UNIVERSITA' DEGLI STUDI DI TORINO
FACOLTA' DI SCIENZE M.F.N.
DIPARTIMENTO DI FISICA GENERALE

MEASUREMENT OF COSMOGENIC RADIONUCLIDES IN METEORITES BY HPGe-NaI COINCIDENCE GAMMA-RAY SPECTROSCOPY

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DOTTORATO DI RICERCA IN FISICA FONDAMENTALE, APPLICATA ED ASTROFISICA

XXI CICLO

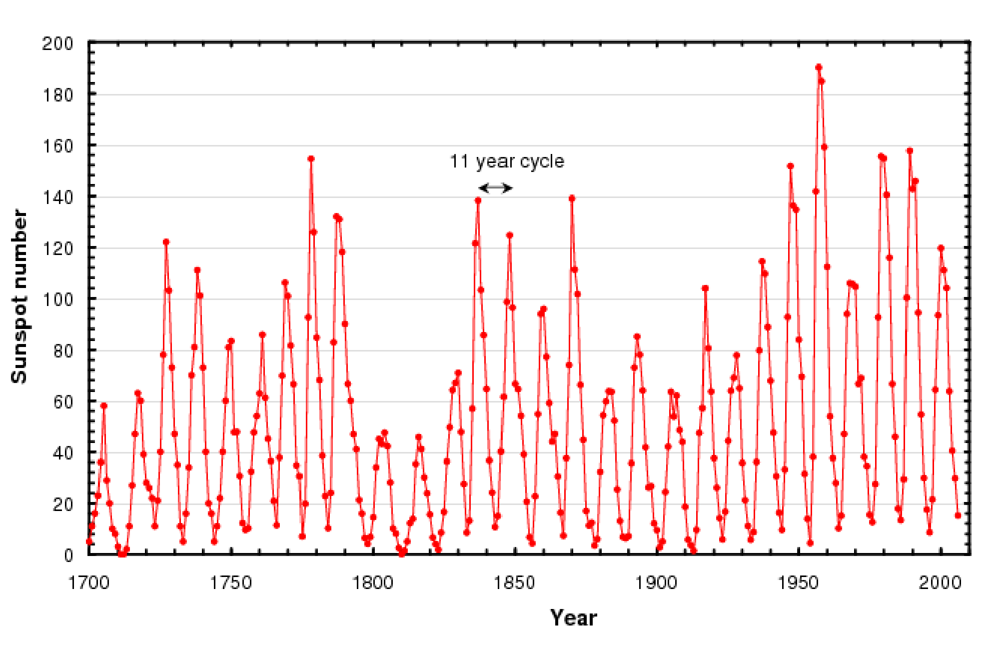
2005 - 2008

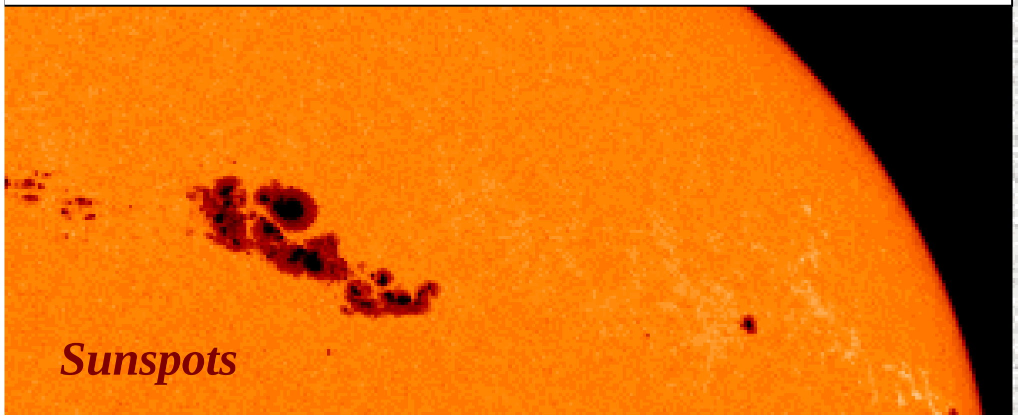
Summary

- Reconstruction of solar activity variations in the past
- Cosmogenic radionuclides: ^{44}Ti in meteorites
- Measurement of ^{44}Ti activity
- Acquisition systems
- Results
- Future plans

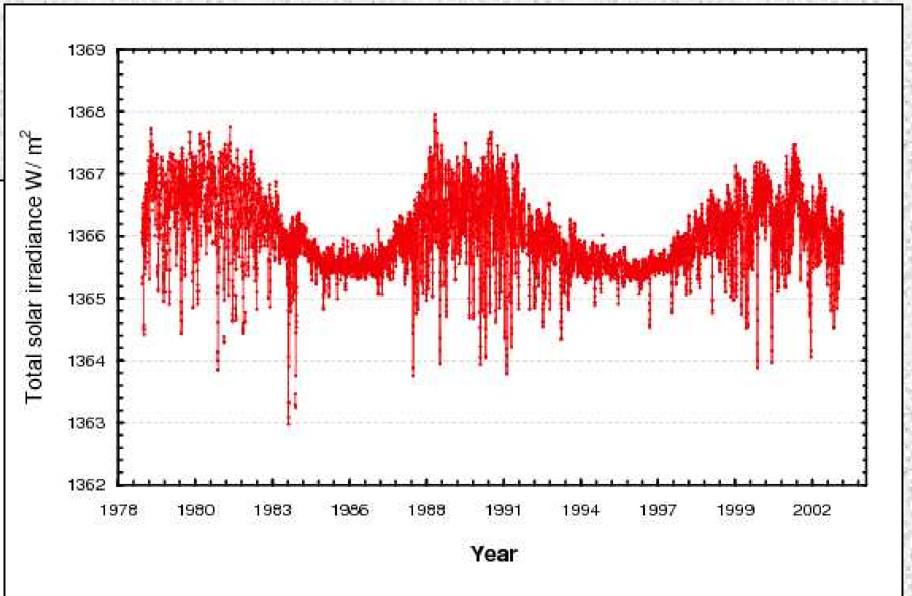
Solar activity variations

- First evidence: <u>sunspot number series</u>:
  - 11 year → Schwabe cycle
  - long-term → Gleissberg cycle





- 11 year cycle is well documented by measurements of <u>Total Solar Irradiance</u>

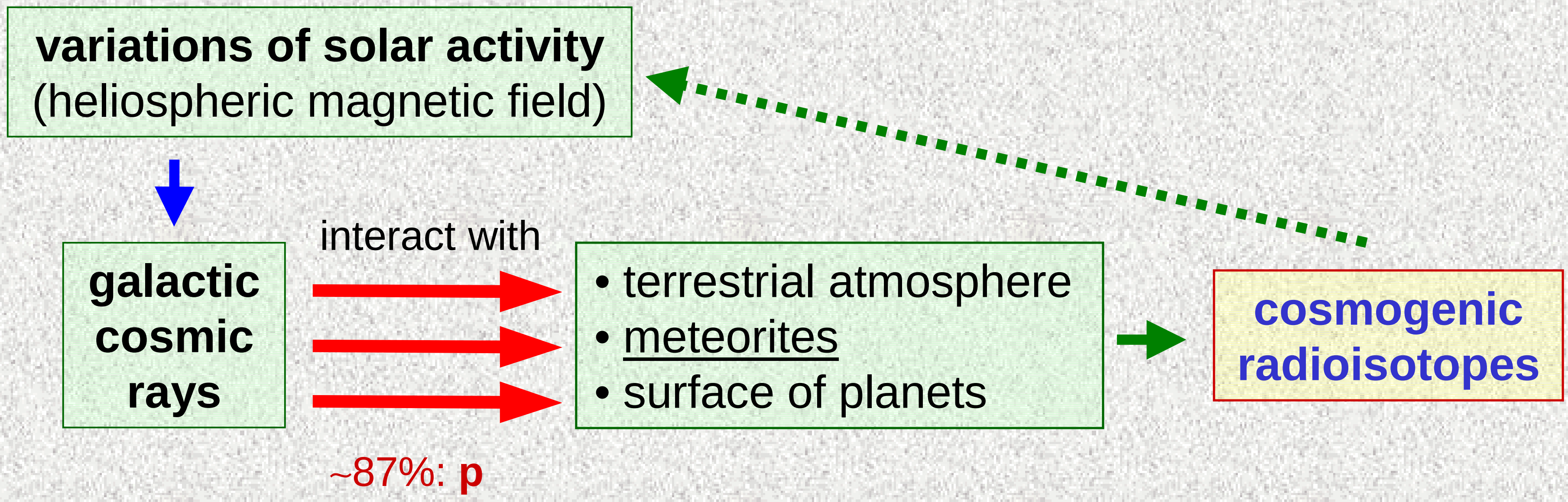


- TSI data since 1979

- Need of proxy data to know solar variations on longer time scales:

- cosmogenic radioisotopes

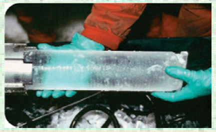
Reconstruction of solar activity in the past: cosmogenic radioisotopes



- production of radioisotopes is anticorrelated to solar activity
- cosmogenic radionuclides of **different** $T_{1/2}$ $\rightarrow$ study on different time scales

Terrestrial archives

- ^{10}**Be** in ice cores
  ($T_{1/2}$ = 1.51×10^{6} y)



- ^{14}**C** in tree rings
  ($T_{1/2}$ = 5730 y)

Information about solar activity is influenced by <u>terrestrial processes</u>:

- geomagnetic field variations
- exchange between terrestrial reservoirs
- temperature and climatic cycles which influence the deposition rates
- concentration of ^{14}**C** related to its production rate through the carbon cycle

^{10}**Be**:

- Stuiver and Quay, *Science*, 1980
- Damon and Sonnet, *The Sun in Time*, 1991

^{14}**C**:

- Lal et al., *Earth & Planet. Sci. Lett.*, 2005
- Beer et al., *Nature,* 1990

^{22}**Na**:

- Bhandari et al., *Meteoritics,* 1994

Meteorites

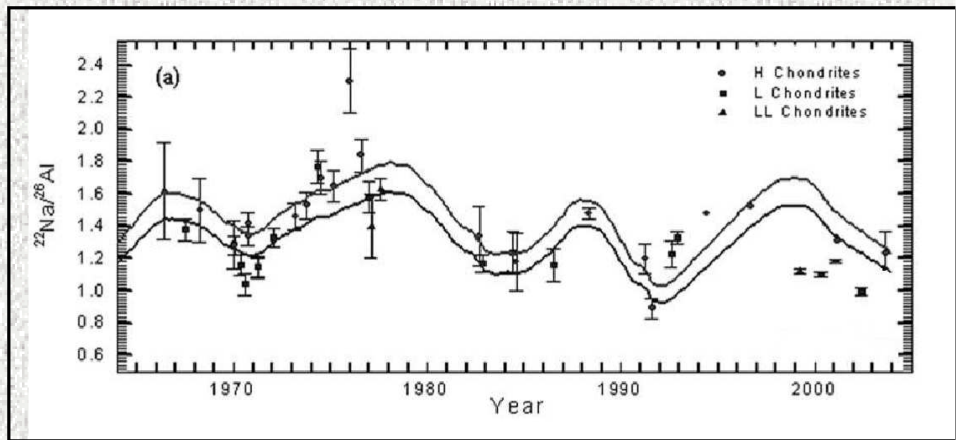
Production <u>free</u> of terrestrial influences:

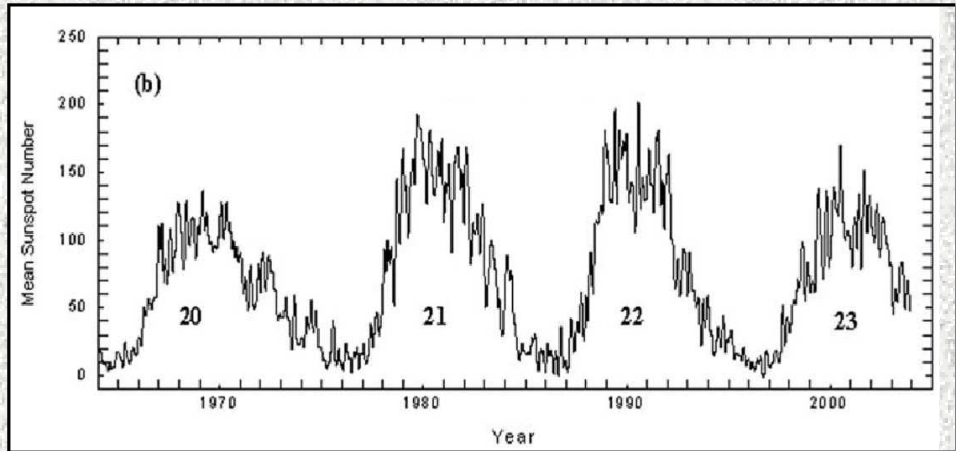
- produced before fall on Earth

Feasibility of such a study evidenced by measuring falls of the last 4 Sun cycles

- ^{22}**Na** ($T_{1/2}$ = 2.6 y)

11 y solar cycle imprint





Measurement of ^{44}Ti activity in meteorites

- **^{44}Ti**

long-term cycles

- $T_{1/2}$ = 59.2 y → information on centennial scale
- produced by GCR interactions (E > 70 MeV)
  protons + **Fe**(**Ni**) nuclei → **^{44}Ti**

Dhajala meteorite, fall 1976

- For this study we select "ordinary chondrites"

- high percentage of Fe and Ni
- most of the observed falls are chondrites

wt %	H	L	LL
Fe	27.2	21.75	19.8
Ni	1.71	1.24	1.06

- more extensive and detailed information available: nuclear tracks density, exposure age, theoretical calculations of depth profiles of ^{44}Ti production rates in meteorites of different sizes

- γ- ray spectrometers: **HPGe + NaI(Tl)**

→ Non destructive measurement

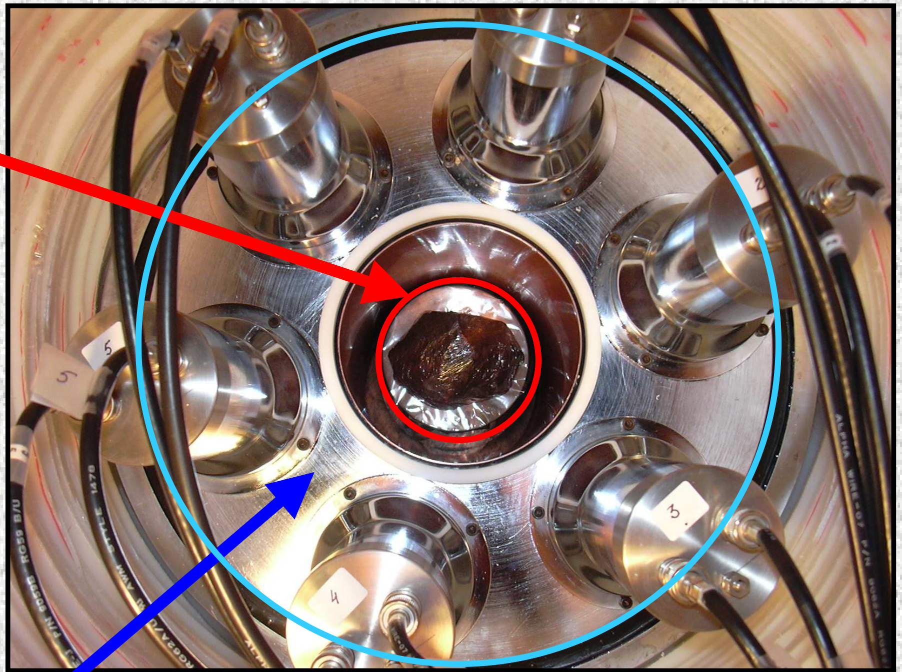
→
- low background
- high efficiency
- high resolution

New HPGe + NaI(Tl) spectrometer

In green: values for the old spectrometer

- HPGe crystal (~3 kg) (~2 kg)
  - *p* type; coaxial *close-end*
  - relative efficiency* = 147 % (95 %)
  - At 1332.5 keV of ^{60}Co:
    resolution (FWHM, keV) = 1.85 (1.96)
    peak to Compton ratio = 104 (88)
  - low background dewar and electronics

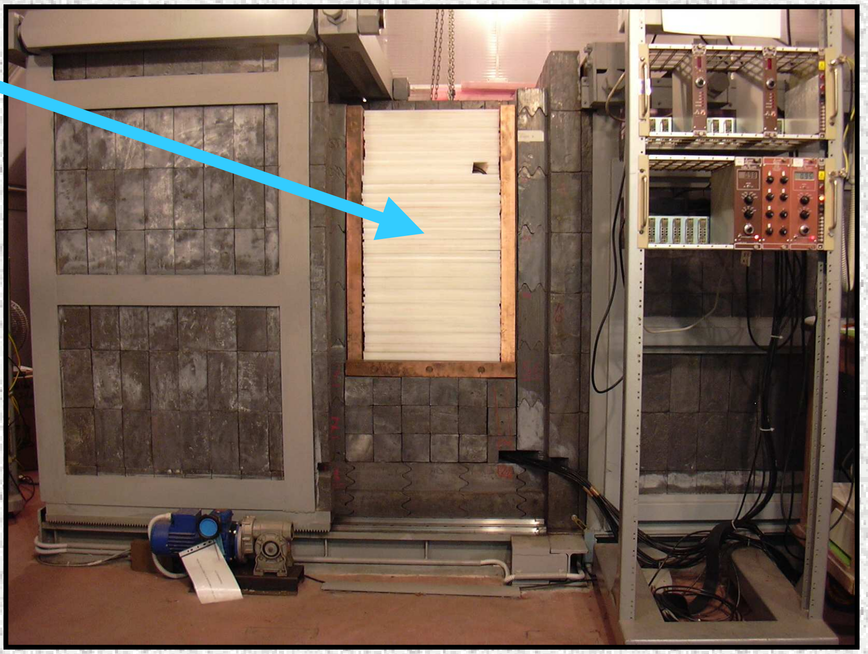
- surrounded by NaI(Tl)
  - *anulus* + "*plug*" ~86 kg (~53 kg)
  - 6+1 photomultipliers



* Photopeak efficiency relative to that of a standard 3'' cylindrical NaI(Tl) scintillation crystal, for the 1332.5 keV γ-rays of a ^{60}Co source on-axis at a distance of 25 cm from the detector.

HPGe + NaI spectrometer shielding

- Detectors are housed in a passive shield:
  - 20 cm lead
  - 1 mm cadmium
  - 5 cm OFHC copper
  - polyethylene for filling internal empty space (radon)

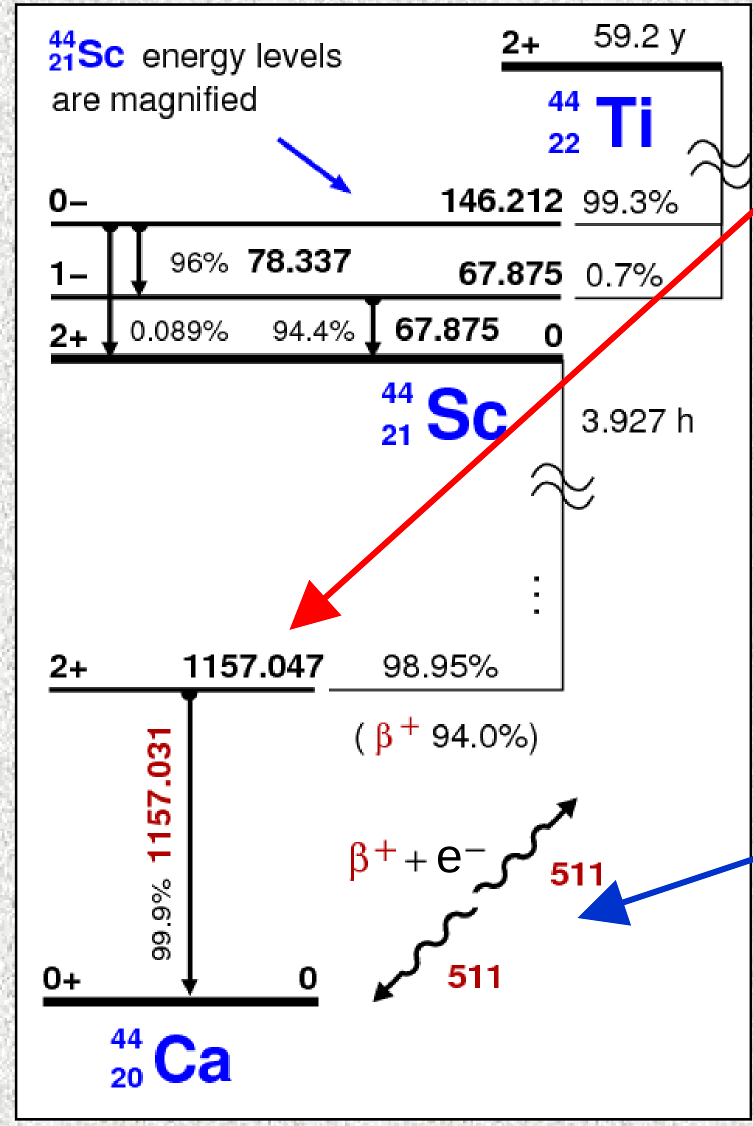


- located in the underground (70 m.w.e.) Laboratory of Monte dei Cappuccini, Torino

- Large samples (~1 kg) can be counted reliably and with high specificity

- The spectrometer operates in normal, anti-coincidence and coincidence modes

^{44}Ti decay scheme



(energies in keV)

Ge detector:

we deduce the activity of **^{44}Ti** by measuring γ at 1157 keV from β^{+} decay of **^{44}Sc**

γ's emitted directly from **^{44}Ti** not considered - lie in low energy region of the spectrum (high background)

NaI detector:

the annihilation γ's from β^{+} decay are detected by the NaI detector as **^{44}Sc**(**^{44}Ti**) decay signature

This COINCIDENCE allows to overcome the main obstacle in the ^{44}Ti detection

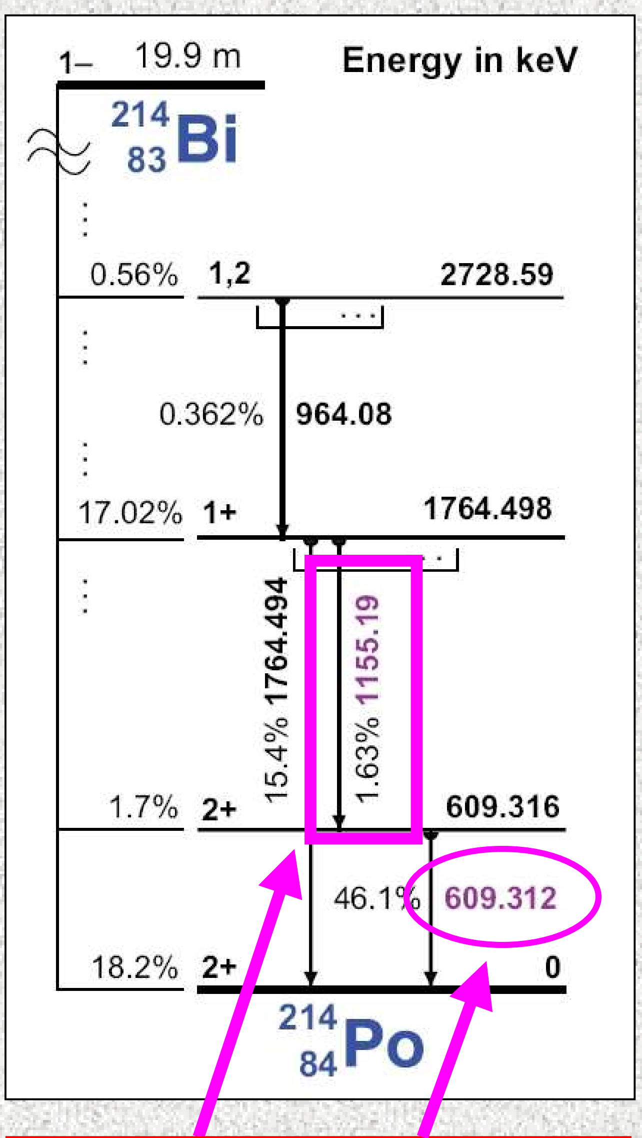
Measurement of ^{44}Ti activity in meteorites

- Main obstacles:
  - low activity level (~ 1 dpm / kg)
  - Interference by naturally occurring γ at ~<u>1155 keV</u> from **^{214}Bi** decay (**^{238}U** chain)

→

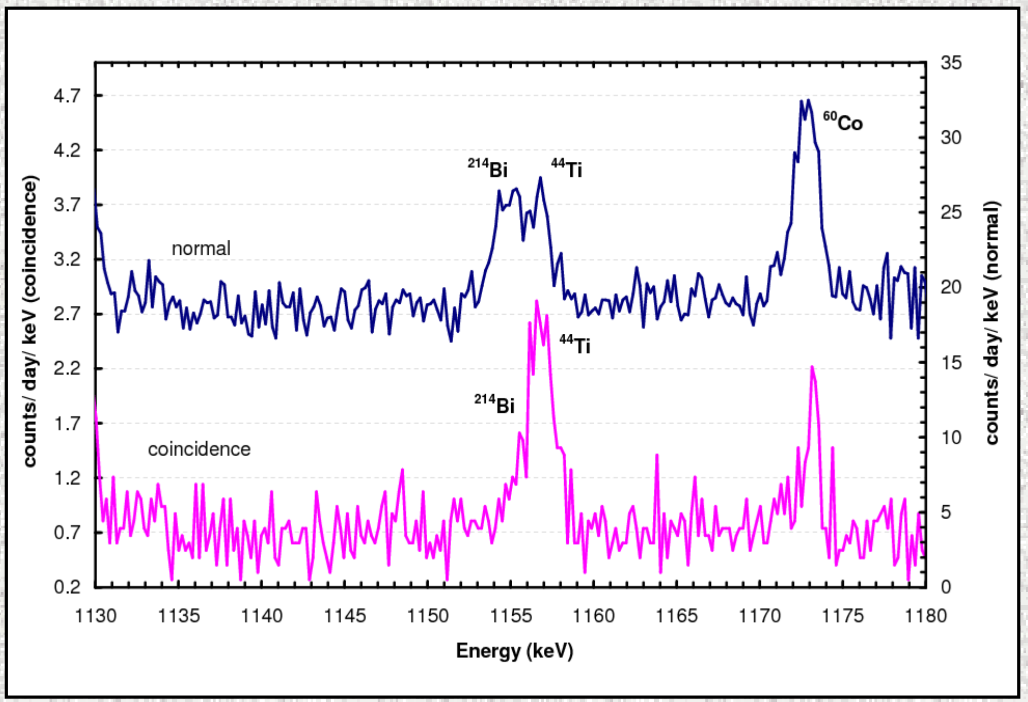
- Solutions:
  - spectrometer: **Hyperpure-Ge**
    - low background
    - high efficiency
    - high resolution
  - ***coincidence*** between:
    - **HPGe:** 1157 keV γ ← **^{44}Ti(^{44}Sc)** decay
    - **NaI(Tl):** 511 keV or (2 × 511 keV) ← β^{+} annihilation photons

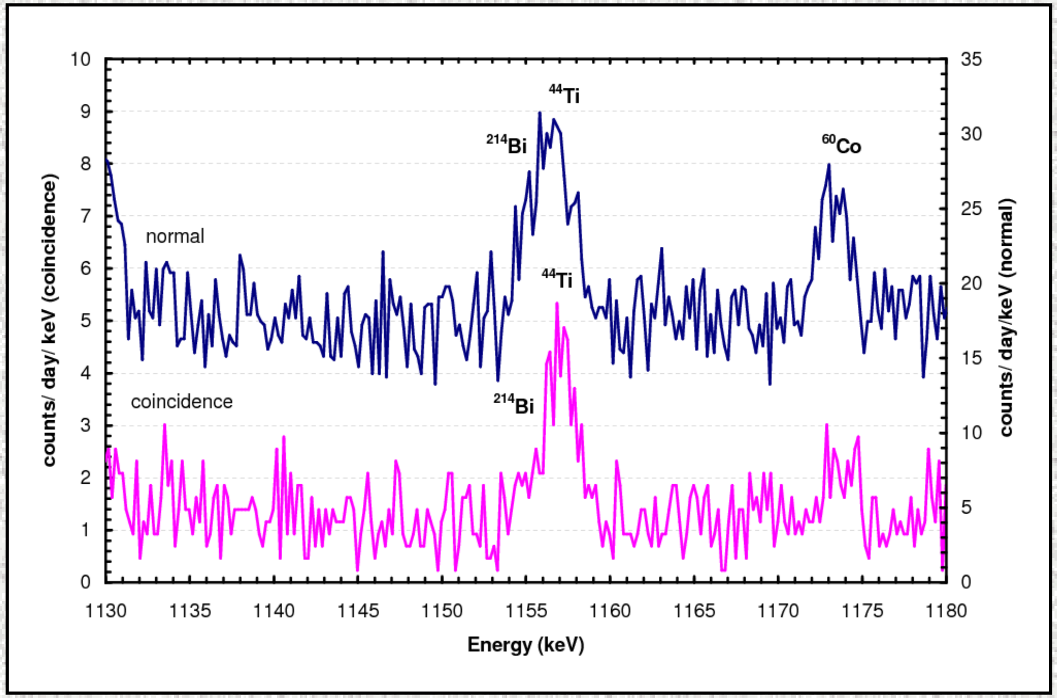
^{214}Bi decay scheme



^{214}Bi emits also a γ at 609.32 keV (~ 511 keV)

The gamma ray spectra of Dhajala (fall 1976) meteorite in normal and coincidence modes.





The gamma ray spectrum of Dergaon meteorite (fall 2001) showing good statistics of ^{44}Ti activity in this recent fall and the reduction of the ^{214}Bi interference.

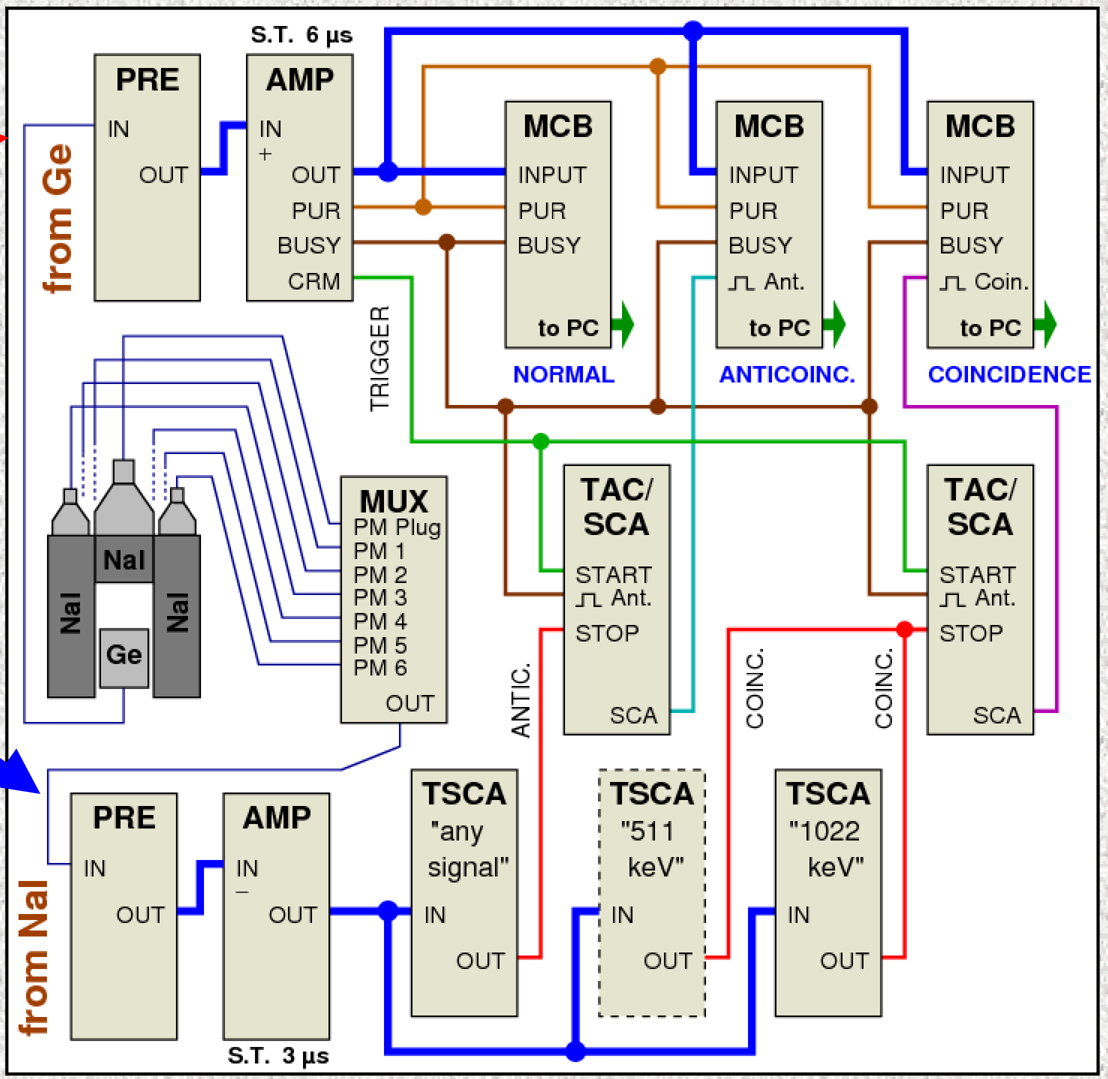
Acquisition system

- **HP-Ge** signal
  - sent directly to **MCB**'s (→ no delay stages)
  - with CRM pulse triggers analysis of (*anti-*)*coincidence* with possible…

- …**NaI(Tl)** signals
  - added → one signal
  - directly analysed by **SCA**'s for
    - *anti-coincidence* and
    - *coincidence* **MCB gate**

➡ **SCA** windows have to be choosen a priori (no re-thinking)

- Timing → by adjusting delays only on logic signals



PRE = preamplifier, AMP = amplifier, PUR = pile-up rejection, CRM = count rate meter, BUSY = time for signal detection, MCB = multichannel analyser with buffer, MUX = multiplexer, TAC = time to amplitude converter, (T)SCA = (timing) single channel analyser,

In red: improvements to the previous setup (which was used for the old spectrometer)

Details of the measured meteorites

Underlined: meteorites measured during my PhD

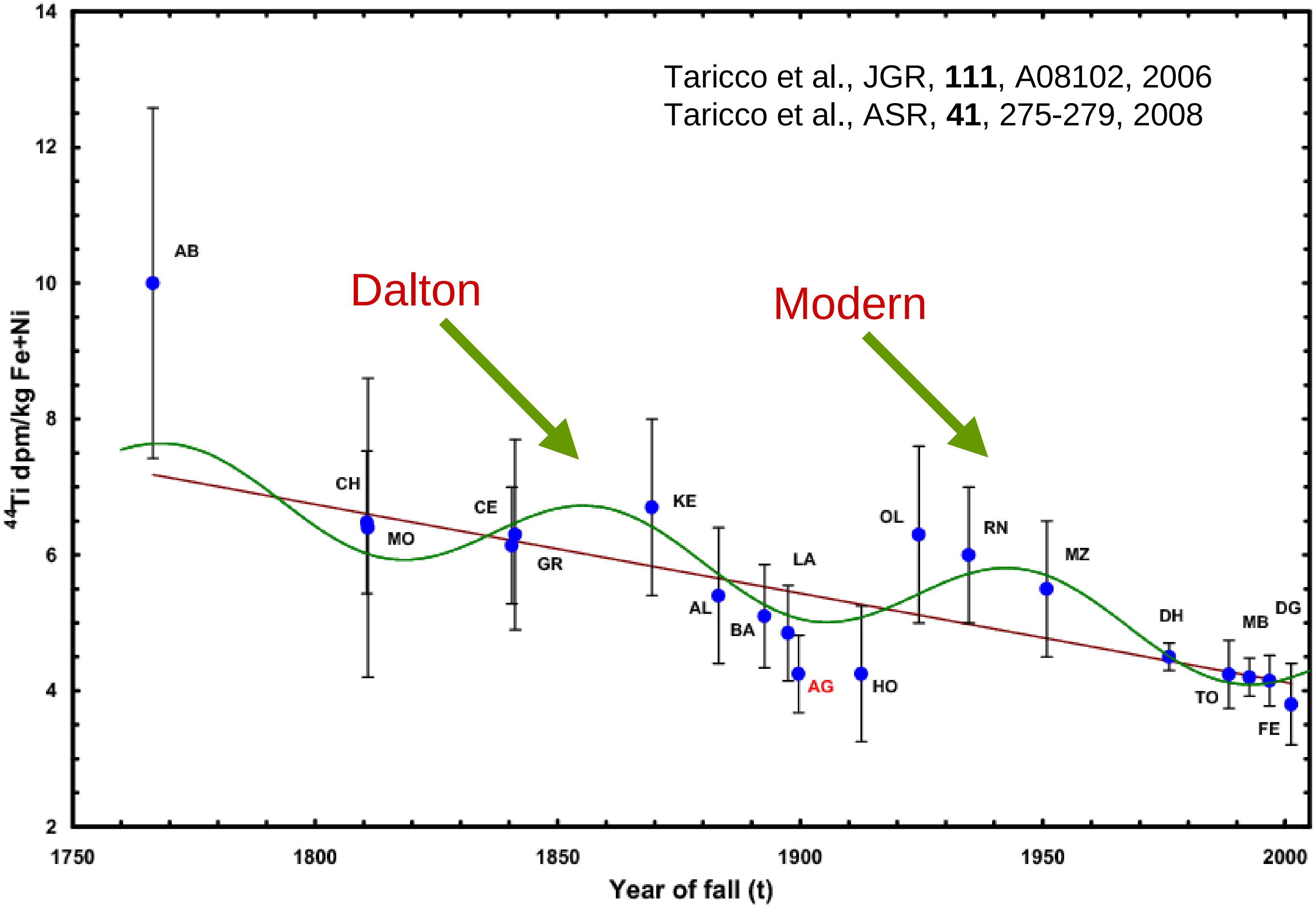
Meteorite	Group	Date of fall	Recovered mass (kg)	Weight of sample (g)
1. Albareto	LL4	July 1766	2	580
2. Mooresfort	H5	August 1810	3.5	1145
3. Charsonville	H5	23 / 11 / 1810	27	524
4. Agen	H5	5 / 9 / 1814	30	683
5. Cereseto	H5	17 / 7 / 1840	6.46	1308
6. Grüeneberg	H4	22 / 3 / 1841	1	717
7. Kernouve’	H6	22 / 5 / 1869	80	820
8. Alfianello	L6	16 / 2 / 1883	228	625
9. Allegan	H5	10 / 7 / 1899	42	296
10. Bath	H4	29 / 8 / 1892	21	539
11. Lancon	H6	20 / 6 / 1897	7	1080
12. Holbrook	L6	19 / 7 / 1912	220	331
13. Olivenza	LL5	19 / 6 / 1924	150	247.4
14. Rio Negro	L4	21 / 9 / 1934	1.31	388
15. Monze	L6	5 / 10 / 1950	unknown	165
16. Dhajala	H3/4	28 / 1 / 1976	45	706
17. Torino	H6	19 / 5 / 1988	0.977	445
18. Mbale A Mbale T	L5	14 / 8 / 1992	150	700 730
19. Fermo	H3	25 / 9 / 1996	10.2	800
20. Dergaon	H5	2 / 3 / 2001	>12	1330

Results

- Decreasing trend of ~43 % in ^{44}Ti activity during the past 235 years
- Superimposed on it, a ~87 years oscillation with amplitude ~20%, revealing GCR flux maxima (solar activity minima) around 1800 and 1900

Chondrites:

AB = Albareto
CH = Charsonville
MO = Moorefort
CE = Cereseto
GR = Grüneberg
KE = Kernouvé
AL = Alfianello
BA = Bath
LA = Lancon
HO = Holbrook
OL = Olivenza
RN = Rio Negro
MZ = Monze
DH = Dhajala
TO = Torino
MB = Mbale
FE = Fermo
DG = Dergaon



^{44}Ti activity (dpm/kg Fe+Ni), corrected for shielding and target element composition as a function of time.

New multiparametric acquisition system

New system requirements

- high stability (energy, resolution)
- data acquisition compatible with previous:
  - ADC technology (SAC with sliding-scale linearization)
  - Gedcke-Hale live-time calculation
- system control
  - autonomous data acquisition and storage (PC may be off)
  - accessible from different workstations in case of PC failure
  - monitor system operation
- *open source* to obtain more flexibility

Choice of technology

- ← reliable electronics, e.g.
  - EM interferences shielding
- ← CAMAC ADC's of same producer of MCB's
  - same technology
- ← CAMAC controller with *on-board*
  - microcomputer
  - non-volatile memory for script
  - LAN interface
  - RS232 serial port
  - NIM signals I/O
- ← CAMAC controller with embedded *open source* control software
  - Linux Operating System
  - Lua, C-like scripting language (extensible)

New acquisition system

Hardware setup optimization

- layout of modules in racks
- length of cables
- prevent ground loops
- heat flow from modules
- timing
- a stand for holding meteorite samples, especially heavy ones, to protect Ge detector from mechanical strain

Other improving procedures

- precise photomultiplier alignment
- thermal cycle for crystal “reset” and for cryo-regenerate vacuum

Software development on CAMAC controller

- workarounds for some bugs in firmware
- Lua scripting language (*open source*) to implement embedded control sw
- defined CAMAC acquisition procedure
- modified & installed function libraries for TCP/IP additional functions (Lua) to:
  - read config. files from FTP disk
  - save log info to FTP disk
  - store data safely in case of failure
  - (newly defined) append to FTP file
- RS232 control of MCB (sync start/stop)
- system monitor:
  - CAMAC acquisition
  - mains failure → UPS power supply
  - data storage
  - MCB active

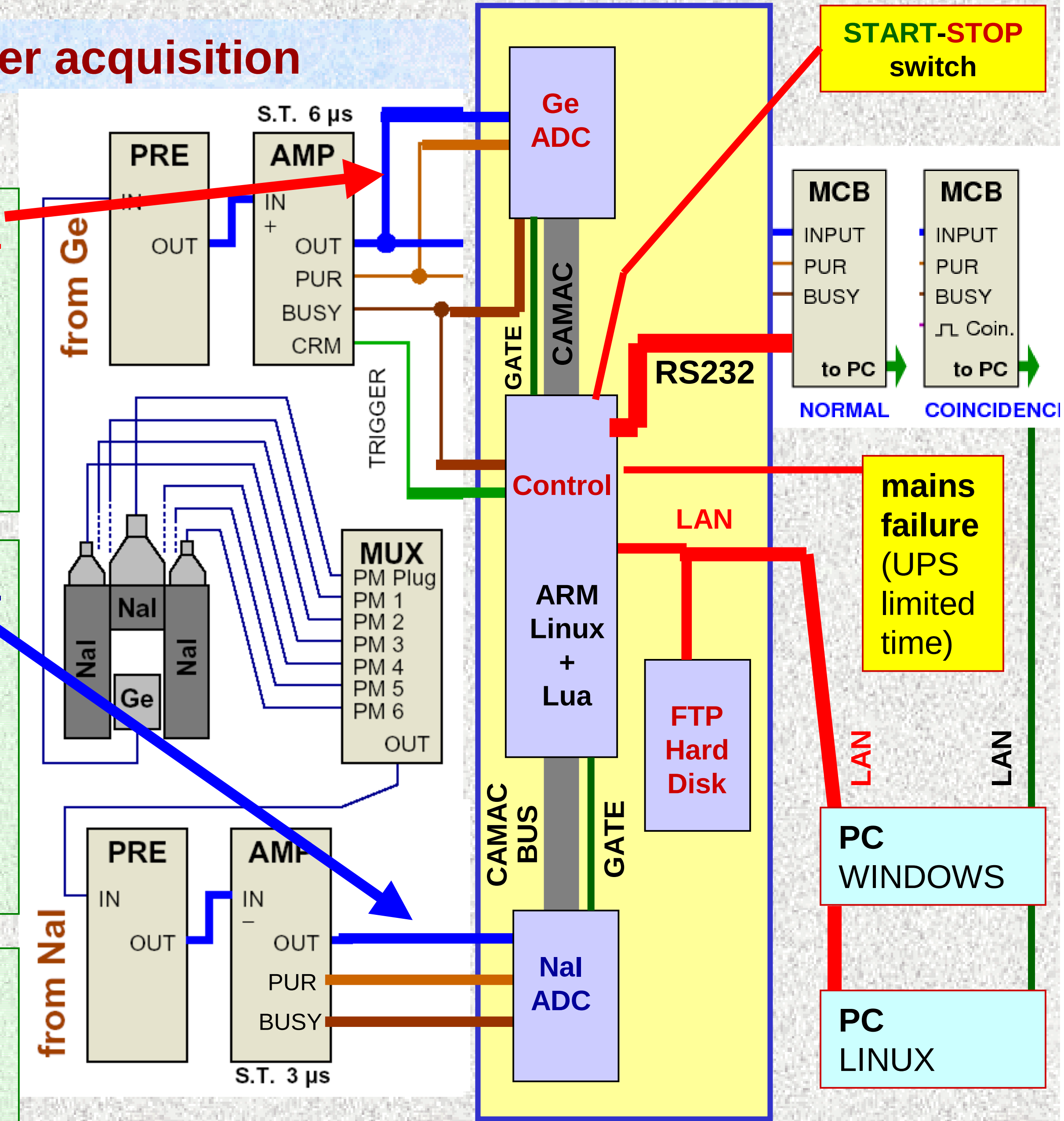
New Ge-NaI multiparameter acquisition

- HP-Ge signal → **parameter 1**
  - sent directly to **MCB**'s and CAMAC **ADC**
  - triggers both **ADC**'s and **SCA** analysis

- NaI(Tl) signal → **parameter 2**
  - acquired in coincidence with Ge signal
  - analysed by **SCA** for **MCB**
    - *anti-coincidence* or
    - *coincidence gating*

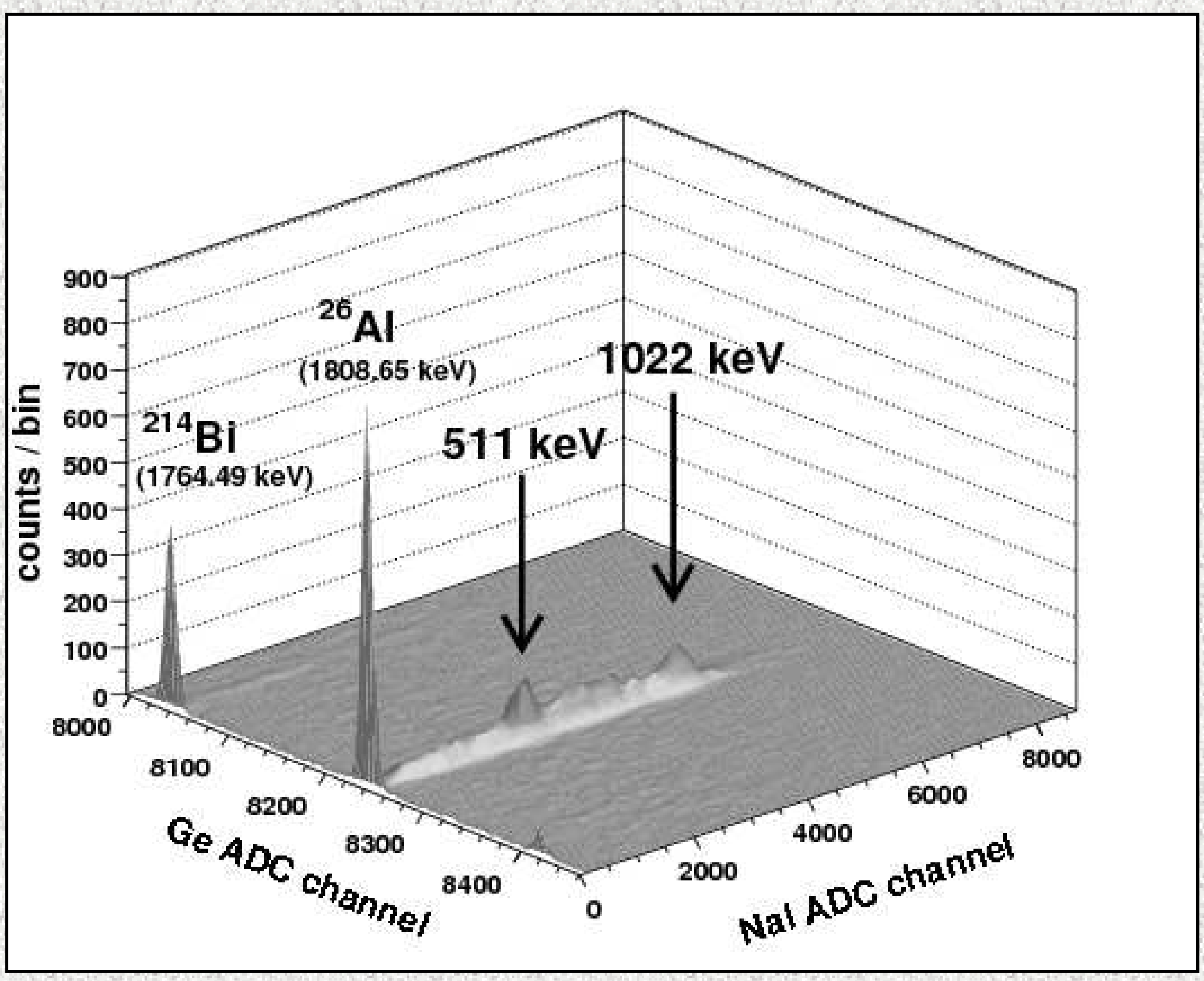
- **CAMAC data** → a posteriori choose NaI windows by sw

- **MCB**'s → monitor acq. and check CAMAC data accuracy



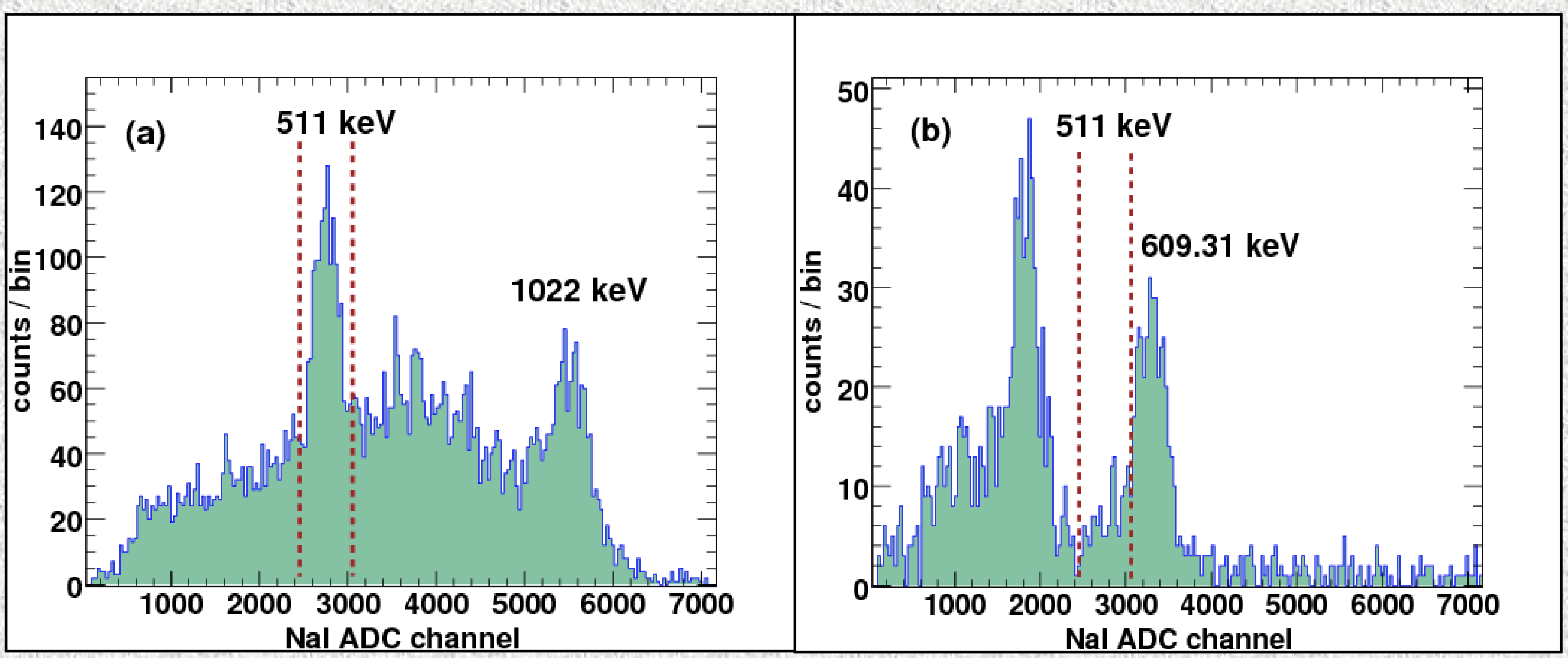
PRE = preamplifier, AMP = amplifier,
MUX = multiplexer, ADC = analog to digital converter

First multiparametric results



Dhajala meteorite Ge-NaI 2-dimensional spectrum in the Ge energy region around ^{26}Al 1808.65 keV peak, for which corresponding NaI detection of β^+ annihilation γ's is visible, as opposed to mostly single ^{214}Bi 1764.51 keV γ.

First multiparametric results



NaI spectrum of Dhajala meteorite acquired in coincidence with Ge events in the region of ^{26}Al 1808.65 keV peak (a) and of ^{214}Bi 1120.52 keV peak (b) respectively.

Conclusions

1. Measurement of meteorites fallen in the last 235 years using the new spectrometer

2. Setup of a new acquisition system and tests measuring Dhajala meteorite

Future plans

1. Development of the analysis of the data acquired with the new system and determination of coincidence windows

2. Measurement of other meteorites using the new system in order
   (a) to determine the centennial ^{44}Ti cycle with a better accuracy and
   (b) to obtain information about solar activity before 1800

Publications

1) “Heliospheric modulation of cosmic rays based on ^{44}Ti in stony meteorites over the past 250 years”, C. Taricco, N. Bhandari, P. Colombetti, N. Verma; *29th International Cosmic ray Conference ICRC*, **2**, 195-198, 2005

2) “Galactic cosmic ray flux decline and periodicities in the interplanetary space during the last three centuries revealed by ^{44}Ti in meteorites”, C. Taricco, N. Bhandari, D. Cane, P. Colombetti, N. Verma; *Journal of Geophysical Research*, **111**, No. A8, A08102, 2006

3) “Experimental set-up and optimization of a new gamma-ray spectrometer for the measurement of cosmogenic radionuclides in meteorites”, C. Taricco, N. Bhandari, P. Colombetti, N. Verma, G. Vivaldo, *Nuclear Instruments and Methods in Physics Research A*, **572**, 241-243, 2007

4) “Mid 19th century minimum of Galactic cosmic ray flux inferred from ^{44}Ti in Allegan meteorite”, C. Taricco, N. Bhandari, P. Colombetti and N. Verma, *Advances in Space Research,* **41**, 275-279, 2008

5) “A large cavity gamma ray spectrometer for measurement of cosmogenic radionuclides in astromaterials by whole rock counting”, C. Taricco, N . Bhandari, P. Colombetti, N. Verma and G. Vivaldo, *Proceedings of 10th ICATPP conference on Astroparticle, Particle, Space Physics, Detectors, and Medical Physics applications*, 2007, submitted

Internal reports

1) *Solar Activity Variations and Paleoclimatology: Experimental Studies Based on Meteorites and Marine Sediments Cores*; C.Taricco, S. Alessio, A. Romero, P. Colombetti, N. Verma, G. Vivaldo, C. Battigelli; INAF-Istituto di Fisica dello Spazio Interplanetario, Torino, Annual Report 2005, Chapter 4, pages 43-47

2) *Experimental set-up and optimization of a gamma-ray spectrometer for measurement of cosmogenic radionuclides in meteorites*, P. Colombetti, C. Taricco, N. Bhandari, N. Verma, G. Vivaldo, Internal Report for Istituto di Fisica dello Spazio Interplanetario (INAF), N.12/2006

3) *Cosmic ray flux variation during mid-19th century revealed by low ^{44}Ti activity in Allegan meteorite*, C. Taricco, N. Bhandari, P. Colombetti, N. Verma, G. Vivaldo, Internal Report for Istituto di Fisica dello Spazio Interplanetario (INAF), N.1/2007

4) *Minimi secolari del flusso dei raggi cosmici galattici rivelati mediante la misura del ^{44}Ti in meteoriti,* C. Taricco, N. Bhandari, P. Colombetti, N. Verma, G. Vivaldo, Internal Report for Istituto di Fisica dello Spazio Interplanetario (INAF), N.12/2007

Conference participation (1)

1) “Heliospheric modulation of cosmic rays based on ^{44}Ti in stony meteorites over the past 250 years”, C. Taricco, N. Bhandari, P. Colombetti, N.Verma*; *Proceedings of 29th ICRC (International Cosmic Ray Conference)*; **2**, p.195 -198, Pune, India, August, 2005

2) “Variabilita’ climatica millenaria rivelata negli ultimi 20000 anni in sedimenti del Mar Tirreno”, C. Taricco, S. Alessio, C. Battigelli*, P. Colombetti, N. Verma, *XCI Congresso Nazionale, Società Italiana di Fisica*, September, Catania, Italy, 2005

3) “Experimental set-up and optimization of a new gamma-ray spectrometer for the measurement of cosmogenic radionuclides in meteorites”, C. Taricco, N. Bhandari, P. Colombetti, N. Verma, G. Vivaldo, *X Pisa Meeting – Frontier Detectors for Frontier Physics*, La Biodola, Isola d’Elba, Italy, May 2006

4) “^{44}Ti in meteorites and Galactic Cosmic Ray flux over the past 235 years“, C.Taricco, N. Bhandari*, D. Cane, P. Colombetti, N. Verma, G. Vivaldo, *COSPAR 06 (Committee on Space Research),* Bejing, China, July 2006

5) “Cosmic ray flux variation during mid-19th century revealed by low ^{44}Ti activity in Allegan meteorite”, C. Taricco, N. Bhandari, P. Colombetti, N. Verma*, G. Vivaldo, *69th Annual Meeting of the Meteoritical Society*, ETH Zurich, Switzerland, August 2006

6) “Ottimizzazione di uno spettrometro HPGe+NaI per la misura di radioisotopi cosmogenici in meteoriti”, C. Taricco, N . Bhandari, P. Colombetti*, N.Verma, G. Vivaldo, *XCII Congresso Nazionale, Società Italiana di Fisica,*Torino, Italy, September 2006

* Presenter

Conference participation (2)

7) "Variazioni del flusso dei raggi cosmici galattici negli ultimi 250 anni da misure di radioisotopi cosmogenici in meteoriti", C. Taricco, N . Bhandari, P. Colombetti, N. Verma*, G. Vivaldo, *XCII Congresso Nazionale, Società Italiana di Fisica,* Torino, Italy, September 2006.

8) "Minimi secolari del flusso dei raggi cosmici galattici rivelati mediante la misura del ^{44}Ti in meteoriti", Taricco C., N. Bhandari, P. Colombetti*, N. Verma, G. Vivaldo, *XCIII Congresso Nazionale, Società Italiana di Fisica*, Pisa, Italy, September 2007

9) "A large cavity gamma ray spectrometer for the study of interplanetary radiations by whole rock radioactivity measurement of astromaterials", C. Taricco, N . Bhandari, P. Colombetti*, N. Verma, *10th ICATPP conference on Astroparticle, Particle, Space Physics, Detectors, and Medical Physics applications,* Villa Olmo, Como, 8-12 October 2007

* Presenter