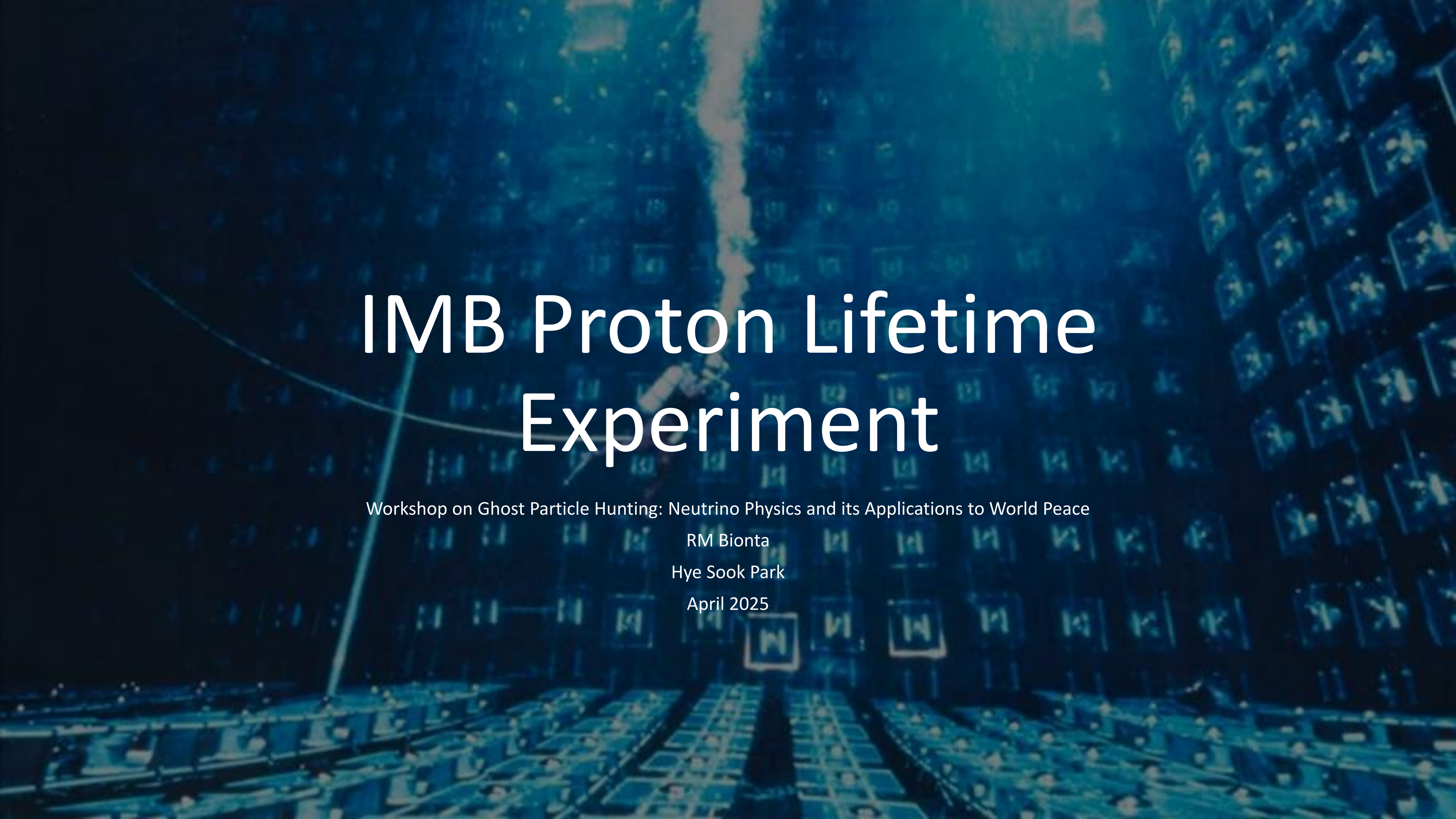


IMB Proton Lifetime Experiment

Workshop on Ghost Particle Hunting: Neutrino Physics and its Applications to World Peace

RM Bionta

Hye Sook Park

April 2025

Tokyo Conference, August 1978:
Grand Unification Theories

Proposal, May 31, 1979

"Minimal" SU_5 was predicting a proton lifetime of 10^{29} years for the mode $p \to e^+ \pi^0$

1954, Reines, Cowan, and Goldhaber:
$t > 10^{22}$ years (Phys Rev 96, 1157)

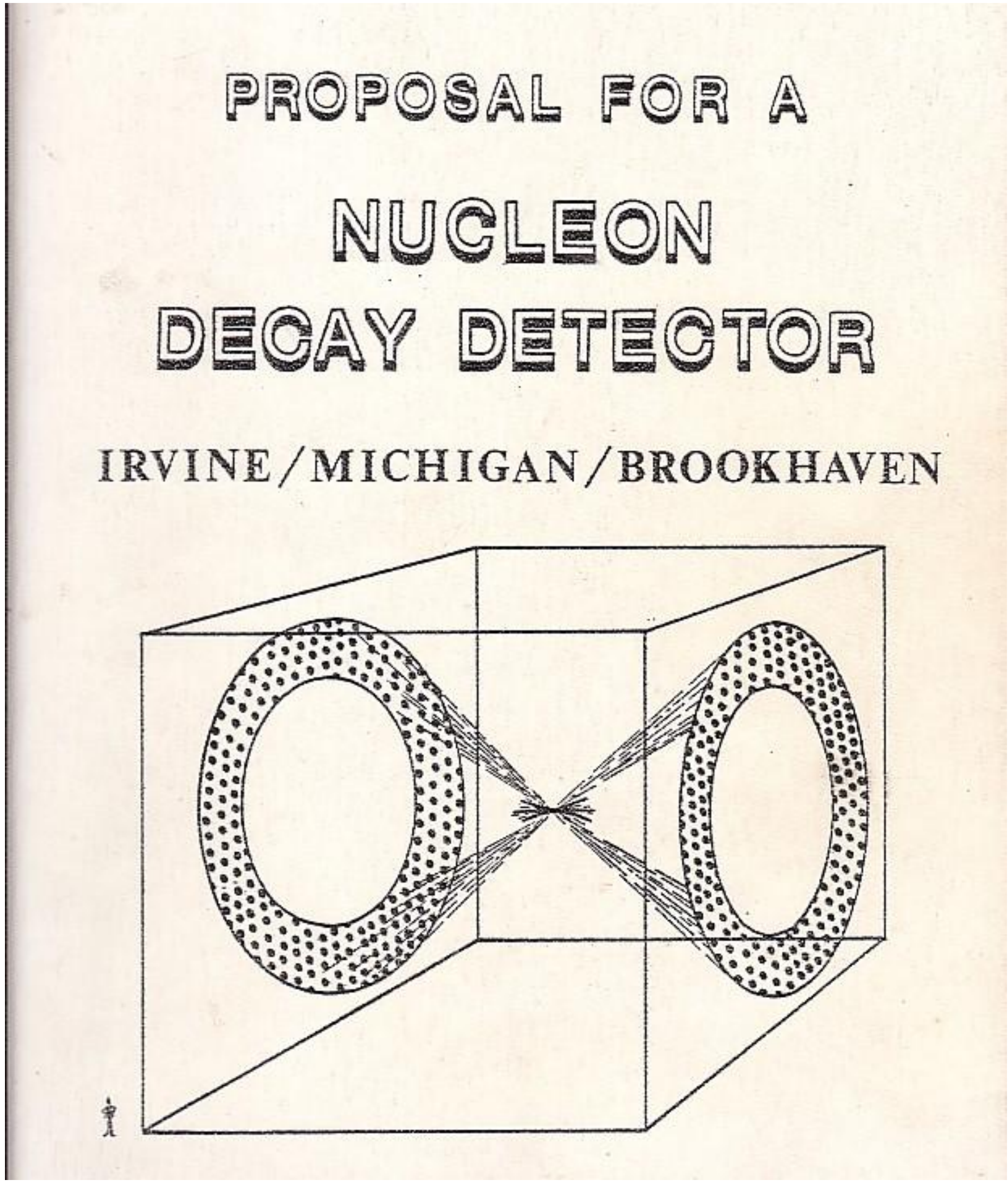
1960 Backenstoss et al. (Nuovo Cimento 16 749)
$t > 10^{26}$ years

1974, Reines and Crouch: (Phys Rev Lett 32 493)
$t > 10^{30}$ years (for modes with muon)

January '79.

At a meeting in Irvine W. Kropp, J. Learned, R. March, F. Reines, J. Schultz, D. Sinclair, H. Sobel, L. Sulak, and J. van der Velde signed up.

M. Goldhaber was soon added, and letters of support were solicited from Glashow, Gell-Mann, Salam and Weinberg.



Proposal Presentation, Washington, May 31, 1979

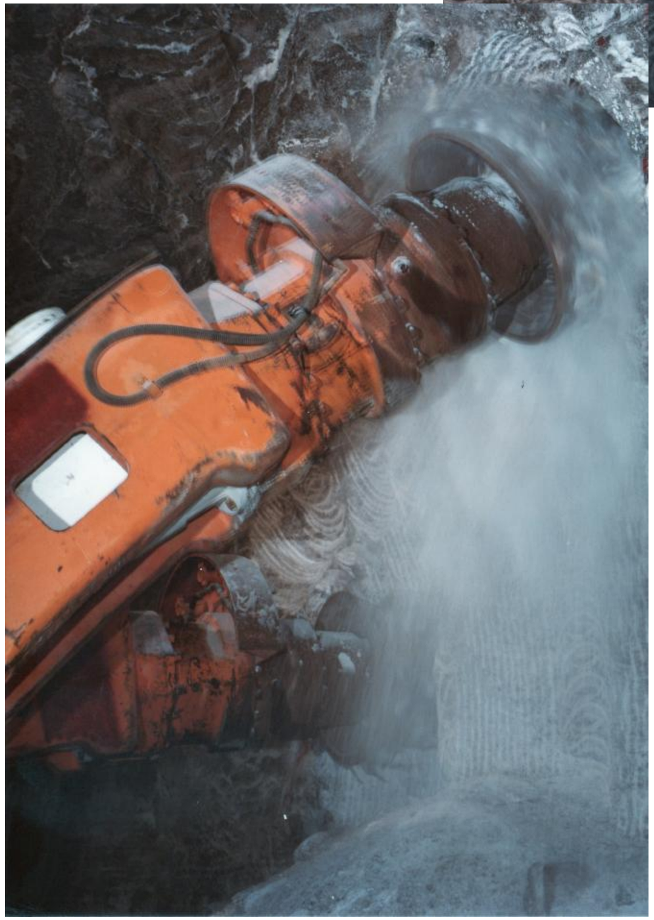
Proposal Presentation, Washington, May 31, 1979

Einstein LoSecco

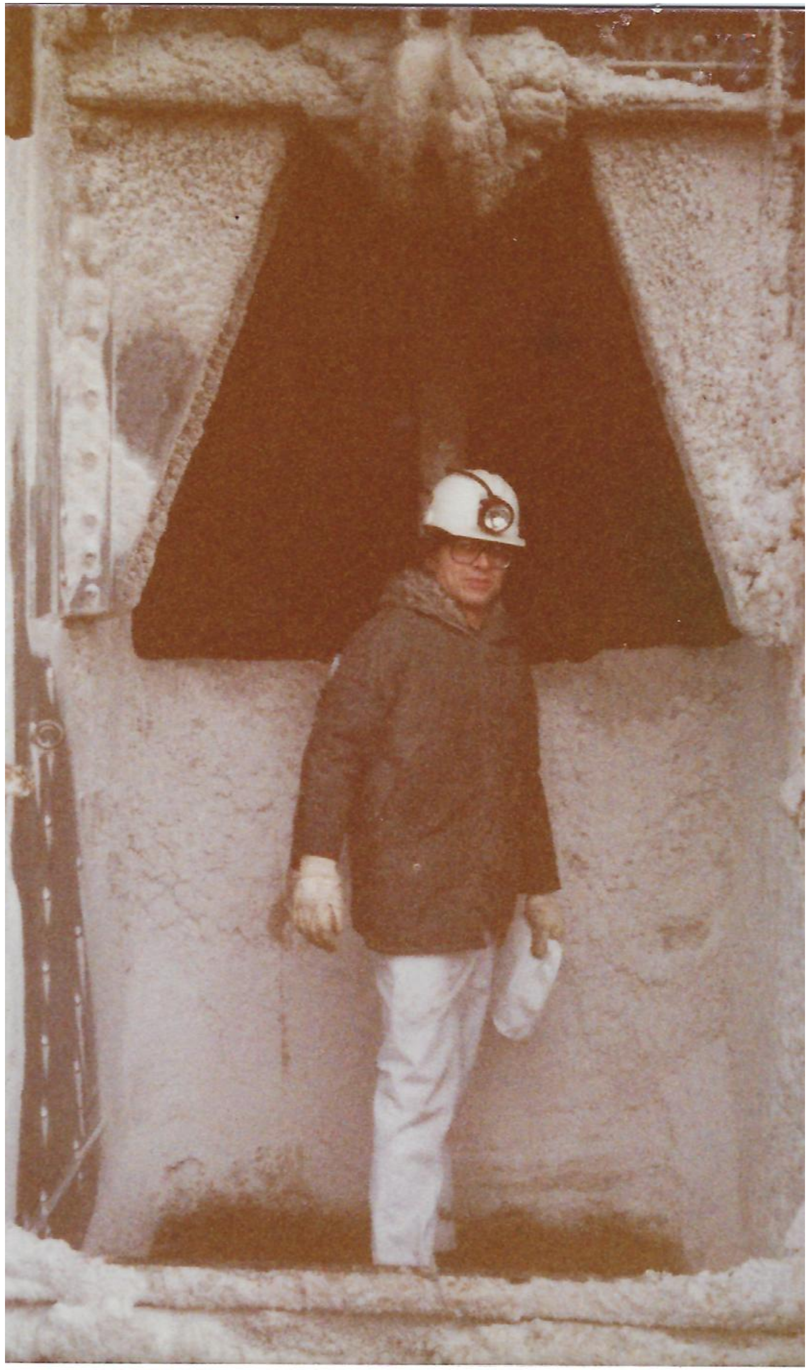
Smith Wuest Sinclair Learned Cortez

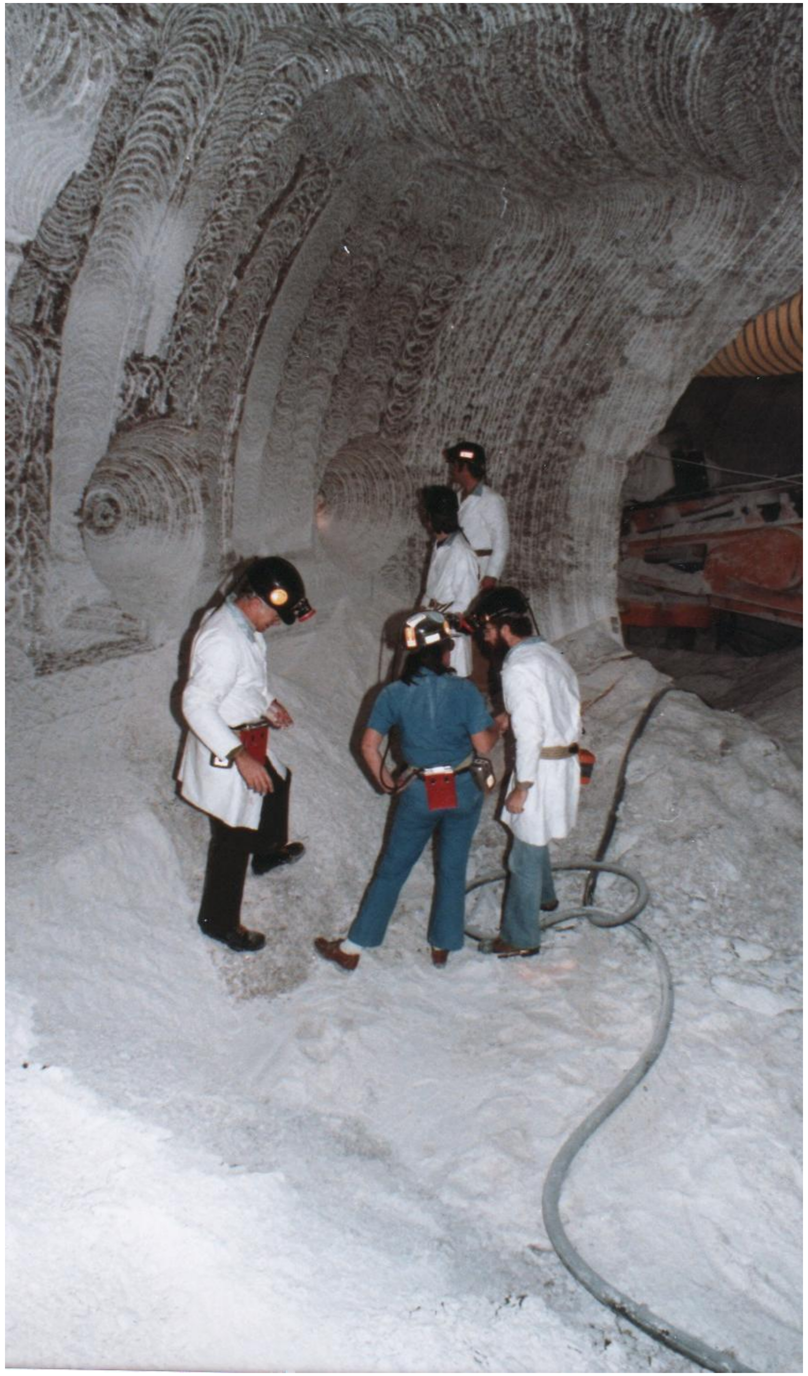
Bratton Sobel Van der Velde Goldhaber Reines Sulak

The Dosco Machine …



… sculpted the cavern leaving lots of dust (FC – Fine Crushed salt)





September 1981

Phototube assembly and testing was done at UCI and UM

Hauling two halves of the photomultiplier test tank on John's old Camaro at UCI

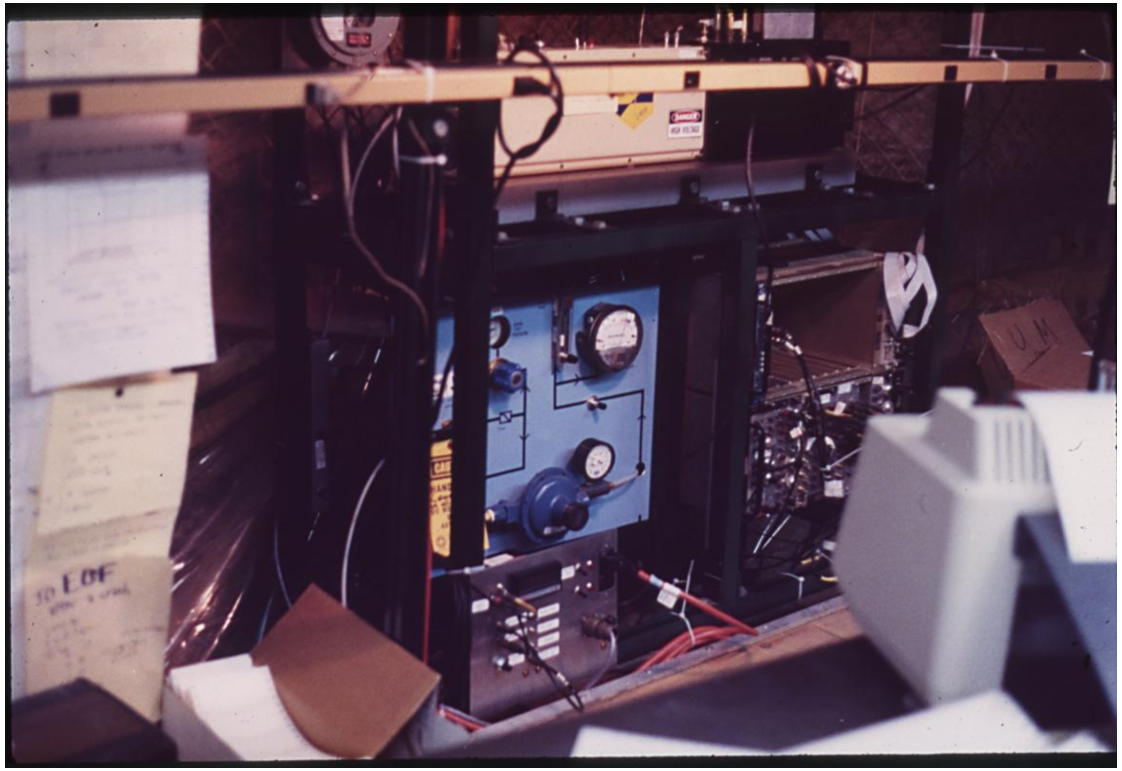
Hauling two halves of the photomultiplier test tank on John's old Camaro at UCI

Colleen in the HEP office at UCI , September 1980.

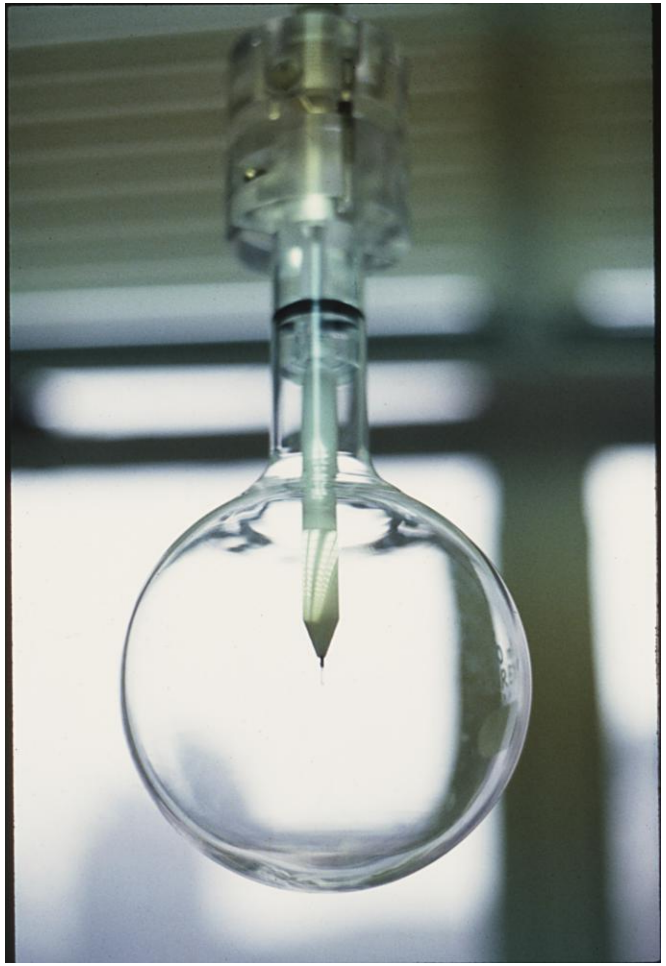
Collaboration meetings at Laguna Beach CA …

… were a favorite of the folks from UM

New technologies were developed for calibration

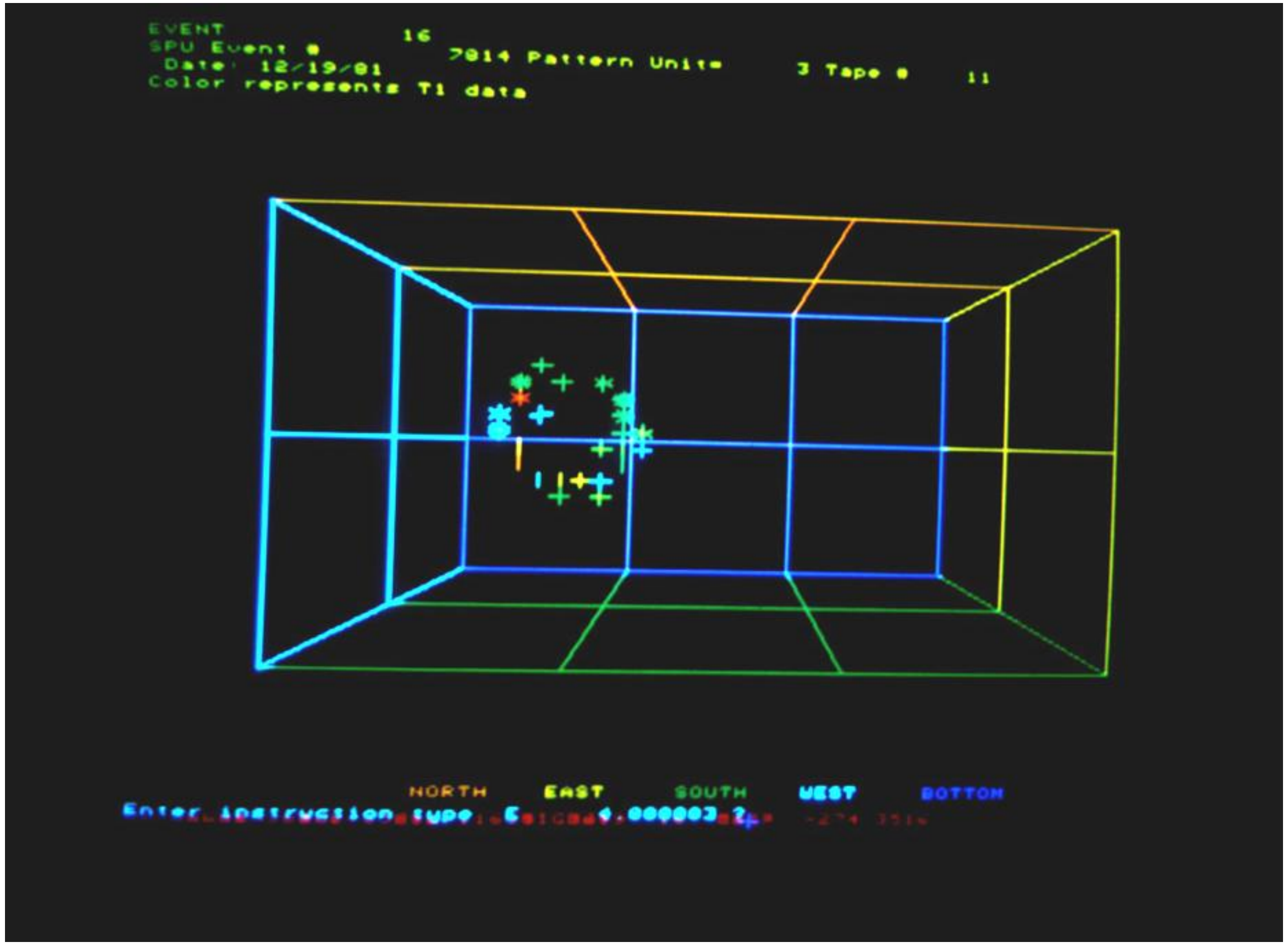


N2 Laser



4π radiator

Displaying phototube time and charge data

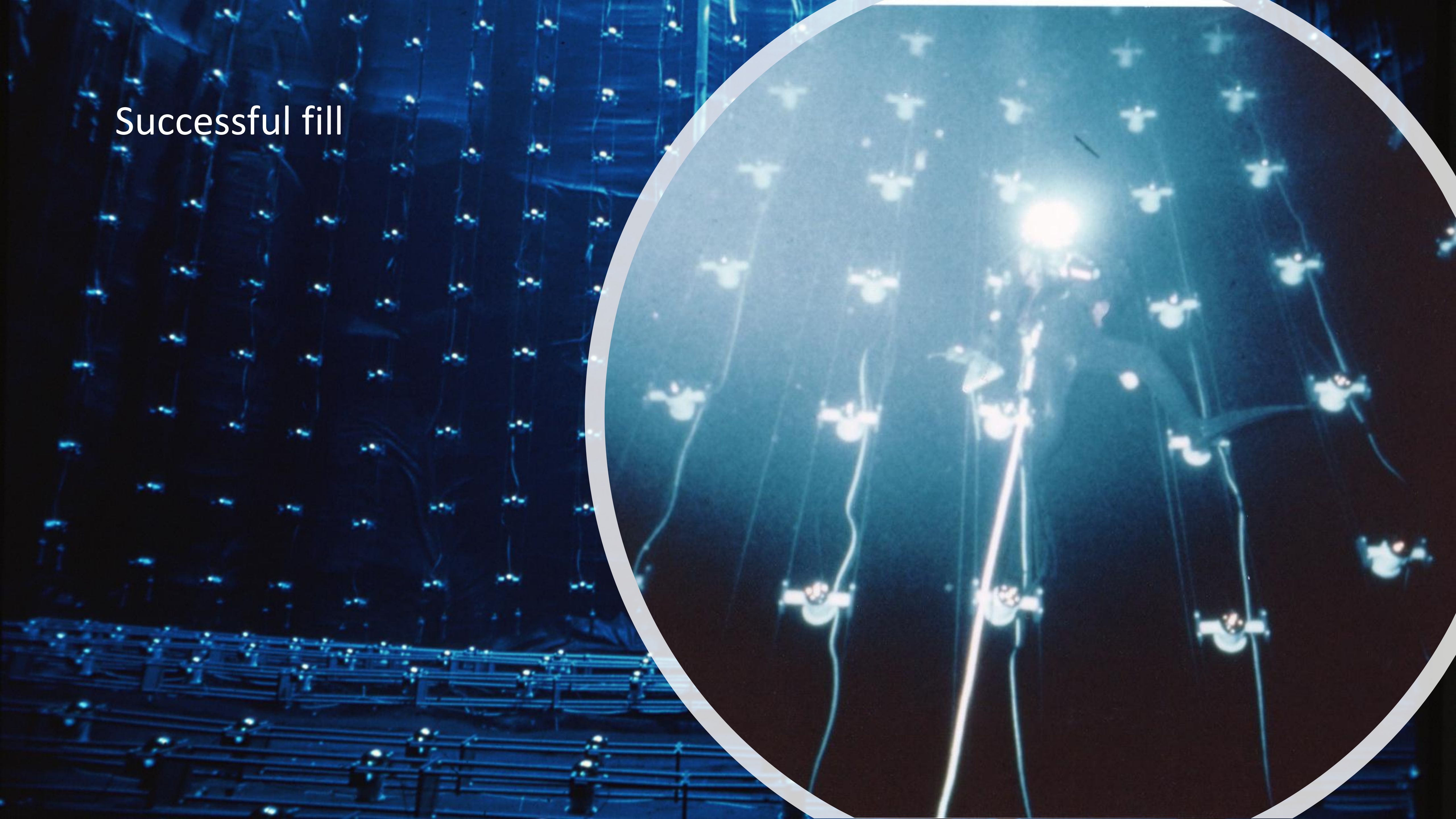


Stopping muon in 10 feet of water

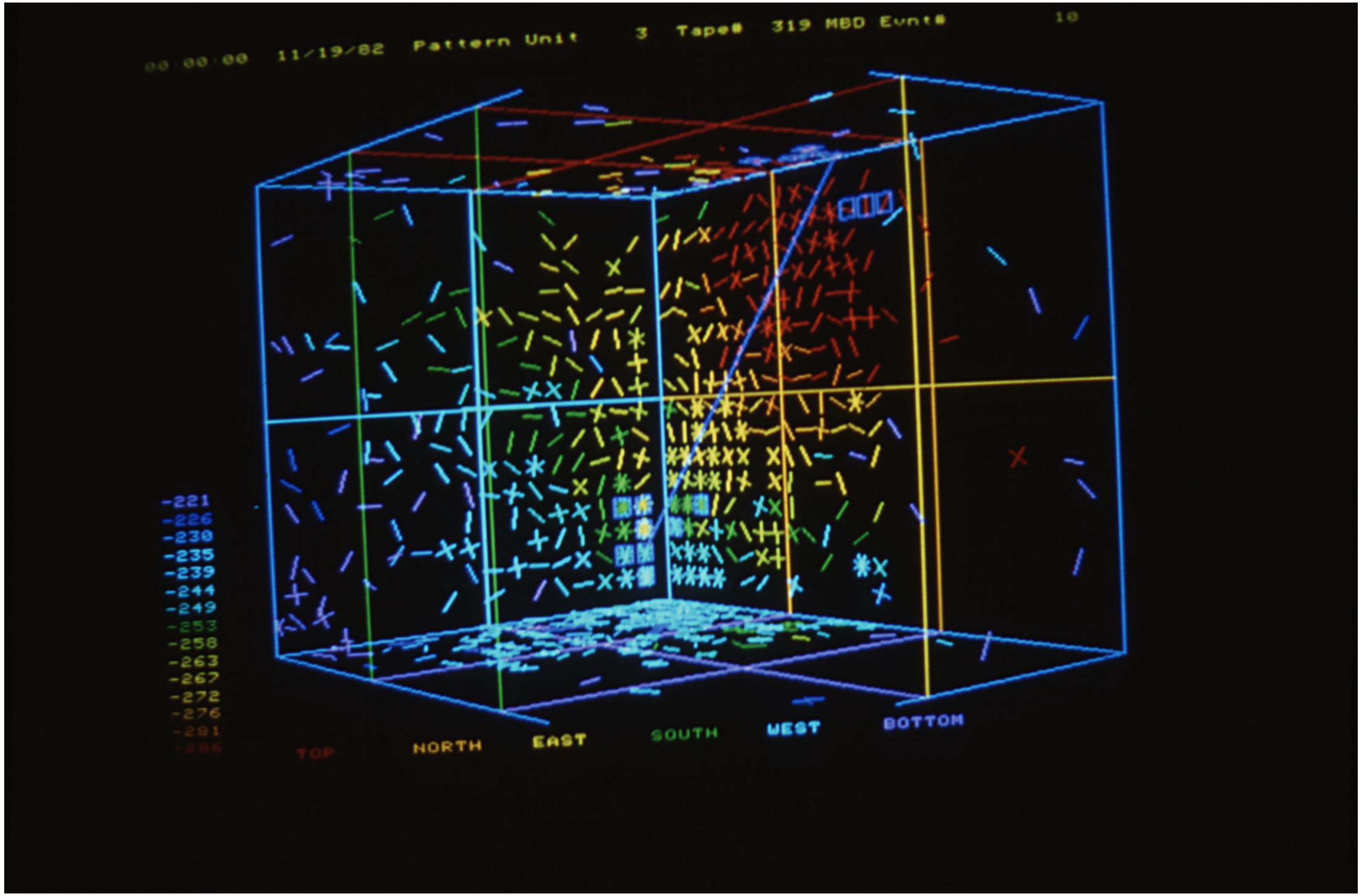
Use color for time,
number of slashes for Q.

First version had 6 views:
North, east, south, west, top, bottom

Successful fill



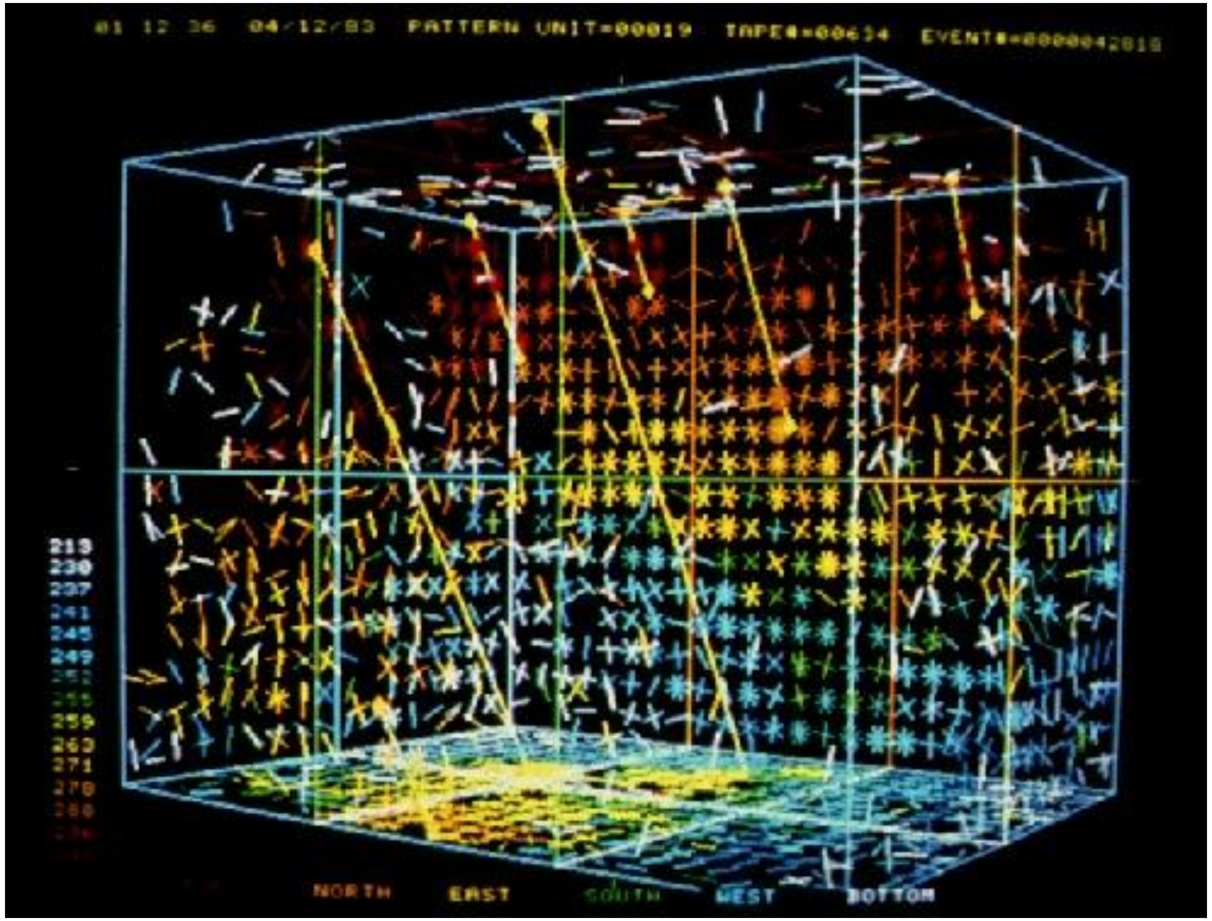
Muons !



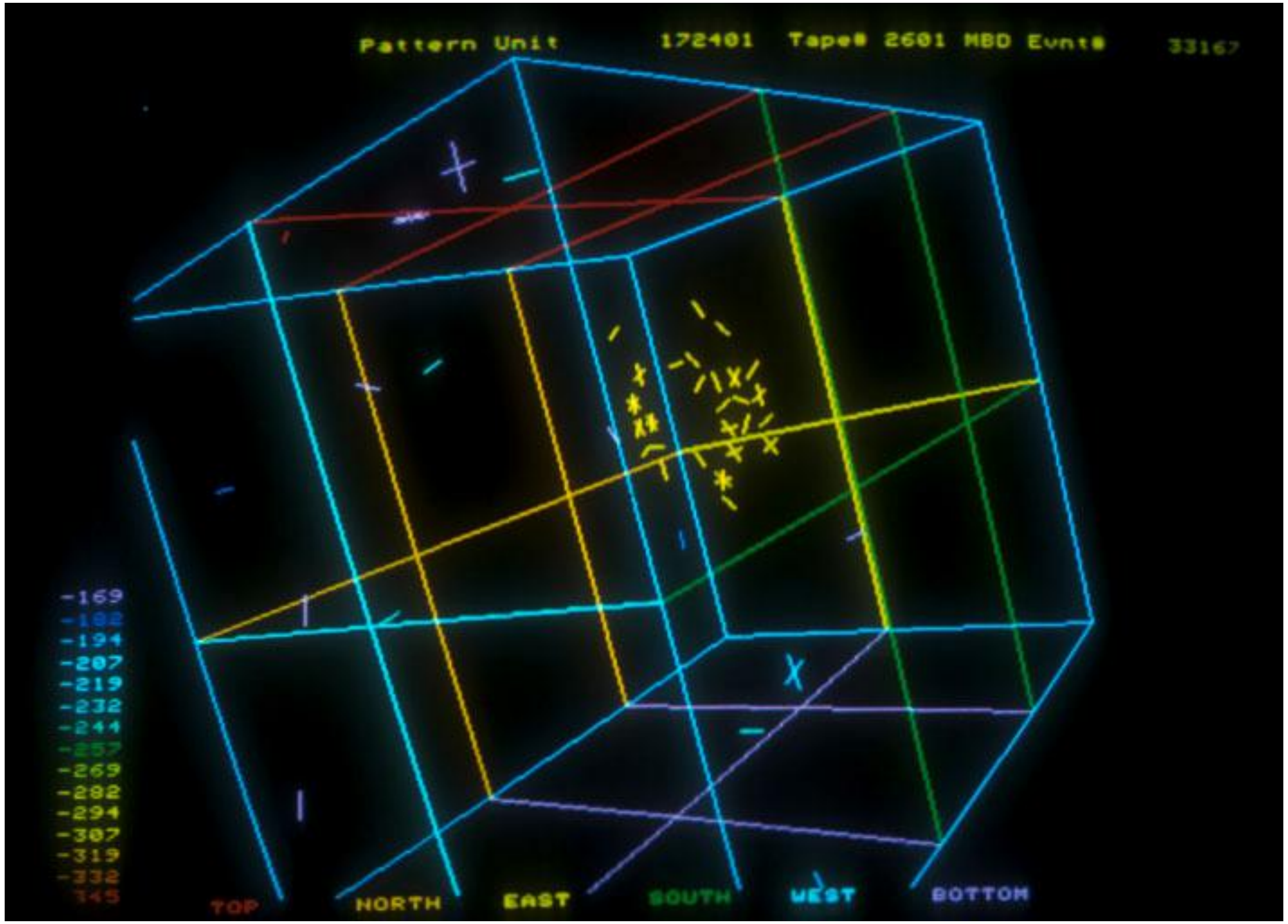
Upgraded display allows viewing from any angle.

Muons crossed detector at 3/second.

Easy to track: Draw line from earliest 10 phototubes to 10 brightest



Showers of multiple muons also observed

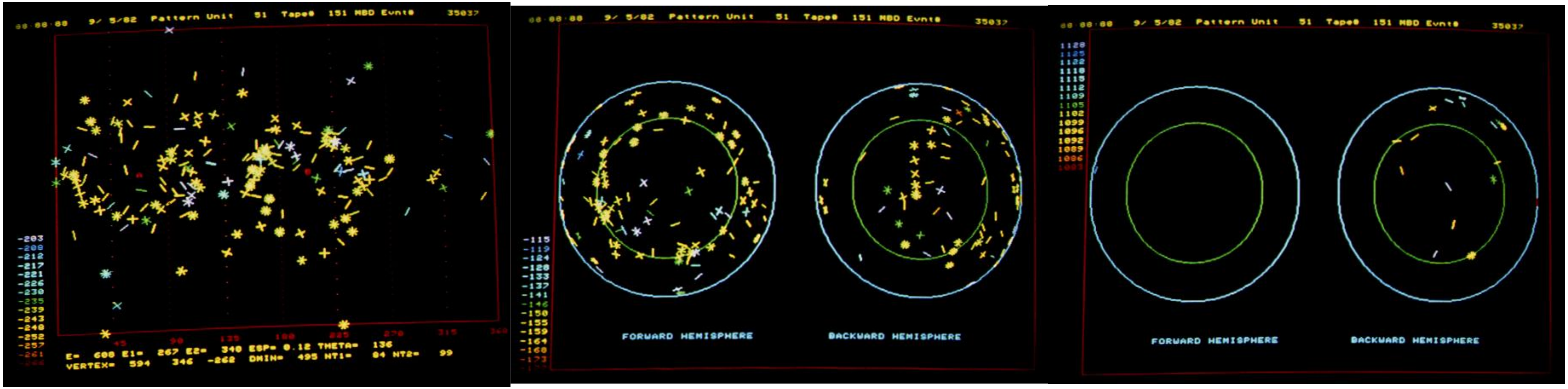


Contained neutrino event – track originates inside the detector

SN 1987a neutrino at UT 7:35:42.0

A handful of proton decay candidates were obtained …

… but all were rejected.



“Unroll plot” – phototubes were projected to a cylinder surrounding the vertex. The unrolled cylinder showed the angle between the tracks

This one was close to proton decay, but the energy was too large, the angle was less than 180 degrees, and a muon decay was observed

Search for Proton Decay into $e^+\pi^0$

R. M. Bionta, G. Blewitt, C. B. Bratton, B. G. Cortez,[a] S. Errede, G. W. Forster,[a] W. Gajewski, M. Goldhaber, J. Greenberg, T. J. Haines, T. W. Jones, D. Kielczewska,[b] W. R. Kropp, J. G. Learned, E. Lehmann, J. M. LoSecco, P. V. Ramana Murthy,[c] H. S. Park, F. Reines, J. Schultz, E. Shumard, D. Sinclair, D. W. Smith,[d] H. W. Sobel, J. L. Stone, L. R. Sulak, R. Svoboda, J. C. van der Velde, and C. Wuest

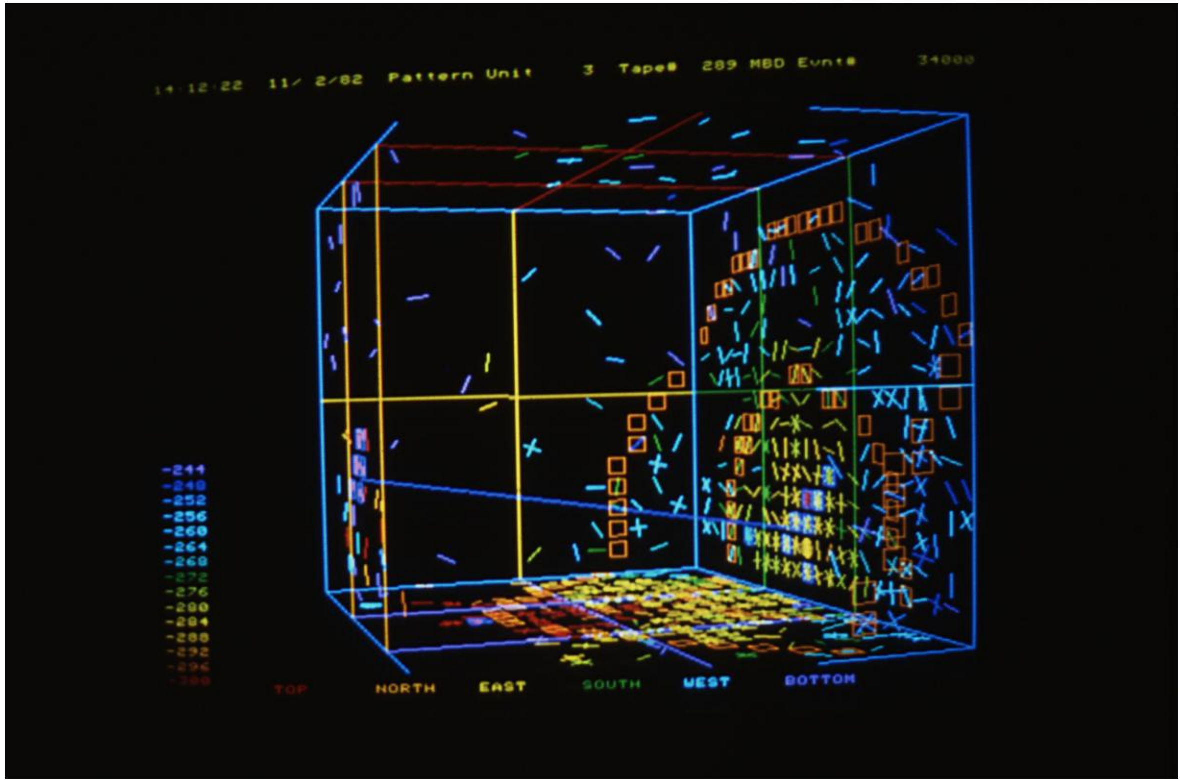
The University of California at Irvine, Irvine, California 92717, and The University of Michigan, Ann Arbor, Michigan 48109, and Brookhaven National Laboratory, Upton, New York 11973, and California Institute of Technology, Pasadena, California 91125, and Cleveland State University, Cleveland, Ohio 44115, and The University of Hawaii, Honolulu, Hawaii 96822, and University College, London WC1E 6BT, United Kingdom

(Received 13 April 1983)

Observations were made 1570 meters of water equivalent underground with an 8000-metric-ton water Cherenkov detector. During a live time of 80 d no events consistent with the decay $p\to e^+\pi^0$ were found in a fiducial mass of 3300 metric tons. It is concluded that the limit on the lifetime for bound plus free protons divided by the $e^+\pi^0$ branching ratio is $\tau/B > 6.5\times 10^{31}$ yr; for free protons the limit is $\tau/B > 1.9\times 10^{31}$ yr (90% confidence). Observed cosmic-ray muons and neutrinos are compatible with expectations.

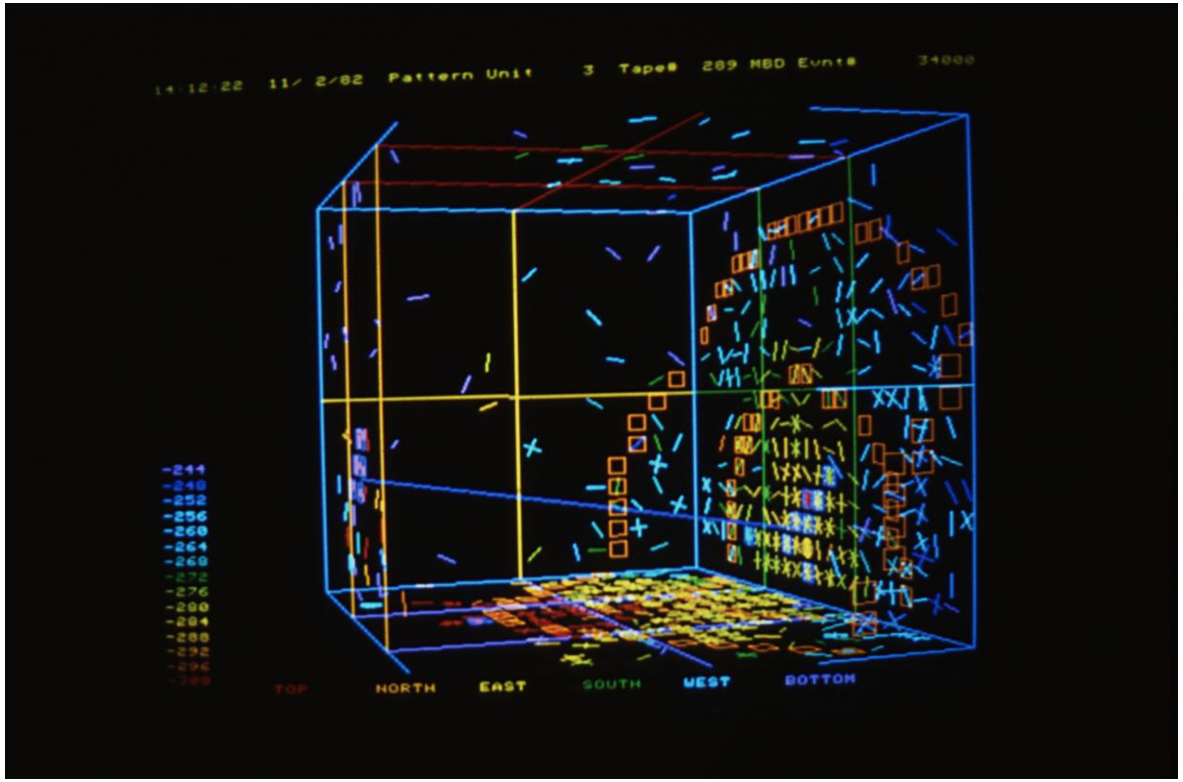
PACS numbers: 13.30.Eg, 11.30.Ly, 14.20.Dh

Search for upward muons

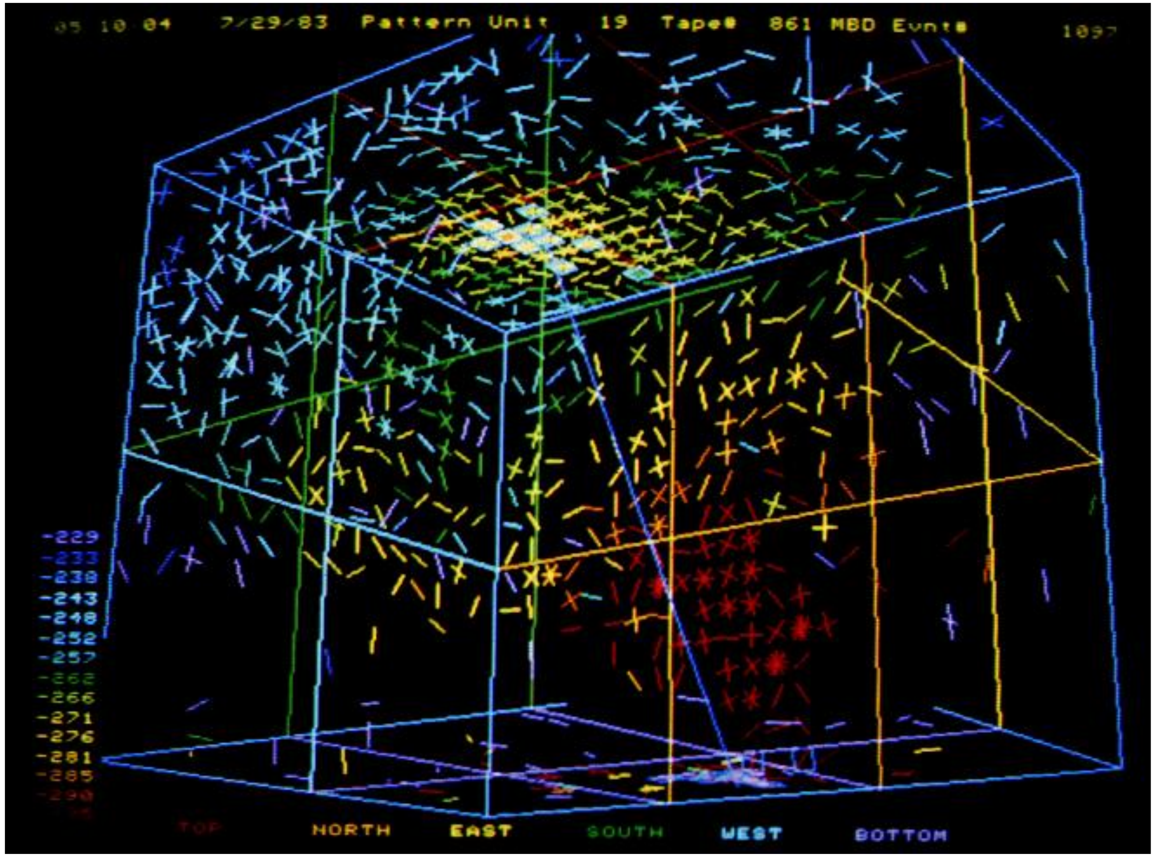


New trigger implemented to capture upward going events

Search for upward muons

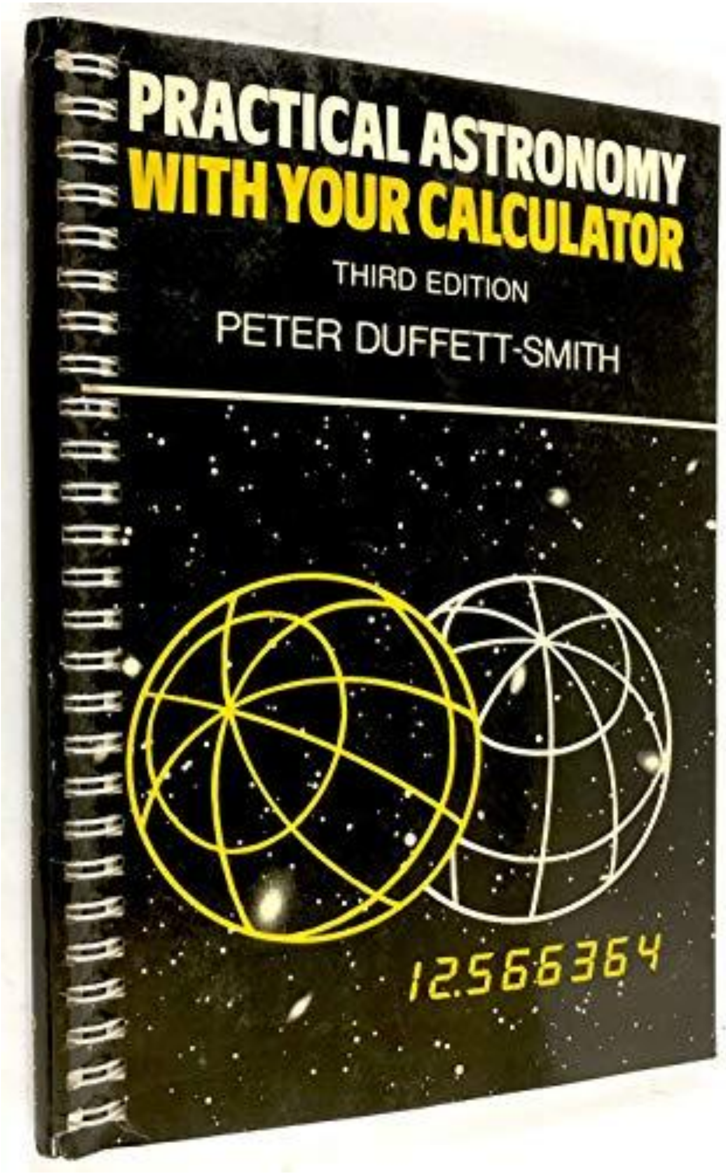


New trigger implemented to capture upward going events

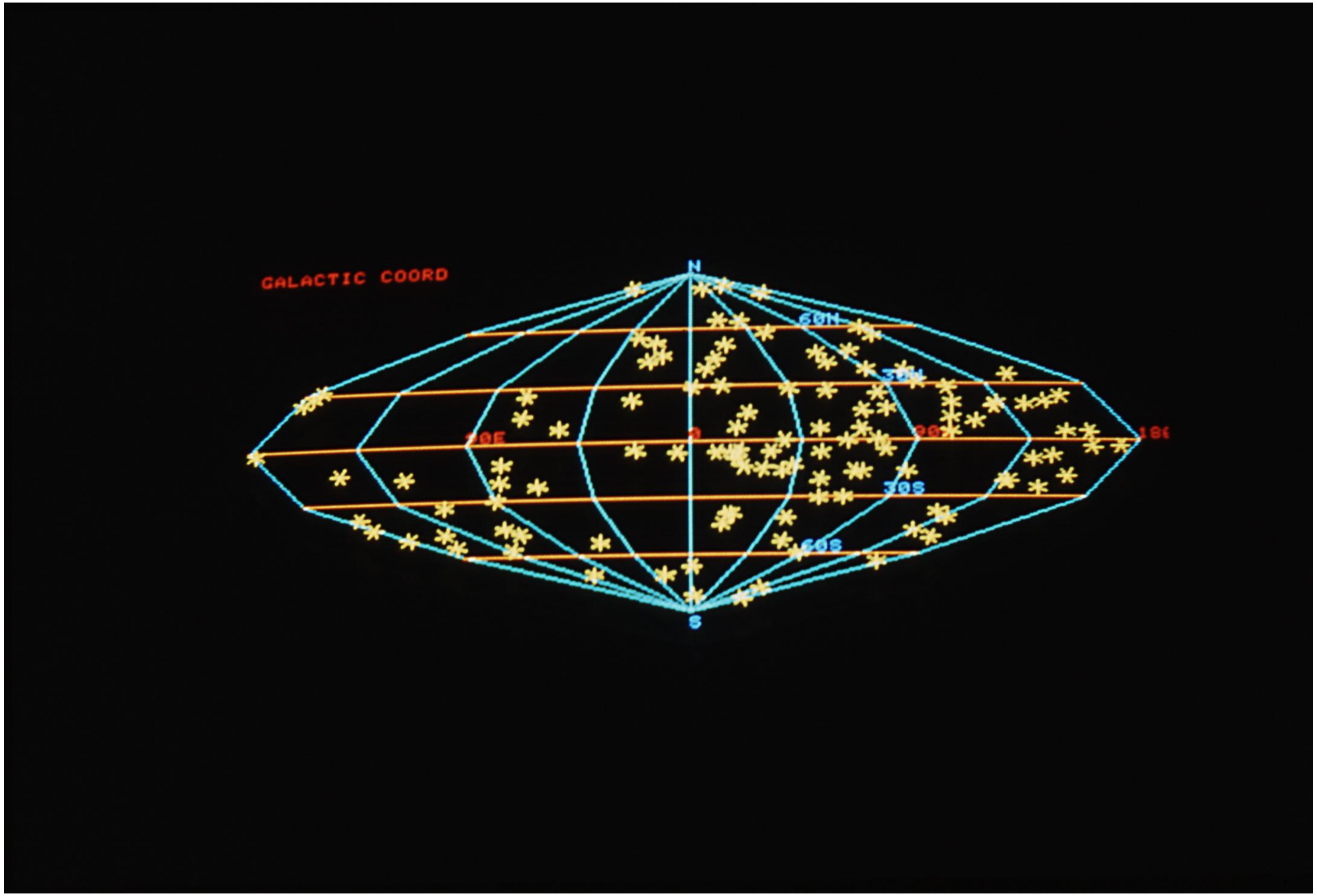


Muon from neutrino interaction under the detector

Tracking muons to their source



Upward muon source distribution



The true beginning of neutrino astronomy

1985 PRL paper *"Baskin-Robbins" paper*

VOLUME 54, NUMBER 1 PHYSICAL REVIEW LETTERS 7 JANUARY 1985

Experimental Limits on the Nucleon Lifetime for Two- and Three-Body Decay Modes

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

1	2	3	4	5	6	7	8	9	10
Mode	Requirements				Effic. with Nuclear Corr.	Effic. without Nuclear Corr.	Candi-dates Observed	No. of Bkgnd. Est. -50%, +100%	Limit on τ/B ($\times 10^{31}$yr) 90% C.L.
	E_C (Mev)	A	#μ	Back to Back					
$p \to e^+\gamma$	750-1100	< 0.3	0	0	0.66	0.66	0	0.1	18.
$p \to e^+\pi^\circ$	750-1100	< 0.3	0	0	0.46	0.75	0	0.1	12.
†$p \to e^+K^\circ$	300-500	< 0.5	1		0.12	0.12	i	2	
	750-1100	< 0.3	0		0.14	0.14	0	0.2	4.9
$p \to e^+\eta^\circ$	750-1100	< 0.3	0		0.37	0.54	0	0.2	
	400-650	< 0.5	1		0.07	0.15	0	2	12.
$p \to e^+\rho^\circ$	200-600	0.1-0.5	1		0.16	0.30	i	4	2.5
$p \to e^+\omega^\circ$	300-600	0.1-0.5	1		0.19	0.39	i	3	
	750-1100	< 0.3	0		0.05	0.06	0	0.2	4.0
$p \to \mu^+\gamma$	550-900	< 0.5	1	2	0.52	0.52	0	0.4	14.
$p \to \mu^+\pi^\circ$	550-900	< 0.4	1	1	0.32	0.44	b	0.2	5.1
†$p \to \mu^+K^\circ$	150-400	0.1-0.5	1,2		0.19	0.20	f,i	2	
	550-900	<0.5	1		0.14	0.14	a,b	2	2.9
$p \to \mu^+\eta^\circ$	550-900	< 0.5	1		0.23	0.44	a,b	2	
	200-400	< 0.5	1,2		0.12	0.22	f,i	2	3.1
$p \to \mu^+\rho^\circ$	150-400	0.1-0.5	1,2		0.10	0.16	f,i	2	1.2
$p \to \mu^+\omega^\circ$	200-450	0.1-0.5	1,2		0.18	0.32	f,i	2	
	650-900	< 0.5	1		0.03	0.05	a,b	0.8	2.1
$p \to \nu K^+$	150-375	0.3-0.6	1		0.08	0.08	3	4	0.7
$p \to \nu \rho^+$	300-600	0.2-0.5	1		0.07	0.19	1	3	1.1
$p \to \nu K^{*+}$	250-500	0.3-0.6	1		0.09	0.19	4	4	0.7
$p \to e^+e^+e^-$	750-1100	< 0.3	0		0.93	0.93	0	0.2	25.
$p \to u^+u^+u^-$	200-425	< 0.5	2,3		0.58	0.58	f	0.2	9.
$n \to e^+\pi^-$	450-950	< 0.5	0		0.40	0.55	c,e,g,h	4	2.5
$n \to e^-\pi^+$	400-700	< 0.5	1		0.10	0.24	0	2	
	700-950	< 0.5	0		0.10	0.07	c,e	2	2.5
$n \to e^+\rho^-$	400-800	< 0.4	0		0.20	0.42	c,d,e,g	2	1.2
$n \to e^-\rho^+$	400-800	< 0.4	0,1		0.22	0.57	a,c,d,e,g	3	1.2
$n \to \mu^+\pi^-$	200-700	< 0.5	1		0.30	0.43	i	4	3.8
$n \to \mu^-\pi^+$	200-500	< 0.5	1,2		0.29	0.45	f,i	3	2.7
$n \to \mu^+\rho^-$	300-550	< 0.5	1		0.07	0.29	i	2	0.9
$n \to \mu^-\rho^+$	300-550	< 0.5	1,2		0.10	0.41	f,i	2	0.9
$n \to \nu \gamma$	350-600	0.5 <	0		0.77	0.77	28	19	1.1
$n \to \nu \pi^\circ$	350-600	0.5 <	0		0.51	0.82	28	19	0.7
$n \to \nu K^\circ$	450-700	0.2-0.5	0		0.10	0.11	2	2	1.0
$n \to \nu \eta^\circ$	450-800	0.1-0.5	0		0.29	0.56	4	3	1.8
$n \to \nu \rho^\circ$	150-500	0.1-0.4	0,1		0.05	0.11	7	3	0.2
$n \to \nu \omega^\circ$	200-450	0.2-0.5	1		0.08	0.24	1	2	
	650-950	< 0.3	0		0.03	0.06	0	0.3	1.6
$n \to \nu K^{*\circ}$	200-700	.15-0.5	1		0.06	0.11	1	4	0.7
$n \to e^+e^-\nu$	500-850	< 0.5	0		0.41	0.41	4	3	2.6
$n \to \mu^+\mu^-\nu$	150-375	0.2-.65	1,2		0.31	0.31	4	7	1.9

Fairport Harbor August 2024

Morton Salt Mine APS Historic Site

Thank you John for your inspiration through the years!
Happy Birthday!

John and the IMB collaboration inspired me into cosmic rays and astrophysics

Pictures for Upgrade Proposal to D.O.E.

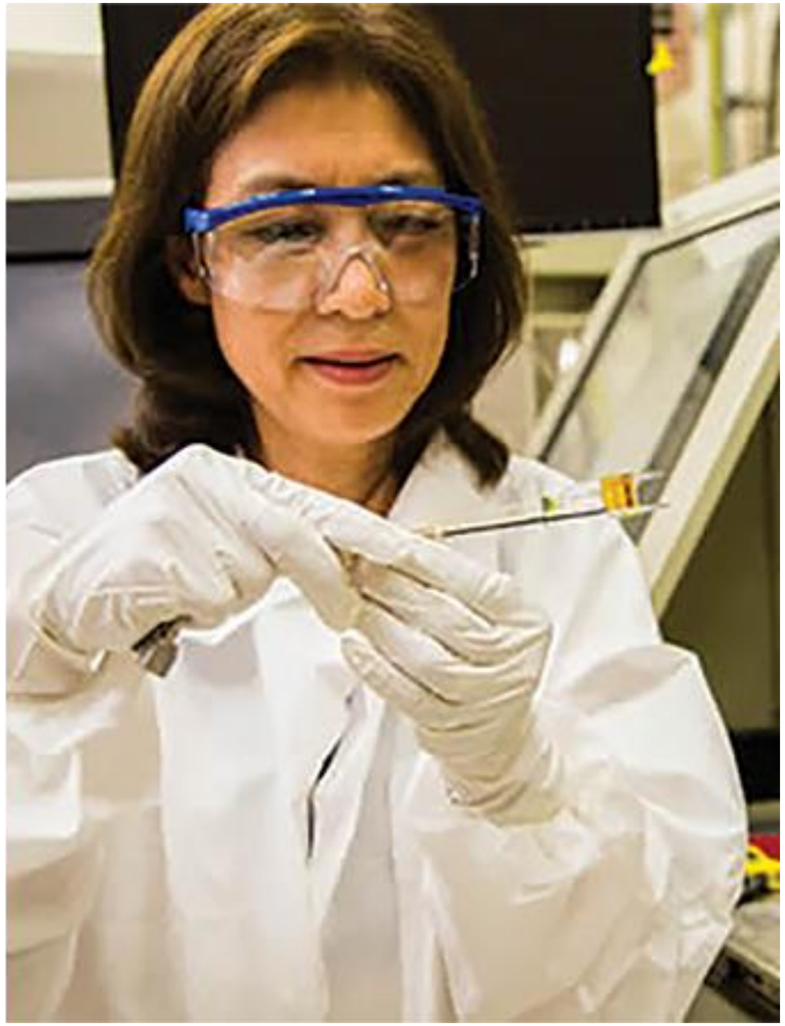
Tallest/biggest person in the group, Eric Shumard, holding 8” PMT

Shortest/smallest person in the group, Hye-Sook, holding 20” PMT

- As a first-generation graduate student, I built and tested the PMTs in the elevator shaft in Michigan
- Cleaned every single cm^2 of the inner liner with alcohol and acetone after the big leak
- Numerous over-nights looking for upgoing muons and neutrinos

~35 years later – still working on astrophysics problems

Hye-Sook, holding 20” PMT

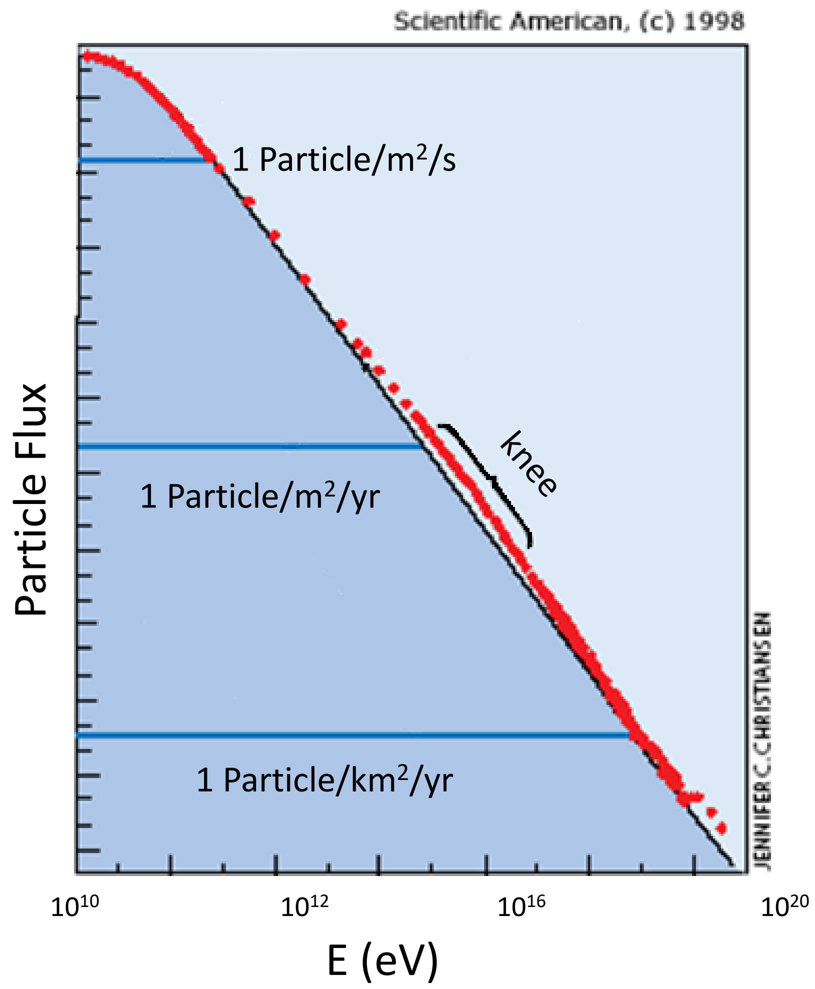


Hye-Sook, holding a NIF target

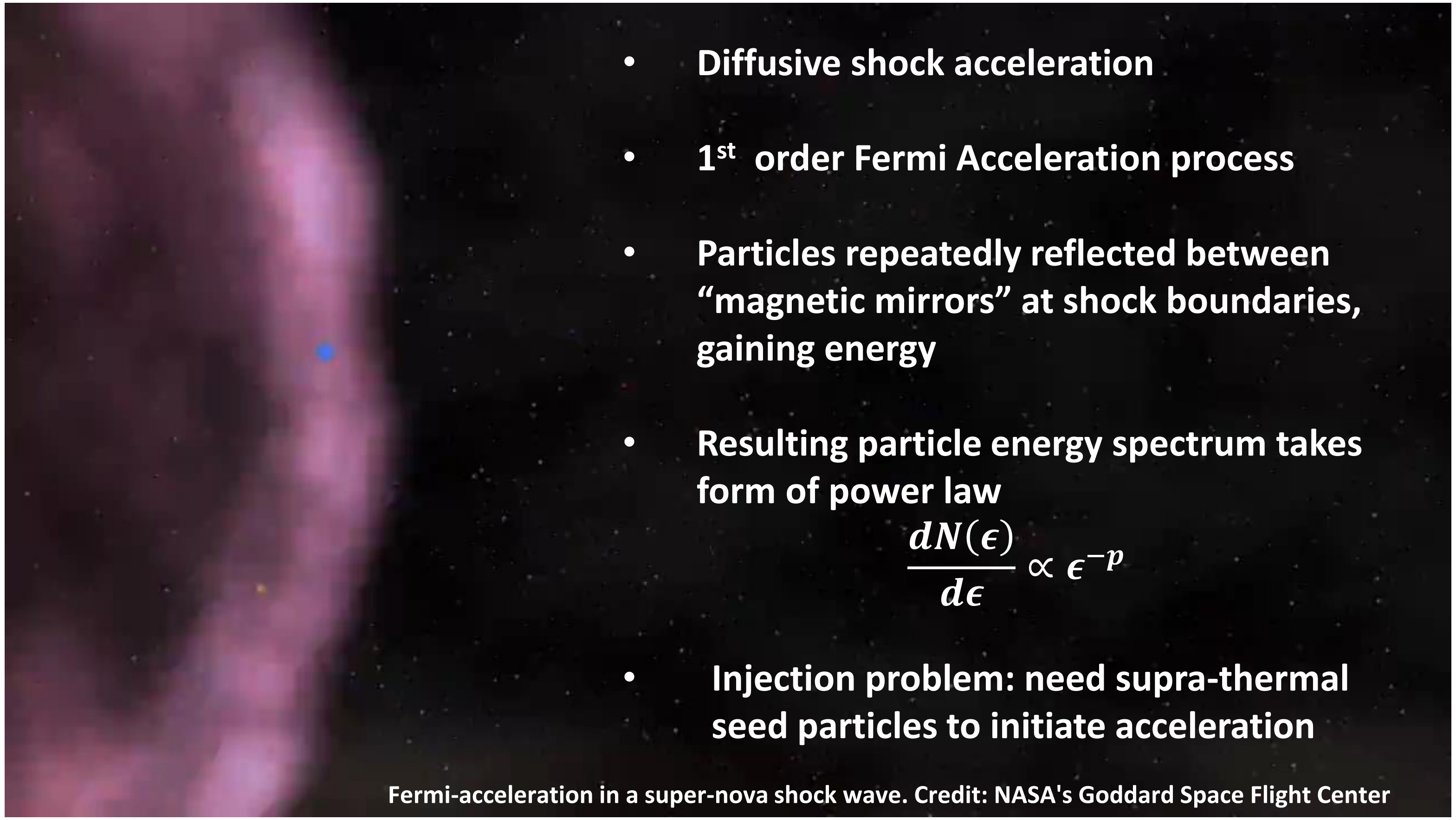
ScienceNews Nov 12, 2020
https://www.sciencenews.org/article/supernova-star-death-giant-lasers-explosive-mysterious-physics

Studying cosmic ray acceleration mechanisms in the laboratory: Super-nova remnants, collisionless shocks, particle acceleration

Acceleration mechanisms for high energy cosmic rays have been interests to astrophysical community over many decades



Fermi-acceleration in a super-nova shock wave is a favorite theory



- Diffusive shock acceleration
- 1^{st} order Fermi Acceleration process
- Particles repeatedly reflected between "magnetic mirrors" at shock boundaries, gaining energy
- Resulting particle energy spectrum takes form of power law

$$\frac{dN(\epsilon)}{d\epsilon} \propto \epsilon^{-p}$$

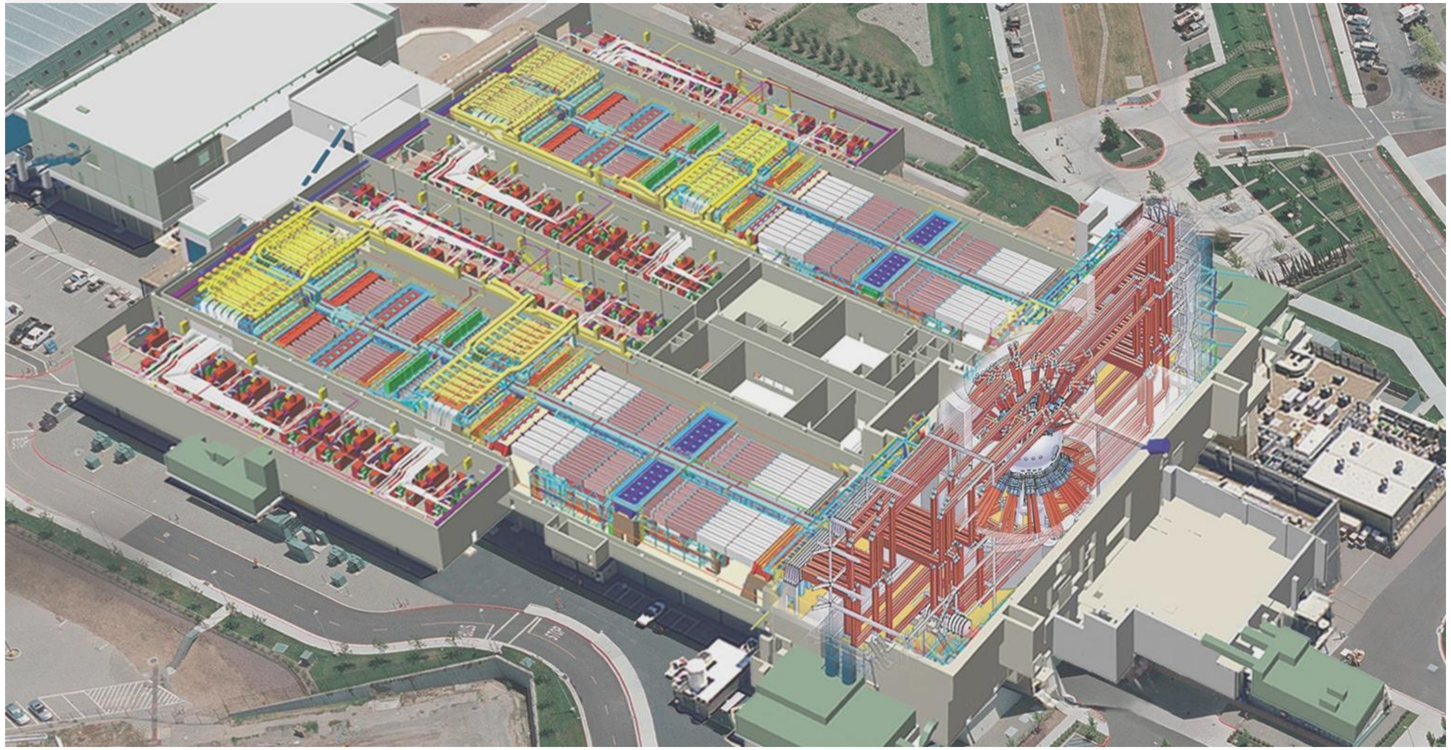
- Injection problem: need supra-thermal seed particles to initiate acceleration

Fermi-acceleration in a super-nova shock wave. Credit: NASA's Goddard Space Flight Center

R. D. Blandford, J. P. Ostriker, AP J, 221, L29 (1978)
A. R. Bell, MNRAS, 182, 147, 1978; A. R. Bell, PRA, 38, 1363 (1988)

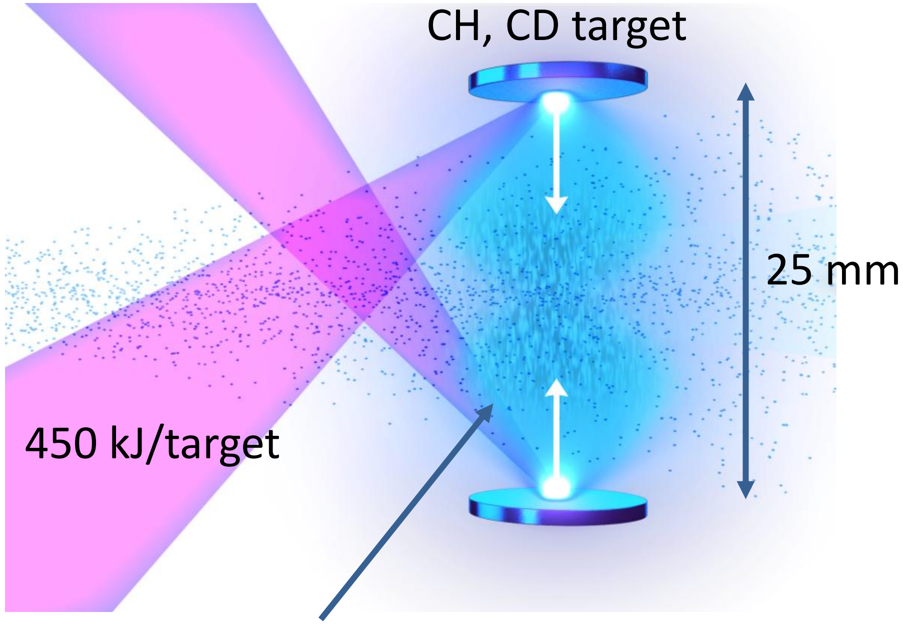
We study particle acceleration mechanisms by creating collisionless shocks of SN remnants using high-power lasers

National Ignition Facility



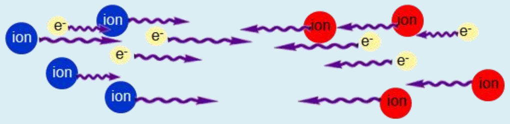
192 laser beams
2.2 MJ/440 TW
scale ~ 300 m
2 soccer fields

Located in Livermore, CA near San Francisco

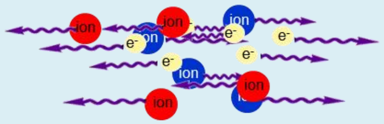


- Interpenetrating plasma flows: 1800 km/s (4M miles/hr)
- Diagnostics:
  - Optical Thomson Scattering
  - Particle spectrometer
  - X-ray imaging

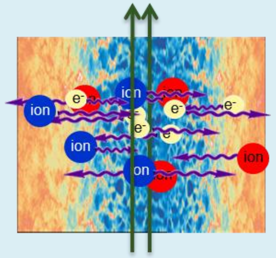
How are collisionless shocks formed?

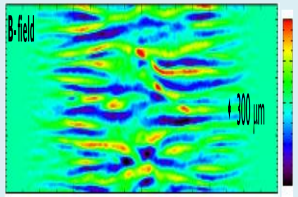


Coulomb mean free path is large



Clean penetration is expected



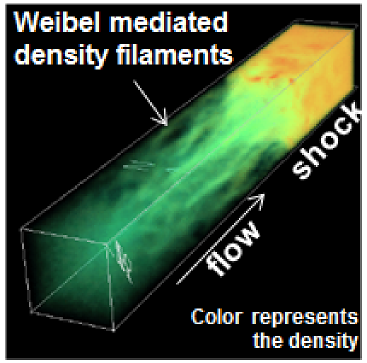


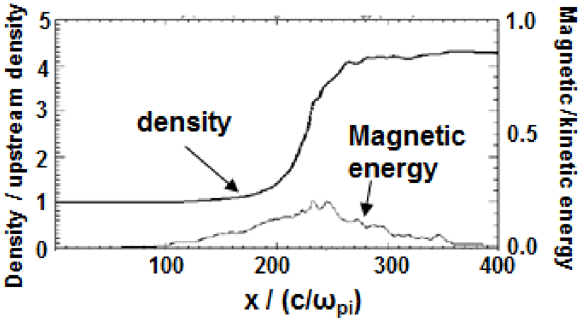
Plasma instabilities can cause shock formation

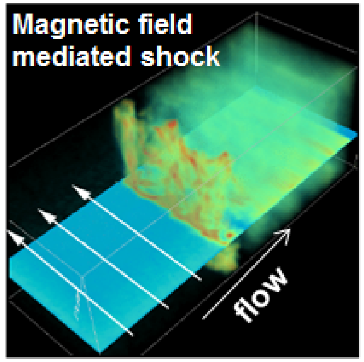
Two main mechanisms for creating collisionless shocks are considered:

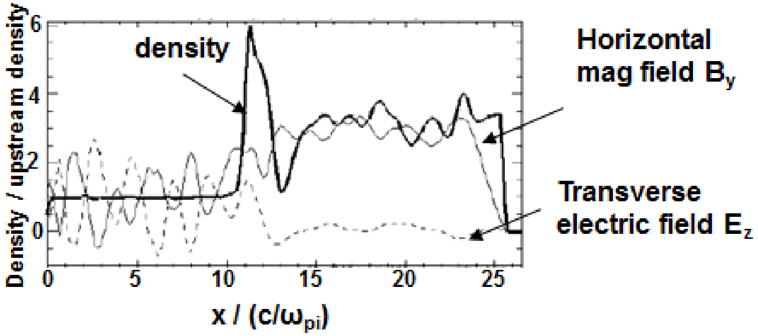
1) For low initial B field, particles are deflected by self-generated magnetic fields in filamentation / Weibel instabilities

2) For large initial B field, particles are deflected by compressed magnetic fields





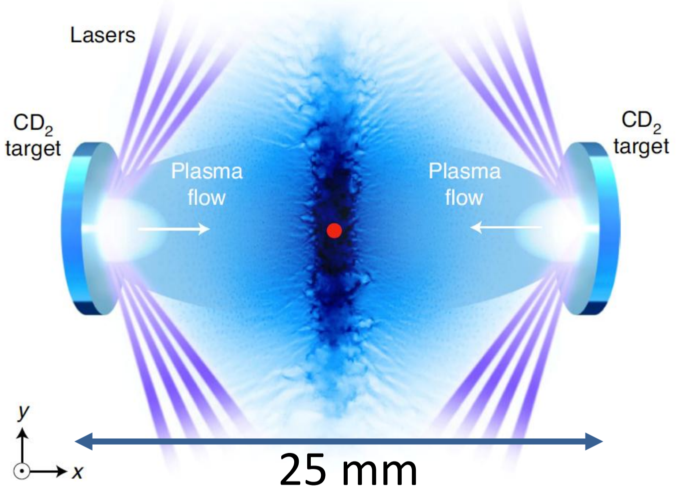


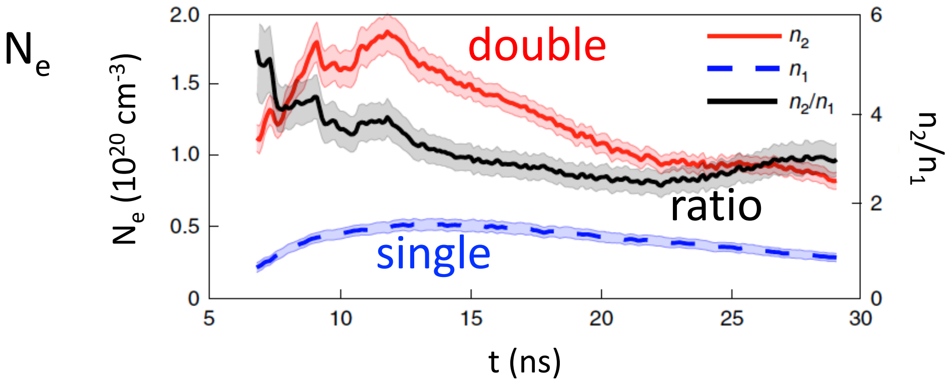


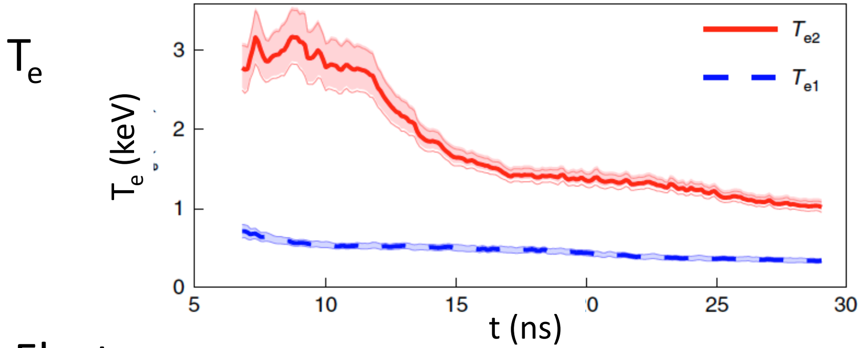
Spitkovsky, ApJ, 2009

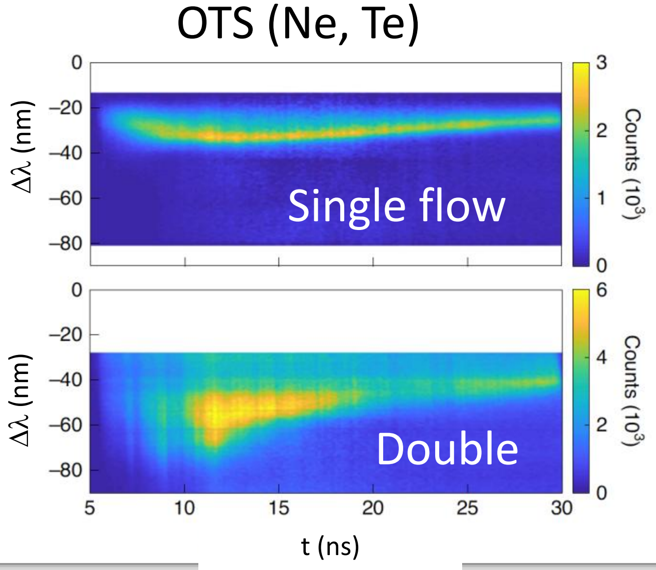
NIF experiments achieved fully formed collisionless shocks and non-thermal particle acceleration

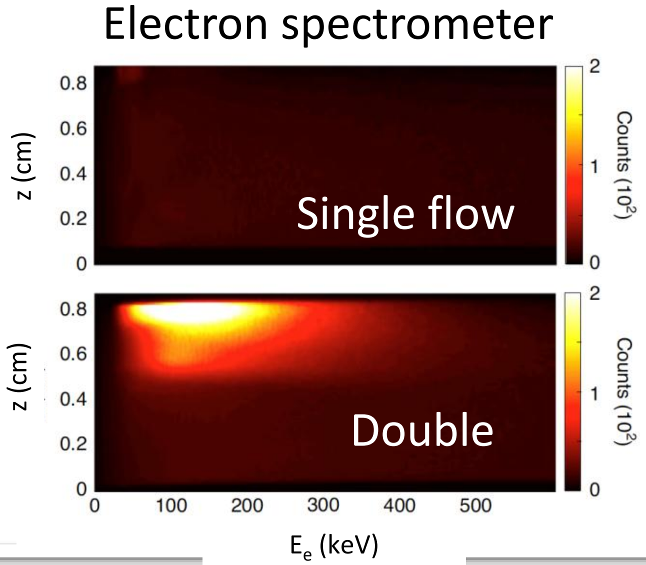
900 kJ
25 mm separation,
8 mm illumination area
increase N_e, L, v

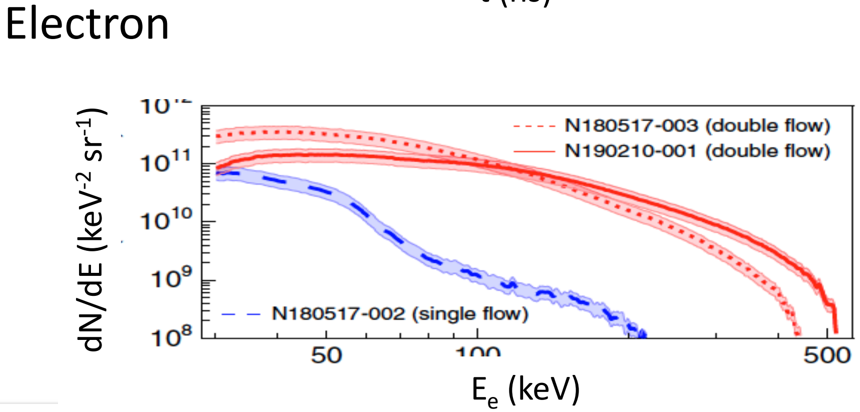












F. Fiuza et al., Nature Physics, 2020

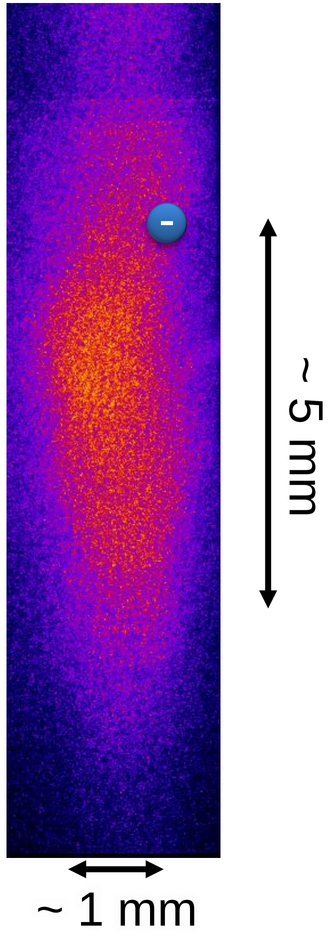
The observed electron energy spectrum is consistent with shock acceleration based on the measured experimental parameters

Observed maximum electron energy (500 keV) is consistent with estimates based on observed shock parameters

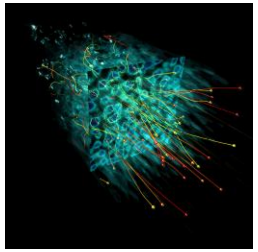
- We estimate $B \sim 100\ \mathrm{T}$, $E = 500\ keV$ gyro radius is $r_g \sim 30\ \mu\mathrm{m}$
- 30µm is much smaller than observed shock width.
- Electrons are therefore trapped and must escape via transverse diffusion
- **<u>Hillas limit</u>**: Maximum energy is work done by E-fields over the transverse width of shock $L_\perp \sim 5mm$, $v_{flow} \sim 1000\ \mathrm{kms}^{-1}$:

$$E_{max} = BL_\perp e \frac{v_{flow}}{c} \sim 500\ \mathrm{keV}$$

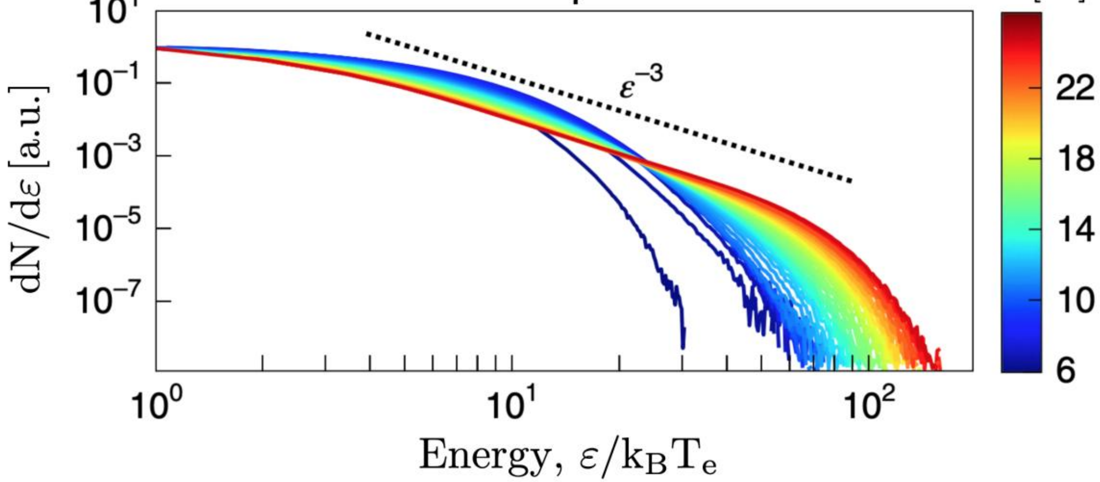
Trapped electron escapes via transverse diffusion



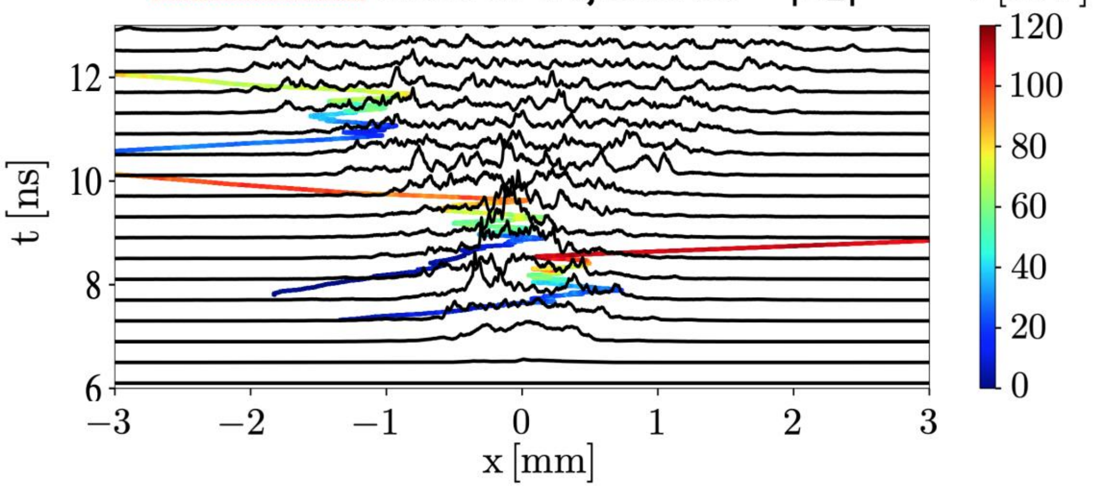
Kinetic simulations reveal electron acceleration due to small scale turbulence in shock transition



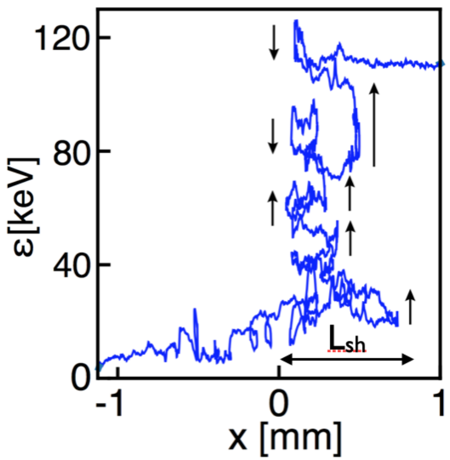
Electron spectrum



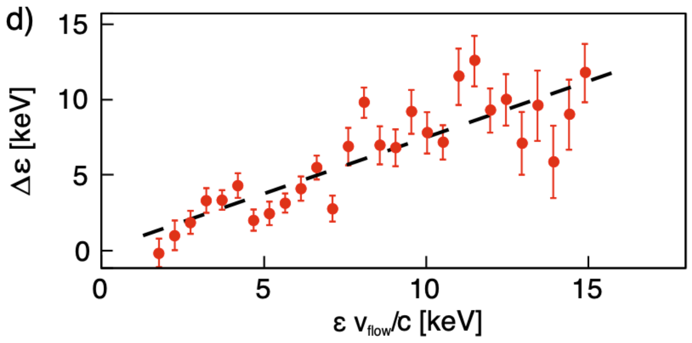
Nonthermal electron trajectories + $|B_\perp|^2$



Electron trajectory



Ist order Fermi mechanism

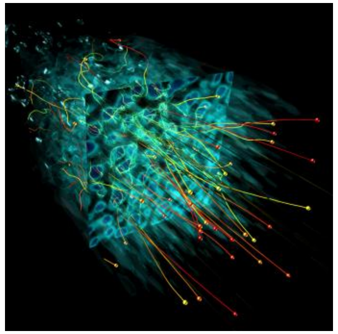


Electrons are accelerated on ns time scale

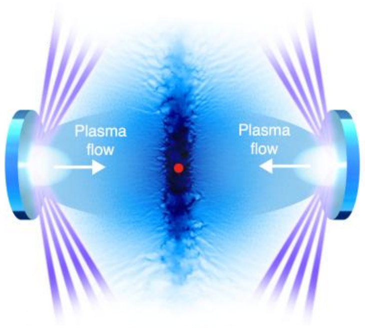
$$t_{acc} \sim \frac{D(\varepsilon)}{v_{flow}^2} \sim \mathrm{ns} \qquad D(\varepsilon) \sim \frac{2\varepsilon c}{3eB}$$

Injected spectral index expected to be steeper than DSA, p ≥ 2, given than velocity jump experienced is smaller $v_u/v_d \leq 4$

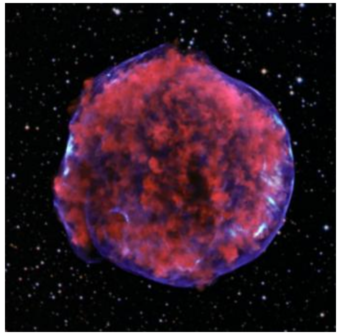
Opening new windows into the inner workings of cosmic accelerators



Space and astrophysical observations indicate that electrons can be significantly heated and accelerated in collisionless shocks but microphysics is still not well understood



Laboratory experiments at NIF observed nonthermal electron acceleration consistent with modified diffusive shock acceleration due to microturbulence within shock transition



Ongoing studies being extended to study electron-ion temperature ratio and electron acceleration in magnetised shocks

Combination of laboratory experiments and kinetic simulations is opening unique windows to probe relevant shock microphysics and test models

Thank you John for your inspiration through the years!

Happy Birthday!

Lawrence Livermore
National Laboratory