Stefan Meyer Institute

Austrian Academy of Sciences

Pauli Exclusion Principle tests with VIP2

Johann Marton for the VIP2 Collaboration
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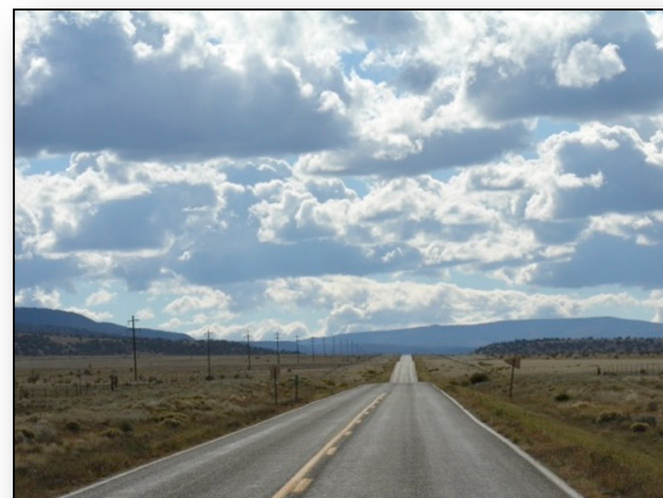
Vienna

Project P25529-N20

Outline

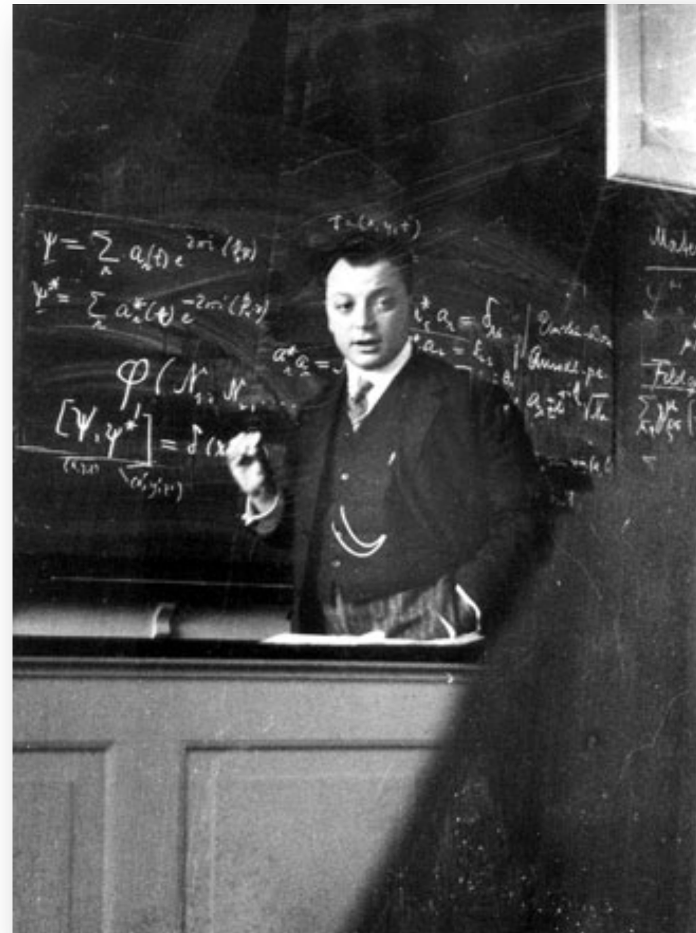
- Motivation for testing
  a solid rule of nature (i.e. pillar of QM)
- Experimental Method of VIP/VIP2
- Results obtained so far
- New experimental setup VIP2
- Summary and outlook



W. Pauli 1925

"In an atom there cannot be two or more equivalent electrons for which the values of all four quantum numbers coincide. If an electron exists in an atom for which all of these numbers have definite values, then the state is occupied."

W.Pauli, Über den Zusammenhang des Abschlusses der Elektronengruppen im Atom mit der Komplexstruktur der Spektren, Zeitschrift für Physik 31 (1925) 765.



Motivation

PEP lacks a clear, intuitive explanation

... Already in my original paper I stressed the circumstance that I was unable to give a logical reason for the exclusion principle or to deduce it from more general assumptions.

I had always the feeling and I still have it today, that this is a deficiency.

... The impression that the shadow of some incompleteness [falls] here on the bright light of success of the new quantum mechanics seems to me unavoidable.

<u>W. Pauli, Nobel lecture 1945</u>

Motivation

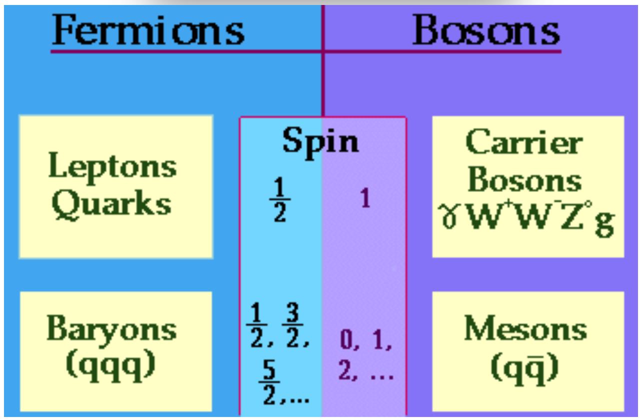
If something in fundamental physics can be tested, then it absolutely must be tested

(L. Okun)

The Pauli Principle and the spin statistics connection

Ralph Kronig (1904-1995) suggested that electrons have spin (1925).
Pauli: *"it is indeed a very clever idea but has nothing to do with reality"*

Our Knowledge today:
Bosons and Fermions
Symmetric states → bosons
(possibly many particles
in the same quantum state)
Anti-symmetric states → fermions
(one particle per quantum state)
→ Different statistics



Pauli and spin-statistics

OCTOBER 15, 1940 PHYSICAL REVIEW

The Connection Between Spin and St

W. PAULI
Physikalisches Institut, Eidg. Technischen Hochschule, Zür
and Institute for Advanced Study, Princeton, New

(Received August 19, 1940)

In the following paper we conclude for the relativistically invaria
particles: From postulate (I), according to which the energy must
of *Fermi-Dirac* statistics for particles with arbitrary half-integral s
according to which observables on different space-time points with
commutable, the necessity of *Einstein-Bose* statistics for particles wi
It has been found useful to divide the quantities which are irreduci
formations into four symmetry classes which have a commutable m
$+\epsilon$, $-\epsilon$ with $\epsilon^2=1$.

Hence we come to the result: *For integral spin the quantization according to the exclusion principle is not possible. For this result it is essential, that the use of the D_1 function in place of the D function be, for general reasons, discarded.*

On the other hand, it is formally possible to quantize the theory for half-integral spins according to Einstein-Bose-statistics, *but according to the general result of the preceding section the energy of the system would not be positive.* Since for physical reasons it is necessary to postulate this, we must apply the exclusion principle in connection with Dirac's hole theory.

In conclusion we wish to state, that according to our opinion the connection between spin and statistics is one of the most important applications of the special relativity theory.

Consequences

Some examples:

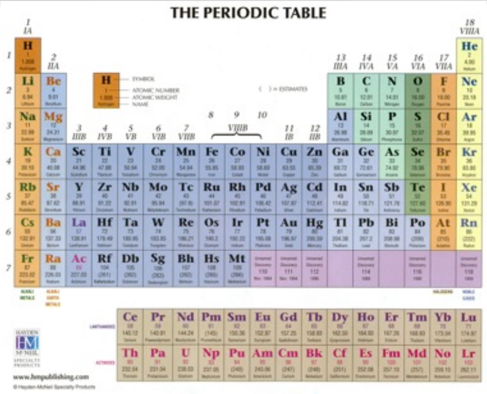
Periodic table of the elements

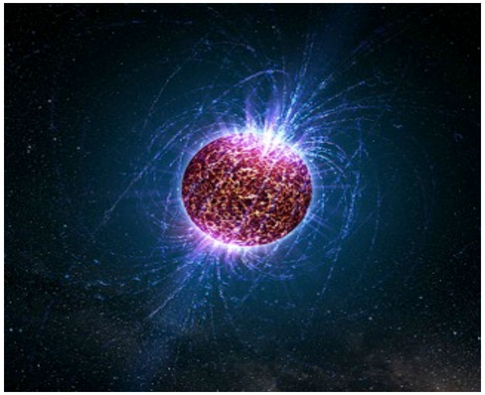
Stability of matter

Neutron stars

…… etc

So far no violation of the spin-statistics could be found
- but violations can arise in string theory





..The Pauli Exclusion Principle is one of the basic principles of modern physics and,even if there are no compelling reasons to doubt its validity, it is still debated today because an intuitive, elementary explanation is still missing.." [Bartalucci et al., 2006]

Many attempts were already made to accomplish small/tiny violation of the Pauli Principle.

The parameter “β ”

Ignatiev & Kuzmin model

creation and destruction operators connect 3 states

- the vacuum state $|0\rangle$
- the single occupancy state $|1\rangle$
- the non-standard double-occupancy state $|2\rangle$

through the following relations:

$$a|0\rangle = 0 \qquad a^{+}|0\rangle = |1\rangle$$
$$a|1\rangle = |0\rangle \qquad a^{+}|1\rangle = \beta|2\rangle$$
$$a|2\rangle = \beta|1\rangle \qquad a^{+}|2\rangle = 0$$

The parameter β quantifies the degree of violation in the transition $|1\rangle \rightarrow |2\rangle$. It is very small and for β→0 we can have the Fermi - Dirac statistic again.

PHYSICAL REVIEW D 78, 126009 (2008)

Spin-statistics violations in superstring theory

Mark G. Jackson*

Particle Astrophysics Center and Theory Group, Fermi National Accelerator Laboratory, Batavia, Illinois 60510, USA

(Received 28 October 2008; published 29 December 2008)

Experimental constraints

-Energy scale → high energy experiments

-Coupling constant → precision experiments
(like deviations from fermionic spin statistics)

$$\frac{\beta^2}{2} \leq 4.5 \times 10^{-28}.$$

VIP 2006

This bound is expected to improve another 2 orders of magnitude over the next few years due to larger integrated currents. Though the energy scale is low at only 8 keV, the incredible precision means this might be a viable way of detecting superstring-motived violations.

PRL 105, 051601 (2010) PHYSICAL REVIEW LETTERS week ending 30 JULY 2010

Non-Pauli Transitions from Spacetime Noncommutativity

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(Received 2 April 2010; published 26 July 2010)

The consideration of noncommutative spacetimes in quantum theory can be plausibly advocated from physics at the Planck scale. Typically, this noncommutativity is controlled by fixed "vectors" or "tensors" with numerical entries like $\theta_{\mu\nu}$ for the Moyal spacetime. In approaches enforcing Poincaré
particle state vectors. We
vents to Pauli-forbidden
tical spinorial particles.
sitions, we infer that the
scale beyond the Planck

TABLE I. Bounds on the noncommutativity parameter χ.

Experiment	Type	Bound on χ (length scales)	Bound on χ (energy scales)
Borexino	Nuclear	$\lesssim 10^{-43}$ m	$\gtrsim 10^{24}$ TeV
Kamiokande	Nuclear	10^{-42} m	10^{23} TeV
NEMO	Atomic	10^{-15} m	10^{8} eV
NEMO-2	Nuclear	10^{-41} m	10^{22} TeV
Maryland	Atomic	10^{-22} m	10^{3} TeV
VIP	Atomic	10^{-23} m	10^{4} TeV

Methods to test PEP

- Atomic transitions → VIP, VIP2
- Nuclear transitions
- Nuclear reactions
- Anomalous atomic structure
- Anomalous nuclear structure
- Statistics of neutrinos
- Astrophysics and cosmology

Methods to test PEP

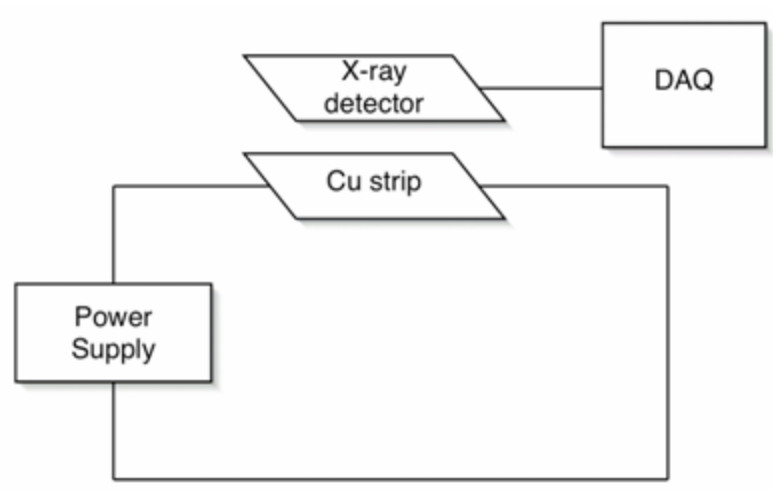
- Different methods – different assumptions
- Different systems, e.g. atoms, nuclei ...
- Clearest method: „new“ fermions testing PEP
- Avoiding Greenberg-Messiah superselection
- How to get „new“ fermions?
  - Radioactive source
  - Circulating current (Ramberg-Snow)
  - Pair production

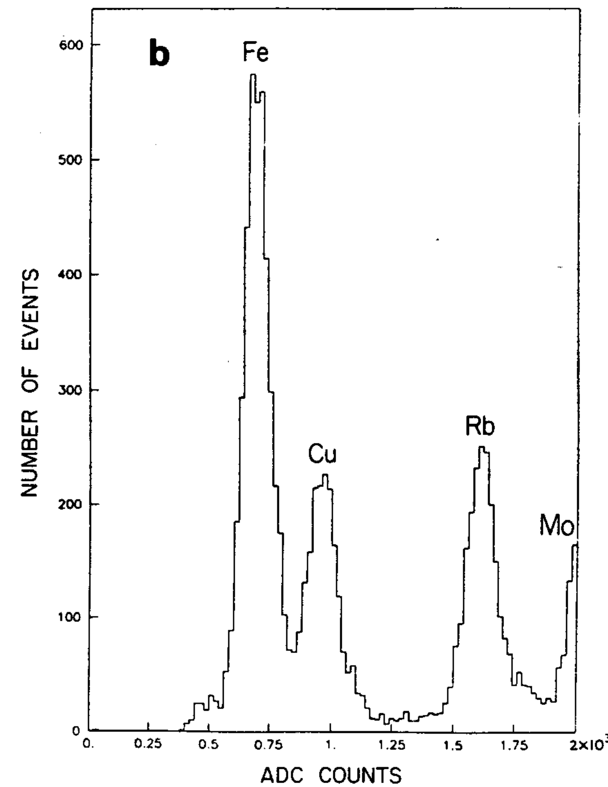
The pre-VIP experiment limit

Ramberg and Snow (RS)

Phys. Lett. ***B238*** *(1990) 438*

X-ray detector:
Closed proportional tube
Detector calibration
ΔE ~ 1200 eV @ 8keV

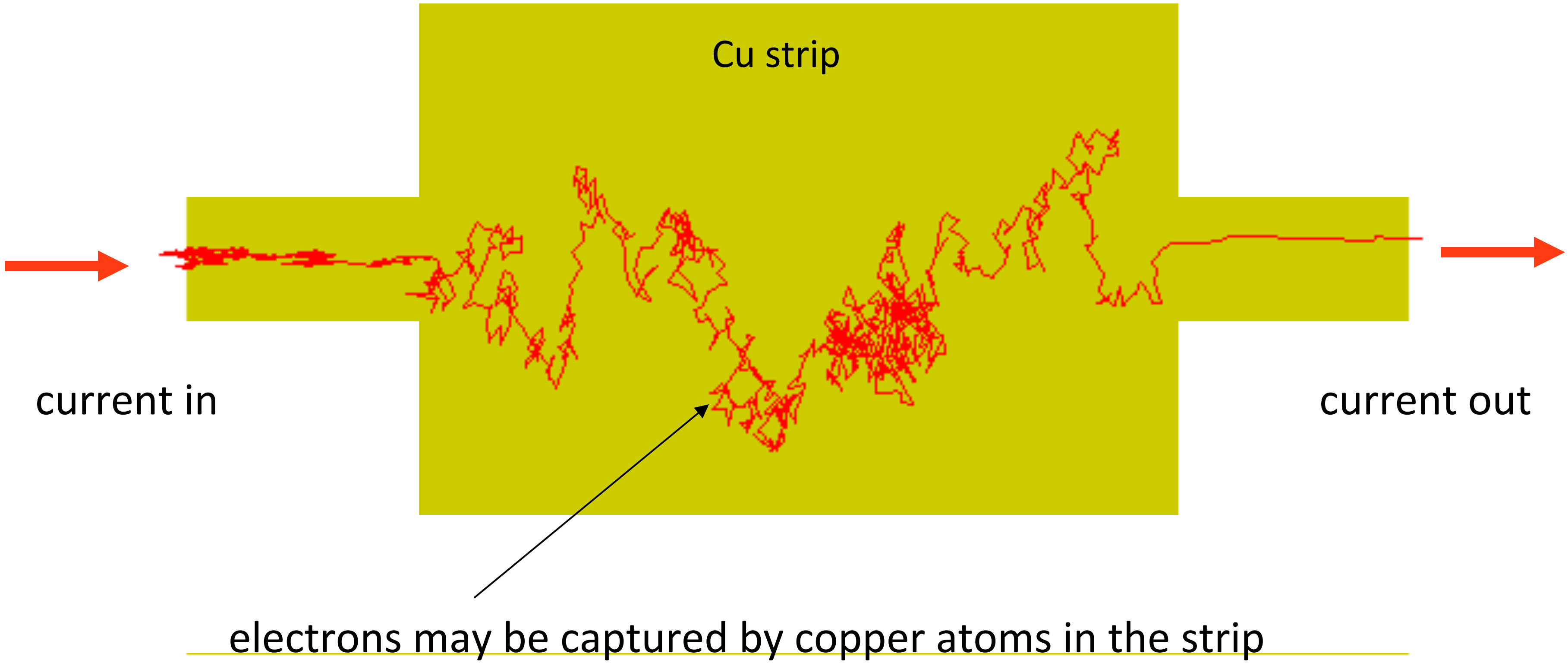




$$N_X \geq \beta^2 \left(0.90 \cdot 10^{28}\right)$$

$$\beta^2 / 2 \leq 1.7 \cdot 10^{-26} (> 95\% C.L.)$$

random walk of the conduction electrons in the copper strip



PEP Tests with atomic transitions

From S.R. Elliott et al., Found. Phys. 42 (2012) 1015

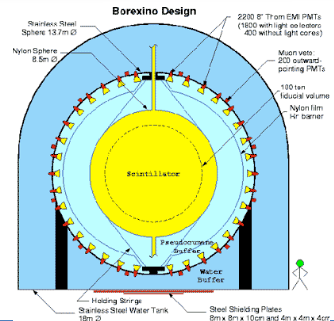
Process	Type	Experimental limit	$\frac{1}{2}\beta^2$ limit
Atomic transitions			
$\beta^- + \text{Pb} \to \check{\text{Pb}}$	Ia		3×10^{-2}
$e^-_{pp} + \text{Ge} \to \check{\text{Ge}}$	Ia		1.4×10^{-3}
$e^-_I + \text{Cu} \to \check{\text{Cu}}$	II		1.7×10^{-26}
$e^-_I + \text{Cu} \to \check{\text{Cu}}$	II		4.5×10^{-28}
$e^-_I + \text{Cu} \to \check{\text{Cu}}$	II		6.0×10^{-29}
$e^-_I + \text{Pb} \to \check{\text{Pb}}$	II		1.5×10^{-27}
$e^-_f + \text{Pb} \to \check{\text{Pb}}$	IIa		2.6×10^{-39}
$\text{I} \to \check{\text{I}} + \text{X-ray}$	III	$\tau > 2 \times 10^{27}$ sec	3×10^{-44}
$\text{I} \to \check{\text{I}} + \text{X-ray}$	III	$\tau > 4.7 \times 10^{30}$ sec	6.5×10^{-46}

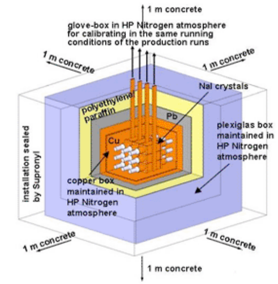
Recently created fermions interacting with system

Distant fermions interacting with system

Stable system transition

Best limits for PEP Violation





Simplified schema of ~ 100 kg NaI(Tl) set-up

Nuclear transition	$^{12}C \rightarrow {}^{11}B + p$	BOREXINO @LNGS	$\frac{\beta^2}{2} < 7.4 \cdot 10^{-60}$	G. Bellini et al., PRC 81 (2010) 034,317
Atomic transition	$I \rightarrow I + \gamma$	DAMA @LNGS	$\frac{\beta^2}{2} < 4.7 \cdot 10^{-46}$	R. Bernabei et al., Eur. Phys. J. C62 (2009) 327

PHYSICAL REVIEW C **81**, 034317 (2010)

New experimental limits on the Pauli-forbidden transitions in ^{12}C nuclei obtained with 485 days Borexino data

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F. Calaprice,[4] A. Chavar
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I. Machulin,[8] A. Sabelni
S. Gazzana,[10] C. Ghiano,[10] Aldo Ianni,[10] G. Korga,[10] D. Montanari,[10] A. Razeto,[10] R. Tartaglia,[10] M. Goeger-Neff,[11] T. Lewke,[11] Q. Meindl,[11] L. Oberauer,[11] F. von Feilitzsch,[11] Y. Winter,[11] M. Wurm,[11] C. Grieb,[12] S. Hardy,[12] M. Joyce,[12] S. Manecki,[12] L. Papp,[12] R. S. Raghavan,[12] D. Rountree,[12] R. B. Vogelaar,[12] W. Maneschg,[13] S. Schönert,[13] H. Simgen,[13] G. Zuzel,[13] M. Misiaszek,[14] M. Wojcik,[14] F. Ortica,[15] and A. Romani[15]
(Borexino Collaboration)

However: Stable system transitions !

Nuclear Physics in Astrophysics IV — IOP Publishing
Journal of Physics: Conference Series **202** (2010) 012039 — doi:10.1088/1742-6596/202/1/012039

Exclusion

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[8] University of Jing Gangshan, Jiangxi, China

Abstract. Searches for non-paulian nuclear processes, i.e. processes normally forbidden by the Pauli–Exclusion–Principle (PEP) with highly radiopure NaI(Tl) scintillators allow the test of this fundamental principle with high sensitivity. Status and perspectives are briefly addressed.

Goal of VIP (**VI**olation of the **P**auli Principle)

The VIP experiment has the scientific goal of reducing by four orders of magnitude the limits on the probability of a possible violations of the Pauli exclusion principle for the electrons

From:

(Ramberg & Snow -1990)

$$\beta^2/2 \leq 1.7 \cdot 10^{-26} (> 95\% \ C.L.)$$

to

$$\beta^2/2 \leq 10^{-30}$$

THE INTERNATIONAL VIP COLLABORATION

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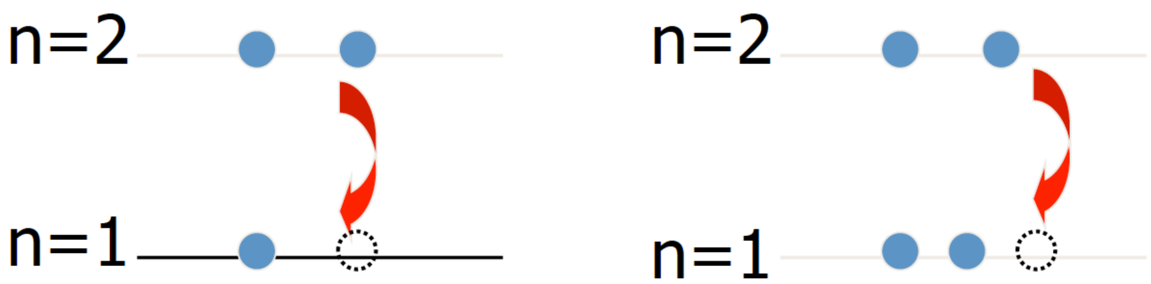
VIP Method: Improved Ramberg-Snow method: Introducing electrons via a current for probing

Search for anomalous X-ray transitions



Normal 2p →1s transition

2p →1s transition violating Pauli principle

8.05 keV in Cu

~ 7.7 keV in Cu

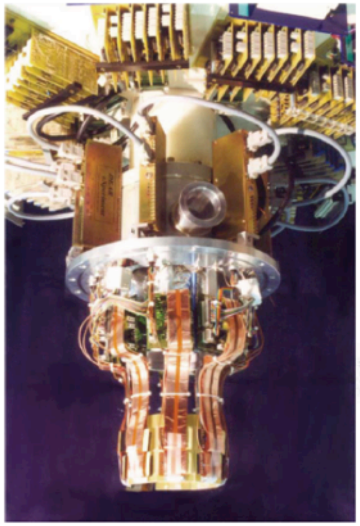
Transition energies of anomalous X-rays in Cu

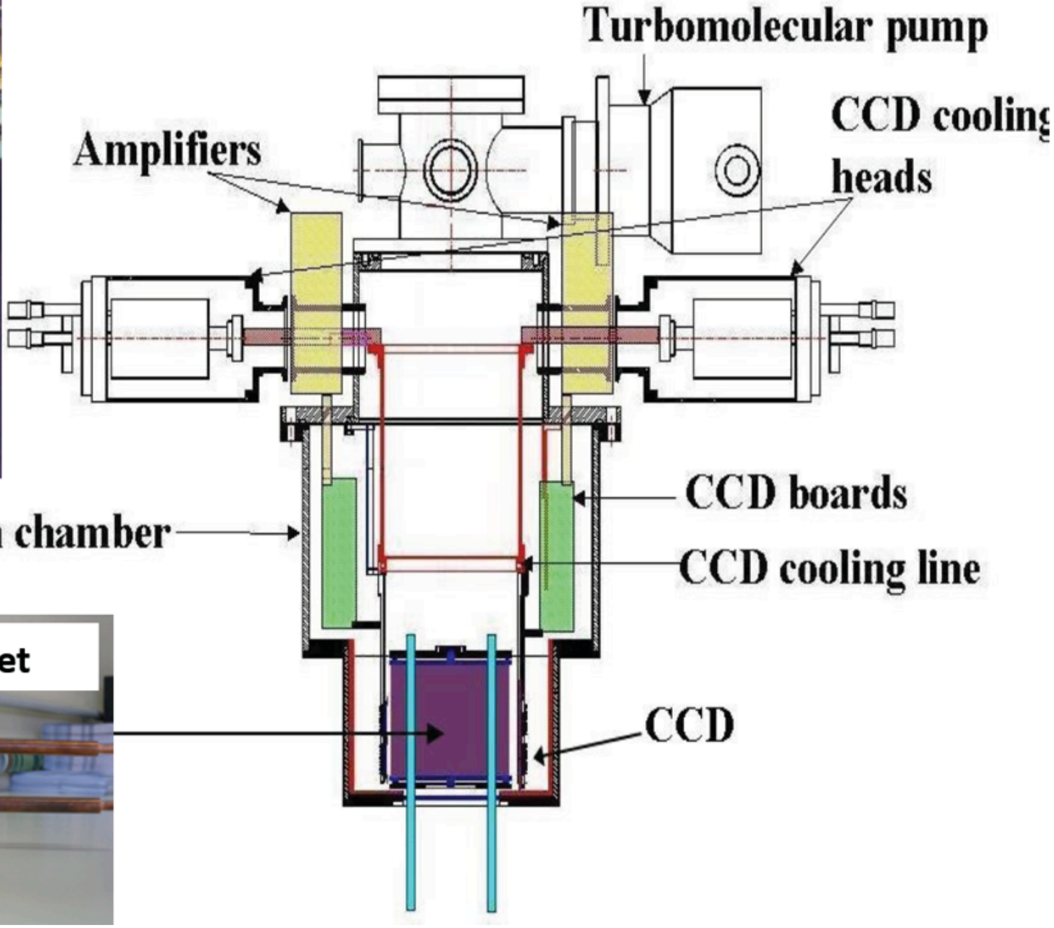
Multiconfiguration Dirac-Fock approach
(including rel. corrections, lamb shift, Breit operator, radiative corrections)

Transition	Initial en.	Final en.	Transition energy (eV)	Radiative transition rate (s-1)	Multipole order	
$2p_{1/2}$ - $1s_{1/2}$	-45799	-53528	7729	2.63E+14	E1	K_α
$2p_{3/2}$ - $1s_{1/2}$	-45780	-53528	7748	2.56E+14	E1+M2	
$3p_{1/2}$ - $1s_{1/2}$	-44998	-53528	8530	2.78E+13	E1	K_β
$3p_{3/2}$ - $1s_{1/2}$	-44996	-53528	8532	2.68E+13	E1+M2	

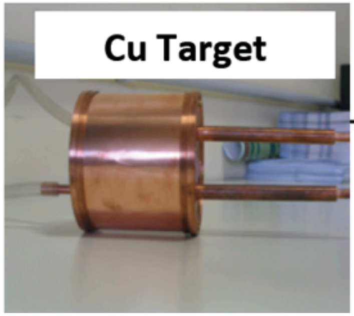
"Normal" 2p-1s transition in Cu @ 8040 eV → ~ 300 eV difference in energy, experimentally resolvable

VIP Apparatus

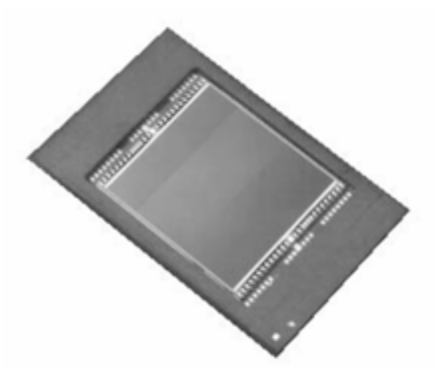




High purity Cu (99.997%)
R= 45 mm
H=88 mm
D=50 μm

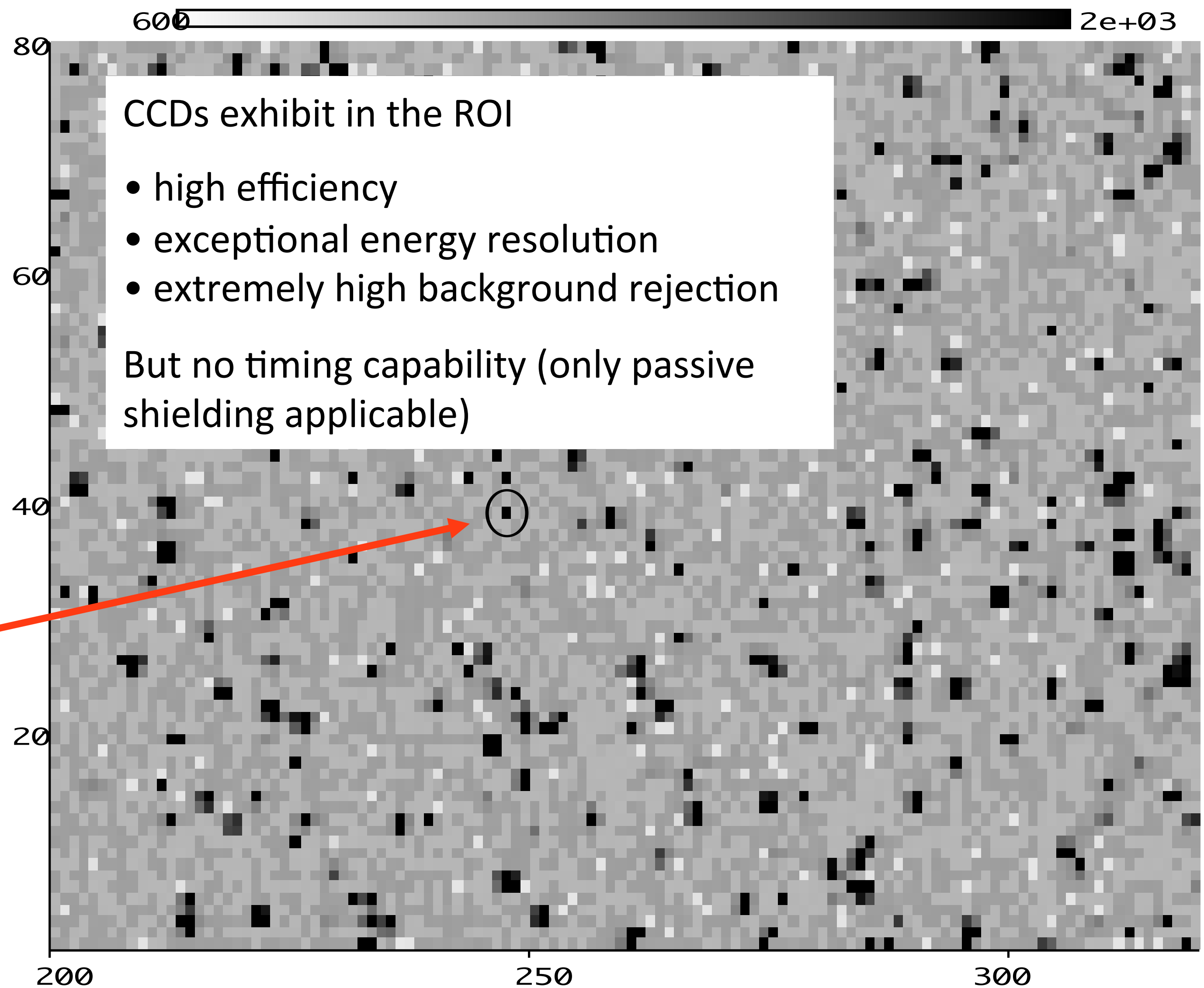


The VIP X-ray detectors: CCDs



EEV CCD55
(1252 x 1152 pixels,
22.5 μm x 22.5 μm)

single pixel event,
X-ray photon



CCDs exhibit in the ROI

- high efficiency
- exceptional energy resolution
- extremely high background rejection

But no timing capability (only passive shielding applicable)

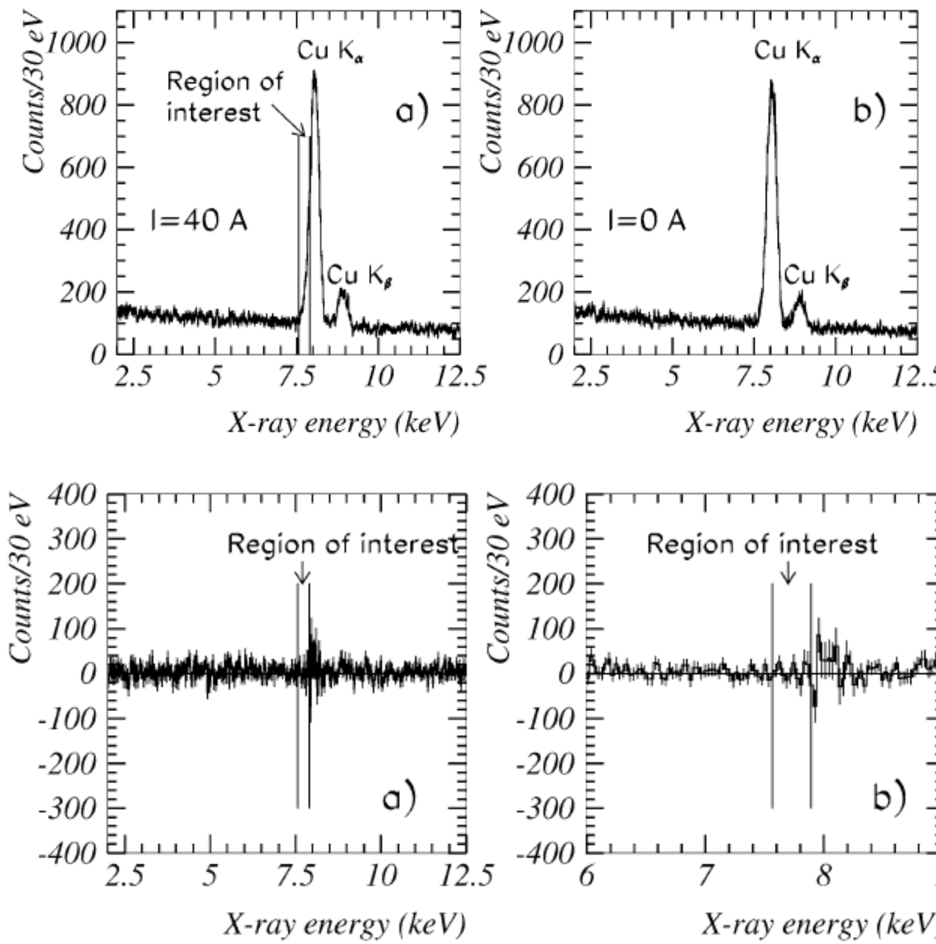
X-ray spectra with the VIP final setup at LNF

2 types of measurements:

14510 min with I=40A
14510 min with I=0A

Subtraction gives:

$$\Delta N_X = -21 \pm 73$$



Analysis of VIP with RS method:

$$\int_T I(t)dt = 34.824\cdot 10^6 C$$

$$D = 0.088m$$

$$\mu = 3.9\cdot 10^{-8} m$$

$$\rho = 8.96\cdot 10^3 kg\cdot m^{-3}$$

$$f_g \approx 0.01$$

$$\Delta N_X \geq \frac{1}{2}\beta^2 N_{new}\frac{N_{int}}{10} f_g = \frac{\beta^2(\Sigma I\Delta t)D}{e\mu}\frac{1}{20} f_g$$

$$\Delta N_X \geq \frac{\beta^2}{2}\left(4.9\cdot 10^{29}\right)$$

$$\Delta N_X = -21 \pm 73$$

$$\frac{\beta^2}{2} \leq \frac{3\cdot 73}{4.9\cdot 10^{29}}$$

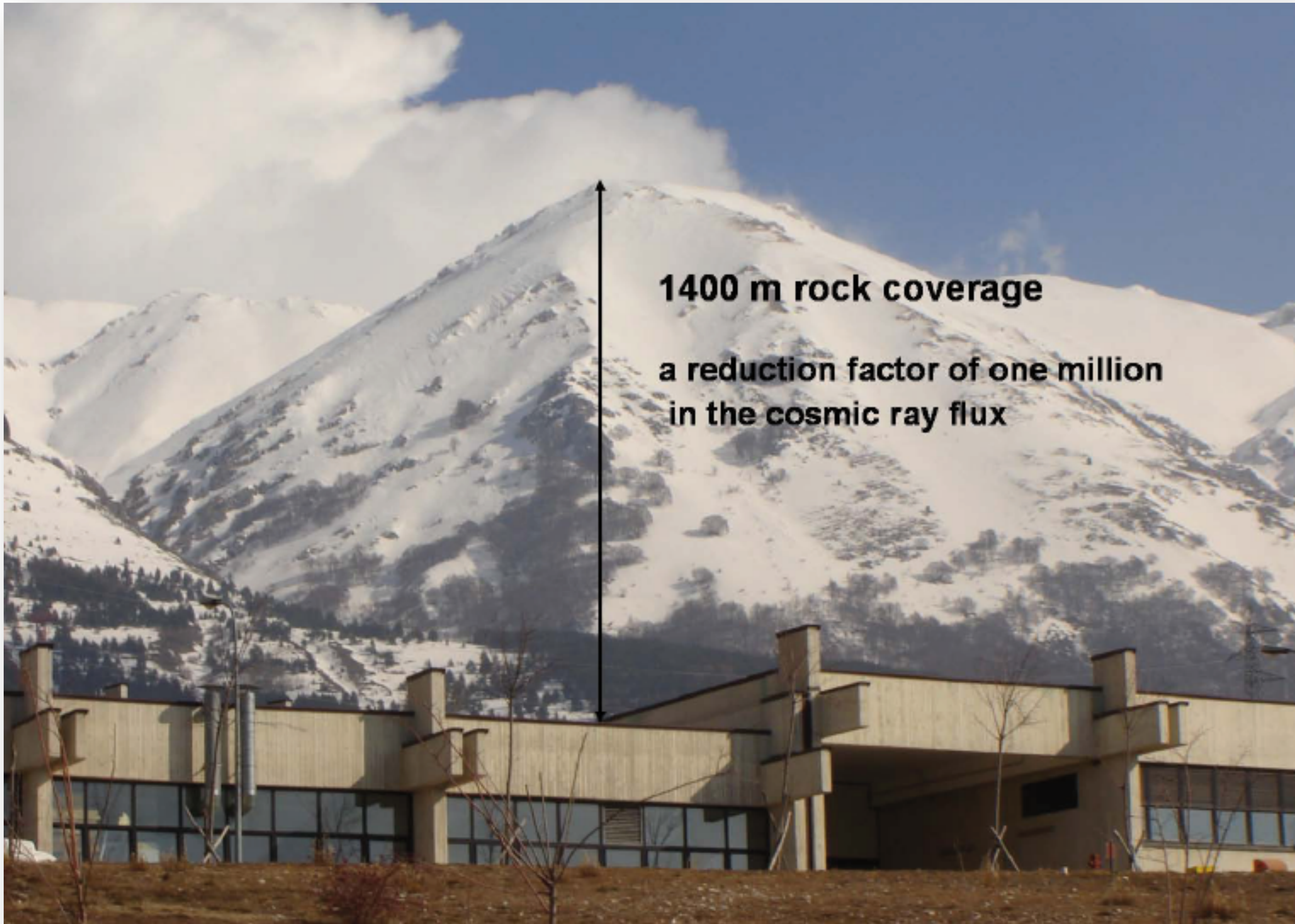
$$\frac{\beta^2}{2} \leq 4.5\cdot 10^{-28} \quad at\, 99.7\, C.L.$$

S. Bartalucci, et. al, Physics Letters B 641, 18 (2006).

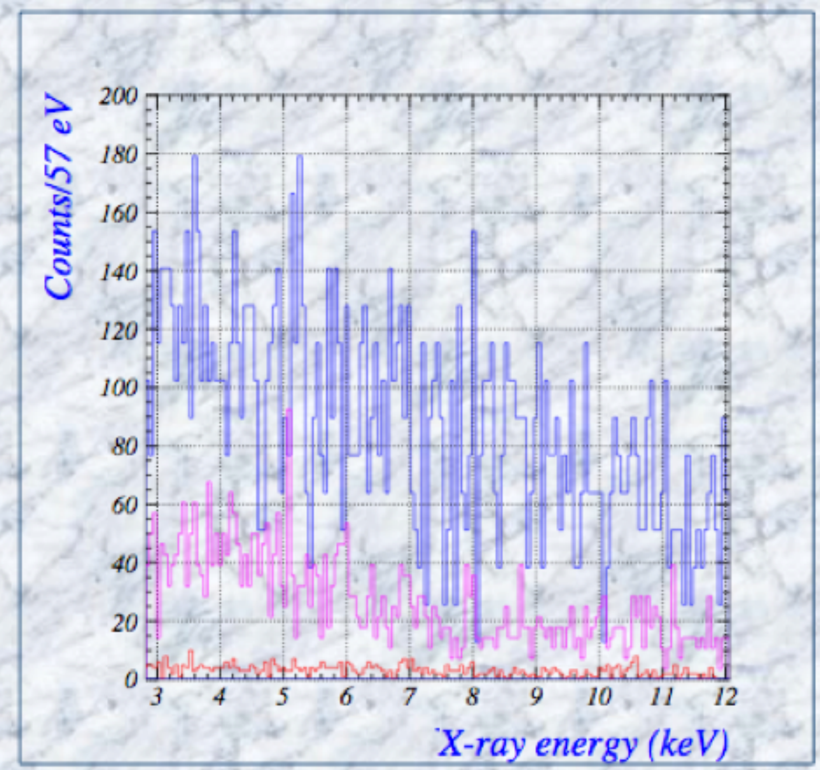
Test site and final location:

Laboratori Nazionali del Gran Sasso (LNGS), Istituto Nazionale di Fisica Nucleare

LNGS


1400 m rock coverage
a reduction factor of one million
in the cosmic ray flux

Why at LNGS ?



2 CCD test setup – normalized distributions

— Lab no sh.

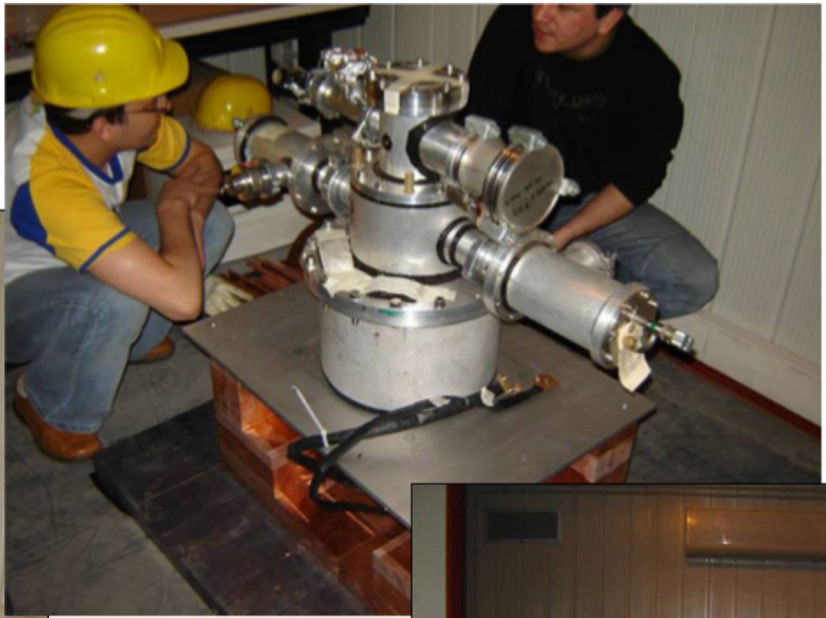
— Lab with sh.

— LNGS with sh.

Background reduced by a factor ~ 20

SIF - XCIII Congresso Nazionale   Pisa, 24-29 Settembre 2007   10

VIP Setup at LNGS




VIP Experiment at LNGS Thu Apr 13 2006 12:19:35

VIP-LNGS result

After about 2 years running

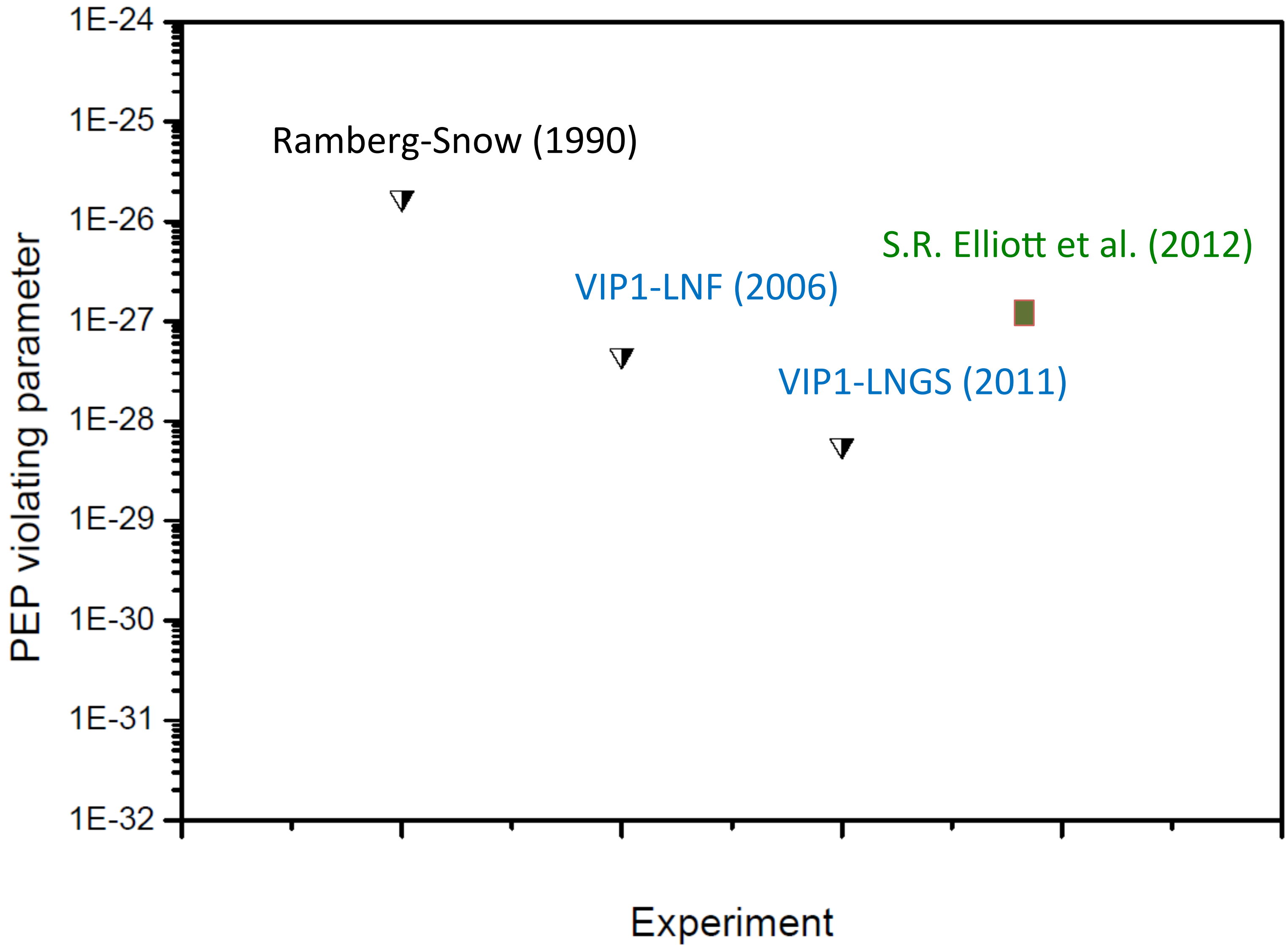
$$\beta^2/2 < 4.7 \times 10^{-29}$$

(Preliminary)

L. Sperandio Ph. D. Thesis, Univ. Roma2, 2008
C. Curceanu et al., Phys. Proc. 17 (2011) 40
C. Curceanu et al., Journal of Physics: Conference Series 361 (2012) 012006
J. Marton et al., J. Phys., Conf. Ser. 447 (2013) 012070

Experiments testing PEP using "fresh" electrons

Experiment	Year	Material	Limit	Source	Publication
M. Goldhaber, G. Scharff Goldhaber	1948	Pb	$3 \cdot 10^{-2}$	electrons from β^- decay	PR 73 (1948) 1492
E. Ramberg, G.A. Snow	1990	Cu	$1{,}7 \cdot 10^{-26}$	electric current	PLB 238 (1990) 438
S. Bartalucci et al. (VIP)	2006	Cu	$4{,}5 \cdot 10^{-28}$	electric current	PLB 641 (2006) 18
C. Curceanu et al. (VIP)	2011	Cu	$4{,}7 \cdot 10^{-29}$	electric current	Phys. Proc. 17 (2011) 40
S.R. Elliott et al.	2012	Pb	$1{,}5 \cdot 10^{-27}$	electric current	Found. Phys. 42 (2012) 1015


1E-24
1E-25
1E-26
1E-27
1E-28
1E-29
1E-30
1E-31
1E-32
PEP violating parameter
Ramberg-Snow (1990)
VIP1-LNF (2006)
S.R. Elliott et al. (2012)
VIP1-LNGS (2011)
Experiment

How to increase the sensitivity?

- More „fresh“ electrons – higher current limited by heat dissipation
- Higher x-ray efficiency: increase of detector solid angle, intrinsic efficiency
- Reduce background: small efficient detectors
- Better energy resolution
- Optimize shilding: low activity material (inner layer), active shielding

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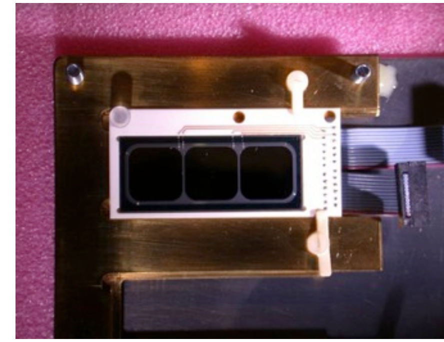
Improved experiment VIP2

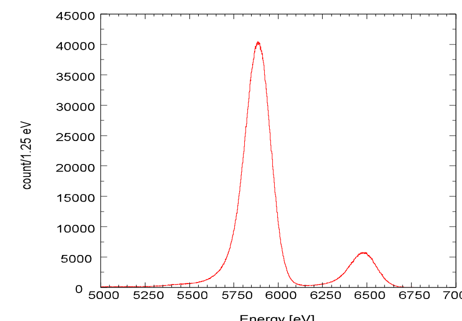
- Large (1 cm^2) SDDs provide excellent energy resolution (even superior than CCDs at 8keV)

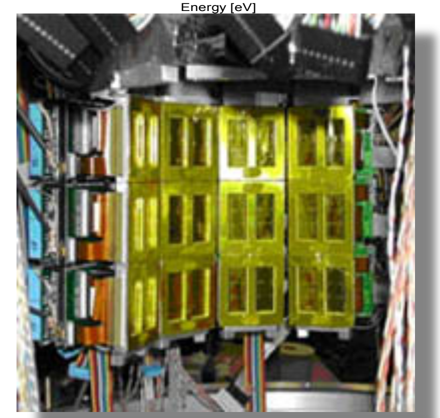
- Timing capability for triggering

- Compact design suitable for gaining larger solid angle

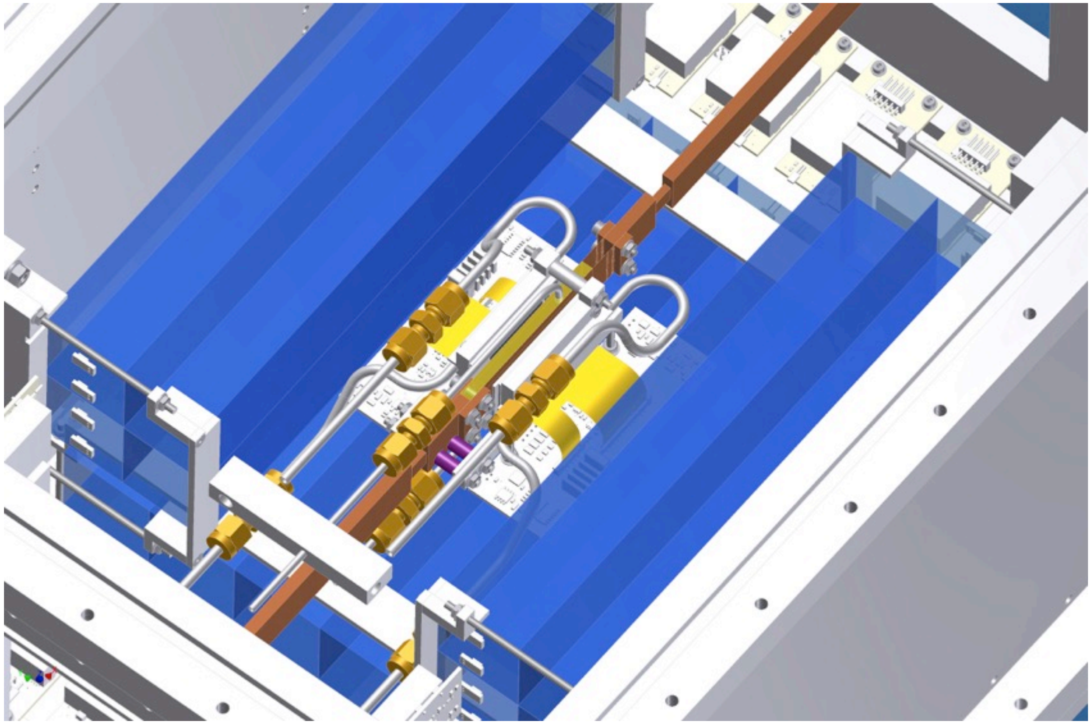
- Successfully used in the detection of kaonic atom x-ray spectroscopy at DAFNE (SIDDHARTA) with large background reduction

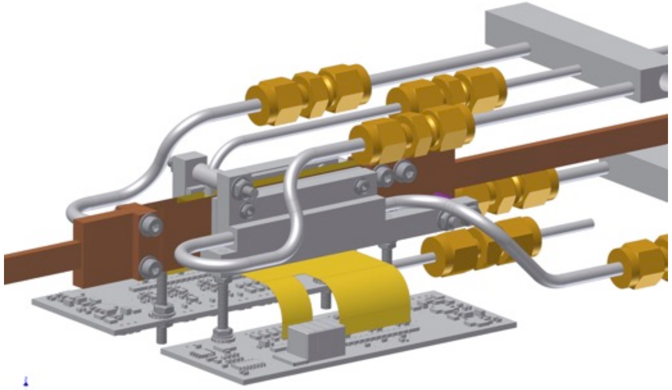


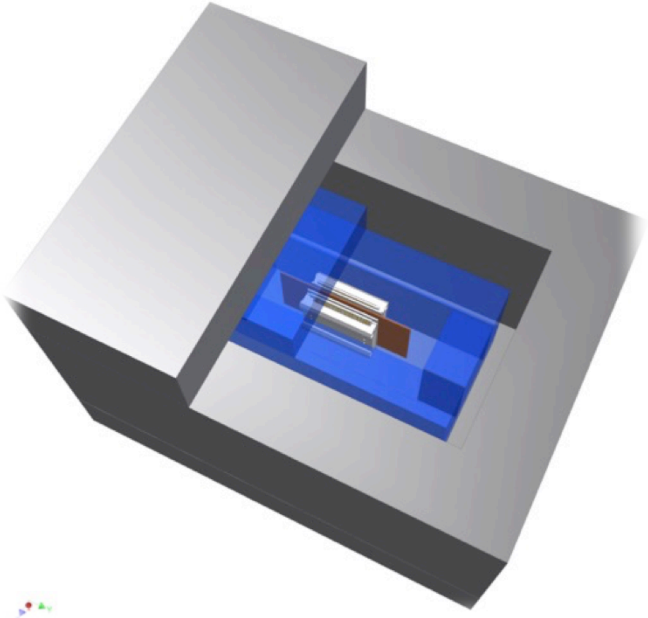




Sketch of the VIP2 Setup: Cu foil, 2x3 SDD x-ray detectors



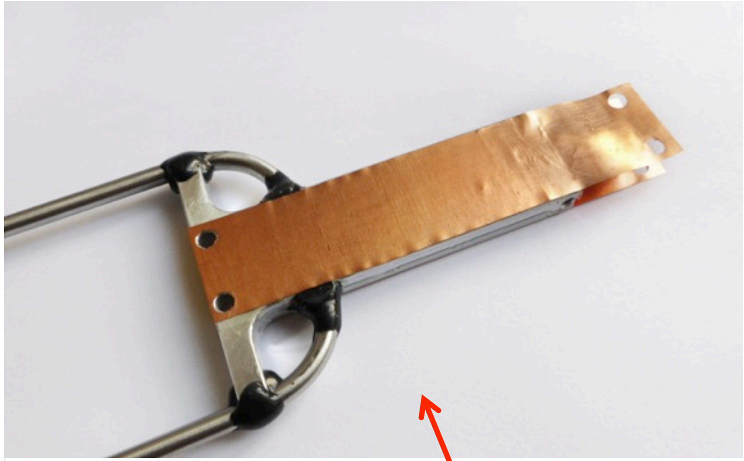


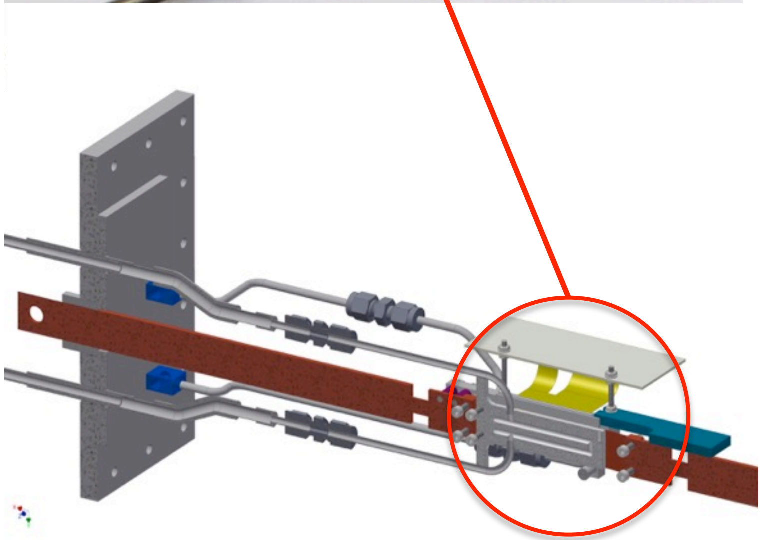


Copper target VIP2

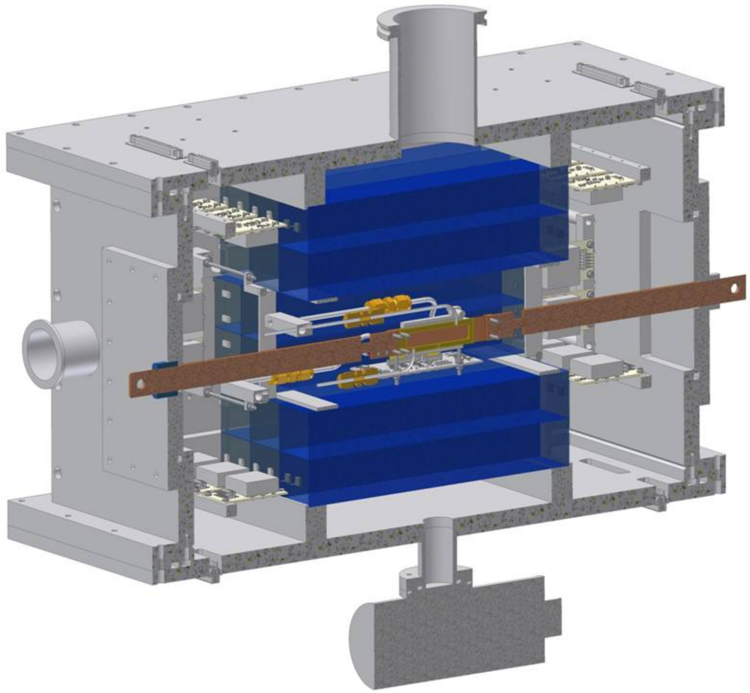
Length: 30 mm
Width: 10 mm
Cross section: 0.4 mm^2

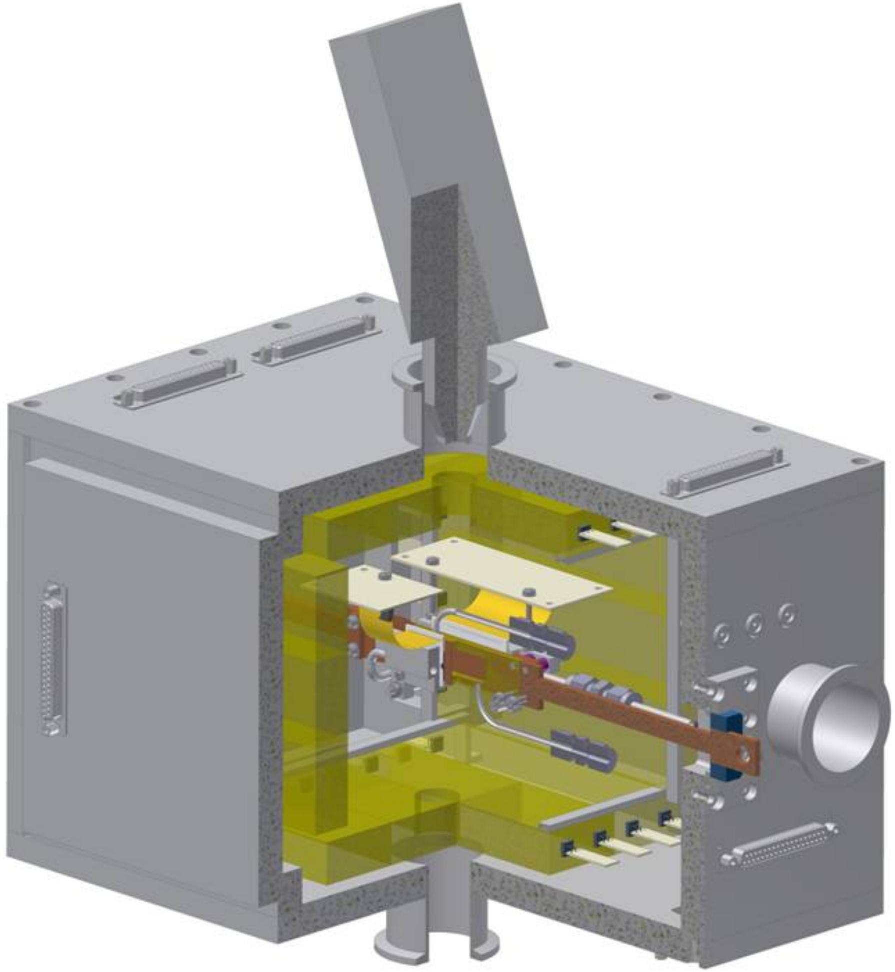
Current: 100 A



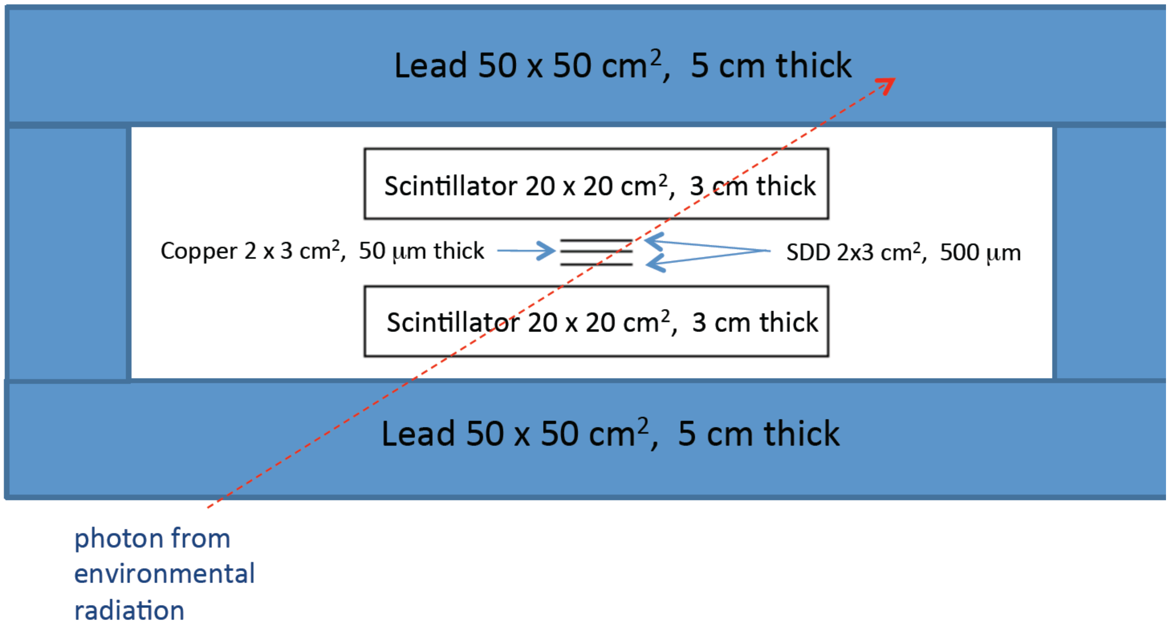


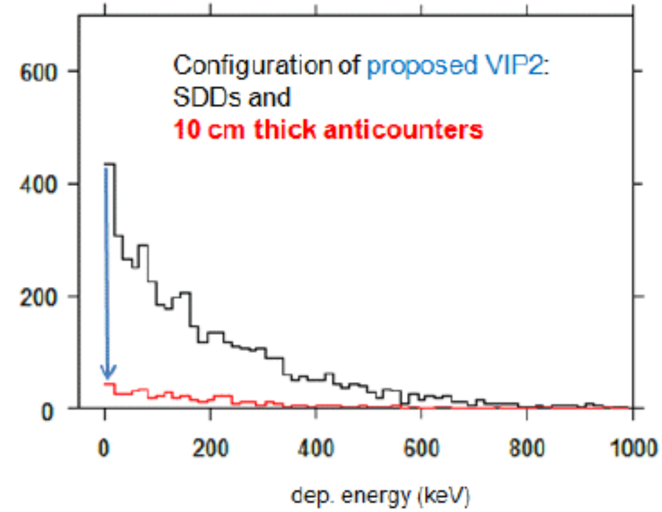
Sketch of the VIP2 Setup
Passive shielding removed





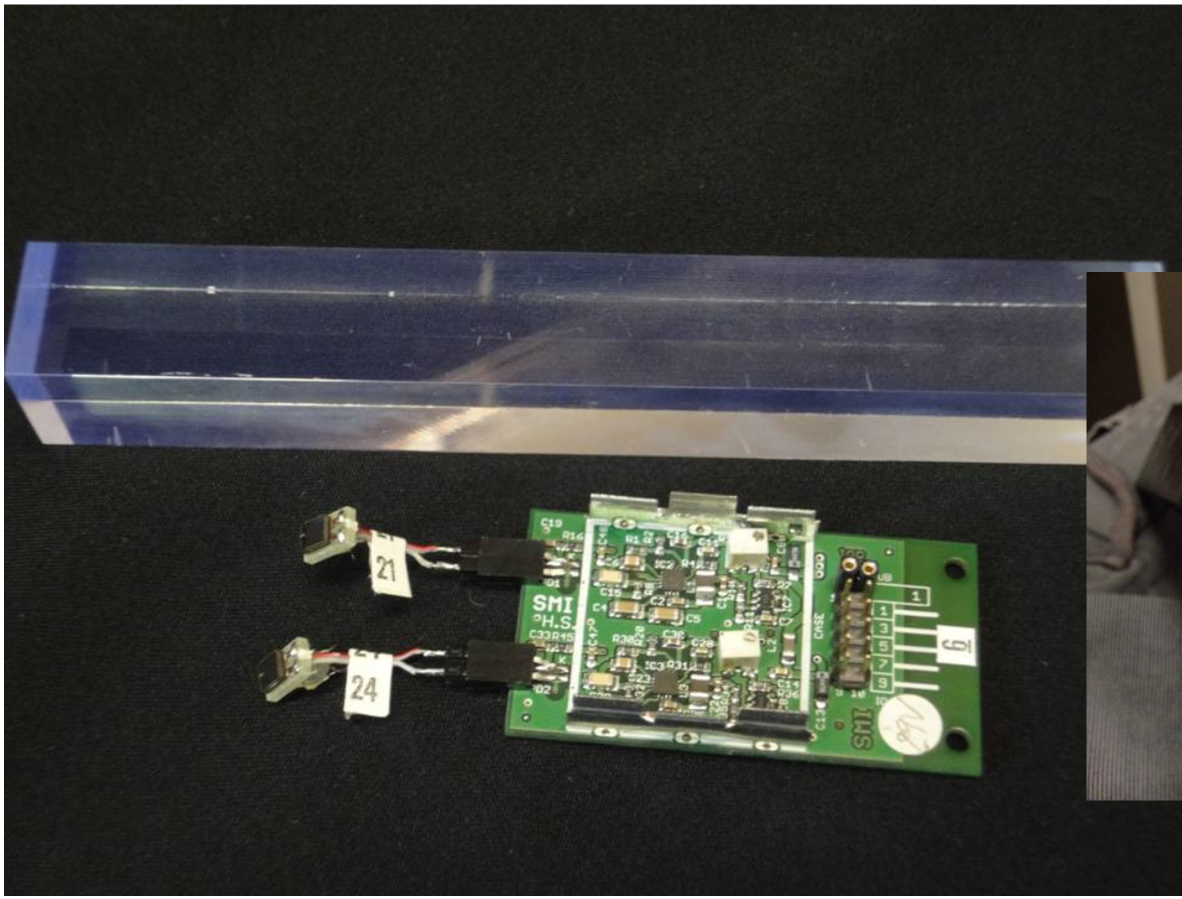
Background reduction for VIP2 by active shielding



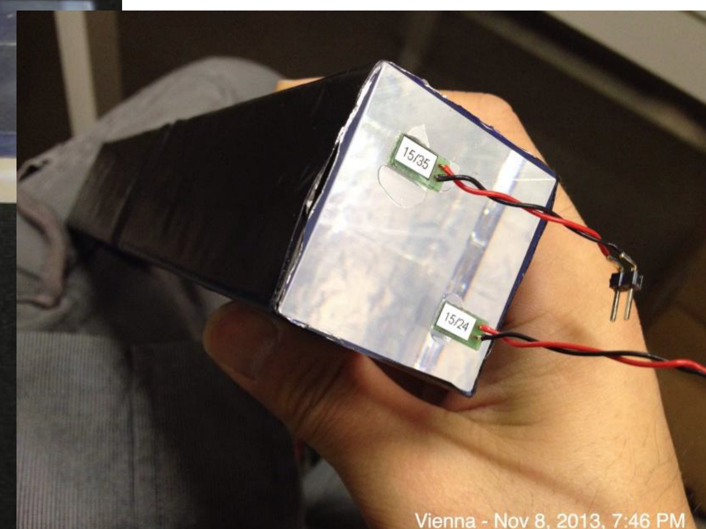


Scheme of a setup with plastic scintillators sandwiching the SDD x-ray detectors (scheme for Monte-Carlo simulation)

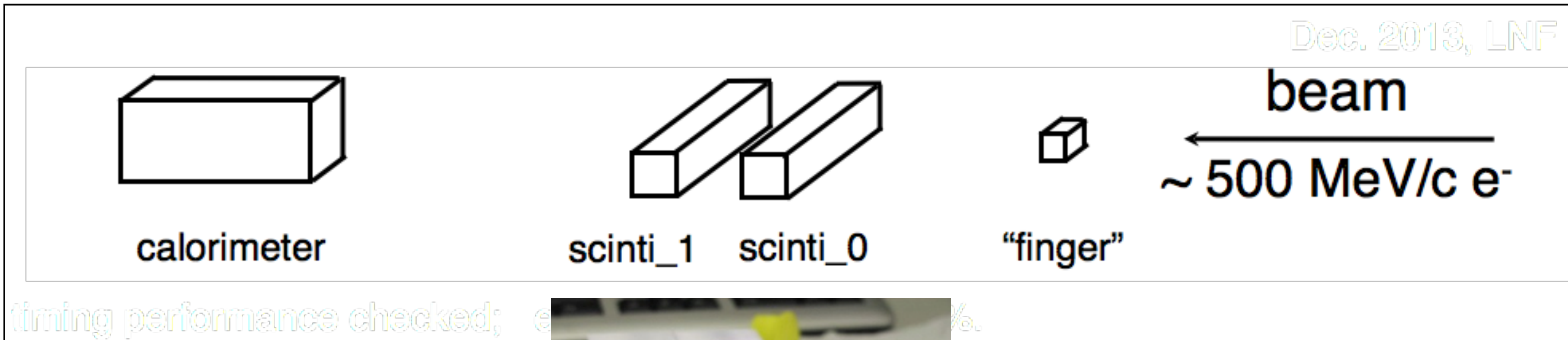
VIP2 Active shielding with scintillators

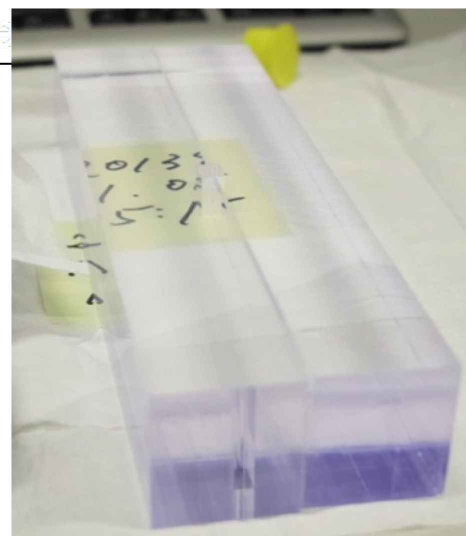


Scintillator module
For VIP2 active shielding
Readout with SiPM



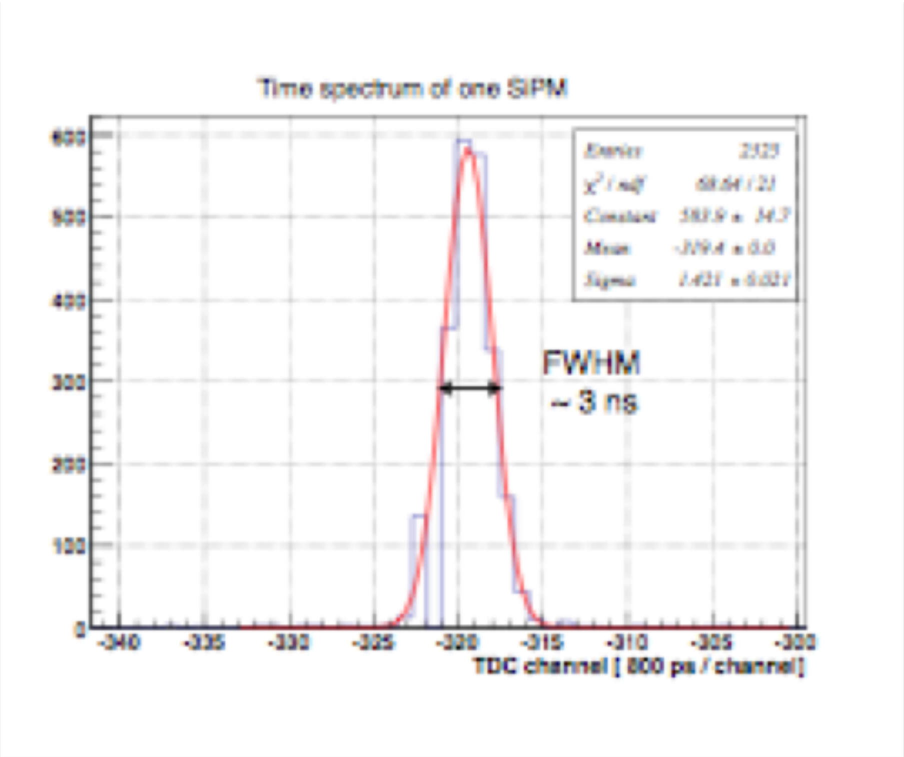
Scintillator timing tests at BTF

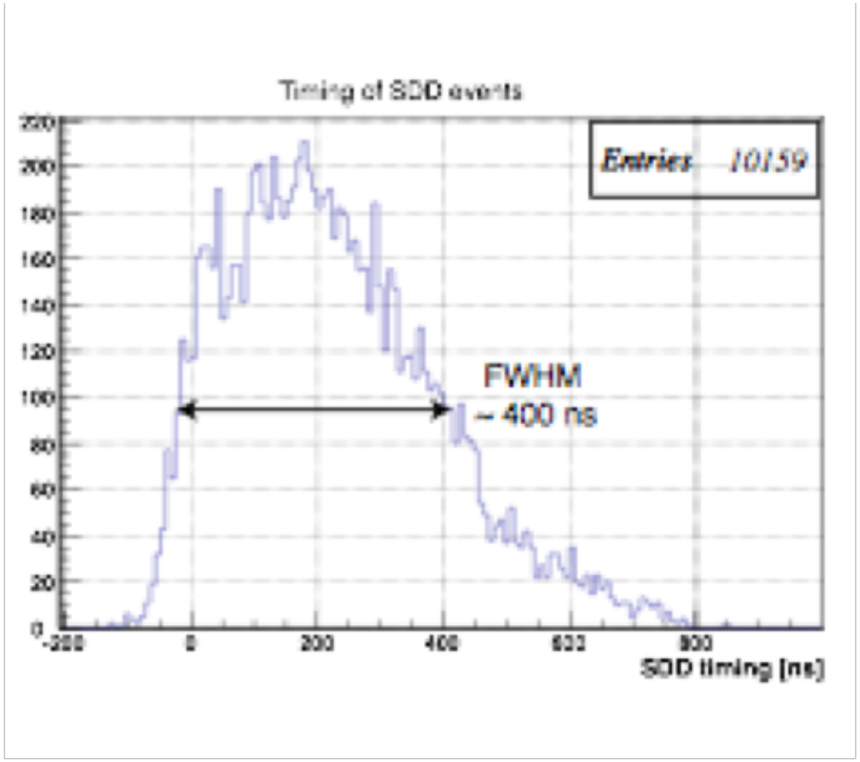




Timing performance tested
Detection efficiency >97%

Detector timing performance

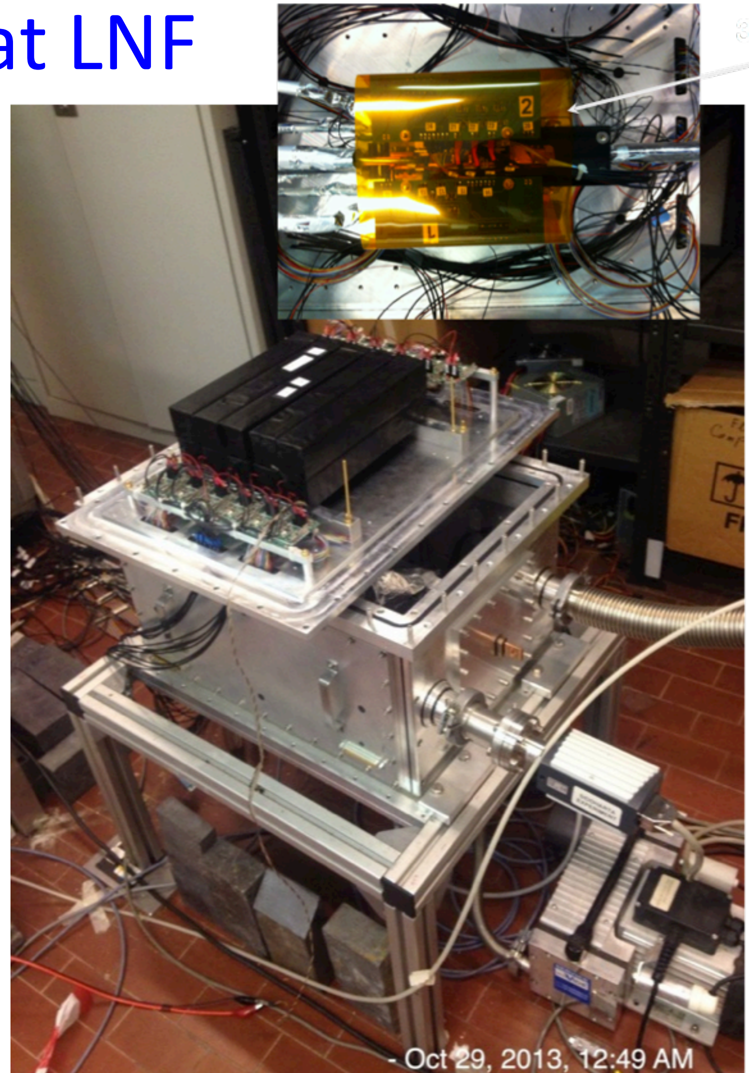




time resolution of scintillator from BTF measurement

time resolution of SDDs from test setup measurement of cosmic rays

Test setup at LNF



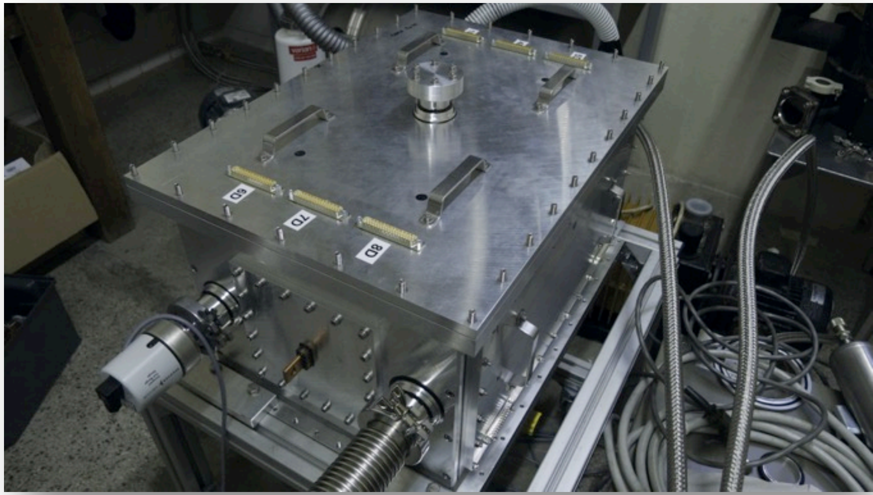
10 Scintillation detectors for active shielding with SiPM readout

VIP2 Features

Changes		Factor
Acceptance	12% (1%)	12
Higher current	100A (50A)	2
Reduced length	3 cm (8.8 cm)	1/3
Total linear factor		8
Better SDD energy resolution	170 eV (340 eV)	4
Reduced active area	6 cm2 (114 cm^2)	20
Better shielding and veto		5-10
Higher SDD efficiency		1/2
Background reduction		200-400
Overall improvement		>120

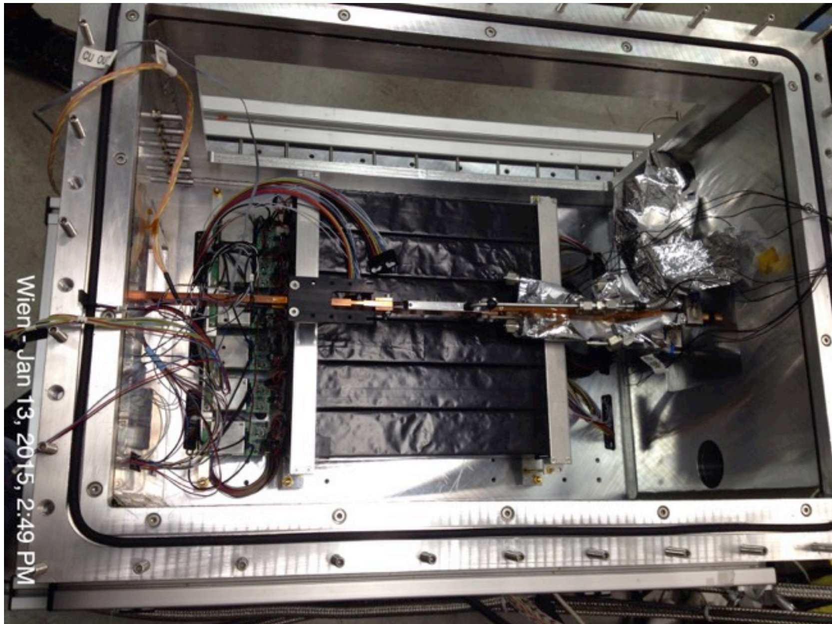
→ Limit from 10^{-29} to 10^{-31}

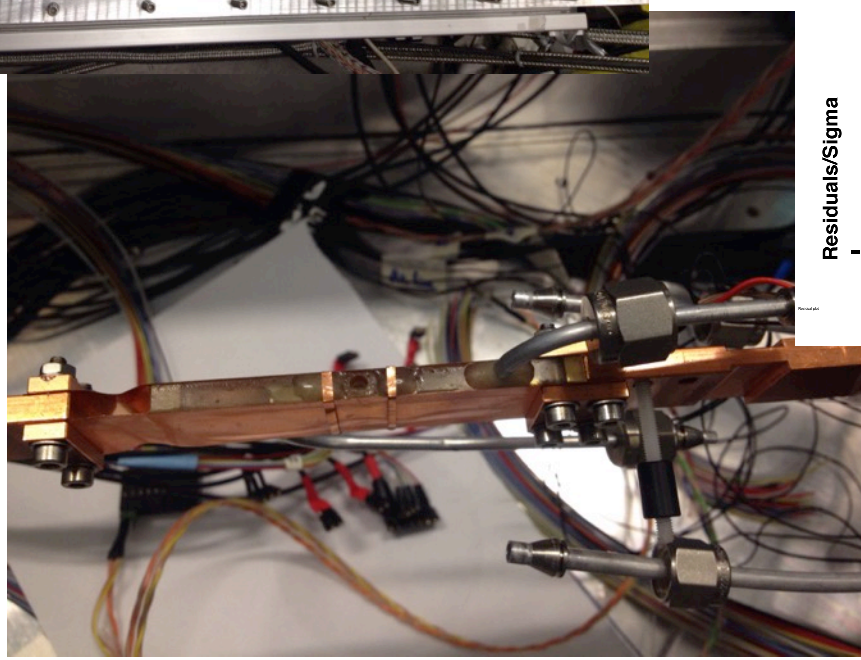
Current Status

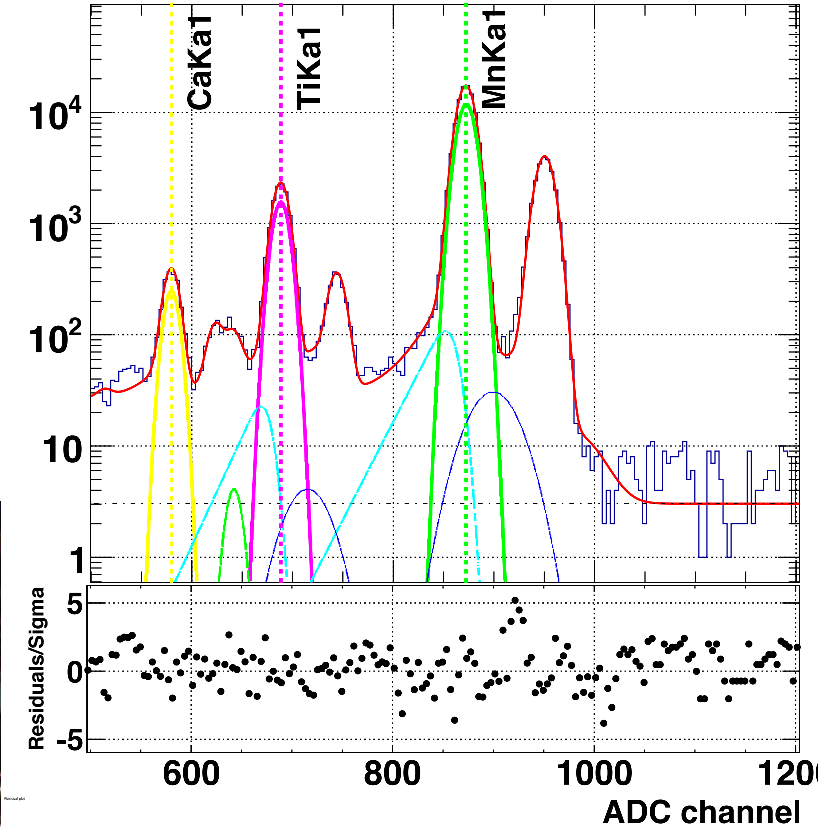


- VIP2 inner setup under test in the laboratory
  - Cooling/Cryogenics
  - SDDs: stability, calibration, energy resolution
  - Active shielding tests
  - Tests with current (target up to 180A operated)

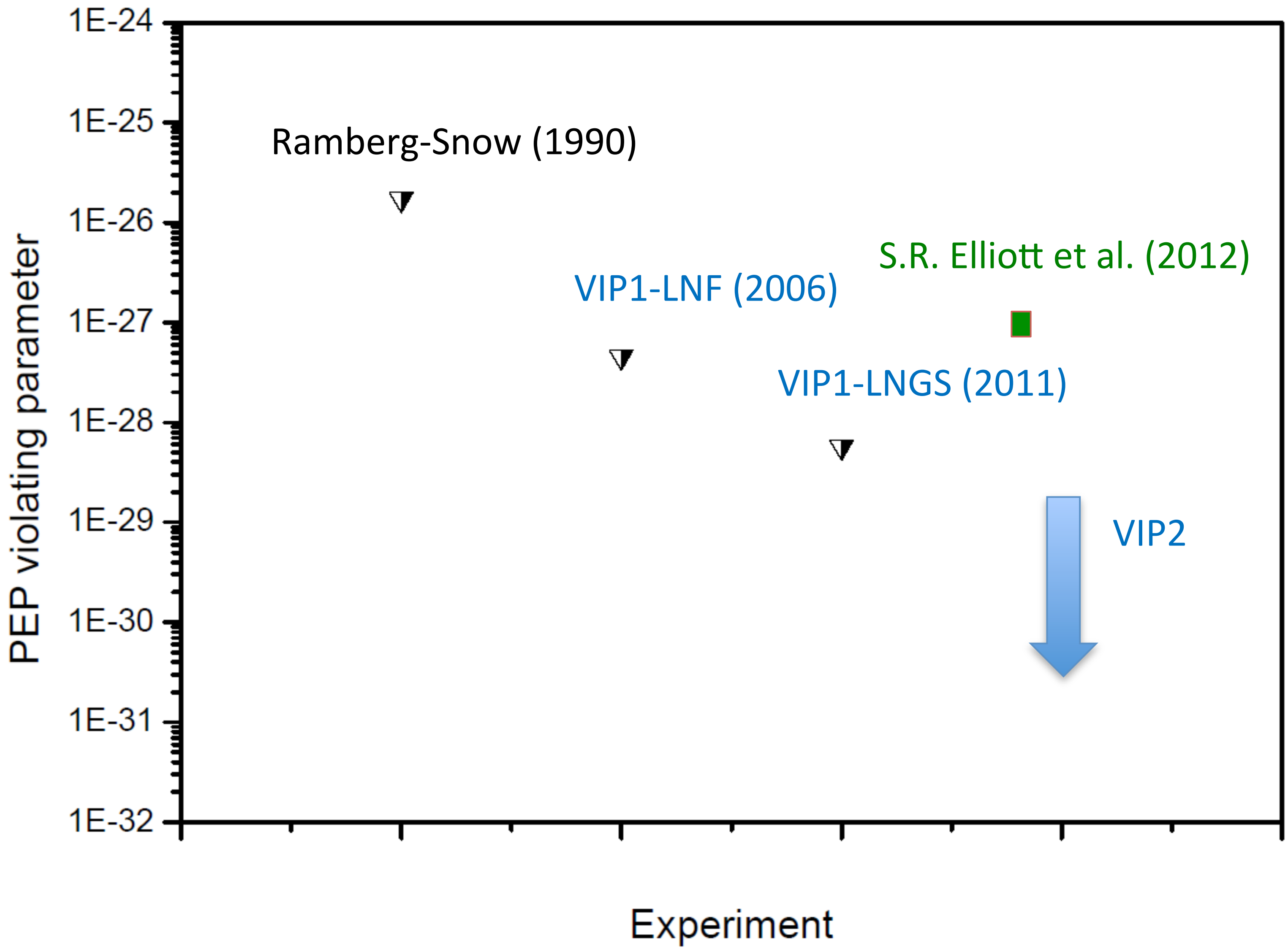
- Setup at LNGS in 2015







SDD Calibration: radioactive Source, X-ray tube


1E-24
1E-25
1E-26
1E-27
1E-28
1E-29
1E-30
1E-31
1E-32
PEP violating parameter
Ramberg-Snow (1990)
VIP1-LNF (2006)
S.R. Elliott et al. (2012)
VIP1-LNGS (2011)
VIP2
Experiment

Summary and Outlook

- Pauli principle – a fundamental rule of nature but difficult to explain in a simple way.
- Pauli principle violation can be studied searching for Pauli-forbidden atomic transitions (using "new" electrons) with very high sensitivity.
- VIP experiment in Gran Sasso set the best limit ($\approx 10^{-29}$) for PEP violation for electrons using the Ramberg-Snow method.
- VIP aims at improving the sensitivity by orders of magnitudes (new X-ray detectors, active shielding).

Thank you for your attention

Oscar W. Greenberg (2012)

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The search for fundamental properties of the physical world is crucial
for our understanding of Nature.
A great deal of effort has been devoted to testing special relativity,
that the speed of light is the maximum velocity of propagation of physical
effects. Similar efforts have been devoted to testing the validity of CPT
symmetry. The Pauli exclusion principle is another basic property that should
be tested to high accuracy. Any detection of violation of the exclusion
principle will have far reaching impact on physics.
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Spare

Cosmological limits

Process	Type	Experimental Limit	$\frac{1}{2}\beta^2$ limit
Astrophysics and Cosmology			
Solar burning and p-p bound state	IIa		$< 1.6 \times 10^{-15}$
Primordial nucleosynthesis and $^5\tilde{Li}$	I	$^5\tilde{Li}/^6Li < 8 \times 10^{-18}$	$< 2 \times 10^{-28}$
Supernova neutrons and anomal. nuclei	Ia	$\tilde{O}/O < 10^{-18}$	$< 10^{-17}$
Neutrino stat. and primordial nucleosyn.	I	^{4}He production	
Thermal evolution of the Universe	I		$< 10^{-15} - 10^{-17}$

Different interpretation

Alternative analysis S.R. Elliott, Found. Phys. 42 (2012) 1015

Consider free electron collisions with atoms

$$\frac{\beta^2}{2} < \frac{\Delta N_X}{g_f} \frac{1}{P N_{new}^{free} N_{\mathrm{int}}^{free}}$$

$$N_{\mathrm{int}}^{free} = \Delta t \frac{v_f}{\mu}$$

$$N_{new}^{free} = N_e V$$

Experiment	N_e (/cm^3)	V (cm^3)	v_f (cm/s)	$N_{int}^{free} \times N_{new}^{free}$	$\frac{N_{3\sigma}}{\epsilon_{tot}}$	$\frac{1}{2}\beta^2$
VIP-UG	8.41×10^{22}	1.2	1.57×10^8	1.03×10^{44}	5×10^4	8.4×10^{-39}
This Work	1.33×10^{23}	36.1	1.83×10^8	6.88×10^{45}	1.64×10^5	2.6×10^{-39}

PRL 105, 051601 (2010) PHYSICAL REVIEW LETTERS week ending 30 JULY 2010

Non-Pauli Transitions from Spacetime Noncommutativity

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(Received 2 April 2010; published 26 July 2010)

The consideration of noncommutative spacetimes in quantum theory can be plausibly advocated from physics at the Planck scale. Typically, this noncommutativity is controlled by fixed "vectors" or "tensors" with numerical entries like $\theta_{\mu\nu}$ for the Moyal spacetime. In approaches enforcing Poincaré invariance, these deform or twist the method of (anti)symmetrization of identical particle state vectors. We argue that the Earth's rotation and movements in the cosmos are "sudden" events to Pauli-forbidden processes. This induces (twisted) bosonic components in state vectors of identical spinorial particles. These components induce non-Pauli transitions. From known limits on such transitions, we infer that the energy scale for noncommutativity is $\gtrsim 10^{24}$ TeV. This suggests a new energy scale beyond the Planck scale

TABLE I. Bounds on the noncommutativity parameter χ.

Experiment	Type	Bound on χ (length scales)	Bound on χ (energy scales)
Borexino	Nuclear	$\lesssim 10^{-43}$ m	$\gtrsim 10^{24}$ TeV
Kamiokande	Nuclear	10^{-42} m	10^{23} TeV
NEMO	Atomic	10^{-15} m	10^{8} eV
NEMO-2	Nuclear	10^{-41} m	10^{22} TeV
Maryland	Atomic	10^{-22} m	10^{3} TeV
VIP	Atomic	10^{-23} m	10^{4} TeV

Assumption:
Lifetime atomic process 10^{-16} s
Lifetime nuclear 10^{-23} s

Atomic transitions