Underground Laboratories

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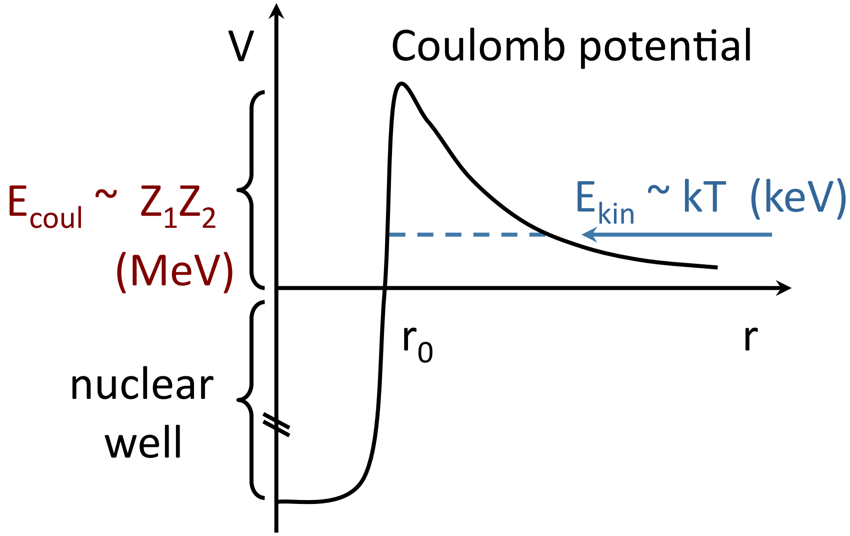
Nuclear reactions between charged particles

charged particles → Coulomb barrier

energy available: from thermal motion

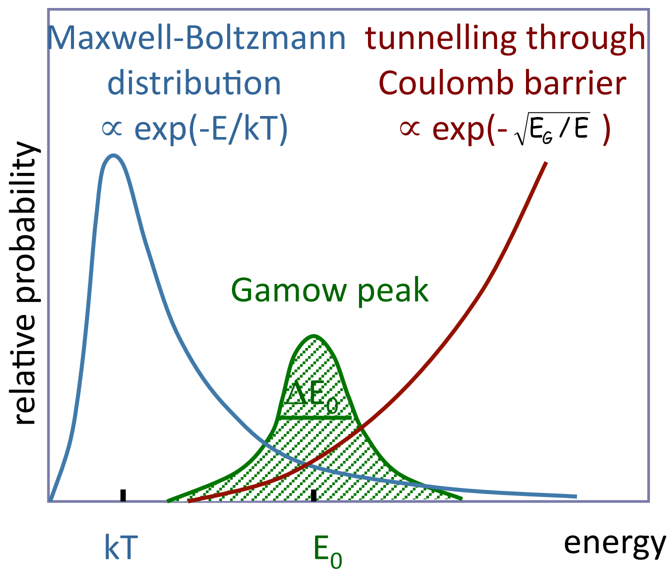


during static burning: $kT \ll E_{coul}$

$T \sim 15 \times 10^6$ K (e.g. our Sun) $\Rightarrow$ $kT \sim 1$ keV

reactions occur through TUNNEL EFFECT

→ tunneling probability $P \propto \exp(-2\pi\eta)$



Gamow peak: energy of astrophysical interest where measurements should be carried out

$kT \ll E_0 \ll E_{coul}$

10^{-18} barn $< \sigma < 10^{-9}$ barn

↓

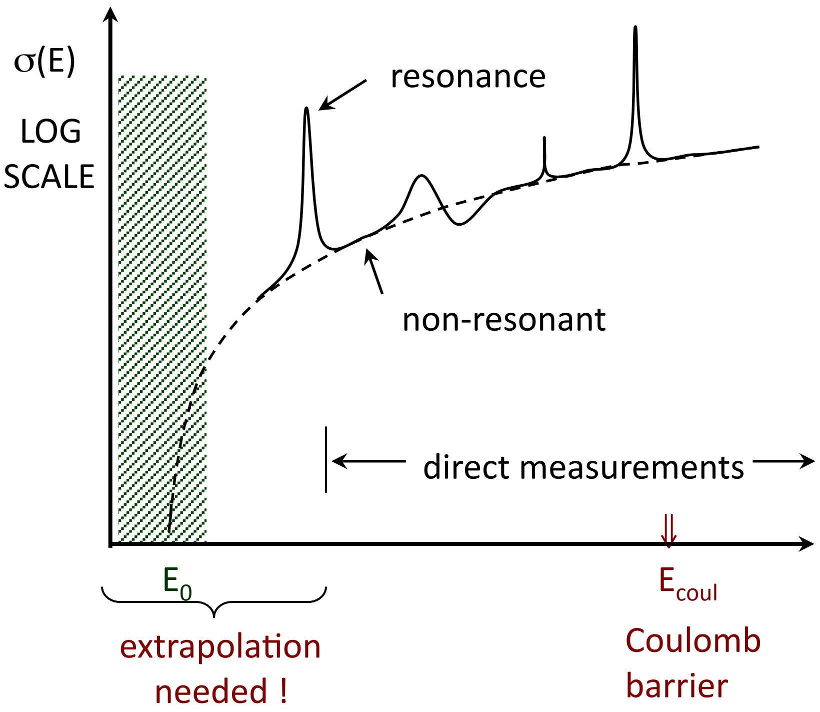
major experimental challenges

Experimental approach:

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

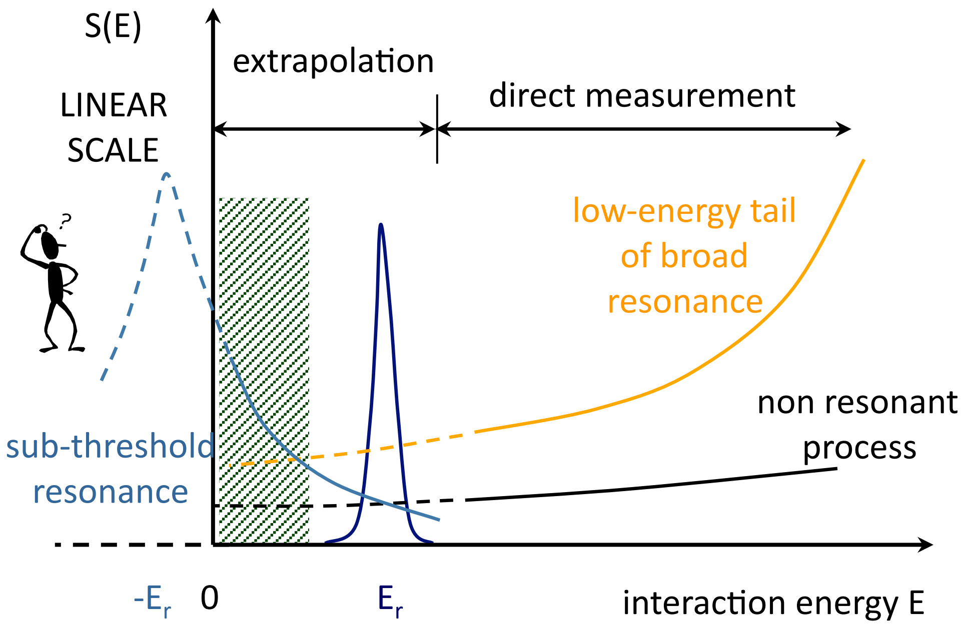
CROSS SECTION

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



S-FACTOR

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



DANGER OF EXTRAPOLATION !

what is measured in the laboratory: reaction yield

$$Y = N_p \, N_t \, \sigma \, \varepsilon$$

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

Y = 0.3-30 counts/year

challanges

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:

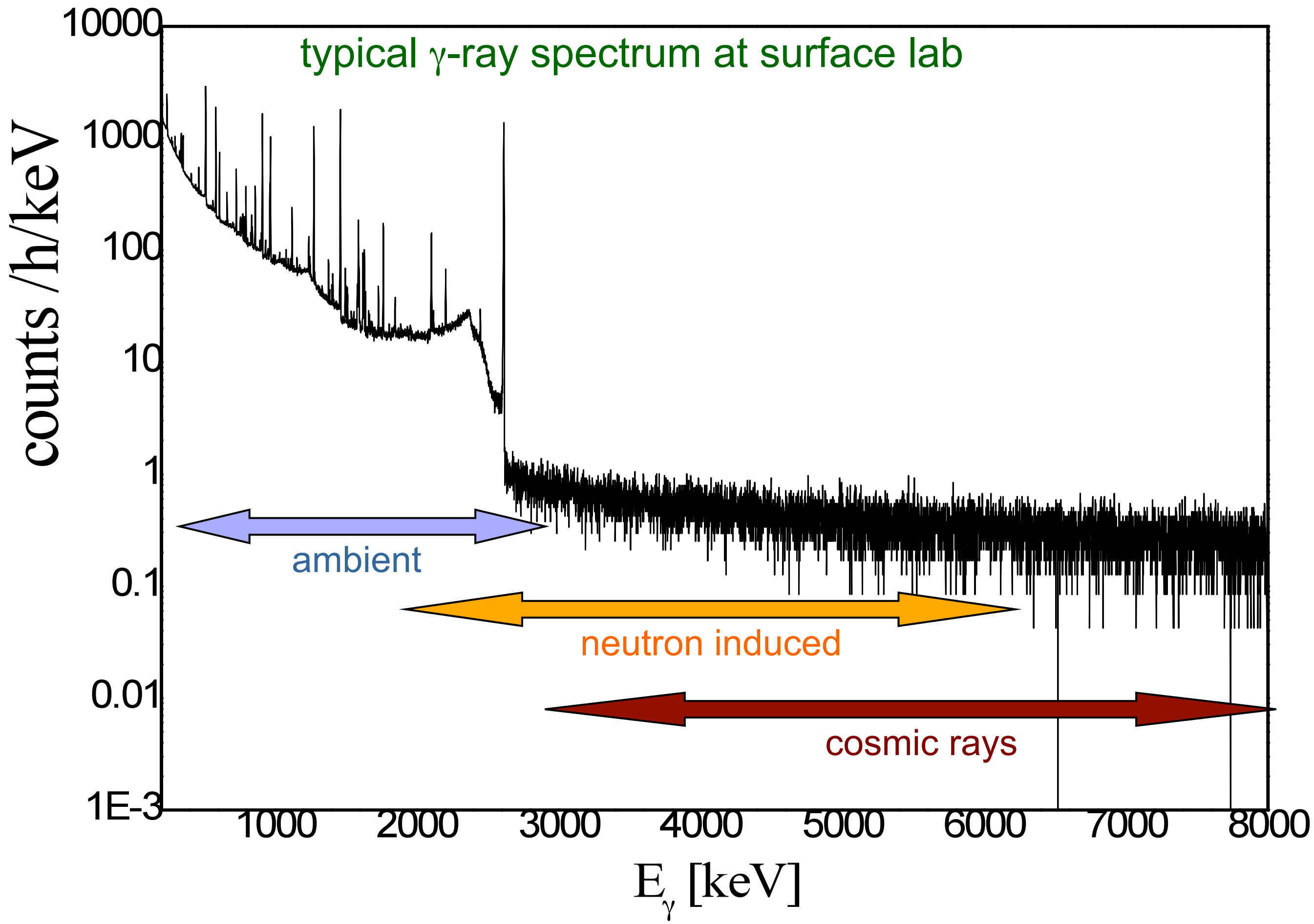
- interaction of cosmic muons with detection setup
- charged particles from natural background
- neutron-induced reactions

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

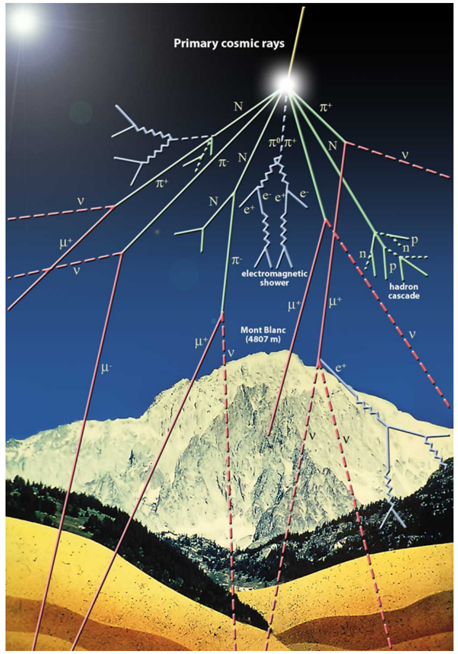
Main Sources of Background:

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



underground location

+ low U and Th environment



major advantages:

in all cases where background is dominated by cosmic rays

poor signal-to-noise ratio at surface level (e.g. neutron-induced background)

limited, though not negligible, advantages:

in all cases where background is mostly beam-induced

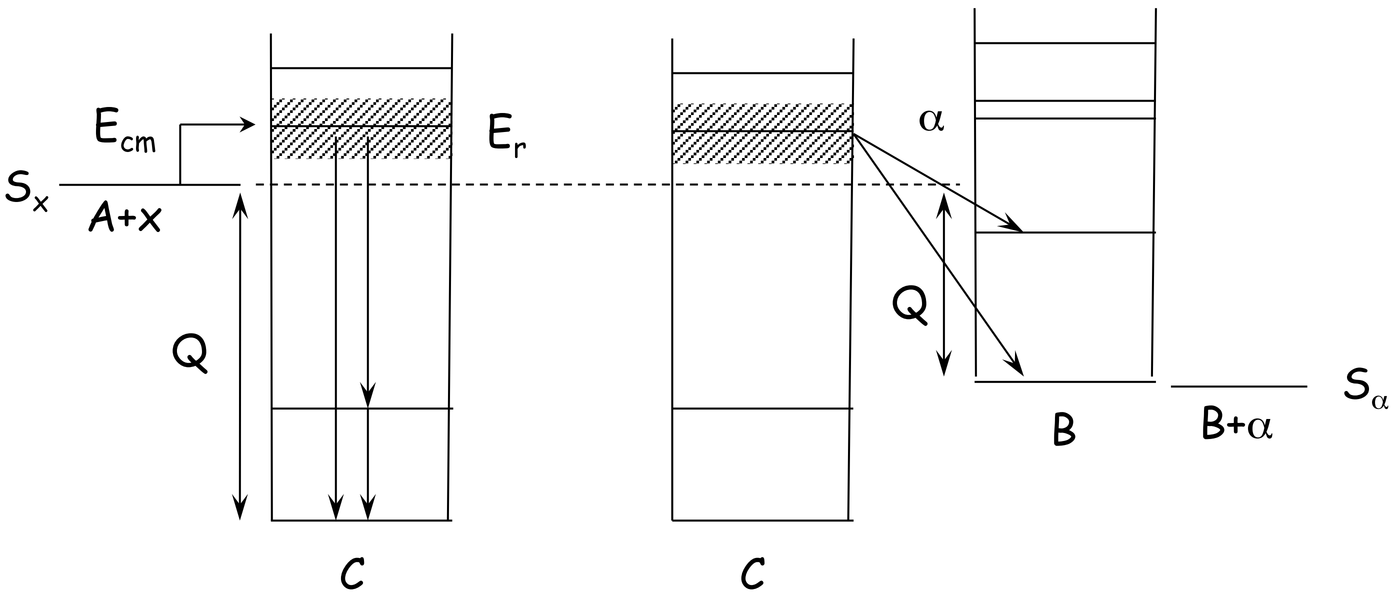
background arising from laboratory environment reactions of interest to astrophysics:

radiative capture: (p,γ) or (α,γ)

transfer reactions: (p,α) or (α,p)

entrance channel energy is low

outgoing particle's and/or gamma-ray's energies dominated by reaction Q-value:

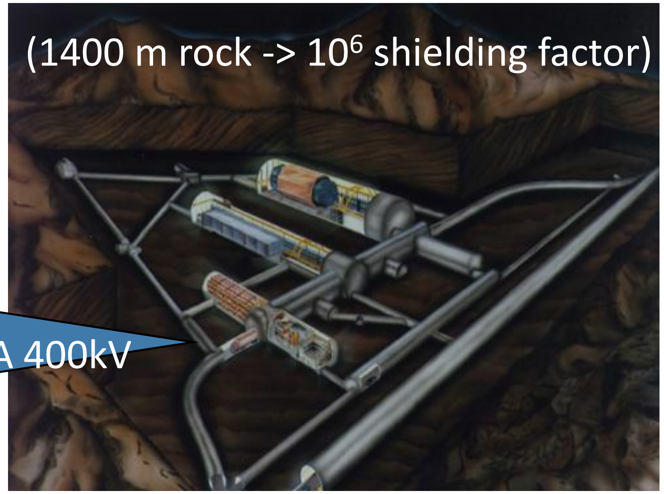


The LUNA facility

LUNA (Laboratory Underground for Nuclear Astrophysics)

Gran Sasso - Italy

Laboratori Nazionali del Gran Sasso



Radiation	LNGS/surface
muons	10^{-6}
neutrons	10^{-3}
photons	10^{-1}

The (present) LUNA Collaboration

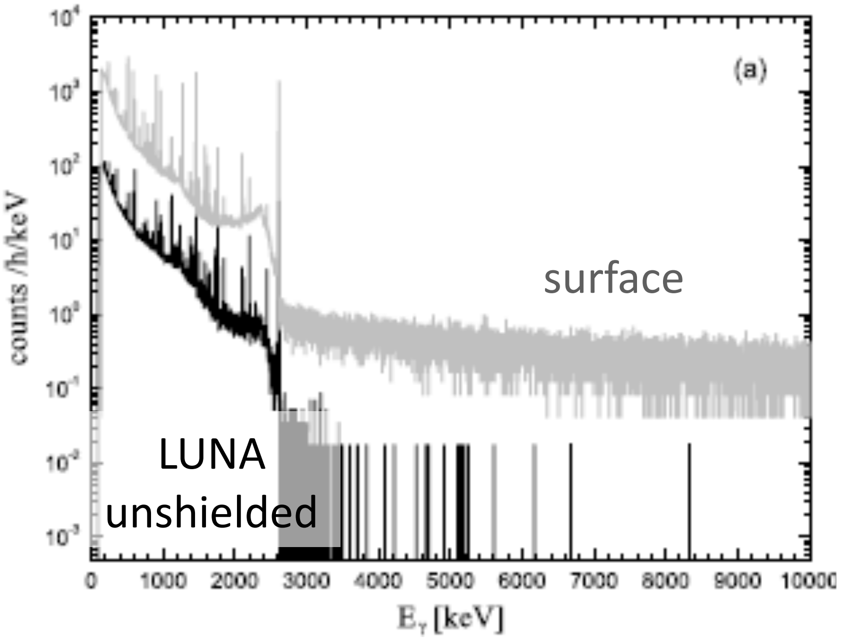
Italy (INFN Gran Sasso, Napoli, Genova, Padova, Milano, Torino)

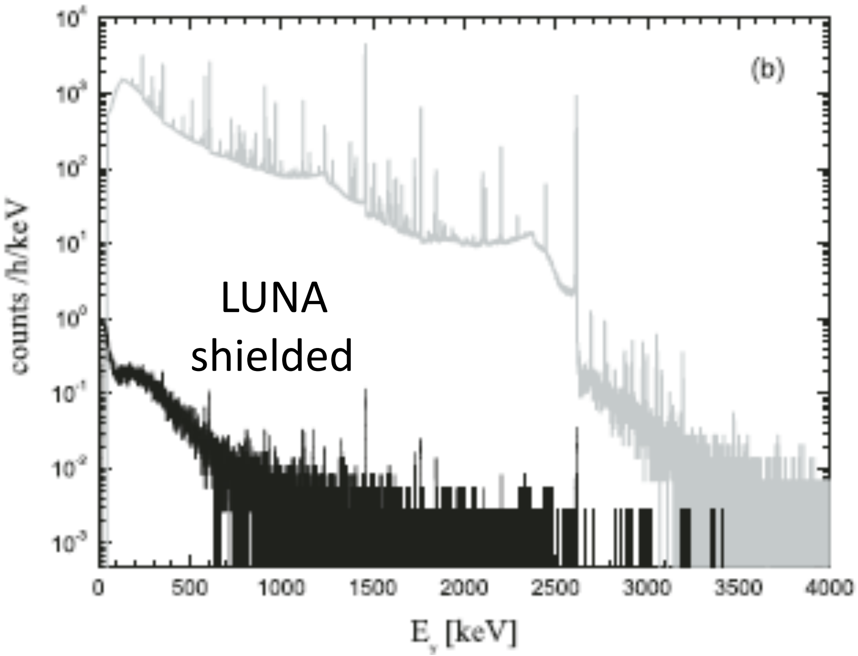
Germany (Bochum, Dresden)

Hungary (Debrecen)

UK (Edinburgh)

γ-ray background at Gran Sasso





with lead shielding

much higher suppression factor
than with shielding at surface lab

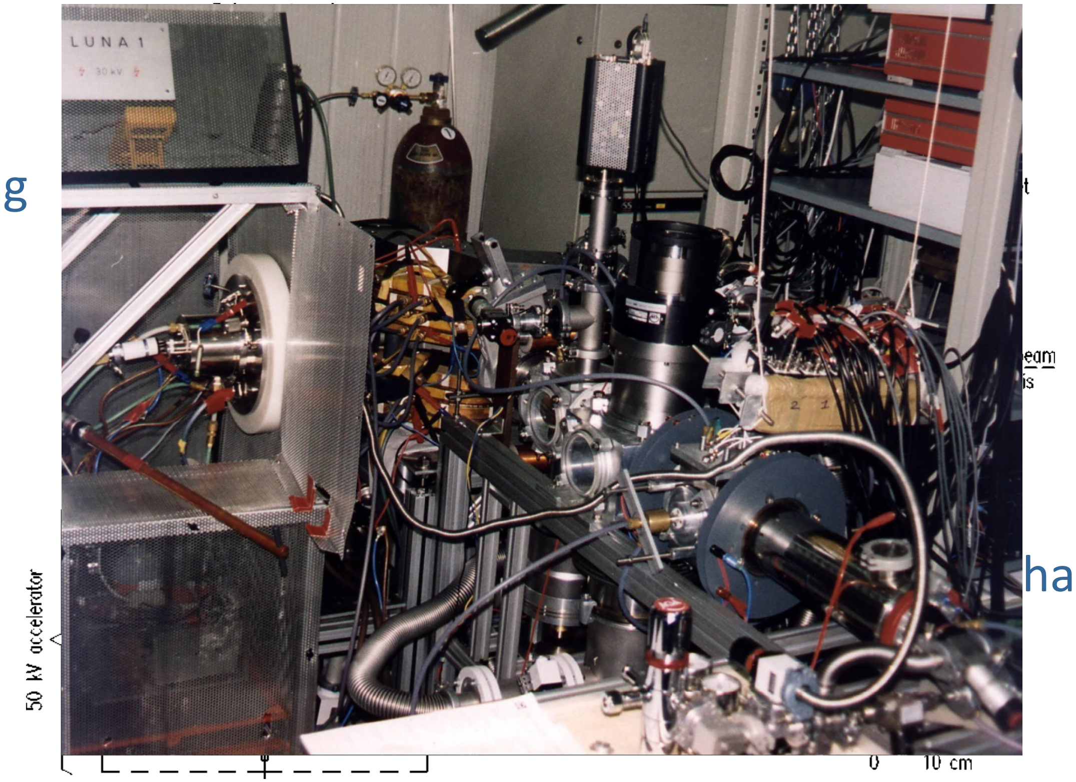
NB shielding becomes even more efficient underground

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

investigate reactions in solar pp chain

90° analysing magnet

duoplasmatron ion source on 50kV platform



hamber

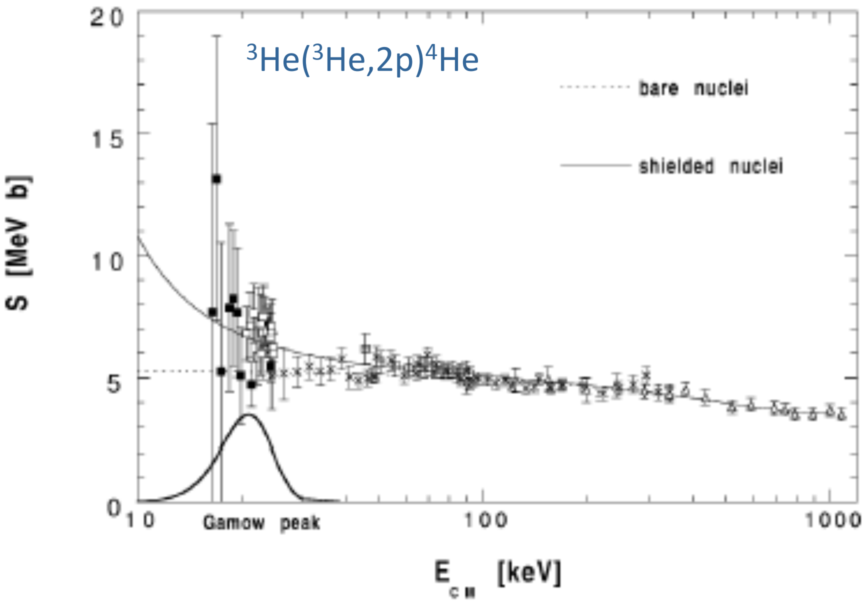
entirely built by students!

LUNA (use the Moon to study the Sun)

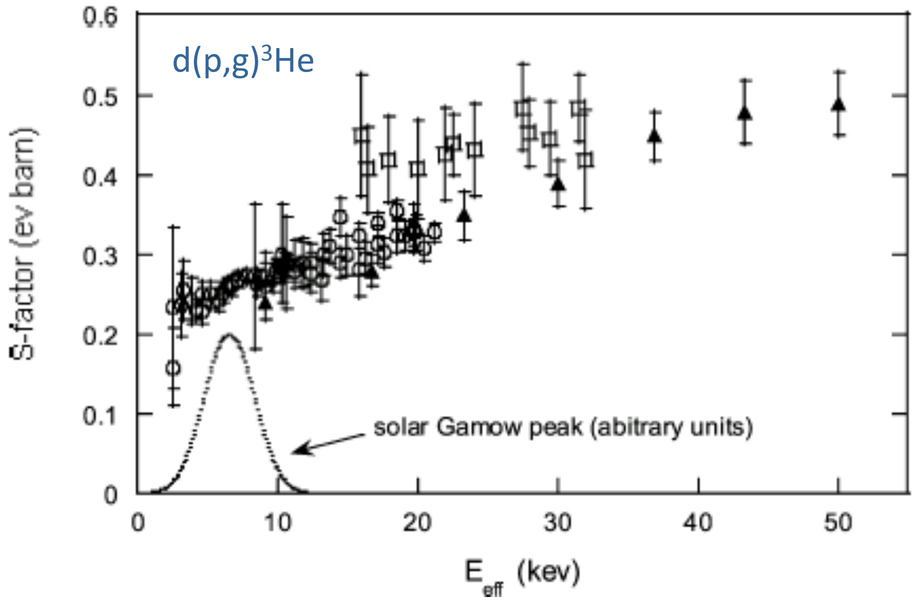
LUNA – Phase I: 50 kV accelerator (1992-2001)

investigate reactions in solar pp chain

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



C. Casella et al.: Nucl. Phys. A706 (2002) 203-216



@ lowest energy:

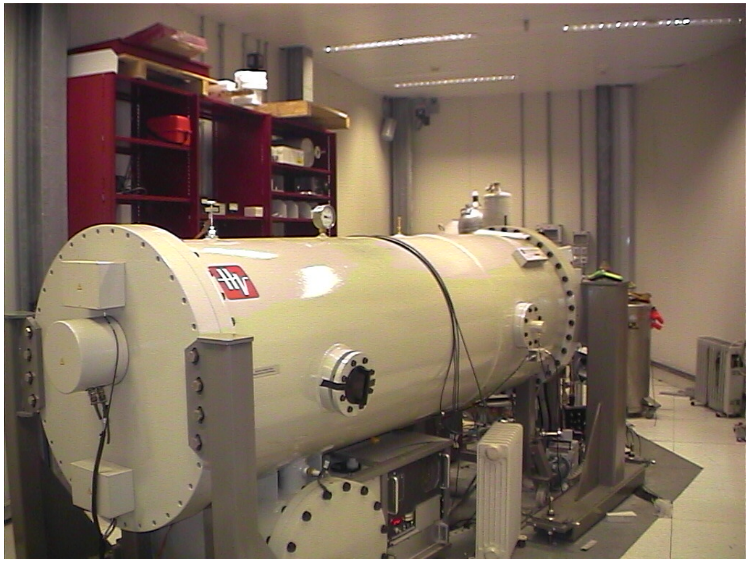
σ ~ 20 fb → 1 count/month

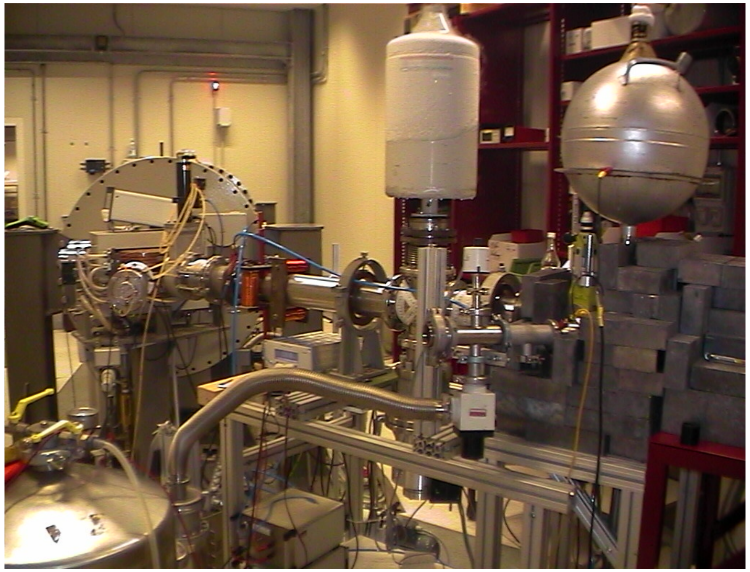
@ lowest energy:

σ ~ 9 pb → 50 counts/day

only two reactions studied directly at Gamow peak

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

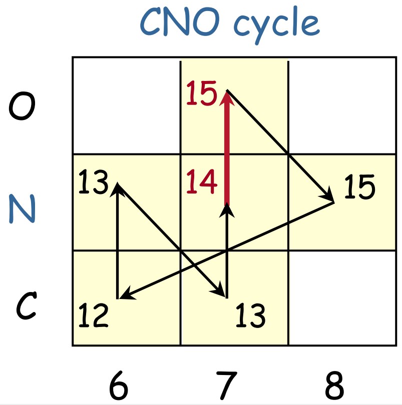




$^{14}N(p,\gamma)^{15}O$

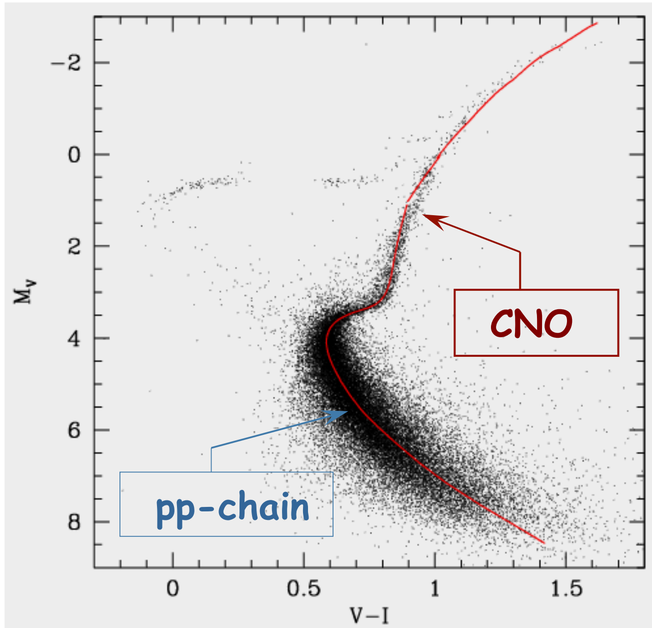
slowest reaction

in CNO cycle



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 !!

Reactions measured so far at or near Gamow region:

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

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

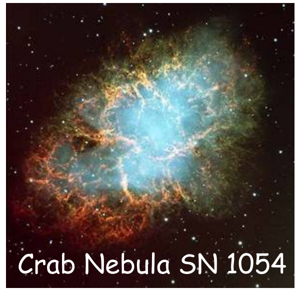
Limitations

- 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

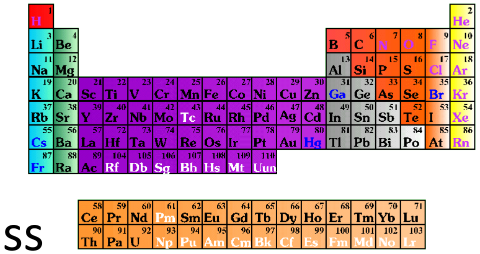
!! new underground facilities are very much needed !!

key open questions



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

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



- *where and how are heavy elements produced?*

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

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

  Ne, Na, Mg and Al nucleosynthesis [(p,g) and (p,a) reactions]

Late stages of stellar evolution

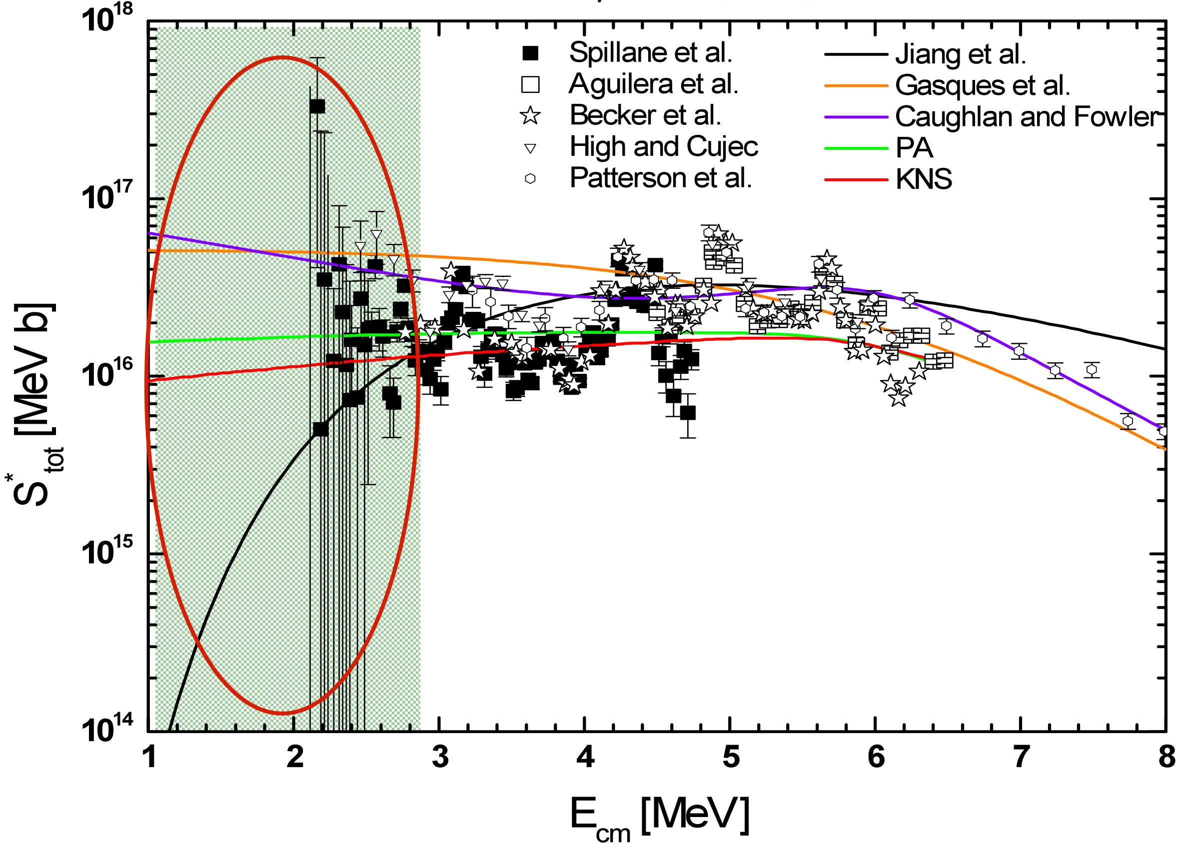
$^{12}C+^{12}C$

importance: evolution of massive stars

astrophysical energy: 1 – 3 MeV

minimum measured E: 2.1 MeV (by γ-ray spectroscopy)

Strieder, J. Phys. G35 (2008) 14009



extrapolations differ by 3 orders of magnitude

large uncertainties in astrophysical models of stellar evolution and nucleosynthesis

options for improvements of surface measurements: exhausted

underground measurements required

Neutron sources for heavy elements

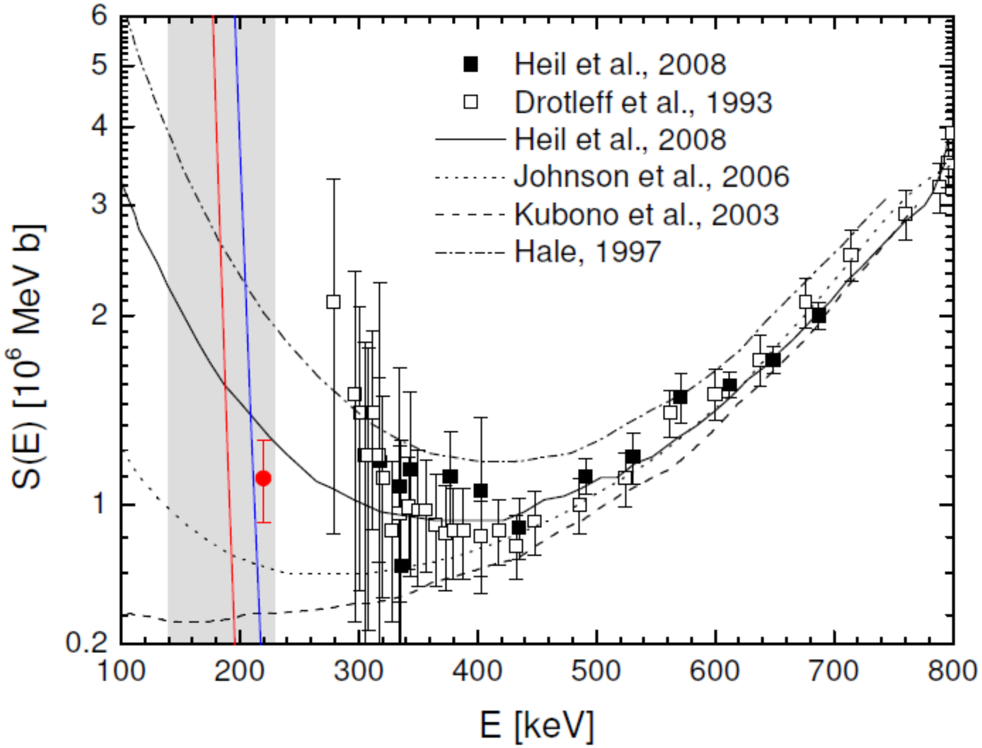
$^{13}C(\alpha,n)^{16}O$

importance: neutron source for *s-process* in AGB stars

astrophysical energies: 130 - 250 keV

minimum measured E: 270 keV

(s-process = *slow* neutron-capture for heavy elements nucleosynthesis)



options for improvements of surface measurements: exhausted

underground measurements required

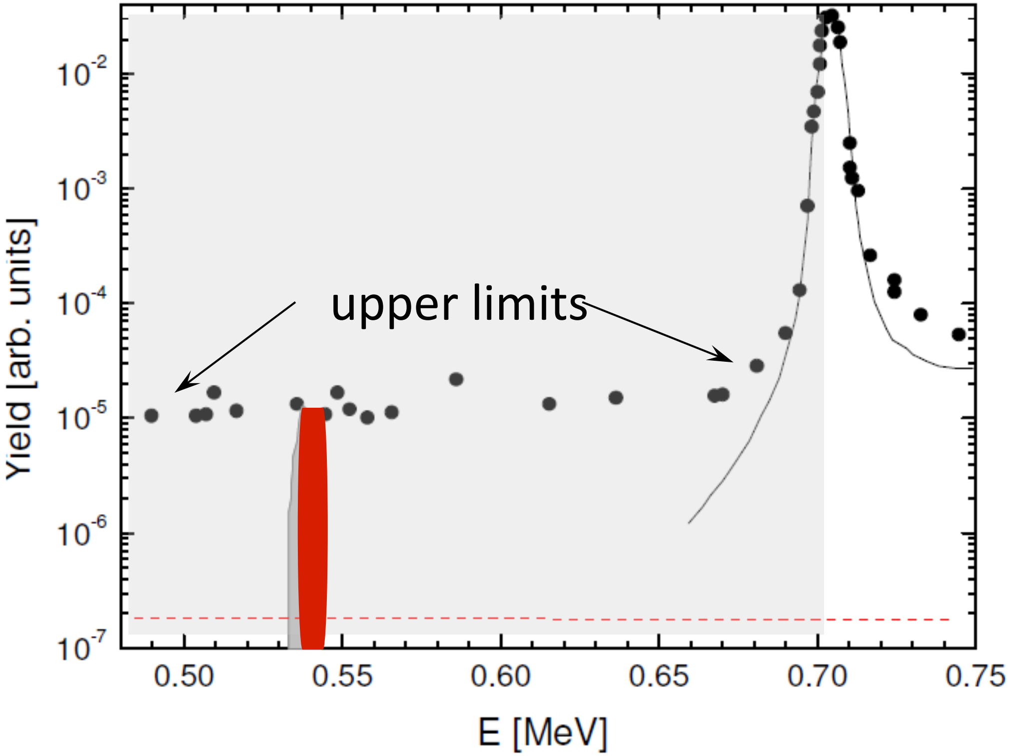
$^{22}Ne(\alpha,n)^{25}Mg$

importance: s-process in AGB stars

astrophysical energies: 400 - 700 keV

minimum measured E: ~680 keV

current status



options for improvements of surface measurements: exhausted

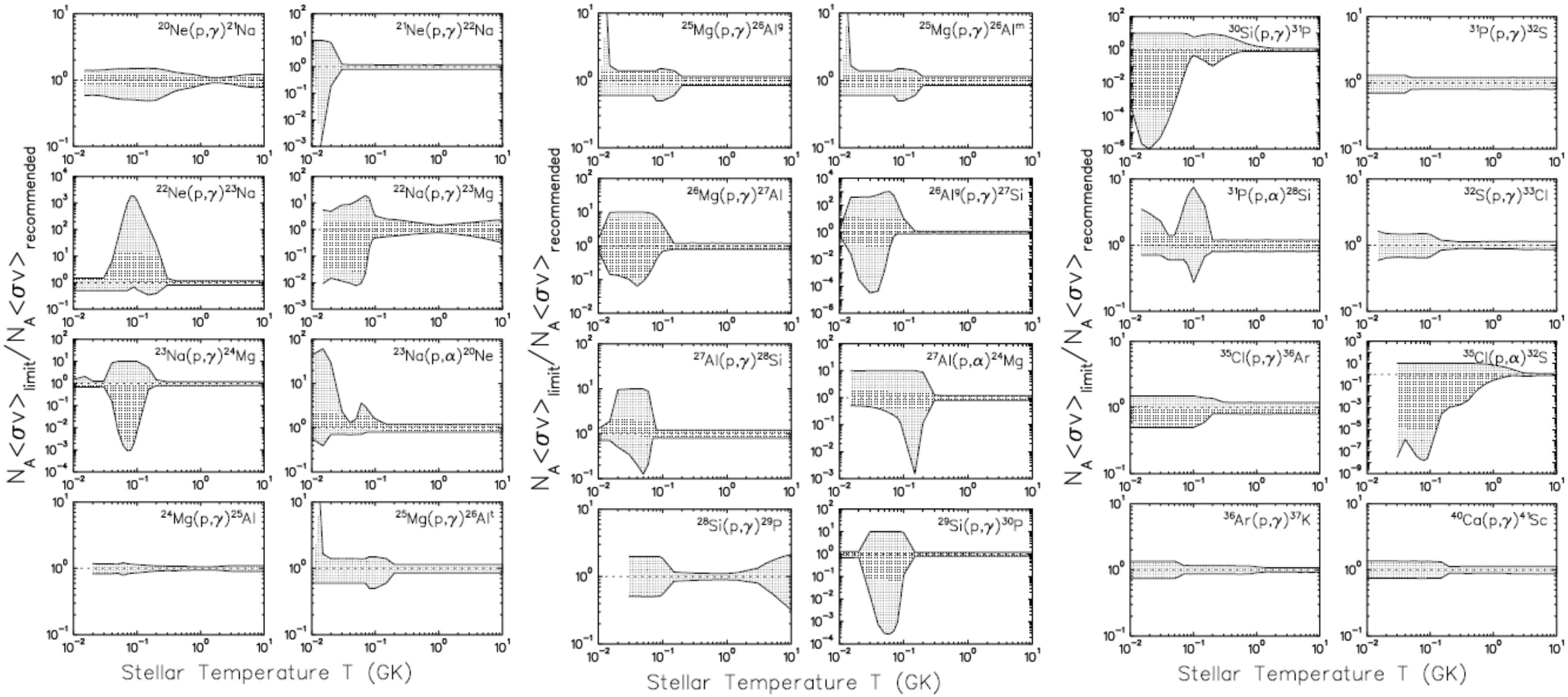
underground measurements required

Other examples

abundances of Ne, Na, Mg, Al, … in AGB stars and nova ejecta

affected by many (p,γ) and (p,α) reactions

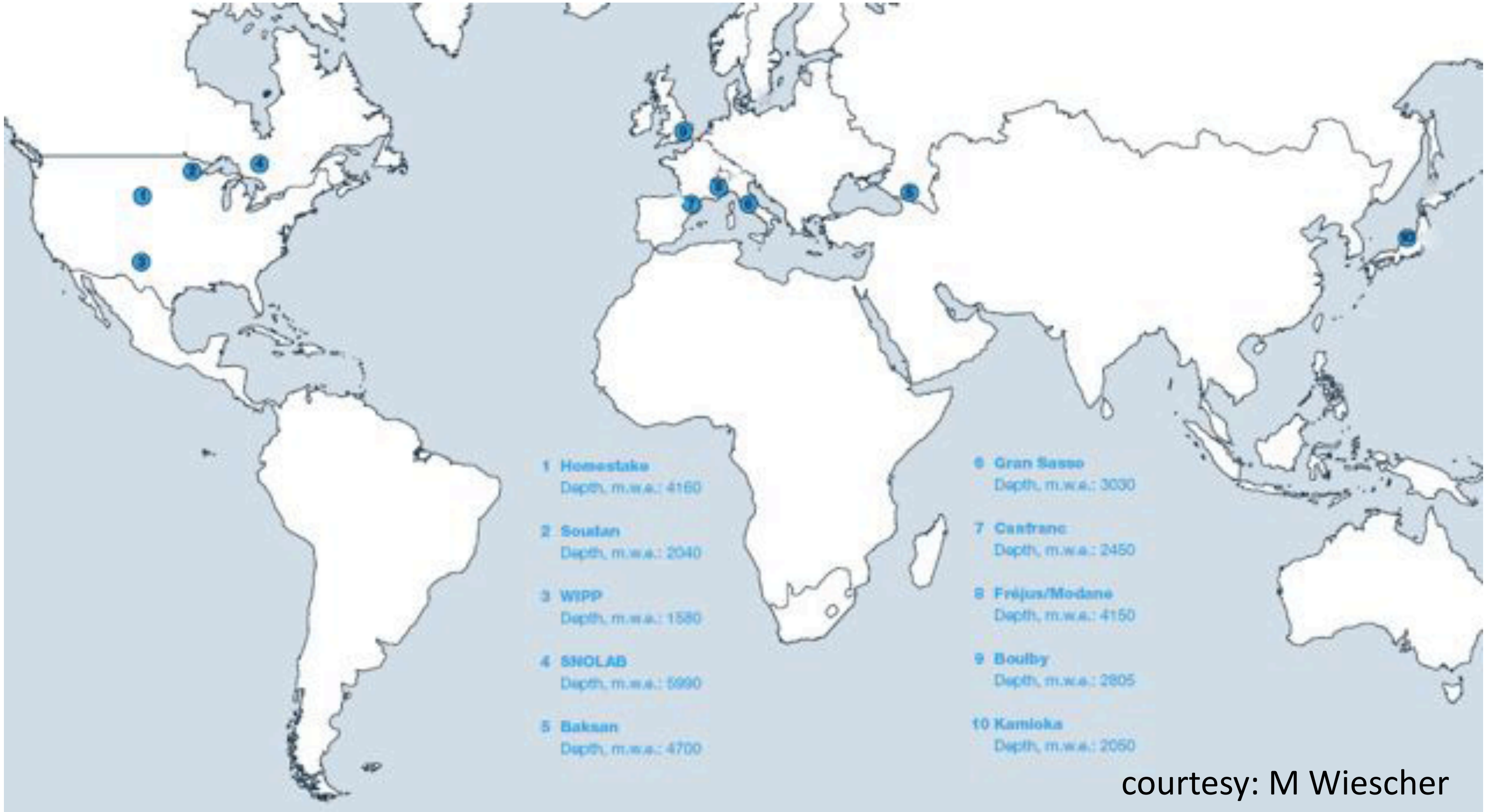
shaded areas indicate order of magnitude(s) uncertainties



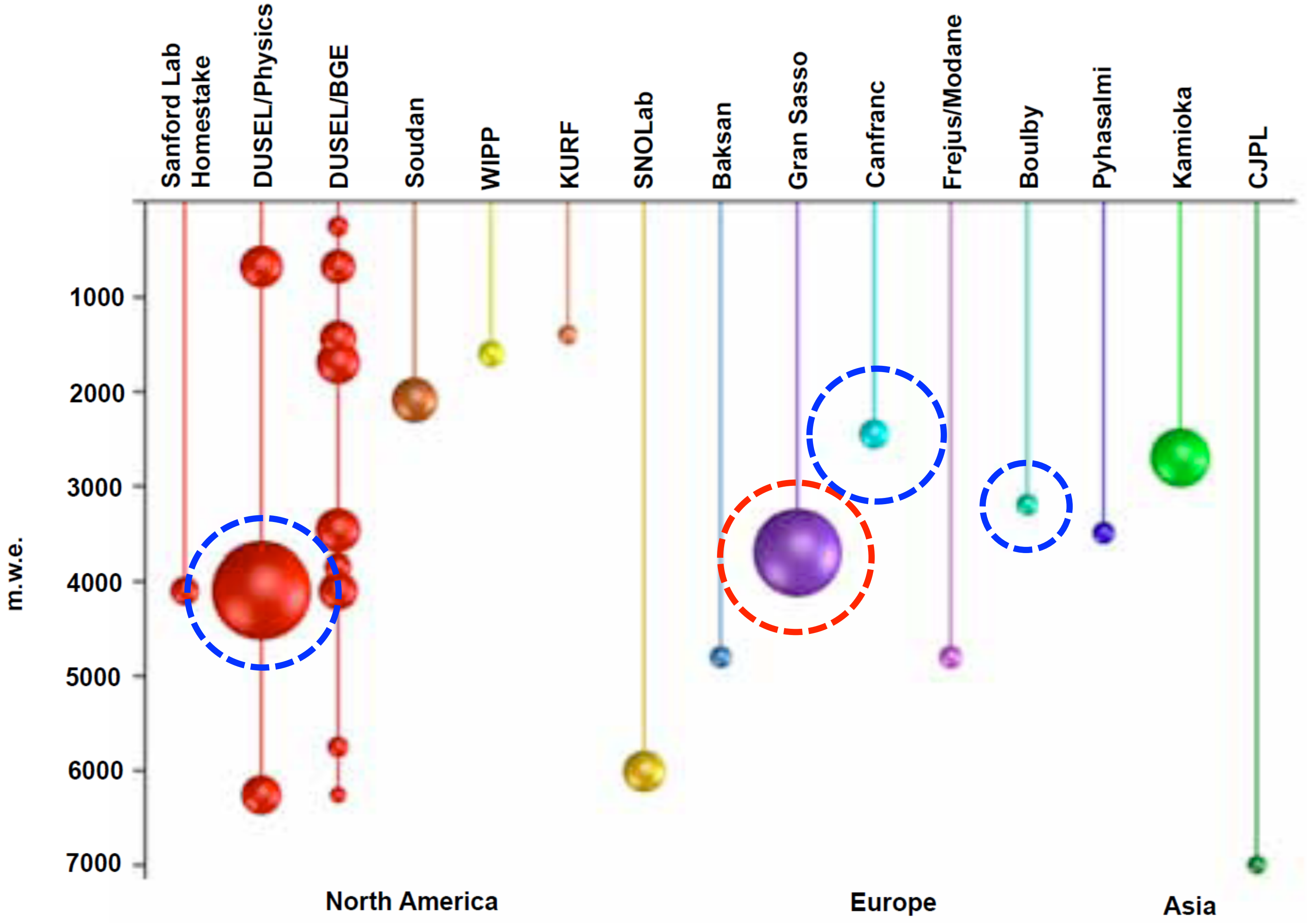
Iliadis et al. ApJ S134 (2001) 151; S142 (2002) 105; Izzard et al A&A (2007)

!! underground measurements are necessary !!

LUNA at Gran Sasso (Italy) ONLY underground NA laboratory in the WORLD



courtesy: M Wiescher



New projects: Andes, Argentina-Chile; INO, Saha Institute, Kolkata, India

projects in Europe

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

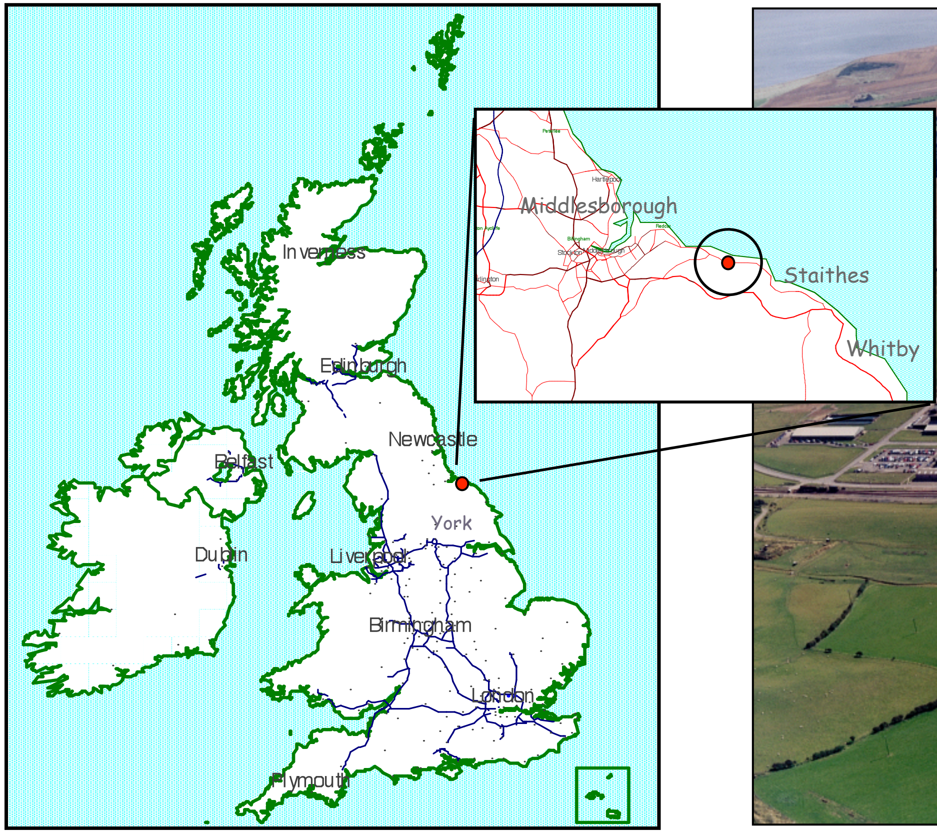
projects elsewhere

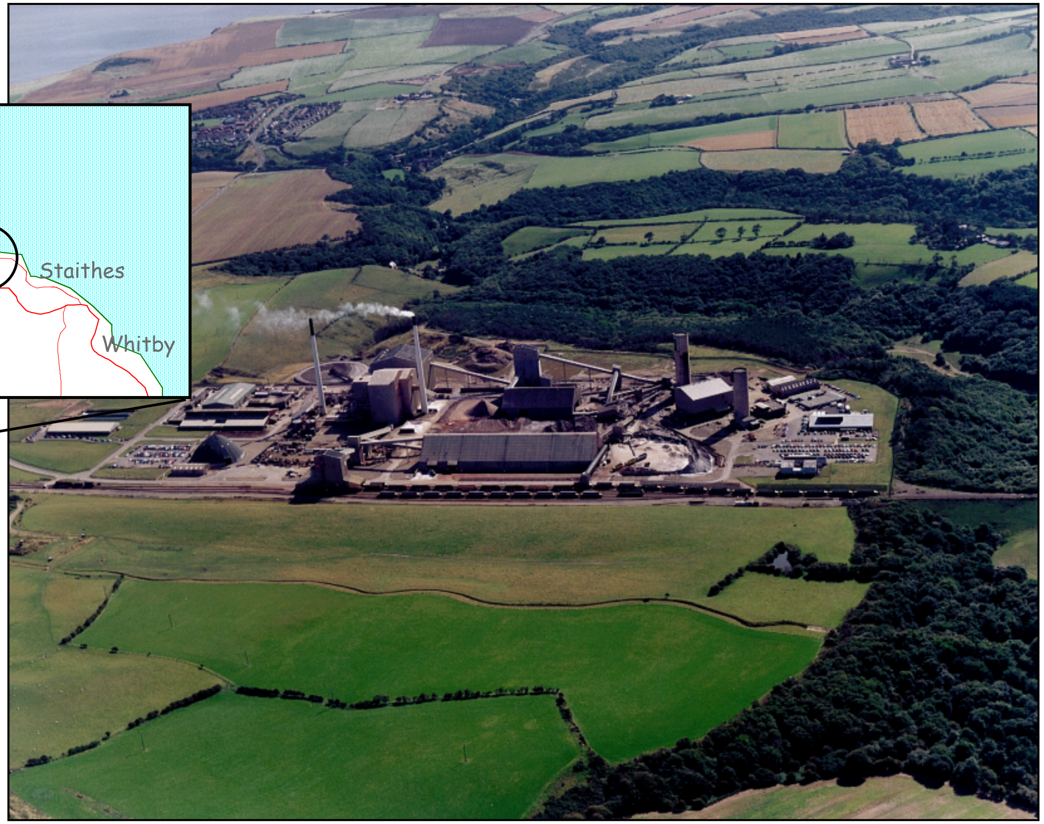
DIANA (US)
Andes (Chile/Argentina)
China
India

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)



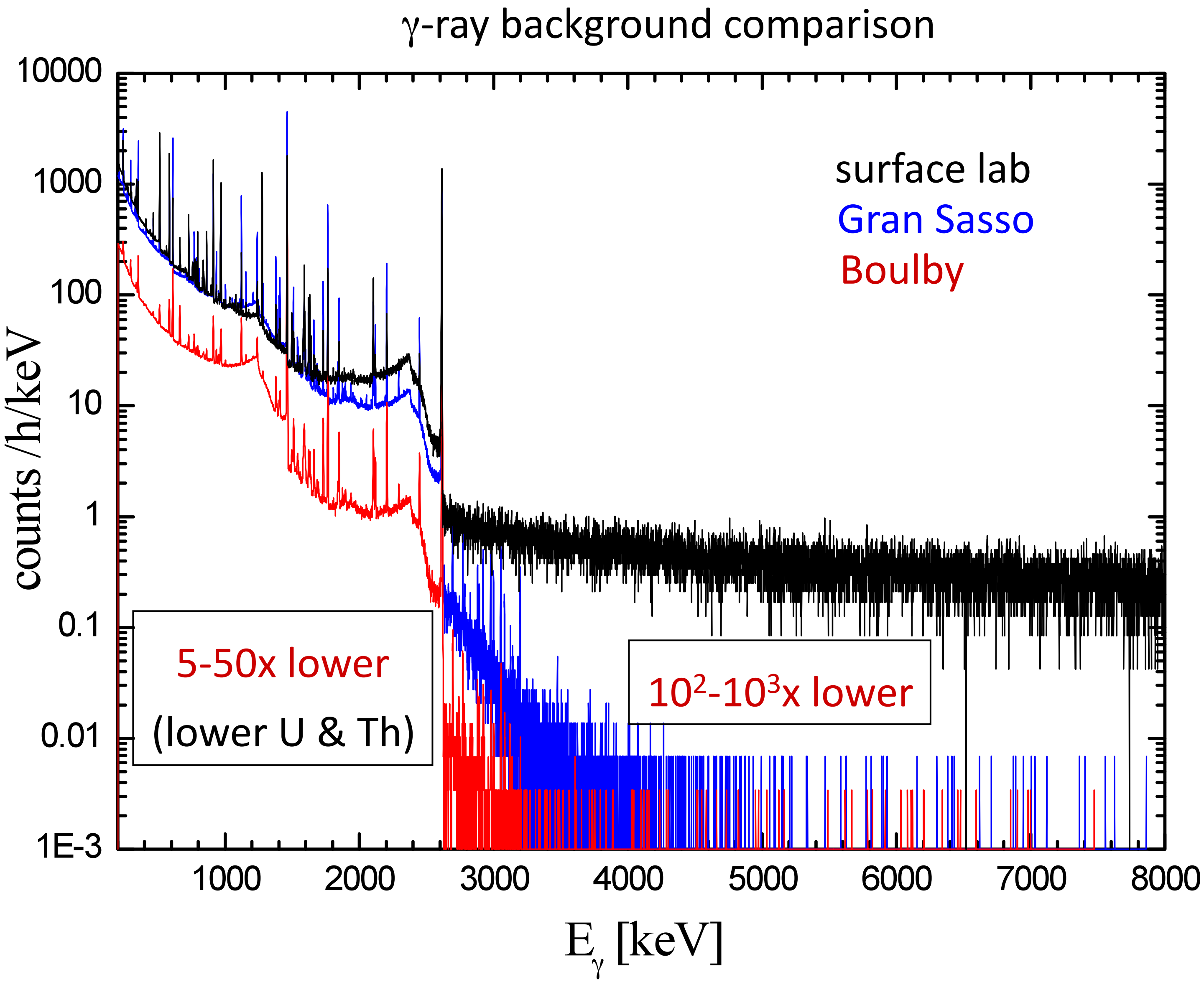


why is Boulby *ideal* for Nuclear Astrophysics?

deep mine 1100 m (2800 m.w.e.)	→ ~10^6 reduction in CR + uniform shielding
salt environment: low in U/Th	→ lower n- and γ-background
no space constraints	→ no *interference* issues
easy access for equipment	→ vertical shafts + underground transport
mine management support	→ infrastructure & services

BUT: following recent major cuts in the UK, proposal for feasibility study not funded

Background comparison



Canfranc Laboratory

LUNA MV Project

Felsenkeller Laboratory

The Canfranc Railway Tunnel

- neutron background measurements underway
- LoI to be submitted in October 2011
- pre-engineering design by end of 2011
- permit for excavation expected by 2012

LUNA MV upgrade

see Alessandra Gugliemetti's talk for further details

Felsenkeller

Shallow-underground option (47 m of rock overburden) in Dresden (Germany)

existing γ-analytics facility, established 1982

since 2009, also scientific use by HZDR and TU Dresden

background ~3 times worse than deep underground

currently looking for used accelerator

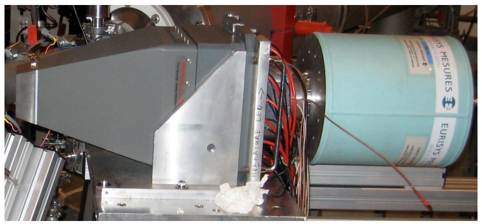
courtesy: D. Bemmerer

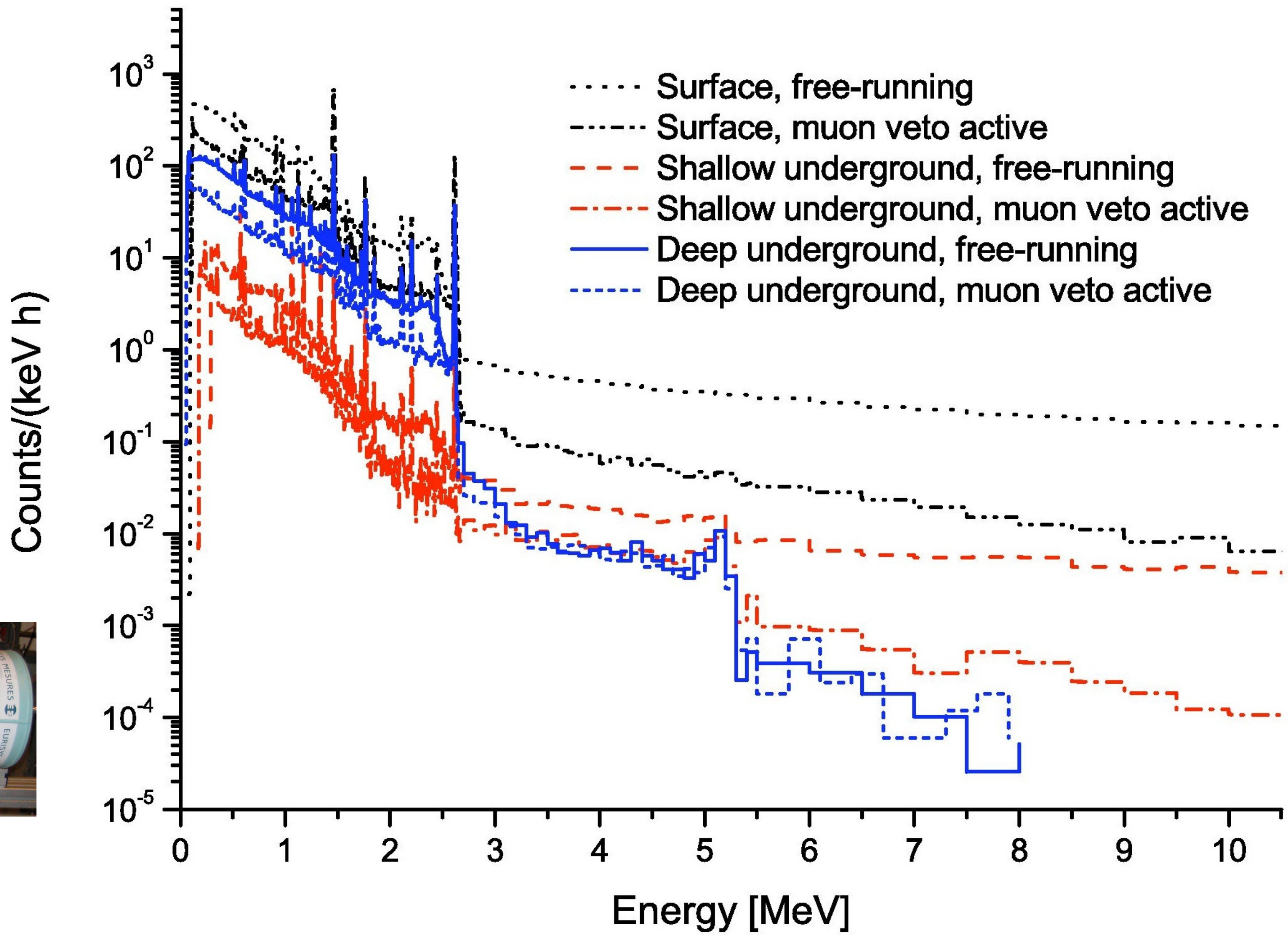
γ-background comparison in a "traveling" HPGe detector, combining rock overburden with active shield (muon veto)

CLOVER HPGe detector, with BGO anti-Compton shield

+at LUNA
T. Szücs et al., Eur. Phys. J. A 44, 513 (2010)

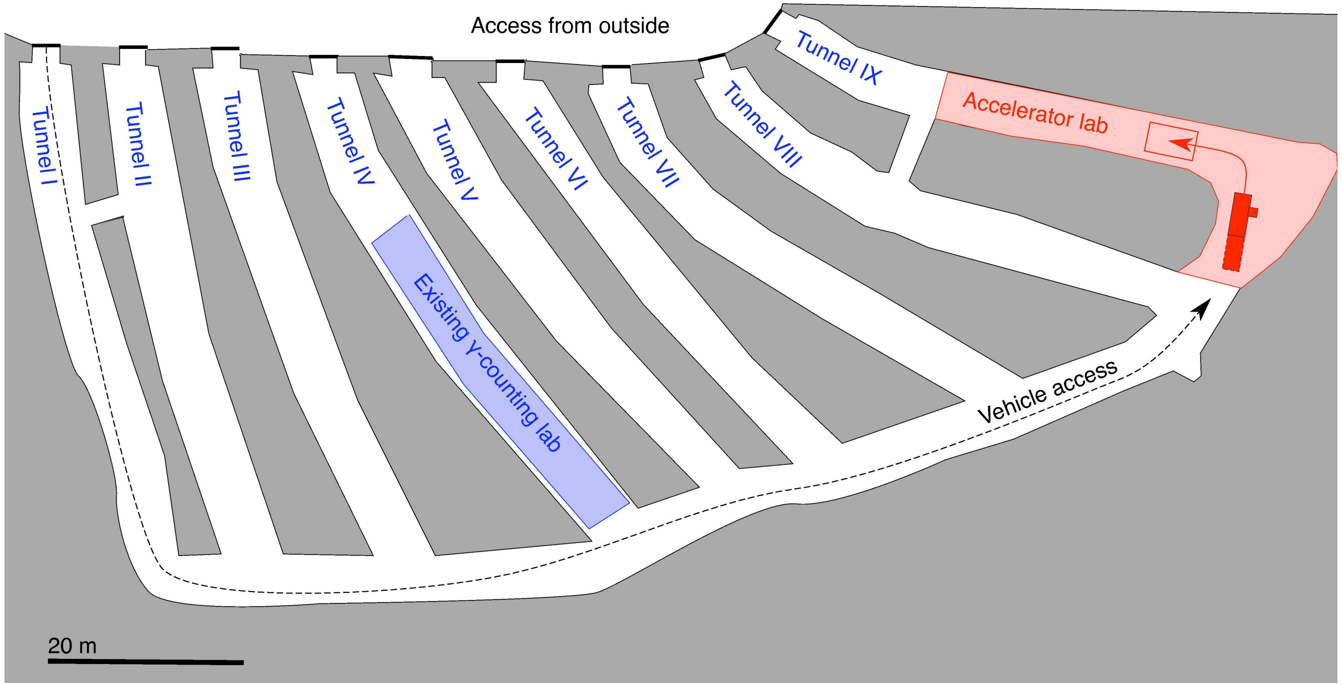
+at Felsenkeller





courtesy: D. Bemmerer

possible site for an accelerator

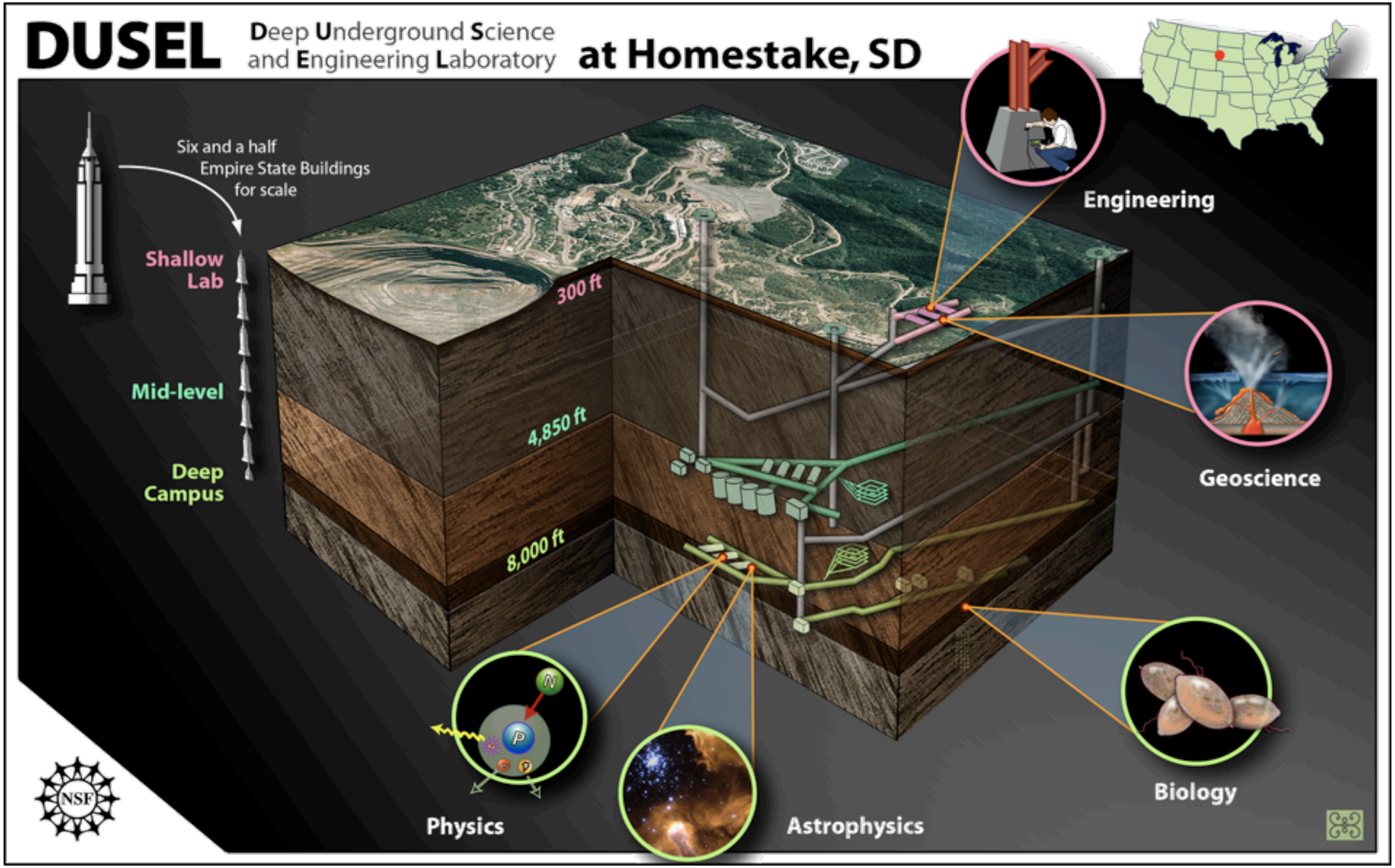


- Tunnels exist since the 1850s, currently used for storing sausage skins, truck parking, etc
- Startup possible with a used accelerator (ideally 3 MV, ion source on HV terminal)
- Open to international users
- May be part of a staged approach helping deeper-underground projects gather speed

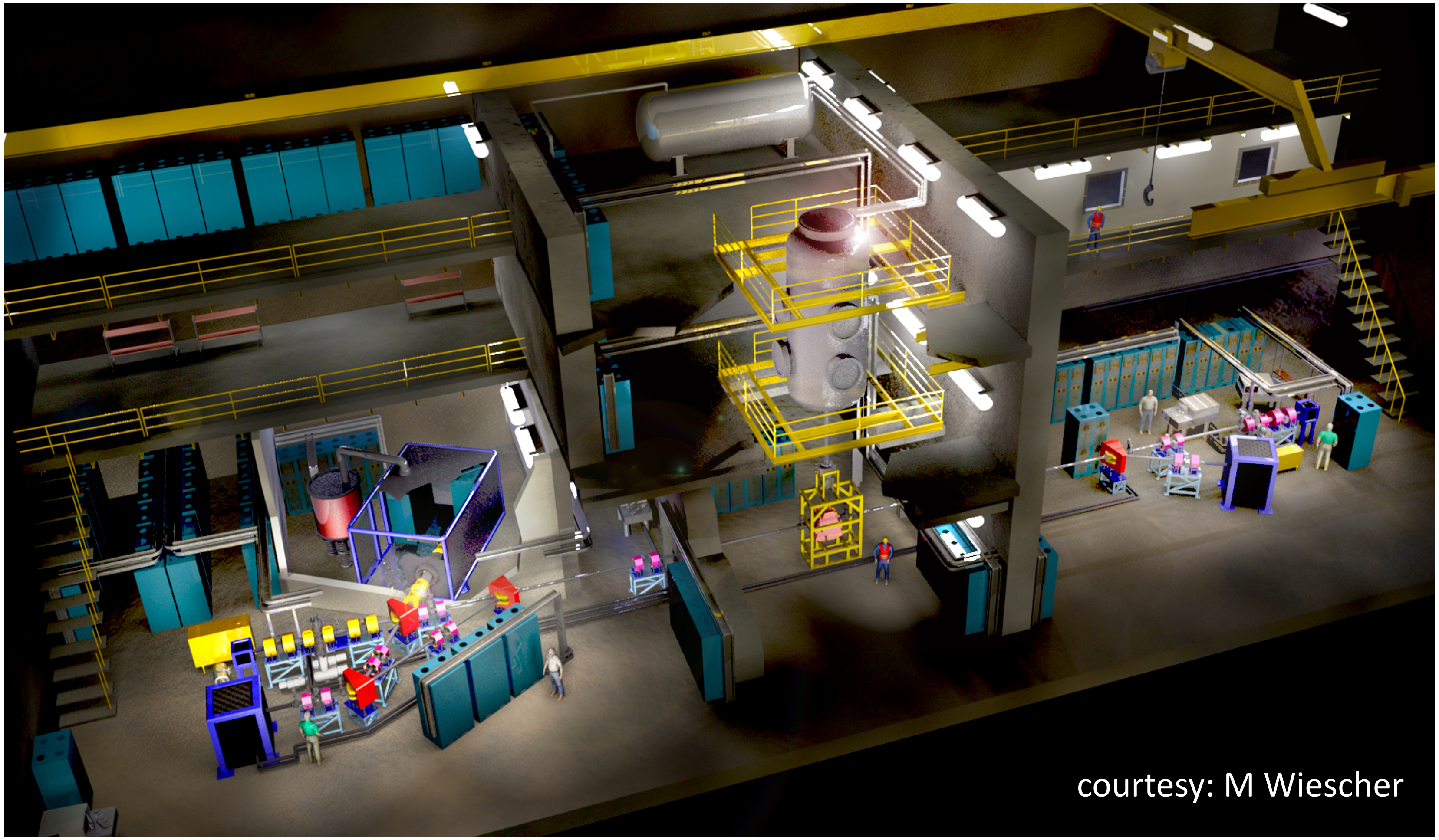
courtesy: D. Bemmerer

The DIANA Laboratory

Dual/Dakota/DUSEL Ion Accelerator for Nuclear Astrophysics



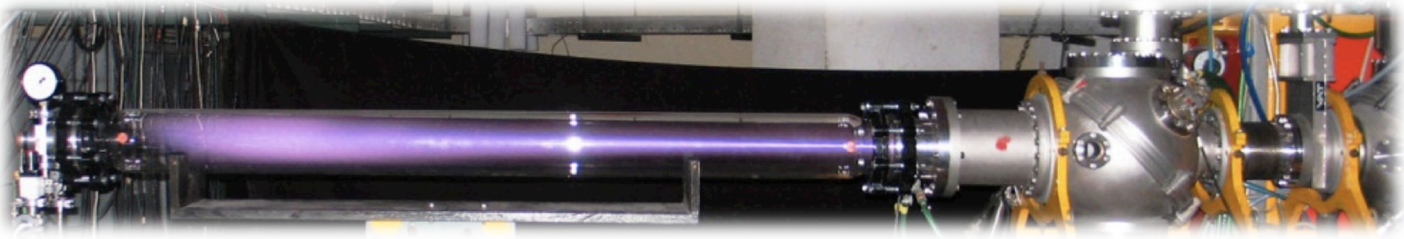
DIANA design



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

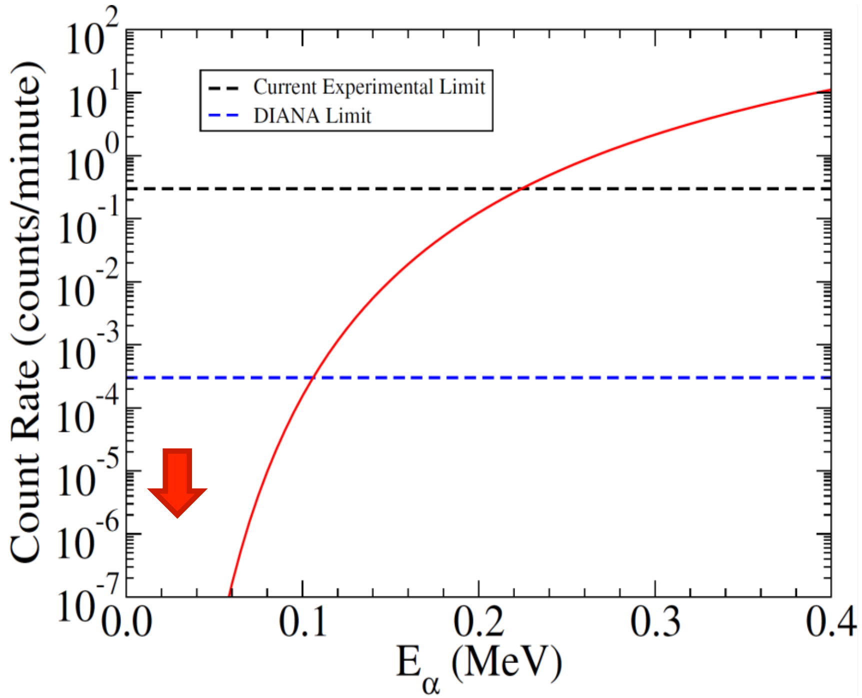
p, α, HI beams
100 x LUNA luminosity

Yield and count rate estimate

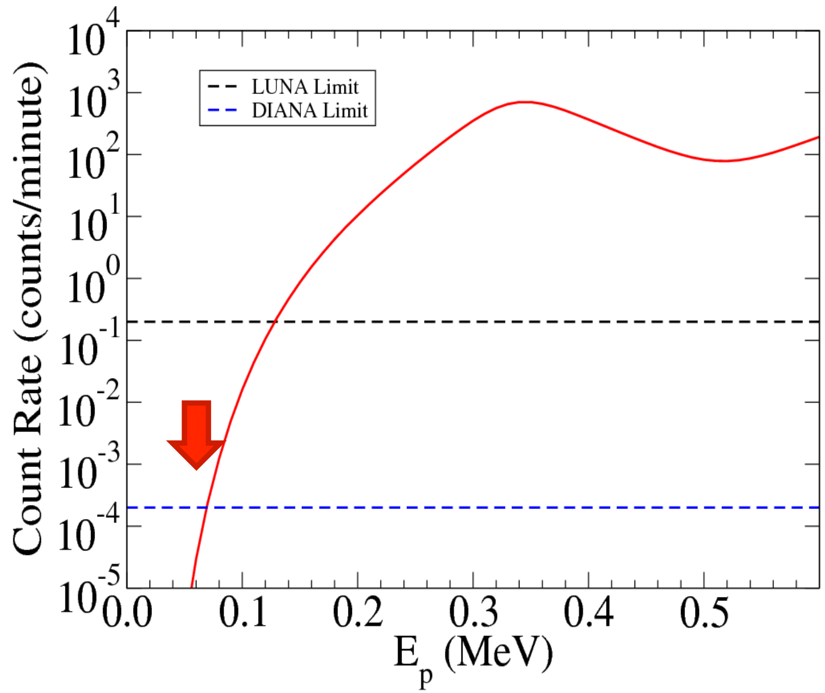


Beam intensity: 10mA, target density 10^{18} g/cm^2 gas jet

$^3He(\alpha,\gamma)^7Be$



$^{15}N(p,\gamma)^{16}O$



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

courtesy: M Wiescher

The ANDES Laboratory

background:

- strategic importance to increase exportation to Asian market
- Brazil and Argentina export by boat from Chile
- existing passes cannot cope with increasing demands (particularly in winter)
- alternatives based on low-altitude passes currently looked for
- tunnel construction expected in 2012 at Agua Negra Pass

The ANDES Laboratory features

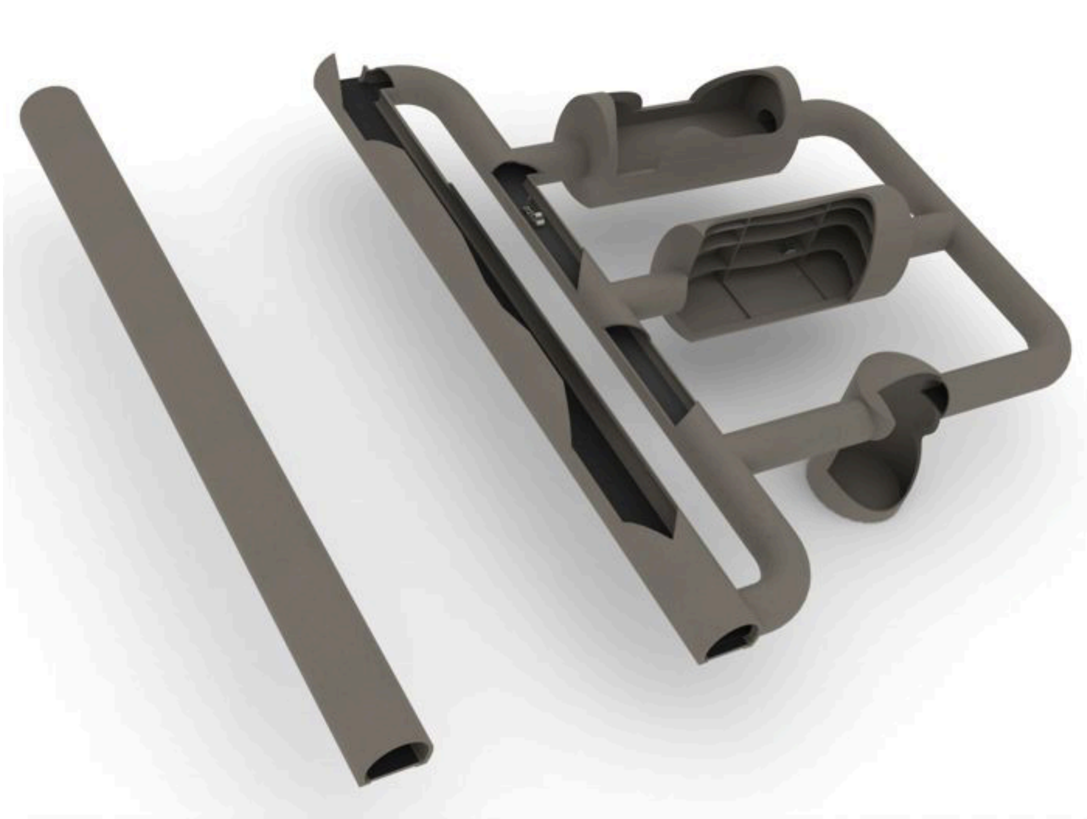
pass located at 3700m of altitude - relatively remote
"hot" tunnel ≈ 30 – 40○ C
deepest point at ≈ 1750m depth (≈ Frejus-Modane) 4500-4800 mwe
ideal depth for an Underground Laboratory

main rock: andesite
density ~2.7 g/cm3
low radioactivity

3 big halls:
hall 1: (20x25x50) m^3
hall 2: same size, 3-4 floors
hall 3: pit ϕ 15-20 m, 20m depth

Linear tunnel for interferometer/ accelerator

Total cost ≈ 10MU$D
+ 2 external labs
+ experiments cost



courtesy: M Wiescher

scientific involvement

- ion source
  - ECR, RF, duoplasmatron, sputtering
  - high intensity (several 100s mA) beams
  - (p, d, $^{3,4}He$, C, N, O, Mg, Al, … isotopes)

- accelerator
  - high long-term stability
  - small energy spread (~10 eV)
  - acceleration voltage accuracy ~ 10^{-4}

- targets development
  - windowless (re-circulated) gas target systems
  - high purity solid state targets

- detector development
  - gamma-ray arrays (Compton suppressed)
  - low-background neutron detectors
  - silicon detectors for low-energy "heavy ion" detection

- theoretical approaches for low-energy nuclear reactions
  - R-matrix, direct capture, nuclear structure

Summary & Outlook

- few nuclear reactions studied at/near Gamow peak (LUNA)
- many key reactions remain beyond current capabilities
- new underground laboratories needed and fully endorsed by NA community
- initiatives in Europe currently pursued (call for interest recently circulated)
- several initiatives taking place around the world
- potential for major breakthrough in the field





THANK YOU