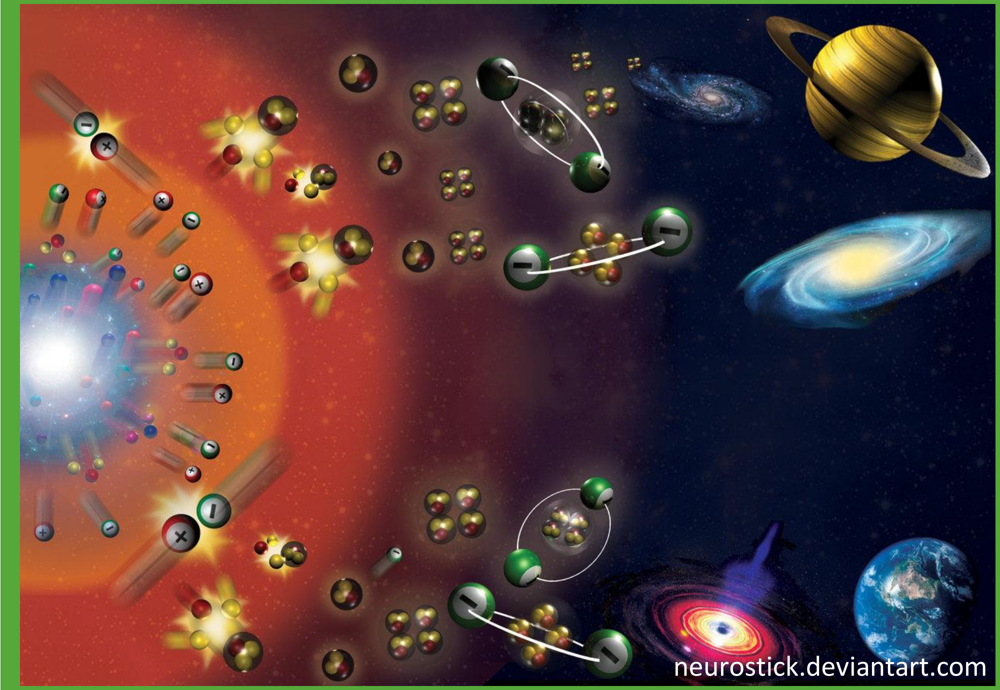
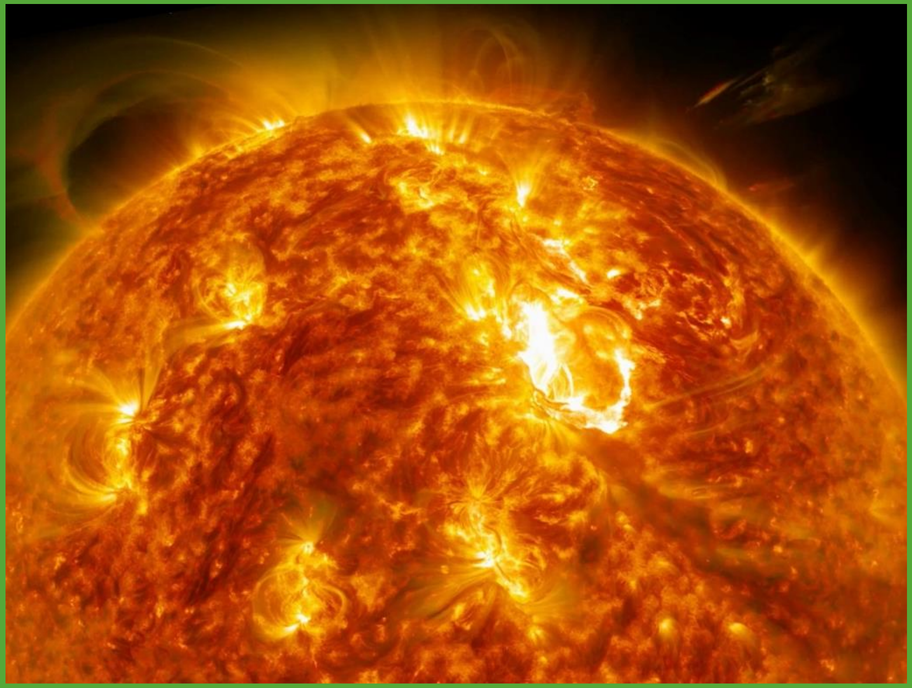
Experimental low energy nuclear astrophysics





Helmholtz International Summer School

"NUCLEAR THEORY AND ASTROPHYSICAL APPLICATIONS"

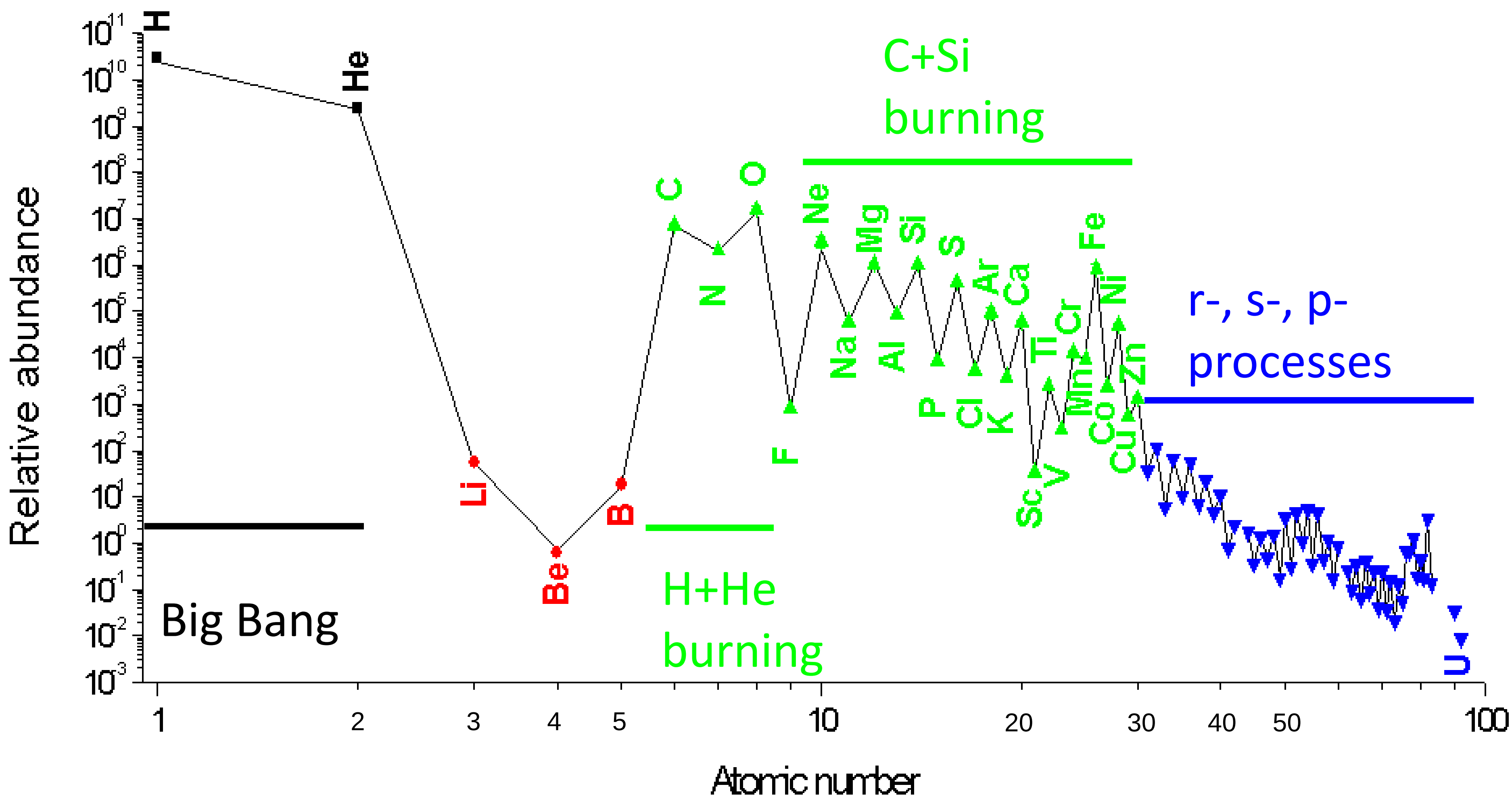
Dubna, Russia, July 10 – 21, 2017

Tamás Szücs

Experimental nuclear astrophysics

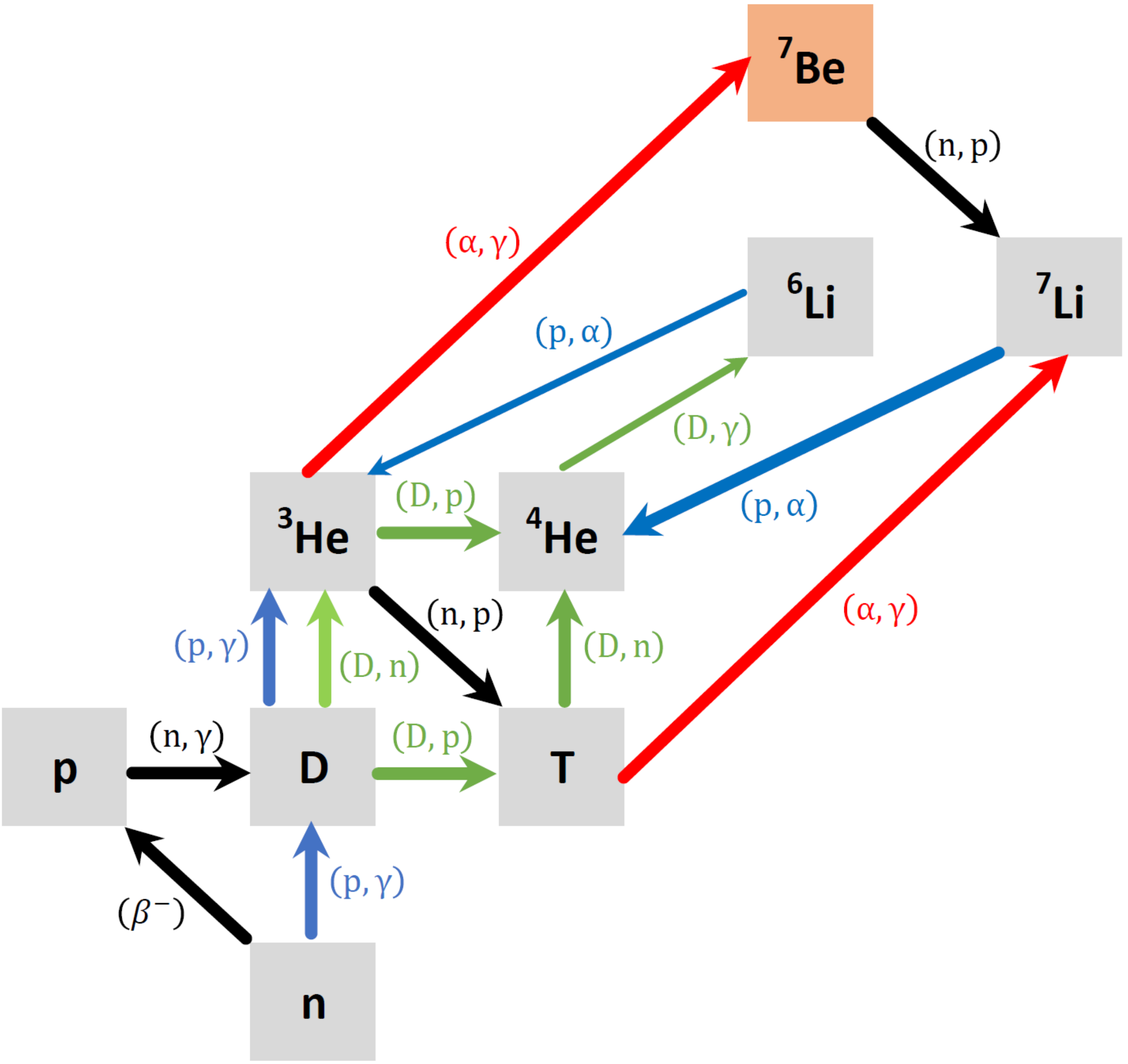
- Nuclear reactions building up the material of our universe
- Charged particle induced reaction
  - Thermal movement
  - Coulomb barrier
  - Typical energy region
  - Extrapolation
- Laboratory background in the detector
  - Sources
  - Reduction techniques
  - Importance of the underground measurements

Origin of the chemical elements



Charged particle induced reactions

Big Bang Nucleoshynthesis



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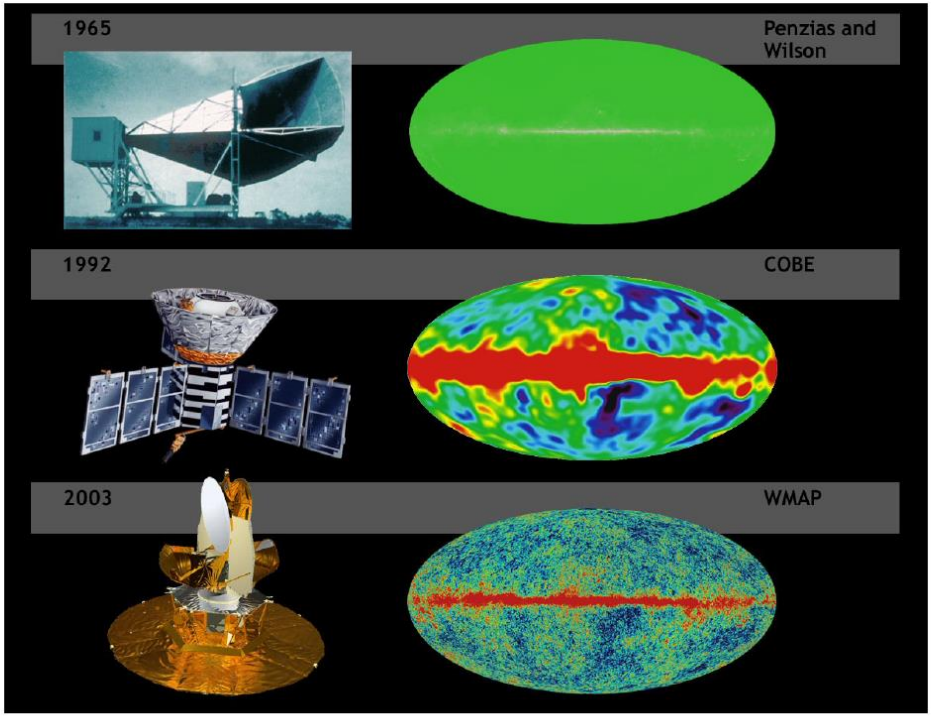
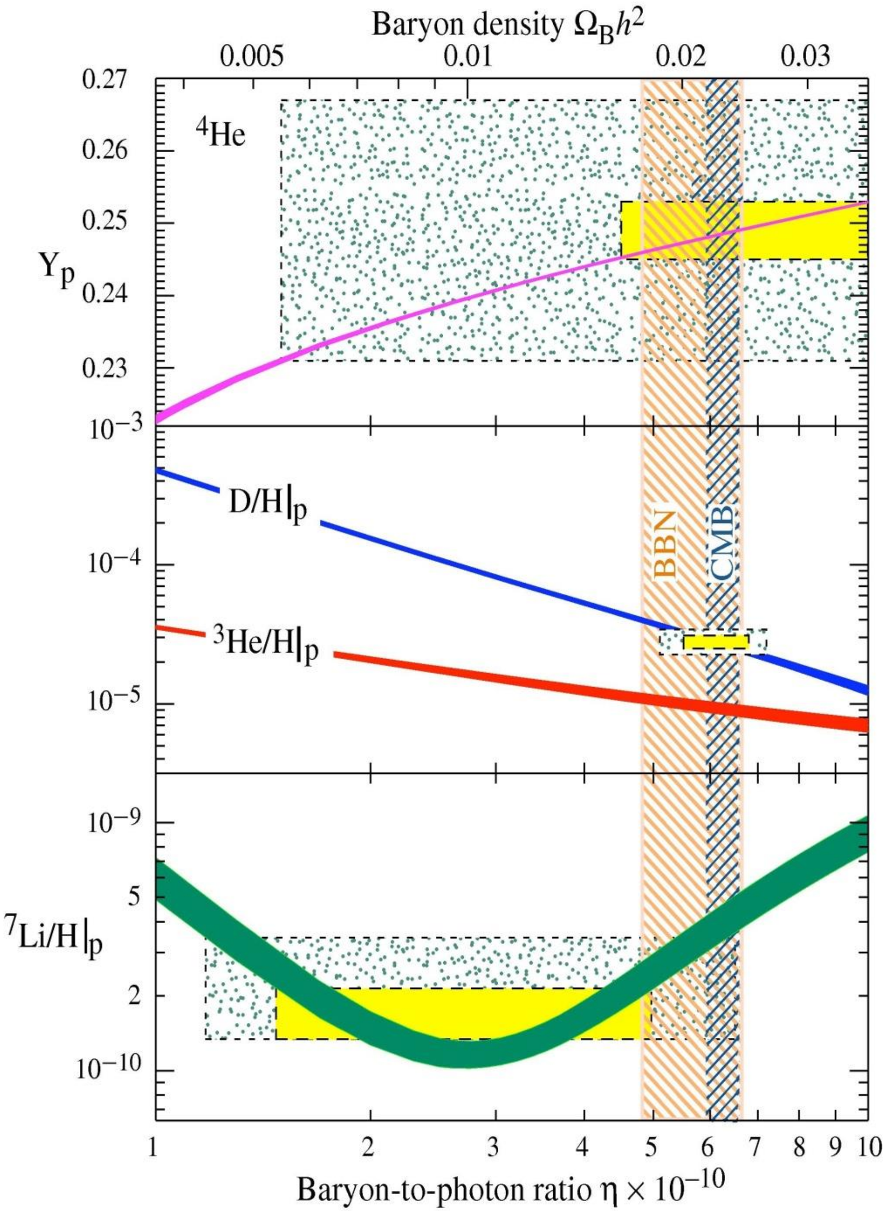
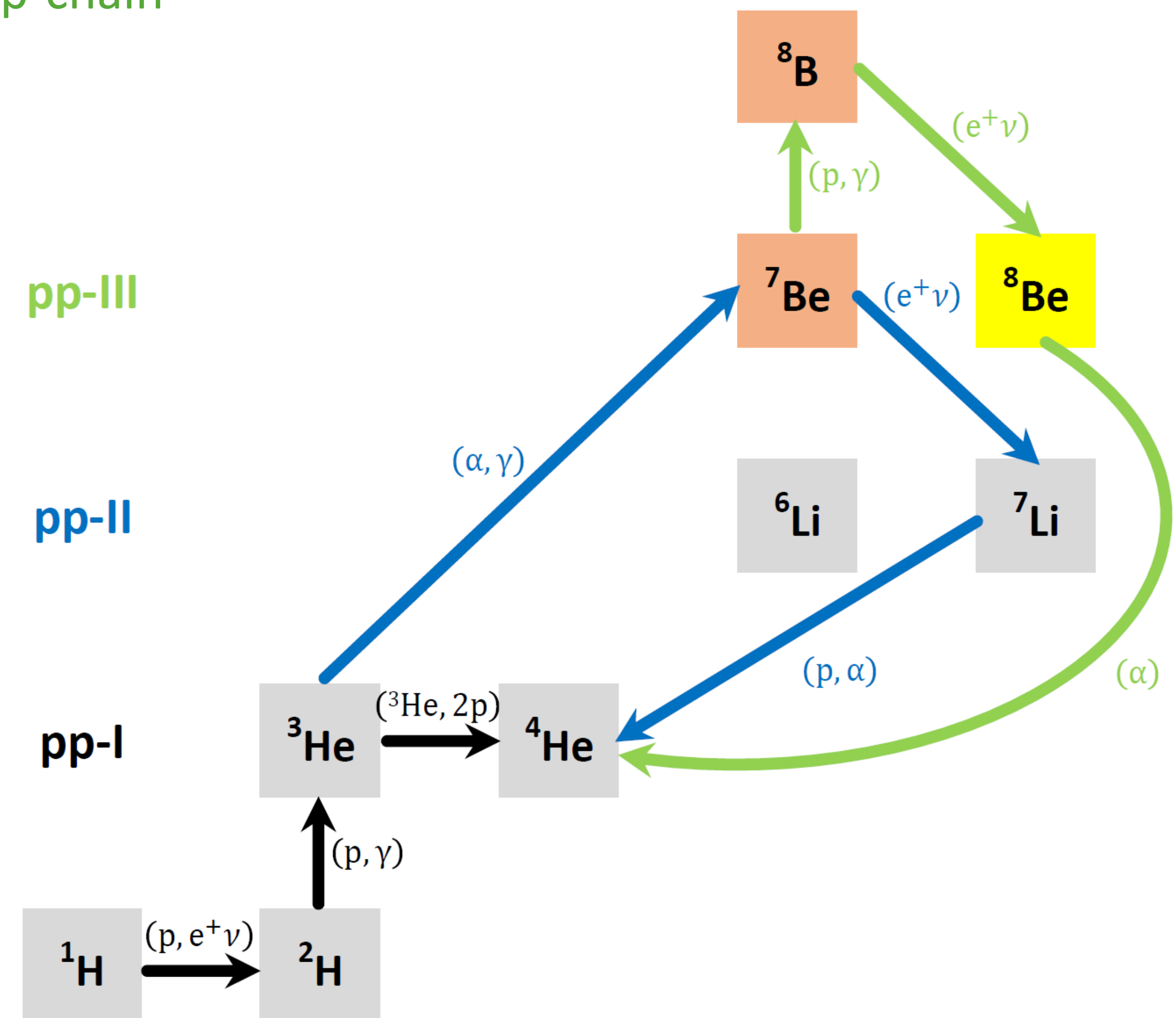
The Li problem

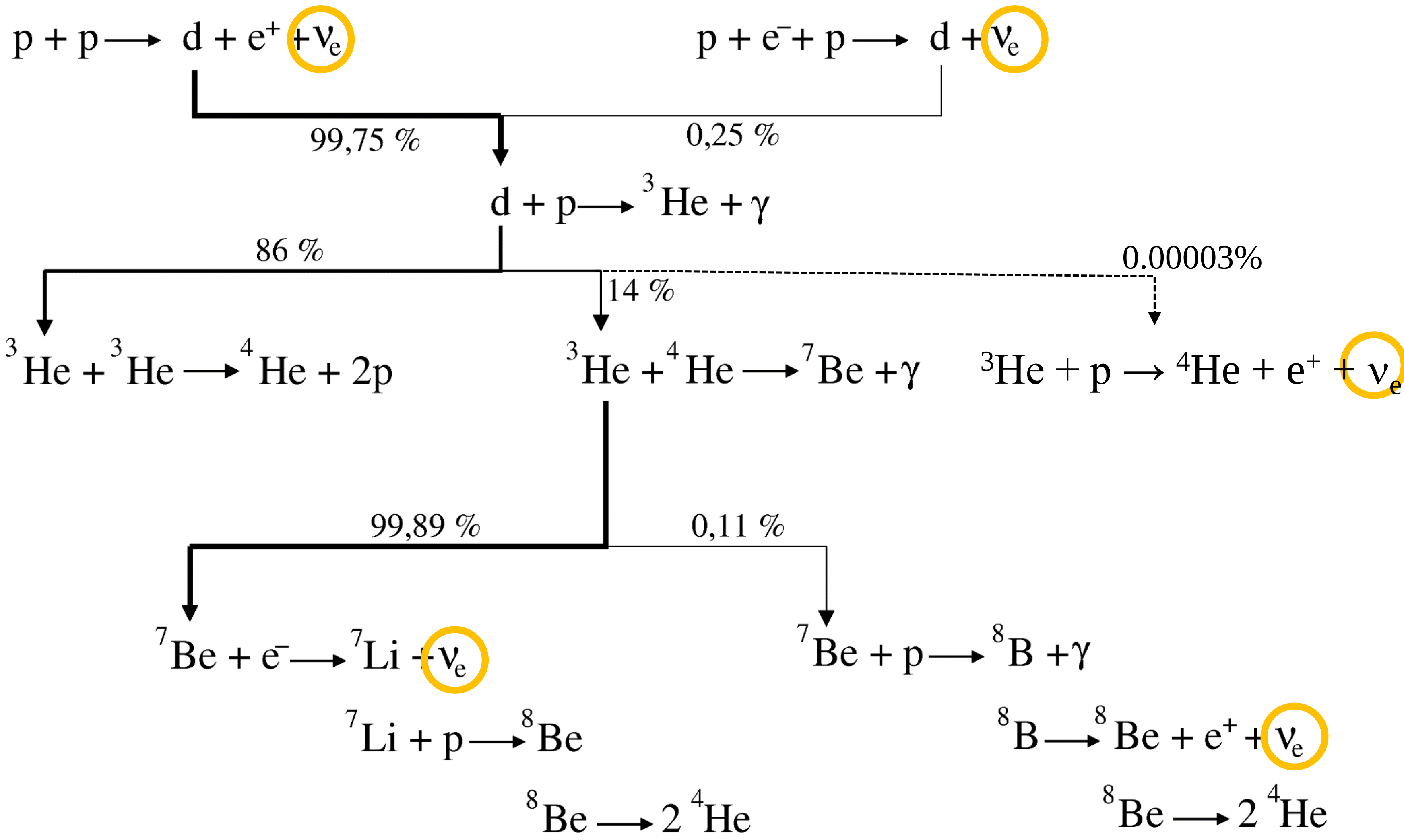




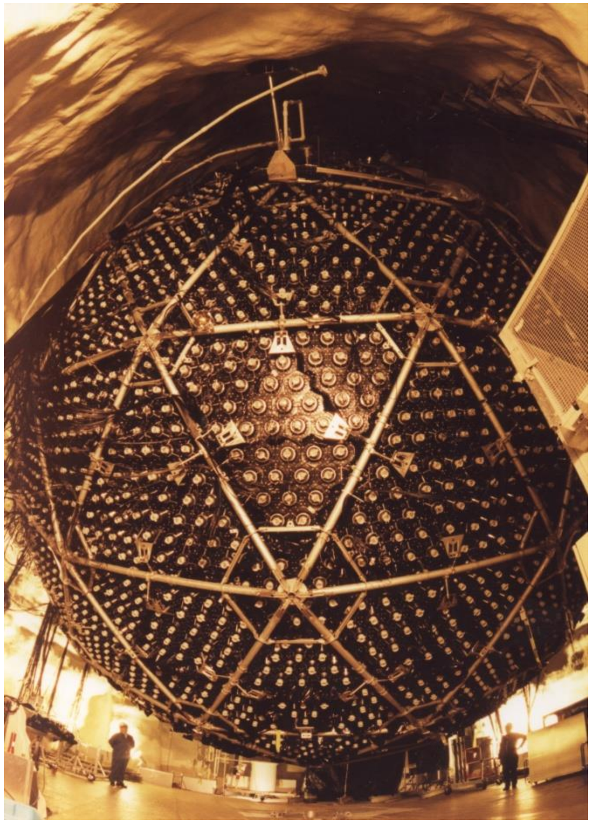
Solar pp-chain

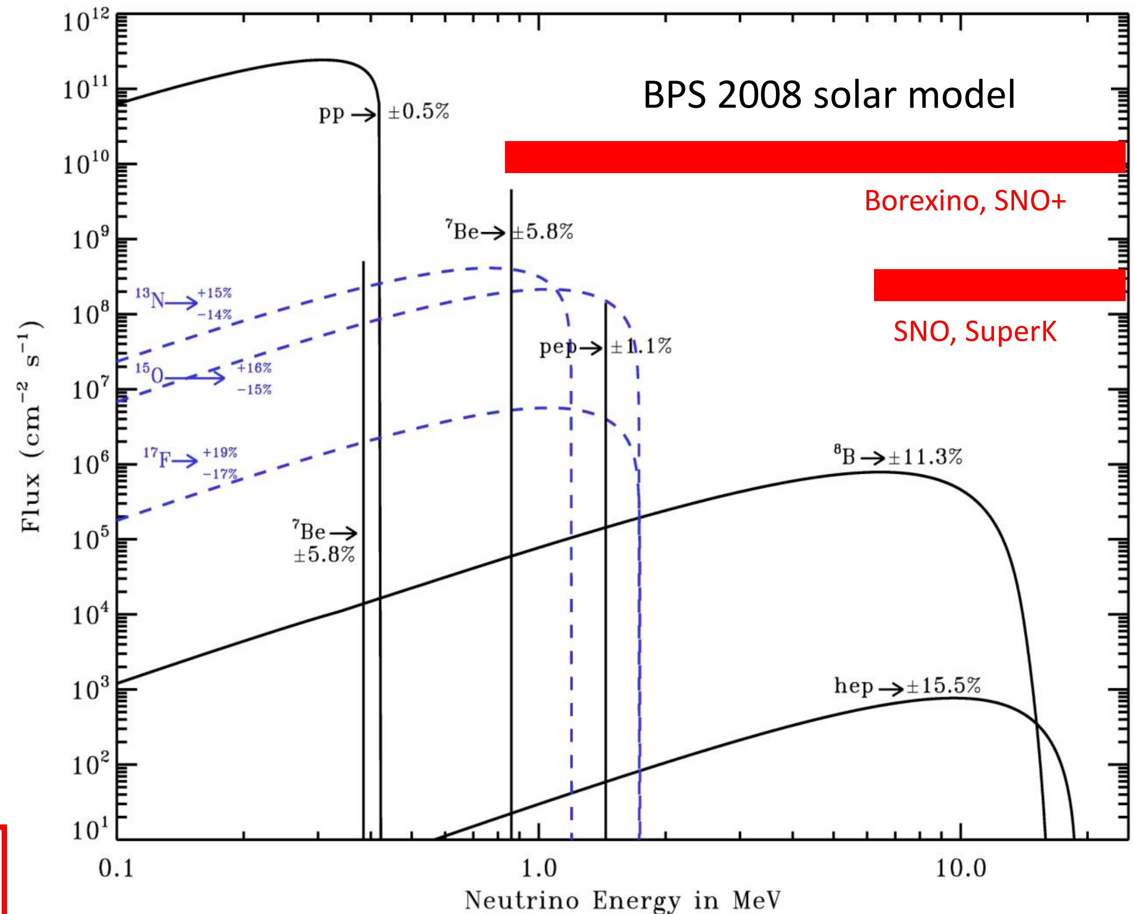


Solar neutrino problem



An age of precision for solar neutrinos from the pp-chain





Nuclear data must match the precision of ν-astronomy:

Water-Cherenkov detectors, assuming large neutrino mixing angle:

2% precision for solar ^{8}B neutrino flux (SNO, SuperK) [B. Aharmim et al., PRC 87, 025501 (2013)]

5% precision for solar ^{7}Be neutrino flux (Borexino) [G. Bellini et al., PRD 89, 112007 (2014)]

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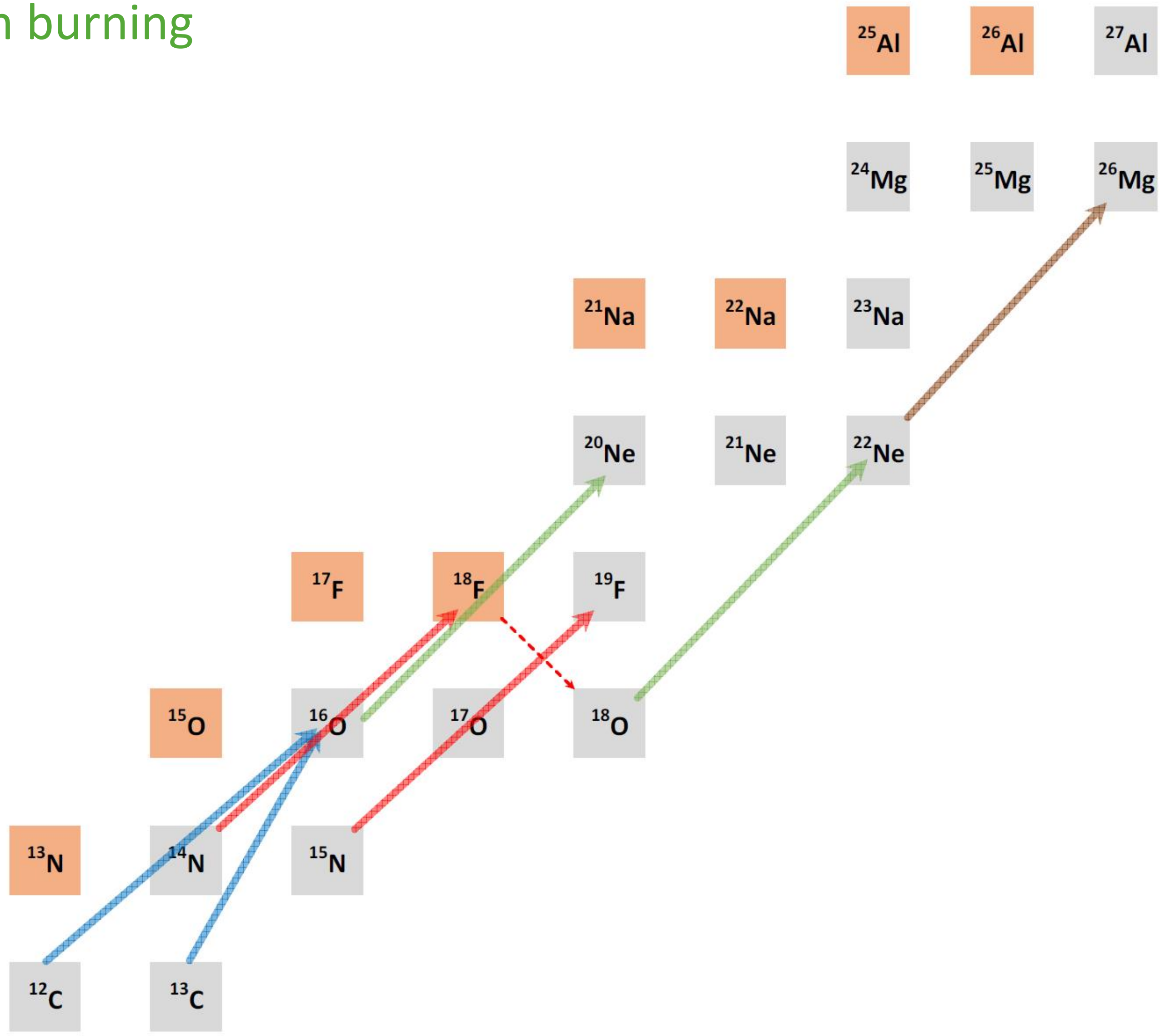
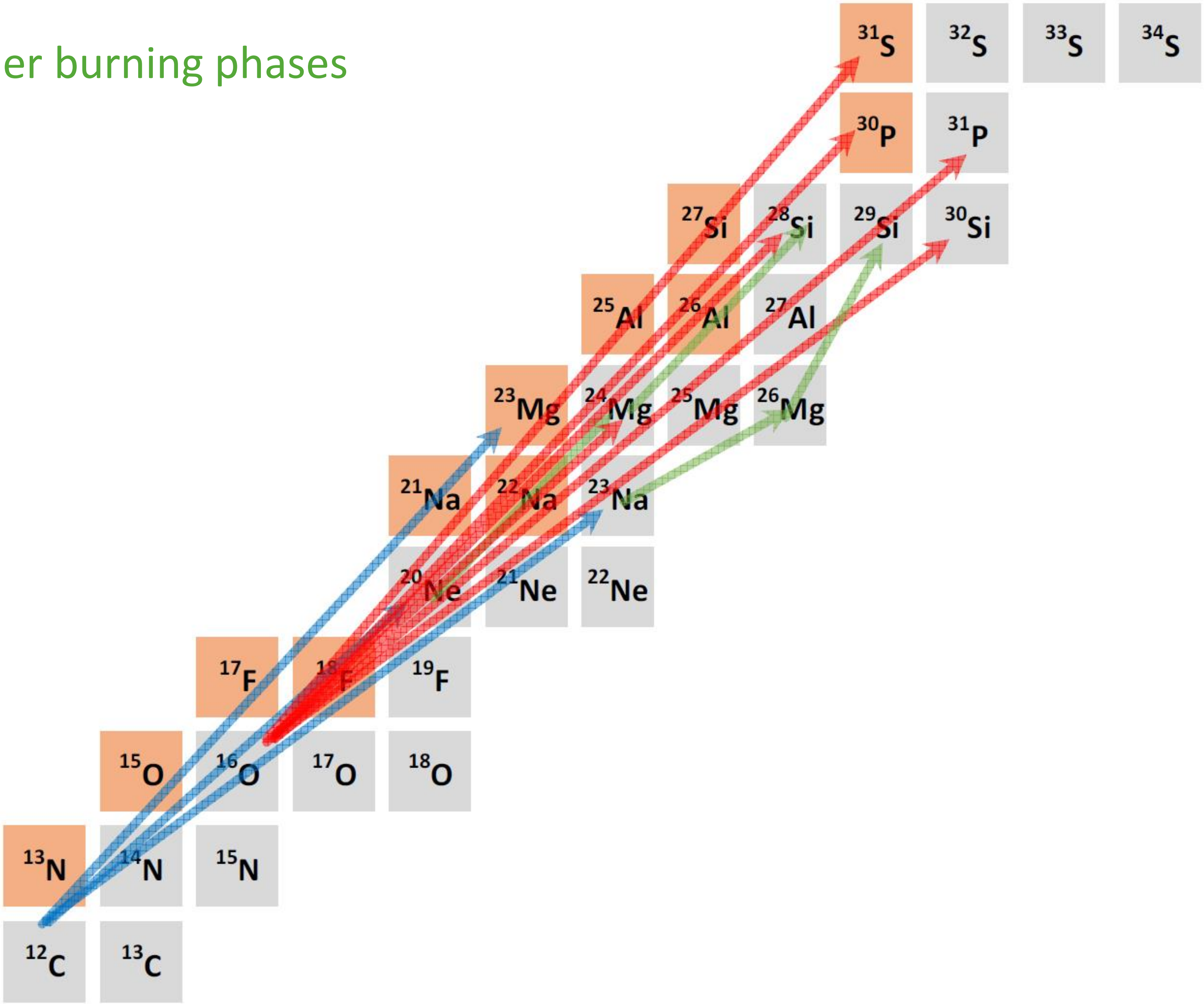
Helium burning



Other burning phases



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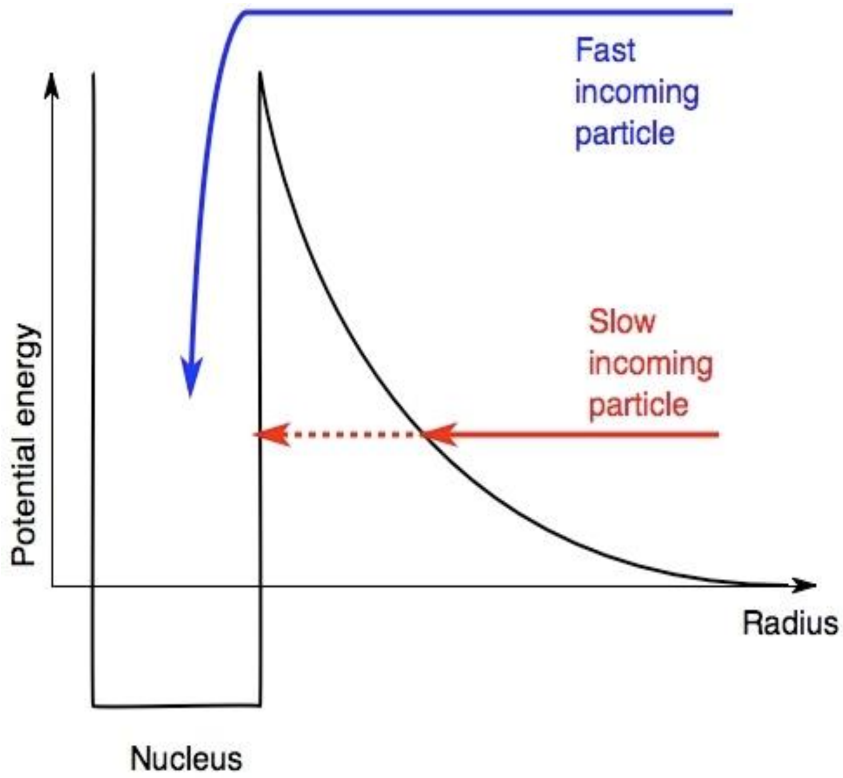
Nuclear reaction cross section (σ) for charged particles



Typical Coulomb barrier height : ~ MeV

Typical temperature k_B * T ~ keV

→The energy dependence of the cross section is dominated by the tunneling probability.

Tunneling probability
(for relative angular momentum l=0):

$$\propto \exp\left[-Z_1 Z_2 \alpha \sqrt{\frac{\mu}{E}}\right]$$

Thermal neutron capture: ~1 barn

Charged-particle capture at astrophysical energies: σ ~ 1 nanobarn!!

→"NANO - ASTROPHYSICS"

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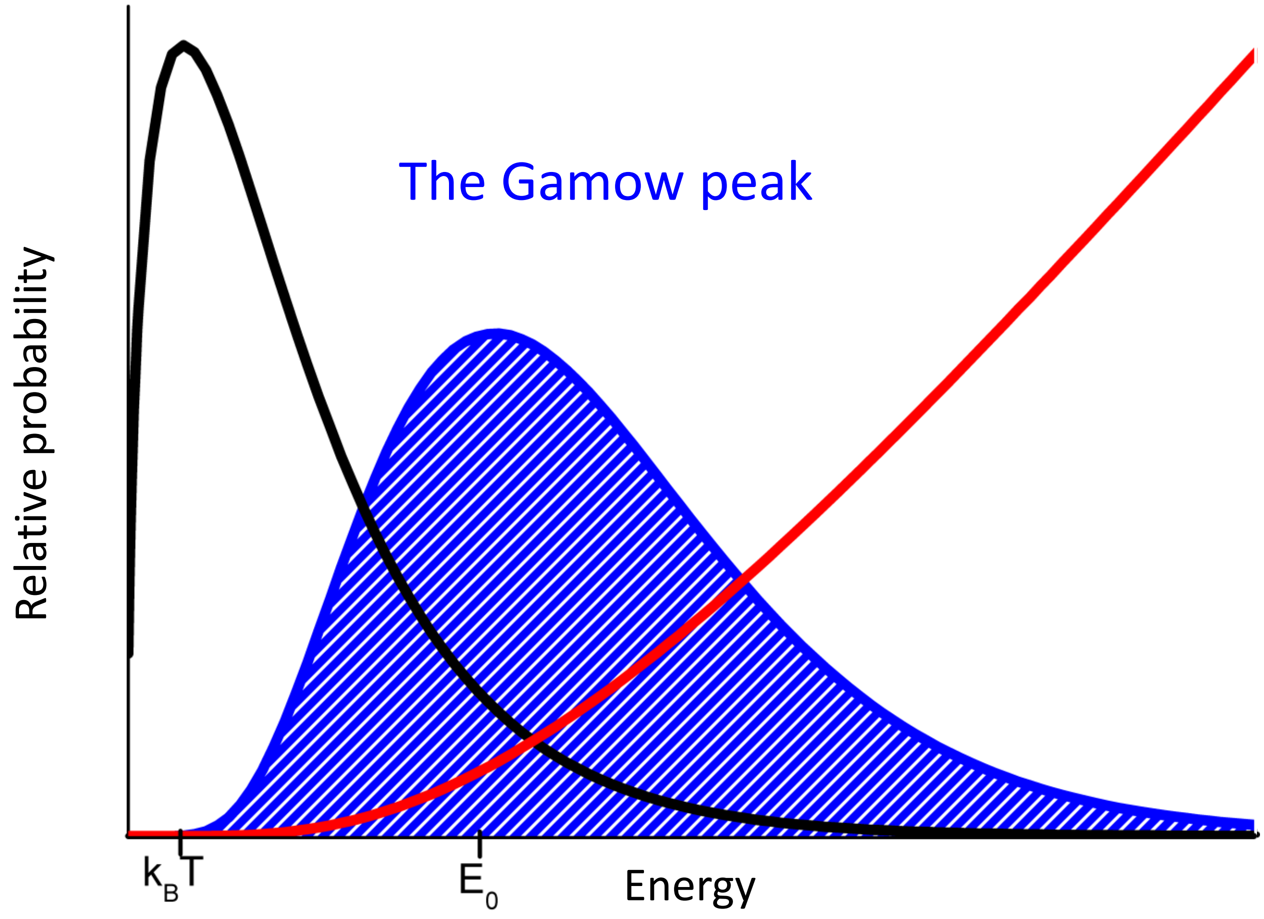
How much is the astrophysically relevant energy?

Maxwell-Boltzmann velocity distribution



Tunneling probability (for zero relative angular momentum):

$$\propto \exp\left[-Z_1 Z_2 \alpha \sqrt{\frac{\mu}{E}}\right]$$

The Gamow peak, some examples

Scenario	**Reaction**	E_G**[keV]**	**σ [barn]**	**Detected events/hour**
Sun (16 MK)	$^{3}He(\alpha,\gamma)^{7}Be$	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)	$^{3}He(\alpha,\gamma)^{7}Be$	160	10^{-9}	10^{-1}
	$^{2}H(\alpha,\gamma)^{6}Li$	96	10^{-11}	10^{-3}

1 barn= 10^{-24} cm^2; assume 10^{16} h^{-1} beam, 10^{18} at/cm^2 target, 10^{-2} detection efficiency

➔Extrapolations seem to be necessary.

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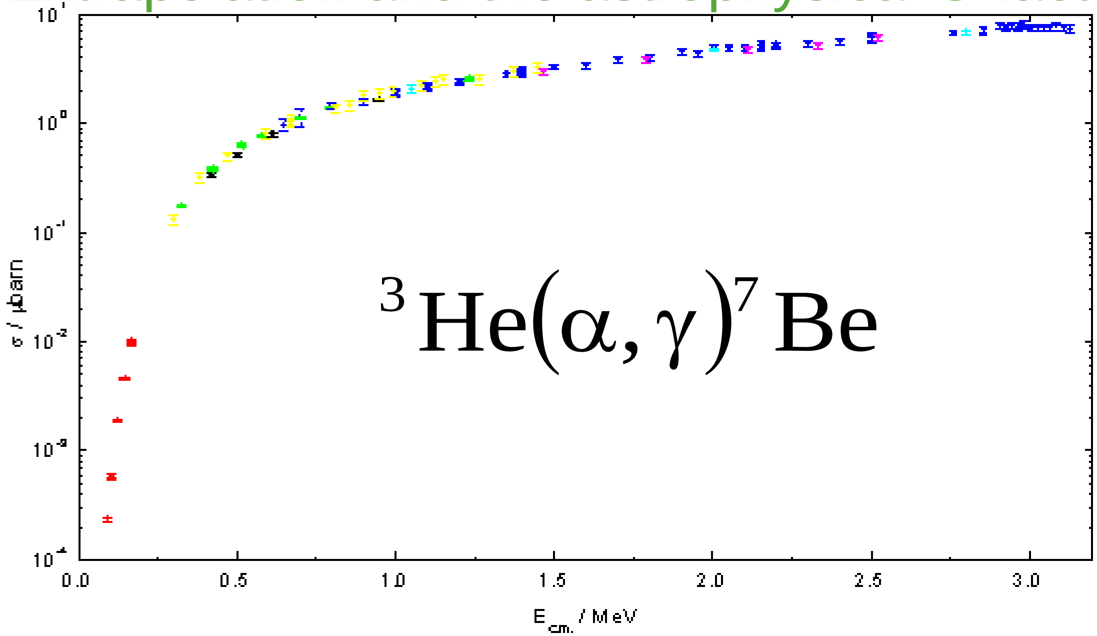
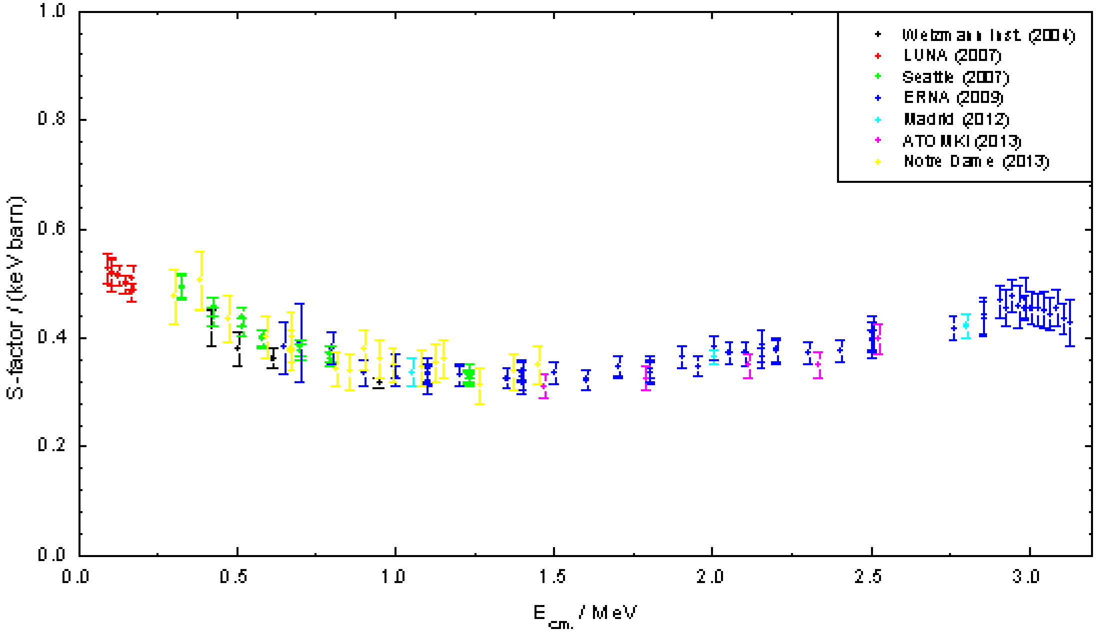
Extrapolation and the astrophysical S-factor





$$\sigma(E) \equiv \frac{1}{E} e^{-2\pi\eta} S(E)$$

Geometrical cross section

s-wave Coulomb Barrier transmission

$$2\pi\eta \equiv Z_1 Z_2 \alpha \sqrt{\frac{\mu}{E}}$$

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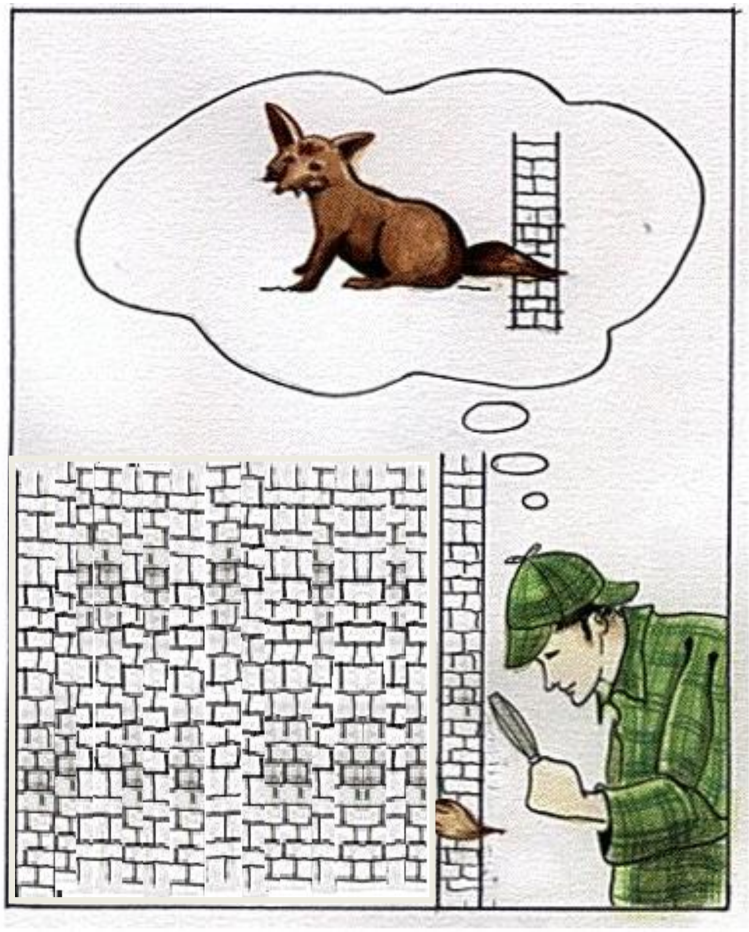
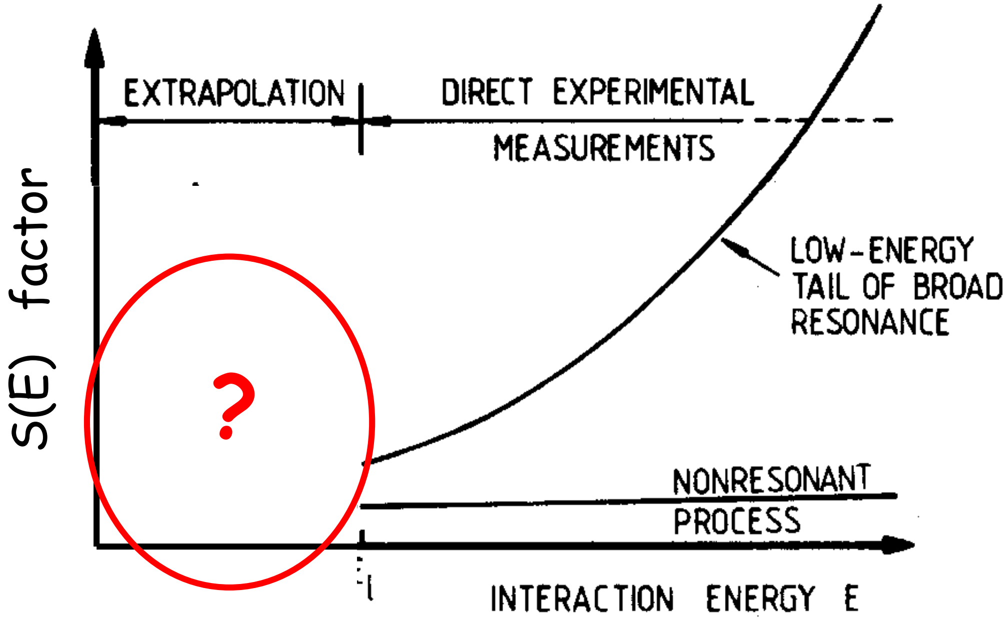
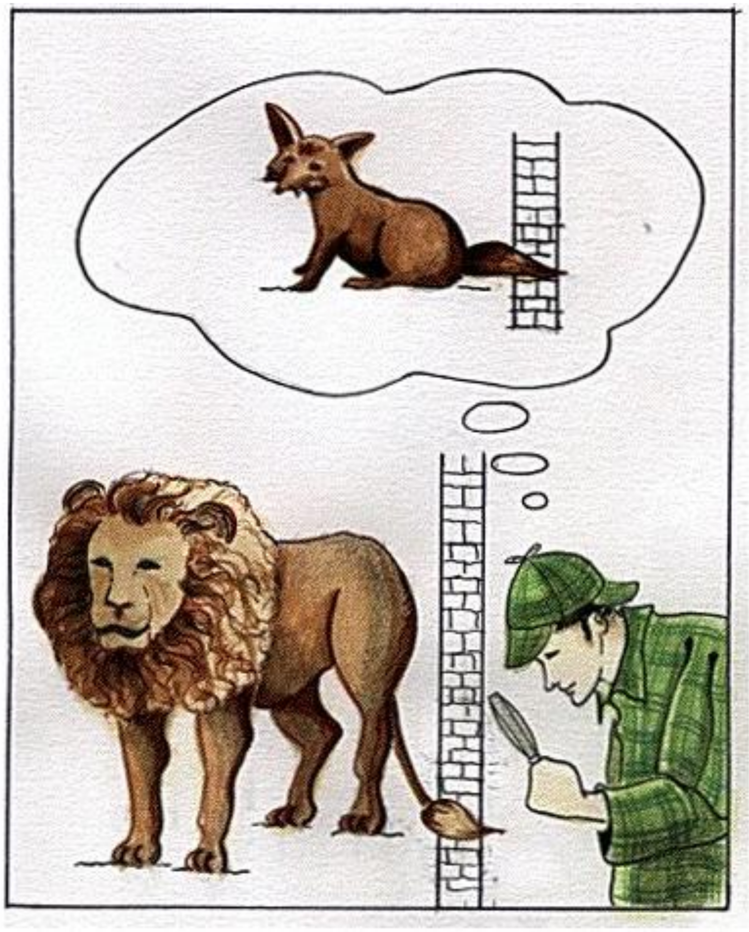
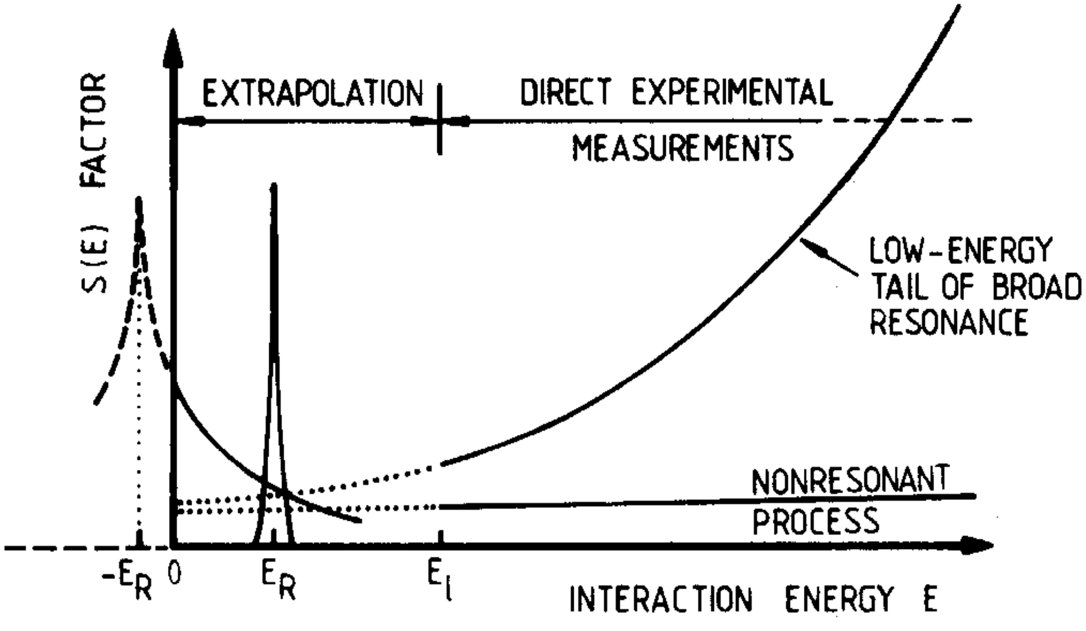
Advantages of extrapolation





And the drawbacks…





It is mandatory to measure as close to the relevant energy region as possible

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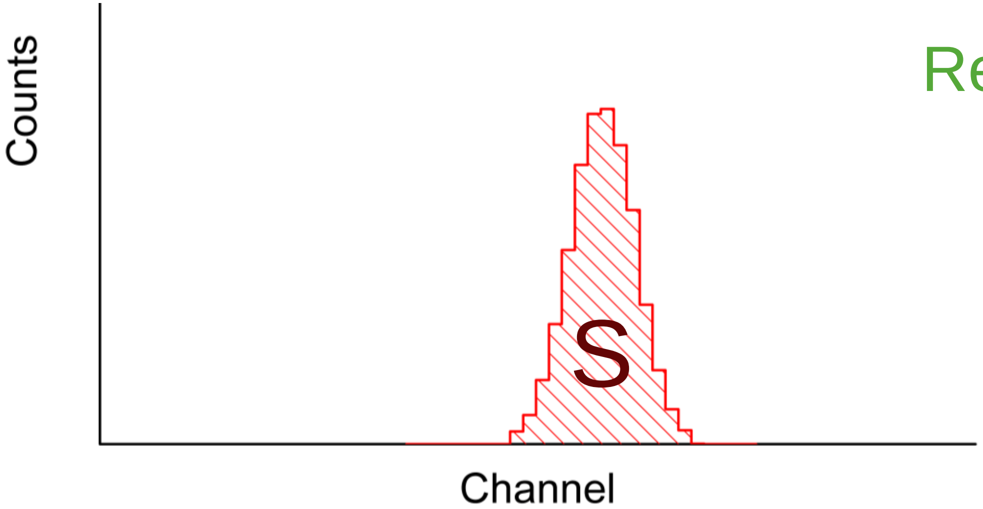
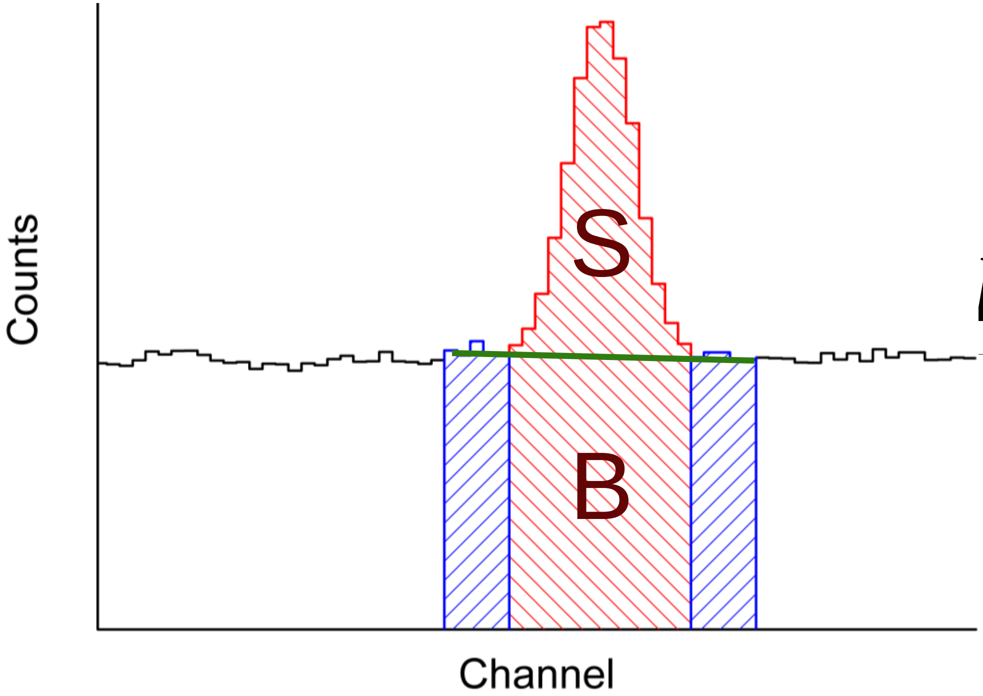
Typical signal



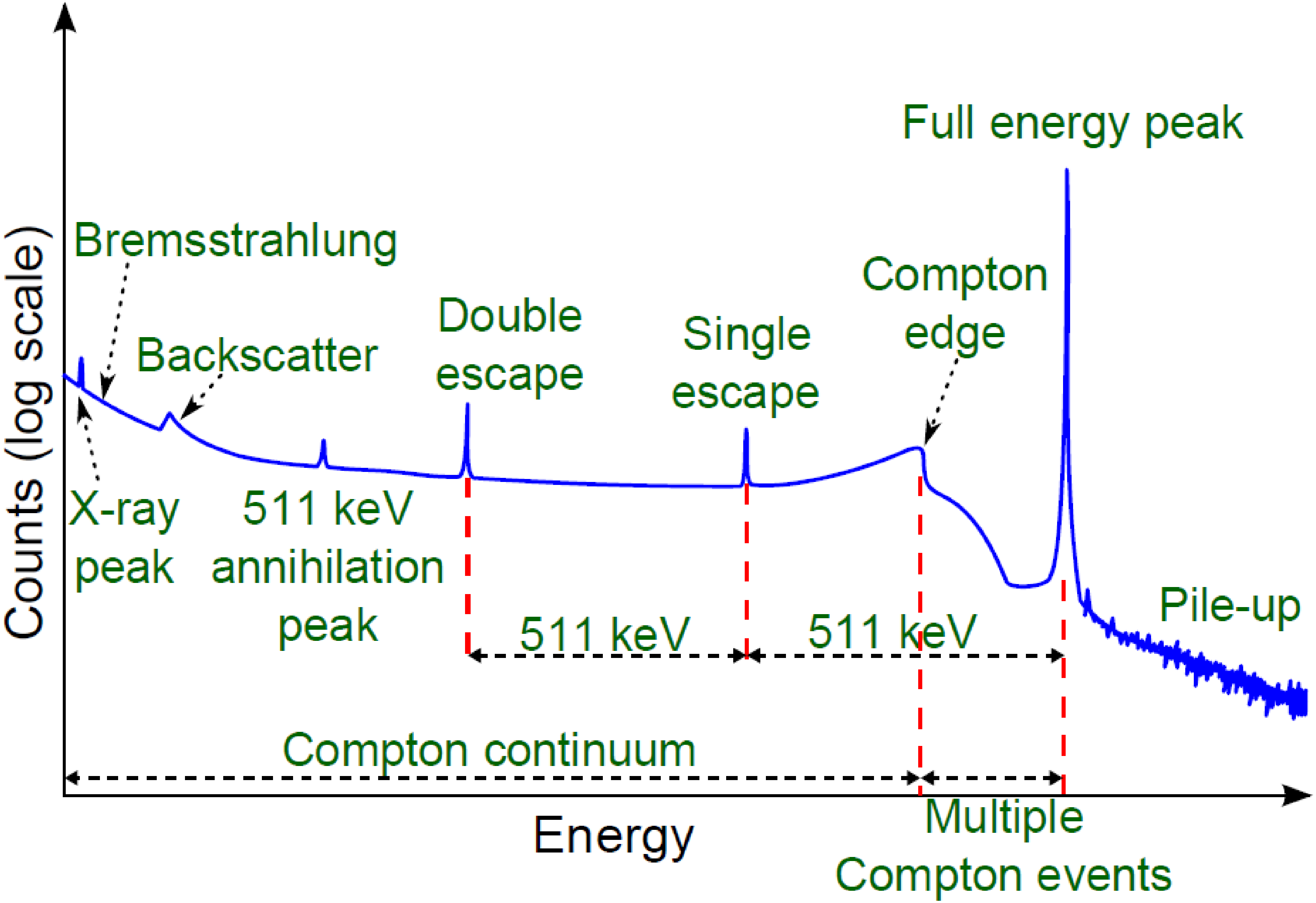
Relative error of the peak area:

$$\frac{k\sqrt{S}}{S} = k\sqrt{\frac{1}{S}}$$

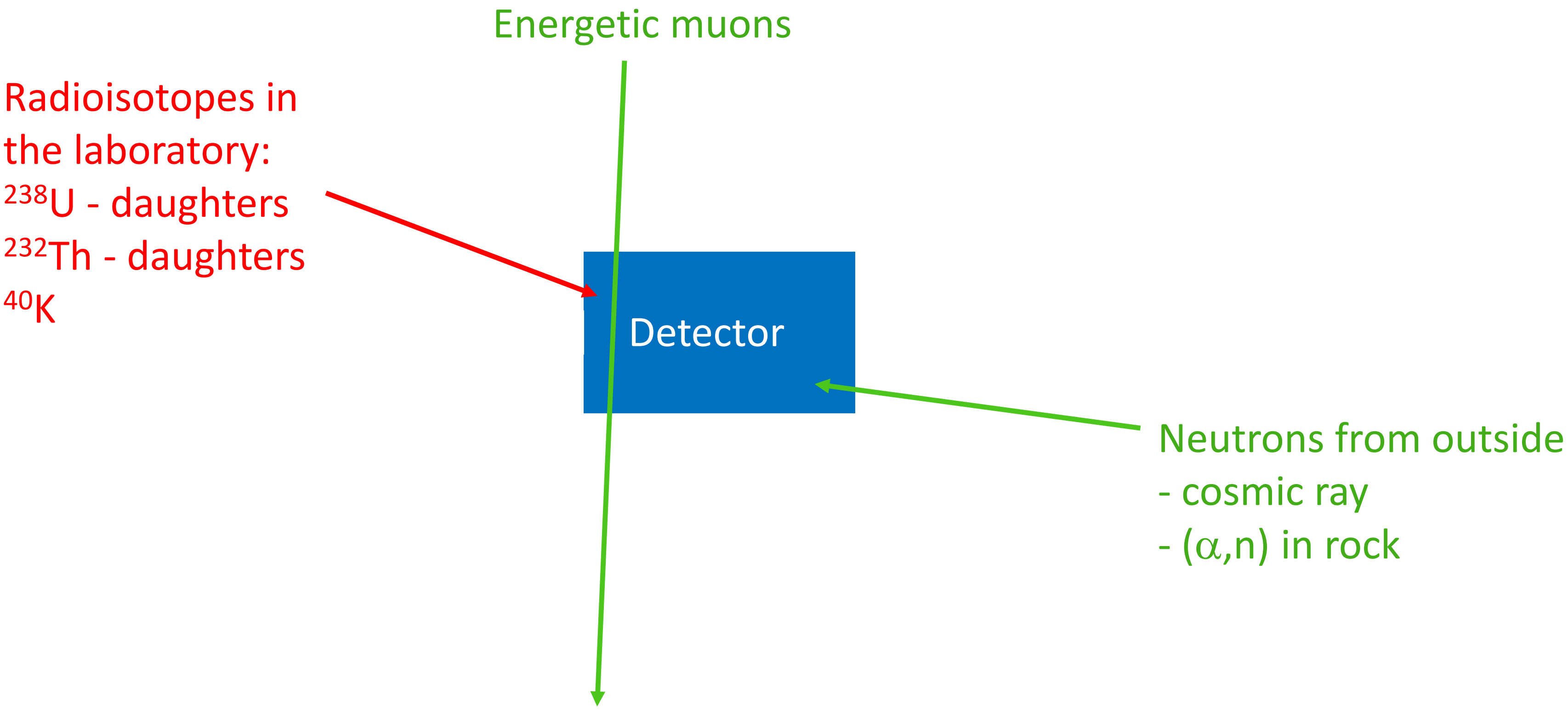


$$\frac{k\sqrt{S+2B}}{S} = k\sqrt{\frac{1}{S} + \frac{2B}{S^2}}$$

HPGe detector response for monoenergetic gamma-rays



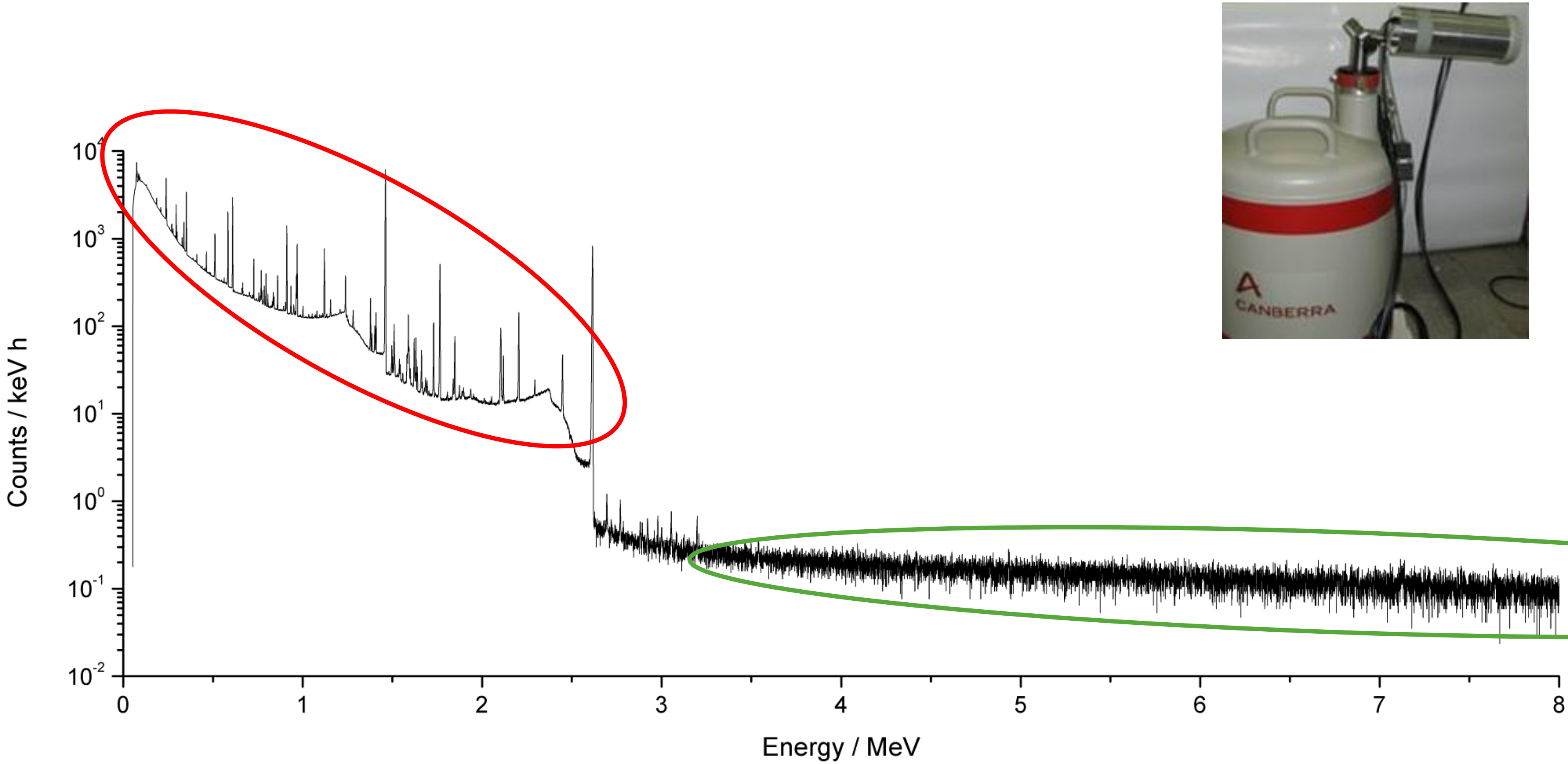
What contributes to the laboratory background?



Red: $E_\gamma < 3$ MeV

Green: $E_\gamma < 3$ MeV and $E_\gamma > 3$ MeV

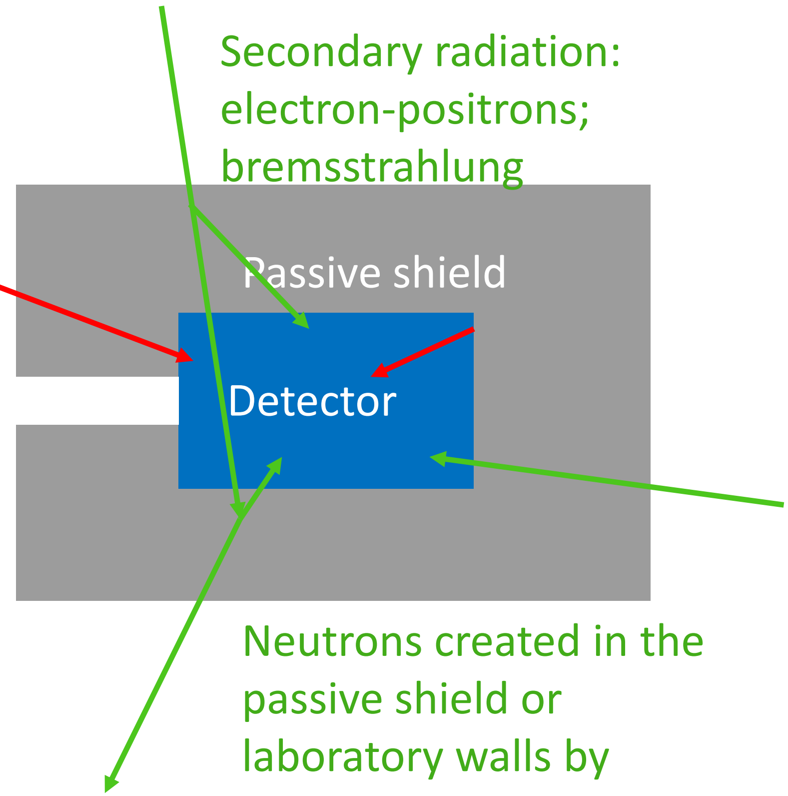
Laboratory background at the Earth's surface



Natural radioisotopes

Cosmic-rays, mainly muons

What contributes to the laboratory background?



Red: $E_\gamma < 3$ MeV

Green: $E_\gamma < 3$ MeV and $E_\gamma > 3$ MeV

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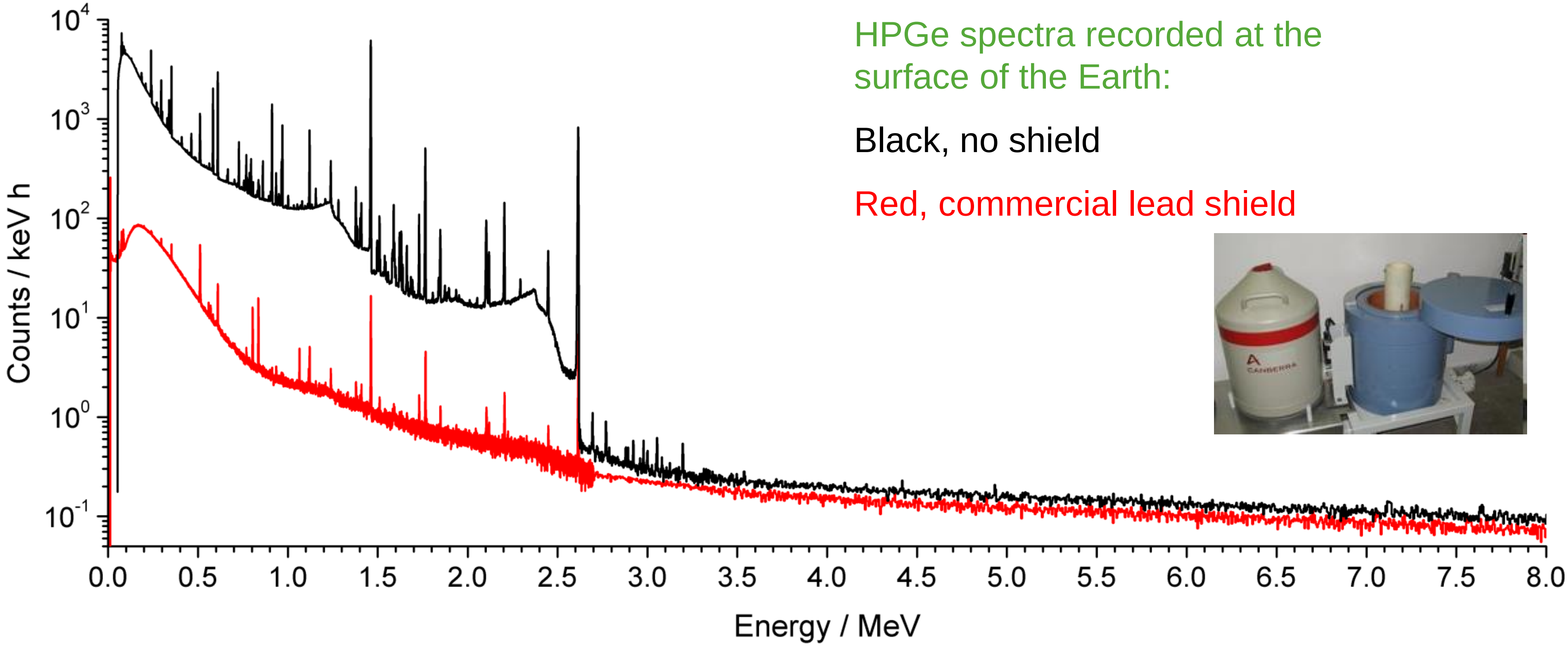
Laboratory background at the Earth's surface using passive shield



HPGe spectra recorded at the surface of the Earth:

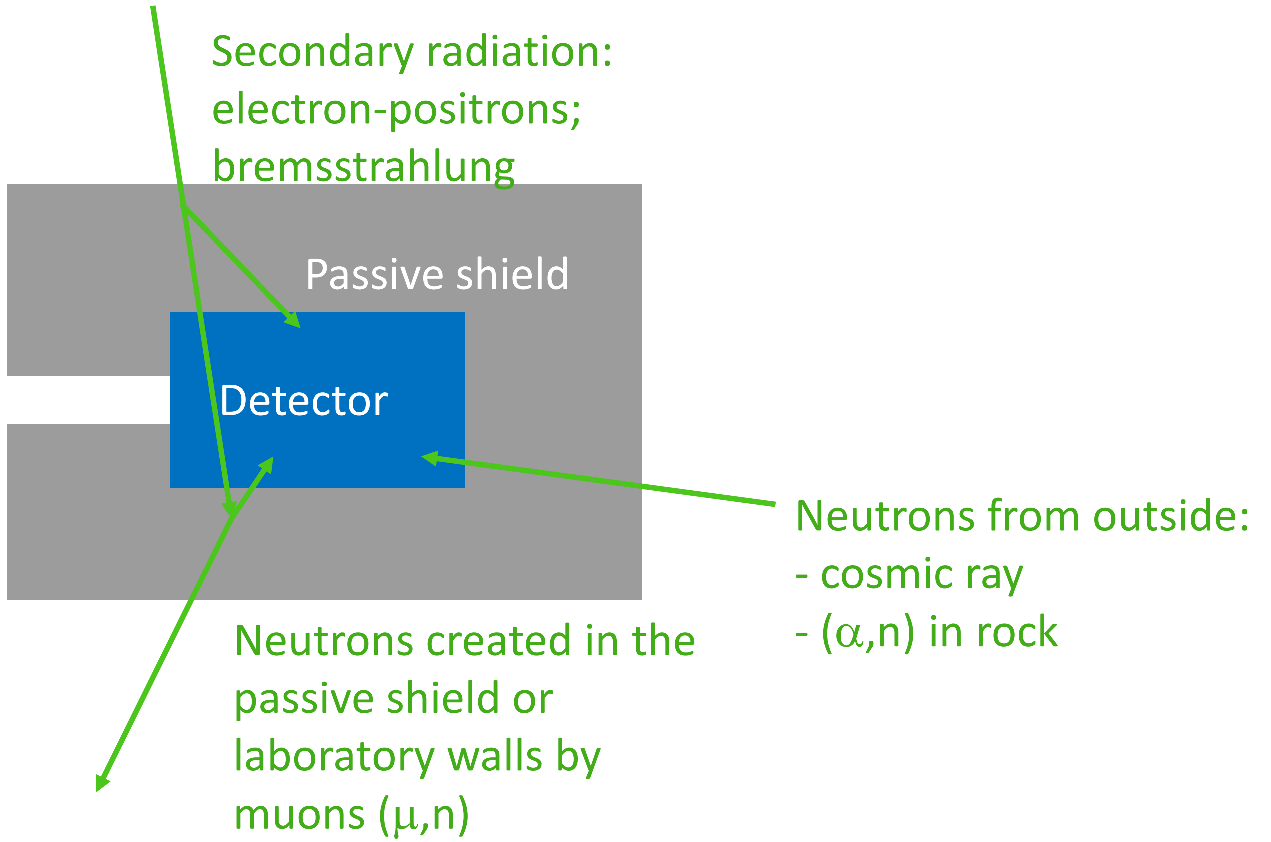
Black, no shield

Red, commercial lead shield

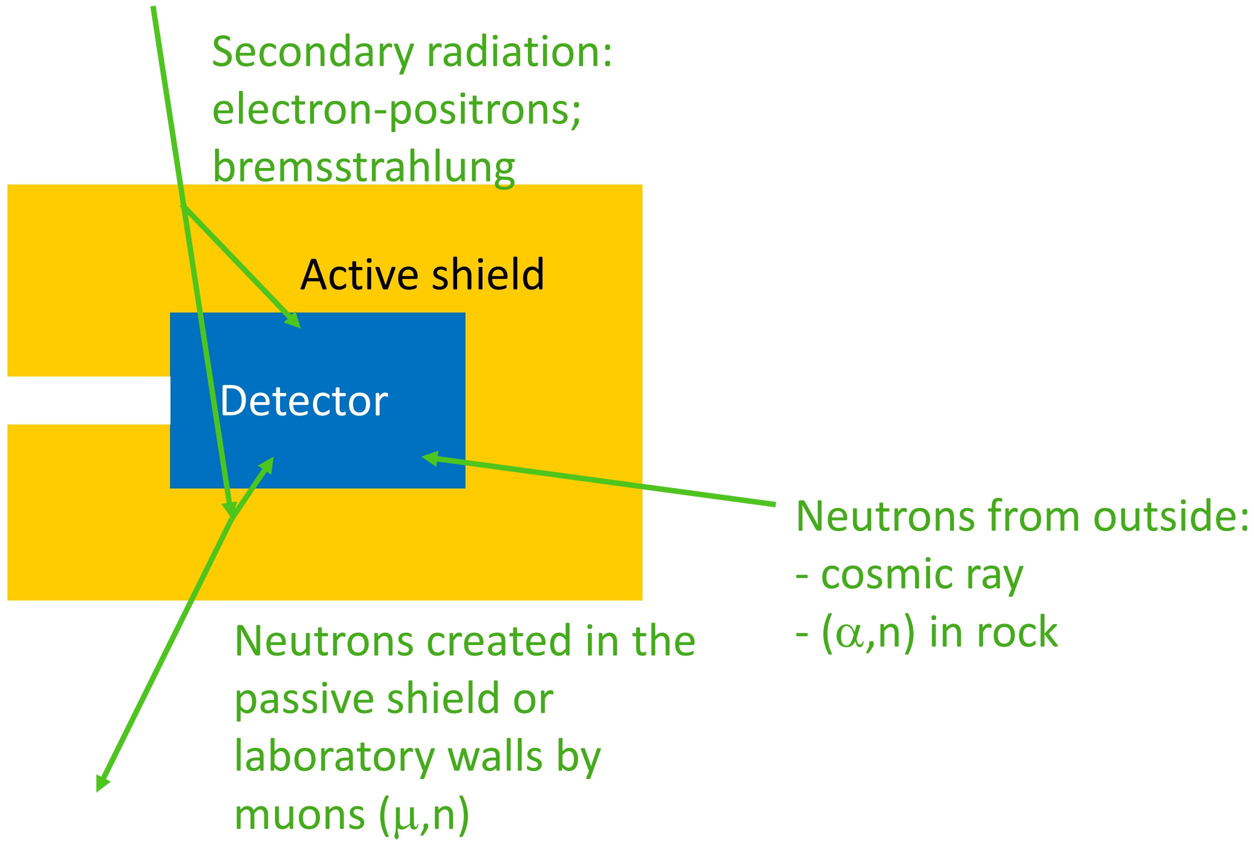
Factor of 20 – 80 reduction at E_γ < 3 MeV

Lead does not do much at E_γ> 3 MeV.

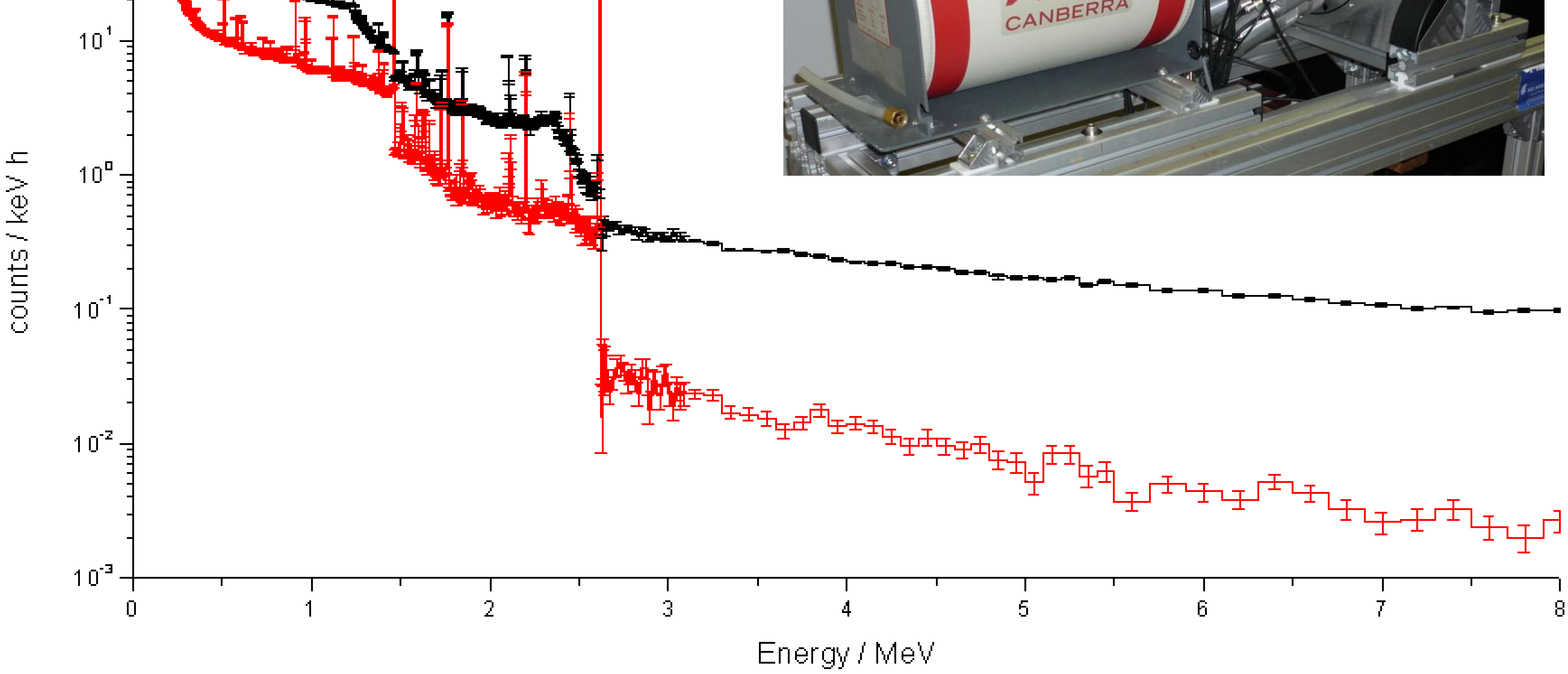
What contributes to the laboratory background?



What contributes to the laboratory background?



Laboratory background at the Earth's surface using active shielding



Factor of 3 – 4 reduction at E_γ < 3 MeV

Factor of 10 – 1000 reduction at E_γ> 3 MeV

Is it not enough?

Is it enough?

Scenario	Reaction	E_G[keV]	σ [barn]	Detected events/hour
AGB stars (80 MK)	$^{14}N(p,\gamma)^{15}O$	81	10^{-12}	10^{-4}

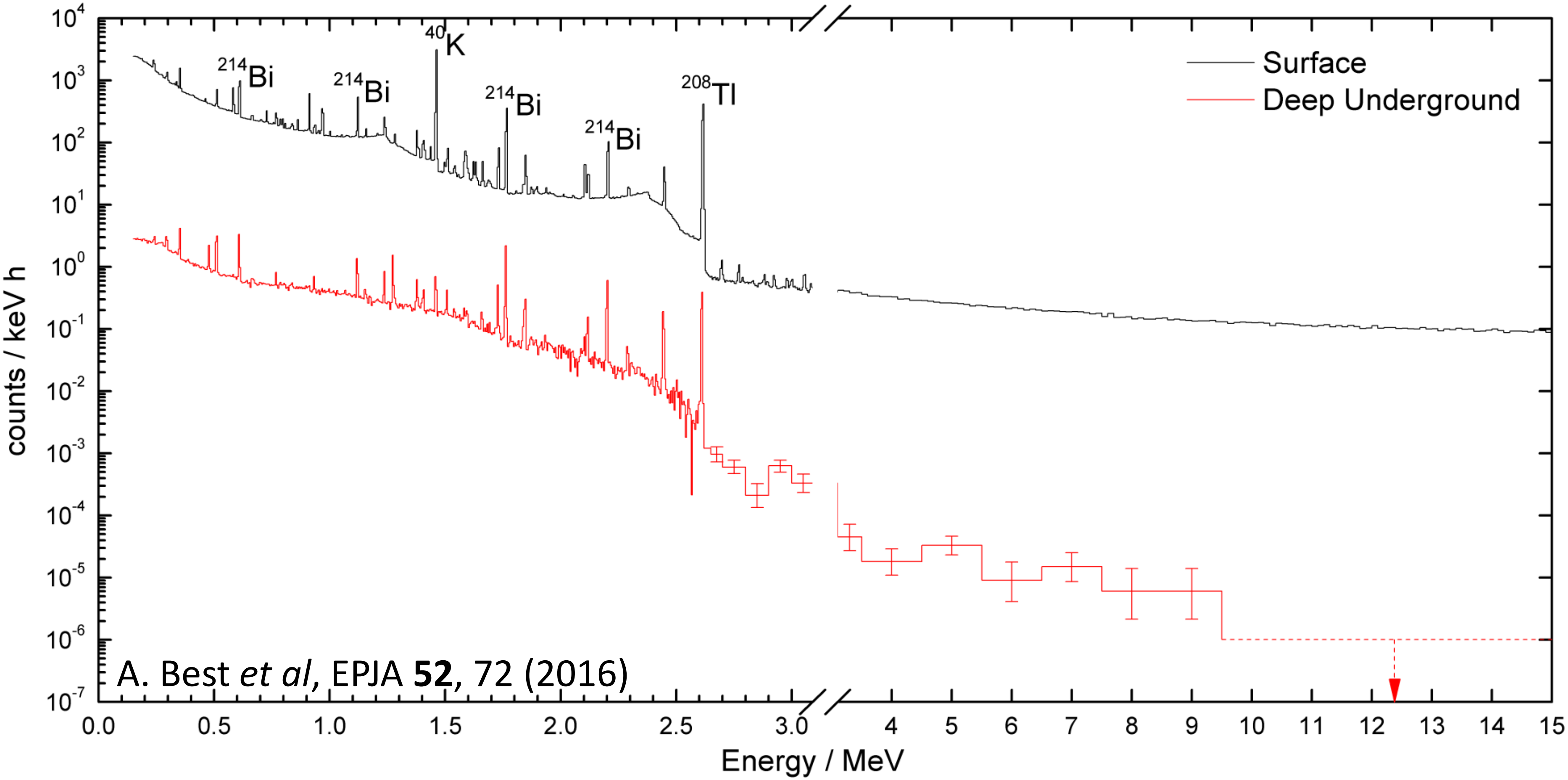
1 barn= 10^{-24} cm^2; assume 10^{16} h^{-1} beam, 10^{18} at/cm^2 target, 10^{-2} detection efficiency

Without background, for 10% precision one need 100 counts. With this count rare it would take 115 years. This is practically impossible.

BUT approach as close as possible: Consider 100 times higher rate. (10^{-2} event/h)

	Background count rate (event / hour)	Time needed to reach 10% precision (years)
Without background	0	**1.1**
Typical overground settings with active shield	$2*10^{-2}$	5.7

Laboratory background at deep underground



Factor of 100 – 1000 reduction at E_γ < 3 MeV

Factor of 1000 – 10000 reduction at E_γ> 3 MeV

Above 10 MeV practically empty background!

Why to go underground, an example

Scenario	Reaction	E_G[keV]	σ [barn]	Detected events/hour
AGB stars (80 MK)	$^{14}N(p,\gamma)^{15}O$	81	10^{-12}	10^{-4}

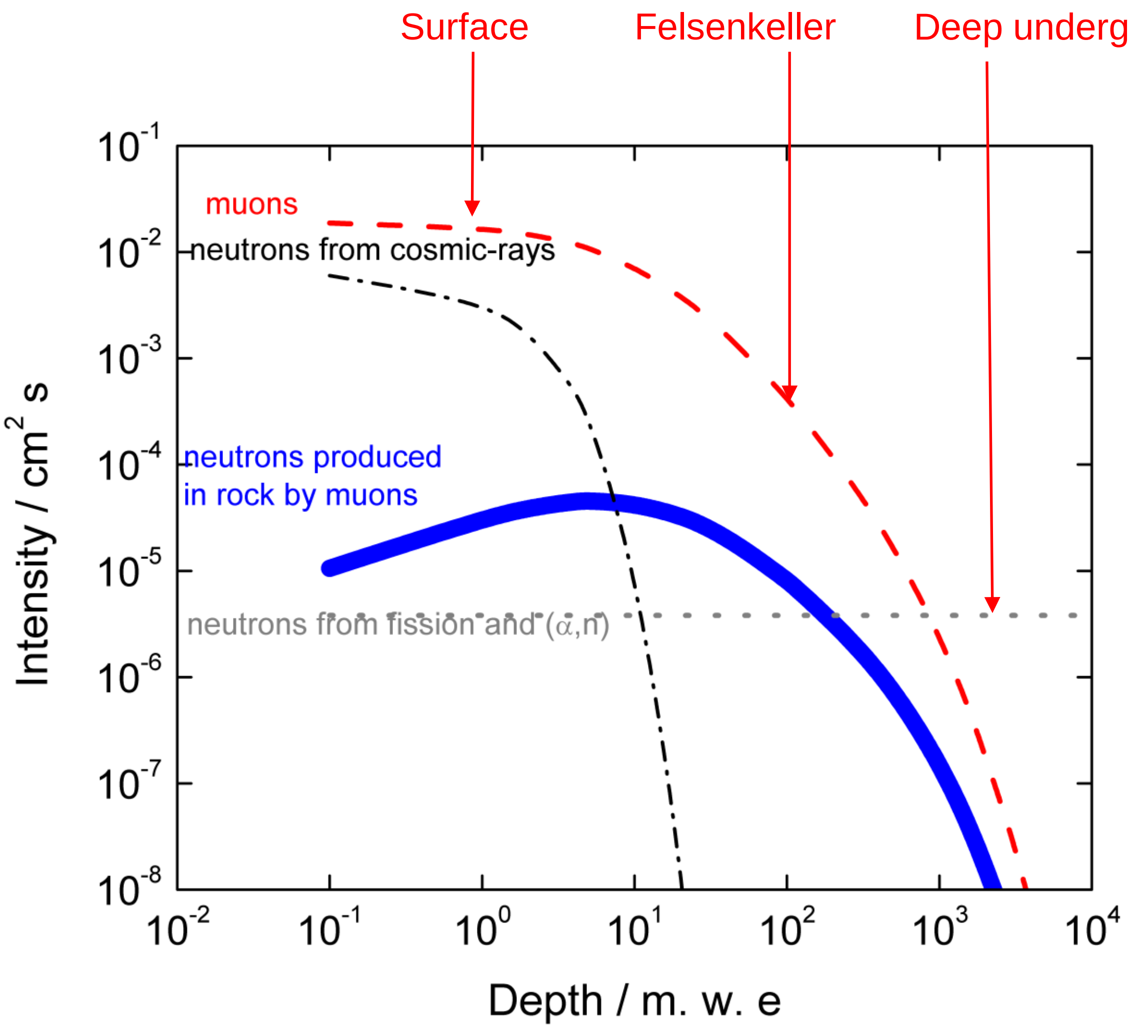
1 barn= 10^{-24} cm^2; assume 10^{16} h^{-1} beam, 10^{18} at/cm^2 target, 10^{-2} detection efficiency

Without background, for 10% precision one need 100 counts. With this count rare it would take 115 years. This is practically impossible.

BUT approach as close as possible: Consider 100 times higher rate. (10^{-2} event/h)

	Background count rate (event / hour)	Time needed to reach 10% precision (years)
Without background	0	**1.1**
Typical overground settings with active shield	$2*10^{-2}$	5.7
Deep underground	$4*10^{-4}$	**1.2**

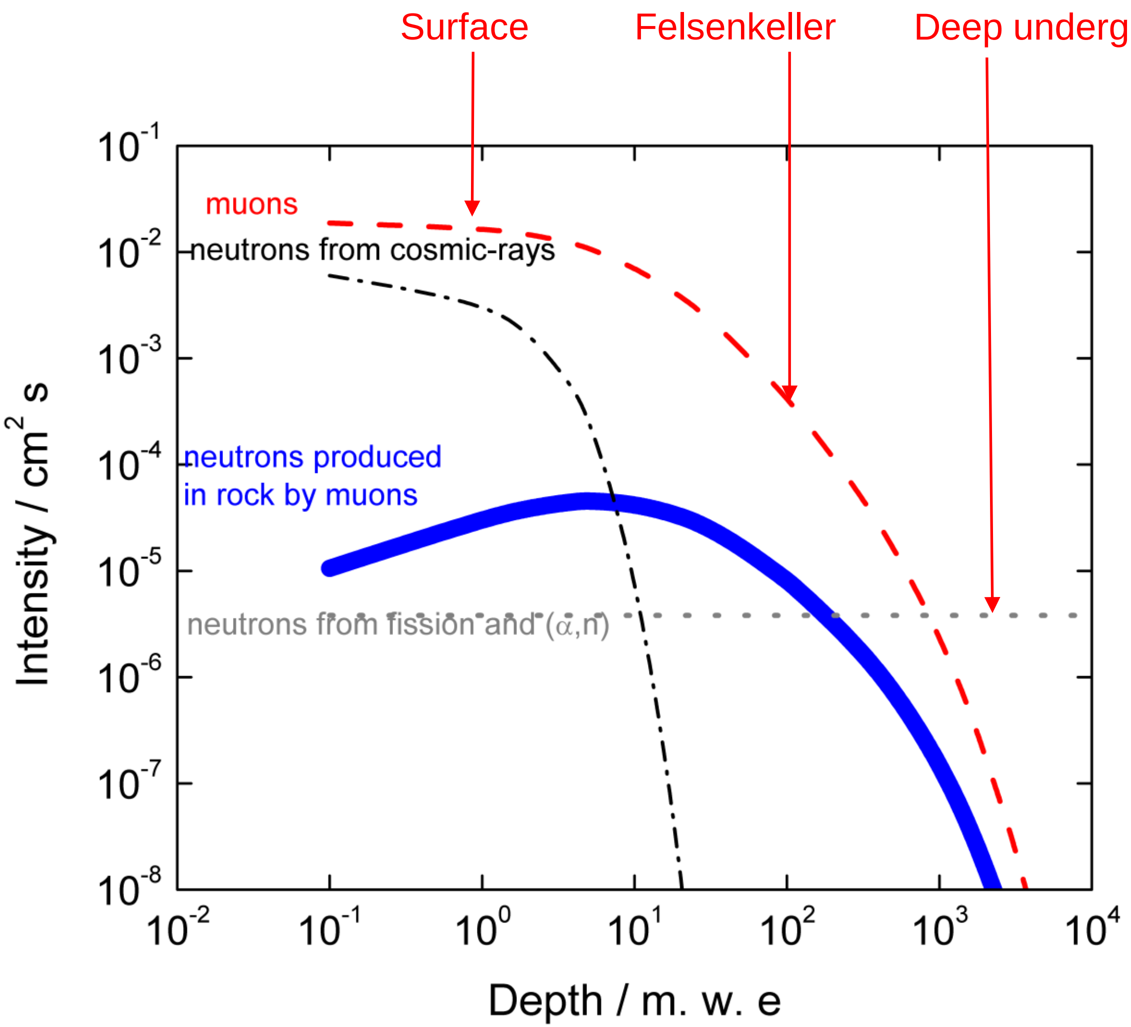
Attenuation of the laboratory background underground



Signals in a gamma detector

- Direct ionisation:
- continuous energy deposit
- up to 100MeV
- Inelastic scattering; continuous energy deposit of several tens of MeV
- Inelastic scattering; continuous energy deposit of several tens of MeV
- Neutrons up to max 5-8MeV but mainly thermalized neutrons
- Elastic, inelastic scattering, and nuclear reactions producing max. ~10MeV γ-rays

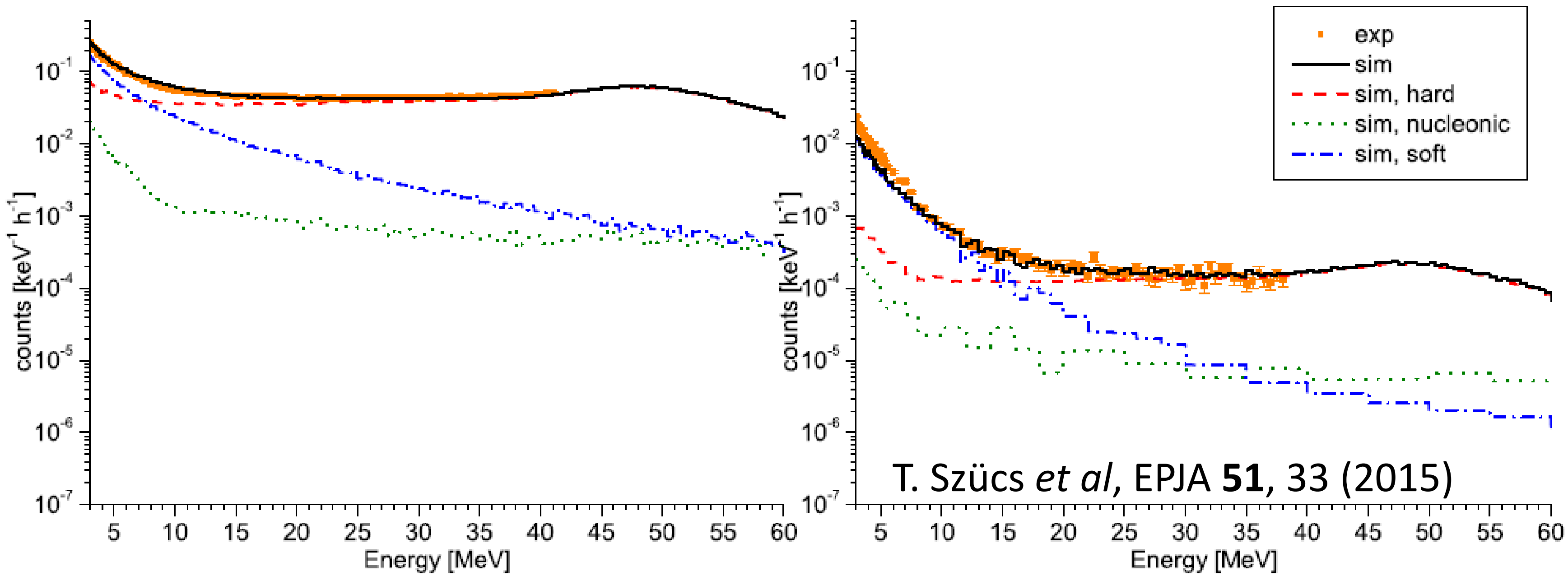
Attenuation of the laboratory background underground



The issues are:

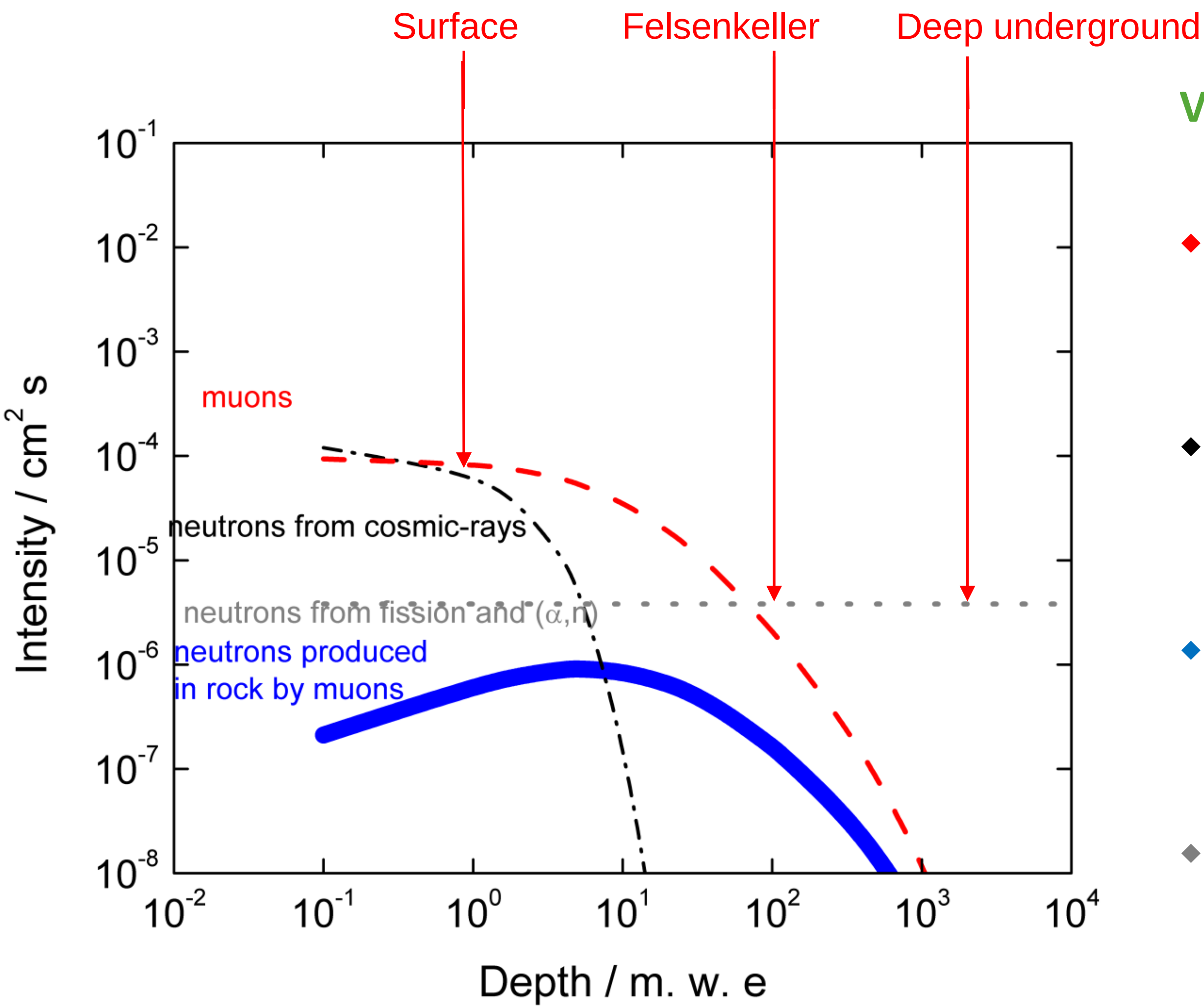
- Energy loss of passing muons in the detector
  → Active shield
- Interaction of cosmic-ray nucleons in the detector
  → 10m rock
- (α,n) neutrons from natural radioactivity in the walls
  → Passive shield
- Neutrons generated by muons
  → 500m rock

GEANT4 simulation of the signal of the cosmic-ray components in HPGe detectors



- Overground the soft component dominates below 10 MeV
- This component becomes negligible if a 15 cm thick lead shield is applied

What if active shielding is applied?



Veto factors

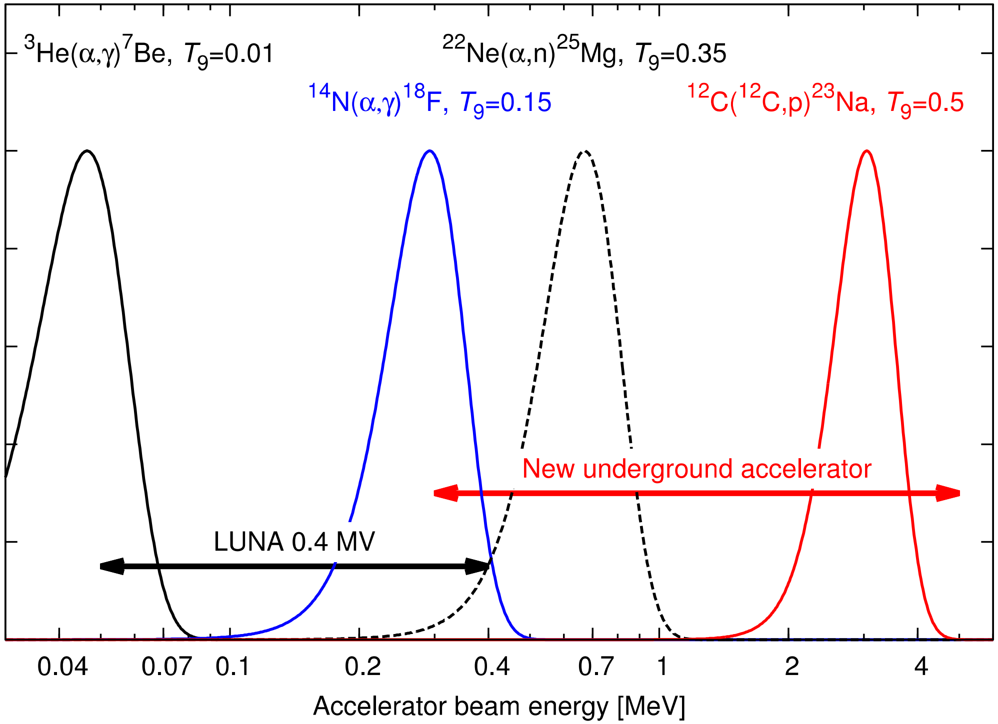
- 200-300
- 50-80
- 50-80
- No effect

Need for higher-energy underground accelerator

NuPECC Long Range Plan 2010-2020:

"An immediate, pressing issue is to select and construct the next generation of underground accelerator facilities. (...) There are a number of proposals being developed in Europe and it is vital that construction of one or more facilities starts as soon as possible."

Gamow peak for selected stable-ion reactions:



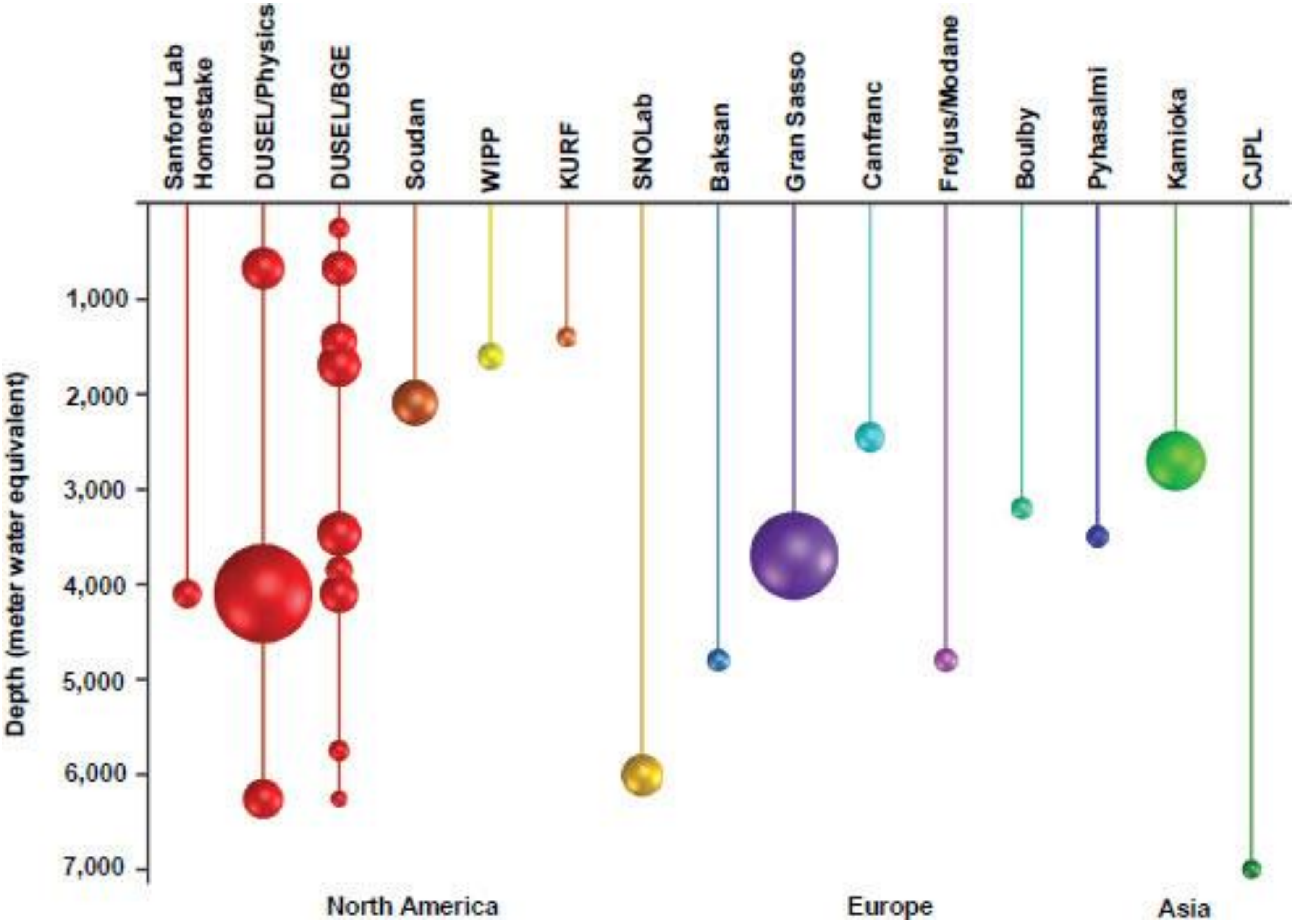
LUNA 0.4 MV

- Solar fusion
- Big-Bang nucleosynthesis
- Hydrogen burning

New underground accelerator

- Solar fusion
- Big-Bang nucleosynthesis
- Helium burning
- Carbon burning
- ^{44}Ti production and destruction

Deep underground laboratories all around the world



Background, in a typical HPGe detector in the Felsenkeller (45 m)

- Combination of active veto and 45m of rock shielding gives a factor of 500 background reduction
- Final value close to deep-underground background
  T. Szücs *et al*, EPJA **48**, 8 (2012)