The Boulby mine:
An opportunity for Nuclear Astrophysics

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Thermonuclear Reactions in Stars

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

Yield = $N_{projectiles}$ × N_{target} × cross section × detection efficiency

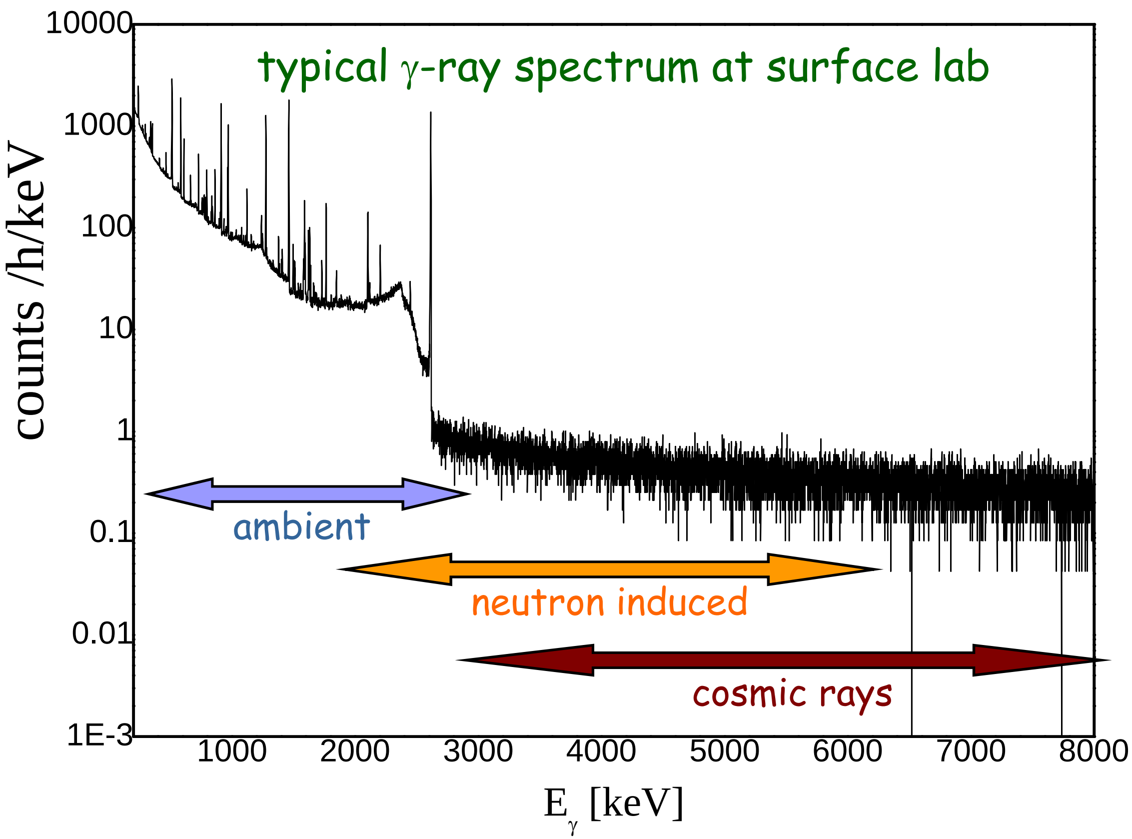
<u>maximising the yield requires:</u>

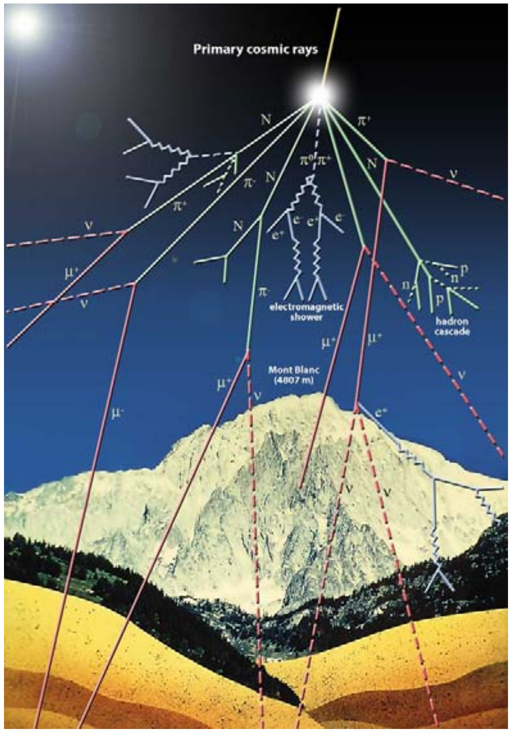
- improving "signal" (e.g. high beam currents, high target density, high efficiency)
- reducing "noise" (i.e. background)
- combination of both

the underground solution

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 (α,n) reactions and fission





ideal location: underground + low concentration of U and Th

Current status

measurements of key reactions at astrophysical energies

only 4 reactions: $^{3}He(^{3}He,2p)^{4}He$ $d(p,\gamma)^{3}He$ $^{14}N(p,\gamma)^{15}O$ $^{3}He(^{4}He,\gamma)^{7}Be$

rates measured directly (@ LUNA underground facility in Gran Sasso)

all other reactions:

rates entirely based on extrapolations

⬇

large uncertainties in astrophysical models and predictions

LUNA Limitations

⬇

many critical reactions for astrophysics BEYOND current capabilities

!! new underground facilities are very much needed !!

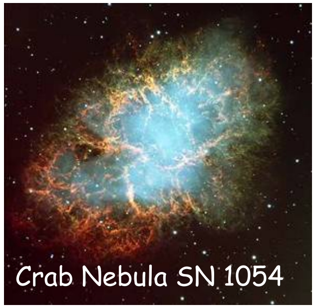
Late stages of stellar evolution

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

importance: evolution of massive stars

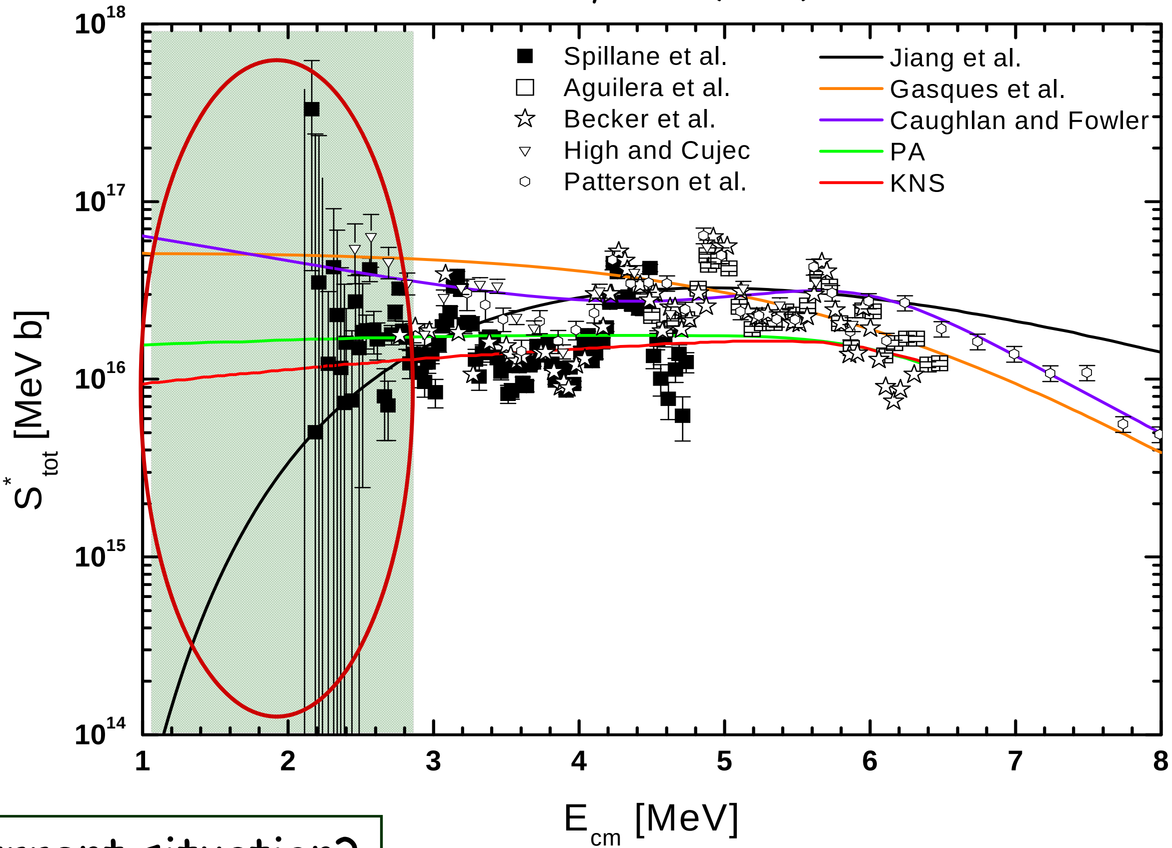
astrophysical energy: 1 – 3 MeV

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



Crab Nebula SN 1054

Strieder, J. Phys. G35 (2008) 14009



extrapolations differ by 3 orders of magnitude

↓

large uncertainties in astrophysical models of stellar evolution and nucleosynthesis

can we improve on current situation?

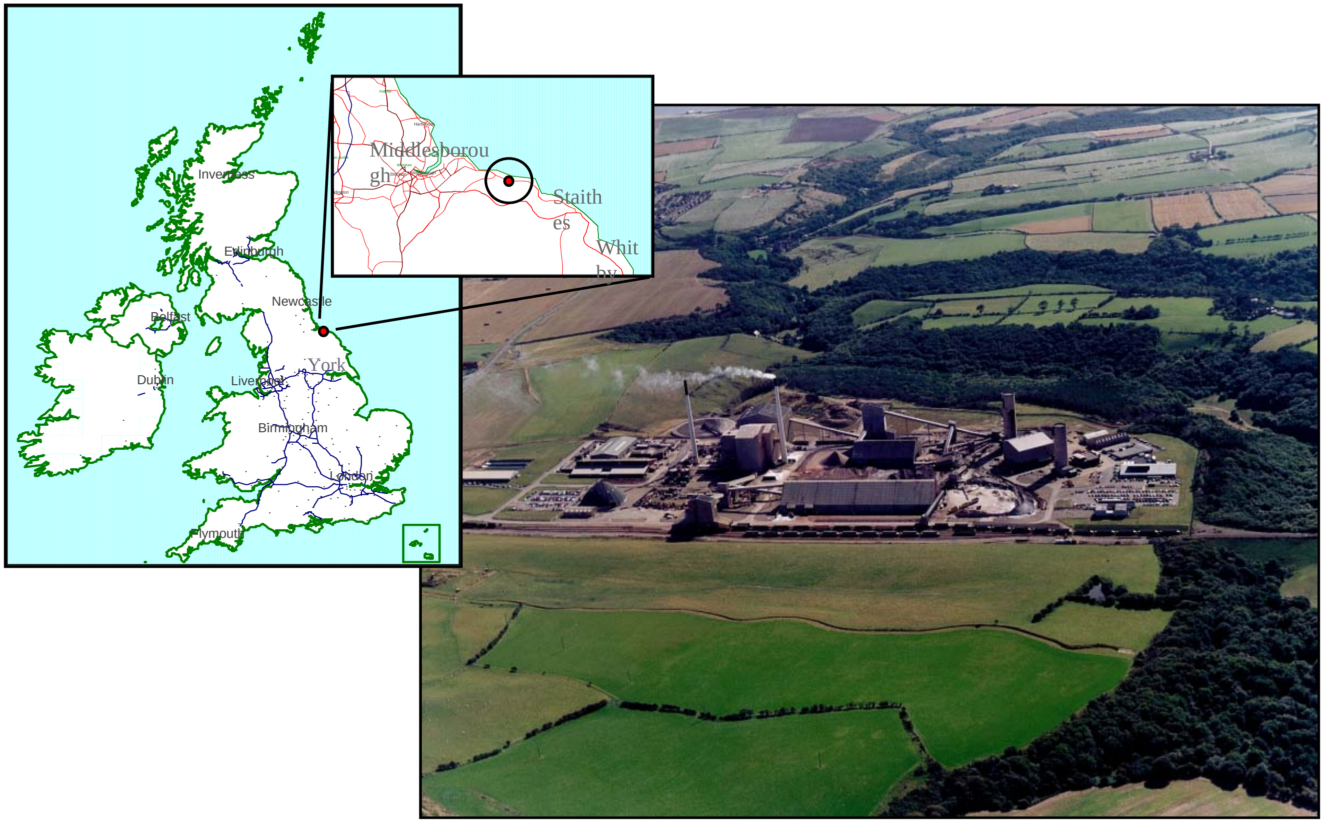
the project

European Laboratory for Experimental Nuclear Astrophysics

the Boulby mine

Boulby: commercial potash and salt mine (Cleveland Potash Ltd)

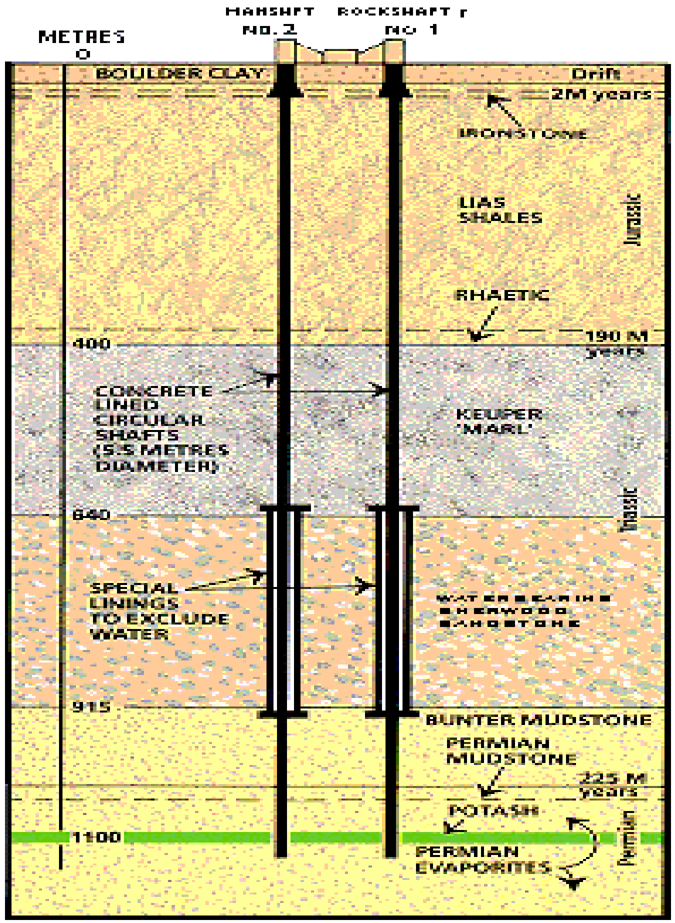
deepest mine in Britain (~ 1100 m deep)



➢ The Mine:

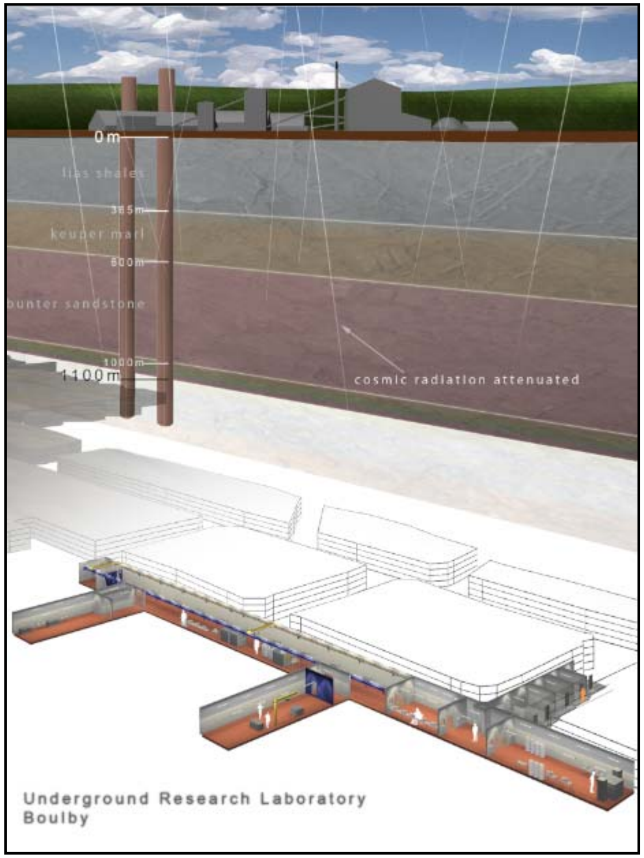
over 40km of tunnel dug each year in potash and rock salt layer

(now > 1000km in total)



➢ Underground facility (Dark Matter):

1000m^2 lab space, workshops, cranes, power, communications, air conditioning & filtration



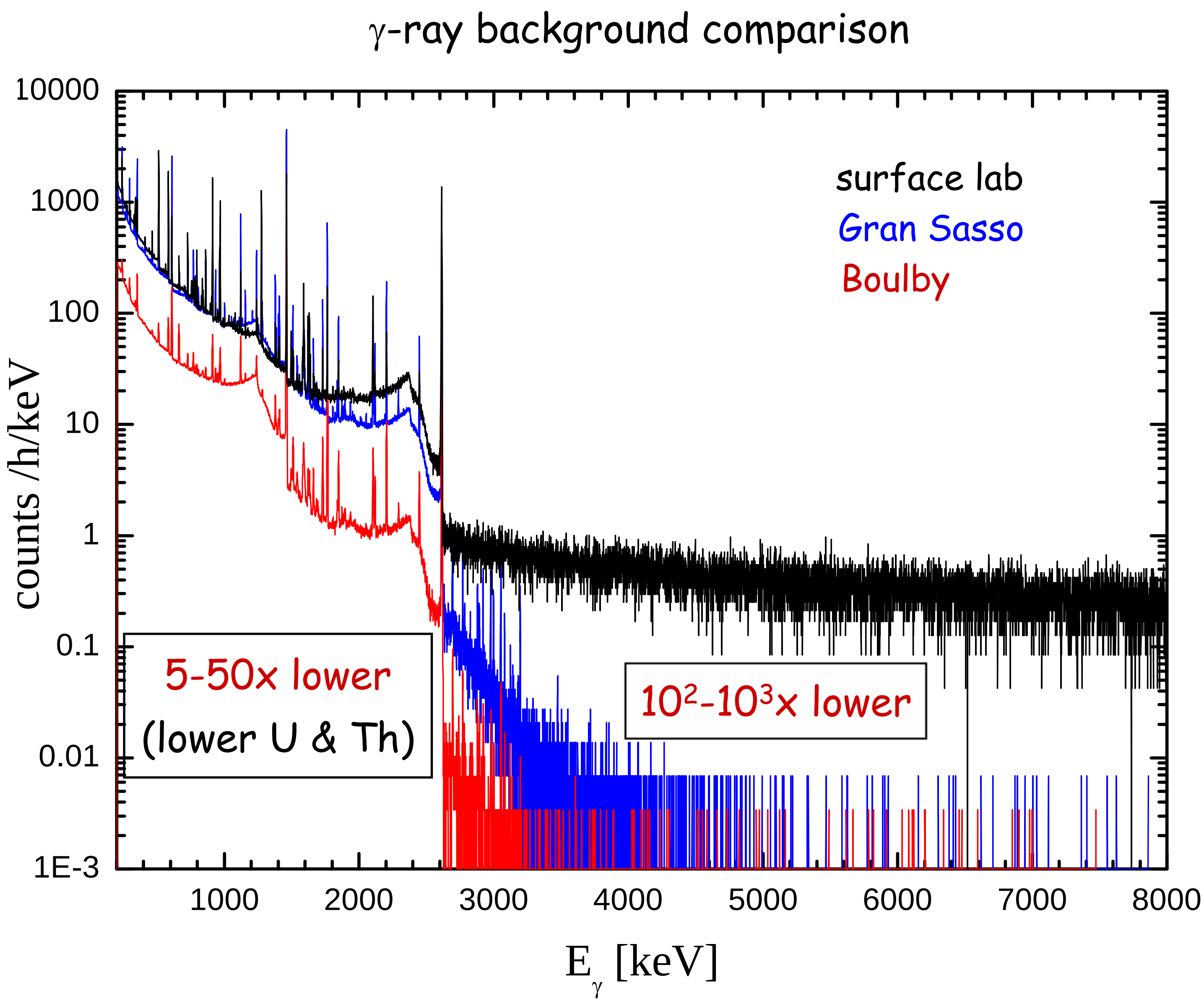
Proximity of services

Why Boulby?

why is Boulby *ideal* for Nuclear Astrophysics?

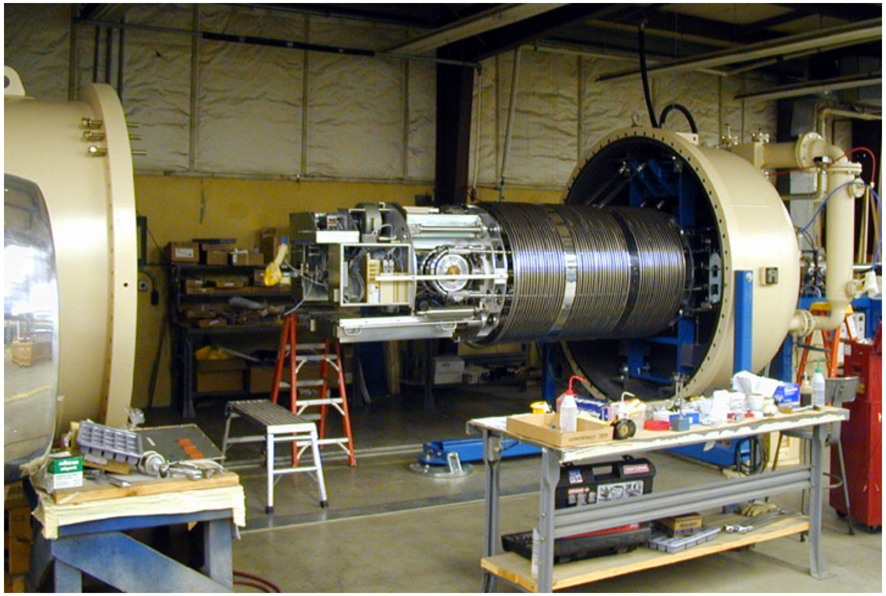
deep mine 1100 m (2800 m.w.e.)	→ ~10^6 reduction in CR + uniform shielding
salt environment low in U/Th	→ lower n- and γ-background
no space constraints	→ no *interference* issues
easy access for equipment	→ vertical shafts + underground transport
mine management support	→ infrastructure & services

Background comparison



the facility

the accelerator



beams

Ion (charge state)	Particles per second
H^{+}	5.0×10^{14}
He^{+}	5.0×10^{13}
He^{2+}	1.0×10^{13}
Xe^{17+}	2.9×10^{12}
Kr^{15+}	4.1×10^{11}
Ar^{11+}	5.6×10^{11}
Ne^{6+}	1.0×10^{12}
Fe^{11+}	5.7×10^{11} (estimated)
Ni^{11+}	5.7×10^{11} (estimated)

- 3 MV single-ended machine (e.g. NEC, Pelletron)
- ECR source (e.g. for high intensity (~500 μA) ^{12}C beam at high charge states)
- Beam-lines + detection systems (gamma, neutron, charged particles)

studies possible both in <u>direct</u> and <u>inverse</u> kinematics

estimated cost for accelerator + ECR source: ~2.5 M€ = 1.7 M£

The ELENA Project

Stage I: Feasibility Study & Design

(duration: 24 months, cost: £410k)

- neutron & γ-ray background measurements at Boulby
- infrastructure design (by engineering company)
- accelerator and beam tests

Stage II: Construction, Commissioning, Exploitation

(duration: ~24 months (C,C) + 60 months (E); cost: ~ £6M)

- construction of laboratory infrastructure
- commissioning of accelerator + ion source facility
- initial scientific exploitation (5 years)

ELENA - Stage I

Feasibility Study and Design

proposal submitted to STFC

but not funded at present

Work Breakdown Structure

ELENA-I Workpackages

WP1: Background measurements
WP2: Accelerator & ion source tests
WP3: Scientific equipment & requirements
WP4: Laboratory design
WP5: Health & Safety

Overall Objectives

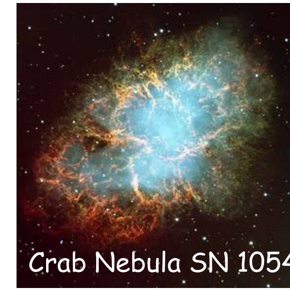
- identification of site for infrastructure
- accelerator specifications
- experimental requirements
- laboratory design and specifications
- total cost and timescale estimates

International Workshop to establish financial/scientific contributions to "ELENA – Stage II" from (inter)national NA community

The Science

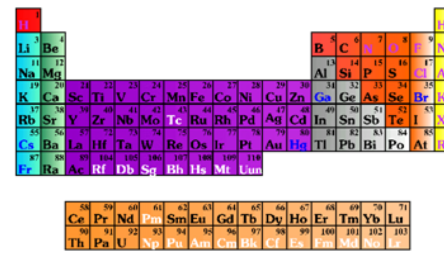
hot topics in Astrophysics

key open questions



- *fate of massive stars (<u>supernovae</u> explosions)?*

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



- *where and how are <u>heavy elements</u> produced?*

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

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

  <u>Ne, Na, Mg and Al nucleosynthesis</u> [(p,γ) and (p,α) reactions]

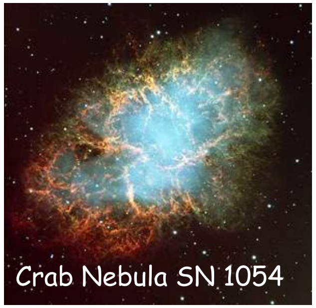
Late stages of stellar evolution

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

importance: evolution of massive stars

astrophysical energy: 1 – 3 MeV

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

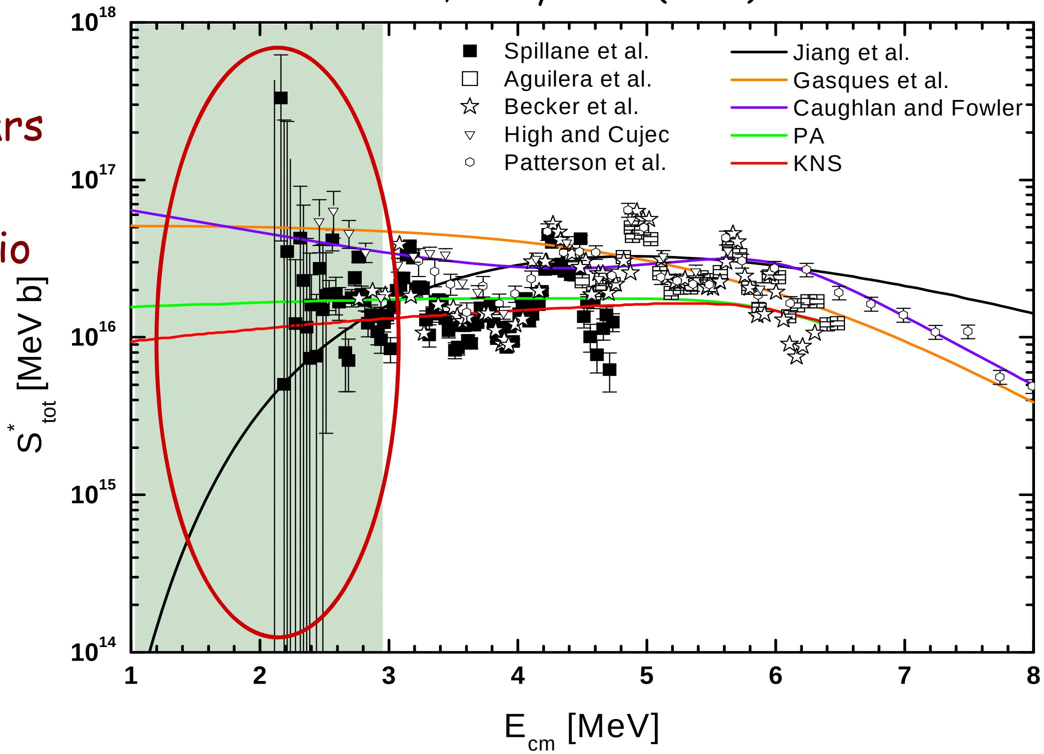


large error bars

⇓

poor S/N ratio

Strieder, J. Phys. G35 (2008) 14009



options for improvements of surface measurements: exhausted

underground measurements required

what improvements at Boulby?

- exploit lower γ-ray background → γ-ray measurements

$$^{12}C+^{12}C \rightarrow p + ^{23}Na^* \rightarrow ^{23}Na + \gamma \qquad E_\gamma = 440\ keV$$

$$\alpha + ^{20}Ne^* \rightarrow ^{20}Ne + \gamma \qquad E_\gamma = 1.63\ MeV$$

- expected background at least 100x lower than on surface
- lowest energy achievable E_{cm}~1.5 MeV
- greatly improved precision (~ 10-15%, i.e. 10x better than present)

astrophysical impact

- constrain/discriminate between extrapolations
- determine ignition temperature for $^{12}C+^{12}C$ fusion
- show if lower-mass stars end up as supernovae
- solve current discrepancy on mass estimates of SN progenitors

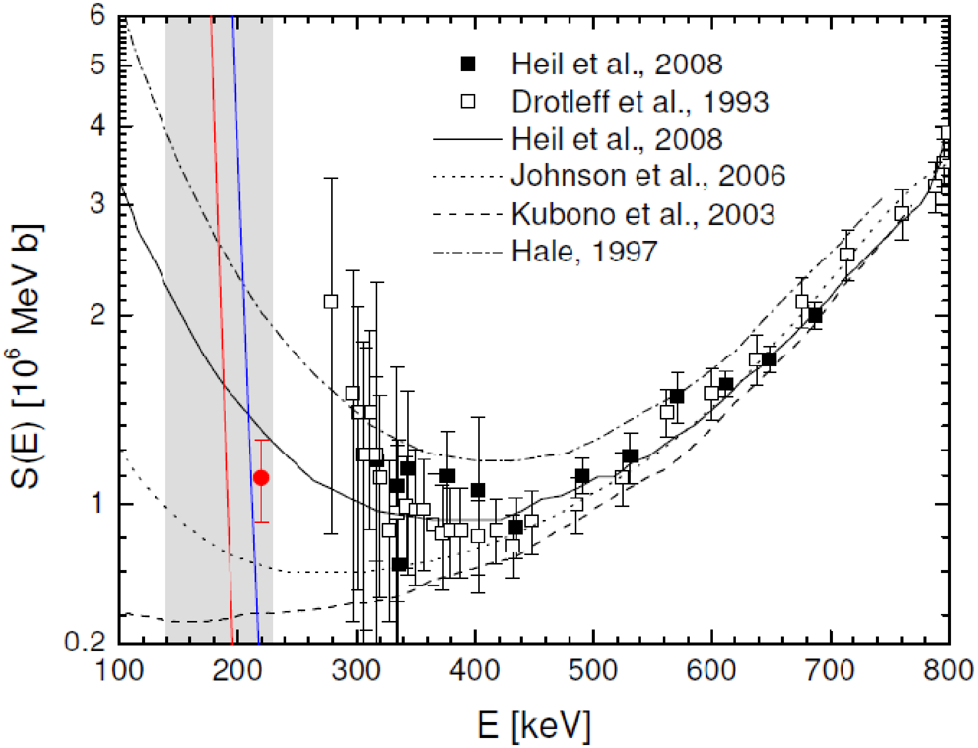
Neutron sources for heavy elements

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

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)

current status



improvements at Boulby

- neutron detection
- expected n-background ~ 50x lower
- lowest energy achievable E_{cm}~200 keV
- greatly improved precision (~15%)

astrophysical impact

- neutron density for s-process
- nucleosynthesis paths & abundances

options for improvements of surface measurements: exhausted

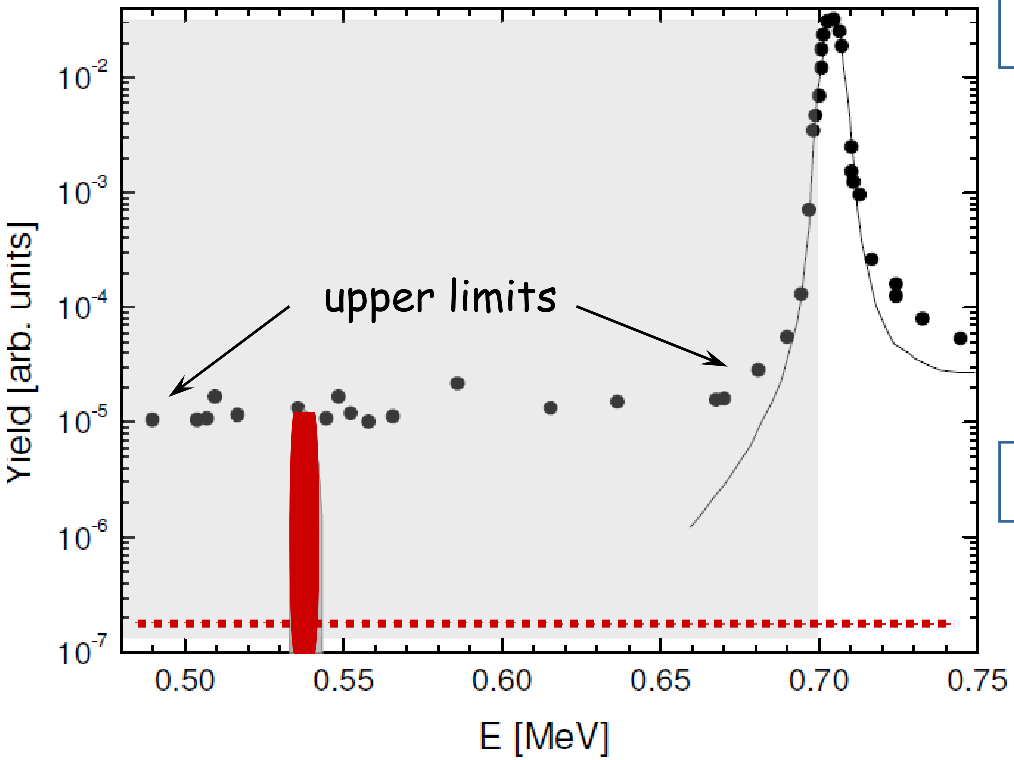
underground measurements required

Neutron sources for heavy elements

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

importance:	s-process in AGB stars
astrophysical energies:	400 - 700 keV
minimum measured E:	~550 keV

current status reference



improvements at Boulby

- neutron detection
- increased sensitivity ~ 100x
- lowest energy achievable E_{cm}~ 537 keV
- greatly improved precision (~ 15%)

astrophysical implications

- alter nucleosynthesis paths
- change elemental abundances

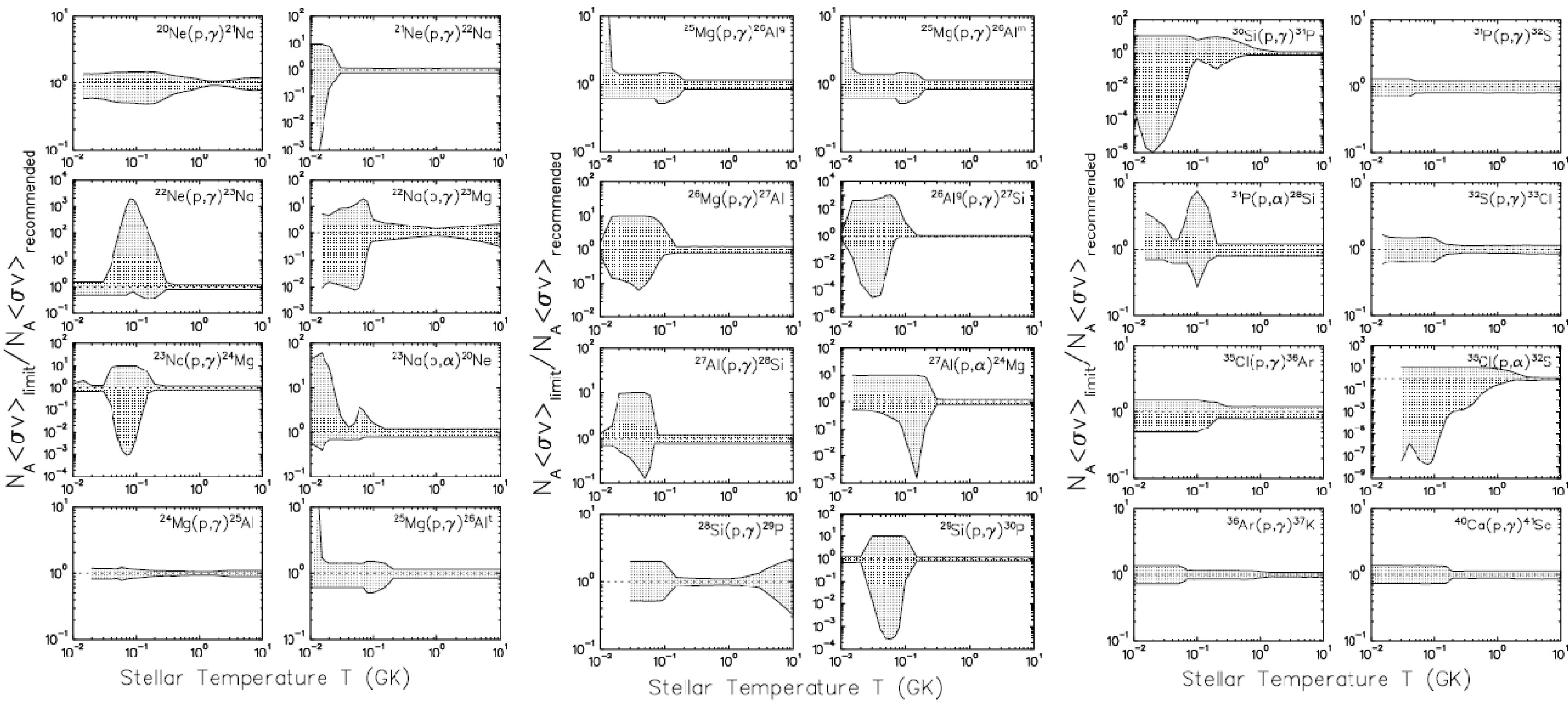
options for improvements of surface measurements: exhausted

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 !!

opportunities for international

nuclear astrophysics community

- scientific involvement in nuclear astrophysics studies

- ion source

  ECR, RF, duoplasmatron, sputtering
  high intensity (several 100s μA) 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

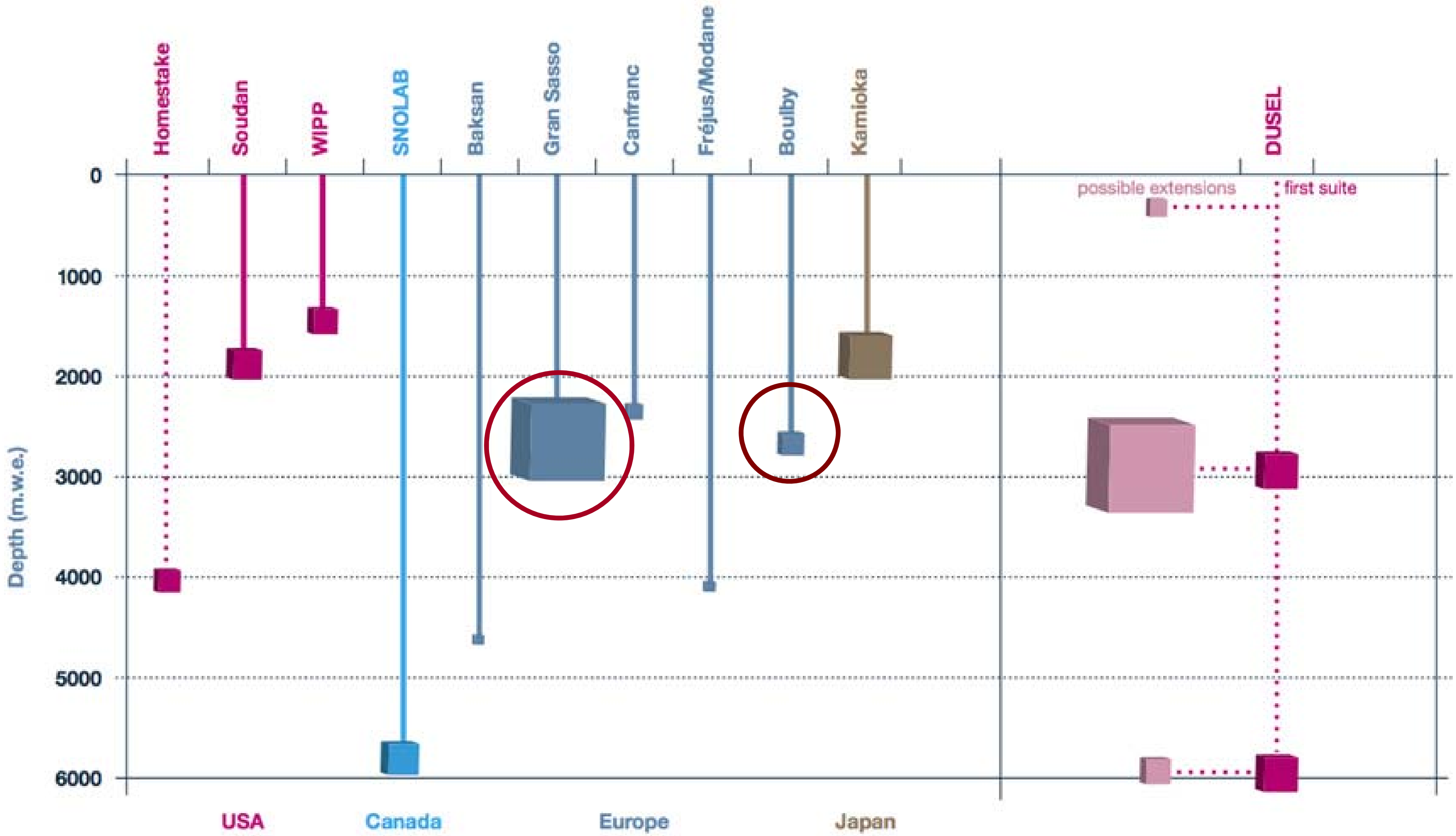
  gamma-ray arrays (Compton suppressed)
  low-background neutron detectors
  silicon detectors for low-energy "heavy ion" detection

- theoretical approaches for low-energy nuclear reactions

  R-matrix, direct capture, nuclear structure

ELENA in the International Context

Underground Laboratories Worldwide



Underground Labs for Nuclear Astrophysics

At present, LUNA at Gran Sasso (Italy) ONLY underground laboratory in the WORLD

LUNA (Italy)

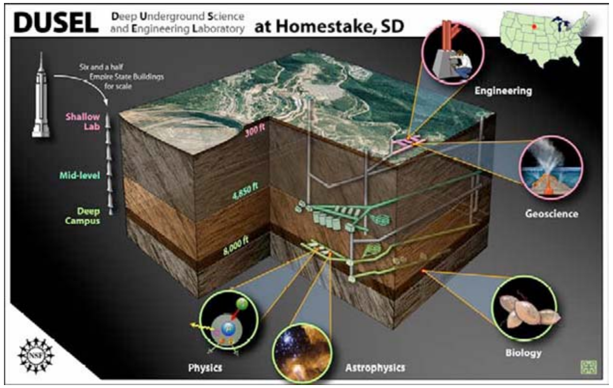
Main Limitations

- beam species (only protons, alphas, no heavy ions)
- neutron production NOT allowed
- space constraints for upgrade

CANFRANC (Spain)

workshop to explore opportunities for NA
19-20 February 2009

postdoctoral position recently opened



DUSEL

(Deep Underground Science & Engineering Laboratory)

site selected (10 July 2007): gold mine at Homestake
NSF approved funding for feasibility study

New underground facilities clearly needed and
fully endorsed by international Nuclear Astrophysics Community

Boulby salt mine

- no space constraints
- no interference with other scientific programmes
- well-established safety and support infrastructures
- lower background (lower U & Th content) w.r.t. other sedimentary rocks

world-class opportunity

unique facility worldwide

- well beyond current capabilities
- unique leadership opportunity for European science

science output

- fundamental impact in our understanding
- key questions (energy generation, nucleosynthesis)

UK community

- exploitation of strength and expertise
- potential for major international involvement

high quality research environment

- excellent training opportunities for PhD students
- links with industry involvement and spin-out technologies at cutting edge


THANK YOU

Stage I: Feasibility Study and Design

PI:	Marialuisa Aliotta*	University of Edinburgh	UK
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	Lucio Gialanella*	INFN, Naples	Italy
	Cristina Bordeanu*	HH-NIPNE	Romania
	BPG$	Rutherford Appleton Lab	UK
	David Pybus	Cleveland Potash Ltd, Boulby	UK
	PDRA*$	University of Edinburgh	UK

(*) expertise in Nuclear Astrophysics
($) expertise in Underground Science

+ strong support from RAL & CPL