Nuevos retos de la astrofísica española

VII Reunión Científica de la SEA

Barcelona, 12-15
septiembre 2006

Review of
Astroparticle Physics experiments
(in Europe)

Antonio Ferrer

IFIC-Universitat de València

Particle Astrophysics

Particle Astrophysics is the field that uses high energy (particle) physics techniques to study astrophysical processes

- **Astronomer:**
  - Extension of observation to all electromagnetic spectrum
- **Astrophysicist:**
  - Explanation of astrophysical processes O(10^{26} m) with particle physics phenomena O(10^{-17} m)
- **Particle Physicist (& Cosmologist):**
  - Only possibility to access to extremely high energies (BigBang)

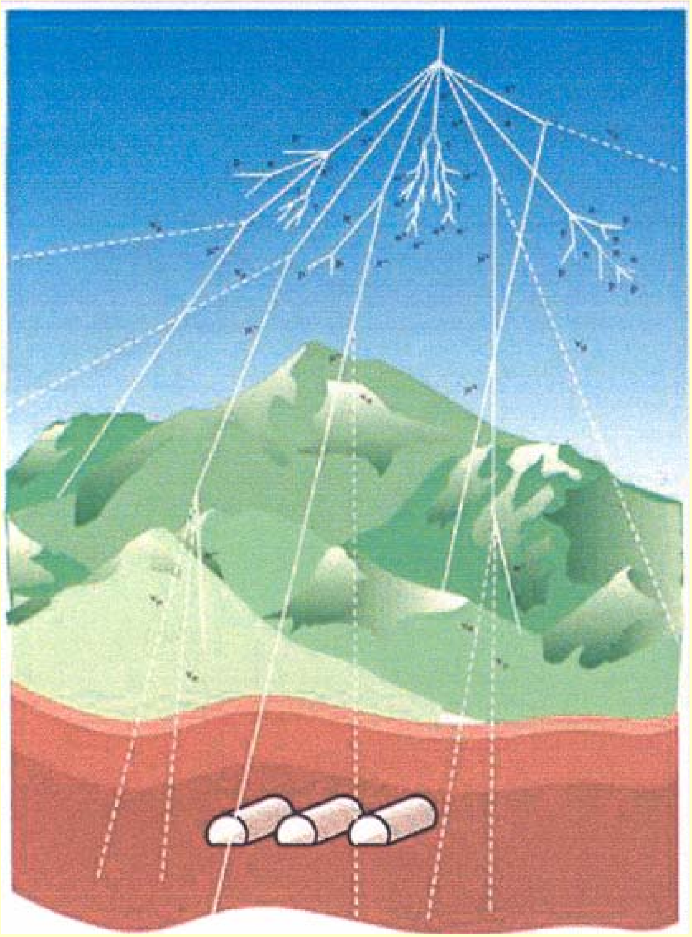
Particle Astrophysics ~ Cosmic Ray Physics

"Cosmic ray particles which we detect directly on earth, at the top of the atmosphere and in the interplanetary medium are the only high energy particles of genuinely cosmic origin which we can detect"

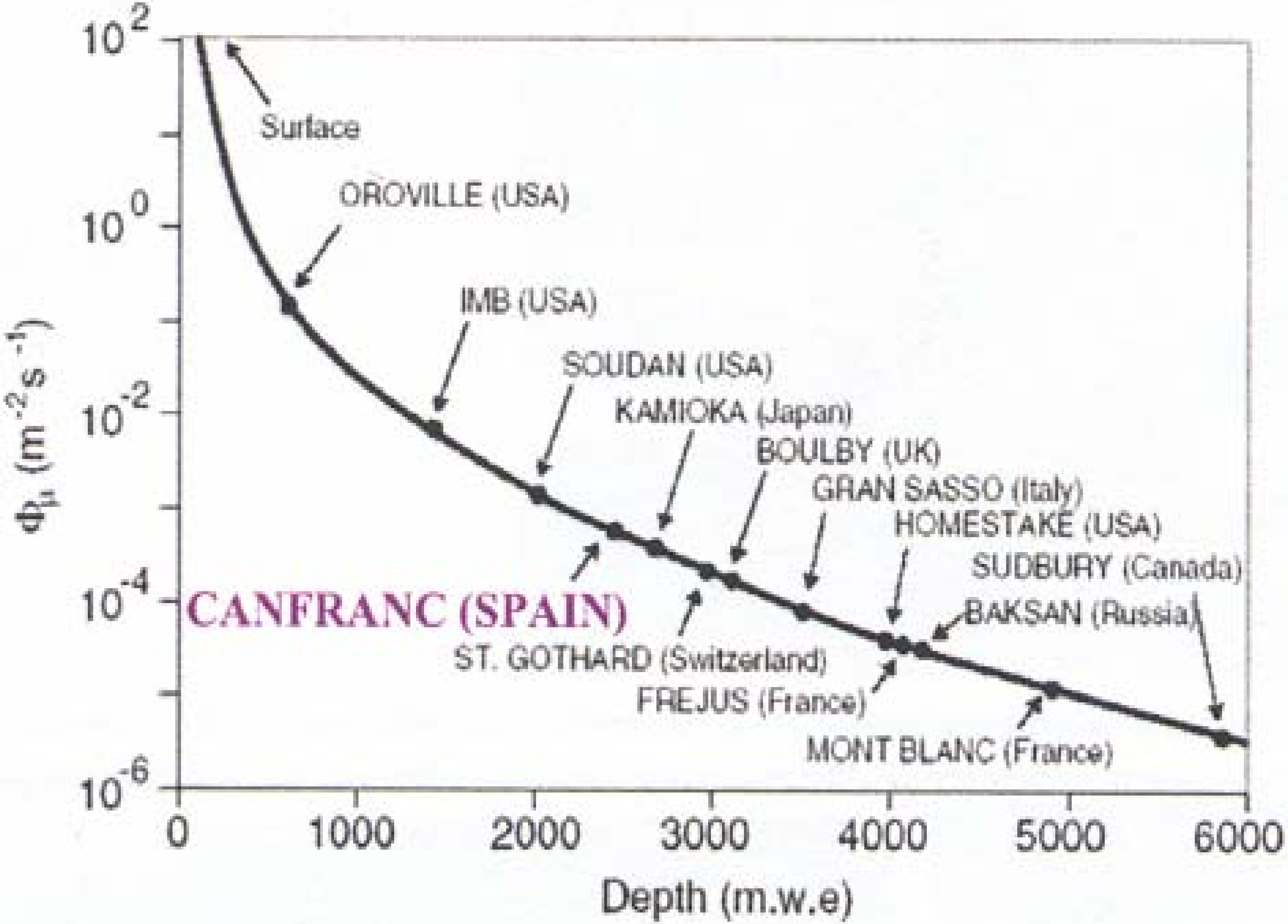
M.S.Longair *High Energy Astrophysics*

Underground Physics

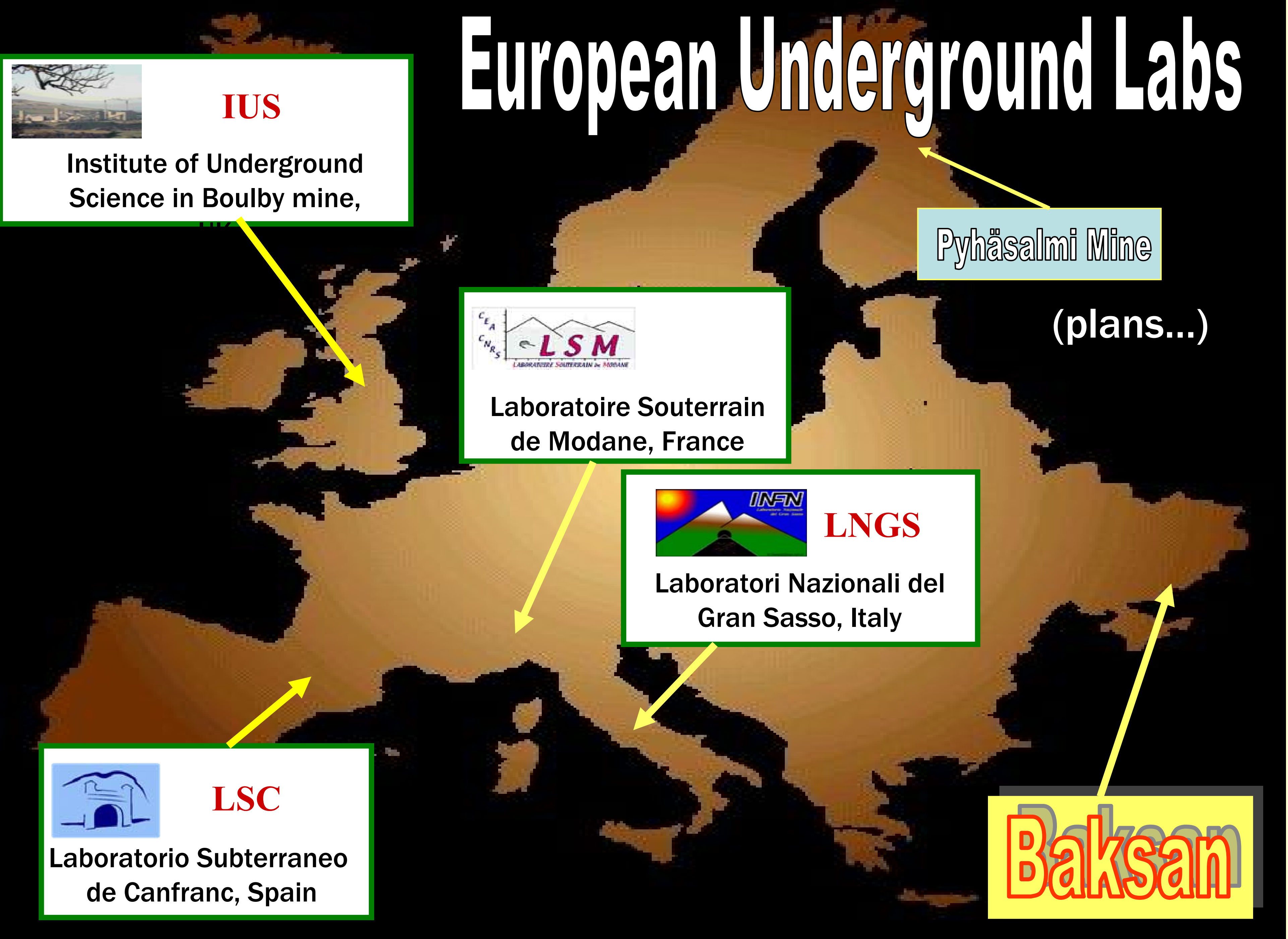
- Physics in Underground Labs. developed during last 20 years with discoveries of great scientific impact.
- screening of cosmic rays coming from space (one muon per cm^2 per minute in the earth surface).
- PROTON DECAY
- NEUTRINO PHYSICS
- DARK MATTER SEARCH



Underground Laboratories



European Underground Labs



IUS

Institute of Underground Science in Boulby mine, UK

LSM

Laboratoire Souterrain de Modane, France

LNGS

Laboratori Nazionali del Gran Sasso, Italy

LSC

Laboratorio Subterraneo de Canfranc, Spain

Pyhäsalmi Mine

(plans...)

Baksan

International Somport road tunnel

Laboratorio Subterráneo de Canfra

ApPEC

- Astroparticle Physics European Coordination
  - *Steering Committee*
  - *Peer Review Committee*
- Formed by large *funding agencies* for APP in Belgium, Germany, France, Greece, UK, Italy, Netherlands, Portugal, Switzerland and Spain
- Further countries joined or are going to join: Finland, Ireland, Poland, Slovenia, Tchechia, Sweden, …

ApPEC

ILIAS Networks, JRAs, Transnational Access DUA

KM3

ASPERA (ERANET; as ASTRONET)

- Web page
- Database
- Roadmap

ILIAS

~1200 scientists, budget ~10 M€

Integrated Large Infrastructures for Astroparticle Science

Networking Activities

(N2) Deep Underground science laboratories
(N3) Direct dark matter detection
(N4) Search on double beta decay
(N5) Gravitational wave research
(N6) Theoretical astroparticle physics

**gravitational waves,
dark matter
double beta decay**

Joint Research Activities (R&D Projects)

(JRA1) Low background techniques underground
(JRA2) Double beta decay European observatory
(JRA3) Study of noise in gravitational wave detectors

Transnational Access Activities

(TA1) Access to the EU Deep Laboratories

www.ilias.in2p3/fr

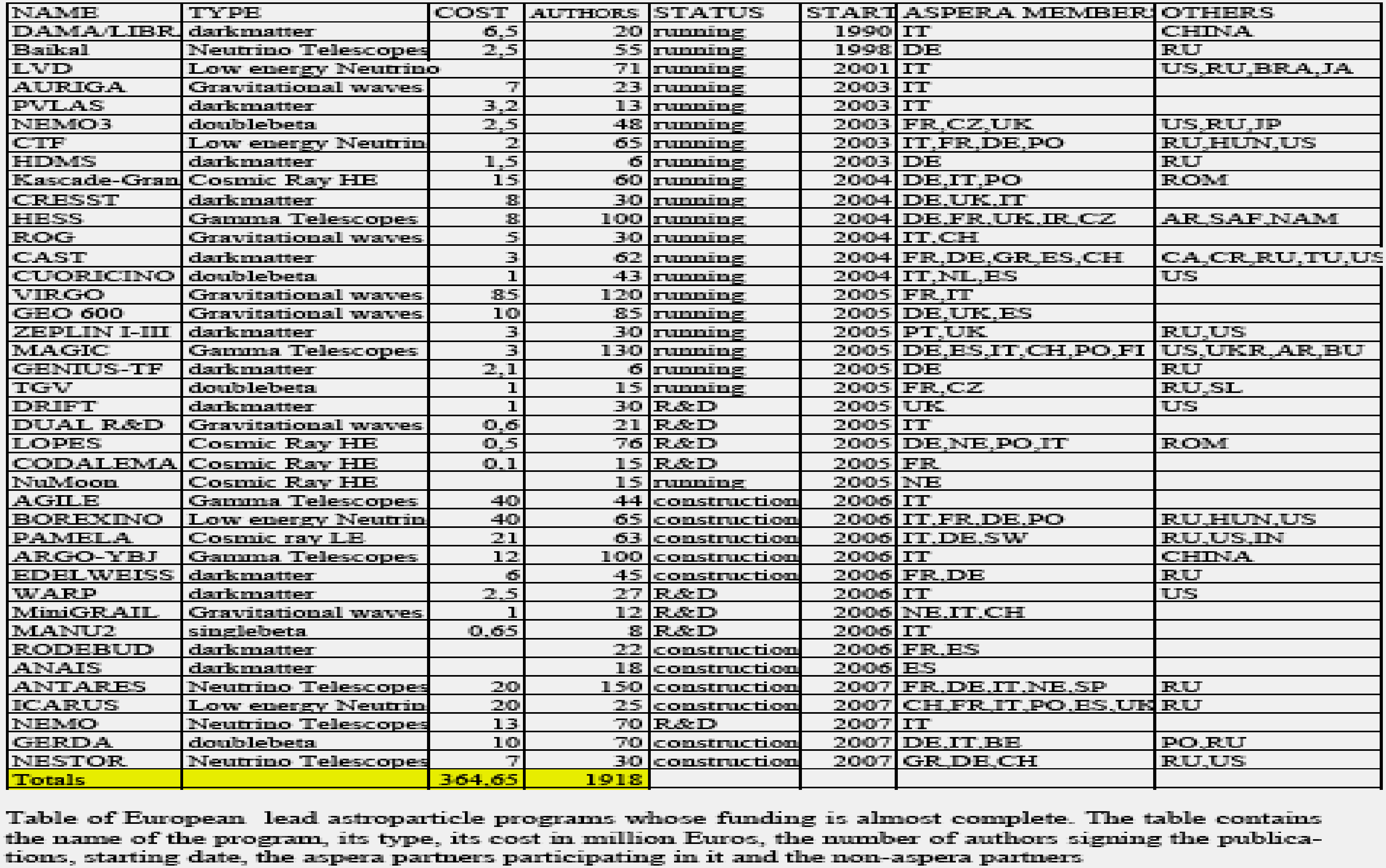
"ASPERA"

- ERA-Net „Implementation of European Coordination in Astroparticle Physics“
- 2.8 M€, among others for:
  - Communication Structure
  - ApPEC secretariat
  - ApPEC web page
  - AppEC roadmap
  - Meetings
  - Support of bottom-up activities (like ILIAS)
  - Framework to direct part of the national rescources of the agencies to transnational reserach programs

Has just been approved !

Programs running or in construction

European leadership



NAME	TYPE	COST	AUTHORS	STATUS	START	ASPERA MEMBER	OTHERS
DAMA/LIBR	darkmatter	6,5	20	running	1990	IT	CHINA
Baikal	Neutrino Telescopes	2,5	55	running	1998	DE	RU
LVD	Low energy Neutrino		71	running	2001	IT	US,RU,BRA,JA
AURIGA	Gravitational waves	7	23	running	2003	IT	
PVLAS	darkmatter	3,2	13	running	2003	IT	
NEMO3	doublebeta	2,5	48	running	2003	FR,CZ,UK	US,RU,JP
CTF	Low energy Neutrin	2	65	running	2003	IT,FR,DE,PO	RU,HUN,US
HDMS	darkmatter	1,5	6	running	2003	DE	RU
Kascade-Gran	Cosmic Ray HE	15	60	running	2004	DE,IT,PO	ROM
CRESST	darkmatter	8	30	running	2004	DE,UK,IT	
HESS	Gamma Telescopes	8	100	running	2004	DE,FR,UK,IR,CZ	AR,SAF,NAM
ROG	Gravitational waves	5	30	running	2004	IT,CH	
CAST	darkmatter	3	62	running	2004	FR,DE,GR,ES,CH	CA,CR,RU,TU,US
CUORICINO	doublebeta	1	43	running	2004	IT,NL,ES	US
VIRGO	Gravitational waves	85	120	running	2005	FR,IT	
GEO 600	Gravitational waves	10	85	running	2005	DE,UK,ES	
ZEPLIN I-III	darkmatter	3	30	running	2005	PT,UK	RU,US
MAGIC	Gamma Telescopes	3	130	running	2005	DE,ES,IT,CH,PO,FI	US,UKR,AR,BU
GENIUS-TF	darkmatter	2,1	6	running	2005	DE	RU
TGV	doublebeta	1	15	running	2005	FR,CZ	RU,SL
DRIFT	darkmatter	1	30	R&D	2005	UK	US
DUAL R&D	Gravitational waves	0,6	21	R&D	2005	IT	
LOPES	Cosmic Ray HE	0,5	76	R&D	2005	DE,NE,PO,IT	ROM
CODALEMA	Cosmic Ray HE	0,1	15	R&D	2005	FR	
NuMoon	Cosmic Ray HE		15	running	2005	NE	
AGILE	Gamma Telescopes	40	44	construction	2006	IT	
BOREXINO	Low energy Neutrin	40	65	construction	2006	IT,FR,DE,PO	RU,HUN,US
PAMELA	Cosmic ray LE	21	63	construction	2006	IT,DE,SW	RU,US,IN
ARGO-YBJ	Gamma Telescopes	12	100	construction	2006	IT	CHINA
EDELWEISS	darkmatter	6	45	construction	2006	FR,DE	RU
WARP	darkmatter	2,5	27	R&D	2006	IT	US
MiniGRAIL	Gravitational waves	1	12	R&D	2006	NE,IT,CH	
MANU2	singlebeta	0,65	8	R&D	2006	IT	
RODEBUD	darkmatter		22	construction	2006	FR,ES	
ANAIS	darkmatter		18	construction	2006	ES	
ANTARES	Neutrino Telescopes	20	150	construction	2007	FR,DE,IT,NE,SP	RU
ICARUS	Low energy Neutrin	20	25	construction	2007	CH,FR,IT,PO,ES,UK	RU
NEMO	Neutrino Telescopes	13	70	R&D	2007	IT	
GERDA	doublebeta	10	70	construction	2007	DE,IT,BE	PO,RU
NESTOR	Neutrino Telescopes	7	30	construction	2007	GR,DE,CH	RU,US
Totals		364,65	1918				

Table of European lead astroparticle programs whose funding is almost complete. The table contains the name of the program, its type, its cost in million Euros, the number of authors signing the publications, starting date, the aspera partners participating in it and the non-aspera partners

350M€/5 years investments and 2000 physicists

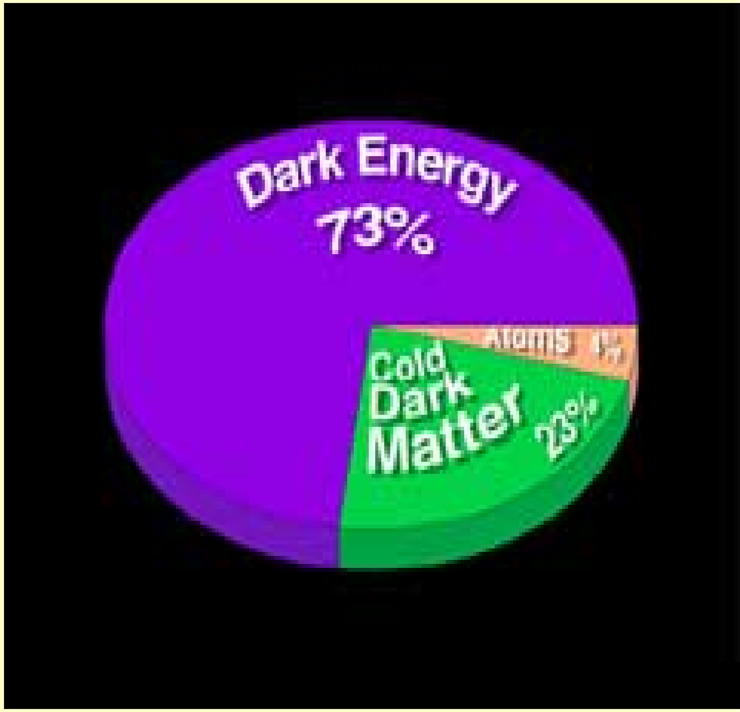
6 questions*
(Astroparticle physics)

1. What is the Universe made of ?
2. Do protons have a finite life time ?
3. What are the properties of neutrinos ? What is their role in cosmic evolution ?
4. What do neutrinos tell us about the interior of Sun and Earth, and about Supernova explosions ?
5. What is the origin of cosmic rays ? What is the view of the sky at extreme energies ?
6. What is the nature of gravity ? Can we detect gravitational waves ? What will they tell us about violent cosmic processes ?

*"Science is the art of replacing unimportant questions that can be answered by important ones which cannot" Edward B. Ferguson Jr. 1976.

1) What is the Universe made of?

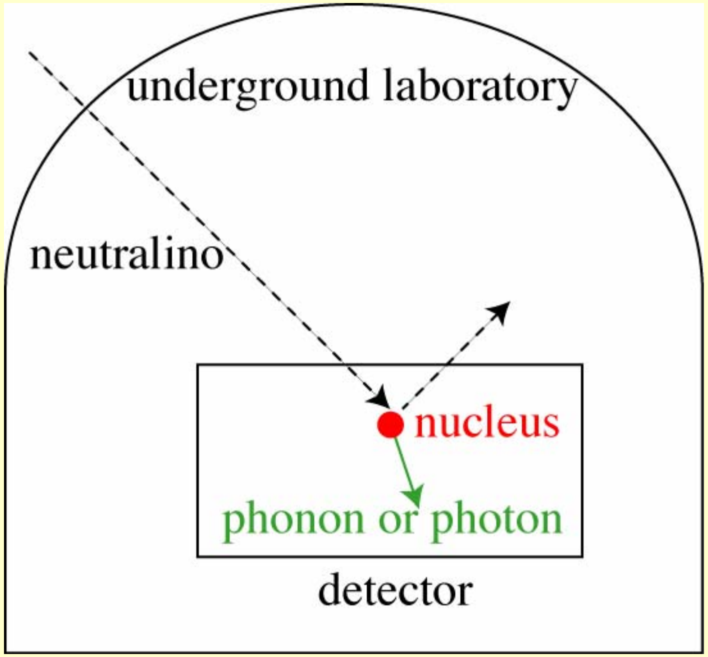
- 3 main experimental questions of today:
  - What is the mechanism of inflation?
    - From WMAP to PLANCK(2008) and beyond ex. SAMPAN(2020)
  - What is the equation of state of dark energy?
    - From a ground program to space ex.SNAP/DUNE(2015)
  - **What is the nature of dark matter particles?**
    - One ton observatory of dark matter particles based on bolometers or noble liquids (2011)



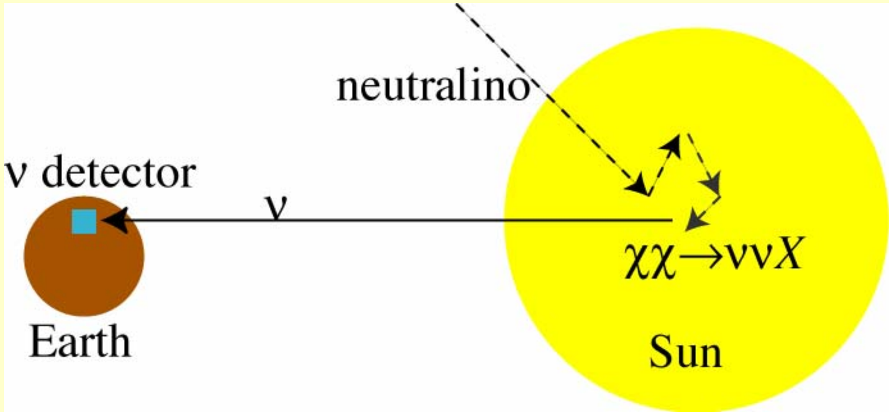
- Of the 3 questions
  - The last is definitively included in the roadmap
  - The inclusion of the second is under discussion in ApPEC and in the CERN Strategy group
  - The first is considered in other roadmaps (ASTRONET) with participation of the astroparticle community

Detection of Dark Matter

- Direct detection
- CDMS-II, Edelweiss, DAMA,



- Indirect detection
- SuperK, AMANDA, ICECUBE, Antares, etc

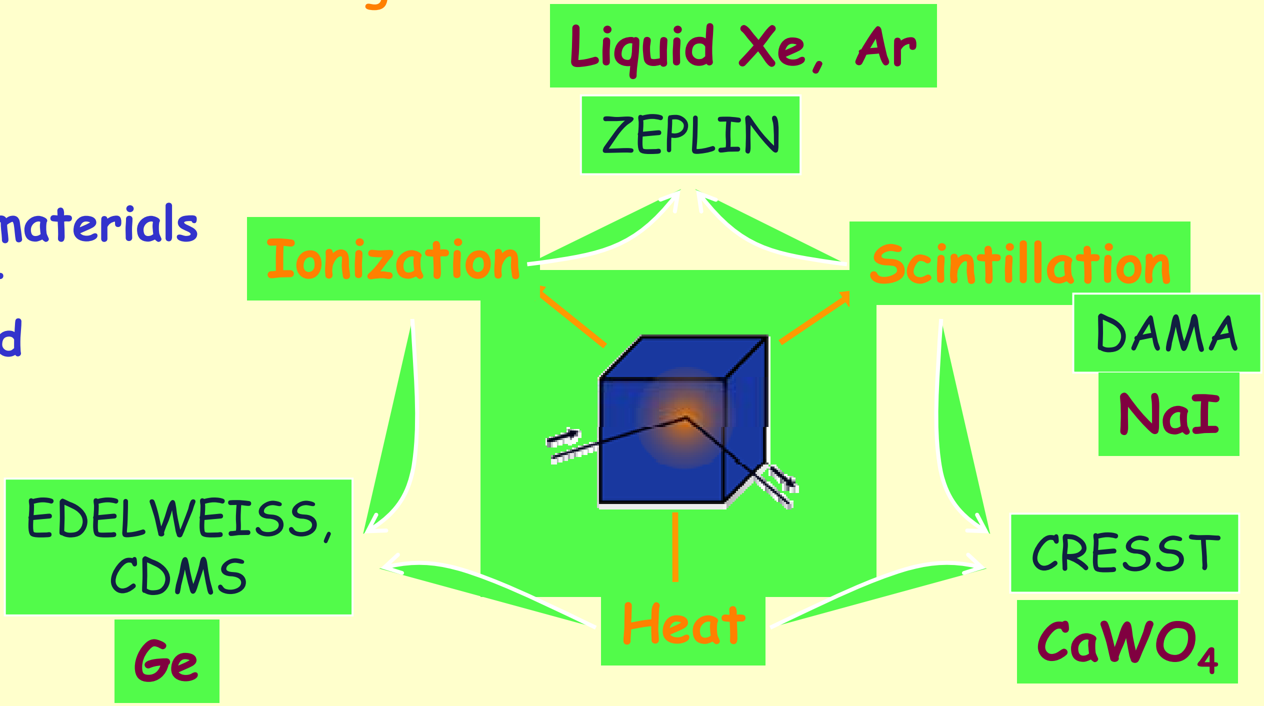


complementary techniques are getting into the interesting region of parameter space

Dark matter, Detection methods

WIMP: elastic scattering on detector nucleus

$\ll$ 1evt / kg / day $\Rightarrow$
- Deep underground
- Low radioactivity of materials
- Discrimination against radioactive background



Liquid Xe, Ar

ZEPLIN

Ionization

Scintillation

DAMA

NaI

EDELWEISS, CDMS

Ge

Heat

CRESST

$CaWO_4$

Nuclear (vs. electronic) recoil discrimination: event by event or statistical

WIMP signal

Radioactive background

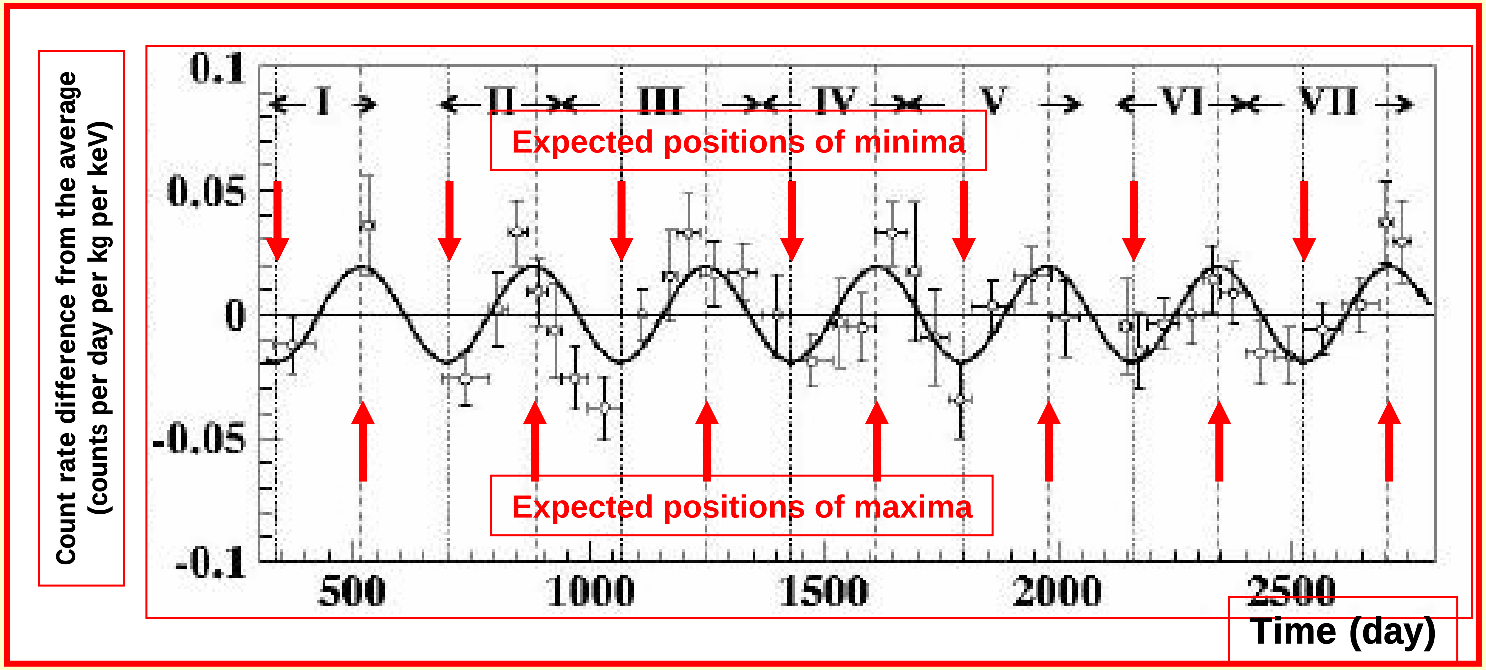
NaI scintillation experiments

EXPERIMENT AND SITE	M (Kg)	E_{Thr} (KeV)	B (c/KeV Kg day) (Average) Before PSD	OBSERVATIONS
DAMA LNGS	9 x 9.70	2	1~1.5 (at 2-3 KeV) 1.5~2 (at 3-6 KeV) 0.5 (at 2.5 KeV) BEST CRYSTAL	Annual modulation effect reported along four annual cycles (4s) 5th and 6th cycles soon Phys. Lett. B450 (99)448, ibid B480 (2000) 23 COMPLETED
ELEGANT Oto Cosmo	670	4-5	8-10 (at Threshold)	Old set-up upgraded. Large BKG from ^{210}Pb (10 mB/Kg)
ANAIS LSC, Canfranc Prototype running	PROTOTYPE 10.7 FINAL SET 10 x 10.7	2	~1.5 (at 4-10 KeV)	107 Kg intended for ann. mod. search. Old set upgraded plus new radiopure crystals. Preliminary 1200 Kg day. R+D in course In operation Phase I.
NAIAD (Boulby)	SET OF 48→56kg (8 crystals)	2	~6-10 (4-20 keV)	Set of NaI encapsulated and unencapsulated In operation.
LIBRA **IN DAMA** LNGS	250			Set of NaI crystals. R+D on detector radiopurity crystals from ultrapure powders (DAMA-ST.GOBAIN). In operation.

DAMA: Final results

Exposure 107731 Kg day (approx. 300 Kg year)

ANNUAL MODULATION MODEL INDEPENDENT RESULT



Residual of the rate versus time, for the energy interval 2 to 6 keV

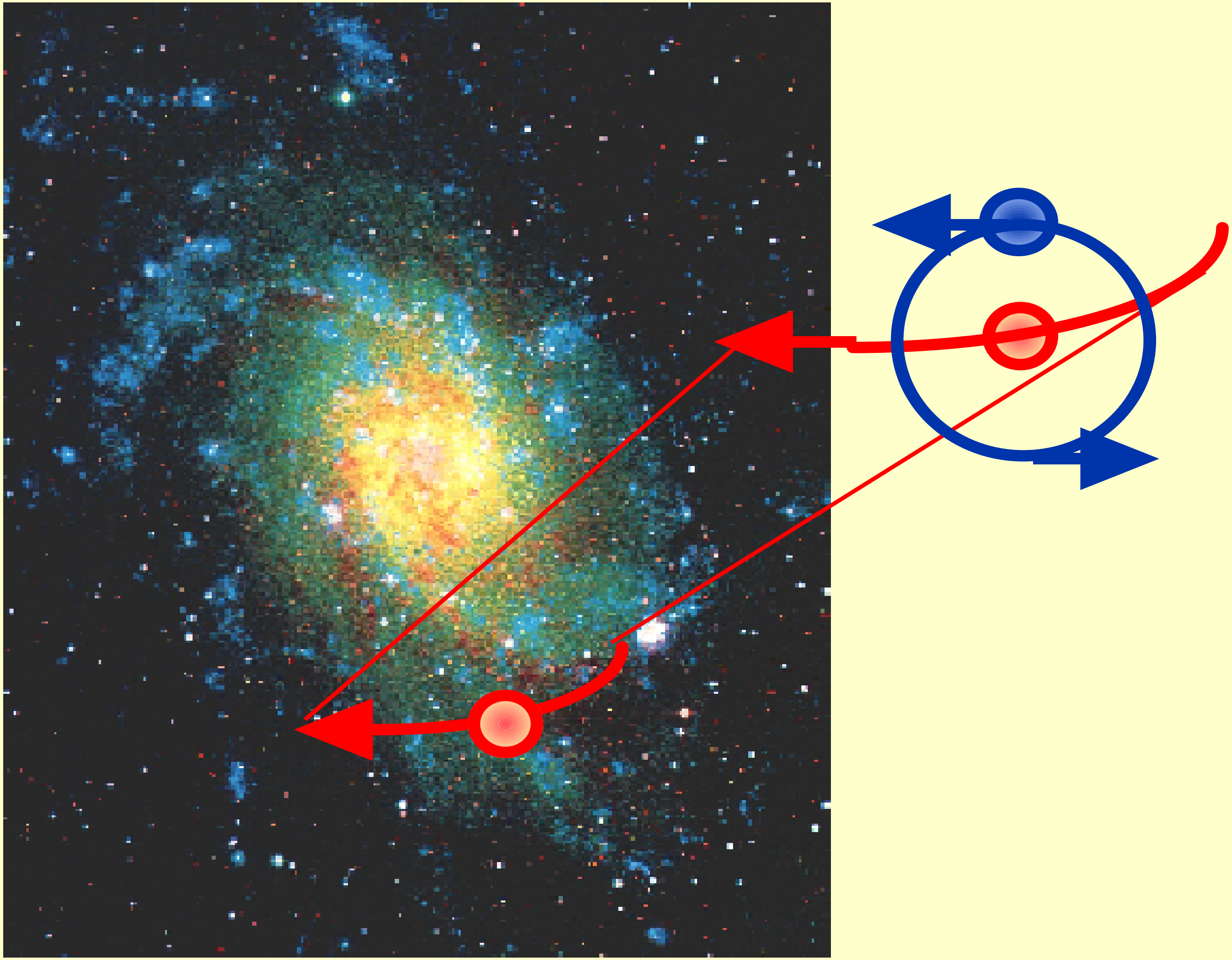
A cos ω (t - t_o) , t_o=152.5 d , T=1 y (continuous line)

Fitted (all parameters free):

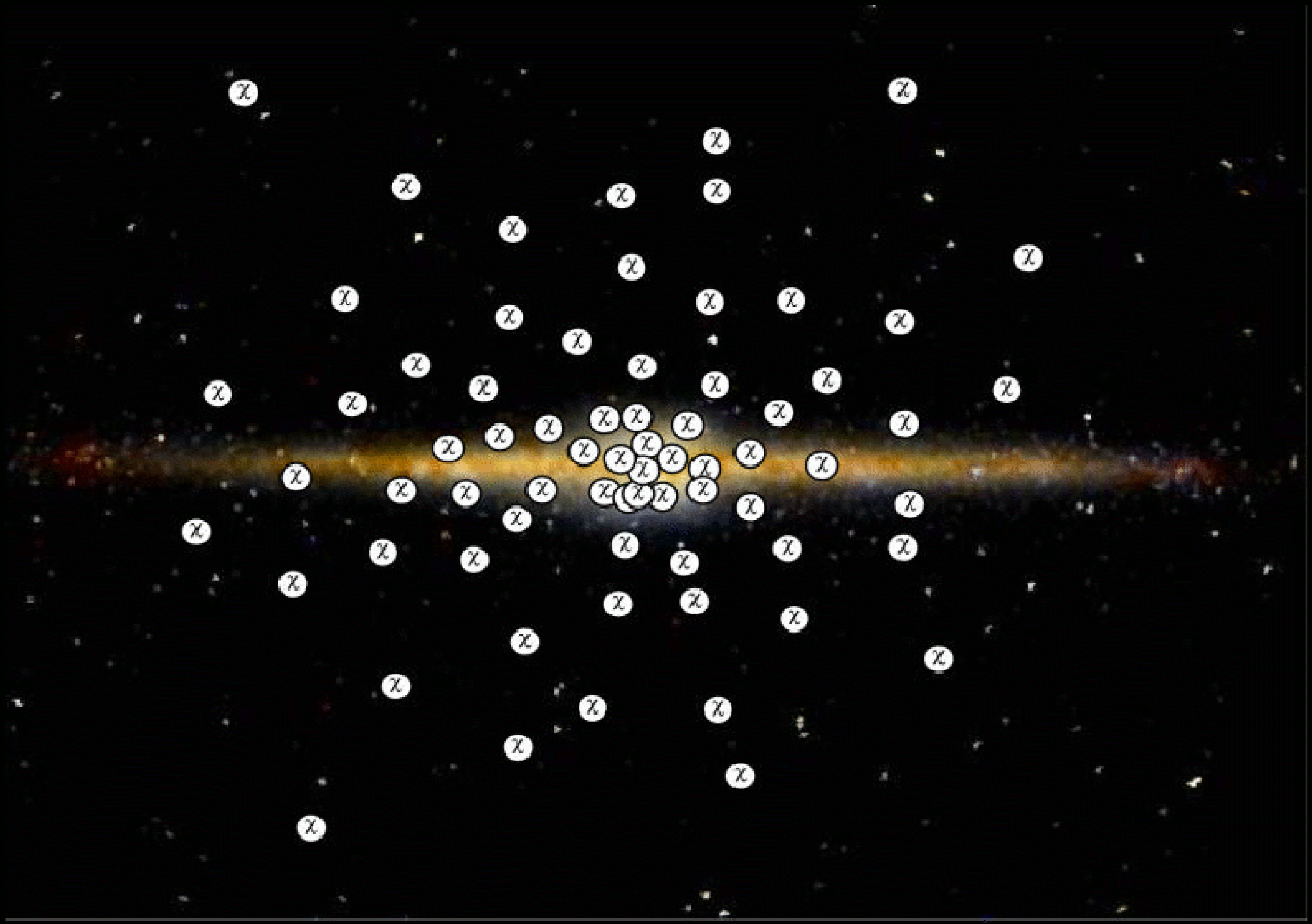
A = (0.0200+/-0.0032) counts/keV/kg/day

t_o= (140+/-22) d T= (1.00+/-0.01) y

Annual modulation effect



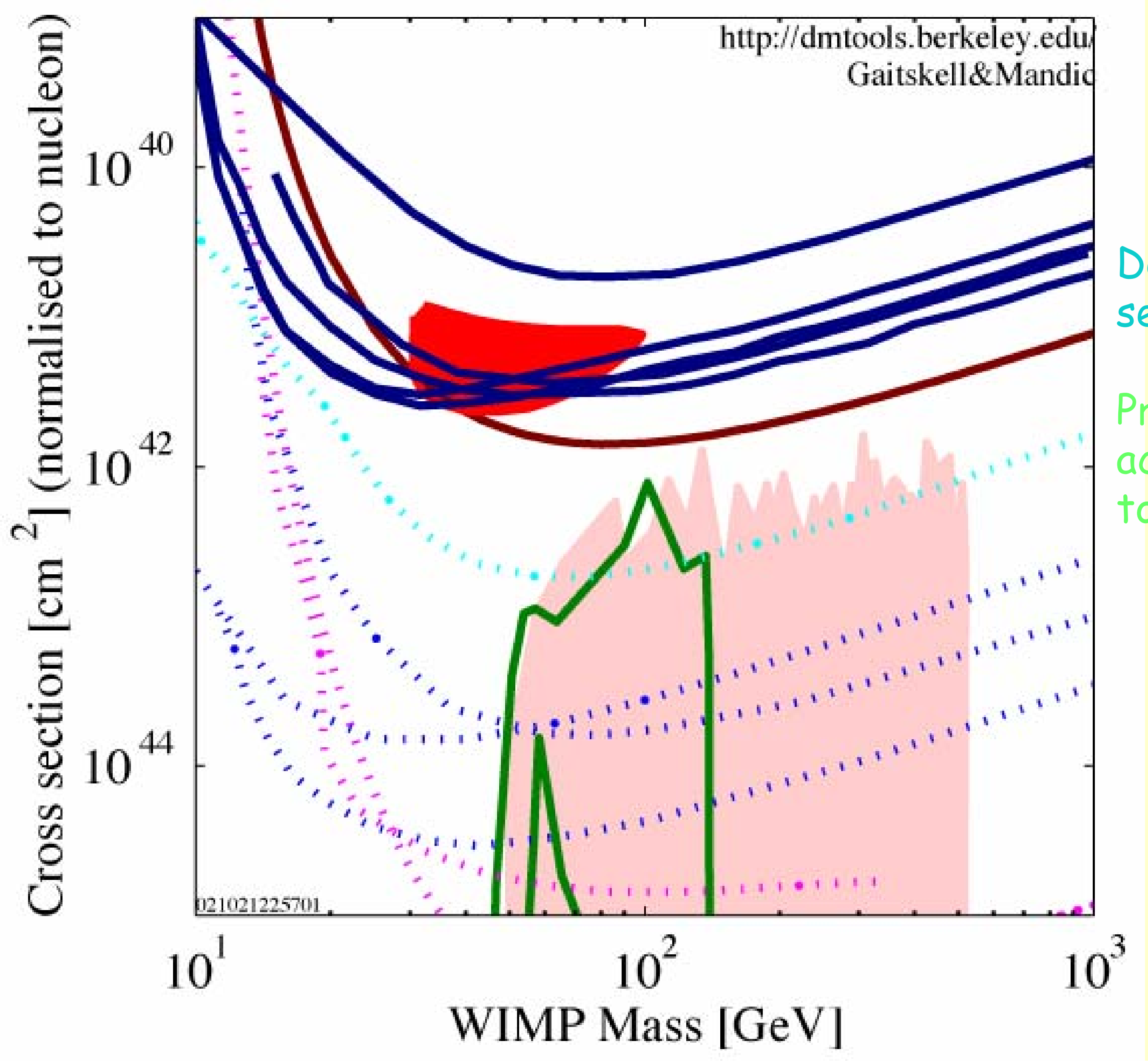
Model for Neutralino Galactic Halo:



$\rho_{\text{local}} \sim 0.3$ GeV/cm^3, $v/c \sim 10^{-3}$, $m_\chi \sim 100$ GeV

$\Rightarrow$ flux 10^3 cm^{-2} s^{-1} sr^{-1} !

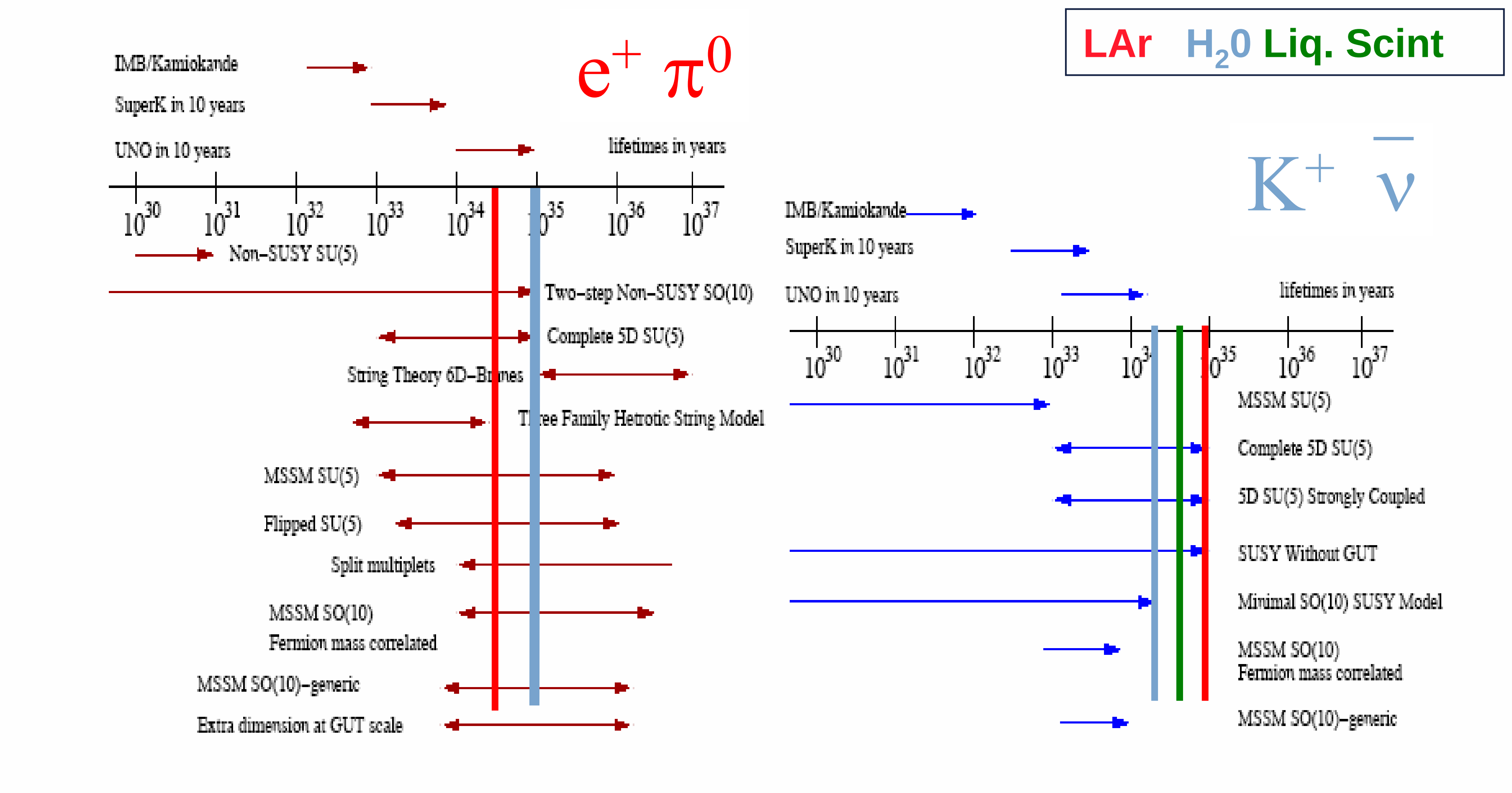
Dark matter search limits



Detect Dark Matter to see *it is there.*

Produce Dark Matter in accelerator experiments to see *what it is.*

2) Proton decay & next generation large underground detectors

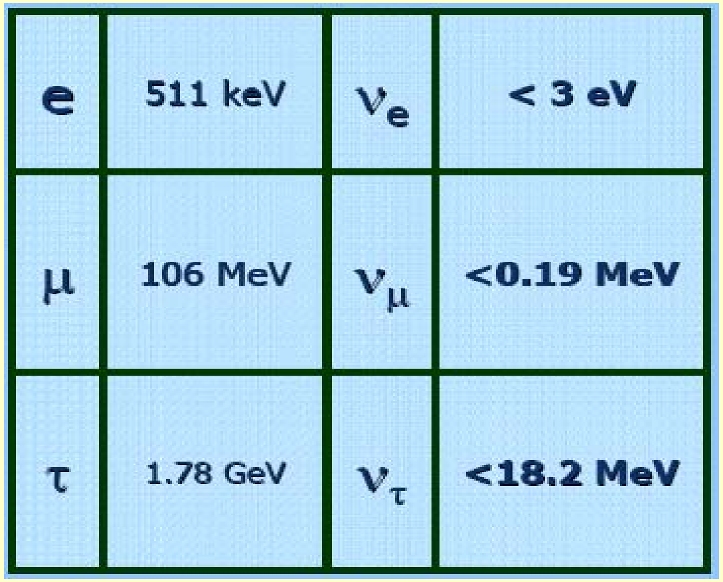


Higher dimension models (eg. 6D SO(10)) not included

Definitively not exhaustive neither p channels nor n decay…

3) ¿Qué sabemos de los neutrinos?

- Existen 3 neutrinos ligeros (LEP): N_ν=2.994 ± 0.012
- Son mucho más ligeros que sus compañeros leptónicos cargados (¿por qué?):



e	511 keV	ν_e	< 3 eV
μ	106 MeV	ν_μ	<0.19 MeV
τ	1.78 GeV	ν_τ	<18.2 MeV

- Existe un déficit de neutrinos solares, atmosféricos, reactores y aceleradores: evidencia de oscilación de neutrinos ➡ **son masivos**
- Los autoestados de masa y débiles son diferentes ➡ **oscilaciones**
- Oscilaciones de neutrinos es la primera indicación de **física más allá del Modelo Estándar**

The Neutrino mass

Experimental detection of neutrino oscillations

$\Downarrow$

Neutrinos have got mass

How large is $m(\nu_e)$, what is the mass hierarchy?

1. Tritium β-decay

$m(\nu_e)^2 = -0{,}6 \pm 2{,}2 \pm 2{,}1\ \mathrm{eV}^2$ **Mainz**

$\Rightarrow m(\nu_e) \leq 2{,}3\mathrm{eV}\ (95\%)$

2. 0νββ-decay

$\langle m(\nu_e)\rangle \approx 0{,}4\ \mathrm{eV}$ **to be confirmed**

3. ν-Oscillations

$7{,}3 \cdot 10^{-5}\mathrm{eV}^2 < \Delta m_{12}^2 < 9.3 \cdot 10^{-5}\mathrm{eV}^2$ **solar**

$1{,}6 \cdot 10^{-3}\mathrm{eV}^2 < \Delta m_{23}^2 < 3.6 \cdot 10^{-3}\mathrm{eV}^2$ **atm.**

$\Rightarrow$ There is a ν with $m_{\nu i} \geq 0{,}009\mathrm{eV}$ and one with $m_{\nu j} \geq 0{,}05\mathrm{eV}$

4. Cosmology

$\sum m_{\nu i} \leq 0{,}7\mathrm{eV}$

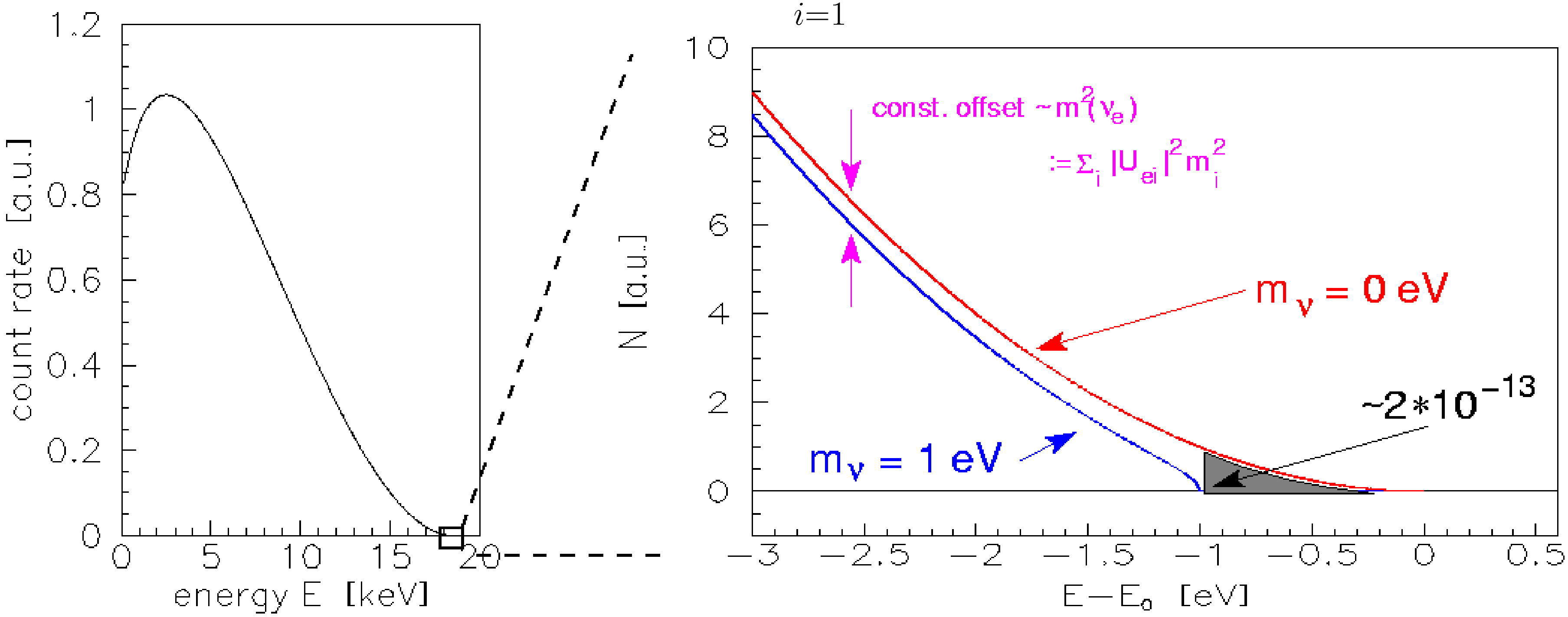
Tritium β-decay

Tritium β Decay: $^3H \rightarrow {}^3He^+ + \enclose{circle}{e^-} + \nu_e$

Superallowed
E_0 = 18.6 keV
$t_{1/2}$ = 12.3 a

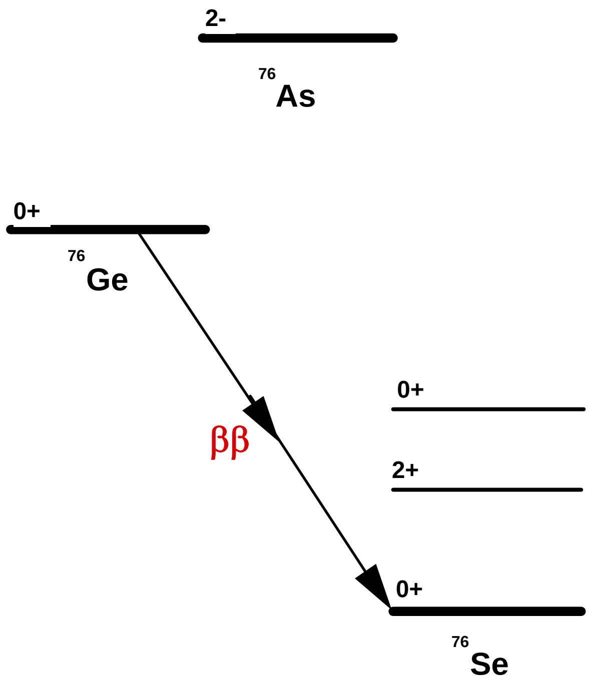
$$dN/dE = K\ F(E,Z)\ p\ E_{tot}\ (E_0-E_e)\ \Sigma\, |U_{ei}|^2\, [\, (E_0-E_e)^2 - \mathbf{m(\nu_i)^2}\ ]^{1/2}$$

$$m(\nu_e)^2 = \sum_{i=1}^{3} |U_{ei}|^2\, m(\nu_i)^2$$

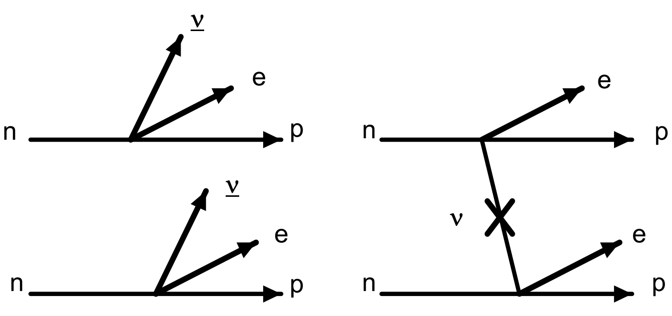


Double beta decay

- Large number of even-even nuclei undergo double-beta decay, but not single-beta decay
- Standard Model process of 2νββ is also allowed of course
- Enrichment procedure in place for about 10 isotopes
- You do not search for peaks in unknown places: you always know where to look
- Q value of the decay is well known (difference in mass between two isotopes)



$$|\langle m_\nu \rangle| = |c_3^2 c_2^2 m_1 + s_3^2 c_2^2 e^{i\phi_2} m_2 + s_2^2 e^{i\phi_3} m_3|$$

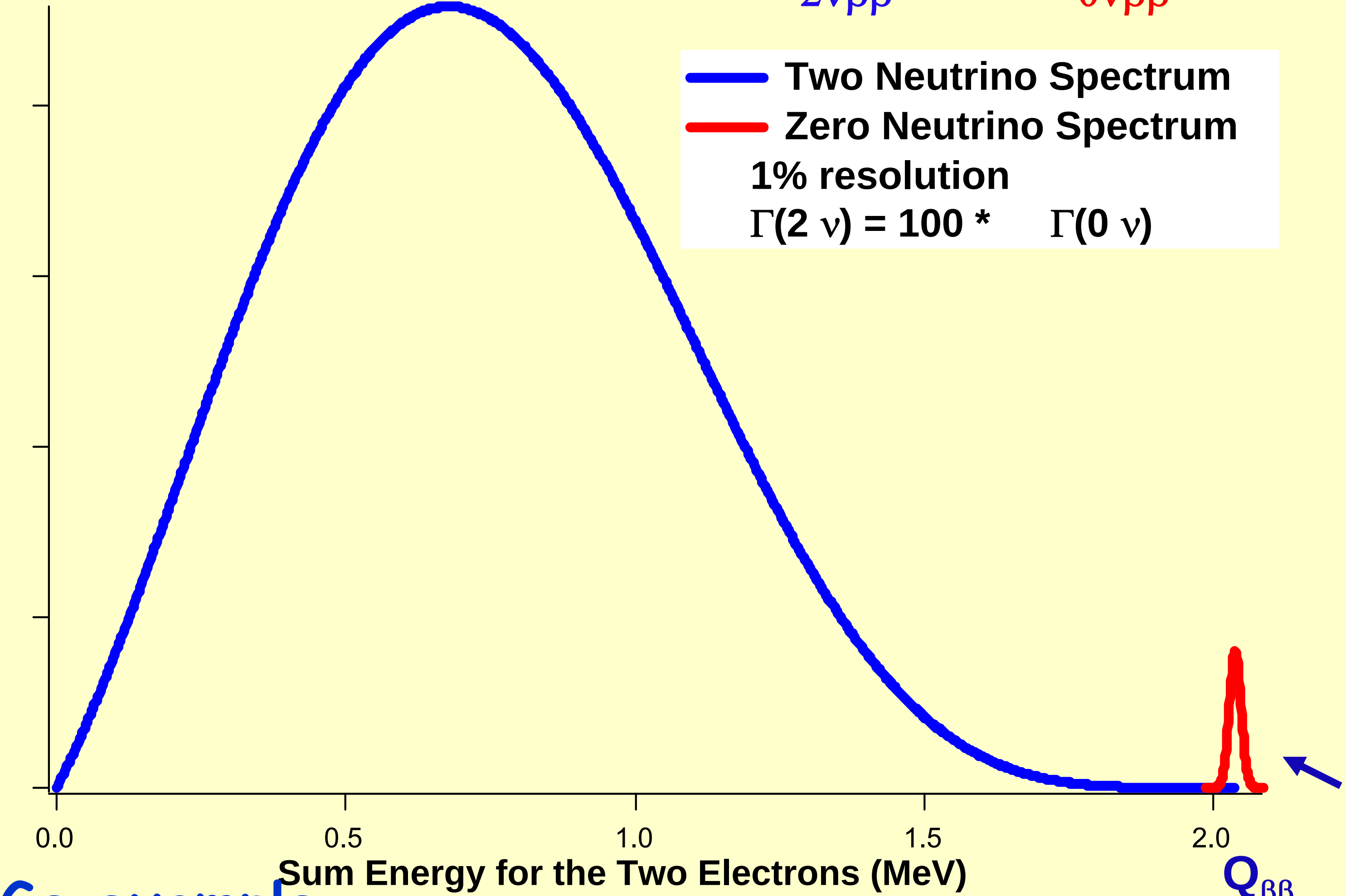


2νββ 0νββ

$^{76}Ge \rightarrow {}^{76}Se + e^- + e^- + (\nu + \nu)$

Double beta decay

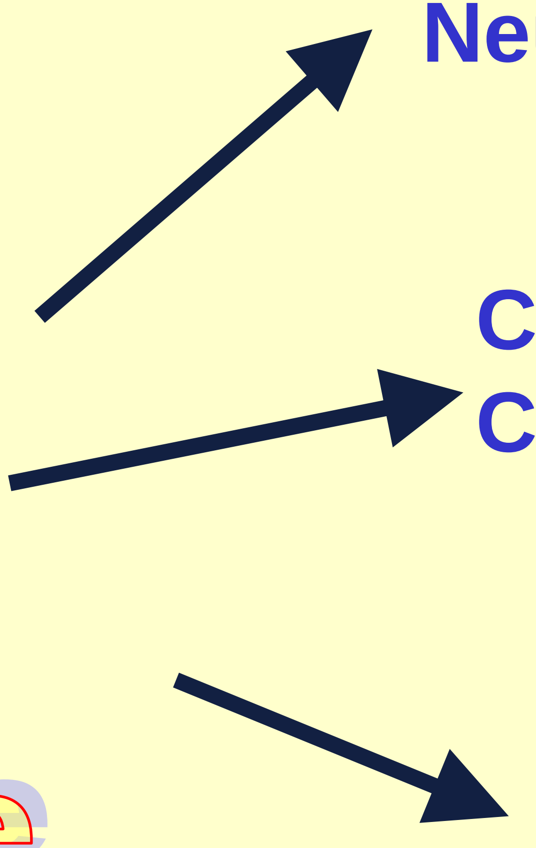
$2\nu\beta\beta$ $0\nu\beta\beta$



^{76}Ge example

$Q_{\beta\beta}$
Endpoint
Energy

The High Energy Universe

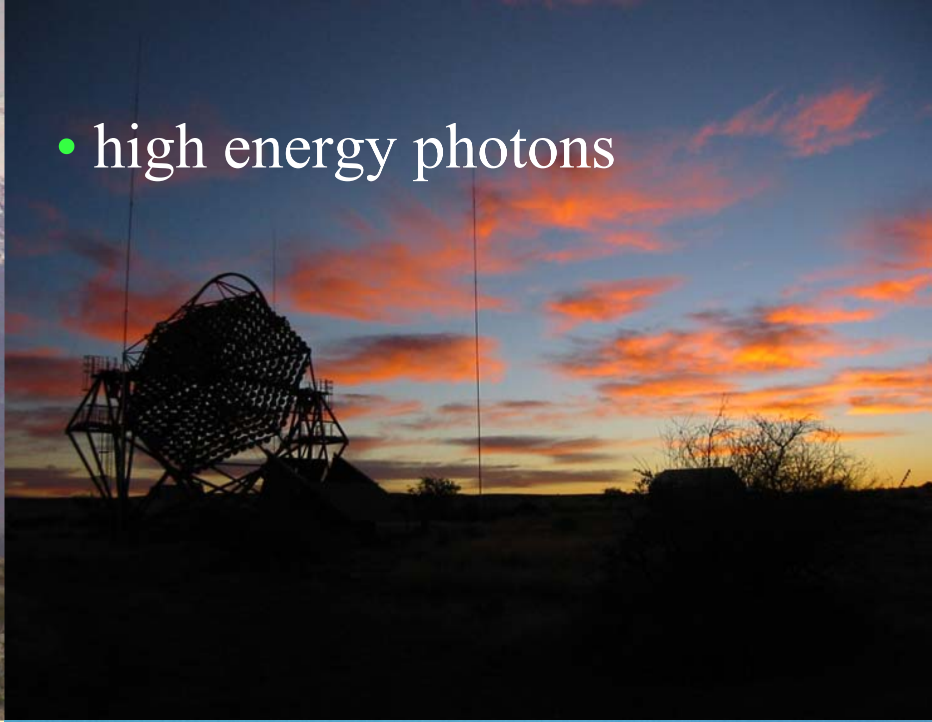


Neutrinos

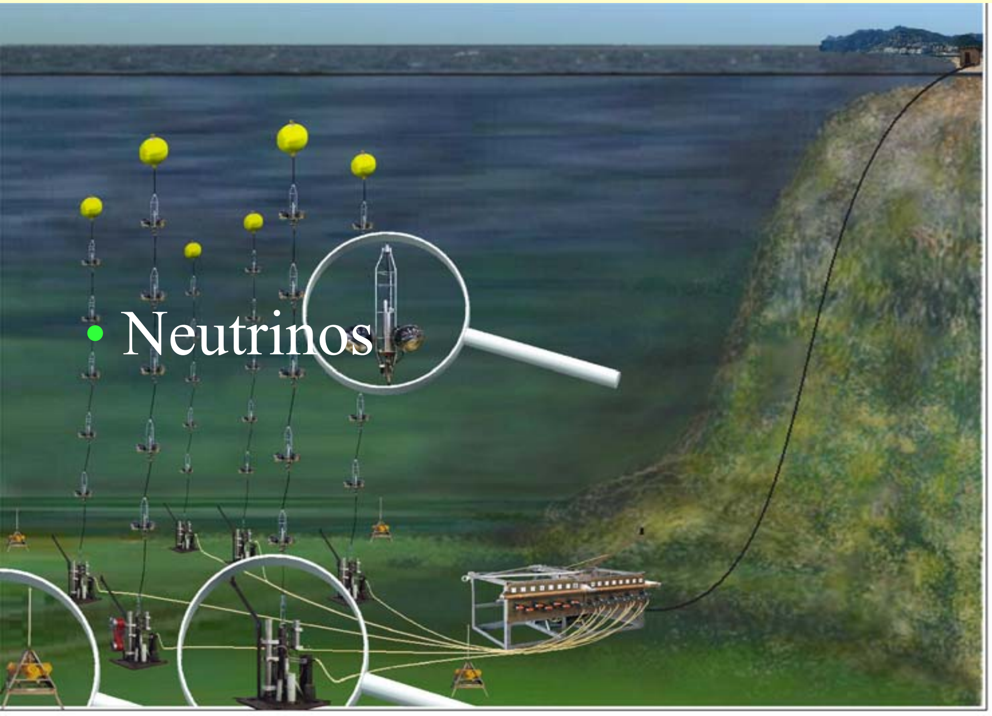
Charged Cosmic Rays

Gammas

- Ultra-high energy cosmic rays



- high energy photons



- Neutrinos

- Gravitational waves

Neutrino Sources

There are many sources of neutrinos, “natural” and “artificial”:

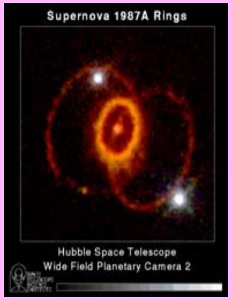
1) “Fission neutrinos”: bombs and reactors. (~ 10^{11} $cm^{-2}s^{-1}$)
2) Accelerator neutrinos. (~10^{6} $cm^{-2}s^{-1}$)
   These have been the standard HEP ν-sources since the 60’s:
   a) “Classical” (K, π decay)
   b) Beam Dump (ν_τ just discovered)
   c) Future Hadron Machines
   d) Future Muon-Colliders (ν-factories)
3) Solar neutrinos. (~ 10^{11} $cm^{-2}s^{-1}$)
4) Atmospheric neutrinos. (~ 10 $cm^{-2}s^{-1}$)
5) Supernova neutrinos.
6) Other astrophysical sources.
7) Big-bang neutrinos (the ultimate chalenge).

Neutrino sources

Natural sources

Sun

Atmosphere



Supernovas

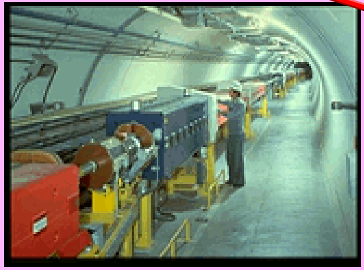
BigBang

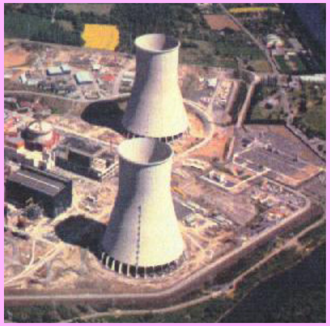
detected

undetected

Artificial sources

Accelerators





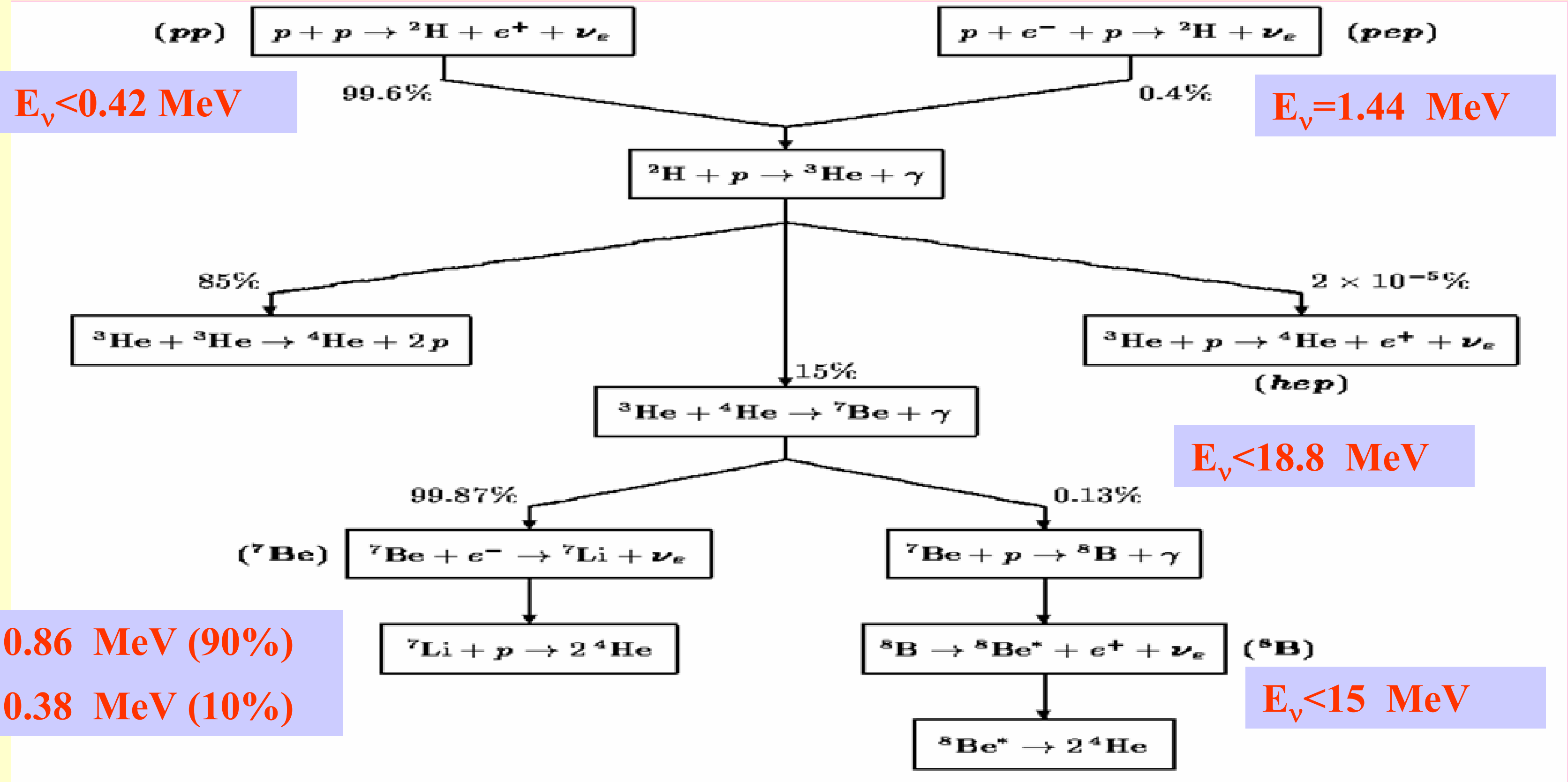
Reactors,
Bombs

Solar Neutrinos

- The flux of solar neutrinos is calculated in the framework of the Standard Solar Model, J. Bahcall et al. The model assumes hydrostatic and thermal equilibrium luminosity = rate of energy production:
  - $\mathcal{L} = 3.846\times10^{26}$ **watts**
- L° is directly related to the total ν_e flux. There are several fusion reaction chains, but they all amount to:
  - $4p \rightarrow {}^4He + 2e^+ + 2\nu_e \quad (Q=24.68\ MeV)$
- e^+s (with e^-) give $\gamma\gamma$. Assuming that γ's and kinetic energy (except that of the ν's) go to heat, the heat production per reaction is $W = Q+4m_ec^2-\langle E\nu's\rangle = 26.1\ MeV$
- The total number of ν_e's produced by the Sun is then:
  - $N_\nu = 2\ \mathcal{L}/W = 1.8\times30^{38}\ \nu_e\ .\ s^{-1}$
  - Flux on Earth surface = 6.4×10^{10} ν_e/cm^2s !!!
  - (day and night)

Solar Fusion Reactions

A) The pp cycle



(pp) $p + p \to {}^{2}\mathrm{H} + e^{+} + \nu_e$

$E_\nu < 0.42$ MeV

(pep) $p + e^{-} + p \to {}^{2}\mathrm{H} + \nu_e$

$E_\nu = 1.44$ MeV

${}^{2}\mathrm{H} + p \to {}^{3}\mathrm{He} + \gamma$

${}^{3}\mathrm{He} + {}^{3}\mathrm{He} \to {}^{4}\mathrm{He} + 2p$

${}^{3}\mathrm{He} + {}^{4}\mathrm{He} \to {}^{7}\mathrm{Be} + \gamma$

${}^{3}\mathrm{He} + p \to {}^{4}\mathrm{He} + e^{+} + \nu_e$ (hep)

$E_\nu < 18.8$ MeV

(^{7}Be) ${}^{7}\mathrm{Be} + e^{-} \to {}^{7}\mathrm{Li} + \nu_e$

${}^{7}\mathrm{Li} + p \to 2\,{}^{4}\mathrm{He}$

$E_\nu = 0.86$ MeV (90%)

$E_\nu = 0.38$ MeV (10%)

${}^{7}\mathrm{Be} + p \to {}^{8}\mathrm{B} + \gamma$

${}^{8}\mathrm{B} \to {}^{8}\mathrm{Be}^{*} + e^{+} + \nu_e$ (^{8}B)

$E_\nu < 15$ MeV

${}^{8}\mathrm{Be}^{*} \to 2\,{}^{4}\mathrm{He}$

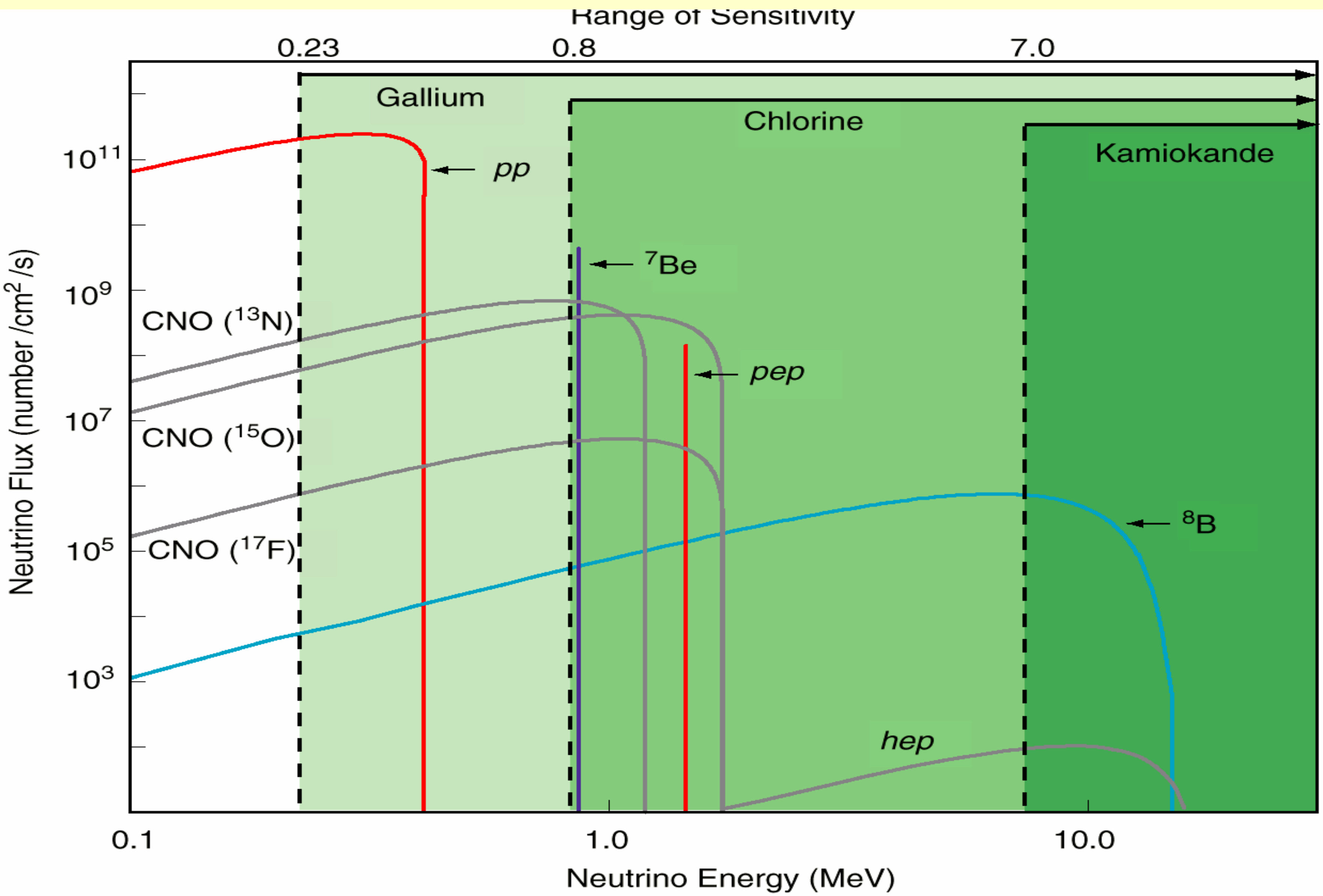
B) The Carbon-Nitrogen-Oxygen Cycle (CNO-cycle)

$$p + {}^{15}N \to {}^{12}C + {}^{4}He$$
$$p + {}^{12}C \to {}^{13}N + \gamma$$
$${}^{13}N \to {}^{13}C + e^{+} + \nu_e$$
$$p + {}^{13}C \to {}^{14}N + \gamma$$

$$p + {}^{15}N \to {}^{16}O + \gamma$$
$$p + {}^{16}O \to {}^{17}F + \gamma$$
$${}^{17}F \to {}^{17}O + e^{+} + \nu_e$$
$$p + {}^{17}O \to {}^{14}N + {}^{4}He$$

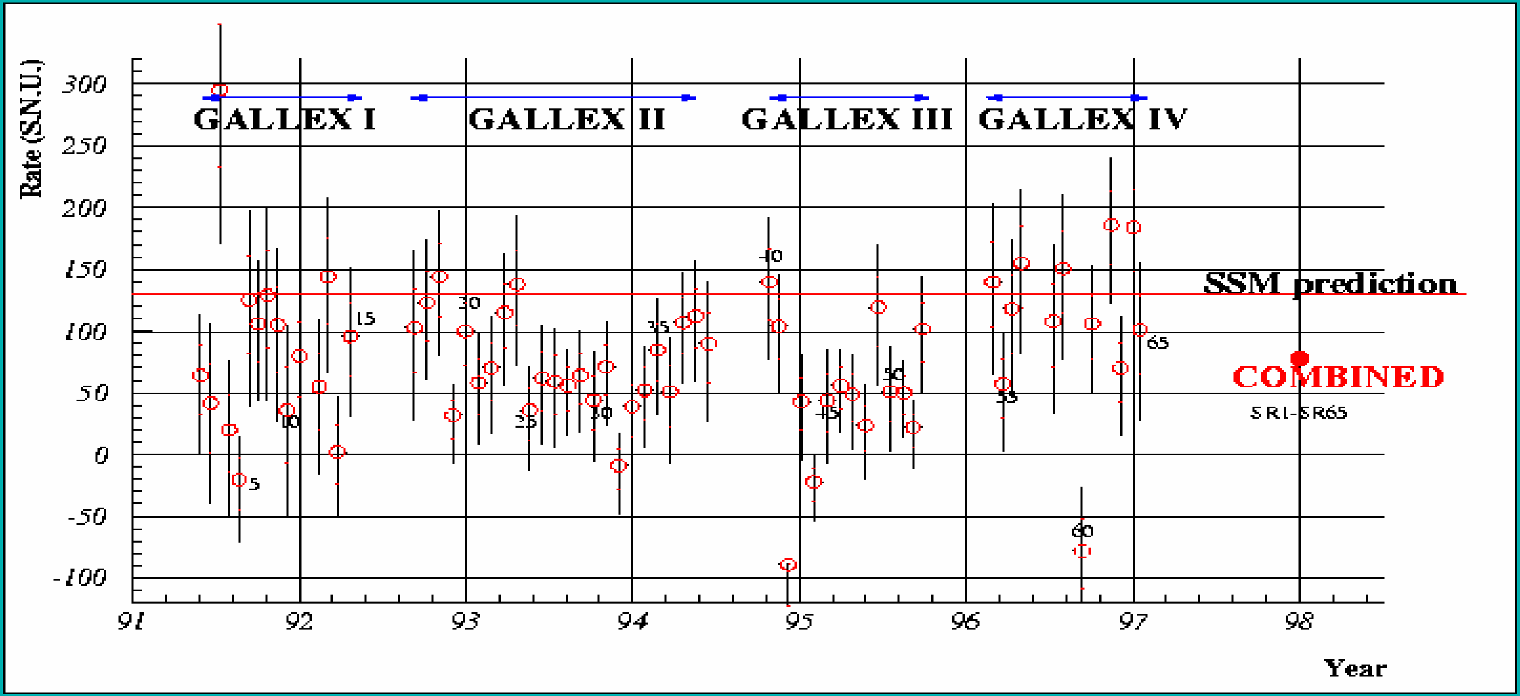
$$p + {}^{15}N \to {}^{16}O + \gamma$$
$${}^{15}O \to {}^{15}N + e^{+} + \nu_e$$

Solar Neutrino Flux



Solar Neutrino Experiments

GALLEX RESULTS



Combined Result (SR1-SR65): 77.5 +- 6.2 (stat) $^{+4.3}_{-4.7}$ (sys)

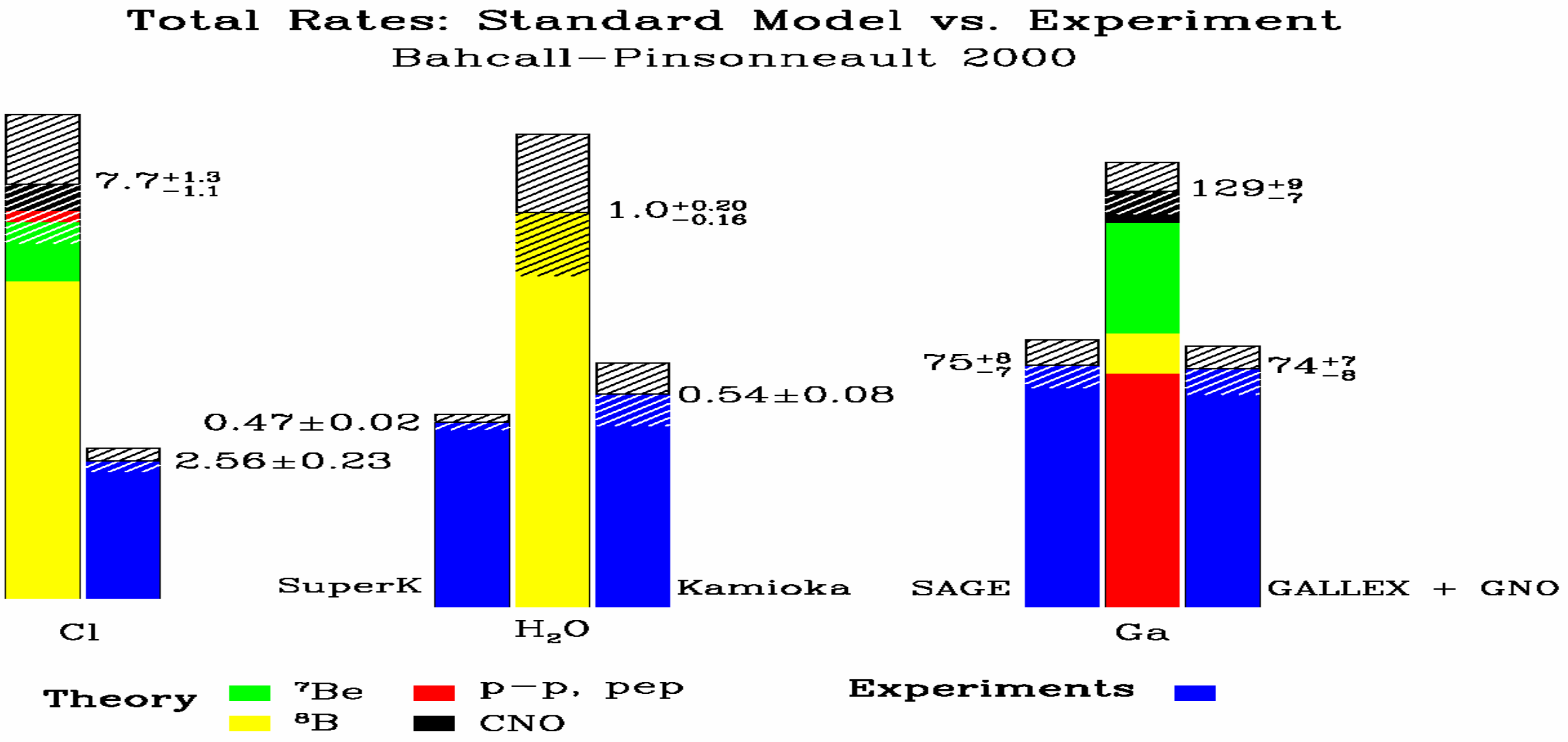
Phys.Lett. B447 (1999) 127

SSM prediction : 129 SNU

SAGE : $66.7^{+7.1+5.4}_{-6.8-5.7}$ SNU

GALLEX $77.5^{+7.6}_{-7.8}$ SNU

Solar Neutrino Experiments

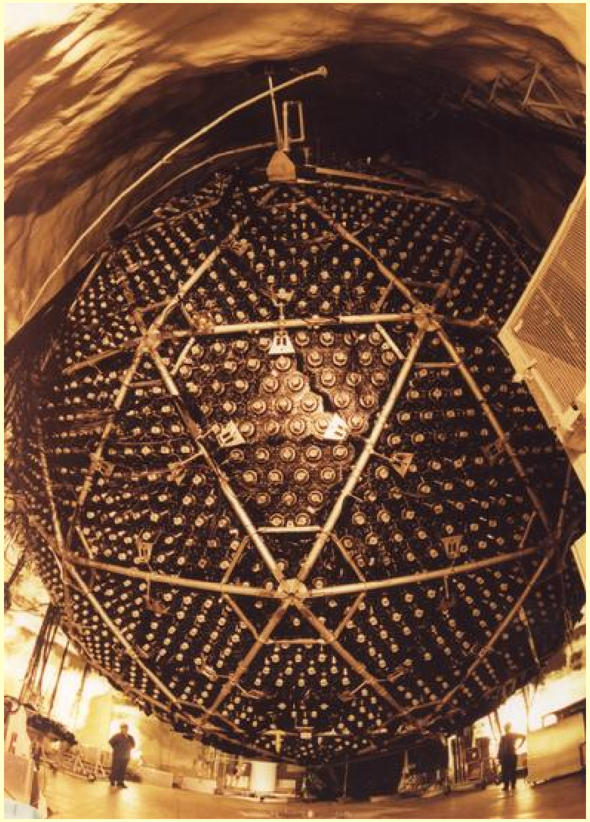


Total Rates: Standard Model vs. Experiment
Bahcall–Pinsonneault 2000

Simple algebraic equations can be set to obtain independently the different contributions to the solar neutrino flux.

SNO (Canadá)

2000



CC $\nu_e + d \Rightarrow p + p + e^-$

ES $\nu_x + e^- \Rightarrow \nu_x + e^-$

NC $\nu_x + d \Rightarrow p + n + \nu_x$

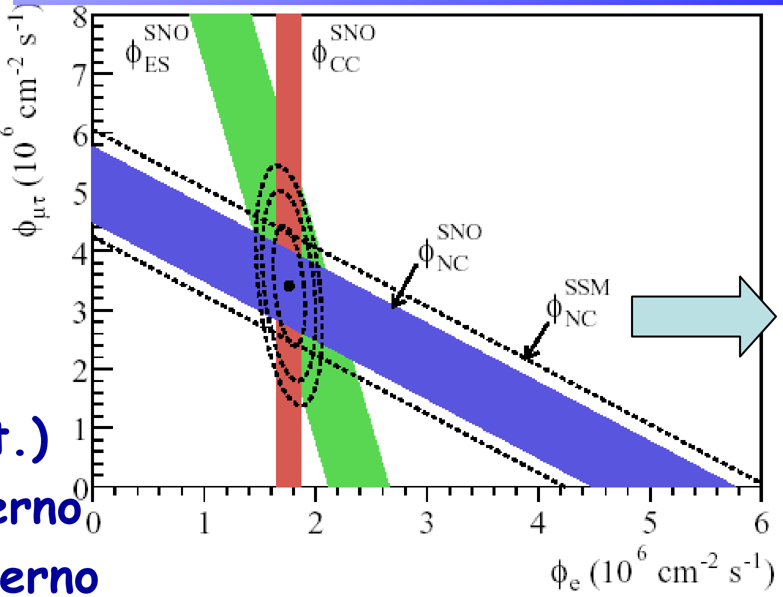
En ausencia de oscilaciones:

$$\Phi_{CC} = \Phi_{NC} = \Phi_{ES}$$

$$\Phi_{CC} = \phi_e = 1.76^{+0.06}_{-0.05}(stat)^{+0.09}_{-0.09}(sys)$$ **(x 10^6 cm^{-2} s^{-1})**

$$\Phi_{ES} = \phi_e + 0.15 \cdot \phi_{\mu\tau} = 2.39^{+0.24}_{-0.23}(stat)^{+0.12}_{-0.12}(sys)$$

$$\Phi_{NC} = \phi_e + \phi_{\mu\tau} = 5.09^{+0.44}_{-0.43}(stat)^{+0.46}_{-0.43}(sys)$$



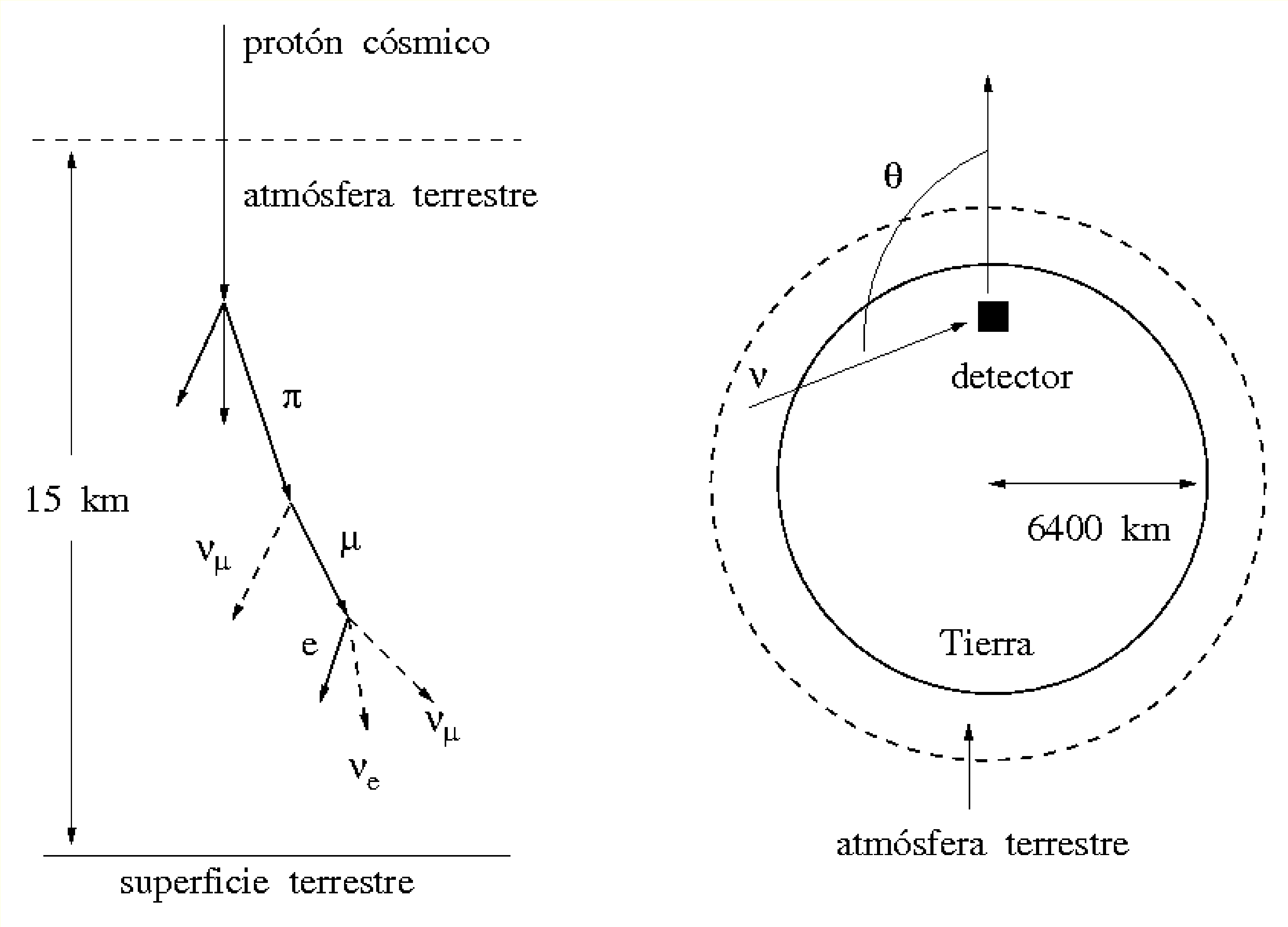
Flujo total medido igual al predicho

ν_e parecen transformarse en ν_μ, ν_τ

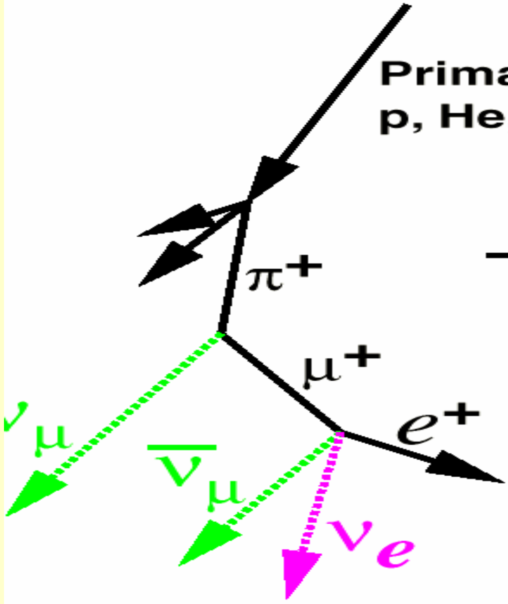
SNO: Sudbury neutrino observatory (Canadá)

- 1 KT D_2O
- 9500 PMT's
- 12 m diámetro (bola ext.)
- 1.7 KT H_2O tanque interno
- 5.4 KT H_2O tanque externo

Atmospheric Neutrinos



ATMOSPHERIC NEUTRINOS



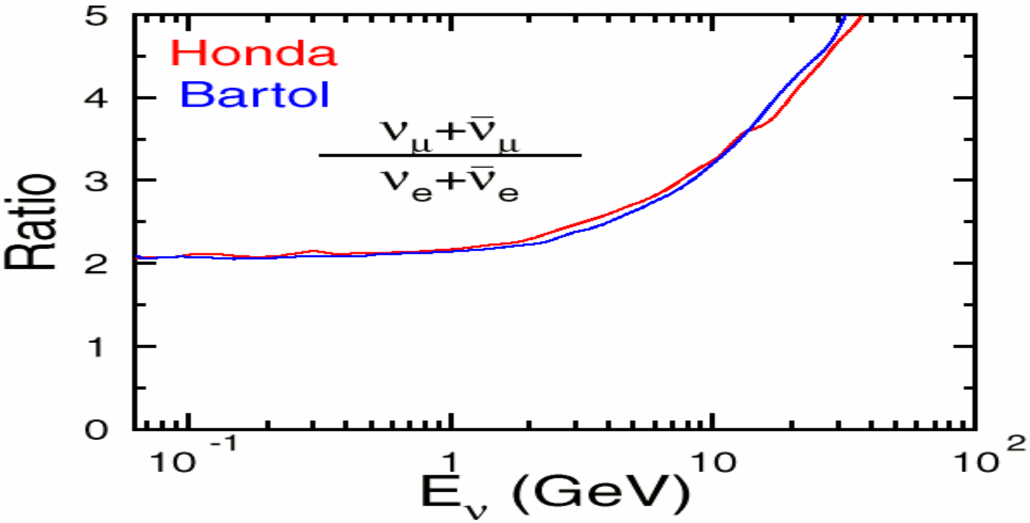
Primary cosmic ray
p, He, . . .

$$\frac{\nu_\mu + \bar{\nu}_\mu}{\nu_e + \bar{\nu}_e} \cong 2$$

ν Flux ~20% uncertain

↓

5% uncertain

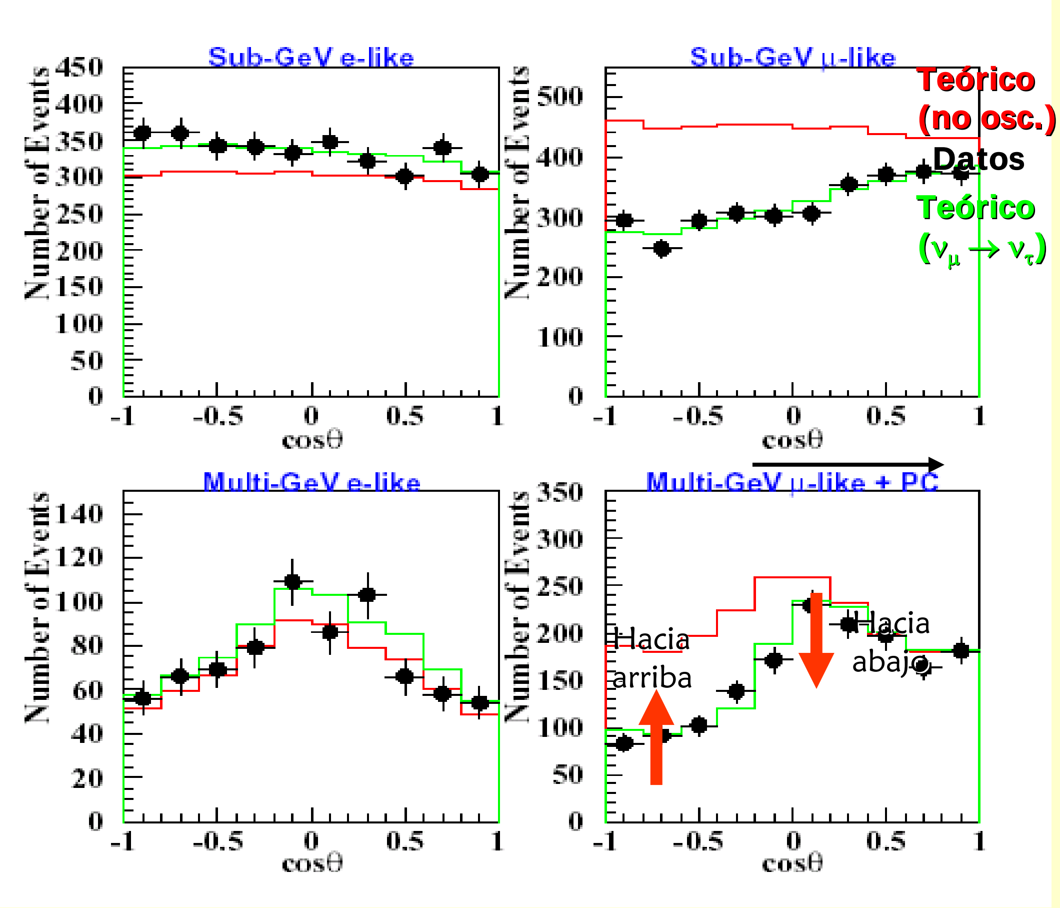


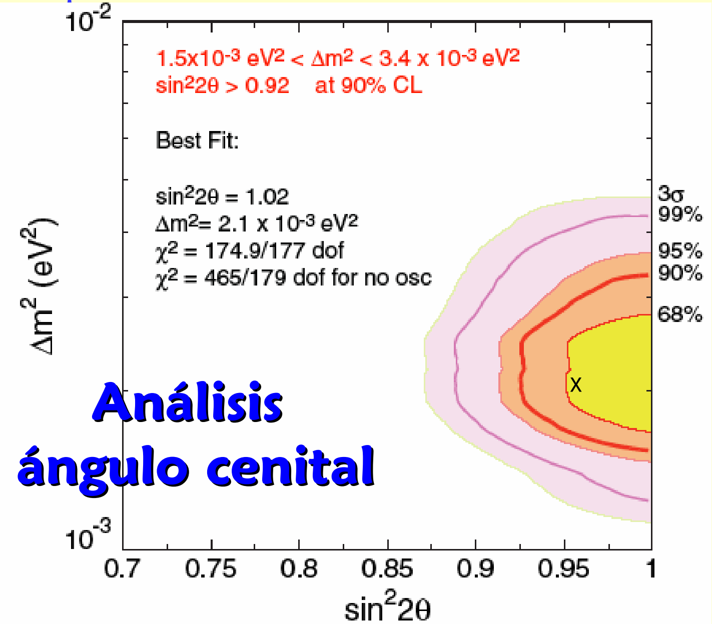
$$\mathbf{R} = \frac{\left(\dfrac{\nu_\mu + \bar{\nu}_\mu}{\nu_e + \bar{\nu}_e}\right)_{\mathbf{DATA}}}{\left(\dfrac{\nu_\mu + \bar{\nu}_\mu}{\nu_e + \bar{\nu}_e}\right)_{\mathbf{M.C.}}}$$

1998

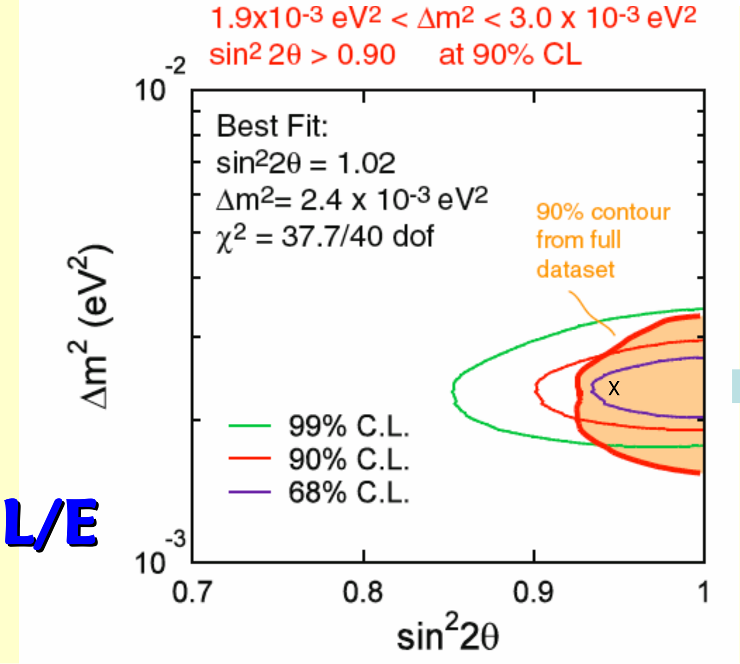
Oscilaciones $\nu_\mu \rightarrow \nu_\tau$

SK observa un déficit de ν_μ





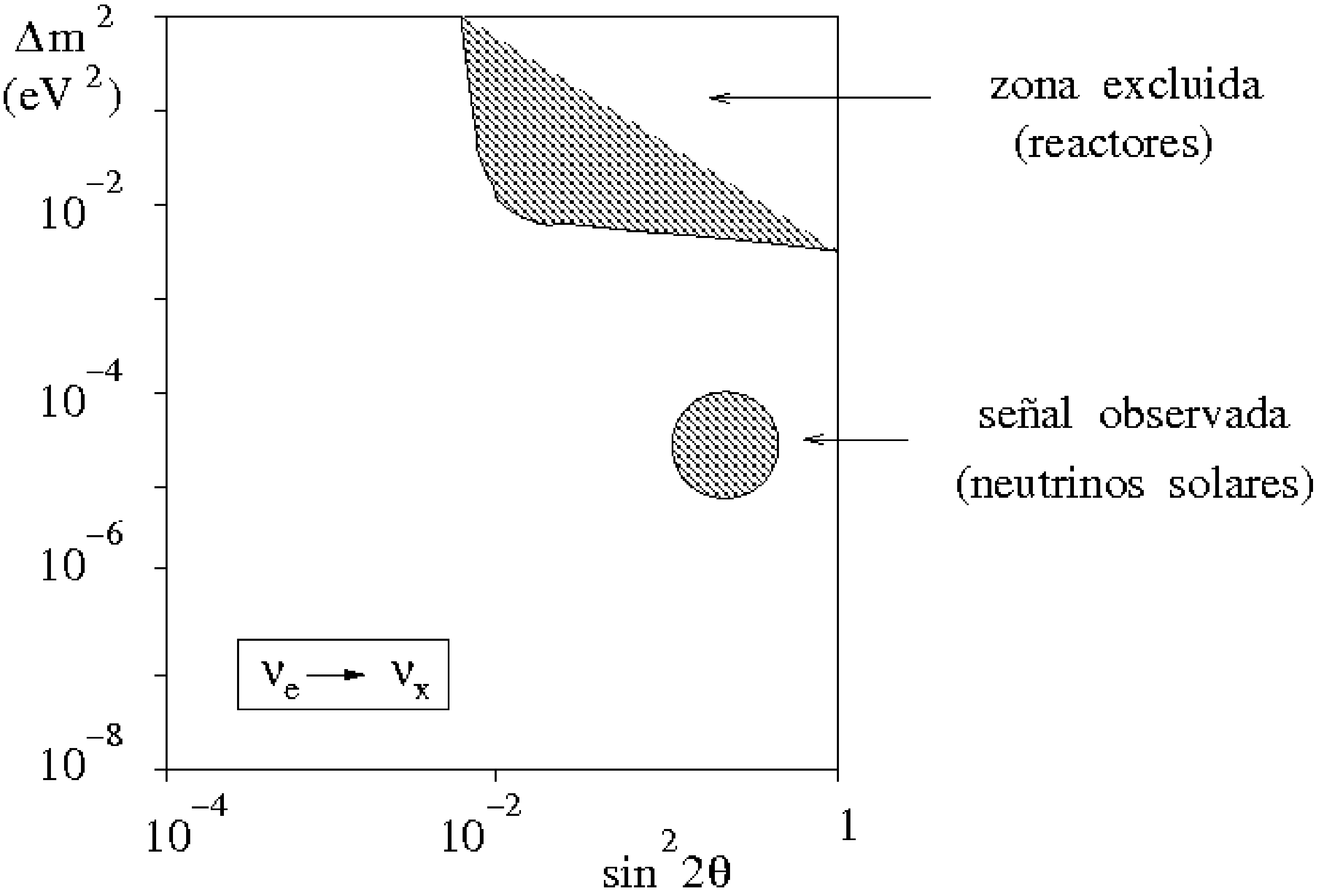
Análisis ángulo cenital



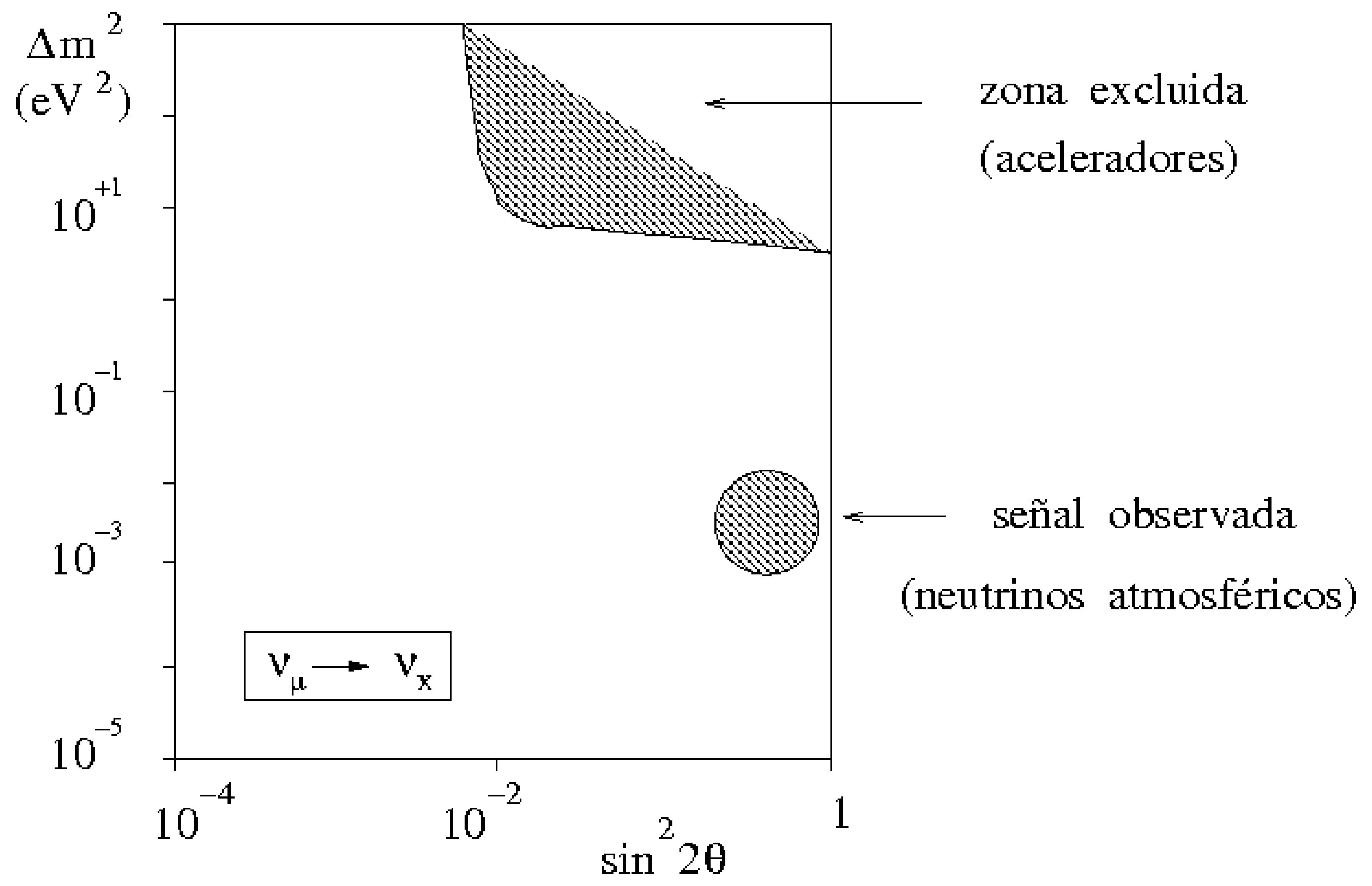
Análisis L/E

Máxima oscilación

Oscilaciones (ν-solares)

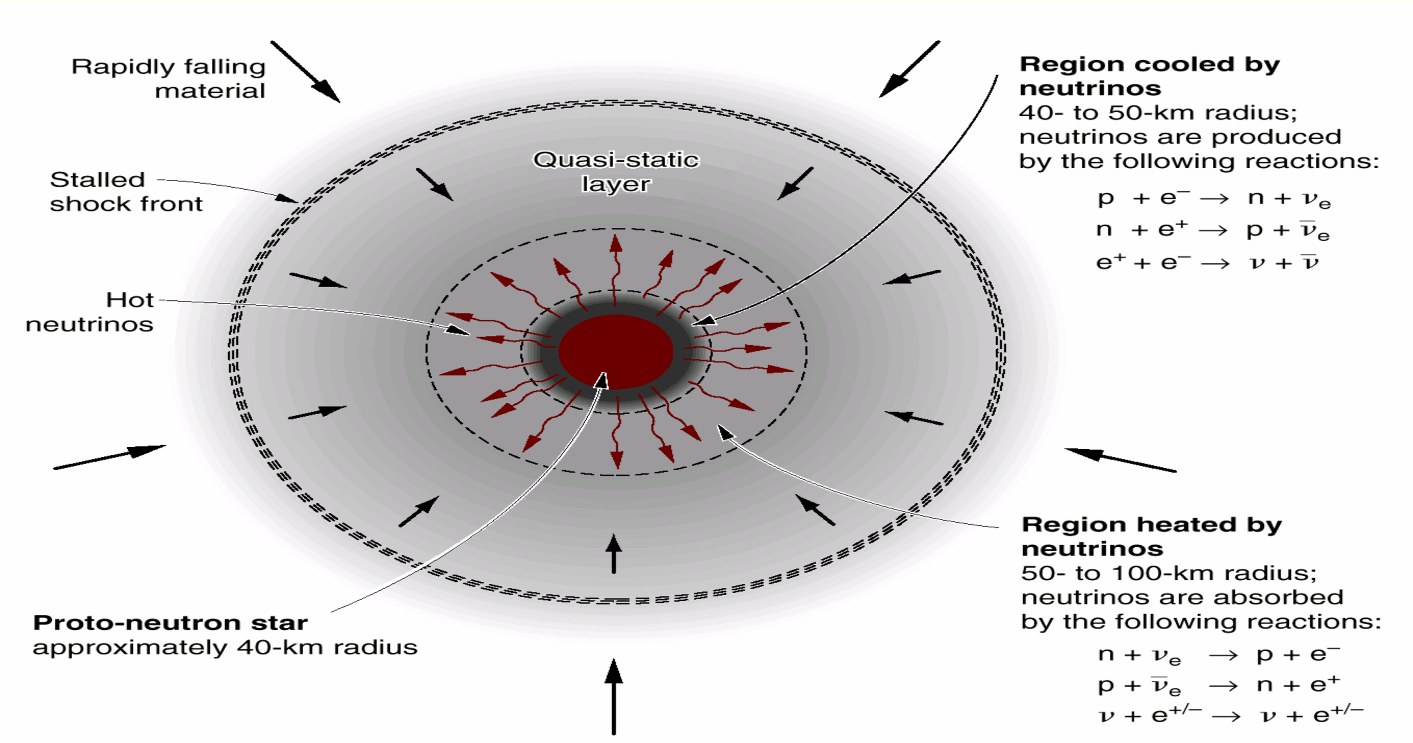


Oscilaciones (ν-atmosféricos)



Supernova Neutrinos

Type-II supernovae



Region cooled by neutrinos
40- to 50-km radius;
neutrinos are produced
by the following reactions:

$$p + e^- \rightarrow n + \nu_e$$
$$n + e^+ \rightarrow p + \overline{\nu}_e$$
$$e^+ + e^- \rightarrow \nu + \overline{\nu}$$

Region heated by neutrinos
50- to 100-km radius;
neutrinos are absorbed
by the following reactions:

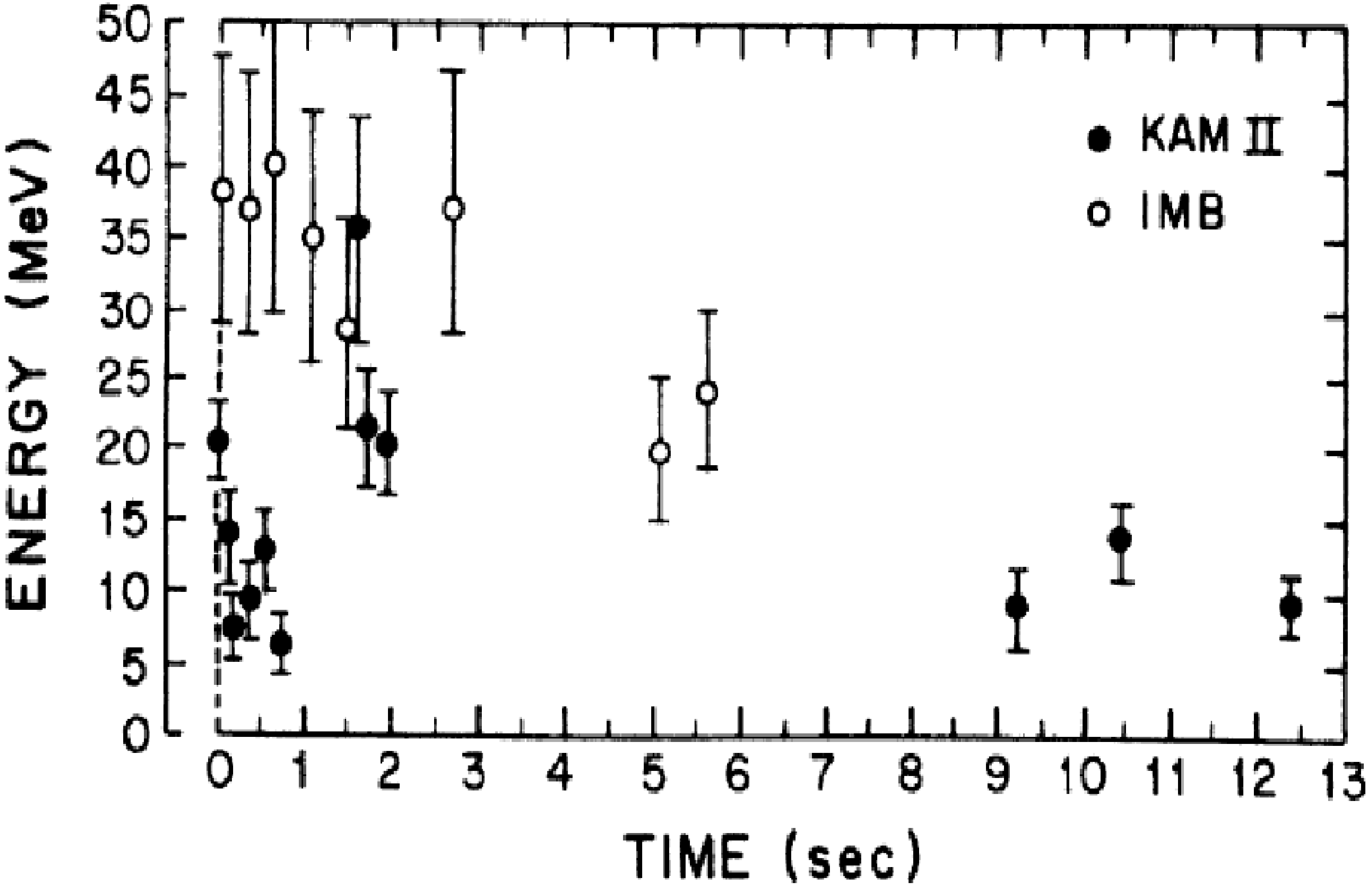
$$n + \nu_e \rightarrow p + e^-$$
$$p + \overline{\nu}_e \rightarrow n + e^+$$
$$\nu + e^{+/-} \rightarrow \nu + e^{+/-}$$

Proto-neutron star
approximately 40-km radius

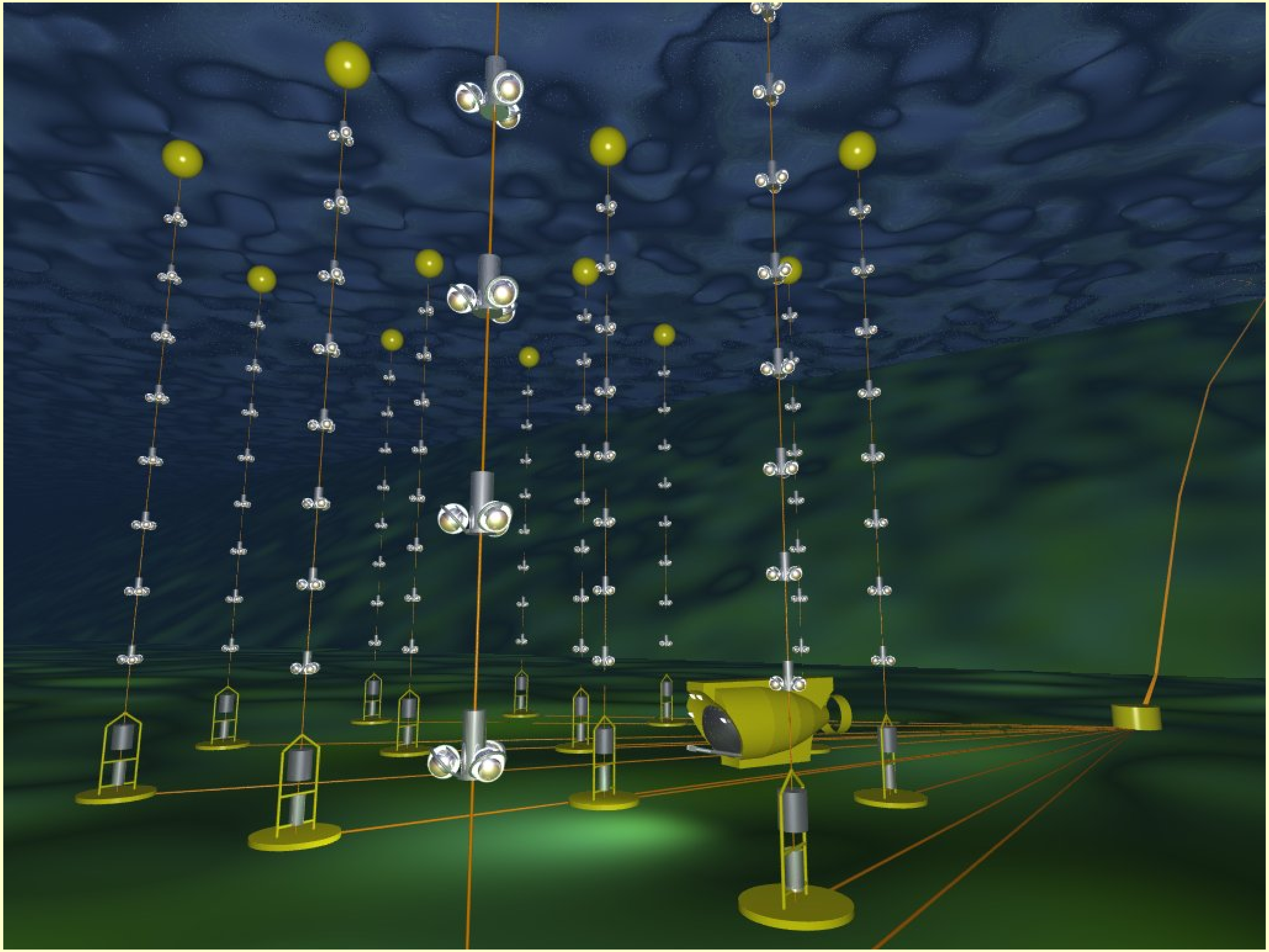
Neutrinos are responsible for the core cooling and, ultimately, for the supernova explosion.

Actually detected in 1987 by the Kamiokande-II and IMB detectors from Supernova 1987A.

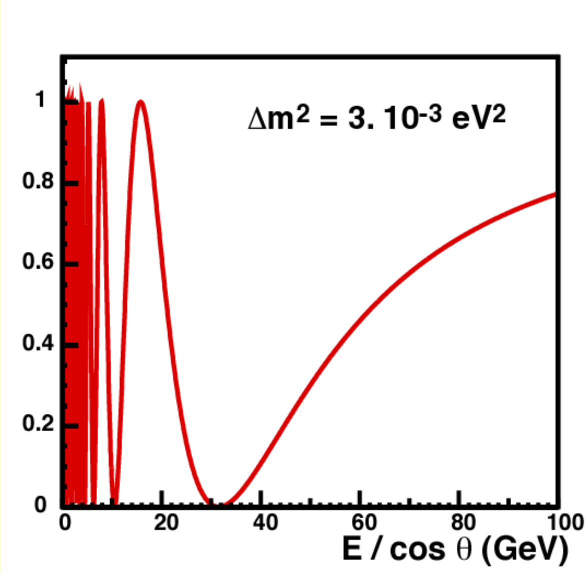
SN1987 A neutrinos

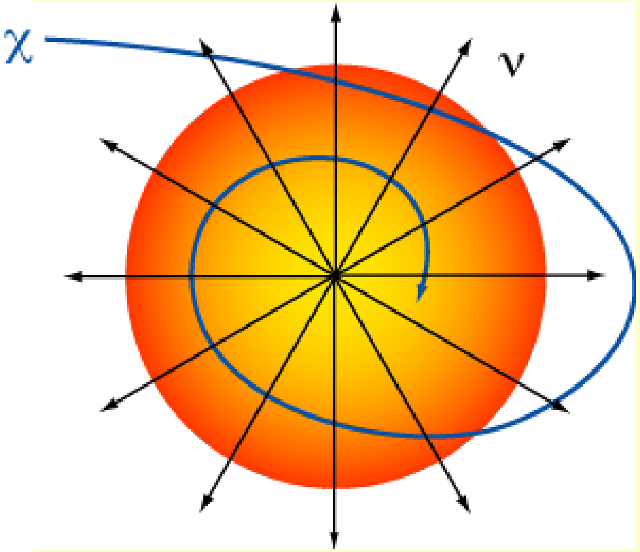


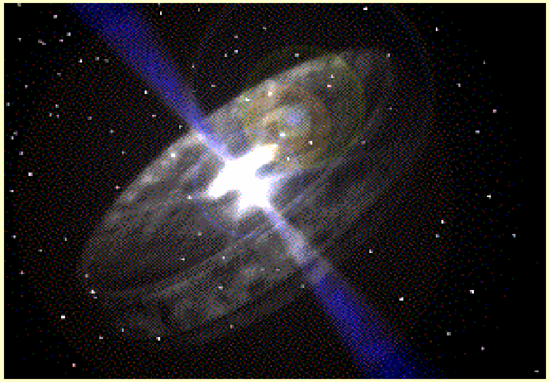
ANTARES   0.1 km^2 detector



Antares: Scientific scope







Low Energy	Medium Energy	High Energy
10 GeV < E_ν < 100 GeV	10 GeV < E_ν < 1 TeV	E_ν > 1 TeV

ν oscillations

(Observation of first oscillation minimum)

Neutralino search

Self-annihilation at center of Earth, Sun, Galaxy

$\chi\chi \rightarrow X \rightarrow \nu$

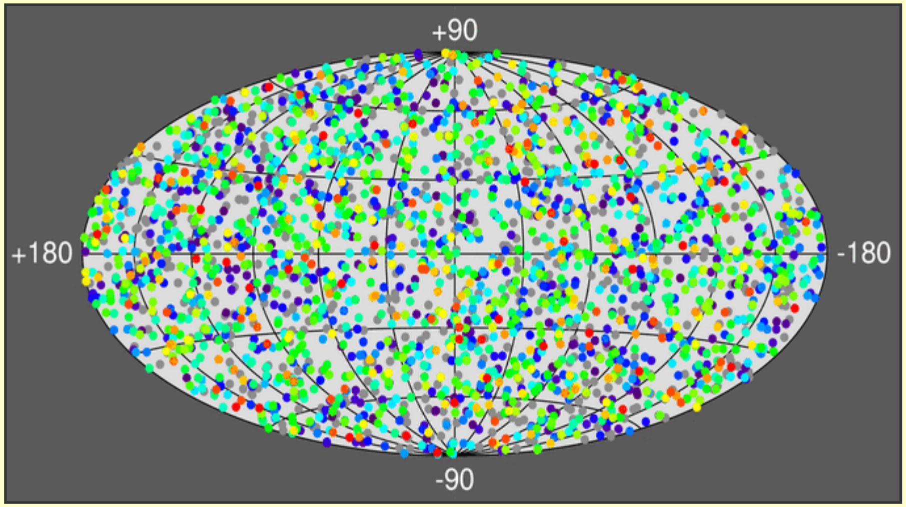
ν from (extra-) galactic sources

SN remnants, AGN, GRB, ...

Pointlike sources

Wide range of predictions of neutrino fluxes for pointlike sources

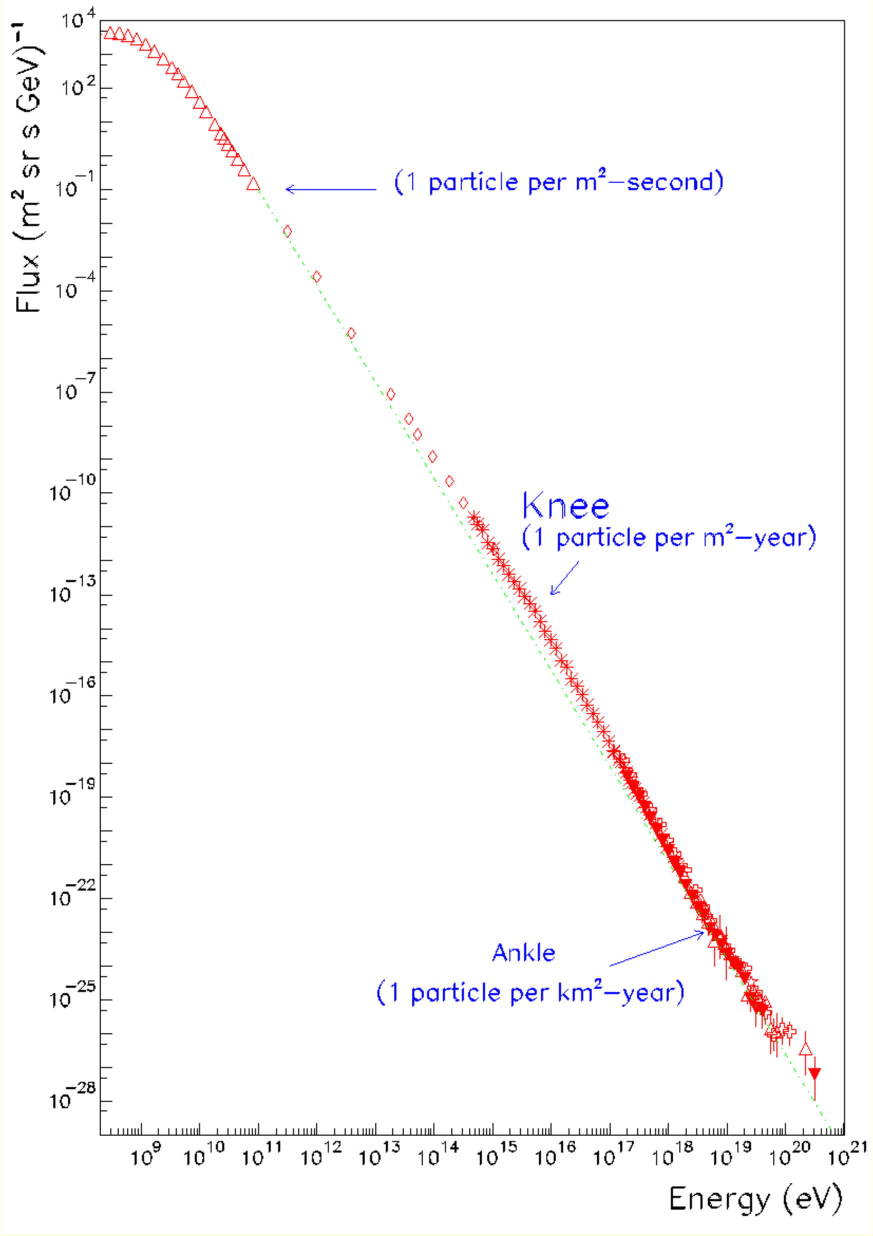
EGRET source	# of sources	ANTARES 43ºN	AMANDA S Pole
All	271	89%	43%
AGN	94	86%	52%
Pulsars	5	100%	40%
Unidentified:			
Gal. Plane	55	93%	36%
Off Gal. Plane	116	90%	40%
Observ.		source dep.	100%



GRB's

ANTARES will keep all its data within ±100 secs of a GRB warning signal.

5) Cosmic Rays Spectrum

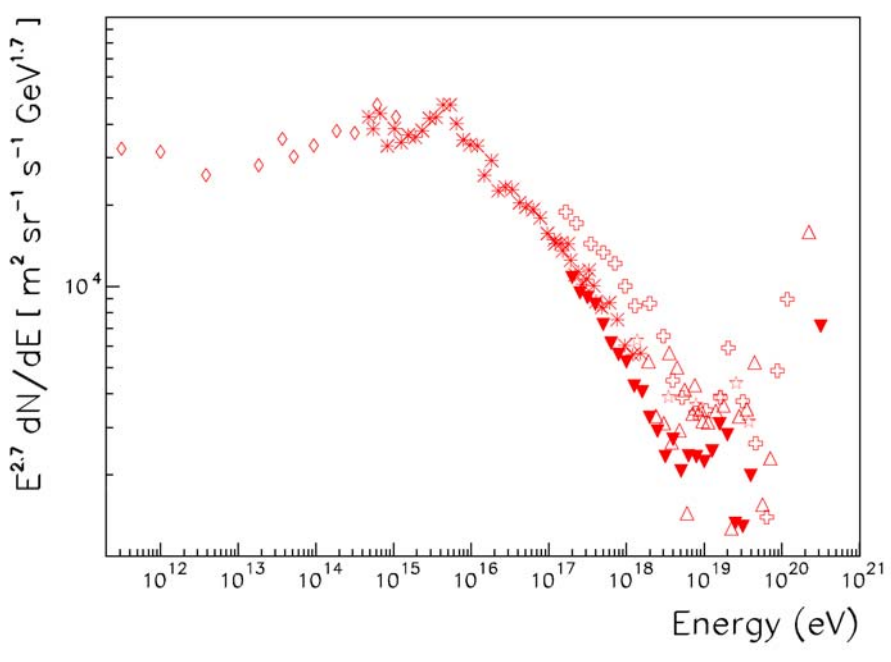


- >12 orders in Energy
- >30 orders in Flux
- Power Law $\Phi = \Phi_0 E^{-\gamma}$

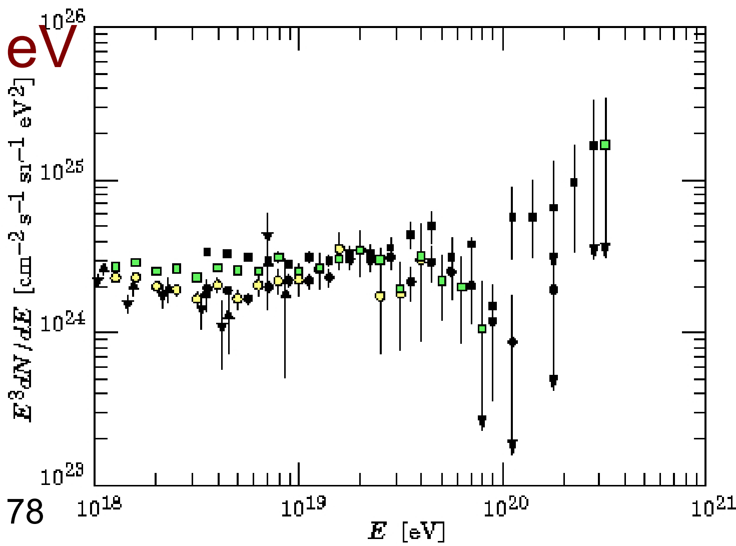
$E<10^{15}$ $\gamma\sim2.7$ ***Galactic***

$10^{15}<E<10^{19}$ $\gamma\sim3.0$

$E>10^{19}$ $\gamma\sim2.8$ ***Extragalactic***



Cosmic Ray Spectrum - Ankle



- Ultra High Energy Cosmic Rays E~10^{20} eV
  - Spectral index back to ~-2.8
  - Macroscopic energy (50 J)
  - AGN most likely sources
    - No one found <100 Mpc
- GZK cutoff Greisen, Phys. Rev. Lett 16 (1966) 748
  Zatsepin,Kuzmin Sov. Phys. JETP Lett. 4 (1966) 78
  - Universe becomes opaque because of interaction with CMB photons

$$\gamma_{2.7K} + p \to \Delta^+ \to p + \pi^0$$
$$\to n + \pi^+$$

$$\lambda_i = \frac{1}{\rho_{CMB}\,\sigma} \sim 10^{25}\,\mathrm{cm} \sim 5-10\,\mathrm{Mpc}$$

$$\rho_{CMB} = 400\,\mathrm{cm}^{-3}$$

$$\sigma = 2\times10^{-28}\,\mathrm{cm}^{-2}$$

$$E_{th} = m_\pi \frac{M_p + m_\pi/2}{2q} = \frac{4.26}{y}\times10^{20}\,\mathrm{eV}$$

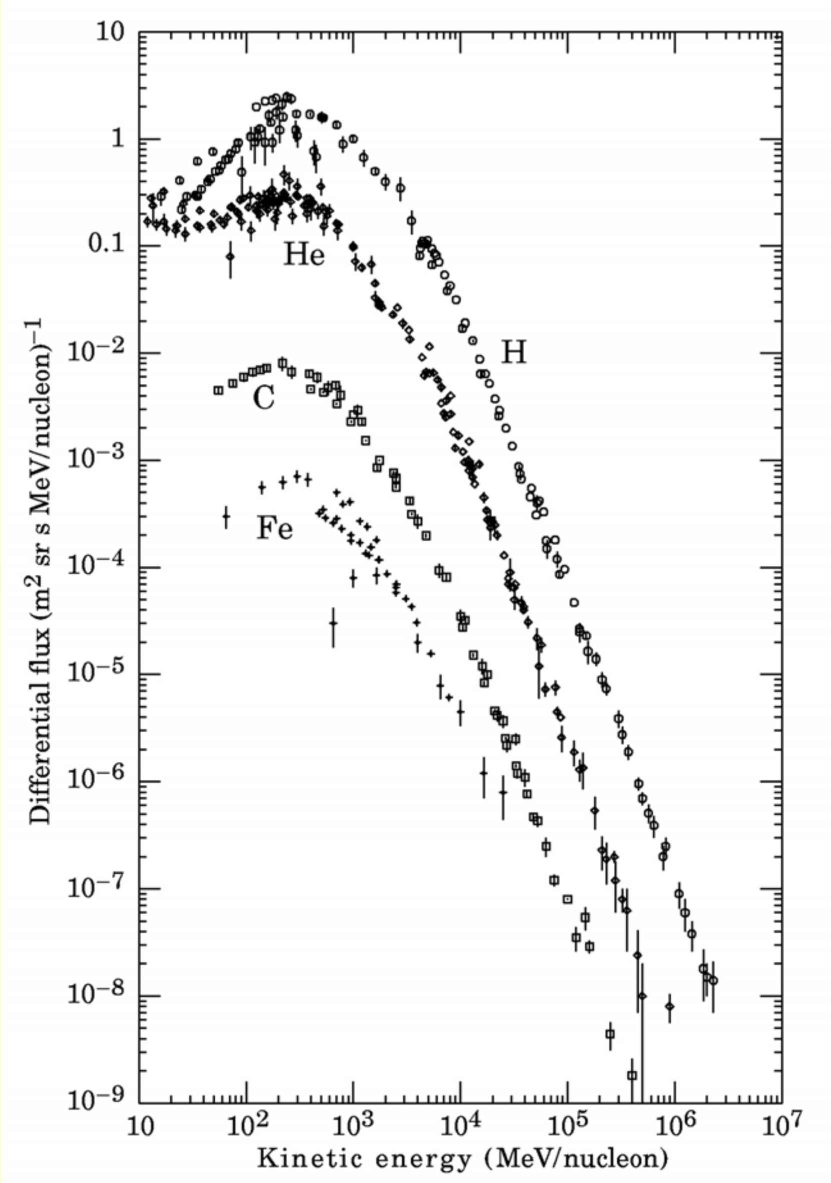
$$qc \quad ykT$$

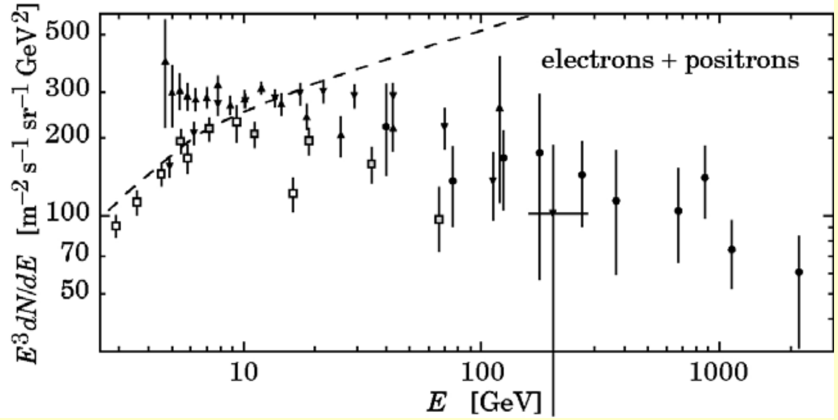
10 Mpc is comparable to size of galaxy cluster

No cutoff implies sources of UHECR are nearby

Cosmic Ray Composition

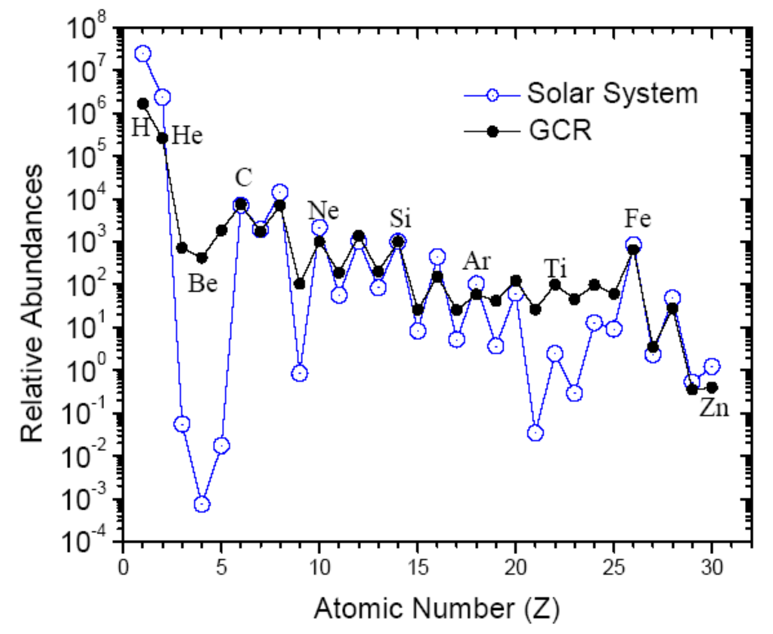
- 98% nuclei
  - 87% protons
  - 12% He
  - 1% heavier elements
- All elements present up to Uranium
- Atoms reach heliosphere fully ionized
- 2% electrons and positrons
  - Steeper spectra at top of the atmosphe
  - $e^+/(e^++e^-)$ ~0.2 (<1 GeV) ~0.1(2 GeV)





Cosmic Ray Composition

- CR chemical composition similar to Solar system abundances
  - Li,Be,B,F enriched
  - Sc,Ti,V,Cr,Mn enriched
- Apart from Li, these ions are not primordial nor produced in stars
  - Produced by spallation reactions in interstellar medium
- Composition points to stellar origin
  - Odd products more frequent in thermonuclear reactions in stars
  - C,N,O and Fe peaks compatible with thermonuclear chains in stars
- Li,Be,B energy spectra steeper than C or O
  - At higher energies less fragmentation



ACE News#83 http://www.srl.caltech.edu/ACE/ACENew

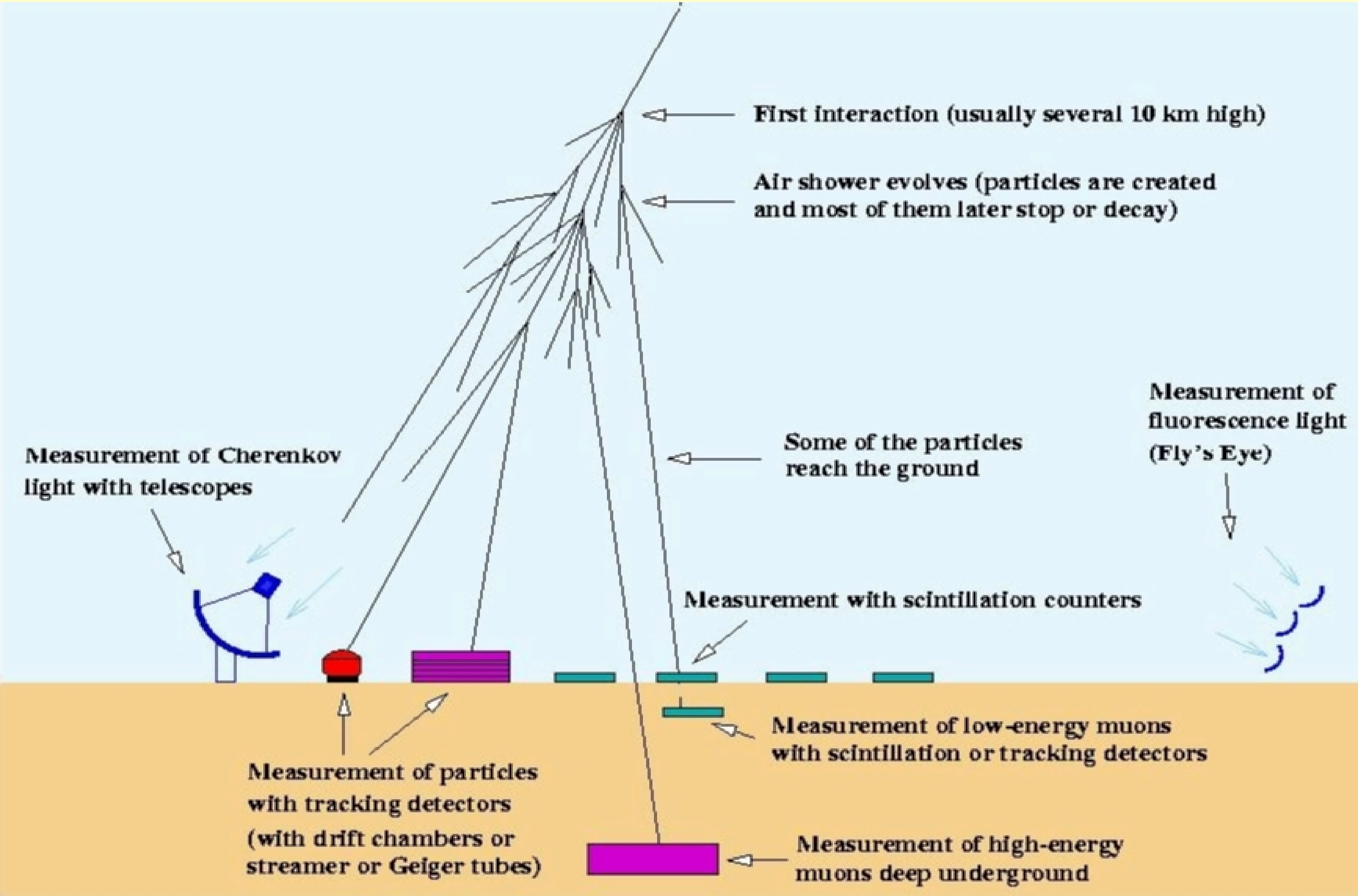
GCR.
Data taken at Solar minimum Aug 1997-Apr 1998

H-He	BESS	170 MeV/nuc
^{3}Li-^{28}Ni	CRIS	170 MeV/nuc
^{29}Cu-^{30}Zn	CRIS	150-550 MeV/nuc

K.Lodders Ap.J., 591 (2003) 1220

Solar system.
Photospheric spectroscopy
CI Chondritic meteorites

Exp. techniques in HE cosmic rays



First interaction (usually several 10 km high)

Air shower evolves (particles are created and most of them later stop or decay)

Some of the particles reach the ground

Measurement of Cherenkov light with telescopes

Measurement of fluorescence light (Fly's Eye)

Measurement with scintillation counters

Measurement of low-energy muons with scintillation or tracking detectors

Measurement of particles with tracking detectors

(with drift chambers or streamer or Geiger tubes)

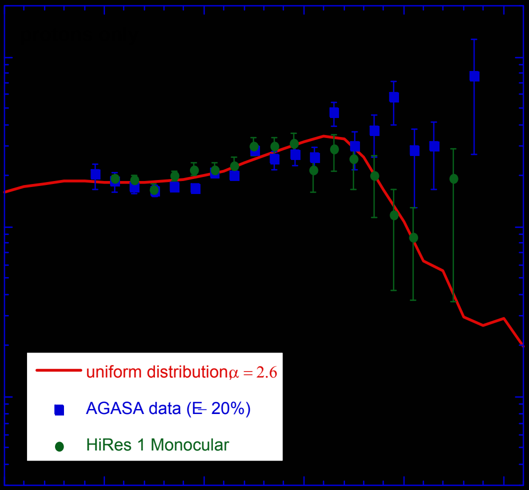
Measurement of high-energy muons deep underground

Pierre Auger Observatory

How UHECR are accelerated?

- Why are they not attenuated by CMB?
- What is their composition?
- Are they decay products of new particles?

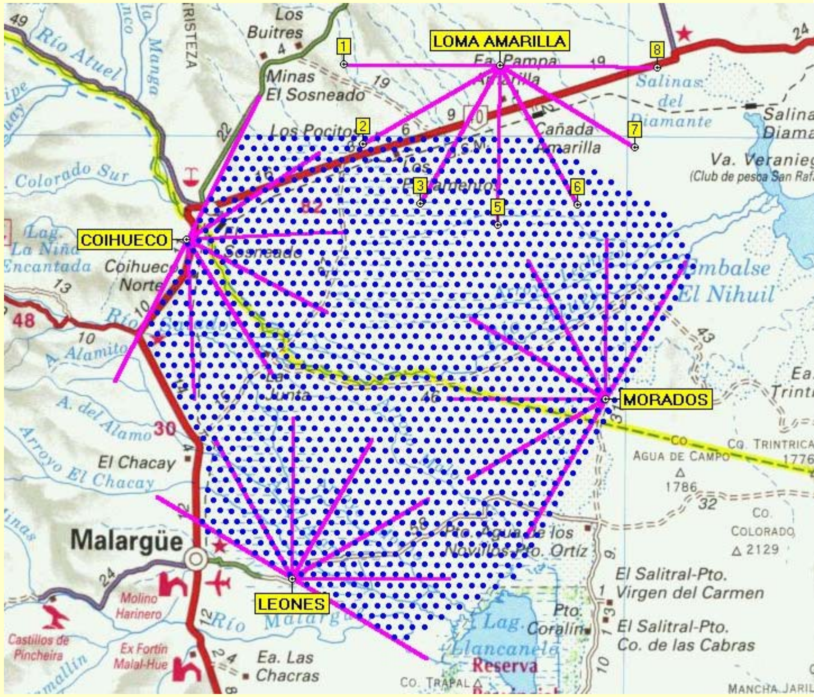
The riddle



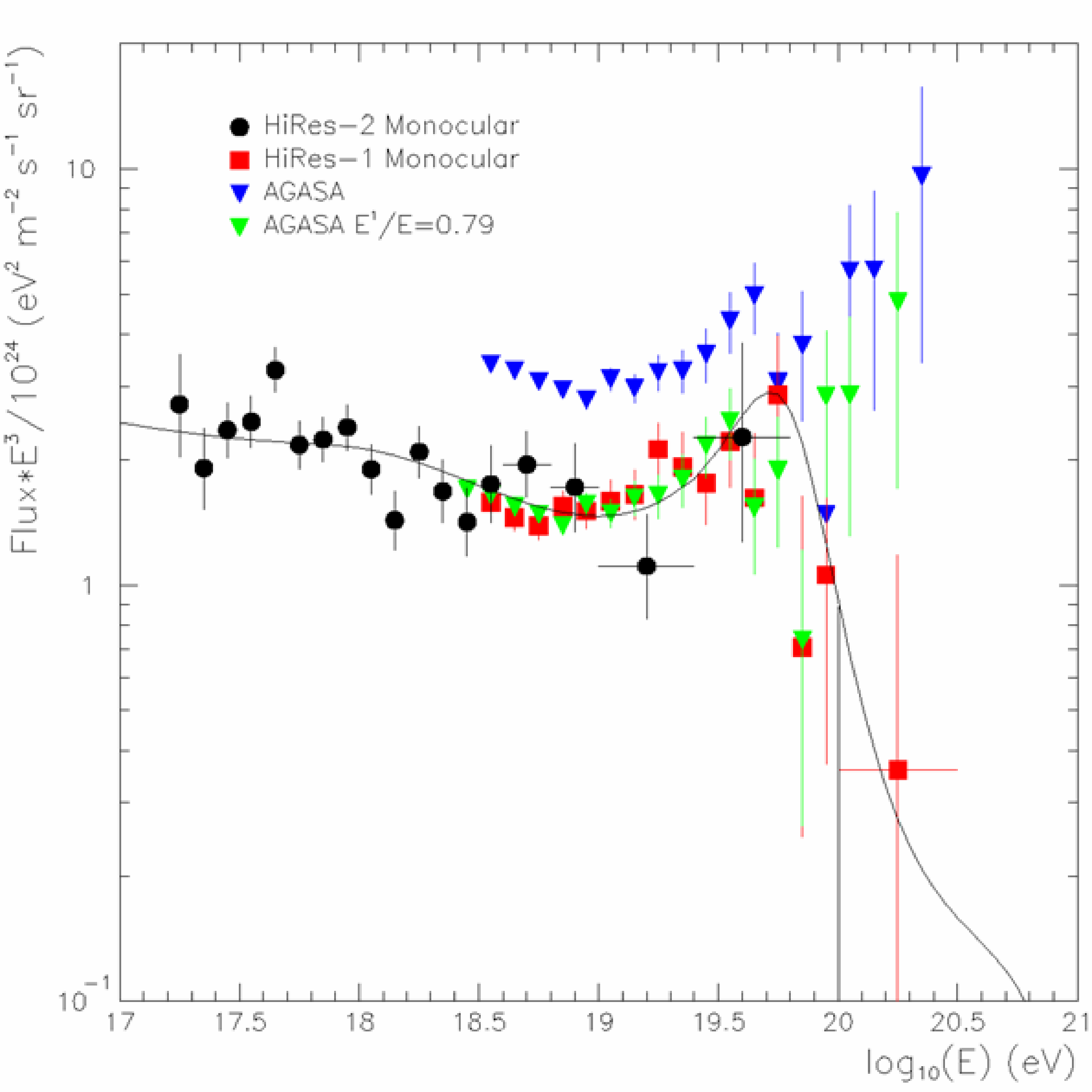
Detection of ground particles by an array of 1600 Cherenkov water tanks with spacing of 1.5 km, (total surface of 3000 km^2)
Detection of fluorescence light induced by the shower in the atmosphere.
Currently 2/3 deployed, end 2007.
First conclusive results mid-2007

Pierre Auger Observatory

- Apparatus
  - –Total surface 3000 km^2
  - –1600 round Water-Cerenkov detectors
    - $11.3\text{m}^2 \times 1.2\text{m}$ in a 1.5 km array
  - –24 fluorescence detectors in 4 stations
    - 12 m^2 mirrors
    - 440 PM
  - –Combines strengths of both techniques
- Physics
  - –UHECR spectra and composition E>10^{19} eV
    - Independent measurement techniques allow control of systematic
    - Reliable energy and angle measurement
    - Primary mass measured in complementary



HE Cosmic Rays

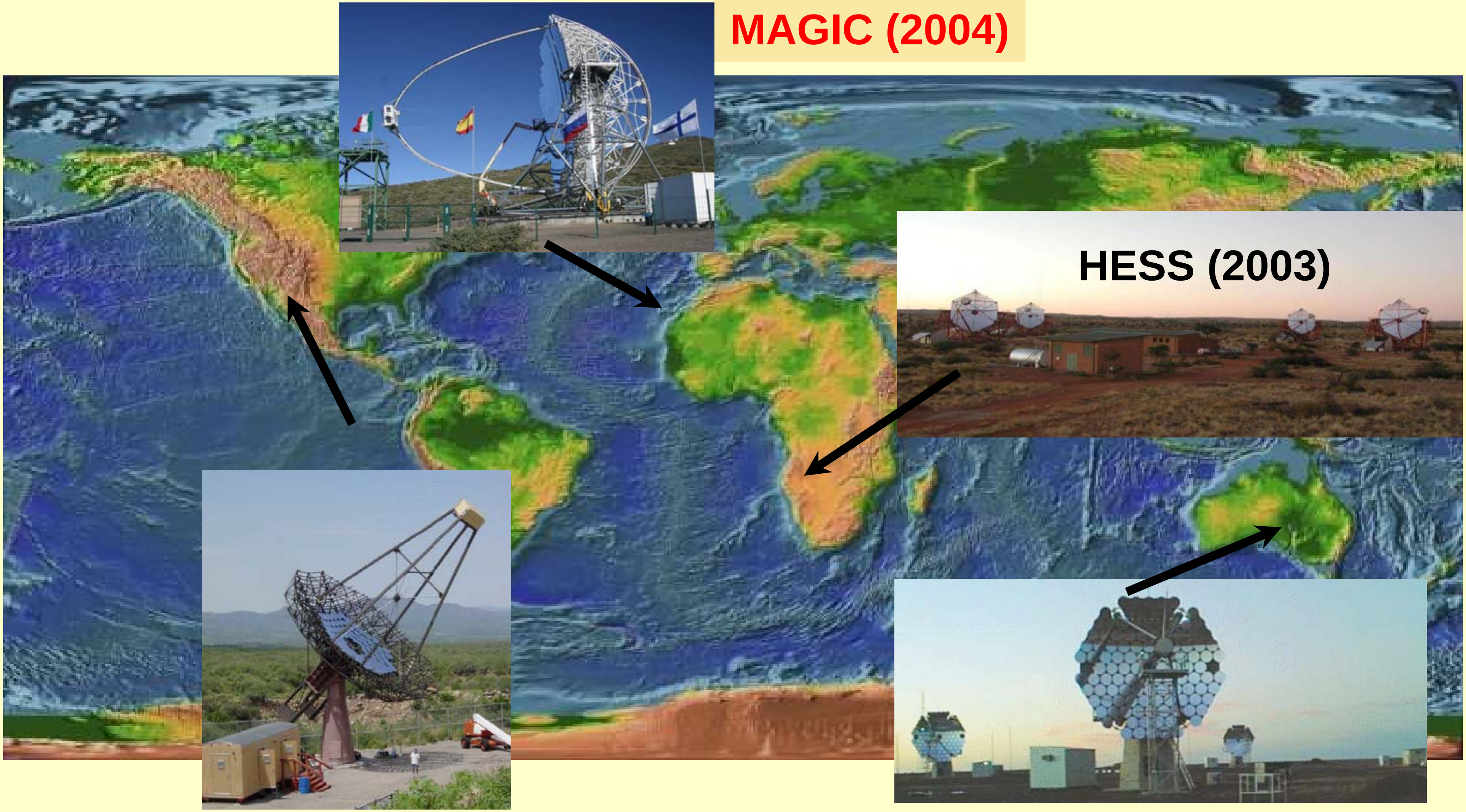


HiRes

AGASA

AUGER

Second generation γ telescopes



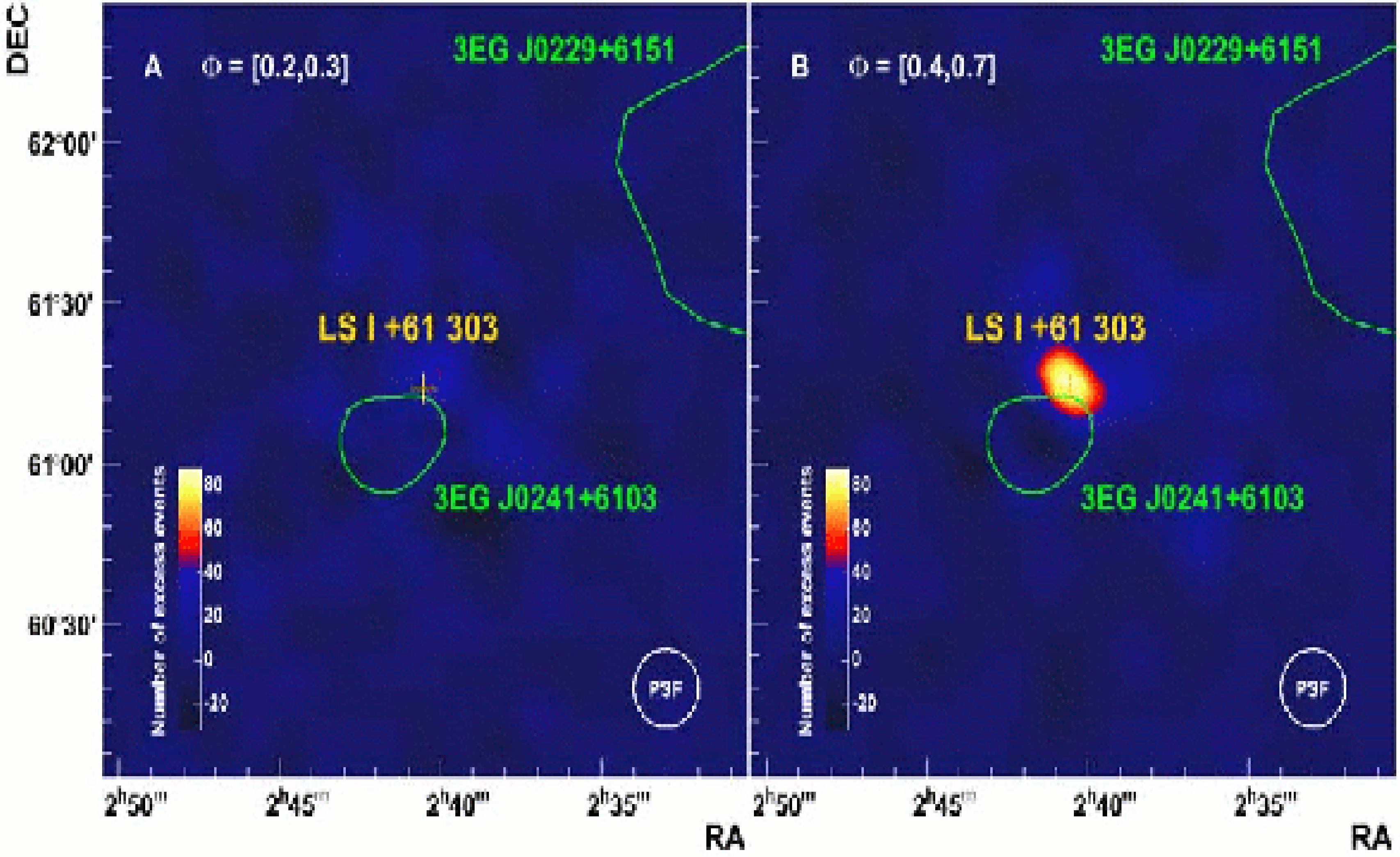
MAGIC (2004)

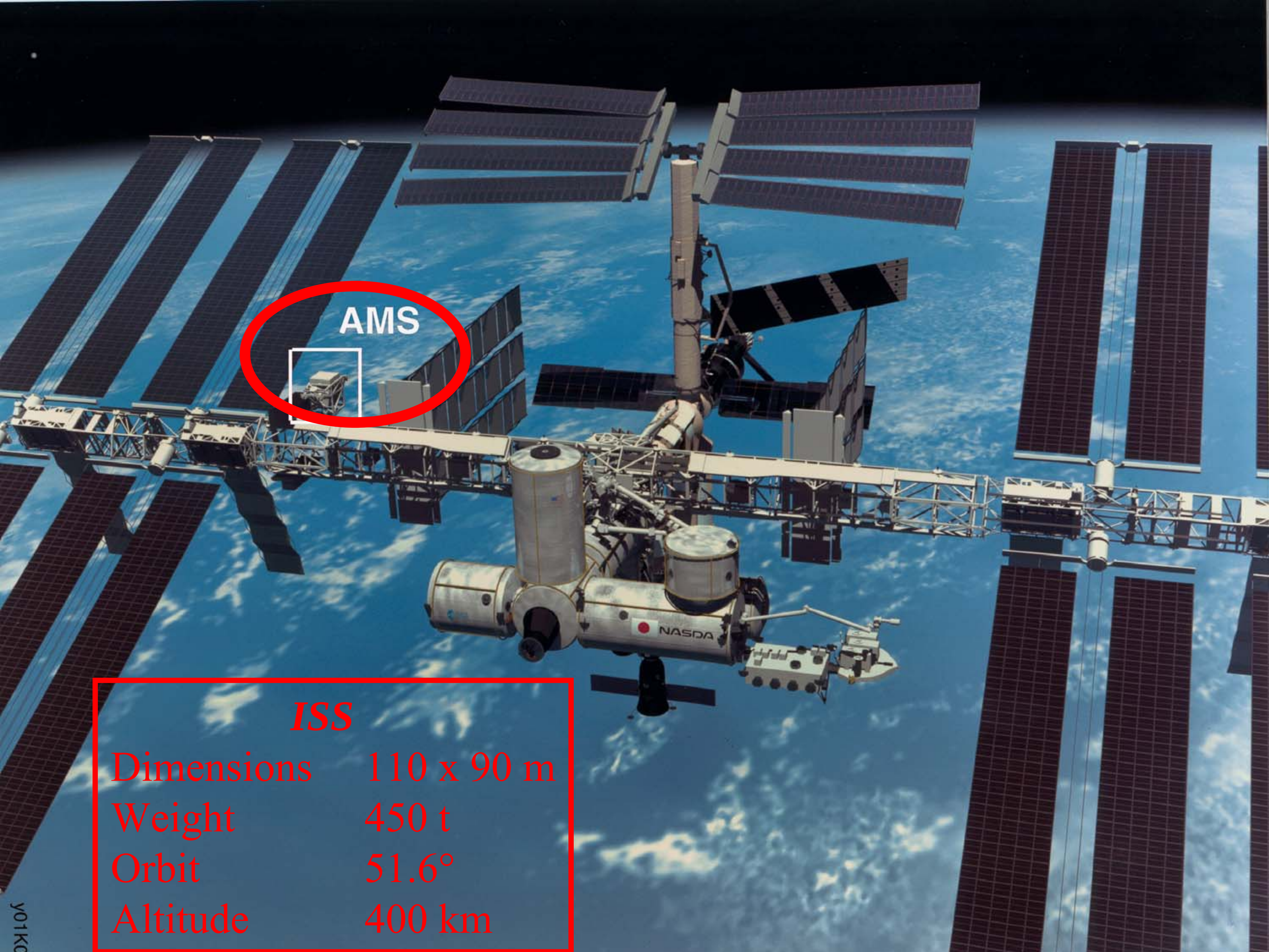
HESS (2003)

VERITAS (2006)

CANGAROO-III (2004)

Microquasar (MAGIC)

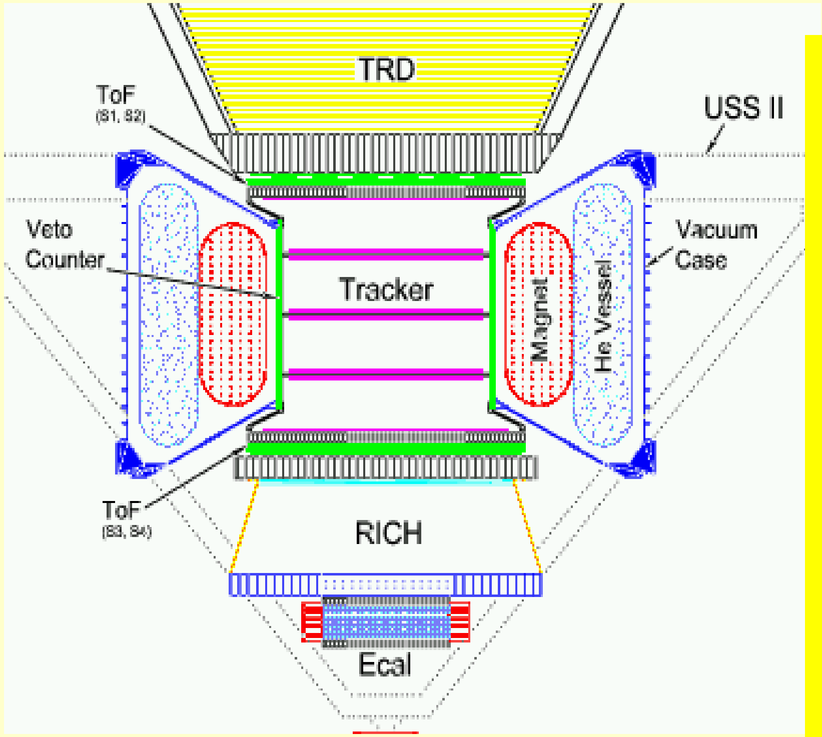




ISS

Dimensions	110 x 90 m
Weight	450 t
Orbit	51.6°
Altitude	400 km

AMS-02 Spectrometer



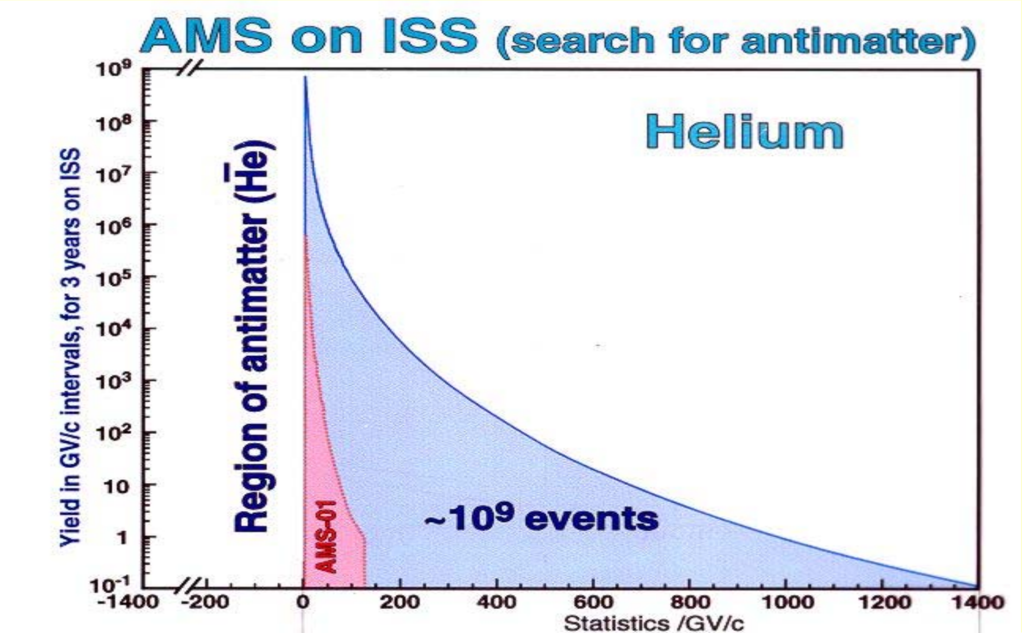
- Superconducting Magnet
- Silicon Tracker
- Scintillator System
- Transition Radiation Detector
- Ring Imaging Cerenkov
- Electromagnetic Calorimeter

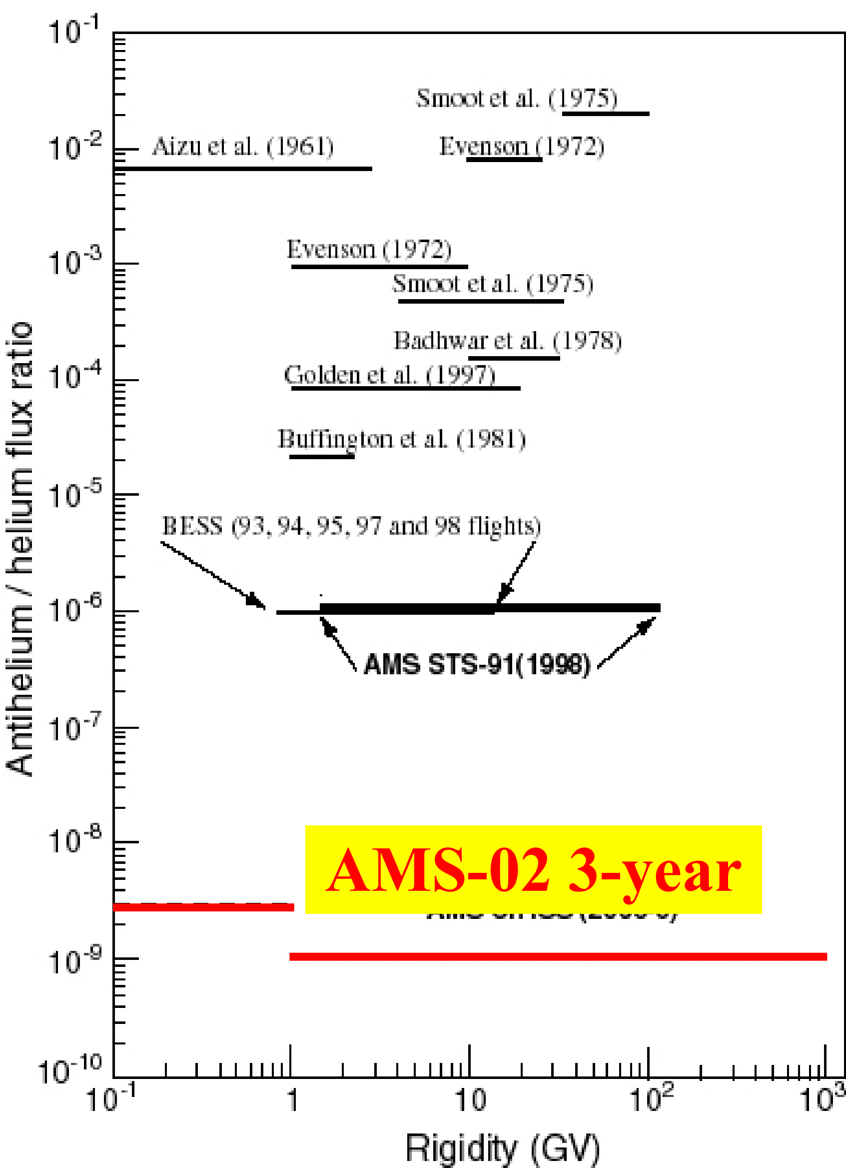
Weight	6 t
Power	2 kW

Acceptance: 0.45 m^2sr

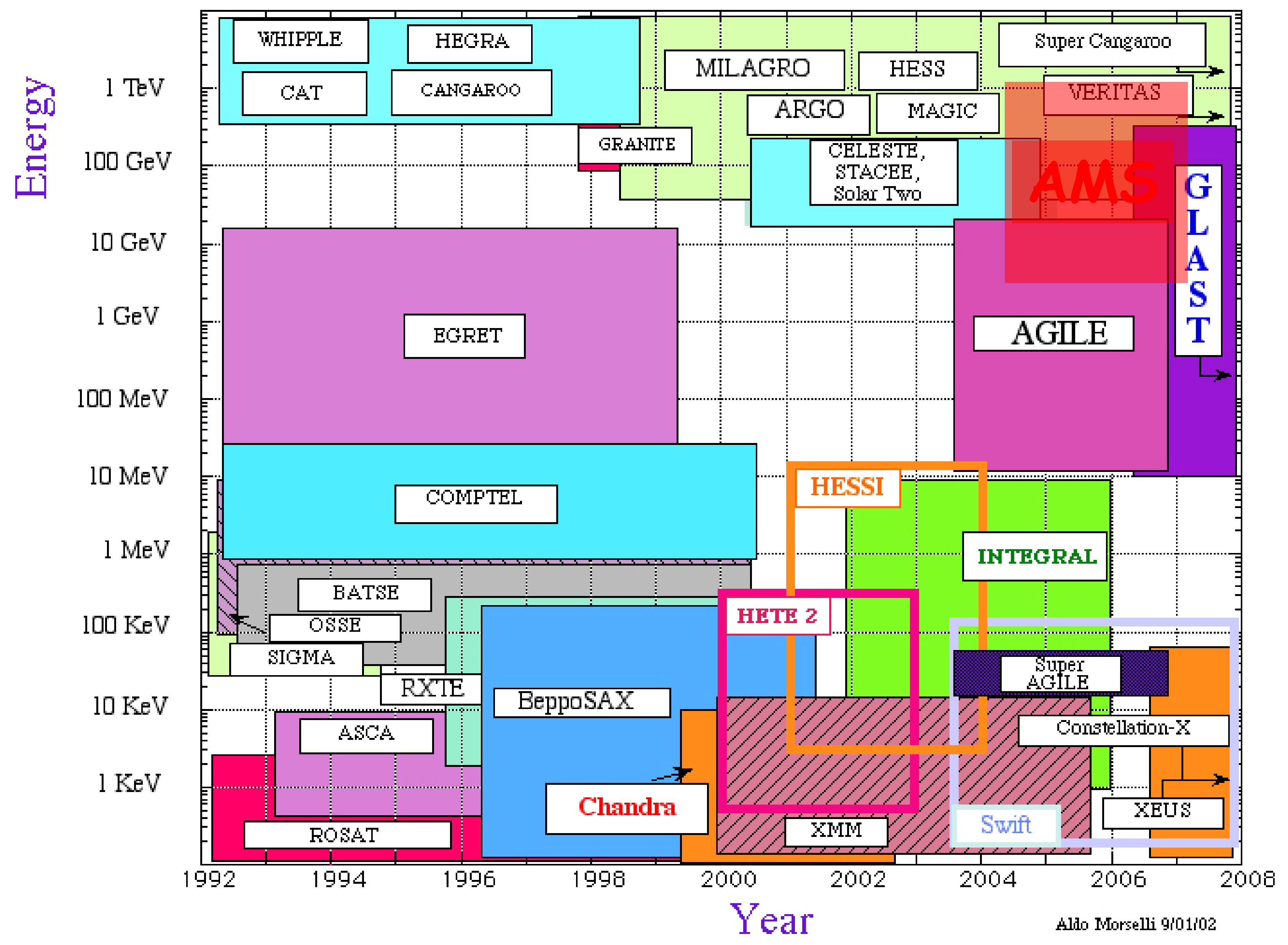
AMS-02 Antimatter Sensitivity

In 3 years AMS will collect 10^9 He with E $\lesssim$ 1 TeV





AMS/γ Sky Survey



Aldo Morselli 9/01/02

AMS-02 (2009?)

- Understand the spectra and composition of cosmic ray particles,
- Are there cosmic antiparticles?
- Are there dark matter decay products?
- In order to search for new physics one must first understand the CR in our galaxy

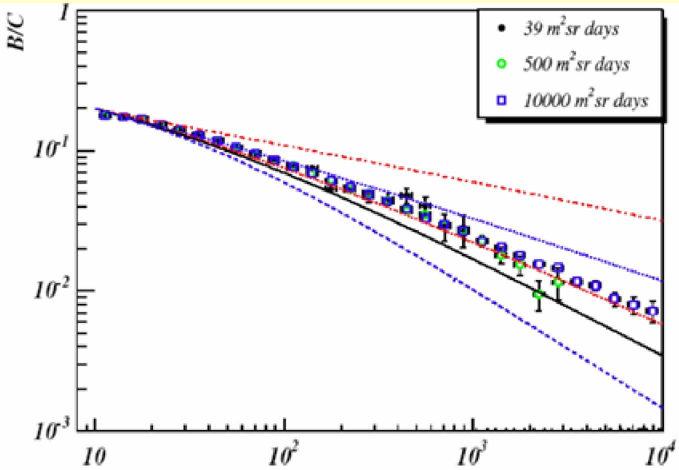
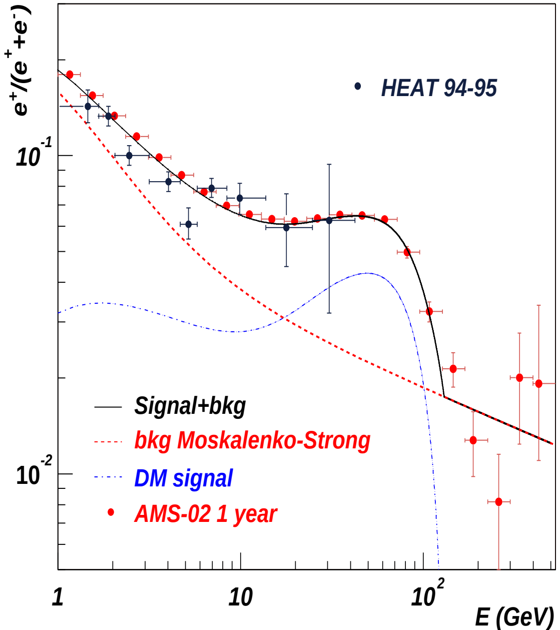
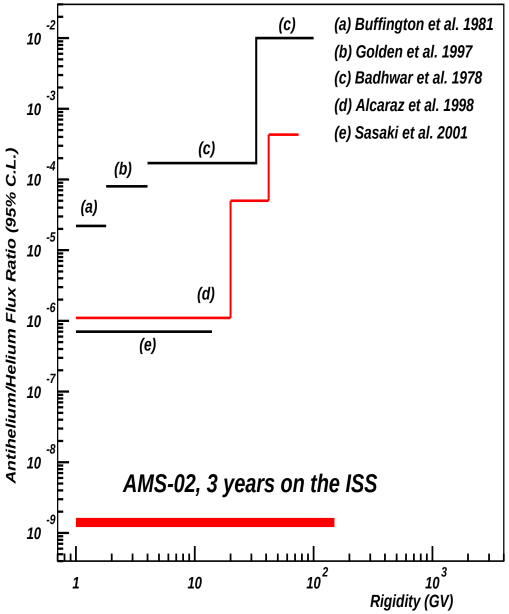


Figure 1 - Rapport B/C en fonction de l'énergie en GeV/nucleon. Les courbes correspondent aux différentes valeurs compatibles avec les données à basse énergie de l'indice spectral du coefficient de diffusion, de haut en bas δ=0.3–0.46–0.6–0.7–0.85. Les symboles sont le résultat d'une simulation basée sur les statistiques de comptage attendues (voir texte).

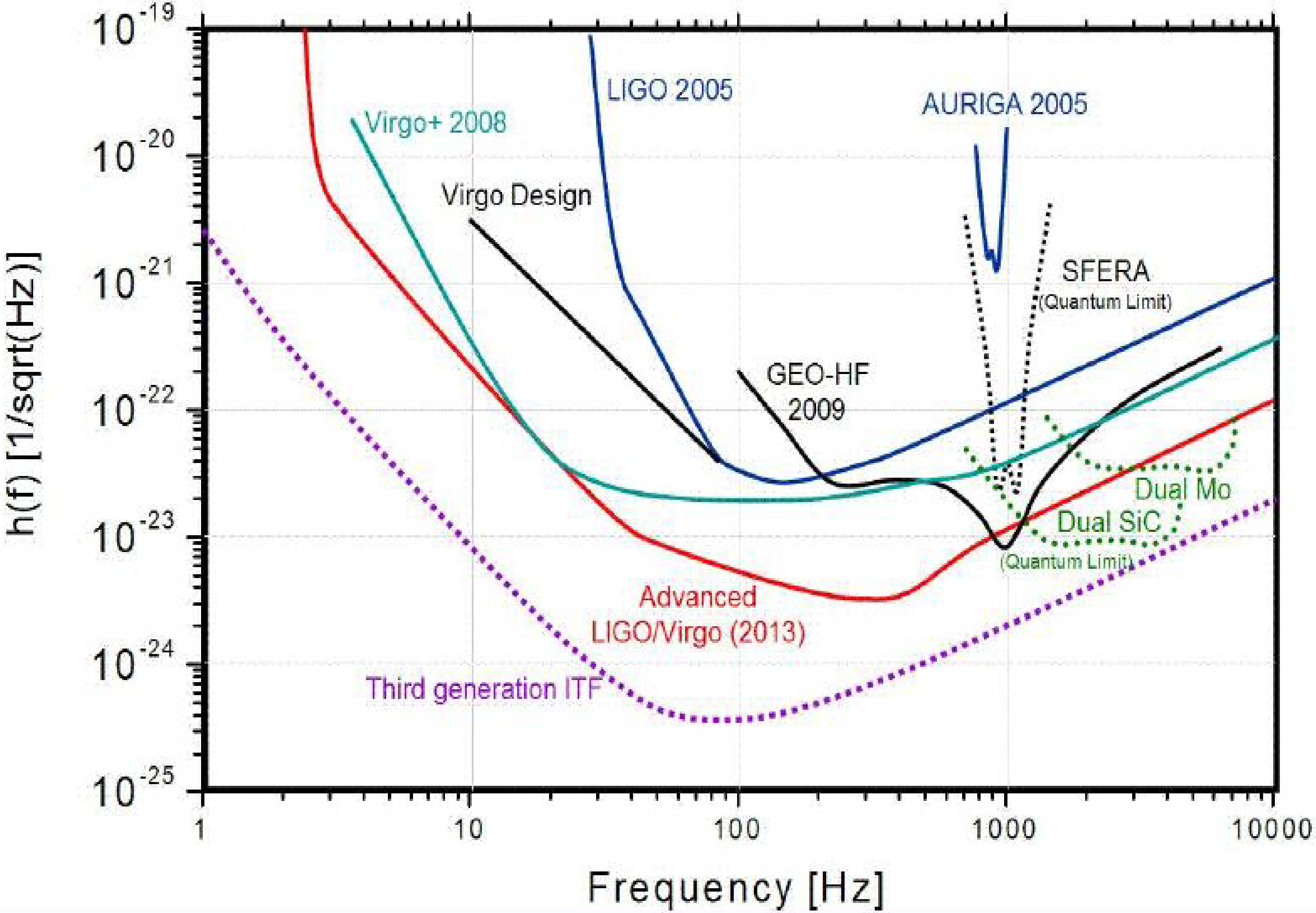




6) What is the nature of Gravity?
Can we detect gravitational waves?
What will they tell us about violent cosmic processes

- Now: GEO-600, VIRGO (+ upgrades)
- > 2010:Adv VIRGO (within budget), Adv LIGO
- > 2014 LISA in space
- >2015: Large underground interferometer
  - Understand mergers, pulsars, supernova, stochastic background
  - Move from astrophysics to cosmology
  - Tests of General relativity

ApPEC Roadmap (GW Detectors Summary)



Conclusions

Astroparticle Physics is becoming an attractive discipline in Science

ApPEC coordination fruitful

Lot of experiments in progress

Lot of work to do

Still many important questions to be answered