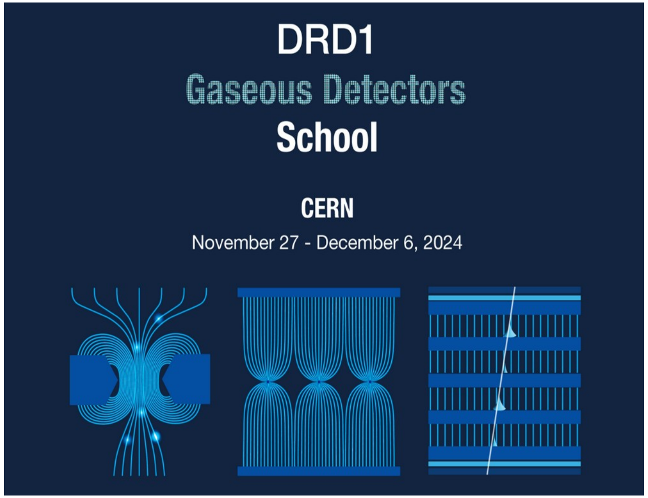
# Applications beyond fundamental research




Jona Bortfeldt
LMU Munich

December 6th 2024

# Overview

detector developers are widely interested people → many applications beyond fundamental research exist

separation between fundamental research and other research/application/use not always clear

→ subjective & incomplete selection of different detector technologies in applications from

**muography**

**neutron detection**

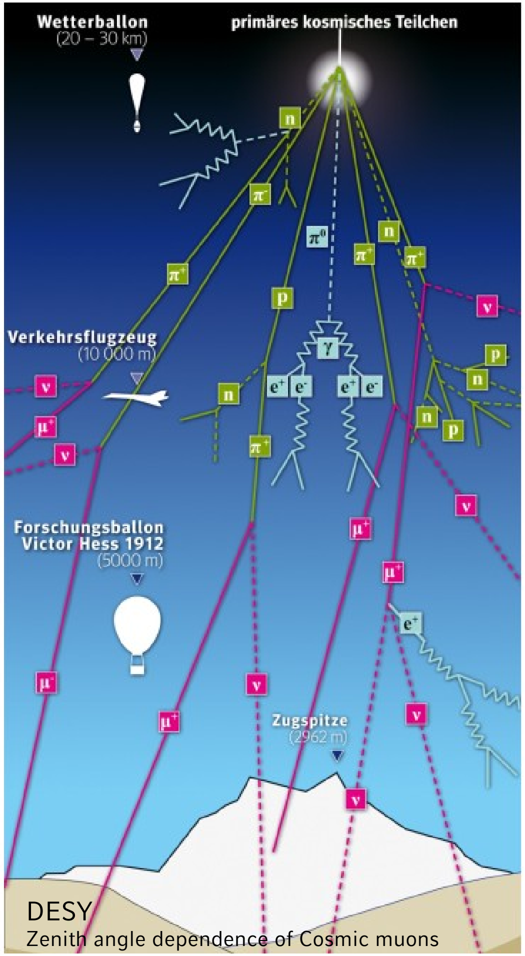
**medical applications**

# Muography

imaging with cosmic muons

# Muography: The Basics

- cosmic muons: primary cosmic radiation (mainly protons) hit atmosphere → hadronic interactions → pions & kaons → decay into muons
- lifetime 2.2μs but $p_\mu \sim 4$GeV → decay length O(20km)
- rate ~ 1/s dm²
- angular distribution ~ $\cos^2 \vartheta$: # vertical = 8 # horizontal



DESY
Zenith angle dependence of Cosmic muons

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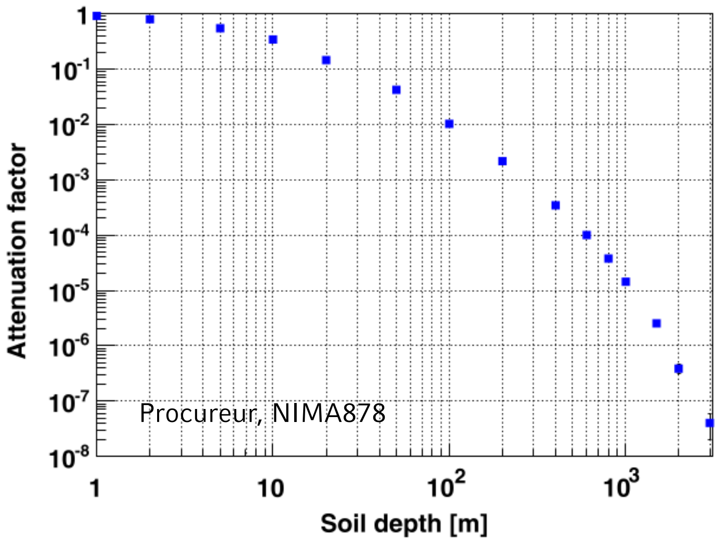
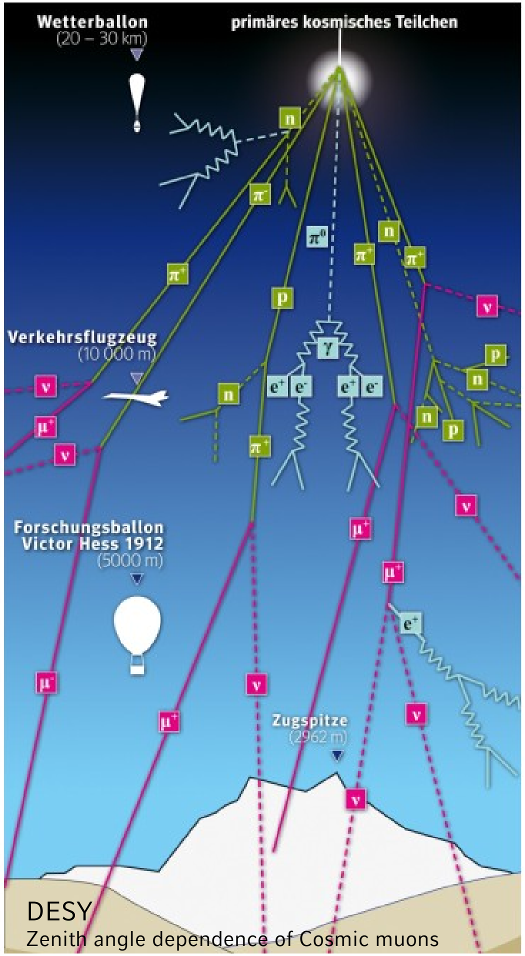
- rate ~ 1/s dm²
- angular distribution ~ cos² ϑ: # vertical = 8 # horizontal
- no hadronic interactions, no bremsstrahlung → can traverse large scale or shielded structures



# Muography: Concepts

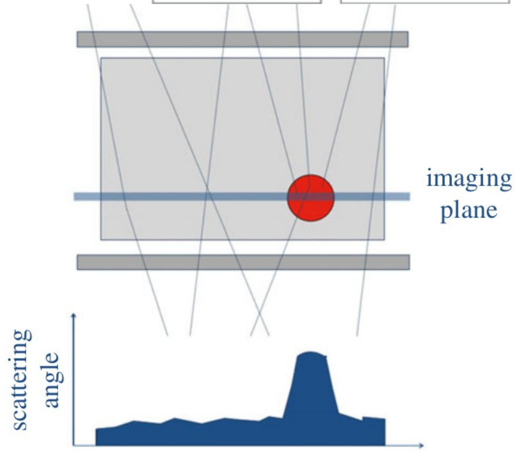
## scattering-based muography

$$\sigma_\theta = \frac{13.6\,MeV}{\beta c p} z \sqrt{\frac{x}{L_{rad}}}\left[1+\frac{1}{9} lg\left(\frac{x}{L_{rad}}\right)\right]$$

- tracklet upstream & downstream of object → point of closest approach
- object thin enough: only one major scattering event

## muon metrology

- no object, compare tracklets in two trackers → determine relative position




Kaiser, 10.1098/rsta.2018.0049

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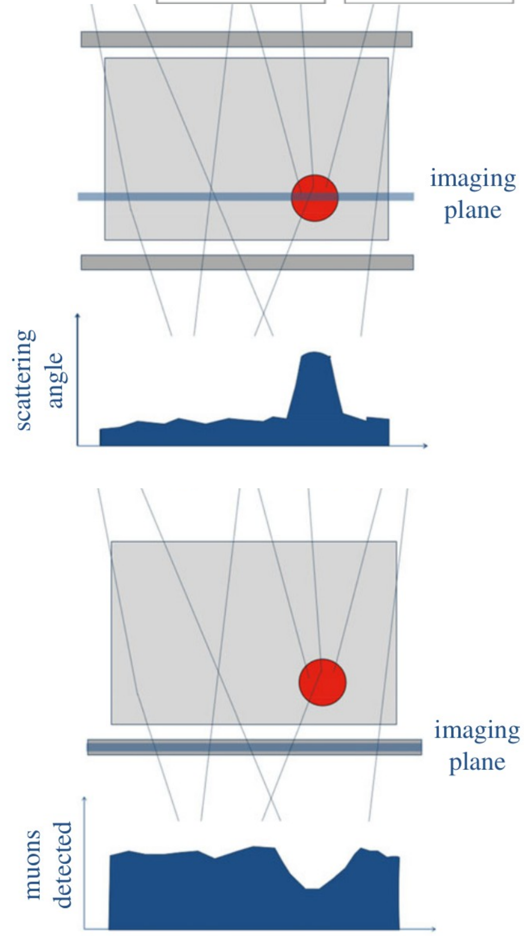
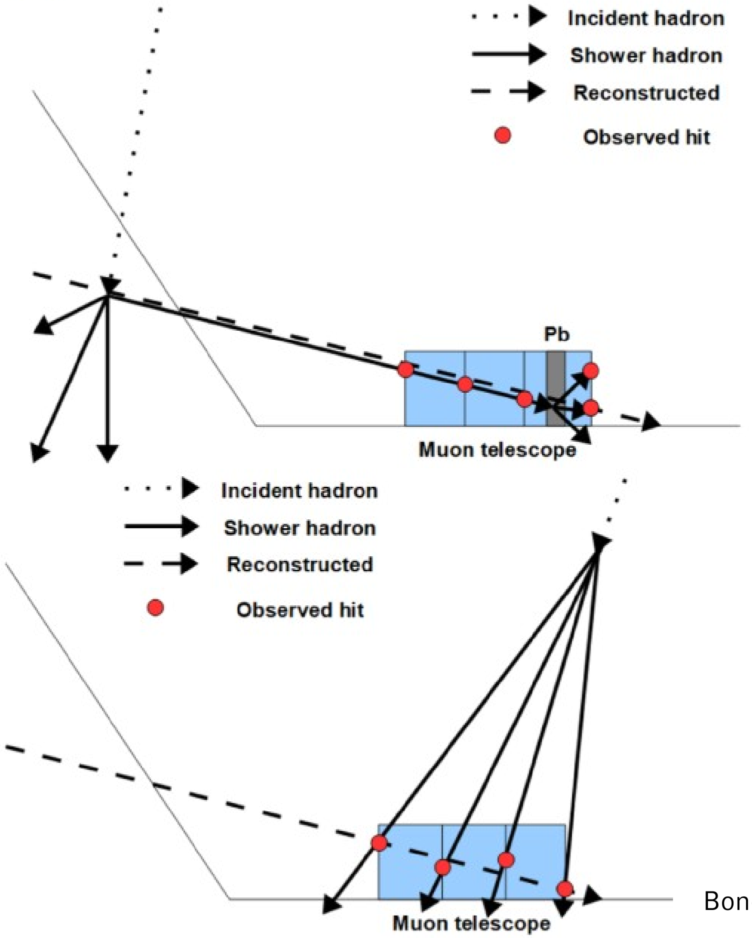
## absorption-based (transmission) muography

- muons have finite range in matter + polyenergetic spectrum → more muons absorbed by more opaque material
- determine change in muon flux w.r.t. free sky measurement → opacity along line of sight
- objects of several 100m thickness




Kaiser, 10.1098/rsta.2018.0049

# Muography Background Events




Bonechi 10.1016/j.revip.2020.100038

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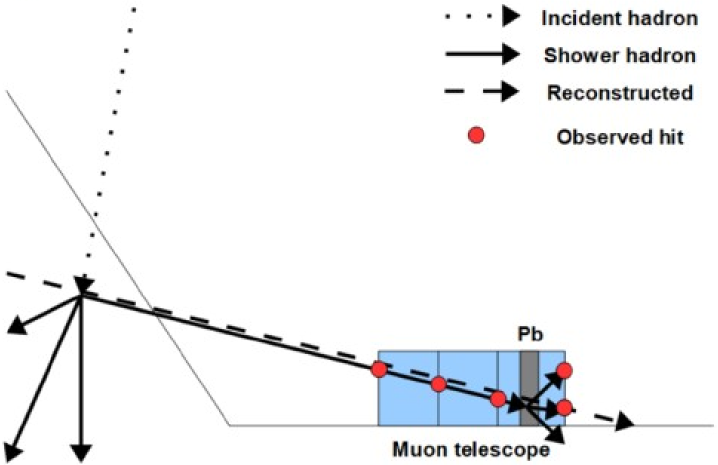
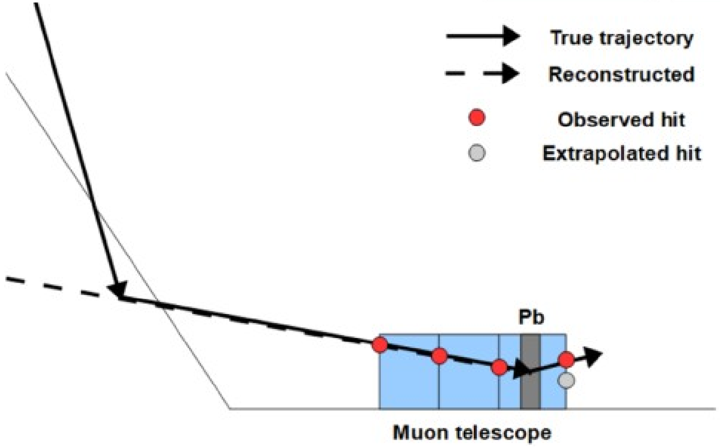
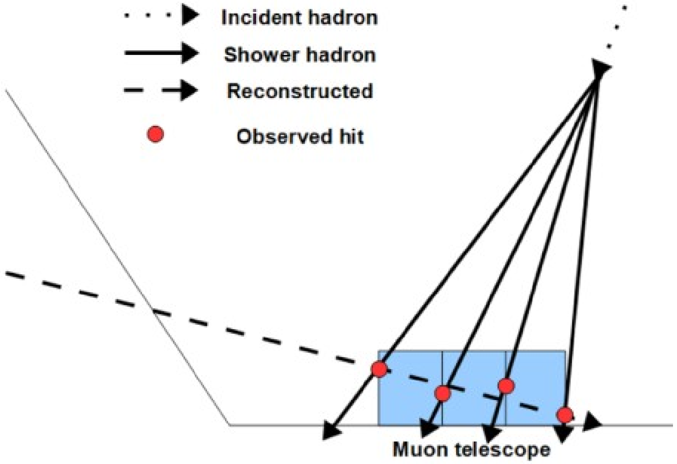
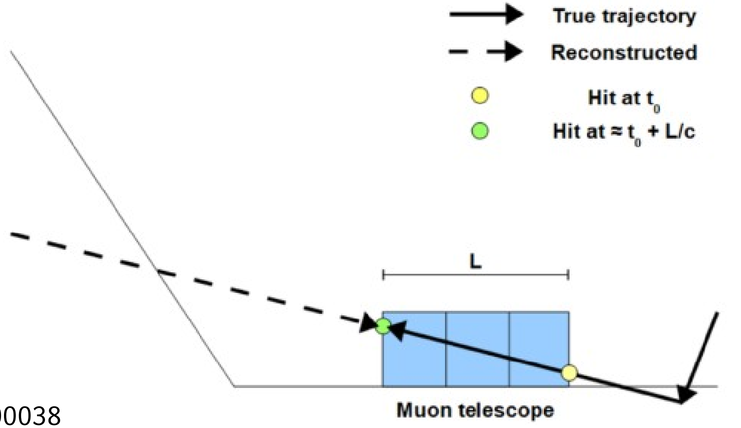



Bonechi 10.1016/j.revip.2020.100038

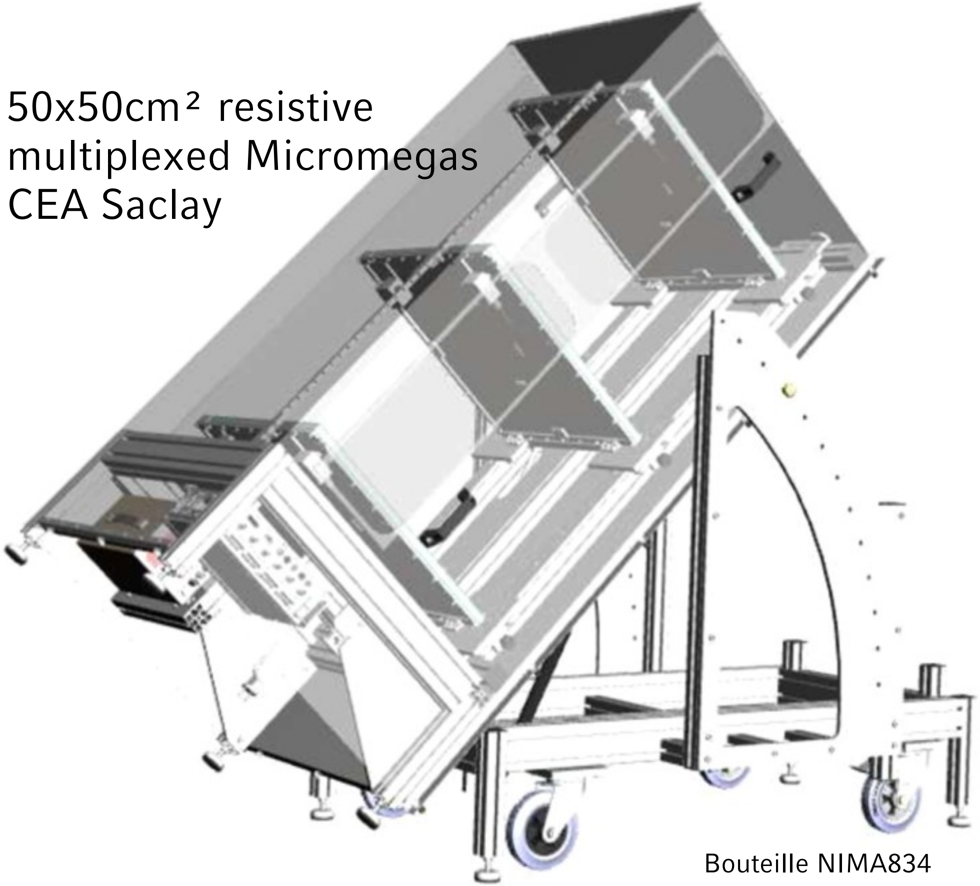
# Suitable Instruments

**nuclear emulsions**
- no power during acquisition
- very good spatial resolution
- lengthy off-line readout (scanning)

**plastic scintillators**
- online events
- coarse spatial resolution

**gaseous detectors**
- good spatial resolution
- online events
- power & gas supplies needed
- temperature & pressure dependence

50x50cm² resistive
multiplexed Micromegas
CEA Saclay



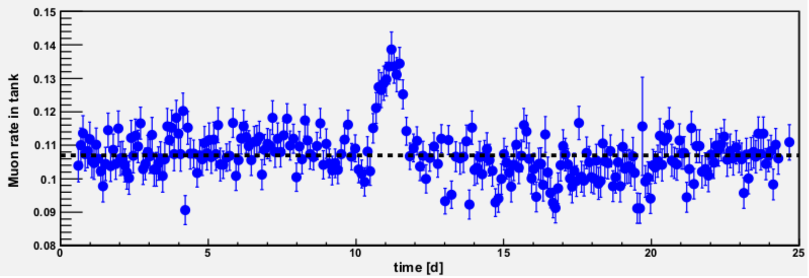
Bouteille NIMA834

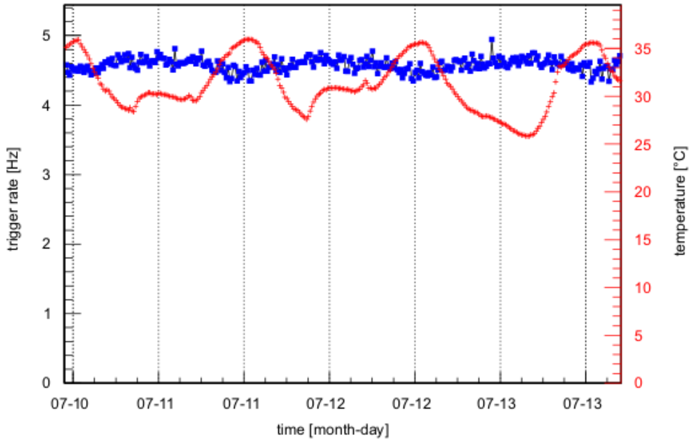
# Water Tower Muography

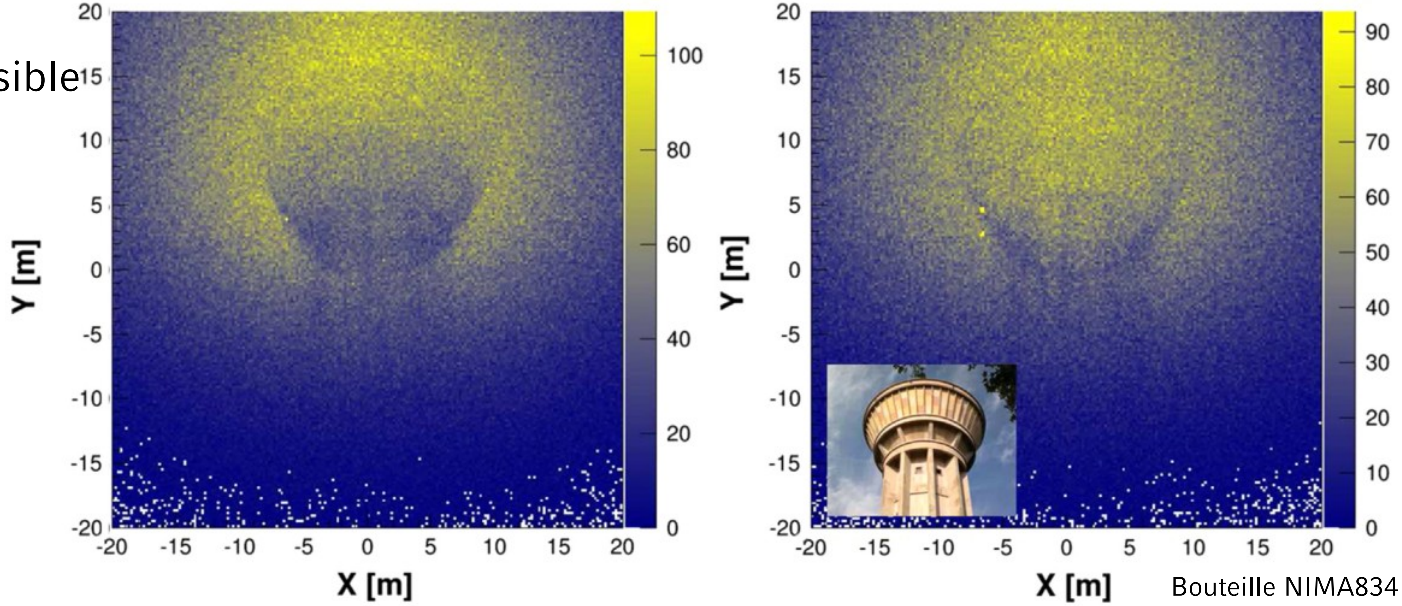
four 50x50cm² Micromegas

- test autonomous operation
- implement correction for pressure & temperature variations
- image water tower at Saclay, also during yearly emptying

→ dynamic imaging outdoors possible



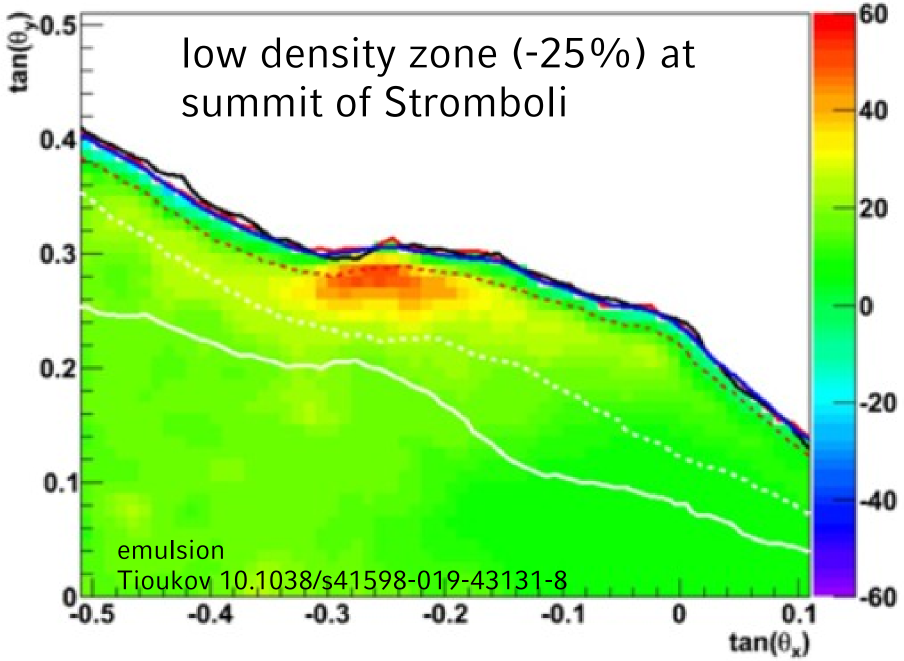




Bouteille NIMA834

# Volcano Muography

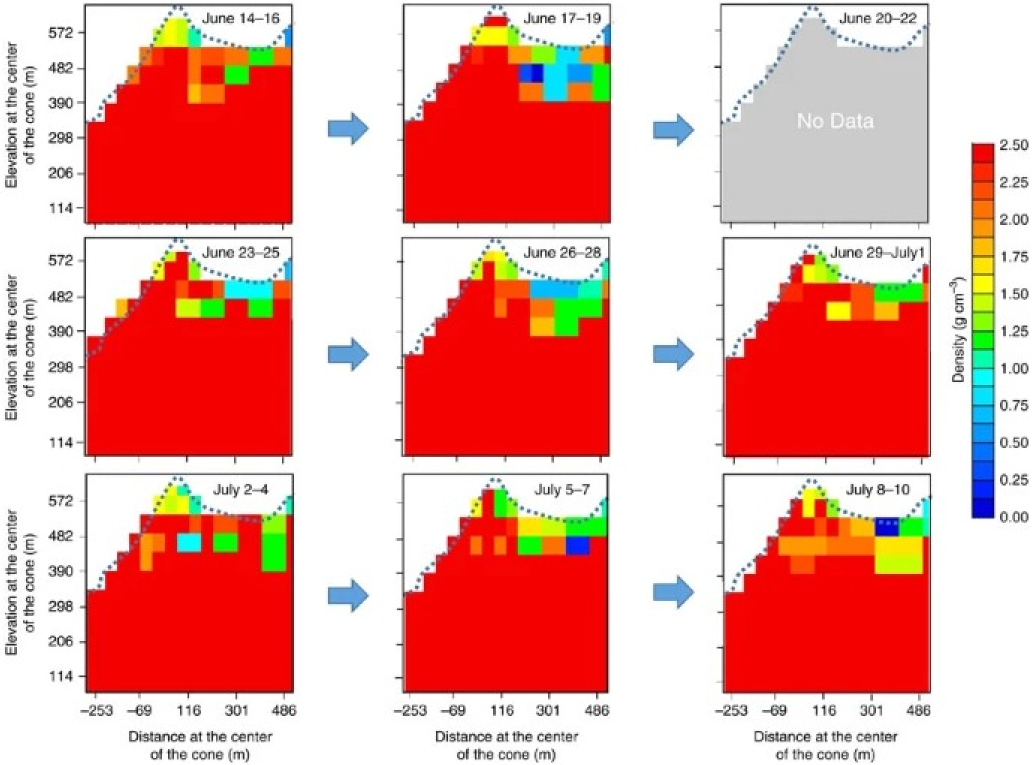
## static Muography

- investigate internal structures → understand stability, internal mechanisms, ...




## dynamic Muography

- risk assessment & eruption monitoring

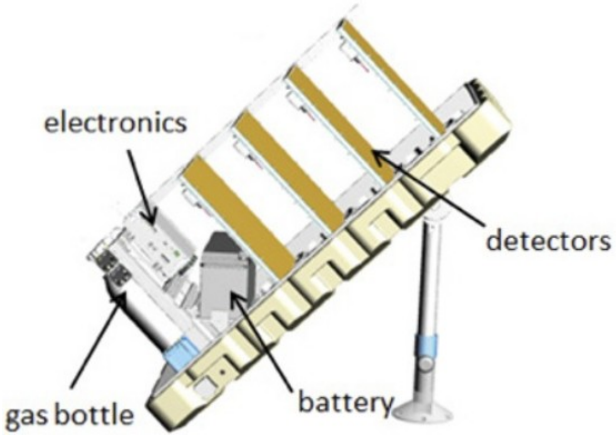


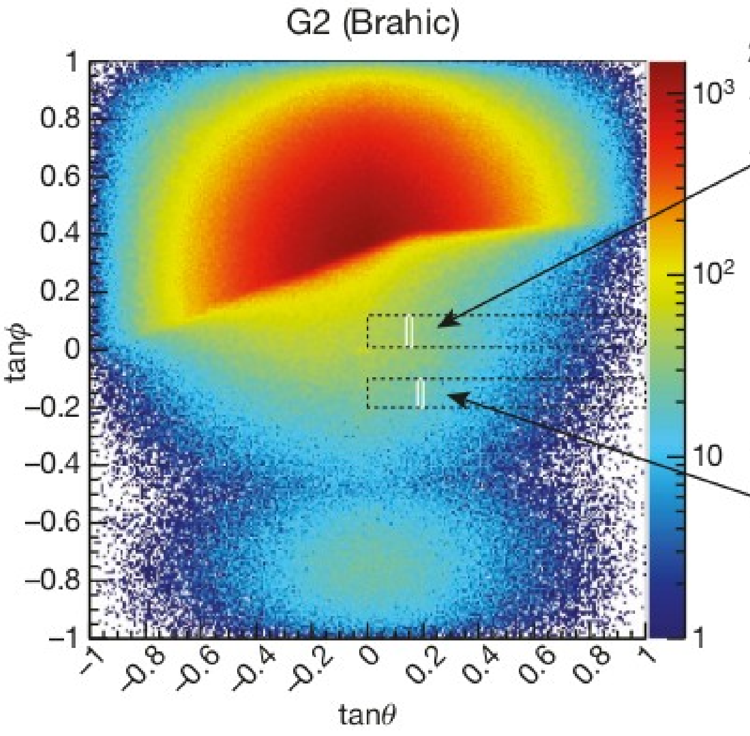

plastic scintillators, Tanaka 10.1038/ncomms4381

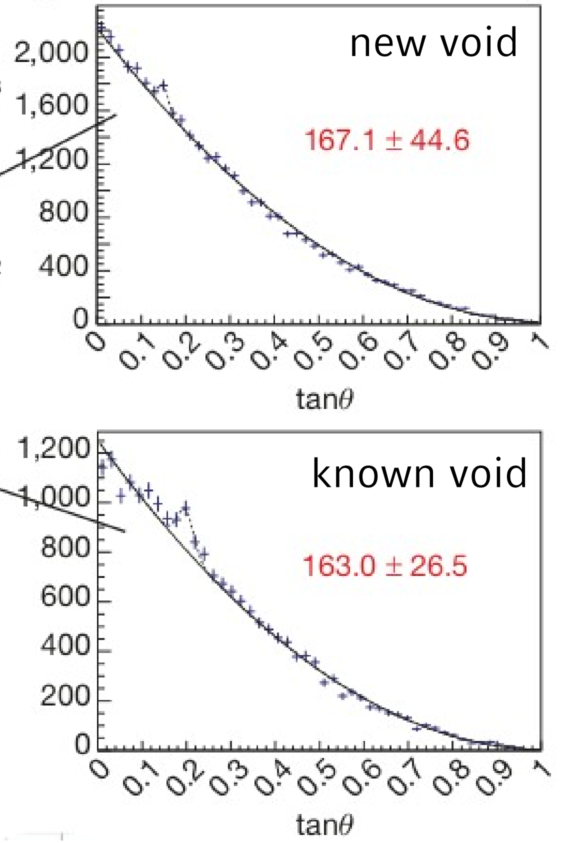
# Muography: Archeology Khufu's Pyramid

**ScanPyramids project**
- combined measurements with emulsion, scintillators, Micromegas
- unknown void (length>30m) discovered

**two Micromegas telescopes**
- four 50x50cm² resistive multiplexed Micromegas each
- $10^7$ track candidates in 2 months
- 35W power consumption



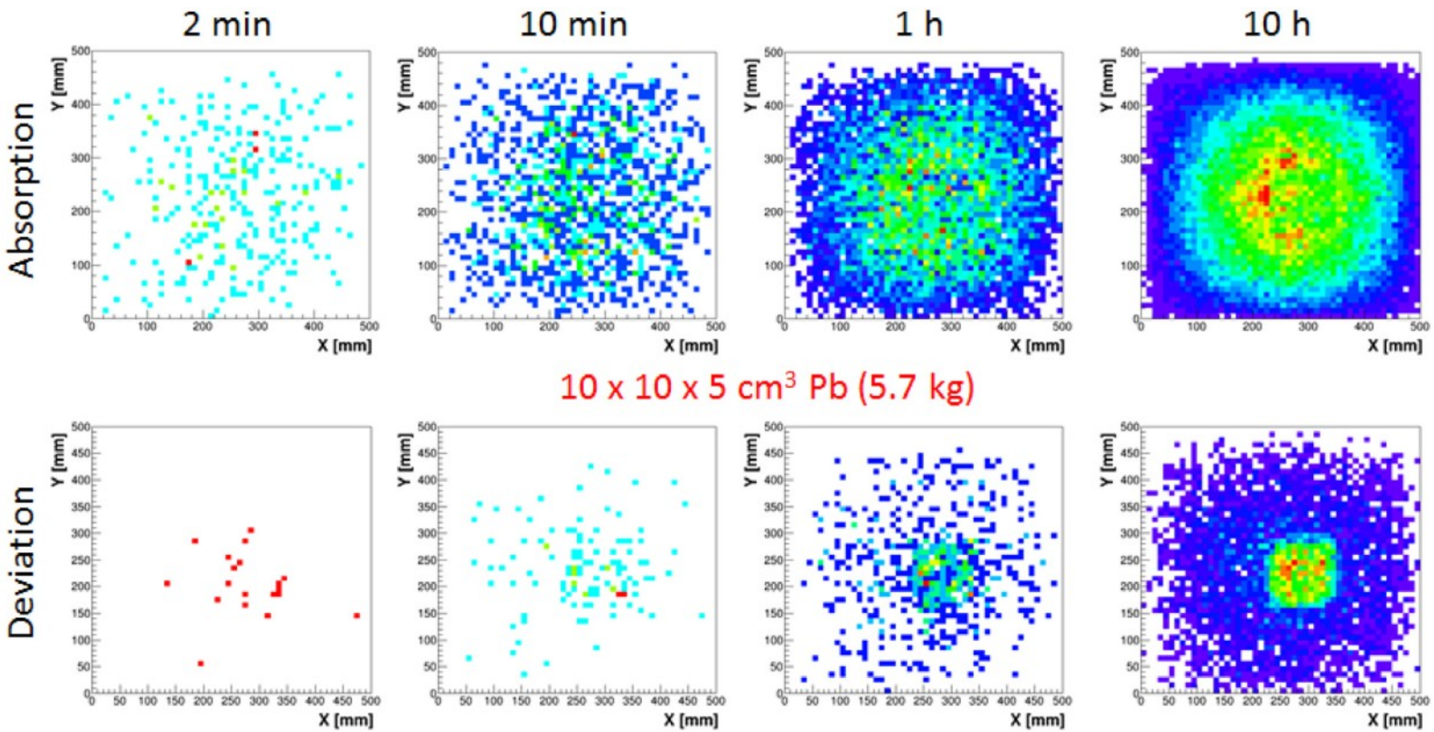




Mosishima 10.1038/nature24647

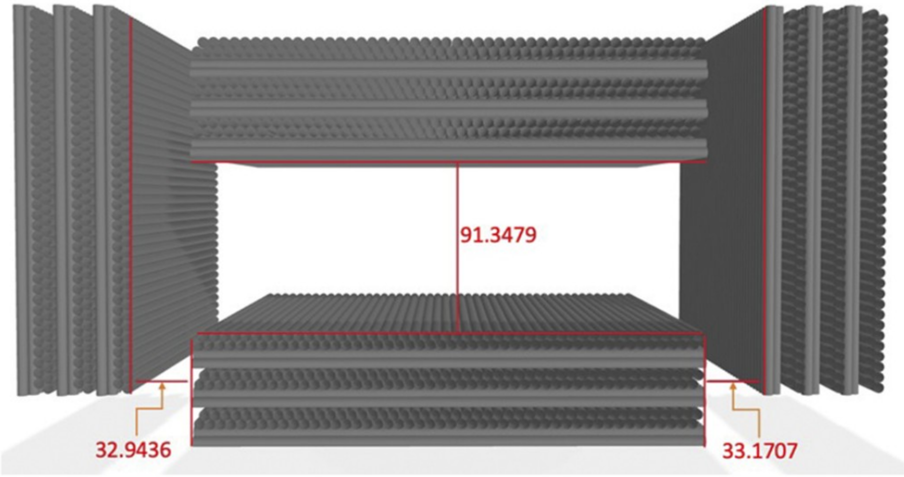
# Scattering vs Absorption Muography

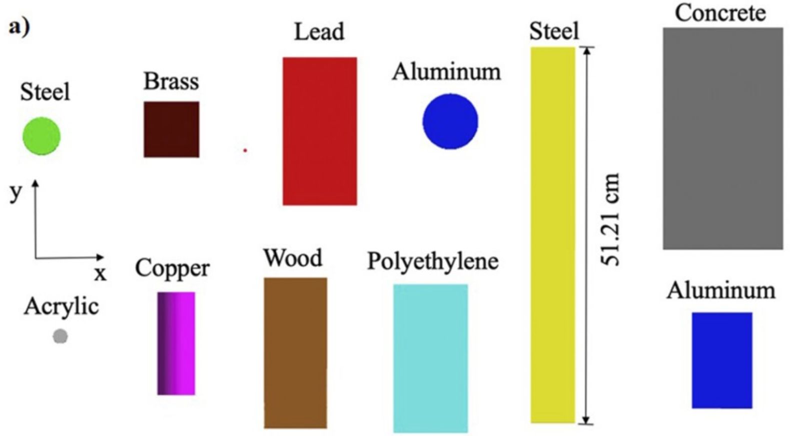
- scattering muography only possible for smaller objects
- lead brick imaged in Saclay telescope
- sensitivity in scattering mode considerably faster
- in principle: detection of high-density or high-Z material within lower density material possible (container, casks, trucks, ...)
- hot topic for „special nuclear material" detection




Procureur NIMA878

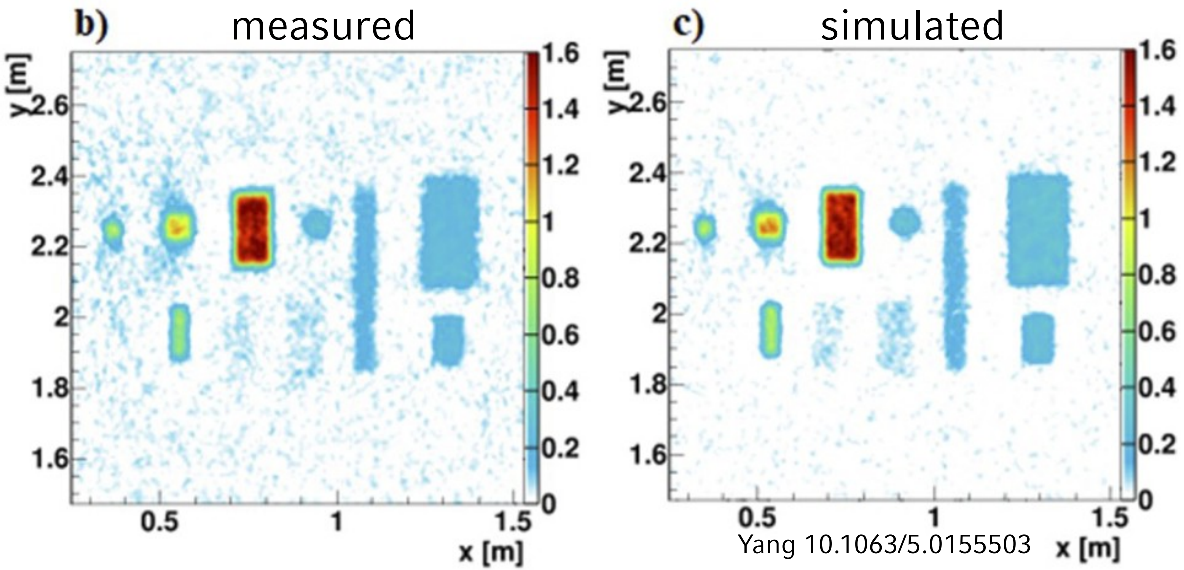
# LANL: Spent Fuel Cask Inspection




**drift tube modules**

- enclosed volume: 0.9 x 1.8 x 2.4m³
- 1900 tubes with 51mm radius, sealed
- scattering muography on test samples
- 63h → $6 \times 10^{7}$ tracks



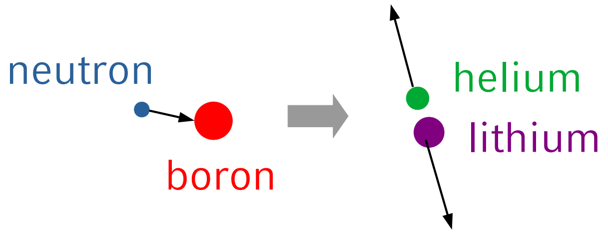

Yang 10.1063/5.0155503

# Neutron Detection

# Neutron Detection in MPGDs

neutron interaction in typical gas mixtures quite unlikely
→ „convert" into charged particle
→ use MPGD features (spatial resolution, timing, ...) to register charged products

**solid converters** $^{6}Li(n,\alpha)^{3}H$, $^{10}B(n,\alpha)^{7}Li$, U(n,f), ...
→ strongly ionizing charged particles



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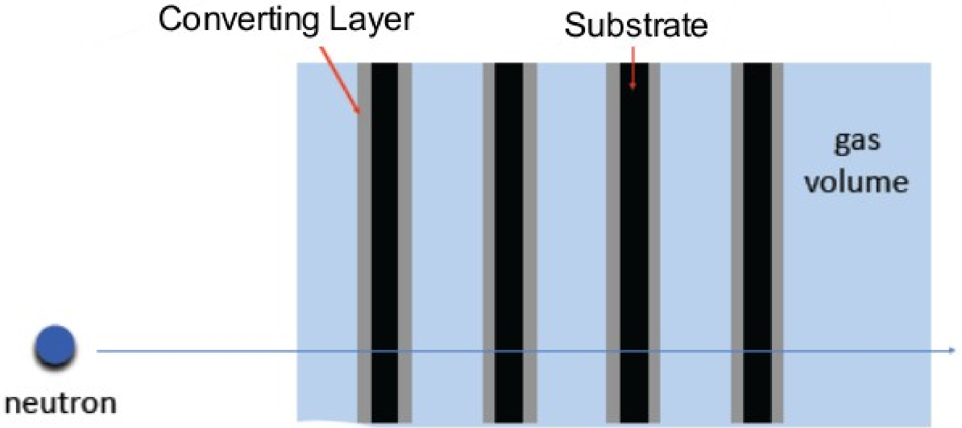
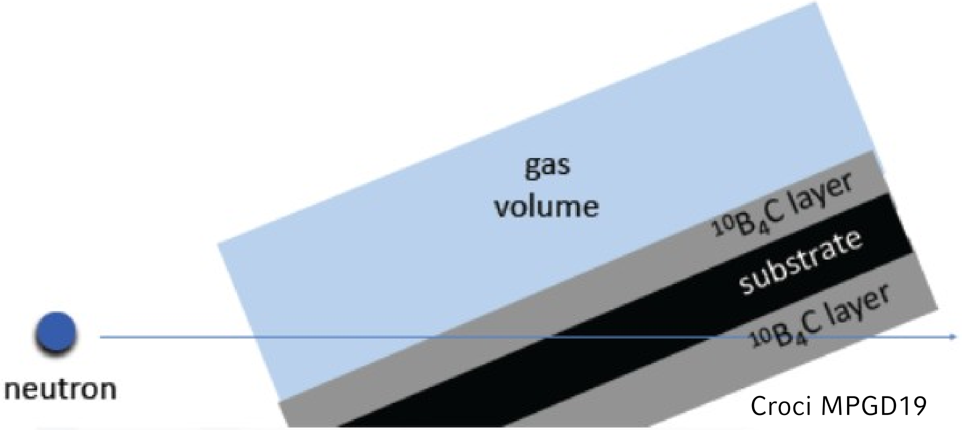
- charged particles only useful inside gas
  → limited thickness → single layer efficiency ~ 5%
- multi-layer
- grazed incidence




Croci MPGD19

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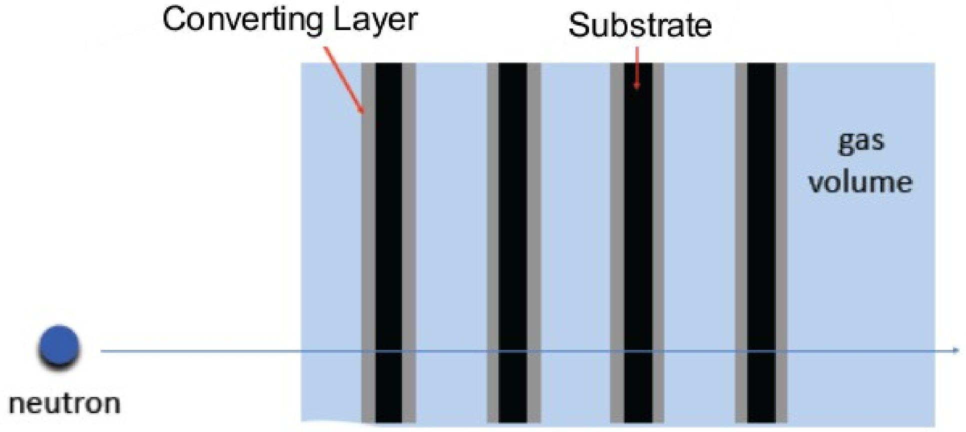
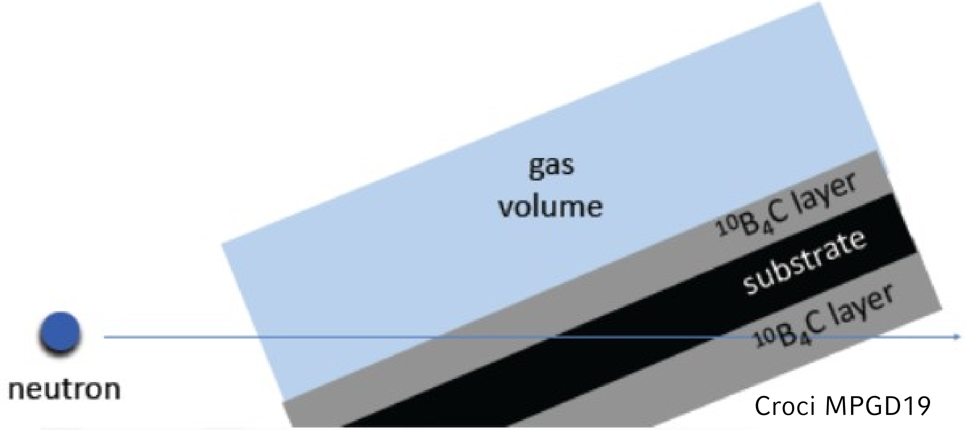
**solid converter** Gd: (n,gamma) → electrons, photon

**high energy n**: elastic interaction

- similar-mass interaction partners
- add He or protons ($CH_4$, $C_4H_{10}$) to gas mixture
- (thick) plastic + (thin) aluminum window

Segui 10.18429/JACoW-IBIC2019-MOBO04

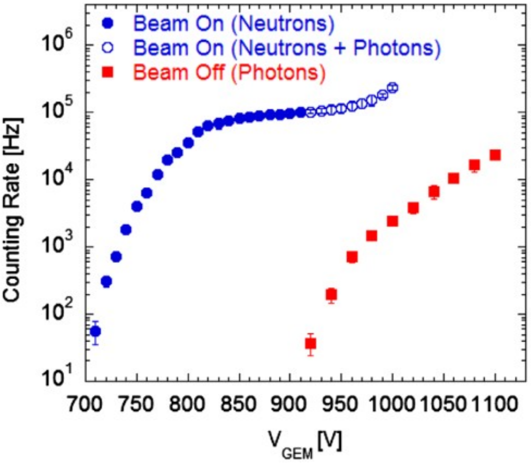


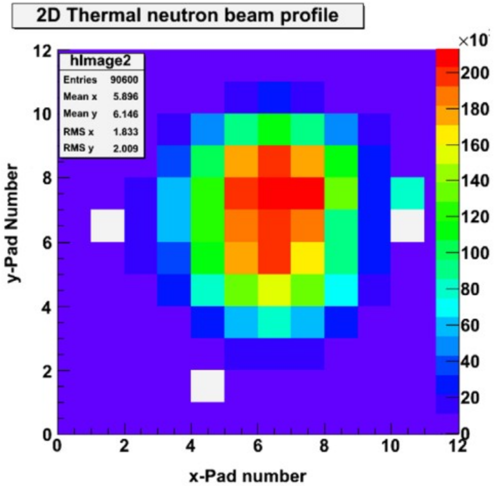



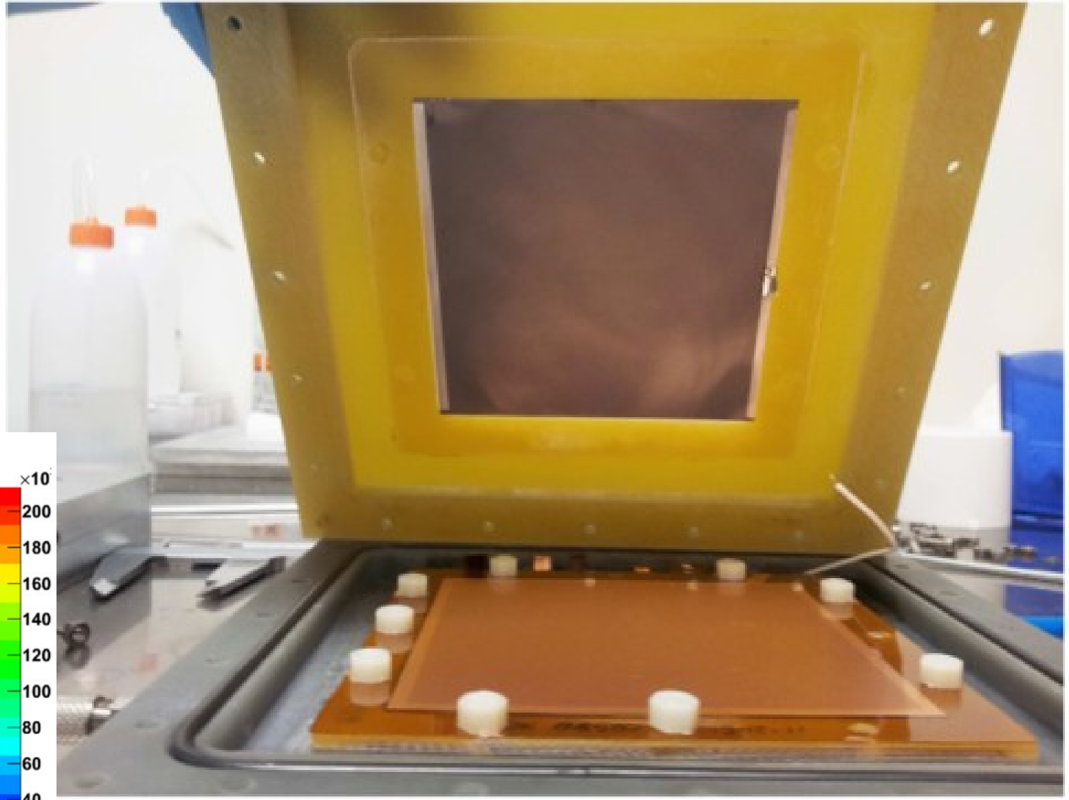

Croci MPGD19

# Boron triple-GEM detector

- 400µm aluminum cathode + 1µm $^{10}B_4C$
- 12x12 readout pads with 8x8mm²
  → rate capability
- thermal neutrons interact with boron
- Li or alpha (back-to-back) can escape cathode,
  E ~ O(1MeV)
- $\Delta E_{neutron}$ >> $\Delta E_{photon}$ (activation)
- efficiency O(1%) → BAND-GEM *(Albani NIMA957)*



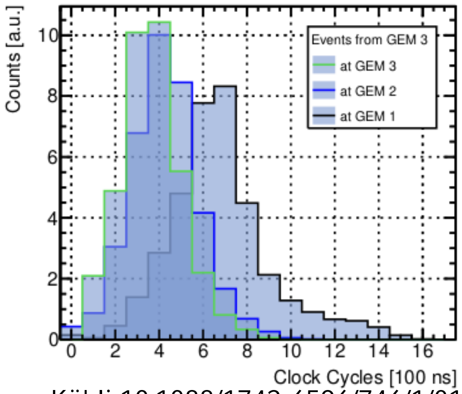



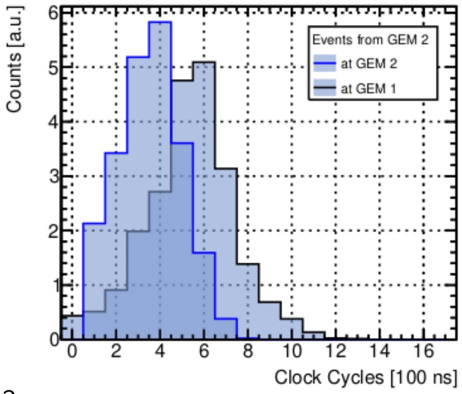



Croci NIMA732

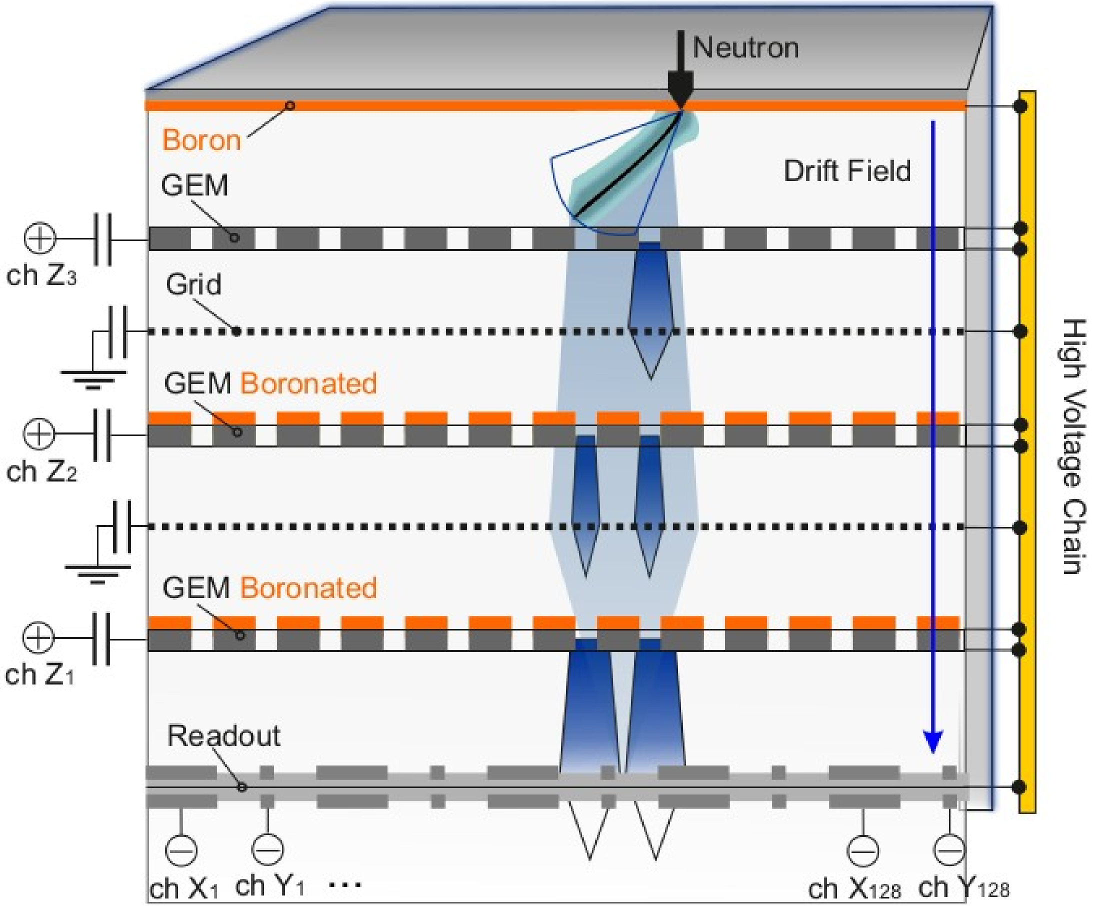
# Cascade GEM Detector

- 20x20cm² triple GEM doublet detector back-to-back
- 6 $^{10}$B layers on cathodes + GEMs
- GEMs read out → identify interacting $^{10}$B layer → time resolution 100ns
- meshes: shield GEMs electrically
- crossed readout strips (128)
- O(50%) efficiency




Köhli 10.1088/1742-6596/746/1/012003



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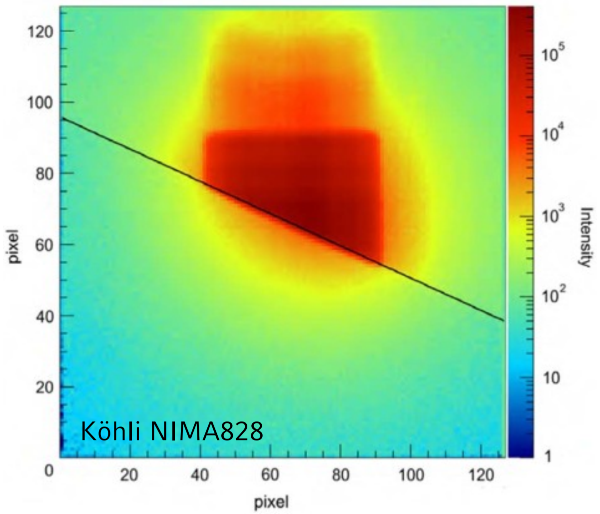
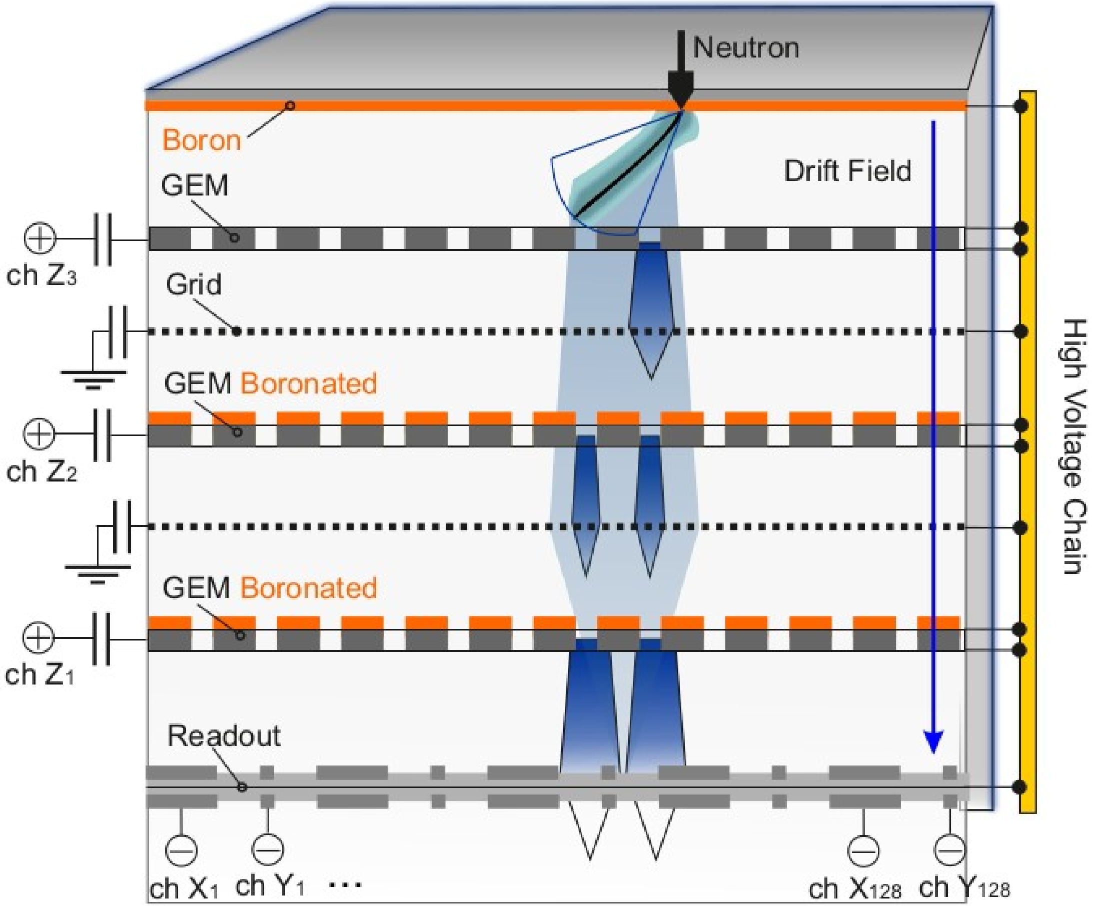
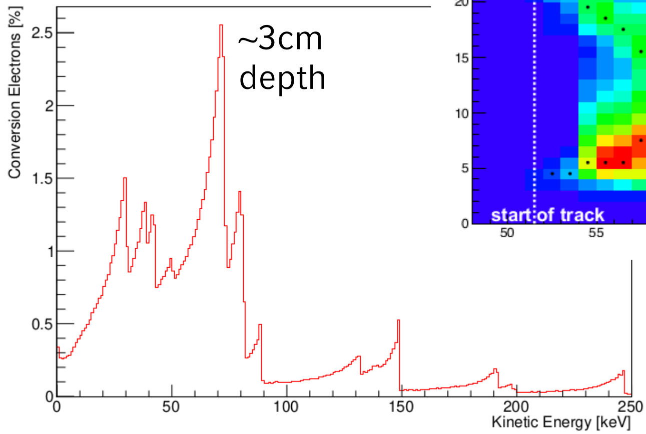


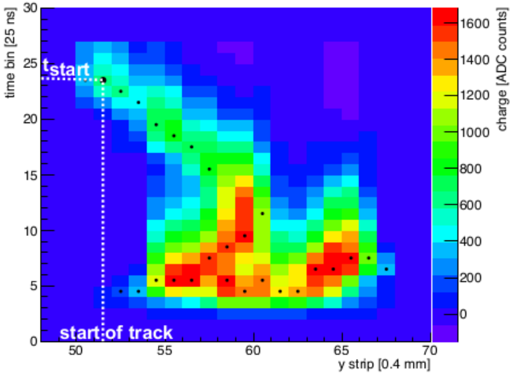



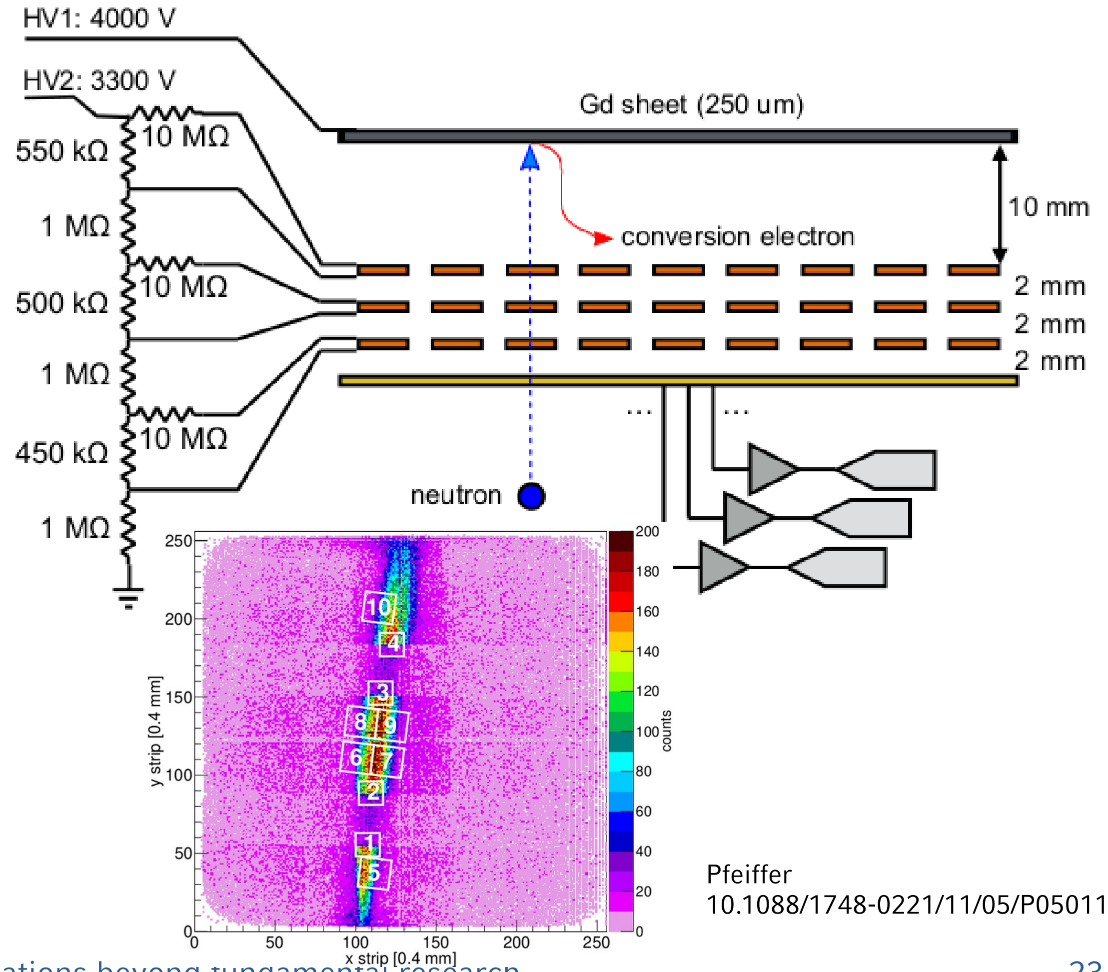
# Gadolinium GEM

250µm Gd: high n-capture cross section
→ prompt gamma emission + conversion electrons

- triple-GEM with 2x 256 strips (400µm pitch)
- µTPC mode → reconstruct conversion point




Pfeiffer
10.1088/1748-0221/11/05/P05011

# Medical Applications

# Medical Applications

diagnostics and treatment monitoring heavily based on particle and photon detectors

- different level of reliability, accuracy and fail safety needed, if radiation used on living beings
- non-laboratory environment: supplies, operation by non-experts, construction, certification
- medicine is conservative environment
  - experimental operation ethically difficult
  - new technologies only accepted, if considerably better than previous

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imaging

- pre-clinical photon imaging
- (non-clinical) positron emission imaging
- ion radiography and tomography

beam monitoring and control

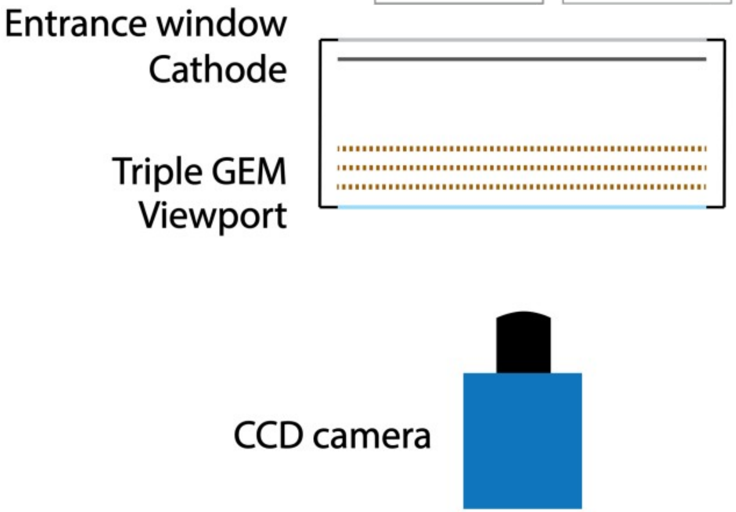
- beam monitor chambers for pre-clinical and clinical radiation

dosimetry and beam characterization

- characterization of (pre-)clinical treatment beams

# Soft X-Ray Imaging with Optically Readout GEM Detector

- soft X-rays interact via photo effect in Ar:$CF_4$
- gas amplification in triple GEM stack → charge + de-excitation light (270 & 620nm) → observe with cooled camera



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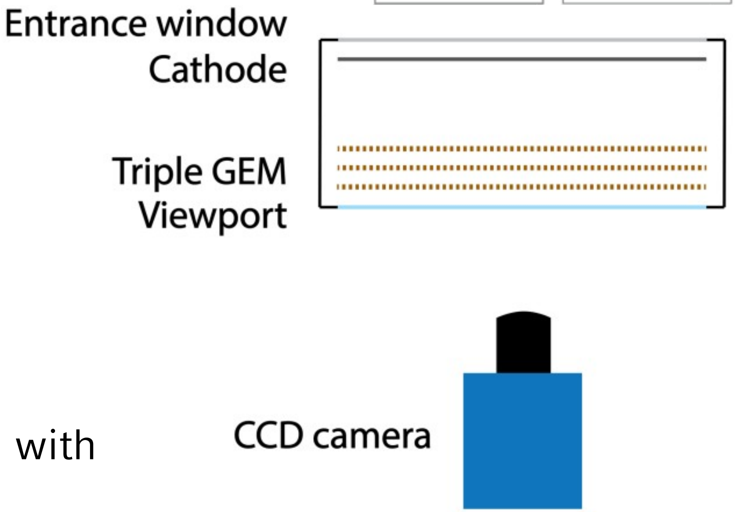
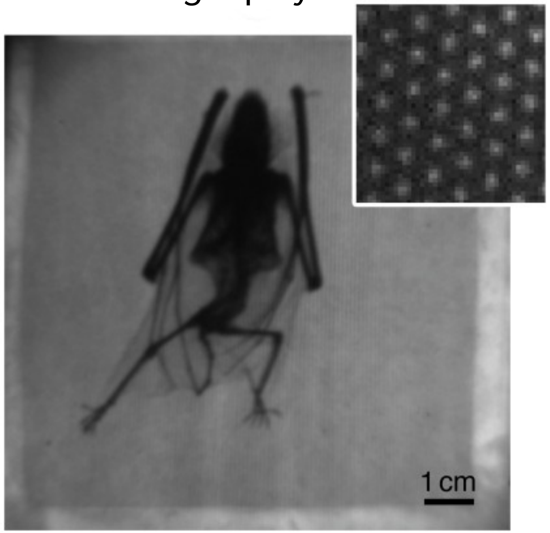
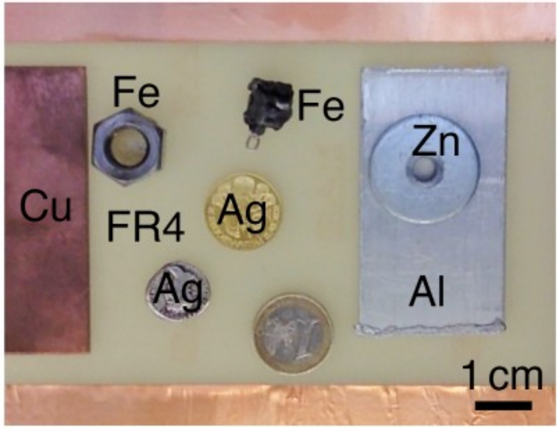
- radiographic, tomographic & fluoroscopic imaging possible
- light amplitude <=> energy deposition <=> photon energy

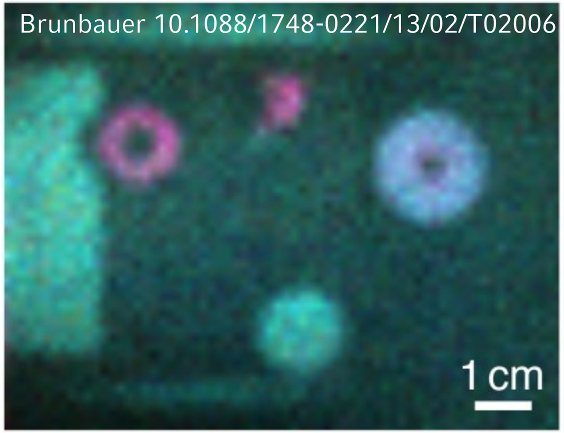



bat radiography 8keV



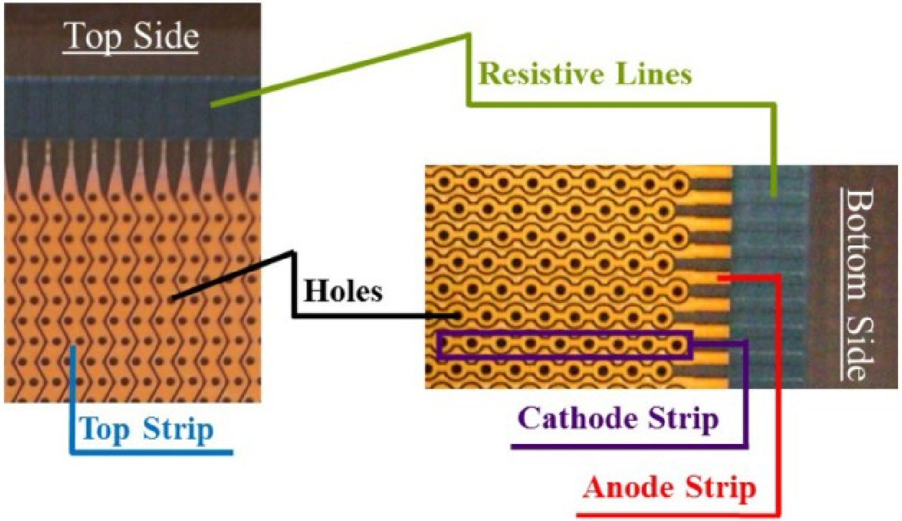

fluorescence imaging with 20keV illumination



# Soft X-Ray Imaging with THCOBRA Charge Readout

- soft X-rays (<50 kVp) interact in Ne:CH4 via photoeffect
- ionization charge amplified in THCOBRA structure (holes and between lower strips)
- top strips connected by resistive line → read out on both sides (2 channels)
- anode strips connected by resistive line → read out on both sides (2 channels)



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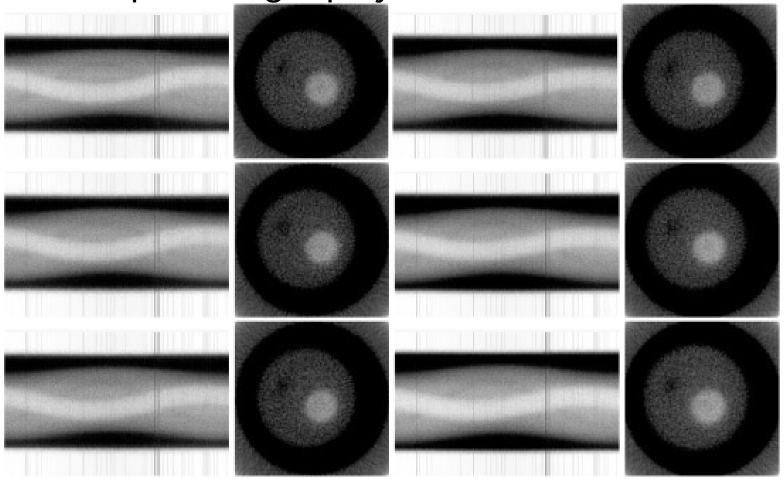
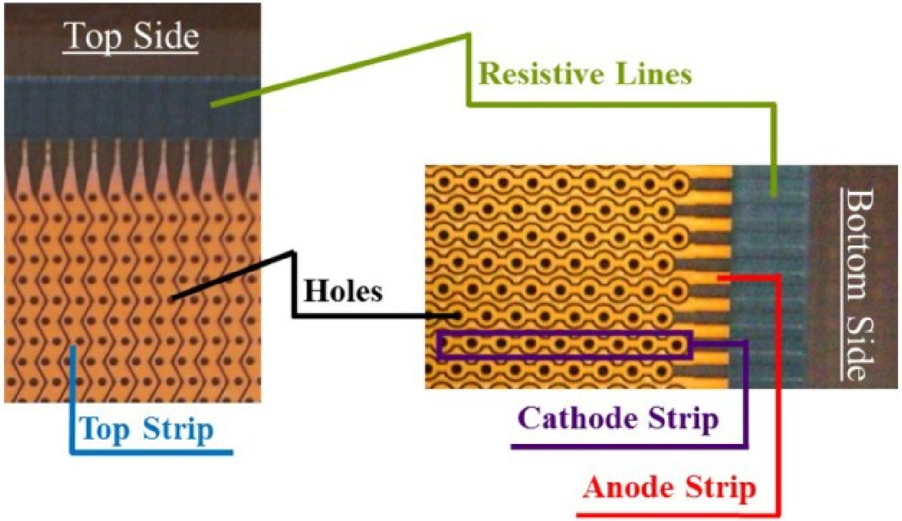
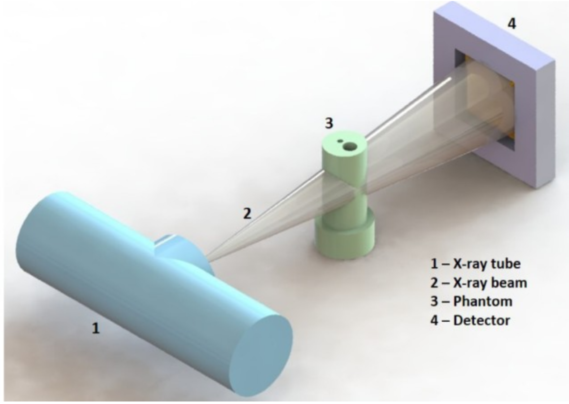
25kVp tomography: 47min, PMMA, chalk





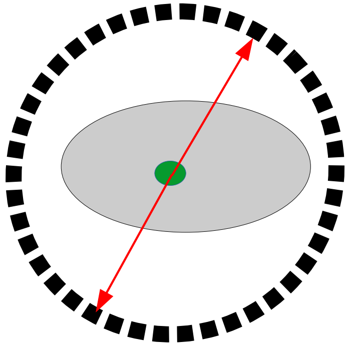




Carramate NIMA947

# Positron Emission Imaging

Positron Emission Tomography: well established modality to image physiological activity in patients

- radioactive tracer ($^{18}$F, $^{15}$O, $^{11}$C, ...) coupled to biologically active molecule (e.g. glucose mimetic)
- enrichment of tracer in „energy-consuming" tissues (e.g. tumor)
- $\beta^+$ decay → positron diffuses & annihilates with electron → two collinear 511keV photons
- tomographic image with O($10^9$) detected pairs



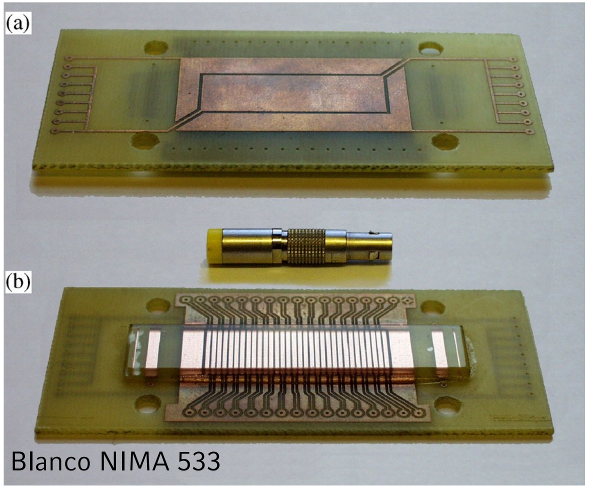
gaseous detectors?

pro: large area coverage & price

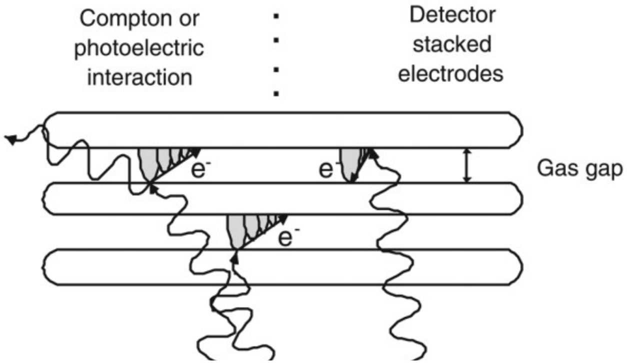
con: low efficiency to 511keV photons

# PET Imaging with Gas Detectors

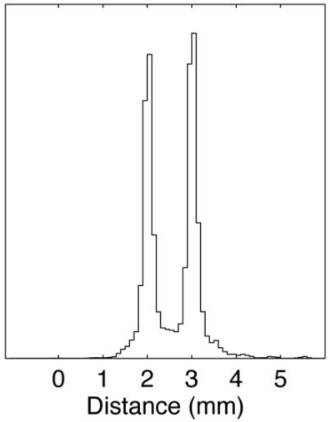
## Multi-Gap Resistive Plate Chambers



Blanco NIMA 533



Blanco 10.1109/TNS.2006.876005




- two modules with 16 stacked RPCs
- 32 pick-up strips & layer info
- tests with $^{22}$Na-source in PMMA
- 0.31mm FWHM image resolution
- efficiencies optimizable: lead electrodes, different glass types/thickness & O(100) layers

→ by x20 better than current clinical PET

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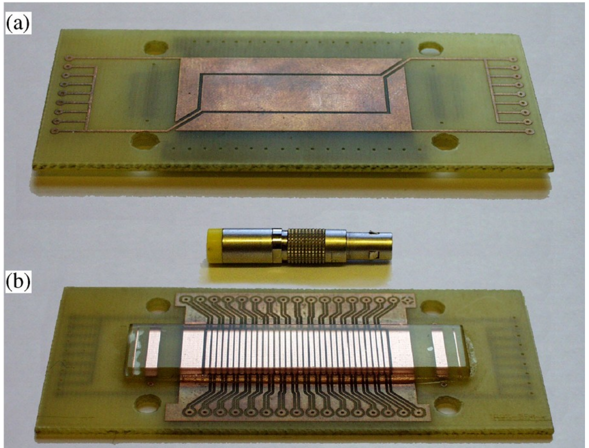
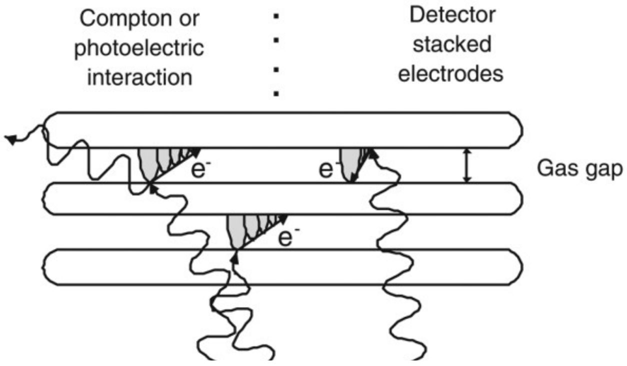


Blanco NIMA 533



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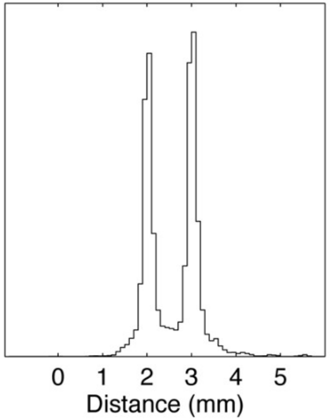


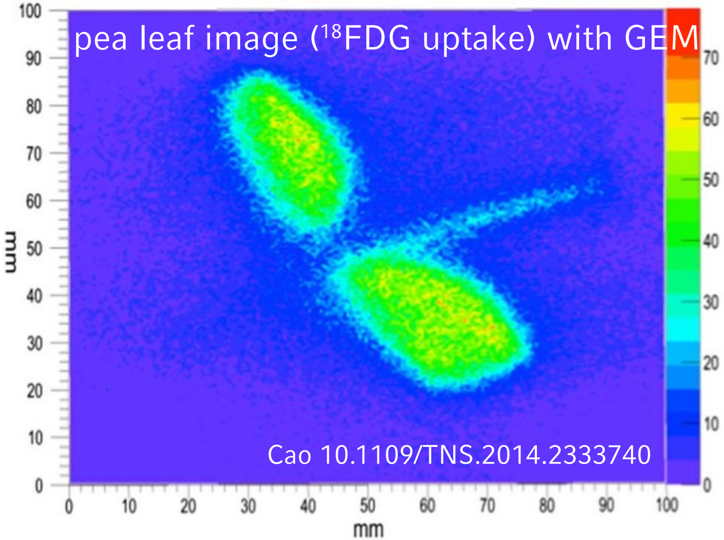

## think different: directly detect positron from thin samples

- MPGD: very low material budget & good spatial resolution

→ expose living plants to $^{11}CO_2$ or $^{18}$FDG

→ visualize physiology

- also possible in cell samples



Cao 10.1109/TNS.2014.2333740

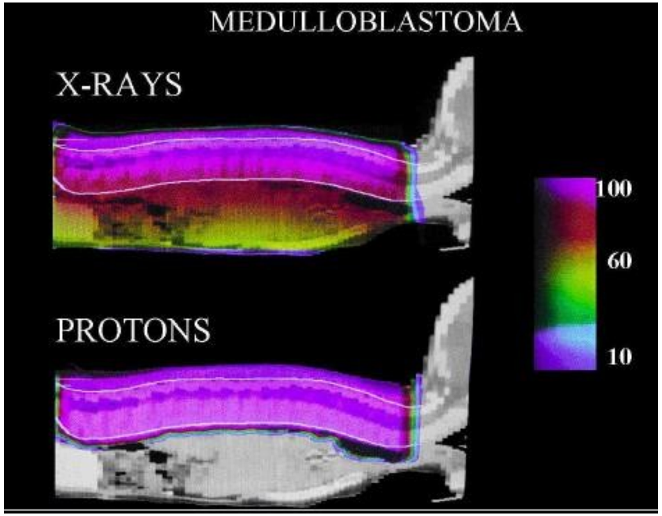
# Context: Particle Therapy

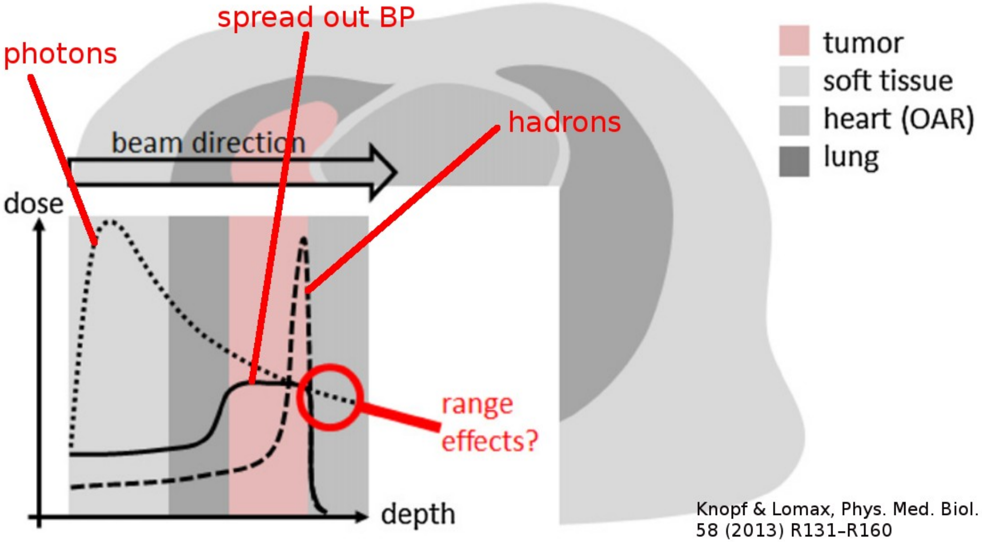
low energy ions: $dE/dx \sim 1/\beta^2$

→ favorable depth-dose:

- none behind tumor
- low in entrance

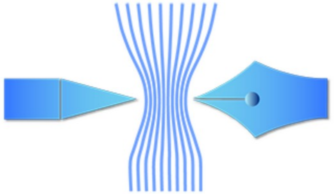
better tumor conformality → low out-of-field dose



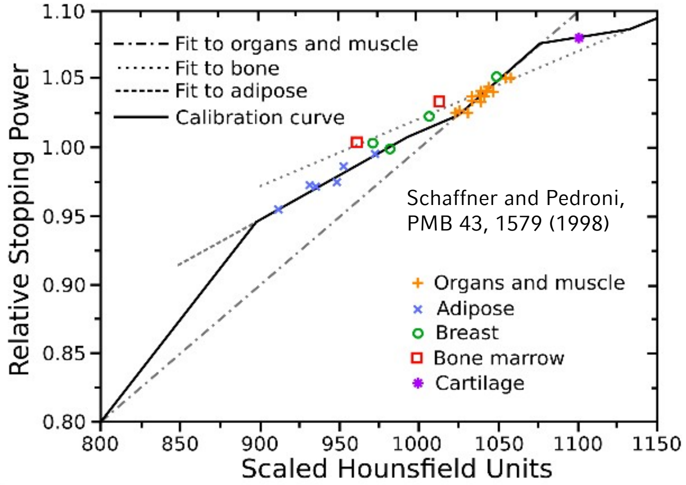

Knopf & Lomax, Phys. Med. Biol. 58 (2013) R131–R160

ballistic advantages obvious BUT
therapeutical advantages not fully demonstrated



# Concept: Proton Radiography & Tomography

1. imaging: X-ray Computed Tomography
2. treatment planning: photon absorption <=> dE/dx
3. fractionated treatment



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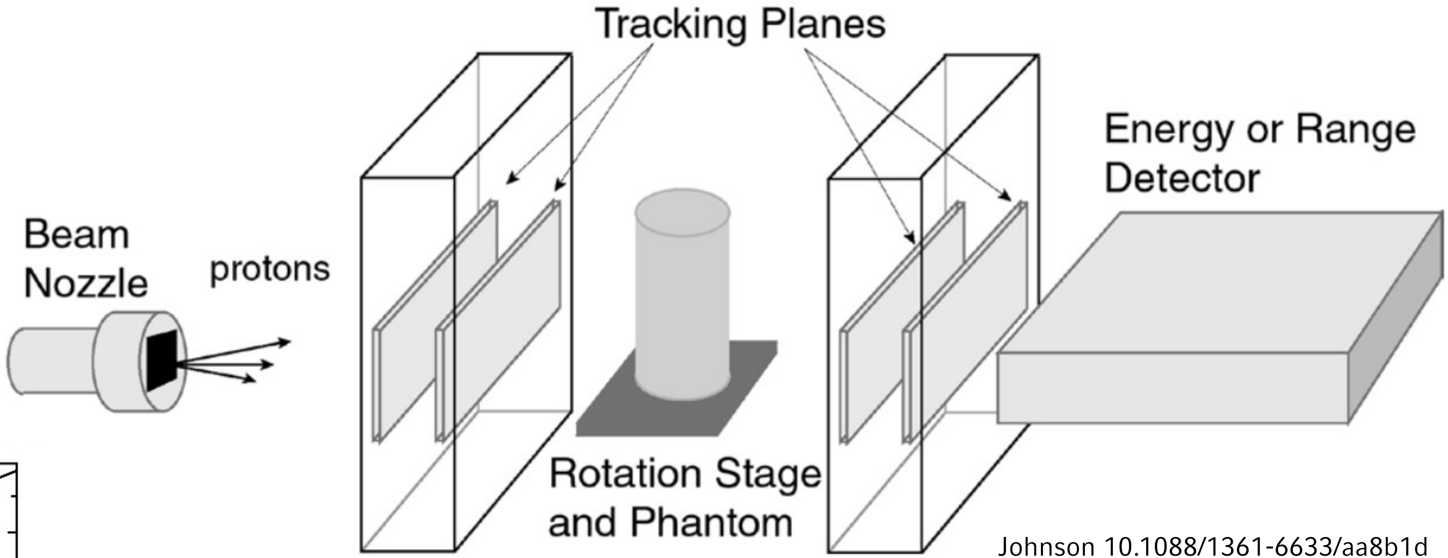
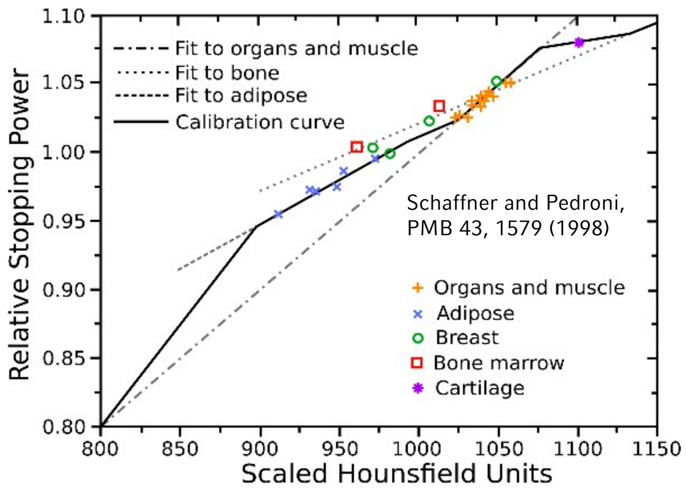



Johnson 10.1088/1361-6633/aa8b1d




**ion range uncertainties: 3% + artifacts**

- photon X-ray to stopping power conversion
- patient anatomy changes
- patient positioning

**→ mitigate: proton CT just before treatment**

# AQUA Proton Radiography Detector 10x10cm²

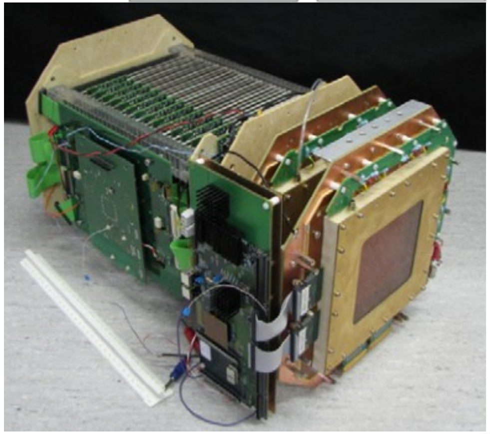
no upstream tracker

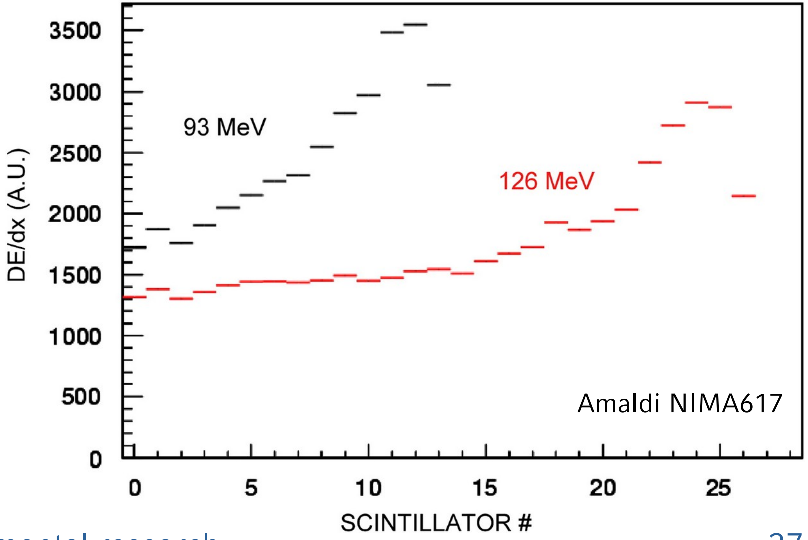
downstream tracking detectors
- pair of 10x10cm² triple GEM tracking detectors with strip readout

→ position and direction of proton trajectory

range detector
- 28 3mm thick plastic scintillator tiles
- interfaced by WLS fibers + SiPMs
- single particle range resolution 1.4 mm
- suitable for 20 to 130MeV protons

integrated readout electronics
- O(100kHz) rate → radiography in 10s
- too slow for tomography





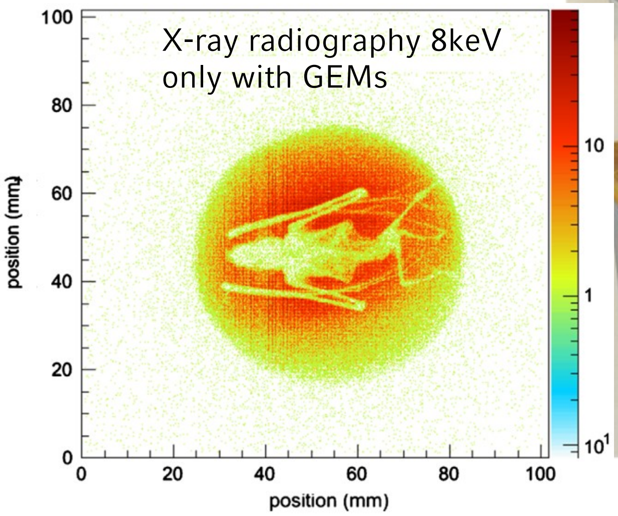
# AQUA Proton Radiography System 30x30cm²

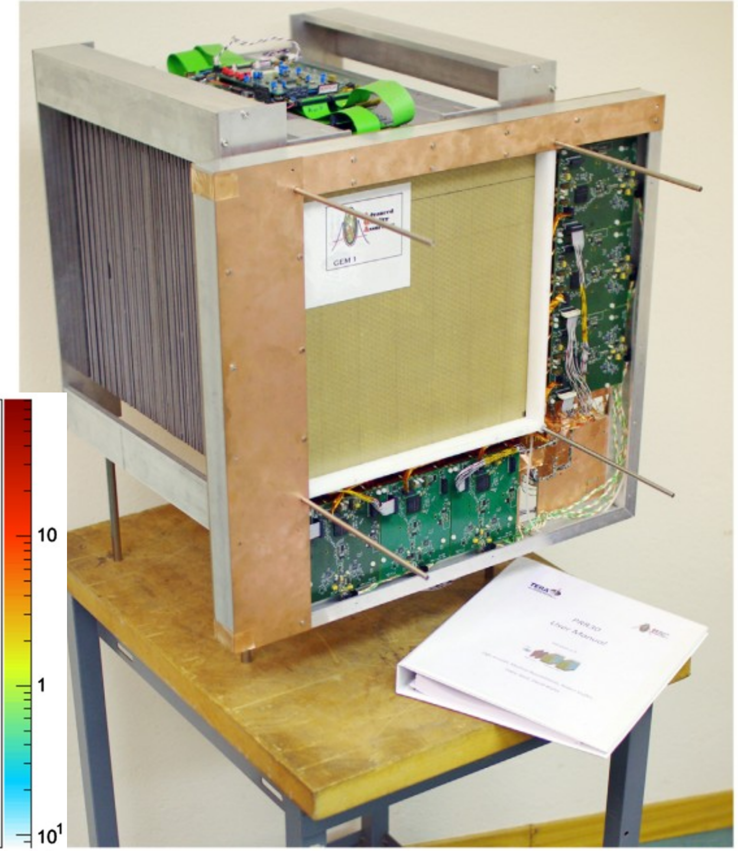
downstream tracker
- pair of 30x30cm² triple GEM detectors with strip readout
- possibility to mount third GEM detector

range detector
- 48 3.2mm thick plastic scintillator tiles
- interfaced by WLS fibers + SiPMs
- suitable for 20 to 190MeV protons

improved integrated readout electronics
- 1MHz readout rate
  → radiography in 1s

promising system, currently at HEPHY



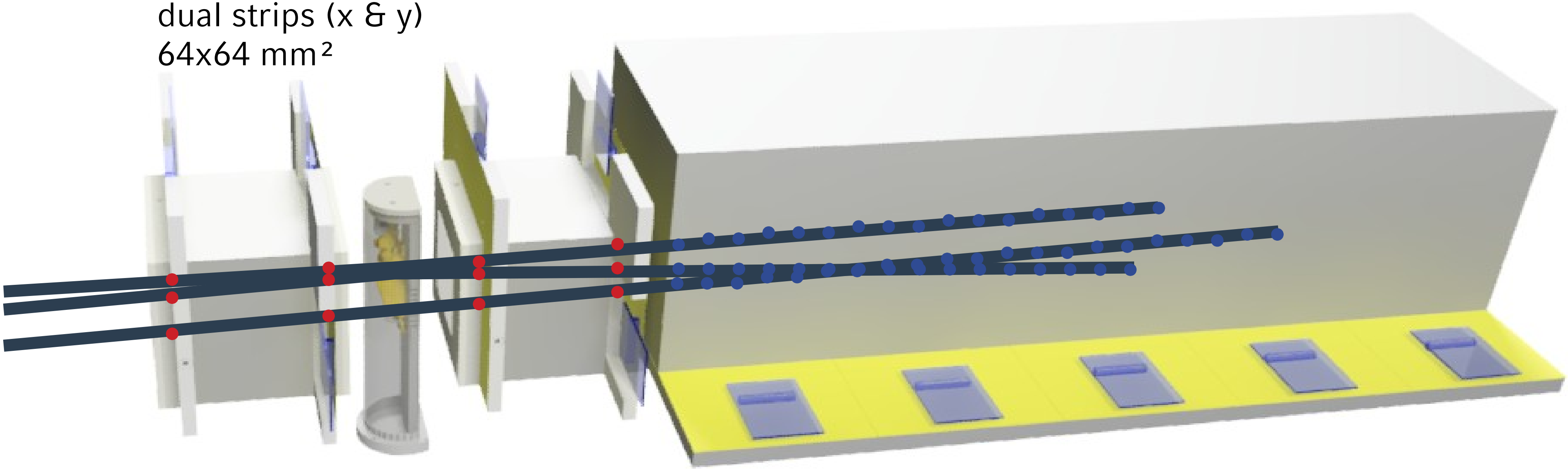



Bucciantonino NIMA732

# SIRMIO Small Animal Proton Tomography System

spatial information from 2d floating strip Micromegas trackers
residual range (→ energy loss) from TPC with vertical absorbers

**4 aluminum floating strip Micromegas trackers**
dual strips (x & y)
64x64 mm²



**mouse holder**
x, y, z, φ movement
sterile environment

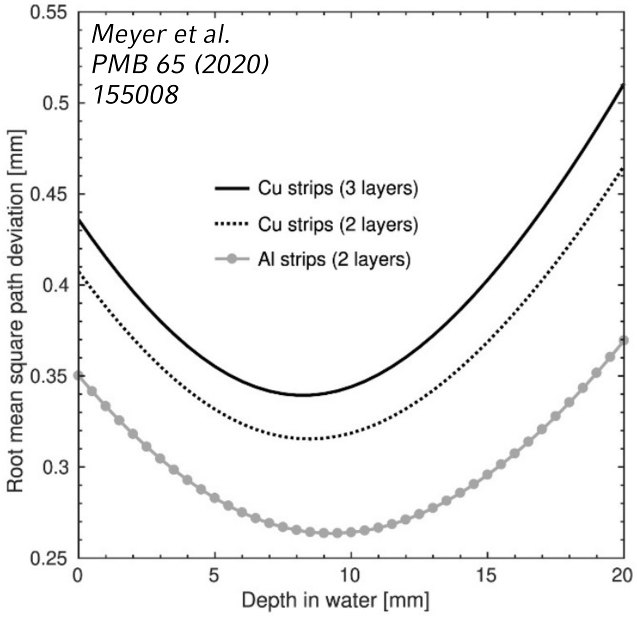
**Time Projection Chamber range detector**
65 absorber foils (600µm Mylar+Kapton)
8mm gaps in between

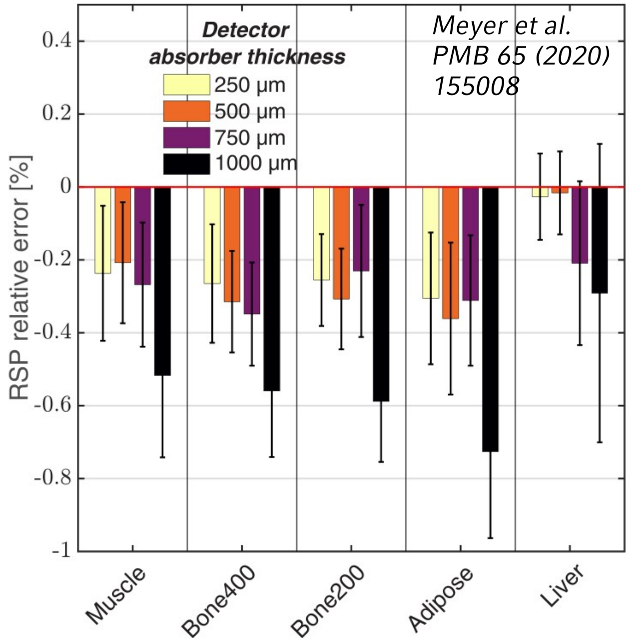
# FLUKA Simulation: Geometry & Parameters

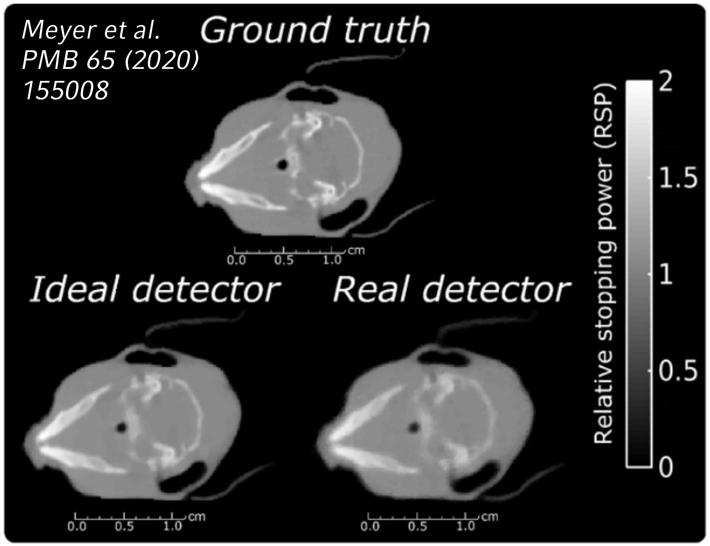
detailed simulation of trackers, object & TPC range detector

→ trackers with aluminum electrodes considerably better & spacing > 7cm: **mean path resolution 0.18mm**

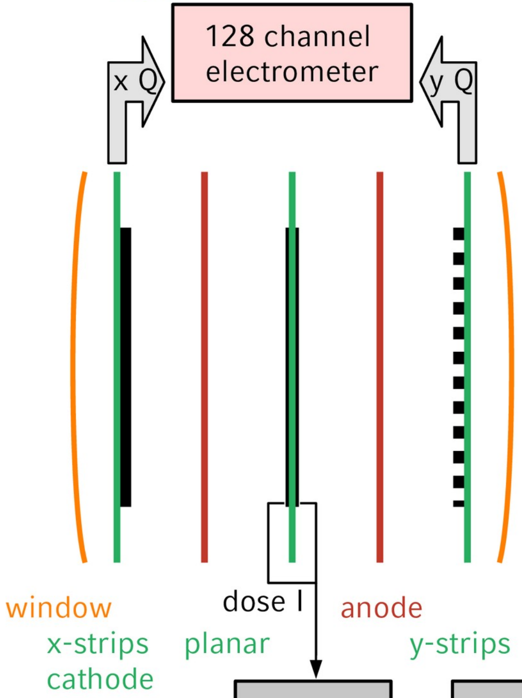
→ TPC absorber thickness 500 – 750μm: compromise between complexity & **RSP accuracy < 0.3%**

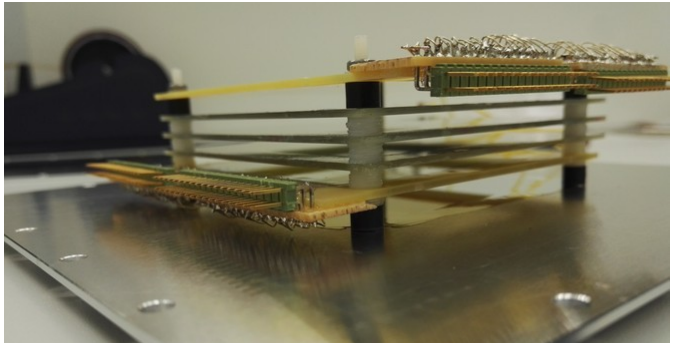


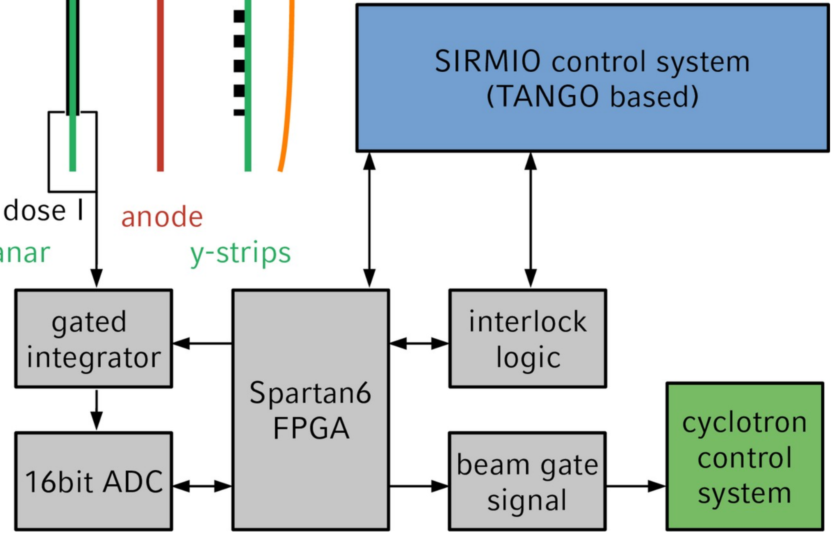



# Ultra-Thin Beam Monitor Chambers



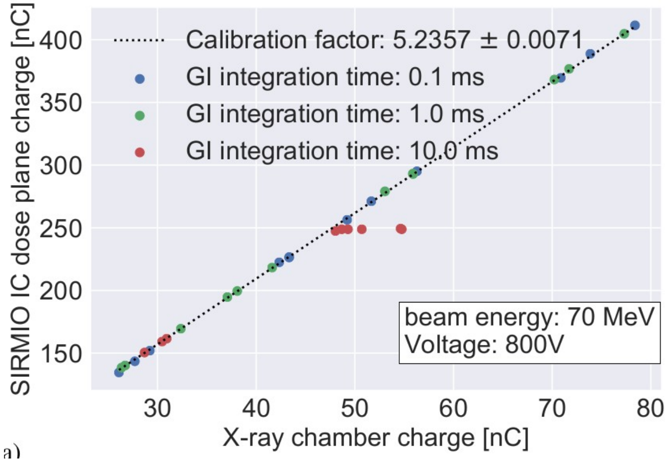



active area 64x64mm²

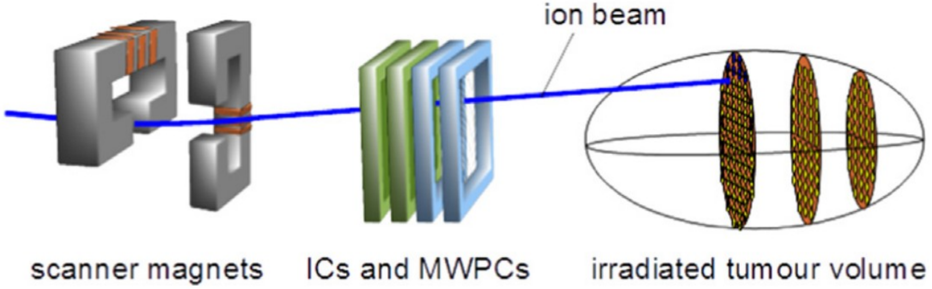
- 2 strip planes (64 strips, 40nm Alu on 10µm Kapton)
- 1 dose gap (unsegmented, 40nm Alu on 2µm Mylar)

stability O(0.1%) needed

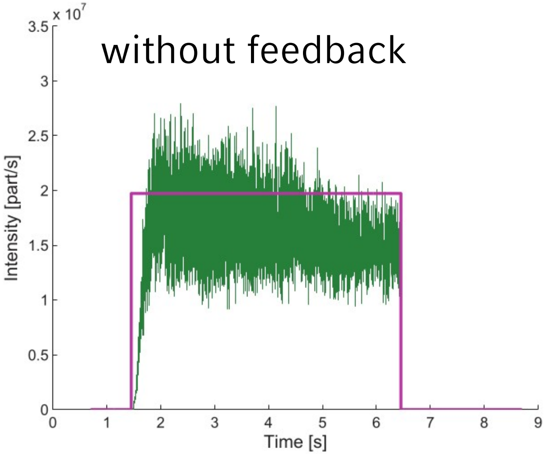
- long term stable electronics
- correct p & T effects on density

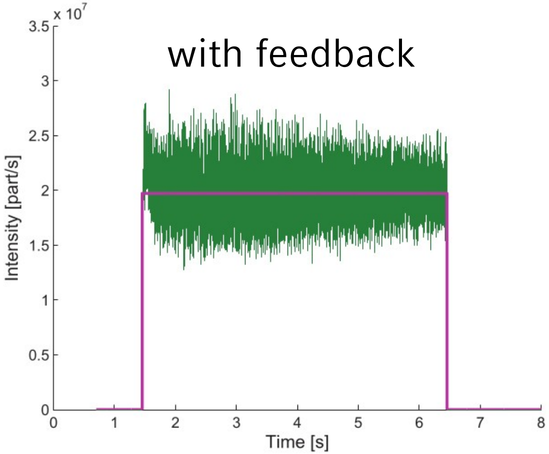


# Clinical Ion Beam Monitor Chambers (HIT)




Schömers et al., NIMA 795 (2015) 92–99




Schömers IPAC 2013, ISBN 978-3-95450-122-9

- active area: 25 x 25 cm²
- three ionization chambers (unsegmented)
  - 1: monitor & control spot dose
  - 1: feedback to synchrotron (stabilize slow extraction)
  - 2 & 3: interlock, if their values deviate from 1

two Multi-Wire-Proportional Chambers
  - two wire layers: x, y, wire pitch 2mm
  - 1: monitor & control spot position
  - 1: feedback to scanning magnets
  - 1: monitor spot shape
  - 2: interlock, if its values deviate from 1

# 6MV Photon Beam Profiling with Glass Thick-GEM

O(50%) of all cancer patients receive irradiation treatment. Vast majority treated with photons.

clincal linac

- compact 5 to 20MeV electron accelerator
- electrons steered onto tungsten target
  → bremsstrahlung
- photon field shaped by tungsten multi-leaf collimator
- field intensity and shape needs to be known with high accuracy → accurate treatment planning & delivery

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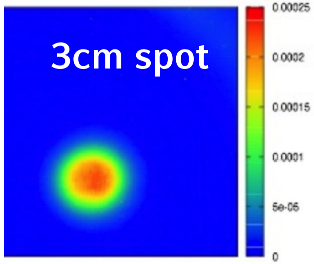
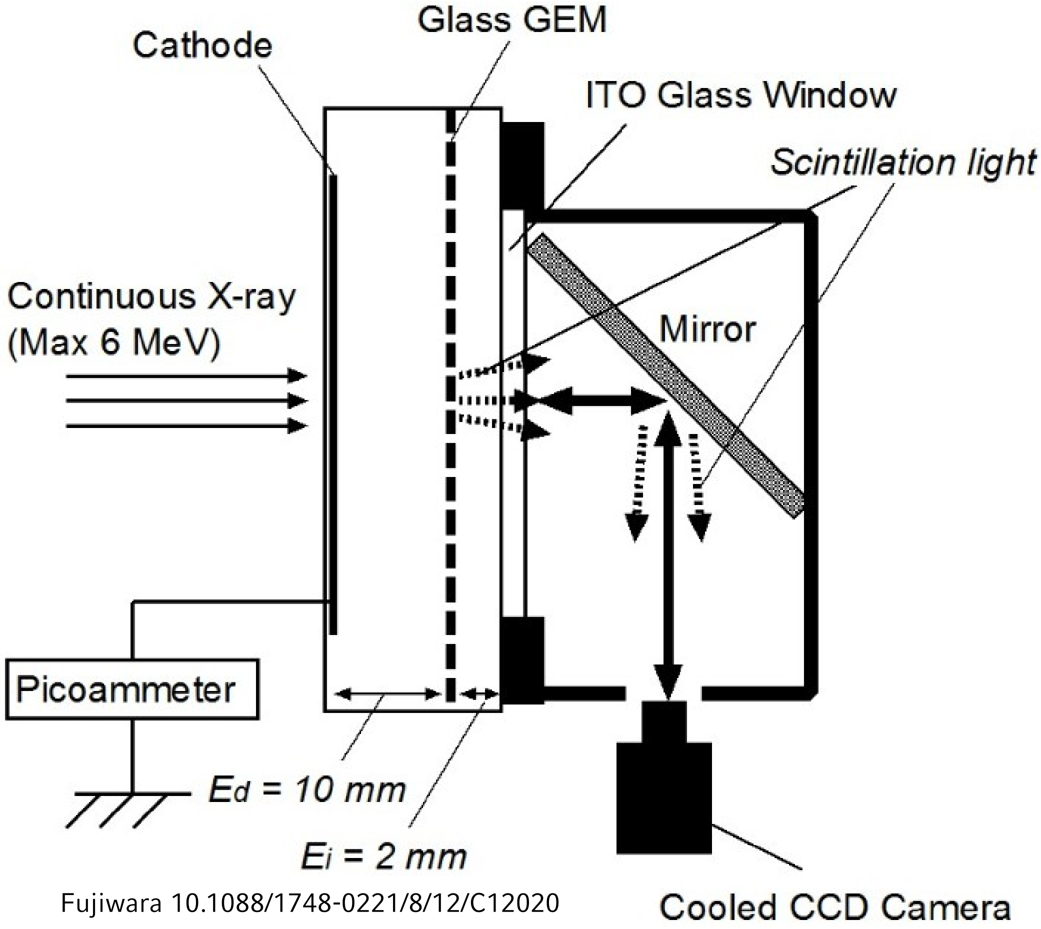
gaseous detectors well suited for routine QA: low quenching good linearity




Fujiwara 10.1088/1748-0221/8/12/C12020

# Pre-clinical Proton Beam Profiler


**requirement**: scan beam profile (20mm → 0.5mm ) and position longitudinally prior to irradiation
→ beam parameters for treatment planning

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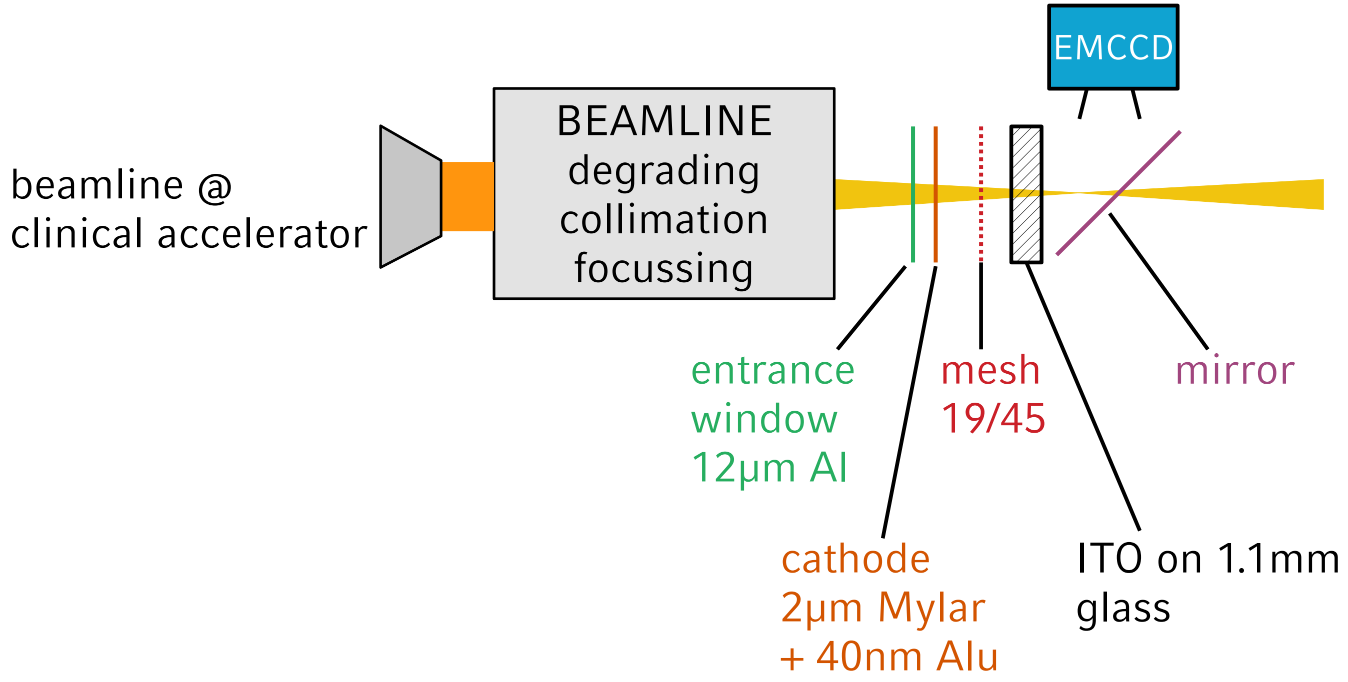


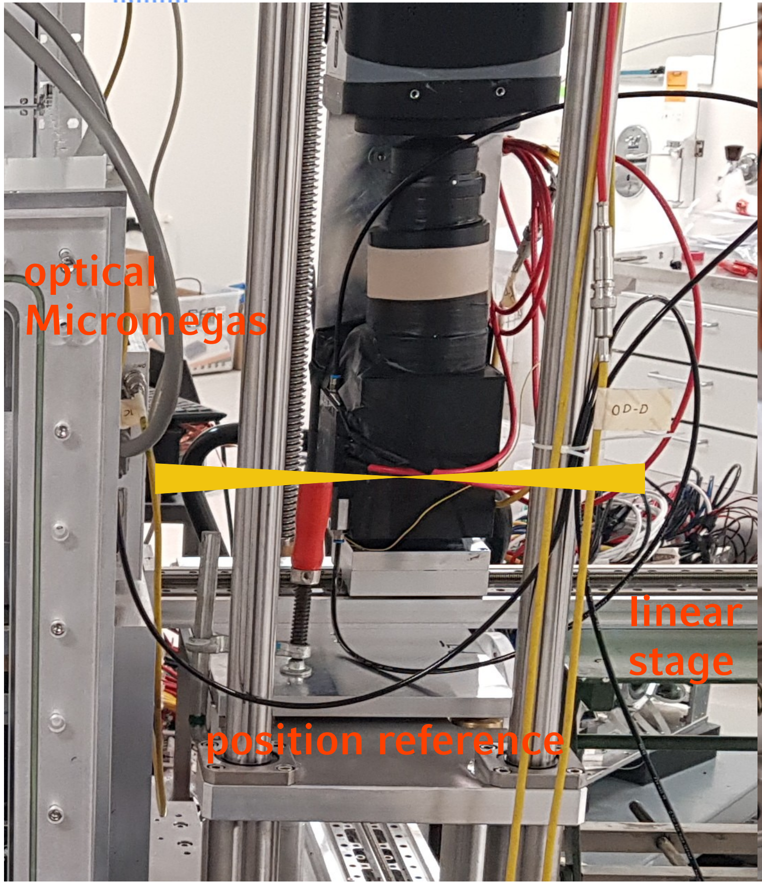

ITO: indium tin oxide
EMCCD: Electron-Multiplying CCD

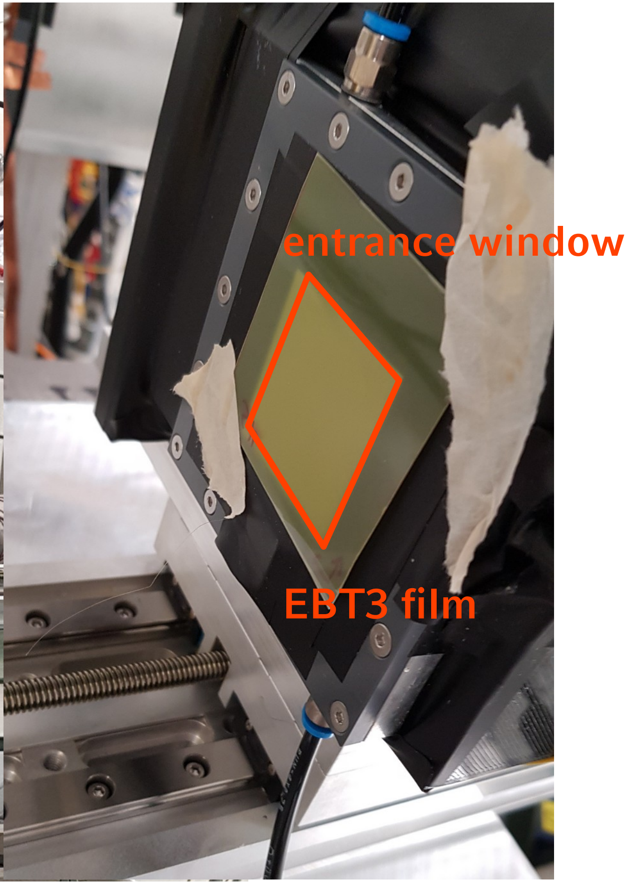
**requirement**: scan beam profile (20mm → 0.5mm ) and position longitudinally prior to irradiation
→ beam parameters for treatment planning

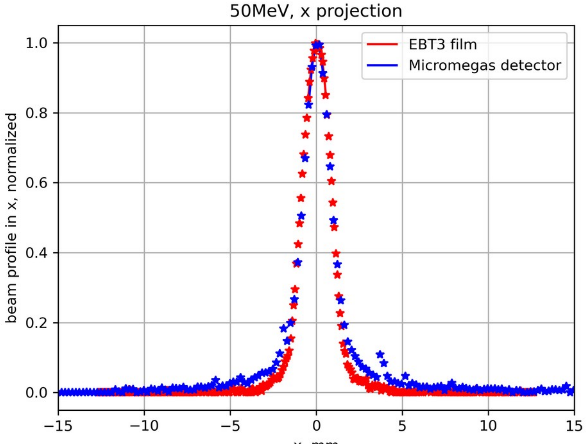
**constraints**
- good 2d resolution → pixels
- no beam distortion before measurement (~20-50MeV)
- large dynamic range

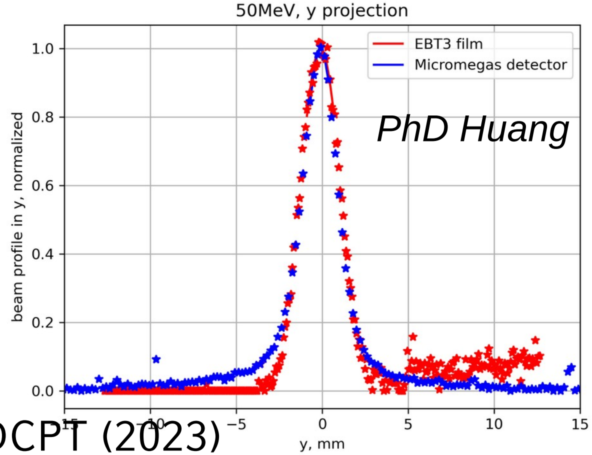
**solution** (inspired by Brunbauer et al. 2018 JINST 13 T02006 & Iguaz, RD51 CM 2018)
→ Glass Micromegas with optical readout
→ mounted on linear stage

# Profiling Pre-clinical SIRMIO Beam @ DCPT




successfully used in beam line characterization @ PSI (2021), DCPT (2022), DCPT (2023)

# Summary

numerous experimental & advanced applications of MPGDs outside fundamental research

**muography**

- scattering or absorption
- vulcanology, archeology, cargo scanning

**neutron detection**

- converters
  - B, Li, ... → hadrons
  - H (elastic) → protons
  - Gd → electrons
- beam profiling, reaction products

**medical applications**

- imaging (X-ray and proton CT)
- beam monitoring
- beam characterization

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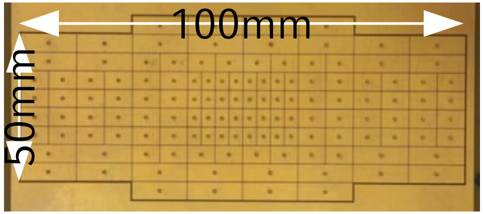
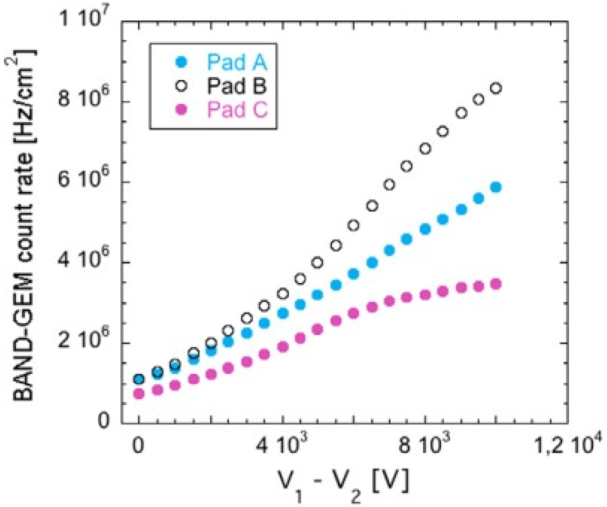
Thank you for your attention!

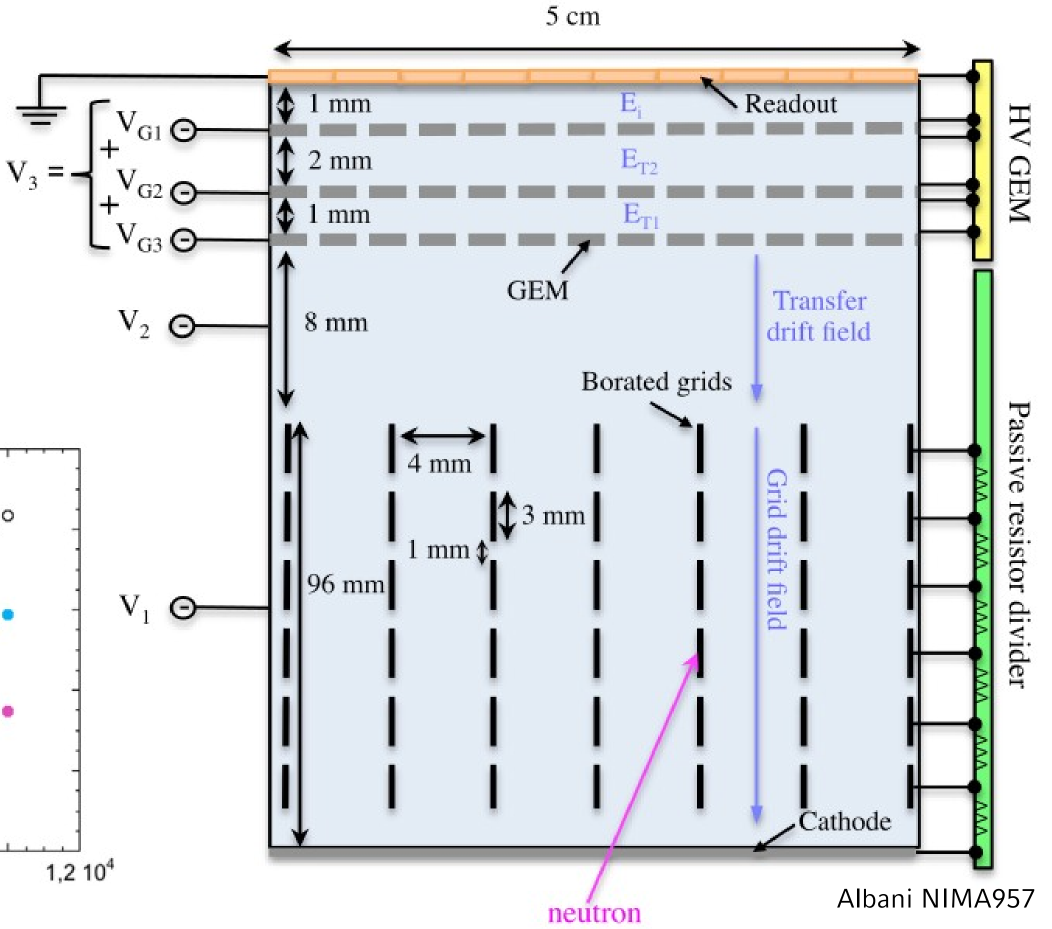
# backup

# *B*oron *A*rray *N*eutron *D*etector GEM

- converter: 24 aluminum grids + 1µm $^{10}B_4C$
  → 10kV extraction voltage
- detector tiled by 5° → increase efficiency
- high count-rate reachable
- efficiency not limited by neutron conversion but electron extraction from grid
- full module: 50% efficiency reachable
- long conversion region → bad timing accuracy



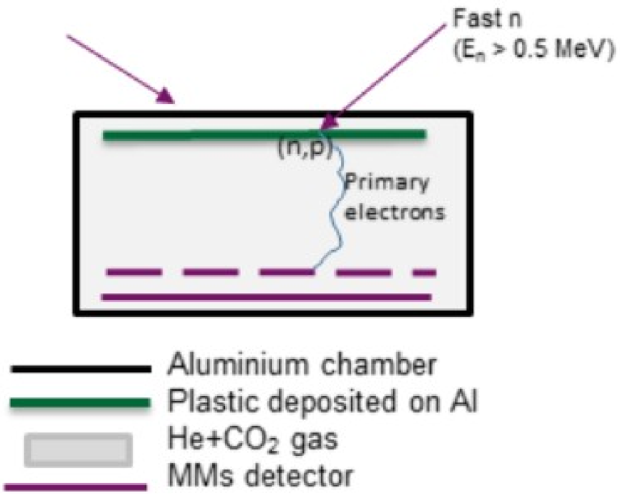



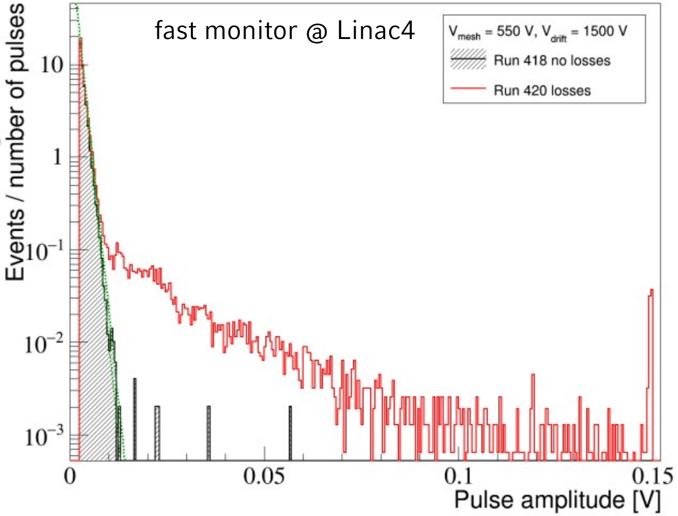

Albani NIMA957

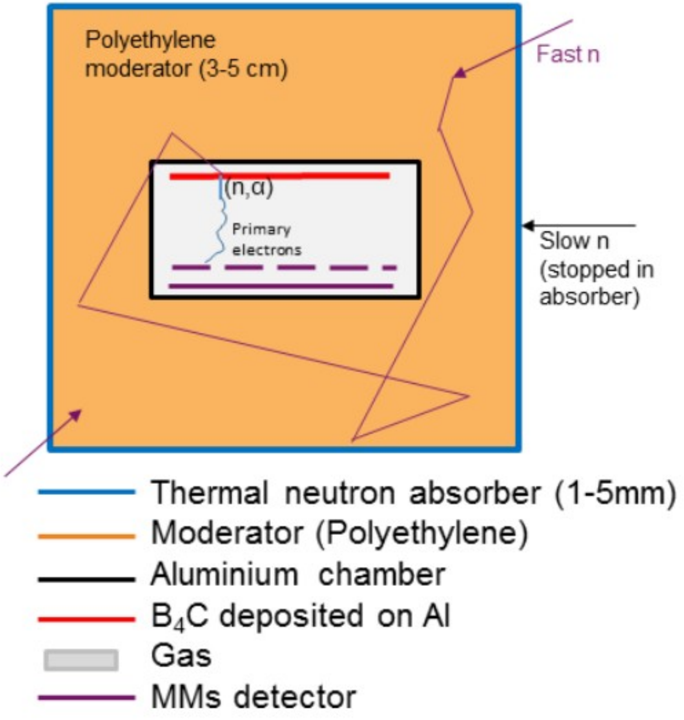
# neutron Beam Loss Monitor @ ESS

ESS linac: proton beam up to 2GeV, 62.5mA
→ detect starting beam losses essential

Micromegas based neutron BLM in low energy region
- fast losses monitor: 128µm Mylar as n → p converter
- slow losses monitor: $^{10}B_4C$ cathode




Segui 10.18429/JACoW-IBIC2019-MOBO04