Light yield non-proportionality of LYSO(Ce) scintillators to x/γ rays and measurement of the Birks-Onsager quenching parameters.

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INFN-TIFPA

Coordinating Panel for Advanced Detectors (CPAD) Workshop
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Scintillating materials

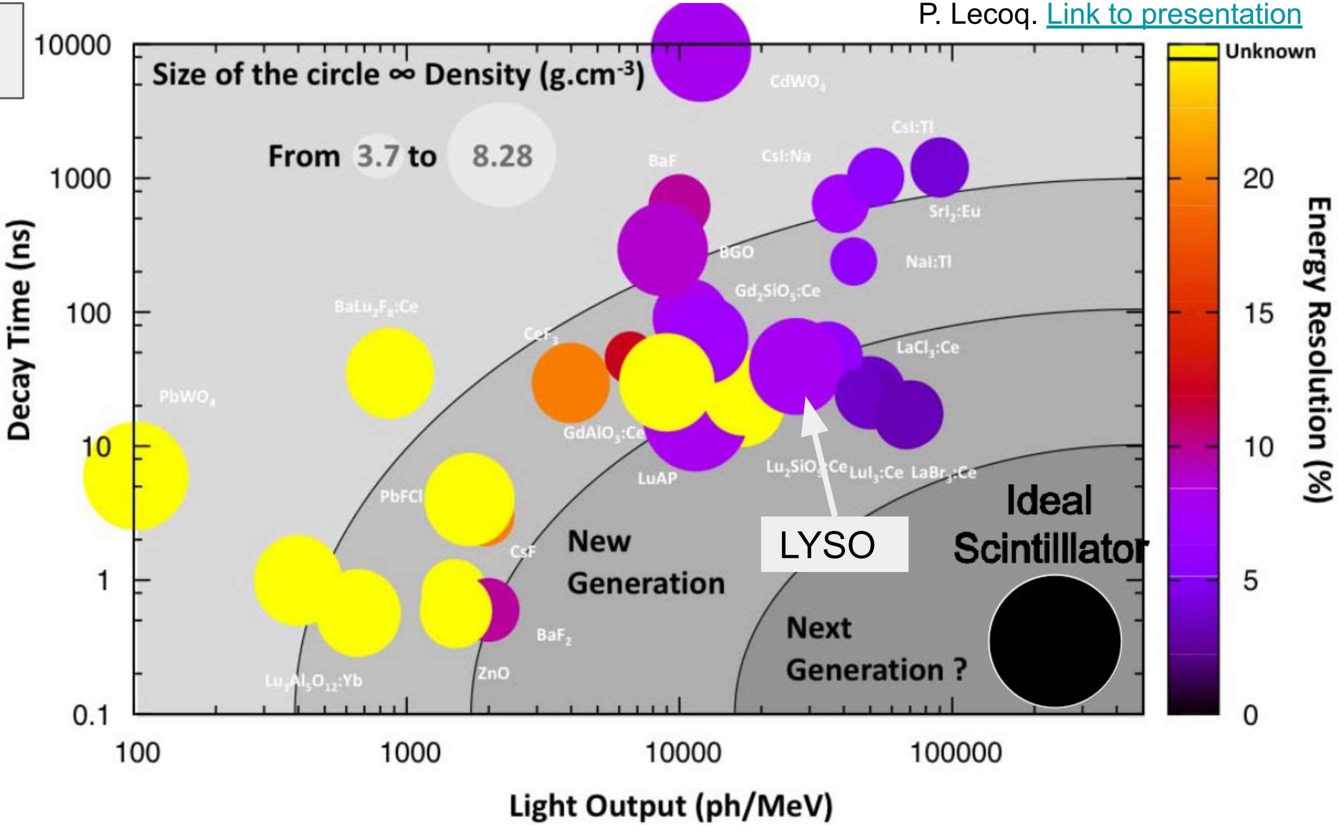
Ideal Scintillator

- High Light output
- Fast decay time
- Very dense
- High Z

Light output should be **linear** with **Energy release**

Important to characterise its response

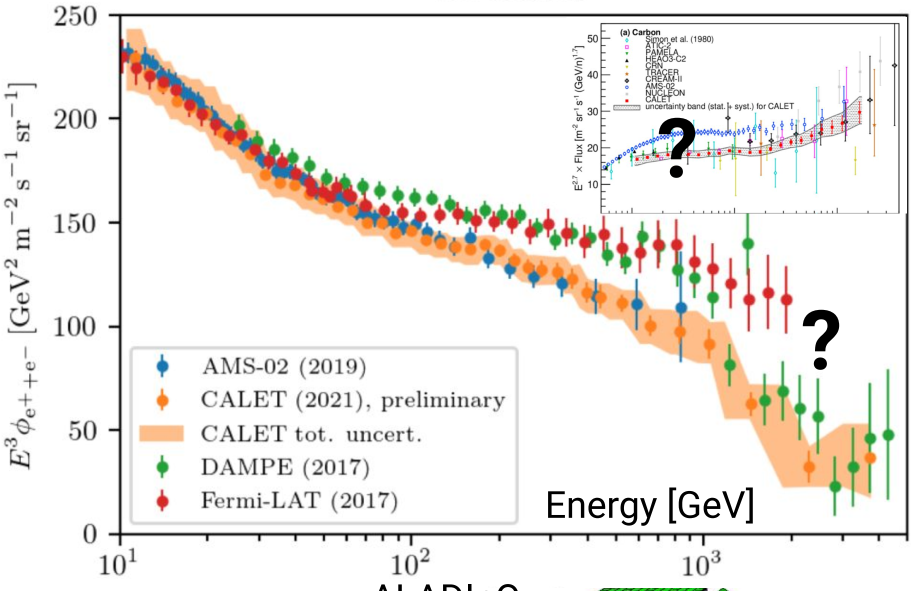
P. Lecoq. [Link to presentation]

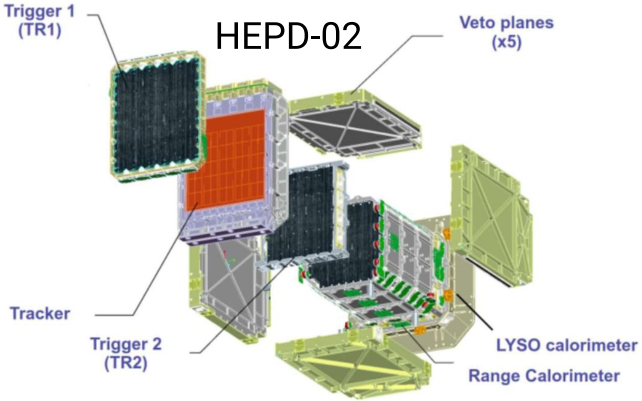


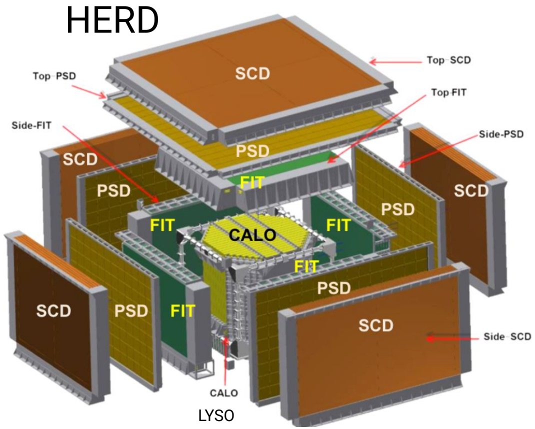
LYSO calorimeters in space

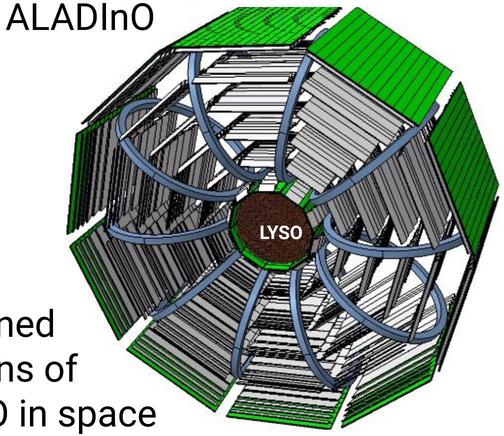
LYSO(Ce) Lutetium-Yttrium Oxyorthosilicate
is **fast** (~40ns) **dense** (7.1g/cm^3) **high Z** (Z_{eff}~60)
strong and good scintillator (LY~30ph./keV)
For this reason is adopted in medical devices, in current space experiments and in planned space calorimeters.

However LYSO is non-proportional (& slightly radioactive)
Response of LYSO needs an accurate calibration to avoid systematic effects in measured particle fluxes at high-E



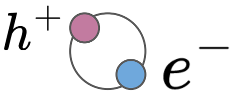






planned
2 Tons of
LYSO in space

Non-proportional light response at high dE/dx (the Birks quenching)



Excitons: neutral carriers, higher mobility

High dE/dx →

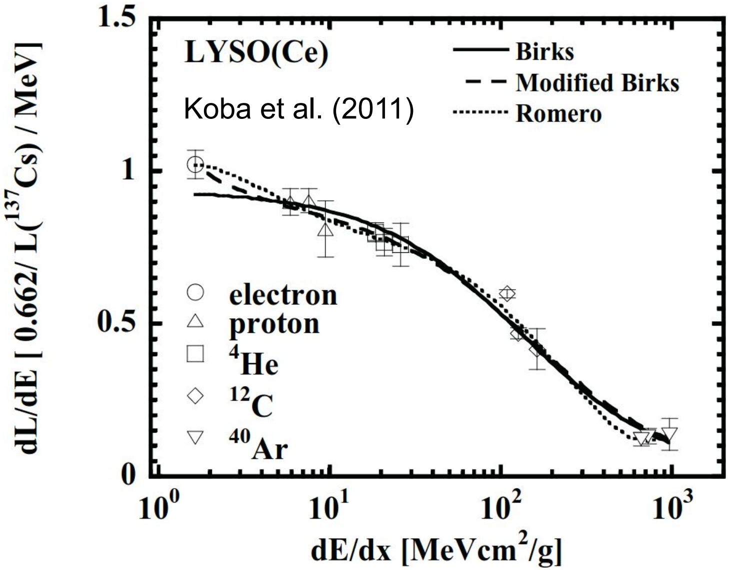
exciton	exciton (higher energy)
exciton	NR recomb. = phonons

$$\frac{dL}{dx} = \frac{dL}{dE}\frac{dE}{dx}$$

Koba et al. "Scintillation Efficiency of Inorganic Scintillators for Intermediate-Energy Charged Particles"
DOI: 10.15669/pnst.1.218 *Prog.Nucl.Sci.Tec.*1(2011)218

$$\frac{dL}{dE} = \frac{a}{1 + k_B \frac{dE}{dx}}$$

	NaI(Tl)	CsI(Tl)	GSO(Ce)	LSYO(Ce)
Birks				
a	0.905	1.08	1.03	0.938
k_B	9.10x10^{-4}	1.29x10^{-3}	3.22x10^{-3}	7.60x10^{-3} g/(cm^{2}MeV)

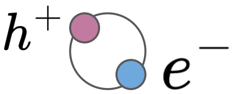


Koba et al. "Light Output Response of LYSO(Ce) Crystal to Relativistic Helium and Carbon Ions" Vol.3 2007 *IEEE Nucl.Sci.Symp.Conf.Rec. DOI:10.1109/NSSMIC.2007.4436606*

- k_B = **5.68 × 10^{-3} cm/MeV** Helium beam
- k_B = **1.03× 10^{-3} cm/MeV** Carbon beam

?? puzzling

Non-proportional light response at high dE/dx (generalised Birks)



Excitons: neutral carriers, higher mobility

High dE/dx ⇒

exciton	exciton (higher energy)
exciton	NR recomb. = phonons

$$\frac{dL}{dx} = \frac{dL}{dE}\frac{dE}{dx}$$

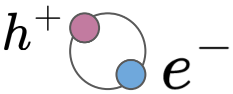
G. Tarle,The Astrophysical Journal, 230:607–620, June 1979.

$$\frac{dL}{dE} = \frac{1}{1 + k_B \frac{dE}{dx}} \longrightarrow \frac{1-\eta_H}{1 + k_B(1-\eta_H)\frac{dE}{dx}} + \eta_H$$

Introducing a percentage of carriers escaping the ionization cylinder

escaping fraction of carriers that radiatively recombines

Non-proportional light response at low dE/dx (the Onsager term)



Excitons: neutral carriers, higher mobility

Low dE/dx

$$\eta_{e/h}$$

Fraction of initial electrons and holes that do not form excitons. They can combine to form new excitons if they are closer than the Onsager radius

$$L_o = 1 - \eta_{e/h} e^{-\frac{dE/dx}{(dE/dx)_o}}$$

Stephen A., IEEE Transactions on Nucl. Sci., 56(6):2506–2512, 2009

A reference model for non-proportional light response in scintillator is:

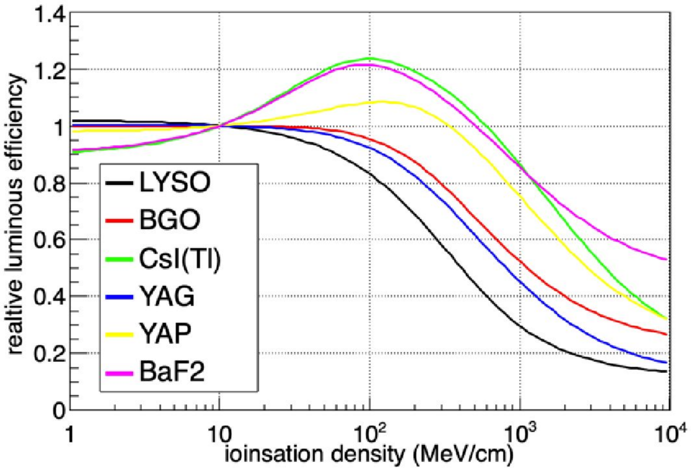
$$\frac{dL}{dE} = \left[\frac{1-\eta_H}{1+k_B(1-\eta_H)\frac{dE}{dx}} + \eta_H\right]\left[1 - \eta_{e/h}\exp\left(-k_o\frac{dE}{dx}\right)\right]$$

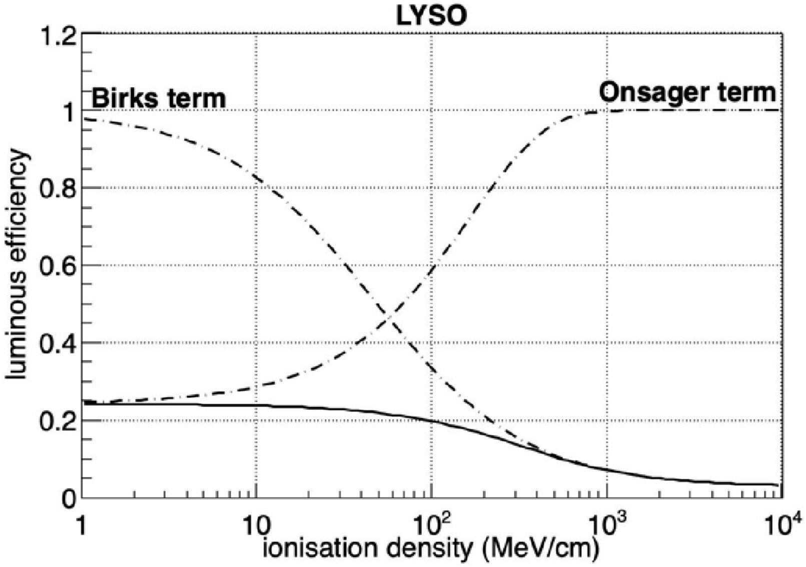
Generalised Birks term

Onsager term

Non-proportional light response

Adriani et al, 2022 JINST 17 P08014 “Light yield non-proportionality of inorganic crystalscand its effect on cosmic-ray measurements”





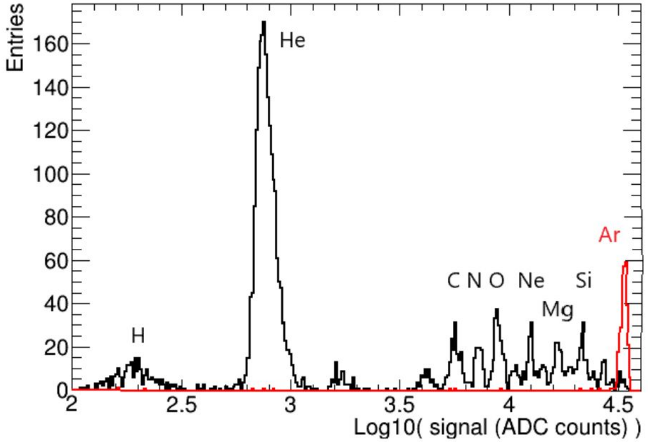
$$\frac{dL}{dE} = \underbrace{\left[\frac{1-\eta_H}{1+k_B(1-\eta_H)\frac{dE}{dx}} + \eta_H\right]}_{\text{Generalised Birks term}} \underbrace{\left[1-\eta_{e/h}\exp\left(-k_o\frac{dE}{dx}\right)\right]}_{\text{Onsager term}}$$

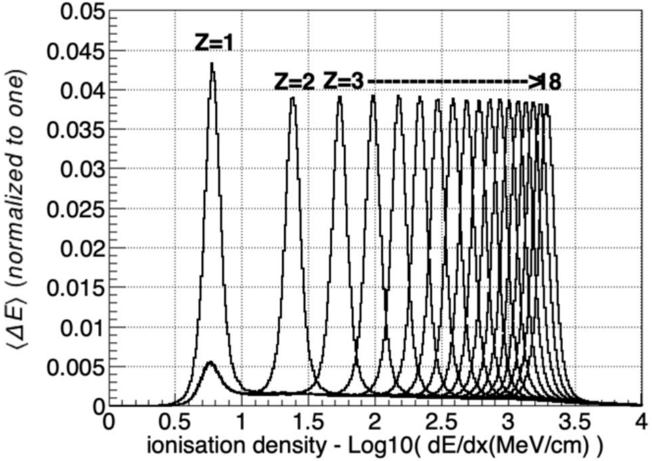
Generalised Birks term

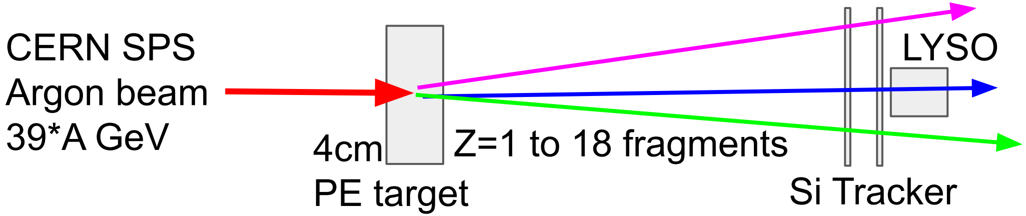
Onsager term

The measurements of Adriani et al. (2022)

JINST 17 20220 P08014







Quenching measured with (Minimum Ionizing) relativistic nuclei with Z ranging from 1 to 18

Results in term of (mod.) Birks-Onsager reference model:

Material	$\eta_{e/h}$	$(dE/dx)_O$ MeV/cm	η_H	$1/k_B$ MeV/cm
BGO	0.159 ± 0.033	98 ± 45	0.1884 ± 0.0039	364 ± 42
CsI(Tl)	0.326 ± 0.010	34.1 ± 2.8	0.121 ± 0.012	1338 ± 64
LYSO	0.758 ± 0.045	164.7 ± 8.4	0.0274 ± 0.0048	45.1 ± 9.1

$\eta_{e/h}$ is not compatible with 0 => not "pure" Birks, Onsager term is required

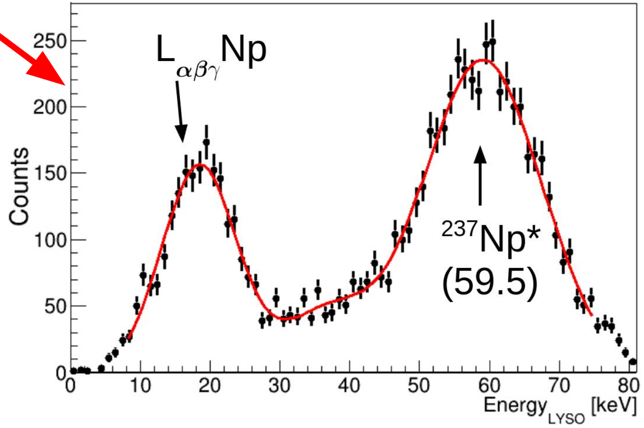
How to compare with other/previous LYSO data?

1) **Complementary information from response to x/γ ray**
2) **Koba et al (2011-2007): He-C have $1/k_B$ = 180 to 1000 MeV/cm**
3) **HEPD-02 Proton beam test (analysis still ongoing)**

Our measurement of LYSO Light Yield with γ rays @ INFN/TIFPA

Hamamatsu
R5946 PMT LYSO (7.9 g)

we calibrate the detector with gamma rays from ^{241}Am ^{133}Ba ^{176}Lu ^{22}Na ^{137}Cs and ^{60}Co sources



(“by-product” of the search for rare EC decay in ^{176}Lu)

PHYSICAL REVIEW C **107**, 045504 (2023)

DOI: 10.1103/PhysRevC.107.045504

Search for electron capture in ^{176}Lu with a lutetium yttrium oxyorthosilicate scintillator

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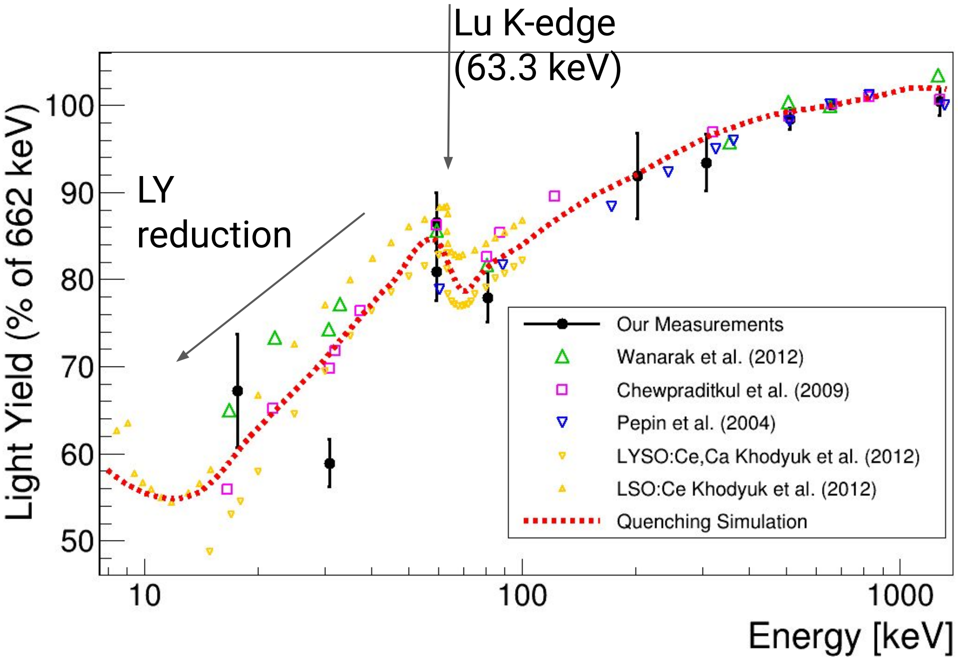
INFN-TIFPA and Department of Physics, Trento University, Via Sommarive 14 I-38123 Trento, Italy

50% reduction of Light Yield of LYSO for 10 keV x/γ rays

LYSO non-proportionality is non-negligible below 100 keV

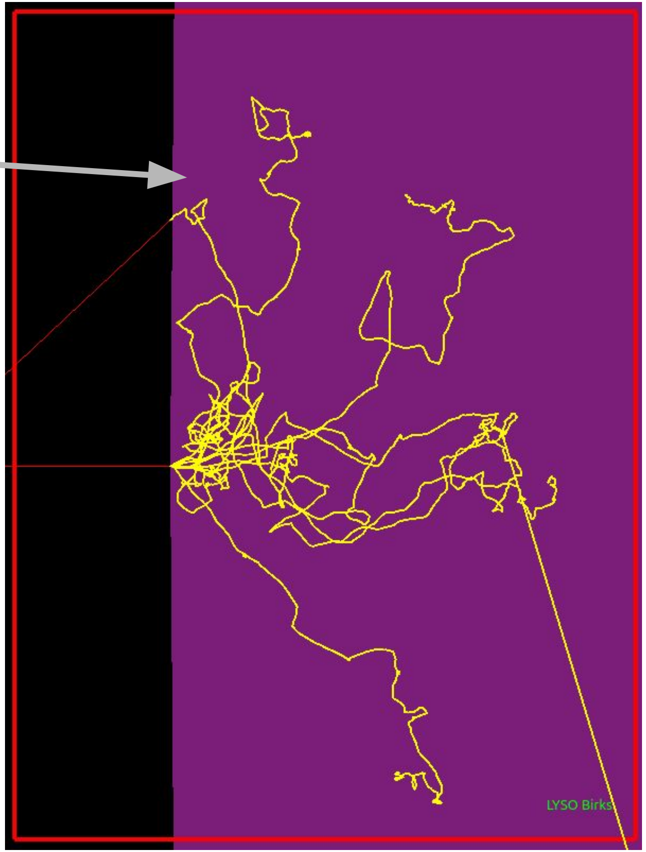
X-ray photon < 100 keV → emitted one or more “slow” electrons → High dE/dx → Lower Light Yield



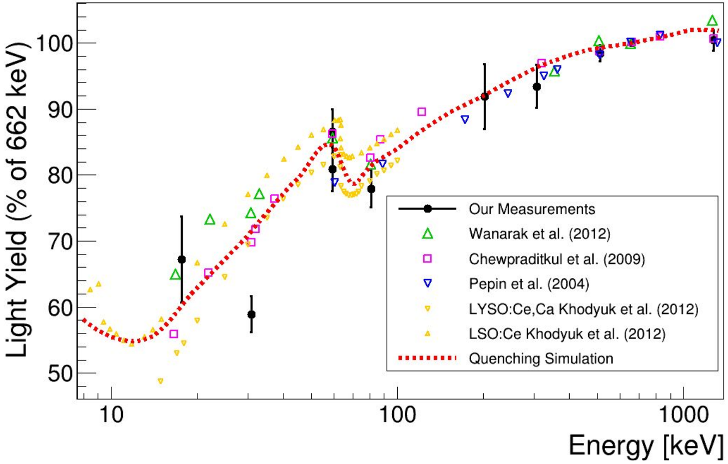
- **confirmation of the effect observed by many measurements in the past**
- **the existing measurements have not negligible (not quoted) systematic errors**
- **is hard to reject the ^{176}Lu background (40Bq/g)**

the Geant4 simulation:

To characterize and calibrate the LYSO crystal:
- Adopted the Birks+Onsager quenching model
- Geant4 simulation with **very high spatial resolution** 10nm maxstep and 1nm secondary production cuts (FTFP_BERT + G4StandardEM_op4 + G4EmLowEPPhysics)
- At each step we computed the contribution to the LY based on the dE/dx locally computed.



fit of experimental data and inference of parameters based on the G4 MC simulations



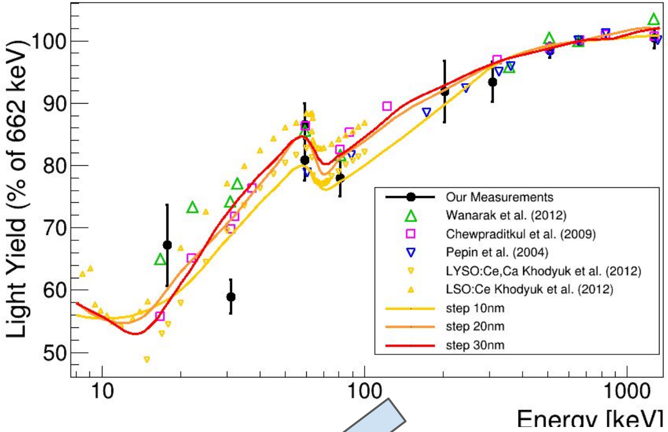
Geant4-based MonteCarlo Fit

Set Parameters:
k_B, η_H, $\eta_{e/h}$ $(dEdx)_O$

gamma ray Energy

Geant4 application:
- Mod. Birks
- Onsager
- Small steps

Scan in Energy



Exploration of the 4D parameter space

- Minimization of the χ^2
- Estimate of the parameter

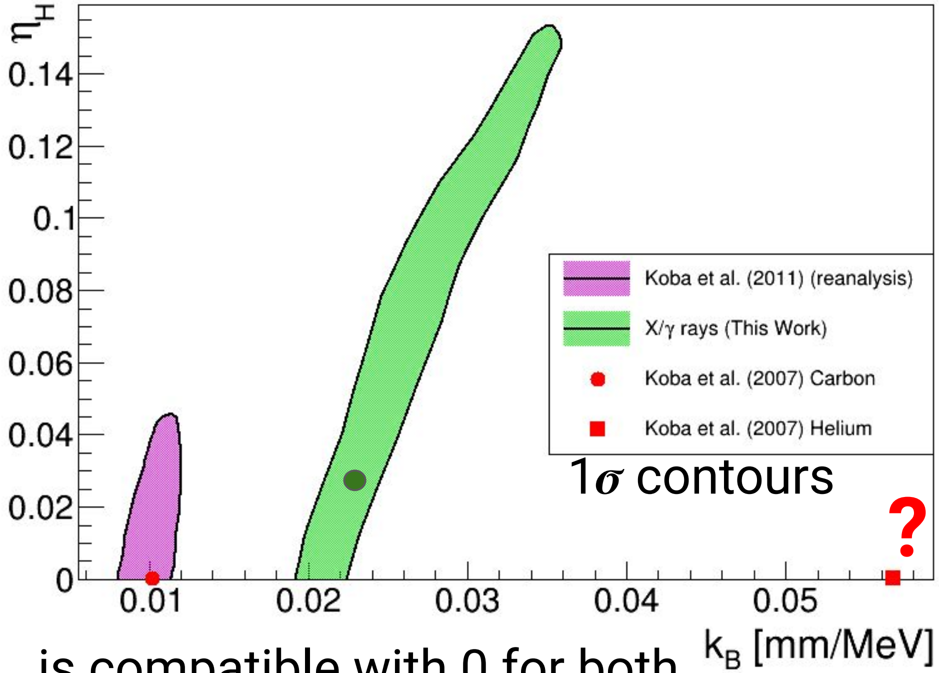
Heavy load of computation

+

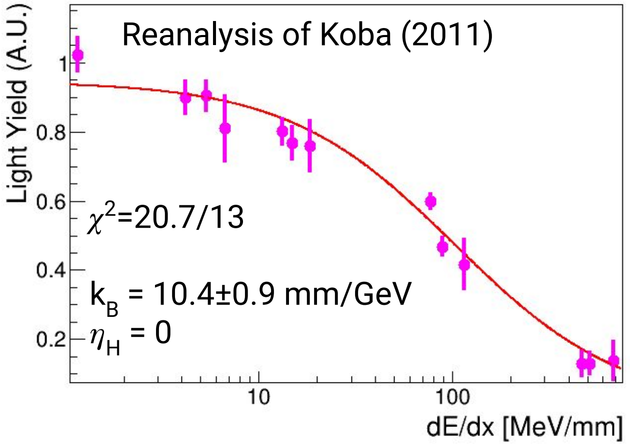
found (expected) dependence on step size. Systematic related to MC under investigation

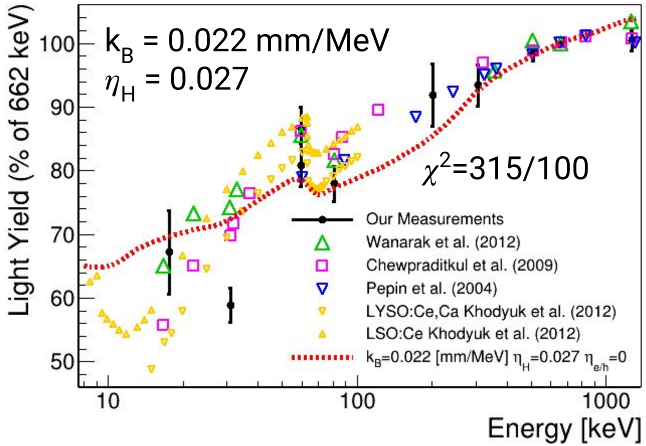
Results: forcing $\eta_{e/h}$ = 0 ("pure" Birks, no Onsager)

- not good chisquares are obtained
- forcing $\eta_{e/h}$ = 0 not full compatibility
- Koba (2007) He beam result "puzzling"



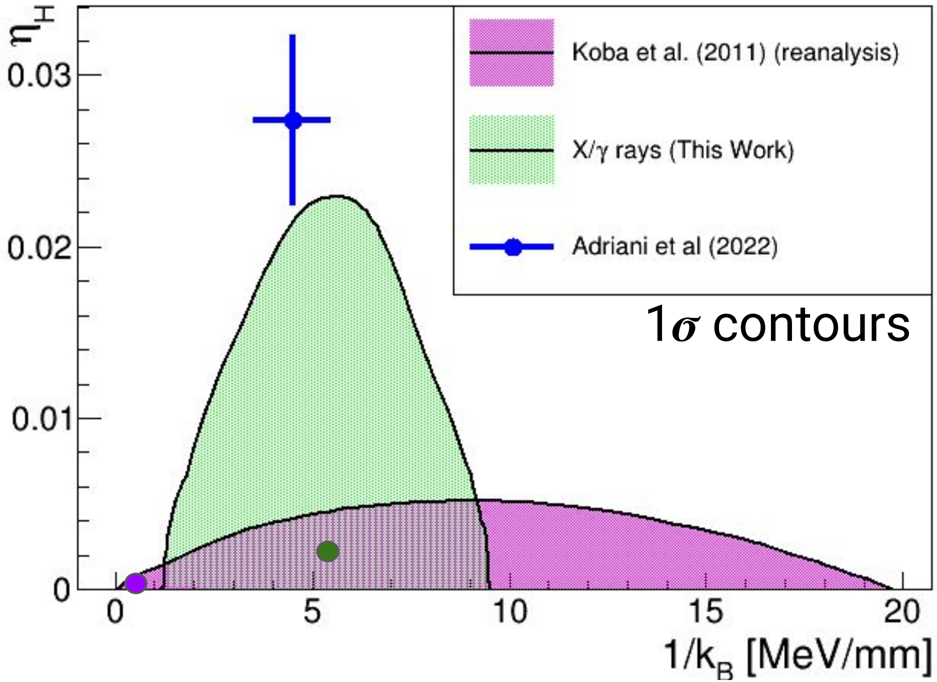
η_H is compatible with 0 for both

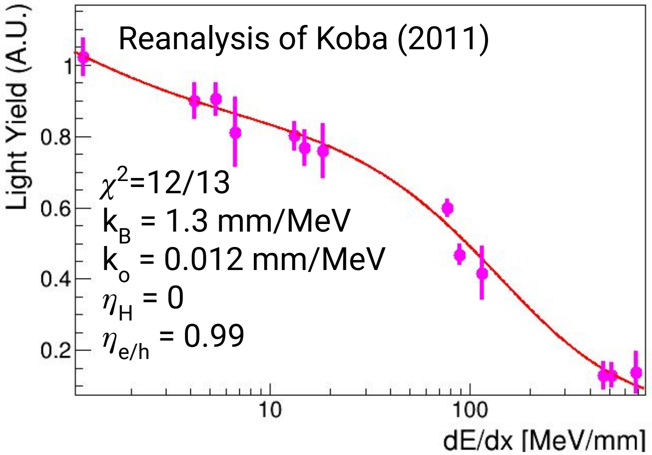


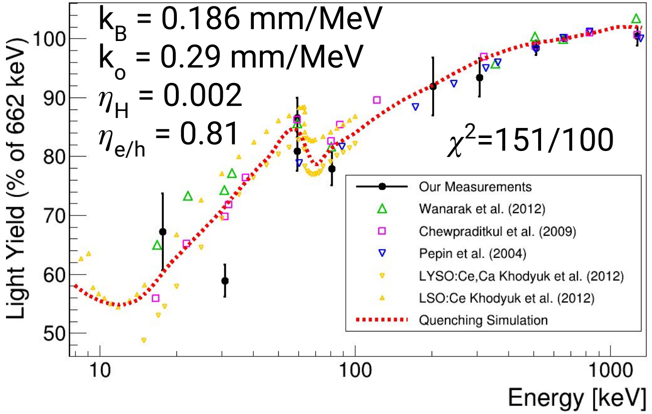


Results: $\eta_{e/h} > 0$ (the "reference" model Birks + Onsager)

k_B are compatible with Adriani (2022)
$\eta_H = 0$ is preferred by Koba & x/γ rays







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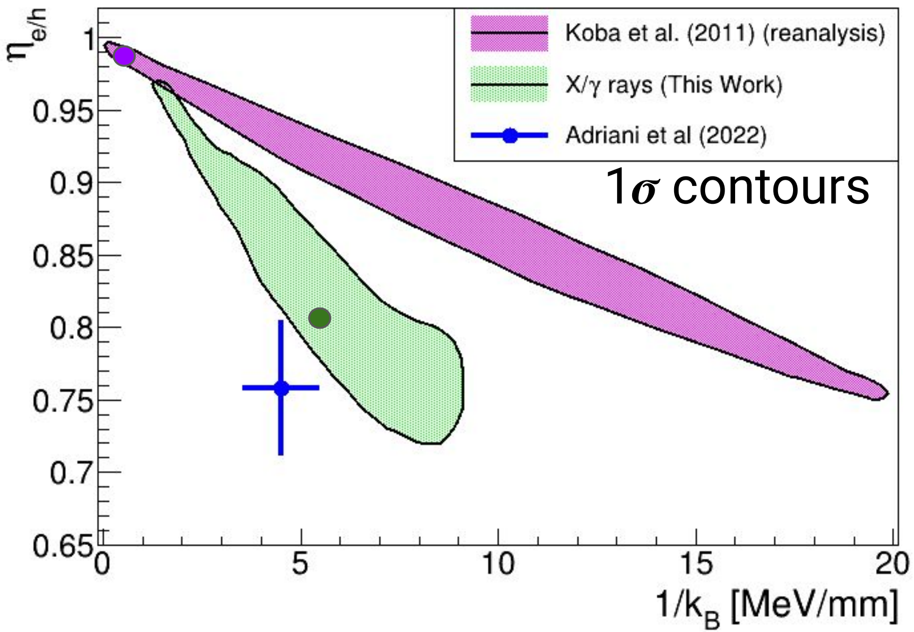
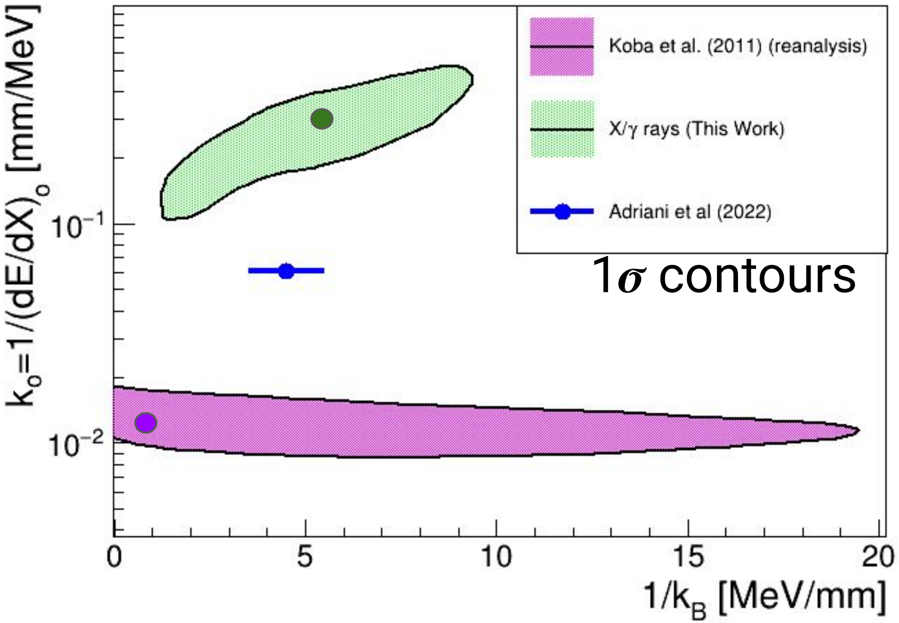




- observed the (expected) strong correlation of k_B and $\eta_{e/h}$
- indication for a relatively large $\eta_{e/h}$ comes from all the measurements
- a "pure" Birks ($\eta_{e/h}= 0$) rejected with high C.L.
- x/γ rays information is "folded" and cannot give precise inference of k_o

Conclusion / to-do list

The qualitative picture:

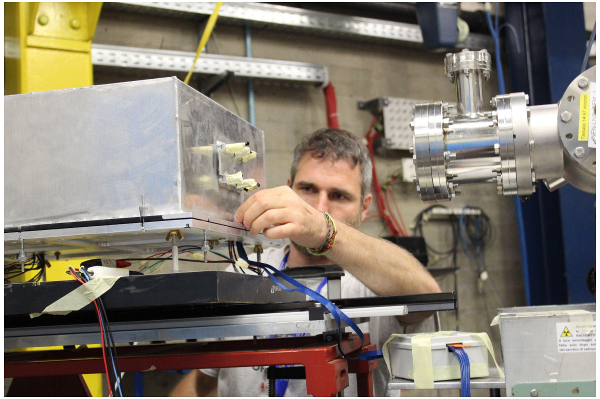
- Birks-Onsager model works from few keV electrons to few GeV nuclei

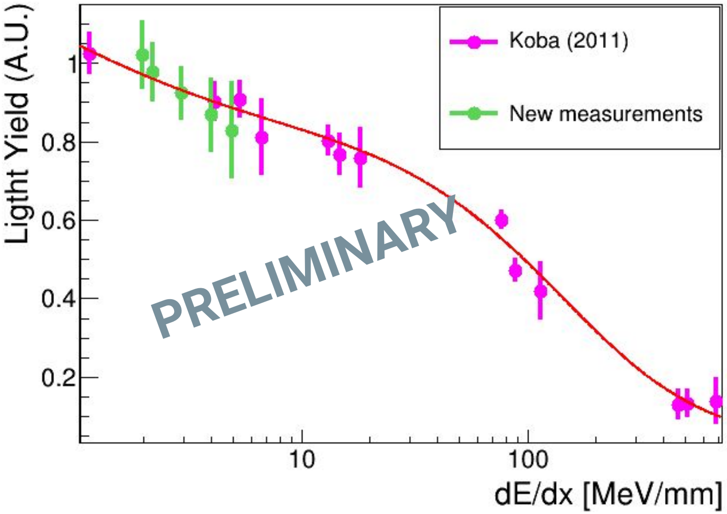
The quantitative agreement is not perfect:

- would be nice to plot the 1σ contours from Adriani et al. (2022)
- possible systematics in measurements [e.g. He vs C in Koba et al. (2007)]
- (ongoing study) systematics of the heavy MC computation for x/γ rays

A new proton beam test made in 2023:

@ INFN-TIFPA
for LYSO used in
HEPD-02 detector
(analysis ongoing)





Thank you!