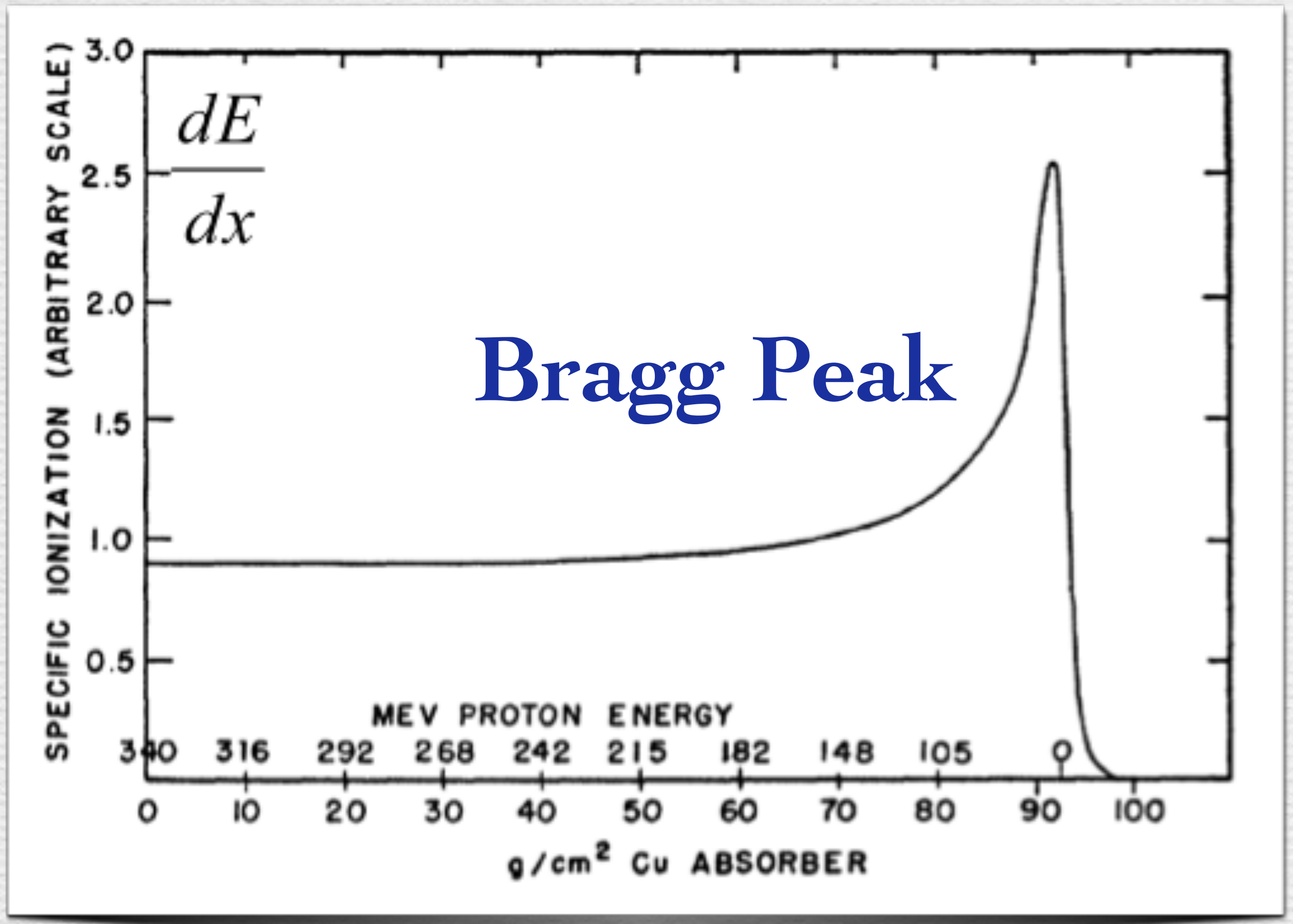
SIGLA INFN
GRUPPO V

# MOnitor for Neutron Dose in hadrOntherapy

Michela Marafini

# Particle Therapy

**Particle Therapy (PT) is an extremely effective method for destroying tumors while preserving healthy tissues that exploits the properties of energy deposit within the matter of heavy charged particles, described by the Bragg Peak distribution.**




- **The most common beams are Protons and Carbon ions but new ions have been recently proposed (Helium, Oxygen);**

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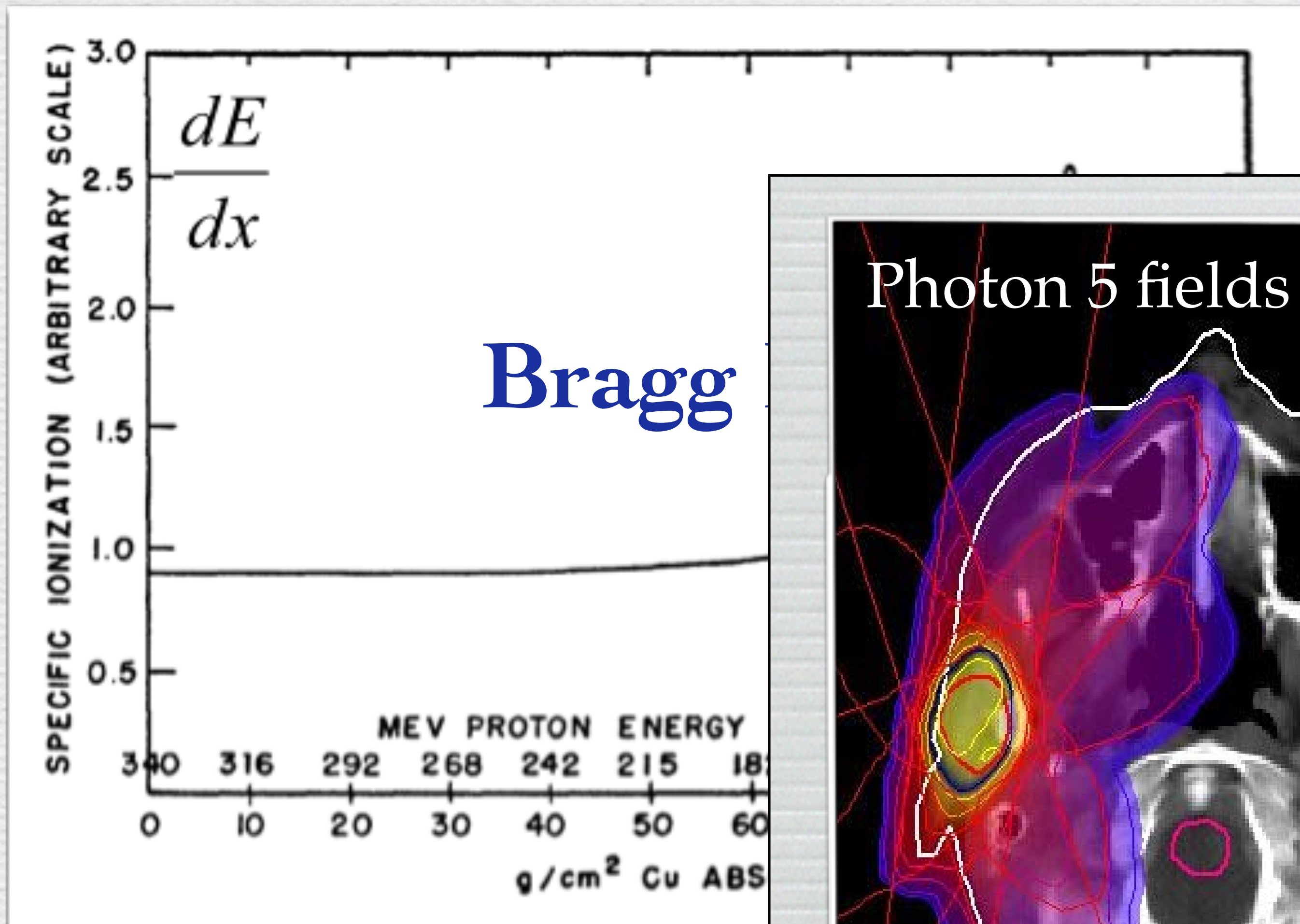
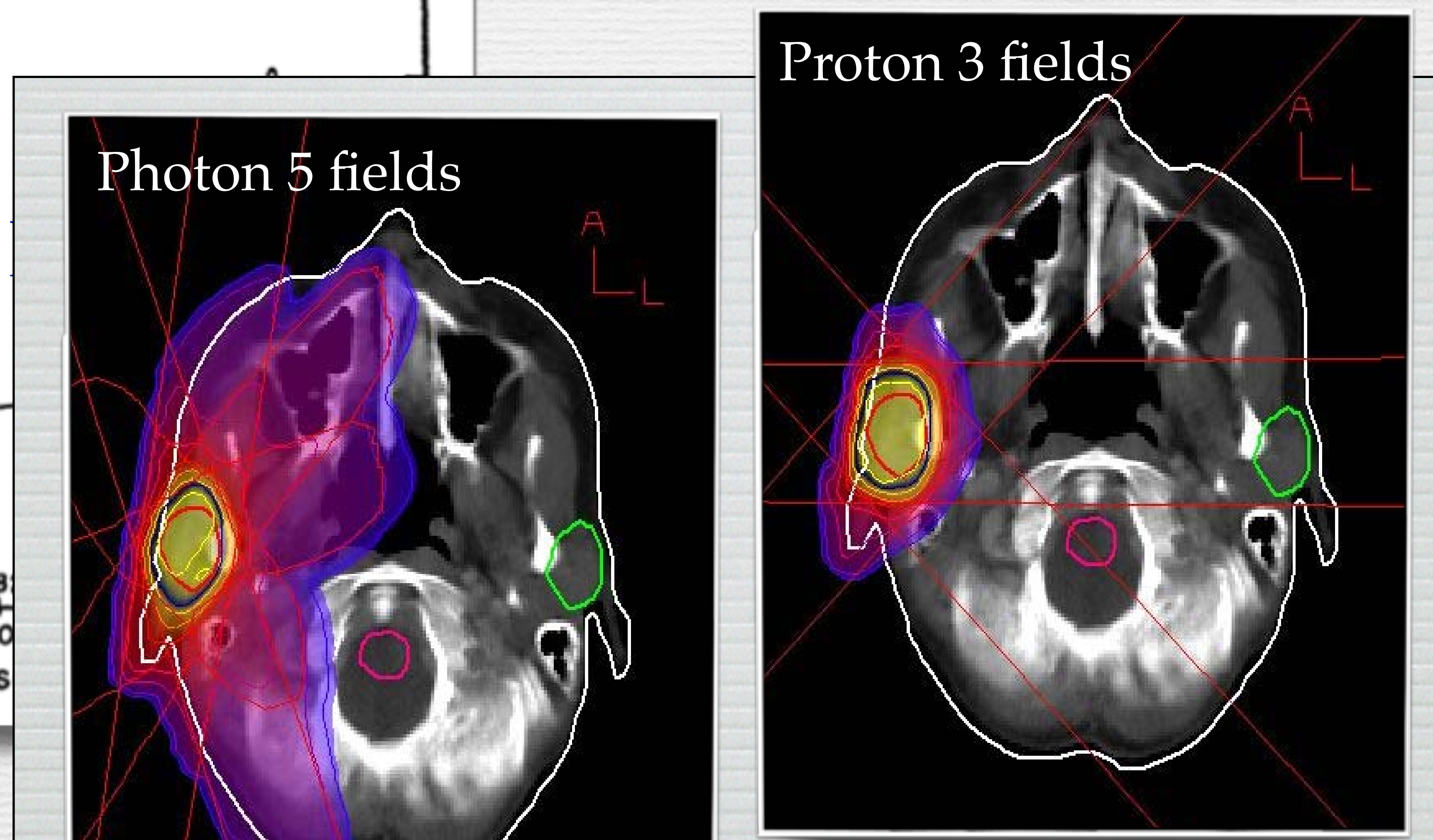


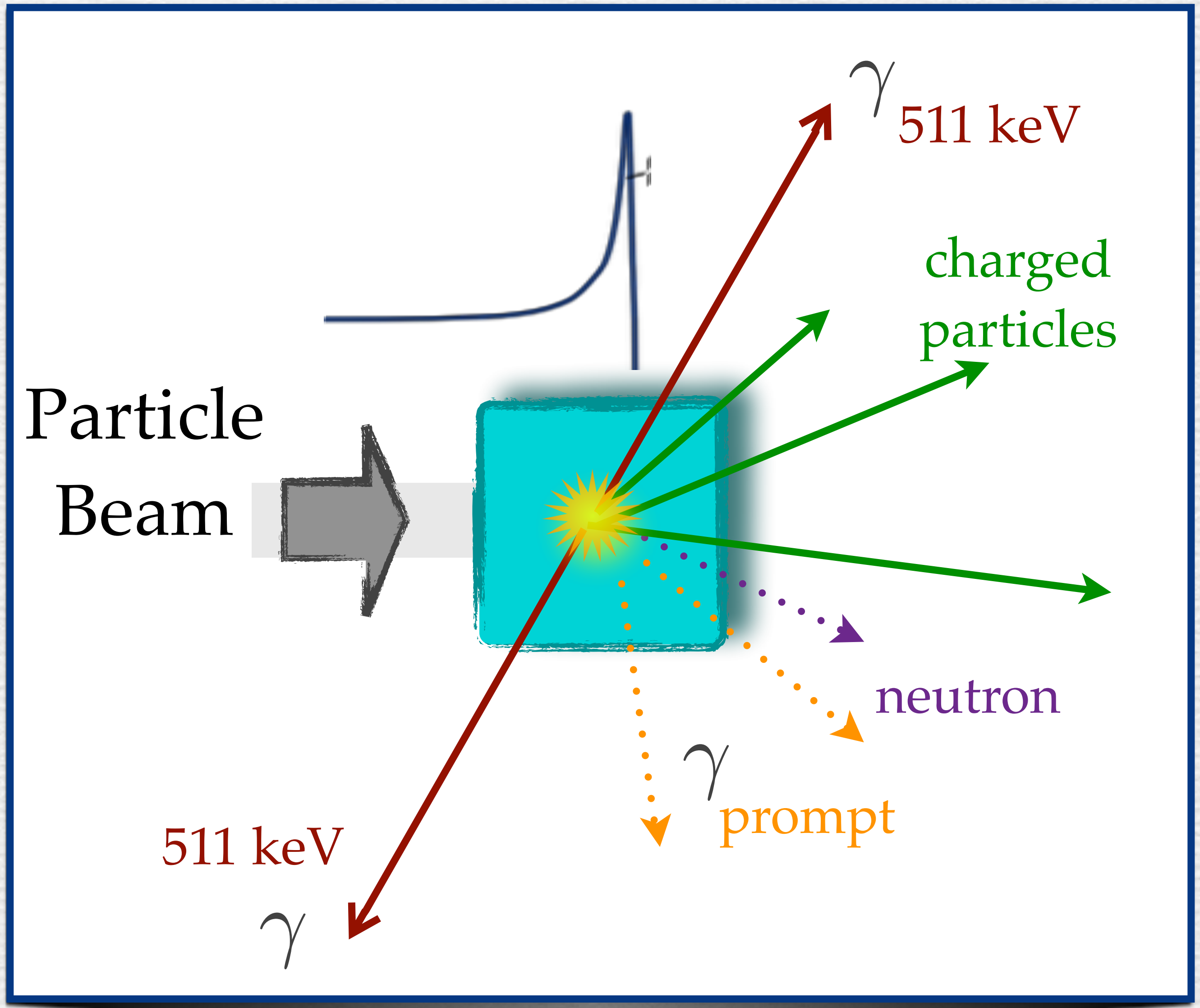

Universitätsklinik für
Strahlentherapie und
Strahlenbiologie, AKH, Wien

# Particle Therapy

**Particle Therapy (PT) is an extremely effective method for destroying tumors while preserving healthy tissues that exploits the properties of energy deposit within the matter of heavy charged particles, described by the Bragg Peak distribution.**

An high precision Bragg Peak position **monitoring** is mandatory for PT applications.

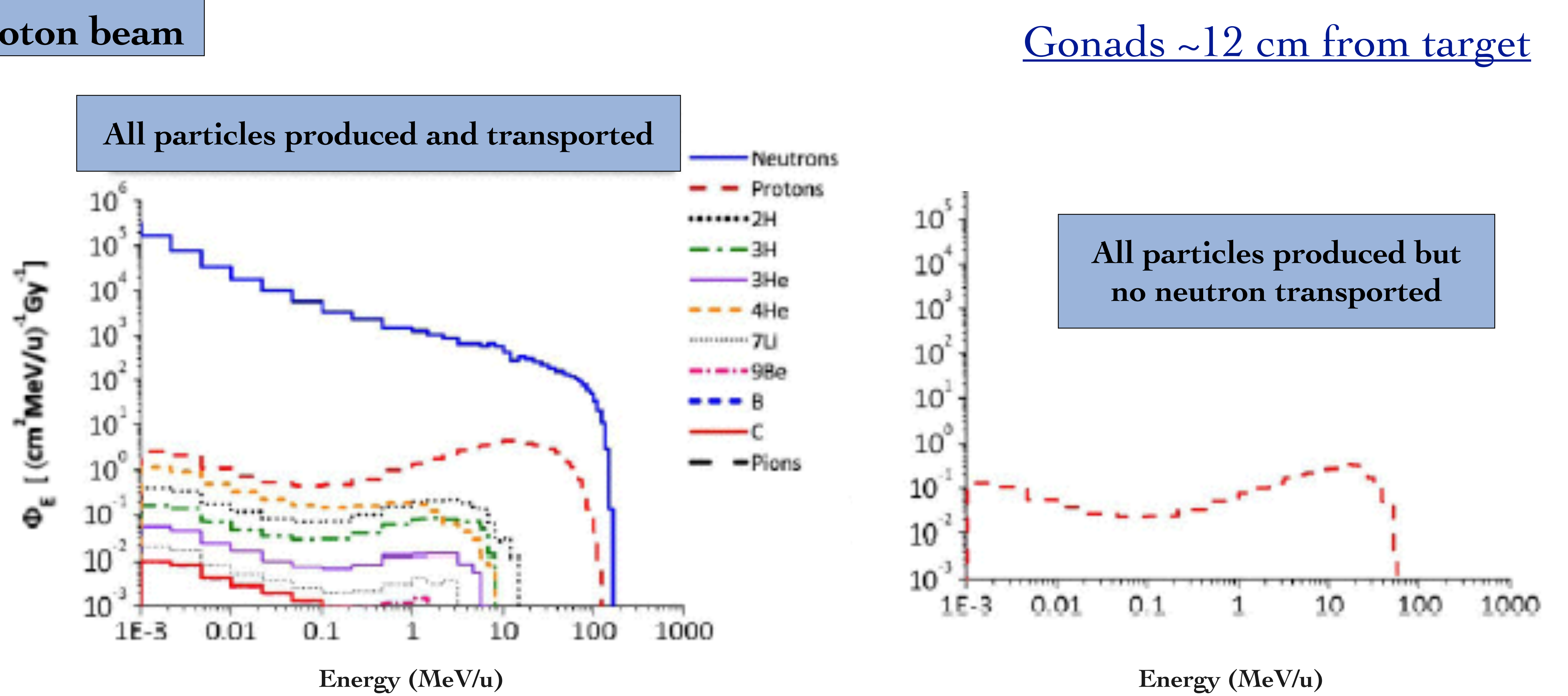
Since the primary beam is absorbed inside the patient, **range monitor technologies have to exploit the abundant flux of emitted secondary particles**: photons, charged nuclear fragments and neutrons



# Particle Therapy

While the MC simulation are predicting a large flux of neutrons, a precise experimental knowledge of such fluxes, together with their angular distribution, is currently still missing.

**172 MeV Proton beam**




Hultqvist and Gudowska, PMB 55,2010

# Neutrons

- Given its important biological effect it is mandatory to achieve precise knowledge of neutron flux produced during a treatment to minimize the patient secondary complications risk (e.g Secondary Malignant Neoplasm)

The SMNs can be developed in tissues that are located *in-field* (in the path of the therapeutic beam) and *out-of-field* (outside the path of the therapeutic beam).

The risk of developing a radiogenic second malignant neoplasm (SMN), years or decades after undergoing a PT treatment is one of the main concerns in PT administration and planning, in particular in pediatric treatments

**The children prospect of long-term survival has increased impressively as an effect of the major advances in cancer therapies**. Approximately 80% of children and adolescents that are now treated for cancer survive more than 5 years, but unfortunately nearly 73% of them develop anyway treatment-related complications.

**W.D.Newhauseret al., PMB 54 (2009) 2277–2291**

**M. Durante, Nature 11 2011**

# Neutrons

- Given its important biological effect it is mandatory to achieve precise knowledge of neutron flux produced during a treatment to minimize the patient secondary complications risk (e.g Secondary Malignant Neoplasm)
- for radio-protection calculations, like shielding=> e.g. shielding, staff safety,
- for induced radioactivity evaluations;

**Neutron measurements are elaborate due to the low neutron interaction probability in matter**

⇨ The development of a detector capable of measuring the secondary neutrons direction and energy is thus fundamental

MONDO

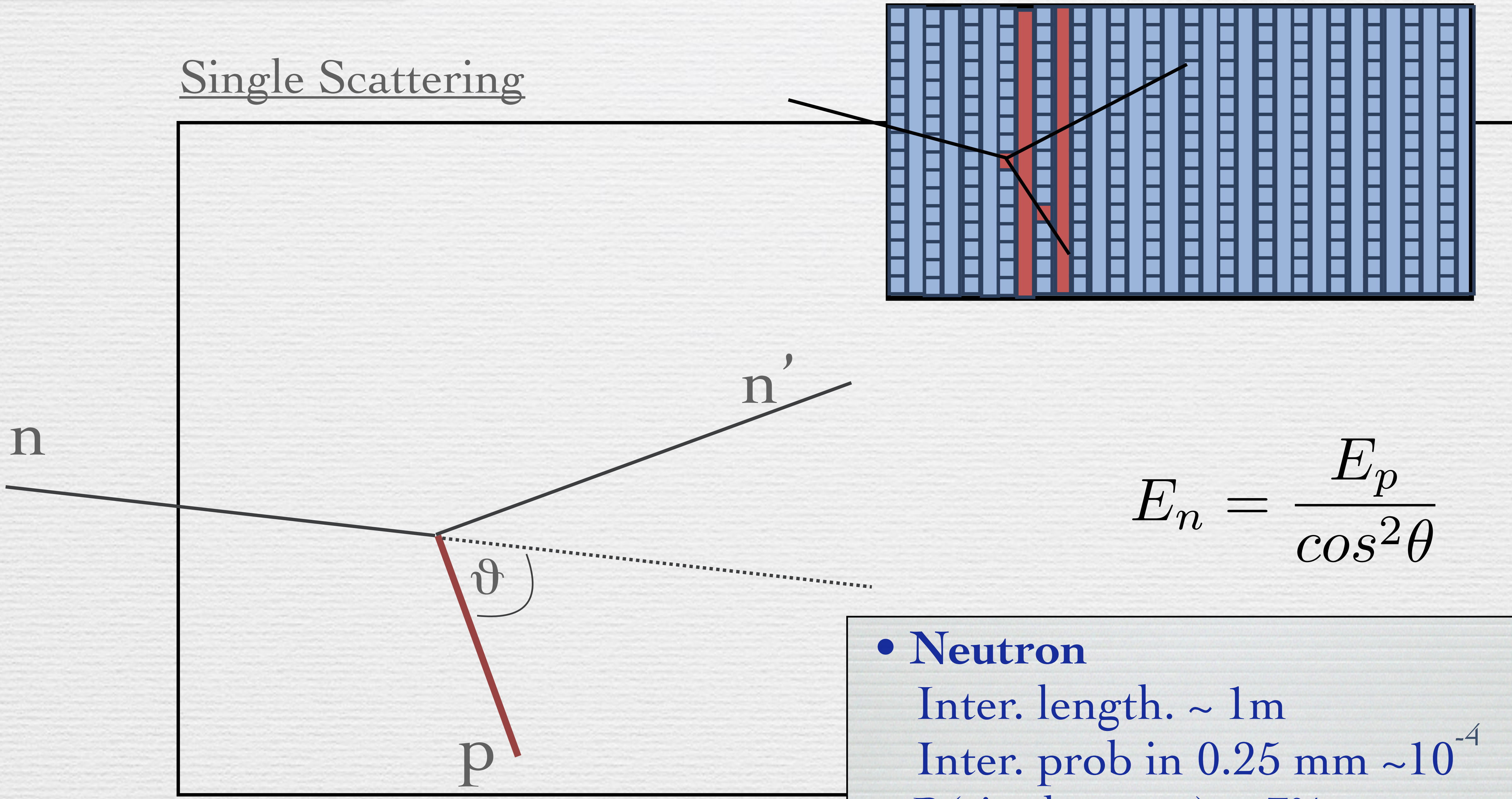
# MOnitor for Neutron Dose in hadrOntherapy

## NEUTRON TRACKER DETECTOR

By exploiting elastic scattering of emitted neutrons in the 20-200 MeV energy range we propose to measure their energy and emission point.

# MONDO

Single Scattering

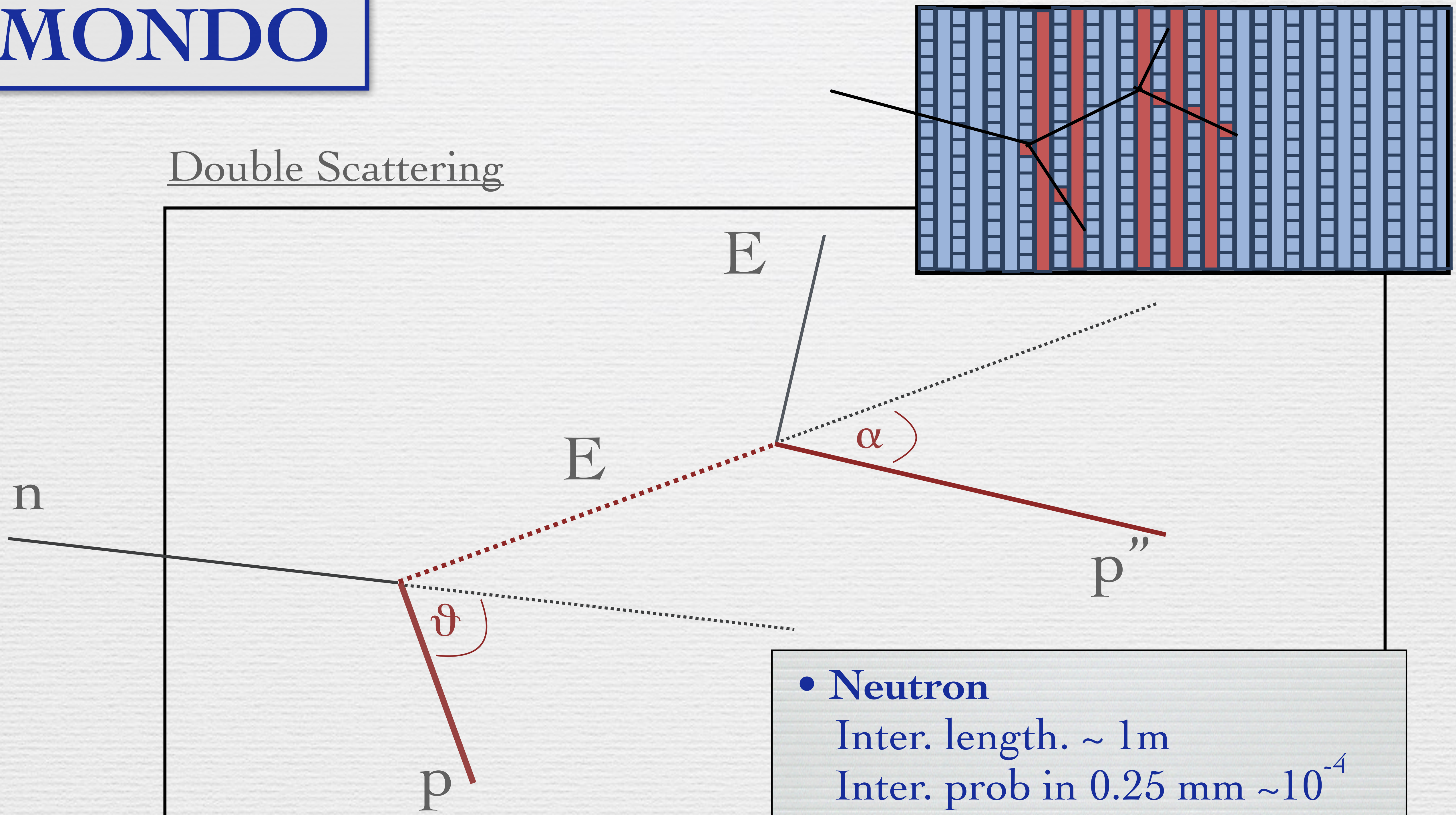



$$E_n = \frac{E_p}{cos^2\theta}$$

- **Neutron**
  Inter. length. ~ 1m
  Inter. prob in 0.25 mm ~$10^{-4}$
  P(single scatt.) ~ 7%
- **Proton mean path**
  T = 100 MeV=> 8 cm
  T = 50 MeV=> 2 cm
  T = 30 MeV=> 1 cm
  T = 10 MeV=> 0.1 cm

# MONDO

Double Scattering

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- **Proton mean path**
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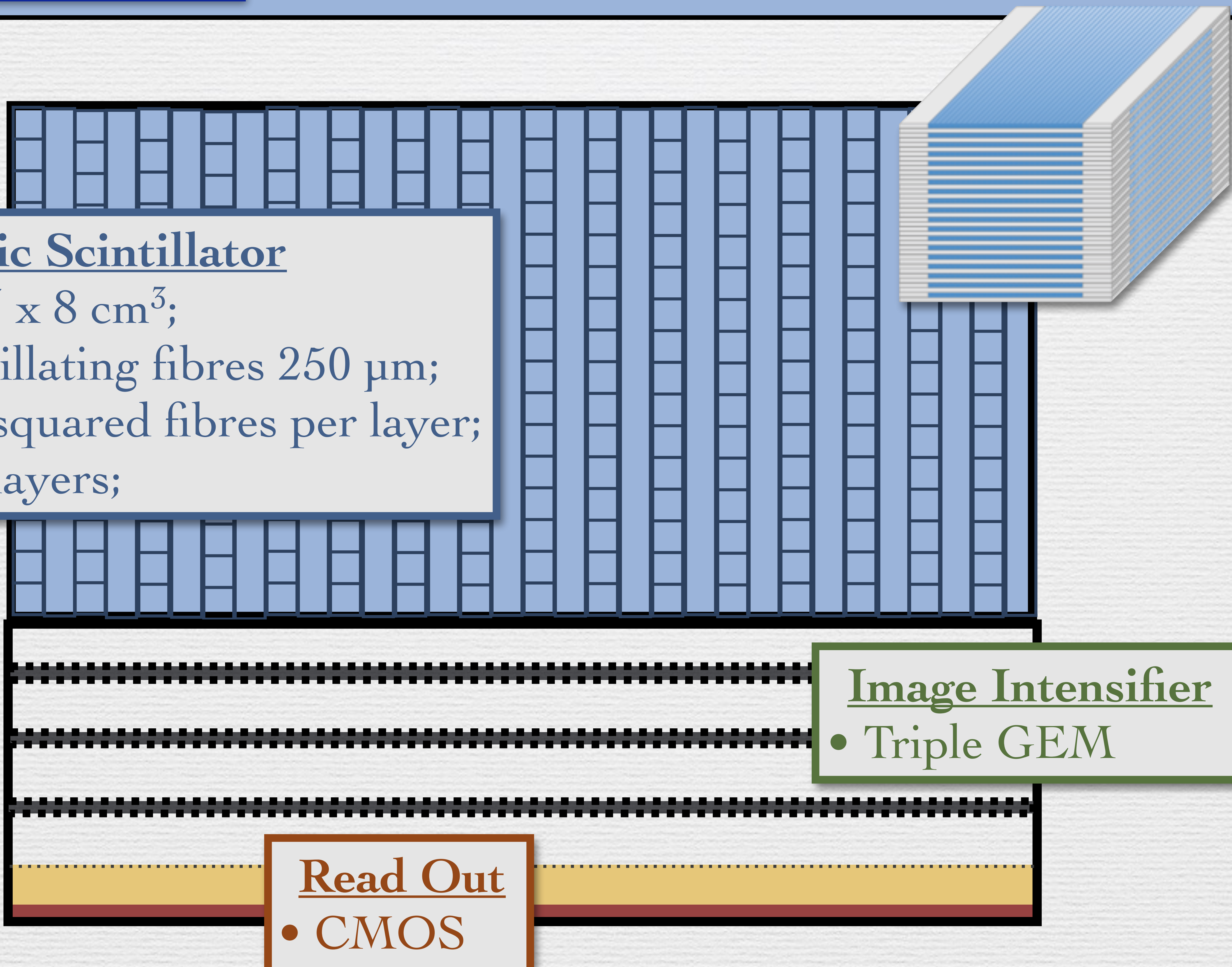
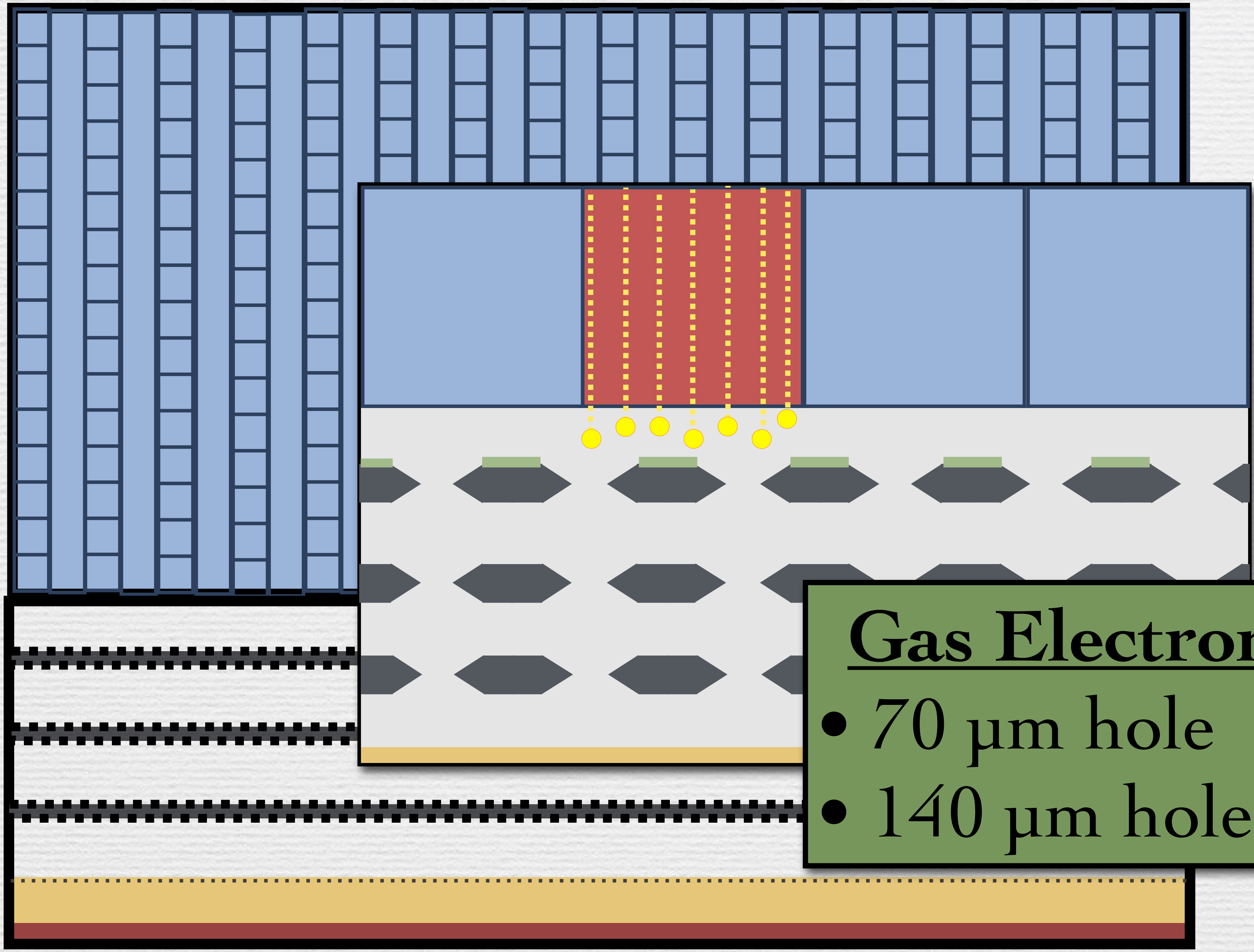
  T = 30 MeV=> 1 cm
  T = 10 MeV=> 0.1 cm

# Detector Design



# MONDO

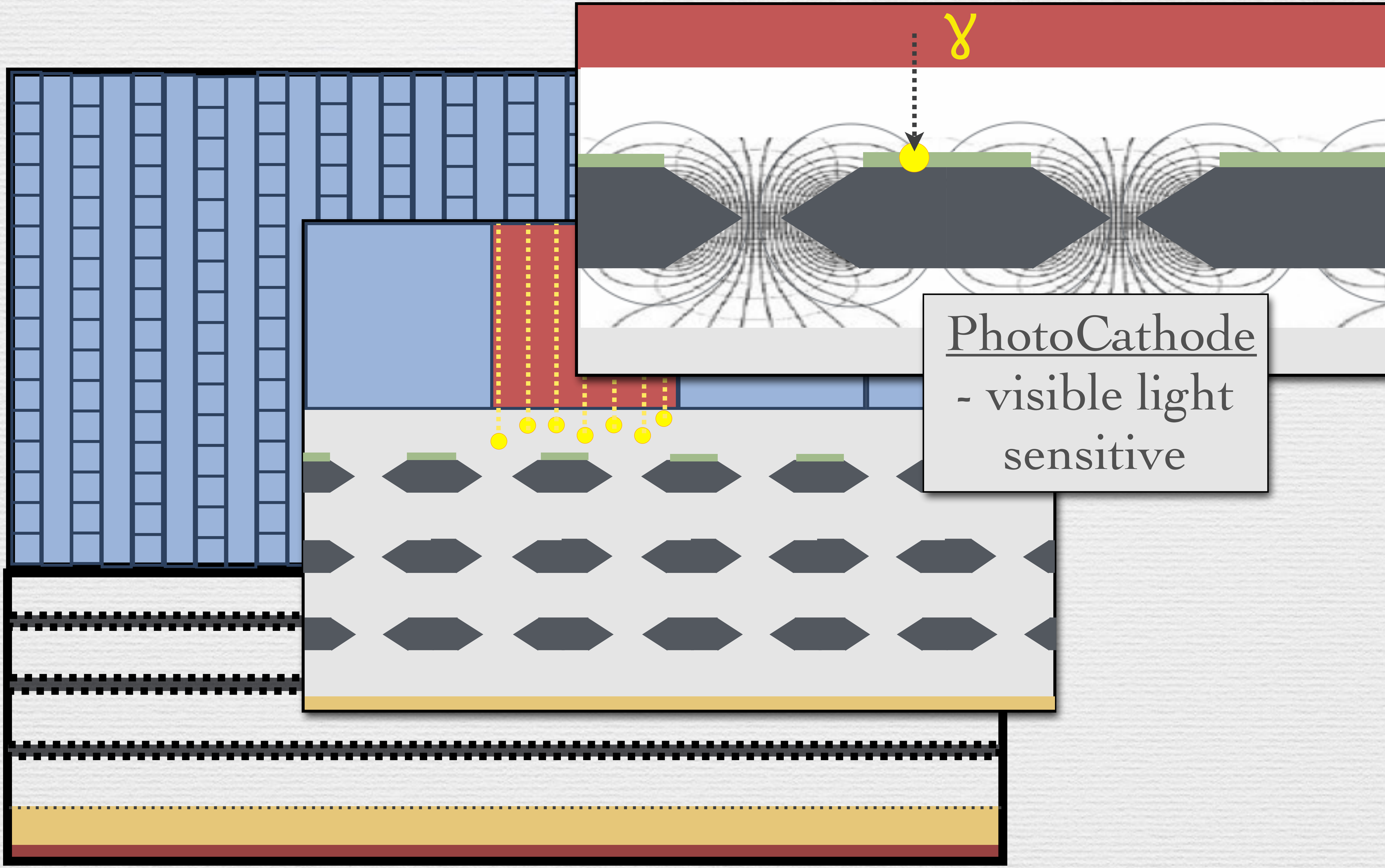
## Detector: GEM



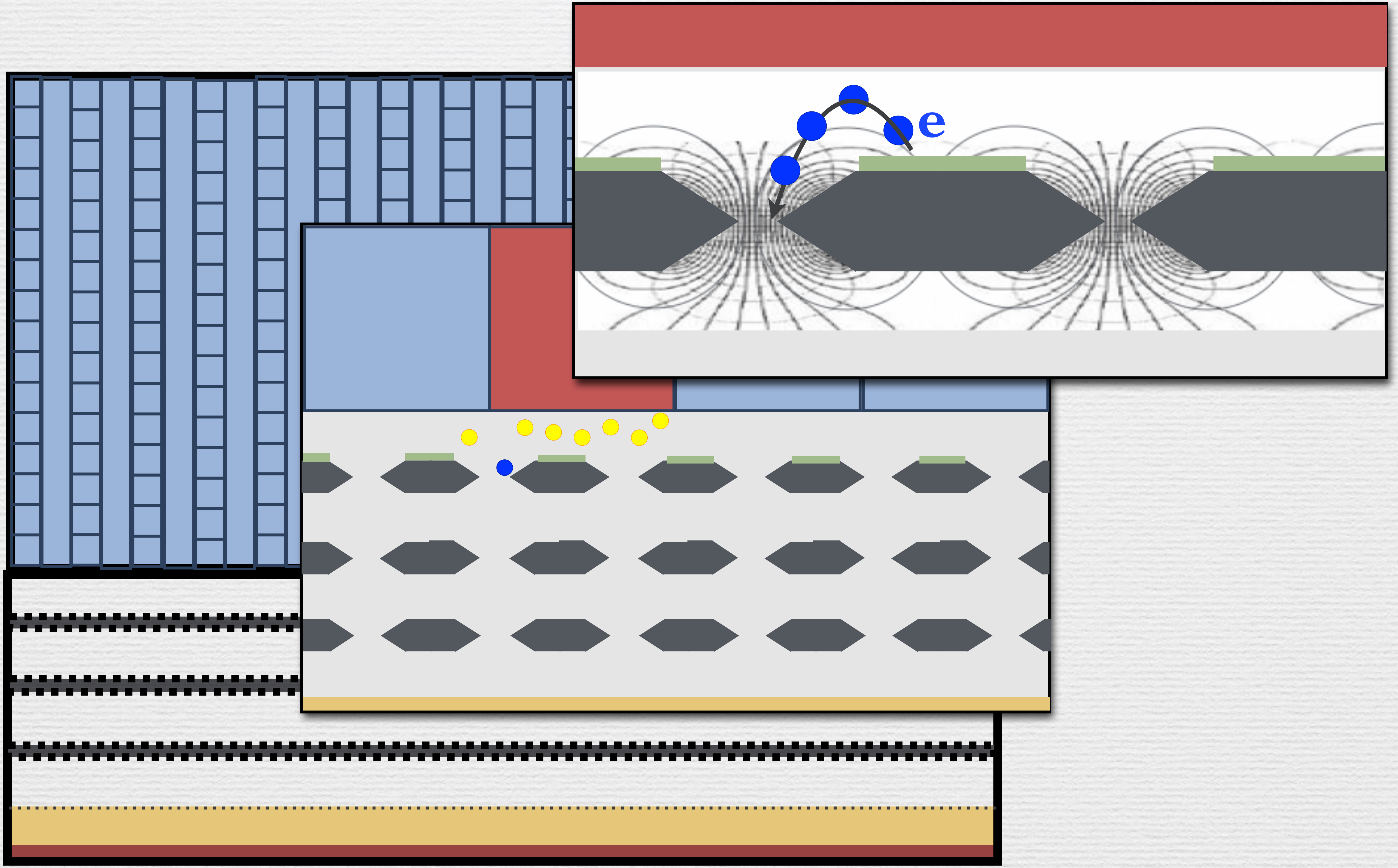
**Gas Electron Multiplier**

- 70 μm hole
- 140 μm hole pitch

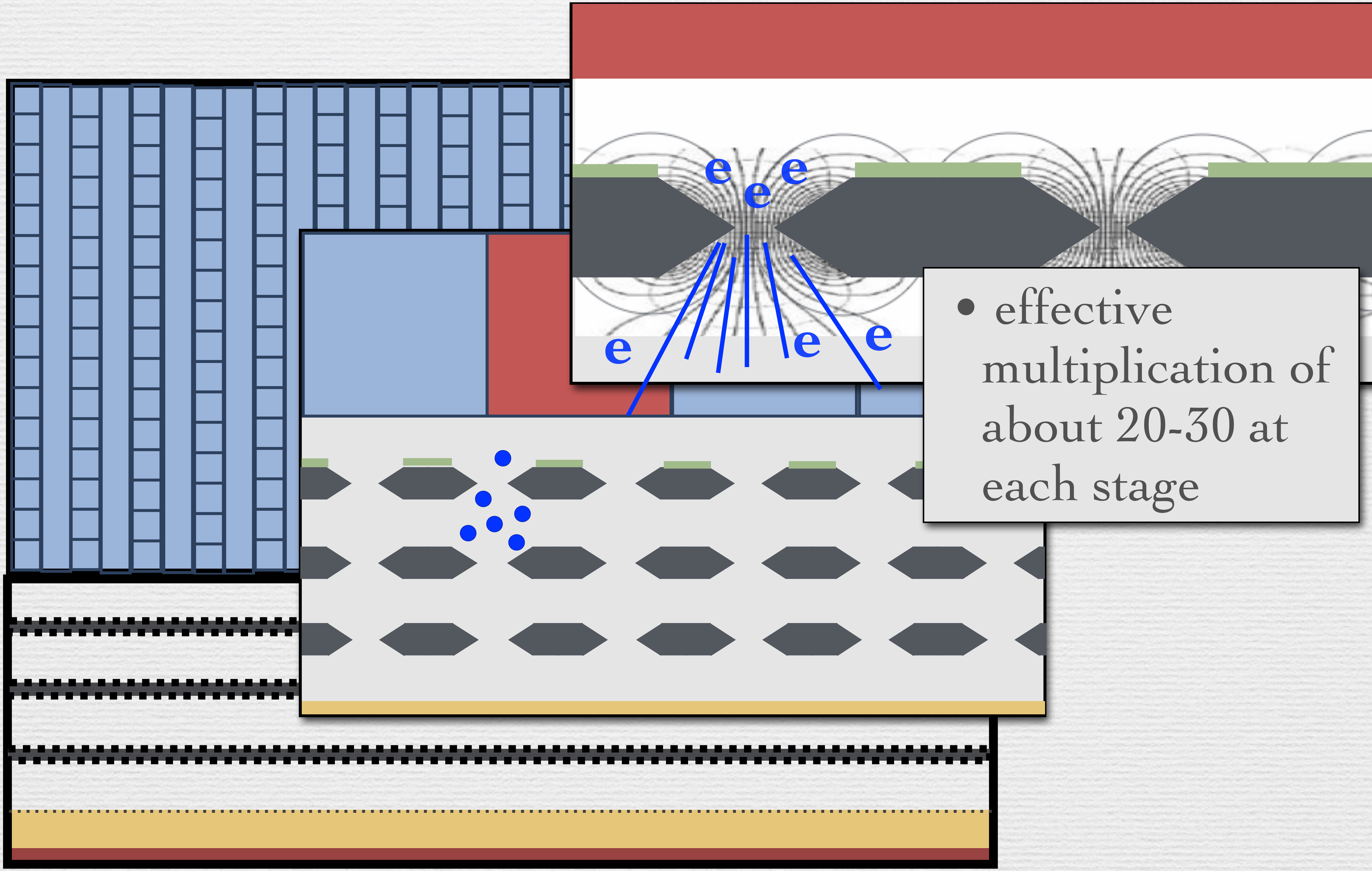
# Detector: GEM



# Detector: GEM

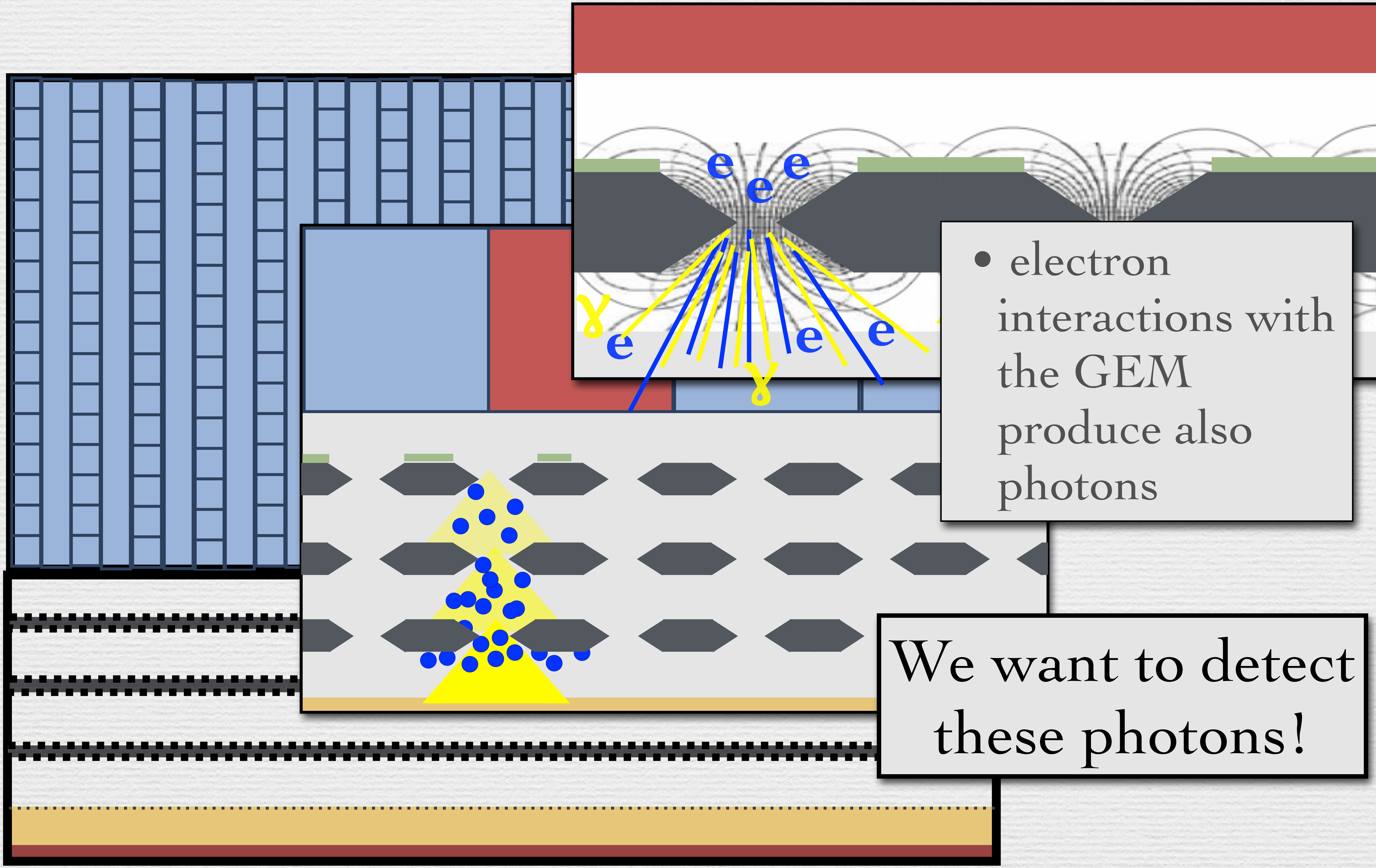


# Detector: GEM




- effective multiplication of about 20-30 at each stage

# Detector: GEM

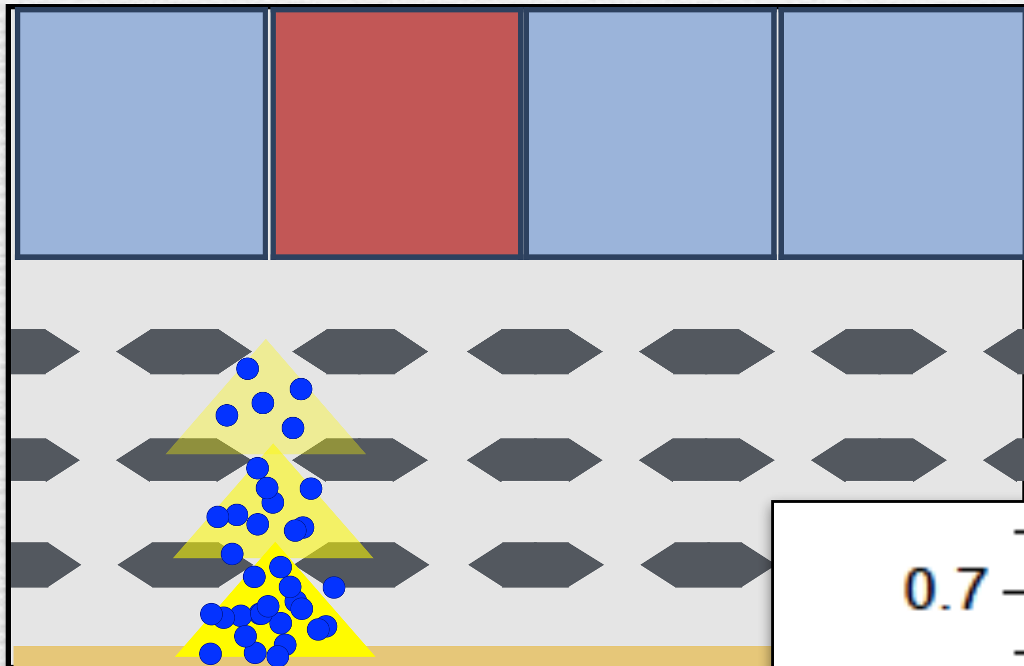



- electron interactions with the GEM produce also photons

We want to detect these photons!

# MONDO

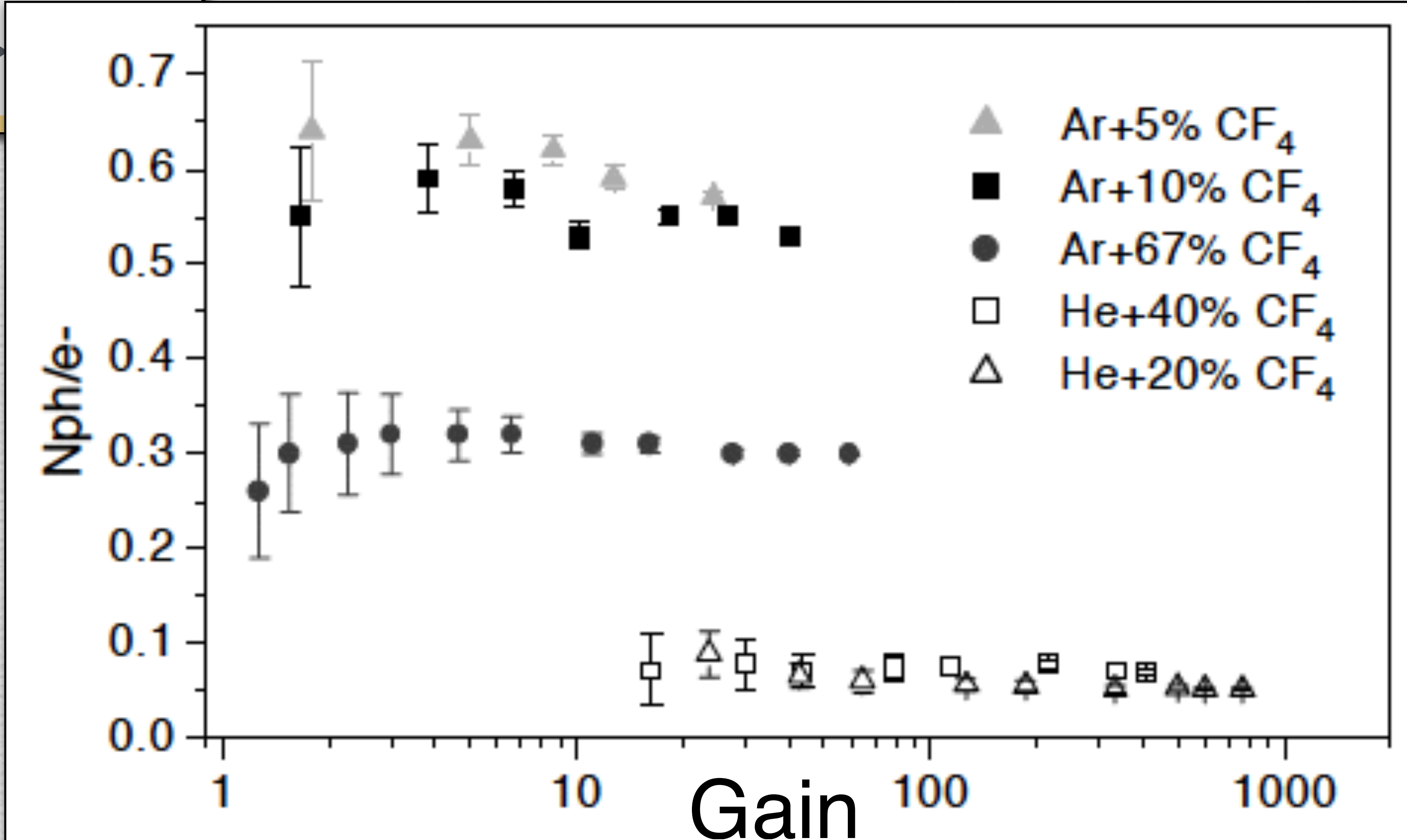
## Detector: GEM



With a triple GEM system a gain of $10^4$

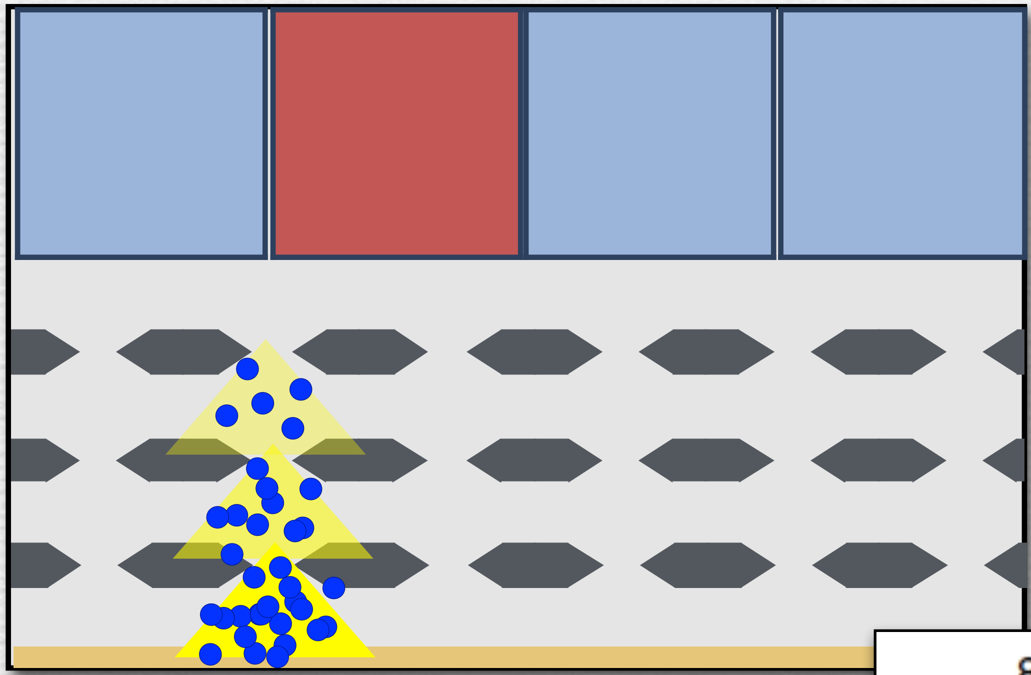
$N_\gamma / N_e$ depends on the gas mixture and on the hole size (best for 45 μm)

Fraga et al, NIM A 478 (2002) 357-361



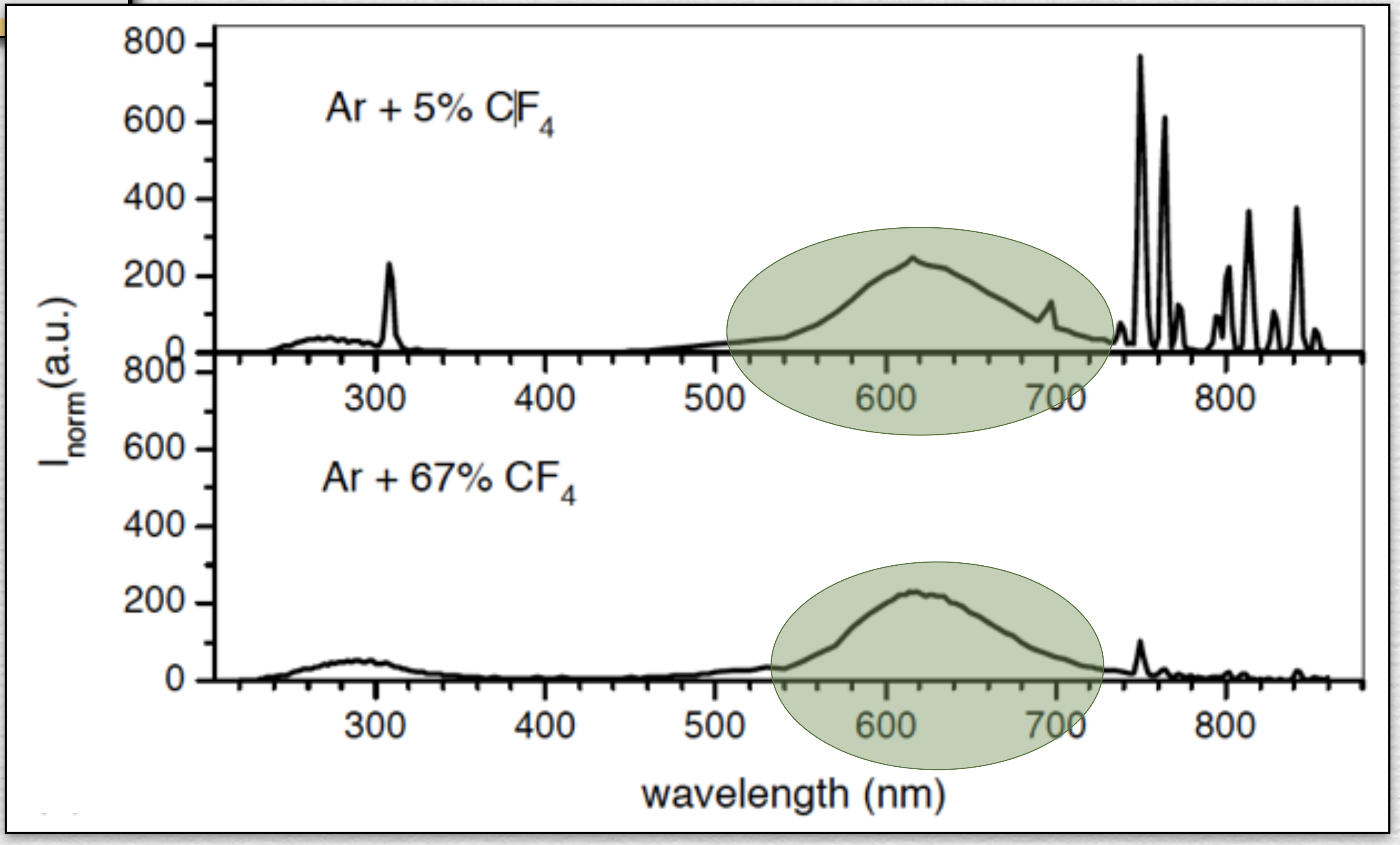

Fraga et al, NIM A 504 (2003) 88-92

# Detector: GEM



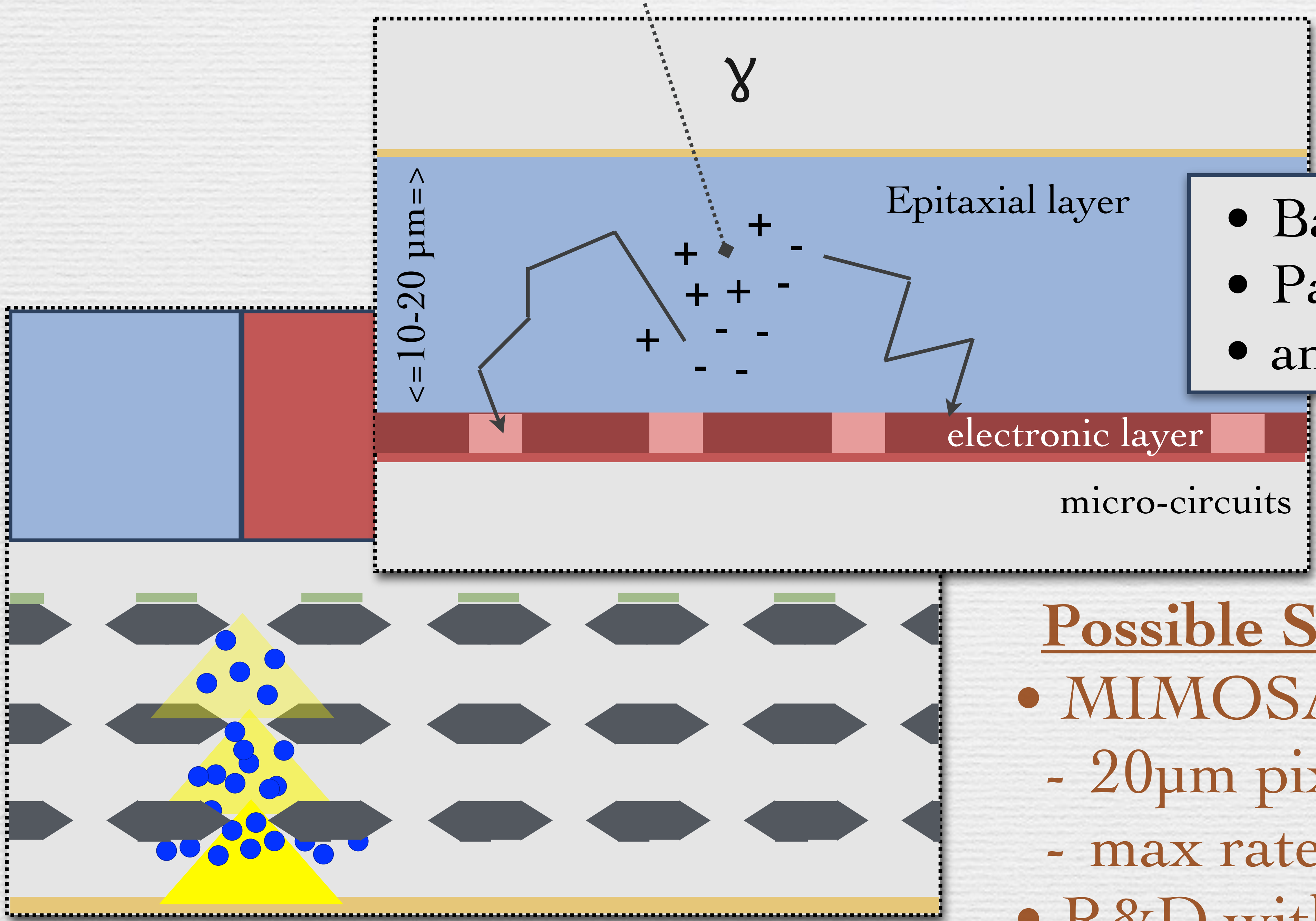
With a triple GEM system a gain of $10^4$

The emitted photons energy spectra depends on the gas mixture




Fraga et al, NIM A 504 (2003) 88-92

# Detector: CMOS

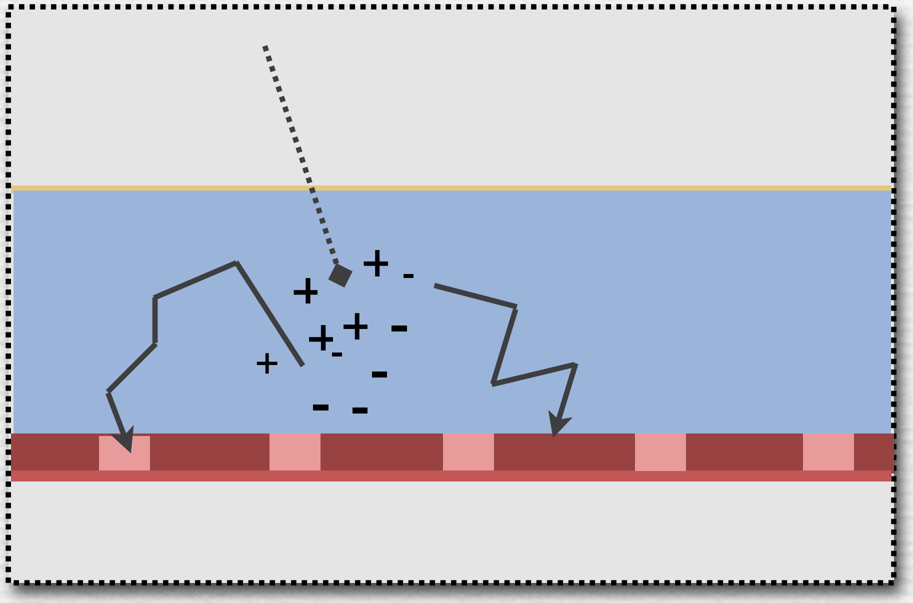


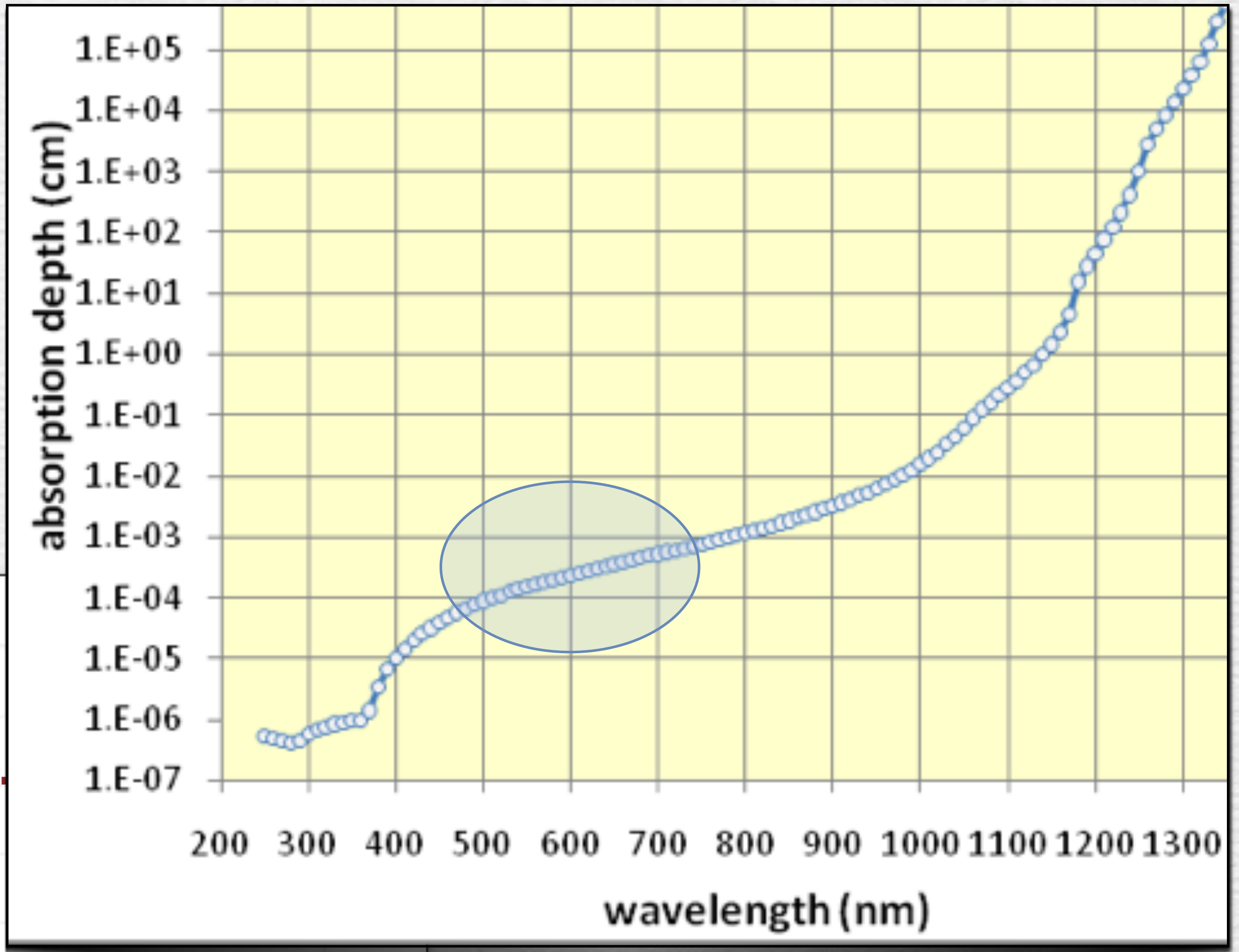

- Back-illuminated
- Passivated face ~1μm
- antireflective coating

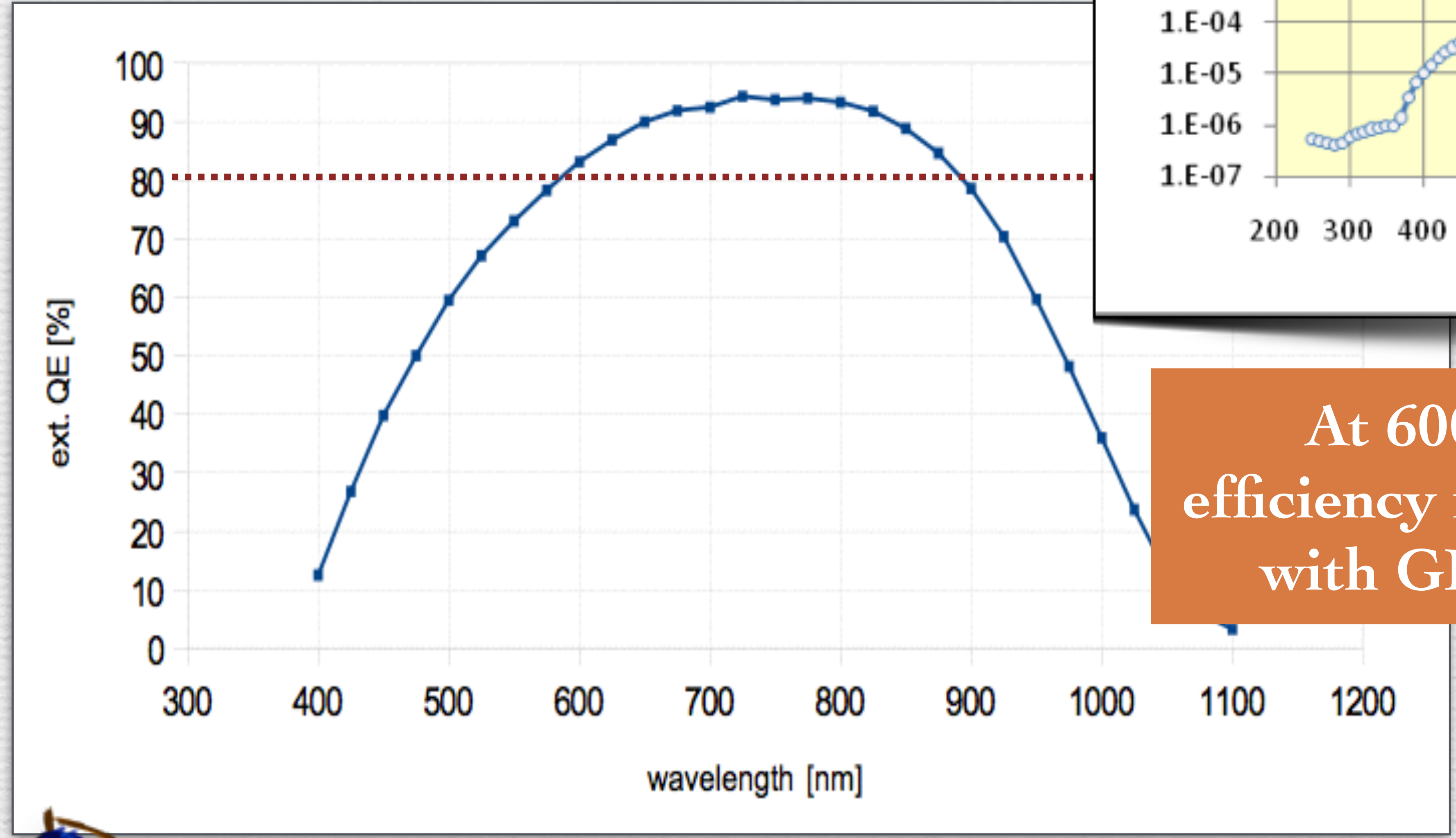
## Possible Sensors:

- MIMOSA28
  - 20μm pixel
  - max rate 10kHz
- R&D with Strasbourg
  - 50μm pixel
  - rate 100kHz
- FBK

# Detector: CMOS




At 600 nm the quantum efficiency is > 80%. Good match with GEM photoemission!

MONDO

# Expected Resolution

The expected performances on neutron energy and direction angle are based on what obtained by [SONTRACK]

$$\sigma_E/E \sim 5\%$$

$$\sigma_\theta \sim 4.6\ degrees$$

at 35 MeV, improving with energy

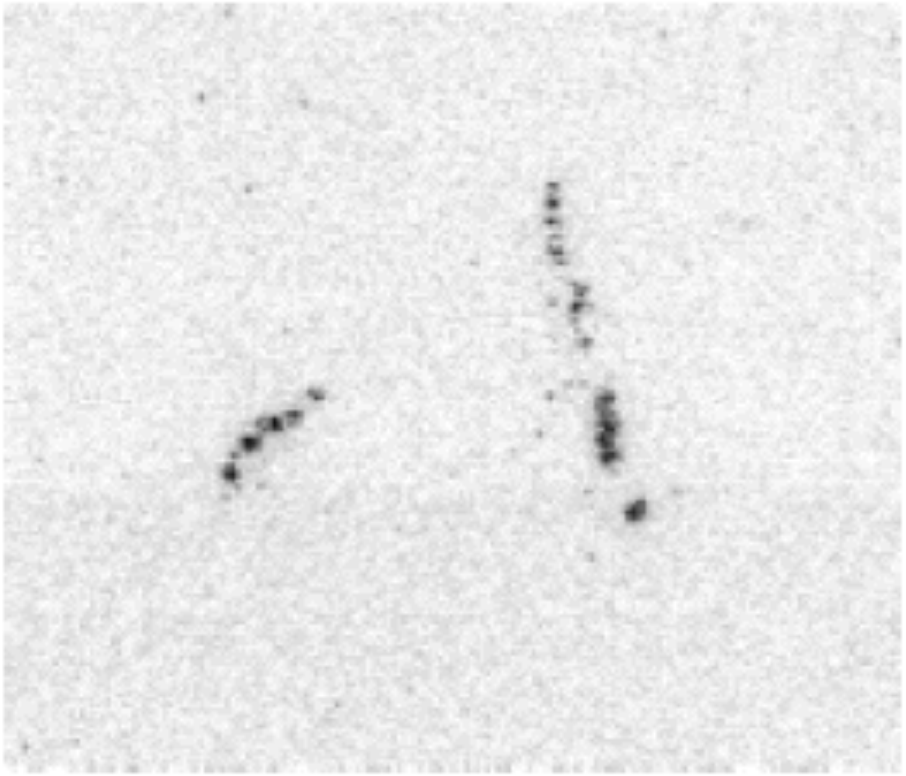
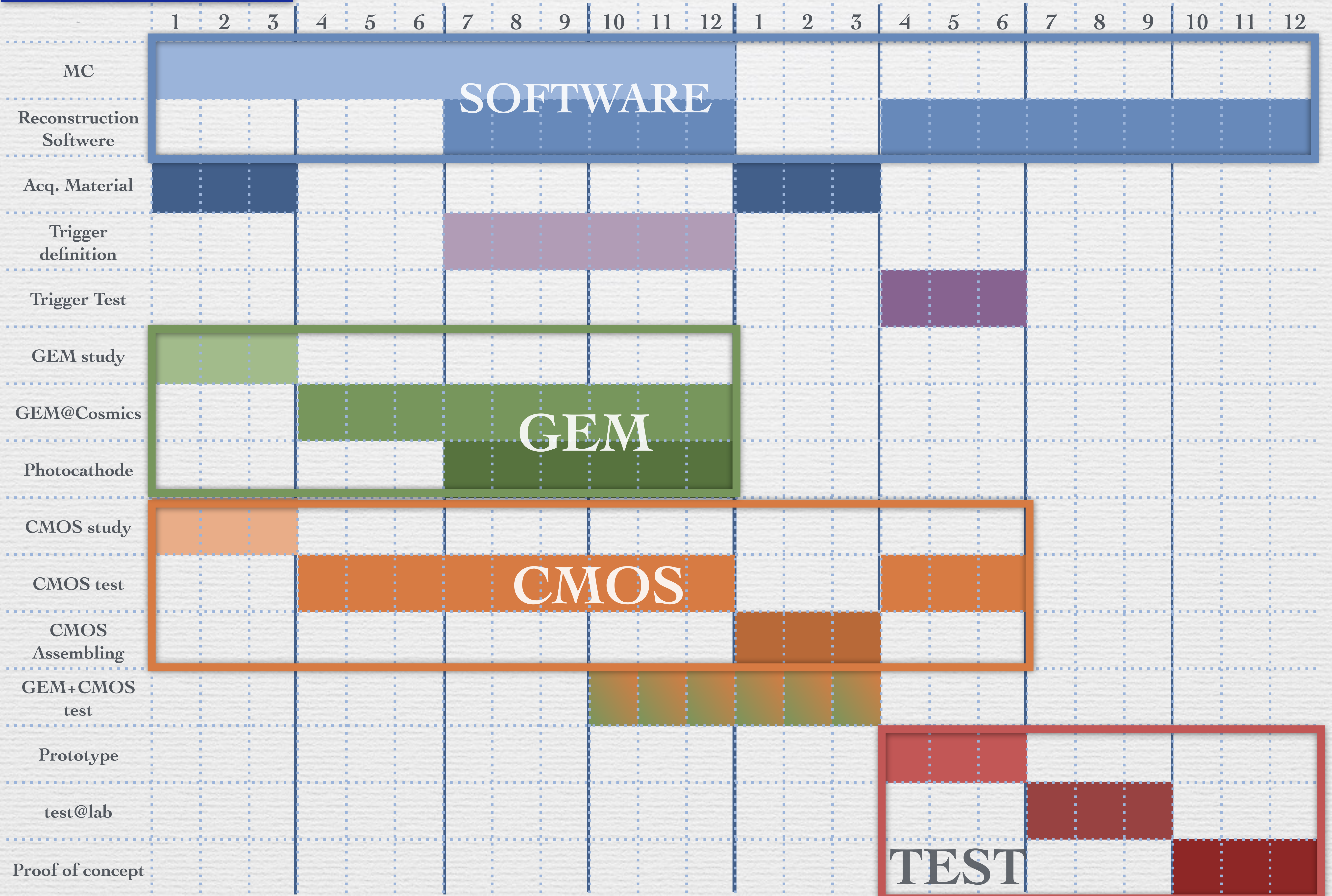


Figure 3. Raw CCD image of a double scatter from a ~65 MeV neutron incident from the top.

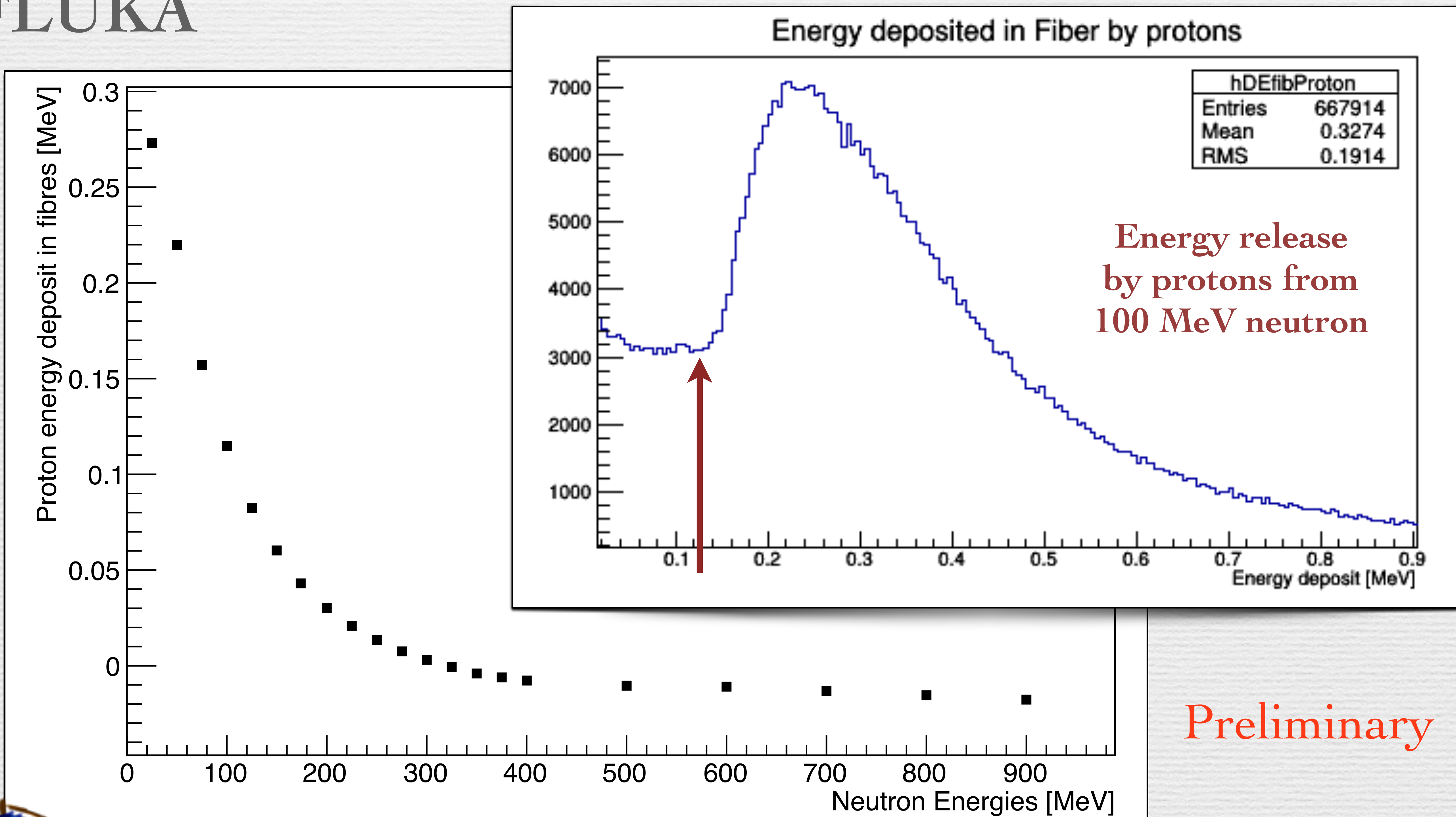
R.S. Miller et al, NIM A 505 (3003) 36-40

# Timetable



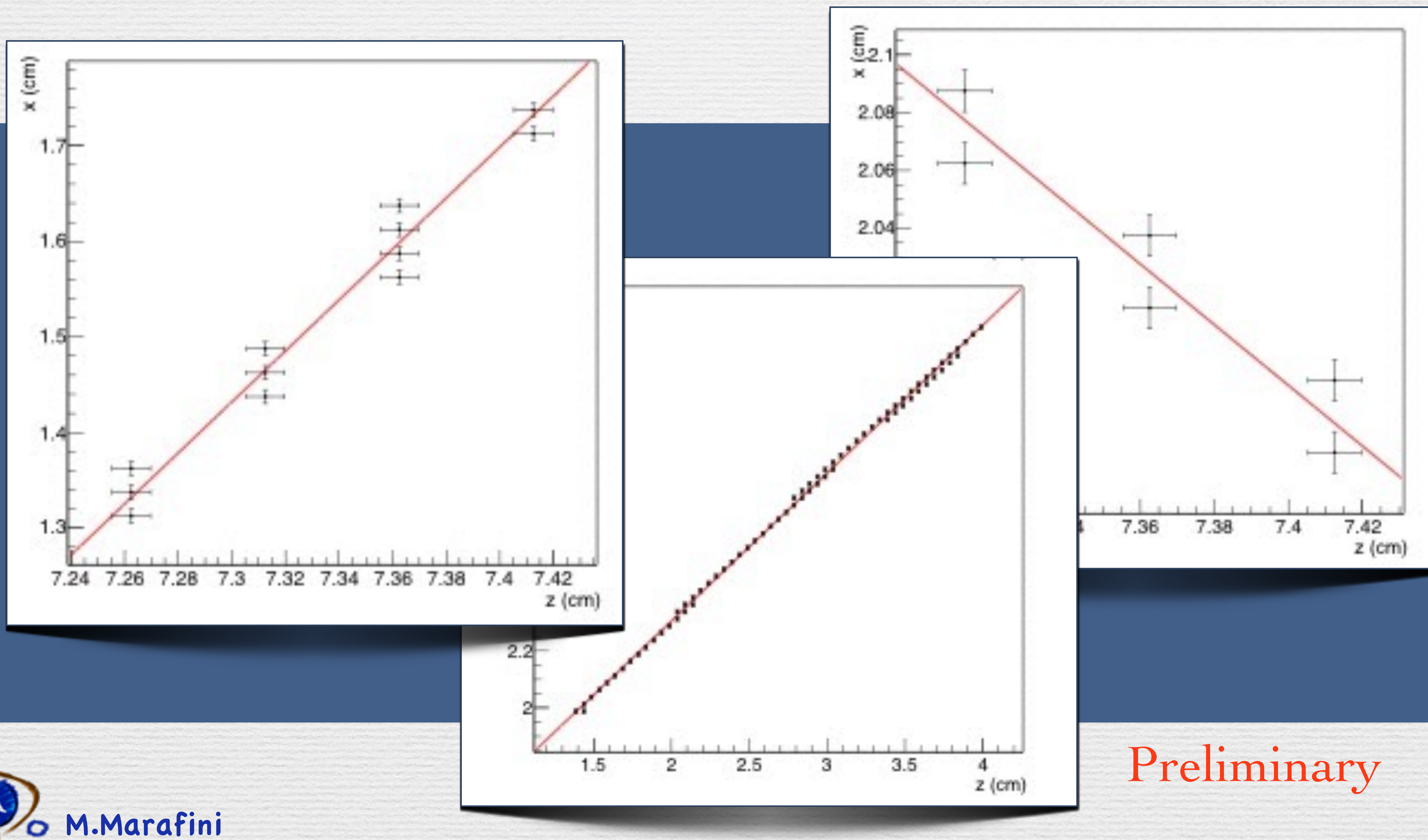
1 2 3 4 5 6 7 8 9 10 11 12 1 2 3 4 5 6 7 8 9 10 11 12
MC
Reconstruction Softwere
SOFTWARE
Acq. Material
Trigger definition
Trigger Test
GEM study
GEM@Cosmics
Photocathode
GEM
CMOS study
CMOS test
CMOS Assembling
CMOS
GEM+CMOS test
Prototype
test@lab
Proof of concept
TEST


# FLUKA




Preliminary

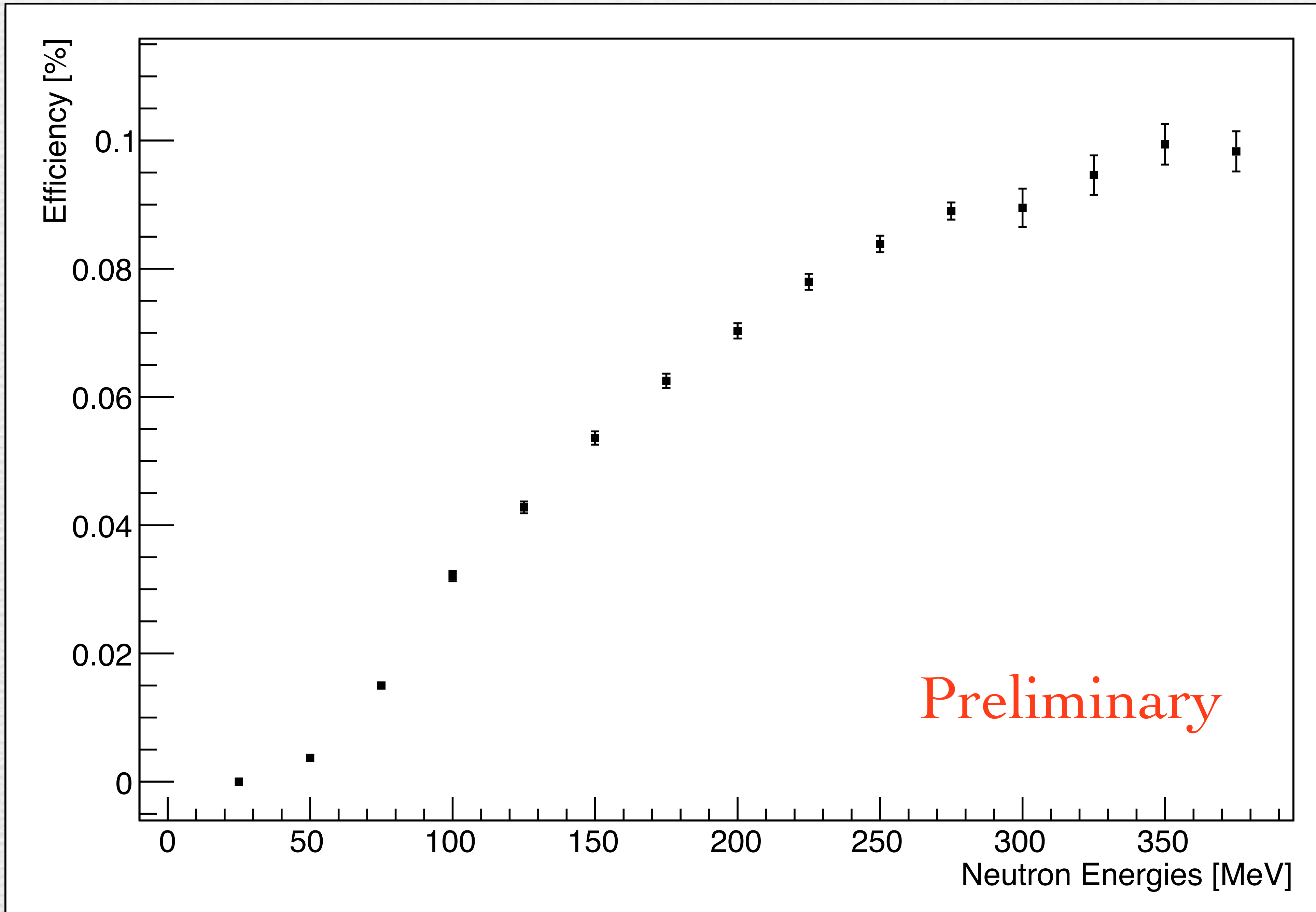

# FLUKA




Preliminary

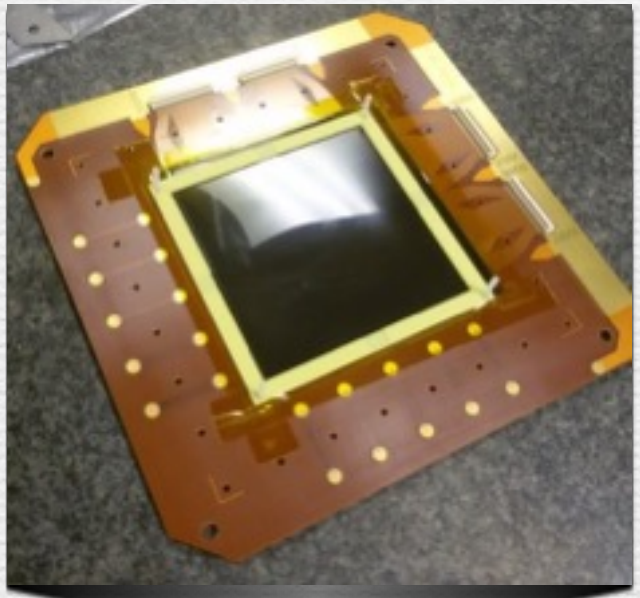

# FLUKA

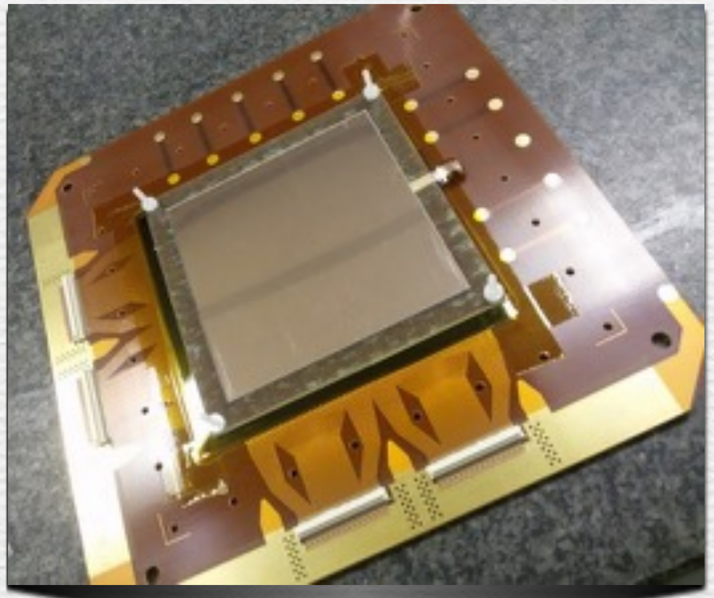
**The neutron energy can be computed by measuring the proton range ONLY if both protons are contained.**

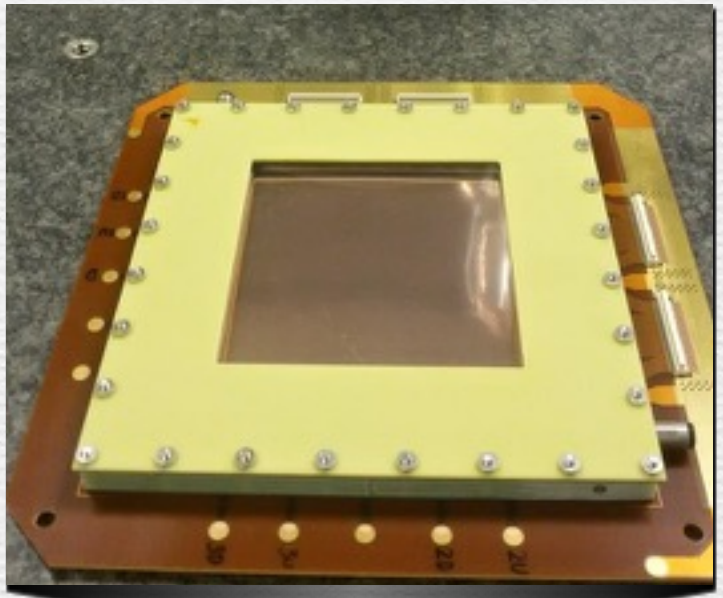



M.Marafini


We used the clean room (class 10000) of sezione INFN and we assembled the first Triple-GEM-detector



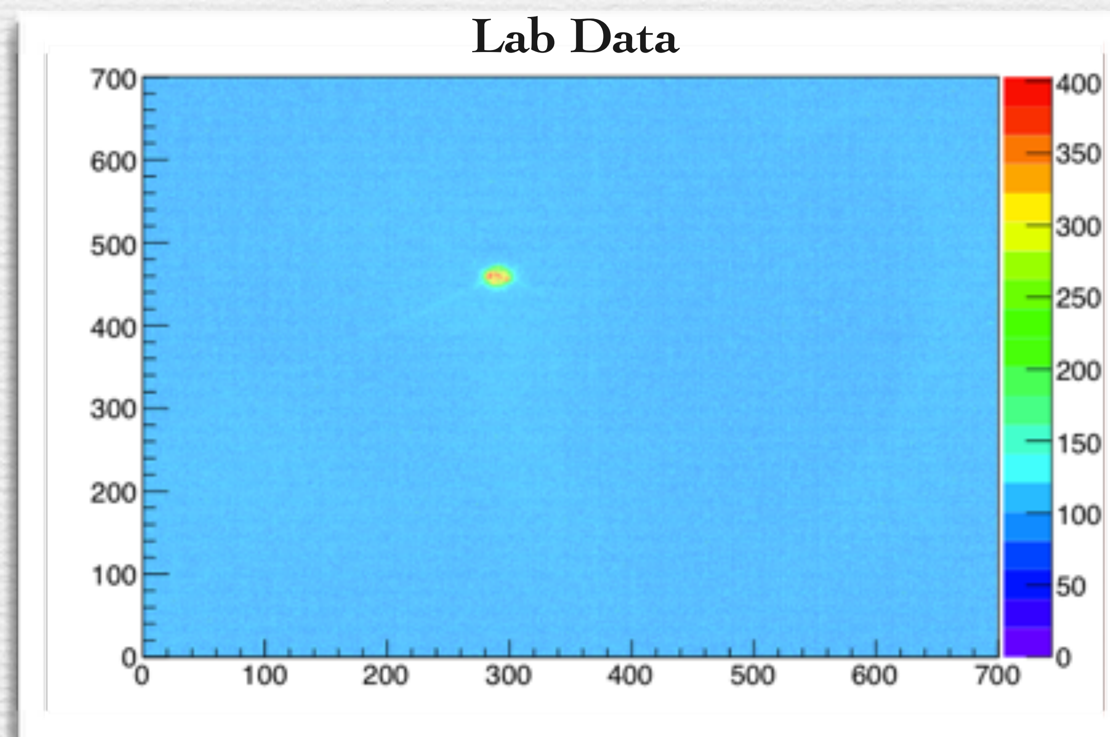




Replacing the readout plane with a transparent window we are going to detect photons

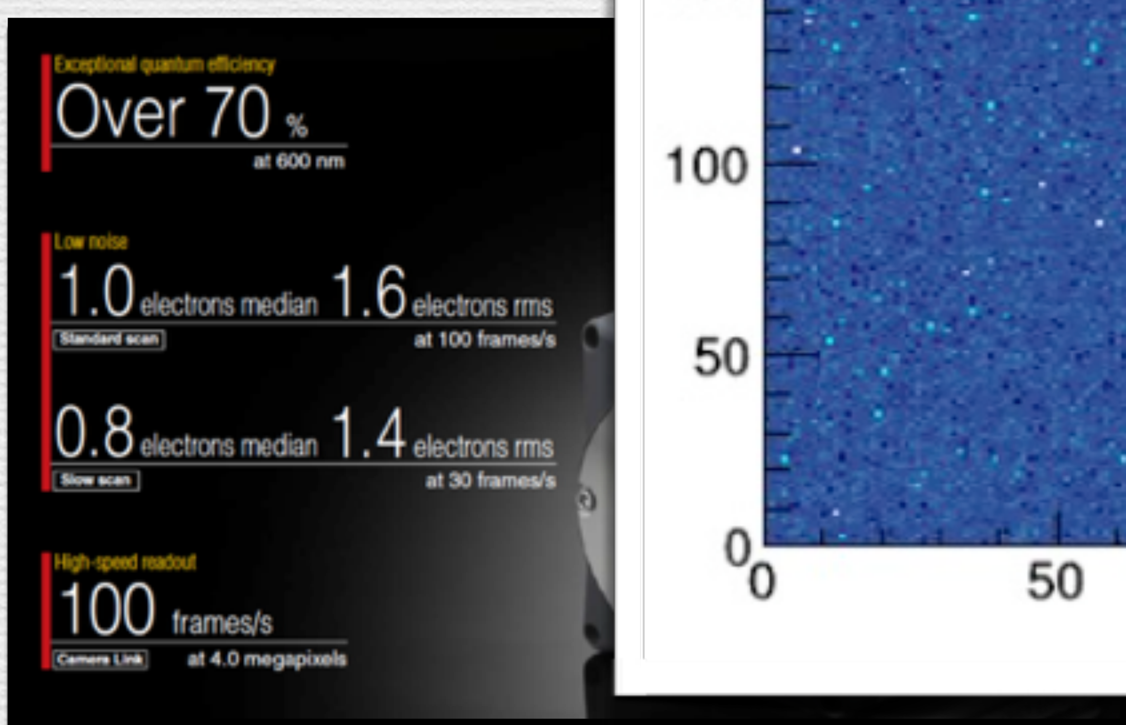
*Thanks to ATLAS and ALICE that were the main users

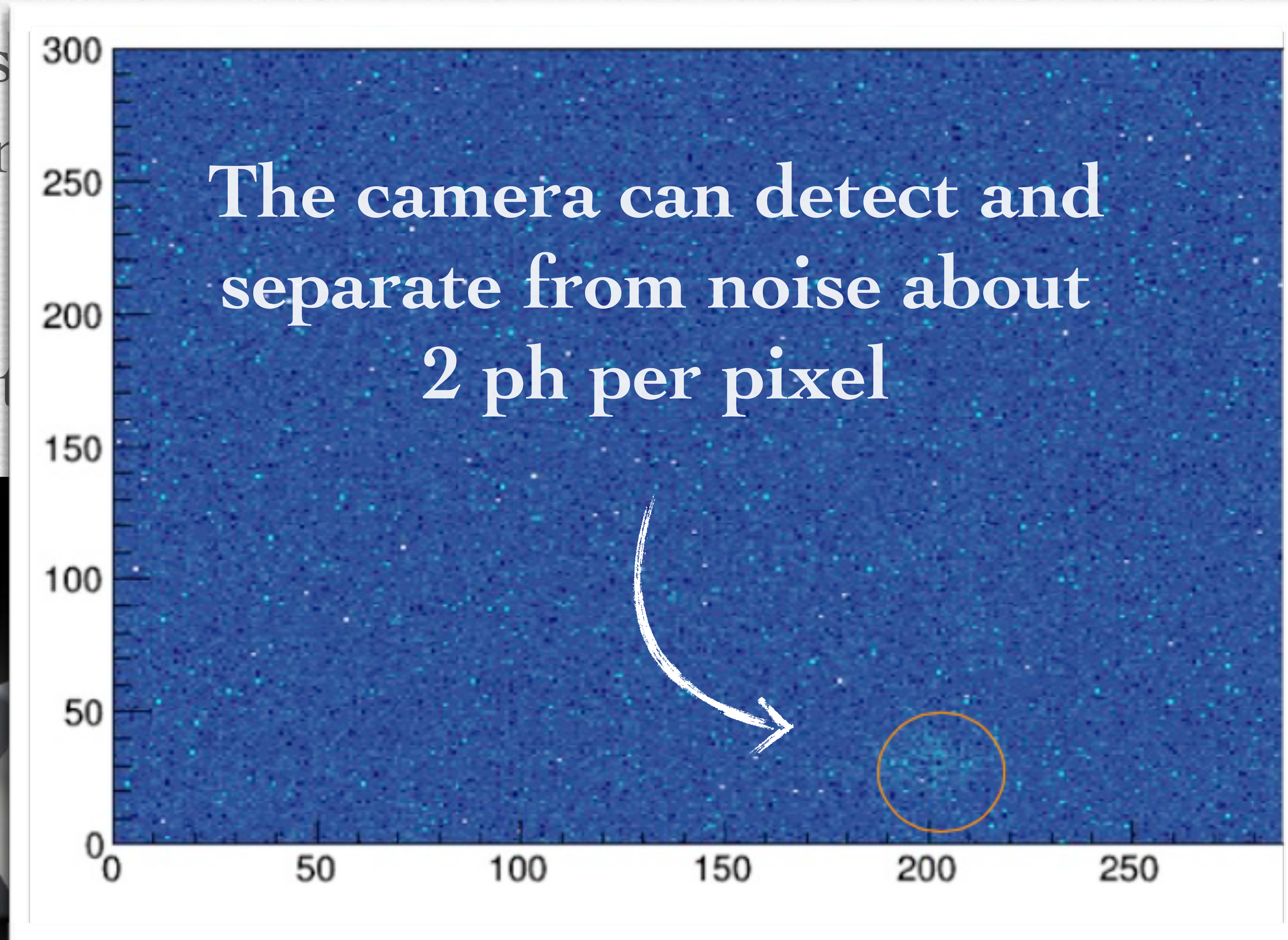

- We are investigating the different possible solution of CMOS sensors: Strasbourg Collaboration, FBK..
- In order to test the CMOS sensors capability we started the tests using a cmos-HAMAMATSU camera.


Led spot reconstruction


- We are inves... of CMOS sensor...
- In order to ... ve started the test... .

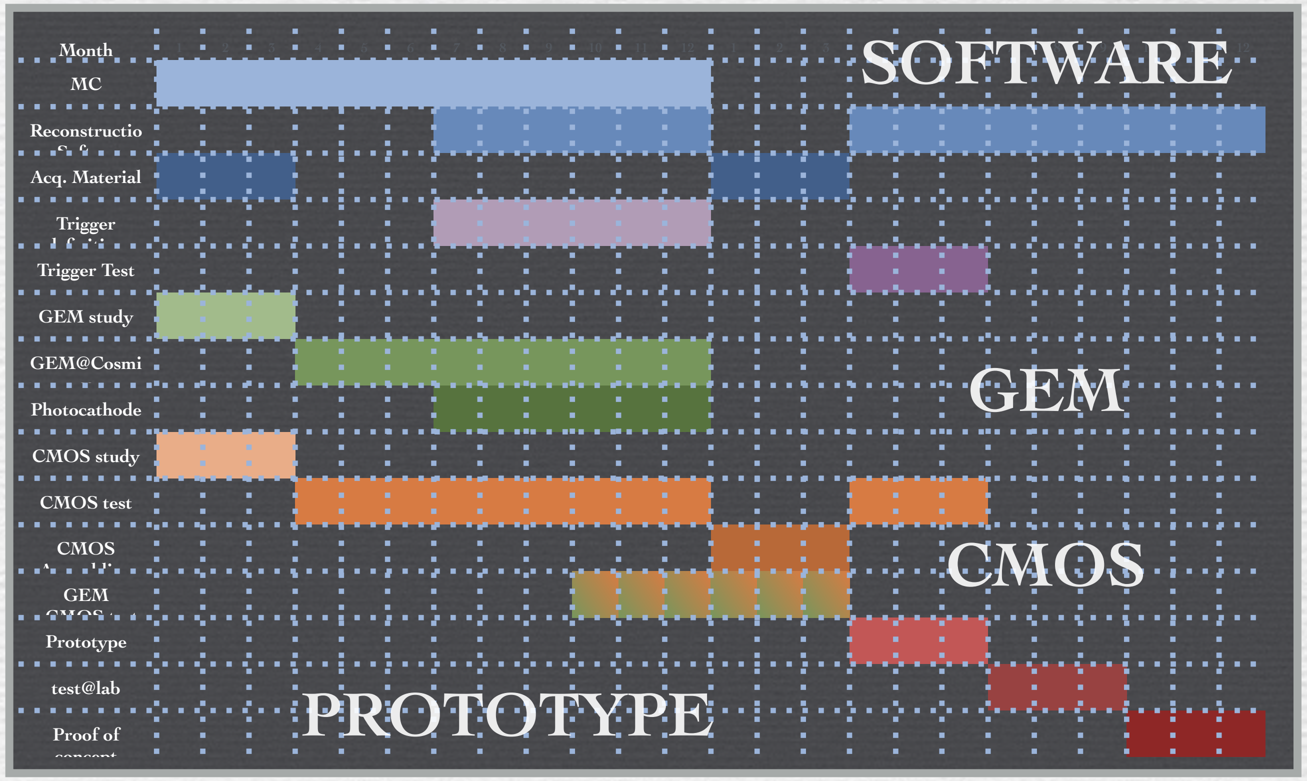



Led spot reconstruction

# Steps and Milestones

1) The detector MC simulation has been implemented. More accurate studies must be done in order to obtain a realistic efficiency calculation. The realization of the track reconstruction software in ongoing.




2) The study on the GEM for photon intensification is started. The test on the first GEM will start this next week. The RD51 group (CERN) express his interest in collaborating to this development in particular for the photocathode.

3) The CMOS sensor study is on going. We are investigating several option and a possible collaboration with FBK is envisaged for short and long term solutions of sensors.

# CONCLUSIONS

- Neutrons are emitted during the patient irradiation and are responsible for the uncorrelated dose released "far" from the affected volume.

- **The MONDO project is dedicated to the development of a neutron tracking device tailored for flux and energy spectra measurements.**

- MONDO is the answer to the compelling need of more detailed information on neutron production in PT. MonteCarlo simulations, therapy centers and physicist community in general would profit of such measurements.

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**- The MONDO proof of principle will seed the neutron tracking based range monitoring technique.**

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- The MONDO detector can measure **charged secondary particles**, tracking easily the p,d,t profiting form the knowledge acquired with the INSIDE project.
- The detector can also work as Compton Camera for tracking **prompt photons**.

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- MONDO is the answer to the compelling need of more detailed information on neutron production in PT. MonteCarlo simulations, therapy centers and physicist community in general would profit of such measurements.

The **GEM (Optic)-CMOS system** is the first attempt combining there two technologies in a single device The system will be largely exploitable in many fields of applied and fundamental physics.

# THANKS TO INFN GRUPPO V
# Grant Giovani Ricercatori

Up to now
small
D.Pinci, E.Spiriti ,V.Patera,
A.Sarti, A.Sciubba
(S.Ruggieri master thesis)

New manpower, technical and scientific support (and students!!) are very welcome

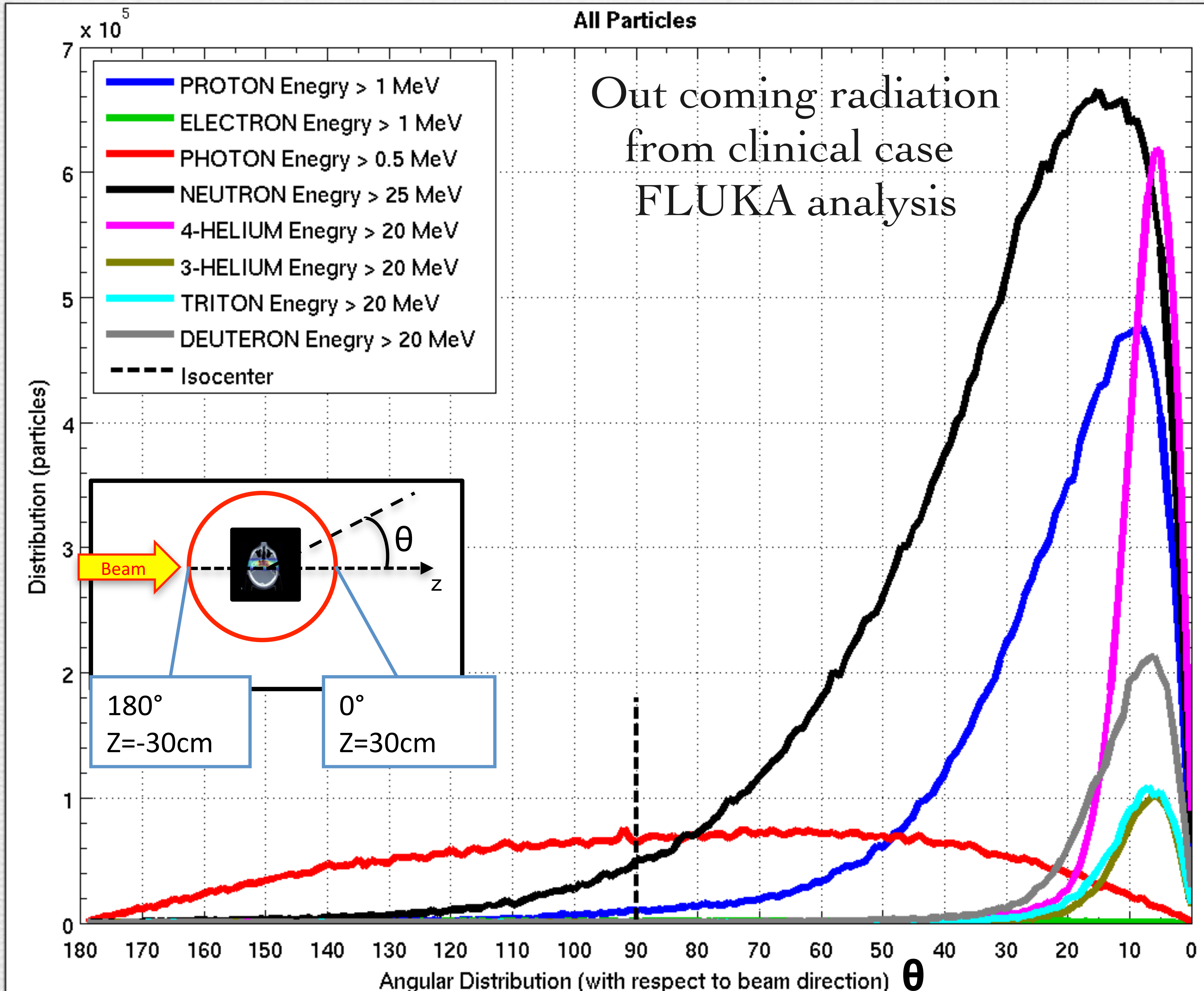
michela.marafini@roma1.infn.it

# Backup

# SIMULATION

Courtesy of F.Cappucci

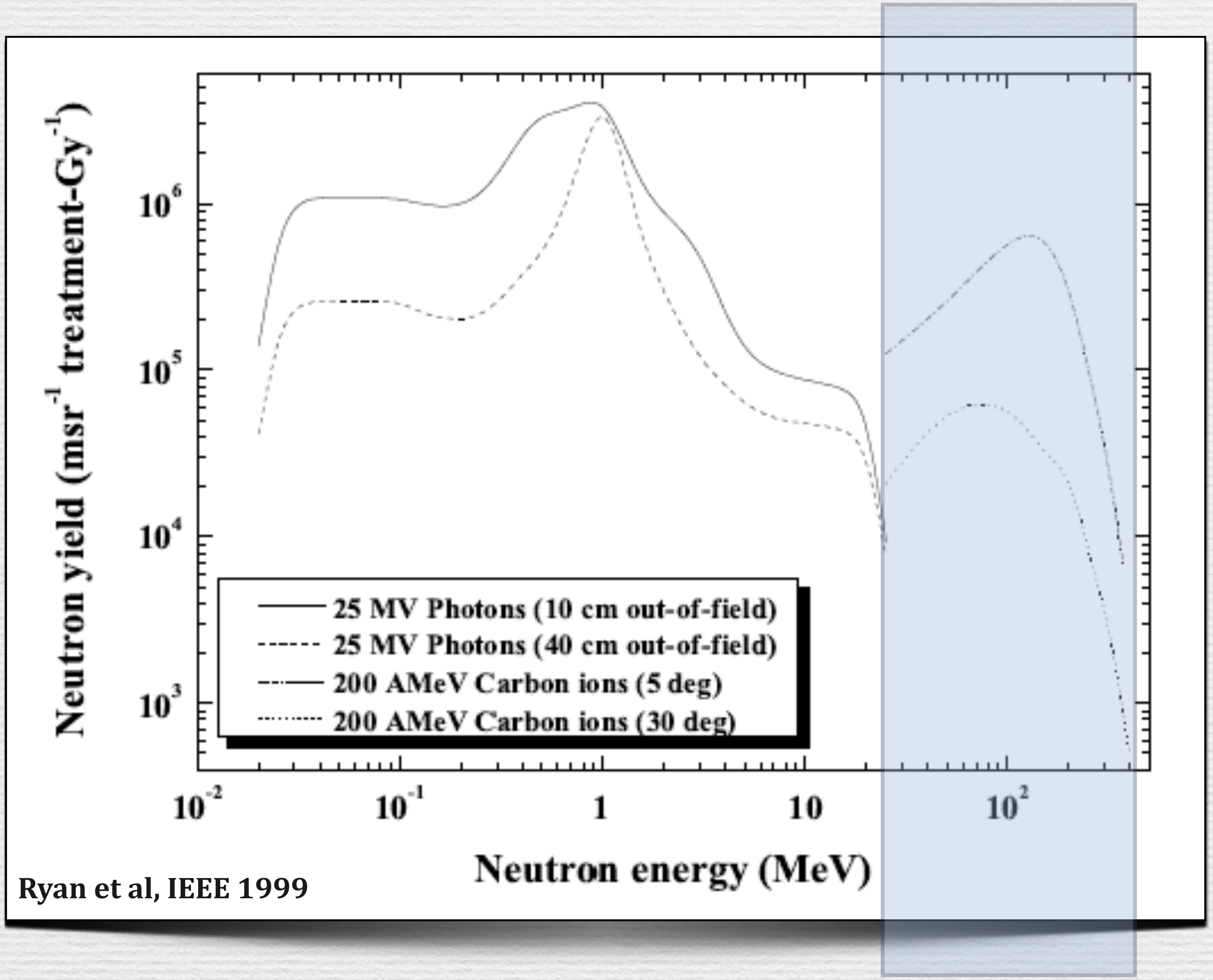
One slice
12C beam
228 MeV/u




M.Marafini

# MONDO

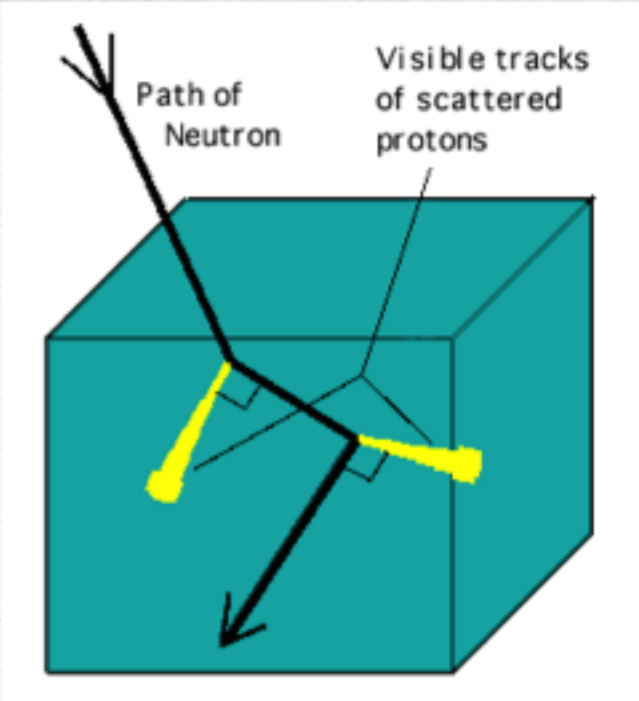
## TRACKER DETECTOR for [20-200] MeV NEUTRON




Ryan et al, IEEE 1999

The expected neutron flux is dominating, by orders of magnitude, the total secondary flux nearly at all energies. While secondary neutrons produced during PT treatments by the beam interaction with the patient are mainly fast neutrons, their energy is degraded after several scattering interactions with the target nuclei so that a large flux of slow neutrons is expected

# Neutron detectors




## SONTRACK Astronomical neutrons [20-200]MeV

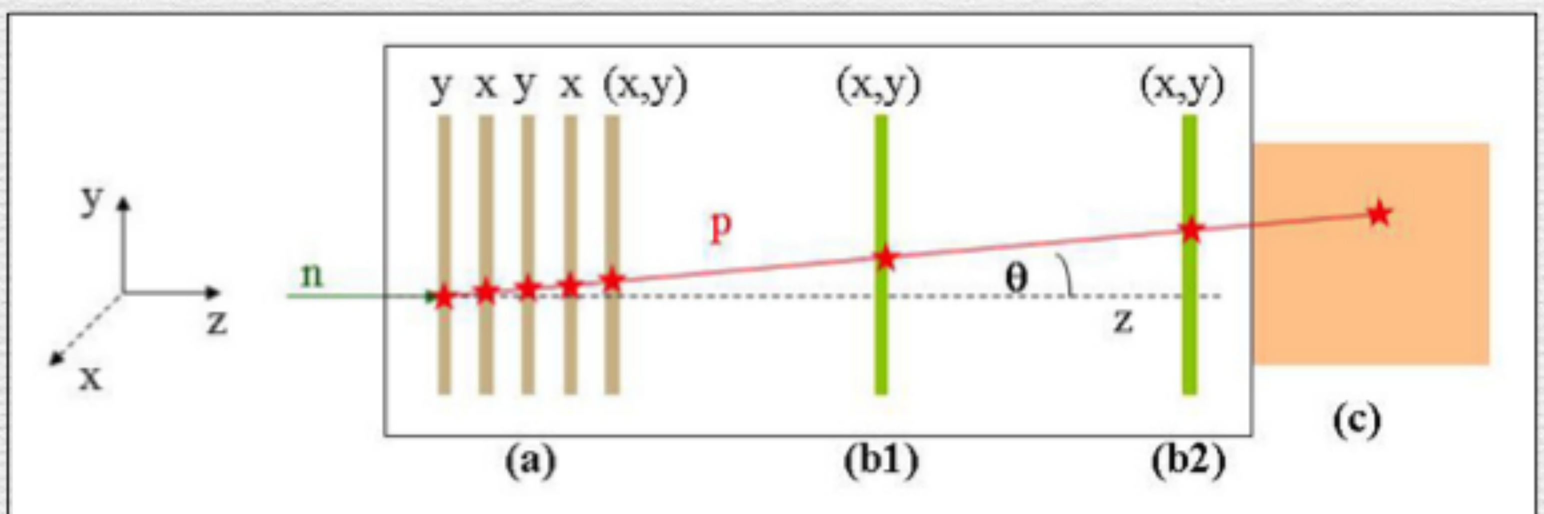
**R.S. Miller et al, NIM A 505 (3003) 36-40**

**Prototype:** Scintillating fibers (0.250 mm) are used as target material (allowing for fast neutrons elastic scattering) as well as active volume, detecting the light produced by the recoiling protons. The read- out is based on optically focused CCD commercial devices.

Science model proton track reconstruction

| Proton energy (MeV) | $\sigma_E/E$ | Angular resolution (degree, $1\sigma$) |
|---|---|---|
| 35 | 4.8 | 4.6 |
| 46.5 | 3.4 | 4.0 |
| 55 | 2.8 | 3.2 |
| 67.5 | 2.1 | 2.3 |

**Proposal**: carbon ion beam characterization (total fluency of the beam measured with respect to known standard cross-sections and energy spectrum and angular distribution of the emitted neutrons.)

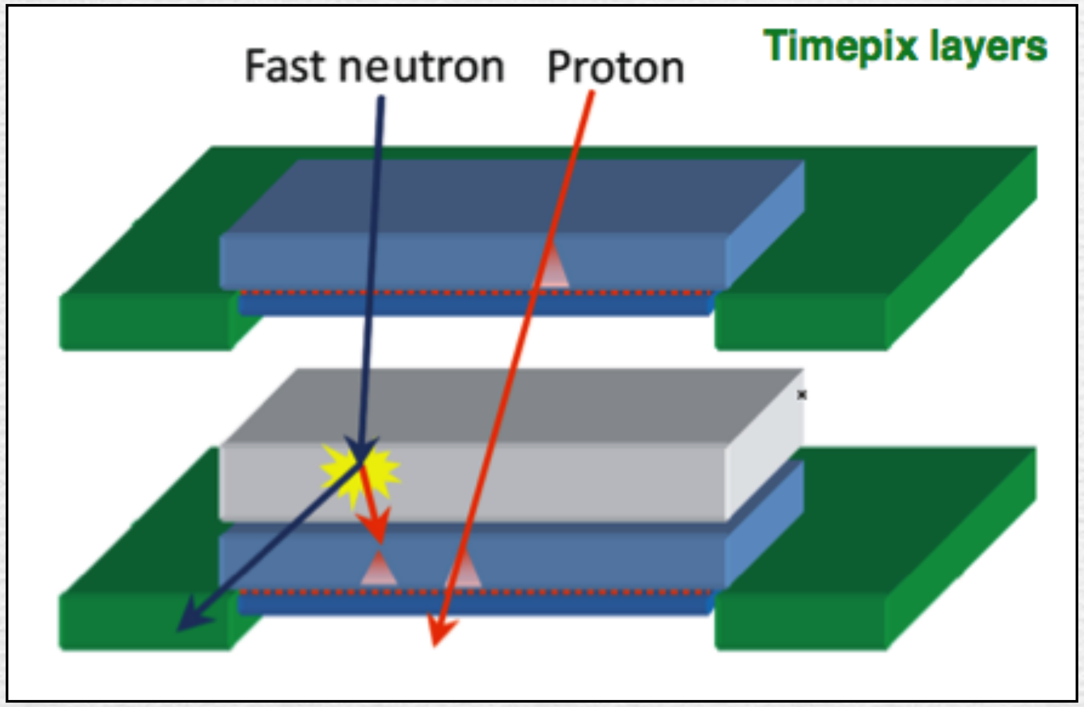



Energy resolution that ranges from about 20% at the lowest neutron energy to about 2% at 160 MeV.

**A. Donzella et al, NIM A 613, I 1, (2010) 58–64**

- 4 plastic scintillator strips 12 mm wide, 50 mm long and 0.4 mm thick;
- a cylindrical plexiglass light guide connects each strip to a photomultiplier tube. The plastic strips (active target) are followed by silicon detectors (300 μm of thickness) for a total active area of 5 cm x 5 cm divided into 16 strips in both sides but orthogonally oriented.
- For the residual proton energy measure, a cylindrical 3” x 3” CsI(Tl) scintillator coupled by a photomultiplier tube is used.

# Neutron detectors

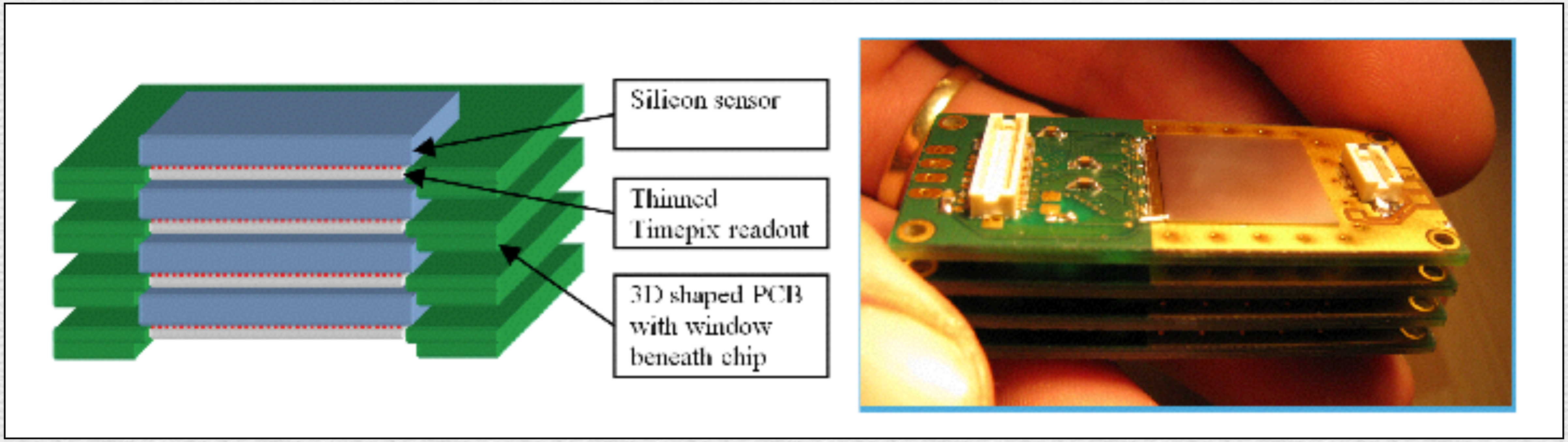



## TIMEPIX

**J. Jakubek et al.**

The technique uses a 3D sensitive voxel detector composed of several layers of Timepix pixel detectors. These layers are interlaced with an hydrogen rich material (plastic) that maximize the elastic scattering cross section and the relative production of recoiling protons.
corresponding to different particles: photons, light charged particles, heavy charged particles and neutrons (slow and fast).

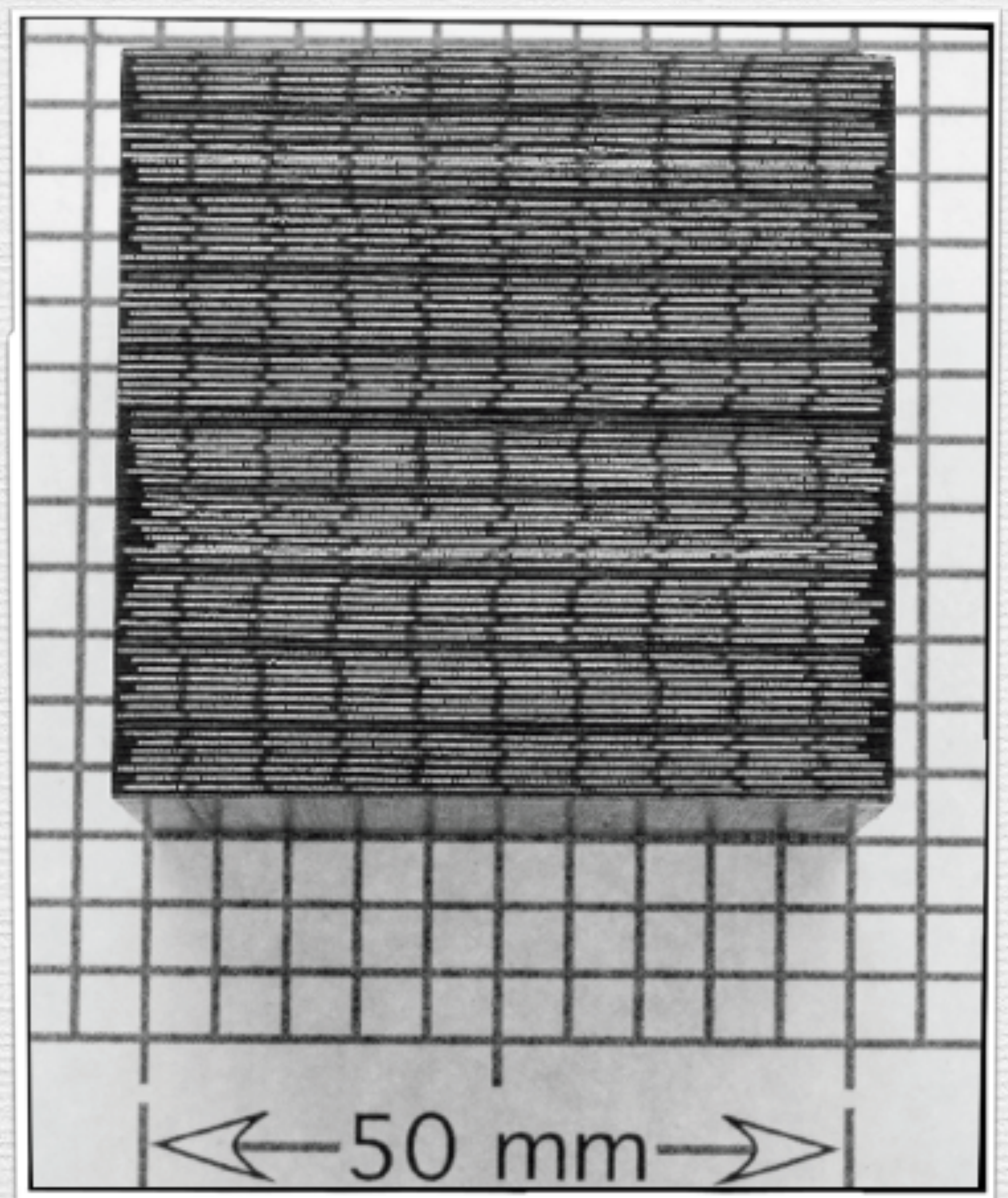
**For certain particle types (ions) it is even possible to generate their 2D distribution on the surface of the irradiated volume.**
**the device to neutrons needs to be determined and calibrated.**

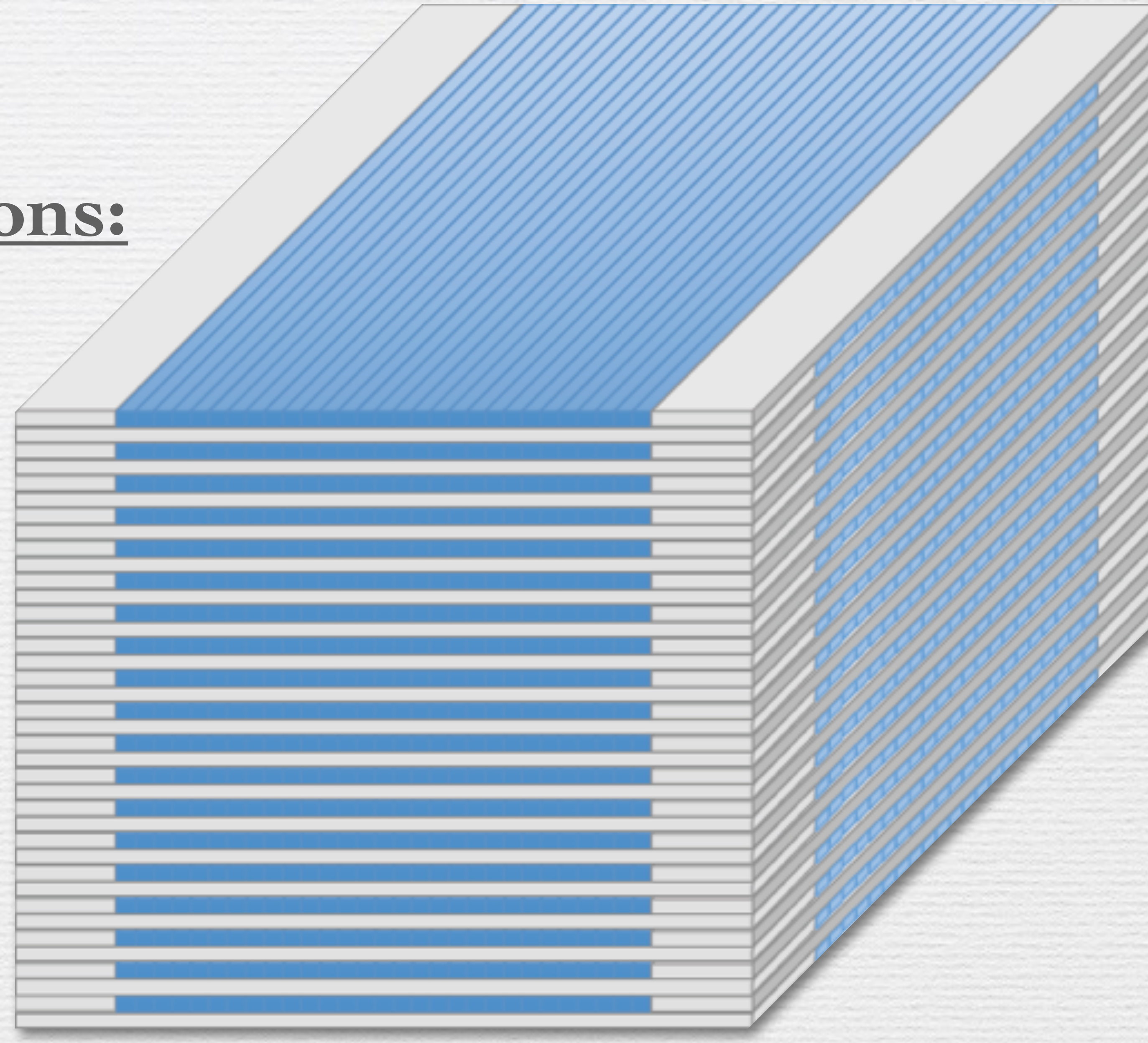


# MONDO Design

**Possible mechanical solutions:**

- San Gobain fibers package
- Homemade assembling



**SONTRAC**

- 5 x 5 x 5 $cm^3$ detector (0.250 mm fibres)

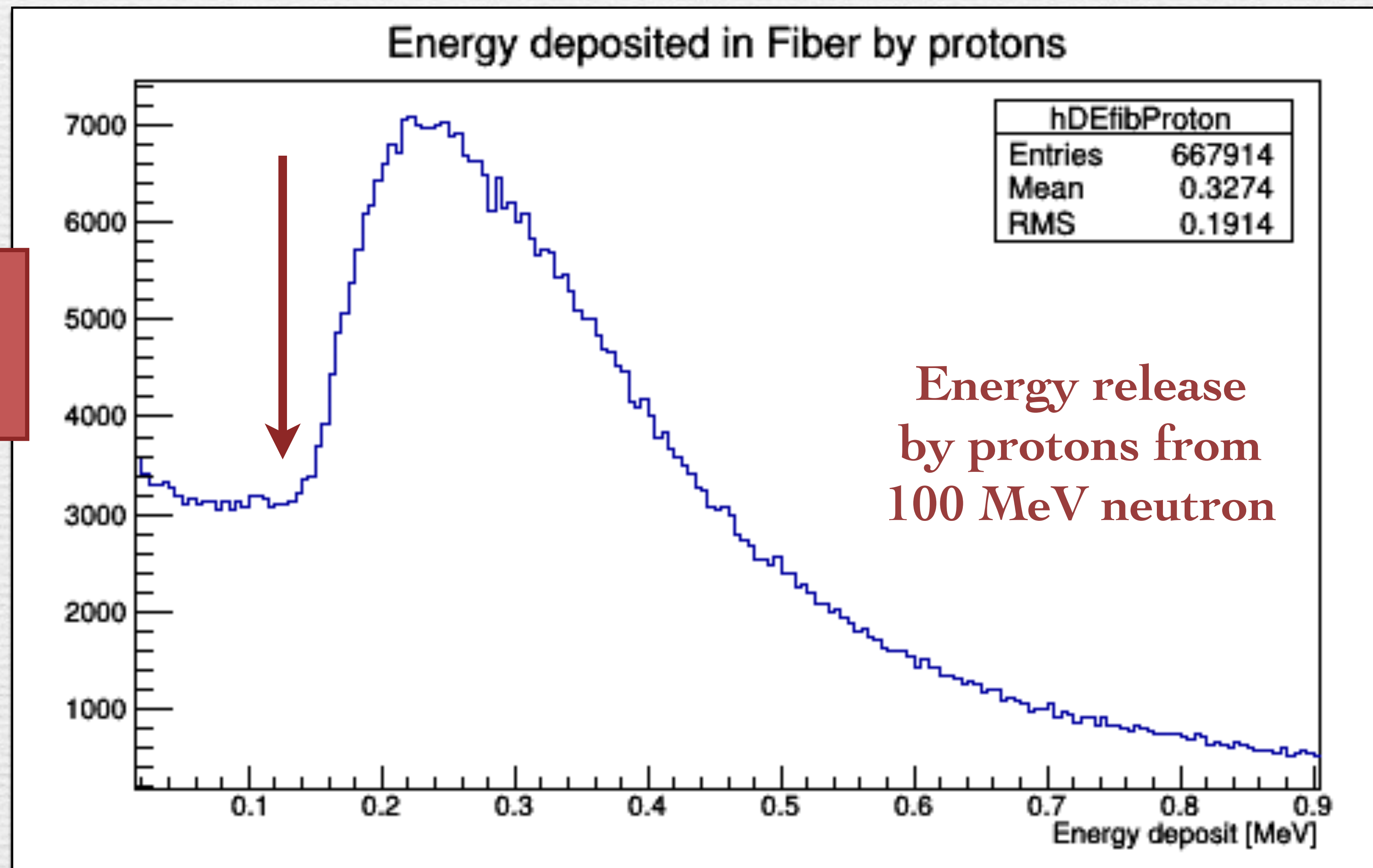
**R.S. Miller et al, NIM A 505 (3003) 36-40**

# Ph.Electrons

The ph.e. produced by the GEM cathode, due to a proton signal in a can be estimated using realistic parameters:

- Minimum Energy: >150 KeV (50 KeV m.i.p.)
- Fiber light yield: $9 \times 10^3$ photons/MeV
- Fiber collection eff: 4%
- Photo Cathode eff: 20%

p produces ~ 10 ph.e.
m.i.p produces 5 ph.e.

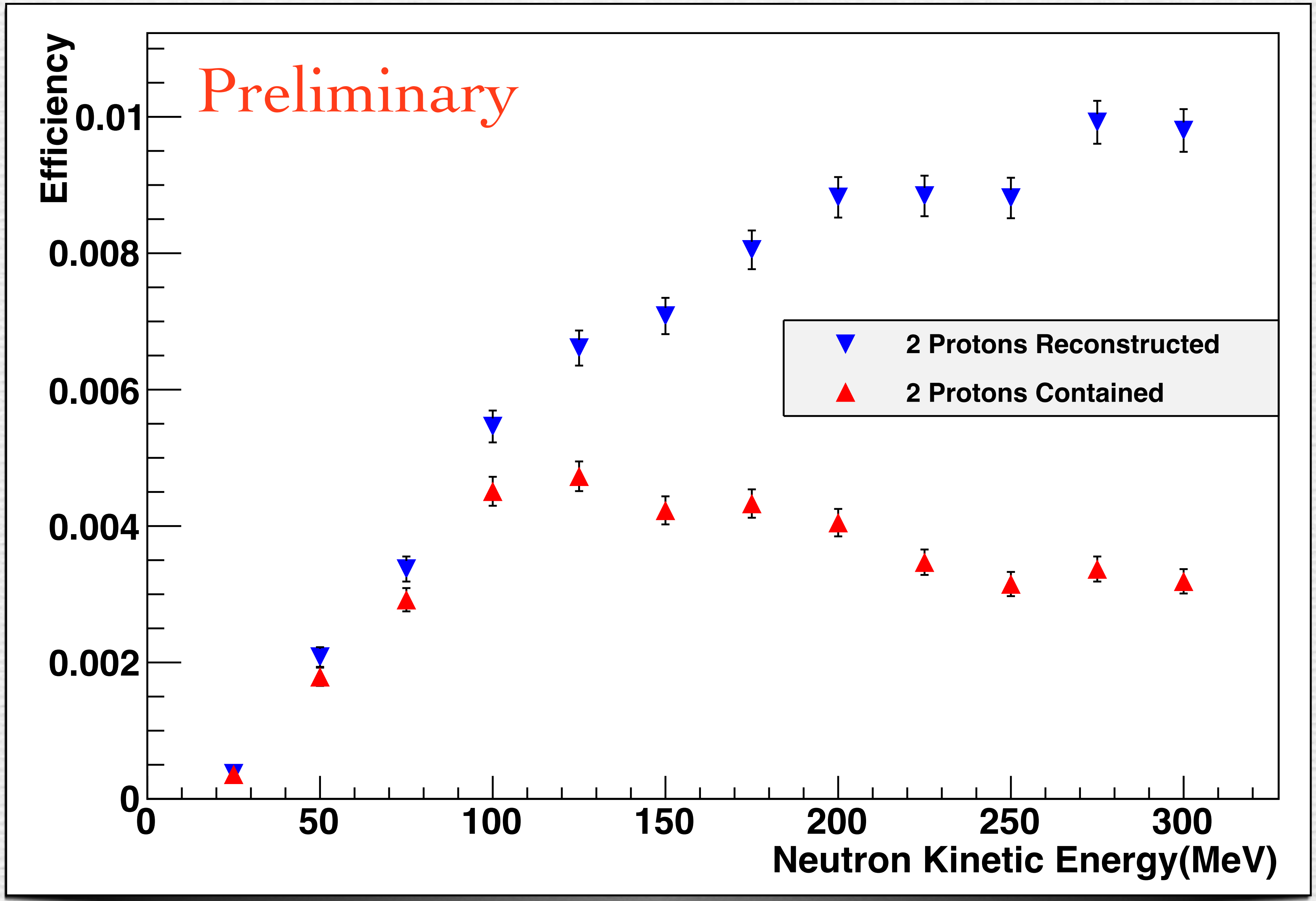


# Reconstruction Efficiency

FLUKA

- Events are reconstructed only if 2 protons have a signal over threshold in more than 6 fibers;
- To release a signal over threshold in a given fiber, the proton must deposit more than 100 KeV

**The neutron energy can be computed by measuring the proton range ONLY if both protons are contained.**

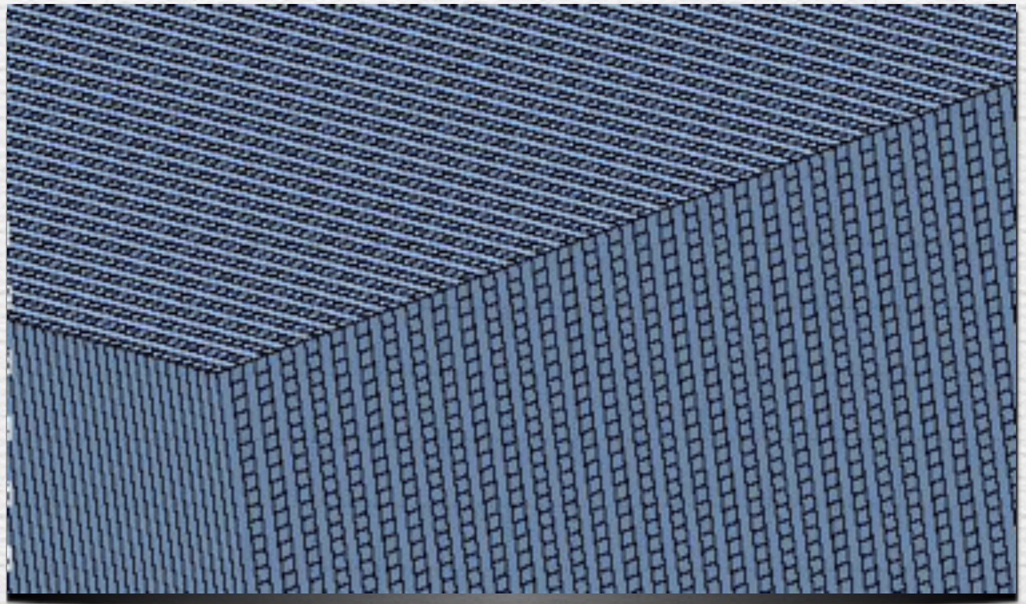


# Ph.Electrons

The photons reaching a single CMOS pixel
realistic parameters:

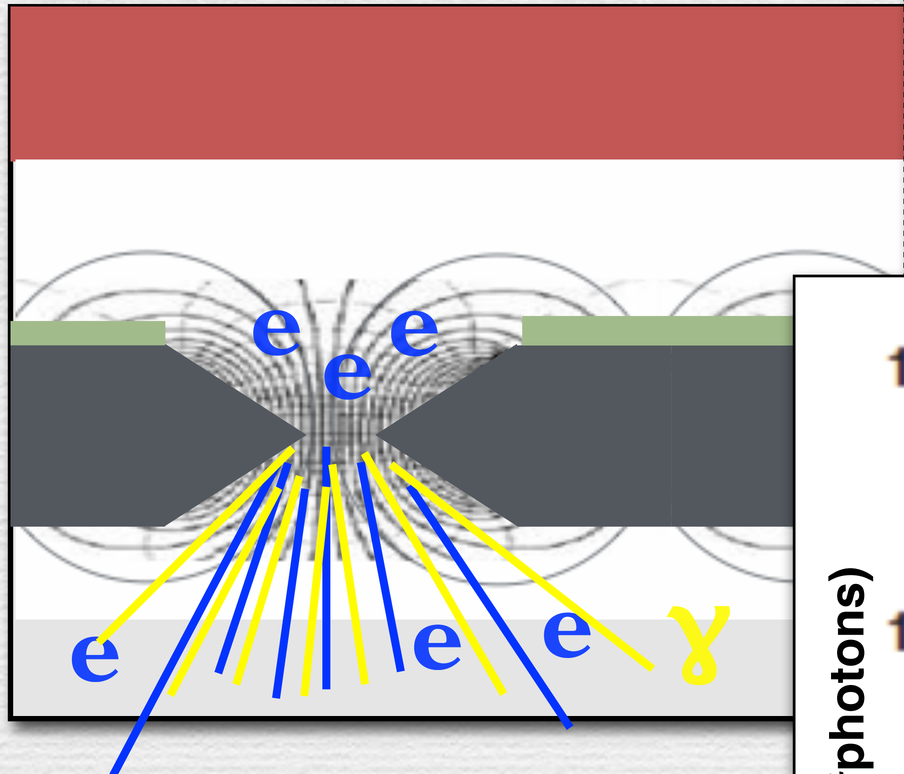
- 50 ph.e per fiber
- 50 ph.e x 20% photocathode effQ => 10 ph.e
- 10 ph.e x 30% photocathode effGeo => 3 ph.e
- 3 x $10^4$ photons after the last stage
- x 50% GEM effGeo [half of the electrons (and photons) goes in the wrong direction]
- 15000 from 250 μm => 600 ph per pixel (50μm)
  => 100 ph per pixel (20μm)

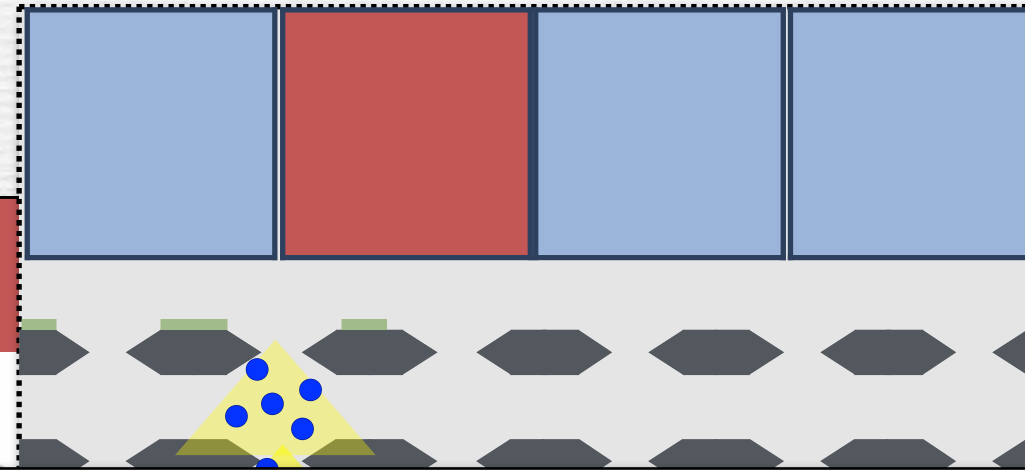
in CMOS sensor: 15 pair of bkg
=> 100 ph -> 100 pairs
=> 50 ph -> 50 pairs

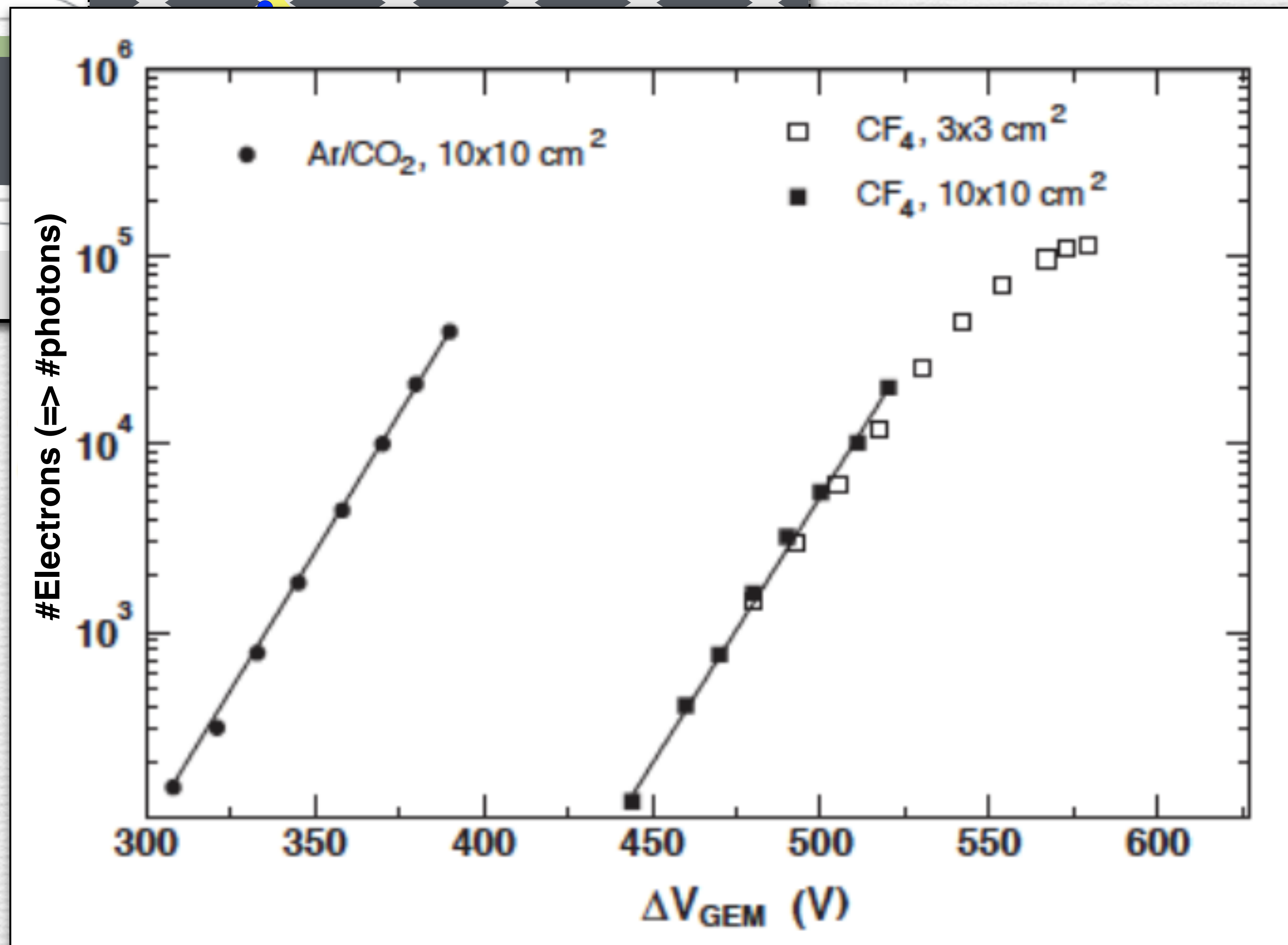


# MONDO Design

# GEM





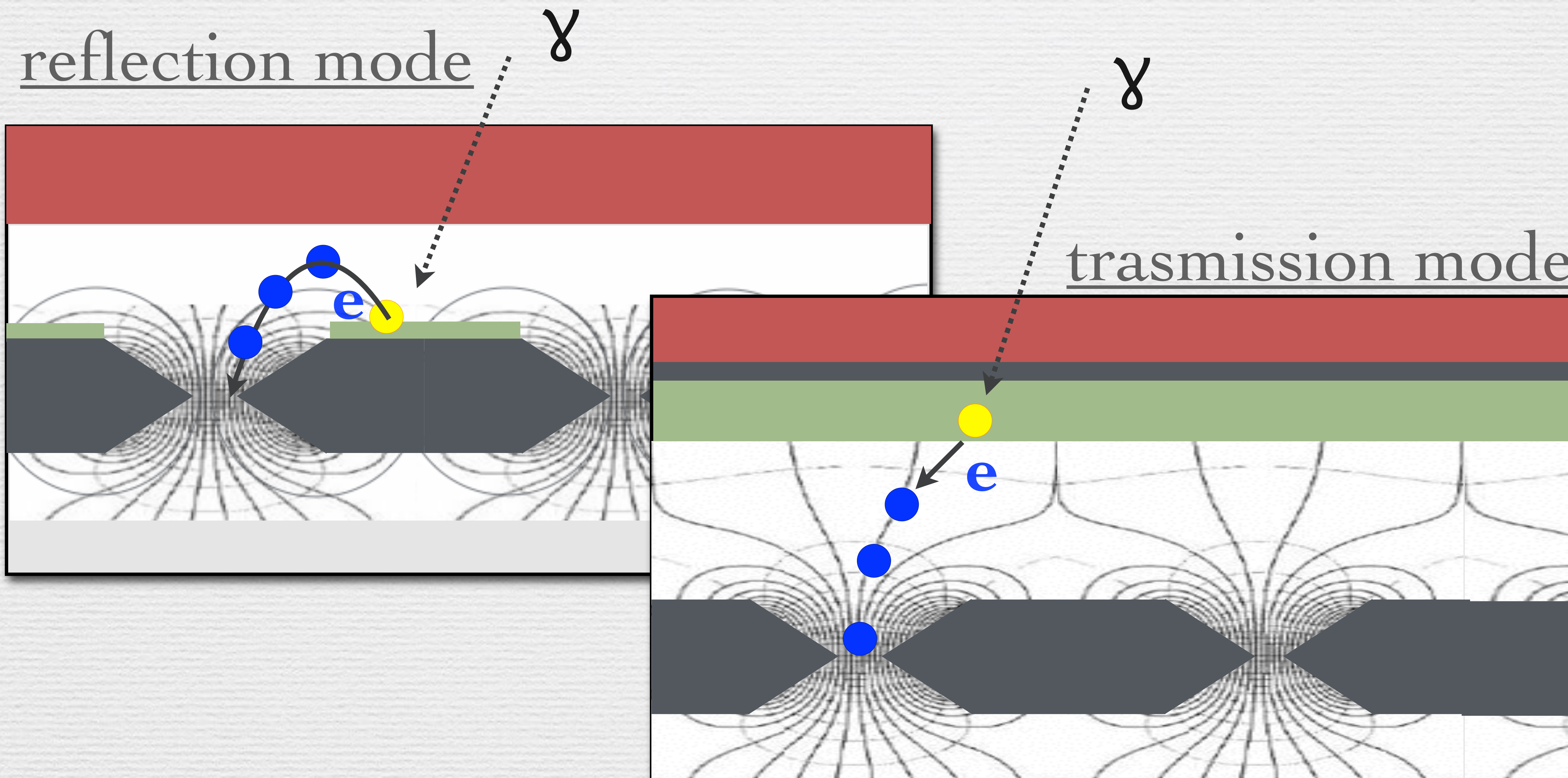

With a triple GEM system a gain of $10^4$ is achievable

Fraga et al, NIM A 504 (2003) 88-92

M.Marafini

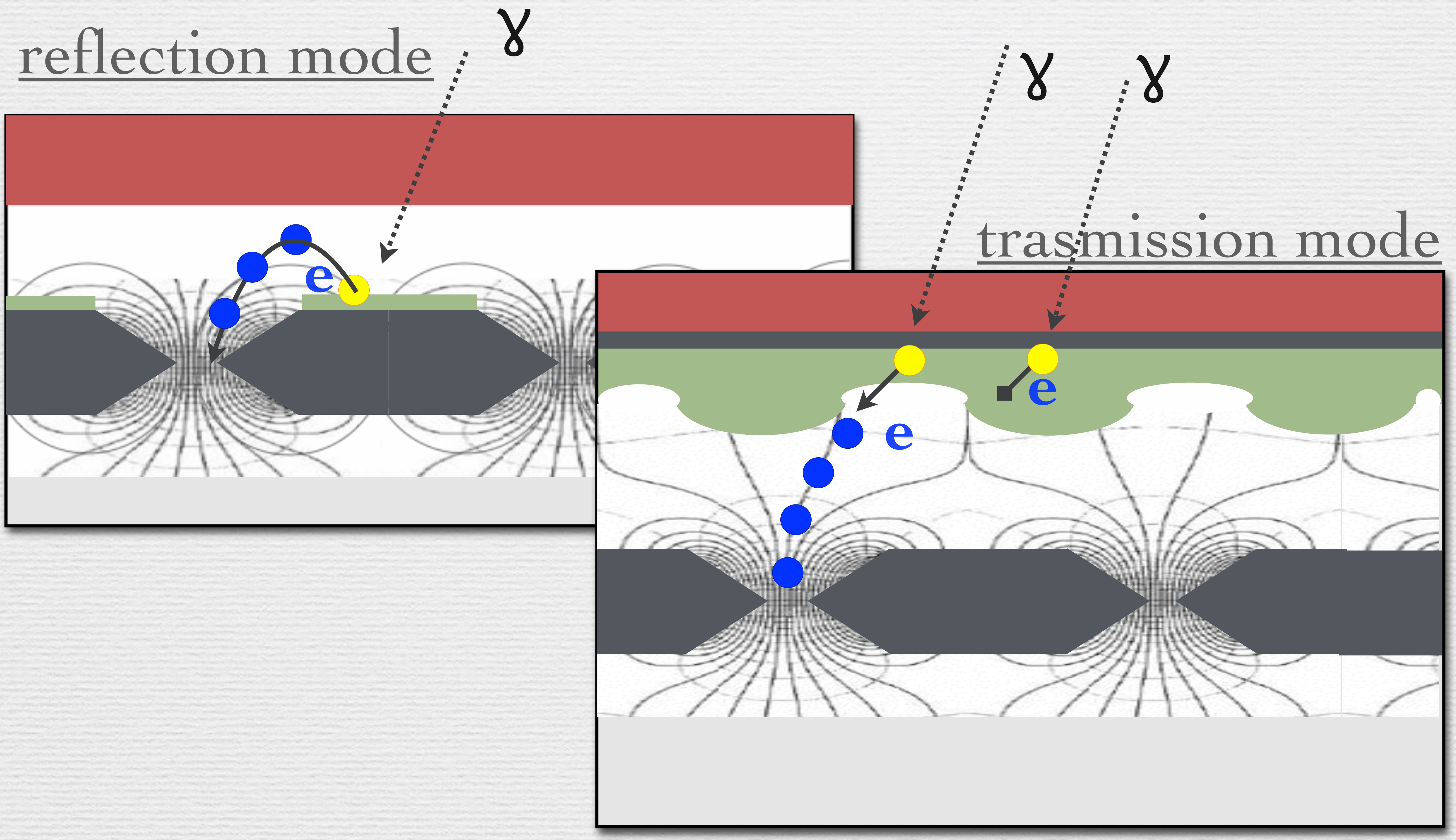
# PHOTOCATHODE

reflection mode

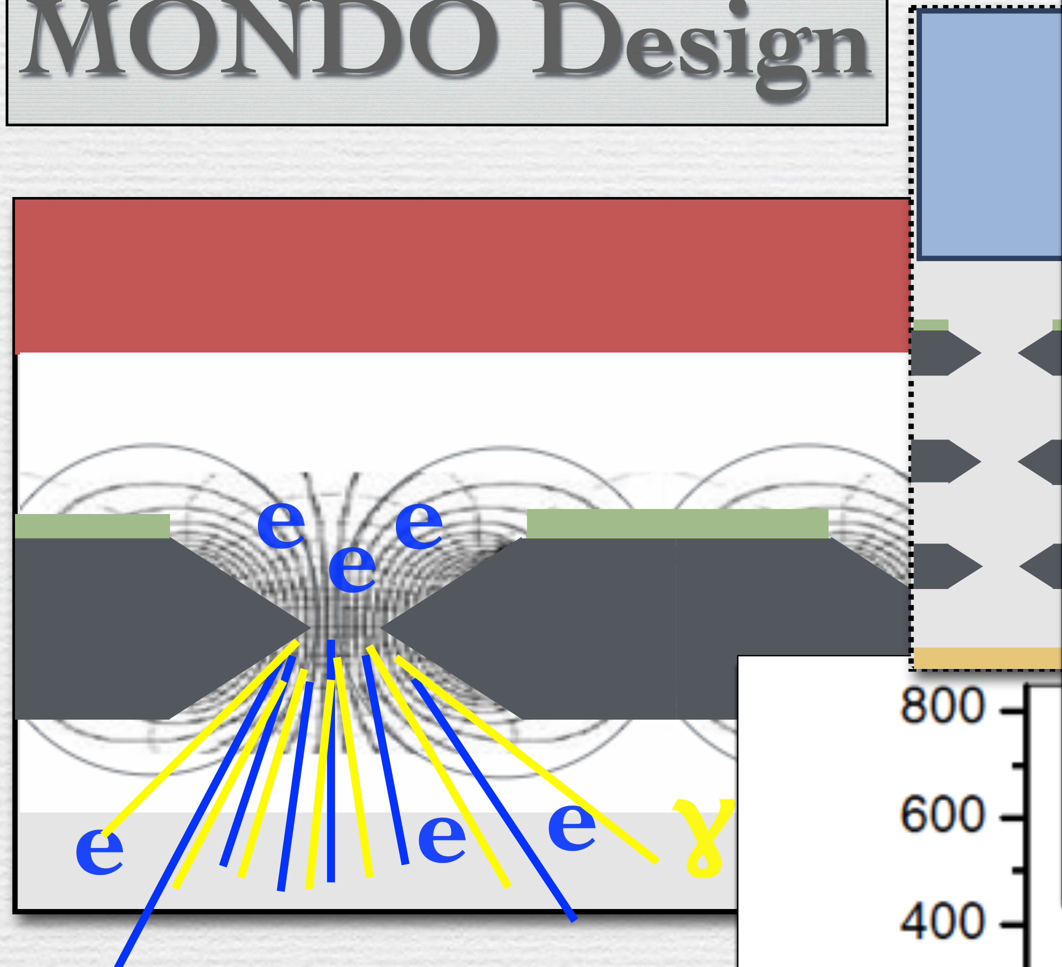


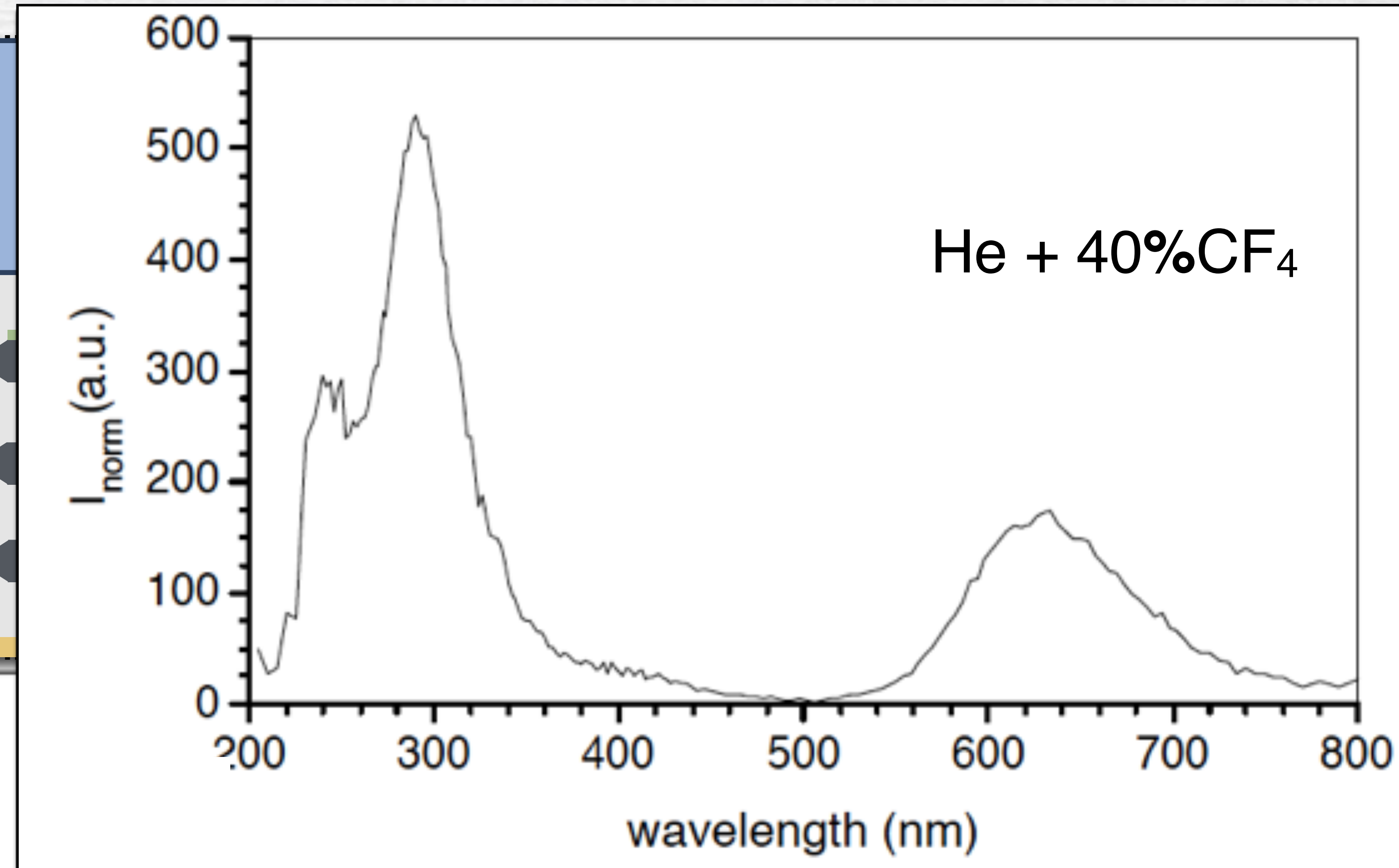

- Ec ~ 50%

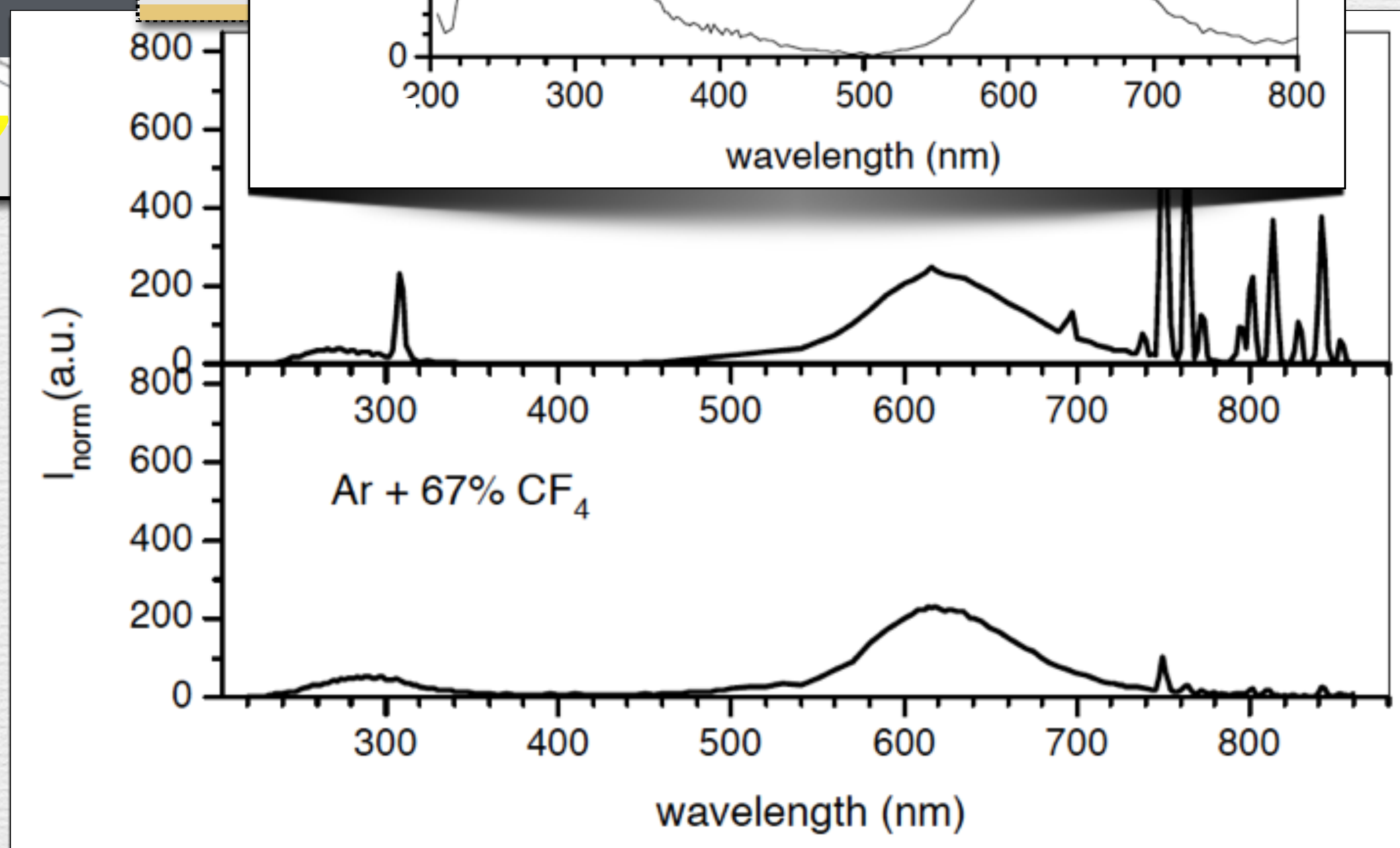
# PHOTOCATHODE



# MONDO Design




The emitted photons energy spectra depends on the gas mixture

Fraga et al, NIM A 504 (2003) 88-92

# GEM

The GEMs with 45 um holes have higher light emission than the other GEMs

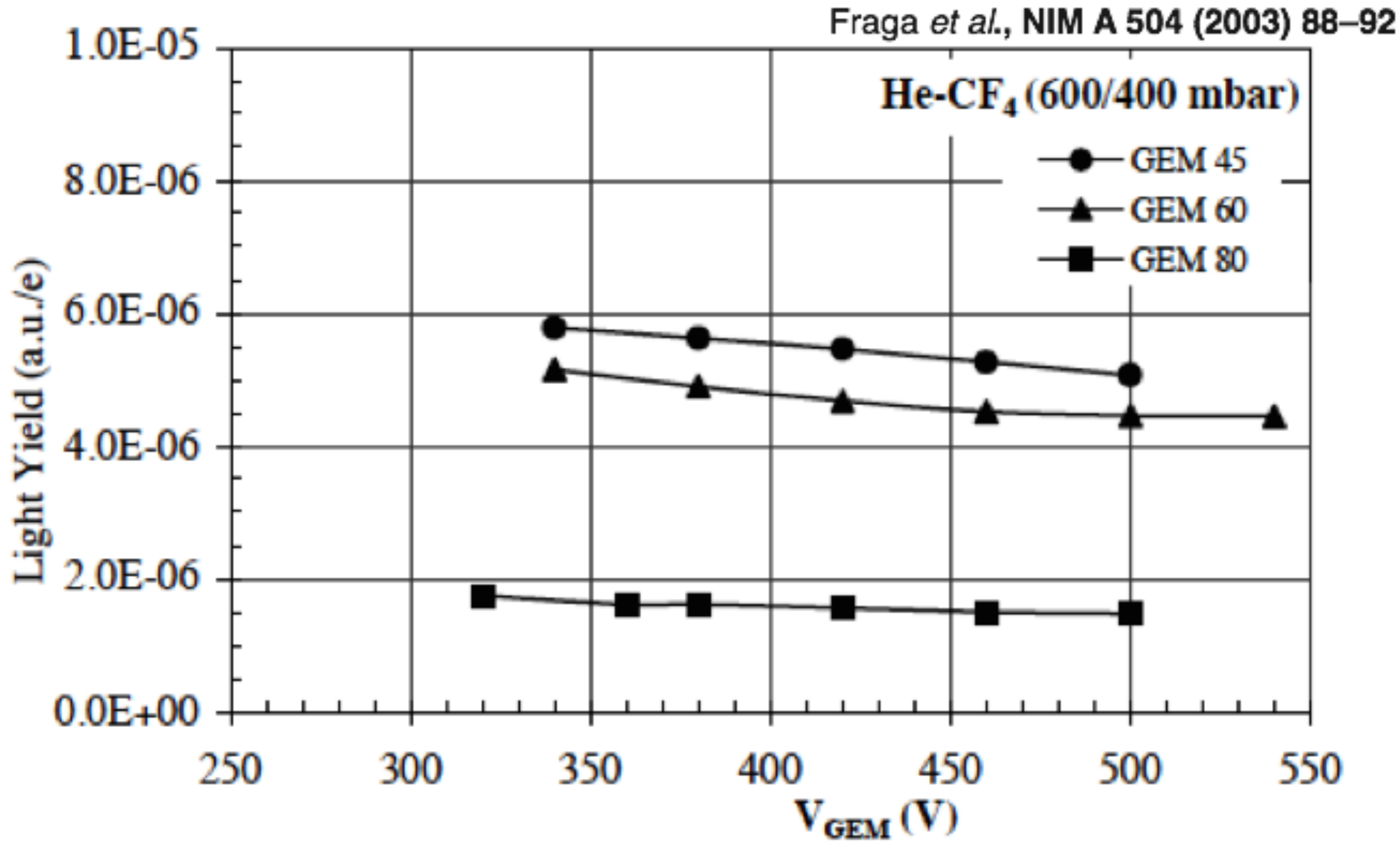
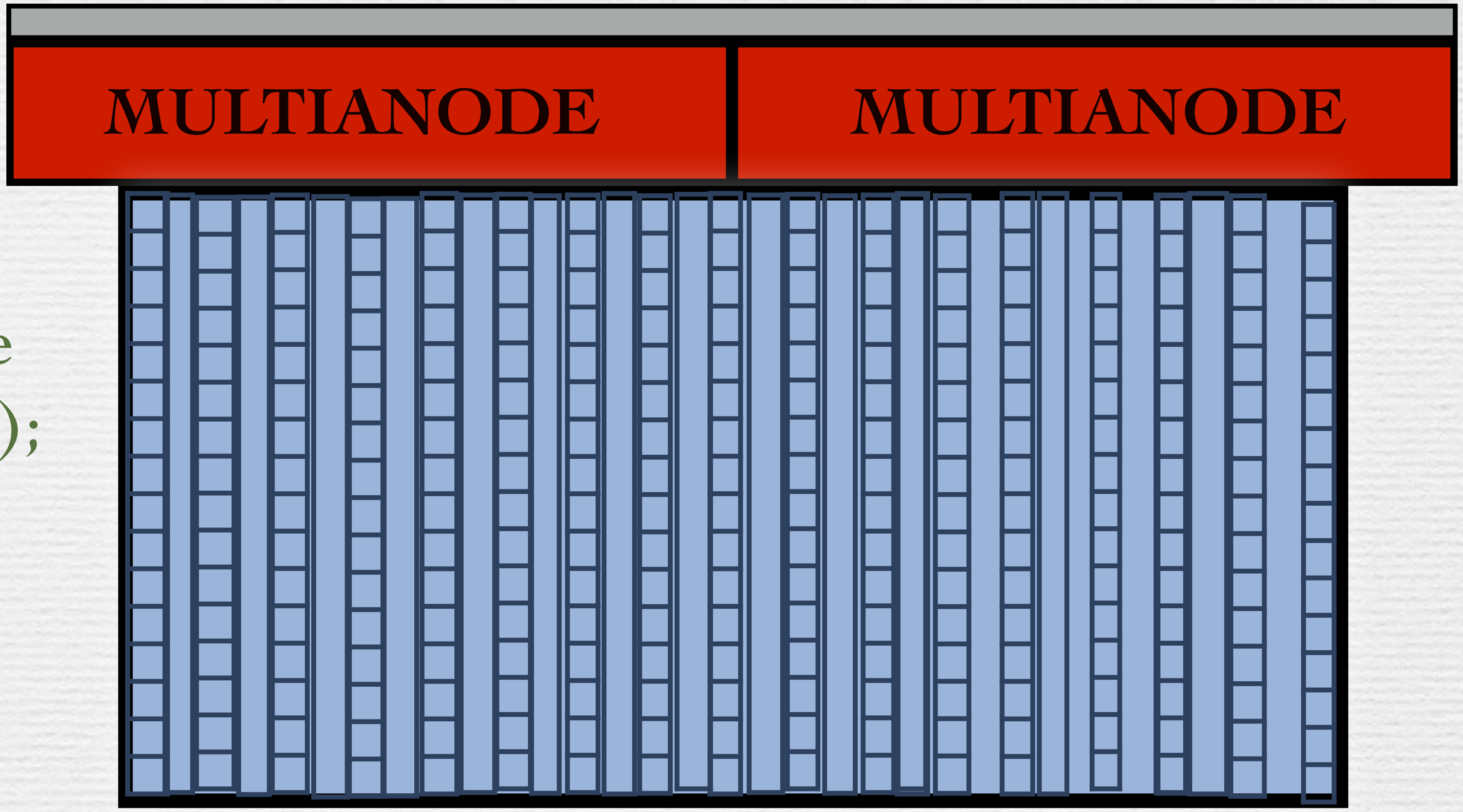



Fig. 2. Ratio of emitted light over secondary electron current versus $V_{GEM}$ measured in He (600 mbar) + $CF_4$ (400 mbar) for GEMs with 45, 60 and 80 μm hole diameter.

# TRIGGER




- The trigger will be performed with Multi-anode PMTs (64 ch. 5.8 x 5.8 $mm^2$);

- PMTs readout chip [AGE Scientific s.r.l.]

- TRIGGER STRATEGY:

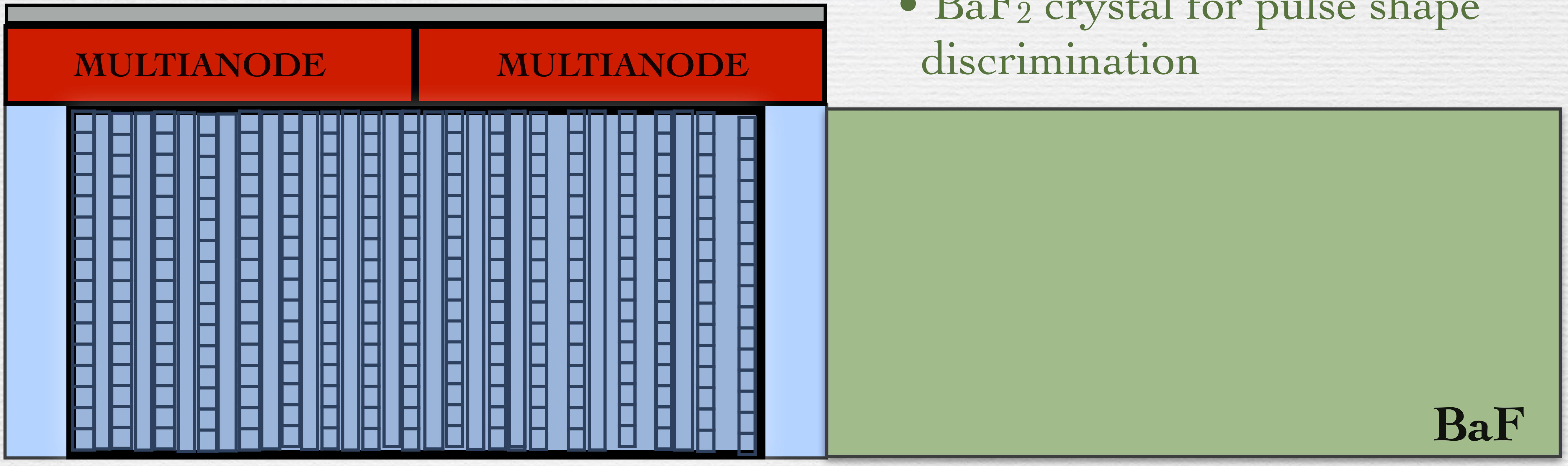
=> Fast (using the first two dynodes of each PMTs)

=> Slow (logic programmable with the total information of the devices )

=> For the first measurements (total flux, device background study, implementation of the patter recognition, etc.) an easier one-level trigger is more coherent with the effectively man power of the project.

M.Marafini

# TEST SYSTEM




- $BaF_2$ crystal for pulse shape discrimination