…my search for the unification of all forces and all particles

are diamonds forever?

...ashes to ashes, dust to...light?

the demise of the proton

Larry Sulak

Boston University

what to discuss?

the last of the anatomical views of the proton…its ultimate fate

Recap first two lectures, the protonic birth and structure

- the standard model of particle and forces
- the GUT period, immediately following the big bang

Putting quarks and leptons into same multiplet implies transitions

How long will we live? How to recognize proton decay?

How could one ever conceive of searching for it?

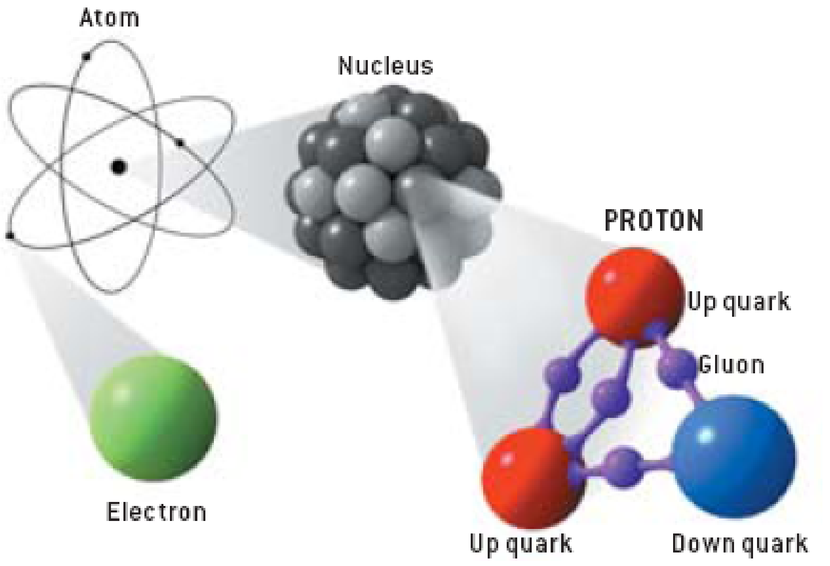
Two generations of massive water Cherenkov ring-imagers

Surprises along the way

Patience, my friend…

…our conception of the proton,

the simplest of nuclei, the center of the hydrogen atom

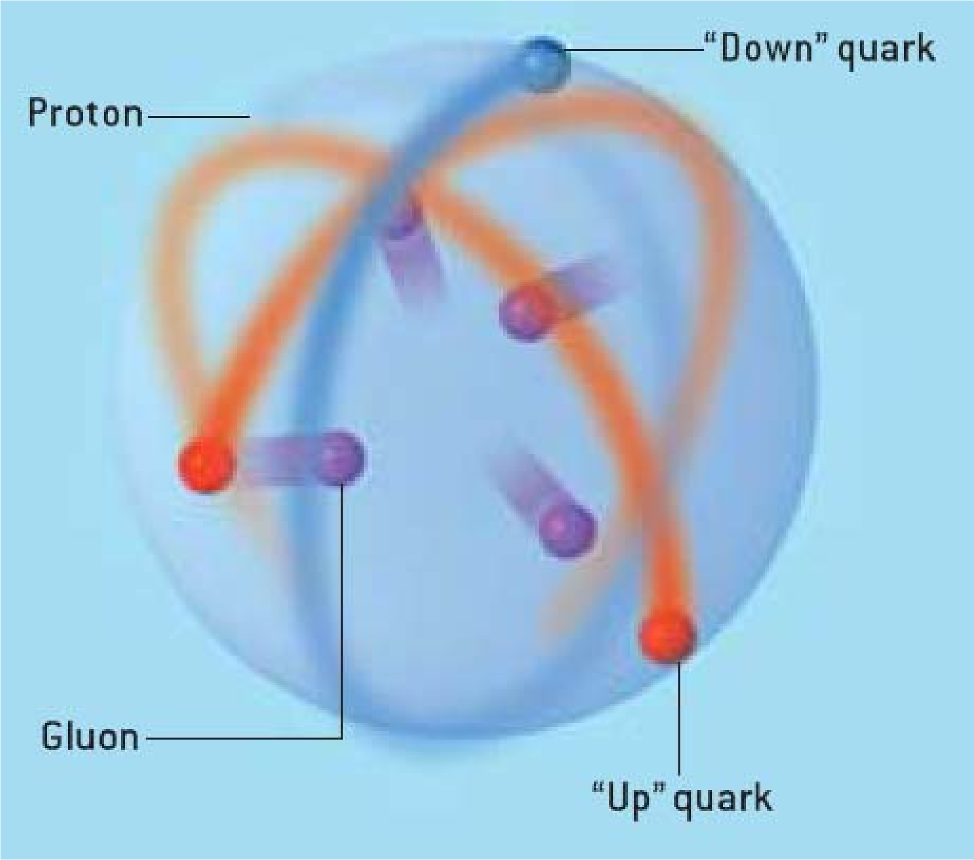


Sci Am

generally ~ 3 point-like colored quarks,

held together by gluons of the strong force

…anatomy of a proton as seen graphically…



Sci Am

…artist's error: colored quarks and bi-color gluons are *point-like* inhabiting a "bag" ~1 fermi = 10^{-13} cm across (10^{-5} of atom)

…the Standard Model

Fermions (on the left)

- Quarks and leptons

most fundamental particles

- Ordinary matter

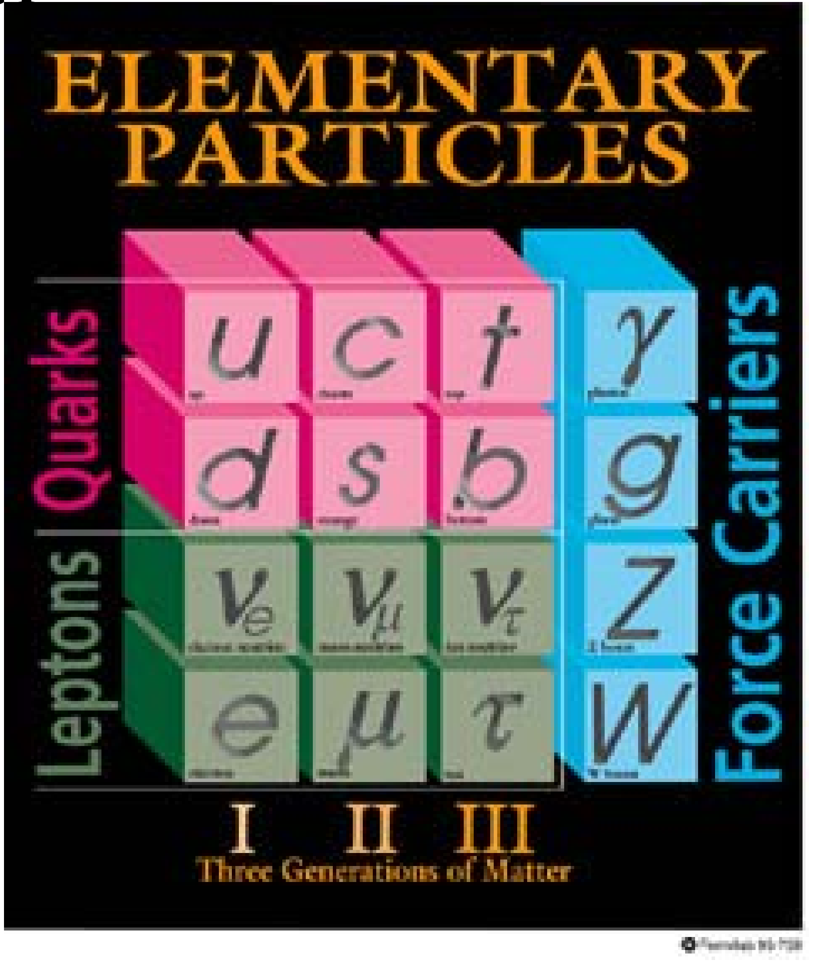
up & down quarks and electrons

- Other quarks and leptons

cosmic rays & particle accelerators

(Each particle

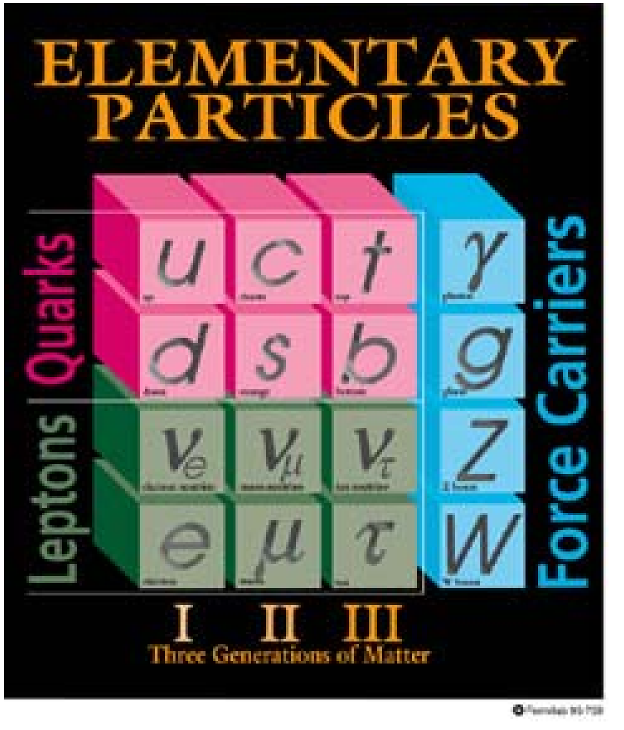
a corresponding antiparticle)



M. Carleton

The Standard Model

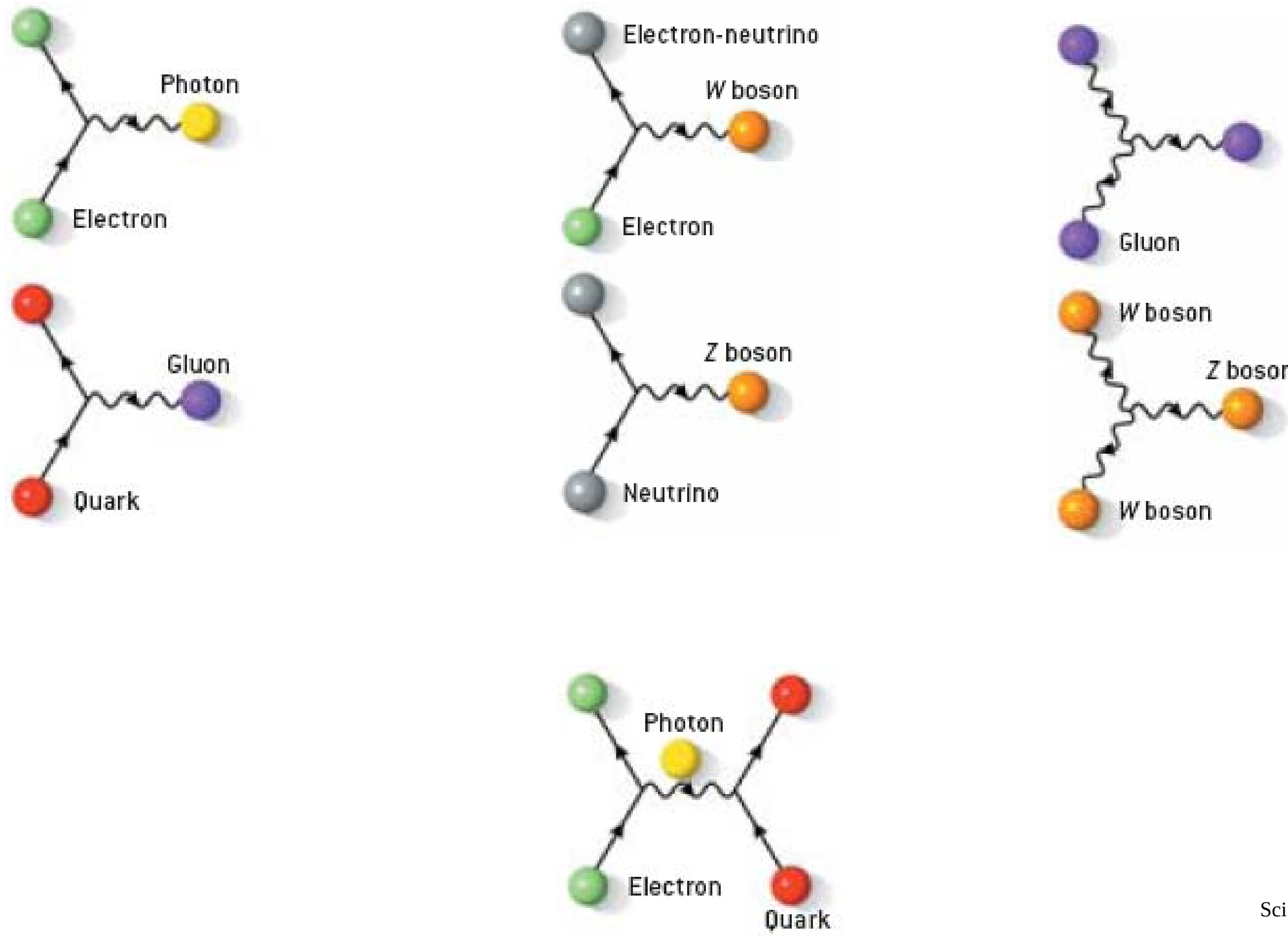
Bosons (the force carriers)



- Photons mediate electromagnetic interactions
- Gluons carry strong force – hold quarks together
- Z and W bosons induce weak interactions, beta decay

M. Carleton

…the interactions Feynman taught us about…



Sci Am

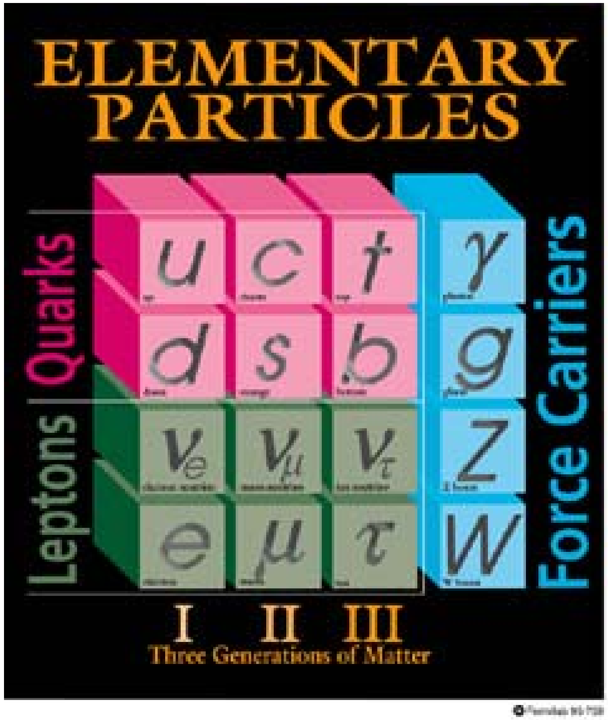
…successes of the Standard Model

- Predicts all known particles and three out of four forces
- All predicted particles found experimentally (except Higgs)
- Simple, yet explains

hundreds of particles

their complex interactions

with only 6 quarks, 6 leptons and a 4 force-carrying particles

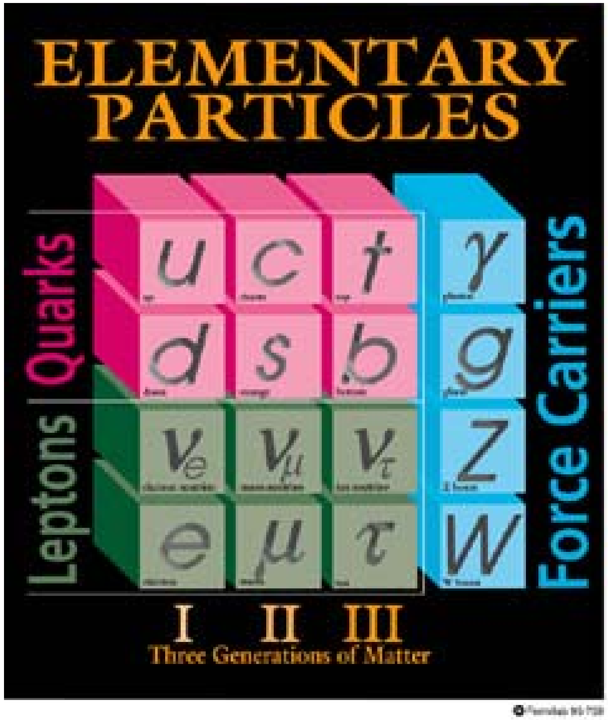


M. Carleton

…but the failures of the Standard Model?

Does not account for

- Origin of mass (waiting for the LHC) Gravity
- Dark matter and dark energy
- No explanation of the structure of the "periodic table"



M. Carleton

…enter Grand Unification

…embedding 2 × 2 electroweak with 3 × 3 of strong force…

	d_R^{red}	d_R^{green}	d_R^{blue}	e_R^+	$\bar{\nu}_e$
d_R^{red}	g^0, γ, Z^0	$g^{r \to g}$	$g^{r \to b}$	$X^{red}_{-\frac{4}{3}}$	$X^{red}_{-\frac{1}{3}}$
d_R^{green}	$g^{g \to r}$	g^0, γ, Z^0	$g^{g \to b}$	$X^{green}_{-\frac{4}{3}}$	$X^{green}_{-\frac{1}{3}}$
d_R^{blue}	$g^{b \to r}$	$g^{b \to g}$	g, γ, Z^0	$X^{blue}_{-\frac{4}{3}}$	$X^{blue}_{-\frac{1}{3}}$
e_R^+	$X^{red}_{\frac{4}{3}}$	$X^{green}_{\frac{4}{3}}$	$X^{blue}_{\frac{4}{3}}$	γ, Z^0	W^+
$\bar{\nu}_e$	$X^{red}_{\frac{1}{3}}$	$X^{green}_{\frac{1}{3}}$	$X^{blue}_{\frac{1}{3}}$	W^-	Z^0

Coughlan

Get SU 5… with new "x bosons," violating lepton number!!!

…unification yields multiplets of 5,

with leptons and quarks in the same vector…

$$\bar{5} = \begin{bmatrix} \nu_e \\ e^- \\ \bar{d}_R \\ \bar{d}_B \\ \bar{d}_G \end{bmatrix}_{\mathrm{LH}} \quad \begin{array}{l} \rfloor\ W^- \\ \\ \rceil\ X \\ \\ \rfloor\ G_{BG} \end{array} .$$

	I_3	Q
ν_e	$+\frac{1}{2}$	0
e^-	$-\frac{1}{2}$	-1
$\bar{d}_R$	0	$+\frac{1}{3}$
$\bar{d}_B$	0	$+\frac{1}{3}$
$\bar{d}_G$ (LH)	0	$+\frac{1}{3}$

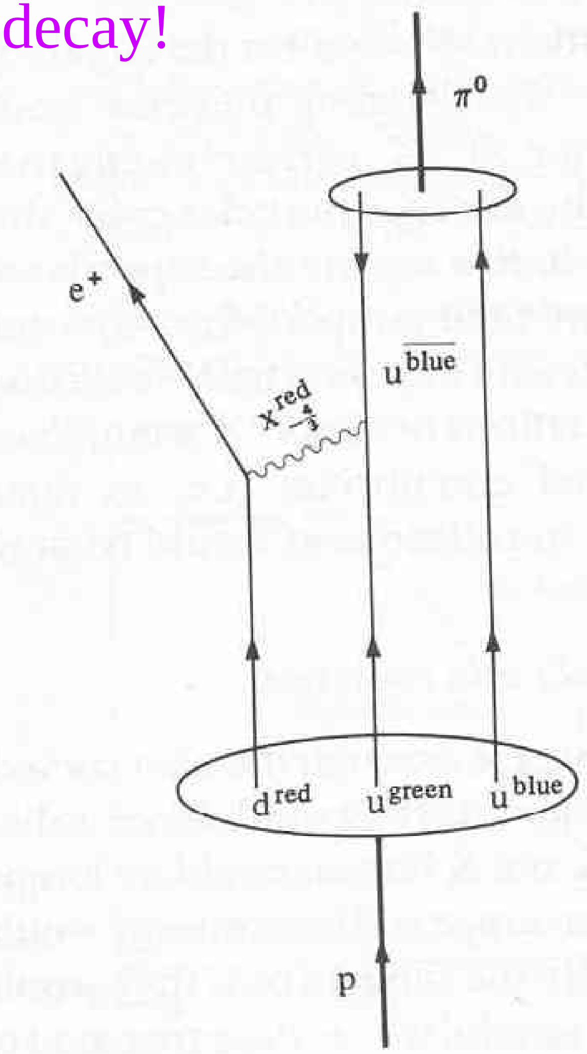
Solving old mysteries…

Perkins

Why are the electro-weak proportions 3/8? ($\sin\theta_w$)

How can the electric charge of the point electron = integrated charge fuzzy composite proton, exactly?

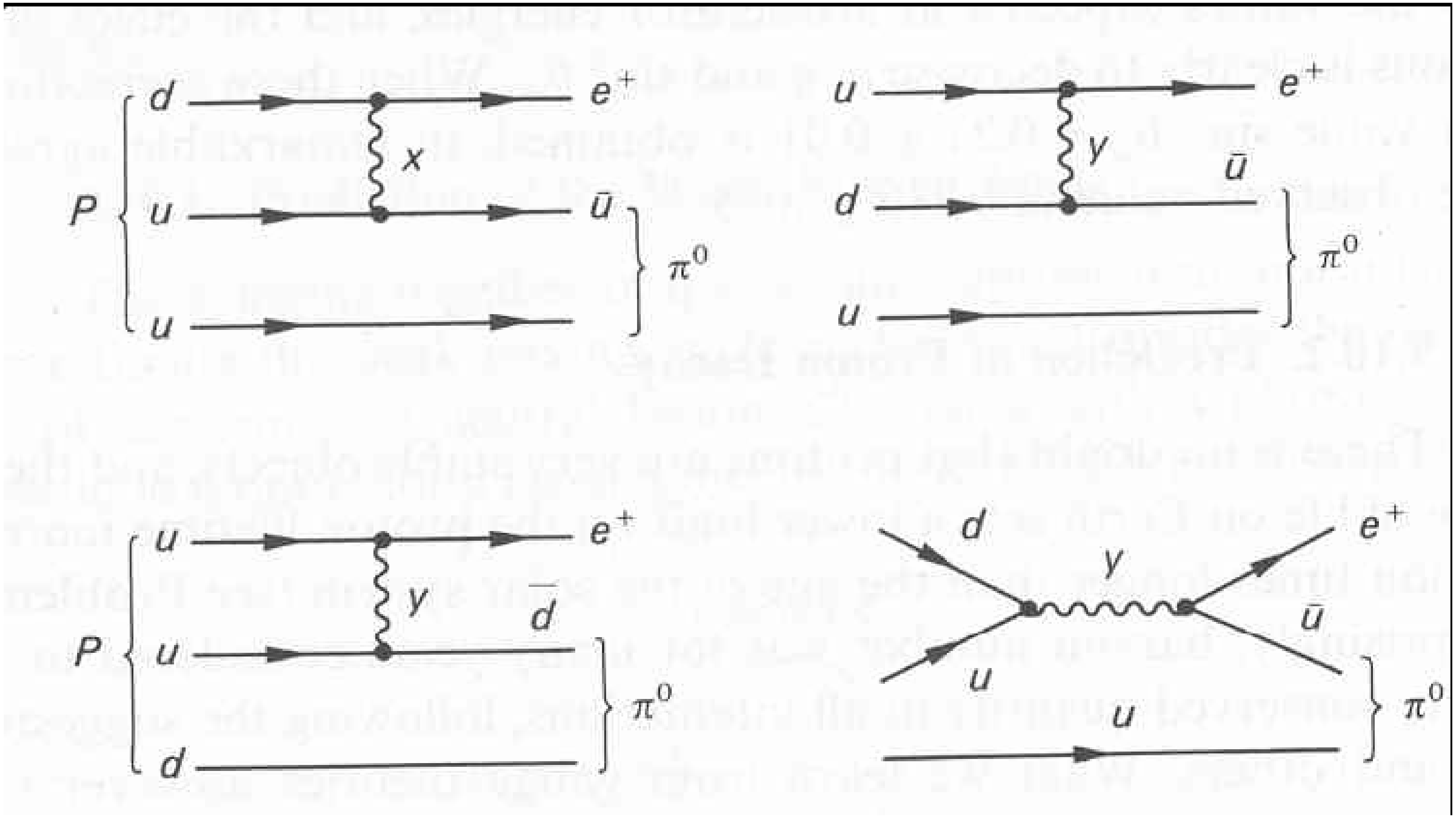
…but there is a flaw: proton decay!



Coughlan

down-quark becomes positron, up-quark becomes anti-up

…other modes of proton decay, all transforming…*to light*



Coughlan

…combine with the e⁻ floating around from the hydrogen atom

$e^+ + e^- \rightarrow \gamma + \gamma, \qquad \pi^\circ \rightarrow \gamma + \gamma$

…but at what rate, this proton decay?   what lifetime?

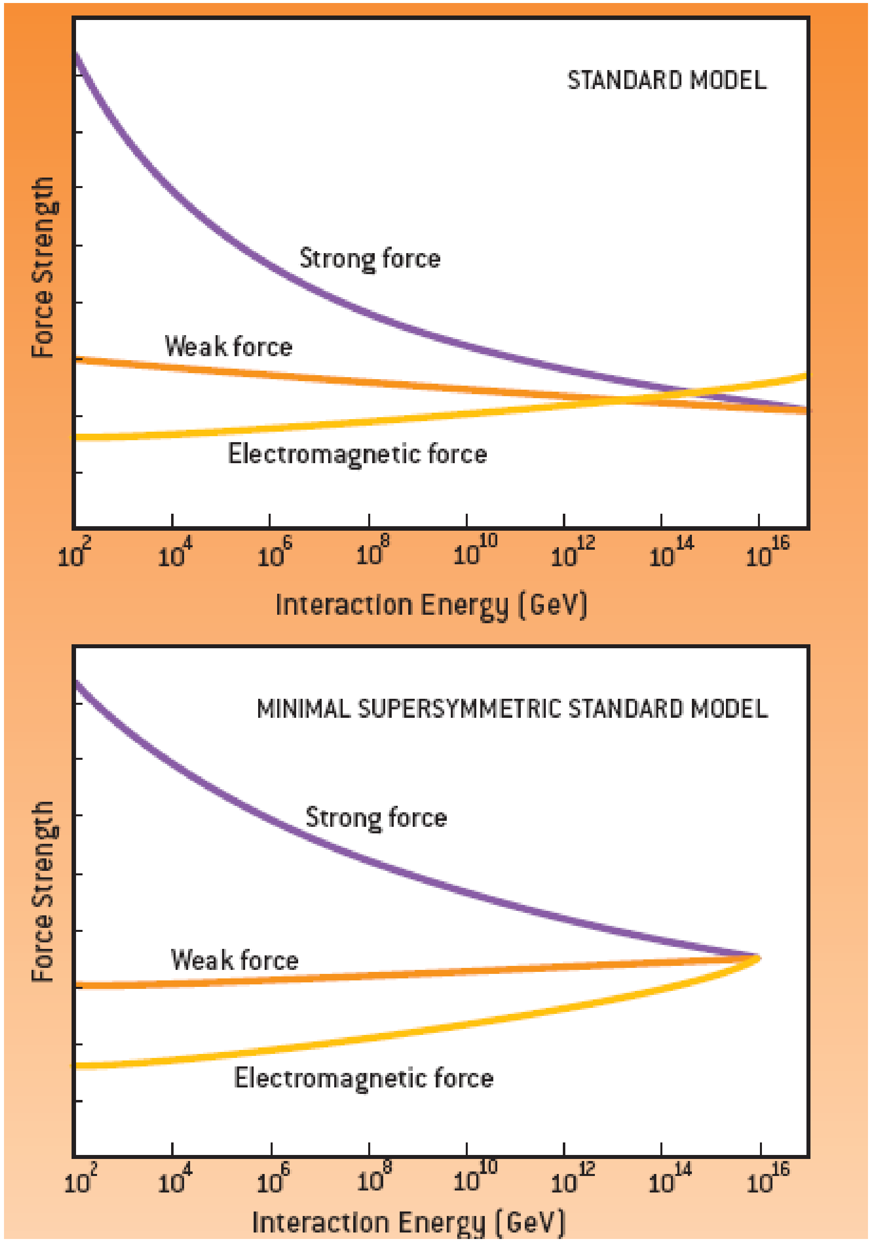
Extrapolate to high energy,

All three forces unite at
    unique energy
    unique force…

Giving a lifetime of $10^{29\pm2}$ years
    cf. universe is $\sim10^{10}$ years

…alternative model (supersym)
    ~ perfect unification of forces

For higher energies,
    a truly Grand Unified Theory
    of the four forces



Sci Am

“Supersymmetry...
has generated so many thousands of papers it must be correct”
Shelly Glashow at a WOGU

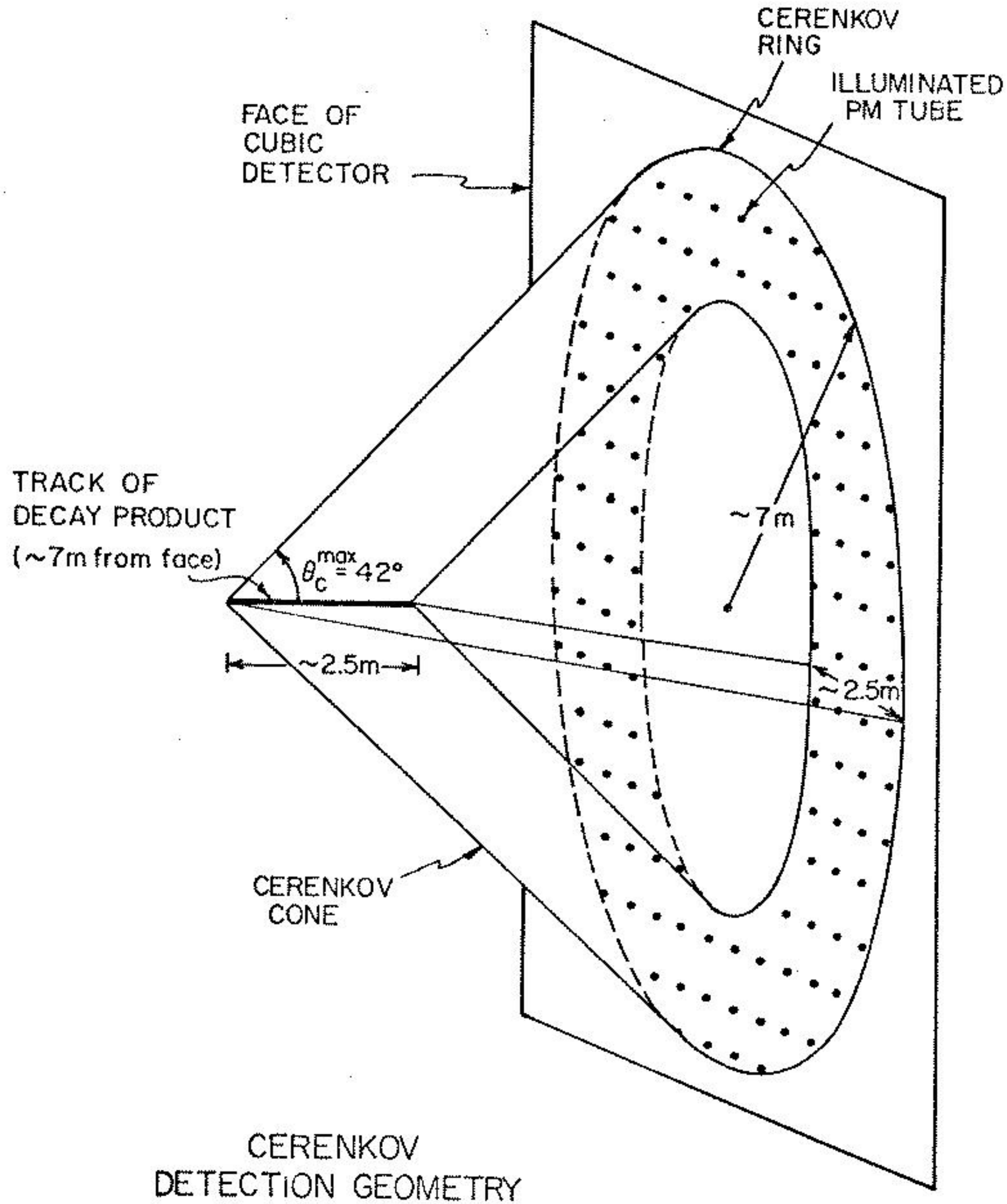
…how to see the decay products?

Cherenkov radiation in a research reactor

…get 10^{31} clocks to run for a year, cheaply

...a charged particle track

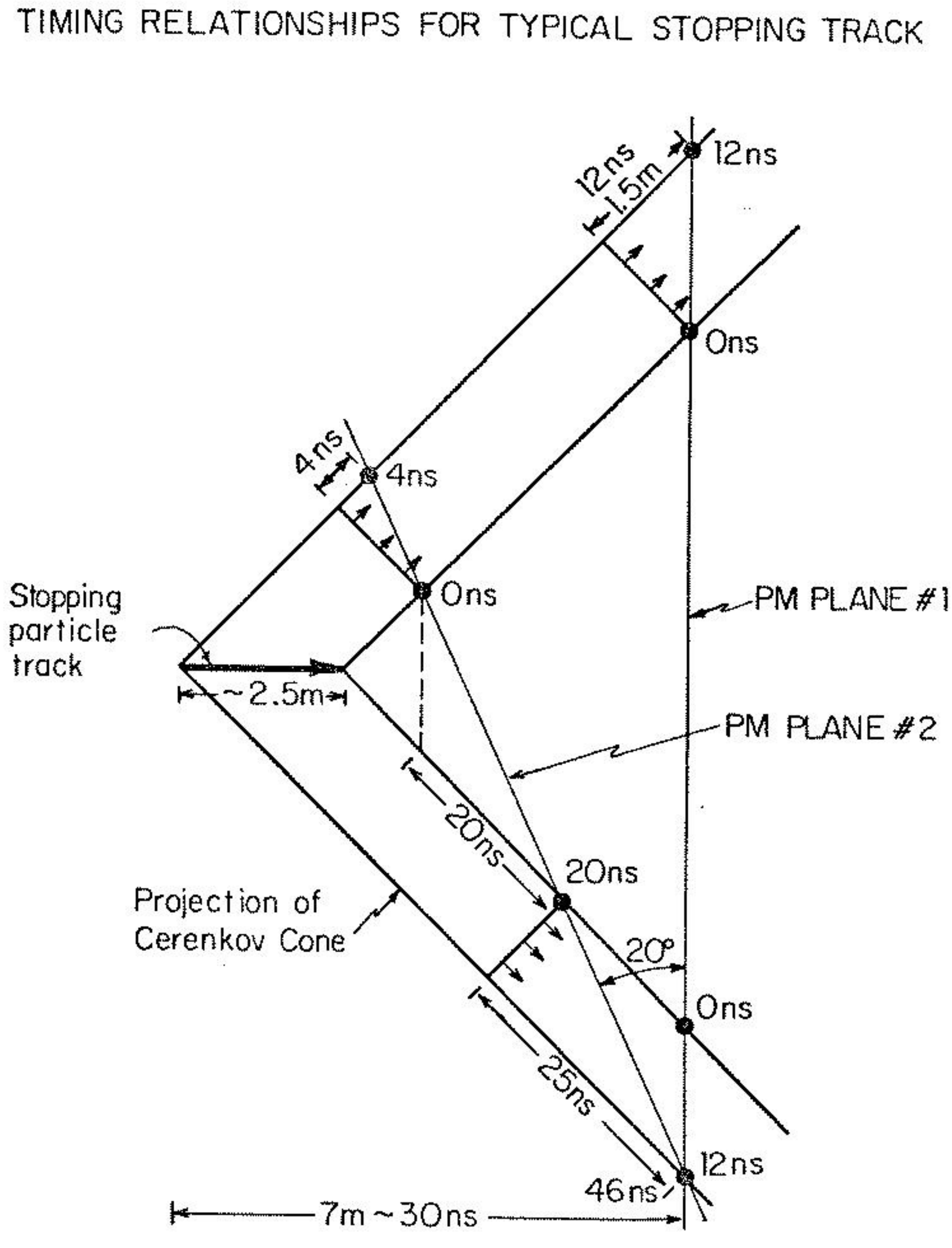
what does it look like?



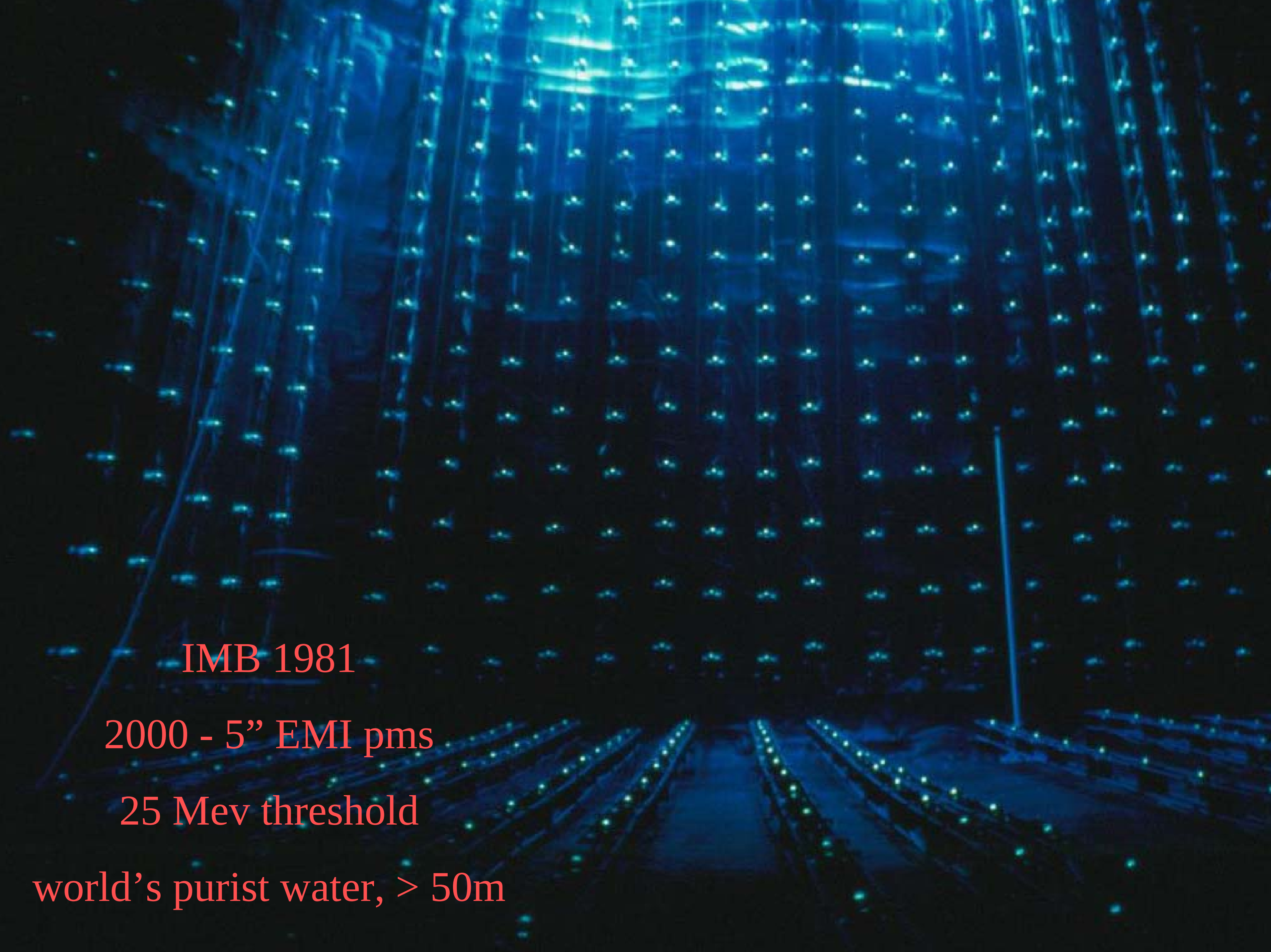
FWOGU, 1980 and
"Neutrino '79, Bergen" LRS

...why is timing so important?

Cherenkov light is directional

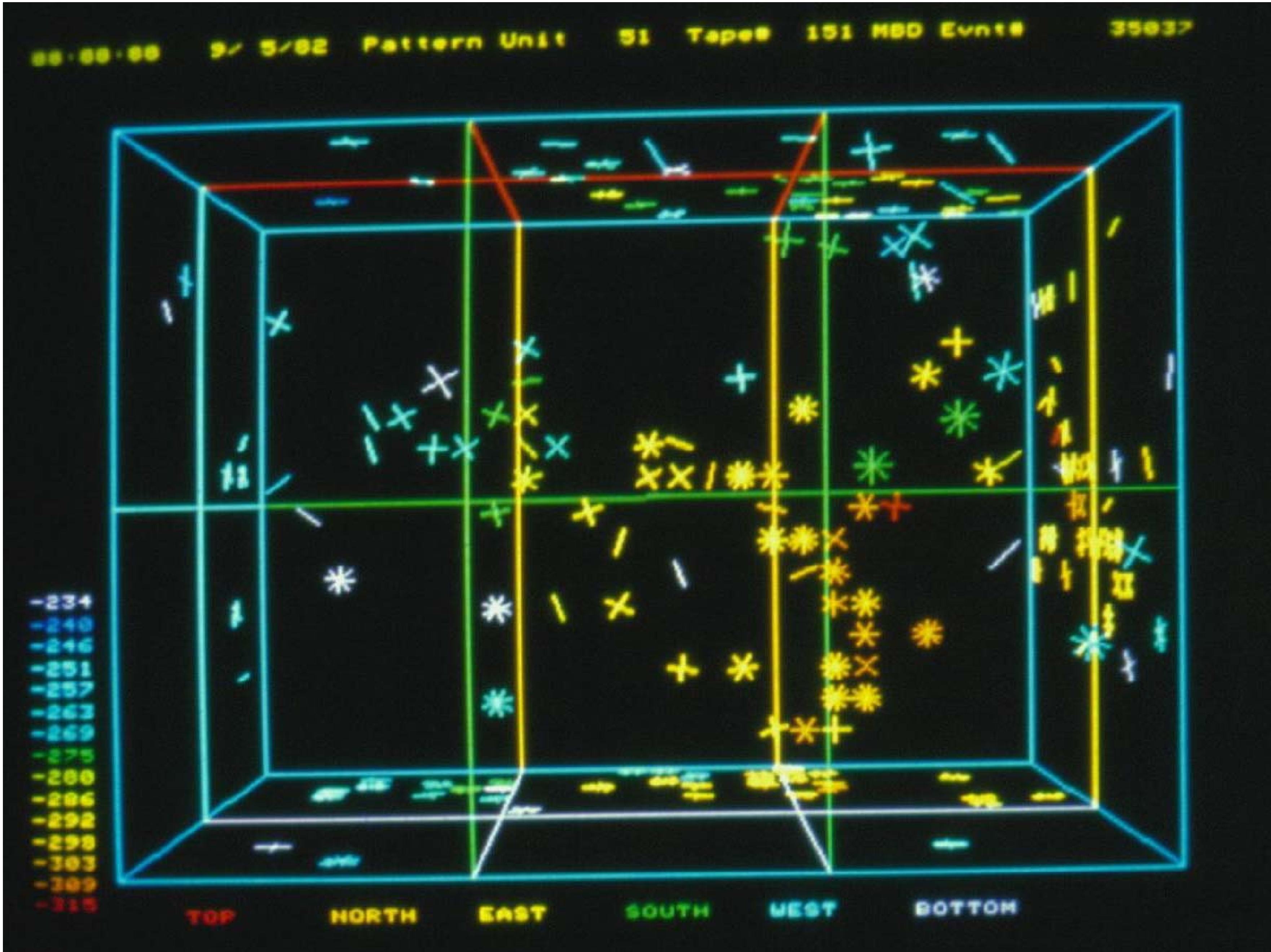


“FWOGU, 1980” and
“Neutrino ’79, Bergen ,” LRS


IMB 1981
2000 - 5” EMI pms
25 Mev threshold
world’s purist water, > 50m


2000 - 8 inch pms and
light collectors
dry suit diver/physicist

IMB: best proton decay candidate...pm code = timing in color, 1 pe/slash

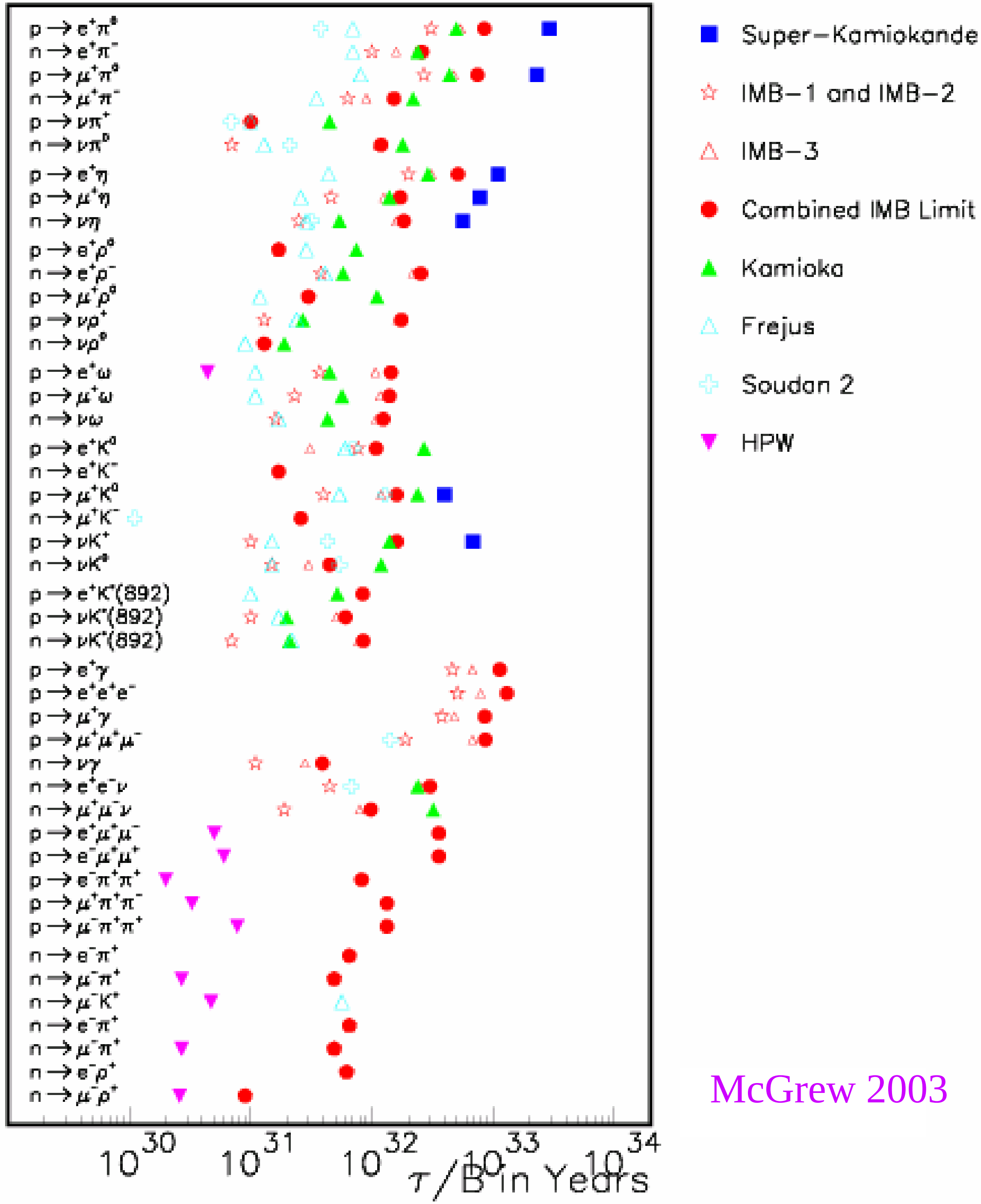


Nucleon Lifetime Limits

IMB: 45 decay modes

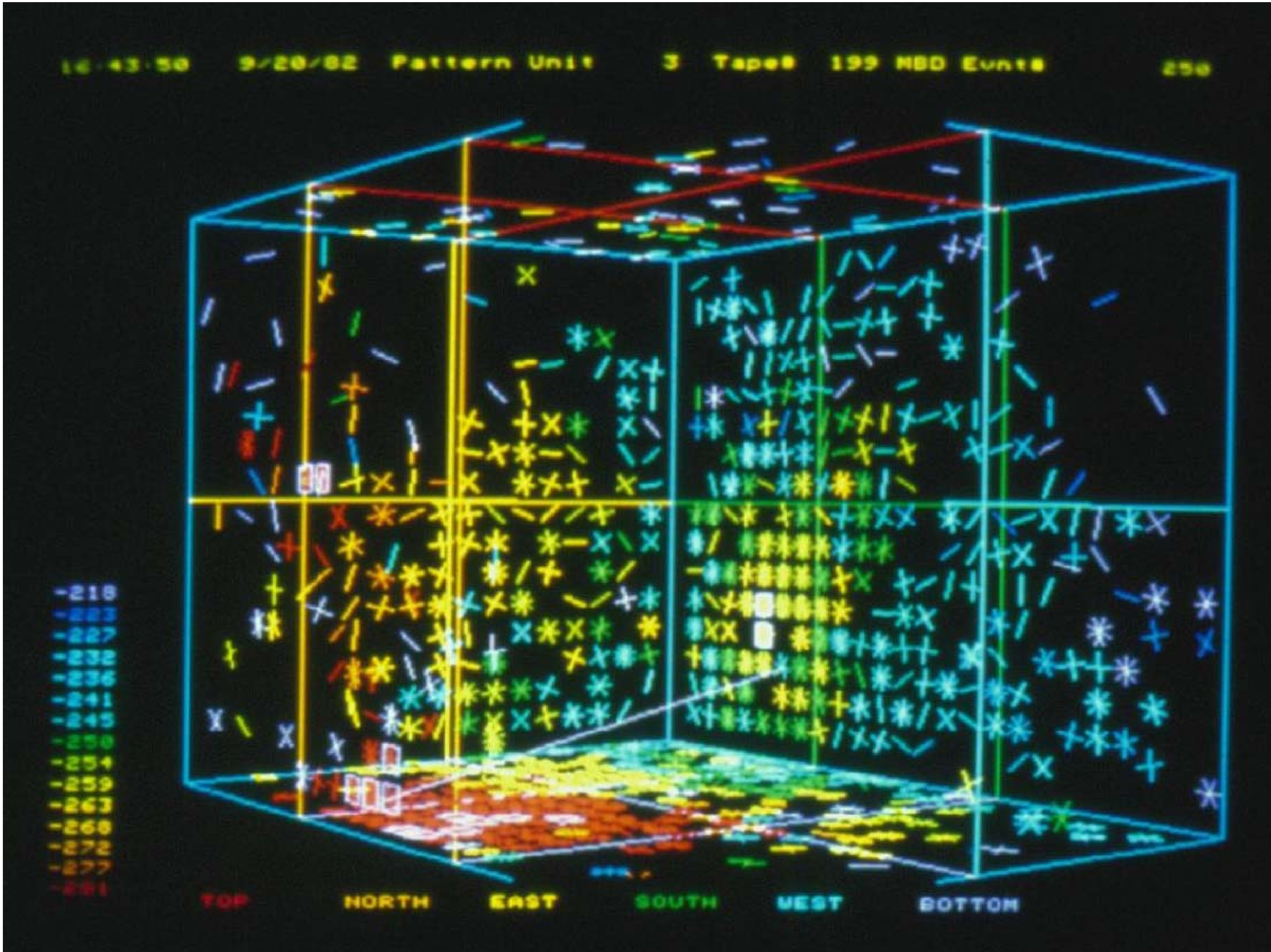
mass is everything,

MEGATON is needed



McGrew 2003

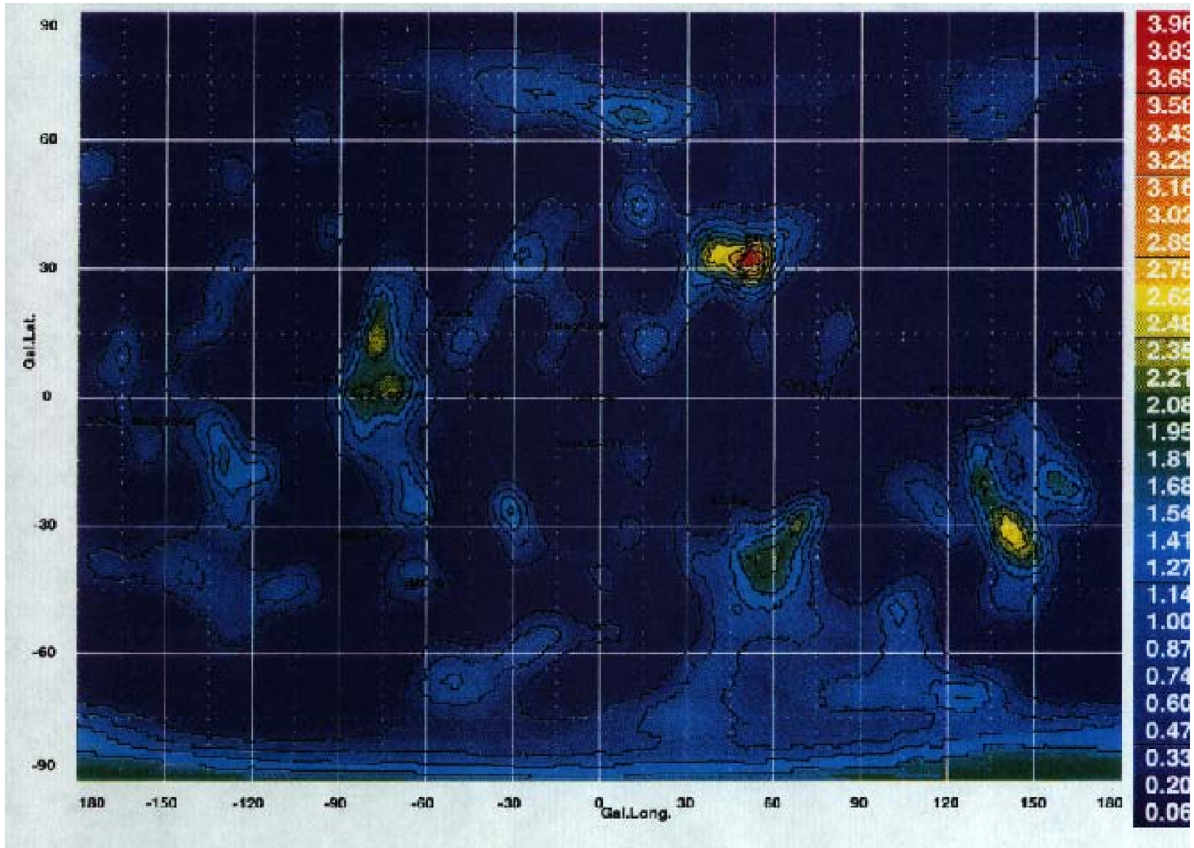
…an up-going muon...red entry spot, yellow exit...



IMB: Do the neutrino-induced up-going muons point back to a source?

Galactic

Latitude



Galactic Longitude

…sun, moon, galactic center? with 496 IMB events, no

...with Super-K? no, see Shantanu Desai's new PhD thesis

...setting the stage for Antares, IceCube...

IMB “anomaly:” see only 75% of expected muon-neutrinos...

VOLUME 57, NUMBER 16 PHYSICAL REVIEW LETTERS 20 OCTOBER 1986

Calculation of Atmospheric Neutrino-Induced Backgrounds in a Nucleon-Decay Search

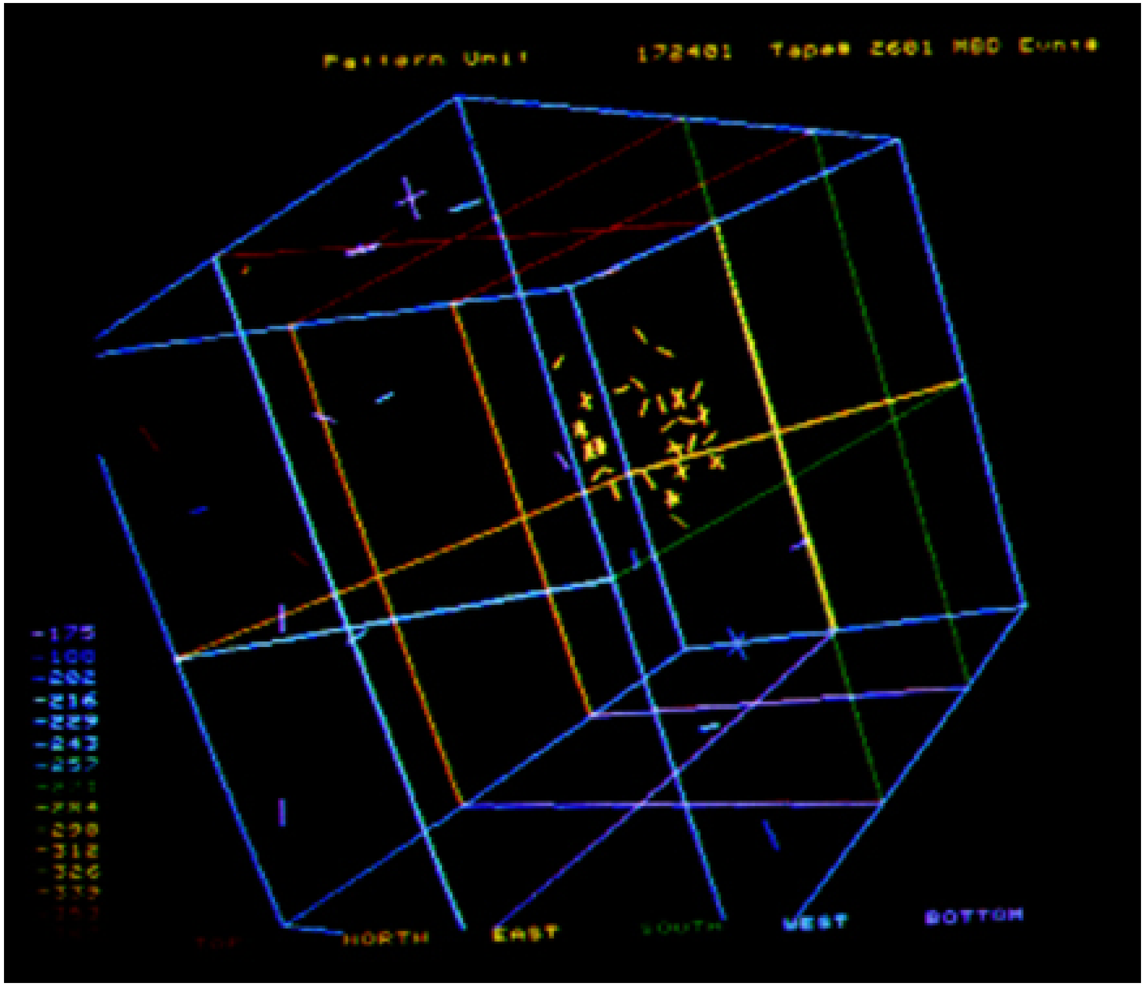
T. J. Haines, R. M. Bionta, G. Blewitt, C. B. Bratton, D. Casper, R. Claus, B. G. Cortez, S. Errede, G. W. Foster, W. Gajewski, K. S. Ganezer, M. Goldhaber, T. W. Jones, D. Kielczewska, W. R. Kropp, J. G. Learned, E. Lehmann, J. M. LoSecco, J. Matthews, H. S. Park, L. R. Price, F. Reines, J. Schultz, S. Seidel, E. Shumard, D. Sinclair, H. W. Sobel, J. L. Stone, L. Sulak, R. Svoboda, J. C. van der Velde, and C. Wuest

simulation predicts that 34% ± 1% of the events should have an identified muon decay while our data has 26% ± 3%. This discrepancy could be a statistical fluctuation or a systematic error due to (i) an incorrect assumption as to the ratio of muon ν’s to electron ν’s in the atmospheric fluxes, (ii) an incorrect estimate of the efficiency for our observing a muon decay, or (iii) some other as-yet-unaccounted-for physics. Any ef-

...but Kamioka finds no muon anomaly (Kajita PhD ’86)...until ‘88

…at 07:35:35 UT…bam…b-bam bam bam…8 times in IMB

…11 in Kamioka



…an entire sun implodes, explodes in 13 seconds

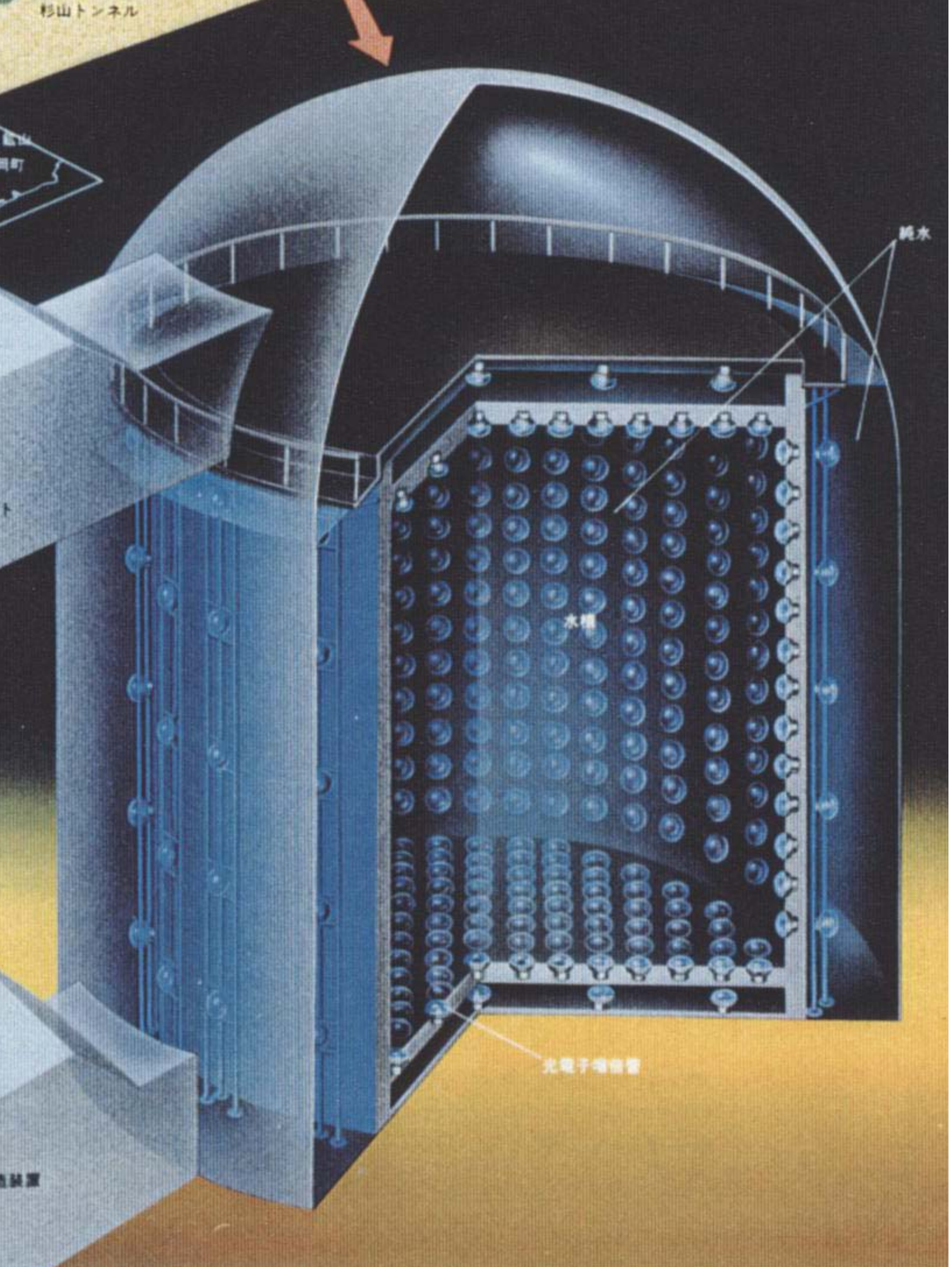
Super Nova…all heavy elements are born....iodine, silver, gold...

the night before 23 Feb

4 hours after neutrino burst

SuperNova!

Cover Story



Kamiokande (1983) :

1000 - 20 inch pms
40% photocathode coverage
outer veto

7 MeV threshold !!!

1 km underground
= 2.7 km of water,
~ Antares

initially no timing
& minimal water filtering
remedied in Kamioka III(1986)

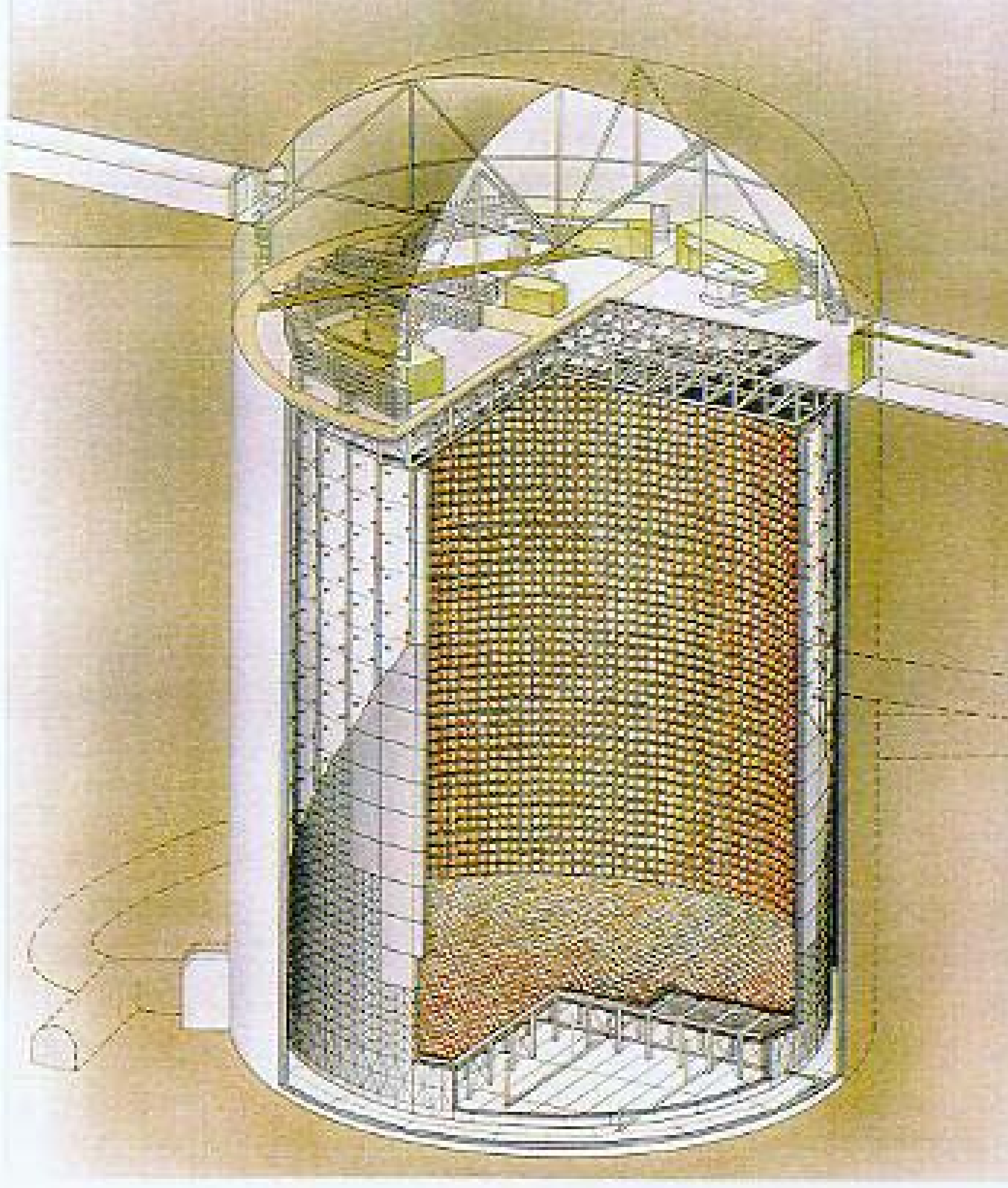
Super-K (1996-2009?)
40 m in height & diameter

inside:

11,000 pms
5 MeV threshold

outer detector:

2,000 pms and light collectors
(refurbished from IMB)



Super-K (1996)

half way up first filling

inner detector -

11,000 20 inch pms

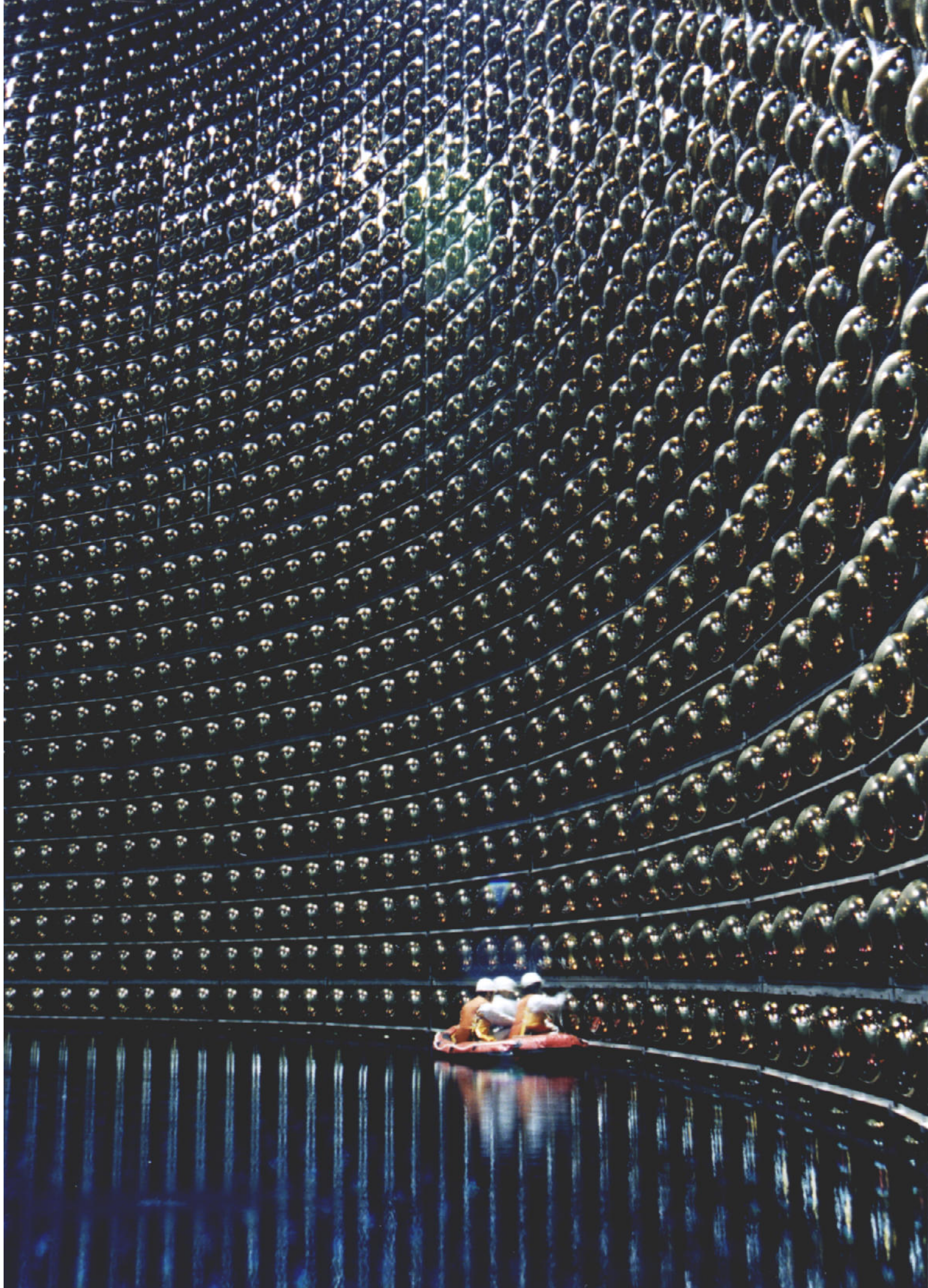
outer detector (not visible)

a reconfigured IMB III

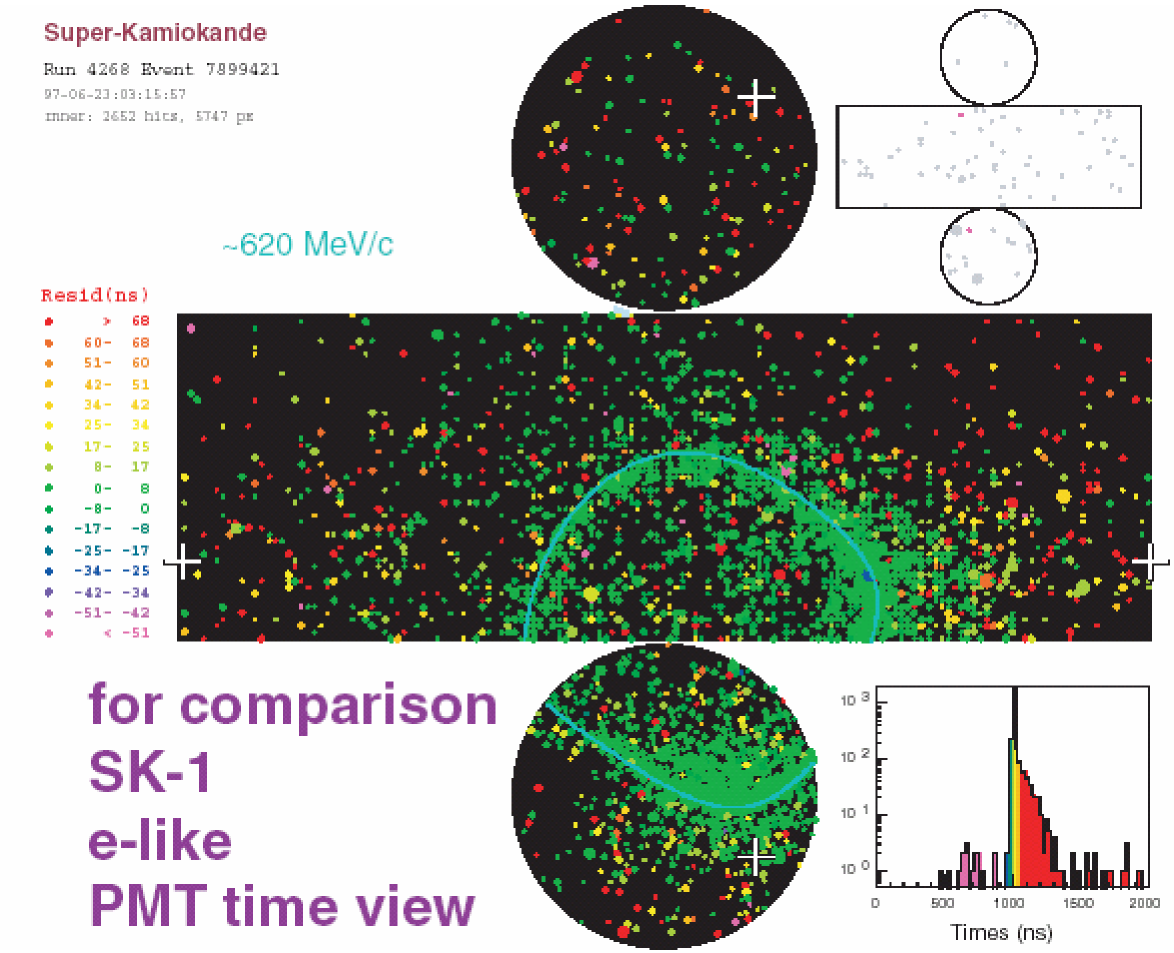
2,000 – 8 inch pms +

wavelength shifting light

collectors



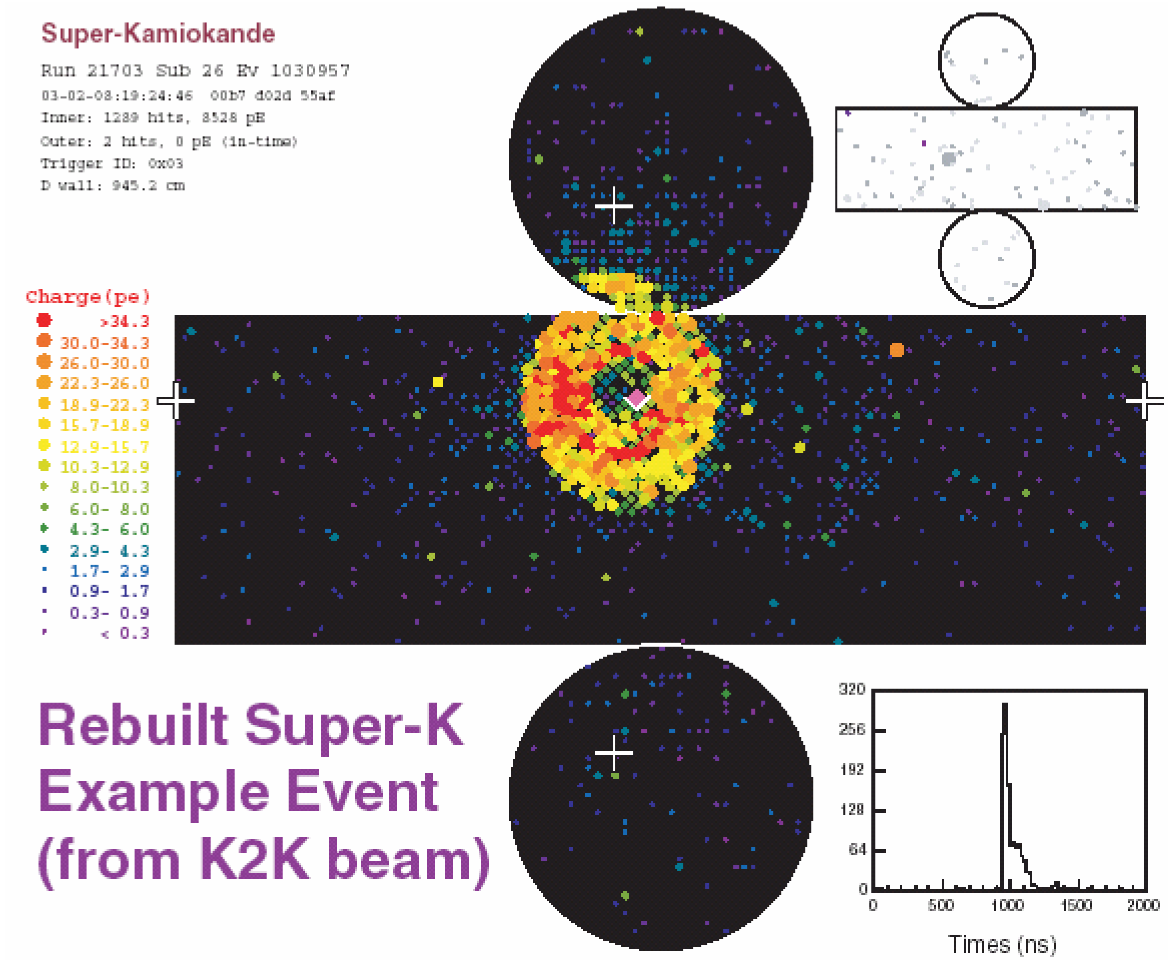
a typical electron track, fuzzy at edges, from initial detector...



for comparison
SK-1
e-like
PMT time view

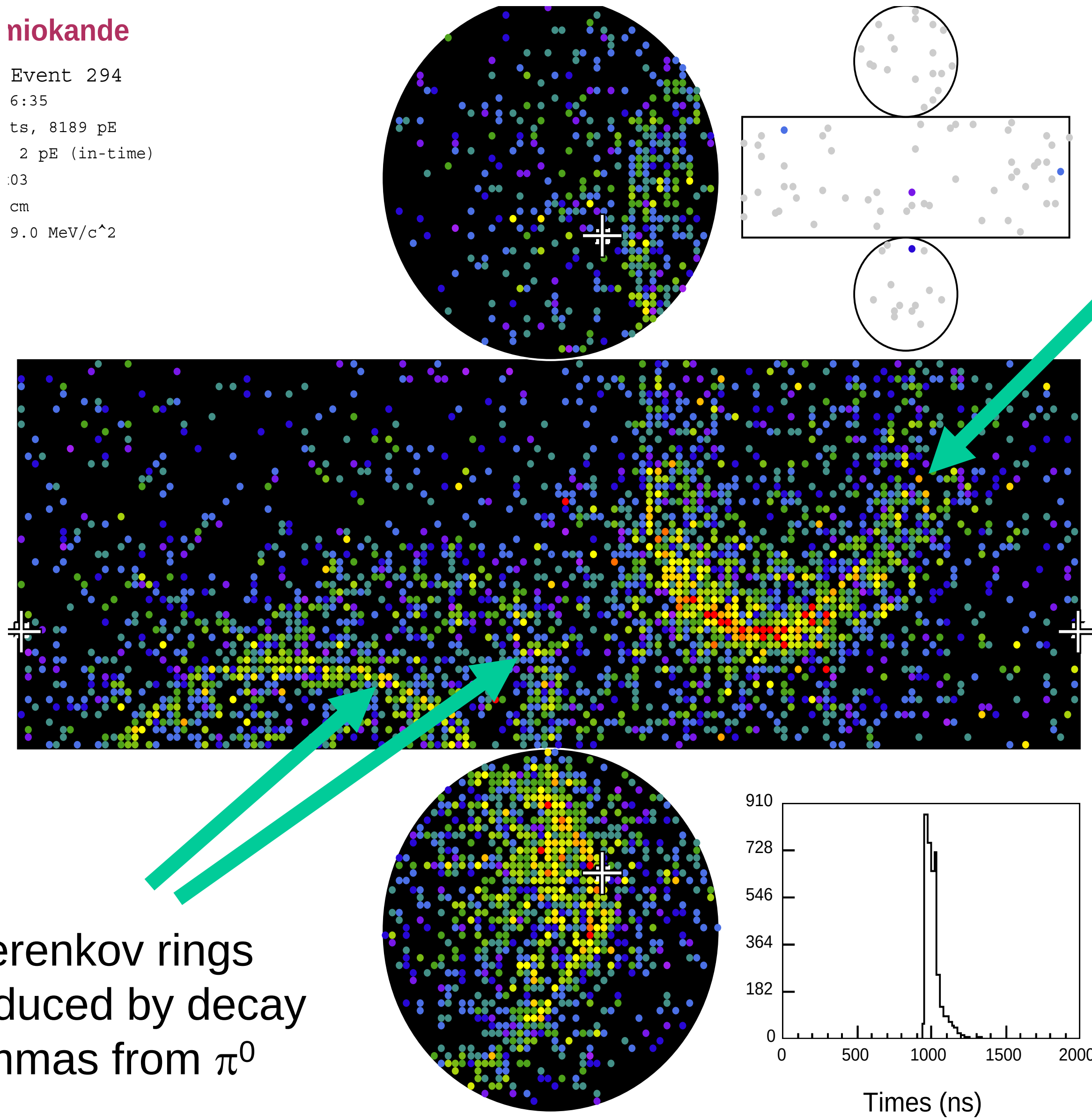
a typical SK II muon-neutrino event (with half the pms in 2003)

...in time with beam pulse from KEK accelerator 300 km away



...sharp ring edges characterize a muon track

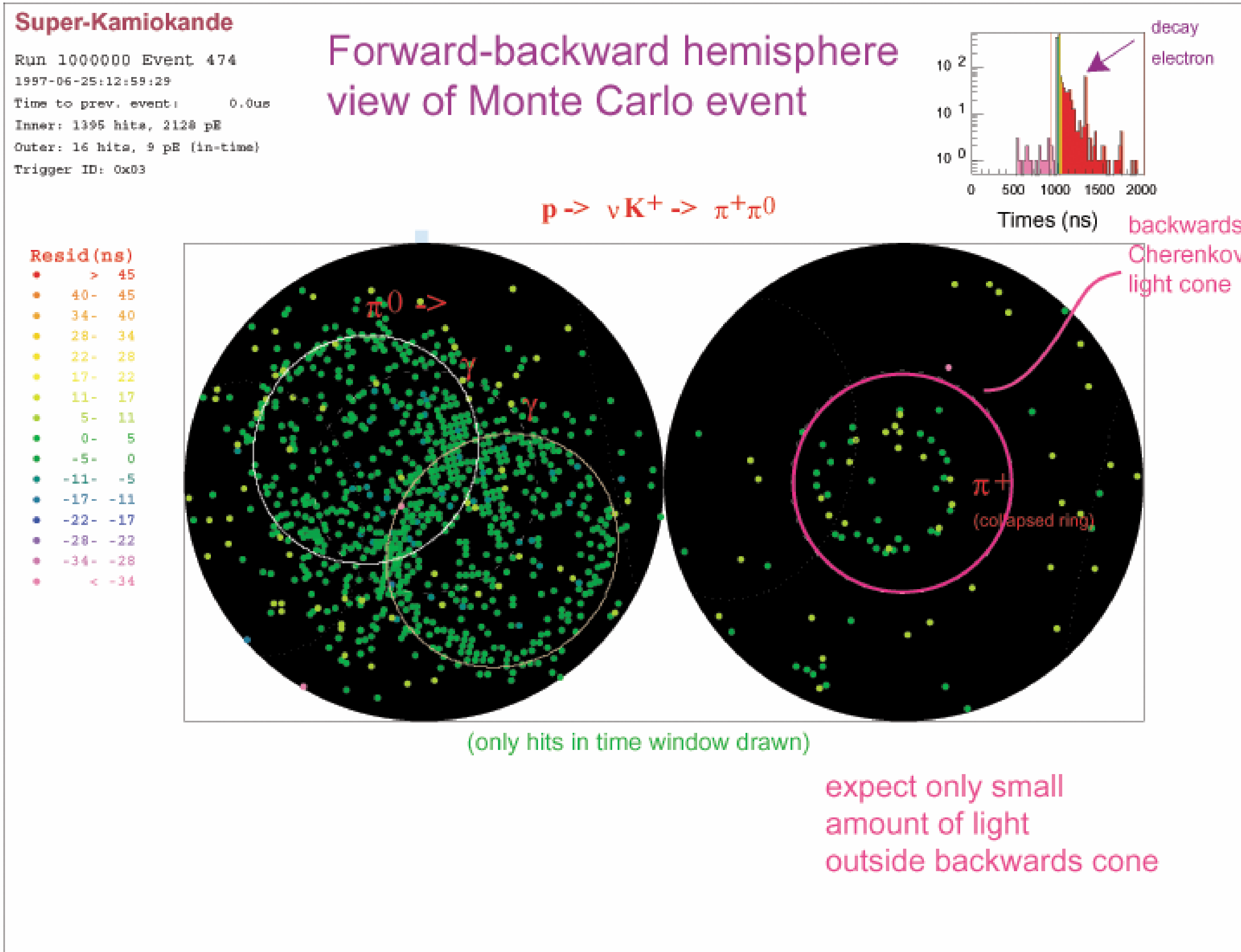
Search for proton decays



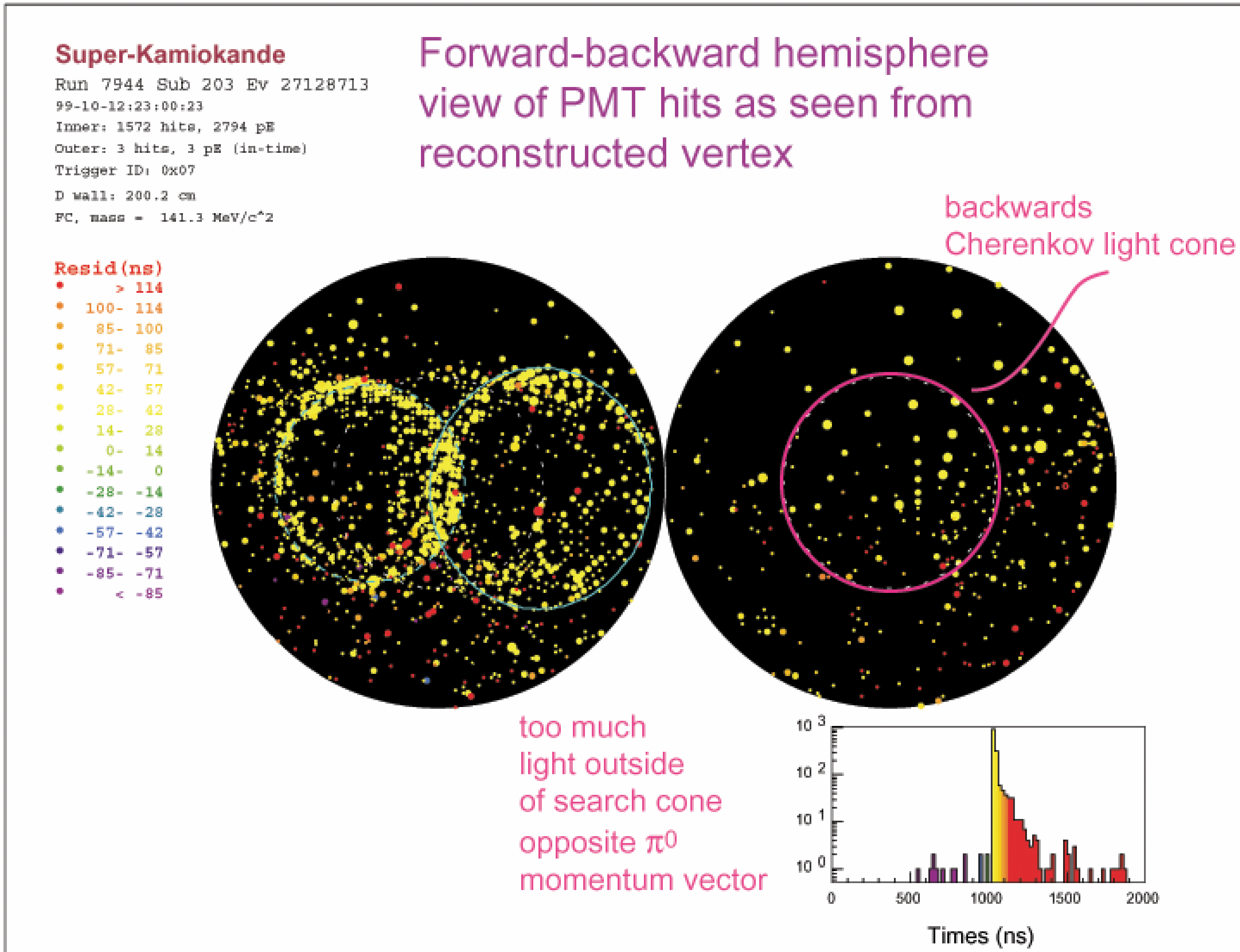
Cherenkov ring produced by a positron

Cherenkov rings produced by decay gammas from π^0

…supersymmetric proton decay…into a neutrino and a kaon?



…but best candidate is missing π^+ light opposite π° direction…



…also looking for classic $e^+ \pi^\circ$ decay of the proton…

Final Conclusions

$p \to (e/\mu)^+\pi^0$ limits for SK-I and SK-II are found.

No candidate events are observed in either the SK-I or the SK-II data.

Limits are placed on the partial lifetime at 90% confidence:

- $e^+\pi^0$ Combined limit: **$\tau/B > 6.9 \times 10^{33}$ years**
- $\mu^+\pi^0$ Combined limit: **$\tau/B > 5.4 \times 10^{33}$ years**

from Scott Clark, Boston PhD thesis

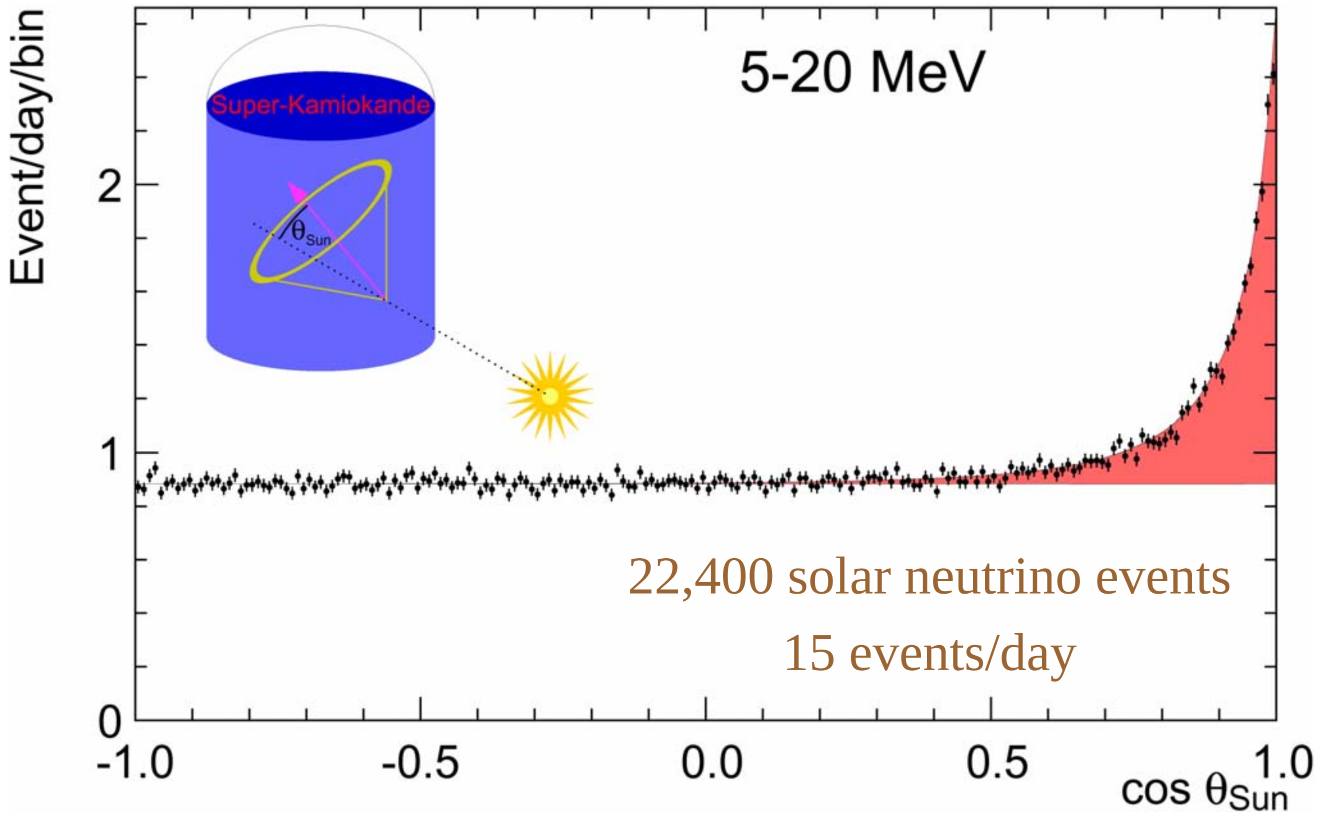
…current nucleon decay lifetime constraints…

Summary of Super-K Limits

mode	exposure (kt• yr)	εB_m (%)	observed event	B.G.	τ/B limit (10^{32} yrs)
$p \rightarrow e^+ + \pi^0$	79	43	0	0.2	50
$p \rightarrow \mu^+ + \pi^0$	79	32	0	0.4	37
$p \rightarrow e^+ + \eta$	45	17	0	0.3	11
$p \rightarrow \mu^+ + \eta$	45	12	0	0	7.8
$n \rightarrow \overline{\nu} + \eta$	45	21	5	9	5.6
$p \rightarrow e^+ + \rho$	61	6.8	0	0.6	6.1
$p \rightarrow e^+ + \omega$	61	3.3	0	0.3	2.9
$p \rightarrow e^+ + \gamma$	70	71	0	0.1	73
$p \rightarrow \mu^+ + \gamma$	70	60	0	0.2	61
$p \rightarrow \overline{\nu} + K^+$	79				16
$K^+ \rightarrow \nu\mu^+$ (spectrum)		33	--	--	4.4
prompt $\gamma + \mu^+$		8.8	0	0.5	10
$K^+ \rightarrow \pi^+\pi^0$		6.8	1	1.7	5.9
$n \rightarrow \overline{\nu} + K^0$	79				3.0
$K^0 \rightarrow \pi^0\pi^0$		9.6	25	33.8	3.2
$K^0 \rightarrow \pi^+\pi^-$		4.6	10	6.7	1.1
$p \rightarrow e^+ + K^0$	70				5.4
$K^0 \rightarrow \pi^0\pi^0$		11.8	1	1.4	8.8
$K^0 \rightarrow \pi^+\pi^-$					
2-ring		6.2	6	1.0	1.5
3-ring		1.4	0	0.2	1.4
$p \rightarrow \mu^+ + K^0$	70				10
$K^0 \rightarrow \pi^0\pi^0$		6.1	0	1.1	6.2
$K^0 \rightarrow \pi^+\pi^-$					
2-ring		5.3	0	1.5	5.4
3-ring		2.8	1	0.2	1.8

Kamioka II (1987): with timing by Penn radon purification (Cortez)

Low energy electron-neutrino events point back to the sun

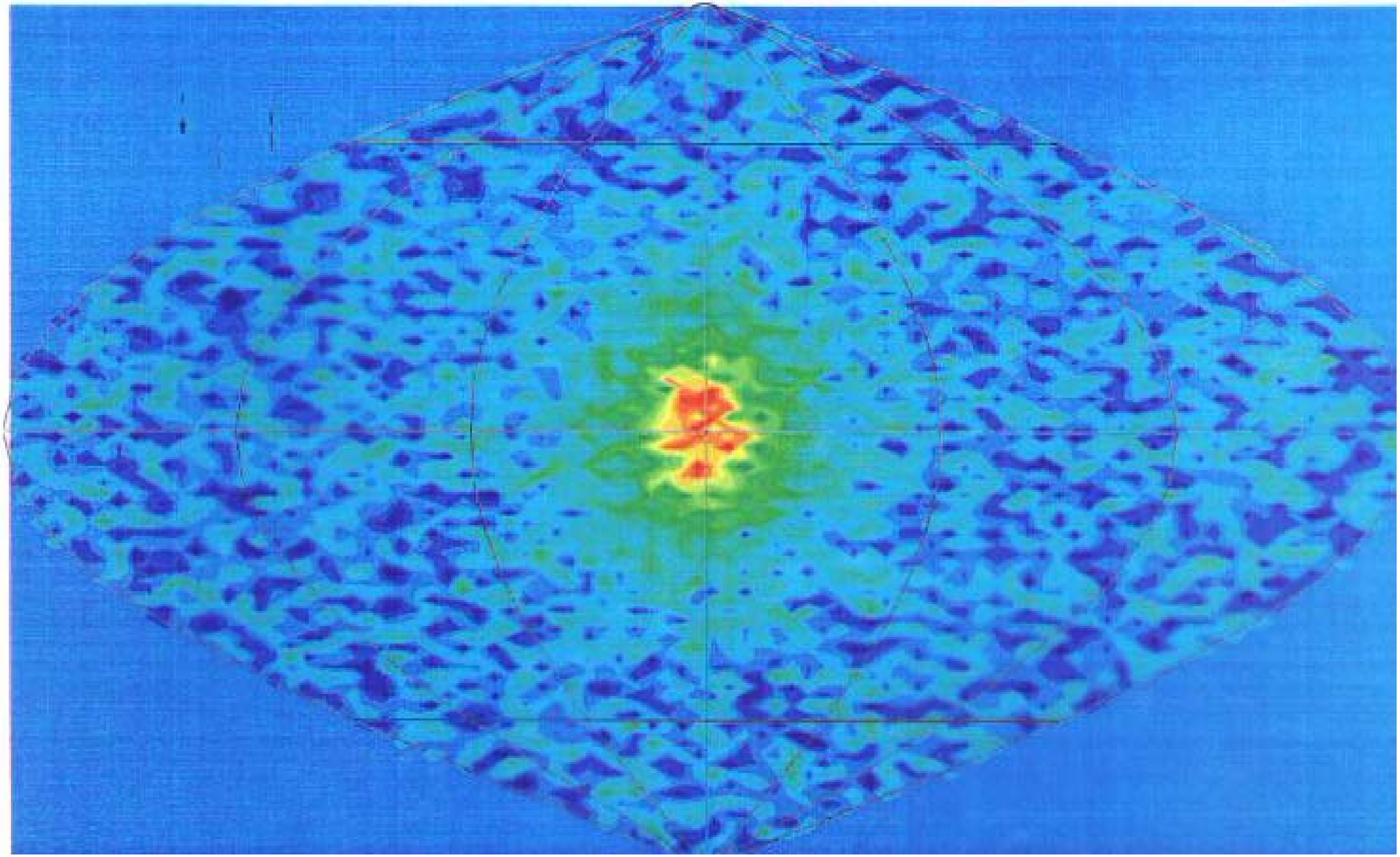


22,400 solar neutrino events

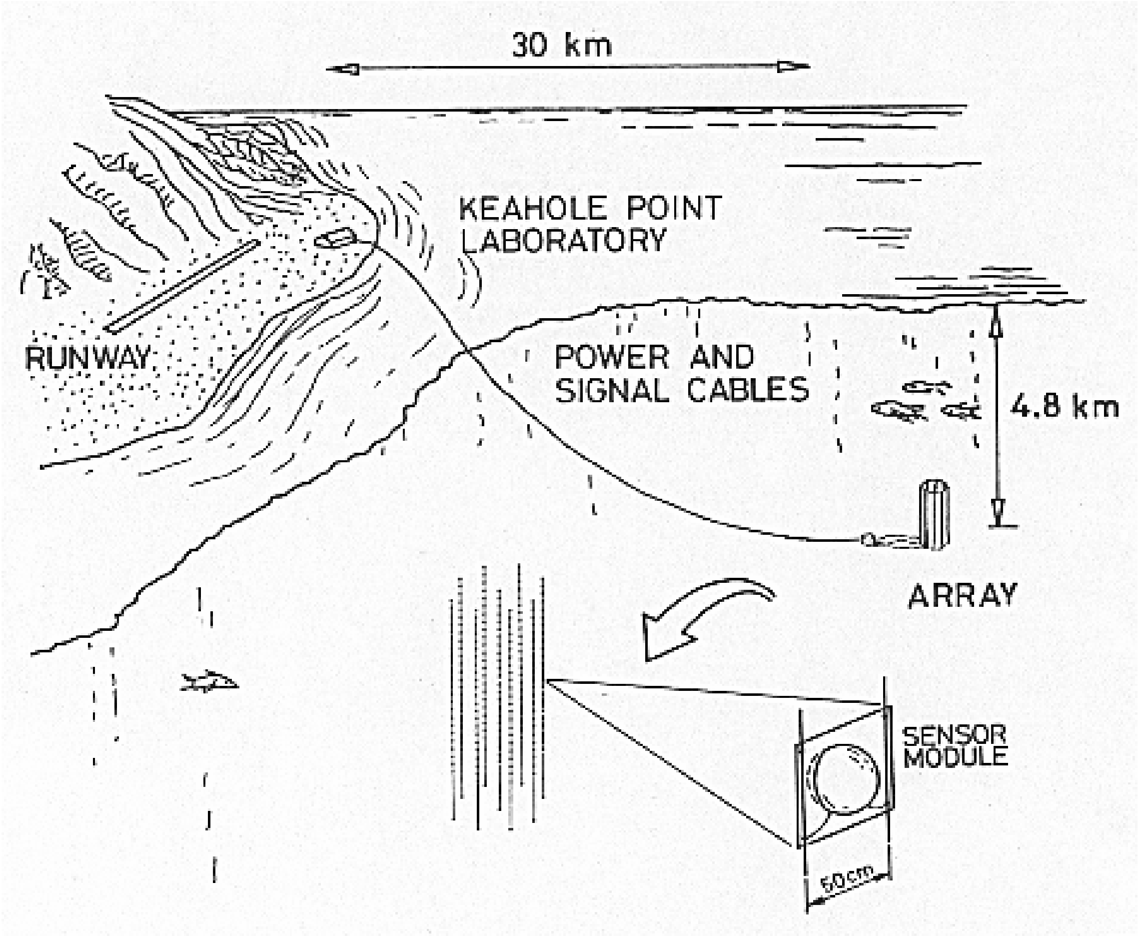
15 events/day

Direction cosine to the sun

result from Super-K…but only 47% of the expected solar model flux low energy electron neutrino events point back to our star…



…Super-K "sees" the sun…a neutrino heliograph the Dumand site:



same distance to shore

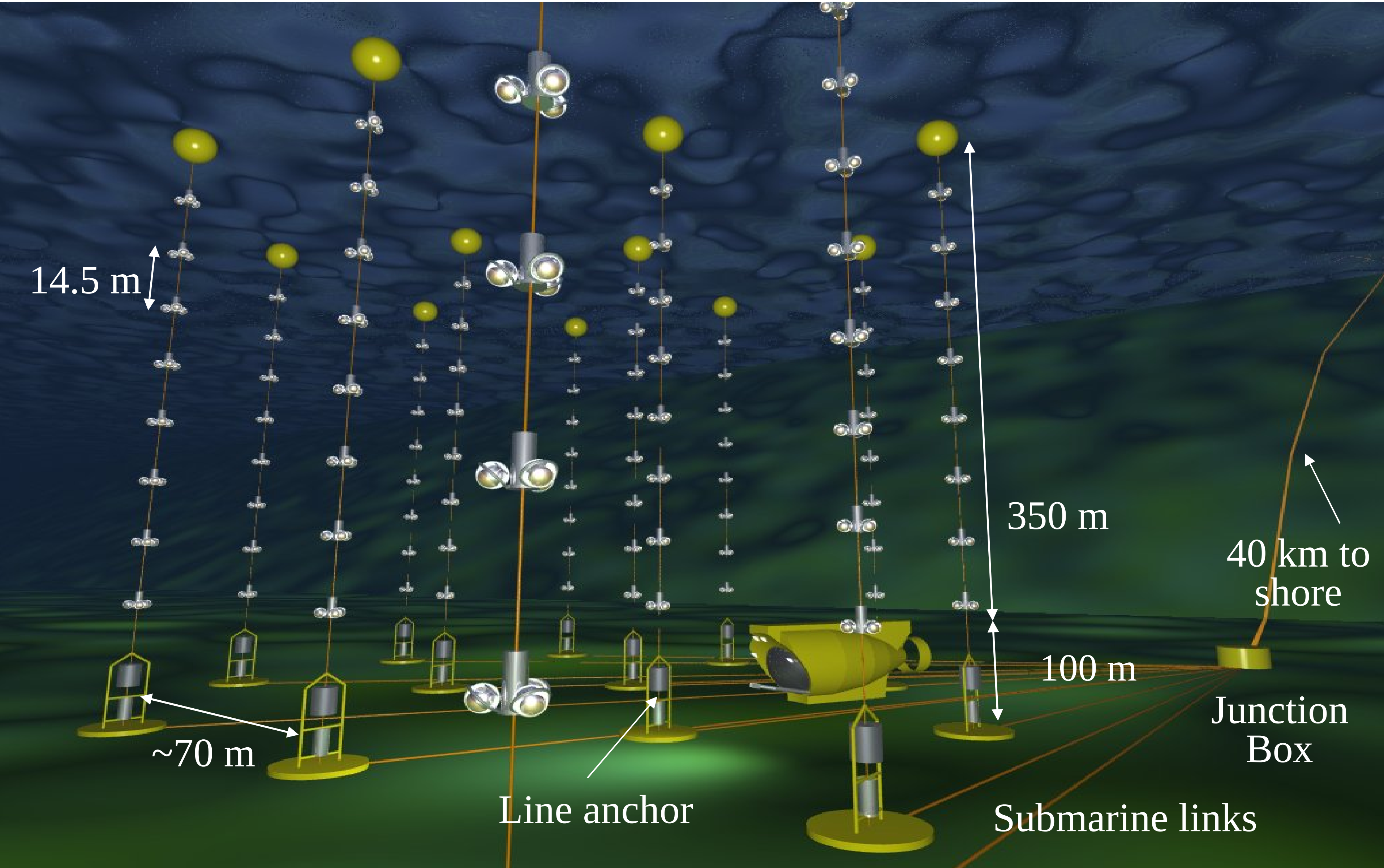
as Antares

but 4.8 km deep,

twice Antares

...we were super conservative in ‘76

ANTARES (2004-6): 900 pms, 12 lines, 25 stories/line, 3 pms/story



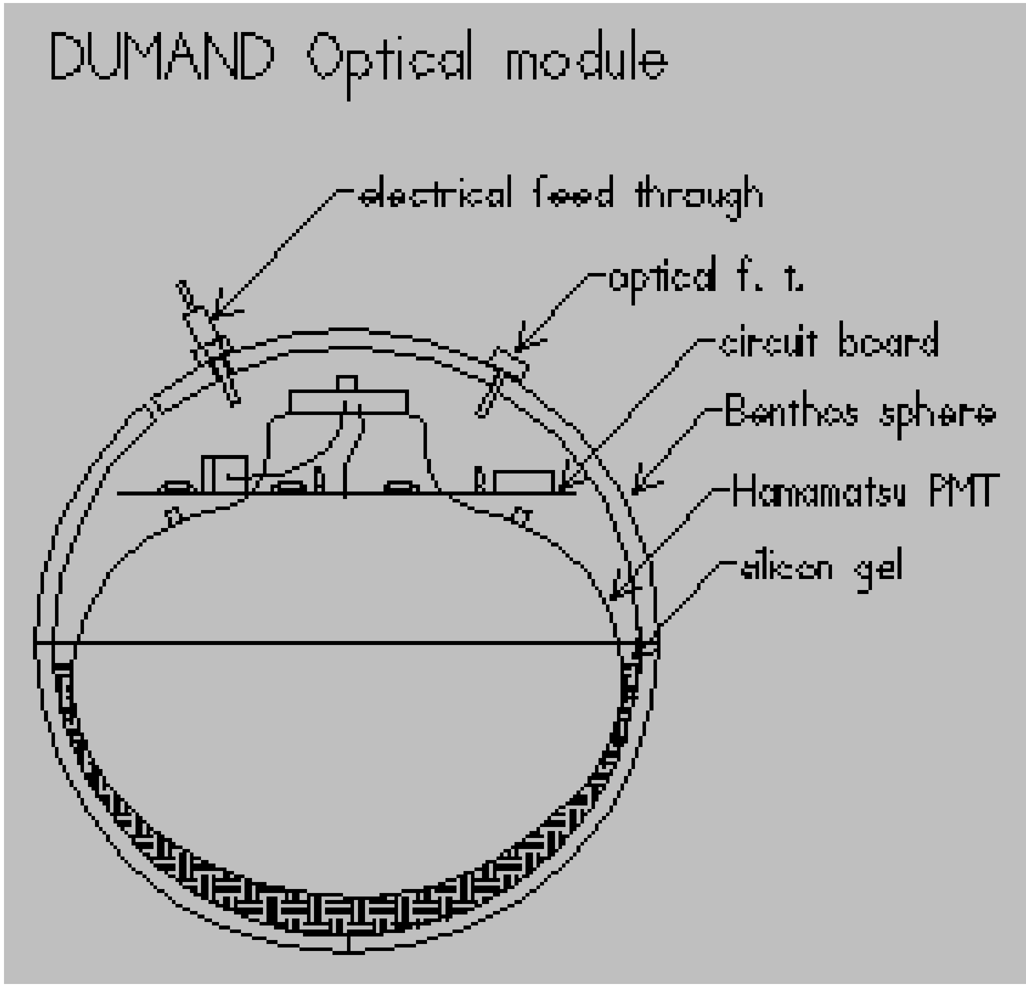
Dumand concept:

photomultipler housing,

precursor for Antares

similar for IMB & the K's,

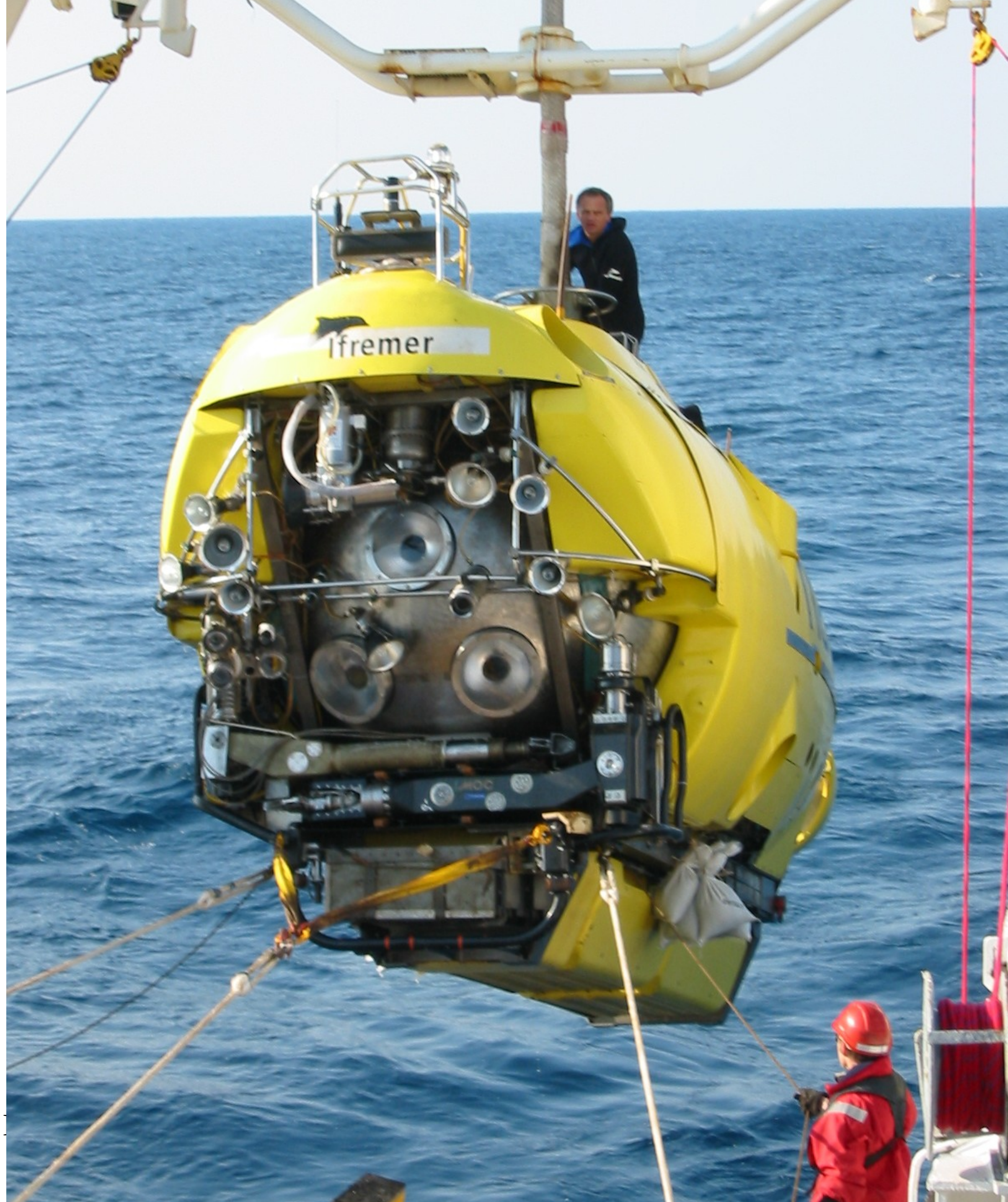
without Benthos spheres



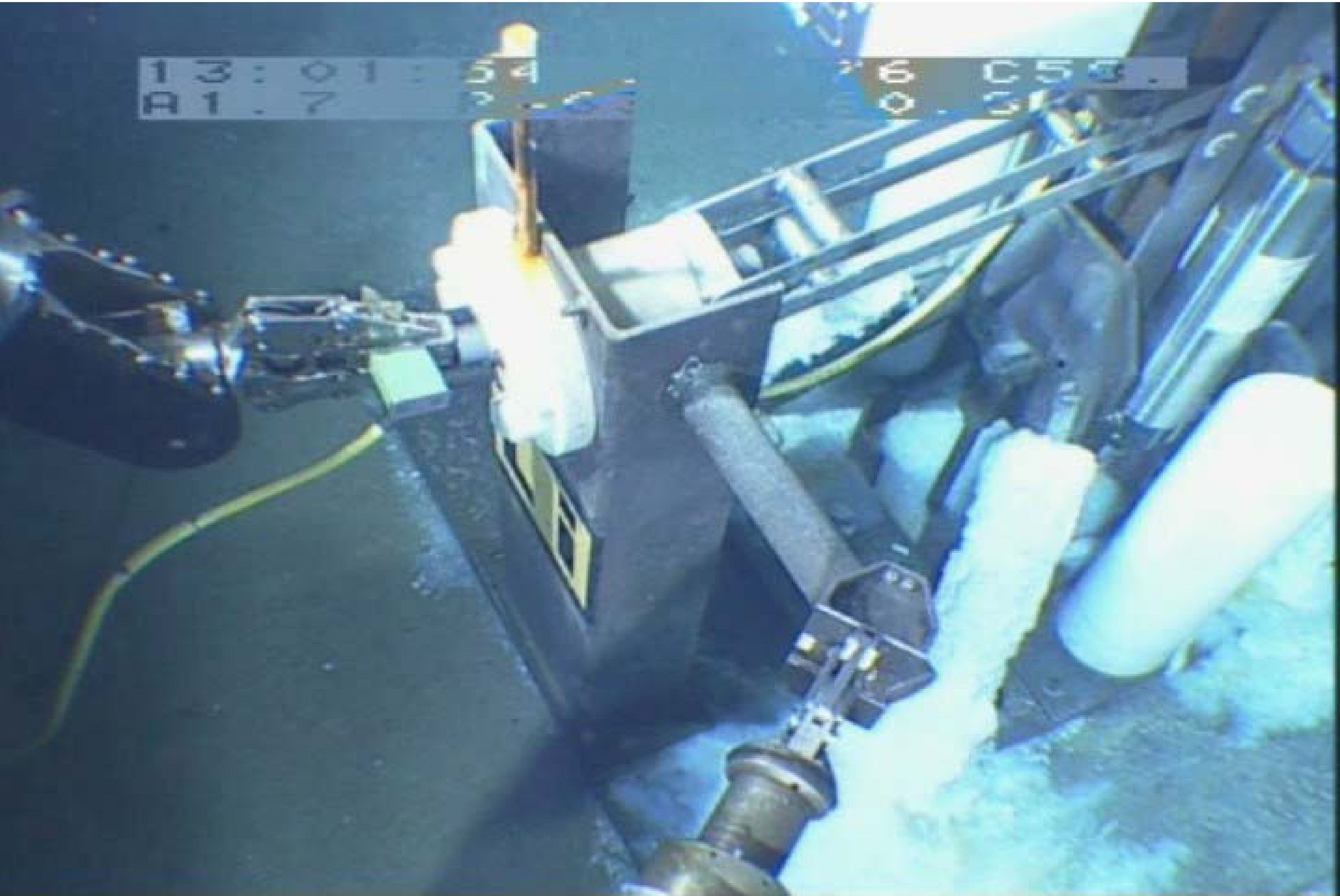
deployment of Antares preproduction prototype

underwater connections
for prototype:

manned sub
1 of 4 from Ifremer
based at Toulon



plugging-in the pre-production prototype at 2.4 km depth



... a quarter century of unification physics

...espousing the search for proton decay and neutrino oscillations

Technology driven by the science:

pixelated, ring-imaging Cherenkov calorimetry...proven

submersible, depth-tolerant pms and electronics

single photoelectron operation

pattern recognition and directionality

Astro-neutrino physics discoveries:

first physics beyond standard model

neutrino mass and oscillation...most cited paper of all time

first extra-terrestrial neutrinos, imaging sun with them

first extra-galactic neutrinos – SN 1987a

grand unification still the ultimate goal, we now need MEGATON

…nucleon decay, high energy neutrino sources *etc*. await discovery!

…but this is an experimental science…surprises are highly likely

stay tuned…and thank you!

Image credits: G. Kane, *Scientific American*, Jan 2005
D. Perkins, *High Energy Physics*, 1987
C. D. Coughlan and J. E. Dodd, *Ideas of Particle Physics*, 1991

…while we pursuing grand unification physics…

we're so glad you are pursuing
pioneering proton radiotherapy/accelerator work

in the late '70s we used the Harvard medical cyclotron
to perfect the detector technology described here

your experimental well wishers
from IMB, Super-K and Antares