Outline: Experimental Nuclear Astrophysics

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Kernphysik Skript

1. LUNA – Gran Sasso
2. reaction yields
3. reactions in solar pp-chain

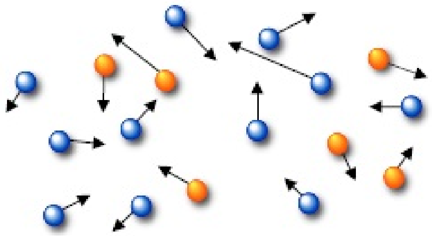
Reaction rates

inside the sun:

Luminosity $L_\odot = 2\cdot10^{39}$ MeV/s

Q-value $Q = 26.73$ MeV

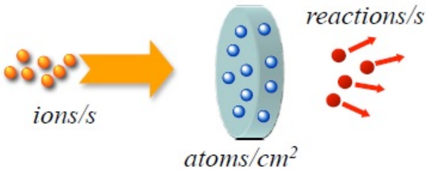
$$r_\odot = \frac{L_\odot}{Q} = 10^{38}\ s^{-1}$$



luminosity is the total amount of energy produced in a star and radiated into space in form of E-M radiation per time

in the lab:

$$r_{lab} = \sigma \cdot \varepsilon \cdot I_p \cdot \rho_s \cdot N_{av}/A$$



$\varepsilon \sim 10\%$

$I_p \sim$ mA

$\rho_s \sim$ mg/cm^2

pb < s < nb

even / month < r_{lab} < event / day

signal rate ≥ background rate

cosmic ray flux at the sea level ~ $2\cdot10^{-2}$ cm^{-2} s^{-1}

on a 10 cm^2 detector ~ 2000 events / day !!!

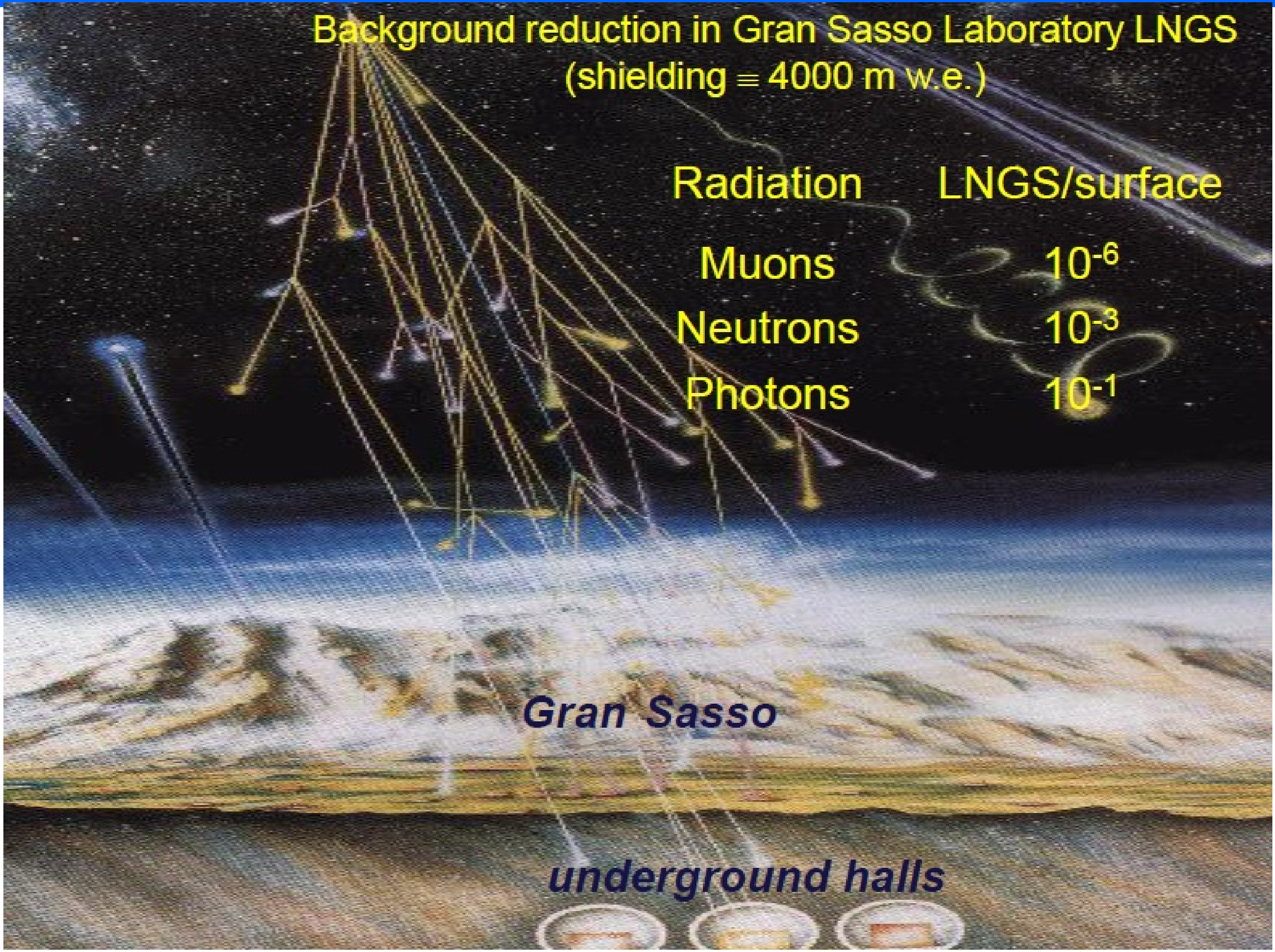
LUNA @ Laboratori Nazionali Gran Sasso

Rock as passive shielding
cosmic ray background
reduction ~ 10^{-4}

4-50 keV accelerator
p-, α-beams ≤ 1 mA

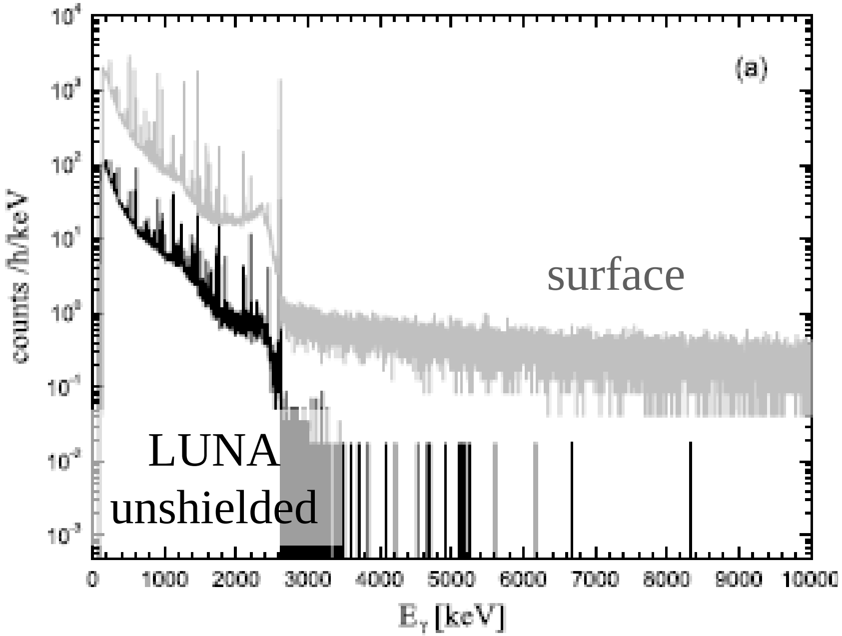
study of pp-chains
e.g. $^3He + {}^3He$

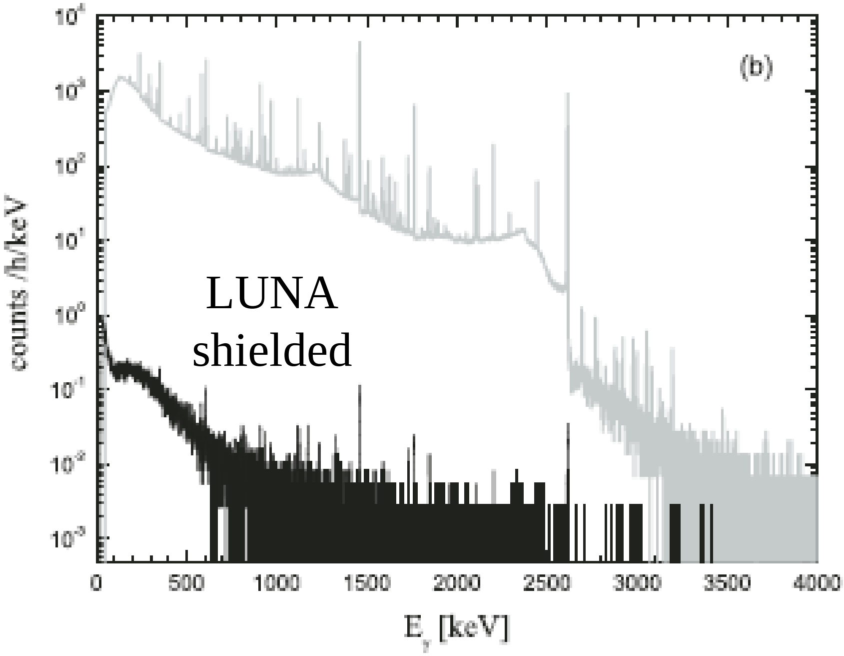
Background reduction in Gran Sasso Laboratory LNGS
(shielding ≡ 4000 m w.e.)



Radiation	LNGS/surface
Muons	10^{-6}
Neutrons	10^{-3}
Photons	10^{-1}

γ-ray background at Gran Sasso





with lead shielding

much higher suppression factor
than with shielding at surface lab

NB shielding becomes even more efficient underground

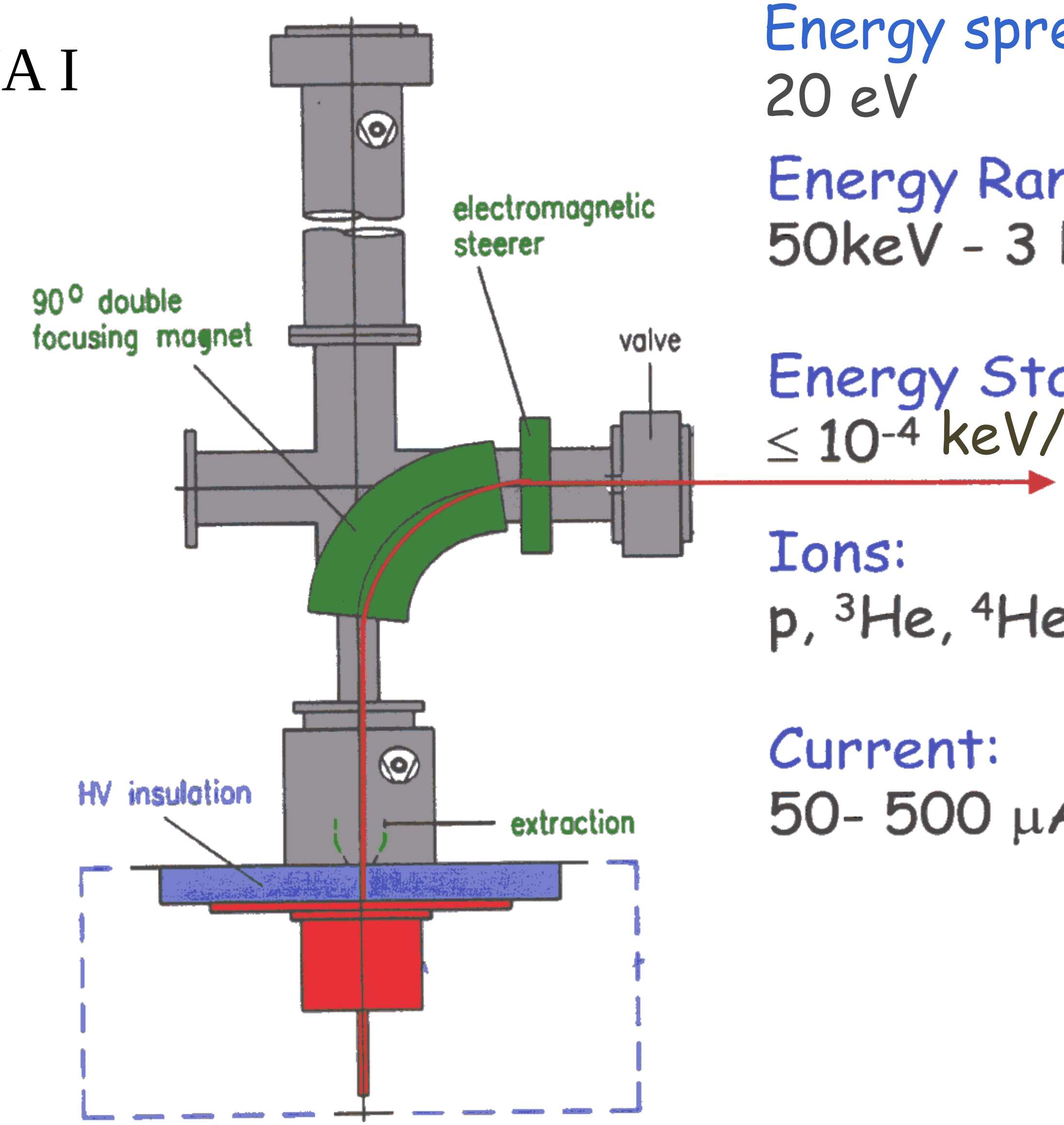
LUNA’s accelerators

50 kV: LUNA I

$^3He(^3He,2p)^4He$

$d(p,\gamma)^3He$

$d(^3He,p)^4He$



Energy spread
20 eV

Energy Range :
50keV - 3 keV

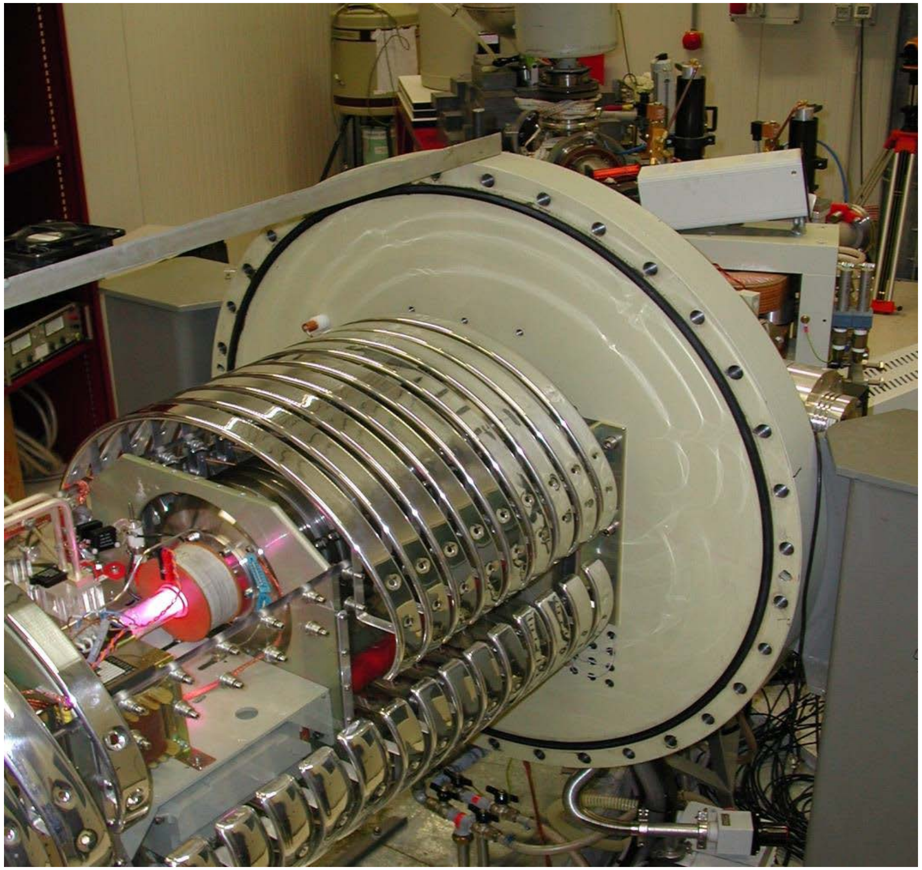
Energy Stability:
$\leq 10^{-4}$ keV/h

Ions:
p, ^3He, ^4He

Current:
50- 500 μA

LUNA’s accelerators

400 kV: LUNA II



U = 50 – 400 kV

I ~ 500 μA for protons
I ~ 250 μA for alphas

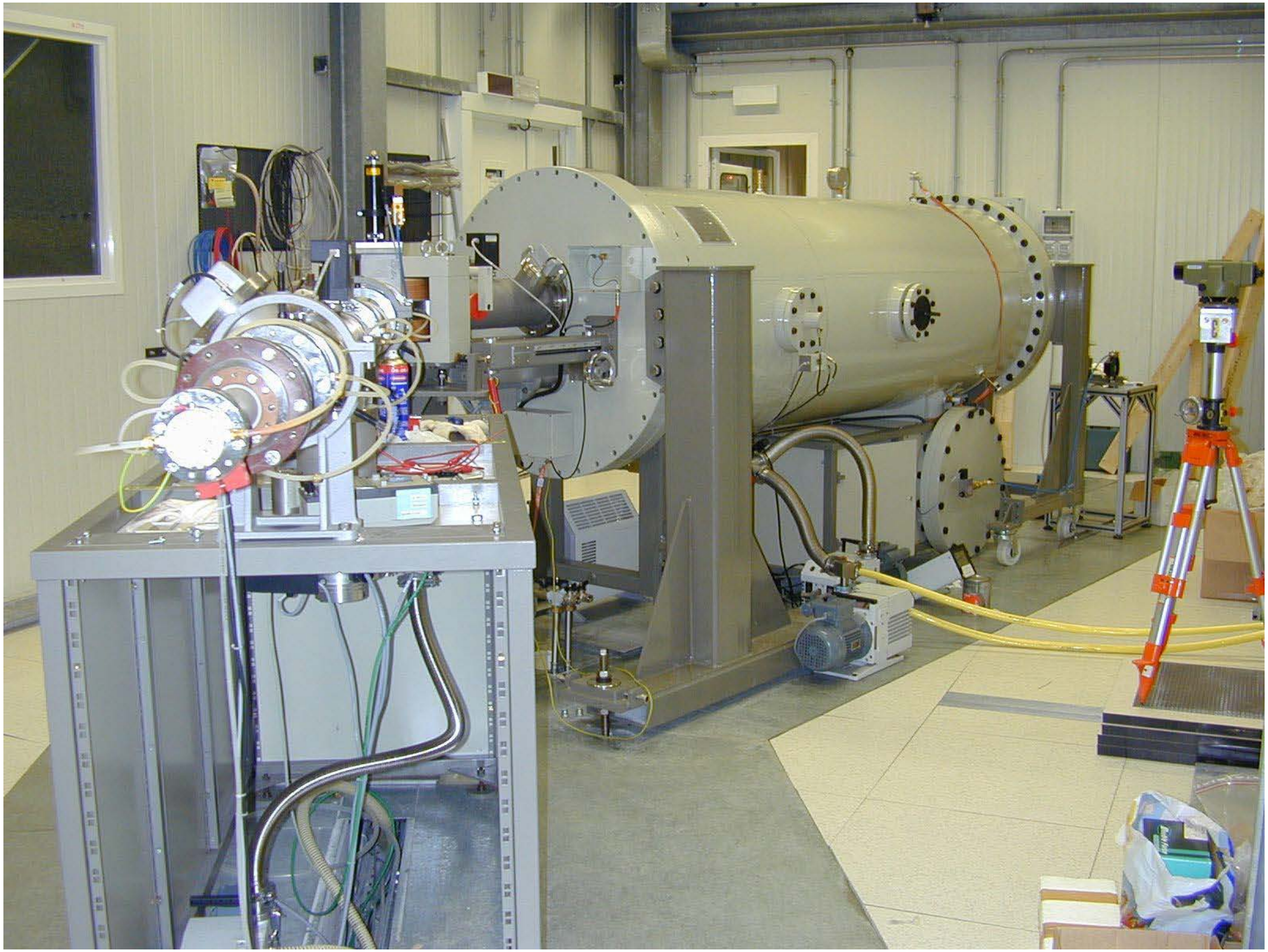
Energy spread ~ 70 eV

long term stability: 5 eV/h

$^{14}N(p,\gamma)^{15}O$ $^{3}He(^{4}He,\gamma)^{7}Be$

LUNA’s accelerators

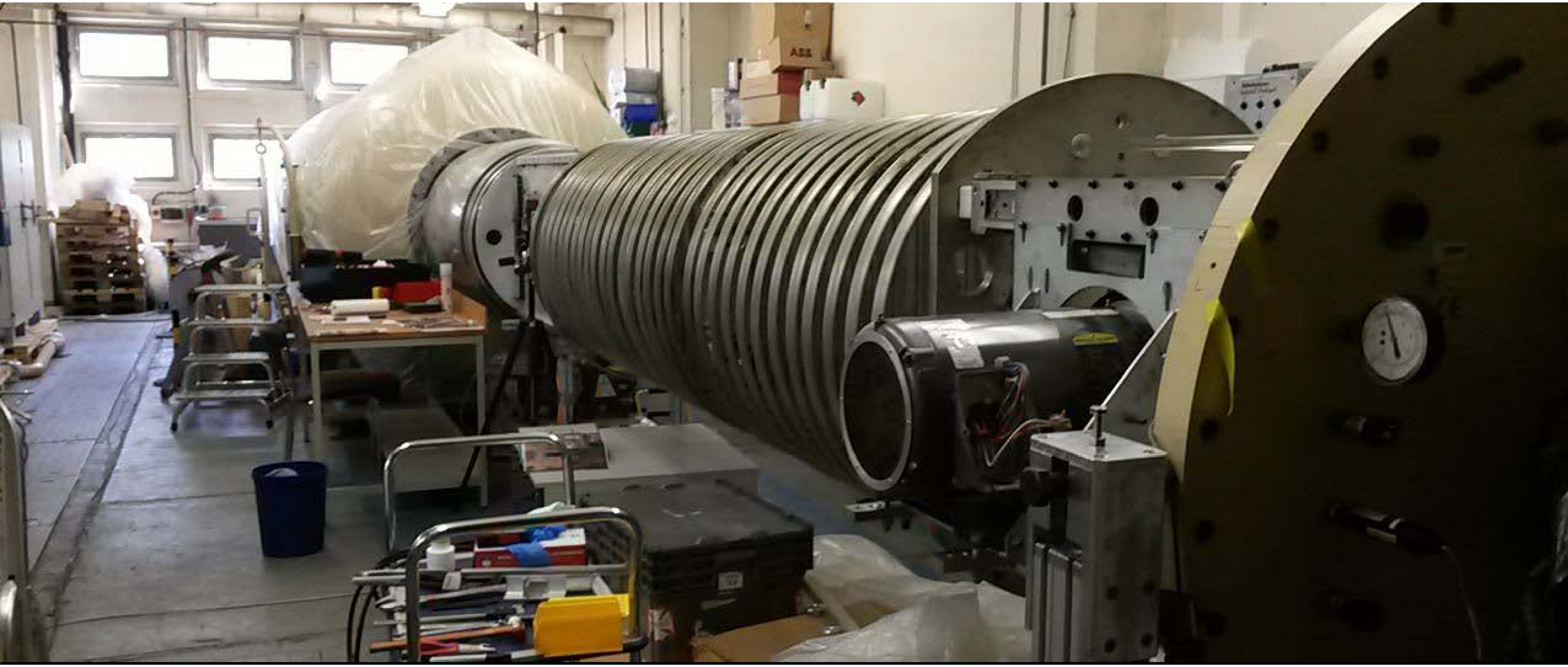
400 kV: LUNA II



LUNA MV

energy range: 200-3500 kV
current: < 1 mA
beam spread: 350 eV
stability: 35 eV/h

This machine will provide not only proton and helium (3/4) but also $^{12}C^{+}$ and $^{12}C^{++}$



The LUNA experiment

LUNA 50 kV (1992-2001) - solar phase
LUNA 400 kV (2000-2018) – CNO, Mg-Al and Ne-Na cycles, BBN
LUNA MV (since 2018) – Helium burning

LUNA accelerator

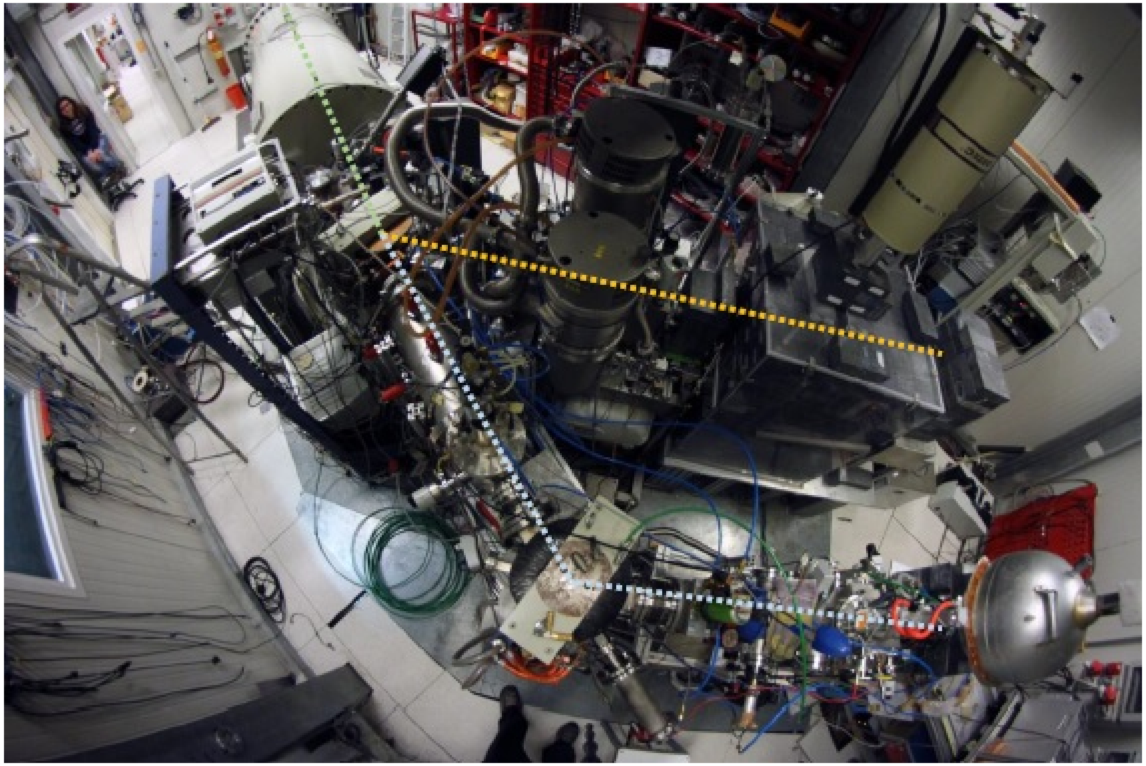
- high current
- long term stability
- high energy accuracy

targets

- windowless gas target
- solid target

detectors

- 137% HPGe
- BGO
- Silicon
- NaI



Two approaches to stellar energies

Extrapolations:

- Measure level gamma widths
- Measure asymptotic normalization constants (ANCs)
- Measure cross sections at high energies
- R-matrix fit for each transition

Extrapolations for each transition are summed to give the total extrapolated cross section at astrophysical energies

Direct Measurement:

- Low laboratory background
- Low ion beam induced background
- High beam intensity
- High detection efficiency

Direct data for the total cross section at astrophysical energies

Underground accelerator – main features

$$\sigma(E) = S(E) \cdot e^{-2\pi\eta(E)}/E$$

Low cross section

$$r_{lab} = \sigma \cdot \varepsilon \cdot I_p \cdot \rho_s \cdot N_{av}/A$$

high beam
current to
increase
reaction rate

long
measurements to
collect statistics

energy stability
during measurement

$$\sigma(E) = S(E) \cdot e^{-2\pi\eta(E)}/E$$

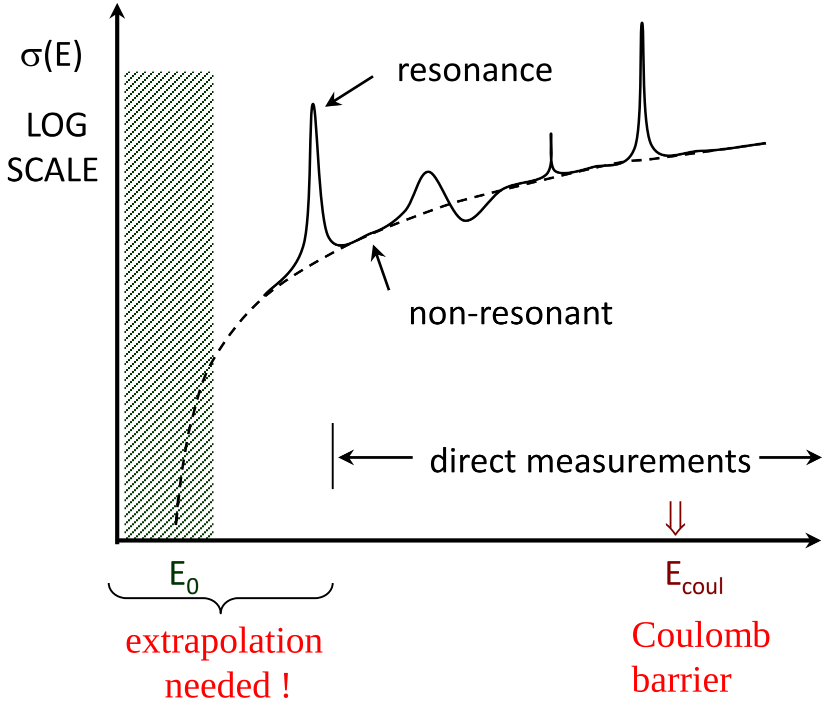
small energy
spread

Experimental approach

measure σ(E) over as wide a range as possible, then extrapolate down to E_0!

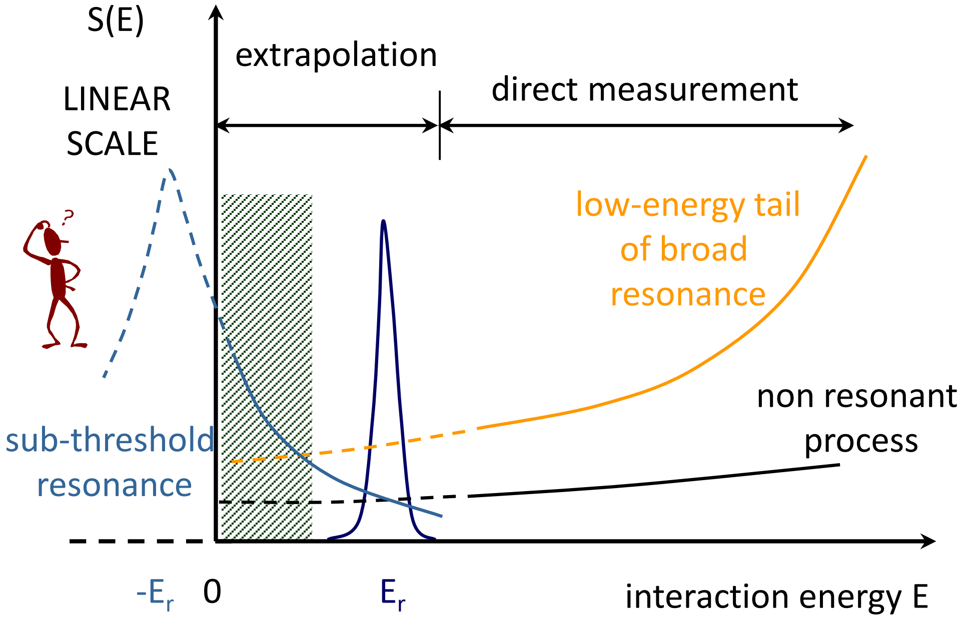
CROSS SECTION

$$\sigma(E) = \frac{1}{E}\exp(-2\pi\eta)\,S(E)$$



S-FACTOR

$$S(E) = E\sigma(E)\exp(2\pi\eta)$$



DANGER OF EXTRAPOLATION !

Targets

H targets

solid CH_2 target (plastic material)

☺	☹
simple to handle	hydrogen depletion
dx ~ 50 - 1000 μg cm^{-2}	non uniformity
	melting problems
	deuterium contamination

He targets

solid implanted target

☺	☹
simple to handle	low concentration
	(n ~ 10^{15} - 10^{17} atoms cm^{-2})

window-confined gas target

☺	☹
higher concentration	background reactions
(depending on pressure)	(e.g. on window materials)

windowless gas target

☺	☹
higher concentration	differential-pumping system
almost background free	high pumping speeds
no physical degradation	

What is measured in the laboratory

reaction yield: $\boxed{Y = N_p\, N_t\, \sigma\, \varepsilon}$

N_p = number of projectile ions

typically, stable beam intensities 10^{14} pps (~100 μA q=1+)

N_t = number of target atoms

typically, 10^{19} atoms/cm^2

σ = reaction cross section (given by nature)

typically, 10^{-15} barn (1 barn = 10^{-24} cm^2)

ε = detection efficiency

typically, 100% for charged particles

~1% for gamma rays

$\boxed{Y = 0.3\text{-}30 \text{ counts/year}}$

Challenges

low cross sections → low yields → poor signal-to-noise ratio

Sources of background:

Beam induced:

- reactions with impurities in the target
- reactions on beam collimators/apertures

non beam-induced:

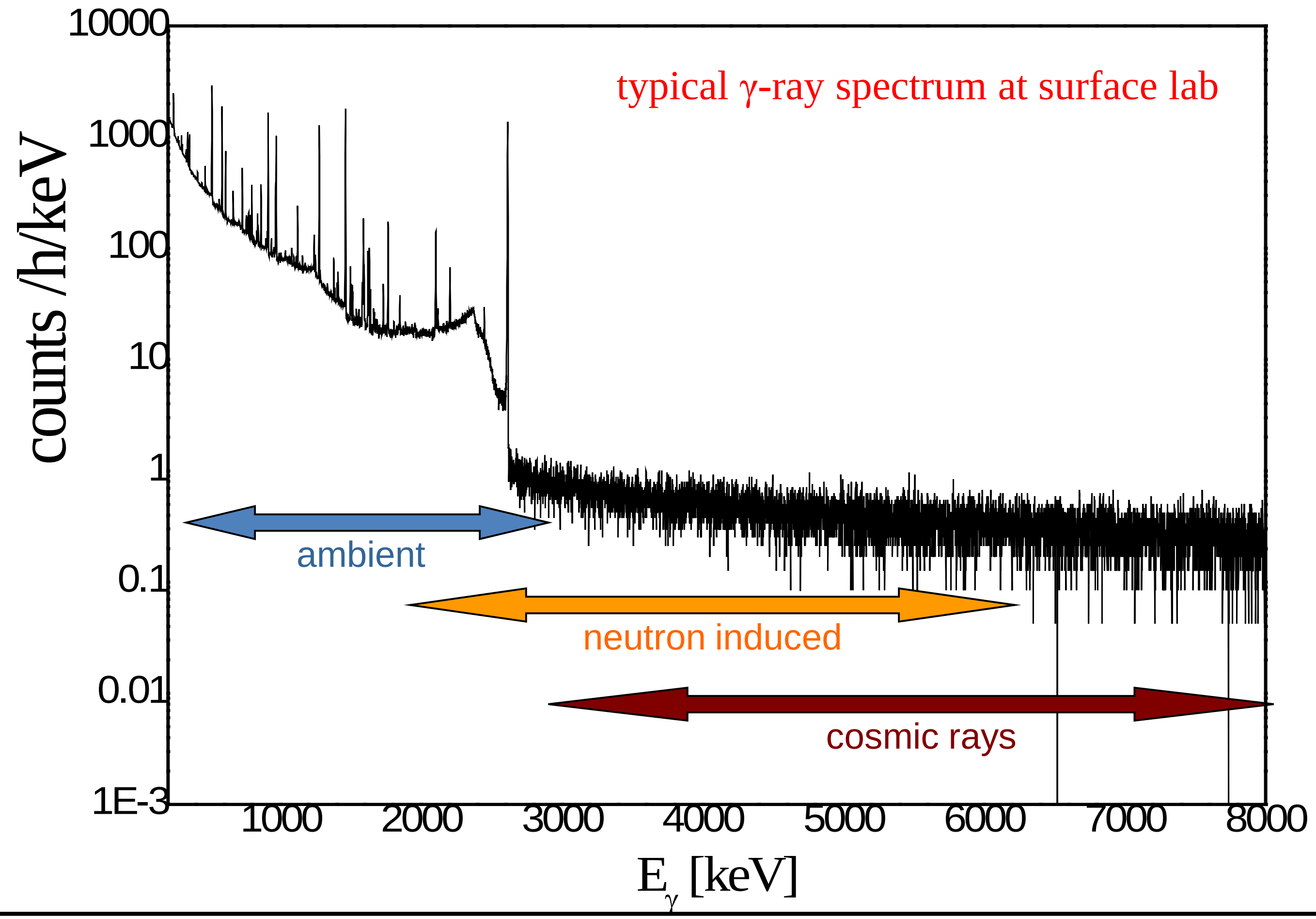
- interaction of cosmic muons with detection setup
- charged particles from natural background
- neutron-induced reactions

maximising the yield requires:

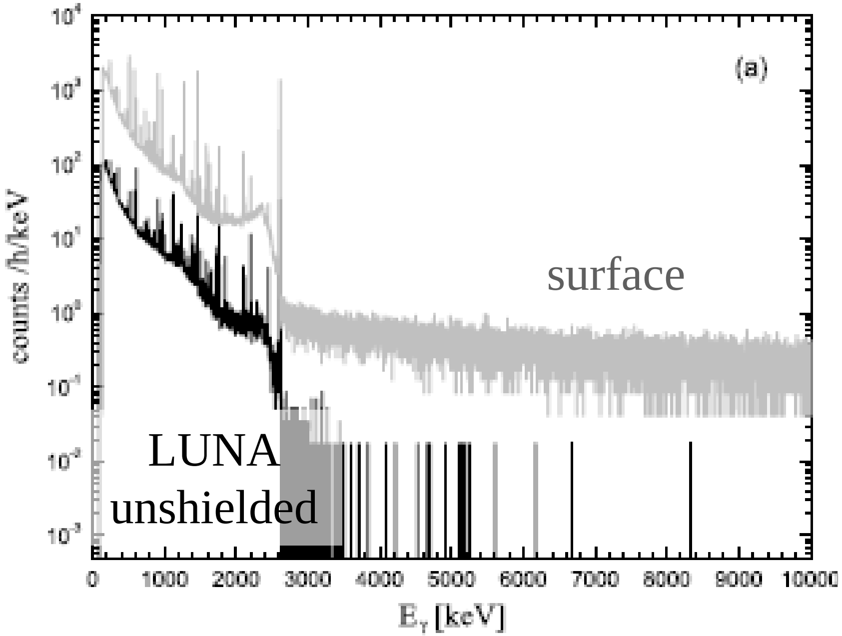
- improving “signal”
  - high beam currents
    - BUT limitations: charge confinement
    - heating effects on target
  - thicker, purer targets
    - BUT limitations: exponential drop of cross section
    - high purities difficult + expensive
- reducing “noise” (i.e. background)
- combination of both

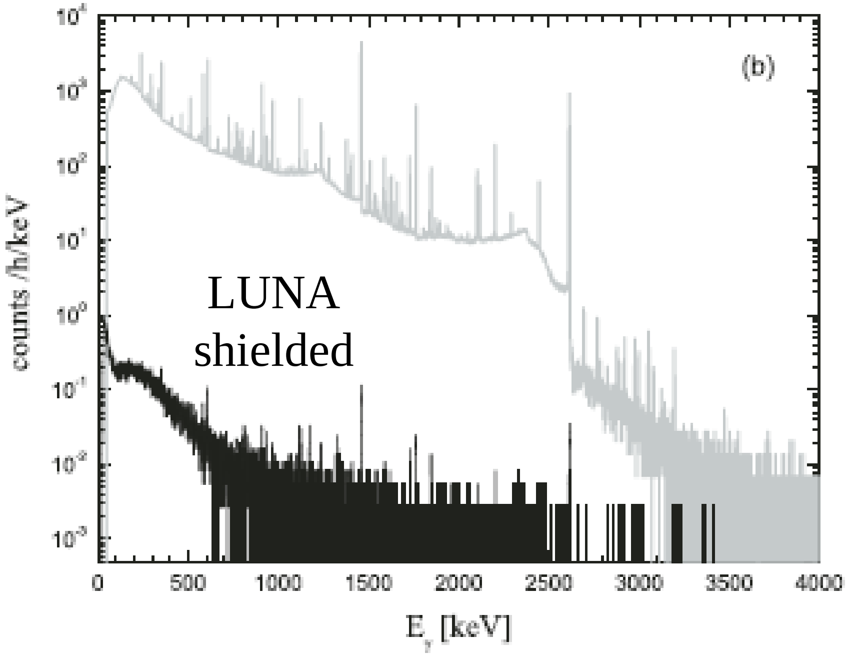
Main source of background

- natural radioactivity (mainly from U and Th chains and from Rn)
- cosmic rays (muons, ^{1,3}H, ^{7}Be, ^{14}C, …)
- neutrons from (α,n) reactions and fission



γ-ray background at Gran Sasso



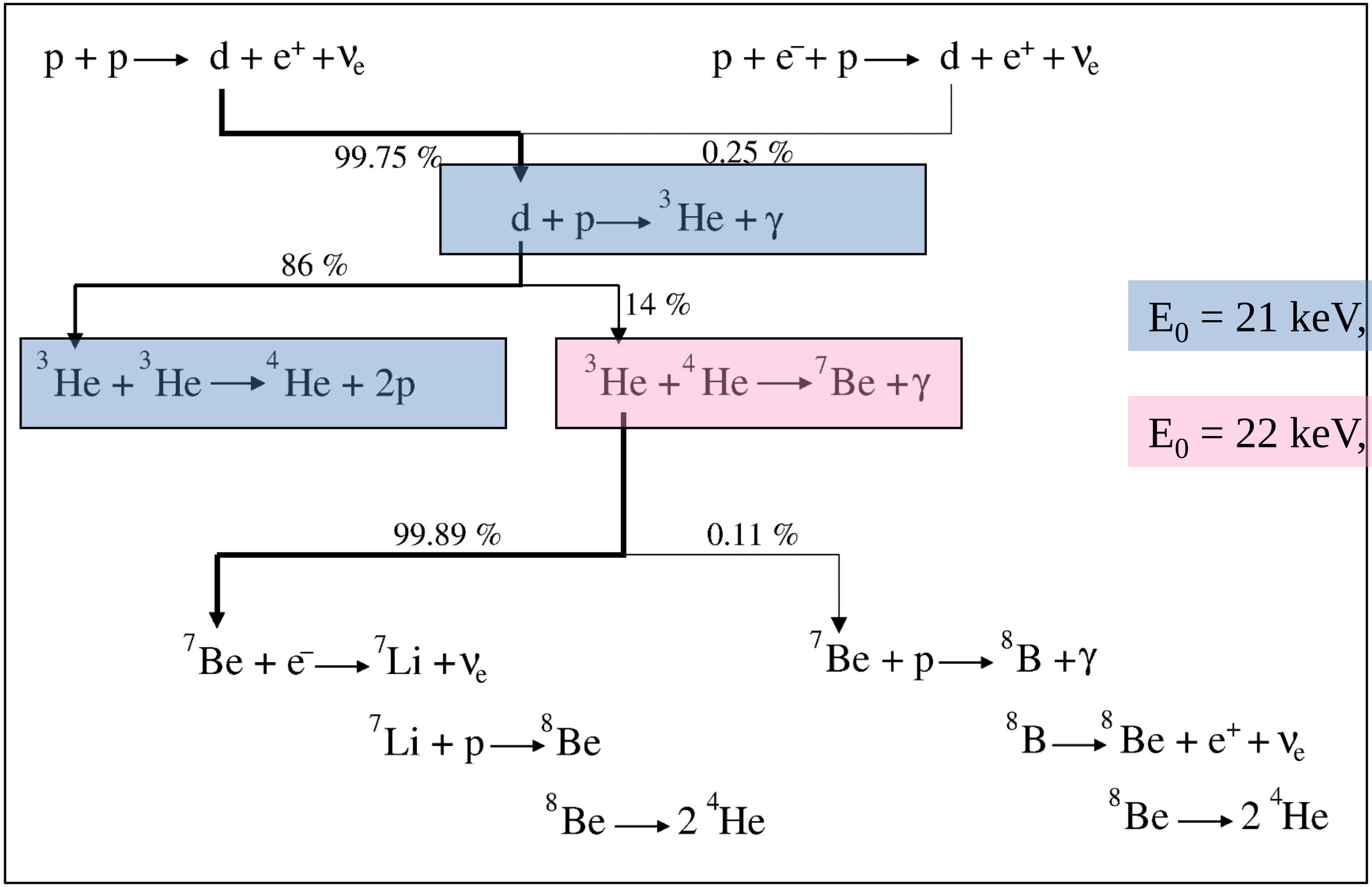


with lead shielding

much higher suppression factor
than with shielding at surface lab

NB shielding becomes even more efficient underground

Precision data for solar models



$p + p \longrightarrow d + e^+ + \nu_e$

$p + e^- + p \longrightarrow d + e^+ + \nu_e$

99.75 %

0.25 %

$d + p \longrightarrow {}^3He + \gamma$

86 %

14 %

${}^3He + {}^3He \longrightarrow {}^4He + 2p$

${}^3He + {}^4He \longrightarrow {}^7Be + \gamma$

99.89 %

0.11 %

${}^7Be + e^- \longrightarrow {}^7Li + \nu_e$

${}^7Li + p \longrightarrow {}^8Be$

${}^8Be \longrightarrow 2\,{}^4He$

${}^7Be + p \longrightarrow {}^8B + \gamma$

${}^8B \longrightarrow {}^8Be + e^+ + \nu_e$

${}^8Be \longrightarrow 2\,{}^4He$

+ CNO

$E_0 = 21$ keV, $\sigma = 7 \cdot 10^{-13}$ barn

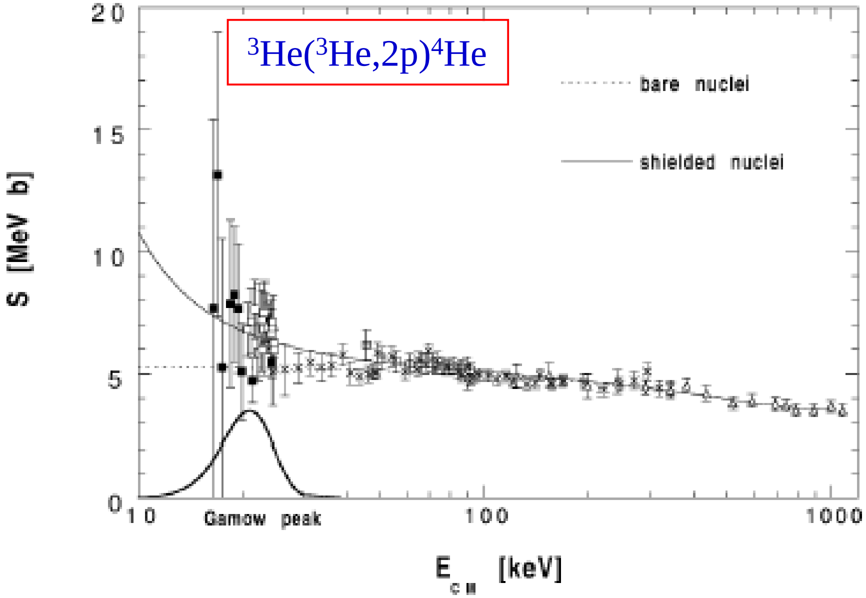
$E_0 = 22$ keV, $\sigma = 9 \cdot 10^{-18}$ barn

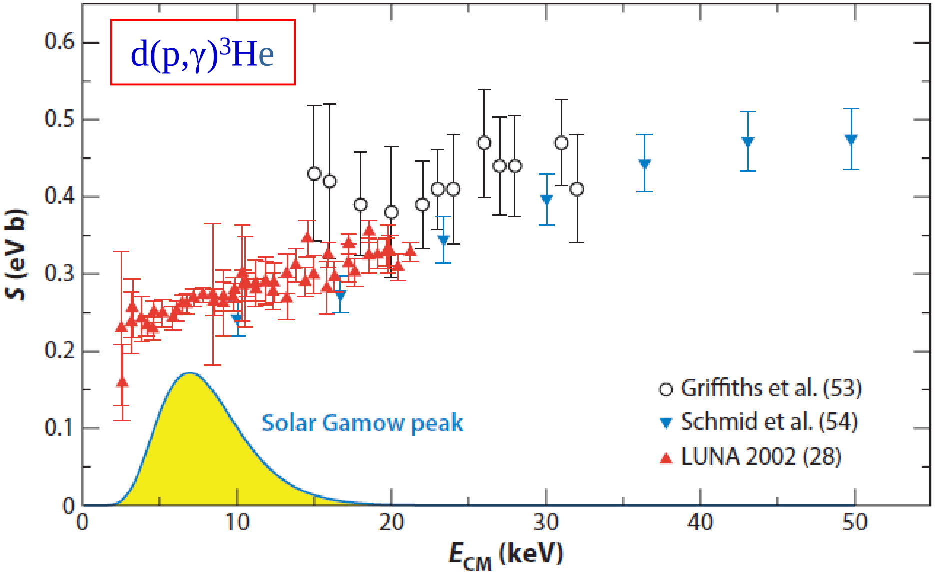
Charged particle reaction cross sections are difficult to measure at astrophysical energies

LUNA – Phase I: 50 kV accelerator (1992-2001)

investigate reactions in solar pp-chain

R. Bonetti et al.: Phys. Rev. Lett. 82 (1999) 5205





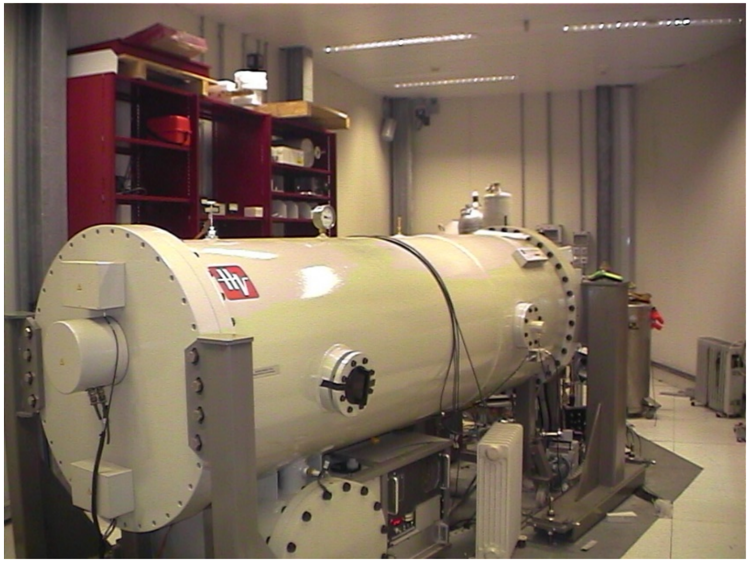
The $^2H(p,\gamma)^3He$ reaction controls the equilibrium abundance of solar deuterium

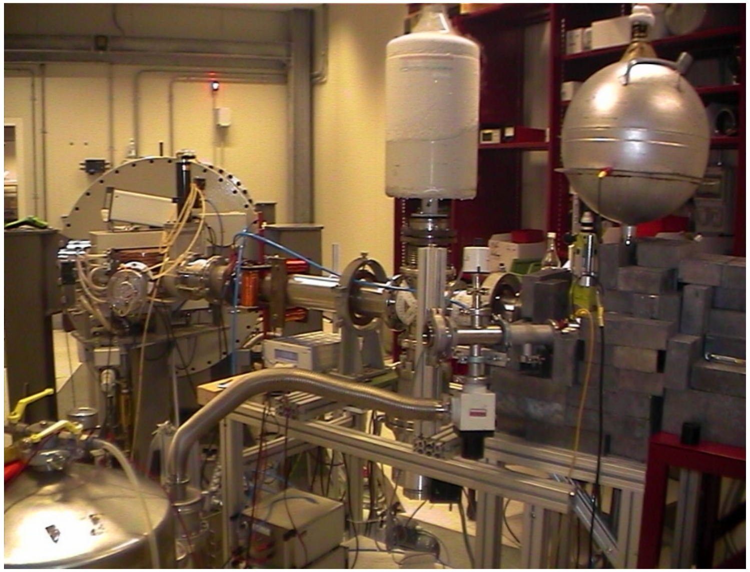
@ lowest energy:
σ ~ 20 fb → 1 count/month

@ lowest energy:
σ ~ 9 pb → 50 counts/day

only two reactions studied **directly** at **Gamow peak**

LUNA – Phase II: 400 kV accelerator (2002-2006)



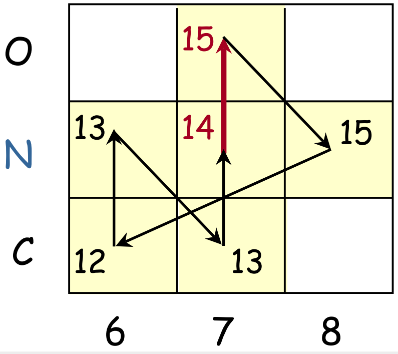


$^{14}N(p,\gamma)^{15}O$

slowest reaction

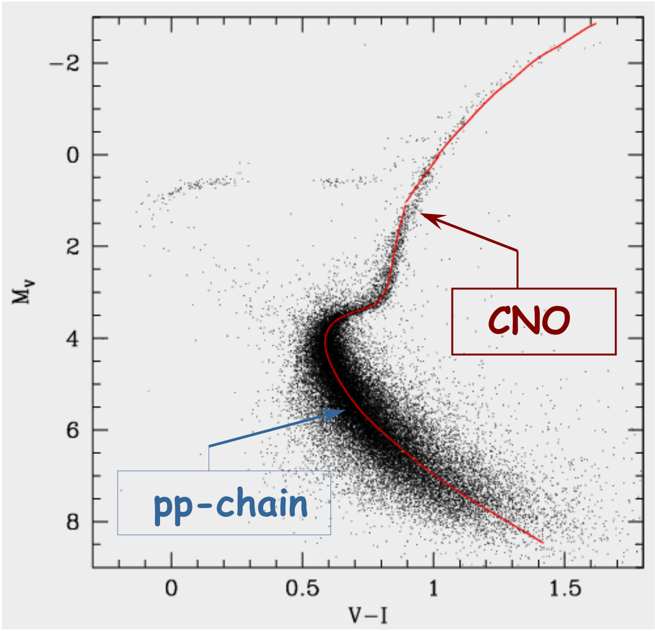
in CNO cycle

CNO cycle



A. Formicola et al. PL B591 (2004) 61-68

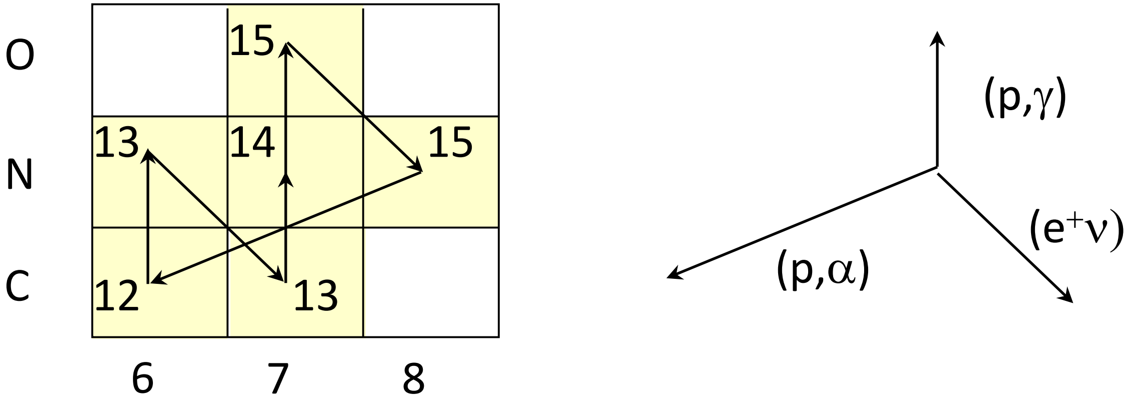
G. Imbriani et al. A&A 420 (2004) 625



- ➢ solar neutrino flux from CNO reduced by factor 2
- ➢ age of globular cluster increased by 1Gy !!

Example of nuclear reaction rates in stars

CNO cycle



$^{12}C(p,\gamma)^{13}N(e^{+}\nu)^{13}C(p,\gamma)^{14}N(p,\gamma)^{15}O(e^{+}\nu)^{15}N(p,\alpha)^{12}C$

cycle limited by β-decay of ^{13}N (t ~ 10 min) and ^{15}O (t ~ 2 min)

CNO isotopes act as catalysts

net result: $4p \rightarrow {}^{4}He + 2e^{+} + 2\nu + Q_{eff}$ $Q_{eff} = 26.73$ MeV

nucleosynthesis **energy production**

changes in stellar conditions ⇒ changes in energy production and nucleosynthesis

need to know REACTION RATE at all temperatures to determine ENERGY PRODUCTION and NUCLEOSYNTESIS

LUNA

Reactions measured so far at or near Gamow region:

$^{3}He(^{3}He,2p)^{4}He$ $^{1}H(p,\gamma)^{3}He$ $^{14,15}N(p,\gamma)^{15}O$ $^{3}He(^{4}He,\gamma)^{7}Be$ $^{25}Mg(p,\gamma)^{26}Al$

$^{2}H(^{4}He,\gamma)^{6}Li$ $^{17}O(p,\gamma)^{18}F$ $^{17}O(p,\alpha)^{14}N$ …

Limitations

- produces & accelerates H and He beams
- no deuteron beams allowed
- reactions producing neutrons not allowed
- only direct kinematics studies are possible

many critical reactions for astrophysics BEYOND current capabilities

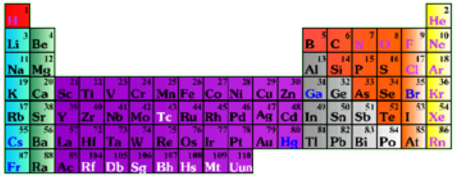
!! new underground facilities are very much needed !!

Key open questions

Crab Nebula SN 1054

- *fate of massive stars (supernovae explosions)?*

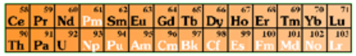
carbon burning [$^{12}C+^{12}C$] in advanced stages of stellar evolution



H																	He
Li	Be											B	C	N	O	F	Ne
Na	Mg											Al	Si	P	S	Cl	Ar
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
Cs	Ba	La	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
Fr	Ra	Ac	Rf	Db	Sg	Bh	Hs	Mt	Uun								

- *where and how are heavy elements produced?*

neutron sources [$^{13}C(\alpha,n)^{16}O$ and $^{22}Ne(\alpha,n)^{26}Mg$] for s-process



Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr

- *AGB stars nucleosynthesis, Novae ejecta, Galaxy composition?*

Ne, Na, Mg and Al nucleosynthesis [(p,γ) and (p,α) reactions]

projects in Europe

Boulby (UK)
Gran Sasso (Italy)
Canfranc (Spain)
Felsenkeller (Germany)

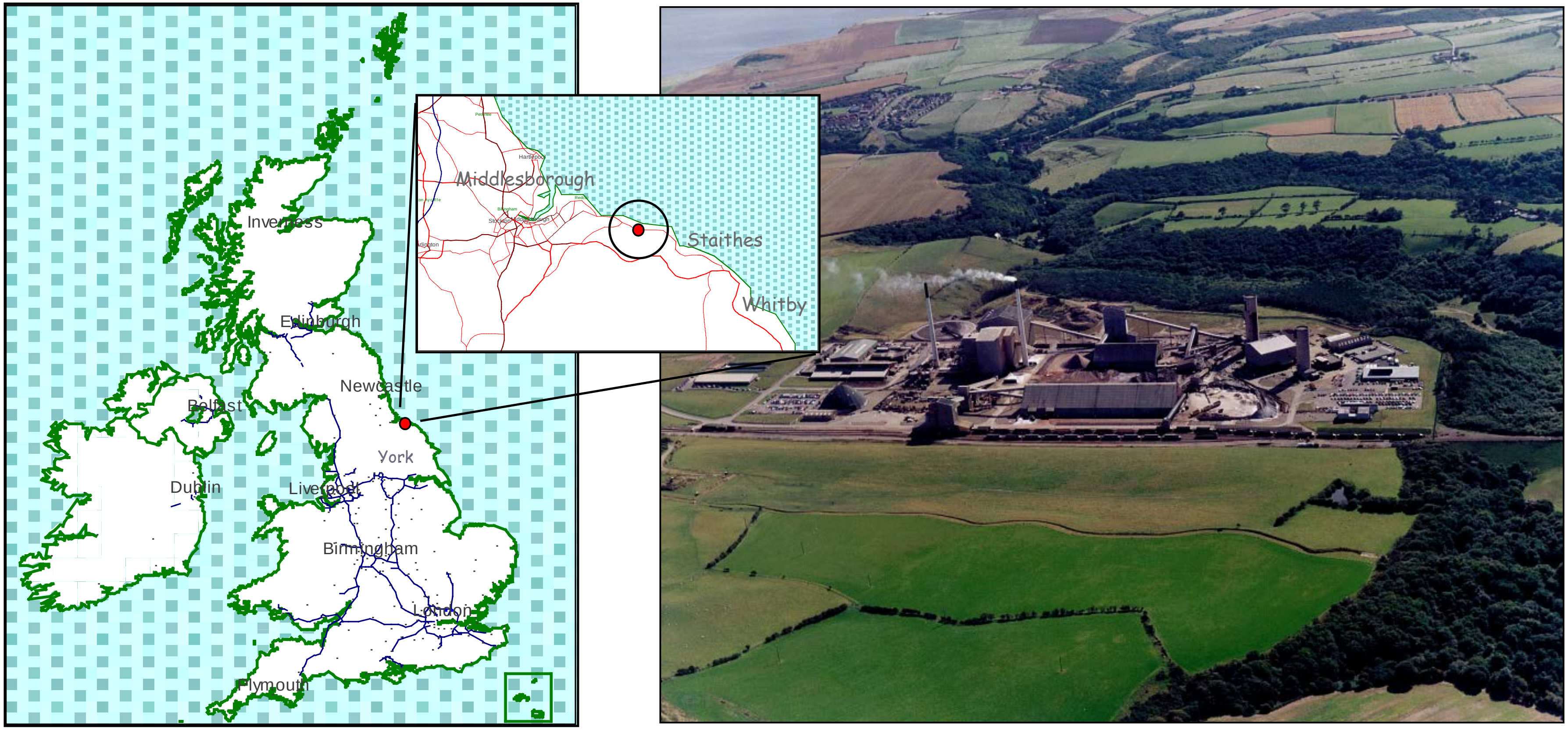
projects elsewhere

DIANA (US)
Andes (Chile/Argentina)
China
India

Boulby mine

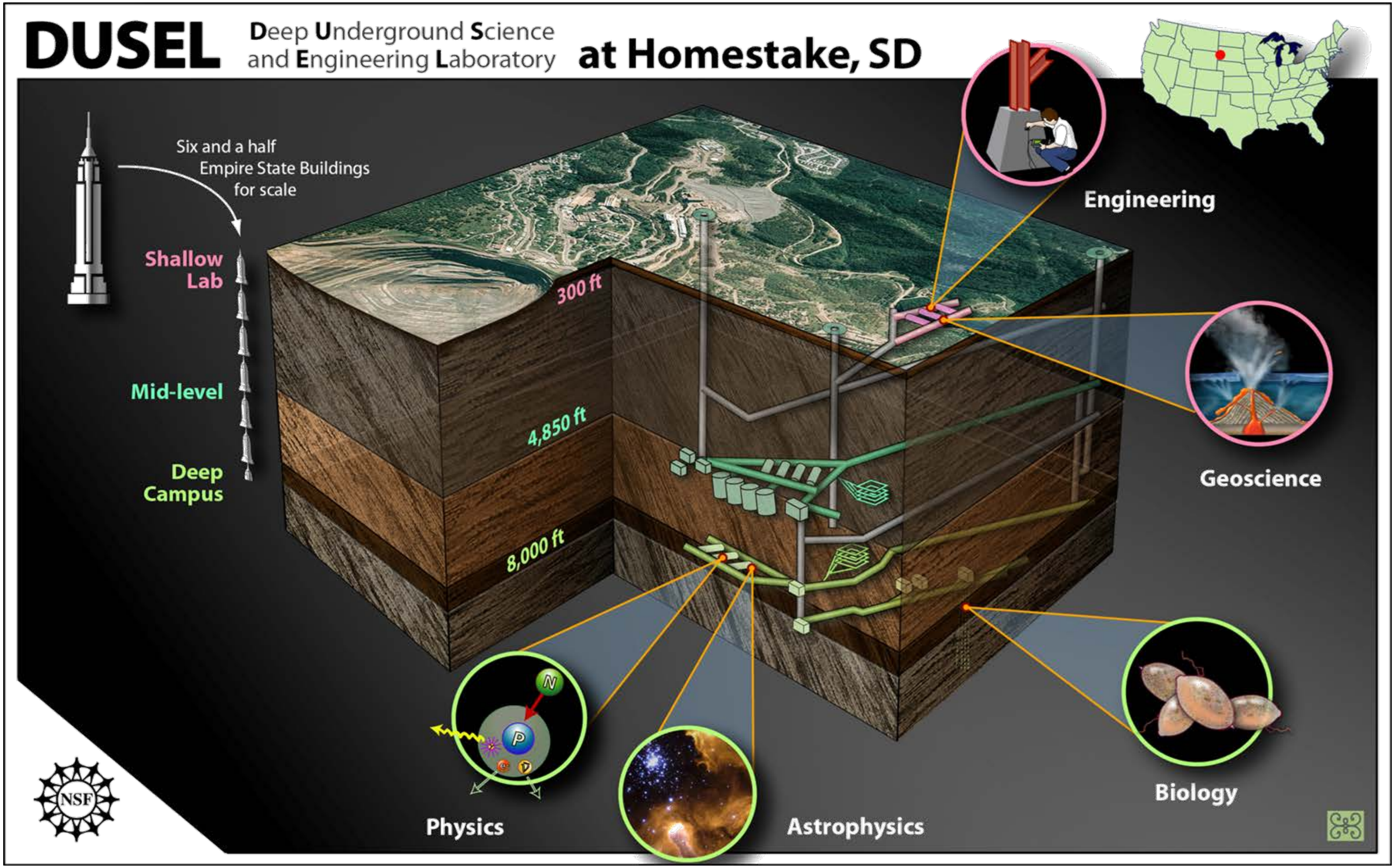
European **L**aboratory for
Experimental **N**uclear **A**strophysics

- commercial potash and salt mine
- Cleveland Potash Ltd
- deepest mine in Britain
  (850m to 1.3km deep)

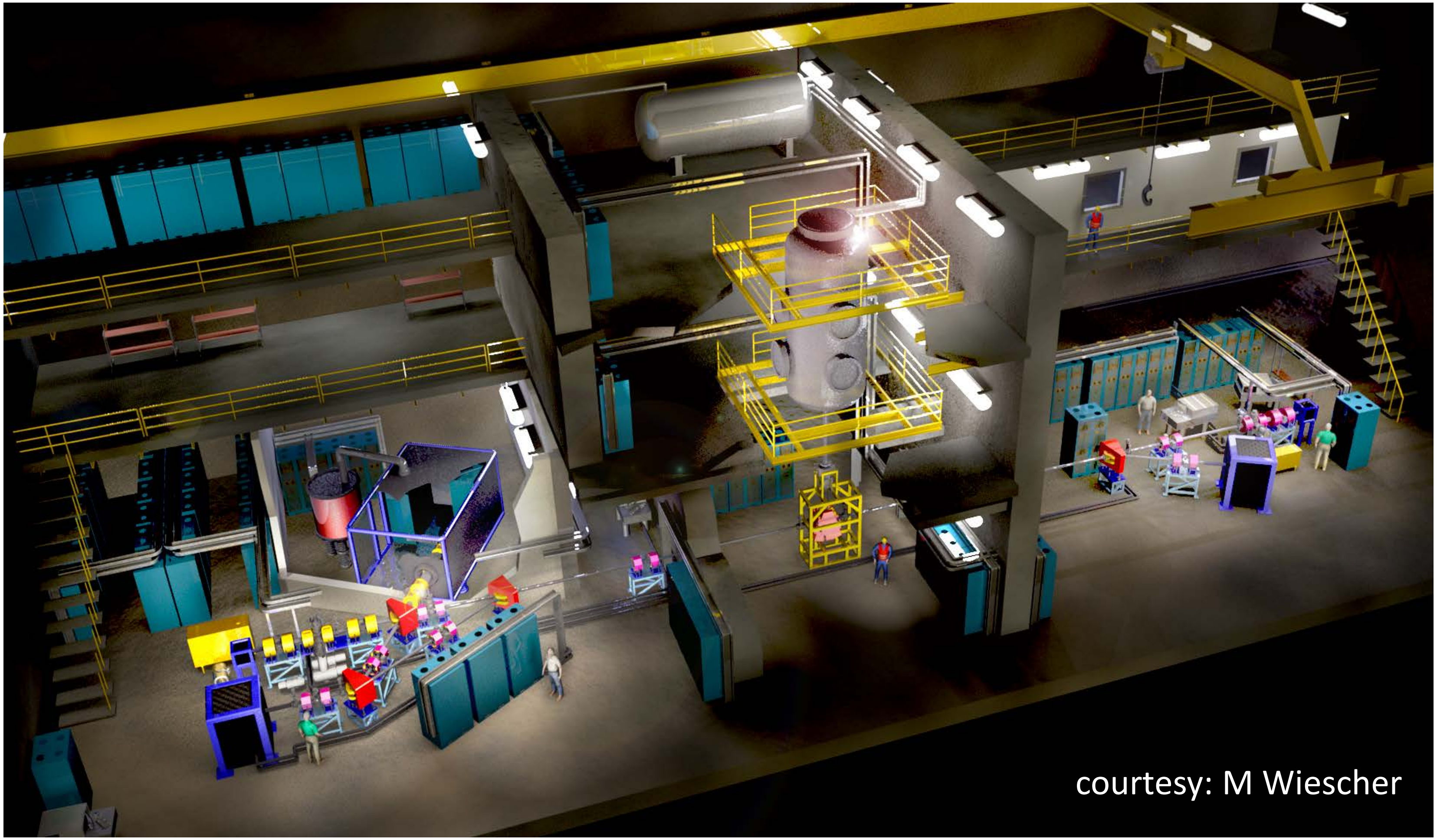


DIANA

Dual/**D**akota/**D**USEL **I**on **A**ccelerator for **N**uclear **A**strophysics



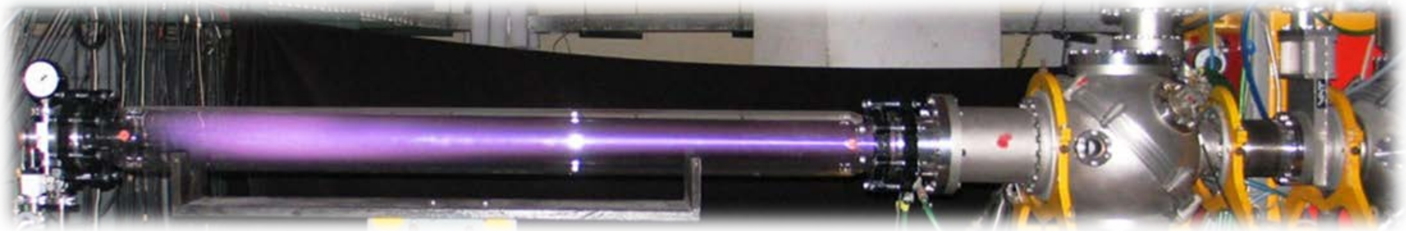
DIANA design


courtesy: M Wiescher

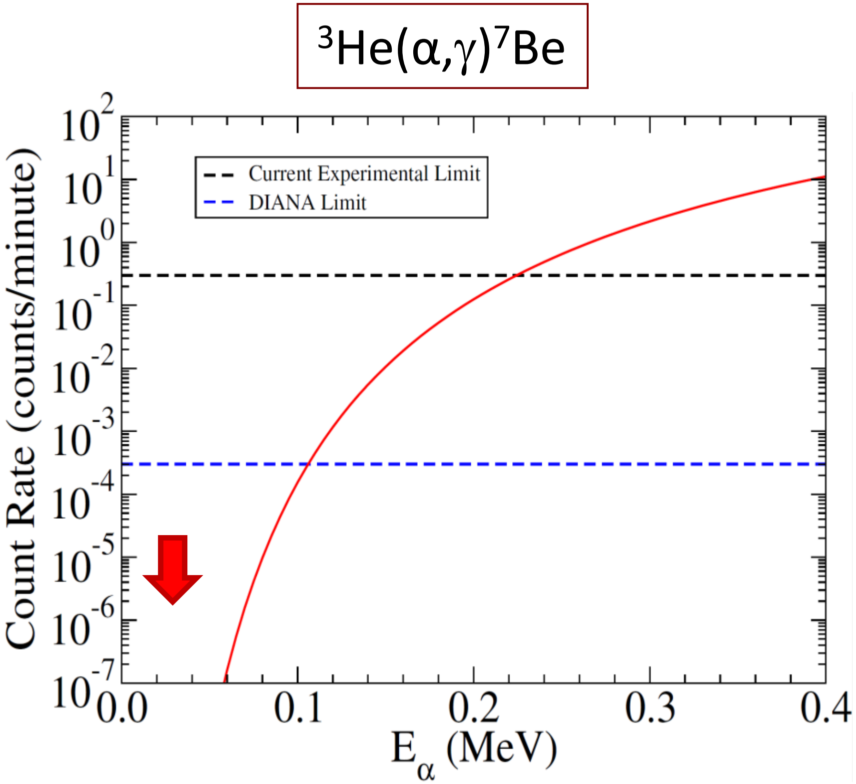
E=10 keV-3.0 MeV
I=0.5 mA to 10 mA
$\rho=10^{19}$ prt/cm^2

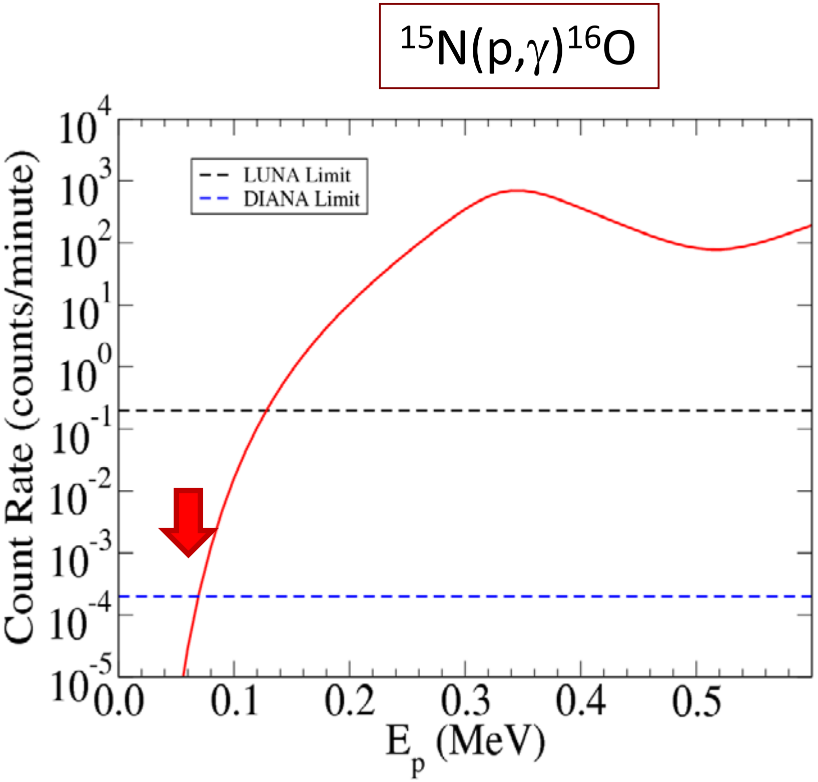
p, α, HI beams
100 x LUNA luminosity

Yield and count rate estimate



Beam intensity: 10mA, target density 10^{18} g/cm^2 gas jet





increase in luminosity → up to 3 orders of magnitude improvement compared to LUNA

courtesy: M Wiescher