Key Trends in Scintillation Physics

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Where we are with knowledge and experience?

Is this knowledge satisfy practice?

What we have improve as the first priority?

1. Are so many scintillator choices have a chance for application?

2. Different modality status and trends

3. Optimal solution for different applications. New results need and cost. (Criteria of an optimal engineering)

Last main reviews of scintillators development and applications

NEEDS, TRENDS and ADVANCES IN INORGANIC SCINTILLATORS

C.Dujardin, E.Auffray, E.Bourret, P.Dorenbos, P.Lecoq, M.Nikl, A.N.Vasil'ev, A.Yoshikawa, R.Zhu

Reent development in X-ray imaging technology

Robert G. Lanier

Development of new scintillators for medical applications

Paul Lecoq

Review of X-ray Detectors for Medical Imaging

Martin Hoheisel (Siemens)

Current Trends in Scintillator Detectors and Materials

William W. Moses

Recent R&D trends in inorganic single-crystal scintillator materials for radiation detection,

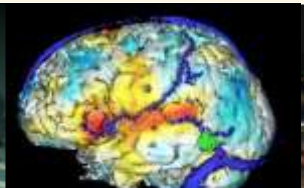
Martin Nikl and Akira Yoshikawa

Takayuki Yanagida , Inorganic scintillating materials and scintillation detectors. **end other !**

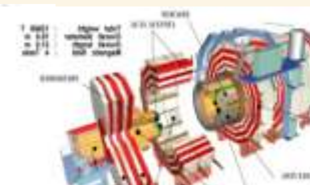
Scintillator market and main driving forces

Key properties for main applications

	Light yield	Resol.	Decay Time	Rad. damage	Back ground	Afterglow	Cost
Nuclear Medicine (SPECT, PET)		+	+				+
Health physics : Dose (particles, photons, neutrons)	+		+				+
Anatomic imaging (X-ray CT)			+			+	+
Security (non-prolifiration, scannin, z-analysis, spectroscopy		+			+		+
High energy phyics: particles, photons			+	++			+
Geology: density, well logging, finding U, Th via spectroscopy	+	+					+
Space (gamma) spectroscopy, neutrons		+			+		
Industry (density, speccopy)	+	+					+



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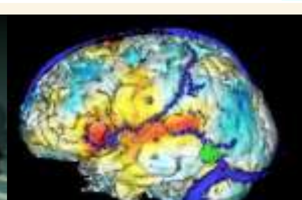




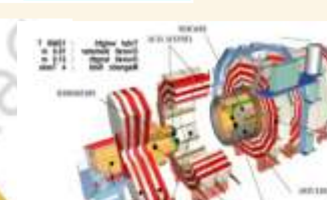

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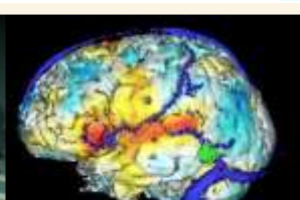
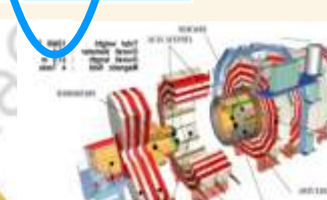
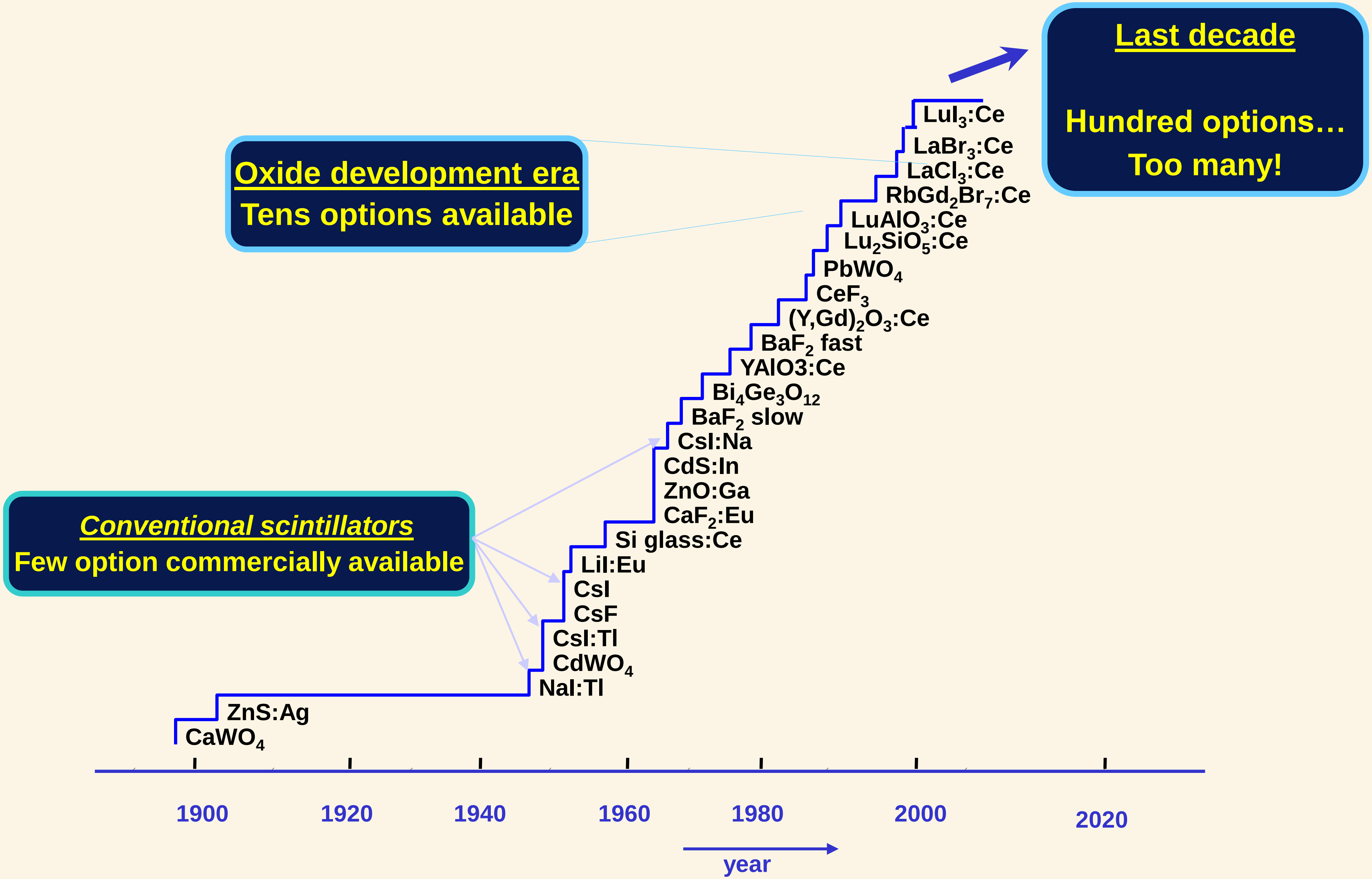


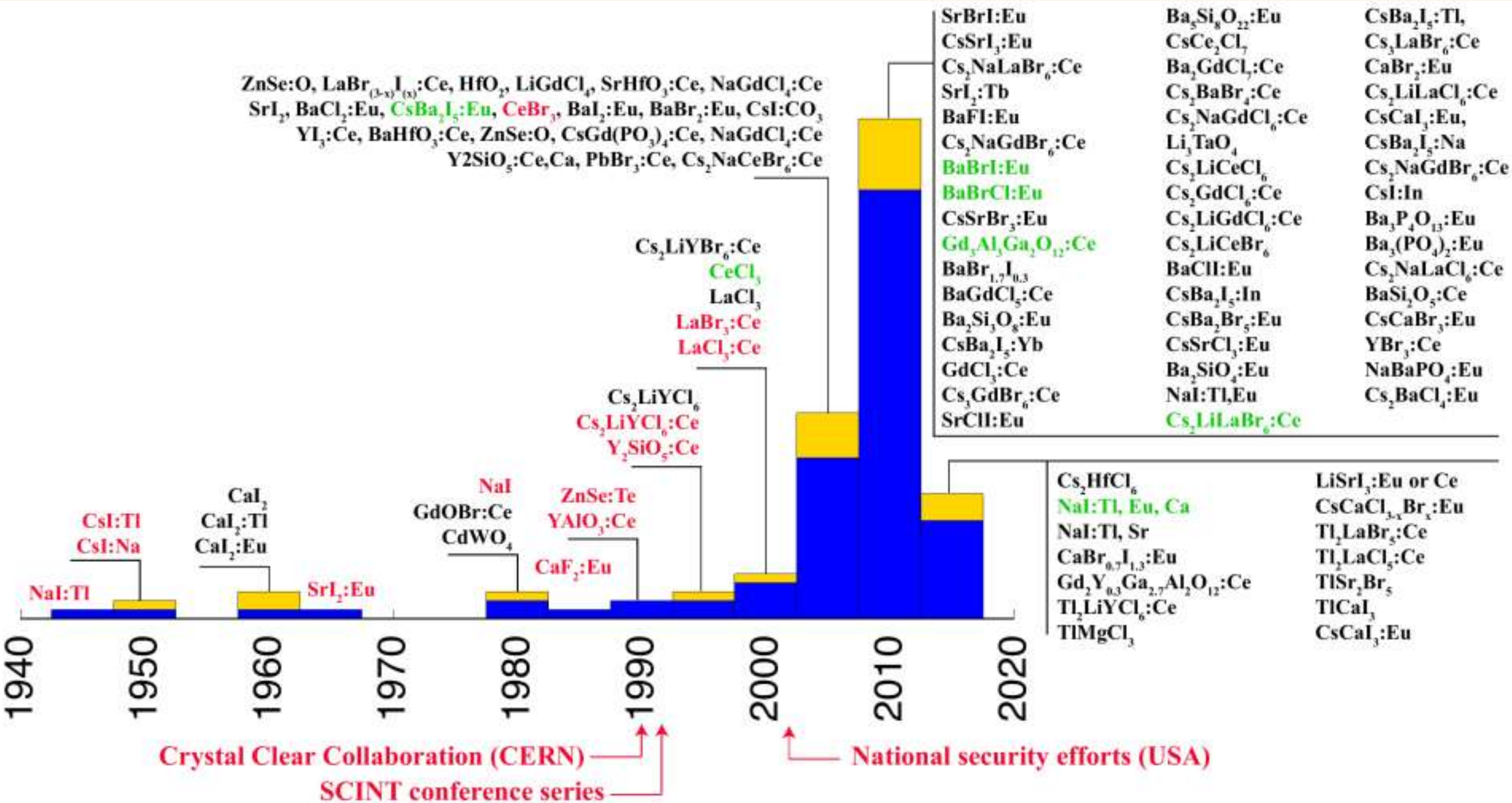


Scintillation discovery key points



New scintillator search and development



C.Dujarden at all 2018

Scintillation parameters for new scintillators

Scintillator	Melting point, °C	Density, g/cm^3	Z_{eff}	LY, ph/MeV	Scintillation decay, ns	ΔE at 662keV, %
$LaBr_3$:Ce 5%	743	5.1	48.3	~65 000	16	**3.2**
SrI_2:Eu	538	4.55	50.3	~100 000	1 000	**2.6**
NaI:Tl	651	3.7	xx	~40 000	230	**6-7**
BaFI:Eu 5%	893	5.45	xx	55 000	xx	**8.5**
BaClBr:Eu 5%	890	4.5	xx	52 000	xx	**3.55**
BaClI:Eu 5%	887	4.6	xx	54 000	xx	**9**
BaBrI:Eu 8%	885	5.2	xx	97 000	xx	**3.4**
KSr_2I_5:Eu 4%	476	4.3	51.4	~94 000	990 (~89%)	**2.4**
KSr_2Br_5:Eu 5%	575	4.0	xx	~75,000	1100 (80%)	**3.5**
KBa_2I_5:Eu	566	4.52	53.2	~84 000	910 (~81%)	**2.6**
K_2BaI_4:Eu	579	4.01	51.2	~57 000	720 (~67%)	**2.9**
$KCaI_3$:Eu 3%	524	3.81	50.6	~70 000	1 000 (~90%)	**3.8**
$CsSrI_3$:Eu 7%	640	4.29	51.1	~73 000	3 000 (90%)	**3.7**
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$Cs_2NaYBr_3I_3$:Ce	508	4.03	48.6	~41 000	56 (~47%)	**3.5**
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Oxide scintillators for new application

Some parameters of oxide scintillators used for low-energy γ-quanta detection

Crystal	Density g/cm^3	Ce^{3+} (Pr^{3+}) 5d-4f emission, nm	Decay time, ns	Max. LY, ph/MeV^{-1}	Energy res., [%] @662 keV
YAG:Ce	4.56	550	90–100	28000	6–7
LuAG:Ce	6.67	525	55–65	24000	6–7
GGAG:Ce	6.2	540	90–170	58000	**4.2–5.2**
LuAG:Pr	6.67	308	20–22	20000	**4.6–5**
LuYAG:Pr	6.2–6.5	310	20–22	33000	**4.4–6**
YAP:Ce	5.35	365	19–25	20000	**4.5–5.5**
YAP:Pr	5.35	247	8–10	12000	11–13
LYSO:Ce, Ca	7.2	400	30–35	32000	8–9
(Gd,La)PS :Ce	5.4–5.7	365–370	45–50	41000	5–6

Materials for neutron detection

Scintillation parameters of main elparolites for neutron detection

	CLYB	CLYC	CLLC	CLLB	CLLBC
Light yield, gamma, ph/MeV neutron, n/MeV	24 000 90 000	20 000 70 000	35 000 110 000	45 000 150 000	45 000 150 000
ER, %@662 keV	4.1	4.0	3.4	2.9	3
Emission, nm	410	370	380	410	410

There are many choices even in the same material type !

Which is the best?
Compare with existed options ?

Last decade newcomer to scintillation market

Important commercially available scintilators and their applications are :

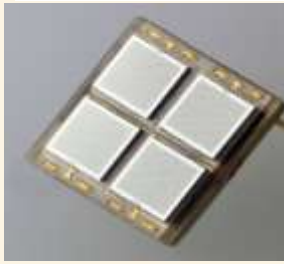
L(Y)SO	PET (medical)
PWO	HEP (CMS)
$LaBr_3$(Ce)	High resolution (HR) gamma spectroscopy
CLYC(Ce)	Neutron detection
SrI_2(Eu)	HR gamma spectroscopy
GAGG	Position sensitive detectors (not hygroscopic crystal)

Important factors for Industrial use:

- Can larger crystals be grown ?
- What is the cost ?
- Is the cost/performance rate corresponds to industry claim?

Market data

The global radiation detection, monitoring, and safety market is expected to reach USD 2.26 billion by 2022 from USD 1.71 billion in 2017



Scintillator market - ~200mln USD

** market structure*

** estimations details*

** complimentary markets (screens, storage etc.)*

Photo receiver market 436 mln USD

(to 2020 – up to 520 mln USD)

PMT - 277 mln (-2.1% trend)

SiPMT – 95 mln (+16% trend)

other – 63 mln

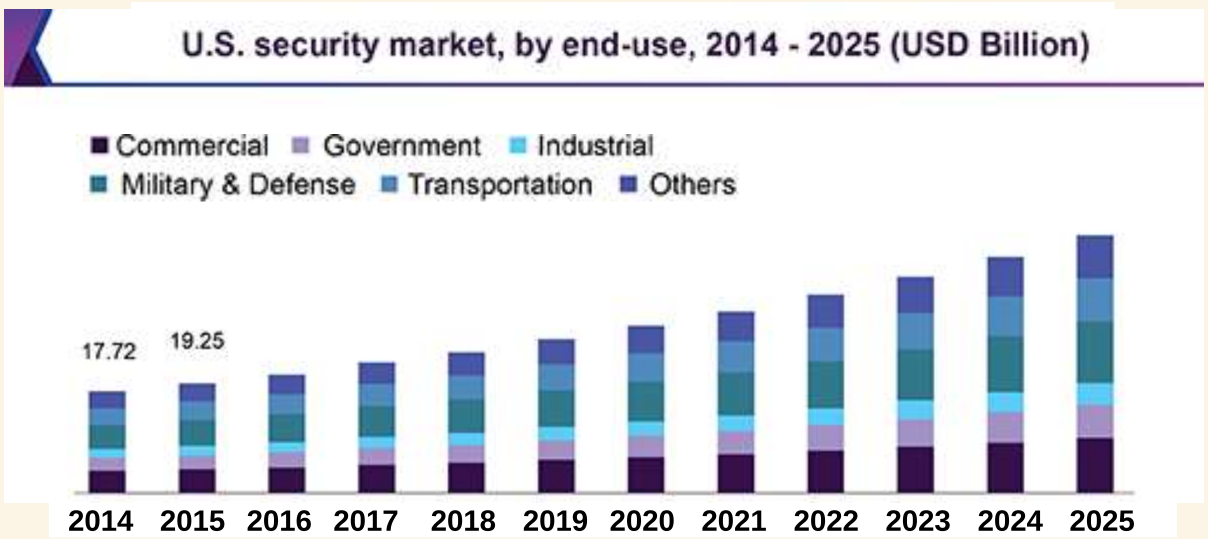
M&M data

NOTES:

- Raw material cost can reach up to 70%
- Photoreceiver is significant part of detector cost
- Electronic cost can exceed scintillatr cost itself
- Phosphor screens comparable with crystal production

Few examples of market trends

Global security market size will rise to 167 bln USD till 2025



* Secure Cities

* Radiation Portal Monitoring

* Material Protection, Control, and Accountability

* Mega ports

* Container Security Initiative

* Second Line of DefenseSecure Cities

Main funding sources. Last state and changes

From: DNDO

DNDO is the primary entity in the U.S. government for implementing domestic nuclear detection efforts

Started at15 April 2005. 563,8 mln $ annual budget

To: CWMD

June 2018

The mission of the Countering Weapons of Mass Destruction (CWMD) Office is to counter attempts by terrorists or other threat actors to carry out an attack against the United States or its interests using a weapon of mass destruction.

Oil explore market

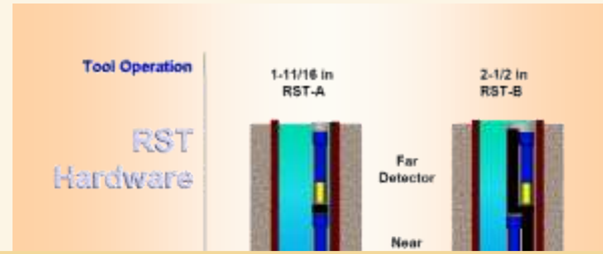
Well logging and scintillators place

Negative trends. Scintillators for minerals and oil explore

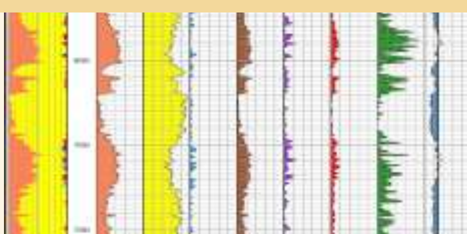
1 step:
Hole drilling

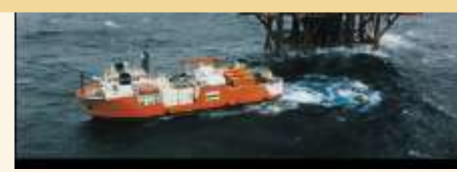
2 step:
Well logging

n and gamma detection



Oil price down
terminate search and development
in this application !



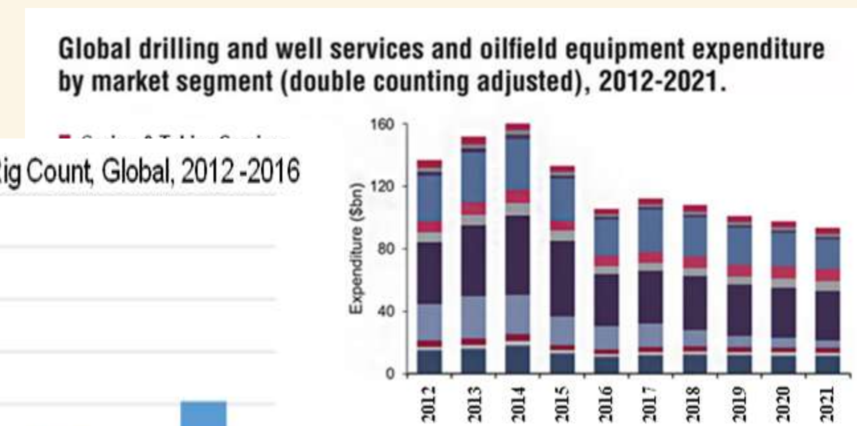


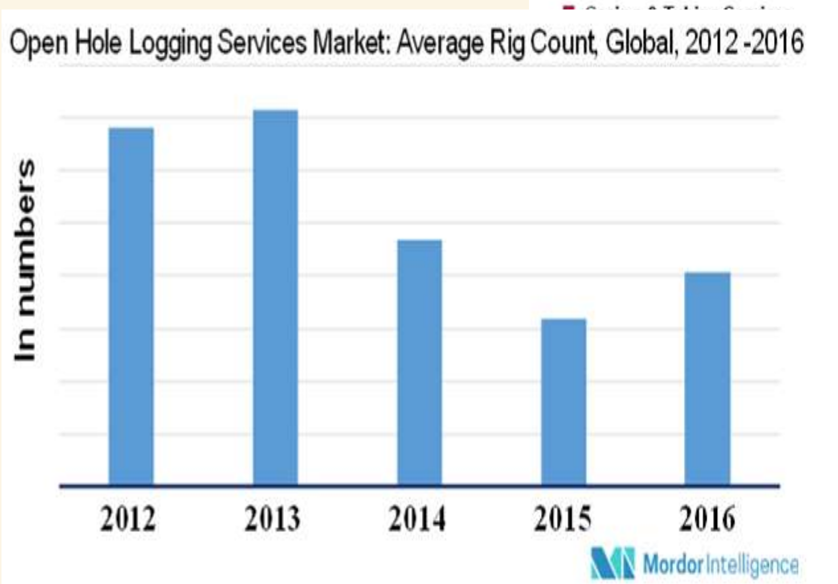
Schlumberger Doll Research

Oil market as diver for scintillator development and production

* Oil market is follows
  oil market price

* Drilling market follows
  general oil market



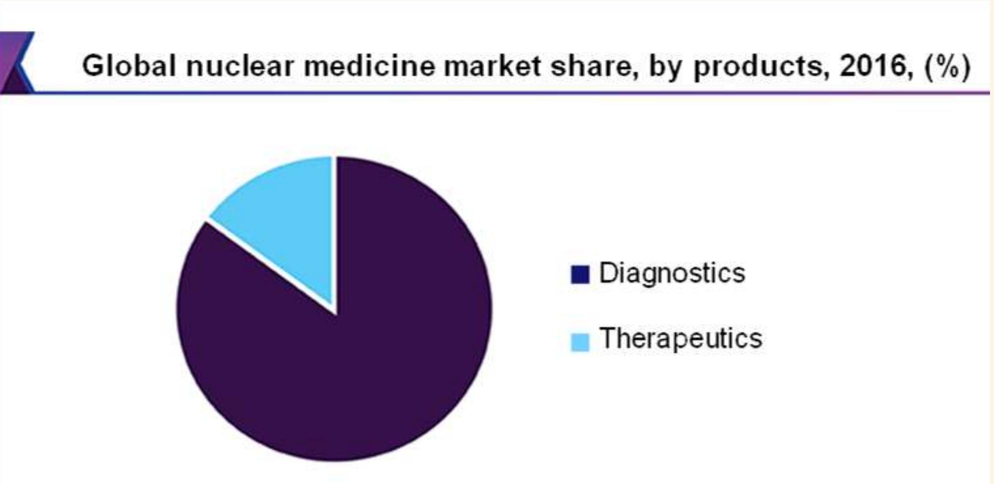


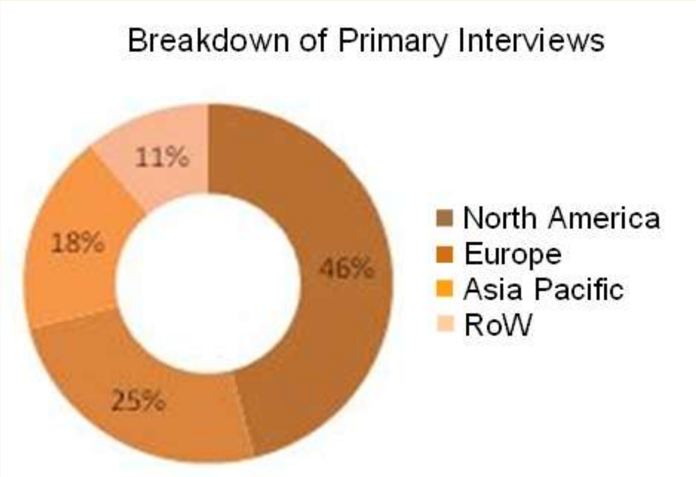
Medical scintillator market.

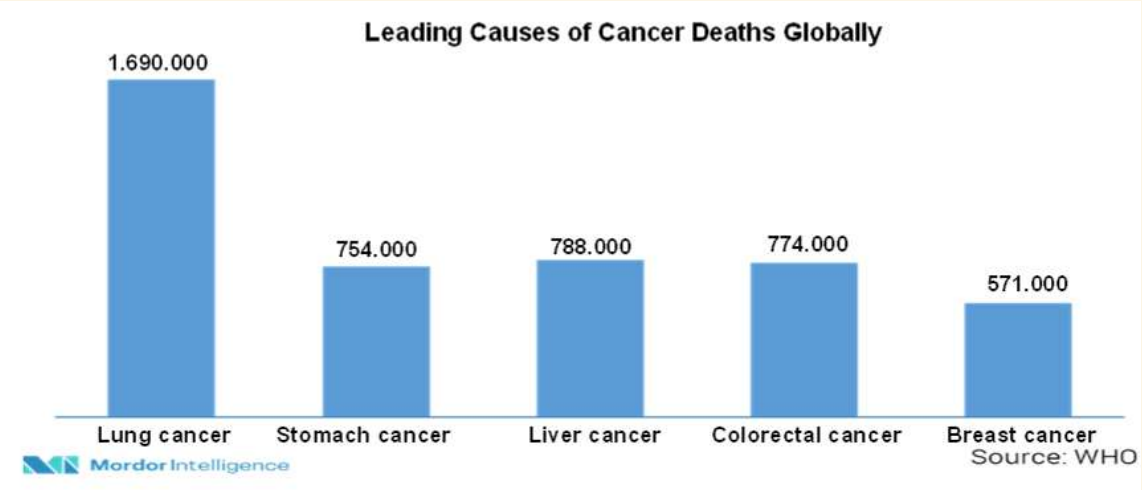
X-Ray materials and designs

Nuclear medicine still is the main market and driving force for scintillator market

Nuclear Medicine Market Size Worth $15.2 Billion By 2025







Imaging systems play the dominant role in detector design and development

but

dominant trends are permanently changed

NM market pluses and minuses

Diagnostic equipment reach 35% of the medical market

“Big Three” does not obviously claim for the cheap solution.

Optimal does not mean the cheap!

Medical market is the most stable for detector (4-5% growth).

The last trends are moved to semiconductor and ceramic detectors

General trends in medical imaging (Siemens note)

- All images become **digital**
- **3D** methods are gaining preference over 2D
- **Combination** of different modalities
- **Functional** imaging
- Imaging for **therapy**
- **Connectivity**

Aims

- better diagnosis
- targeted therapy
- cost optimization
- prevention

- Availability of images throughout the whole health care system
- Tele-medicine
- Electronic patient record

- **Computer-Assisted Diagnosis** (CAD)

Dominant option for X-ray CT detectors

- Amorphous Selenium (a-Se) flat panel technology with active pixel technology.
- Structured CsI (Cesium Iodide) scintillators
- TFT (thin-film transistor) and CMOS (complementary metal–oxide–semiconductor) technology
- CZT (cadmium-zinc telluride) arrays and their associated electronics.
- Ceramic scintillators

90 years ago and today

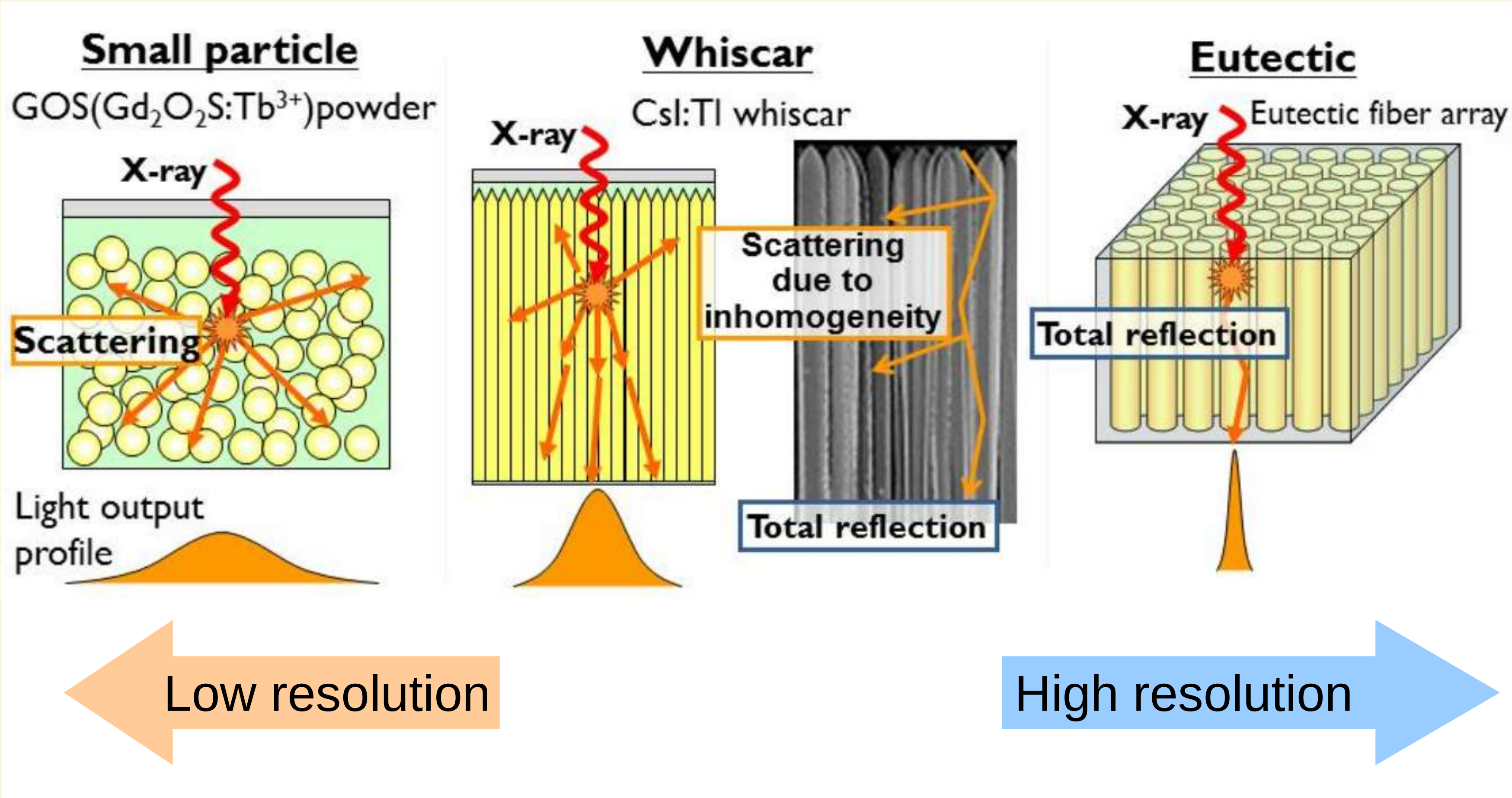
The list of X-Ray CT screening companies

CT - There are many manufacturers and strong competitive landscape for detectors

1. **Flash Pad** - GE
2. **PHOTON 100** - Bruker AXS
3. **XinRay Systems** - Siemens.
4. **Digital Silicon Photomultipliers** – Phillips
5. **CdZnTe (CZT) Detectors** – Redlen
6. **Lensfree Optical Tomography** – UCLA Research
7. **D-SPECT System** - Spectrum Dynamics
8. **XDAS detector boards V3** – Sens Tech
9. **Ultrafast Ceramic Scintillator (UFC)** - Siemens.
10. **Advanced X-Ray Detectors** – DxRay Inc
11. **CCD Detector Development** – MPI Halbleiterlabor,
12. **DEPFET Detectors** - MPI Halbleiterlabor
13. **HICAM Gamma Camera** – HICAM Collaboration
14. **LuAG Scintillator Array** – Japan Research
15. **Strip Detectors** – Baltic Scientific Instruments
16. **The Solid-State X-Ray Image Intensifier (SSXII)** – SUNY Researchers
17. **RadEye™ X-ray Sensor Modules** - Teledyne Rad-icon Imaging
18. **The INTEGRAL Soft Gamma-Ray Imager (ISGRI)** – ACRORAD
19. **CCD 485 with Fiber Optic Faceplate** – Fairchild Imaging
20. **CMOS Linear Arrays** – Fairchild Imaging
21. **Selenium-based Flat panel X-ray Detector** – Toshiba
22. **SAPHIRE (scintillator avalanche photoconductor with high-resolution emitter readout) Detector - .** 23. **(DEXI) diffraction-enhanced x-ray imaging instrument –** Nesch, LLC
24. **Linear scanning sensors with gas-based detector modules for X-ray imaging** – Korean Collaboration
25. **Security Detectors; High-energy X-ray Platforms** – Varian

Big Three (GE, Siemans and Philips) practically fully occupy SPECT and PET markets

Granularity or pixelesation for spatial high reolution



Properties of scintillators used in X-ray CT imaging

- The are many similar candidates
- Electronics compensate some differences between crystals
- Market value as the limit for some updates

Scintillator	Density (g/cm^3)	Thickness to stop 99% of 140 keV X-rays (mm)	Light yield (ph/MeV)/ temperature coefficient (%/°C)	Peak of emission band (nm)	Primary decay time (ms)	Afterglow (% at 3 ms)
CsI(Tl)	4.52	6.1	54,000/ 0.02	550	1	0.5
$CdWO_4$ (CWO)	7.9	**2.6**	28,000/ -0.3	495	2, 15	0.05
$Gd_2O_3:Eu^{3+}$	7.55	**2.6**	–	610	–	–
$(Y,Gd)_2O_3$:Eu,Pr,Tb (YGO)	5.9	6.1	42,000/ 0.04	610	1000	5
Gd_2O_2S:Pr,Ce,F (GOS)	7.34	**2.9**	50,000/ -0.6	520	2.4	0.1
Gd_2O_2S:Tb(Ce) (GOS)	7.34	**2.9**	50,000/ -0.6	550	600	0.6
La_2HfO_7:Ti	7.9	**2.8**	13,000/ –	475	10	–
Gd_3Ga5O_{12}:Cr,Ce	7.09	4.5	39,000/ –	730	150	0.1

What are the mutual trends for all scintillators development?

Which claims are mutual?

Can we unify material claims to minimize list of scintillators?

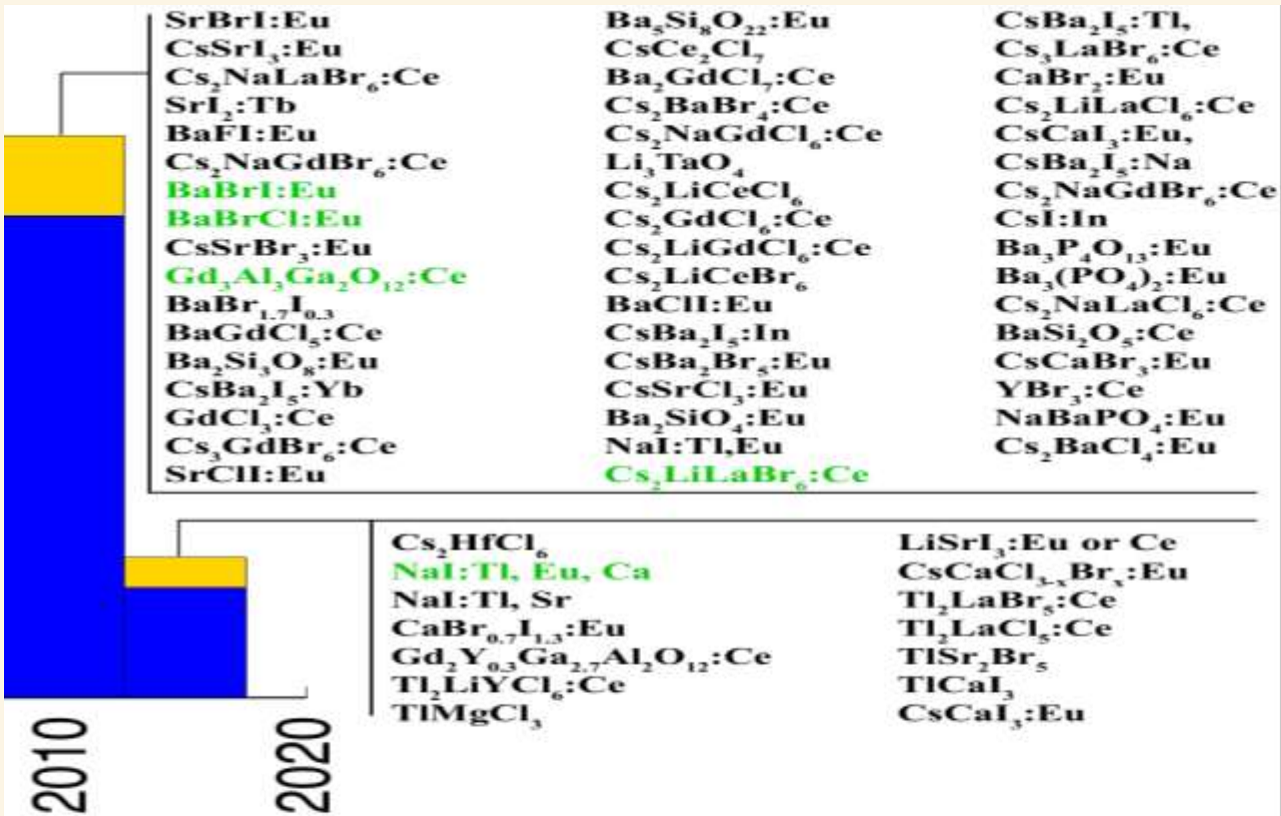
What we can propose as scintillator improvement

* New material search (???)   or conventional scintillators improvement?

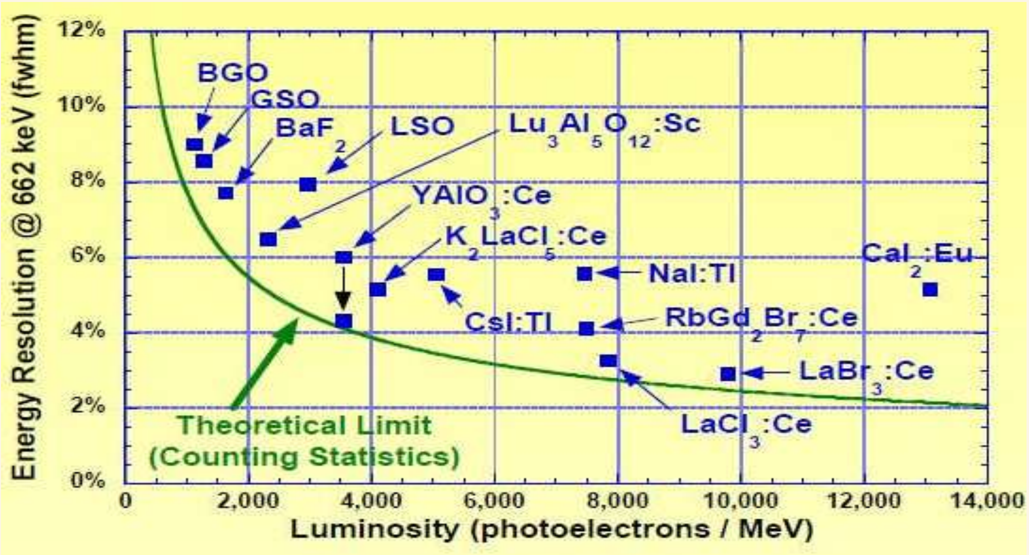
** Co-doping as scintillator improvement method

*** Crystal treatment of data processing improvement

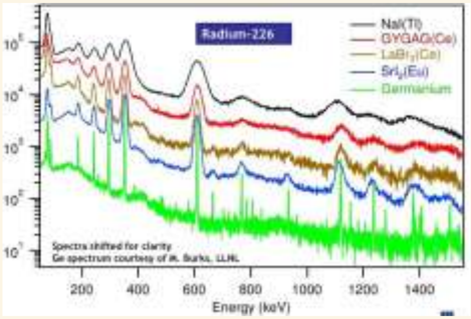
New scintillator search and development



Crystal performance spread… Energy resolution



P.Dorenbos



Isotopes separation

* Theoretical energy resolution spread is not so wide as experimental one

** What are the reasons for such spread?

*** Is resolution really significantly depends on the material

****Can we manage the energy resolution and how we can do it?

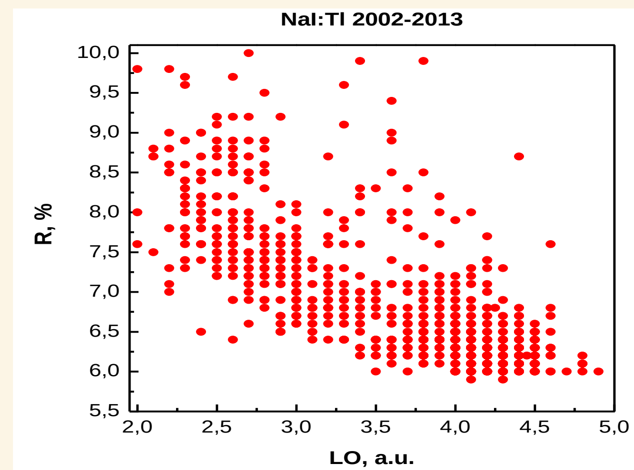
Energy resolution of a scintillator detector

intrinsic scintillator | photon transport | photon statistics | electronic noise

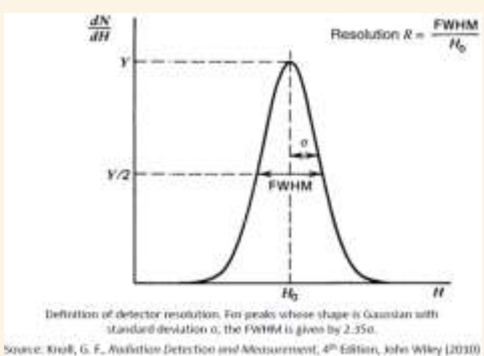
$$R^2 = R_{int}^2 + R_p^2 + R_{stat}^2 + R_{noise}^2$$

$$R_{stat}^2 = 2.355\sqrt{\frac{1+\varepsilon}{N_{pe}}}$$

$$R_{int}^2 = R_{inhom}^2 + R_{nonprop}^2$$



M.Moszynski et al



There no direct correlation between light yield and energy resolution !!!

Do we satisfy with resolution description?

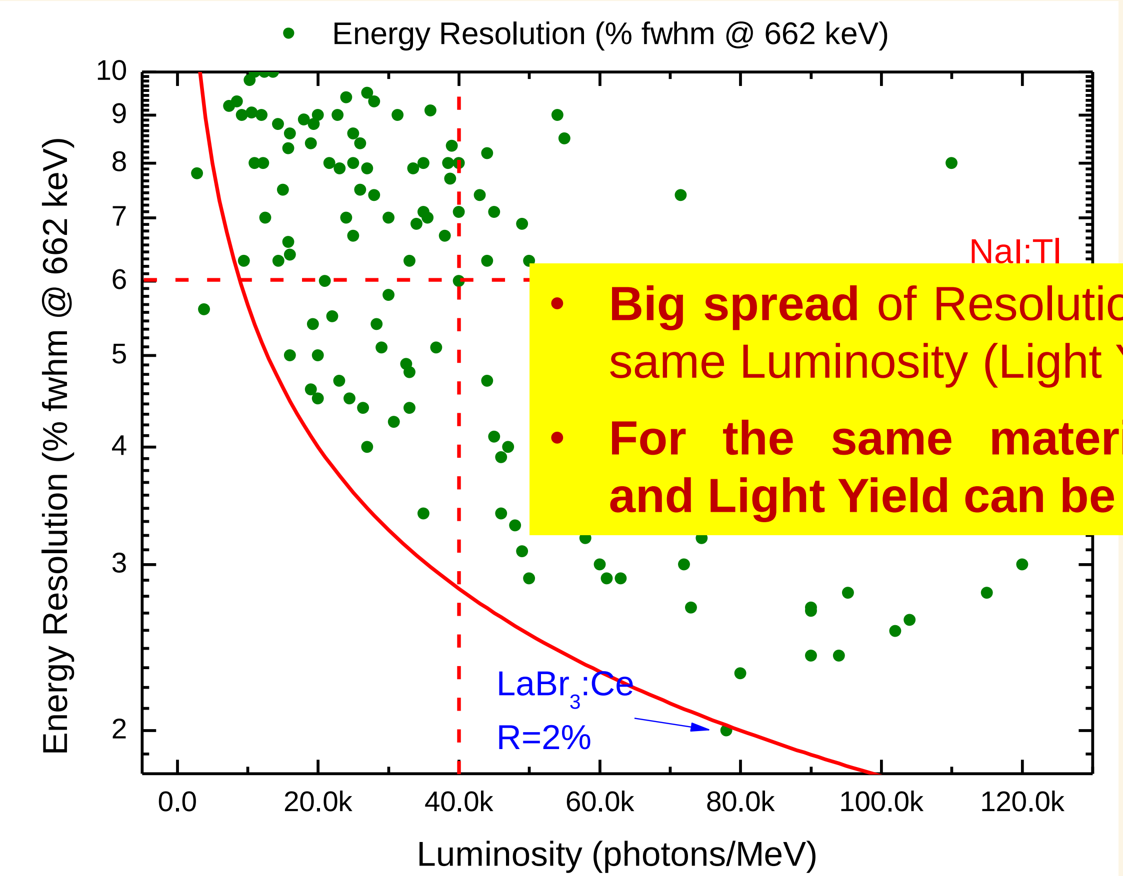
- **Non-proportionality and resolution. Is any direct correlation?**

- **Contrary to definition energy resolution looks like structure sensitive phenomenon**
  - dependence from crystal purity (undoped crystals)
  - dependence from peaking time
  - finally – dependence from the luminescence type

- **Definitions and theory**

Classic theory does not properly describe scintillator !

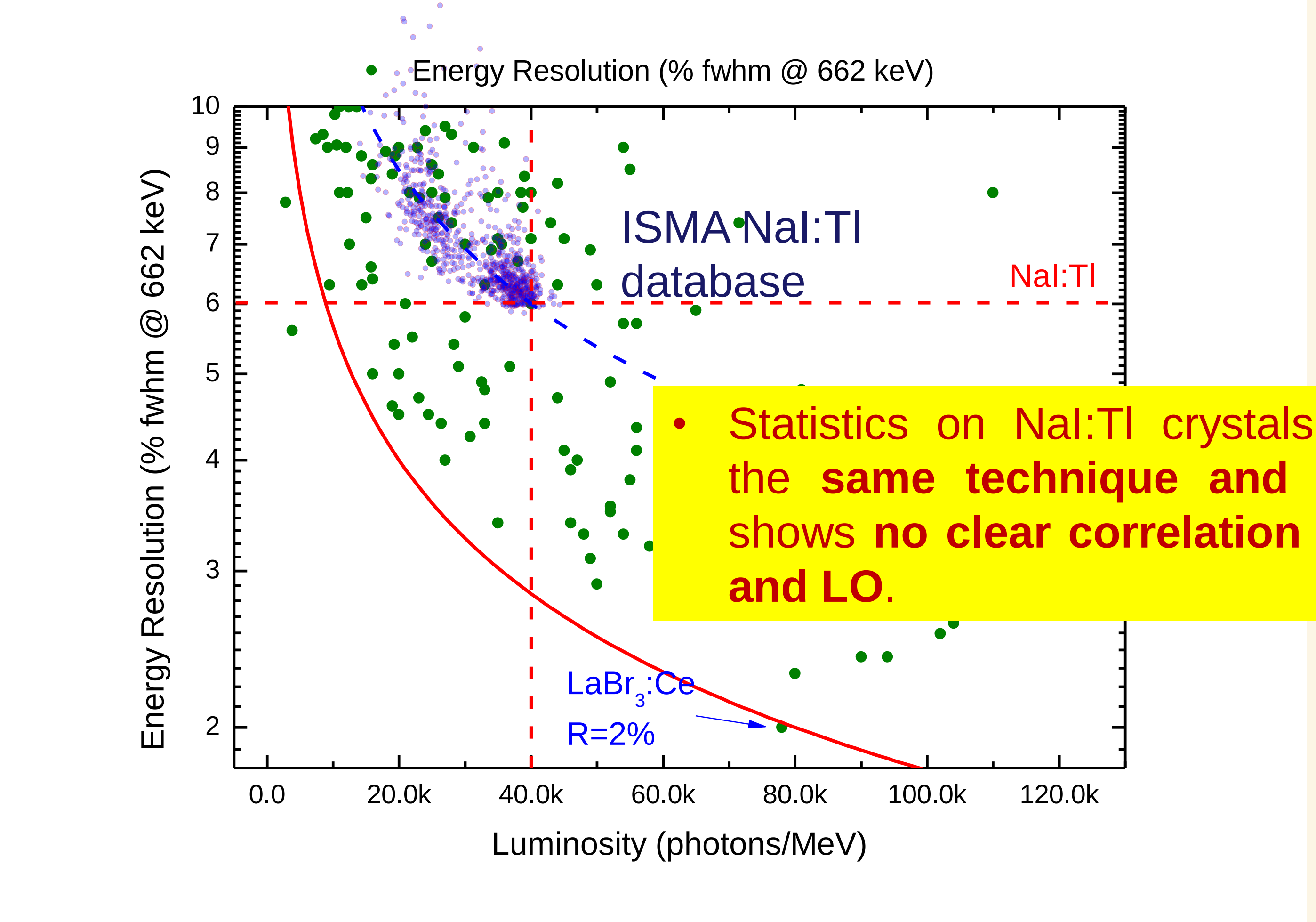
Energy resolution vs Luminosity



- **Big spread** of Resolution values for the same Luminosity (Light Yield) !
- **For the same material, Resolution and Light Yield can be very different**

Compiled by S. Vasyukov from S. Derenzo et al LBNL scintillator database

Energy resolution vs Luminosity



- Statistics on NaI:Tl crystals grown by the **same technique and procedure** shows **no clear correlation** between **R and LO**.

Compiled by V.Vasil'ev, S. Vasyukov from S. Derenzo et al LBNL scintillator database

What we have to keep in mind

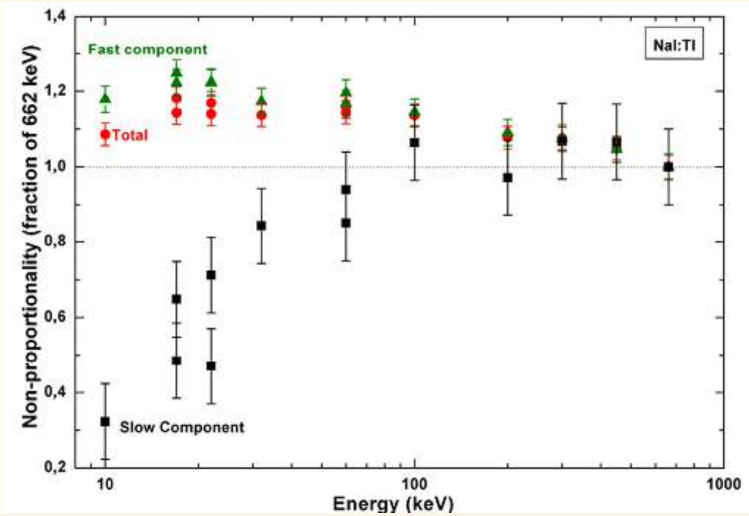
when try to understand resolution

phenomenon?

What we have to keep in mind when try to understand resolution phenomenon?

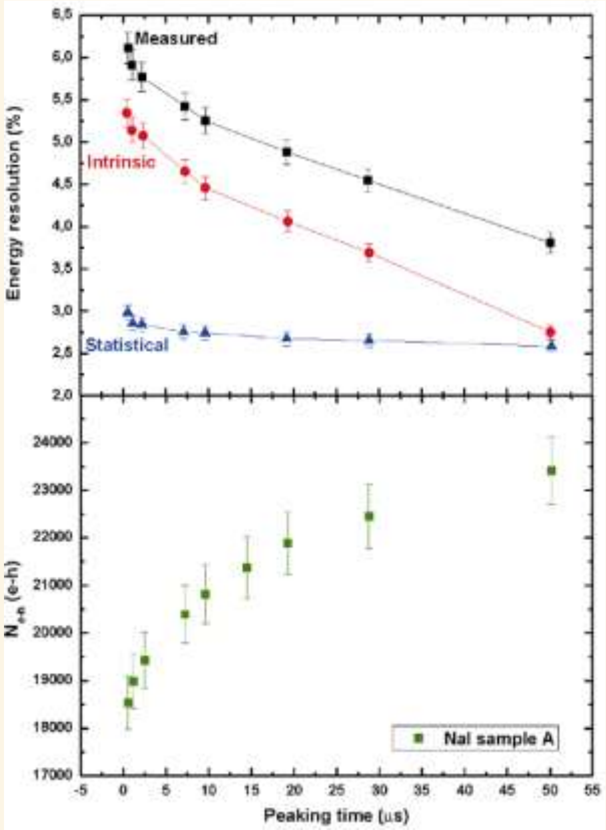
Non-proportionality depends on peaking time

- Peaking (integration) time is an important for exact resolution measurement
- Peaking time measurements reflects contributions of different types of luminescence



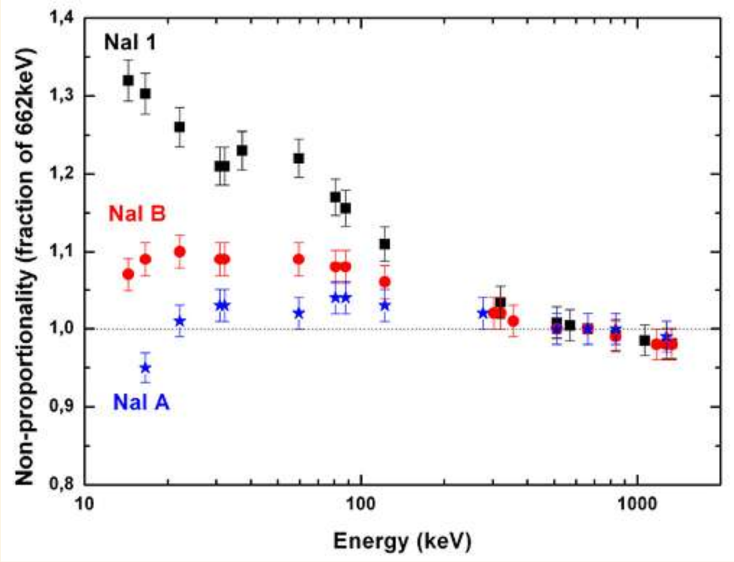
[Moszynski et al.]

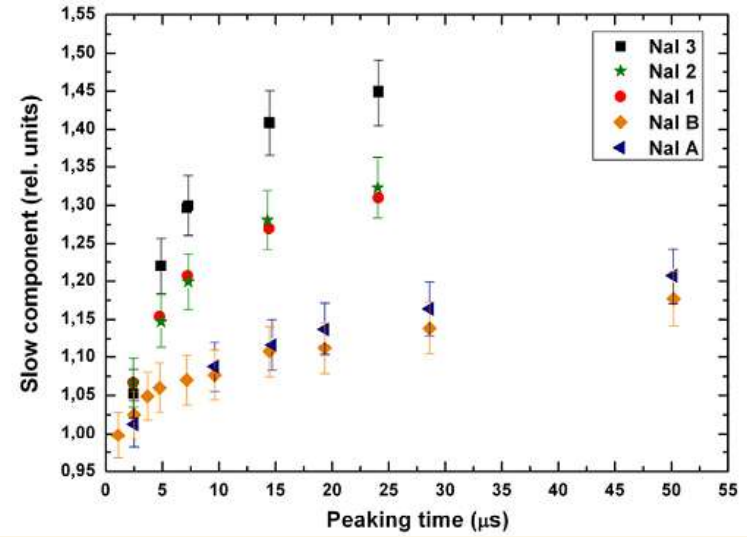
- There is no direct correlation Between non-proportionality and energy resolution



What we have to keep in mind when try to understand resolution phenomenon?

Non-proportionality depends on crystal purity

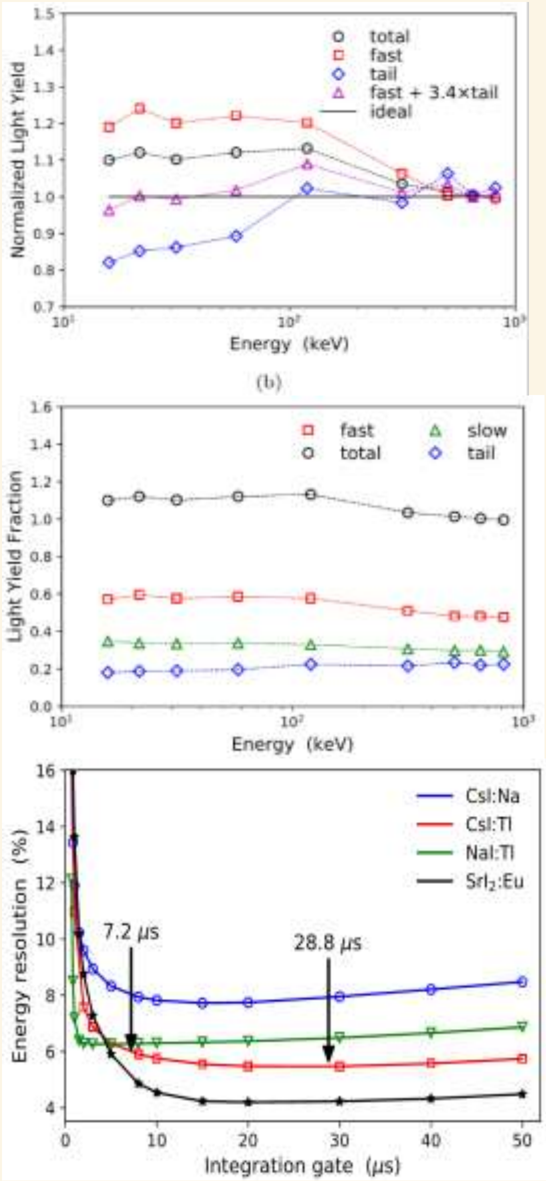




[Moszynski et al.]

- **Pure crystals are nominally pure only**
- **NaI with linear proportionality does not possess with better resolution**
- **The main difference of purity connects with long decay components**

What we have to keep in mind when try to understand resolution phenomenon?



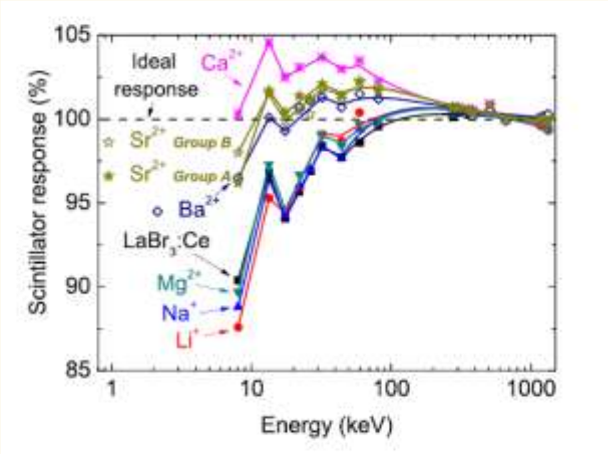
- Non proportionality (NP) and light yield for different decay components are different

- The main difference of purity connects with long decay

- It is possible to modify NP and energy resolution by crystal purification or co-doping

What we have to keep in mind when try to understand resolution phenomenon?

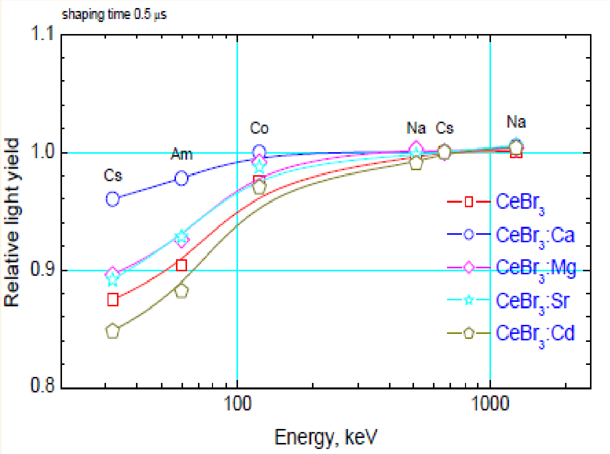
Co-doming (impurity) can change non-proportionality



Non-proportionality of $LaBr_3$:Ce scintillators with different co-dopants: Ca^{2+}, Sr^{2+}, Ba^{2+}, Mg^{2+}, Na^{+}, and Li^{+}.

Co-doping. Impurity strongly affects the scintillator response.

[Alekhin et al.]



Non-proportionality of $CeBr_3$ scintillators with different co-dopants: Ca, Mg, Sr, and Cd.

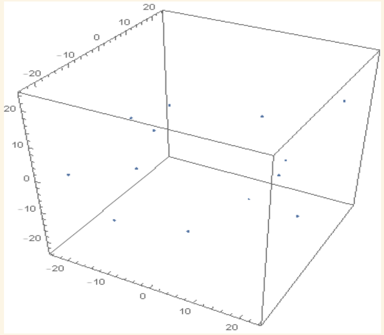
Co-doping. Impurity can improve linearity, or make scintillator less proportional.

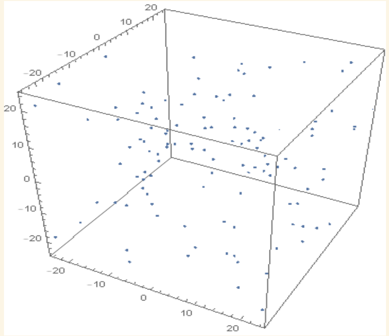
[Schotanus et al.]

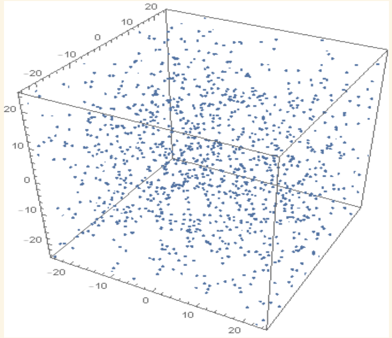
Can we assume the reasons of specific behavior of scintillators?

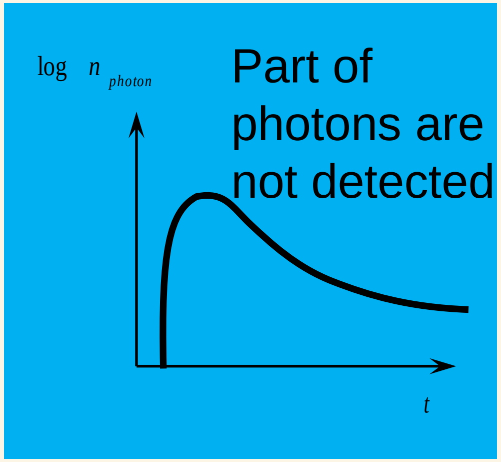
Can we find new approaches for statistic description?

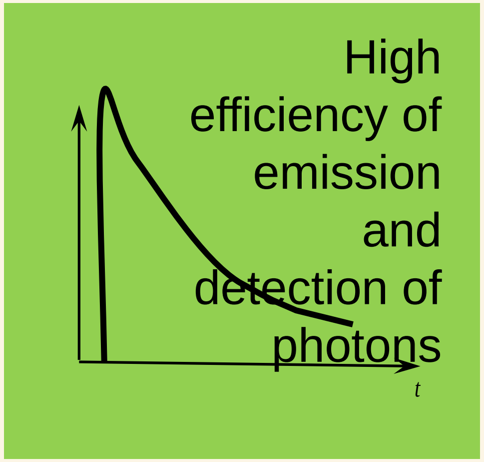
Excitation concentration and kinetics

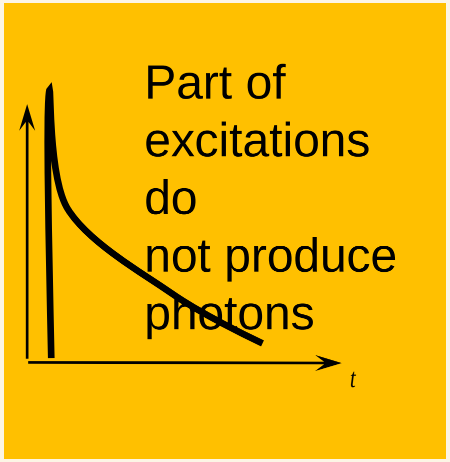






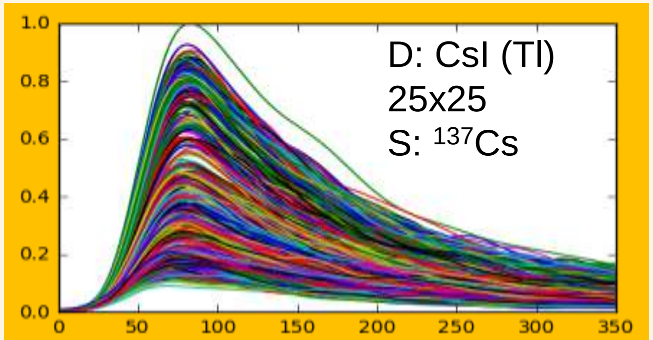


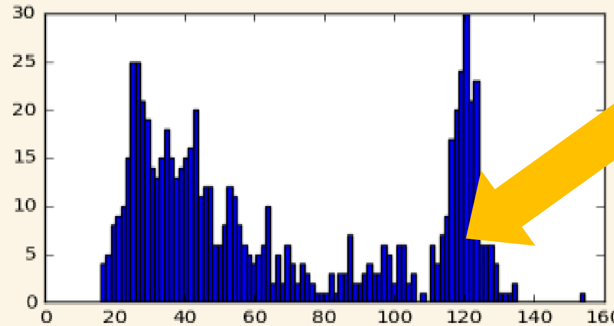


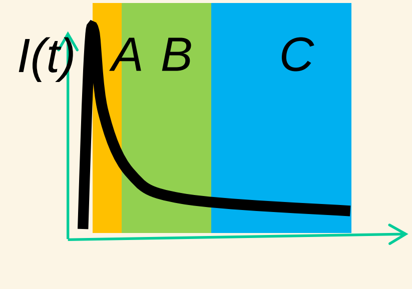


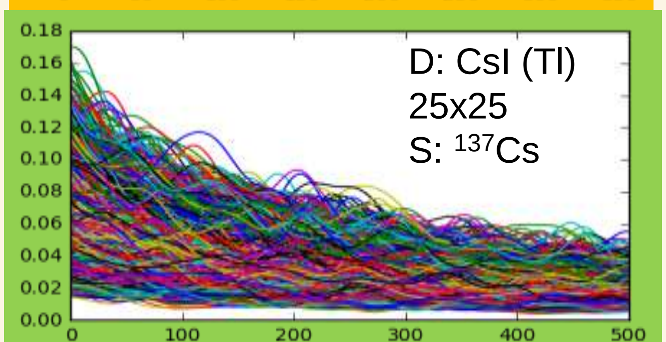
A.Vasil'ev, Fluctuation of track structure in terms of distribution of excitations and fractal dimensions, CCC Meeting, CERN, 2017

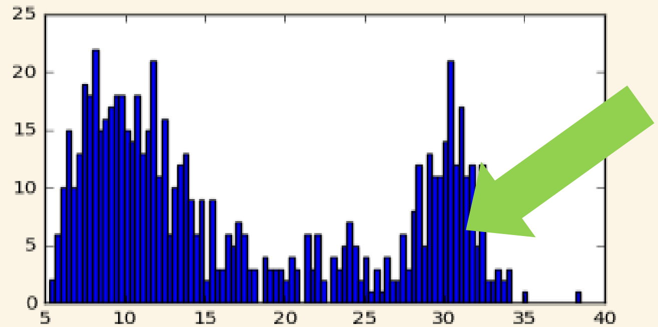
Decomposition of pulses by time



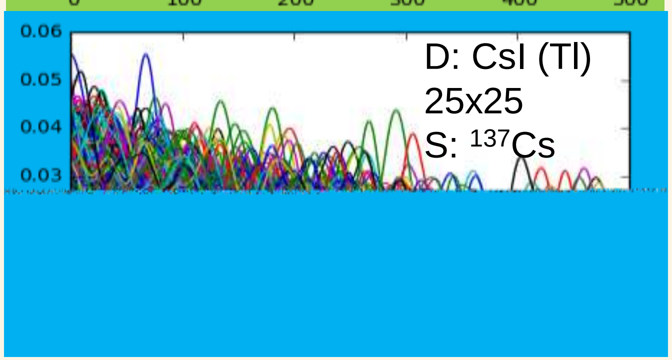


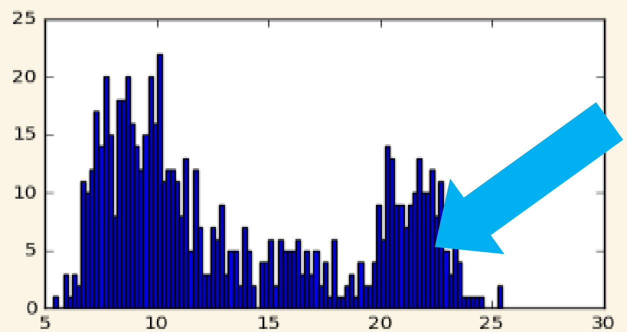






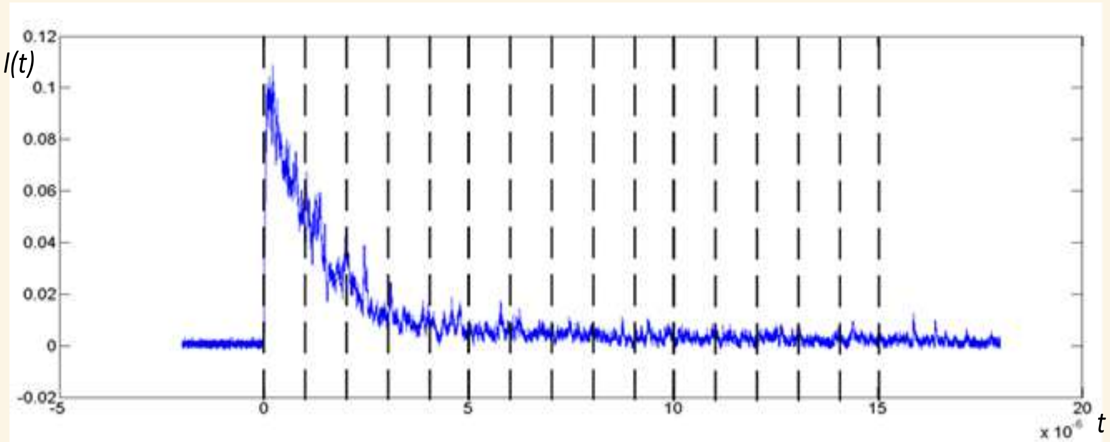
The shape of complete absorption peak is changes

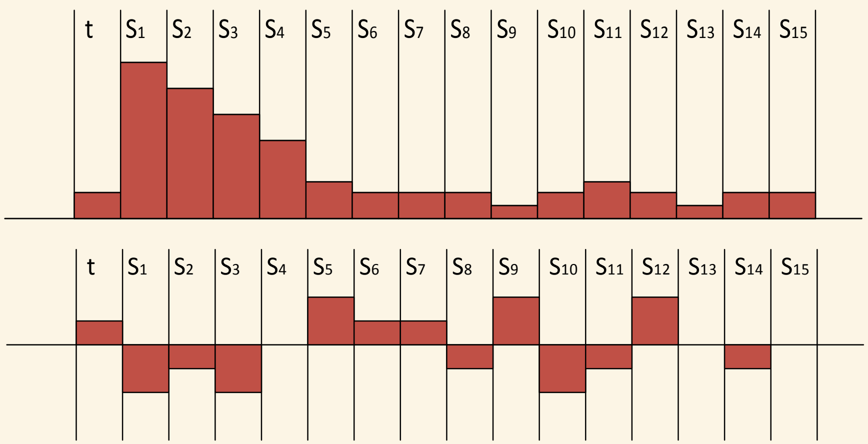




A.Sobolev, LUMDETR 2018

Research idea: What do we do?

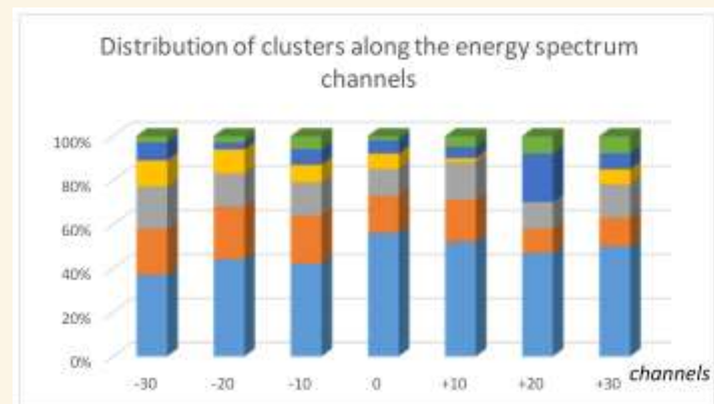




Lets replace PMT pulses to the equivalent vector of partial sums.

Append to the vector the rise time of the signal.

$$S_{pulse} = \sum_{i}^{N} S_i$$



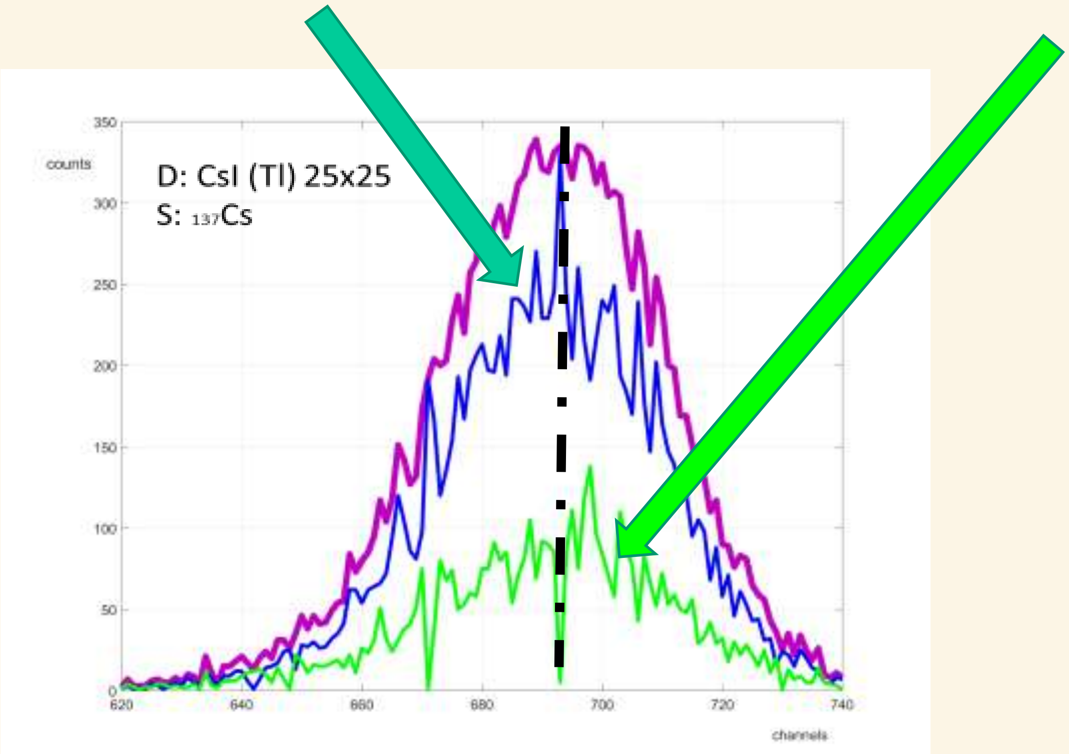
A.Sobolev (LUMDETR 2018)

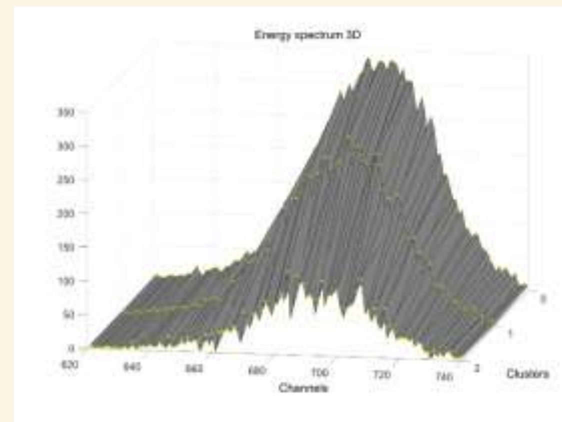
2-clusters decomposition

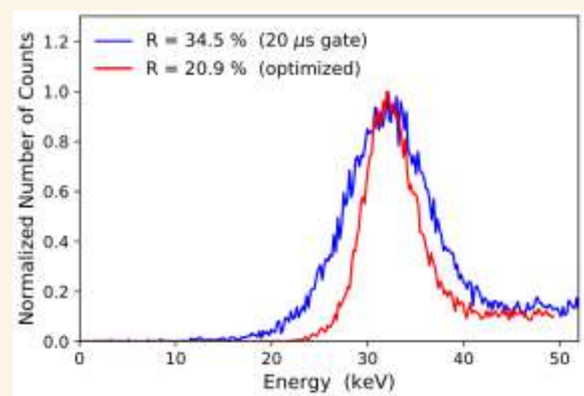
The part of energy spectrum (complete absorption peak)

dominated clusters

non-dominated clusters





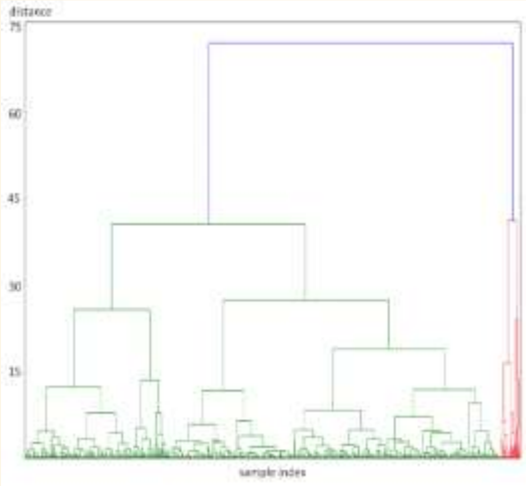


A.Sobolev, LUMDETR 2018

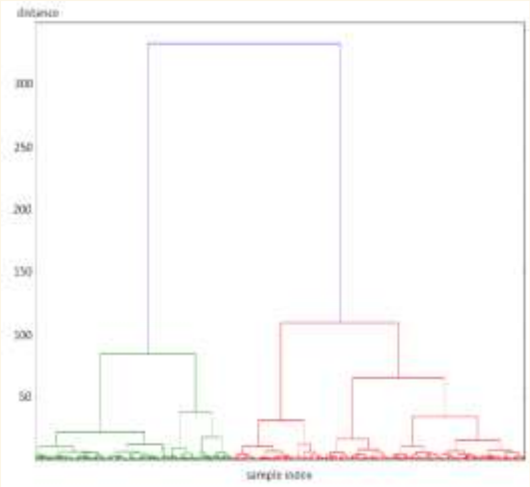
Dendrograms for different crystals

The CsI (Tl) crystal with R=13,9% has large distance between a clusters and it has less number of pulses in dominant clusters

R=6,7%



R=13,9%



CsI:Tl, 25x25

^{137}Cs

Methodology:

- Choose norm (Euclidean, correlation, cosine, minkowski, hamming)
- Calculates distance matrix
- Choose a deep of clustering
- Calculates cluster diameters
- Hierarchical Clustering
- Determine a dominated clusters

New trends

that has not be omitted both in study and development

Important factors for industrial application

General factors:

- Can larger crystals be grown at usable size?

- What is the cost ?

- Is the (superior) performance justified by the price ?

Specific factors:

(Unique property… for example)

High speed / density	-	LYSO (PET)
Very short decaytime	-	PWO(CMS)
Very good resolution	-	LaBr3:Ce, SrI2:Eu

Price idea :

NaI(Tl) detector	76 x 76 mm	:	2 k€	5 $ / cc
BGO detector	76 x 76 mm	:	5-6 k€	20 $ / cc
LaBr3/CeBr3	76 x 76 mm	:	35 k€	100 $ / cc

P.Schotanus

New trends that has not be omitted both in study and development

* Fast emission - Auffray E., Vasil'ev A

* 3D printing - Sokolov P., Lobko A

* Meta structures (composites) - Onufriev Yu

* n-gamma and so on separations – Zhmurin P

* Fibers, thin films - Ruziecka K

* SiPMT - Mazzi A

* Ceramics - Karpuh P

New trends that has not be omitted both in study and development

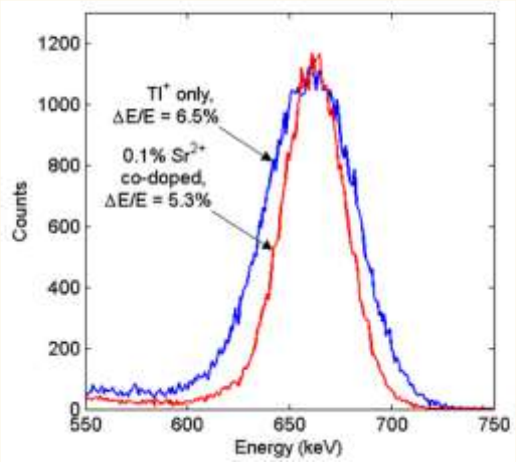
Most “popular” efficient new scintillators

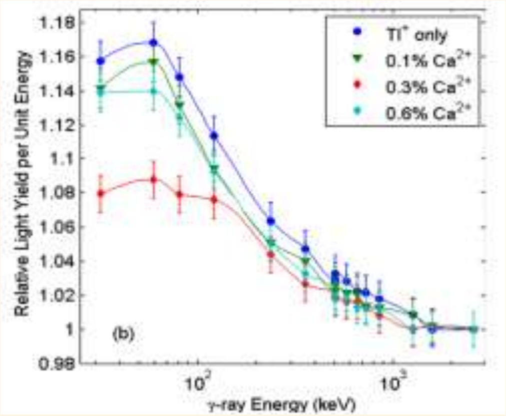
Crystal	ρ g/cm³	Lum λ, nm	LY ph/Mev	R, % Cs^{137}	Decay τ, ns	Hygro-scopy	References
CaI_2 :Eu	3.96	467	110.000	5,2	1.000	strong	Cherepy, Moses, Derenzo, Bizarri, Bourret et al. 2007 - 2012
SrI_2 :Eu	4.55	435	115.000	2.6	1.500	strong	
Ba_2CsI_5 :Eu	4.9	435	102.000	2.55	383;1.500	medium	
$SrCsI_3$:Eu	4,25	458	73.000	3.9	2.200	medium	Zhuravleva et al. 2012
BaBrI :Eu	5.2	413	97.000	3,4	500	low	Bizarri et al. 2011
NaI : Tl	3.67	415	44.000	5.6	230	strong	
CsI : Tl	4.53	560	56,000	6.0	980	no	
CsI : Na		420	46,000	6.4	600	low	

New trends that has not be omitted both in study and development

Co-doping as the method of scintillator improvement

Me^{2+} (Ca in particular) for resolution improvement?





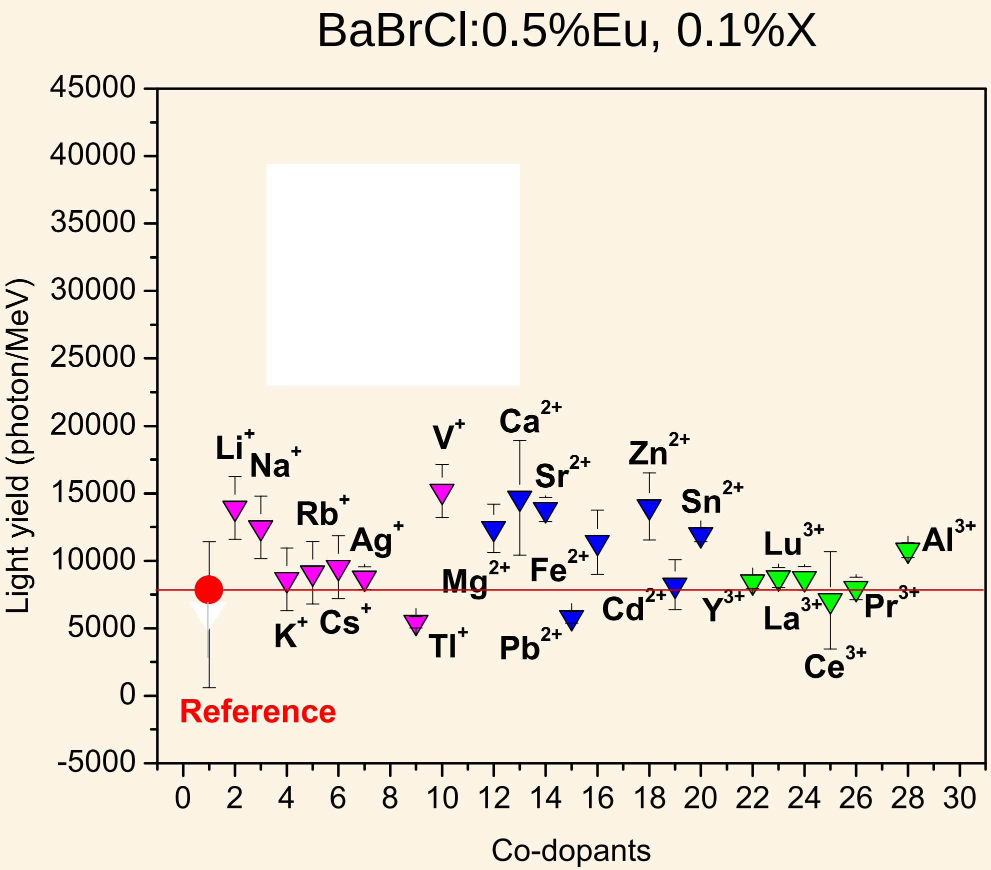
[Yang et al.]

NaI:Tl production	R, %	Co-activators
Saint-Gobain	5.3	Eu, Sr, Ca
ISMA	5.2	Eu, Ca
LBNL	4.9	Eu, Ca
Standard	6.1	-

Resume:

- **Some performance improvement is visible**
- **The trend exists for some other Me^{2+} co-doped combinations**

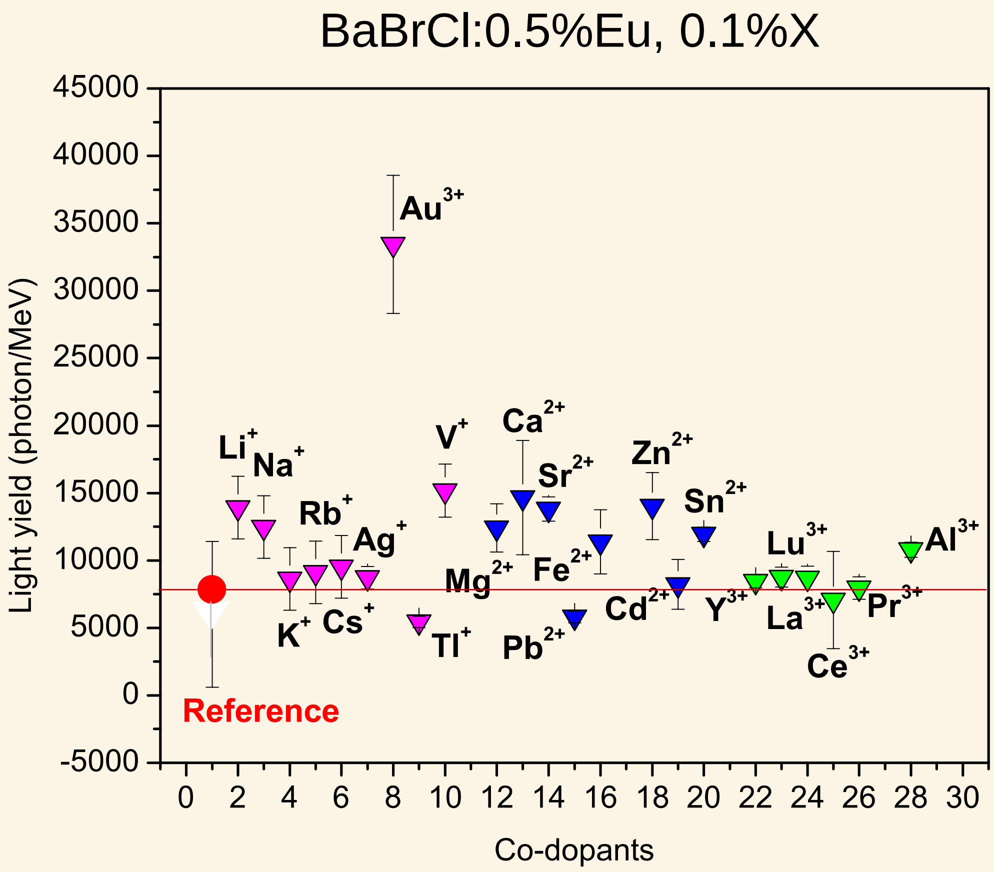
A Case Study: Co-doping of BaBrCl:Eu



- Over 27 different co-dopants have been tested
- Samples obtained through non directional solidification

E.Bourret, LUMDETR 2018

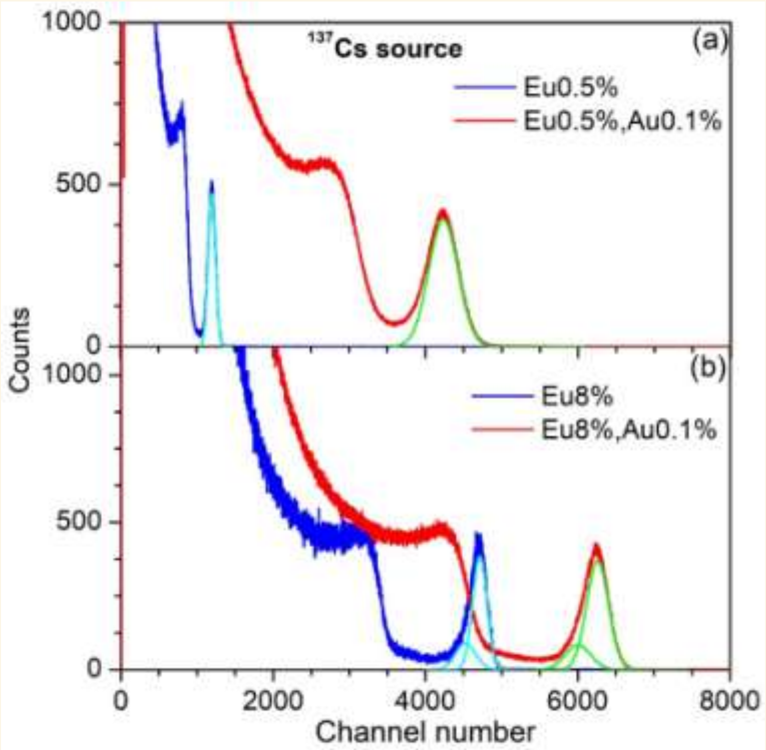
A Case Study: Co-doping of BaBrCl:Eu



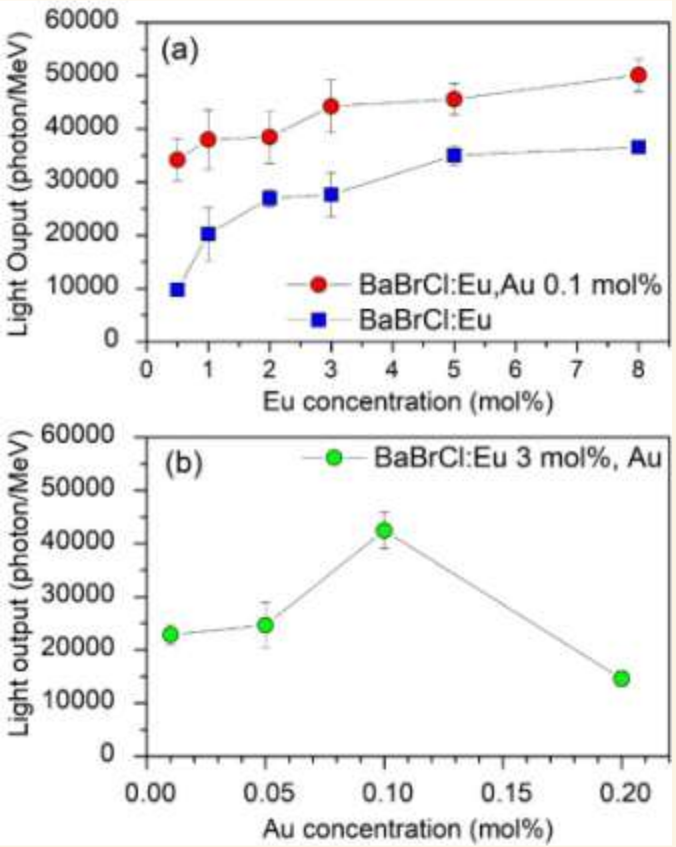
- Over 27 different co-dopants have been tested
- Samples obtained through non directional solidification
- Au co-doping stands out among all the others.

E.Bourret, LUMDETR 2018

Pulse Height Spectra and Light Yield



Representative pulse height spectra of BaBrCl:Eu with and without Au codoping for two different Eu contents



Light yield as a function of Eu and Au concentration

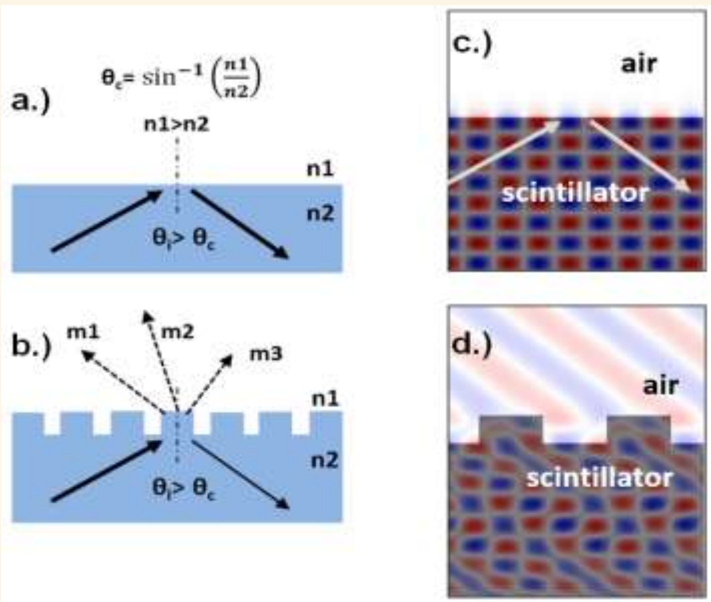
Systematic increase in light output over the entire Eu concentration range
Optimum Au concentration is 0.1 mole%

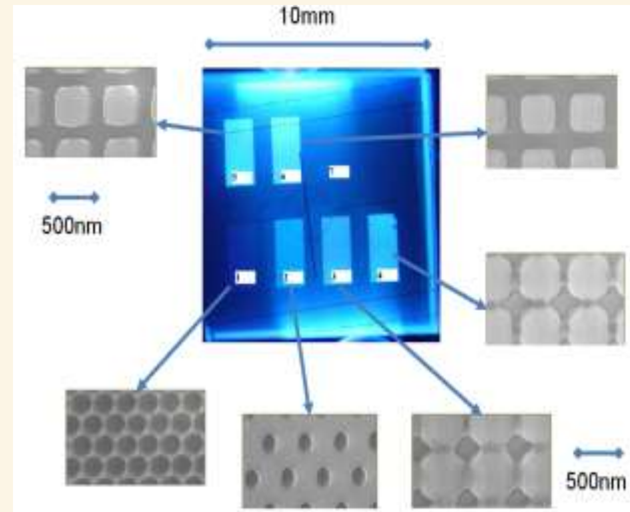
E.Bourret, LUMDETR 2018

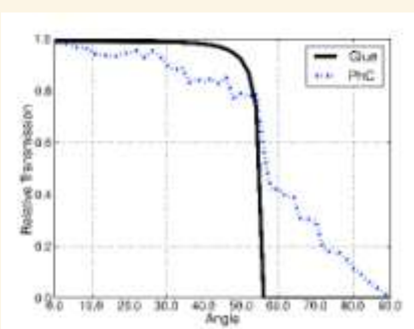
New trends that has not be omitted both in study and development

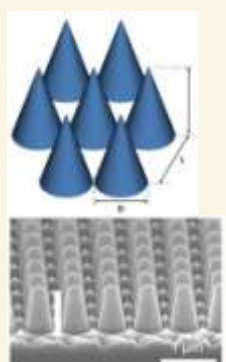
A.Knapitsch, E.Auffray et all

Photonic crystals on scintillators









Surface tuning from nano to macro scale allows to modify light output distribuiton and yield

New trends that has not be omitted both in study and development

Photoreceivers. PMT alternatives

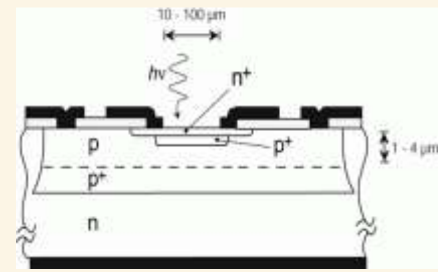
- PMTs
- (PIN) Diodes
- Avalanche Photodiodes (APDs)
- (Drift Diodes)
- (EM) CCDs
- Si-PMs (MPPCs)

PMTs

- Made of glass (fragile + K-40 background)
- Large signals, good S/N ratio, fast (ns)
- Large dimension, low price per cm^2
- Sensitive to B fields
- Existing old technology (vacuum tubes)

PIN diodes

No amplification (small signals)
- Maximum cm size
- Stable (temperature)

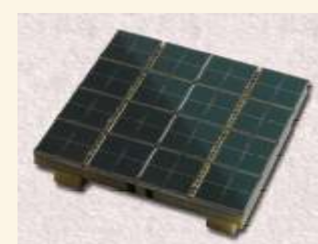


CCDs :
- DC measurement mostly
- Imaging
- For higher radiation fields

APDs
- Amplification 100-1000
- rather Unstable (temp)
- rel expensive, small
  (max 10x10mm)

Drift diodes (for light detection)
- small (not often used)
- still rel. expensive

Silicon Photomultipliers (SiPMs, MPPCs)



New trends that has not be omitted both in study and development

Fast decay importance…

- A fast signal allows high rates (not of interest) and good timing resolution – This is of interest…

- Timing resolution allows coincidence measurements to be made

- With knowledge of the decay scheme, coincidence measurements can be used to identify specific radionuclides and reject background events

- Requirements of decay scheme:

- Eγ > ~100 keV, short lifetime of intermediate state and high probability of γ-emission (low internal conversion coefficient)

Outlines

1. The market needs are the main driving force for scintillator development

2. Different application claim for specific development. Some materials and engineering could be very specific or even unique.

3. There are too many materials were invented last yeas and industry need in only few ones. These materials have to satisfy optimal cost/performance/volume rate

4. Main efforts in material study/development (like co-doping, resolution improvement, electronics upgrade and so on) are directed either to
   * advanced detector development or
   * cost efficient technology development

5. New trends in scintillation development (Fast detectors, 3D printing, Meta materials , n-gamma discrimination, SiPMT, cheap ceramics) will dominate in new detector

6. Conventional scintillator market is waited for improved non-proportionality and energy resolution.

Thank you for attention!

GAGG scintillator as the leader through oxides

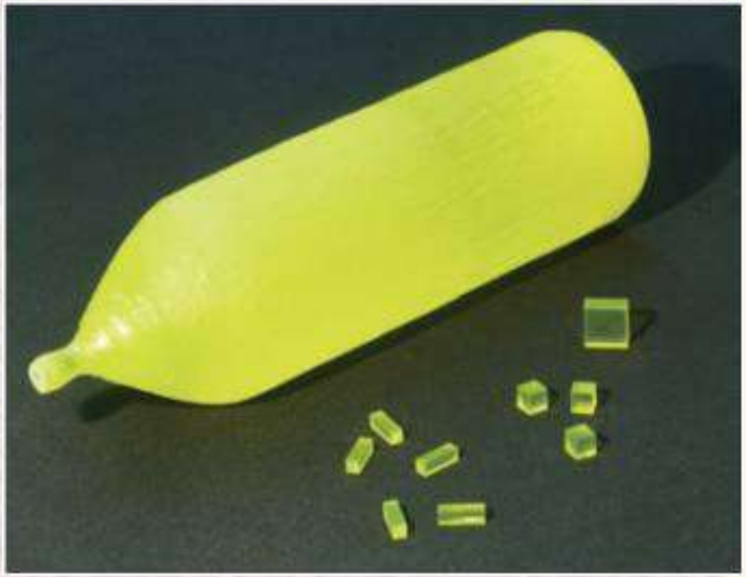
GAGG ($Gd_3Al_2Ga_2O_{12}$) Ce

- 6.6 g/cc
- 520 nm max emission
- 56000 photons / MeV

Proportional, not hygroscopic

FIRST non hygroscopic High LO crystal

High melting point (1850 °C) → cost



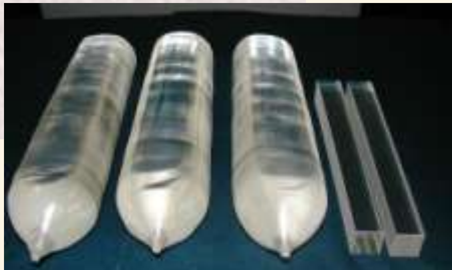
Not used frequently yet

SiPm readout ? Special applications ?

No new generation scintillator will be the "ideal" material = illusion

Often bottom line is COST = growing yield

(material cost is seldom the real issue)

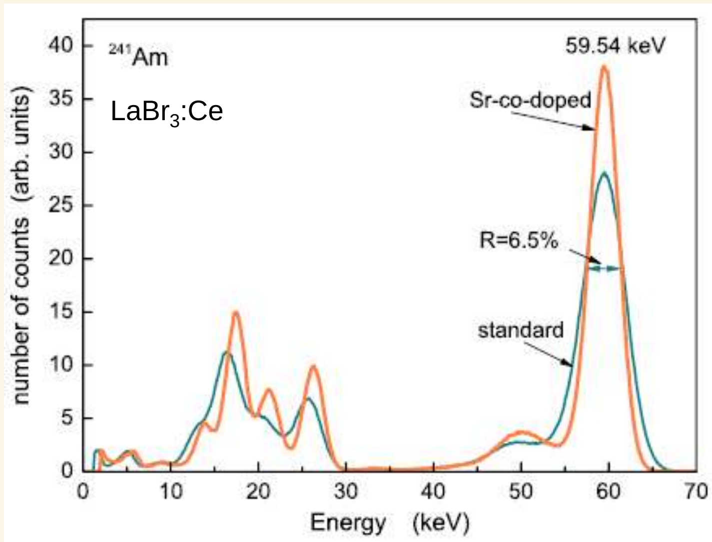


New trends that has not be omitted both in study and development

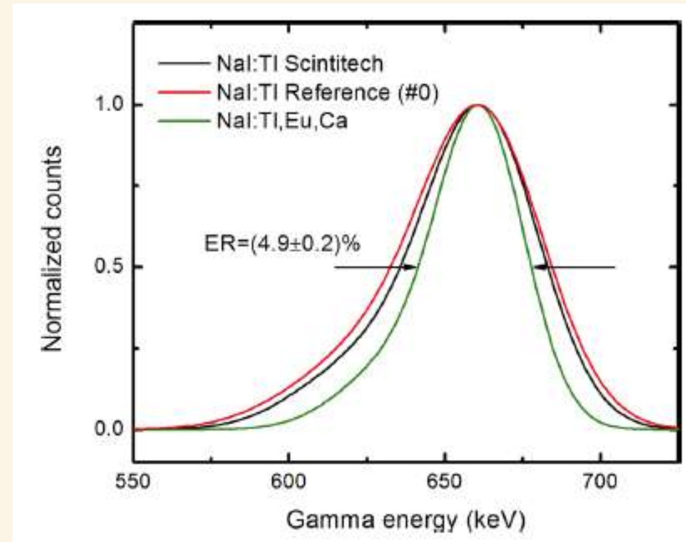
Co-doping in Scintillators

Aliovalent codoping: impact on light yield and energy resolution

Alekhin et al. APL 102 (2013)161915



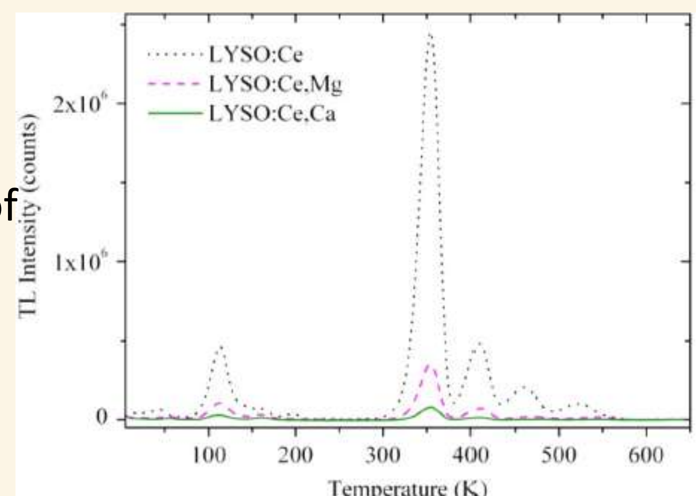
Khodyuk et al. JAP118 (2015) 084901



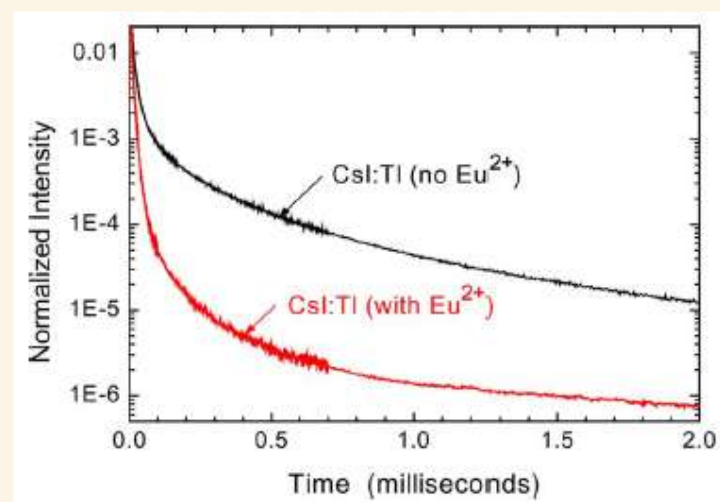
Left: Reduction/ compensation of defects

Right: Reduction of afterglow

Blahuta et al. IEEE TNS 60 (2013) 3134



Nagarkar et al. IEEE TNS 54 (2007) 1378



Resume

Photons generated at different terms of scintillation give different contribution to the energy resolution.

Pulses clustering does refines its statistical description.

Using of clustering and NN-models is perspective for development of new base of knowledge about functional materials.

Digital signal processing can improve the energy resolution.