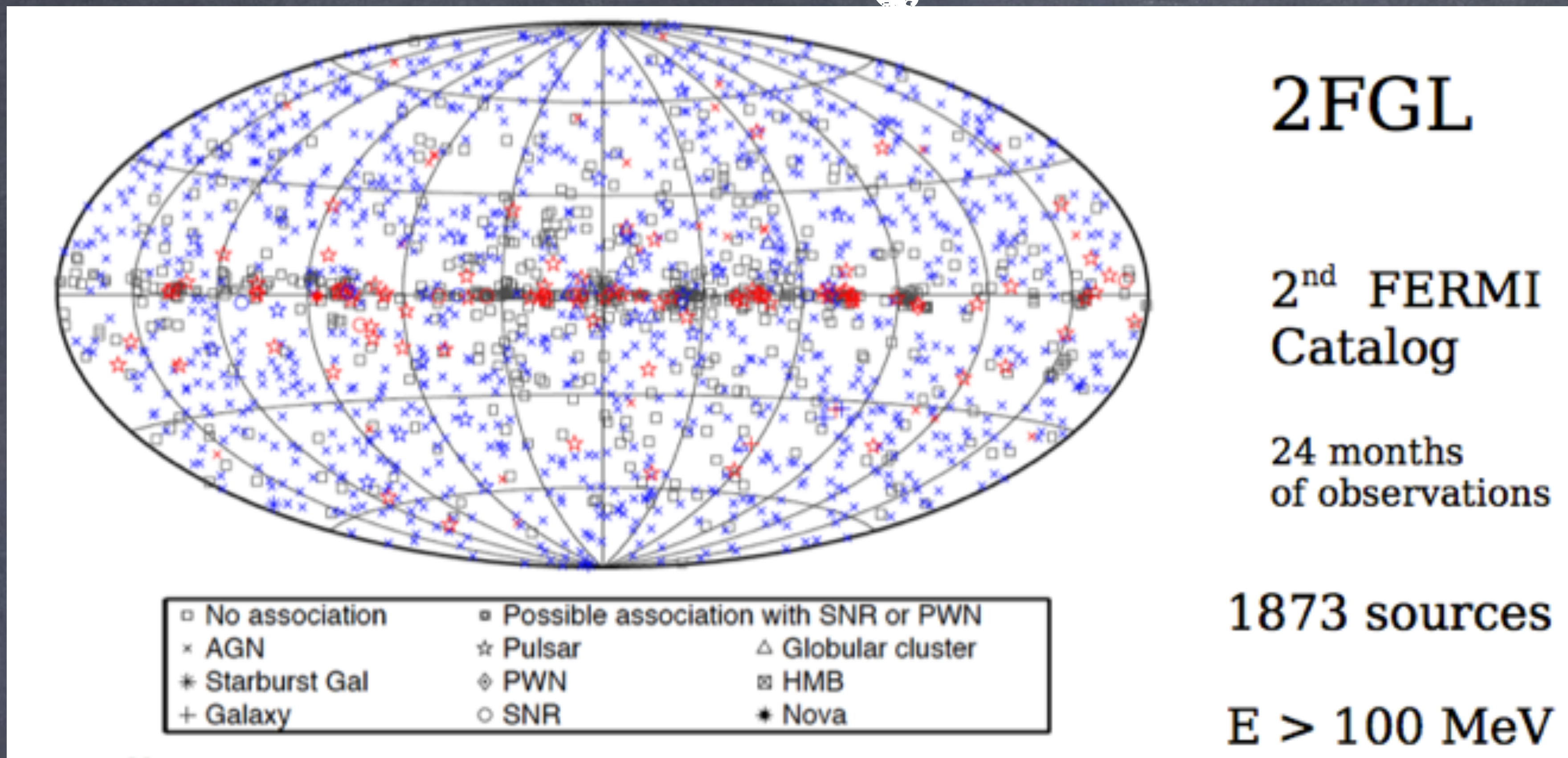


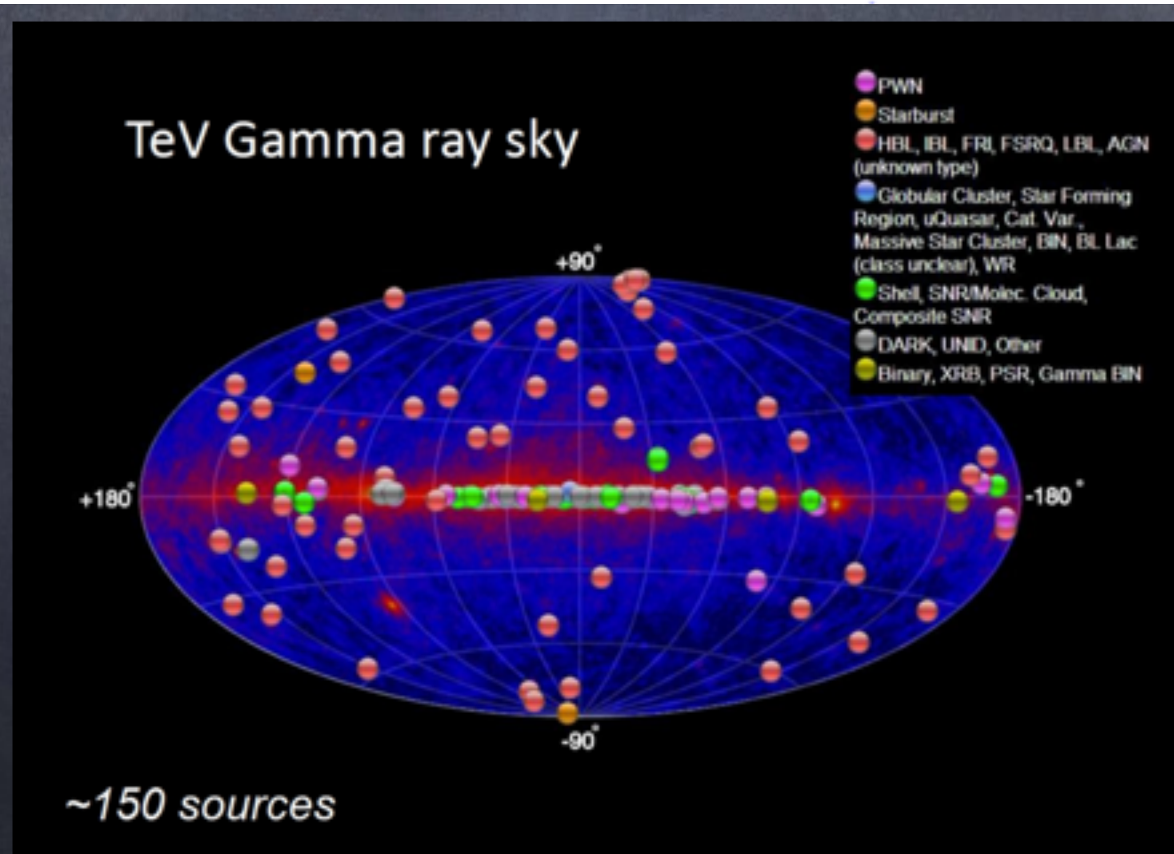
HESS

Astronomy UHE 9

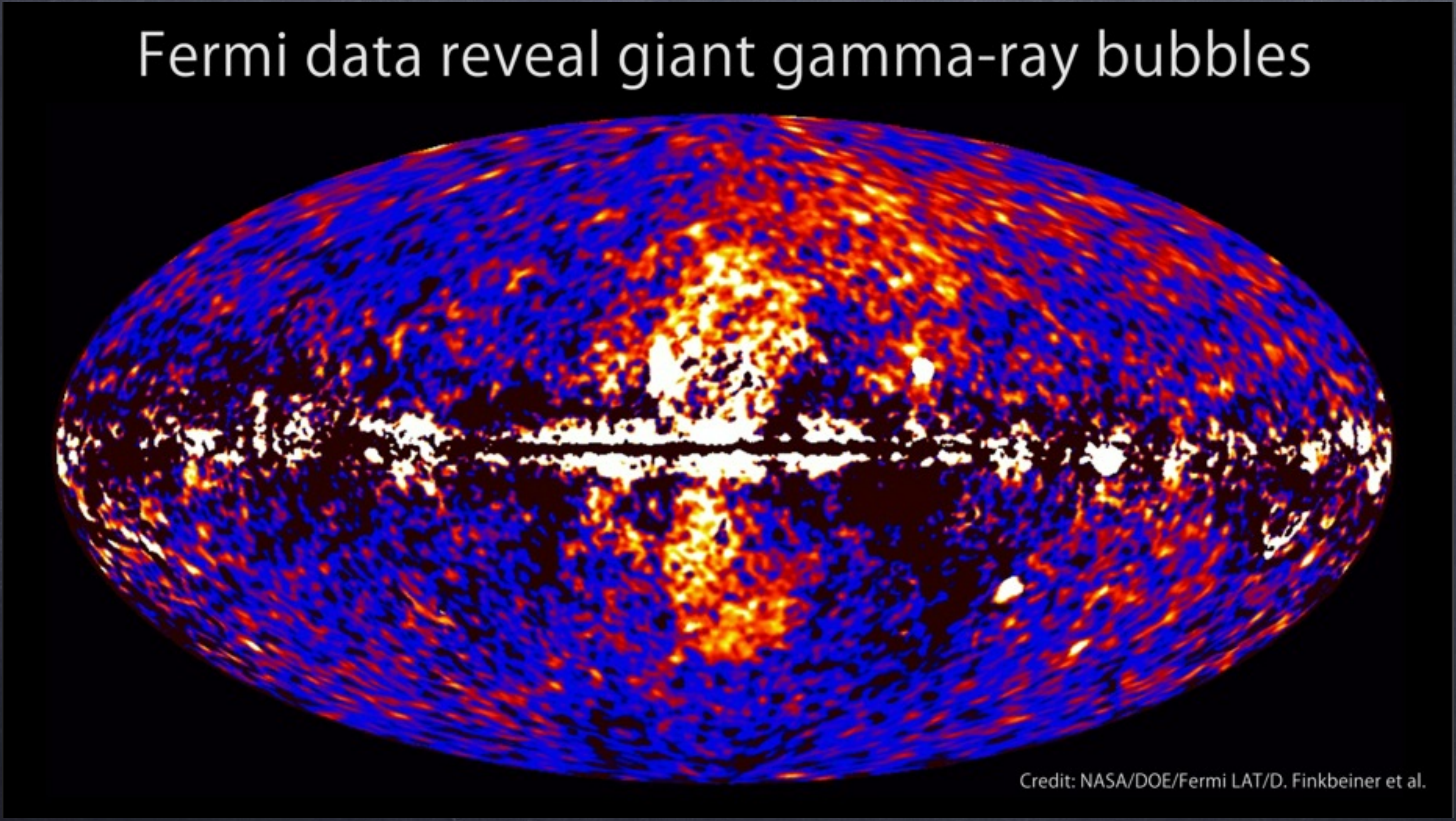


Astronomy UHE 9

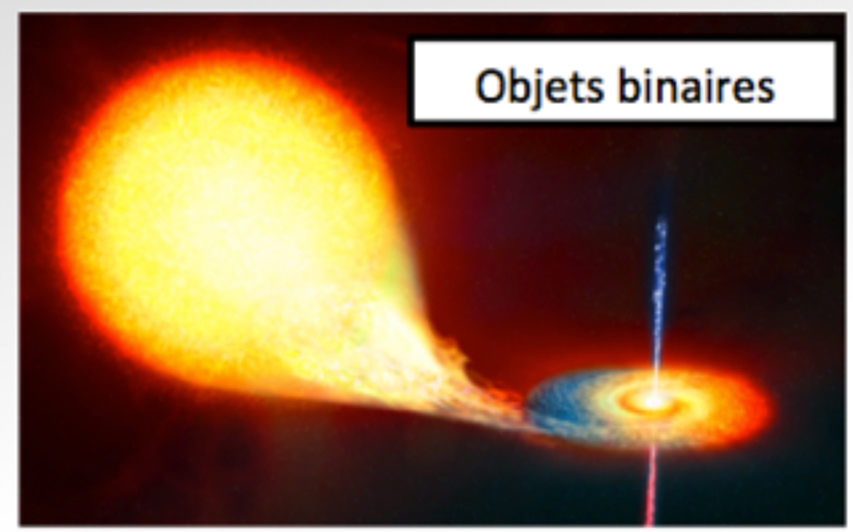


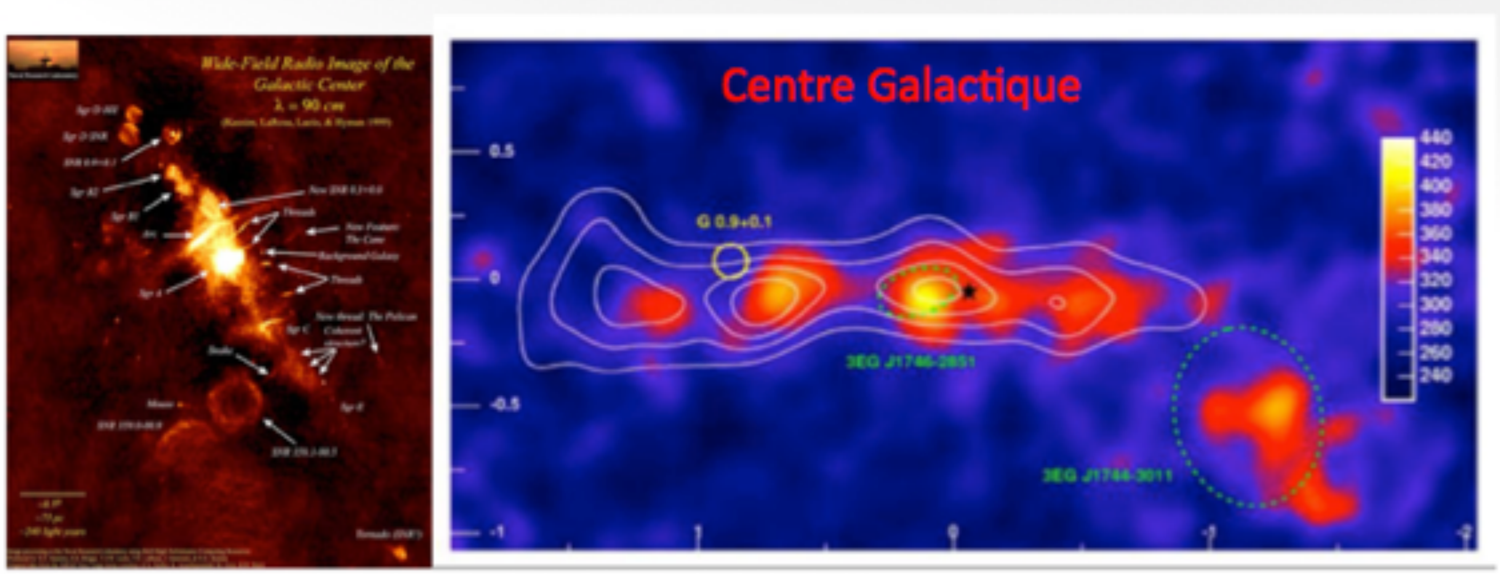


Astronomy VHE 9



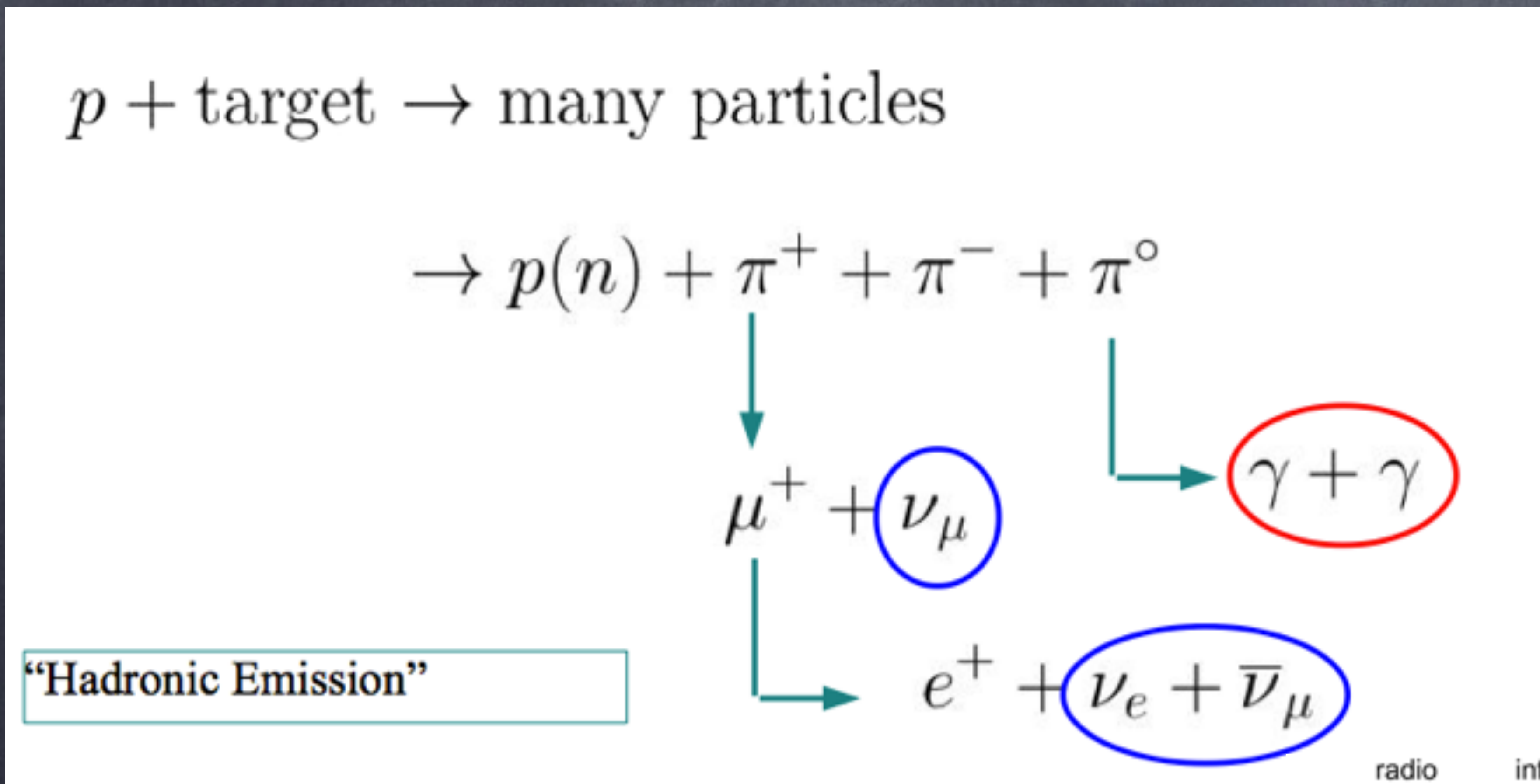
Astronomy UHE 9

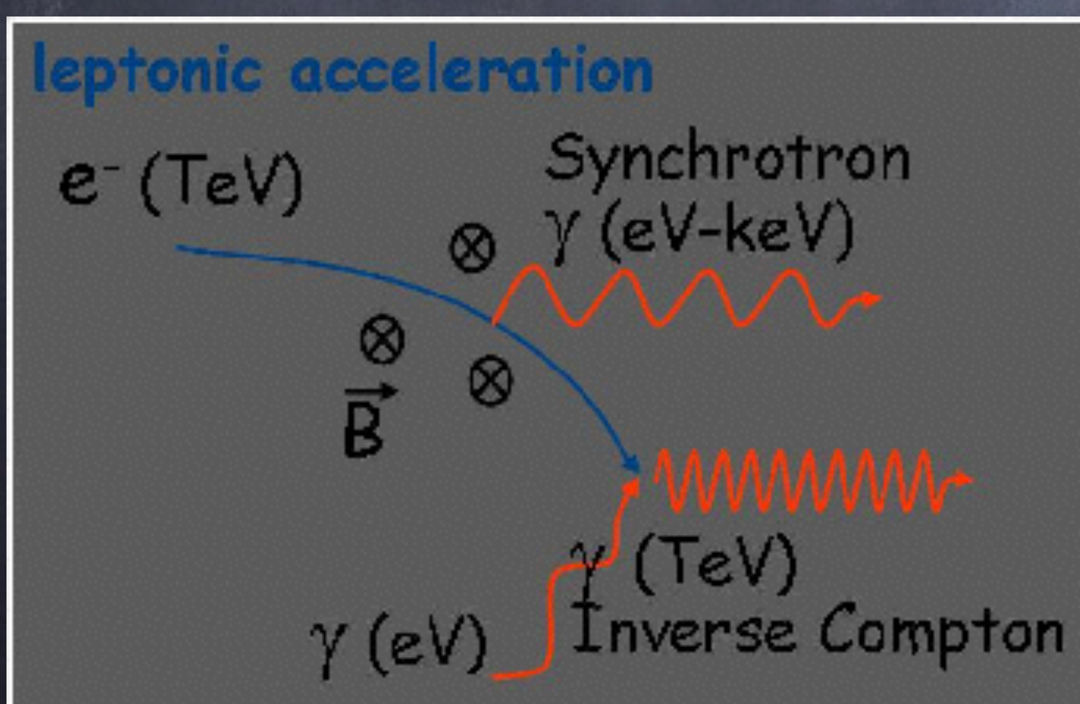


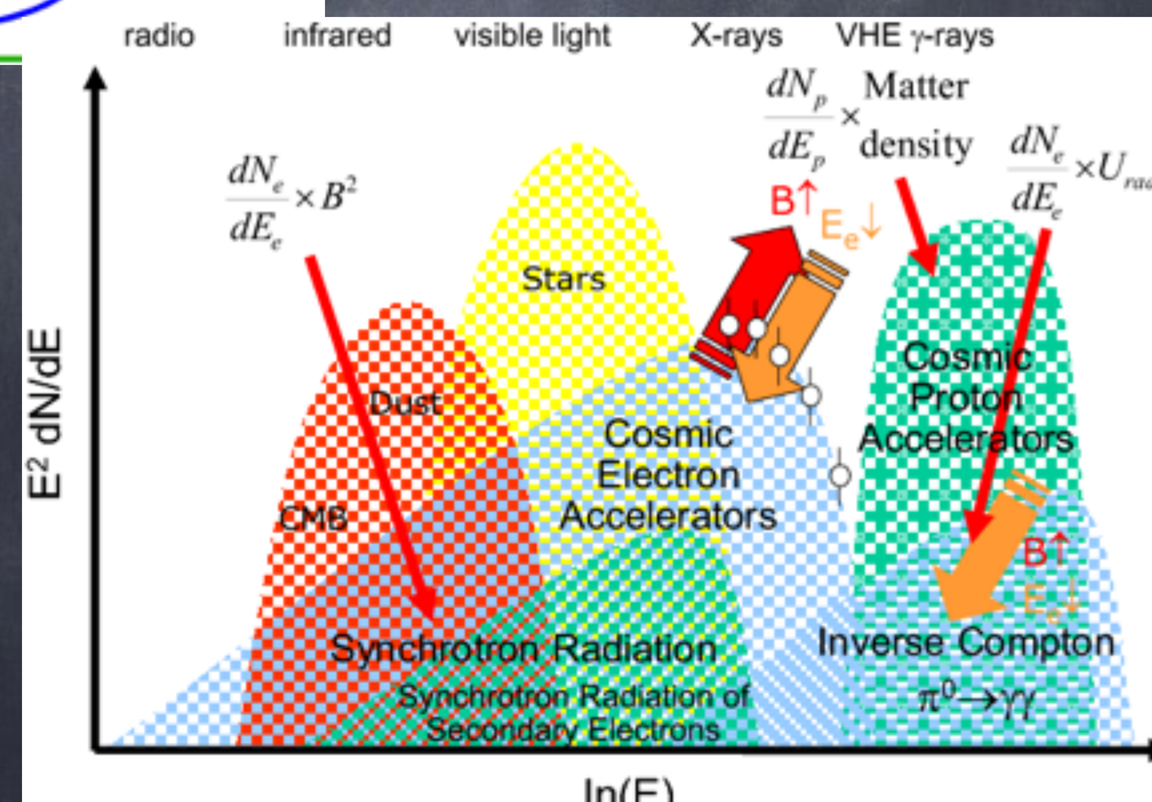


+ amas d'étoiles
+ starburst galaxies
+ amas de galaxie
+ ...

Astronomy VHE 9

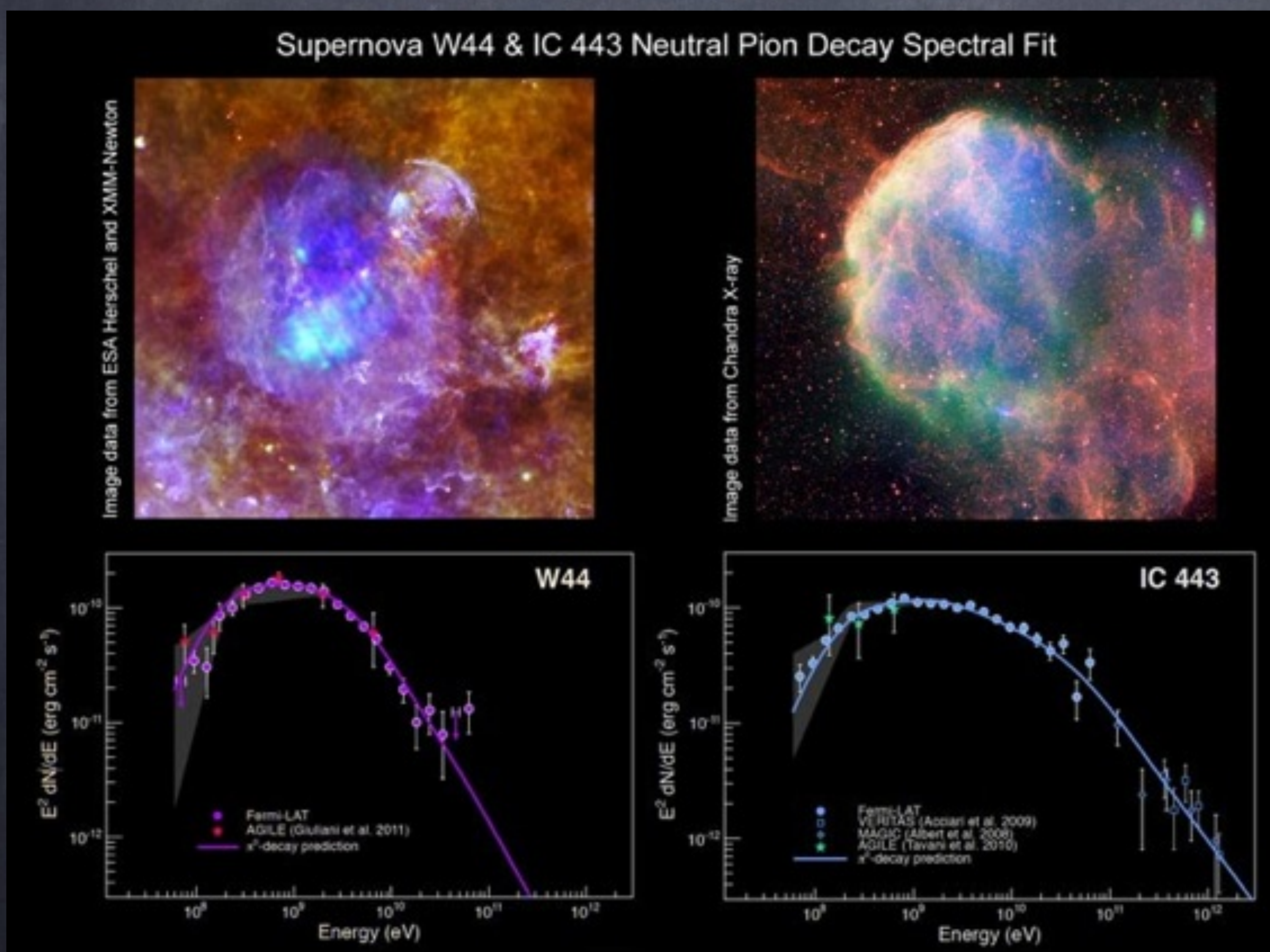


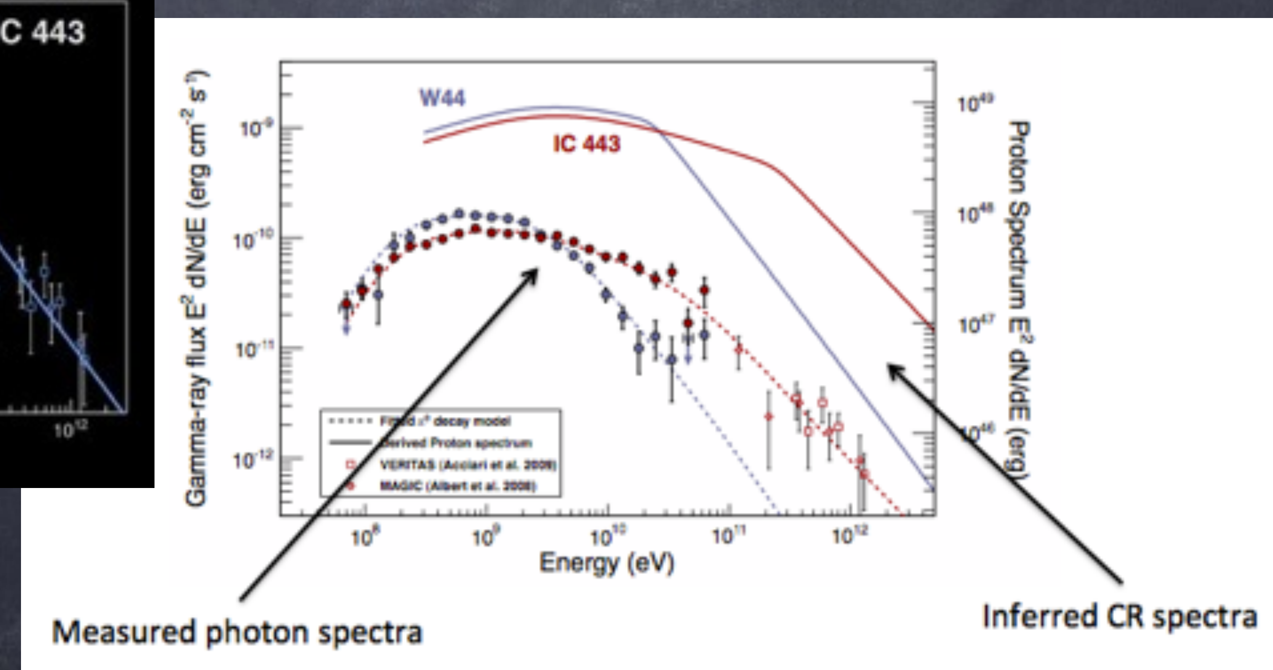




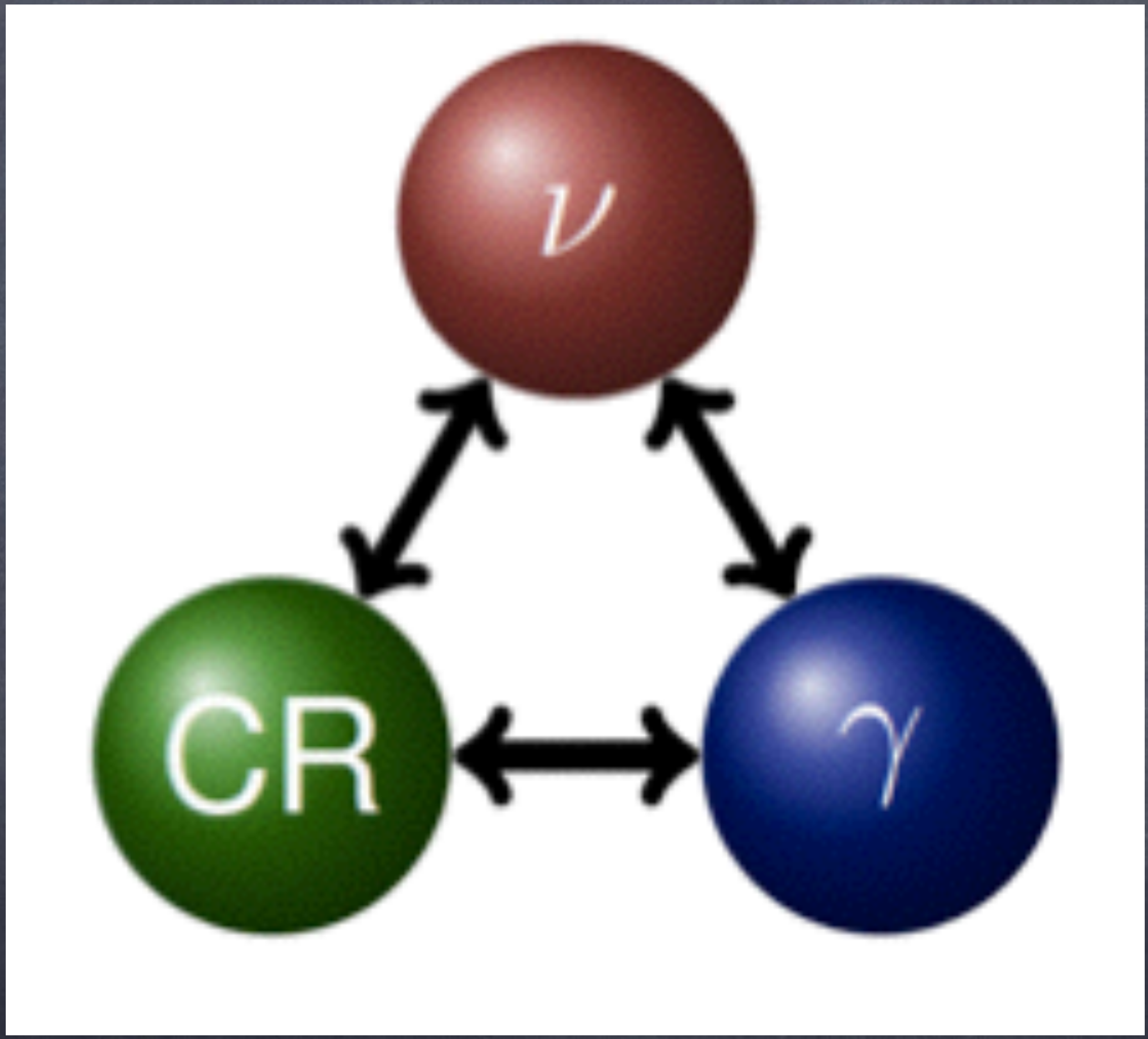
Astronomy VHE g

Up to 10^17 eV, probably SNR are one of the main sources of cosmic rays



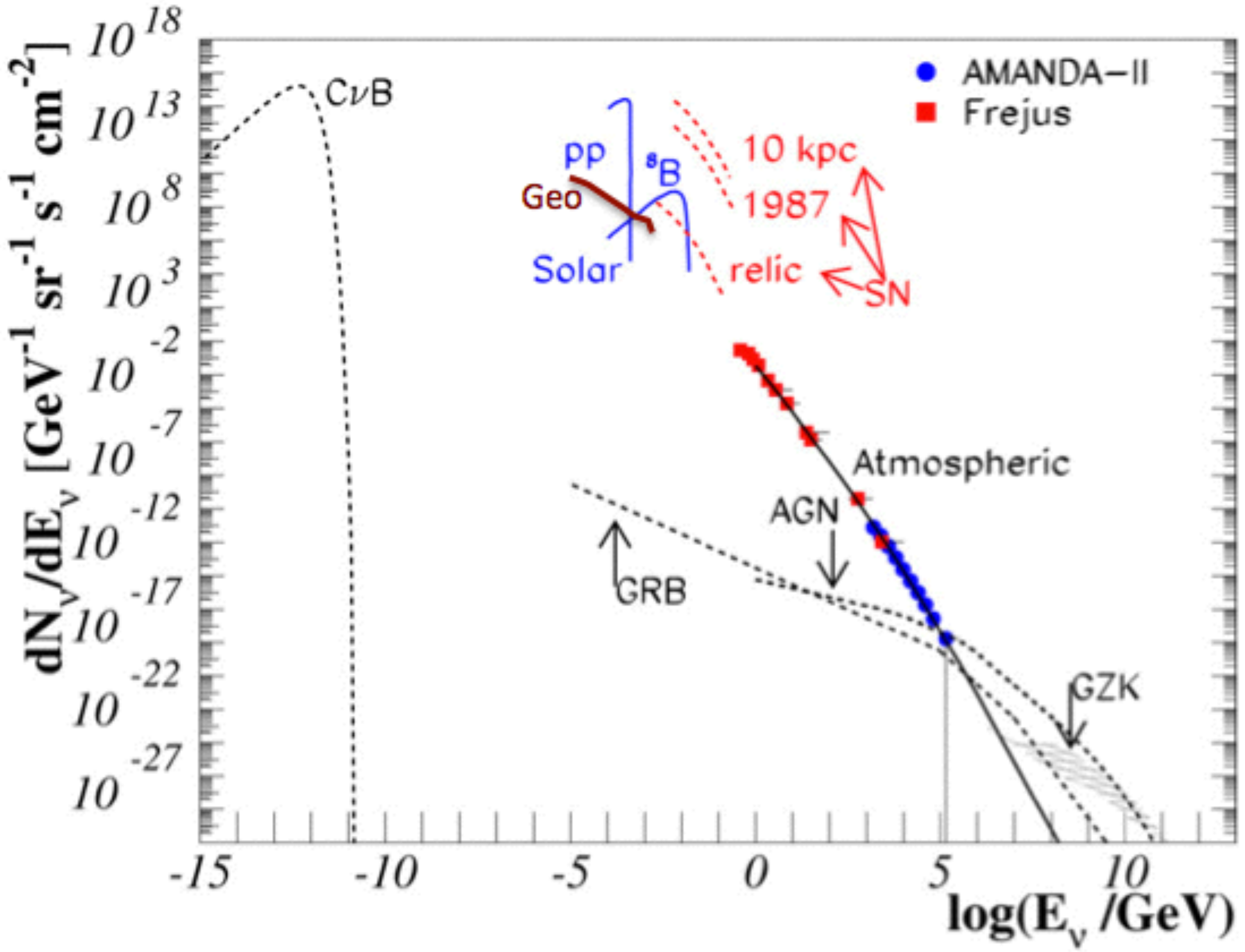


Indirect CR detection



neutrino

J.K. Becker / Physics Reports 458 (2008) 173–246



1987: SN1987A

1998: Atmos ν osc

2000: Solar ν osc

2010: Geo ν

2013: Astro ν

2014: solar pp ν (Borexino)

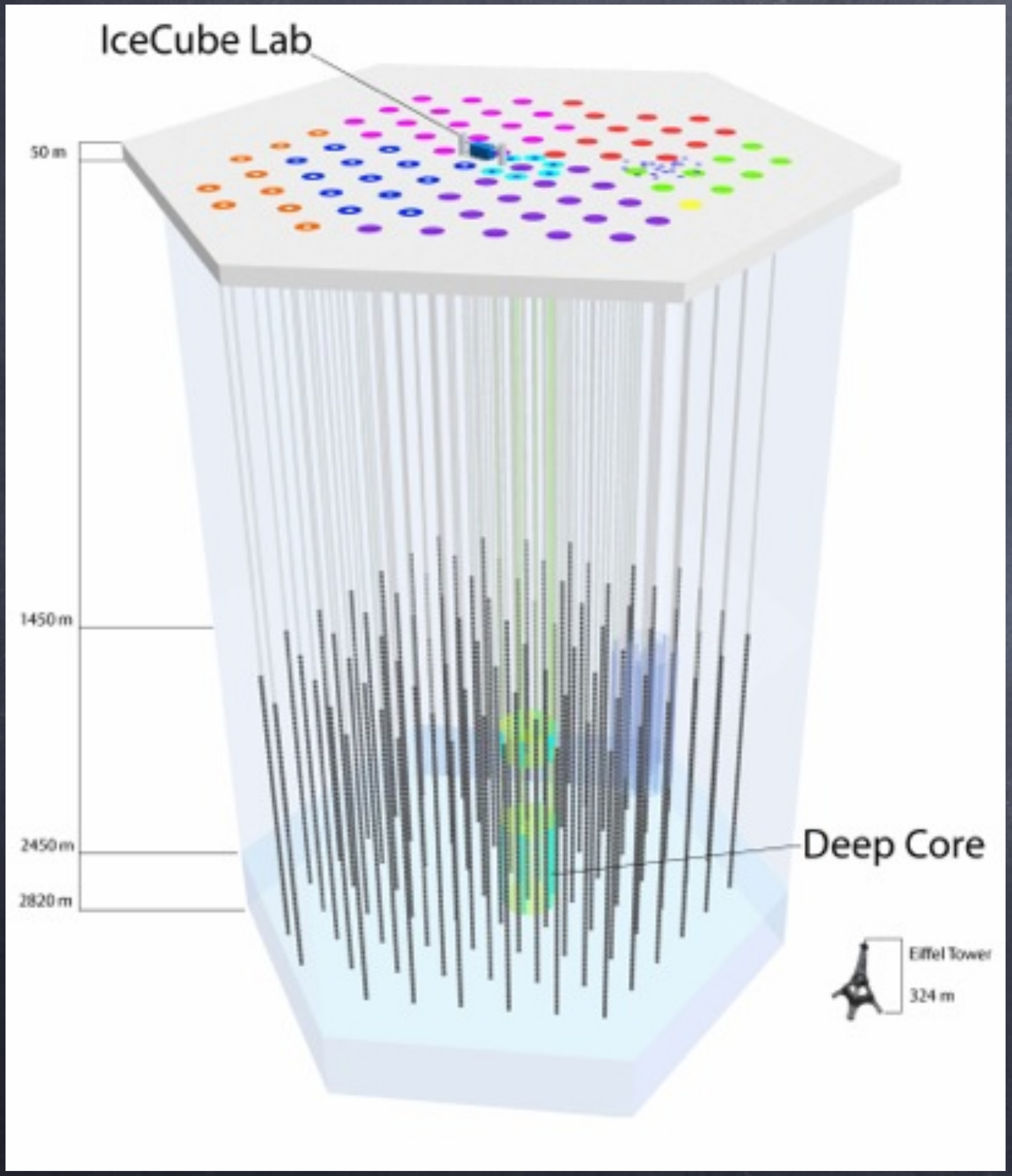
201? Relic SN ν

20?? Cosmogenic ν (GZK)

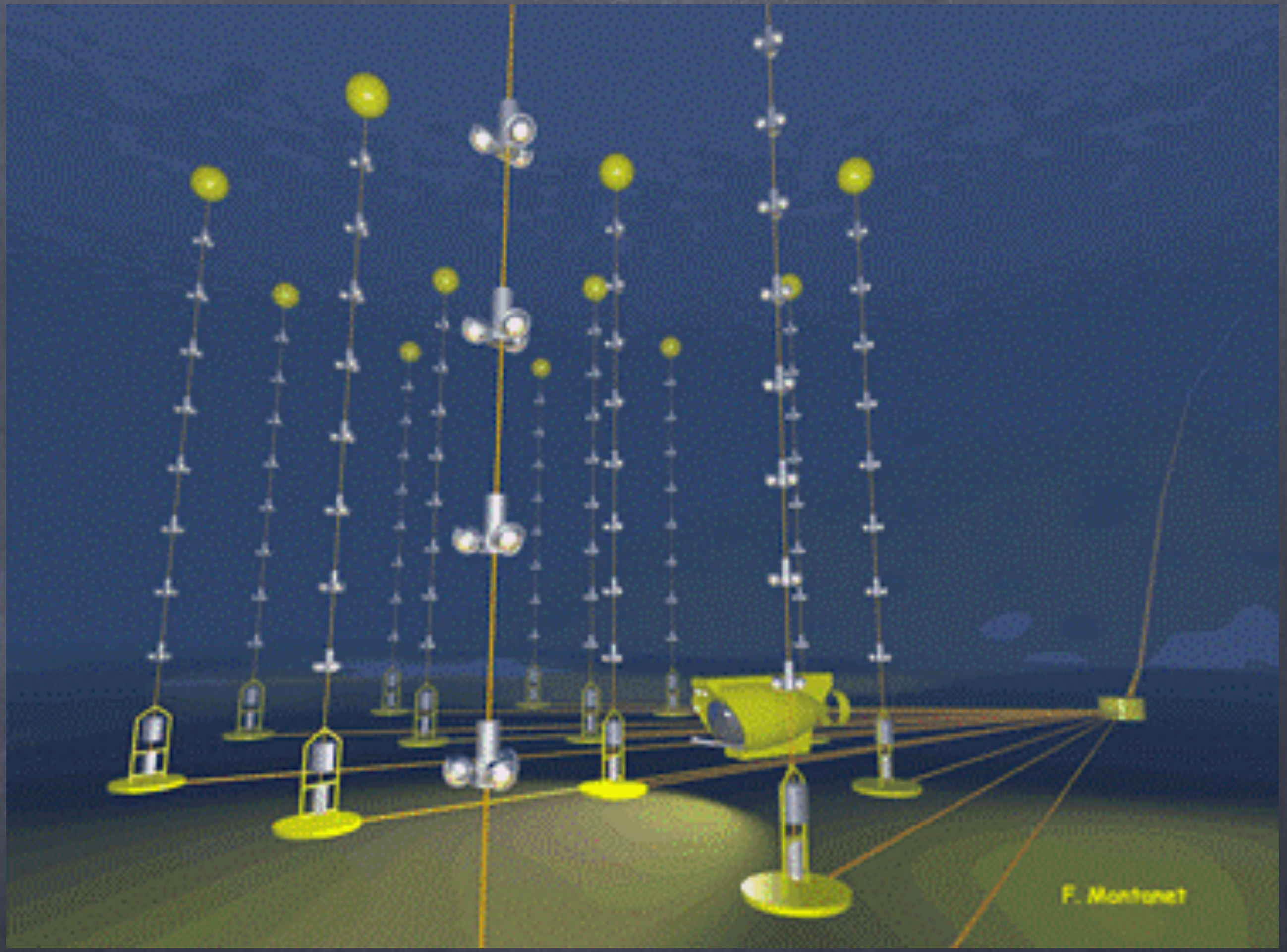
CνB cosmological ν mass?

HE neutrinos

Ice Cube

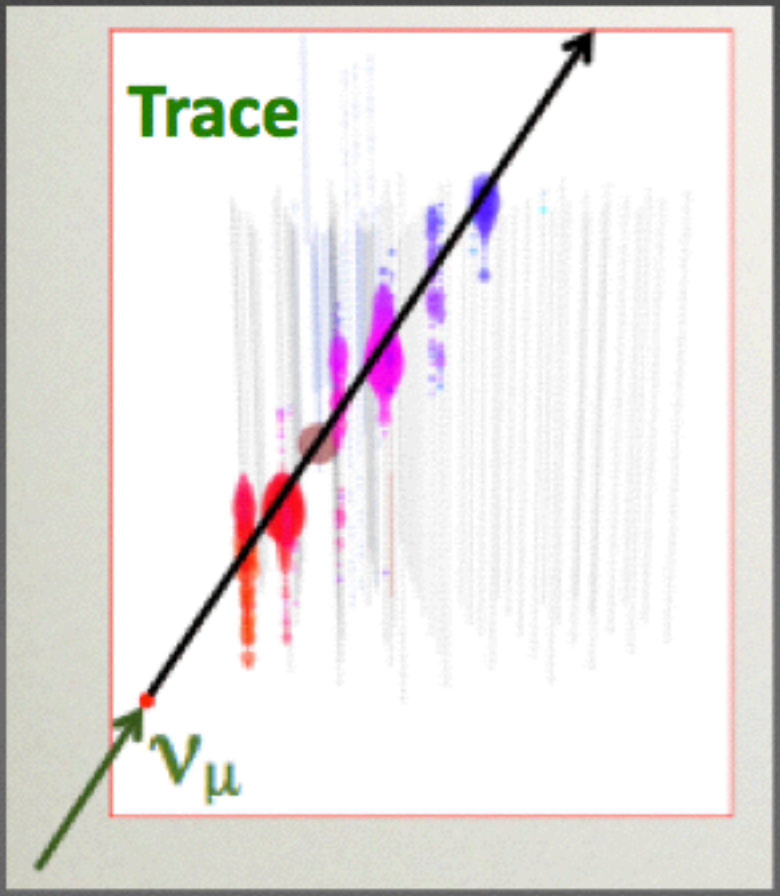


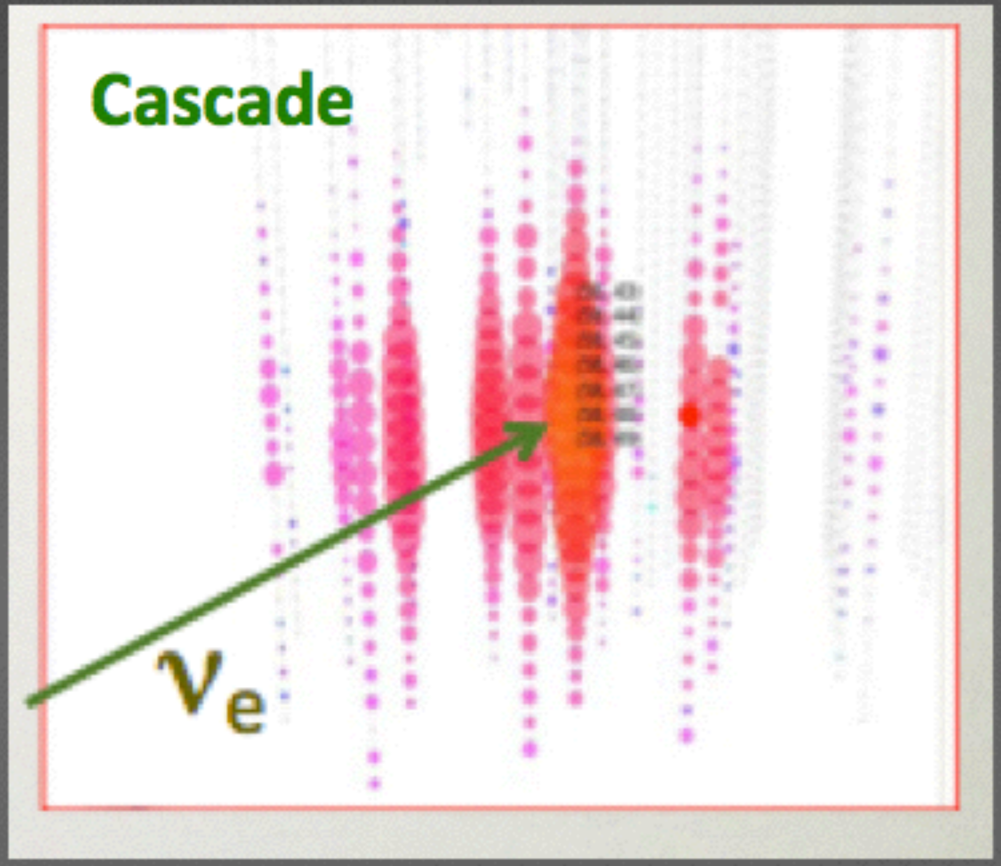
ANTARES



HE neutrino

2 signatures dans le détecteur





Uniquement neutrino muon:
- Très bonne résolution angulaire
=> astronomie
- Grand volume: vertex peut etre en dehors du detecteur

Neutrino electron et tau (+ NC)
- Mauvaise résolution angulaire
- Bonne résolution en énergie

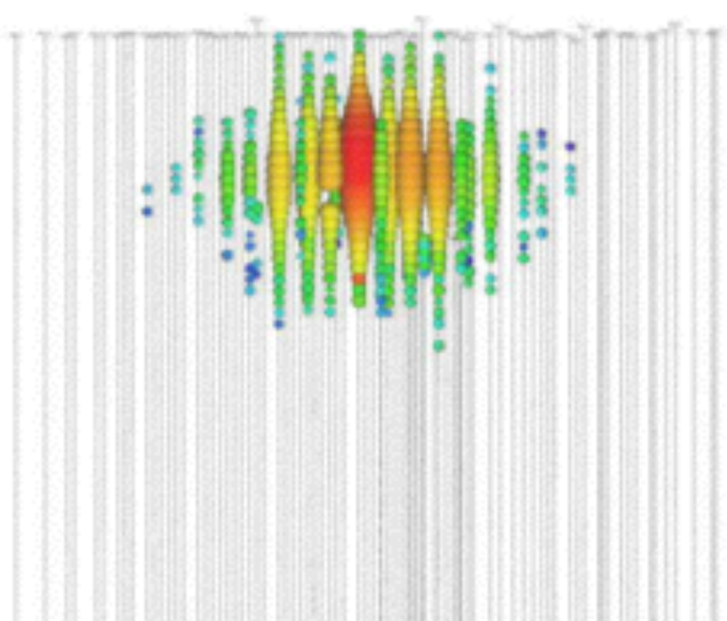
HE neutrino

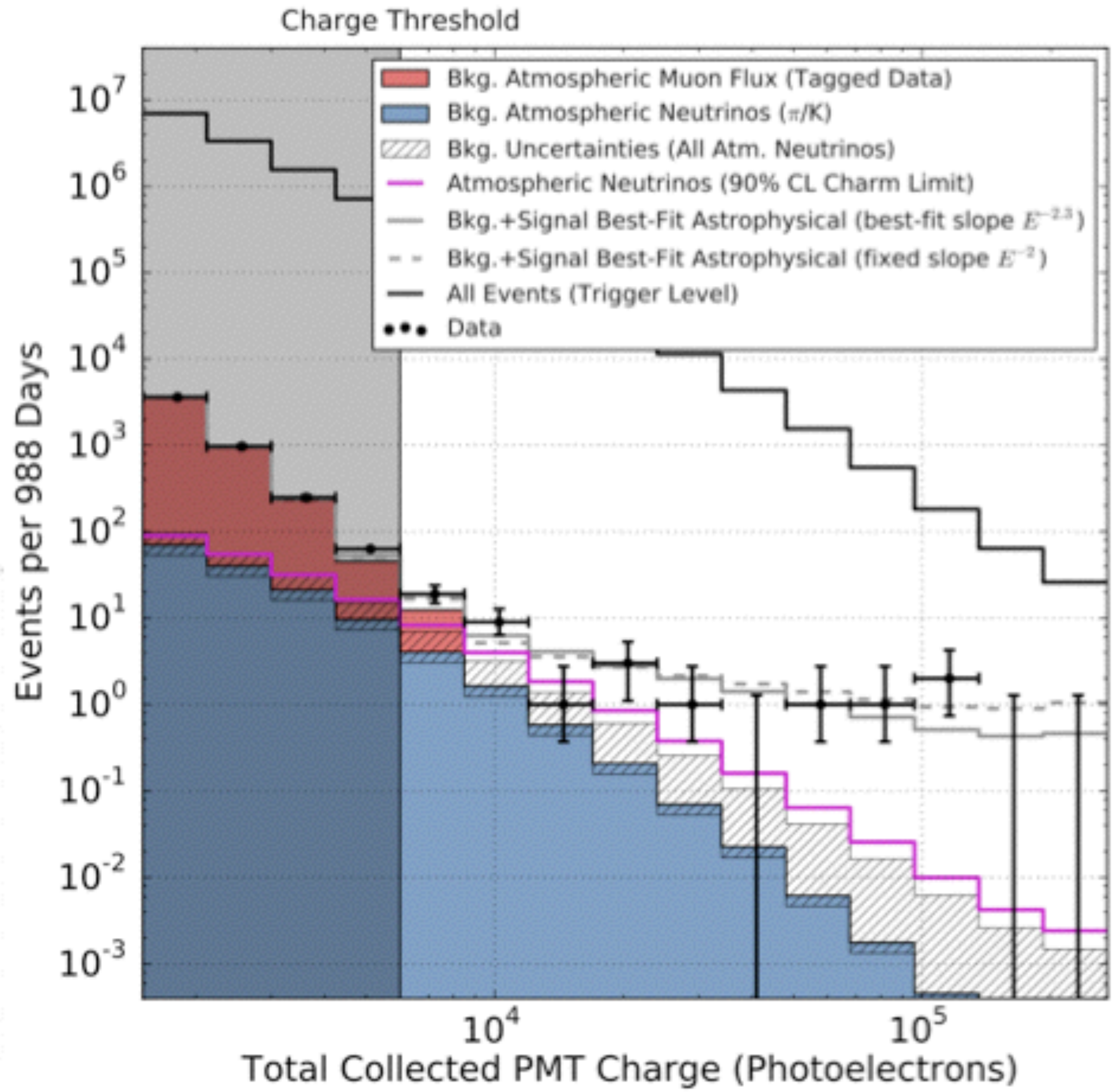
High Energy Starting Event Analysis

3-Year Analysis
PRL **113**, 101101 (2014)

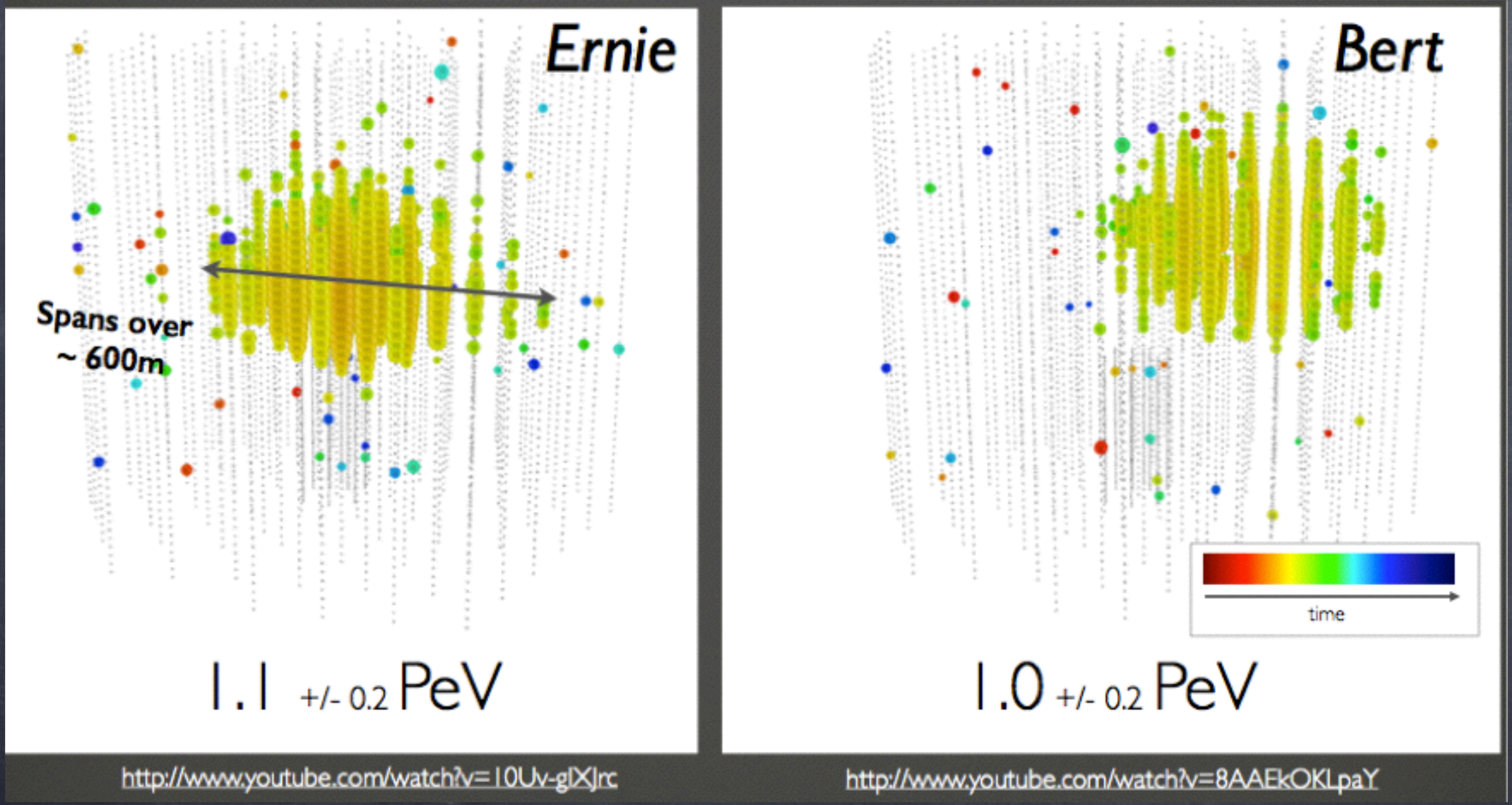
36 events in 3 years

Three > PeV events seen in three years, including a 2-PeV neutrino


"Big Bird"

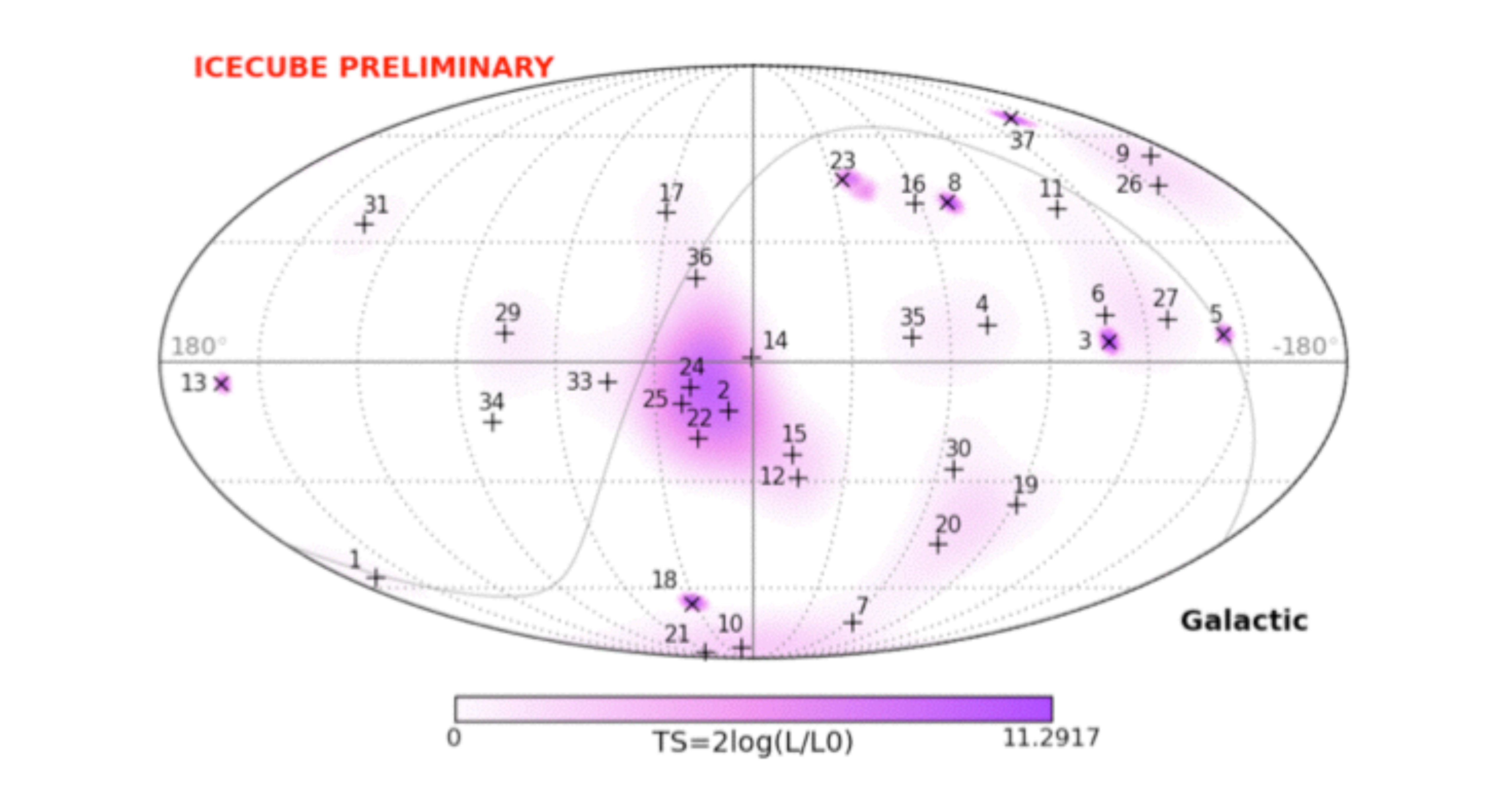


HE neutrino



36 events (~15 bkg): detection à 5sigma

HE neutrino

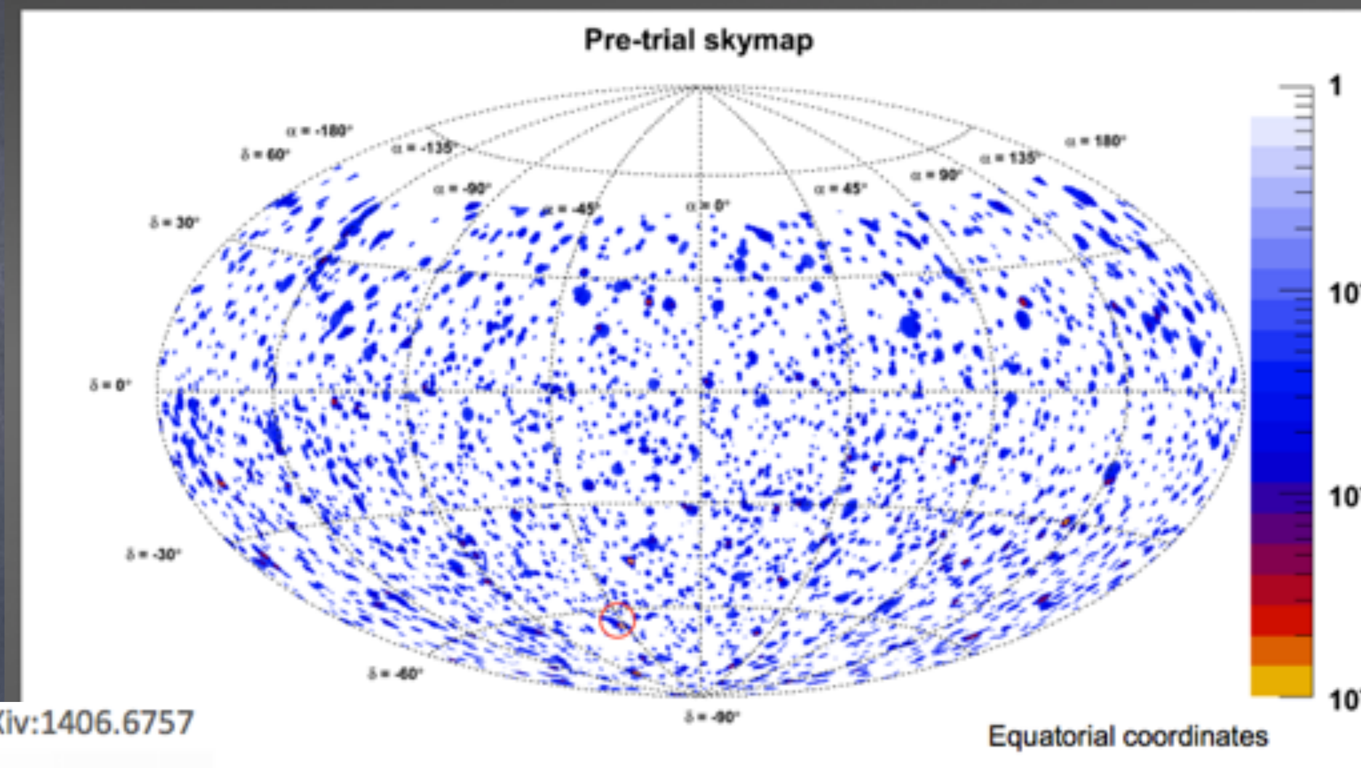


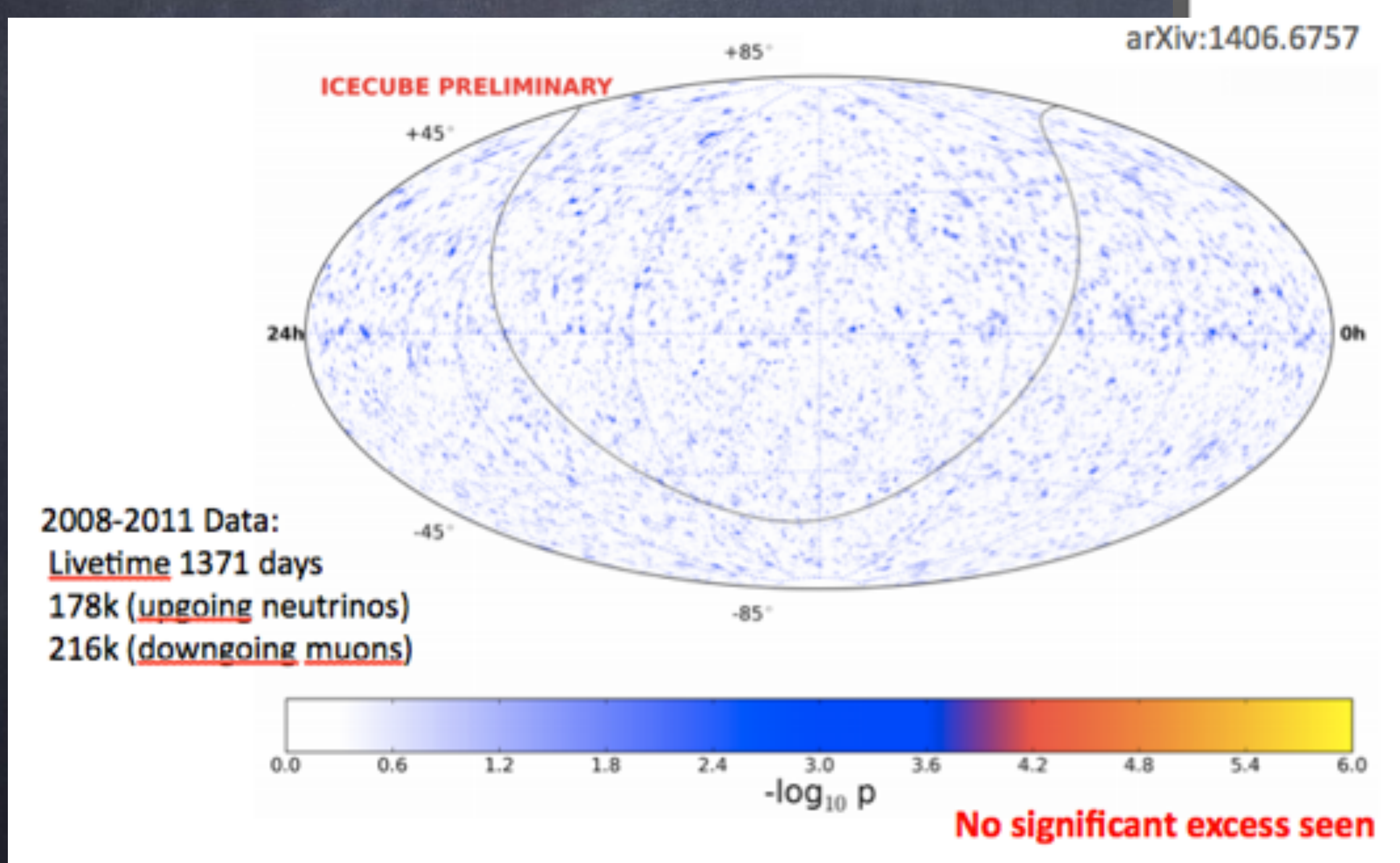
Difficulty: Low Ang. Resol. for cascade event (15deg)

Exclusion of a single PS by ANTARES

HE neutrino

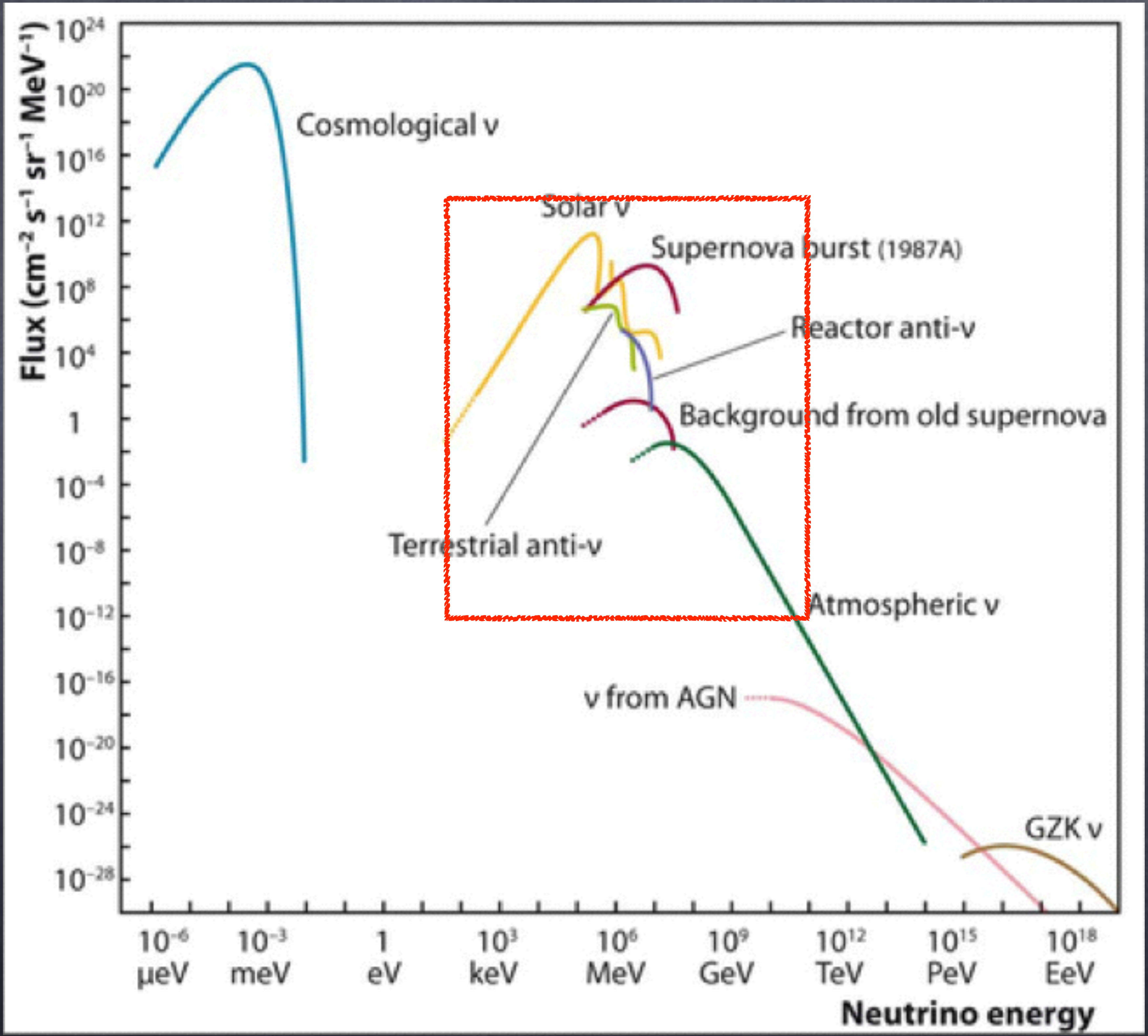
Search for the neutrino sources





?

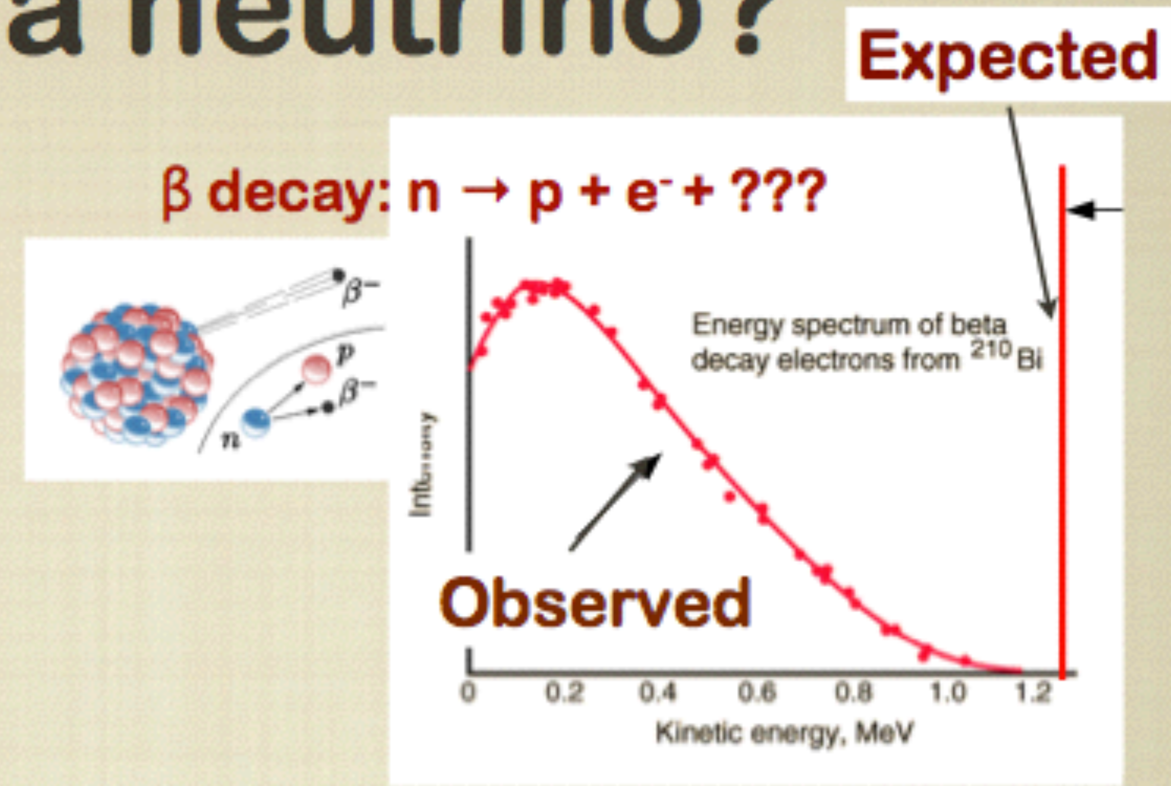
Neutrino


Flux (cm⁻² s⁻¹ sr⁻¹ MeV⁻¹)
Cosmological ν
Solar ν
Supernova burst (1987A)
Reactor anti-ν
Background from old supernova
Terrestrial anti-ν
Atmospheric ν
ν from AGN
GZK ν
10⁻⁶ μeV
10⁻³ meV
1 eV
10³ keV
10⁶ MeV
10⁹ GeV
10¹² TeV
10¹⁵ PeV
10¹⁸ EeV
Neutrino energy

Neutrino

Why do we need a neutrino?

- **1914 - Chadwick: continuos spectrum in the β decay**
  - **Energy not conserved?**
- **1931 - Pauli: new particle escaping the detection that takes the energy**



Dear Radioactive Ladies and Gentlemen,

I have hit upon a desperate remedy to save the law of conservation of energy: the possibility that in the nuclei there could exist electrically neutral particles, which I will call neutrons, that have spin 1/2 and obey the exclusion principle. The mass of the neutrons should be of the same order of magnitude as the electron mass. (...) in beta decay, in addition to the electron, a neutron is emitted such that the sum of the energies of neutron and electron is constant.

I admit that my remedy may seem almost improbable because one probably would have seen them. Thus, dear radioactive people, scrutinize and judge. -

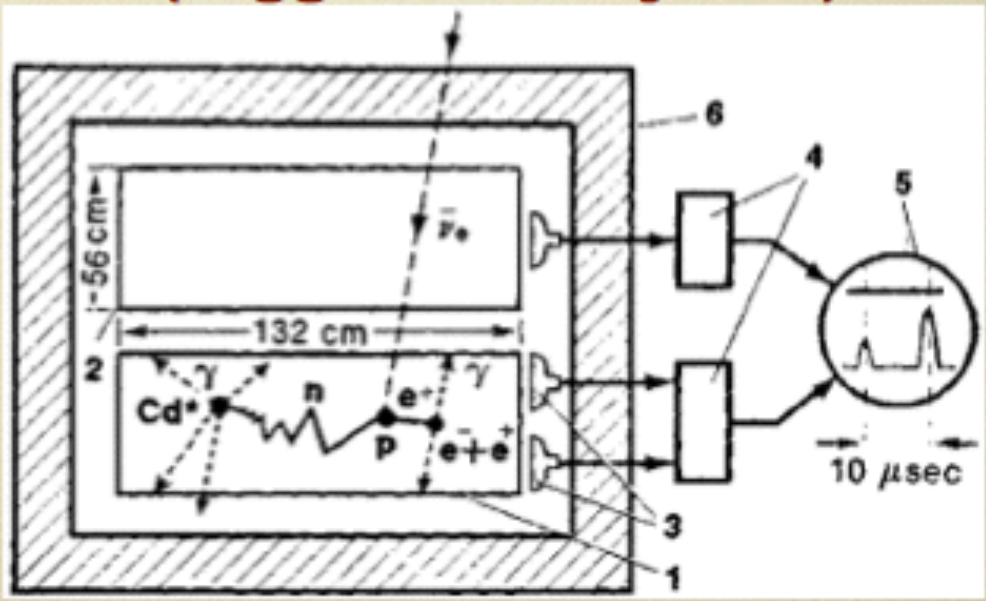
Unfortunately, I cannot personally appear in Tübingen since I am indispensable here in Zürich because of a ball on the night from December 6 to 7.

neutrino

First observation of neutrinos

- If neutrinos are emitted in β-decay why we didn't observe them?
  - Small neutrino cross-section $\sigma \sim 10^{-38}$ cm^2 → Pauli: desperate remedy!
- Bruno Pontecorvo (1946):
  - use inverse β-decay → $\bar{\nu} + p \rightarrow e^+ + n$
  - Intense neutrino sources (Sun or Reactors)
- 1956: Cowan and Reines experiment
- Inverse β-decay at Savannah reactor
  - e+ → 2 γ of 511 keV
  - n+ ^{108}Cd → ^{109}Cd* → ^{109}Cd + γ
- Observed difference between reactor on and reactor off → first detection of antineutrinos

25 years after Pauli remedy!
(Higgs took 50 years)



neutrino

The second neutrino

- 1962: experiment of Lederman, Schwartz, Steinberger
- First man-made neutrino beam produced by pion decay: $\pi \rightarrow \mu + \nu_\mu$
- ν_μ interact into the detector producing a muon track
- $\nu_\mu \neq \nu_e \rightarrow$ at least 2 different neutrino families

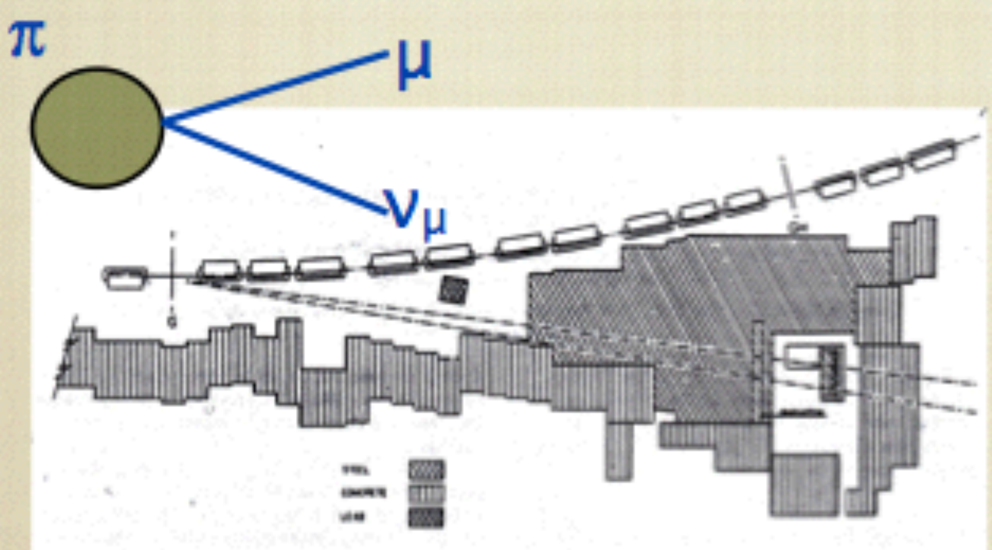
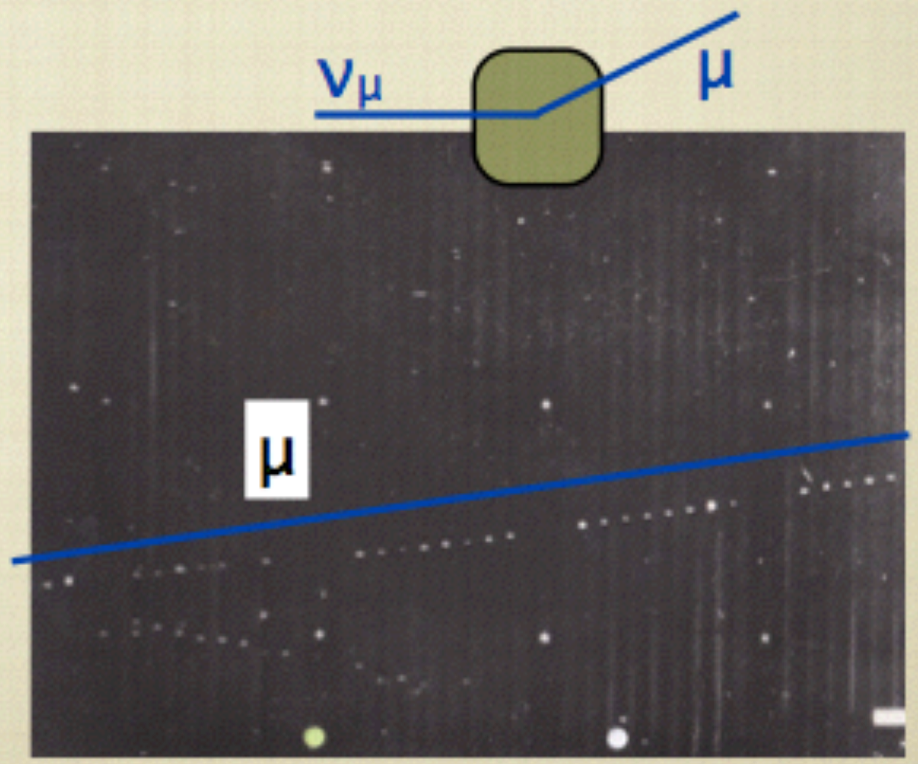
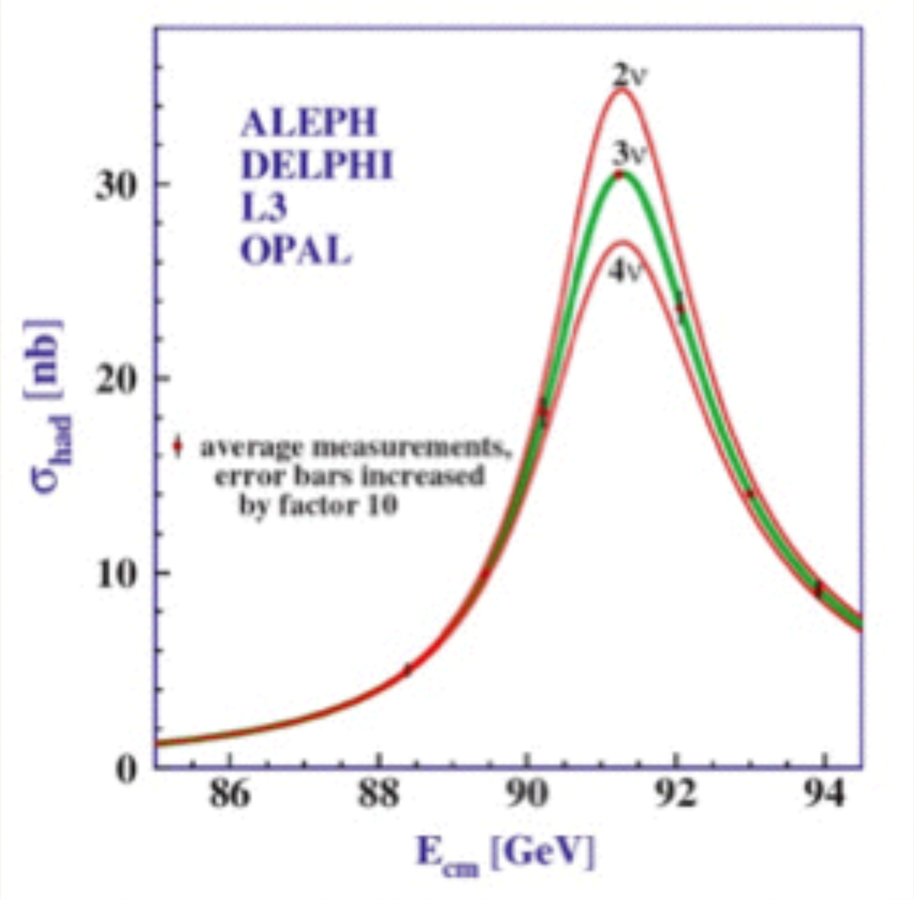


FIG. 1. Plan view of AGS neutrino experiment.



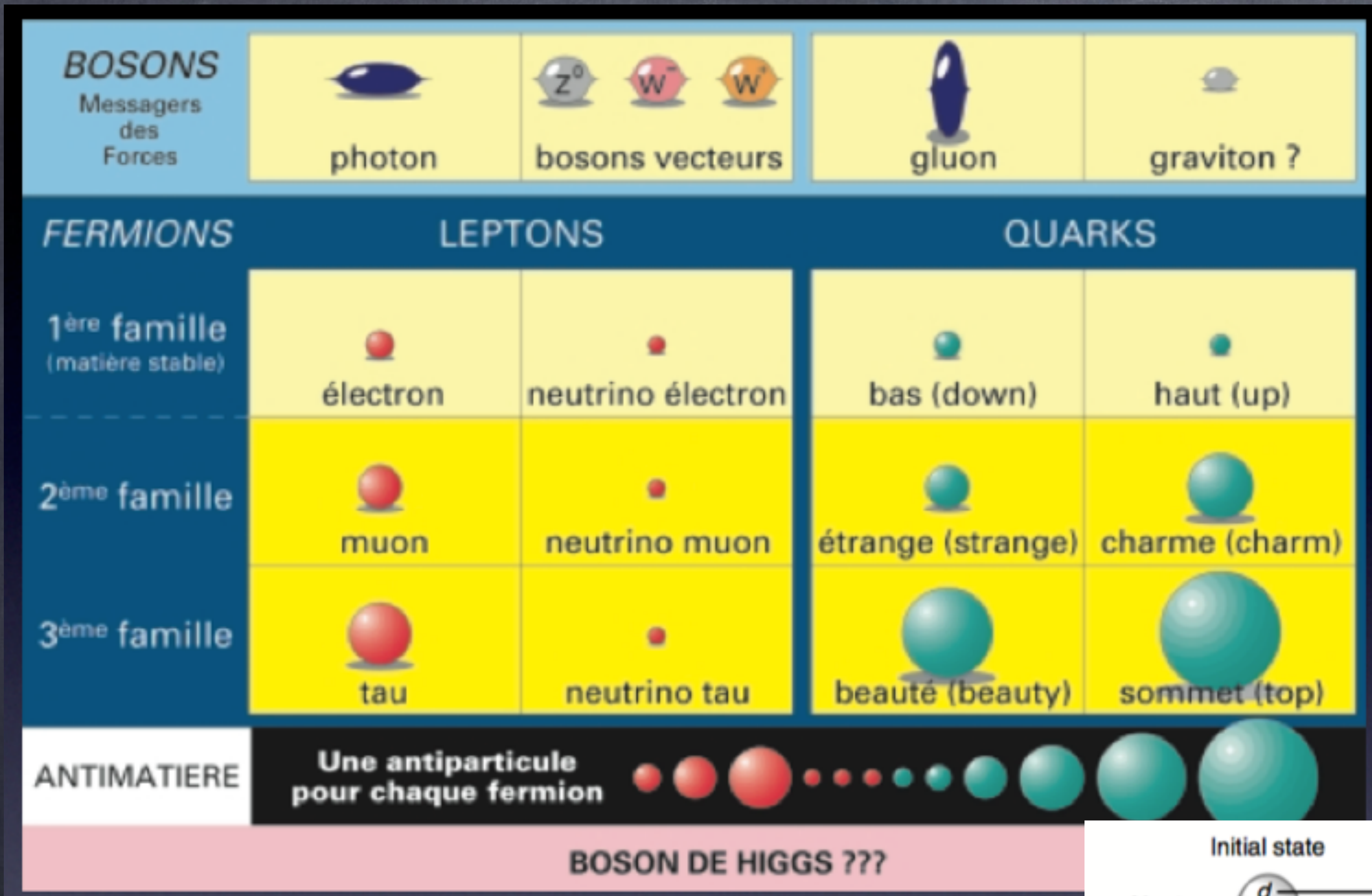
neutrino

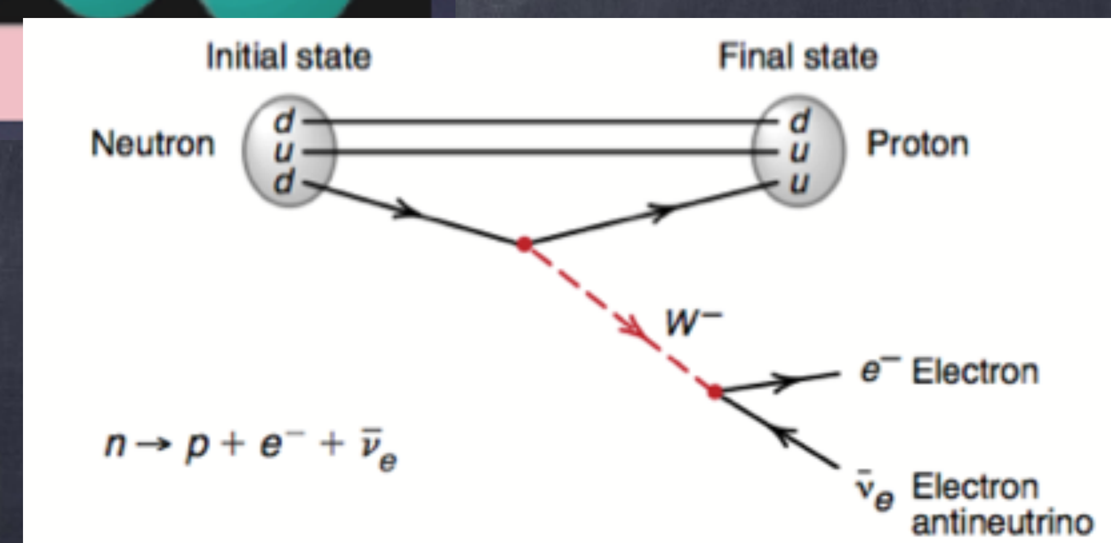
How many neutrinos?



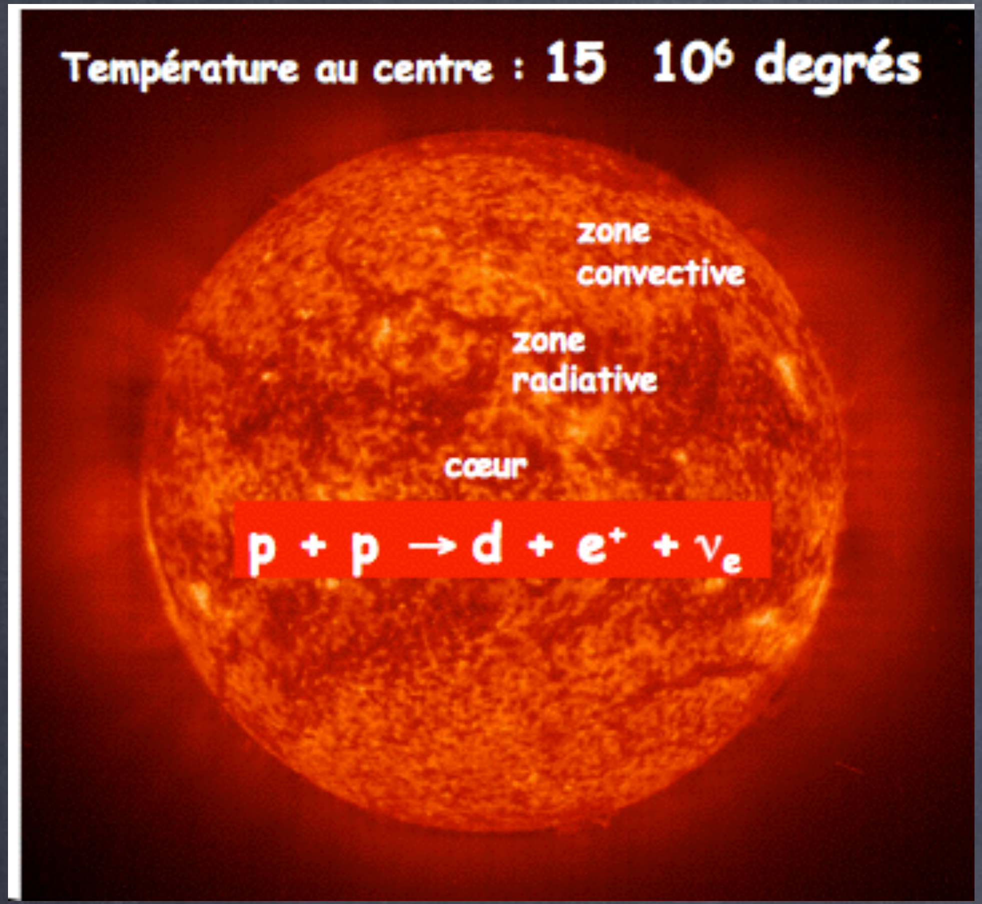
- LEP → look at the invisible Z width: $Z \to \nu\nu$
  - The width depends on the number of neutrino families
- 3 active neutrino families
- ν_τ discovered in 2000 using photographic emulsions

neutrino


BOSONS
Messagers des Forces
photon
bosons vecteurs
gluon
graviton ?
FERMIONS
LEPTONS
QUARKS
1ère famille
(matière stable)
électron
neutrino électron
bas (down)
haut (up)
2ème famille
muon
neutrino muon
étrange (strange)
charme (charm)
3ème famille
tau
neutrino tau
beauté (beauty)
sommet (top)
ANTIMATIERE
Une antiparticule pour chaque fermion
BOSON DE HIGGS ???

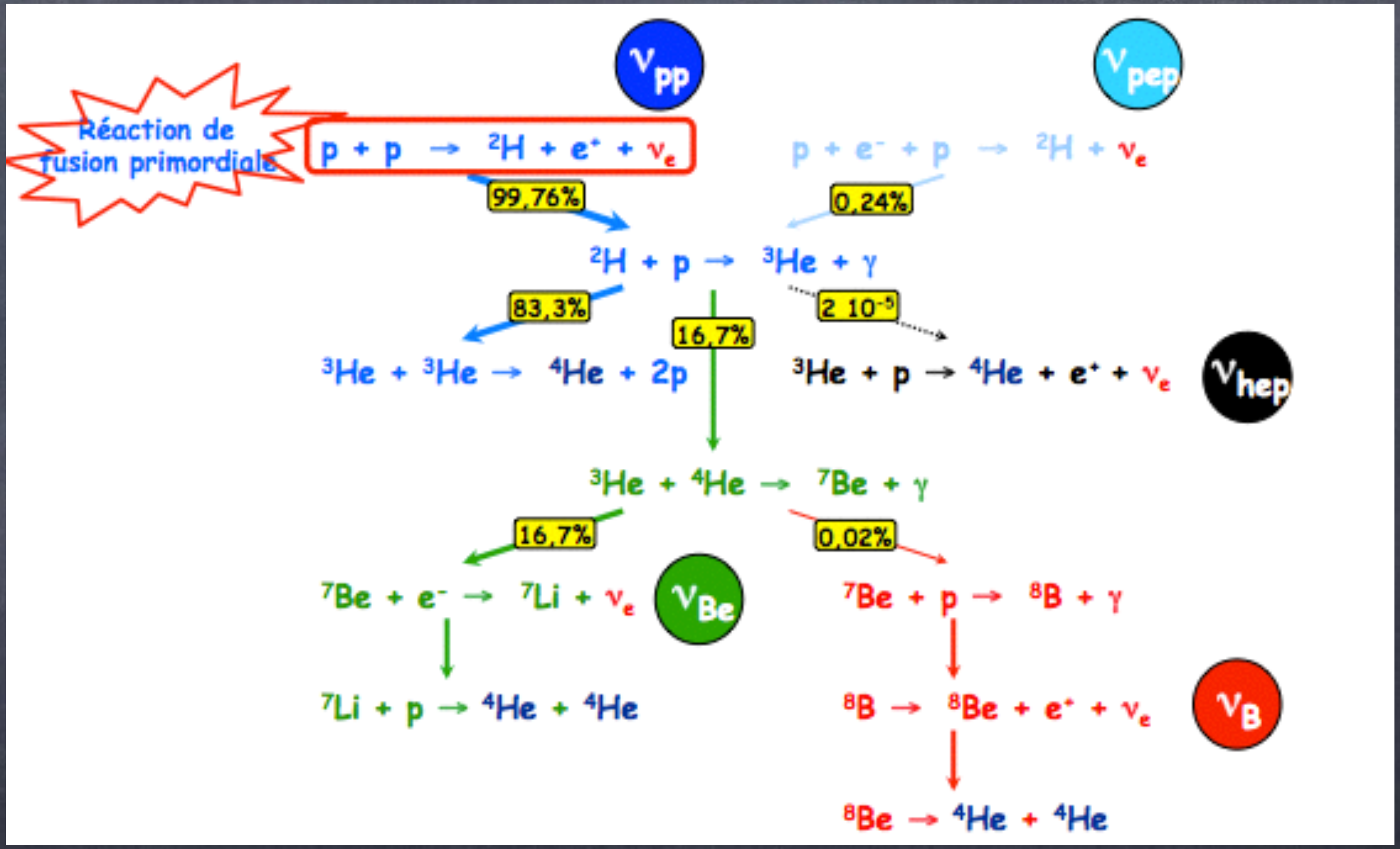

Initial state
Final state
Neutron
Proton
d
u
d
d
u
u
W^-
e^- Electron
$\bar{\nu}_e$ Electron antineutrino
$n \rightarrow p + e^- + \bar{\nu}_e$

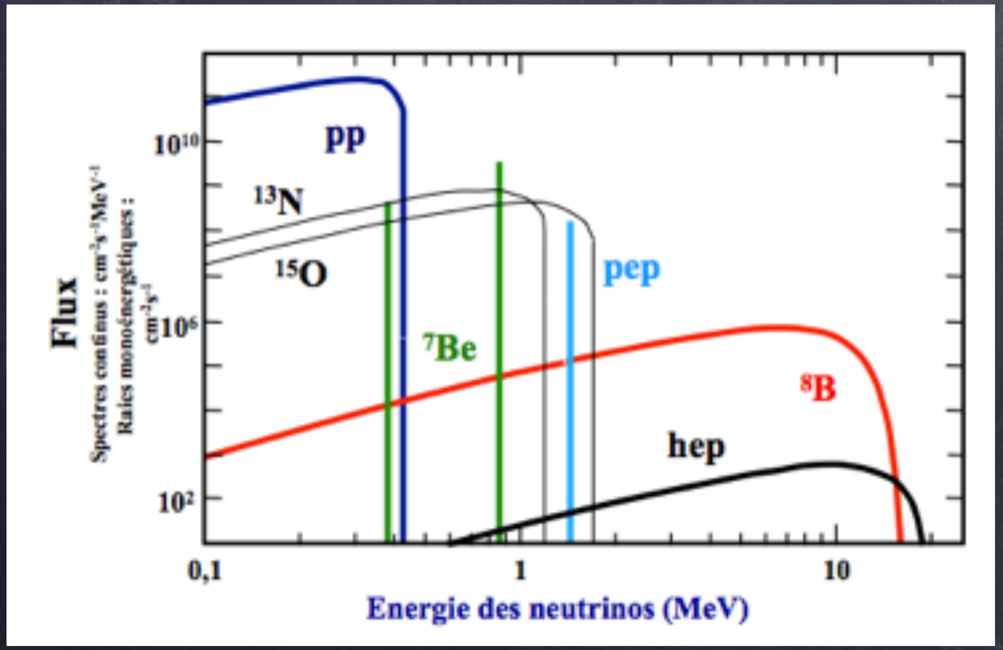
neutrino solaire



➢ Composition :
73% hydrogène (H)
25% hélium (He)
2% autres éléments

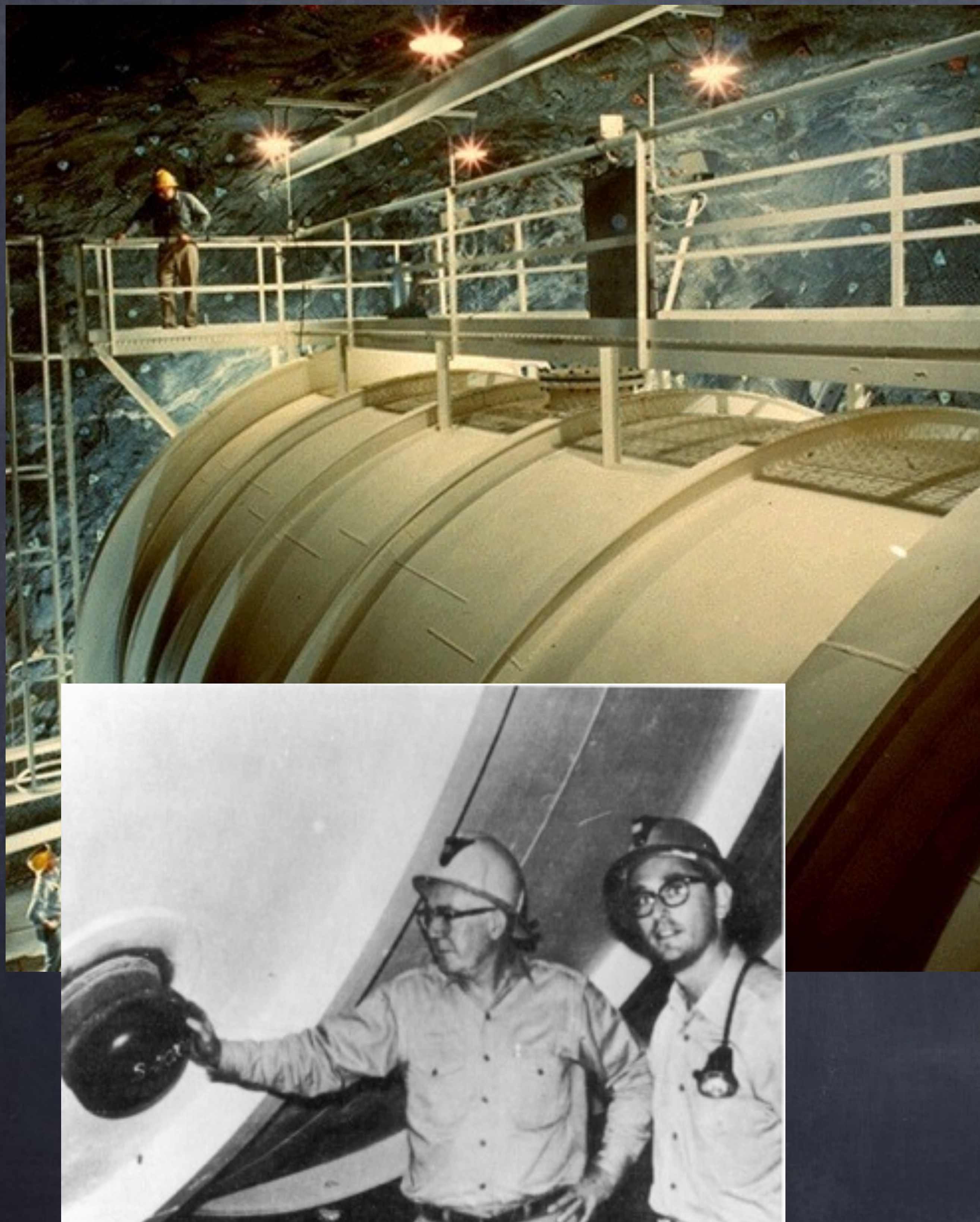
environ 65 milliards/cm^2/s





Mesure du flux de neutrinos: modele standard du soleil

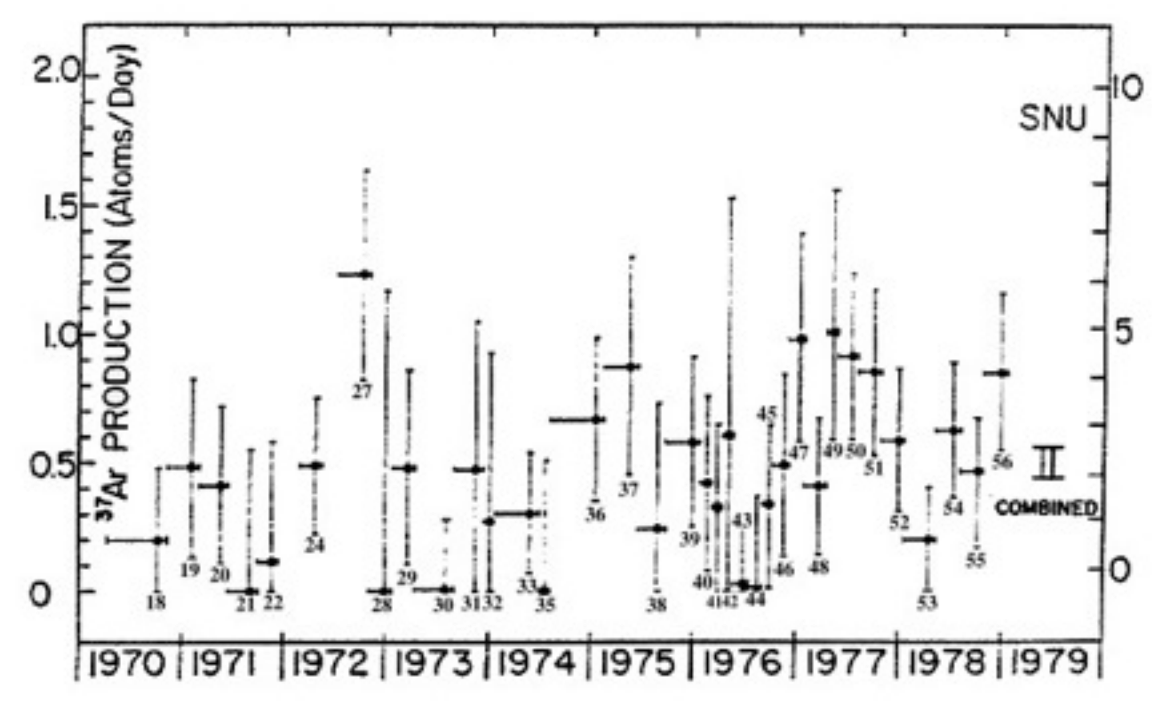
neutrino solaire



Homestake (1968)

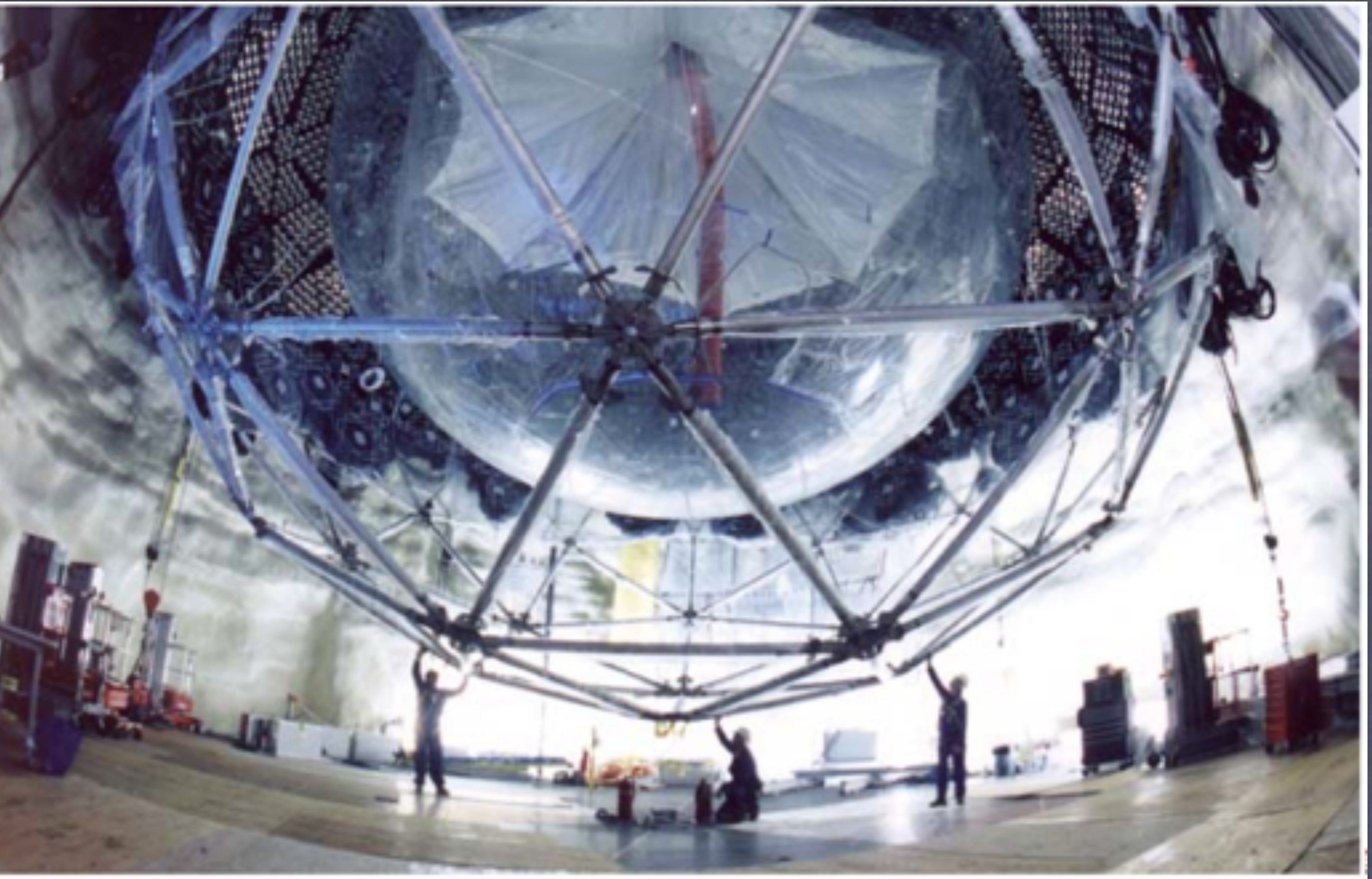
$$\nu_e + {}^{37}\mathrm{Cl} \rightarrow {}^{37}\mathrm{Ar} + e^-$$

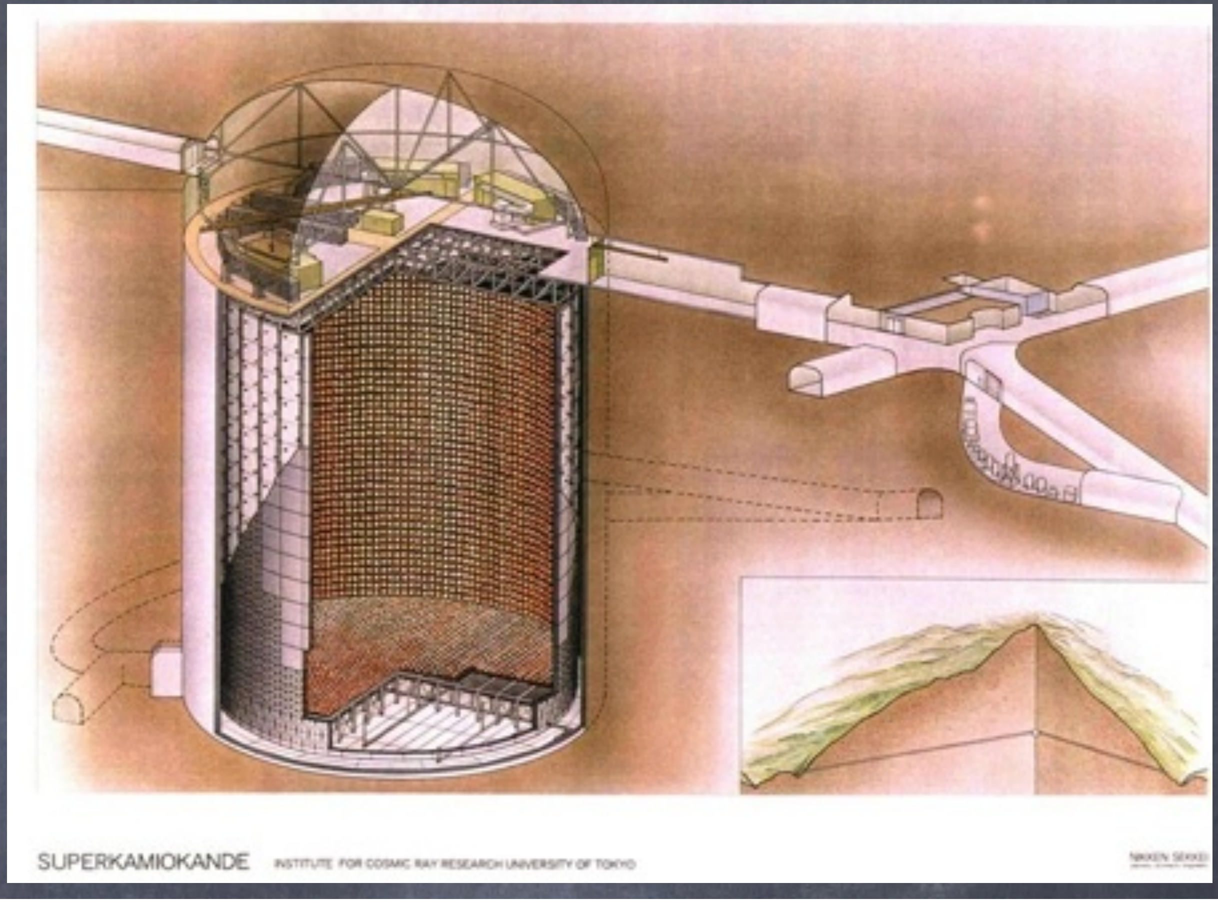
Déficit de neutrinos

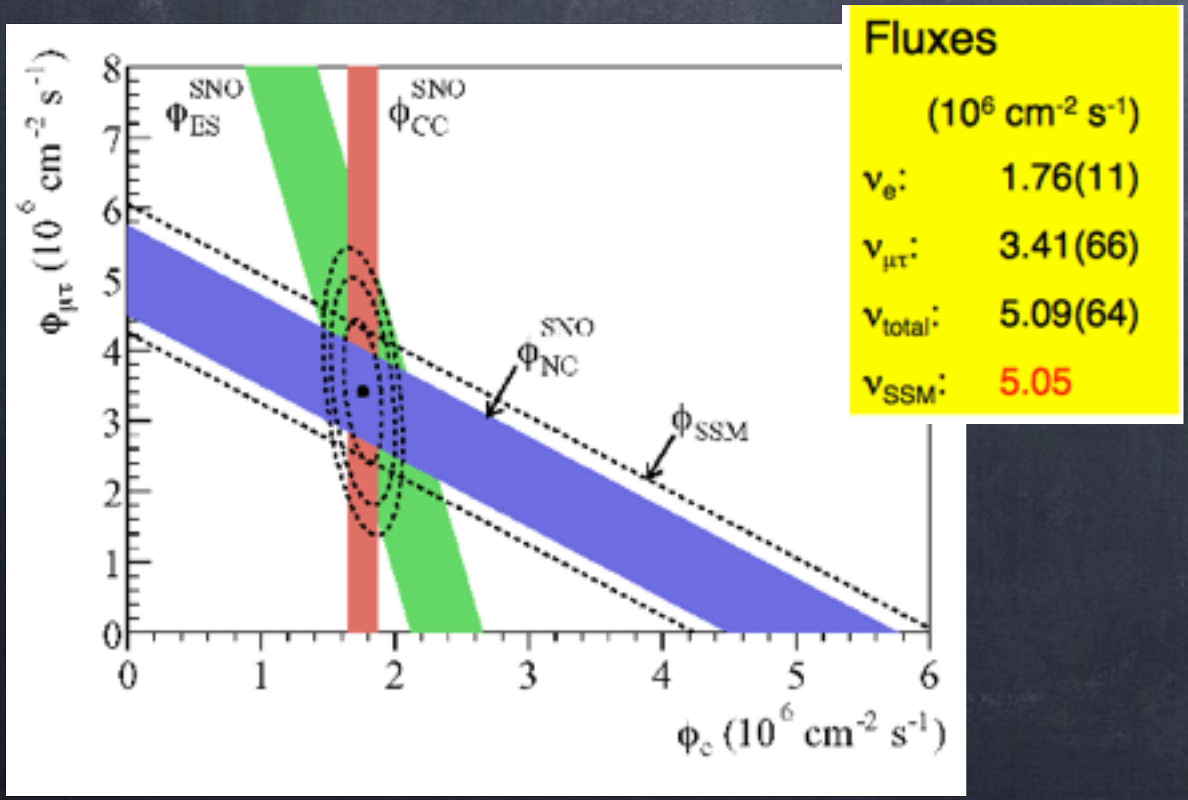


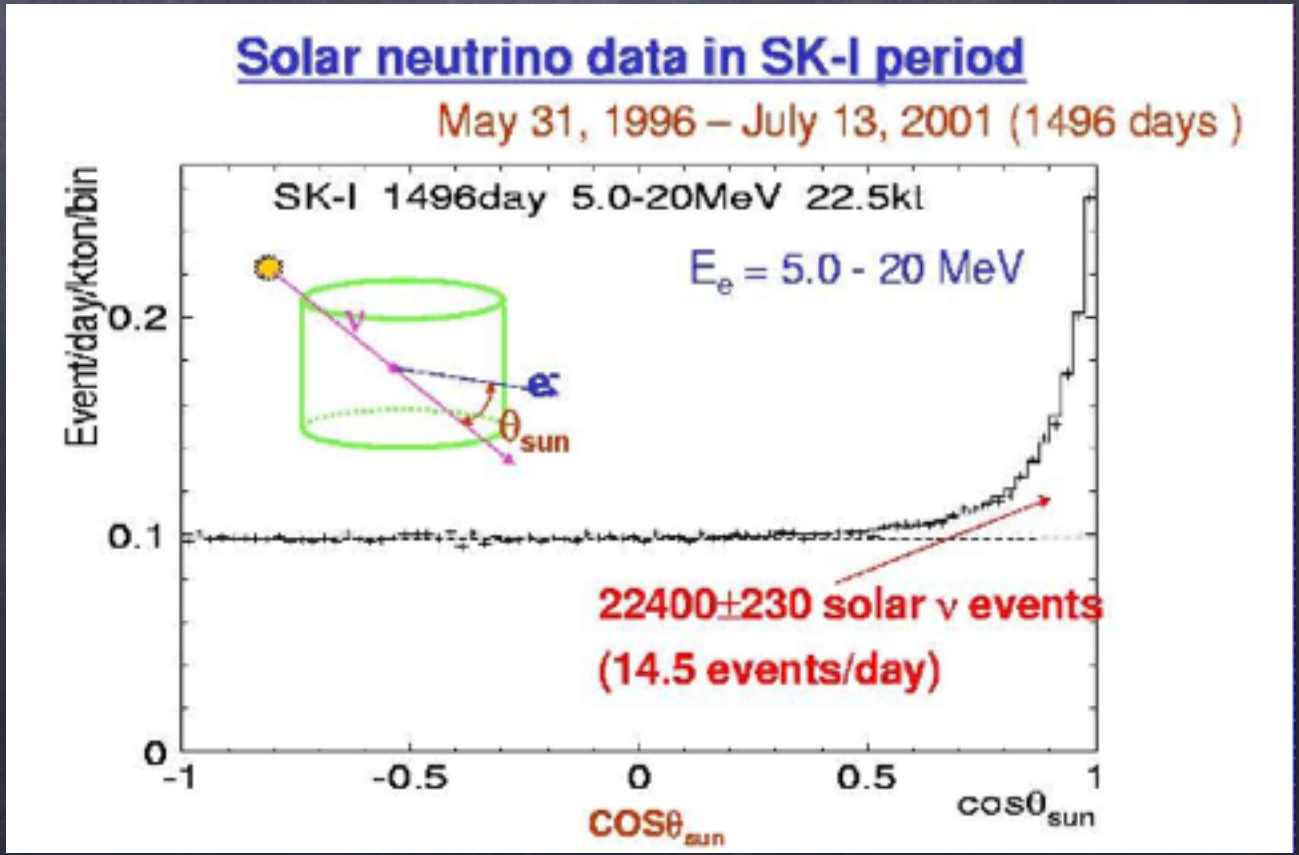
Confirmé par Gallex, Sage

neutrino solaire



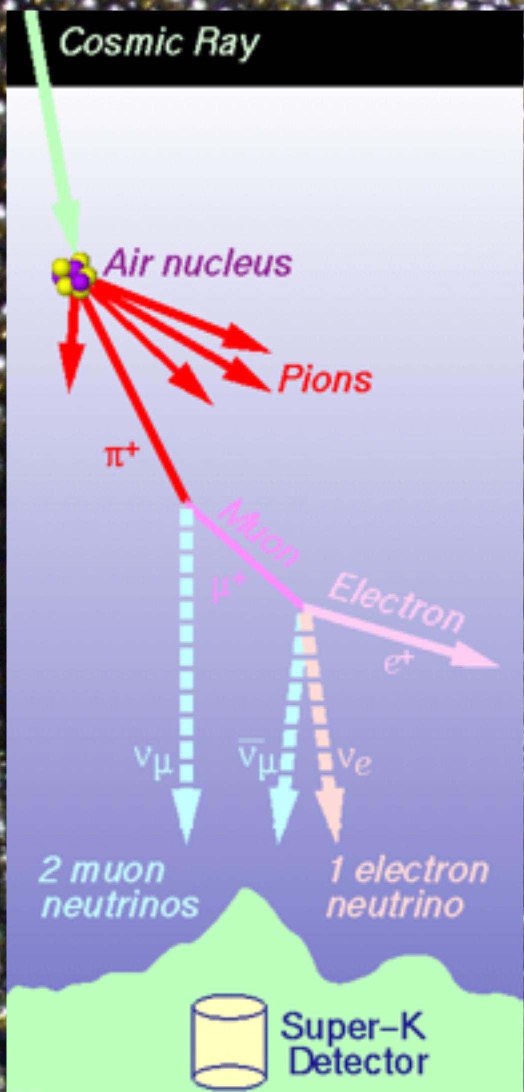


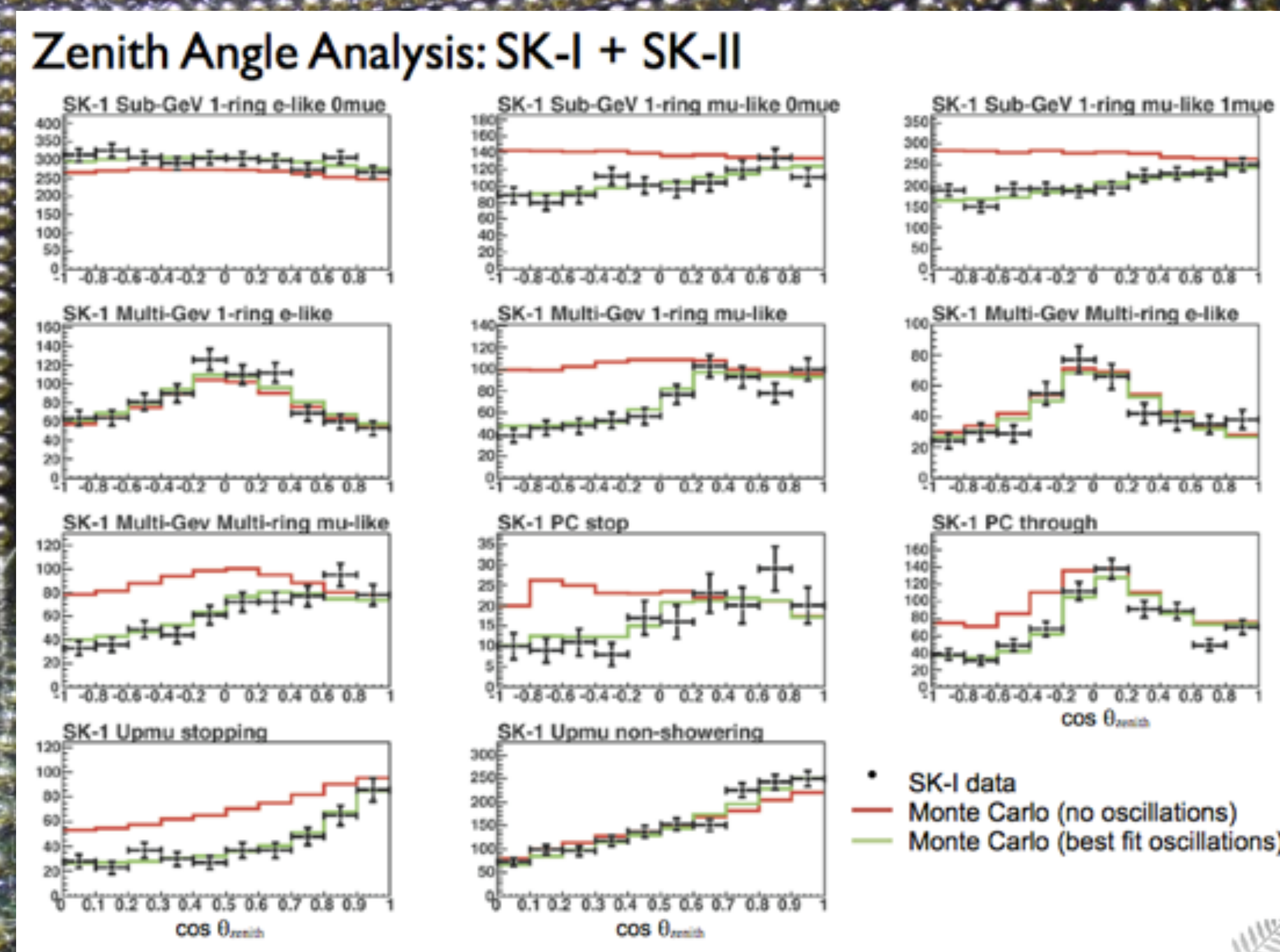




neutrino atmosphérique

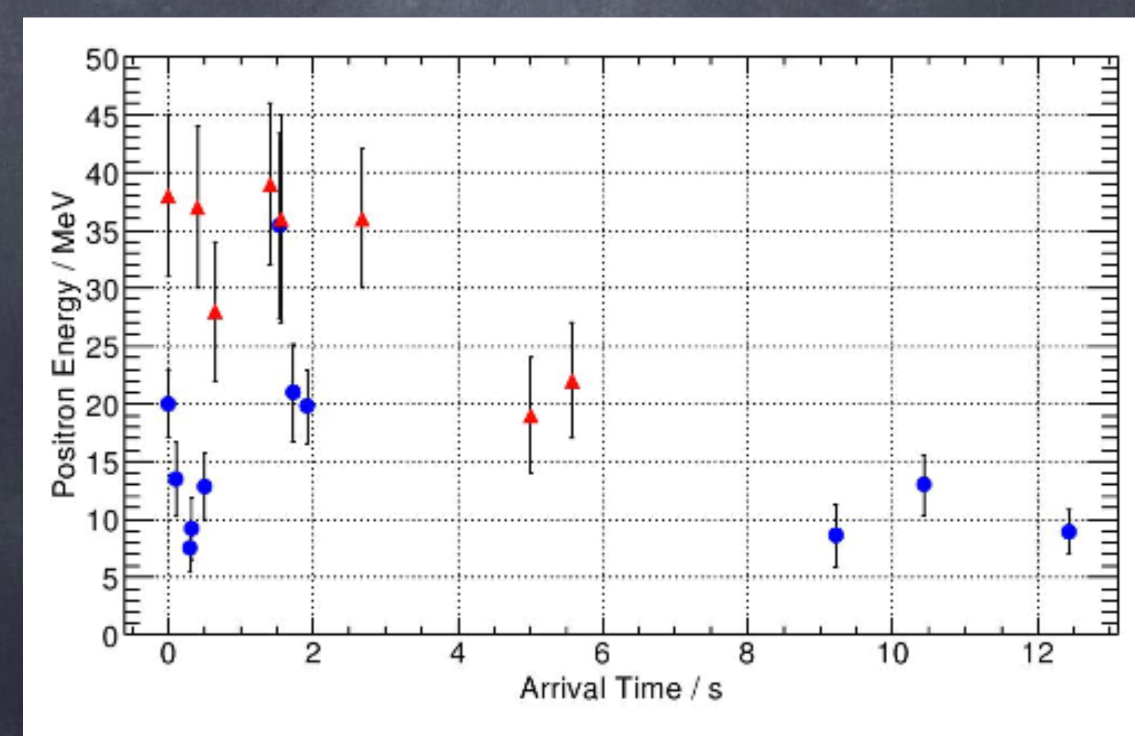
Super-Kamiokande





SN1987a

core-collapse supernova in the Large Magellanic Cloud, 50 kpc away from Earth. Two water Cherenkov detectors, Kamiokande-II and the Irvine-Michigan-Brookhaven (IMB) experiment, observed 19 neutrino interaction events altogether over a 13 s interval at a time consistent with the estimated time of core collapse



confirm the baseline model of core collapse

Typical 3 10^{53} erg SN (10 kpc & <Enu>=15 MeV), the total flux of neutrino flowing through the detector is around 10^{16} m^{-2}

neutrino: oscillation

- First idea by Bruno Pontecorvo in 1957
- Neutrinos are produced in flavor eigenstates → ν_e, ν_μ, ν_τ
- Neutrinos propagate as mass eigenstates → ν_1, ν_2, ν_3 mixture of flavor eigenstates ν_e, ν_μ, ν_τ
- At the detection a flavor eigenstate is detected → it can be different from the one that was produced

Different mixture of $\nu_{1,2,3}$ → μ from ν_μ is detected

ν_e produced in a mixture of $\nu_{1,2,3}$

$\nu_{1,2,3}$ travel at different speed because they have different masses → interference

Neutrino oscillation implies massive neutrinos!

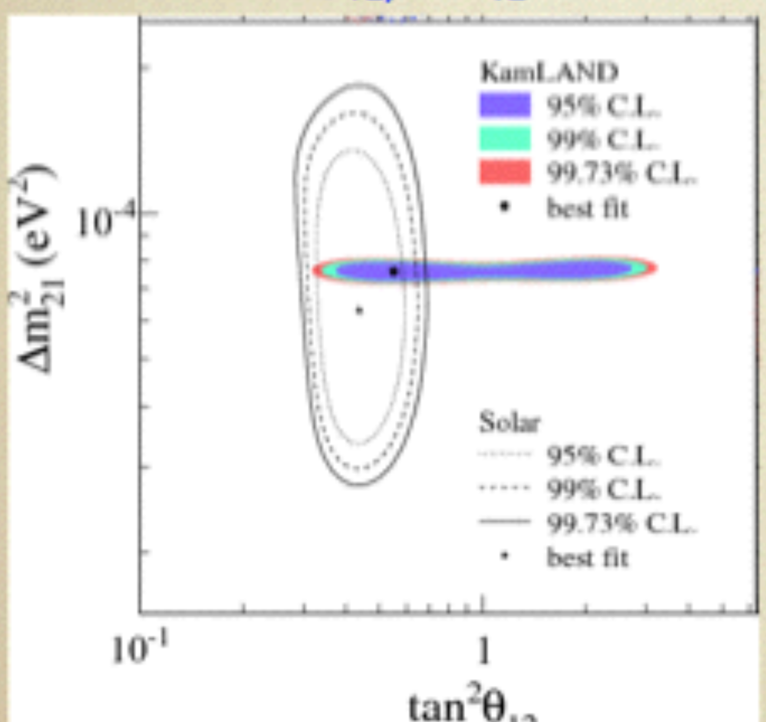
$$P(\nu_\alpha \to \nu_\beta) = \sin^2(2\theta_{ij}) \sin^2\left(\frac{1.27\Delta m^2_{ij} L}{E_\nu}\right)$$

neutrino: PMNS matrix

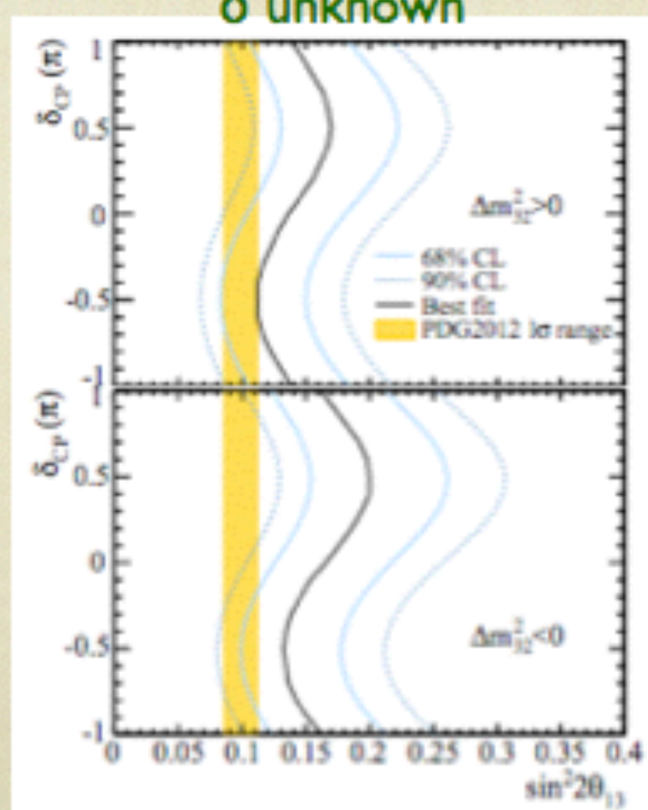
$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}=\begin{pmatrix}\cos\theta_{12} & \sin\theta_{12} & 0\\ -\sin\theta_{12} & \cos\theta_{12} & 0\\ 0 & 0 & 1\end{pmatrix}\begin{pmatrix}\cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -\sin\theta_{13}e^{-i\delta} & 0 & \cos\theta_{13}\end{pmatrix}\begin{pmatrix}1 & 0 & 0\\ 0 & \cos\theta_{23} & \sin\theta_{23}\\ 0 & -\sin\theta_{23} & \cos\theta_{23}\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

3 mixing angles (θ_{12}, θ_{23}, θ_{13}), 2 mass differences → all measured
1 CP violation phase δ → not known yet
Order of neutrino masses (hierarchy) unknown:
$m_{1,2}<m_3$ (normal hierarchy) or $m_3<m_{1,2}$ (inverted hierarchy)

Solar (SNO, KamLand)
→ θ_{12}, Δm_{12}

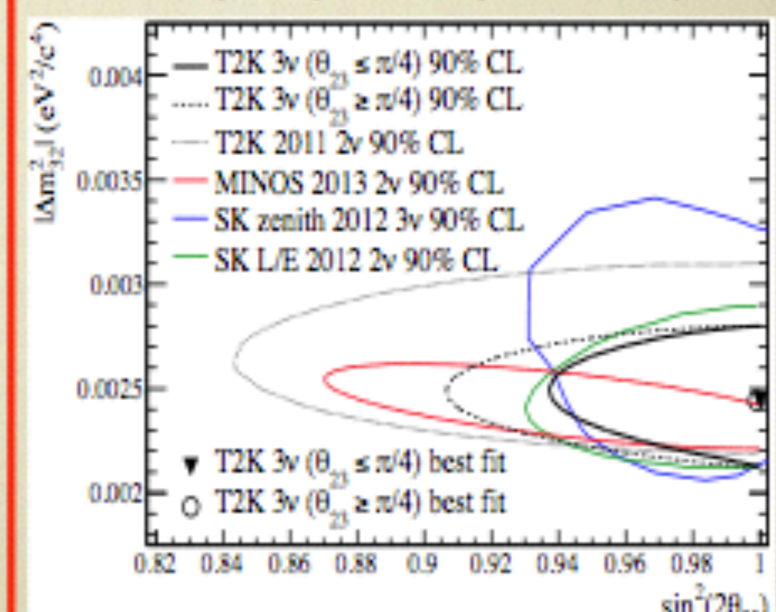


Recently measured $\sin^2(2\theta_{13})$~0.10
δ unknown



Atmospheric (K2K, SK, Minos)
→ θ_{23}, Δm_{23}

Δm_{23}^2 = (2.32±0.10)10^{-3} eV^2
$\sin^2(2\theta_{23})$ > 0.90(90% C.L.)



neutrino: PMNS matrix

Parameters	Neutrino oscillation experiments *	Global-fit results †
Δm^2_{21}	KamLAND ($\overline{\nu}_e \to \overline{\nu}_e$)[134]	$[7.60^{+0.19}_{-0.18}] \cdot 10^{-5}\ \mathrm{eV}^2$
Δm^2_{31}	T2K ($\nu_\mu \to \nu_\mu$)[135]	$+[2.48^{+0.05}_{-0.07}] \cdot 10^{-3}\ \mathrm{eV}^2$ (NH)
	MINOS ($\overline{\nu}_\mu \to \overline{\nu}_\mu$, $\nu_\mu \to \nu_\mu$)[136]	$-[2.38^{+0.05}_{-0.06}] \cdot 10^{-3}\ \mathrm{eV}^2$ (IH)
θ_{12}	solar neutrinos ($\nu_e \to \nu_e$) Borexino[137], SNO[138, 139], Super-Kamionkande I–IV[140]	$34.63^{\circ}{}^{+1.02^\circ}_{-0.98^\circ}$
θ_{13}	Daya Bay ($\overline{\nu}_e \to \overline{\nu}_e$)[141]	$8.80^{\circ}{}^{+0.37^\circ}_{-0.39^\circ}$ (NH)
	RENO ($\overline{\nu}_e \to \overline{\nu}_e$)[142]	$8.91^{\circ}{}^{+0.35^\circ}_{-0.36^\circ}$ (IH)
θ_{23}	atmospheric neutrinos ($\overline{\nu}_\mu \to \overline{\nu}_\mu$, $\nu_\mu \to \nu_\mu$)	$48.9^{\circ}{}^{+1.6^\circ}_{-7.4^\circ}$ (NH)
	Super-Kamiokande I–IV[143]	$49.2^{\circ}{}^{+1.5^\circ}_{-2.5^\circ}$ (IH)
δ	—	$241^{\circ}{}^{+115^\circ}_{-68^\circ}$ (NH)
		$266^{\circ}{}^{+62^\circ}_{-57^\circ}$ (IH)

At present, we have:

$$|U|_{\mathrm{LEP}(3\sigma)} = \begin{pmatrix} 0.799 \to 0.844 & 0.515 \to 0.581 & 0.129 \to 0.173 \\ 0.212 \to 0.527 & 0.426 \to 0.707 & 0.598 \to 0.805 \\ 0.233 \to 0.538 & 0.450 \to 0.722 & 0.573 \to 0.787 \end{pmatrix}$$

Satisfactory progress in last 15 years but still very far from the 'dream' precision:

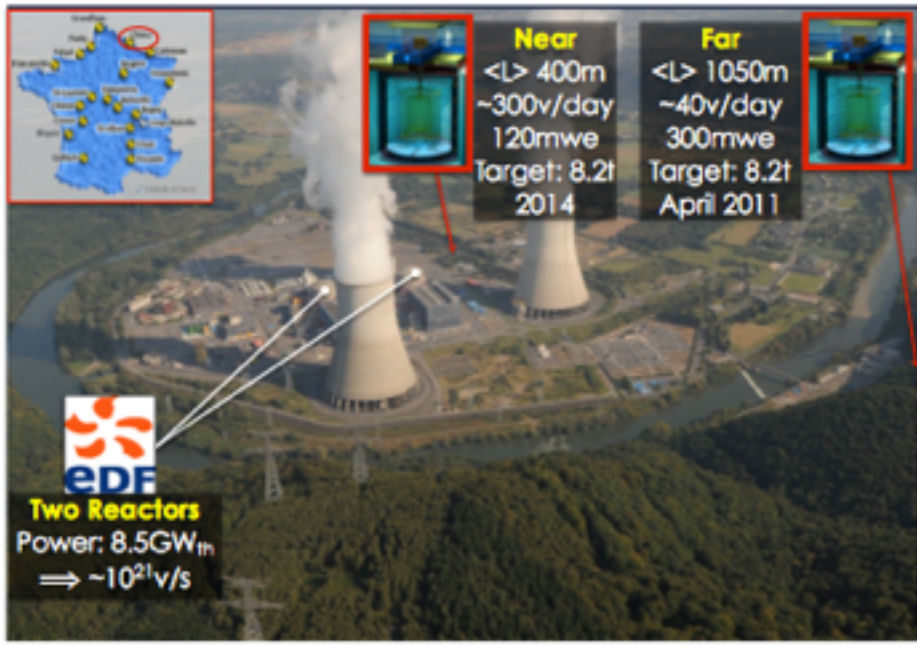
$$|V|_{\mathrm{CKM}} = \begin{pmatrix} 0.97427 \pm 0.00015 & 0.22534 \pm 0.0065 & (3.51 \pm 0.15) \times 10^{-3} \\ 0.2252 \pm 0.00065 & 0.97344 \pm 0.00016 & (41.2^{+1.1}_{-5}) \times 10^{-3} \\ (8.67^{+0.29}_{-0.31}) \times 10^{-3} & (40.4^{+1.1}_{-0.5}) \times 10^{-3} & 0.999146^{+0.000021}_{-0.000046} \end{pmatrix}$$

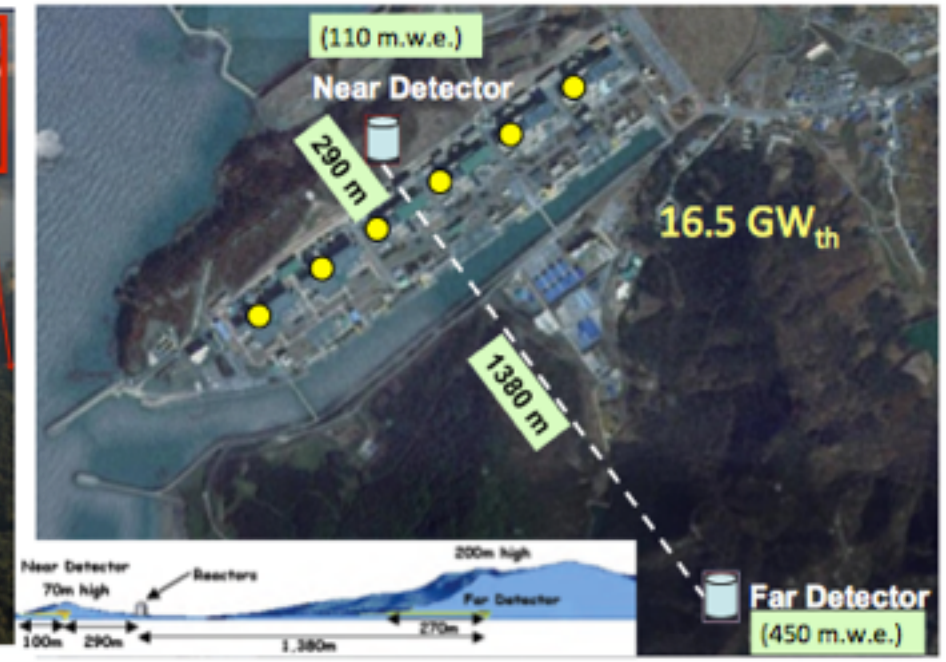
theta 13

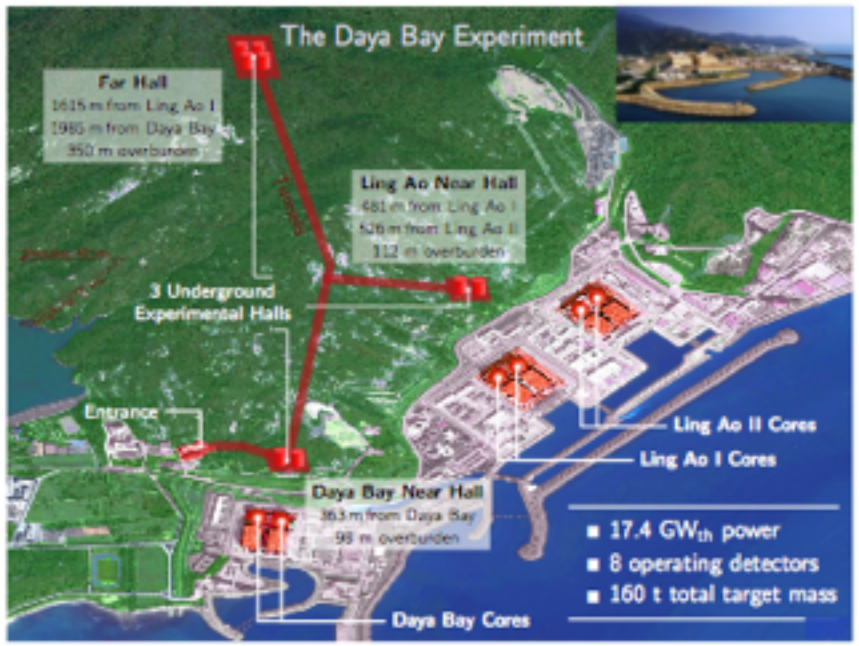
Use Near detector(s) to constrain the reactor flux

Far detector(s) to measure the ν_e disappearance due to θ_{13}

Experimental signature: $\nu_e + p \rightarrow e^+ + n$



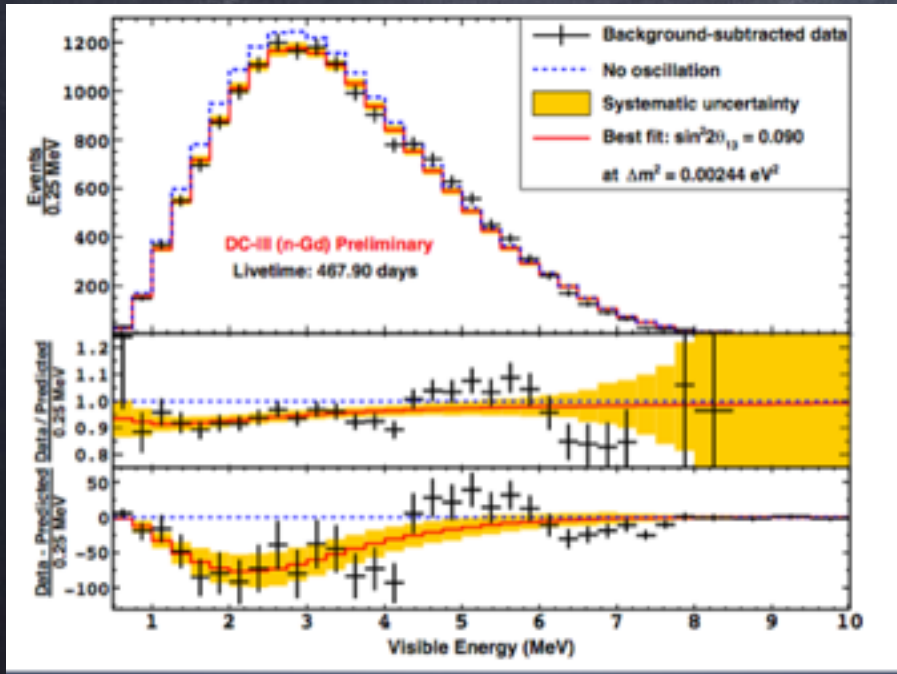


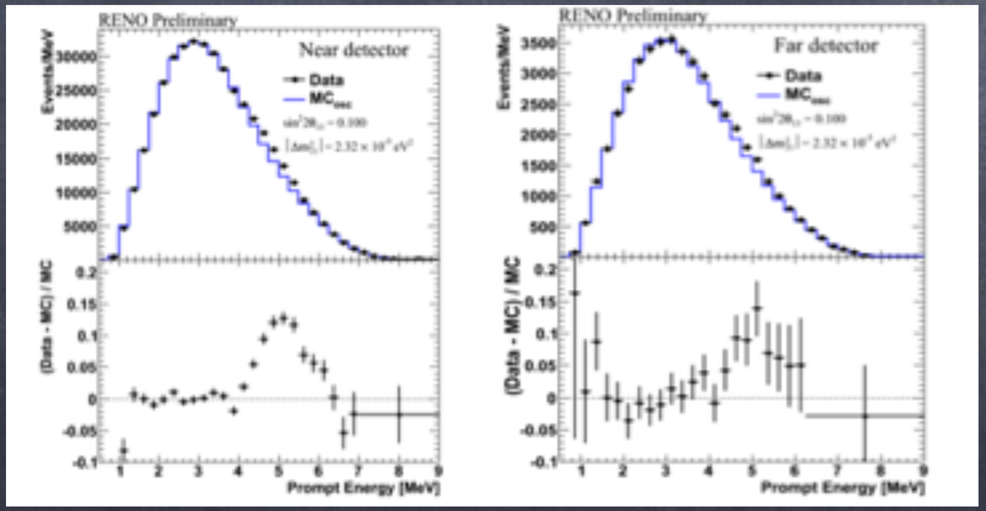


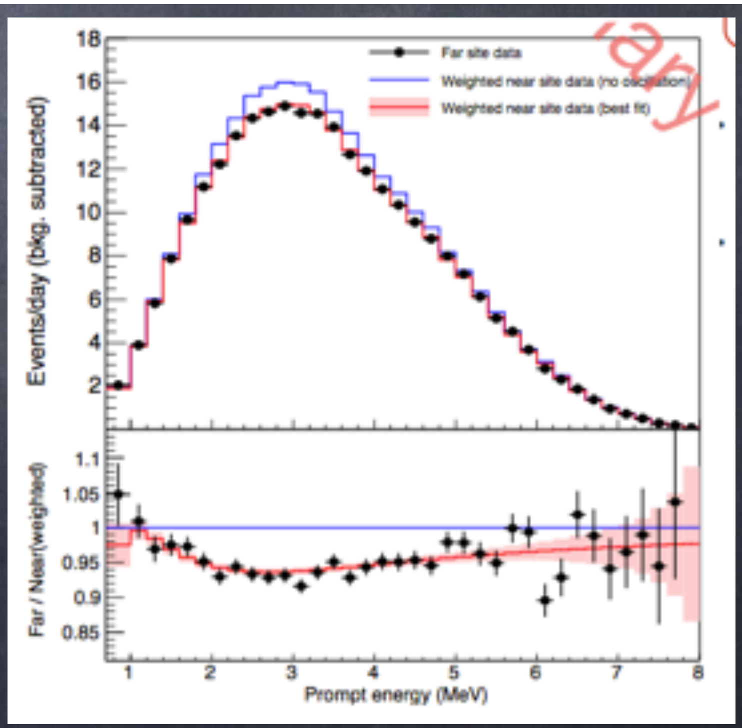
Double Chooz

RENO

Daya Bay







$\sin^2(2\theta_{13}) = 0.09 \pm 0.03$ (χ^2/n.d.f.) = 51.4/40

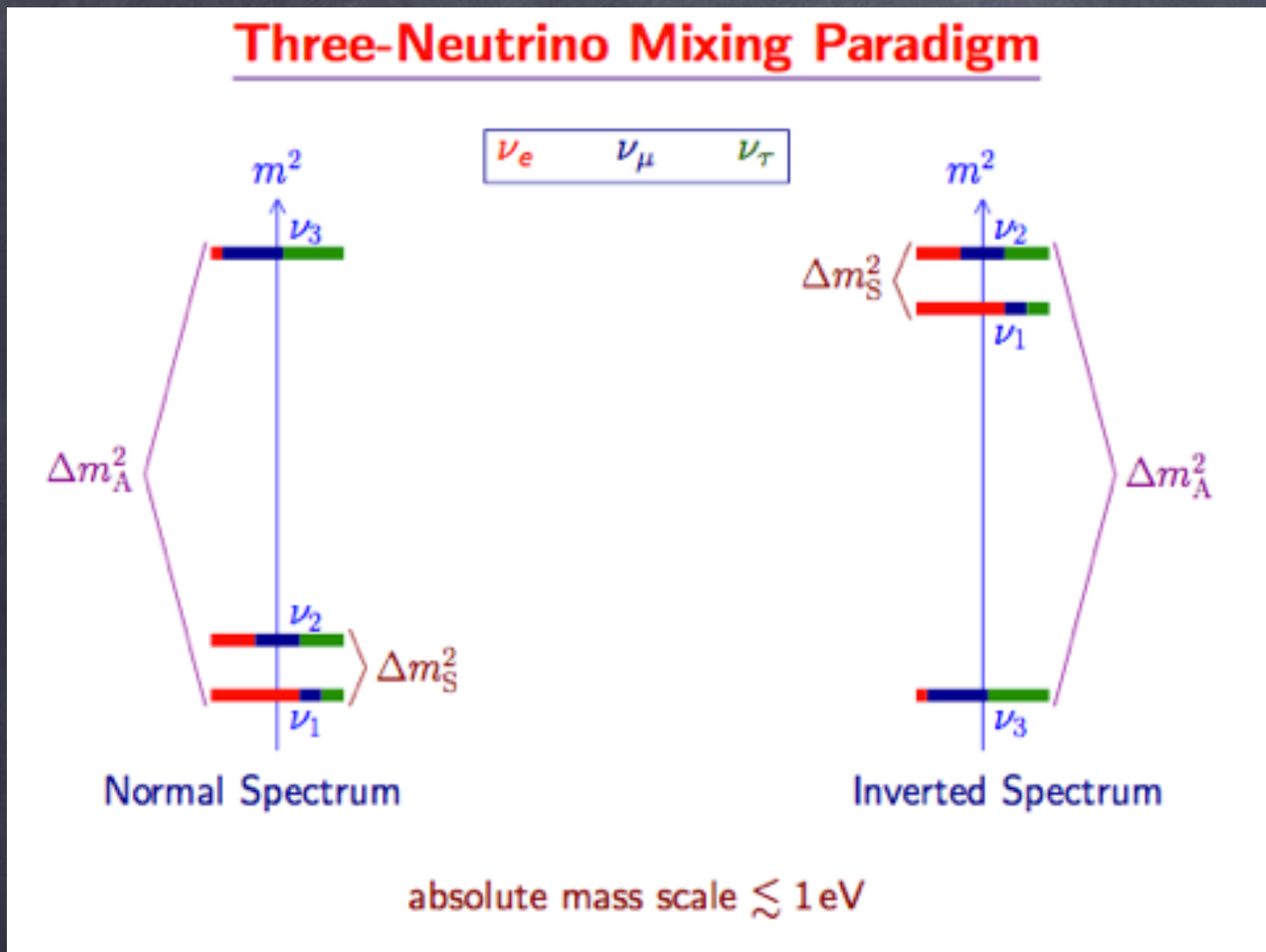
$\sin^2(2\,\theta_{13}) = 0.101 \pm 0.008\,(\text{stat.}) \pm 0.010\,(\text{sys.})$

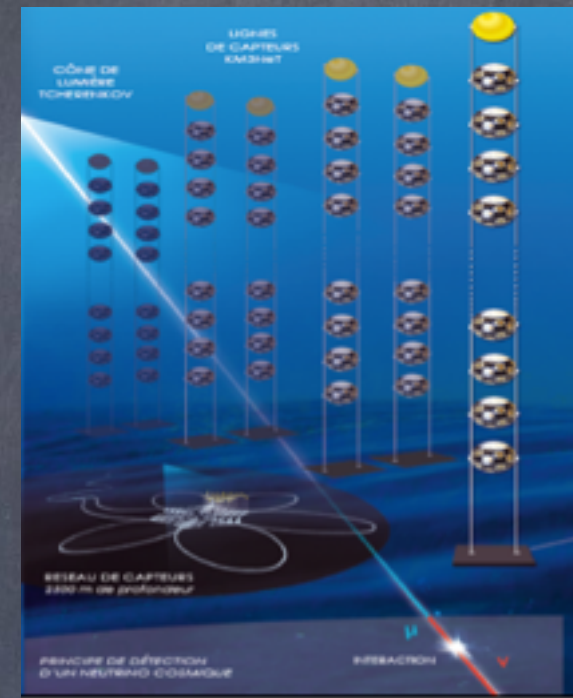
$\sin^2 2\theta_{13} = 0.084^{+0.005}_{-0.005}$

$|\Delta m^2_{ee}| = 2.44^{+0.10}_{-0.11} \times 10^{-3}\text{eV}^2$

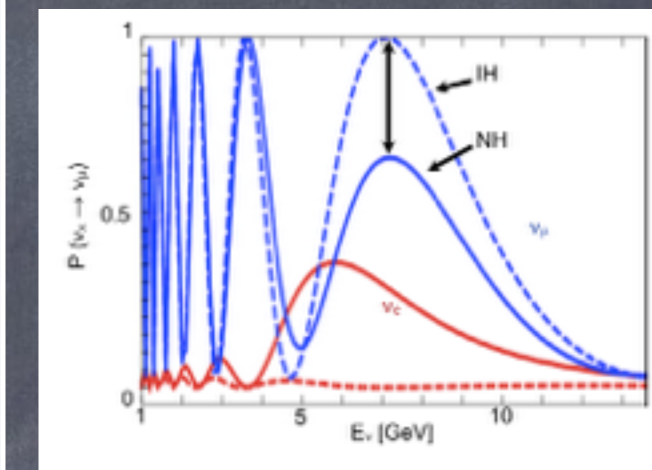
$\chi^2/NDF = 134.7/146$

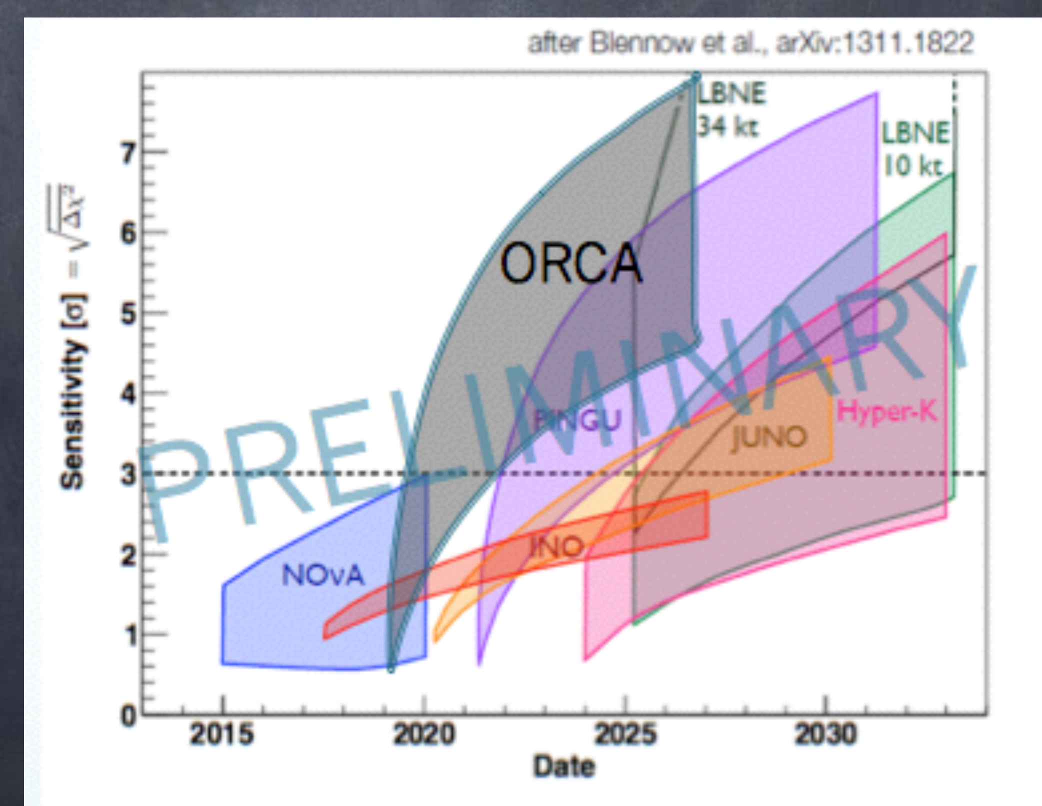
Hierarchie de masse

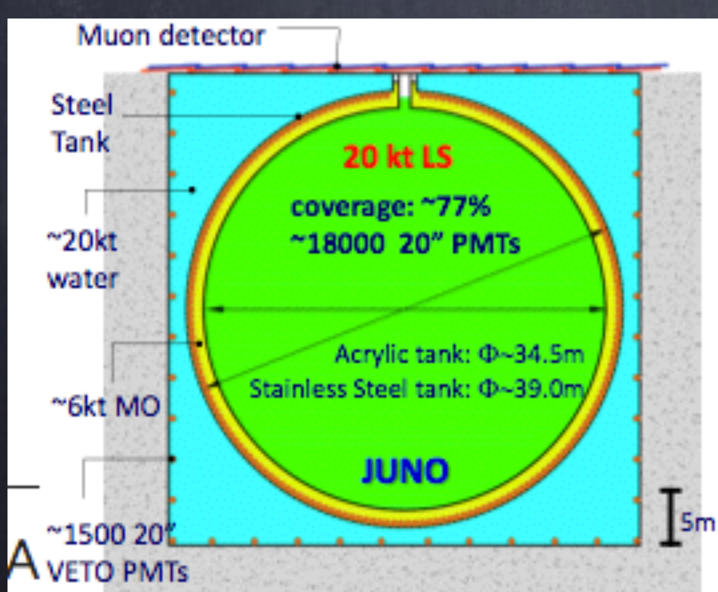


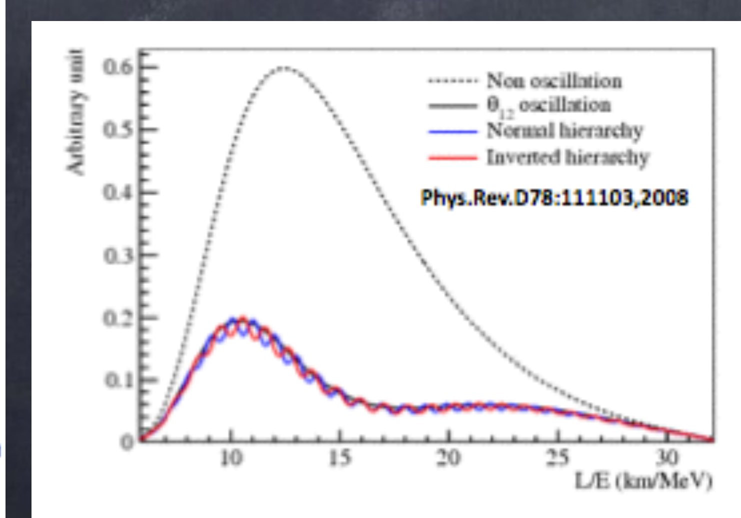


Orca/Pingu

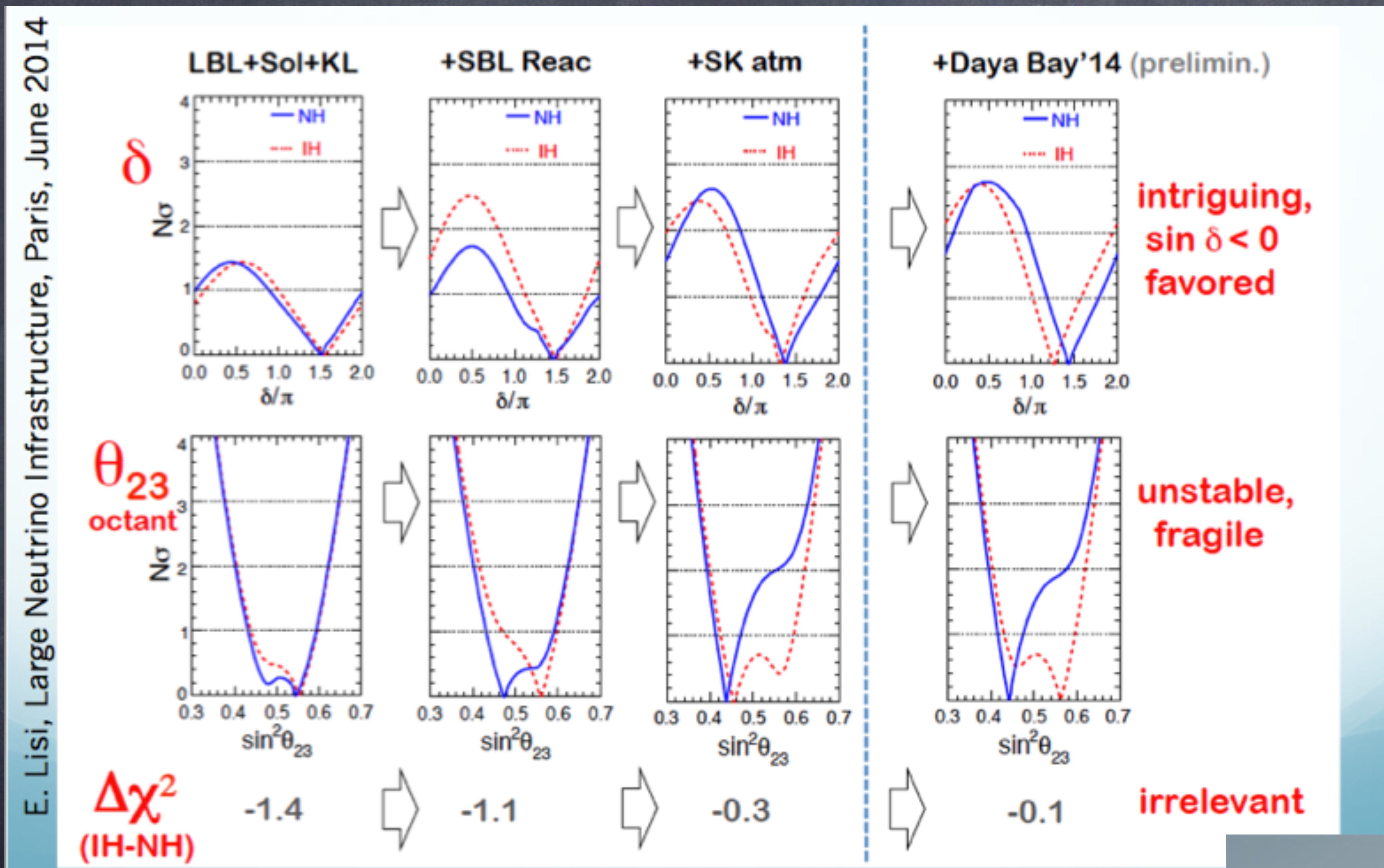








violation CP

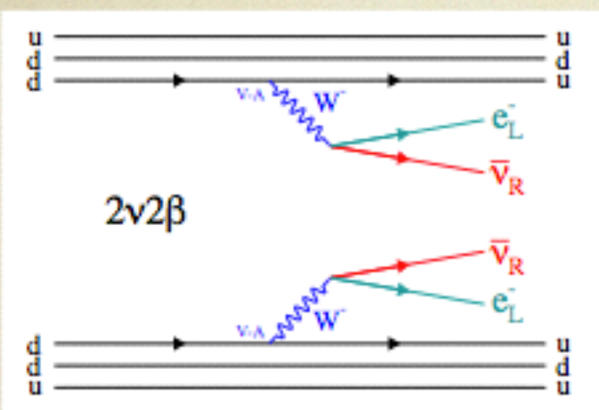


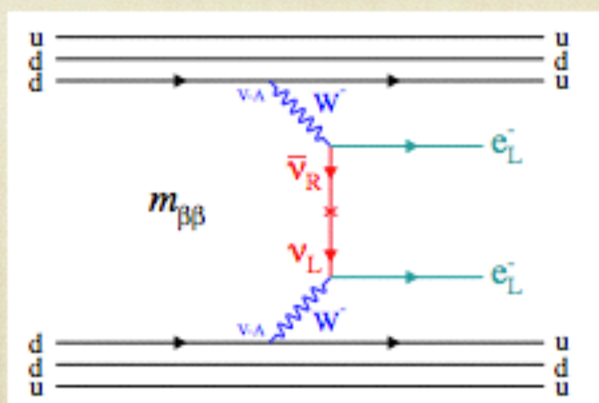
Baryon asymmetry in the Universe: CP violation in baryon not sufficient, need also CP violation in lepton (through leptogenesis)

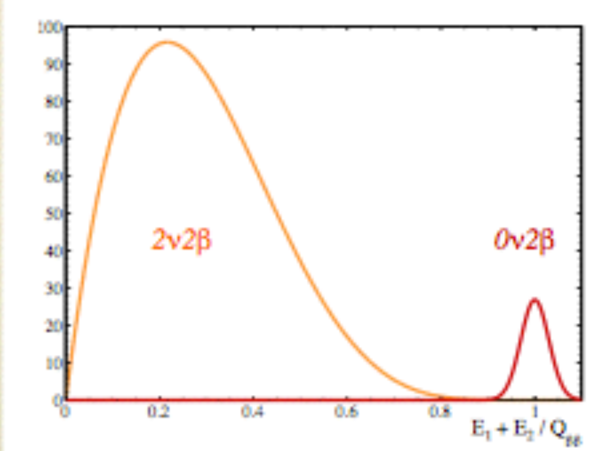
Majorama ou Dirac

Neutrinoless double β decay

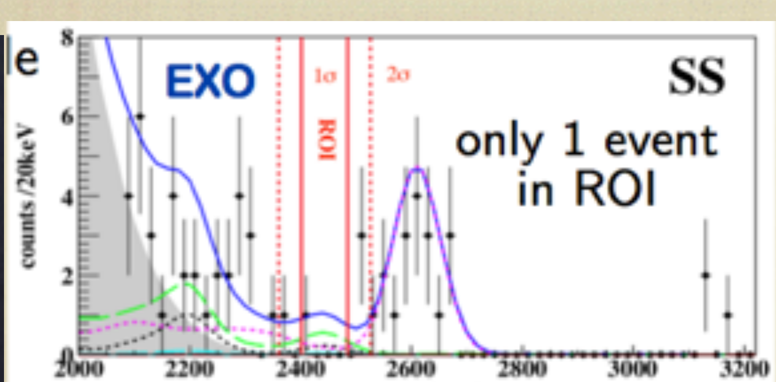
- Neutrinos is the only known fermion that can be its own antiparticle
  - Majorana particles
  - Explain small neutrino masses through the see-saw mechanism
- Search a double β decay where the two electrons take all the available energy($Q_{\beta\beta}$)
- Very difficult experiments because $Q_{\beta\beta}$ is small (few keV)
- Many different techniques but up to now only upper limits

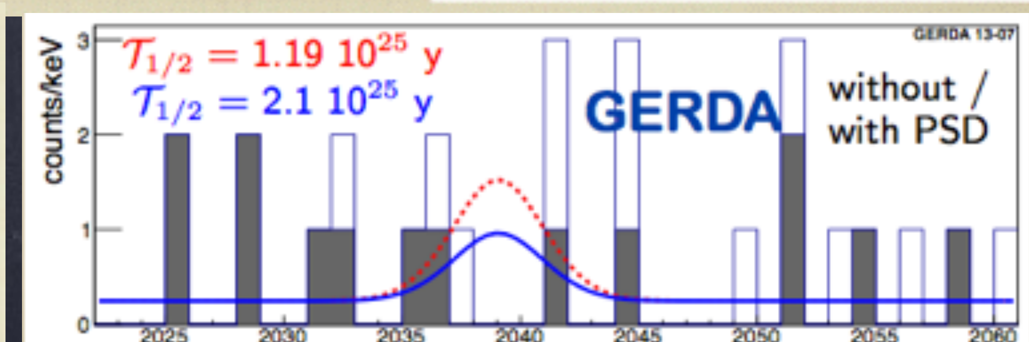


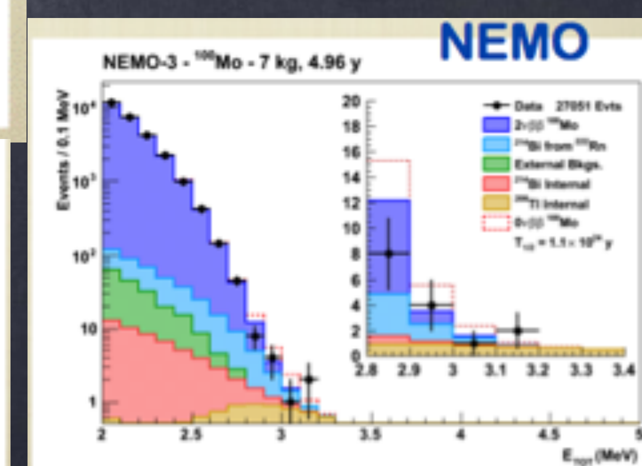




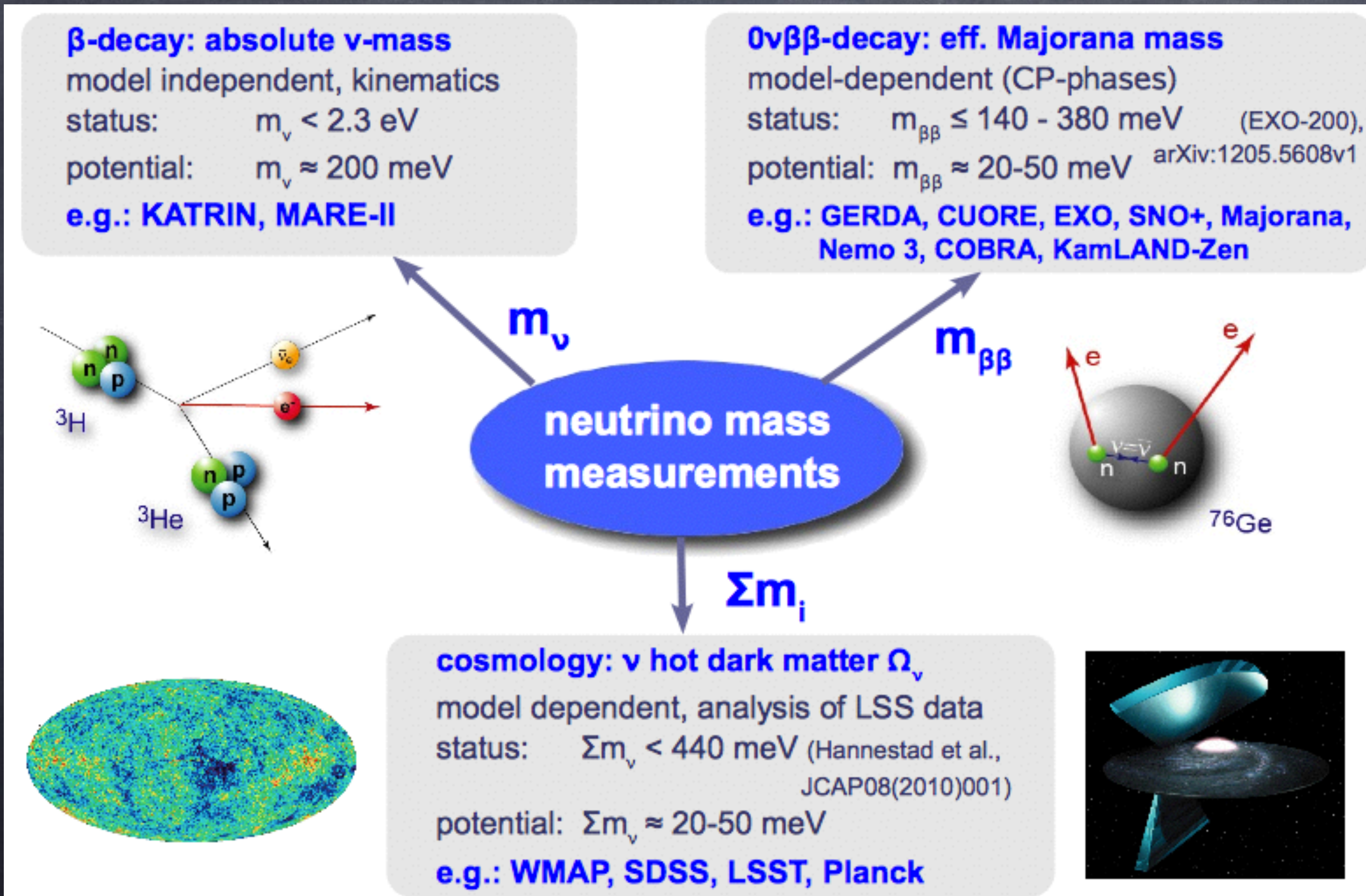
2 e^- energy equal to $Q_{\beta\beta}$





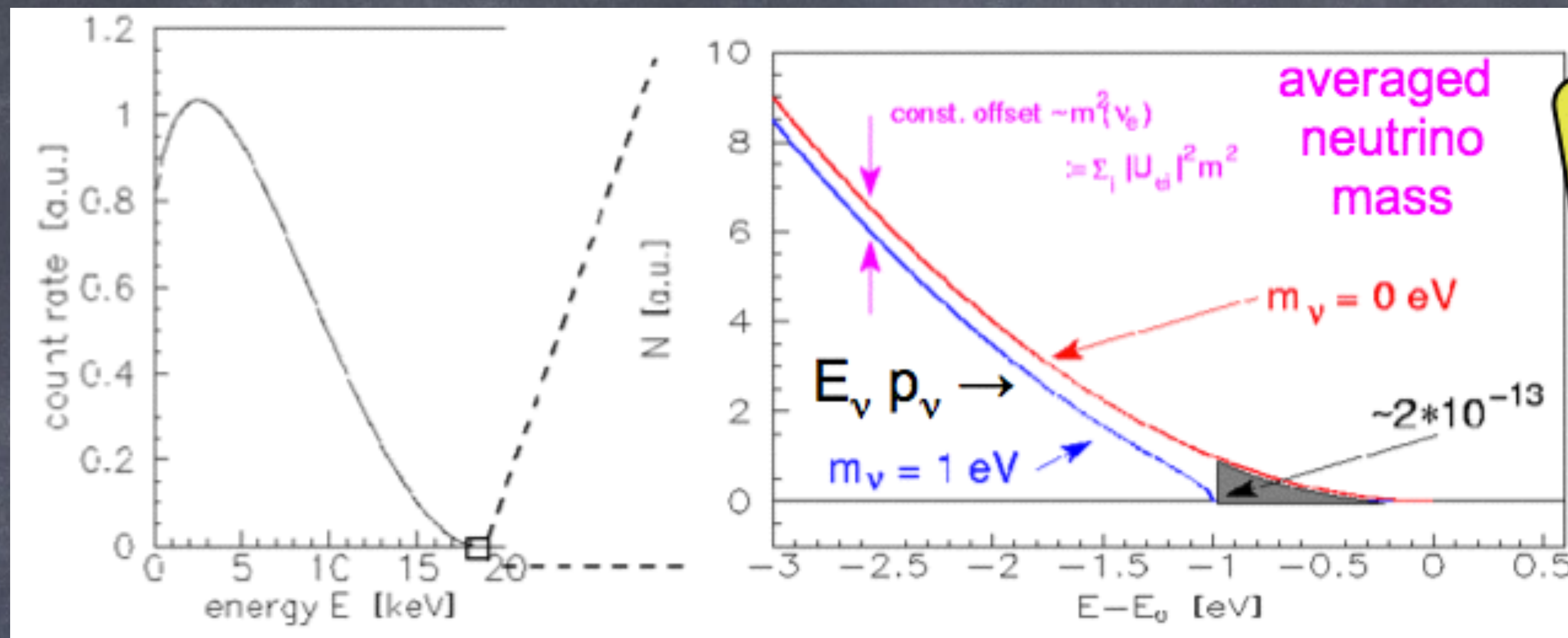


Masse des neutrinos



Masse des neutrinos

KATRIN

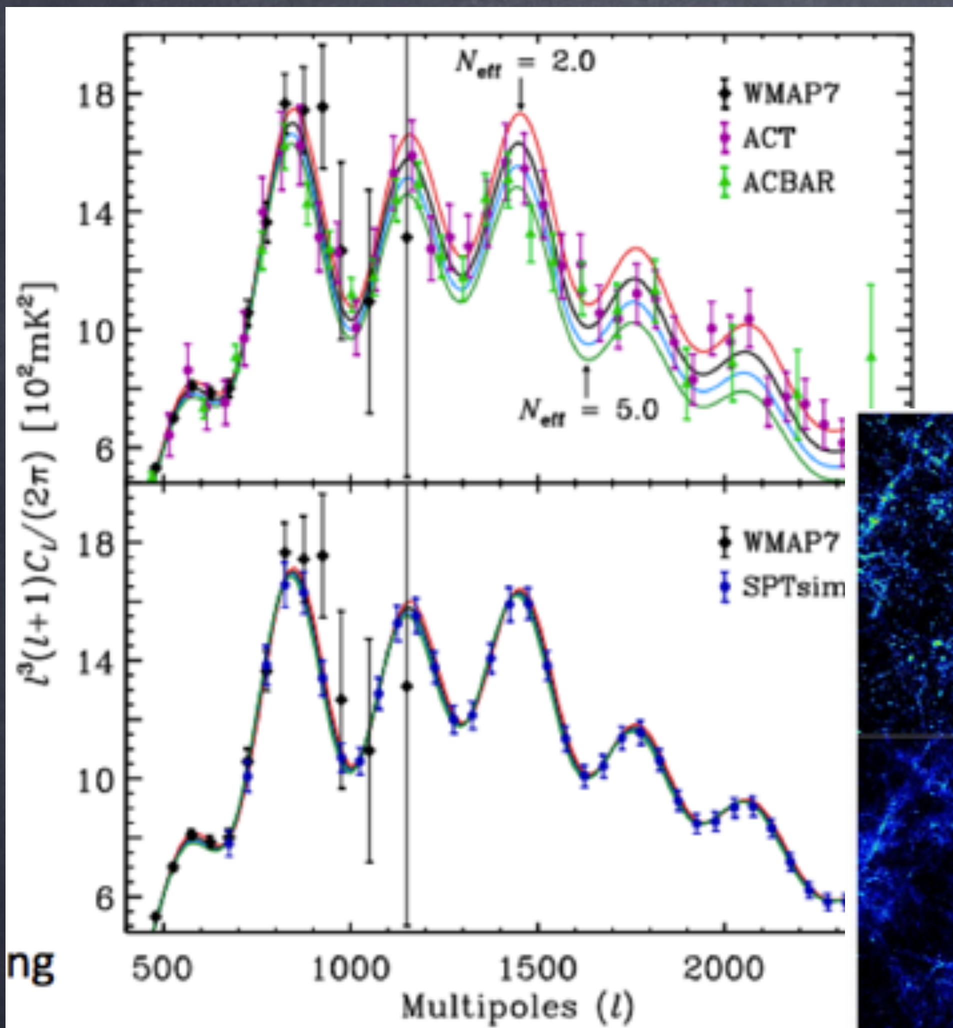


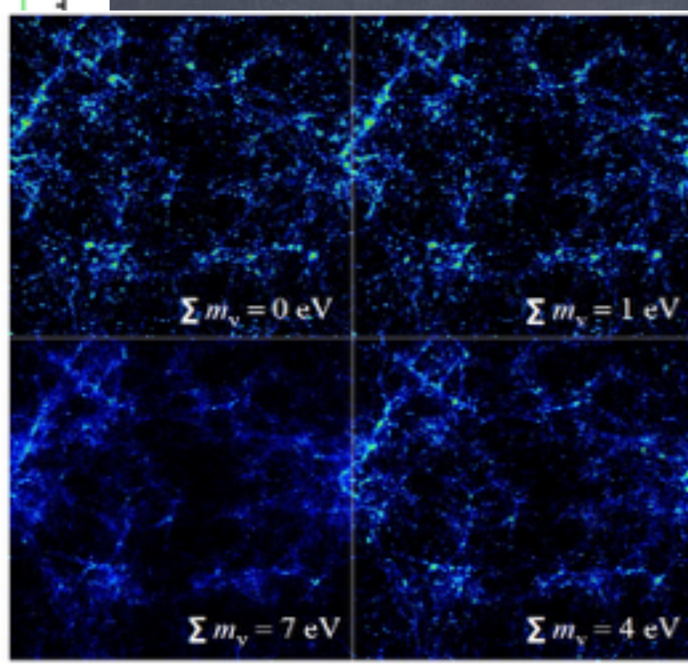
FUTURE $0\nu\beta\beta$				
Isotope	Experiment	Mass	m_{ee}(90%C.L)	
^{76}Ge,enriched	GERDA, Phase 2 of 3	0.1 t	< [90, 290] meV	[31]
^{76}Ge enriched	Majorana, demonstrator	(0.03-0.06) t	< 100 meV	[33]
^{150}Nd,^{82} Se	Super-Nemo	0.1-0.2 t	< [50, 100] meV	[30]
^{130}Te	Cuore	0.75 t	< 30 meV	[34]
^{100}Mo	MOON	0.12 t	< 70 meV	[35]
^{136}Xe, liquid	EXO200	0.2 t	< [133, 186] meV	[36]
^{48}Ca	Candles III	0.3 t of CaF_2	< 500 meV	[37]

FUTURE Single Beta Decay				
Isotope	Experiment	Inventory	m_{ee}(90%C.L)	
^{3}H, gaseous	KATRIN	24 g	< 200 meV	[47]
^{187}Re, solid	MARE II	200 g	< 90 meV	[50]

Cosmologie

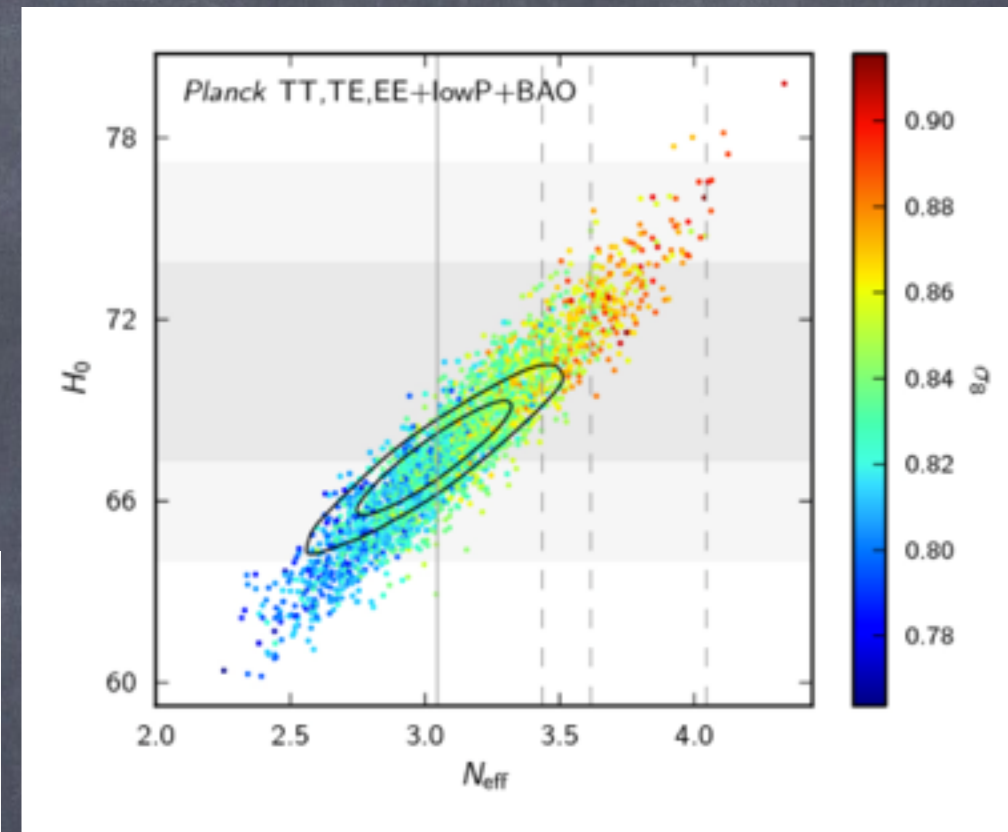
Is there extra radiation on top of photons and standard neutrinos?

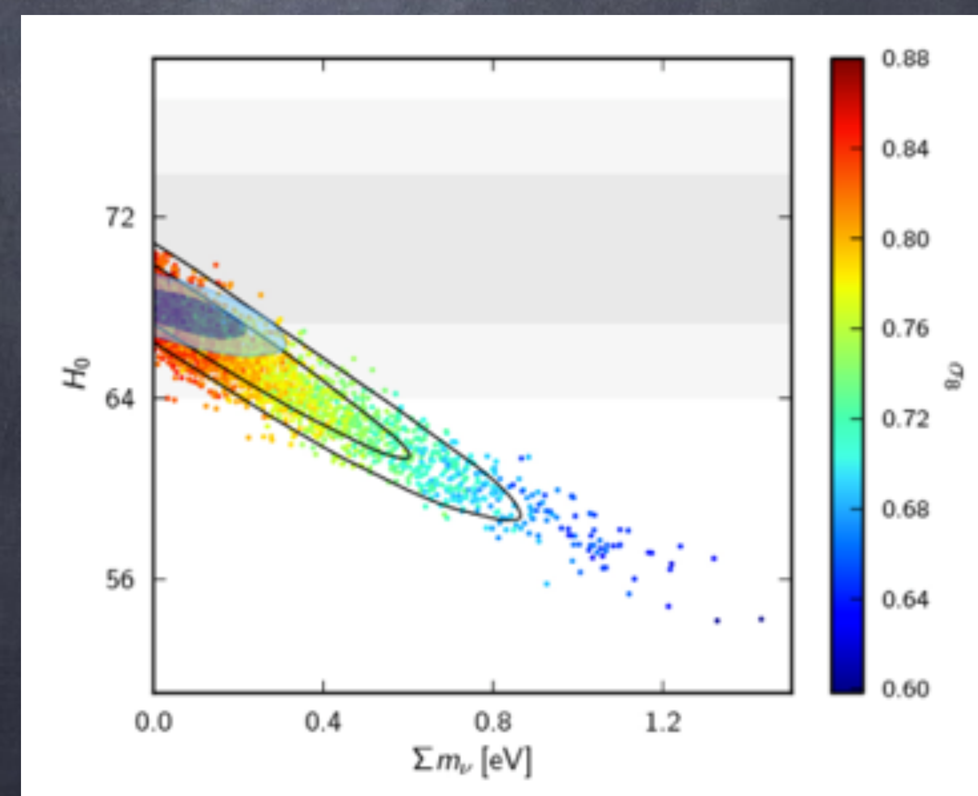




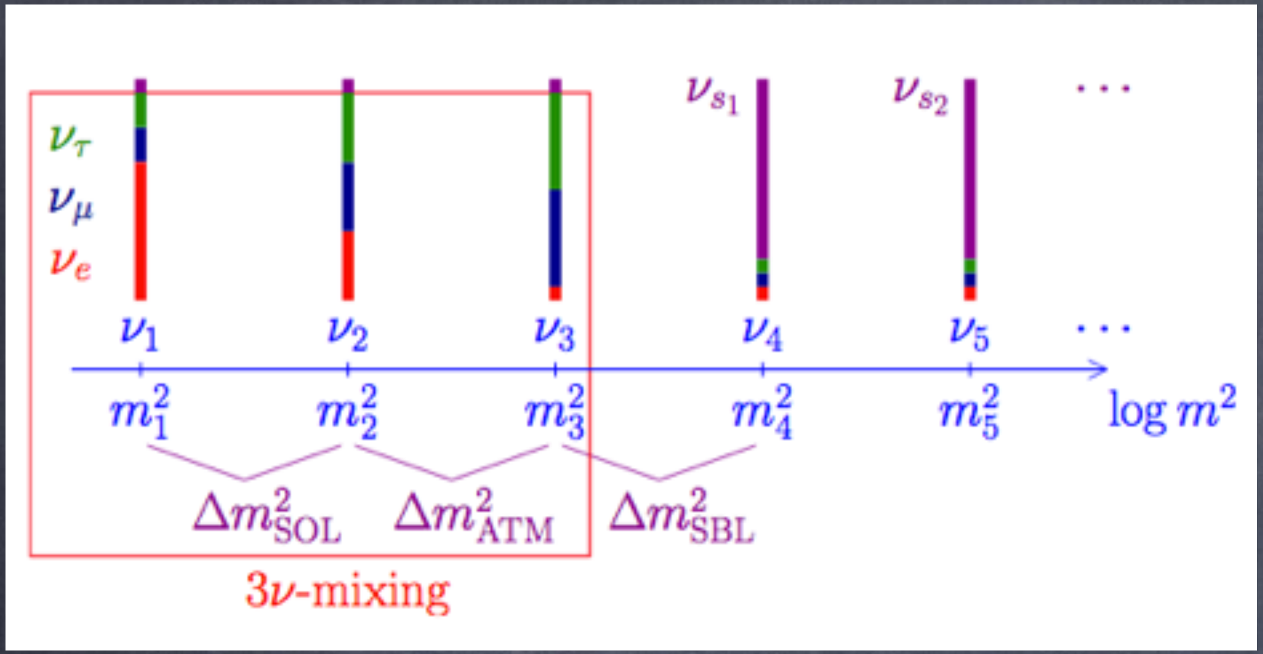
simulation Chung-Pei Ma 1996

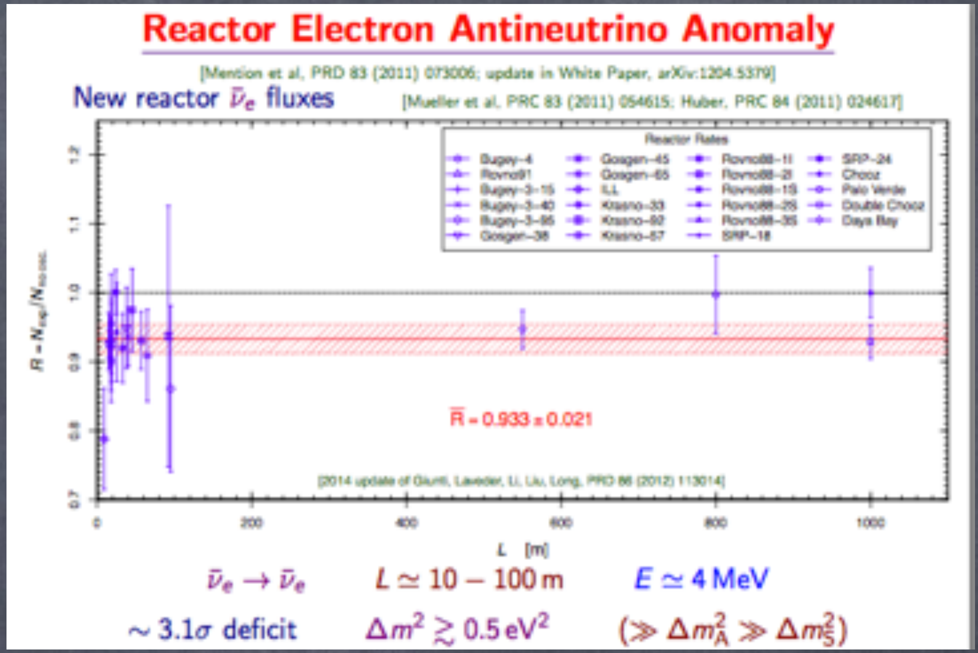
Planck alone (no pol.)	$N_{eff}^{\nu} = 4.55_{-1.4}$
Planck + WP	$N_{eff}^{\nu} = 3.51^{+0.80}_{-0.74}$
Planck + WP + Lensing	$N_{eff}^{\nu} = 3.39^{+0.77}_{-0.70}$
Planck + WP + highL	$N_{eff}^{\nu} = 3.36^{+0.68}_{-0.64}$
Planck + WP + highL + Lensing	$N_{eff}^{\nu} = 3.28^{+0.67}_{-0.64}$

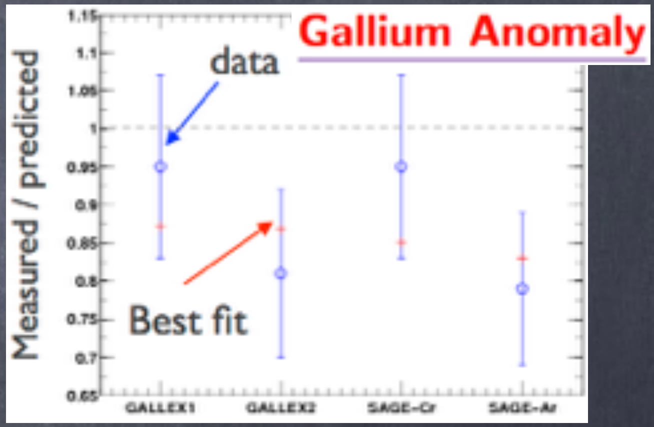




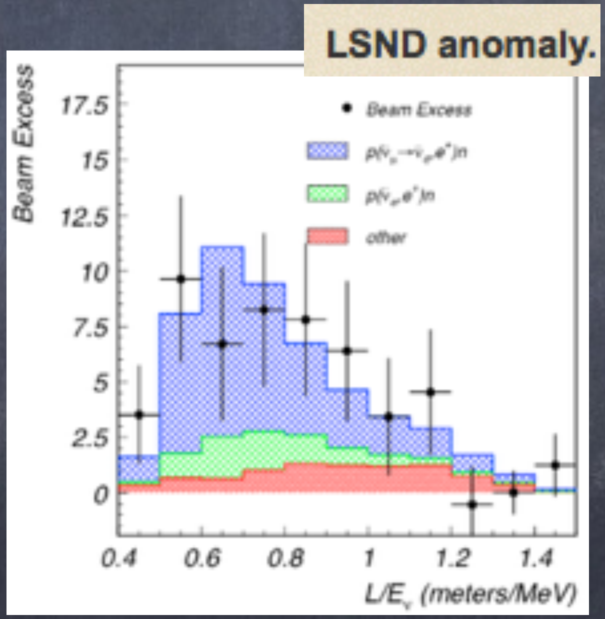
Neutrino sterile ?



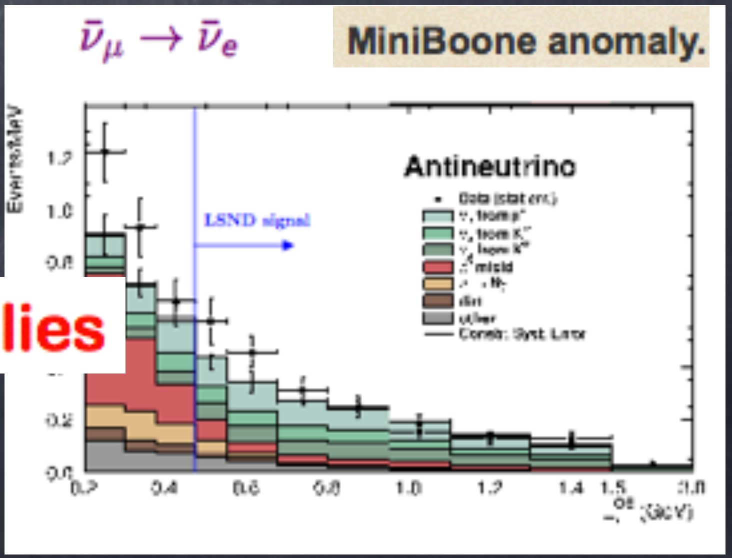


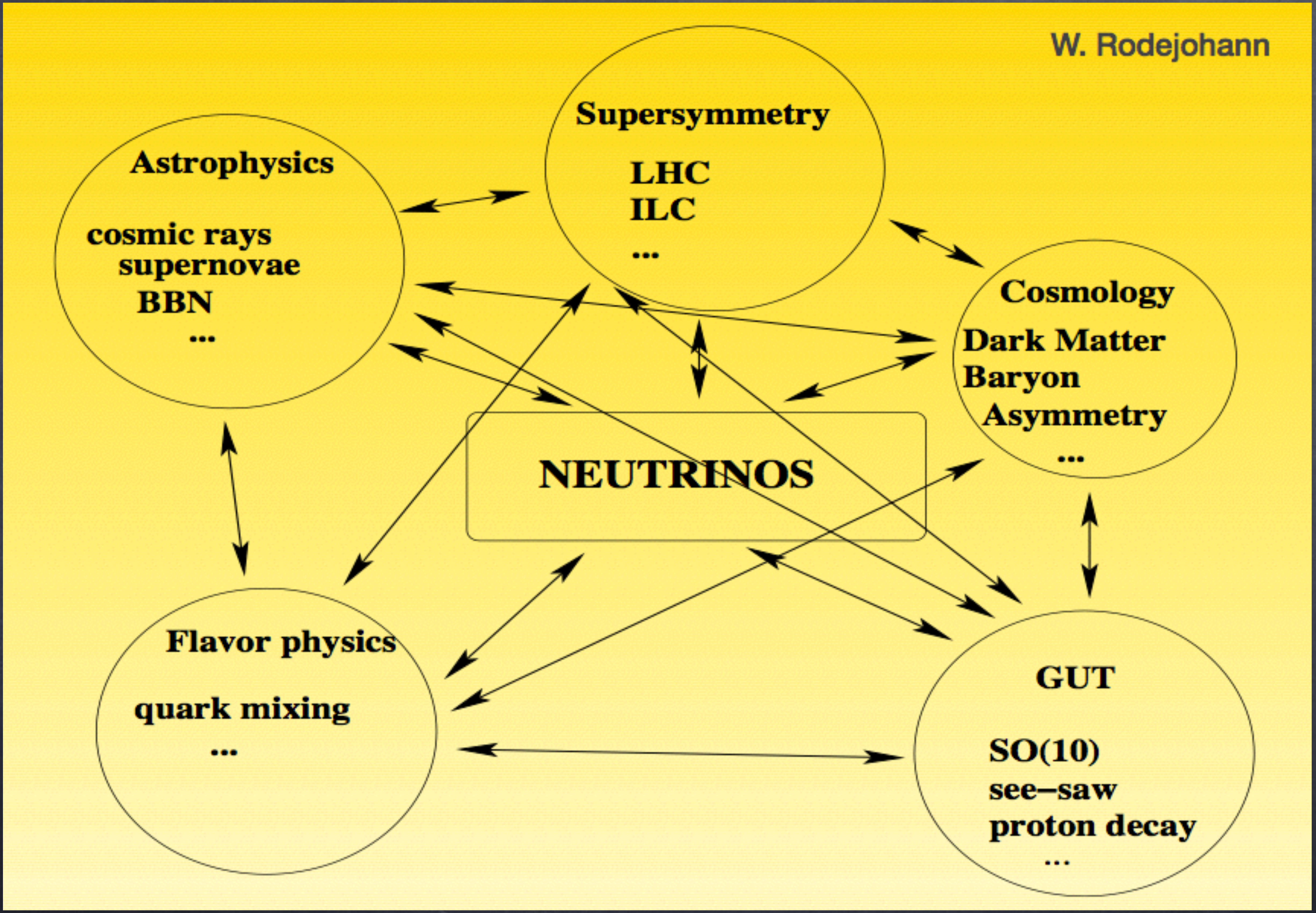


Many small anomalies found in different experiments :
=> difficult to explain in the 3nu scenario
=> possible hints of new neutrinos not coupled with the Z (3+1 favor than 3+2)



2.7 – 3.8 σ anomalies





W. Rodejohann
Supersymmetry
LHC
ILC
...
Astrophysics
cosmic rays
supernovae
BBN
...
Cosmology
Dark Matter
Baryon
Asymmetry
...
NEUTRINOS
Flavor physics
quark mixing
...
GUT
SO(10)
see–saw
proton decay
...