



R&D on Advanced Liquid Scintillators at Mainz, TUM, Padova, Perugia, JYU and INFN Milano

Paolo Lombardi – INFN Milano

Physics Opportunities of Large Liquid Scintillator Detectors (II)

Mainz – Oct. 13, 2026

Outline

01

Group Synergy:

Mainz

Munich TUM

INFN Milano and Perugia Chemical department

Padova University and INFN

JYU Jyväskylä



02

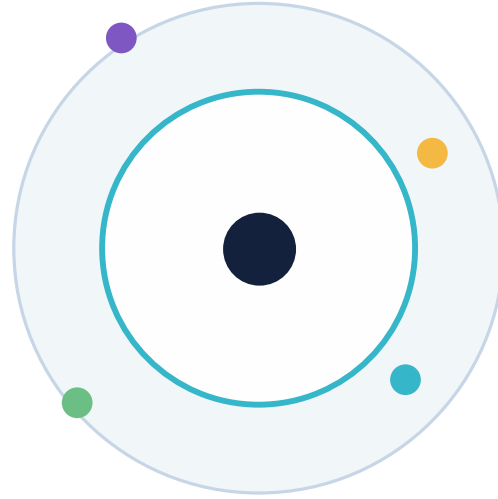
Mainz / TUM / Padova / Jyväskylä activities



03

INFN Milano / Perugia activities





Group Synergy

Group Synergy

- Long time collaboration between our groups since **Borexino** experiment in Gran Sasso
- Since 2014 an even closer collaboration on the **JUNO** liquid scintillator recipe, performance characterization and purification systems:
 - ❑ Design and operation of Juno Distillation and Stripping plants
 - ❑ Design and operation of OSIRIS detector
 - ❑ JUNO filling and data analysis
- Established formal collaboration for the submission of an ERC Synergy grant (2027) on $0\nu\beta\beta$ demonstrator experiment: **INFN, Mainz, TUM, Zaragoza, JYU Jyväskylä**
 - ❑ Slow bi-solvent scintillators ($\tau \geq 10\text{ns}$) for separation of Cherenkov signal and background improvement
 - ❑ Loading Techniques for Organic Scintillator: Te, Mo, Se (see talk from Hans S.)
 - ❑ LS purification techniques
- Some published papers for reference:
 - ❑ *Refractive index in the JUNO liquid scintillator*, NIM A 1069, 2024
 - ❑ *Development of a bi-solvent liquid scintillator with slow light emission*, JINST 19, 2024
 - ❑ *Fluorescence emission of the JUNO liquid scintillator*, JINST 20, 2025
 - ❑ *Doping of a Borexino-like Liquid Scintillator with Tellurium-Diols*, JINST 21, 2026

Groups composition for LS development

➤ Mainz:

- ❑ Michi Wurm, Manuel Böhles,
- ❑ Daniela, Johannes, Daniela Fetzer, Johannes Molins, Maxi Rausch

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➤ TUM :

- ❑ Hans Steiger, Adil Muggo
- ❑ Kilian Porth, Konstantin Walter, Moritz Kolb



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University
of Munich



➤ INFN Milano:

- ❑ Paolo Lombardi, Barbara Caccianiga, Davide Basilico
- ❑ Cecilia Landini, Marco Beretta, Fatima Houria



Istituto Nazionale di Fisica Nucleare

➤ Perugia chemistry department:

- ❑ Fausto Ortica, Aldo Romani, Catia Clementi



➤ Padova:

- ❑ Alberto Garfagnini, Riccardo Brugnera, Andrea Triossi
- ❑ Lorenzo D'Auria, Andrea Serafini

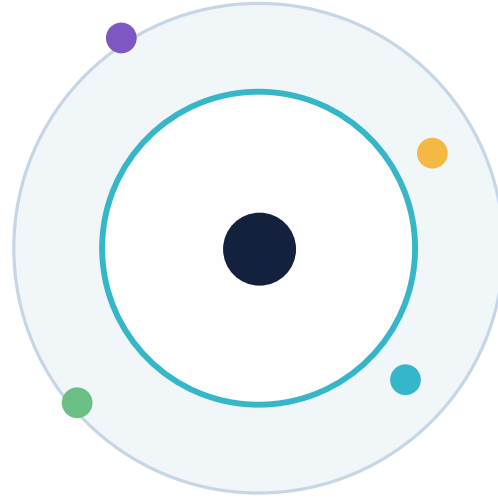


➤ University of Jyväskylä (JYU):

- ❑ Kai Loo, Mariia Fedkevych, Timo Ahola



UNIVERSITY OF JYVÄSKYLÄ



Mainz / JYU / TUM / Padova
activities

Cherenkov and Scintillation Light Separation: How to get the LS slow?

Three ways to get the scintillation emission slow:

• Lower the fluor concentration

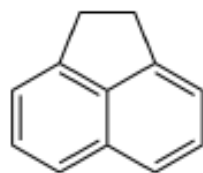
[Guo, Z. et al. – arXiv:1708.07781]

- Low light yields
- Limited PSD capabilities
- Excellent transparency in case of LAB

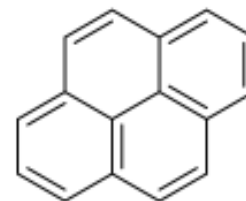
• Slow fluors

[Biller, S. et al. – arXiv:2001.10825]

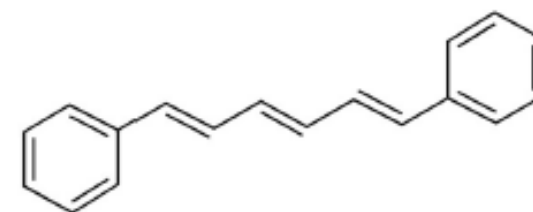
- Expensive substances?
- Toxic or cancerogenic compounds?
- Slow scintillation comes often at the cost of losses in LY
- Often emission wavelength maximum deep in the UV-region!
- PSD?



Acenaphthene ($C_{12}H_{10}$)



Pyrene ($C_{16}H_{10}$)

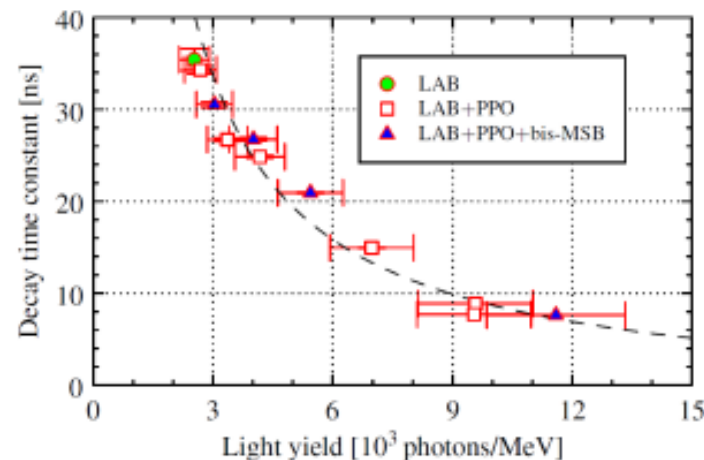


1,6-Diphenyl-1,3,5-hexatriene (DPH, $C_{18}H_{16}$)

• Blended or multi-solvent cocktails

[Steiger, Hans Th. J. et al. – arXiv:2405.01100, 2024]

- LY typically: 10^4 Ph./MeV, $\tau_1 = 12-45$ ns (adjustable)
- LY and PSD can be enhanced with a carefully balanced selection of solvent and co-solvent
- Cheap and easy to clean co-solvents

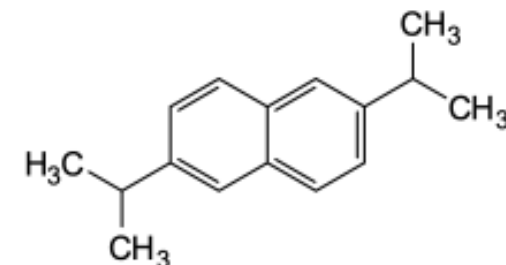


LAB/PPO-mixtures:
Low PPO concentration leads to low LYs and no PSD!

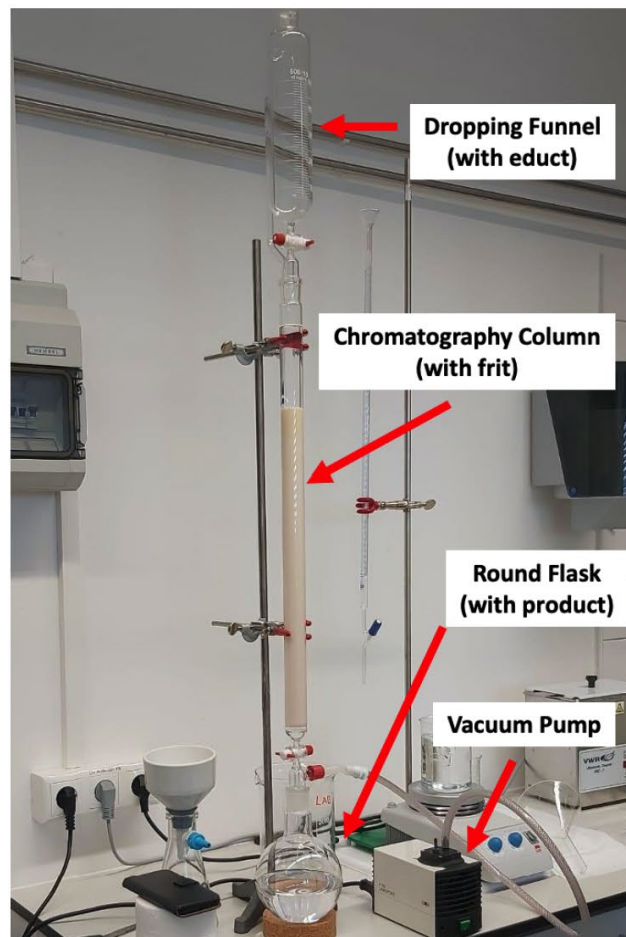
PREPARED FOR SUBMISSION TO JINST

Development of a Bi-solvent Liquid Scintillator with Slow Light Emission

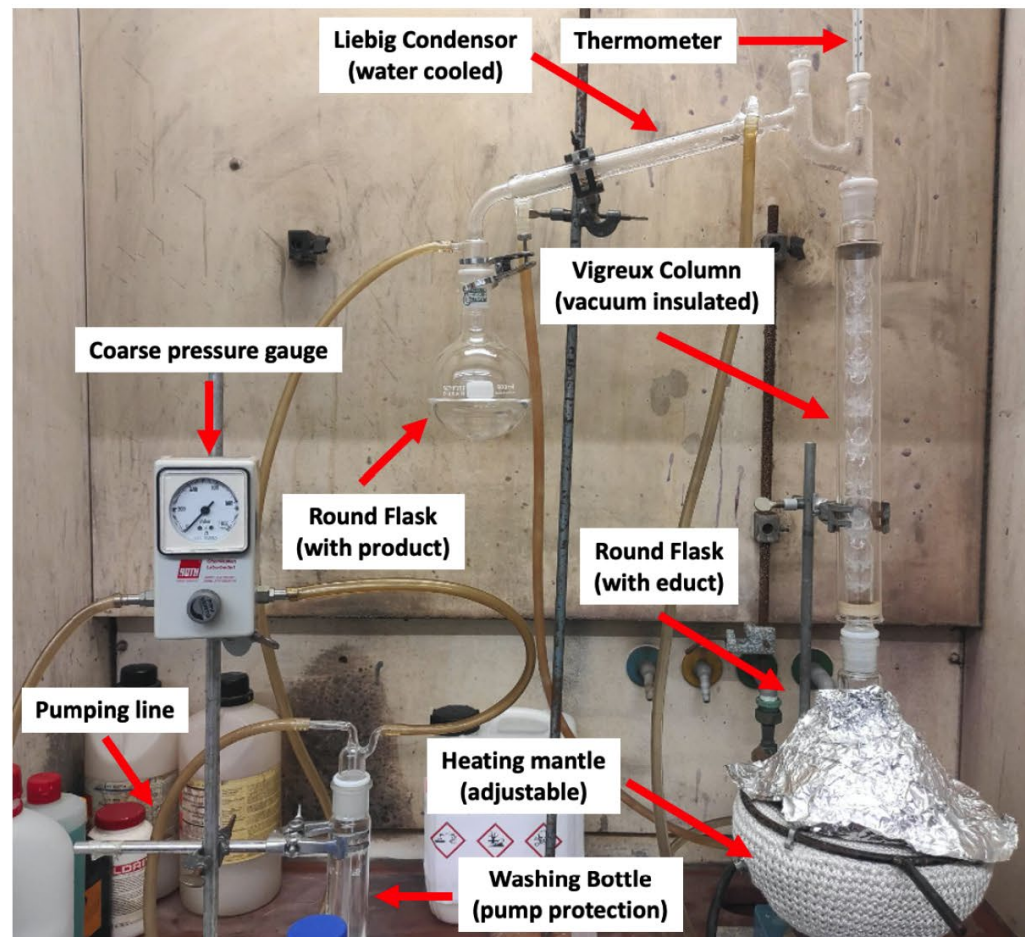
Hans Th. J. Steiger,^{a,b,c,d} Matthias Raphael Stock,^c Manuel Böhm,^{a,b} Sarah Braun,^c Edward J. Callaghan,^{d,e} David Dörflinger,^d Ulrike Fahrenholz,^c Gabriel D. Orebi Gann,^{d,f} T. Kaptanoglu,^{d,g} Lennard Kayser,^c Florian Kübelböck,^c Melissa Lu,^c Lothar Oberauer,^c Korbinian Stangler,^c Michael Wurm,^{a,b} Dorina Zundel^{a,b}



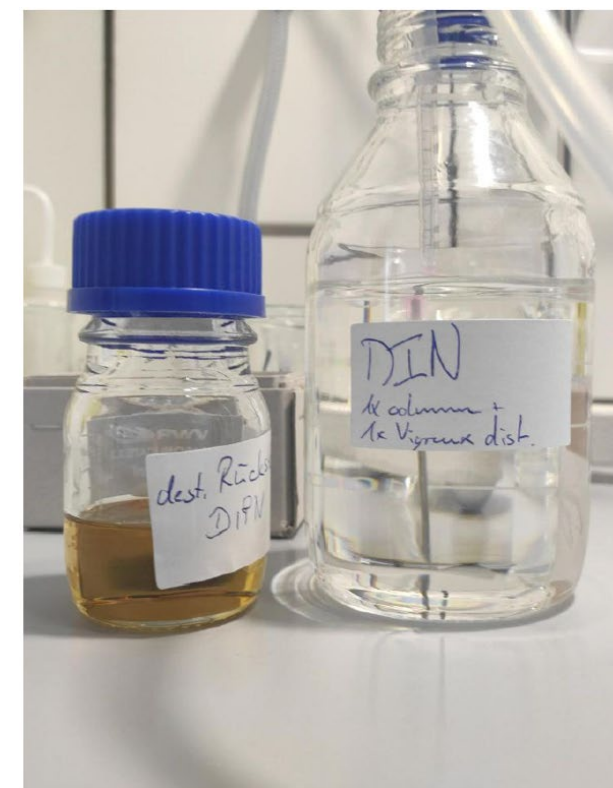
2,6-Diisopropylnaphthalene (DIPN, $C_{16}H_{20}$)



Long and thin Al_2O_3 Column
(basic alumina of activity Super-I)



Low temperature vacuum Distillation + Vigreux Column
(product completely cooled down before exposed to air)



Residue and highly-pure DIN
after Distillation

Additional filtration:
200 nm + 50 nm + 20 nm
(Reduction of scattering!)



Mainz / TUM Purification of DIN (Ruetasolv Di-S): What we reached by now

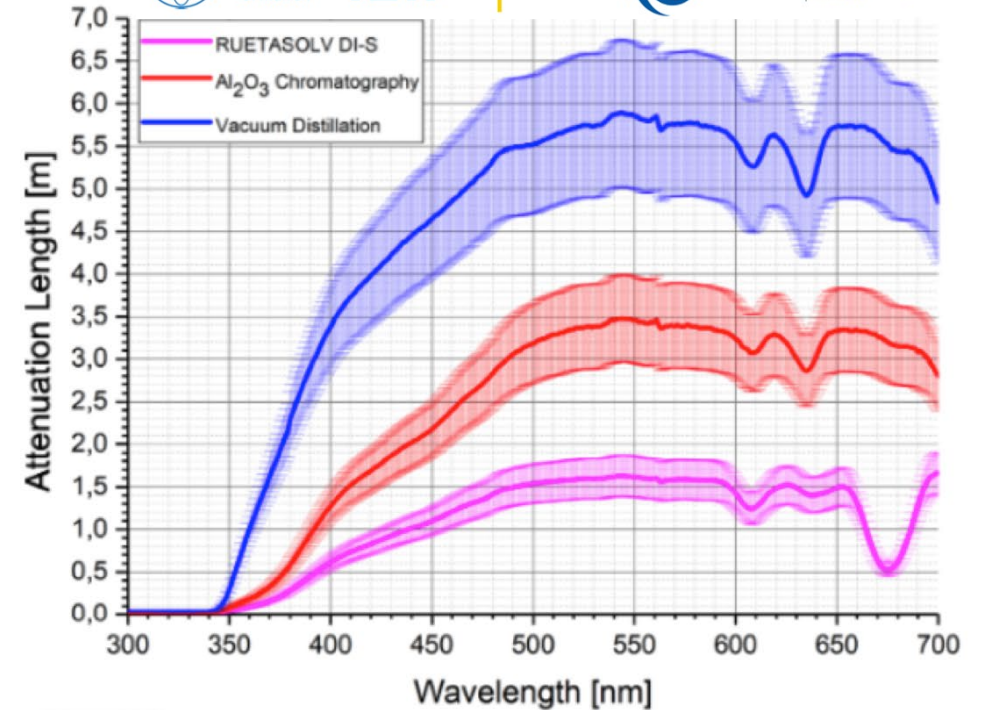


Residue and highly-pure DIN
after Distillation



Attenuation Length with
UV/Vis-Spectrometer:

- Perkin Elmer Lambda 850+
- 10 cm cuvette
- large uncertainties, scattering, ...



Attenuation Length after purification
(Improvement by distillation larger than by alumina column)

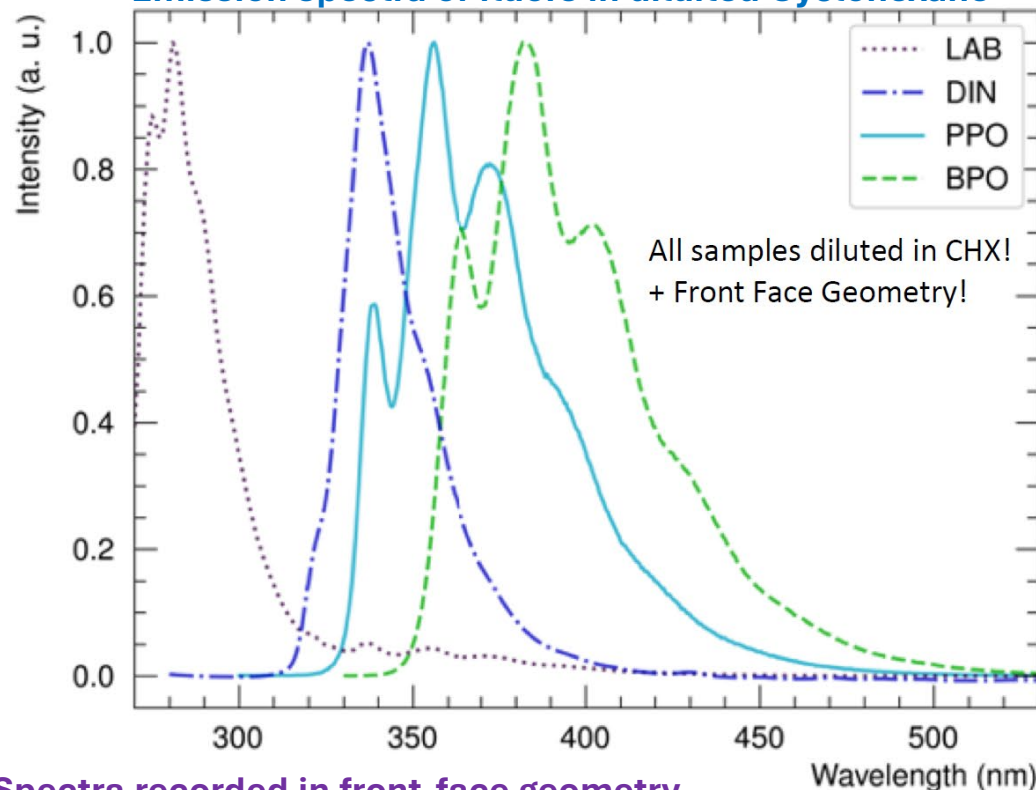
Calculation of the attenuation length of LAB/DIN mixtures
with JUNO-LAB (Daya Bay) with measured att. length:
 $\Lambda_{\text{LAB}}(430 \text{ nm}) = (28.07 \pm 2.94) \text{ m}$
(Measurement: S. Franke, PhD Thesis, PALM)

$$\frac{1}{\Lambda} = \sum_i \frac{1}{\Lambda_i} \quad \begin{aligned} \Lambda_{90/10}(430 \text{ nm}) &= (17.5 \pm 2.3) \text{ m} \\ \Lambda_{80/20}(430 \text{ nm}) &= (13.9 \pm 1.6) \text{ m} \end{aligned}$$

Calculation in agreement
with UV/Vis direct
measurements: $> 13.5 \text{ m}$.

TUM Selection of Wavelength Shifters – Some Scintillator Samples under Investigation

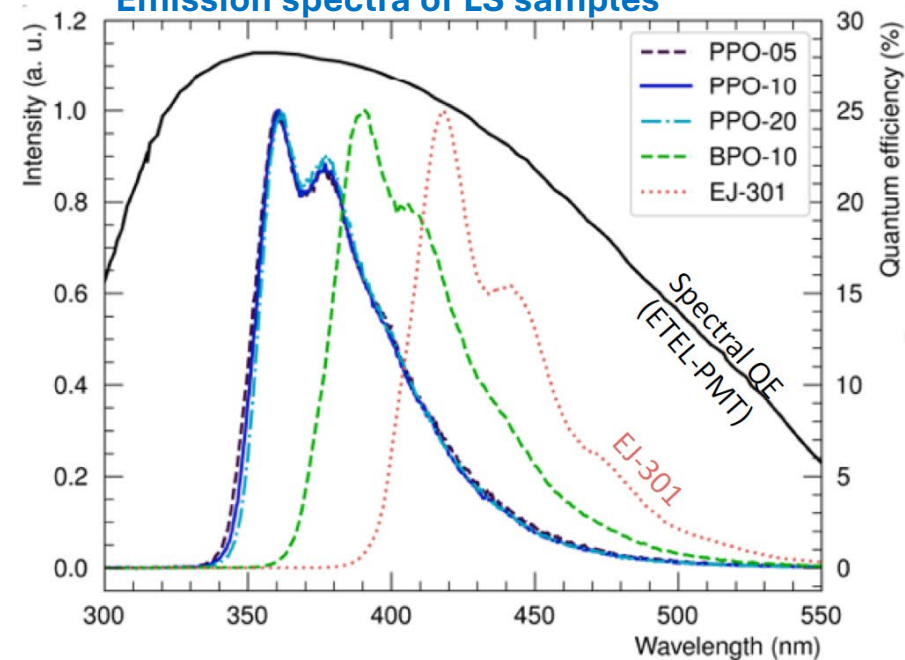
Emission spectra of fluors in diluted Cyclohexane



Spectra recorded in front-face geometry

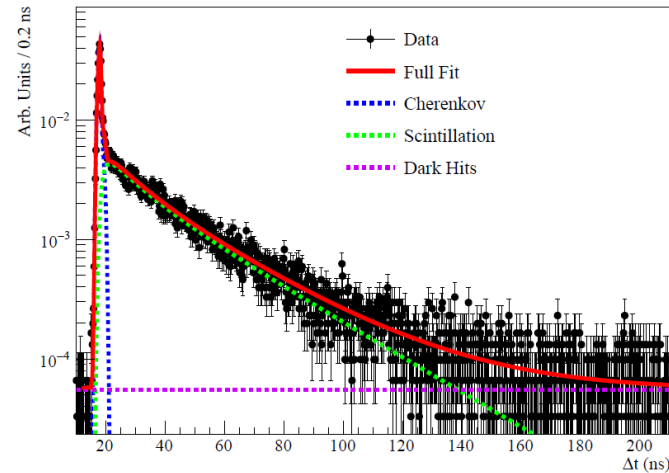
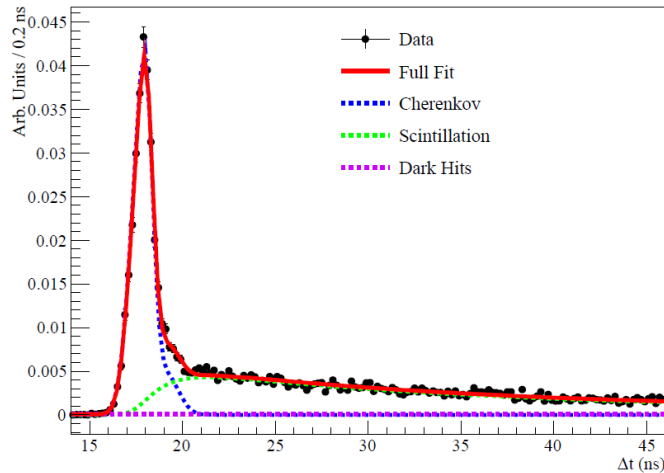
Substance	Chemical Formula	Conc. in CHX	Exc. [nm]	Abs. Max. [nm]	Em. Max. [nm]
LAB	$(C_6H_5) - C_nH_{2n+1}$ with $n = 10 - 13$	10 ml/l	255 ± 1	260 [18]	281 ± 1
DIN	$C_{16}H_{20}$	10 ml/l	255 ± 1	279 [18]	337 ± 1
PPO	$C_{15}H_{11}NO$	40 mg/l	290 ± 1	303 [18]	356 ± 1
BPO	$C_{21}H_{15}NO$	100 mg/l	320 ± 1	320 [18]	383 ± 1

Emission spectra of LS samples

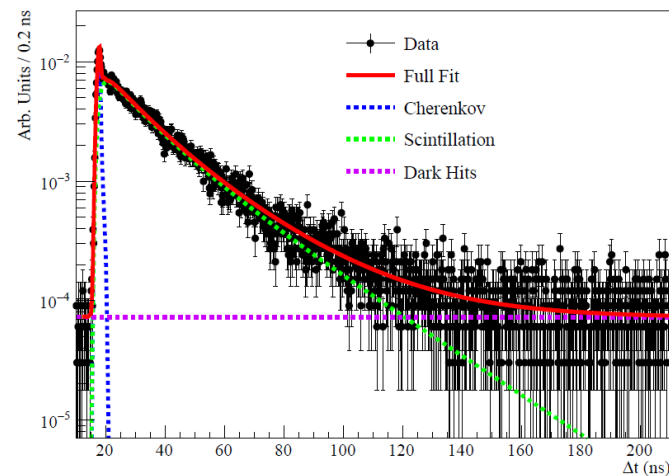
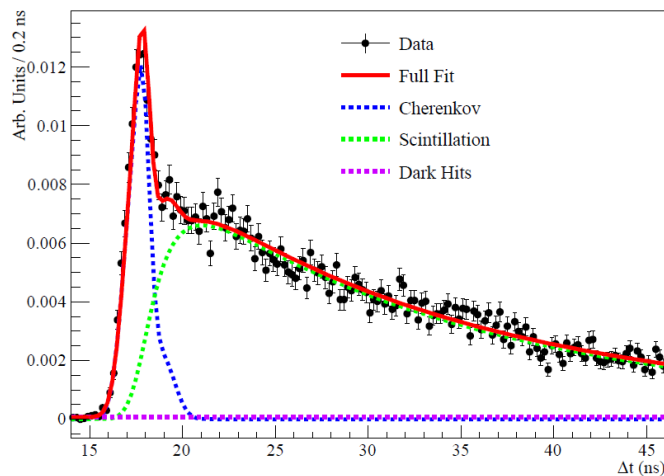


Sample Name	Solvent	Co-Solvent	Fluor	Fluor Concentration
PPO-05	90 % LAB	10 % DIN	PPO	0.5 g/l
PPO-10	90 % LAB	10 % DIN	PPO	1.0 g/l
PPO-20	90 % LAB	10 % DIN	PPO	2.0 g/l
BPO-05	90 % LAB	10 % DIN	BPO	0.5 g/l
BPO-10	90 % LAB	10 % DIN	BPO	1.0 g/l
BPO-20	90 % LAB	10 % DIN	BPO	2.0 g/l
PPO-05-20	80 % LAB	20 % DIN	PPO	0.5 g/l
PPO-10-20	80 % LAB	20 % DIN	PPO	1.0 g/l
PPO-20-20	80 % LAB	20 % DIN	PPO	2.0 g/l

The measured emission timing for β excitation of samples. The measurements are shown in linear scale around the Cherenkov peak (left) and in log scale to highlight the scintillation tail (right).



90% LAB - 10%DIN - 0.5 g/l PPO



90% LAB - 10%DIN - 1.0 g/l PPO



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PSD capabilities of different LS cocktails



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Bundesministerium
für Bildung
und Forschung



SFB 1258



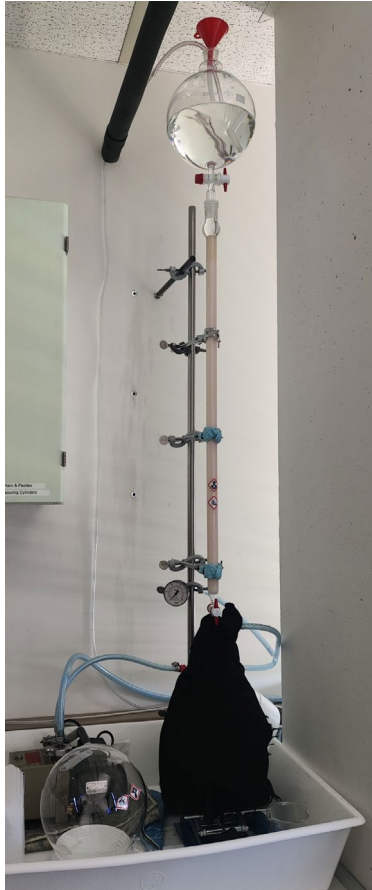
Sample	Maximal tail-to-total difference $\Delta\mu$	Time after time profile peak (ns)
LAB + 0.5 g/l PPO	0.038 ± 0.001	44.33 ± 4.83
LAB + 1.5 g/l PPO	0.067 ± 0.001	16.33 ± 1.29
LAB + 2.0 g/l PPO	0.106 ± 0.004	11.33 ± 1.65
PPO-05	0.118 ± 0.002	61.83 ± 0.96
PPO-10	0.124 ± 0.001	45.83 ± 0.96
PPO-20	0.141 ± 0.003	27.17 ± 0.59
BPO-10	0.164 ± 0.002	43.00 ± 1.08
PC + 1.5 g/l PPO	0.166 ± 0.002	7.83 ± 0.22

A clear improvement in the separation of the pulse shapes is noticeable due to the DIN co-solvent. PSD performance improves with increasing concentration of the fluor (here PPO) for both, pure LAB and LAB/DIN mixtures as solvents.

Using BPO, even at low fluor concentrations, increases both the high light yield and the alpha/beta performances.

XXX-05 /10 /20 = 0.5 /1.0 /2.0 g/l

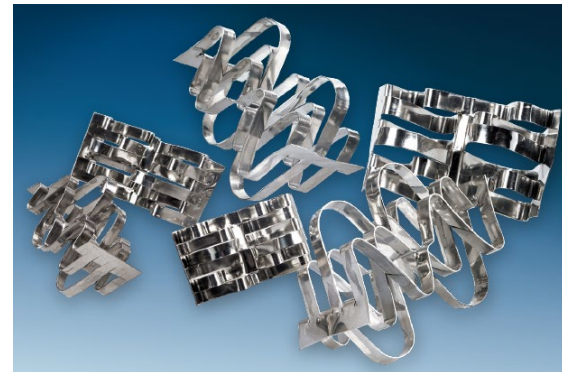
Mainz / TUM purification systems and quality control



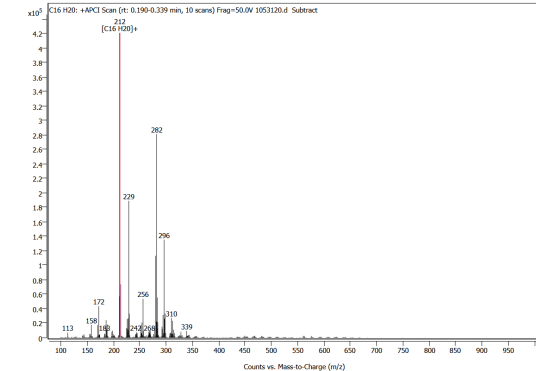
DIN purification using an aluminum oxide column and fractional distillation with Raschig rings



Top: current packing material
Bottom: planned use of Raschig Super-Ring® PLUS



© RASCHIG GmbH



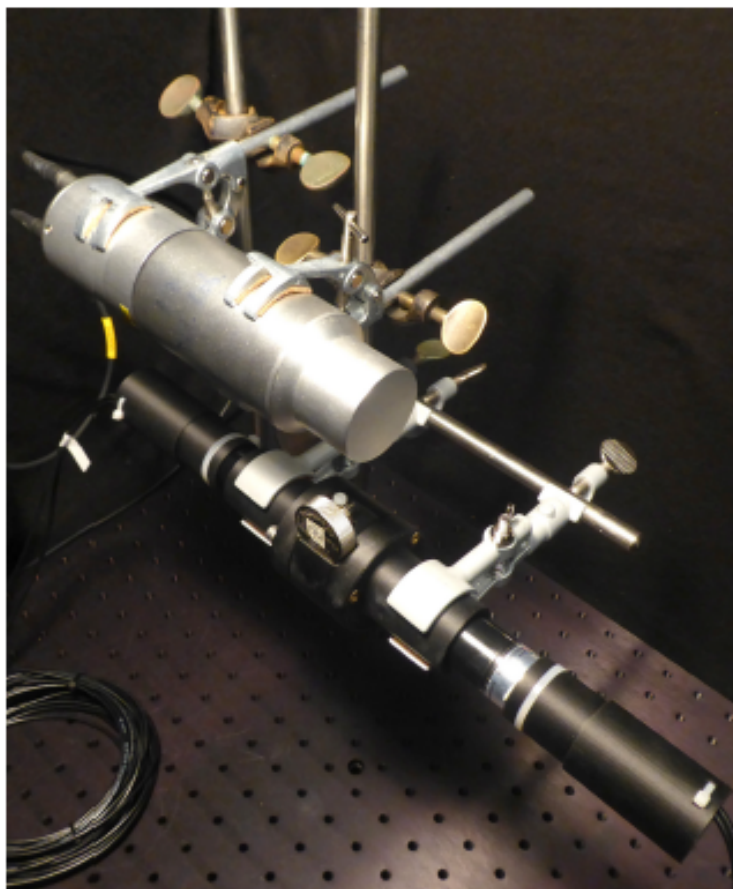
Quality control using ESI mass spectrometry & UV/Vis



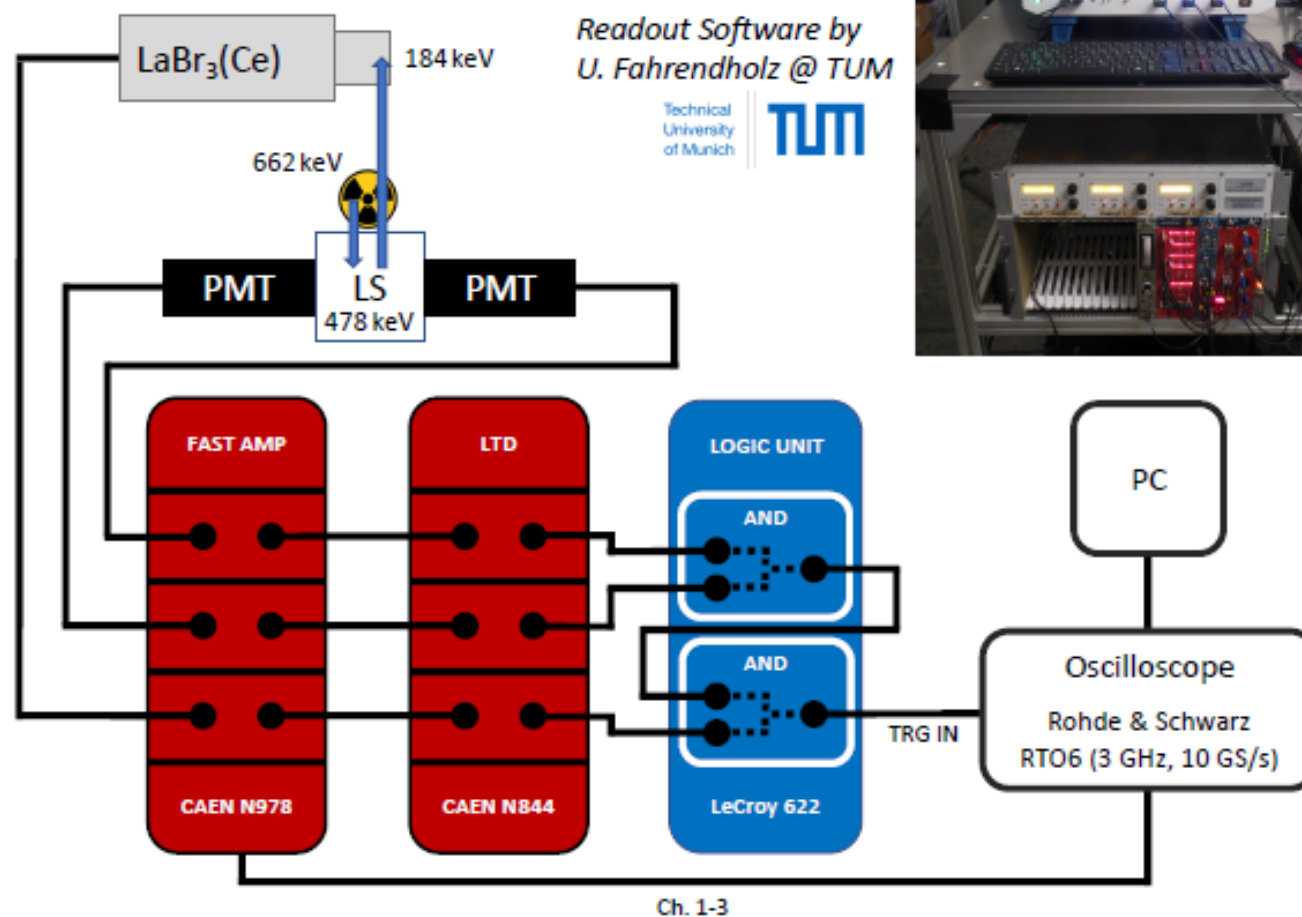
Shimadzu UV2600i @ TUM

Light Yield Study in the Mainz Scintillation LY Setup

Talk from M. Böhles (JGU Mainz)



The Mainz LY Setup
(currently upgraded to a setup for nonlinearity studies)





Cluster of Excellence

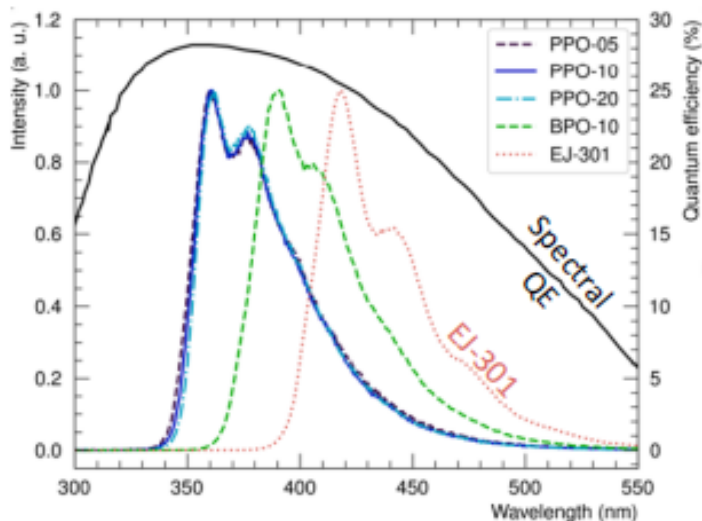
PRISMA++

Mainz Light Yield Study in the Mainz Scintillation LY Setup

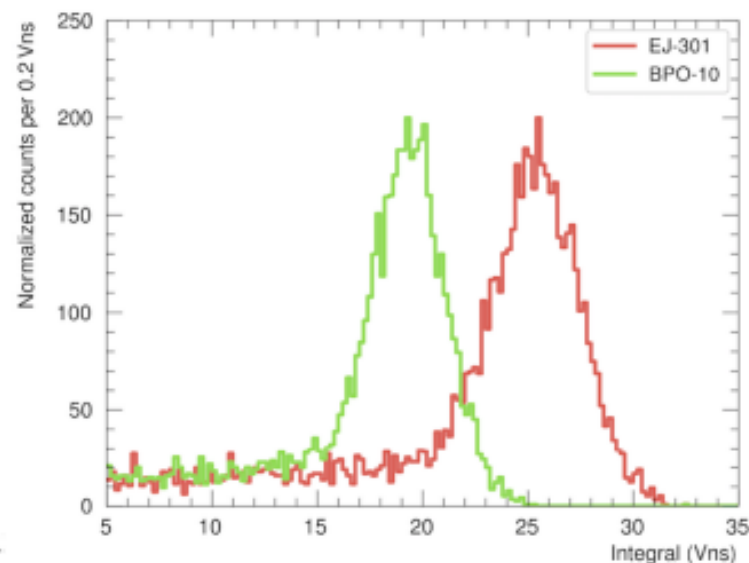
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EJ-301 as standard
(Xylene+Naphtalene + ...)



Spectral Emission and spectral QE of the
PMT have to be considered!



Backscatter Spectra of BPO-10 Sample and EJ-301
(uncorr. LY of EJ-301 larger than BPO-10 sample)

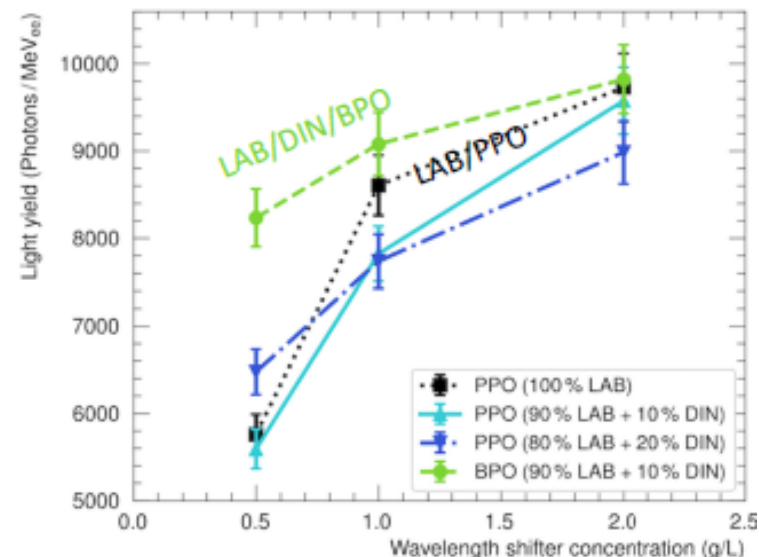
Admixture of DIN:

- With PPO no or nearly no increase in LY compared to pure LAB/PPO!
- **With BPO strong increase in LY especially at low concentrations!**
 - efficient energy transfer
→ low critical concentration of WLS

Note:

All LSs were measured with a **250 ns integration window!**

→ **slow LS would benefit from longer acquisition.**



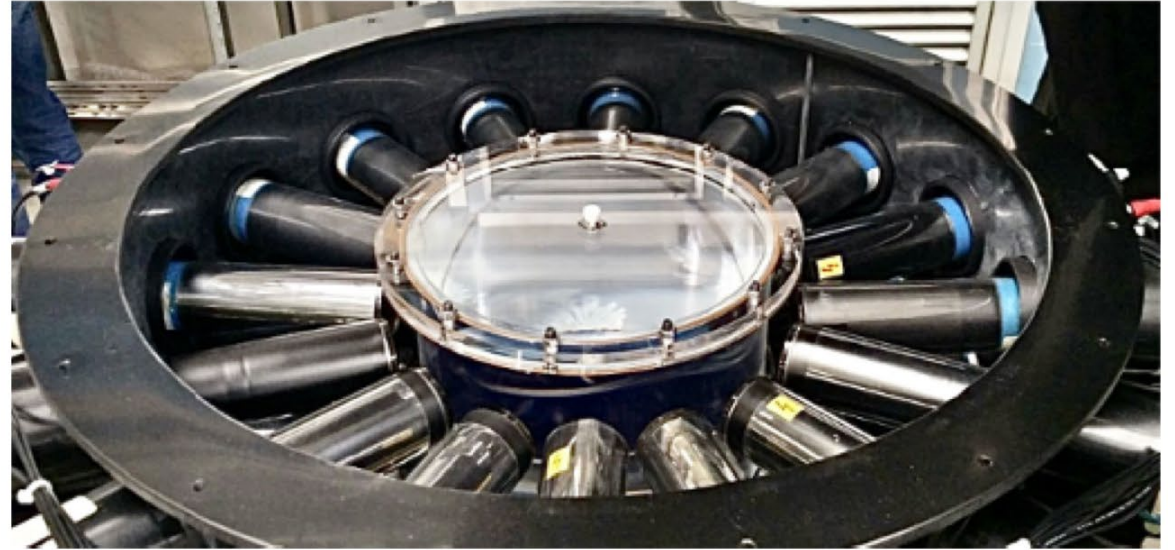
LY with spectral correction of the samples

Sample Name	Rel. LY in %	LY [Ph./MeV]	LY Spectr. Corr. [Ph./MeV]
Anthracene	100	17400	-
EJ-301	78	13572	13572
LAB + 0.5 g/l PPO	39.5 ± 1.6	6877 ± 275	5756 ± 230
LAB + 1.0 g/l PPO	59.1 ± 2.4	10281 ± 412	8605 ± 345
LAB + 2.0 g/l PPO	66.8 ± 2.7	11622 ± 465	9728 ± 390
PPO-05	38.4 ± 1.6	6679 ± 268	5590 ± 225
PPO-10	53.7 ± 2.2	9345 ± 374	7822 ± 314
PPO-20	65.7 ± 2.7	11440 ± 458	9575 ± 384
BPO-05	53.8 ± 2.2	9367 ± 375	8234 ± 330
BPO-10	59.4 ± 2.4	10329 ± 414	9079 ± 364
BPO-20	64.2 ± 2.6	11173 ± 447	9821 ± 393
PPO-05-20	44.5 ± 1.8	7737 ± 310	6476 ± 260
PPO-10-20	53.1 ± 2.2	9244 ± 370	7737 ± 310
PPO-20-20	61.7 ± 2.5	10735 ± 430	8985 ± 360

Testbeam at the INFN-LNL for Slow Scintillators with and without Te-doping (Nov. 2024 & JUNO 2026)



Approx. 50 Tbyte of new data → to be analyzed soon!

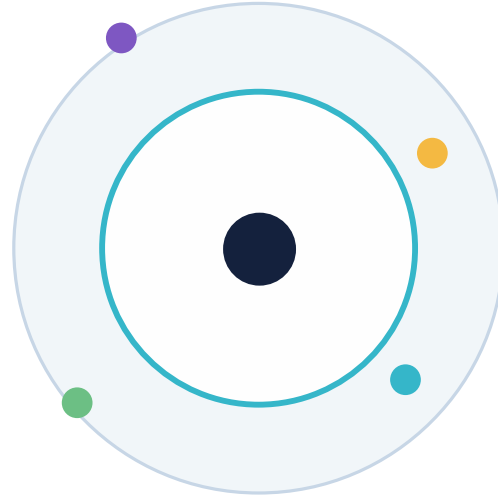


**Filling of Lavatrice: 90% LAB + 10% DIN + 1g/l PPO
(very large amounts of data)**

Samples to be studied for time profile and quenching:

- Borexino LS + 0.3% Te
- JUNO LS + 1% Te
- 95% LAB + 5% DIN + 1g/l PPO
- 95% LAB + 5% DIN + 1g/l BPO
- 90% LAB + 10% DIN + 1g/l BPO + 0.1% Te
- 90% LAB + 10% DIN + 1g/l BPO + 0.3% Te
- 90% LAB + 10% DIN + 1g/l BPO + 0.9% Te
- LAB + 4g/l Acenaphthene + 40mg/l BPO





Milano / Perugia activities

Laboratory infrastructures

Already available several experimental setups to characterize different properties of organic liquid scintillators: SHELDON and S-REWIND facilities

- ☐ Fluorescence time profile (α/β - discrimination)
- ☐ Absorbance spectrum and attenuation length
- ☐ Emission spectrum with spectrofluorometer (Perugia)
- ☐ Refractive index and group velocity
- ☐ Cherenkov contribution

Deeply cooperation with the Perugia group for these measurements and to measure the emission spectrum

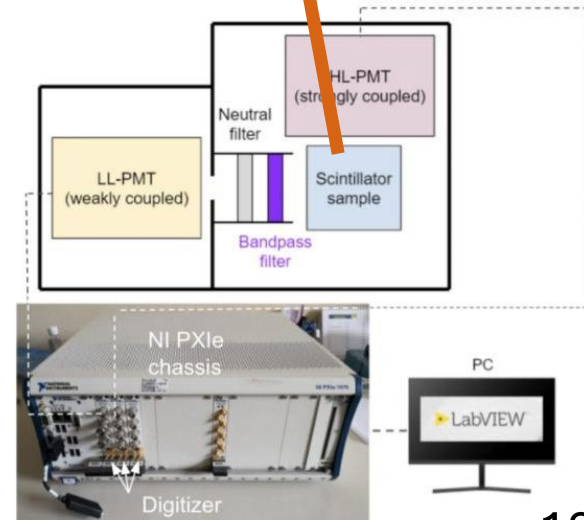
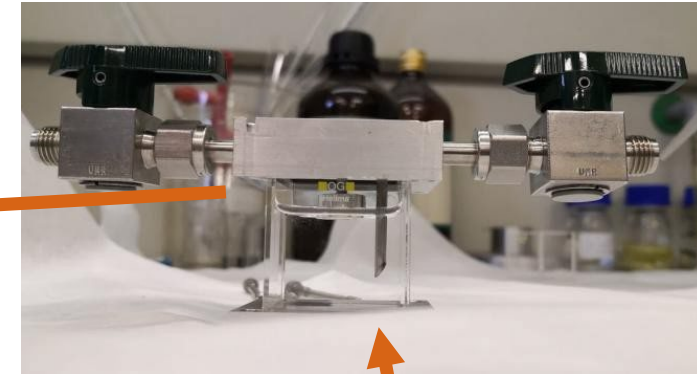
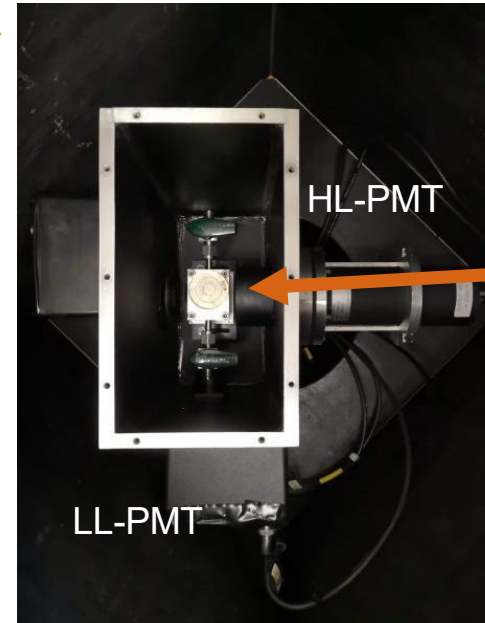
Laboratory UPGRADE:

- ☐ New Light Yield setup
- ☐ Vacuum Distillation glass facility
- ☐ Chemistry for Slow-scintillators, Water Based LS, Deep Eutectic Solvents, Perovskites

Current setups

SHELDON setup

- ❑ System of two photomultiplier tubes in coincidence enabling the use of **Time-Related Single Photon Counting technique**
- ❑ Experimental setup to accurately measure the **fluorescence time profile of liquid scintillators** (400 ps resolution)
- ❑ Reduced-scale LS detector ($3.1 \times 2.8 \times 3.3$) cm³



Current setups

SHELDON setup

- Absorbance spectrum
- Dual ray spectrophotometer: **JASCO V-760**
(Wavelength range: 190 - 1100 nm)
- Measurement with **2 cuvettes**
 - ❑ cuvette with air/cyclohexane for baseline
 - ❑ cuvette with the mixture to be analyzed
 - ❑ cuvette available: 1 cm, 5 cm, 10 cm



Study on Te-doped scintillators

SLOW LS

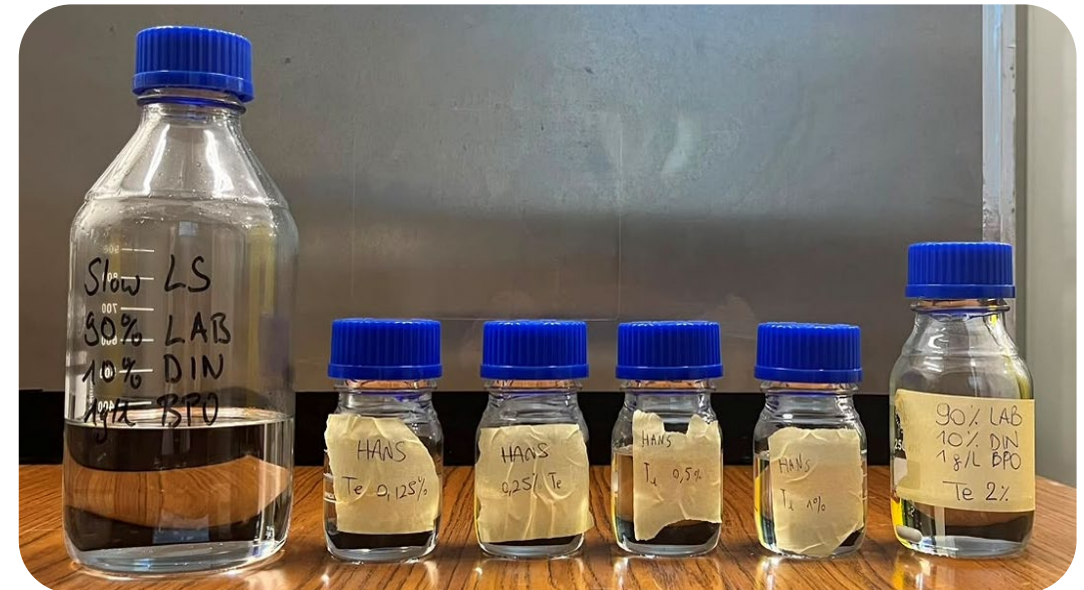
LAB 90% + DIN 10% + 1 g/L BPO

Starting from the samples sent by Hans, we produced samples with different Te concentrations:

- ☐ 0% and 2% provided by Hans
- ☐ 0.125%, 0.25%, 0.5%, 1% produced

We analyzed their optical properties :

- ☐ Time Profiles with α and β sources
- ☐ Absorption spectrum
- ☐ Preliminary measurement of light yield

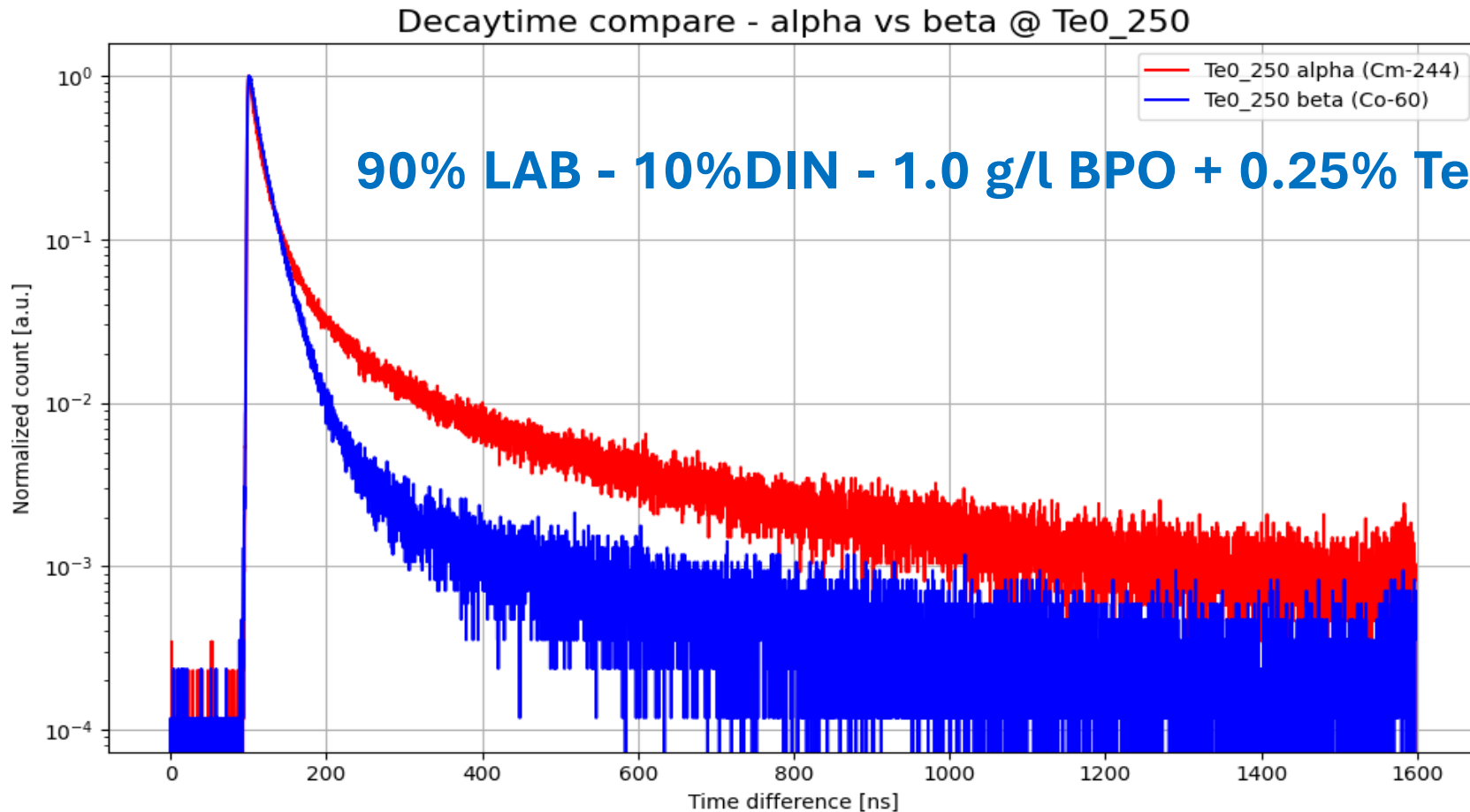


See Hans S. talk

Study on Te-doped scintillators

SLOW LS

Time Profiles with α and β sources



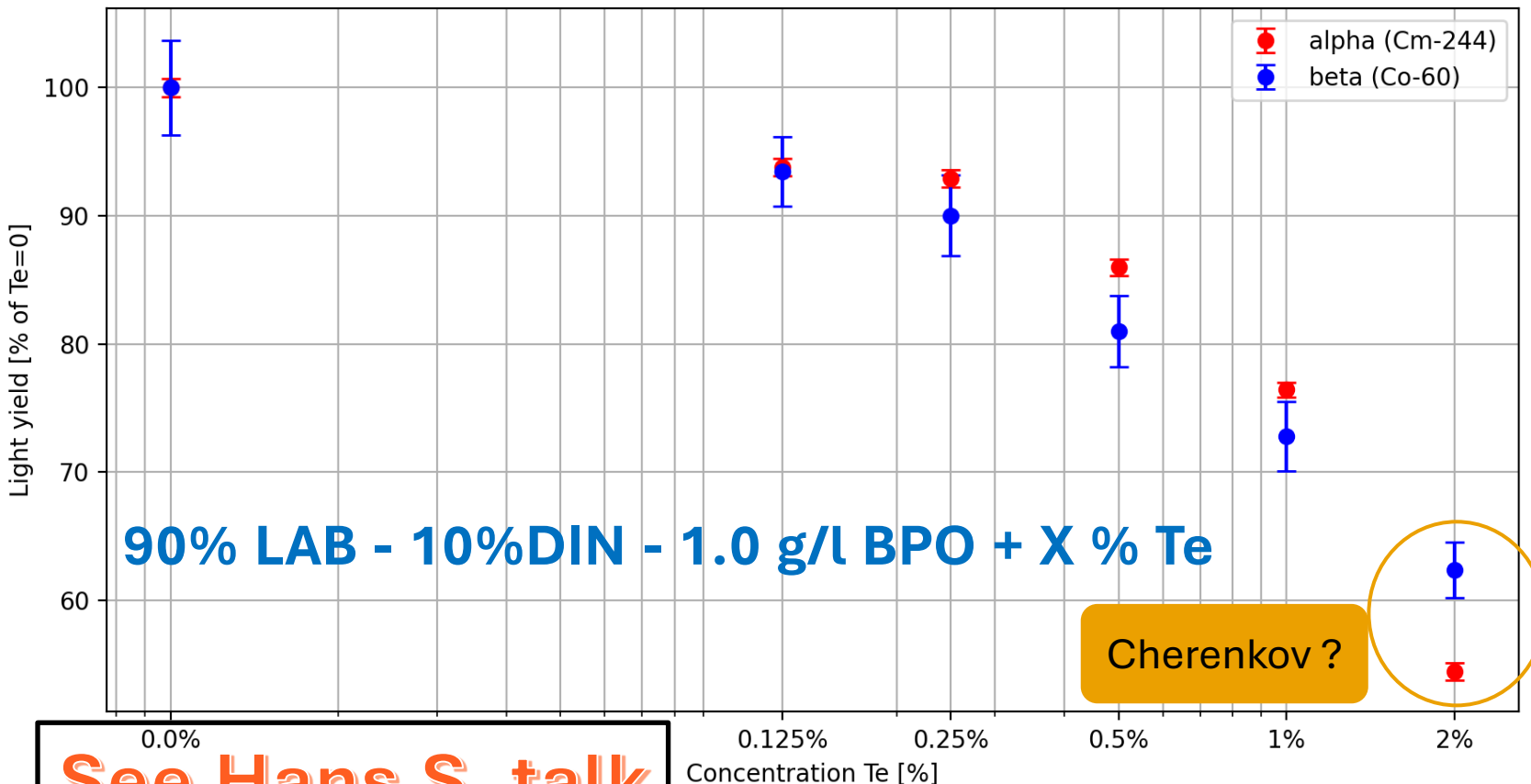
See Hans S. talk 22

Study on Te-doped slow scintillators

SLOW LS

Light yield

Normalized response vs Te concentration



The quenching should affect only scintillation and not the Cherenkov light. So we expect the light yield to decrease for both α and β sources as the Te concentration increase, but for the β case we expect it to reach kind of a plateau due to the Cherenkov contribution which is absent instead for the α case

See Hans S. talk

Study on innovative scintillators

Water based scintillator



We started to collaborate with the Milano chemistry department in order to understand if and how it is possible to produce innovative green scintillator

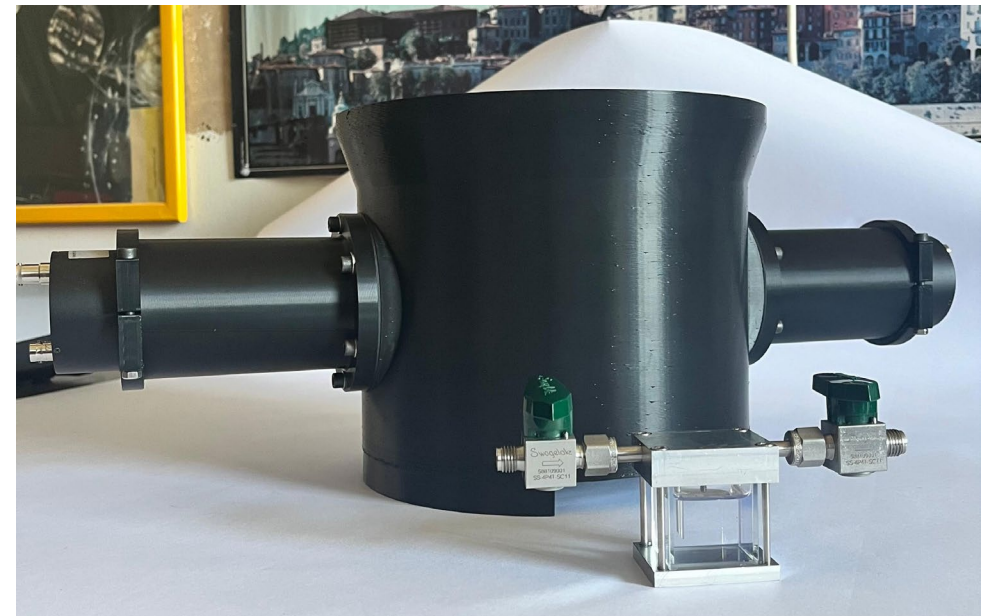
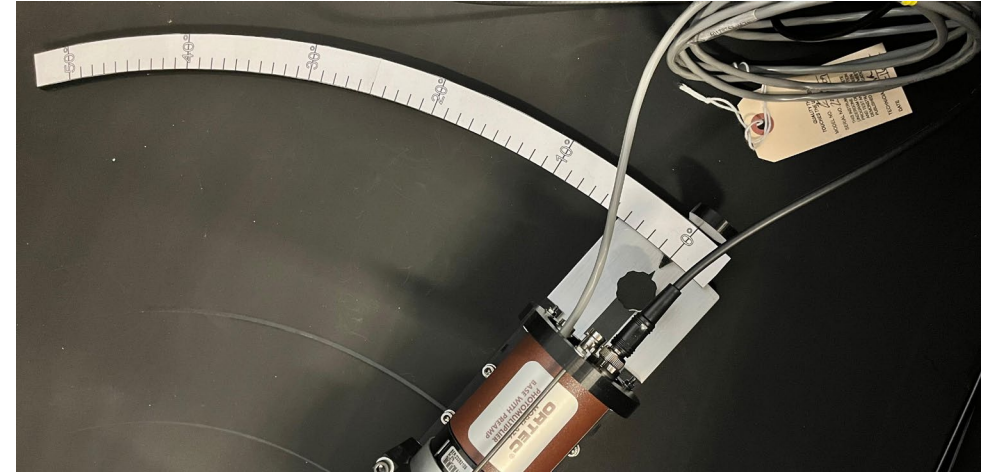
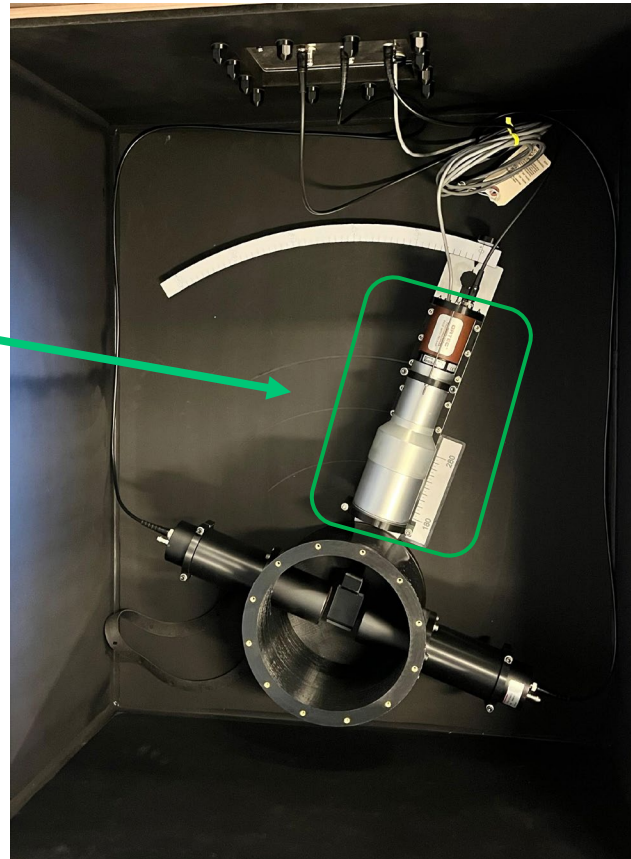
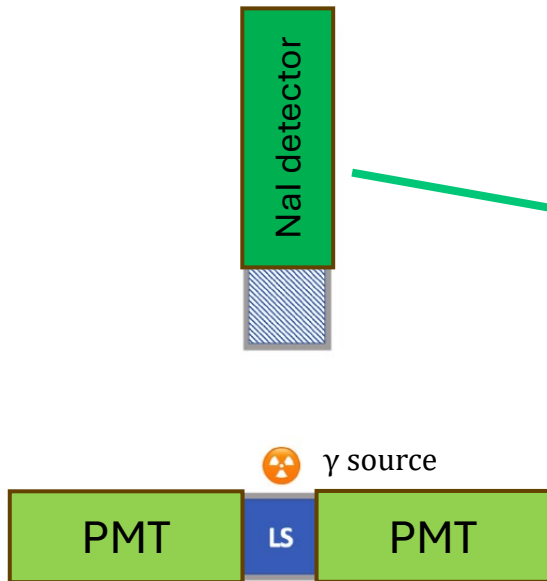
They provide us a **sample of salt**:

- ❑ Chemical formula: $\text{C}_{45}\text{H}_{38}\text{Na}_2\text{O}_8\text{S}_2^{2-}$
- ❑ Exact mass: **816,18 u**
- ❑ soluble in in water (at the level of g/L, order of magnitude)
- ❑ It emits light → potential scintillator

We are currently trying to characterize it to see if its property are suitable for particle detection and if it is scalable to larger scales

Laboratory UPGRADE

New Light Yield setup



Laboratory UPGRADE

Vacuum distillation setup

We are planning to introduce a distillation setup to enhance the optical property of our liquid scintillators

For the moment we just set the order



Thank you for your attention

R&D on Advanced Liquid Scintillators at Mainz, TUM, Padova, Perugia and INFN Milano



MAINZ



TUM



PADOVA



PERUGIA



MILANO

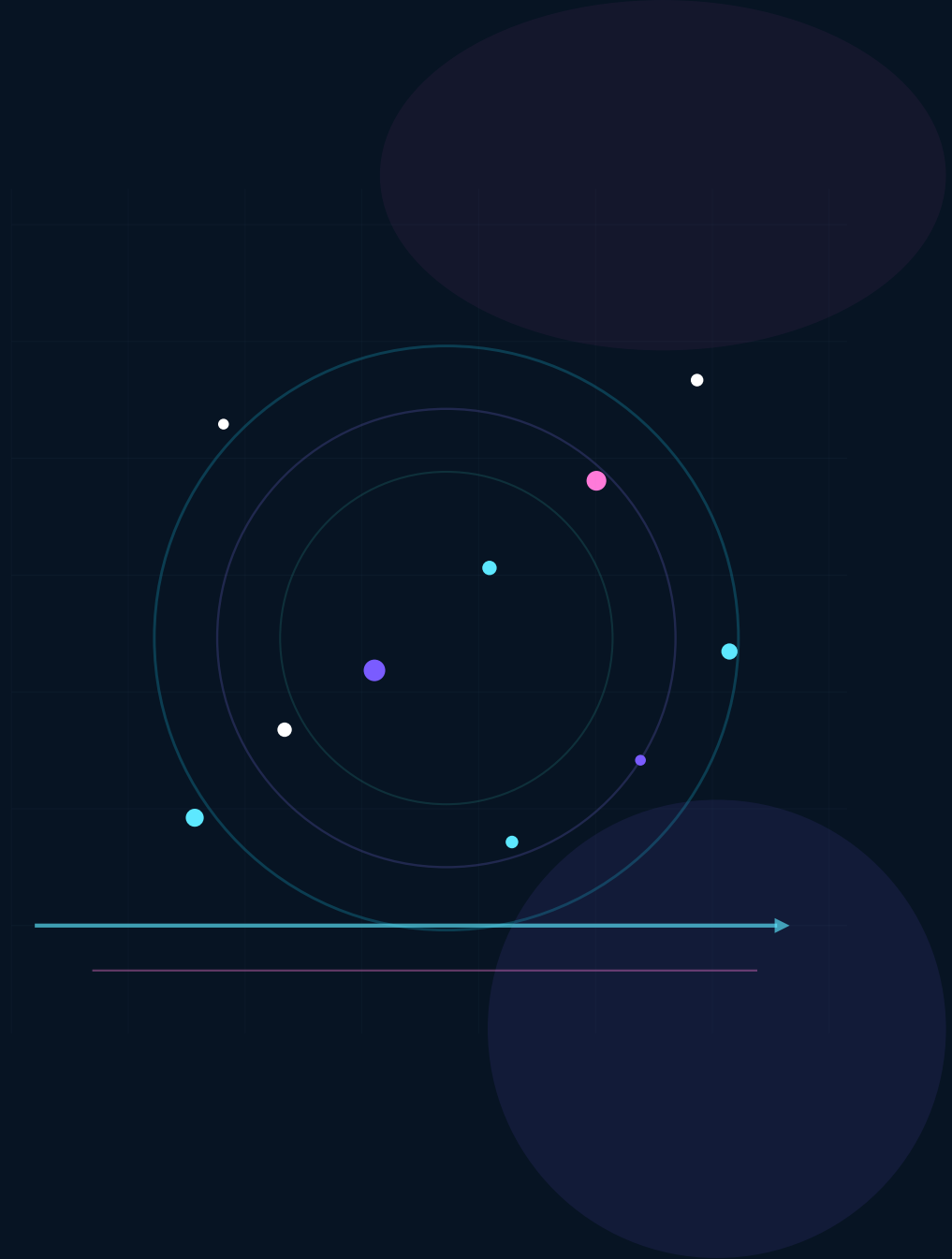


SUPPLEMENTARY MATERIAL

Backup slides

Additional details, cross-checks and supporting results

Physics Opportunities of Large Liquid Scintillator Detectors (II)



Study on Te-doped scintillators

BOREXINO LS

PC + 1.5 g/L PPO

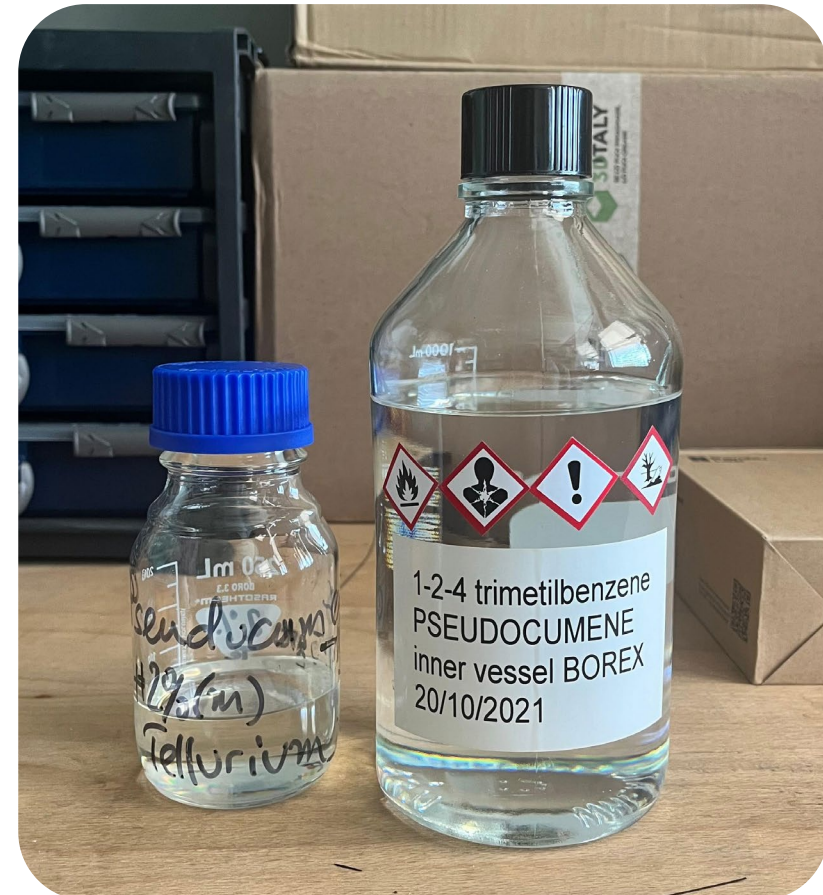
We analyzed different Te concentration:

- ☐ 0% original
- ☐ 2% provided by Hans
- ☐ 0.125%, 0.25%, 0.5%, 1% produced

Analyzed:

- ☐ Time profile

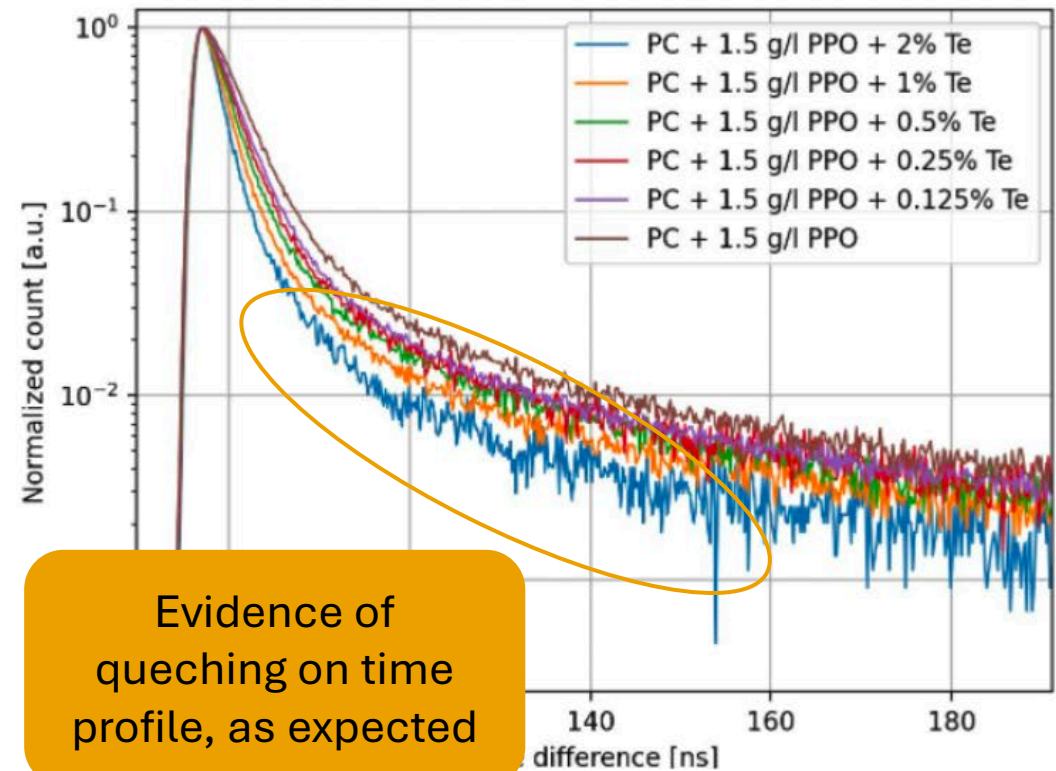
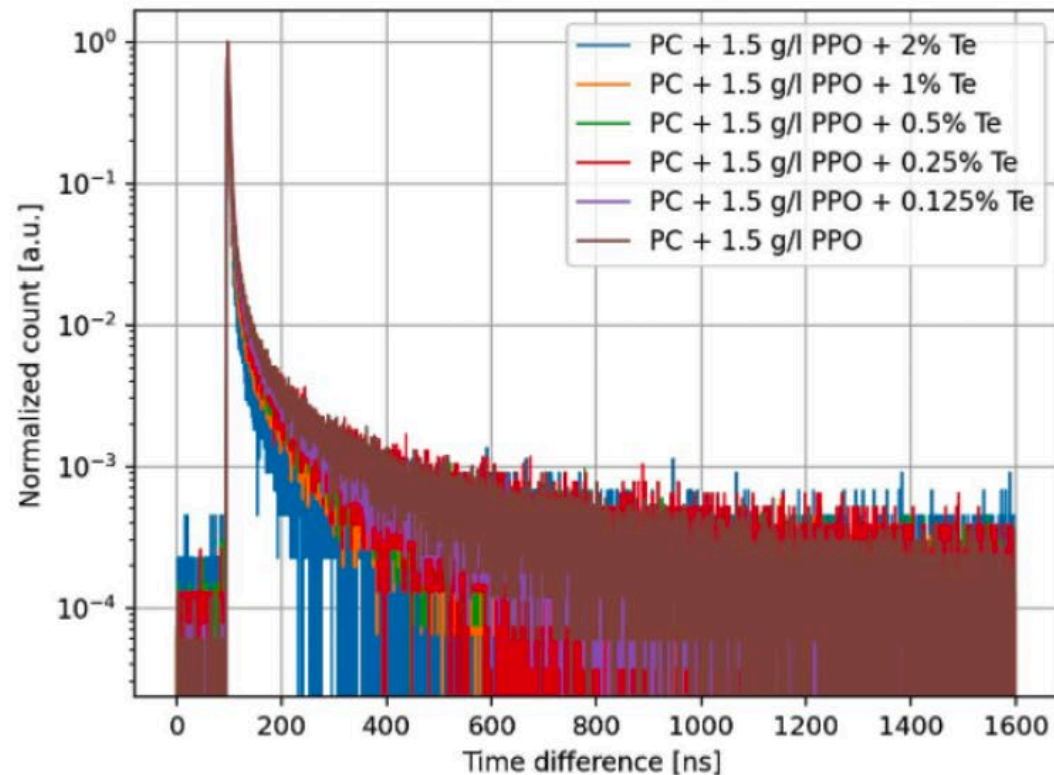
See Hans S. talk



Study on Te-doped scintillators

BOREXINO LS

Time Profiles with α source

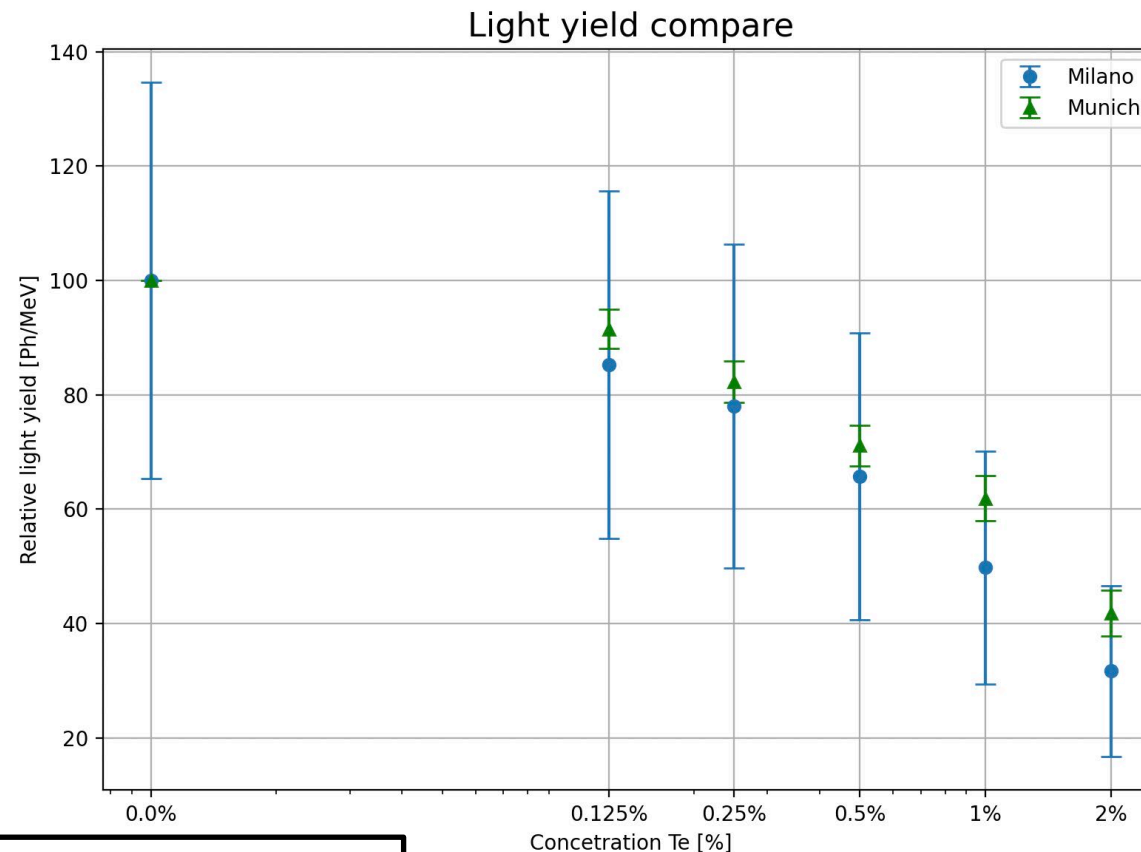


See Hans S. talk

Study on Te-doped scintillators

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Light Yield



Milano = α source
Munich = β source

See Hans S. talk