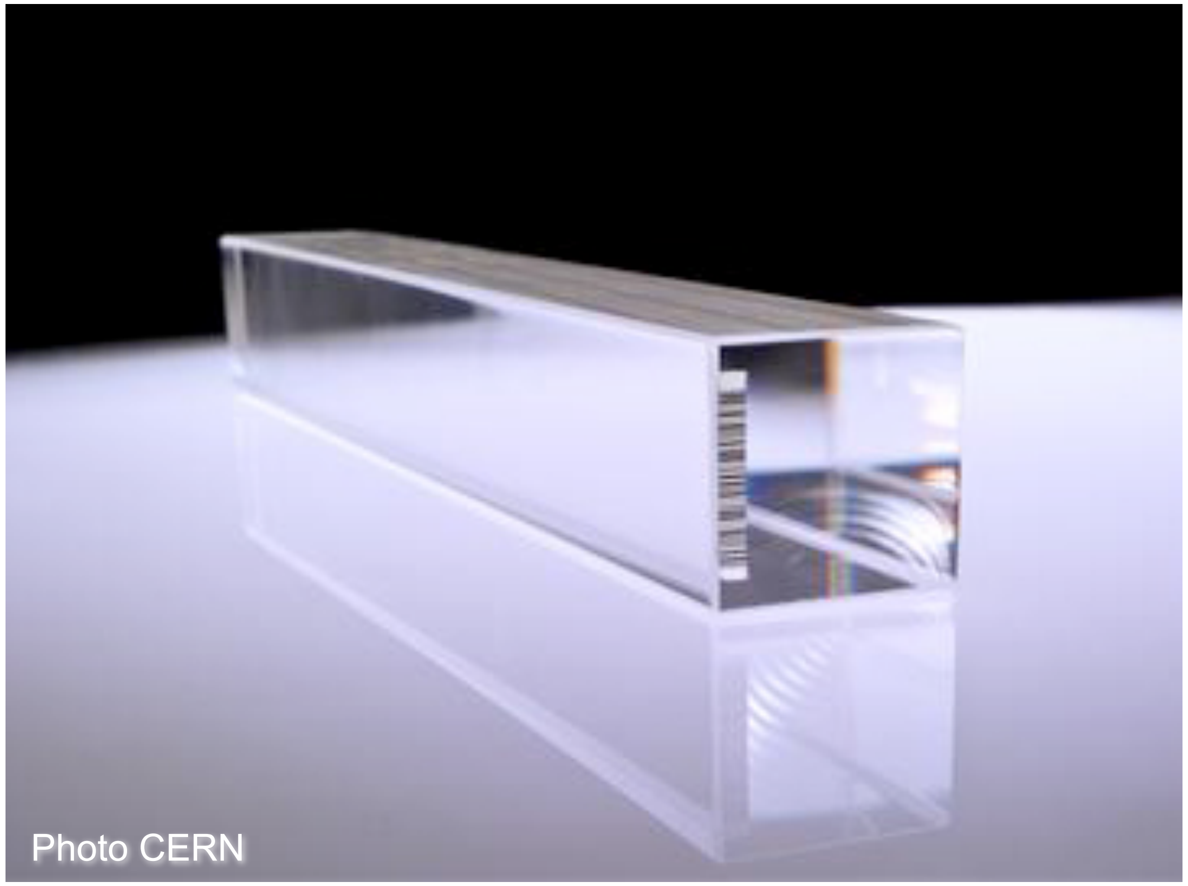
Studies of scintillating crystals for HEP calorimetry exposed to high hadron fluences

CERN PH Detector Seminar

Francesca Nessi-Tedaldi, ETH-Zürich

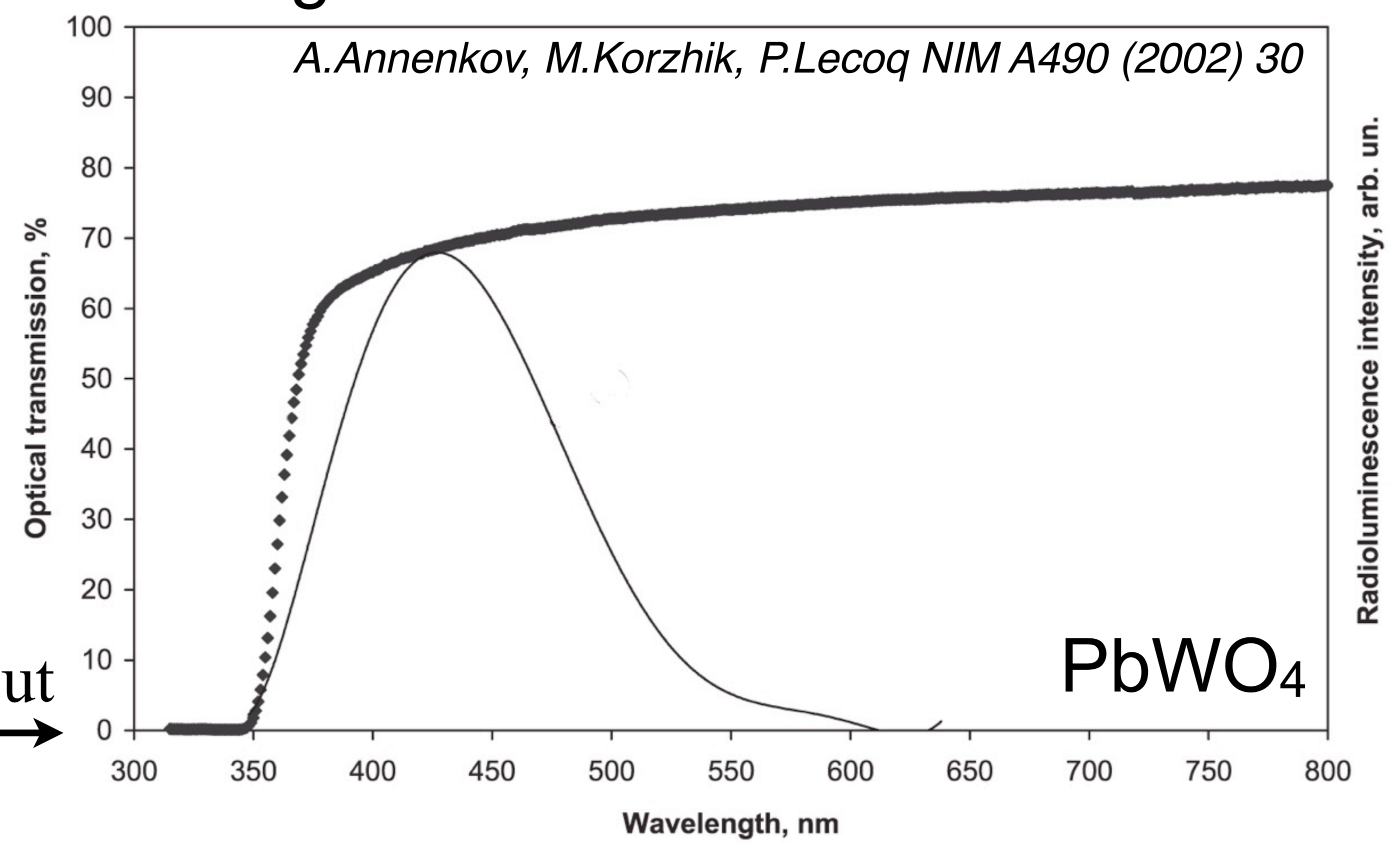
November 6, 2009

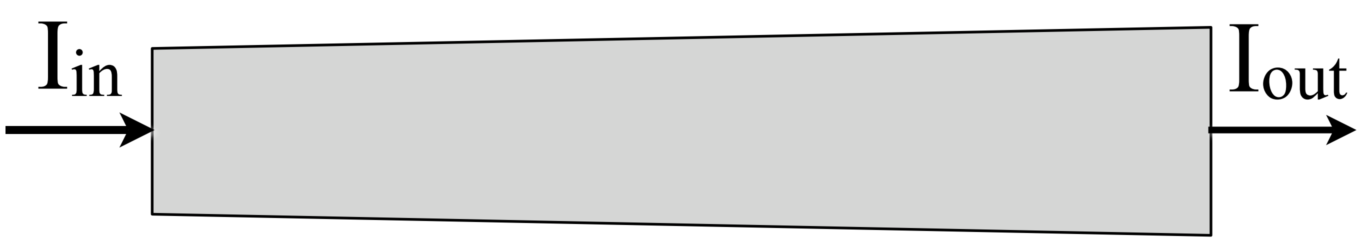
Ingredients



For calorimetry using scintillating crystals, needed are:

- → Scintillation emission
- → Light transmission





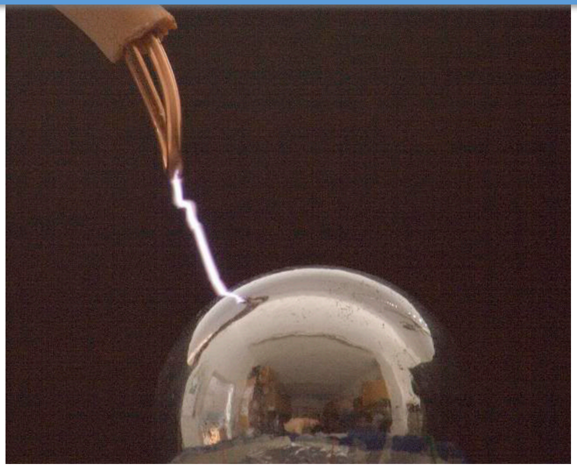
$$LT_0 = I_{out} / I_{in}$$

Depending on the environment, crystals can be exposed to:

- Ionizing radiation levels
- Hadron fluxes

and one needs to worry about how these might affect the above

Ionising radiation effects in crystals



... are known almost as long as electric phenomena

T.J.Pearsall (1830), J. Royal Inst. 1 (1830) 77

→ Electric sparks cause coloration to colorless Fluorite (probably using a Leyden jar)

E. Goldstein, Ann. der Phys und Chem. 54 (1895) 371

→ Cathode rays cause coloration to salt, ”blue halite”

→ the coloration reaches a saturation level

M. Belar, S.B. Akad. Wiss. Wien, IIa, 132 (1923) 45

→ removal of coloration observed in Fluorite, at a speed depending on T

R.W.Pohl (1926), Z. Physik 39 (1938) 36

→ Understanding the mechanism of coloration, concept of “Farbzentren” = color centers

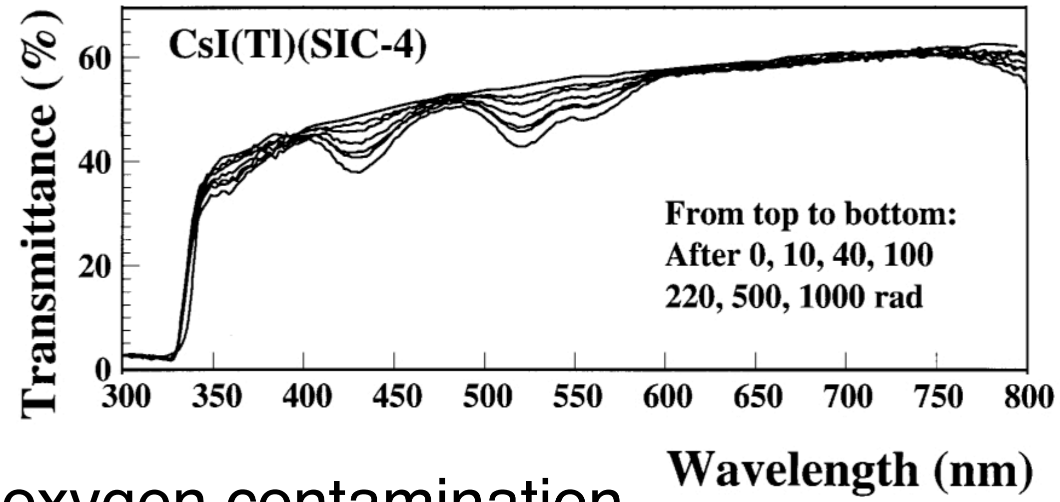
Technical applications:

→ screens for TV and radars, night vision, gem color “enhancement”

J.H.Schulman, W.D. Compton, “Color Centers in Solids”, Pergamon Press (1963)

Ionizing radiation effects in crystals for calorimetry

e.g. R.Y. Zhu, NIM A413(1998) 297-311 & ref. therein



1) Appearance of radiation-induced absorption bands
- Typically narrow in energy ("color centers")
- Reduction of Light Transmission (LT)
- Possibly loss of uniformity in Light Output

alkali halides (BaF_2 , CsI) Radiation damage related to oxygen contamination
oxides (BGO , $PbWO_4$) Radiation damage related to oxygen vacancies and impurities

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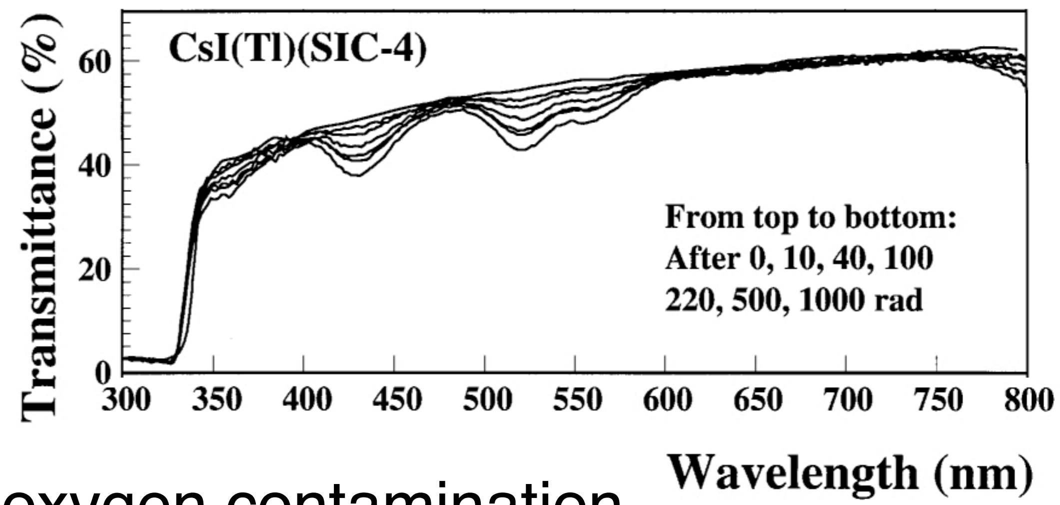

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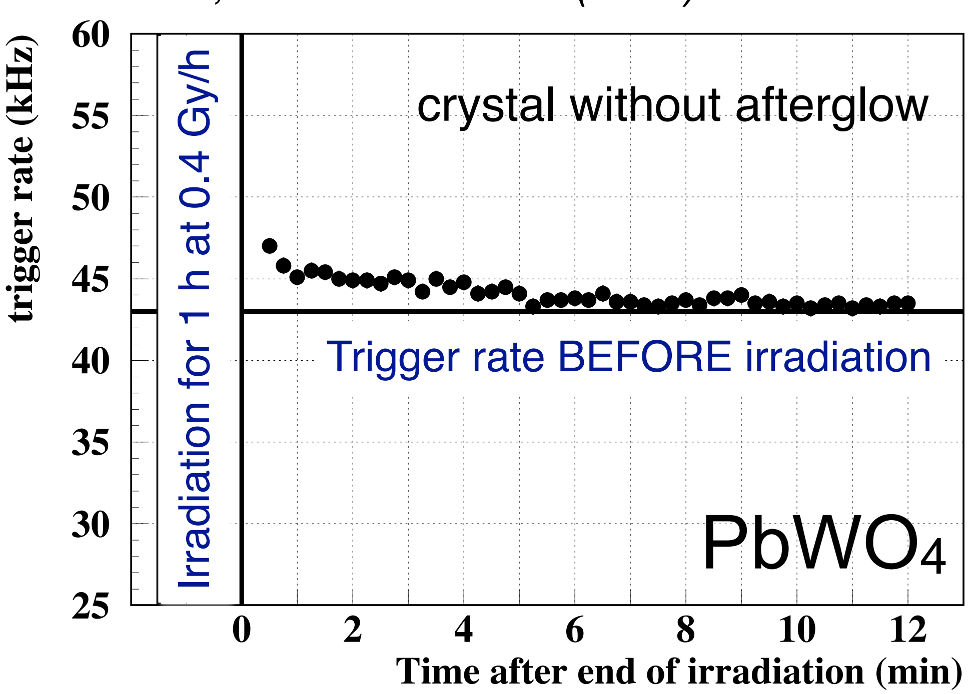
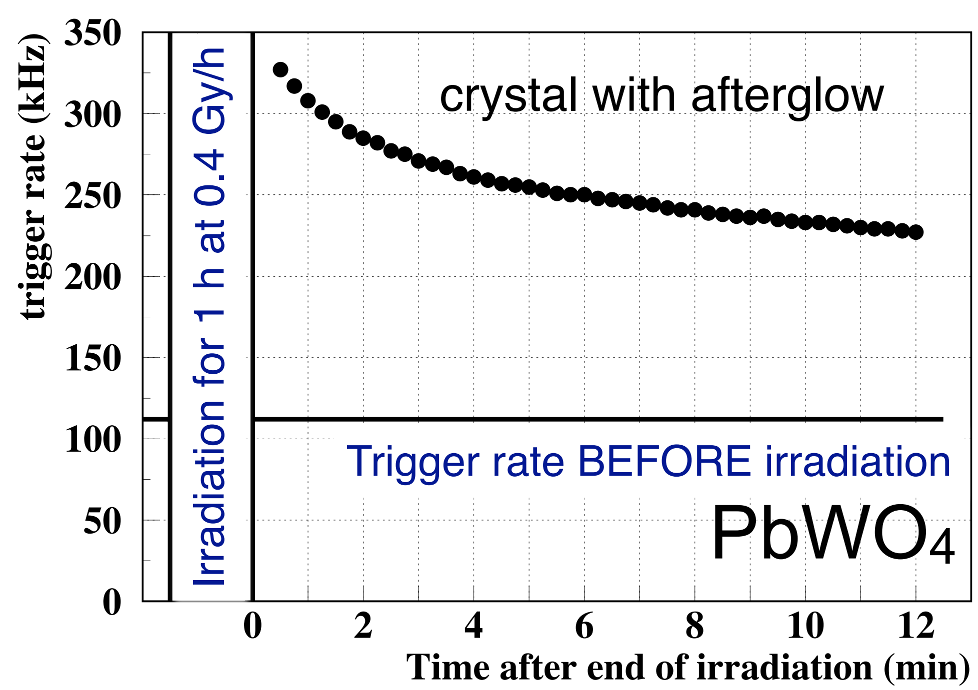
2) Phosphorescence / afterglow

P.Lecomte, F.N-T. et al. A414 (1998) 149-155





Afterglow detected in $PbWO_4$ as photomultiplier single photoelectron counting rate after irradiation.

- Noise increase in detected Light - *energy equivalent contribution negligible e.g. for $PbWO_4$ in LHC experiments* *(R.Y. Zhu et al., NIM A376(1996) 319)*

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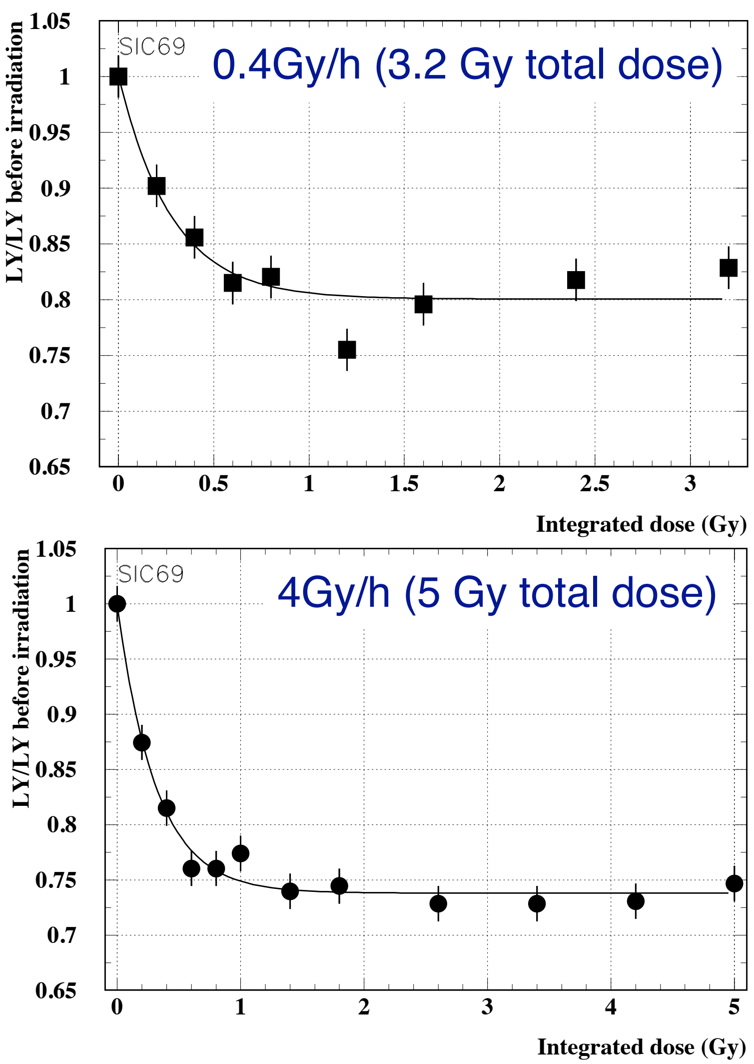

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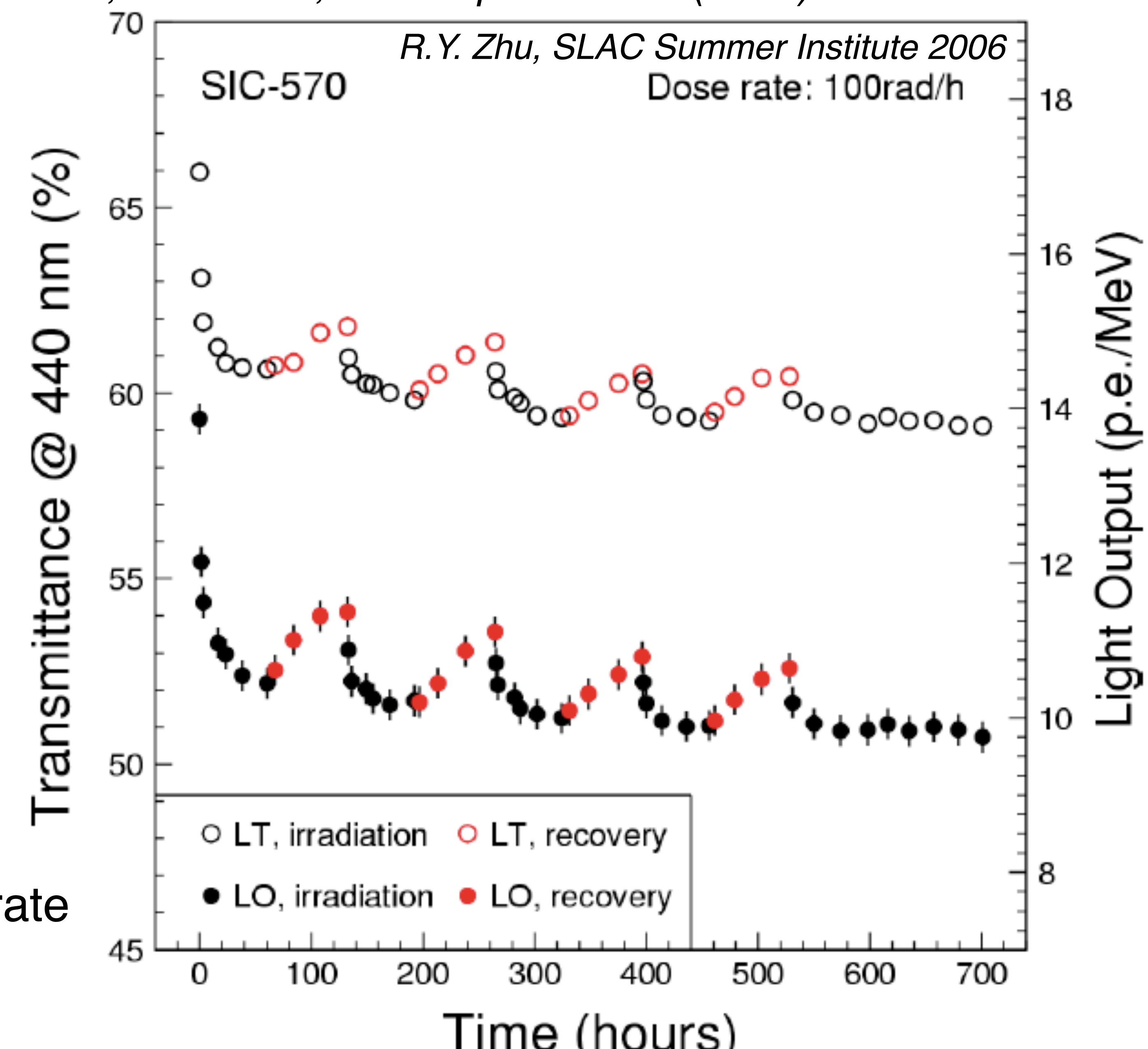


- Damage equilibrium level dependens on dose rate
- Recovery speed ⇔ depth of traps

What about high hadron fluences?

Continuation of studies performed in the past on other calorimeter crystals, e.g.:

BGO, M. Kobayashi et al., NIM 206 (1983) 107-117

CsI, M. Kobayashi et al., NIM A328 (1993) 501-505

Questions

- Is there a specific, possibly cumulative damage from hadrons?
- If so, what is its quantitative importance?
- Does it affect the light transmission only, and can it thus be “easily” monitored?
- Or else, does it alter the scintillation mechanism?

→ Studies on $PbWO_4$

Questions

- Understanding of hadron effects observed in $PbWO_4$
- Complementary tests to confirm our qualitative understanding
- Performance of different crystal types
- Crystals particularly suited for sLHC

→ Studies on CeF_3

→ Studies on LYSO

Main crystals for HEP calorimetry

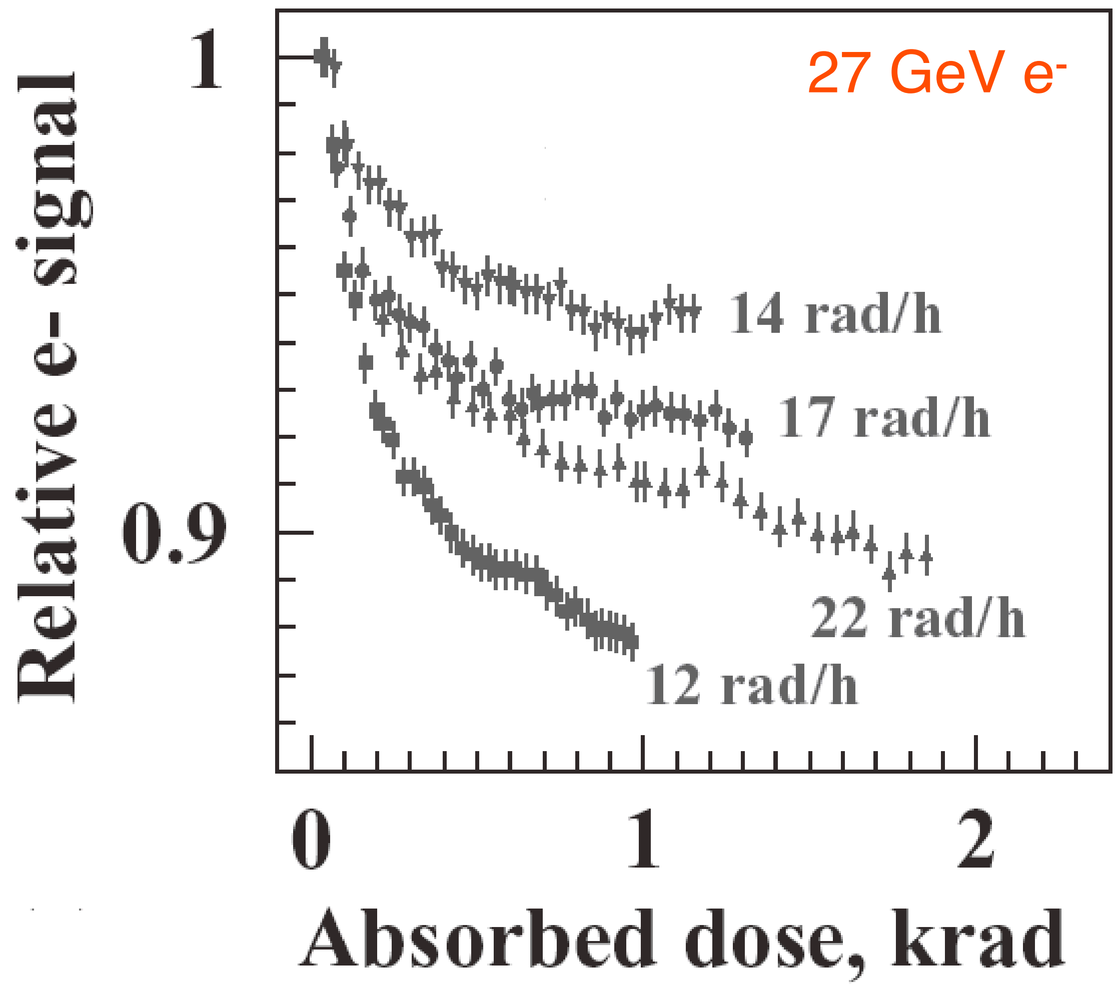
crystal	NaI(Tl)	CsI(Tl)	CsI (pure)	BaF_2	BGO	CeF_3	$PbWO_4$	LYSO(Ce)
Density [g/cm^3]	3.67	4.51	4.51	4.89	7.13	6.16	8.30	7.40
Melting point [°C]	651	621	621	1280	1050	1460	1123	2050
Radiation length [cm]	2.59	1.86	1.86	2.03	1.12	1.70	0.89	1.14
Moliere Radius [cm]	4.13	3.57	3.57	3.10	2.23	2.41	2.00	2.07
dE/dx (mip) MeV/cm	4.80	5.60	5.60	6.60	9.00	7.90	10.20	9.60
Interaction Length [cm]	42.9	39.3	39.3	30.7	22.8	23.2	20.7	20.9
Decay Time [ns]	245	1220	30 6	650 0.9	300	10-30	30 10	40
peak λ emission [nm]	410	550	420 310	300 220	480	310-340	425 420	430
Refractive Index	1.85	1.79	1.95	1.50	2.15	1.62	2.20	1.82
Relative Light Yield [%]	100	165	3.6 1.1	36 4.1	21	7.30	0.30 0.08	85
dLY/dT [%/°C]	-0.2	0.4	-1.4	-1.9 0.1	-0.9	~0	-2.5	-0.2
hygroscopic?	Yes	Slight	Slight	No	No	No	No	No

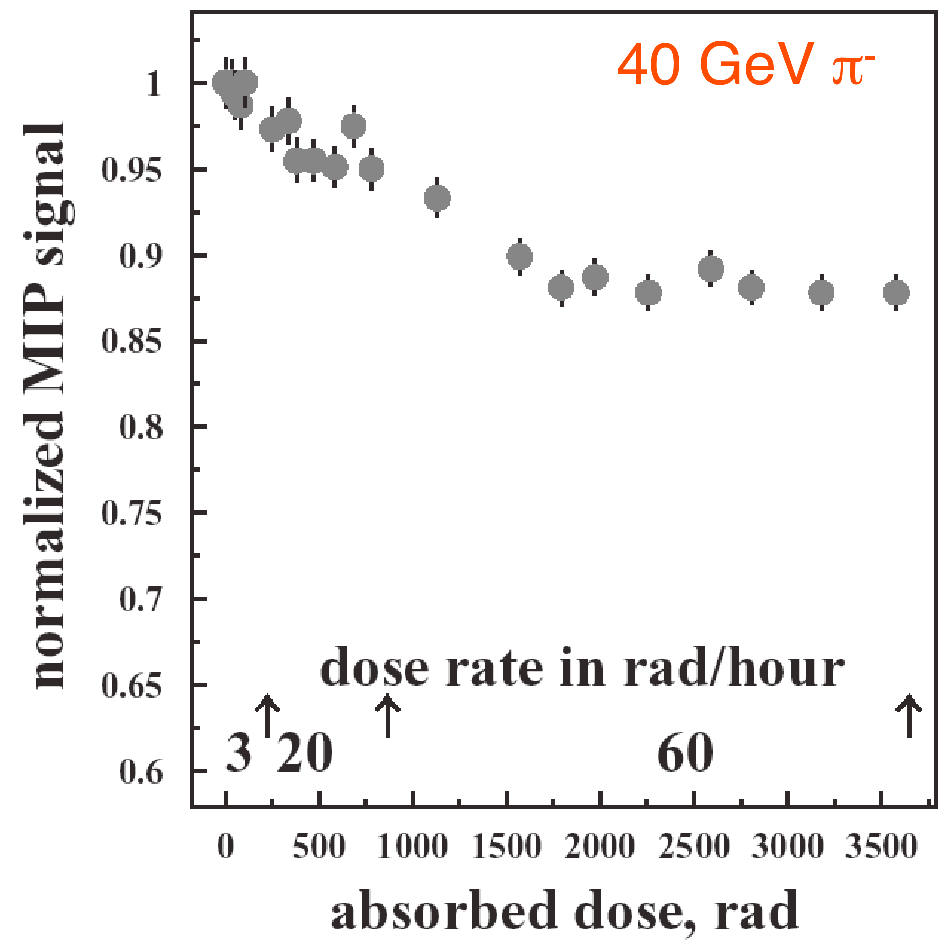
From the Review of Particle Properties, C.Amsler et al., Phys. Lett. B 667 (2008) 1, and earlier versions

e⁻ and π irradiations of $PbWO_4$ at IHEP Protvino

V.Batarin et al, NIM A512 (2003) 488-505
V.Batarin et al, NIM A530 (2004) 286-292
V.Batarin et al., NIM A540 (2005) 131-139

Irradiation studies between 1 and 60 rad/h up to 2 krad





- Behavior similar for e^- and π^-
- Damage appears to reach equilibrium at a dose-rate dependent level
- No indication of damage to scintillation mechanism from π irradiation

Caveat: Total absorbed dose expected at LHC not explored.
Additional, specific, possibly cumulative damage from hadrons not excluded.

Super-intense hadron beam tests of $PbWO_4$ at IHEP Protvino

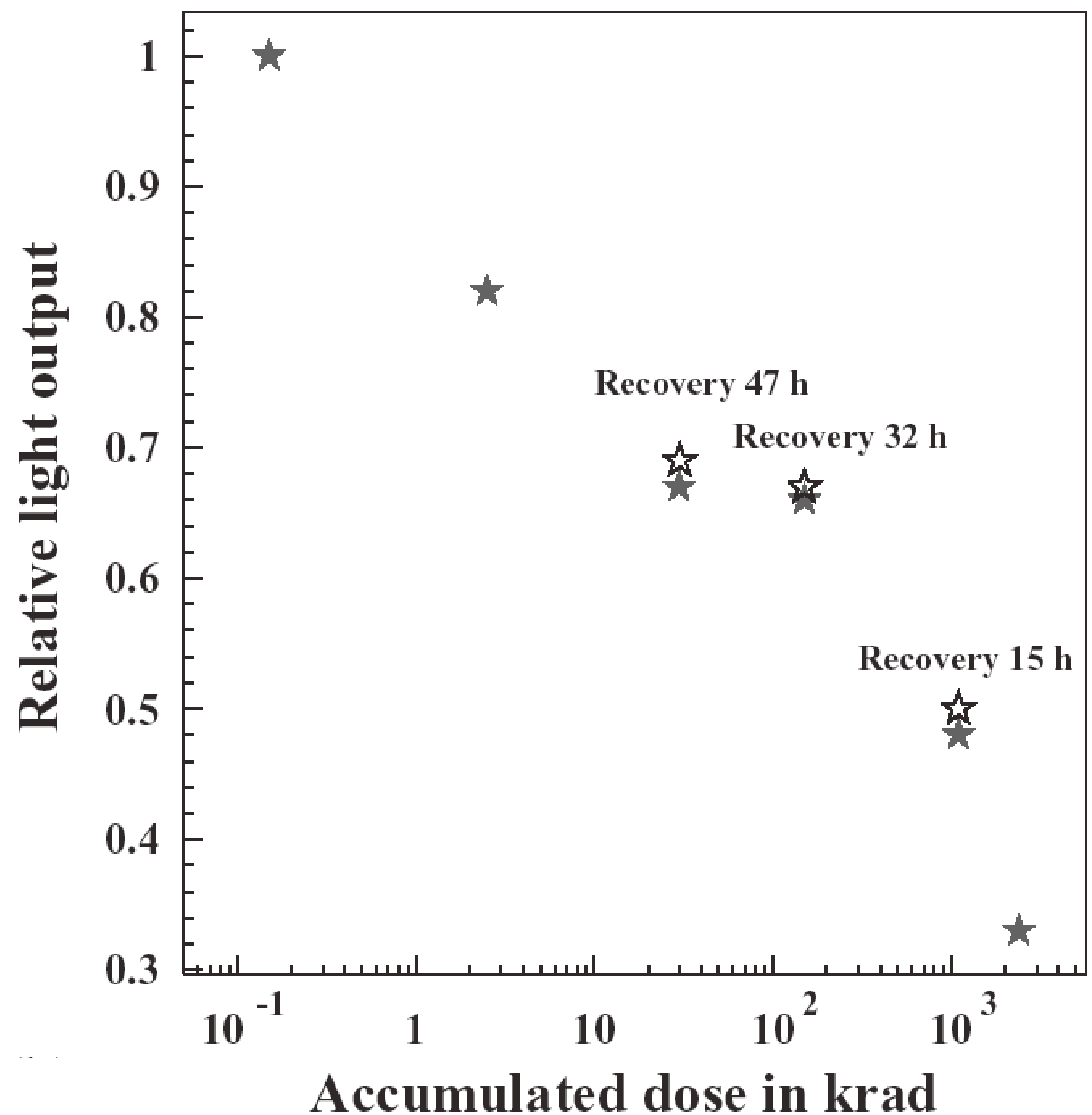
Mixed beam of charged hadrons, neutrons and γ with dose rates of 100 krad/h.

- Constant flux.
Damage increases with accumulated dose

- Unlike purely ionizing radiation damage

- Hint towards an additional, cumulative, hadron-specific contribution

V.Batarin et al, NIM A512 (2003) 488-505



Irradiations

Proton irradiations:

IRRAD1 irradiation zone of the CERN PS

Facility operations and dosimetry by M.Glaser and F. Ravotti.

Demanding beam conditions provided by R. Steerenberg and the CERN-PS accelerator staff.

Radioprotection issues: V. Tromel, M. Widorski

Complementary γ-irradiations:

Performed in the Calliope ^{60}Co irradiation plant at ENEA Rome.

Facility operations by S. Baccaro and her staff

Pion irradiations:

Performed in the high-flux secondary pion beam line πE1 at the PSI 590 MeV Ring Cyclotron

Beam provided by A.-Ch. Mezger and the PSI accelerator staff.

Dosimetry by F. Jaquenod and F. Malacrida

Expected particle fluences [cm^{-2}] for 2500 fb^{-1}

- Barrel ($\eta < 1.5$): ~10^{12} cm^{-2} charged hadrons
- End Caps ($1.5 < \eta < 3$): up to ~10^{14} cm^{-2} charged hadrons

Neutrons:

- Below 20 MeV, no effect besides ionizing dose, tested up to 10^{14} cm^{-2}

  R. Chipaux et al. Proc. Mat Res. Soc. 358 (1994) 481
- Above ~20 MeV, effects as for charged hadrons

Effect on $PbWO_4$ Light Transmission by 20 GeV/c protons and ^{60}Co γ

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

A comparative study of the effect of protons and γ

1) Irradiation using 20 (24) GeV/c protons

- Flux between $5x10^{11}$ p/cm^2/h and 10^{12} p/cm^2/h up to various fluences:
  crystals *a, b, c, d, h*
- Flux of 10^{13} p/cm^2/h up to various fluences:
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2) Complementary ^{60}Co γ irradiations

- Dose rate of 1 kGy/h - as in a flux of 10^{12} p/cm^2/h - up to various total doses: crystals *t, u, v, w, x, y, z*

23 cm (25 X_0) long crystals used, produced by the Bogoroditsk Techno-Chemical Plant.
All crystals of production quality.

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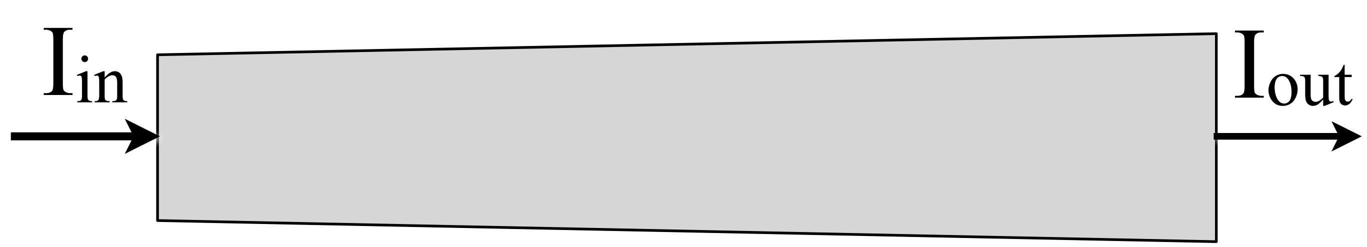

$$LT0 = I_{out} / I_{in}$$

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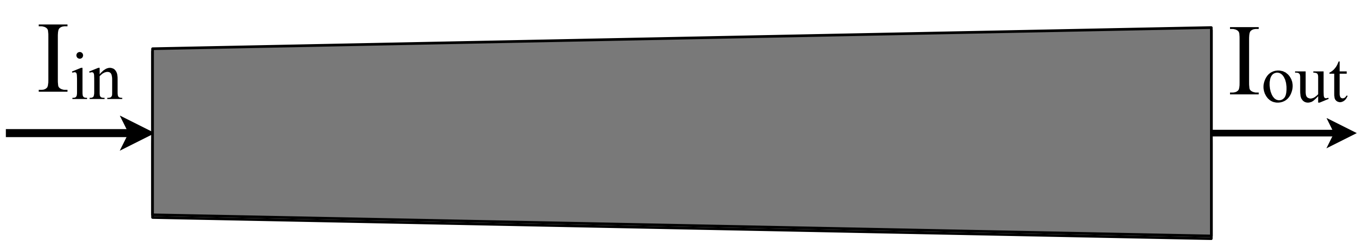

$$LT = I_{out} / I_{in}$$

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

L = crystal length, $[\mu_{IND}]$=m^{-1}

Transmission changes in $PbWO_4$ for 20 GeV/c protons and ^{60}Co γ

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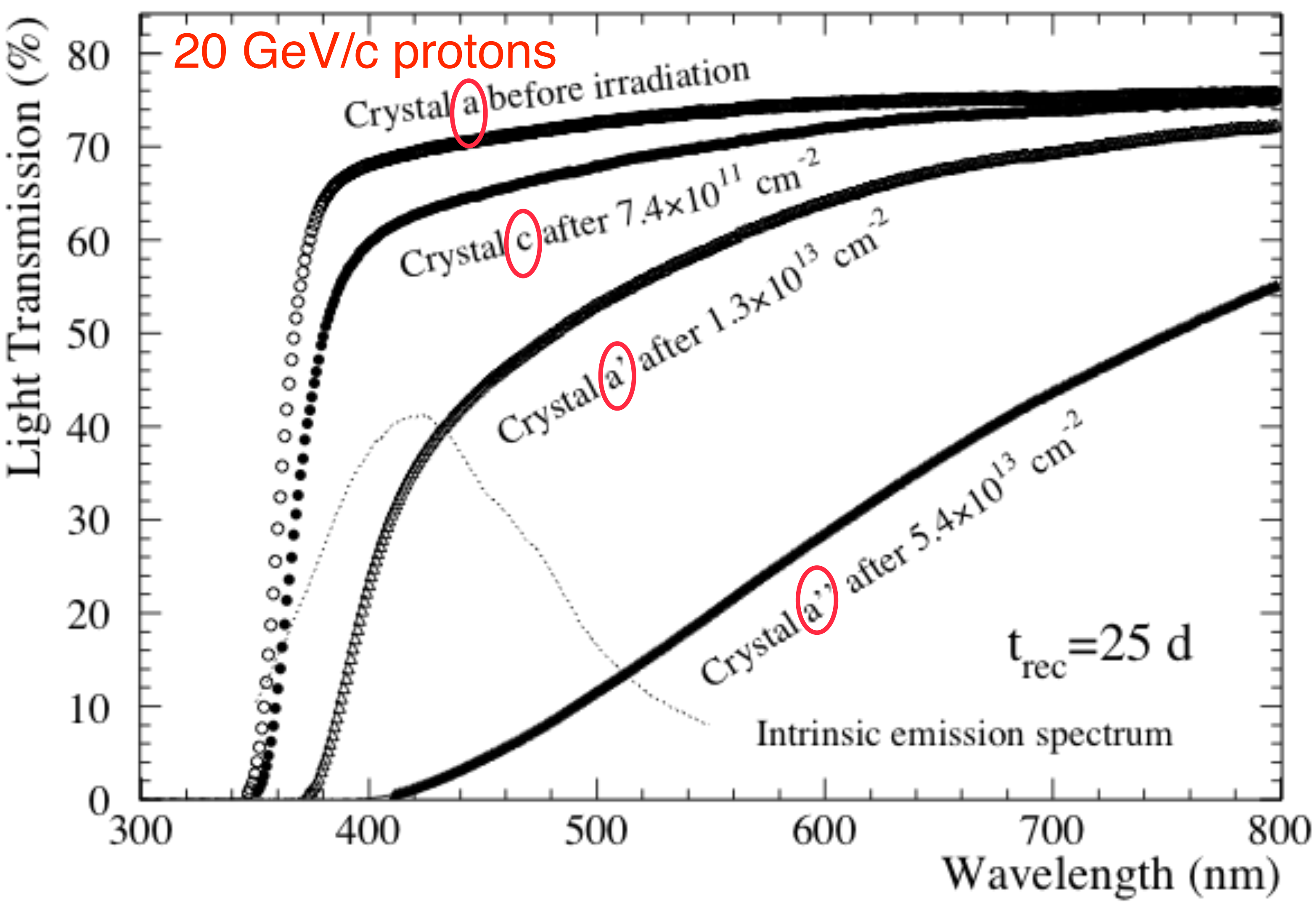

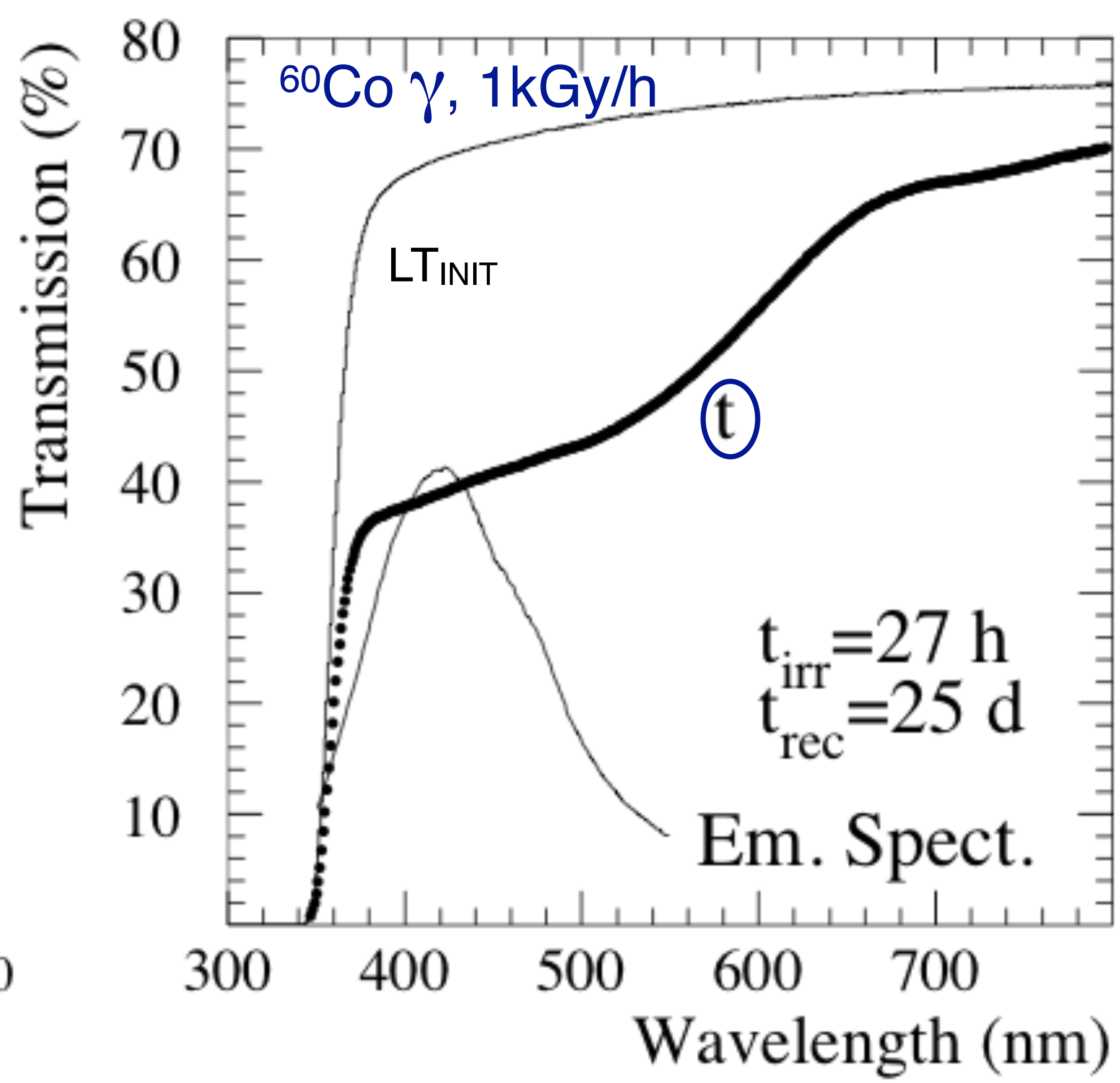

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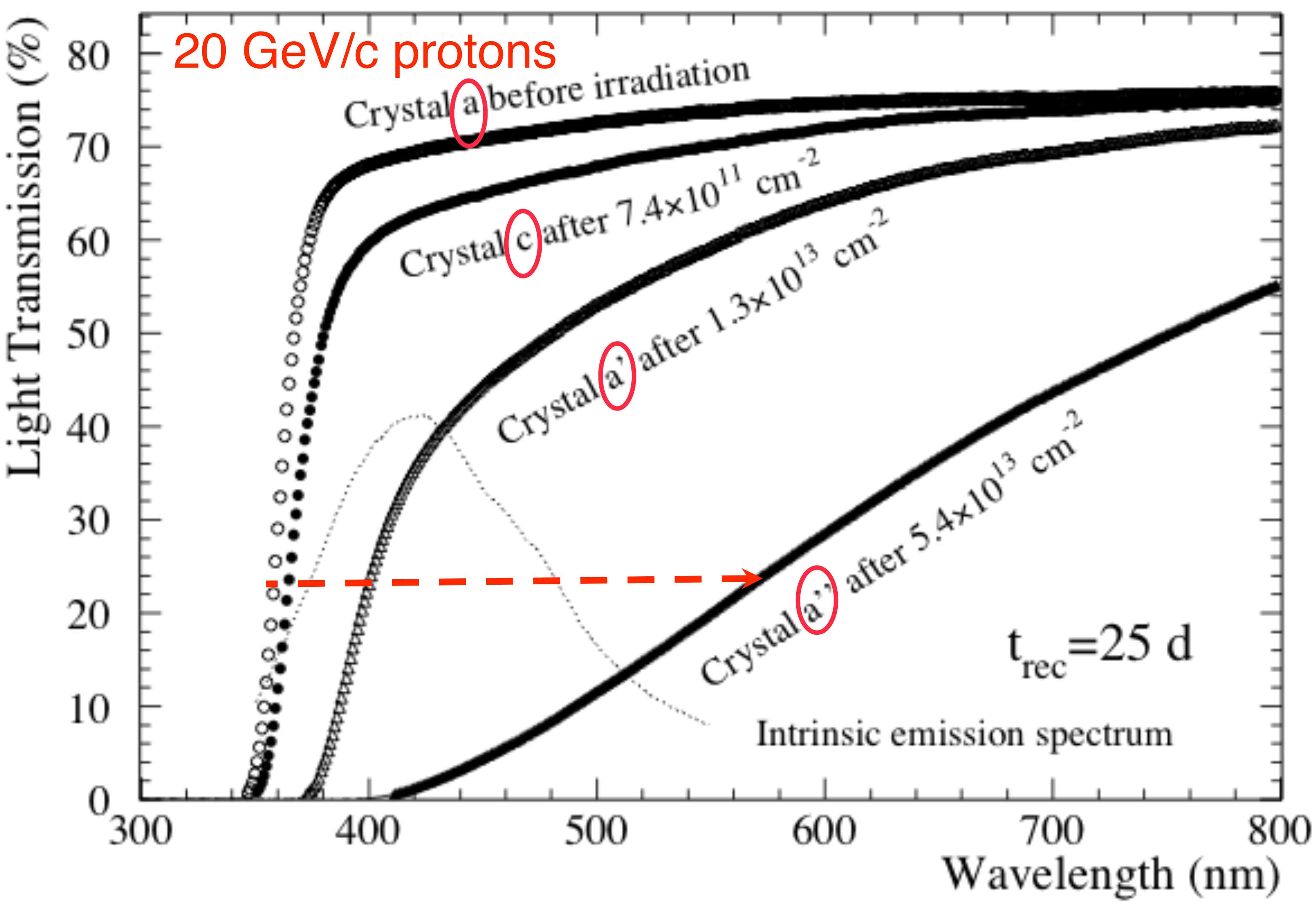
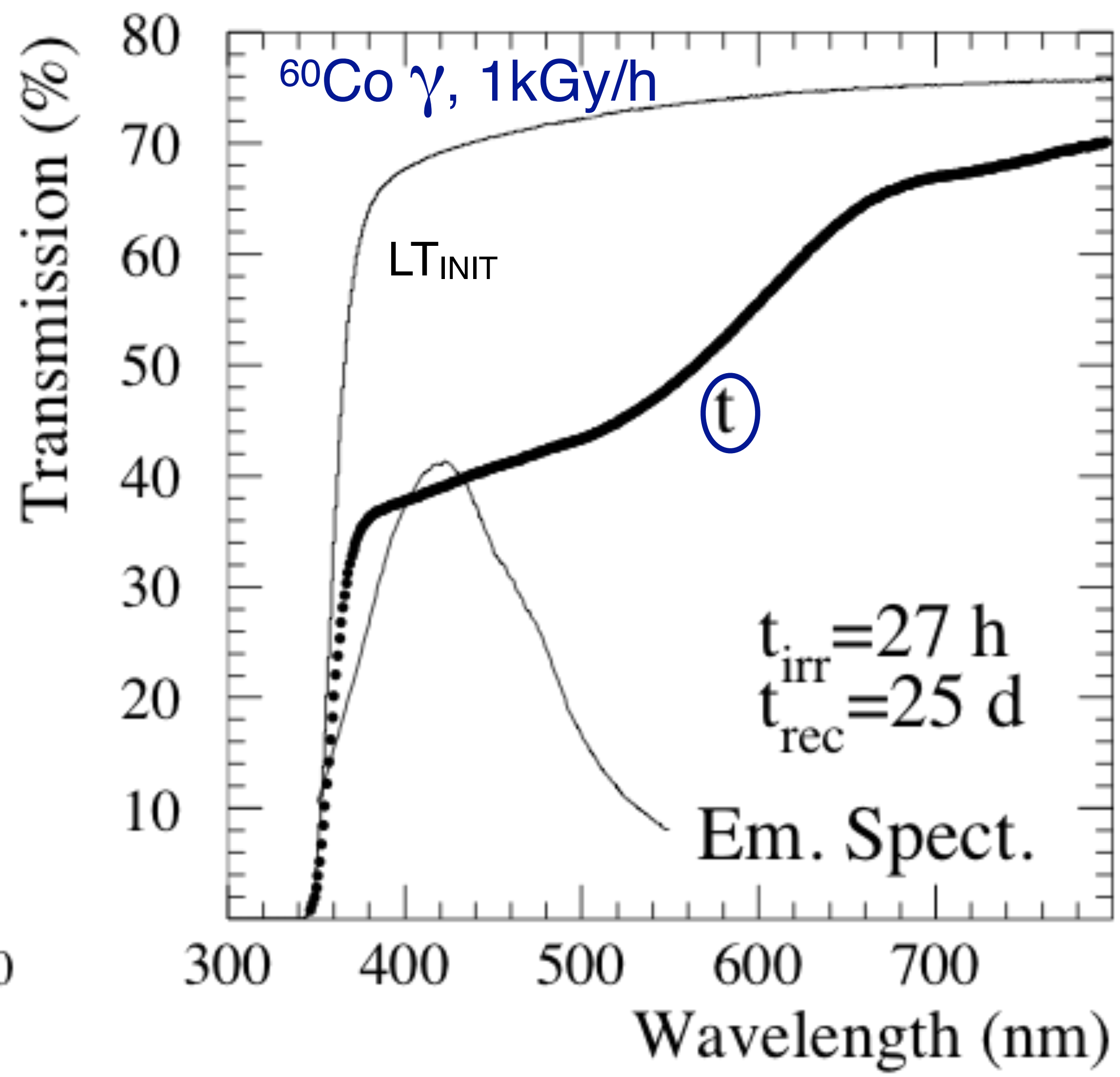
(*) explanation likely to be disorder causing an Urbach-tail





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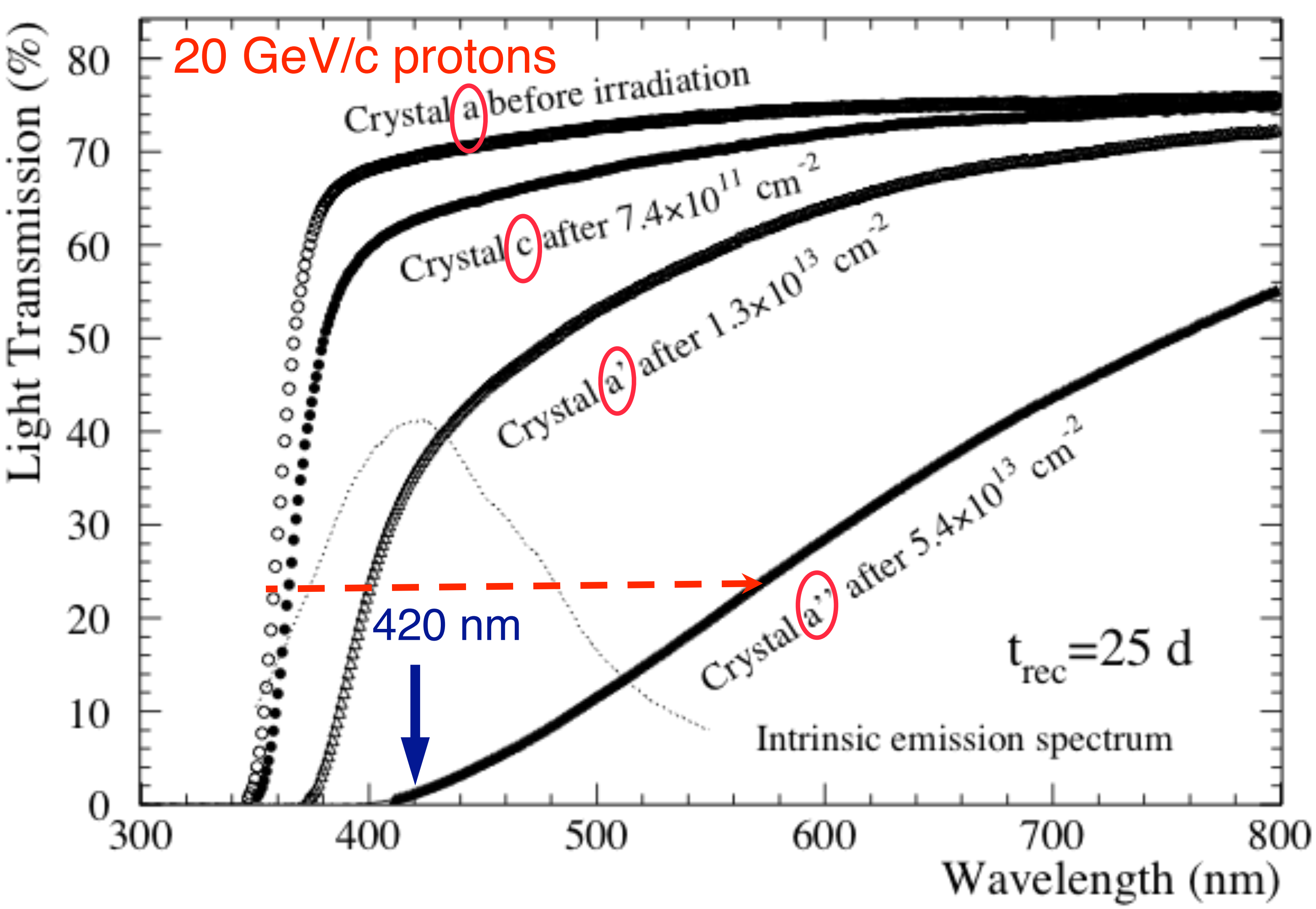
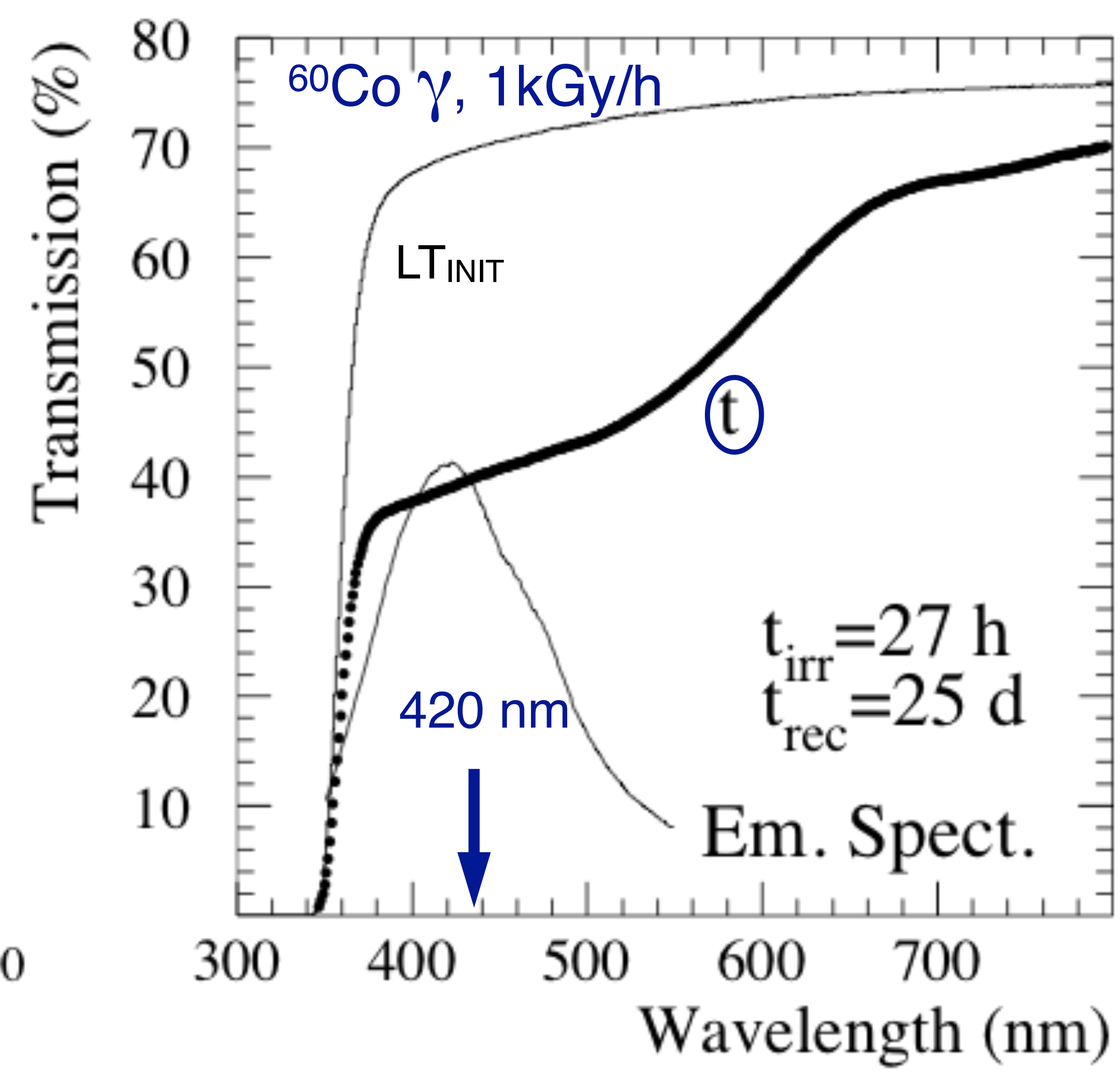
→ evaluate damage further at the peak-of-emission λ = 420 nm





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Features of p-irradiated $PbWO_4$ crystals

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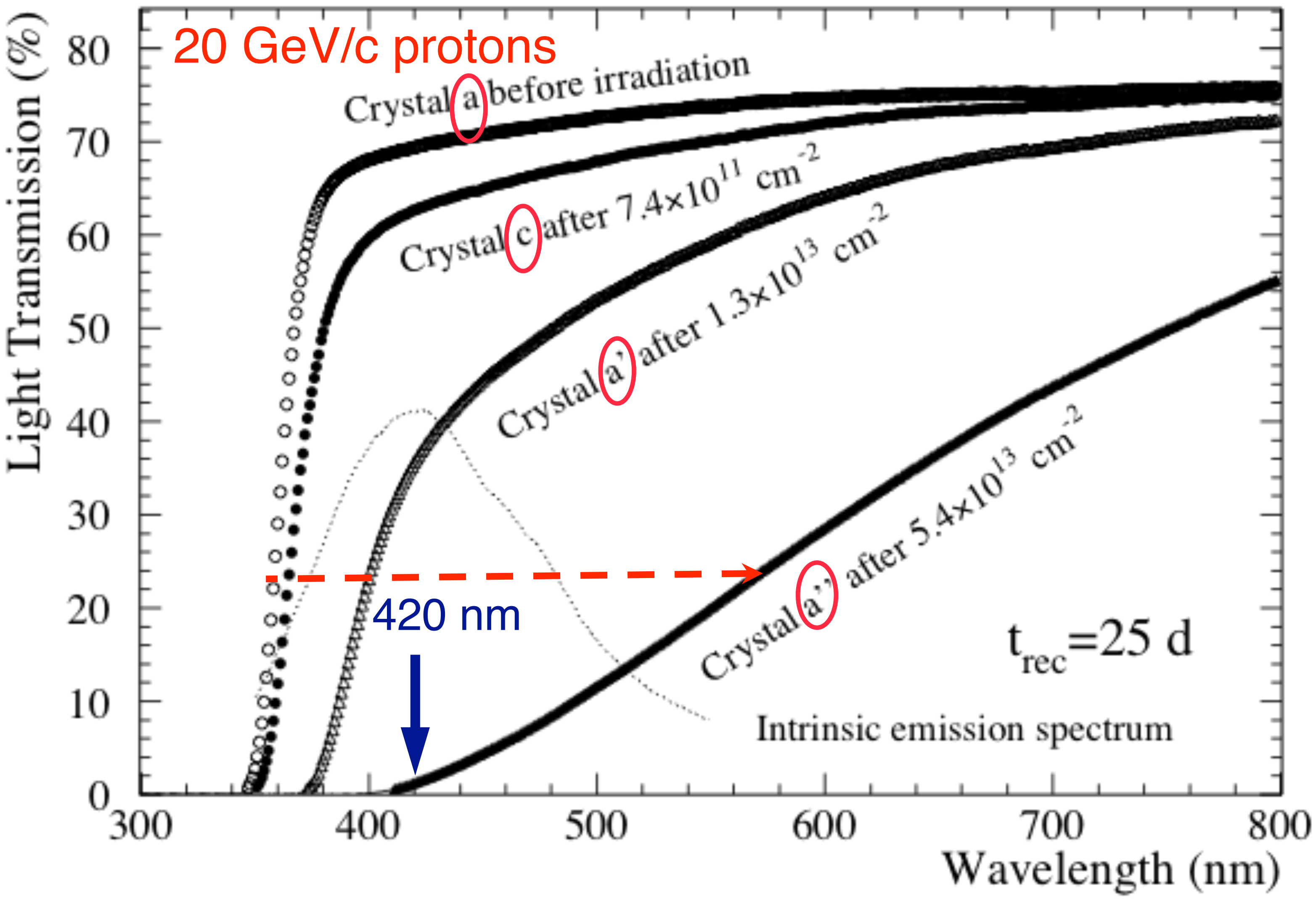

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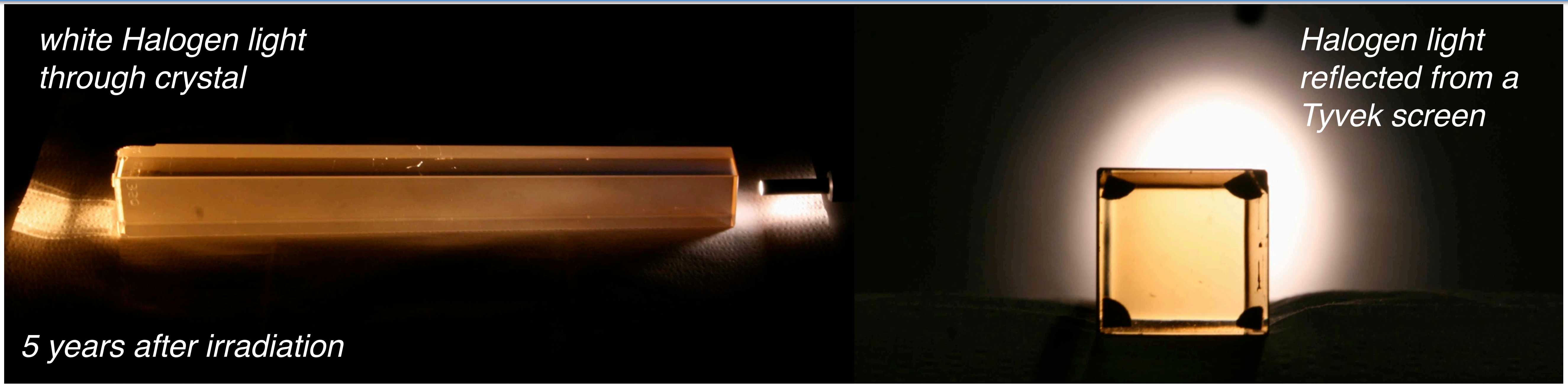

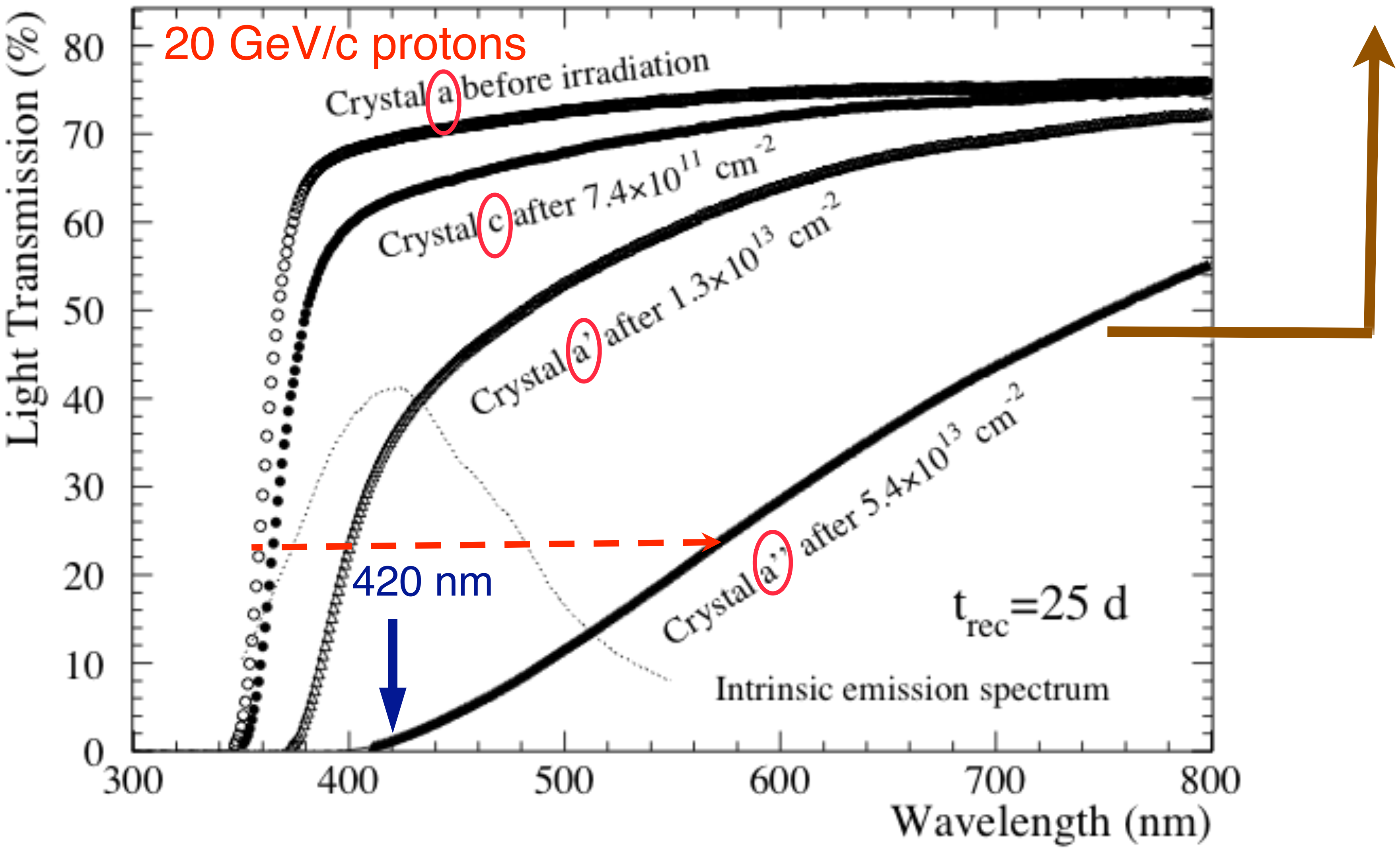

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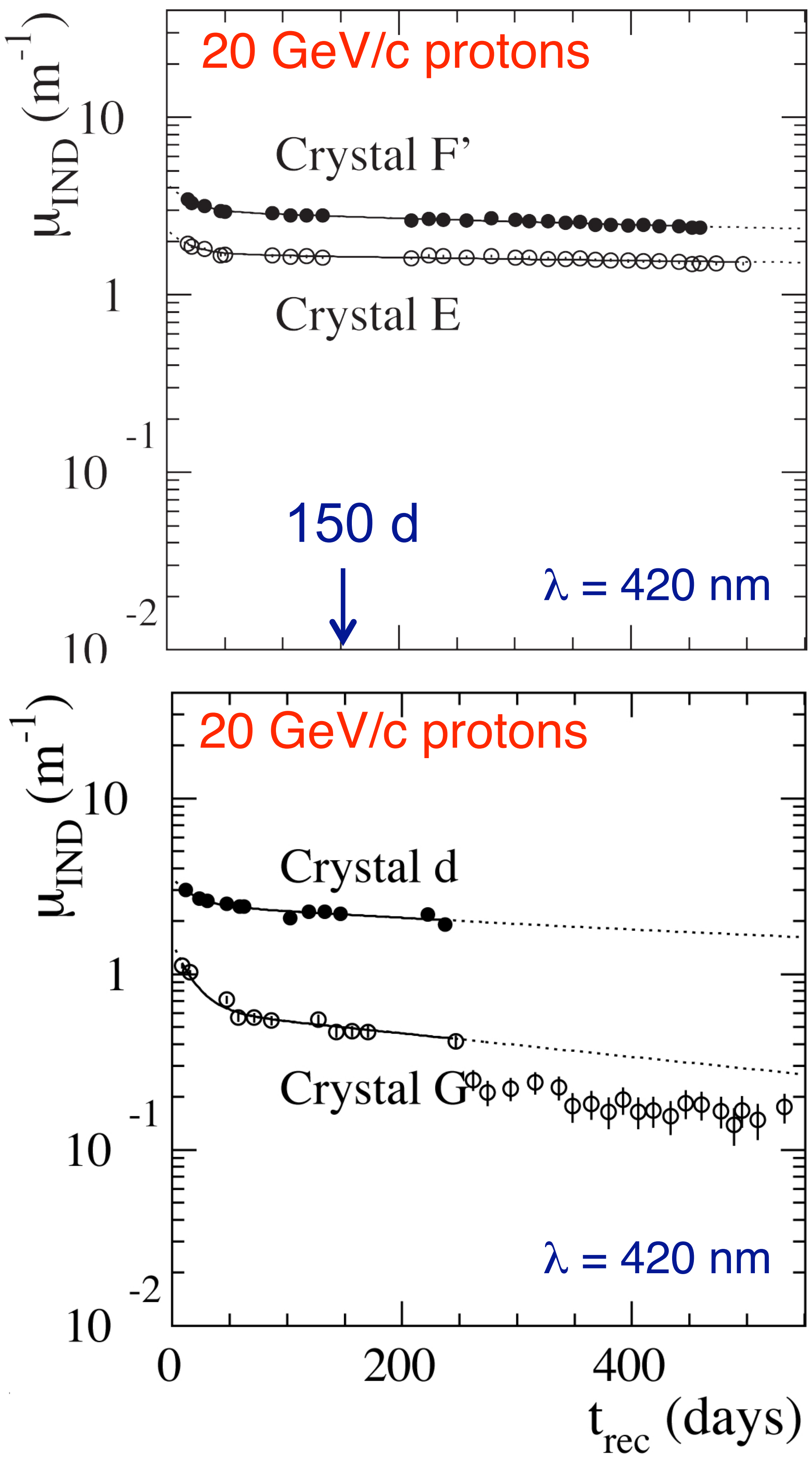
LT recovery features in hadron-irradiated PbWO4



A fraction of the p-damage recovers in the dark, at room-T, with τ_1 = 17.2 days and τ_2 = 650 days, as for γ-damage

Damage at 150 days ~ stable → use for further evaluation

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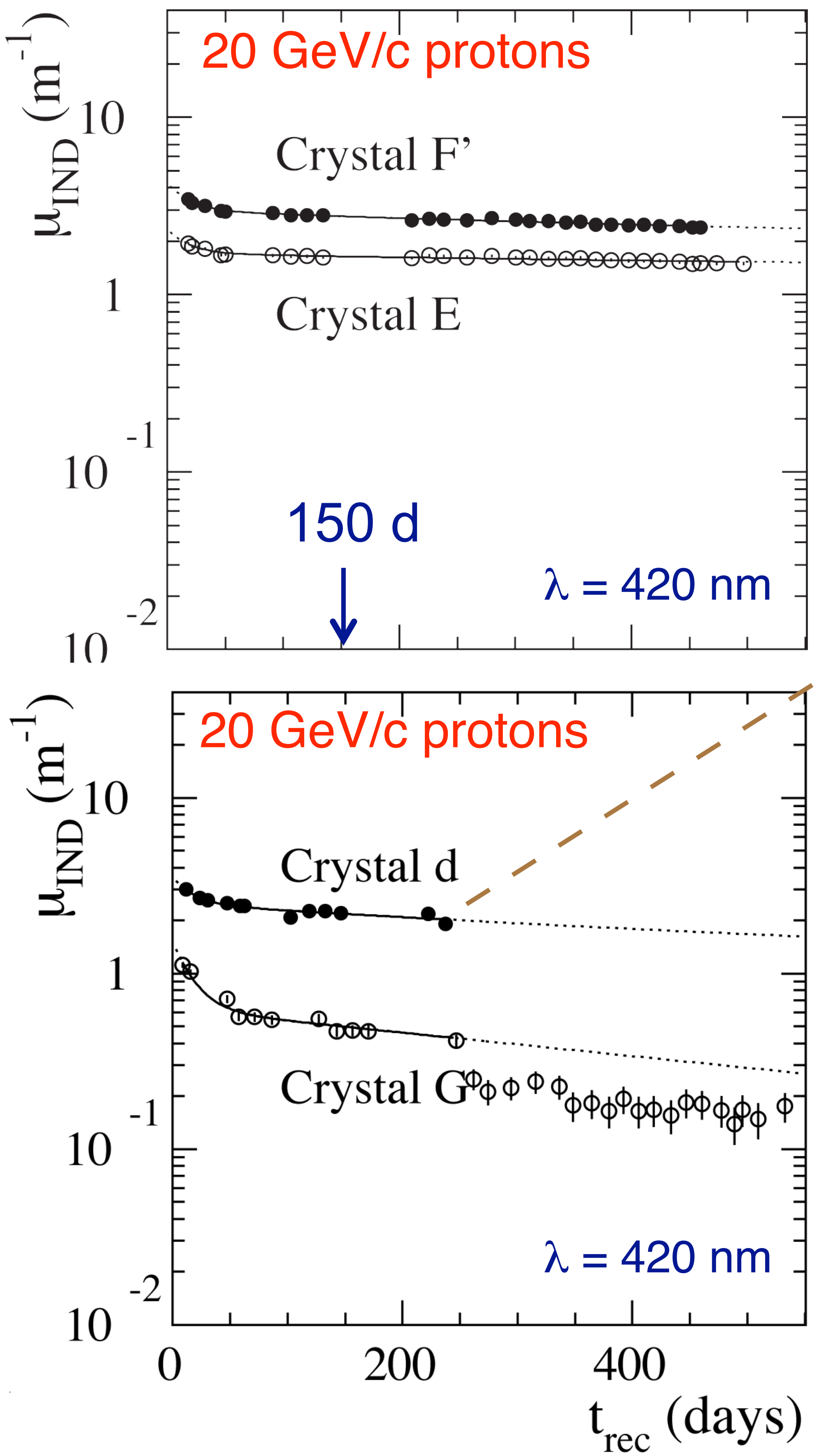

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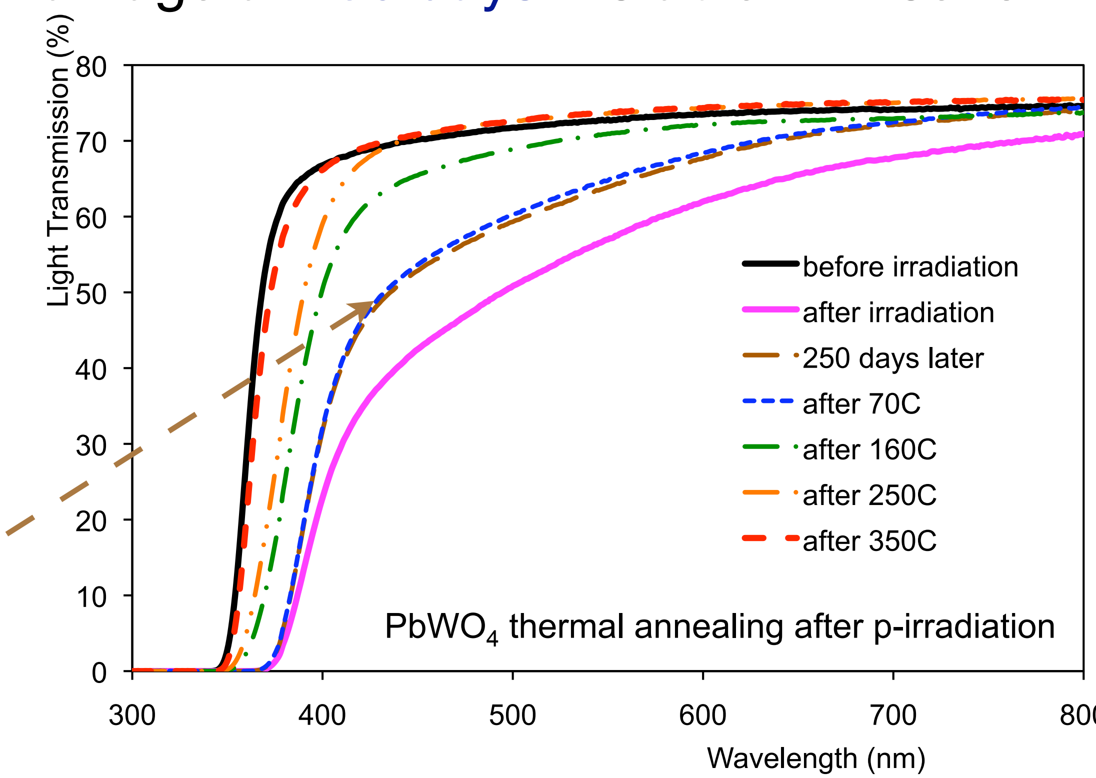

Remark 1:

Hadron-specific damage (band-edge shift included) recovers through 350°C thermal annealing, see crystal d

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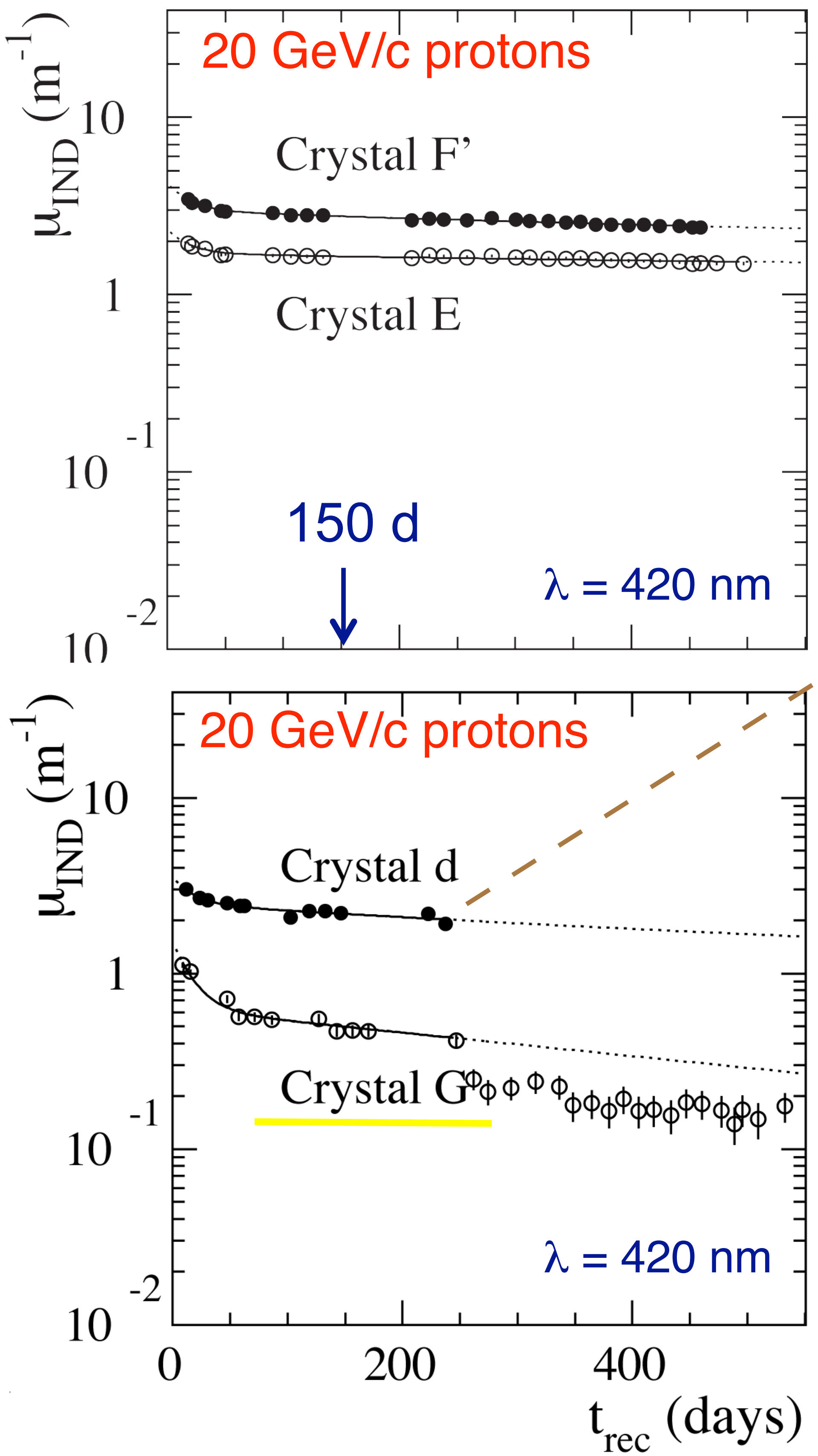

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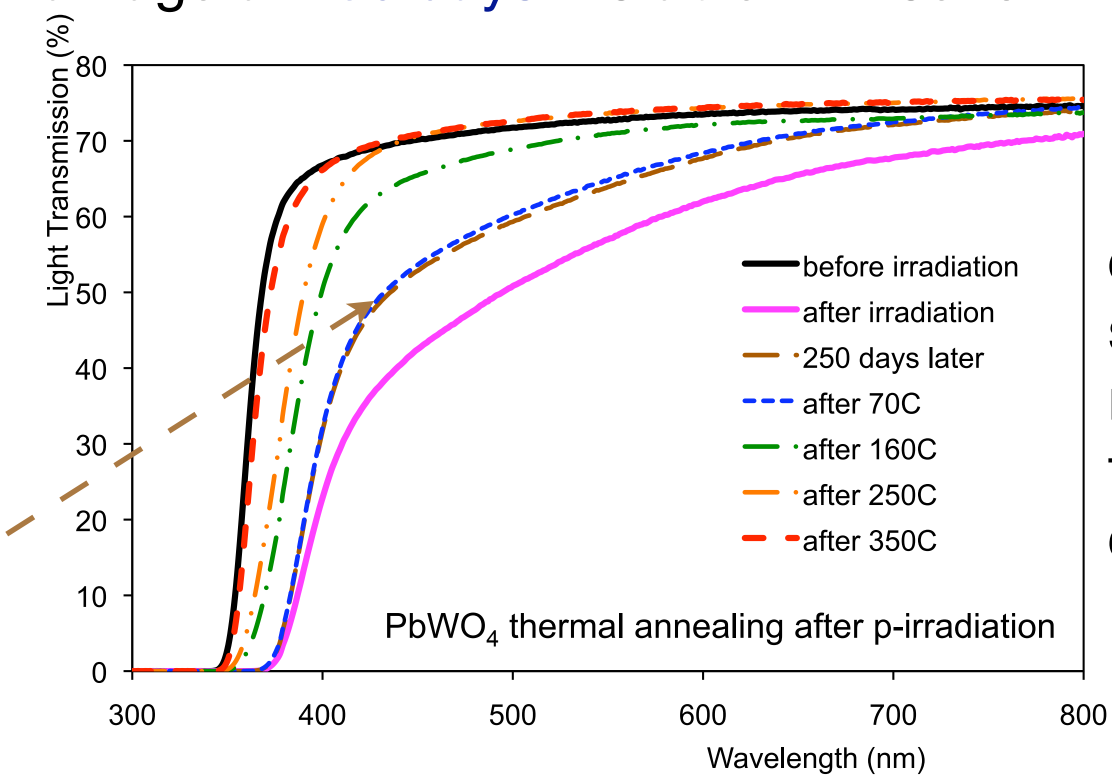

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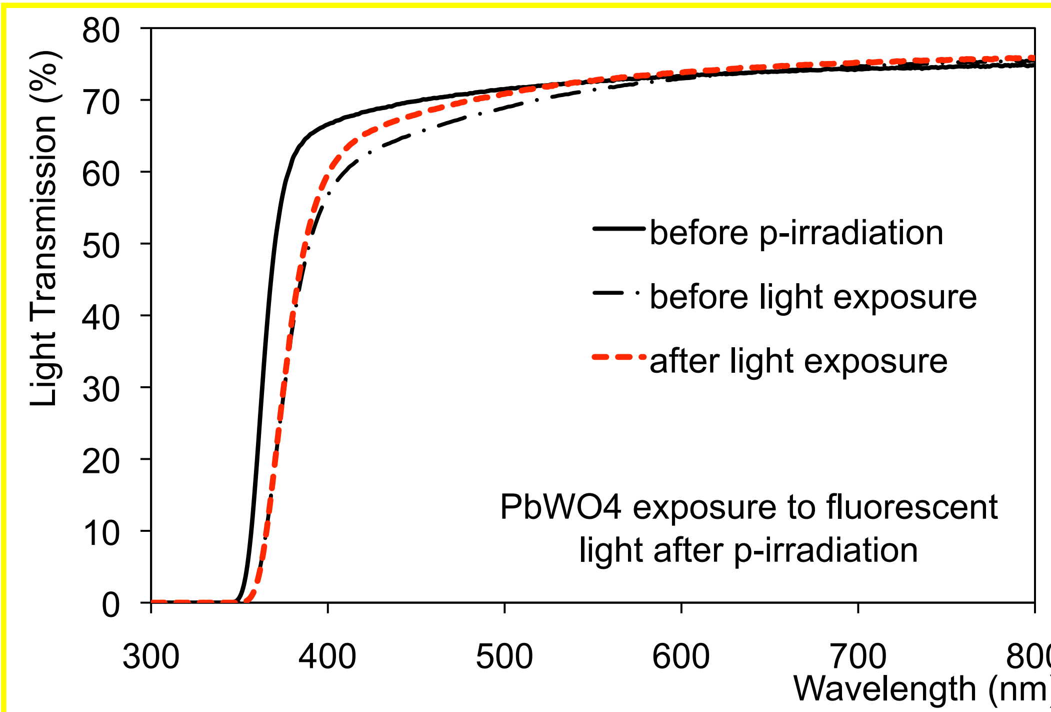
Remark 2:

An accidental exposure to fluorescent light induced some recovery, but no band-edge recovery (crystal G)



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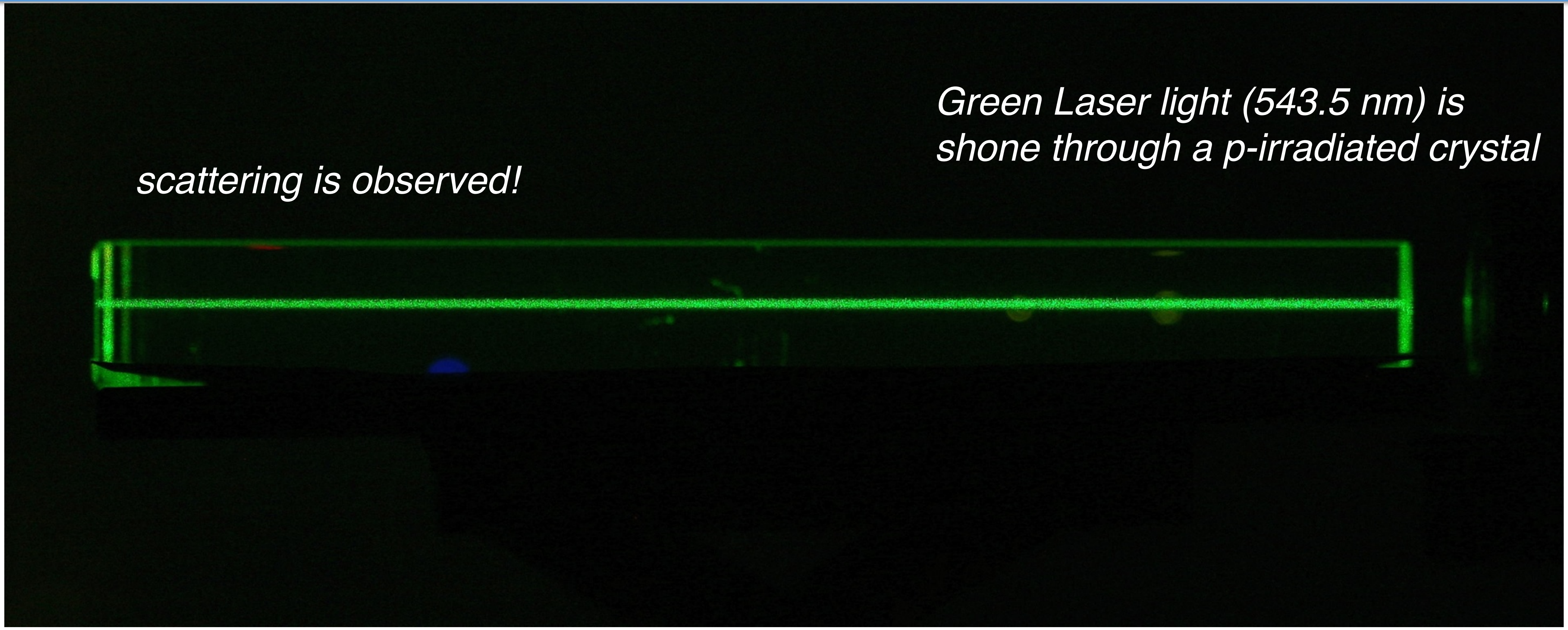

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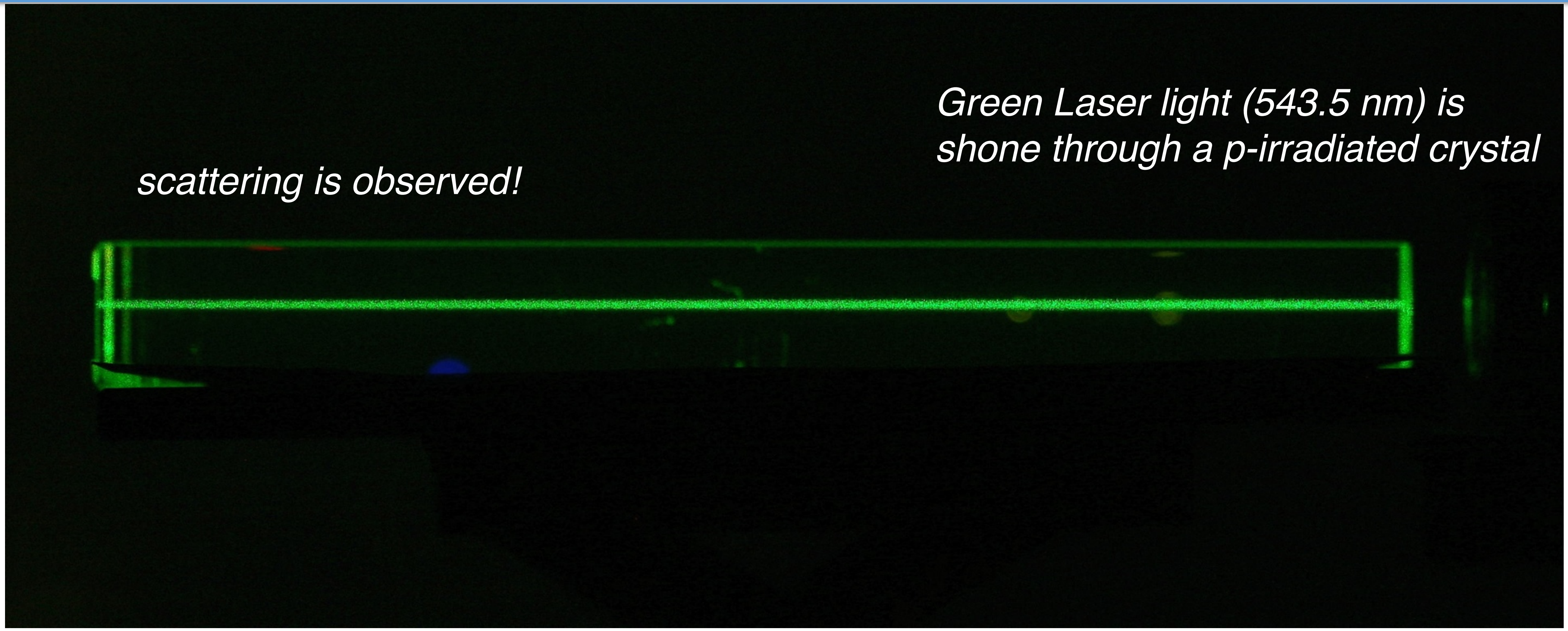

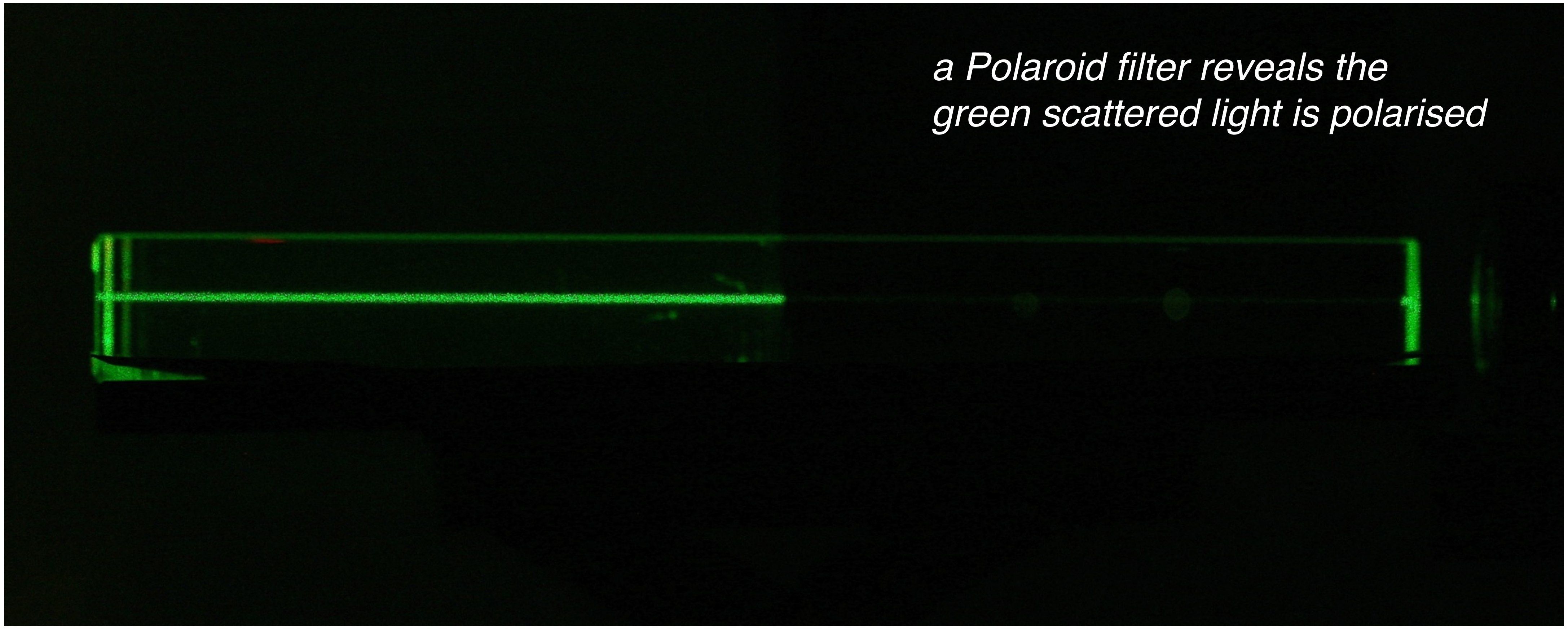

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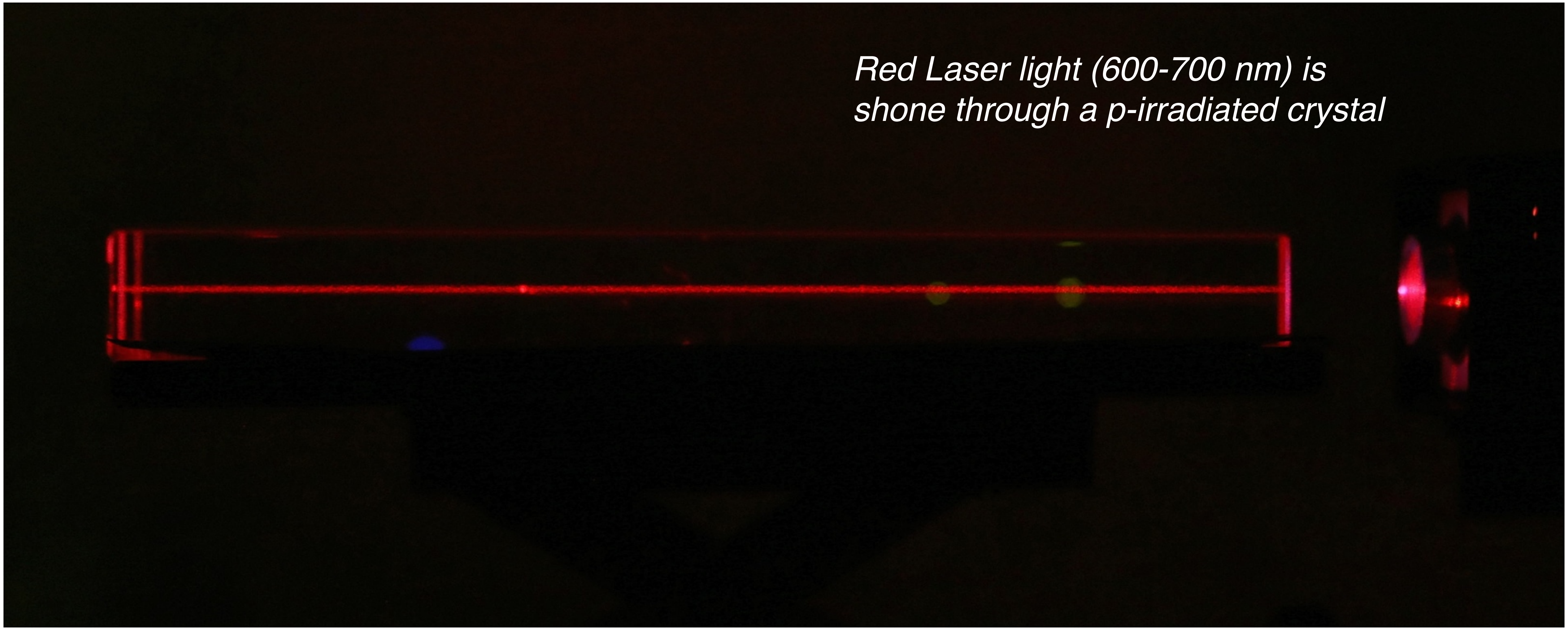

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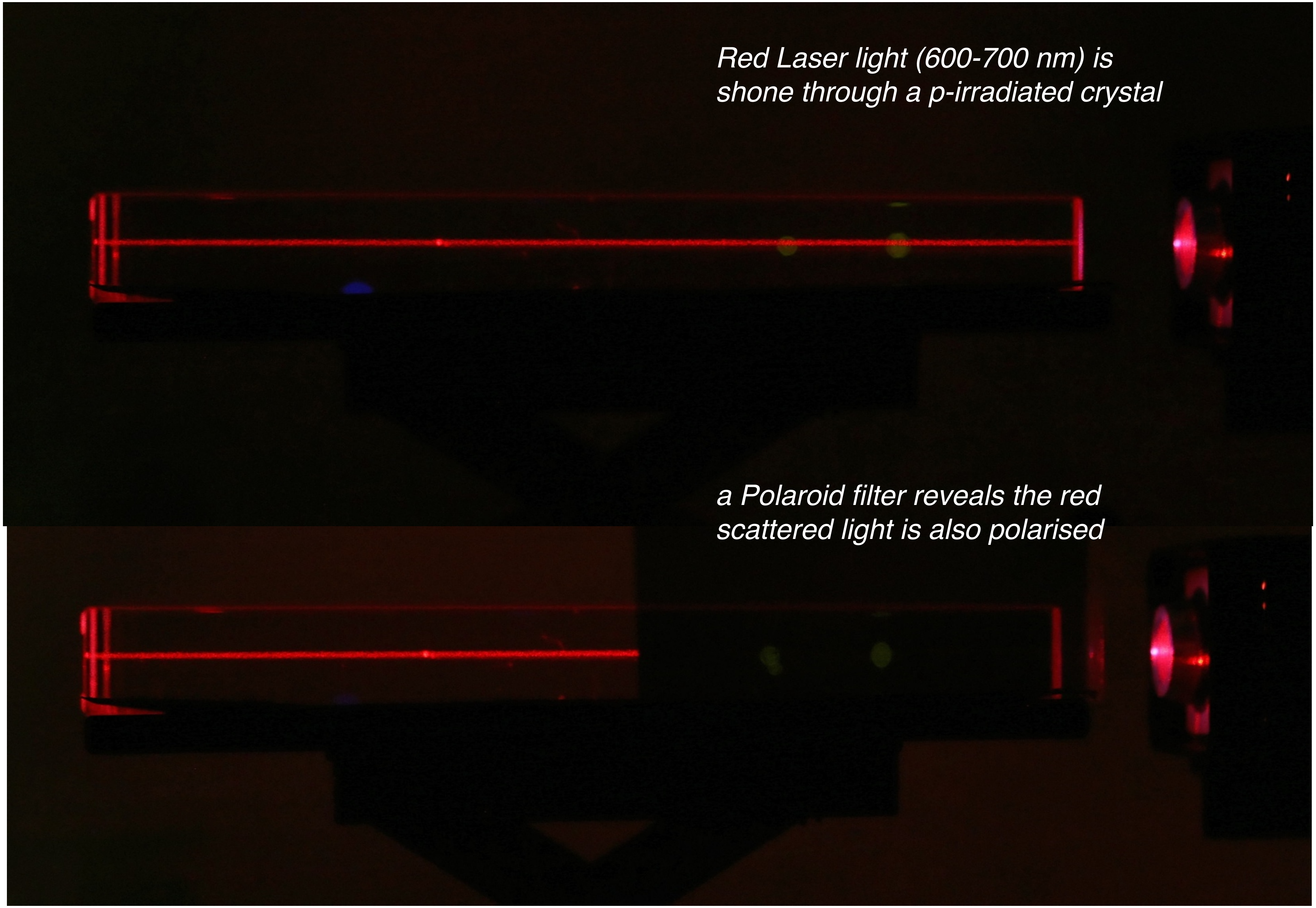


Features of $PbWO_4$ Transmission after p-irradiation

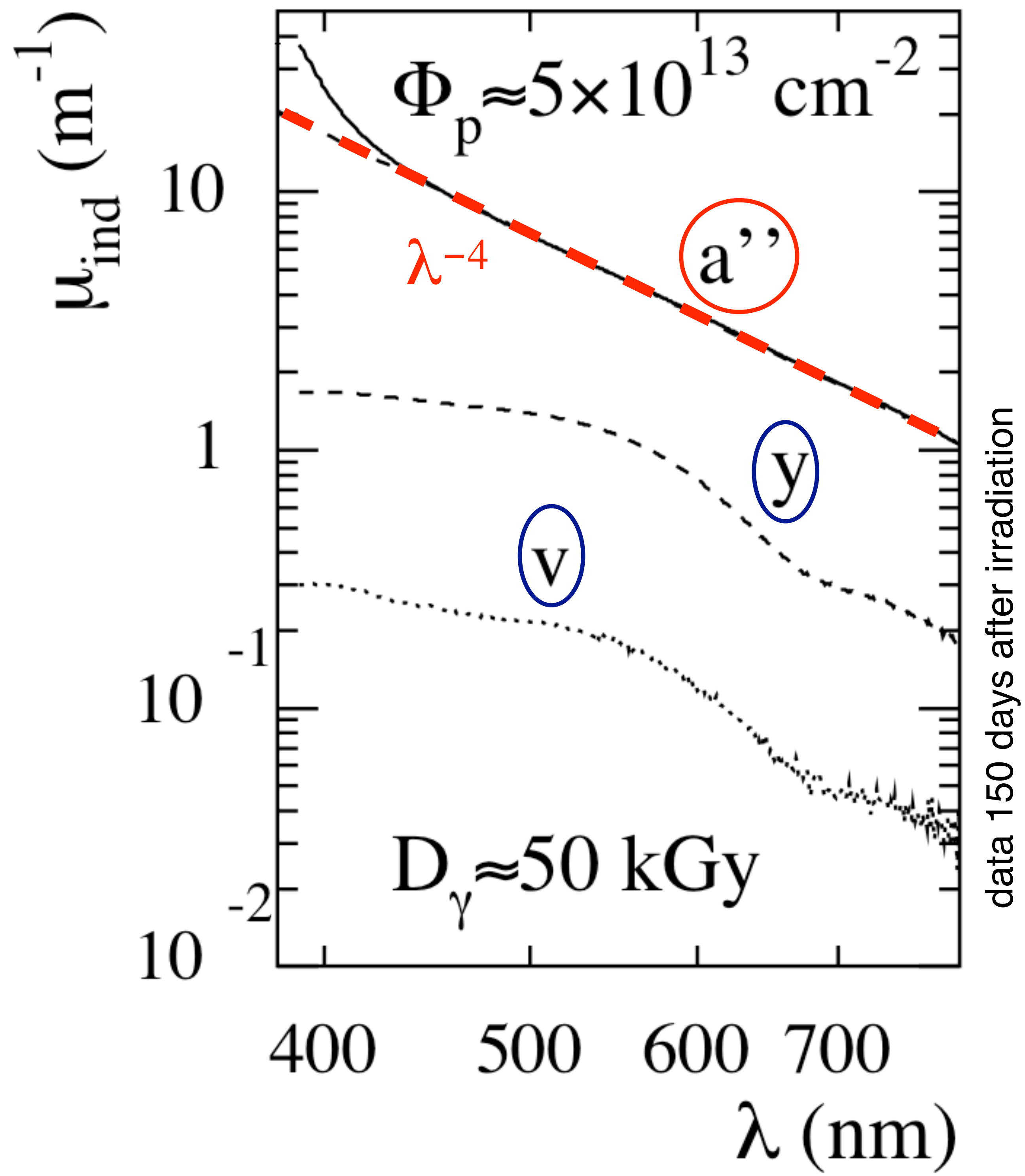
→ $\mu_{IND}(\lambda)$ is qualitatively different between proton - and γ-irradiated crystals

In proton-irradiated crystals, Rayleigh-scattering behavior is observed:
i.e. scattering off "dipoles" with dimension < λ :

→ λ^{-4} dependence (see crystal *a"*)

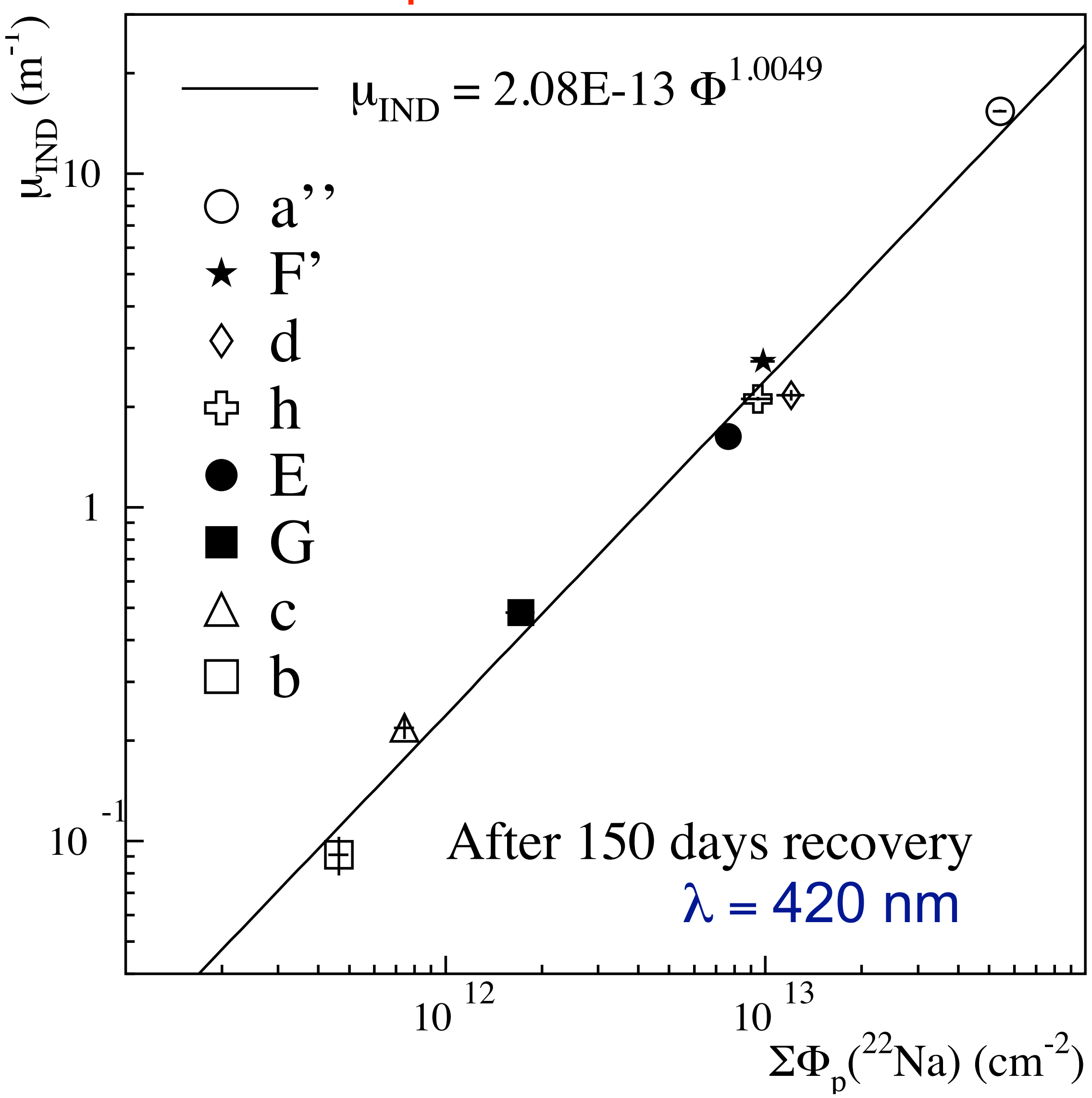
→ scattered light completely polarized

Not observed for γ-irradiated crystals (see crystals v and y)

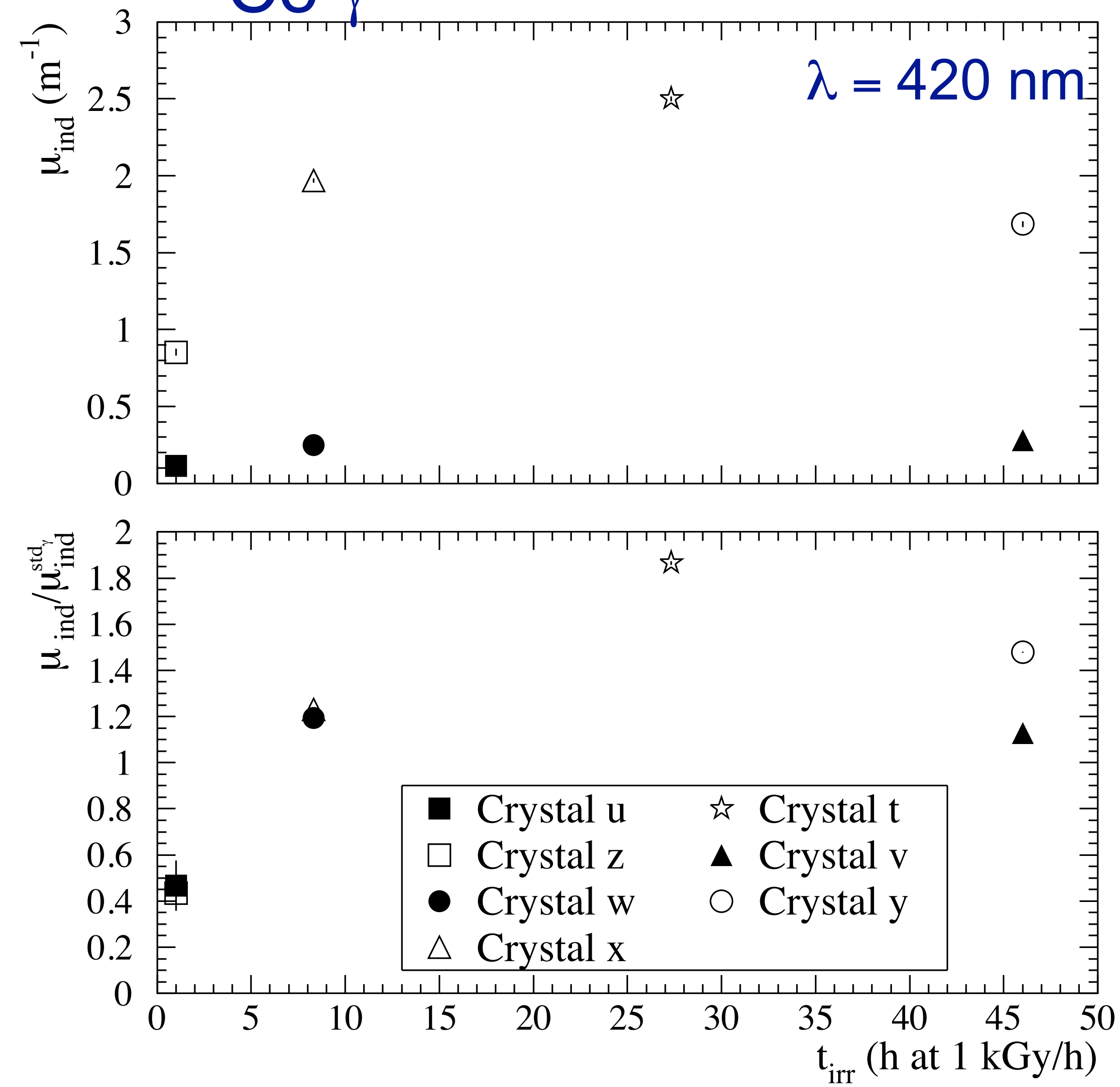


Proton and γ damage vs. fluence in $PbWO_4$

20 GeV/c protons



$^{60}Co\ \gamma$



→ tested up to p-fluence $\phi_p = 5\times10^{13}$ cm^{-2}
→ over 2 orders of magnitude in ϕ_p
→ over a factor 20 in rates.

◆ Stable μ_{IND} component grows linearly with fluence: it is cumulative

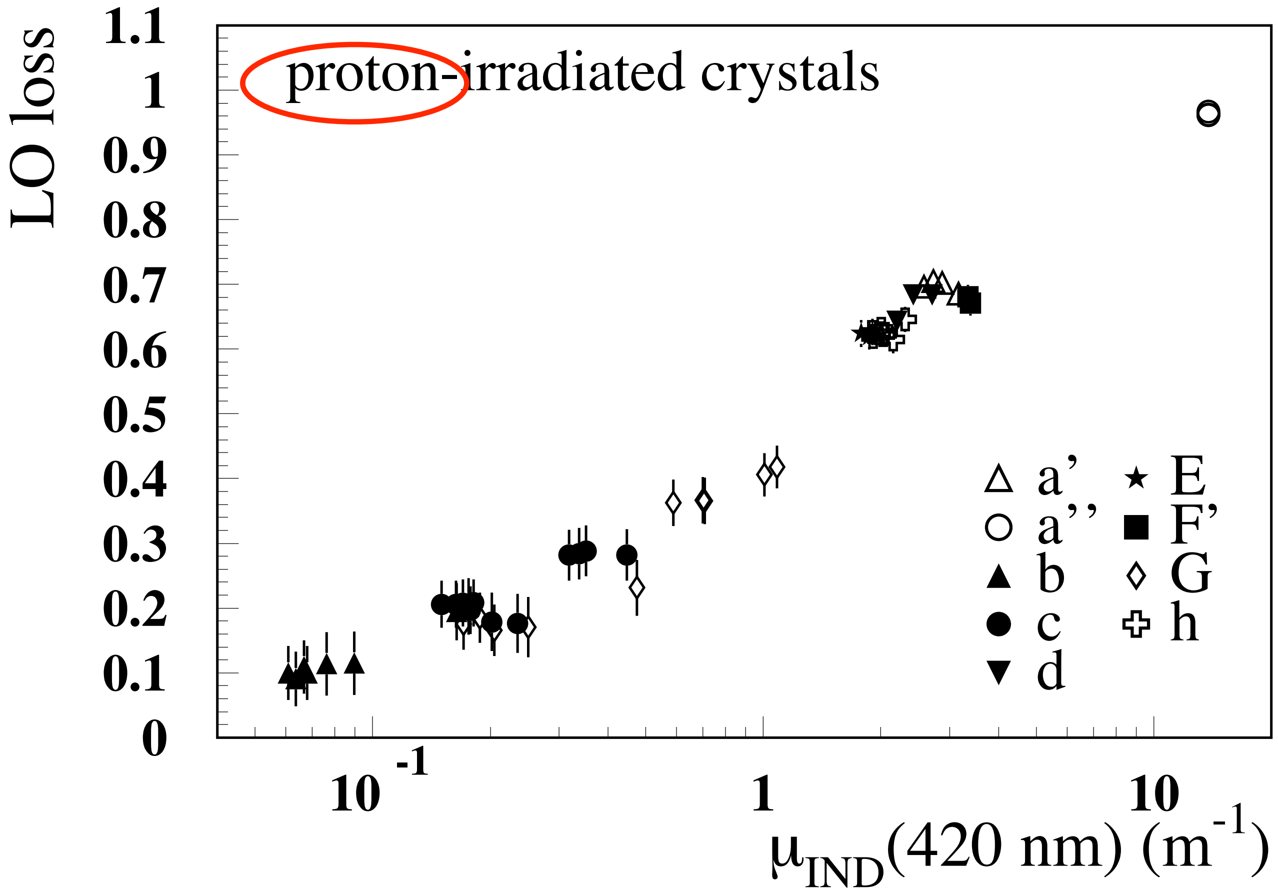
◆ No flux dependence observed

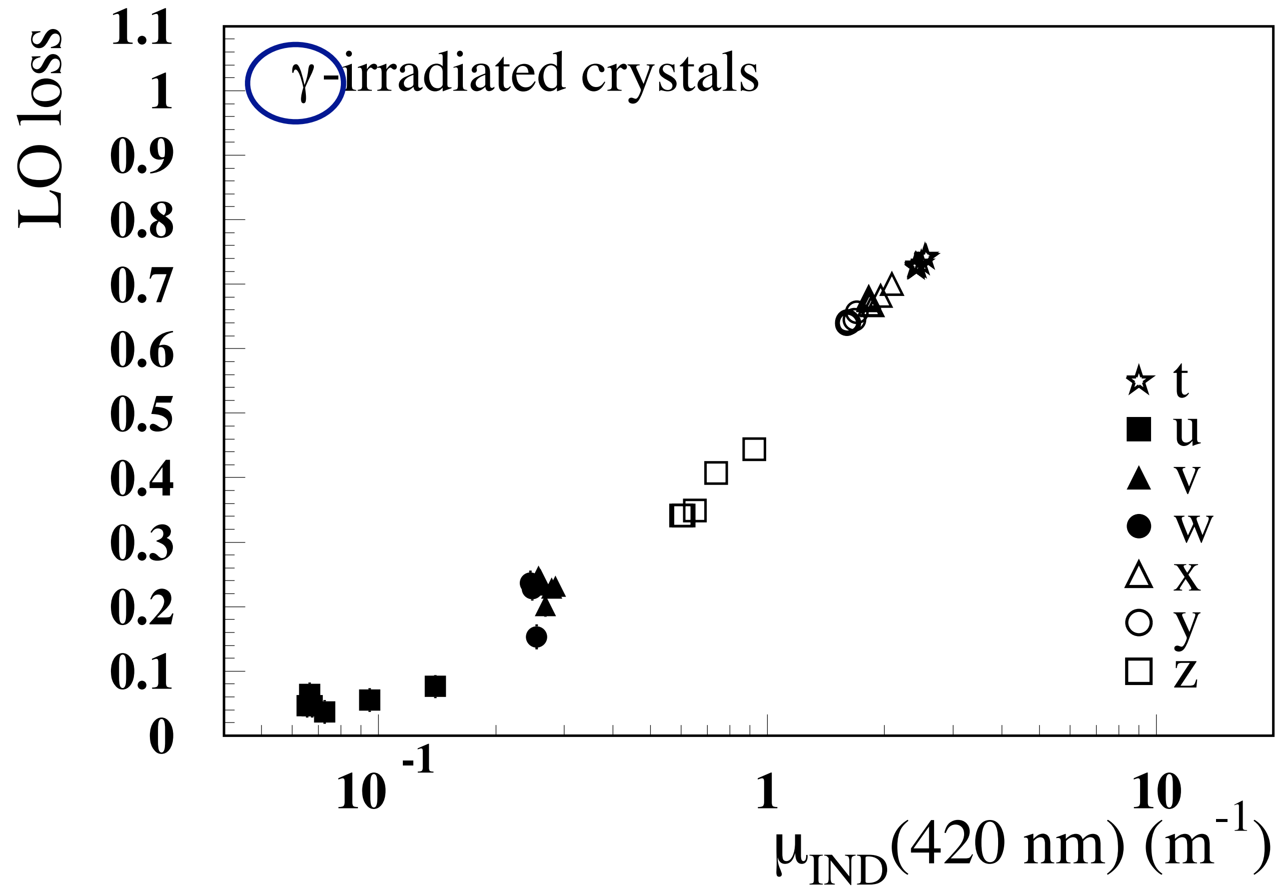
◆ γ-induced damage saturates. Level depends on the initial crystal quality (given by $\mu_{IND}^{\gamma std}$ obtained from standard certification procedure)

Correlation between changes in LT and in Light Output in $PbWO_4$

P.Lecomte, D.Luckey, F.Nessi-Tedaldi, F.Pauss, Nucl. Instr. Meth. A564 (2006) 164-168

Scintillation excited by cosmic muons, light output measured with 2262B Photomultiplier (bi-alkali photocatode)





- Correlation between μ_{IND} (420 nm) and Light Output loss for crystals irradiated with protons

- Correlation between μ_{IND} (420 nm) and Light Output loss for crystals irradiated with γ from a ^{60}Co source

Within the accuracy of the measurement, the two correlations are compatible

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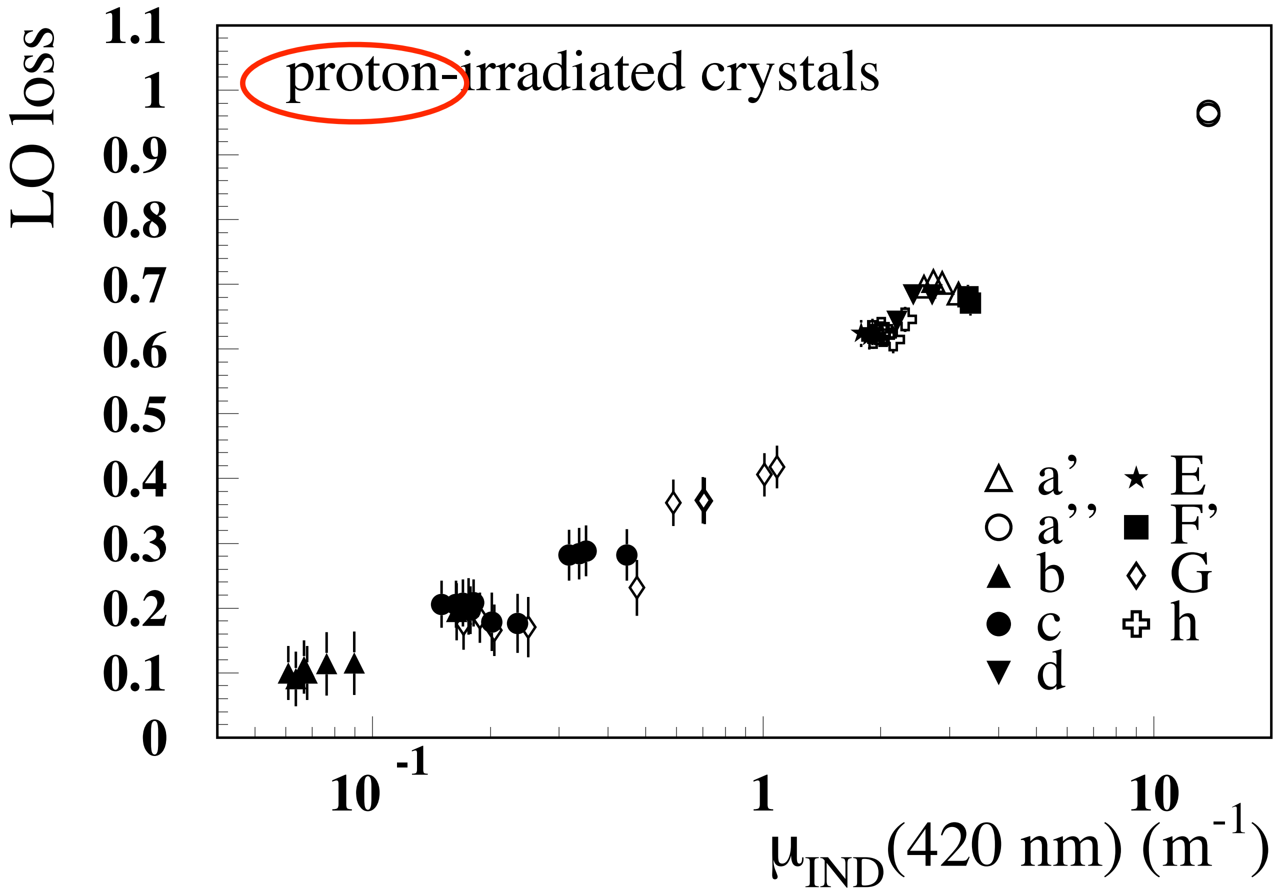

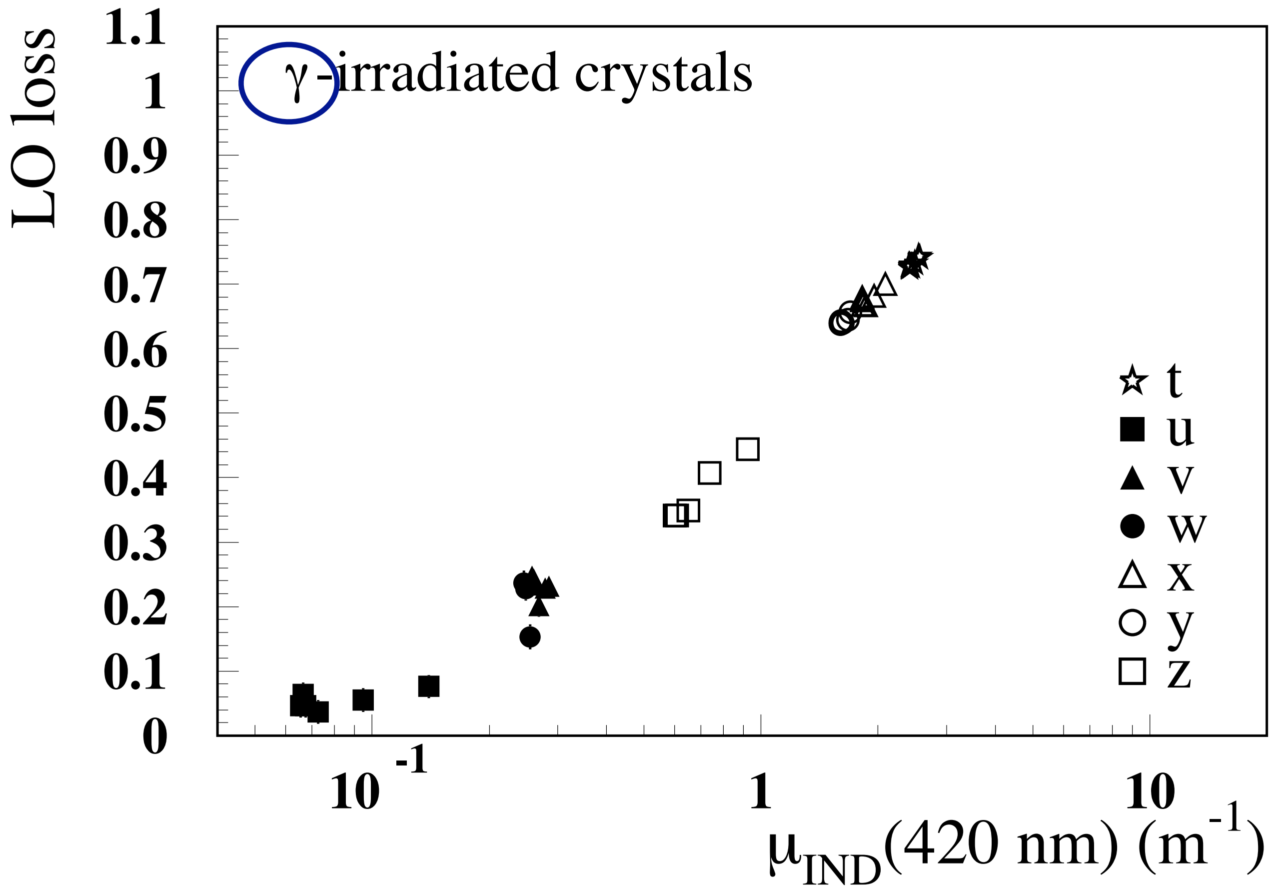

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Within the accuracy of the measurement, the two correlations are compatible

→ No additional, hadron-specific damage to the scintillation mechanisms observed

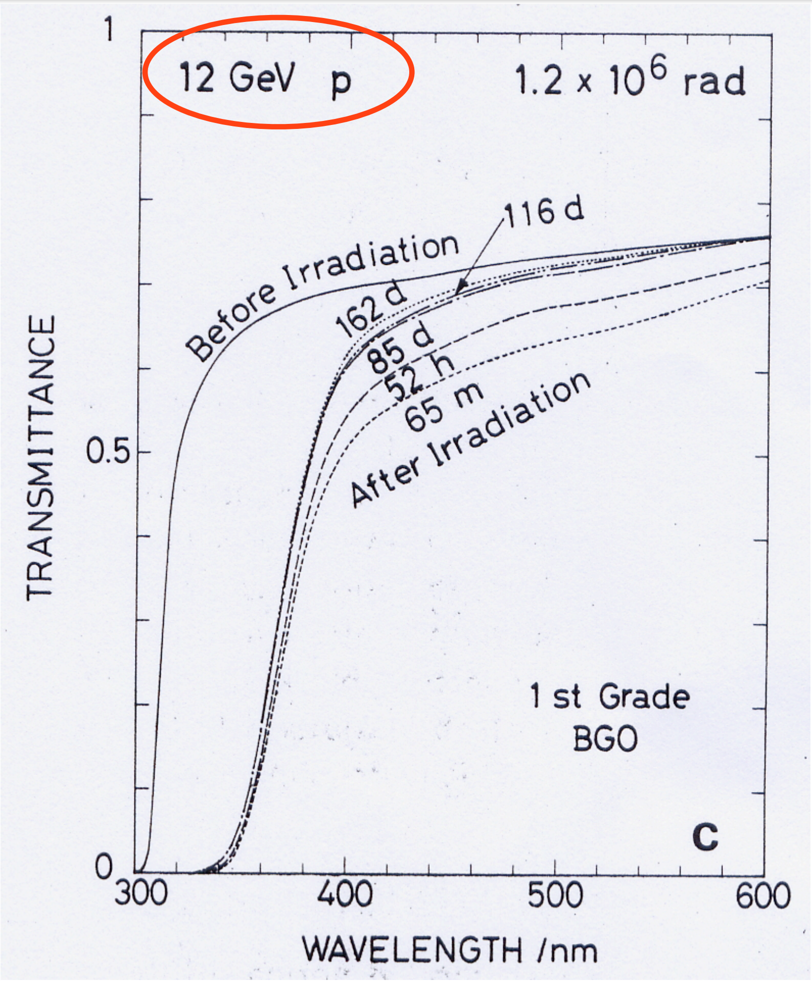
Proton and γ damage in BGO

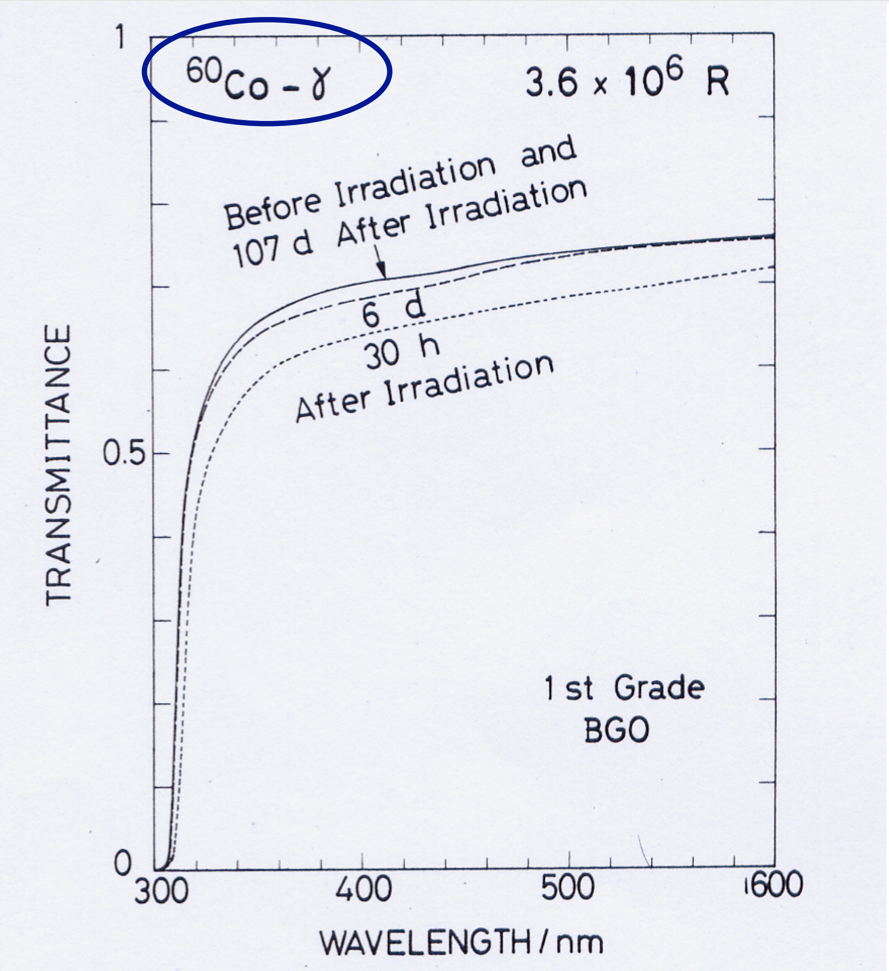
- BGO ($Bi_4Ge_3O_{12}$), used e.g. in L3 and BELLE

Data extracted from M. Kobayashi et al., NIM 206 (1983) 107-117

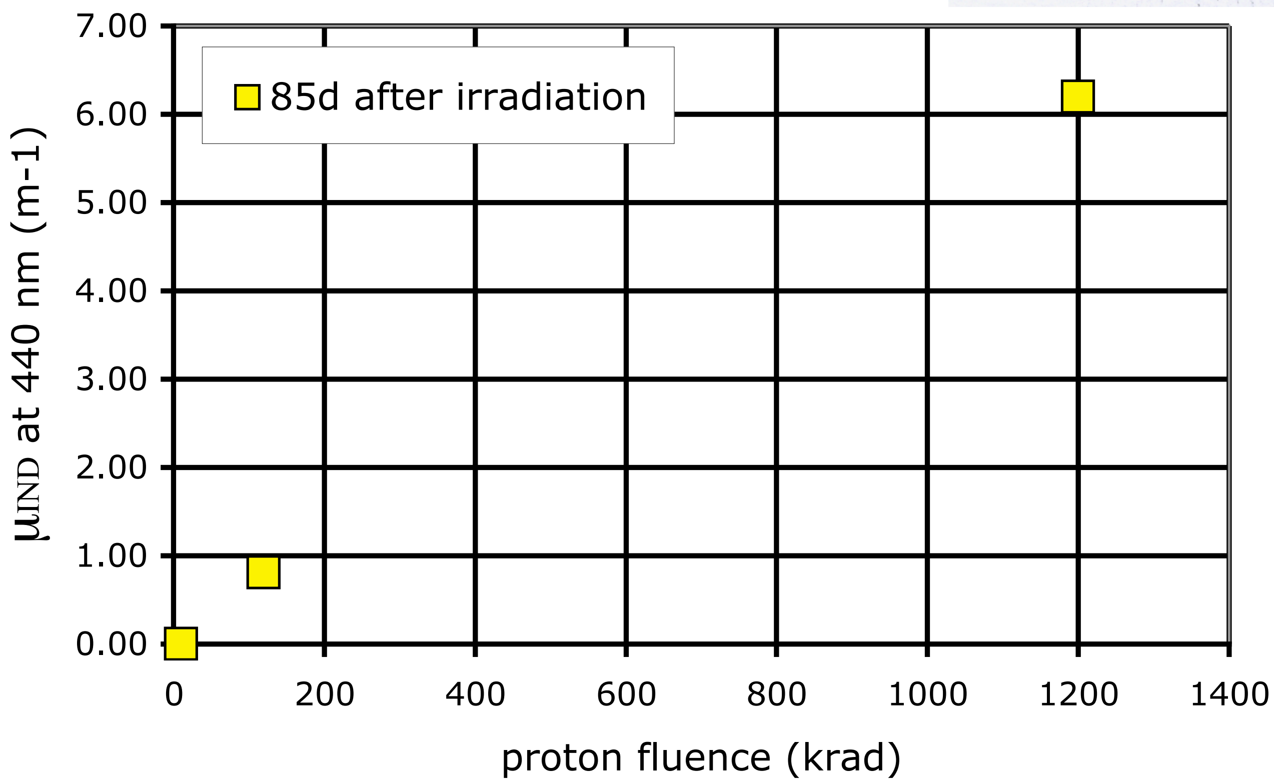
- Band-edge shift present for proton-irradiation, which does not recover with time

- No band-edge shift in γ-irradiations





Proton damage of BGO crystals



- Qualitative behavior of proton damage similar to the one in $PbWO_4$

- Proton damage behavior compatible with a linear dependence on proton fluence

Remark: in CsI, hadron effects totally swamped by the ionizing radiation damage

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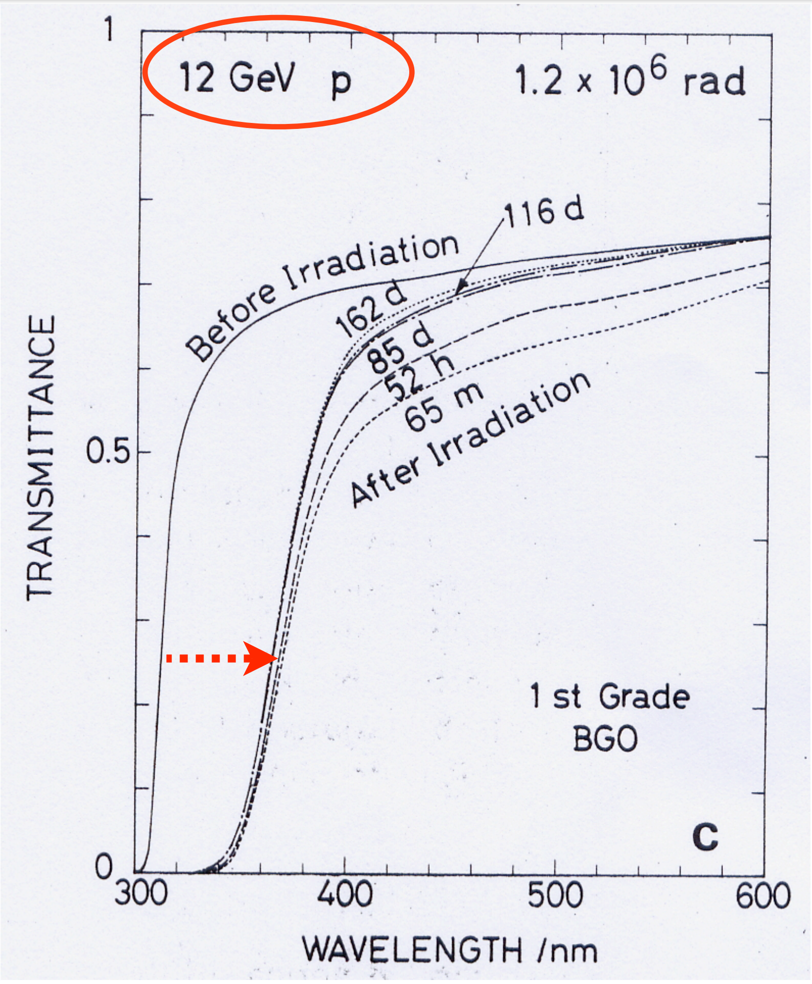

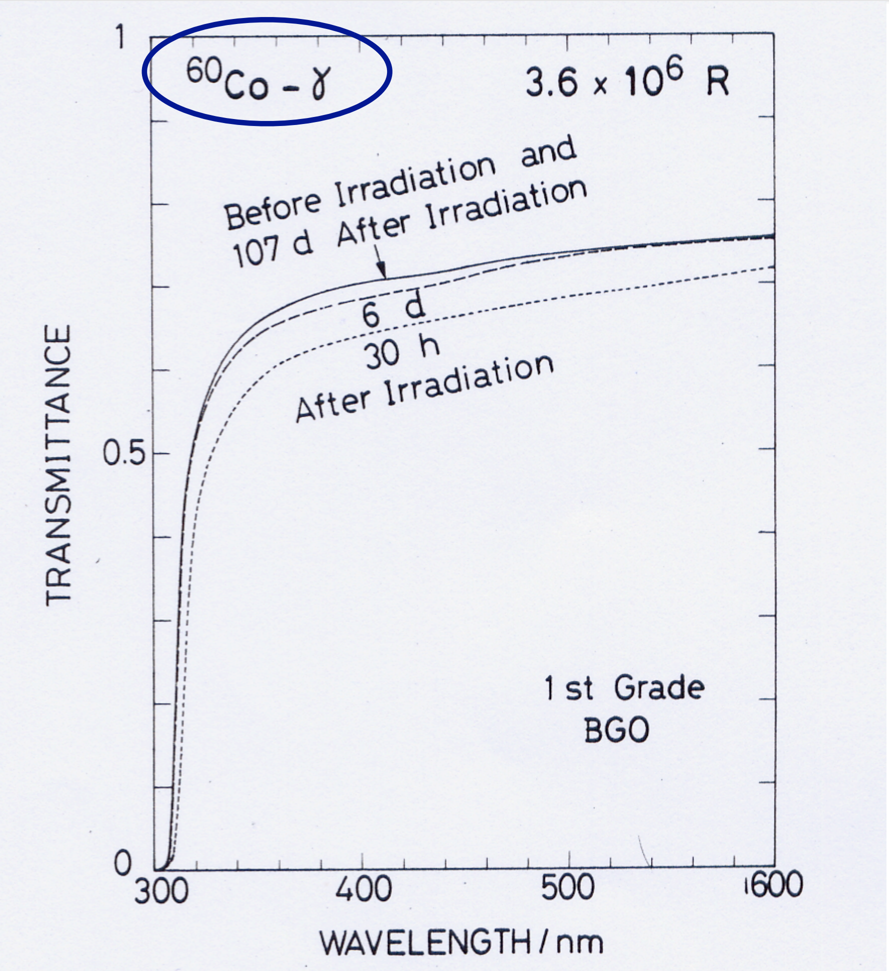

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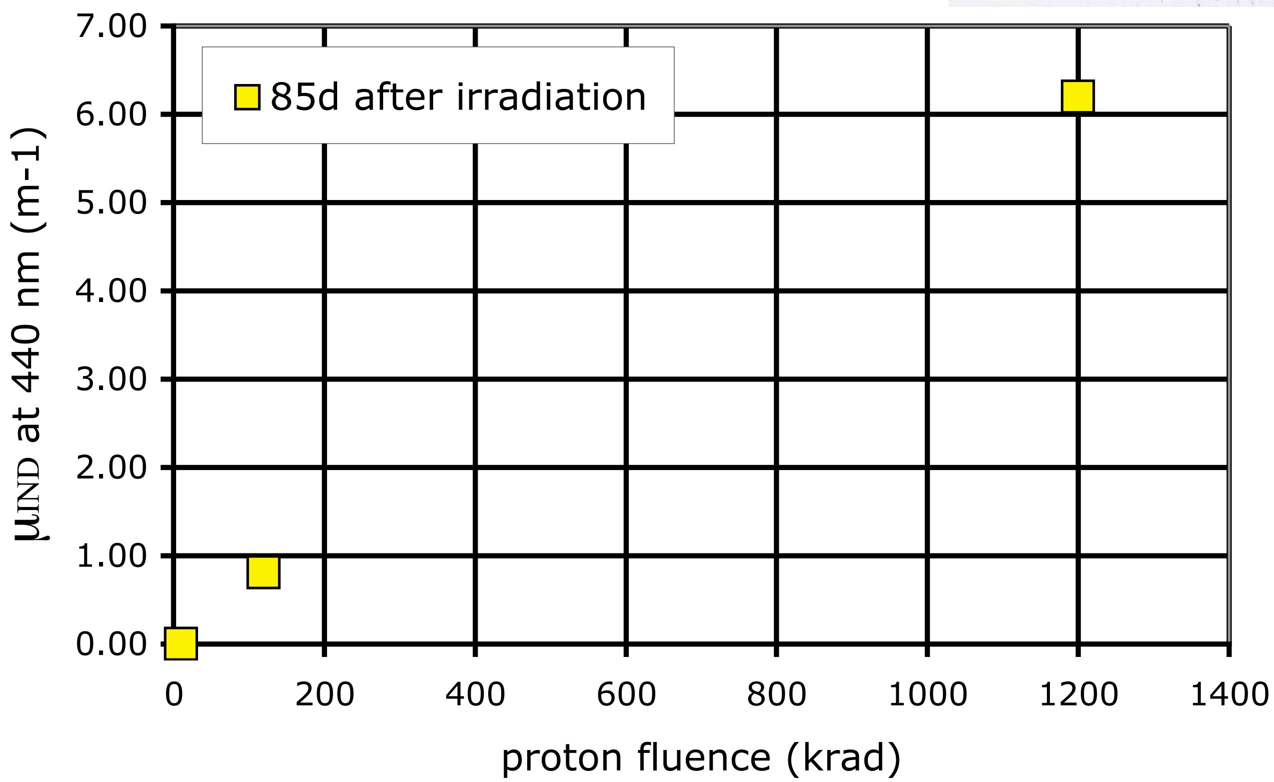

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Understanding hadron damage mechanisms in $PbWO_4$ and BGO

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

Specific features of proton damage:

- It is cumulative: it grows linearly with fluence
- It only affects Light Transmission, and can thus be monitored
- The scintillation mechanism is not altered
- It has a Rayleigh-scattering behavior = scattering off “dipoles” with dimension < λ

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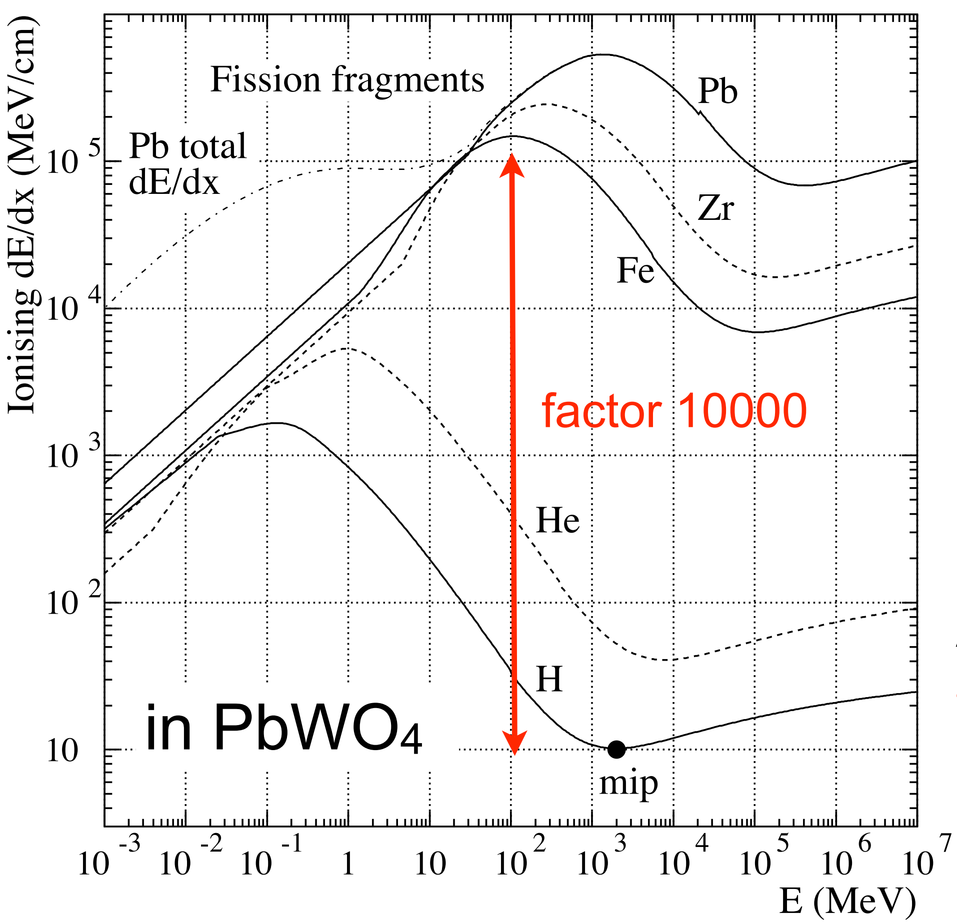

Consistent with:

Fission of Pb, W, Bi above a ~20 MeV threshold, with production of heavy breakup fragments

→ range ≤ 10 µm

→ E ≤ 100 MeV

→ dE/dx ≃ $\mathcal{O}$(10000 x dE/dx (mip))

Along their tracks, the crystal structure is changed permanently
➛ dipole-like regions where displacement, disorder, strain fields

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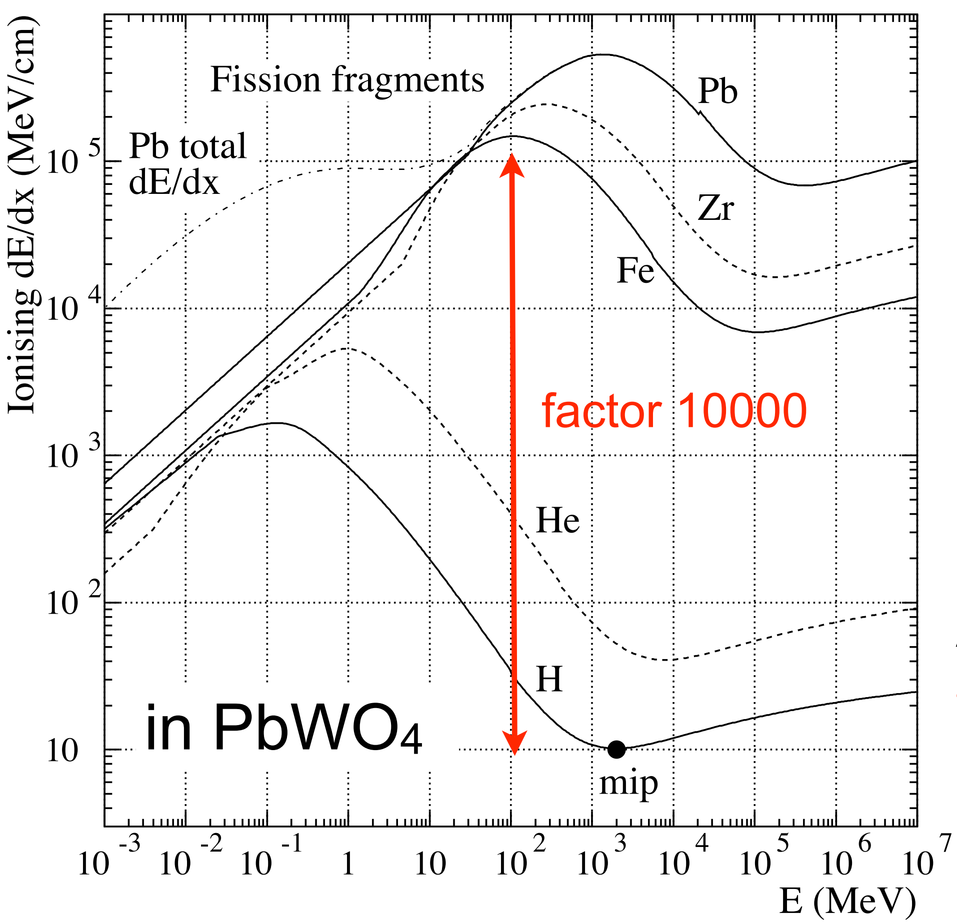

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Along their tracks, the crystal structure is changed permanently

➛ dipole-like regions where displacement, disorder, strain fields

→ This feature should be absent for crystals made out of elements with Z<71 (*)
A test of low-Z crystals should confirm this understanding of damage mechanisms

→ Test CeF_3 and LYSO

(*) *A.S.Iljinov et al.,Phys. Rev. C 39 (1989) 1420-1424*

A phenomenon studied long ago

Tracks from ^{238}U fission in muscovite mica

Fr. Dessauer, Zeit. Physik 12 (1923) 38

→ Concept of thermal spike when an incident ion comes to a stop in matter

J.A. Brinkman, J. Appl. Phys. 25 (1954) 961

→ Concept of displacement spike

L.T. Chadderton, Nature 195 (1962) 987

→ Experimental evidence for the displacement spike from its discontinuous nature

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.L.Fleischer, R.M. Walker, P.B.Price, "Nuclear Tracks in solids" (1975):

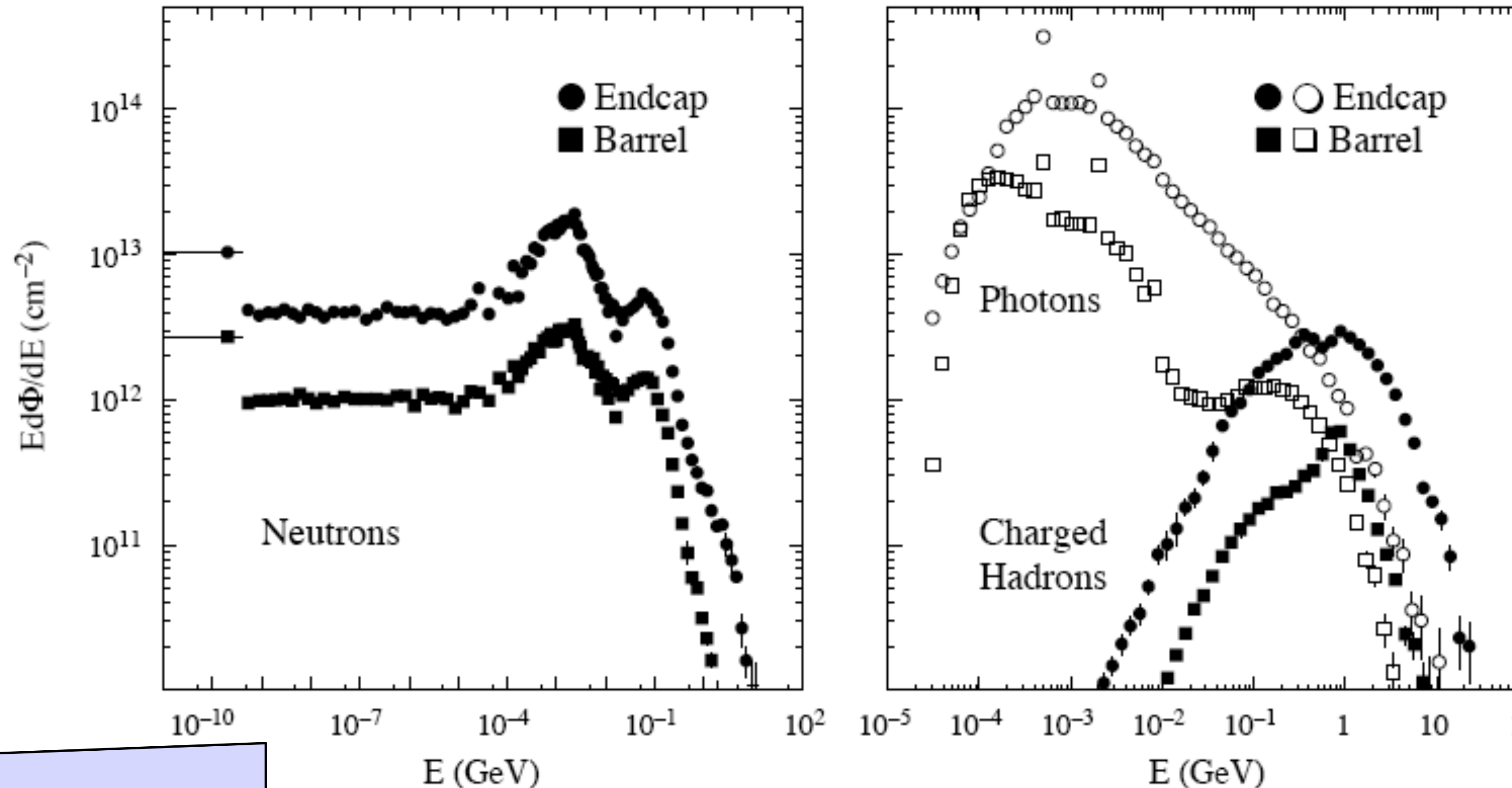
→ Dating based on fission track counting in crystals

Comparative proton and pion damage study in $PbWO_4$

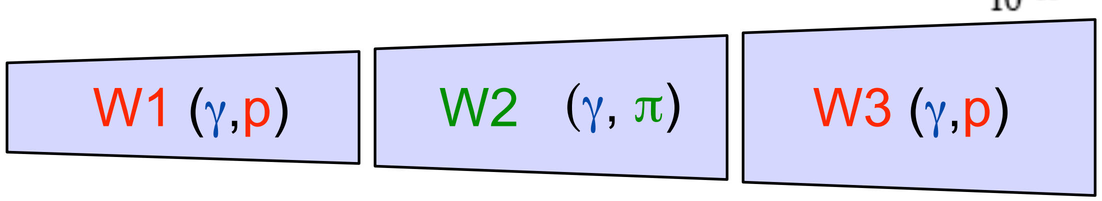
P.Lecomte, D.Luckey, F.Nessi-Tedaldi, F.Pauss, D.Renker, Nucl. Instr. Meth. A587 (2008) 266-271

Hadron fluxes at LHC typically due to charged pions with a few hundred MeV energy

A test with lower-energy pions was performed to understand how damage scales between ~20 GeV/c protons and lower-energy hadron spectrum expected at the LHC



CERN/LHCC 97-33 (1997) p.356



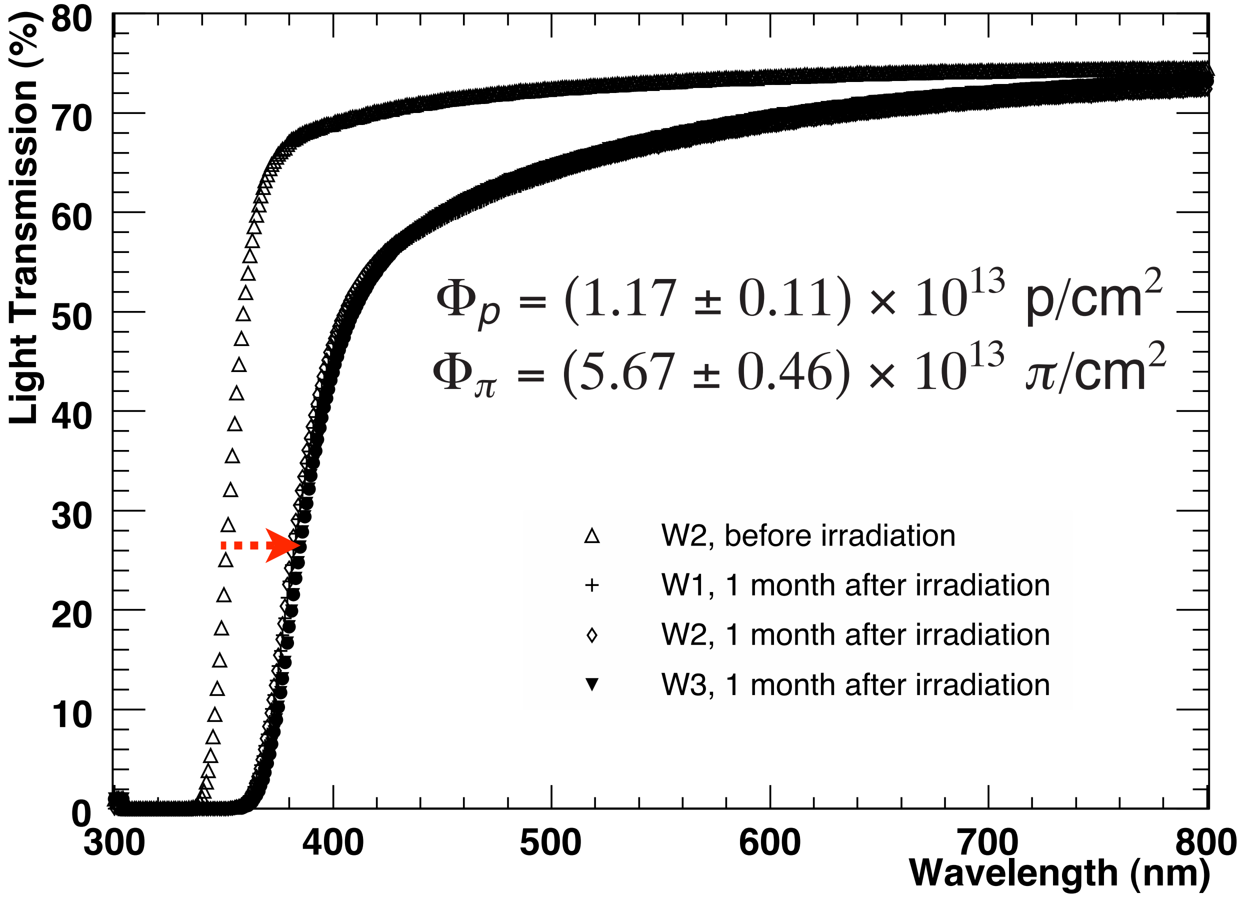
Crystal W, tested with γ in May 2004, was cut into 3 sections, W1, W2 and W3, each 7.5 cm (8.4 X_0) long, and the prior γ damage was annealed by heating.

Three sections (W1, W2 and W3) of the same crystal, each 7.5 cm (8.4 X_0) long

- W1 and W3 irradiated with 24 GeV/c protons up to $\phi_p = (1.17 \pm 0.11)\times10^{13}$ p/cm^2
- W2 irradiated with 290 MeV/c π^+ up to $\phi_\pi = (5.67 \pm 0.46)\times10^{13}$ π /cm^2

at a flux $\varphi_\pi = 4.13 \times 10^{11}$ π /cm^2/h

Light Transmission changes in $PbWO_4$: pions versus protons



→ LT shape similar after p and π irradiations

→ Band edge shift present after π irradiation as well

Same change in Light Transmission shape after p and π irradiation

(magnitudes similar due to suitable choice of fluences)

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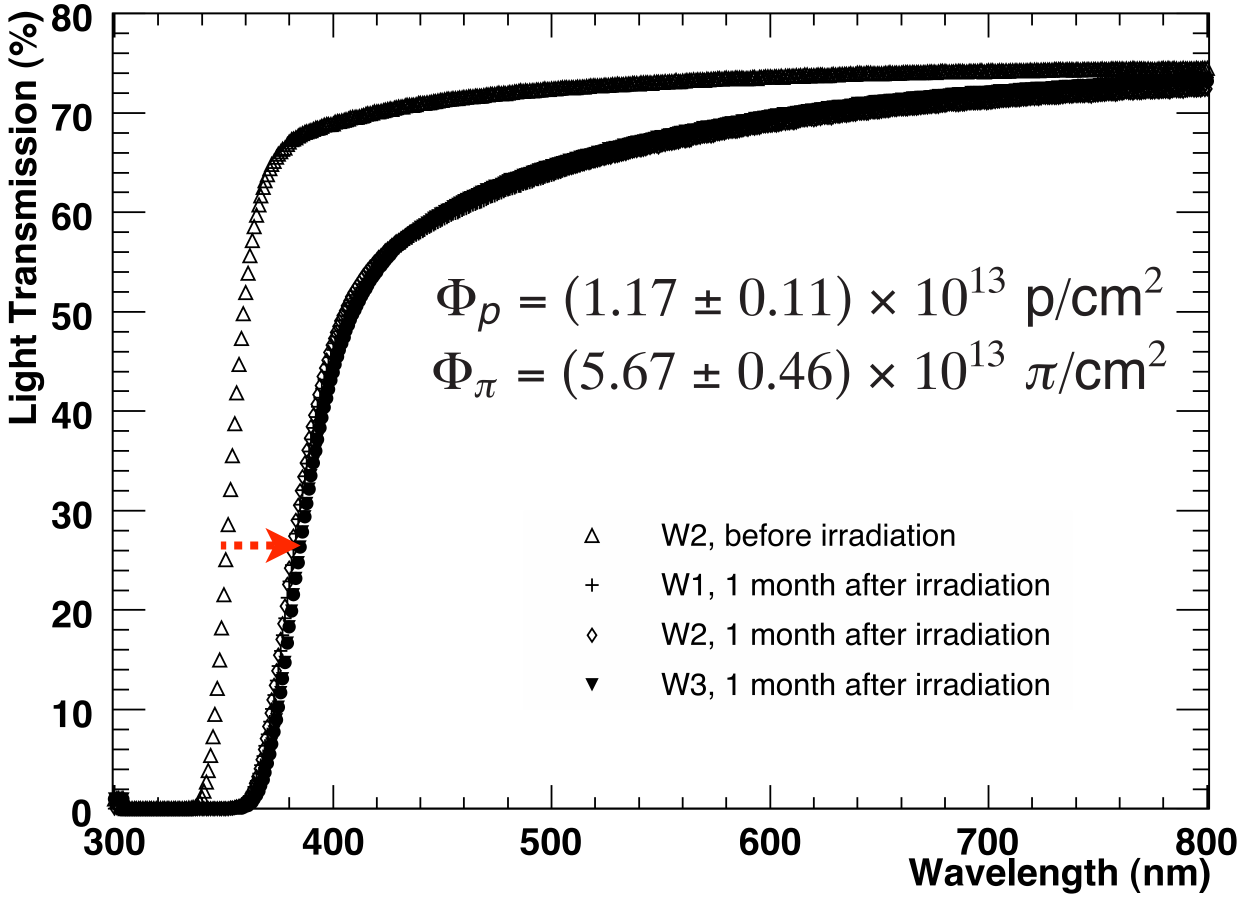

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Same change in Light Transmission shape after p and π irradiation

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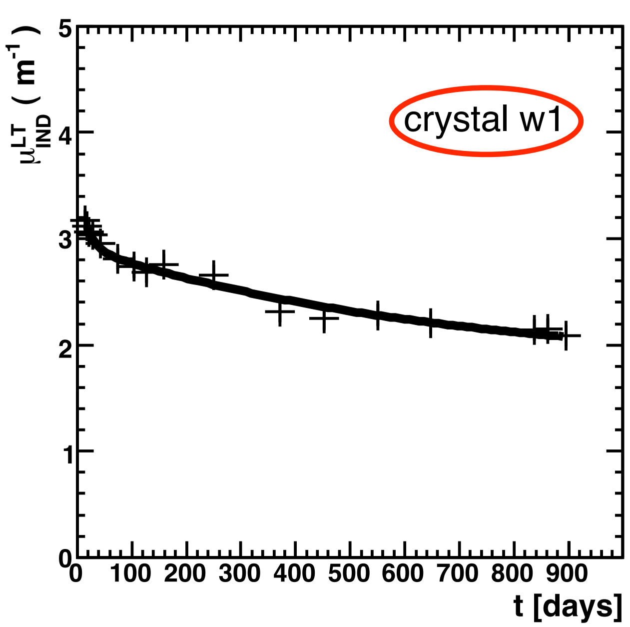
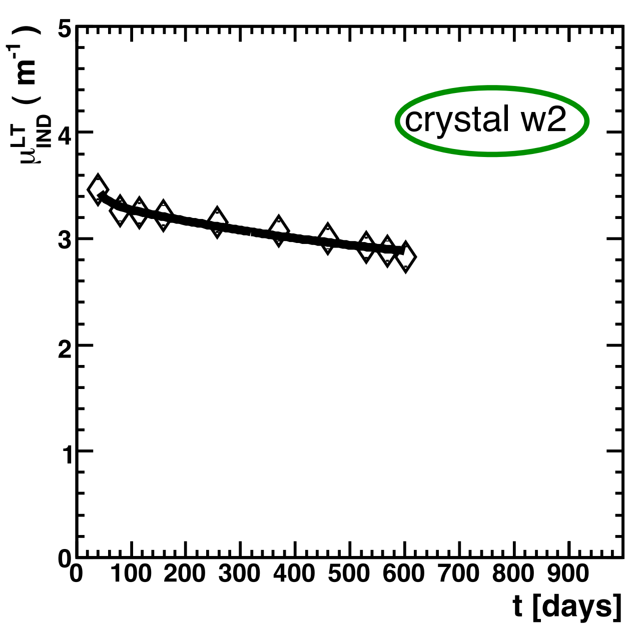
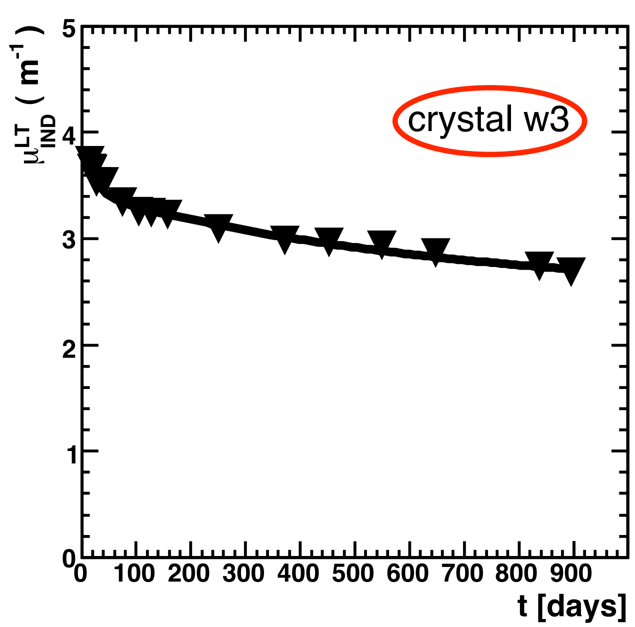
→ Damage can be globally fitted as after proton-irradiation, with τ_1 = 17.2 days and τ_2 = 650 days

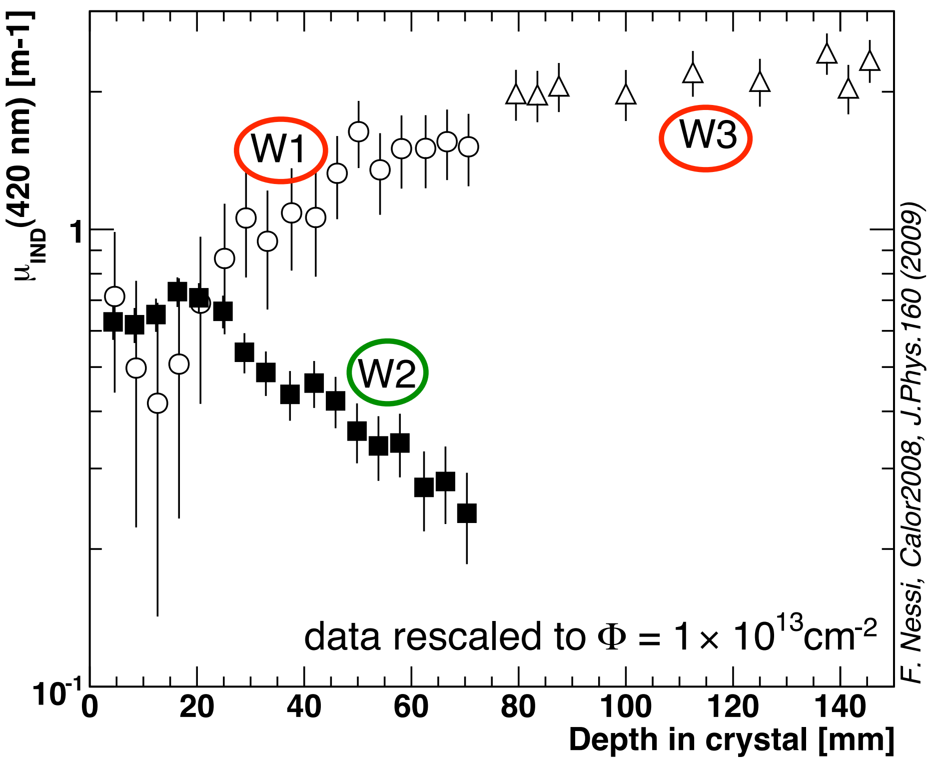


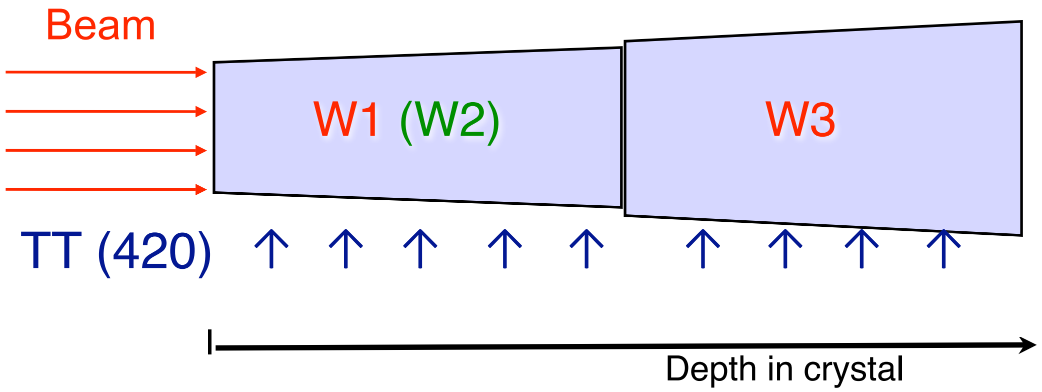




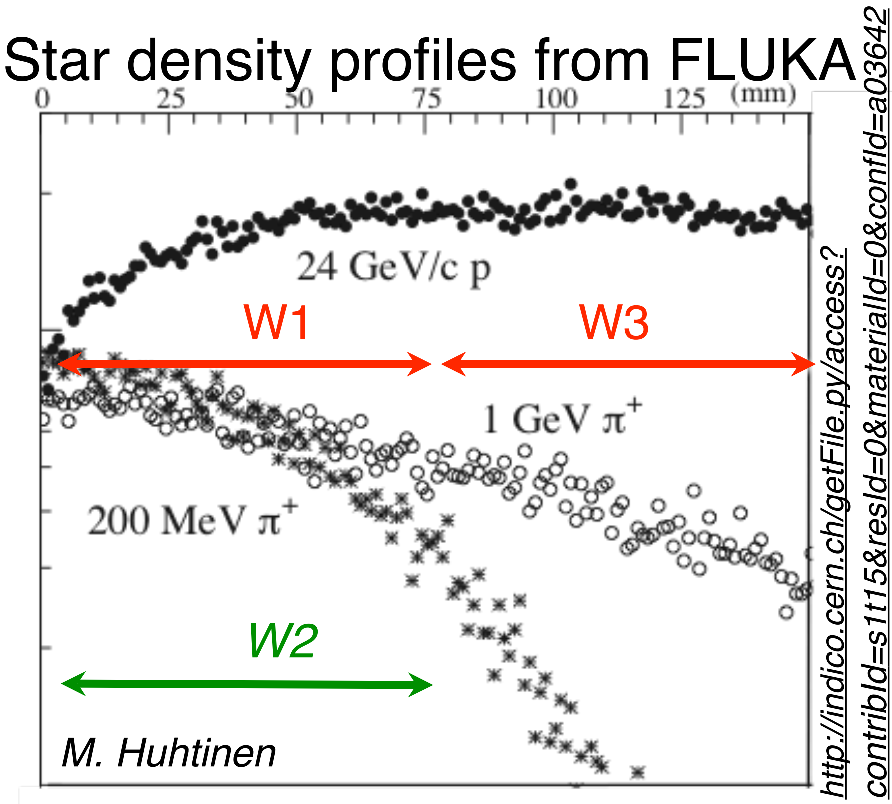
Comparative proton and pion damage study in $PbWO_4$

measured induced absorption





Star density profiles from FLUKA



← The damage profile is the same as the density profile of stars*

→ Between the two environments, hadron damage measured as μ_{IND} scales like the star density ratio from MC calculations normalized to the same luminosity

Caveat for a generalization *(M.Huhtinen, priv. comm.)*:
Pb and W need high-energy projectiles (rather > 100 MeV) to fission, but star densities are calculated down to a 20 MeV threshold
→ a prediction of damage has to take this into account

**inelastic hadronic interaction caused by a projectile above a given energy threshold*

Cerium Fluoride - a bit of history

Apologies for incomplete bibliography

After the pioneering work of understanding CeF_3 luminescence...

F.A. Kröger & J. Bakker, Physica VIII (1941) 628-646

and its rediscovery of its properties as a scintillator...

D.F. Anderson, IEEE TNS 36 (1989) 137-140
W.W. Moses & S.E. Derenzo, IEEE TNS 36 (1989) 173-176

It was subject to an intense research program and studies, mainly in the ’90 ...
Scintillation characteristics, production of long crystals, behavior in γ and MeV-neutron irradiations, matrix performance in particle beams, e.g.:

M. Kobayashi et al., NIM A 302 (1991) 443-446
Crystal Clear Coll., S.Anderson et al., NIM A 332 (1993) 373-394
R. Chipaux et al., NIM A 345 (1994) 440-444
E. Auffray, F. N.-T. et al., NIM A 378 (1996) 171-178
R. Novotny et al., NIM A 486 (2002) 131-135

as Cerium Fluoride was baseline in the CMS and L3P Letters of Intent.

CERN-LHCC-92-003 and CERN-LHCC-92-005

Cerium Fluoride history (contd.)

Summary of characteristics in

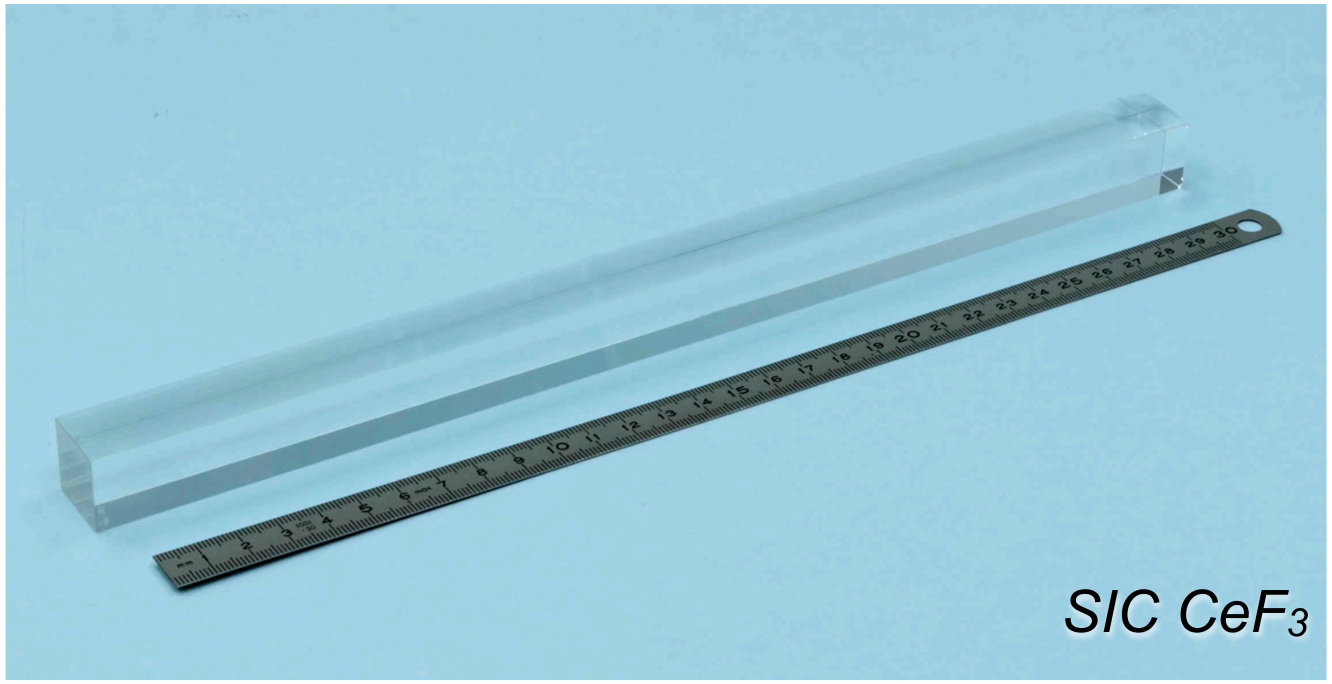
S. Majewski & C. Zorn, "Instr. in High Energy Physics", F. Sauli Ed., World Scientific (1993)

Cerium Fluoride was also considered for medical imaging applications

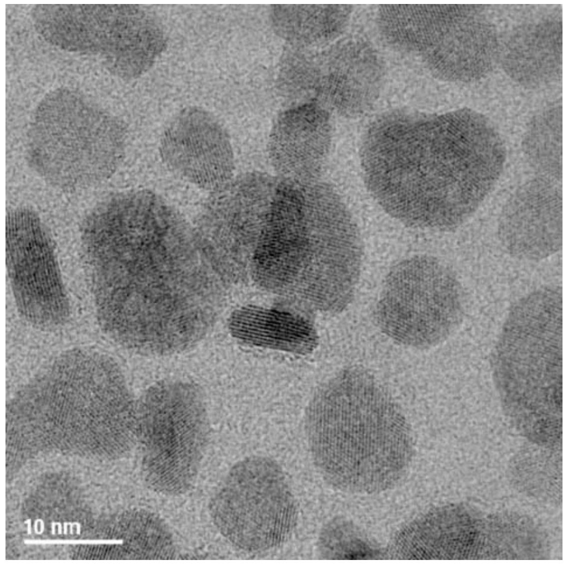
W.W.Moses, S. Derenzo et al., J. Lumin. 59 (1994) 89-100

Ability to grow crystals beyond 30 cm length was demonstrated

but R&D would have to be restarted on it, since no commercial production exists at present.



SIC CeF_3



CeF_3 is still used, e.g. for neutron capture cross-sections measurements!

Transmission electron microscopy picture of 10 μm CeF_3 nanoparticles by S. Stange et al, Los Alamos, IEEE/NSS 2009

Cerium Fluoride p-irradiation procedure

G.Dissertori, P.Lecomte, D.Luckey, F.Nessi-Tedaldi, F.Pauss, IEEE/NSS Dresden 2008
and IEEE/NSS Orlando 2009

Apply same irradiation and measurements procedures used for $PbWO_4$

→ CeF_3:Ba crystal from Optovac from the '90s, 21 x 16 x 141 mm^3 (8.4 X_0)

→ First 24 GeV/c p-irradiation at the CERN-PS IRRAD1 facility, up to

$$\Phi_p = (2.78 \pm 0.20) \times 10^{13}\ \mathrm{p/cm}^2$$

followed by recovery measurements over more than 1 year

→ Second 24 GeV/c p-irradiation up to

$$\Phi_p = (2.12 \pm 0.15) \times 10^{14}\ \mathrm{p/cm}^2$$

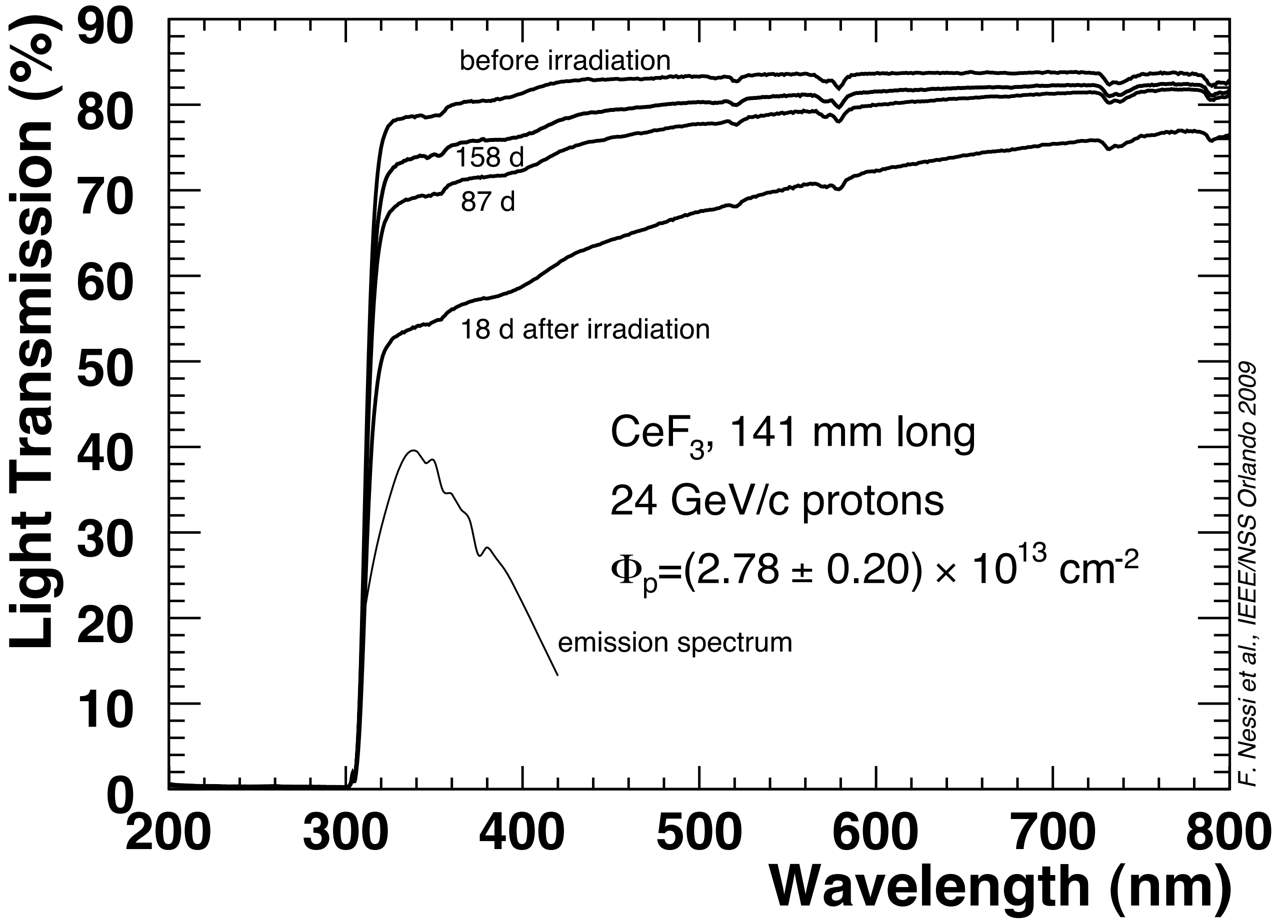
followed by mesurements over 1 year

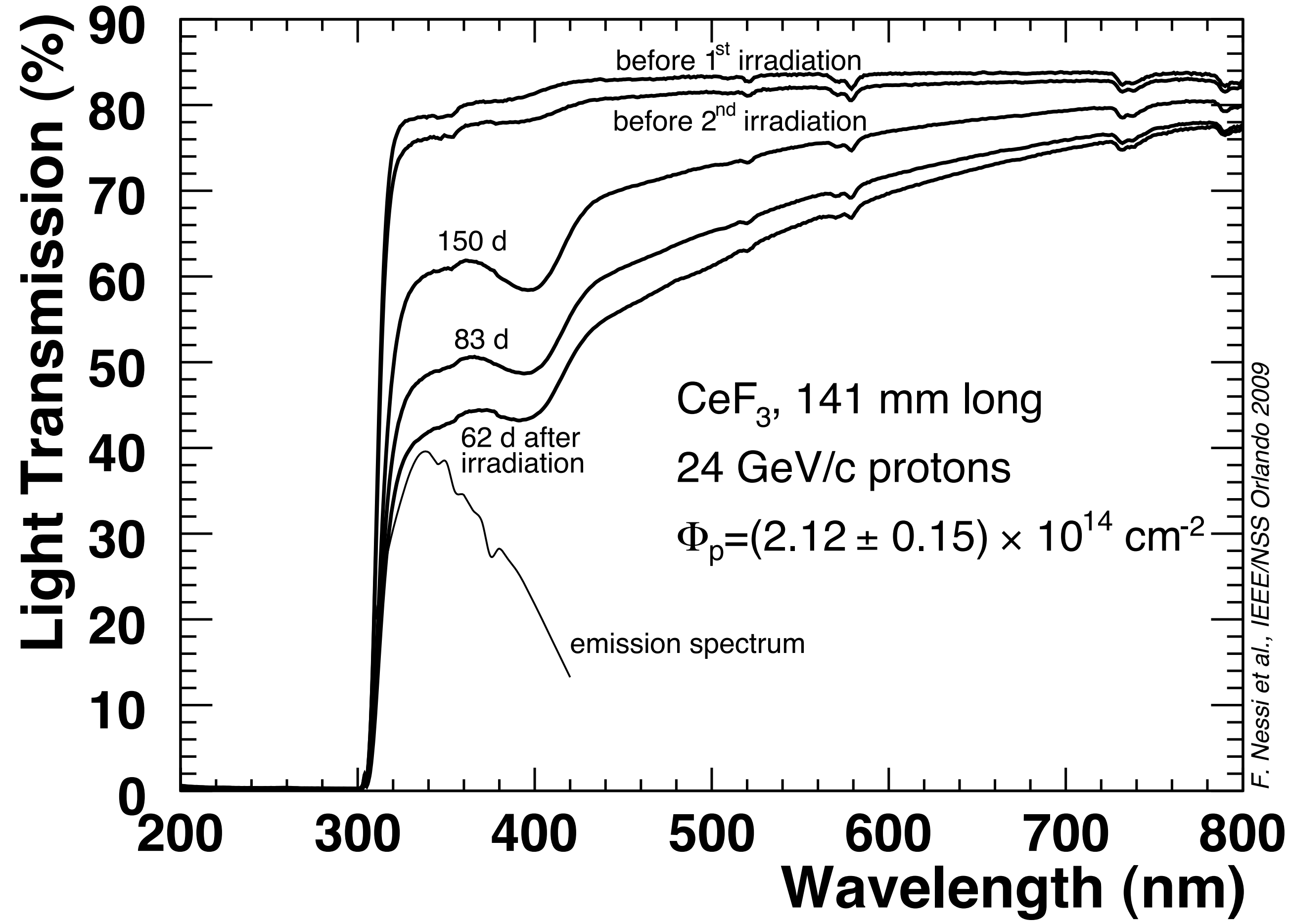
→ Transmission damage evaluated at λ, where peak of scintillation emission, for Ba-doping ~ 340 nm, according to:

W.W. Moses & S.E.Derenzo, IEEE TNS 36 (1989) 173-176
Crystal Clear Coll., S.Anderson et al., NIM A 332 (1993) 373-394

CeF_3 Transmission changes with proton irradiation

important recovery over a few months





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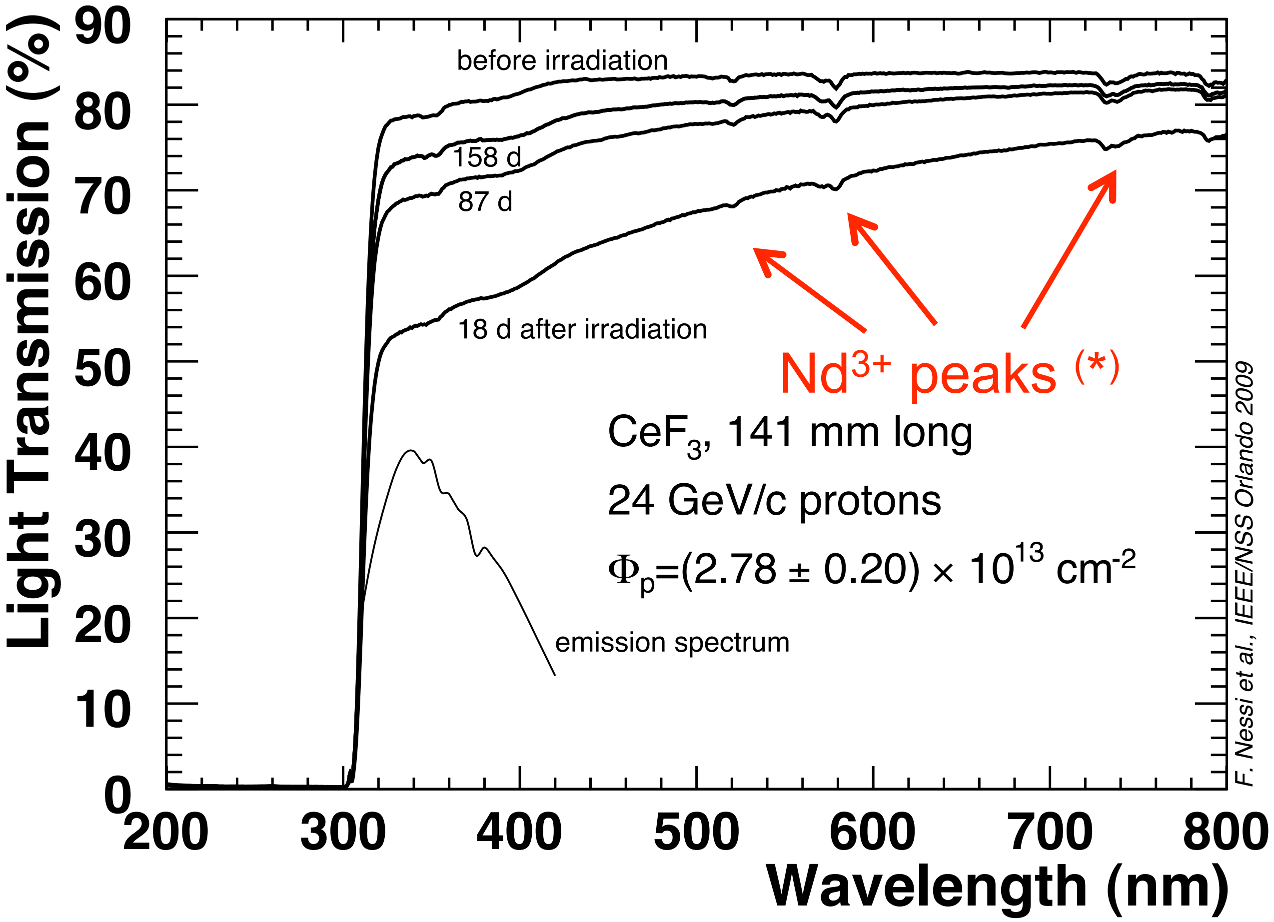

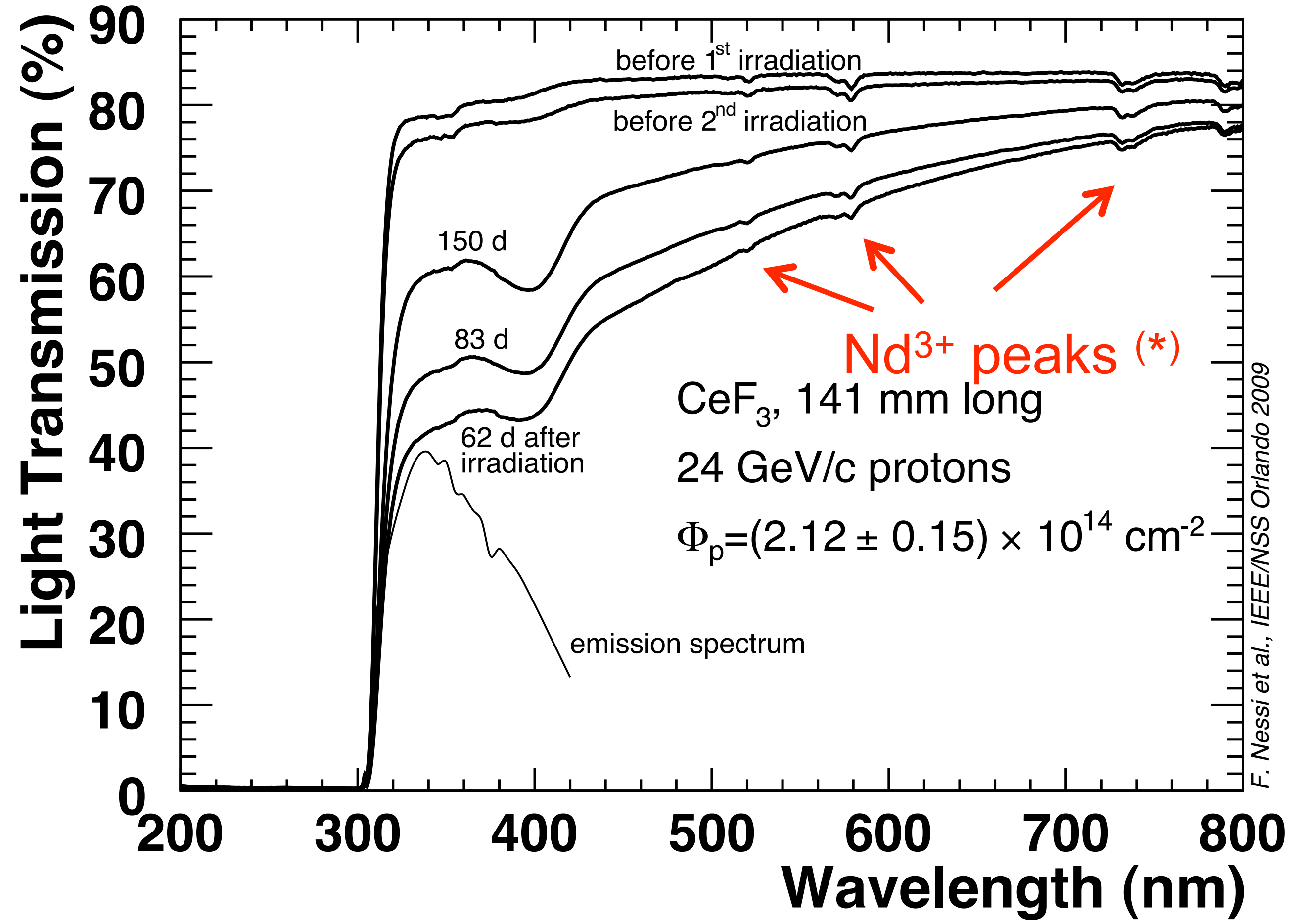

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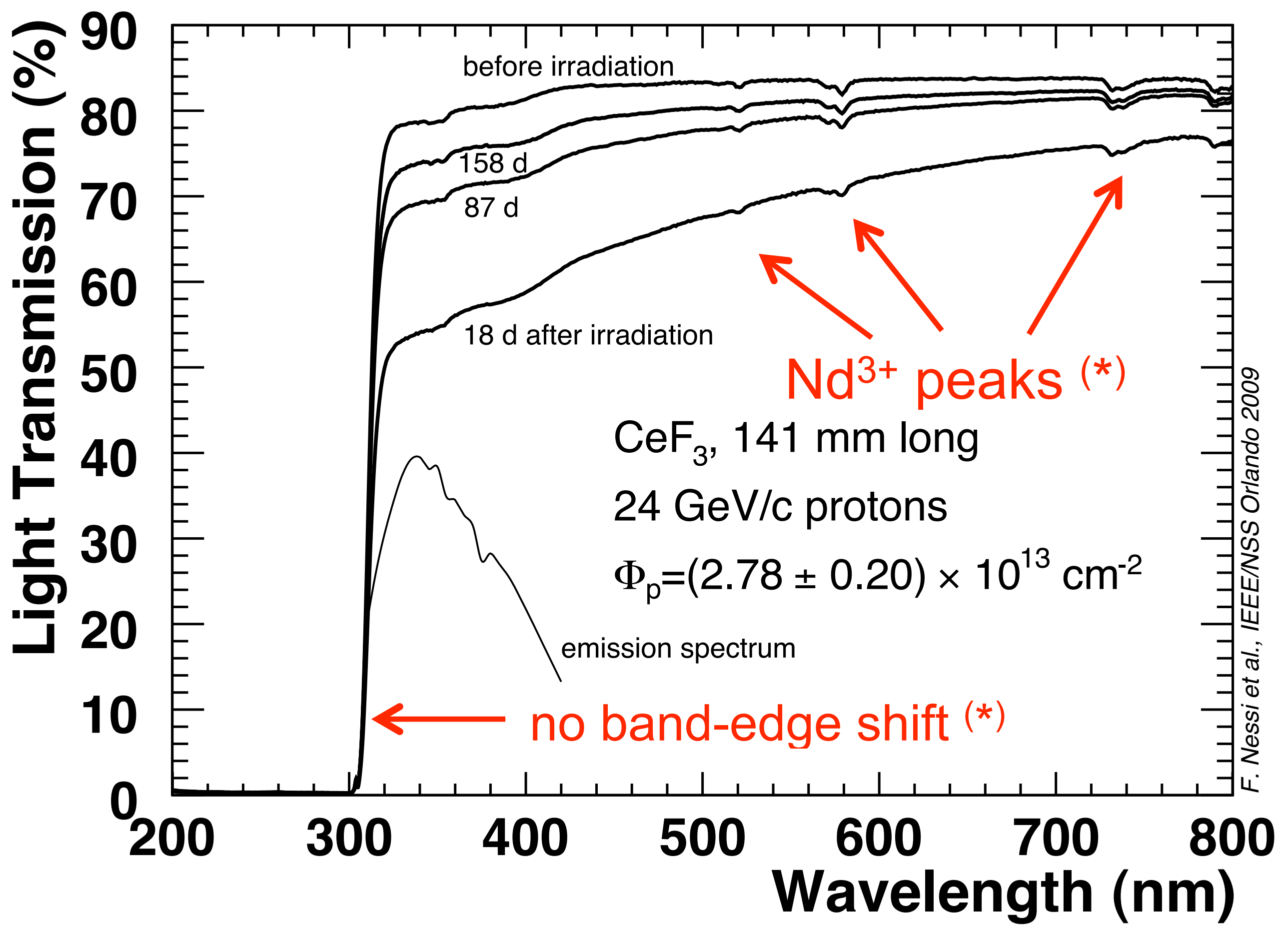

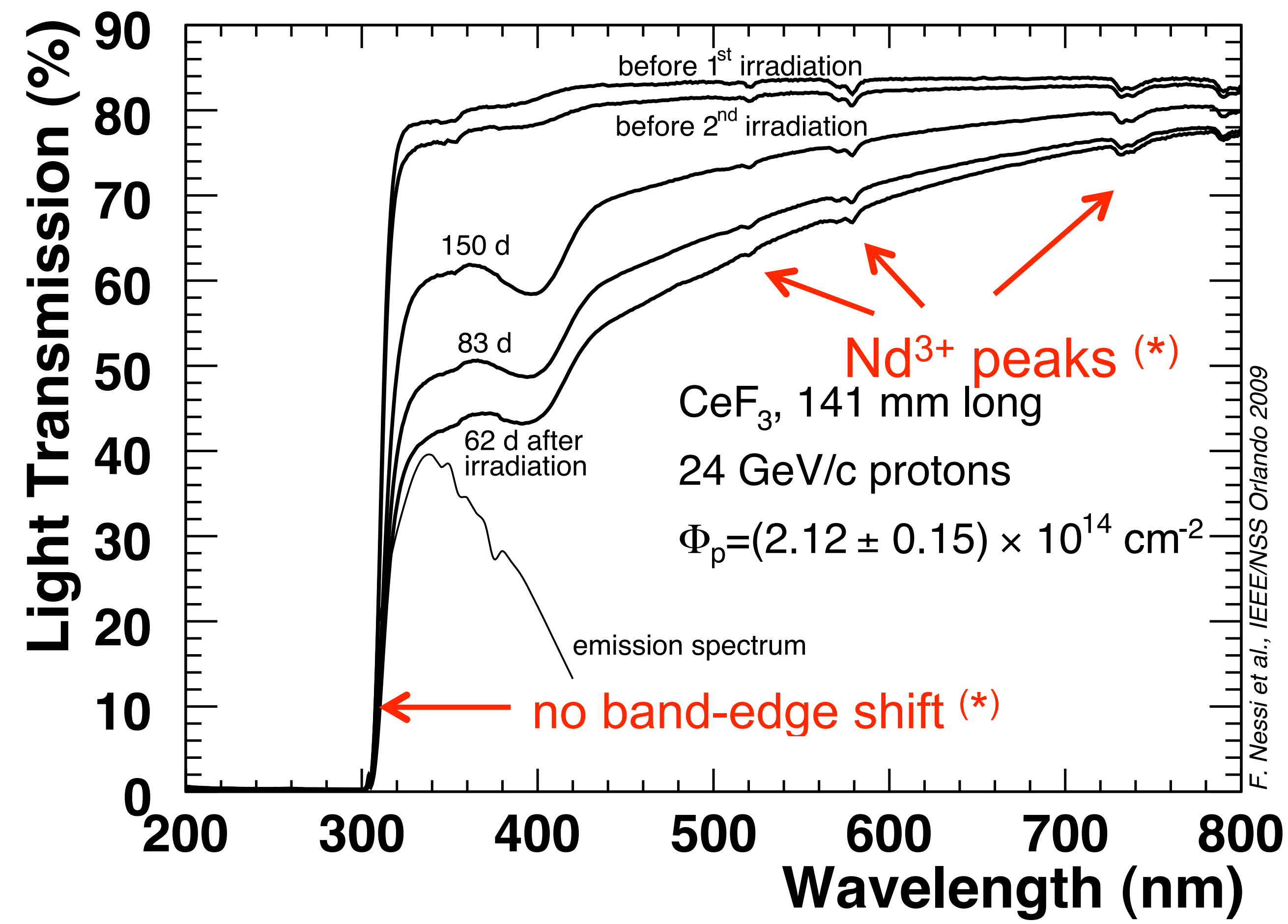

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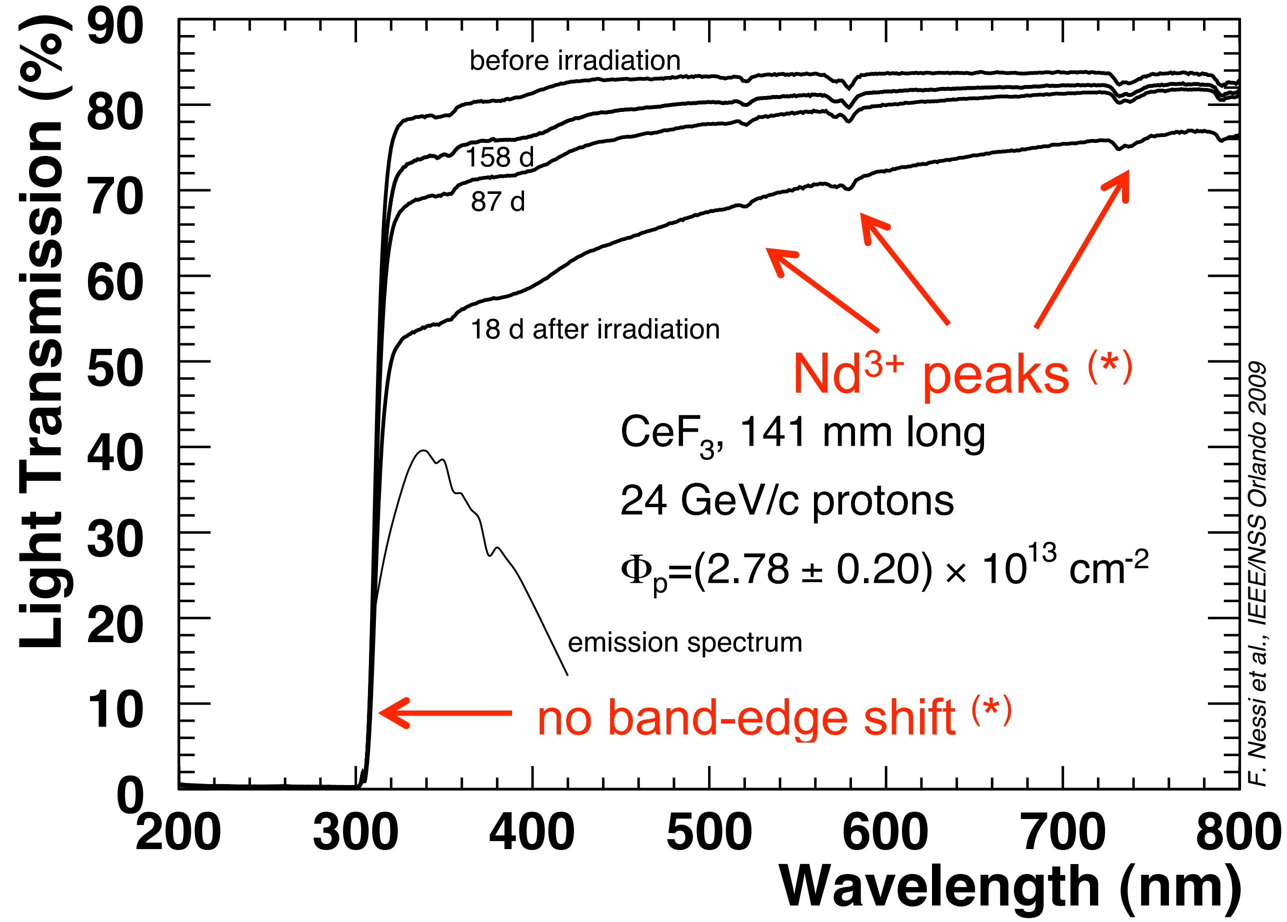

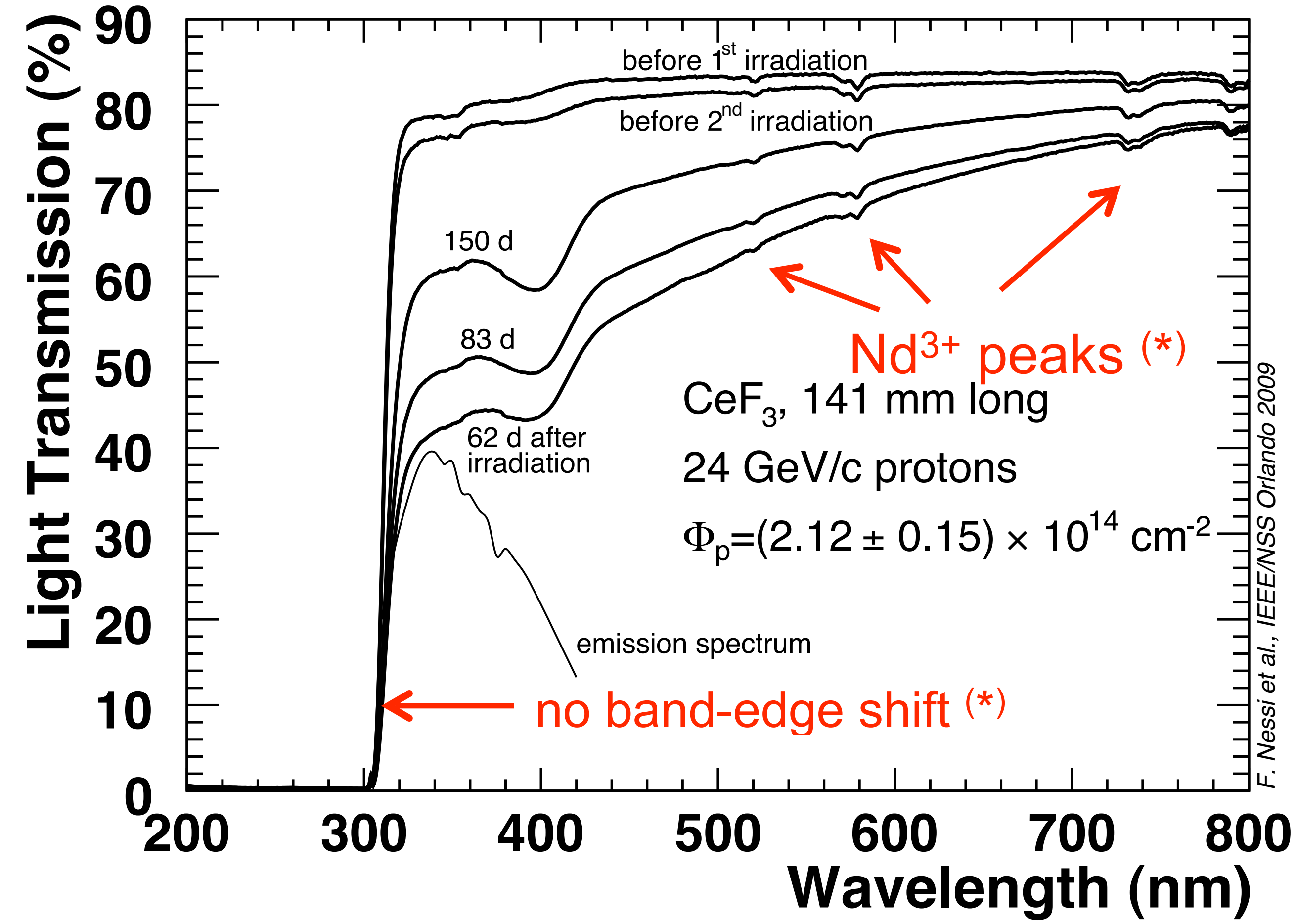

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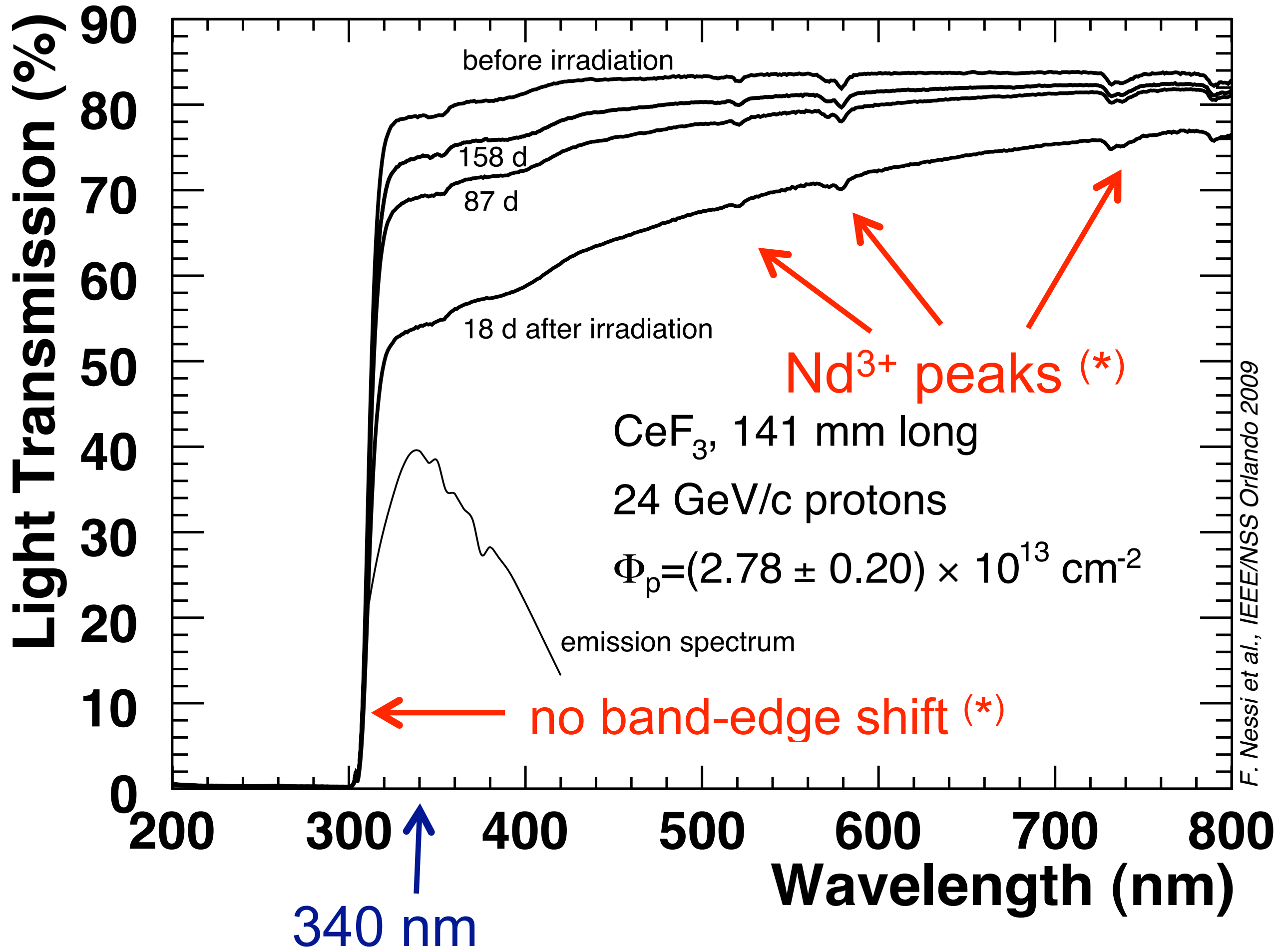

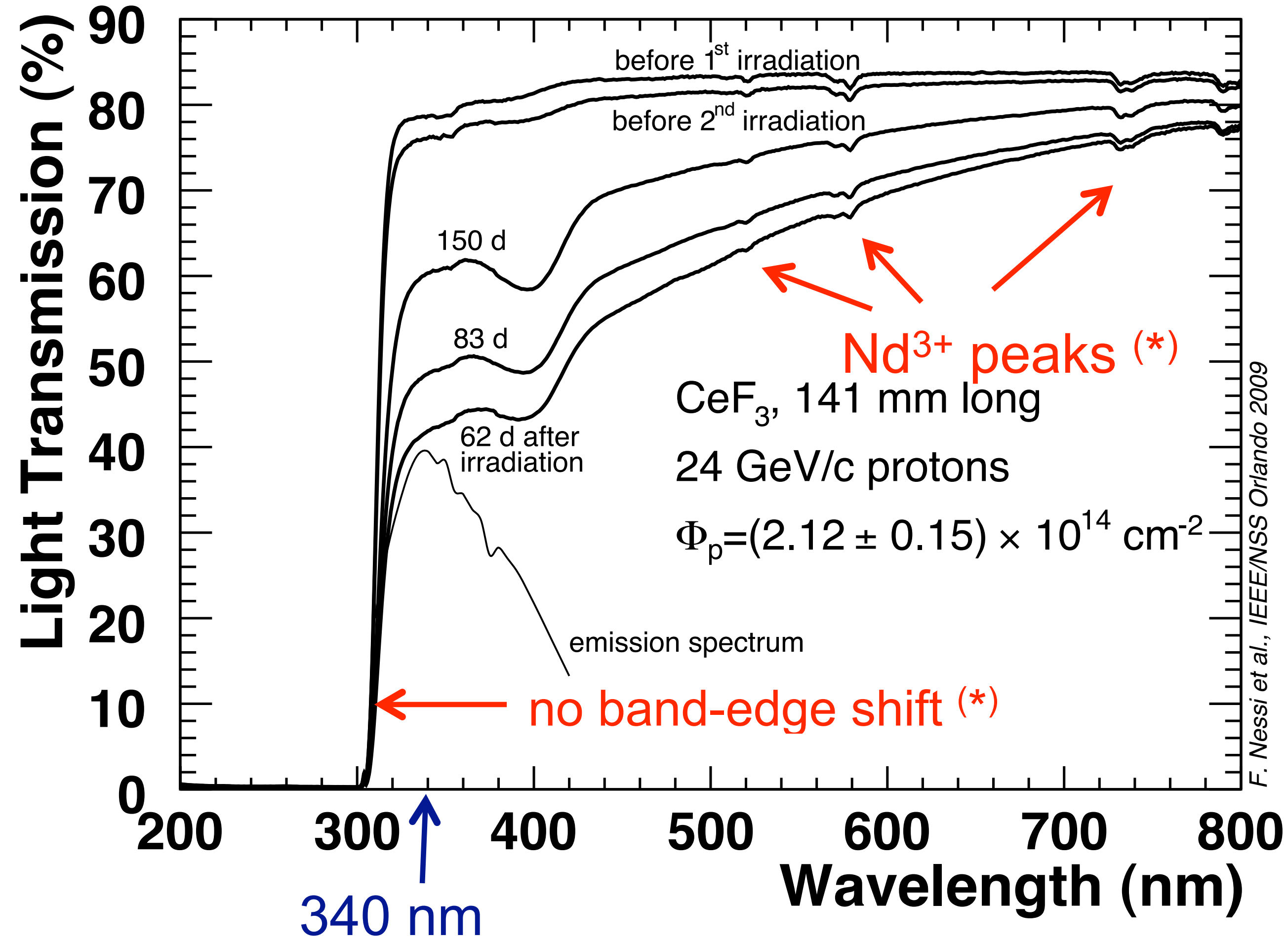

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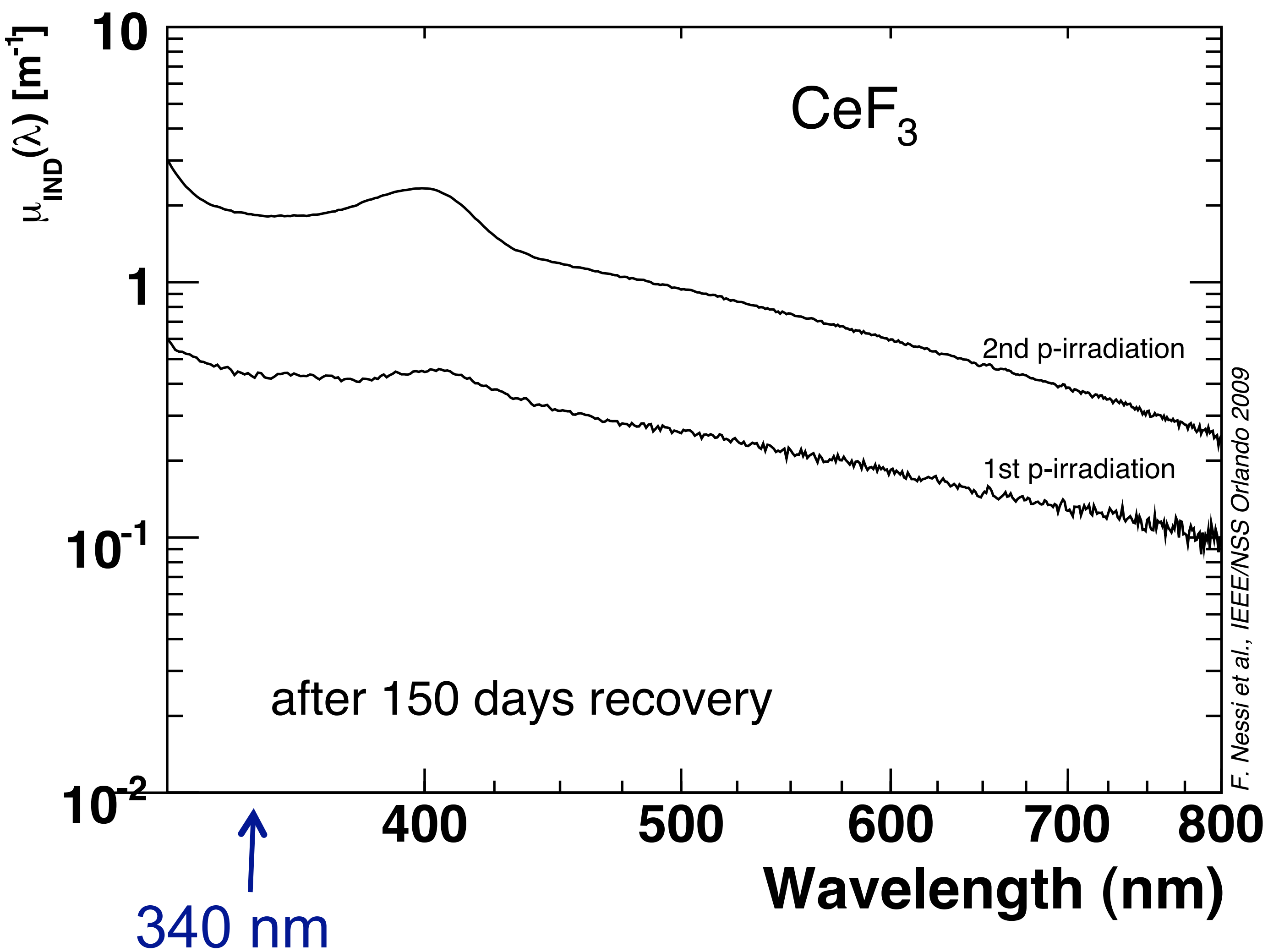
→ evaluate damage further at the peak-of-emission λ = 340 nm

CeF_3 Light absorption after p irradiation

- Rayleigh scattering behavior, as observed for $PbWO_4$ over most of the λ range, is absent

→ this confirms that the dominant Rayleigh scattering observed in $PbWO_4$ is linked to the production of highly ionizing heavy fragments

Remark:
Nd^{3+} dips totally disappear when μ_{IND} is evaluated
→not influenced by radiation
→no hidden bands underneath



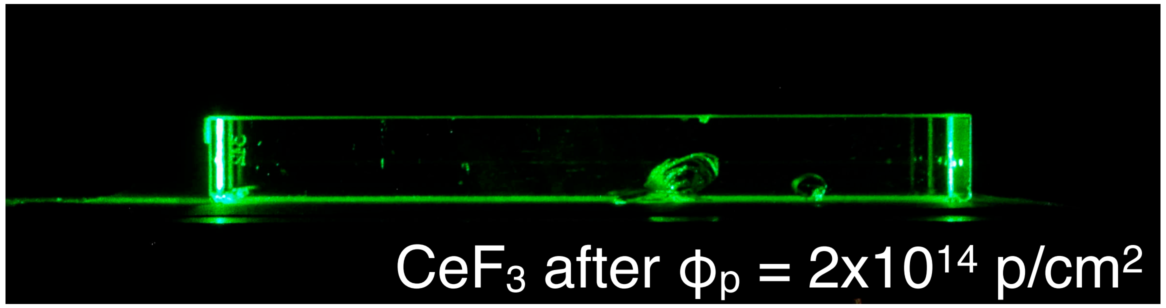
- An absorption band is present at ~400 nm, away from the emission λ, not identified so far. The density of centers N x oscillator strength f calculated according to *D.L.Dexter Phys. Rev. 101 (1956) 48* for the 2nd irradiation is

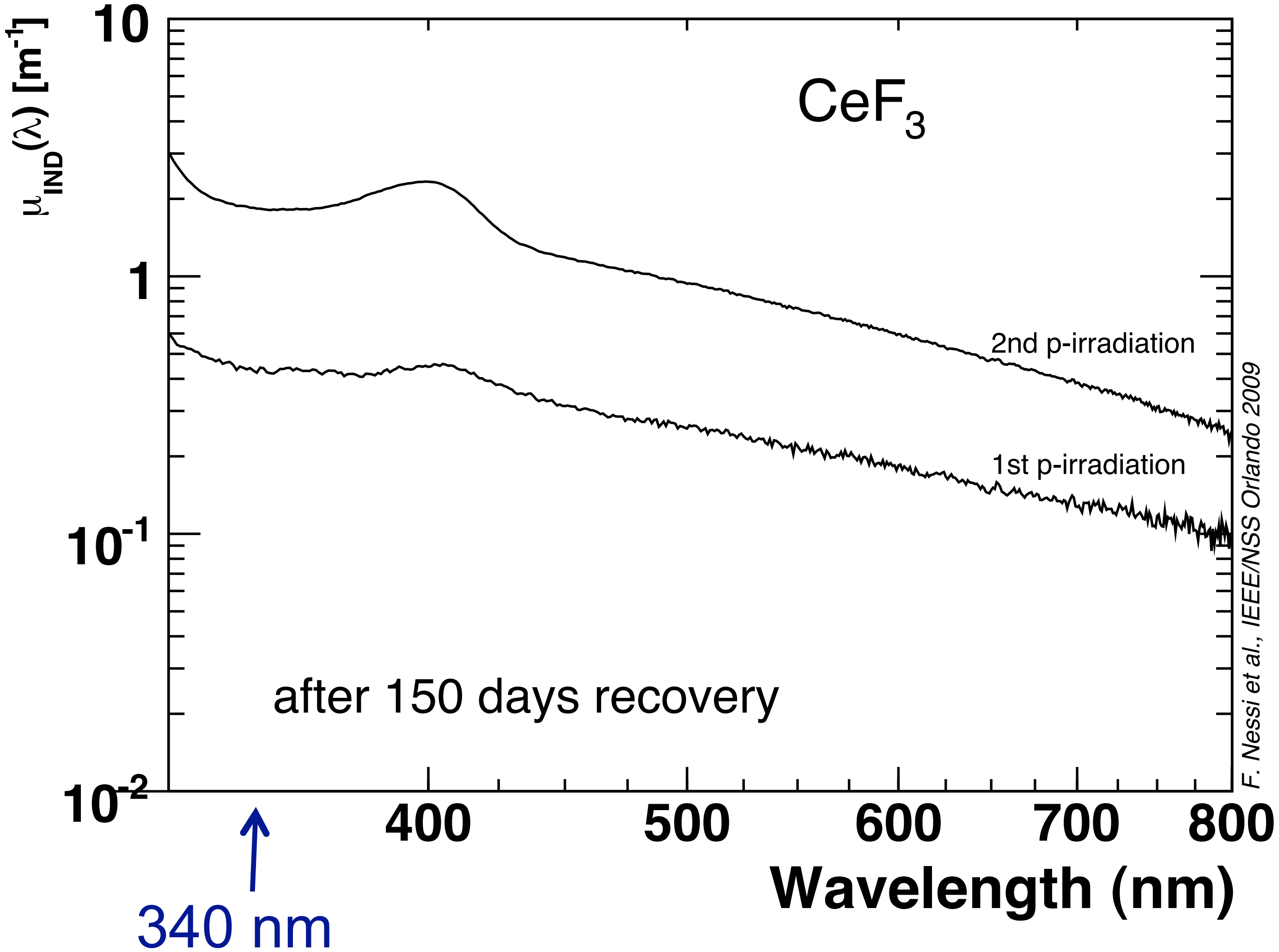
$$N \times f \sim 1.7 \times 10^{13}\ cm^{-3}$$

CeF_3 Light absorption after p irradiation

- Rayleigh scattering behavior, as observed for $PbWO_4$ over most of the λ range, is absent

→ this confirms that the dominant Rayleigh scattering observed in $PbWO_4$ is linked to the production of highly ionizing heavy fragments





Remark:
Nd^{3+} dips totally disappear when μ_{IND} is evaluated
→not influenced by radiation
→no hidden bands underneath

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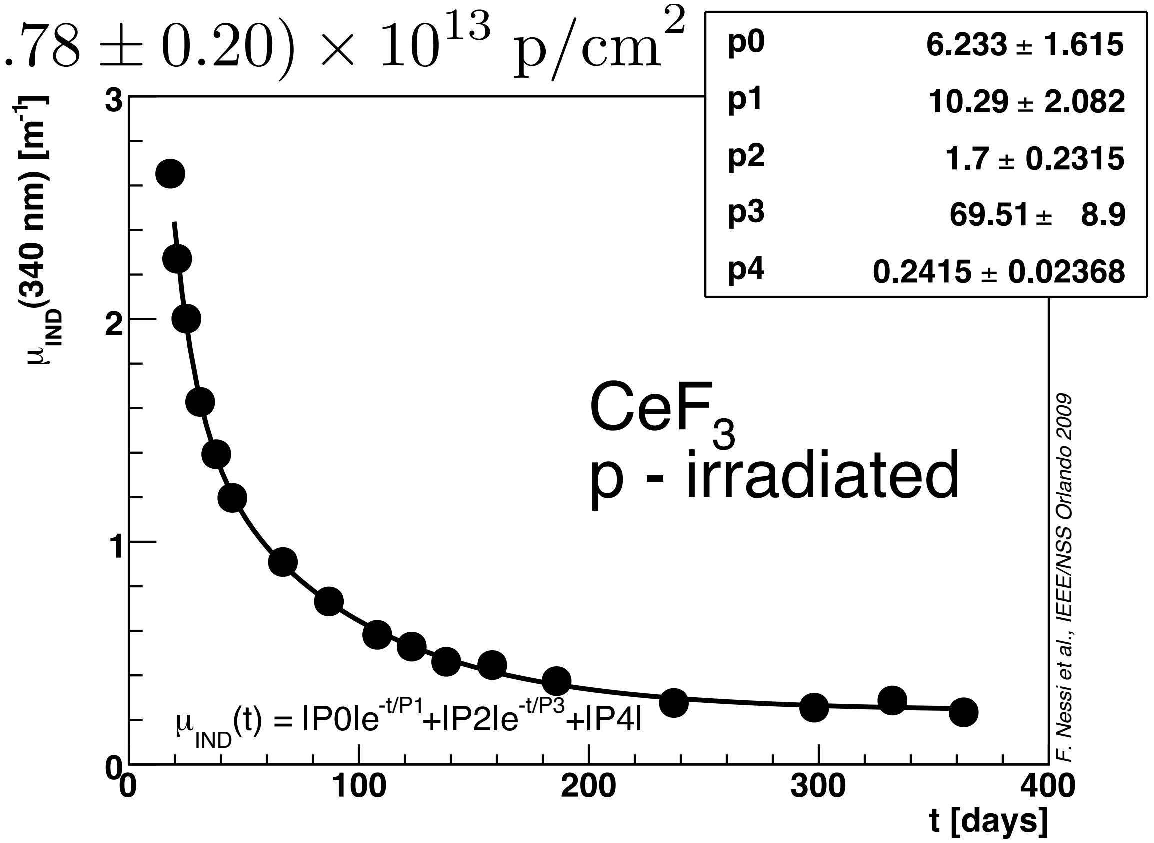
$$N \times f \sim 1.7 \times 10^{13}\ \mathrm{cm}^{-3}$$

Recovery of CeF_3 Transmission after p irradiation

$$\Phi_p = (2.78 \pm 0.20) \times 10^{13}\ \mathrm{p/cm^2}$$



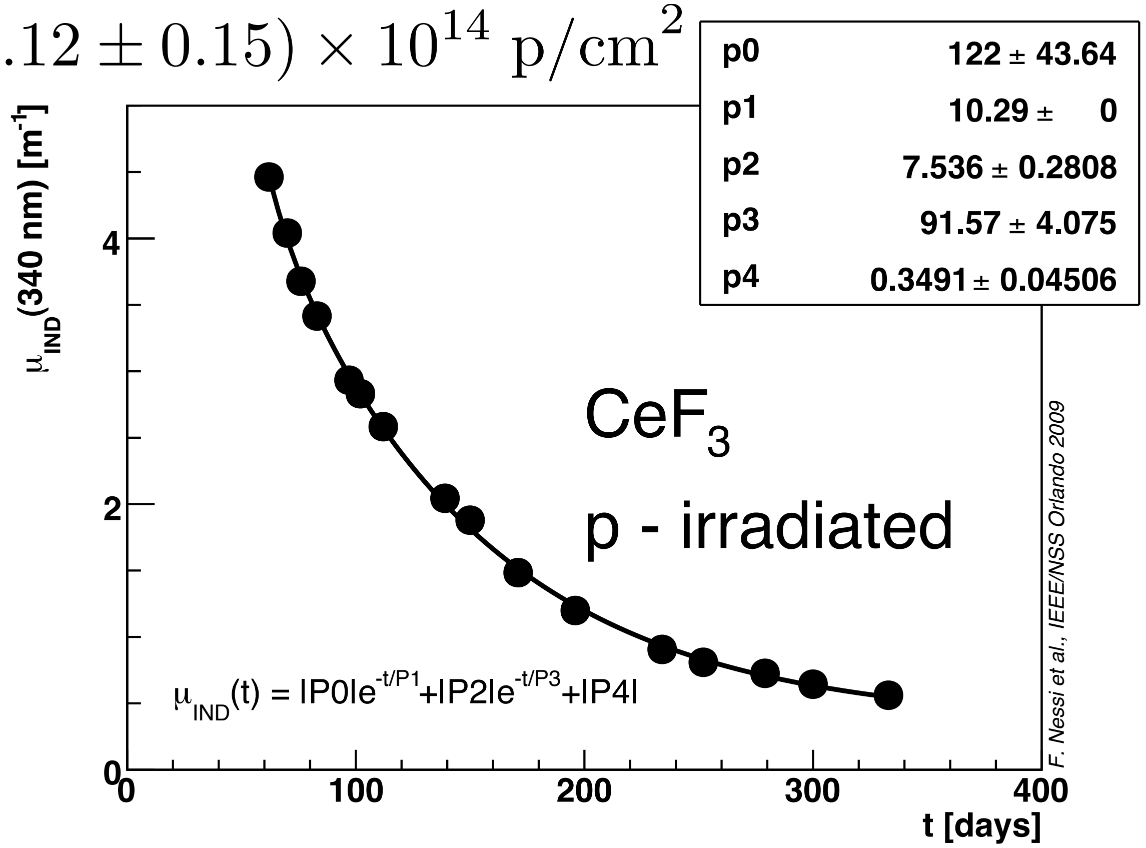
- Crystal left in the dark, at room temperature. Periodic transmission measurements

From 1st irradiation:

→ recovery time constants $\tau_1 = 10 \pm 2$ days and $\tau_2 = 70 \pm 9$ days

→ 90% of the damage observed at 18 d is recovered after 1 year

$$\Phi_p = (2.12 \pm 0.15) \times 10^{14}\ \mathrm{p/cm^2}$$



After 2nd irradiation, radioactivity allowed handling only starting after 2 months:

→ Fix $\tau_1 = 10$ days, and fit $\tau_2 = 70 \pm 9$ days, compatible with 1st irradiation results.

→ Track recovery further, whether complete

→ The amplitudes and time constants of recovery indicate that at sLHC, hadron damage would never build up to a severe level in CeF_3

LYSO - Lutetium Yttrium Orthosilicate

Cerium-doped silicate-based crystals were recently developed for medical applications.

LSO (Lu_2SiO_5:Ce) was first investigated as a phosphor

A.H.Gomes et al., Mat. Res. Bull. 4 (1969) 643.

then rediscovered as a promising scintillator and first grown in 1989

C. Melcher US Patent, No. 4958080, 1990

Mass-production was established for LSO

C. Melcher and J. Schweitzer, IEEE TNS 39 (1992) 502-505

and for LYSO ($Lu_{2(1-x)}Y_{2x}SiO_5$:Ce)

D.W. Cooke et al., J. Appl. Phys. 88 (2000) 7360-7362

T. Kimble et al., Proc. IEEE NSS 2002

Numerous studies of their characteristics have been performed:

R.H.Mao, L.Y.Zang and R.Y. Zhu, IEEE TNS 55 (2008) 1759 and refs. therein

The performance under γ-irradiation was thoroughly investigated:

R.H.Mao, L.Y.Zang and R.Y. Zhu, IEEE TNS 54 (2007) 1319

The performance for precision calorimetry was studied:

M. Thiel, W. M. Döring, V. Dormenev, P. Drexler, R. W. Novotny, M. Rost, A. Thomas, IEEE TNS 55 (2008)1425

Investigation of LYSO under proton-irradiation

G.Dissertori, P.Lecomte, D.Luckey, F.Nessi-Tedaldi, F.Pauss, IEEE/NSS Orlando 2009

→ While no industrial mass-production for CeF_3 is presently set up, LYSO is being mass produced by several companies, since it is heavily used in high-precision Positron-Emission Tomography.

→ LYSO has a very high light yield, and could thus perform adequately even with radiation losses

→ γ-radiation effects have been shown to be small, and dose rate dependent

→ The capability to grow large ingots has been demonstrated. Drawback: Lutetium is rather expensive

Apply same irradiation and measurement procedures used for $PbWO_4$ and CeF_3

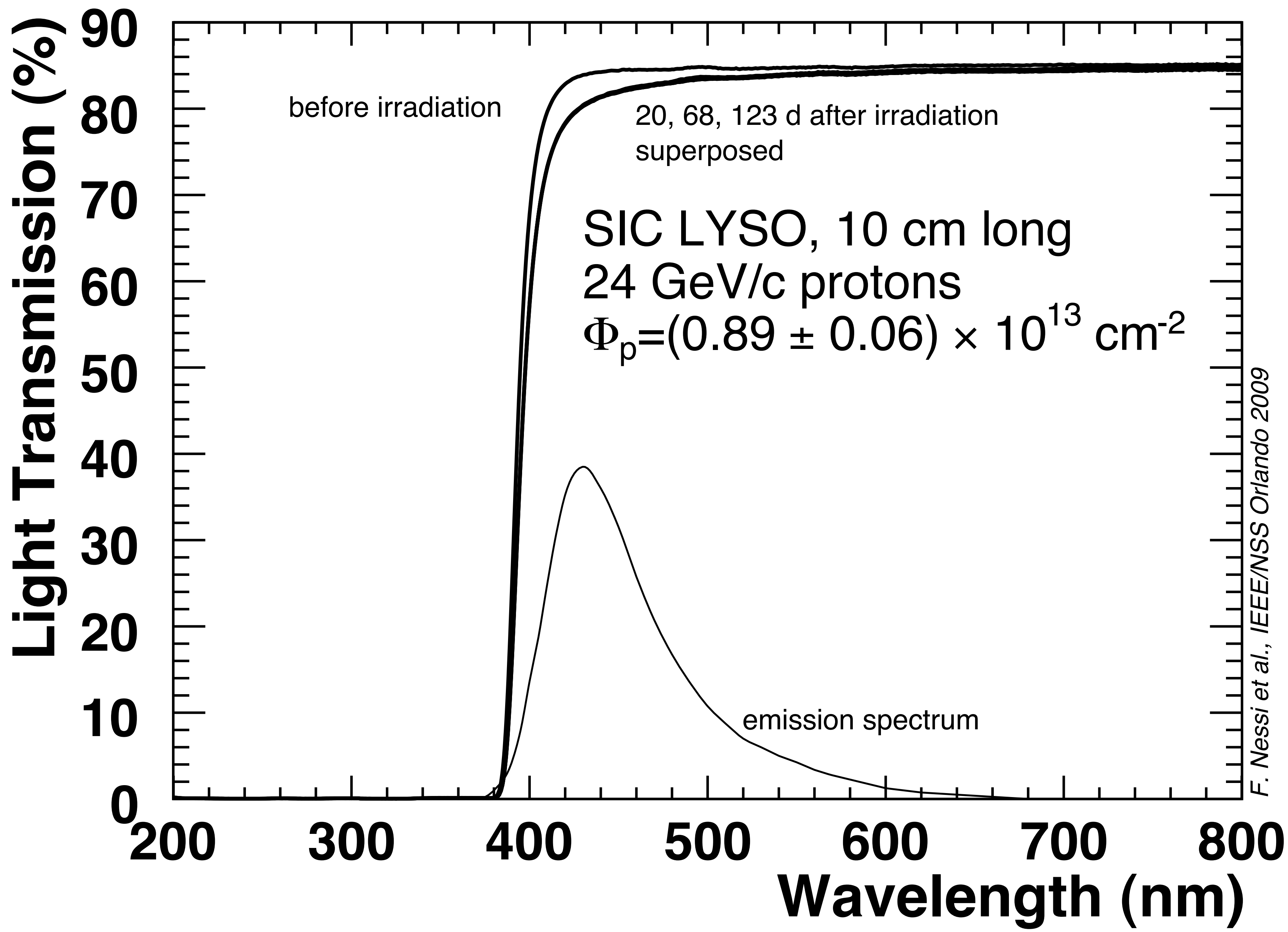
→ LYSO:Ce crystal from SIC, 25 x 25 x 100 mm^3 (8.8 X_0)

→ 24 GeV/c p-irradiation up to $\Phi_p = (0.89 \pm 0.06) \times 10^{13}\ \mathrm{p/cm^2}$

→ Peak of scintillation emission at ~ 430 nm, according to:

R.H.Mao, L.Y.Zang and R.Y. Zhu, IEEE TNS 55 (2008) 1759

LYSO Transmission changes with proton irradiation



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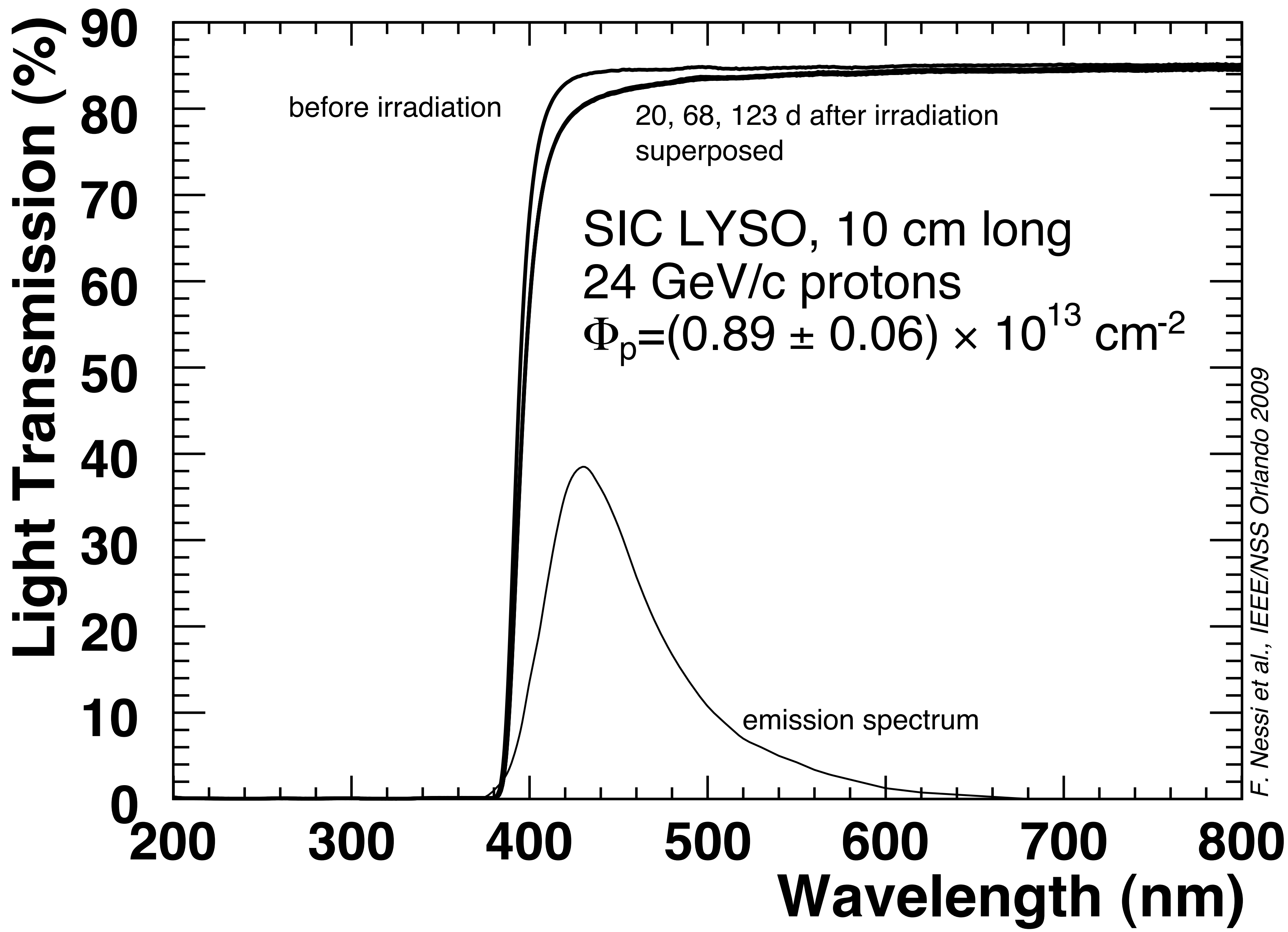
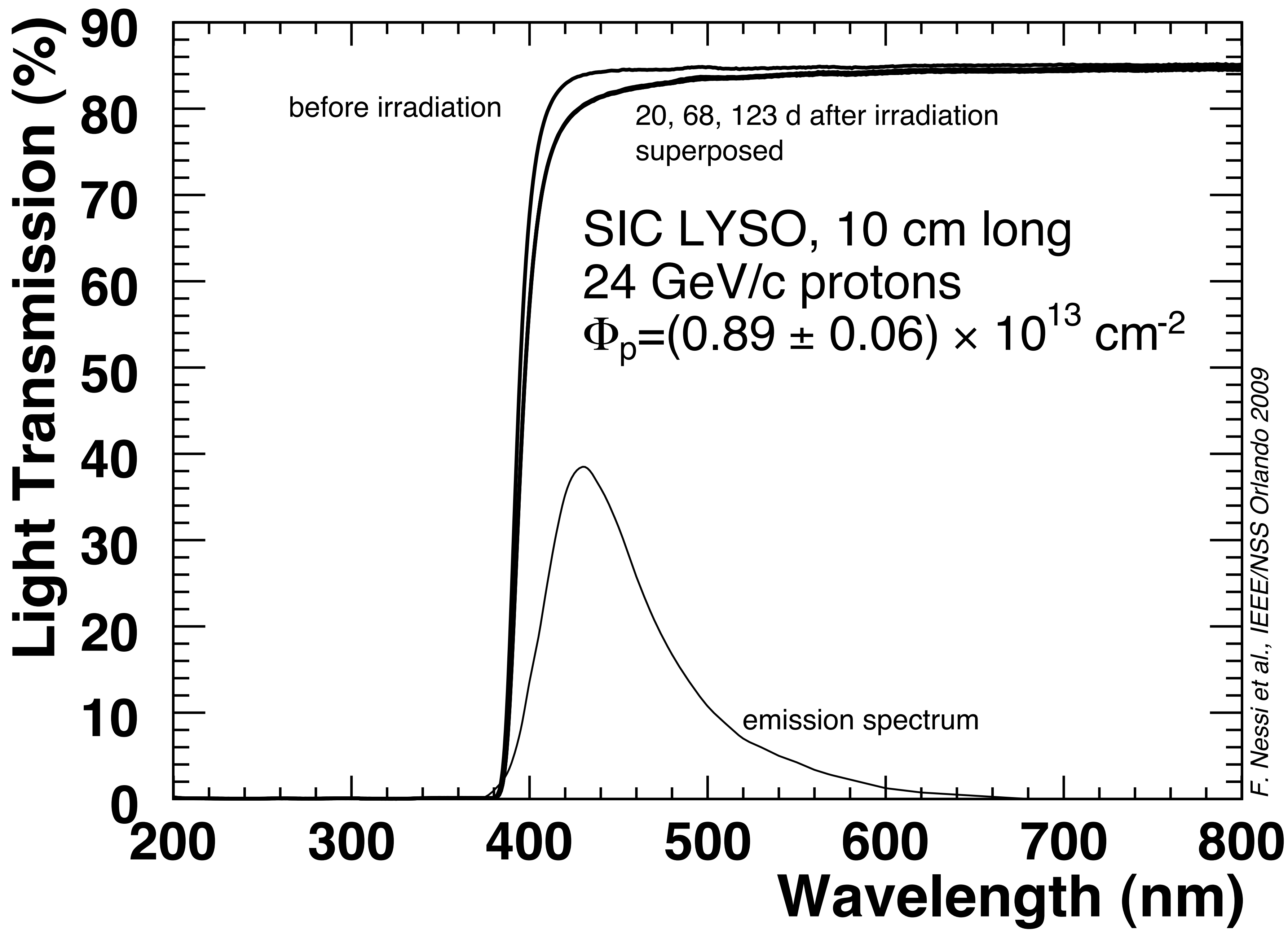


→ The change in Transmission induced by p-irradiation at this fluence in LYSO is quite modest

LYSO Transmission changes with proton irradiation



→ The change in Transmission induced by p-irradiation at this fluence in LYSO is quite modest

→ No recovery overall is observed between 20 days and 123 days after irradiation

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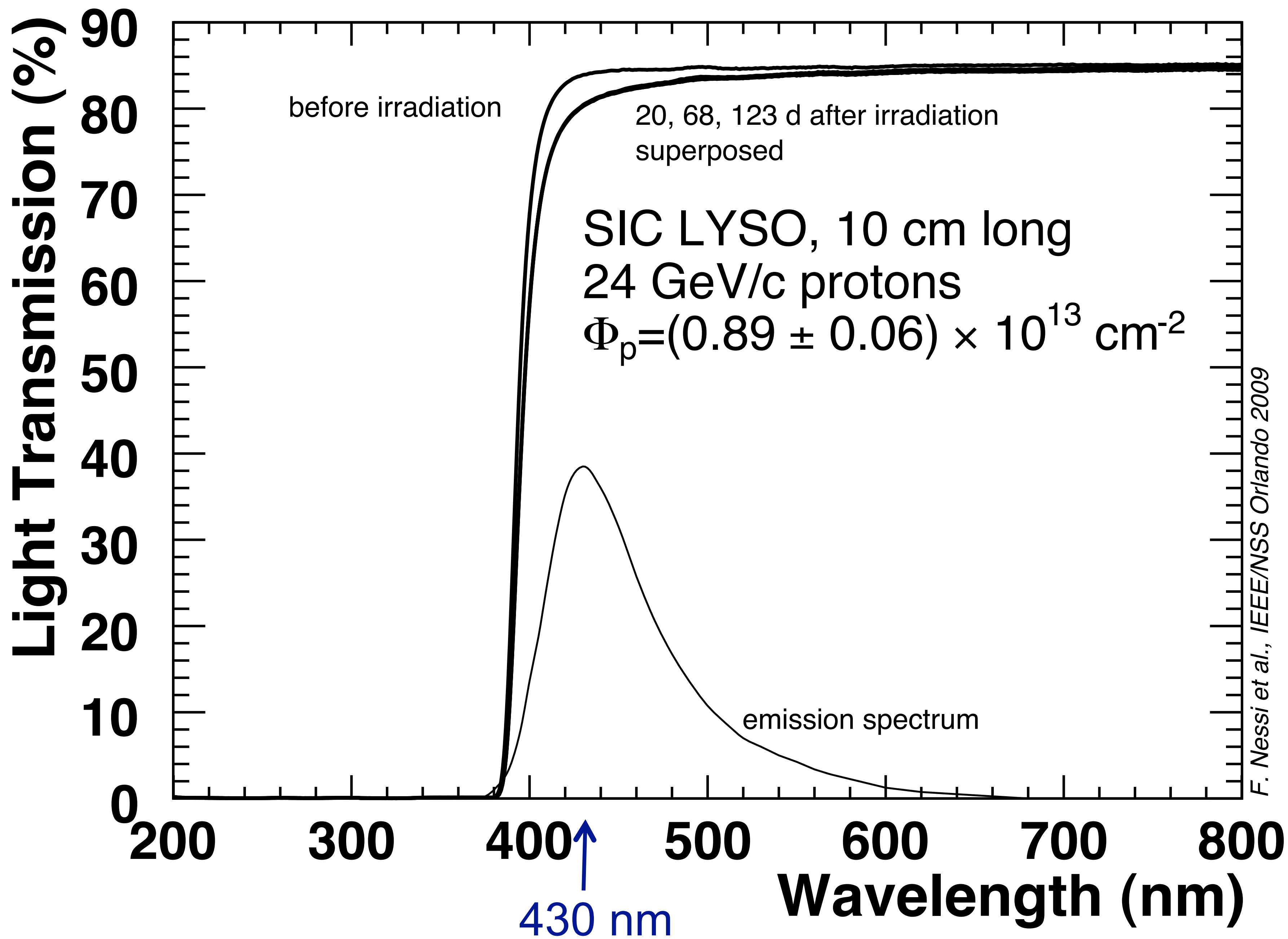

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→ No recovery overall is observed between 20 days and 123 days after irradiation

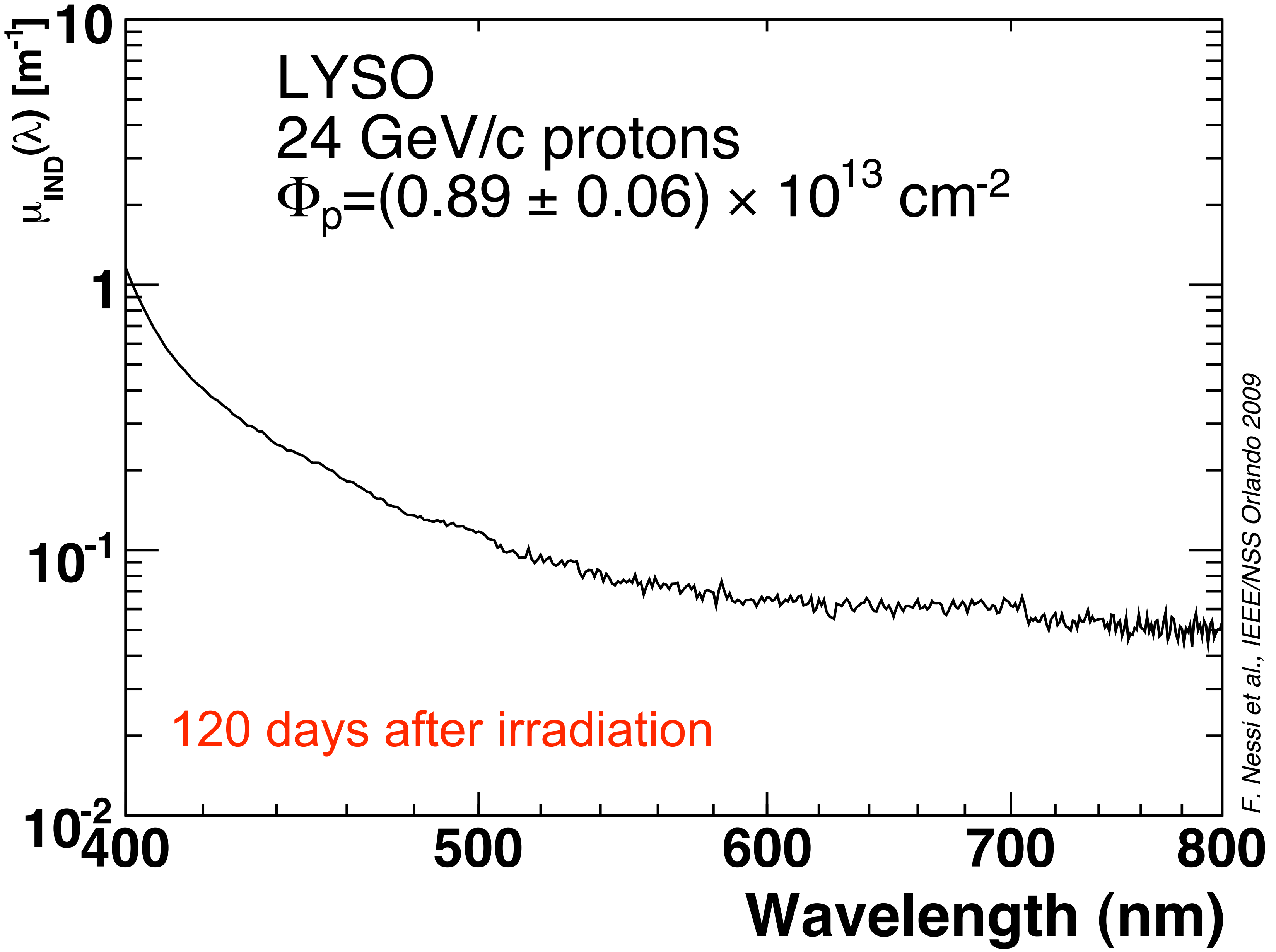
→ evaluate damage further at the peak-of-emission λ = 430 nm

LYSO Light absorption after p irradiation

→ In LYSO, as in CeF_3, Rayleigh scattering behavior, as observed for $PbWO_4$ over most of the λ range, is absent

→ this is a further confirmation that the dominant Rayleigh scattering observed in $PbWO_4$ is linked to the production of highly ionizing heavy fragments.

Such fragments -as anticipated- do not seem to be present in LYSO



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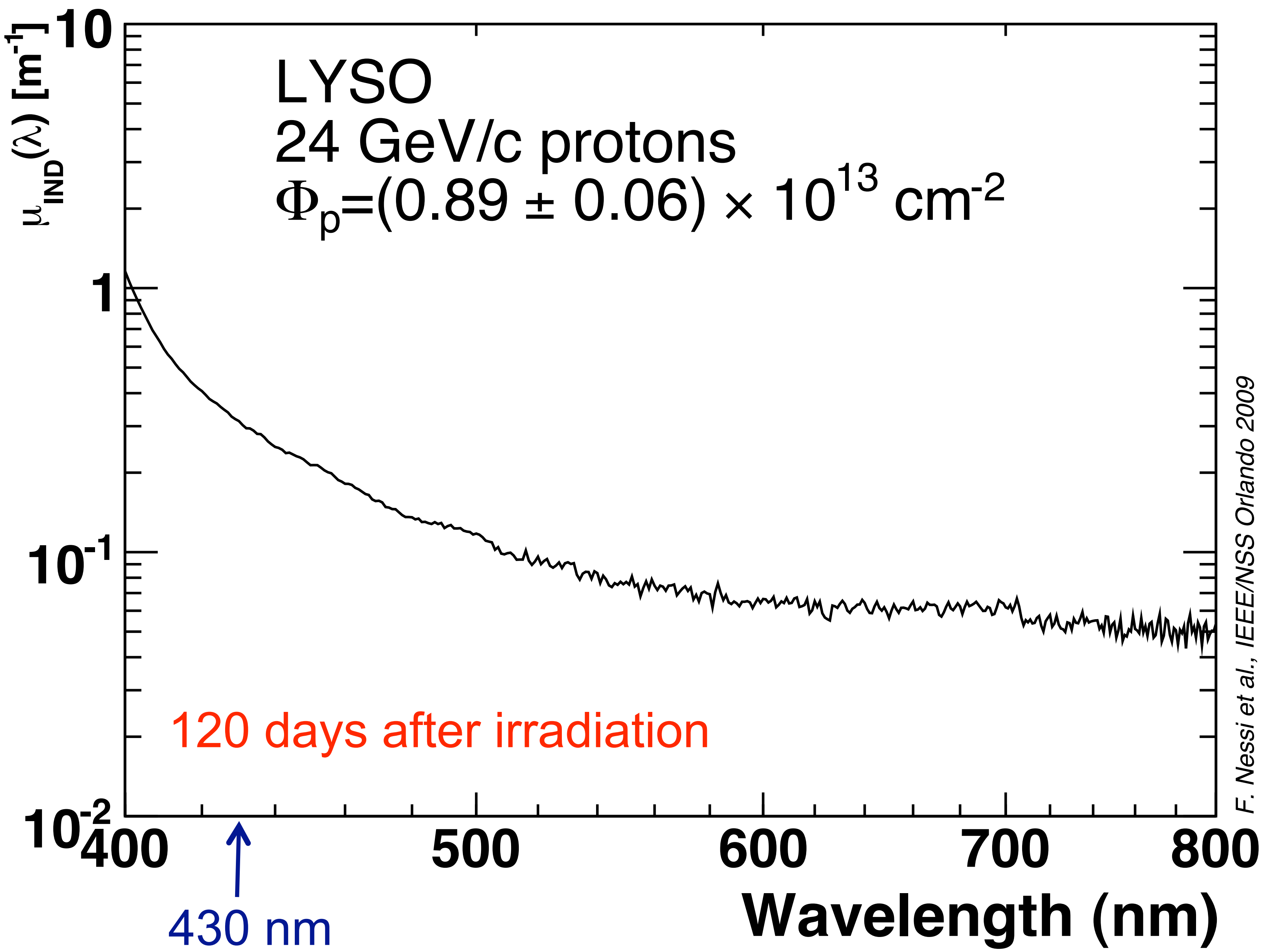

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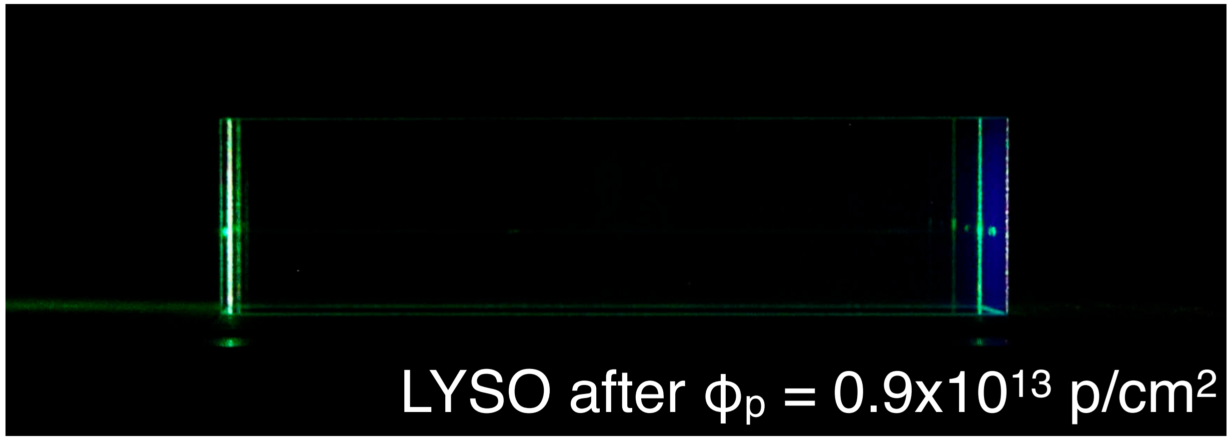
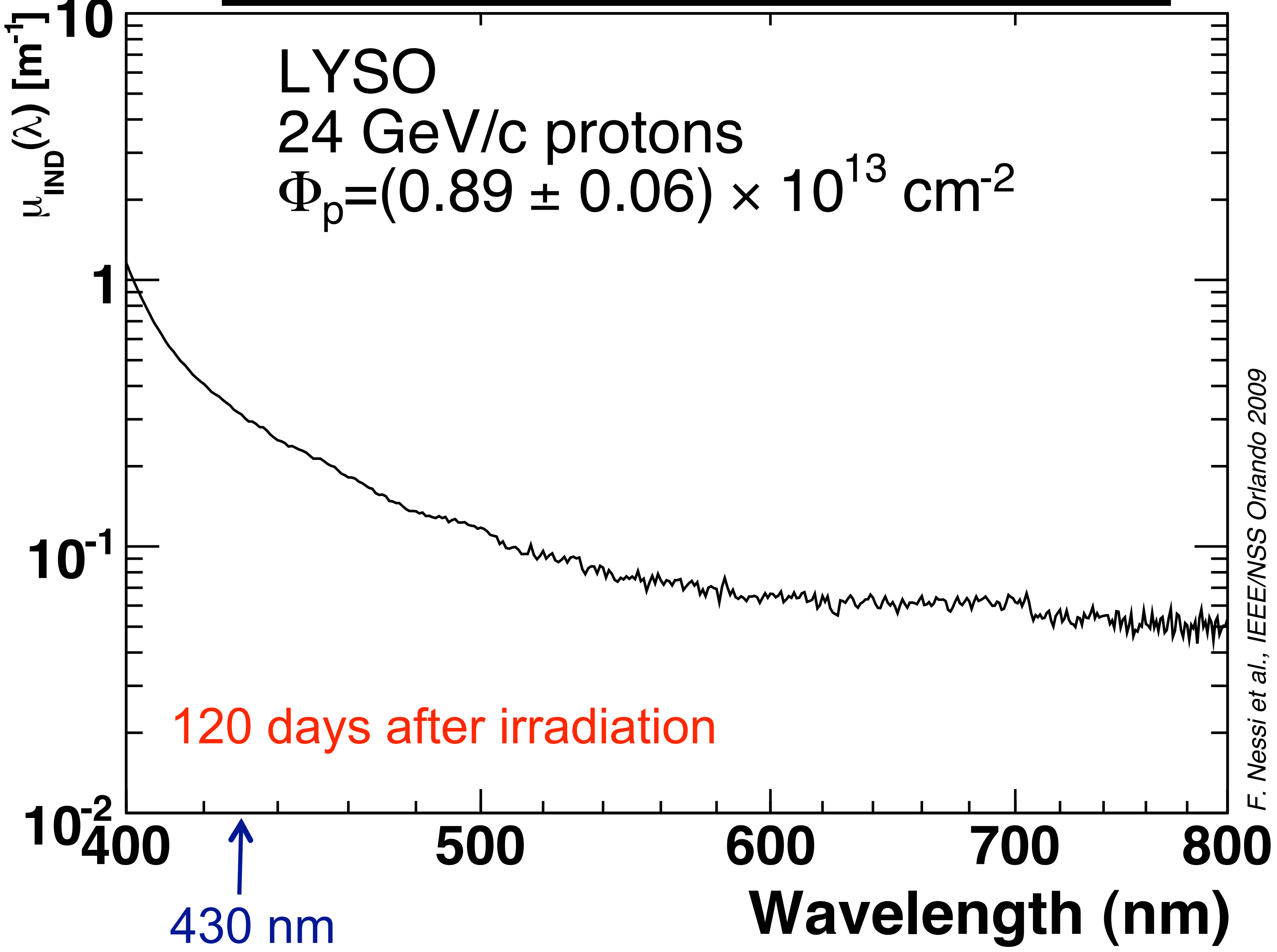
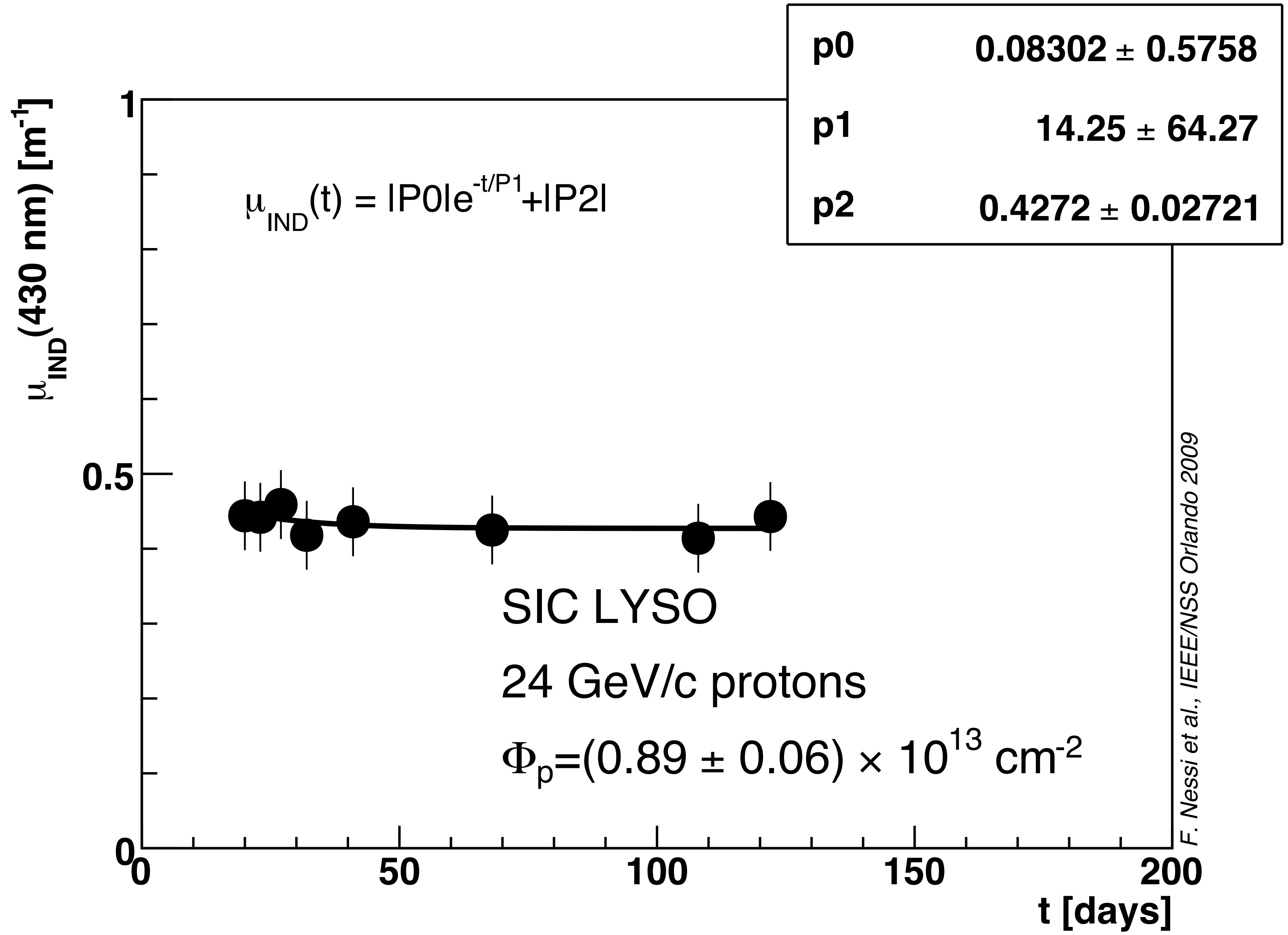




Recovery of LYSO Transmission after p irradiation

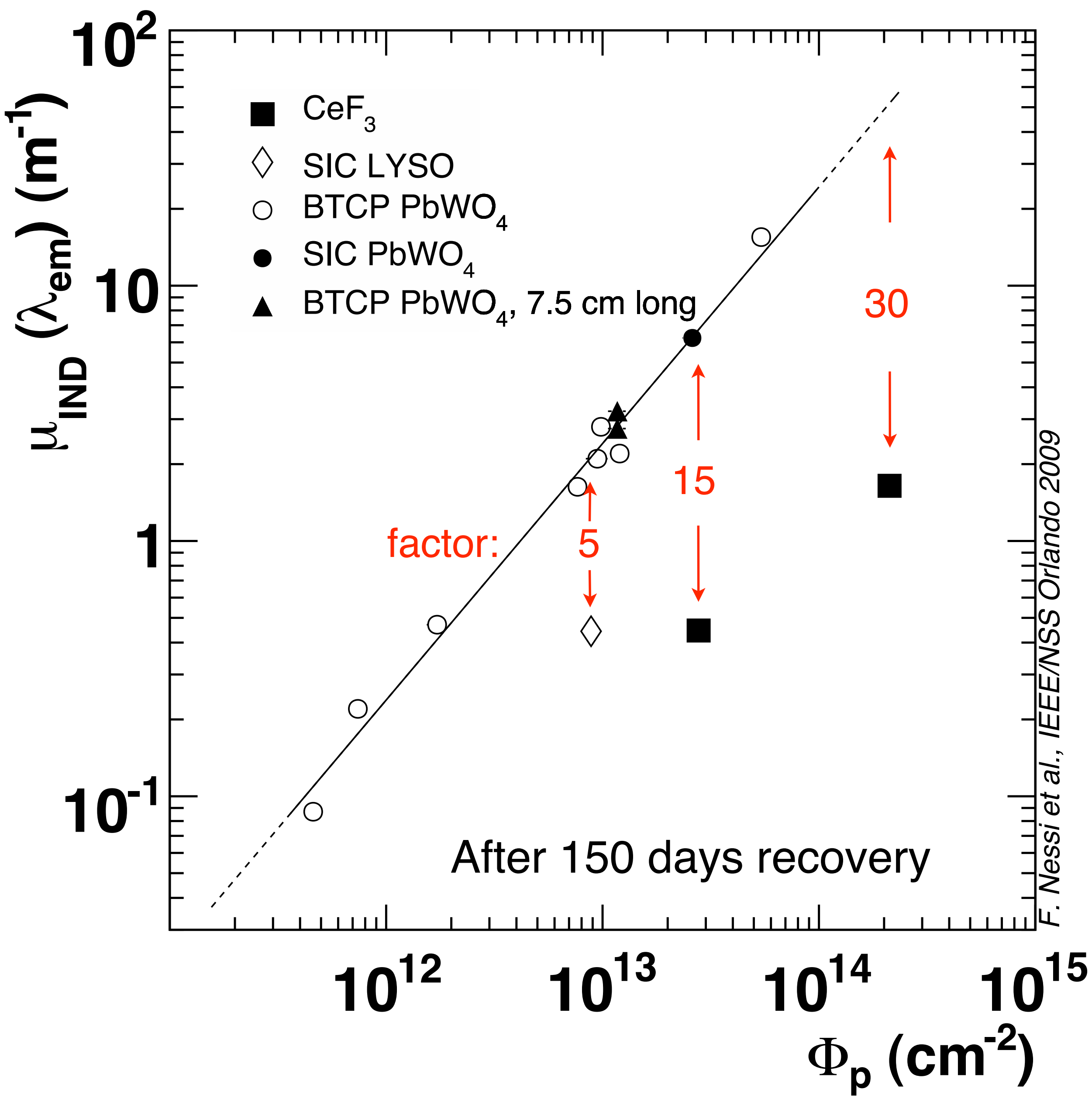


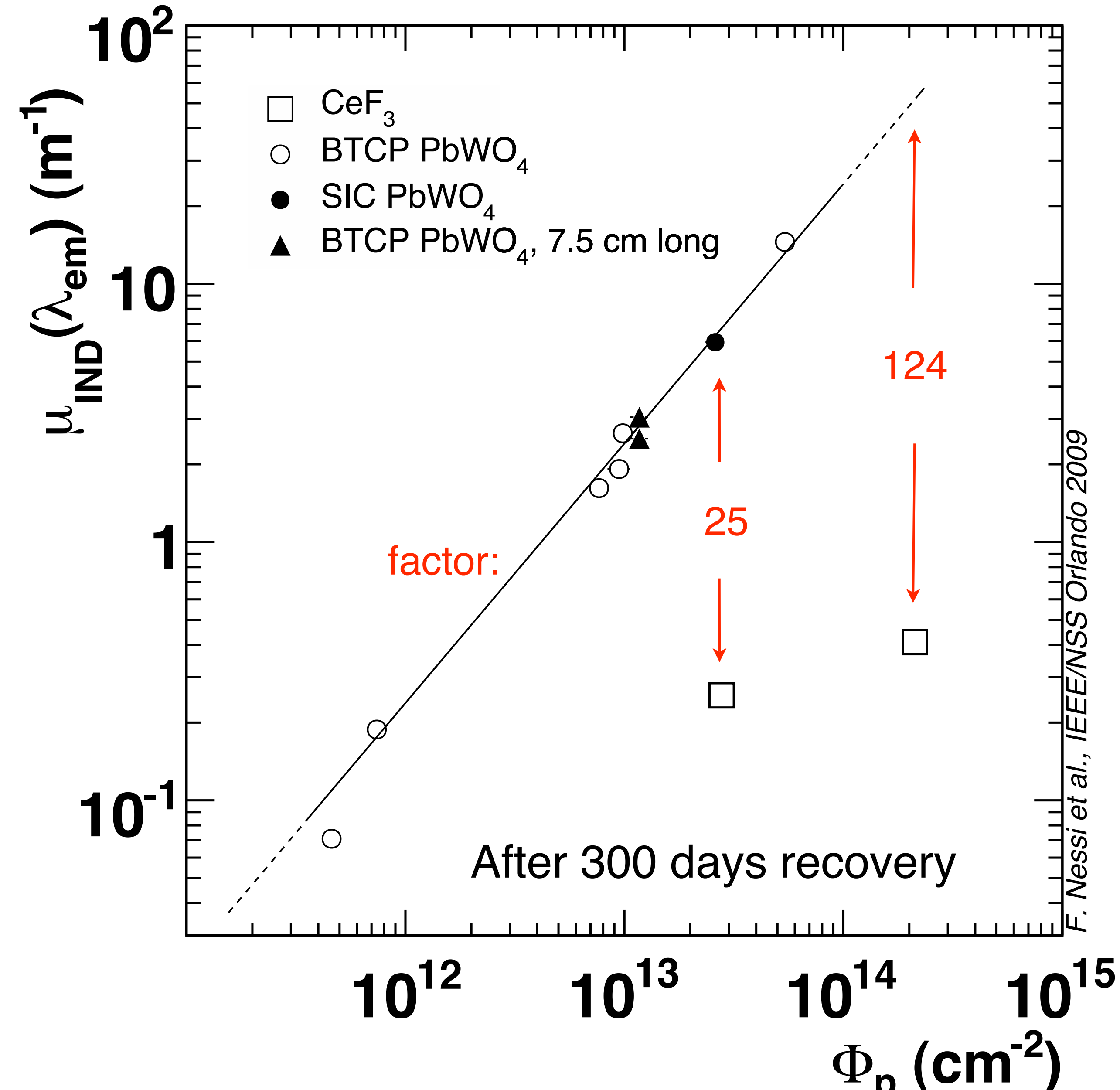
→ The evolution of the absorption induced by p-irradiation in LYSO is compatible with no recovery at all.

→ A fit using one time constant could allow as much as 20% of the damage to recover with τ=14 ± 64 (!) days. Recovery will be tracked further...

→ A second irradiation, at ~10 x fluence, will tell us whether there is any cumulative damage

Damage amplitudes versus p-fluence





→ In $PbWO_4$ a fraction of the damage has a component with $\tau \gg 1$ years : "permanent". Values at 150 d do not change further. Damage is cumulative

→ In CeF_3 damage recovers, thus choice of time after irradiation for comparisons arbitrary. Damage is not cumulative.

→ In LYSO we observe no damage recovery so far. A second irradiation, at ~10 x fluence, will tell us whether there is any cumulative damage

Conclusions

- A hadron-specific, cumulative damage has been observed in $PbWO_4$, which only affects light transmission. All characteristics of the damage are consistent with an intense local energy deposition from heavy Pb- and W-fission fragments and the strain fields they leave behind.

- Measurements of proton-induced absorption up to $\phi_p = 2 \times 10^{14}$ p/cm^2 in CeF_3 show a damage which recovers at room temperature and is not cumulative

- Measurements of proton-induced absorption in LYSO show a damage which does not seem to recover at room-T, but is a factor 5 smaller than in $PbWO_4$ for $\phi_p = 0.9 \times 10^{13}$ p/cm^2. Proton irradiations will be performed at higher fluences
  → they should allow establishing whether the damage is cumulative in LYSO

- The absence of a dominant Rayleigh-scattering component in CeF_3 and LYSO confirms that in $PbWO_4$ it is due to the large energy deposit of heavy fragments.

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- Hadron damage is not entirely about color centers. It is also about nuclear interactions and displacement of atoms!