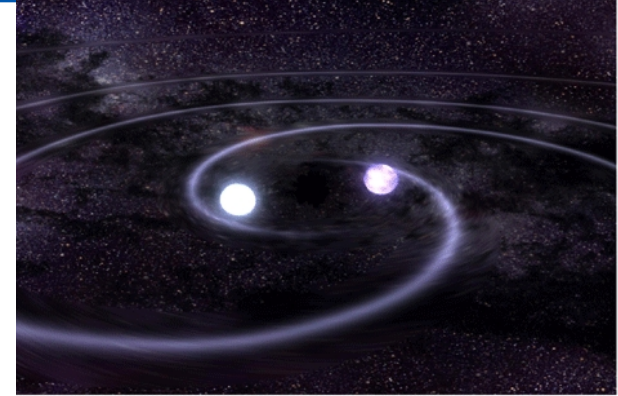
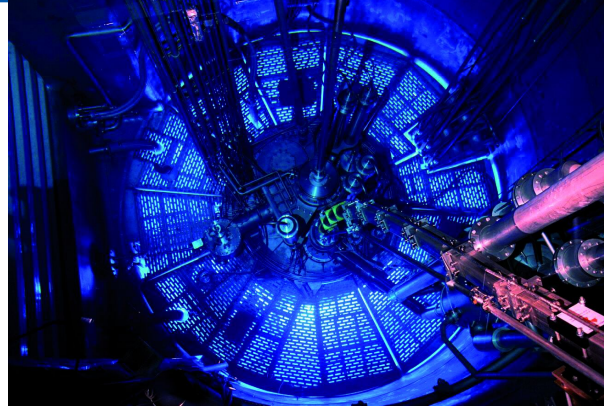
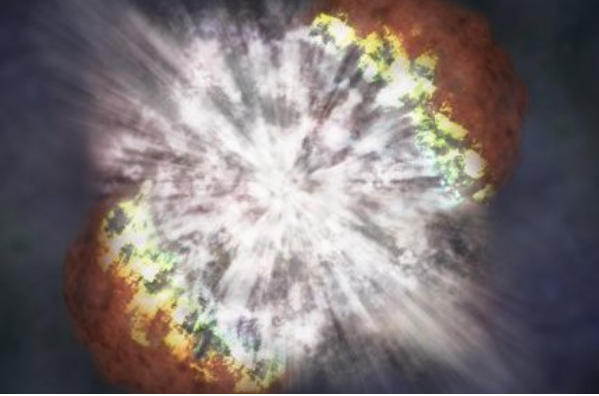




# NEUTRON CAPTURE EXPERIMENTS

*Overview, techniques, examples*

César Domingo Pardo



European Research Council



For many slides thanks to C. Guerrero's talk @ Master in Sevilla, 2017

# Radiative Neutron Capture



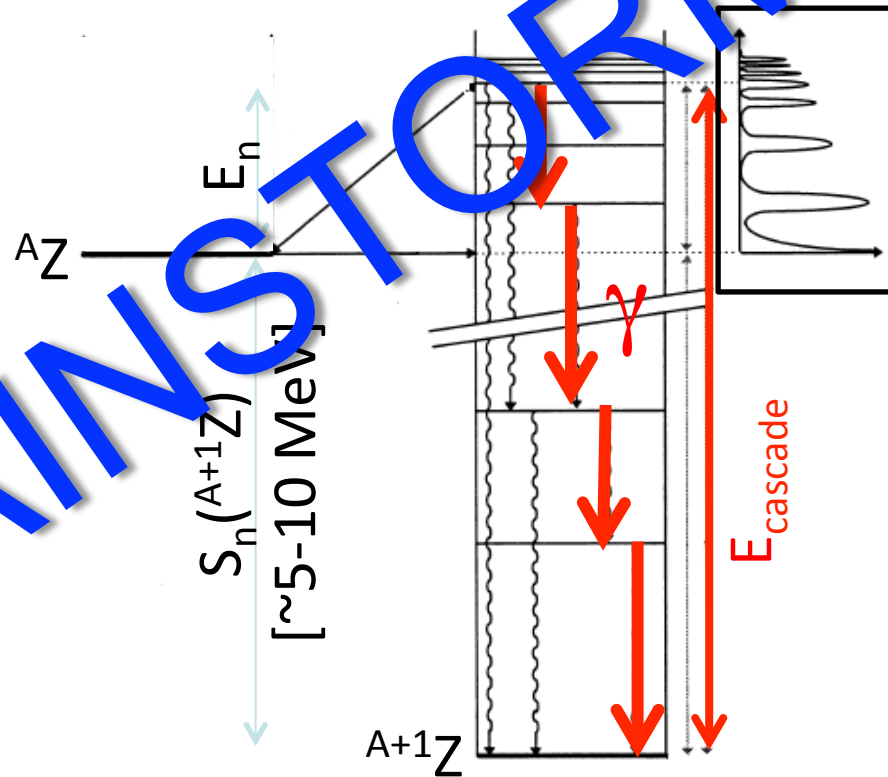
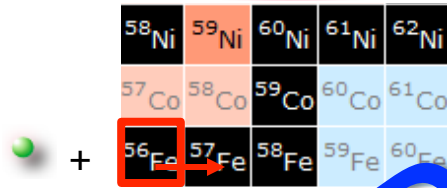
Diagram illustrating the formation of a superheavy nucleus and its subsequent gamma-ray cascade.

The top part shows a neutron (green dot) and a nucleus (cluster of blue and green spheres) combining to form a superheavy nucleus (cluster of red spheres).

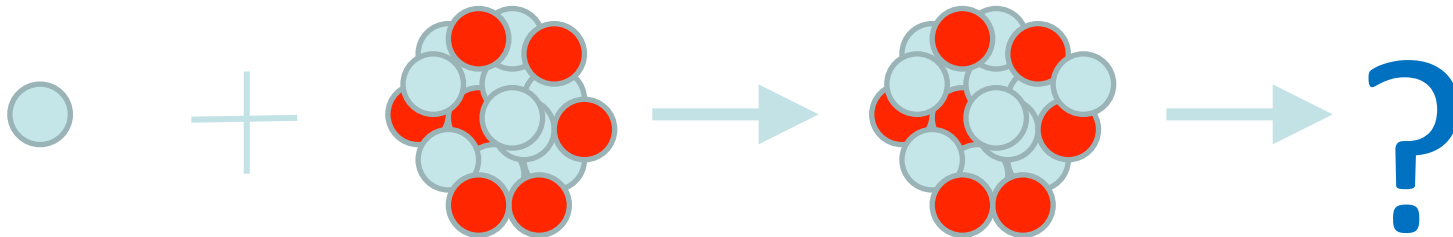
Below this is a table of isotopes for Ni, Co, and Fe:

|       |       |       |       |       |
|-------|-------|-------|-------|-------|
| 58 Ni | 59 Ni | 60 Ni | 61 Ni | 62 Ni |
| 57 Co | 58 Co | 59 Co | 60 Co | 61 Co |
| 56 Fe | 57 Fe | 58 Fe | 59 Fe | 60 Fe |

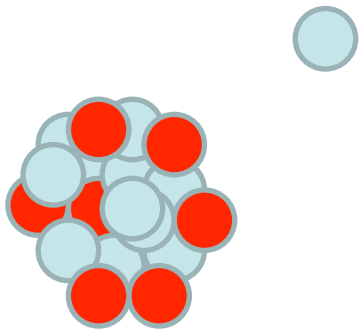
The bottom part shows a vertical energy level diagram for a nucleus with mass number  $A+1$  and atomic number  $Z$ . The diagram illustrates the formation of a superheavy nucleus ( $A+1, Z$ ) and its subsequent gamma-ray cascade ( $E_{\text{cascade}}$ ) as it decays towards a stable state ( $A, Z$ ). The energy levels are labeled  $E_n$ , and the binding energy is  $S_n(A+1, Z)$ .



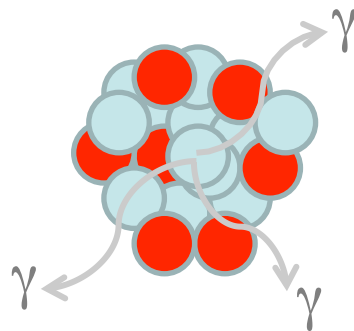
# 1. Neutron-Nucleus interactions?



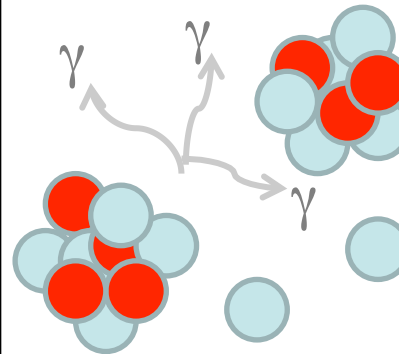
Elastic/Inelastic scattering



Neutron radiative capture



Fission



Many others:  
(n,p), (n, $\alpha$ ),  
knock-out,  
spallation

.....



# Radiative Neutron Capture

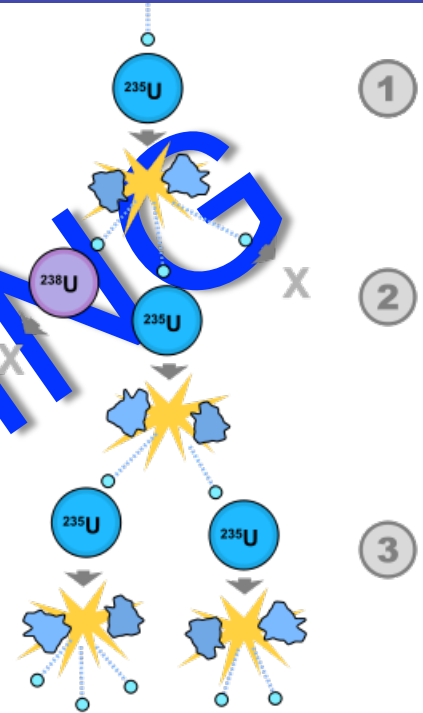
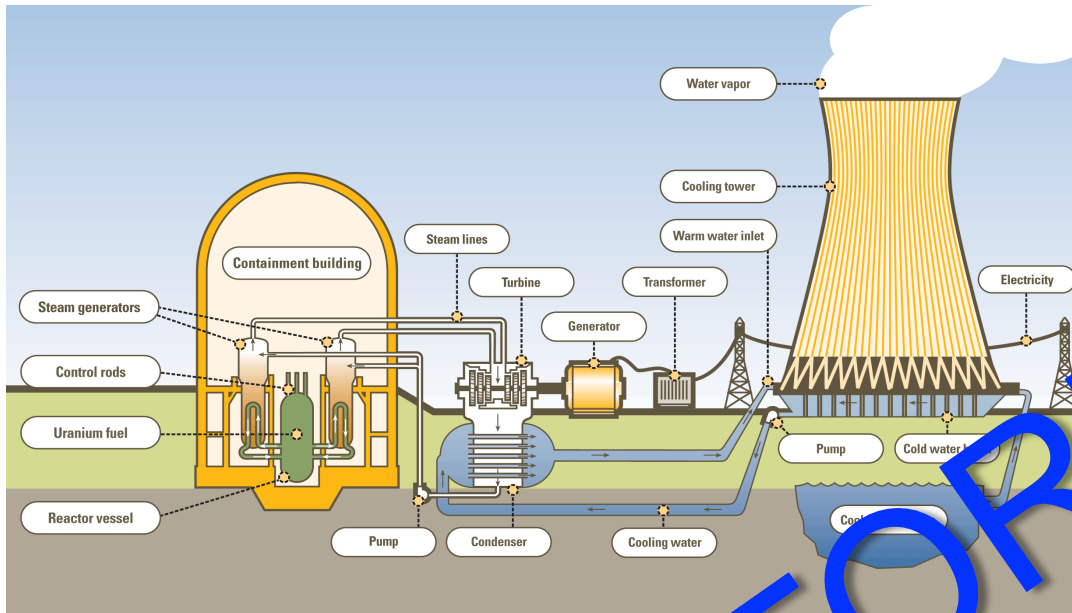
What?

Why?

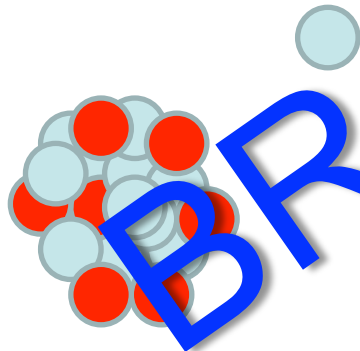
How?

- Applications: New (cleaner & safer) nuclear energy technologies (ADS)
- Basic Science: Nucleosynthesis of heavy elements

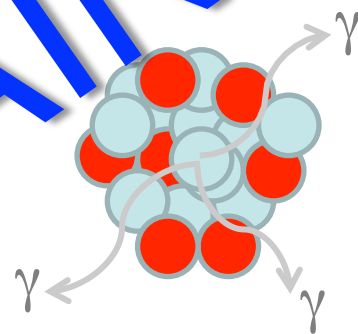
# Neutron-induced reactions in reactors



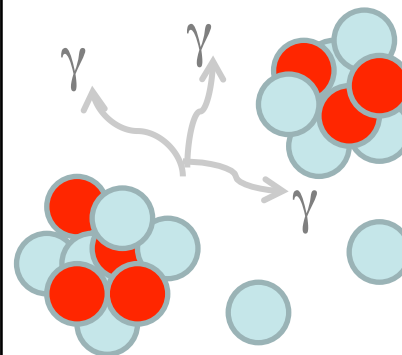
Elastic/Inelastic scattering



Neutron radiative capture



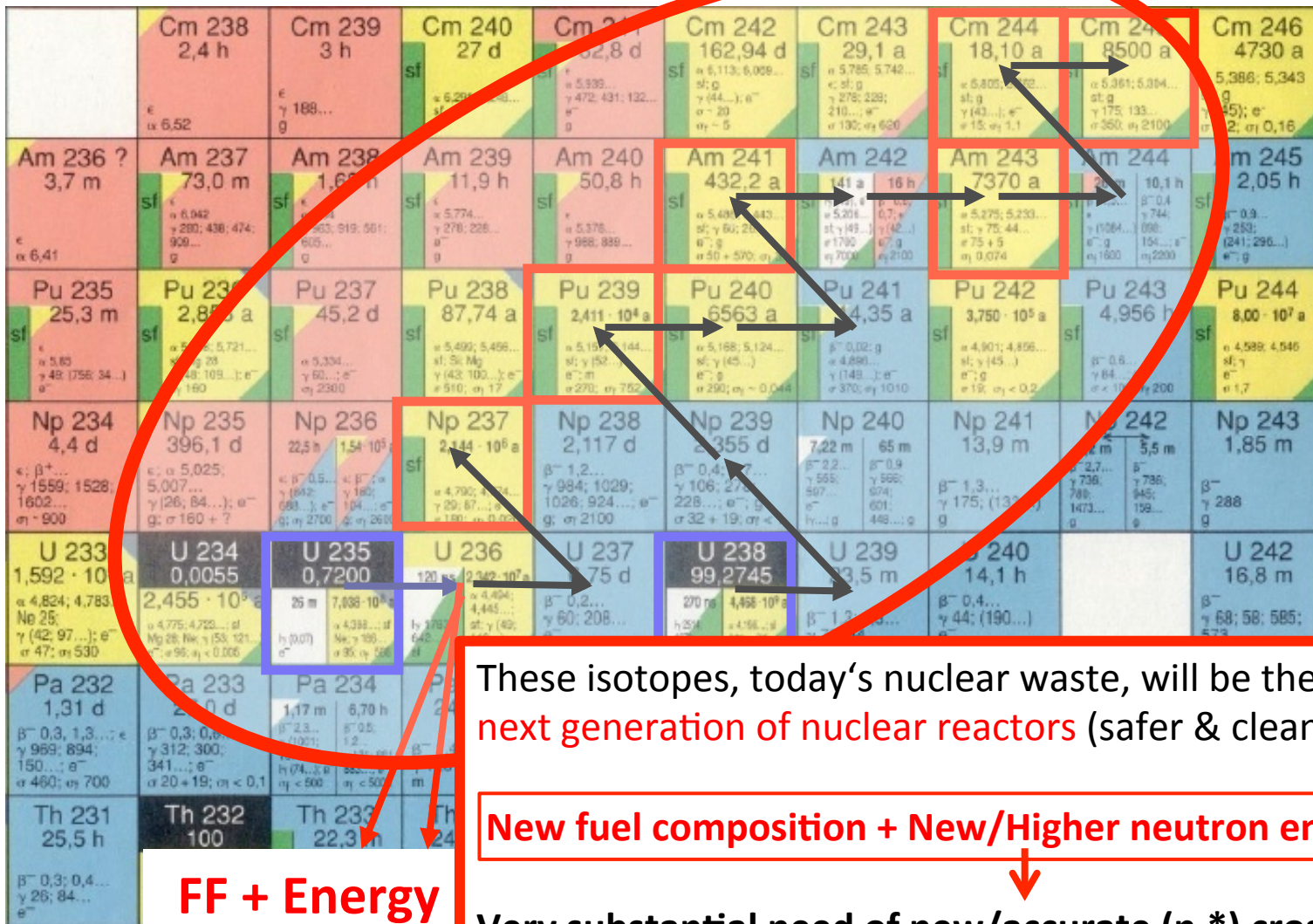
Fission



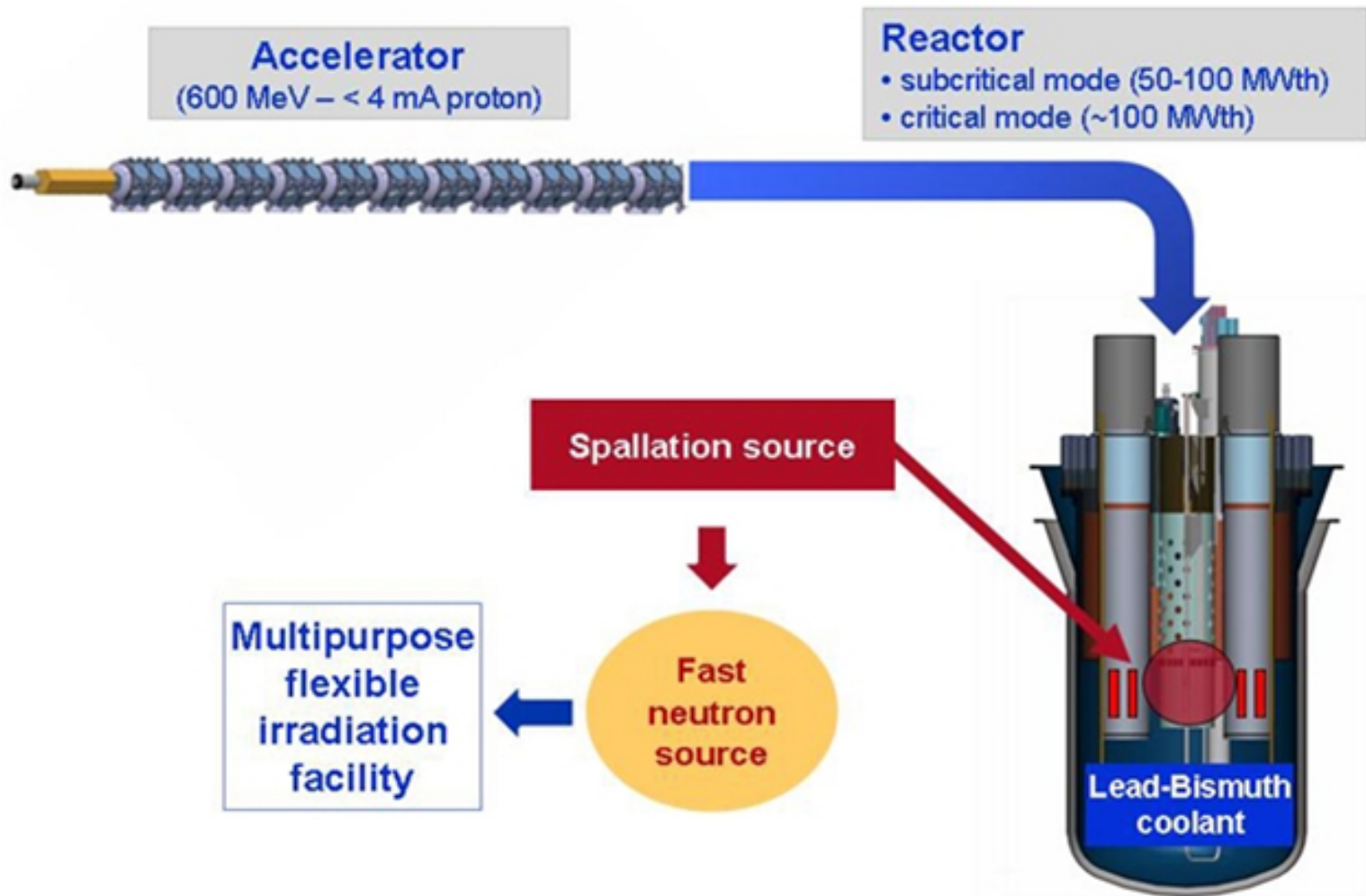
Many others:  
(n,p), (n,α),  
knock-out,  
spallation

....

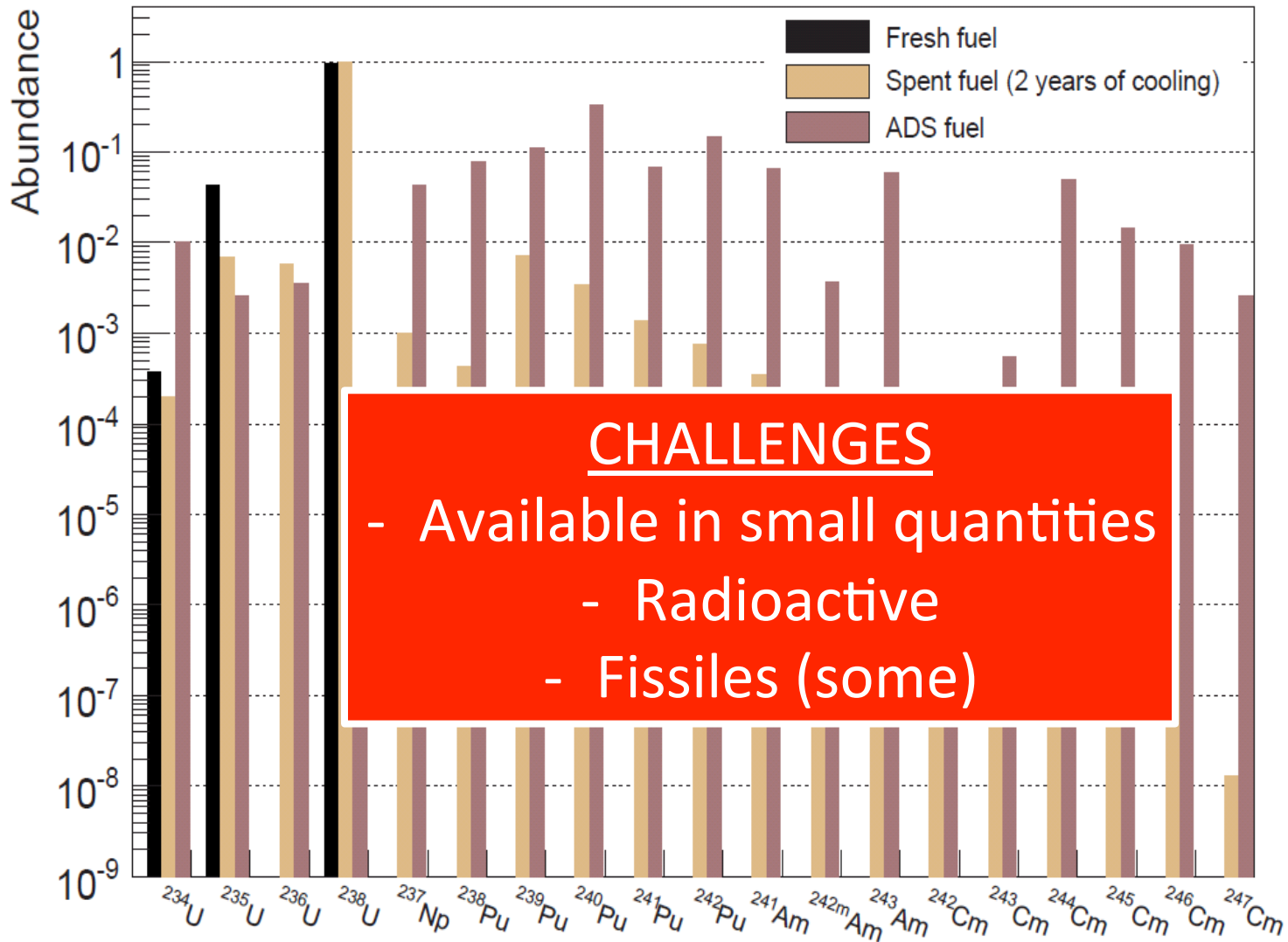
# Neutron-induced reactions in reactors



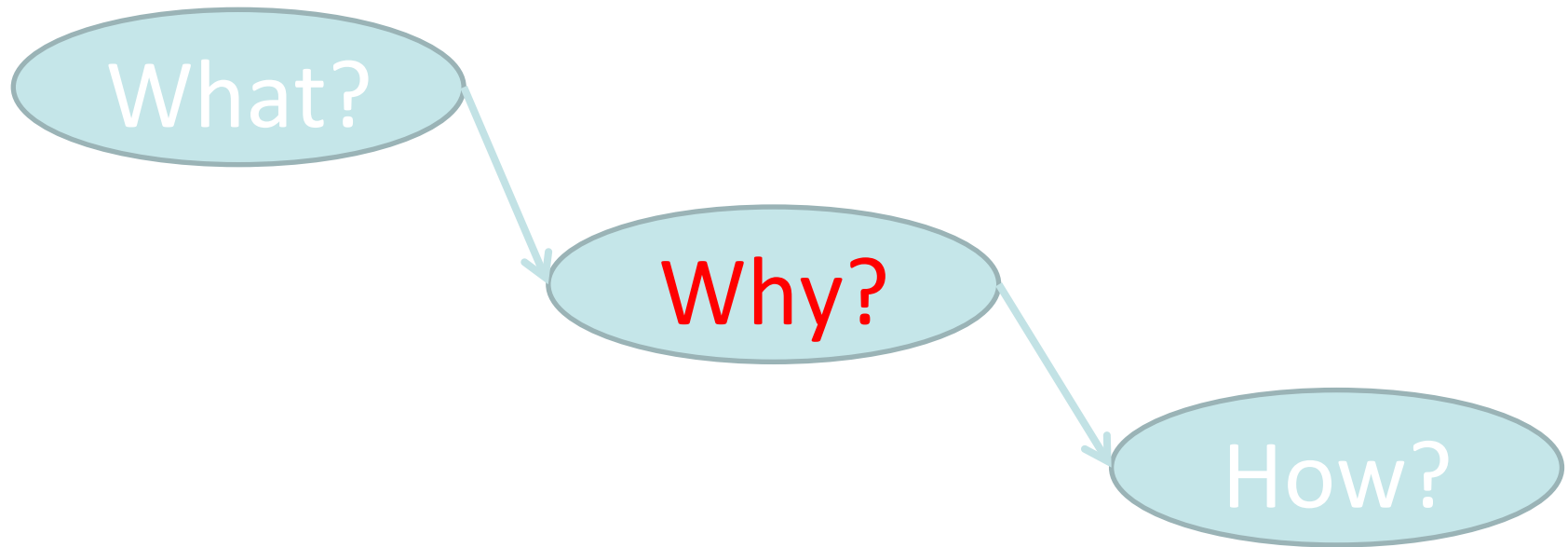
# Neutron-induced reactions in reactors



# Neutron-induced reactions in reactors



# Radiative Neutron Capture



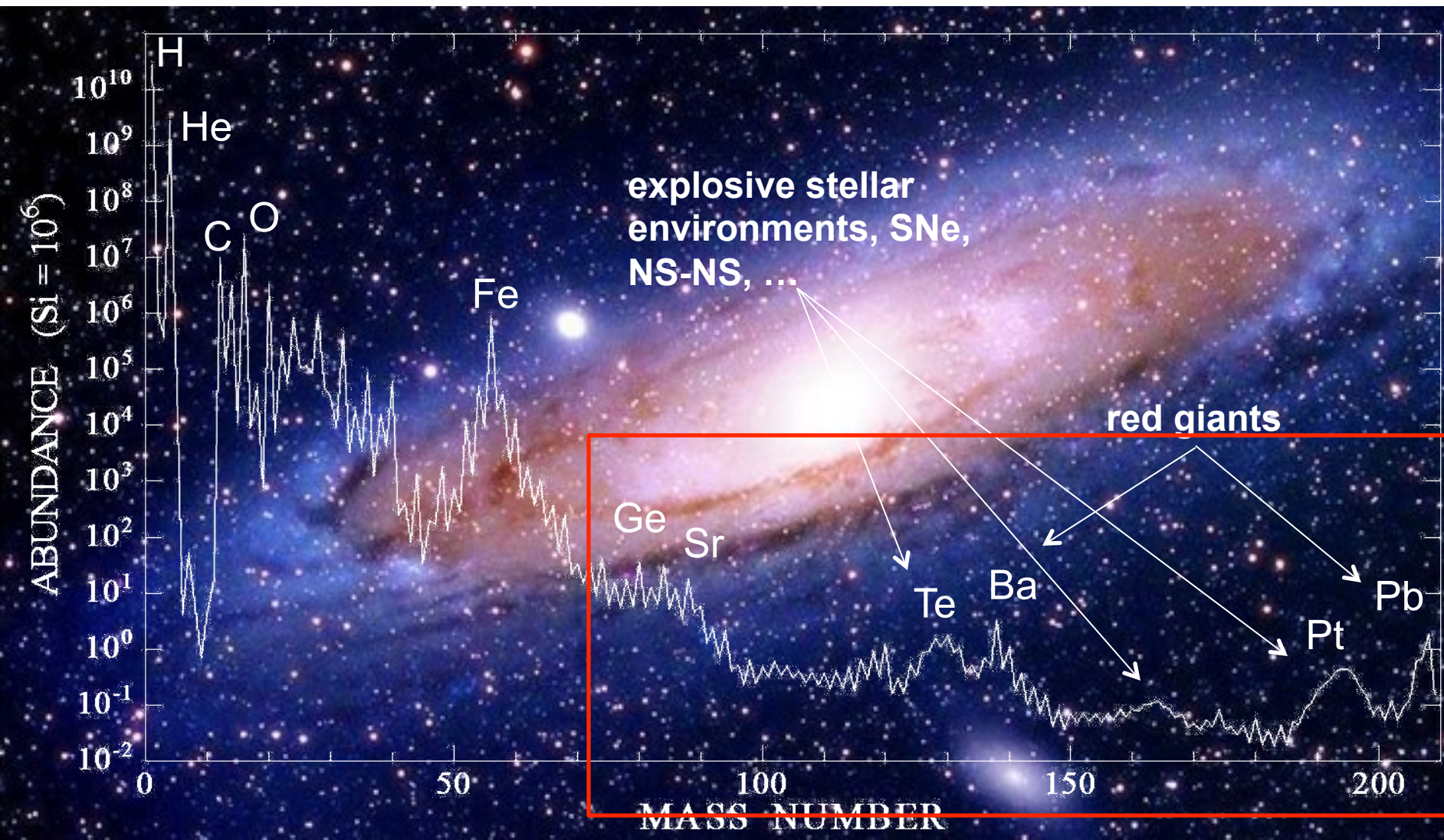
- Applications: New (cleaner & safer) nuclear energy technologies (ADS)
- Basic Science: Nucleosynthesis of heavy elements



# Why (n,g) measurements?: Nucleosynthesis in stars

- Neutrons produce 75% of all the elements
- 0.005% of the total abundances (!)
- 10-12 orders-of-magnitude difference between H and the rarest (heaviest) nuclei (!)

BB ← Fusion → Neutrons →

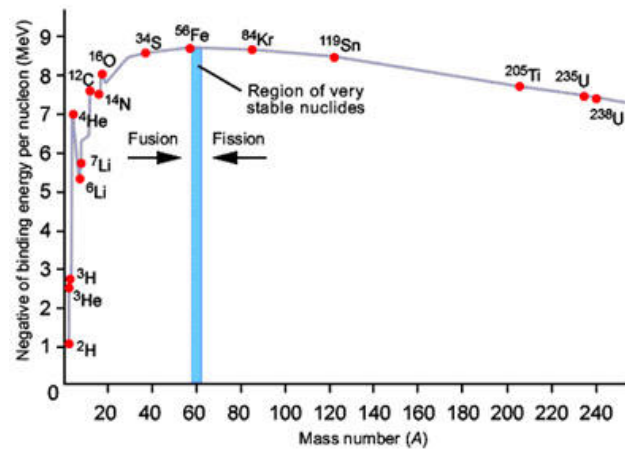
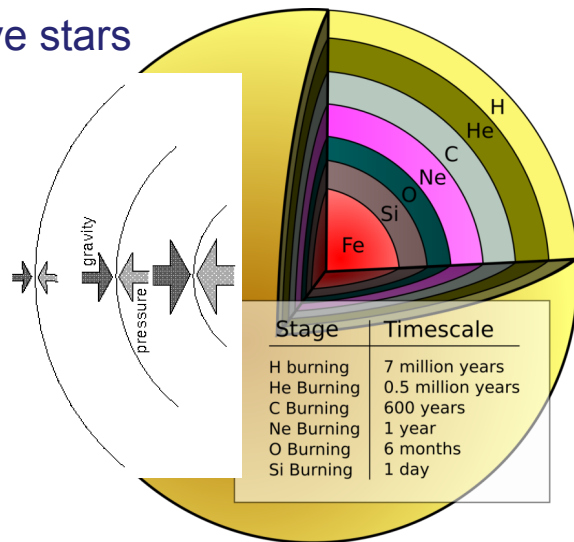




The diagram illustrates the formation of elements from the Big Bang. A red arrow labeled "Big-bang" points from a circled Hydrogen (H) atom to a circled Helium (He) atom. The periodic table includes elements from Hydrogen (1) to Zinc (30), with some elements missing (Boron, Carbon, Nitrogen, Oxygen, Fluorine, Neon, Aluminum, Silicon, Phosphorus, Sulfur, Chlorine, Argon).

|                             |                              |                             |                             |                            |                             |                              |                         |                           |                           |                           |                         |  |  |  |  |                             |                            |                              |                          |                             |                          |
|-----------------------------|------------------------------|-----------------------------|-----------------------------|----------------------------|-----------------------------|------------------------------|-------------------------|---------------------------|---------------------------|---------------------------|-------------------------|--|--|--|--|-----------------------------|----------------------------|------------------------------|--------------------------|-----------------------------|--------------------------|
| 1<br><b>H</b><br>Hydrogen   |                              |                             |                             |                            |                             |                              |                         |                           |                           |                           |                         |  |  |  |  |                             | 2<br><b>He</b><br>Helium   |                              |                          |                             |                          |
| 3<br><b>Li</b><br>Lithium   | 4<br><b>Be</b><br>Beryllium  |                             |                             |                            |                             |                              |                         |                           |                           |                           |                         |  |  |  |  | 5<br><b>B</b><br>Boron      | 6<br><b>C</b><br>Carbon    | 7<br><b>N</b><br>Nitrogen    | 8<br><b>O</b><br>Oxygen  | 9<br><b>F</b><br>Fluorine   | 10<br><b>Ne</b><br>Neon  |
| 11<br><b>Na</b><br>Sodium   | 12<br><b>Mg</b><br>Magnesium |                             |                             |                            |                             |                              |                         |                           |                           |                           |                         |  |  |  |  | 13<br><b>Al</b><br>Aluminum | 14<br><b>Si</b><br>Silicon | 15<br><b>P</b><br>Phosphorus | 16<br><b>S</b><br>Sulfur | 17<br><b>Cl</b><br>Chlorine | 18<br><b>Ar</b><br>Argon |
| 19<br><b>K</b><br>Potassium | 20<br><b>Ca</b><br>Calcium   | 21<br><b>Sc</b><br>Scandium | 22<br><b>Ti</b><br>Titanium | 23<br><b>V</b><br>Vanadium | 24<br><b>Cr</b><br>Chromium | 25<br><b>Mn</b><br>Manganese | 26<br><b>Fe</b><br>Iron | 27<br><b>Co</b><br>Cobalt | 28<br><b>Ni</b><br>Nickel | 29<br><b>Cu</b><br>Copper | 30<br><b>Zn</b><br>Zinc |  |  |  |  |                             |                            |                              |                          |                             |                          |

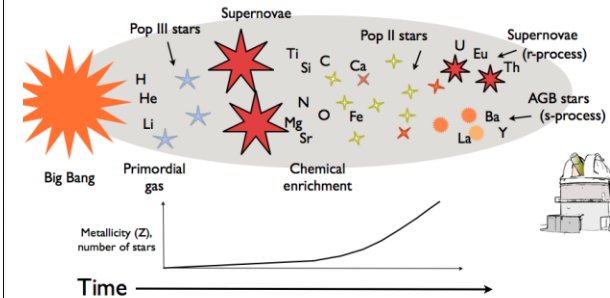
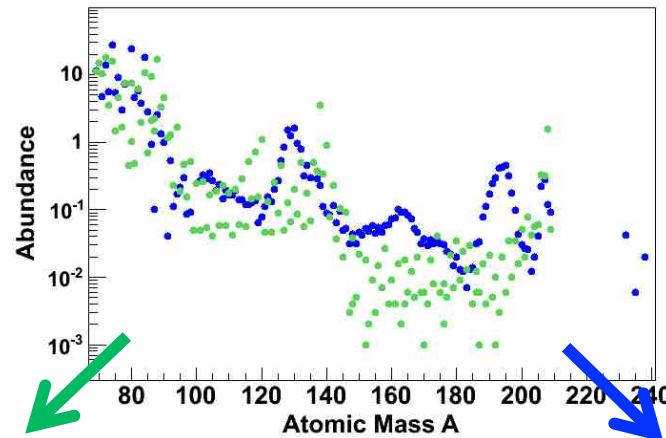
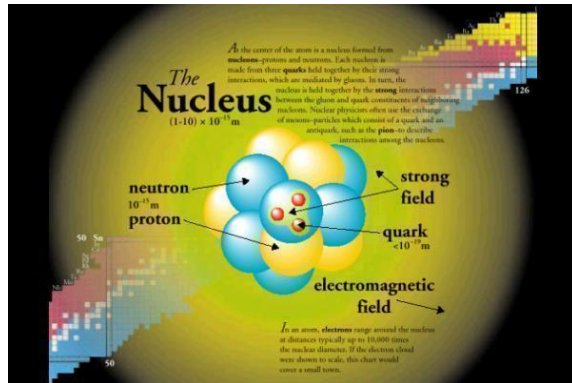
## Fusion reactions in massive stars



|                      |                       |                        |                            |                      |                         |                        |                       |                         |                           |                          |                          |                         |                        |                           |                          |                           |                          |                       |                   |                      |                   |
|----------------------|-----------------------|------------------------|----------------------------|----------------------|-------------------------|------------------------|-----------------------|-------------------------|---------------------------|--------------------------|--------------------------|-------------------------|------------------------|---------------------------|--------------------------|---------------------------|--------------------------|-----------------------|-------------------|----------------------|-------------------|
| 1<br>H<br>Hydrogen   |                       |                        |                            |                      |                         |                        |                       |                         |                           |                          |                          |                         |                        |                           |                          |                           | 2<br>He<br>Helium        |                       |                   |                      |                   |
| 3<br>Li<br>Lithium   | 4<br>Be<br>Beryllium  |                        |                            |                      |                         |                        |                       |                         |                           |                          |                          |                         |                        |                           |                          | 5<br>B<br>Boron           | 6<br>C<br>Carbon         | 7<br>N<br>Nitrogen    | 8<br>O<br>Oxygen  | 9<br>F<br>Fluorine   | 10<br>Ne<br>Neon  |
| 11<br>Na<br>Sodium   | 12<br>Mg<br>Magnesium |                        |                            |                      |                         |                        |                       |                         |                           |                          |                          |                         |                        |                           |                          | 13<br>Al<br>Aluminium     | 14<br>Si<br>Silicon      | 15<br>P<br>Phosphorus | 16<br>S<br>Sulfur | 17<br>Cl<br>Chlorine | 18<br>Ar<br>Argon |
| 19<br>K<br>Potassium | 20<br>Ca<br>Calcium   | 21<br>Sc<br>Scandium   | 22<br>Ti<br>Titanium       | 23<br>V<br>Vanadium  | 24<br>Cr<br>Chromium    | 25<br>Mn<br>Manganese  | 26<br>Fe<br>Iron      | 27<br>Co<br>Cobalt      | 28<br>Ni<br>Nickel        | 29<br>Cu<br>Copper       | 30<br>Zn<br>Zinc         | 31<br>Ga<br>Gallium     | 32<br>Ge<br>Germanium  | 33<br>As<br>Arsenic       | 34<br>Se<br>Selenium     | 35<br>Br<br>Bromine       | 36<br>Kr<br>Krypton      |                       |                   |                      |                   |
| 37<br>Rb<br>Rubidium | 38<br>Sr<br>Strontium | 39<br>Y<br>Yttrium     | 40<br>Zr<br>Zirconium      | 41<br>Nb<br>Niobium  | 42<br>Mo<br>Molybdenum  | 43<br>Tc<br>Technetium | 44<br>Ru<br>Ruthenium | 45<br>Rh<br>Rhodium     | 46<br>Pd<br>Palladium     | 47<br>Ag<br>Silver       | 48<br>Cd<br>Cadmium      | 49<br>In<br>Indium      | 50<br>Sn<br>Tin        | 51<br>Sb<br>Antimony      | 52<br>Te<br>Tellurium    | 53<br>I<br>Iodine         | 54<br>Xe<br>Xenon        |                       |                   |                      |                   |
| 55<br>Cs<br>Cesium   | 56<br>Ba<br>Barium    | 57<br>La*<br>Lanthanum | 72<br>Hf<br>Hafnium        | 73<br>Ta<br>Tantalum | 74<br>W<br>Tungsten     | 75<br>Re<br>Rhenium    | 76<br>Os<br>Osmium    | 77<br>Ir<br>Iridium     | 78<br>Pt<br>Platinum      | 79<br>Au<br>Gold         | 80<br>Hg<br>Mercury      | 81<br>Tl<br>Thallium    | 82<br>Pb<br>Lead       | 83<br>Bi<br>Bismuth       | 84<br>Po<br>Polonium     | 85<br>At<br>Astatine      | 86<br>Rn<br>Radon        |                       |                   |                      |                   |
| 87<br>Fr<br>Francium | 88<br>Ra<br>Radium    | 89<br>Ac**<br>Actinium | 104<br>Rf<br>Rutherfordium | 105<br>Db<br>Dubnium | 106<br>Sg<br>Seaborgium | 107<br>Bh<br>Bohrium   | 108<br>Hs<br>Hassium  | 109<br>Mt<br>Meitnerium | 110<br>Ds<br>Darmstadtium | 111<br>Rg<br>Roentgenium | 112<br>Cn<br>Copernicium | 113<br>Uut<br>Ununtrium | 114<br>Fl<br>Flerovium | 115<br>Uup<br>Ununpentium | 116<br>Lv<br>Livermorium | 117<br>Uus<br>Ununseptium | 118<br>Uuo<br>Ununoctium |                       |                   |                      |                   |

|                                          |                                 |                              |                               |                              |                              |                               |                              |                                |                                |                             |                                 |                              |                                |
|------------------------------------------|---------------------------------|------------------------------|-------------------------------|------------------------------|------------------------------|-------------------------------|------------------------------|--------------------------------|--------------------------------|-----------------------------|---------------------------------|------------------------------|--------------------------------|
| <sup>*</sup> 58<br><b>Ce</b><br>Cerium   | 59<br><b>Pr</b><br>Praseodymium | 60<br><b>Nd</b><br>Neodymium | 61<br><b>Pm</b><br>Promethium | 62<br><b>Sm</b><br>Samarium  | 63<br><b>Eu</b><br>Europium  | 64<br><b>Gd</b><br>Gadolinium | 65<br><b>Tb</b><br>Terbium   | 66<br><b>Dy</b><br>Dysprosium  | 67<br><b>Ho</b><br>Holmium     | 68<br><b>Er</b><br>Erbium   | 69<br><b>Tm</b><br>Thulium      | 70<br><b>Yb</b><br>Ytterbium | 71<br><b>Lu</b><br>Lutetium    |
| <sup>**</sup> 90<br><b>Th</b><br>Thorium | 91<br><b>Pa</b><br>Protactinium | 92<br><b>U</b><br>Uranium    | 93<br><b>Np</b><br>Neptunium  | 94<br><b>Pu</b><br>Plutonium | 95<br><b>Am</b><br>Americium | 96<br><b>Cm</b><br>Curium     | 97<br><b>Bk</b><br>Berkelium | 98<br><b>Cf</b><br>Californium | 99<br><b>Es</b><br>Einsteinium | 100<br><b>Fm</b><br>Fermium | 101<br><b>Md</b><br>Mendelevium | 102<br><b>No</b><br>Nobelium | 103<br><b>Lr</b><br>Lawrencium |

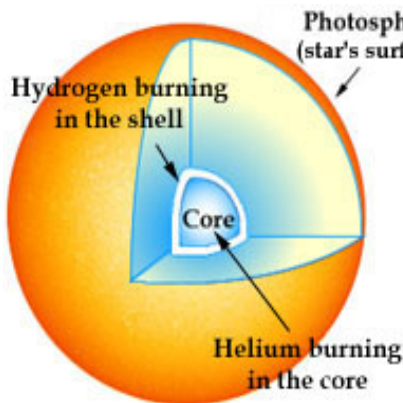
# El origen de los elementos pesados: procesos s y r



## s-process

core He-burning  
 $3-3.5 \cdot 10^8$  K  
 $kT=26$  keV  
 $10^6$  cm $^{-3}$

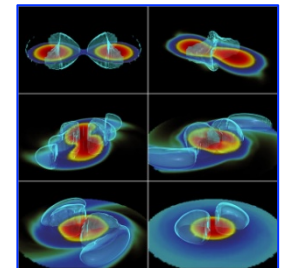
shell C-burning  
 $\sim 1 \cdot 10^9$  K  
 $kT=91$  keV  
 $10^{11}-10^{12}$  cm $^{-3}$



massive stars  $> 8 M_{\odot}$

## r-process

SN, N-Star Mergers, etc ?



- Where is the site?
- How is the environment?
- Entropy
- Rotation, 3D, etc

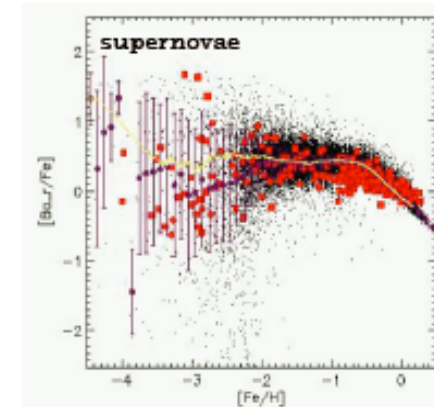
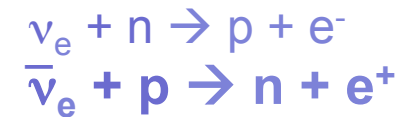
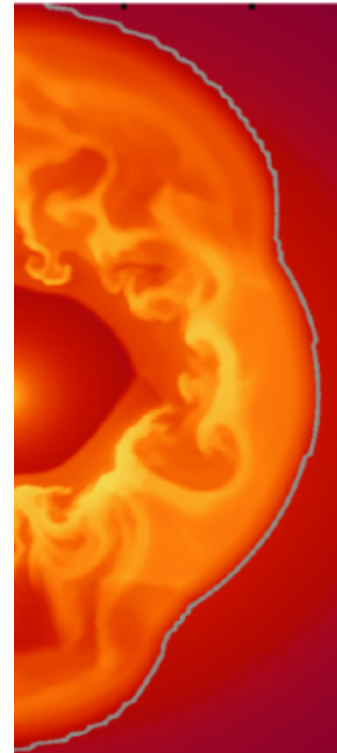
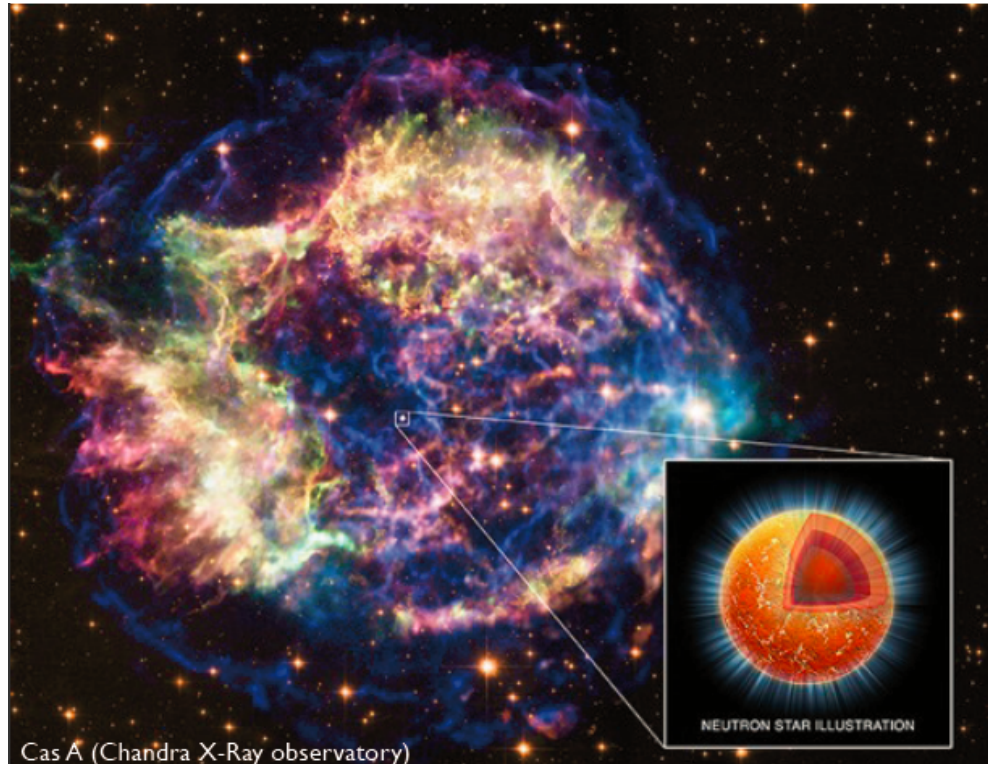
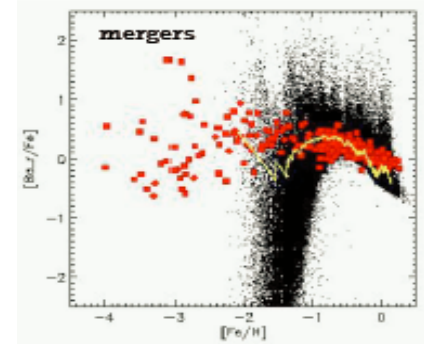
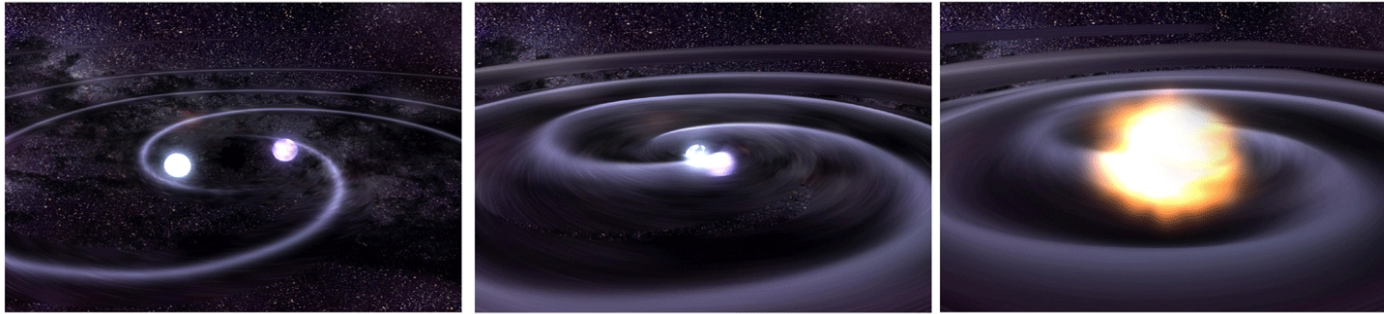


# The rapid (r-) neutron capture process

- Several candidates: SNe, NS-Mergers, NS-BH Mergers, etc
- High entropy and neutron density conditions required

$$T = 10^8\text{-}10^{10} \text{ K}$$

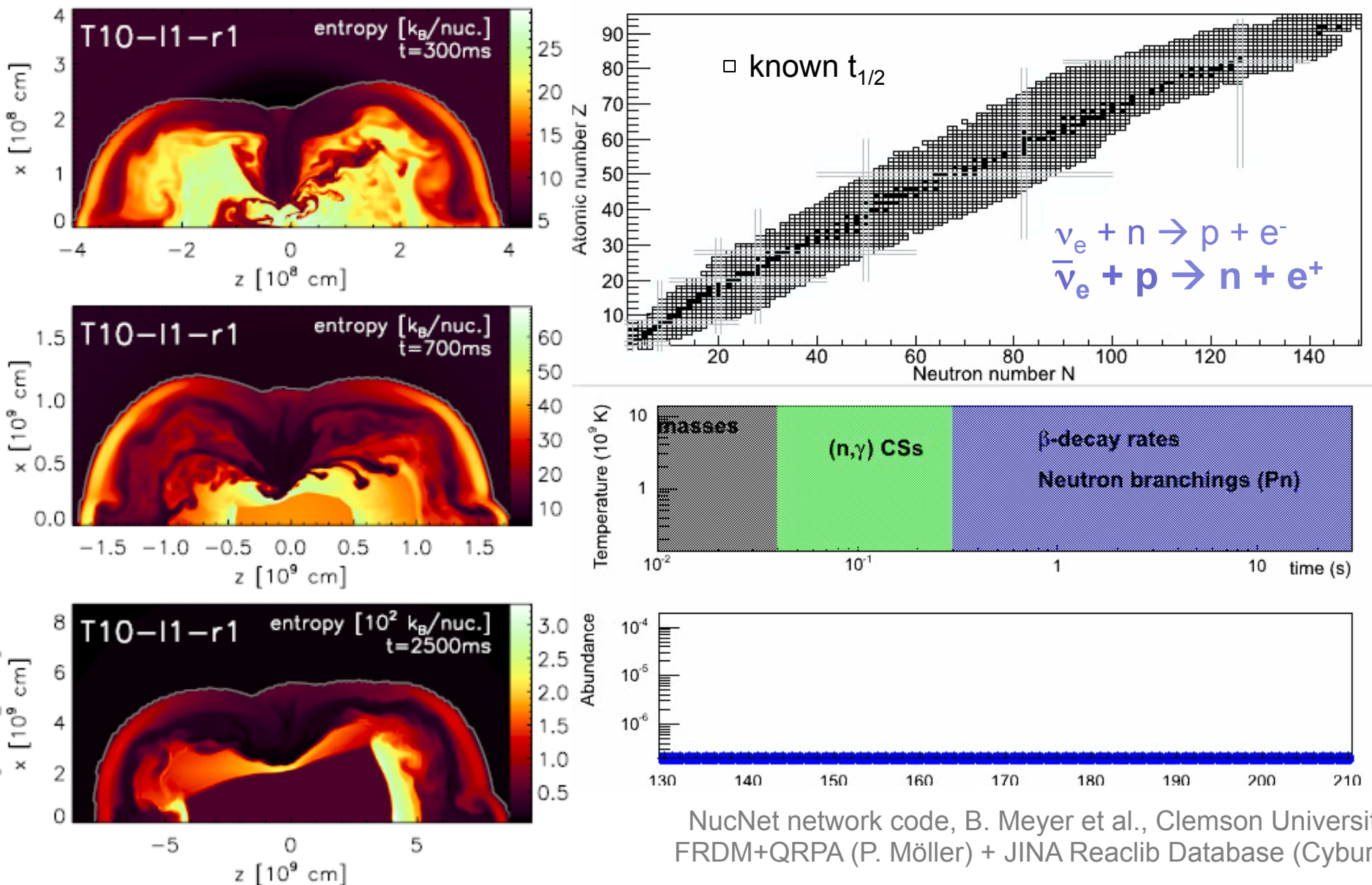
$$N_n = 10^{20}\text{-}10^{27} \text{ cm}^{-3}$$



Argast et al., 2004

Arcones, 2011

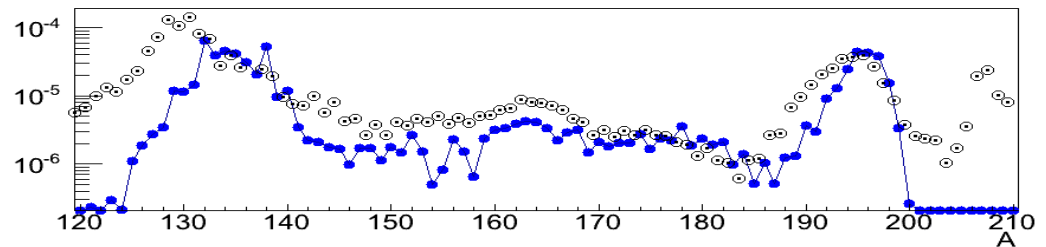
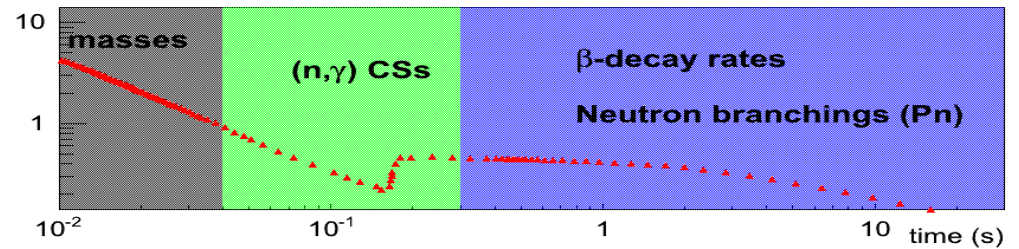
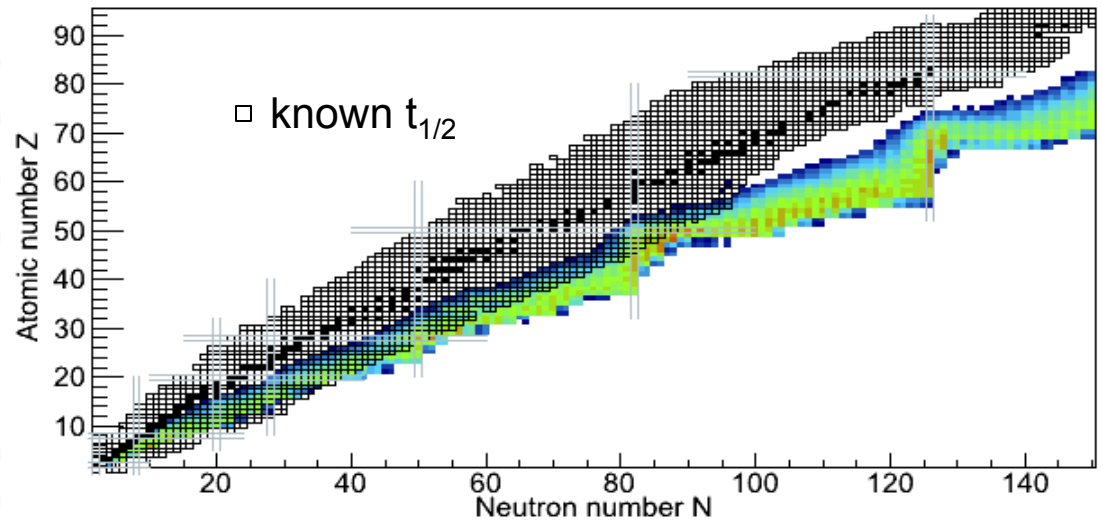
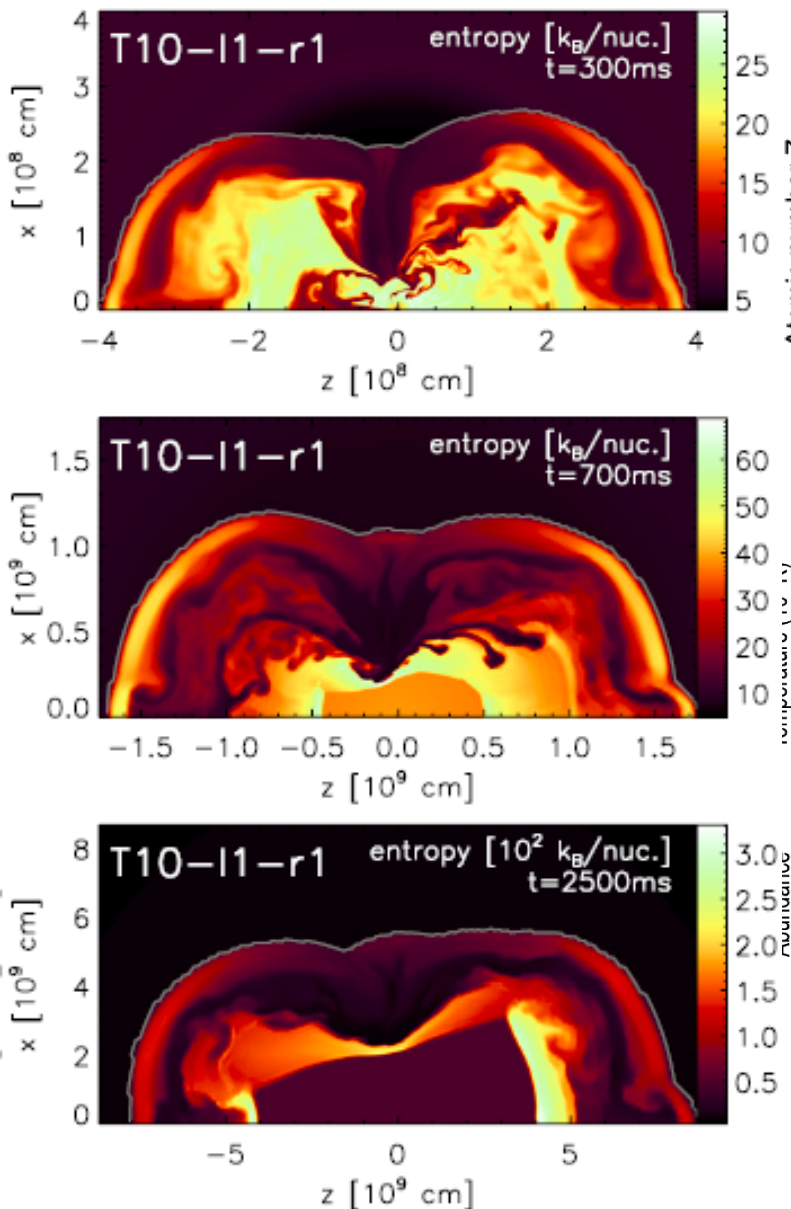
# R-process nucleosynthesis



NucNet network code, B. Meyer et al., Clemson University  
FRDM+QRPA (P. Möller) + JINA Reaclib Database (Cyburt)

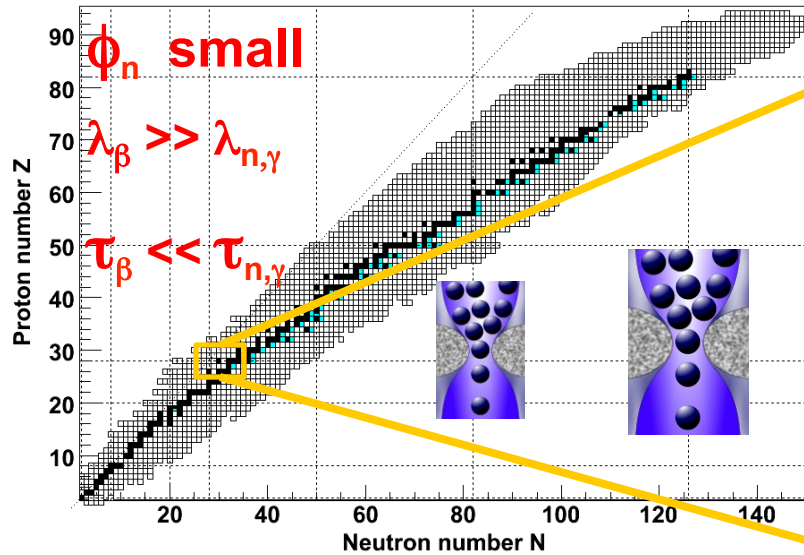


# R-process nucleosynthesis: relevant nuclear input

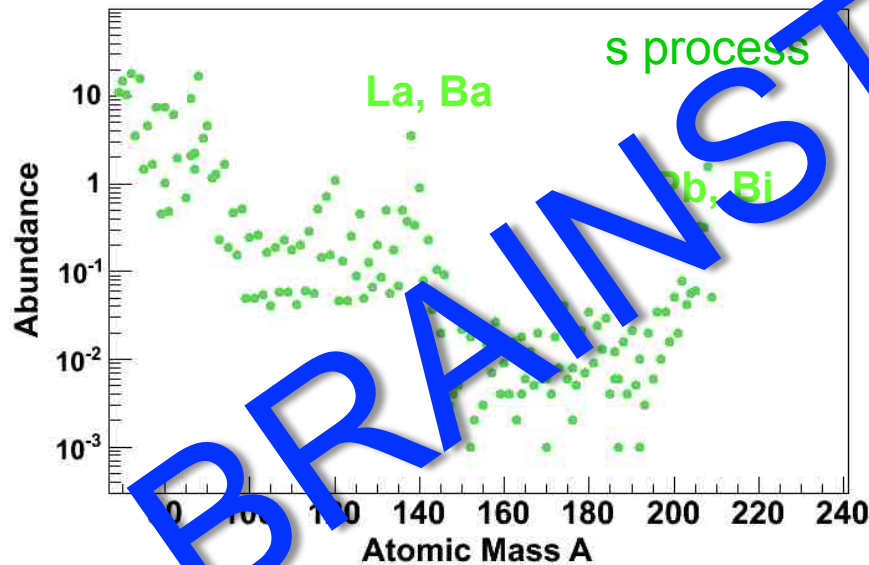
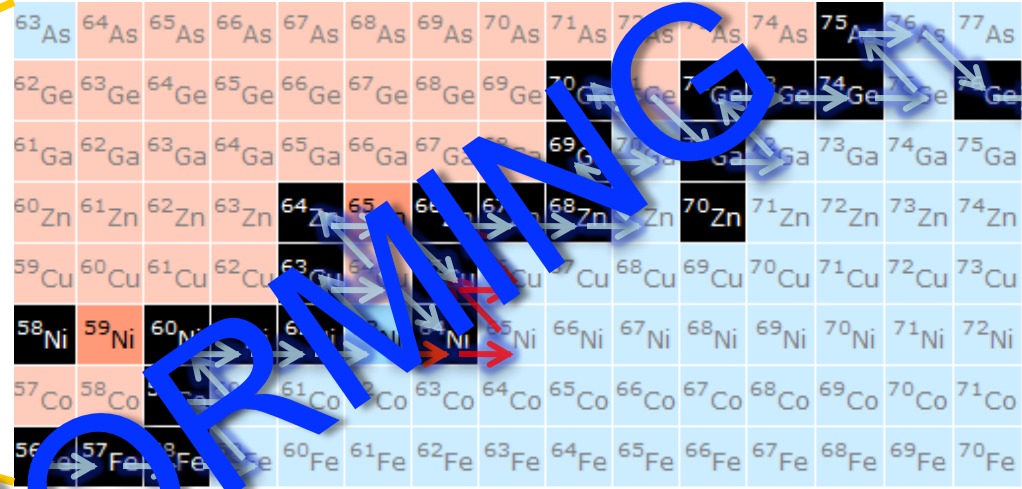


→ Neutron capture dominates most of the reactions over the full r-process flow of matter through higher masses

# The s-process mechanism



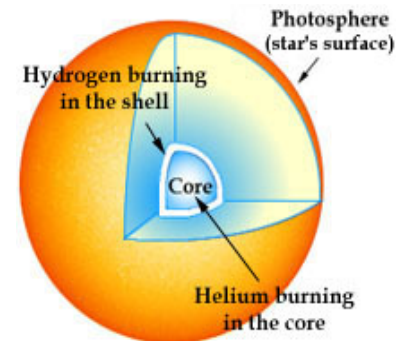
## s process in Massive Stars (Red Giants)



core He-burning      shell C-burning  
 $3-3.5 \cdot 10^8$  K       $\sim 1 \cdot 10^9$  K  
 $kT=25$  keV       $kT=90$  keV  
 $10^6$  cm $^{-3}$        $10^{11}-10^{12}$  cm $^{-3}$   
 $^{22}\text{Ne}(^4\text{He},n)^{25}\text{Mg}$



**(n, $\gamma$ ) Cross Sections**



# Two different s-process sites

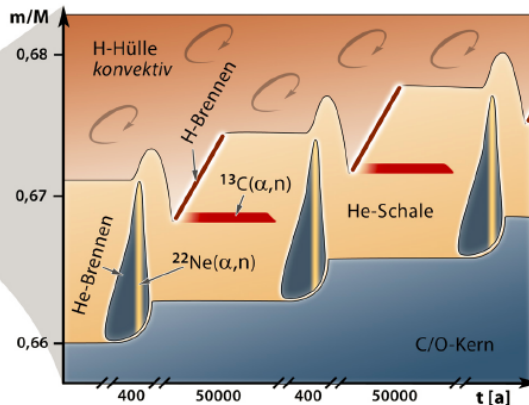
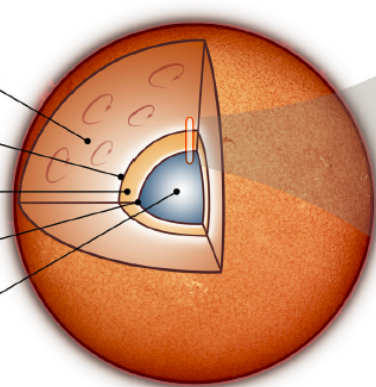
Main s-process  $90 < A < 210$

TP-AGB stars  $1-3 M_{\odot}$

shell H-burning  
 $0.9 \cdot 10^8 \text{ K}$   
 $kT = 8 \text{ keV}$   
 $10^7 - 10^8 \text{ cm}^{-3}$



He-flash  
 $3 - 3.5 \cdot 10^8 \text{ K}$   
 $kT = 23 \text{ keV}$   
 $10^{10} - 10^{11} \text{ cm}^{-3}$



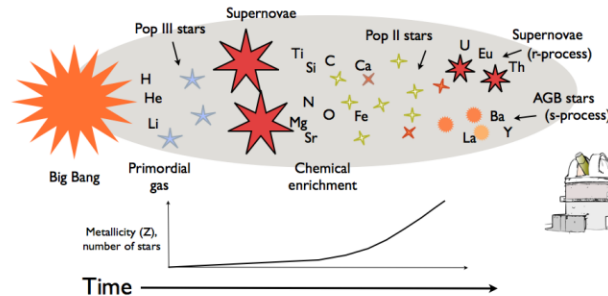
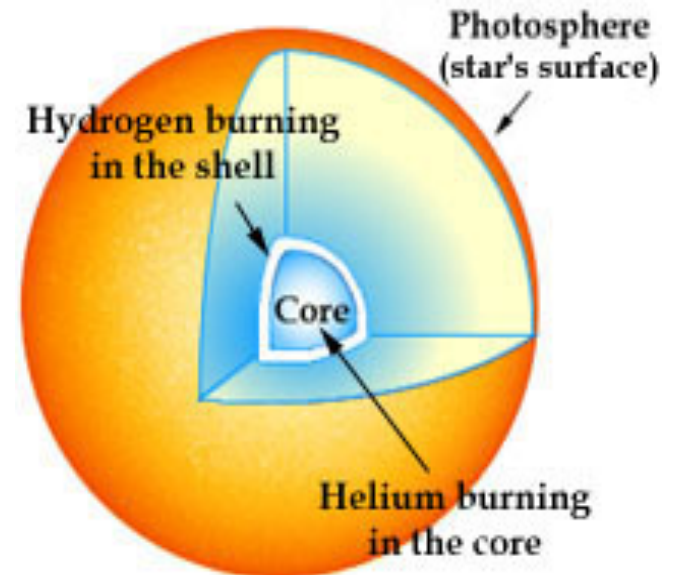
Weak s-process  $A < 90$

massive stars  $> 8 M_{\odot}$

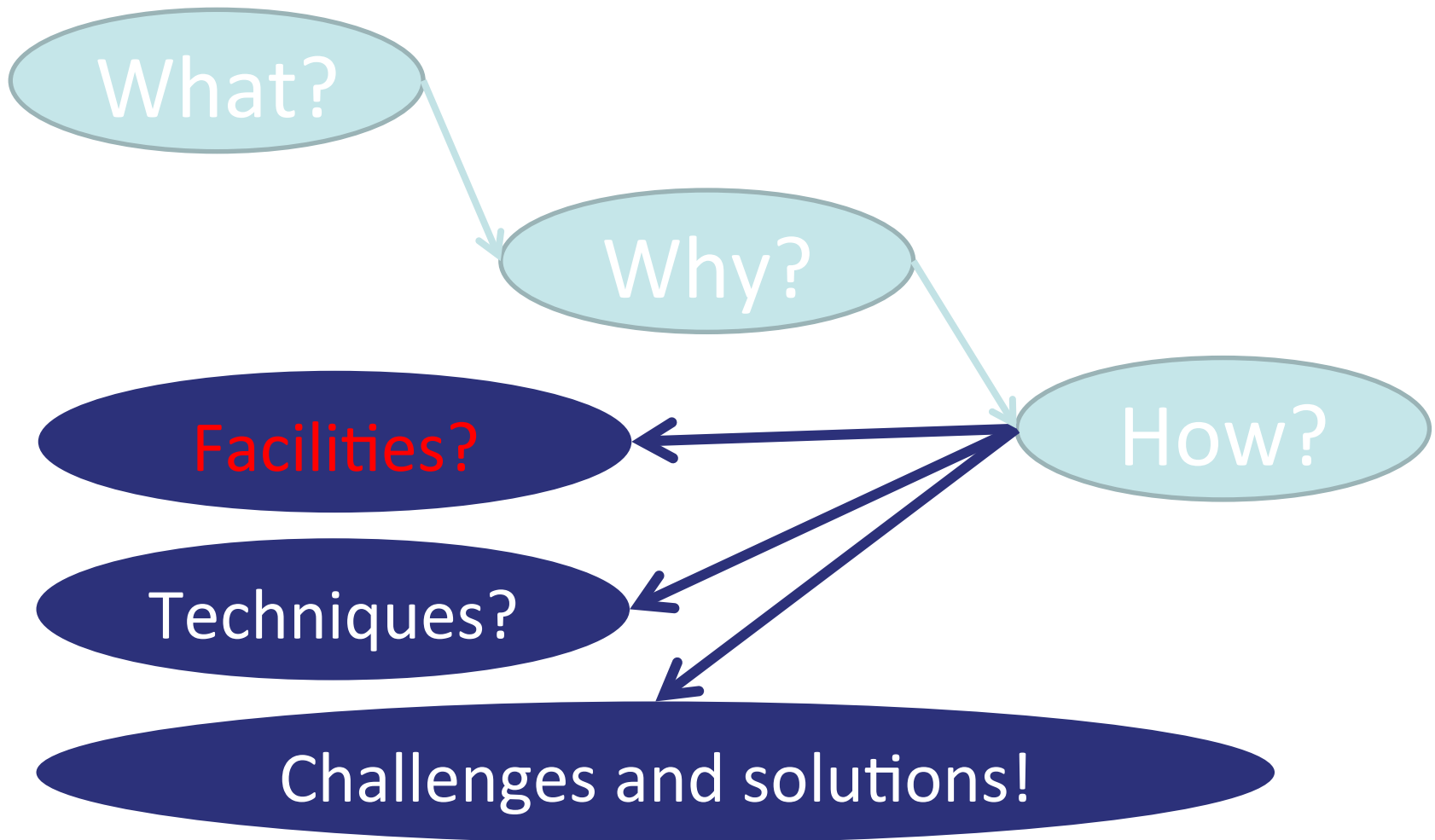
core He-burning  
 $3 - 3.5 \cdot 10^8 \text{ K}$   
 $kT = 26 \text{ keV}$   
 $10^6 \text{ cm}^{-3}$



shell C-burning  
 $\sim 1 \cdot 10^9 \text{ K}$   
 $kT = 91 \text{ keV}$   
 $10^{11} - 10^{12} \text{ cm}^{-3}$



# Radiative Neutron Capture



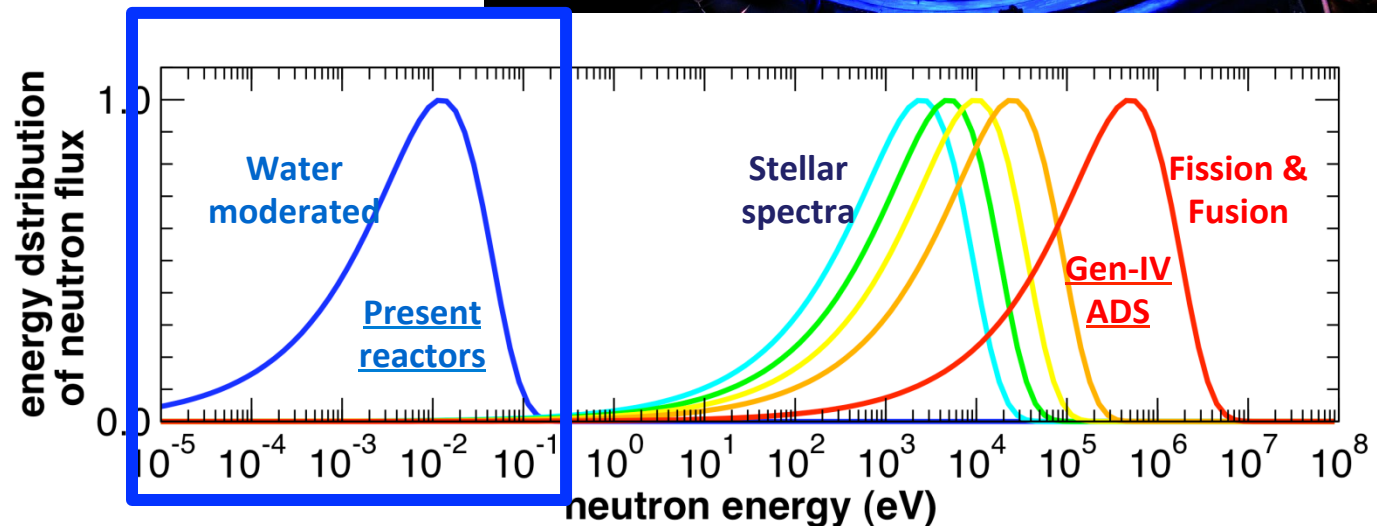
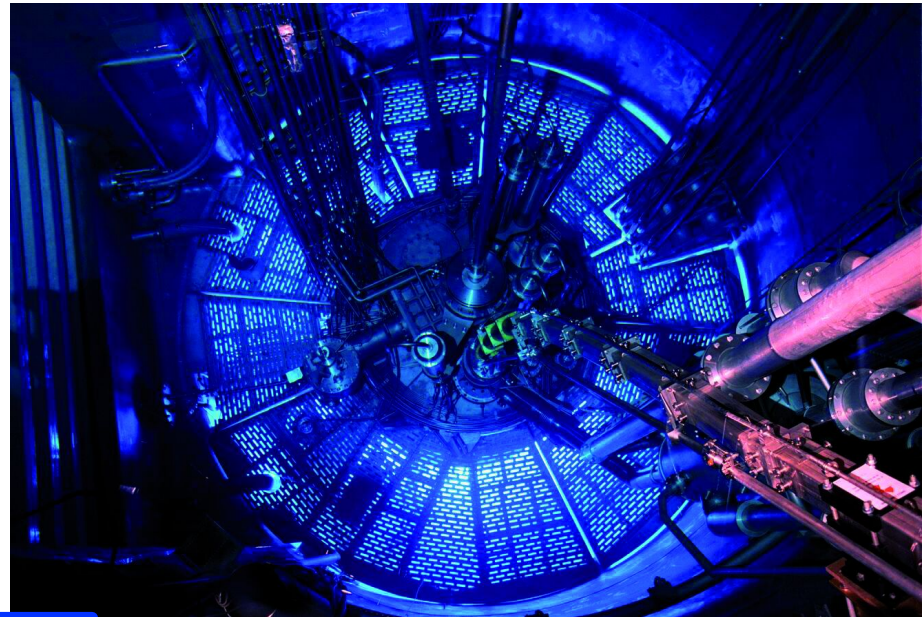


# Production of neutron beams

---

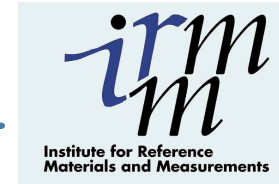
# Production of neutron beams

- Nuclear reactors



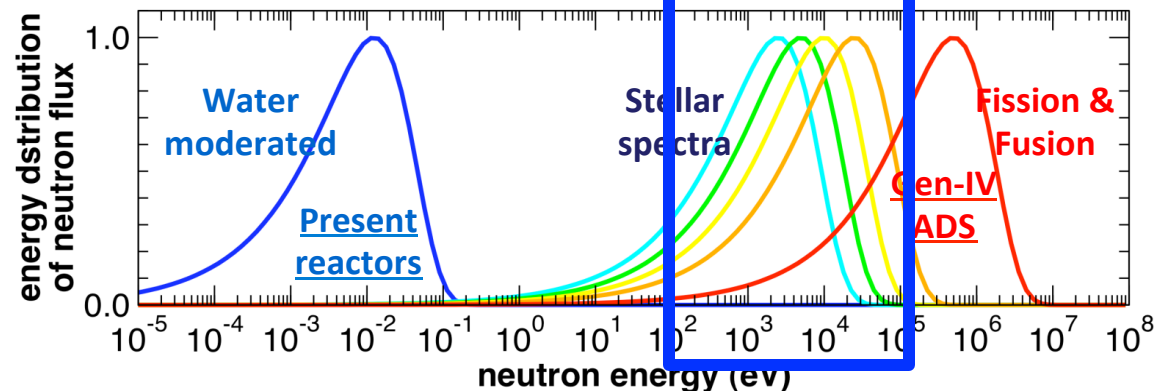
# Production of neutron beams

- Nuclear reactors
- Electron LINACs
  - $e + U \rightarrow \text{Bremsstrahlung} \rightarrow \text{photofission}$



# Production of neutron beams

- Nuclear reactors
- Electron LINACs
  - $e + U \rightarrow \text{Bremsstrahlung} \rightarrow \text{photofission}$
- “Low energy” proton (and D) accelerators
  - $p(^7\text{Li},n)^7\text{Be}$
  - $p(^9\text{Be},n)^9\text{B}$
  - Fusion reactions (D-D or D-T)





# Production of neutron beams

- Nuclear reactors }



- Electron LINACs

- $e + U \rightarrow \text{Bremsstrahlung} \rightarrow \text{photofission}$



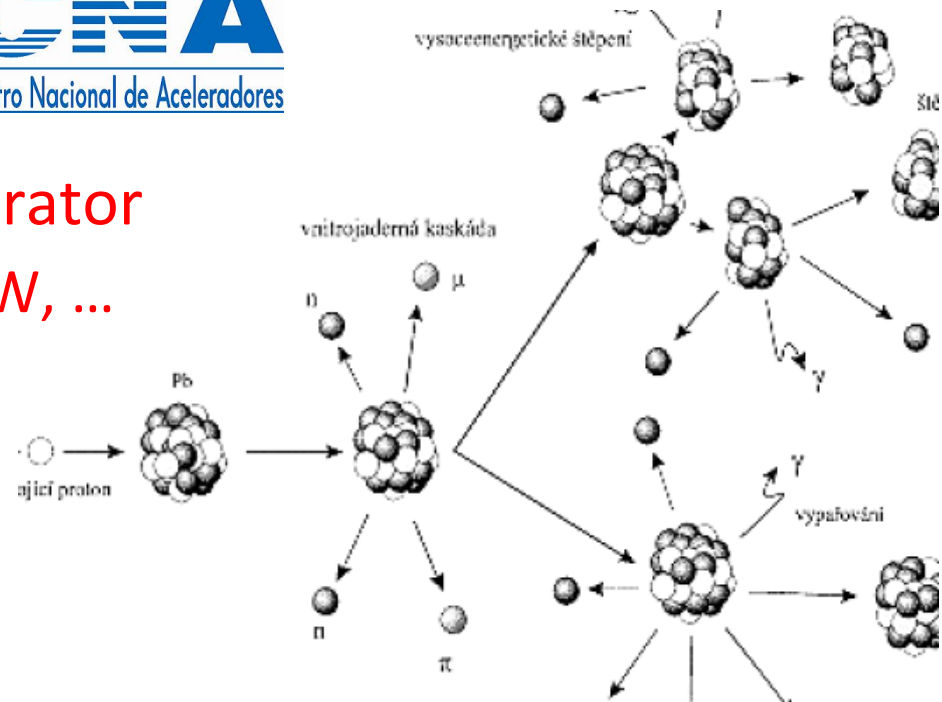
- “Low energy” proton (and D) accelerators

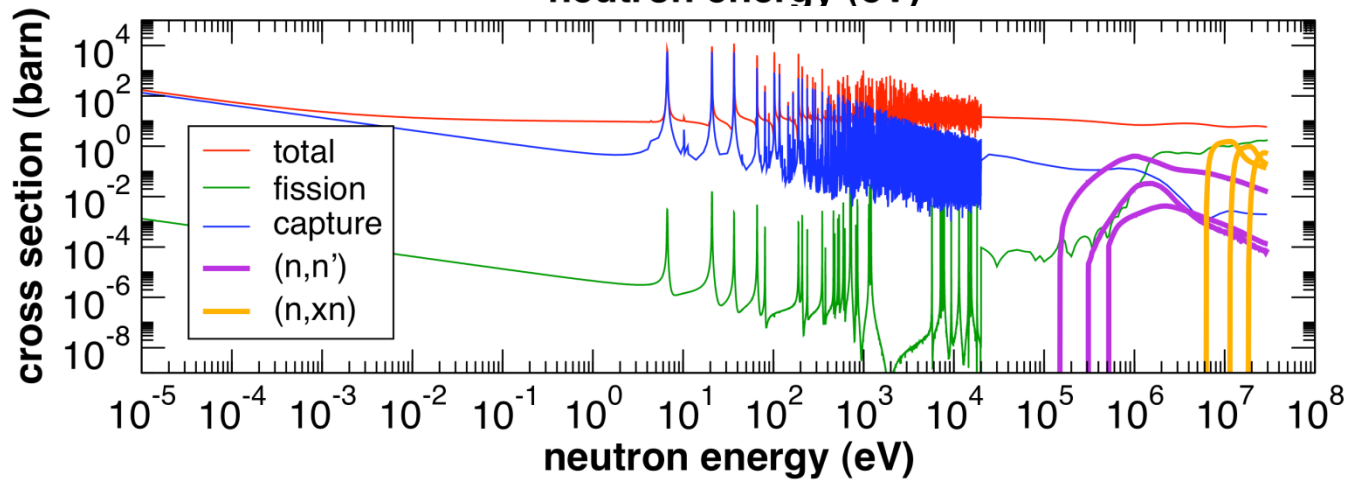
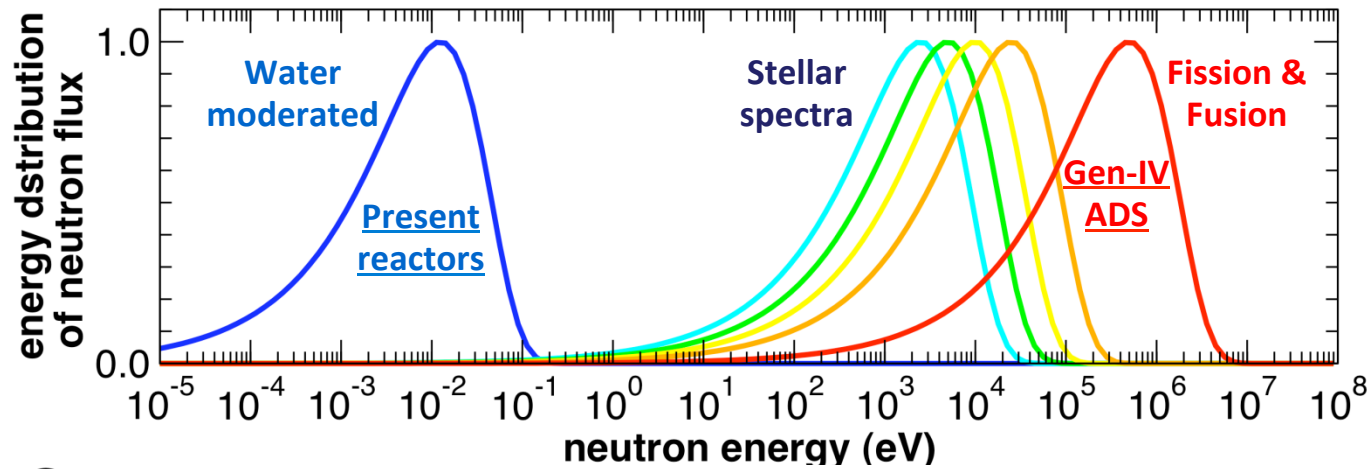
- $p(^7\text{Li},n)^7\text{Be}$
  - $p(^9\text{Be},n)^9\text{B}$



# Production of neutron beams

- Nuclear reactors
- Electron LINACs
  - $e + U \rightarrow \text{Bremsstrahlung} \rightarrow \text{photofission}$
- “Low energy” proton (and D) accelerators
  - $p(^7\text{Li},n)^7\text{Be}$
  - $p(^9\text{Be},n)^9\text{B}$
  - Fusion reactions (D-D or D-T)
- “High energy” proton accelerator
  - Spallation reactions on Pb, W, ...





reactor (ex. ILL)

stellar (ex. FZK)

mono-energetic

unmoderated tof (ex. GANIL-NFS)

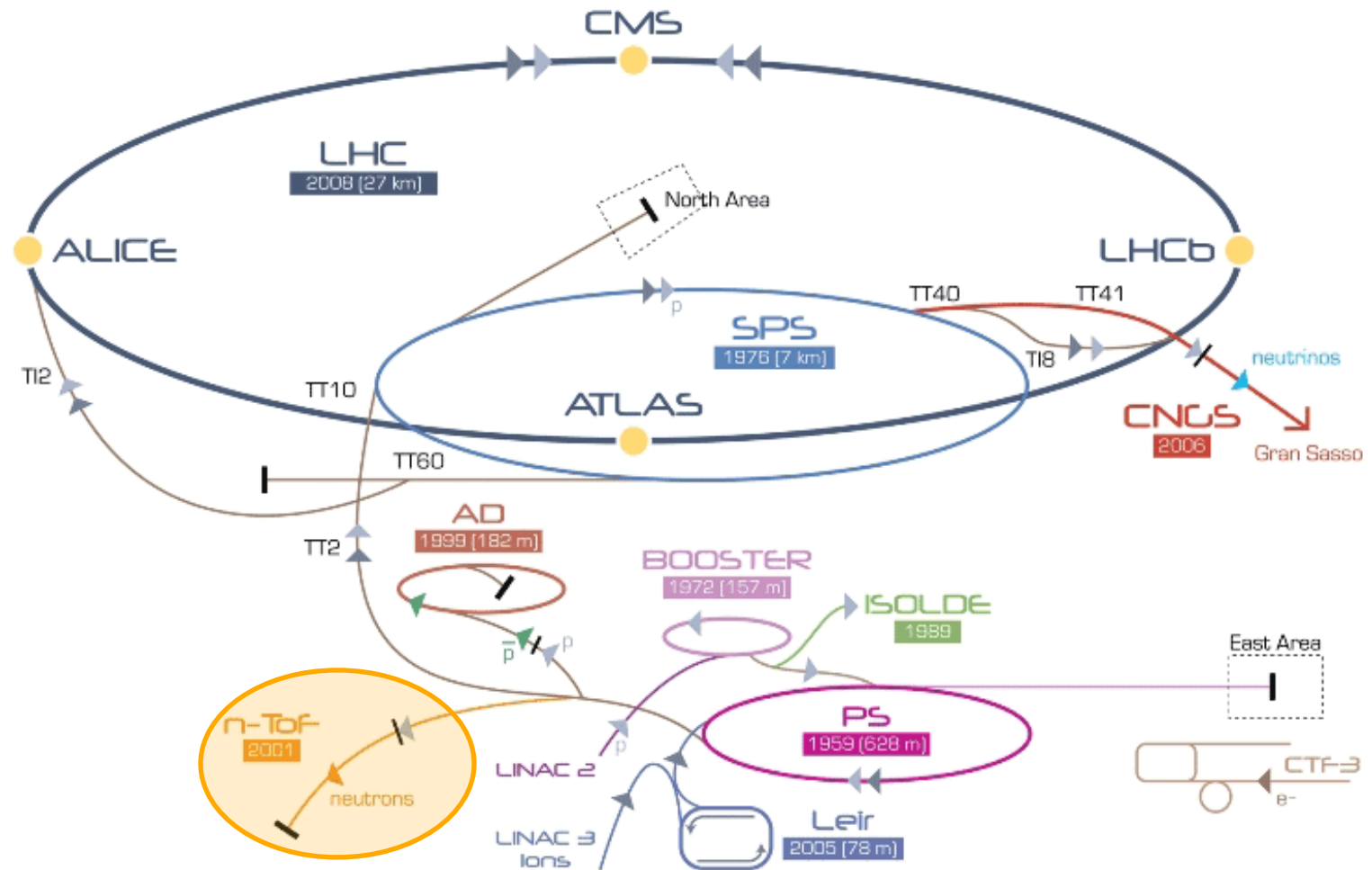
n\_TOF

$p(^7\text{Li},n)^7\text{Be}$  @CNA

D-D, D-T,... @CNA

Many

# CERN n\_TOF facility



C. Rubbia et al., *A high resolution spallation driven facility at the CERN-PS to measure neutron cross sections in the interval from 1 eV to 250 MeV*, CERN/LHC/98-02(EET) 1998.



# CERN n\_TOF facility



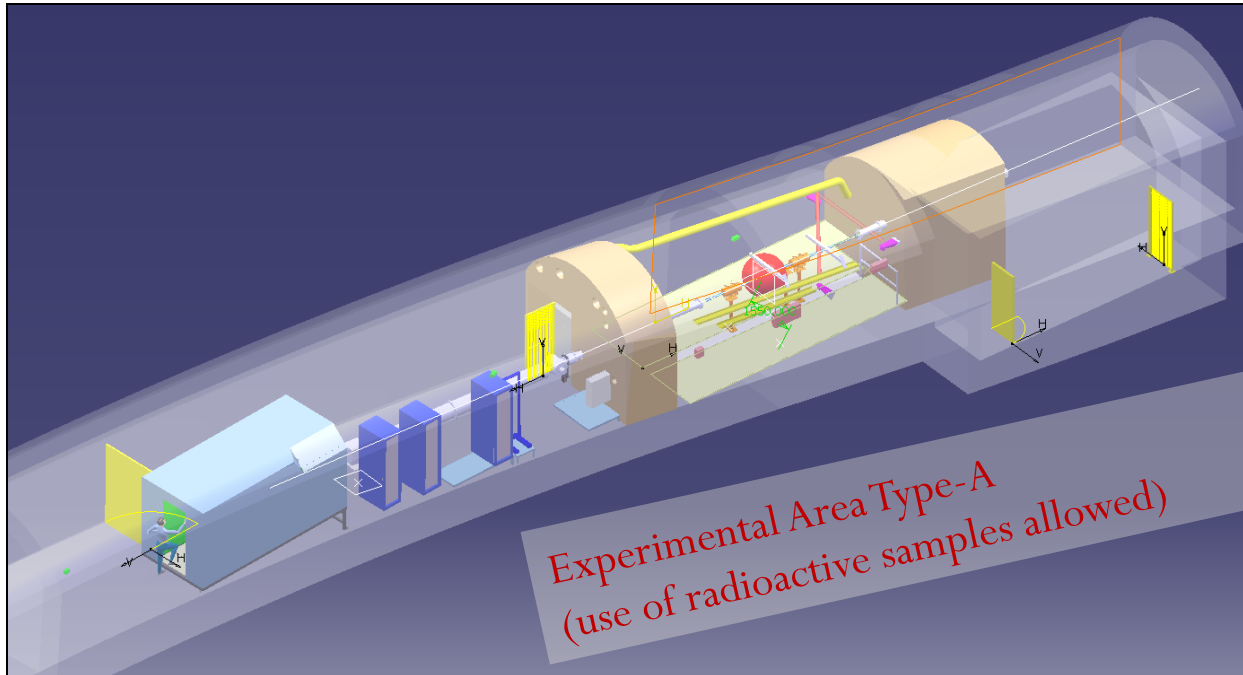


# CERN n\_TOF facility

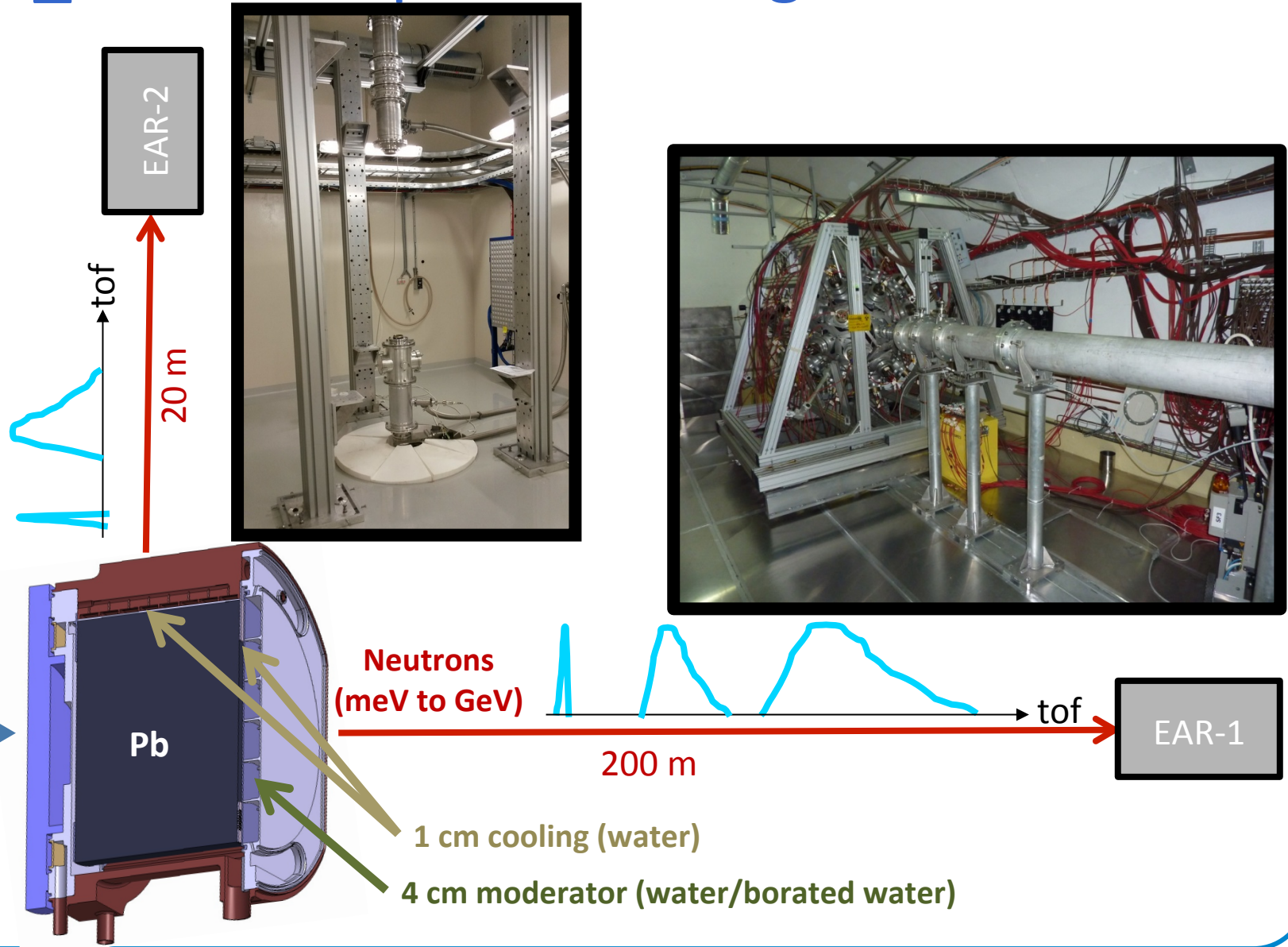




# The n\_TOF lead spallation target



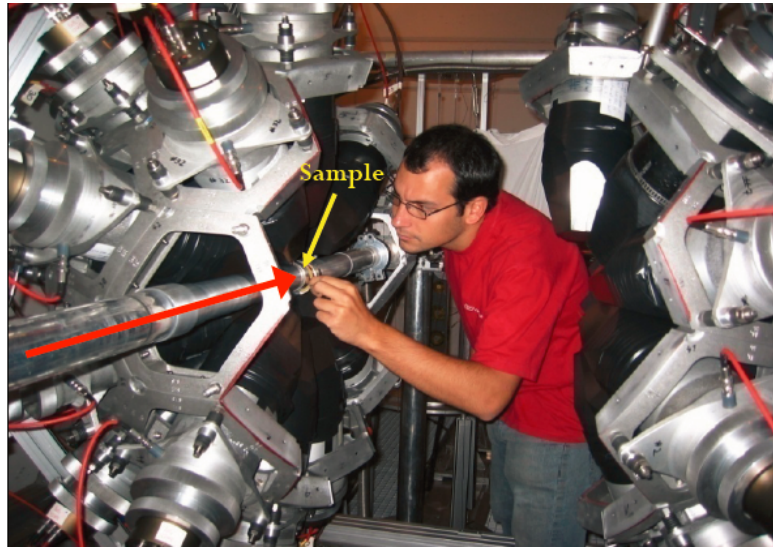
# The n\_TOF lead spallation target



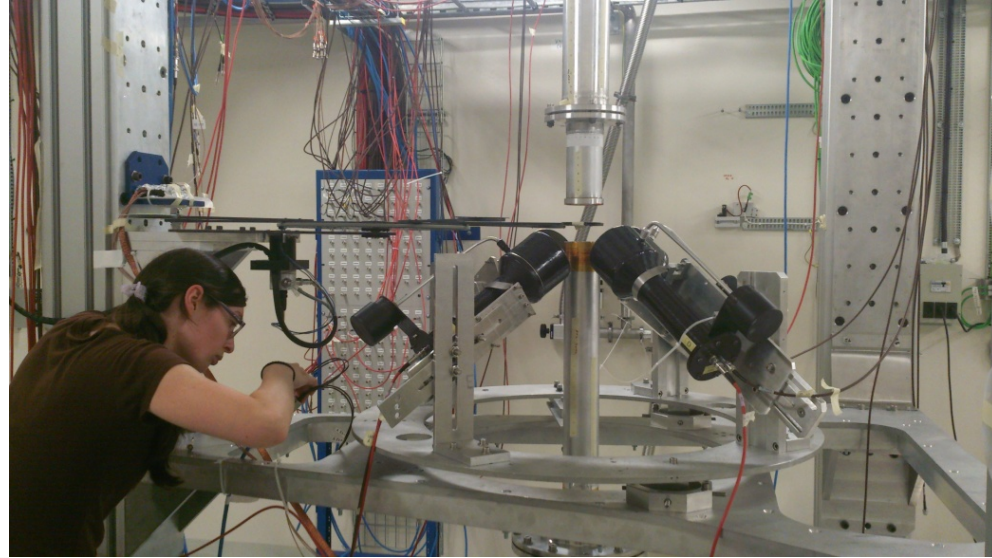


# $(n, \gamma)$ Cross sections via prompt $\gamma$ -ray(s) detection

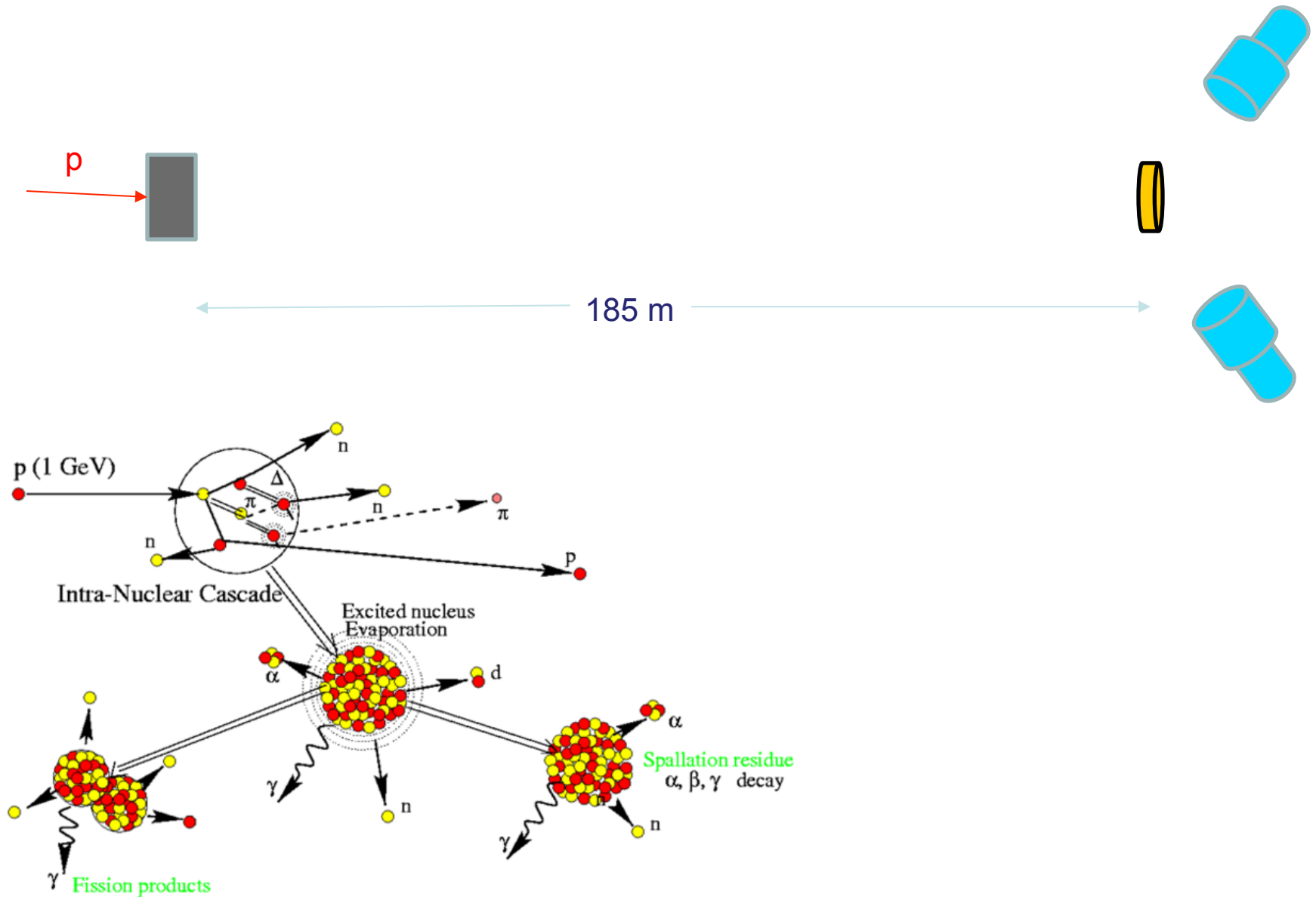
BaF<sub>2</sub> Total Absorption Calorimeter (TAC)



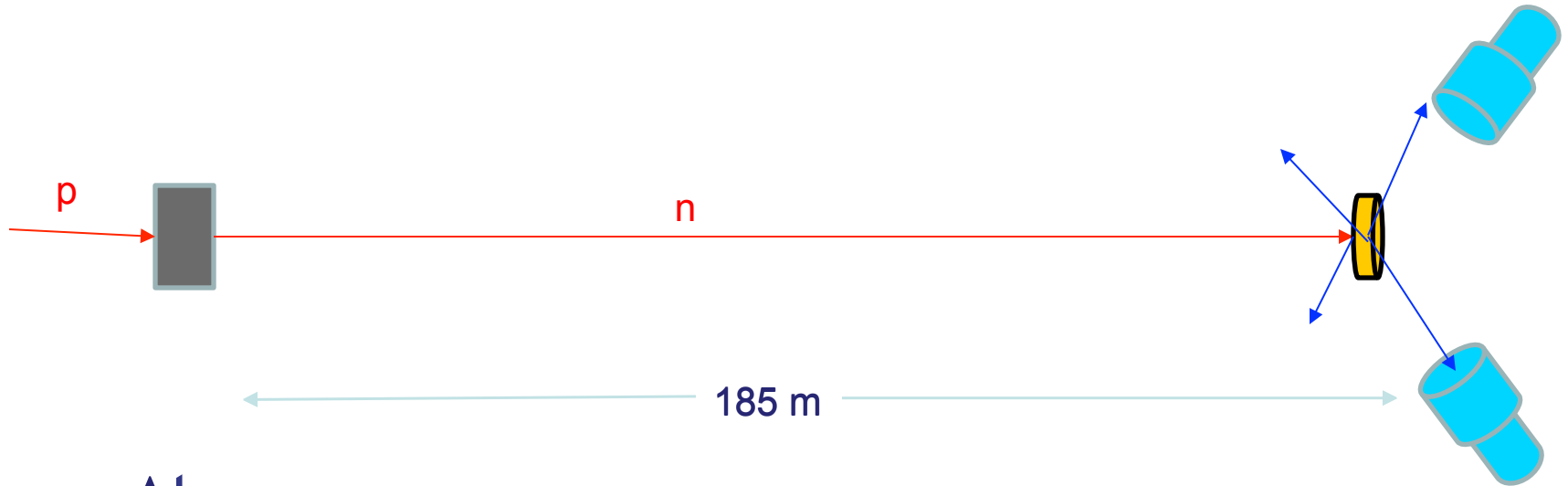
C<sub>6</sub>D<sub>6</sub> based Total Energy Detector (TED)



# The TOF technique:



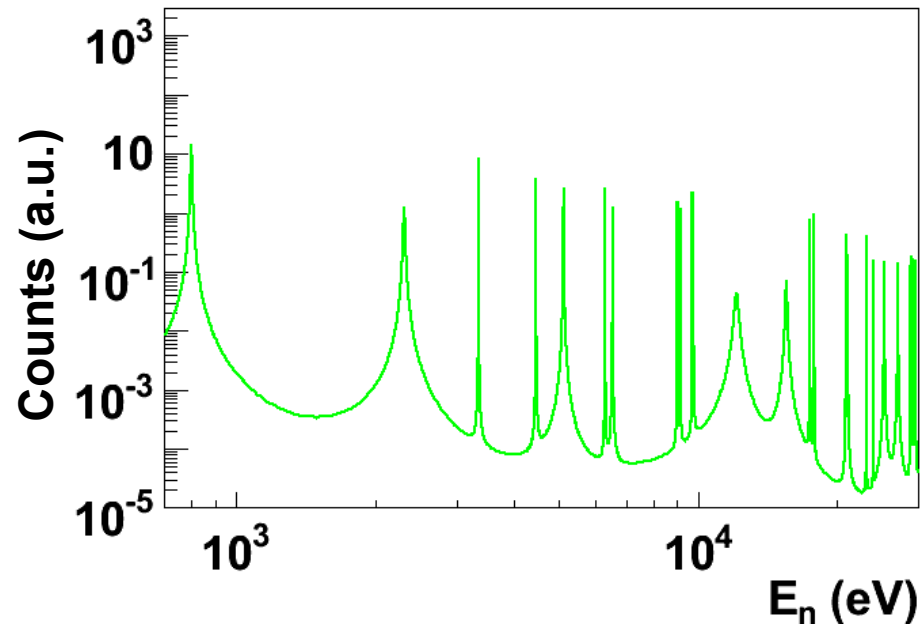
# The TOF technique:



$\Delta t$



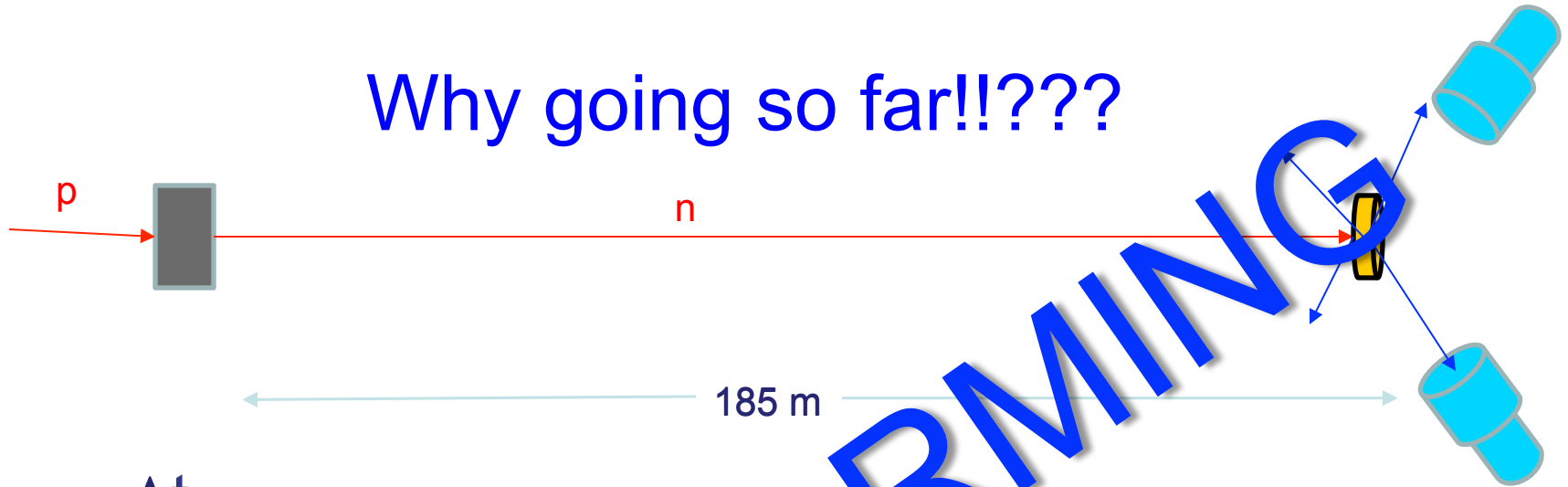
$$E_n = \frac{1}{2} m (L/\Delta t)^2$$





# The TOF technique:

Why going so far!!???



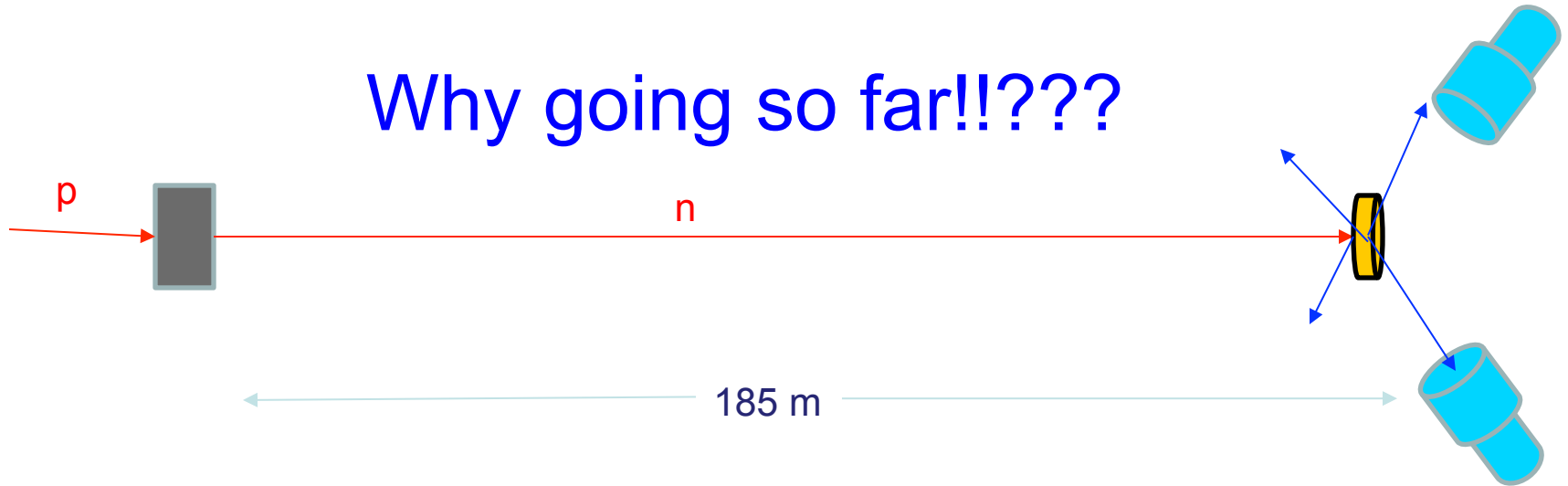
$\Delta t$

$$E_n = \frac{1}{2} m (L/\Delta t)^2$$



e-eighteenth.en.alibaba.com

Why going so far!!???



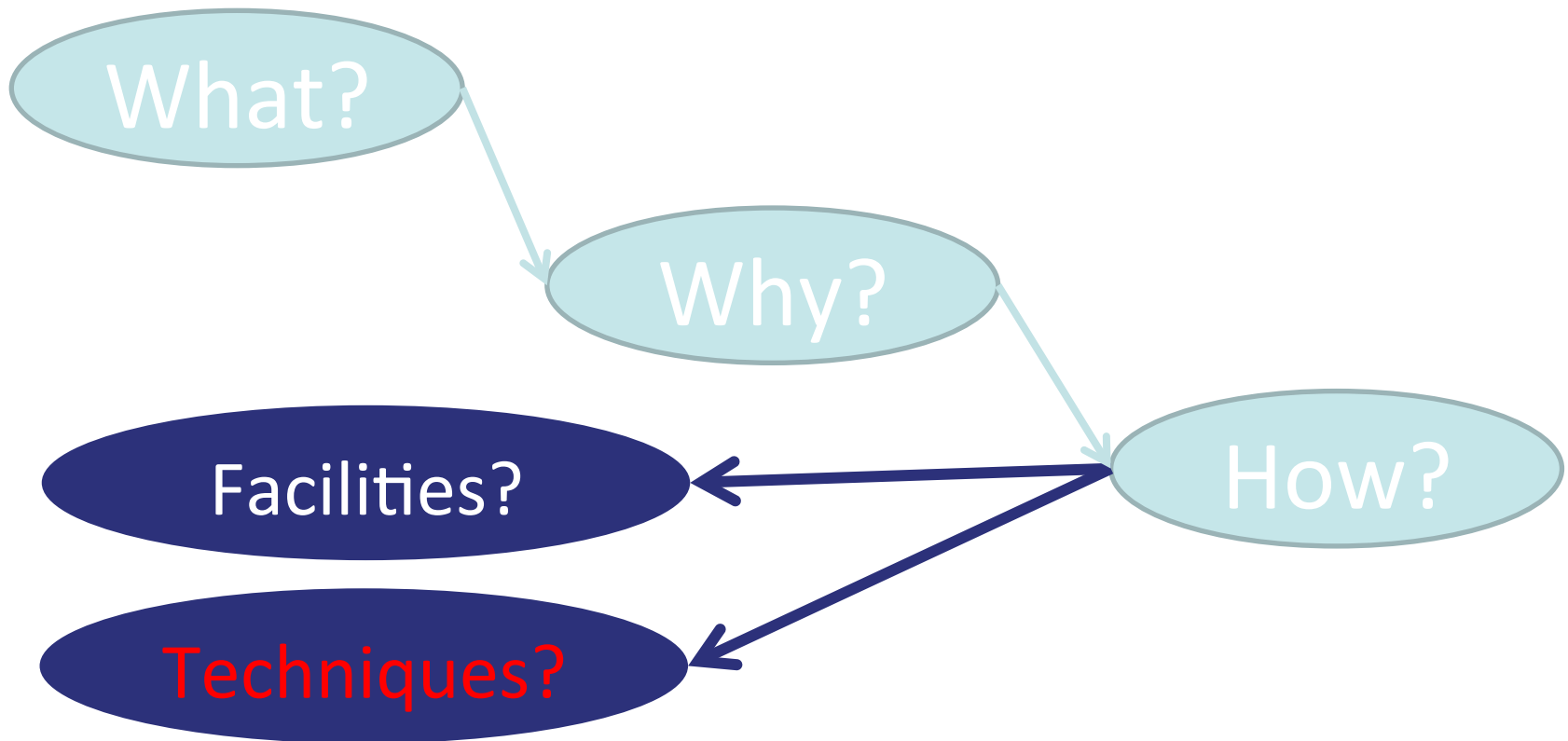
$$E_n = \frac{1}{2} m (L/\Delta t)^2$$

$$dE_n = E_n((d\Delta t/\Delta t) + 2(dL/L))$$

$$dE_n = E_n((d\Delta t/\Delta t)^2 + (2dL/L)^2)^{1/2}$$

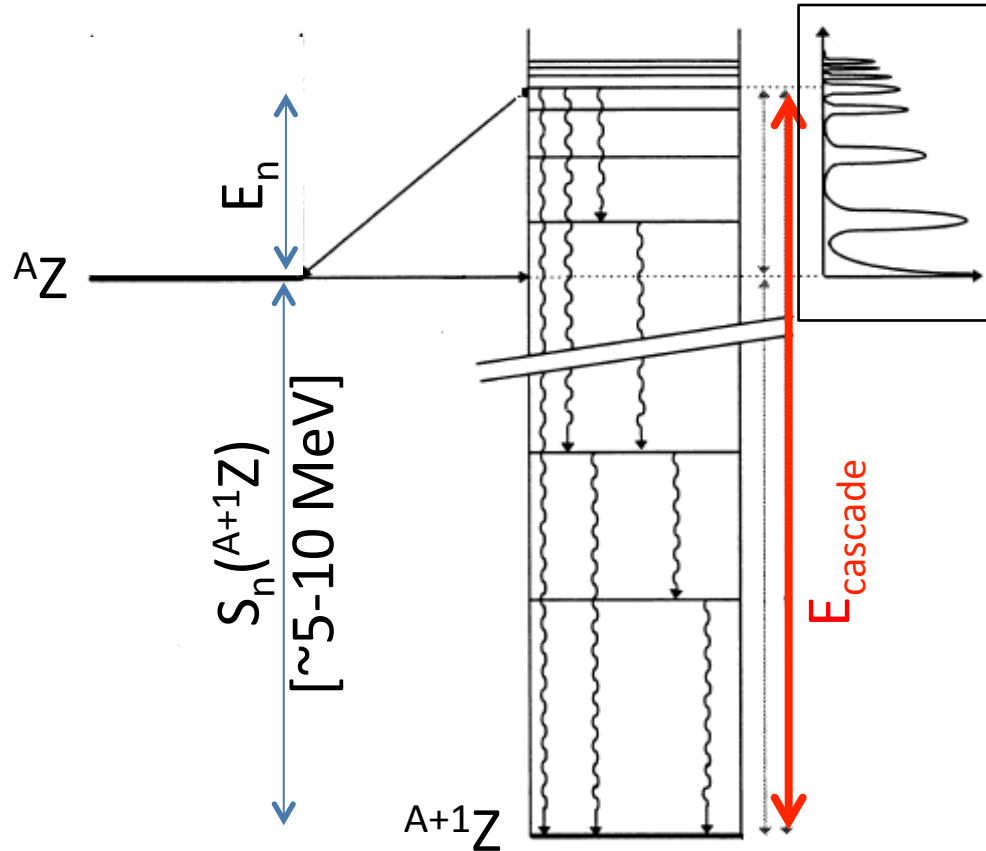
$$dE_n \propto 1/L$$

# Radiative Neutron Capture



- 1) Detect a gamma-ray “characteristic” of the capture cascade
- 2) Detect at most one gamma-ray of the capture cascade
- 3) Detect all the gamma-rays for each capture cascade

# 1) Detect a “characteristic” $\gamma$ -ray

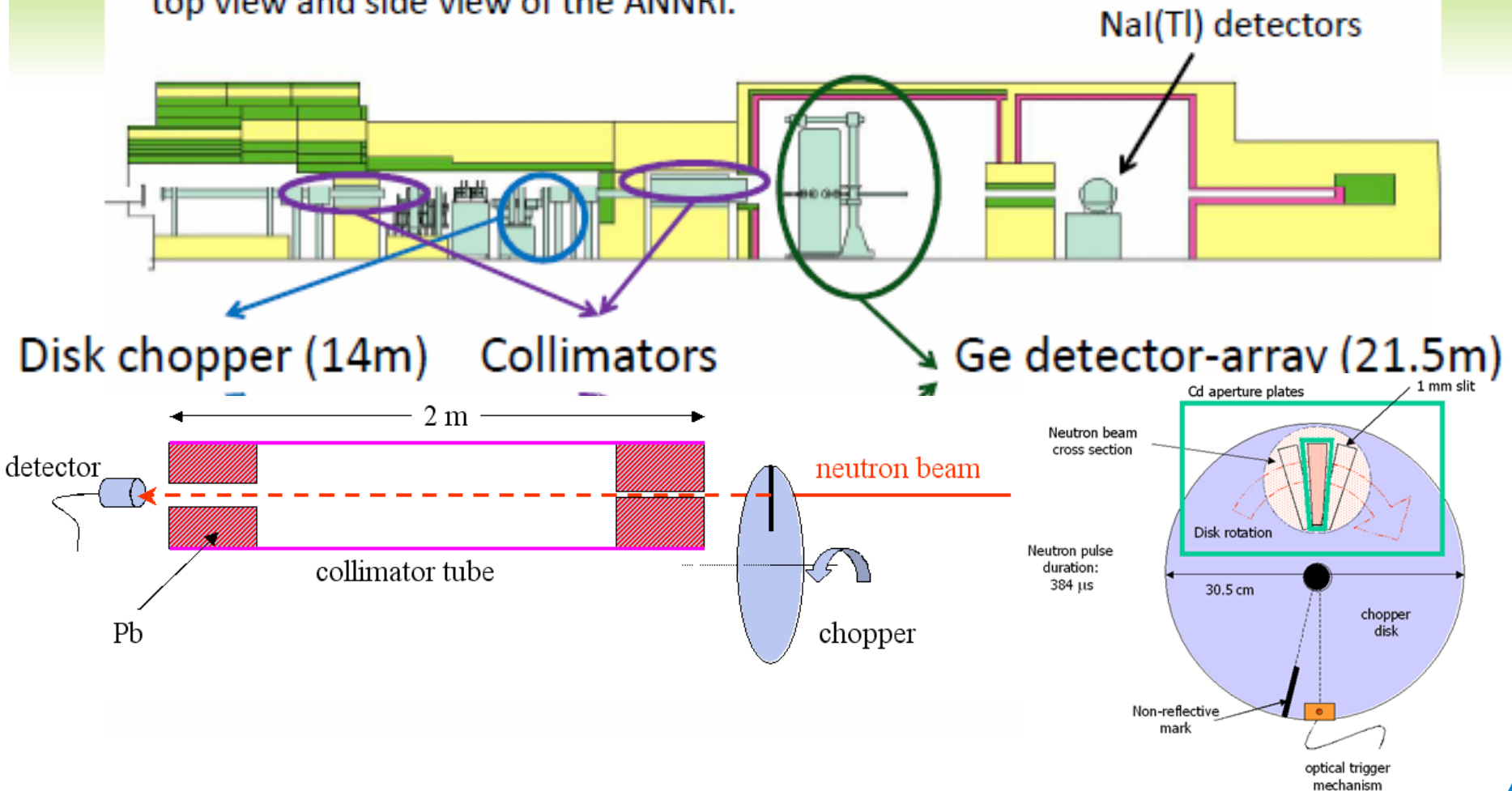




# 1) Detect a “characteristic” $\gamma$ -ray

- ANNRI @ J-PARC (Japan)

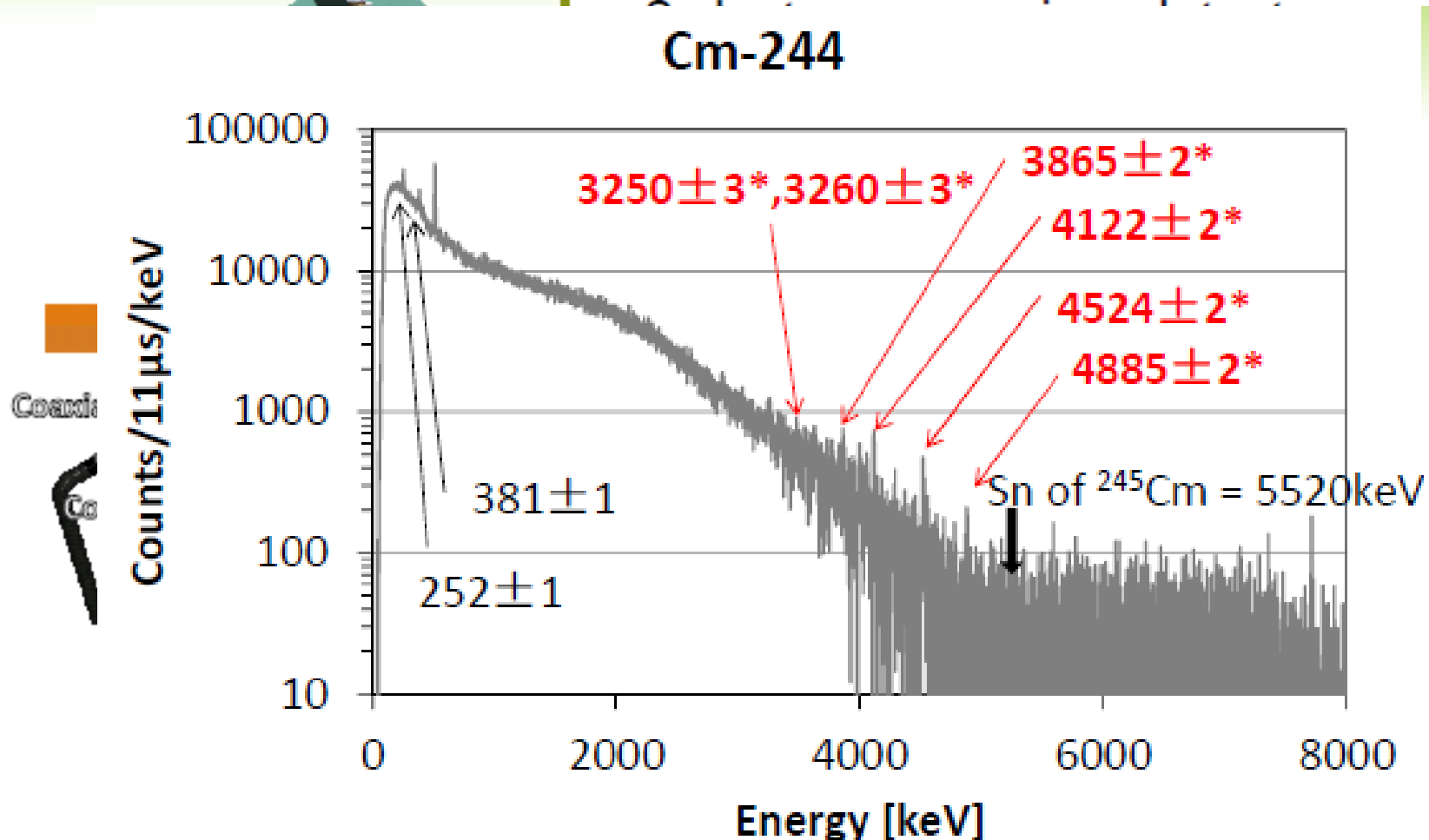
top view and side view of the ANNRI.



# 1) Detect a “characteristic” $\gamma$ -ray

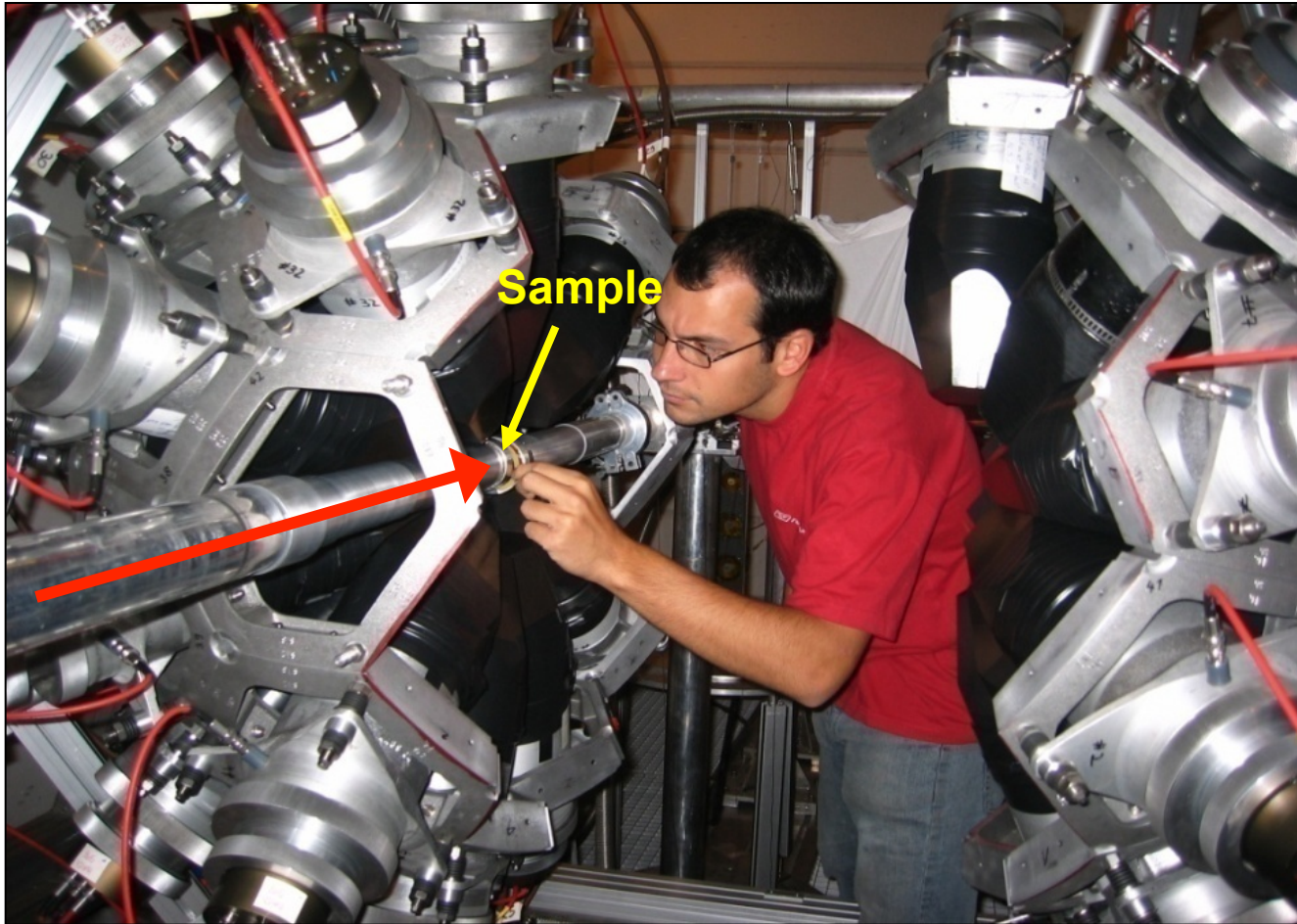
## Limitation in accuracy:

One needs to know the “intensity” of the characteristic(s)  $\gamma$ -ray line(s)

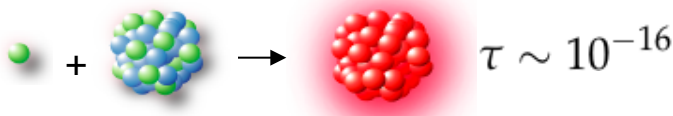


## 2) Detect all $\gamma$ -rays of the cascade

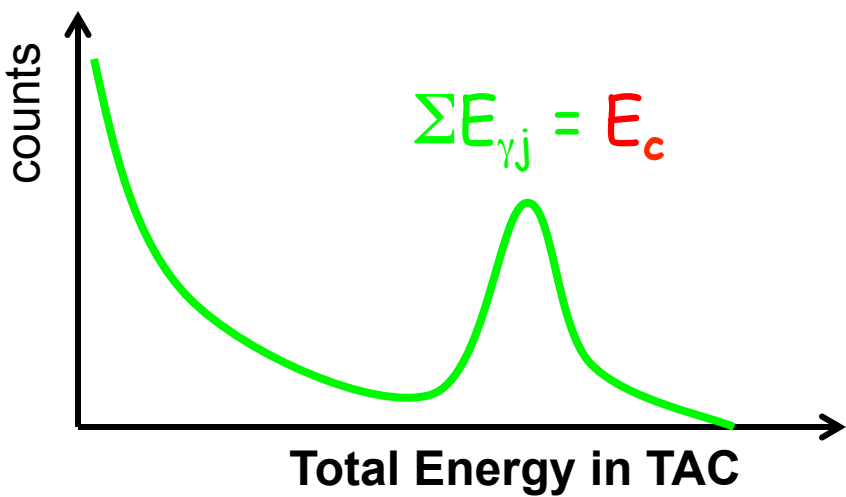
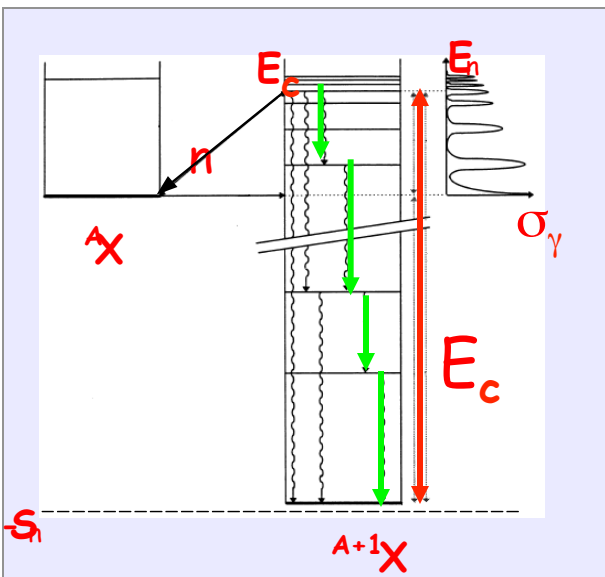
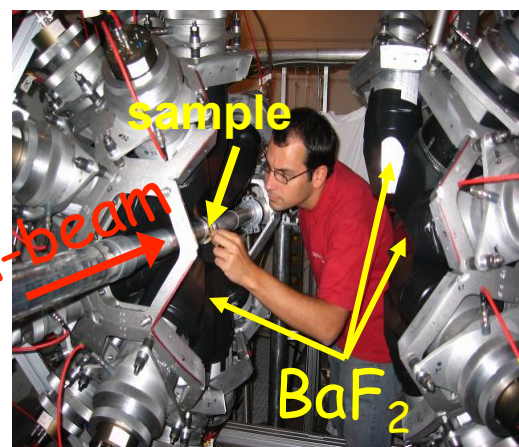
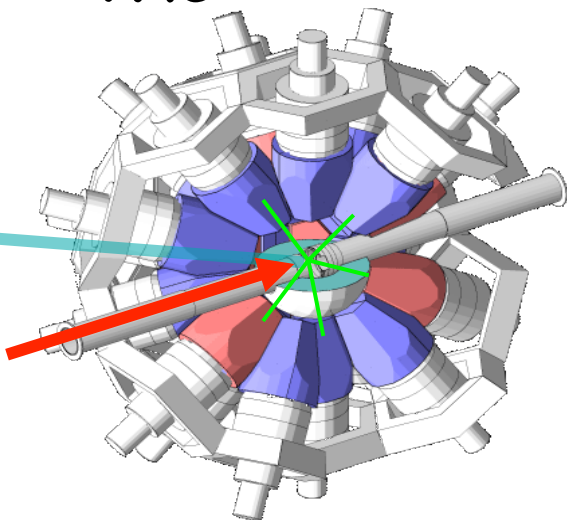
The **TAC** consists in **40 BaF<sub>2</sub> crystals** (12 pentagonal and 28 hexagonal) with a thickness of 15 cm. It has a nearly 100% efficiency for detecting capture events.



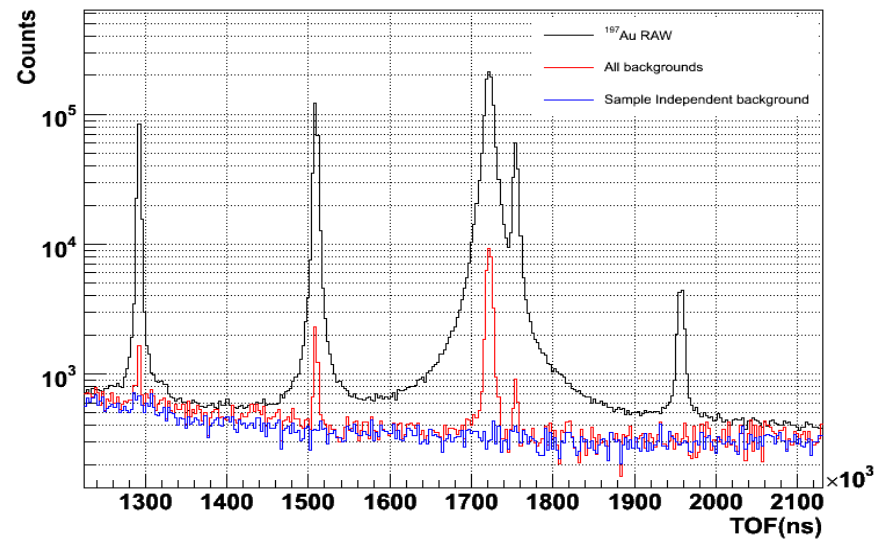
# 2) Detect all $\gamma$ -rays of the cascade



TAC

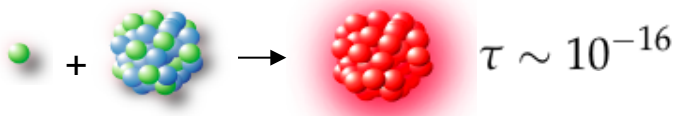


TAC rate as a function of TimeOfFlight,  $m > 2$  &  $2.5 < E(\text{MeV}) < 7.5$

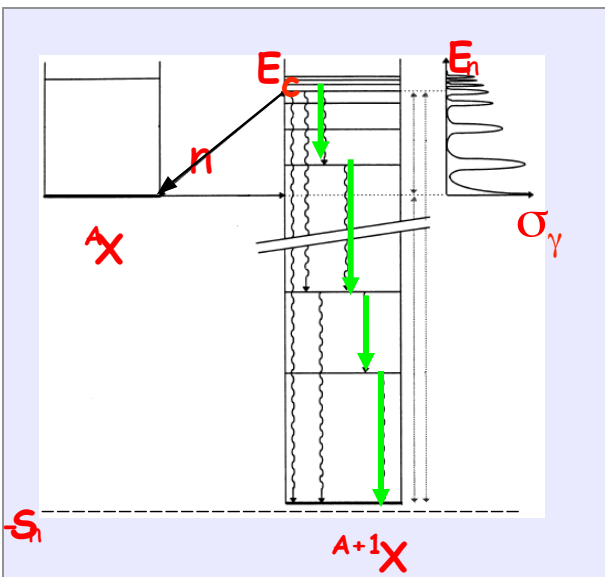
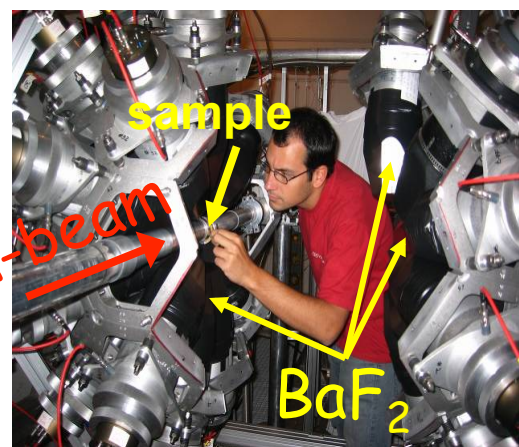
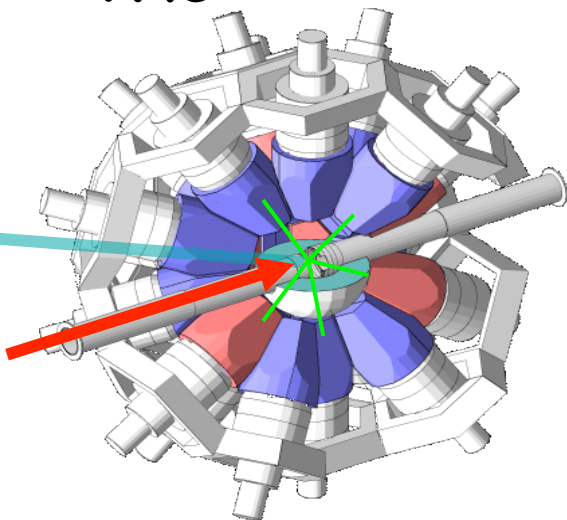




# 2) Detect all $\gamma$ -rays of the cascade

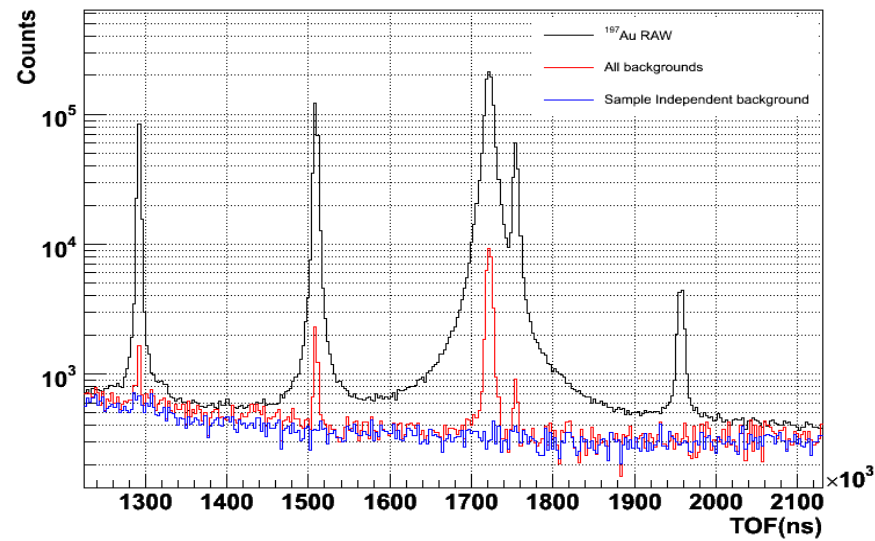
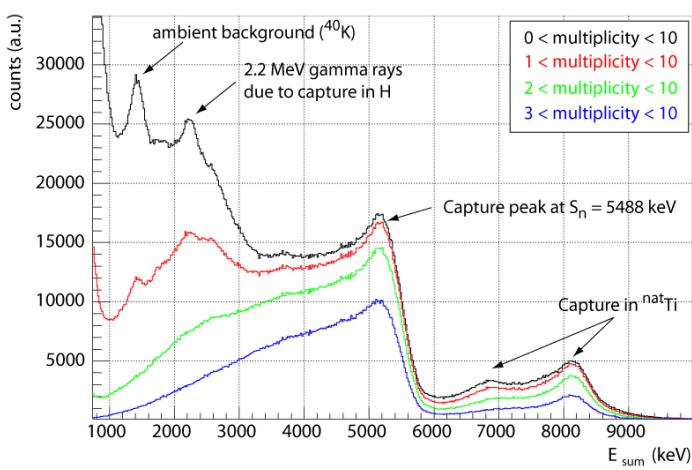


TAC

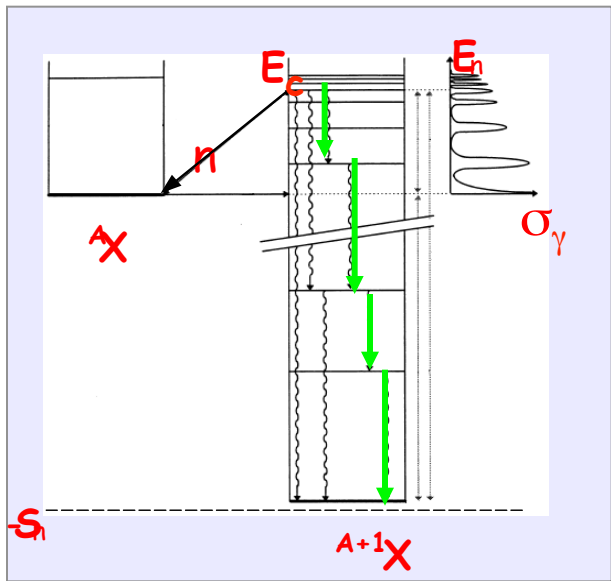


TAC rate as a function of TimeOfFlight,  $m > 2$  &  $2.5 < E(\text{MeV}) < 7.5$

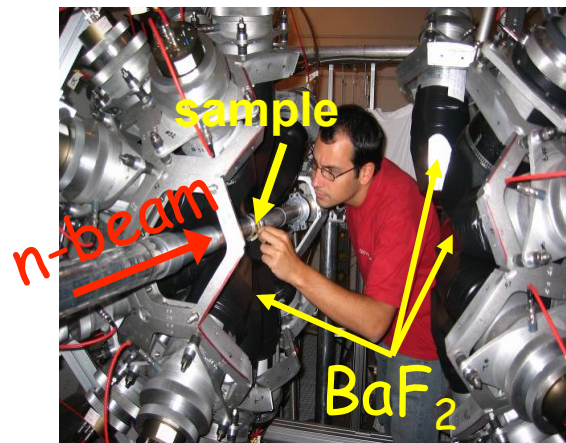
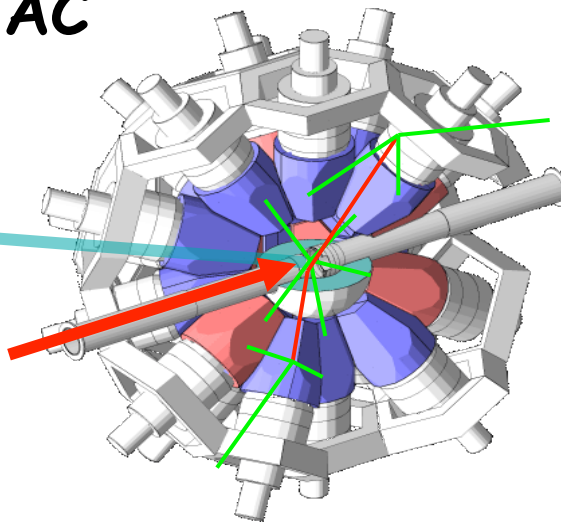
Energy deposition spectrum for  $^{237}\text{Np}$  in the neutron energy range 1 eV - 10 eV



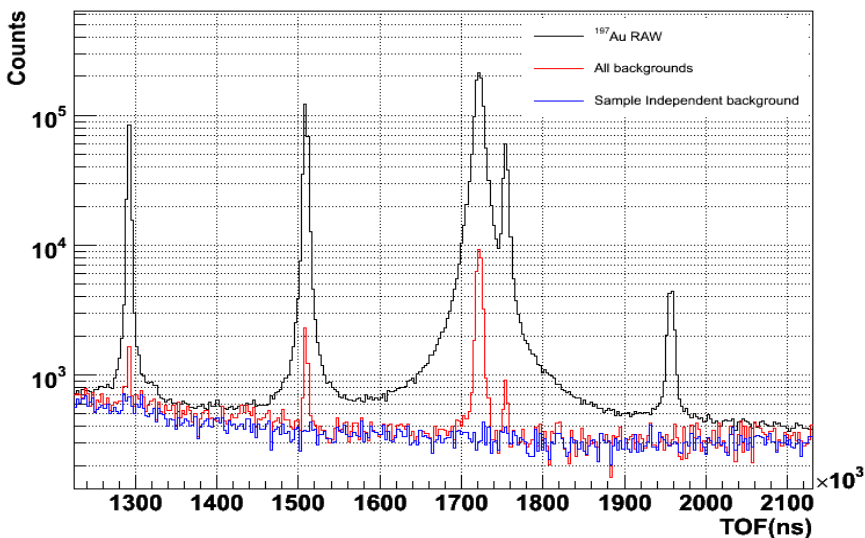
## 2) Detect all $\gamma$ -rays of the cascade



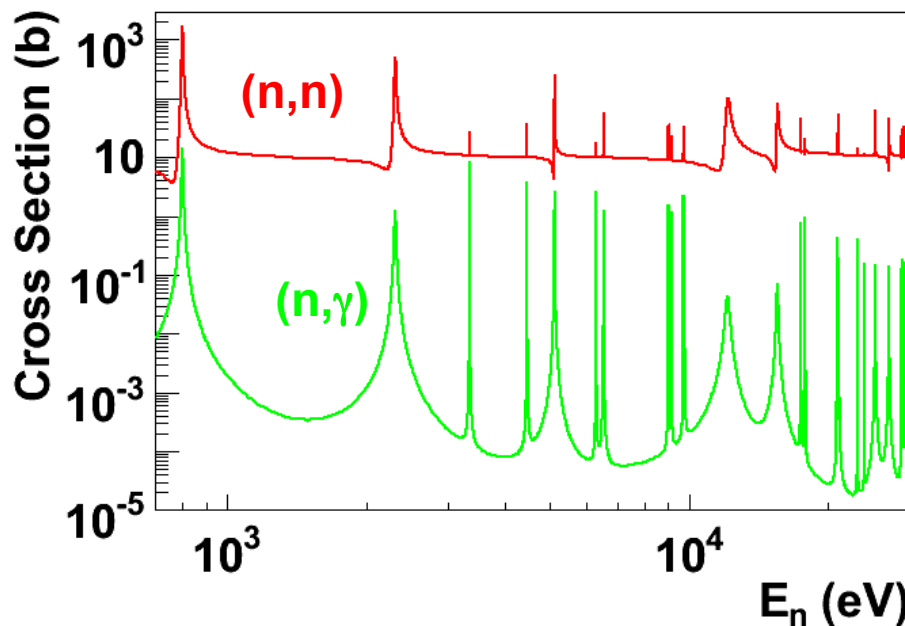
TAC



TAC rate as a function of TimeOfFlight,  $m > 2$  &  $2.5 < E(\text{MeV}) < 7.5$



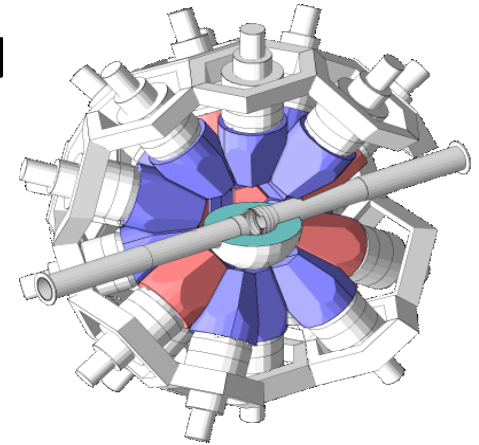
End of s-process path, Pb/Bi isotopes:



# ToF: Total Absorption detectors worldwide

The Total Absorption Calorimeter (TAC) at CERN

40  $\text{BaF}_2$  crystals covering  $4\pi$   
(based on the original at FZK)



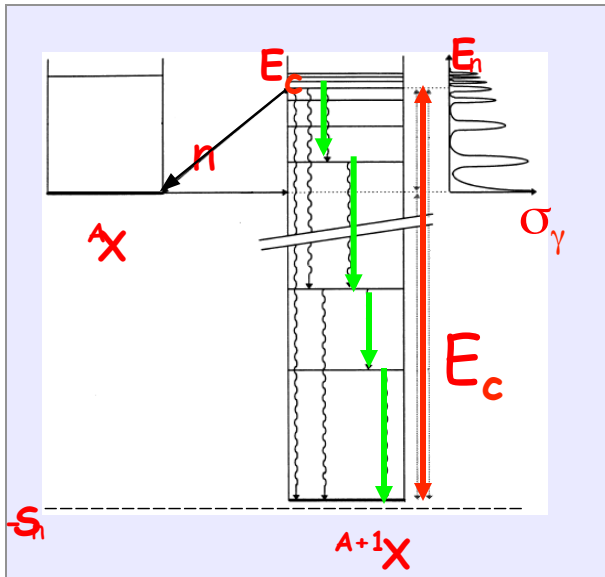
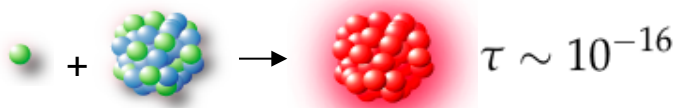
The Detector for Advance Neutron Capture Experiments (DANCE) at Los Alamos (USA)

162  $\text{BaF}_2$  crystals covering  $4\pi$



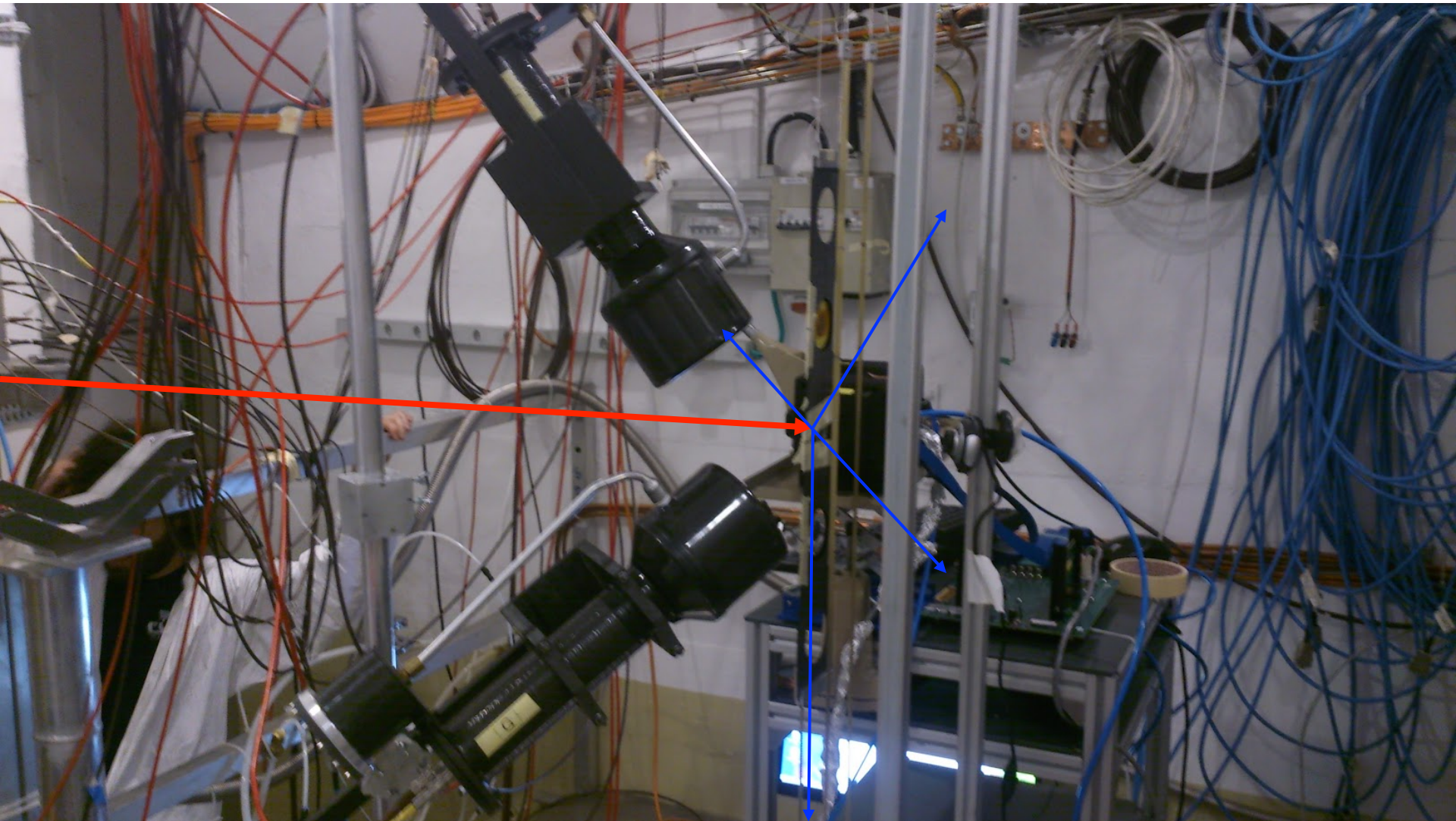
Future: a TAC made of high resolution ( $\text{LaBr}_3$ , etc.) crystals?

### 3) Detect at most one $\gamma$ -ray of the cascade



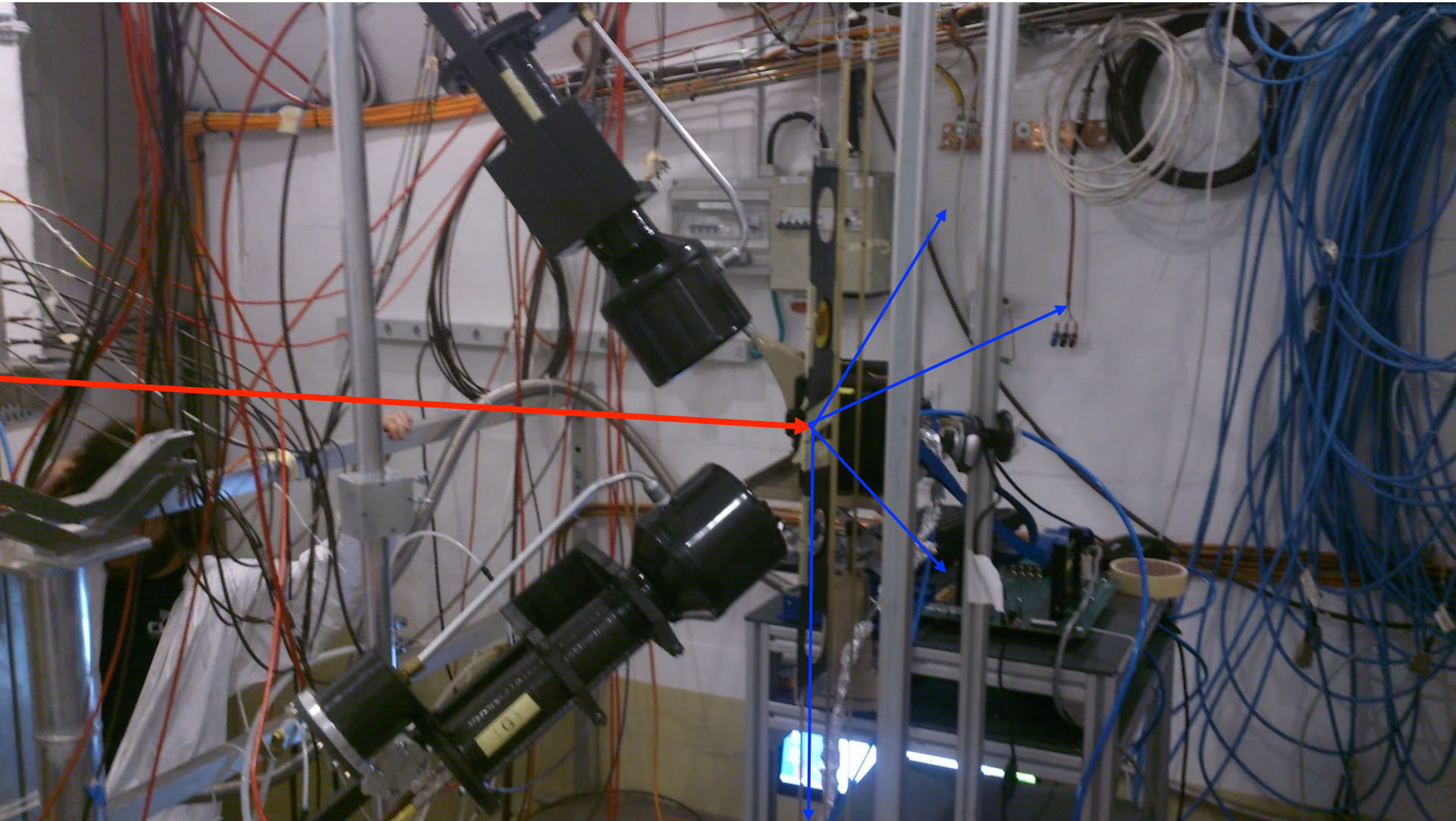


### 3) Detect at most one $\gamma$ -ray of the cascade

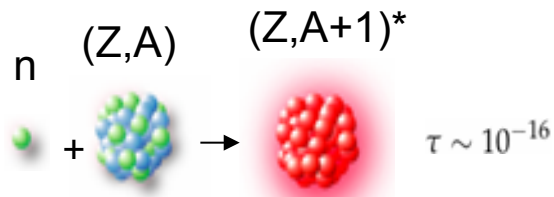




### 3) Detect at most one $\gamma$ -ray of the cascade



# Radiative capture ( $n,\gamma$ ) and Pulse Height Weighting Technique

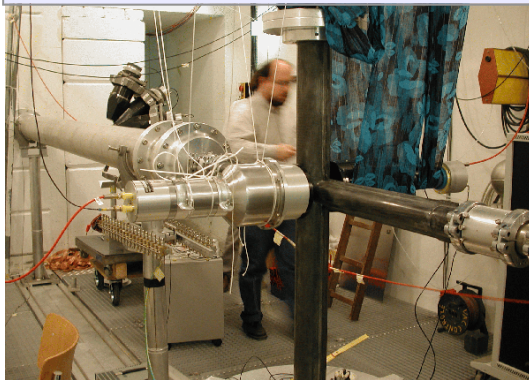
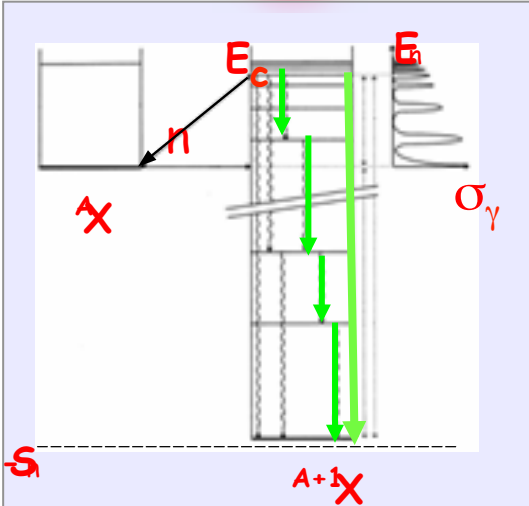
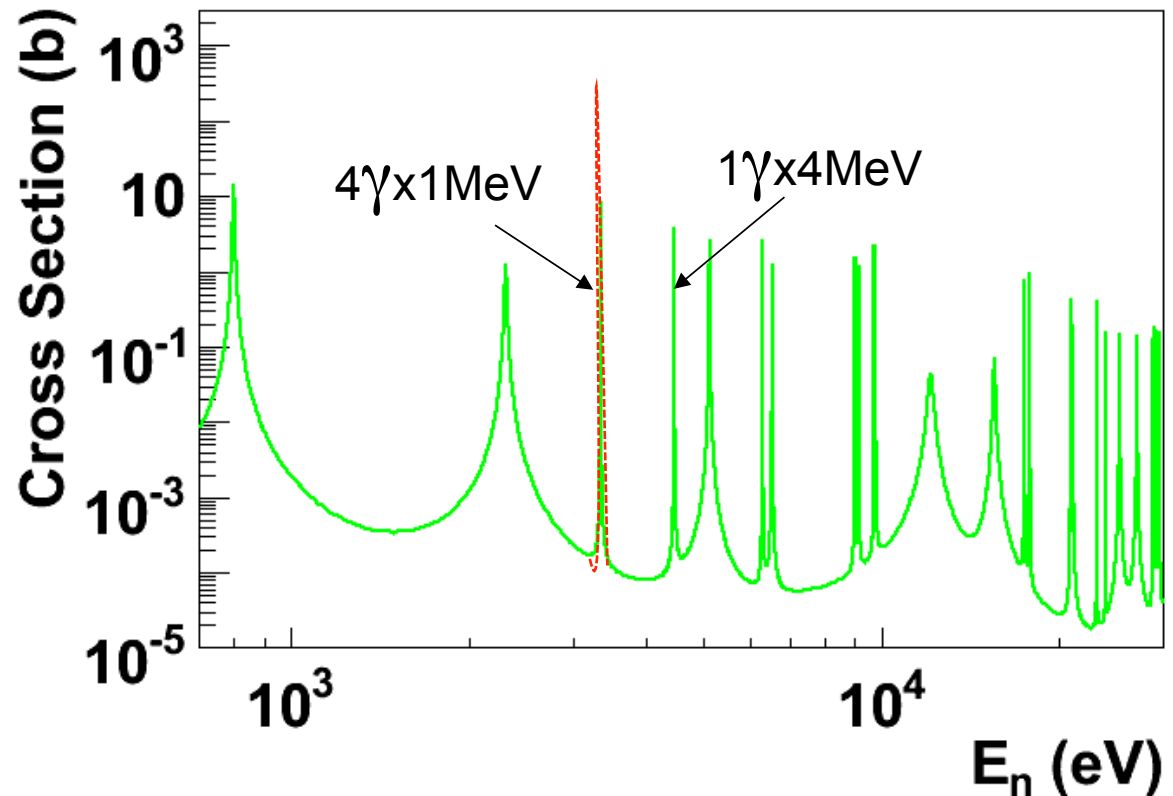


⇒ **Low  $\gamma$ -ray efficiency:  $\epsilon_\gamma \ll 1$**

$\epsilon_c$  is not defined, depends on the  $\gamma$ -ray detected!

⇒ **Efficiency proportional to  $E_\gamma$ :  $\epsilon_\gamma = k E_\gamma$**

**Pulse Height Weighting Technique (PHWT):**



# $C_6D_6$ (TED) for $\sigma(n,\gamma)$

## Deuterated benzene ( $C_6D_6$ ) liquid scintillators

the hydrogen in  $C_6H_6$  is substituted by deuterium to avoid  $(n,\gamma)$  within the detector, reducing the “neutron sensitivity)



**USA:**  $C_6D_6$  @ORELA/ORNL (shutdown)

**EU:**  $C_6D_6$  @GELINA/IRMM

**EU:**  $C_6D_6$  @n\_TOF/CERN

**Japan:** NaI @ANNRI/J-PARC

Remember:

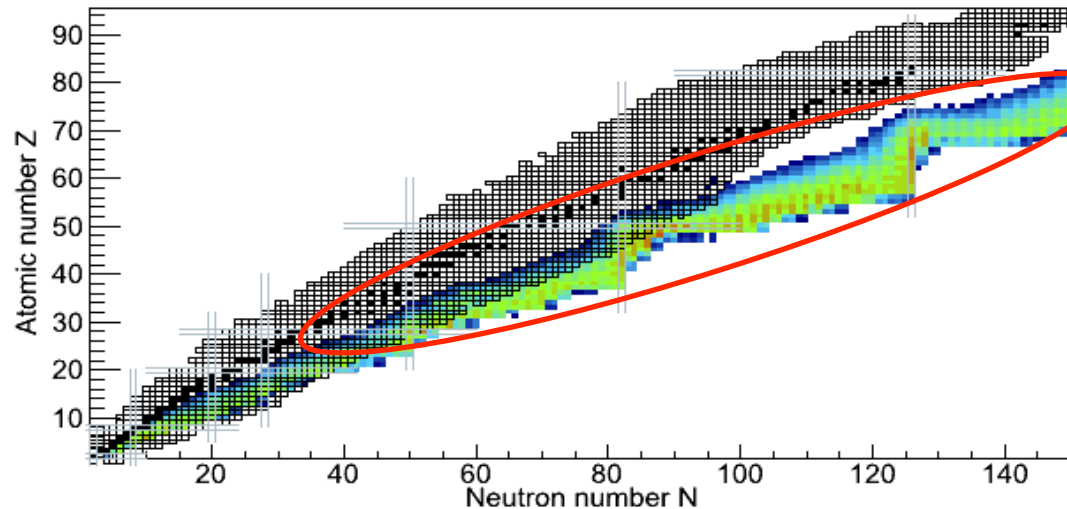
- Low efficiency (by construction)
- Low energy resolution
- Poor background rejection capabilities



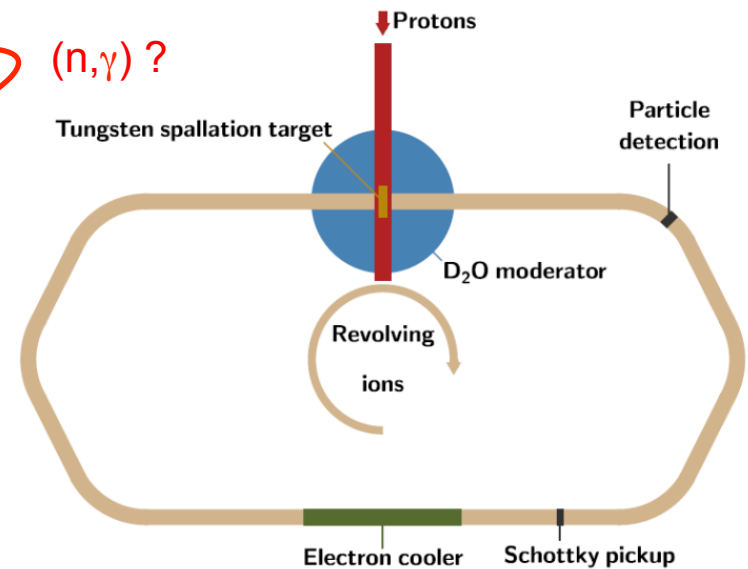
# Radiative Neutron Capture



# Radiative Neutron Capture



$(n, \gamma)$  ?



PHYSICAL REVIEW ACCELERATORS AND BEAMS **20**, 044701 (2017)

## Spallation-based neutron target for direct studies of neutron-induced reactions in inverse kinematics

René Reifarh,\* Kathrin Göbel, Tanja Heftrich, and Mario Weigand  
Goethe-Universität Frankfurt, Frankfurt am Main, 60438 Frankfurt, Germany

Challenges and solutions!

# Radiative Neutron Capture

TABLE III. Feasibility of future TOF measurements on unstable branch-point isotopes at the FRANZ facility.

| Sample            | Half-life (yr)     | $Q$ value (MeV)   | Comment                                                                                                                                               |
|-------------------|--------------------|-------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------|
| $^{63}\text{Ni}$  | 100.1              | $\beta^-$ , 0.066 | TOF work in progress (Couture, 2009), sample with low enrichment                                                                                      |
| $^{79}\text{Se}$  | $2.95 \times 10^5$ | $\beta^-$ , 0.159 | Important branching, constrains $s$ -process temperature in massive stars                                                                             |
| $^{81}\text{Kr}$  | $2.29 \times 10^5$ | EC, 0.322         | Part of $^{79}\text{Se}$ branching                                                                                                                    |
| $^{85}\text{Kr}$  | 10.73              | $\beta^-$ , 0.687 | Important branching, constrains neutron density in massive stars                                                                                      |
| $^{95}\text{Zr}$  | 64.02 d            | $\beta^-$ , 1.125 | Not feasible in near future, but important for neutron density low-mass AGB stars                                                                     |
| $^{134}\text{Cs}$ | 2.0652             | $\beta^-$ , 2.059 | Important branching at $A = 134, 135$ , sensitive to $s$ -process temperature in low-mass AGB stars, measurement not feasible in near future          |
| $^{135}\text{Cs}$ | $2.3 \times 10^6$  | $\beta^-$ , 0.269 | So far only activation measurement at $kT = 25$ keV by Patronis <i>et al.</i> (2004)                                                                  |
| $^{147}\text{Nd}$ | 10.981 d           | $\beta^-$ , 0.896 | Important branching at $A = 147/148$ , constrains neutron density in low-mass AGB stars                                                               |
| $^{147}\text{Pm}$ | 2.6234             | $\beta^-$ , 0.225 | Part of branching at $A = 147/148$                                                                                                                    |
| $^{148}\text{Pm}$ | 5.368 d            | $\beta^-$ , 2.464 | Not feasible in the near future                                                                                                                       |
| $^{151}\text{Sm}$ | 90                 | $\beta^-$ , 0.076 | Existing TOF measurements, full set of MACS data available (Abbondanno <i>et al.</i> , 2004a; Wisshak <i>et al.</i> , 2006c)                          |
| $^{154}\text{Eu}$ | 8.593              | $\beta^-$ , 1.978 | Complex branching at $A = 154, 155$ , sensitive to temperature and neutron density                                                                    |
| $^{155}\text{Eu}$ | 4.753              | $\beta^-$ , 0.246 | So far only activation measurement at $kT = 25$ keV by Jaag and Käppeler (1995)                                                                       |
| $^{153}\text{Gd}$ | 0.658              | EC, 0.244         | Part of branching at $A = 154, 155$                                                                                                                   |
| $^{160}\text{Tb}$ | 0.198              | $\beta^-$ , 1.833 | Weak temperature-sensitive branching, very challenging experiment                                                                                     |
| $^{163}\text{Ho}$ | 4570               | EC, 0.0026        | Branching at $A = 163$ sensitive to mass density during $s$ process, so far only activation measurement at $kT = 25$ keV by Jaag and Käppeler (1996b) |
| $^{170}\text{Tm}$ | 0.352              | $\beta^-$ , 0.968 | Important branching, constrains neutron density in low-mass AGB stars                                                                                 |
| $^{171}\text{Tm}$ | 1.921              | $\beta^-$ , 0.098 | Part of branching at $A = 170, 171$                                                                                                                   |
| $^{179}\text{Ta}$ | 1.82               | EC, 0.115         | Crucial for $s$ -process contribution to $^{180}\text{Ta}$ , nature's rarest stable isotope                                                           |
| $^{185}\text{W}$  | 0.206              | $\beta^-$ , 0.432 | Important branching, sensitive to neutron density and $s$ -process temperature in low-mass AGB stars                                                  |
| $^{204}\text{Tl}$ | 3.78               | $\beta^-$ , 0.763 | Determines $^{205}\text{Pb}/^{205}\text{Tl}$ clock for dating of early Solar System                                                                   |

REVIEW OF MODERN PHYSICS, VOLUME 83, JANUARY–MARCH 2011

## The $s$ process: Nuclear physics, stellar models, and observations

F. Käppeler\*

Karlsruhe Institute of Technology, Campus Nord, Institut für Kernphysik, 76021 Karlsruhe, Germany

Challenges and solutions!

# Example: Temperature in TP AGB Stars

TP-AGB stars 1-3  $M_{\odot}$

shell H-burning

$0.9 \cdot 10^8$  K

$kT = 8$  keV

$10^7 - 10^8$  cm $^{-3}$

$^{13}\text{C}(^4\text{He}, n)^{16}\text{O}$

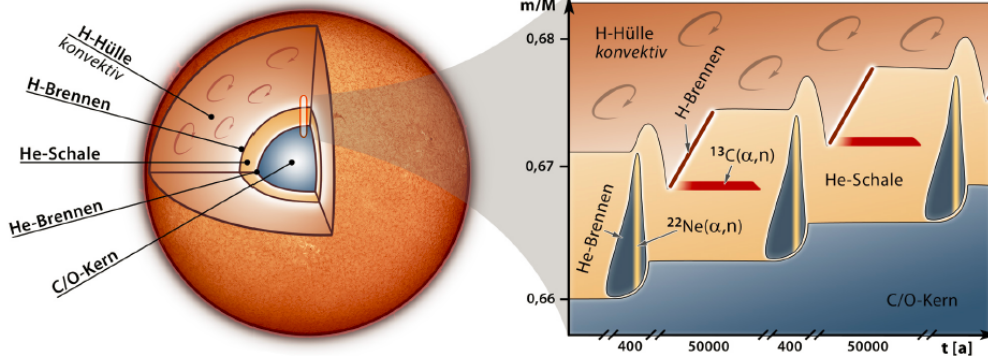
He-flash

$3 - 3.5 \cdot 10^8$  K

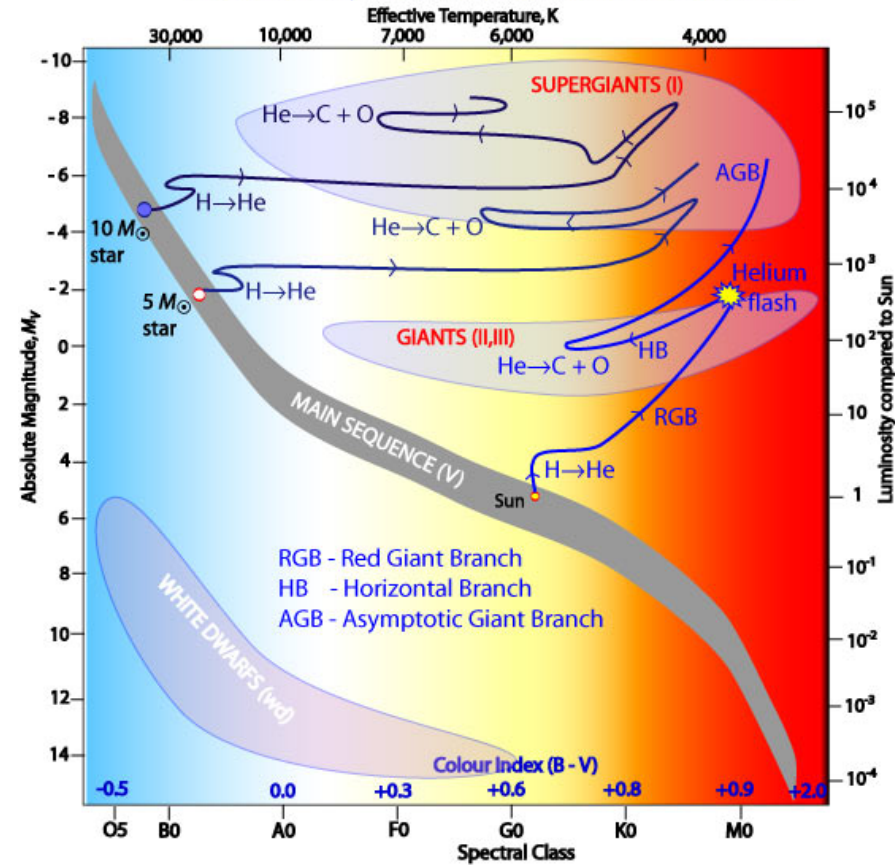
$kT = 23$  keV

$10^{10} - 10^{11}$  cm $^{-3}$

$^{22}\text{Ne}(^4\text{He}, n)^{25}\text{Mg}$



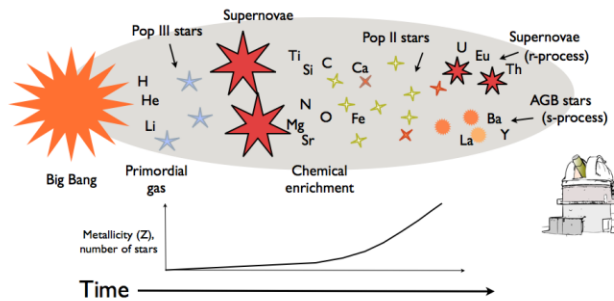
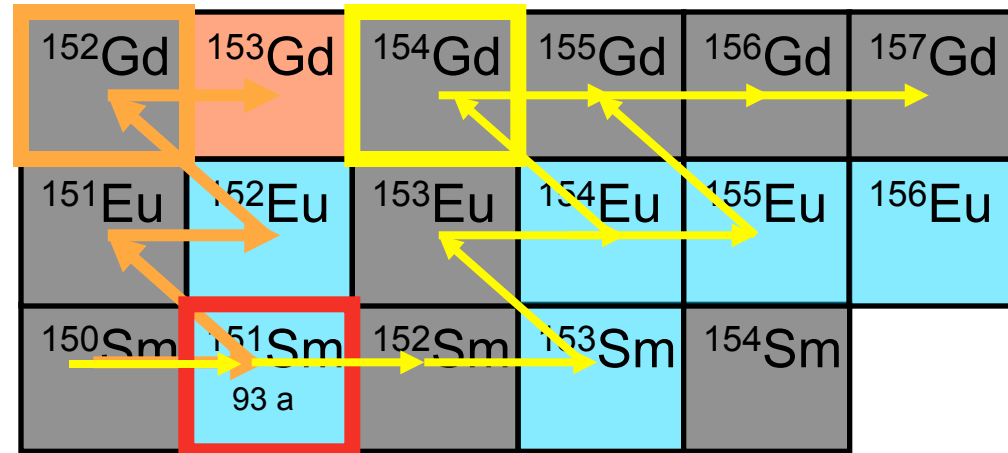
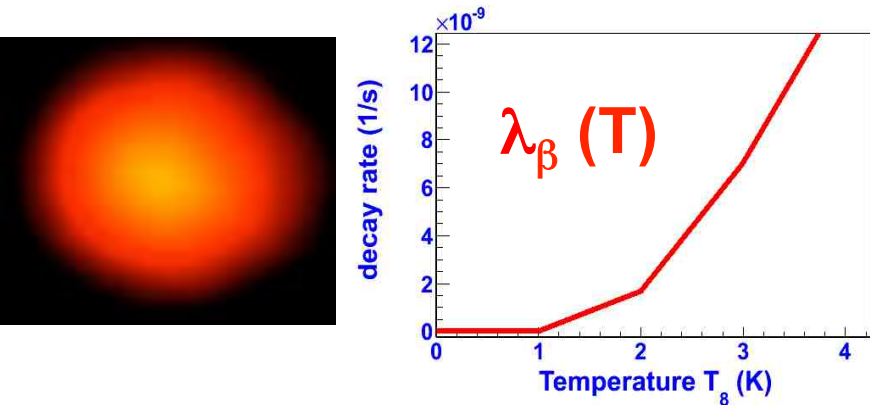
## Evolutionary Tracks off the Main Sequence





# Temperature in TP AGB Stars

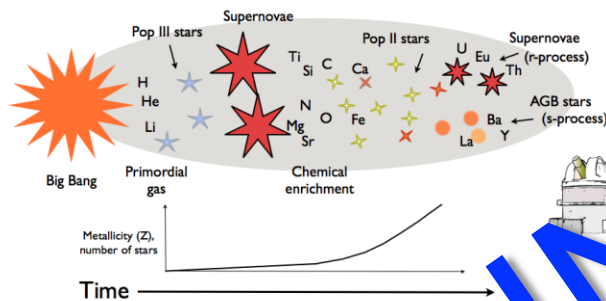
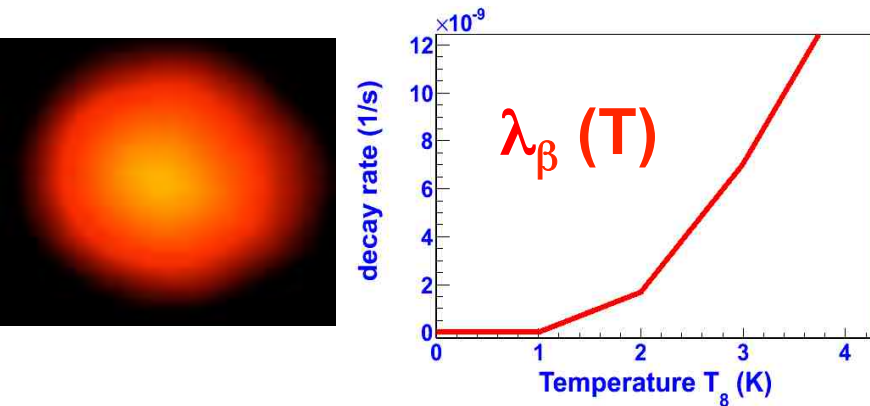
- How **hot** is the stellar environment where s-process nucleosynthesis takes place?



$$N_{s,152\text{Gd}} \quad \& \quad N_{s,154\text{Gd}}$$

# Temperature in TP AGB Stars

- How **hot** is the stellar environment where s-process nucleosynthesis takes place?



$$f_{\beta} = \frac{(\langle \sigma_{\gamma} \rangle N_s)_{152Gd}}{(\langle \sigma_{\gamma} \rangle N_s)_{154Gd}} = \frac{\lambda_{\beta}^{151Sm}(T)}{\lambda_{\beta}^{151Sm} - v_T n_n \langle \sigma_{\gamma} \rangle_{151Sm}}$$

→ Just measure  $\langle \sigma_{\gamma} \rangle_{151Sm}$



$N_{s,152Gd}$

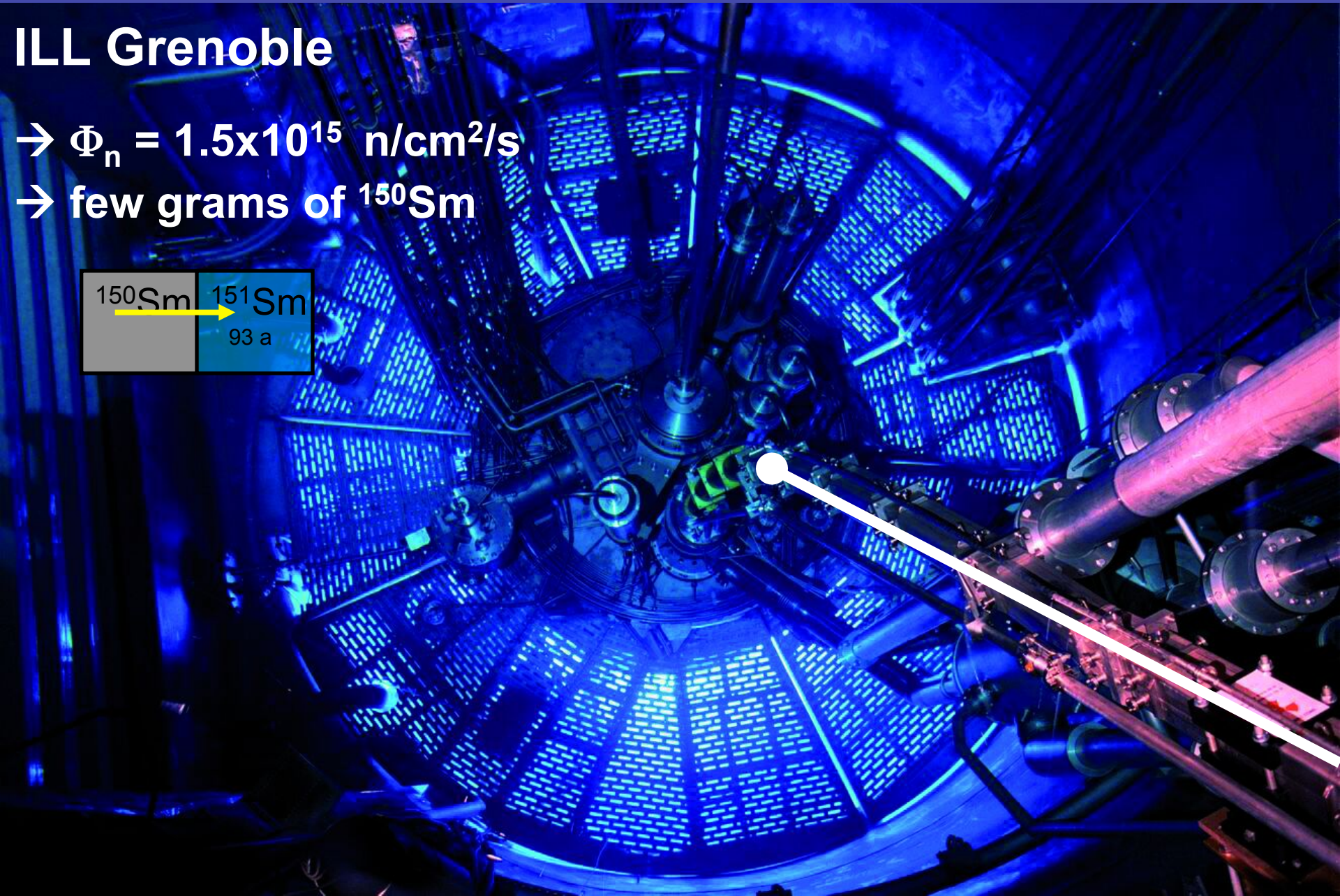
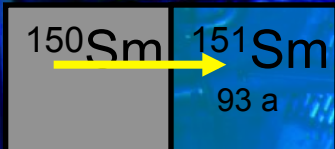
**First challenge:**  
 **$^{151}\text{Sm}$  does not exist in Earth!!!**



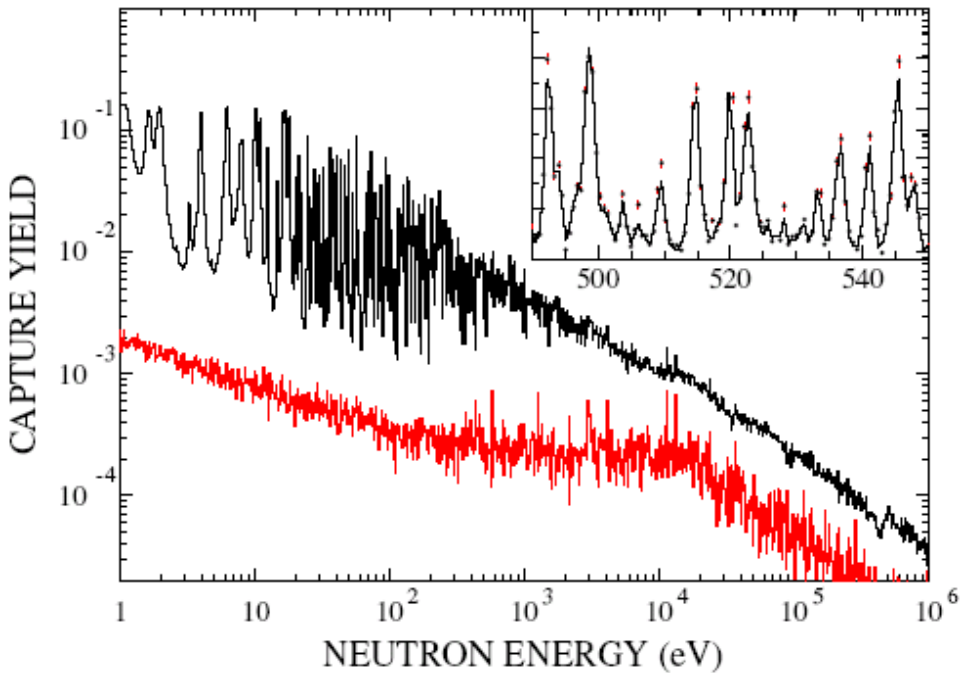
## ILL Grenoble

→  $\Phi_n = 1.5 \times 10^{15} \text{ n/cm}^2/\text{s}$

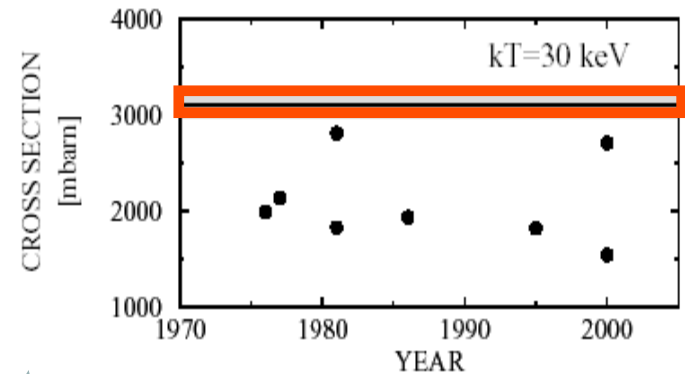
→ few grams of  $^{150}\text{Sm}$



# Temperature in TP AGB Stars

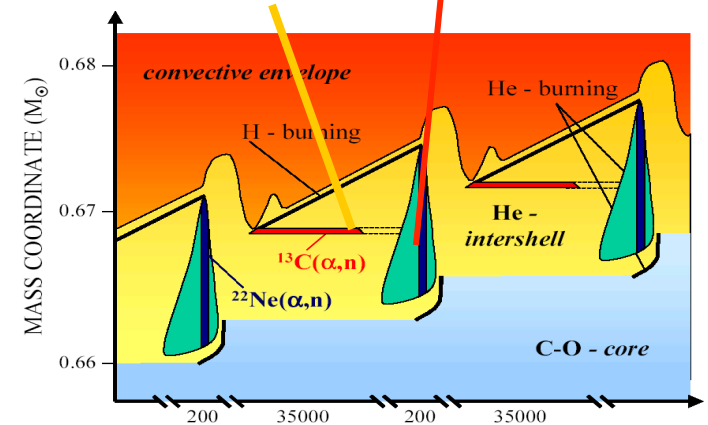


$$\text{MACS-30} = 3100 \pm 160 \text{ mb}$$



$$T_{\text{He}} = 2.5\text{-}2.8 \times 10^8 \text{ K}$$

$$T_{\text{H}} = 1 \times 10^8 \text{ K}$$



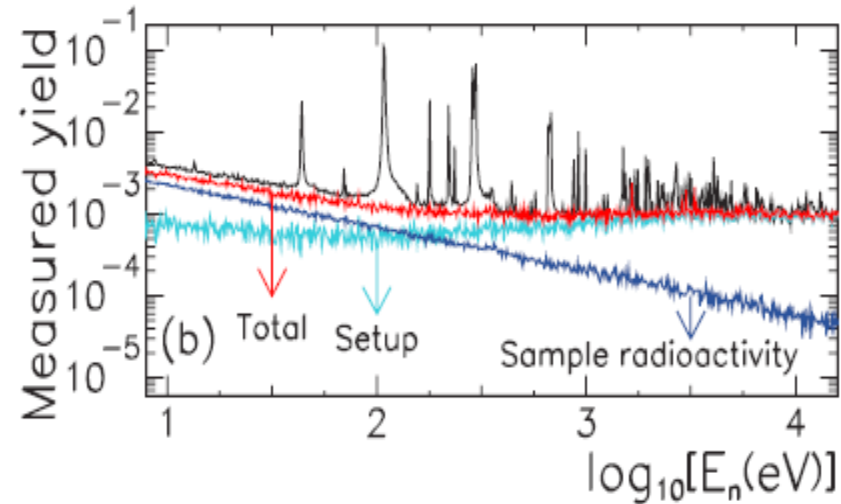


# Need of new developments: illustrated @ $^{93}\text{Zr}(n,\gamma)$

PHYSICAL REVIEW C 87, 014622 (2013)

## The $^{93}\text{Zr}(n,\gamma)$ reaction up to 8 keV neutron energy

G. Tagliente,<sup>1,\*</sup> P. M. Milazzo,<sup>2</sup> K. Fujii,<sup>2</sup> U. Abbondanno,<sup>2</sup> G. Aerts,<sup>3</sup> H. Álvarez,<sup>4</sup> F. Alvarez-Velarde,<sup>5</sup> S. Andriamonje,<sup>3</sup> J. Andzrejewski,<sup>6</sup> L. Audouin,<sup>7</sup> G. Badurek,<sup>8</sup> P. Baumann,<sup>9</sup> F. Bečvář,<sup>10</sup> F. Belloni,<sup>2</sup> E. Berthoumieux,<sup>3</sup> F. Calviño,<sup>11</sup> M. Calviani,<sup>12</sup> D. Cano-Ott,<sup>3</sup> R. Capote,<sup>13,14</sup> C. Carrapiço,<sup>15</sup> P. Cennini,<sup>16</sup> V. Chepel,<sup>17</sup> E. Chiaveri,<sup>16</sup> N. Colonna,<sup>1</sup> G. Cortes,<sup>11</sup> A. Couture,<sup>18</sup> M. Dahlfors,<sup>16</sup> S. David,<sup>9</sup> I. Dillmann,<sup>7,19</sup> C. Domingo-Pardo,<sup>20,19</sup> W. Dridi,<sup>3</sup> I. Duran,<sup>4</sup> C. Eleftheriadis,<sup>21</sup> M. Embid-Segura,<sup>5</sup> A. Ferrari,<sup>16</sup> R. Ferreira-Marques,<sup>17</sup> W. Furman,<sup>22</sup> I. Gonçalves,<sup>15</sup> E. Gonzalez-Romero,<sup>5</sup> F. Gramegna,<sup>12</sup> C. Guerrero,<sup>5</sup> F. Gunsing,<sup>3</sup> B. Haas,<sup>23</sup> R. Haight,<sup>24</sup> M. Heil,<sup>7,19</sup> A. Herrera-Martinez,<sup>16</sup> E. Jericha,<sup>8</sup> F. Käppeler,<sup>7</sup> Y. Kadi,<sup>16</sup> D. Karadimos,<sup>25</sup> D. Karamanis,<sup>25</sup> M. Kerveno,<sup>9</sup> E. Kossionides,<sup>26</sup> M. Krtićka,<sup>10</sup> C. Lamboudis,<sup>21</sup> H. Leeb,<sup>8</sup> A. Lindote,<sup>17</sup> I. Lopes,<sup>17</sup> S. Lukic,<sup>9</sup> J. Marganiec,<sup>6,19</sup> S. Marrone,<sup>1</sup> T. Martínez,<sup>5</sup> C. Massimi,<sup>27</sup> P. Mastinu,<sup>12</sup> A. Mengoni,<sup>13</sup> C. Moreau,<sup>2</sup> M. Mosconi,<sup>7,28</sup> F. Neves,<sup>17</sup> H. Oberhummer,<sup>8</sup> S. O'Brien,<sup>18</sup> C. Papachristodoulou,<sup>25</sup> C. Papadopoulos,<sup>29</sup> C. Paradela,<sup>4</sup> N. Patronis,<sup>25</sup> A. Pavlik,<sup>30</sup> P. Pavlopoulos,<sup>31</sup> L. Perrot,<sup>3</sup> M. T. Pigni,<sup>8</sup> R. Plag,<sup>7,19</sup> A. Plompen,<sup>32</sup> A. Plukis,<sup>3</sup> A. Poch,<sup>11</sup> J. Praena,<sup>12</sup> C. Pretel,<sup>11</sup> J. Quesada,<sup>14</sup> R. Reifarh,<sup>24,19</sup> M. Rosetti,<sup>33</sup> C. Rubbia,<sup>34</sup> G. Rudolf,<sup>9</sup> P. Rullhusen,<sup>32</sup> J. Salgado,<sup>15</sup> C. Santos,<sup>15</sup> L. Sarchiapone,<sup>16</sup> I. Savvidis,<sup>21</sup> C. Stephan,<sup>35</sup> J. L. Tain,<sup>20</sup> L. Tassan-Got,<sup>35</sup> L. Tavora,<sup>15</sup> R. Terlizzi,<sup>1</sup> G. Vannini,<sup>27</sup> P. Vaz,<sup>15</sup> A. Ventura,<sup>33</sup> D. Villamarin,<sup>5</sup> M. C. Vincente,<sup>5</sup> V. Vlachoudis,<sup>16</sup> R. Vlastou,<sup>29</sup> F. Voss,<sup>7</sup> S. Walter,<sup>7</sup> M. Wiescher,<sup>18</sup> and K. Wisshak<sup>7</sup>  
(n\_TOF Collaboration<sup>1</sup>)



- HERMES observations of Nb and Zr in S-type stars
- Determination of the s-process temperature directly in evolved low-mass GSs, using Zr and Nb abundances, independent of stellar evolution models.
- $^{93}\text{Zr}/^{93}\text{Nb}$  provides chronometric information on the time elapsed since the start of the s-process (one-three million years).

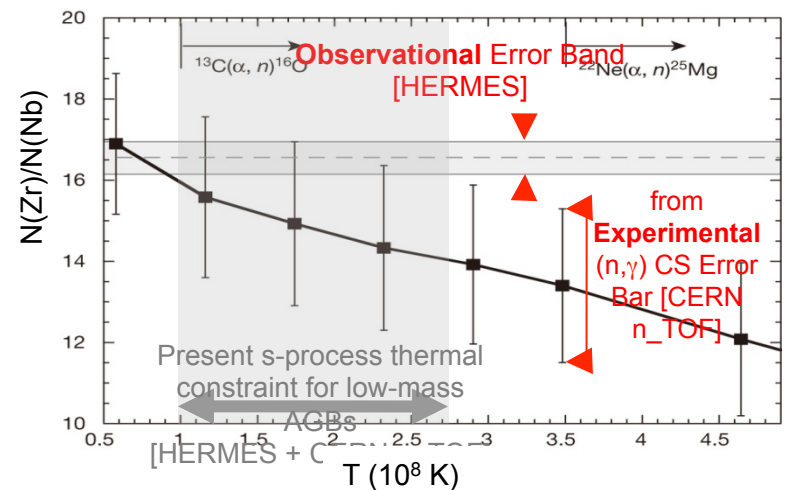
LETTER

nature

## The temperature and chronology of heavy-element synthesis in low-mass stars

P. Neyskens<sup>1</sup>, S. Van Eck<sup>1</sup>, A. Jorissen<sup>1</sup>, S. Goriely<sup>1</sup>, L. Siess<sup>1</sup> & B. Plez<sup>2</sup>

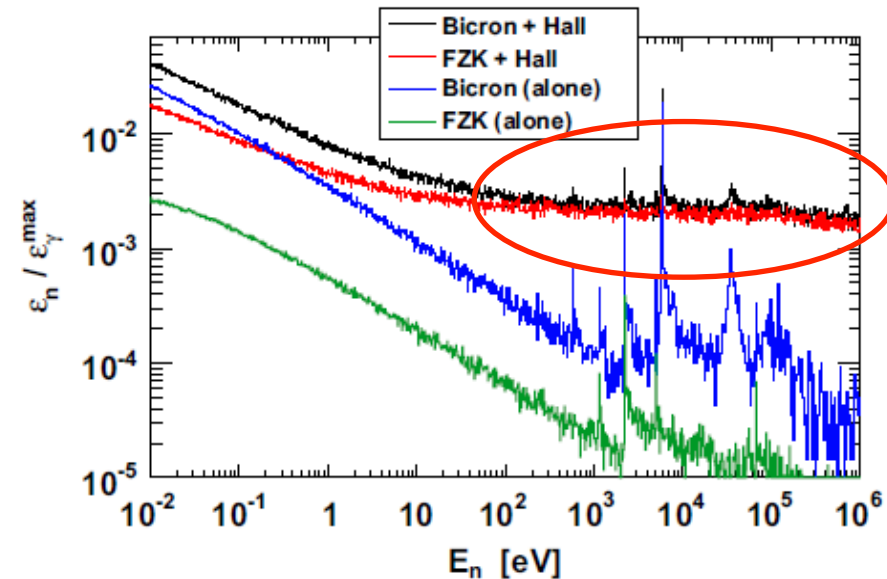
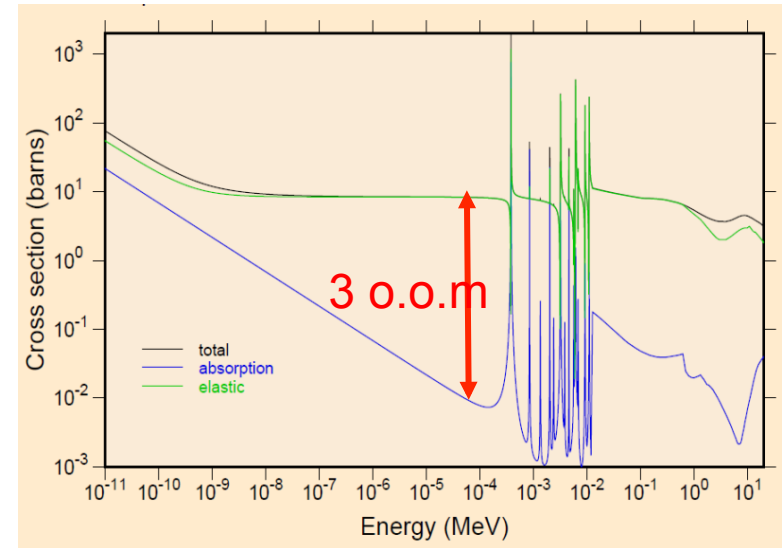
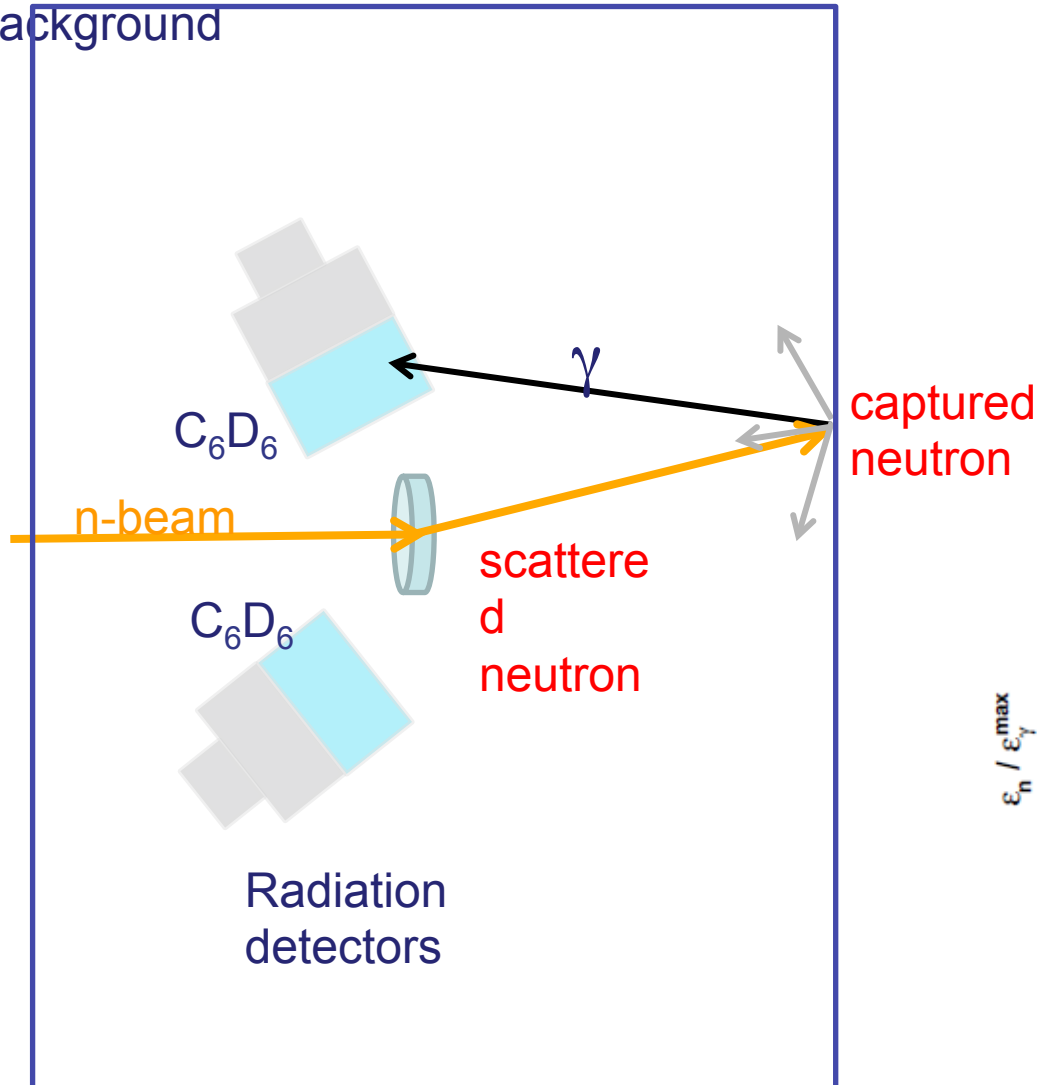
The present determination of the s-process temperature relies on a single assumption, namely that the equilibrium approximation is valid along the Zr isotopic chain, which is known to be true locally<sup>1</sup>. For this reason, the uncertainties in the method are mainly those in the derived abundances and in the experimental Zr cross-section<sup>14,15</sup>, that is, about 5% for the stable Zr isotopes and 11% for  $^{93}\text{Zr}$ . Reducing the  $^{93}\text{Zr}$  error would constrain the s-process operation temperature even more.



Adapted from P. Neyskens et al., *Nature* 517, 174-176 (2015)

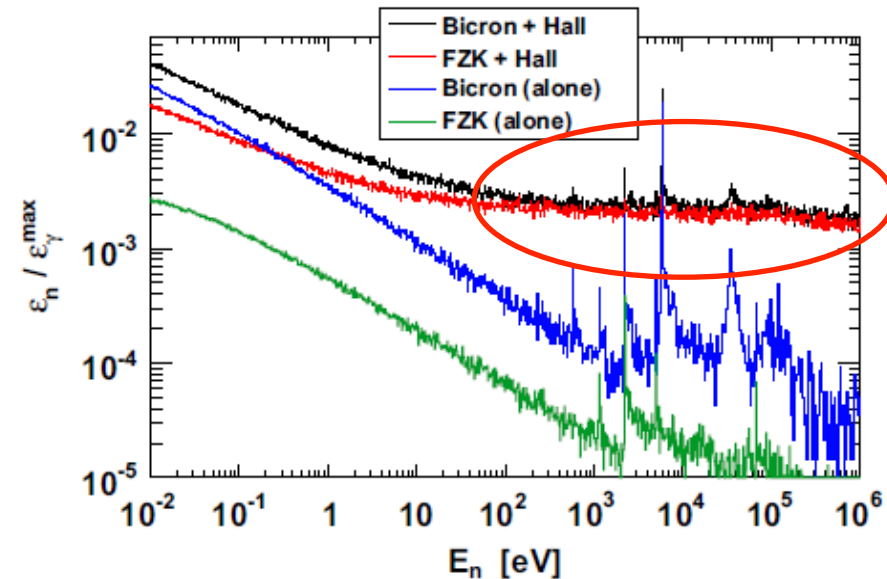
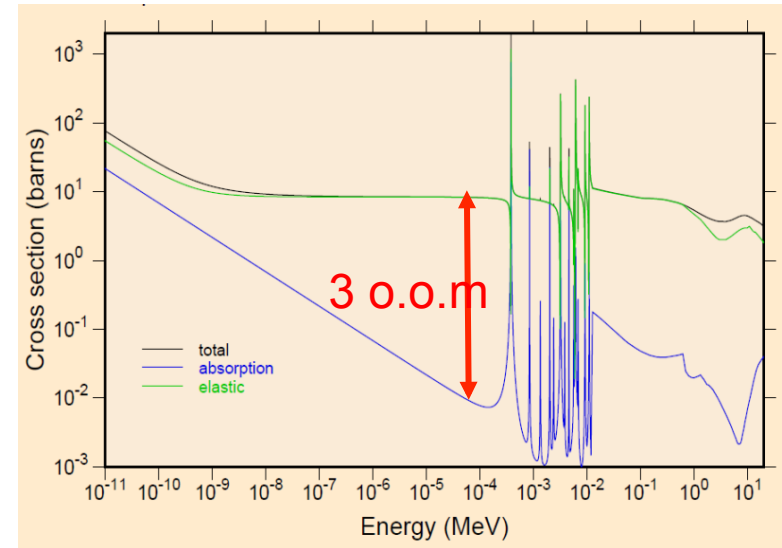
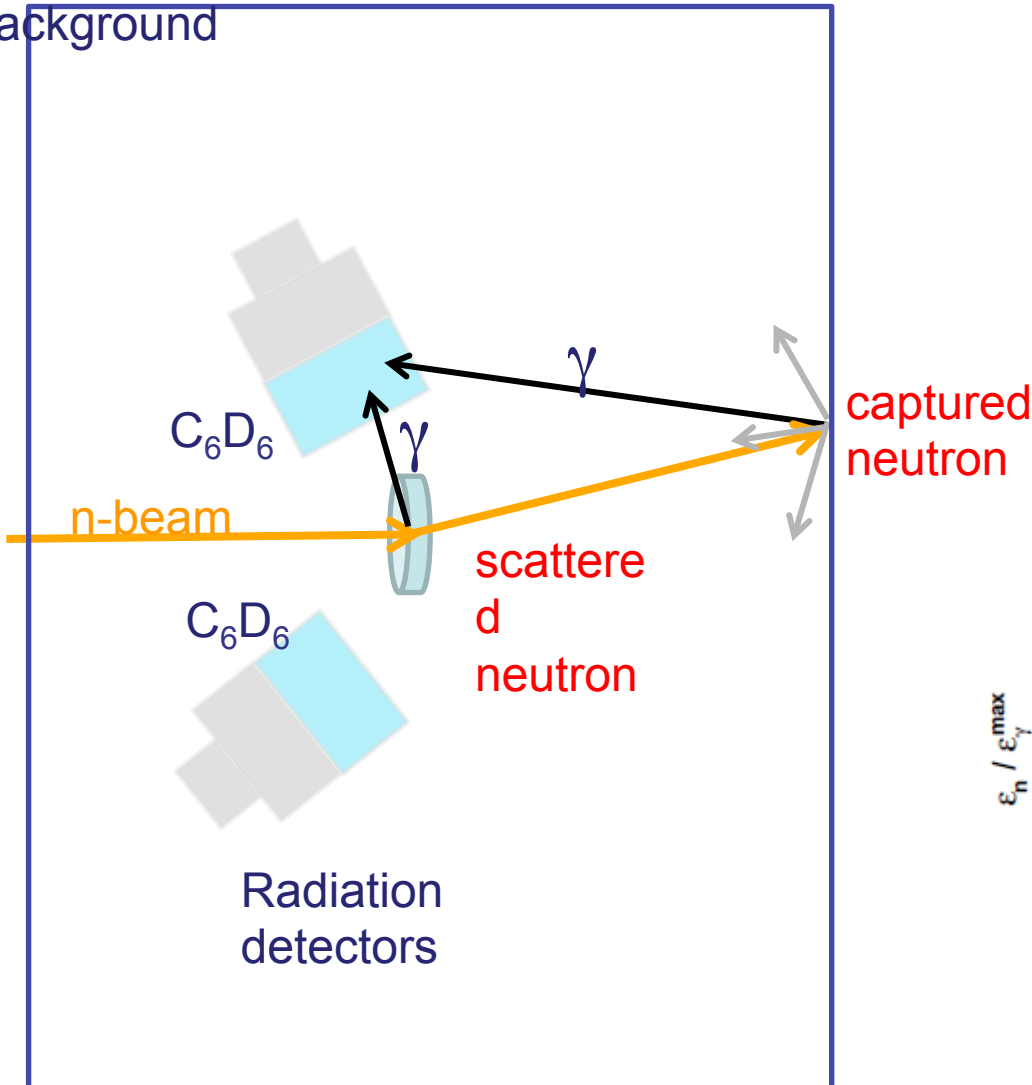
# The i-TED concept

→ Reduce “extrinsic” neutron sensitivity background



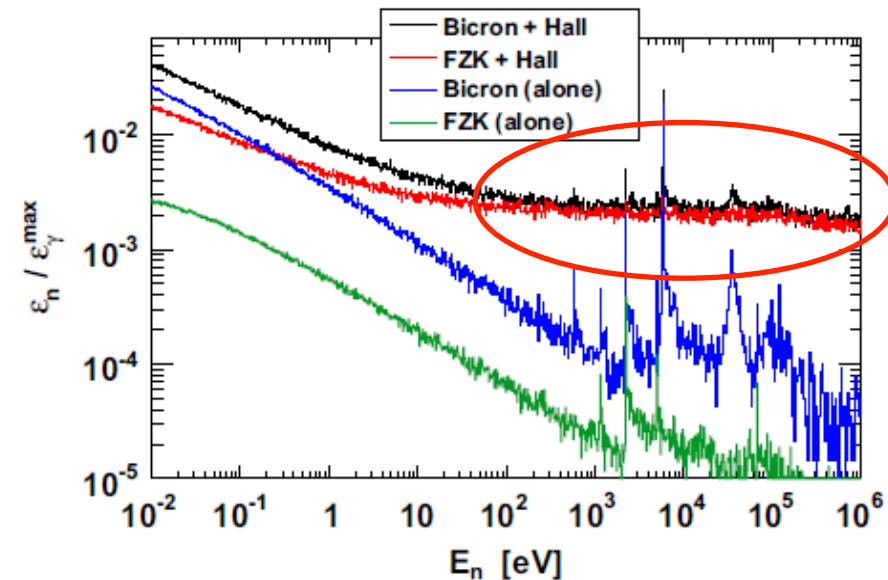
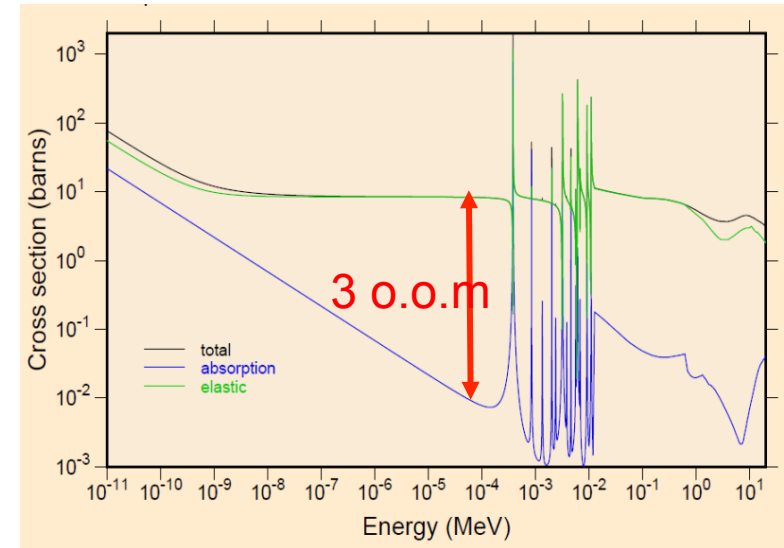
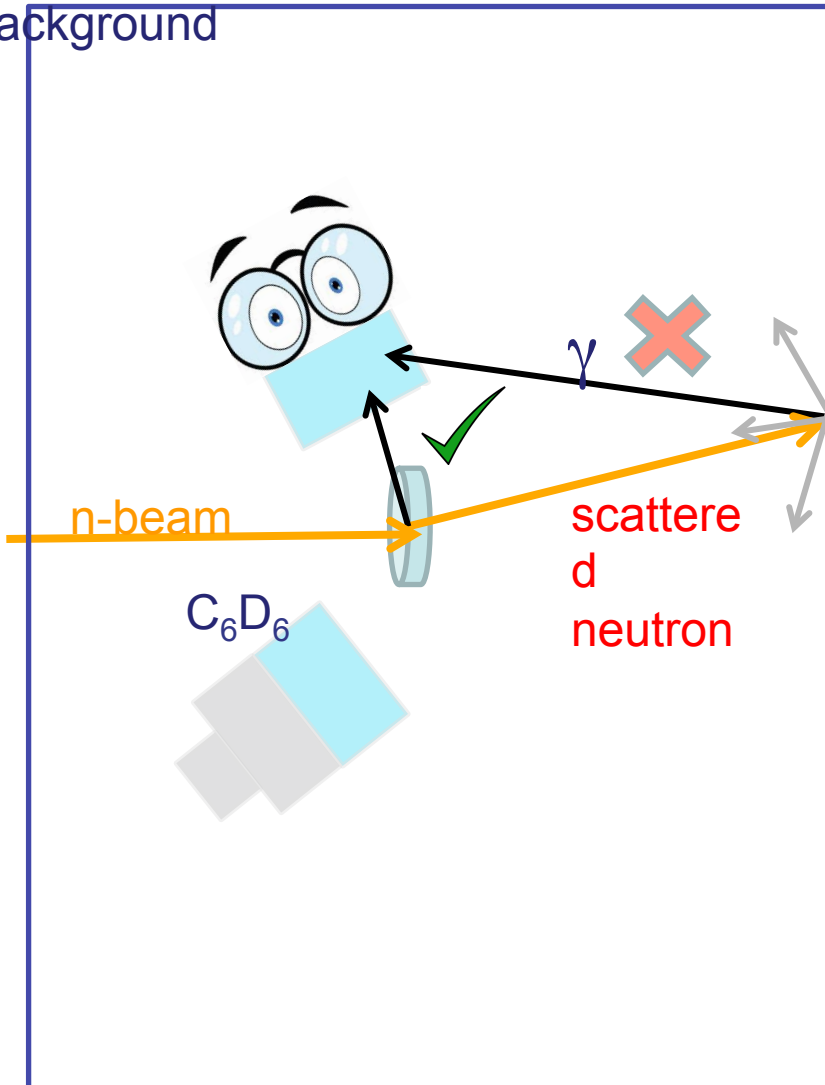
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# The i-TED concept

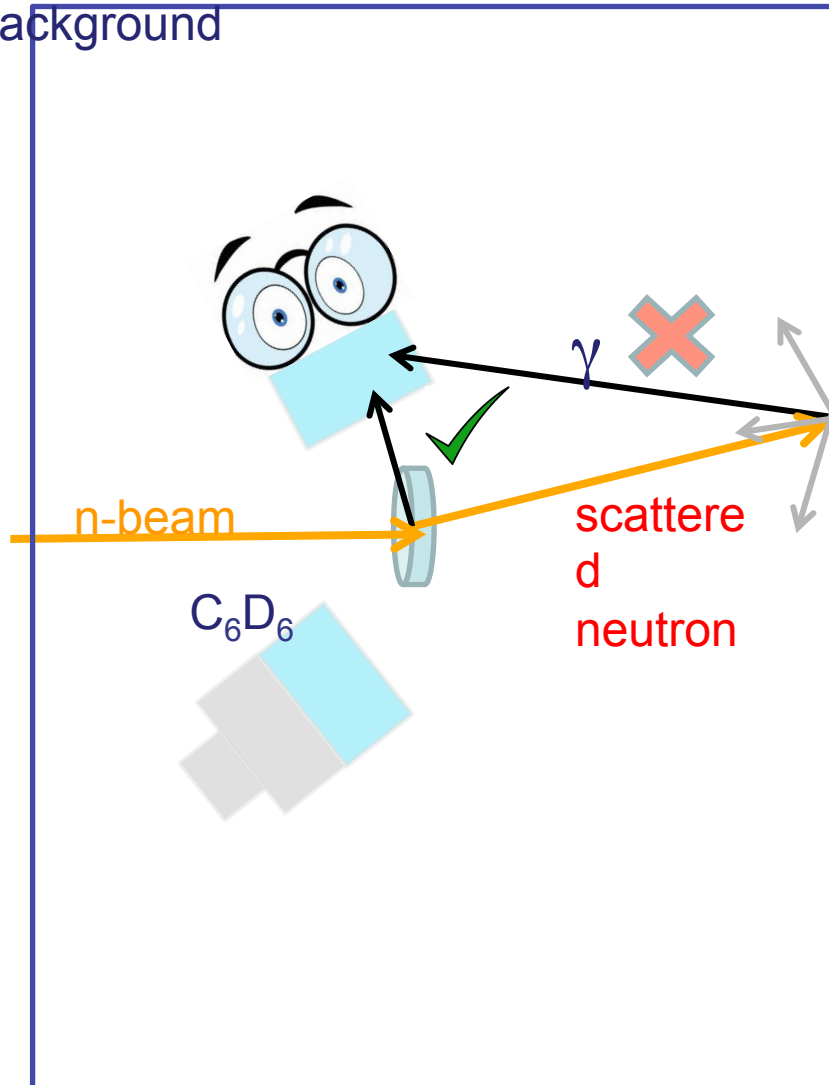
→ Reduce “extrinsic” neutron sensitivity background



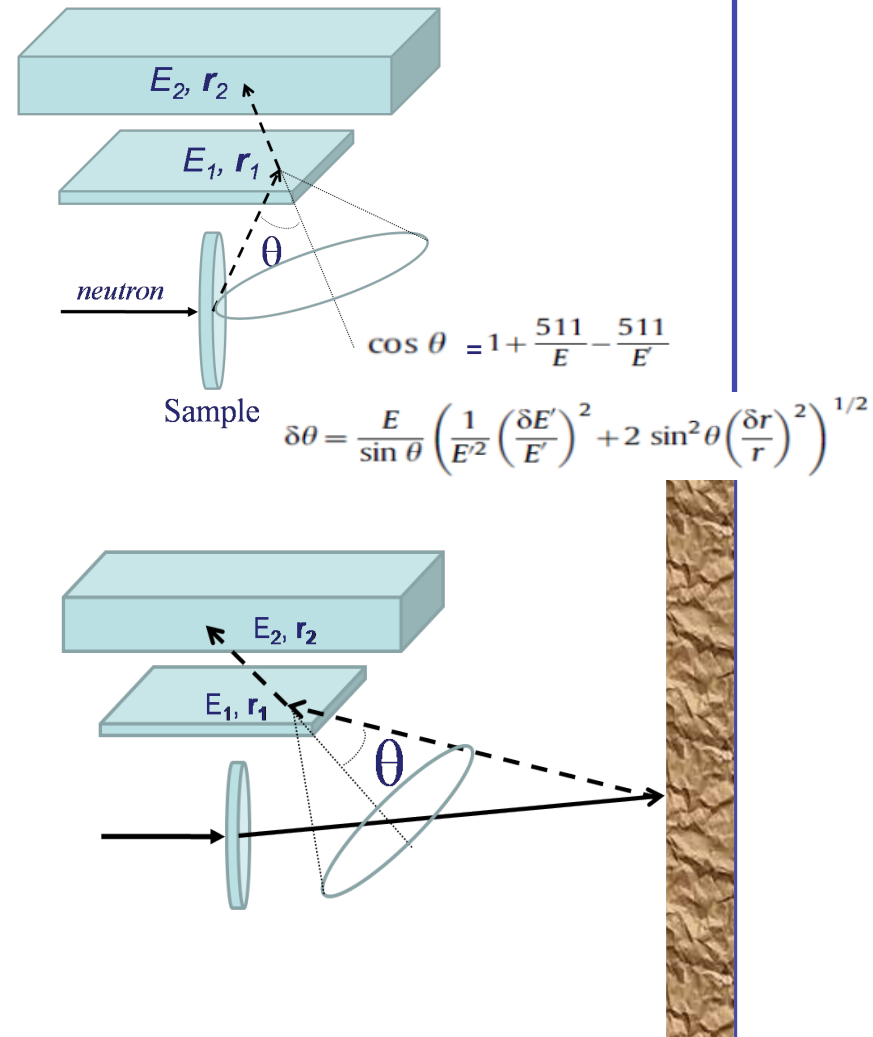


# The i-TED concept

→ Reduce “extrinsic” neutron sensitivity background

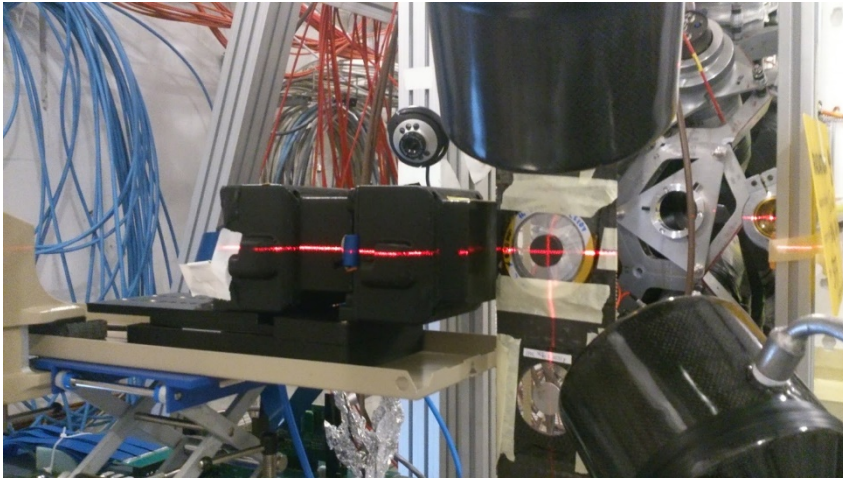


$\gamma$ -Imaging → Better sensitivity

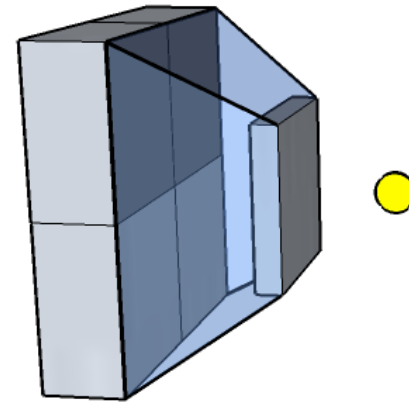


# i-TED: imaging-Total Energy Detector

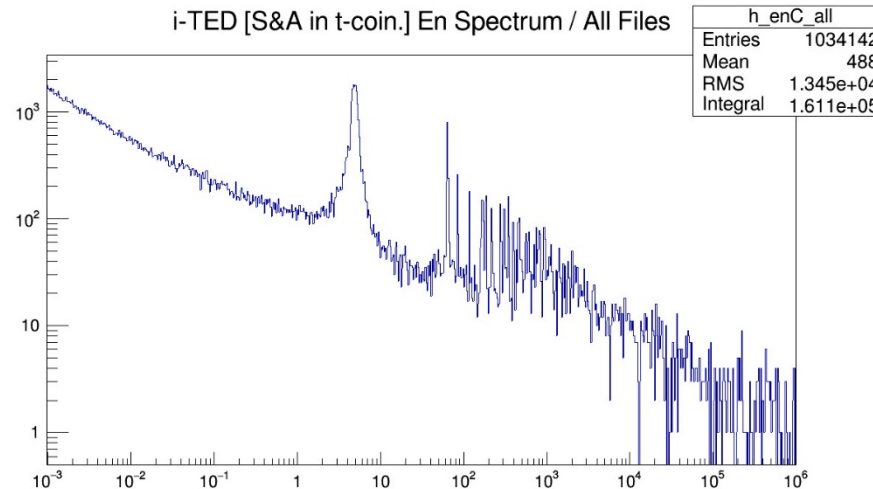
Technical commissioning i-TED Prototype (OK)



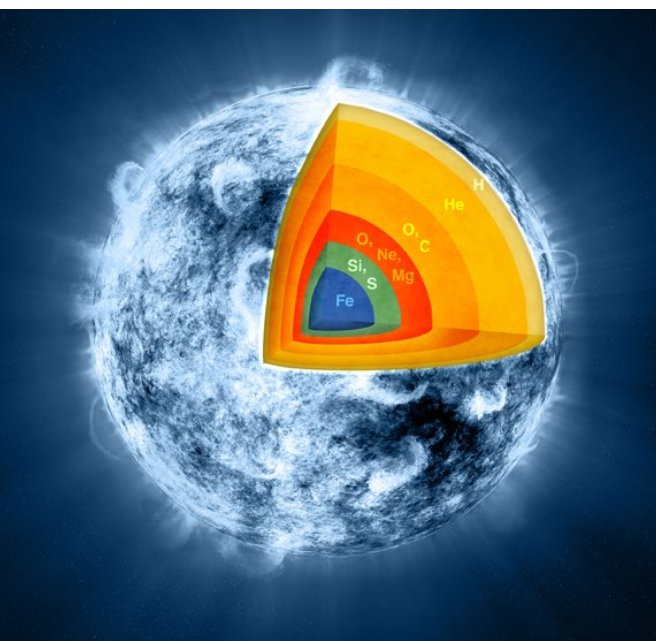
i-TED Demonstrator (i-TED2)



i-TED [S&A in t-coin.] En Spectrum / All Files



# Motivation and Introduction: MSs & Temperature evolution



REVIEWS OF MODERN PHYSICS, VOLUME 84, JANUARY–MARCH 2012

**Rotating massive stars: From first stars to gamma ray bursts**

André Maeder\* and Georges Meynet†

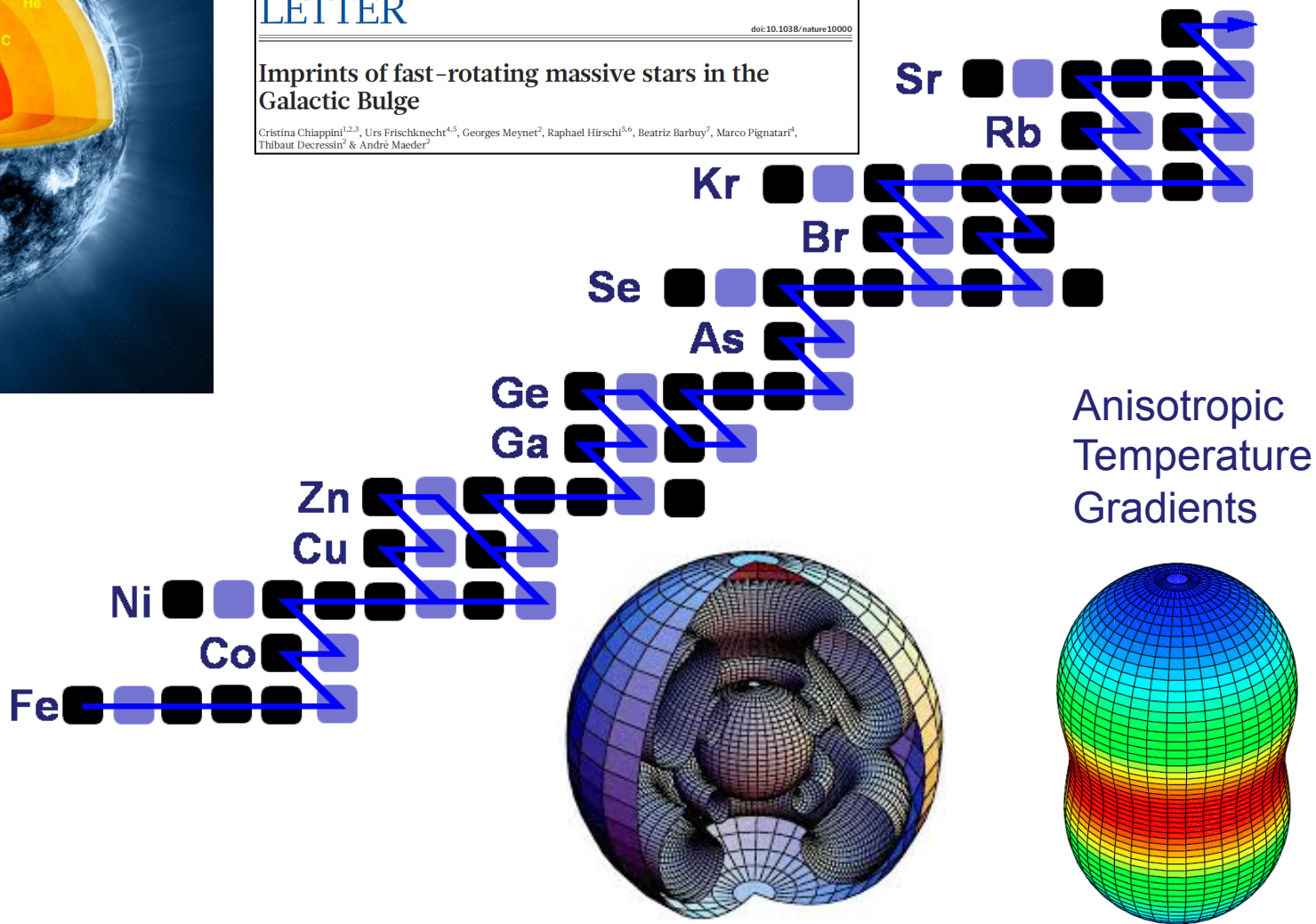
Geneva Observatory, University of Geneva, 51 chemin des Maillettes,  
CH-1290 Versoix, Switzerland

LETTER

doi:10.1038/nature10000

**Imprints of fast-rotating massive stars in the Galactic Bulge**

Cristina Chiappini<sup>1,2,3</sup>, Urs Frischknecht<sup>4,5</sup>, Georges Meynet<sup>2</sup>, Raphael Hirschi<sup>5,6</sup>, Beatriz Barbuy<sup>7</sup>, Marco Pignatari<sup>4</sup>, Thibaut Decressin<sup>2</sup> & André Maeder<sup>2</sup>



Currents, rotation, mixing

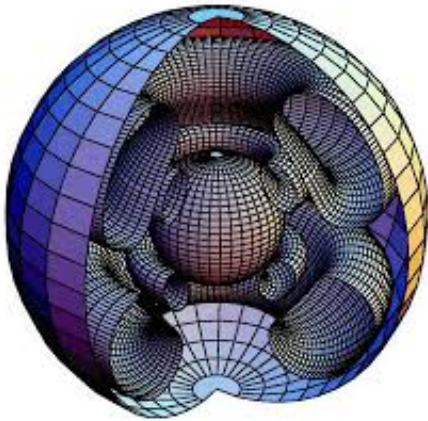
# Motivation and Introduction: MSs & Temperature evolution

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## Rotating massive stars: From first stars to gamma ray bursts

André Maeder\* and Georges Meynet†

Geneva Observatory, University of Geneva, 51 chemin des Maillettes,  
CH-1290 Versoix, Switzerland



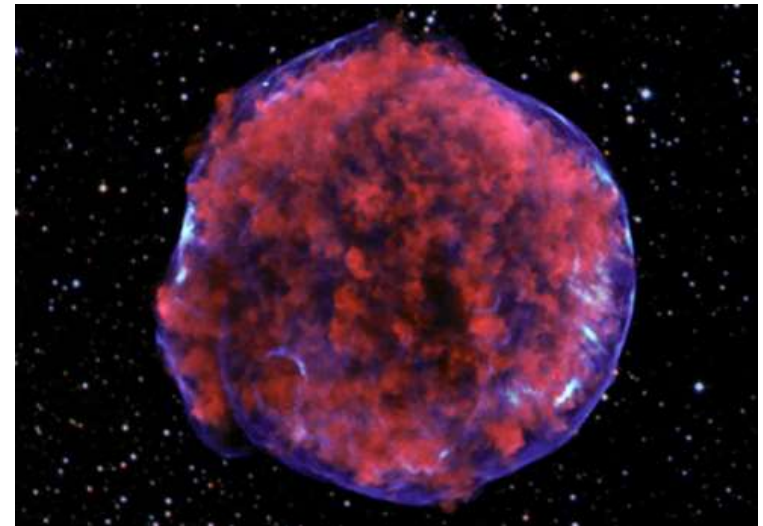
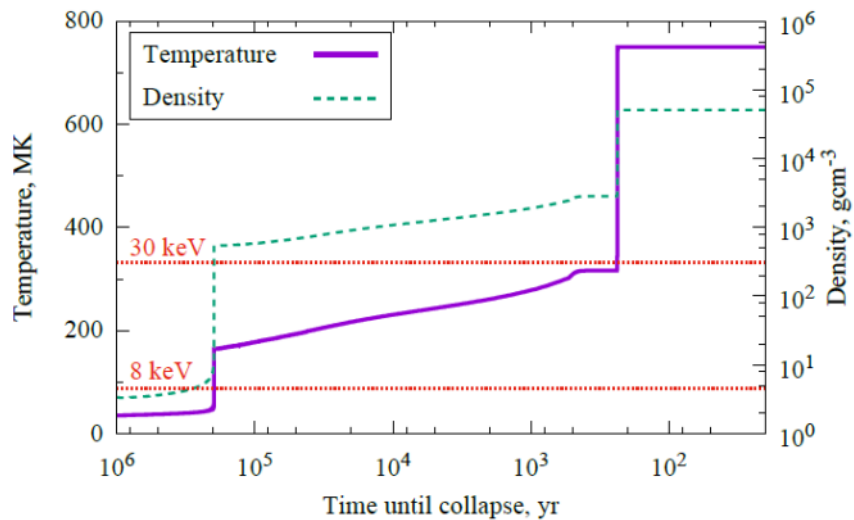
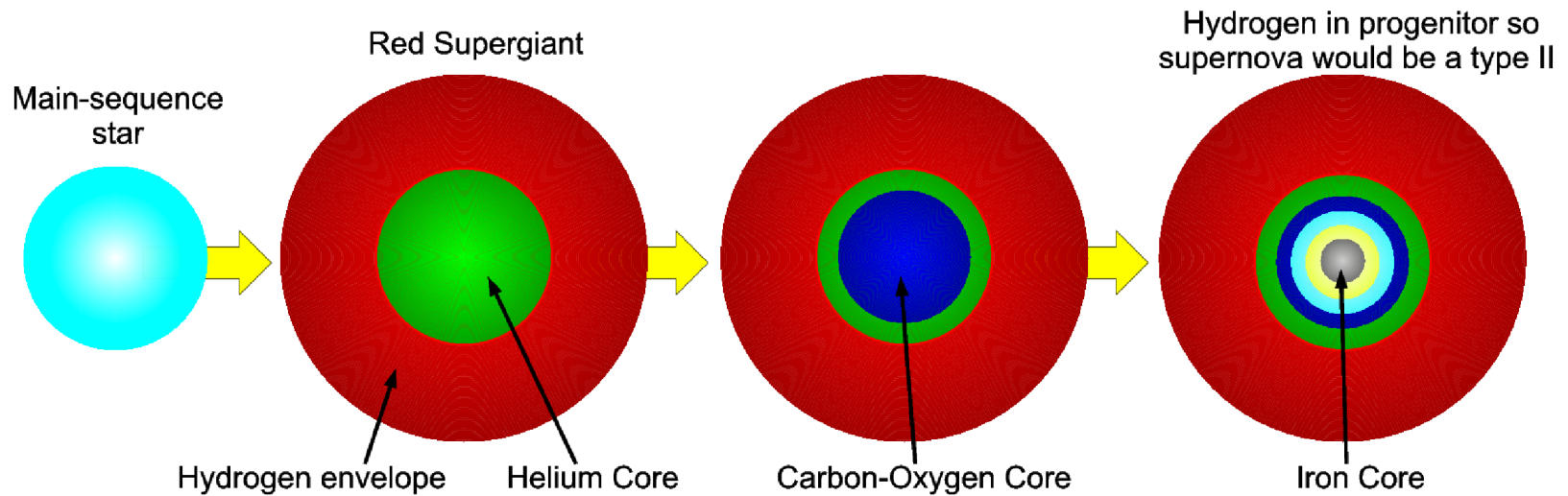
Currents, rotation, mixing

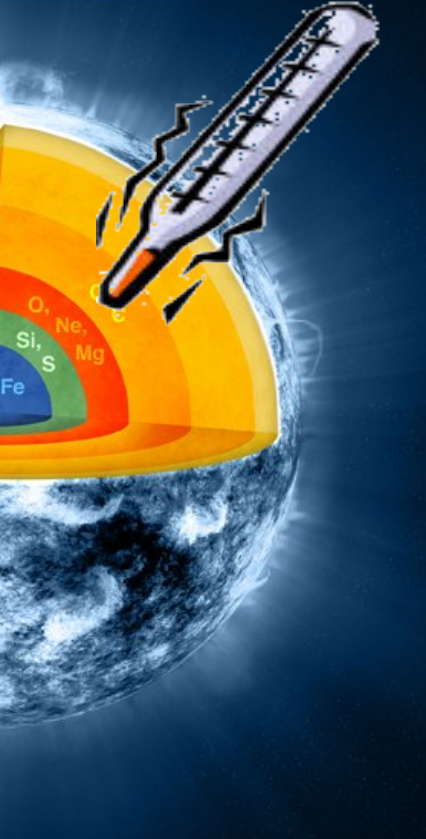
## I. INTRODUCTION

It may be surprising that we emphasize the need of accounting for the effects of rotation in stellar evolution, since in practice all stars are rotating around their axis. However, it must be recalled that the so-called “standard theory” of stellar evolution generally ignores the effects of stellar rotation and treats the stars as nonrotating bodies, despite the fact that stars more massive than about  $1.5M_{\odot}$  rotate fast on the average (Fig. 1).

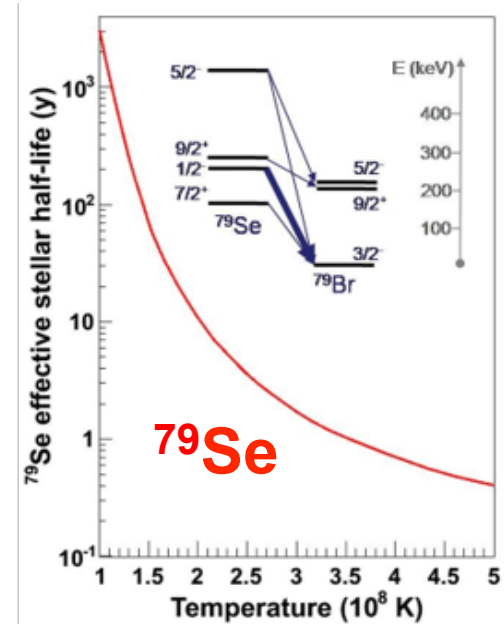
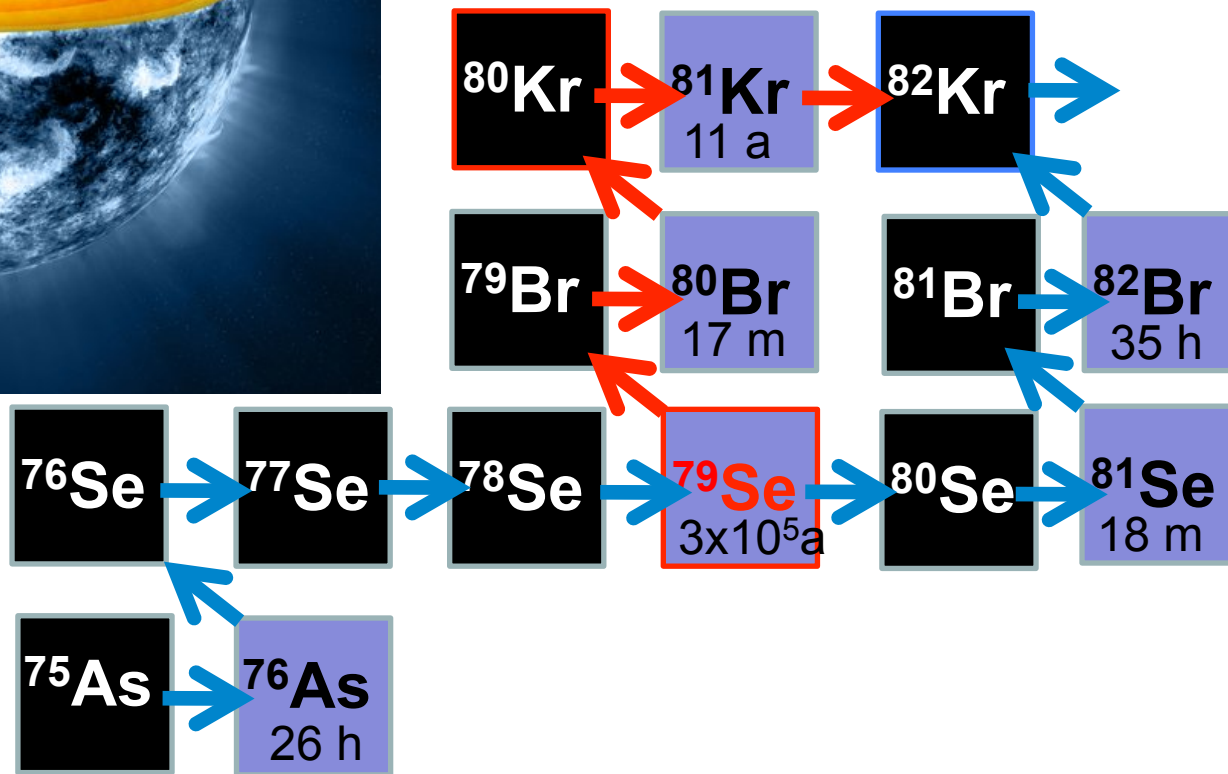


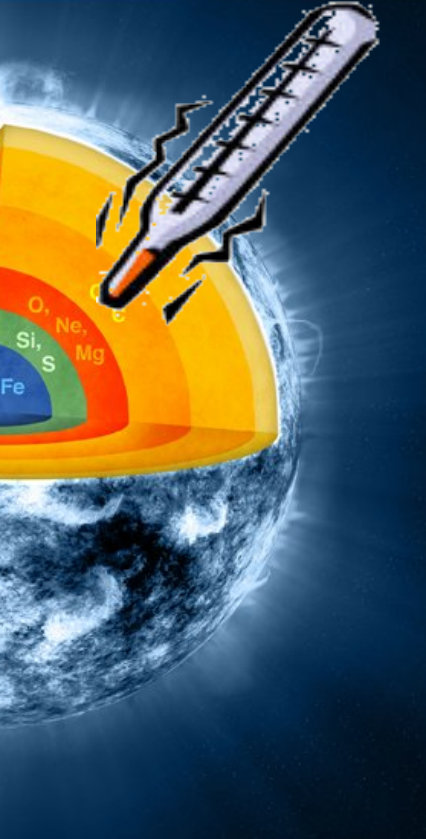
# Temperature: a key ingredient in stellar structure and evolution





# The massive-star nuclear-thermometer

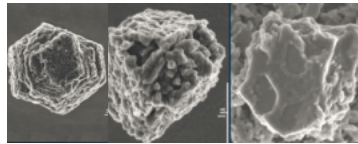




# The massive-star nuclear-thermometer

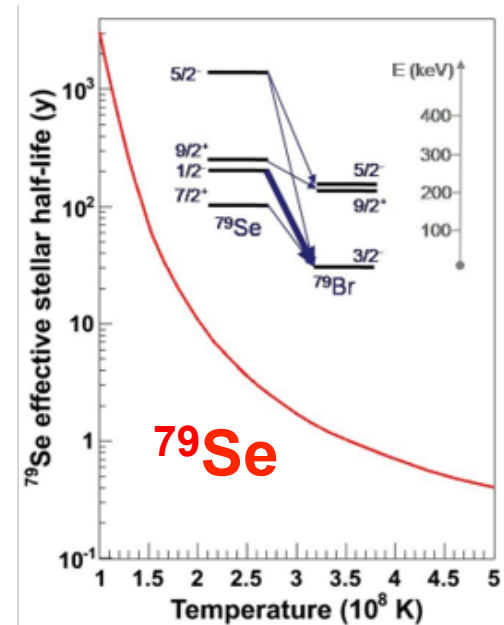
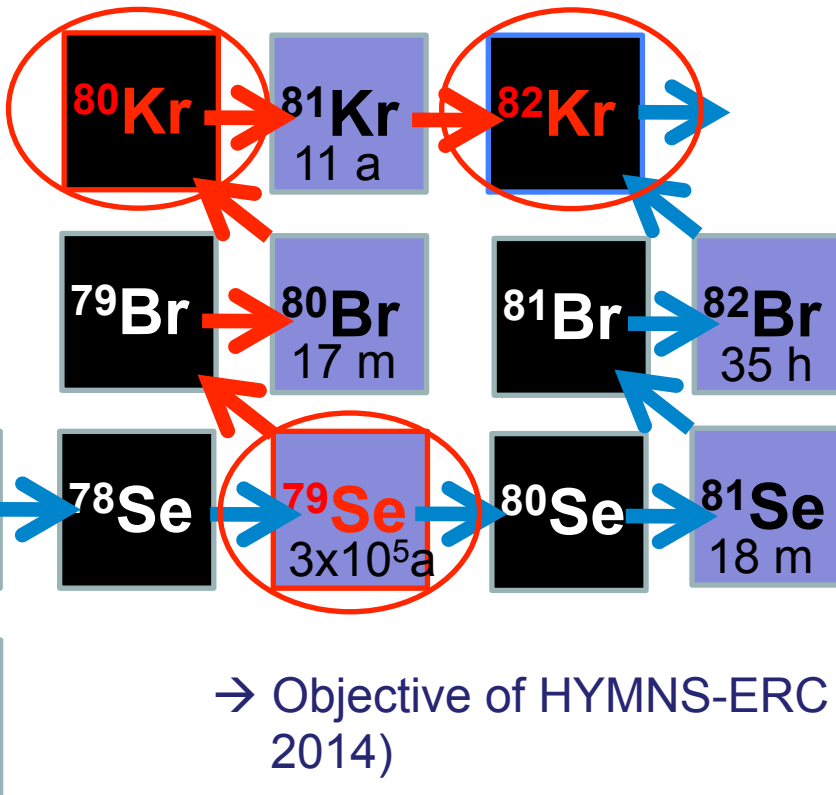
letters to nature

*Nature* 332, 700 - 702 (21 April 1988); doi:10.1038/332700a0



S-process krypton of variable isotopic composition in the Murchison meteorite

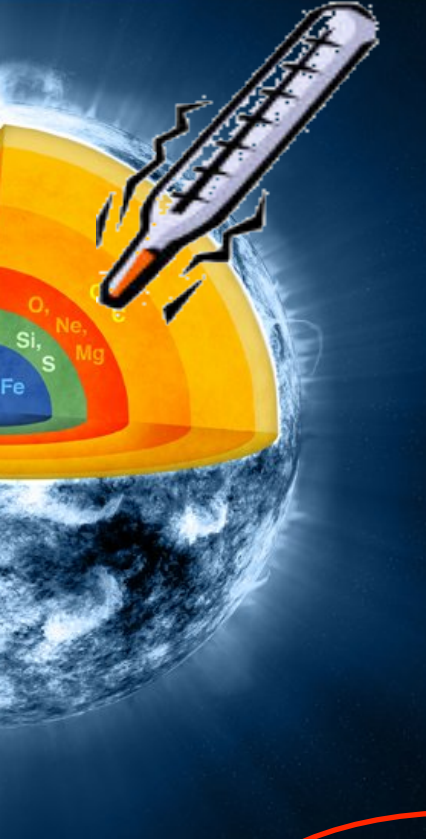
ULRICH OTT\*, FRIEDRICH BEGEMANN\*, JONGMANN YANG†\* & SAMUEL EPSTEIN†



→ Objective of HYMNS-ERC Project (LoI, CERN INT-C 2014)

→ Improvements in the detection system: i-TED

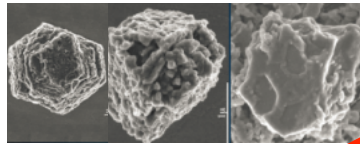
→ Accurate (n,g) CSs of neighbouring nuclei



# The massive-star nuclear-thermometer

letters to nature

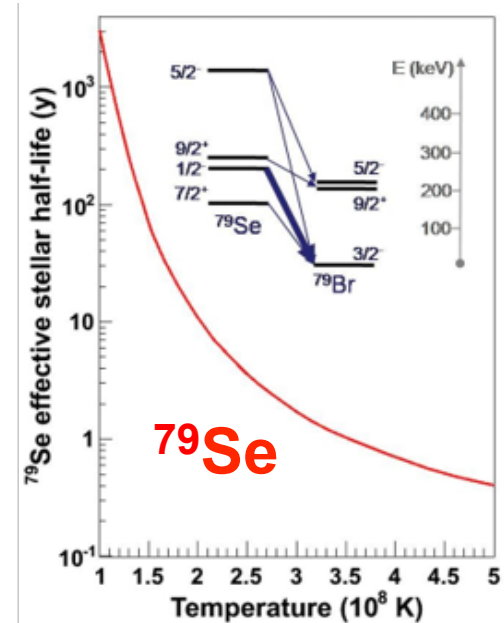
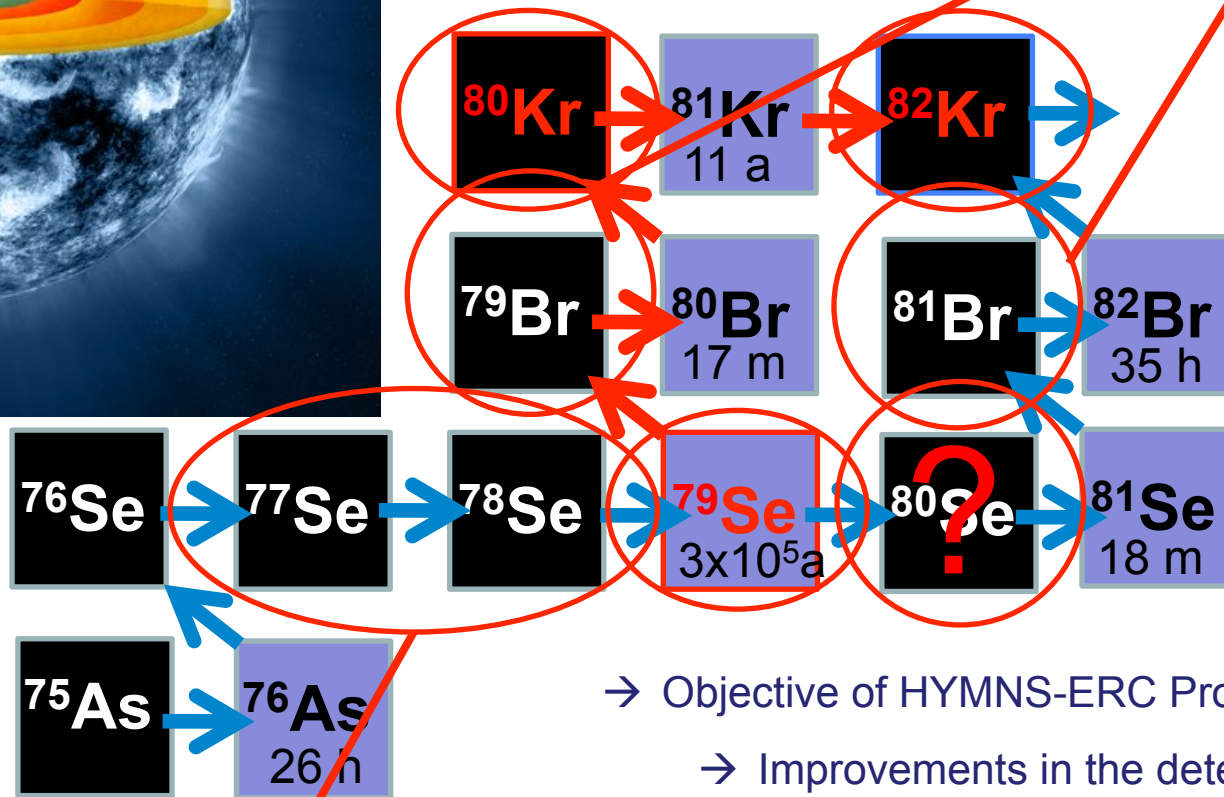
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S-process krypton of variable isotopic composition in the Murchison meteorite

ULRICH OTT\*, FRIEDRICH BEGEMANN\*, JONGMANN YANG†\* & SAMUEL EPSTEIN†

M.Heil et al.  
PRC2008 → Unc.  
(79Br)= 5.5%  
Unc.(81Br)=3%



→ Objective of HYMNS-ERC Project (LoI, CERN INTC 2014)

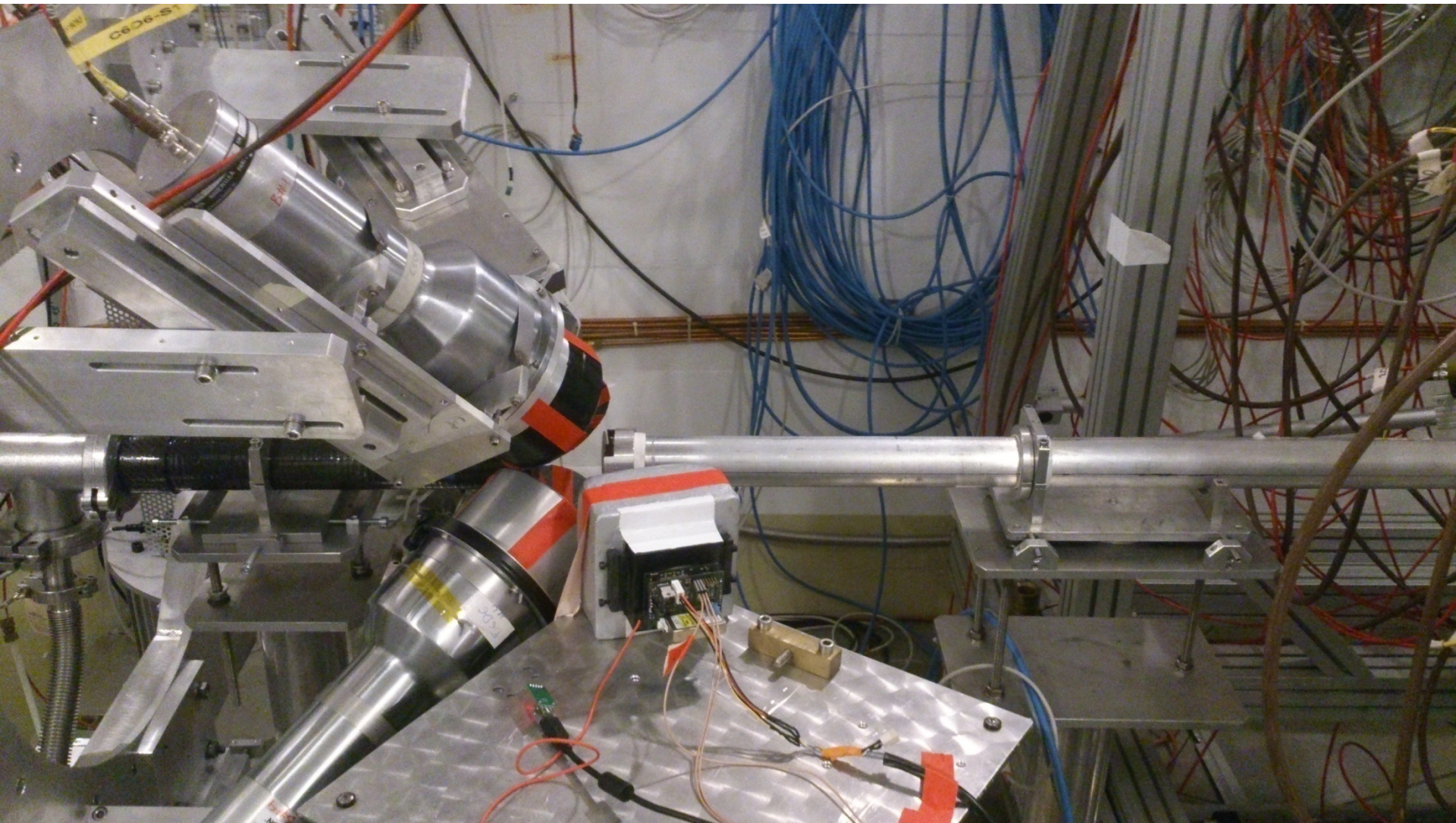
→ Improvements in the detection system: i-TED

→ Accurate (n,g) CSs of neighbouring nuclei

C.Lederer, A. Murphy et al. (n\_TOF Col.), 2017 → CS Uncertainty 4-5%

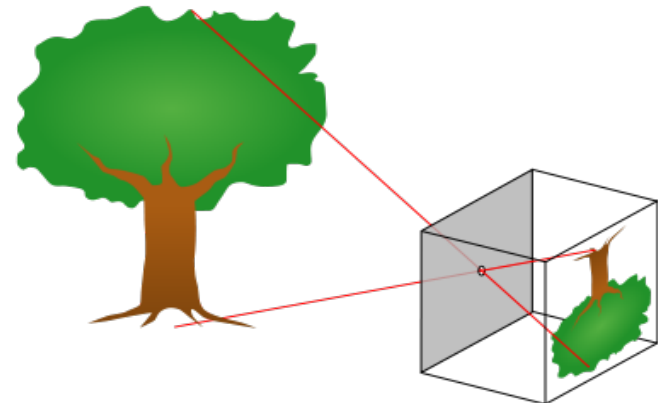
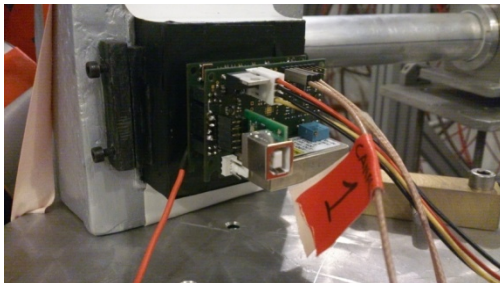
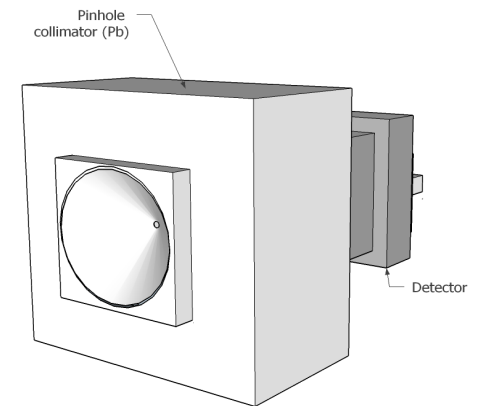
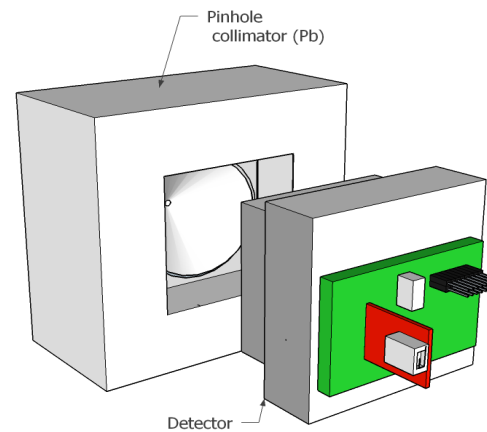
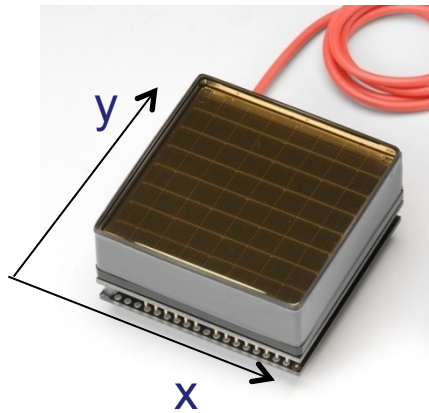
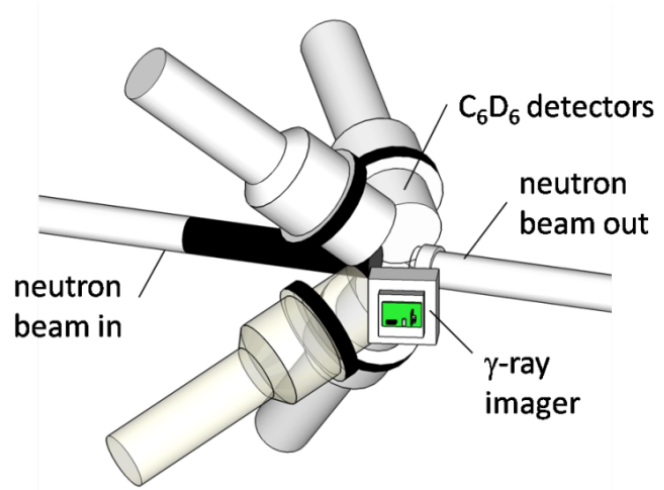


# “Imaging” ( $n,\gamma$ ) cross sections: first tests using a pin-hole gamma-camera



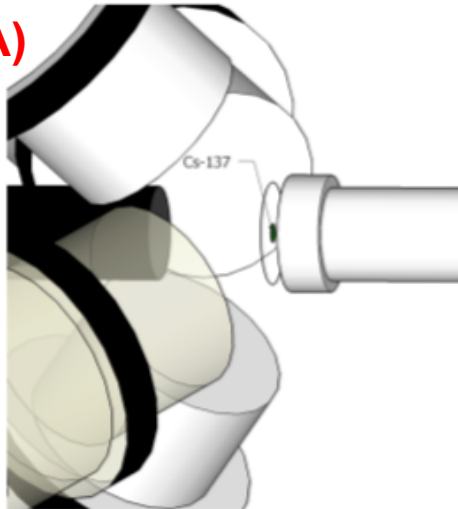


# “Imaging” $(n,\gamma)$ cross sections: first tests using a pin-hole gamma-camera

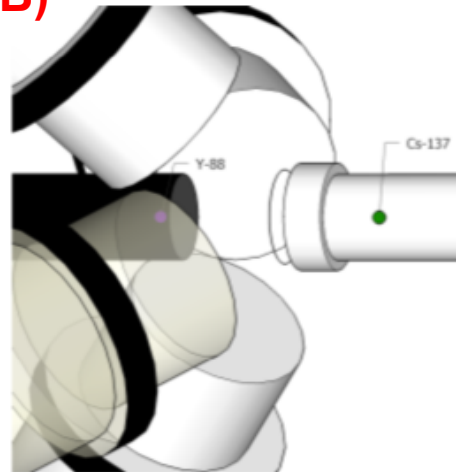


# First tests: $(n,\gamma)$ i-measurements at n\_TOF EAR1

A)

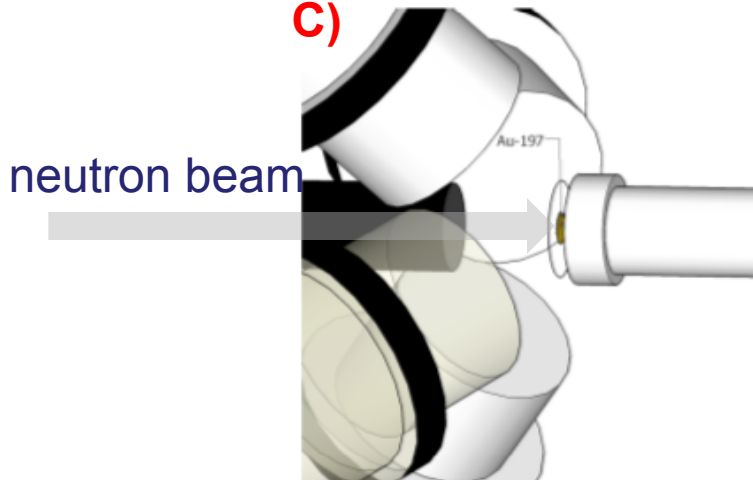


B)

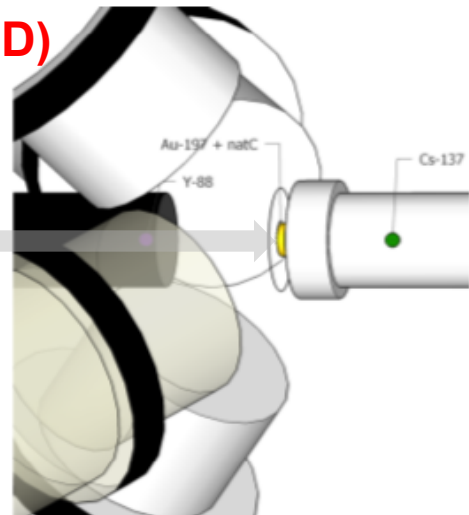


- No beam
- Only sources
- Test imaging performance

C)

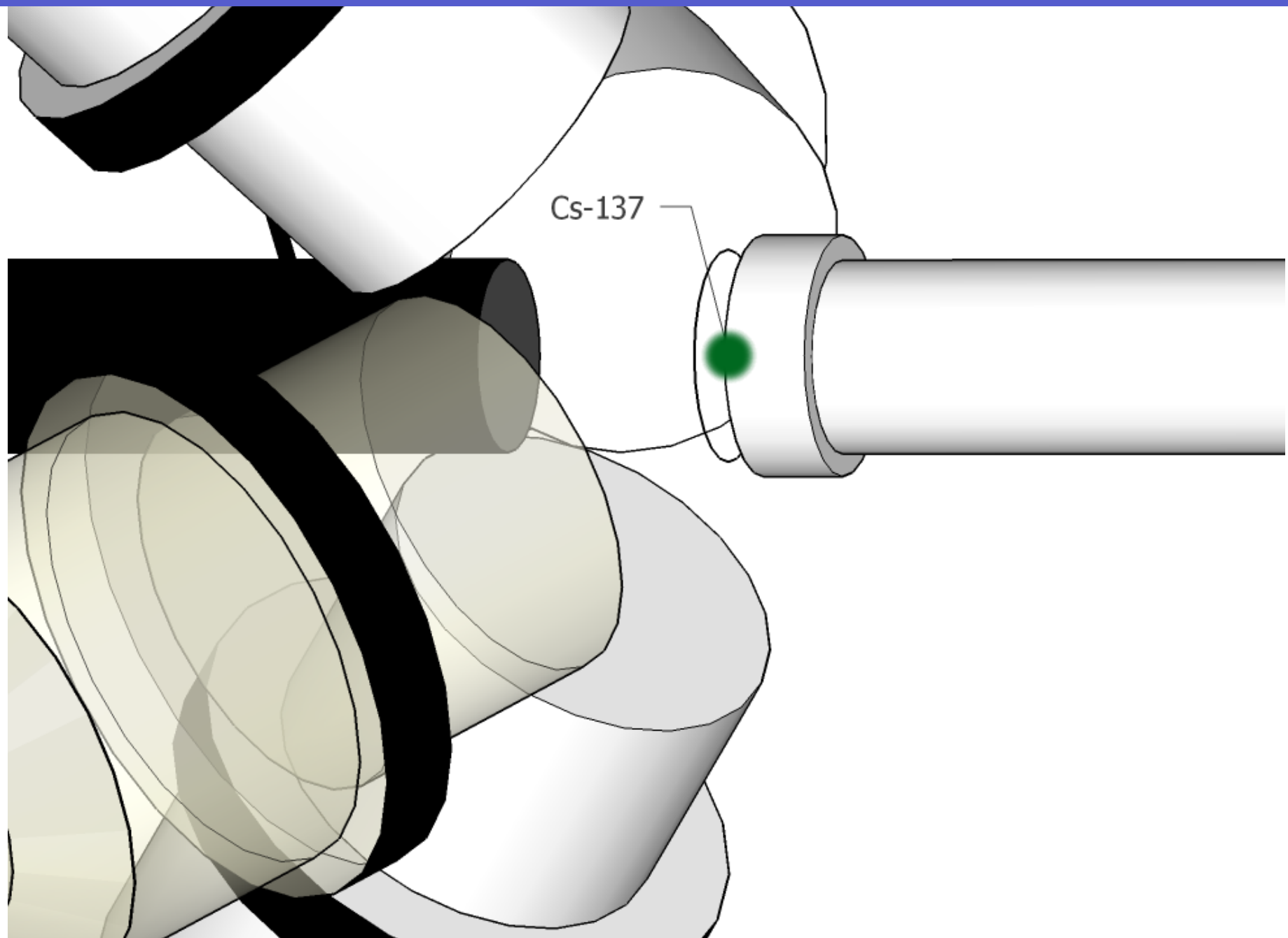


D)



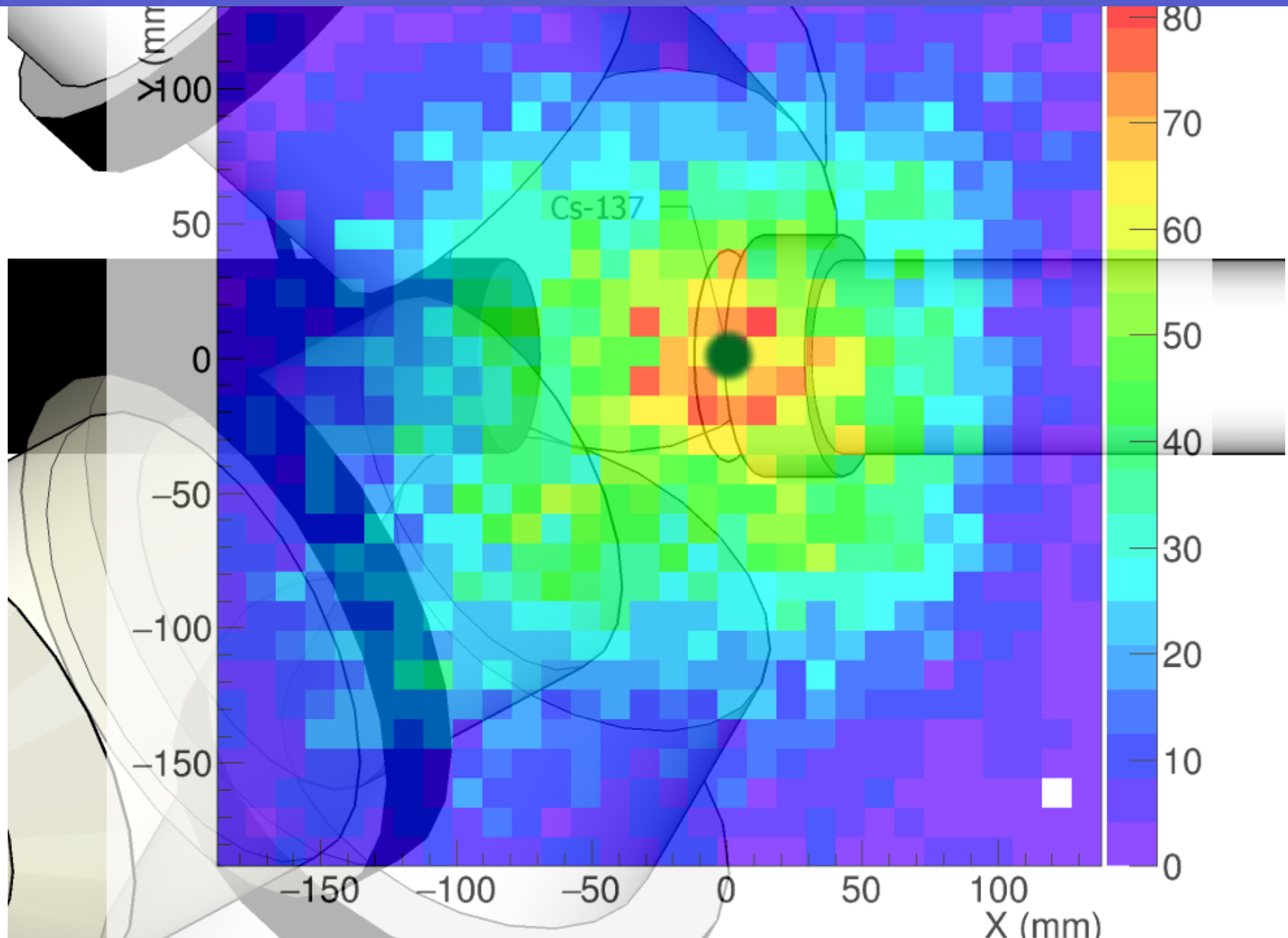
- Neutron beam
- Au(n,g)
- Au(n,g) + Bkg++

# First $\gamma$ -imaging tests at n\_TOF EAR1

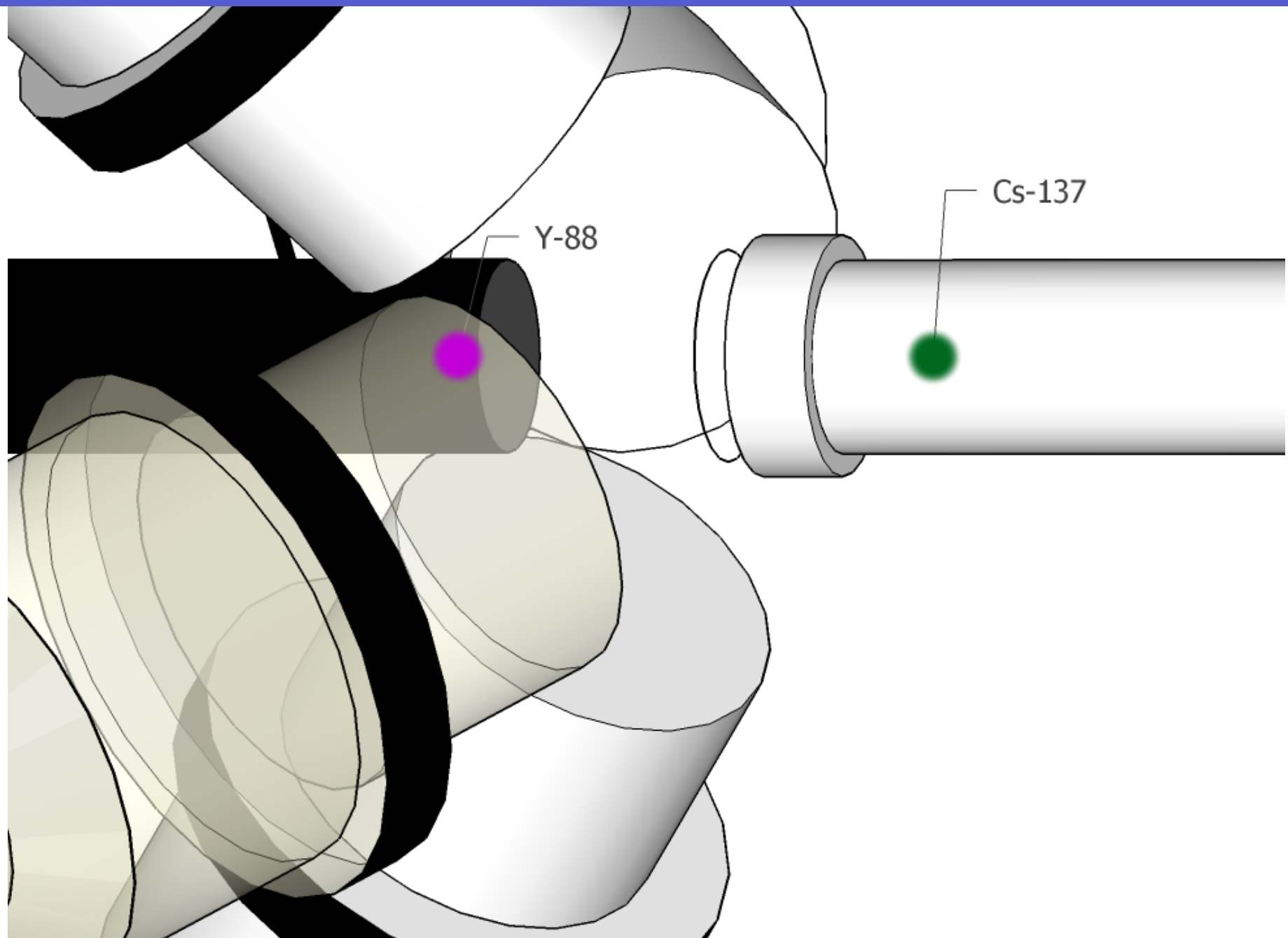




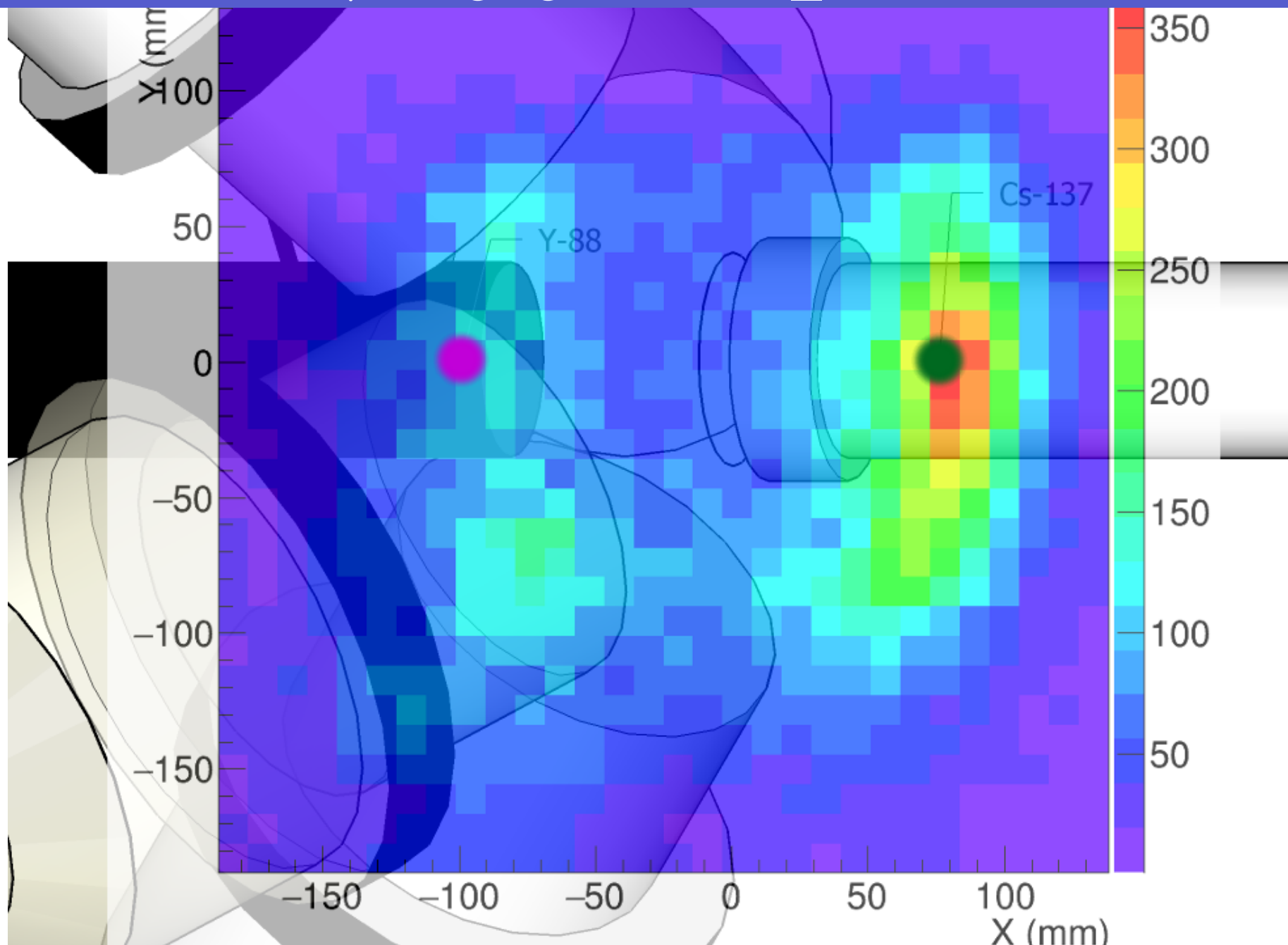
# First $\gamma$ -imaging tests at n\_TOF EAR1



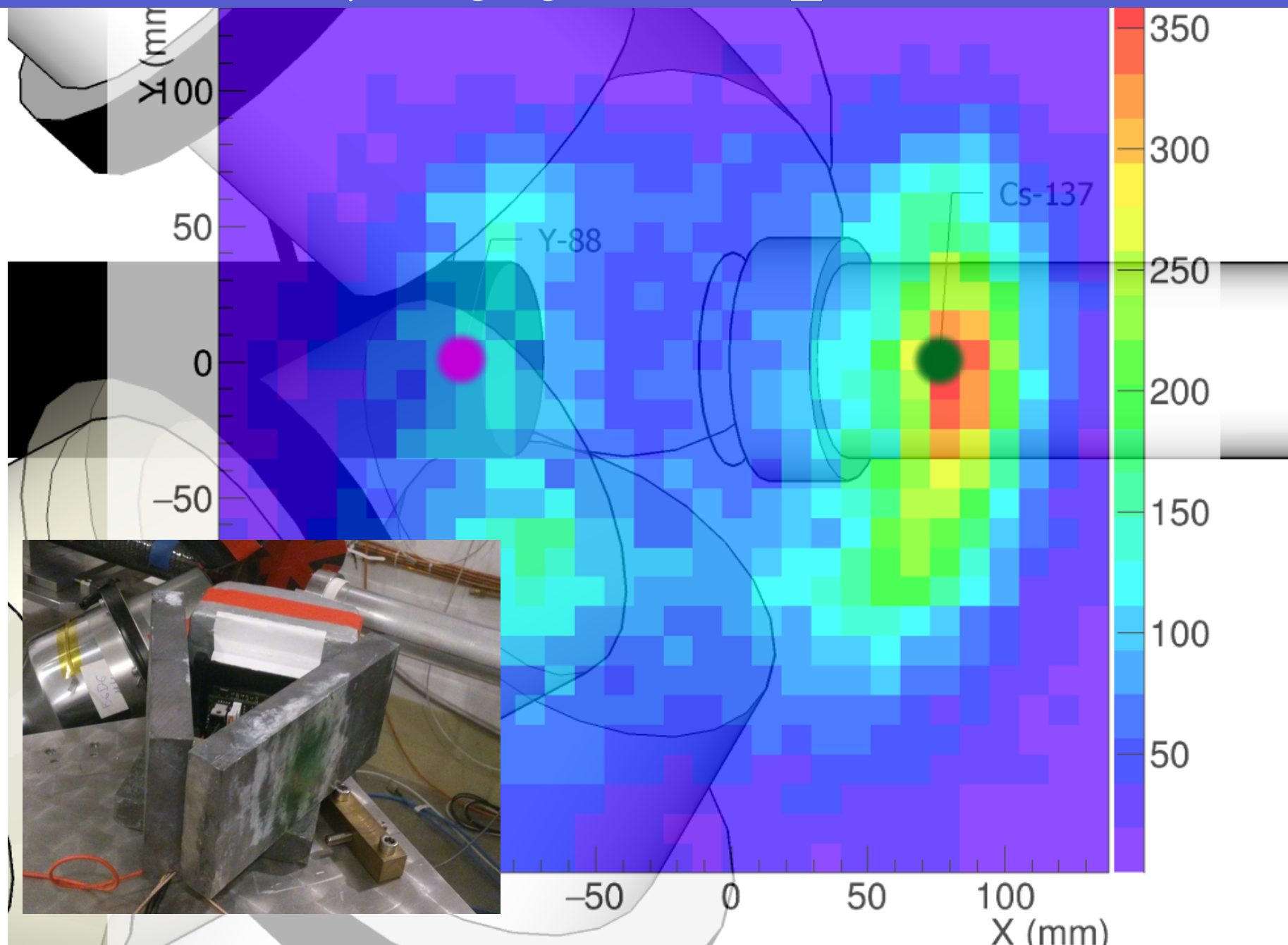
# First $\gamma$ -imaging tests at n\_TOF EAR1



# First $\gamma$ -imaging tests at n\_TOF EAR1

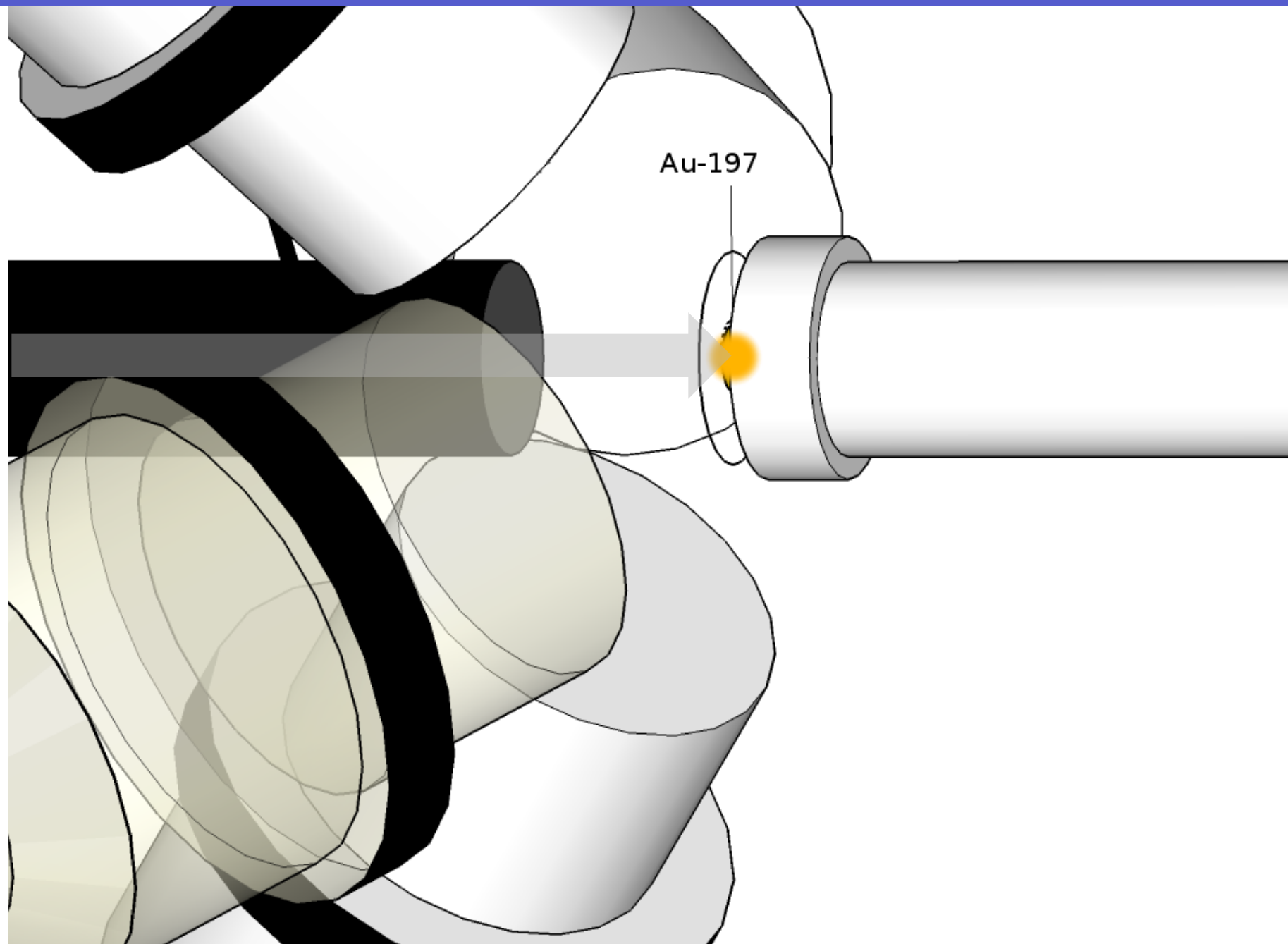


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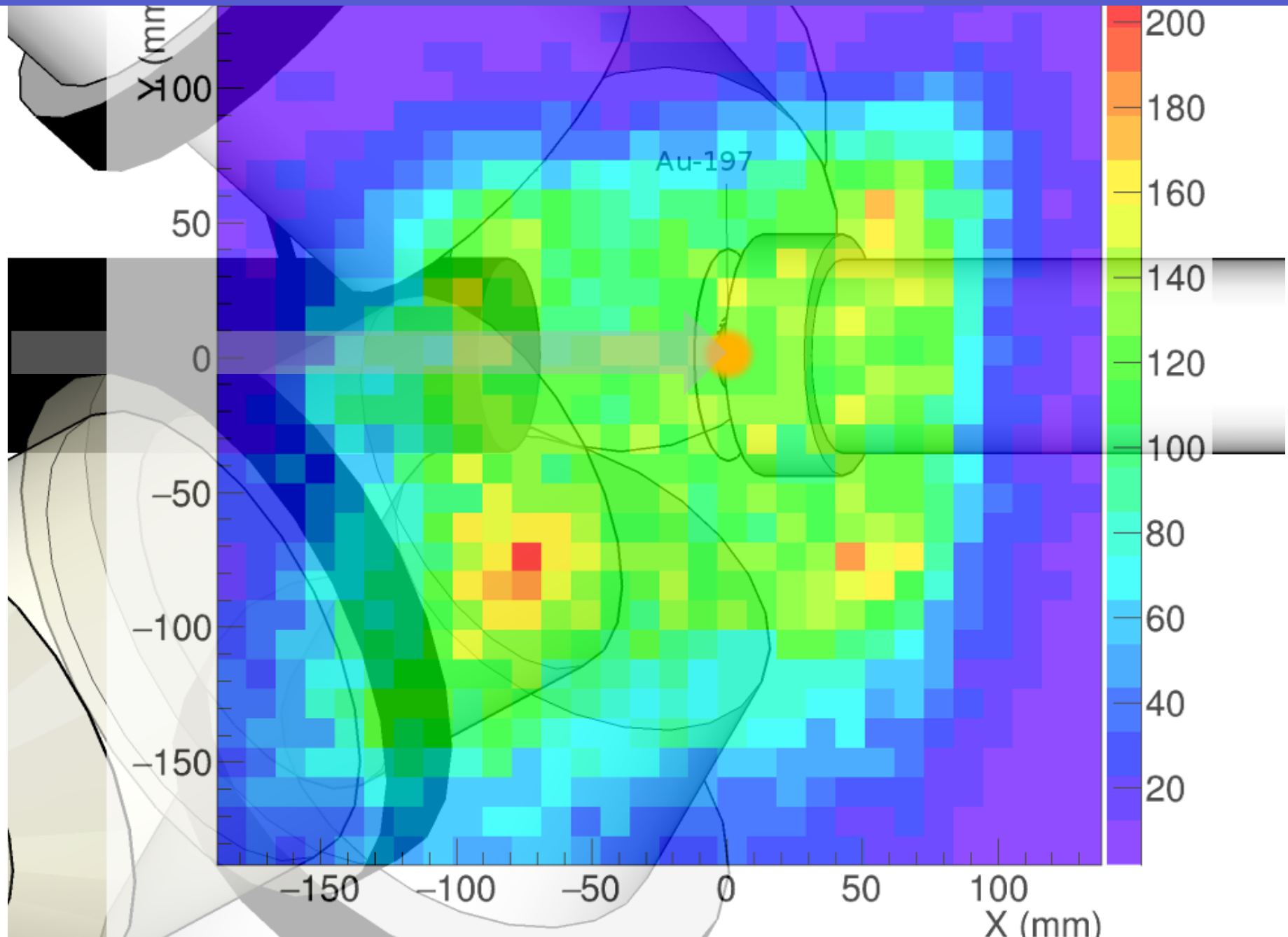




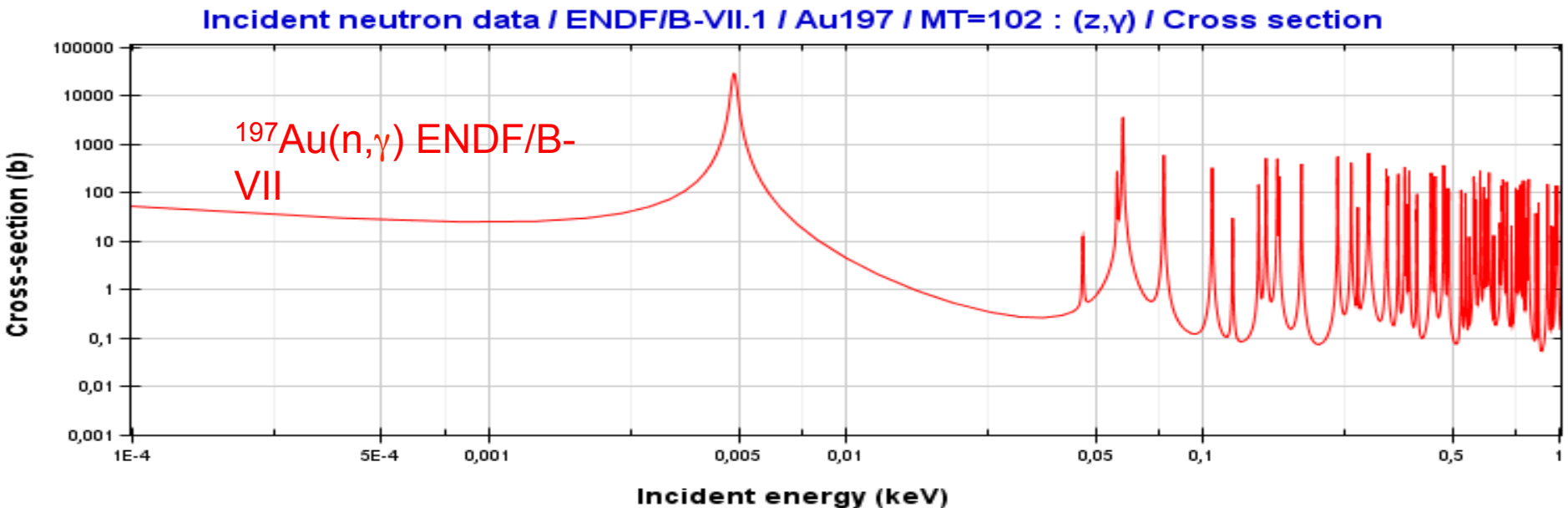
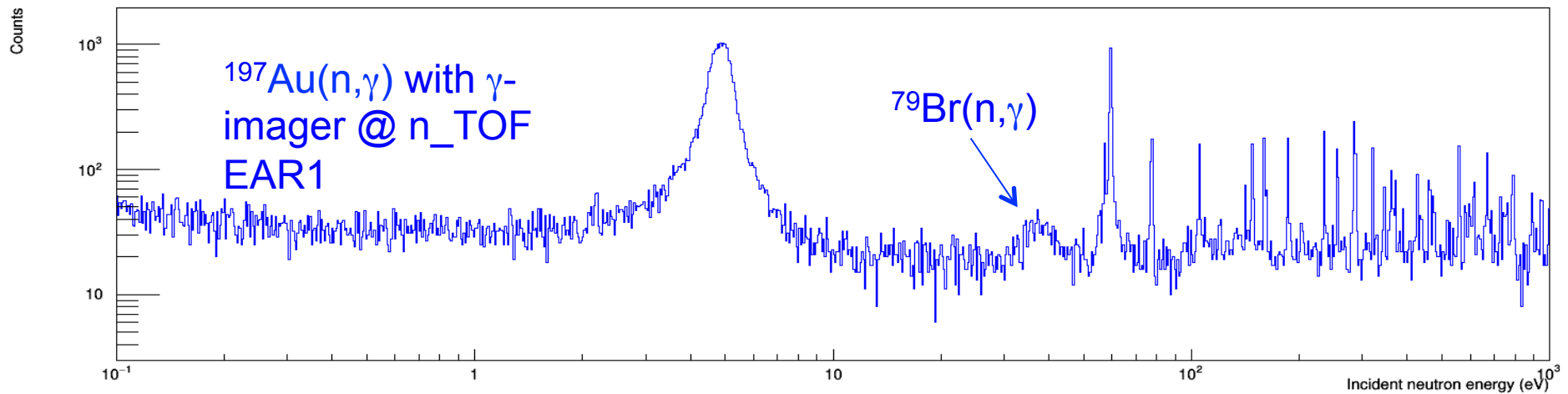
# First $(n,\gamma)$ test-measurements at n\_TOF EAR1



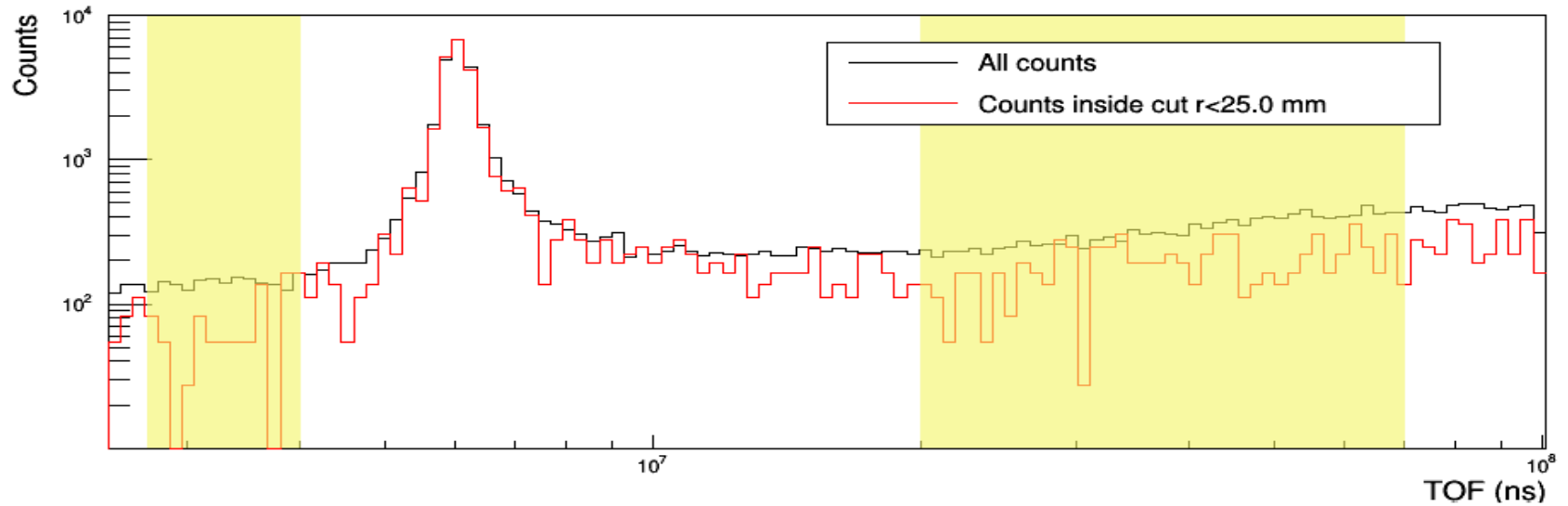
# First tests: $(n,\gamma)$ measurements at n\_TOF EAR1



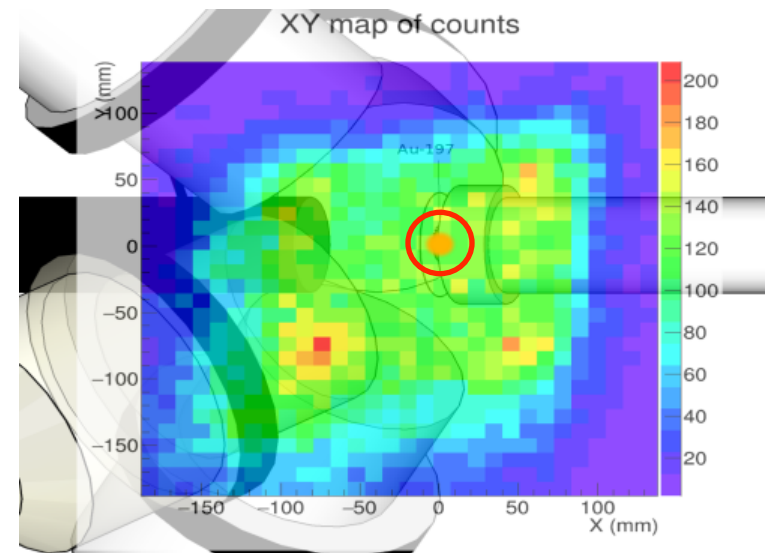
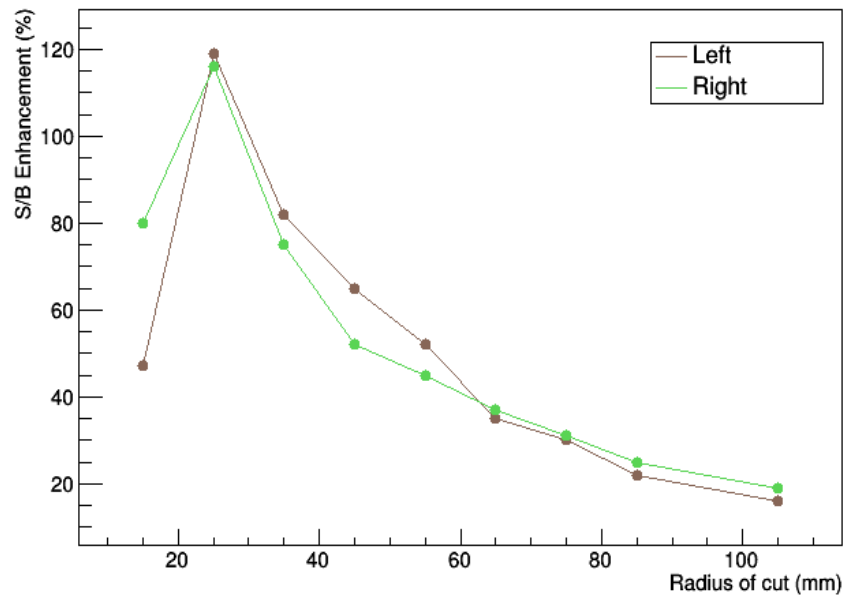
# First tests $^{197}\text{Au}(n,\gamma)$ TOF spectrum with $\gamma$ -imager



# First tests: imaging cuts to enhance S/B-ratio

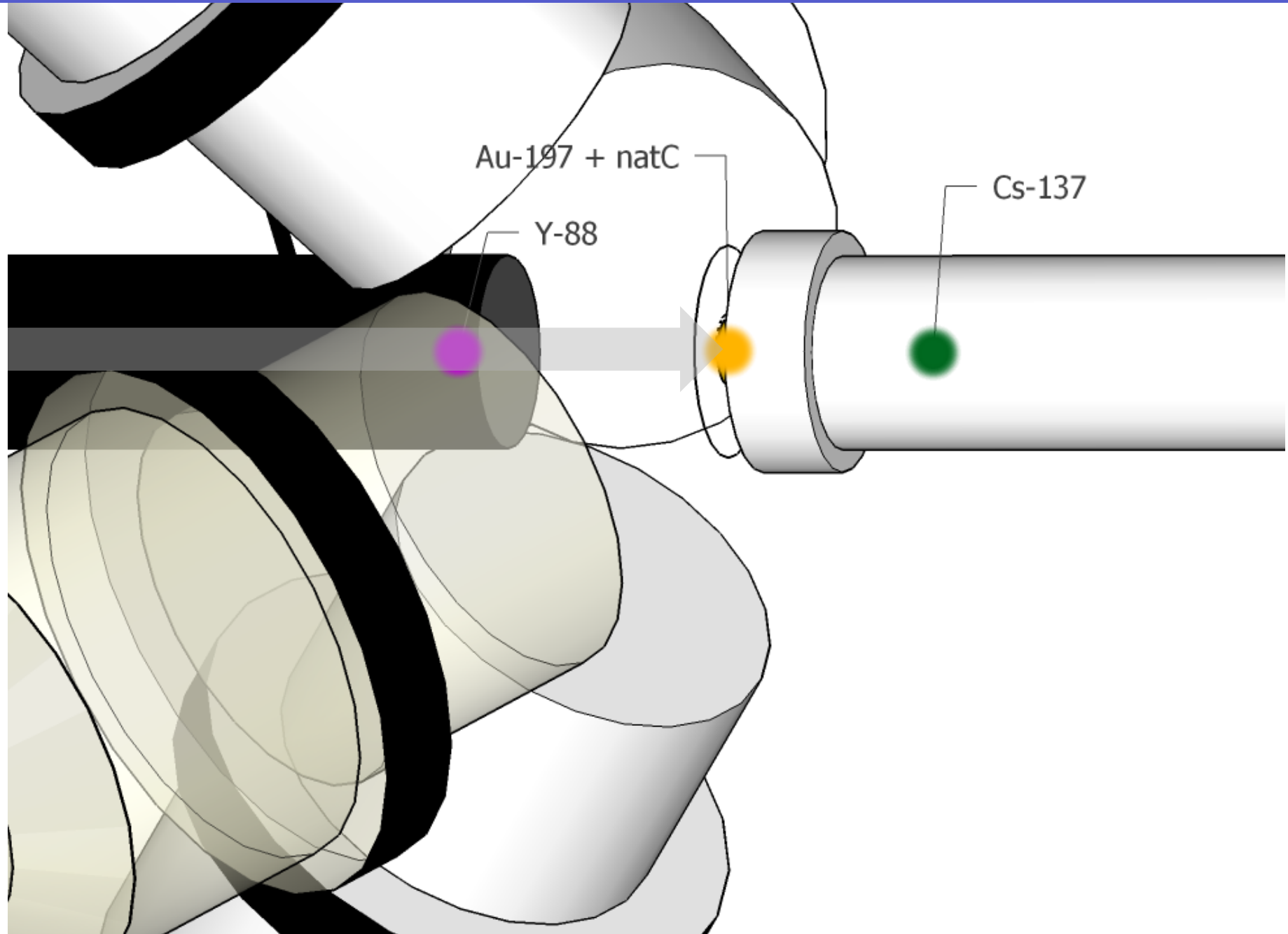


Enhancement of S/B for resonance  $E=4.9$  eV

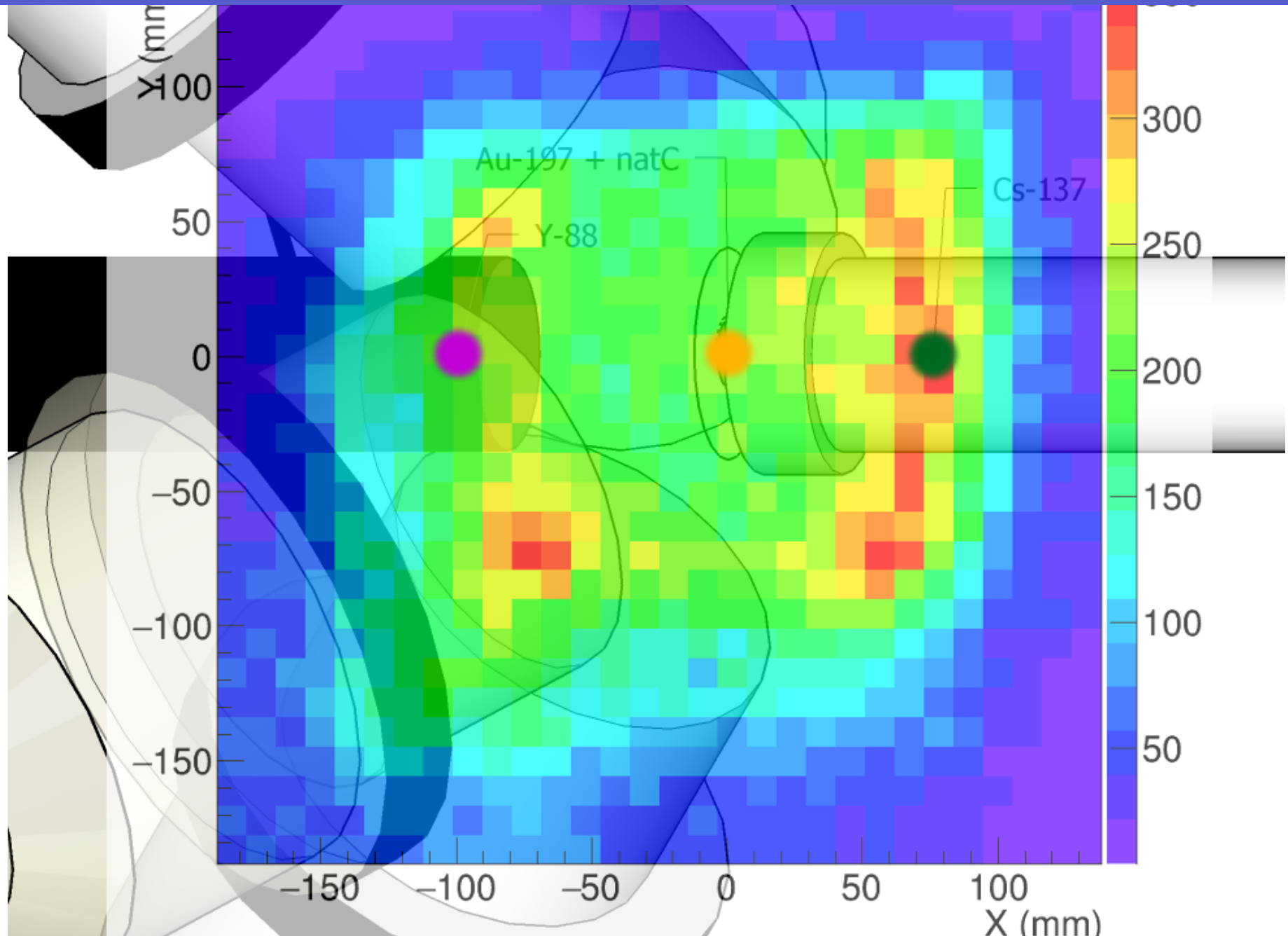




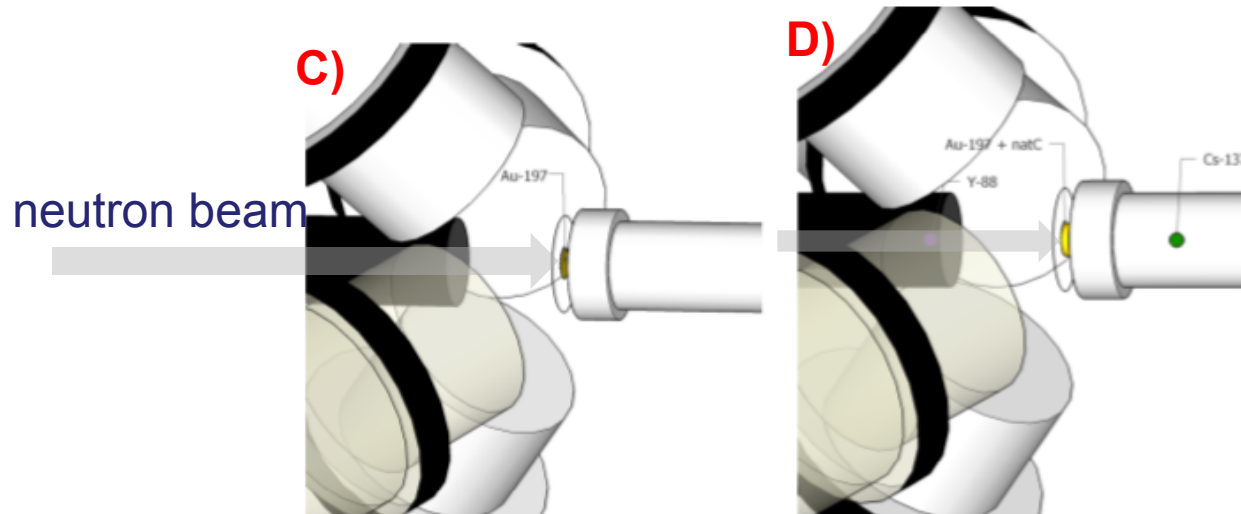
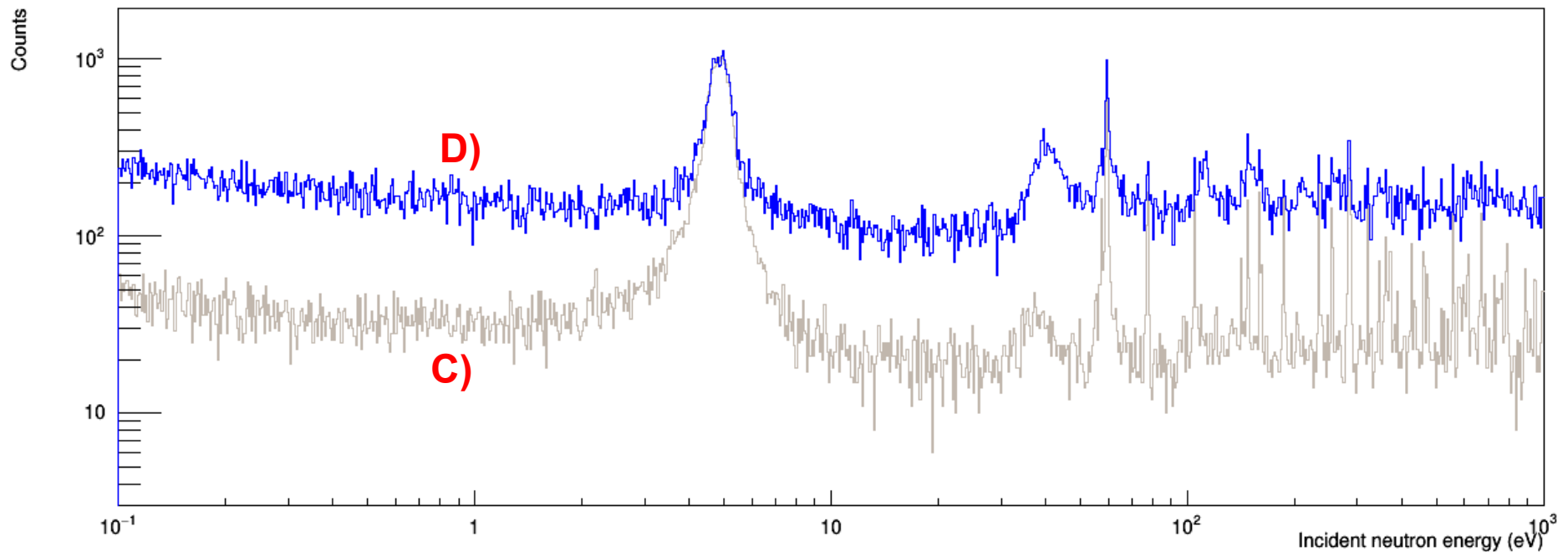
# First tests $^{197}\text{Au}(n,\gamma)$ TOF spectrum with $\gamma$ -imager



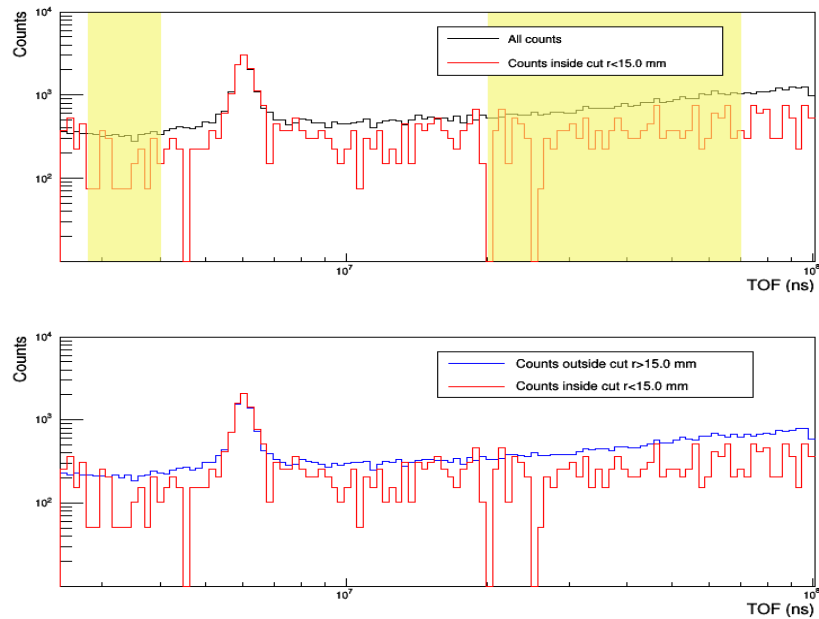
# First tests $^{197}\text{Au}(n,\gamma)$ TOF spectrum with $\gamma$ -imager



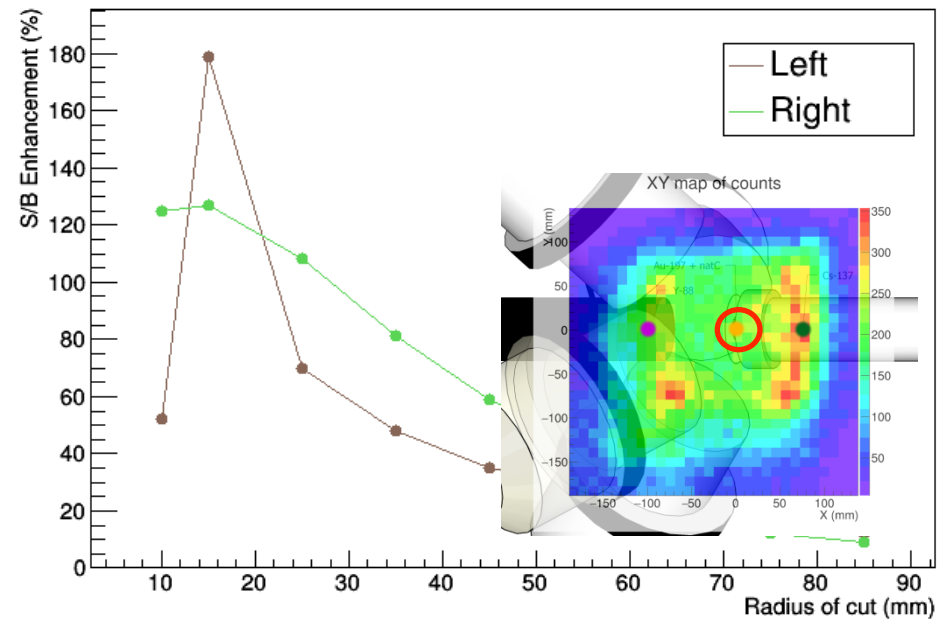
# First tests: imaging cuts to enhance S/B-ratio



# First tests: imaging cuts to enhance S/B-ratio



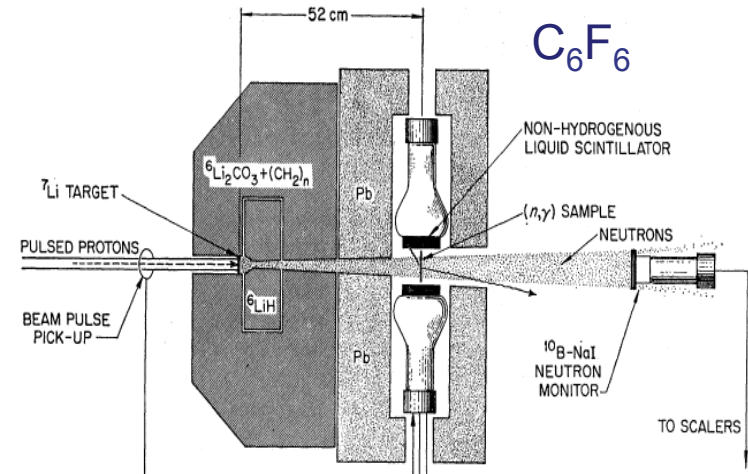
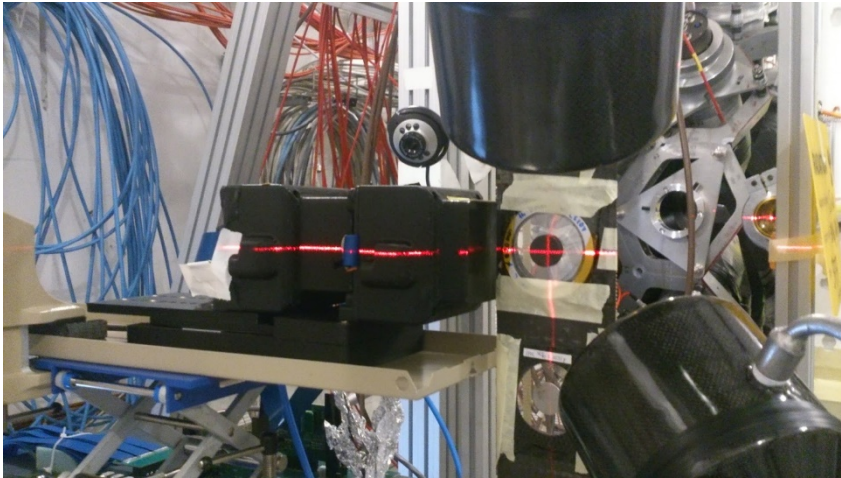
Enhancement of S/B for resonance  $E=4.9$  eV



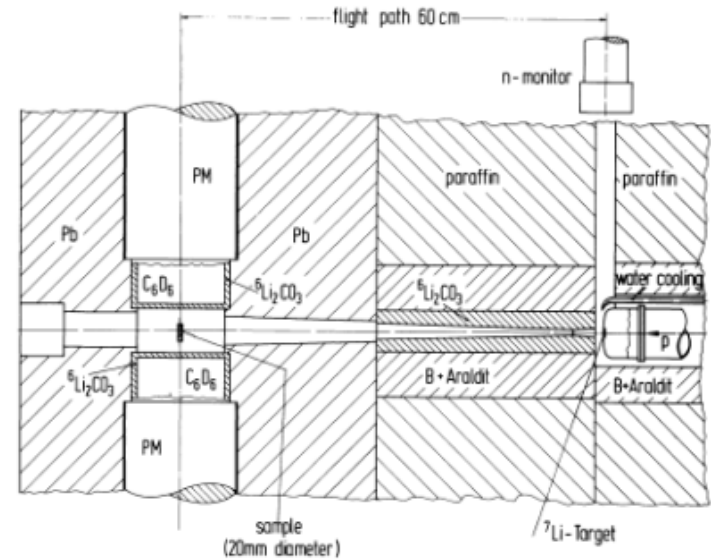
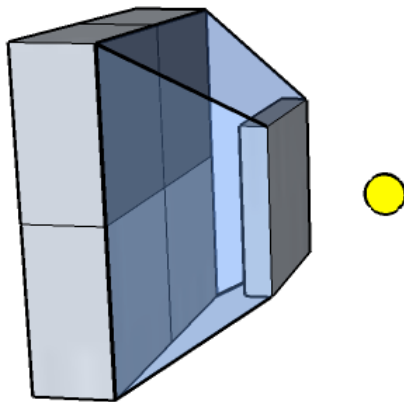


# i-TED: imaging-Total Energy Detector

Technical commissioning i-TED Prototype (OK)



Macklin & Gibbons, ORNL, 1967



G. Walter *et al.*, *Astron. Astrophys.* **167**, 186 (1986)

# Last slide: links to learn more

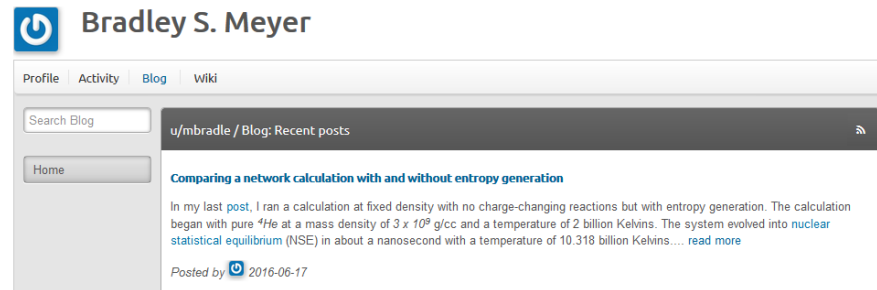
- JINA-CEE youtube seminar series: nucleosynthesis topics, theory, observations and experiments

<https://www.youtube.com/channel/UCTa4Bt0wQ6mYduyOCvsYR5A>



- WEBNUCLEO (B. Meyer's blog and code): nucleosynthesis network code + examples to learn

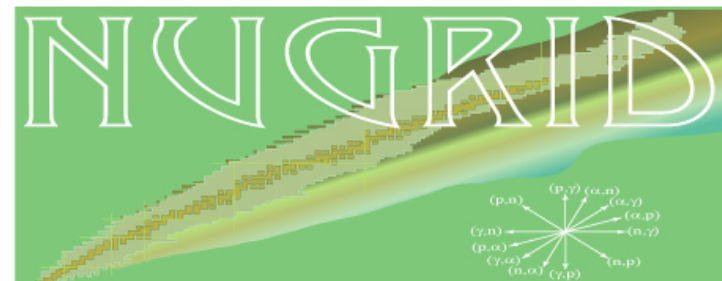
<https://sourceforge.net/u/mbradle/blog/>



- MESA (Modules for Experiments in Stellar Astrophysics) <https://sourceforge.net/projects/mesa/>
- NuGRID: <http://www.nugridstars.org/>

- NuPECC: Nuclear Physics European Collaboration Committee

<http://www.nupecc.org/?display=lrp2010/main>



[inicio](#) | [publications](#) | [projects](#) | [data and software](#) | [meetings](#)

# Summary

Radiative capture measurements needed in several fields, mainly in nuclear technology and nucleosynthesis.

Challenges come from: **small mass samples, radioactive targets, and sometimes neutron scattering and fission issues.**

Mainly 3 techniques for ToF measurements:

- Detection of a characteristic  $\gamma$ -ray [PGA]
- Detection of a  $\gamma$ -ray of the cascade (Total Energy Detectors [TED])
- Detection of the complete  $\gamma$ -ray cascade (Total Absorption [TAC])

Beca FPI Available at Gamma & Neutron Spectroscopy Group of IFIC