Nuclear fusion reaction measurements at LUNA

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NAVI

Partner von DRESDEN concept exzellenz-dresden.de

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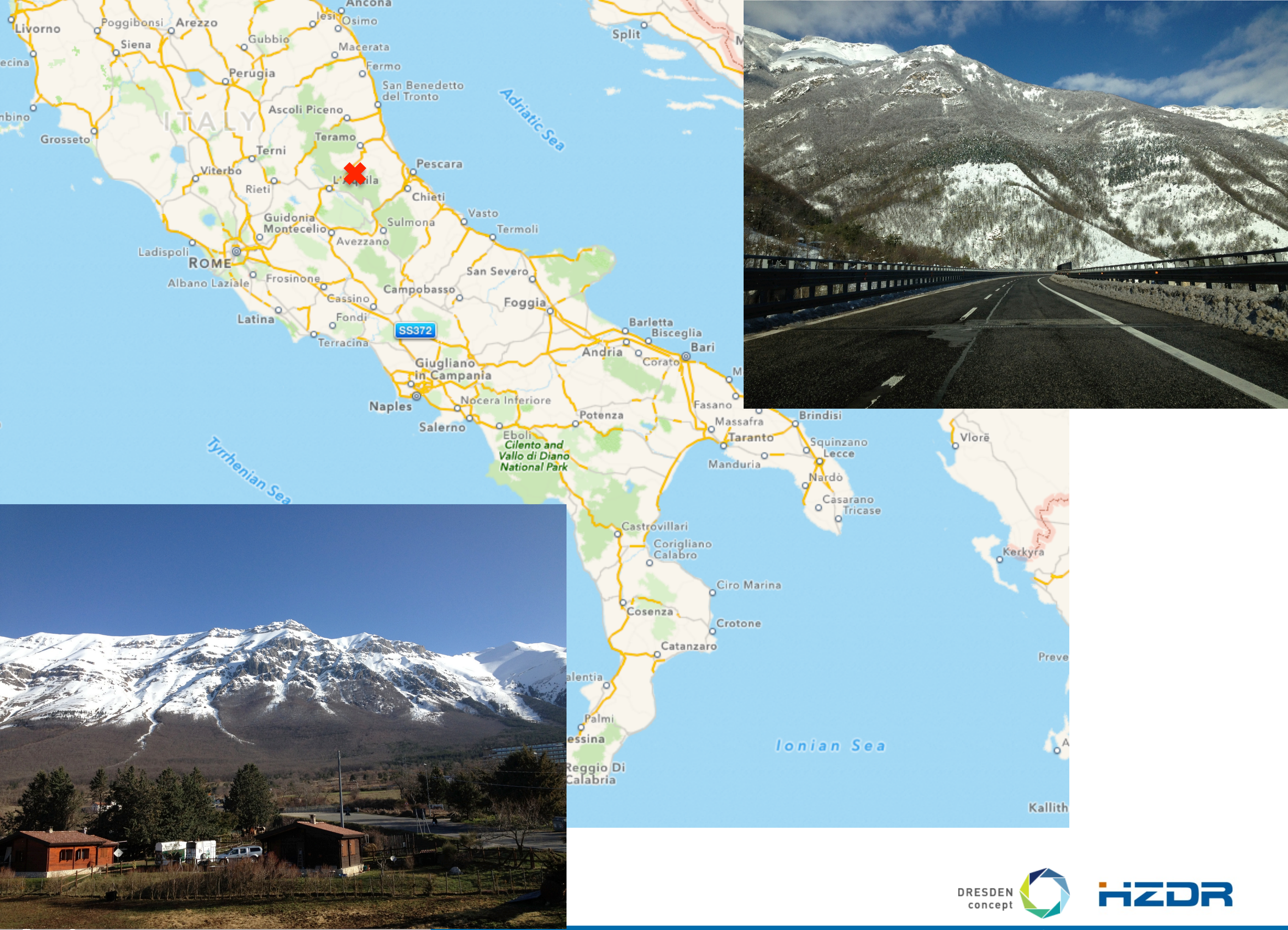
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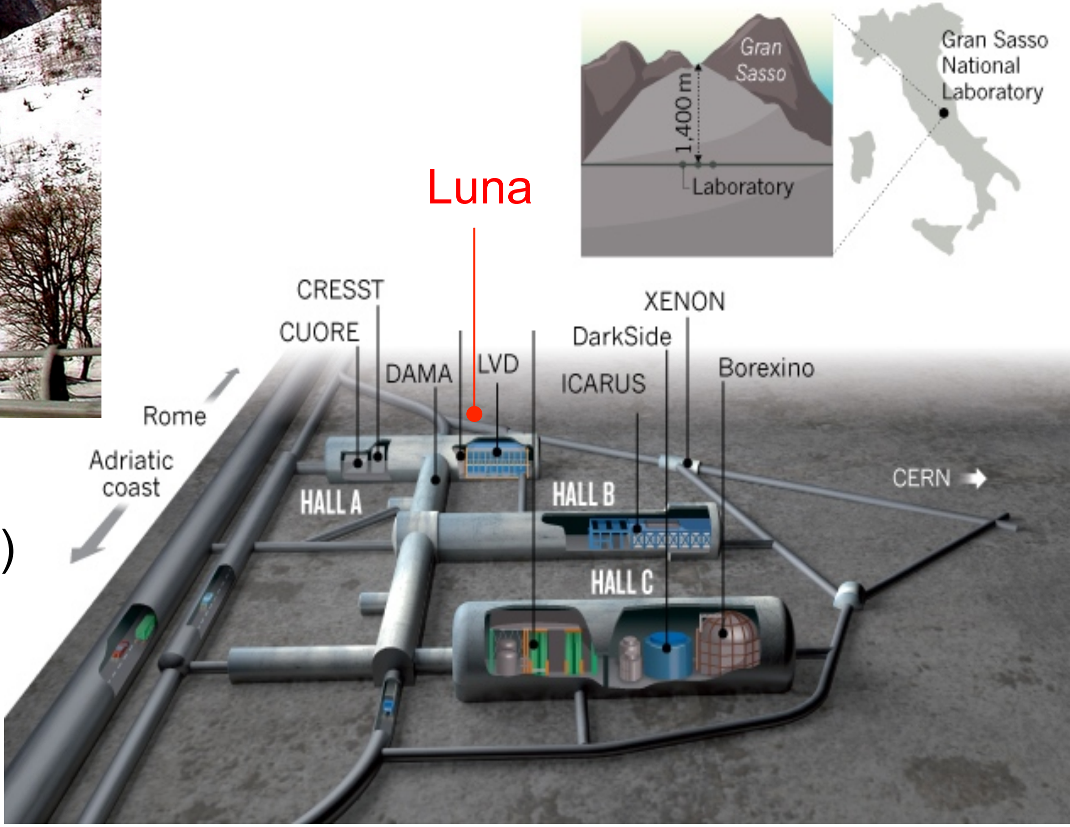
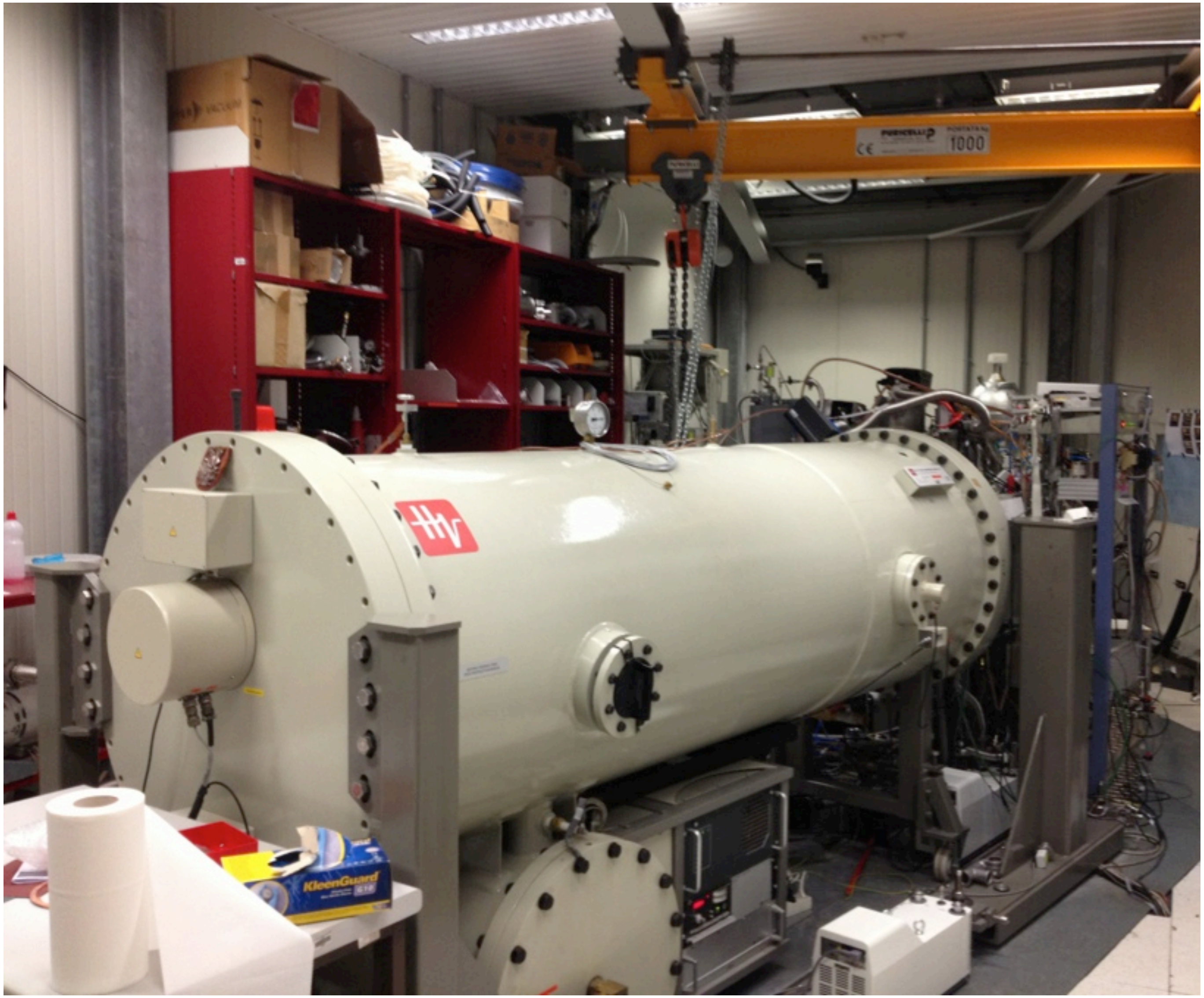
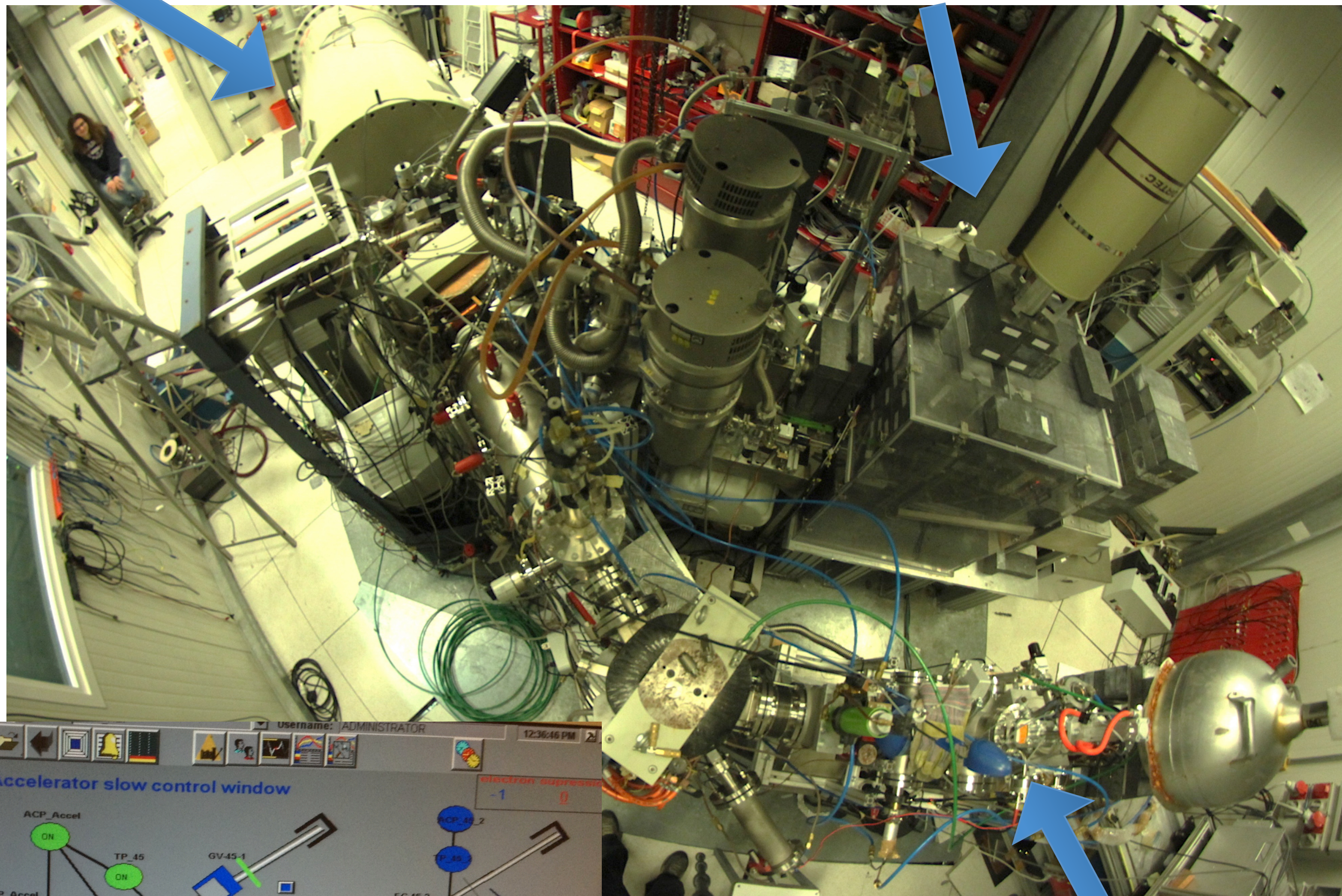


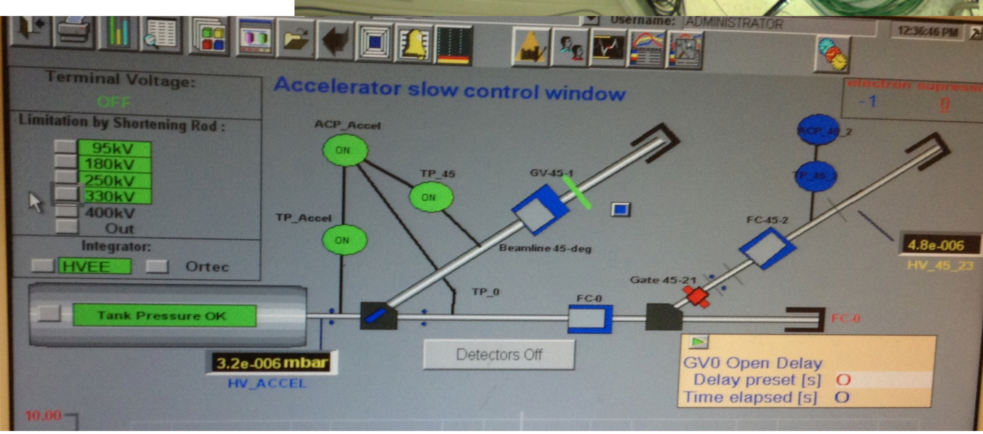
LUNA-II 400 kV



400 kV accelerator

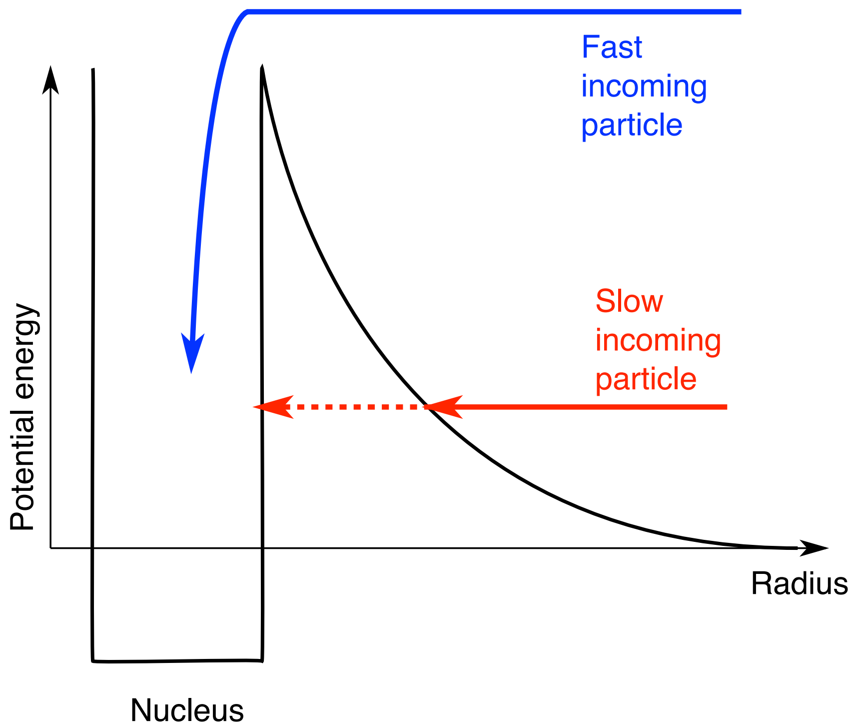
gas target beamline





solid target beamline

Nuclear reaction cross section σ for low-energy charged particles



Typical Coulomb barrier height : ~ MeV

Typical stellar temperature k_B * T ~ keV

↓

Definition of the astrophysical S-factor *S(E)*:

$$\sigma(E) = \frac{\boxed{S(E)}}{E} \exp\left[-2\pi Z_1 Z_2 \alpha \left(\frac{\mu c^2}{2E}\right)^{0.5}\right]$$

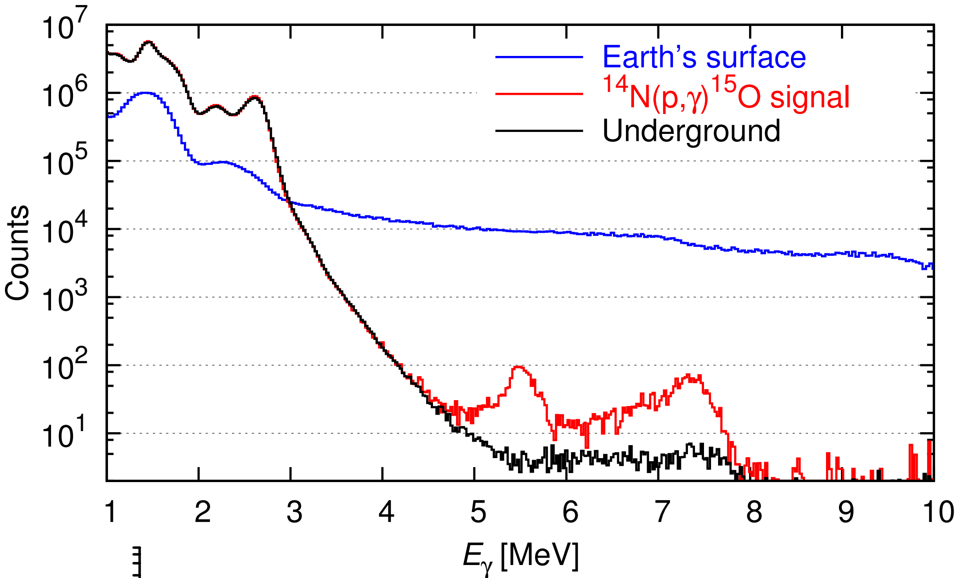
↓

Very low cross sections to be measured!

↓

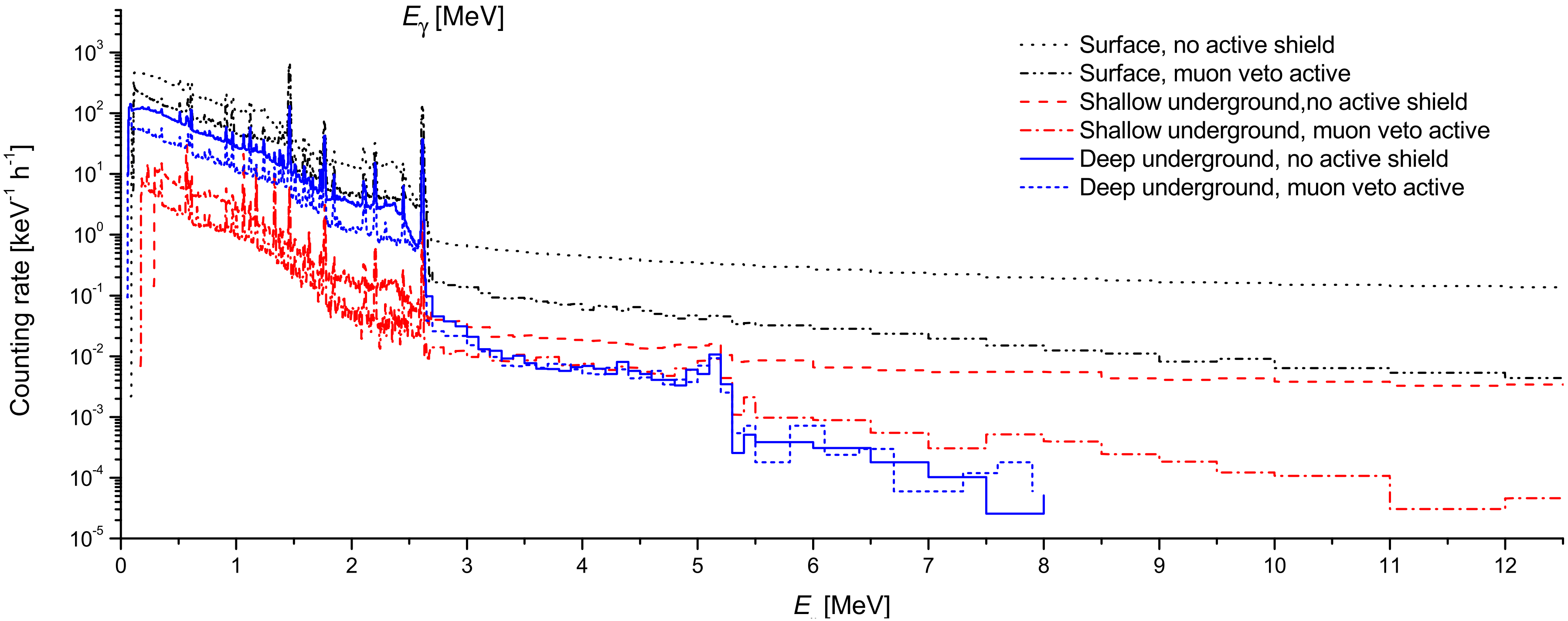
Need for low background!

Uniquely low no-beam background at LUNA



BGO γ-detector (free-running)

HPGe γ-detector
(with cosmic-ray veto)



Thermonuclear reaction rate

- Nuclear reaction represent the main energy source of stars

$$0 + 1 \longrightarrow 2 + 3 \qquad \text{(Q-value)}$$

- Total energy released ~ rate of nuclear reaction

$$R_{01} = \frac{N_R}{Vt} = \sigma(v)\frac{N_0}{V}\frac{N_1}{V}v = n_0 n_1 v\sigma(v)$$

- In the stellar plasma the relative velocity of nuclei **0** and **1** is not constant, but follows Maxwell-Boltzmann distribution

$$P(v)dv = \left(\frac{m_{01}}{2\pi kT}\right)^{3/2} e^{-\frac{m_{01}v^2}{2kT}} 4\pi v^2 dv$$

$$P(E)dE = \frac{2}{\sqrt{\pi}}\frac{1}{(kT)^{3/2}}\sqrt{E}e^{-\frac{E}{kT}}dE$$

- Reaction rate per particle pair

$$R_{01} = n_0 n_1 \int vP(v)\sigma(v)dv \equiv n_0 n_1 \langle \sigma v \rangle$$

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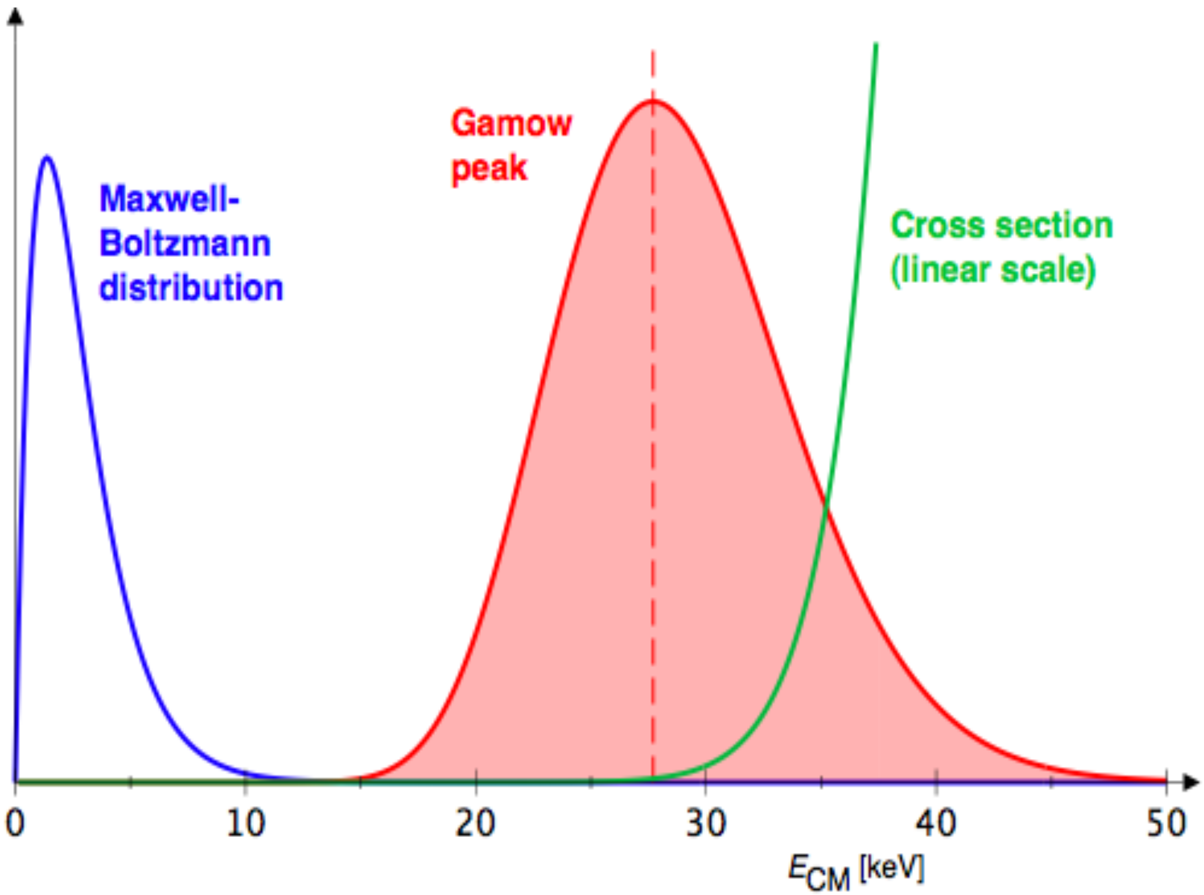
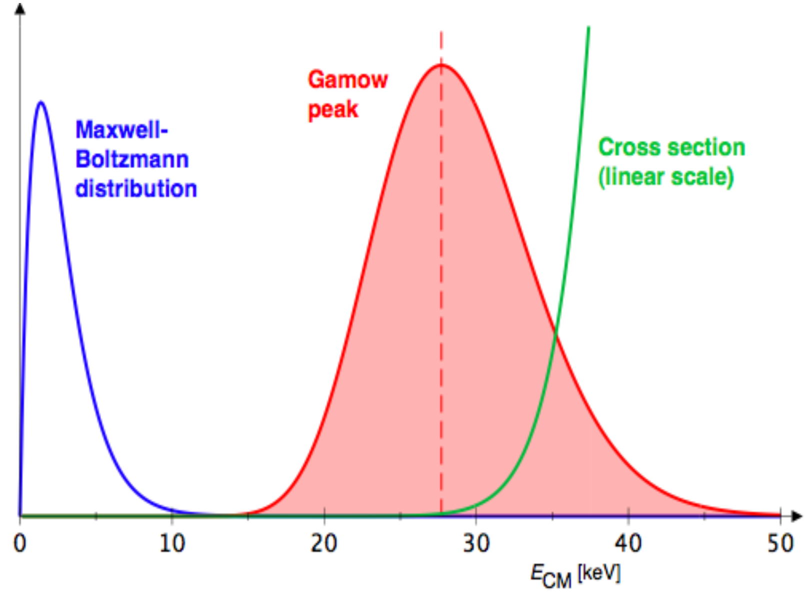
$$\langle \sigma v \rangle = \sqrt{\frac{8}{\pi m_{01}}} \frac{1}{(kT)^{3/2}} \int_0^\infty \underline{E\sigma(E)} \underline{e^{-\frac{E}{kT}}} dE$$





At which energies do the reactions take place in a plasma?

Scenario	Reaction	E_G[keV]	σ [barn]	Detected events/ hour
Sun (16 MK)	$^3He(\alpha,\gamma)^7Be$	23	10^{-17}	10^{-9}
	$^{14}N(p,\gamma)^{15}O$	28	10^{-19}	10^{-11}
AGB stars (80 MK)	$^{14}N(p,\gamma)^{15}O$	81	10^{-12}	10^{-4}
Big bang (300 MK)	$^3He(\alpha,\gamma)^7Be$	160	10^{-9}	10^{-1}
	$^2H(\alpha,\gamma)^6Li$	96	10^{-11}	10^{-3}

Assuming 10^{16} s^{-1} beam
10^{18} at/cm^2 target
10^{-2} detection efficiency

Too low, even for LUNA

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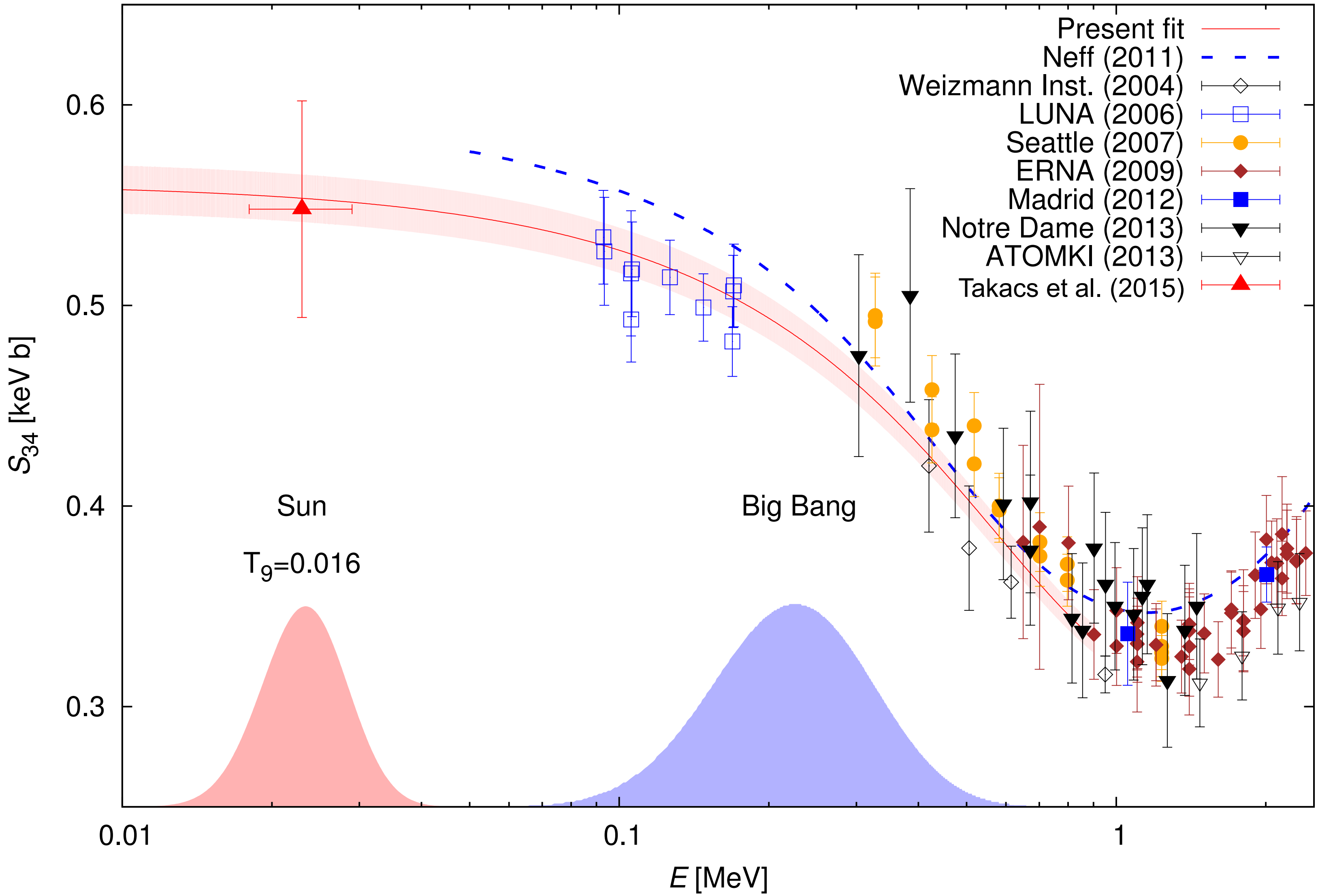
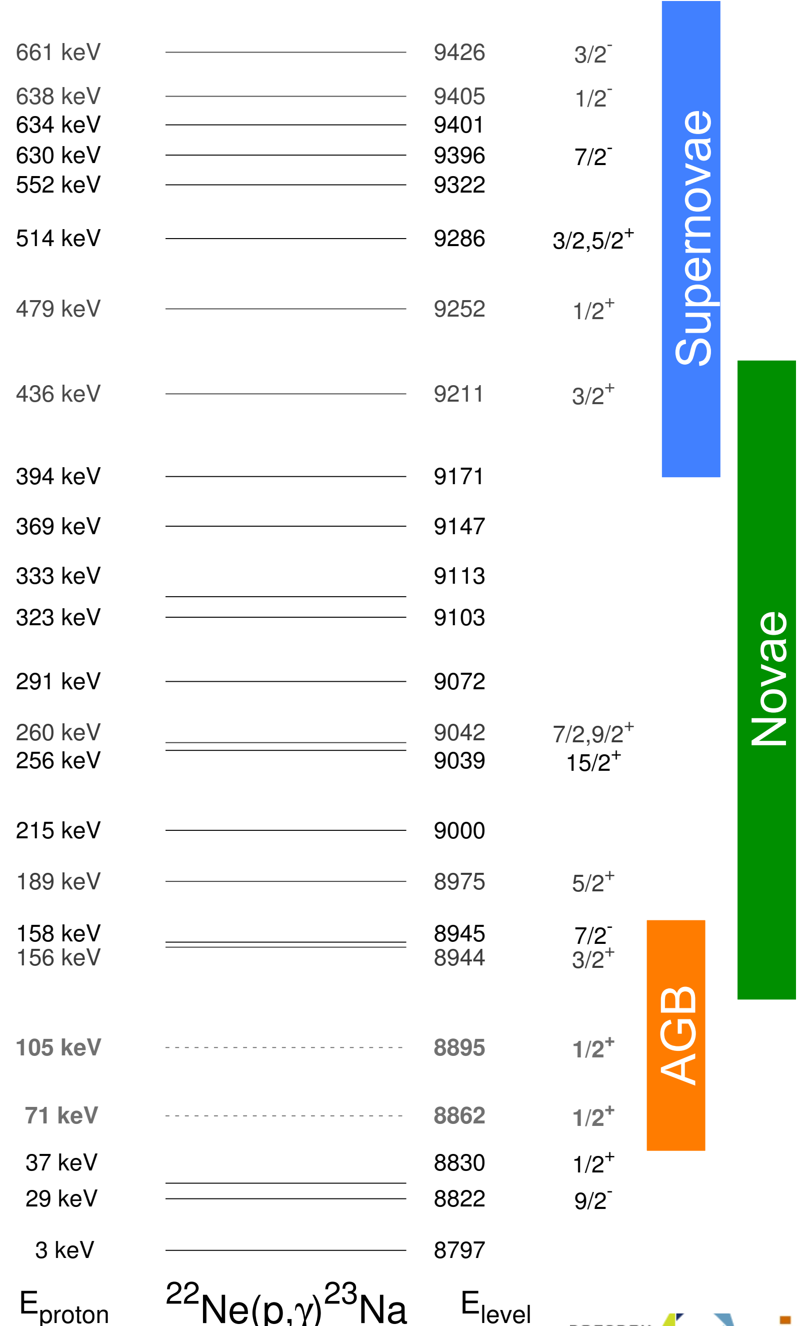

Present fit
Neff (2011)
Weizmann Inst. (2004)
LUNA (2006)
Seattle (2007)
ERNA (2009)
Madrid (2012)
Notre Dame (2013)
ATOMKI (2013)
Takacs et al. (2015)
Sun
T_9=0.016
Big Bang
S_{34} [keV b]
E [MeV]
0.6
0.5
0.4
0.3
0.01
0.1
1

The presence of resonances in the Gamow window can greatly enhance the cross section

Their contribution will dominate the reaction rate



$$\langle \sigma v \rangle = \sqrt{\frac{8}{\pi m_{01}}} \frac{1}{(kT)^{3/2}} \int_0^\infty E\sigma(E) e^{-\frac{E}{kT}} dE$$

- For isolated, narrow resonances the cross section is given by the Breit-Wigner formula

$$\sigma_{BW} = \frac{\lambda^2}{4\pi} \frac{(2J+1)}{(2j_0+1)(2j_1+1)} (1+\delta_{01}) \frac{\Gamma_a \Gamma_b}{(E_r - E)^2 + \frac{\Gamma^2}{4}}$$

λ : de Broglie wavelength $\lambda = \frac{2\pi\hbar}{\sqrt{2m_{01}E}}$

j_i : spin of nuclei 0 and 1

J : spin of the resonance (compound nucleus)

Γ_i : partial width of the entrance (a) and exit (b) channel

Γ : total width of the resonance

$$\omega = \frac{(2J+1)}{(2j_0+1)(2j_1+1)} (1+\delta_{01})$$

$$\langle \sigma v \rangle = \frac{\sqrt{2\pi}\hbar^2}{(m_{01}kT)^{3/2}}\,\omega \int_0^\infty \frac{\Gamma_a \Gamma_b}{(E_r - E)^2 + \frac{\Gamma^2}{4}} e^{-\frac{E}{kT}}\, dE$$

- For narrow resonance the partial width (Γ_a, Γ_b) and the Maxwell-Boltzmann factor approx. constant over the resonance width Γ

$$\langle \sigma v \rangle = \frac{\sqrt{2\pi}\hbar^2}{(m_{01}kT)^{3/2}}\,\omega \frac{\Gamma_a \Gamma_b}{\Gamma} 2 e^{-\frac{E_r}{kT}} \int_0^\infty \frac{\frac{\Gamma}{2}}{(E_r - E)^2 + \frac{\Gamma^2}{4}} dE$$

$$\langle \sigma v \rangle = \left(\frac{2\pi}{m_{01}kT}\right)^{3/2} \hbar^2 e^{-\frac{E_r}{kT}}\, \underbrace{\omega \frac{\Gamma_a \Gamma_b}{\Gamma}}$$

- Resonance strength: $$\omega\gamma = \omega \frac{\Gamma_a \Gamma_b}{\Gamma}$$

Experimental determination of $\omega\gamma$

- In nuclear physics experiments the measured quantity is often the **yield:**

$$Y = \frac{\text{total number of reactions}}{\text{total number of incident particles}} = \frac{N_R}{N_b}$$

- Yield and cross section $\quad Y = \sum_i \sigma_i n_i \Delta x_i$

$$Y = \int_{\text{target}} \sigma(x) n(x)\, dx = \int_{\text{target}} \sigma(x) n(x) \frac{dE}{dx} \frac{dx}{dE}$$

$$Y = \int_{E_p - \Delta E}^{E_p} \frac{\sigma(E)}{\varepsilon(E)} dE$$

Stopping power:

$$\varepsilon(E) = -\frac{1}{n_t} \frac{dE}{dx} \qquad n_t = \frac{N_t}{V}$$

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- Assuming Breit-Wigner cross section the integral can be solved analytically

$$Y = \frac{\lambda_r^2}{2\pi}\frac{1}{\varepsilon_r}\omega\gamma\left[\arctan\left(\frac{E_p - E_r}{\Gamma/2}\right) - \arctan\left(\frac{E_p - E_r - \Delta E}{\Gamma/2}\right)\right]$$

- The maximum yield is achieved if $E_p = E_r + \frac{\Delta E}{2}$

$$Y_{\max} = \frac{\lambda_r^2}{\pi}\frac{1}{\varepsilon_r}\omega\gamma \arctan\left(\frac{\Delta E}{\Gamma}\right)$$

- For charged particle induced capture reactions - for example: (p,γ)

$$\Gamma_p << \Gamma_\gamma \longrightarrow \Gamma = \Gamma_p + \Gamma_\gamma \approx \Gamma_\gamma \approx \text{ (1 meV - 1 eV)}$$

$$\Delta E \approx \text{ (10 keV)}$$

$$\boxed{Y_{\Delta E \to \infty} = \frac{\lambda_r^2}{2}\frac{1}{\varepsilon_r}\omega\gamma}$$

- “Real” experimental yield calculation

$$Y = \frac{N_R}{N_b} = \frac{N_{peak}}{N_b B \eta_{eff} W(\vartheta)}$$

branching ratio

detector efficiency

angular correction

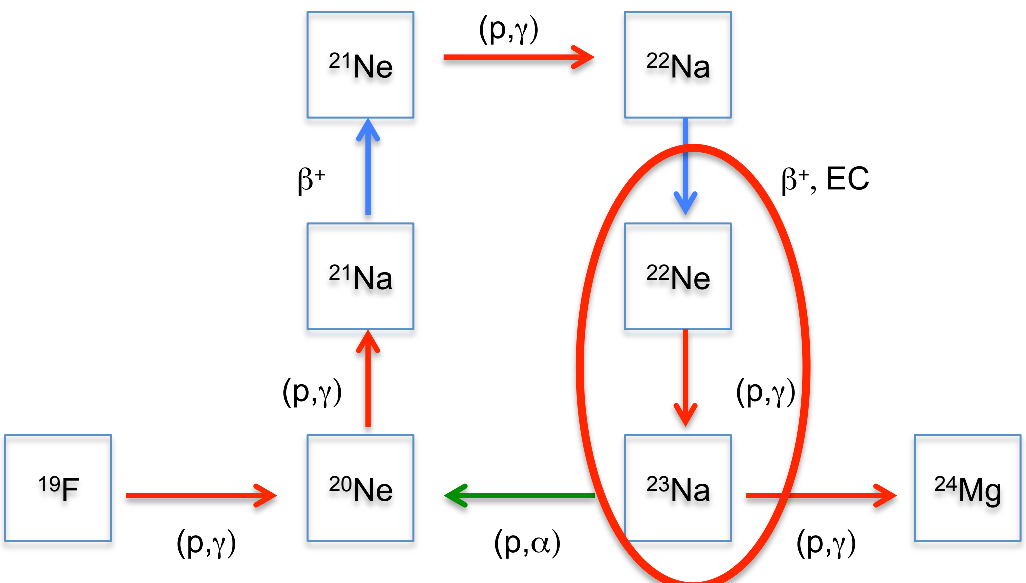
- **Final formula for the experimental resonance strength**

$$\boxed{\omega\gamma = \frac{2}{\lambda_r^2}\varepsilon_r \frac{N_{peak}}{N_b B \eta_{eff} W(\vartheta)}}$$

$^{22}Ne(p,\gamma)^{23}Na$

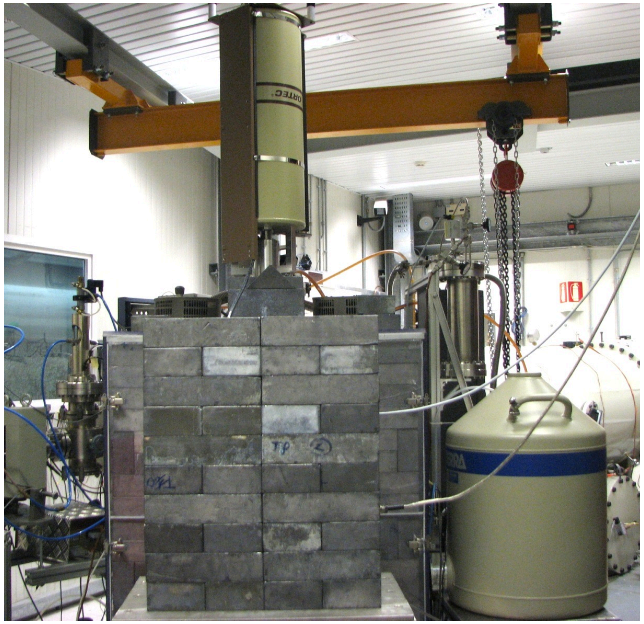
- Importance
  - Second to the slowest reaction in the Ne-Na cycle of hydrogen burning
  - Strong effect on the abundances of ^{22}Ne and ^{23}Na
  - ^{22}Ne is important for neutron-capture driven nucleosynthesis: $^{22}Ne(\alpha,n)^{25}Mg$
  - Large uncertainties regarding its reaction rate

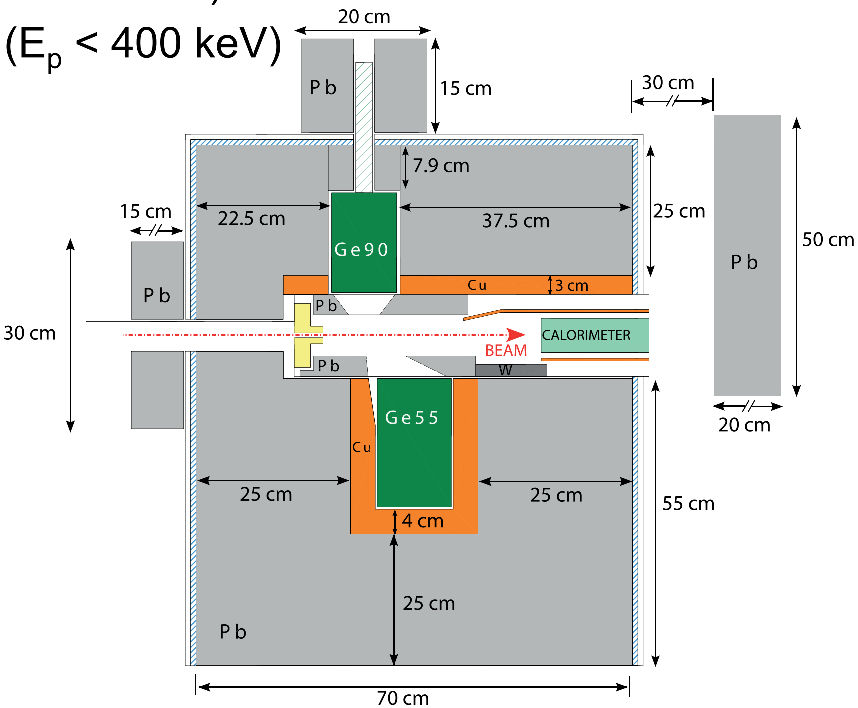
- Astrophysical sites
  - AGB stars
  - Novae
  - Supernovae



Experiment at LUNA

- **Differentially pumped gas target system**
  - Windowless system
  - 3 pumping stages
  - Gas recirculation with purifier
- **HPGe-based first phase**
  - 2 ultra low background (ULB) detectors
  - Placement: 55° (137% rel. eff.) and 90° (90% rel. eff.)
  - Study of selected low energy resonances (E_p < 400 keV)
  - Limit uncertainty by angular distribution





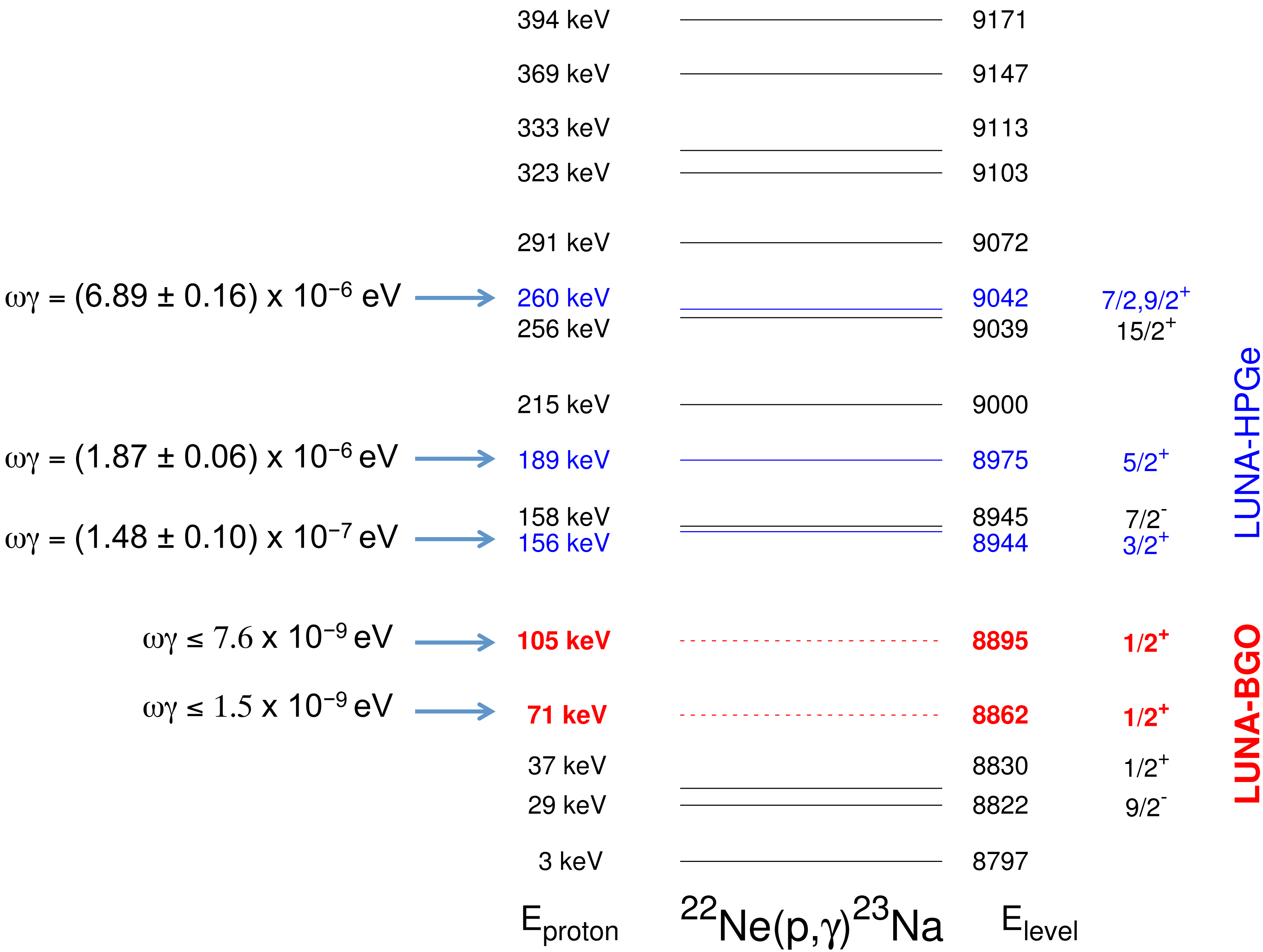
F. Cavanna et al., PRL 115, 252501, 2015

ωγ	E_{proton}	E_{level}	J^π
	394 keV	9171	
	369 keV	9147	
	333 keV	9113	
	323 keV	9103	
	291 keV	9072	
$\omega\gamma = (6.89 \pm 0.16) \times 10^{-6}$ eV →	260 keV	9042	$7/2, 9/2^+$
	256 keV	9039	$15/2^+$
	215 keV	9000	
$\omega\gamma = (1.87 \pm 0.06) \times 10^{-6}$ eV →	189 keV	8975	$5/2^+$
	158 keV	8945	$7/2^-$
$\omega\gamma = (1.48 \pm 0.10) \times 10^{-7}$ eV →	156 keV	8944	$3/2^+$
$\omega\gamma \leq 7.6 \times 10^{-9}$ eV →	**105 keV**	**8895**	$\mathbf{1/2^+}$
$\omega\gamma \leq 1.5 \times 10^{-9}$ eV →	**71 keV**	**8862**	$\mathbf{1/2^+}$
	37 keV	8830	$1/2^+$
	29 keV	8822	$9/2^-$
	3 keV	8797	

E_{proton} $^{22}Ne(p,\gamma)^{23}Na$ E_{level}

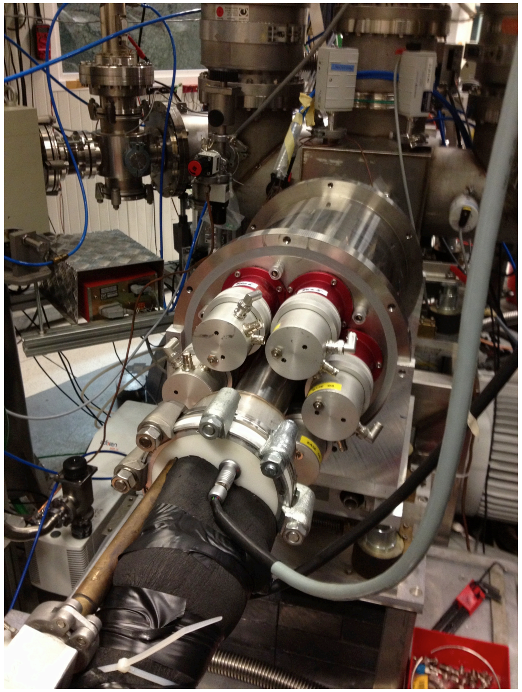
LUNA-HPGe

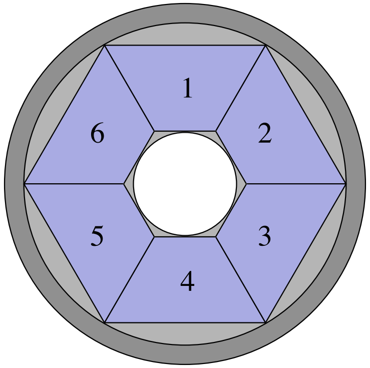
F. Cavanna et al., PRL 115, 252501, 2015

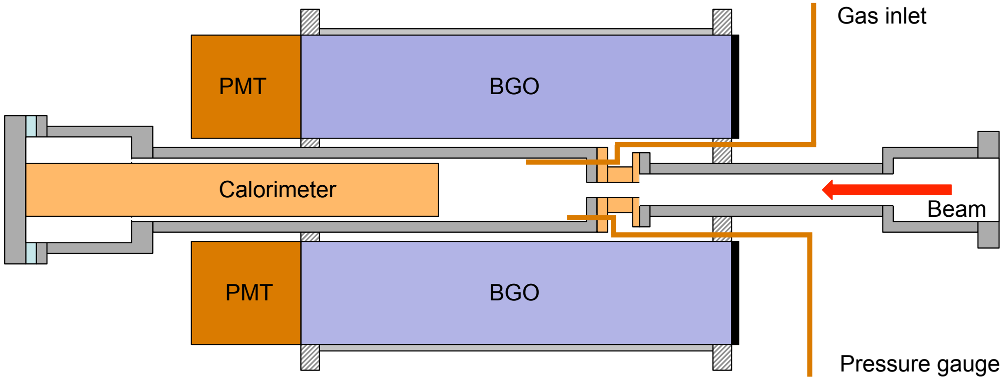


Experiment at LUNA

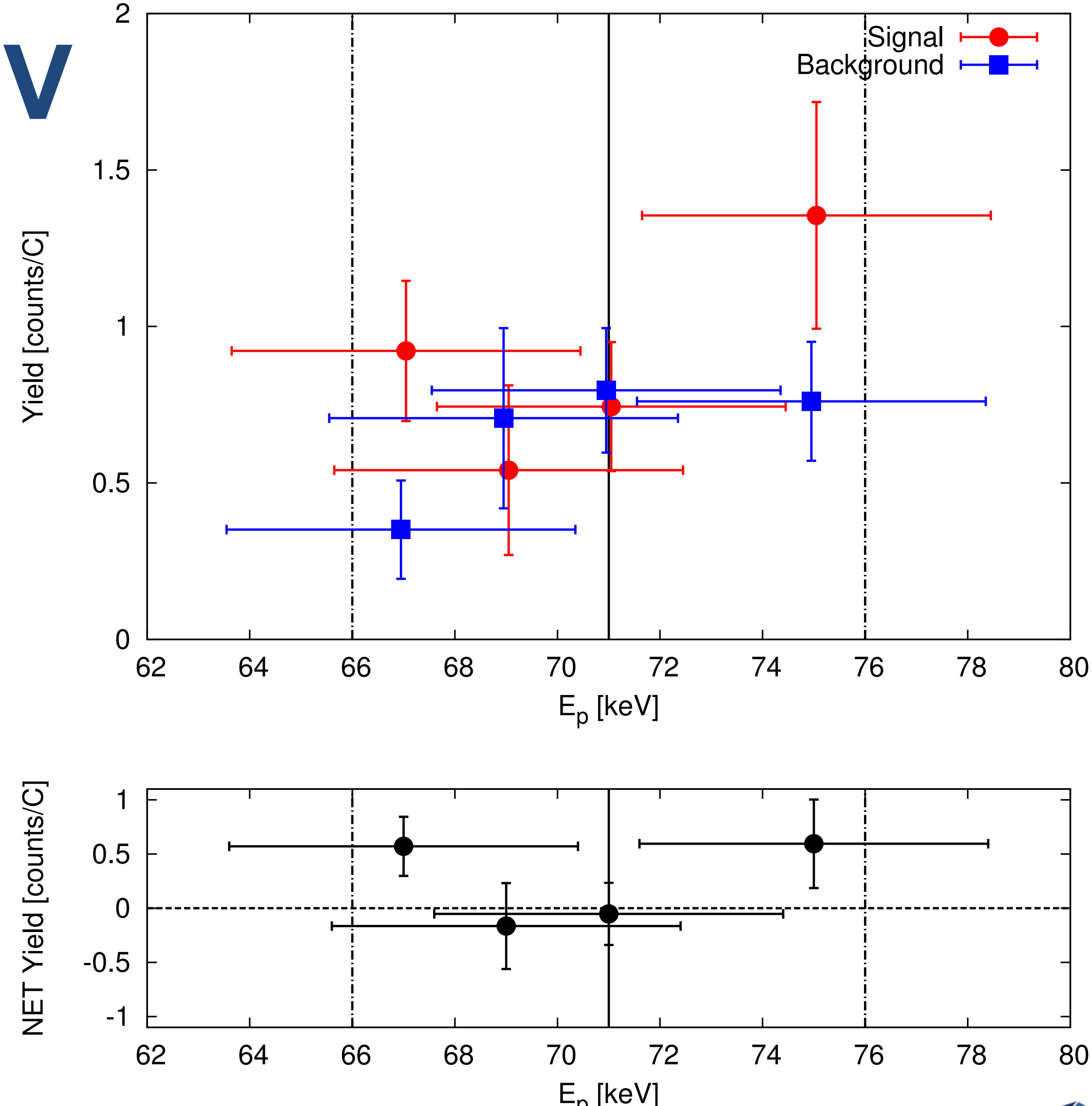
- **BGO-based second phase**
  - 4π bismuth germanate summing crystal
  - 6 sectors with separate PMTs
  - Positioned around the gas target chamber
  - Lowest energy resonances (E_p < 200 keV)
  - Study of direct capture reaction







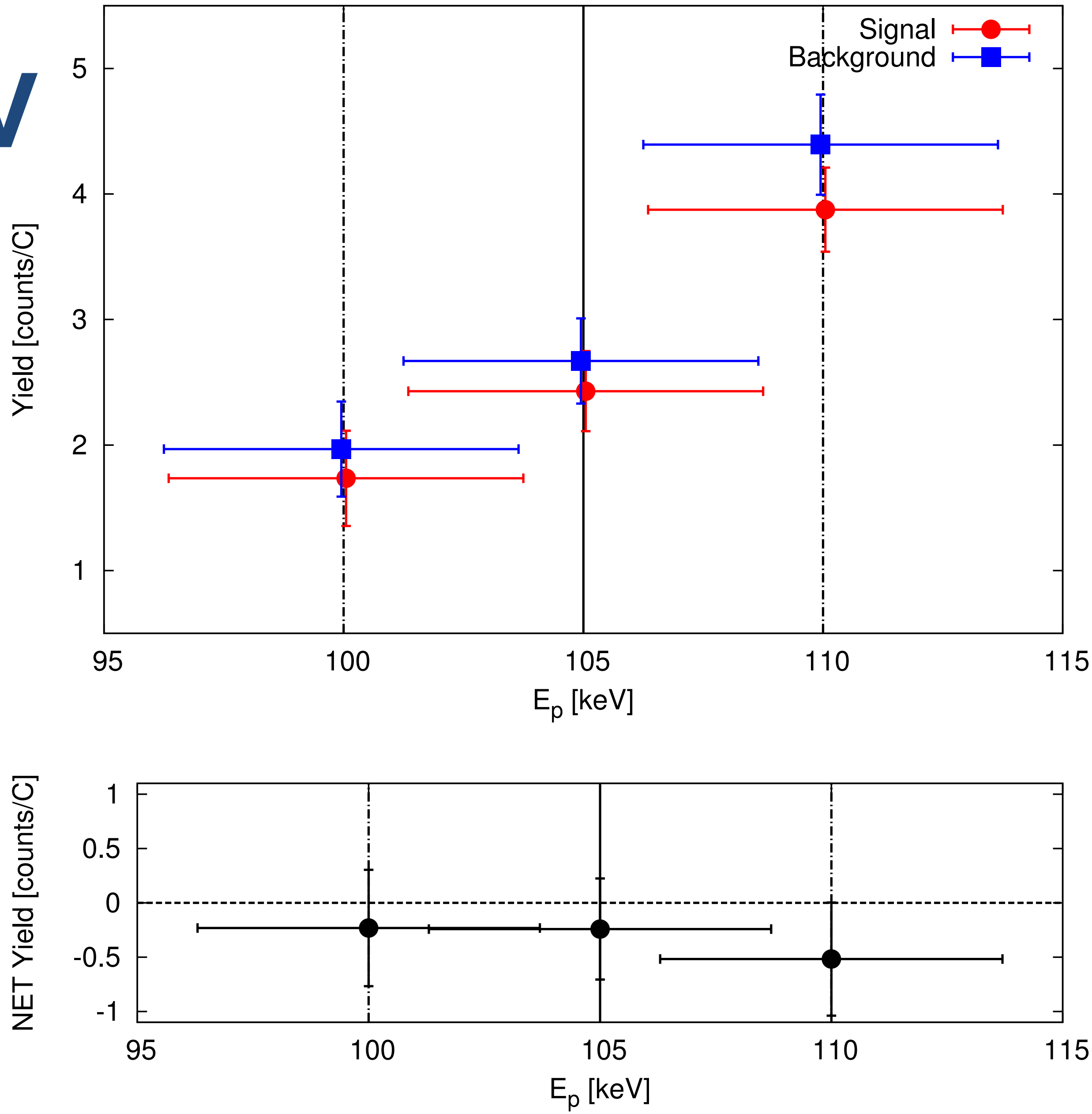
71 keV



Preliminary

(quoted errors are statistical only)

105 keV



Preliminary

(quoted errors are statistical only)

Results – Resonant capture

E_p [keV]	Upper limit LUNA-BGO $\omega\gamma$ [eV]	Upper limit LUNA-HPGe $\omega\gamma$ [eV]
67	$\leq 5.4 \times 10^{-11}$	$\leq 1.5 \times 10^{-9}$
69	$\leq 3.1 \times 10^{-11}$	
71	$\leq 2.5 \times 10^{-11}$	
75	$\leq 8.1 \times 10^{-11}$	
100	$\leq 6.0 \times 10^{-11}$	$\leq 7.6 \times 10^{-9}$
105	$\leq 4.9 \times 10^{-11}$	
110	$\leq 4.1 \times 10^{-11}$	

Preliminary

(F. Cavanna et al., PRL 115, 252501, 2015)

Numbers based on unbound / bound profile likelihood method (90% CL)
W. Rolke et al., NIM A 551 (2005) 493

Creed of LUNA

1. Reduce the background!
2. Measure nuclear reaction at (or near) the relevant energies!
3. Use high beam intensity!
4. Have great patience!