$\beta-\nu$ correlations in light radioisotopes SARAF-I (and II) and projections for IFMIF

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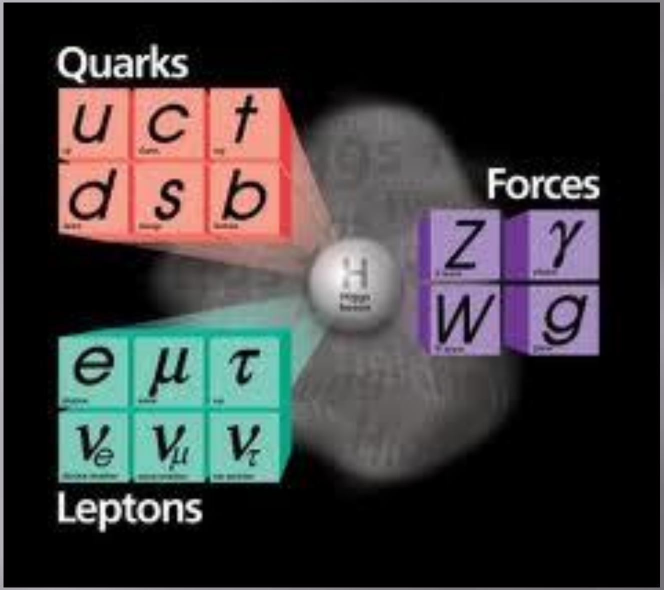
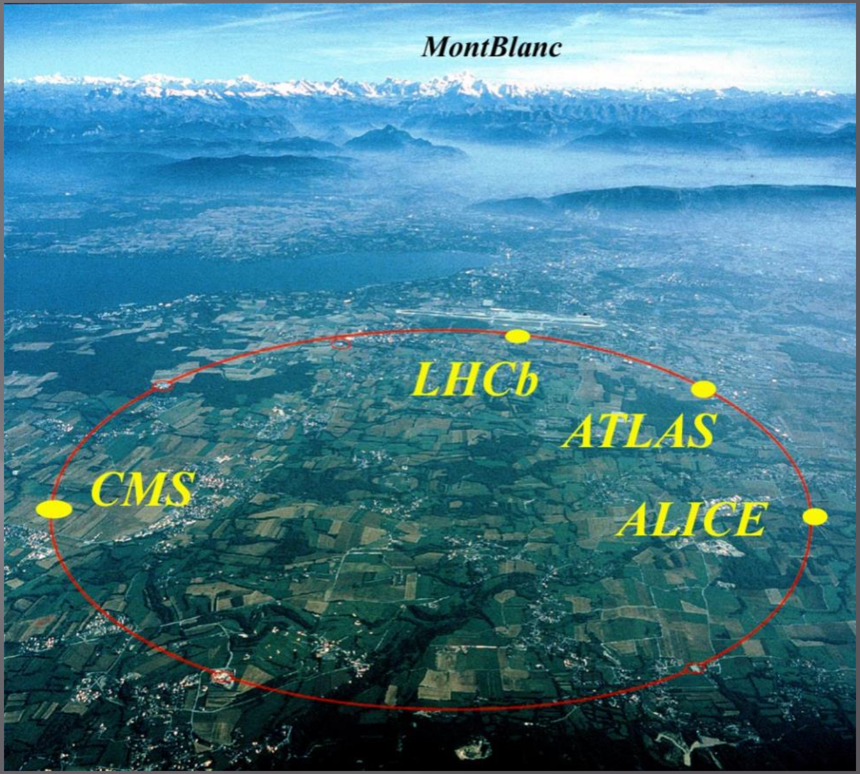
Collaboration between the Nuclear Structure and the molecular and Atomic Physics groups. Also scientists from the Hebrew University, Soreq NRC center, MPIK – Heidelberg and LBL

Ph.D. Thesis of Sergey Vaintraub
Tsviki Hirsh

Ph.D. Student : Yonatan Mishnayot (HUJI/WI)

The Standard Model of Particles and Forces

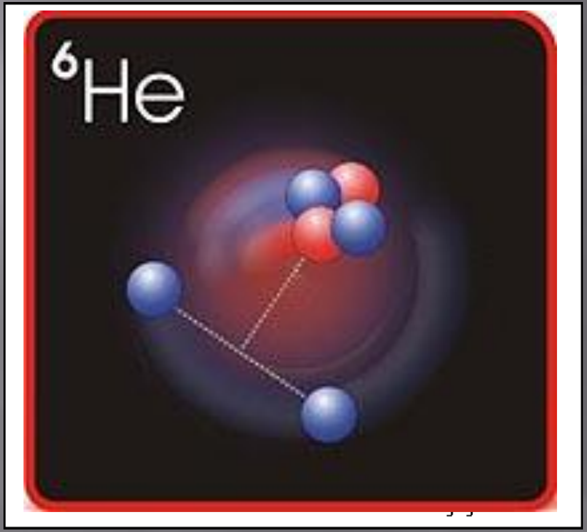


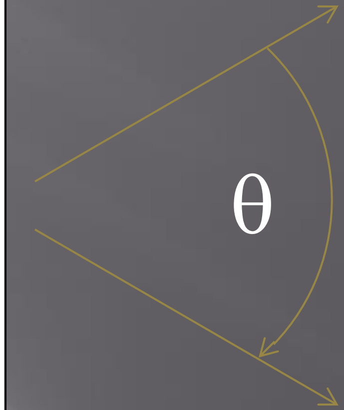


BUT…
Also “Physics Beyond the Standard Model”

Example: ^{6}He beta decay
See, e.g, Flechard et al, PRL (2008)

^{6}Li
daughter nucleus





e^- Electron

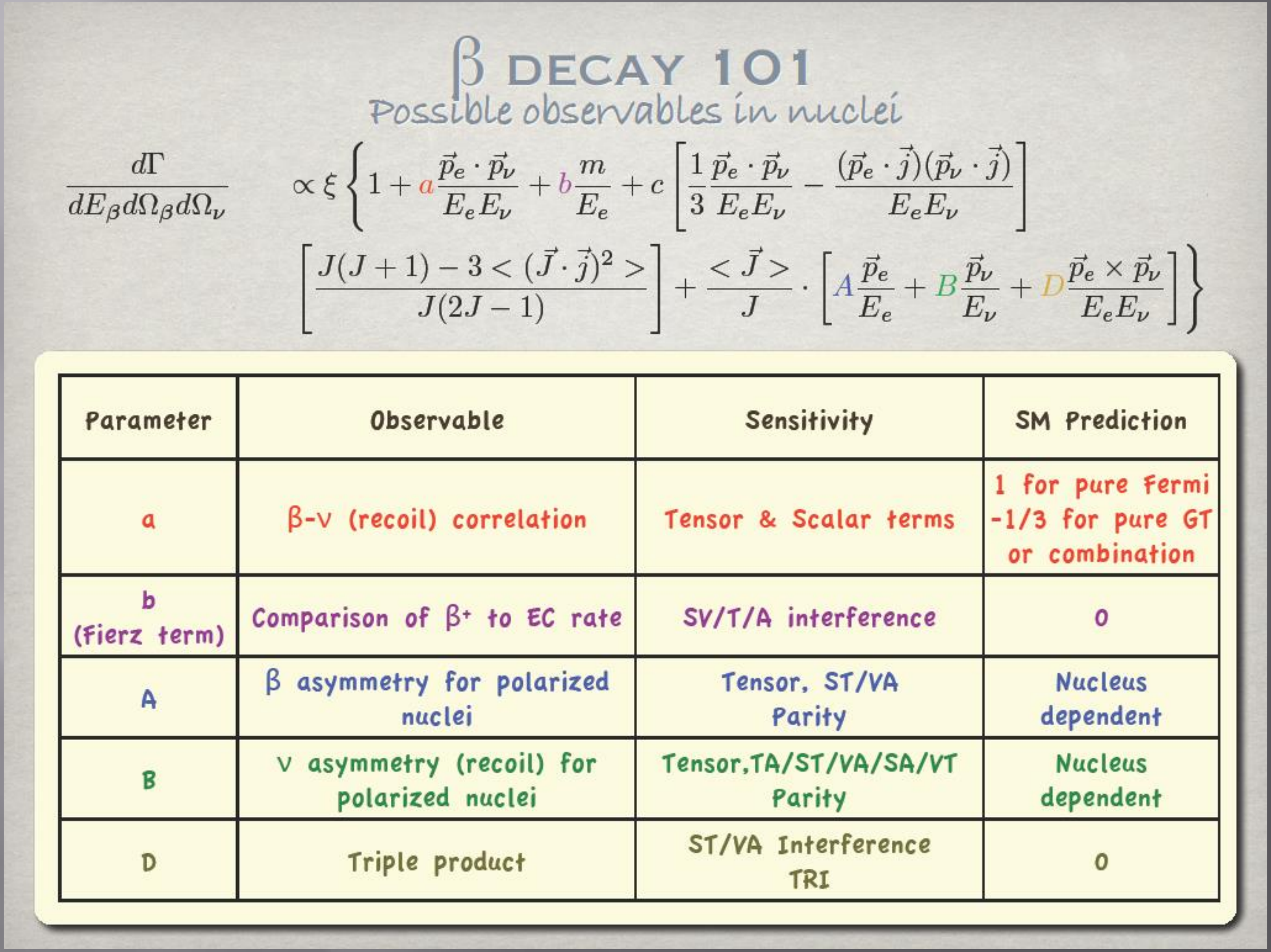
$\bar{\nu}_e$ Electron
anti-neutrino

$$dW \propto a\xi\left(\frac{p_e}{E_e}\cos\theta\right)$$

$$dW_{SM}({}^6He) \propto -\frac{1}{3}\left(\frac{p_e}{E_e}\cos\theta\right)$$

$${}^6He \rightarrow {}^6Li + e^- + \boxed{\overline{\upsilon}_e}$$

- New physics beyond the Standard Model’s
  V–A structure
  “LHC–type” physics at the low energy frontier!



β DECAY 101

Possible observables in nuclei

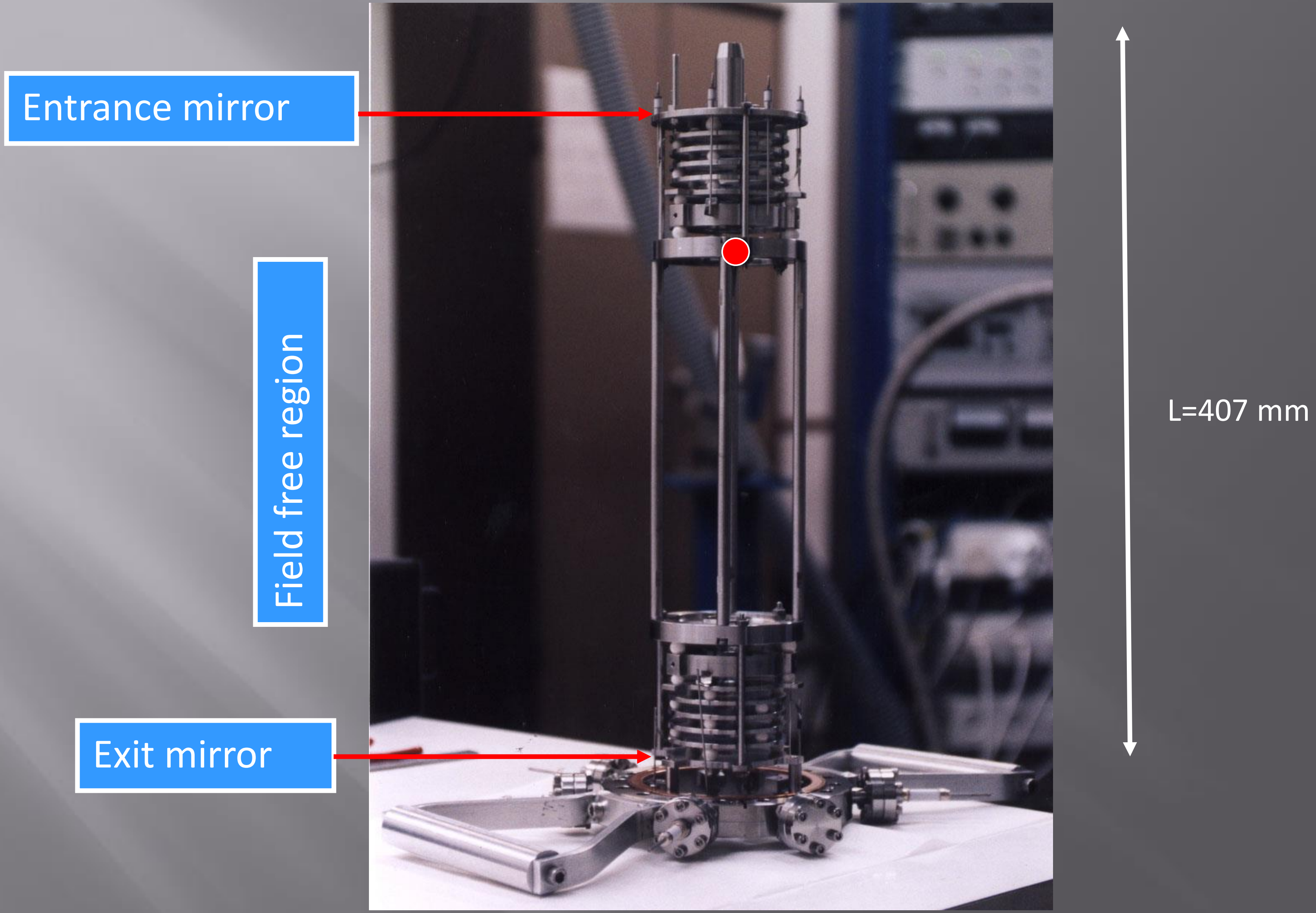
$$\frac{d\Gamma}{dE_\beta d\Omega_\beta d\Omega_\nu} \propto \xi \left\{1 + a\frac{\vec{p}_e\cdot\vec{p}_\nu}{E_eE_\nu} + b\frac{m}{E_e} + c\left[\frac{1}{3}\frac{\vec{p}_e\cdot\vec{p}_\nu}{E_eE_\nu} - \frac{(\vec{p}_e\cdot\vec{j})(\vec{p}_\nu\cdot\vec{j})}{E_eE_\nu}\right]\left[\frac{J(J+1)-3<(\vec{J}\cdot\vec{j})^2>}{J(2J-1)}\right] + \frac{<\vec{J}>}{J}\cdot\left[A\frac{\vec{p}_e}{E_e}+B\frac{\vec{p}_\nu}{E_\nu}+D\frac{\vec{p}_e\times\vec{p}_\nu}{E_eE_\nu}\right]\right\}$$

Parameter	Observable	Sensitivity	SM Prediction
a	β-ν (recoil) correlation	Tensor & Scalar terms	1 for pure Fermi -1/3 for pure GT or combination
b (Fierz term)	Comparison of β⁺ to EC rate	SV/T/A interference	0
A	β asymmetry for polarized nuclei	Tensor, ST/VA Parity	Nucleus dependent
B	ν asymmetry (recoil) for polarized nuclei	Tensor,TA/ST/VA/SA/VT Parity	Nucleus dependent
D	Triple product	ST/VA Interference TRI	0

BETA DECAY STUDIES WORLD WIDE

(PARTIAL LIST)

Isotope	Technique	Group
^{6}He	Electrostatic Trap	WI (Hass) + HUJI (Ron) + LBL (Kolomensky)
^{6}He	MOT	ANL (Mueller) + UW (Garcia)
^{8}Li	Paul Trap	ANL (Savard)
^{38m}K / ^{87}Rb	MOT	TRIUMF (Behr)
$^{17-23}$Ne	MOT	HUJI (Ron)
^{26m}Al / ^{35}Ar / ^{46}V	Penning Trap	Leuven / WITCH (Severijns)
^{6}He / ^{35}Ar	Paul Trap	LPC CAEN (Fléchard)
neutron	Many	Many
^{21}Na	MOT	LBL (Freedman - deceased)
^{16}N	Electrostatic Trap	WI (Hass)
^{21}Na	MOT	KVI (Jungmann)



Entrance mirror

Field free region

Exit mirror

L=407 mm

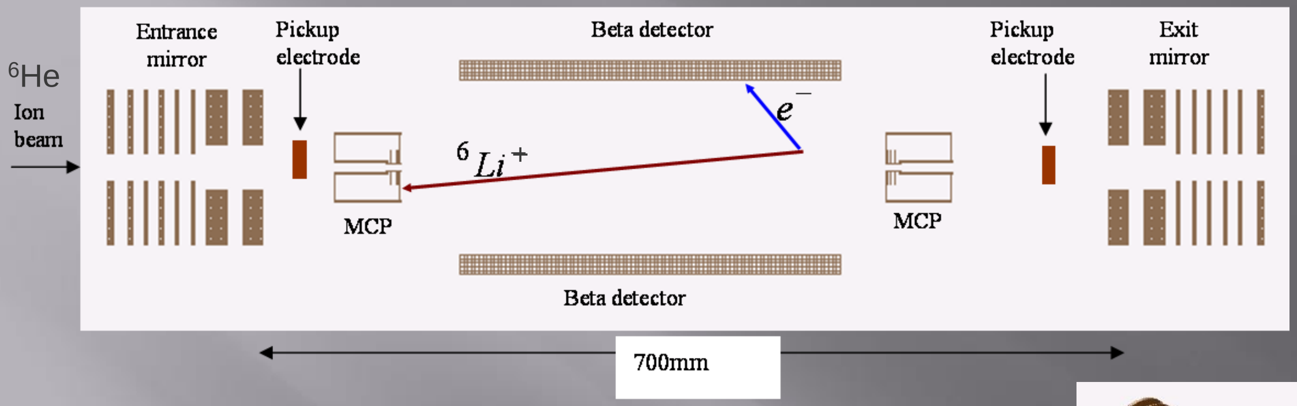
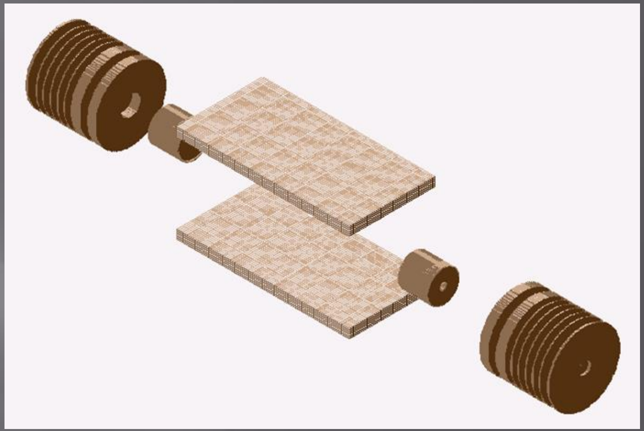


Fig. 2 A schematic view of the EST for β-decay studies. The radioactive ion, like ^{6}He, moves with E_k-4.2 keV between the reflecting electrodes. The β electrons are detected in position sensitive counters while the recoiling ions, due to kinematic focusing, are detected with very high efficiency in either one (determined by the instantaneous direction) of the annular MCP counters.



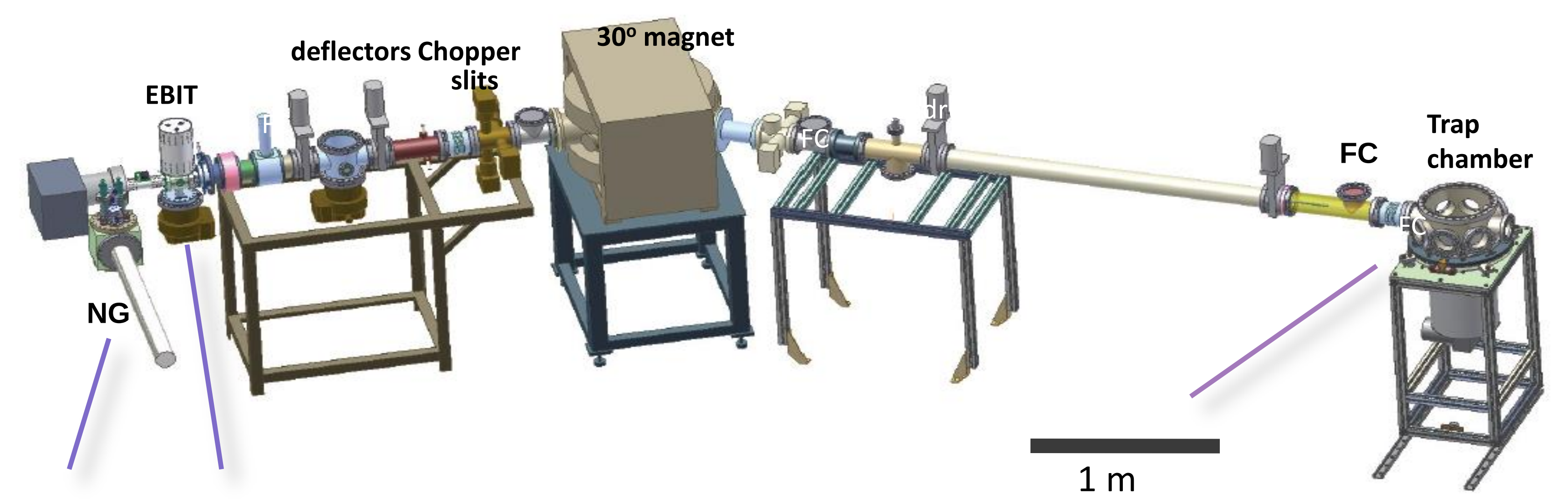
Apparent advantages:

- “Natural” additional kinetic energy of recoils. Kinematics focusing.
- Large solid angles (for BOTH ion recoil and electrons
- Field-free and “equipment-free” inner region
- Simplicity, portability
- Complementary to other method (different systematic errors)
- Full reconstruction of event-by-event - actually measure cos(θ)!

WIRED

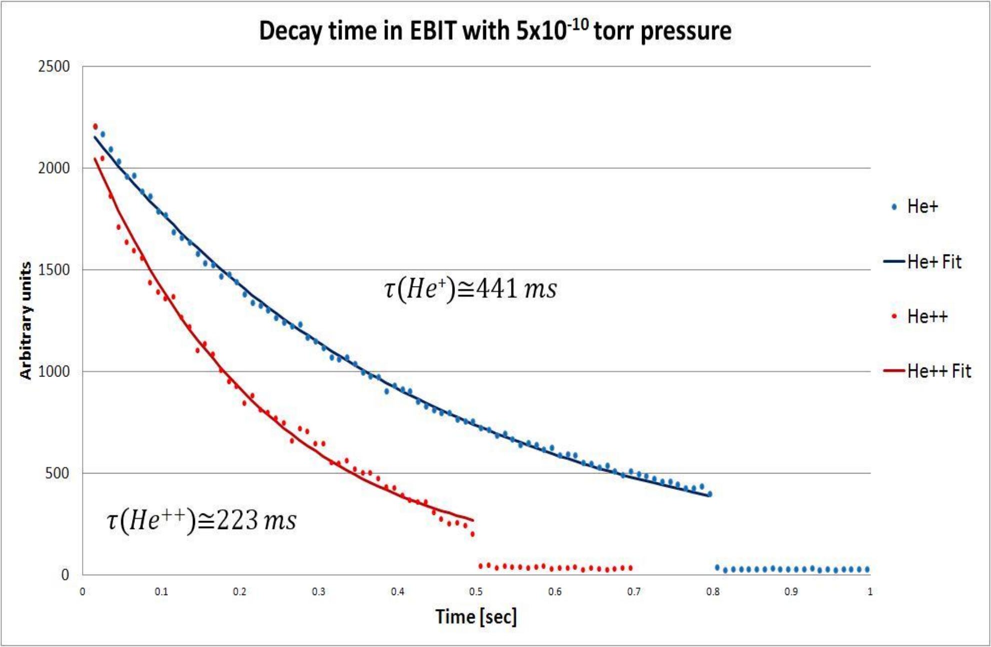
Weizmann Institute Radioactive Electrostatic Device

Experimental scheme

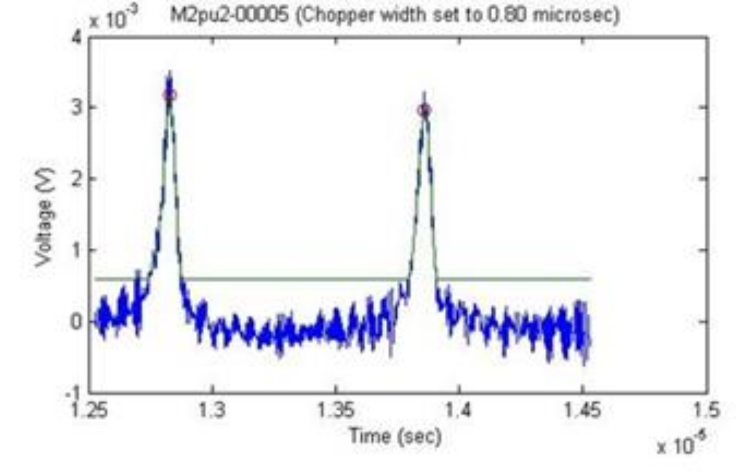


A) High energy (14 MeV) neutrons from a d+t NG hit a hot BeO target; ^{6}He nuclei are produced.
B) ^{6}He atoms are transferred to an EBIT where they get ionized, accumulated, and bunched and guided
C) The ion bunch is injected into the EIBT for beta-decay studies.
D) Data acquisition: signals from detectors are processed, recorded, and analyzed.

Most Recent Results and R&D



Trapping and bunching of stable $^4He^+$ and $^4He^{++}$. As expected, the trapping time of $^4He^{++}$ is shorter than that of $^4He^+$.



- Bunching R&D with ^4He
- Algorithm and tests of a position-sensitive e-detector
- R&D into specialized design of Electron Beam Ion source

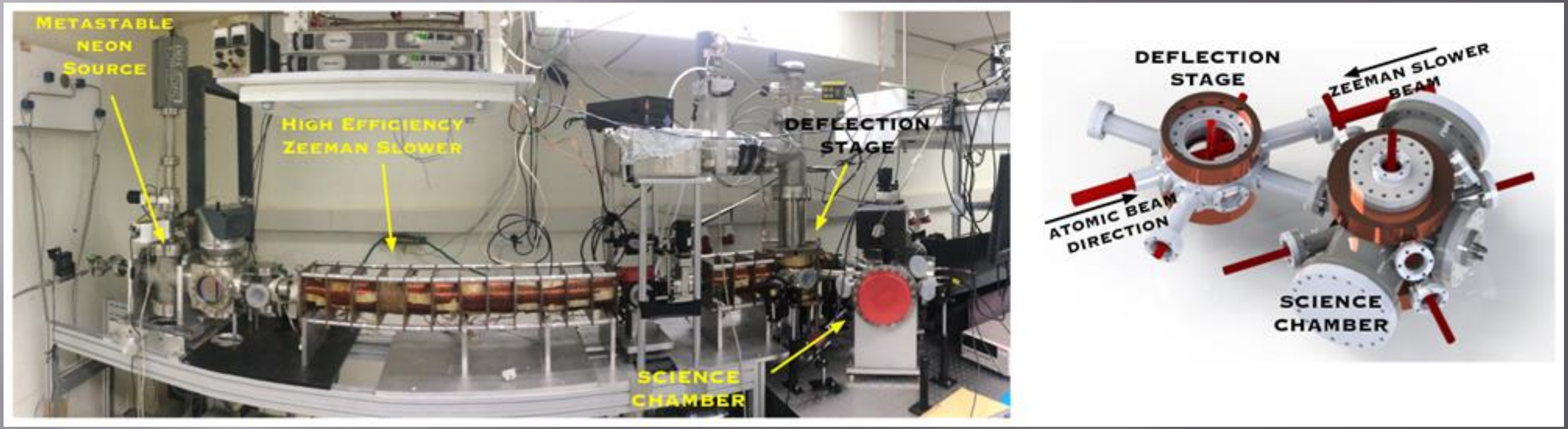
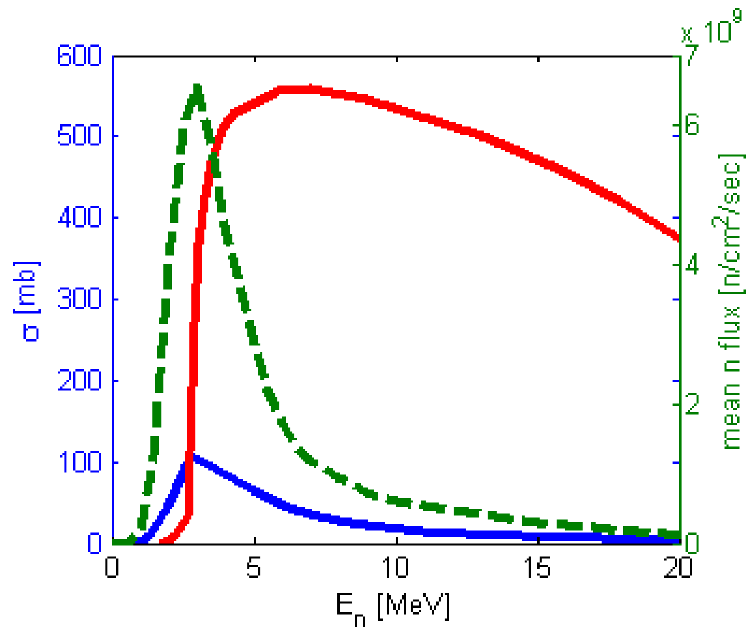


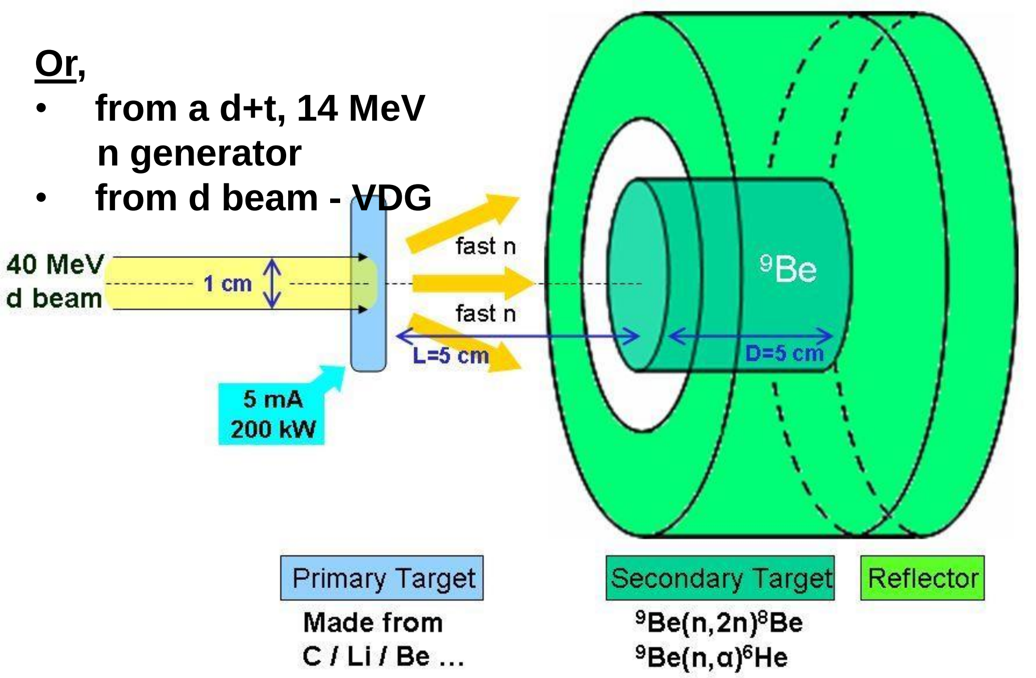
Figure 6. (Left) The MOT setup, containing a high efficiency metastable neon source, a modular Zeeman slower, a deflection stage, and a science chamber. (Right) A schematic of the deflection and trapping region.

Figure 7. The source excites Ne atoms into the metastable state using an rf resonator. The red color is of the $^{3}P_{2}$-$^{3}D_{3}$ neon trapping transition.

Figure 8. Trapped 20Ne atoms (|~100000 atoms)

^{6}He Production





Or,
- **from a d+t, 14 MeV n generator**
- **from d beam - VDG**

Expected Yields for a BeO target:

^{9}Be(n,α)^{6}He

SARAF (40 MeV, 2 mA): **$8 \cdot 10^{12}$**/sec

SPIRAL2 (40 MeV, 5 mA): **$2 \cdot 10^{13}$**/sec

Expected Yields for a BN target:

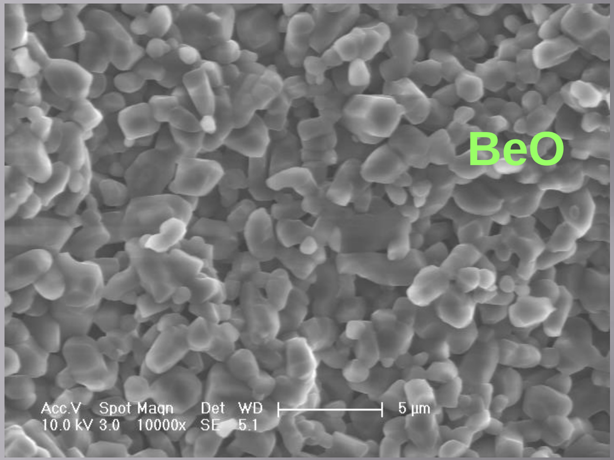
^{11}B(n,α)^{8}Li

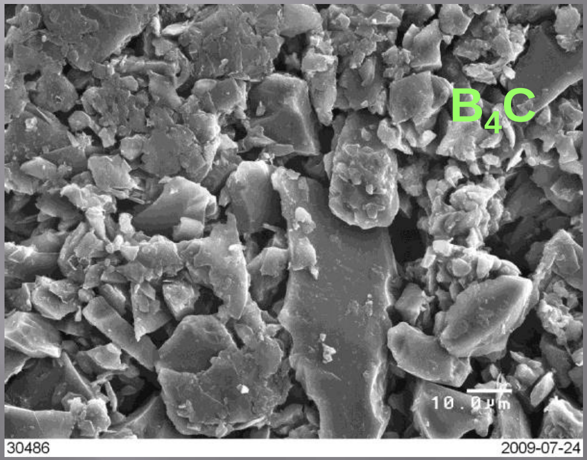
SARAF (40 MeV, 2 mA): **$2 \cdot 10^{12}$**/sec

ALSO: ^{16}O(n.p)^{16}N, ^{23}Na(n,p)^{23}Ne. **ALSO:** Direct production

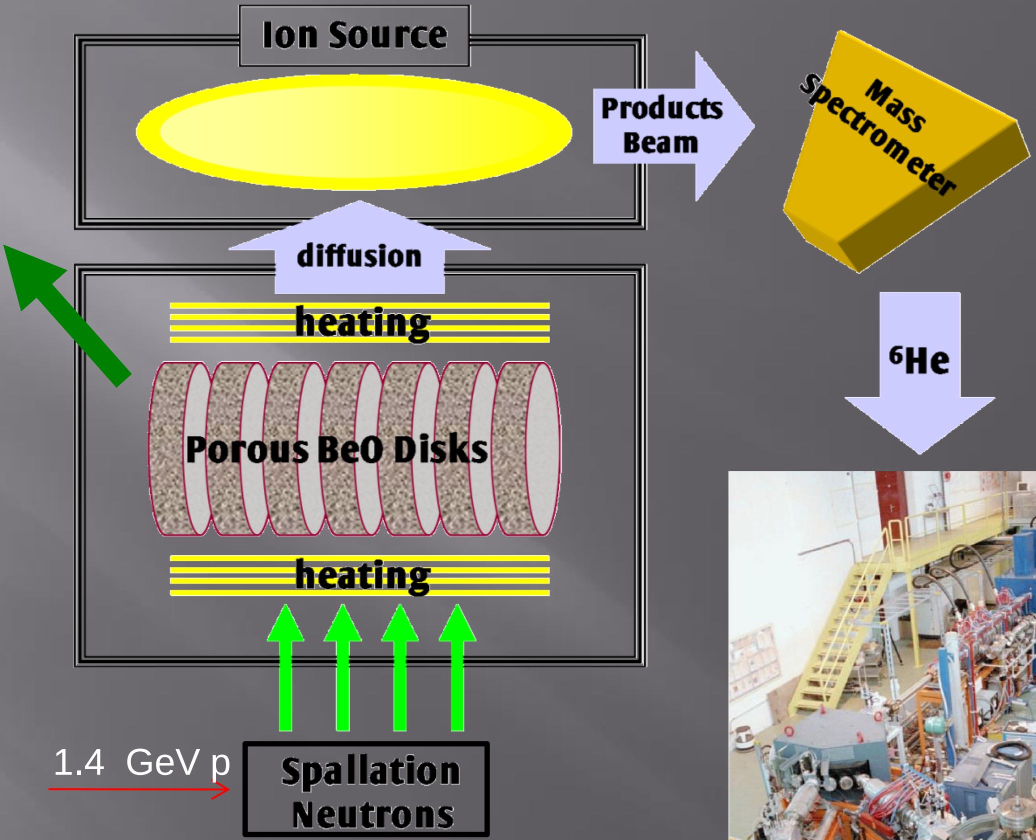
Hass et al., J. Phys. G: Nucl. Part. Phys., 35, 014042 (2008)

^{6}He production at ISOLDE (CERN)





Similar possibilities
With $^{11}B(n,\alpha)^8Li$



Ion Source

Products Beam

Mass Spectrometer

diffusion

heating

Porous BeO Disks

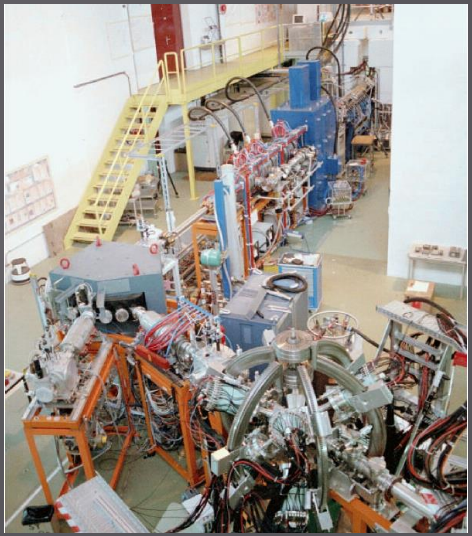
heating

^{6}He

1.4 GeV p

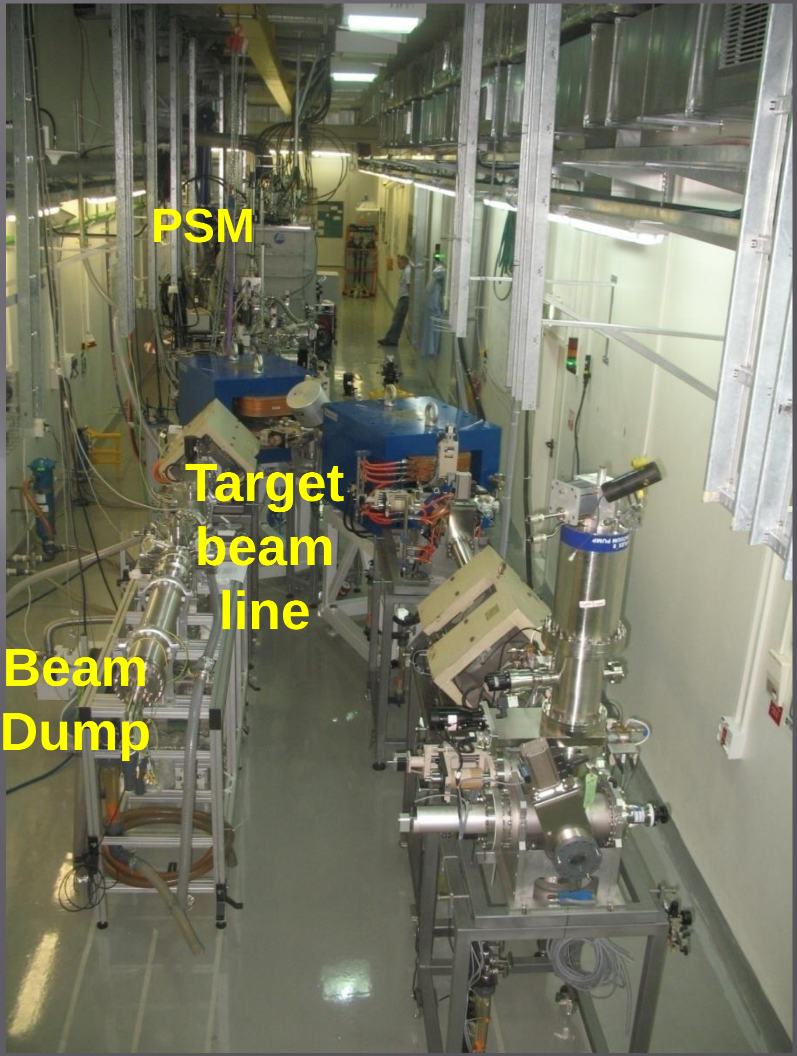
Spallation Neutrons

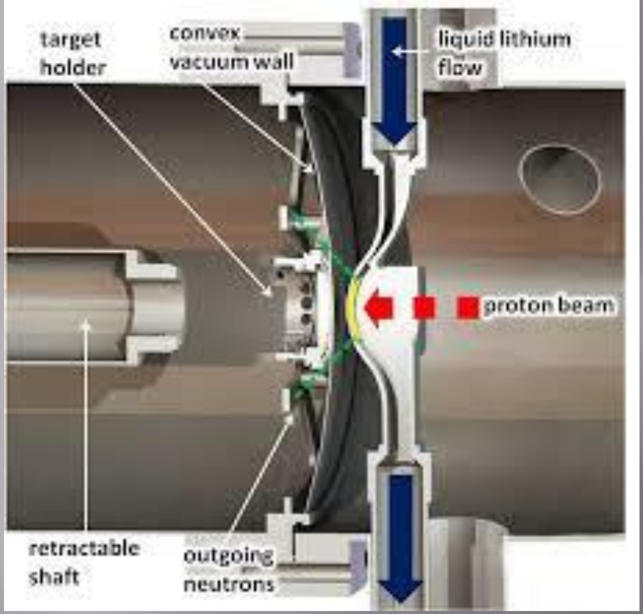
ISOLDE Exp.
17.4.2009



SARAF Phase I
@
Soreq Center - Israel

- Commissioning of Phase-I is approaching finalization
- 1 mA CW proton beam has been accelerated up to an energy of 3.7 MeV
- Low duty cycle (~0.2 mA) deuteron beam has been accelerated up to an energy of 4.3 MeV
- **New Target Room!!! (2016)**
- Phase-II – up to 40 MeV (2020) - SACLAY





The Li Liquid Target (LiLiT@SAEAF
Michael Paul et al. Hebrew Unive. Jerusalem

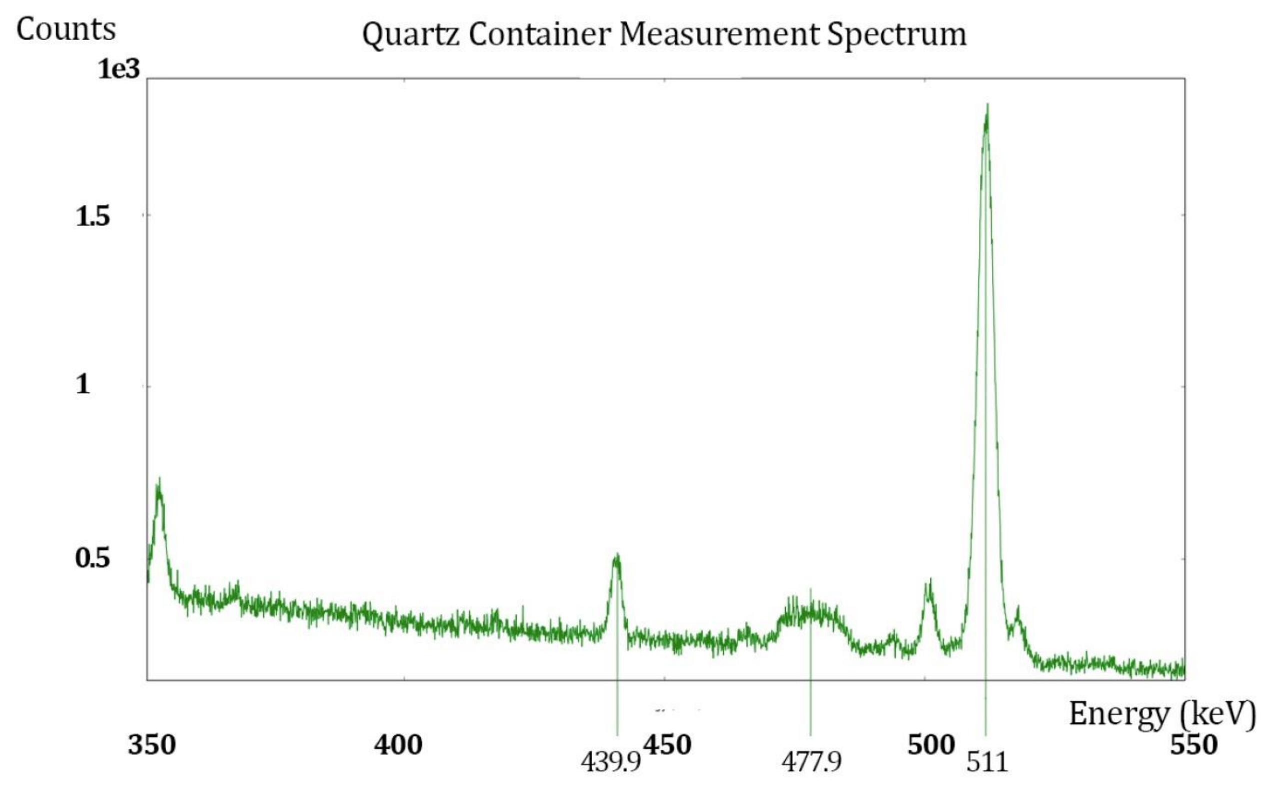
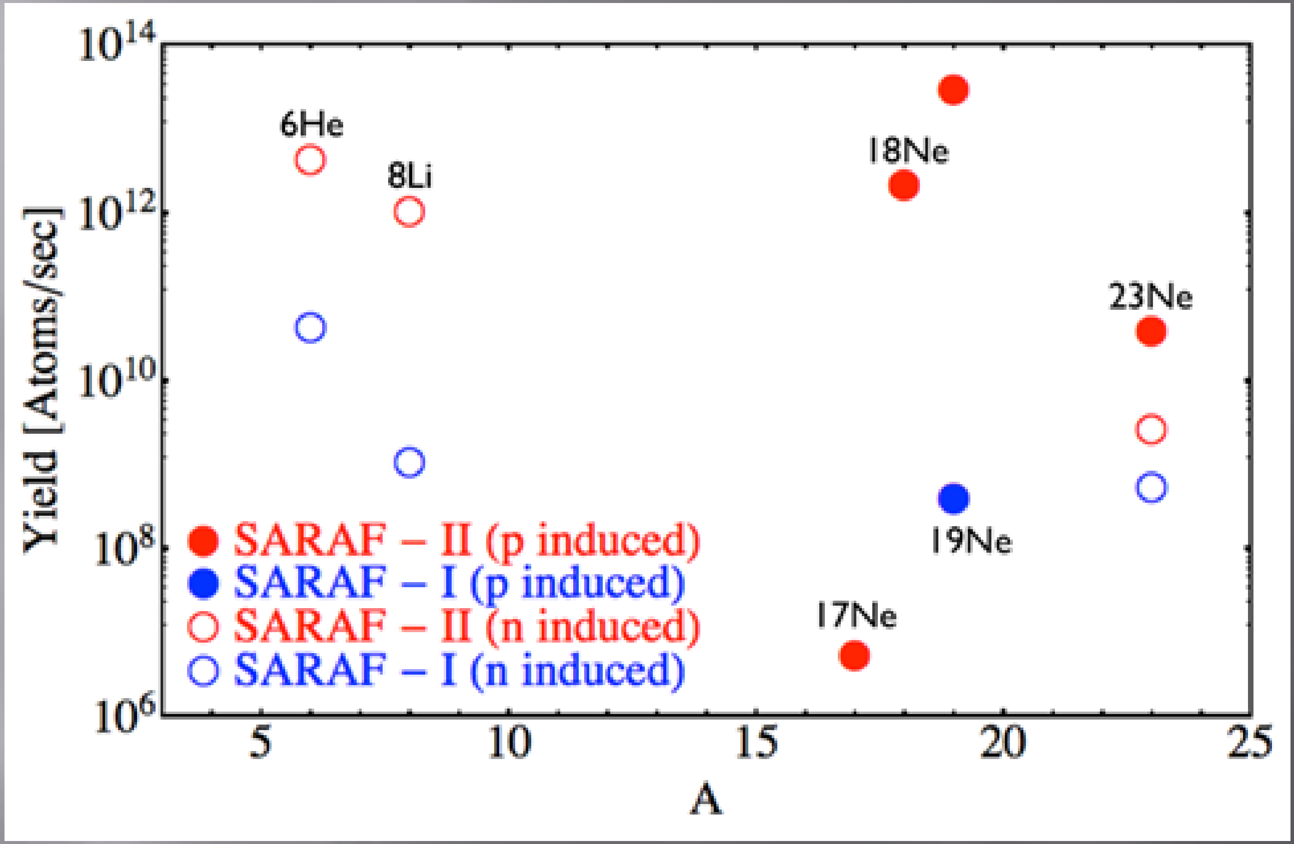
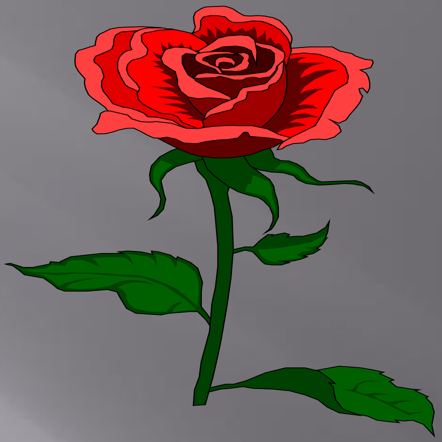


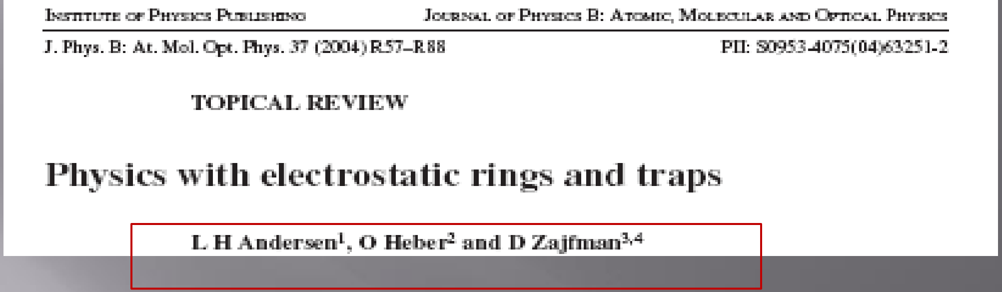
Figure 5. Gamma spectra in the detection chamber after transport of ^{23}Ne. The 439.9 keV gammas are clear indications for the detection of ^{23}Ne.



Yields of several light radioactive isotopes for SARAF-I and SARAF-II



Many thanks to all my colleagues



Institute of Physics Publishing — Journal of Physics B: Atomic, Molecular and Optical Physics

J. Phys. B: At. Mol. Opt. Phys. 37 (2004) R57–R88 — PII: S0953-4075(04)63251-2

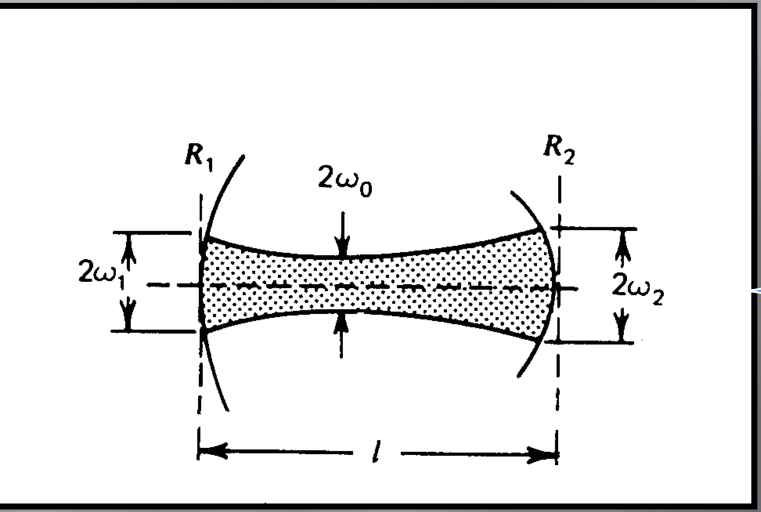
TOPICAL REVIEW

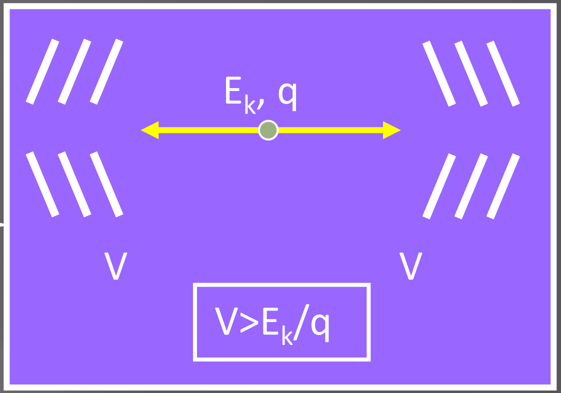
Physics with electrostatic rings and traps

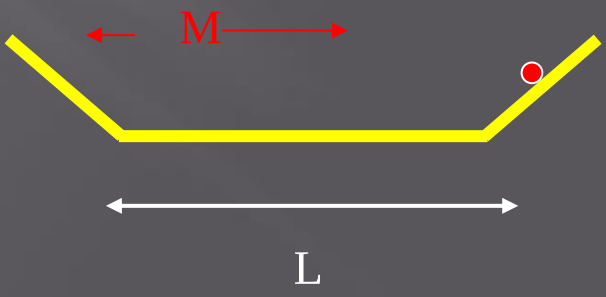
L H Andersen[1], O Heber[2] and D Zajfman[3,4]

Optical resonator

Particle resonator

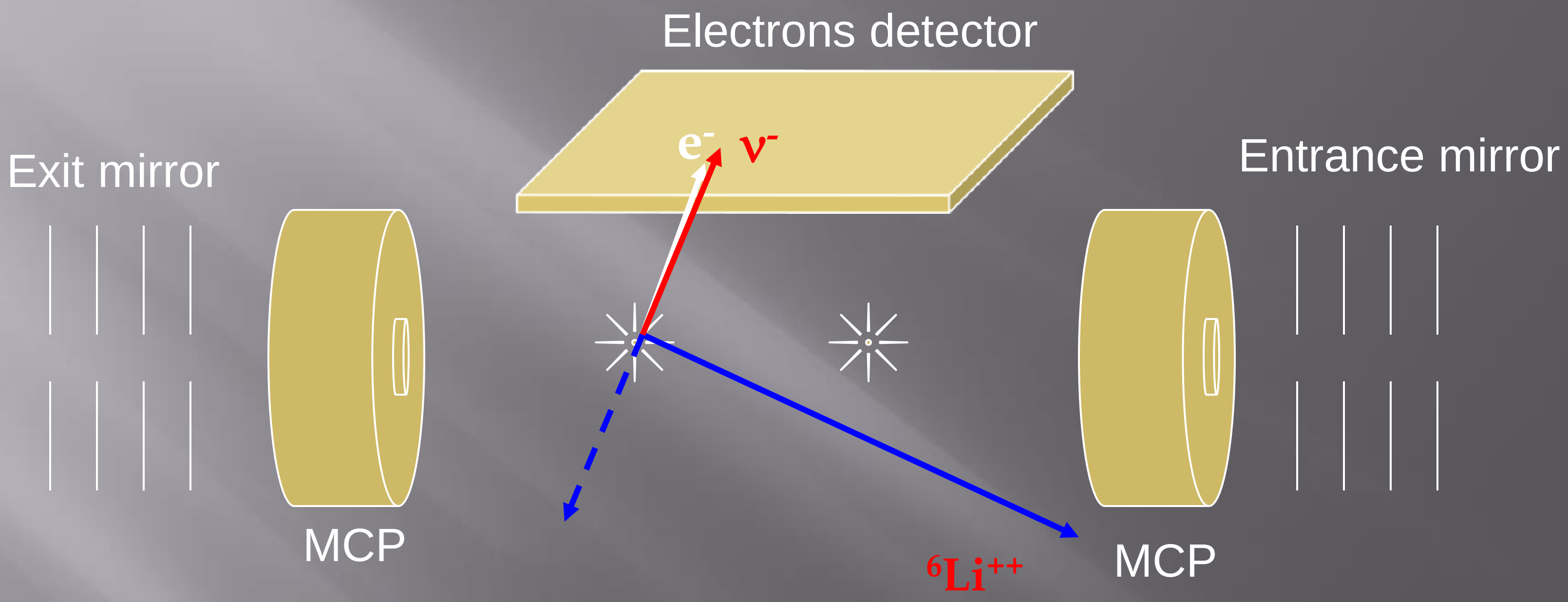






Trapping of fast ion beams using electrostatic field

Cosθ ~ 1



Some of the ^{6}Li ions will miss the MCP at its periphery

“In- House” Research!
R&D steps at the WI

Use infrastructure (Shielding, radiation protection, equipment) from de-commissioned 14 MV Koffler accelerator

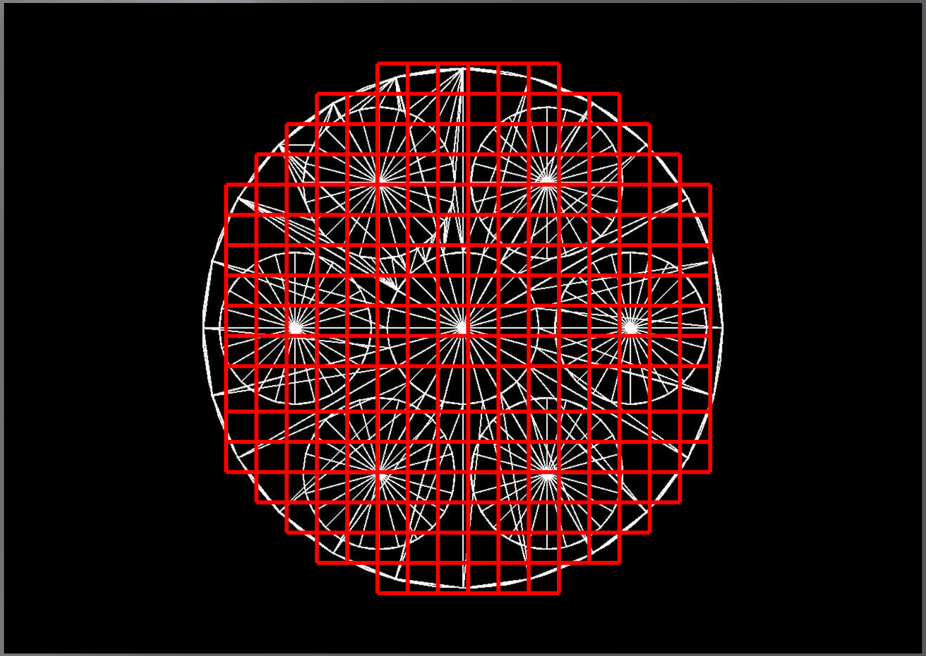
Full E_e determination + position information

Thick plastic scintillator

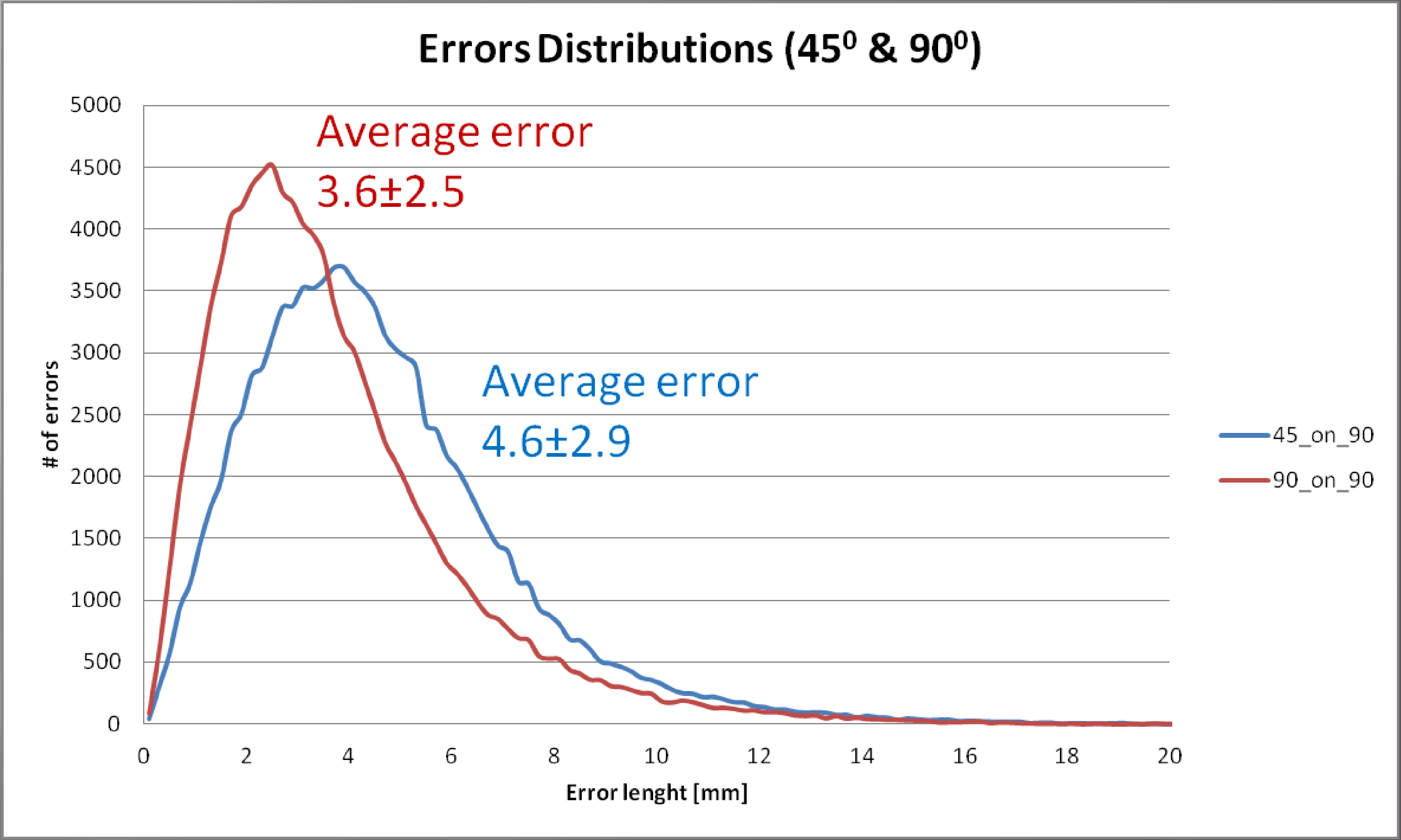
Individual photomultipliers

Geant4 Simulation

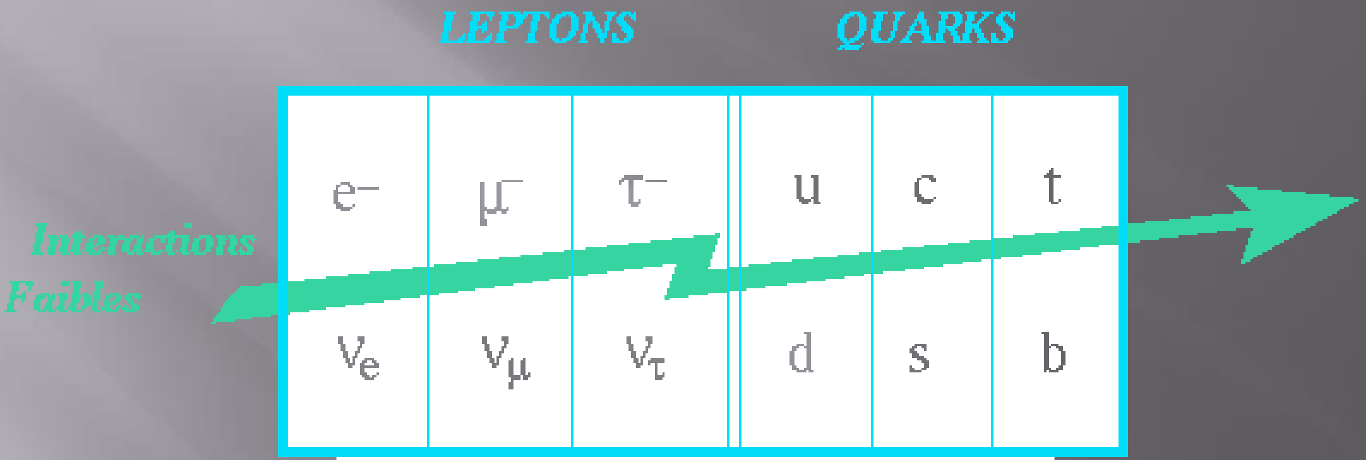
- Dividing area of Detector to squares
- Distribution of Photons in PMTs per square
- Statistical Map



Comparison - Error



The “Standard Model” of Particle Physics



LEPTONS			*QUARKS*		
e^-	μ^-	τ^-	u	c	t
ν_e	ν_μ	ν_τ	d	s	b