A cosmic rays tracking system for the stability monitoring of historical buildings

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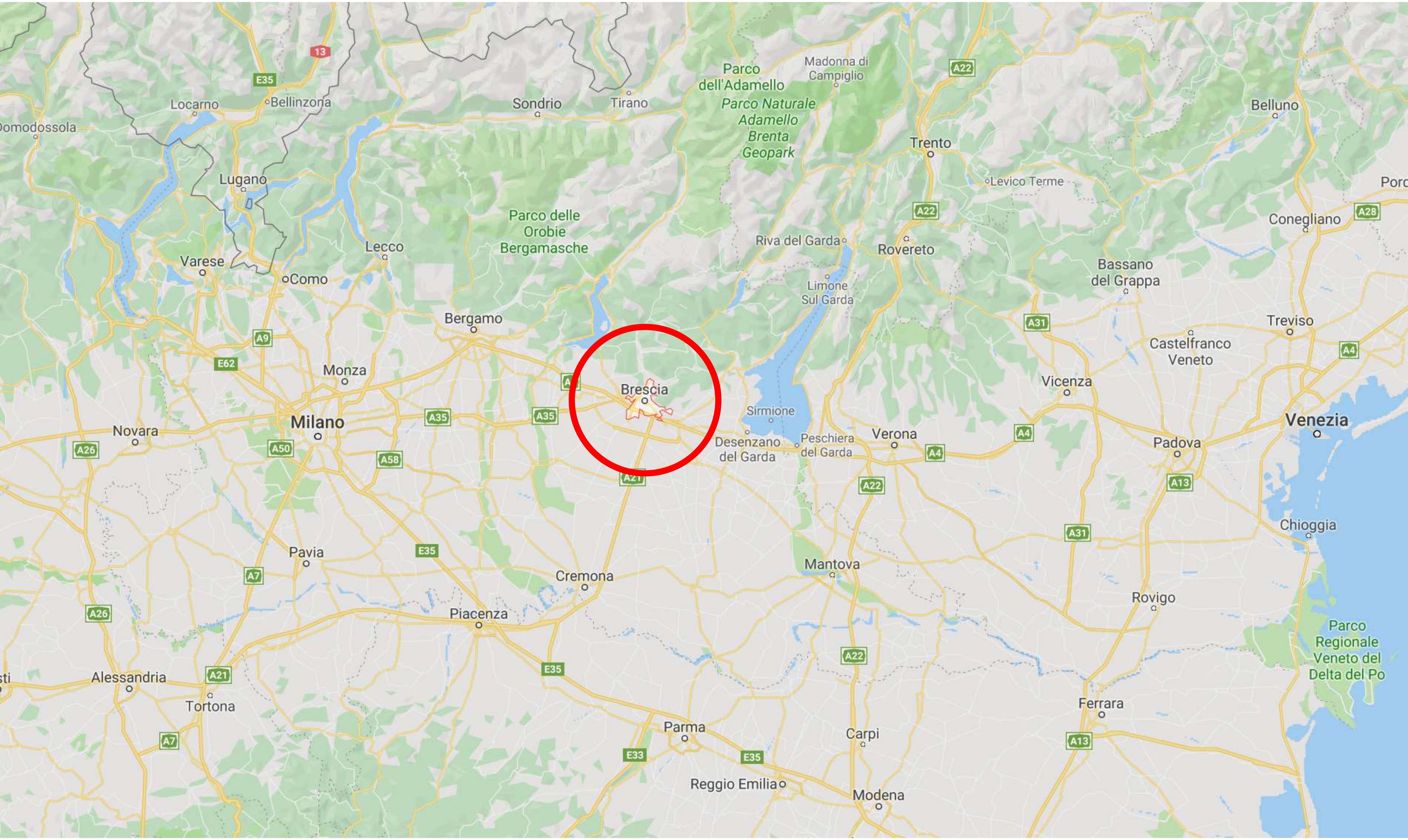
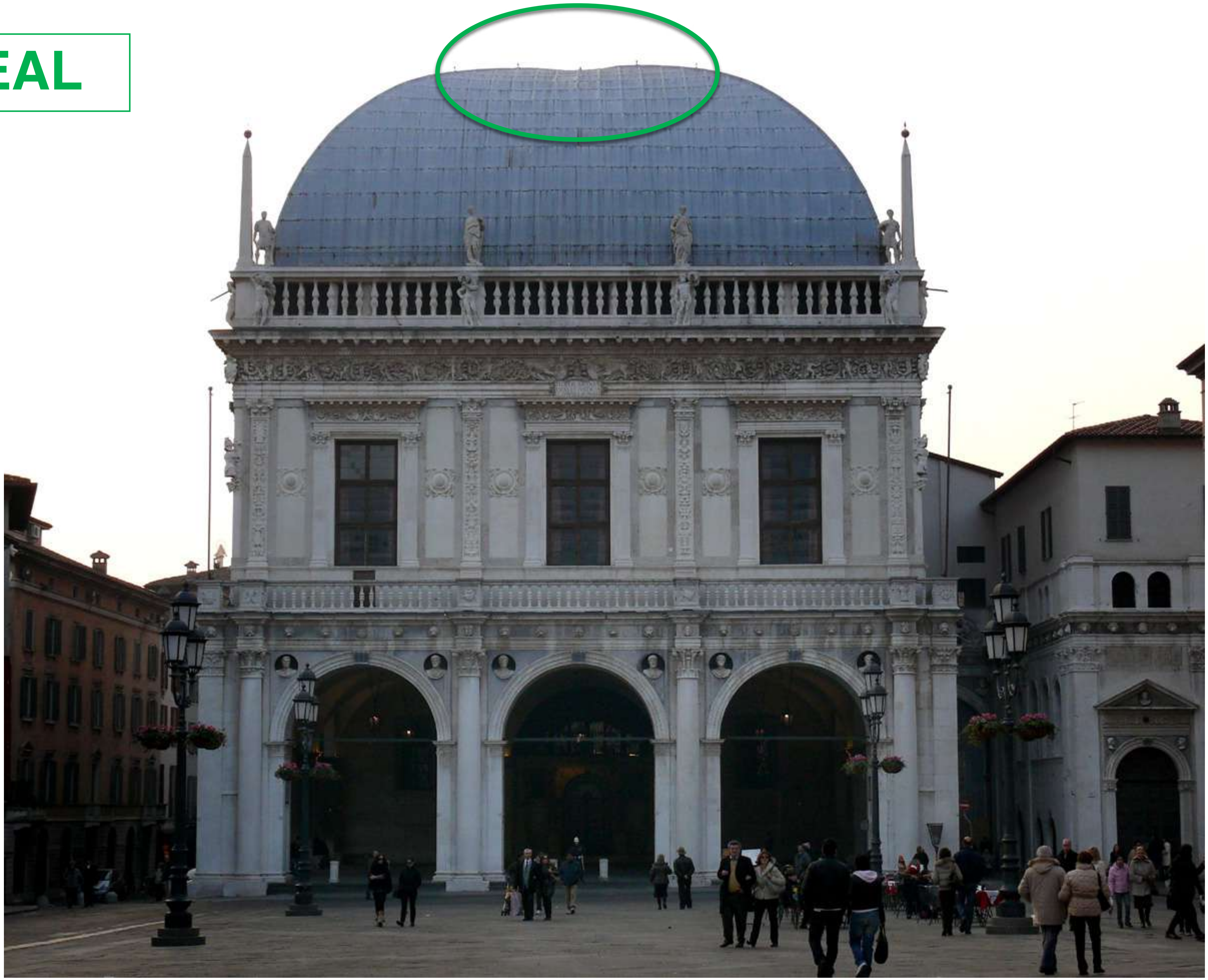
Motivations



FAKE

REAL



Stability monitoring of buildings:

the “Palazzo della Loggia” case

1484 1492 1574 1575 1769 1914

- **Formentone**: first proposal (wooden model)

The “Palazzo della Loggia” case

1484 — **1492** — **1574** — 1575 — 1769 — 1914

- **Formentone**: first proposal (wooden model)

First stone (**1492**) → French invasions (**from 1509**) → Sack of Brescia (**1512**) → Work resumed (**1535**) → End of work (**1574**)

- **Formentone**: first proposal (wooden model)

First stone	French invasions	Sack of Brescia	Work resumed	End of work
1492	**from 1509**	**1512**	**1535**	**1574**

- Original dome destroyed by fire and replaced by a *temporary* roof

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- Temporary roof replaced by an attic

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- Original dome destroyed by fire and replaced by a *temporary* roof
- Temporary roof replaced by an attic
- A new dome, based on the original project, replaced the attic

- Since its reconstruction, the dome exhibited a progressive deformation

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http://www.fondazionemicheletti.eu/italiano/news/dettaglio_news.asp?id=329

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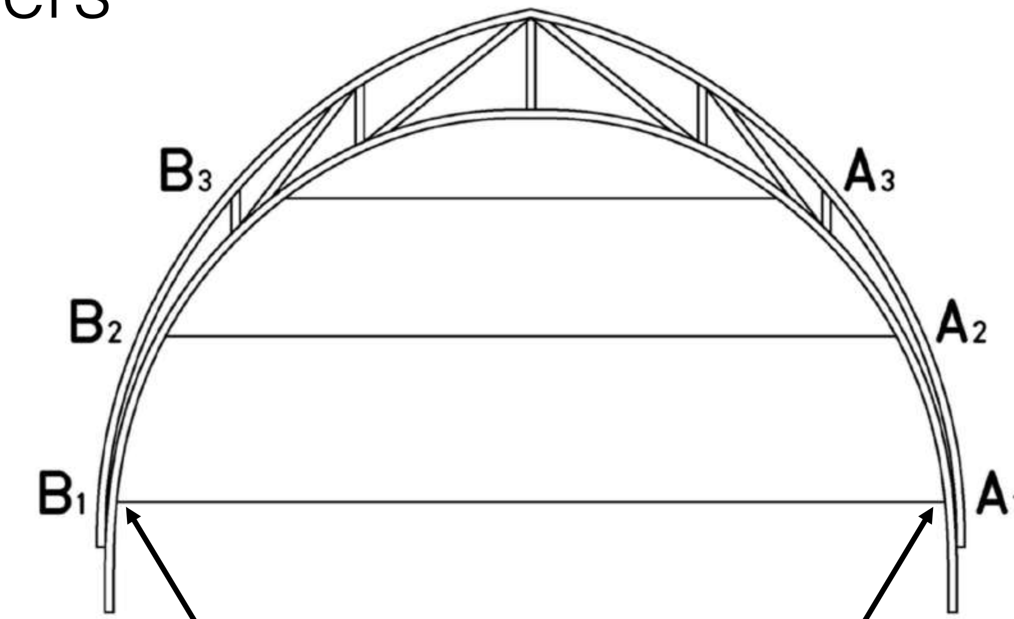
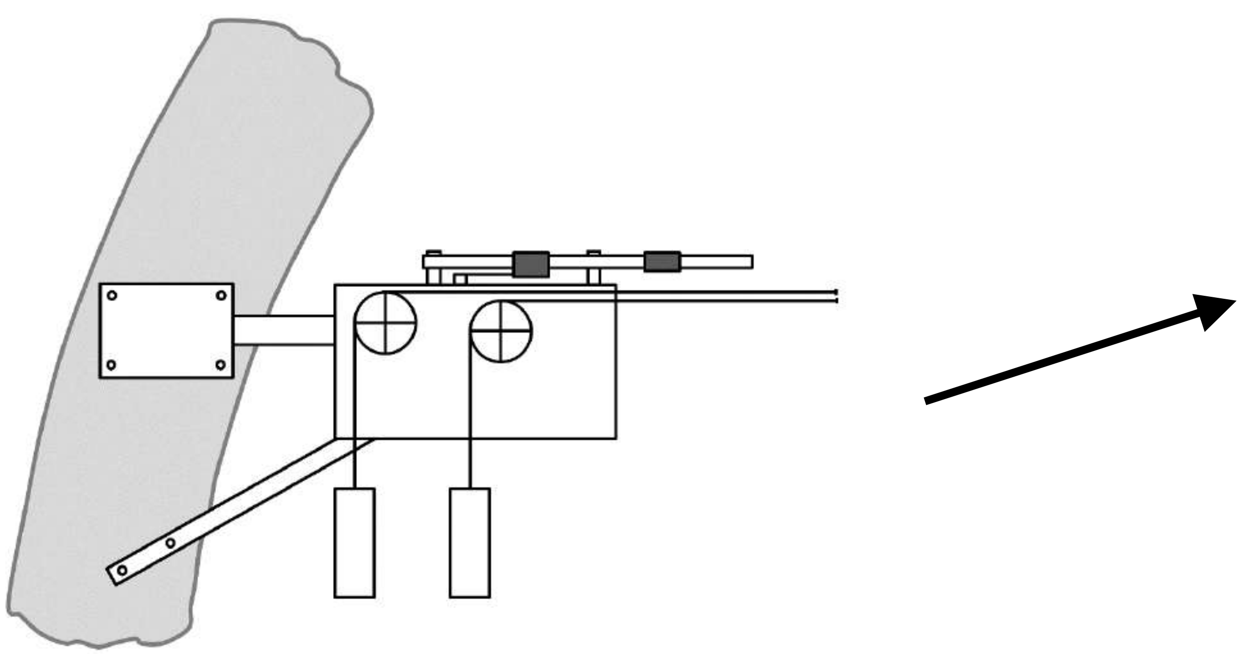
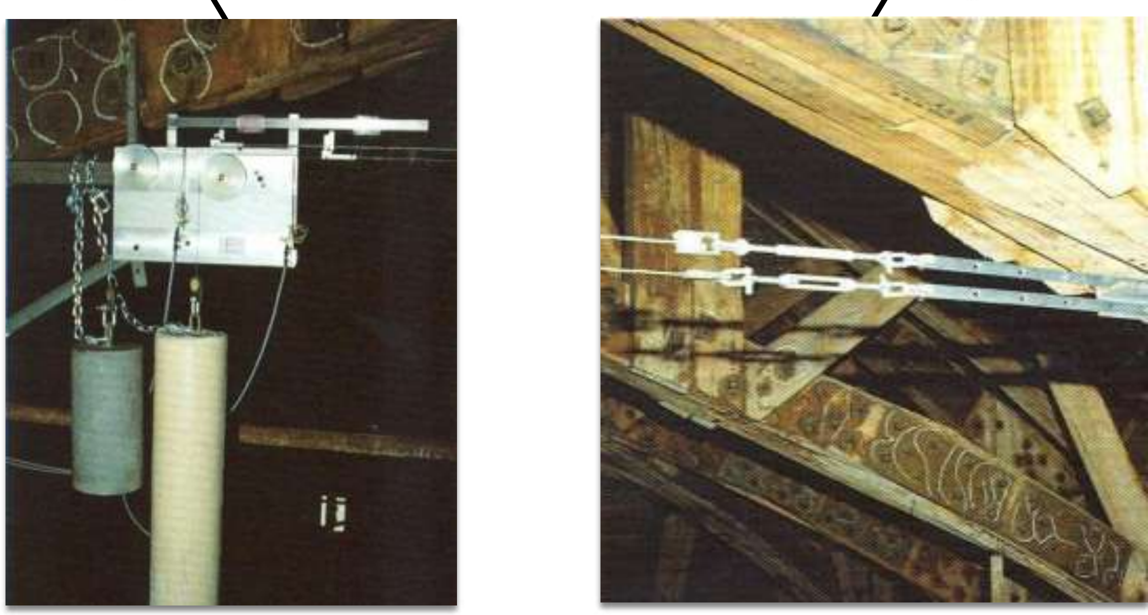
The “Palazzo della Loggia” case

- Since its reconstruction, the dome exhibited a progressive deformation
- For this reason a systematic campaign of monitoring of the dome was performed by using (invasive) extensometers
- Pairs of wires ($\emptyset = 2\ mm$): invar (nikel-iron alloy) and steel
- Mechanical stabilization of the tension

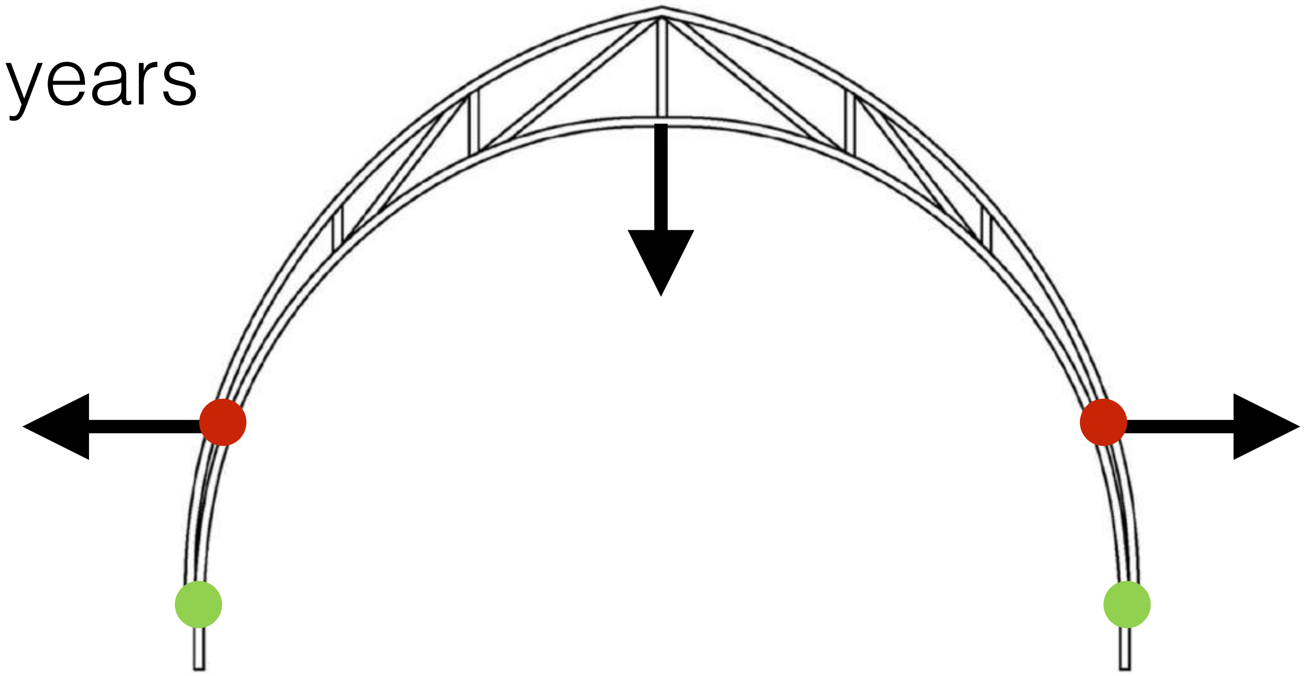


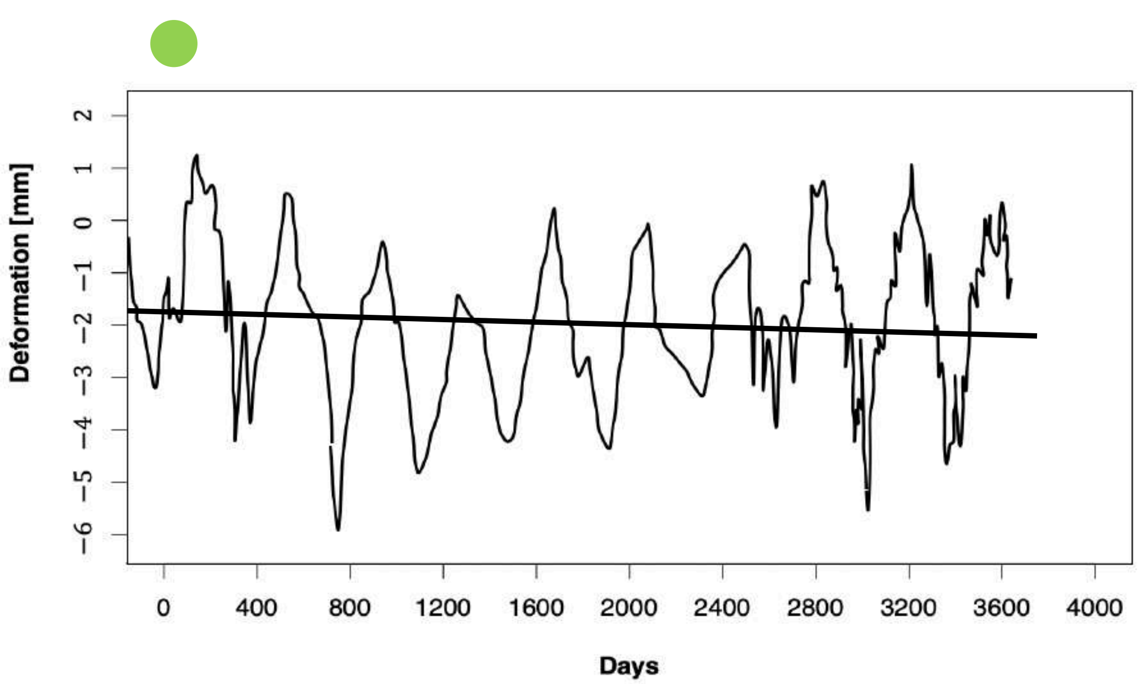


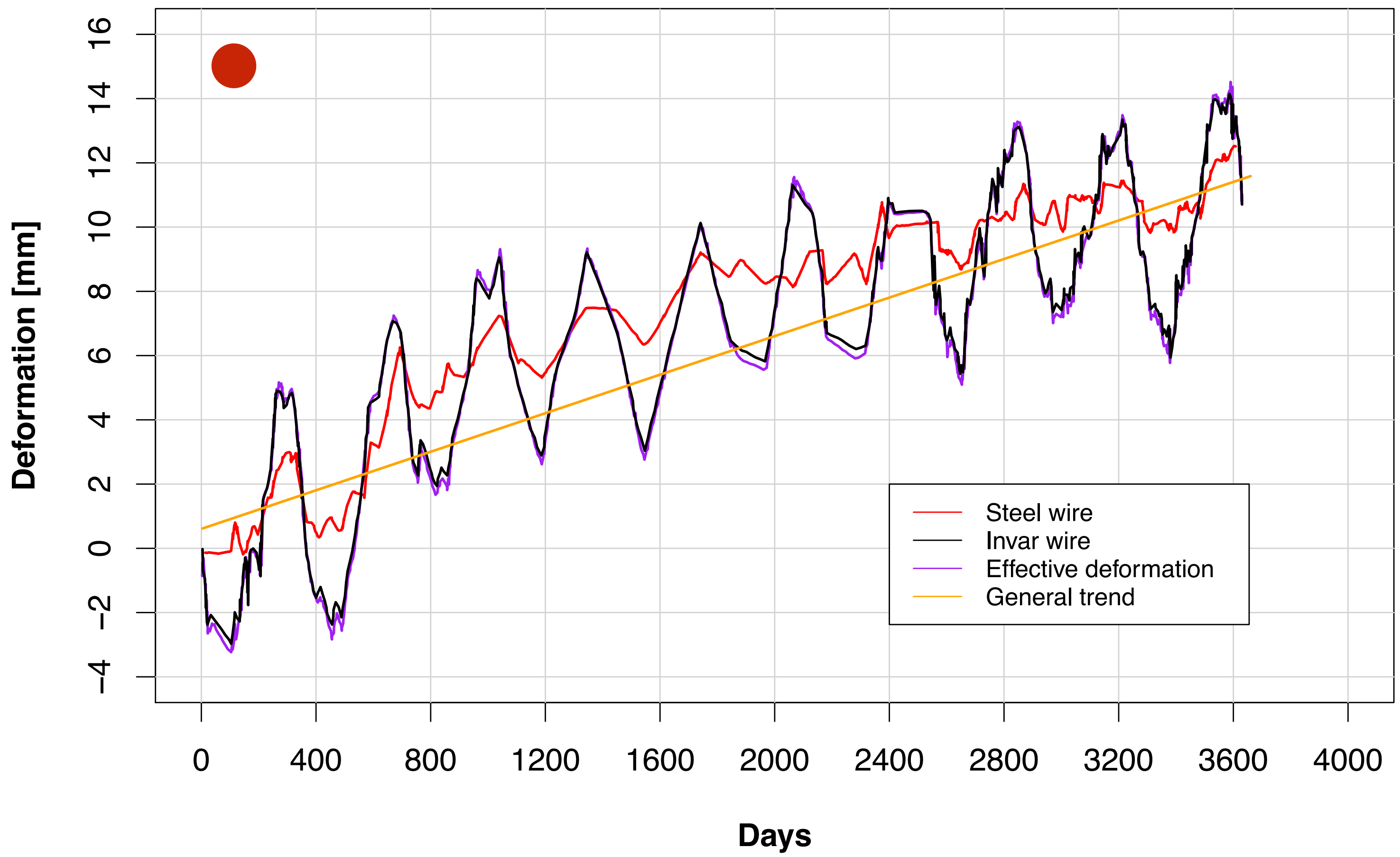


A. Bellini et al., “Il Palazzo della Loggia di Brescia - Indagini e progetti per la conservazione”, Starrylink editrice, 2007

- Data taking lasted for more than 10 years
- A deformation of $\sim 1\ mm/year$ was measured
- Stable load-bearing walls: only the dome is affected







- Stability monitoring for historical buildings is fundamental and their structural vulnerability is also recognized at regulatory level

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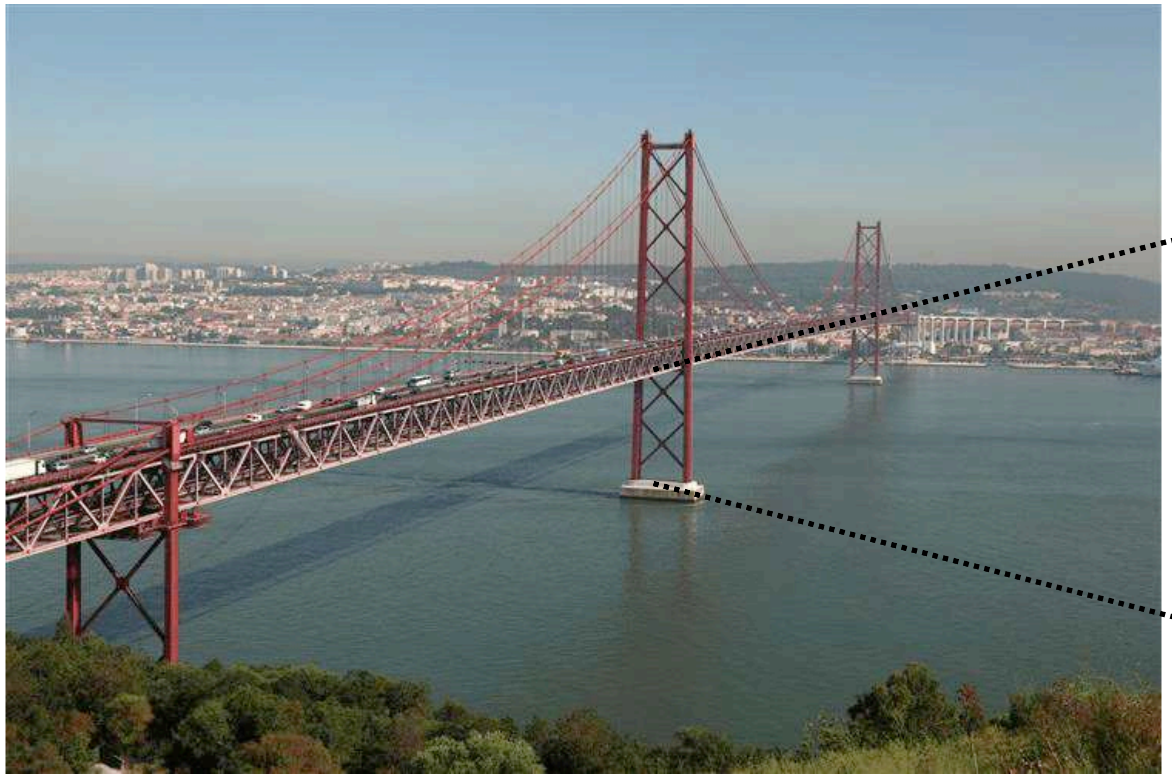
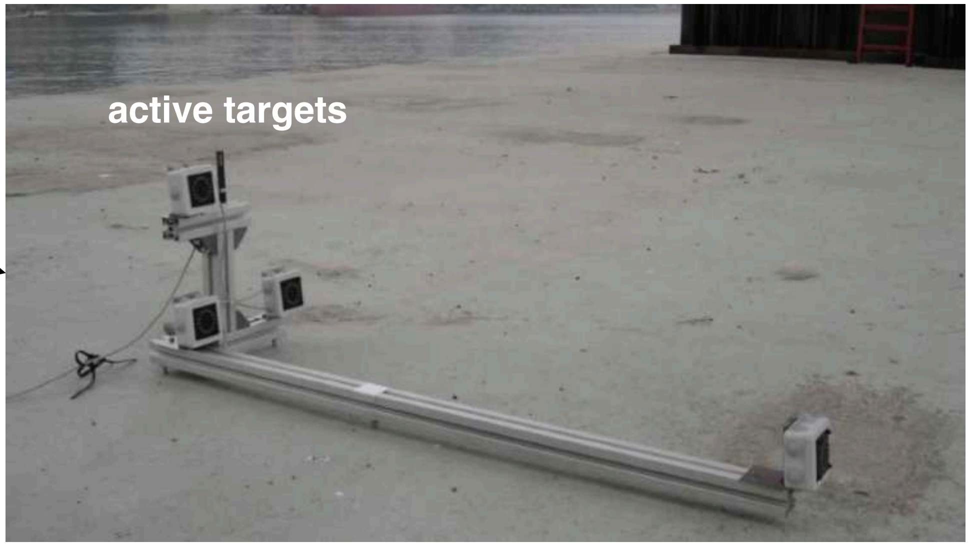
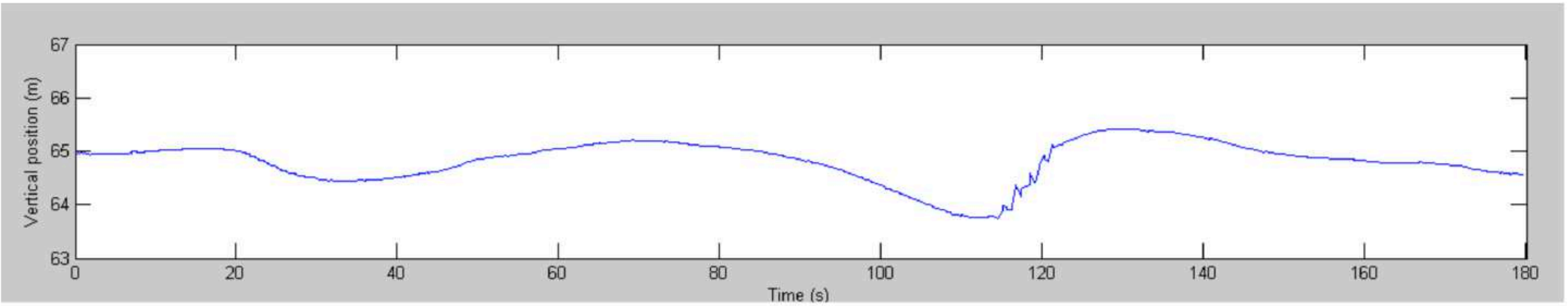
- Current techniques include the use of mechanical or optical systems, vision-based methods, sensors such as accelerometers, etc…

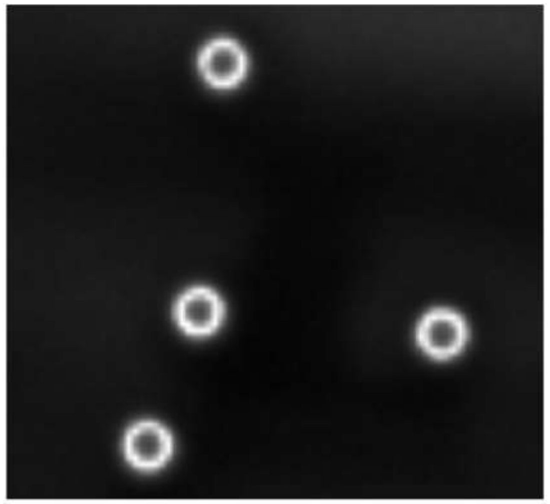
P25A suspension bridge, Lisbon (Portugal)



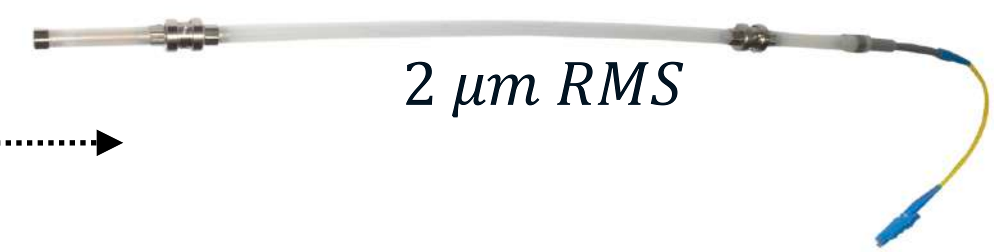
L. Lages Martins, J. M. Rebordão and A. Silva Ribeiro Journal of Physics: Conference Series 588 (2015) 012004

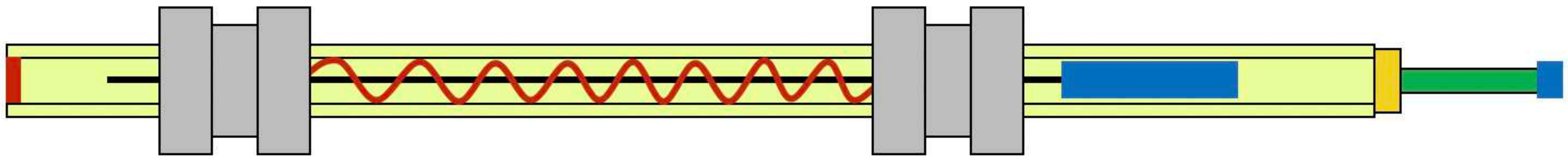




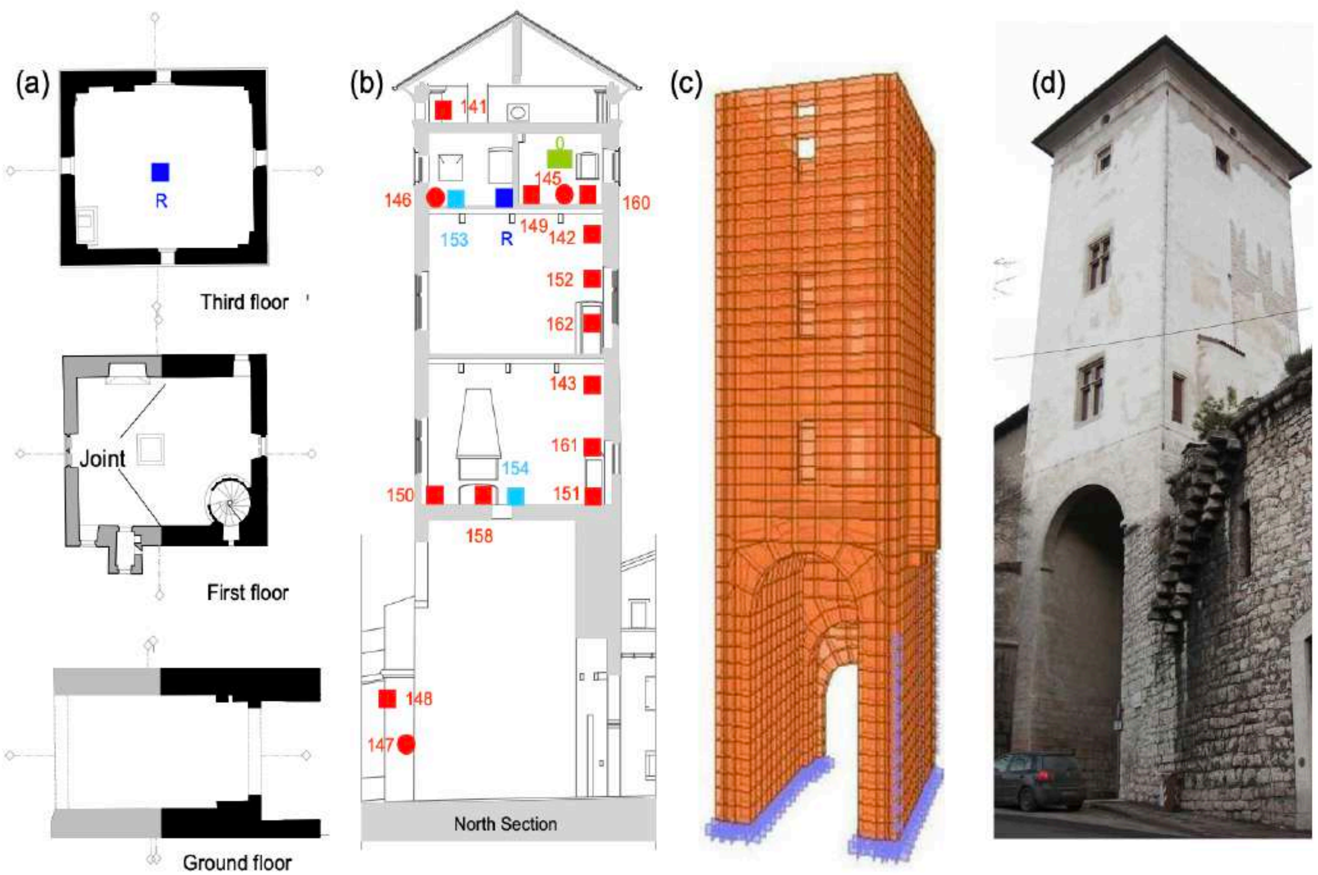


Monitoring system consisting of accelerometers, thermometers and **fiber optic sensors**

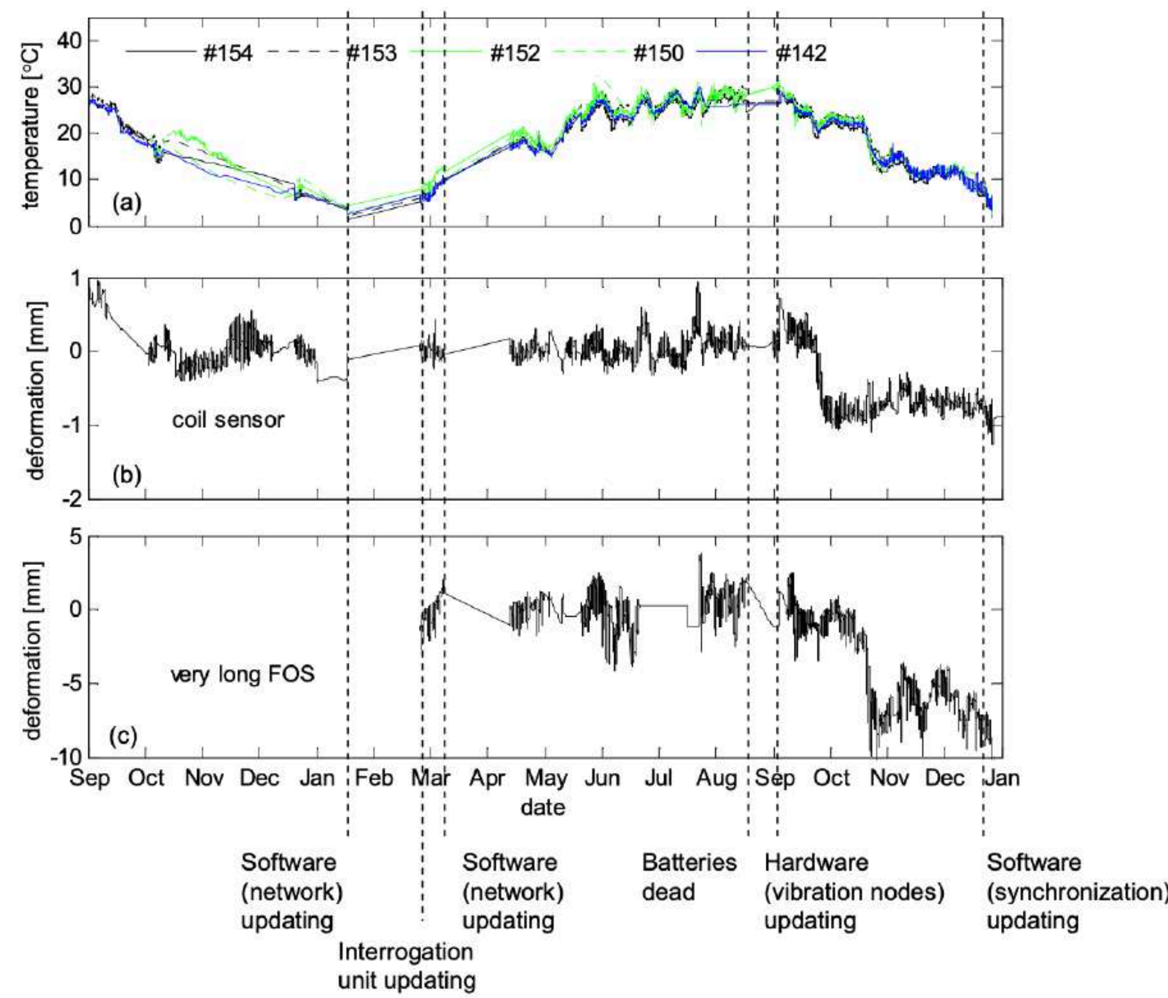




Torre Aquila, Trento, Italy



Advanced Materials Research Vols. 133-134 (2010) pp 235-240



- Current techniques (some of them shown in the previous slides) have some drawbacks:
    - Some are not suitable for continuous monitoring
    - Some are very specific (type of buildings, type of deformation, ...)
    - Many are quite **invasive**
- For historical building strong constraints on invasiveness apply

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- For hist y

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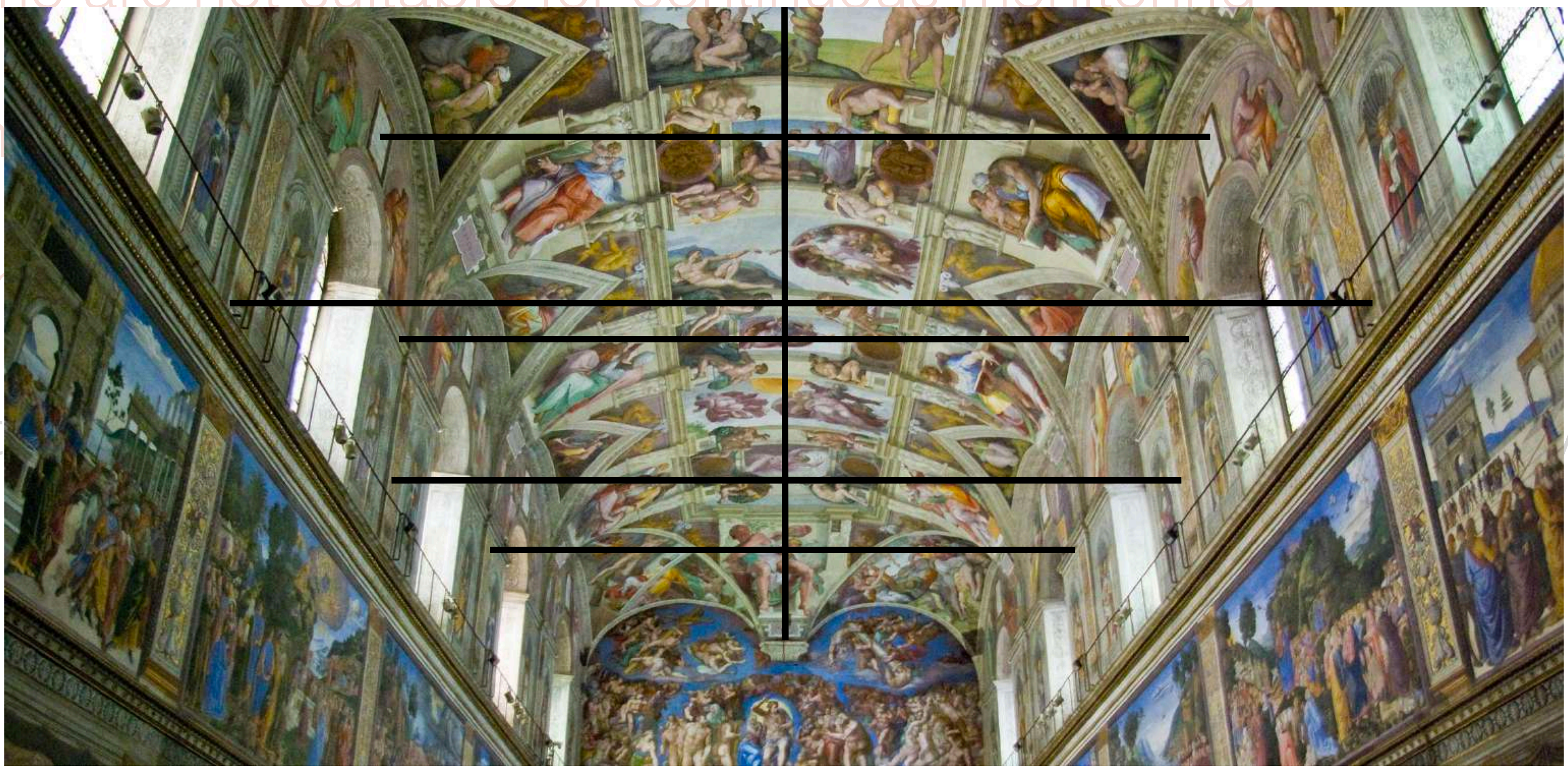

- Current techniques (some of them shown in the previous slides) have some drawbacks:
  - Some are not suitable for continuous monitoring
  - Some are very specific (type of buildings, type of deformation, ...)
  - Many are quite **invasive**
- For historical buildings strong constraints on invasiveness apply
- Therefore we investigated the possibility of a monitoring system based on the reconstruction of cosmic muons by means of *compact* detectors
  - Deformation of historical buildings occur over a *long* period of time, so the limited rate of cosmic muons could not be an issue

👍 use of a free natural source of radiation

👍 muons are highly penetrating: walls and floors are easily traversed

👍 no need of visibility or empty spaces

👍 limited invasiveness

👍 possibility to design a global monitoring system

👎 fixed rate of cosmic muons: (relatively) long data taking

- For all these reasons, the possibility of using cosmic muons for the stability monitoring of historical buildings has been investigated
- *Palazzo della Loggia* in Brescia has been chosen as a benchmark case

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Cosmic ray tracking to monitor the stability of historical buildings: a feasibility study

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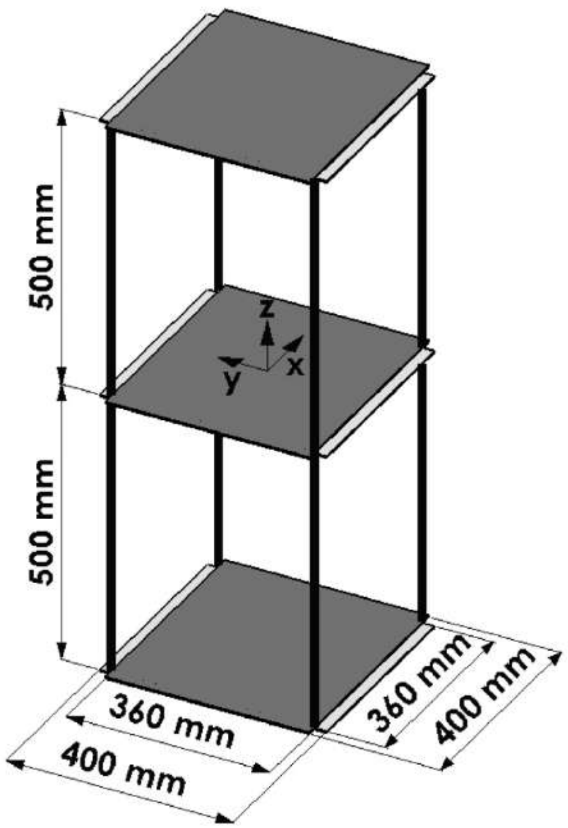
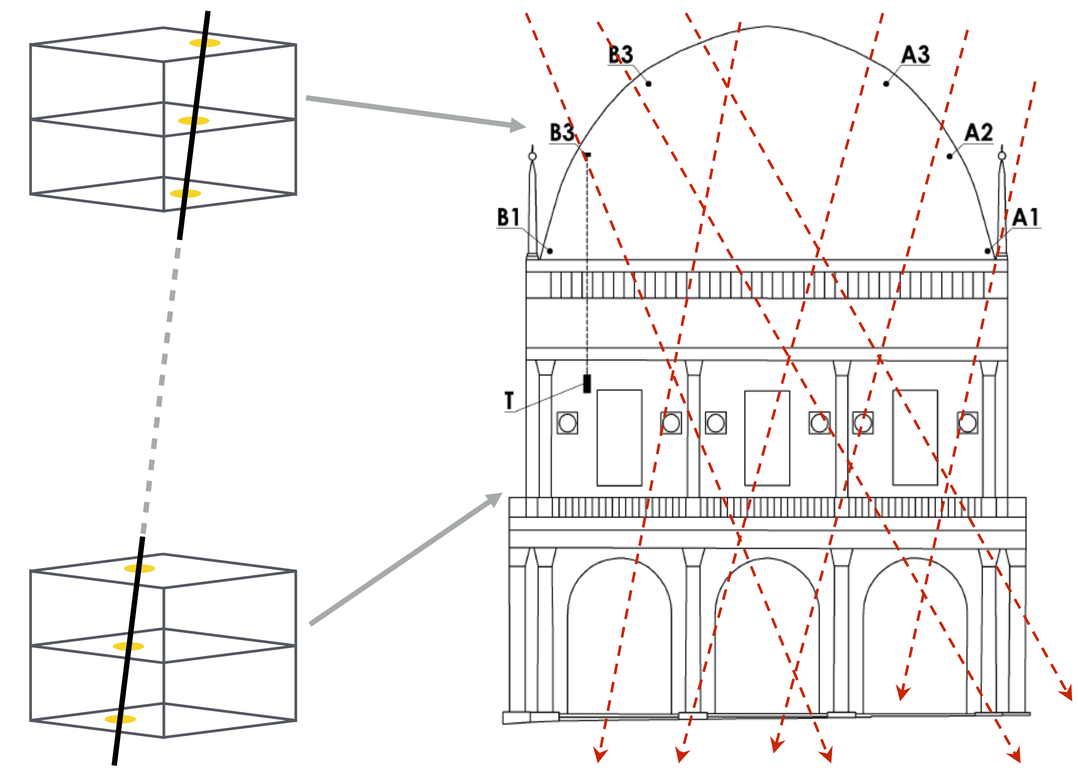
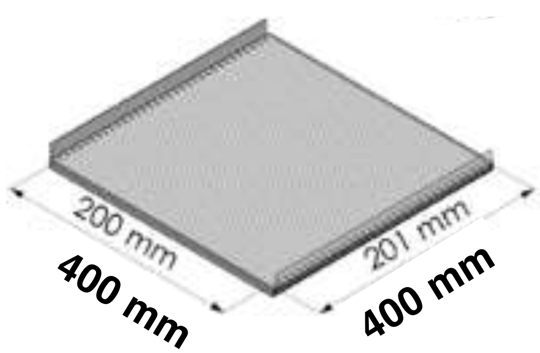
Abstract
A cosmic ray muon detection system is proposed for stability monitoring in the field of civil engineering, in particular for the static monitoring of historical buildings, where conservation constraints are severe and the time evolution of the deformation phenomena under study may be of the order of months or years. The stability monitoring of the wooden vaulted roof of the *Palazzo della Loggia*, located in the town of Brescia, Italy, has been considered as a case study. The feasibility, as well as the performance and limitations of a stability monitoring system based on cosmic ray tracking have been studied by Monte Carlo simulations. A study of possible systematic uncertainties is presented along with a realistic design for the construction of a measurement system prototype.

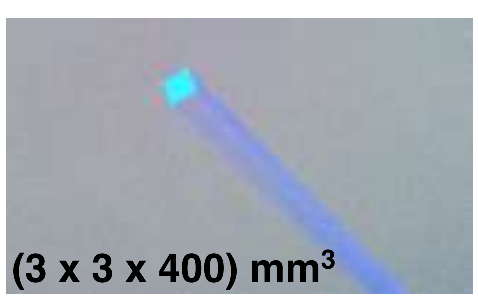


independent detectors



Proposed detector



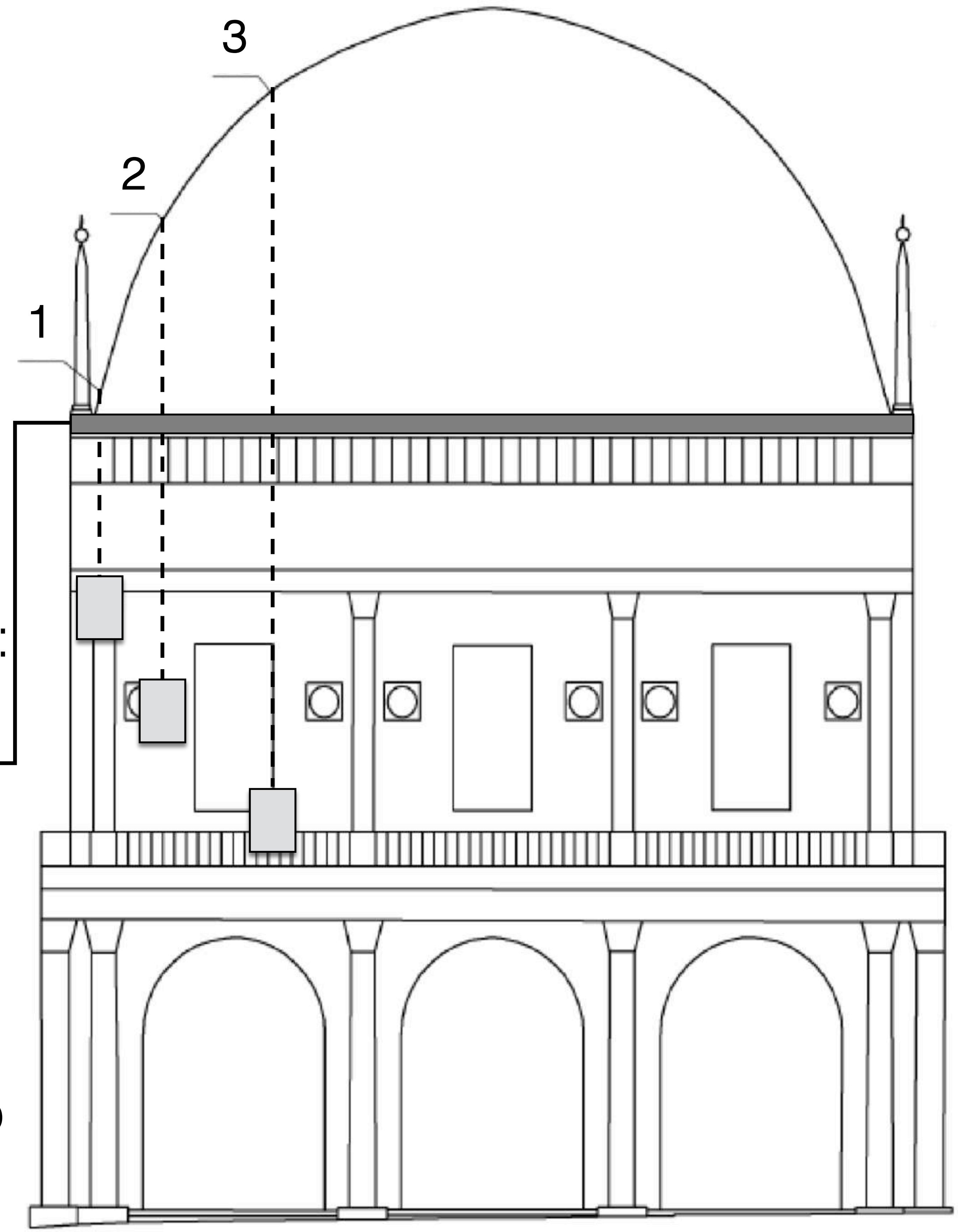


- double layers of scintillating (3×3) mm^2 fibers
- fibers coupled to SiPMs
  - cheap
  - low voltage operation
  - good spatial and time resolution

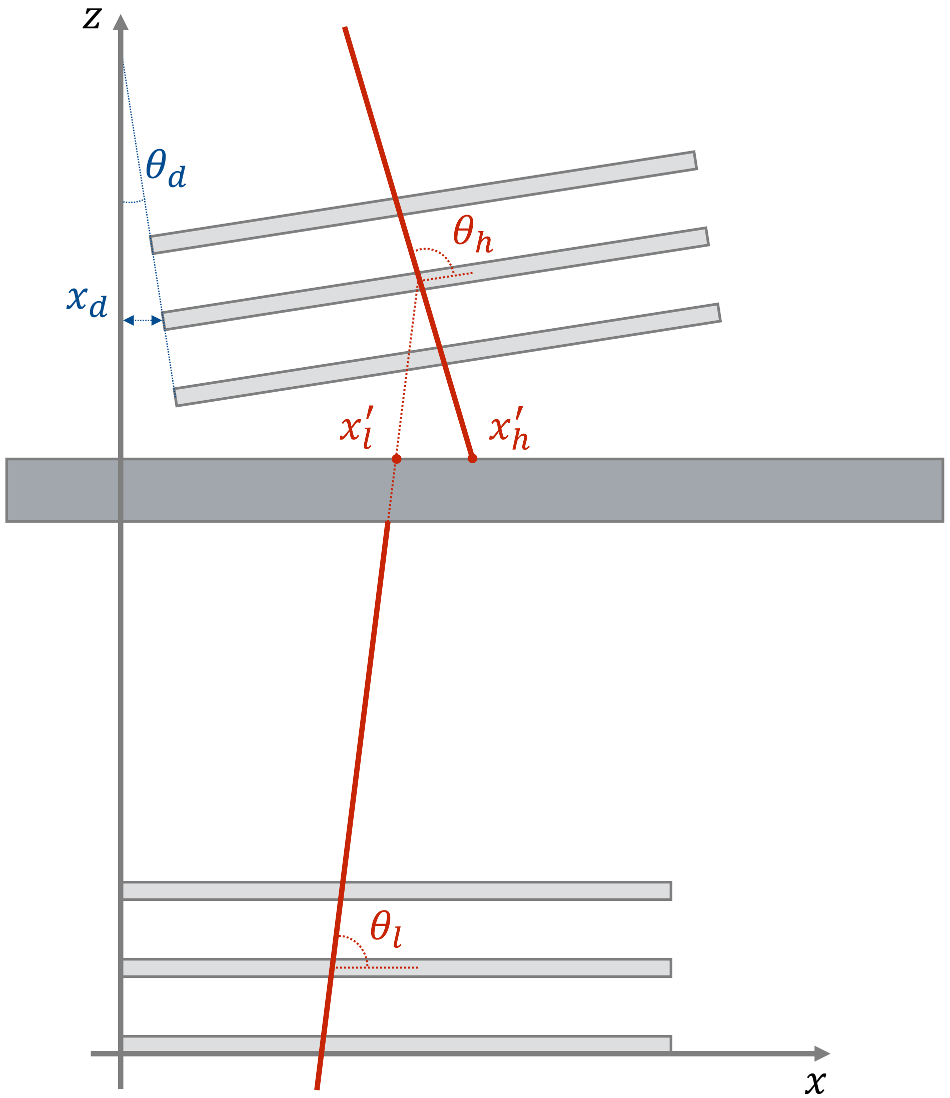
- MC simulations performed in three different configurations:
    - 1: $\Delta z = 350\ cm$
    - 2: $\Delta z = 880\ cm$
    - 3: $\Delta z = 1300\ cm$
- No visibility between the detectors:
    - 15 cm of concrete
- Realistic cosmic muon generator based on experimental data

Bonechi et al. (2005) Proc. 29th Int. Cosmic Ray Conf. vol 9 p 283

- Systematic uncertainties taken into account (details in the next slides)



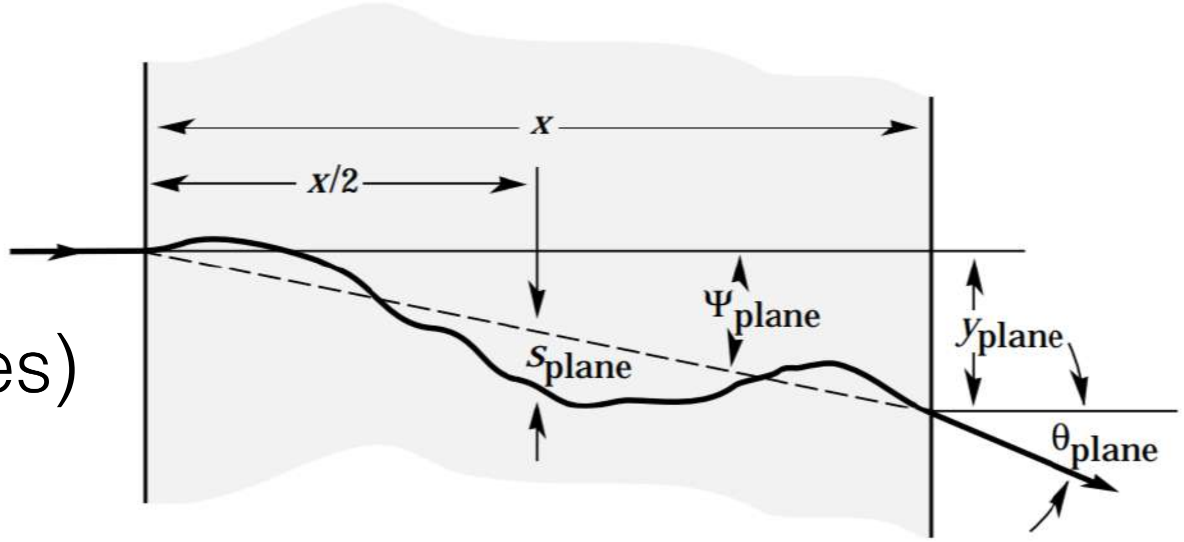
- $x - z$ and $y - z$ views independently reconstructed ($x - z$ case here)
- For perfectly aligned geometry expected values $E[x'_h - x'_l] = 0$ and $E[\theta_h - \theta_l] = 0$
- $x'_h - x'_l$ and $\theta_h - \theta_l$ depend on the parameters of interest x_d and θ_d
- Estimates $\hat{x}_d$ and $\hat{\theta}_d$ from a χ^2 minimization



$$\chi^2 = \sum_i \left[\frac{(x'_{h,i} - x'_{l,i})^2}{(\sigma^2_{x'_h,i} + \sigma^2_{x'_l,i})^2} + \frac{(\theta_{h,i} - \theta_{l,i})^2}{(\sigma^2_{\theta_{h,i},i} + \sigma^2_{\theta_{l,i},i})^2} \right]$$

- Index i runs over the reconstruted muons in the data sample

- Coulomb scattering distribution well represented by the theory of Molière



- Roughly Gaussian (small deflection angles)
- By defining $\theta_0 = \theta_{plane}^{rms} = \frac{1}{\sqrt{2}} \theta_{space}^{rms}$

Highland parametrization

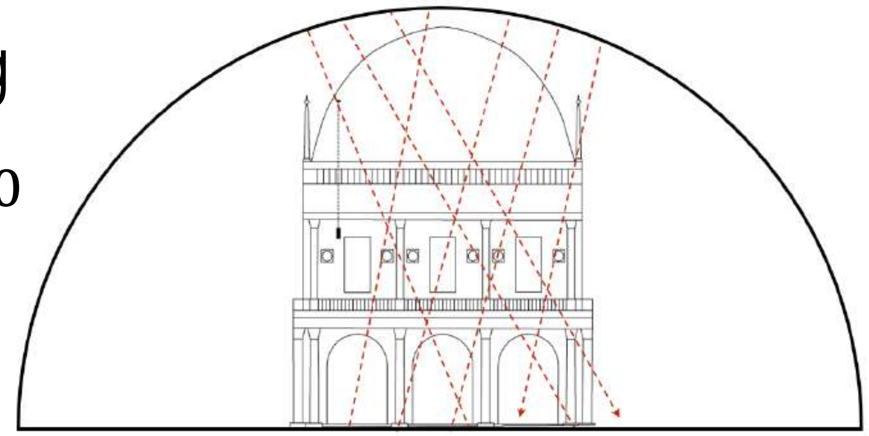
$$\theta_0 \cong \frac{13.6\ \mathrm{MeV}}{\beta c p} z \sqrt{\frac{x}{X_0}} \left[1 + 0.038 \ln\left(\frac{x}{X_0}\right)\right]$$

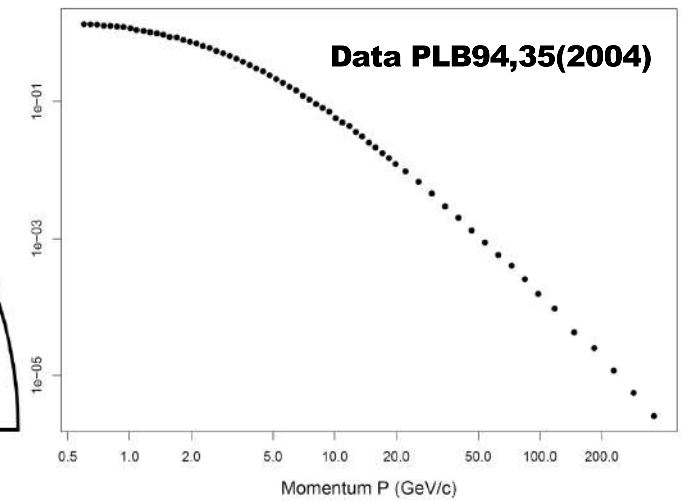
Lynch-Dahl parametrization

$$\theta_0 \cong \frac{\chi_c^2}{1+F^2} \left[\frac{1+v}{v} \ln(1+v) - 1\right]$$

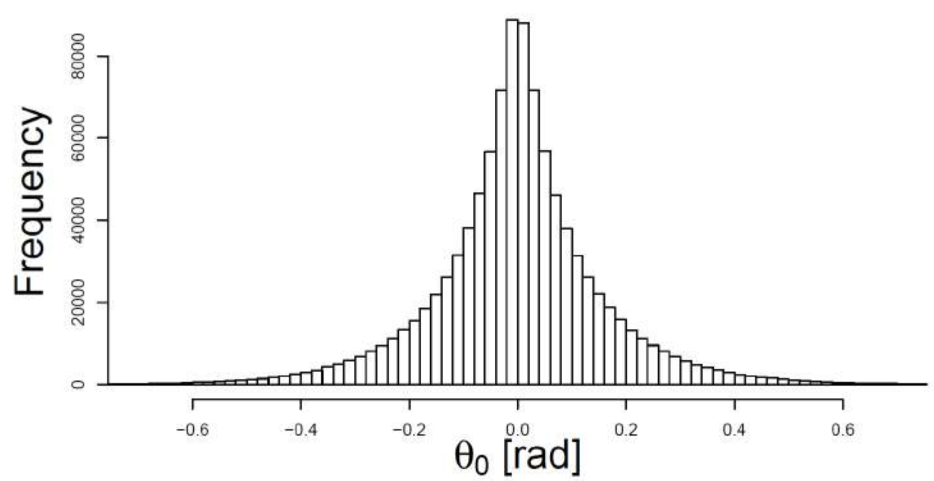
- Scattering "shift": $y_0 = y_{plane}^{rms} \cong \frac{1}{\sqrt{3}} x \theta_0$
- We investigated the possibility of using this information to improve the reconstruction performance

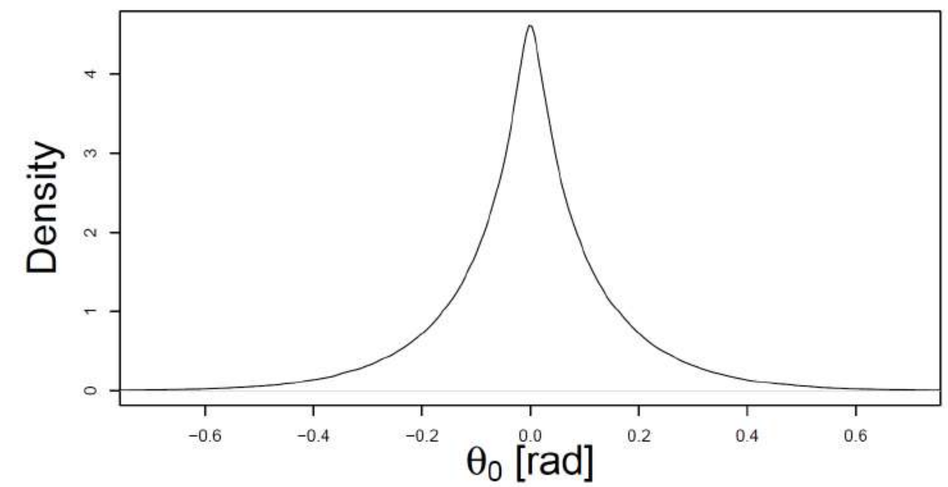
- Knowledge of the interposing material $\Longrightarrow$ pdfs for θ_0 and y_0 (15 cm concrete)



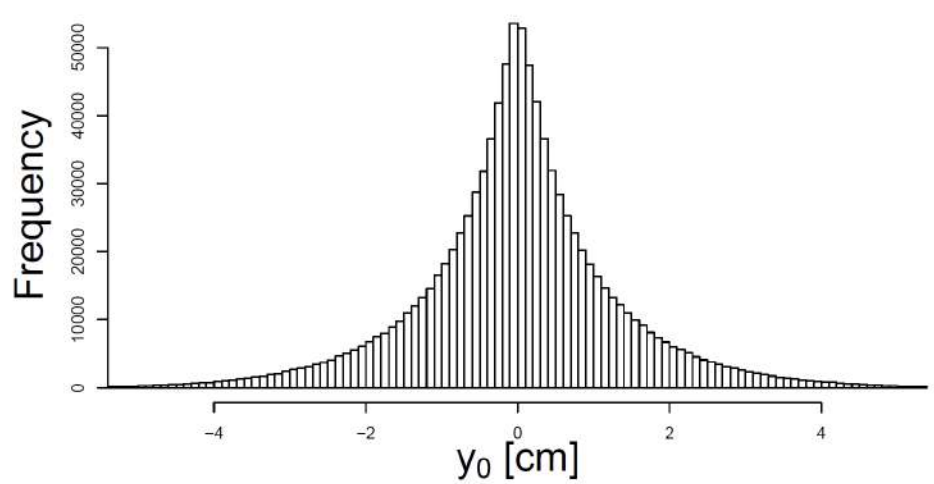


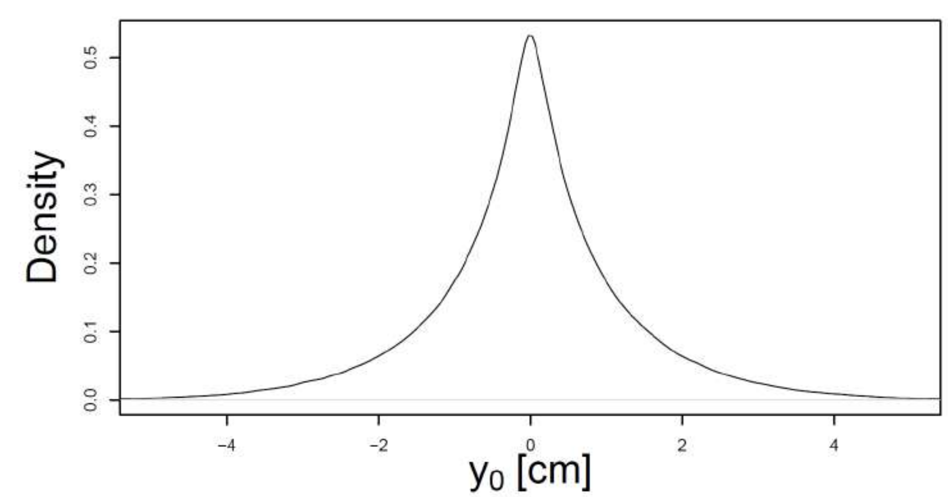
Normal incidence
p integrated





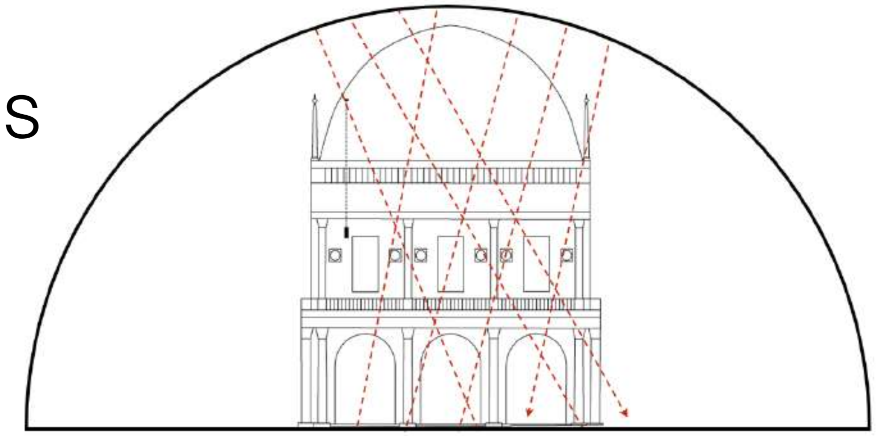
Kernel Density Estimation



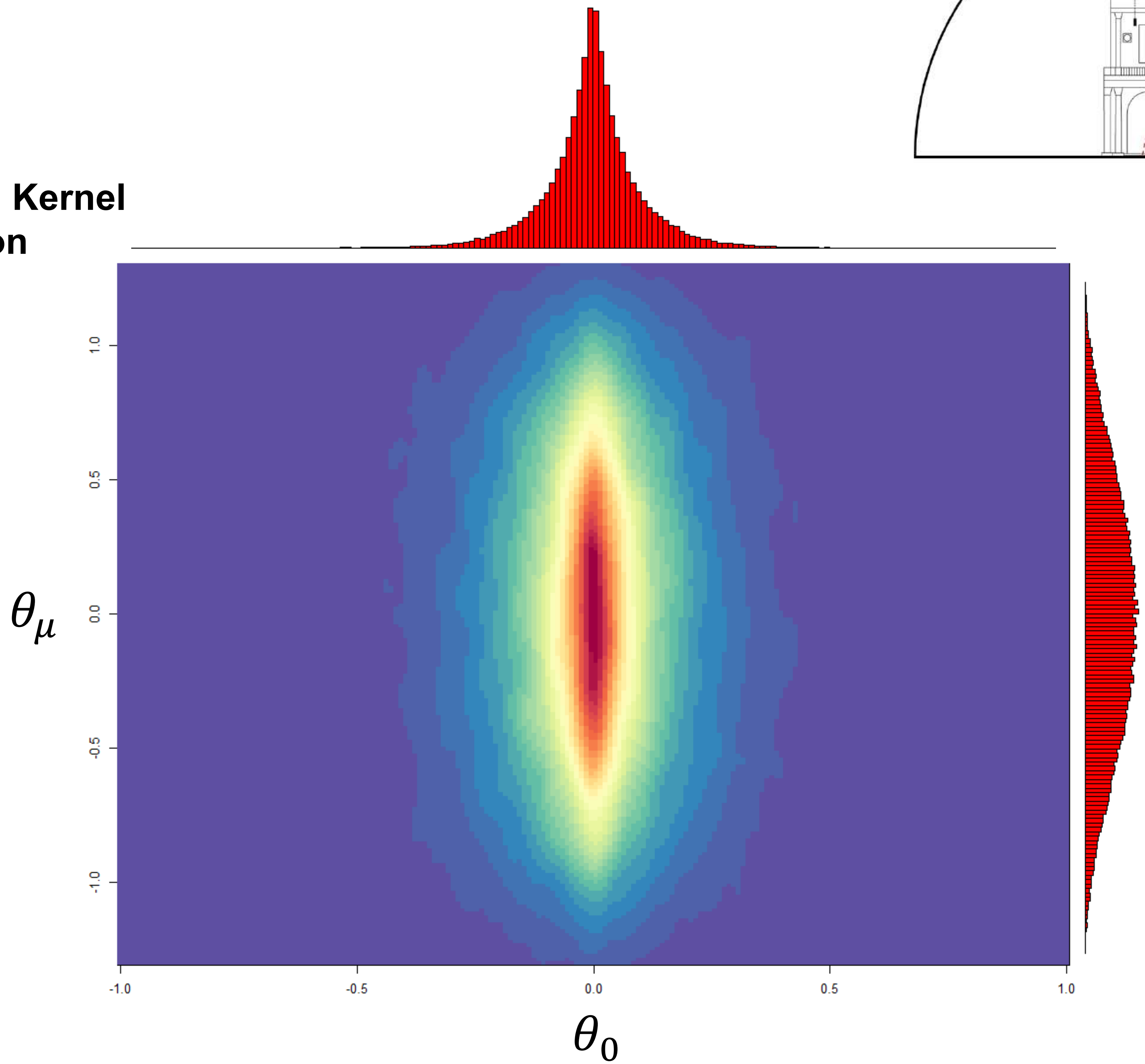


A possible improvement

- Pdfs depend on the incidence angle θ_μ of muons

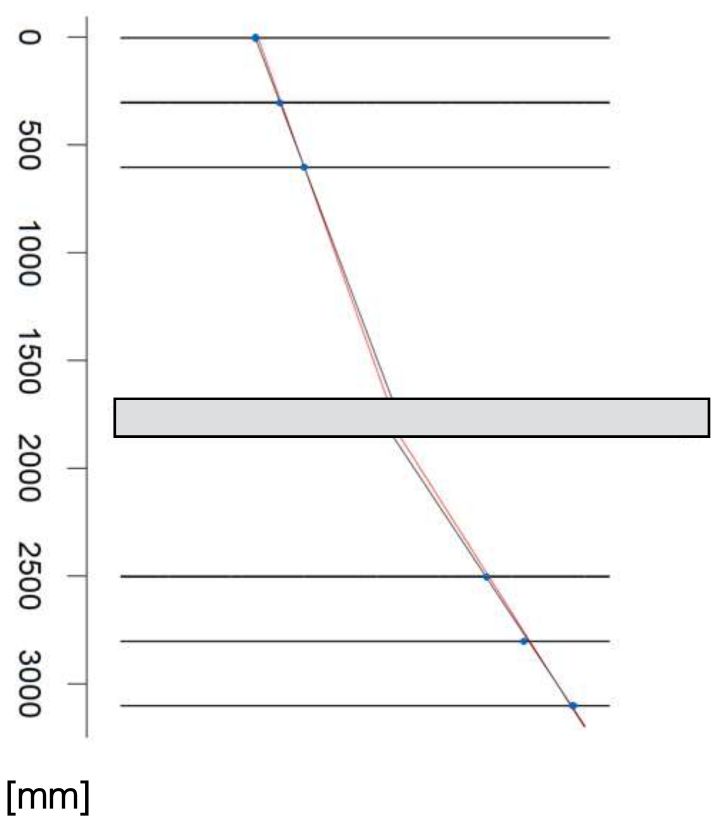


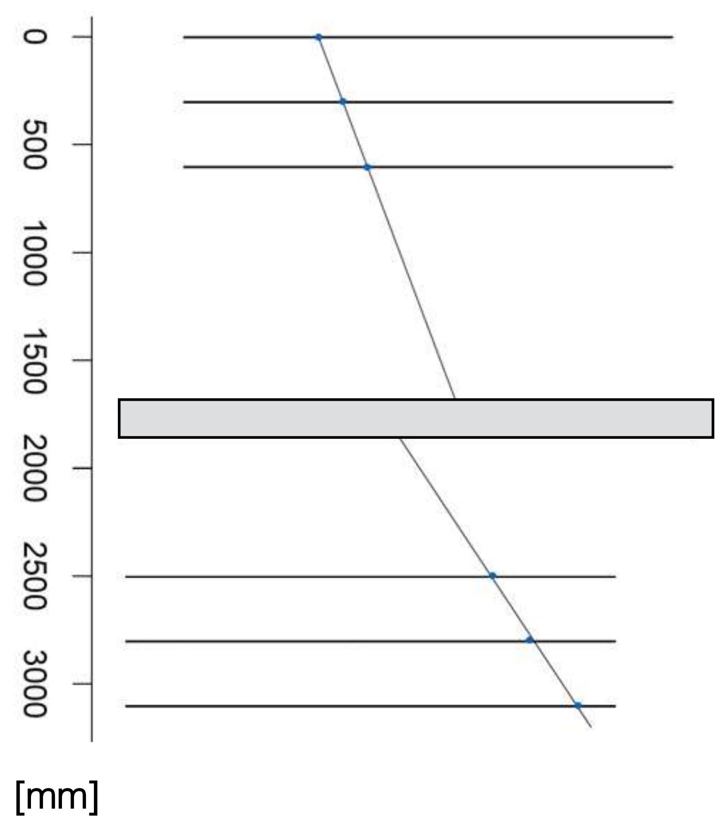
Two-Dimensional Kernel Density Estimation

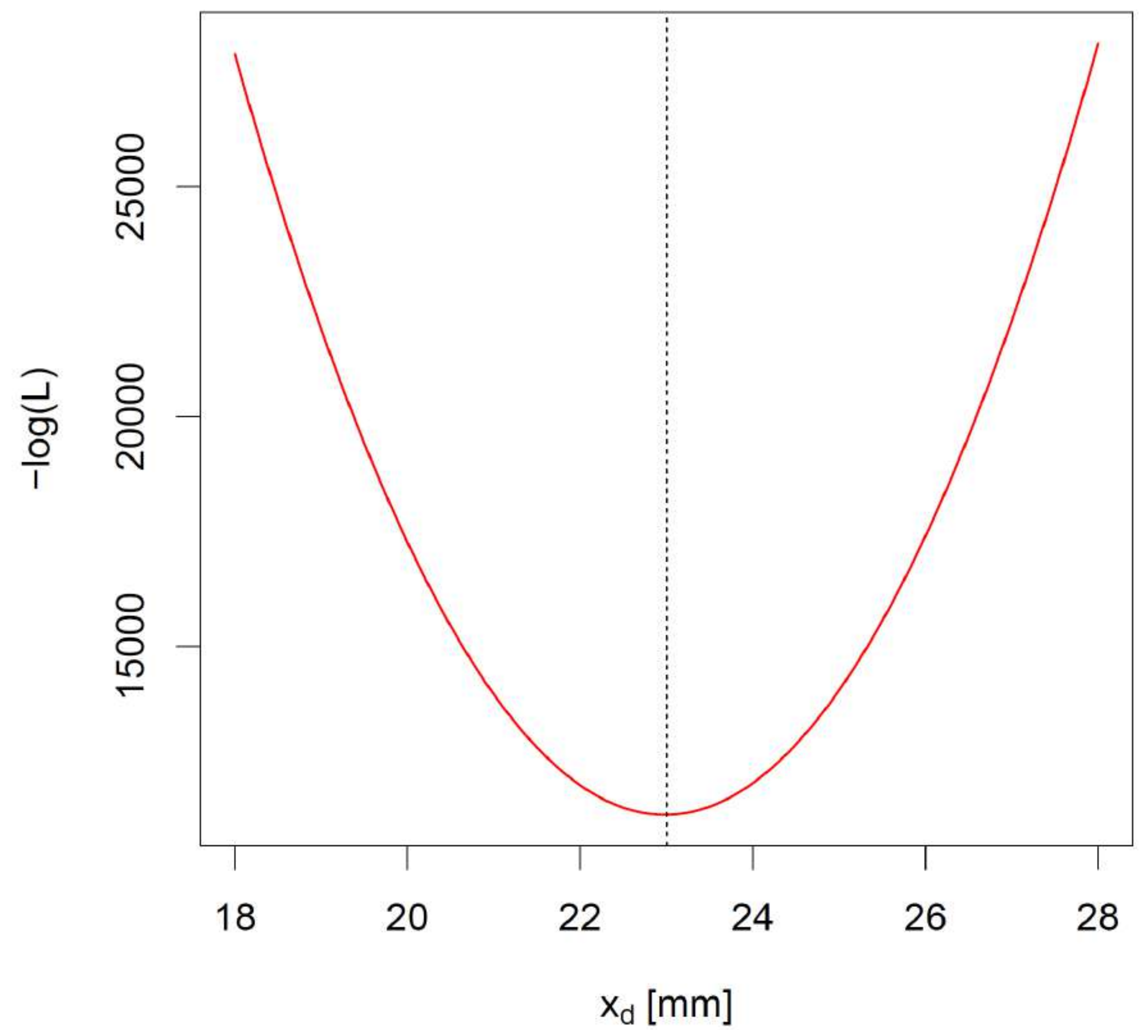


- Estimates $\hat{x}_d$ and $\hat{\theta}_d$ can be obtained by maximazing the likelihood

$$L(x_d,\theta_d) = \prod_i L_{\theta_0}(\theta_{0,i}|\theta_{h,i},x'_{h,i},x_d,\theta_d)\cdot L_{y_0}(y_{0,i}|\theta_{h,i},x'_{h,i},x_d,\theta_d)$$







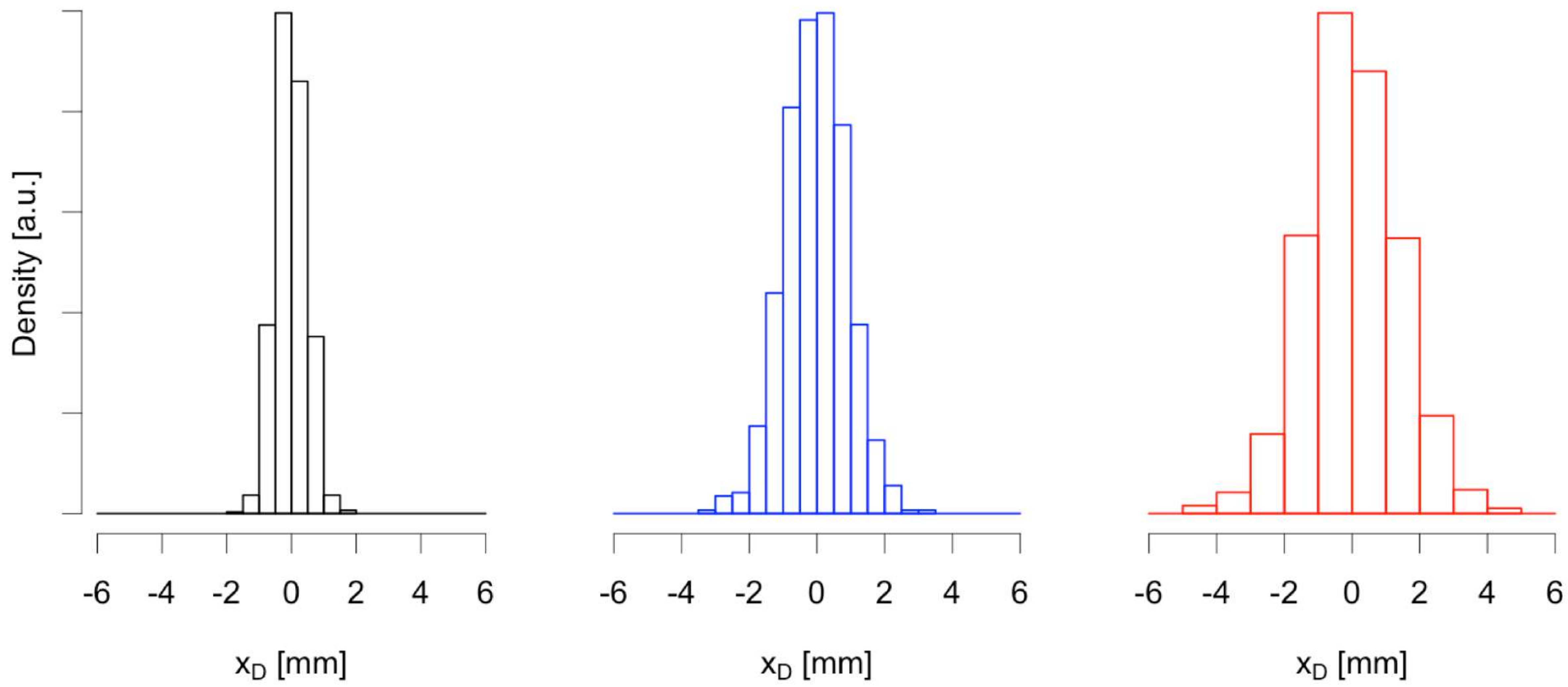
- Better performance in complex configurations with multiple passive materials, etc… but only marginal improvements for our benchmark case

- For a given number of muons, the uncertainties on $\hat{x}_d$ and $\hat{\theta}_d$ were estimated from samples of $\hat{x}_d$ and $\hat{\theta}_d$ obtained from a large number of different MC generations

$\Delta z = \mathbf{350}\ \boldsymbol{cm}$ - 500 muons (1.5 h)

$\Delta z = \mathbf{880}\ \boldsymbol{cm}$ - 500 muons (7.5 h)

$\Delta z = \mathbf{1300}\ \boldsymbol{cm}$ - 500 muons (16 h)

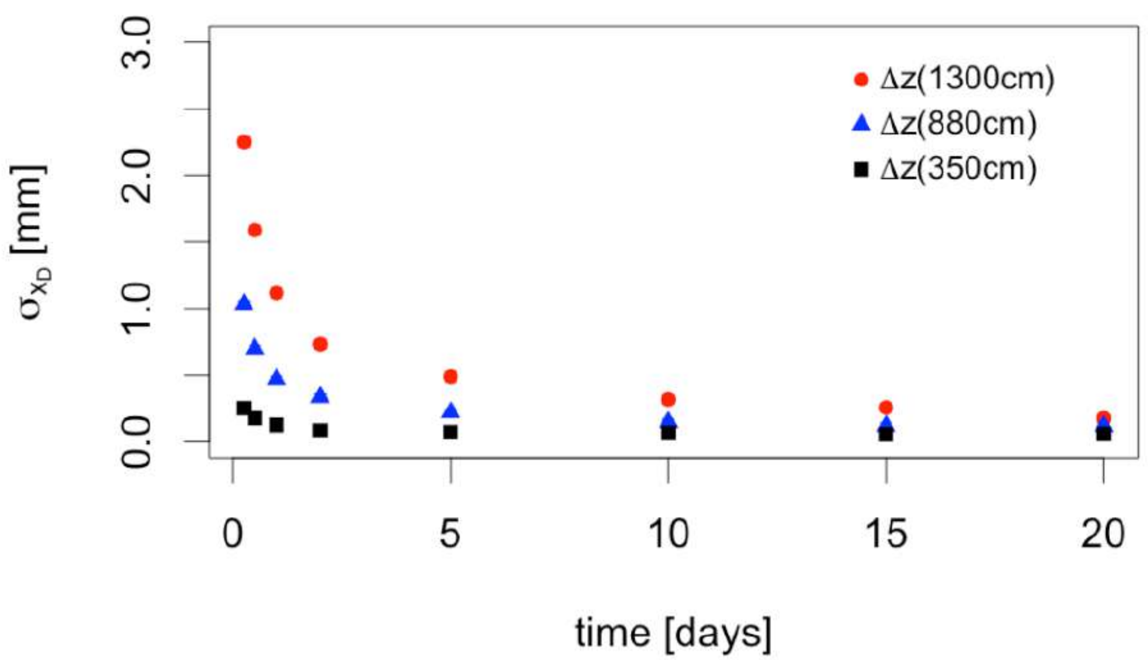


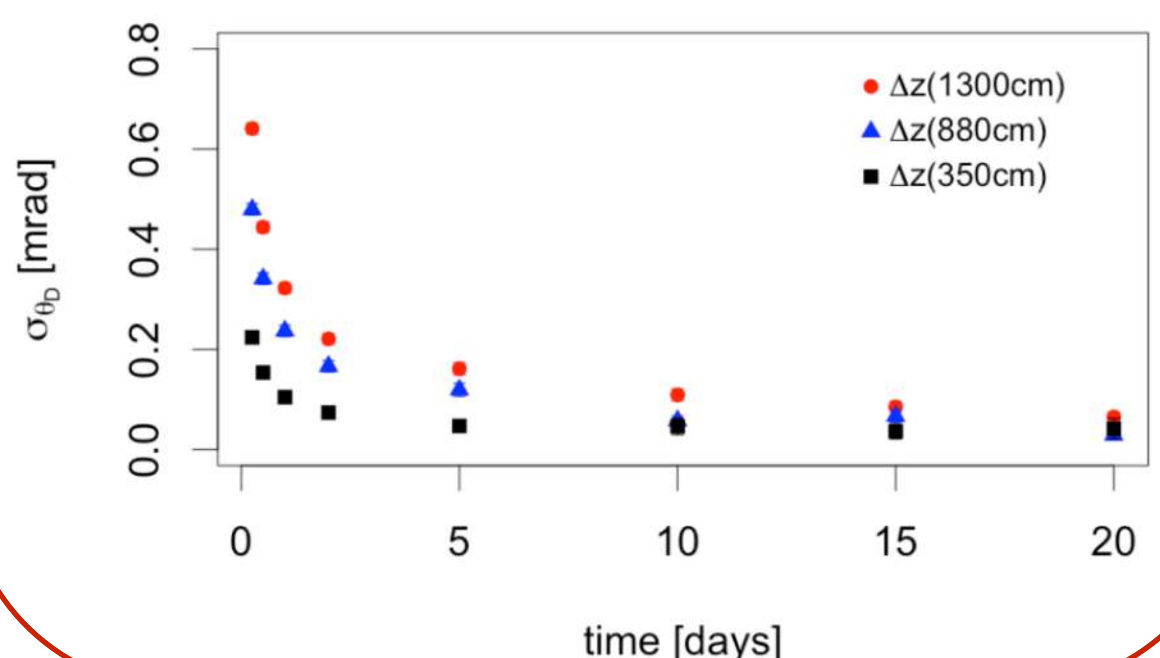
no systematic uncertainties and 100% fiber efficiency

Results

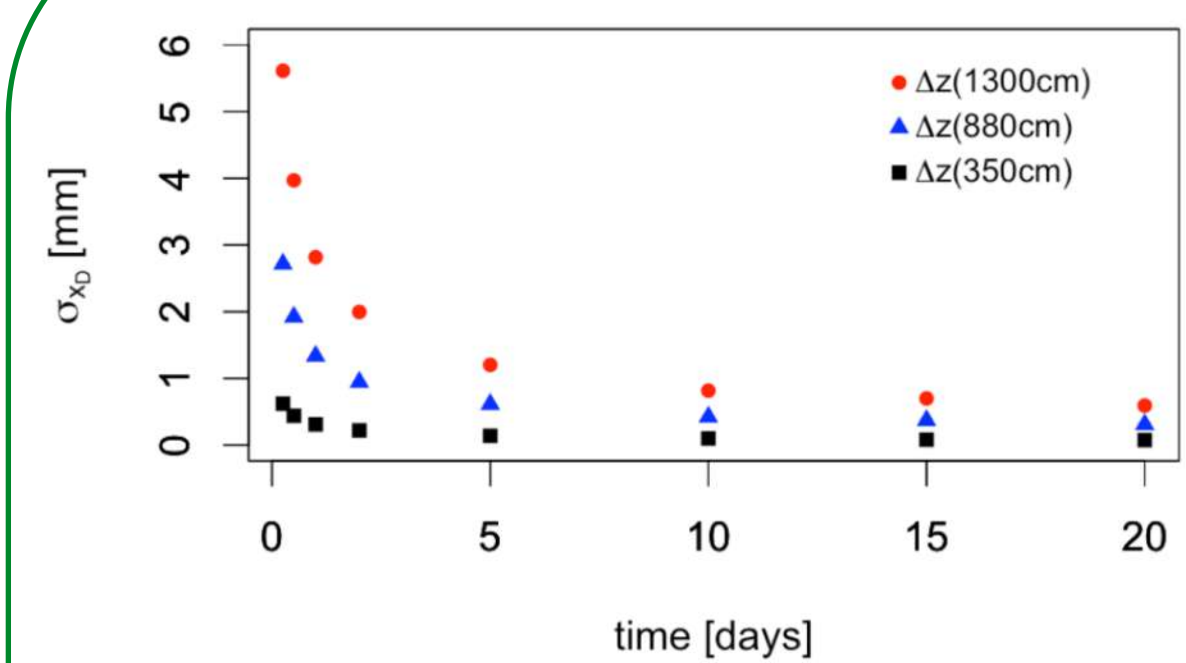
- Systematic uncertainties related to geometrical tollerances in the detectors and to their relative positioning were taken into account

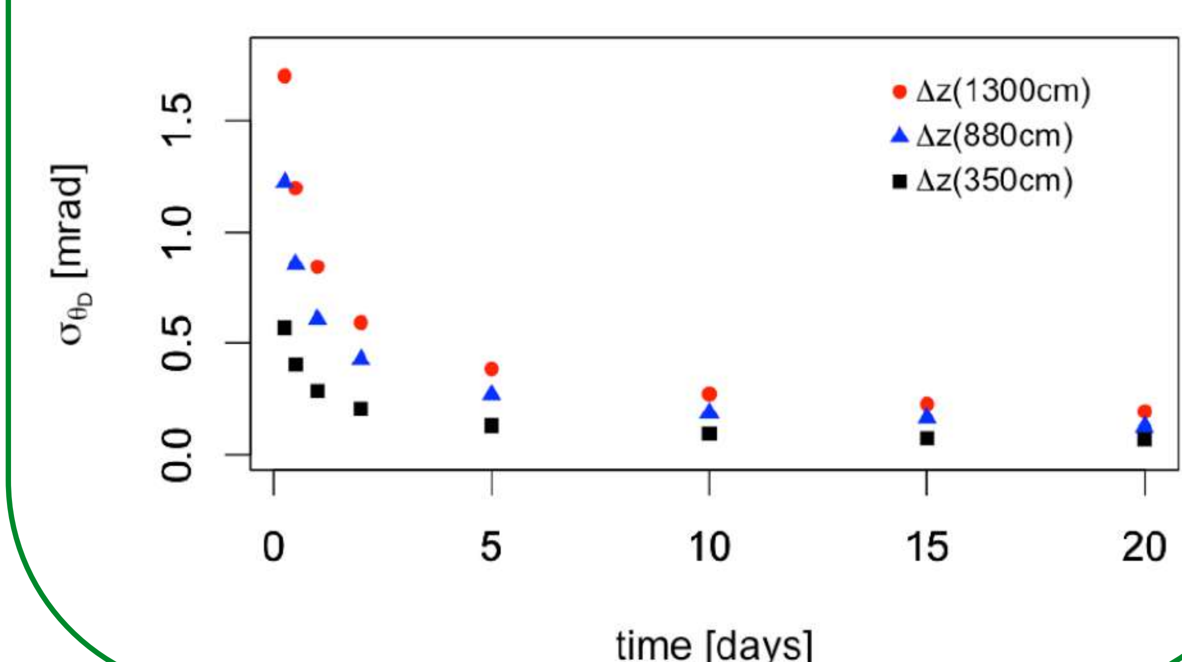
no systematic uncertainties and 100% fiber efficiency





with systematic uncertainties and 68% fiber efficiency

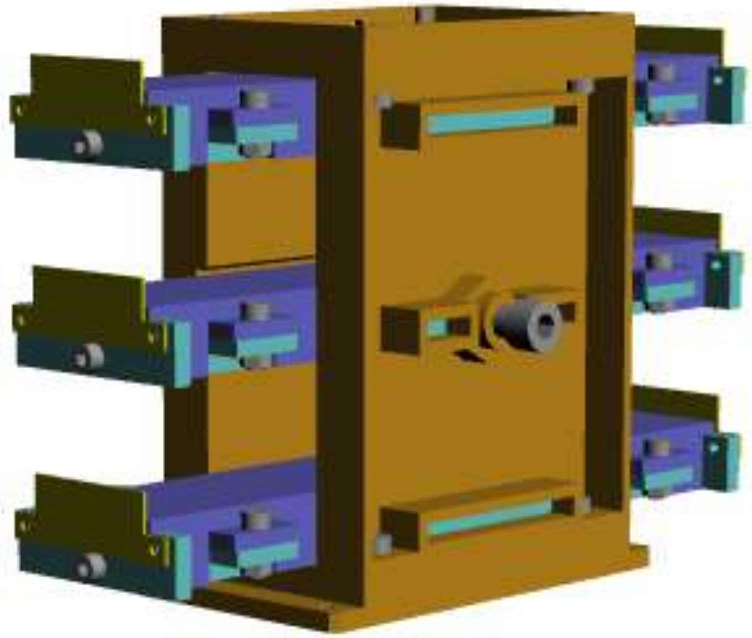


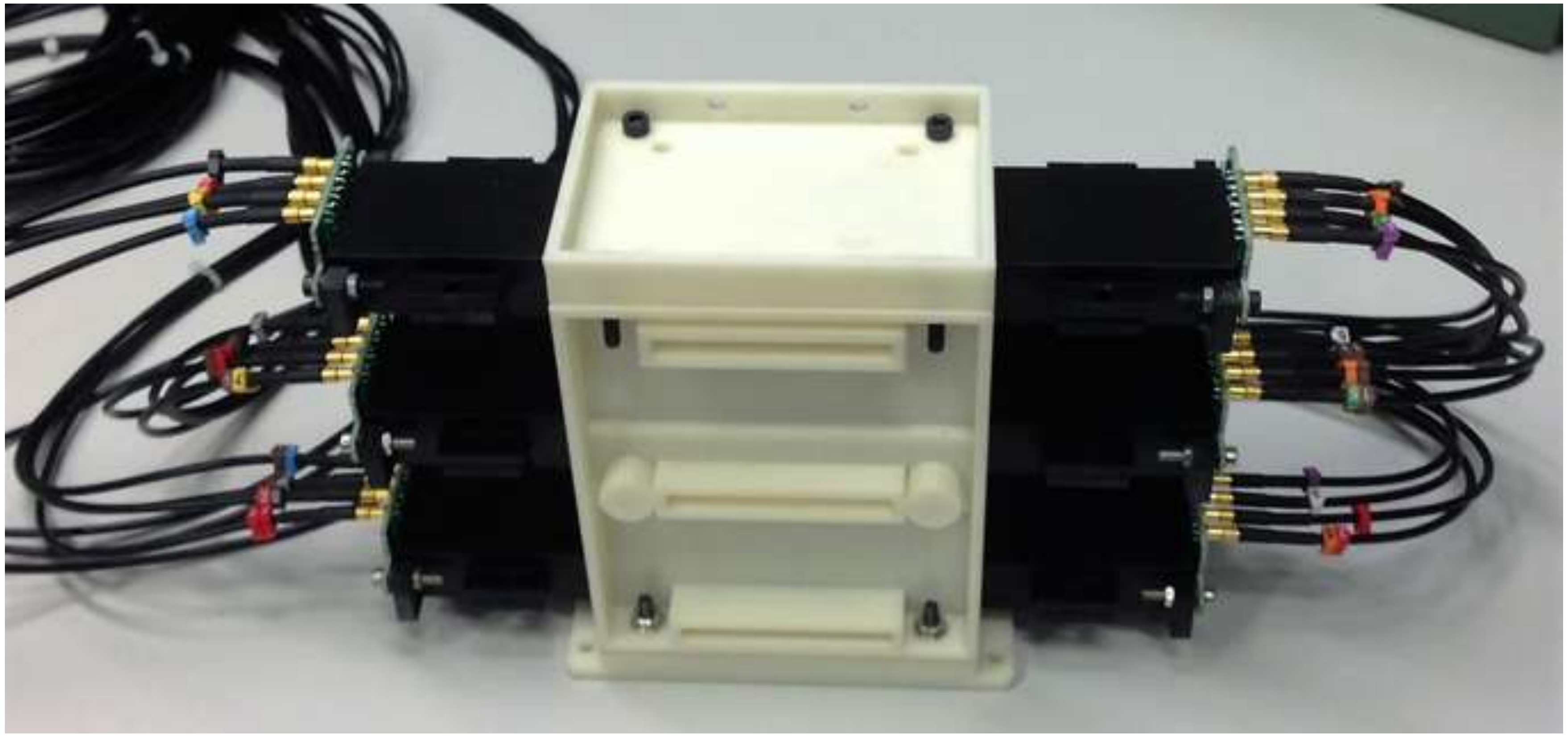


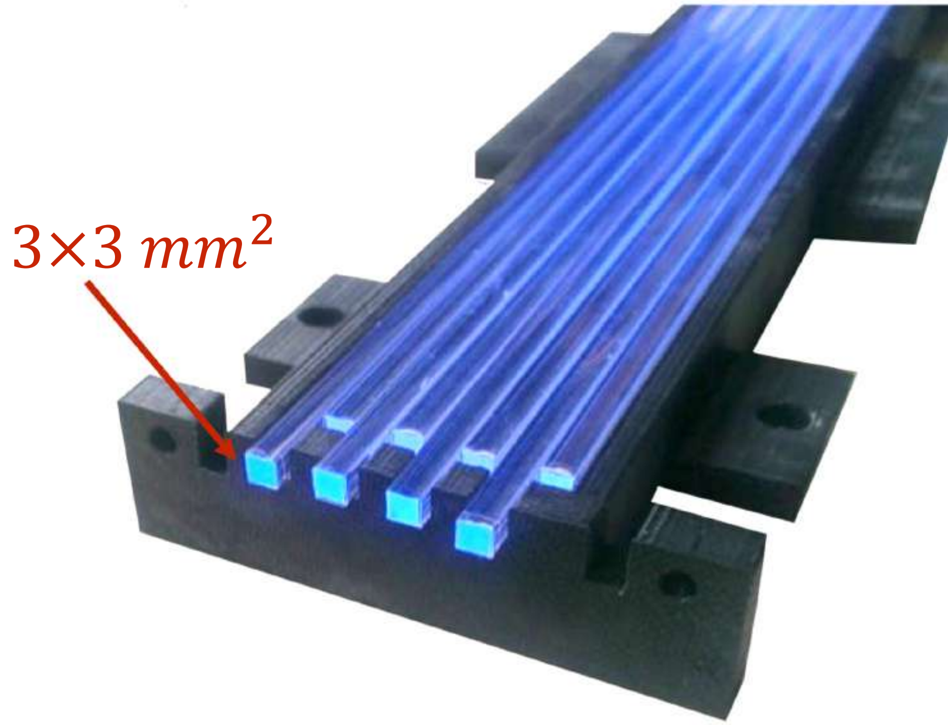
Design and development of a small-scale prototype

The small-scale detector prototype

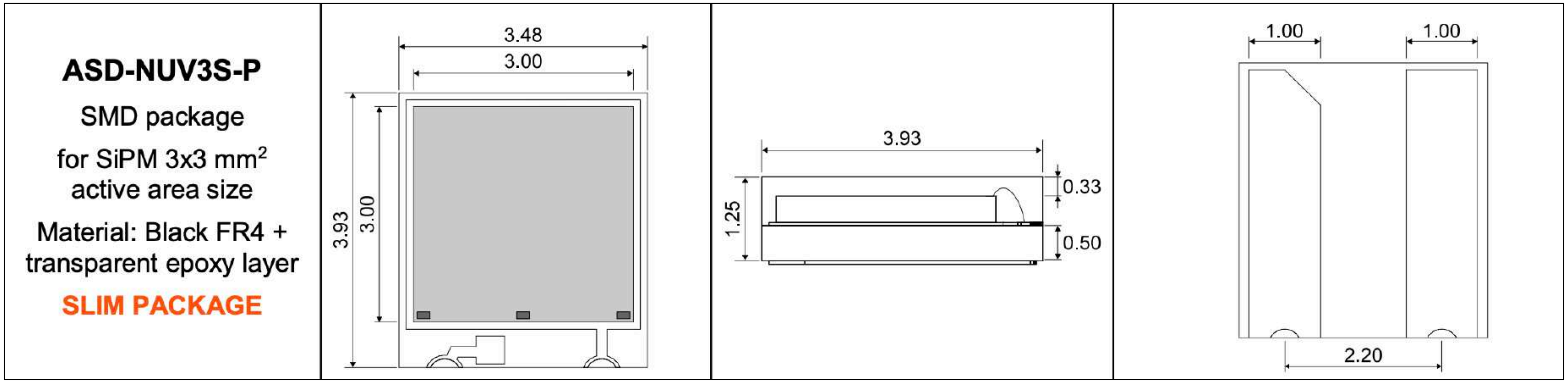
- As a proof of principle a small-scale detection system, consisting of two telescopes with three detecting layers each, was designed and created
- Layers composed by $3{\times}3\ mm^2$ scintillating fibers (BCF-10 from Saint-Gobain)
- ABS mechanical supports created with a 3D printer

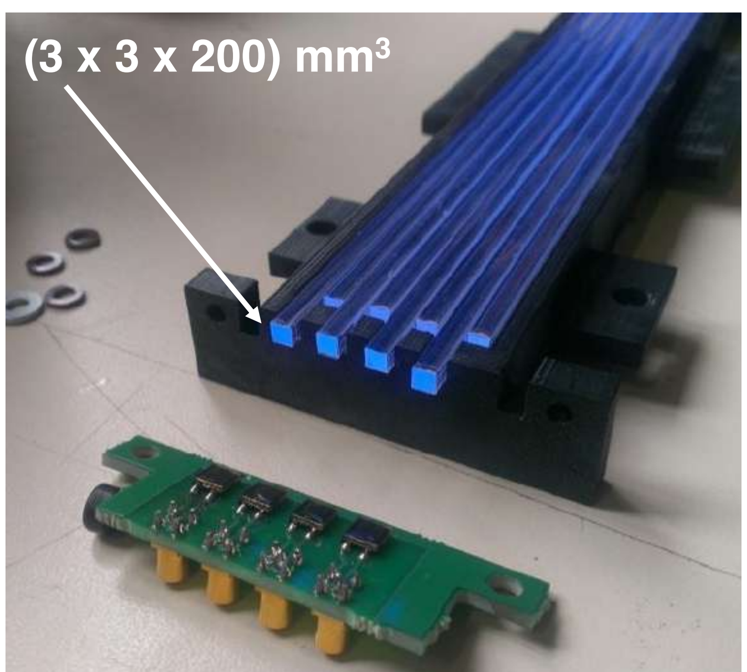






- Scintillating fibers coupled to SiPMs (SiPM3S-P from AdvanSiD)



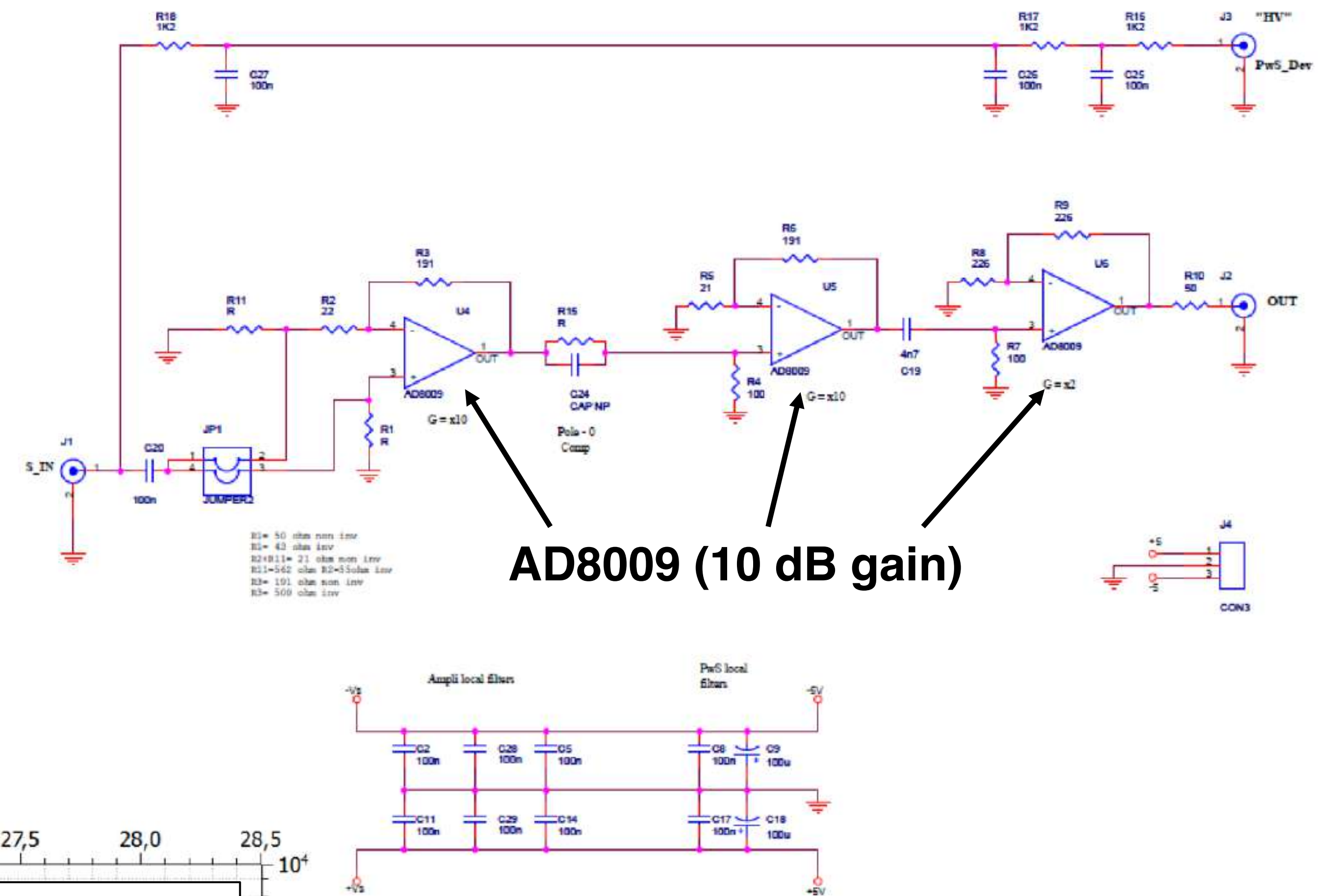


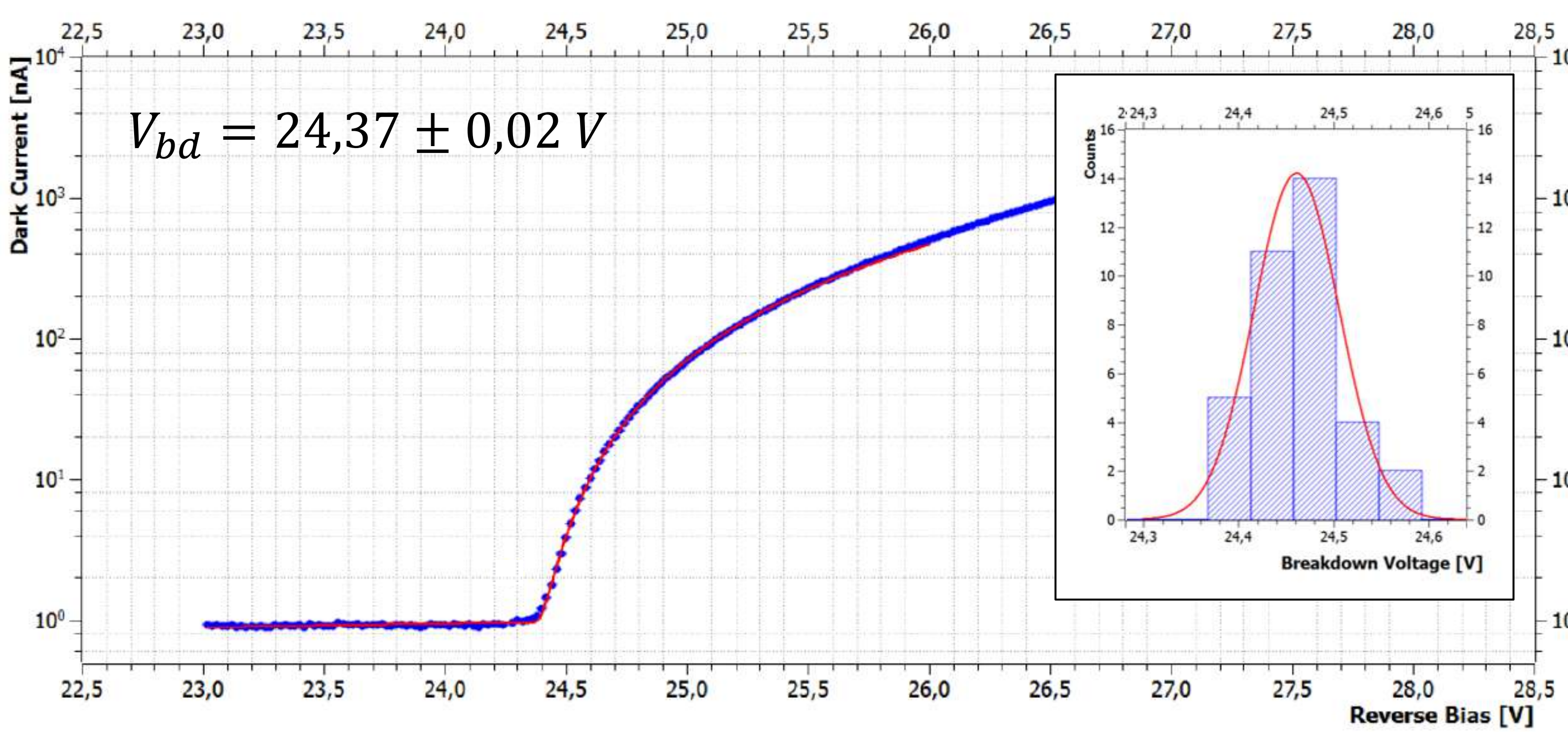
Effective Active Area	3×3	mm^2
Cell Size	50×50	μm^2
Cells number	3600	–
Spectral response range	$350 \div 900$	nm
Peak sensitivity wavelength	390	nm
Photon Detection Efficiency	33	$\%$
Breakdown Voltage	27 ± 2	V
Dark Count	$100 \times 10^3 \div 300 \times 10^3$	Cps/mm^2
Gain	4×10^6	–
Breakdown Voltage temperature sensitivity	26	$mV/°C$

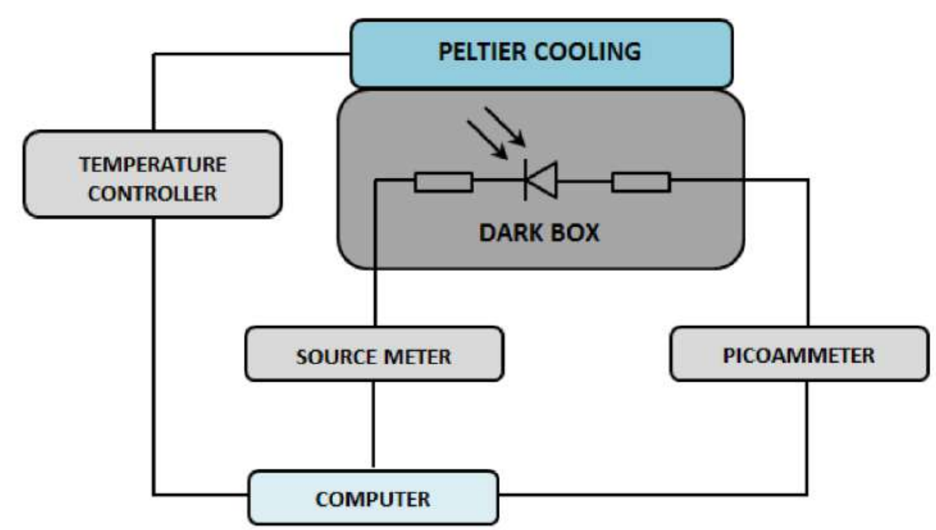
- Signals from SiPMs amplified with a (custom made*) three stages amplification module

- All SiPMs were fully characterized and dependences of V_{bd}, dark counts, etc… on the temperature were studied

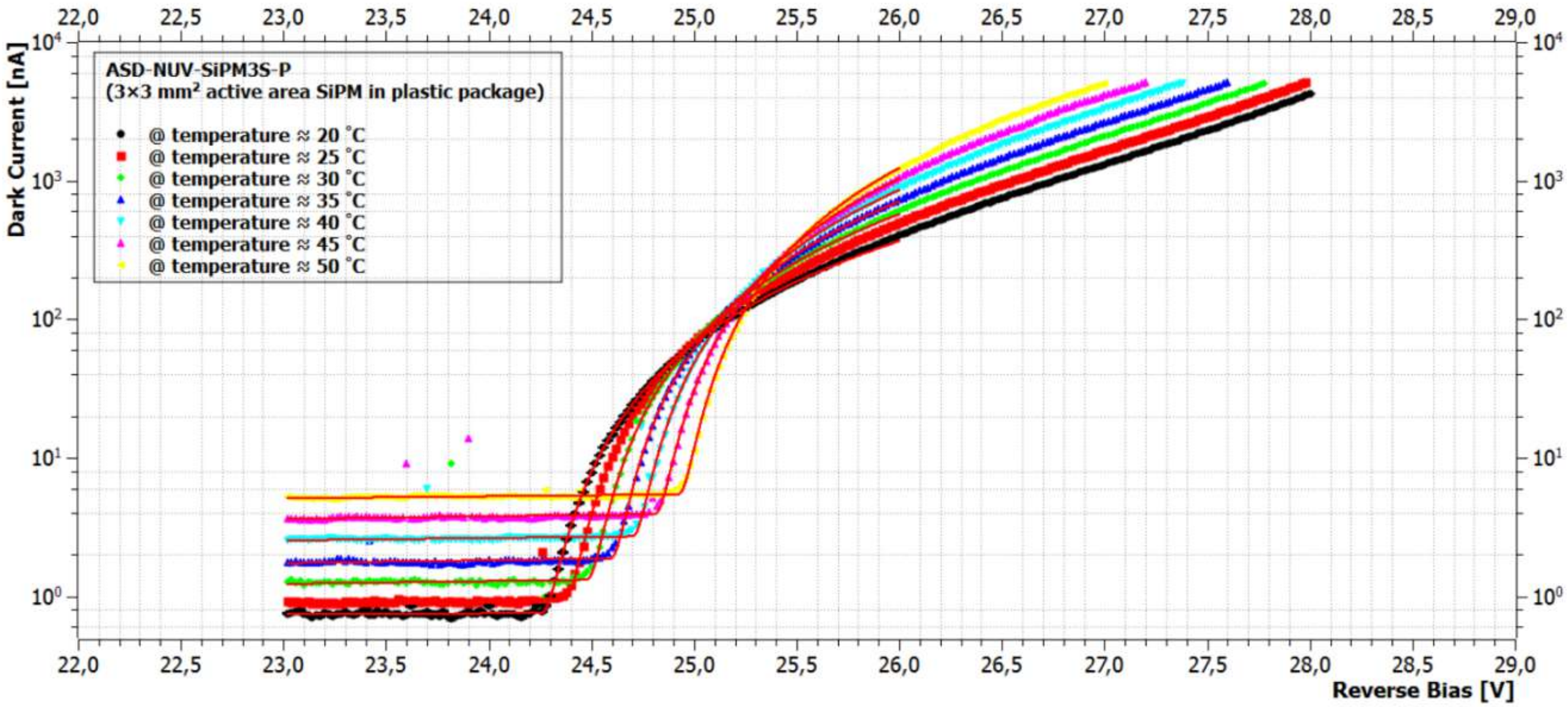
*carried out at University of Pavia & INFN Pavia

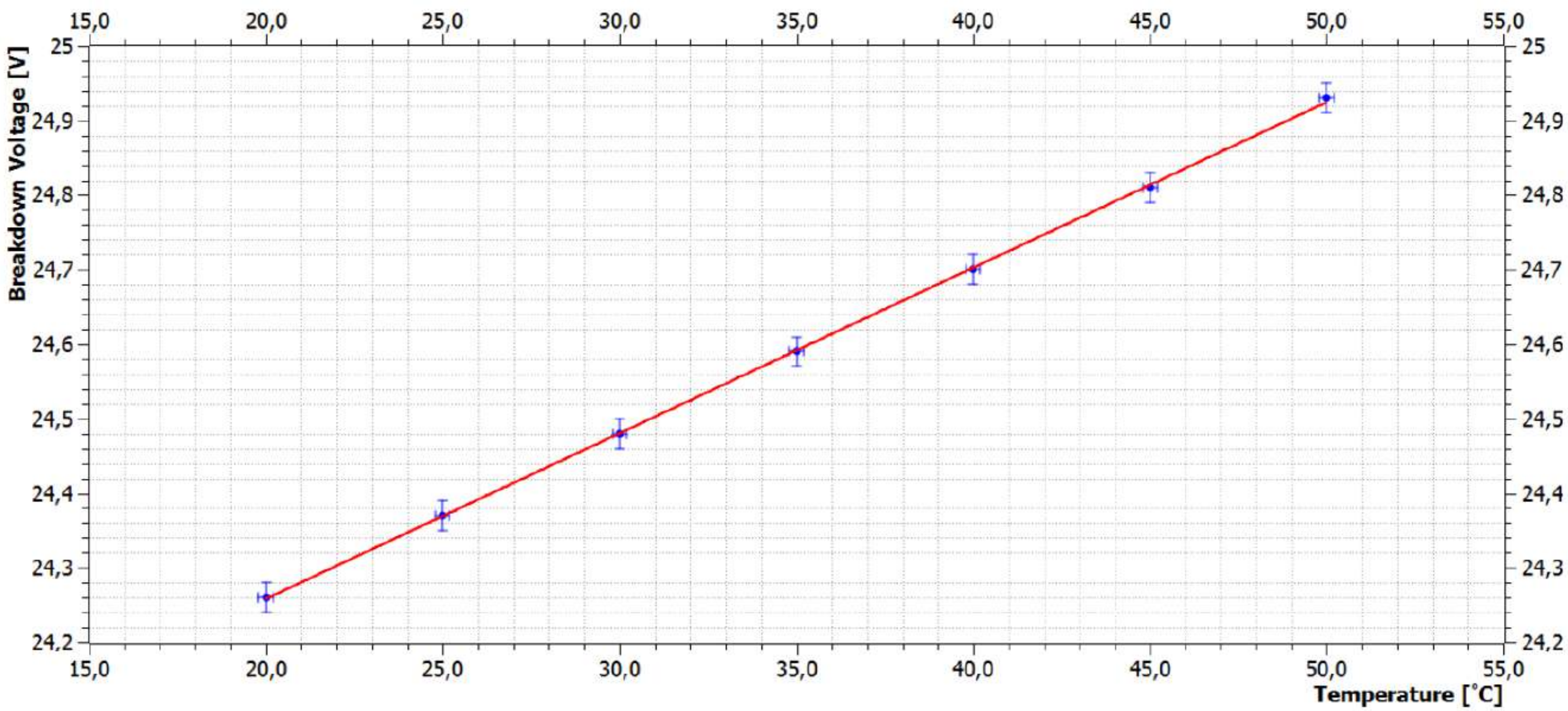


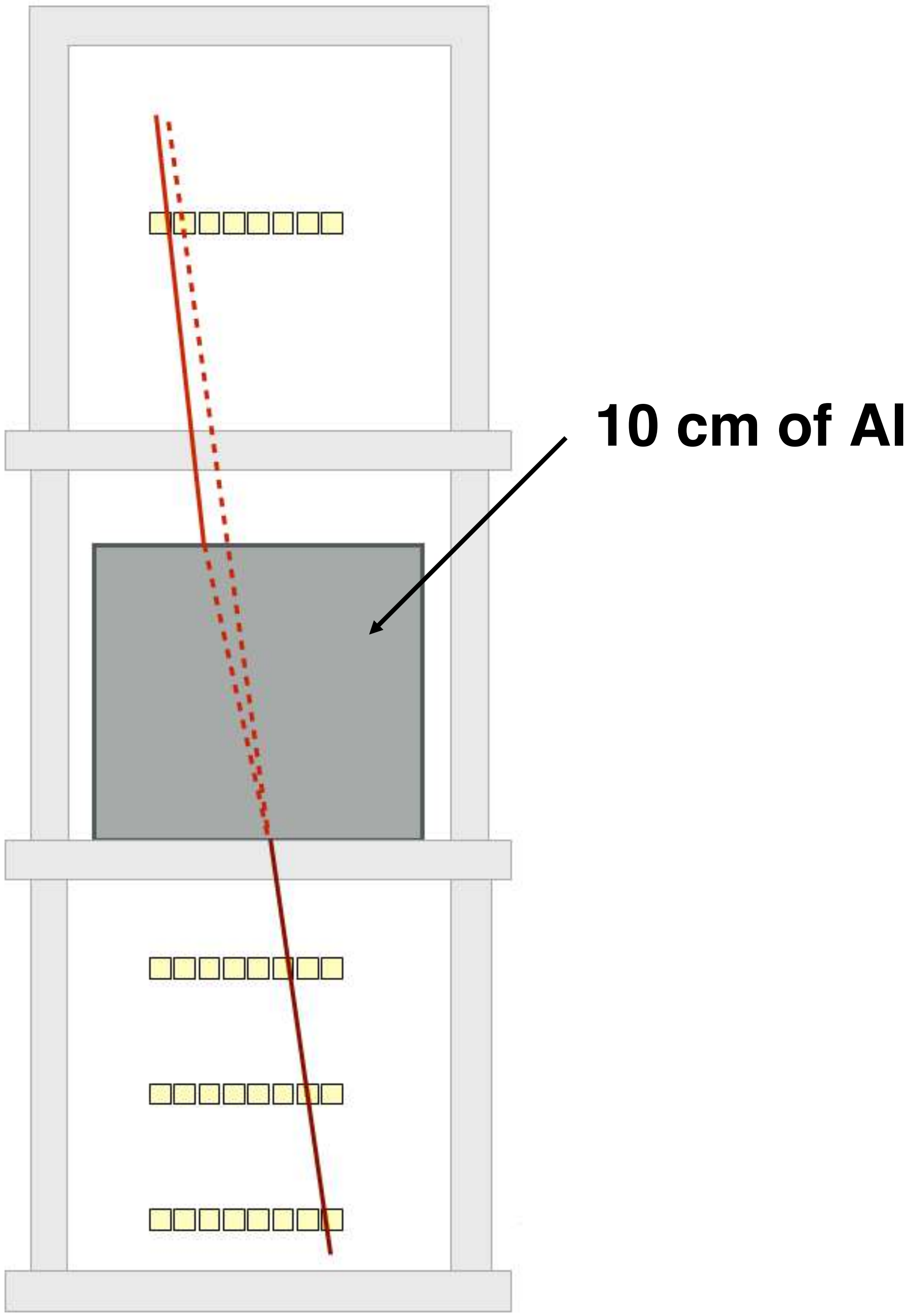


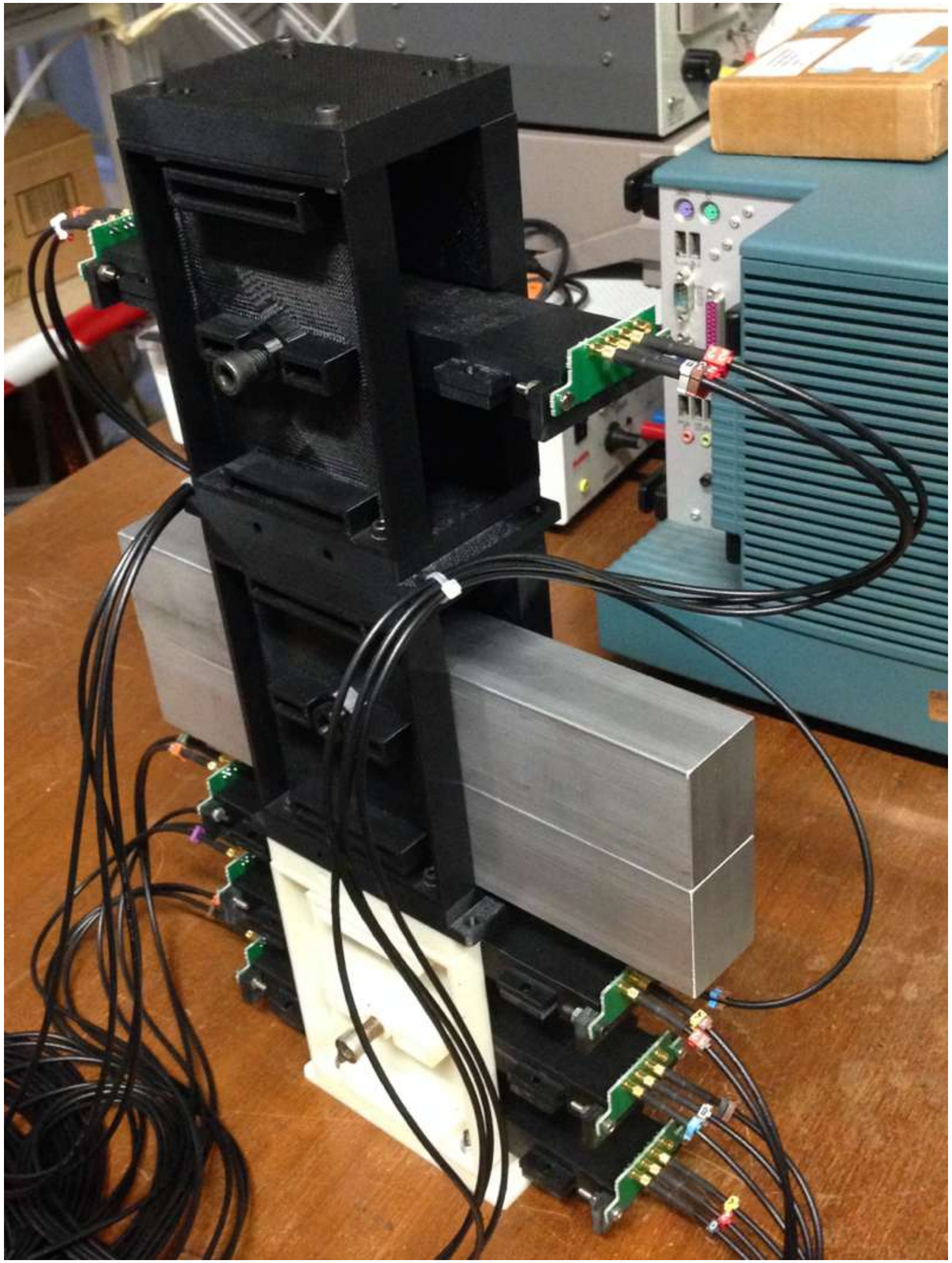


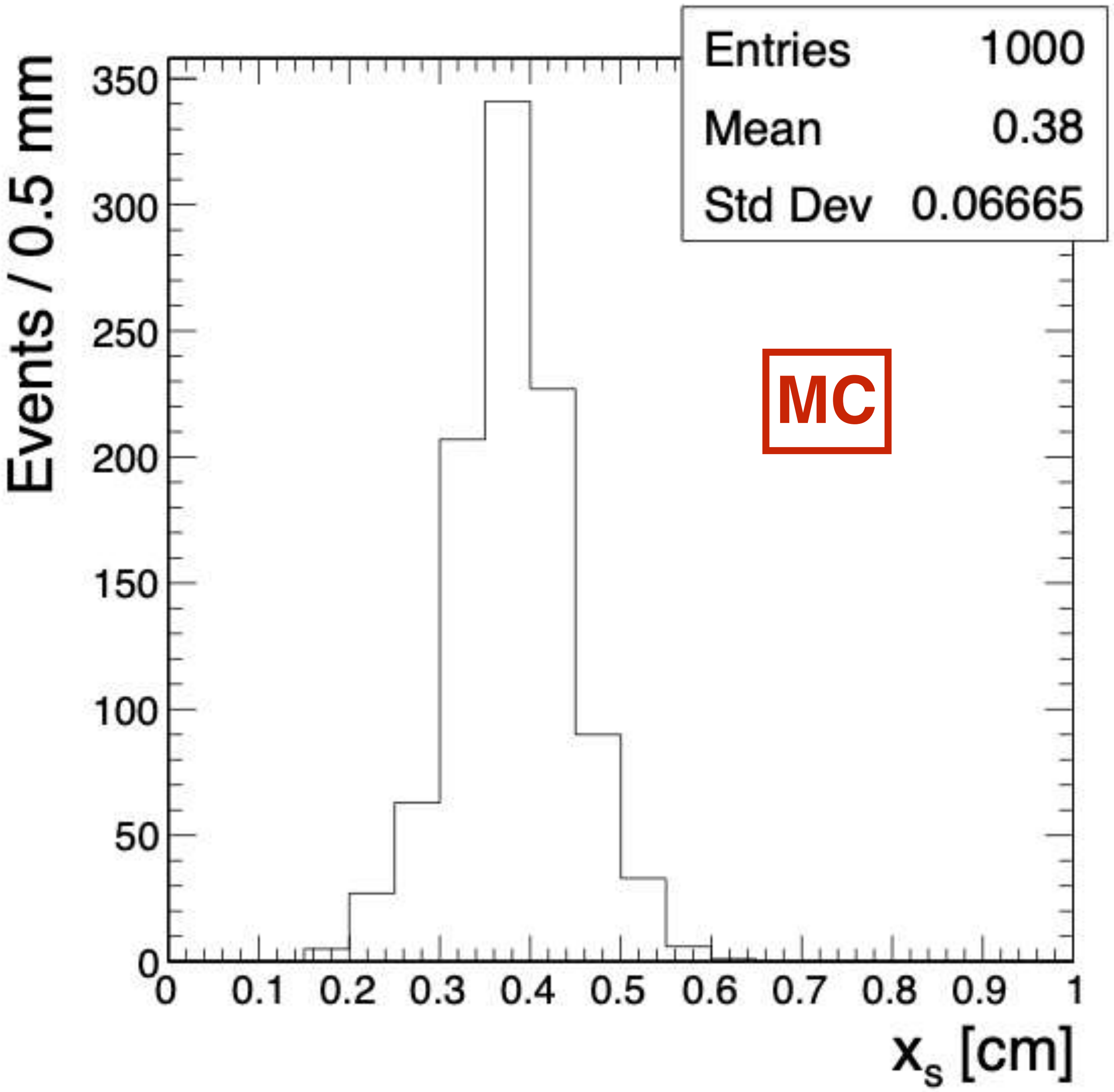
The small-scale detector prototype

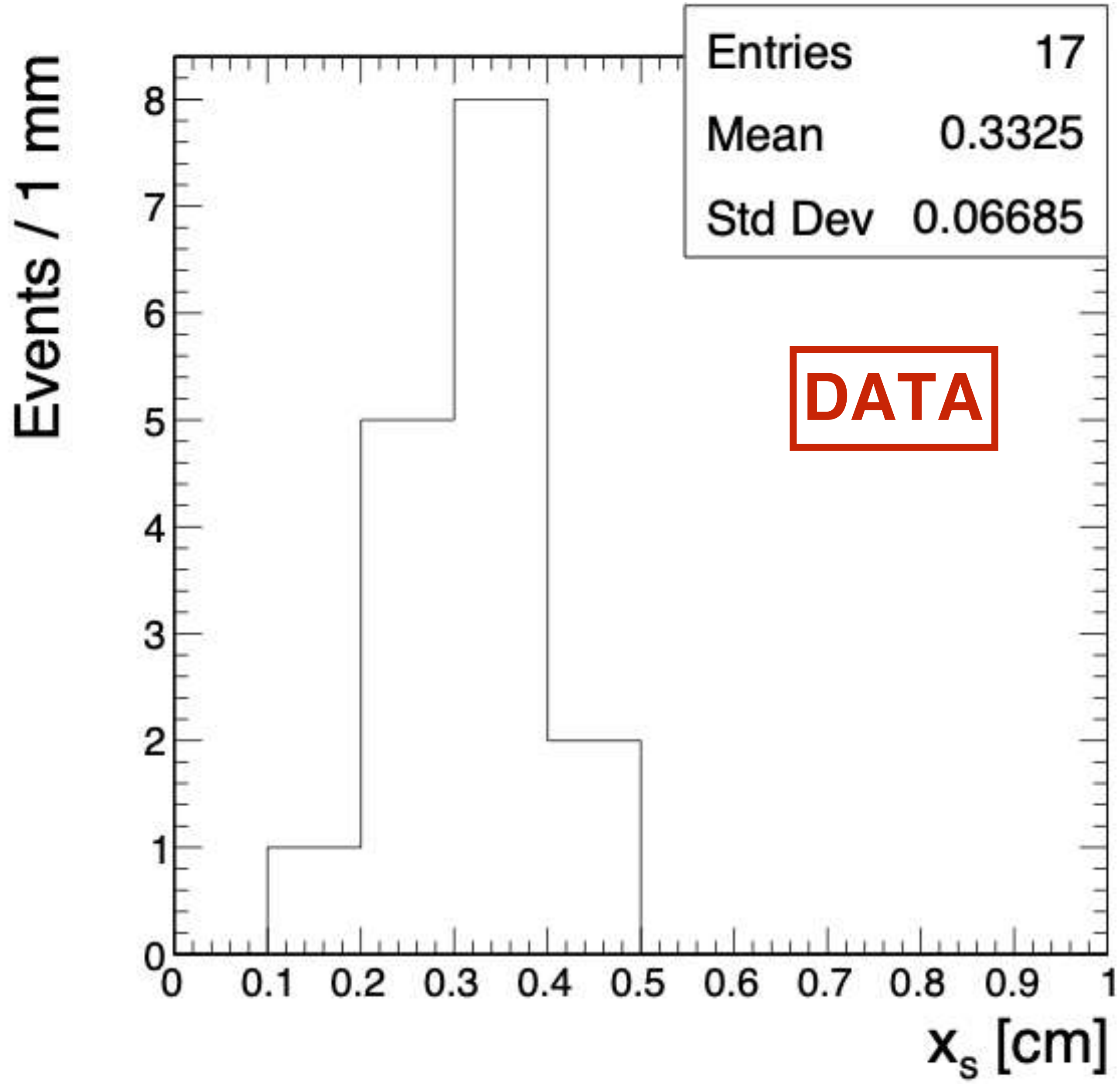





10 cm of Al







1000 samples of 100 events each (~2 days)

17 samples of 100 events each (~2 days)

Conclusions

- We presented a technique and a suitable detector for the stability monitoring of (historical) buildings, using cosmic ray muons
- The technique was applied to a realistic scenario, using the "Palazzo della Loggia" in Brescia a case study
- Three different geometrical configurations (from $\Delta z = 350 \text{ to } 1300\ cm$) were considered
- MC results, including systematic uncertainties, showed that resolutions of 1 mm (or better) could be achieved with data from few days
- As a proof of principle, we also developed a small-scale detector prototype based on the same technology of the proposed detector
- Performance was compared to MC simulations with a good agreement