A visualisation of the damage in Lead Tungstate calorimeter crystals after exposure to high-energy hadrons

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Motivation

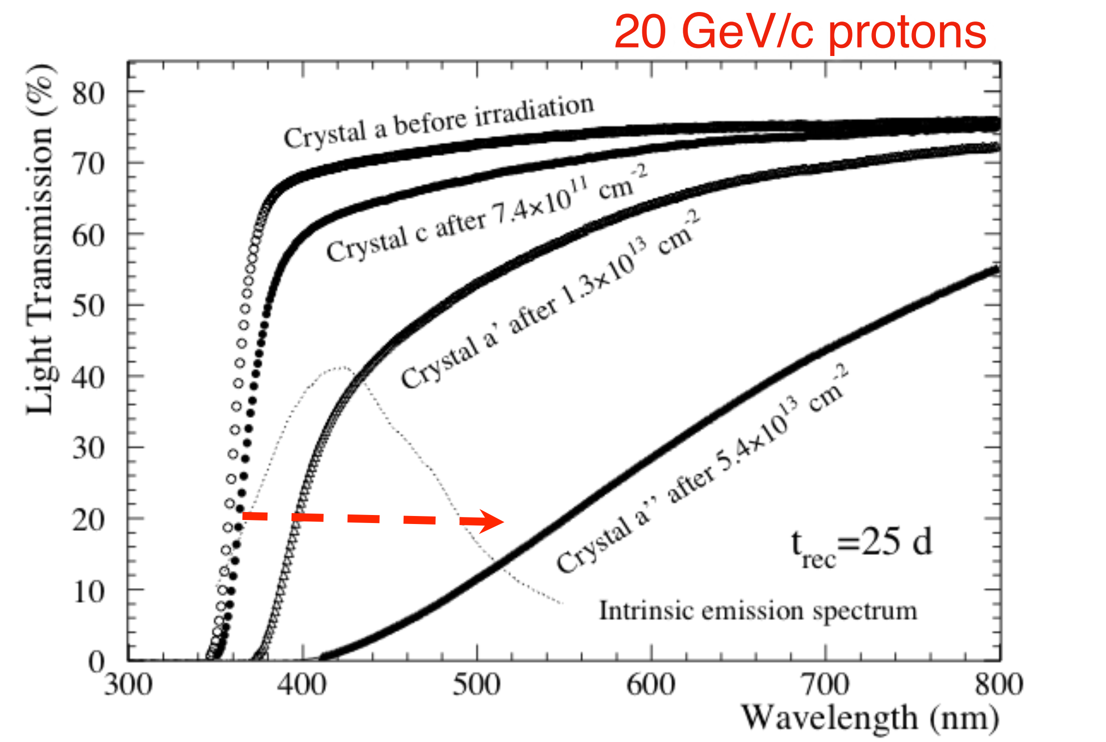
- Multiple indirect evidence existed, that hadron-damage to $PbWO_4$ is due to damage from fission fragments

- A direct visualisation was interesting to pursue, to reach a final proof

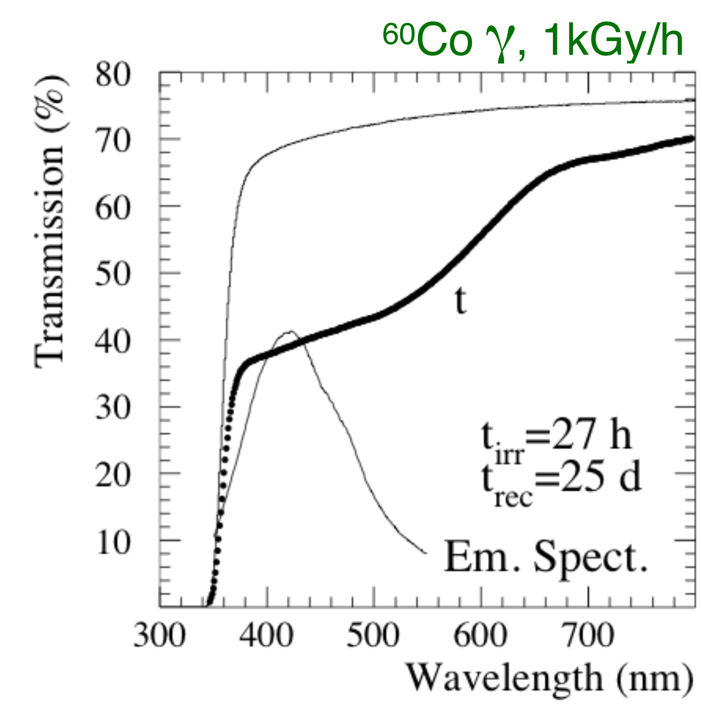
Hadron effects to light transmission of $PbWO_4$

M. Huhtinen, P.Lecomte, D.Luckey, F.Nessi-Tedaldi, F.Pauss, Nucl. Instr. Meth. A545 (2005) 63-87

- irradiation with high-energy hadrons causes a light transmission loss
  LT0 → LT
  and a transmission band-edge shift



- while γ irradiation causes colour centres

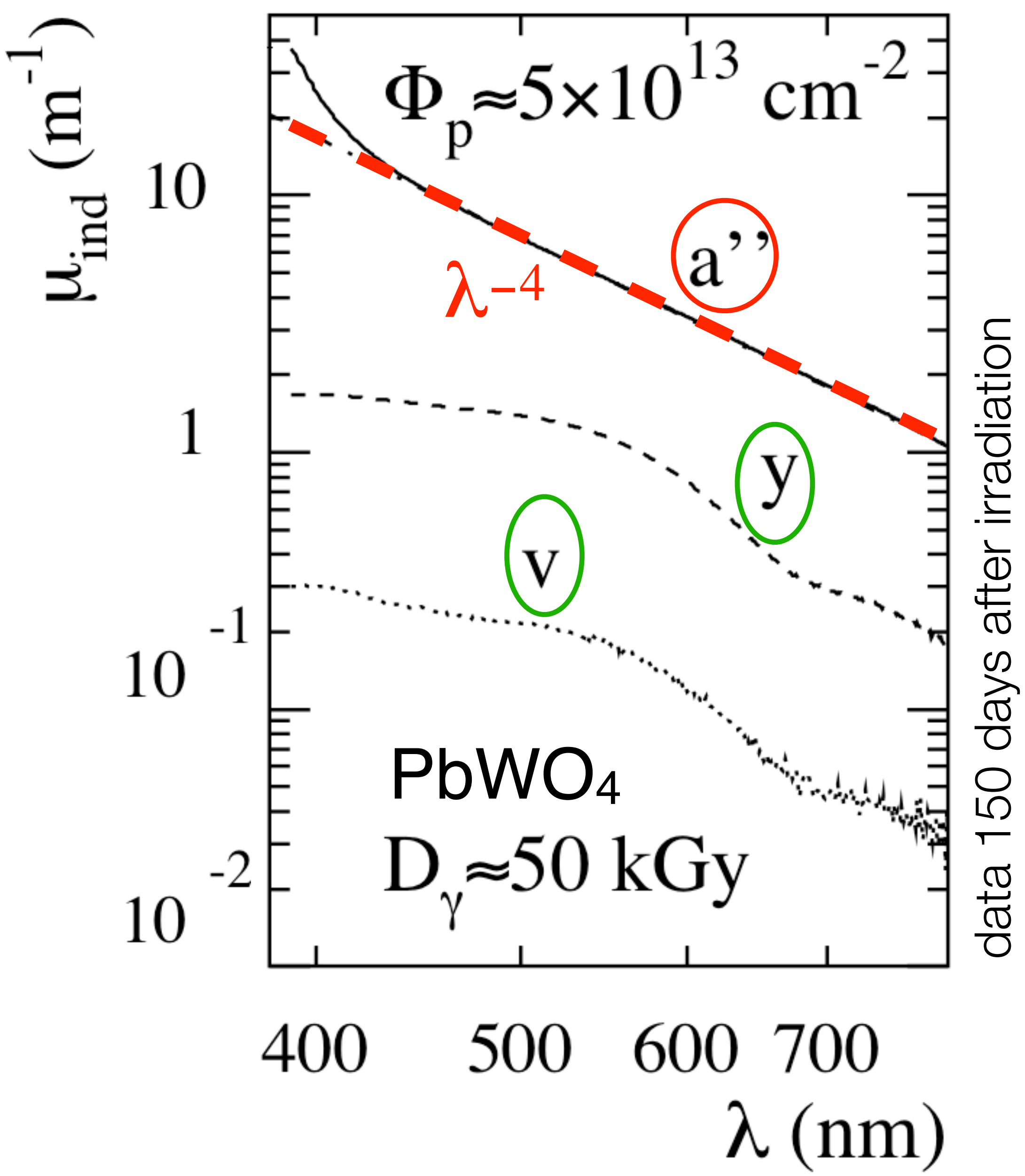


- we examine the induced absorption μ_{IND} given by:

$$\frac{LT(\lambda)}{LT0(\lambda)} = e^{-\mu_{\mathrm{IND}}(\lambda)L}$$

with L = crystal length (here 23 cm)

Hadron effects on induced absorption in $PbWO_4$



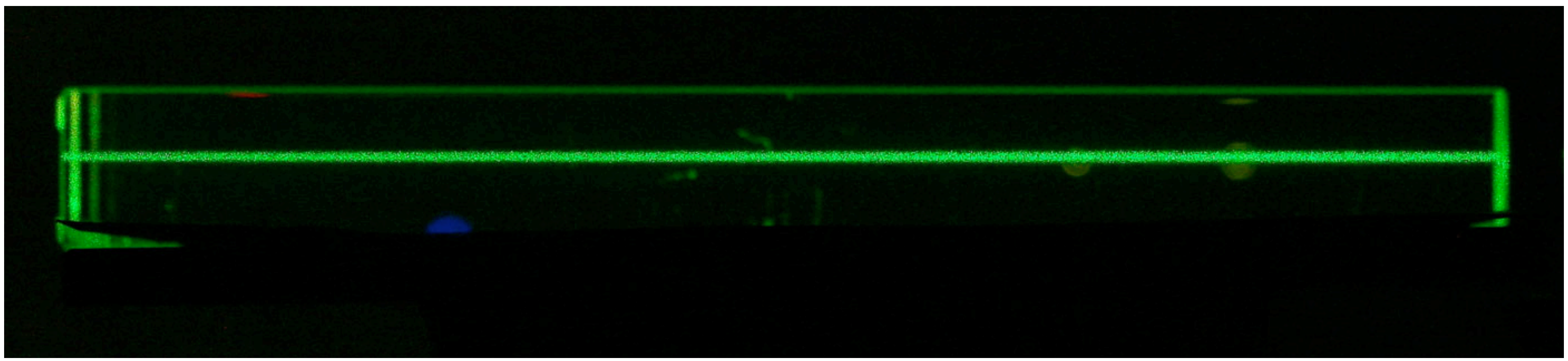
- ✦ In proton-irradiated crystals, λ^{-4} dependence (crystal a") of induced absorption.
- ✦ This is Rayleigh-scattering behavior: i.e. scattering off "dipoles" with dimension < λ/10
- ✦ Not observed for γ-irradiated crystals (crystals v and y)

Light scattering is visible by eye

- The presence of scatterers is visualised by LASER light

scattering is observed!

Green Laser light (543.5 nm) is shone through a p-irradiated crystal



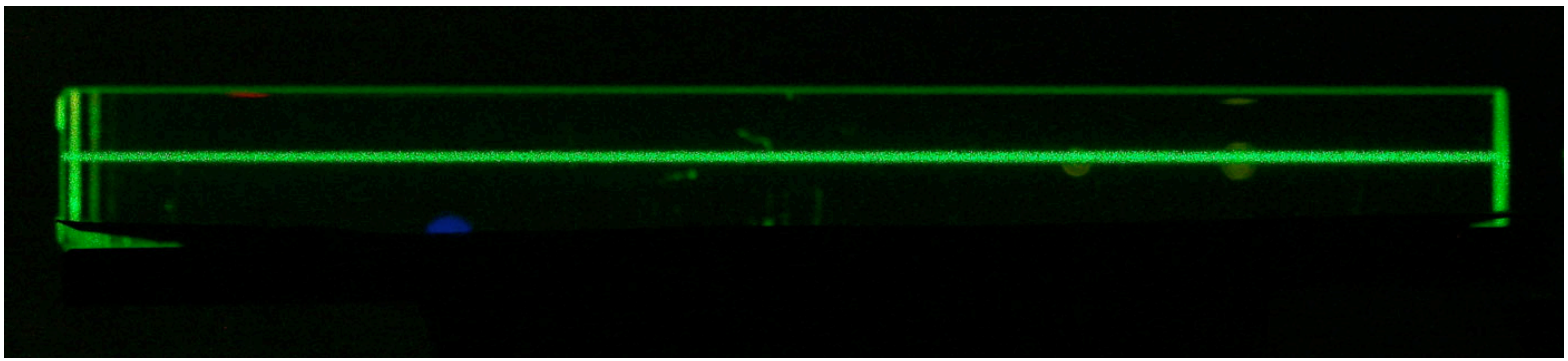
LASER light ←

Light scattering is visible by eye

- The presence of scatterers is visualised by LASER light
- The scattered light is observed to be completely polarised, a further feature of Rayleigh scattering

scattering is observed!

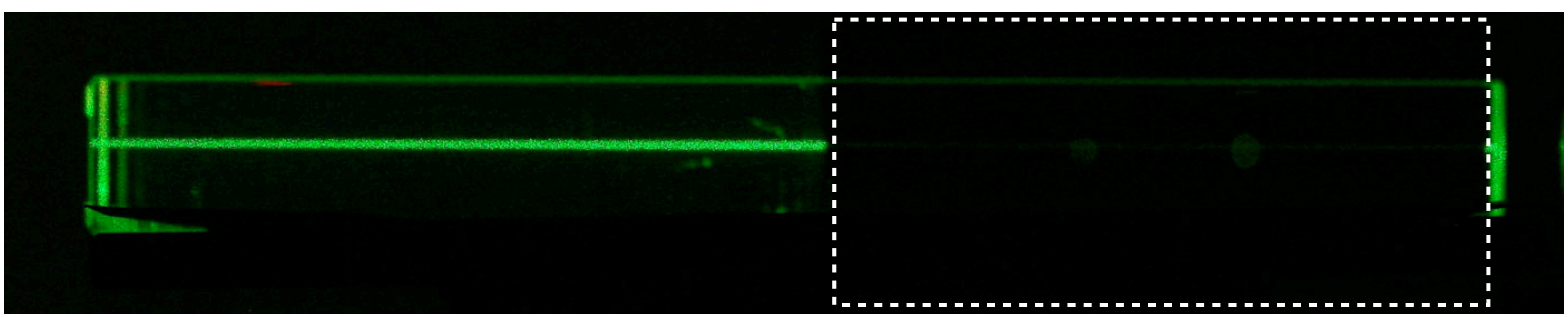
Green Laser light (543.5 nm) is shone through a p-irradiated crystal



LASER light

←

a Polaroid filter reveals that the green scattered light is polarised



LASER light

←

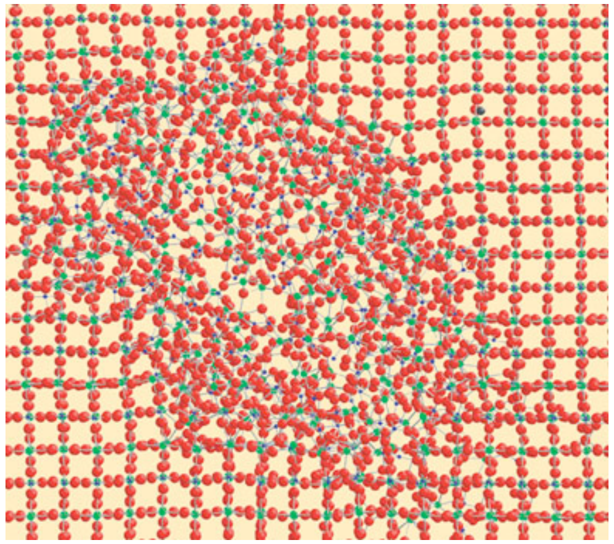
Possible cause: fission fragments

- Each energetic hadron produces a cascade of nuclear interactions, a “hadron shower”, that penetrates through the crystal

- Lead and Tungsten undergo fission

- The heavy fission fragments deposit a lot of energy along their short track, leaving regions within the crystal where the lattice structure is modified: it can remain disturbed, strained, disordered, or re-oriented

- These damage regions have different optical and mechanical properties from the surrounding crystal lattice



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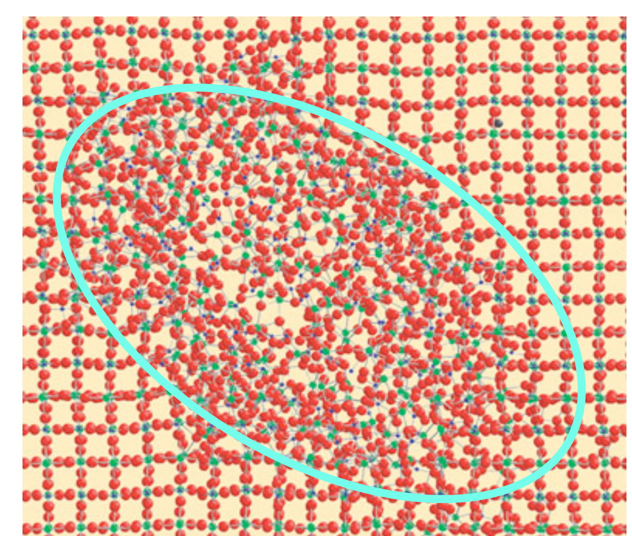
- They can act as scatterers for the light



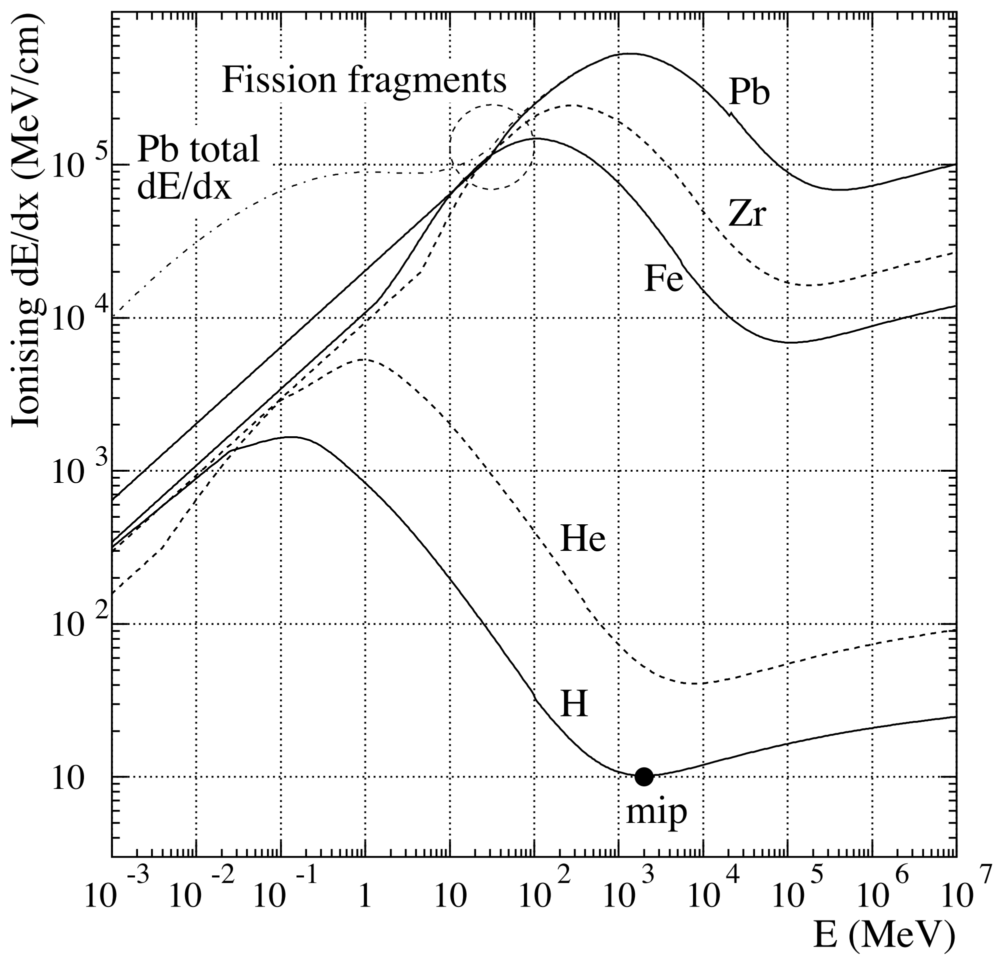
Observations for different crystals

- After exposure to high-energy hadrons, cumulative damage due to hadrons has been observed in

Lead Tungstate	$PbWO_4$
BGO 1)	$Bi_4Ge_3O_{12}$
LYSO 2)	$Lu_{2(1-x)}Y_{2x}SiO_5$:Ce

- No cumulative damage, nor light scattering have been observed in

Cerium Fluoride 3)	CeF_3



- This is consistent with highly-ionising fission fragments being produced in crystals made of elements with Z>71[4)]

1) F. N.-T., Proc. 9th ICATPP Conference (Como, Italy, 2005) http://arxiv.org/abs/physics/0511012v1
2) G. Dissertori, F..N.-T. et al., NIM A745 (2014) 1-6
3) G. Dissertori, F..N.-T. et al., NIM A622 (2010) 41-48
4) A. S. Iljinov et al., PR C39 (1989) 1420

Fission-track damage in literature

- *Fr. Dessauer, Zeit. Physik 12 (1923) 38:* Concept of **thermal spike** when an incident ion comes to a stop in matter

- *L.T. Chadderton, "Fission damage in crystals" (1969):* "Along the heated cylindrical track of the fragment the crystalline matter is disturbed, decomposed, or removed. The subsequent arrangement is not necessarily perfect and strain centres or dislocations remain"

- *R. Fleischer, J. Mat. Sci. 39 (2004) 3901:* **Ionization spike model** Charged particle passage causes ionization - ions are ejected due to Coulomb repulsion - a region of atomic disorder is left behind

- whatever the detailed mechanism:

a region remains, with optical characteristics different from the original lattice

a "fission track"

for the unbelieving

…the ultimate proof

The approach at visualising fission-tracks

Fission track analysis, a well established method used in geochronology, for the visualisation of tracks entering muscovite mica slides, after keeping them in intimate contact with Lead Tungstate during irradiation.

performed with the Zeiss Axio Imager Z1M of the Geneva University Department of Mineralogy

Visualisation of the fission tracks in mica

- Fission track analysis is a technique commonly used in geochronology

  A. J. W. Gleadow, Nuclear Tracks 5 (1981) 3-14

- From a natural phenomenon...

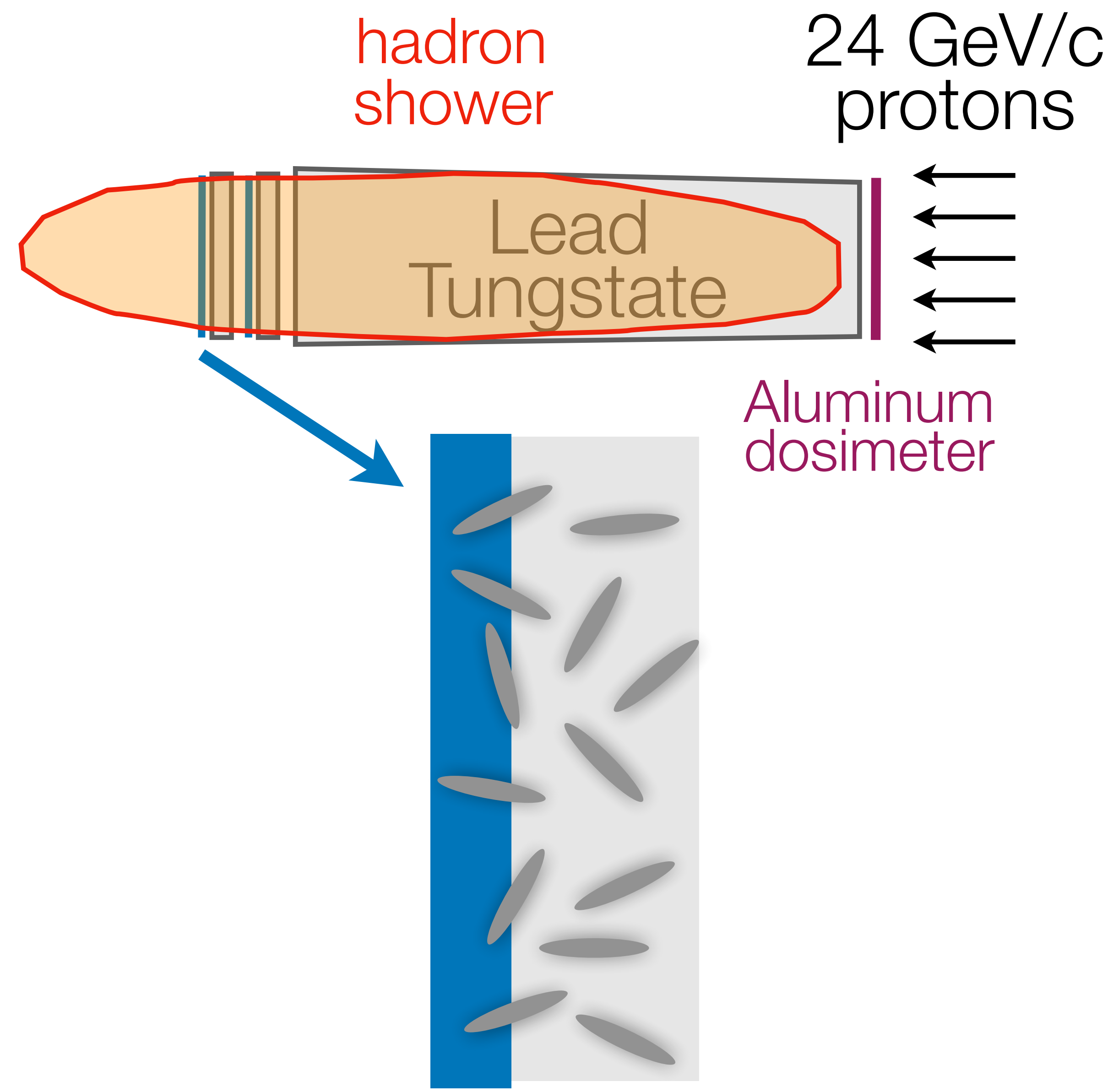
Muscovite mica naturally occurring near an Uranium-containing ore exhibits tracks due to fission fragments from surrounding minerals

- ... to a scientific method

Synthetic mica, $KAl_2(AlSi_3O_{10})(F,OH)_2$, contains only elements below the fission threshold: it only "records" damage tracks that originate outside of it: for this reason, mica is used as an "external detector" in geochronology.

Irradiation setup for damage visualization

- The irradiations have been performed at the CERN PS IRRAD1 facility
- Lead Tungstate slides, 2 mm thick, are placed behind a 7.5 cm long Lead Tungstate crystal, i.e. at a depth where the hadron shower is well developed
- A synthetic muscovite mica slide is placed in intimate contact with each of the Lead Tungstate slides



The mica is expected to "record" fission tracks that originate in Lead Tungstate

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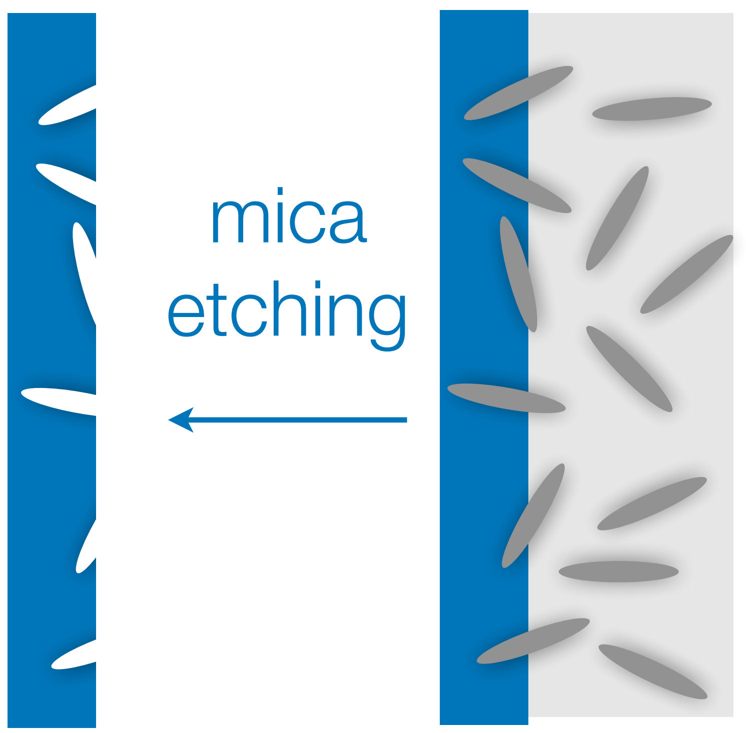

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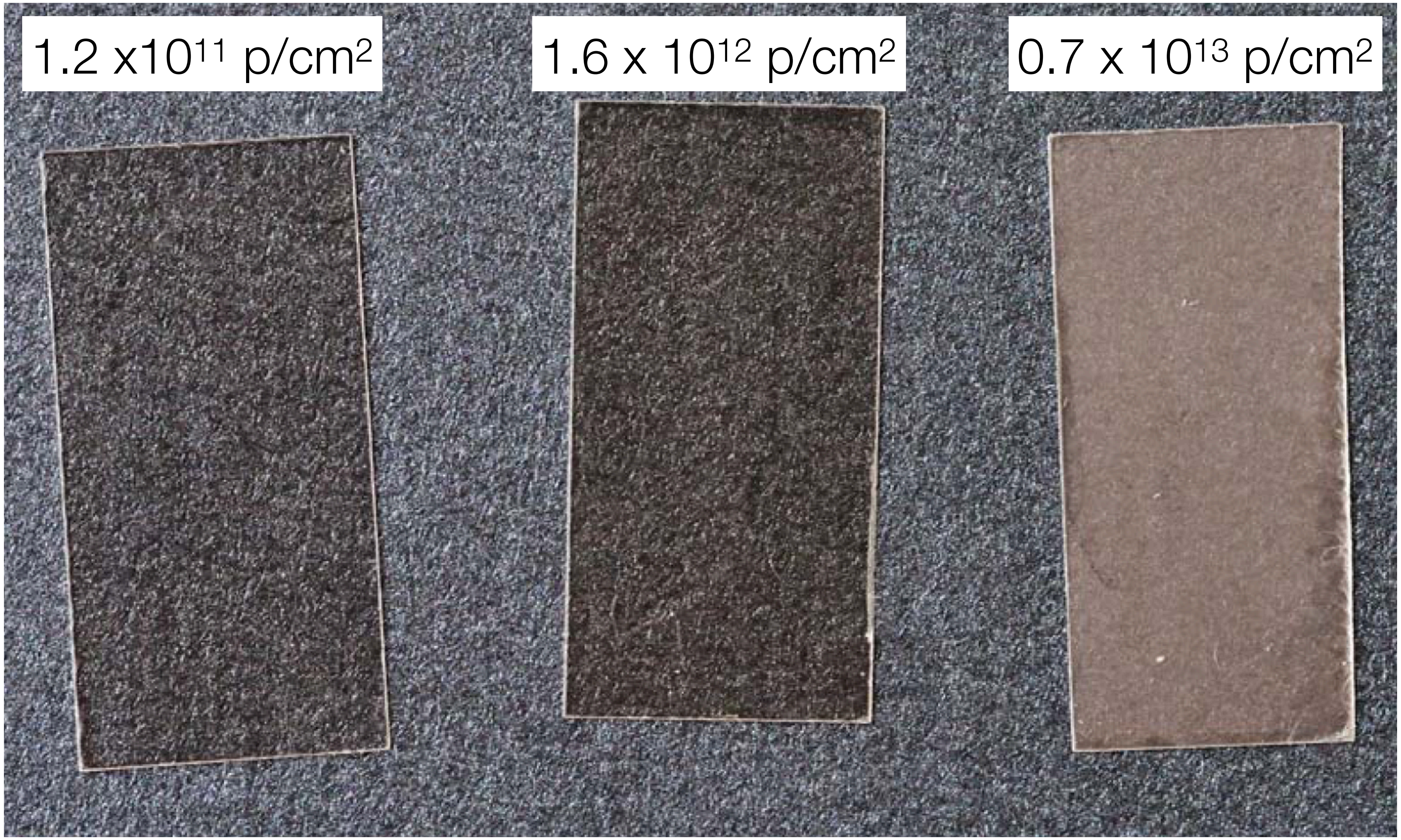
The damage in Mica is in a known metamictic state: it can be etched, to make it easily visible under the microscope

Visual examination of etched mica slides

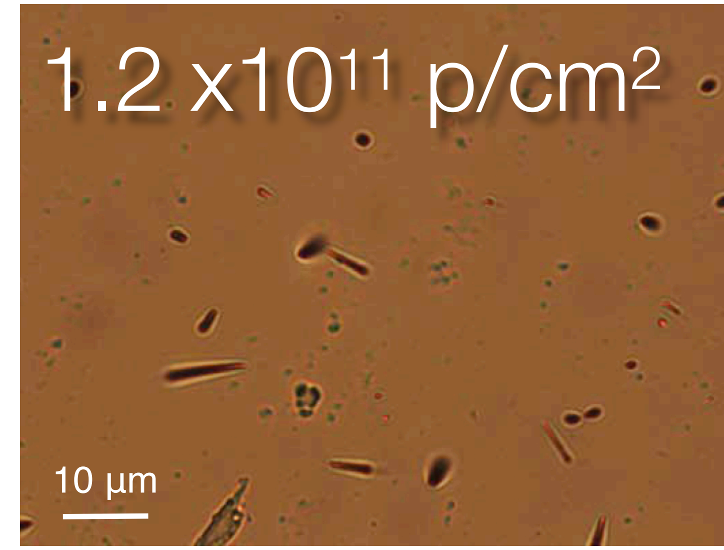


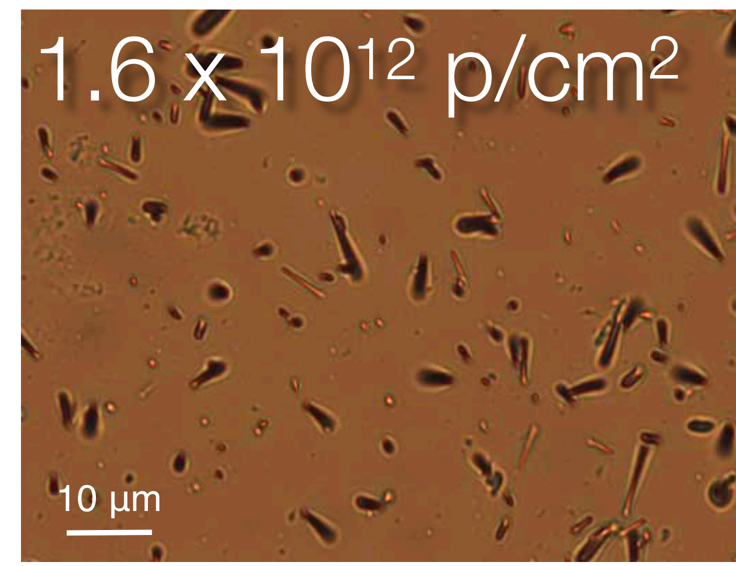
Slide dimensions: 10 mm x 20 mm x 0.1 mm

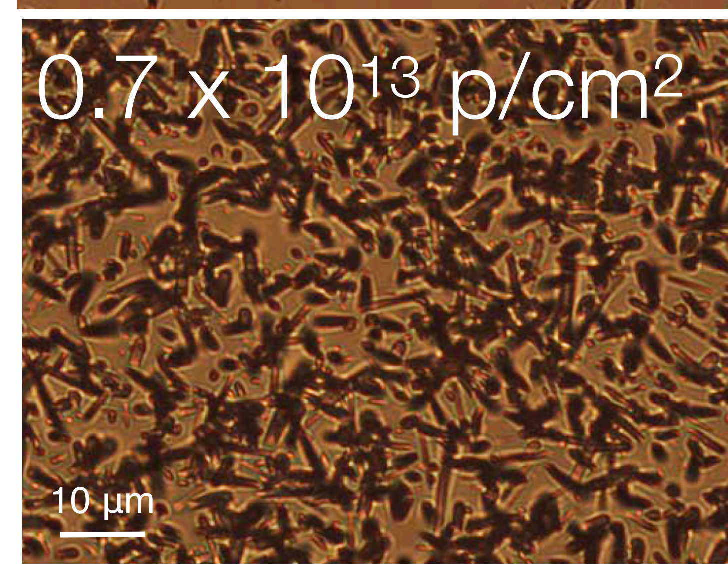
Etched mica under the microscope

- Tracks entering the mica are revealed under the optical microscope with 1000 x magnification
- Track density is proportional to irradiation fluence

proton fluence [cm^{-2}]	track density [cm^{-2}]	Ratio fluence/density
$(1.17 \pm 0.09)\times10^{11}$	2.9×10^{5}	$(4.0 \pm 0.3)\times10^{5}$
$(1.59 \pm 0.13)\times10^{12}$	2.8×10^{6}	$(5.6 \pm 0.5)\times10^{5}$
$(0.73 \pm 0.09)\times10^{13}$	no accurate count possible	N.A.







Results from visual mica examination

- There is a clear relationship between damage density and irradiation fluence
- All linear damage tracks intersect the mica face towards the $PbWO_4$ and there are no etched confined tracks, nor do they penetrate through the mica: the source of the damage tracks is external to the mica.
- The damage tracks are straight and occur in random orientations, as expected from fission within a hadron shower, and they don't follow any pre-existing fabric in the mica
- The average length of the damage tracks is visually similar to that formed by daughter isotopes from apatites and zircons.
- Only possible origin: the projection of break-up fragments from nuclei in the $PbWO_4$ that underwent fission

Conclusions - the understanding reached

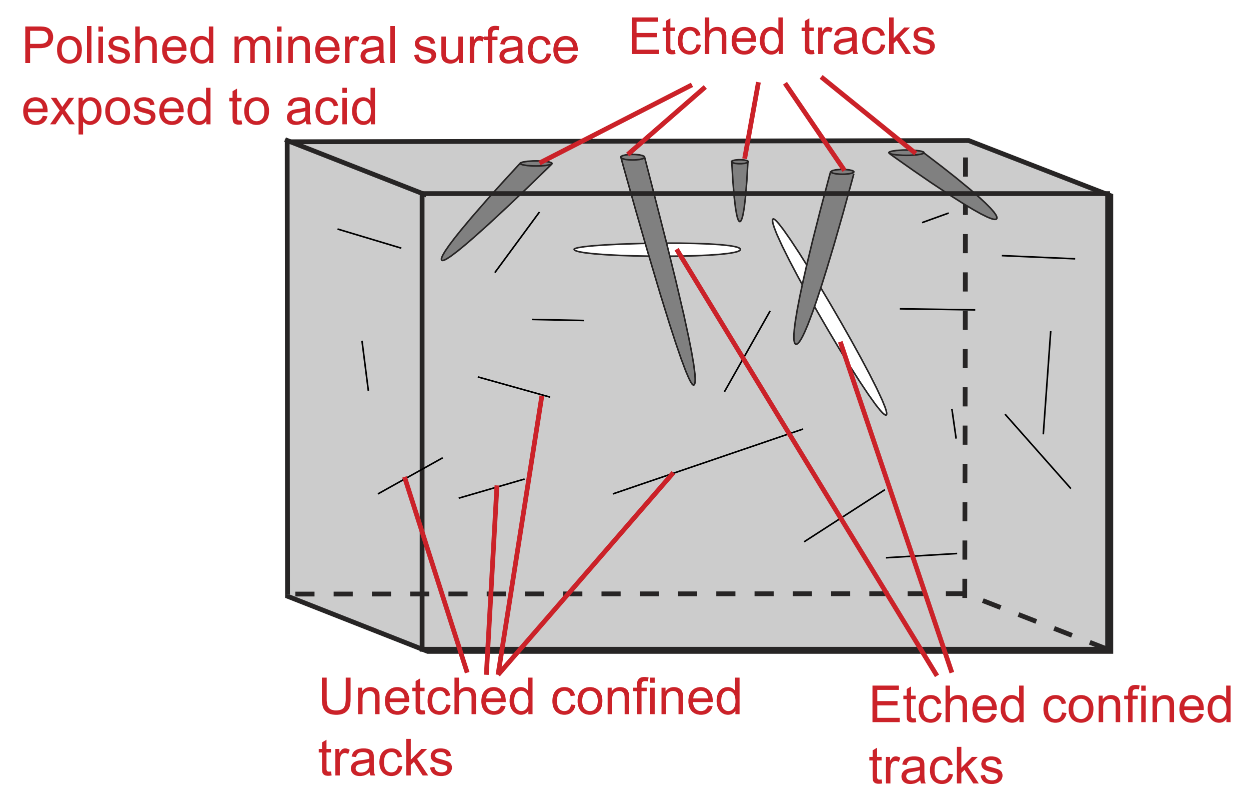
- Macroscopic observations show that light scattering centres are left in Lead Tungstate by hadron irradiation, which are permanent at room T
- Rayleigh-type light scattering occurs against the damage regions having "optical boundaries"
- These have been visualised as fission tracks entering mica used as an external detector

Backup slides

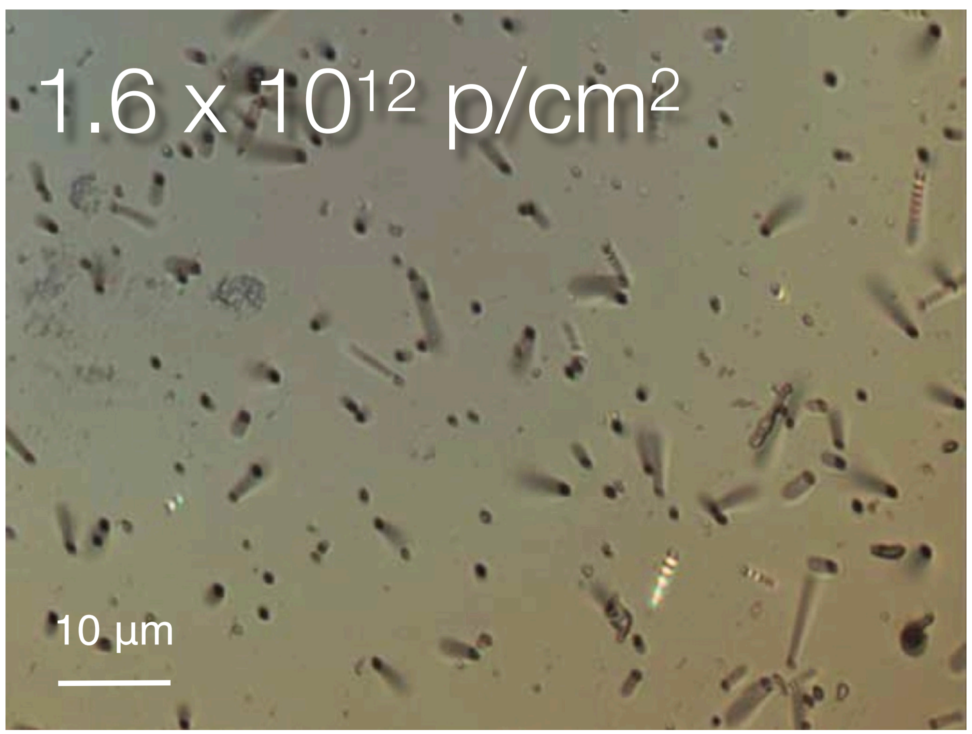
Track origin external

- No tracks exit the back side of the mica
- Reflected light images reveal no etched, confined tracks

➝ Tracks originate outside the mica



reflected light



transmitted light