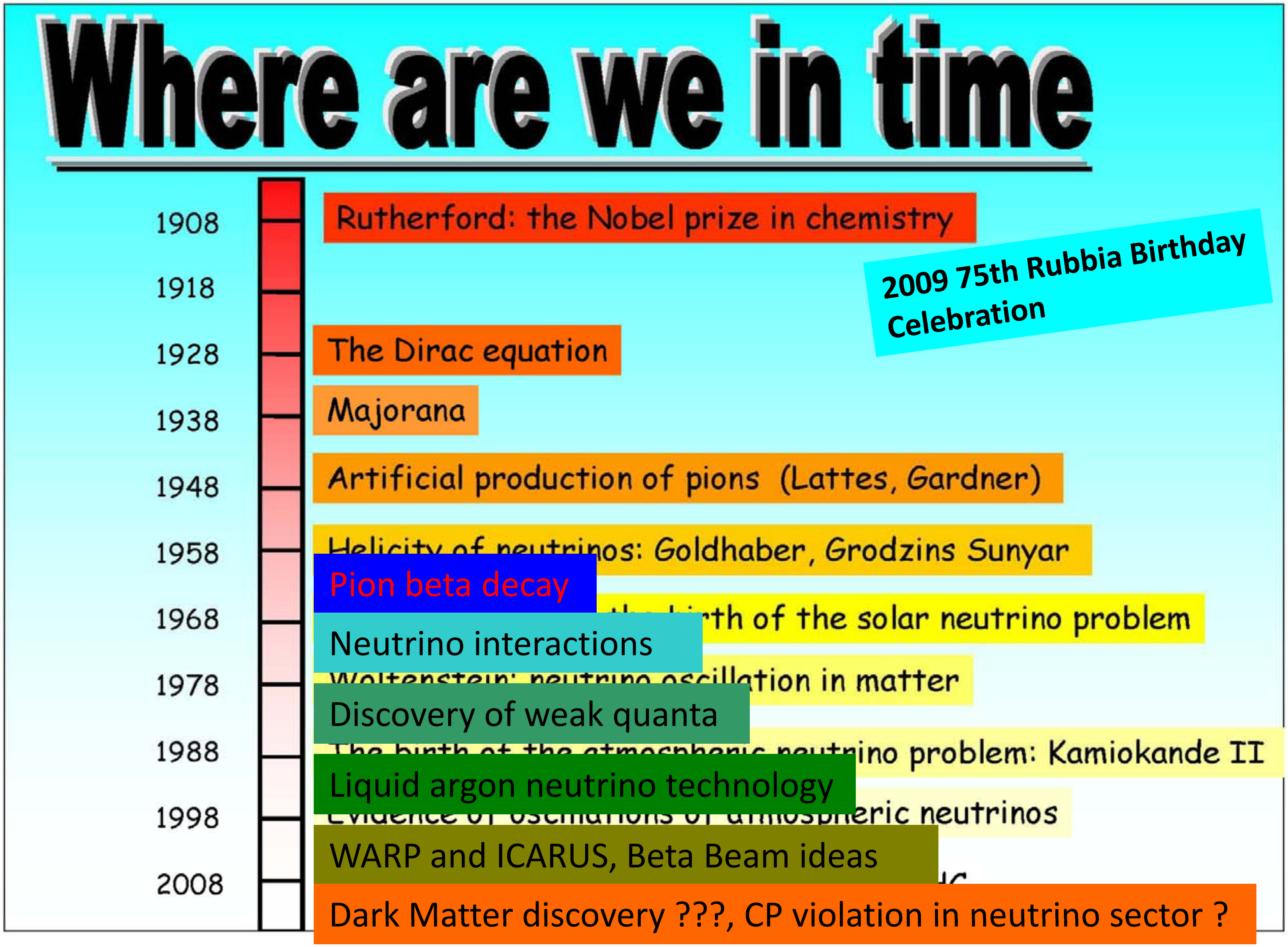
NEUTRINO PHYSICS AND ASTROPHYSICS

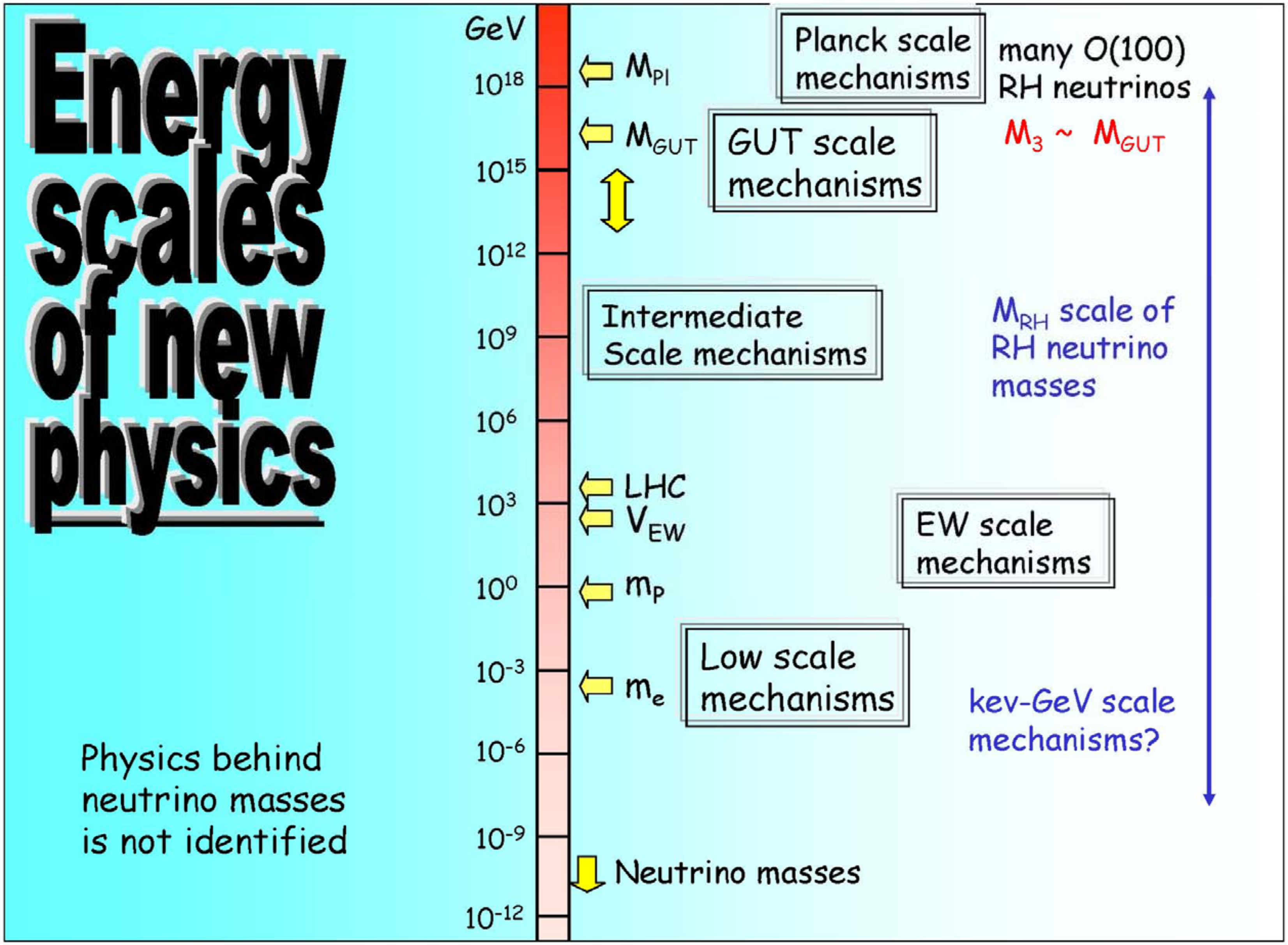
In the light of Carlo Rubbia's work

OUTLINE

- Generalities
- Neutrinos and weak interactions
  - Pion beta decay
  - Neutrino scattering
  - Weak quanta
- Neutrino technologies and related issues (p decay, dark matter…)
  - Water Cherenkov volume detectors
  - Liquid argon imaging detectors
  - Beta beams



Where are we in time
1908
1918
1928
1938
1948
1958
1968
1978
1988
1998
2008
Rutherford: the Nobel prize in chemistry
2009 75th Rubbia Birthday Celebration
The Dirac equation
Majorana
Artificial production of pions (Lattes, Gardner)
os: Goldhaber, Grodzins Sunyar
Pion beta decay
th of the solar neutrino problem
Neutrino interactions
ation in matter
Discovery of weak quanta
ino problem: Kamiokande II
Liquid argon neutrino technology
eric neutrinos
WARP and ICARUS, Beta Beam ideas
Dark Matter discovery ???, CP violation in neutrino sector ?


Energy scales of new physics
GeV
10^{18}
10^{15}
10^{12}
10^{9}
10^{6}
10^{3}
10^{0}
10^{-3}
10^{-6}
10^{-9}
10^{-12}
M_{Pl}
M_{GUT}
LHC
V_{EW}
m_P
m_e
Neutrino masses
Planck scale mechanisms
many O(100) RH neutrinos
GUT scale mechanisms
M_3 ~ M_{GUT}
Intermediate Scale mechanisms
M_{RH} scale of RH neutrino masses
EW scale mechanisms
Low scale mechanisms
kev-GeV scale mechanisms?
Physics behind neutrino masses is not identified

Phenomenology of the scenario

Solar neutrinos

Long baseline experiments

Atmospheric neutrinos

Supernova neutrinos

Cosmic neutrinos

Relic neutrinos

Reactor neutrinos

WEAK INTERACTIONS

To large extend phenomenology of standard scenario has been elaborated; in some cases - in great details

Still some areas exist (cosmic, supernova neutrinos) where active research continues now

Few spots are not covered yet

Cosmic neutrinos

New level of studies

Sources:

AGN

GRBs

core-collapse supernovae

SN remnants

microquasars

blasars

Related to developments of γ-astronomy

E ~ 1 GeV – 10^4 TeV

Detailed computations of the neutrino yield (output) at different conditions

Propagation:

Vacuum oscillations

Conversion in matter of source

studies of various non-standard effects

for maximal 2-3 mixing and 2 : 1 : 0 original ratio flavor equilibration:
1 : 1 : 1

deviations from 1 : 1 : 1

- ν production mechanism
- $\theta_{23} = \pi/4$

Toward the neutrino technologies

WATER CERENKOV

LIQUID ARGON, BETA BEAM

Also dark matter, proton decay, CP leptonic

Monitoring of nuclear reactors

Tomography of the Earth

- absorption
- oscilltion

Geo-neutrinos

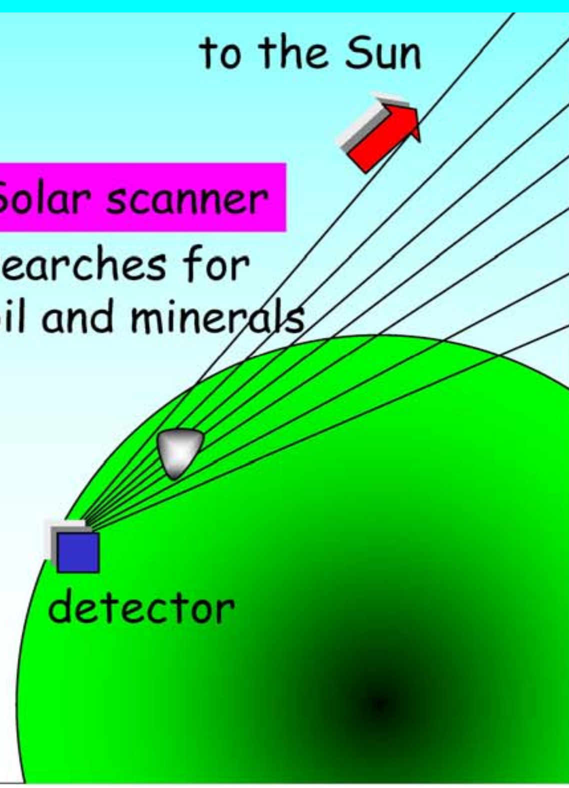
Mossbauer effect for neutrinos

Neutrino as a probe…

Neutrino communication systems
Galactic communication

Solar scanner

searches for
oil and minerals



J. Learnd,
S. Pakvasa
A. Zee

WEAK INTERACTIONS

- Beta decay
- Neutrino interactions
- Weak Quanta

Carlo and beta decay

- **P. DEPOMMIER, J. HEINTZE, A. MUKHIN, C. RUBBIA, V. SOERGEL and K. WINTER, *``Determination of the π+ → πo + e+ + ν decay rate"*, Proceedings of the International Conference on High Energy Physics, CERN, 1962, p. 411.**
- **P. DEPOMMIER, J. HEINTZE, A. MUKHIN, C. RUBBIA, V. SOERGEL and K. WINTER, *``Experimental evidence for structure effects in the π+ → e+ + ν + γ decay process"*, Proceedings of the International Conference on High-Energy Physics, CERN, 1962, p. 414.**
- **P. DEPOMMIER, J. HEINTZE, A. MUKHIN, C. RUBBIA, V. SOERGEL and K. WINTER, *``Determination of the π+ → πo + e+ + ν decay rate"*, Phys. Letters, 2, 23, 1962.**
- **P. DEPOMMIER, J. HEINTZE, C. RUBBIA and V. SOERGEL, *``Further measurements of the π+ → πo + e+ + ν decay rate"*, Phys. Letters, 5, 61, 1963.**
- **P. DEPOMMIER, J. HEINTZE, C. RUBBIA and V. SOERGEL, *``Further measurements of the decay π+ → e+ + ν + γ"*, Phys. Letters, 7, 285, 1963.**

Carlo and neutrino scattering

HPWf neutrino scattering experiment

1970-1980

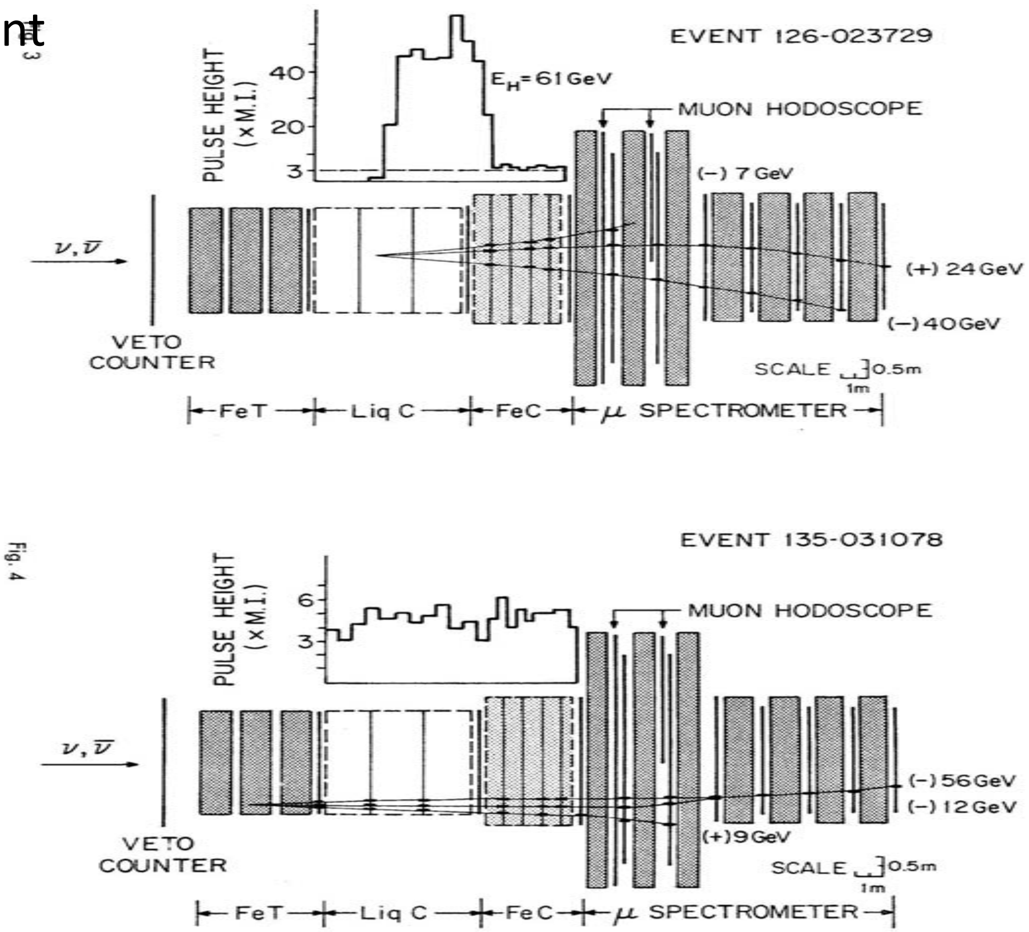
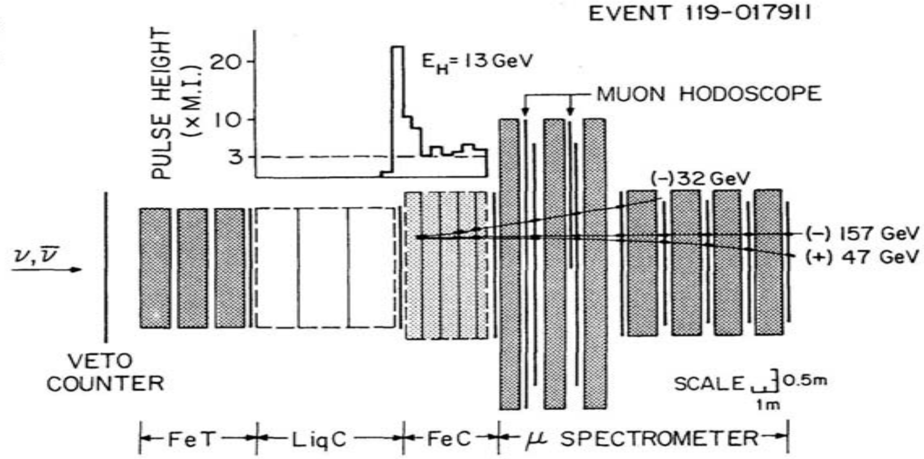


Fig. 5



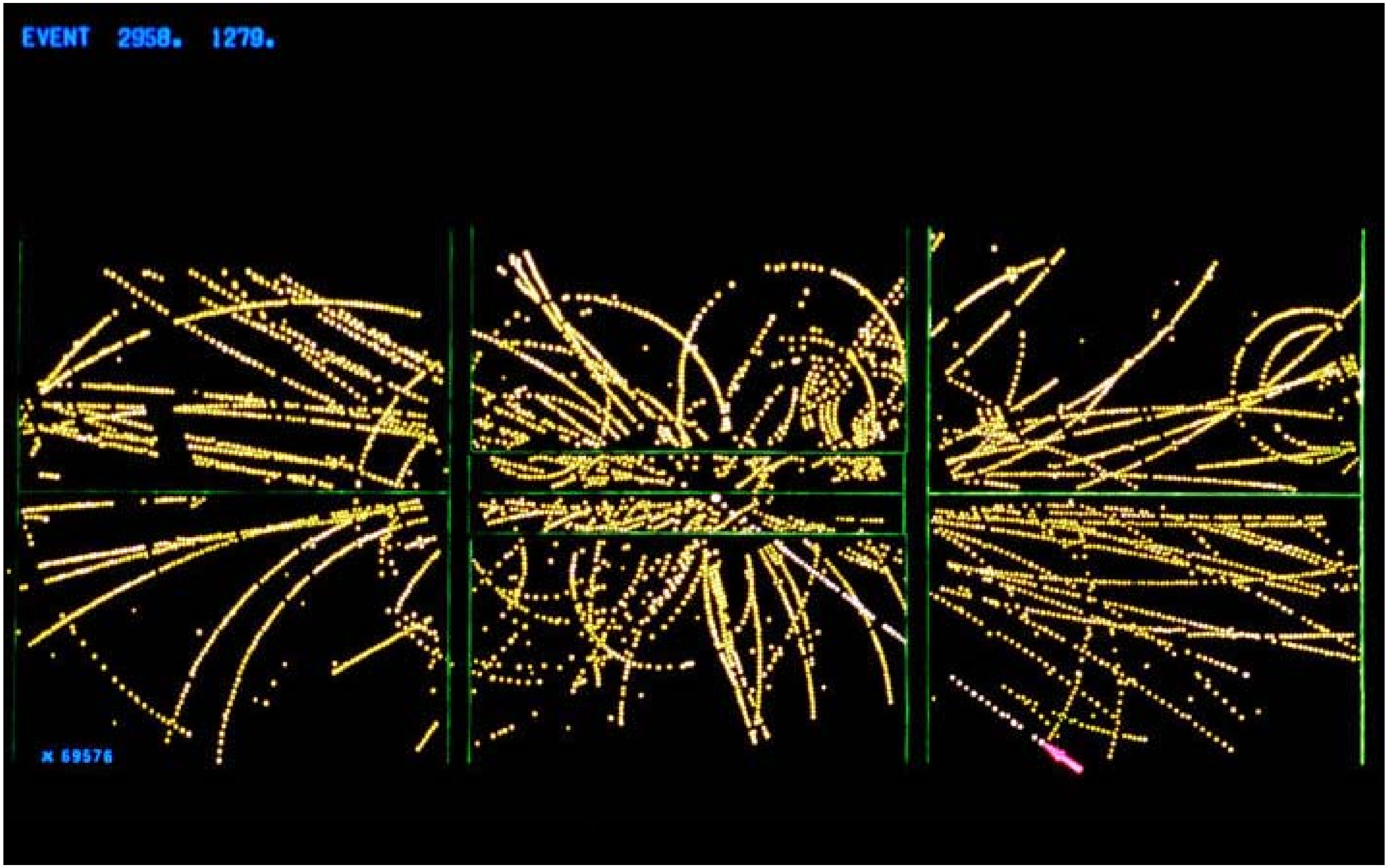
443

TABLE 3

Event	[illegible] $/10^{-4}$
58	< 0.03
119	0.003
126	0.1
135	0.02
138	0.09
146	0.005

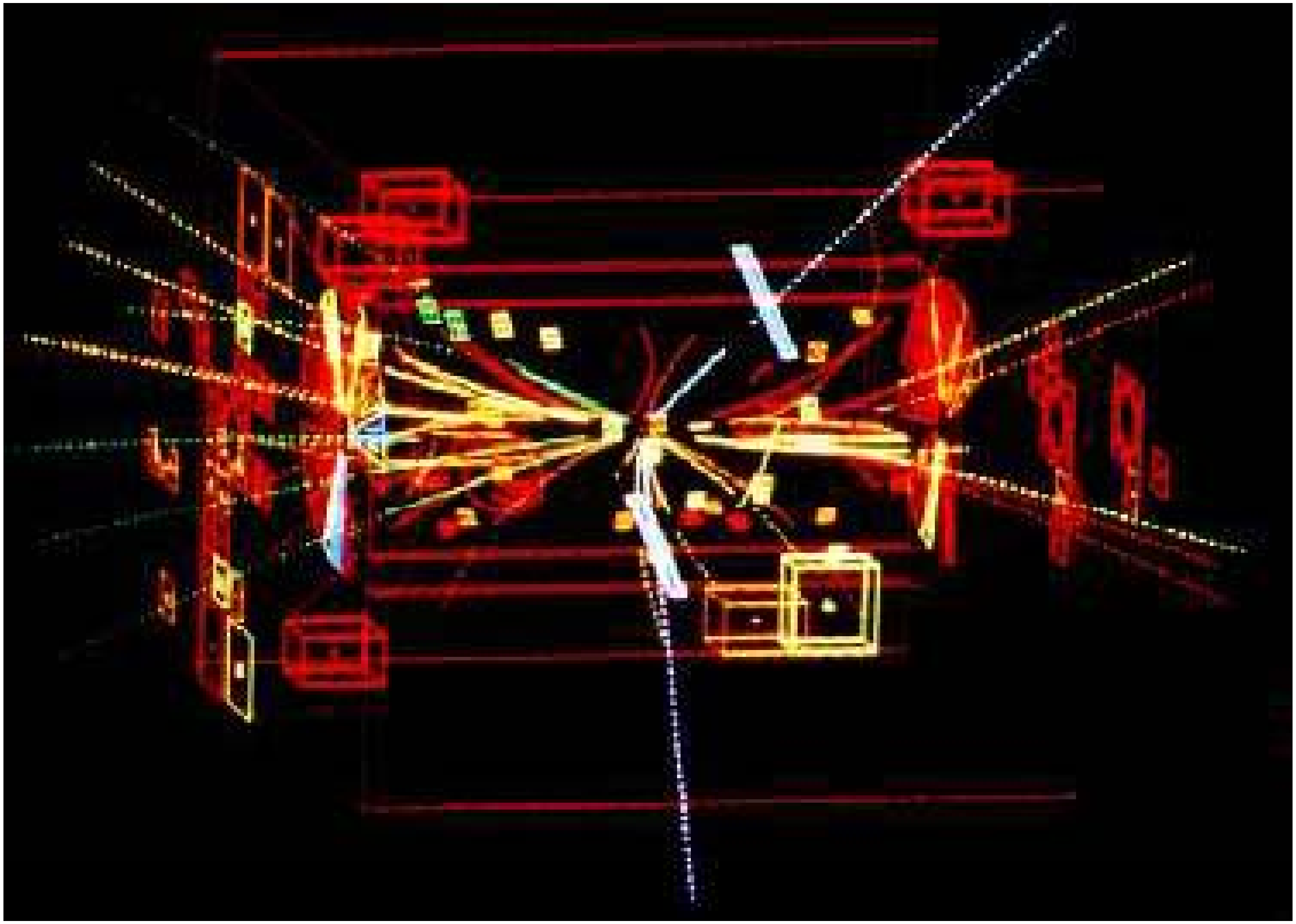
One of the first observation of Neutral Currents
Di, Tri muon events: first evidence of Charm

FIRST W's: MISSING ENERGY



1983

FIRST Z



Carlo and neutrino technologies

- Volume water Cherenkov and future perspective
- Liquid Argon and future perspective
- Beta beams and CP violation in the neutrino sector

First Water Cherenkov Volume Detector

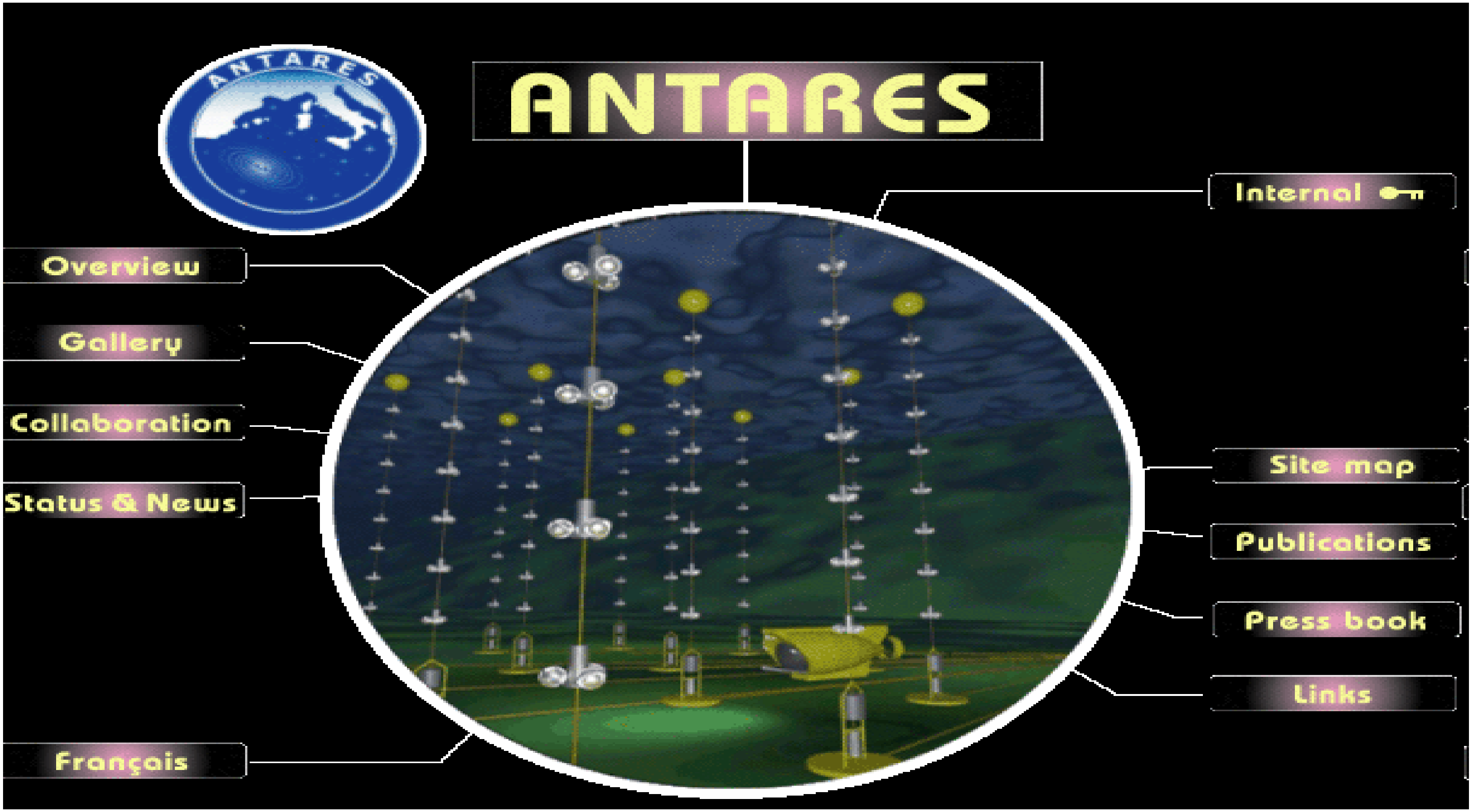
1) **Status Of The Hpw Nucleon Decay Detector.**
J.A. Gaidos *et al.* 1982.
In *Argonne 1982, Proceedings, Proton Decay Experiments*, 131-149.

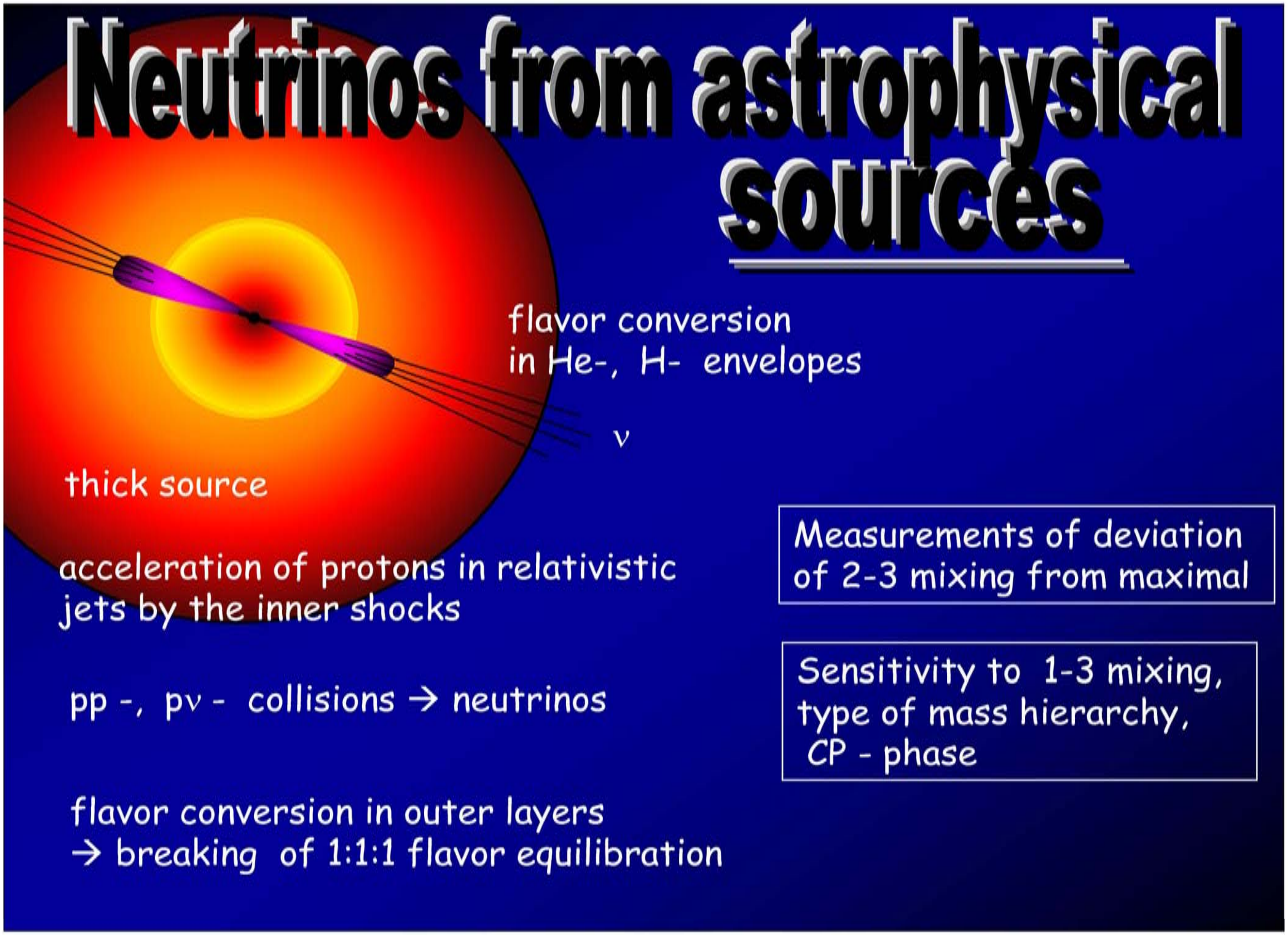
2) **The Harvard-Purdue-Wisconsin Proton Decay Detector. (Talk).**
J.A. Gaidos *et al.* 1981.
In *Wailea 1981, Proceedings, Neutrino '81, Vol. 1*, 215-223. (See Conferecne Index).

3) **The Study Of 0.1-Gev - 50-Gev Neutrinos In A Water Cherenkov Detector Located In A Deep Mine. (Talk, Abstract Only).**
J. Blandino *et al.* 1979.
In *Kyoto 1979, Proceedings, 16th International Cosmic Ray Conference, Vol. 10*, 305.

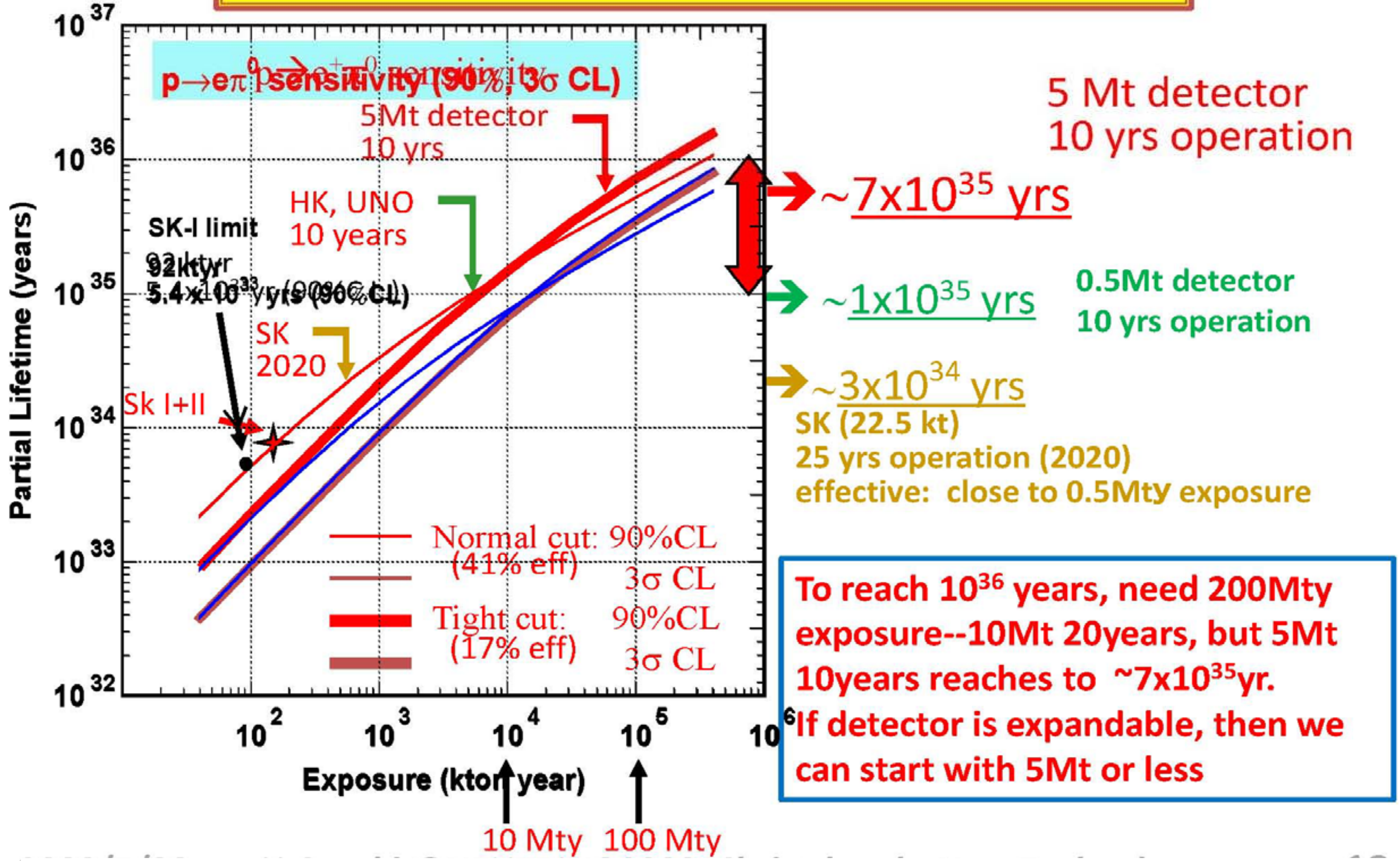
4) **A Search For Nucleon Decay To A Lifetime Of 10**35-Years. (Talk).**
J. Blandino *et al.* 1979.
In *Bergen 1979, Proceedings, Neutrino '79, Vol.2*, 145-155.

Towards KM3Net Neutrino Astronomy




Neutrinos from astrophysical sources
flavor conversion
in He-, H- envelopes
ν
thick source
acceleration of protons in relativistic
jets by the inner shocks
pp -, pν - collisions → neutrinos
flavor conversion in outer layers
→ breaking of 1:1:1 flavor equilibration
Measurements of deviation
of 2-3 mixing from maximal
Sensitivity to 1-3 mixing,
type of mass hierarchy,
CP - phase

Sensitivity for $p \rightarrow e^+\pi^0$

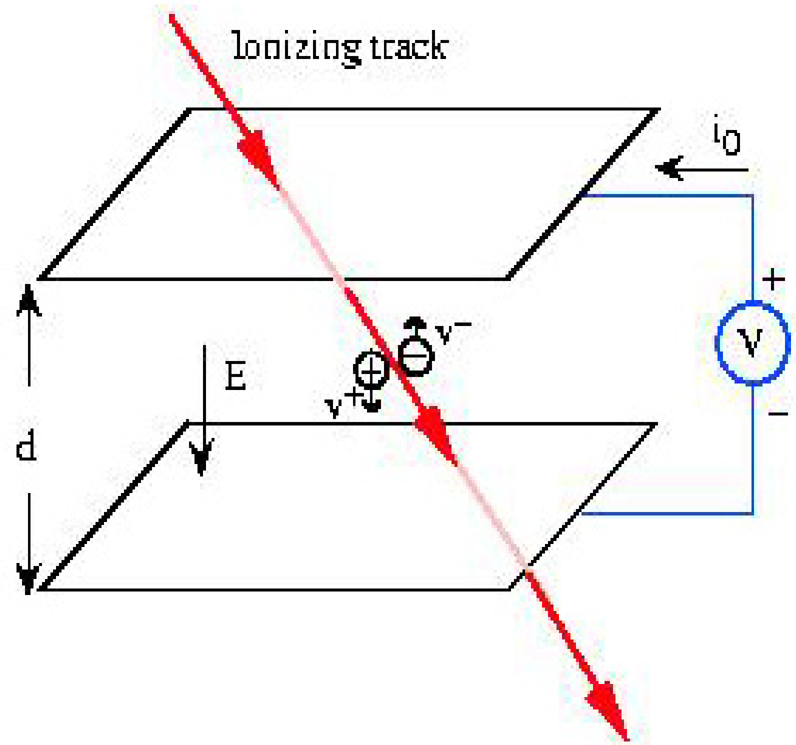


Extrapolation needs water Cherenkov volume detector !!

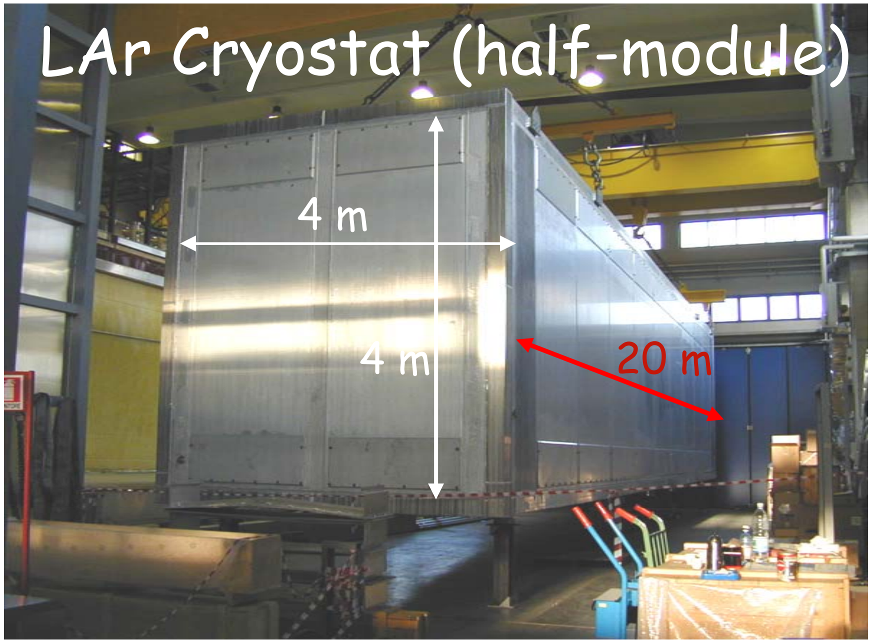
The new Carlo's technique for neutrino observatory

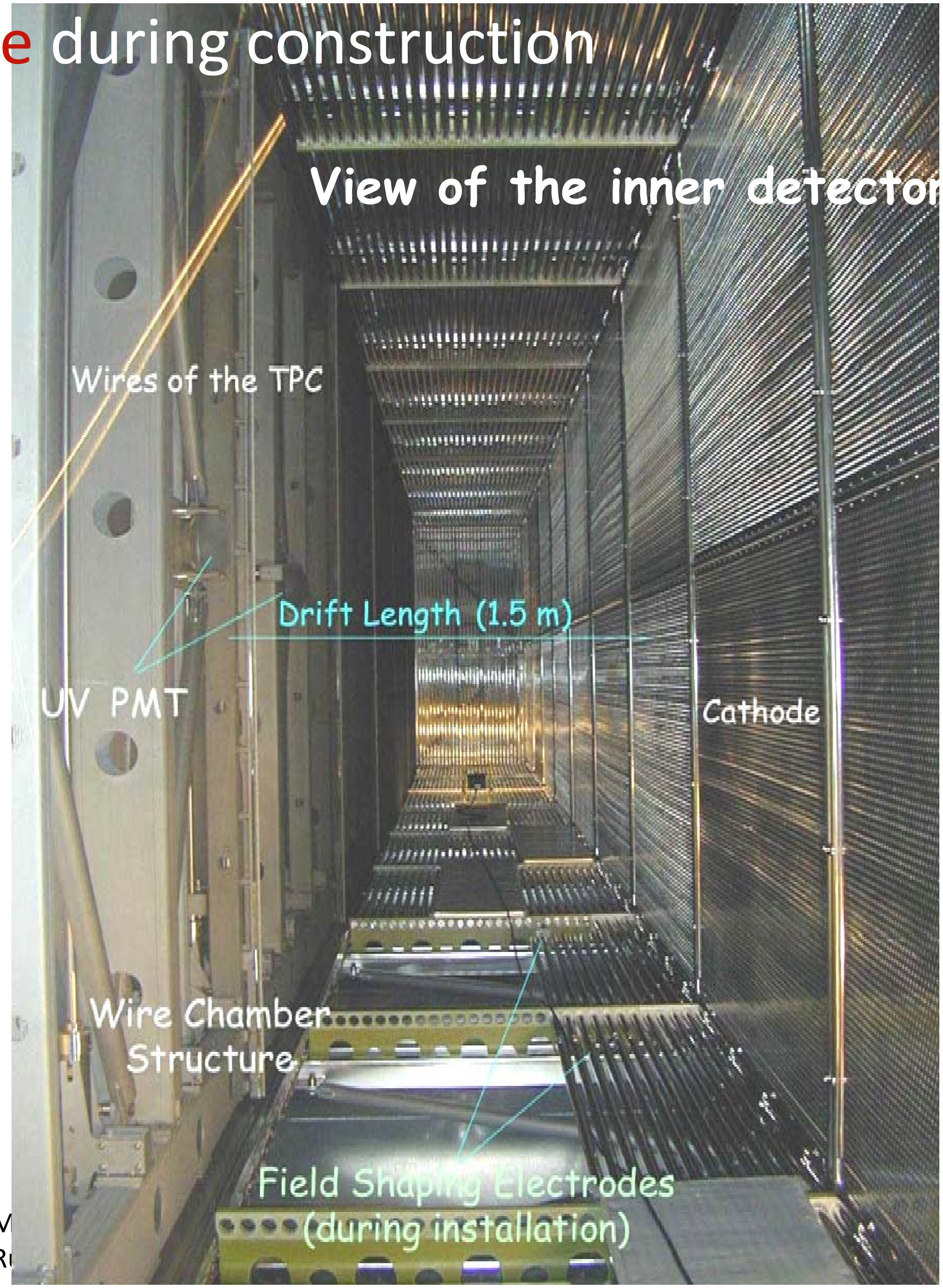
Operating principles of the ICARUS LAr TPC:

- ionizing events taking place in a volume of LAr (where a uniform electric field is applied) produce electron-ion pairs
- These charges drift along the field lines. The motion of the much faster electrons induces a current on the anode. The electrons can drift several metres if the LAr is highl purified (electronegative impurities < 0.1 ppb O_2 equiv.)

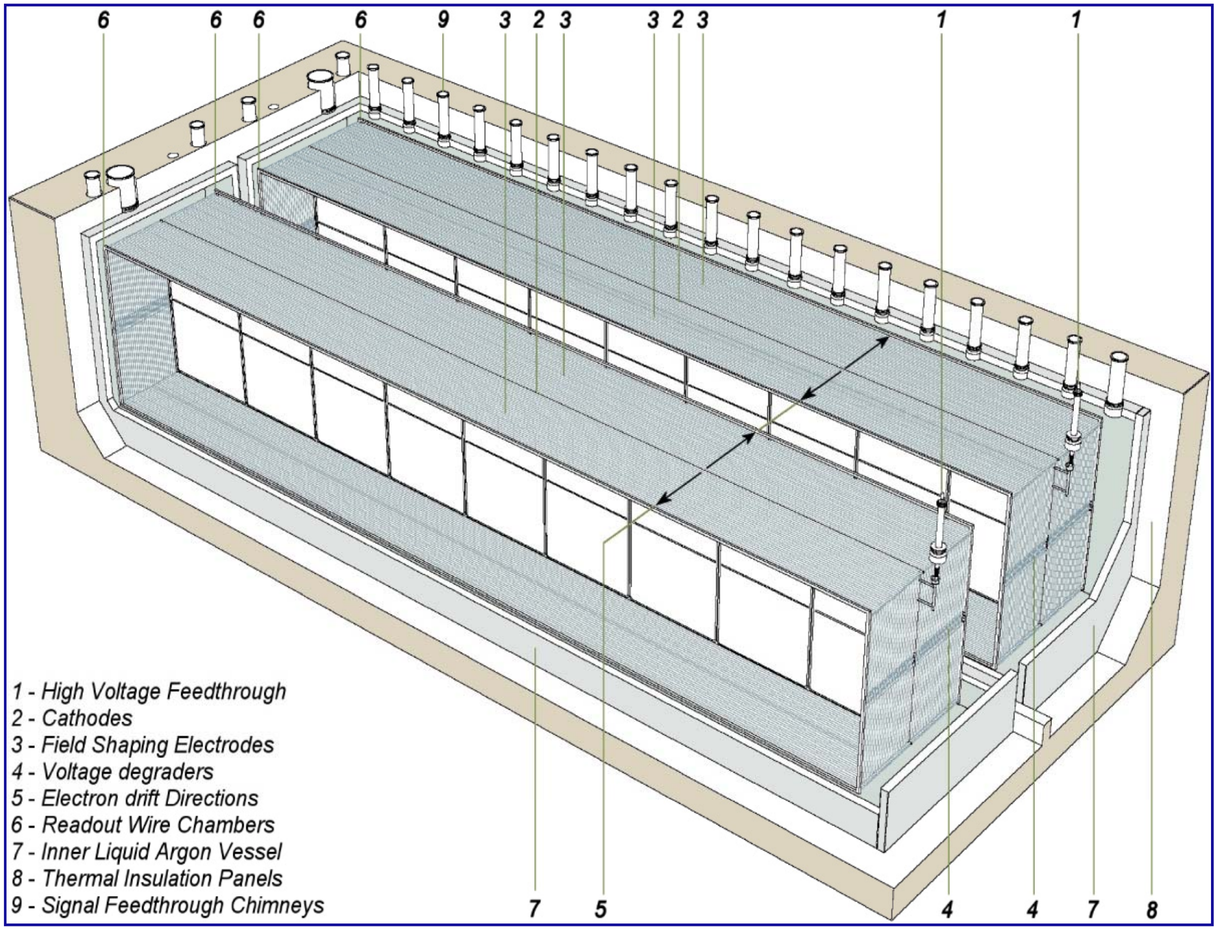


The T600 Module during construction





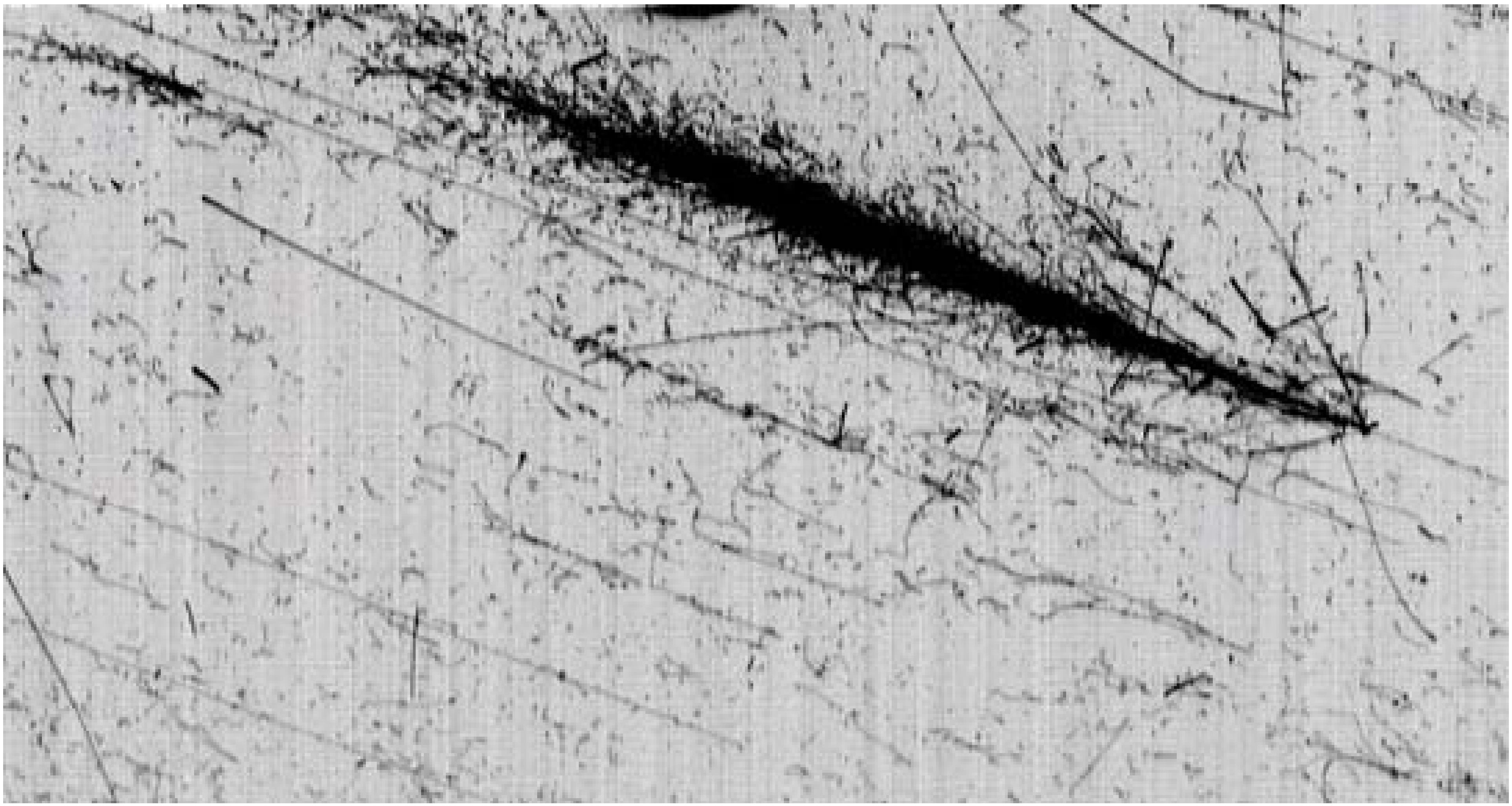
The T600 Module



- Two separate containers
  - inner volume/cont. = **3.6 x 3.9 x 19.6 m^3**
- Sensitive mass = **476 t**
- 4 wire chambers with 3 readout planes at 0°, ±60° (two chambers / container)
  - ≈ 54000 wires (chann.)
- Maximum drift = 1.5 m
  - HV = -75 kV @ 0.5 kV/cm
- Scintillation light readout with 8" VUV sensitive PMTs

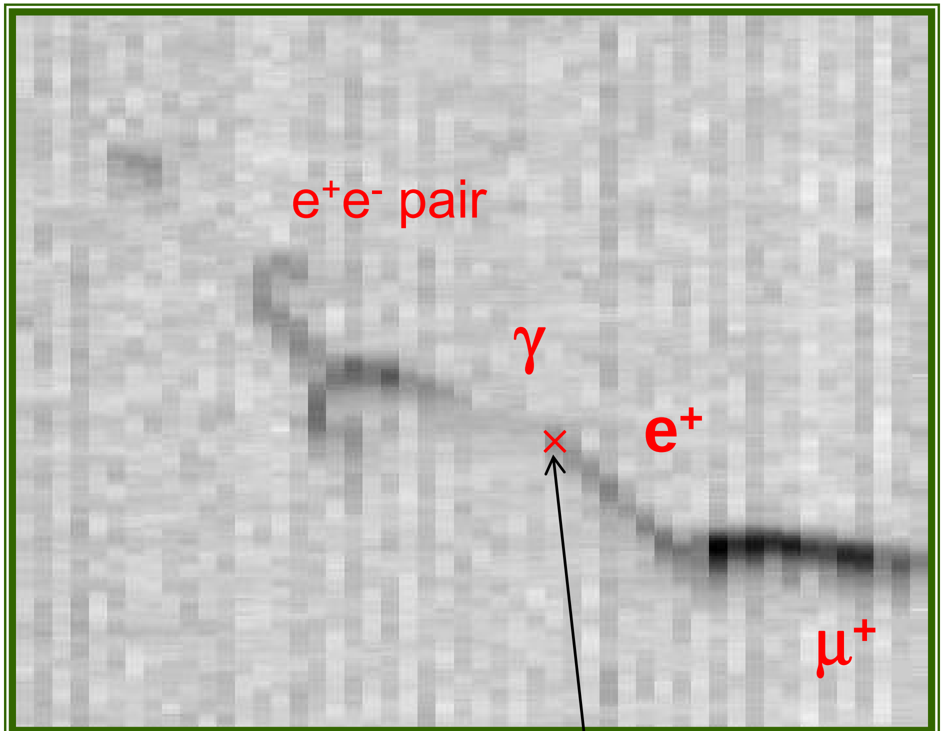
e.m + hadron shower

2.2 m



In-flight annihilation of positron

≈20% of positrons from μ decays expected to annihilate before stopping

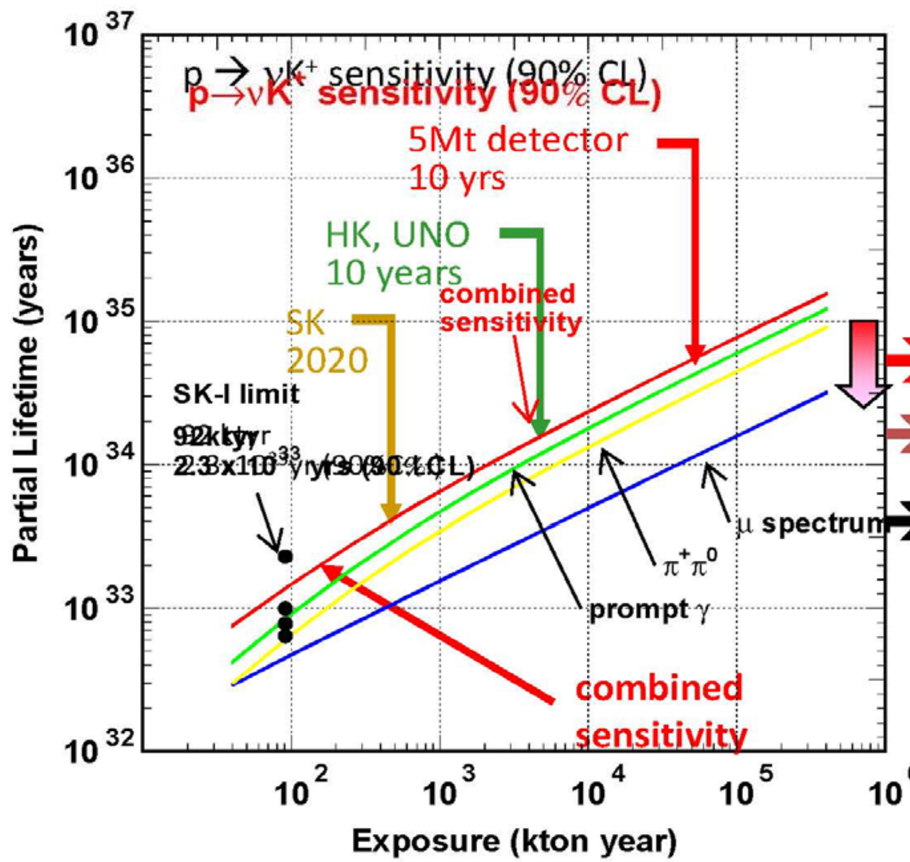


Collection view

annihilation point

Induction 2 view

Sensitivity for p →νK+



Once you find the proton decay by $e\pi^0$ mode, then νK will constrain models.

5 Mt detector
10 yrs operation

→ ~$7x10^{34}$ yrs

→ ~$2x10^{34}$ yrs

0.5 Mt
10yrs opereration

→ ~$4x10^{33}$ yrs

SK (22.5 kt)
25 yrs operation (2020)

If the detector is expandable, you can continue to study the sensitive regions.

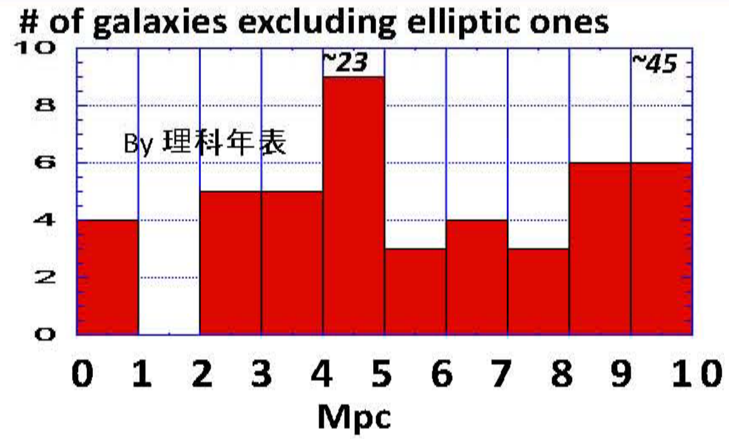
Could liquid argon do better ?

Supernova Rate **WATER C**

- **Galactic SN rate**
  - **Every 30 ~50 years in our Galaxy**
    - ← SN rate external Gal., Galactic ^{26}Al abundance, Historical Gal. SN, ……..,
- **Number of Galaxies**
  - **23 within 5 Mpc**
  - **45 within 10 Mpc**

➔ 1 SN every 1~2 years (5~10Mpc)

- **There are Galaxies beyond 2 Mpc where SNe have frequently happened**



- **NGC6946 (5.9 Mpc) *10 in 90yr***
  1917A, 1939C, 1948B, 1968D, 1969P, 1980K, 2002hh, 2004et
- **M83 (4.3Mpc) *6 in 60yr***
  1923A, 1945B, 1950B, 1957D, 1968L, 1983N
- **NGC2403 (3.3Mpc) *3 in 50yr***
  1954J, 2002kg, 2004dj

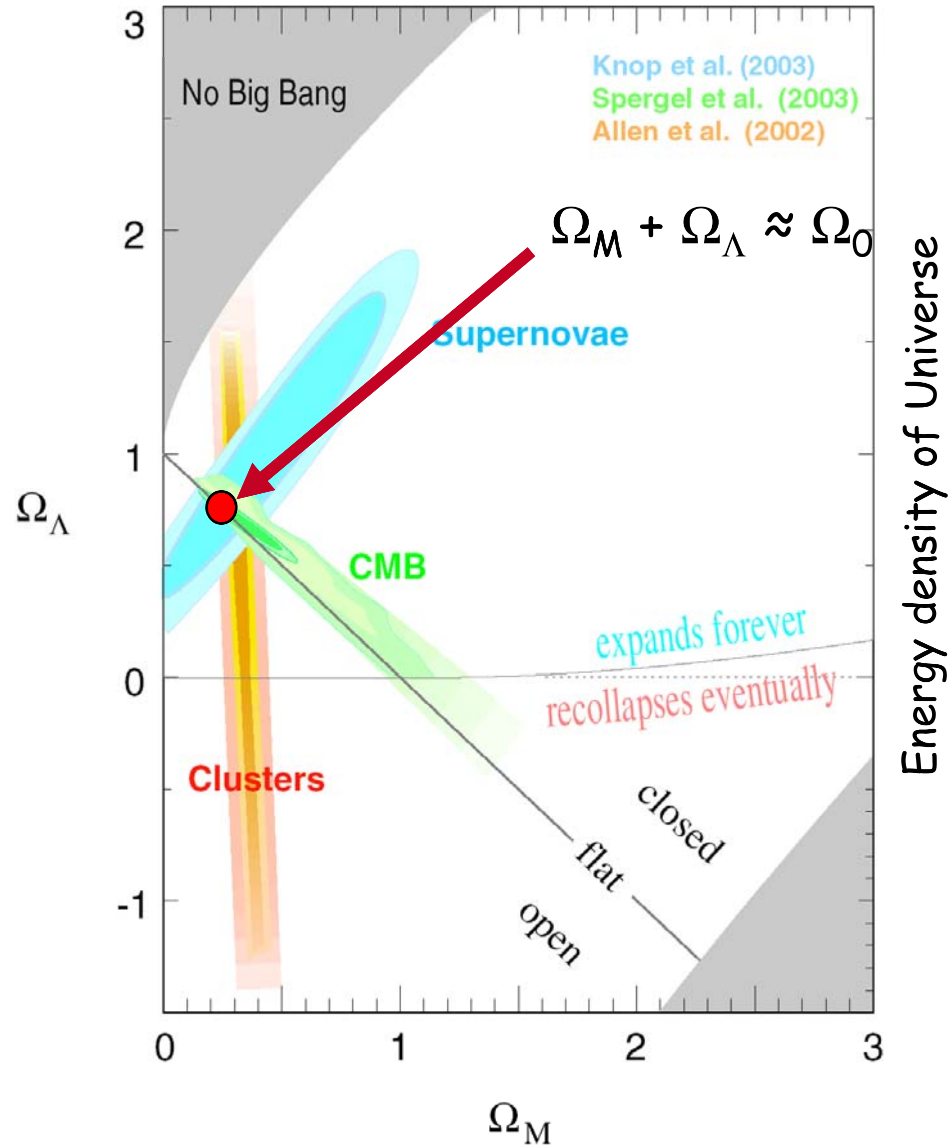
➔ 1 SN every year (within 5 Mpc) is not bad estimate

DIFFUSE SUPERNOVAE SIGNAL: Liquid Argon ?

Cosmology: a few established facts

- BBN is firmly set to Ω_{BBN} = 0.044 ± 0.004
- Need for Dark, non baryonic matter, since

  $\Omega_M - \Omega_{BNN} \approx 0.226 \pm 0.06$!
- What is the origin of such a difference ?
- Neutrino's contribution insufficient ($0.0005 < \Omega h^2 < 0.0076$)
- Cold dark matter hypothesis preferred by cosmological considerations
- But Cold + Warm dark matters not excluded



Ordinary matter from BB Nucleosynthesis (baryons)

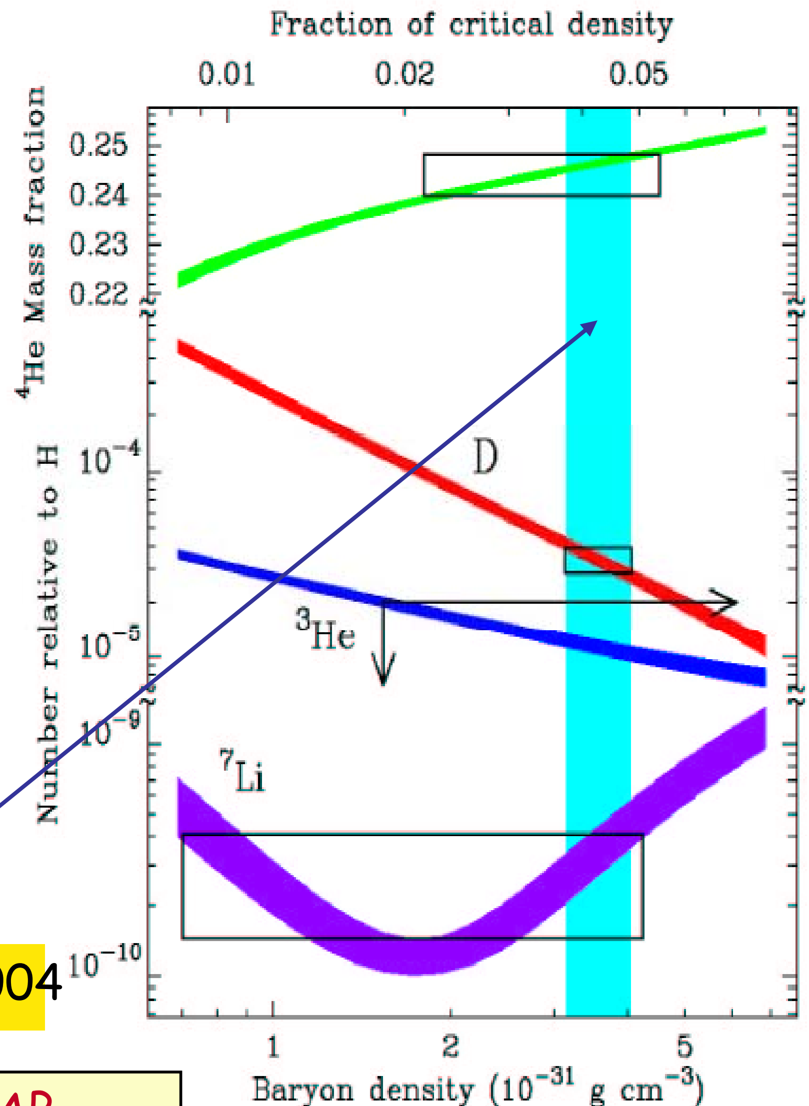
- Big−Bang Nucleosynthesis depends sensitively on the baryon/photon ratio, and we know how many photons there are, so we can constrain the baryon density.
- Result:

$$\Omega_{baryon} \approx 0.05$$

- [Burles, Nollett, Turner]

Ω_{BBN} = 0.044 ± 0.004

It confirms WMAP result



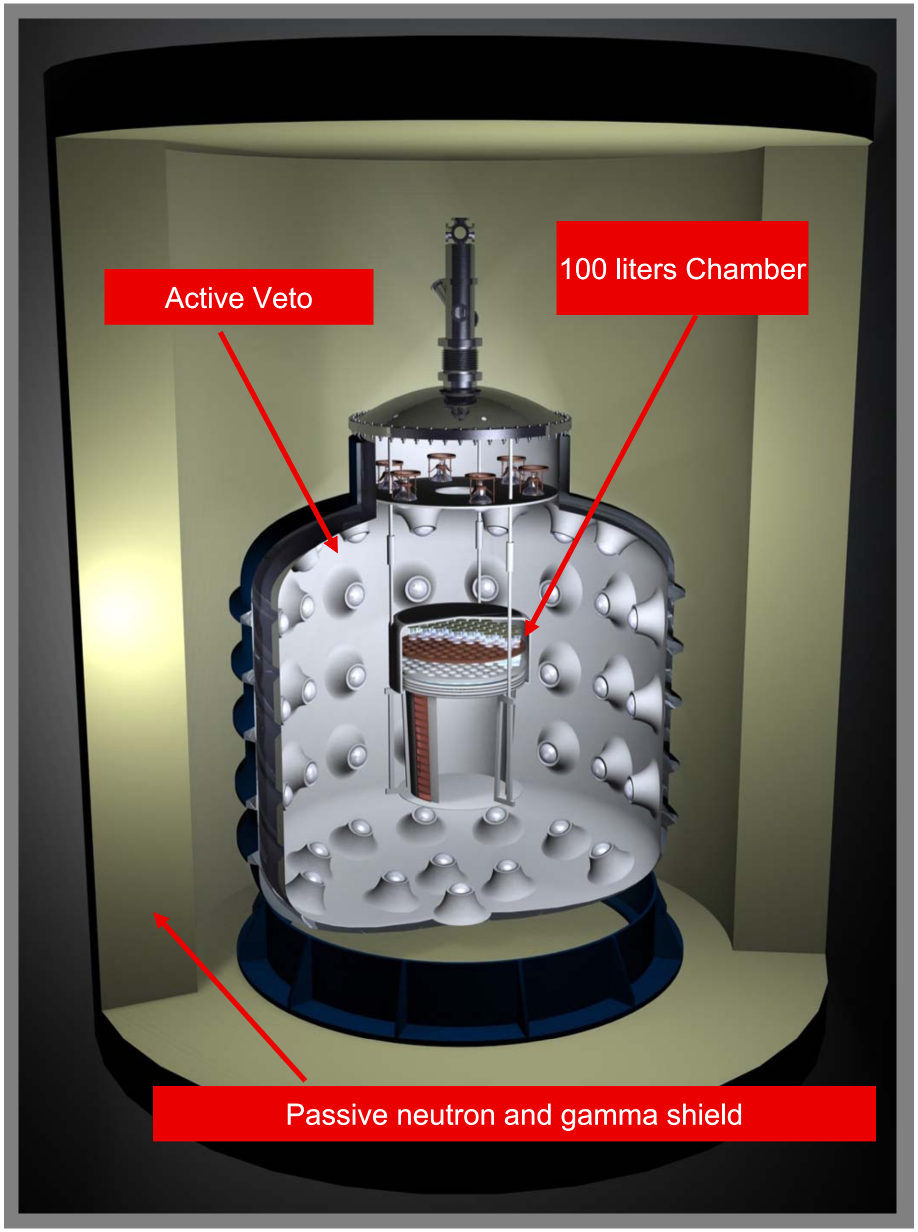
The WARP detector at GranSasso Laboratory

- 140 kg active target, will possibly allow to reach sensitivity up to 10^{-45} cm^2 WIMP nucleon cross section (covering the most critical part of SUSY parameter space)

- ➢Complete neutron shield
- ➢4π active neutron veto (8 tons Liquid Argon, 300 PMTs)
- ➢3D event localization and definition of fiducial volume for surface background rejection

Cryostat designed to allocate a possible 1400 kg detector

S-WARP of > 10 tons under consideration for the LNGS with Ar-39 depleted cryogenic liquid



NON BARYONIC DARK MATTER (personal)

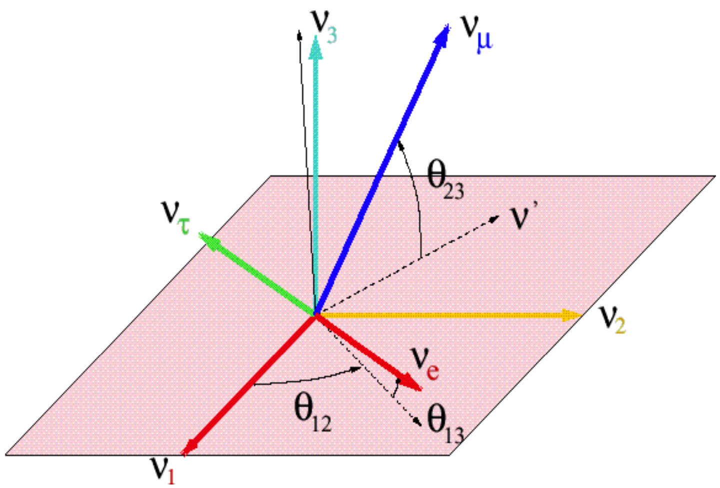
- A major issue which is ripe for discoveries in the next ten years
- LHC, direct and indirect detections now mature and up to the likely needed sensitivity
- CERN should be involved in all three

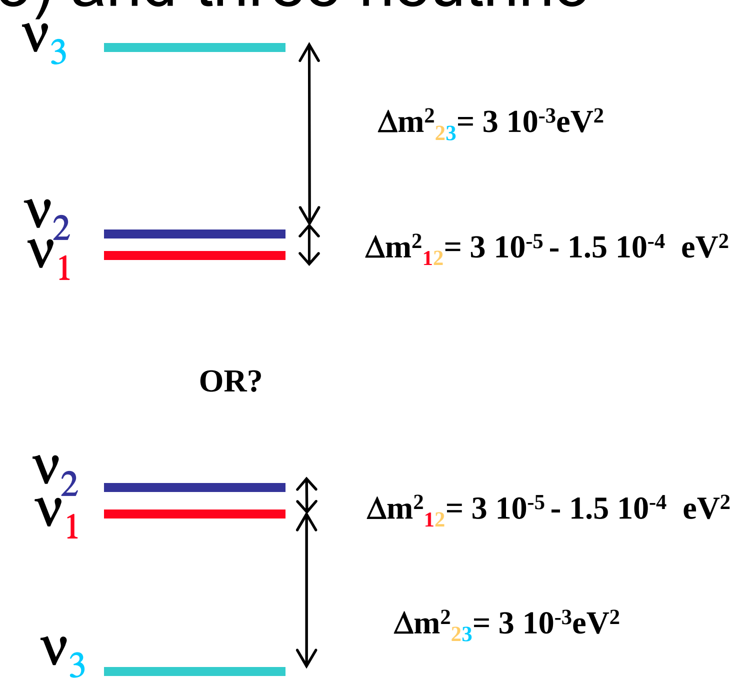
NEUTRINO PROPERTIES

- Dirac or Majorana
- Neutrino masses
- Neutrino oscillations

Neutrino oscillations
CKM in quark sector -> MNS in neutrino sector

- Three neutrino mass states (1,2,3) and three neutrino flavors (e,μ,τ)



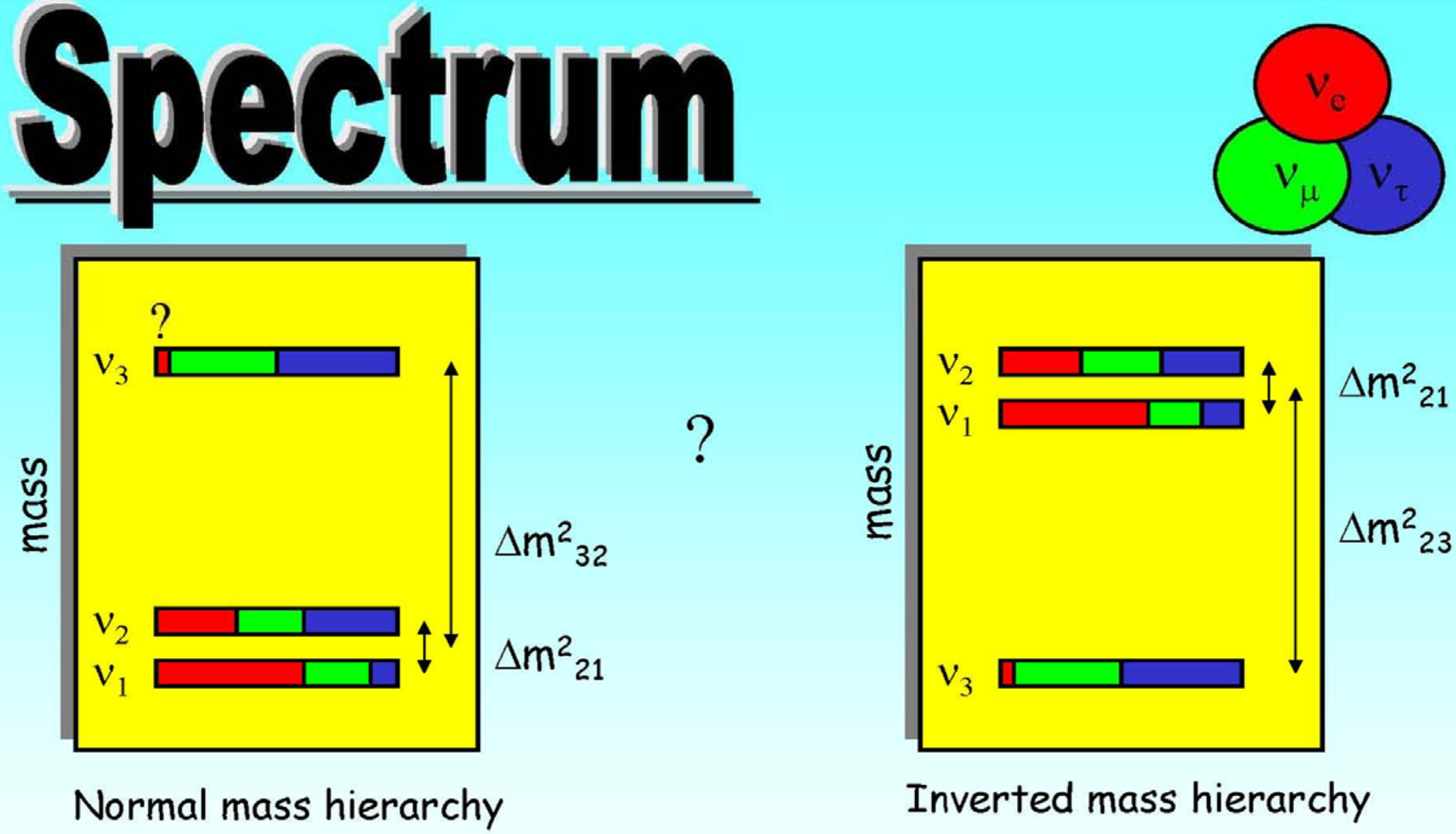


θ_{23} (atmospheric) = 45^0, θ_{12} (solar) = 30^0, θ_{13} (Chooz) < 13^0

$$U_{MNS}: \begin{pmatrix} \sim \frac{\sqrt{2}}{2} & \sim -\frac{\sqrt{2}}{2} & \sin\theta_{13}\, e^{i\delta} \\ \sim \frac{1}{2} & \sim \frac{1}{2} & \sim -\frac{\sqrt{2}}{2} \\ \sim \frac{1}{2} & \sim \frac{1}{2} & \sim \frac{\sqrt{2}}{2} \end{pmatrix}$$

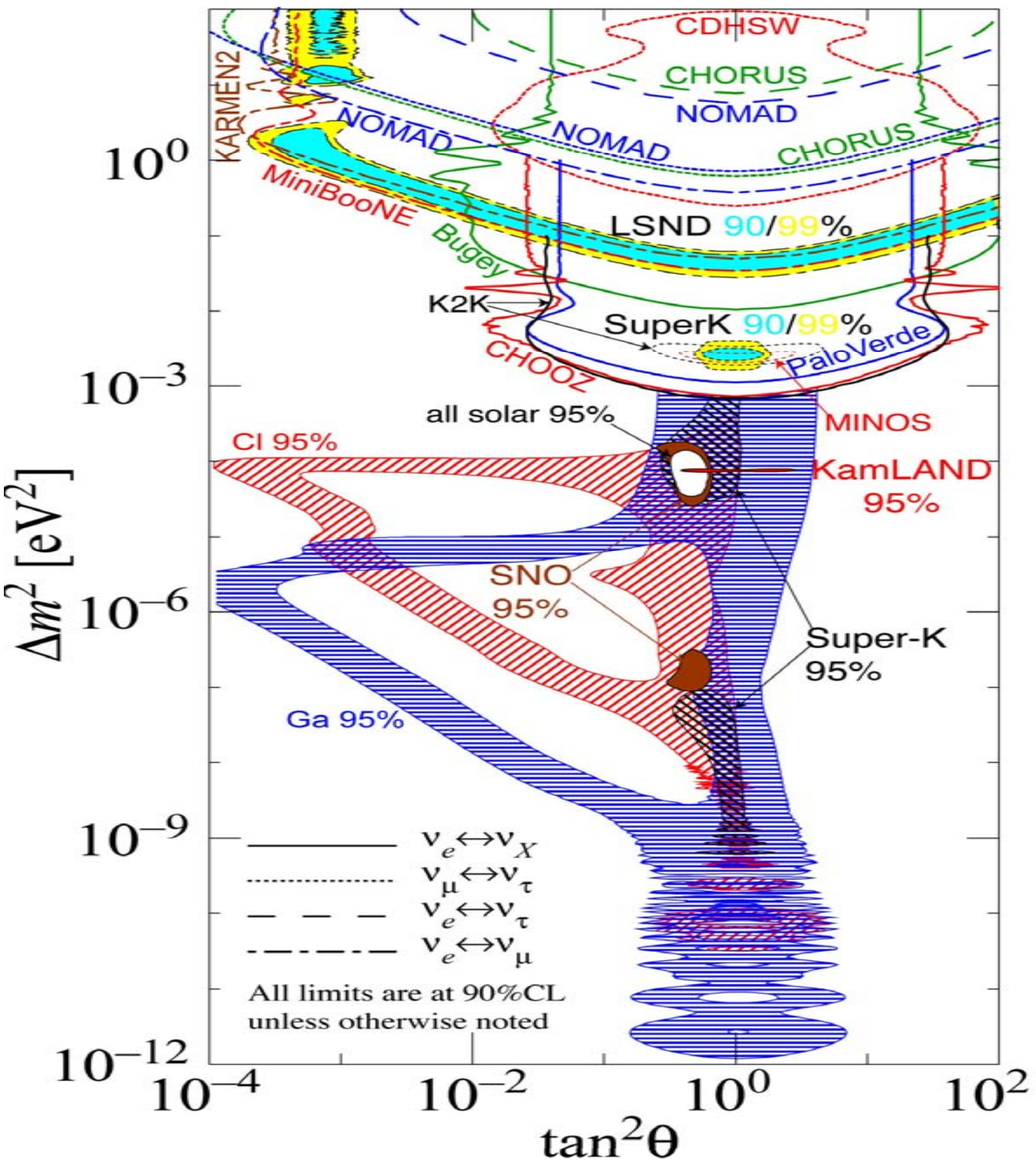
Unknown or poorly known even after approved program:
θ_{13} , phase δ , sign of Δm_{13}

Spectrum



$\nu_f = U_{PMNS}\, \nu_{mass}$

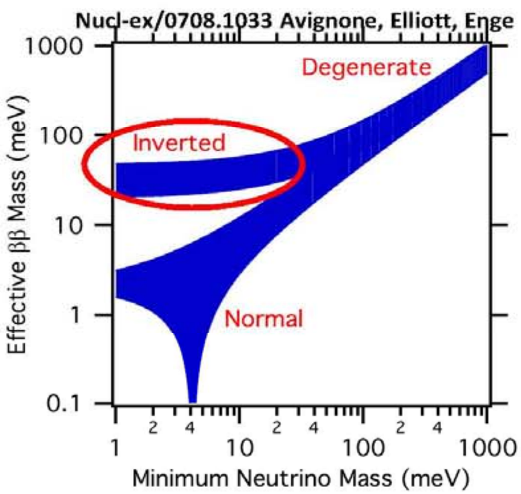
$U_{PMNS} = U_{23}\ I_\delta\, U_{13}\, I_{-\delta}\, U_{12}$



http://hitoshi.berkeley.edu/neutrino

The next 'Standard' neutrino-less double beta decay experiments

- Double beta decay is much important than Proton Decay (T. Yanagida)
- Aim to search for **30meV～50meV**
  - Cover the region for inverted mass hierarchy



'Next' DB experiments

Experi-ments	Nucleus	Det.mass (kg)	Sensitivity (meV)	start (yr)
GERDA	^{76}Ge	15~100	780~30	2008~
SuperNEMO	^{82}Se	100	130~40	2012~
	^{150}Nd	100	70	2012~
CUORE	130Te	220	120~20	2012~
EXO-200	^{136}Xe	160	550~90	2007~
others				

LIQUID NOBLE GAS Xe?

Neutrino oscillations : CP violation in the leptonic sector

- Sacharov has pointed out that a strong CP violation in non-equilibrium conditions may lead to matter over antimatter dominance shortly after the big-bang.
- If so, an equivalent CP violation may be present also in the leptonic sector. It can be demonstrated experimentally studying neutrino oscillations, provided the unknown angle $\theta_{13} \neq 0$. Both νe and $\nu\mu$ must not be "sterile", i.e. energies of O(1GeV).
- The experimental programme is very costly and difficult and it requires two main bold steps forward, namely:

Neutrino oscillations : CP violation in the leptonic sector

- A new long distance, powerful low energy neutrino beam, capable of identifying νe and $\nu\mu$ neutrino species down to << 10^{-3}. Under consideration are:
  - Super beams, in which an ordinary $\nu\mu$ beam is either off-axis or otherwise it has a strongly νe reduced background.
  - Beta-beams, in which a β-decaying nucleus is accelerated and decays in an appropriate storage ring pointing at the target, producing a very pure νe beam.
  - .Muon beams, in which a cooled muon beam is accelerated and it decays in an appropriate storage ring.
- A new detector of much greater mass and with a very high particle identification capabilities. Liquid Argon is definitely the best choice at present.

The EURISOL scenario (Zuchelli)

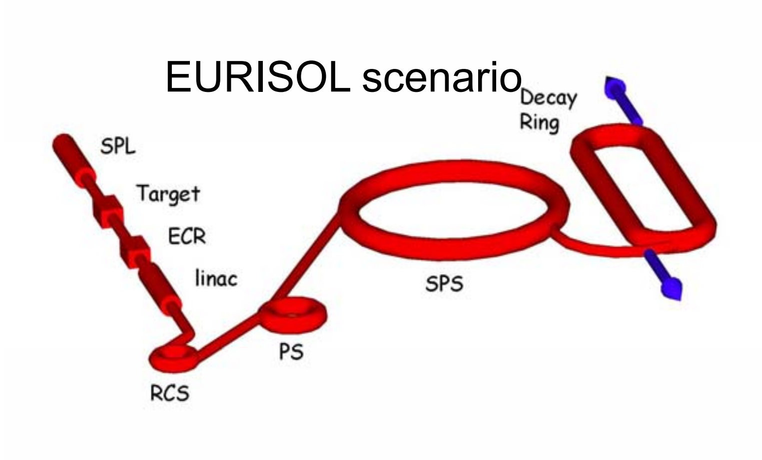
- Based on CERN boundaries
- Ion choice: ^{6}He and ^{18}Ne

- Relativistic gamma=100/100
  - SPS allows maximum of 150 (^{6}He) or 250 (^{18}Ne)
  - Gamma choice optimized for physics reach

- Based on existing technology and machines
  - Ion production through ISOL technique (SPL)
  - Post acceleration: ECR, linac
  - Rapid cycling synchrotron
  - Use of existing machines: PS and SPS

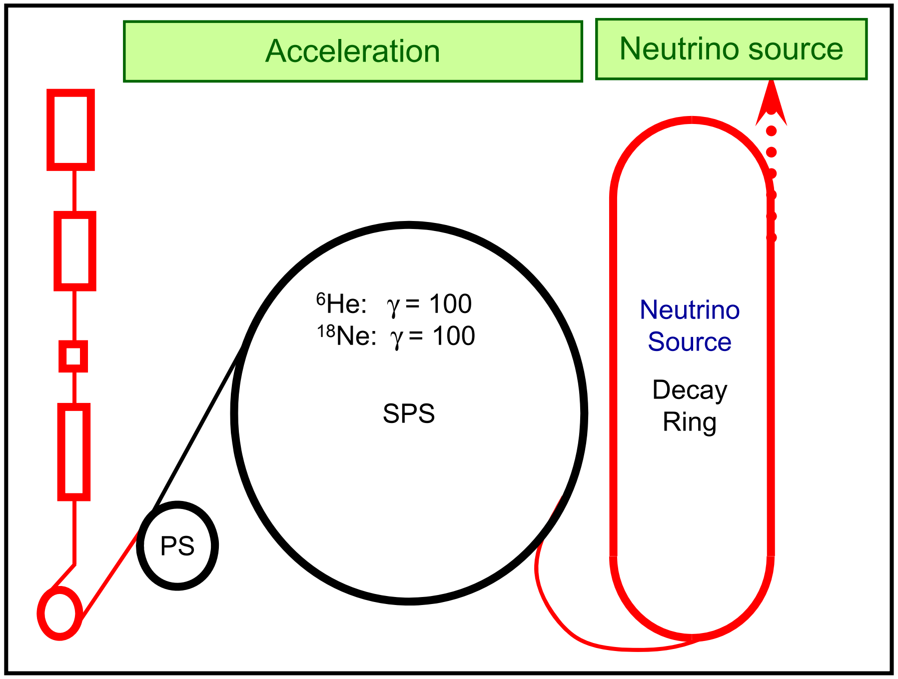
- Achieve an annual neutrino rate of either
  - $2.9*10^{18}$ anti-neutrinos from ^{6}He
  - Or $1.1\ 10^{18}$ neutrinos from ^{18}Ne

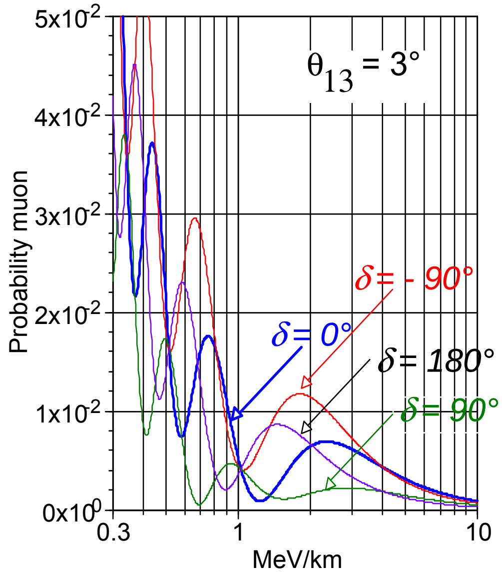
- Once we have thoroughly studied the EURISOL scenario, we can "easily" extrapolate to other cases. EURISOL study could serve as a reference.



Beta beams

- Zucchelli has proposed a neutrino beam from the β-decay of a short lived nucleus (He-6) followed by acceleration and decay in a dedicated high energy storage ring.
- The advantage of this method is that a very pure νe beam may be produced, with a ν_μ contamination nearly zero, $O(\nu_\mu) \leq 10^{-5}$.
- However ν_e 's introduce (f.i. via neutral currents) a large number O(1) of pions, indistinguishable in the proposed 400 kton fiducial water detector from the tiny $O(10^{-3})$ $\nu_e \rightarrow \nu_\mu$ conversions due to θ_{13} and CP violation effects.



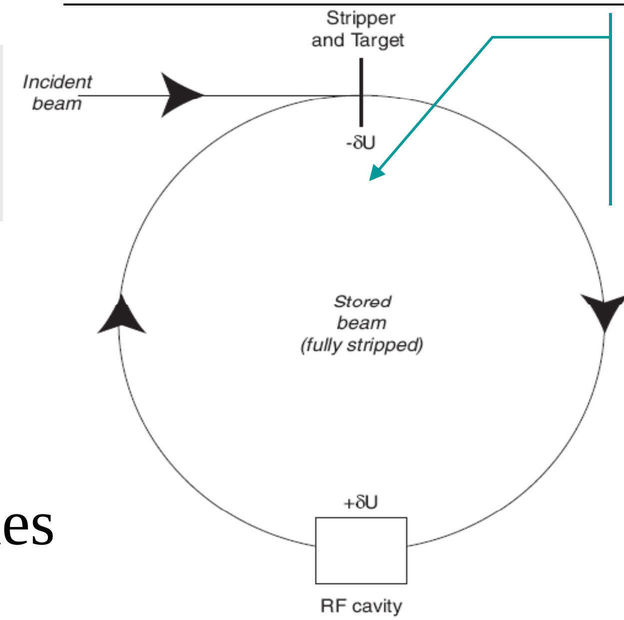


A new approach for the production

Beam cooling with ionisation losses – C. Rubbia, A Ferrari, Y. Kadi and V. Vlachoudis in NIM A, In press

“Many other applications in a number of different fields may also take profit of **intense beams of radioactive ions**.”

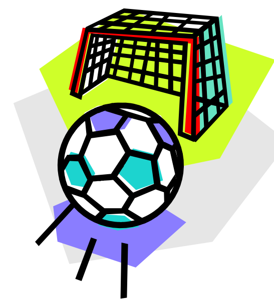
^{7}Li
^{6}Li



$^{7}Li(d,p)^{8}Li$
$^{6}Li(^{3}He,n)^{8}B$

15 MeV Q value

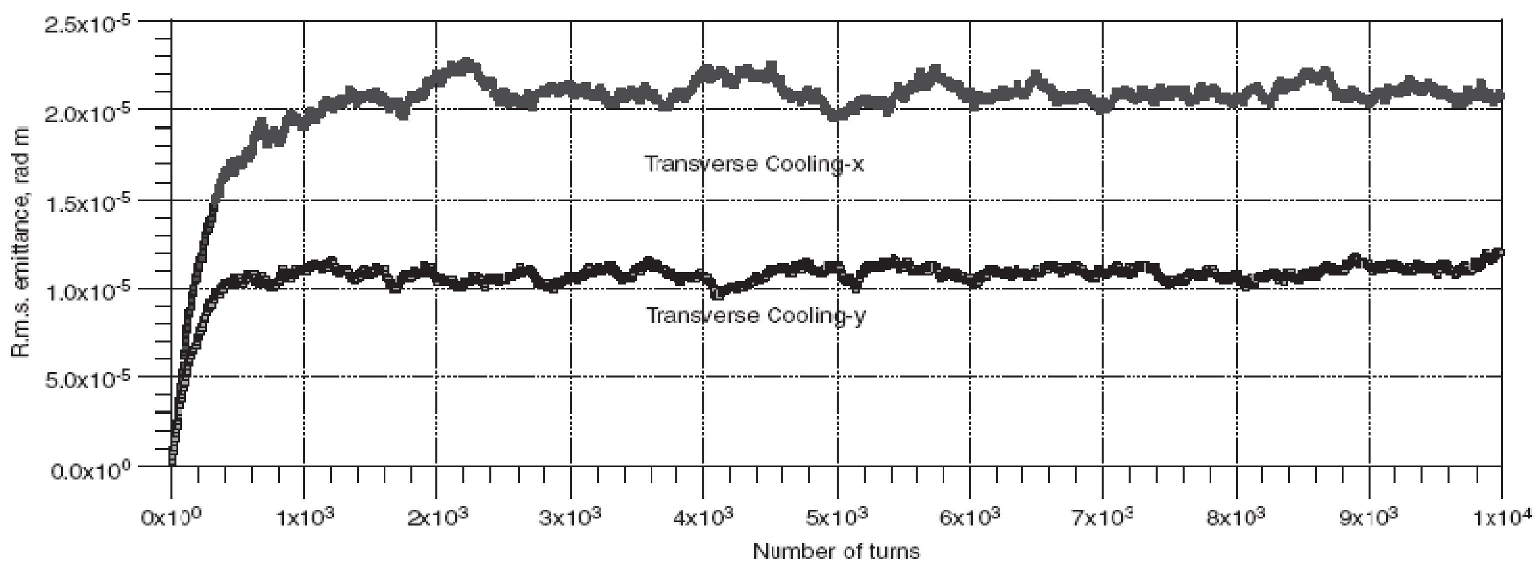
Missed opportunities



See also: Development of FFAG accelerators and their applications for intense secondary particle production, Y. Mori, NIM A562(2006)591

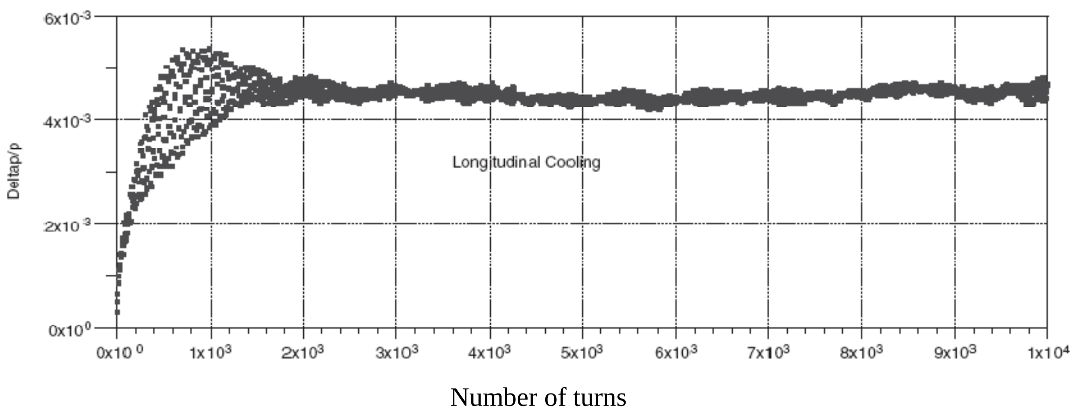
Transverse cooling in paper by Carlo Rubbia et al.

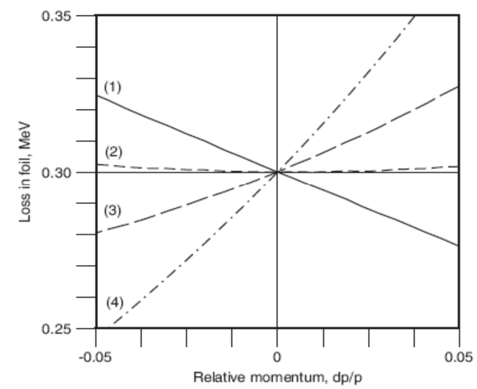
"In these conditions, like in the similar case of the synchrotron radiation, the transverse emittance will converge to zero. In the case of ionisation cooling, a finite equilibrium emittance is due to the presence of the multiple Coulomb scattering."



Longitudinal cooling in paper by Carlo Rubbia et al.

"In order to introduce a change in the dU/dE term — making it positive in order to achieve longitudinal cooling — the gas target may be located in a point of the lattice with a chromatic dispersion. The thickness of the foil must be wedge-shaped in order to introduce an appropriate energy loss change, proportionally to the displacement from the equilibrium orbit position."



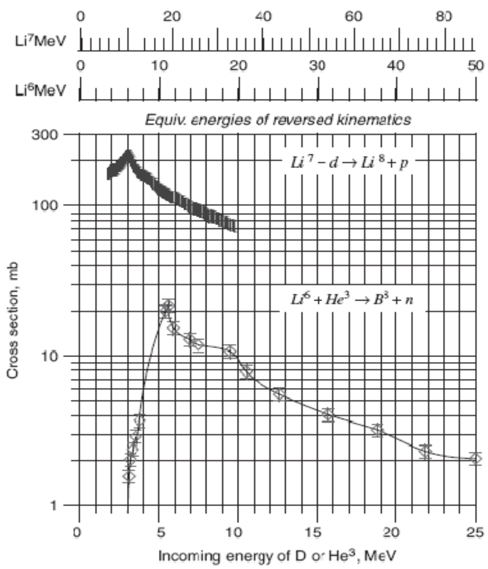


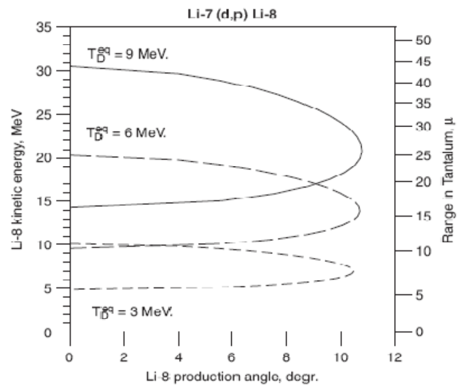
1) Without wedge, dU/dE<0
2) Wedge with dU/dE=0, no longitudinal cooling
3) Wedge with dU/dE=0.0094
4) Electrons, cooling through synchrotron radiation

Inverse kinematics production and ionisation parameters in paper by Carlo Rubbia et al.

$^{7}Li(d,p)^{8}Li$

$^{6}Li(^{3}He,n)^{8}B$





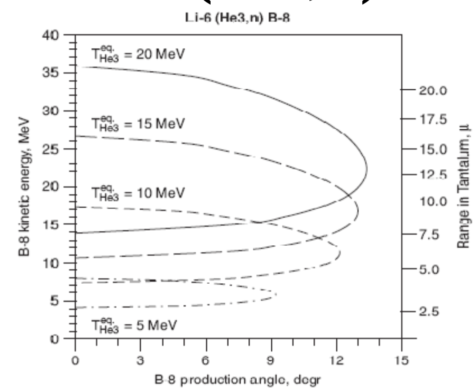


Table 1
Some ionisation parameters for ^{6}Li and ^{7}Li in the energy interval of interest

Energy, T (MeV)	dE/dx (MeV/(mg/cm^2))		$\sqrt{\langle Z \rangle^2}$		δE (keV) for loss of 0.3 MeV	
	^{6}Li	^{7}Li	^{6}Li	^{7}Li	^{6}Li	^{7}Li
5	3.356	3.355	2.94	2.89	10.646	9.866
10	2.120	2.014	3.00	3.00	11.751	10.205
15	1.660	1.573	3.00	3.00	13.340	11.714
20	1.356	1.329	3.00	3.00	14.752	12.999
25	1.116	1.092	3.00	3.00	16.102	14.174
30	0.965	0.890	3.00	3.00	17.331	15.323
35	0.861	0.778	3.00	3.00	18.428	16.309

Reactions to study for our application

- $^{20}Ne(p,t)^{18}Ne$
  - H.Backhausen et al, RCA,29(1981)1
- $^{16}O(^{3}He,n)^{18}Ne$
  - V.Tatischeff et al, PRC,68(2003)025804
- $^{6}C(CO_2,^{6}He)^{18}Ne$?
  - K.I.Hahn et al, PRC,54(1996)1999
- $^{7}Li(T,A)^{6}He$

CONCLUSIONS (Personal)

- I had the chance to work with you, Carlo, on UA1.

I learned a lot !

- It's always a pleasure to discuss Physics with you, Carlo
- It's sometimes tough
- It's always rewarding

THANKS CARLO !