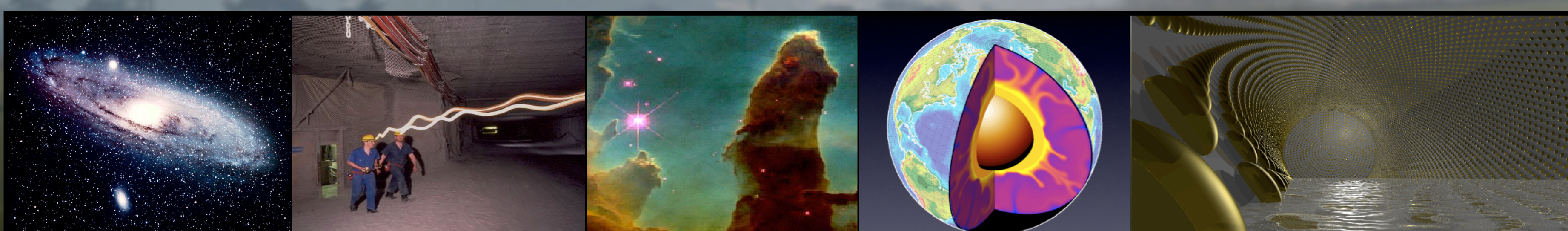
LAGUNA

Toward a Particle Astrophysics Detector the size of a Mountain and what it will tell us about the Meaning of Life and Everything

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

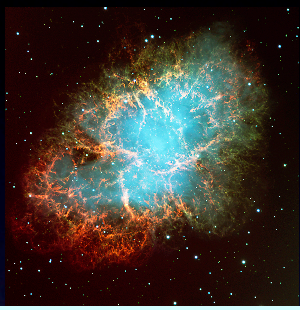
Abstract: ***I will describe a new global effort to construct a massive detector deep underground using liquid argon to answer such questions as: does the proton, the building block of us, ever decay?, why is there so much matter and little antimatter?, what is the dark matter of the Universe?, why does our most common fundamental particle, the neutrino, have mass? why is the Earth much hotter than we expect?, what makes a supernova explode? and why can such questions only be answered using a hard hat and battery powered head torch.***



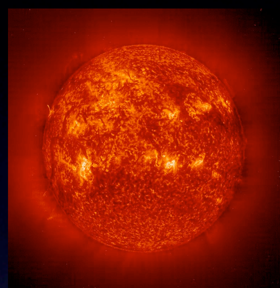
Neil Spooner and Phil Lightfoot - University of Sheffield

Science of LAGUNA

Non-accelerator Physics

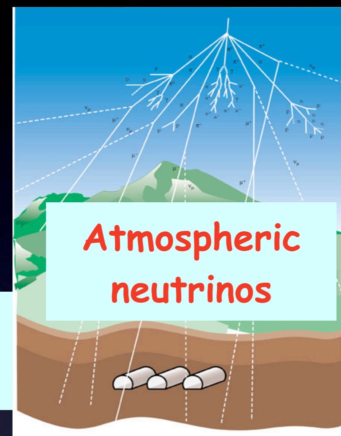


Supernova neutrinos



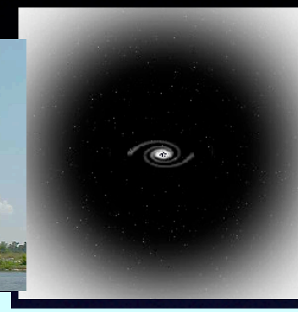
Solar neutrinos

Nucleon stability



Atmospheric neutrinos

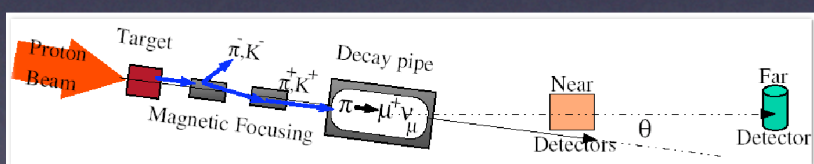
Reactor Neutrinos



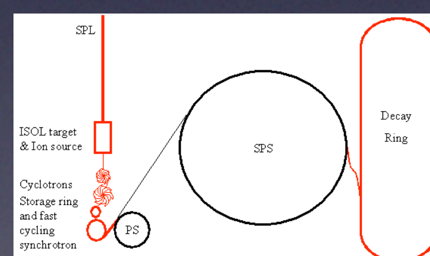
Dark Matter

Neutrino Physics at accelerators

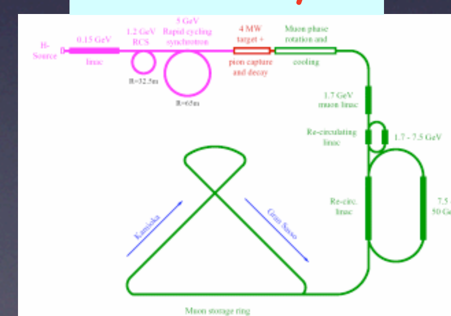
Super Beams



Beta Beams



ν Factory



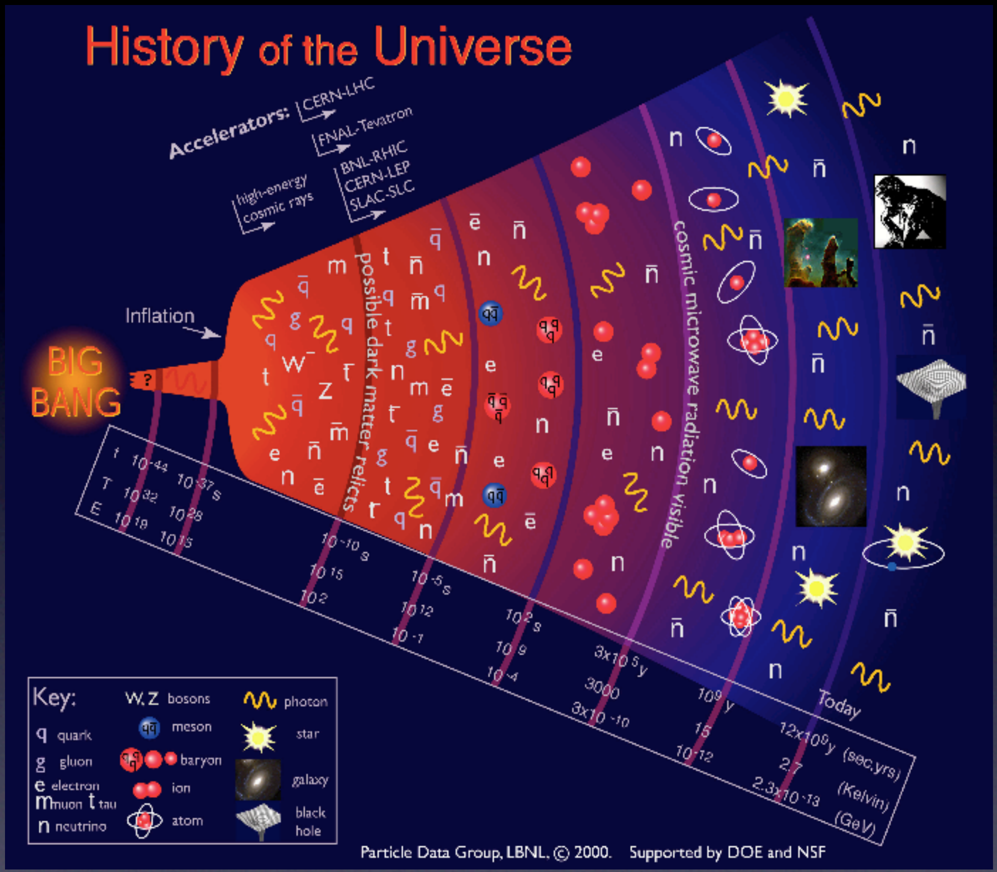
Particle Astrophysics and Particle Physics

Why do we exist?

Fundamental questions remain..

The Big Bang origin of the Universe requires matter and antimatter to be equally abundant at the very hot beginning

We are in a Matter dominated Universe!



The Great Annihilation

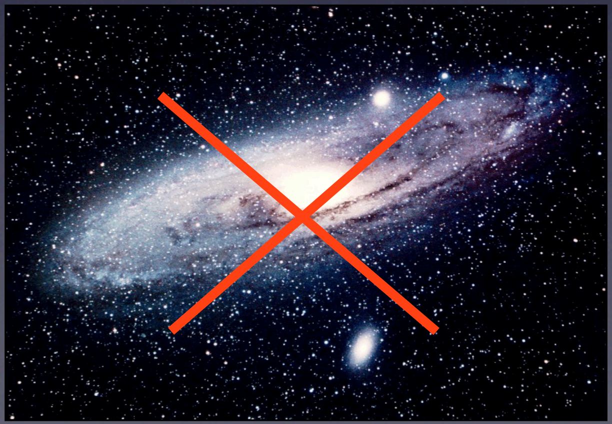
Galaxies are made of matter

$$\eta = \frac{n_b - n_{\bar{b}}}{n_\gamma} \approx 10^{-10}$$

1 particle out of 10 billion pairs of particles and anti-particles left over…

No anti-galaxies around!

Baryogenesis



So, how to explain the asymmetry???

CP Violation and Proton Decay

CP symmetry refers to the fact that physical processes in nature occur in precisely the same manner if all particles were converted to their antimatter opposites using the CP transformation.

If CP is violated then initial matter/antimatter balance in early Universe broken

parity transformation (spatial transformation)

charge conjugation transformation

The symmetry was believed to be exact until 1964, when an experiment by Fitch et al. showed that for K^0 mesons, CP symmetry breaks down 0.2% of the time

A clue....

CP violation does exist, but → Has been observed in “s” and “b” quark systems and in agreement with the Standard Model But too small
Need new type of CP-violation to explain amount of baryons in Universe

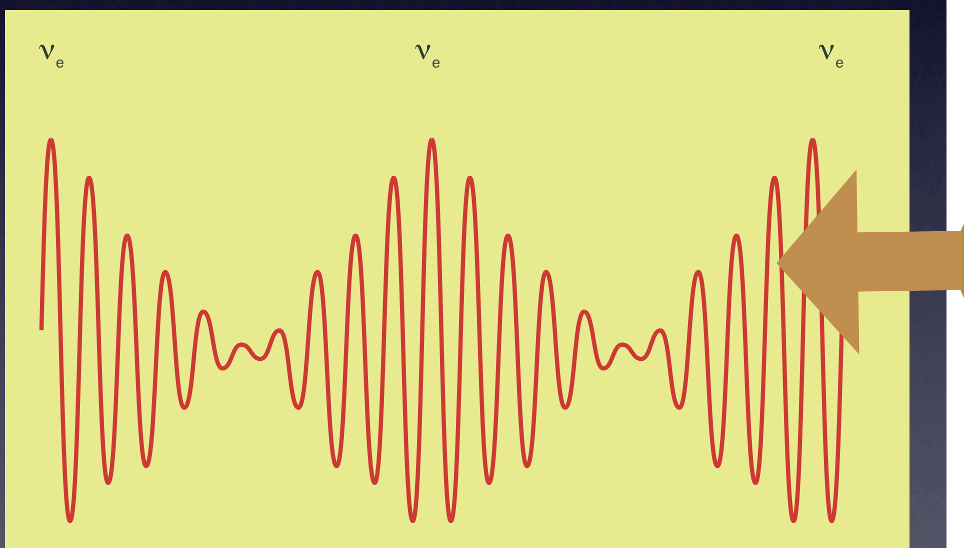
Baryon number violation → Grand Unified Theories (GUTs)

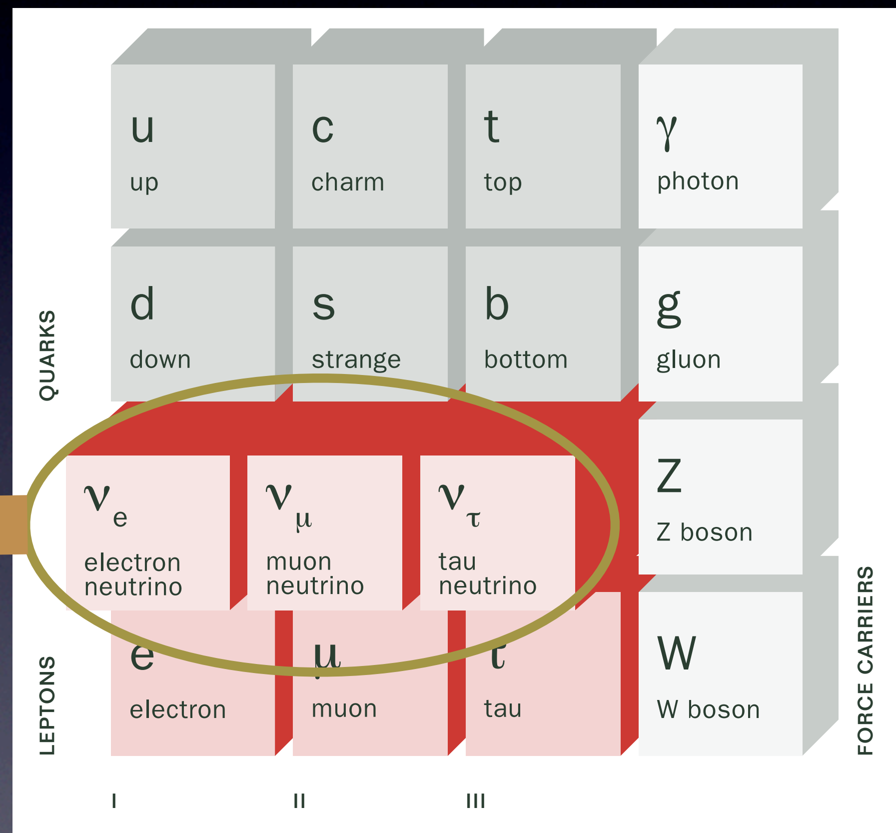
Proton decay

The New Neutrino Physics

Neutrino found to oscillate (or BEAT) between types: - neutrinos have mass; new physics beyond the Standard Model; may be a clue that we have CP violation in the lepton sector, could then lead to Baryogenesis.

Interactions where B + L is conserved create first a lepton asymmetry which implies then baryon creation:

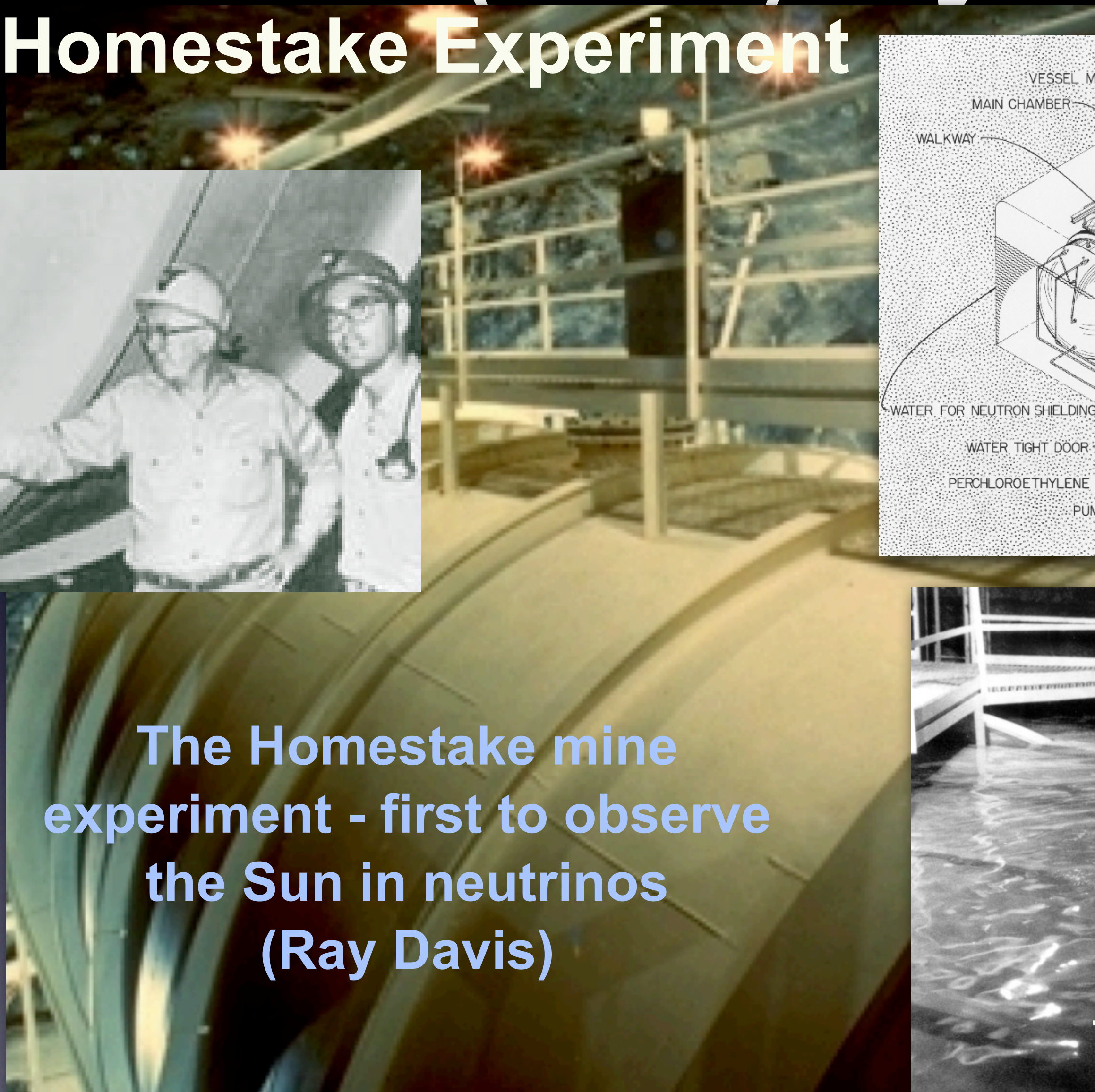




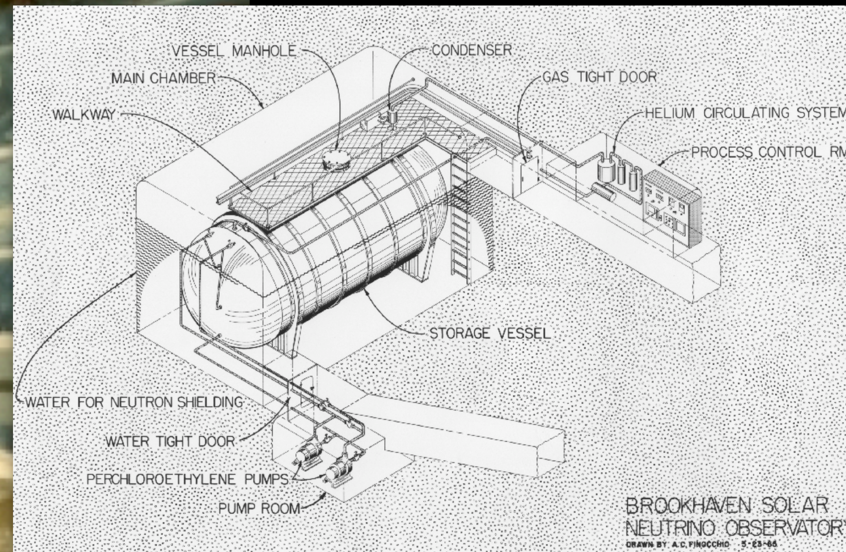
Is there a new type of CP violation in the lepton sector?
leptogenesis --> baryogenesis

Neutrino (astro)Physics (history)

Homestake Experiment



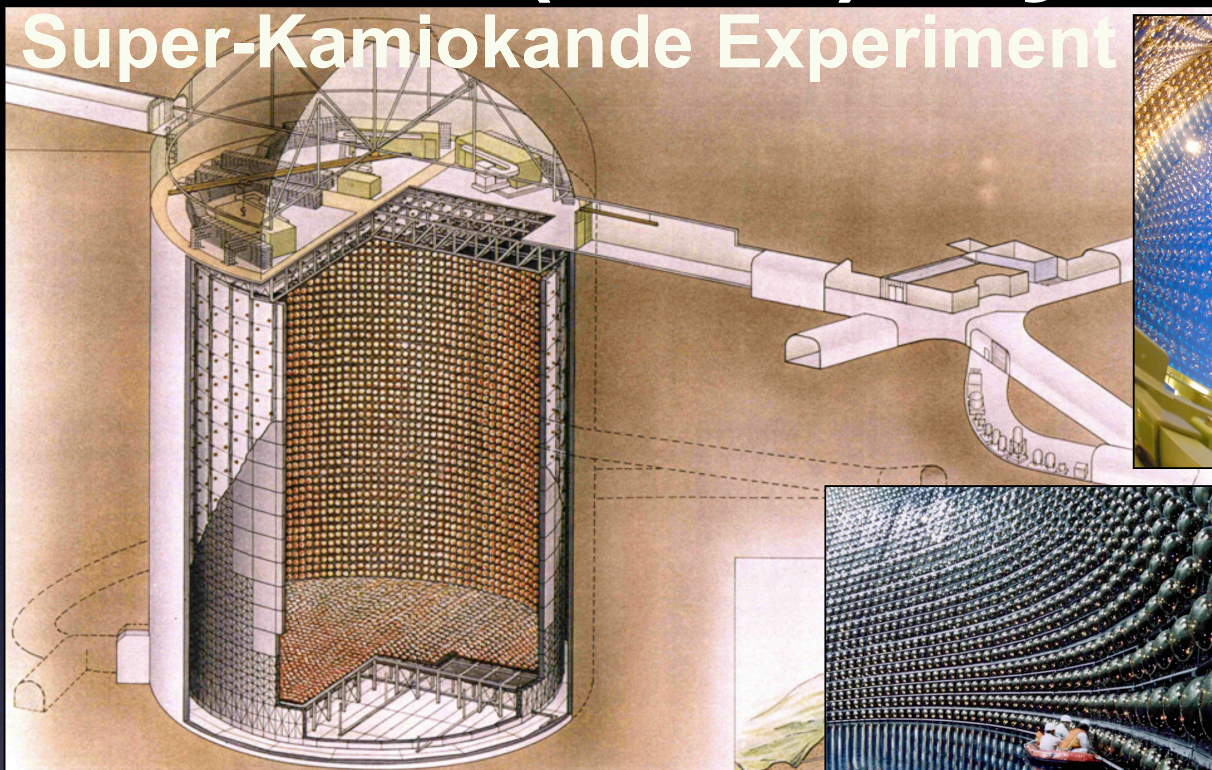
The Homestake mine experiment - first to observe the Sun in neutrinos (Ray Davis)

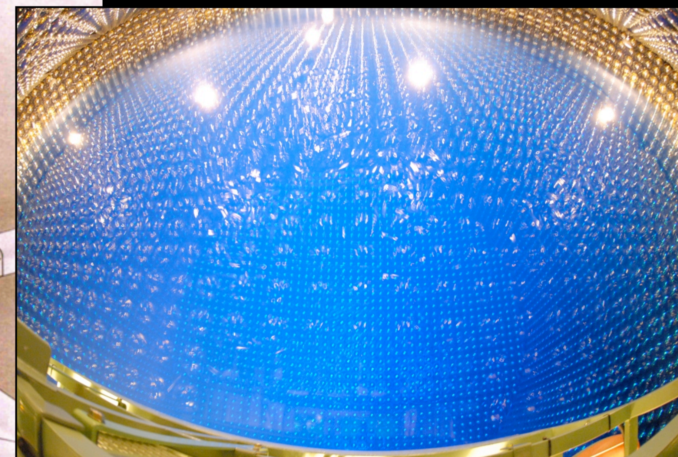


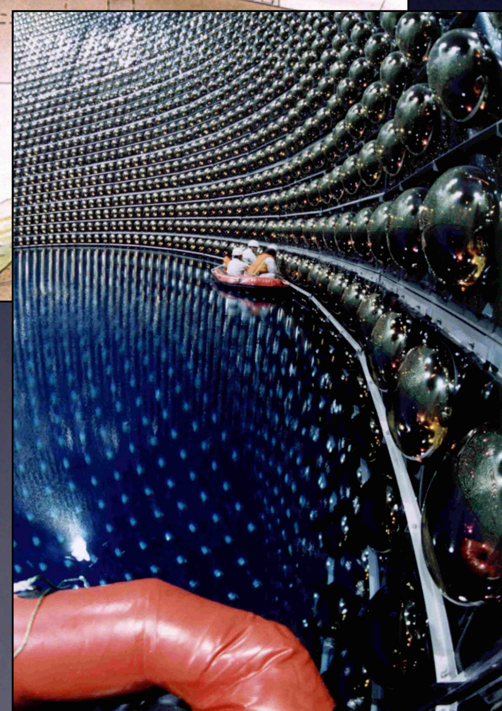
6 trillion per second through your open hand

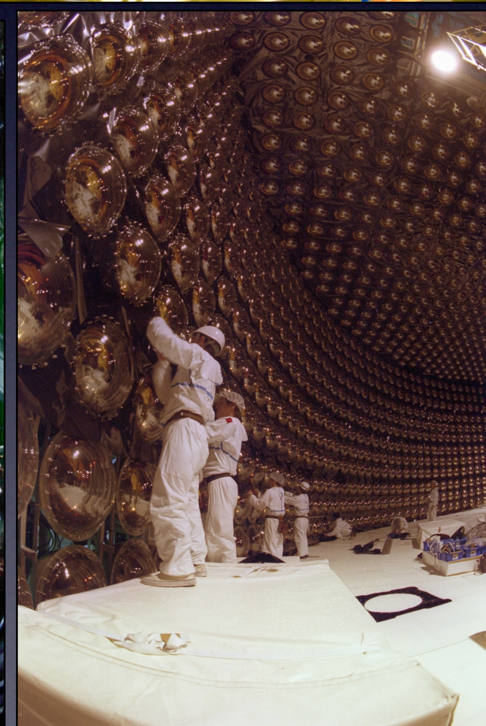
Neutrino (astro)Physics (history)

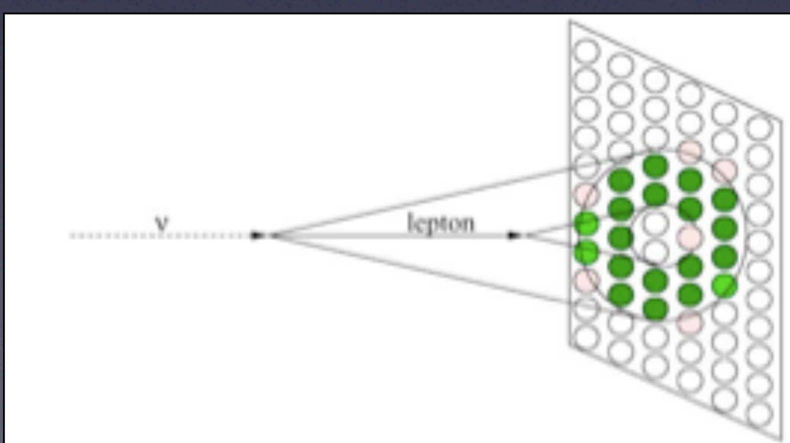
Super-Kamiokande Experiment







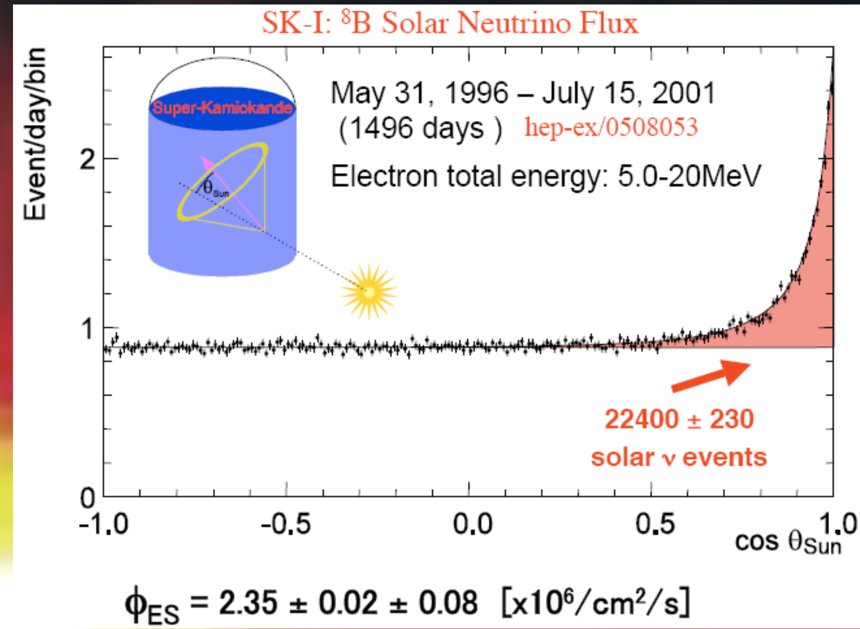




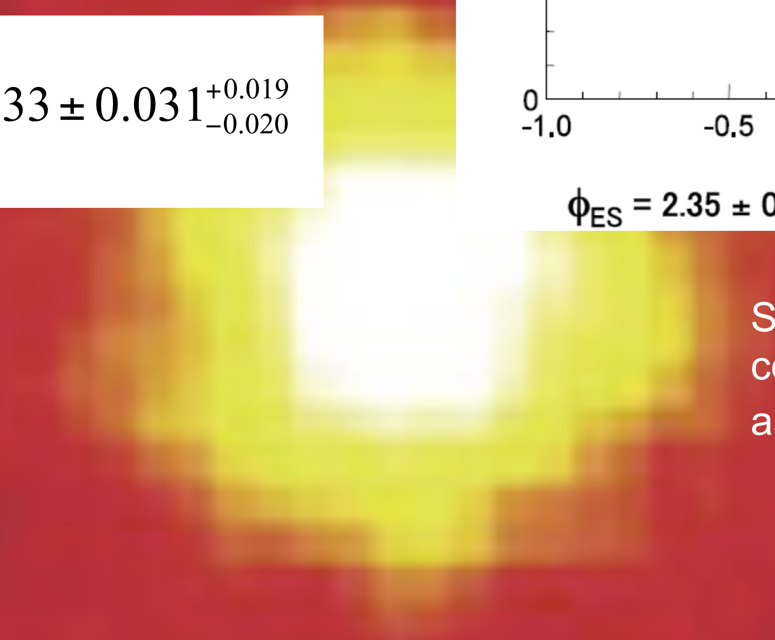
Super-Kamiokande III

- SK-III reconstructed in 2006
- 50 Ktons water - the largest underground experiment
- purifying water since October 2006

$$\frac{N-D}{(N+D)/2} = 0.033 \pm 0.031^{+0.019}_{-0.020}$$



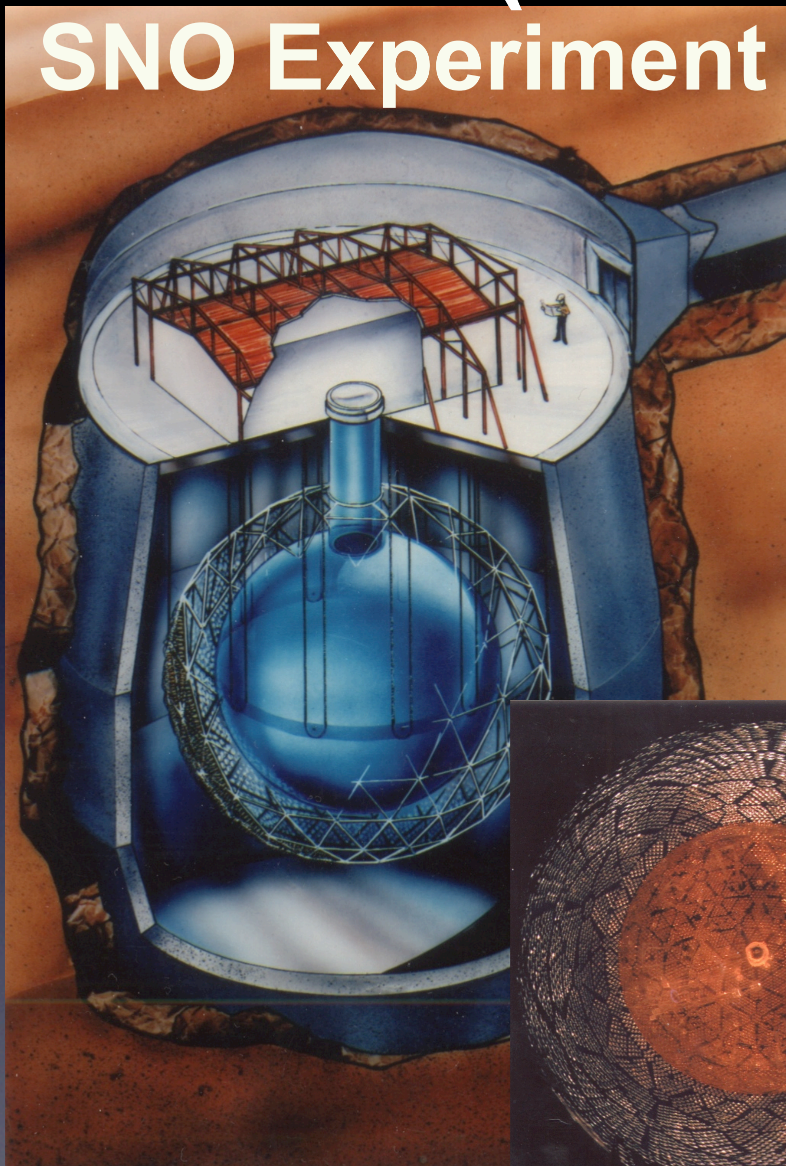
SK-I day-night asymmetry converted to SNO-style ν_e asymmetry

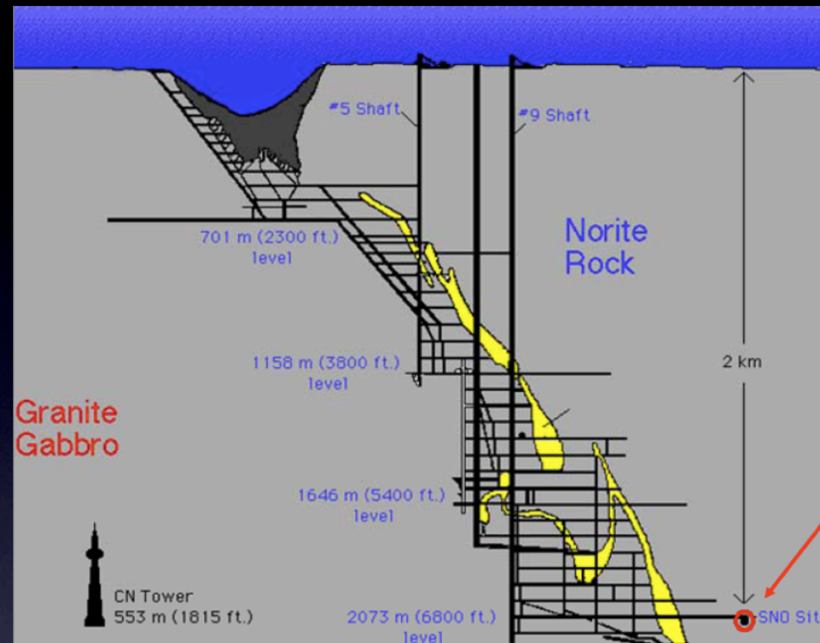


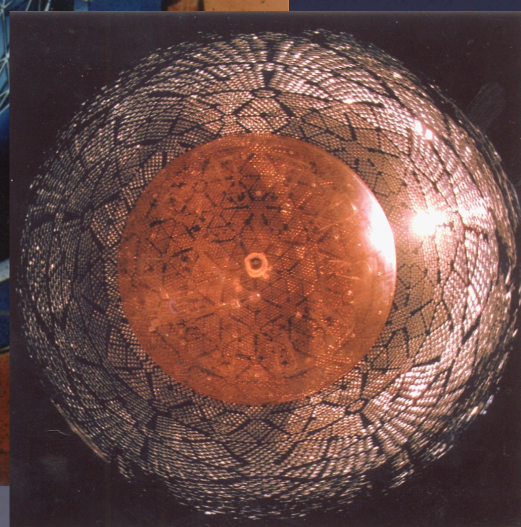
Super-K produced this neutrino “image” of the Sun by detecting neutrinos from nuclear fusion in the solar interior. (IMAGE : Institute for Cosmic Ray Research, Tokyo)

Neutrino (astro)Physics (history)

SNO Experiment





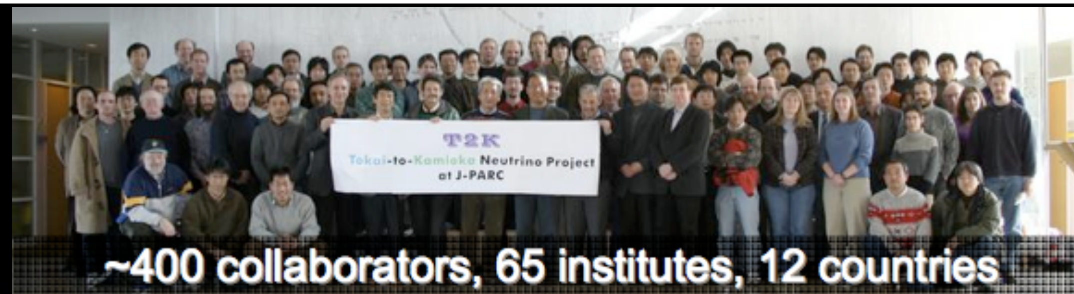


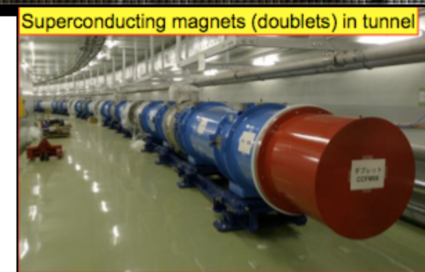
SNO experiment final confirmation of neutrino oscillations

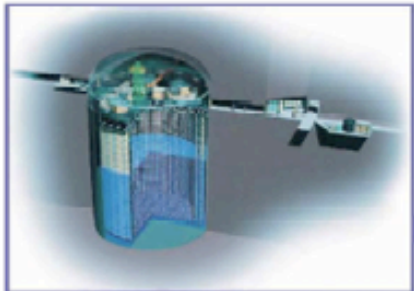
e.g. direct measure of the averaged survival probability of ^{8}B solar ν

$$\frac{\phi_{CC}}{\phi_{NC}} = 0.340 \pm 0.023(\text{stat.})^{+0.029}_{-0.031}$$

What Now
T2K in Japan

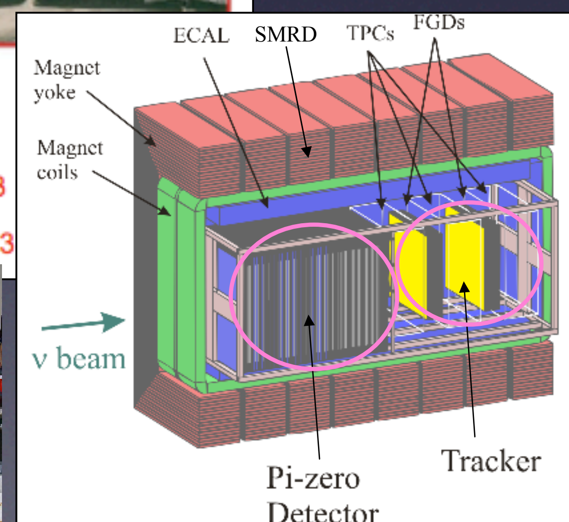






Tokai-to-Kamioka neutrino oscillation experiment

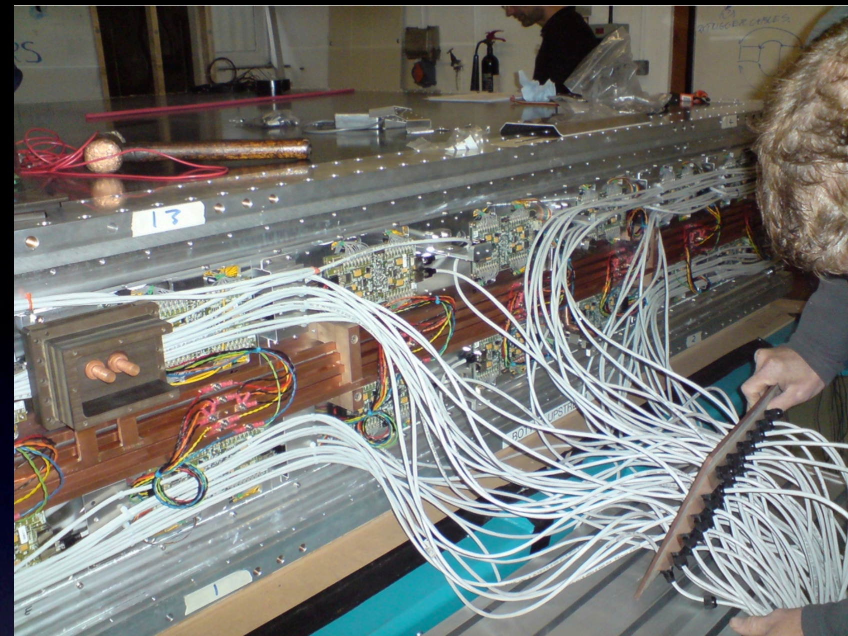
- to precisely measure the ν_μ disappearance, i.e. θ_{23} and Δm^2_{23}
- to intensively search for $\nu_\mu \rightarrow \nu_e$ appearance, i.e. non-zero θ_{13}

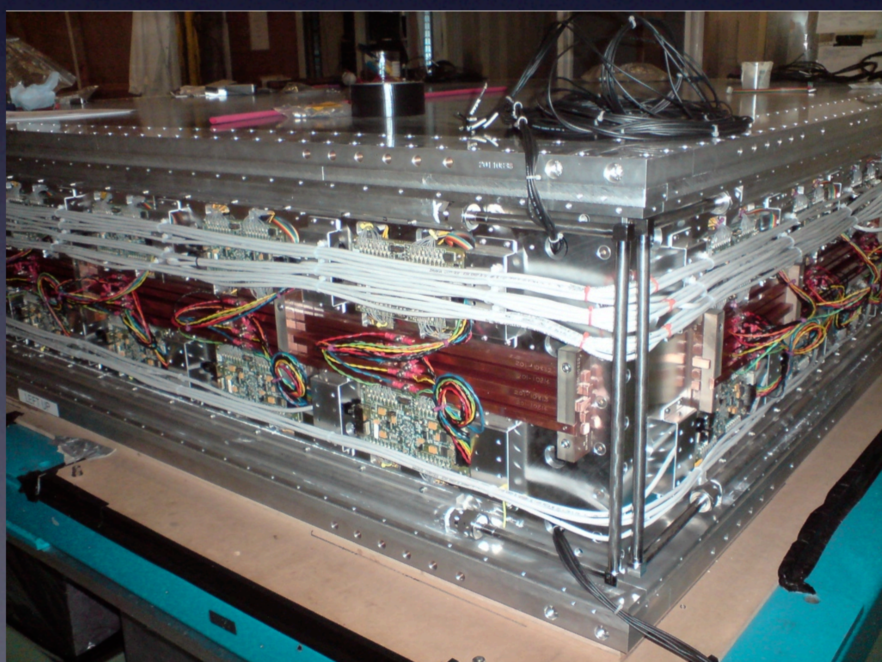


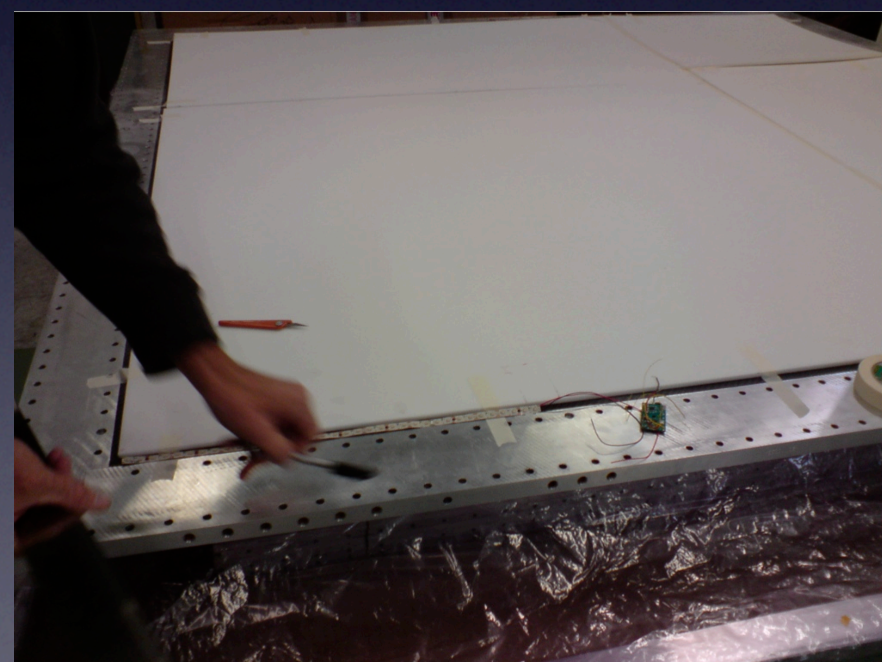
Major contribution from UK Including Sheffield

Sheffield T2K

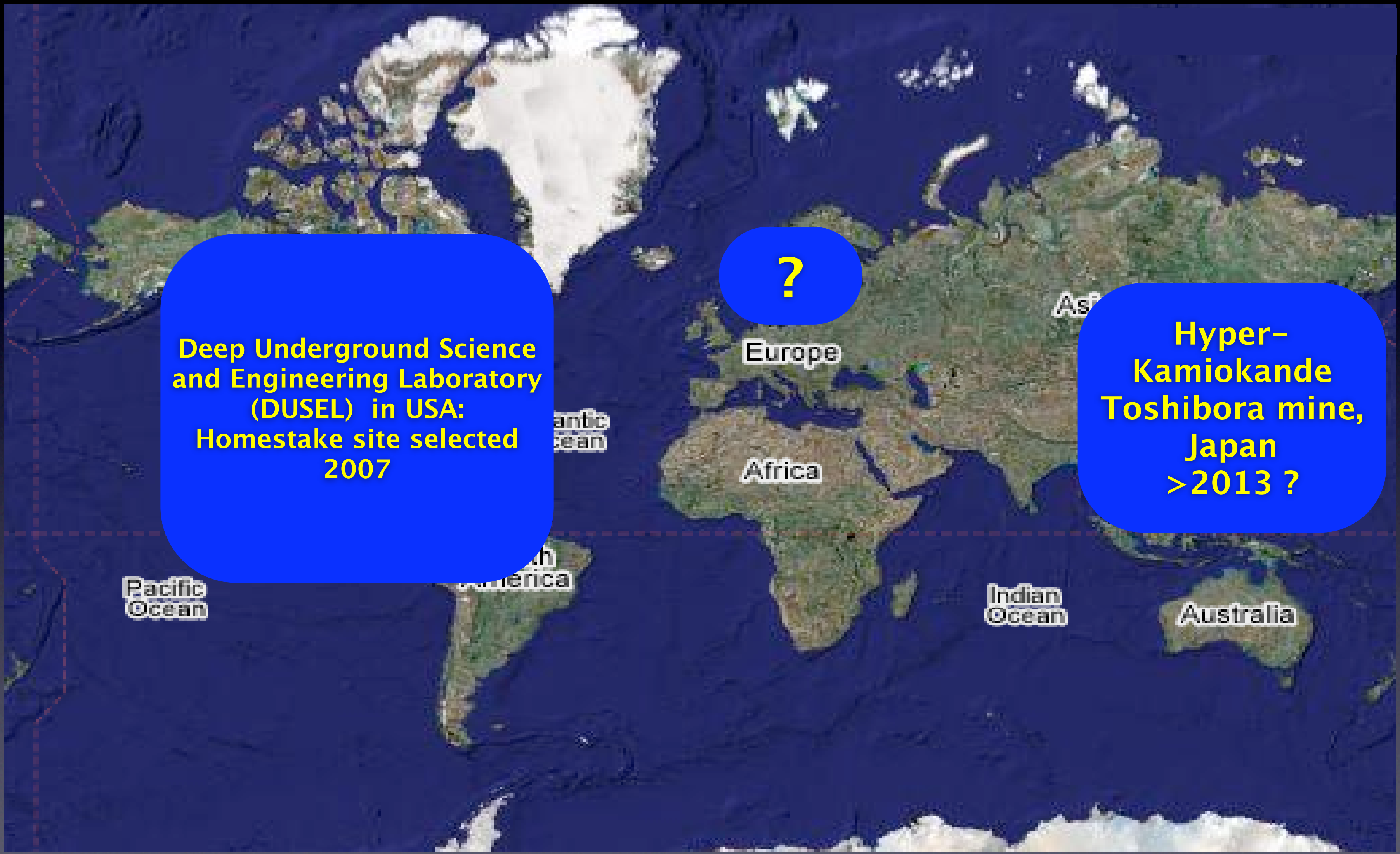
ECAL detector







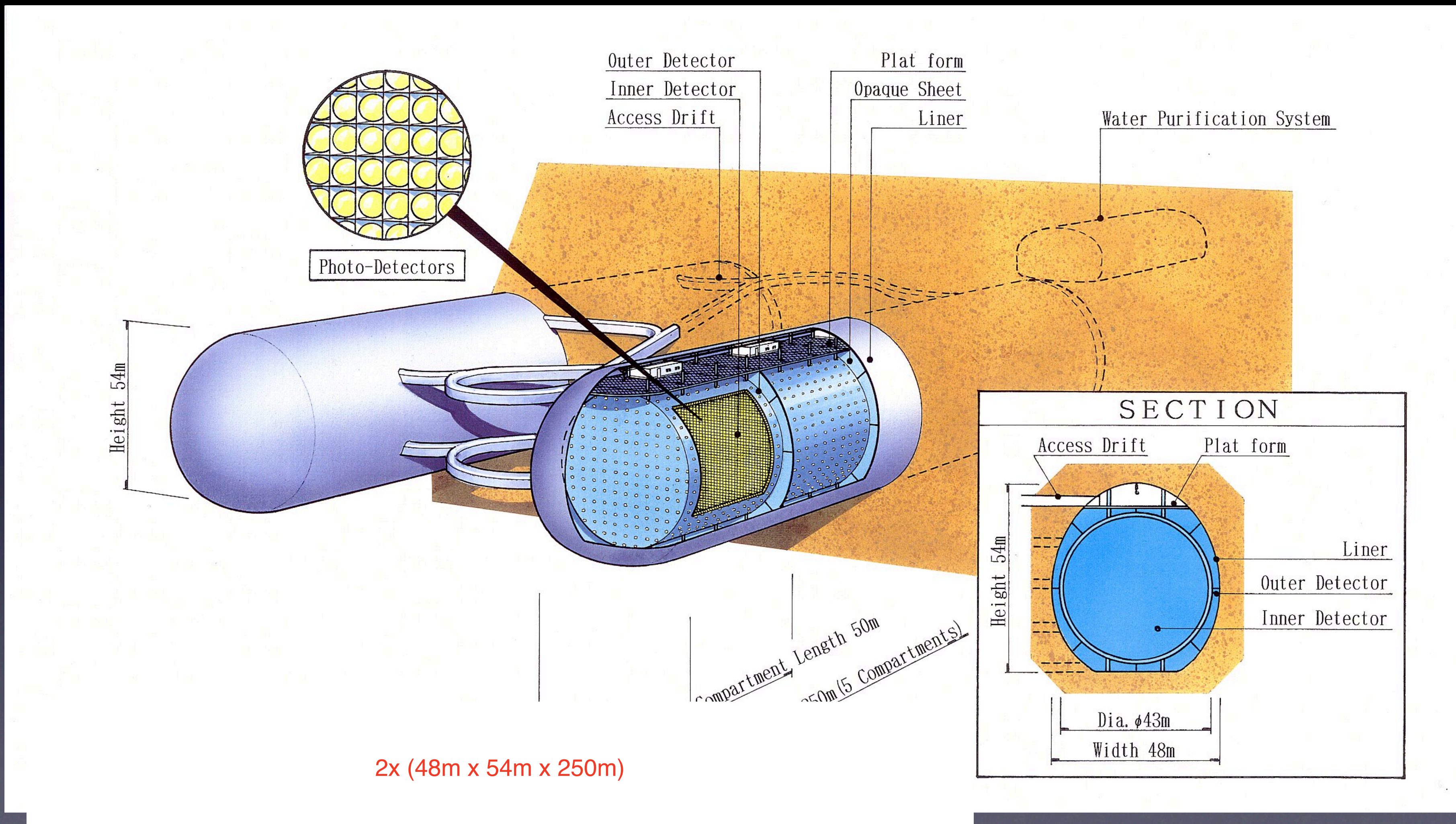
What Next - go BIG



very large volumes - 100 - 1000 kton!

HyperK Proposal in Japan

Water Čerenkov 500kt→1Mt

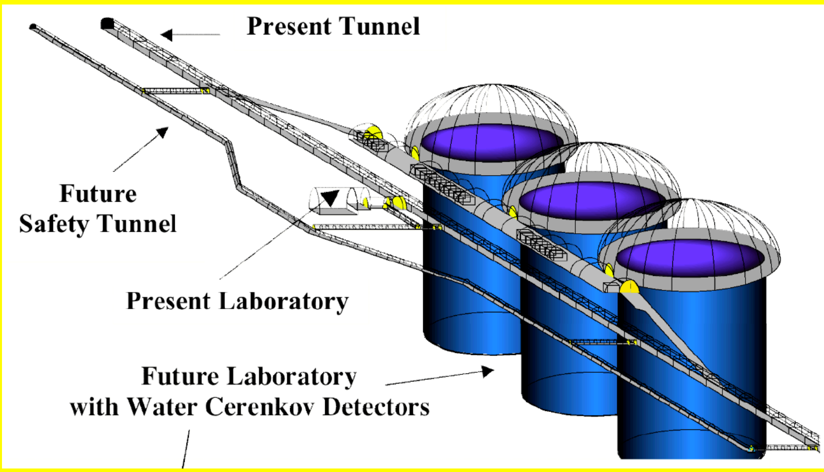


2x (48m x 54m x 250m)

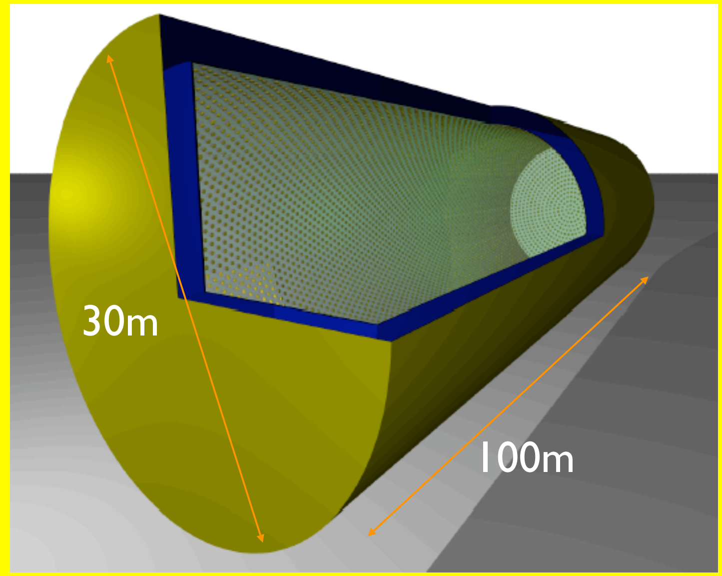
European Proposals

- Three experiments proposed

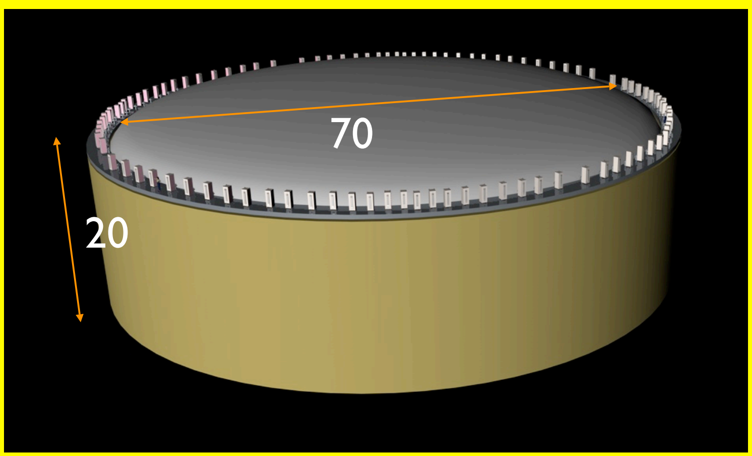
MEMPHYS



LENA Liquid Scintillator (→ 50 kton)



GLACIER Liquid Argon (≈10→100 kton)



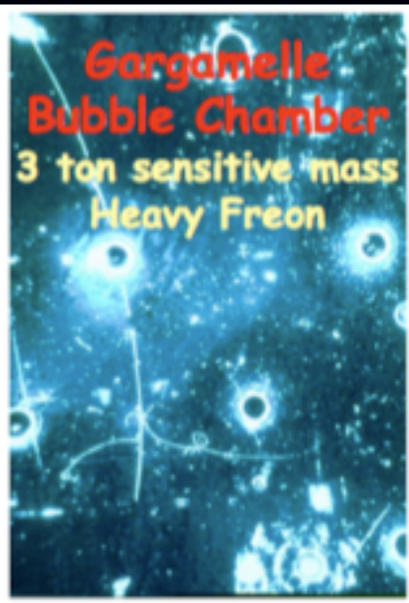
List of people: J. Aystö, A. Badertscher, A. de Bellefon, L. Bezrukov, J. Bouchez, A. Bueno, J. Busto, JE. Campagne, C. Cavata, R. Chandrasekharan, S.Davidson, J. Dumarchez, T. Enqvist, A. Ereditato, F. von Feilitzsch, S. Gninenko, M. Göger-Neff, C. Hagner, K. Hochmuth, S.Katsanevas, L. Kaufmann, J. 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?

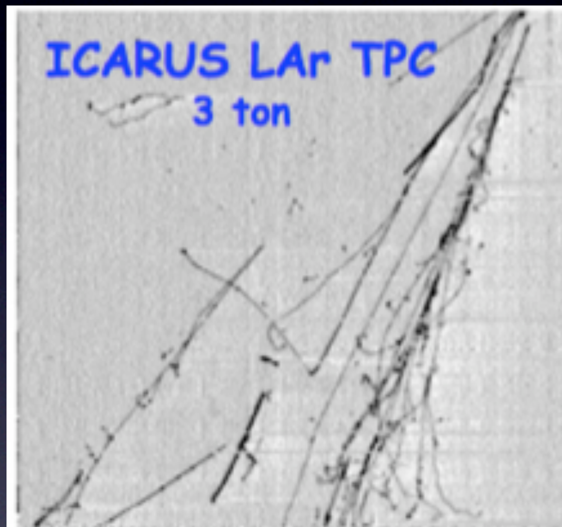
- New technology is maturing
    - Liquid scintillator
    - Liquid argon
    - Photosensors
- New opportunities, and experience of, deep sites
- New understanding of ultra low background control
- An explosion in underground SCIENCE

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



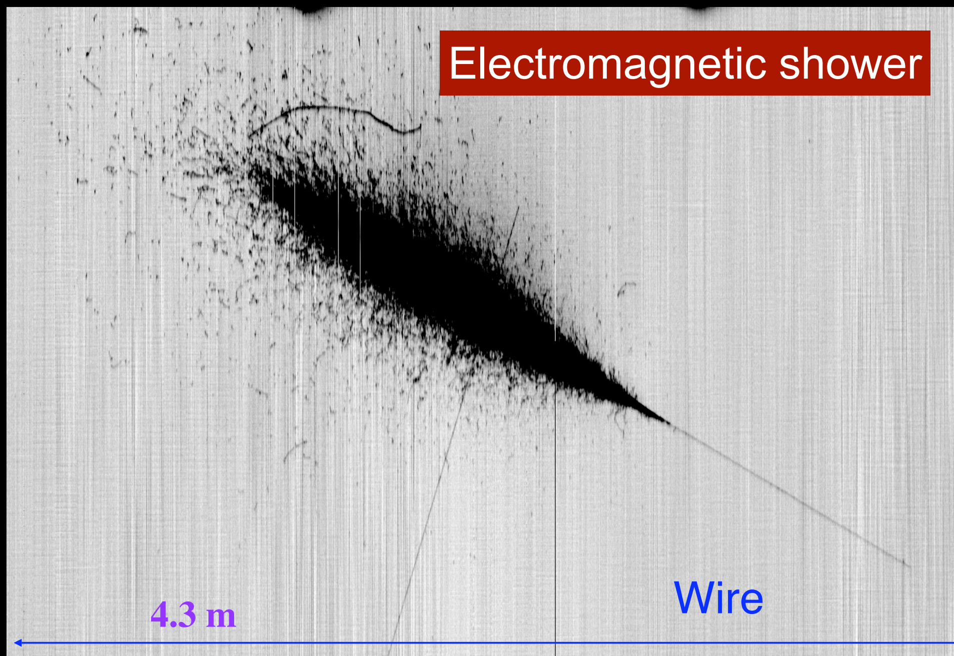
Bubble ∅ (mm)	3
Density (g/cm³)	1.5
X_0 (cm)	11.0
λ_T (cm)	49.5
dE/dx (MeV/cm)	2.3

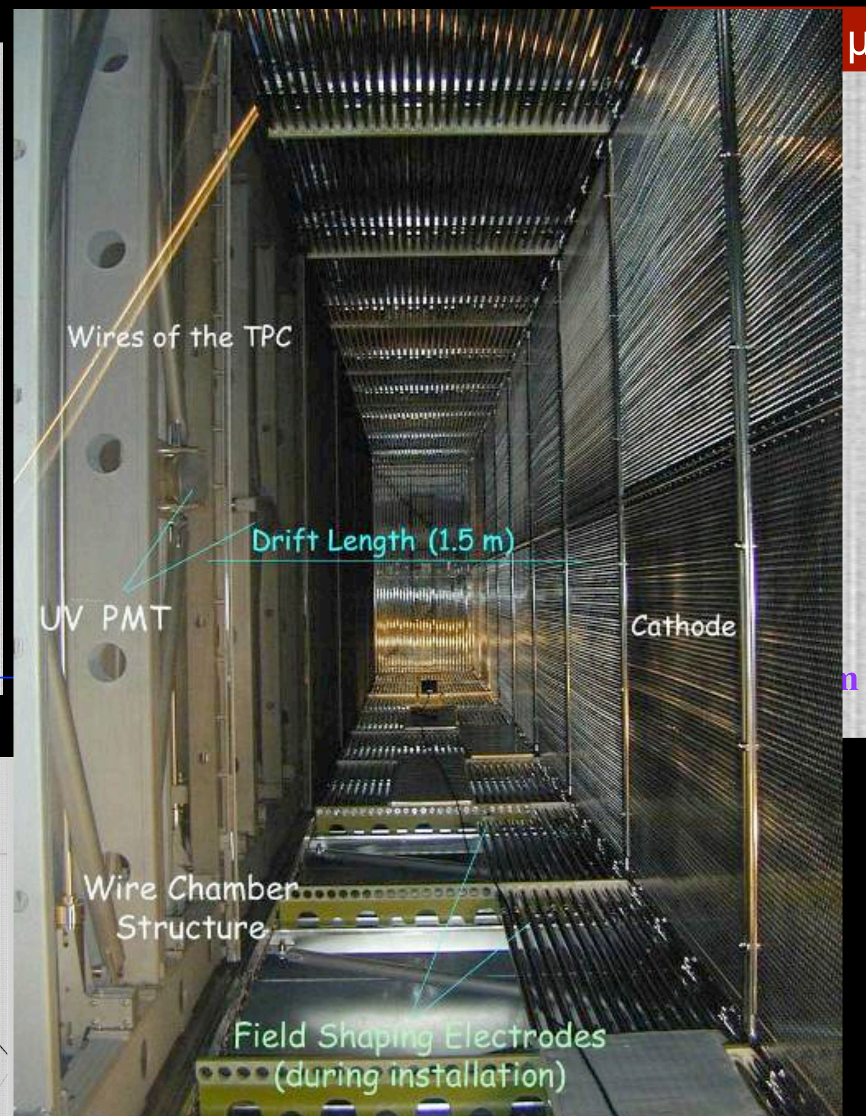


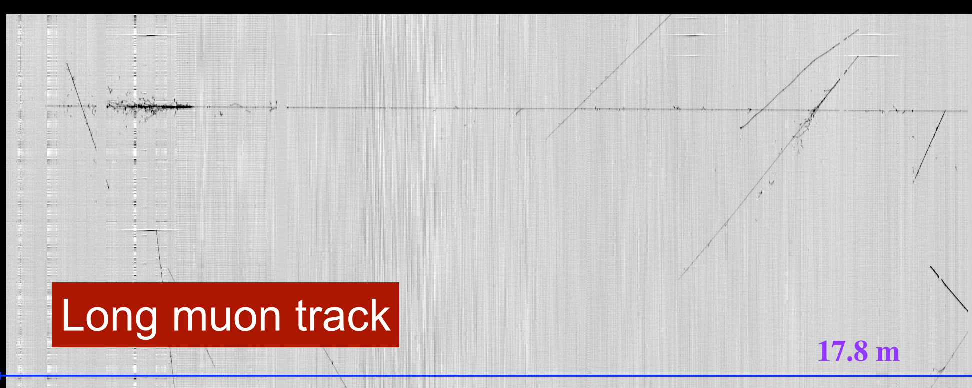
Resolution (mm³)	2×2×0.2
Density (g/cm³)	1.4
X_0 (cm)	14.0
λ_T (cm)	54.8
dE/dx (MeV/cm)	2.1

ICARUS T300 test on surface (2001)

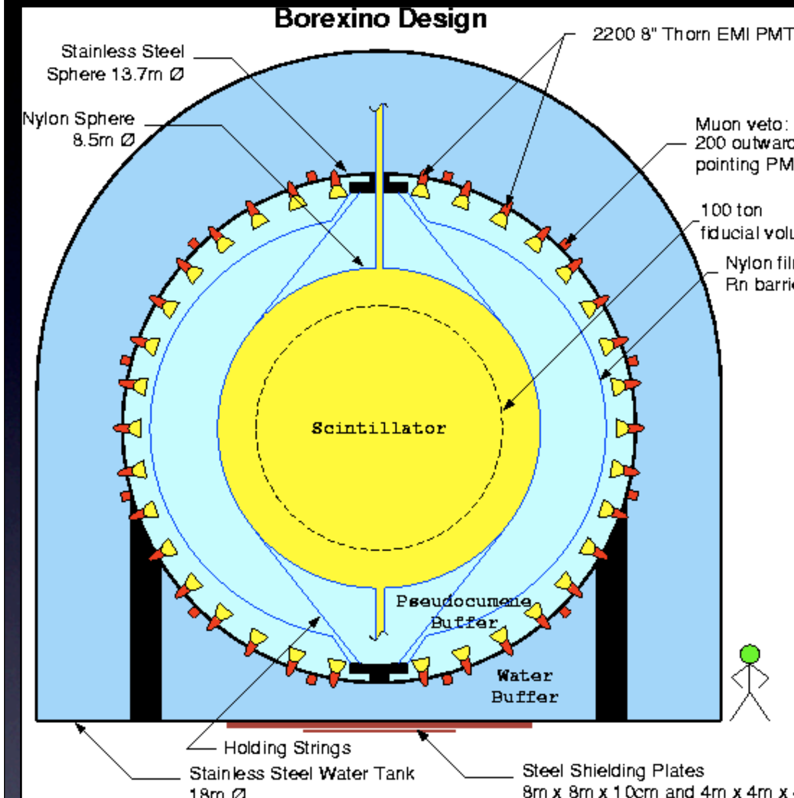
Data from test run: 27000 triggers from cosmic ray interactions





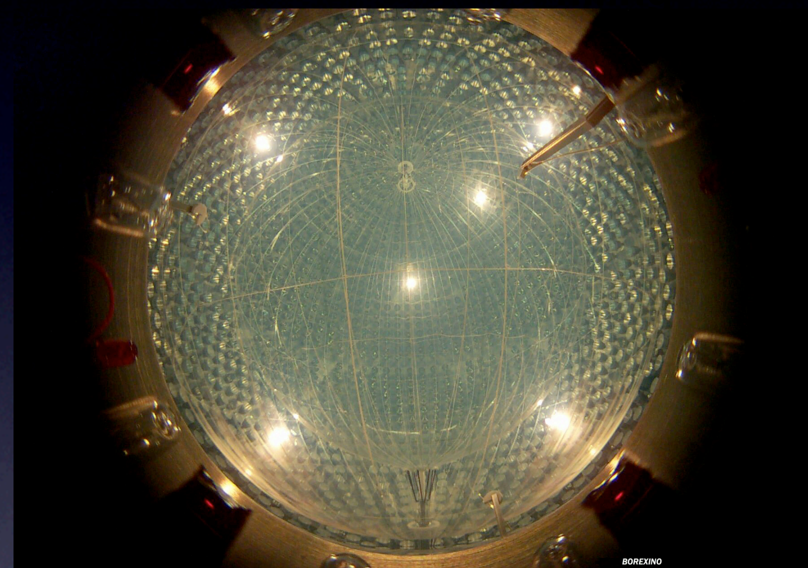


e.g. Scintillator Success



87 tons
500 p.e./MeV

Solar Neutrinos BOREXINO



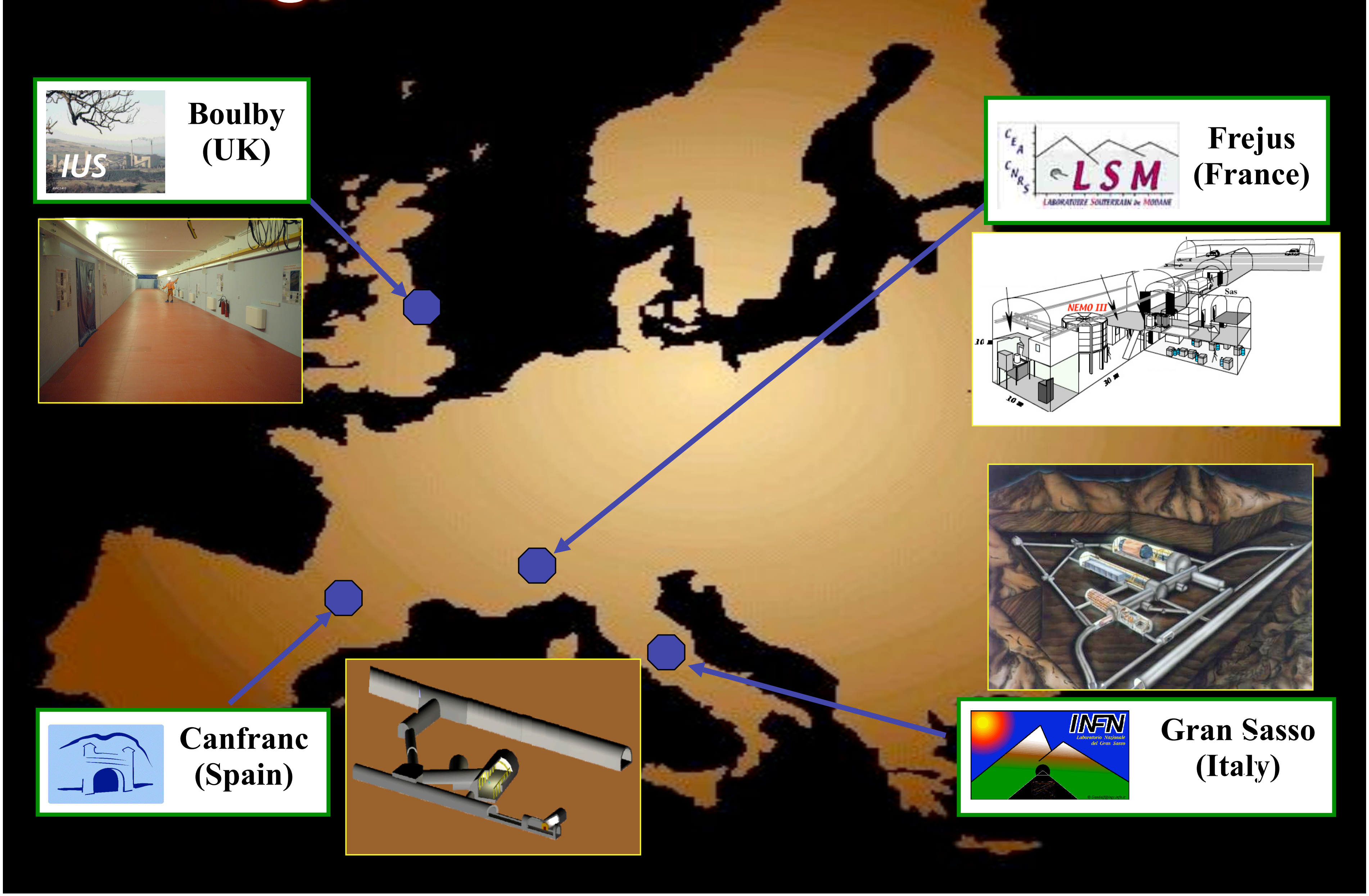
$47 \pm 7_{stat}$ cpd/100tons
for 862 keV ^{7}Be solar ν

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

e.g. Excavation!

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

e.g. Success with EU Sites



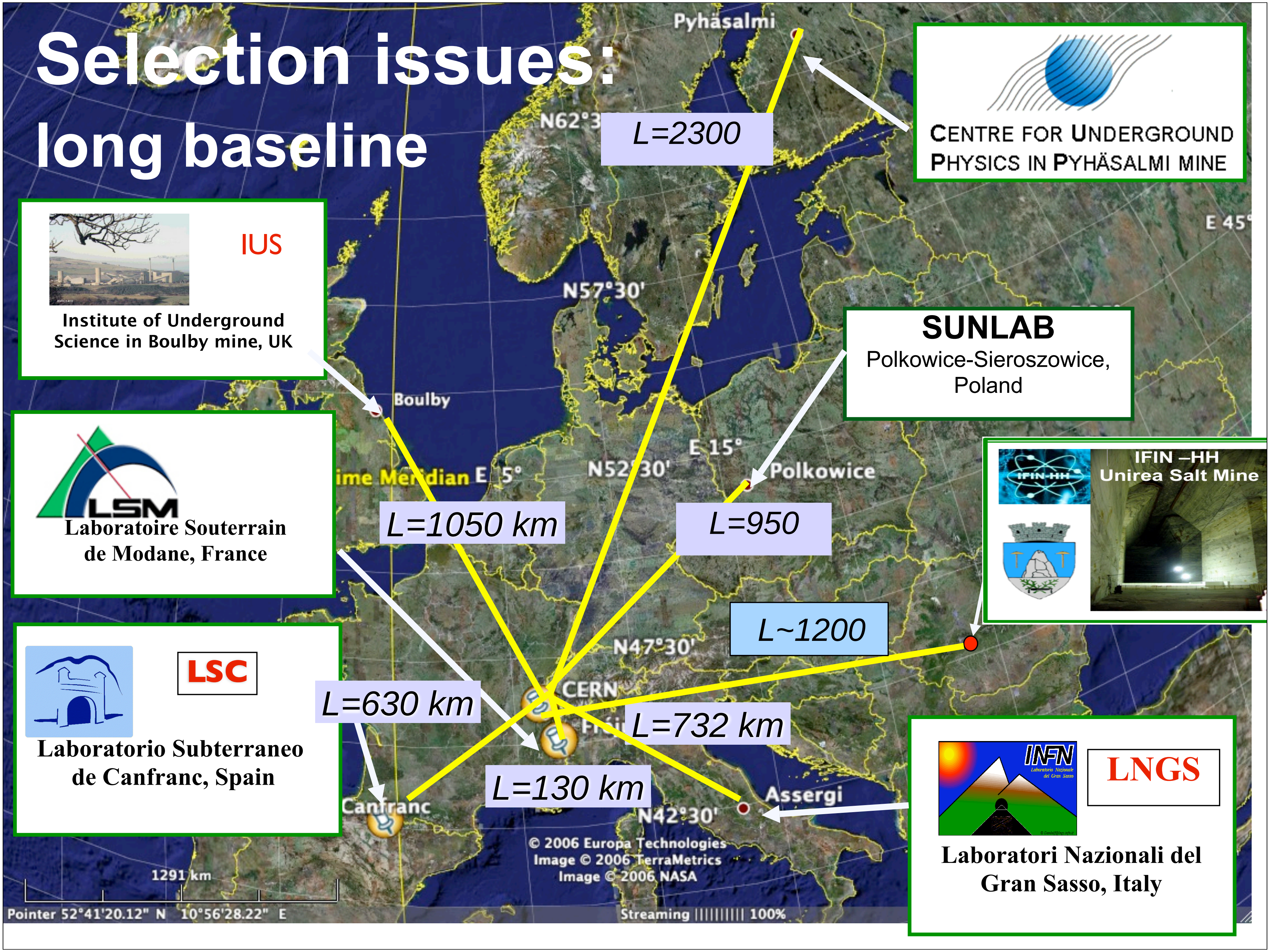
The LAGUNA Collaboration

Consortium composed of 21 beneficiaries

- **9 higher education entities (ETHZ, U-Bern, U-Jyväskylä, UOULU, TUM, UAM, UDUR, USFD, UA)**
- **8 research organizations (CEA, IN2P3, MPG, IPJ PAN, KGHM CUPRUM, GSMiE PAN, LSC, IFIN-HH)**
- **4 SMEs (Rockplan, Technodyne, AGT, Lombardi)**
- **Additional higher education participants (IPJ Warsaw, U-Silesia, U-Wroclaw, U-Granada**

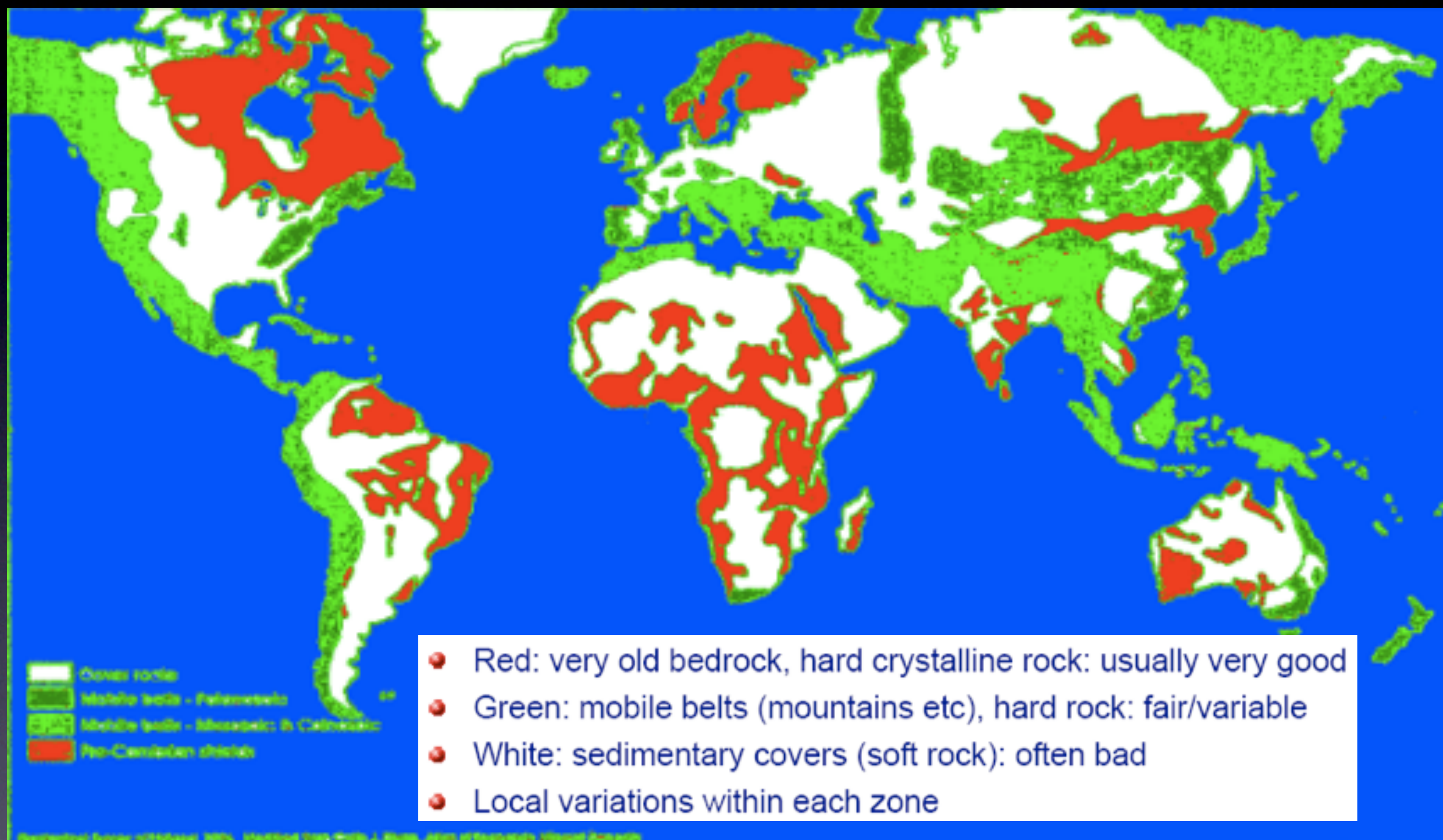
Kickoff meeting at ETH Zurich 3/4 July 2008:

Selection issues: long baseline



New sites: Slanic, Romania

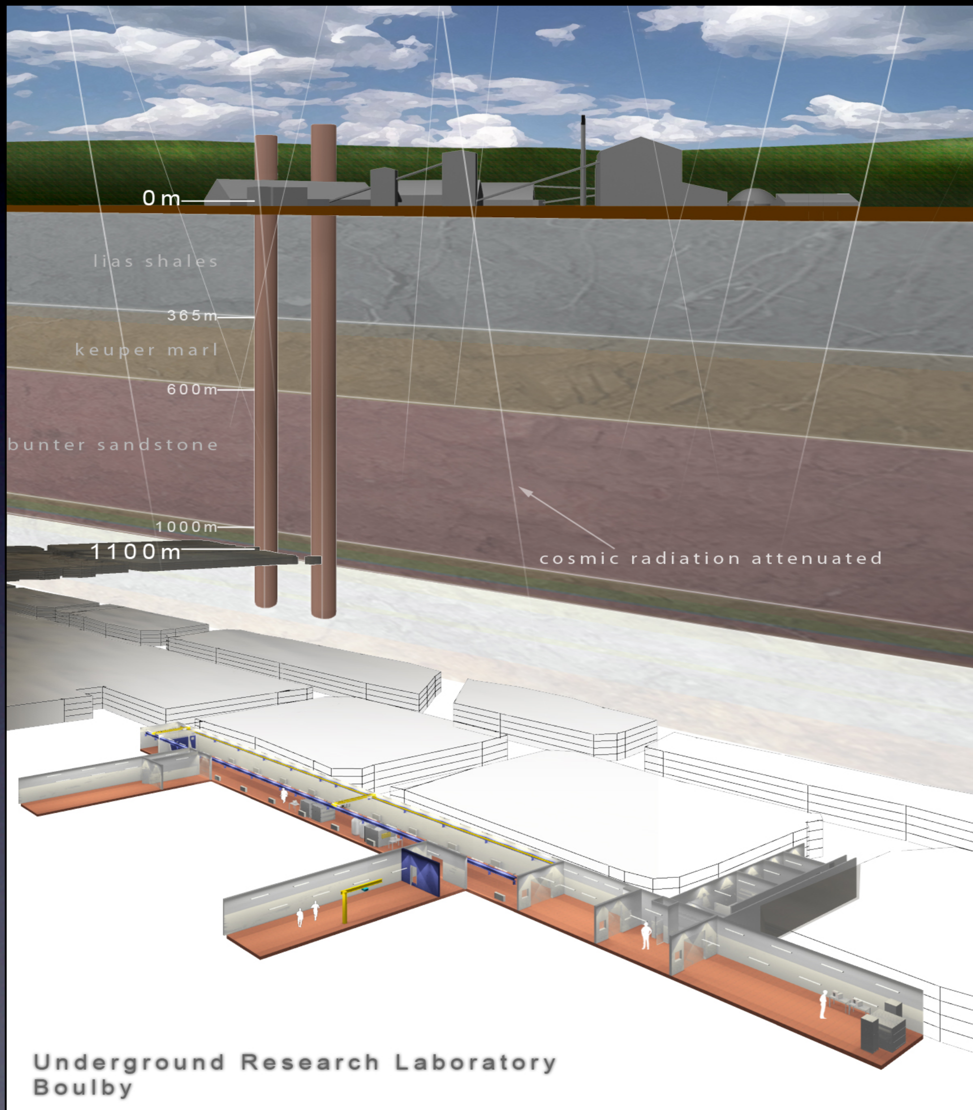
Selection issues:
quality of the rock, the depth



- Ability to create large caverns up to 100m
- Seismology and water issues

Boulby

opened by Lord Sainsbury in April 2003



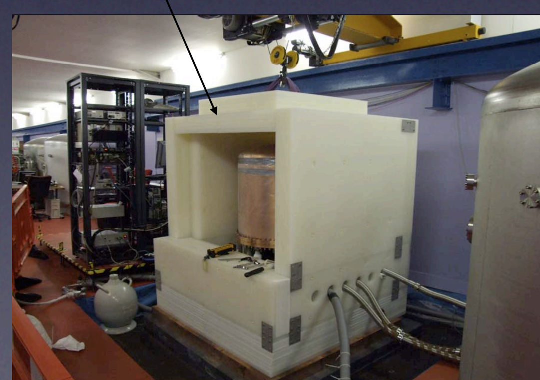
Boulby - Status (Dark Matter)

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

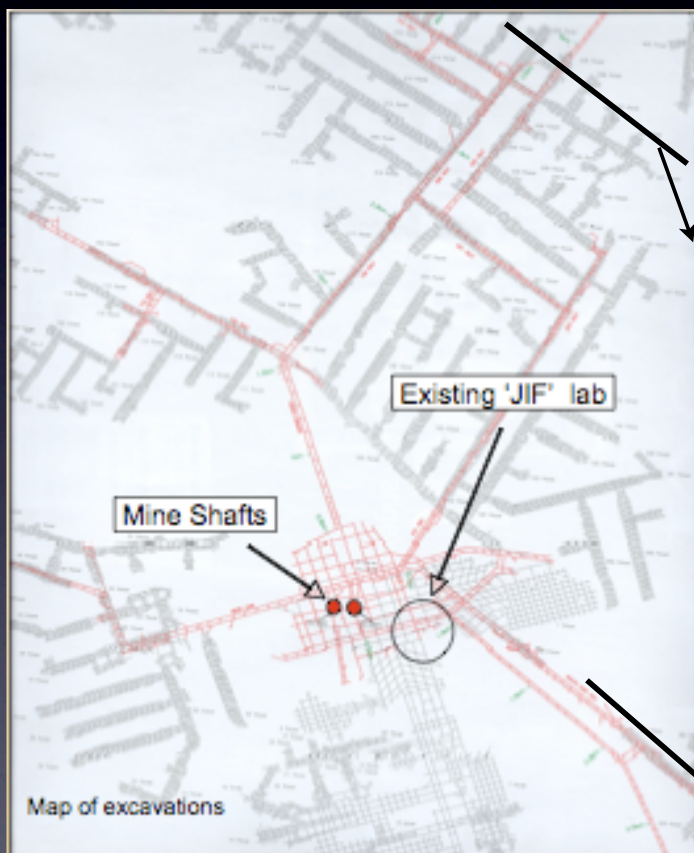
Two phase liquid Xenon Dark Matter detectors

ZEPLIN-III



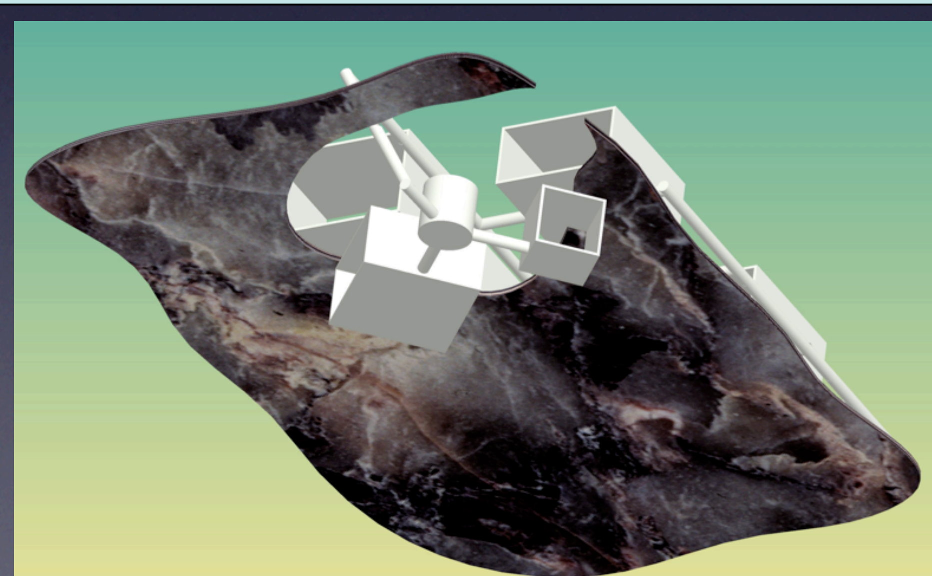
Boulby Expansion?

New regional development proposal for deeper, hard rock labs funded by ONE - 2 years to excavation



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

New CPL-University partnership seeking feasibility study



So What New Physics...

	Water Cerenkov	Liquid Argon TPC	Liquid Scintillator
Total mass	500 kton	100 kton	50 kton
$p \to e\,\pi^0$ in 10 years	$1.2\text{x}10^{35}$ years $\varepsilon = 17\%$, ≈ 1 BG event	$0.5\text{x}10^{35}$ years $\varepsilon = 45\%$, <1 BG event	?
$p \to \nu\,K$ in 10 years	$0.15\text{x}10^{35}$ years $\varepsilon = 8.6\%$, ≈ 30 BG events	$1.1\text{x}10^{35}$ years $\varepsilon = 97\%$, <1 BG event	$0.4\text{x}10^{35}$ years $\varepsilon = 65\%$, <1 BG event
SN cool off @ 10 kpc	194000 (mostly $\nu_e p \to e^+ n$)	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 !

Proton Decay

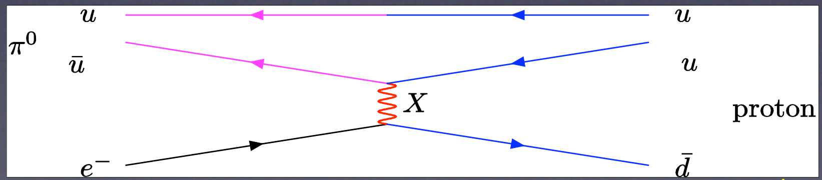
Motivation

- 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

$$\tau / B(p \rightarrow e^+\pi^o) \sim 10^{29\pm2}\ years$$

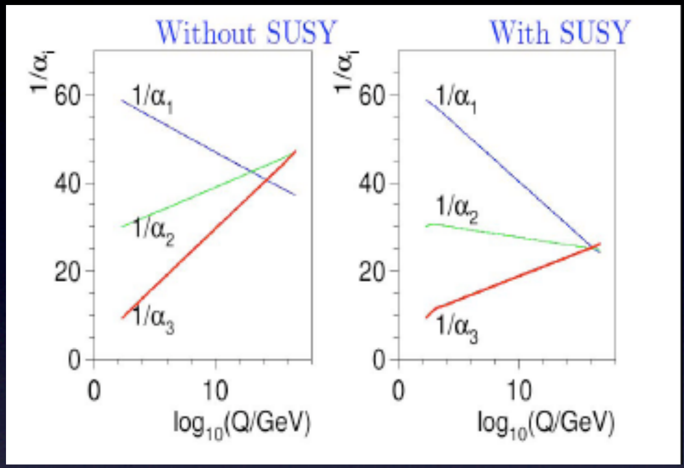


- Introducing SUSY increases coupling scale by x10, lifetime by x10^4

Proton Decay

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

"minimal" SUSY SU(5)



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

- Typical lifetimes then: $\tau / B(p \rightarrow \bar{\nu}K^+) \geq 2.9 \times 10^{30}\ years$
  - 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)

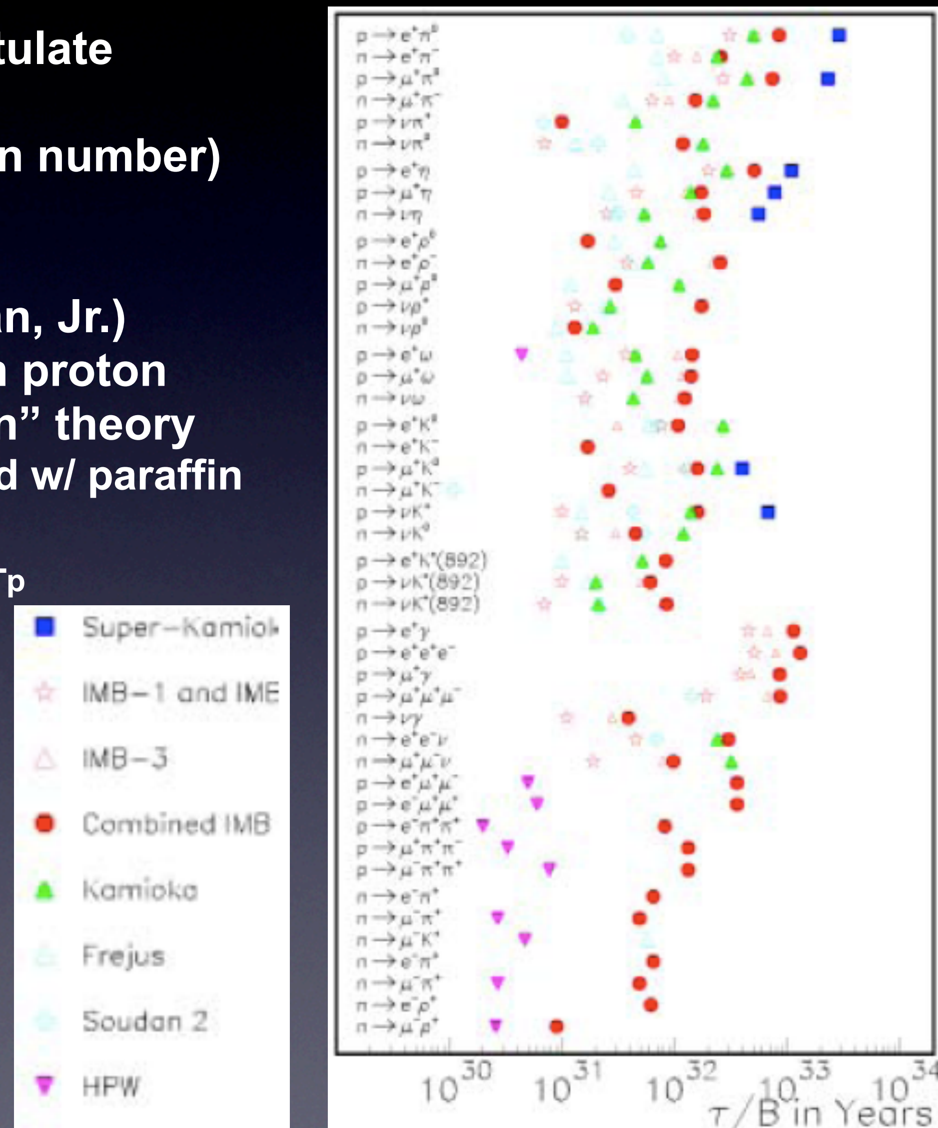
Proton Decay History

1929: Weyl suggests absolute stability of proton

1938: Stuckelberg and 1949: Wigner postulate existence and
conservation of a “heavy charge” (baryon number) associated w/ heavy particles

1954: M. Goldhaber (w/ Reines and Cowan, Jr.) publishes the first experimental result on proton lifetime inspired by “Continuous Creation” theory
– using a liquid scintillator detector (shielded w/ paraffin +lead) containing
~3x10^{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)

Best limits:
dominated by water
Cherenkov detectors

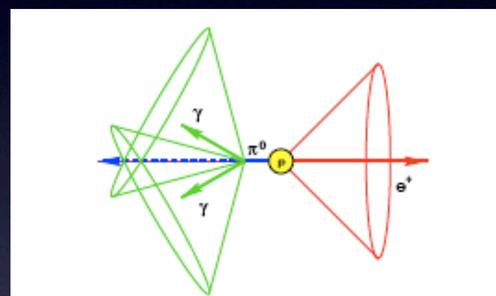


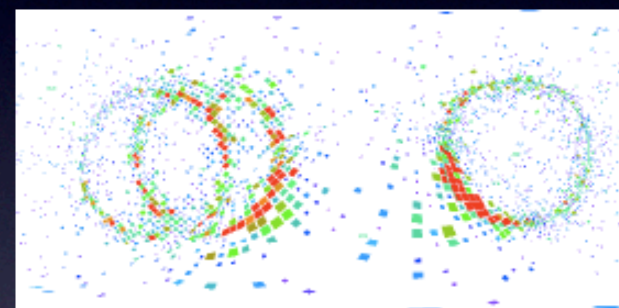
SK Results

■ 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.)

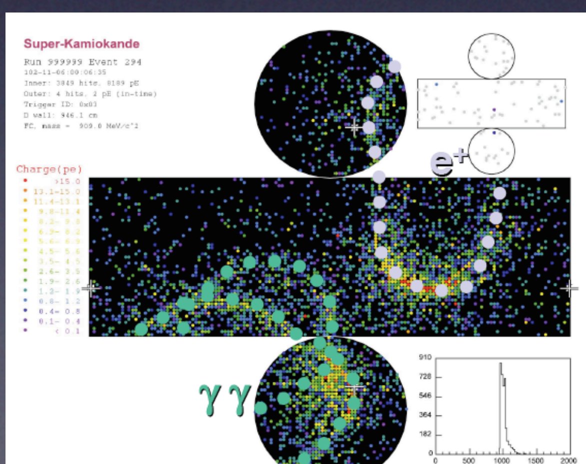
- SK - ring imaging water Cherenkov counter at Kamioka at 2700 mwe depth with 50 Ktons
  - cuts and selection criteria tuned to select decay modes
  - efficiencies calculated and comparison made with MCs

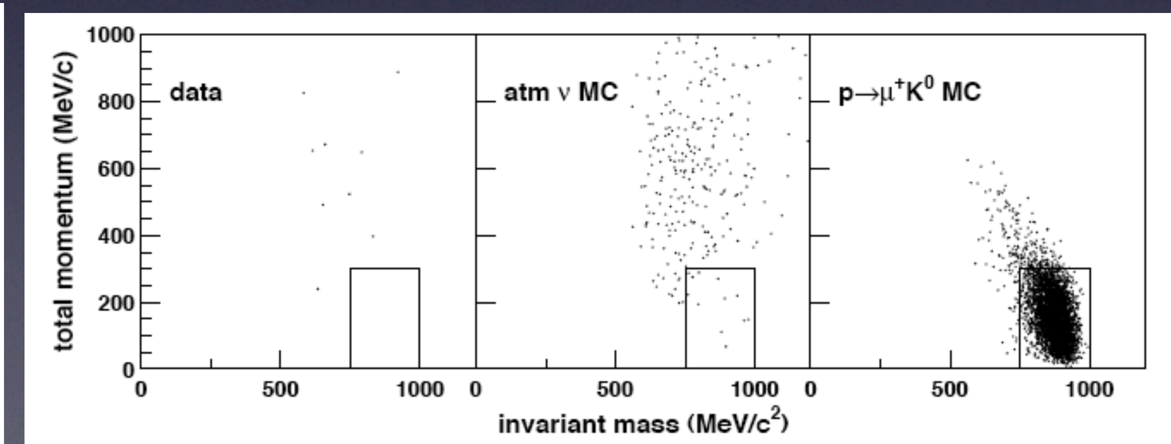
Idealized $p \to e^+\pi^\circ$ decay in Super-Kamiokande.





real event





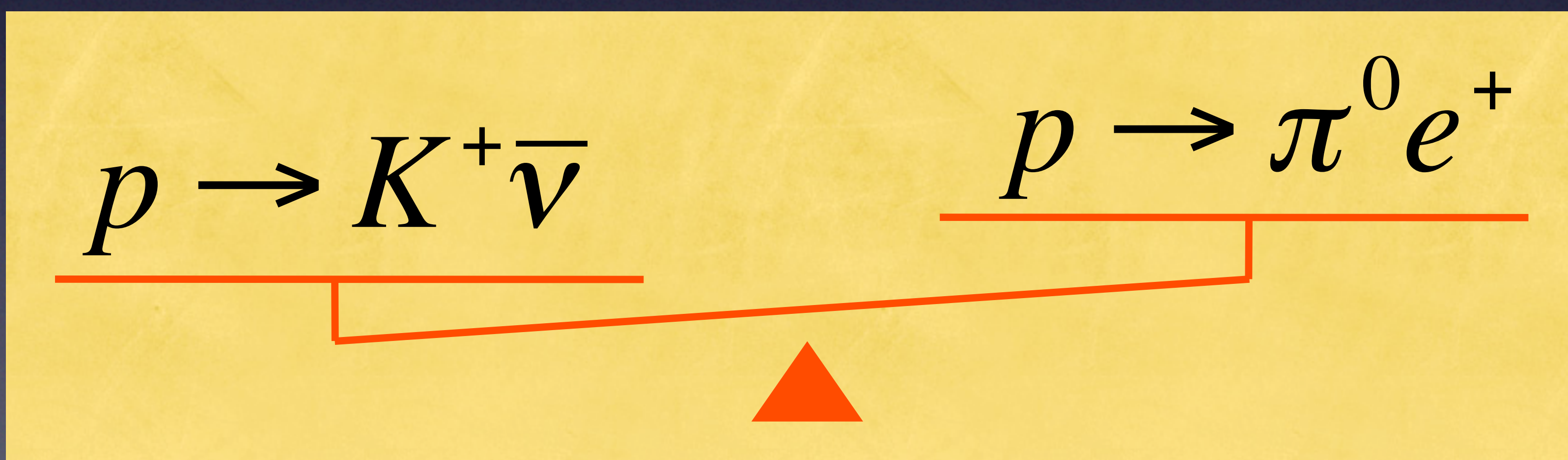
Proton Decay Summary

SUSY GUTs predict proton & neutron decay with lifetimes exceeding BUT near Super-K bounds

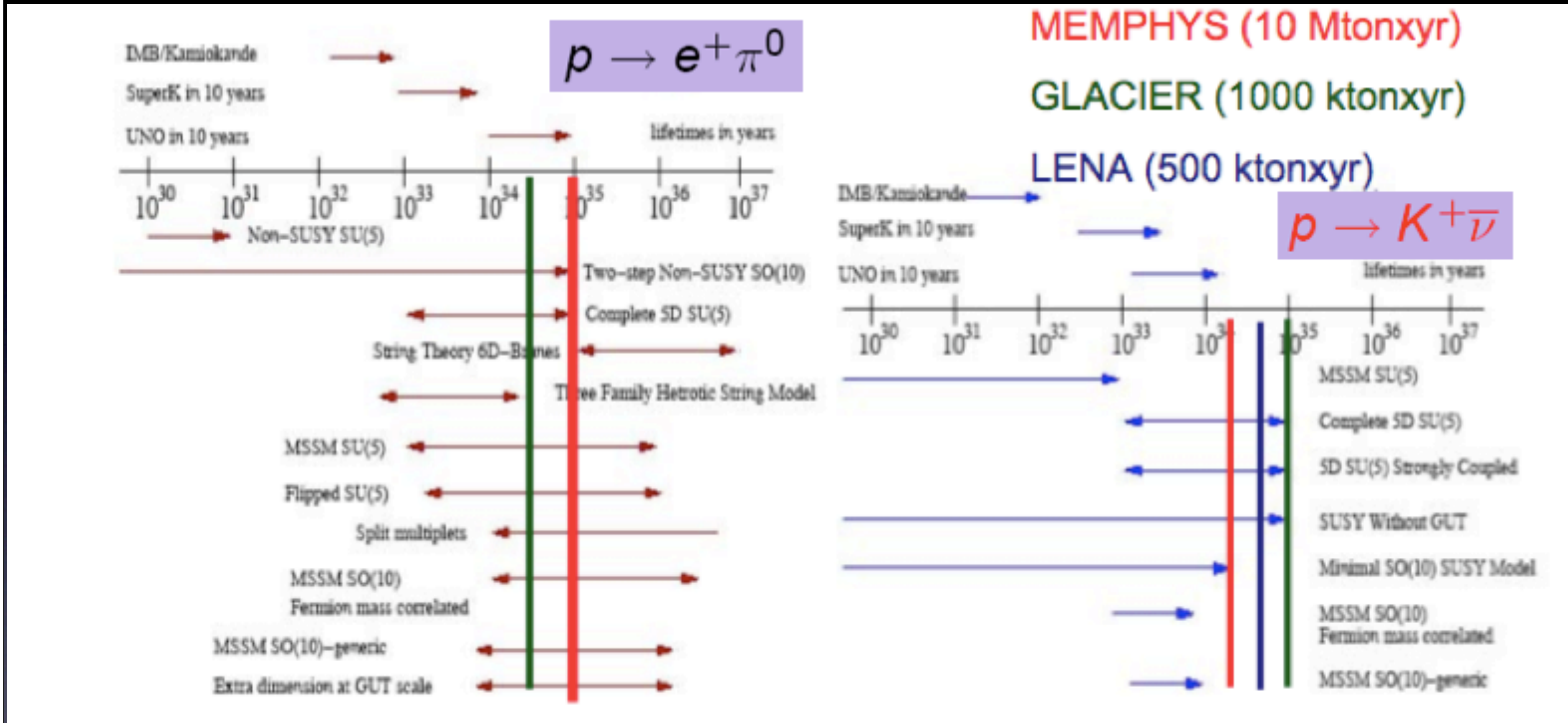
Proton decay should be just around the corner

BUT which mode dominates ?

The answer is model dependent !!



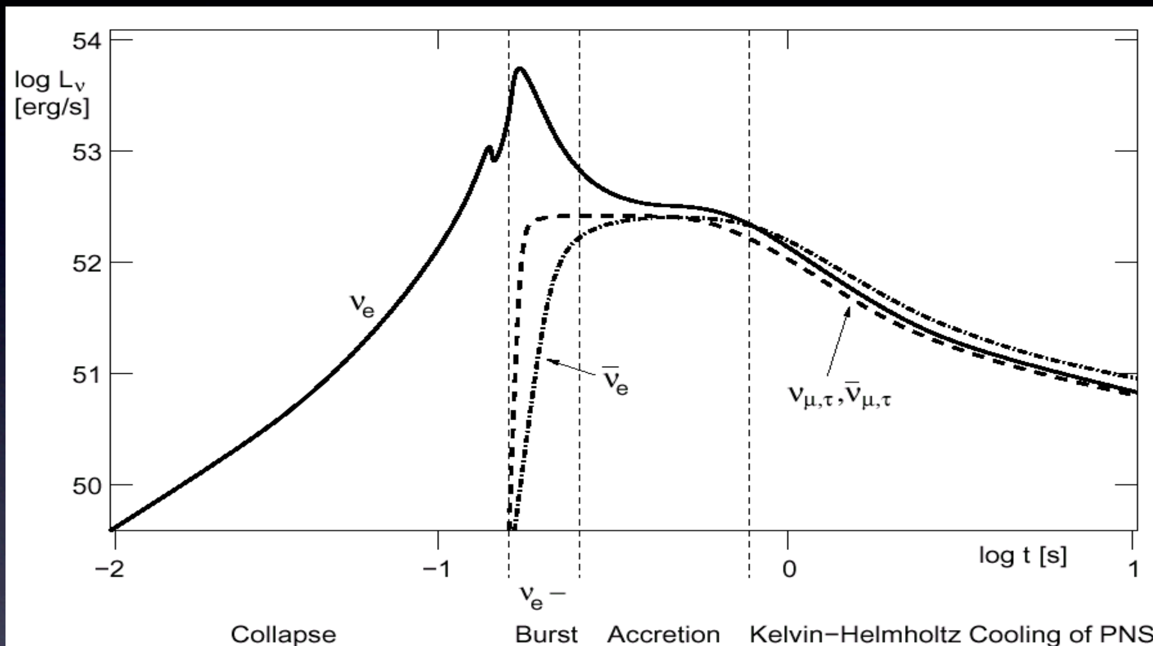
Comparison with Theory

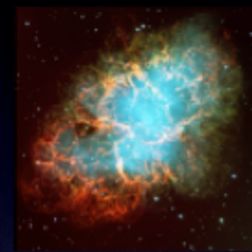


- Not exhaustive, (e.g. 6D SO(10) not included)

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

SN neutrino rates

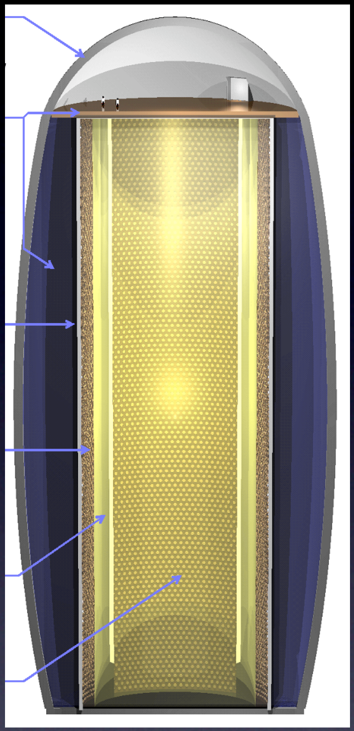
- 8 $M_\odot$ ($3 \cdot 10^{53}$ erg) at D = 10 kpc (center of our galaxy)

In LENA detector: ~15000 events

Possible reactions in liquid scintillator

- $\overline{\nu}_e + p \to n + e^+$; $n + p \to d + \gamma$ ~9000 events
- $\overline{\nu}_e + {}^{12}\mathrm{C} \to {}^{12}\mathrm{B} + e^+$; ${}^{12}\mathrm{B} \to {}^{12}\mathrm{C} + e^- + \overline{\nu}_e$ ~250 events
- $\nu_e + {}^{12}\mathrm{C} \to e^- + {}^{12}\mathrm{N}$; ${}^{12}\mathrm{N} \to {}^{12}\mathrm{C} + e^+ + \nu_e$ ~400 events
- $\nu_x + {}^{12}\mathrm{C} \to {}^{12}\mathrm{C}^* + \nu_x$; ${}^{12}\mathrm{C}^* \to {}^{12}\mathrm{C} + \gamma$ ~1000 events
- $\nu_x + e^- \to \nu_x + e^-$ (elastic scattering) ~700 events
- $\nu_x + p \to \nu_x + p$ (elastic scattering) ~2000 events

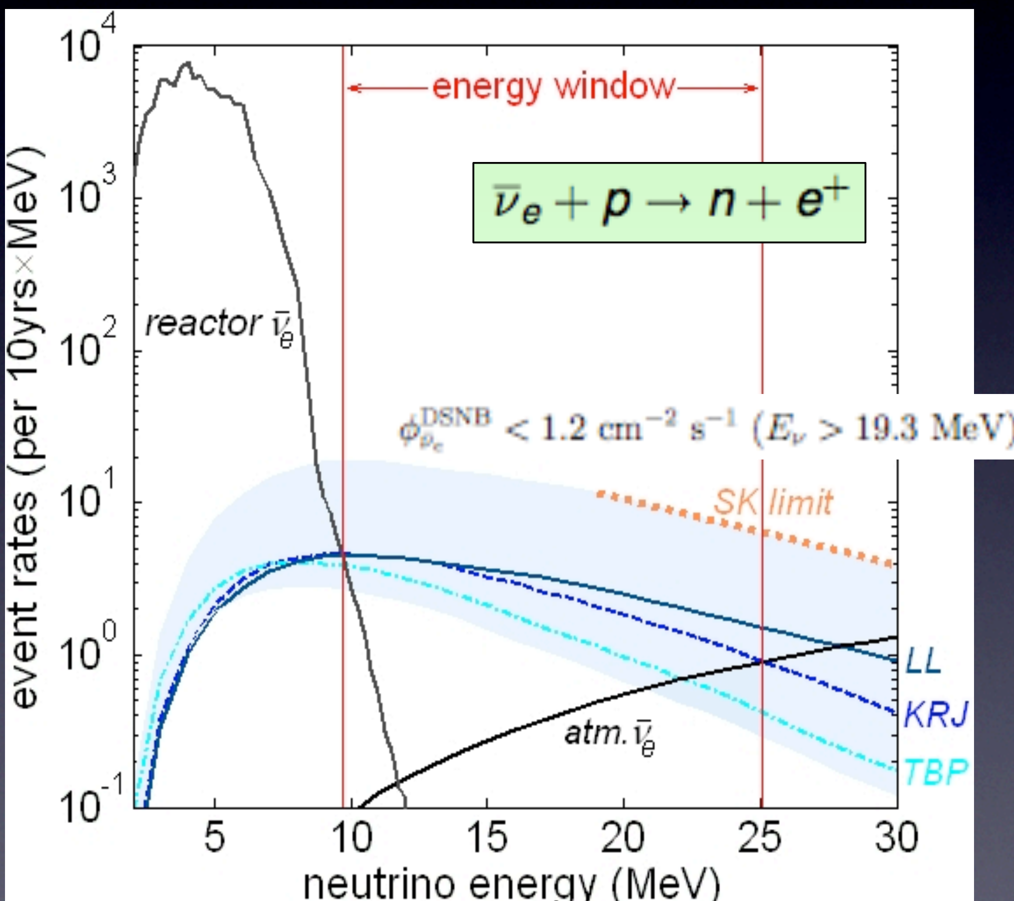
Diploma thesis by J.M.A. Winter (TU München)



- IBD is golden channel for MEMPHYS and LENA
- 11 neutrinos detected from 1987a!! produced 1000s of papers

SN Diffuse Neutrino rates

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



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

Selection issues:

backgrounds - (un)natural activity

UNIVERSITY of OULU

Nuclear reactor background

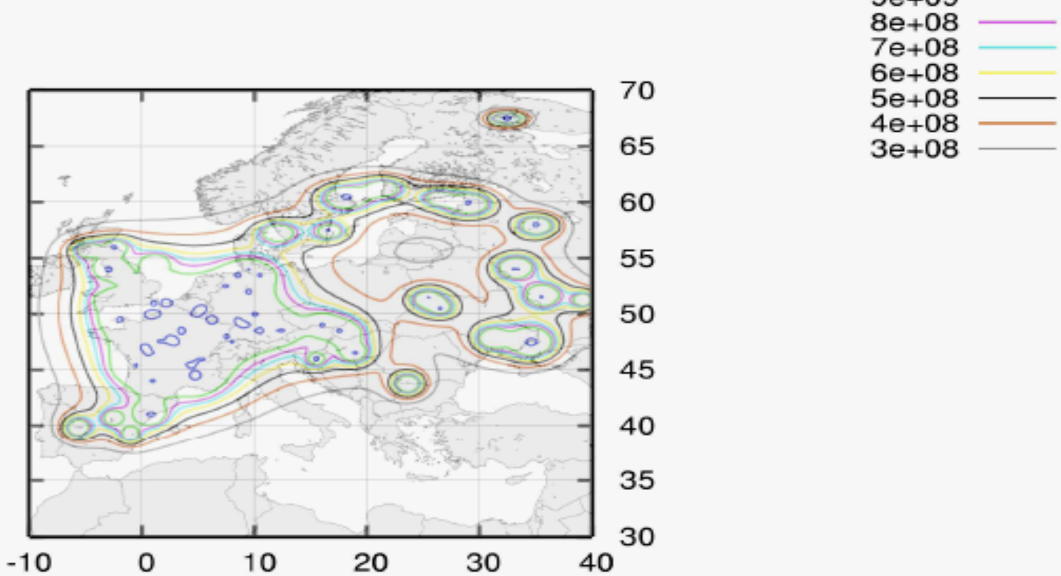
- Relevant mostly for LENA
- Reactor fluxes estimated globally
- Marine reactors irrelevant?

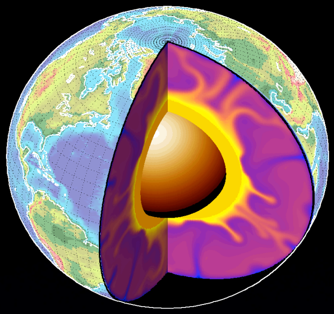
Location	ν $(10^8\ 1/m^2\ s)$
Pyhäsalmi	40
Gran Sasso	54
Frejus	175
Canfranc	196
Boulby	190
Kamioka	408
Sudbury	100
Soudan	33
Pylos	12

2005

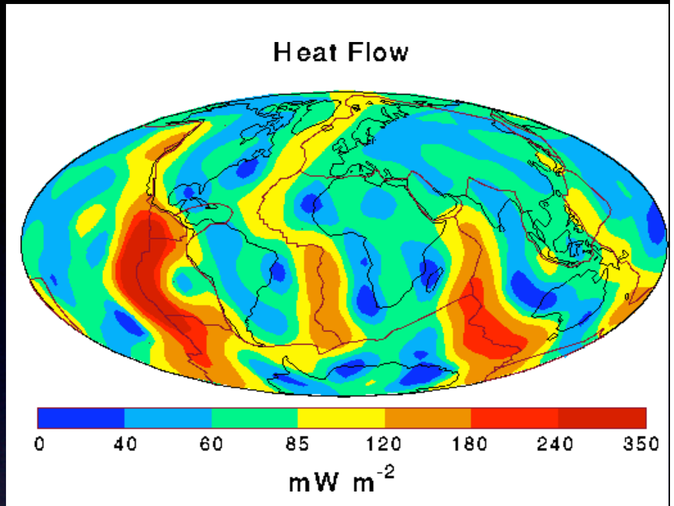
Reactor electron anti-neutrino flux density

Prediction for 2015





Geo-neutrinos



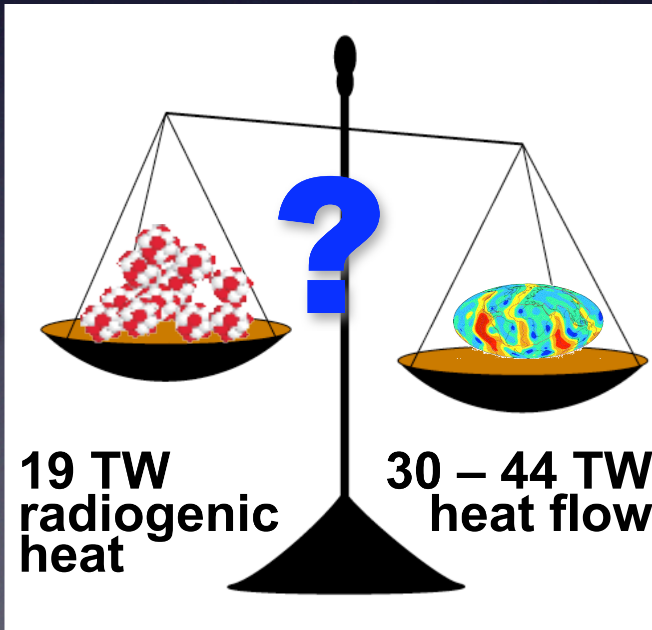
- Heat flow from the Earth is the equivalent of some 10000 nuclear power plants

  $$H_{Earth} = (30 - 44)\,TW$$

- 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

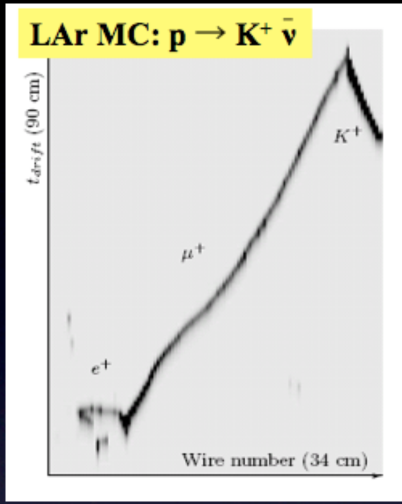
- Unorthodox or even heretical models have been advanced…



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

So what about Liquid Argon?

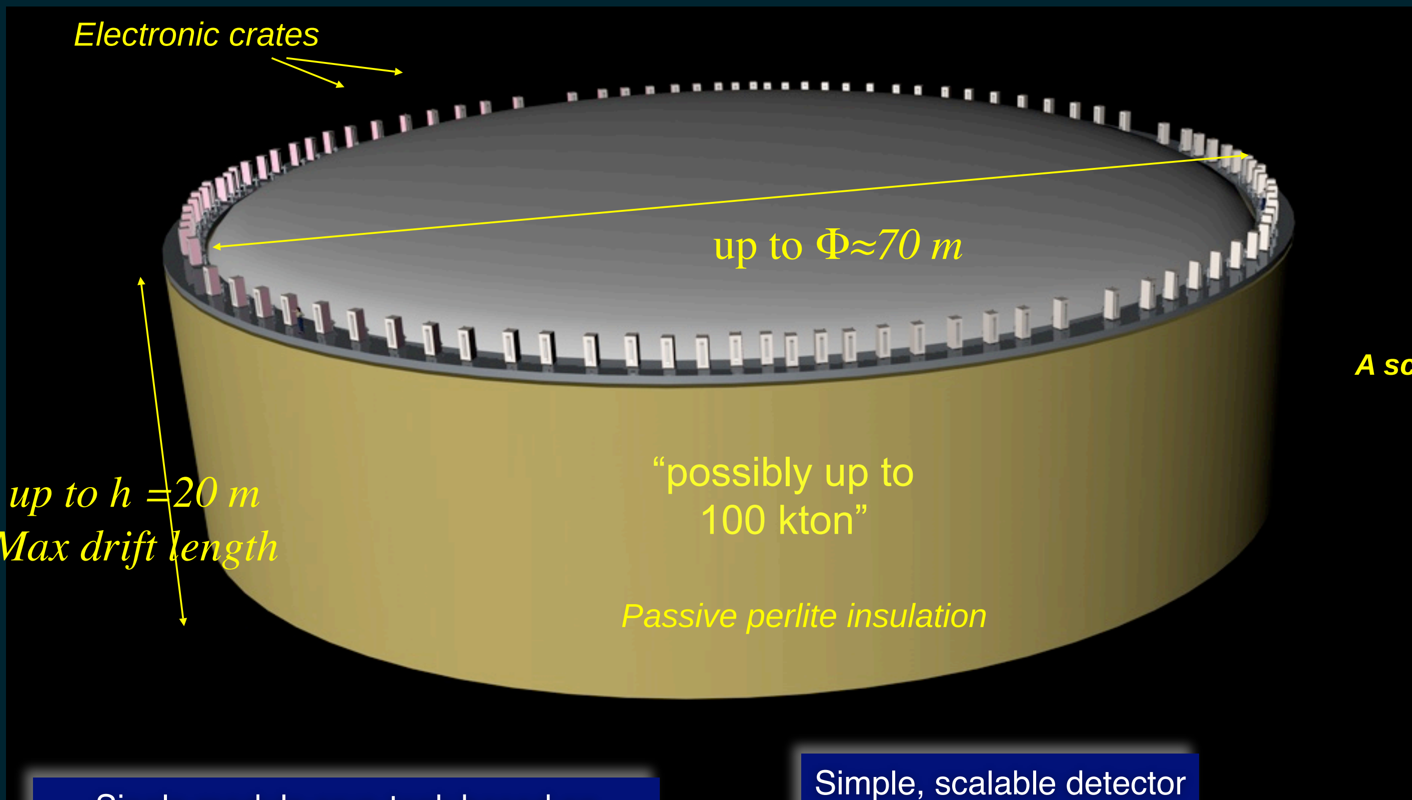
- LAr TPC has many advantages
  - Excellent tracking and calorimetric resolution
  - Background rejection and topology of events
  - Ionisation, scintillation, cerenkov light
  - Possible to instrument large masses
  - Not too expensive...



Medium/ Property	BP @ 1atm	Density liquid g/cm^3	W (eV) Q_0=E/W	electron mobility (cm^2/Vs)	W_γ (eV)	Scintillation wavelength (nm)	Lifetime of scintillation	Long-lived metastable isotope
Ar ≈$1/kg	87.3K	1.40	23.8	400	25.0	128	≈10ns / 1.6μs	^{39}Ar ^{42}Ar

This is UK's (Sheffield) interest

GLACIER: Giant Liquid Ar Charge Imaging ExpeRiment



A scalable design:

Single module cryo-tank based on industrial LNG technology

Simple, scalable detector design, possibly up to 100 kton

Modest excavation requirements for "megaton-scale-physics"

Based on LAr LEM-TPC readout

Big Cryogenic Tanks are Easy - LPG

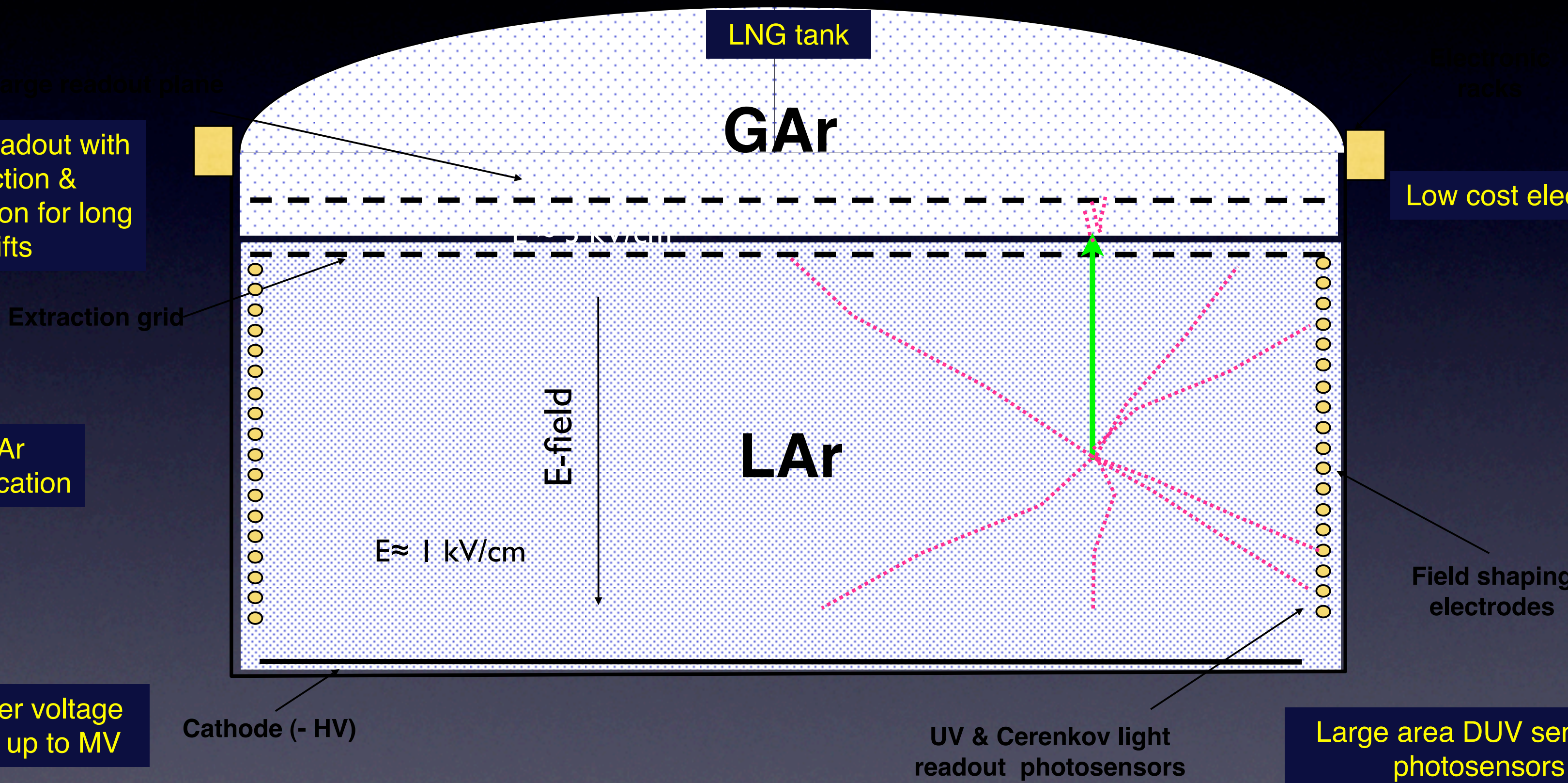
Many large LNG tanks in service

Vessel volumes up to 200000 m^3

Excellent safety record

Last serious accident in 1944, Cleveland, Ohio, due to tank with low nickel content (3.5%)

GLACIER and liquid argon detectors



Charge readout with extraction & amplification for long drifts

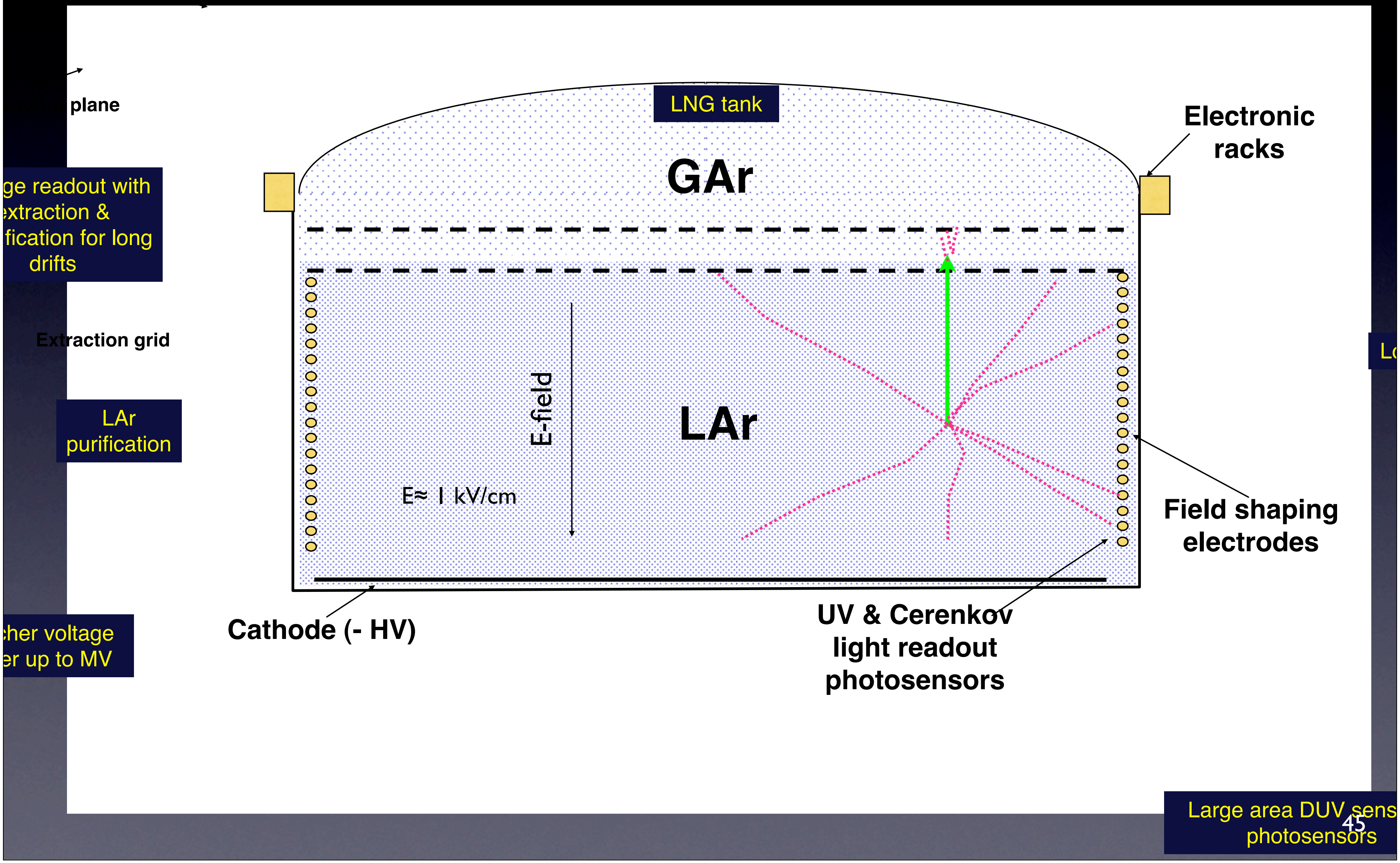
Low cost electronics

LAr purification

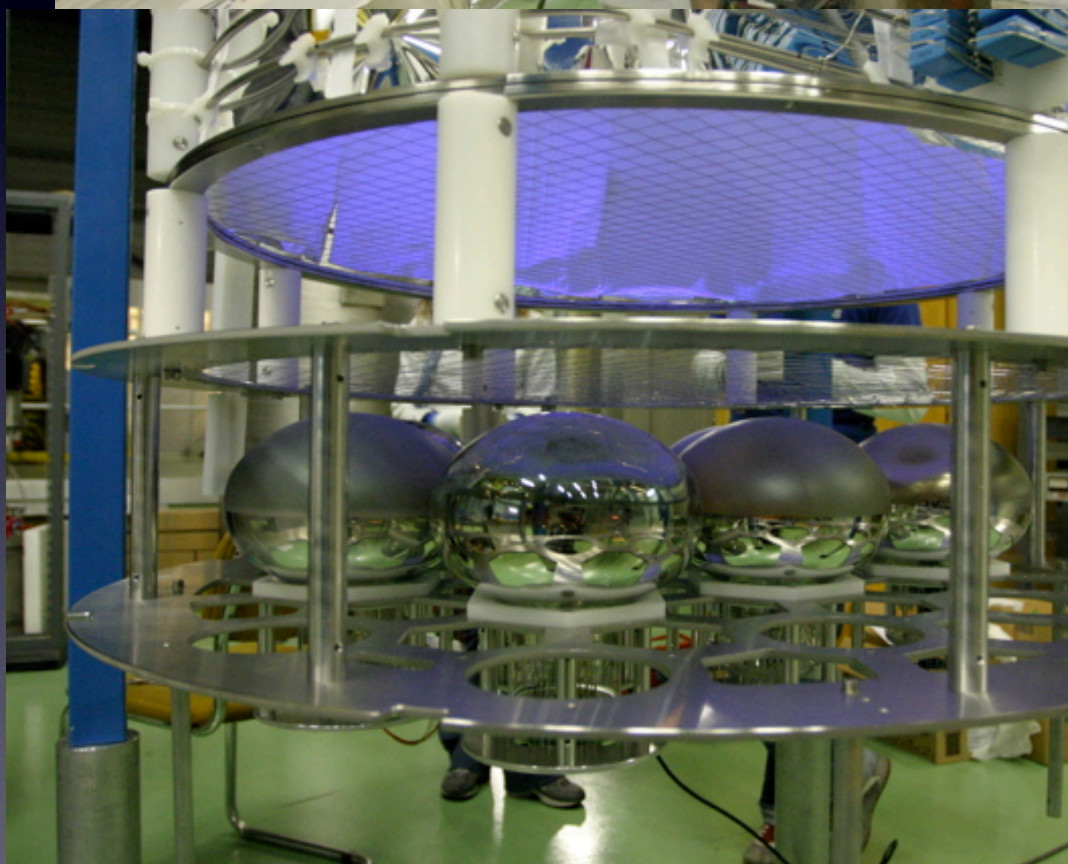
Greinacher voltage multiplier up to MV

Large area DUV sensitive photosensors

GLACIER and liquid argon detectors

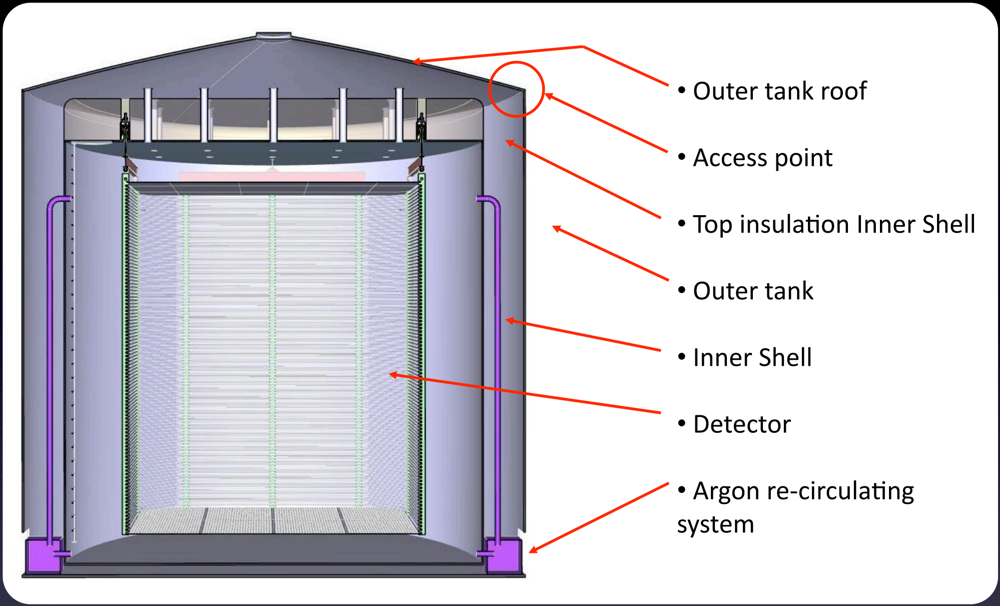


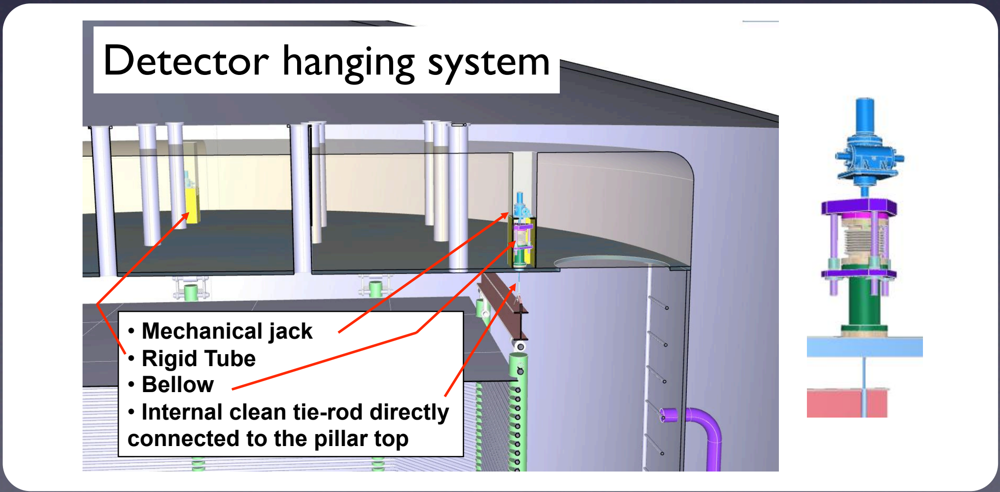
ArDM - 1ton surface test at CERN



1 kton tentative general features

NEXT STEP - 1 kton detector as upgrade to T2K/JPARC



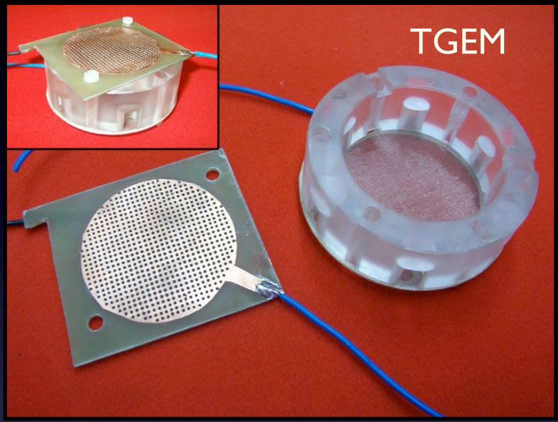


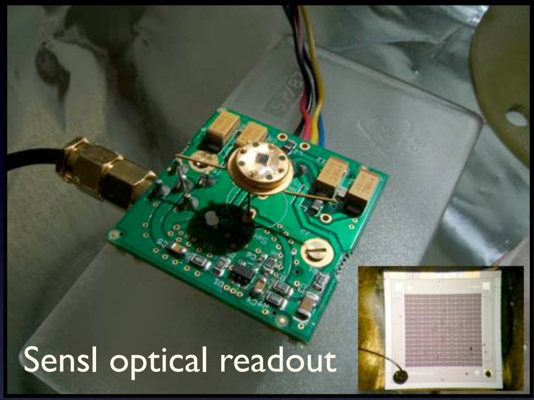
LAr challenges

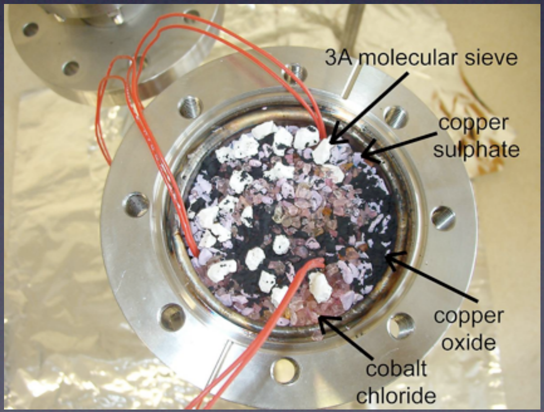
- Tank/dewar
- Argon purification - drift distances
- High voltage
- Readout/electronics
- ...

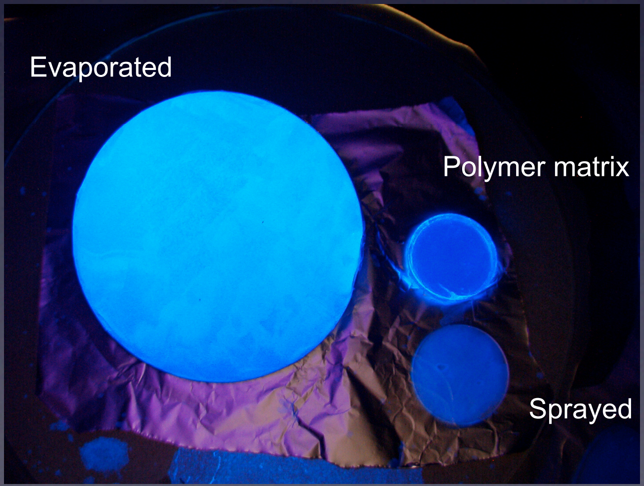
Sheffield LAr R&D

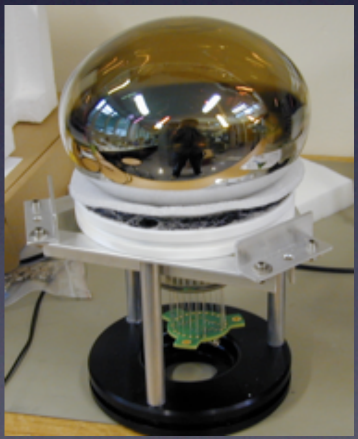
We have achieved some pioneering new detector concepts that can greatly simplify the construction of a very large Liquid Argon detector by elliminating the need for the gas phase.









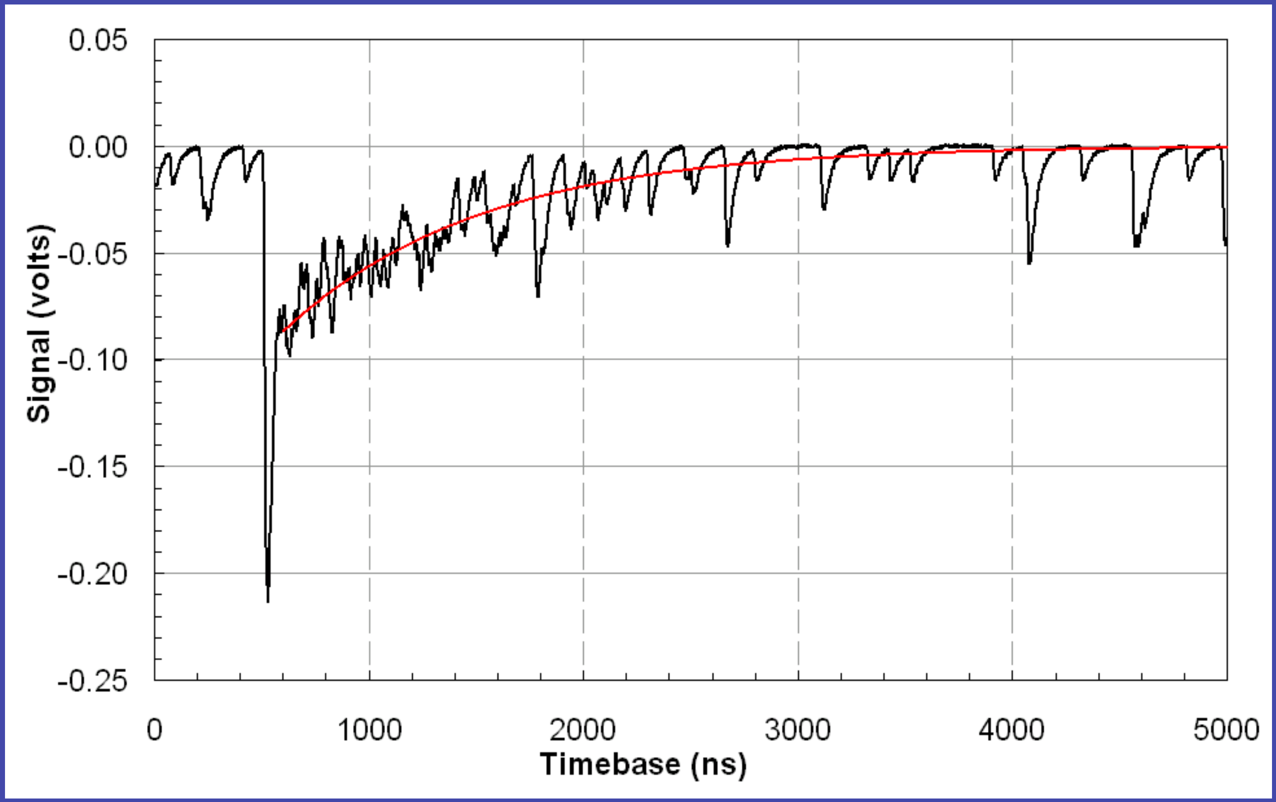


Over to Phil Lightfoot......

Liquid argon as a target for LAGUNA

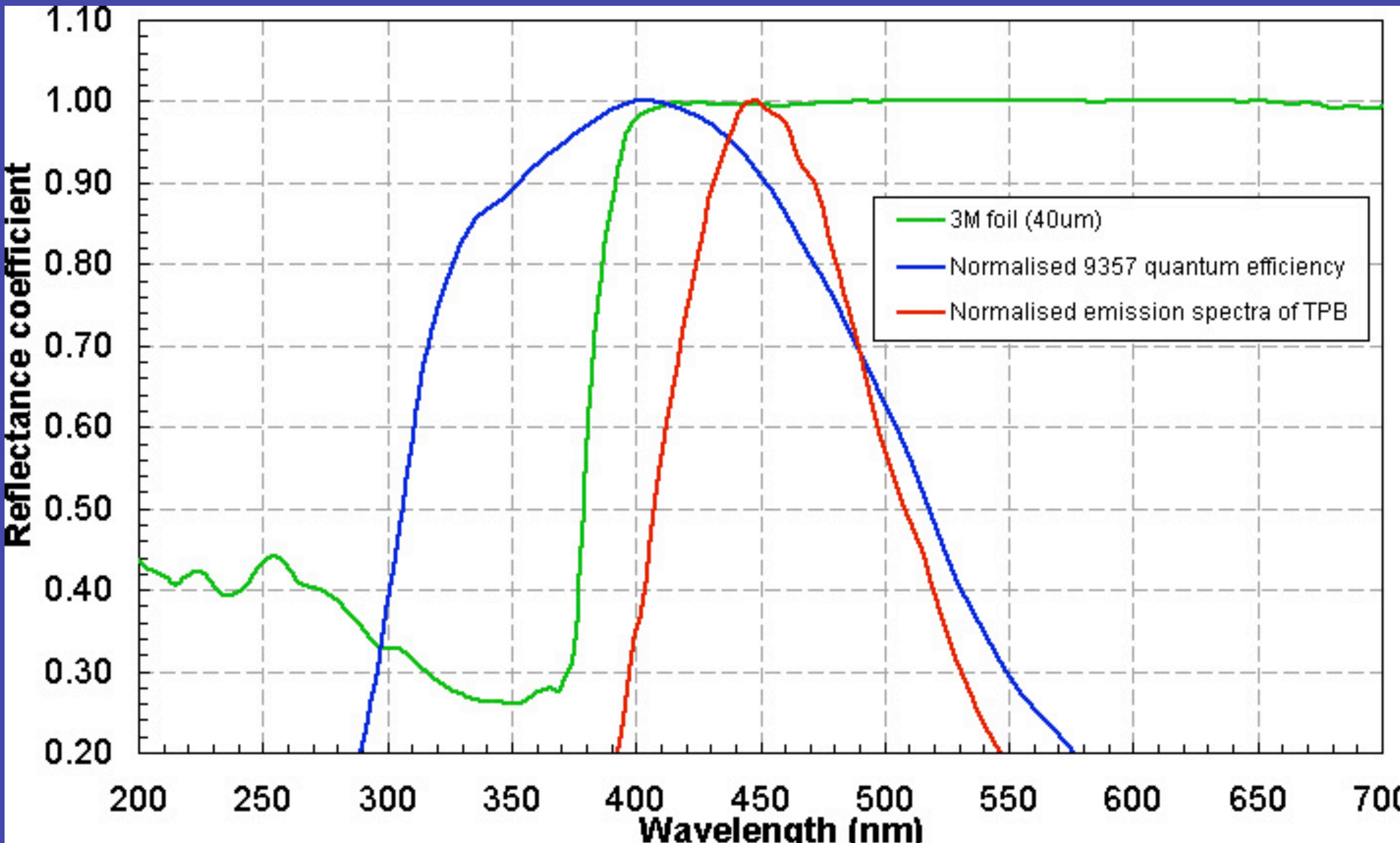
This detection technology has the best performance in identifying the topology of interactions and decays of particles, thanks to excellent imaging performance.

Interactions in liquid noble gases leads to the formation of excimers in either singlet or triplet states, which decay to the ground state with characteristic fast (6ns) and slow (1.6μs) lifetimes in liquid argon with the photon emission spectrum peaked at 128nm.



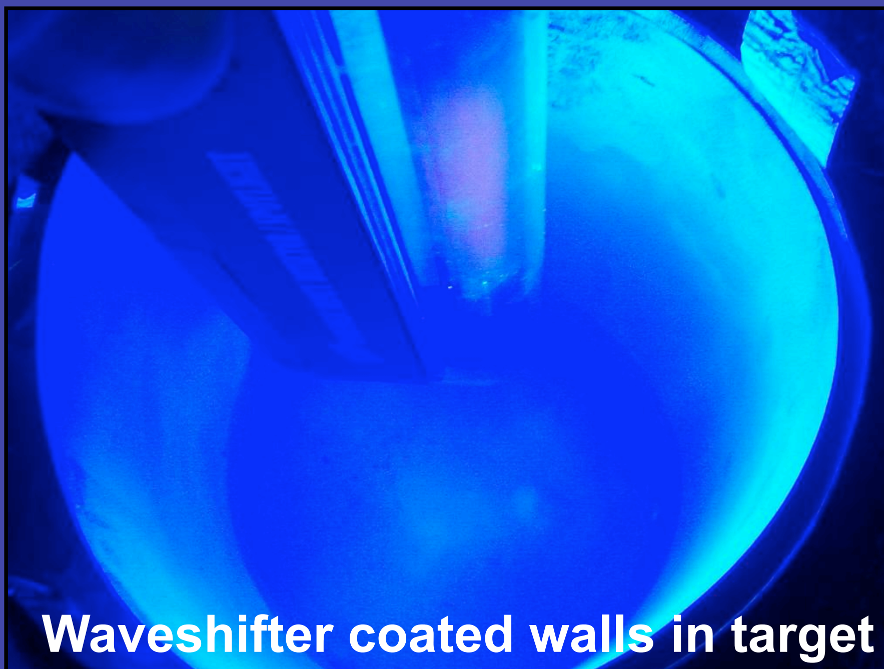
Liquid argon as a target for LAGUNA

Waveshifting: Argon emits VUV scintillation light at 128nm. A waveshifter is needed to shift direct 128nm VUV light to 460nm visible light and thus into the sensitive region of the PMT.



Liquid argon as a target for LAGUNA

Waveshifting: Examples of waveshifter applications.



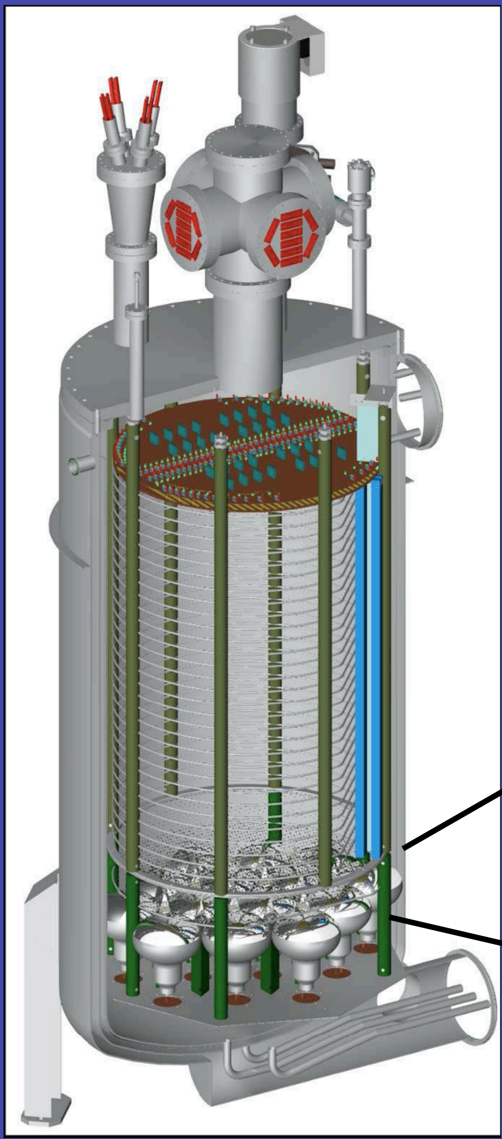
Waveshifter coated walls in target

Waveshifter coated PMT face

Waveshifter gel

Waveshifter on quartz and in plast

Liquid argon as a target for LAGUNA



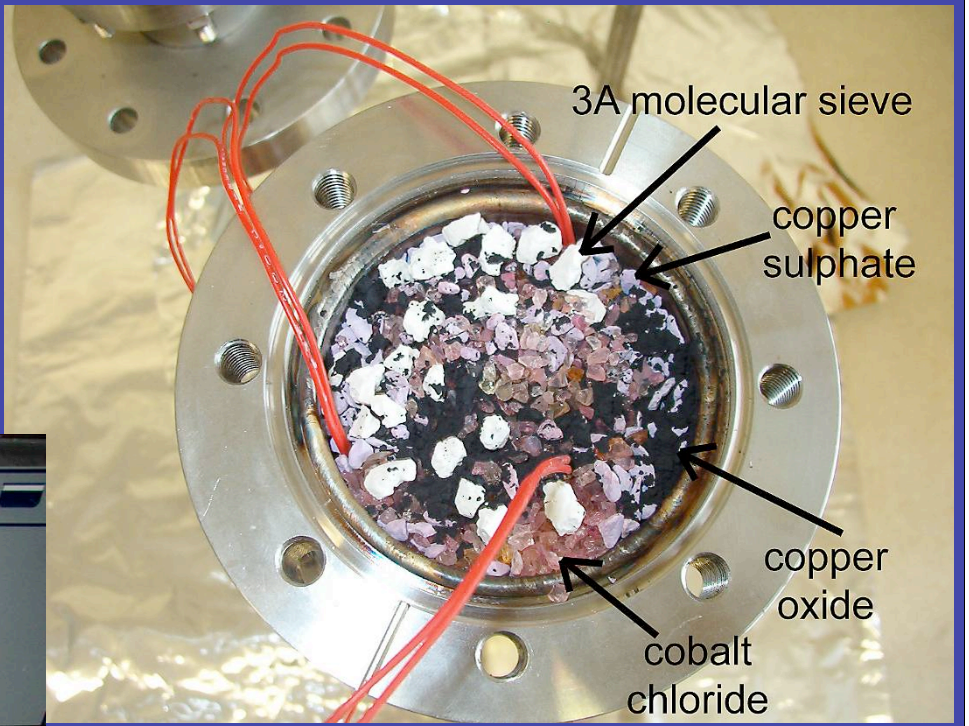
Multi-tonne liquid argon targets cannot be built without first demonstrating proof of principle in a smaller module….

This is the 1 tonne ArDM (Argon Dark Matter) experiment which reads out light and charge using PMTs at the base and a thick gas electron multiplier at the top in double phase argon.

Liquid argon as a target for LAGUNA

Argon is supplied at a purity of 1 part impurity to 1,000,000 parts argon !!!!!

But we require at least 1 part per billion purity. This is achieved both by distillation and chemical purification.



Gaseous argon is passed from its cylinder through a purification cartridge containing a blend of powdered copper, a molecular sieve, anhydrous compounds and phosphorus pentoxide to remove the bulk of impurities.

The argon is then passed through a SAES getter to clean the gas to less than1ppb.

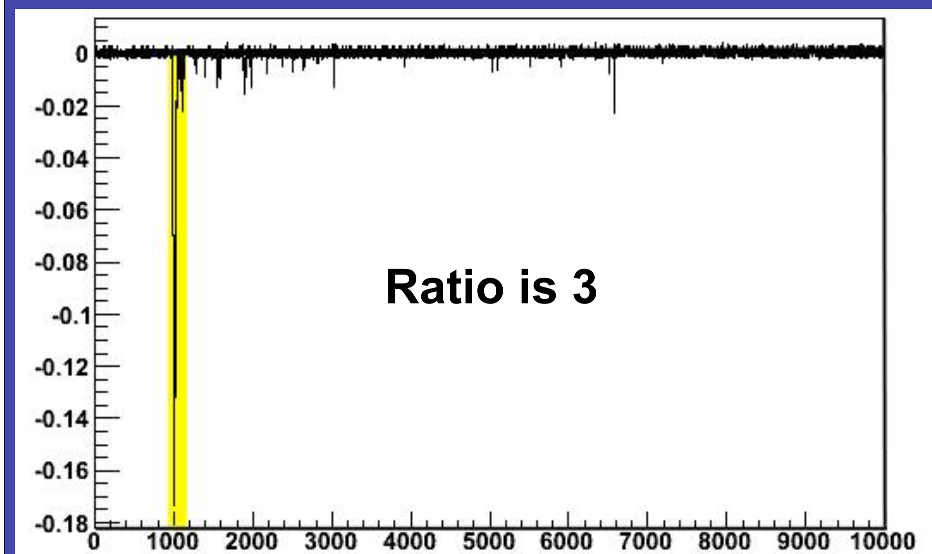
Liquid argon as a target for LAGUNA

Fraction of dimers in singlet or triplet state depends on the incident particle type.

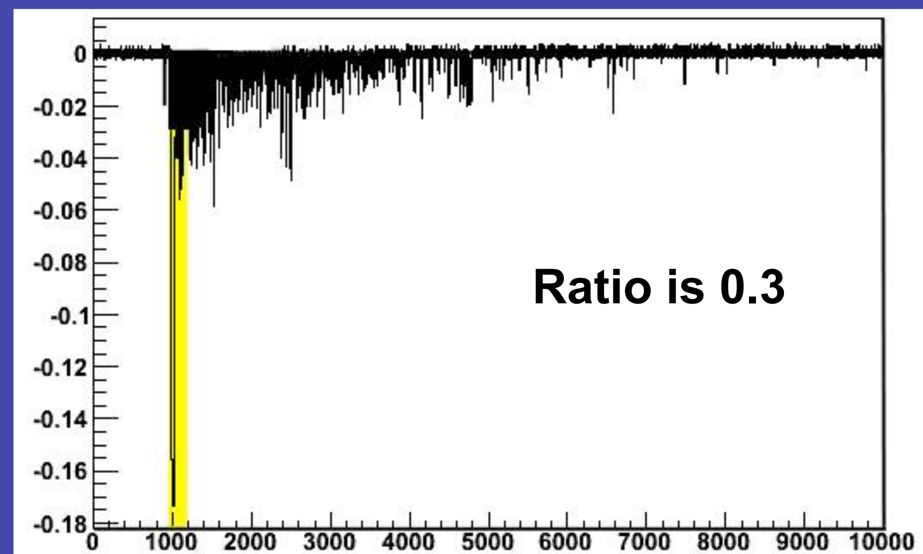
Yellow: Prompt photon emission region due to singlet

Ratio: Prompt (6 ns) light / Slow (1.6 µs) light

An event due to neutron interaction



An event due to electron interaction

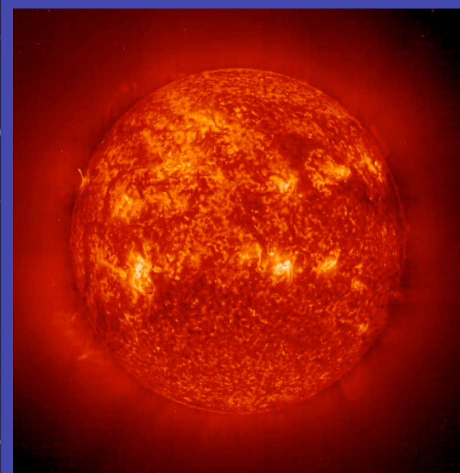


Discrimination between nuclear and electron recoils can be achieved by pulse shape discrimination.

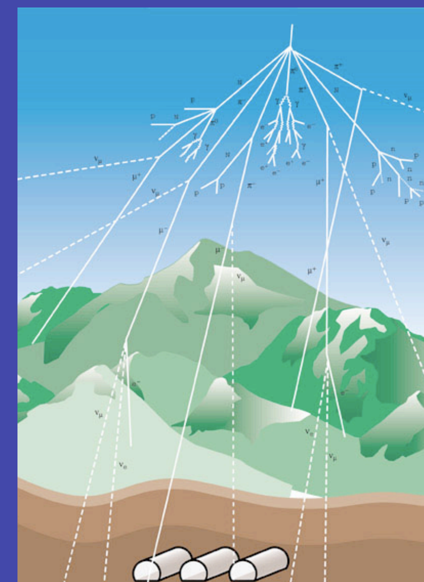
Liquid argon as a target for LAGUNA

Physics potential of GLACIER

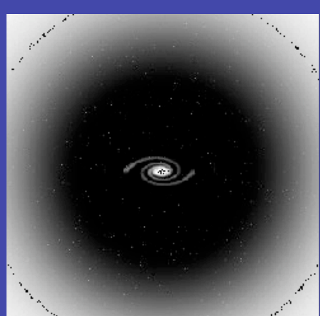
Supernova neutrinos



Solar neutrinos

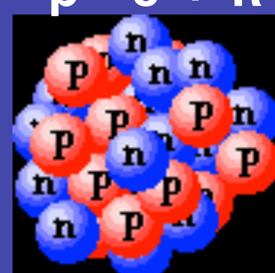


Atmospheric neutrinos



Dark Matter

$p \rightarrow e^{+} + \pi^{0}$

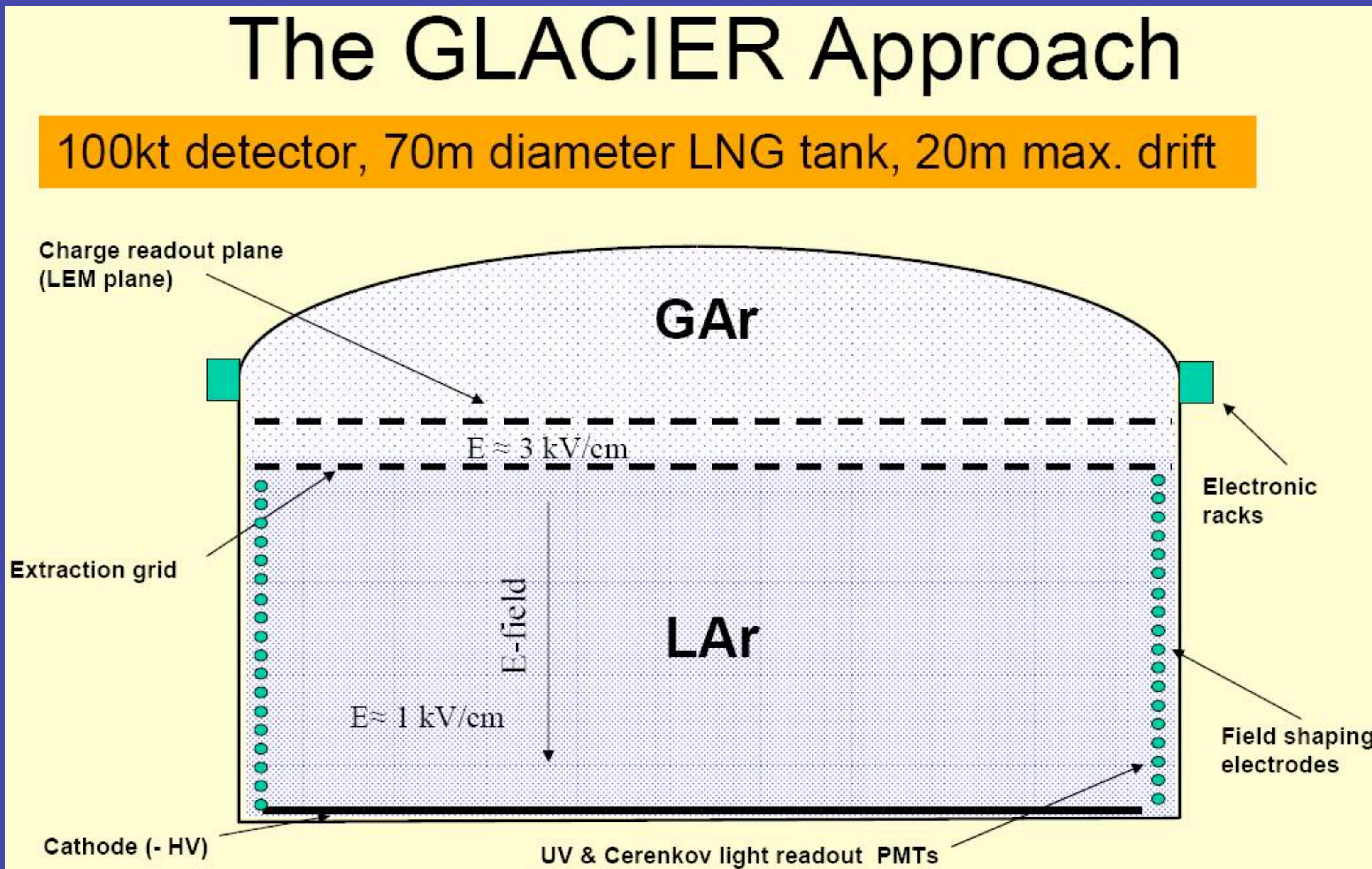


Nucleon stability

Reactor neutrinos

Liquid argon as a target for LAGUNA

Discrimination is provided in liquid noble gas detectors by combined measurement of charge, primary light, and secondary light.



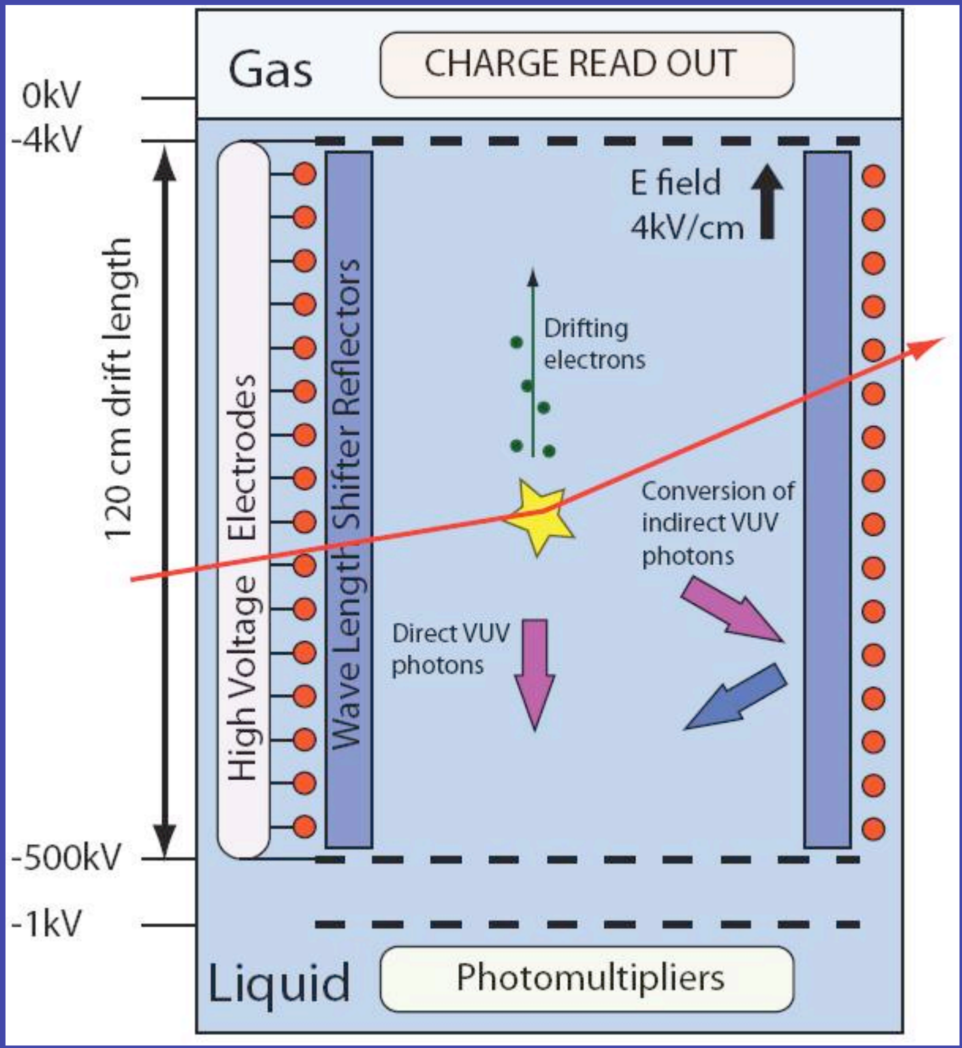
Liquid argon as a target for LAGUNA

Electrons and gammas interact with shell electrons creating light and charge.
Neutrons do the same but the charge quickly recombines.

In both cases any charge produced is drifted upwards in the field to the charge readout where it is detected.

Light is converted to 460nm and detected by photomultipliers.

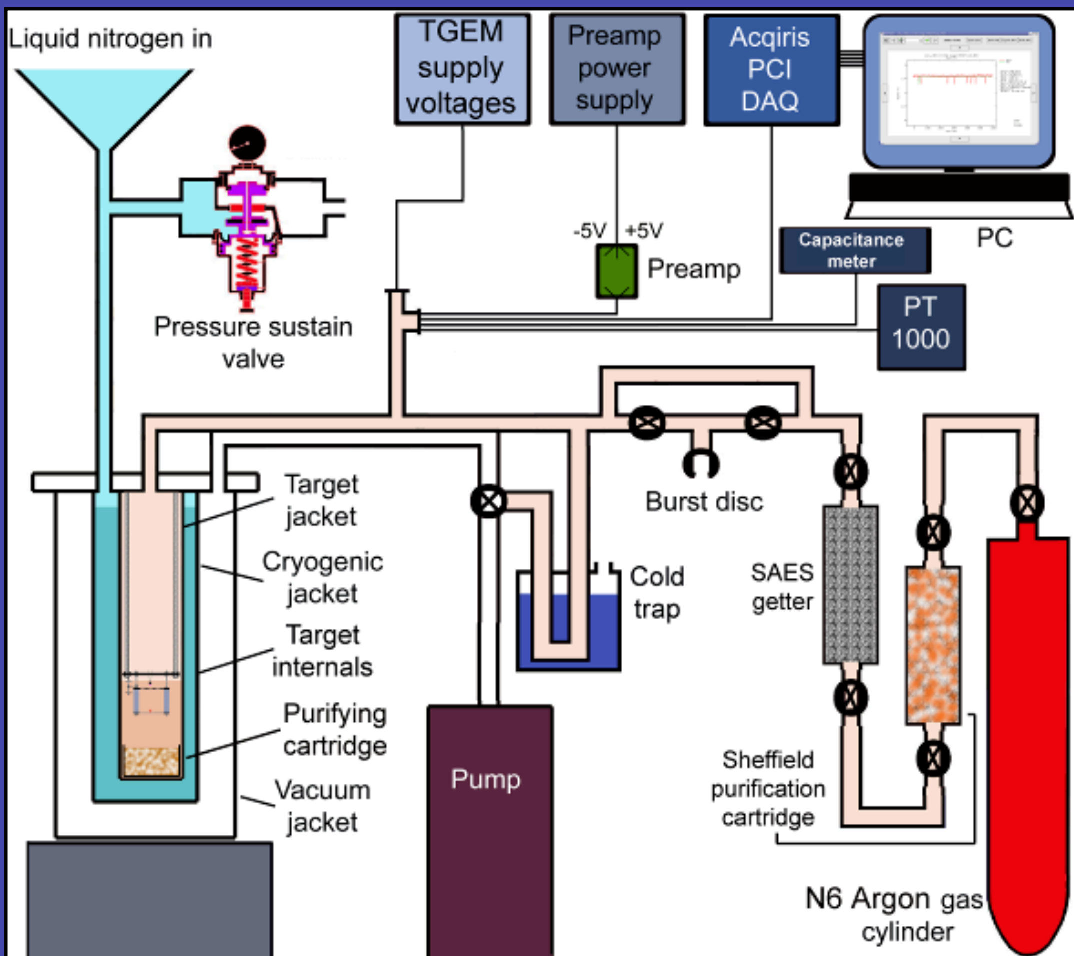
Background rejection possibilities:
– Different light/charge ratios
– Different shape of the scintillation light (ratio fast/slow components)



A segmented charge readout allows the XY coordinate to be determined and the time of flight following the scintillation pulse provides the Z coordinate.

Liquid argon as a target for LAGUNA

Held within an inner target chamber surrounded by a pressurised liquid nitrogen filled cryogenic jacket, tests are carried out in both the cold gas phase of a double phase argon system and completely immersed in liquid argon.



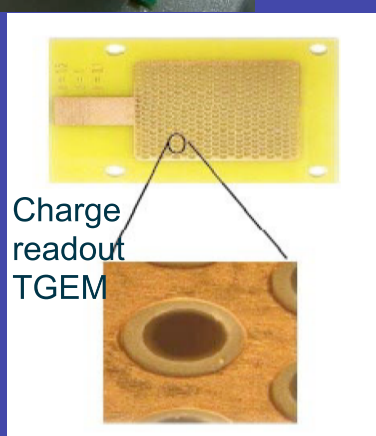
Liquid argon as a target for LAGUNA

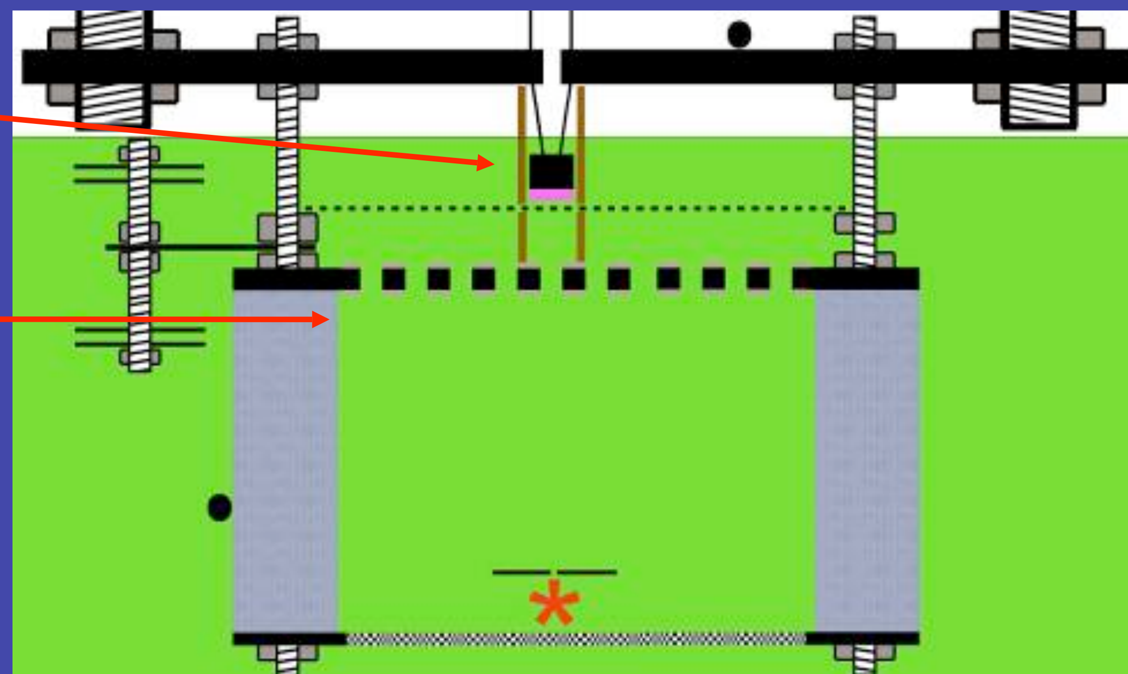
To simplify the design of multi-tonne liquid argon targets it would be advantageous to operate only in liquid dispensing with the gas volume in which charge is amplified.

All attempts to operate charge readout in liquid argon have failed.

However the fields required to produce UV secondary photon emission by excitation of atomic argon are considerably lower. This could be used to transduce charge information from drifted tracks into an optical signal within the high field region of the readout.

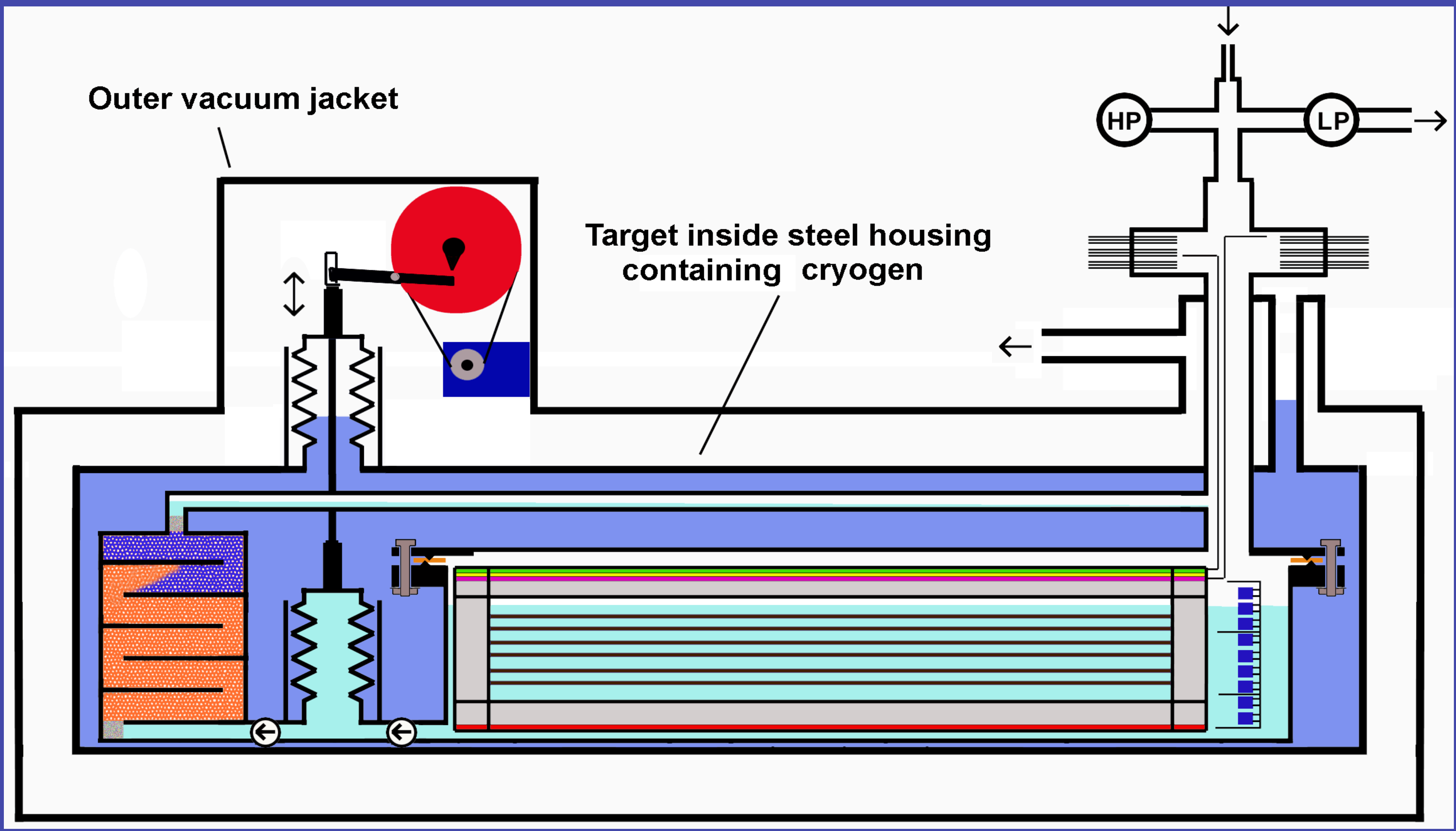
Silicon PMT





Liquid argon as a target for LAGUNA

Sheffield is planning an R&D programme for next 2-3 years aimed at constructing a 1m x 1m prototype module (25cm drift) that will test many of our systems on LAr volumes, TGEM's, charge/light detection and readout concepts.



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
- http://laguna.ethz.ch:8080/Plone/