An Underground Lab in India

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Horizons in Particle Accelerators & Laboratory-based Quantum Sensors – ICTS (17th Nov 2022)

Plan of talk

1. Some background to underground research in India

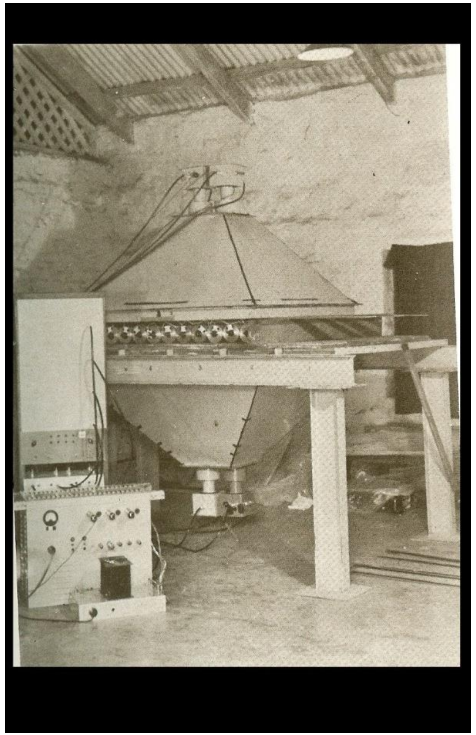
2. Need for an underground lab - possible experiments

3. Outlook

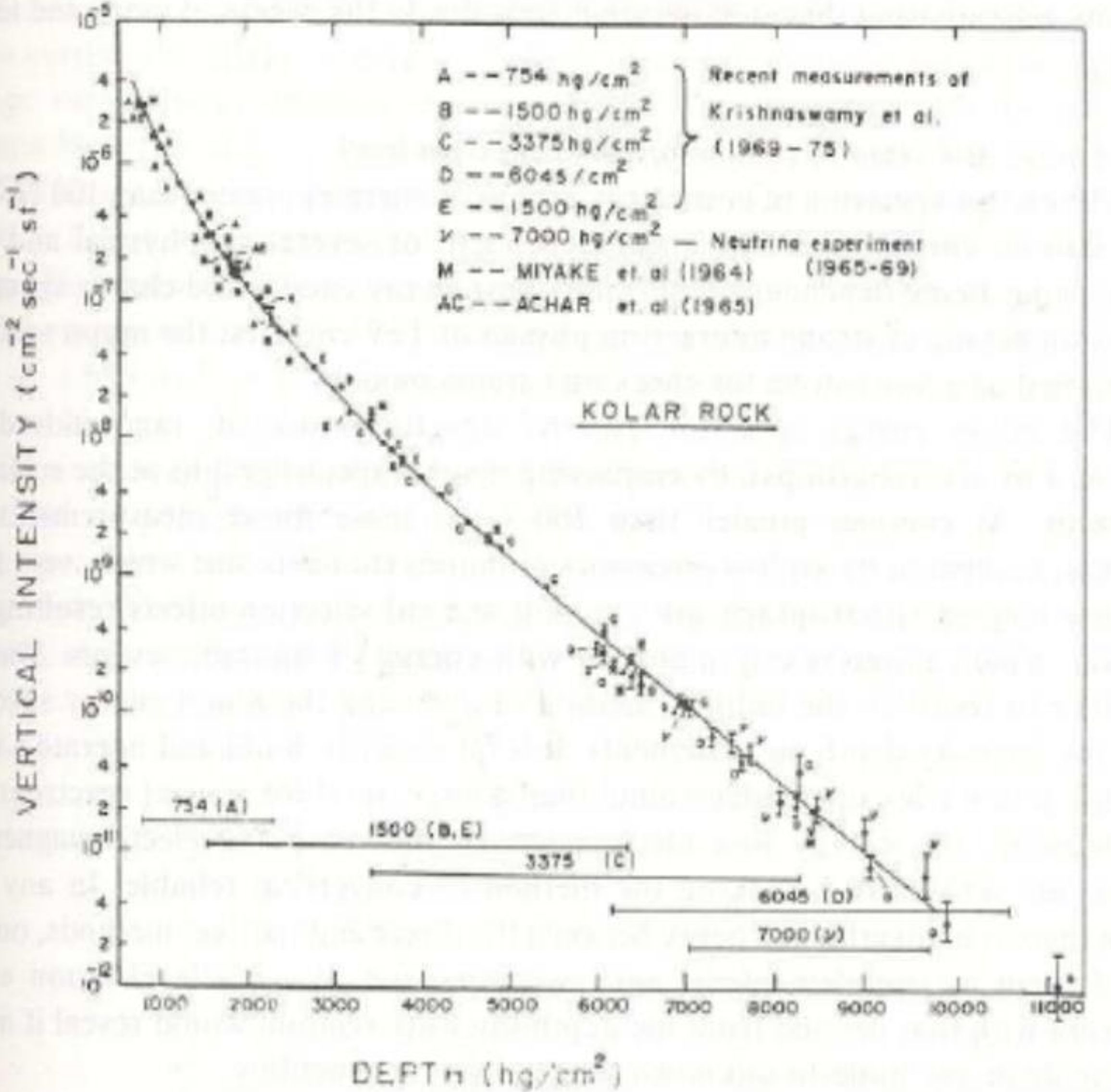
1. Some background to underground research in India (Sreekantan, Resonance 2005)

- Homi Bhabha founded TIFR at B'lore in 1945 which soon moved to Bombay. ~1951 he got a group led by Prof. Sreekantan to begin a series of experiments measuring cosmic ray muons at various depths in Kolar Gold Fields.

Estimating the rock density as a function of depth, the muon flux vs depth can be used to estimate the cosmic muon energy spectrum.

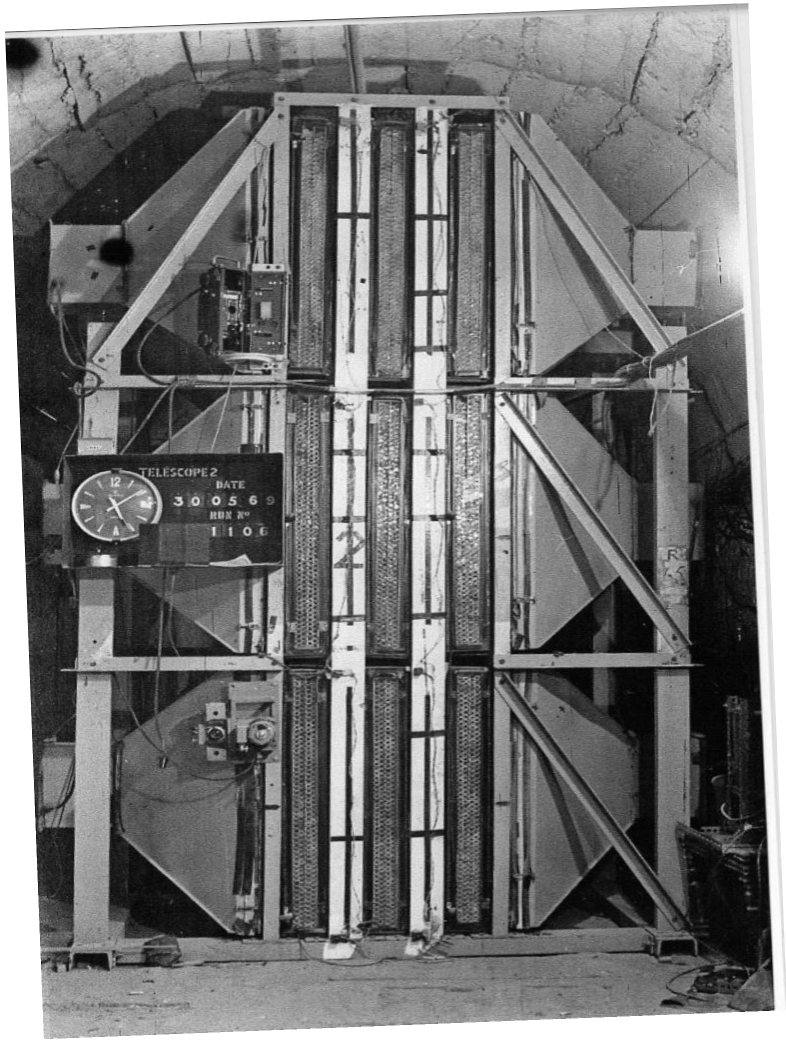


Most comprehensive depth-muon intensity curve



THE CONSOLIDATED DEPTH-INTENSITY RELATION FROM ALL WORKS DONE UNDER KOLAR ROCK

Atmospheric neutrino detection in 1965



Atmospheric neutrino detector at Kolar Gold Fields –1965

DETECTION OF MUONS PRODUCED BY COSMIC RAY NEUTRINO DEEP UNDERGROUND

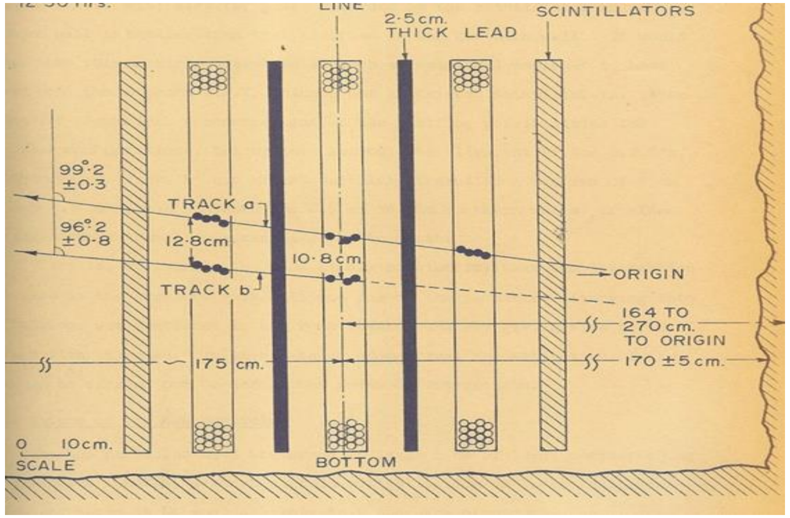
C. V. ACHAR, M. G. K. MENON, V. S. NARASIMHAM, P. V. RAMANA MURTHY and B. V. SREEKANTAN,
Tata Institute of Fundamental Research, Colaba, Bombay

K. HINOTANI and S. MIYAKE,
Osaka City University, Osaka, Japan

D. R. CREED, J. L. OSBORNE, J. B. M. PATTISON and A. W. WOLFENDALE
University of Durham, Durham, U.K.

Received 12 July 1965

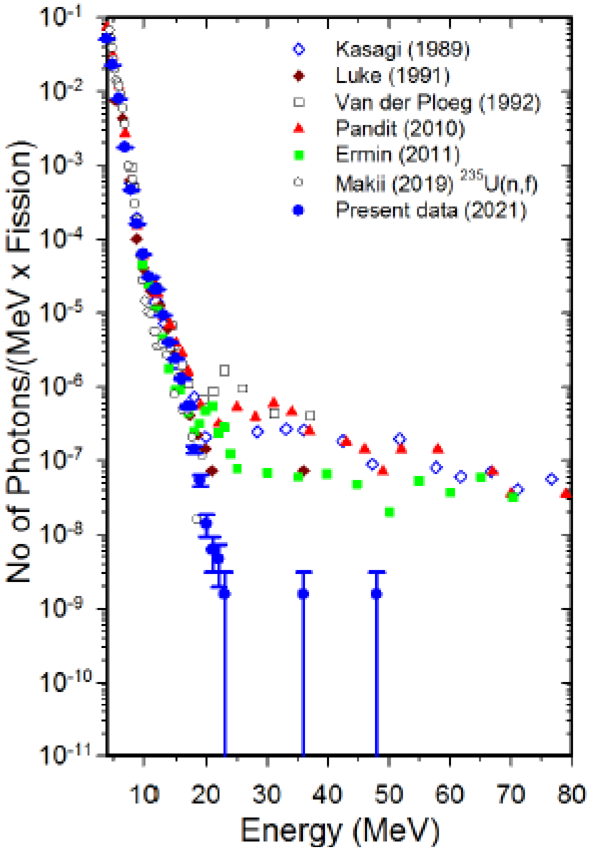
Physics Letters **18**, (1965) 196, dated 15th Aug 1965



Coming to more recent times…

- A small UL at Jadugoda mine in Jharkhand (depth 550m) working since 09/2017.
- Muon flux, fast and slow neutron and γ -ray backgrounds measured
- Upper bound on the γ-ray yield (25-80 MeV) in ^{252}Cf (s.f.) contradicted earlier result by the same group in an overground experiment

  Deepak Pandit *et al.*, Phys. Lett. B **823**, 136760 (2021)



2. Need for an underground lab - possible experiments & programmes

- Many experiments involving neutrinos, rare decays, ultra low cross sections are ultimately limited by cosmic ray background.
- While some experiments can be done at depths of a few 100m, others require the largest possible depts/rock overburden $\sim$2km or larger.
- Seismic measurements may also require deep sites to reduce noise.

Experiments proposed (EOI meeting @TIFR: 6-7Aug 2022)

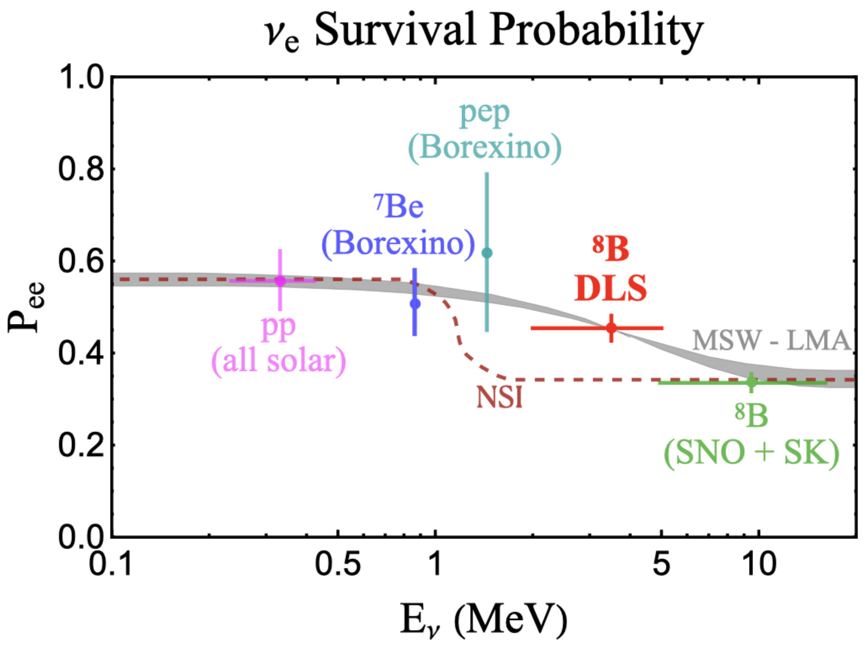
- Experiments involving neutrinos:
  - Atmospheric (μ) neutrinos with 51 kton ICAL detector (Indumathi talk)
  - Solar & Supernovae neutrinos with a 1 kton Deuterated Liquid Scintillator
  - $0\nu 2\beta$ decay in ^{124}Sn (Vandana talk)
- Dark matter search (cryogenic CsI, Si; superheated liquid)
- Nuclear astrophysics (LE accelerator, gas jet target, recoil mass separator)
- Rare nuclear decays ; low background lab
- Geophysics (seismic, gravimetric, geomagnetic, radiogenic)

A versatile low energy neutrino detector – deuterated liquid scintillator

- 1 kton D_2O @ SNO measured solar νs via Cerenkov light and solved the solar neutrino problem ($E_{thr} \sim 5$ MeV)
- Deuterated Liquid Scintillator would have a much lower E_{thr} possibly ~ 100s keV
- Can measure both neutrinos and anti-neutrinos : e-type via CC, all types e,μ,τ (via NC)

Interaction	CC/NC	- Q (MeV)
$\bar{\nu}_e + d \rightarrow e^- + p + p$	CC	1.44
$\nu_e + d \rightarrow e^+ + n + n$	CC	4.03
$\bar{\nu}_x + d \rightarrow \bar{\nu}_x + p + n$	NC	2.22
$\nu_x + d \rightarrow \nu_x + p + n$	NC	2.22
$\nu_e + e^- \rightarrow e^- + \nu_e$	CC + NC	0.0
$\bar{\nu}_{\mu\tau} + e^- \rightarrow \bar{\nu}_{\mu\tau} + e^-$	NC	0.0
$\nu_{\mu\tau} + e^- \rightarrow \nu_{\mu\tau} + e^-$	NC	0.0

What science can a 1 kton DLS detector do?



Solar νs

- ν_e survival probability in 2 MeV ≤ E ≤ 5 MeV
- MSW vs NSI (beyond SM)
- Day-Night effect (5-10%, SK & SNO : 1σ -2σ)

- **Supernova νs** & anti- νs of all flavours
- Will signal appearance of SN before EM signal (SN Watch, multi-messenger astronomy)
- ν mass ordering, ν- ν interaction signatures

J. Cosmol. & Astropart. Phys. **11**, 005 (2021), *A DLS for SN neutrino detection*, Chauhan, Dasgupta, Datar

India is best placed to build DLS

- India is the largest producer of D_2O in the world
- Heavy Water Board has capability of manufacturing 1 kton DLS once R&D carried out by research groups at BARC

Immediate goals: develop HW-soluble LS (say 95% D_2O + 5% H-LAB) since a fully deuterated LS (LAB/xylene/toluene based) appears challenging. A group has been formed to develop DLS and a 2^{nd} group is developing a science case.

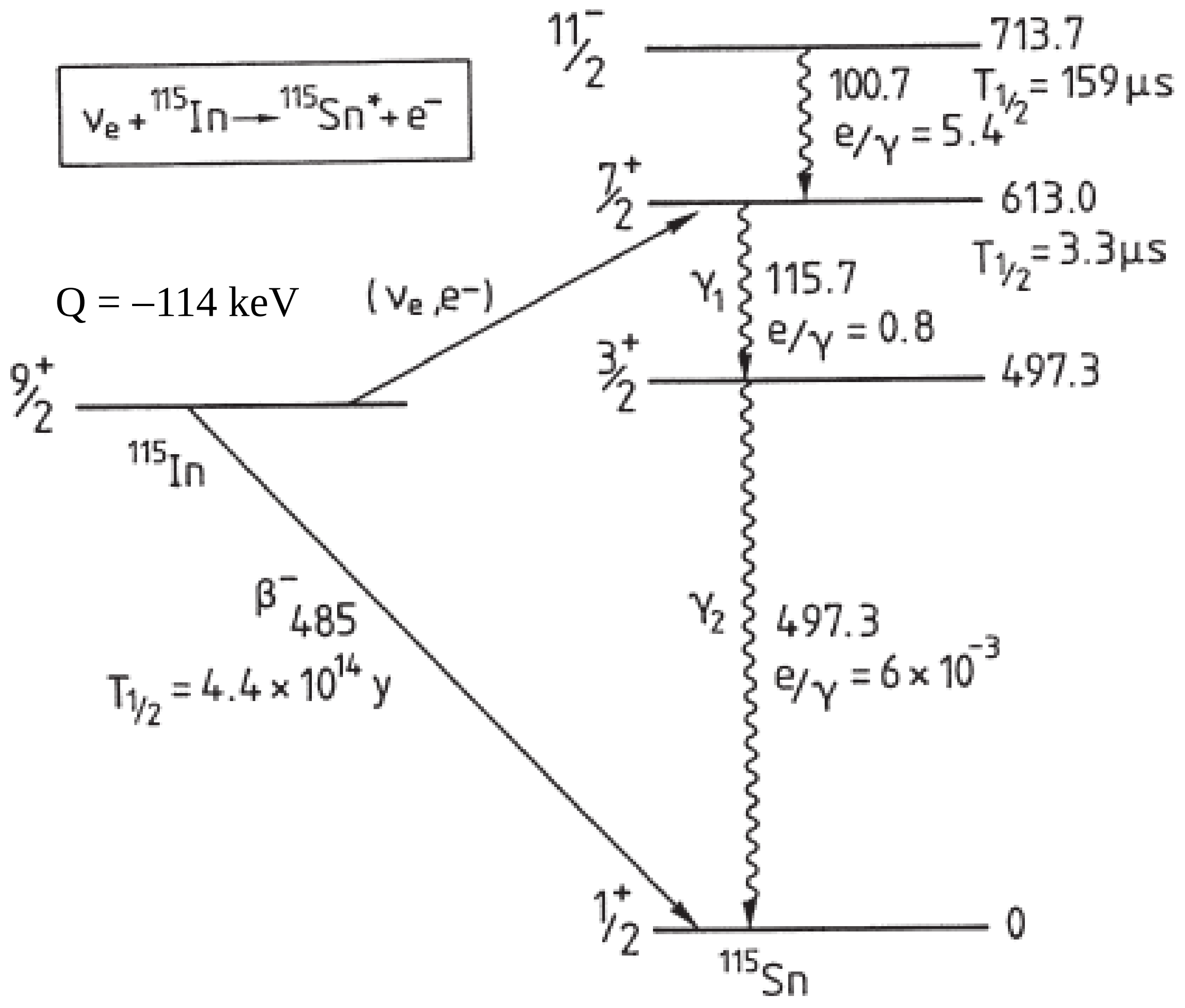
An Indium detector for solar neutrinos?

- Raghavan proposed a real-time Indium detector for solar neutrinos [PRL **37**, 259 (1976)]. After many years proposed LENS – a segmented 8% In-loaded 125 ton LS detector – "photon lattice" with LS divided into 3" sized cubical units.
- Segmentation needed to reduce huge random coincident background

from natural β decay of ^{115}In (95% abundance) – 3" resol. in X, Y, Z.

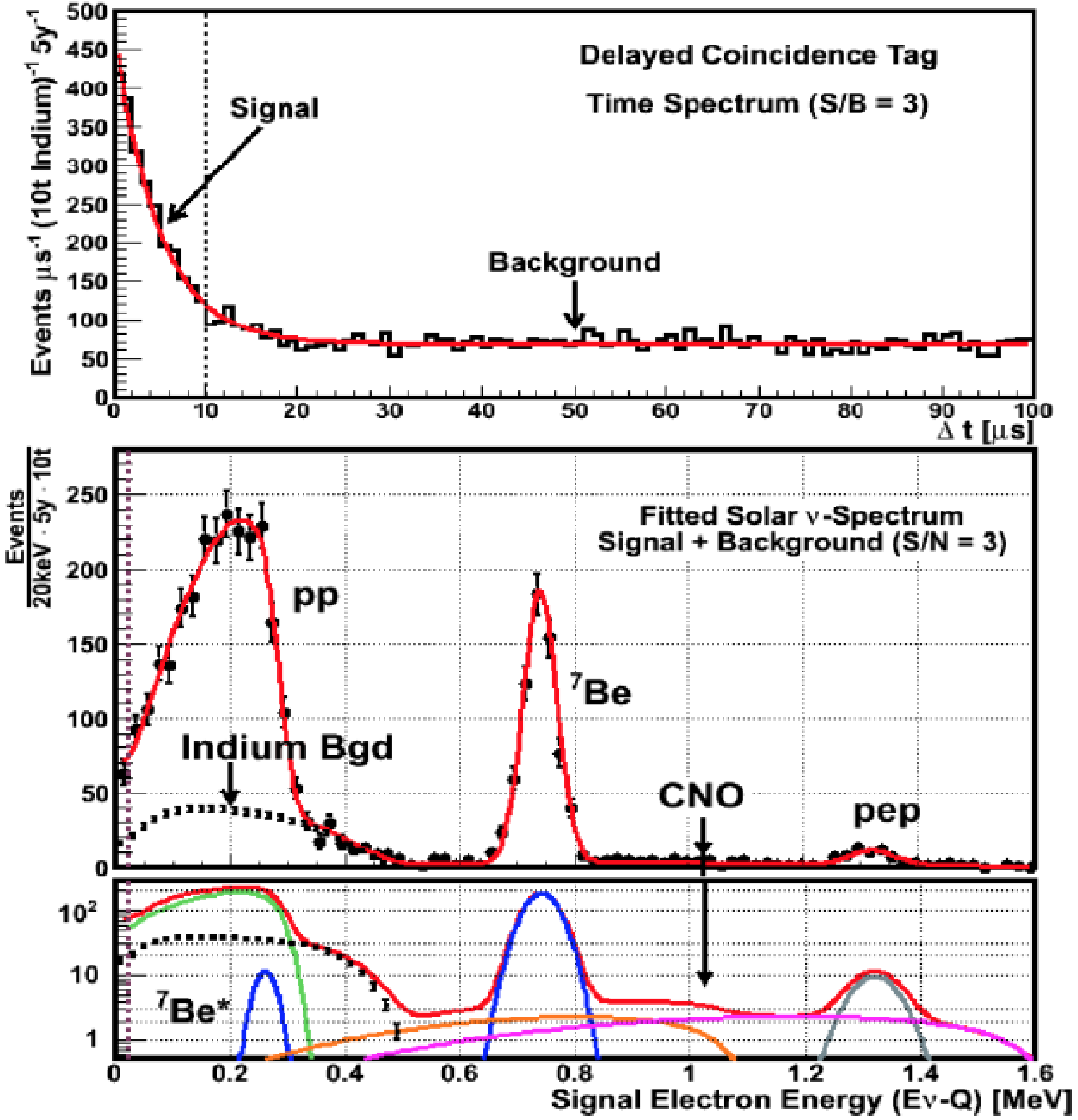
- Booth (1987) explored possibility of measuring q-p in superconducting In
- A cryogenic bolometer of In metal (or a suitable compound)?
- Could provide an independent measure of the temperature of sun's core using the shift and broadening of the ^{7}Be and pp spectrum.

Levels excited in low energy ν_e CC interaction with ^{115}In

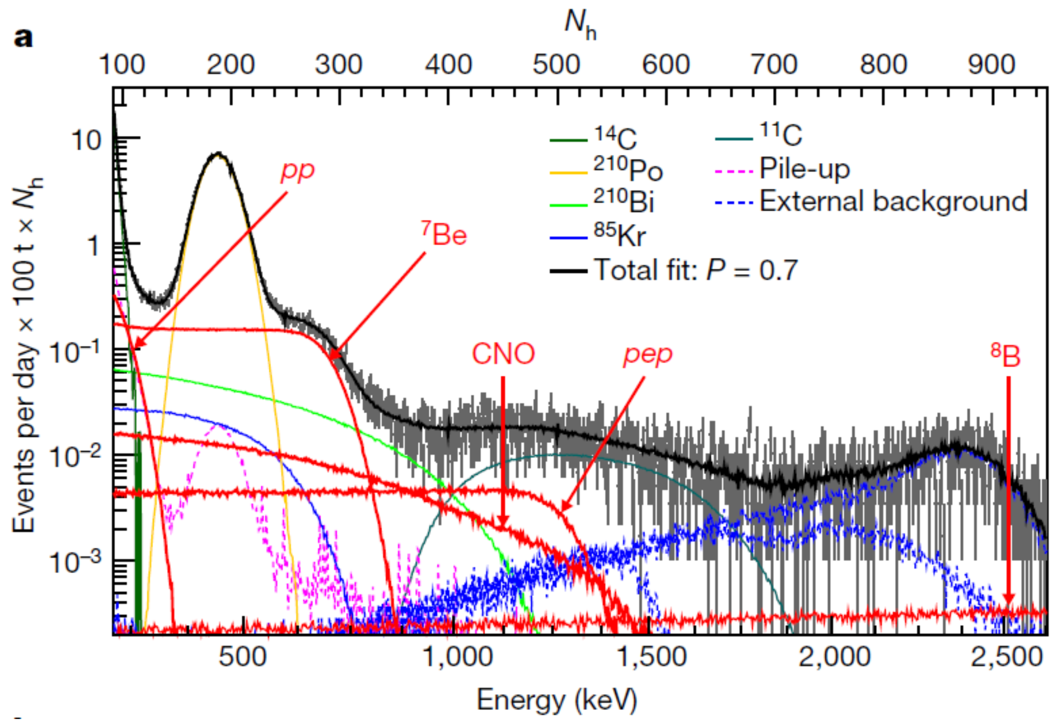


Signal:

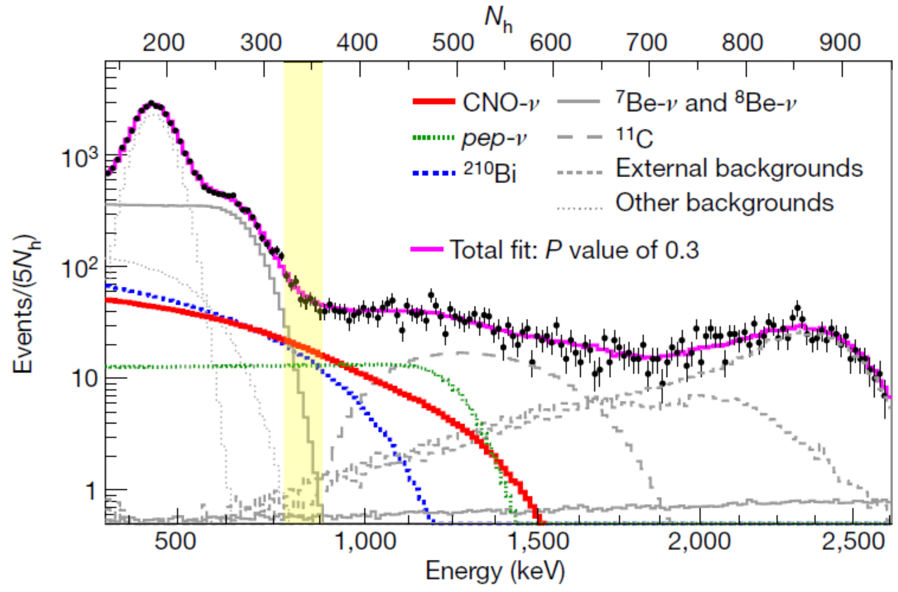
IBD e^- - delayed γ_{116} - prompt γ_{497}



Ref. Raghavan's Physics Colloquium at BARC (26 Oct 2010)

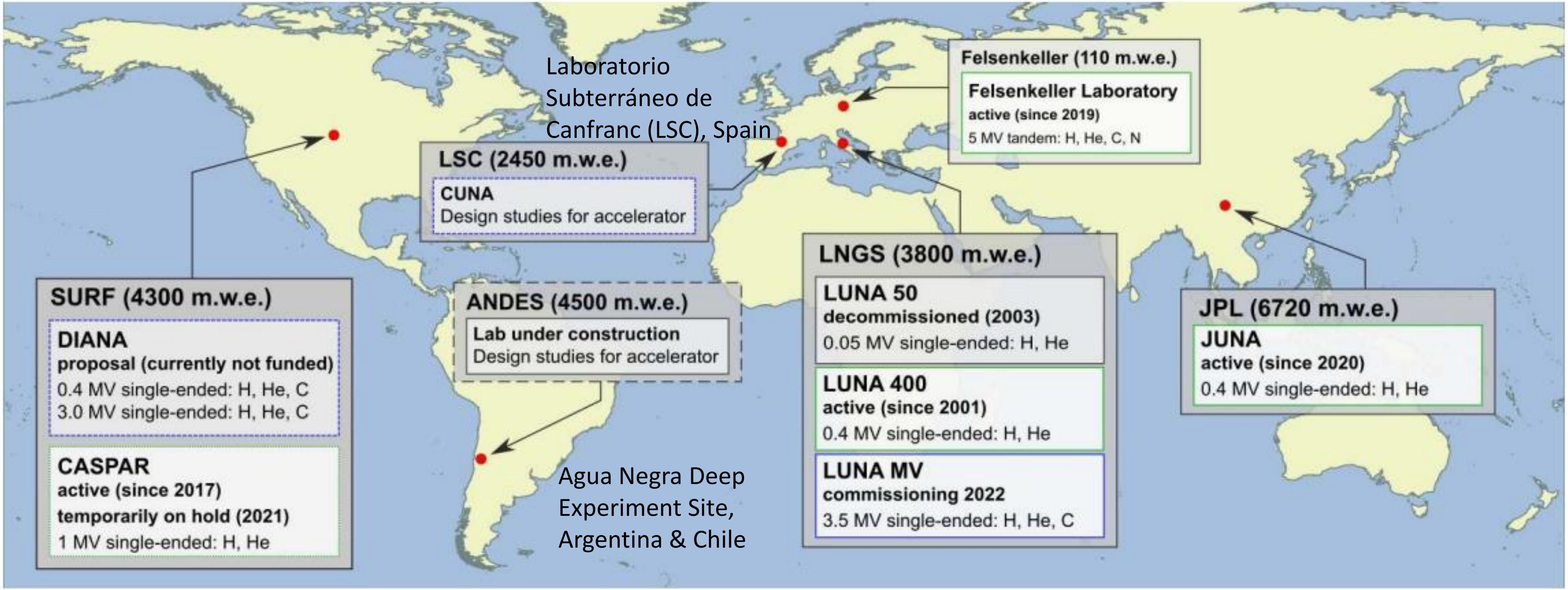


pp, *⁷Be* neutrinos measured: Nature **512**, 383 (2014)



CNO νs ~1% Φ_ν (tot): Nature **587,** 577 (2020)

Nuclear Astrophysics - Underground accelerator facilities



SURF:Sanford underground Research Facility, South Dakota

CASPAR:Compact Accelerator System for Performing Astrophysical Research

6 Major facilities:

5 of them are very recent (within last 5 years)

from **S.Santra**

Reactions of interest - 1

Reactions	Physics	Gamow peak (keV)	X-section (barn)	Labs interested	Existing error	Reference
$^{14}N(p,\gamma)^{15}O$	CNO	148	10^{-13}	LUNA, CASPER		
$^{12}C+^{12,13}C$	C burning	820	10^{-13} (2.4 MeV)	LUNA		
$^{13}C(\alpha,n)^{16}O$	Heavy Ion synthesis, AGB	300	10^{-16}	LUNA, JUNA, CUNA, CASPER	60%	ApJ **414**, 735 (1993)
$^{22}Ne(\alpha,n)^{25}Mg$	Heavy Ion synthesis, AGB			LUNA, CUNA, CASPER		
$^{22}Ne(p,\gamma)^{23}Na$	Synthesis in AGB stars	190	2.4×10^{-3} (290 keV)	LUNA	Up to 3 orders	

from **S.Santra**

Reactions of interest - 2

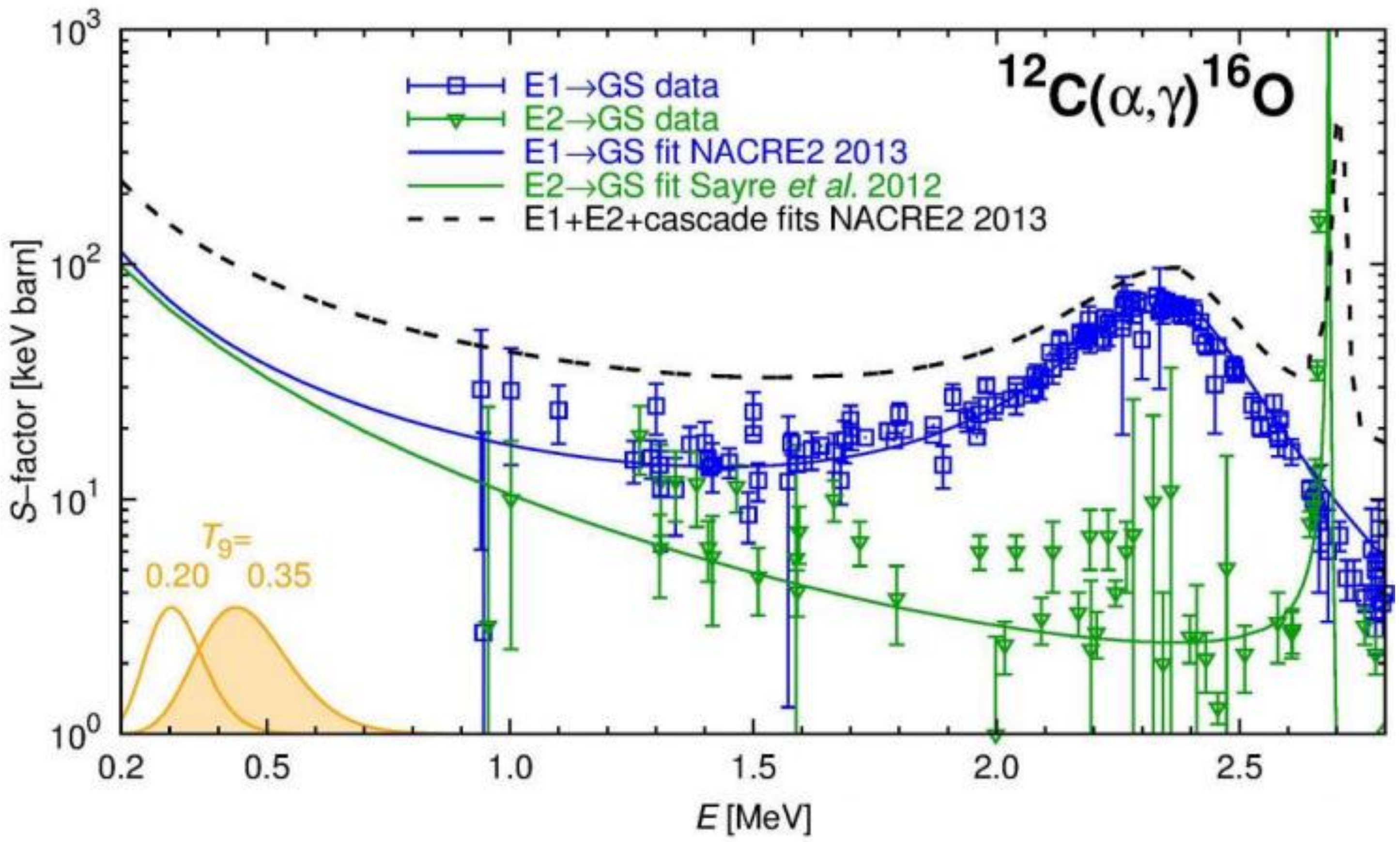
Reactions	Physics	Gamow peak (keV)	X-section (barn)	Labs interested	Existing error	Reference
$^{12}C(\alpha,\gamma)^{16}O$	**Massive star**	300	10^{-17}	**LUNA, JUNA**	60%	NPA, **758** (2005) 363
$^{18}O(p, \alpha)^{15}N$	**CNO**	160	$3x10^{-5}$ (240 keV)	**LUNA**		
$^{19}F(p, \alpha)^{16}O$	**F abundance**	100	$7x10^{-9}$	**JUNA**	**80%**	PLB, **748** (2015) 178
$^{25}Mg(p, \gamma)^{26}Al$	**Galaxy ^{26}Al**	58 (res)	$2x10^{-13}$	**JUNA**	**20%**	PLB **707** (2012) 60

Gamow energies ~ a few keV to 100's of keV

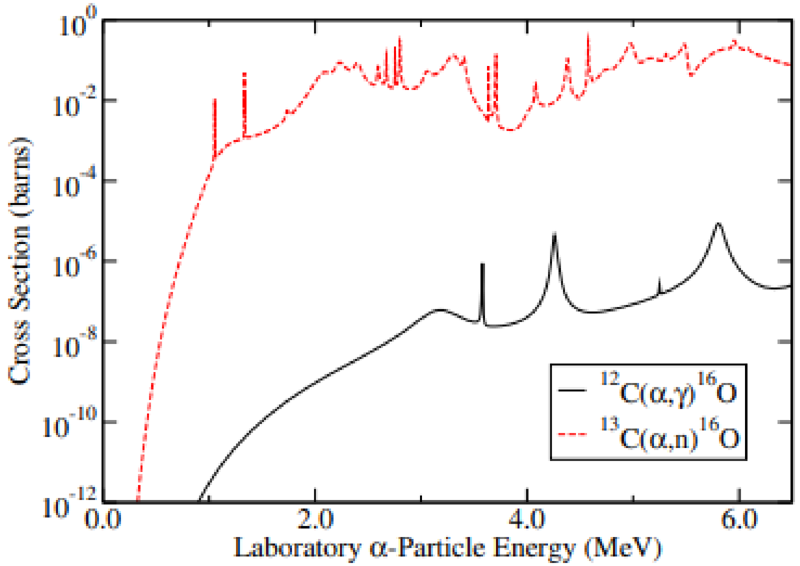
Cross sections ~ as low as 10^{-17} barn → not possible to measure over ground due cosmic background

from **S.Santra**

$^{12}C(\alpha,\gamma)^{16}O$, holy grail in Nuclear Astrophysics



- **Highly sought-after reaction data related to carbon/oxygen ratio in the Universe.**
- JUNA approach: high-intensity alpha beam on carbon target



Felsenkeller: Carbon beam on helium gas target, inverse kinematics ($^{13}C(\alpha,n)^{16}O$ x-section is 10^5 times more, target contamination a problem)

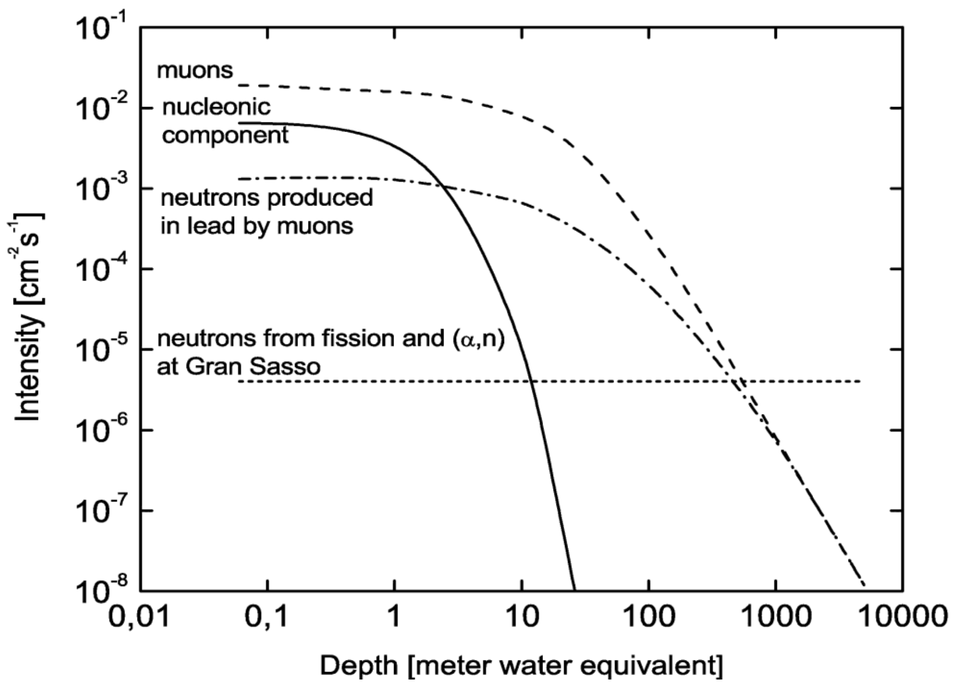
Recoil mass separator at underground lab: first time

- **LUNA Data** precision limited by backgrounds: natural, beam induced and target

→RMS can provide a solution: NOT used underground so far

Inverse kinematics → interchange target, projectile

→ improves accuracy: reduces systematic errors



CUPAC-NE-BARC Concepts: AJT+RMS

- **AJT:** Reduce systematic errors (use ^{3}He,^{3}H gas target with recirculation target)
- **RMS:** **Eliminate** beam and natural background and target impurity
- **Novel RMS design: very compact** PIMS + HIRA ED1 slot+ RIB optics for IKR

Radon in closed spaces

$^{222,\ 220}$Rn In air is produced by decay of ^{226,224}Ra present rocks/walls in buildings (^{238}U and ^{232}Th parentage).

Typical ^{222}Rn concentration

Open air: 10–20 Bq/m^3

Underground cavities: upto 1 kBq/m^3

U-mines: ~ upto 1 MBq/m^3

- Equilibrium Rn concentration depends on the emanation rate and ventilation.
- Rn can be reduced by orders of magnitude in limited regions by fluxing pure N_2 or "Rn free" air produced by dedicated structures

Studies that can be taken up by BARC in UL

- Baseline study of Radon and its progeny in underground laboratories - essential for designing the ventilation systems.
- Setting up of a clean radon free laboratory for specific nuclear physics experiments
- Radon emanation and exhalation monitoring at various depths and its effect due to seismic stress buildup in the bed rock

High sensitivity measurement of relative gravity (‘g’) anomaly inside the Indian Himalayan Neutrino Observatory

(S.Rajesh et al, Wadia Institute of Himalayan Geology)

Rationale

- Subsurface gravity (Δg) changes are sensitive to the periodic and aperiodic changes of masses due to tidal forces and earthquake processes, respectively.

- Himalayan region quite prone to earthquakes of different magnitude. Long term vertical ground acceleration data measured by a sensitive Gravity meter inside a cave under low noise conditions could even record density changes due to pressurised/de-pressurised subsurface fluid flow linked with fault movements or creep processes and is a potential earthquake precursor tool.

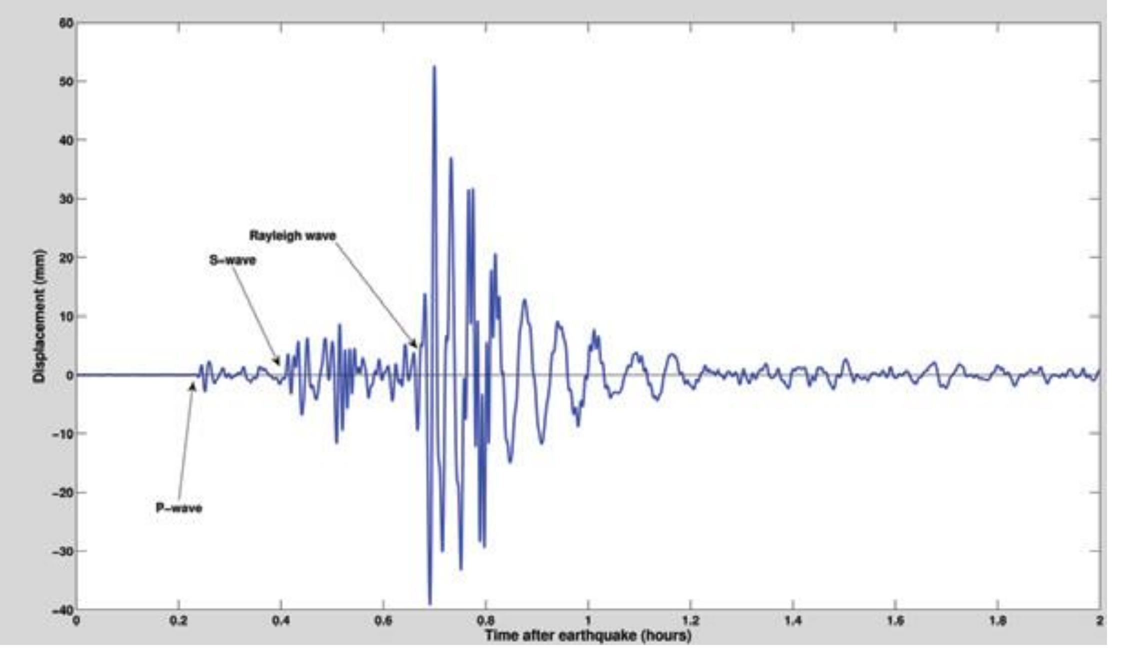
Objectives

- To study the behavior of subsurface temporal gravity change (Δg) in the observatory associated with different Magnitude earthquakes and the development of micro-cracks due to subsurface fluid flow and its linkage with Rd/He gas emissions.
- To study the long period vertical ground acceleration of various seismic phases related with different magnitude earthquakes under low noise conditions.

Measurement Resolution : 1 nm/s^2 (0.1 μGal)

Sensor: Spring tension system

Range: 7000 mGal



Various seismic phases recorded by gPhone gravimeter for a Mw 8.7 Magnitude Kiril Island Earthquake in 2007

3. Outlook

- A tunnel based underground lab with >1.5 km rock overburden all around and ~2km vertically will make it competitive worldwide.
- Possible sites being explored given the situation with the Theni site in Tamil Nadu.

Acknowledgements to members of

INO Collaboration

NDBD collaboration

Nuclear Astrophysics group (Cotton U., Delhi U., IIT-R, NPD-BARC, TIFR…)

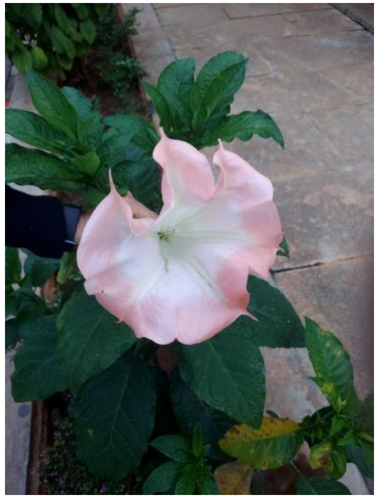
Nuclear Physics groups (VECC, SINP)

Seismology lab (Wadia Institute of Himalayan Geology)

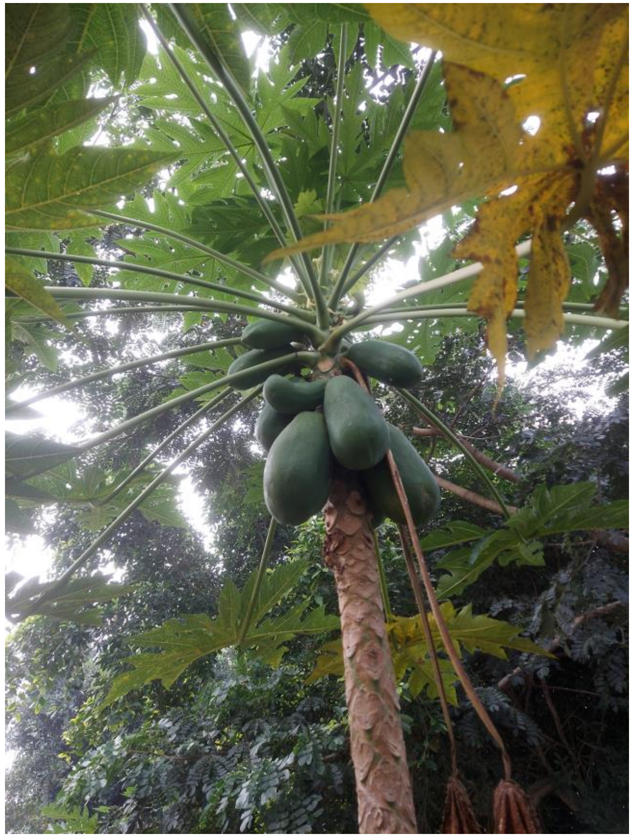
Radon lab (RP&AD, BARC)

Geomagnetism lab (Indian Institute of Geomagnetism)



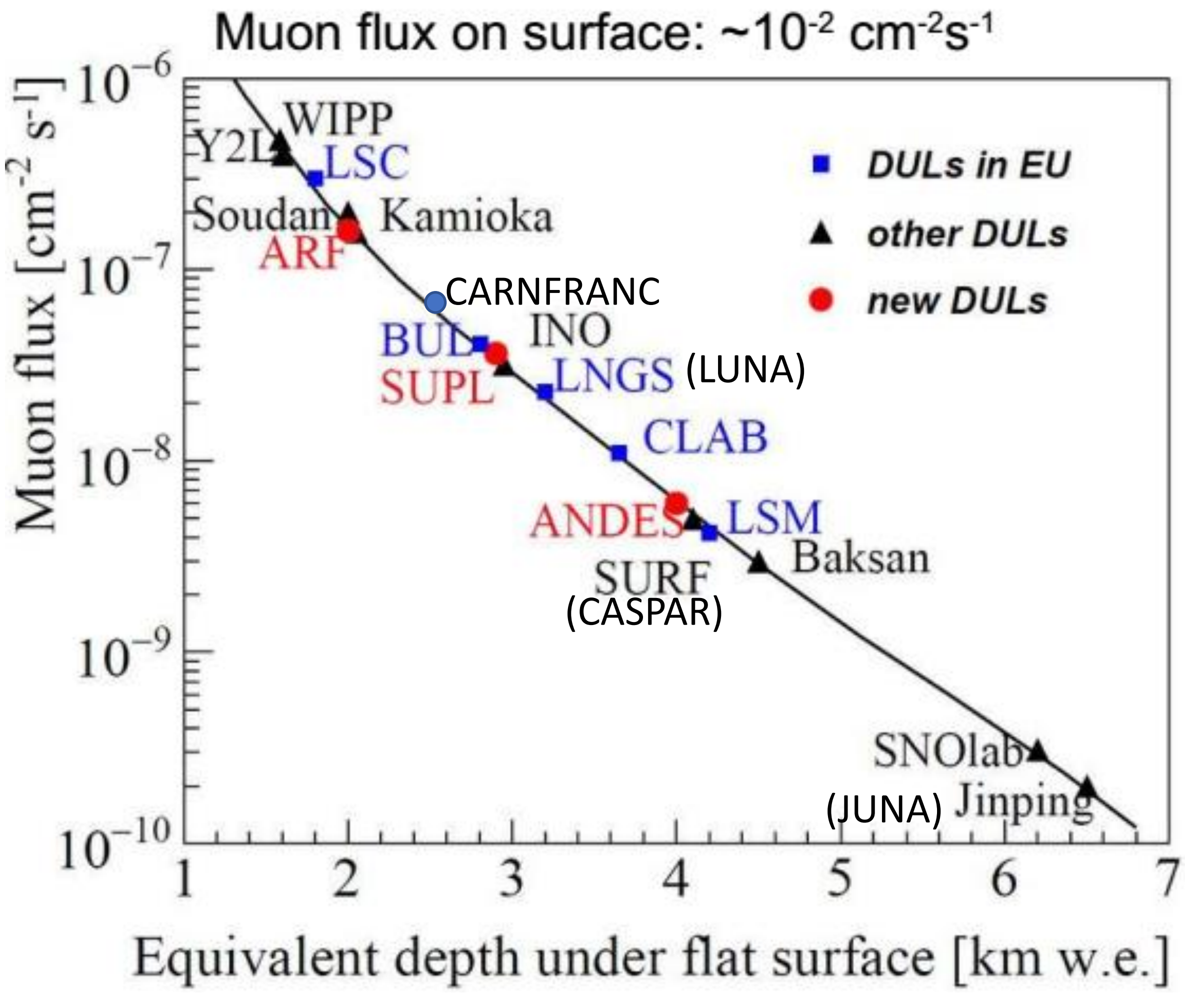




Thank you



Extras

Flux attenuation at different underground labs



Facility	Depth	Flux attenuation		
	km (kmwe)	Muon	Neutron	Gamma
LUNA (Italy)	1.4 (3.1)	10^{-6}	10^{-3}	10^{-3}
JUNA (China)	2.4 (6.72)	10^{-8}	10^{-5}	10^{-5}
CASPER (USA)	1.5 (4.3)	10^{-6}	10^{-3}	10^{-3}
Felsenkeller (Germany)	0.05 (0.14)	$4x10^{-1}$		$4x10^{-1}$
CANFRANC (Spain)	0.85 (2.5)	$5x10^{-7}$		
ANDES (S America)	1.75 (4.5)	10^{-6}		

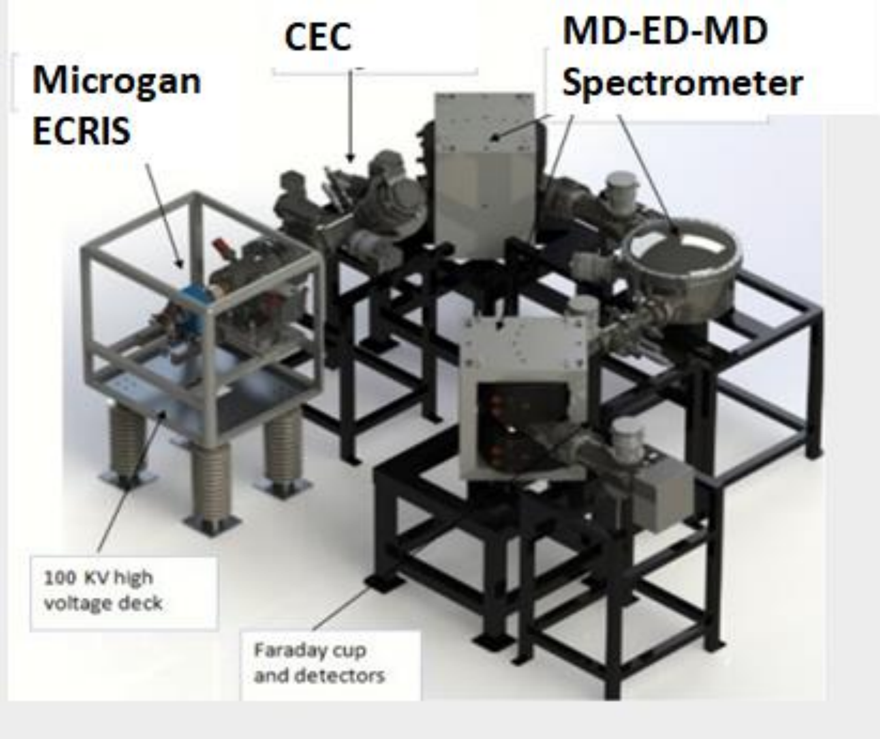
from **S.Santra**

Recoil mass separator at underground lab

Propose: A Rotatable PIMS spectrometer: MD-ED-MD
Doubly focusing spherical ED, No quadrupoles

Novelty of the concept: MD-ED-MD similar to HIRA (ED-MD-ED)

1. Compact foot print, no quadrapoles, hardware corrections of aberrations
2. Spherical doubly focusing ESA (Electrostatic Analyzer) [Das 1997]
3. Anode slot like HIRA for High current operation [Sinha 1997]



PIMS spectrometer

Science goals of a In-loaded LS

- Measure E spectrum of *pp*, ^{7}Be, *pep* neutrinos (~50–1500 keV) in real time
- Measure core temperature of sun *directly* via Doppler broadening of ^{7}Be neutrinos [Bahcall] as well as the *p-p* neutrinos [Grieb, Raghavan].
- Search for a possible sterile neutrino-electron neutrino mixing using a radioactive ν_e source or one made online using a high current p/d beam on a suitable target [6].
- Search for neutrino-antineutrino oscillations using strong anti-ν_e source or one made online using a high current p/d beam on a suitable target.
- Search for dark matter (2-body) decay and/or annihilation through unidentified peak in neutrino spectrum.

C. Grieb, R. Raghavan, PRL **98**, 141102 (2007)

TABLE I. Neutrino energies and thermal shifts.

	q(lab) keV	$+\Delta\langle E\rangle$ keV	$+\delta\langle E\rangle$ keV	$+\Delta E$ keV	$+\delta E$ keV
pp	420.2[a]	3.41[b]	1.6	5.2[c]	1.7
pep	1442.2	6.65[b]	4.54		
^{7}Be	861.8	1.29[b]	0.81		

[a] Q-value

[b] Mean energy shift (for *pp* in range 110-340 keV)

[c] Shift of max. energy in spectrum

$\delta\langle E\rangle$ Precision attainable in $\Delta\langle E\rangle$

⇐

Thoughts on a cryogenic Indium detector

- Potentially excellent energy resolution of cryogenic detector ($\sim$ few keV) using Indium especially suited for the items 2 and 5.
- Cryogenic detector (10 mK) needs segmentation into units of between 1-3 cm dimension (a full cost-benefit analysis necessary) with total mass $\sim$10 tons (Vol $\sim$ 1m^3)
- 5-10 modules each with its own shielding. In view of the internal ^{115}In radioactivity the shielding could be placed *outside* the cryostat
- Timing < 0.5 μs needed. NTDGe slow ($\tau_{resp} \sim$ 0.1 sec), TES, !
- Measuring quasi-particles (broken e-e pairs) possible (Booth 1987)

Phonon detection using a Series Array of Superconducting Tunnel Junctions

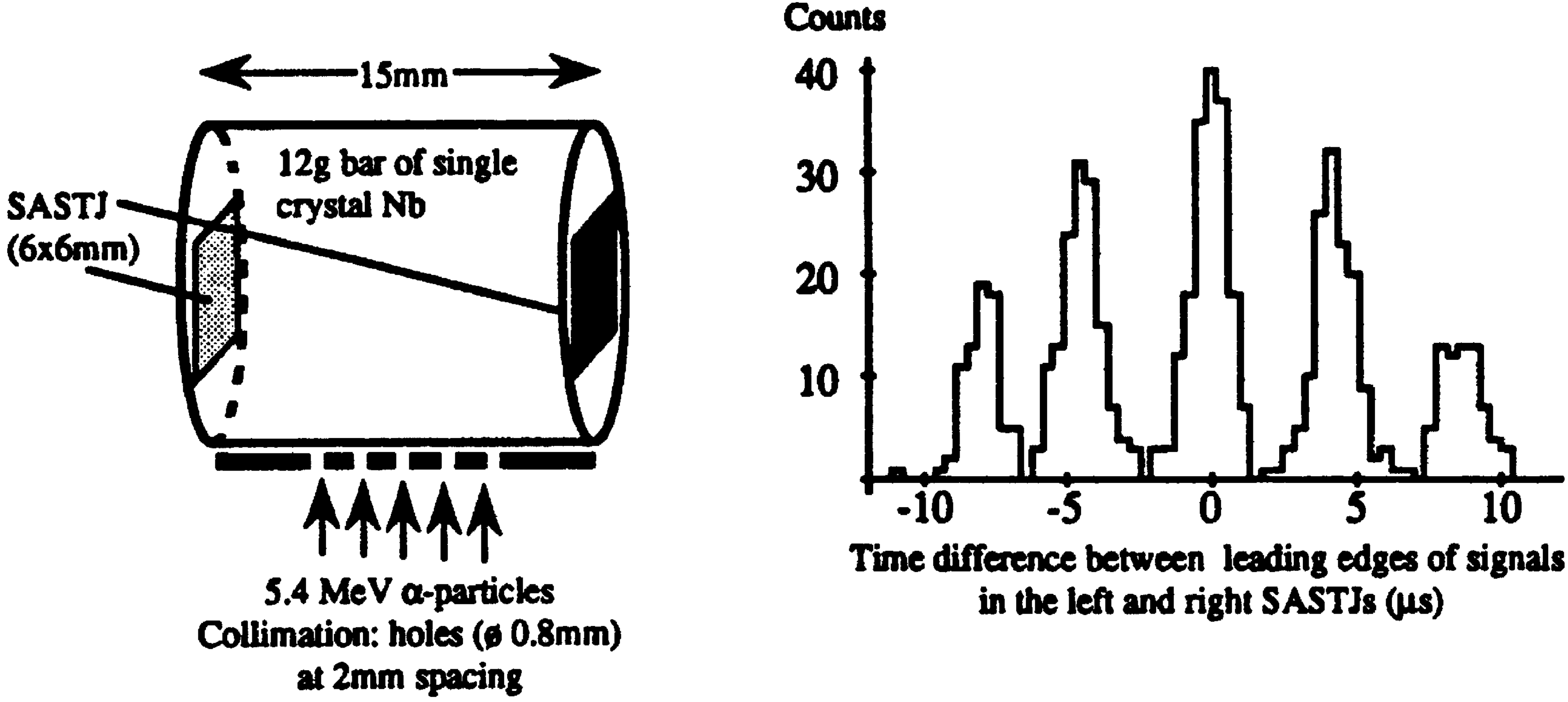


Fig. 14 from N. Booth, B. Cabrera and E. Fiorini, Ann. Rev. Nucl. Part. Sc. **46**, 471 (1996)