# SNRI

## Seminario Nazionale Rivelatori Innovativi

# Neutron Detectors, Status and Applications
## part 1


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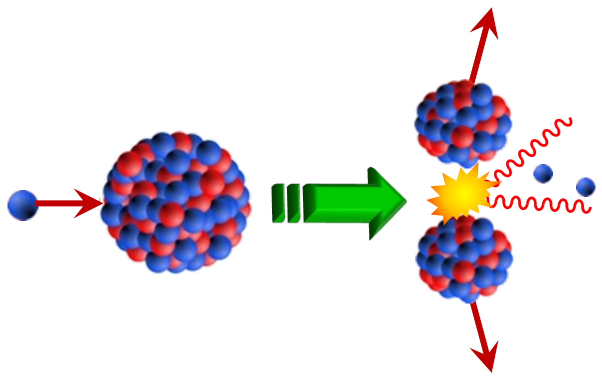
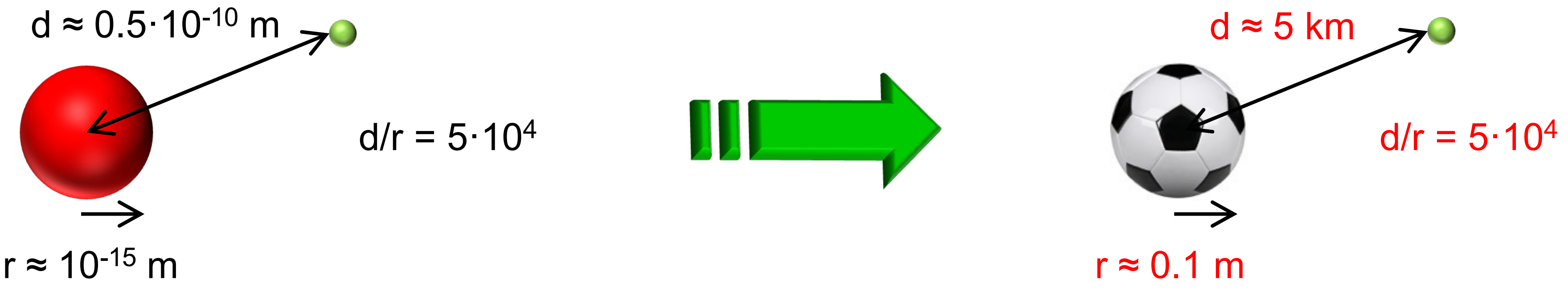


**The world how we see it in our everyday life is gravity and electromagnetism**

**mechanics**

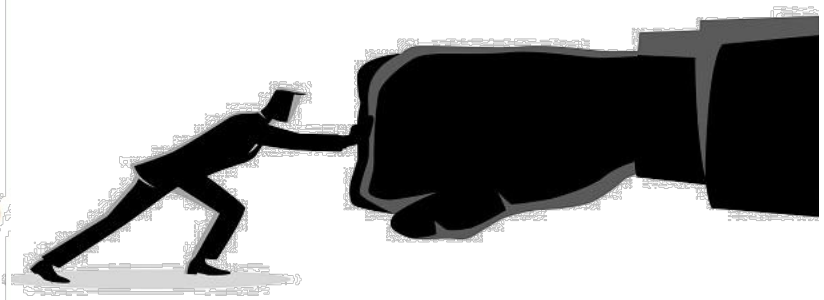
**chemistry**

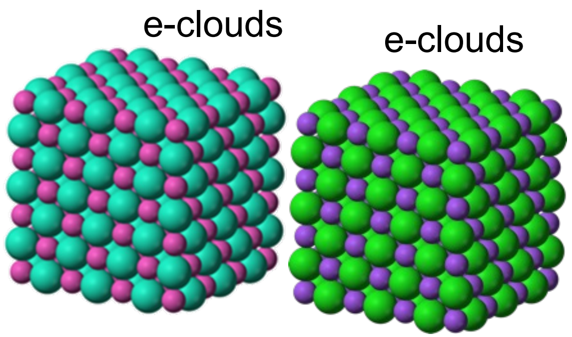

## Things we (should) know but often do not consider properly

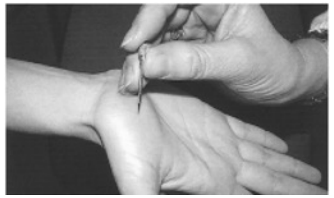



## matter is almost totally EMPTY

## Compactness and impenetrability of matter is illusory





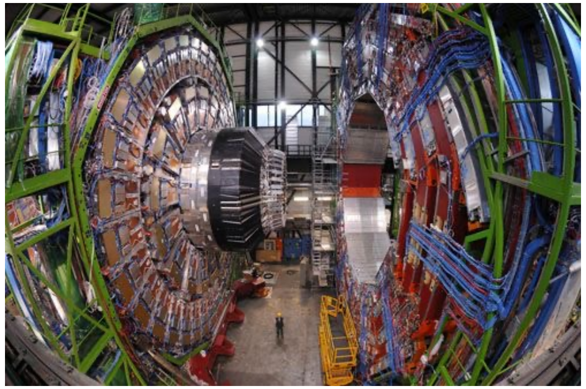



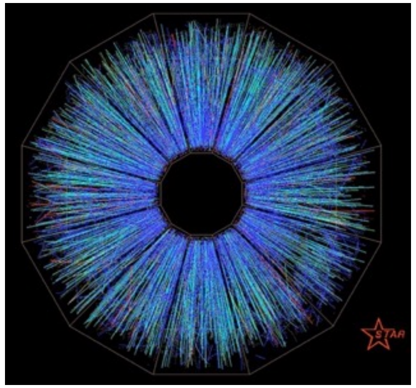
just clouds of electrons repelling other clouds of electrons

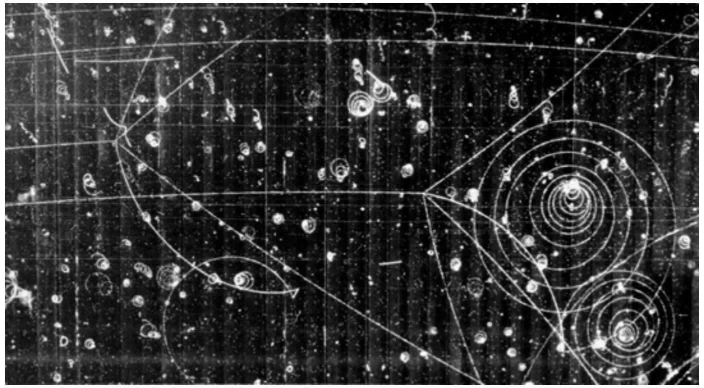
this because the Coulomb force has long range

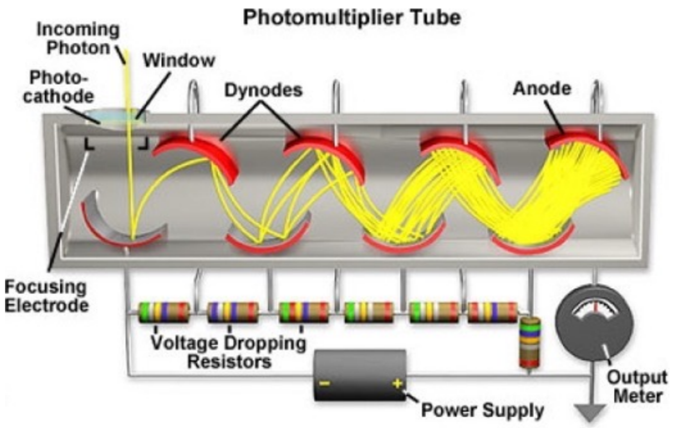
## The subatomic world how we see it in our job is electromagnetism

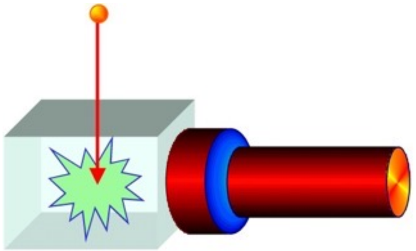
**charged particles interact electromagnetically with matter and produce electrical "signals" (light, pulses, images,...)**



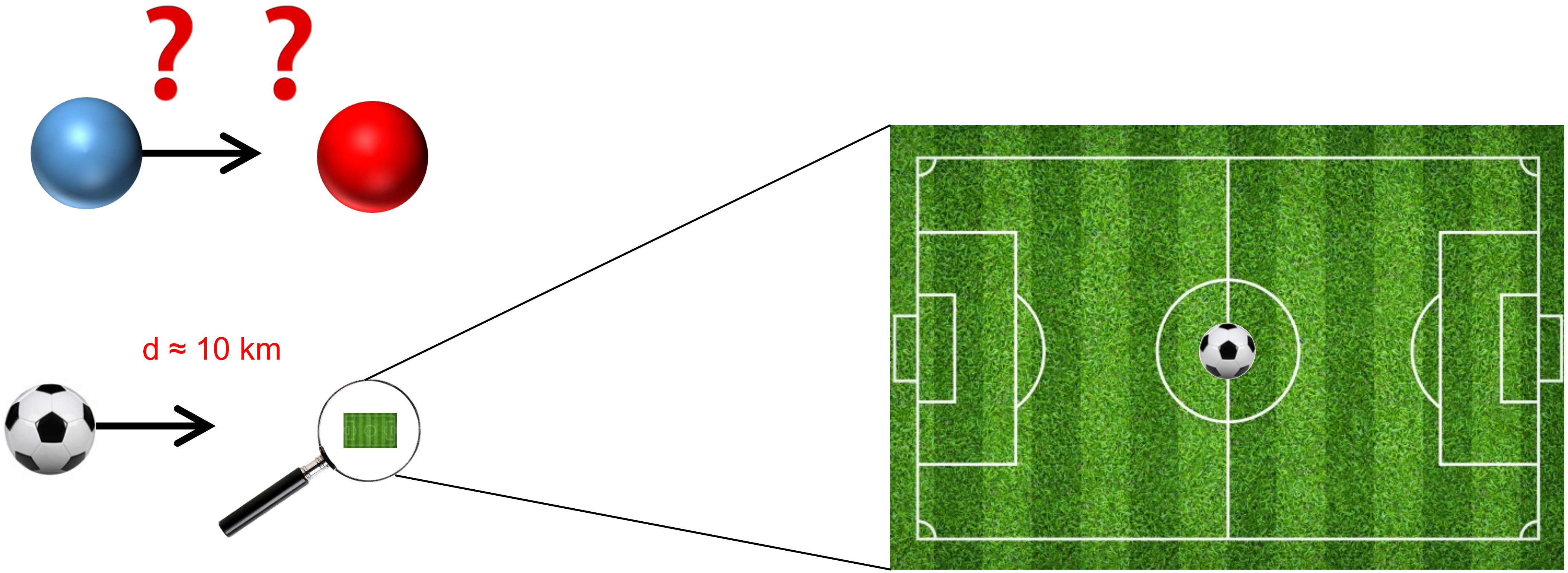




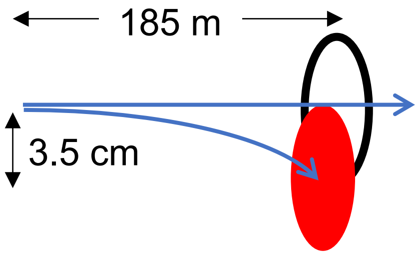


a neutron thrown to hit a proton...




...is like a ball thrown from 10 km away to hit another one!!!




**neutron has no electric charge**

it only feels the nuclear interaction (range ≈ $5 \cdot 10^{-15}$ m)

...but feels gravitation: thermal neutrons **fall down 3.5cm** after flying 185m at n_TOF EAR1

in order to be detected it has to "hit" a nucleus and produce ionizing particles or radiation

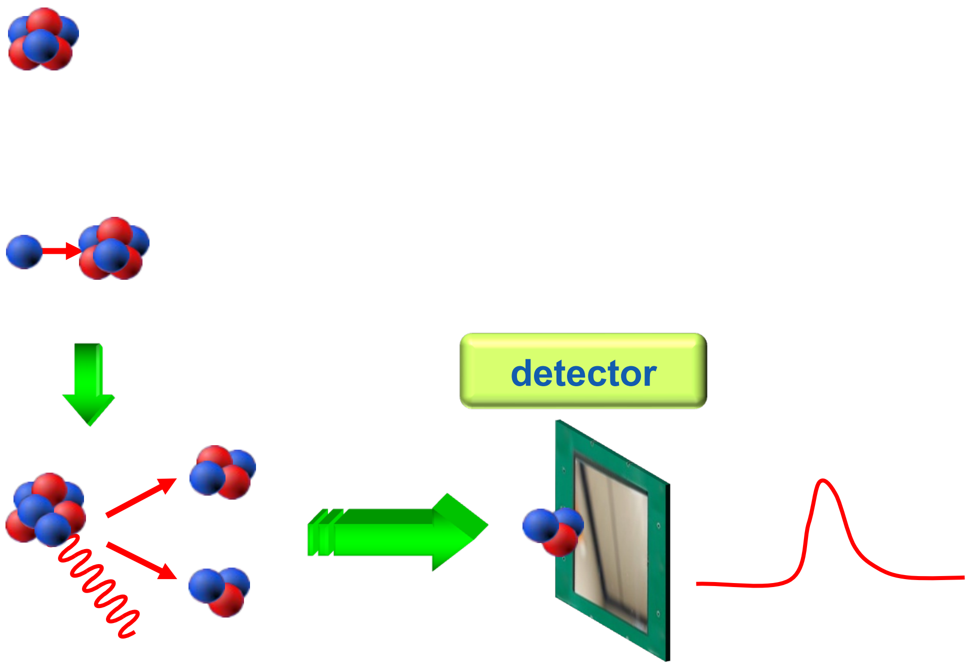
n ● ● p

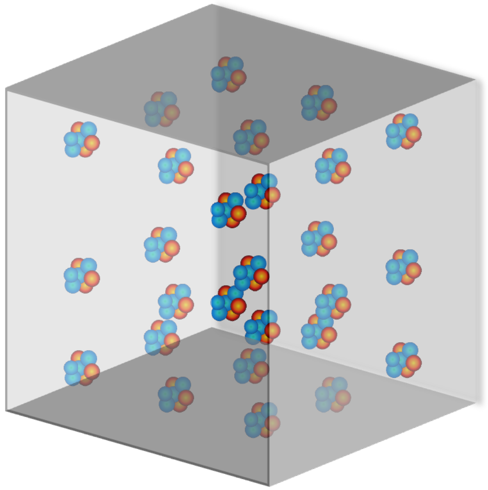
matter is almost empty for neutrons: small cross section

converter

neutron-converter interaction

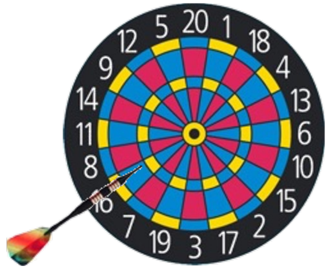
ionizing particle(s) / radiation



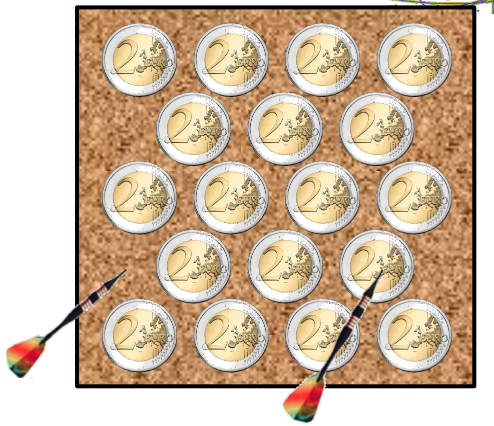
what is cross section?

# cross section is an area...



hit

hit & spark

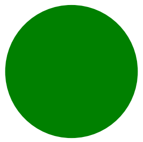


**hit probability**

(# bouncing darts) / (# darts shot) =
(total coin area) / (square box area)

**hit cross section $\sigma_{hit}$**

(hit probability) / (#coins/area)

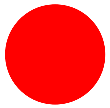


**spark probability**

(# sparking darts) / (# darts shot) =
(total gilded area) / (square box area)

**spark cross section $\sigma_{spark}$**

(spark probability) / (#coins/area)

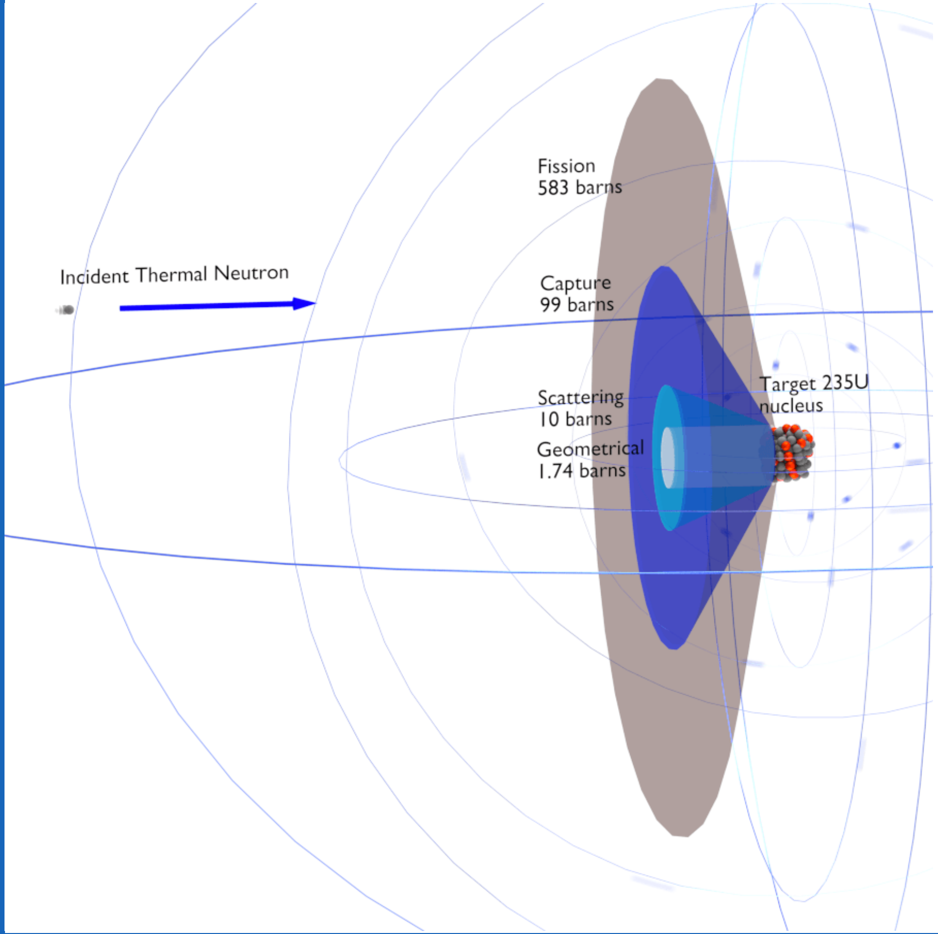


...and represents an interaction probability expressed in barn [$10^{-24}$ cm$^2$]

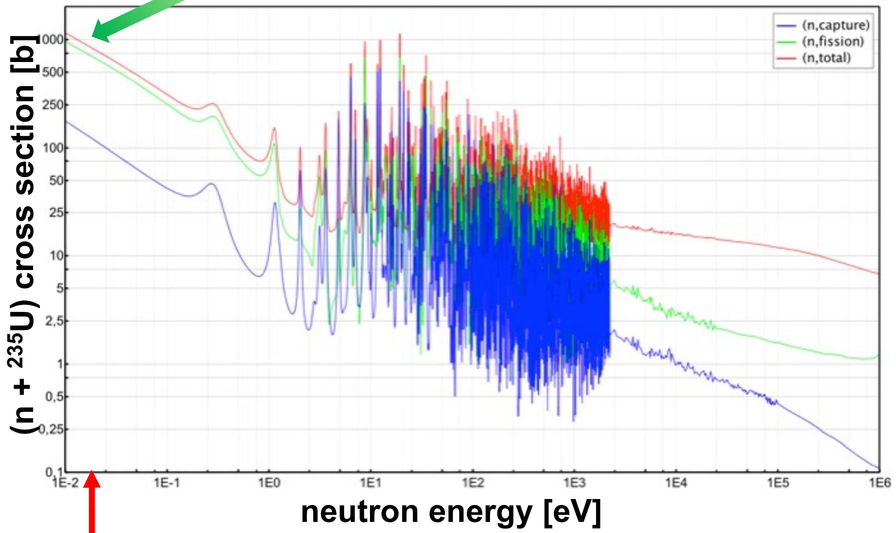
INFN LNS

# cross section is a function of: incident particle, energy, physical process

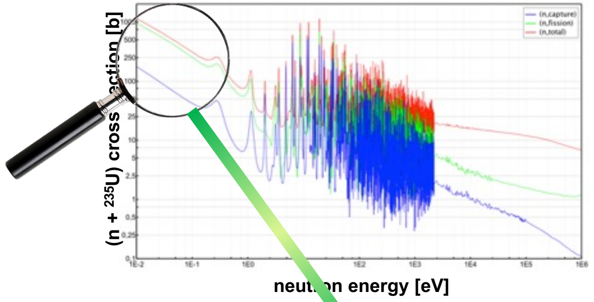
## (n + $^{235}$U) cross section




slow neutrons ➡ large σ



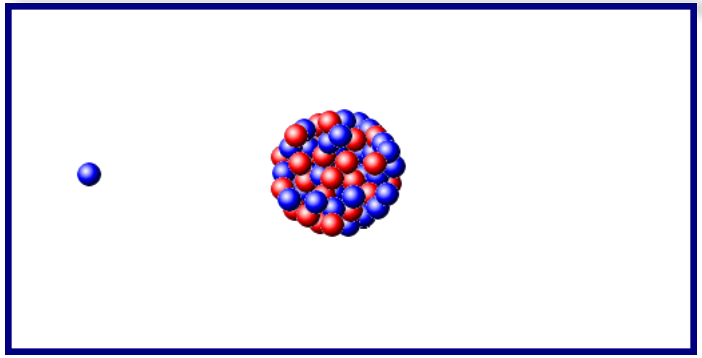

thermal $kT_{298}$ = 25 meV

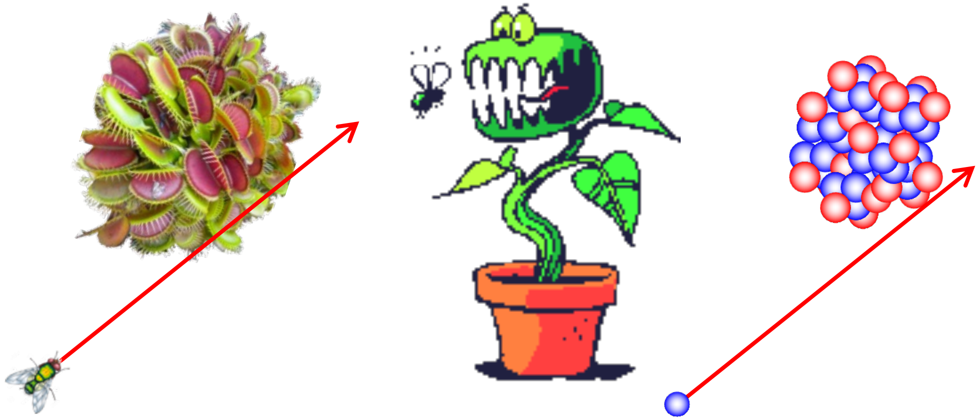


$\sigma \propto 1/v$

**the larger the transit time,**
**the higher the capture probability**

**capture and fission**

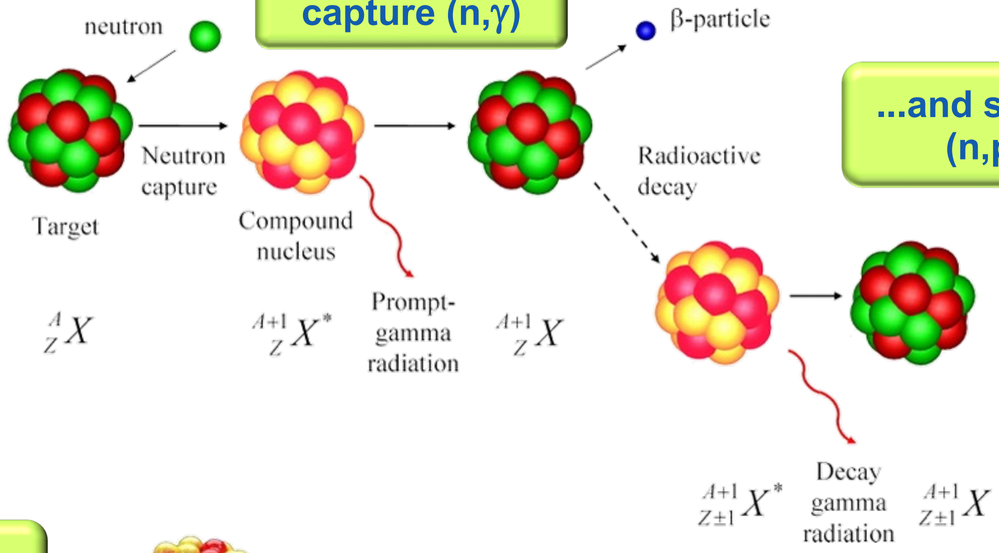




Dionaea muscipula (Venus Flytrap)
is a carnivore plant of the Droseraceae family

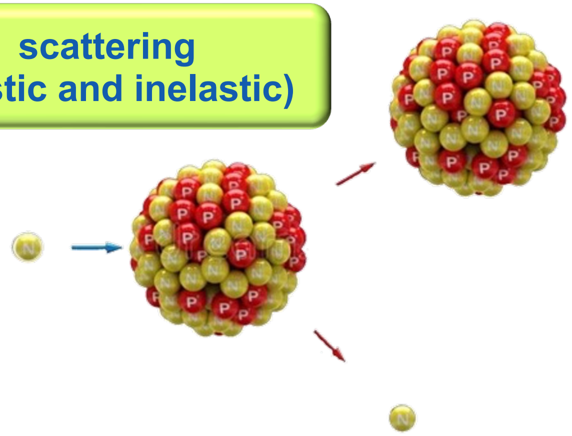
# what happens when a neutron hits a nucleus?

## capture (n,γ)

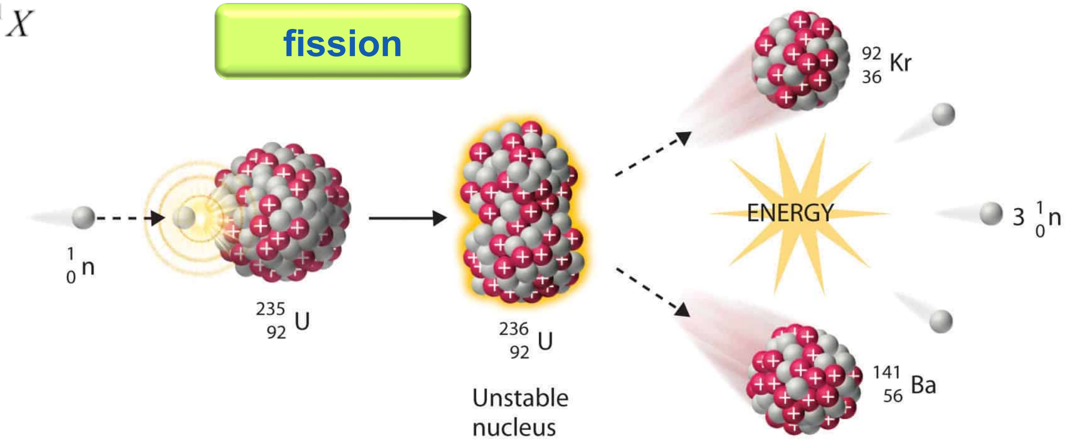



## ...and several other possible reactions
## (n,p), (n,d), (n,t), (n,α), (n,xn),...

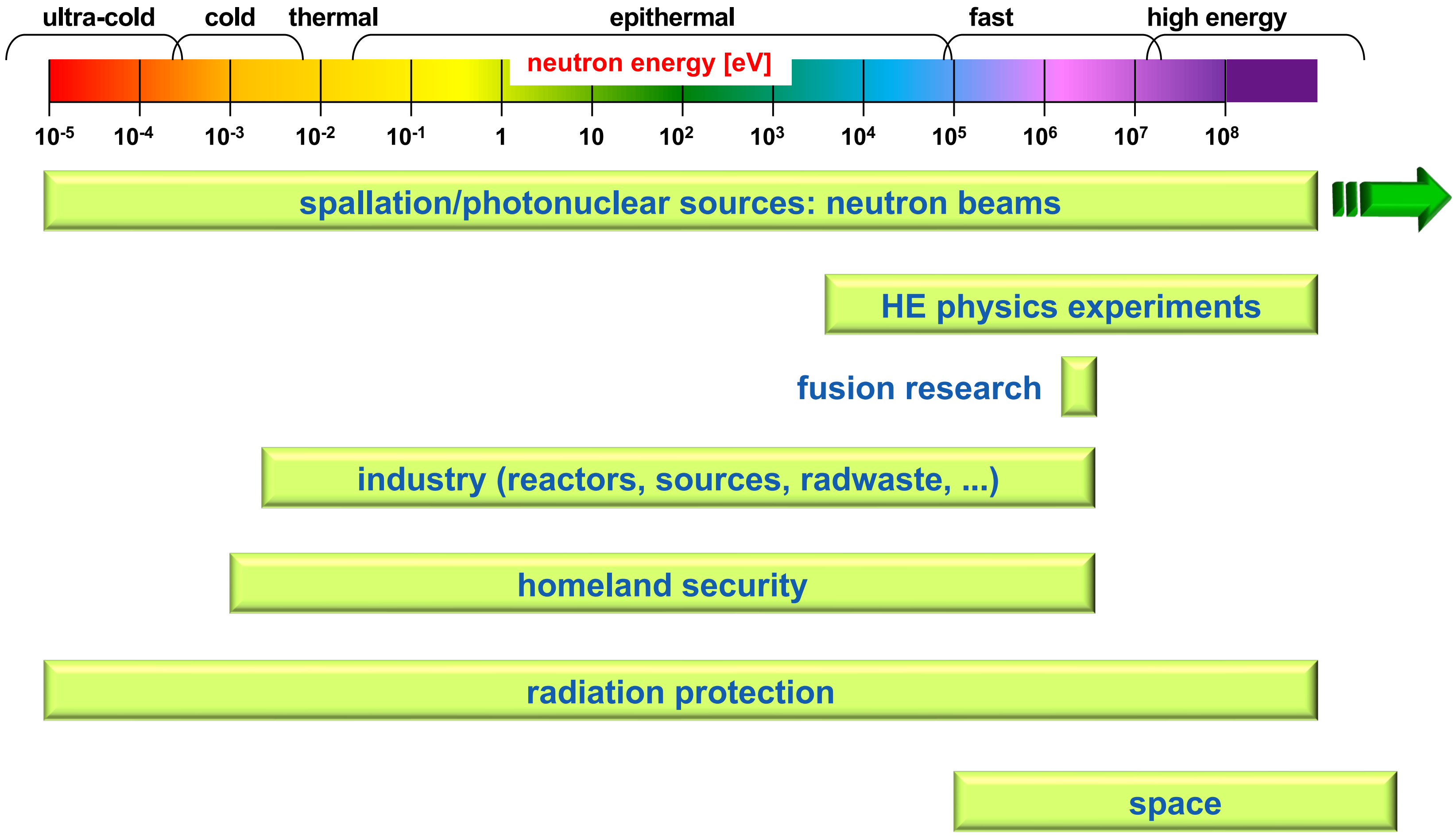
## scattering
## (elastic and inelastic)



## fission



# neutrons where




Spallation
nTOF, ISIS, LANSCE, ESS, ...

Photonuclear
GELINA, ...

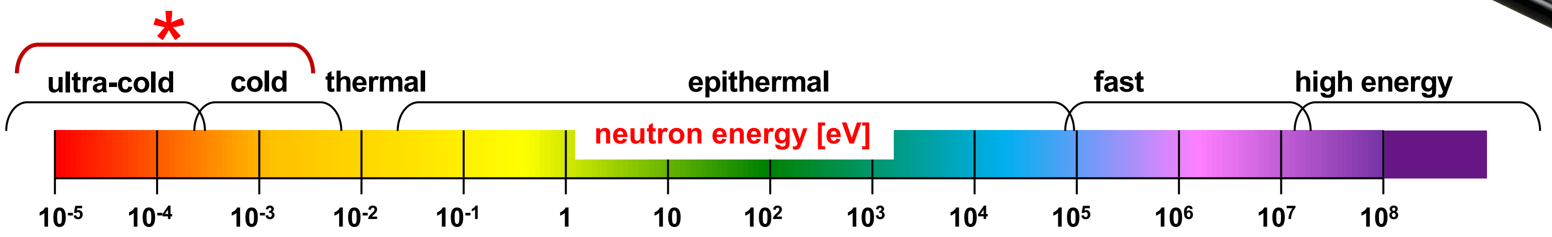
Reactors
FRM II, ILL, ...

dd, dt neutron generators

radioactive neutron sources

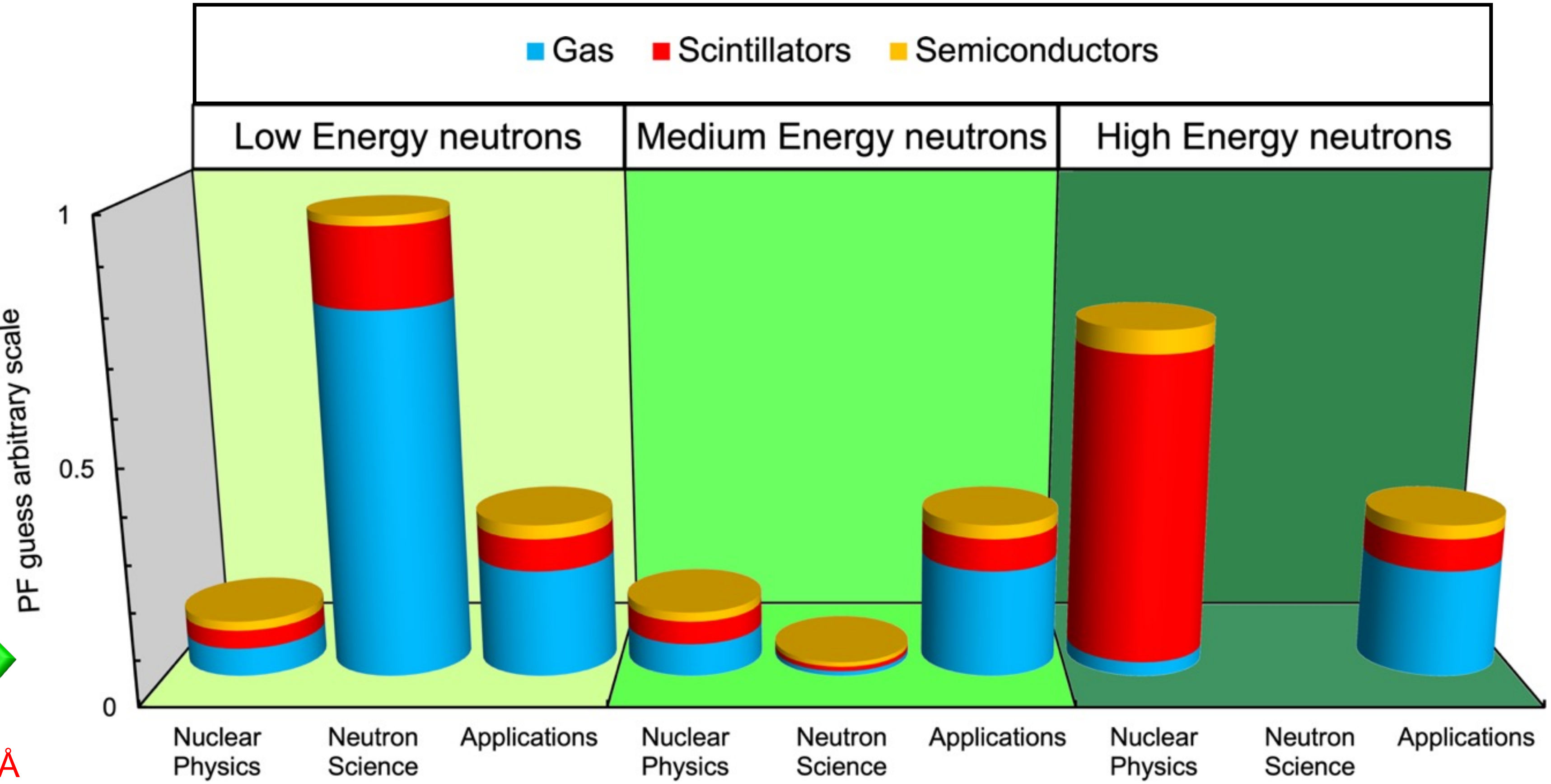
# detecting neutrons can be challenging

(rough) neutron energy classification
≈ arbitrary



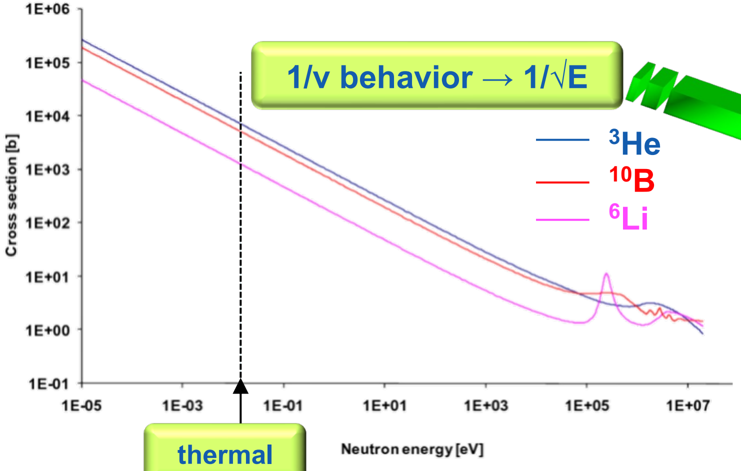

| | |
|---|---|
| ultra-cold | μeV |
| cold | meV |
| thermal | 25 meV |
| epithermal | 100 meV - 100 keV |
| fast | 100 keV – 100 MeV |
| high energy | > 100 MeV |

my (educated) guess of active neutron detectors use




* quantum effects: 1-10 meV → λ ≈ 3-9 Å

# neutron cross section




1/v behavior → $1/\sqrt{E}$

thermal

thermal neutrons → 25.3 meV

25.3 meV · $10^6$ = 25 keV → σ is reduced by a factor $10^3$

easier detecting thermal neutrons
*[for fast neutrons (n,p) scattering is exploited but...]*

$N_A$ = N·thickness

$\sigma \cdot N_A$ = interaction probability

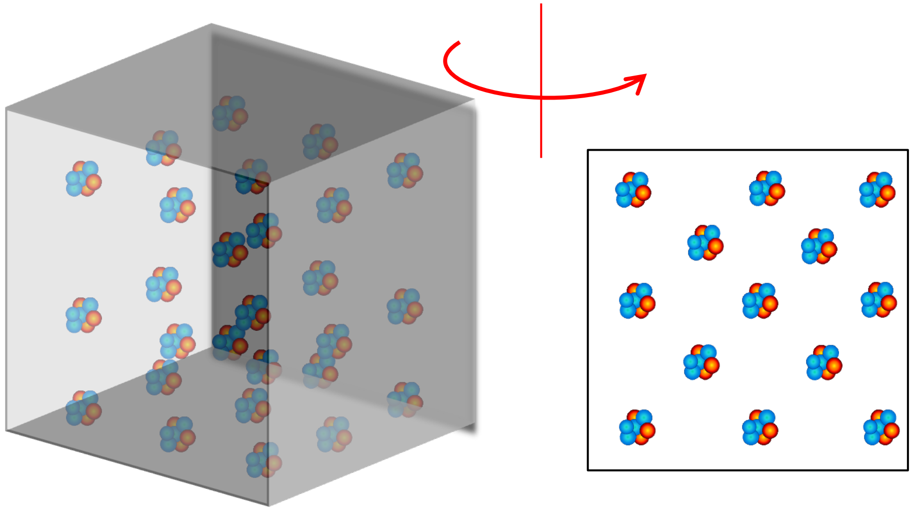
σ·N = interaction probability per unit length

λ = 1/(σ·N) = average length per interaction

λ = mean free path

attenuation of a beam of neutrons through matter

$$N = N_0 e^{-\frac{x}{\lambda}}$$



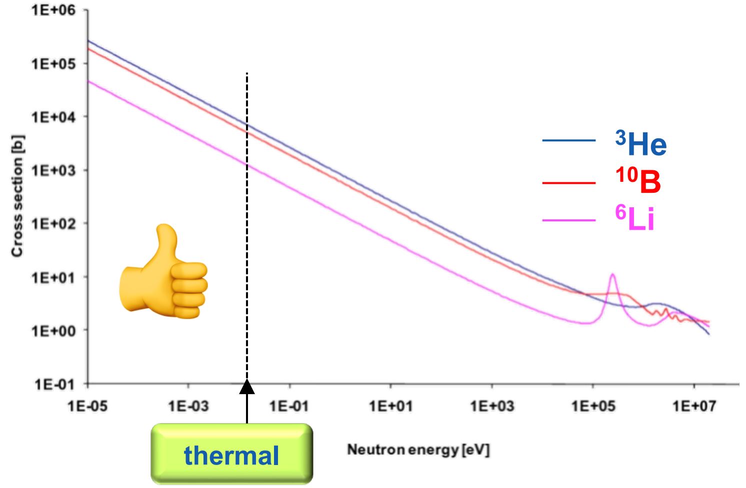
N = n. of atoms per unit volume

$N_A$ = n. of atoms per unit area

## $\sigma \cdot N_A$ = interaction probability

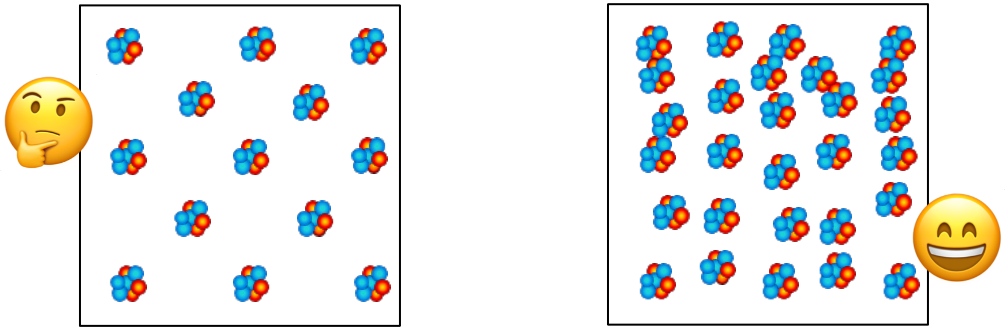
$\sigma$ = cross section

**much easier to detect slow than fast neutrons**




$N_A$ = n. of atoms per unit area

**higher density is more convenient**



# neutron moderation (i.e. slowing down)

neutron mass = 1
nucleus mass = A

energy $E_n$ of the neutron after the collision

$$\left(\frac{A-1}{A+1}\right)^2 E_0 \le E_n \le E_0$$

if colliding with a proton (mass = 1)

$$0 \le E_n \le E_0$$

"simple" kinematic calculations
see W.R.Leo, Techniques for Nuclear and Particle Physics Experiments, chapter 2.8

**light materials (moderators) to slow down neutrons: H-rich, carbon**

why

when hitting a heavy nucleus it retains most of its kinetic energy

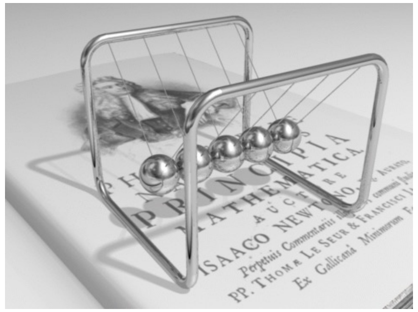
when hitting a proton or neutron it can even stop


hit

bounce

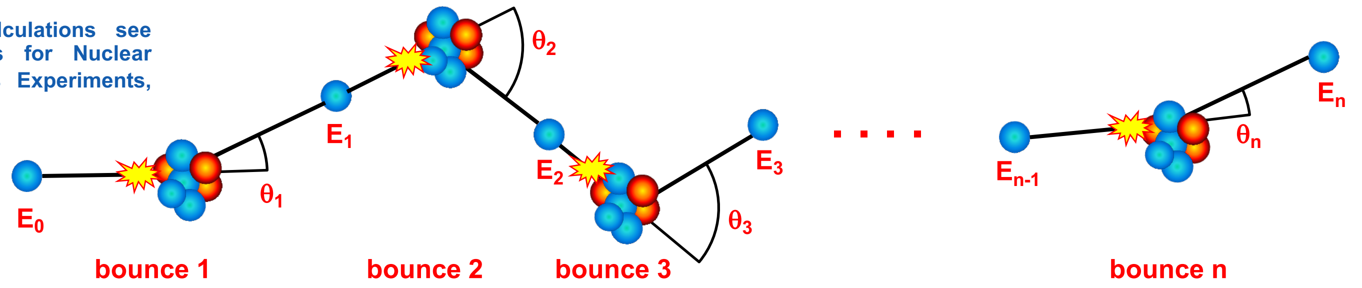
large target mass: small energy loss

equal masses: max energy transfer



# neutron moderation (i.e. slowing down)

for the detailed calculations see W.R.Leo, Techniques for Nuclear and Particle Physics Experiments, chapter 2.8




after each elastic bounce the neutron is deflected by an angle θ, and its energy decreases from $E_{n-1}$ to $E_n$

we call **lethargy** the quantity $$-\frac{\Delta E}{E} = \Delta u$$ that is the relative energy change in a collision

its average value (average over all the possible scattering angles) is $$\langle \Delta u \rangle = \xi = 1 + \frac{(A-1)^2}{2A} ln \frac{A-1}{A+1}$$

and only depends on the mass number of the target nucleus

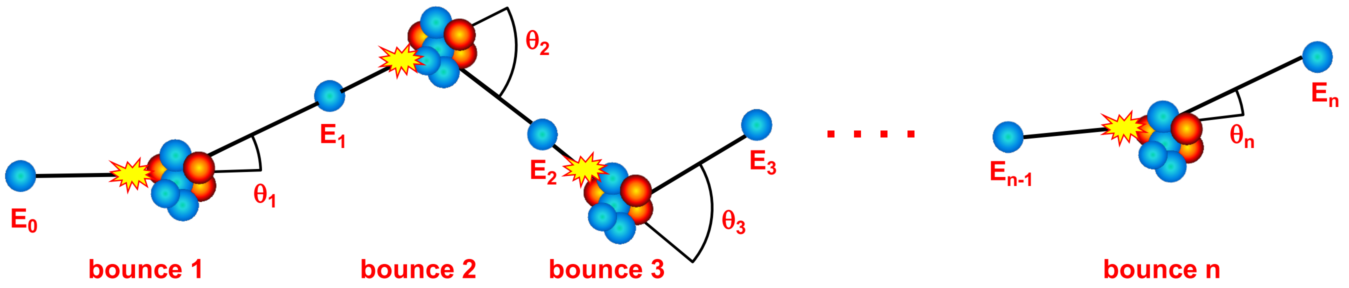
the total lethargy in n collisions (i.e. with the energy going from the initial $E_0$ to the final E) is

$$u \approx \int_{E_0}^{E} -\frac{dE}{E} = [-lnE]_{E0}^{E} = lnE_0 - lnE = ln\frac{E_0}{E}$$

therefore the average number of elastic collisions required to reduce the energy from E0 to E is

$$n = \frac{u}{\langle \Delta u \rangle} = \frac{u}{\xi} \approx \frac{1}{\xi} ln \frac{E_0}{E}$$

# neutron moderation (i.e. slowing down)




lethargy in one collision with proton

$$\xi = 1$$

average number of elastic collisions with protons required to reduce the energy 6MeV to 25meV is

$$n = \frac{u}{\langle \Delta u \rangle} = \frac{u}{\xi} \approx \frac{1}{1} ln \frac{E_0}{E} = 19.3$$

polyethylene $CH_2$ density 0.935 g/cm3

we neglect the role of C (n = 122 collisions)

assume $<\sigma_{H\_elastic}> \approx 20$ b

mean free path $\lambda \approx 0.62$ cm

total path to thermalize L ≈ 12 cm

$$\cos\theta_{lab} = \frac{A\cos\theta_{cm} + 1}{\sqrt{A^2 + 1 + 2A\cos\theta_{cm}}}$$

$<cos(\theta_{lab})> \approx 0.66$

$<\theta_{lab}> \approx 0.85$

$CH_2$ thickness to thermalize 6 MeV neutrons

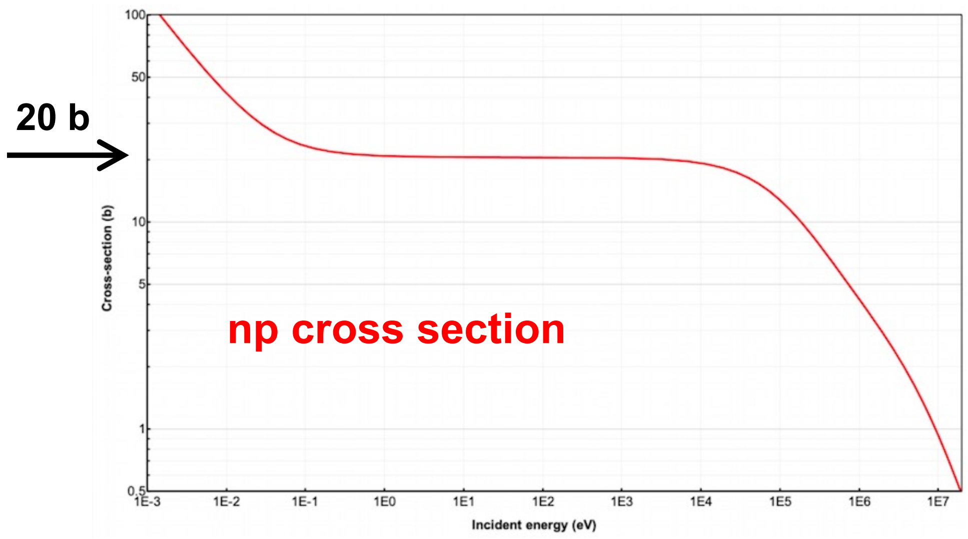
≈ 12 x 0.66 = 8 cm

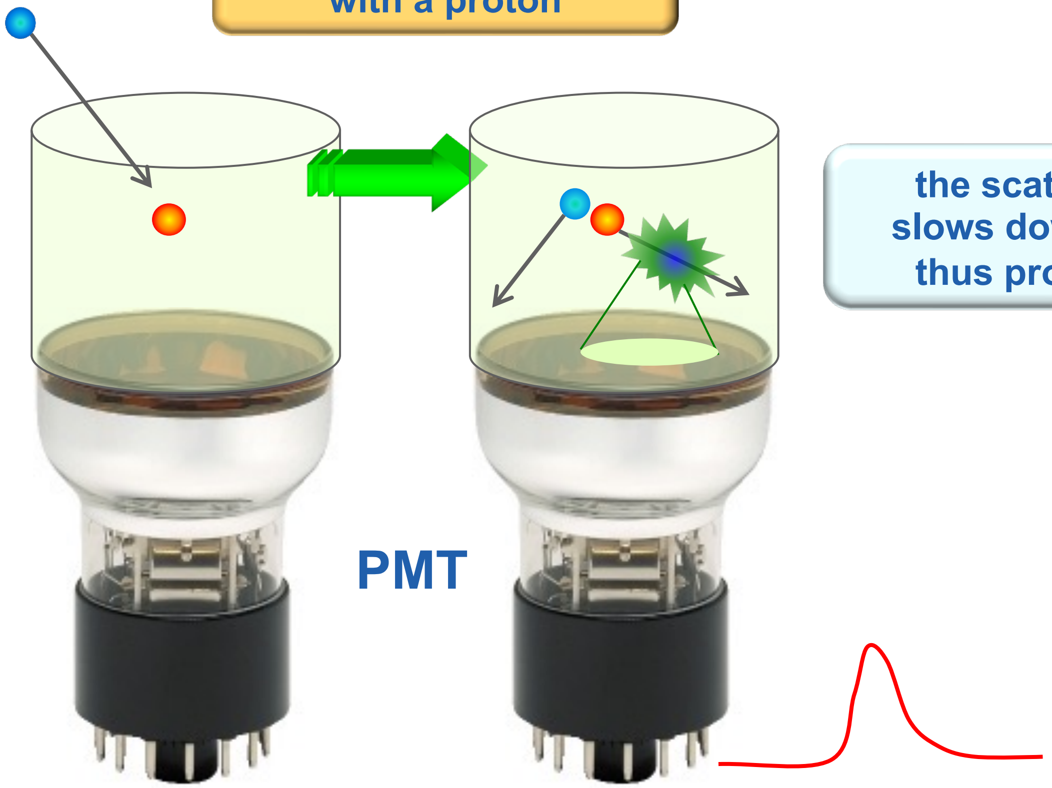
# detecting fast neutrons

n p

a neutron enters
the liquid scintillator
(rich with hydrogen)

elastic collision
with a proton




the scattered proton
slows down and stops,
thus producing light

# materials for neutron conversion

the geometrical cross section is smaller than the white central dot

## cross sections for incident thermal neutrons

| Species | σ [b] |
|---|---|
| $^{235}U(n,f)$ | 600 |
| $^{6}Li(n,\alpha)$ | 1000 |
| $^{10}B(n,\alpha)$ | 3800 |
| $^{3}He(n,p)$ | 5300 |
| $^{113}Cd(n,\gamma)$ | 20000 |
| $^{157}Gd(n,\gamma)$ | 250000 |

$^{235}$U dangerous strategic material

$^{6}$Li

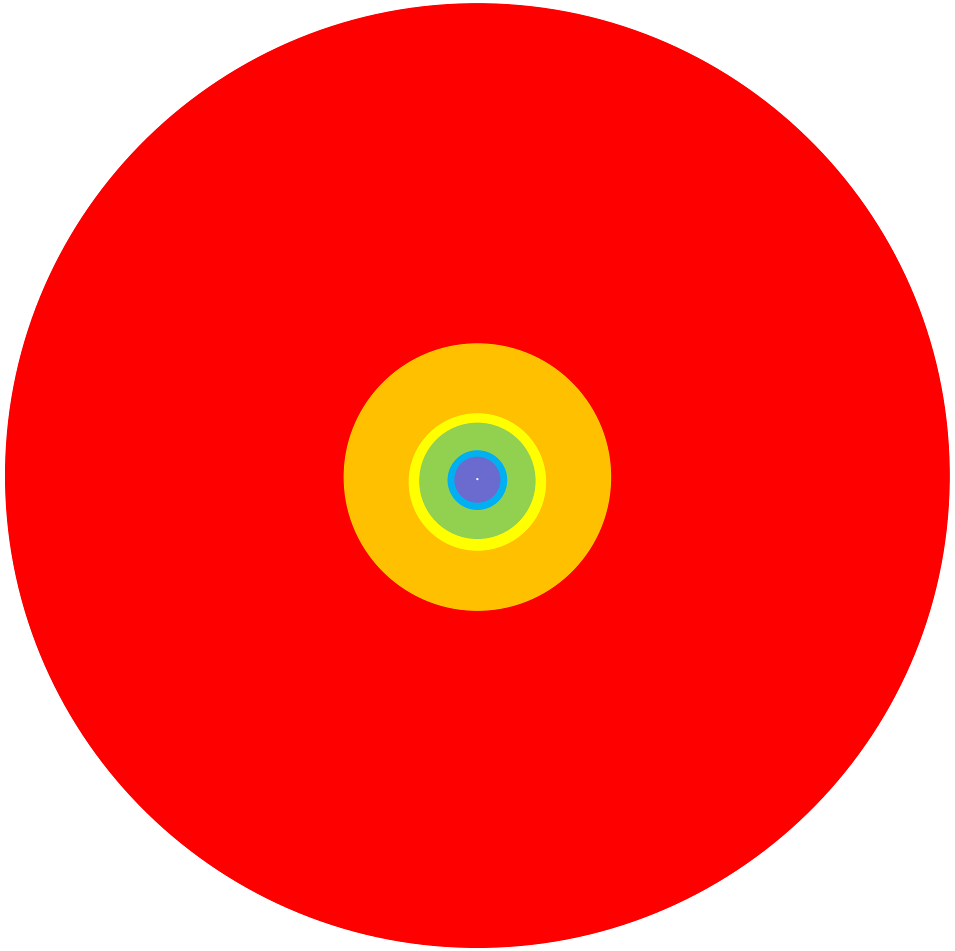
$^{10}$B

$^{3}$He

$^{113}$Cd too many gammas (and toxic)

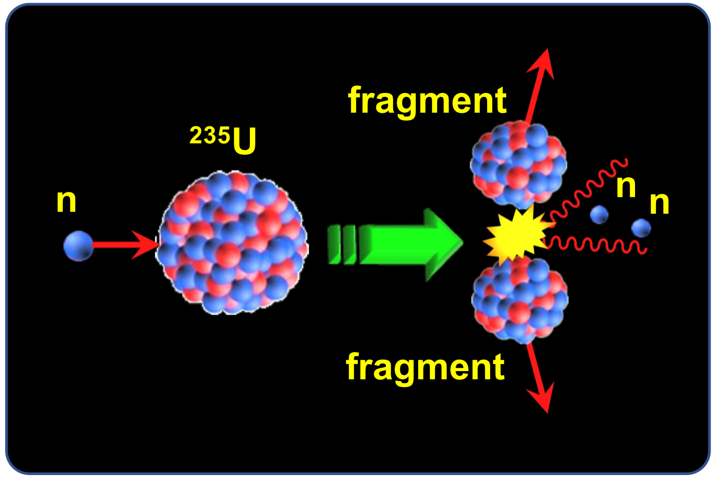
$^{157}$Gd too many gammas (and toxic)

$^{235}$U, $^{113}$Cd, $^{157}$Gd are sometimes used as well



## materials for thermal neutron conversion: which one?


$^{235}U$




$\sigma(0.025) \approx 570$ b

available E
≈ 200 MeV

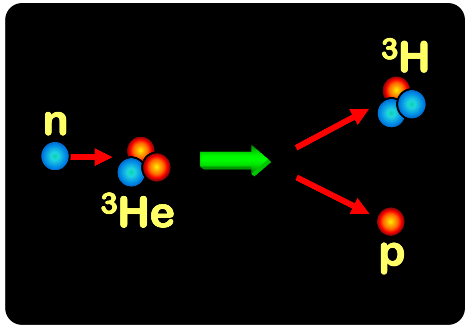
...heavy fragments easily stopped, gas chamber needed

## materials for thermal neutron conversion

**$^3He$**

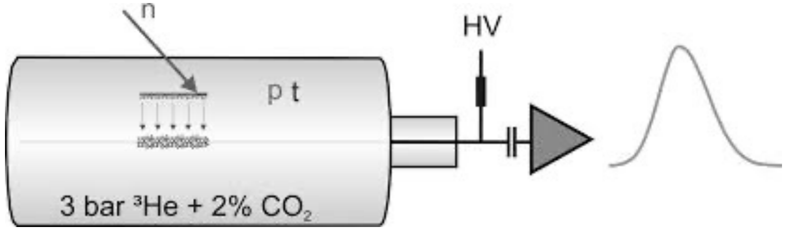
σ(0.025) ≈ 5330 b

available energy
0.76 MeV
no gamma rays




- p and $^3H$ ionize the gas
- the produced ions are collected by means of an electric field
- the produced signal indicates the detection of a neutron

**perfect gas detector**

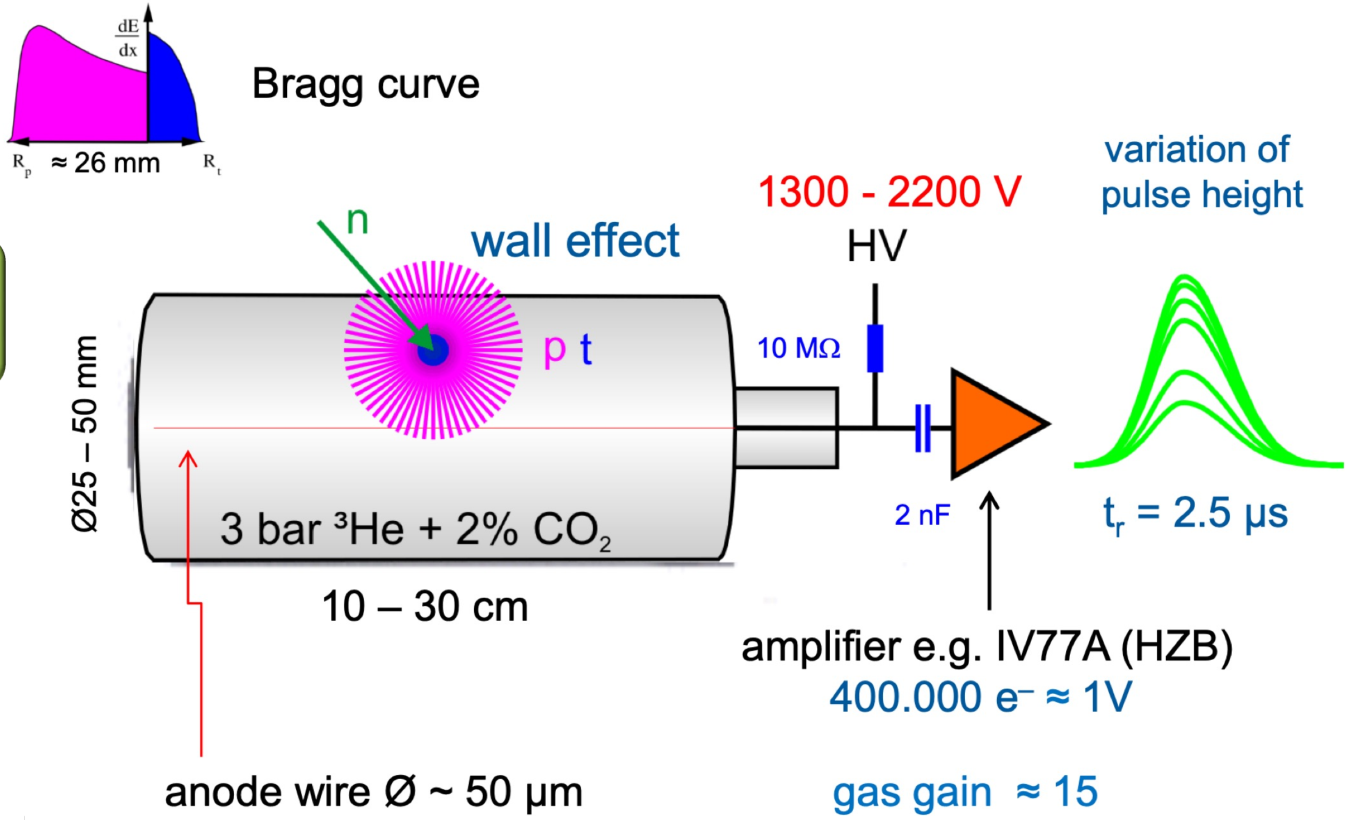


# $^3$He Proportional Counter (Tube)

HZB Helmholtz Zentrum Berlin

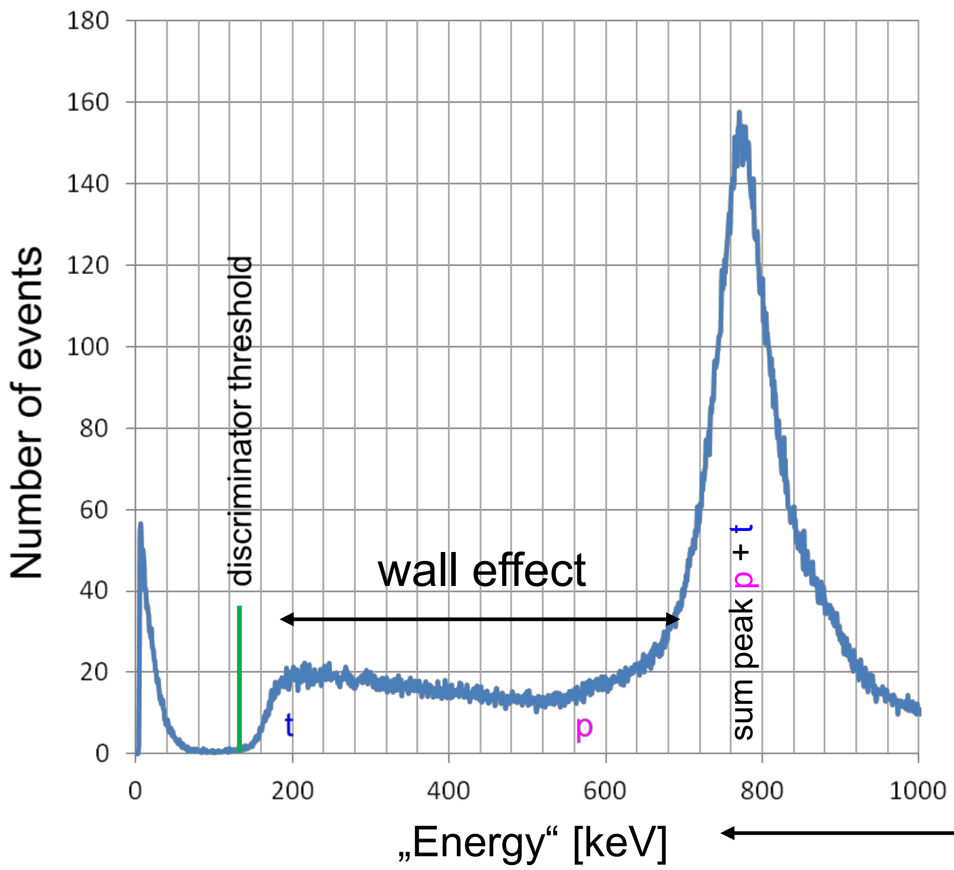
$^3He(n,p)^3H$  p = 573 keV , $^3H$ = 191 keV ($E_{tot}$ = 764 keV, $q_p \approx 2.5\cdot10^4\ e^-$)

**the king of neutron detectors:**
**$^3$He proportional counter (tube)**




CREMLIN Workshop, May 13-16, 2018, St. Petersburg Th. Wilpert, HZB $^3$He Detectors

# $^{3}$He-Tube – Pulse Height Spectrum




The pulse height spectrum is influenced by

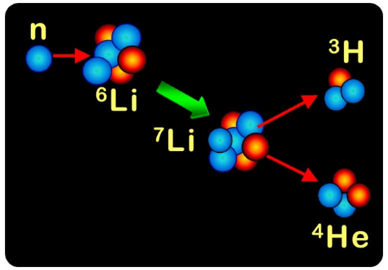
- Pressure in tube
- Geometry (size vs. pressure)
- Gas composition & quality
- Properties of amplifier (shaping)
- $\gamma$-background
- Count rate
- BUT: not by neutron energy

$^{3}$He(n,p)t (Q = 764 keV)

CREMLIN Workshop, May 13-16, 2018, St. Petersburg    Th. Wilpert, HZB    ³He Detectors

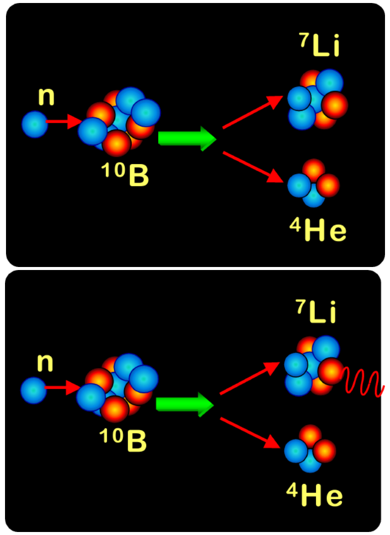
## materials for thermal neutron conversion: which one?


$^{6}$Li



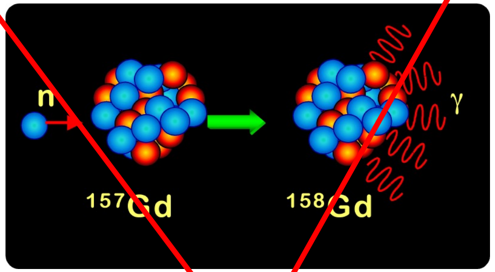

$\sigma(0.025)$
$\approx$ 940 b
available E
4.78 MeV


$^{10}$B



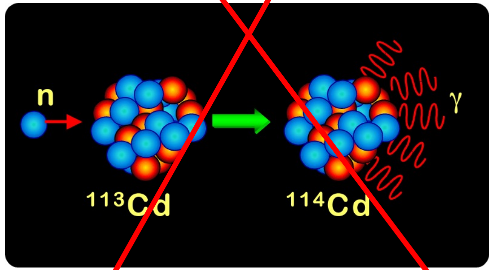

$\sigma(0.025)$
$\approx$ 3840 b
available E
2.79 MeV
(and gamma rays)

$^{157}$Gd




$\sigma(0.025)$
$\approx$ 240 kb

$^{113}$Cd

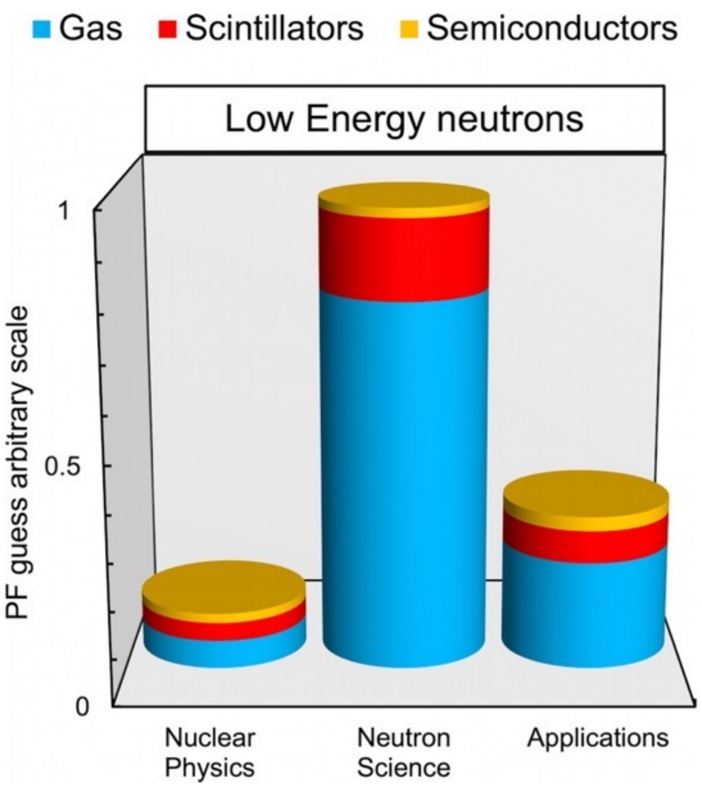


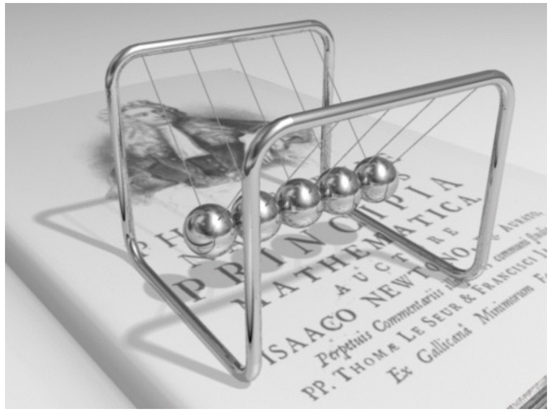

$\sigma(0.025)$
$\approx$ 20 kb

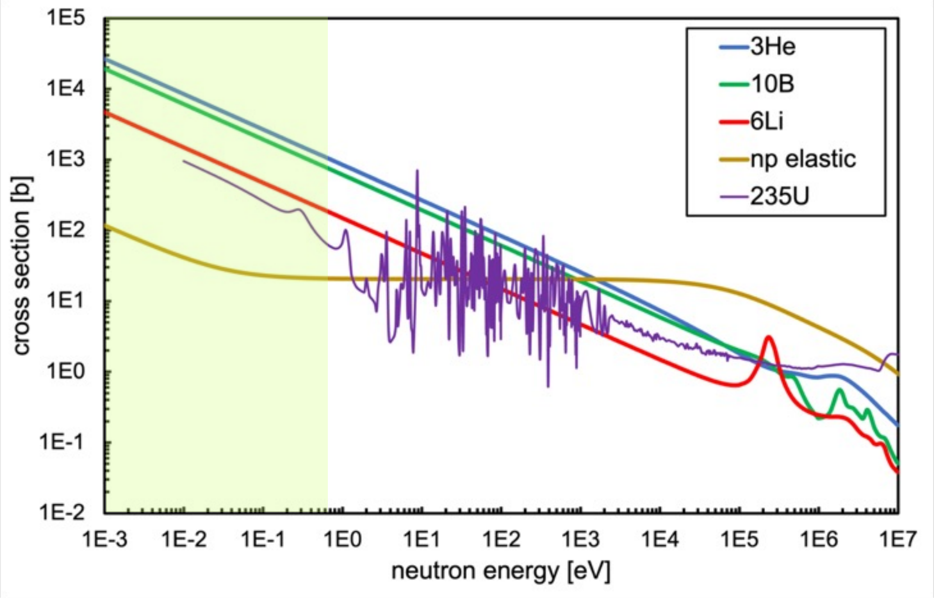
large available E
but in form of gamma rays:
difficult neutron identification

# low energy
## neutrons can be already slow
## or require moderation (H-rich materials)

$^{3}He(n,p)^{3}H$
$^{10}B(n,\alpha)^{7}Li$
$^{6}Li(n,t)\alpha$
$^{235}U(n,fission)$
~~$^{1}H(n,p)n$~~

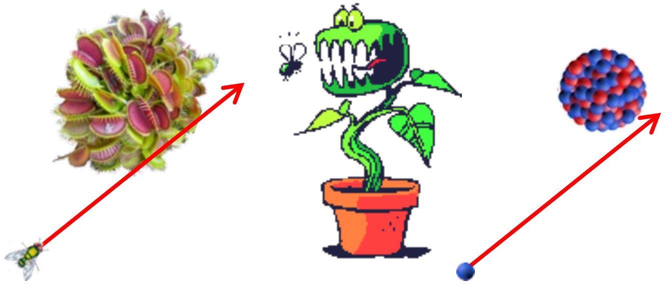


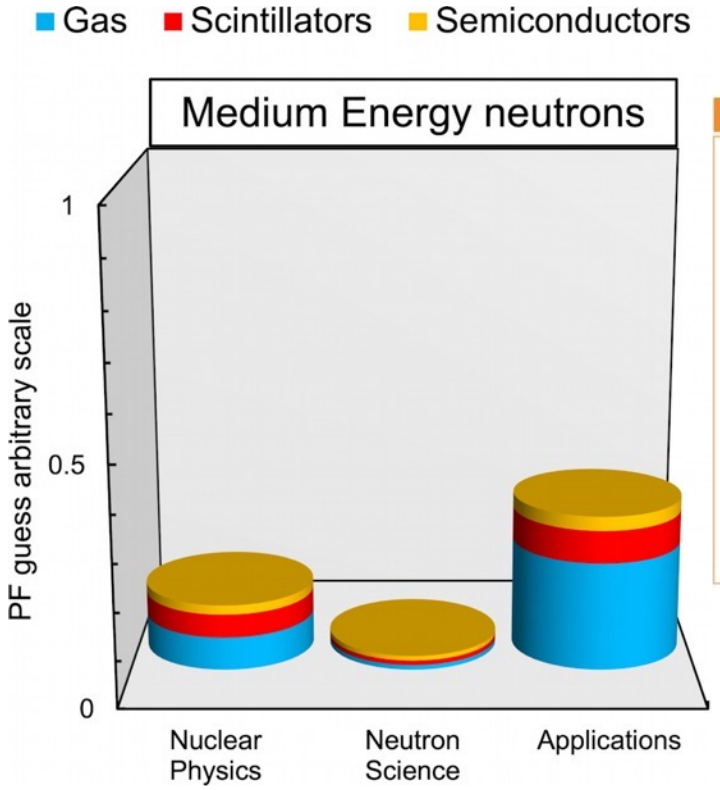


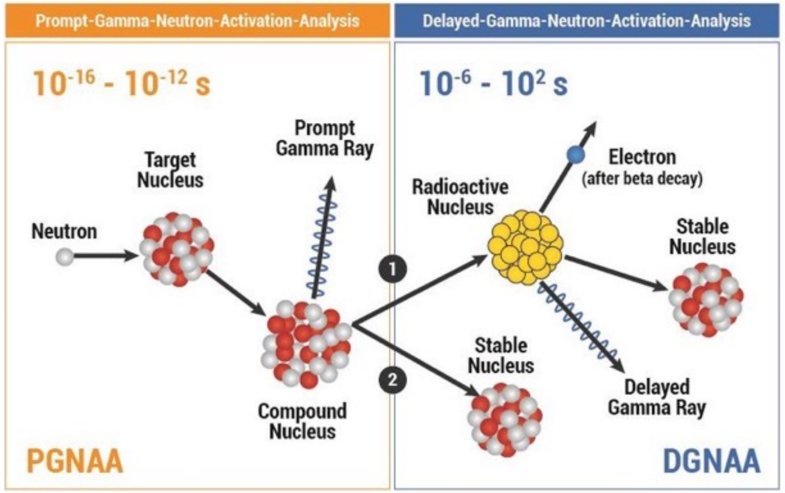

$\sigma \propto 1/v$

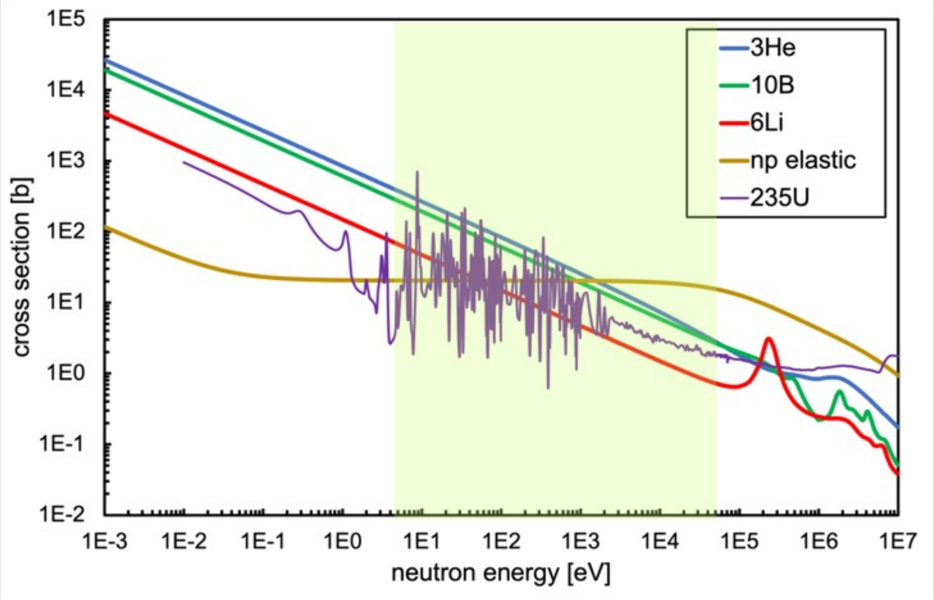
the longer the transit time,
the higher the capture probability



## medium energy
**more difficult event-by-event detection**
**radiative capture, fission**
**or require moderation**

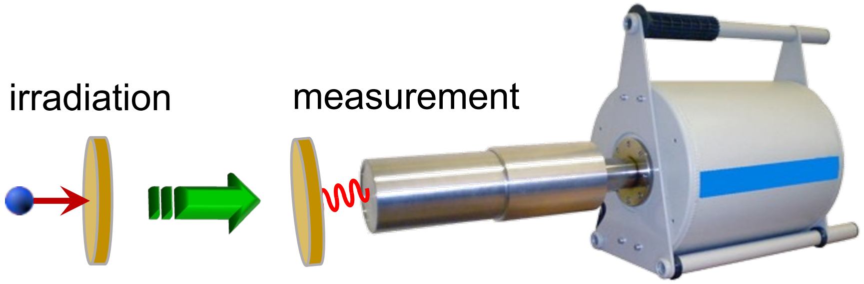


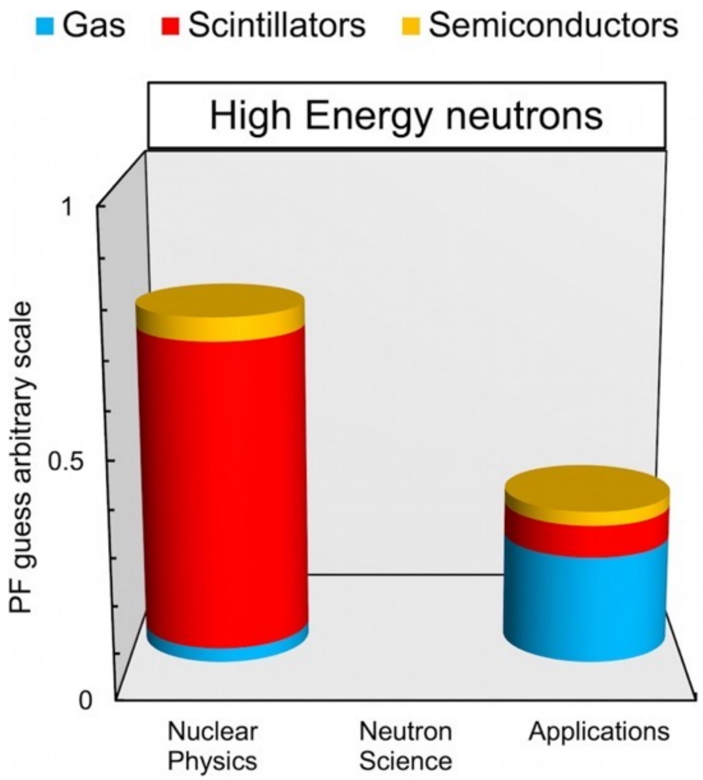



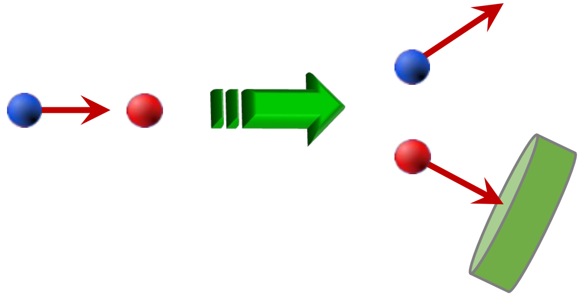

**activation foils**
**resonance foils**
**threshold foils**

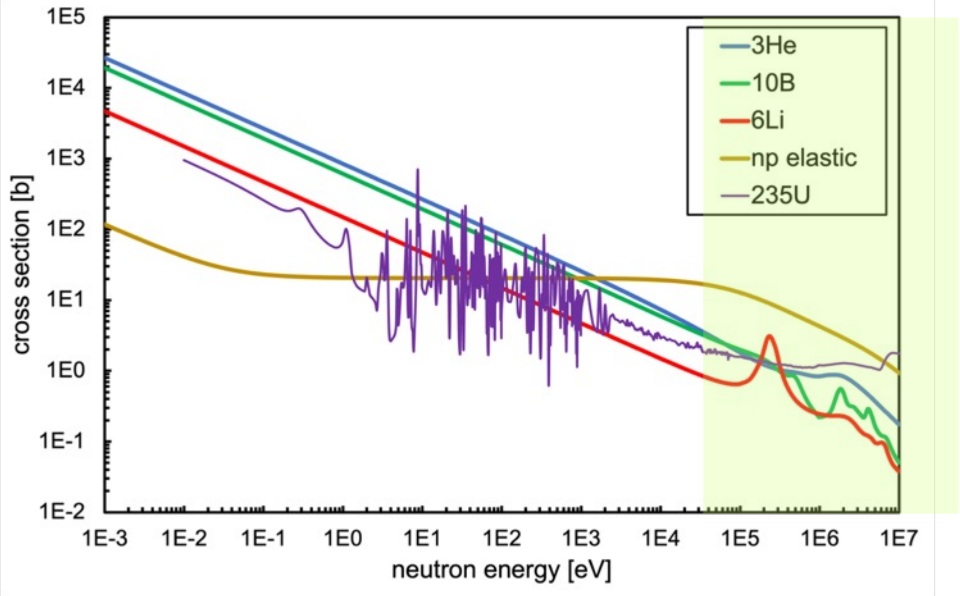
$^{23}$Na, $^{55}$Mn, $^{59}$Co, $^{63}$Cu, $^{65}$Cu, $^{115}$In, $^{123}$I, $^{197}$Au, ...



high energy
np scattering → p recoil
fission
or require moderation



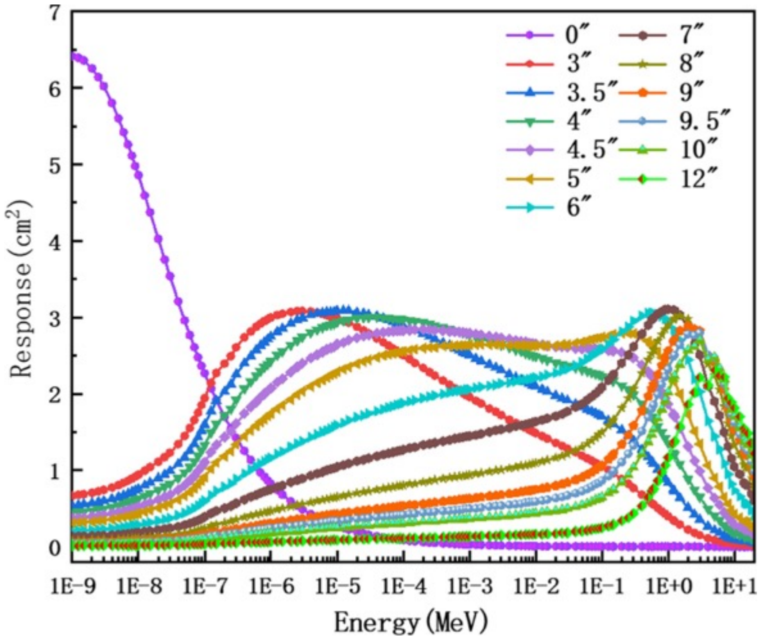


# neutron spectrometry (measuring neutron energy)

## Bonner spheres

require bayesian unfolding

## Geant4 response simulation

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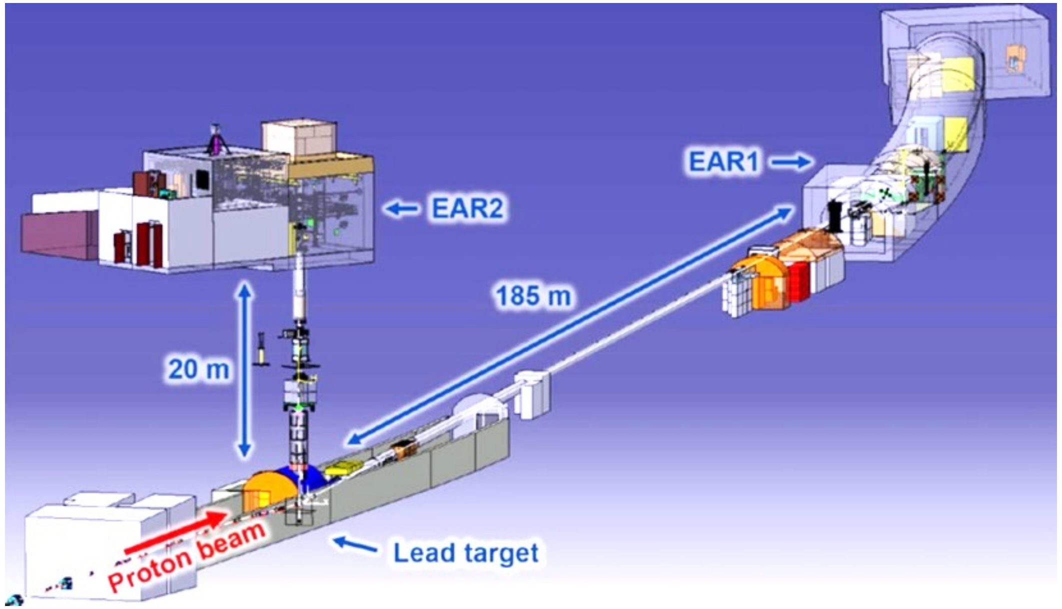
https://doi.org/10.1007/s41365-022-01139-2

spectrum, not event by event

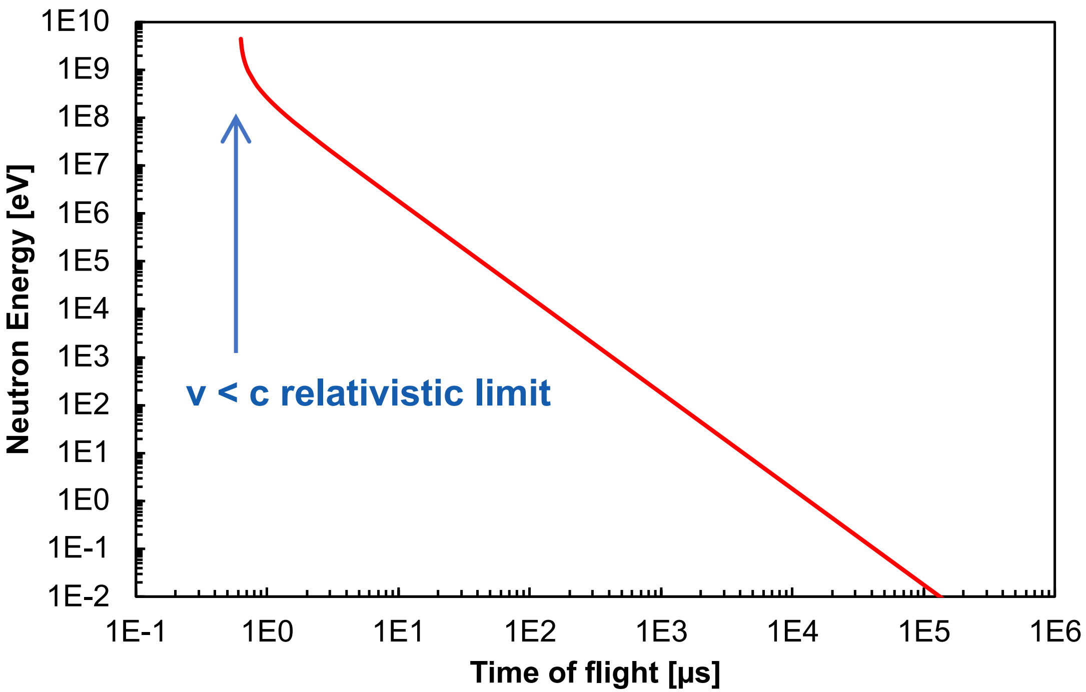
# neutron spectrometry (measuring neutron energy)

## Time Of Flight

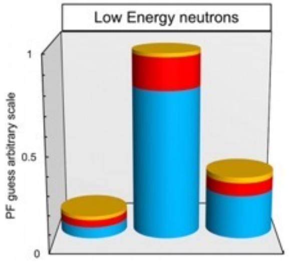



requires a start signal (gamma flash)

## ToF to Energy




event by event




**gas technology highly consolidated especially in neutron science mainly exploited at low energy**

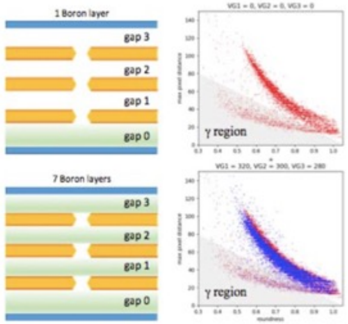
## gas detectors

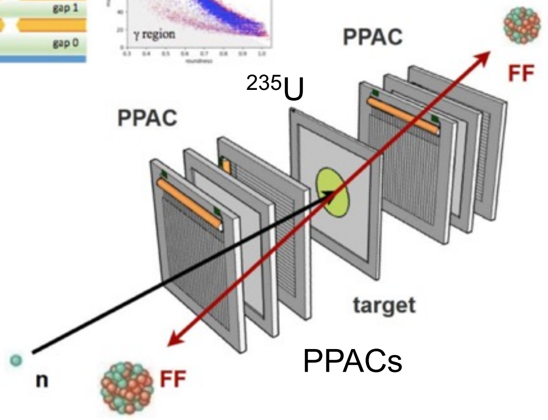
- Proportional Counter
- Ionization Chamber
- Fission Chamber (LE, HE $^{235}U$, $^{nat}U$)
- Parallel Plate Avalanche Counter
- Multi Wire Proportional Counter
- Micro Strip Gas Detector
- Micromegas
- Gas Electron Multiplier (1x, 2x, 3x)
- Straw Tube
- Big *Instruments* at neutron facilities
- ...

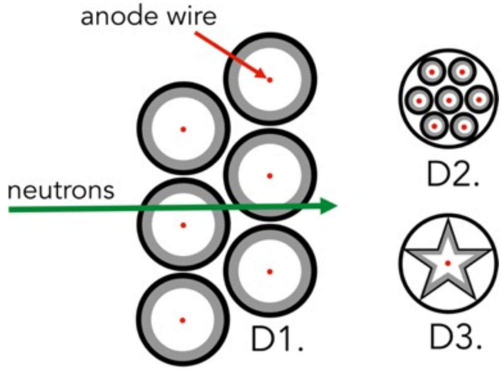
## converters

- pure $^{3}He$ or in mixture, $BF_3$
- solid $^{10}B$, $^{6}Li$, $^{235}U$ converter:
- standard gas, converter liner
- standard gas, converter plates/blades
- standard gas, converter in structures
- standard gas, converter on electrodes
- high pressure $CH_4$, $C_3H_8$ (p recoil at HE)

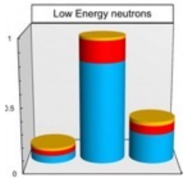
Borated GEM



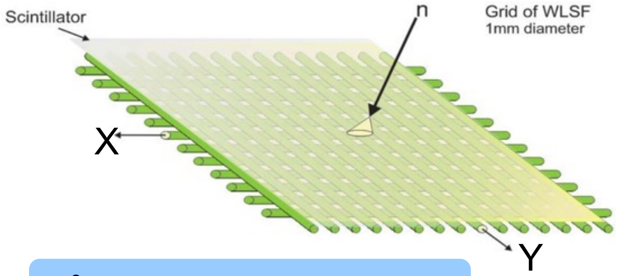

Straw tubes



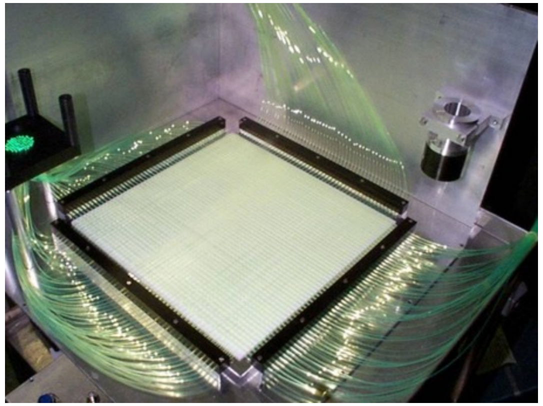

**low energy**

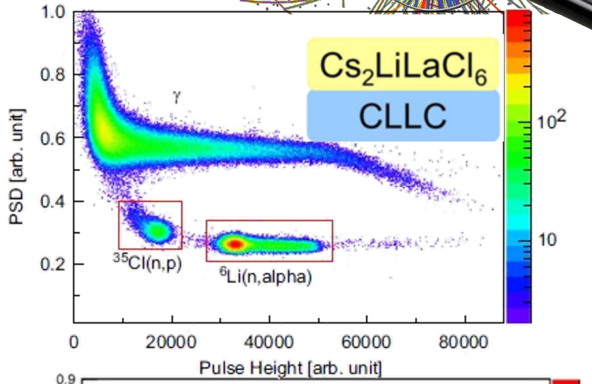
**scintillators**

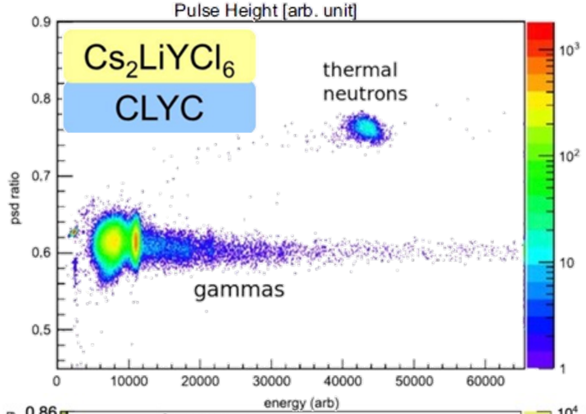
- crystals containing $^6$Li (CLYC, CLLC, CLLB, LiI)
- organics (plastics, liquids) containing $^6$Li or $^{10}$B
- + Pulse Shape Discrimination (PSD)
- $^6$Li/ZnS(Ag) screens (+XY WLS fibers)
- Gd based screens (+ camera)
- Li or B glass (+ camera)
- Li or B SFOP (+ camera)

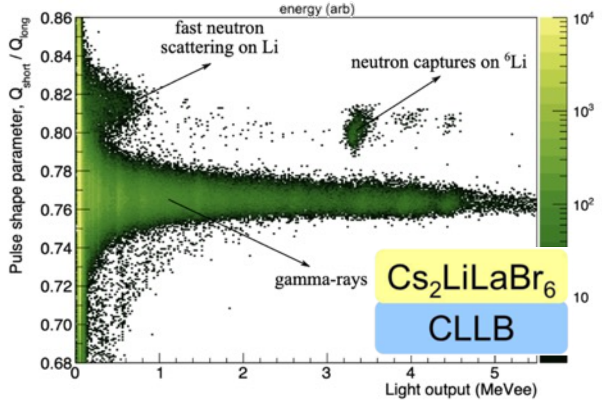


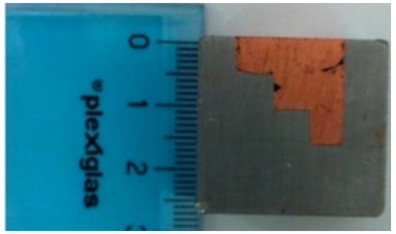

$^6$Li/ZnS(Ag) fiber detector

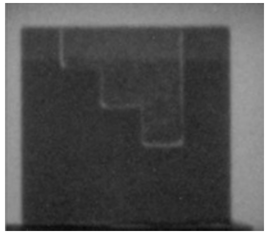




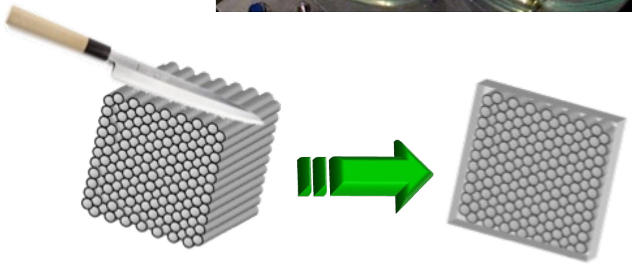



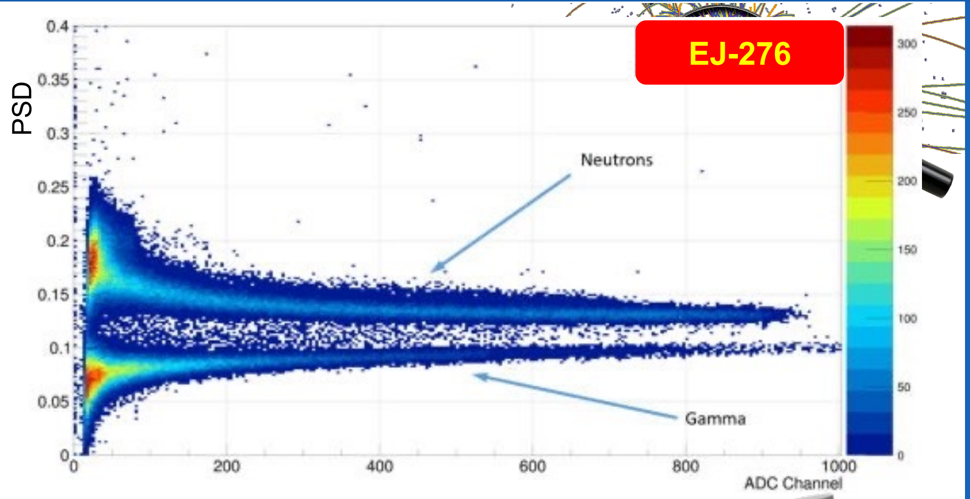
$^6$Li/ZnS(Ag) screen



SFOP
Scintillating Fiber Optic Plate

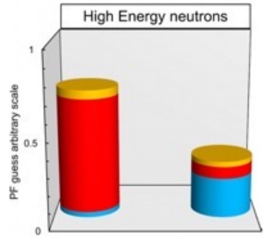
# scintillators

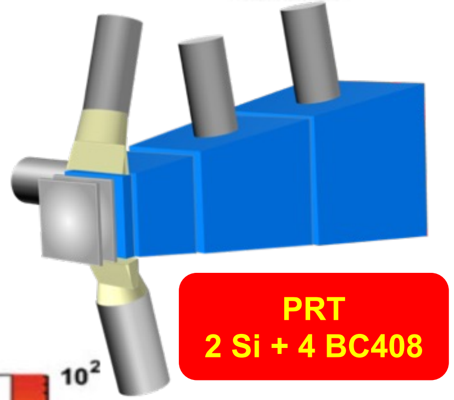
- plastic scintillators
- liquid scintillators
- + Pulse Shape Discrimination (PSD)
- scintillating gas (He + Xe)
- C6D6 capture → gamma (ME to HE)
- proton recoil telescope (up to 500 MeV)



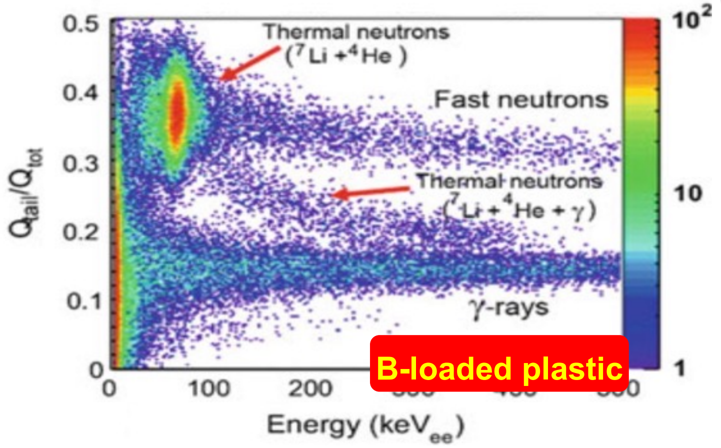

EJ-276

## high energy

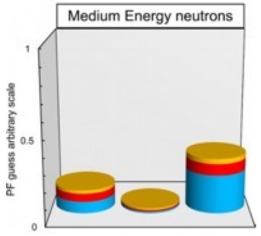


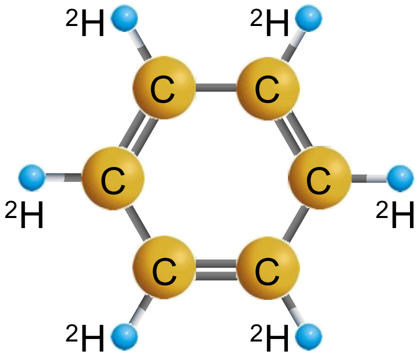
PRT
2 Si + 4 BC408



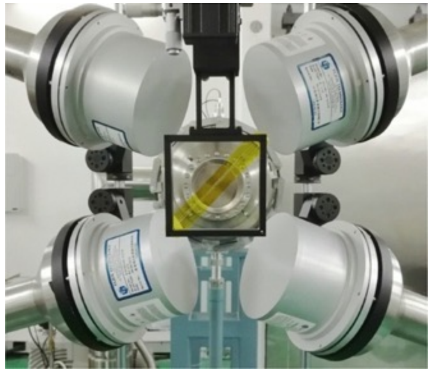

B-loaded plastic




C6D6
insensitive to neutrons

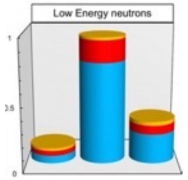



## medium energy



# semiconductors

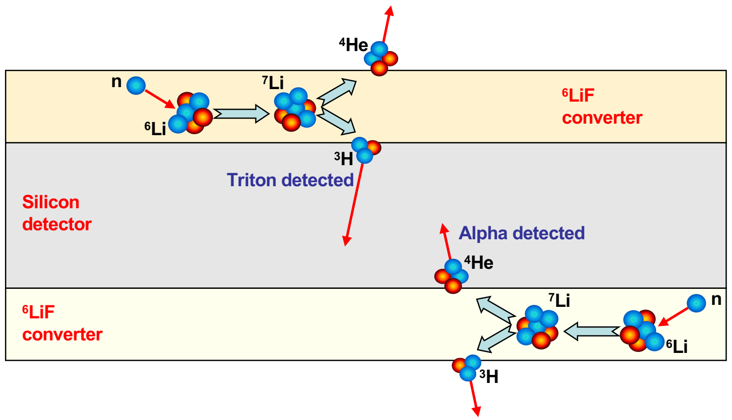
- diodes: Si, GaAs, Schottky, SiC (+ converter)
- SiLiF (Silicon + $^{6}$LiF plates)
- BOLAS (Silicon + $^{10}$B plates)
- Timepix (+ converter)
- MSND (Micro Structured Neutron Detector)
- CZT (+Gd converter, also exploits $^{113}$Cd)
- diamond (with or without converter)
- Micro Channel Plate with borated glass (actually not a semiconductor)



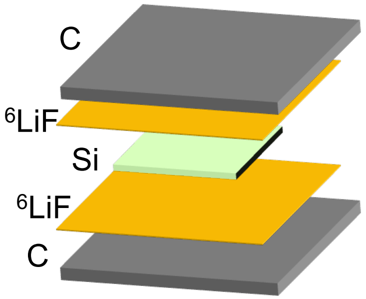

## low energy

## semiconductors

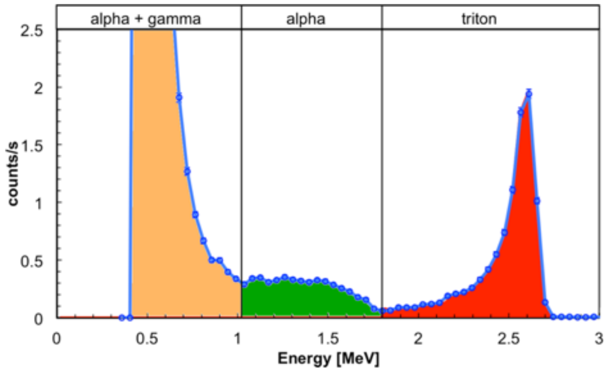
## SiLiF (Silicon + $^6$LiF plates)



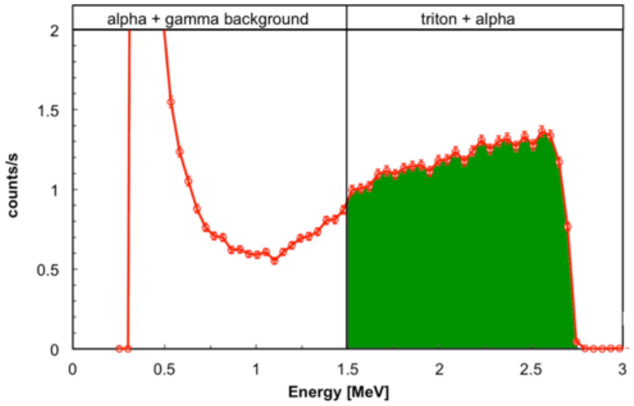

2-sided silicon diode + converter




3x3 cm$^2$ SiLiF thin $^6$LiF converter

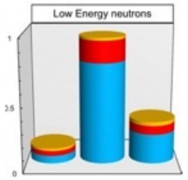



3x3 cm$^2$ SiLiF thick $^6$LiF converter




5% detection efficiency with gamma/n ~ $10^{-10}$

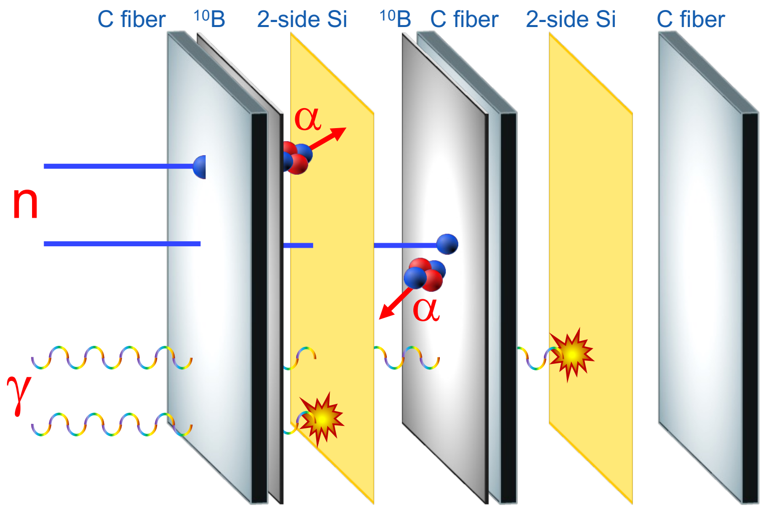
9% detection efficiency with gamma/n ~ $10^{-5}$




## low energy

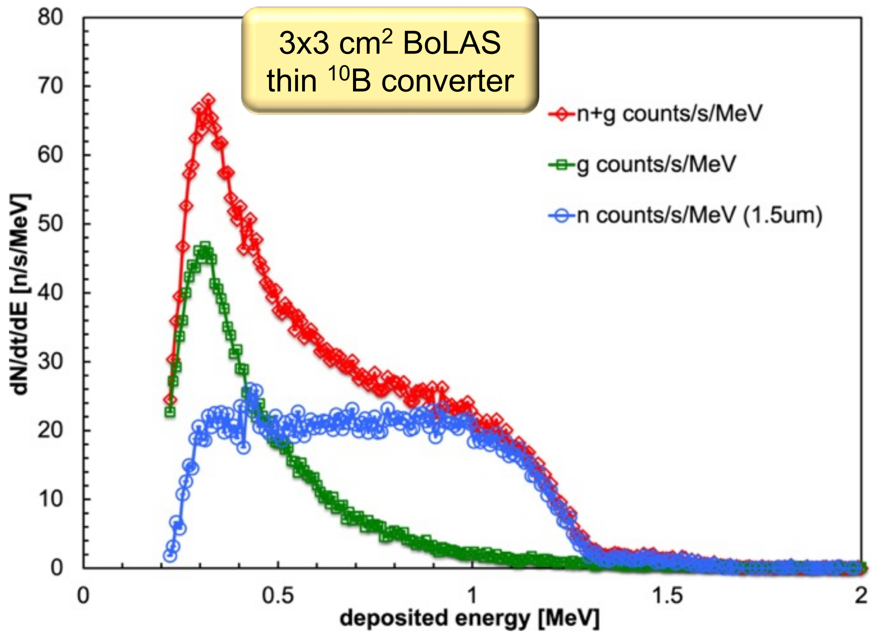
## semiconductors

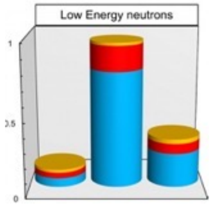
### BoLAS (Silicon + $^{10}$B plates)




lower detection efficiency than SiLiF

$^{10}$B instead of $^{6}$LiF, requires an additional detector for gamma contribution subtraction





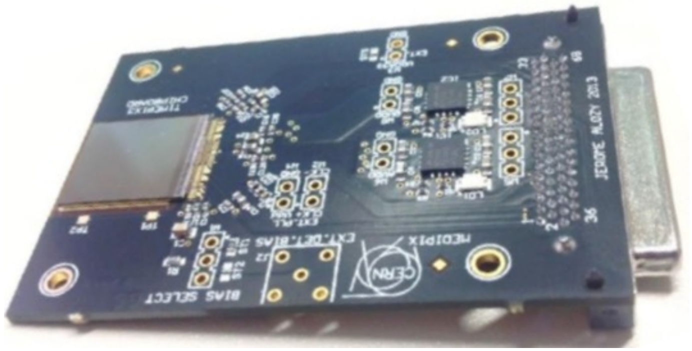

**low energy**

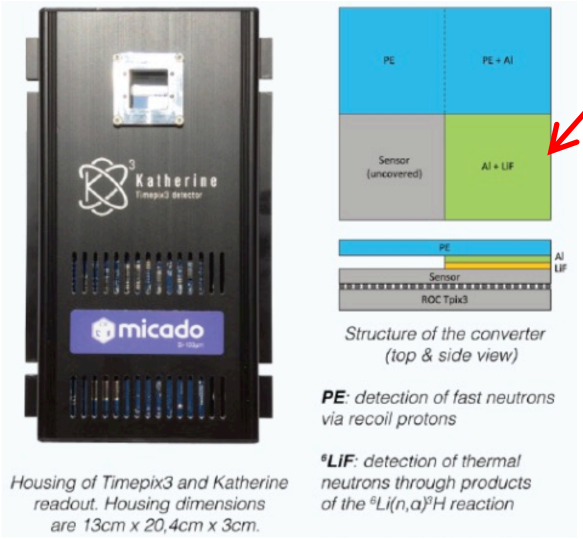
**semiconductors**

particle identification
based on cluster shape/size

TimePix 300μm silicon
256x256 pixels (1"sq)

$^{6}$LiF test converter



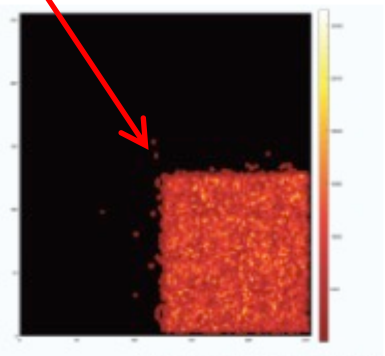


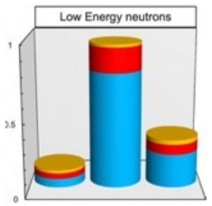
Housing of Timepix3 and Katherine readout. Housing dimensions are 13cm x 20,4cm x 3cm.

Structure of the converter (top & side view)

**PE**: detection of fast neutrons via recoil protons

**$^{6}$LiF**: detection of thermal neutrons through products of the $^{6}Li(n,\alpha)^{3}H$ reaction



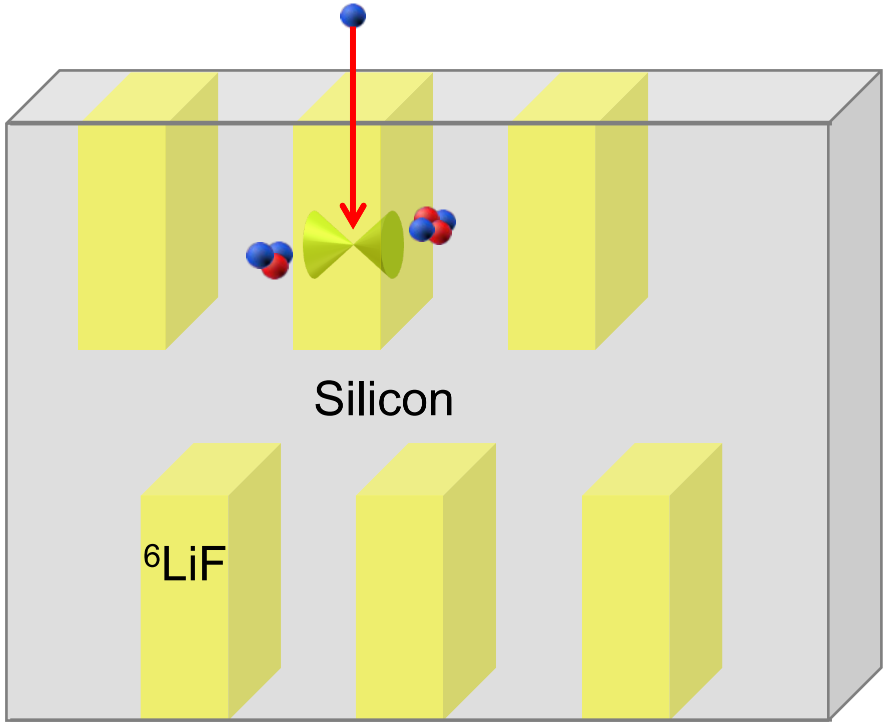


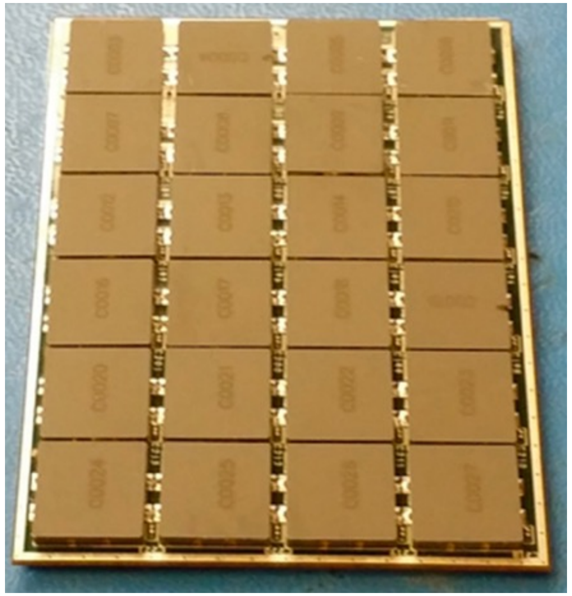

## low-energy

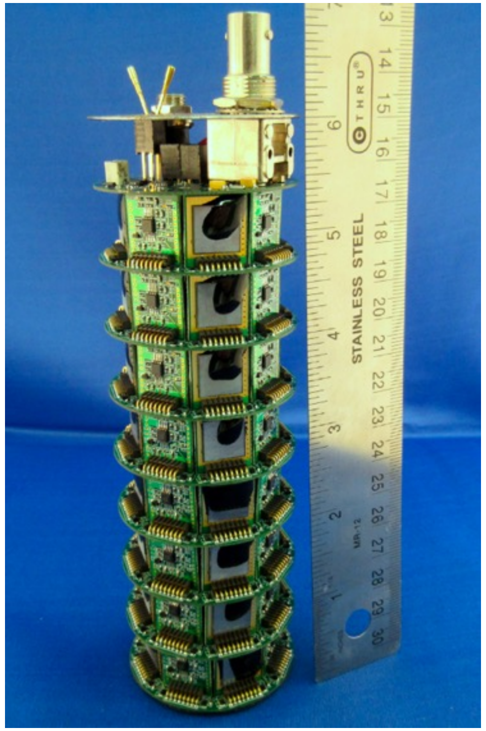
## semiconductors

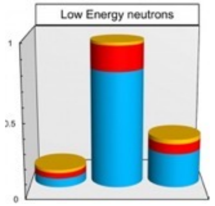
up to >30% detection efficiency, gamma/n ~ $10^{-5}$

### Double Sided Multi Structured Neutron Detector



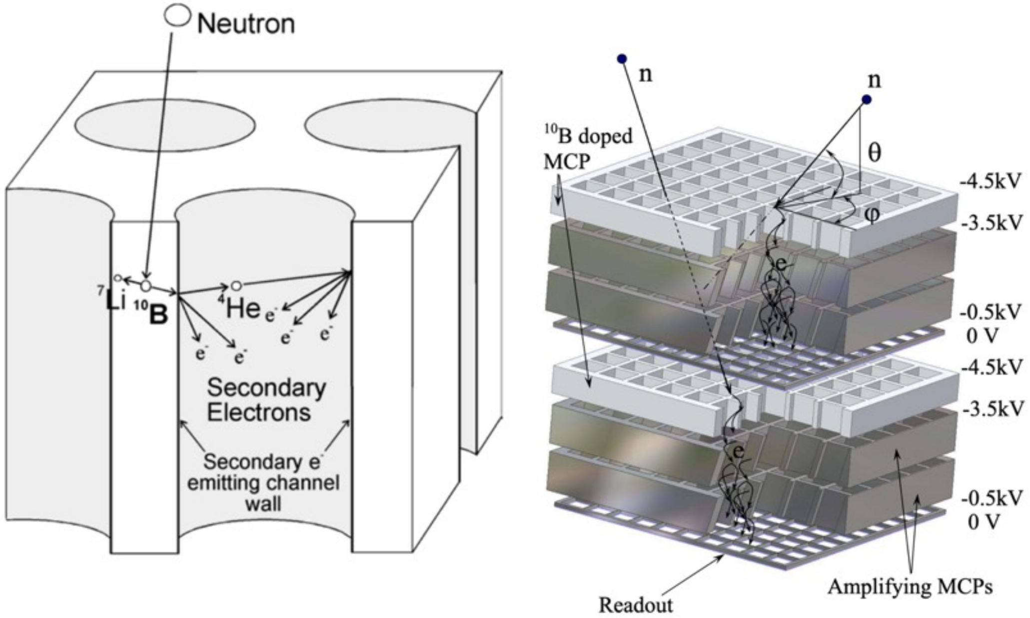


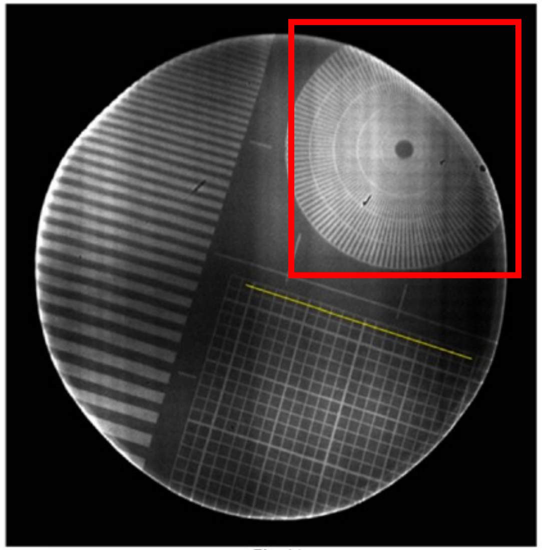


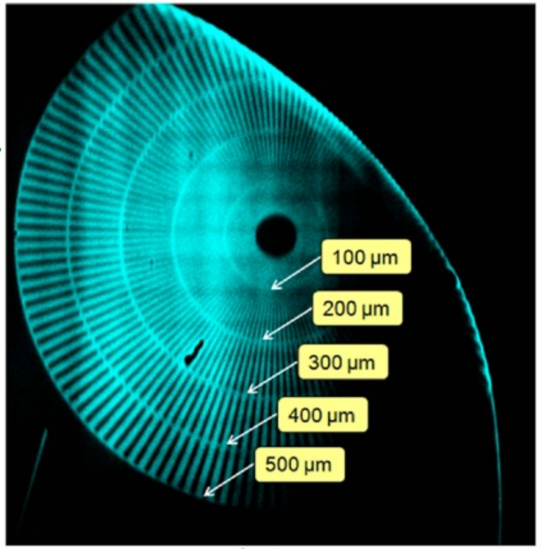

low-energy

semiconductors

Micro Channel Plate
actually NOT semiconductor!

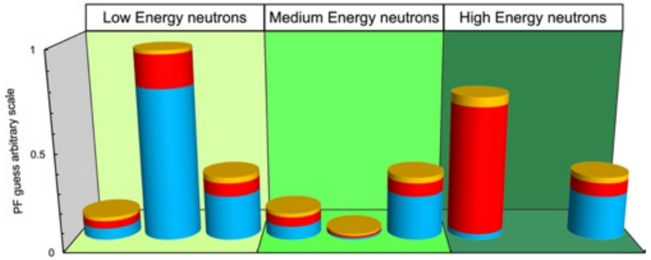





borated glass Micro Channel Plate
direct neutron detection

MCP coupled to Gd layer
neutron detection via Gd



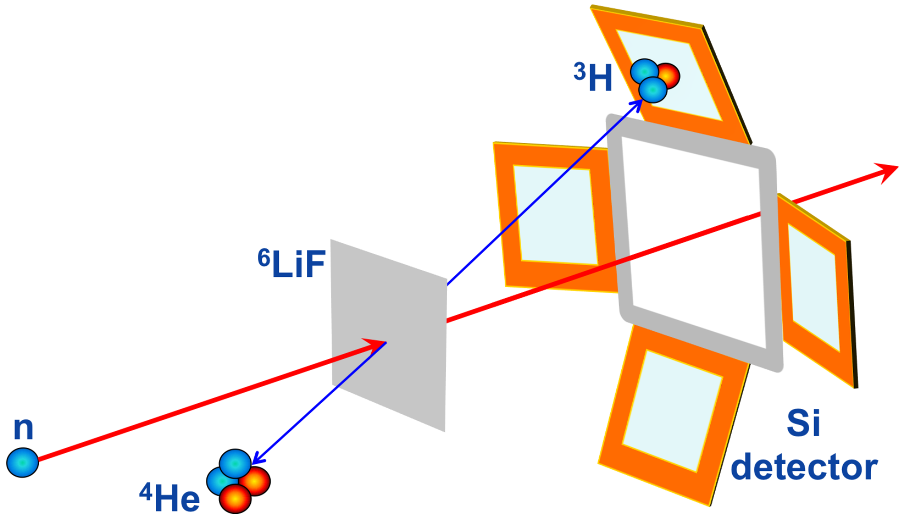

**low, medium, high energy**

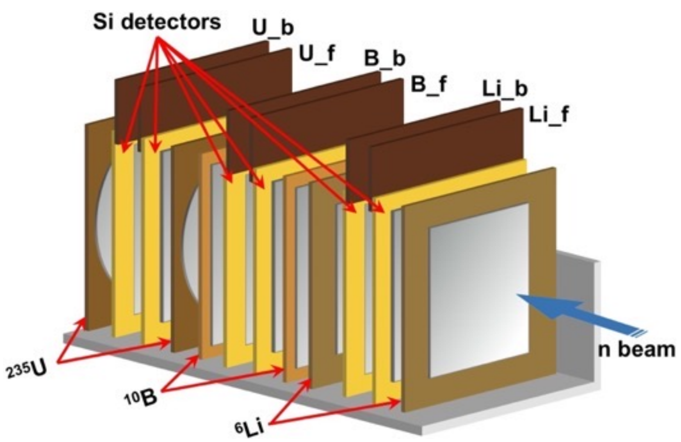
**semiconductors**

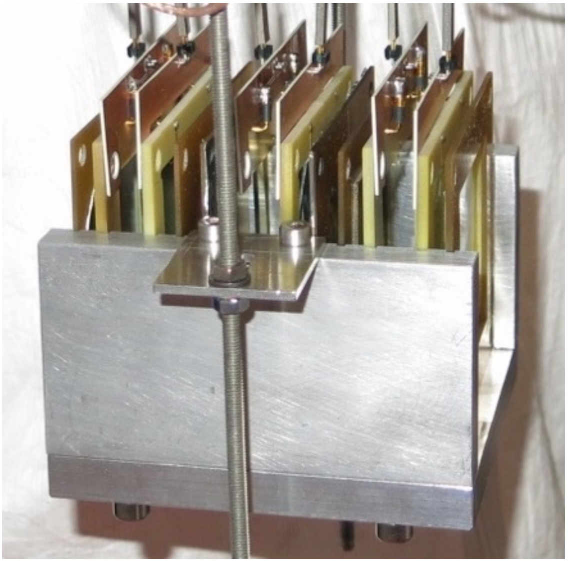
Silicon supersandwich
6 detectors + 6 targets: 2x $^{6}$LiF, 2x $^{10}$B, 2x $^{235}$U

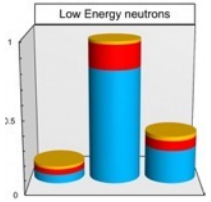
Neutron beam monitor SIMON
useful between thermal and ~1 MeV

made possible to measure $^{235}$U(n,f) cross section
new standard between thermal and 170 keV



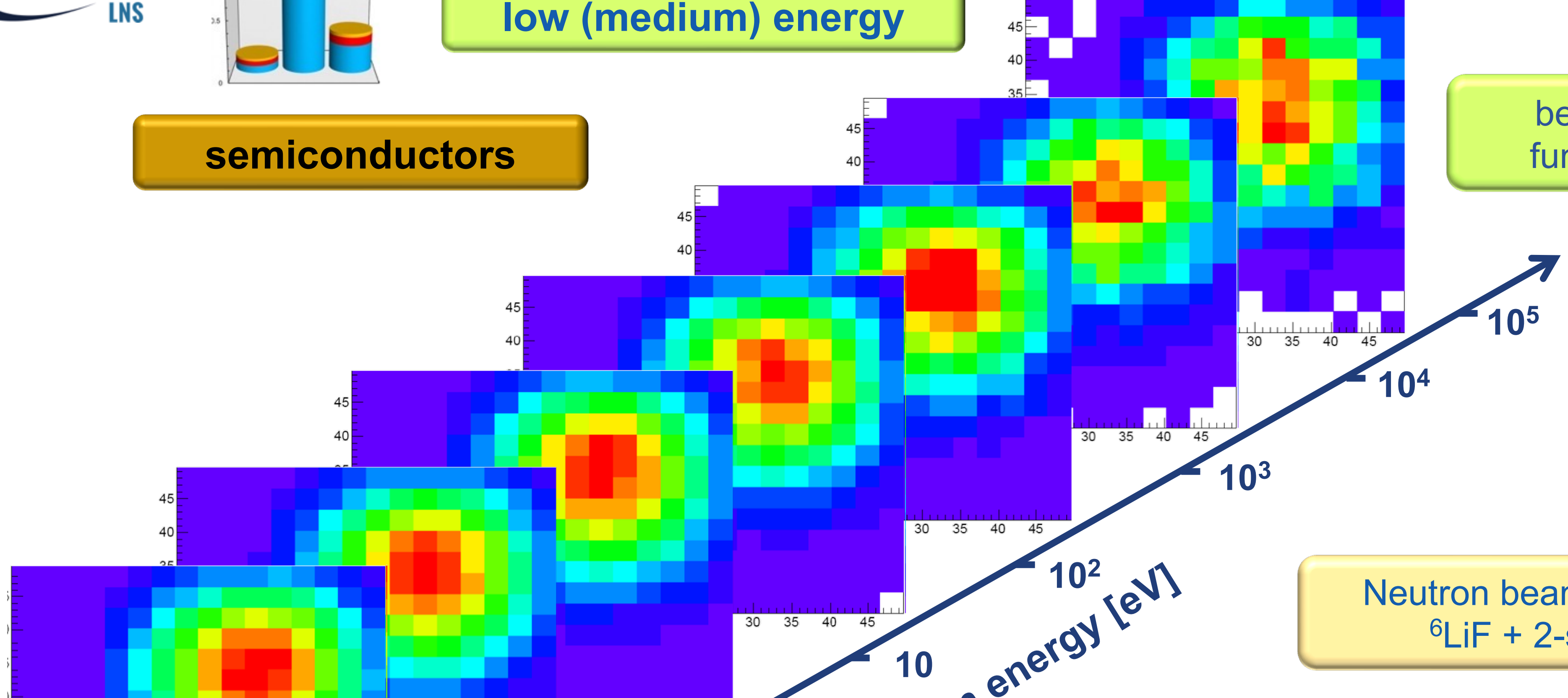
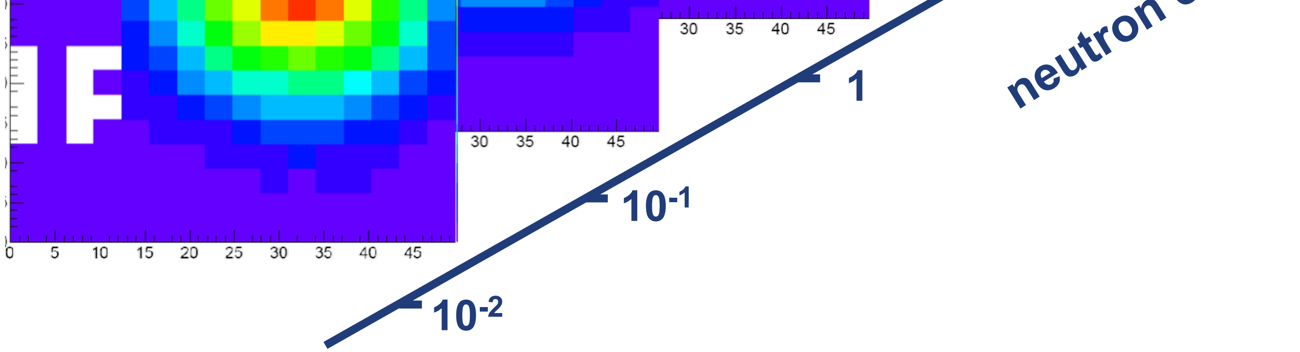





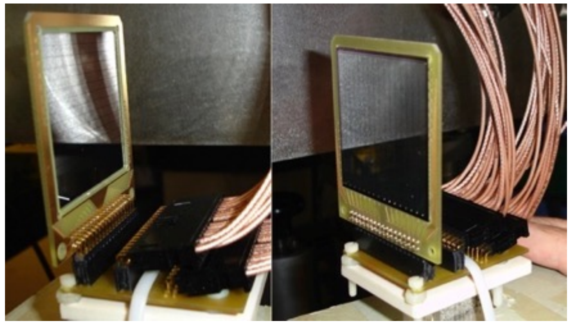

**low (medium) energy**

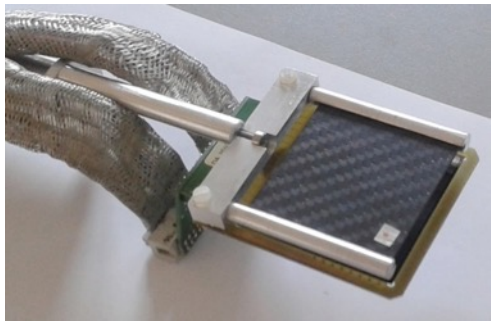
**semiconductors**

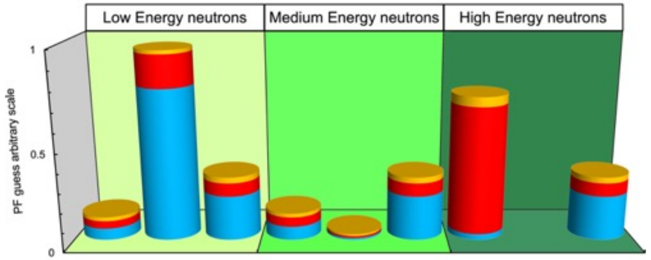
beam profile as a function of energy


Neutron beam monitor SIMON-2D
$^6$LiF + 2-sided strip silicon



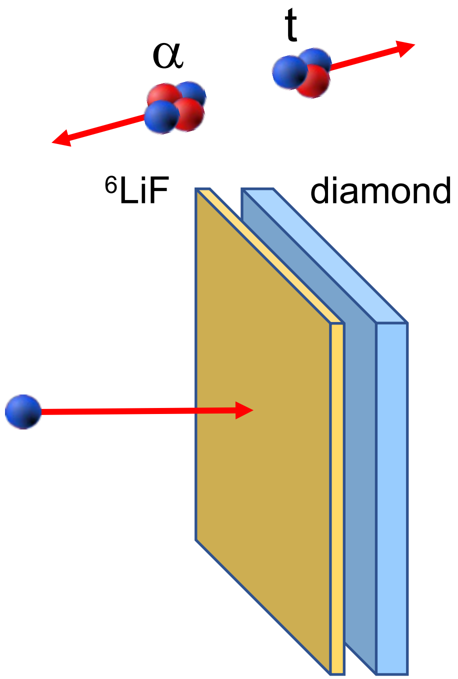




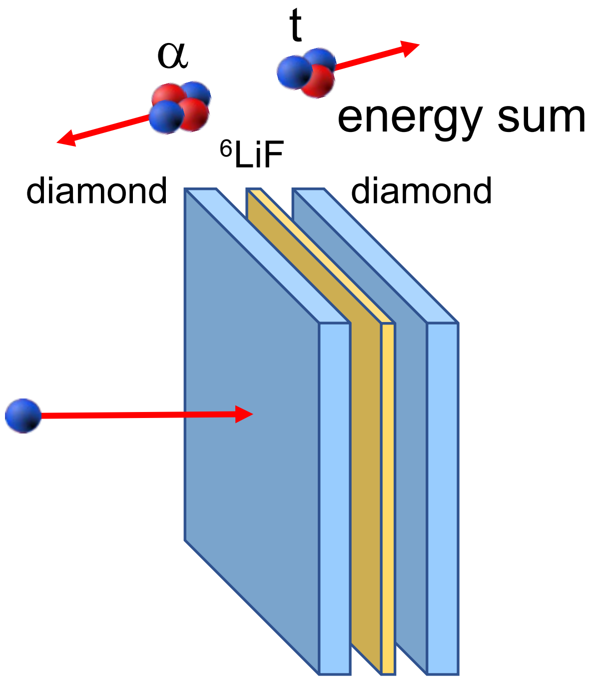

# low, medium, high energy high flux

## ~~semiconductors~~ diamond

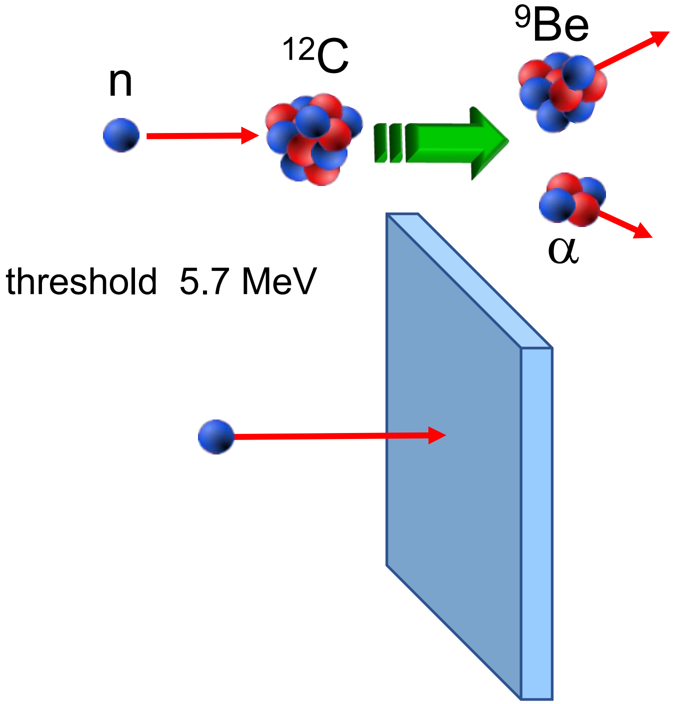
### low energy




### medium energy




### high energy



## Conclusions

- neutron detection: a very broad field
- neutron science mainly with (ultra)cold and slow neutrons
- consolidated powerful instruments at neutron science facilities
- wide choice of detection techniques for nuclear physics and applications
- new technologies to replace $^{3}He$ already in operation
- most promising based on semiconductors and diamond

# Thank you