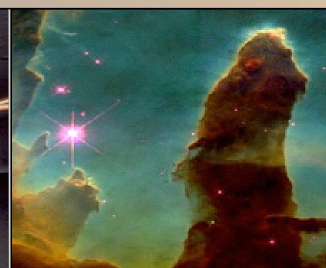
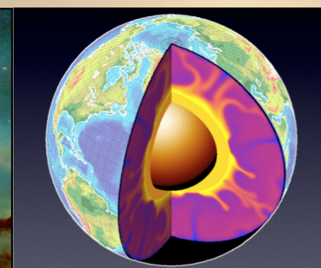
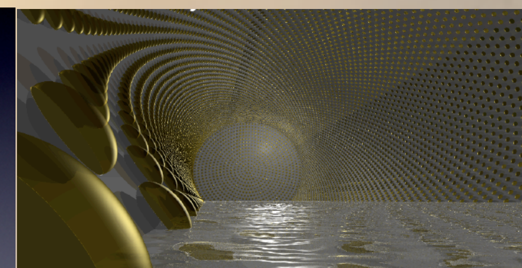
LAGUNA

Proton decay and beyond



Design of a pan-European infrastructure for Large Apparatus for Grand Unification and Neutrino Astrophysics (LAGUNA)

Proton decay
Supernova neutrinos
Diffuse SN neutrinos
Solar neutrinos
Atmospheric neutrinos
Geo-neutrinos
Reactor neutrinos
Neutrino beams
Indirect dark matter
(direct DM and DBD)

Neil Spooner - University of Sheffield

Journal of Cosmology and Astroparticle Physics
An IOP and SISSA journal

Large underground, liquid based detectors for astro-particle physics in Europe: scientific case and prospects

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Broad and Rich Physics Programme

- Direct evidence for Grand Unification (Proton decay)
- Low energy neutrino astronomy (SN, solar, geo, atm)
- Long baseline neutrino beam ($\not{C}P$)

Possibly combine accelerator & non-accelerator physics

Worldwide context: very large volumes

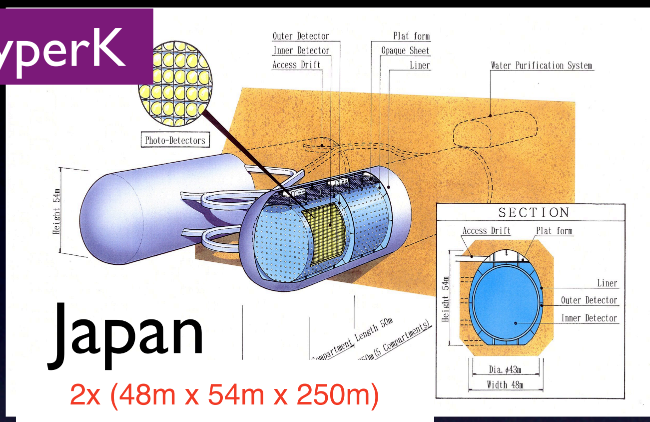
Europe enjoys today the most experience in underground science and sites, but lacks a coordinated plan for a possible future infrastructure of very large size

Some detectors presented at NNN Workshops

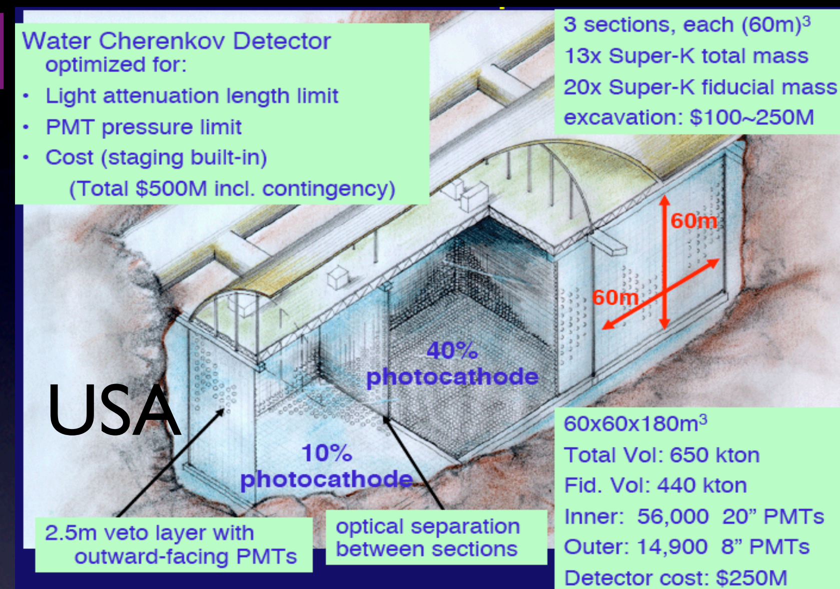
Megaton-scale-physics

Stony Brook 1999, ..., Aussois 05, Seattle 06, Hamamatsu Oct 07, Paris 08

HyperK



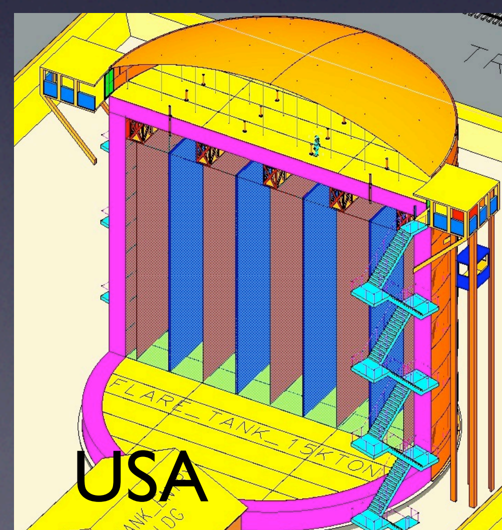
UNO/3M



Water Čerenkov 500kt→1Mt

LArTPC

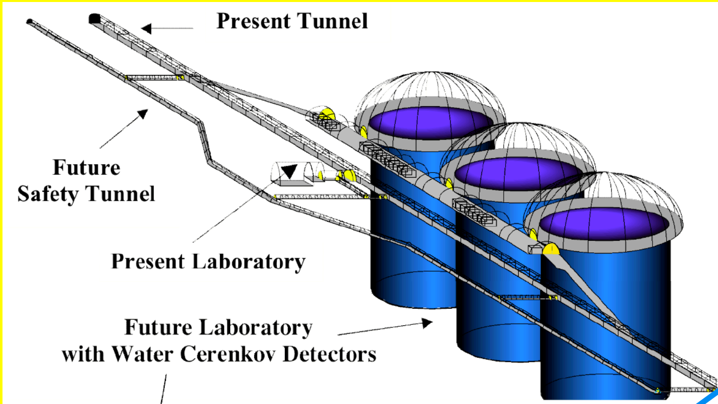
Liq. Argon→100kt



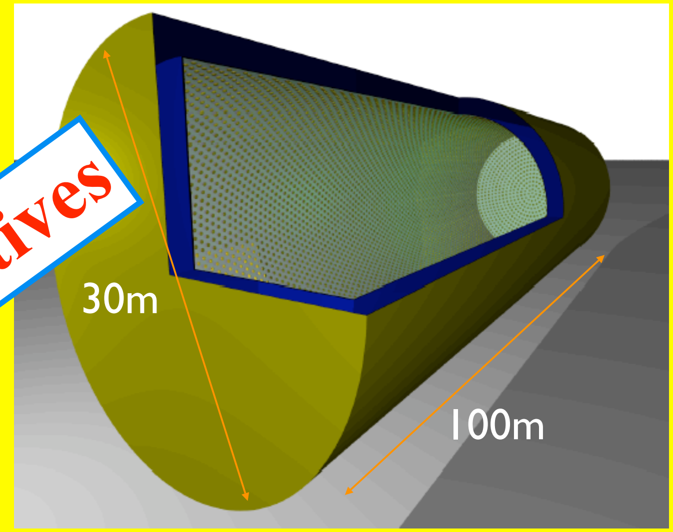
Large Underground Detectors

- Three experiments proposed

MEMPHYS

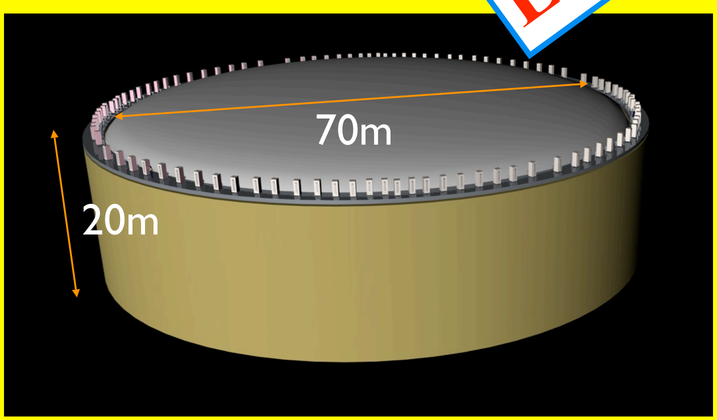


LENA Liquid Scintillator (→ 50 kton)



European initiatives

GLACIER Liquid Argon (≈1 … on)



List of people: J. Äystö, A. Badertscher, A. de Bellefon, L. Bezrukov, J. Bouchez, A. Bueno, J. Busto, JE. Campagne, C. Cavata, R. Chandrasekharan, S.Davidson, J. Dumarchez, T. Enqvist, A. Ereditato, F. von Feilitzsch, S. Gninenko, M. Göger-Neff, C. Hagner, K. Hochmuth, S.Katsanevas, L. Kaufmann, J. Kisiel, T. Lachenmaier, M. Laffranchi, M. Lindner, J. Lozano, A. Meregaglia, M. Messina, M. Mezzetto, L. Mosca, S. Navas, L.Oberauer, P. Otyougova, T. Patzak, J. Peltoniemi, W. Potzel, G. Raffelt, A. Rubbia, N. Spooner, A. Tonazzo, T.M. Undagoitia, C. Volpe, M. Wurm, A. Zalewska, R. Zimmermann

Why Now - New Motivation?

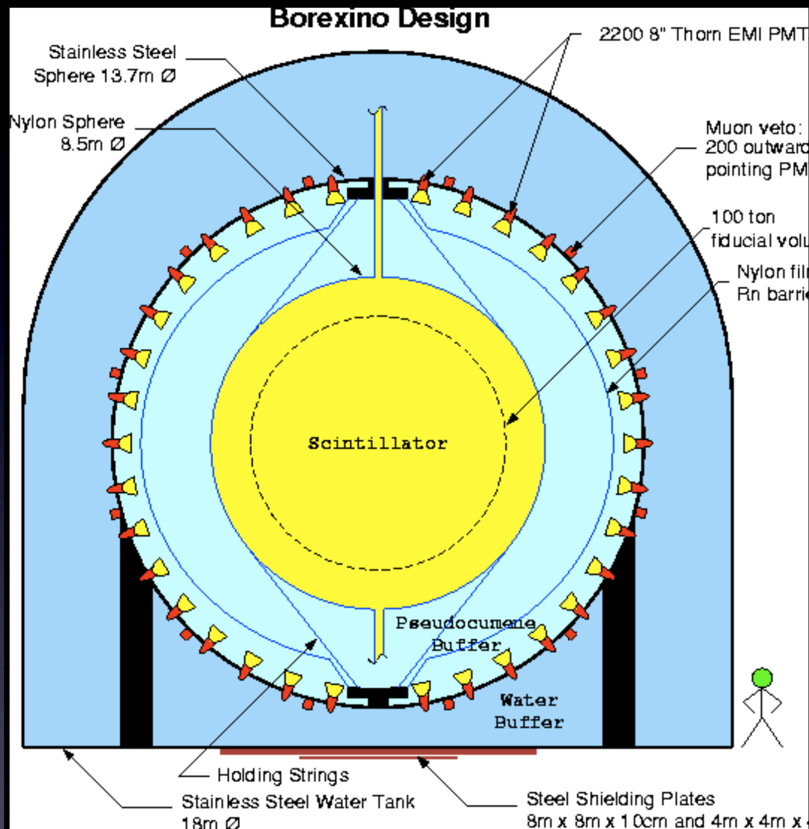
- New technology is maturing
    - Liquid scintillator
    - Liquid argon
    - Photosensors
- New opportunities, and experience of, deep sites
- New understanding of ultra low background control
- An explosion in underground SCIENCE

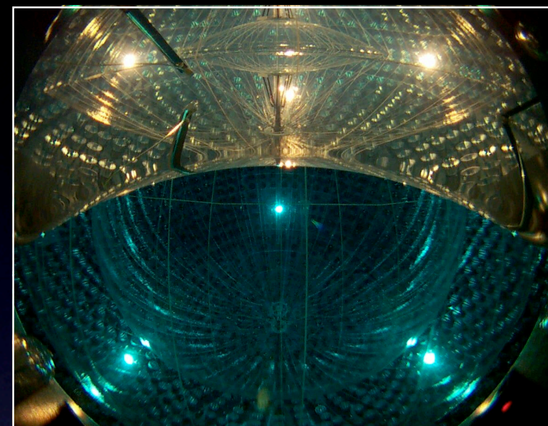
Agency View

A neutrino detector optimized for proton decay searches is also well matched to detect neutrinos of <~ 1 GeV

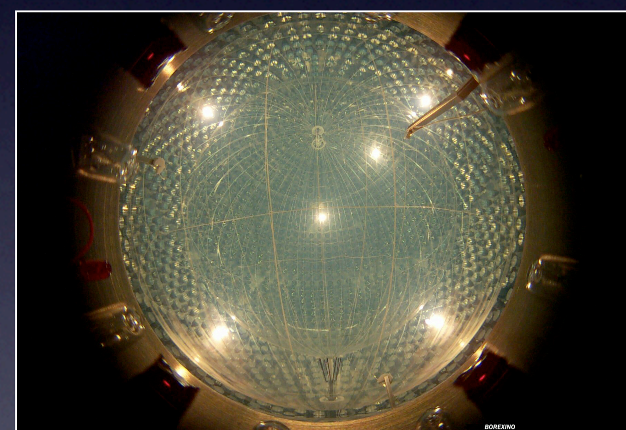
- **Japan**: Super -K (50 kton) → Hyper-K (1 Mton) (T2K phase II)
- **US**: Report of the US long baseline neutrino experiment study "A well instrumented very large detector, in addition to its accelerator based neutrino program, could be sensitive to proton decay which is one of the top priorities in fundamental science… Indeed, there is such a natural marriage between the requirements to discover leptonic CP violation and see proton decay that it could be hard to imagine undertaking either effort without being able to do the other"
- **Europe**: ApPEC recommendation "We recommend that a new large European infrastructure is put forward as a future international multi-purpose facility on the 100 – 1000 ktons scale for improved studies of proton decay and of low-energy neutrinos from astrophysical origin. The detection techniques … should be evaluated in the context of a common design study, which should also address the underground infrastructure and the possibility of an eventual detection of future accelerator neutrino beams"

e.g. BOREXINO success





During PC filling



filled

Total effective fid. vol. -->87 tons
LY≈500 p.e./MeV

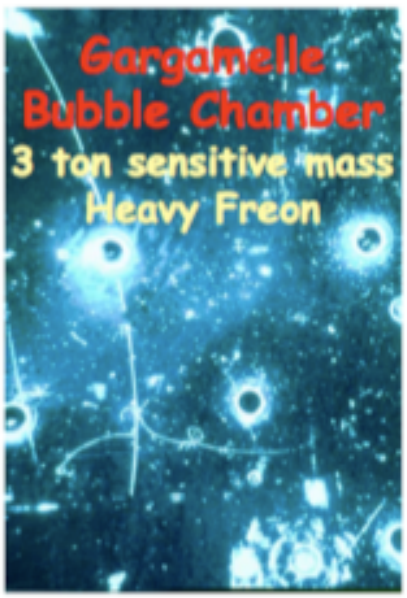
< 6.6 10^{-18} g/g ^{232}Th equivalent

$47 \pm 7_{stat}$ cpd/100tons
for 862 keV ^{7}Be solar ν

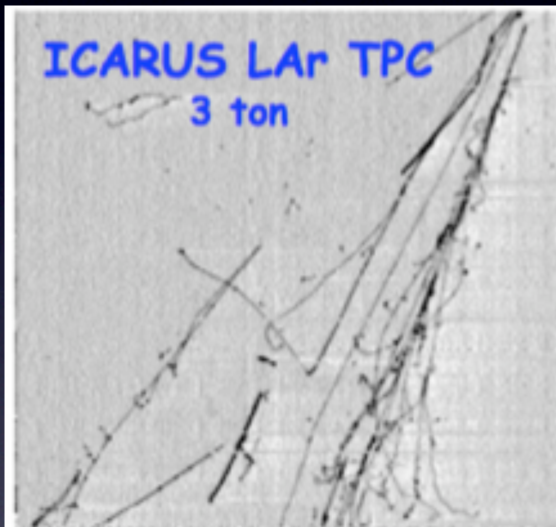
More details in arXiv:0708.2251

e.g. Liquid Argon Success

- A real time bubble chamber - a new way to observe events
  - High granularity: readout pitch ~3mm, local deposition measurement, particle type identification

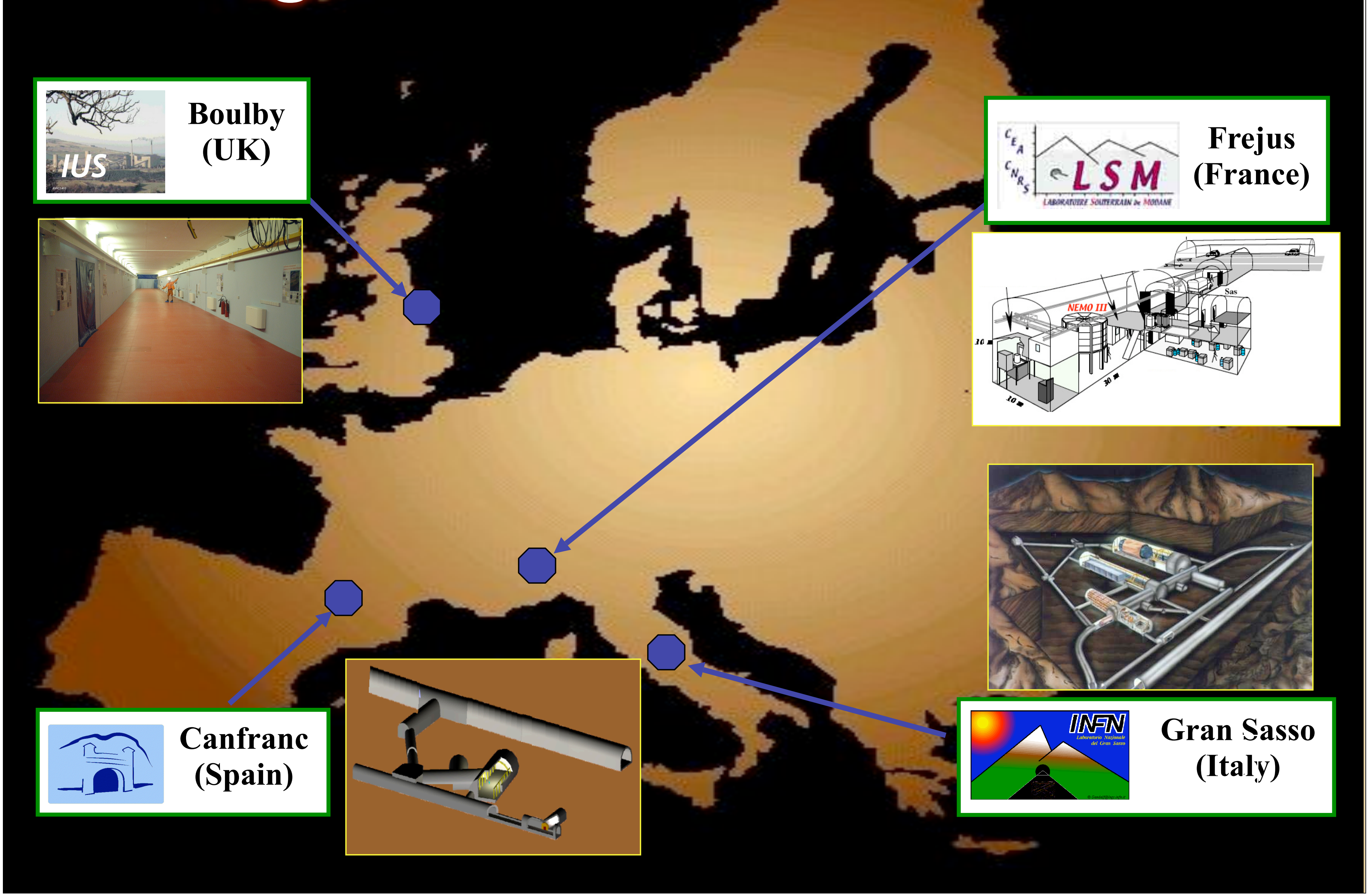


Bubble ∅ (mm)	3
Density (g/cm^3)	1.5
X_0 (cm)	11.0
λ_T (cm)	49.5
dE/dx (MeV/cm)	2.3



Resolution (mm^3)	2×2×0.2
Density (g/cm^3)	1.4
X_0 (cm)	14.0
λ_T (cm)	54.8
dE/dx (MeV/cm)	2.1

e.g. Success with EU Sites



e.g. New Potential Sites

SLANIC (ROMANIA)

SUNLAB Sieroszowice mine (Poland)

CUPP (Finland)

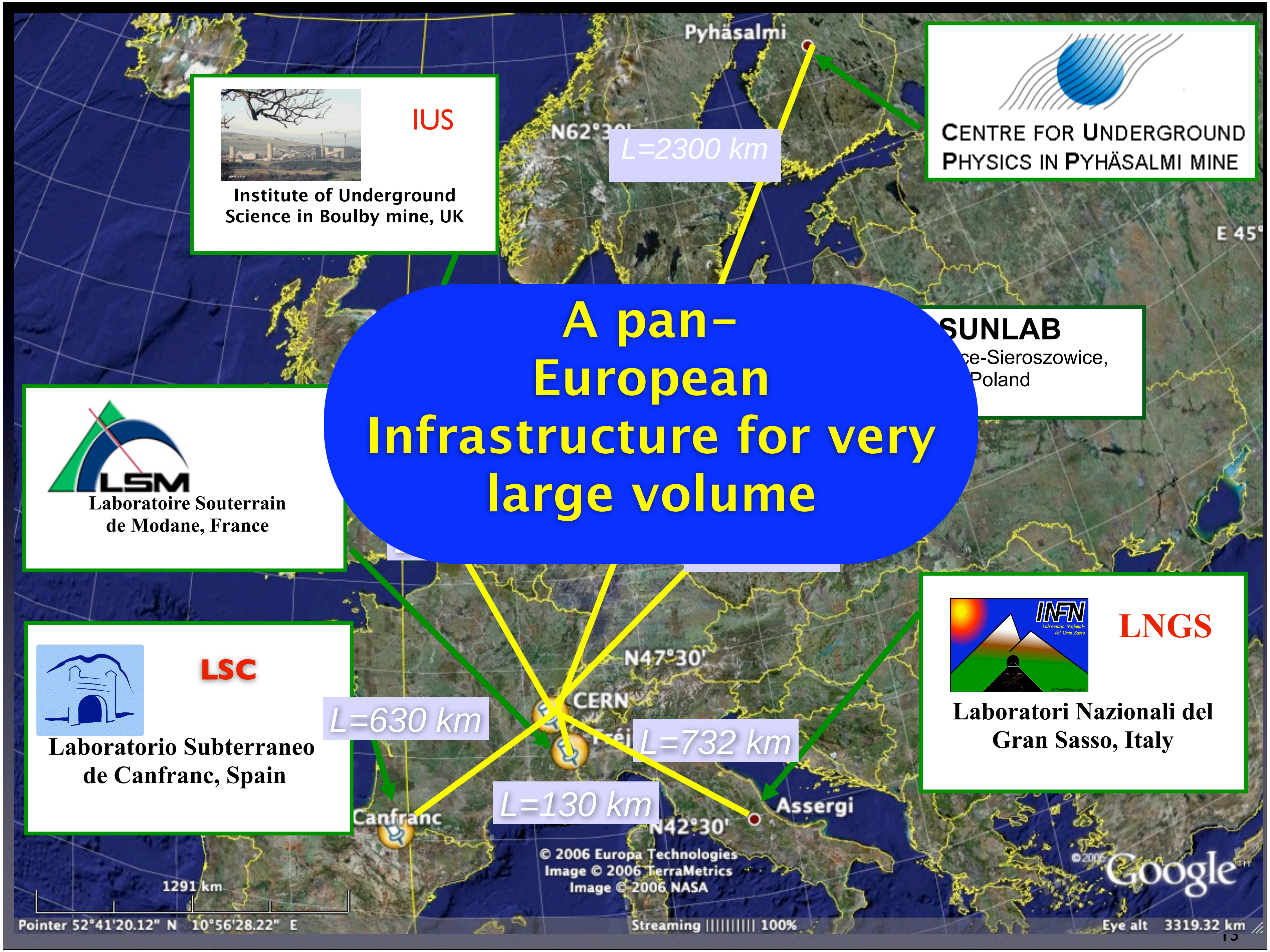
None of these laboratories can host next generation very large volume observatories. Extension are needed.

•What depth?

•What other synergies? (beamline distance from artificial sources at accelerators)

•What is the distance from reactors?

•Which model ?


A pan-European Infrastructure for very large volume
IUS
Institute of Underground Science in Boulby mine, UK
Centre for Underground Physics in Pyhäsalmi Mine
SUNLAB
ce-Sieroszowice,
Poland
LSM
Laboratoire Souterrain de Modane, France
LSC
Laboratorio Subterraneo de Canfranc, Spain
INFN
LNGS
Laboratori Nazionali del Gran Sasso, Italy
L=2300 km
L=630 km
L=732 km
L=130 km
Pyhäsalmi
CERN
Canfranc
Assergi
N62°30'
N47°30'
N42°30'
E 45°
1291 km
© 2006 Europa Technologies
Image © 2006 TerraMetrics
Image © 2006 NASA
Google
Pointer 52°41'20.12" N 10°56'28.22" E
Streaming |||||||||| 100%
Eye alt 3319.32 km

Site Characteristics

Site	Boulby	Canfranc	Fréjus	Gran Sasso	Pyhäsalmi	Sieroszowice
Location	UK	Spain	Italy–France border	Italy	Finland	Poland
Dist. from CERN (km)	1050	630	130	730	2300	950
Type of access	Mine	Somport tunnel	Fréjus tunnel	Highway		
Tunnel	Mine	Shaft				
Vert. depth (m.w.e.)	2800	2450	4800	3700	4000	2200
Type of rock	Salt	Hard rock	Hard rock	Hard rock	Hard rock	Salt and rock
Type of cavity			Shafts		tunnel	Shafts
Size of cavity			$\Phi = 65$ m $H = 80$ m		$(20 \times 20 \times 120)$ m^3	$\Phi = 74$ m $H = 37$ m
μ flux (m^{-2} day^{-1})	34	406	4	24	9	Not available

ILIAS

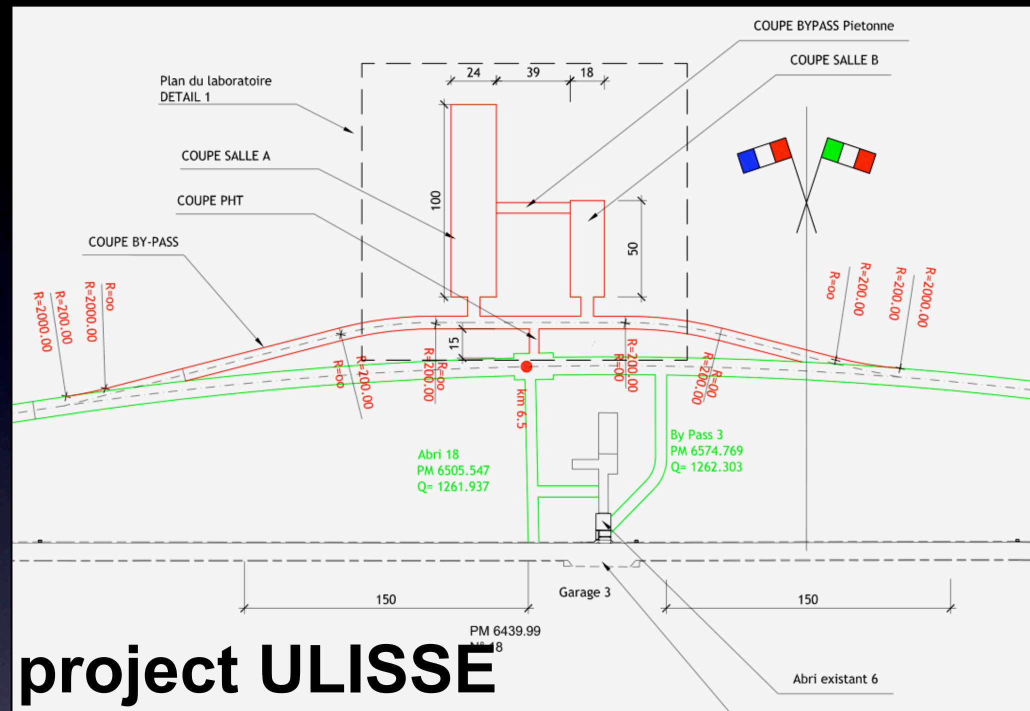
ILIAS and the Deep Underground Labs in Europe

Coordination of European deep underground labs

LSM Extensions?

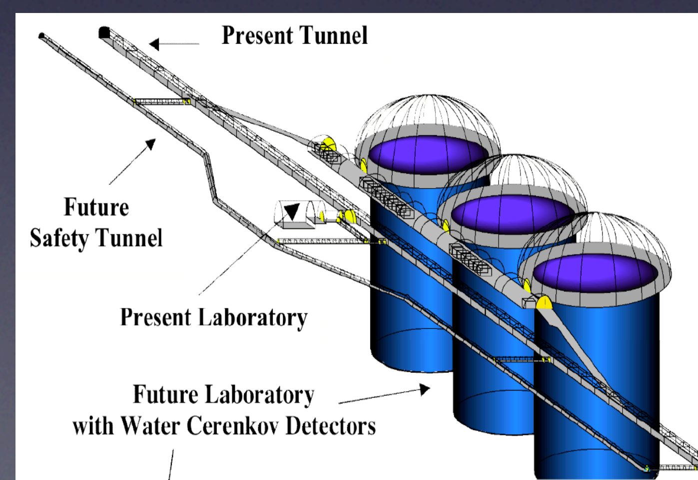
(1) 50,000 m^3
volume = 1/3 of one LNGS hall

- middle size projects for deep site
- third generation DBD and DM searches
(100 kg to 1T)
- low level radioactive environment
- small size neutrino detectors

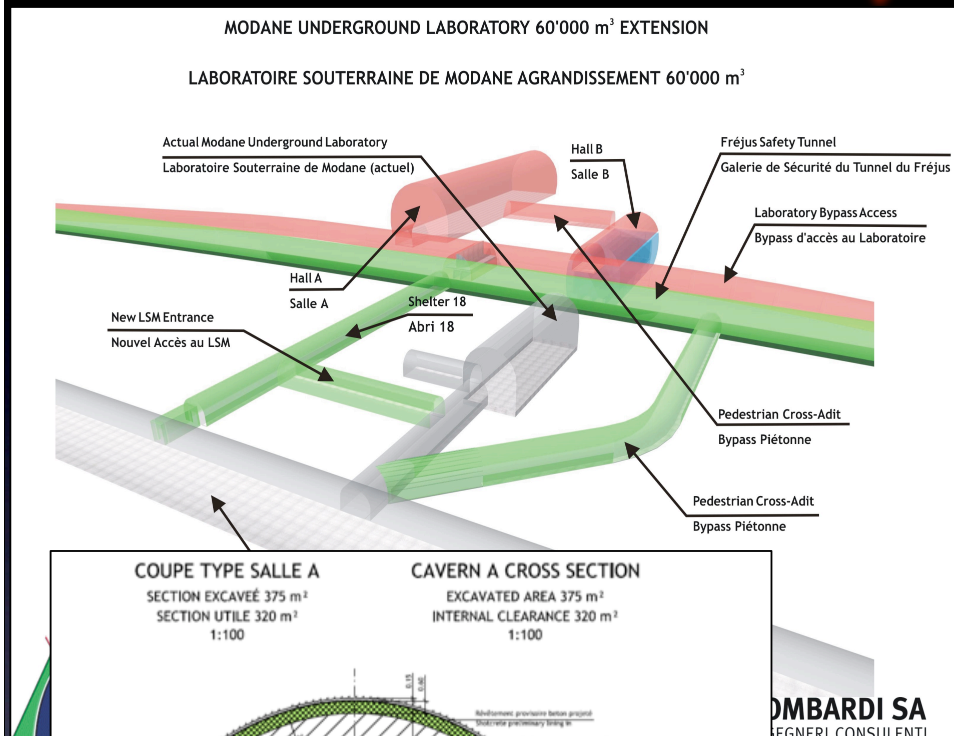


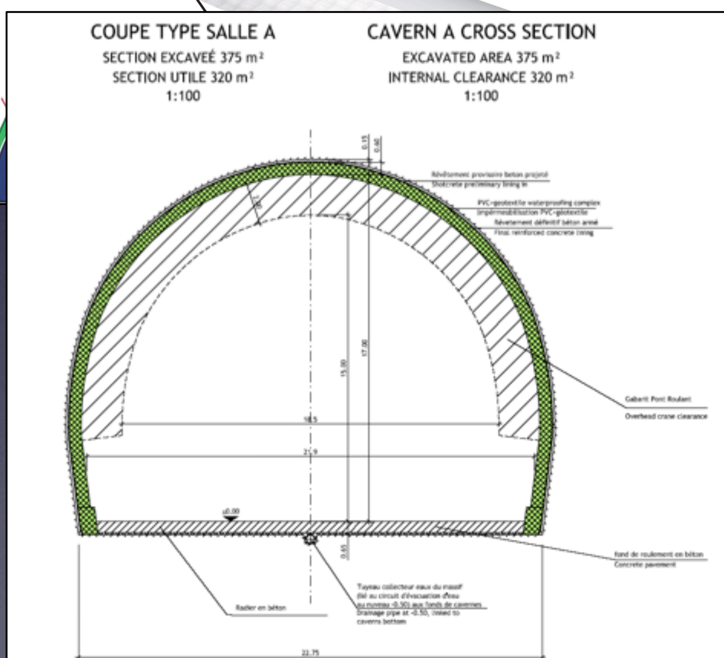
(2) 1,000,000 m^3
major international laboratory

- neutrino properties
- proton decay - MEMPHYS
- supernovae

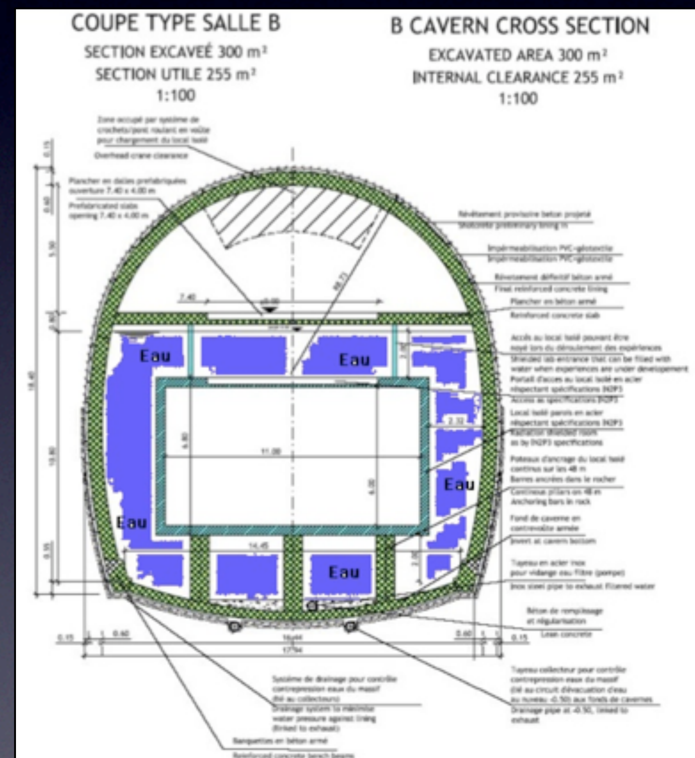


LSM Project ULISSE





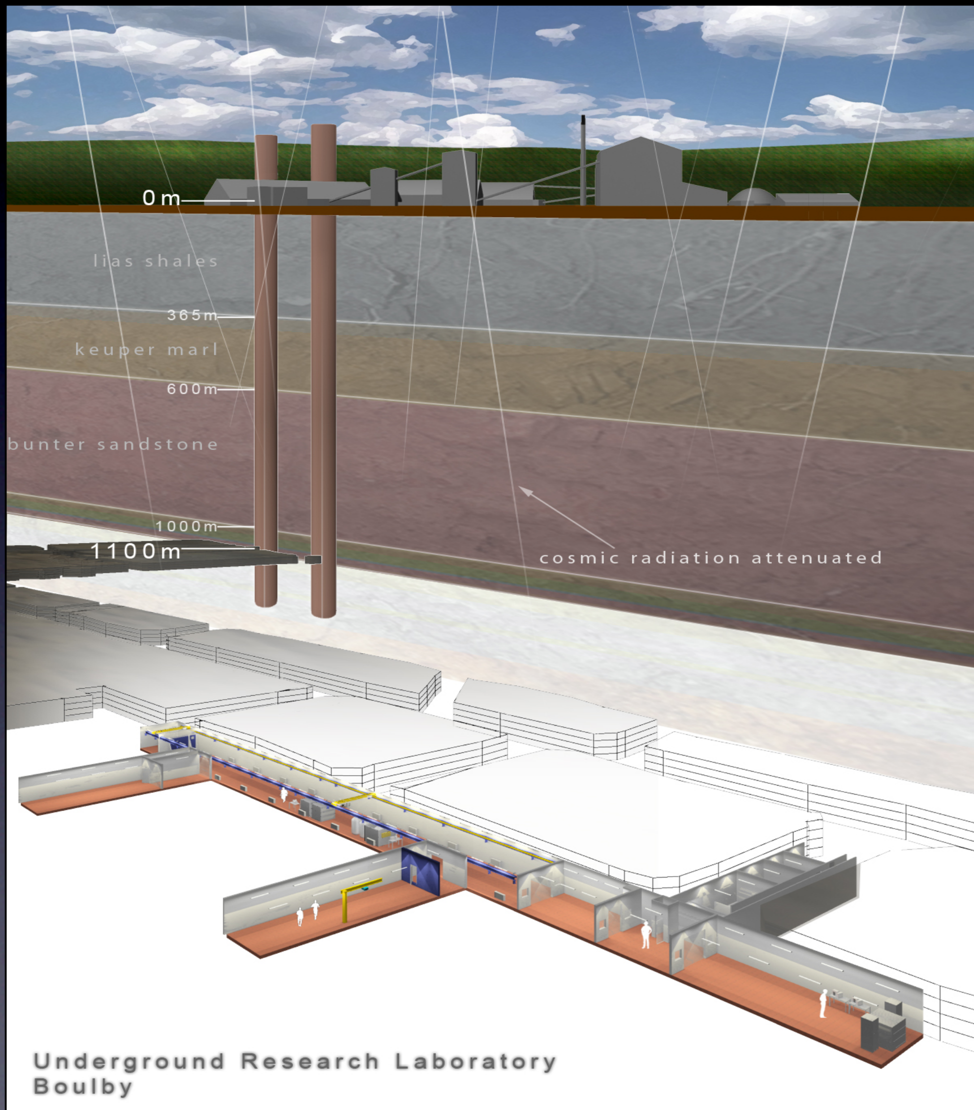
Shield of 2m of water
2 openings of 4x7 m, crane outside
Internal protected volume : 11x40x6 m
Internal shield of low activity steel (300 T). Radon free



HALL A
(SuperNEMO)
tunnel shape : 24 m x100 m

Boulby JIF award 1999....

opened by Lord Sainsbury in April 2003

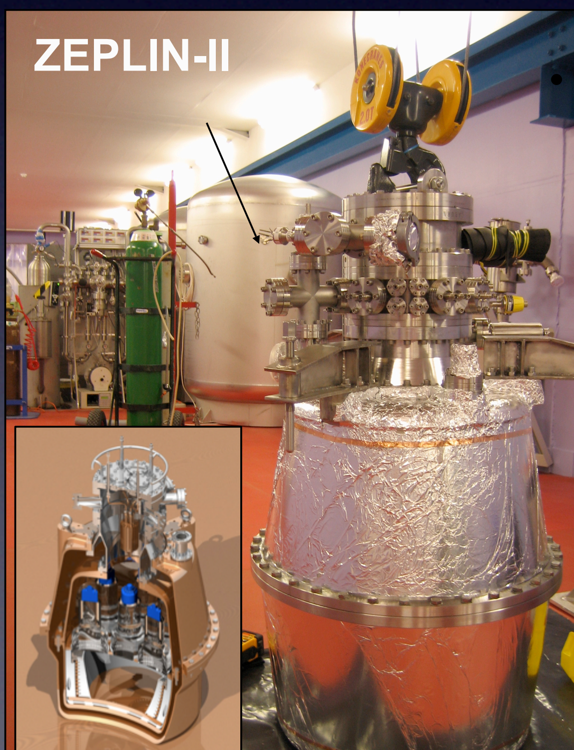


Boulby

Boulby - Status

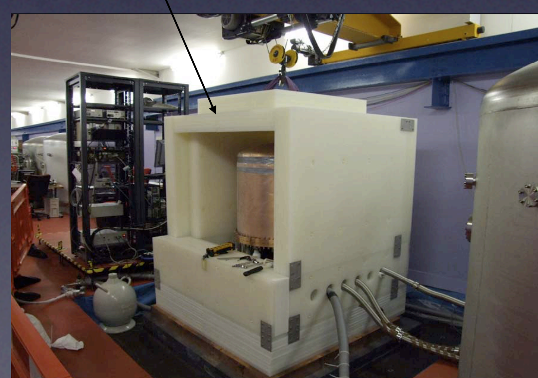
Science. Dark matter
ZEPLIN II (LXe 2 phases, 30 kg)
ZEPLIN III (LXe 2 phases)
DRIFT II (tracking, low pressure)
Low radioactivity measurements
Geophysics

DRIFT-II



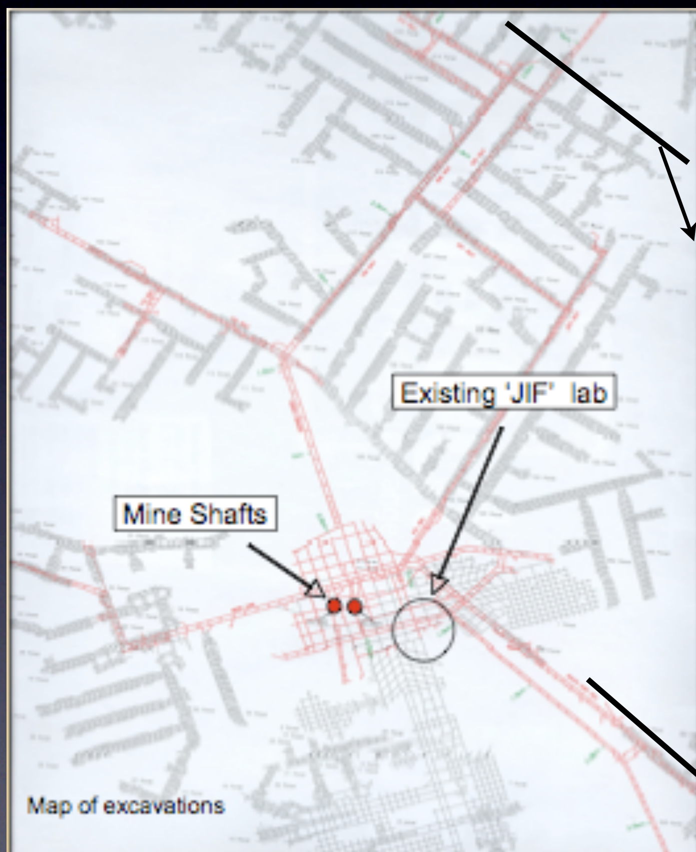
Two phase liquid Xenon Dark Matter detectors

ZEPLIN-III



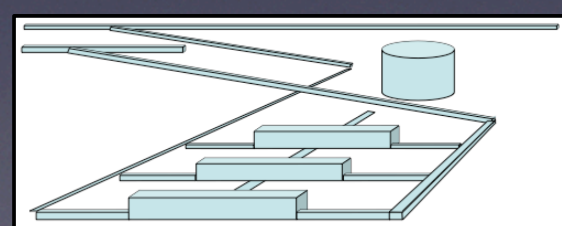
Boulby Expansion?

New regional development proposal for deeper, hard rock labs to be submitted - 2 years to excavation



- **Possibility of larger, sable caverns - 30m high?**
- **50 year+ mine lifetime**

New CPL-University partnership seeking feasibility study

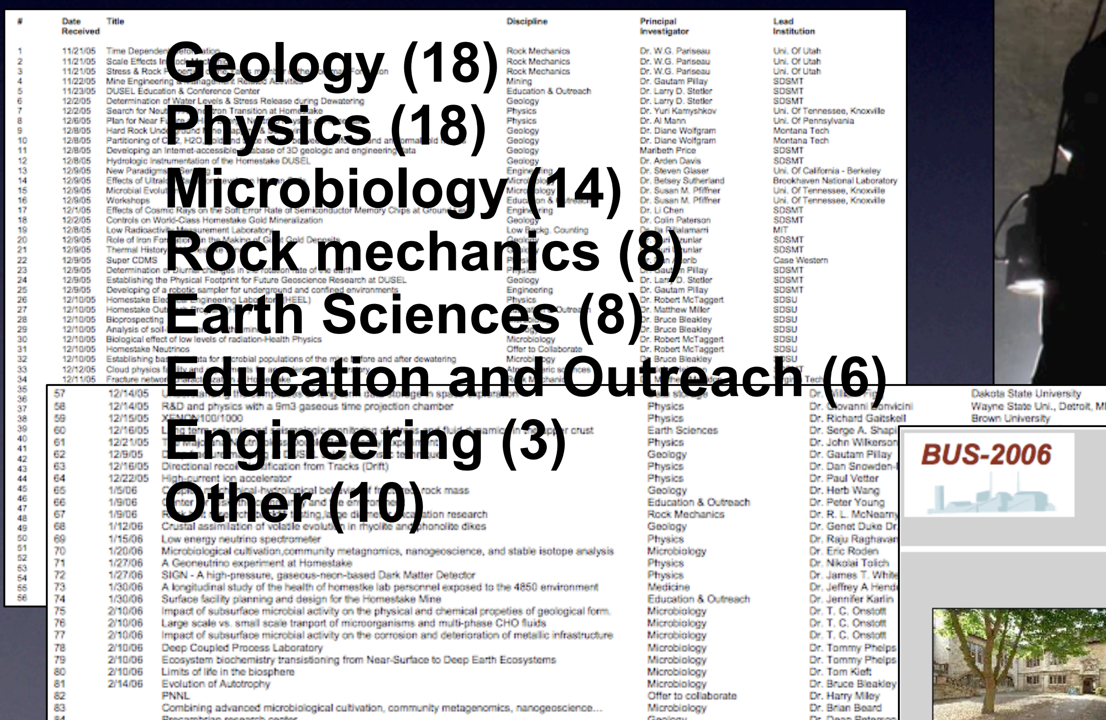


Excavation!

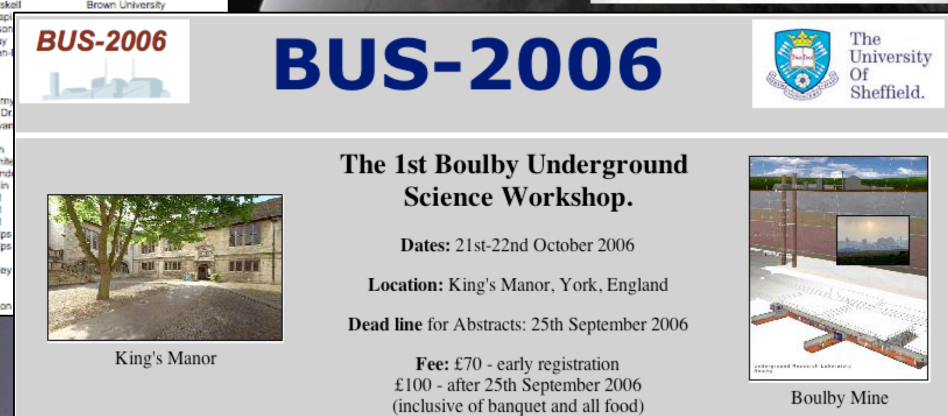
- Actually not a critical path cost, typically $20/m^3

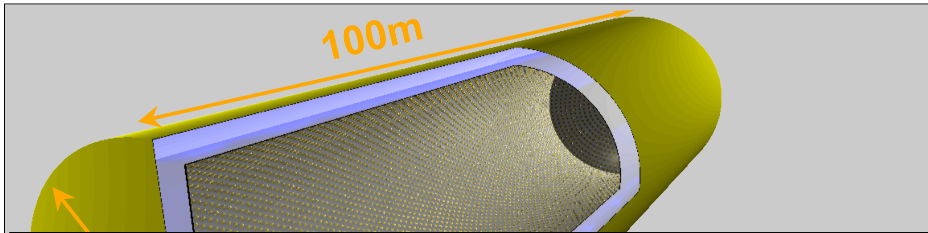
US-DUSEL @ Homestake

- US moves to $0.5B site
- Homestake mine got ~100 proposals



- Geology (18)
- Physics (18)
- Microbiology (14)
- Rock mechanics (8)
- Earth Sciences (8)
- Education and Outreach (6)
- Engineering (3)
- Other (10)



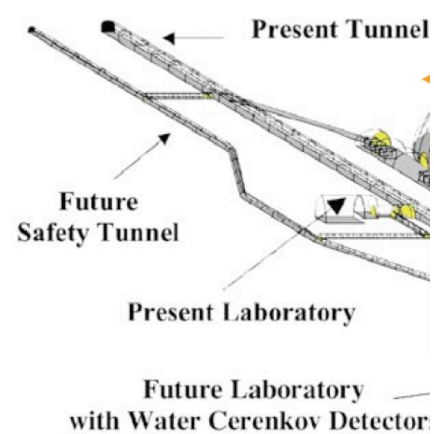


LAGUNA

Large Apparatus for Grand Unification and Neutrino Astrophysics

- Cherenkov: cheap target, well proven
- Liquid Scint... energy resolution, ...nergy e.g. solar/ geo neutrin...
- Liquid Argo...nts - like bubble chamber

Proton decay
Supernova neutrinos
Diffuse SN neutrinos
Solar neutrinos
Atmospheric neutrinos
Geo-neutrinos
Reactor neutrinos
Neutrino beams
Indirect dark matter
(direct DM and DBD)



MPHYS

T
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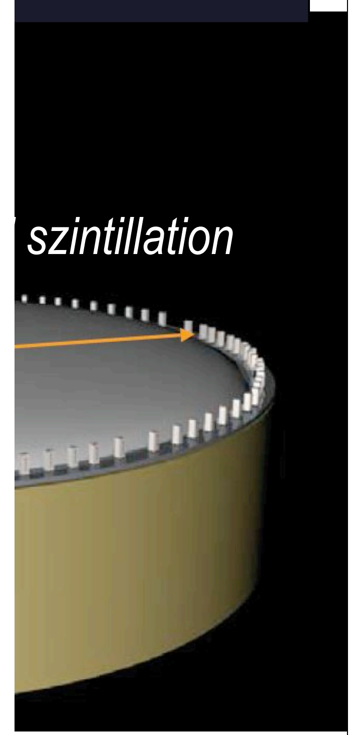
vert.
-800

T
R
er
. 0.2% $GdCl_3$)
00
PMTs
coverage

ampl. in
gas phase;
Cher. light: 27 000
8″ PMTs,
~20% coverage;
scint. light: 1000
8″ PMTs



Proton Decay

Motivation

- Grand-Unification (GUT): seeking to unify strong and electroweak forces - motivated by apparent merging of forces at ~10^{16}GeV
- GUT Generic prediction: a fundamental symmetry between quarks and leptons - transmutation possible and hence proton (and neutron bound inside nucleus) unstable
- Exchange of massive boson between two quarks in proton (neutron)

$$q \rightarrow l, q \rightarrow \bar{q}$$

- Favoured decay based on "minimal" SU(5) $p \rightarrow e^+ \pi^o$ with lifetime scale as M_X^4

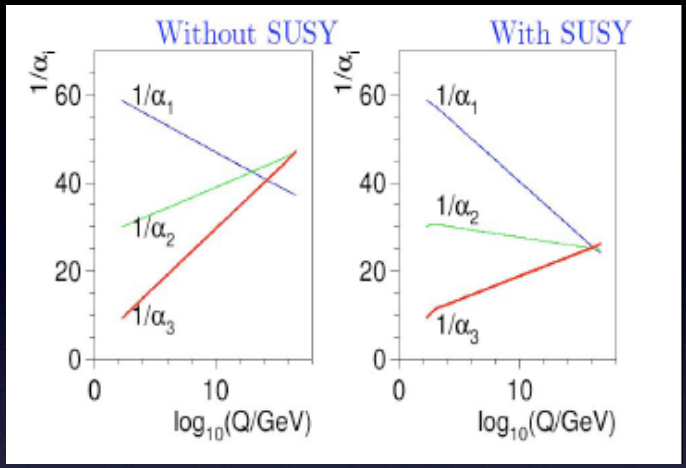
$$\tau / B(p \rightarrow e^+ \pi^o) \sim 10^{29 \pm 2} \, years$$

- Introducing SUSY increases coupling scale by x10, lifetime by x10^4

Proton Decay

- In fact in SUSY GUT models tranisition to anti-strange quark is favored resulting in K meson

"minimal" SUSY SU(5)



$$p \to \bar{\nu}K^+, n \to \bar{\nu}K^o$$

- Typical lifetimes then: $\tau / B(p \to \bar{\nu}K^+) \leq 2.9 \times 10^{30}\ years$
- But many new free parameters means suppression possible, and other models, e.g. SO(10) (incoporating neutrino mass)
- Many models are within reach of next generation detectors (even SK)

Proton Decay

Model	Decay modes	Prediction	References
Georgi–Glashow model	—	ruled out	[1]
Minimal realistic non-SUSY $SU(5)$	All channels	$\tau_{\mathrm{p}}^{\mathrm{upper}} = 1.4 \times 10^{36}$	[2]
Two step non-SUSY $SO(10)$	$p \to e^+\pi^0$	$\approx 10^{33-38}$	[3]
Minimal SUSY $SU(5)$	$p \to \bar{\nu}K^+$	$\approx 10^{32-34}$	[4]
SUSY $SO(10)$ with 10_H, and 126_H	$p \to \bar{\nu}K^+$	$\approx 10^{33-36}$	[5]
M-theory (G_2)	$p \to e^+\pi^0$	$\approx 10^{33-37}$	[6]
$SU(5)$ with 24_{F}	$p \to \pi^0 e^+$	$\approx 10^{35-36}$	[7]
Renormalizable adjoint $SU(5)$	$p \to \pi^0 e^+$	$\approx 10^{35-36}$	[8]

The unification of the electromagnetic, weak and strong forces
Represented by **SU(3)xSU(2)xU(1)**

History

1929: Weyl suggests absolute stability of proton

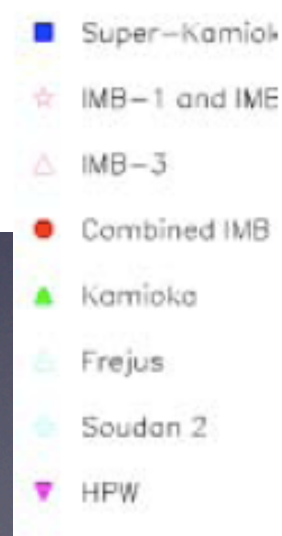
1938: Stuckelberg and 1949: Wigner postulate existenc
conservation of a “heavy charge” (baryon number) ass
heavy particles

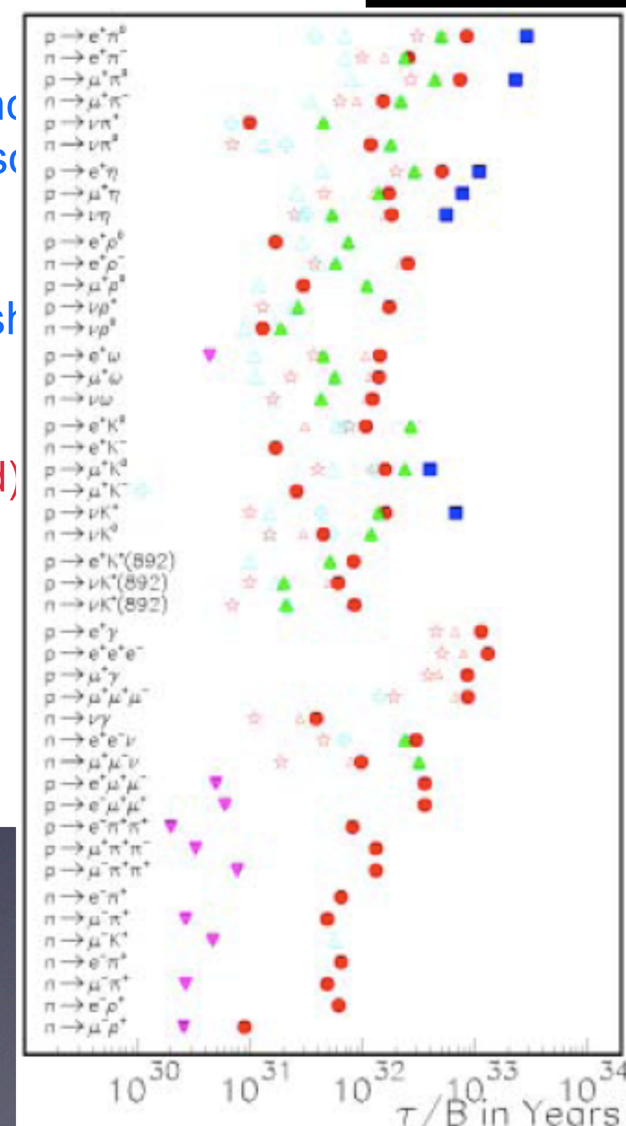
1954: M. Goldhaber (w/ Reines and Cowan, Jr.) publisl
experimental result on proton lifetime

using a liquid scintillator detector (shielded w/ paraffin+lead)
~3×10^{28} protons, he obtains lower limits on τ_p
$\tau_p > 10^{21}$ years (for free protons)
$\tau_p > 10^{22}$ years (for bound nucleons)

since then…

Best limits:
dominated by water
Cherenkov detectors





Proton Decay

- Recent limits (water Cherenkov and iron calorimeter)

SK:

$$p \to \bar{\nu} K^{+} : 6.7 \times 10^{32}\ years$$

$$n \to \bar{\nu} K^{o} : 8.6 \times 10^{31}\ years$$

$$p \to \mu^{+} K^{o} : 1.2 \times 10^{31}\ years$$

$$p \to e^{+} K^{o} : 1.5 \times 10^{31}\ years$$

Non supersymmetric Grand Unified Theories

Dominant decay mode: $p \to e^+ \pi^0$ $\tau \sim 10^{36}$ y

Supersymmetry (SUSY)

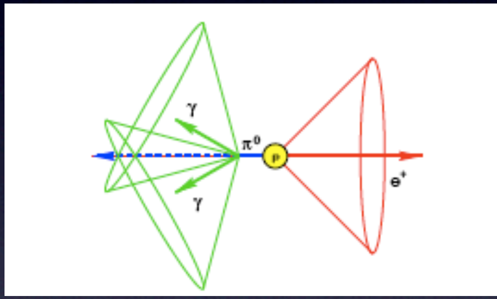
Dominant decay mode: $p \to K^+ \overline{\nu}$ $\tau \sim 10^{34}$ y

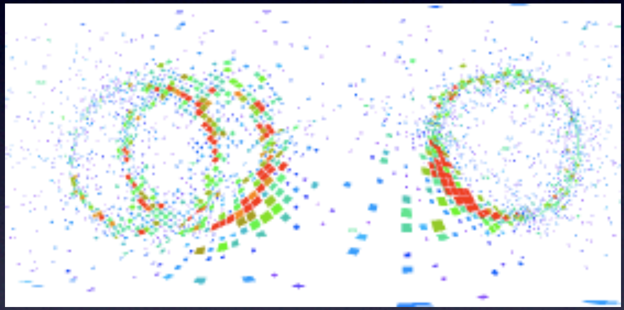
- Superkamiokande: $\tau(p \to e^+ \pi^0) \gtrsim 5.4 \cdot 10^{33}$ y (90% C.L.)
  $\tau(p \to K^+ \overline{\nu}) \gtrsim 2.3 \cdot 10^{33}$ y (90 % C.L.)

SK Results

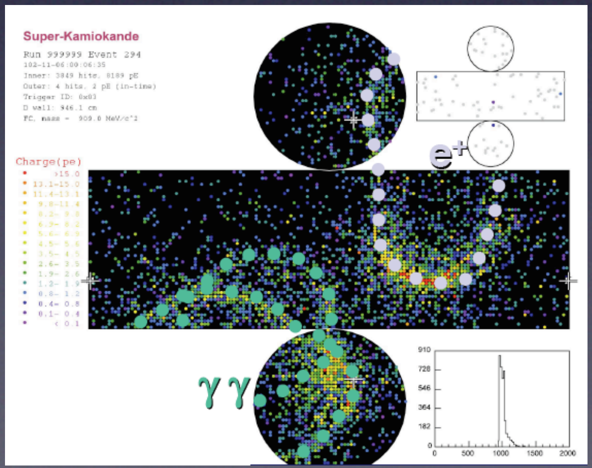
- SK - ring imaging water Cherenkov counter at Kamioka at 2700 mwe depth with 50 Ktons
  - cuts and selection criteria tuned to select decay modes
  - efficiencies calculated and comparison made with MCs

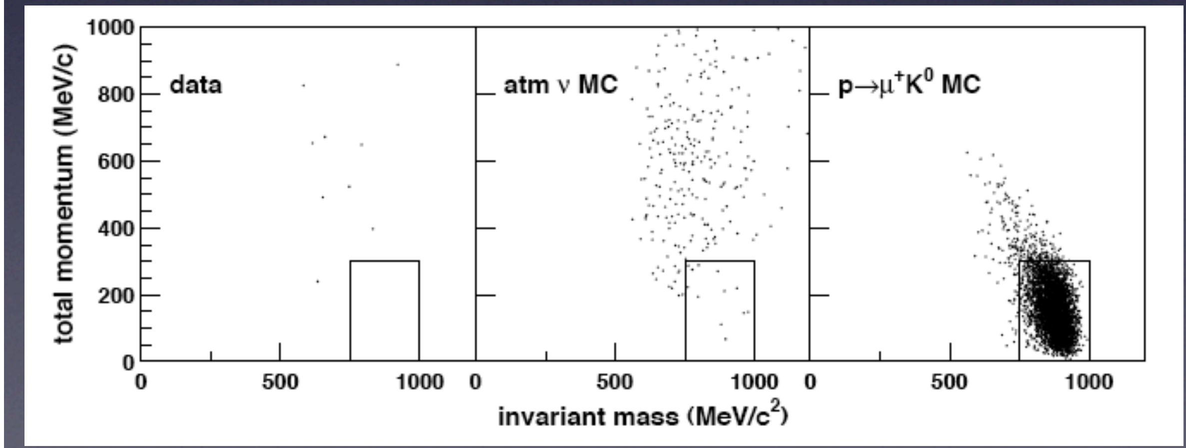
Idealized p → $e^+\pi^\circ$ decay in Super-Kamiokande.





real event





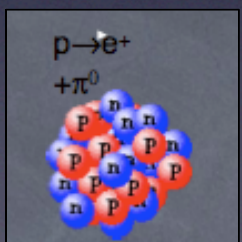
LAGUNA Proton Decay

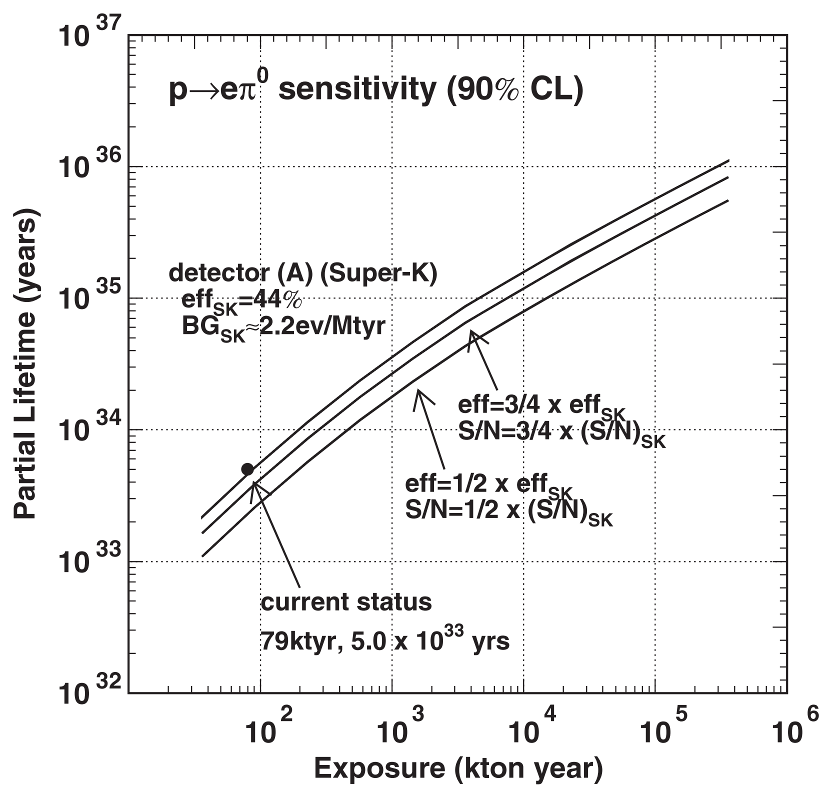
	GLACIER	LENA	MEMPHYS
$e^+\pi^0$			
$\epsilon(\%)$/bkgd (Mton yr)	45/1	—	43/2.25
τ_p/B (90% C.L., 10 yr)	0.4×10^{35}	—	1.0×10^{35}
$\bar{\nu}K^+$			
$\epsilon(\%)$/bkgd (Mton yr)	97/1	65/1	8.8/3
τ_p/B (90% C.L., 10 yr)	0.6×10^{35}	0.4×10^{35}	0.2×10^{35}

MEMPHYS

$p \rightarrow e^+\pi^\circ$

Sensitivity to the $p \rightarrow e^+\pi^\circ$ proton decay mode compiled by UNO collaboration. MEMPHYS corresponds to case (A)

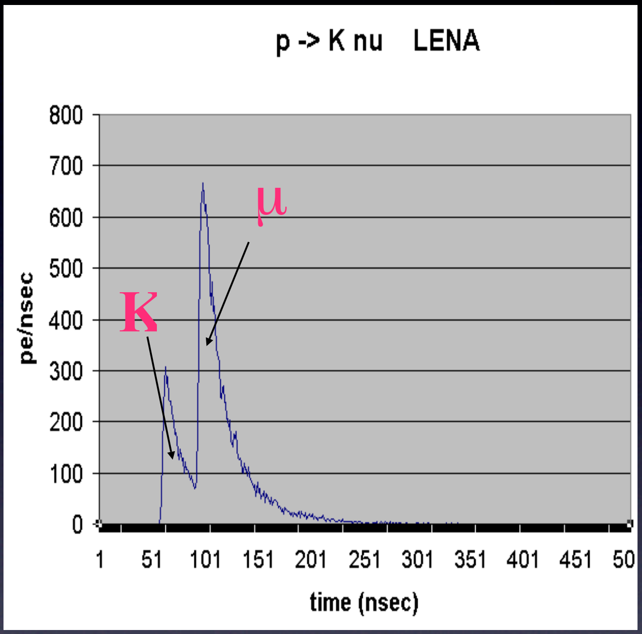




LAGUNA Proton Decay

LENA $P \rightarrow K^{+} \nu$ event structure:

- This decay mode is favoured in **SUSY** theories
- The primary decay particle K is invisible in Water Cherenkov detectors
- It and the K-decay particles are visible in scintillation detectors (prompt 105 MeV, then signal from decay - two main channels)
- Better energy solution further reduces background



LAGUNA Proton Decay

GLACIER

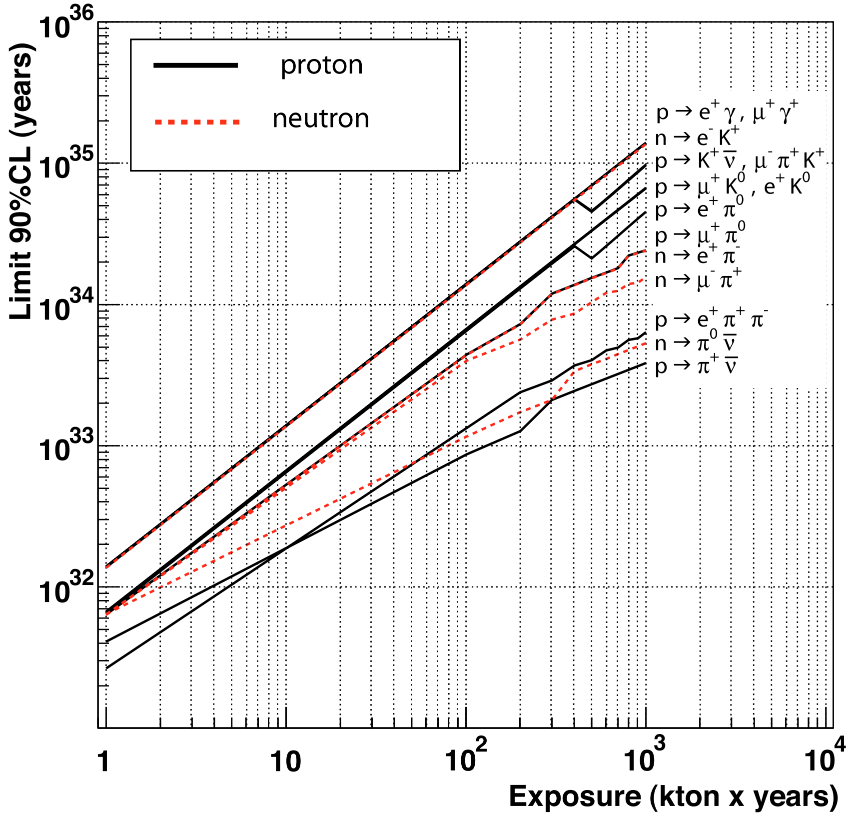
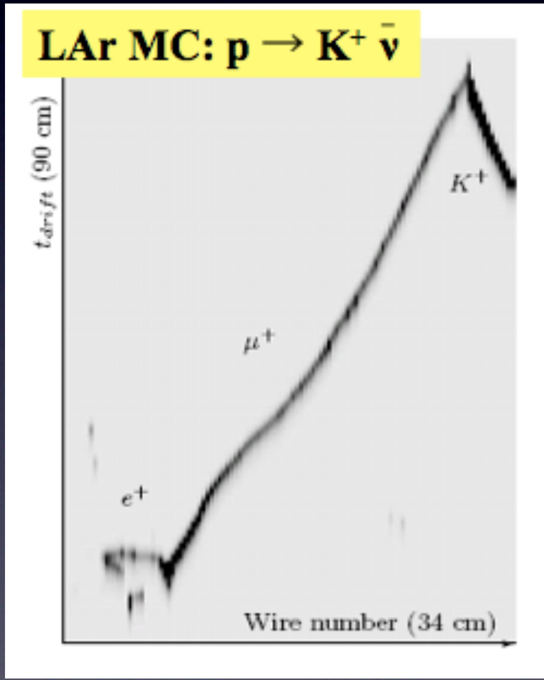


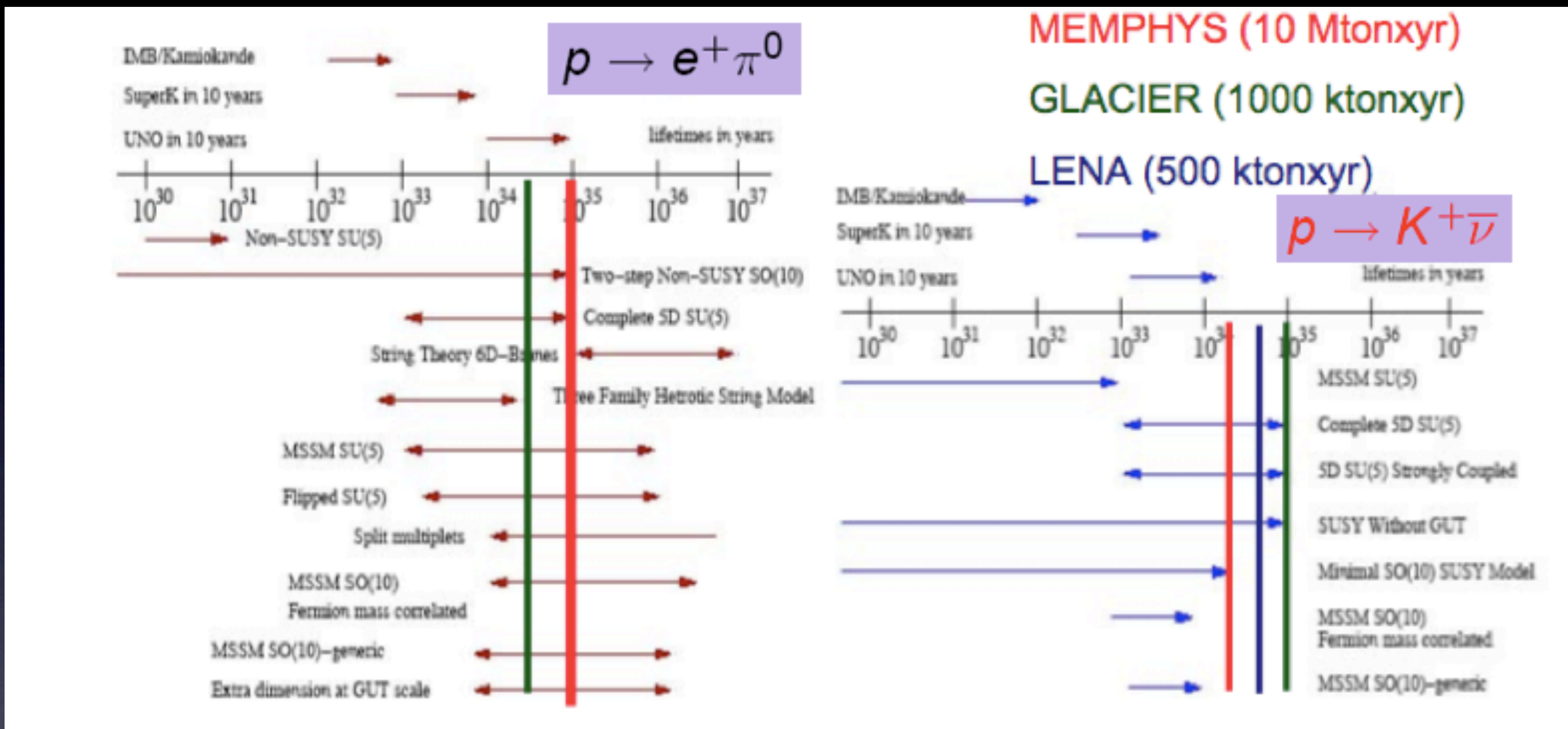
Figure 6. Expected proton decay lifetime limits (τ/B at 90% C.L.) as a function of exposure for GLACIER. Only atmospheric neutrino background has been taken into account. Reprinted figure with permission from [58].

Expected proton decay lifetime limits (90% cl) vs. exposure for GLACIER (only atmospheric neutron background has been taken into account).



dE/dX vs. range discrimination is powerful for background, in fact could go to shallower depth

Comparison with Theory



- Not exhaustive, (e.g. 6D SO(10) not included)

Astrophysical Neutrinos

- A glorious recent track record, the functionig of stars and the properties of neutrinos
  - Supernovae
  - The Sun
  - Interactions of primary CRs with the Earth's atmosphere

  - Nobel Prizes - M. Koshiba, R. Davis

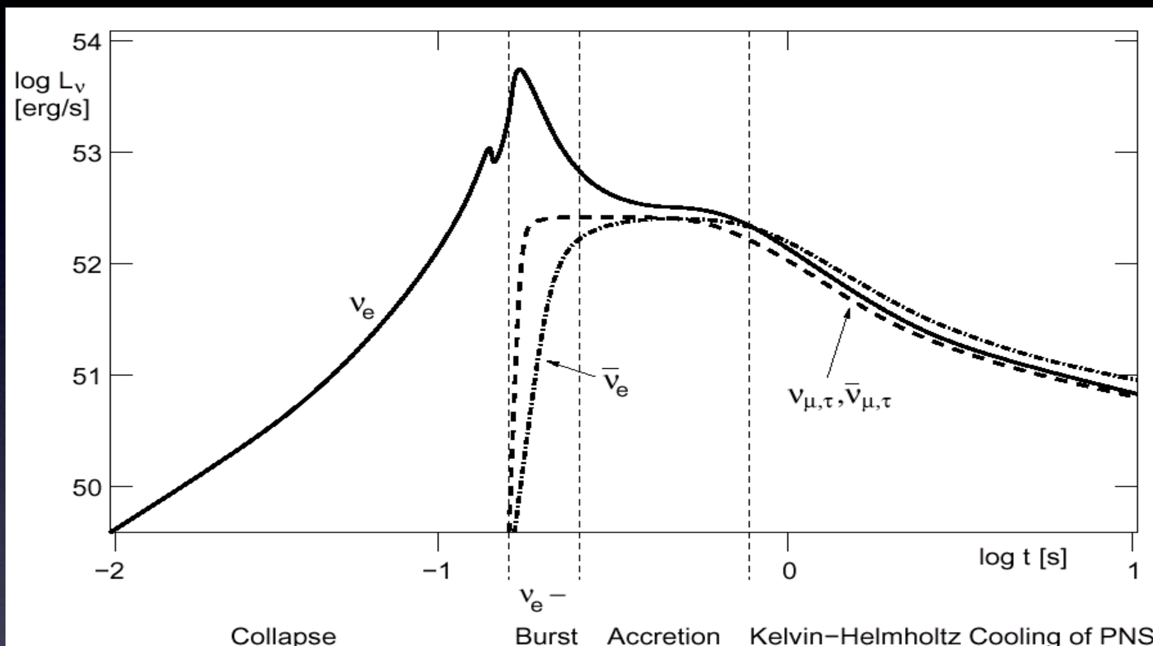
- New avenues now feasible
  - Energy spectra of stellar neutrinos - conditions of production zone
  - Solve evolution mechanism of collapsed stars - Supernova
  - First identification of diffuse Supernova background
  - Solve sub-dominant oscillation phenomena - atmospheric neutrinos

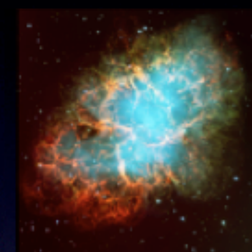
e.g. LENA solar physics

- ^{7}Be ν's: $\sim$ 5400 d^{-1}
  - Small time fluctuations
- pep ν's: $\sim$ 150 d^{-1}
  - Information about the pp-flux $\rightarrow$ Solar luminosity in ν's
- CNO ν's: $\sim$ 210 d^{-1}
  - Important for heavy stars
- ^{8}B ν's: CC on ^{13}C: $\sim$ 360 y^{-1}

Astrophysical Neutrinos

Supernova neutrino luminosity (rough sketch)





T. Janka, MPA

- Relative size of the different luminosities is not well known - depends on uncertainties in the explosion mechanism and equation of state of the hot neutron star matter
- Need information on all flavours and energies

LENA SN neutrino rates

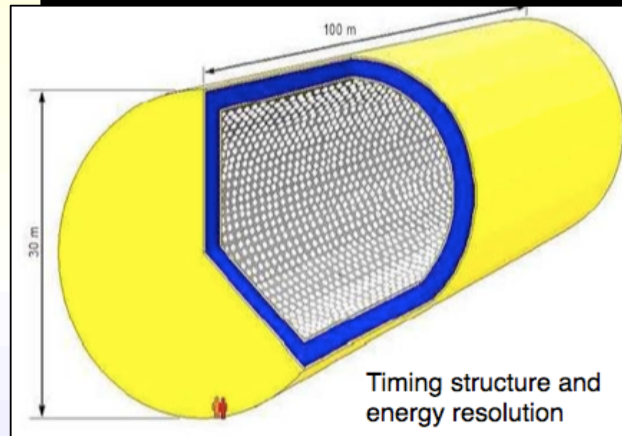
- 8 $M_\odot$ ($3 \cdot 10^{53}$ erg) at D = 10 kpc (center of our galaxy)

In LENA detector: $\sim$15000 events

Possible reactions in liquid scintillator

- $\overline{\nu}_e + p \rightarrow n + e^+;\ n + p \rightarrow d + \gamma$ $\sim$9000 events
- $\overline{\nu}_e + {}^{12}\mathrm{C} \rightarrow {}^{12}\mathrm{B} + e^+;\ {}^{12}\mathrm{B} \rightarrow {}^{12}\mathrm{C} + e^- + \overline{\nu}_e$ $\sim$250 events
- $\nu_e + {}^{12}\mathrm{C} \rightarrow e^- + {}^{12}\mathrm{N};\ {}^{12}\mathrm{N} \rightarrow {}^{12}\mathrm{C} + e^+ + \nu_e$ $\sim$400 events
- $\nu_x + {}^{12}\mathrm{C} \rightarrow {}^{12}\mathrm{C}^* + \nu_x;$
- $\nu_x + e^- \rightarrow \nu_x + e^-$ (elast
- $\nu_x + p \rightarrow \nu_x + p$ (elastic s

Diploma thesis by J.M.A. Winter (TU Münch



MEMPHYS		LENA		GLACIER	
Interaction	Rates	Interaction	Rates	Interaction	Rates
$\bar{\nu}_e$ IBD	2×10^5	$\bar{\nu}_e$ IBD	9.0×10^3	$\nu_e^{CC}({}^{40}\mathrm{Ar}, {}^{40}\mathrm{K}^*)$	2.5×10^4
$\overset{(-)}{\nu}{}_e^{CC}({}^{16}\mathrm{O}, X)$	1×10^4	ν_x pES	7.0×10^3	$\nu_x^{NC}({}^{40}\mathrm{Ar}^*)$	3.0×10^4
ν_x eES	1×10^3	$\nu_x^{NC}({}^{12}\mathrm{C}^*)$	3.0×10^3	ν_x eES	1.0×10^3
		ν_x eES	6.0×10^2	$\bar{\nu}_e^{CC}({}^{40}\mathrm{Ar}, {}^{40}\mathrm{Cl}^*)$	5.4×10^2
		$\bar{\nu}_e^{CC}({}^{12}\mathrm{C}, {}^{12}\mathrm{B}^+)$	5.0×10^2		
		$\nu_e^{CC}({}^{12}\mathrm{C}, {}^{12}\mathrm{N}^-)$	8.5×10^1		

Neutronization burst rates

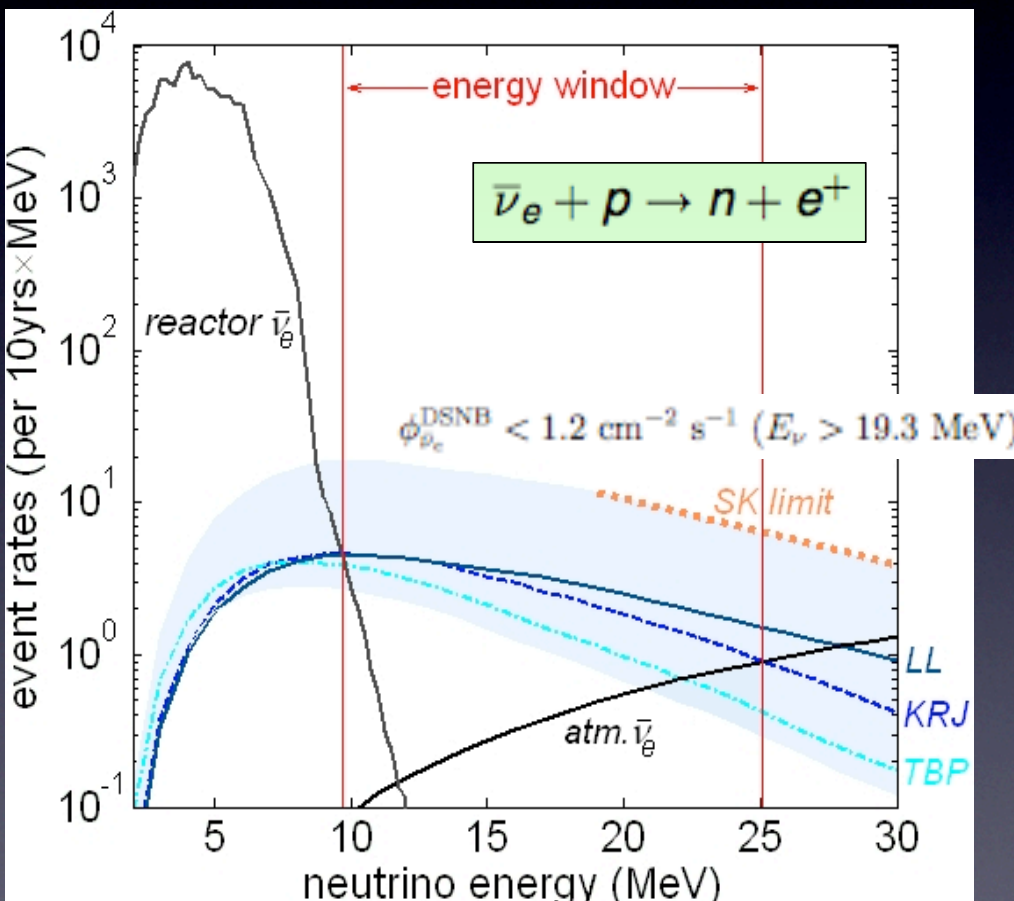
MEMPHYS	60	ν_e eES
LENA	70	ν_e eES/pES
GLACIER	380	$\nu_x^{NC}({}^{40}\mathrm{Ar}^*)$

- IBD is golden channel for MEMPHYS and LENA

SN Diffuse Neutrinos rates

- SN neutrinos from difuse flux of undetected past SN explosions (DSNB)

LENA



- Predictions not far below current SK limit
- Sensitivity depends on proximity of reactors - Phyasalmi site best
- Different SN models can be distinguished

DSNB Rates

Interaction	Exposure	Energy Window	Signal/bkgd
GLACIER			
	0.5 Mton yr		
$\nu_e + {}^{40}\mathrm{Ar} \rightarrow e^- + {}^{40}\mathrm{K}^*$	5 yr	(16–40) MeV	(40-60)/30
LENA at Pyhäsalmi			
$\bar{\nu}_e + p \rightarrow n + e^+$			
$n + p \rightarrow d + \gamma$	0.4 Mton yr		
(2 MeV, 200 μs)	10 yr	(9.5–30) MeV	(20–230)/8
1 MEMPHYS module + 0.2% Gd (with bkgd at Kamioka)			
$\bar{\nu}_e + p \rightarrow n + e^+$			
$n + \mathrm{Gd} \rightarrow \gamma$	0.7 Mton yr		
(8 MeV, 20 μs)	5 yr	(15–30) MeV	(43–109)/47

- SN neutrinos from diffuse flux of undetected past SN explosions
- LENA ~ 10 per year

Neutrino Beams - long baseline

- Bonus - availability of neutrino beams from future accelerators, in particular $\theta_{13}, \delta, \mathrm{sgn}(\Delta M^2)$
  - the mixing angle ϑ_{13}
  - CP violating phase in the mixing matrix
- e.g. low energy beta-beam from CERN to Frejus (130 km)
- e.g. high energy beams for long baselines, e.g. Phyasalmi (O2000km)

$\nu_\mu \rightarrow \nu_e$

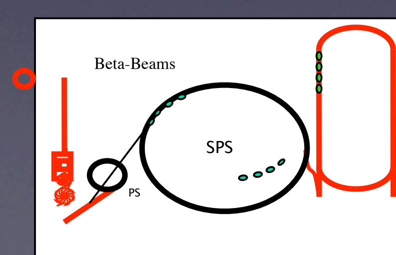
High intensity low energy conventional neutrino sources

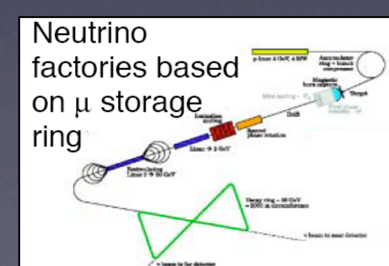
“superbeams” ?
MW power >2016

2/4 GeV p ? 50 GeV p ?
400 GeV ?

$\nu_e \rightarrow \nu_\mu$

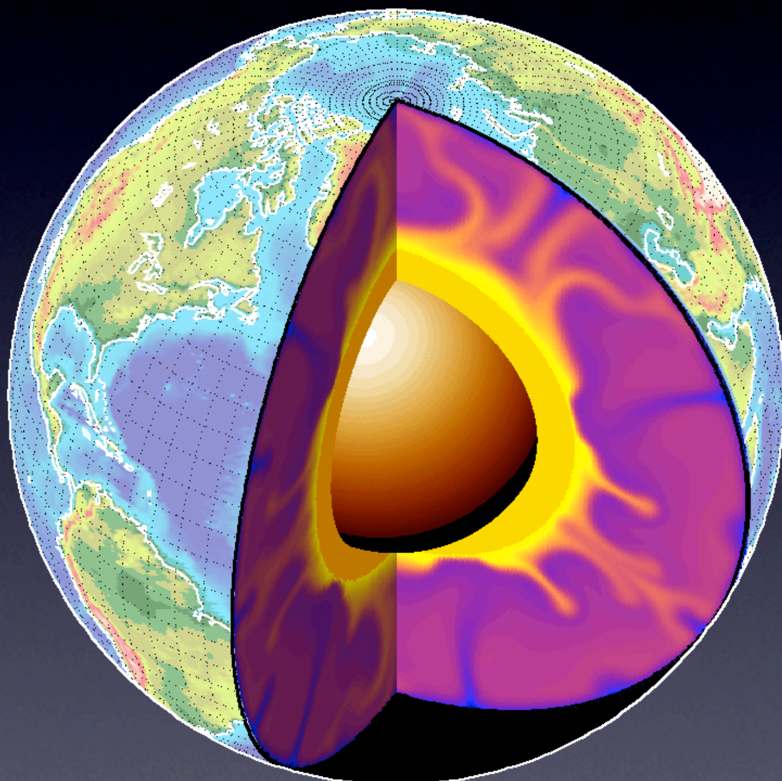
New neutrino production technology >2020 ?





Geo-Neutrinos

- A new window on the Earth's interior - observation of neutrinos produced in the decay of heavy elements.

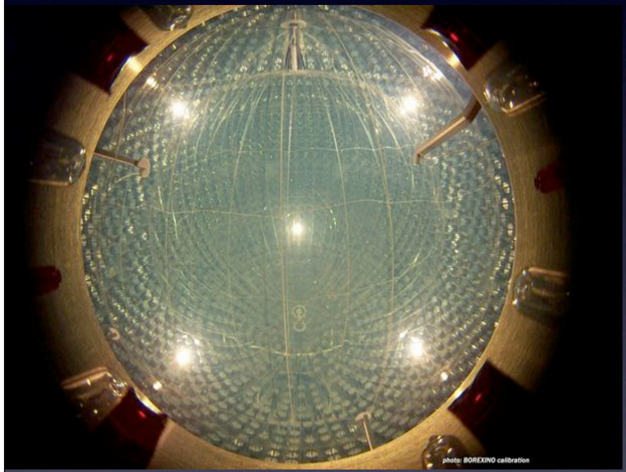


- **They escape freely and instantaneously from Earth's interior.**
- **They bring to Earth's surface information about the chemical composition of the whole planet.**

LAGUNA Geo-neutrino prospects

$\bar{\nu}_e + p \rightarrow n + e^+$ Araki T et al , 2005 Nature 436 499

- KAMLAND (1 kton) result (constrained by reactor neutrinos and radon contamination 25^{+19}_{-18}



Borexino at Gran Sasso

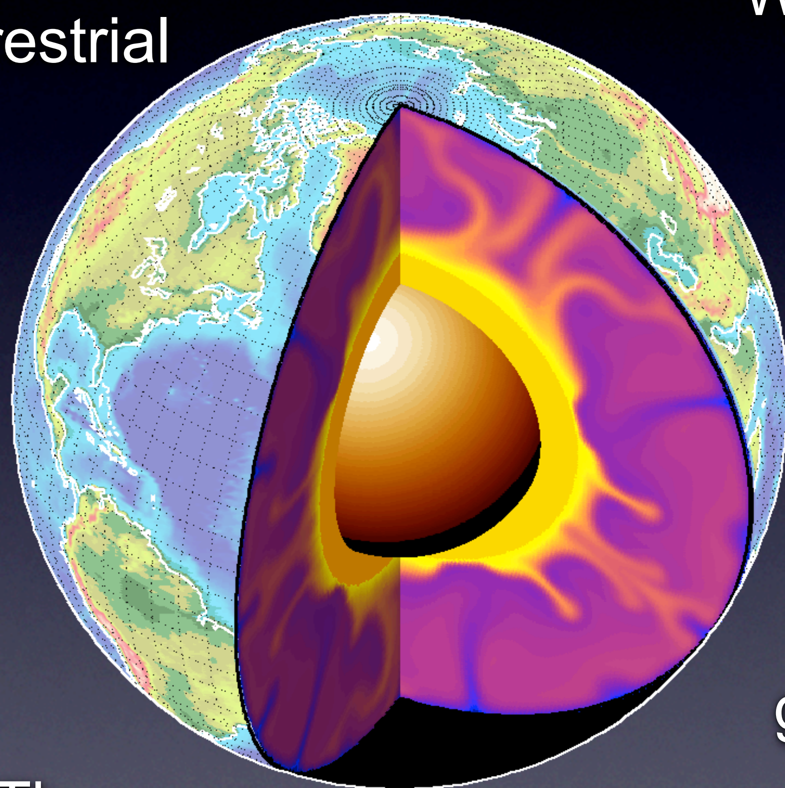
- **A 300-ton liquid scintillator underground detector, running since may 2007 - expect 5-7 events/yr (BSE)**

- LENA at CUPP: expected rate ~1000/yr
- GLACIER $\bar{\nu}_e + {}^{40}\mathrm{Ar} \rightarrow e^+ + {}^{40}\mathrm{Cl}^*$

Open questions about natural radioactivity in the Earth

What is the radiogenic contribution to terrestrial heat production?

What is hidden in the Earth's core? (geo-reactor, ^{40}K, …)

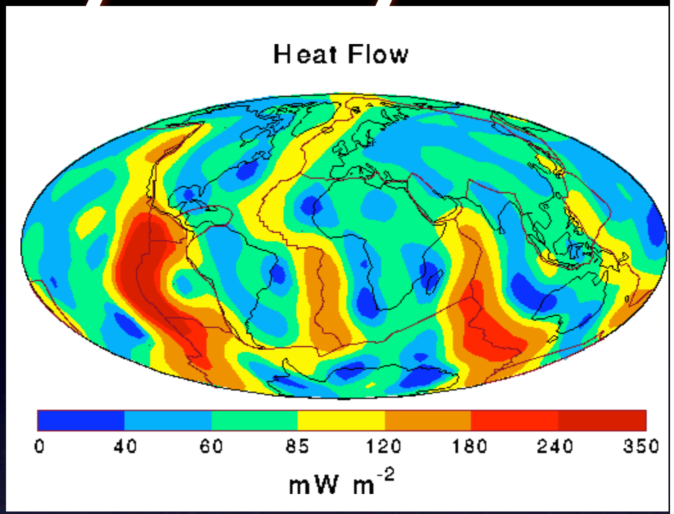


How much U and Th in the crust?

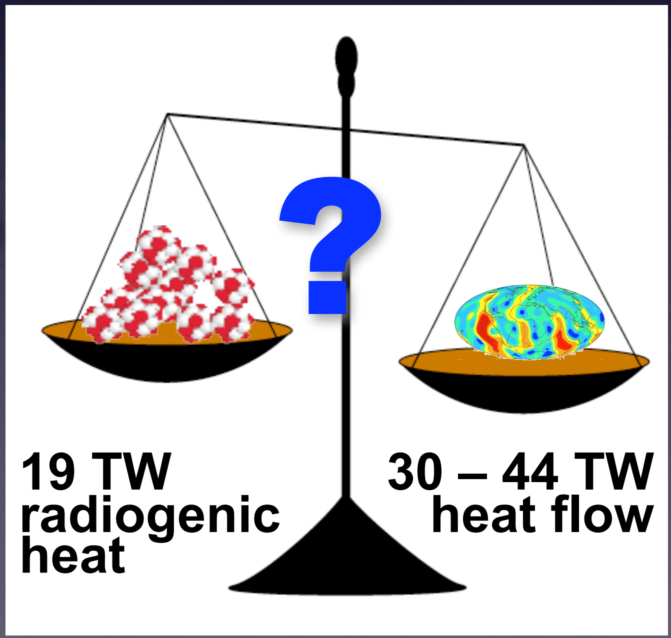
How much U and Th in the mantle?

Is the standard geochemical model (BSE) consistent with geo-neutrino data?

Earth energetics mystery



- Heat flow from the Earth is the equivalent of some 10000 nuclear power plants
  H_{Earth} = (30 - 44)TW
- The BSE canonical model, based on cosmochemical arguments, predicts a radiogenic heat production ~ 19 TW:
-
  ~ 9 TW estimated from radioactivity in the (continental) crust
  ~ 10 TW supposed from radioactivity in the mantle
  ~ 0 TW assumed from the core
- Unorthodox or even heretical models have been advanced…



* D. L. Anderson (2005), Technical Report, www.MantlePlume.org

Geo-neutrino solution

U, Th and ^{40}K in the Earth release heat together with anti-neutrinos, in a well fixed ratio:

Decay	$T_{1/2}$ [10^9 yr]	$E_{\max}$ [MeV]	Q [MeV]	$\varepsilon_{\bar{\nu}}$ [$\mathrm{kg}^{-1}\mathrm{s}^{-1}$]	ε_H [W/kg]
$^{238}\mathrm{U} \to {}^{206}\mathrm{Pb} + 8\,{}^4\mathrm{He} + 6e + 6\bar{\nu}$	4.47	3.26	51.7	7.46×10^7	0.95×10^{-4}
$^{232}\mathrm{Th} \to {}^{208}\mathrm{Pb} + 6\,{}^4\mathrm{He} + 4e + 4\bar{\nu}$	14.0	2.25	42.7	1.62×10^7	0.27×10^{-4}
$^{40}\mathrm{K} \to {}^{40}\mathrm{Ca} + e + \bar{\nu}$ (89%)	1.28	1.311	1.311	2.32×10^8	0.22×10^{-4}

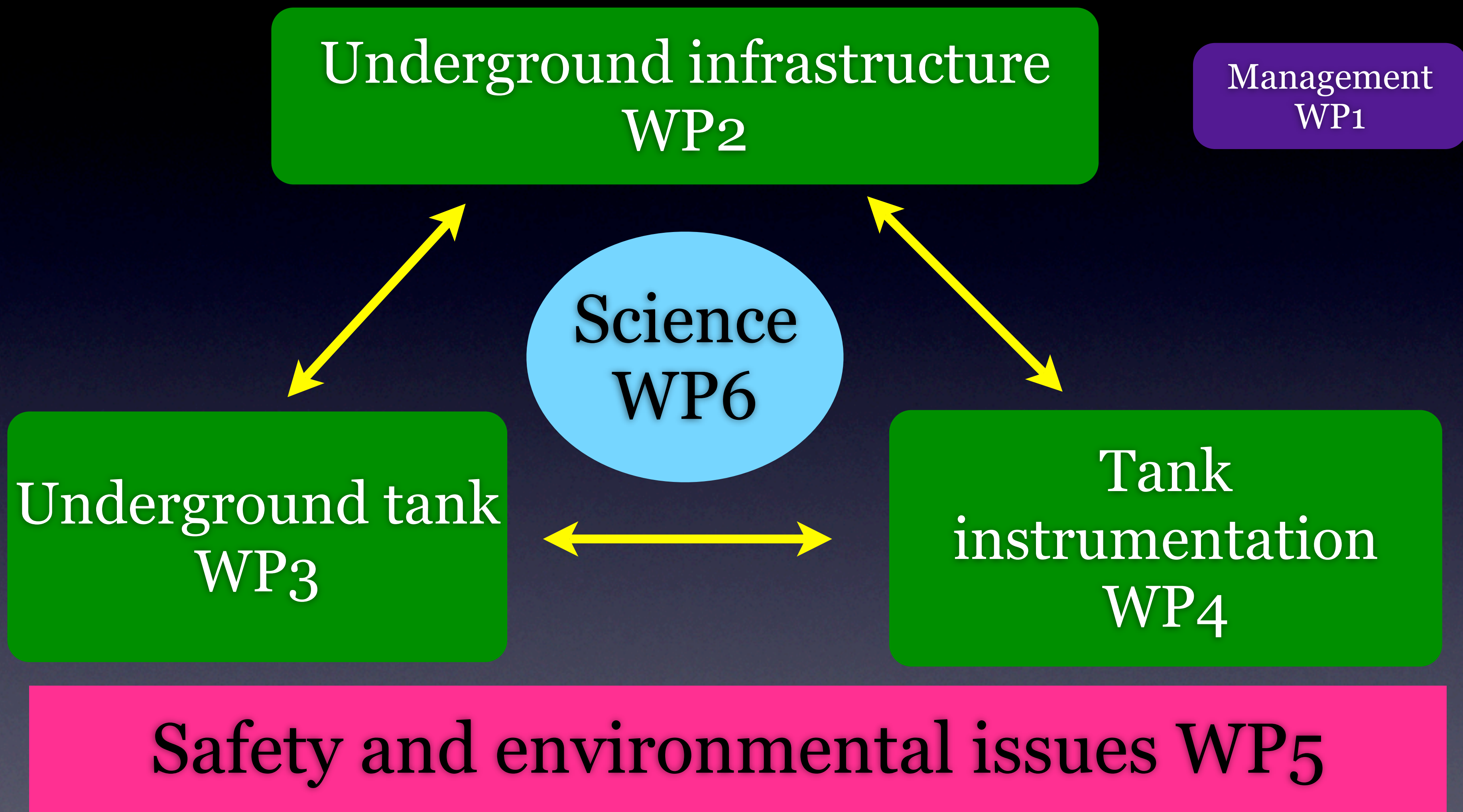
- **Earth emits (mainly) antineutrinos $\Phi_{\bar{\nu}} \sim 10^6\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ whereas Sun shines in neutrinos.**
- **A fraction of geo-neutrinos from U and Th (not from ^{40}K) are above threshold for inverse β on protons:**
- **Different components can be distinguished due to different energy spectra: e. g. anti-ν with highest energy are from Uranium.**

$$\bar{\nu} + p \to e^+ + n - 1.8\ \mathrm{MeV}$$

Status of LAGUNA Design Study

- LAGUNA DS was positively recommended by the EC expert panel
  - ★ *"The need for a very large underground laboratory for particle astrophysics detectors of the largest scale is well recognized. Such an infrastructure accommodating* ***megatonne-scale detectors*** *would enable unprecedented studies of nucleon decay and neutrino physics of all kinds answering some of the most fundamental scientific questions today. ApPEC rightly points out that a major underground facility is* ***a necessary complement to energy-frontier accelerators*** *such as the LHC and ILC. Particle astrophysics* ***can indirectly access energies approaching the Planck scale****, whereas terrestrial accelerators will be limited to the few TeV scale for the foreseeable future."*
- Negotiation phase ("Grand Agreement") procedure expected to start early next year
- Up to 1.7M€ EC funding expected compared to 4.9M€ desired. EC funding to be focused on WP2 ("underground infrastructures") and to lesser extent WP3 ("tanks"), WP5 ("safety + environmental impact") and WP6 ("physics")
- WP4 ("detector R&D") not to be funded by EC but must rely on national funding ➠ ApPEC/ASPERA coordination would be most welcome / mandatory in this context

Structure of LAGUNA DS



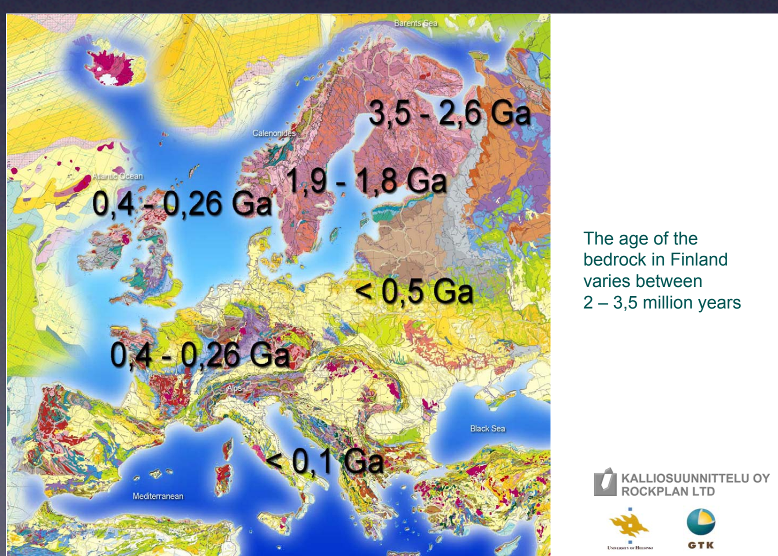
24 participants: ETH Zürich, Bern, Jyväskylä, Oulu, Rockplan, CEA/DSM/DAPNIA, IN2P3, MPG, TUM, Hamburg, IFJ PAN, IPJ, US, UWr, KGHM CUPRUM, IGSMiE PAN, LSC, Granada, Durham, Sheffield, Technodyne, ETL, Aarhus, AGT

The main “deliverable”

- The LAGUNA DS should lead to a “conceptual design report” for a new infrastructure, to allow policy makers and their advisors to prepare the relevant strategic decisions for the development of a new research infrastructure in Europe.

- The deliverables contain the elaboration of “decision factors”:

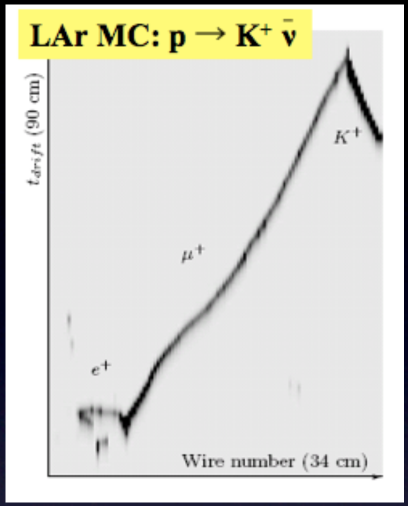
(i) technical feasibility (cavern, access, safety, liquid procurement,
(ii) cost optimization of infrastructure (digging, safety, ...)
(iii) physics performance (e.g. depth, baseline, ...



WP2 ➠Detailed feasibility studies (for all potential sites) including thorough rock sampling & rock simulations
➠Pre-plan for construction
➠Cost estimates

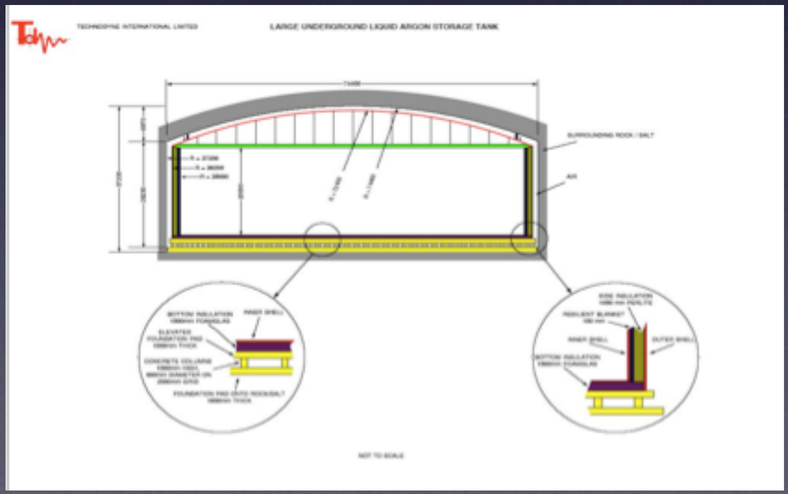
What about Liquid Argon?

- LAr TPC has many advantages
  - Excellent tracking and calorimetric resolution
  - Background rejection and topology of events
  - Ionisation, scintillation, cerenkov light
  - Possible to instrument large masses
  - Not too expensive...



- LAr challenges

- Tank/dewar
- Argon purification - drift distances
- High voltage
- Readout/electronics
- ...



World effort: Many Detectors

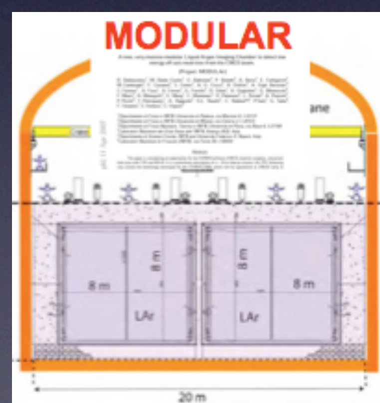
ICARUS 1985

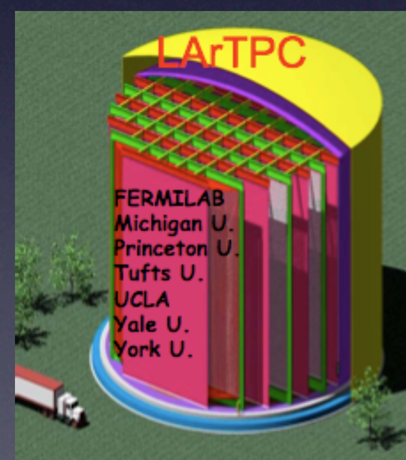
LANND 2001

GLACIER 2003

LArTPC2005

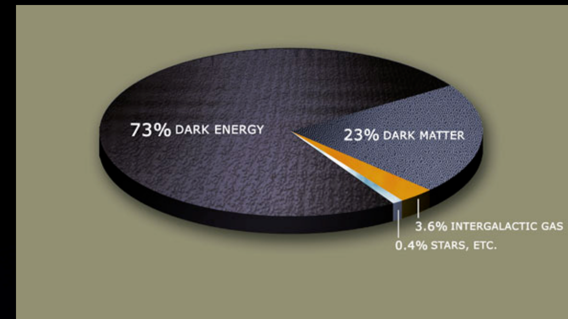
MODULAR 2007

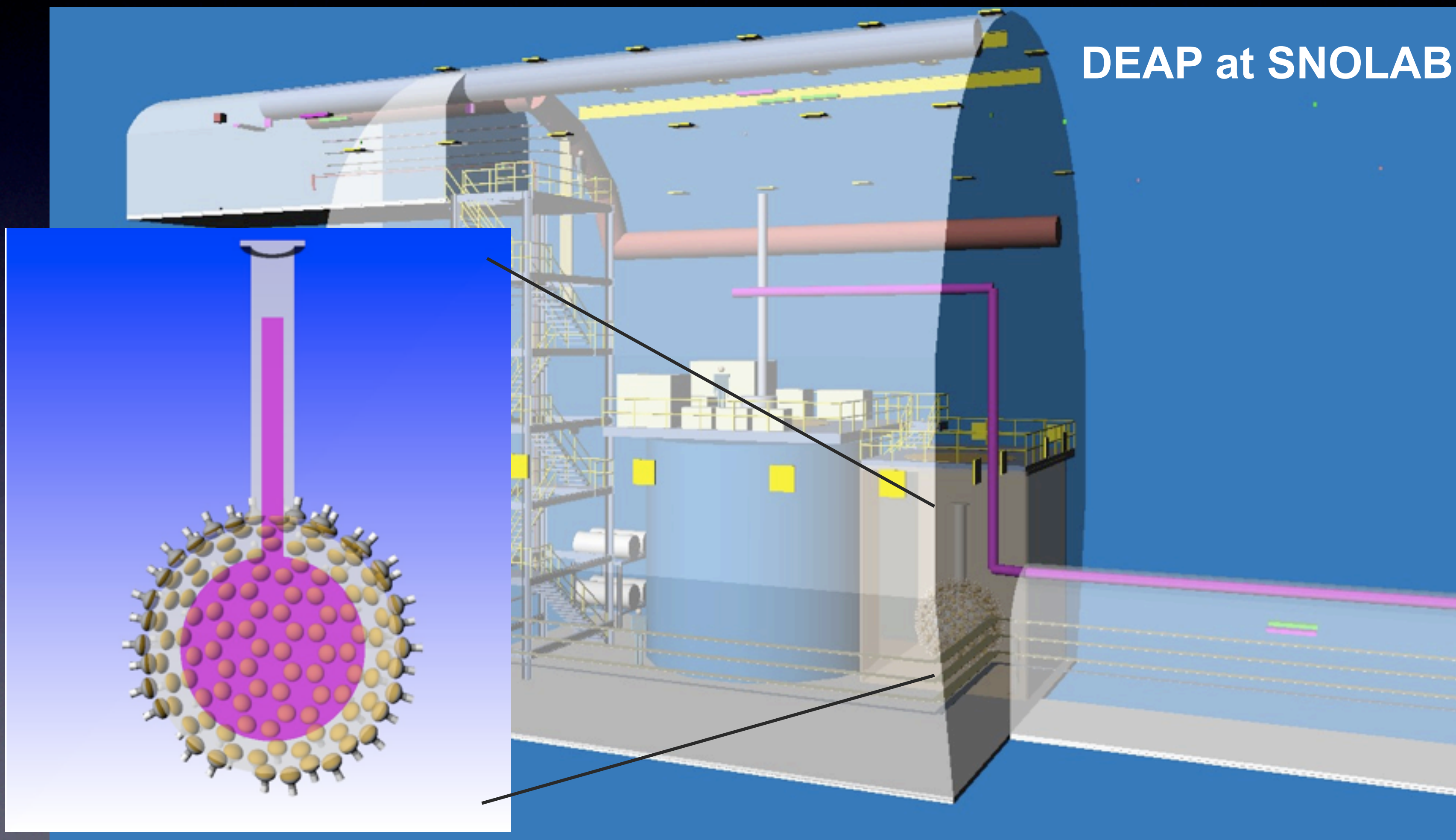




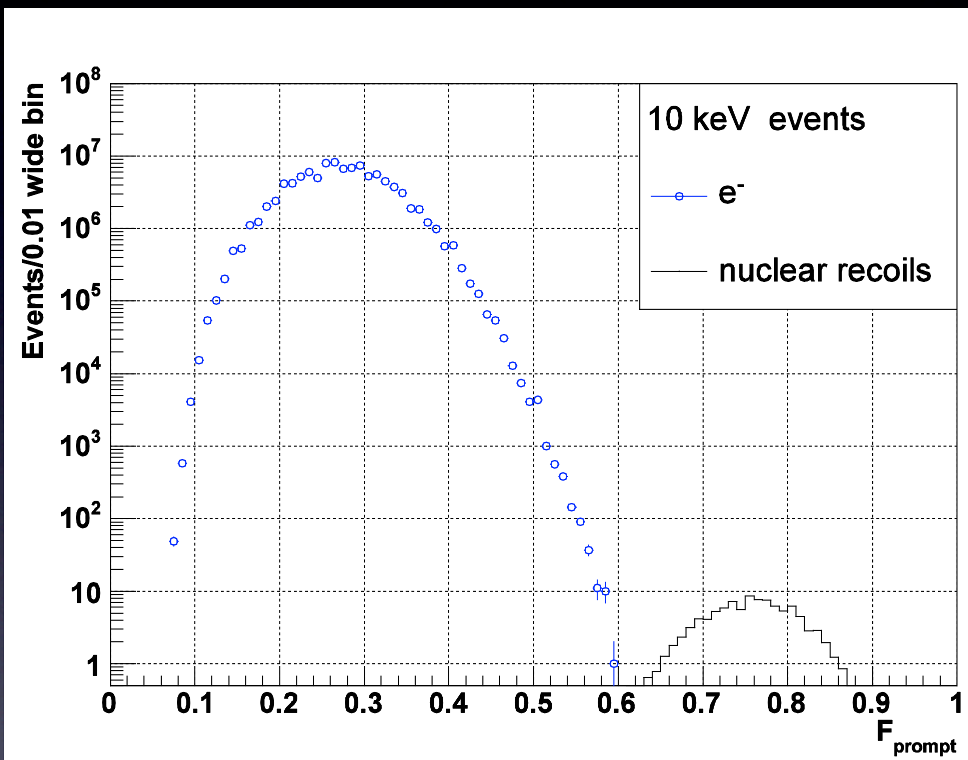
LAr - Dark Matter

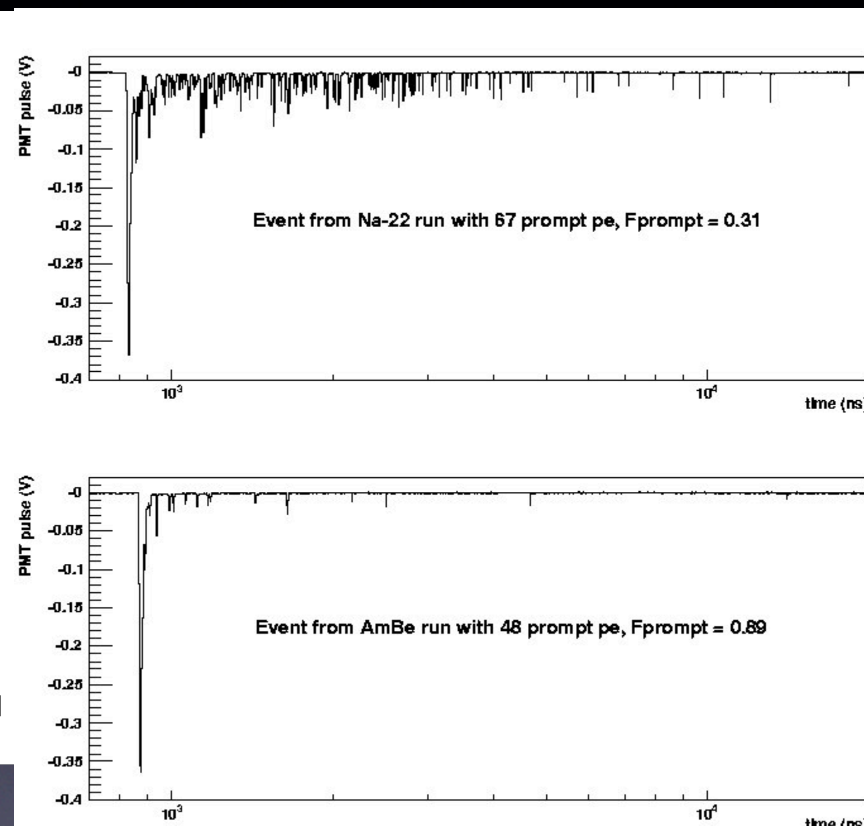
WARP, ArDM, CLEAN, DEAP,...





LAr - Dark Matter - DEAP





- Pulse shape discrimination in LAr - potential to reject electron background at 10^9

UK Participation and effort?

- UK has unique expertise in establishing mine-based deep laboratories for science (Boulby...)
- UK has pioneered new technology...Tanks - Technodyne
- Of course a long history in neutrino and underground physics and theory (Soudan, SNO, MINOS...)
- LAGUNA key involvement (Boulby, Sheffield, Durham, Technodyne Ltd., SensL)
  - Site studies, rock, safety, costs
  - Liquid argon and large tank R&D
- LAM (Liquid Argon Module) R&D (Sheffield, Warwick, SensL Ltd.)

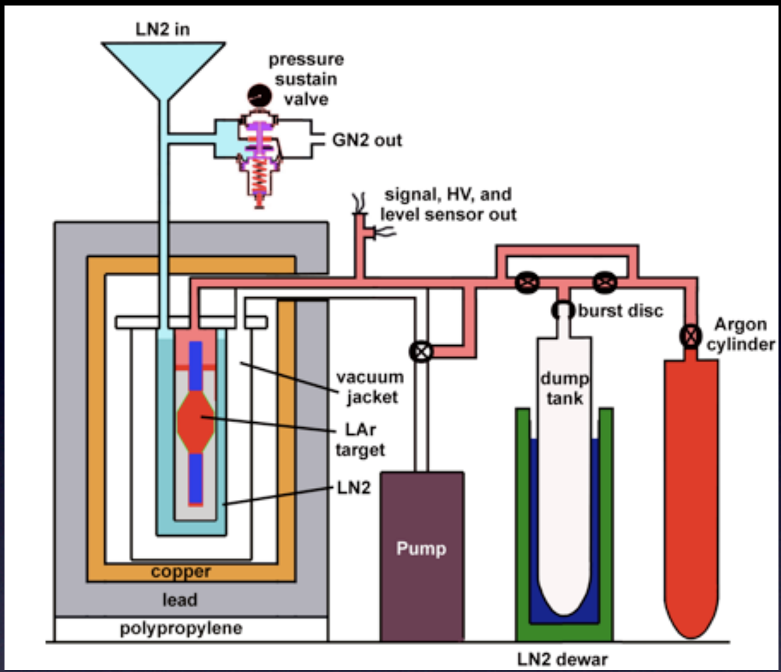
A Liquid Argon Module for Combined Tracking and Calorimetry

C.M. Booth, P.K. Lightfoot, S. Paganis and N.J.C. Spooner (University of Sheffield)
J. Thompson (Technodyne Int. Ltd.)
G. J. Barker, S.B. Boyd, P.F. Harrison and Y.A. Ramachers (University of Warwick)

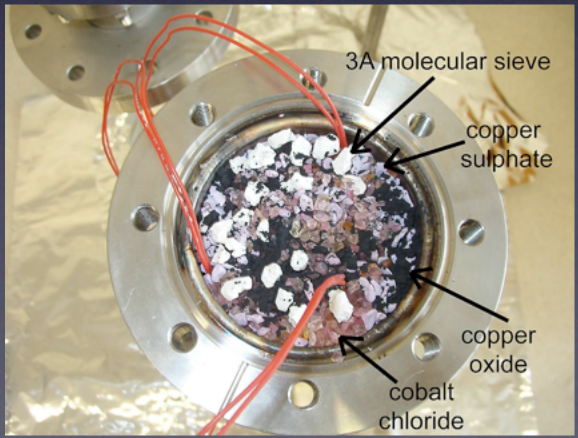
- 200 kg module with LEM charge readout in liquid
- Large scale purification studies
- Charge and light readout
- Participation in ArDM (ETHZ, CERN) and GLACIER

LAr R&D

Sheffield



Aims:
(i) develop purification/recirculation
(ii) test bed for optical and charge readout devices
(iii) construction of LAM

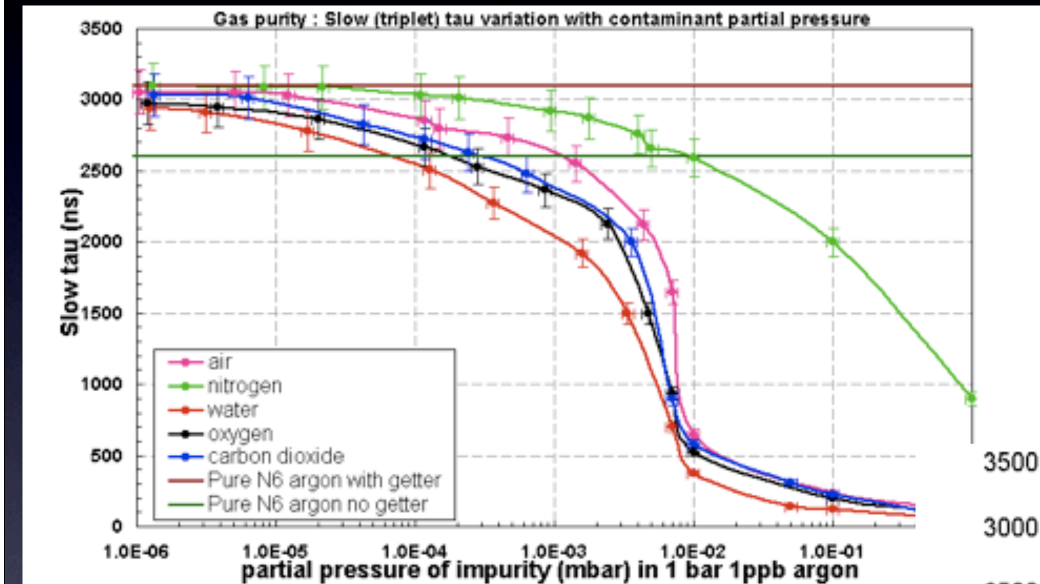


Novel chemical blends used in a dedicated purifying cartridge to remove oxygen, water, carbon dioxide, and all organics. (Activation of the chemicals is achieved by heating to 200C.)

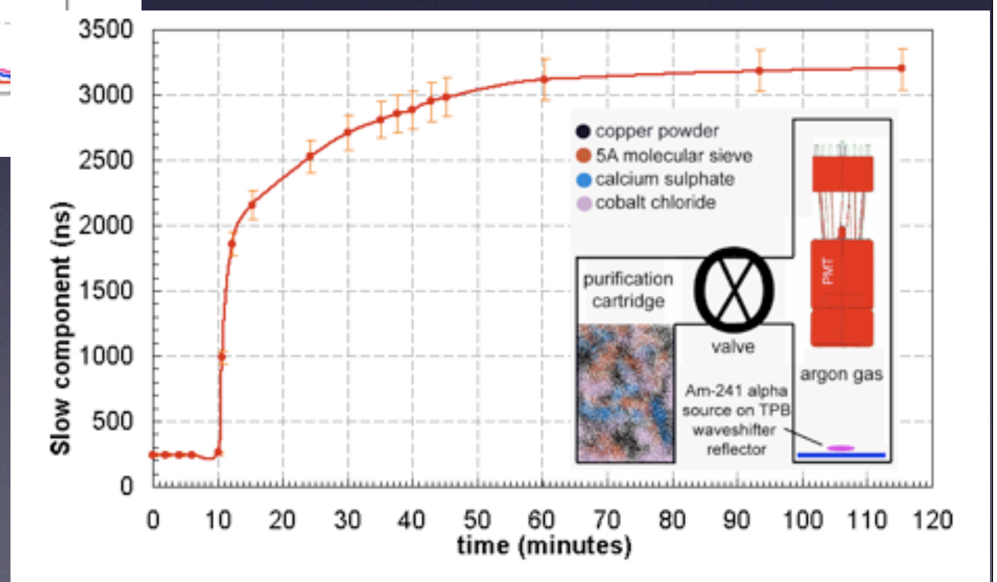
LAr R&D

Sheffield

The effect of adjusting the partial pressure of typical impurities within 99.9999999% pure argon gas at 1bar on the slow component from alpha excitation (maximum value for clean gas is 3200ns) has been measured.

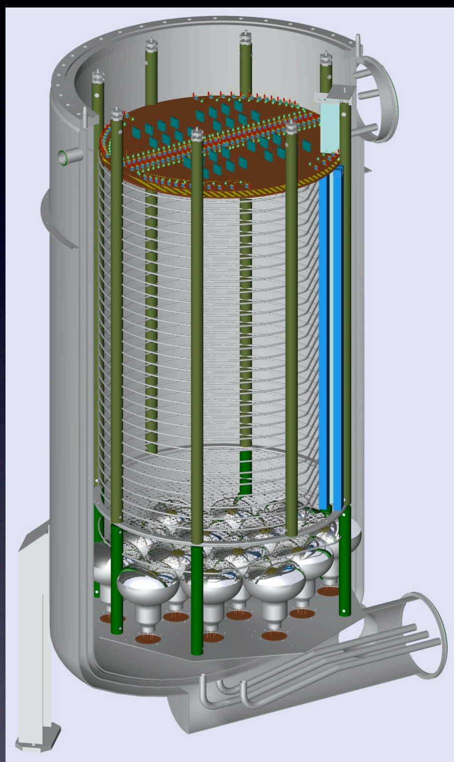


Improvement in purity (measured via the slow component from 1 bar gaseous argon excited by alphas) following exposure of N3 argon (99.9%) to purification chemicals, (valve opened after 10 minutes).



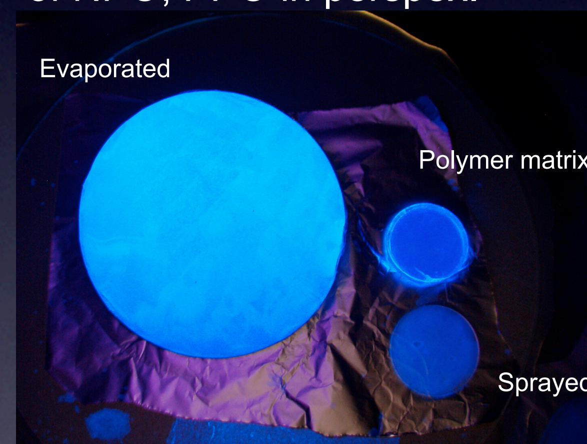
LAr R&D - 1 tonne (ArDM)

Two-stage LEM

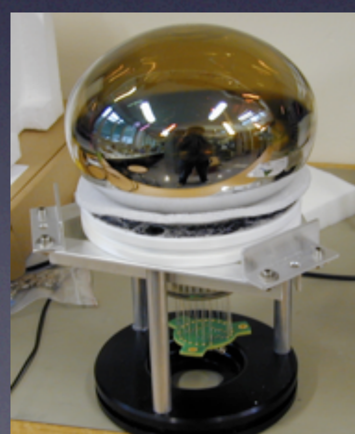


Greinacher chain high voltage

Waveshifter impregnated within polymer matrices of Perspex, Polystryrene, and Polyvinylacetate. Comparison of spray coating of TPB on glass and a polymer matrix of NPO, PPO in perspex.



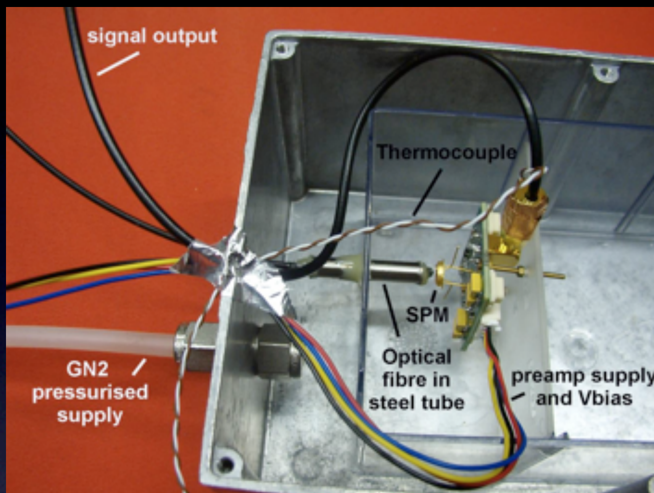
14 PMTs below cathode

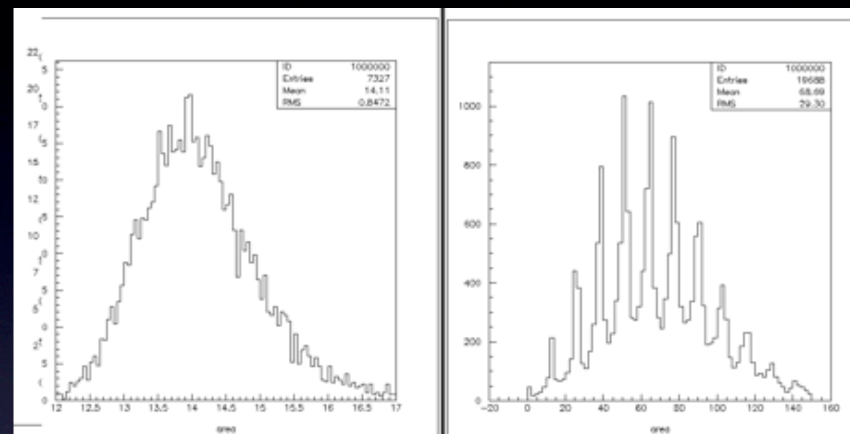


Hamamatsu R5912-02MOD, 20 cm
Wavelength shifter Tetra-Phenyl-Butadiene evaporated

Reflectivity @430nm ~97%
Shifting eff. 128 to 430 nm ~97%

Warwick LAr R&D - (LAM)





Single photoelectron area at -158degC 29V_{bias} and (d) single photoelectron quantisation from LED pulse triggered from LED pulse generator.

GEM/LEM/TGEM production and test

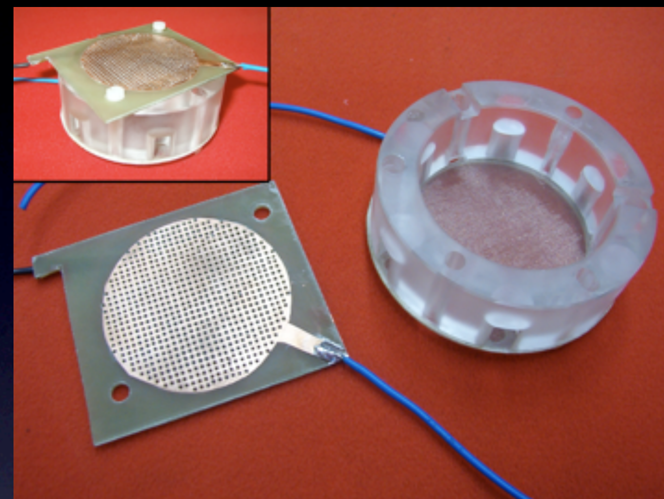
LAr R&D - (LAM)

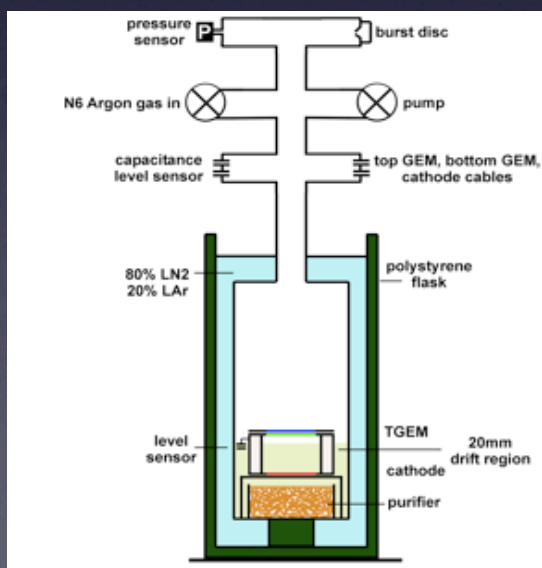
Warwick/
Sheffield

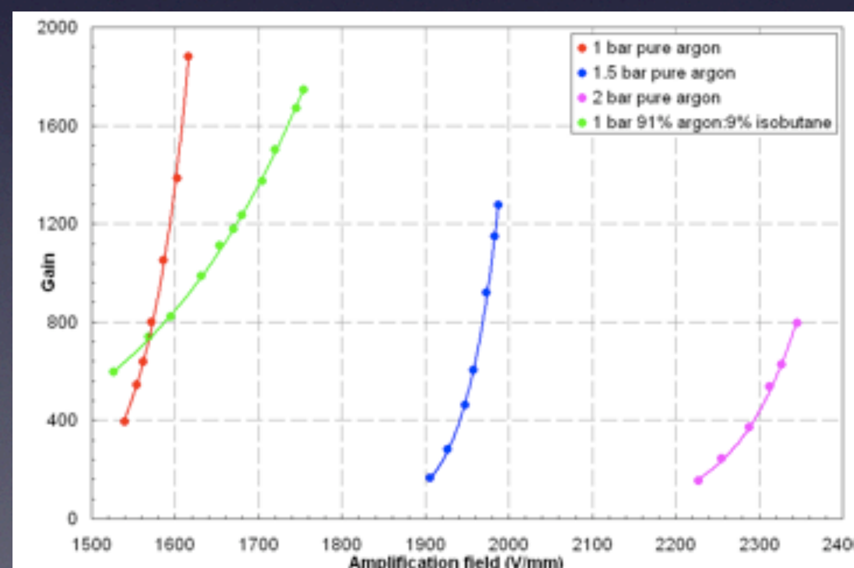
In-house production and test of bulk TGEMs

First gain tests complete

Aim: show charge readout in the liquid (low gain)







Conclusions and Outlook

LAGUNA - outstanding non-accelerator physics

	Water Cerenkov	Liquid Argon TPC	Liquid Scintillator
Total mass	500 kton	100 kton	50 kton
$p \to e\,\pi^0$ in 10 years	1.2×10^{35} years ε= 17%, ≈ 1 BG event	0.5×10^{35} years ε= 45%, <1 BG event	?
$p \to \nu K$ in 10 years	0.15×10^{35} years ε= 8.6%, ≈ 30 BG events	1.1×10^{35} years ε= 97%, <1 BG event	0.4×10^{35} years ε= 65%, <1 BG event
SN cool off @ 10 kpc	194000 (mostly $\bar{\nu}_e p \to e^+ n$)	38500 (all flavors) (64000 if NH-L mixing)	20000 (all flavors)
SN in Andromeda	40 events	7 (12 if NH-L mixing)	4 events
SN burst @ 10 kpc	≈250 ν-e elastic scattering	380 ν_e CC (flavor sensitive)	≈30 events
SN relic	250(2500 when Gd-loaded)	50	20-40
Atmospheric neutrinos	56000 events/year	≈11000 events/year	5600/year
Solar neutrinos	91250000/year	324000 events/year	?
Geoneutrinos	0	0	≈3000 events/year

Clear complementarity between techniques !

Conclusions and Outlook

LAGUNA - outstanding non-accelerator physics

- LAGUNA can provide an exceptional physics programme
- The LAGUNA design study will provide the means to perform site studies, develop a mature conceptual design with a credible cost estimate and a means to elaborate the information needed to make a site/concept choice
- LAGUNA can provide a "convergence" point for European efforts in very large detectors, beyond national interests and/or international competition
- There are big opportunities and challenges ahead for the community - UK can play a key role *In order to manage the possible, one has to imagine the impossible...*