A novel method for calibration and monitoring of time synchronization of TOF-PET scanners by means of cosmic rays

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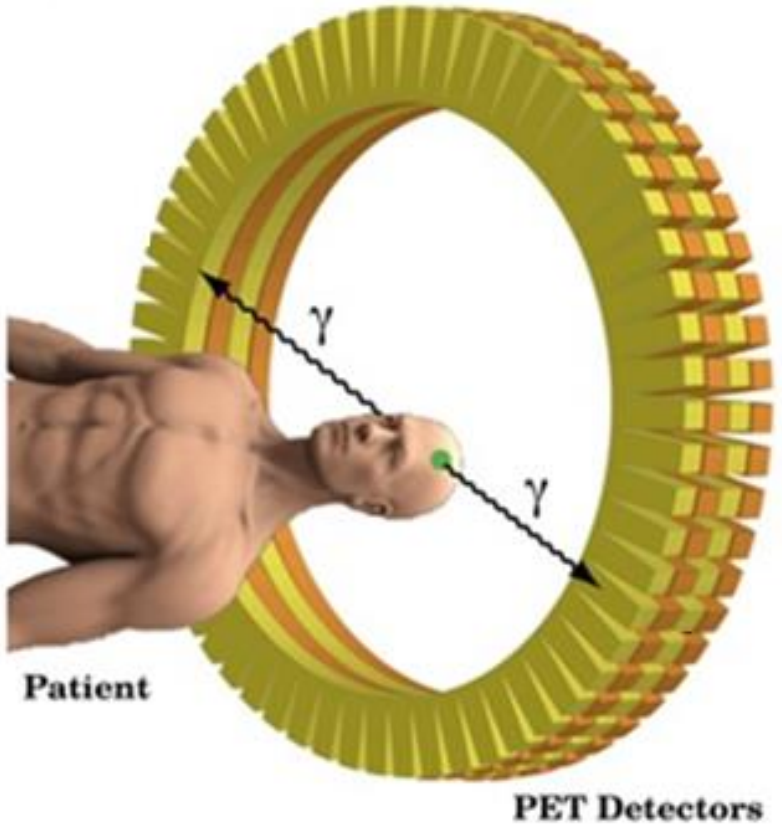
- State of the art and limitations of present methods
- Cosmic rays as a tool for TOF-PET
  - Time calibration
  - Energy calibration
  - Monitoring
- Summary and outlook

Symposium on Positron Emission Tomography, September 19th - 22nd 2013, Kraków

State of the art of present methods

- All calibration methods are based on radioactive sources (e.g. ^{22}Na, ^{68}Ge, …)
- One or more sources placed at fixed positions inside the diagnostic chamber
- Source orbiting along the detector ring
- Statistical analysis, event sorting, etc.

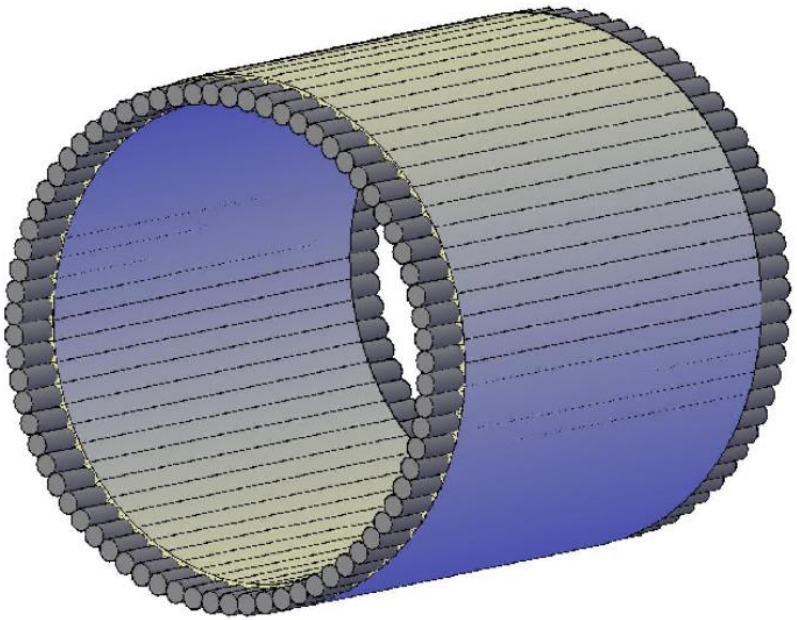


Calibration constants ⇒ distributions of time difference for pairs of detectors + known positions of source

Limitations of present methods

- The calibration and monitoring usually can not be done while patient examining without exposing for additional dose

- Radioactive sources: storage and decay time
- Additional apparatus and personel training
- Low frequency of calibration (usually ones per day)



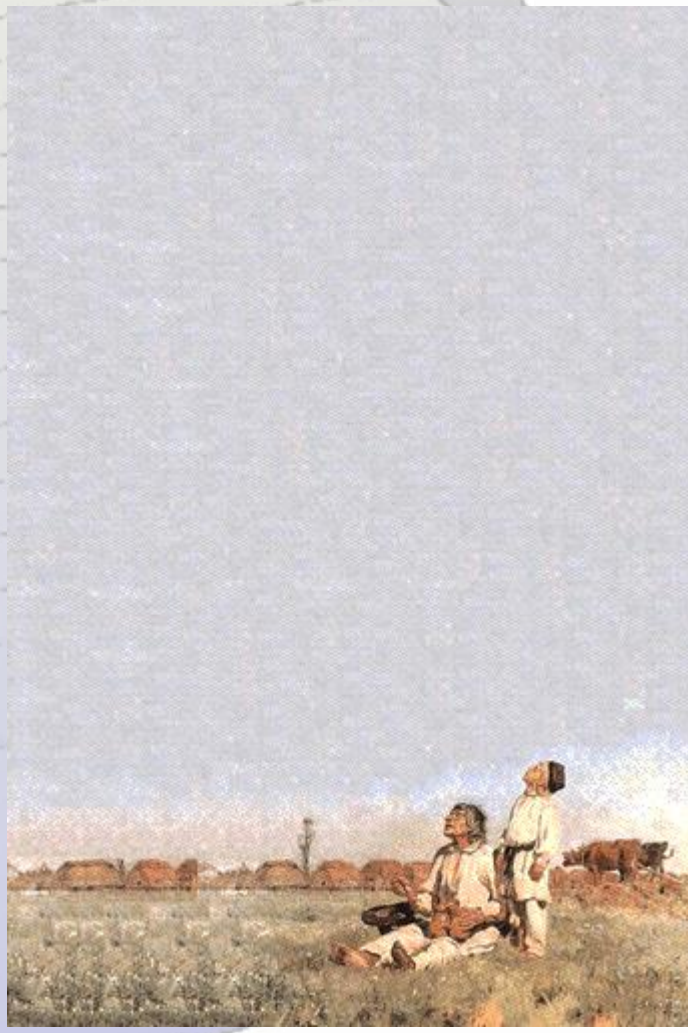
- **Not suitable for long detectors as in Strip-PET**

- **Necessity for some alternative methods…**

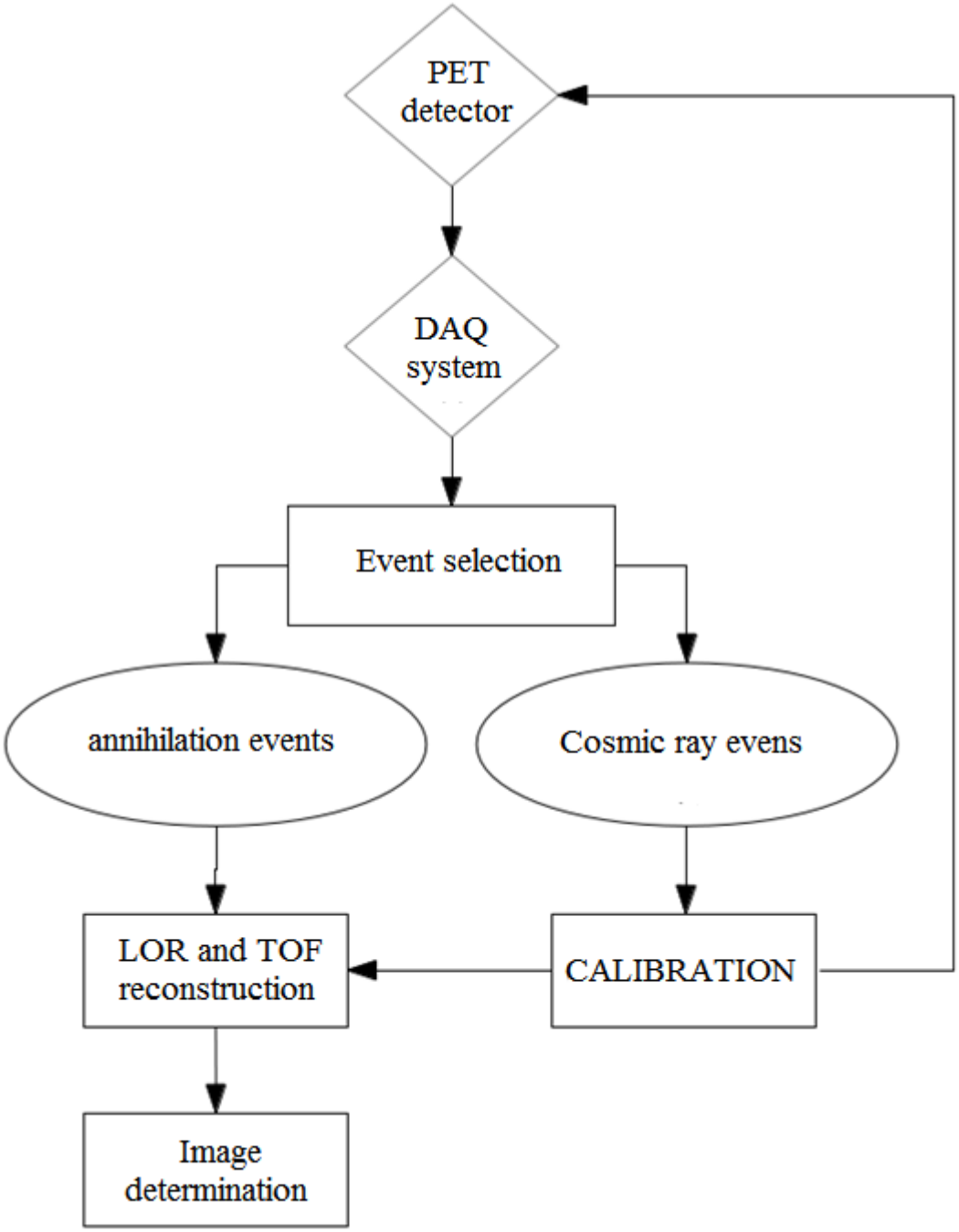
….what about cosmic rays?

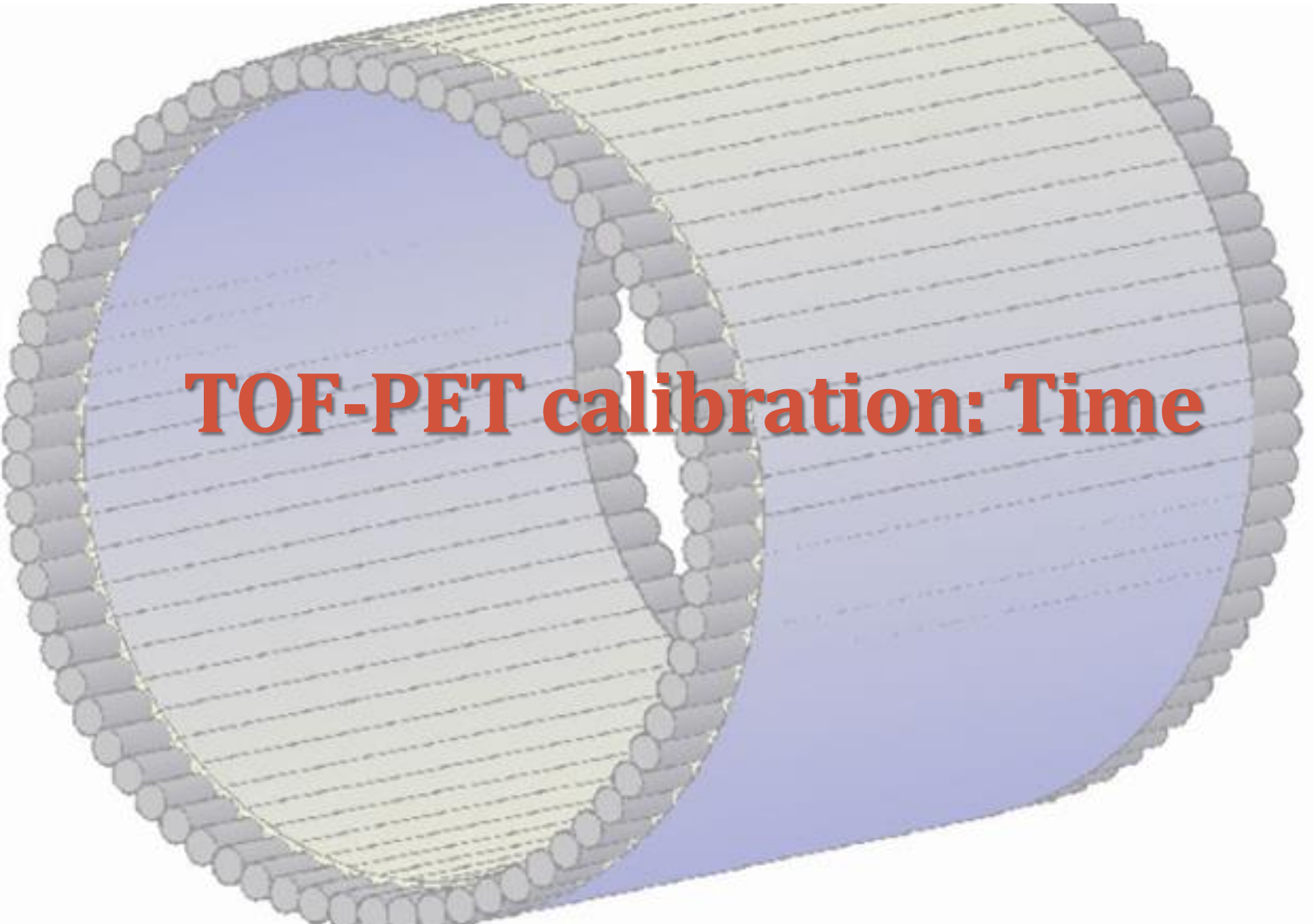
Cosmic rays as a tool for TOF-PET

- „Free” source of radiation not limited by isotope lifetime
- Calibration performed during the usual operating time of the tomograph
- No exposure for additional radiation dose
- Detailed monitoring of the whole detection setup
- Applied with great success in Particle Physics experiments



http://www2.ipj.gov.pl/pl/info/dzialalnosc.htm

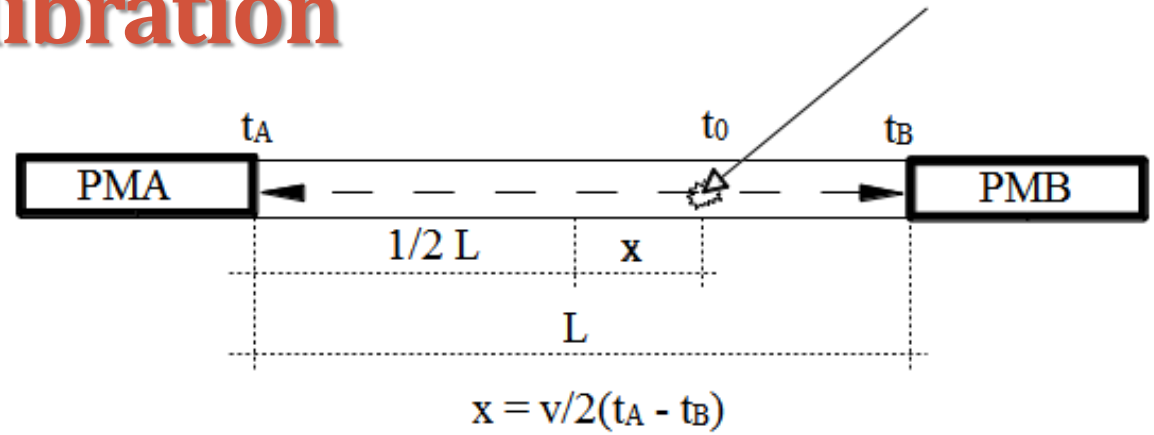

PET detector
DAQ system
Event selection
annihilation events
Cosmic ray evens
LOR and TOF reconstruction
CALIBRATION
Image determination



TOF-PET calibration: Time

Single module calibration

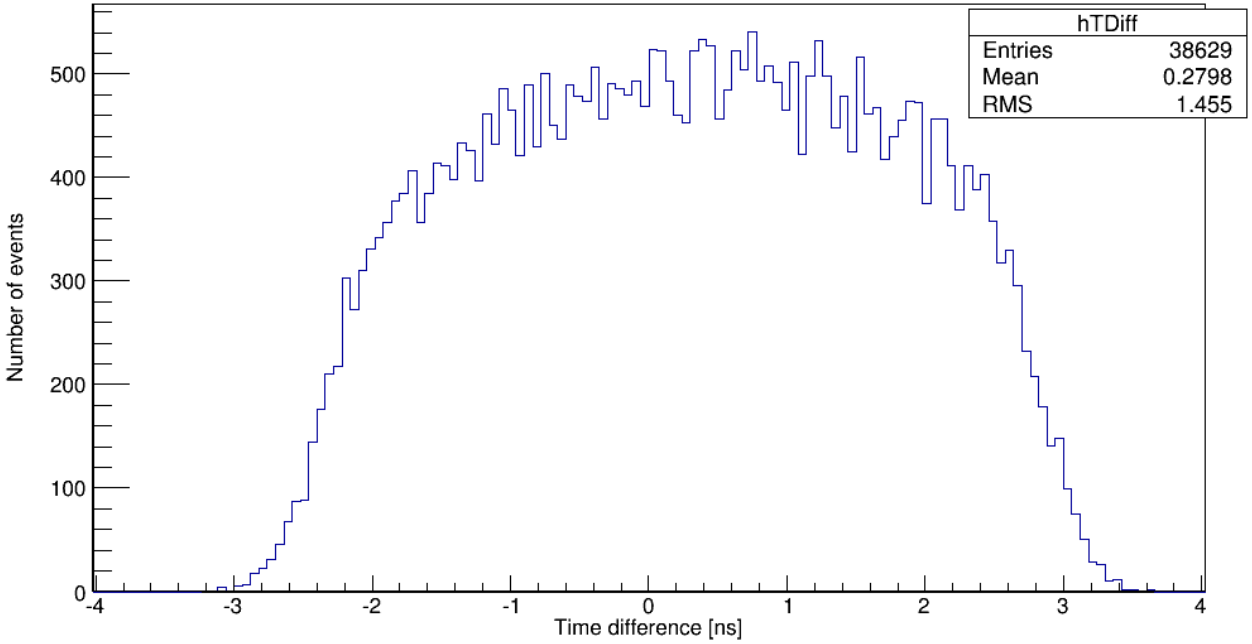
- Cosmic rays provide an uniform irradiation of all modules



Electronics offset

$$t_{A(B)} = t_0 + t^p_{A(B)} + t^o_{A(B)}$$

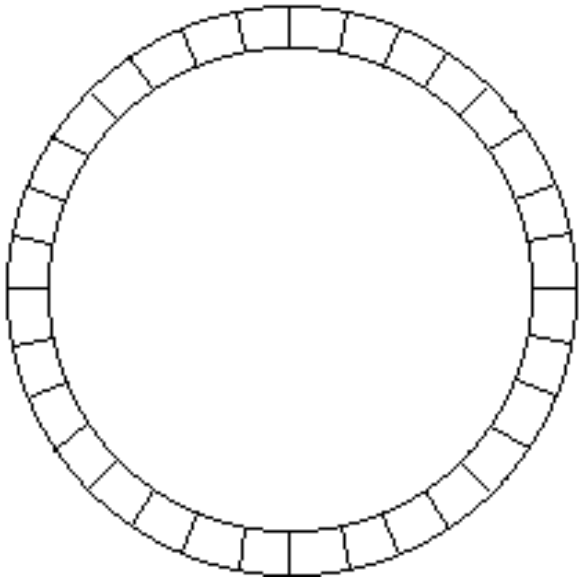
Propagation of light

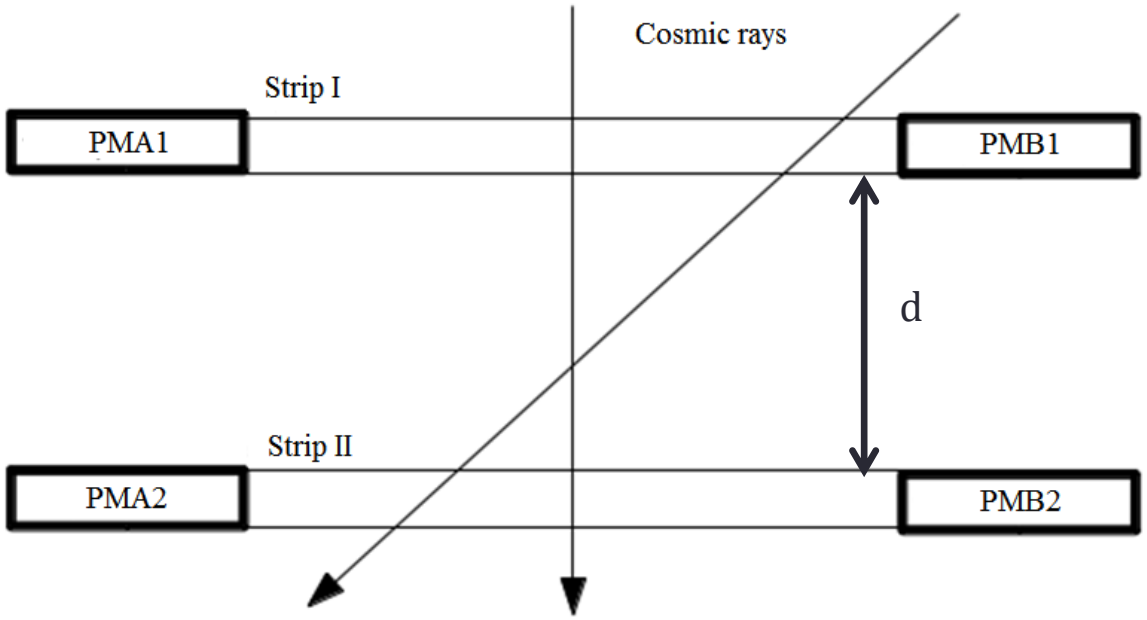


$$\Delta t_{AB} \in \left[\Delta t^o_{AB} - \frac{L}{v}; \Delta t^o_{AB} + \frac{L}{v}\right]$$

$$N(\Delta t_{AB}) = \frac{A}{\left\{1 + exp\left[\left(-\Delta t_{AB} + \Delta t^o_{AB} - \frac{L}{v}\right)/\sigma_t\right]\right\}\left\{1 + exp\left[\left(\Delta t_{AB} - \Delta t^o_{AB} - \frac{L}{v}\right)/\sigma_t\right]\right\}}$$

Synchronization of different modules



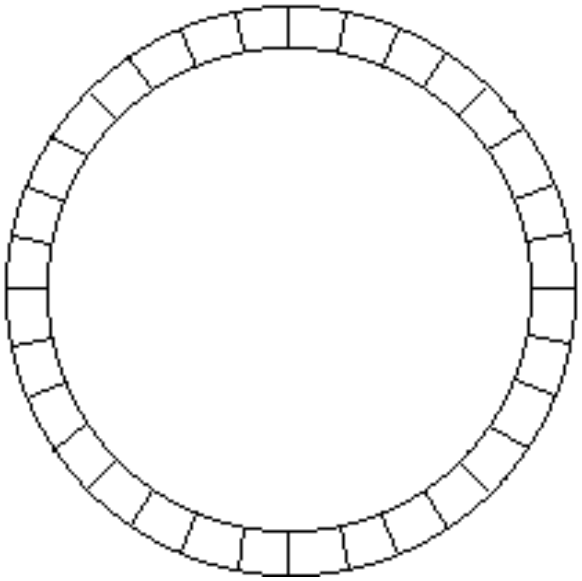


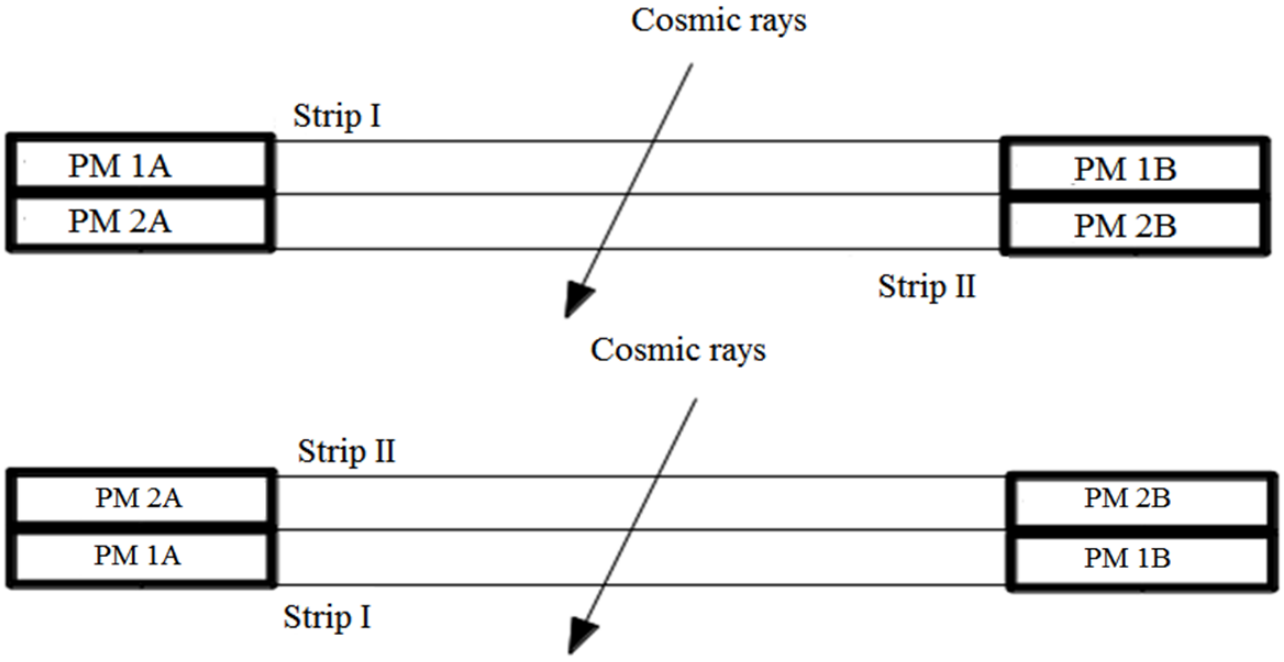
$$\Delta t = \Delta t_0 + \Delta t^{o}_{I\text{-}II}$$

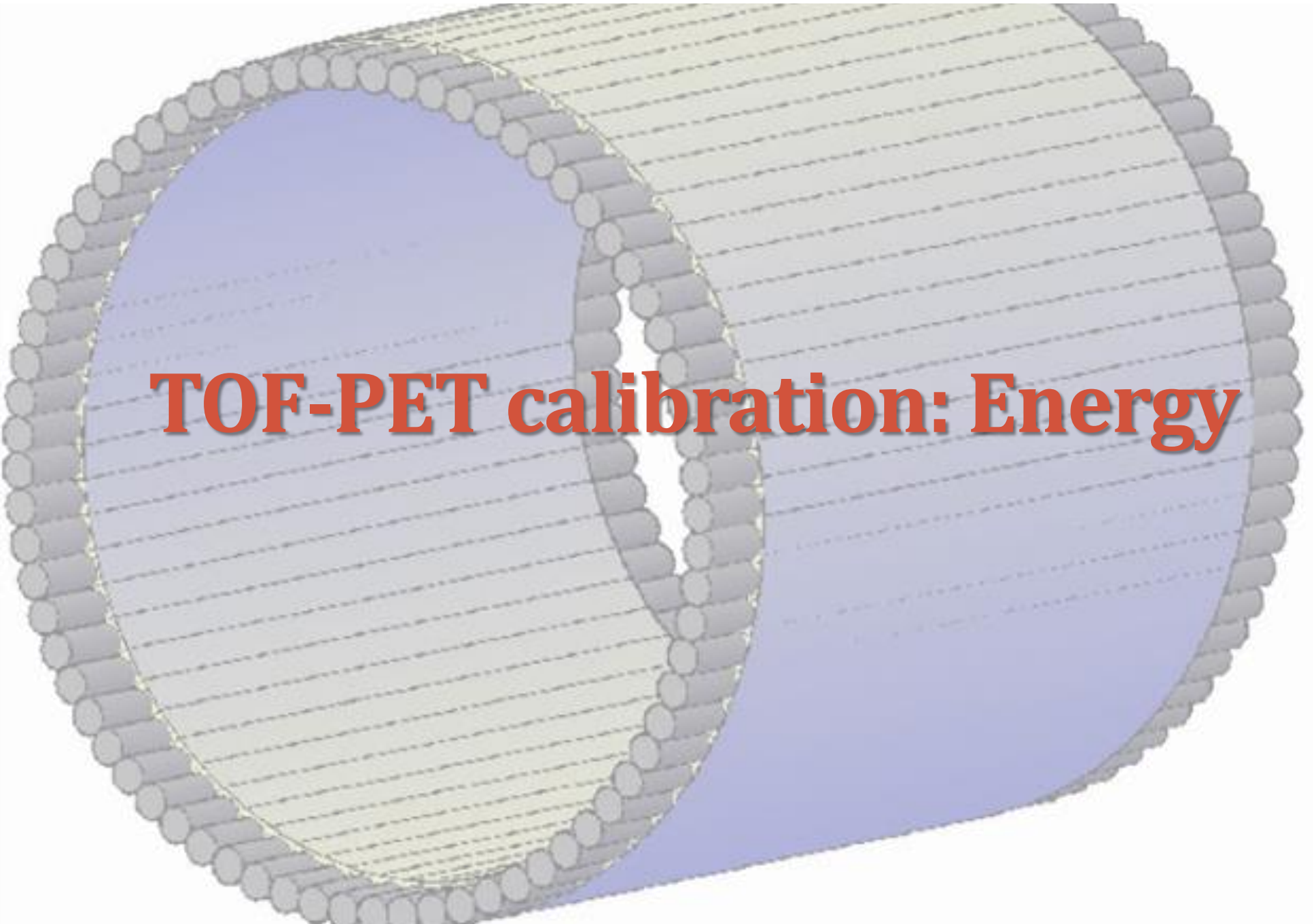
- At the sea level most of the cosmic rays are muons
- The distribution of muons velocities are well known
- **Relative time offsets ⇒ known distance between modules + mean muon time of flight**
- Measurements at different positions along strips and different muon distances allow for solid statistical analysis and accurate offsets determination

Synchronization of different modules

- Synchronization without information about cosmic rays velocity distribution
- Model distributions of cosmic rays TOF measurement
- Fit with time offsets as a free parameters



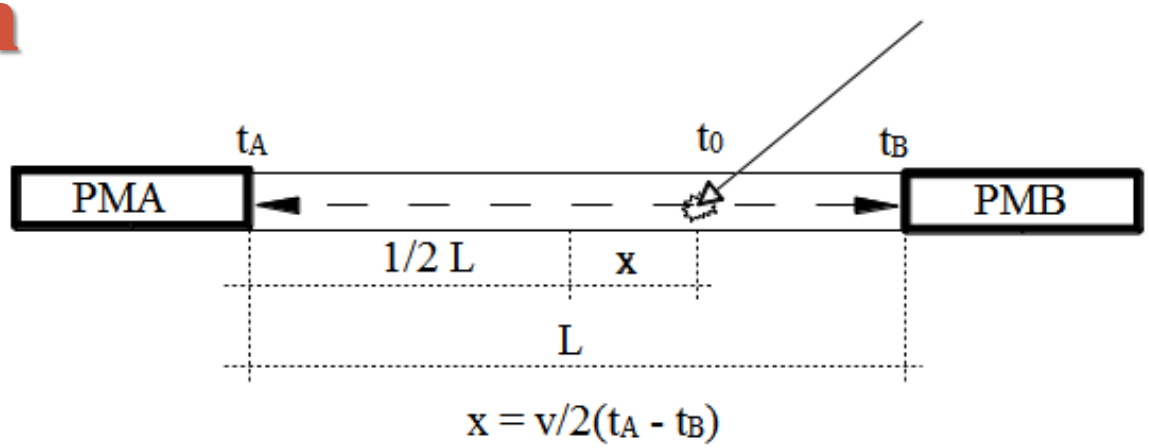




TOF-PET calibration: Energy

Energy calibration

Quantum efficiency and gain of PM



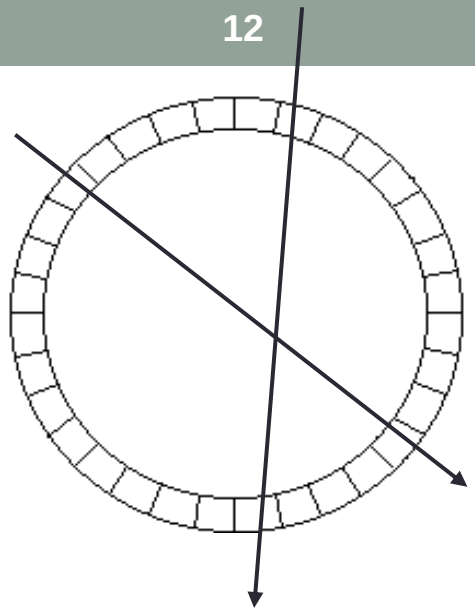
$$Q_{A(B)}(E_d, x) = \beta_{A(B)}\, f(x)\, E_d$$

Deposited energy

$$f(x) \cong e^{-\lambda\left(x+\frac{L}{2}\right)}$$

- Charge measured at both ends of detection module is proportional to the deposited energy
- Two procedures need to be developed:
  - Gains adjustment and monitoring
  - Charge⇔ Deposited energy relation

Energy calibration

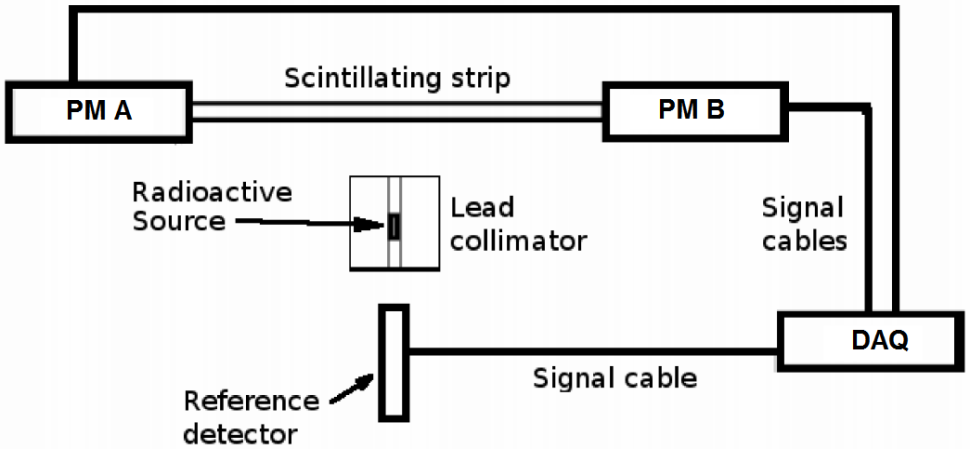


❖ Gains adjustment and monitoring

- Experimental determination of $f(x)$ for fixed deposited energy as a function of the position along the strip
- Known *gain (HV)* dependence + cosmic rays measurement

⇓

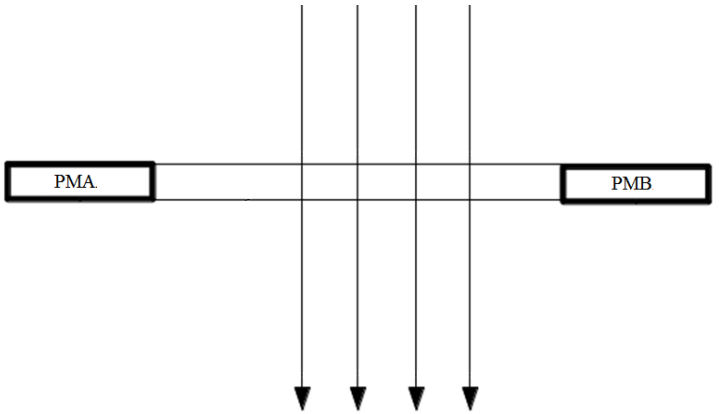
New HV value determination



- But…

Energy calibration

- Gains adjustment and monitoring



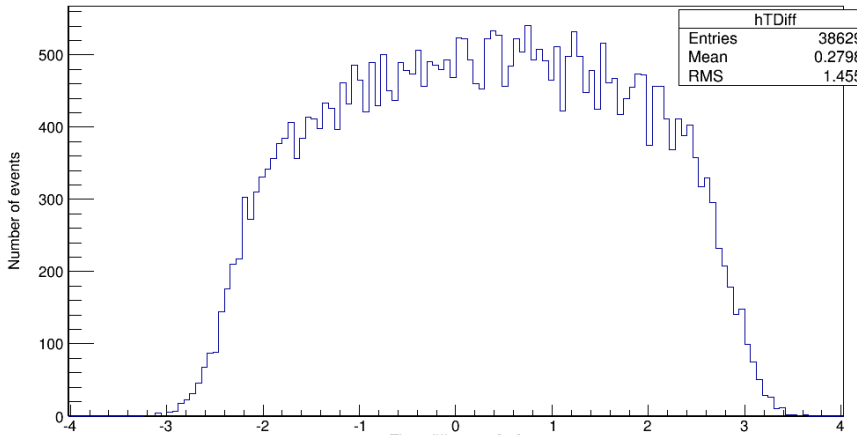
  - … assuming $Q_{A(B)}(E_d, x) = E_d \beta_{A(B)} e^{-\lambda\left(x+\frac{L}{2}\right)}$
  - Linear fit to the $ln\left(\frac{Q_A}{Q_B}\right)(x)$ distribution

$$ln\left(\frac{Q_A}{Q_B}\right)(x) = -2\lambda x + ln\left(\frac{\beta_A}{\beta_B}\right)$$

⇓

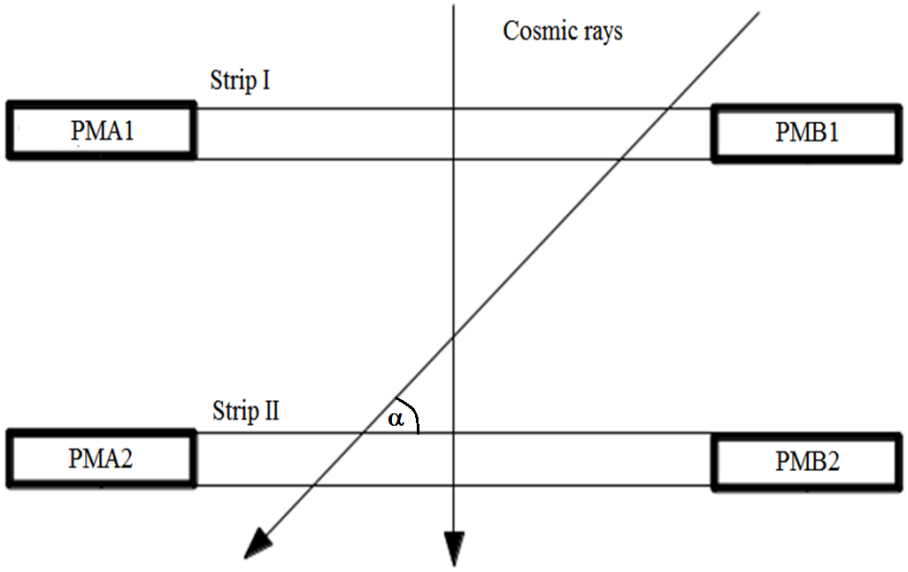
attenuation length + relative gain

  - Method for quick material and gains monitoring



$$f\left(ln\left(\frac{Q_A}{Q_B}\right)\right) = \frac{N}{\left\{1 + exp\left[\left(-ln\left(\frac{Q_A}{Q_B}\right) - \lambda L + ln\left(\frac{\beta_A}{\beta_B}\right)\right)/\sigma_Q\right]\right\}\left\{1 + exp\left[\left(ln\left(\frac{Q_A}{Q_B}\right) - \lambda L - ln\left(\frac{\beta_A}{\beta_B}\right)\right)/\sigma_Q\right]\right\}}$$

Energy calibration



- Charge ⇔ Deposited energy relation

$$\sqrt{Q_A Q_B}\,C = E_d$$

- Charge measurements for different α ⇒ different E_d
- For every α bin we know the mean deposited energy of cosmic rays:

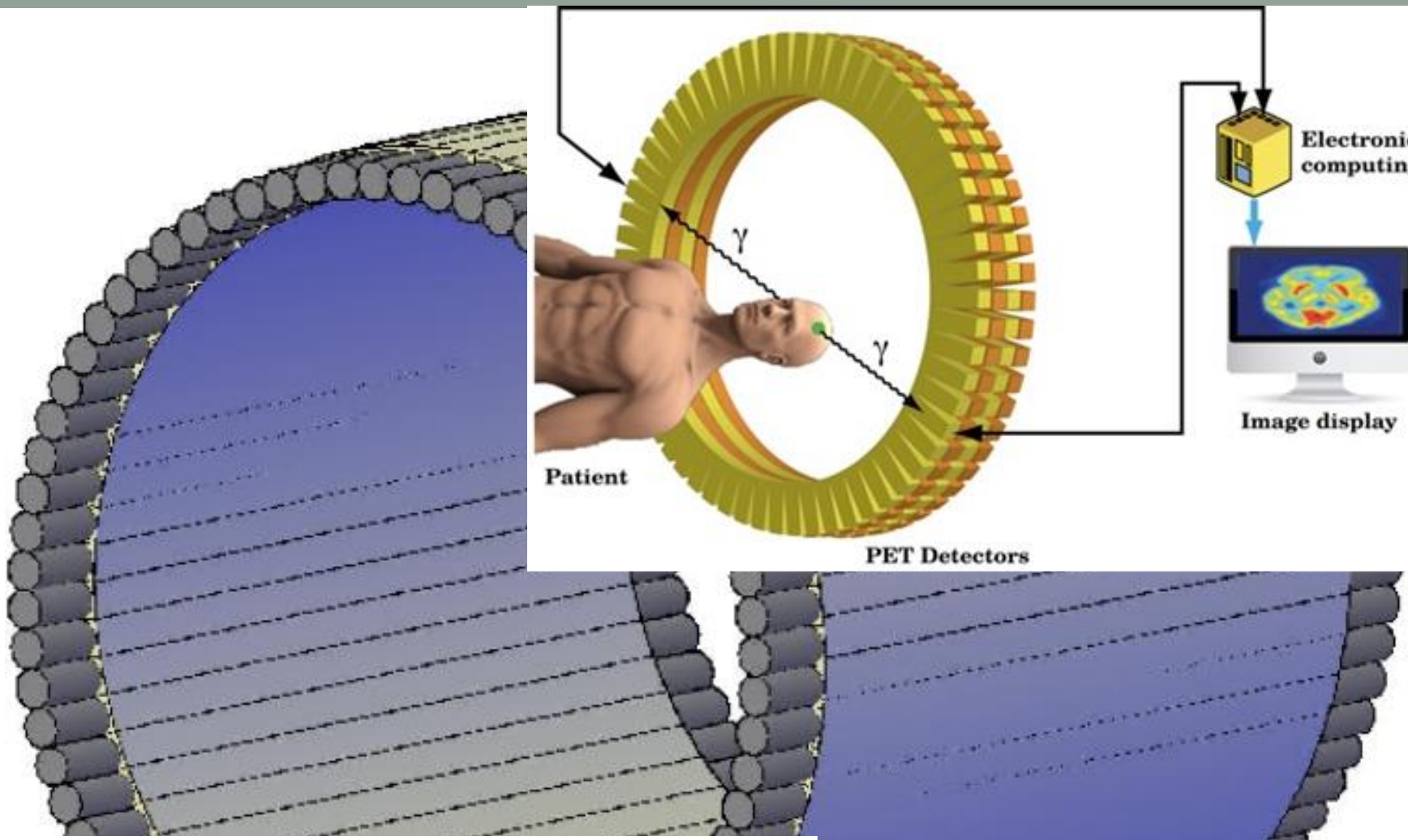
$$\langle\sqrt{Q_A Q_B}\rangle(\Delta\alpha)C = \langle E_d\rangle(\Delta\alpha)$$

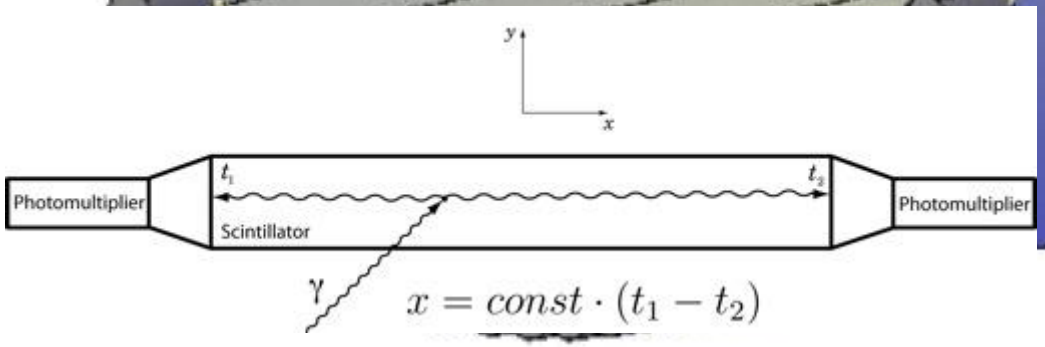
- The relation could be determined and moniotored also using radioactive sources and model E_d distribitions for cosmic rays

Summary and outlook

- Present methods of calibration and monitoring have some drawbacks and are not suited for the new Strip-PET concept
- Cosmic rays may be a very good alternative to the classical radiation sources
- The new methods may allow detailed monitoring of the whole detection setup
- Patent pending
- We are starting to confront the theory with reality

THANK YOU FOR ATTENTION


Electronics and computing system
Image display
γ
γ
Patient
PET Detectors


y
x
Photomultiplier
Photomultiplier
Scintillator
γ
$x = const \cdot (t_1 - t_2)$