Scintillators - Applications

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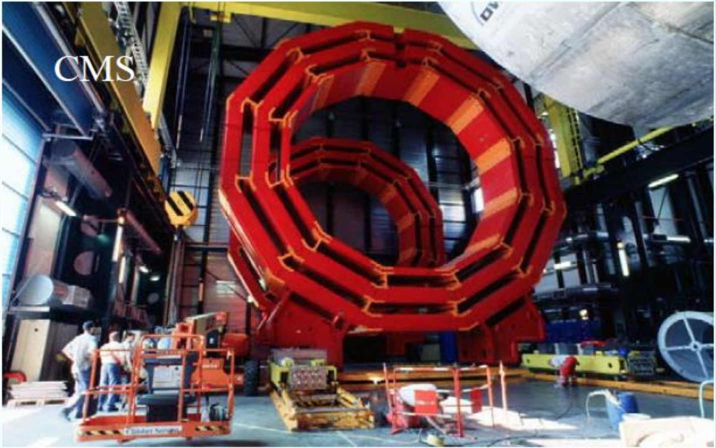
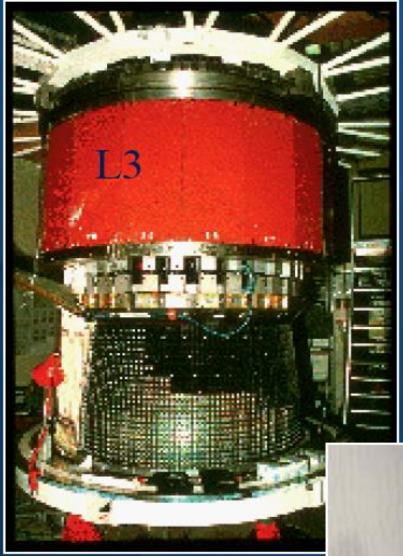
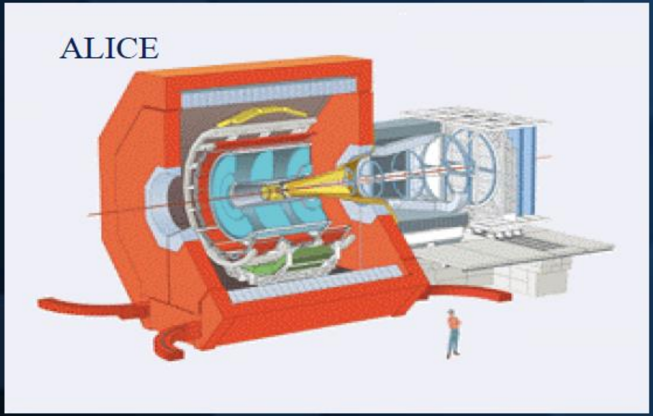
Outlook

- Lecture 1: Scintillator fundamentals
  - Organic scintillators
  - Inorganic scintillators
    - Scintillation mechanisms
    - Limits to the light yield and decay time
    - Energy resolution and non-proportionality
- Lecture 2: Scintillator applications
  - Crystal growth techniques
  - High energy physics and dark matter searches
  - Space borne missions
  - Medical applications
  - Geophysical exploration
  - Homeland security

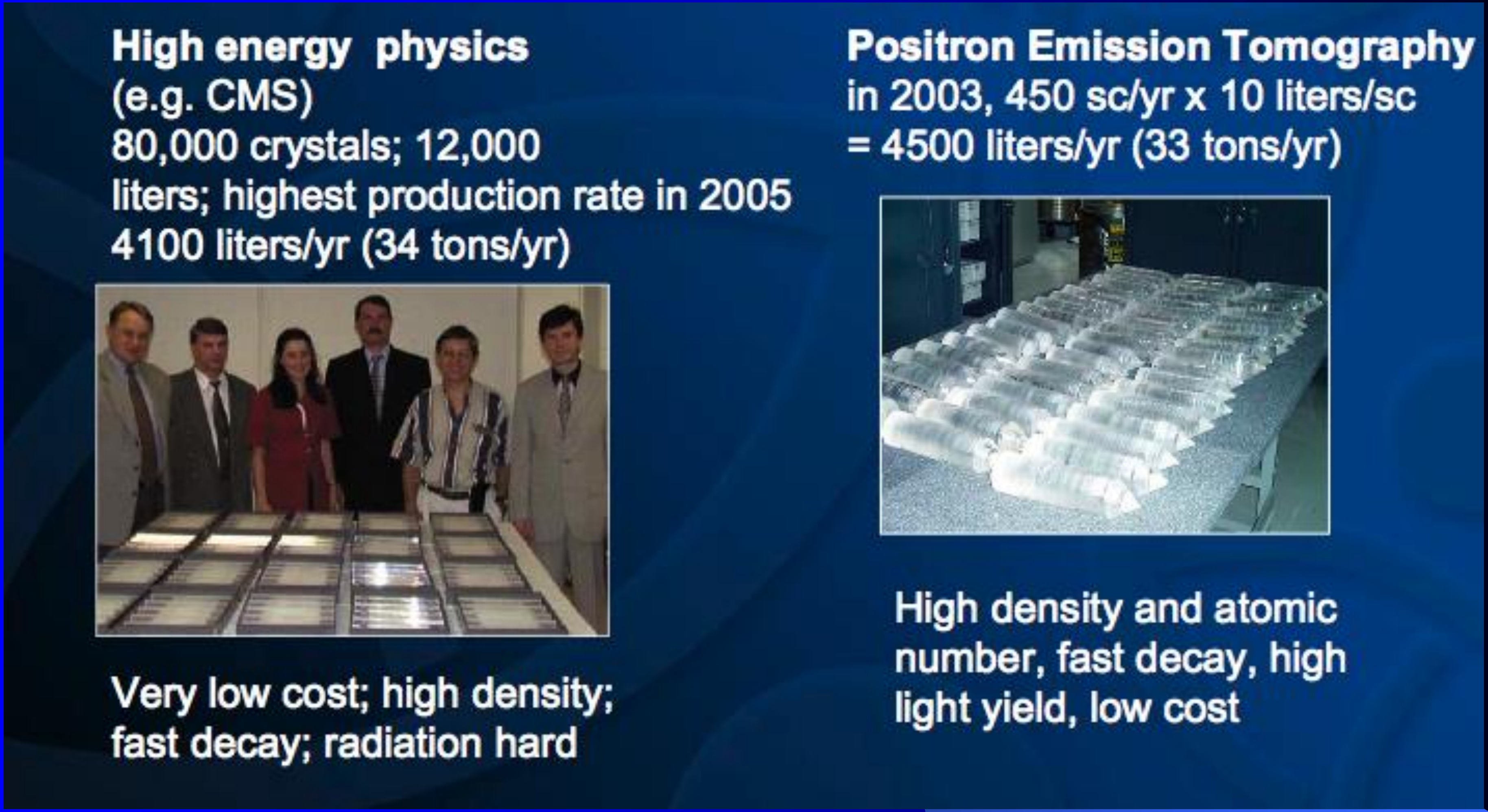
What drives sthe devlopment of new scintillators







HEP and PET use the largest volume of scintillators



High energy physics
(e.g. CMS)
80,000 crystals; 12,000 liters; highest production rate in 2005
4100 liters/yr (34 tons/yr)

Very low cost; high density; fast decay; radiation hard

Positron Emission Tomography
in 2003, 450 sc/yr x 10 liters/sc
= 4500 liters/yr (33 tons/yr)

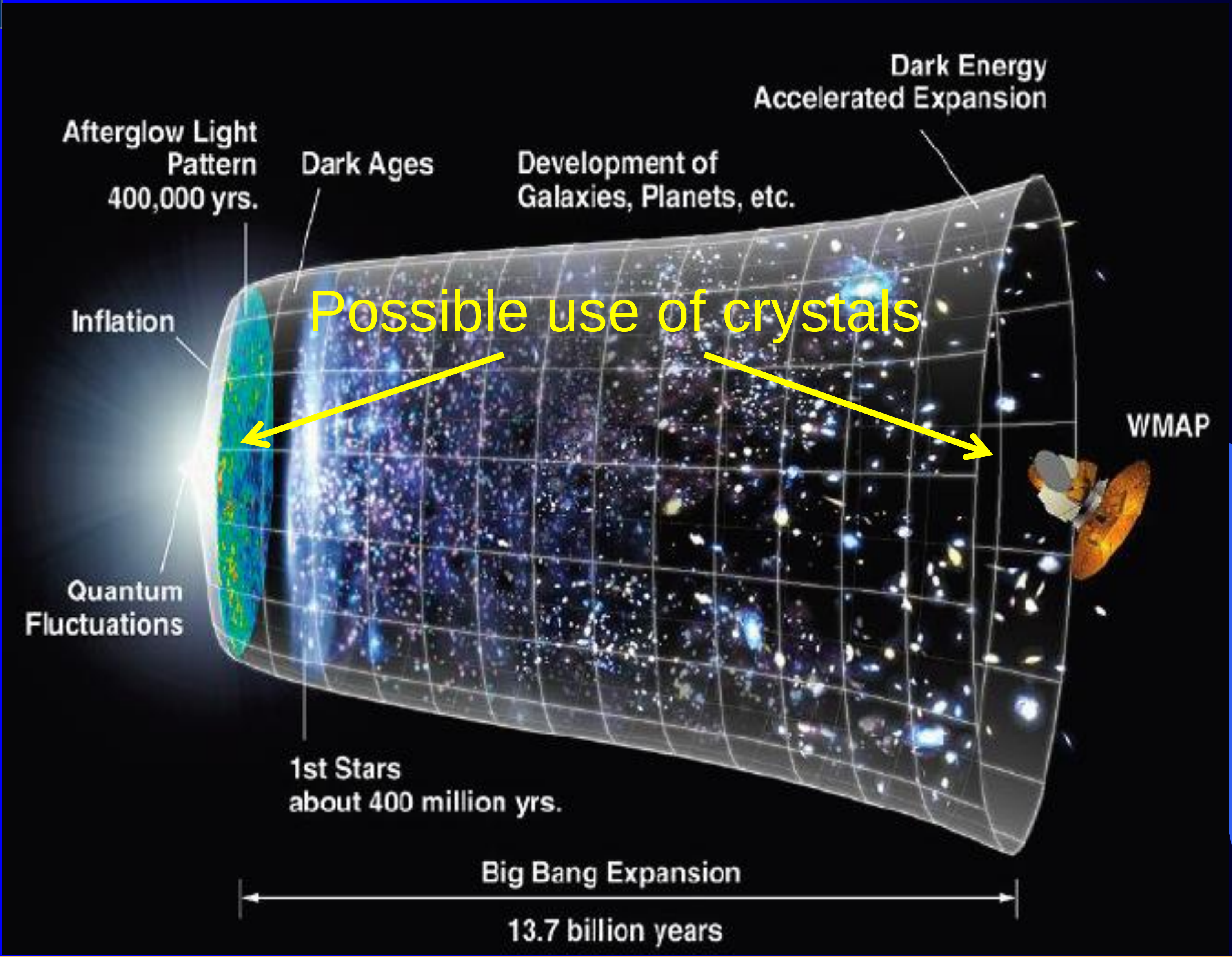
High density and atomic number, fast decay, high light yield, low cost

Various appelications of scintillators

Detection and spectroscopy of energetic photons (and neutrons) in:

- High energy particle physics
- Nuclear physics
- Positron emission tomography
- X-ray computed tomography
- Security monitoring
- Treaty verification
- Geophysical exploration
- Non-destructive testing
- Radiation monitoring

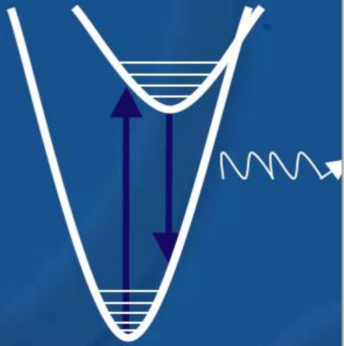
Back to Creation



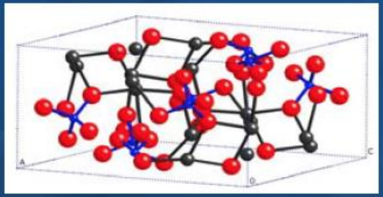
Possible use of crystals

Limits of scintillator properties

Scintillation eff.[1]: $\eta = \beta SQ$
where b is the number of e-h pairs
S is the transfer efficiency to luminescent centers
Q is the quantum efficiency of the luminescent centers

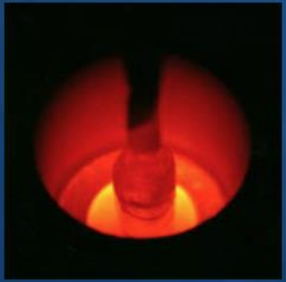


Radiative lifetime[2]: (for electric dipole emission) $\tau_r = 1.5 \times 10^{-5} \times \lambda^2/((f/9)(n^2 + 2)^2 \times n)$
where l is the emission wavelength
f is the oscillator strength
n is the refractive index



Density: limited by elemental composition and crystal structure, not many candidates > 10 g/cm^3

Atomic number: limited only by the periodic table



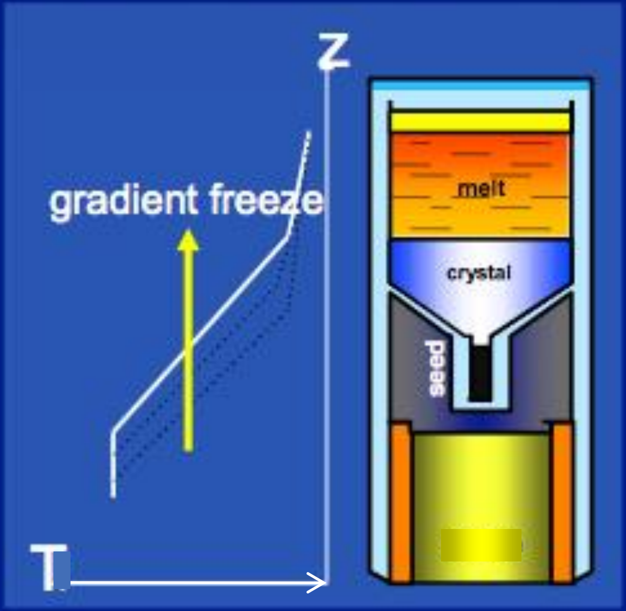
Cost: raw material abundance
purification cost
crystal growth or other manufacturing process

[1] *Lempicki, Nucl. Instr. Meth.*

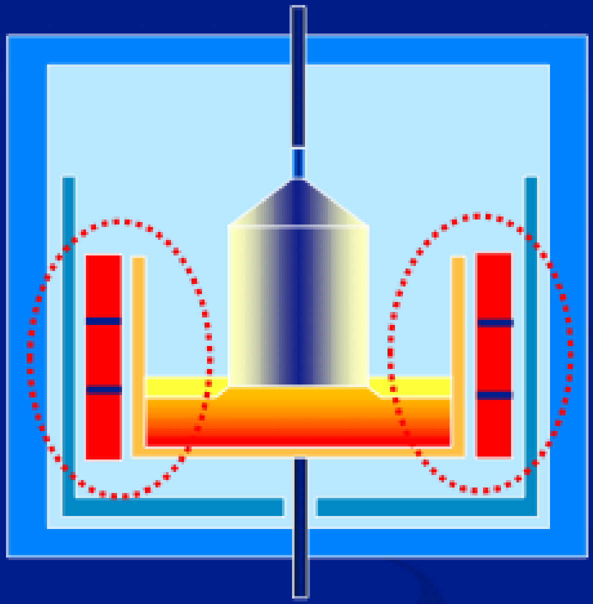
[2] *Henderson and Imbush, Optical Spectroscopy of Inorganic Solids (1989)*

Most frequently used crystal growth technologies

Bridgman–techniques



Czochralski–techniques

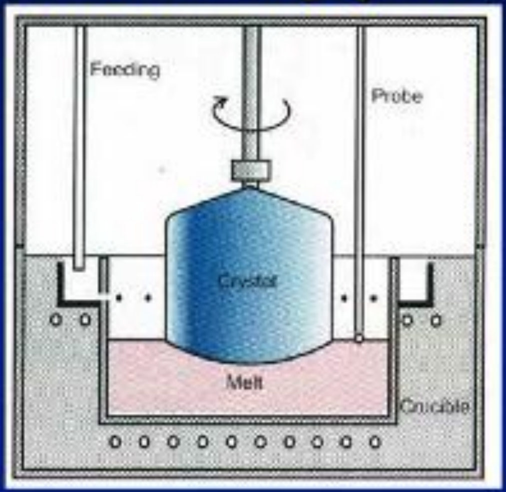


From principles to practice

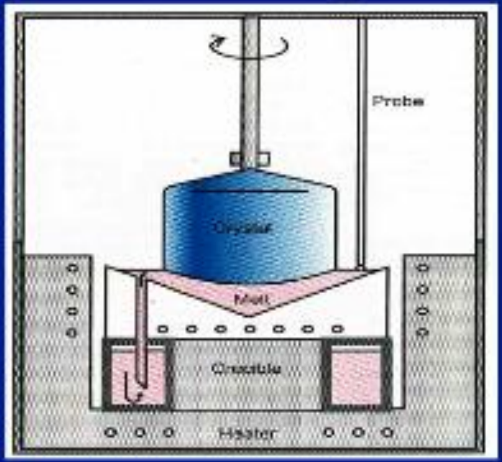
Industrial NaI(Tl) growth area

Continuous crystal growth

Powder feeding system



Melt feeding



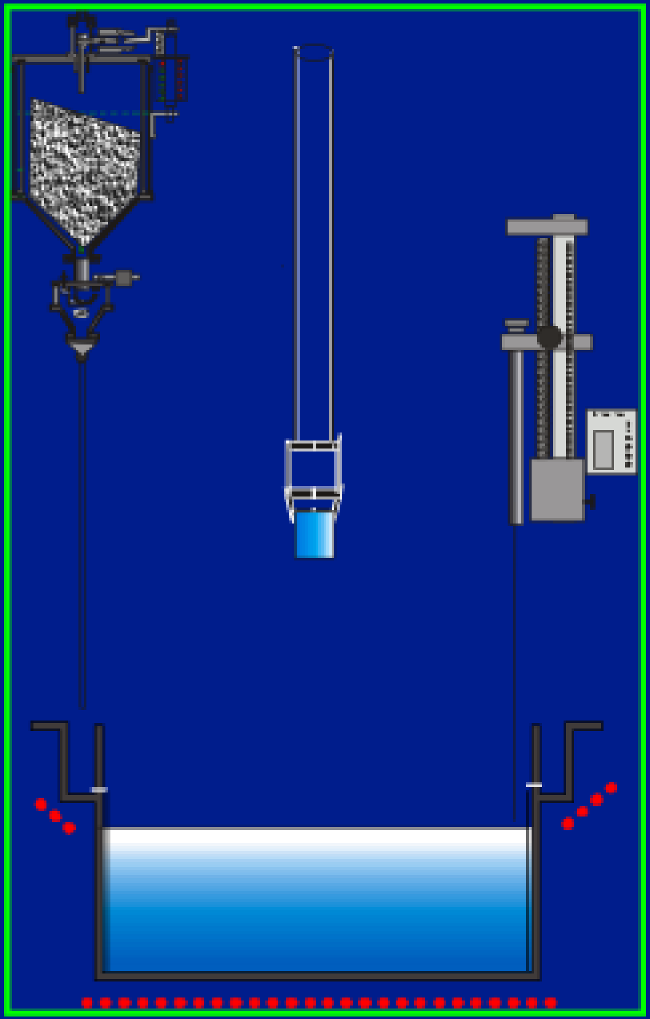
Advantages:

1. Continuos growth process (large size of crystal)
2. Fixed "crystal-melt" interface
3. Feeding by raw material and activator
4. Good melt convection
5. Simple melt level control
6. Crystal and crucible rotation

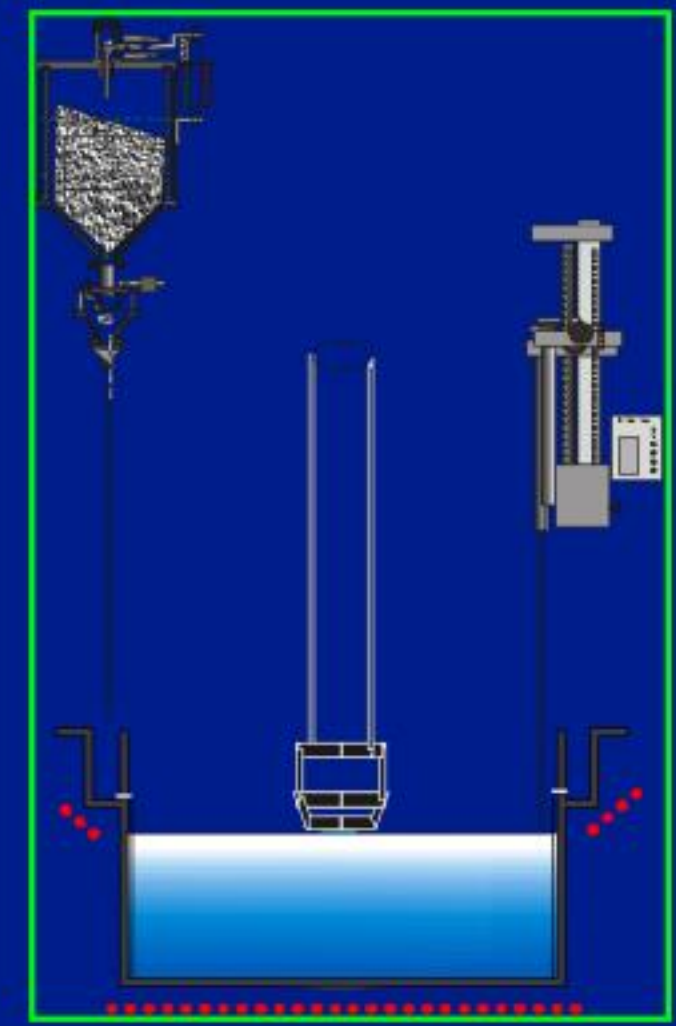
Disadvantages:

1. Large melt volume
2. Large melt surface (activator evaporation)
3. Purification – ?
4. Powder feeding

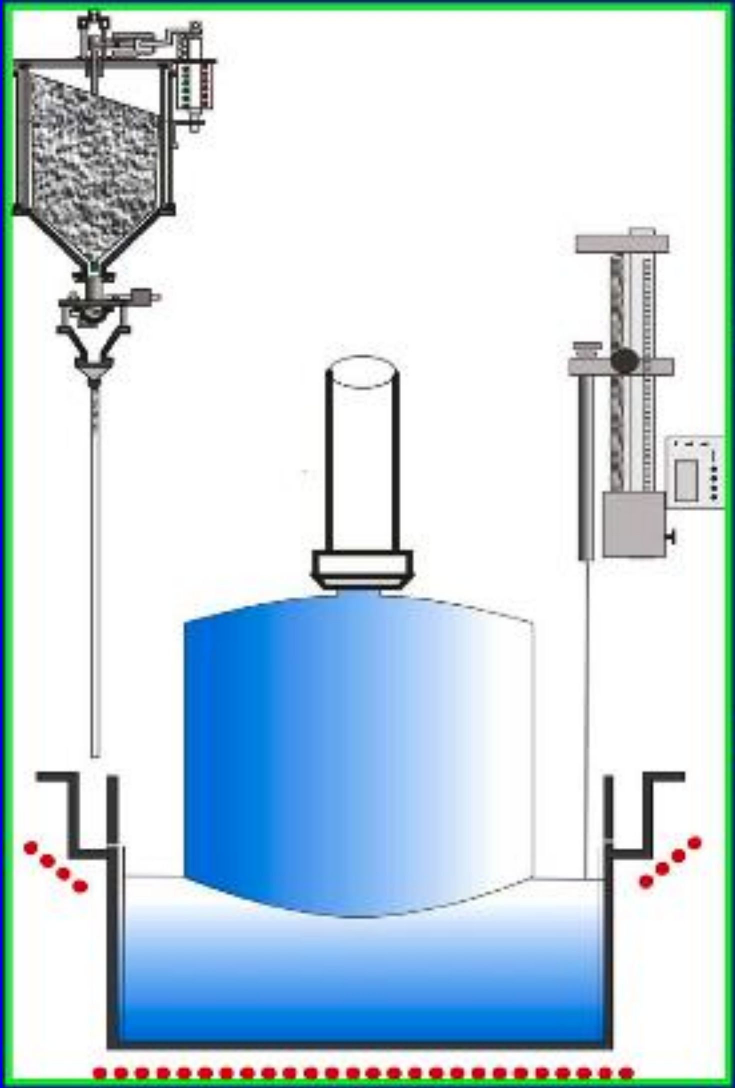
Continuous crystal growth

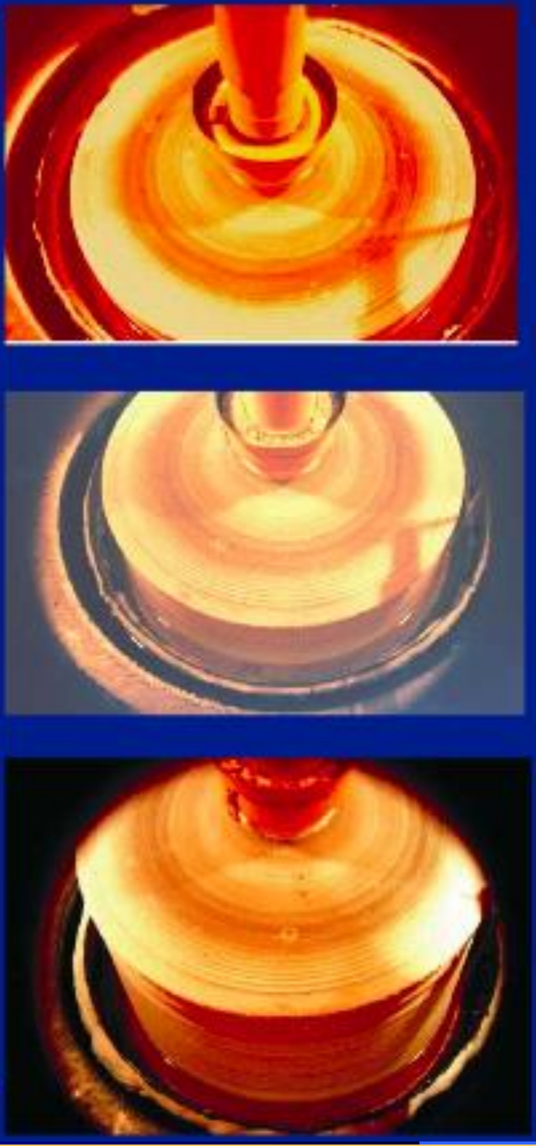


Continuous crystal growth



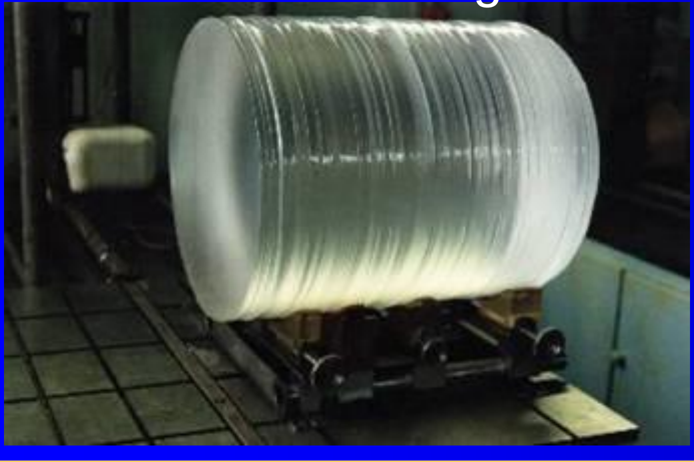
Continuous crystal growth





Preparation of large size plates for SPECT cameras

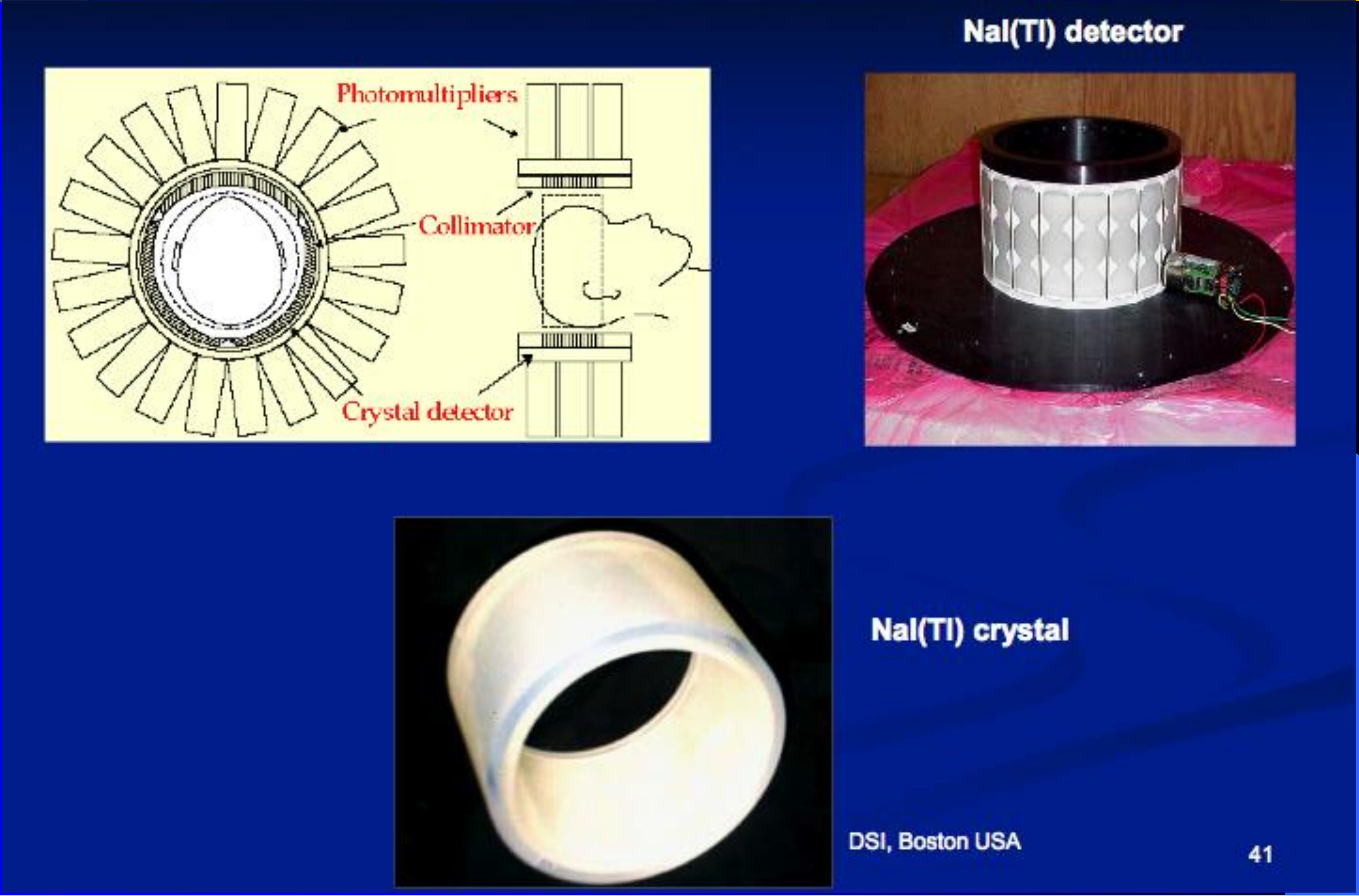
NaI:Tl single crystal
∅520 mm,
mass > 550 kg



- After growth the NaI:Tl crystal is cut and pressed at high temperature to prepare large area plates for SPECT cameras

Institute of Single Crystals
Kharkhov, Ukraine

NaI cylindrical detectors



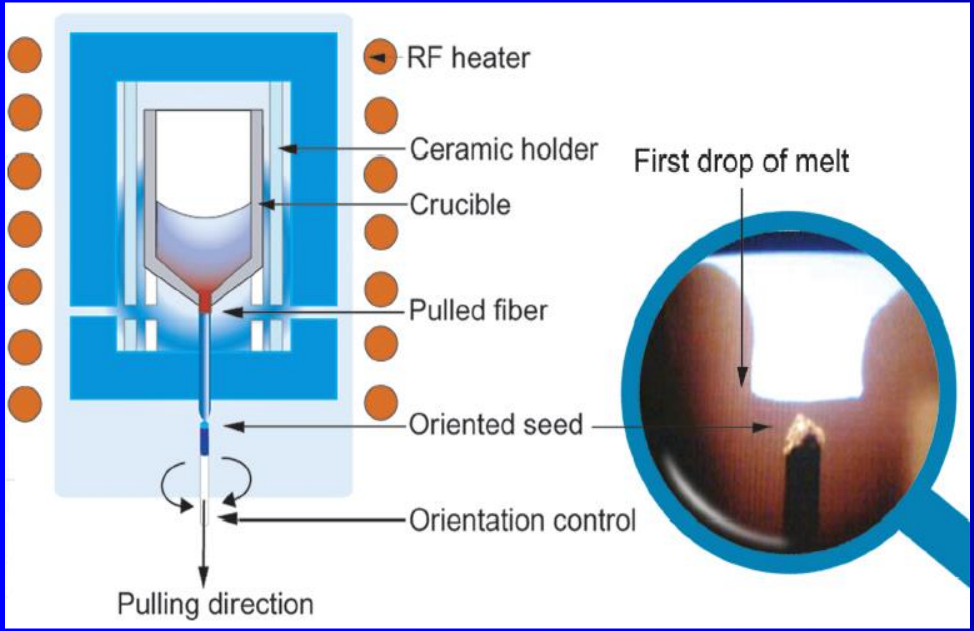
NaI(Tl) detector

NaI(Tl) crystal

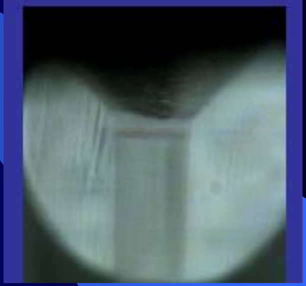
DSI, Boston USA

41

Micro-pulling-down crystal fiber growth



Crucible and fiber



BGO

Φ=400μ

YAG:Ce

Φ=1mm

LYSO:C

Φ=2mm

YAP:Ce

Φ=2mm

Courtesy Fibercryst, Lyon

Ceramics

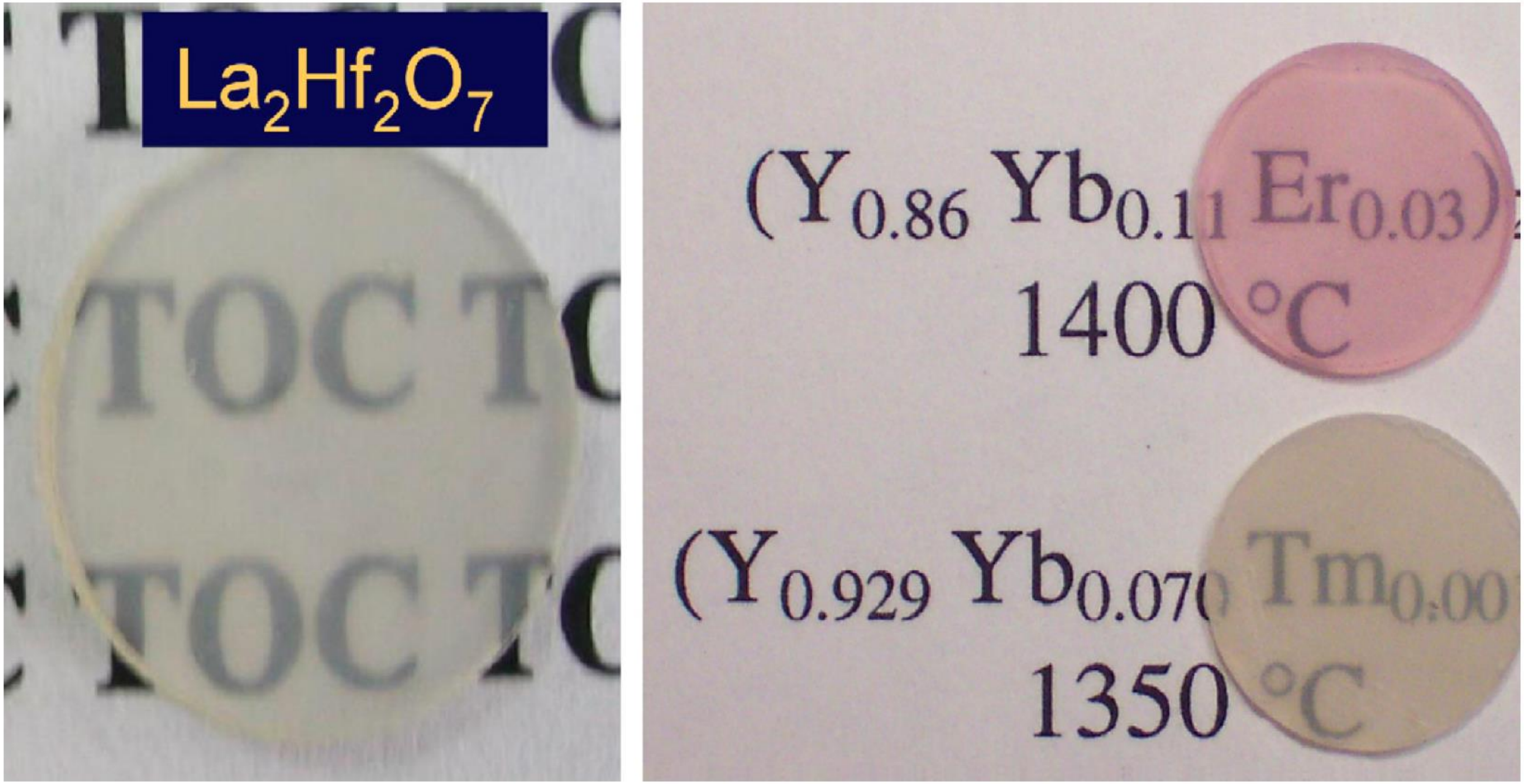
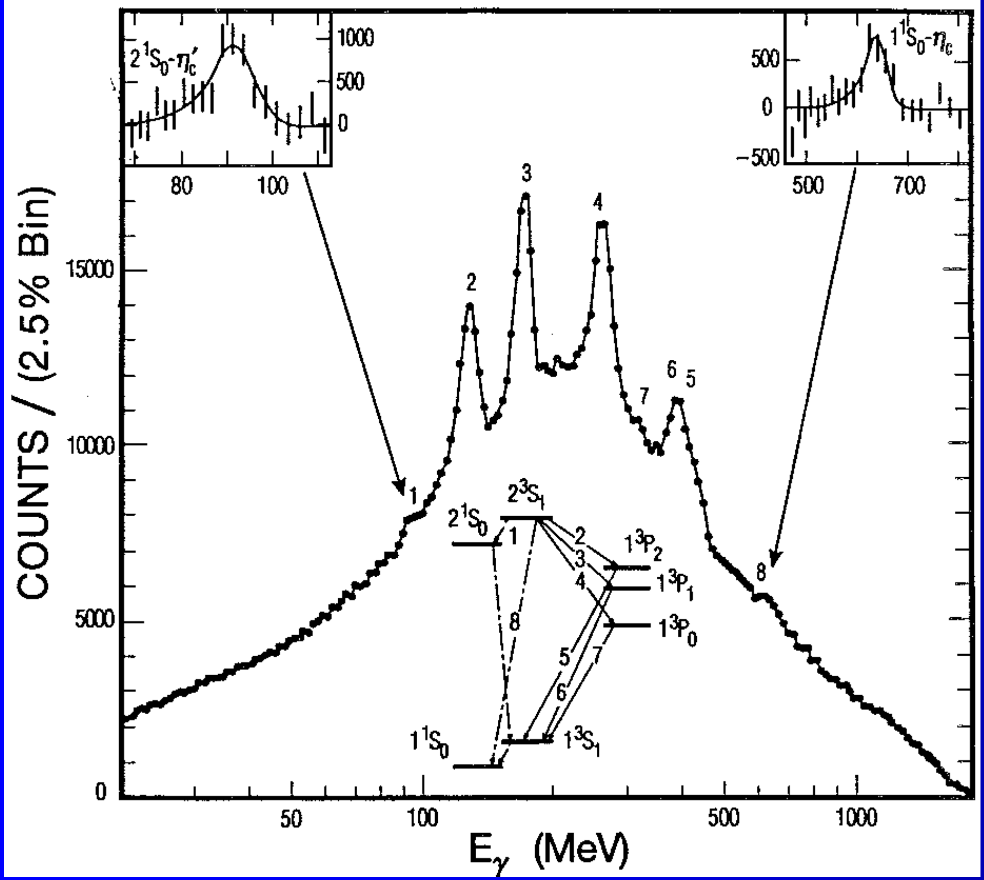


Fig. 17: Transparent ceramics of different heavy scintillators prepared with pre-reacted nanopowders

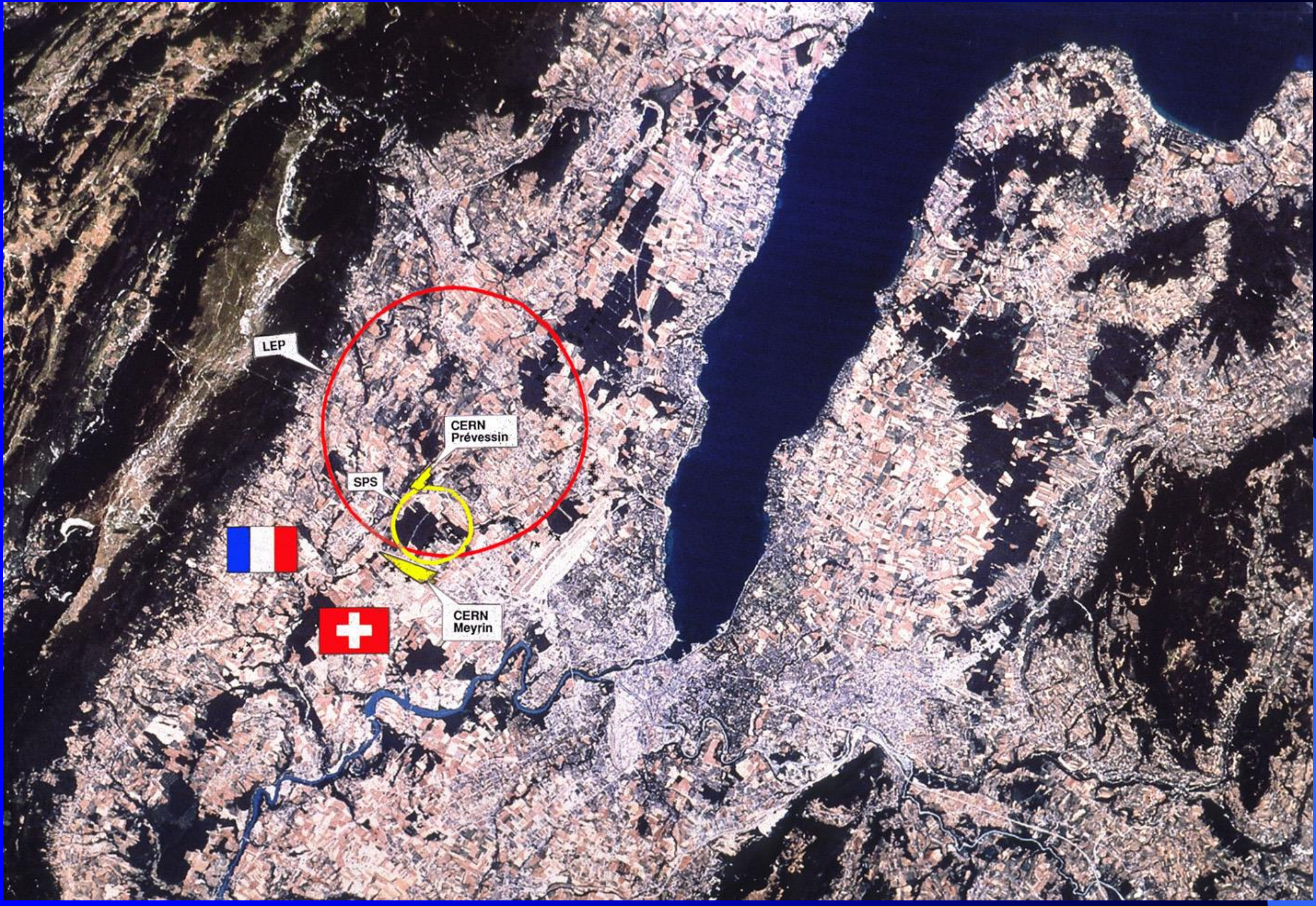
Crystal Calorimetry: a Powerful Tool for Particles Spectroscopy

Charmonium spectroscopy – Crystal Ball - SLAC

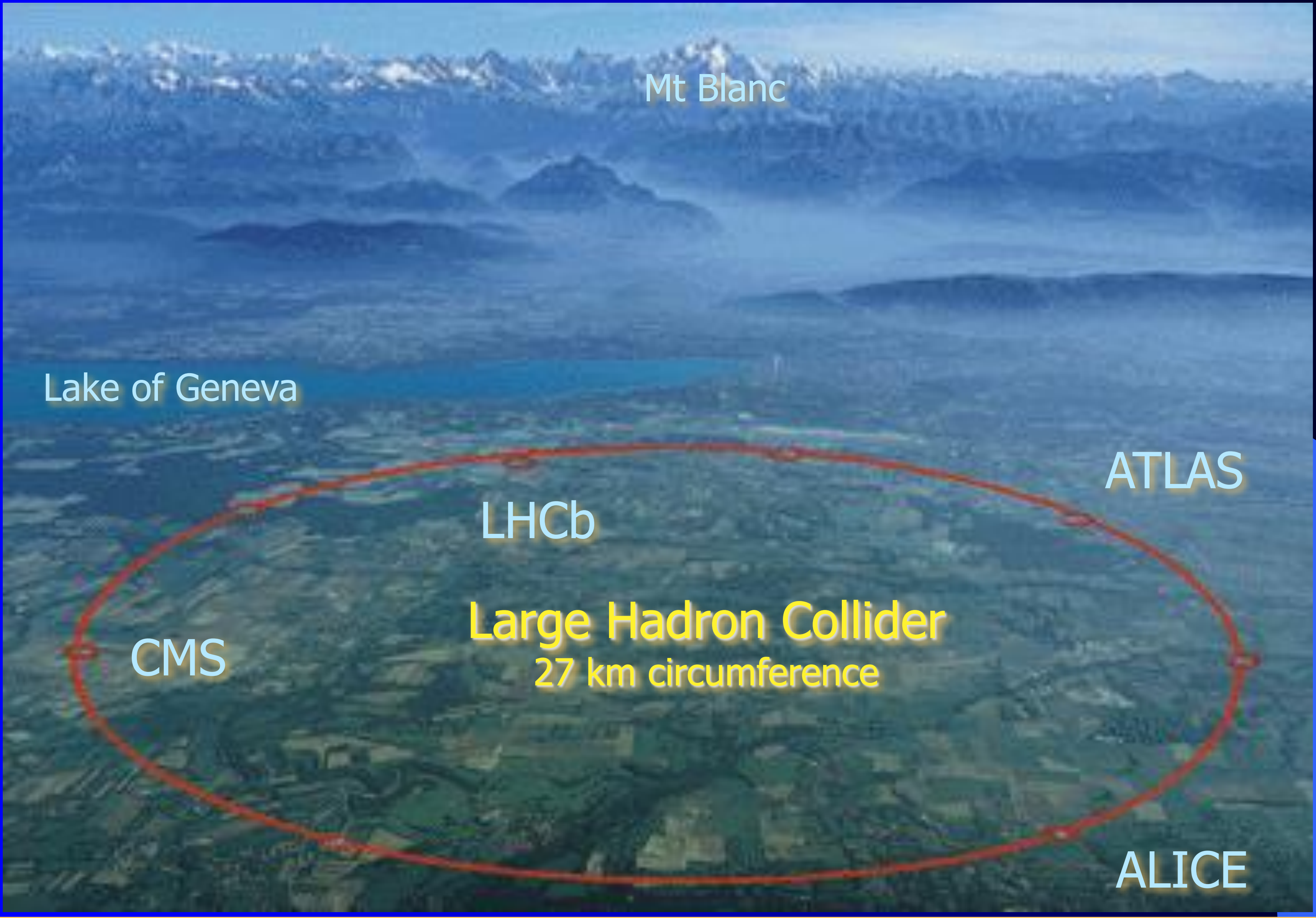


- 50cm diameter spherical ball of NaI(Tl) crystals
- 672 crystals 42cm long, PMT readout
- Very good resolution allowed precise spectroscopic study of charmonium states

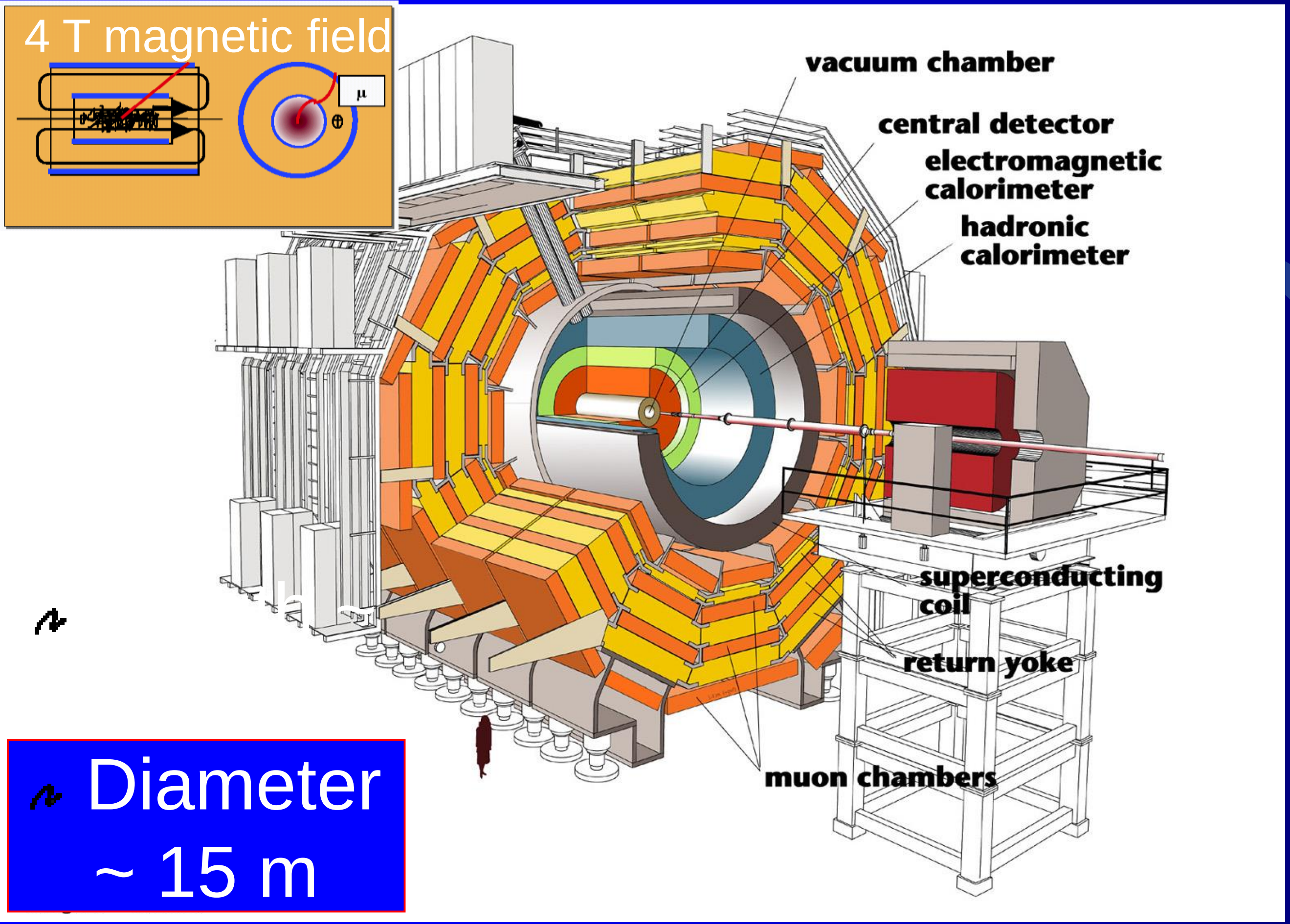
CERN in Geneva area



The Large Hadron Collider LHC

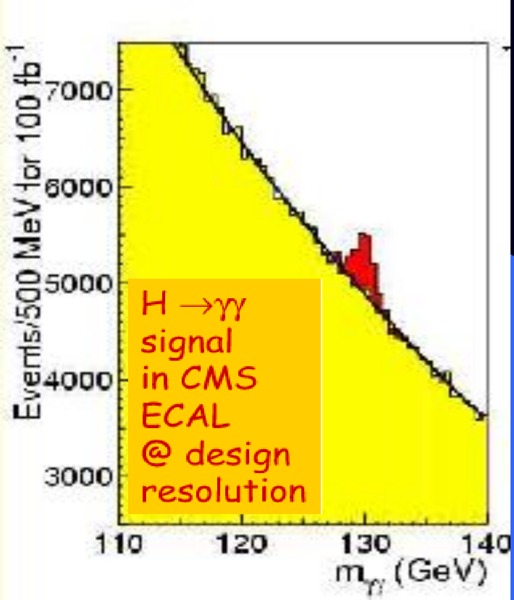


Compact Muon Solenoid



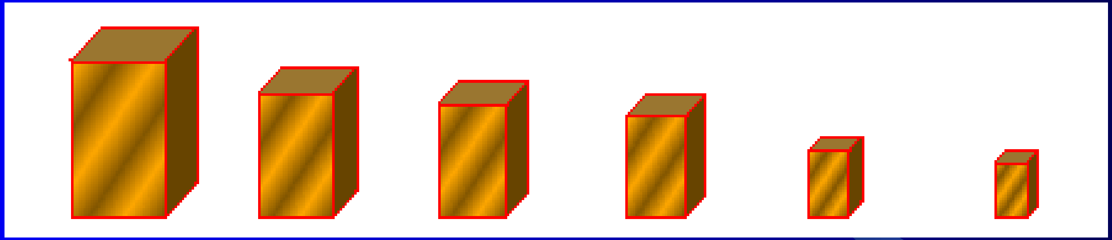
- Diameter ~ 15 m
- Weight ~ 14500 t

Main CMS goal: search for Higgs and new physics



For a light Higgs (as suggested by present data)
H→γγ best channel. Narrow width, irreducible background:
ECAL resolution crucial !

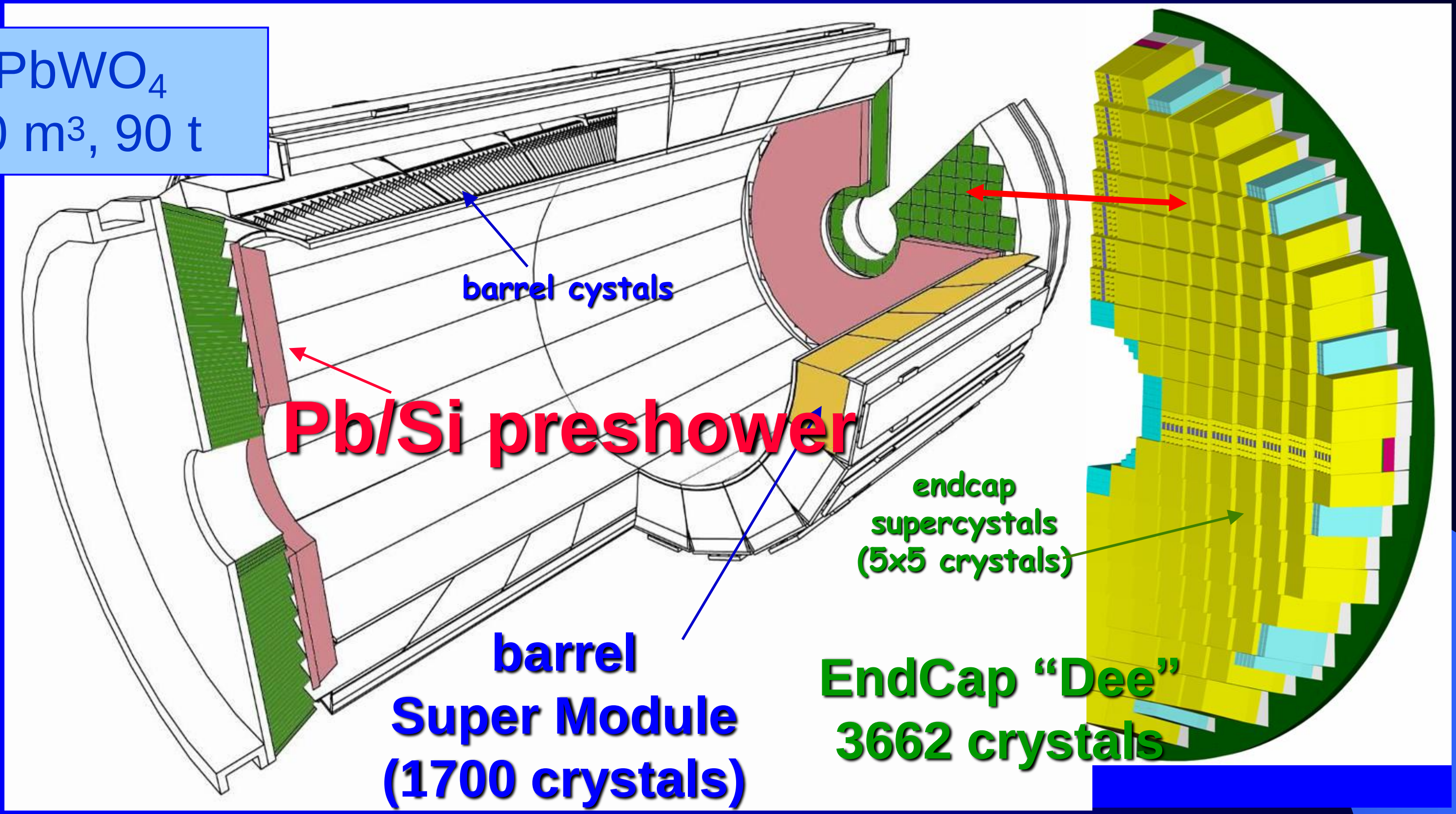
Some popular crystals in HEP



	NaI(Tl)	BaF_2	CsI(Tl)	CeF_3	BGO $Bi_4Ge_3O_{12}$	PWO $PbWO_4$
Xo [cm]	2.59 ☹	2.03 ☹	1.86 😐	1.66 😐	1.12 🙂	0.92 🙂
ρ [g/cm^3]	3.67 ☹	4.89 ☹	4.53 ☹	6.16 🙂	7.13 🙂	8.2 🙂
τ [ns]	230 ☹	0.6 🙂 620 ☹	1050 ☹	30 🙂	340 😐	15 🙂
λ [nm]	415 🙂	230 🙂 310 😐	550 🙂	310 😐 340 😐	480 🙂	420 😐
$n@\lambda_{max}$	1.85 😐	1.56 🙂	1.80 😐	1.68 🙂	2.15 ☹	2.3 ☹
LY [%NaI]	100 🙂	5 ☹ 16 ☹	85 🙂	5 😐	10 🙂	0.5 ☹

ECAL layout

PWO: $PbWO_4$
about 10 m^3, 90 t



barrel cystals

Pb/Si preshower

endcap supercystals (5x5 crystals)

barrel
Super Module
(1700 crystals)

EndCap “Dee”
3662 crystals

Barrel: $|\eta| < 1.48$
36 Super Modules
61200 crystals ($2 \times 2 \times 23 cm^3$)

EndCaps: $1.48 < |\eta| < 3.0$
4 Dees
14648 crystals ($3 \times 3 \times 22 cm^3$)

Production facilities in Bogoroditsk

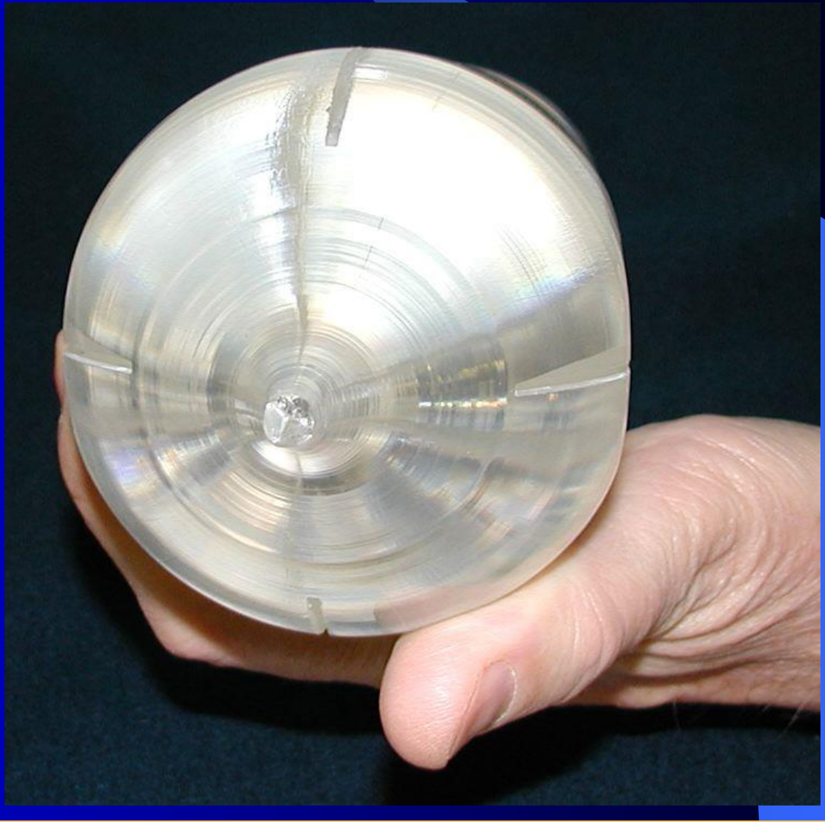
159 Lazurit 3M growth ovens

12 low gradient annealing ovens

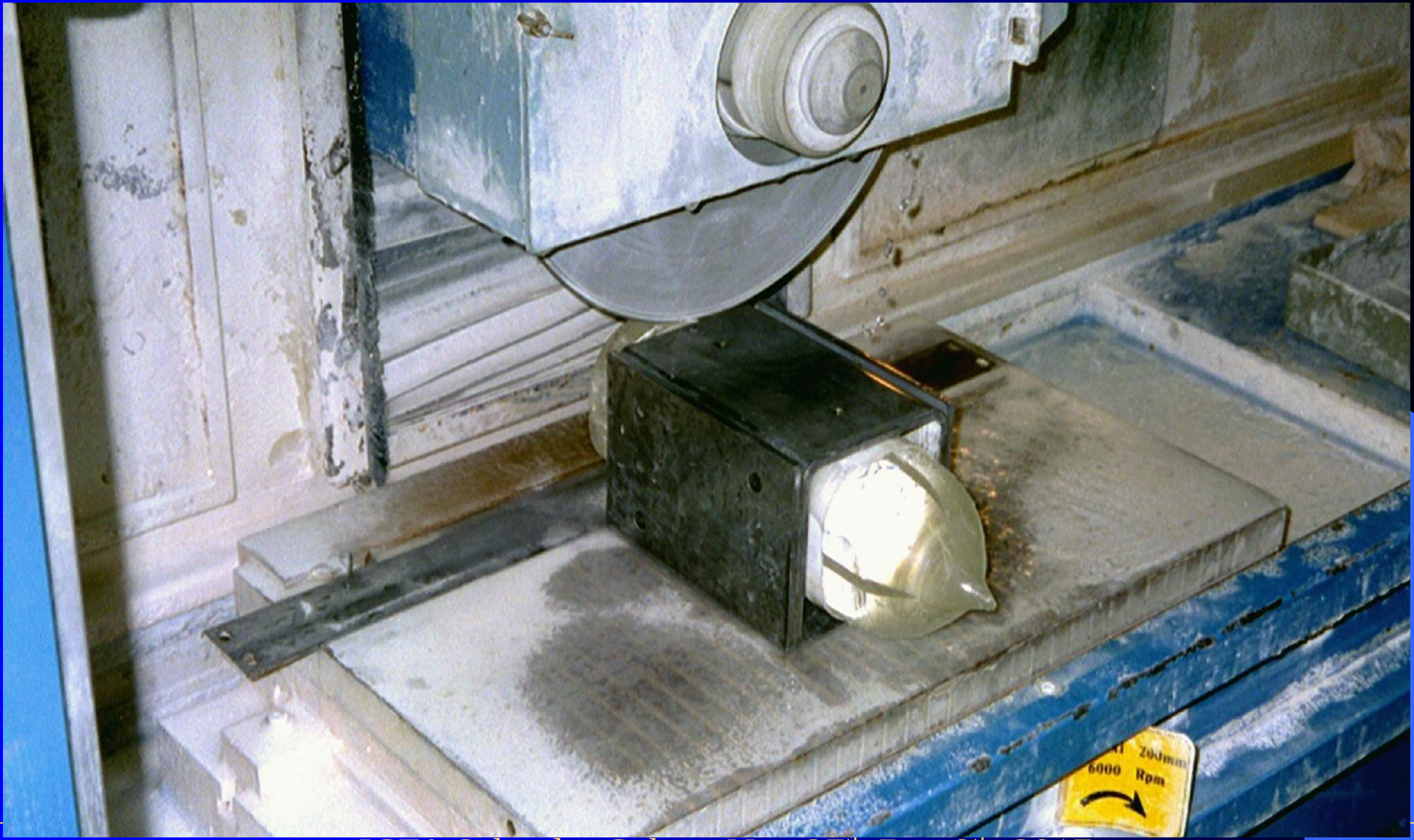
PWO growth of large ingots

- Replace 120mm Pt crucible by new 170mmcomposite Pt crucibles

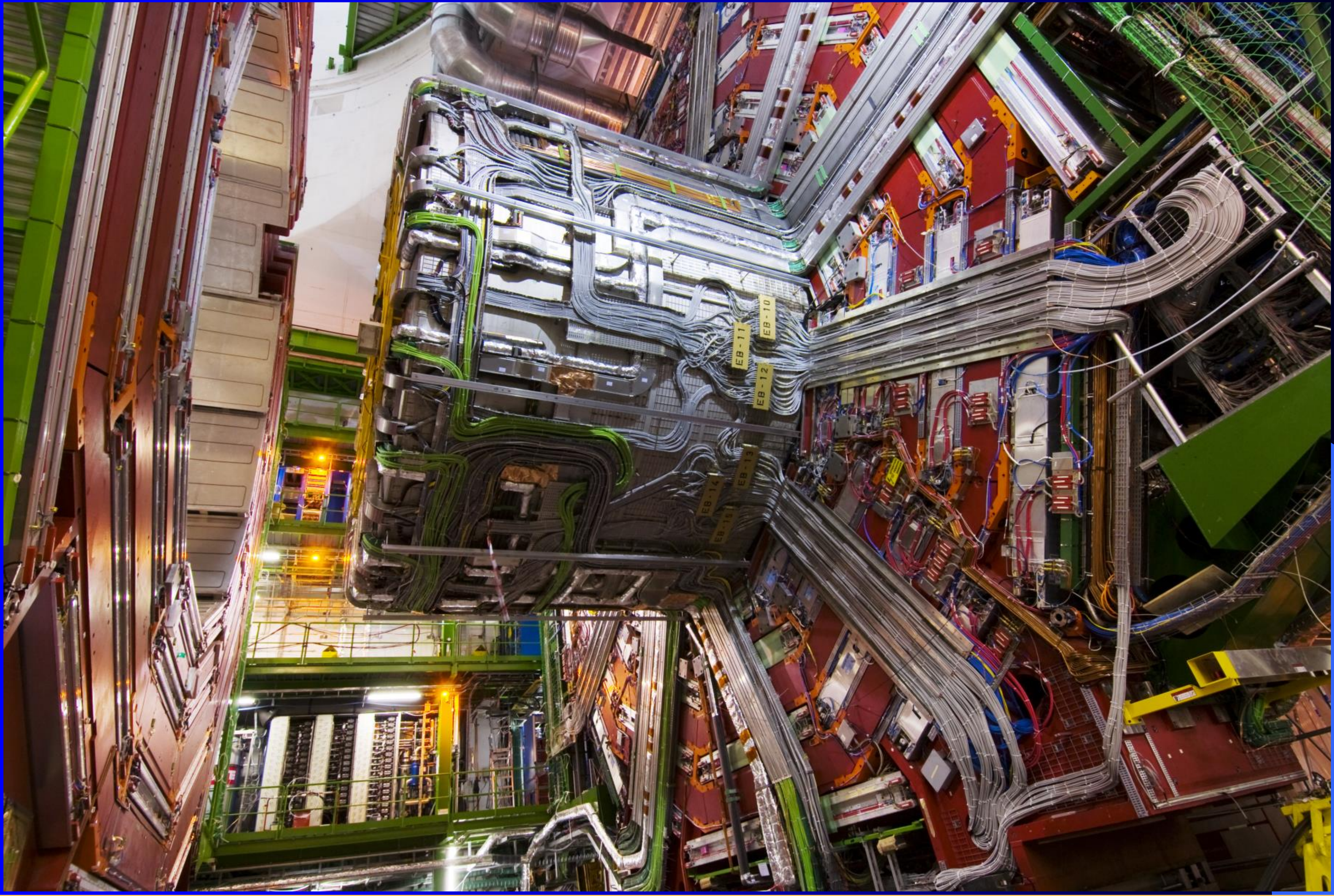
- Upgrade the Rf power cycle for heating, smelting, pulling and cooling
- Optimization of procedure for crystal ingot extraction from crystallization unit



Square end cut 85mm



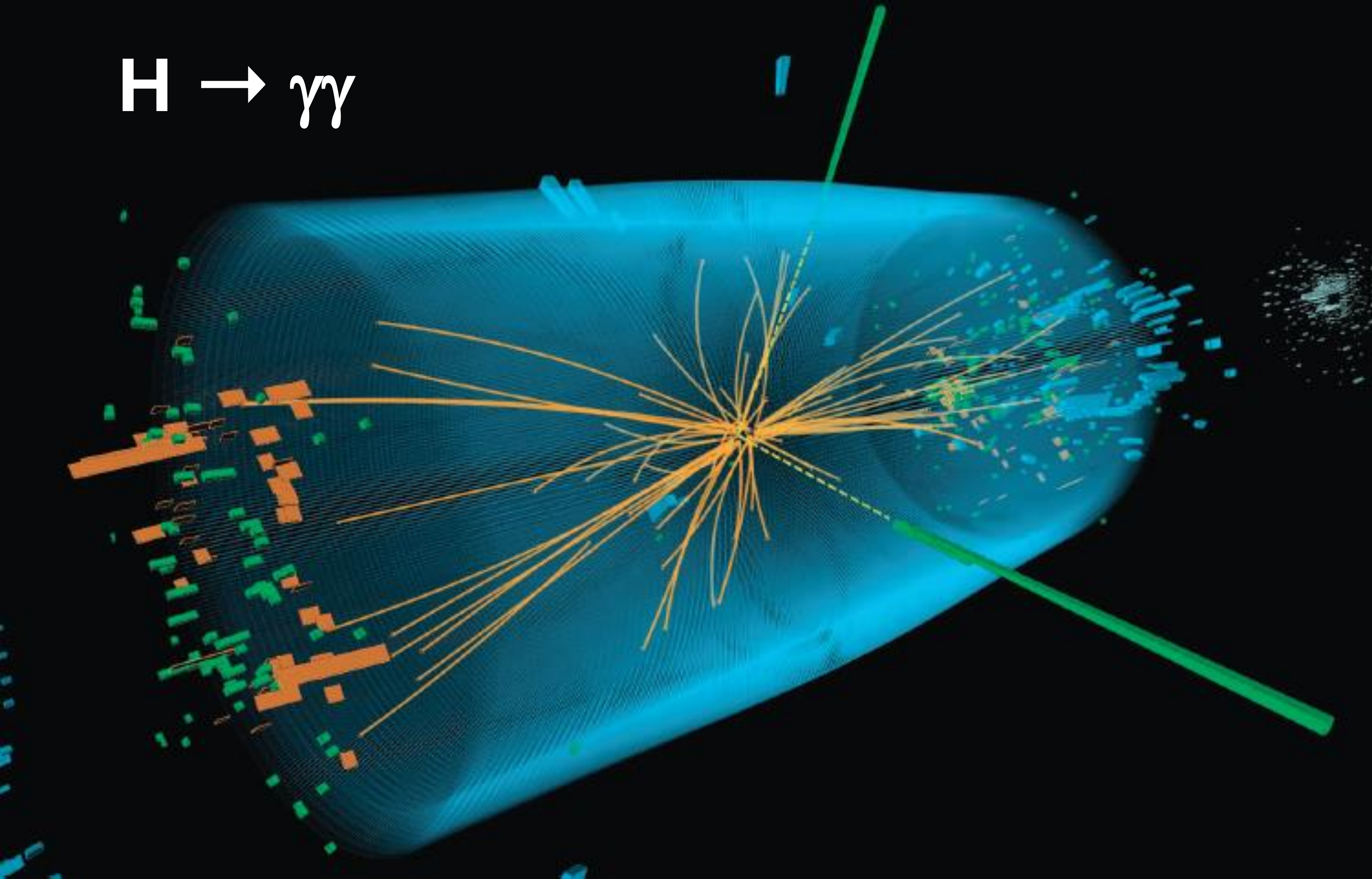
CMS Barrel



CMS Endcaps

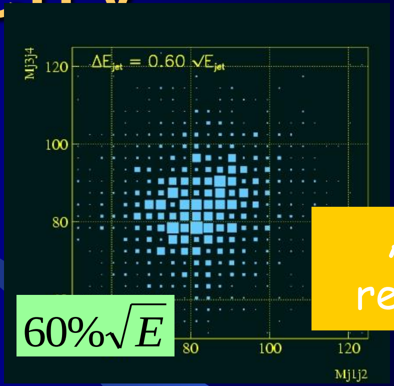
16 years of effort

And finally!!


$H \rightarrow \gamma\gamma$

A different detector concept for precise jet calorimetry

- A conventional approach is limited to about 60% - 70%/ √E

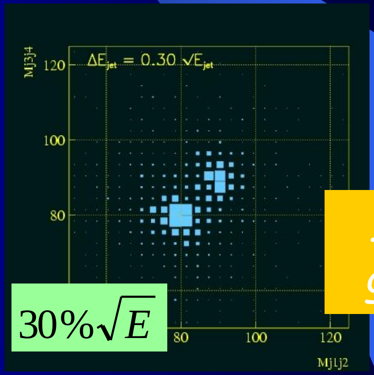


$60\%\sqrt{E}$

ALEPH resolution

New approaches have been proposed

- Particule Flow for a 3D imaging calorimeter
  - Each particle in a jet measured individually
  - Requires very high granularity
  - Limitations
    - Complex Integration due to huge number of channels
    - Identification of individual particles in a jet challenging at very high energy

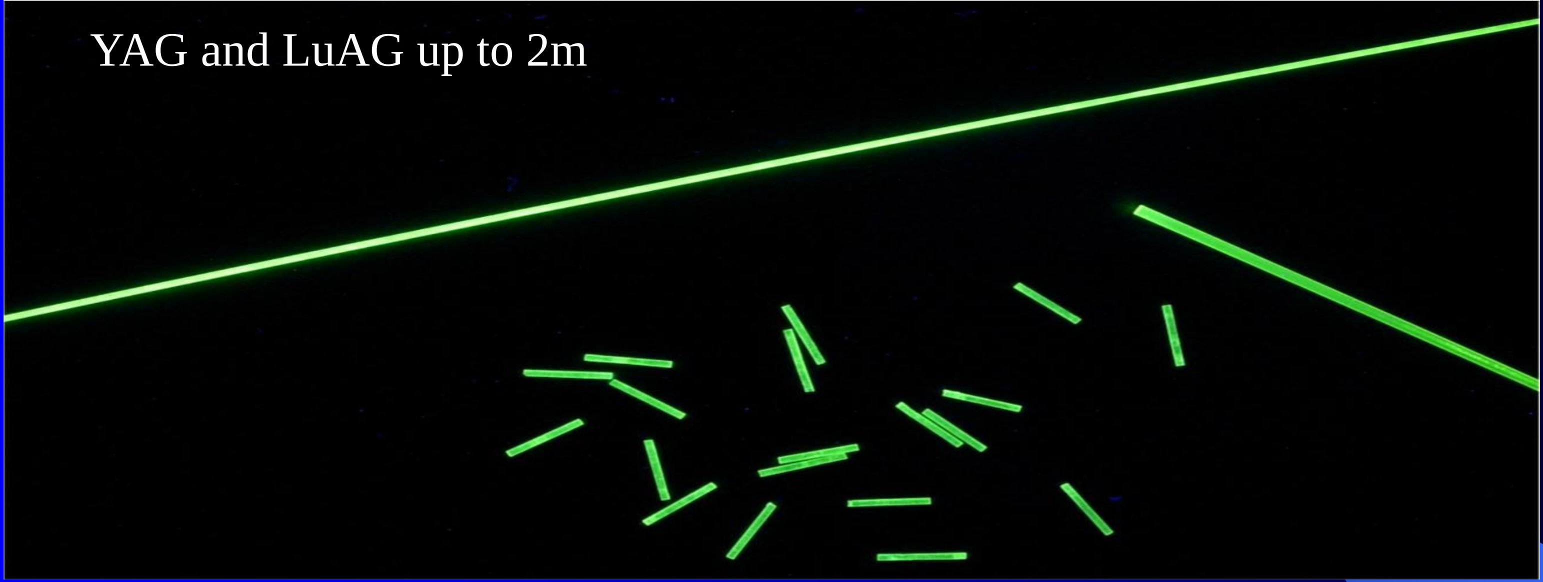


$30\%\sqrt{E}$

ILC goal

- Dual readout method
  - Measure event by event the electromagnetic fraction of the hadronic shower by separating Cerenkov and scintillation light

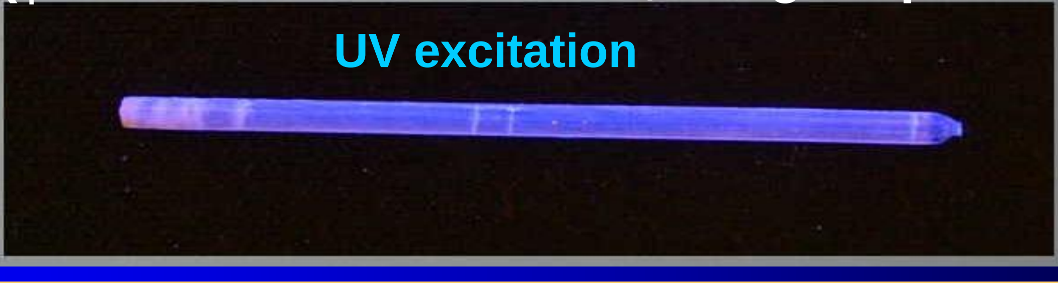
Some crystal fibers



YAG and LuAG up to 2m

BGO (ϕ : from 0.6 mm to 3 mm ; Length up to 30 cm)

LYSO:Ce (ϕ : from 0.6 mm to 3 mm ; Length up to 20 cm)



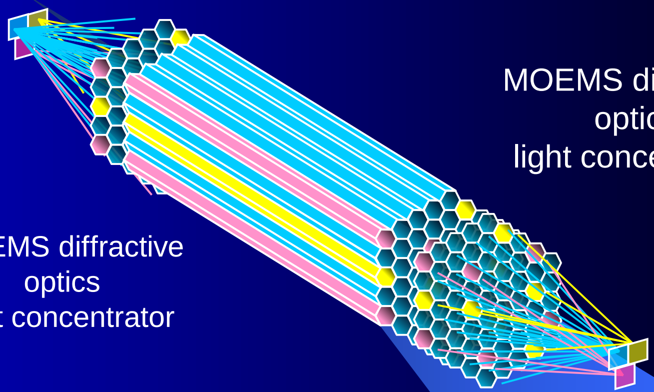
UV excitation

Dual readout based on Metamaterials

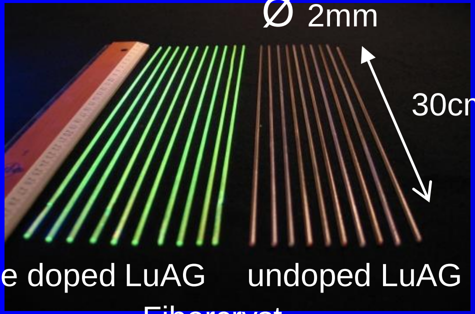
- Select a non-intrinsic scintillating material (unlike BGO or PWO) with high bandgap for low UV absorption

- The undoped host will behave as an efficient Cerenkov: heavy material, high refraction index n, high UV transmission

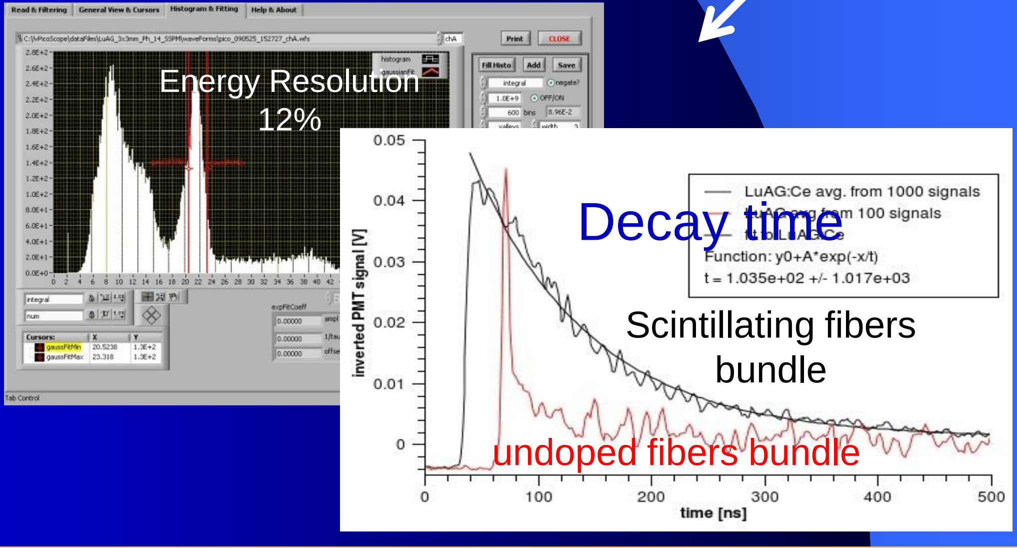
- Cerium or Praesodinum doped host will act as an efficient and fast scintillator
  - ≈ 60ns decay for Ce
  - ≈ 20ns decay for Pr



LuAG is an excellent candidate



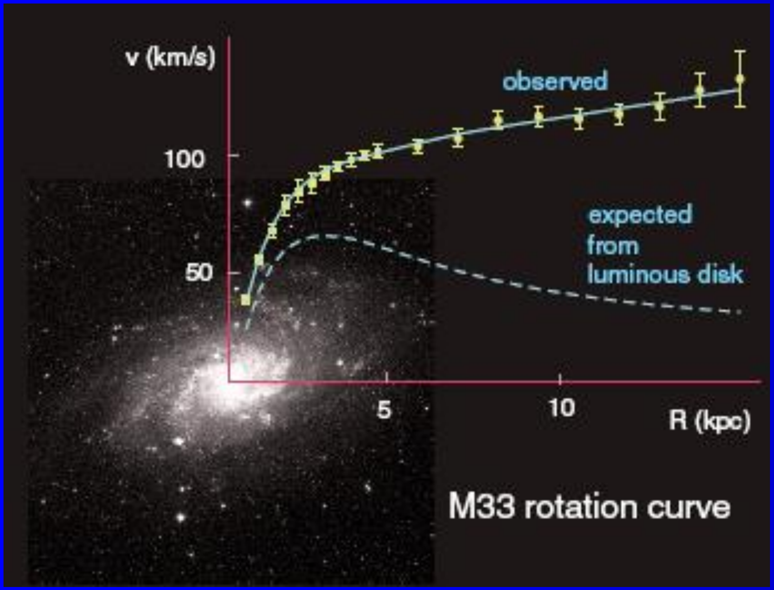
Fibercryst



WIMP-Dark matter searches

Evidence of Dark Matter

Rotation curve of spiral galaxies



L.Bergstrom Rep.Progr.Phys.63 (2000) 793

$V=(GM/r)^{1/2}$

$\Omega_M \sim 0.3 \quad \Omega_X \sim 0.7$

Direct detection - elastic scattering off nuclei

Features:

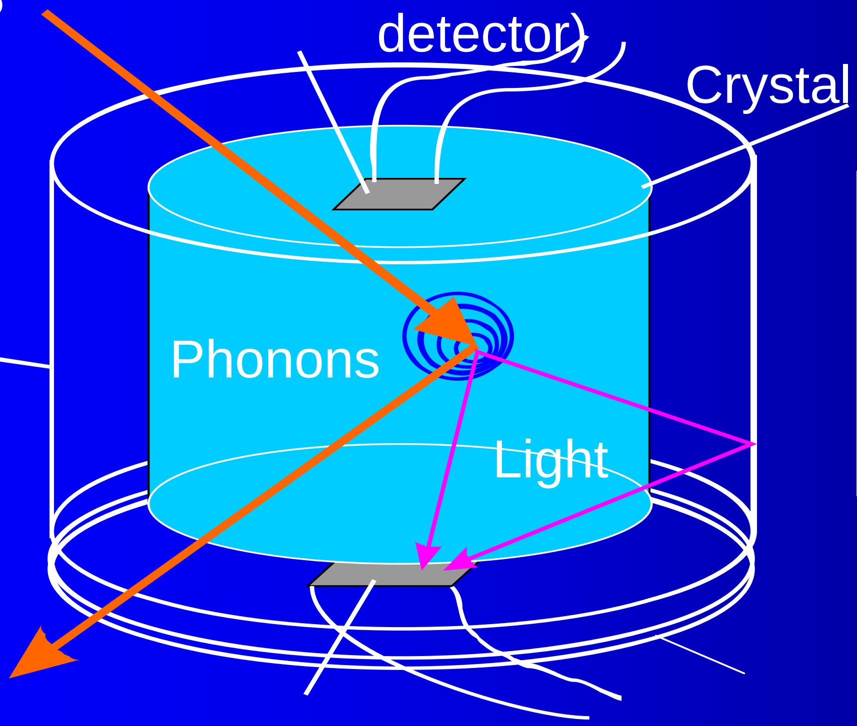
1. Low energy → Low energy threshold (~10 keV)
2. Expected event rate < 0.1/kg day

- Detector mass 1kg-100 kg
- High radiopurity of detector and construction materials
- Underground location
- Background rejection

Why cryogenic scintillator? CREST detector

- **Sensitivity + Selectivity**

  high-energy resolution of cryogenic phonon detector + discrimination of events with low detection threshold (≤10 keV)



WIMP

W-thermometer (phonon detector)

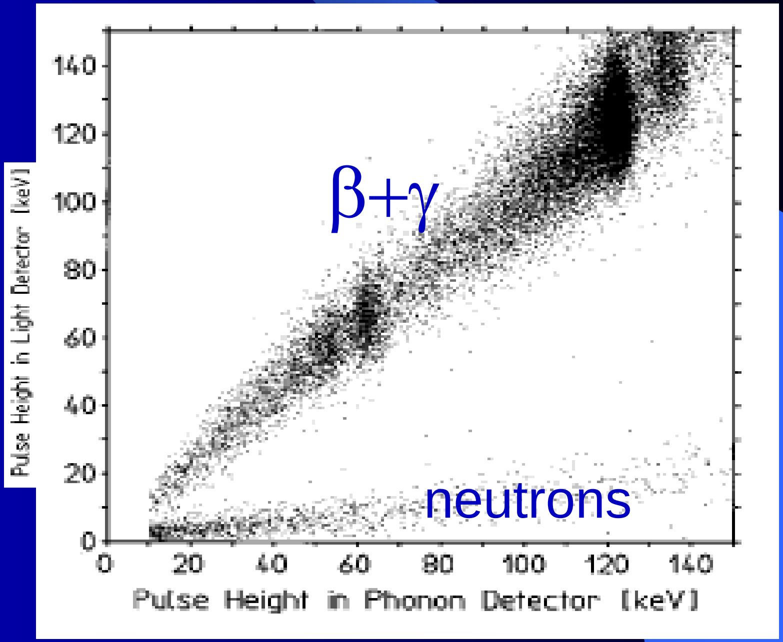
Crystal

Reflector

Phonons

Light

light detector

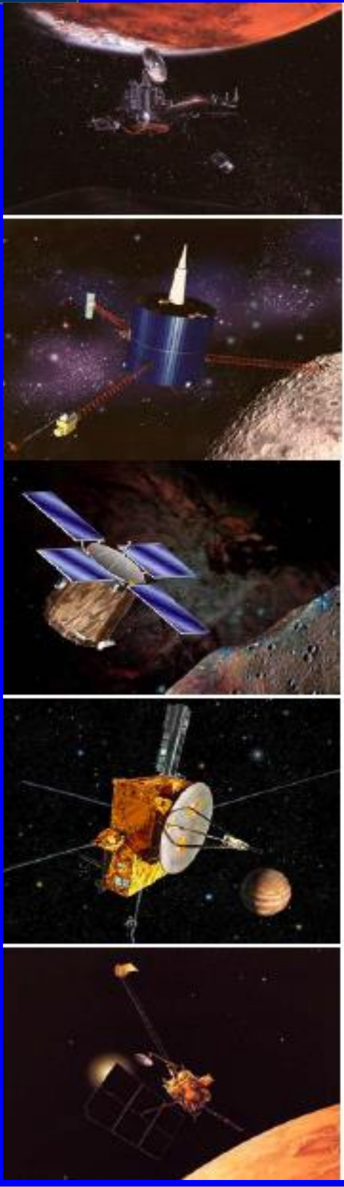


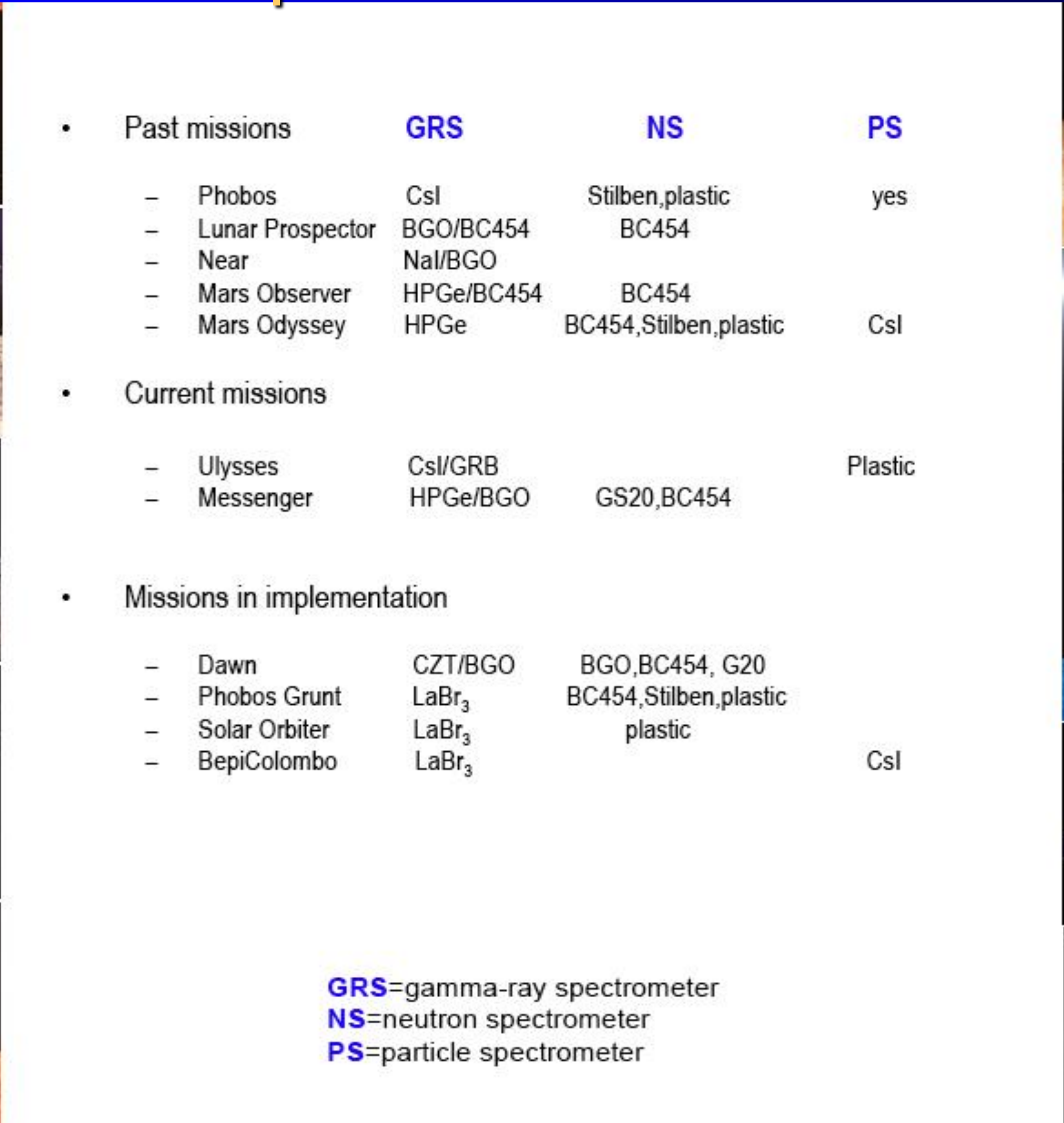
P.Meunier et al, Appl.Phys.Let 75 (1999) 1335

Scintillator requirements

- high light yield at low temperatures
  - ✓ low threshold,
  - ✓ good energy resolution
- Radiopurity (ex Lu, Rb, K, U, Th)
- Suitable thermodynamics characteristics
- Possible candidates
  - ✓$CaWO_4$ – satisfactory choice, currently in use, large ongoing effort to improve the material
  - ✓$ZnWO_4$ – scintillator under development for cryogenic application
  - ✓$CaMoO_4$ and $CdMoO_4$– material under investigation

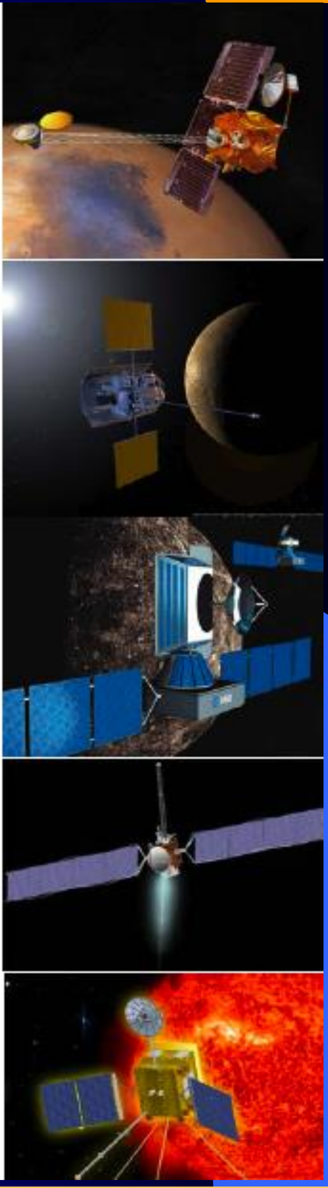
Scintillation Detectors on Space Missions



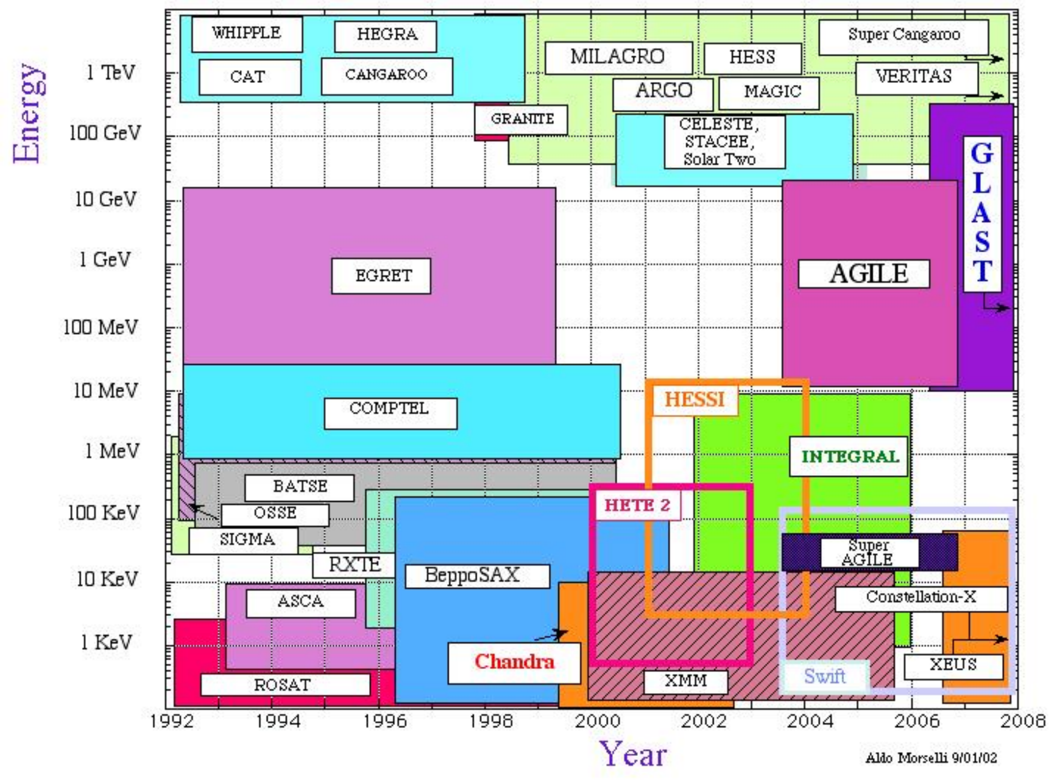


	GRS	NS	PS
Past missions			
Phobos	CsI	Stilben,plastic	yes
Lunar Prospector	BGO/BC454	BC454	
Near	NaI/BGO		
Mars Observer	HPGe/BC454	BC454	
Mars Odyssey	HPGe	BC454,Stilben,plastic	CsI
Current missions			
Ulysses	CsI/GRB		Plastic
Messenger	HPGe/BGO	GS20,BC454	
Missions in implementation			
Dawn	CZT/BGO	BGO,BC454, G20	
Phobos Grunt	$LaBr_3$	BC454,Stilben,plastic	
Solar Orbiter	$LaBr_3$	plastic	
BepiColombo	$LaBr_3$		CsI

GRS=gamma-ray spectrometer
NS=neutron spectrometer
PS=particle spectrometer



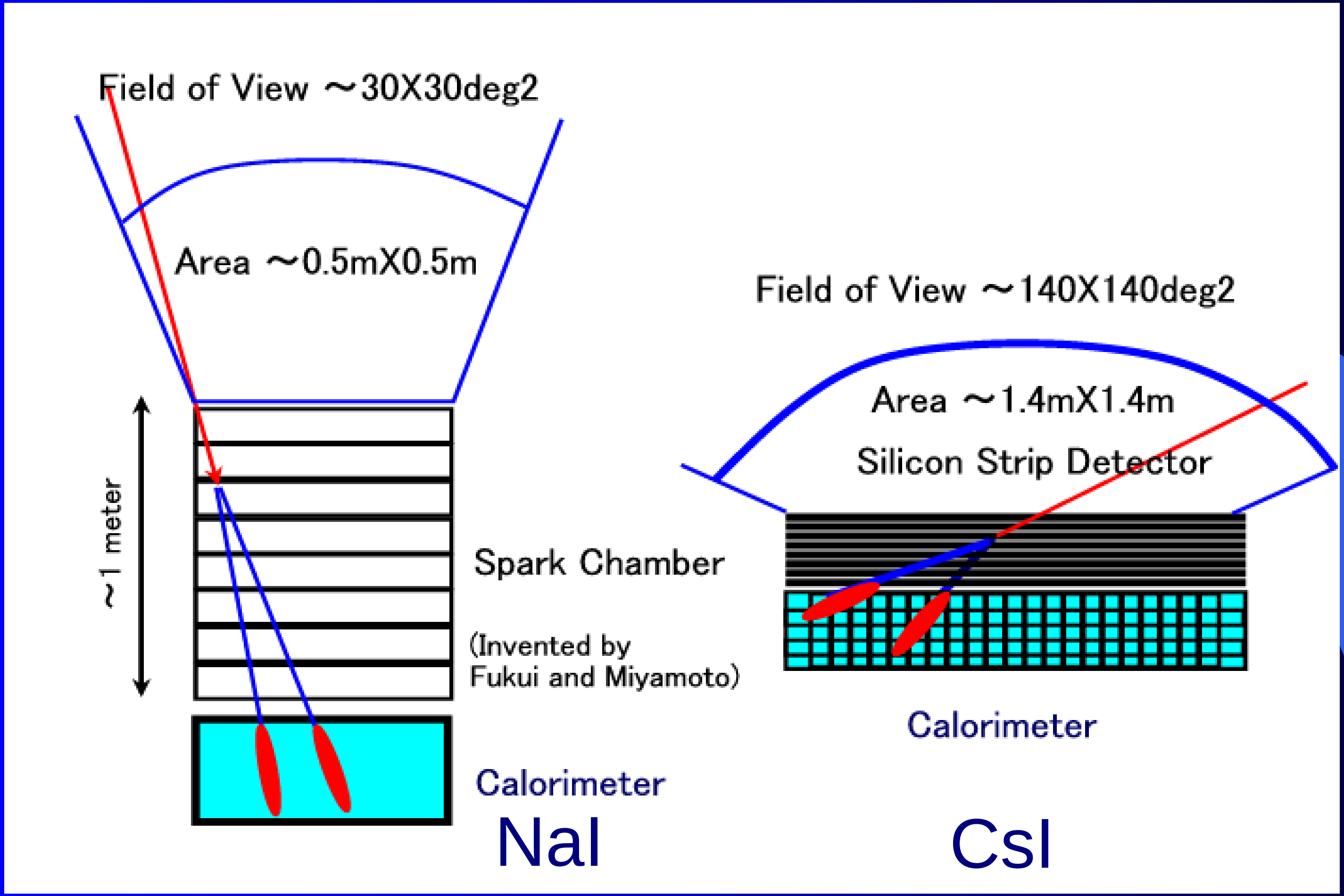
Important Projects for Gamma Astrophysics



Parameter	EGRET	GLAST (Minimum Spec.)
Energy Range	20 MeV - 30 GeV	20 MeV – 300 GeV
Peak Effective Area[1]	1500 cm^2	>8000 cm^2
Field of View	0.5 sr	>2 sr
Angular. Resolution[2]	5.8° (100 MeV)	<3.5° (100 MeV) <0.15° (>10 GeV)
Energy Resolution[1]	10%	<10%
Deadtime per Event	100 ms	<100 μs
Source Location Determination[4]	15'	<0.5'
Point Source Sensitivity[5]	-I x 10^{-7}cm^{-2} s^{-1}	<6 x 10^{-9} cm^{-2} s^{-1}

EGRET – Energetic Gamma Ray Experiment Telescope
GLAST – Gamma Ray Large Area Space Telescope

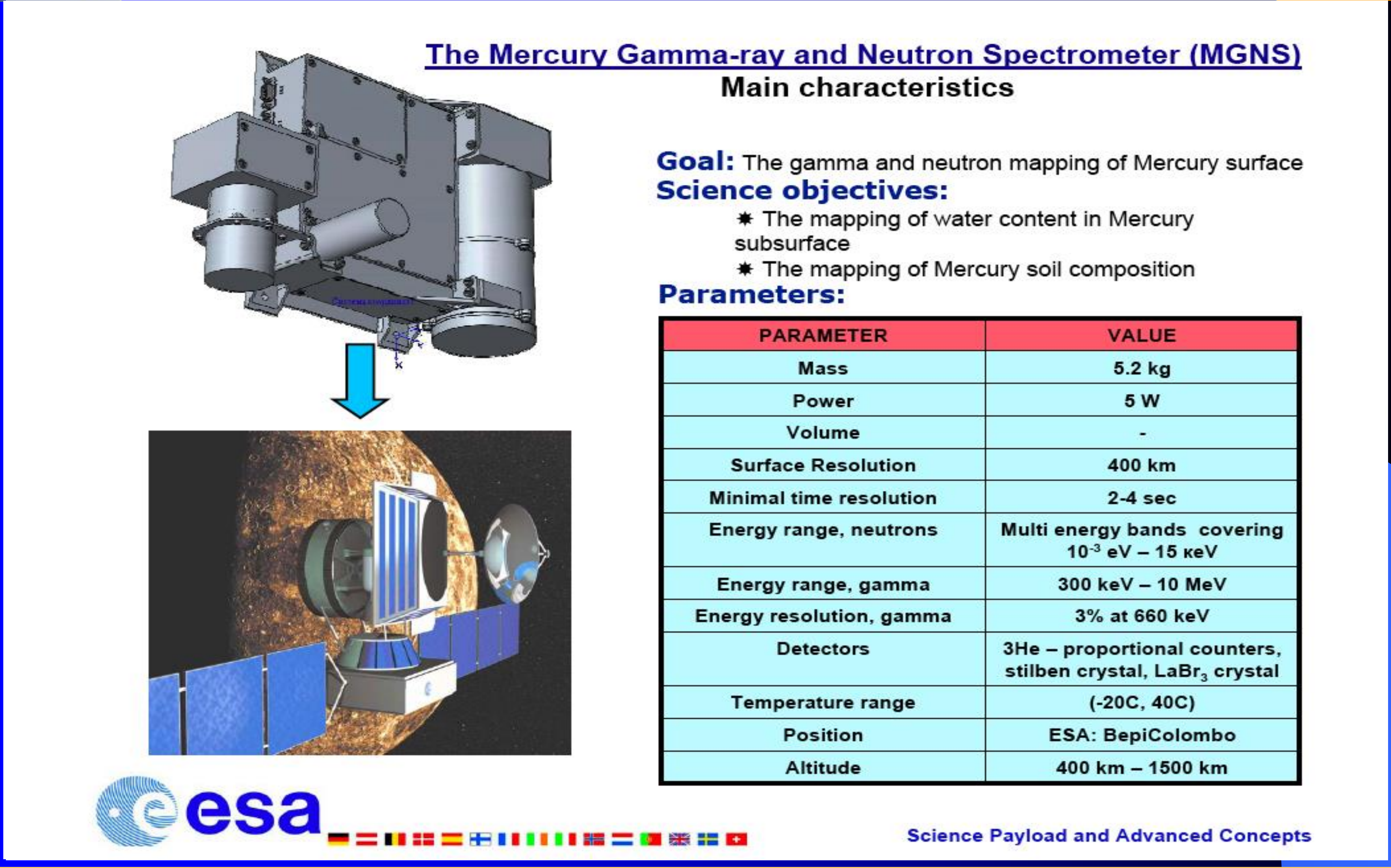
EGRET versus GLAST



EGRET on Compton GRO (1991-2000)

GLAST Large Area Telescope (2006-2015)

The BepiColombo Mercury mission



The Mercury Gamma-ray and Neutron Spectrometer (MGNS)

Main characteristics

Goal: The gamma and neutron mapping of Mercury surface

Science objectives:

- The mapping of water content in Mercury subsurface
- The mapping of Mercury soil composition

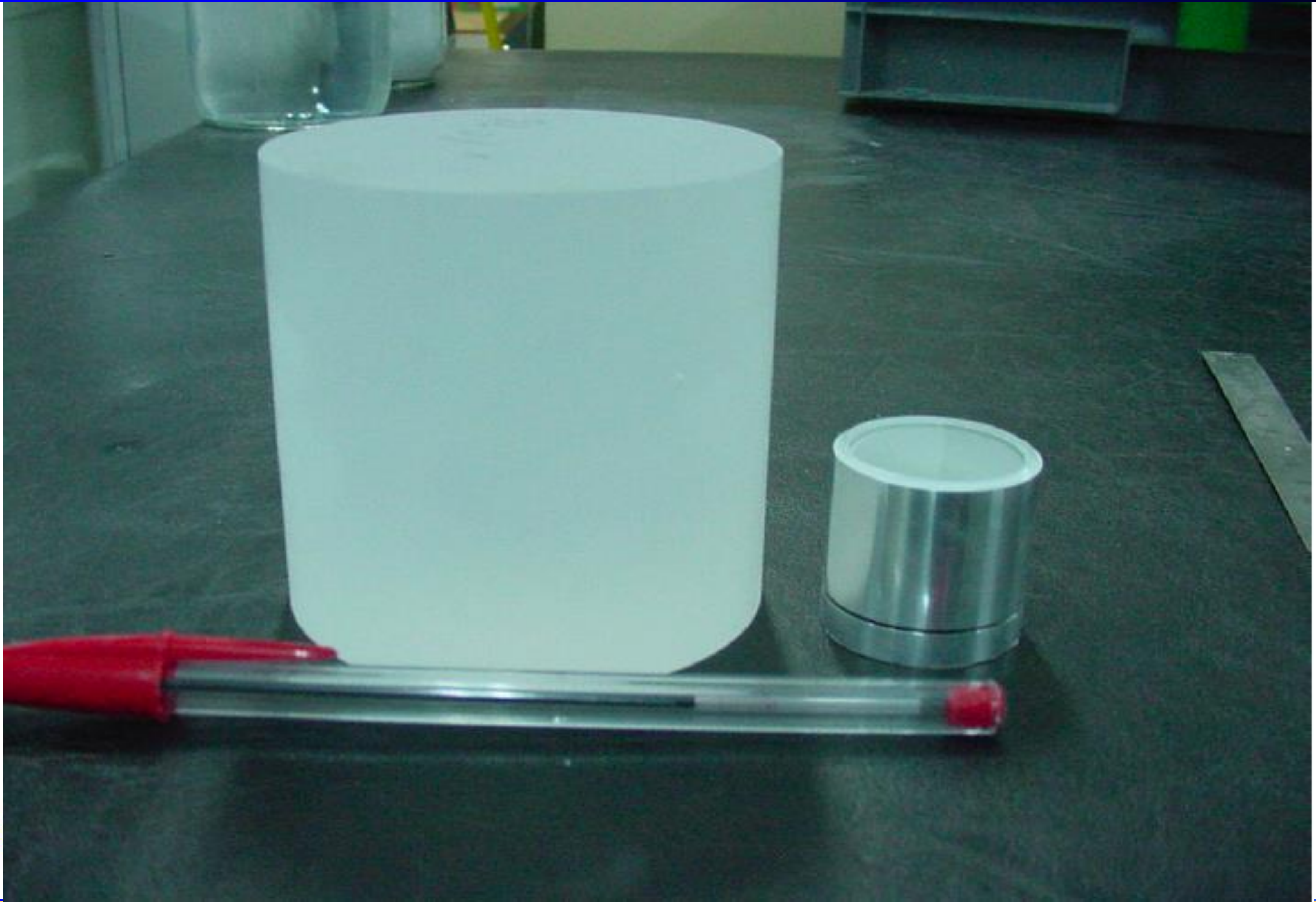
Parameters:

PARAMETER	VALUE
Mass	5.2 kg
Power	5 W
Volume	-
Surface Resolution	400 km
Minimal time resolution	2-4 sec
Energy range, neutrons	Multi energy bands covering 10^{-3} eV – 15 кeV
Energy range, gamma	300 keV – 10 MeV
Energy resolution, gamma	3% at 660 keV
Detectors	3He – proportional counters, stilben crystal, $LaBr_3$ crystal
Temperature range	(-20C, 40C)
Position	ESA: BepiColombo
Altitude	400 km – 1500 km

esa

Science Payload and Advanced Concepts

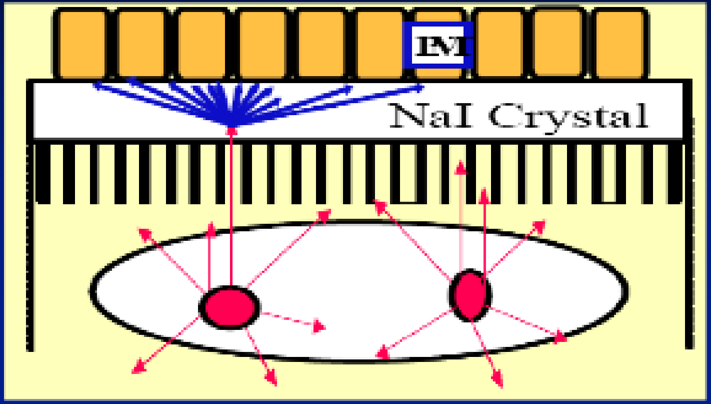
History- LaBr$_3$ development program

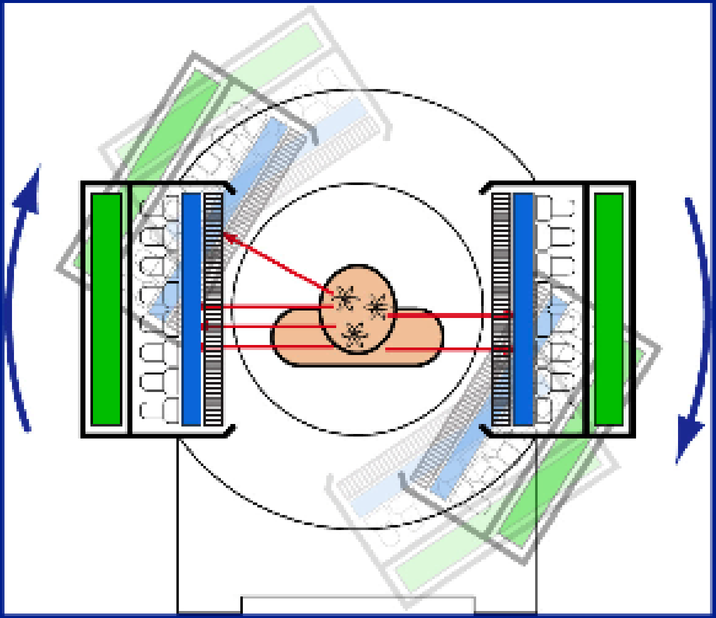


Scintillators in nuclear medicine

- High detection efficiency for different type of radiations, particularly γ-rays
- Good energy resolution
- Very good timing
- High counting rate capability
- Great variety in size and composition

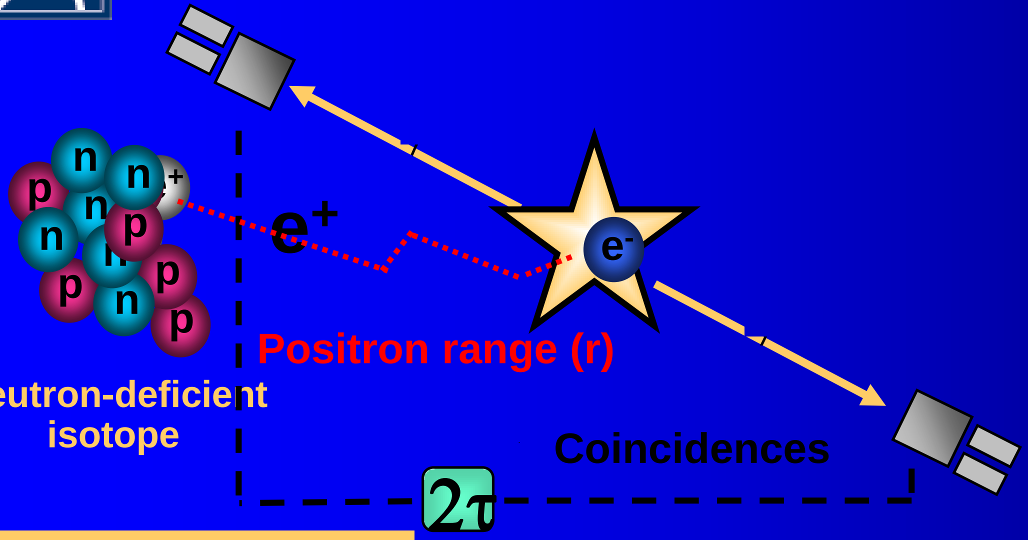
SPECT principle
Spatial resolution



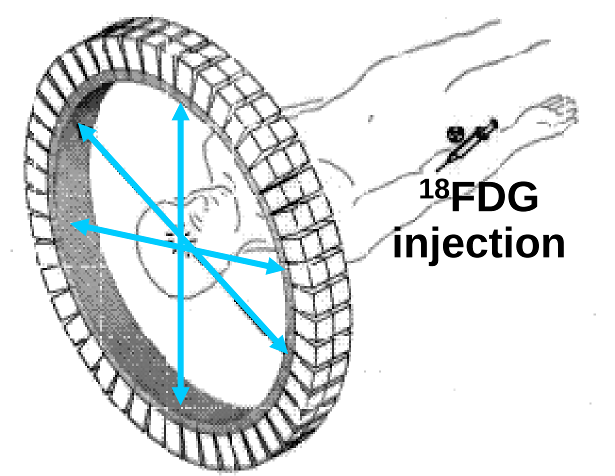


- **Collimator – Ability of the collimator to localize the γ-ray source in the patient (~6-12 mm)**
- **Intrinsic – Ability of the NaI(*Tl*) crystal and PMT to localize the γ-ray interactions in the crystal (~3-4 mm)**
- **Extrinsic – Overall system resolution combining collimator and intrinsic factors. Quadratic sum of FWHM of intrinsic and collimator resolution.**

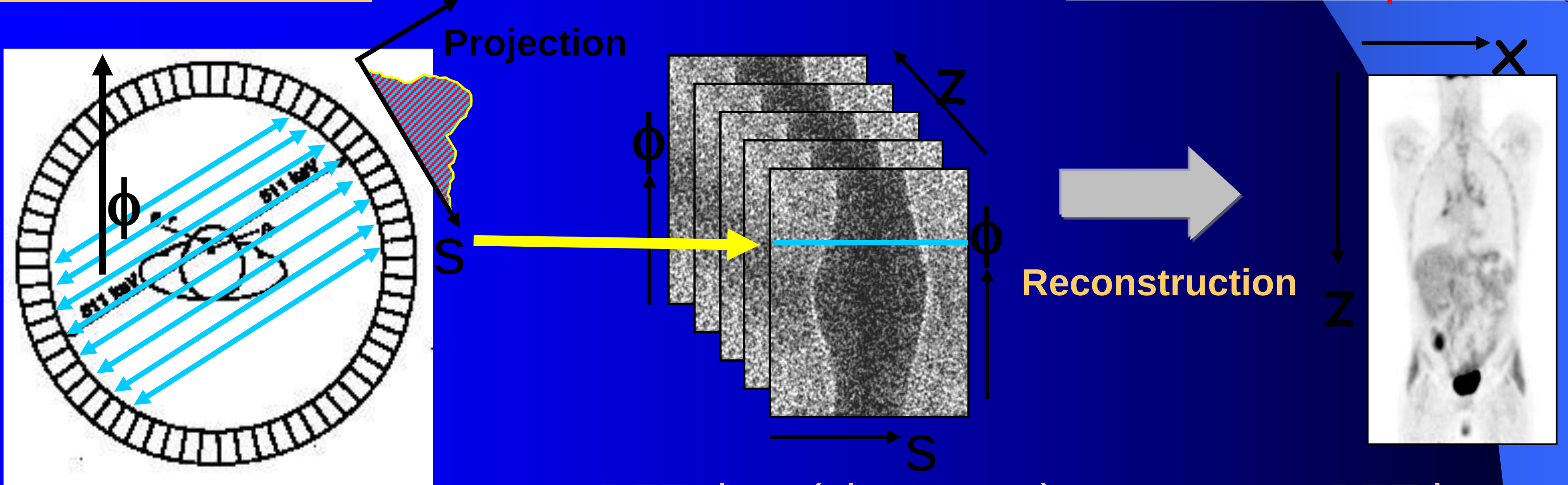
PET Principles



(6p; 5n)➔(5p; 6n)



PET data acquisition

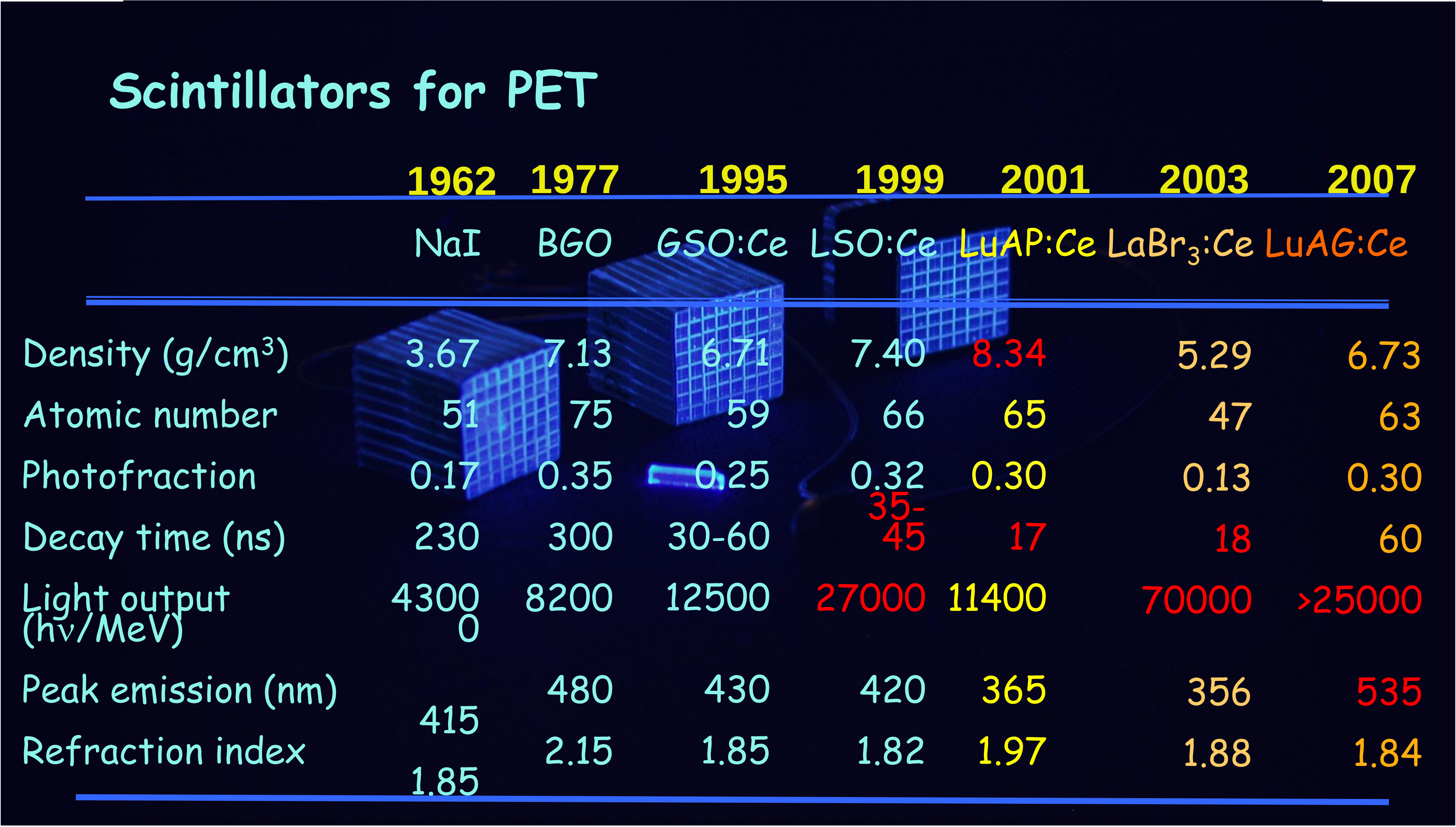


Parallel projections

PET data (sinograms)

PET images

Scintillators for PET



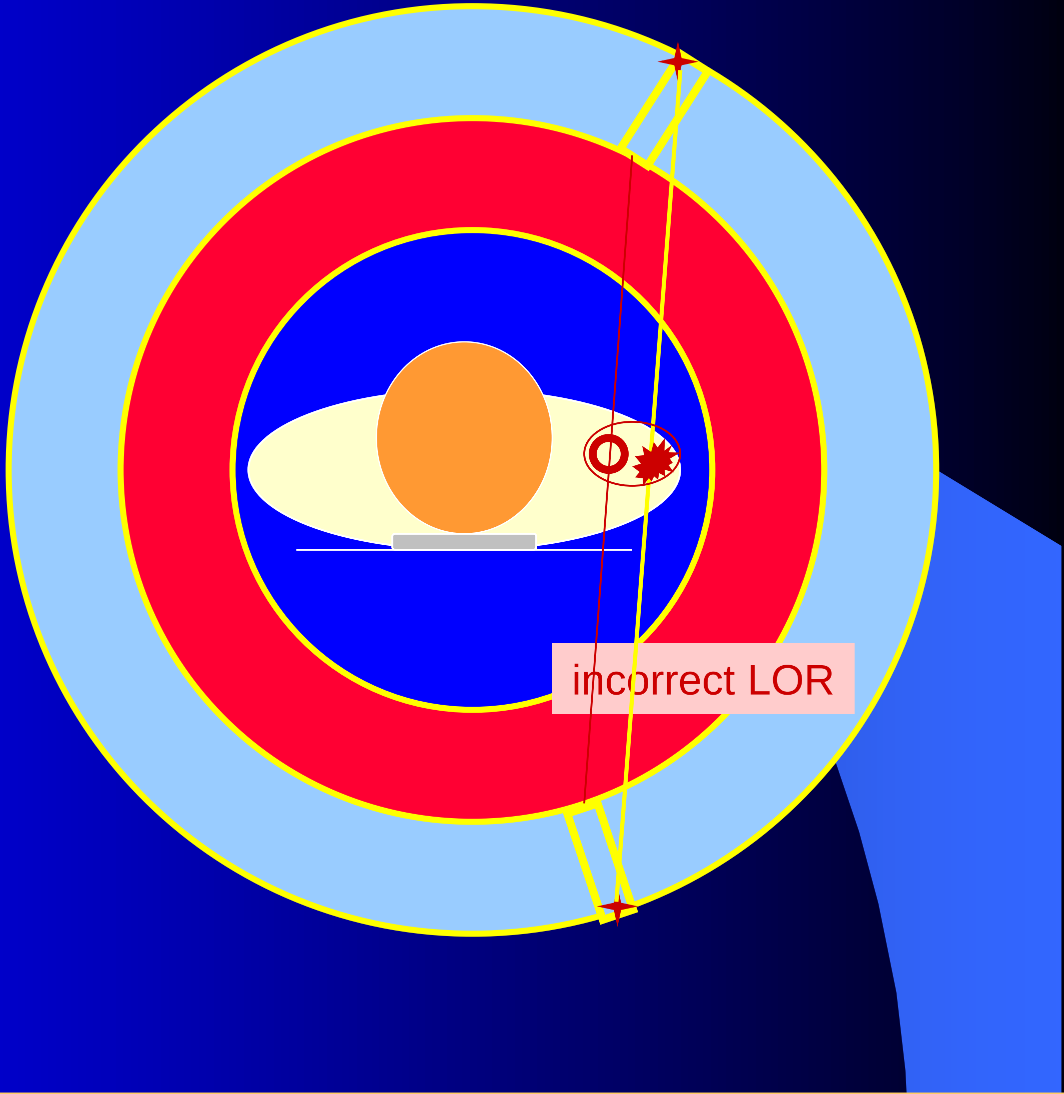
Scintillators for PET

	1962	1977	1995	1999	2001	2003	2007
	NaI	BGO	GSO:Ce	LSO:Ce	LuAP:Ce	$LaBr_3$:Ce	LuAG:Ce
Density (g/cm^3)	3.67	7.13	6.71	7.40	8.34	5.29	6.73
Atomic number	51	75	59	66	65	47	63
Photofraction	0.17	0.35	0.25	0.32	0.30	0.13	0.30
Decay time (ns)	230	300	30-60	35-45	17	18	60
Light output ($h\nu$/MeV)	43000	8200	12500	27000	11400	70000	>25000
Peak emission (nm)	415	480	430	420	365	356	535
Refraction index	1.85	2.15	1.85	1.82	1.97	1.88	1.84

Parallax error in PET

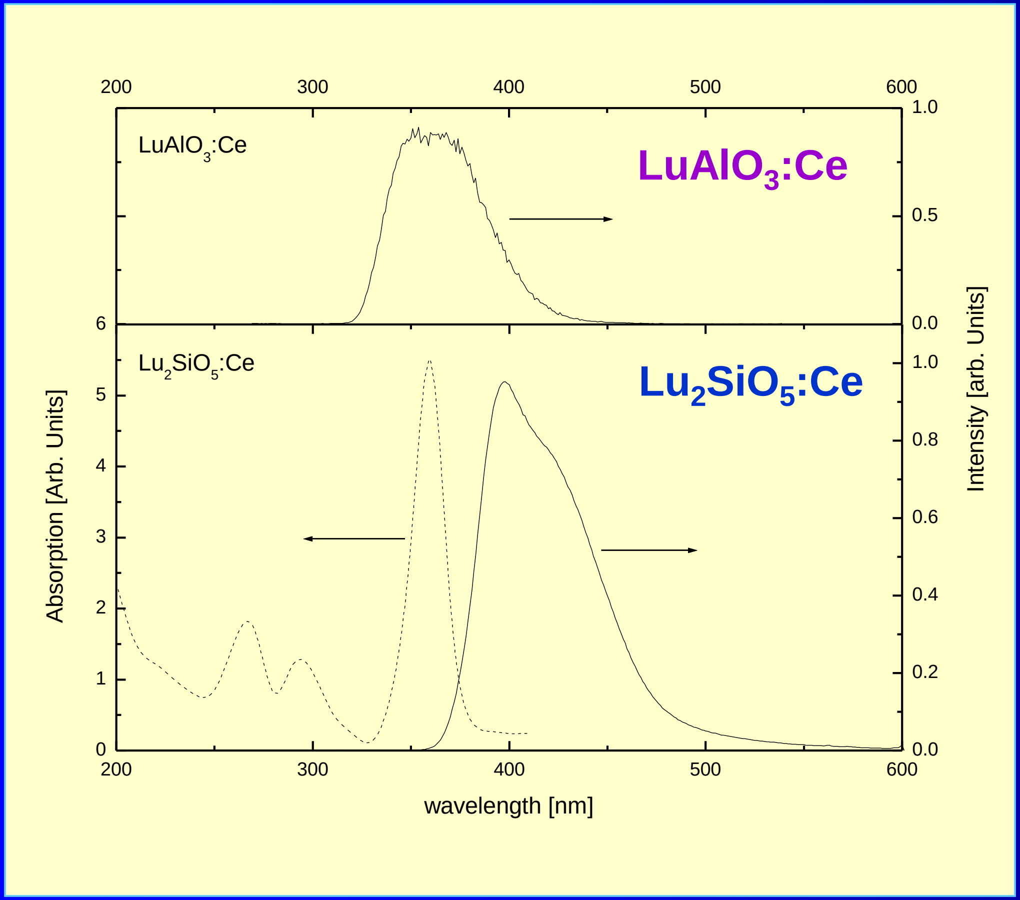
Spatial Resolution - Depth-of-interaction

DOI

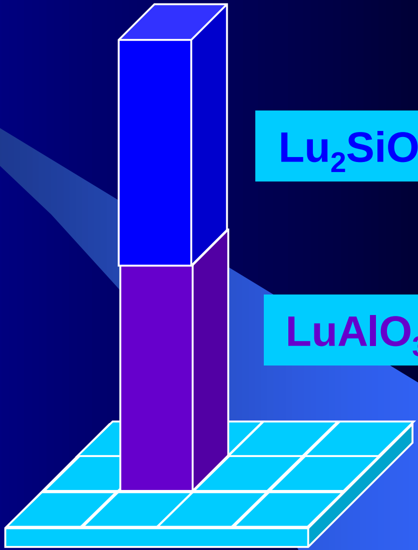


Depth-of-interaction (DOI) information is needed to maintain good resolution at off-centre positions

Phoswich configuration in PET



columns



DOI

Lu$_2$SiO$_5$:Ce

LuAlO$_3$:Ce

APD array
or
multi-anode PMT

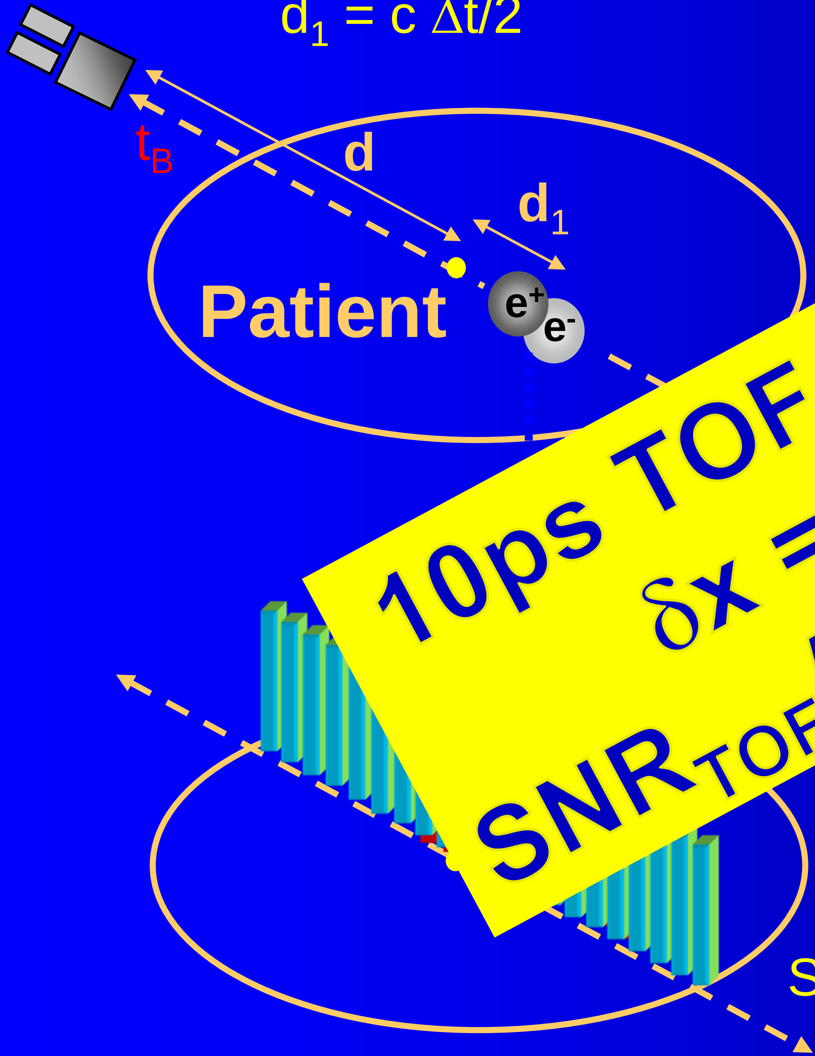
Different response time and/or wavelength

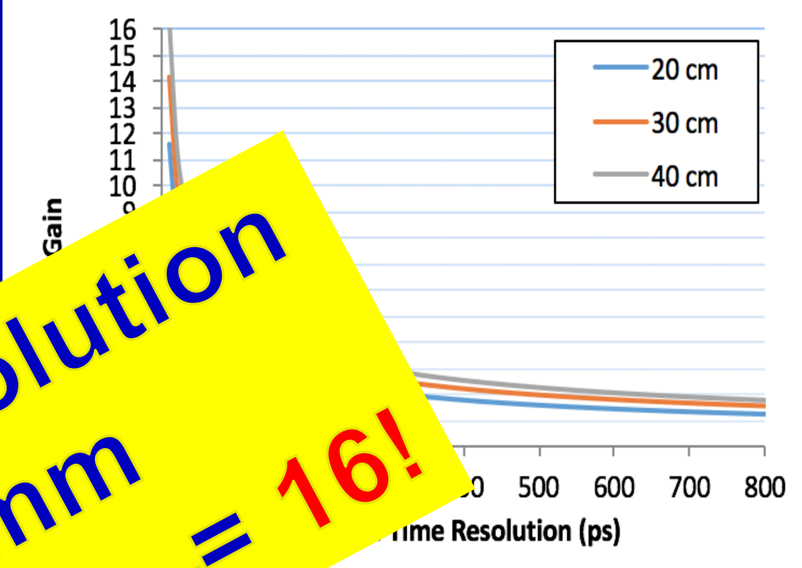
Time of Flight PET

$\Delta t = t_A - t_B = [(d+d_1) - (d-d_1)]/c$

$d_1 = c\,\Delta t/2$

Detector B





10ps TOF resolution

δx = 1.5mm

$\mathrm{SNR}_{\mathrm{TOF}}/\mathrm{SNR}_{\mathrm{CONV}}$ = 16!

$_{OF} = \sqrt{(2D/cDt)} \cdot \mathrm{SNR}_{conv}$

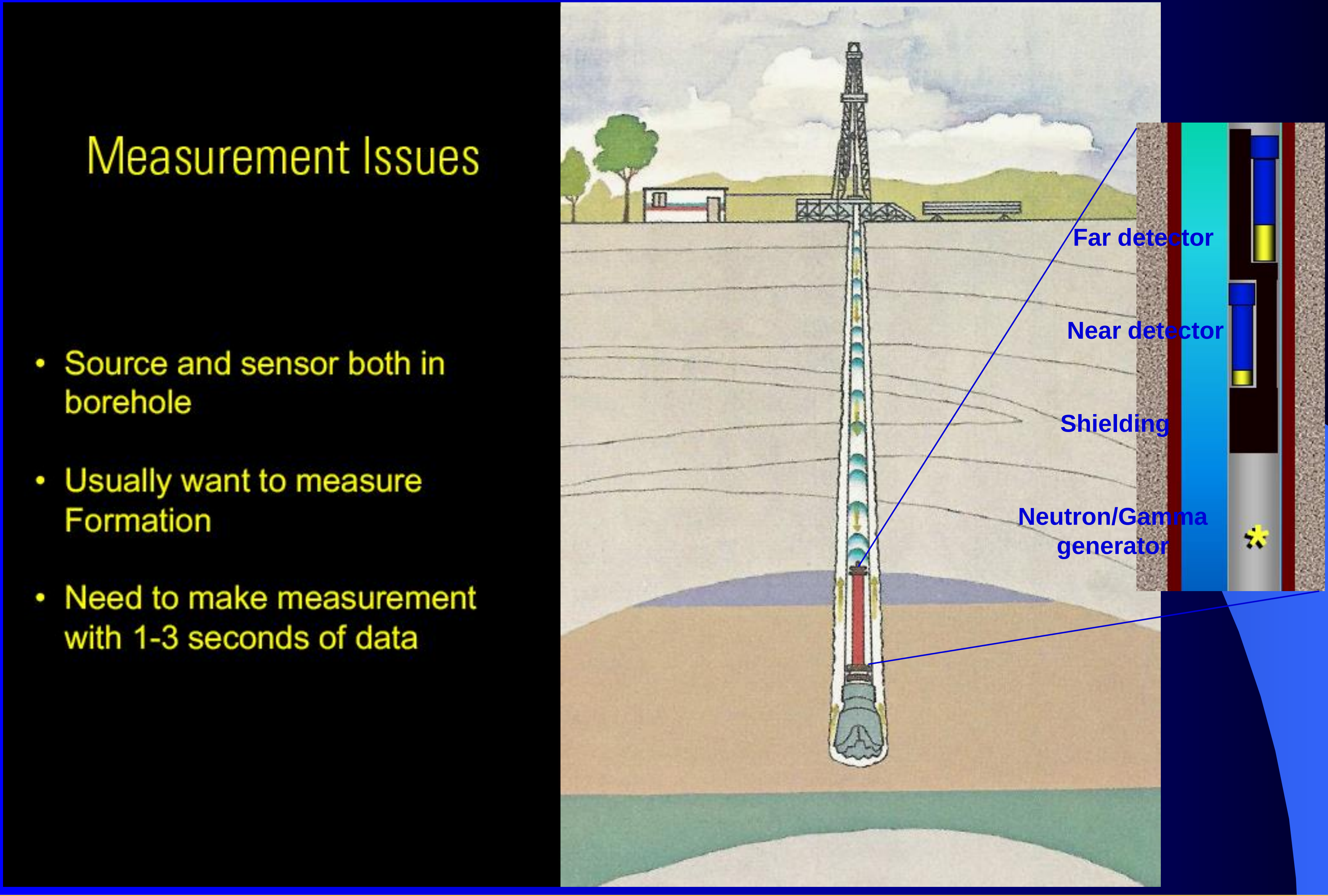
δt (ps)	δx (cm)	SNR*
10	0.15	16
100	1.5	5.2
300	4.5	3.0
500	7.5	2.3

State-of-the-art: 500 / 7.5 / 2.3

** SNR gain for 40 cm phantom*

Scintillators for Geophysical Exploration

Oil Well Logging



Measurement Issues

- Source and sensor both in borehole
- Usually want to measure Formation
- Need to make measurement with 1-3 seconds of data

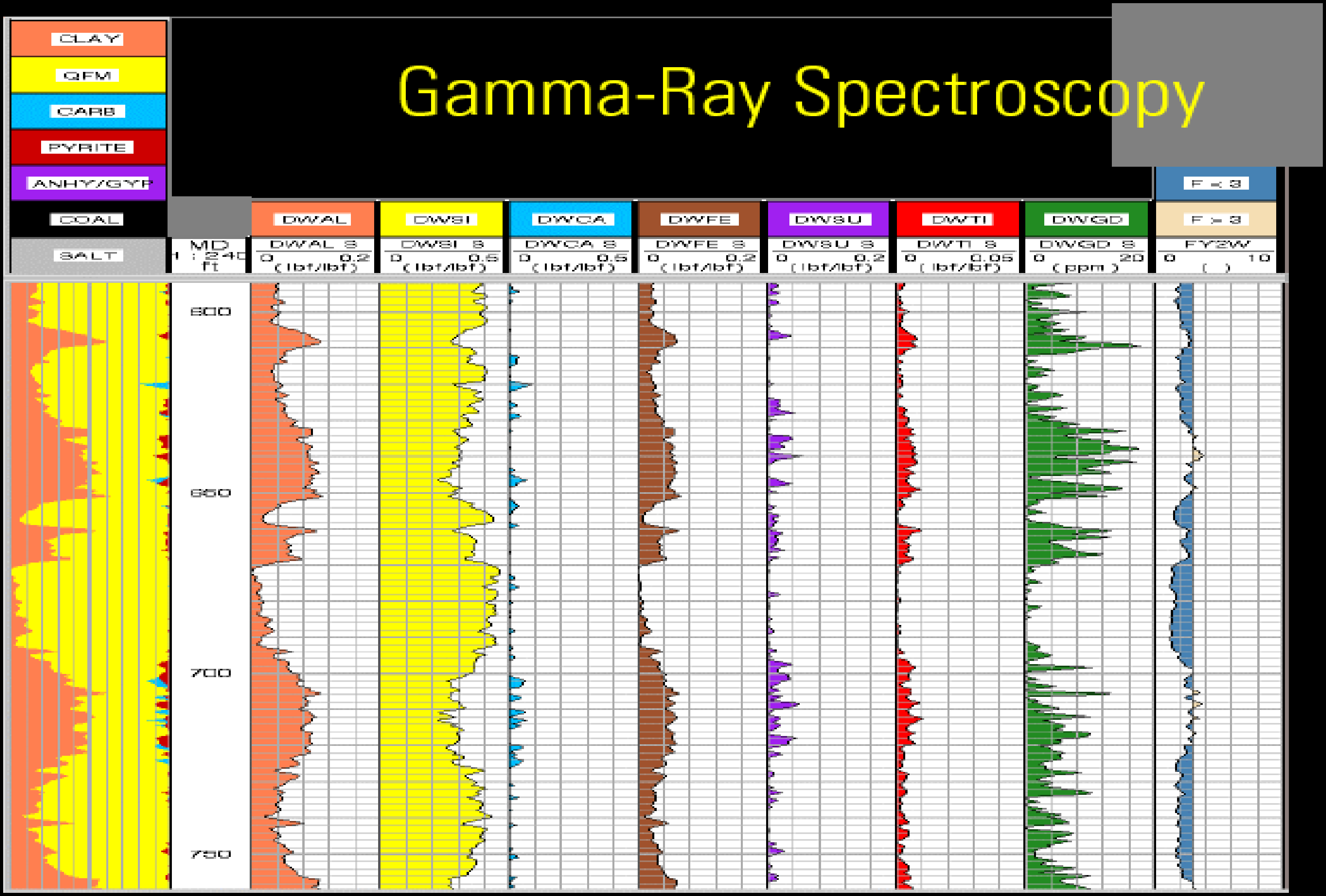
Far detector

Near detector

Shielding

Neutron/Gamma generator

Nuclear Tools



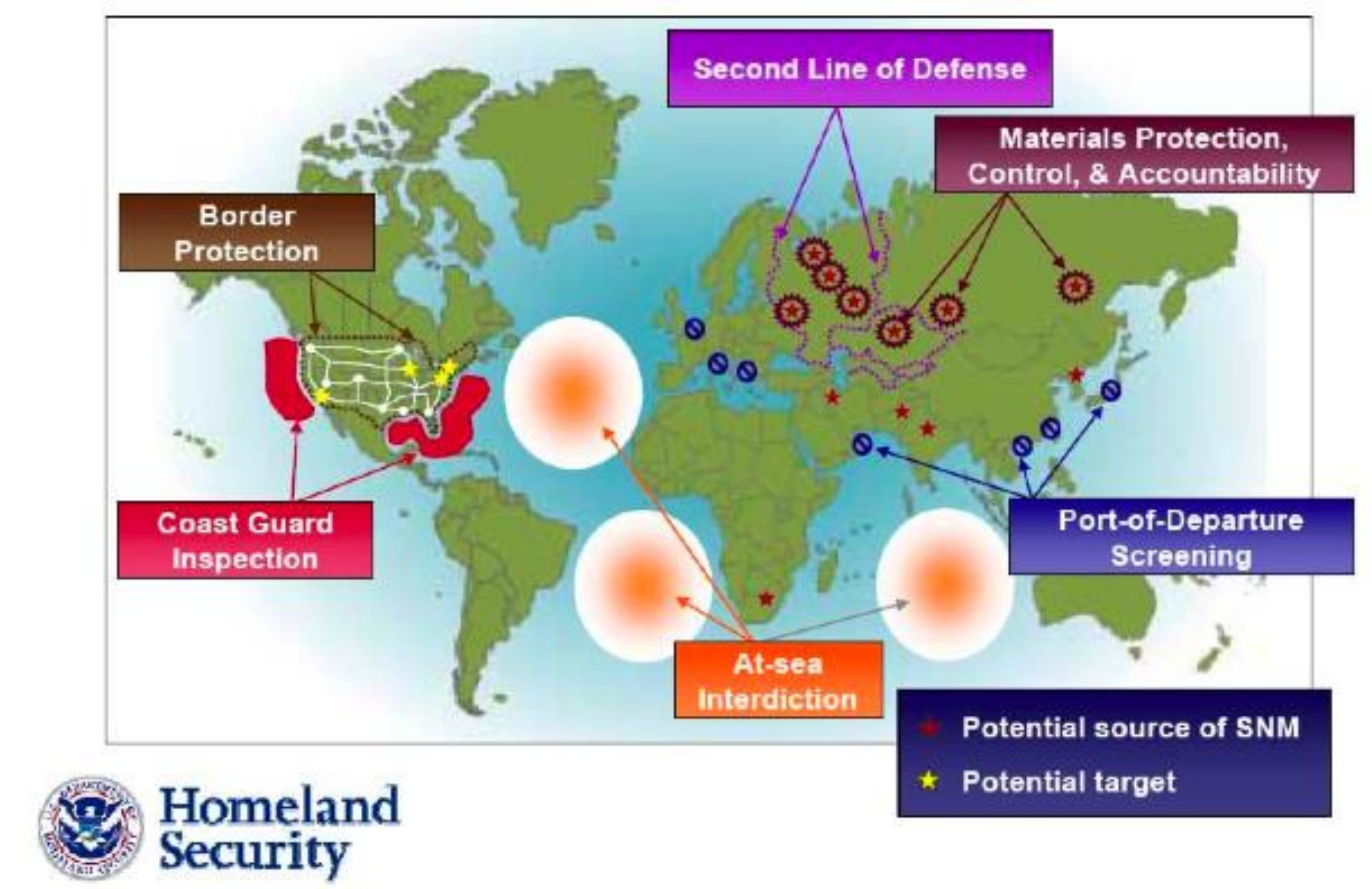
Desirable Scintillator Properties

- High Density, High Z
- Good Resolution (all Energies)
- High Countrate Capability
- Reasonable Size
- Non-Hydroscopic
- Light Output (350 – 450 nm)
- Rugged
- Good High Temperature Performance
  - Resolution
  - Wavelength
  - Decay Time

- NaI
- BGO
- GSO

- *LuAP ?*

Homeland security



Passive instrumentation

Hand-held, mobile, transportable, and fixed position

NaI, $LaBr_3$, PVT

Spectrometers and counters

7 Managed by UT-Battelle
for the Department of Energy

Scintillator Applications in Homeland Security

Active Instrumentation

Mobile and fixed position; X ray, ^{60}Co, ^{137}Cs

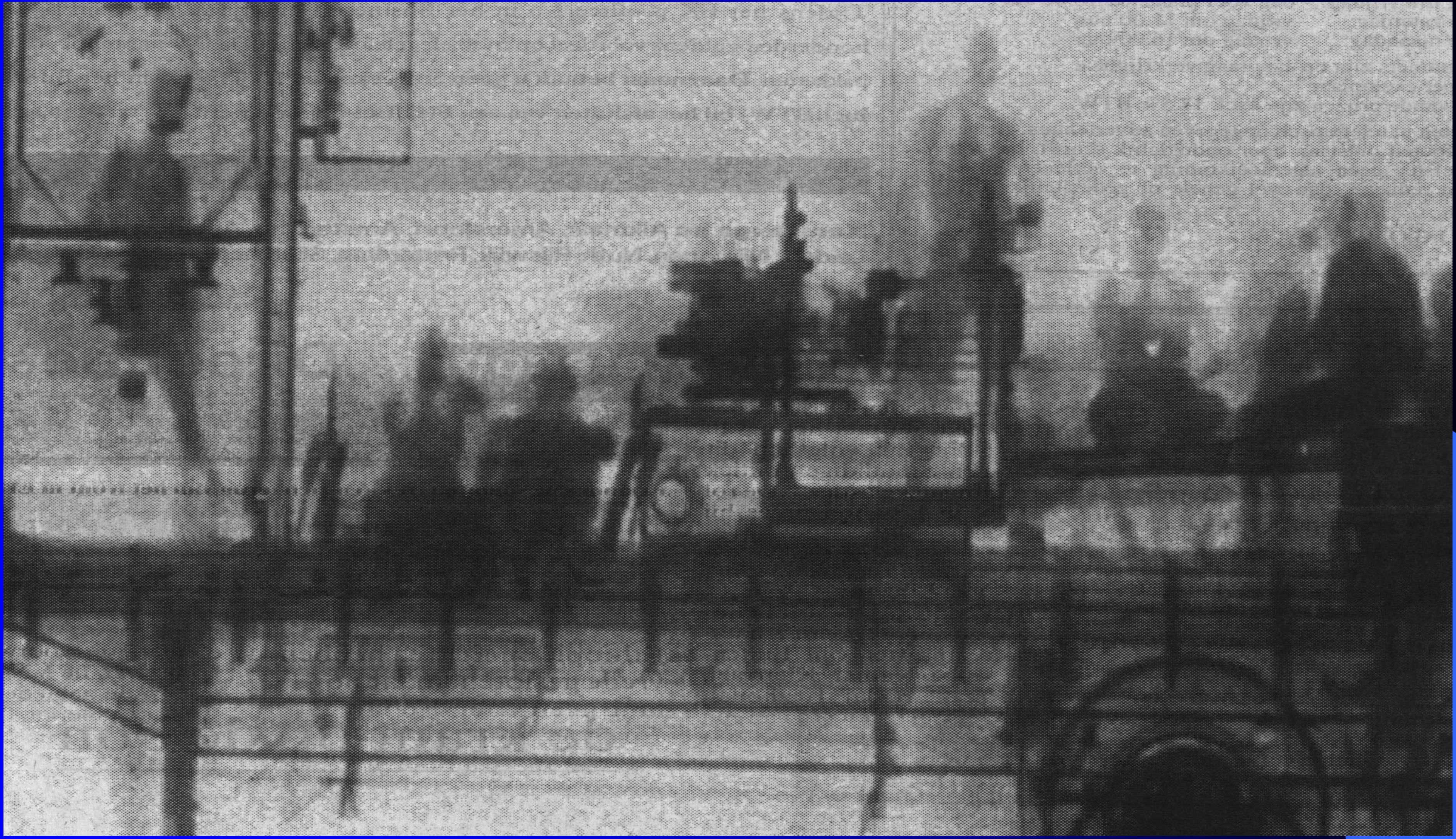
NaI, $CdWO_4$, BGO

Spectrometers, counters, imagers

8 Managed by UT-Battelle
for the Department of Energy

OAK RIDGE
National Laboratory

Border control



Conclusion 1

- Scintillators are widely used in a large number of scientific and industrial domains
- The ideal scintillator does not exist and research should continue on new materials and new production technologies (micro-pulling down)
- Structuring at the nanoscale gives access to quantum confinment phenomena and increases the range of optical electric and magnetic properties that can be engineered
- Metamaterials based on quantum dots, photonic crystals and photonic crystal fibers can open the way to new detection paradigms with huge design flexibility

Conclusion 2

- A number of good scintillators have been discovered that have proved difficult to manufacture – e.g. LuPO4:Ce
- An alternative approach is to start with materials of known manufacturability, and improve the scintillation properties – e.g. PWO, YAG, GGG
- *"One of the continuing scandals i … ciences is that it remains in gene … dict the structure of eve … line solids from a knowl … al composition."*

  , editor of Nature (1988)

Not true anymore!!!