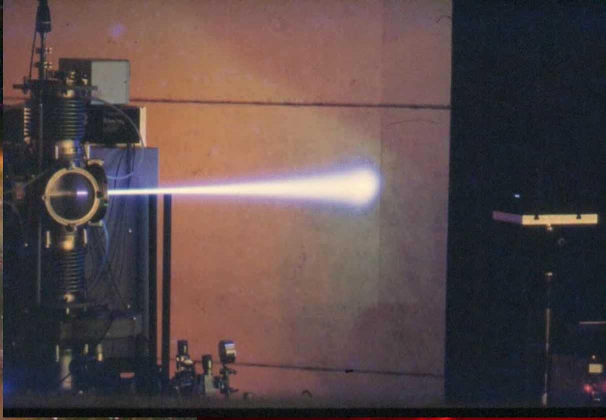
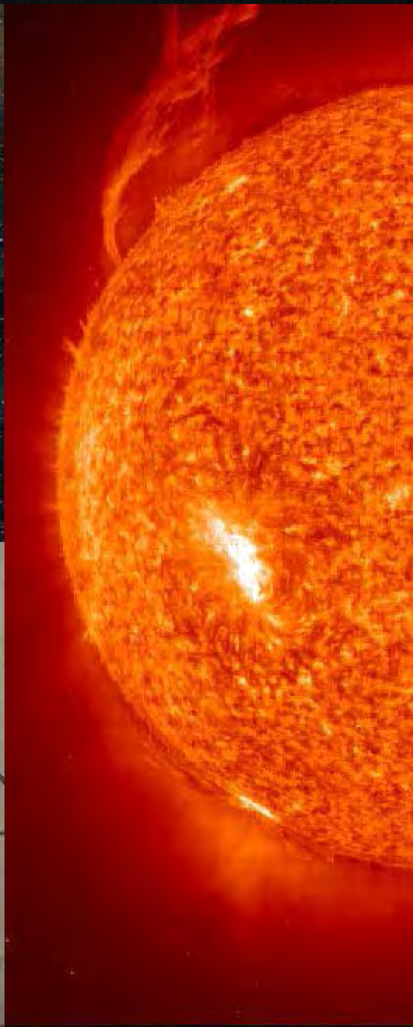
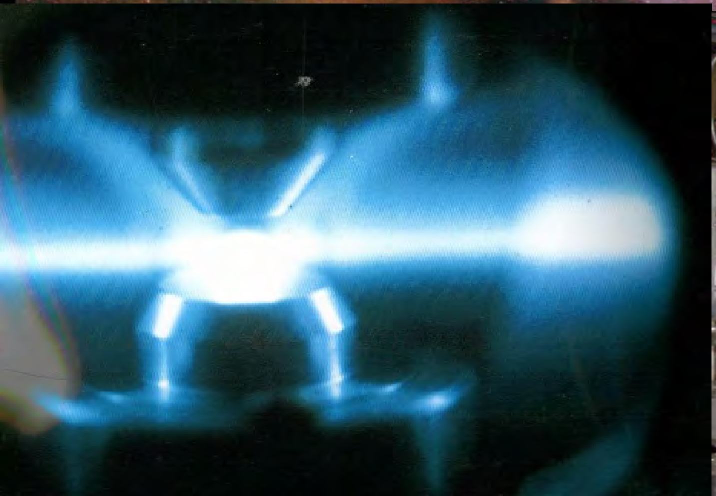
Underground Nuclear Astrophysics

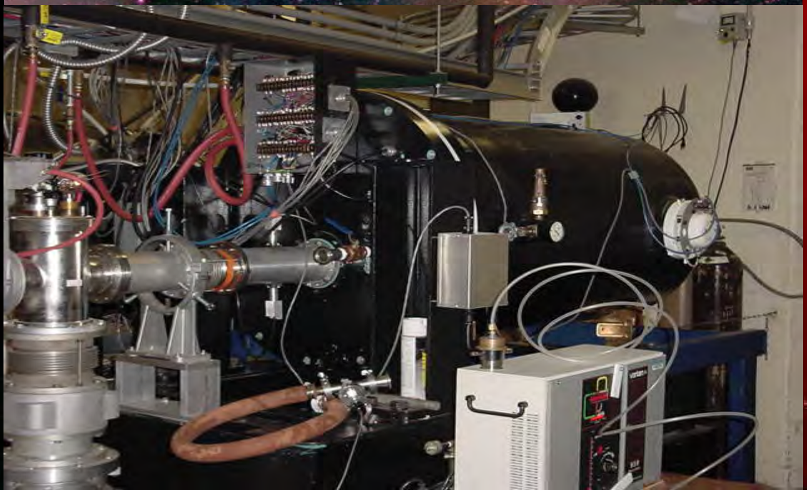
Frank Strieder
South Dakota School of Mines & Technology

The 2016 R-Matrix Workshop on Methods and Applications
Santa Fe, New Mexico, USA
June 28th, 2016

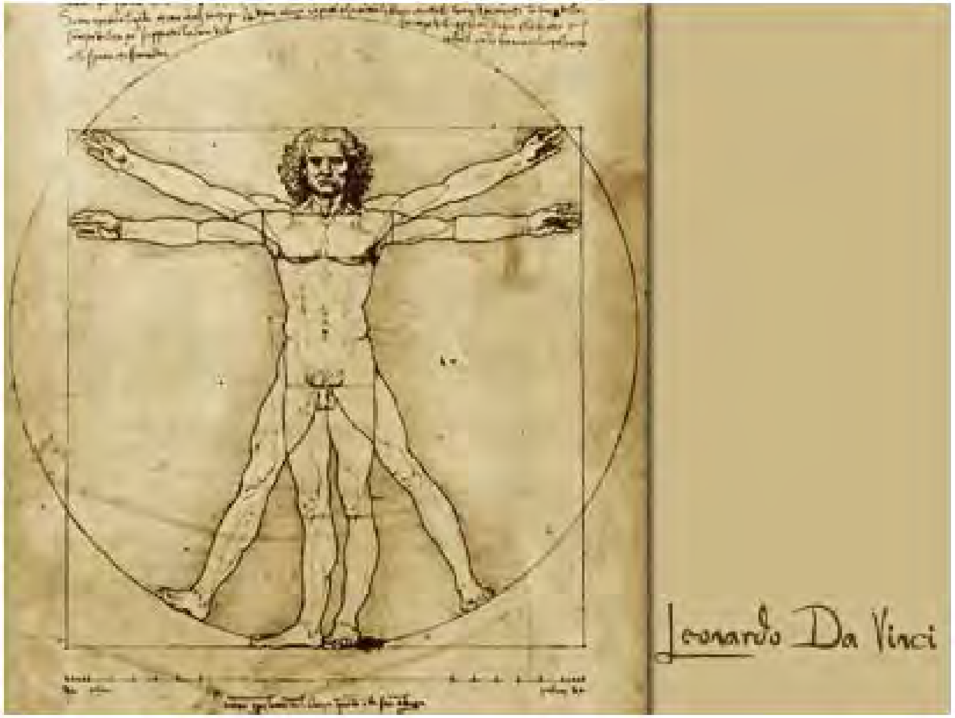




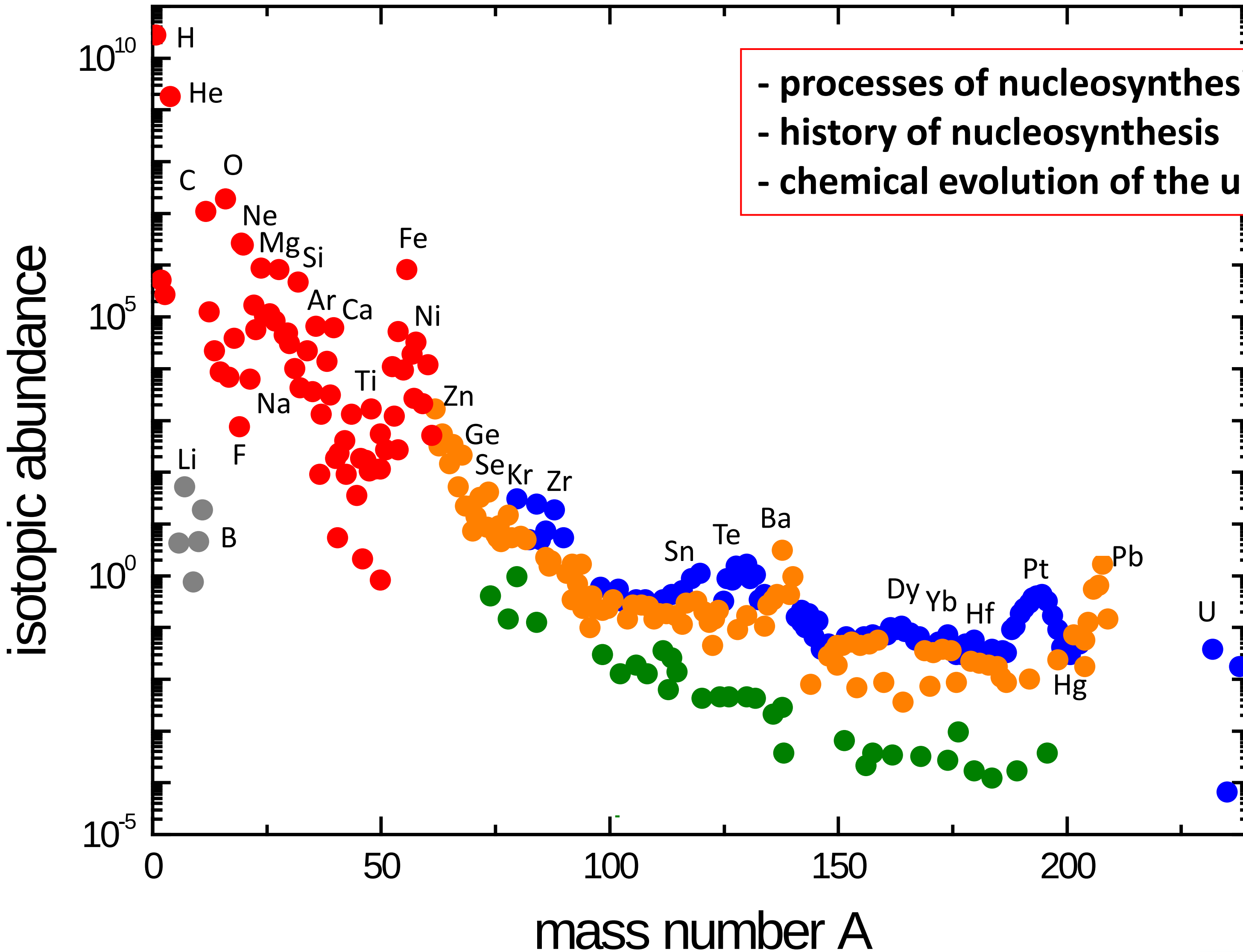




What is Matter made of?



Solar system isotopic abundance

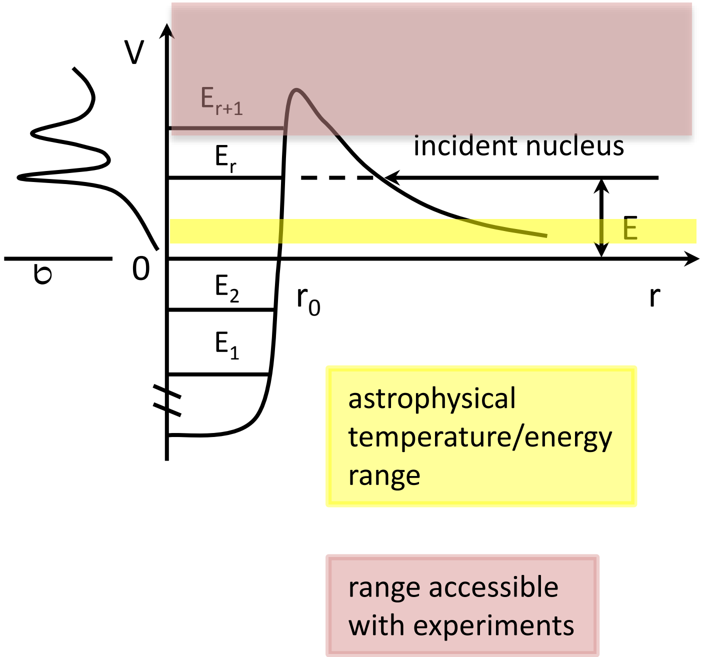


- **processes of nucleosynthesis**
- **history of nucleosynthesis**
- **chemical evolution of the universe**

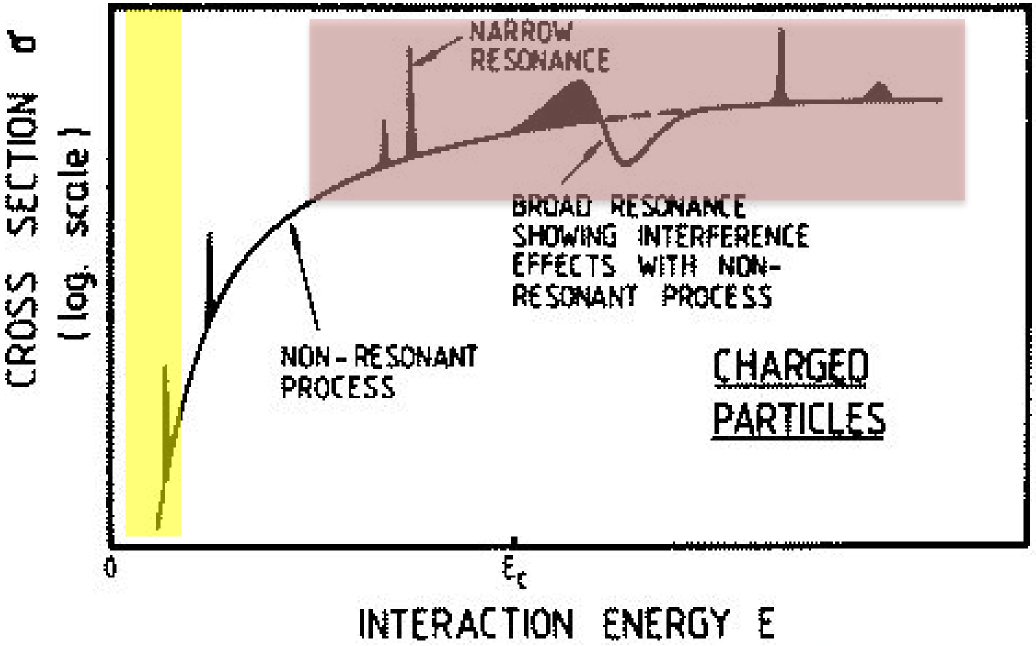
Nuclear reactions at astrophysical energies

nuclear reactions important to provide energy and the neutrons for nucleosynthesis

e.g. pp chain, $^{13}C + \alpha \rightarrow {}^{16}O + n$ or $^{22}Ne + \alpha \rightarrow {}^{25}Mg + n$

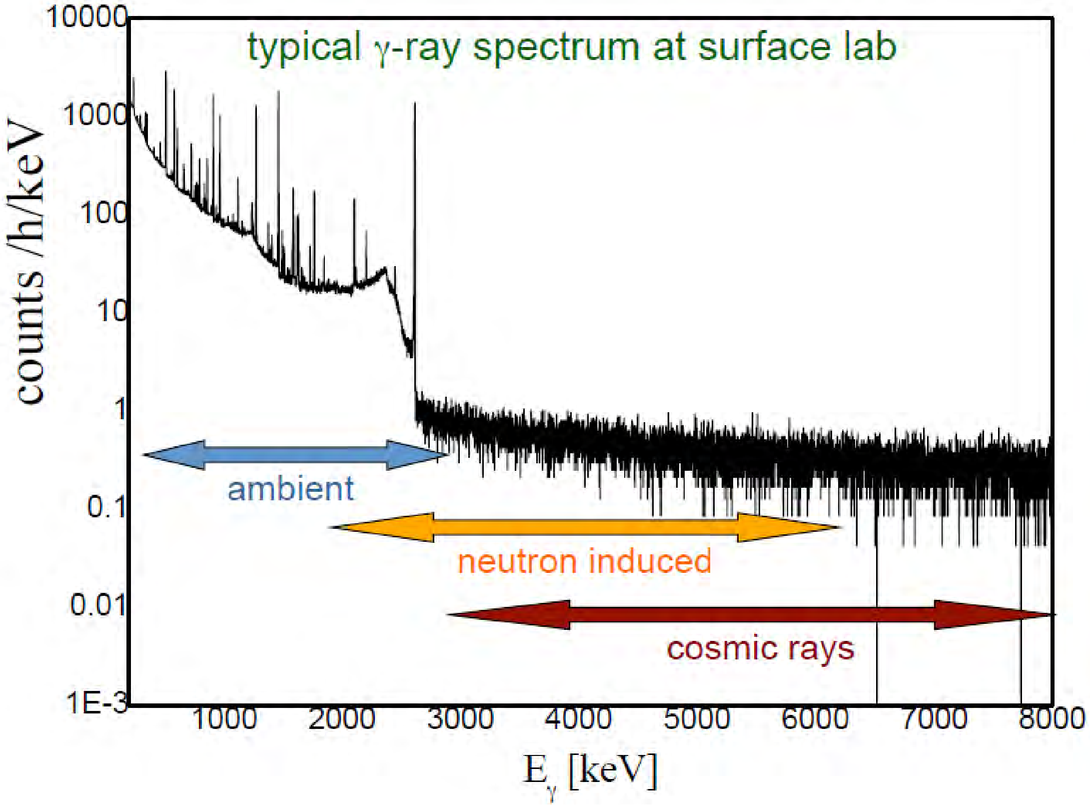


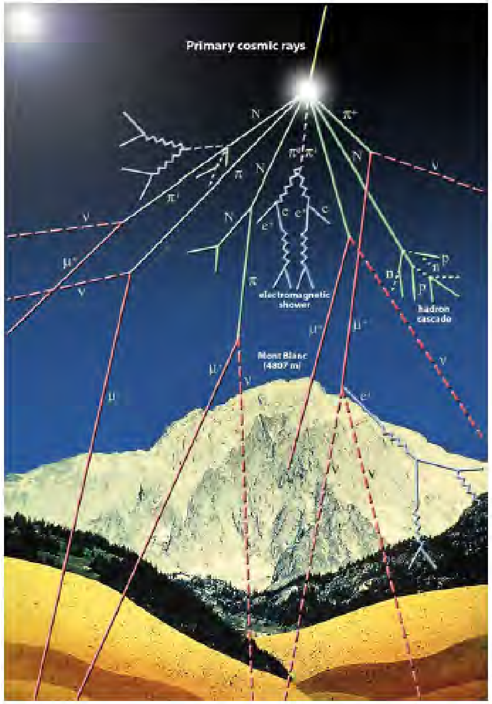
- occurs at specific energies
- cross section has STRONG energy dependence



Main Source of Background

- natural radioactivity (from U and Th chains and from Rn)
- cosmic rays
- neutrons from (α,n) reactions and fission

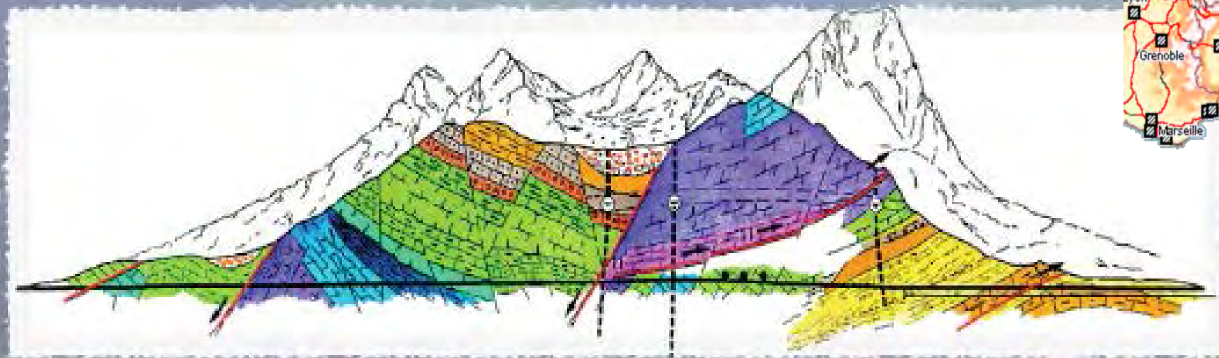




courtesy A. Formicola

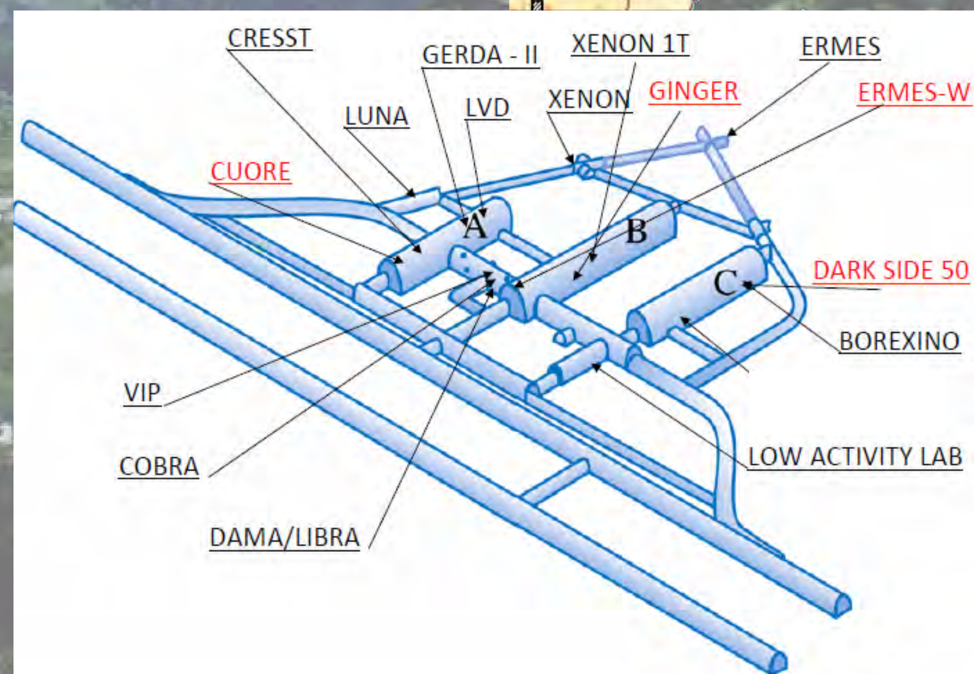
Laboratori Nazionali del Gran Sasso

Laboratory for Underground Nuclear Astrphysics



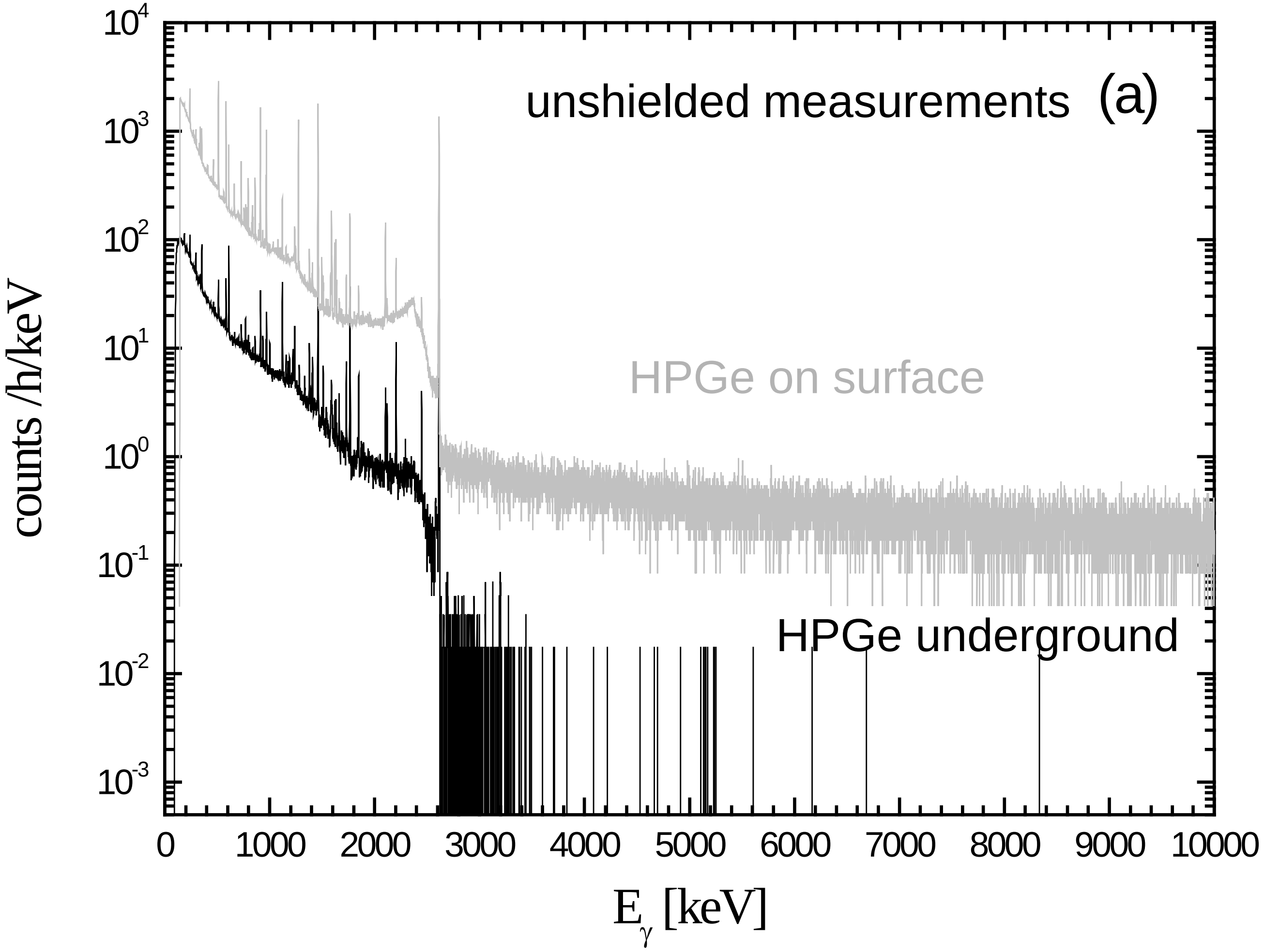
- 1400 m rock overburden (=4000 m w.e.)
- Flux attenuation: n 10^{-3} ($CaCO_3$)
  μ 10^{-6} (1/m^2 h)

- underground area 18000 m^2
- support facilities on the surface



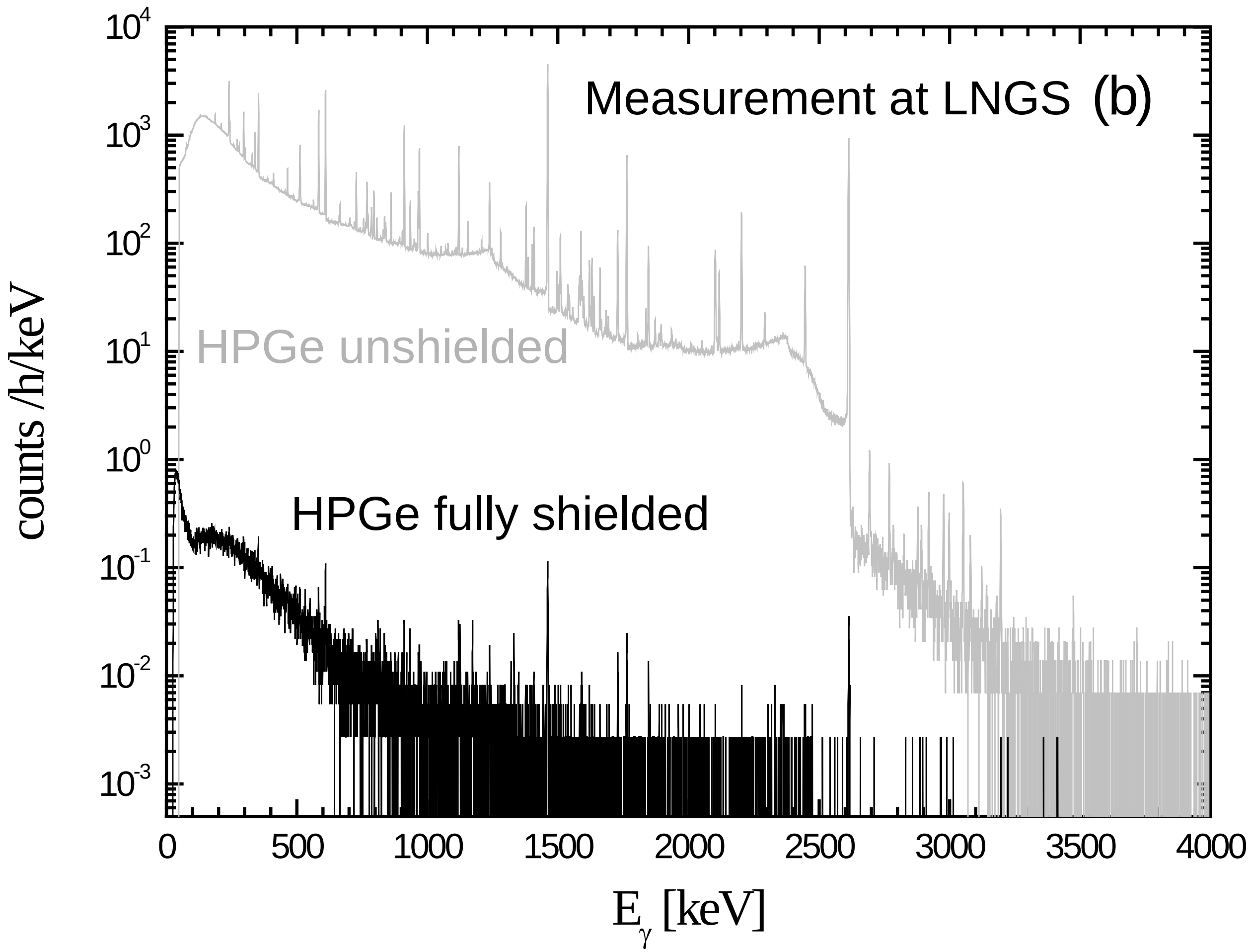
Benefit of an Underground Laboratory

in γ-ray spectroscopy



Benefit of an Underground Laboratory

in γ-ray spectroscopy



Underground Accelerator: LUNA – The Beginning

1992: Installation of LUNA 50 kV accelerator @ LNGS

participating teams & institutions:

Ruhr-Universität Bochum

2 full time PhD students: Uwe Greife, Matthias Junker

few part time PhD students + senior researcher

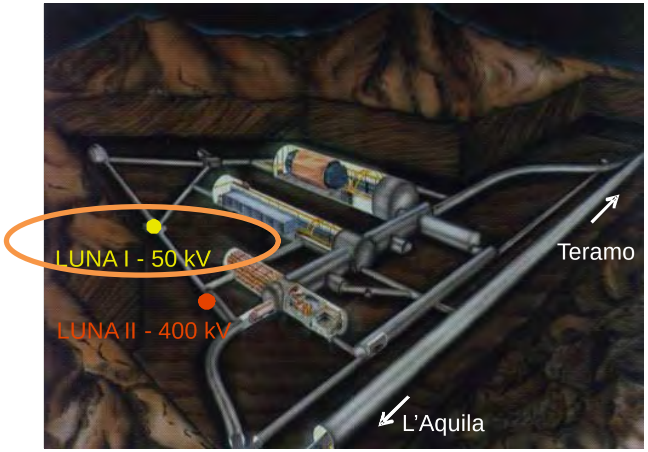
Laboratorio Nazionale del Gran Sasso

part time senior researcher: Cristina Arpesella

later PhD student: Alessandra D'Alessandro

INFN Genova

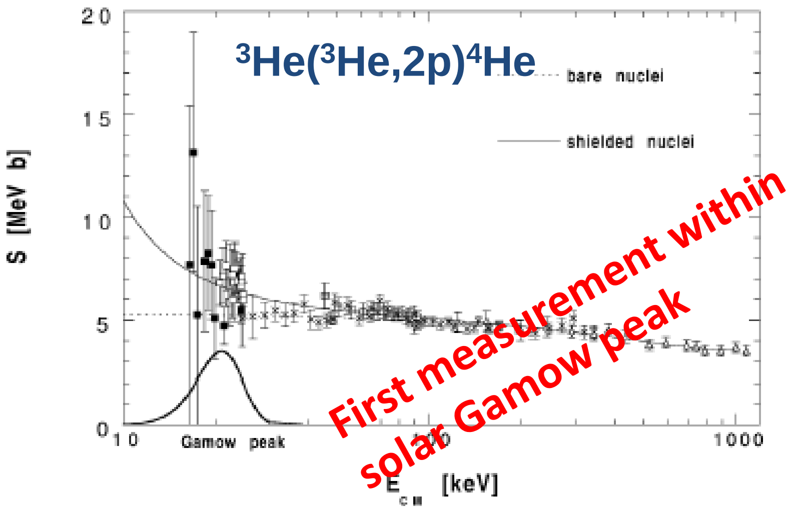
part time senior researcher: Piero Corvisero, Paolo Prati



→ **50 kV accelerator & gas target entirely built by students**

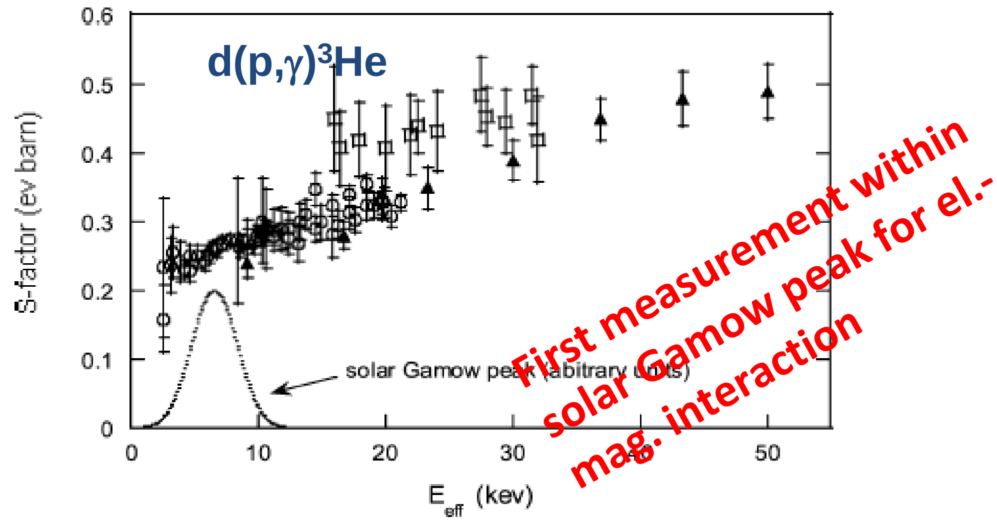
LUNA I – Achievements Underground

Two reactions (solar pp chain) already studied at Gamow energies:



at lowest energy: σ ~ 20 fb → 1 event/2 month

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



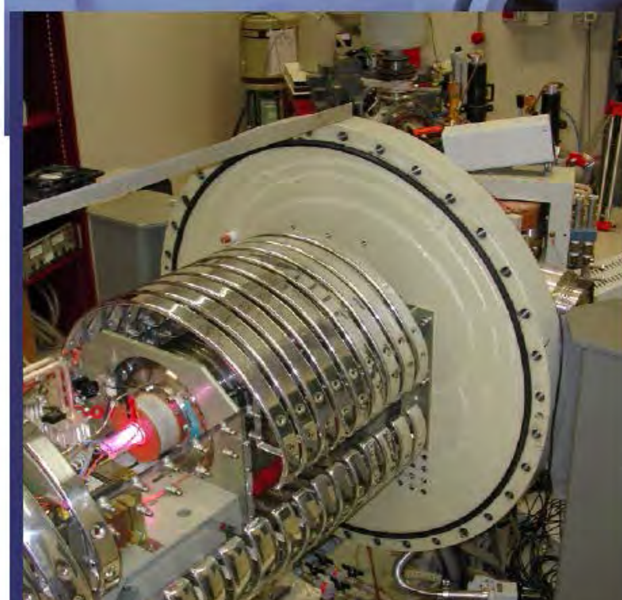
at lowest energy: σ ~ 9 pb → 50 counts/day

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

Definition of astrophysical S factor S(E)

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

LUNA II – 400 kV Accelerator (2000 – 2018(?))



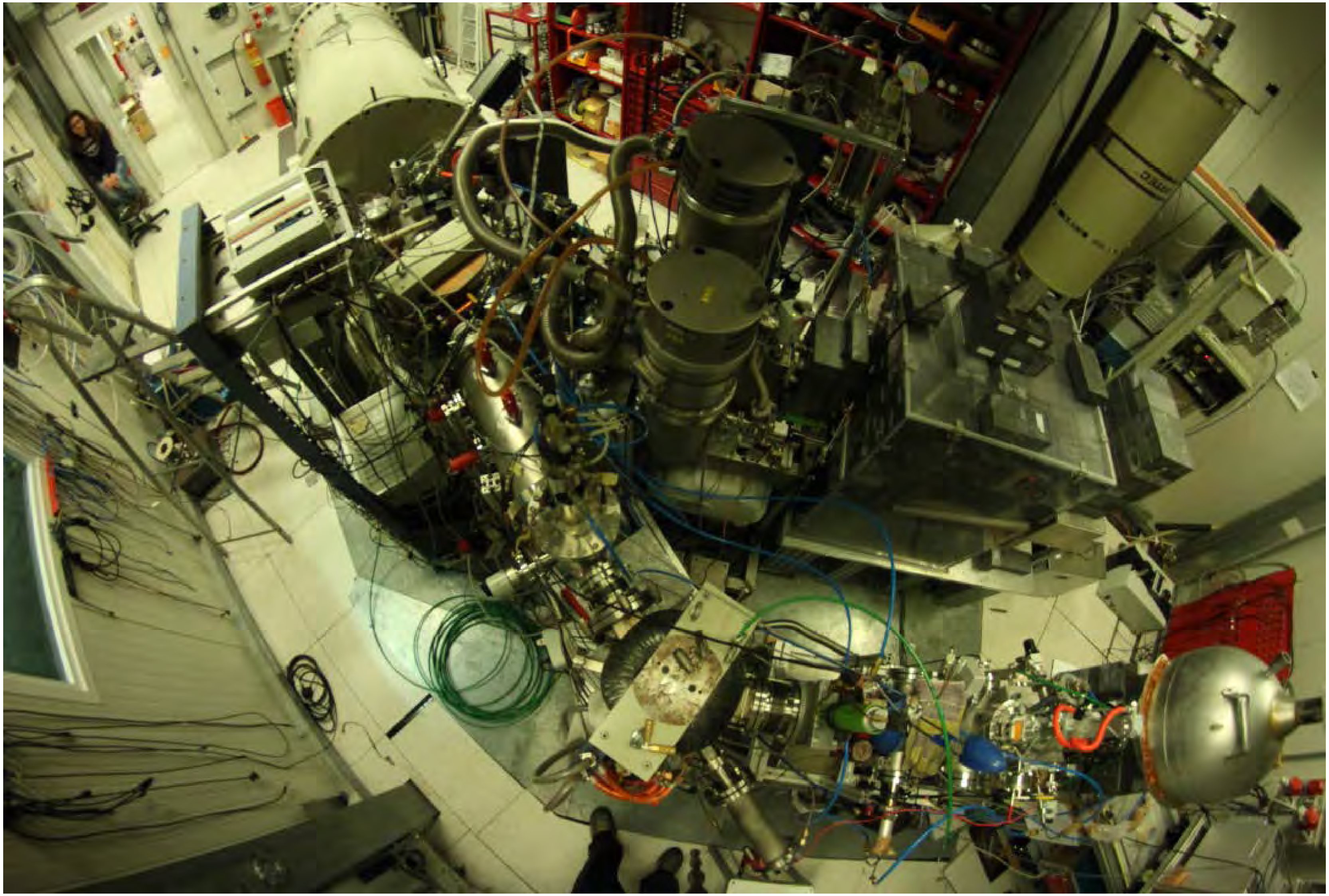
$U_{terminal}$ = 50 – 400kV

I_{max} = 500μA (on target)

ΔE = 0.07keV

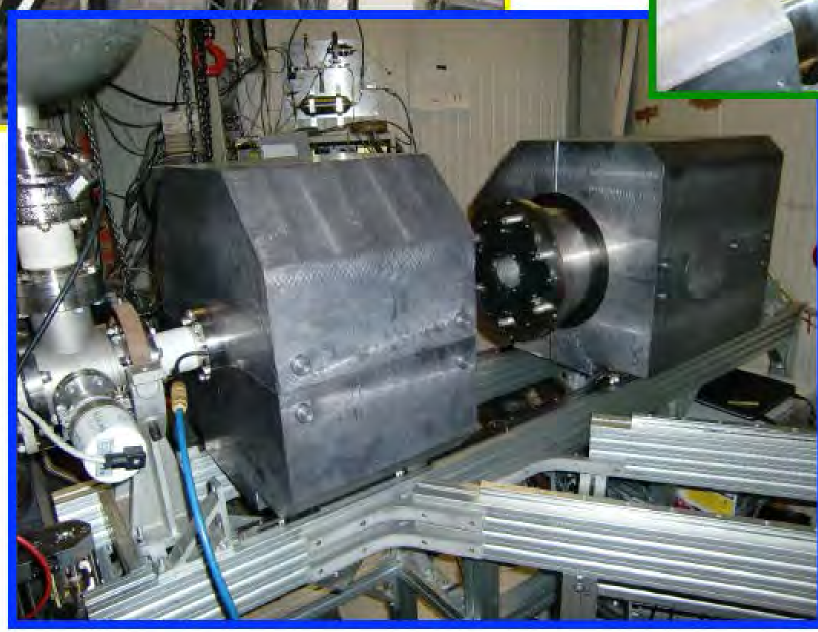
Allowed beams: H^+, ^4He, (^3He)

LUNA II – 400 kV Accelerator (2000 – 2018(?))



courtesy A. Formicola

LUNA II – 400 kV Accelerator (2000 – 2018(?))



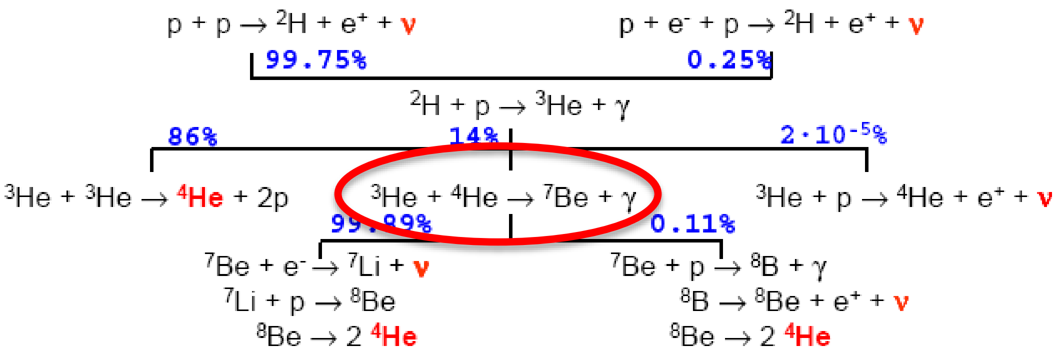
passive shielding
very effective underground
mainly at low γ-ray energies

higher γ-ray energies shielding
through rock overburden

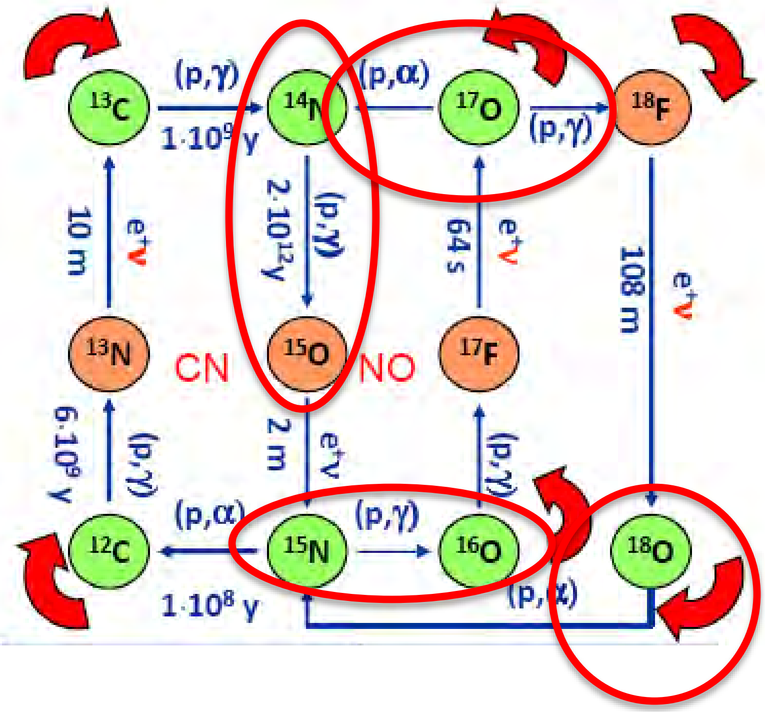
courtesy A. Formicola

LUNA II – Key Studies

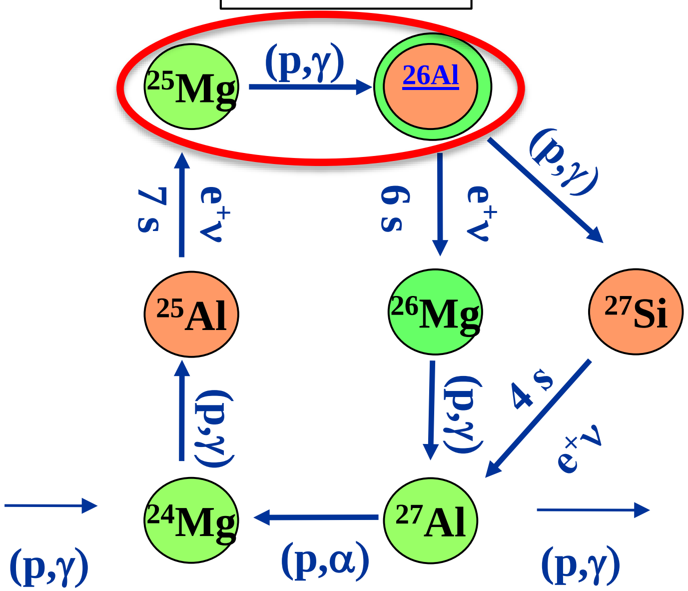
pp chain



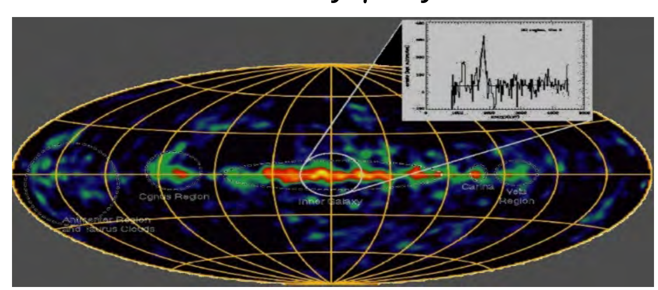
CNO cycle



MgAl cycle

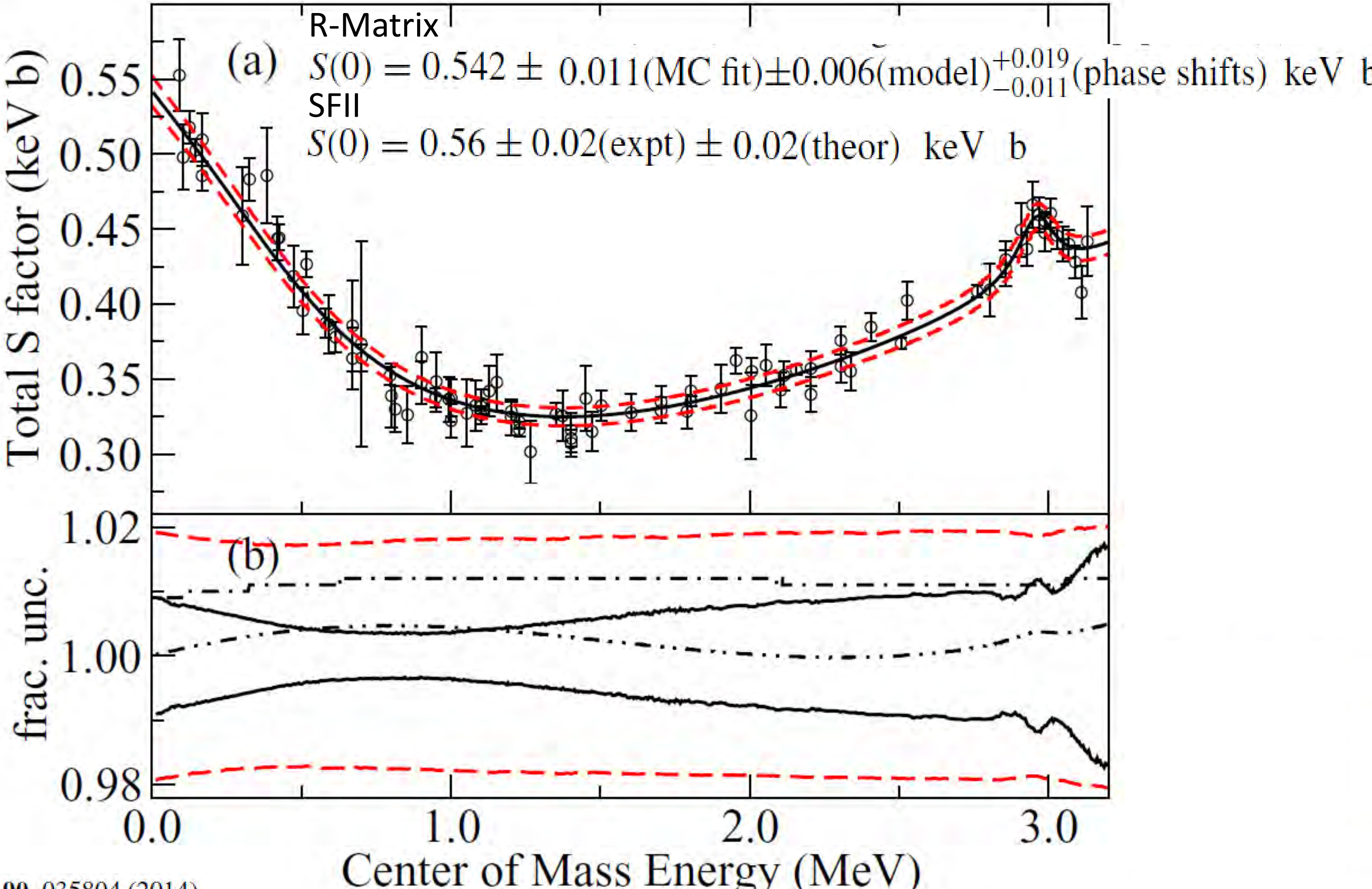


1.8 MeV ^{26}Al decay γ-ray line



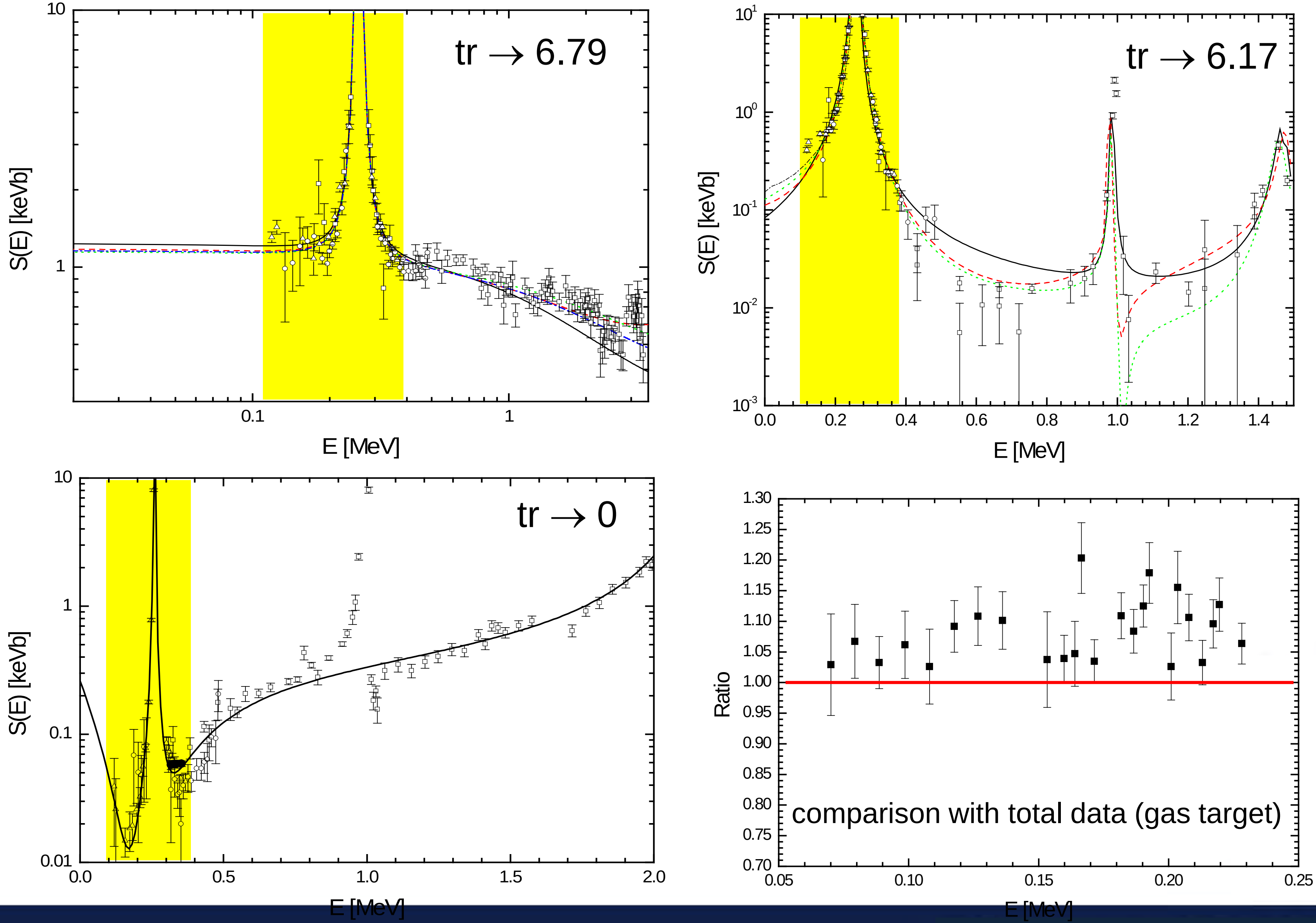
$^3He(\alpha,\gamma)^7Be$ – best example for combination of high and low energy data

now: very good R-Matrix fit over large energy region, but differences to models



R. J. DEBOER *et al.*
PHYSICAL REVIEW C **90**, 035804 (2014)

LUNA II – $^{14}N(p,\gamma)^{15}O$ CNO bottleneck reaction



Solar Fusion II – Adelberger et al., 2010

Compact Accelerator System for Performing Astrophysical Research

SOUTH DAKOTA SCHOOL OF MINES & TECHNOLOGY

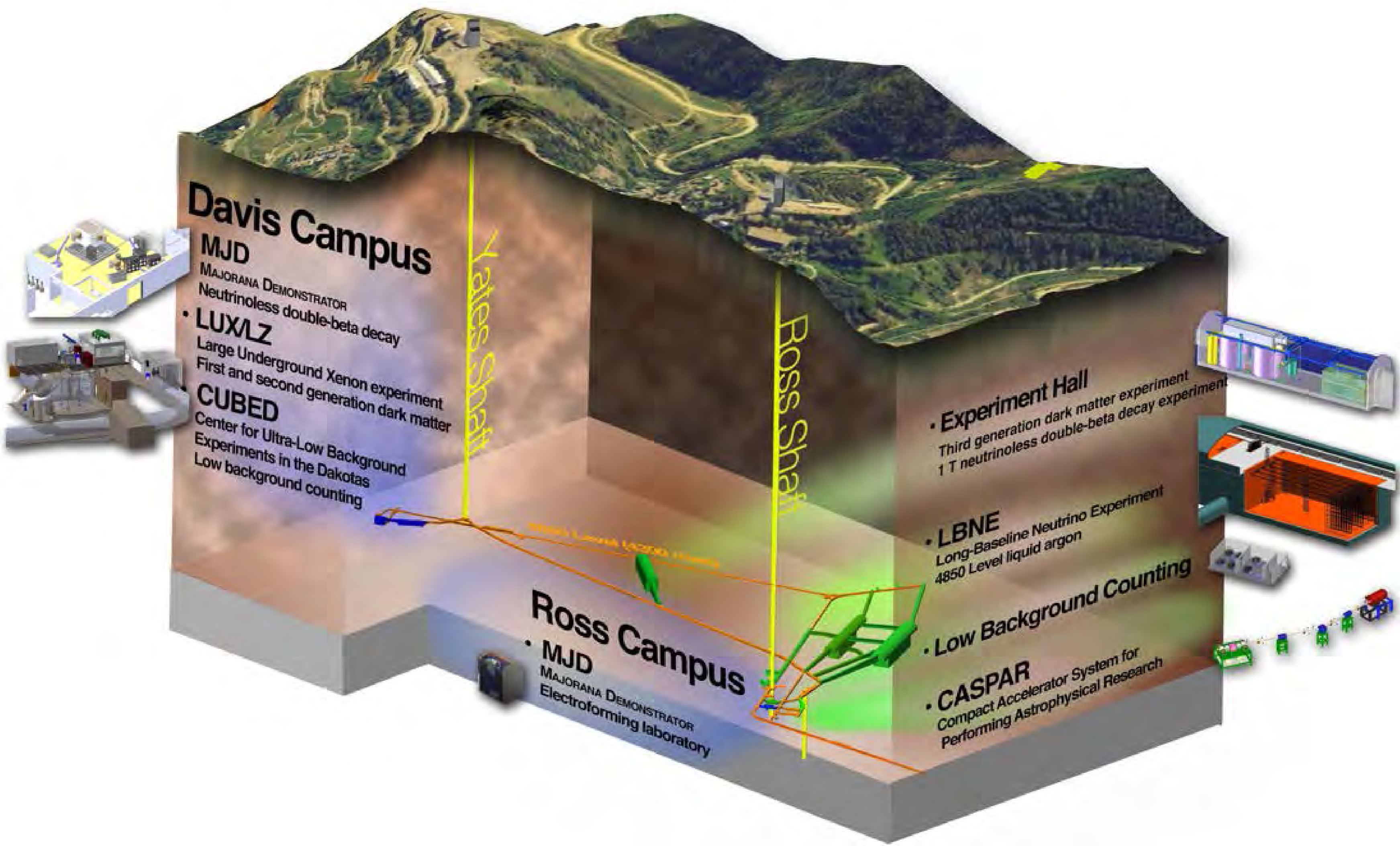
Frank Strieder (PI)
Doug Wells
Tyler Borgwardt
Mark Hanhardt
Thomas Kadlecek
Joe VanDriel
John Harrison
Lucas Lindholm

Dan Robertson (TC)
Manoel Couder
Michael Wiescher
Rory Hamilton
Zach Meisel
Bryant Vande Kolk

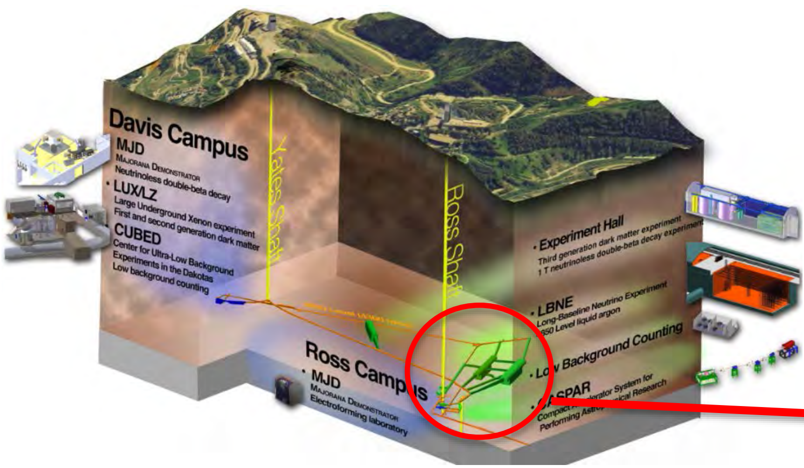
Uwe Greife

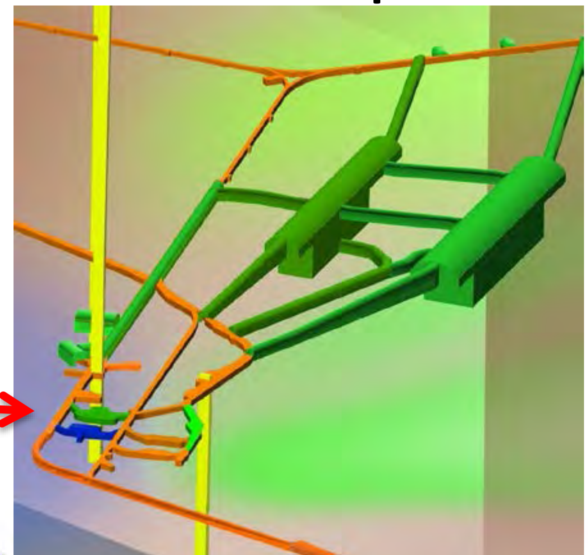

SURF
Lead, South Dakota

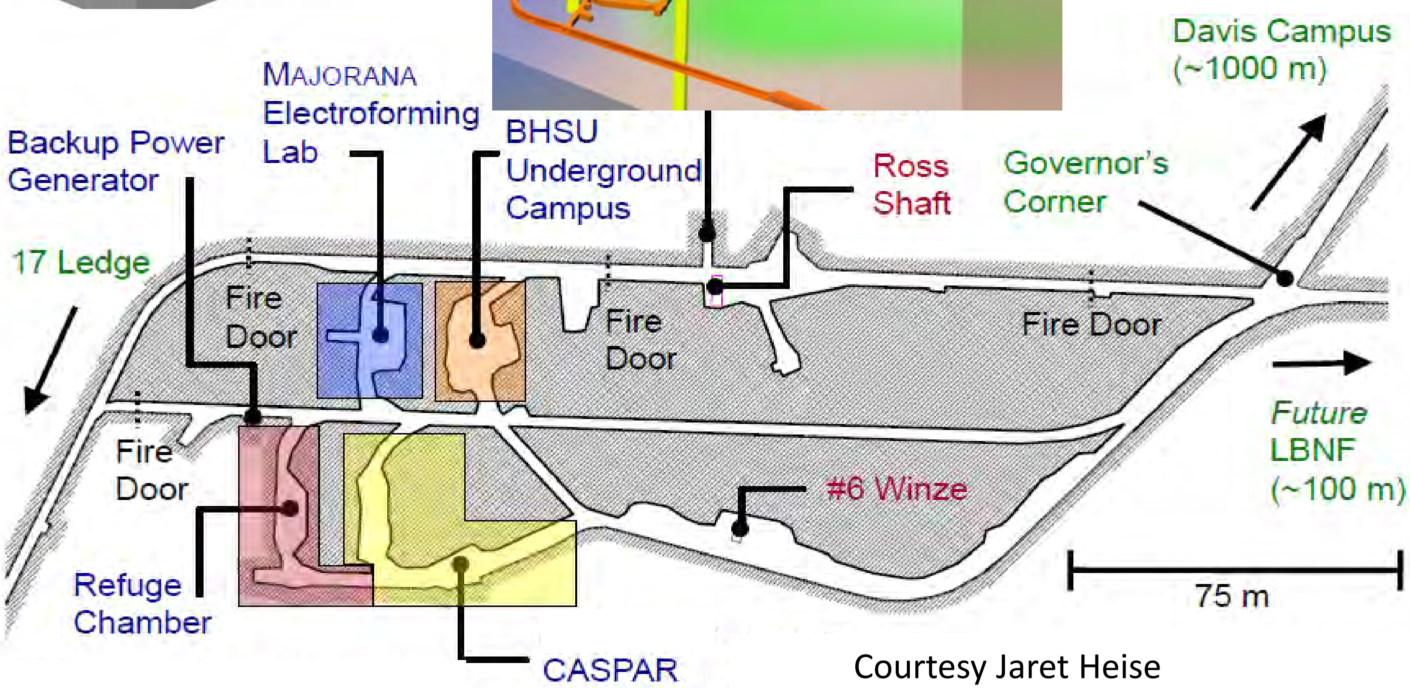
Sanford Underground Research Facility



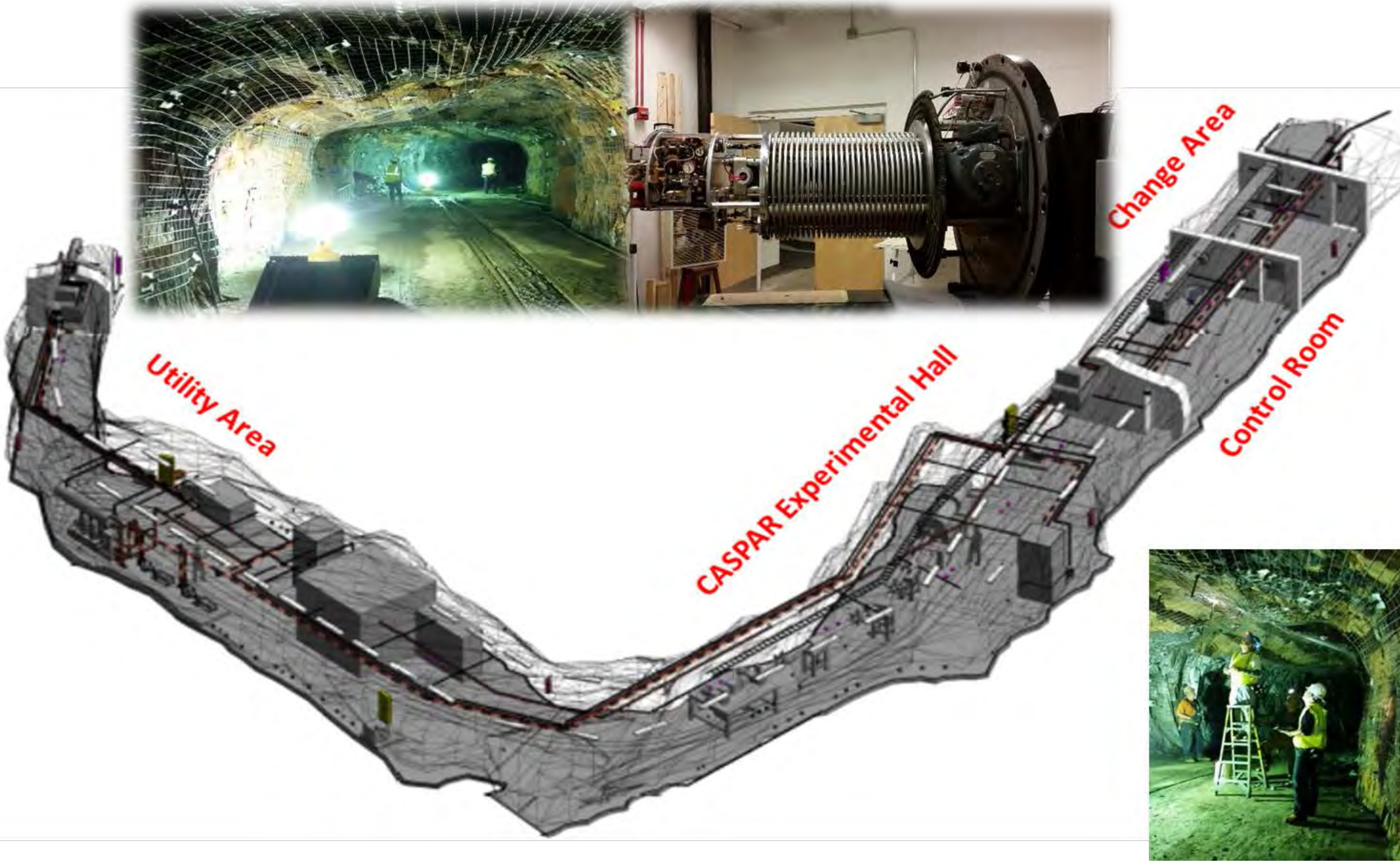
SURF 4850 L Ross Campus



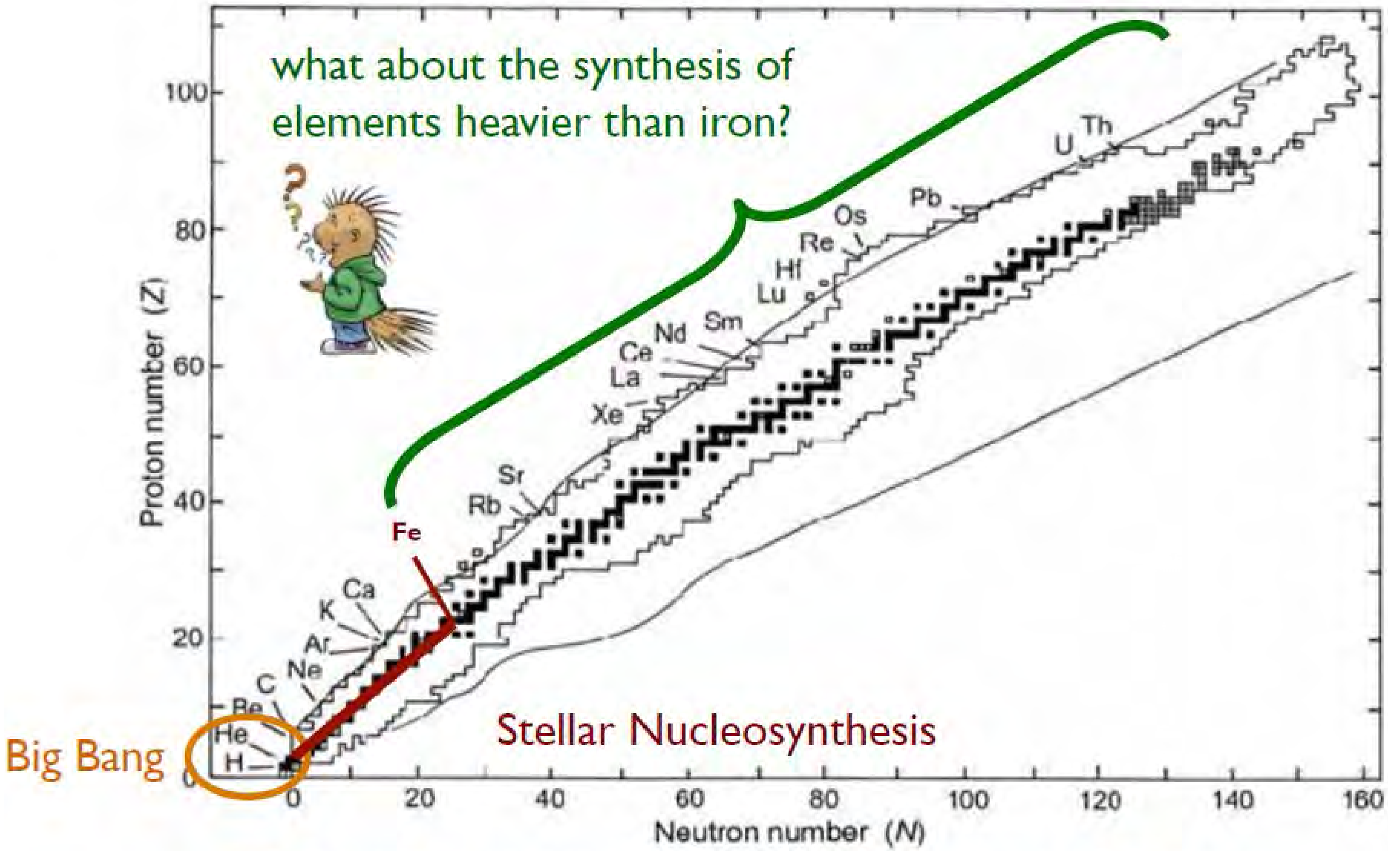




Courtesy Jaret Heise

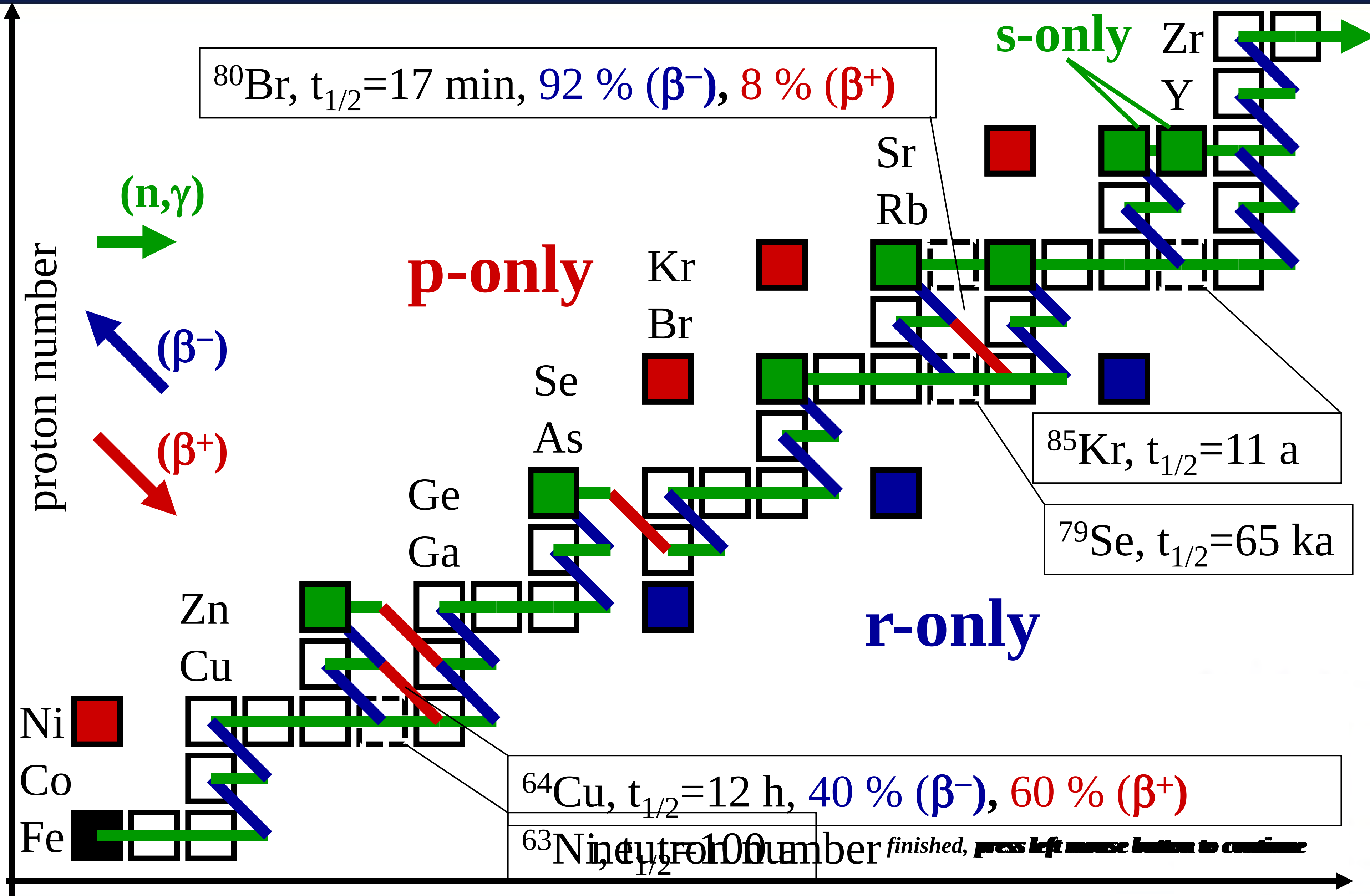

Utility Area
CASPAR Experimental Hall
Change Area
Control Room

How were Elements from Iron to Uranium made?



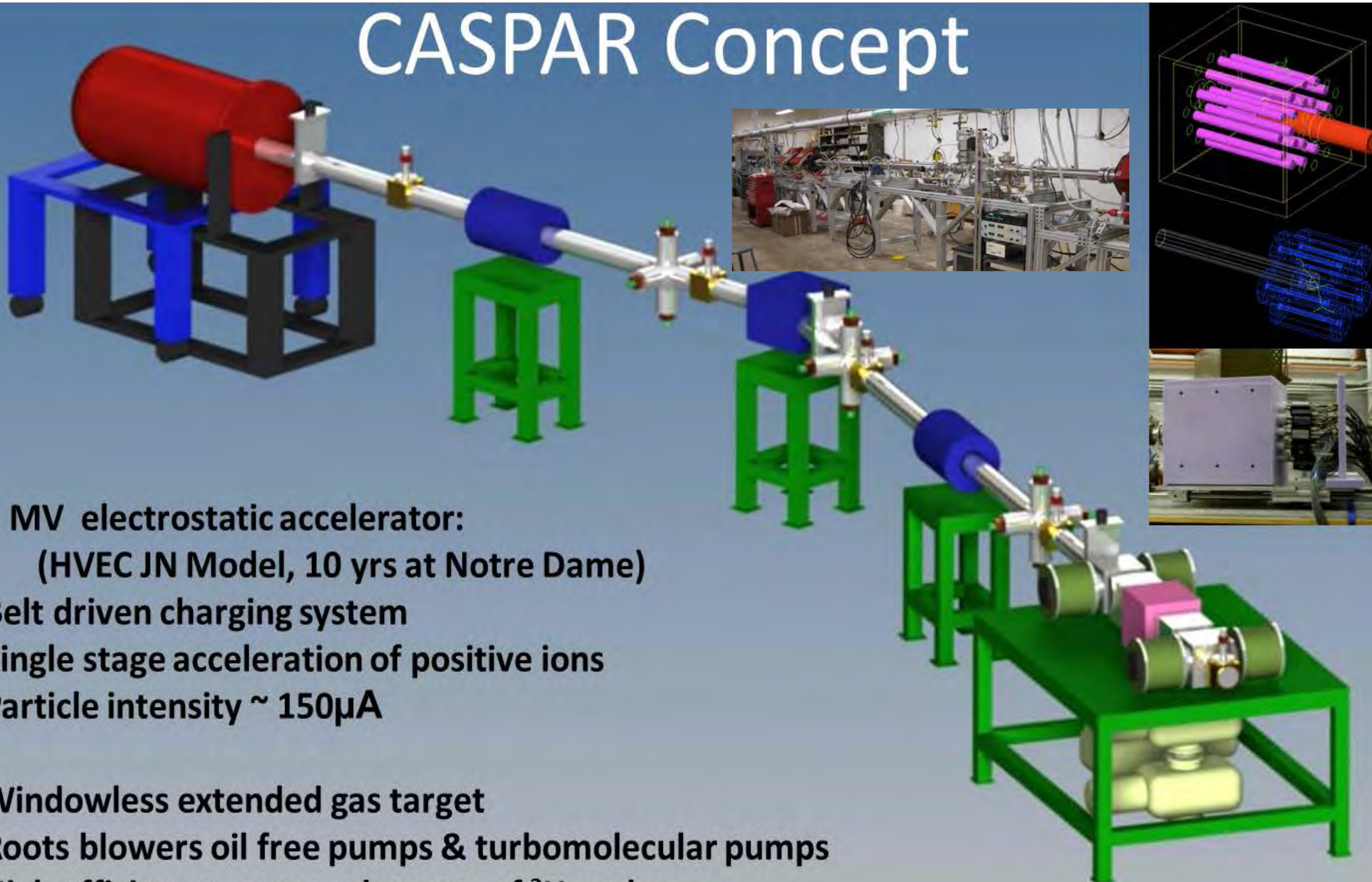
"The 11 Greatest Unanswered Questions of Physics"

from: National Academy of Science Report, 2002



s-only
Zr
Y
Sr
Rb
Kr
Br
Se
As
Ge
Ga
Zn
Cu
Ni
Co
Fe
^{80}Br, $t_{1/2}$=17 min, 92 % (β^-), 8 % (β^+)
(n,γ)
p-only
(β^-)
(β^+)
proton number
^{85}Kr, $t_{1/2}$=11 a
^{79}Se, $t_{1/2}$=65 ka
r-only
^{64}Cu, $t_{1/2}$=12 h, 40 % (β^-), 60 % (β^+)
^{63}Ni, $t_{1/2}$=100 a
neutron number
finished, press left mouse button to continue

CASPAR Concept



1 MV electrostatic accelerator:
(HVEC JN Model, 10 yrs at Notre Dame)
Belt driven charging system
Single stage acceleration of positive ions
Particle intensity ~ 150μA

Windowless extended gas target
Roots blowers oil free pumps & turbomolecular pumps
High efficiency neutron detector of ^{3}He tubes

October 6th, 2015

Photo by Matt Kapust (SURF)

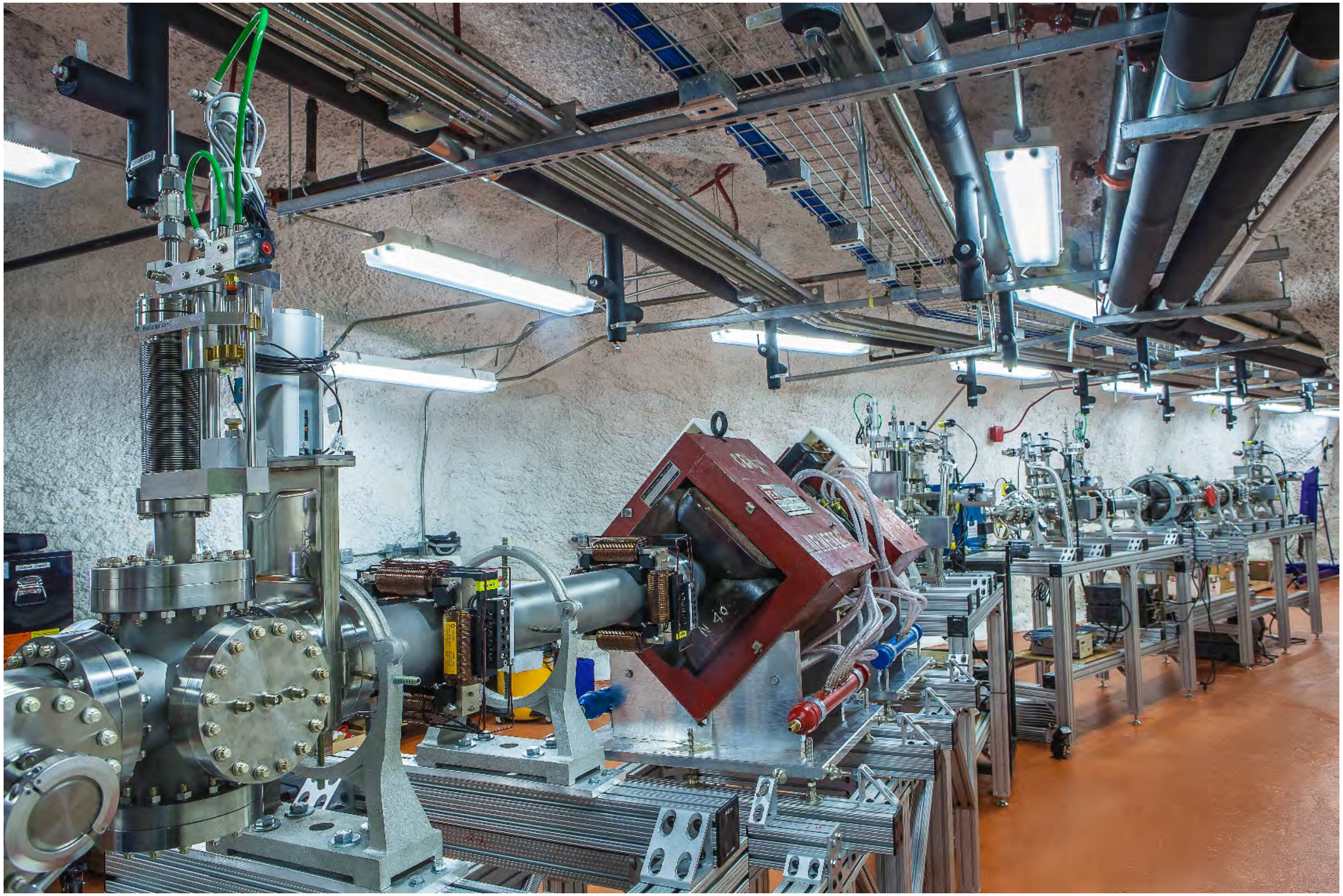
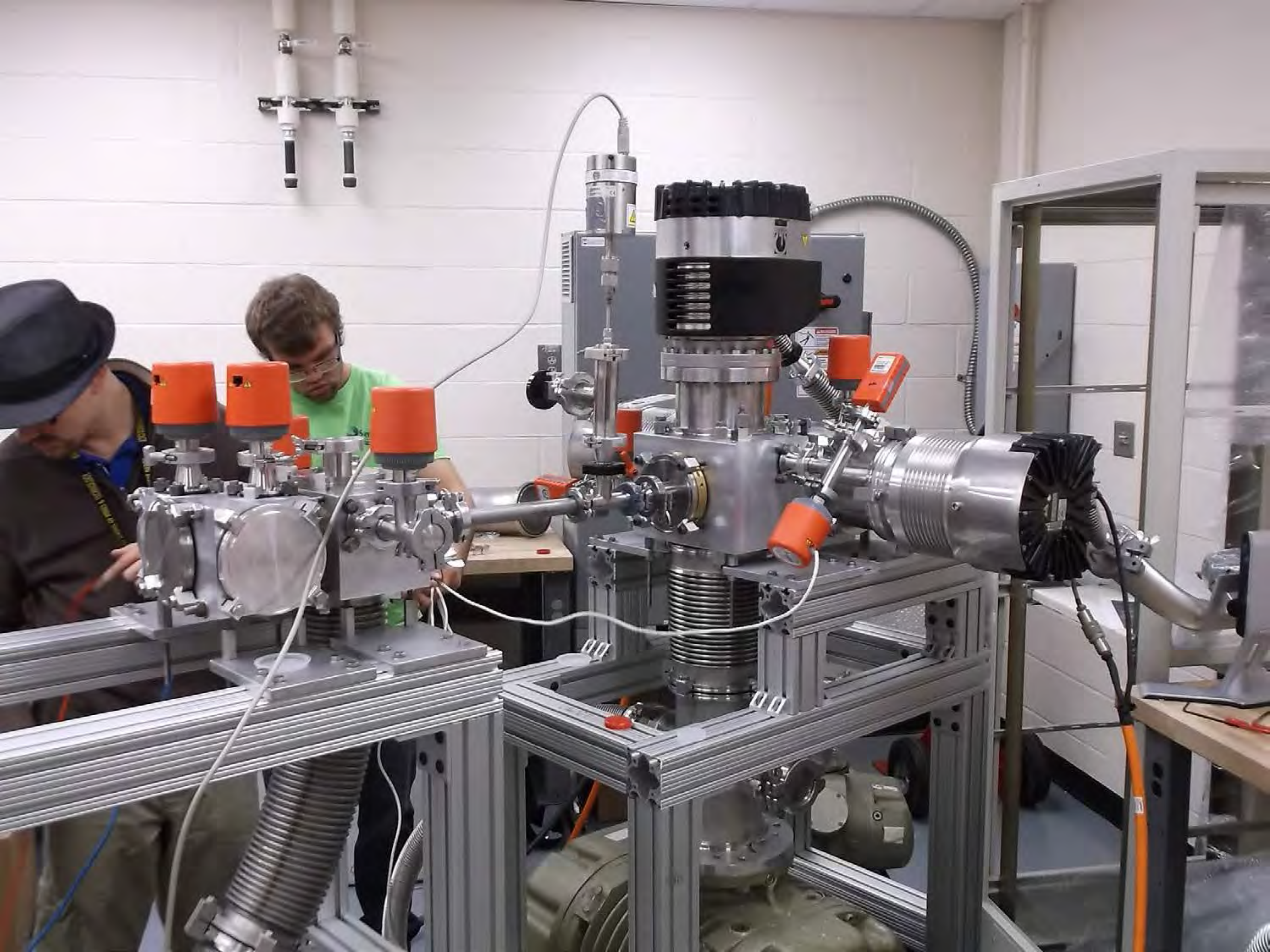
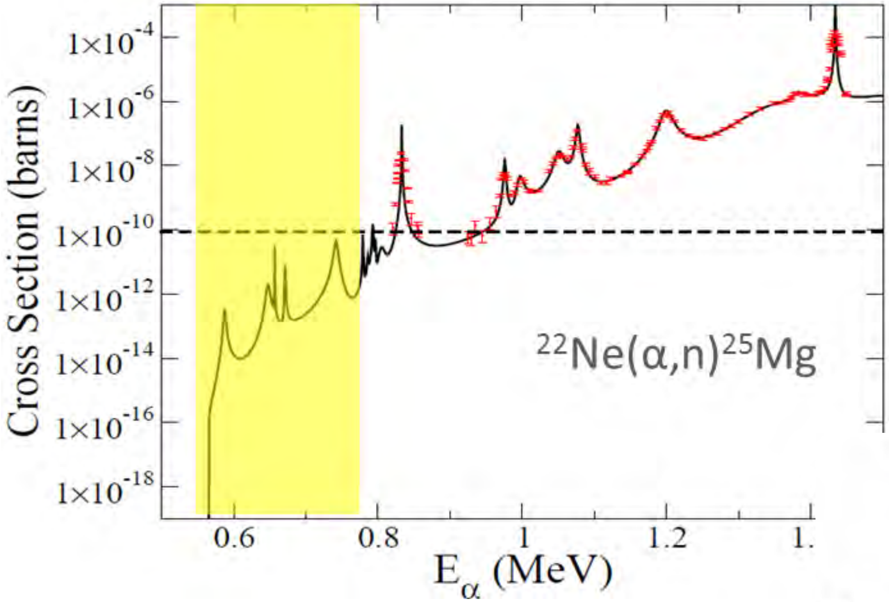


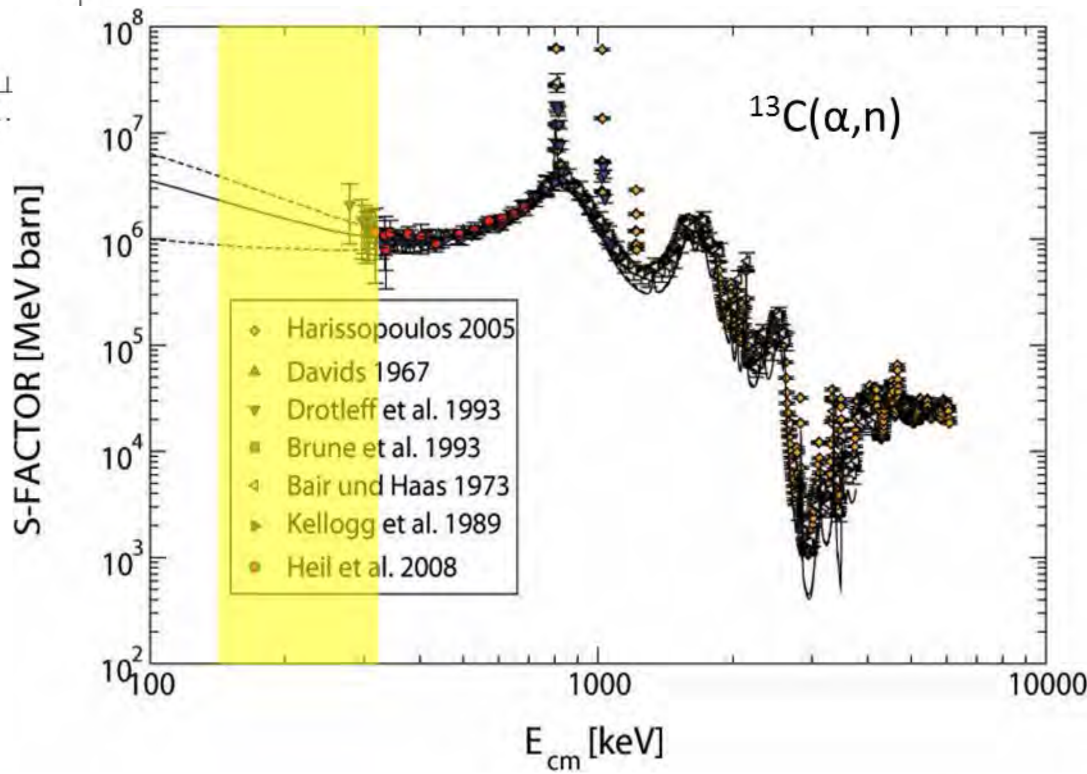
Photo by Matt Kapust (SURF)



Seeds for the s-process

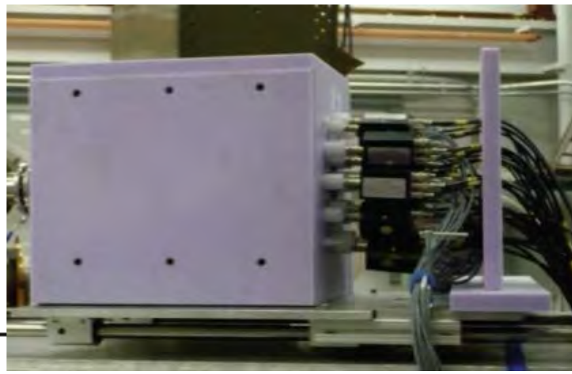


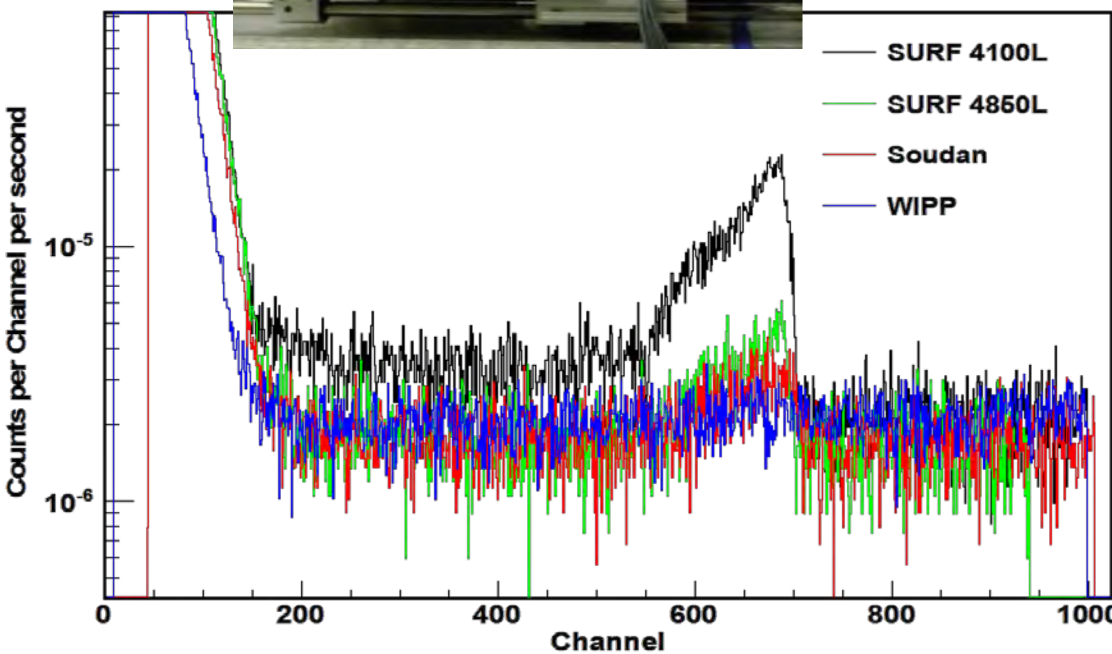
- $^{22}Ne(\alpha,n)^{25}Mg$ and $^{13}C(\alpha,n)^{16}O$
- Neutron sources for the s-process
- Large Uncertainties in astrophysical energy region
- Measurements limited by cosmic-ray induced background

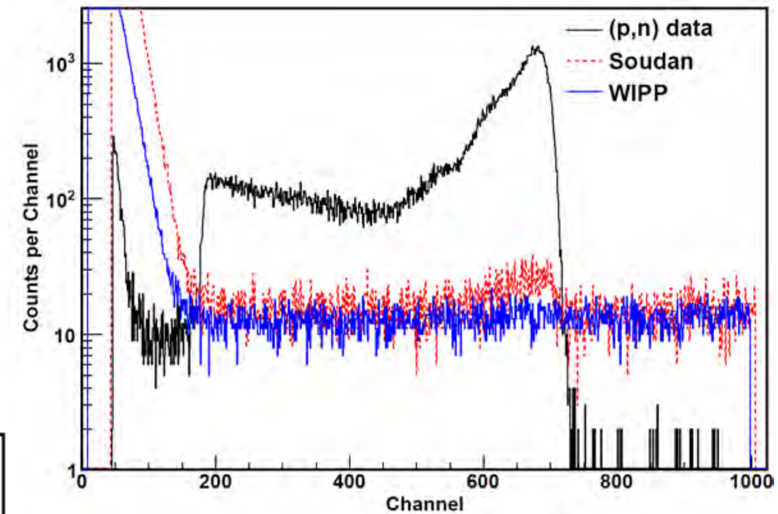


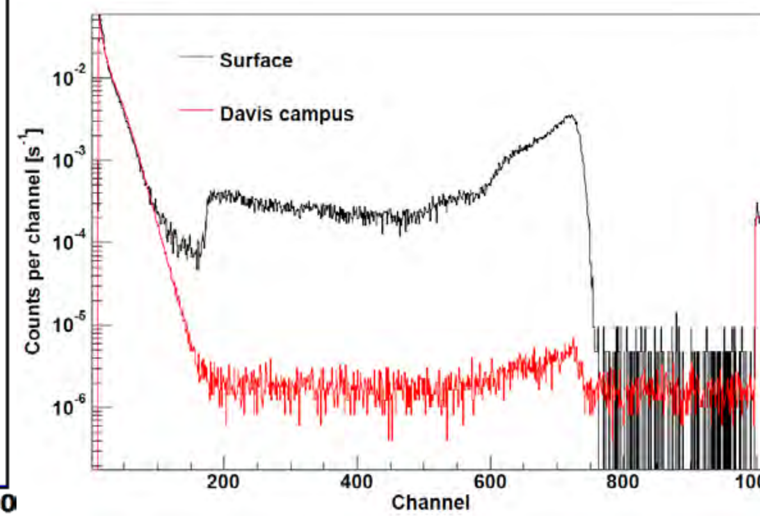
Neutron Background Reduction

^{3}He proportional counter in
a polyethylene moderator matrix









Future Underground Nuclear Astrophysics

Status of the LUNA-MV project at LNGS

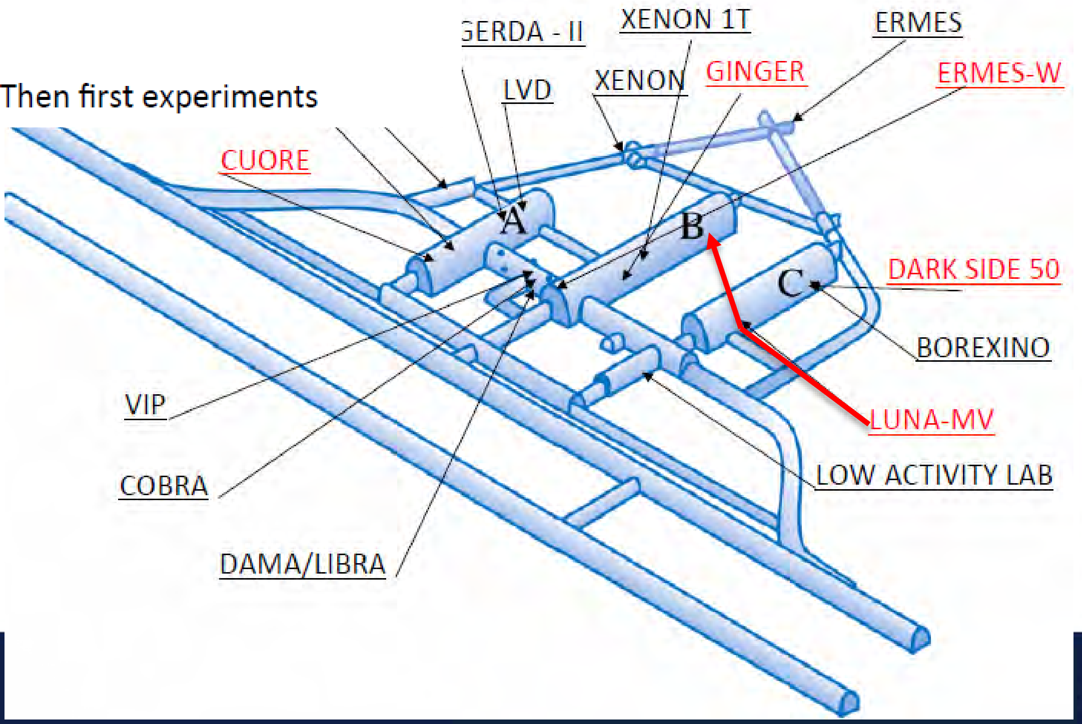
Accelerator:

Intense H^+, $^4He^+$, $^{12}C^+$ e $^{12}C^{++}$ beams in the energy range: 350 keV-3.5 MeV. One beam line with all necessary elements (magnets, pumps, valves,...).

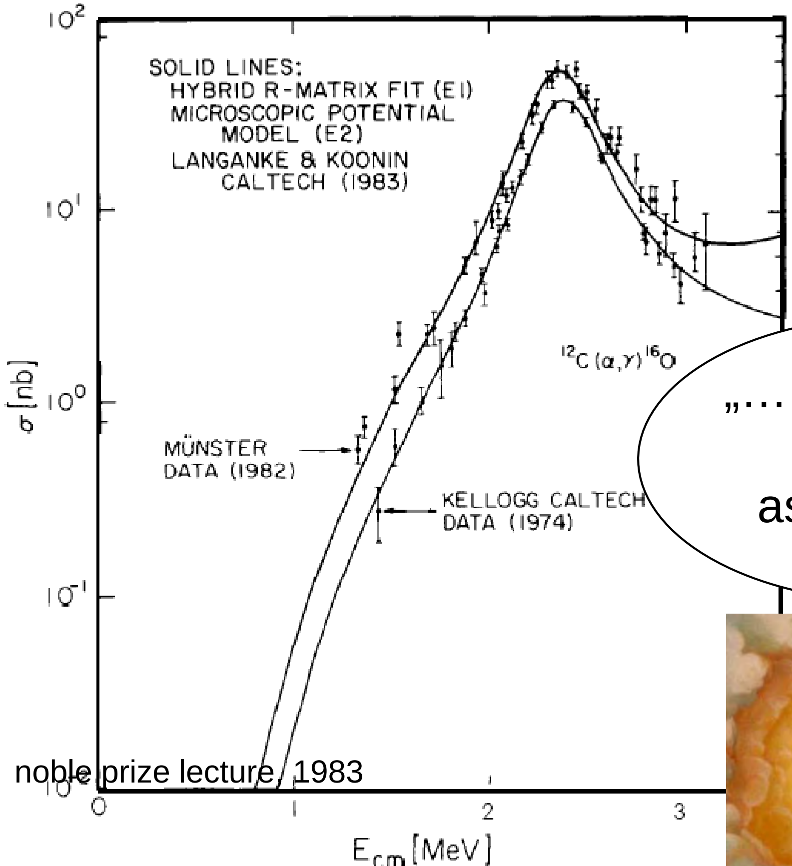
Total budget about 3.9 Meuro: from LUNA MV Premium projects (total 5.3 Meuro)

Tendering procedure: full documentation submitted to INFN central administration at end of february 2015.

Accelerator installed and tested at LNGS by 07/2018. Then first experiments



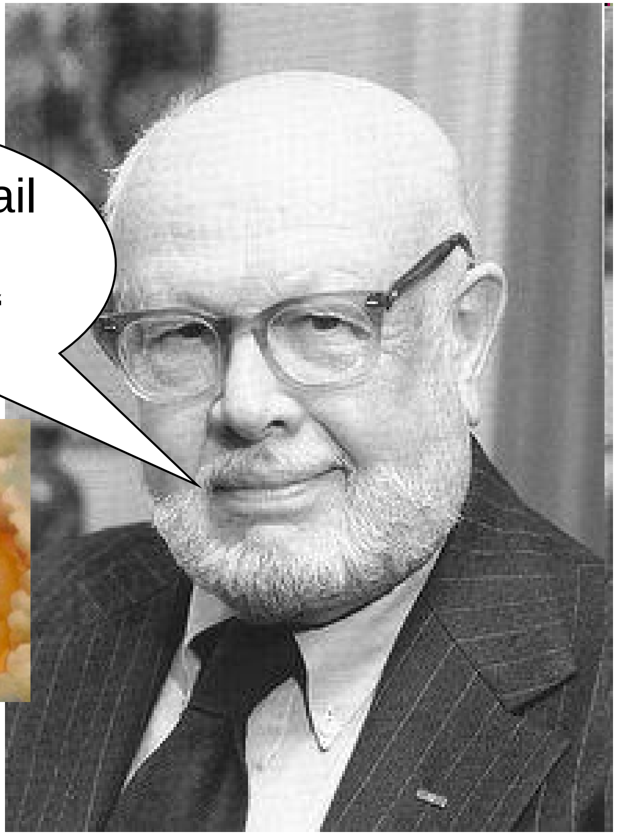
LUNA-MV Physics - $^{12}C(\alpha,\gamma)^{16}O$ more than 40 years



noble prize lecture, 1983

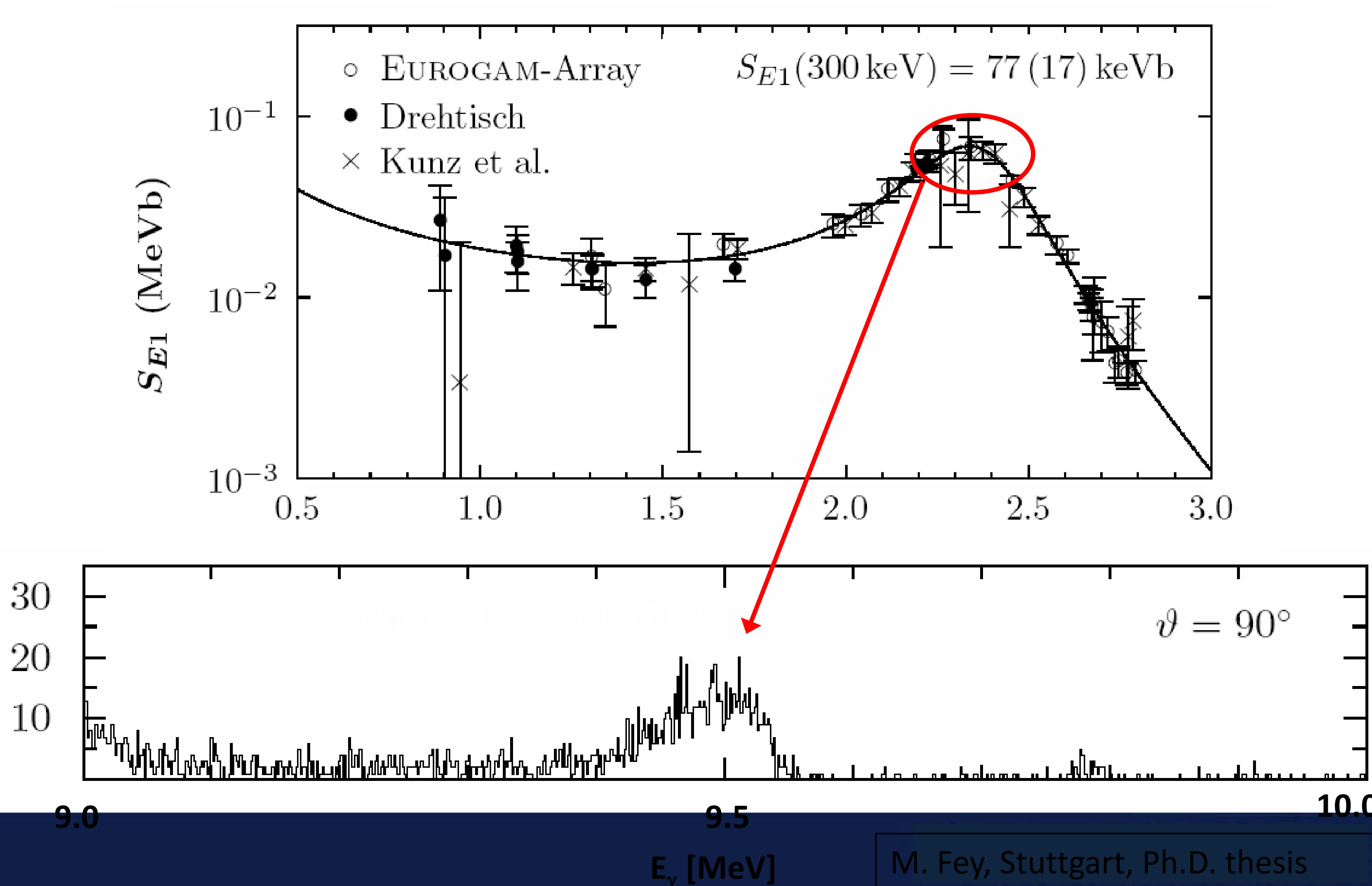
William A. Fowler (1911 – 1995)

„… the holy grail of nuclear astrophysics“



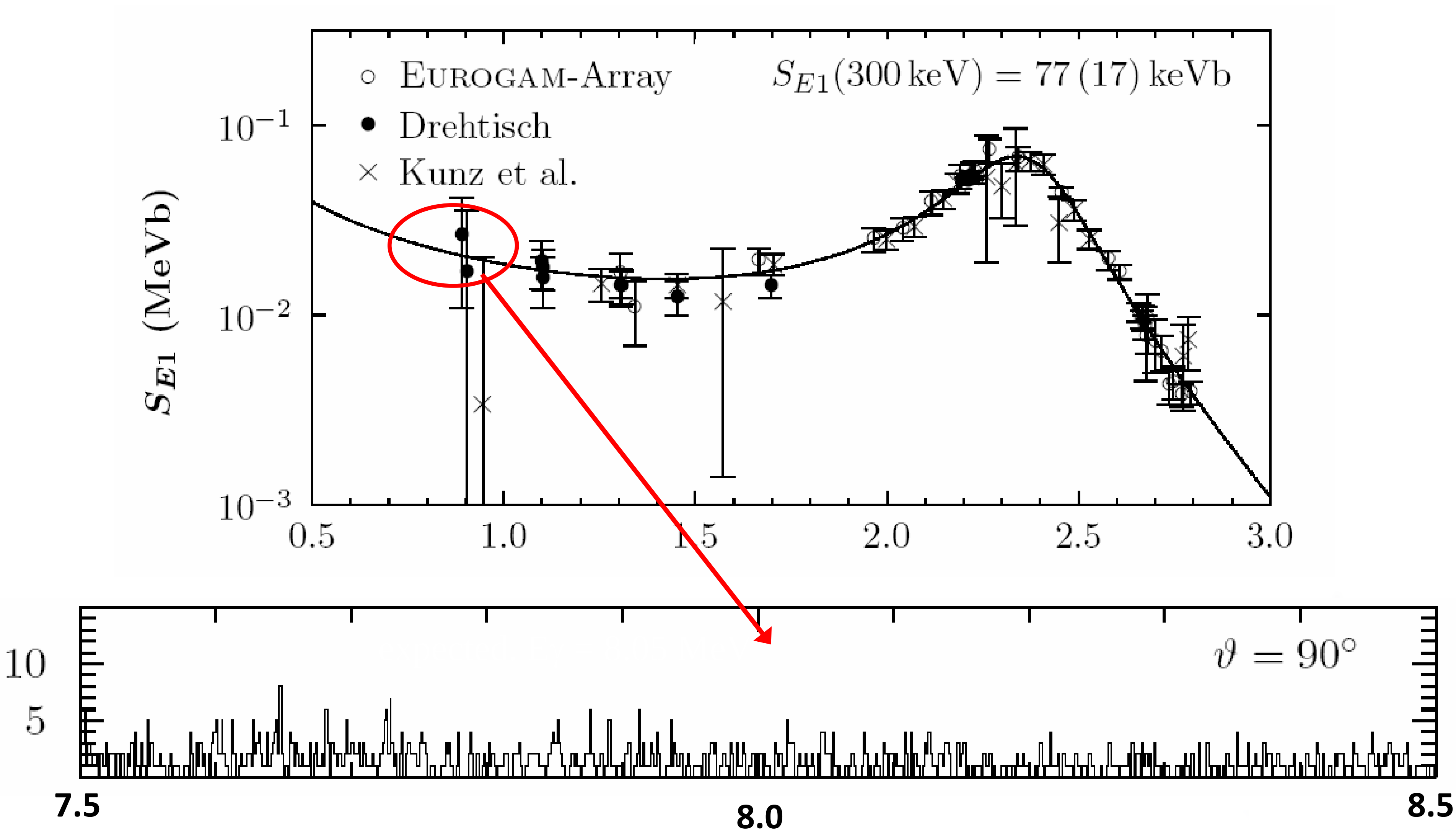
Nobel Prize for Physics (1983)
for „his theoretical and experimental studies of the nuclear reactions of importance in the formation of the chemical elements in the universe“.
(shared with S. Chandrasekhar)

Direct Methods – γ-ray Experiments



M. Fey, Stuttgart, Ph.D. thesis

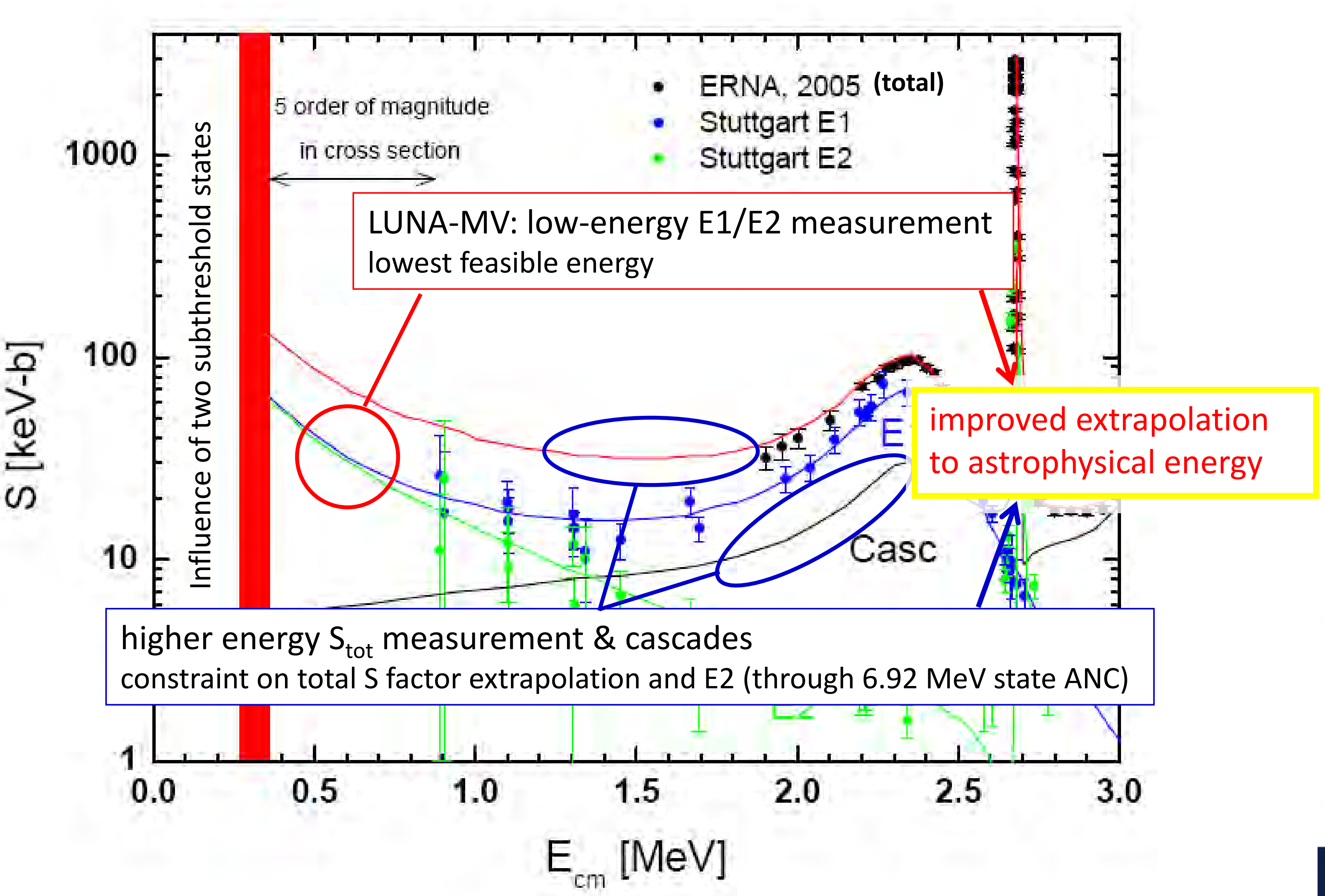
Direct Methods – γ-ray Experiments



E_γ [MeV]

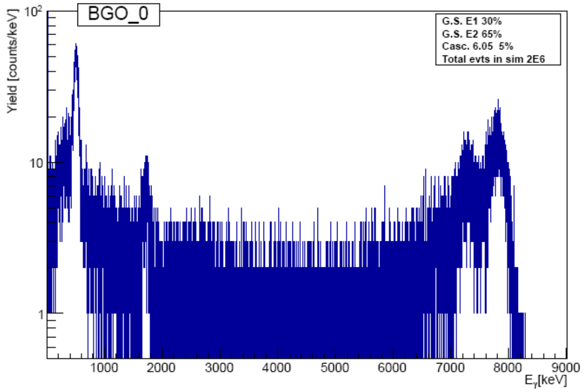
M. Fey, Stuttgart, Ph.D. thesis

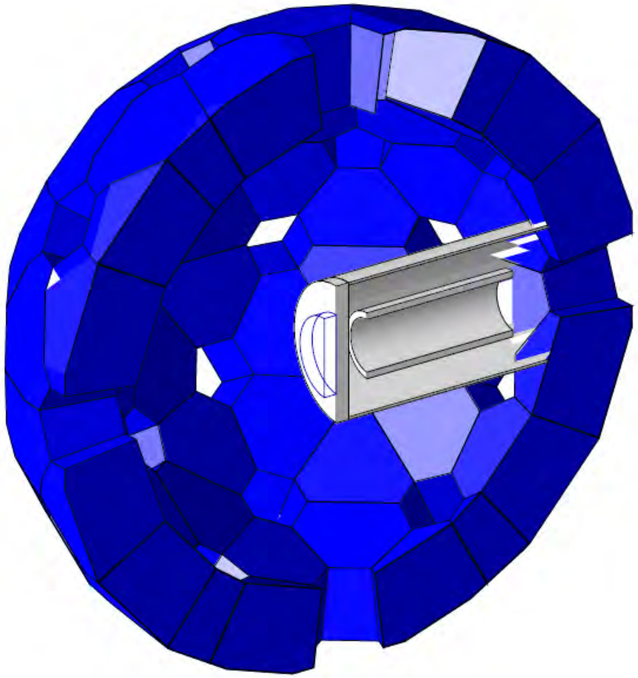
$^{12}C(\alpha,\gamma)^{16}O$ – Aims LUNA-MV/ERNA



$^{12}C(\alpha,\gamma)^{16}O$ – Experimental Issues

GEANT4 simulation of γ-ray array
example: GASP 4π BGO array



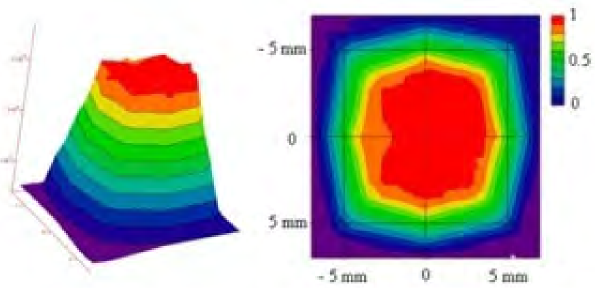


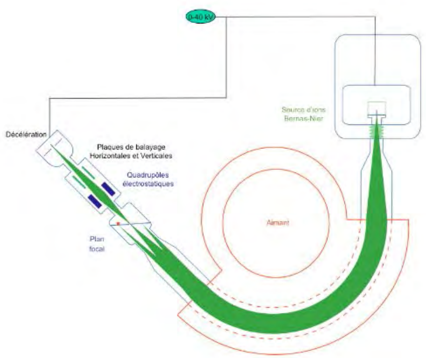
^{12}C target preparation at SIDONI (France)
contact established
preliminary studies in progress

target characterization at LNL
test studies in progress

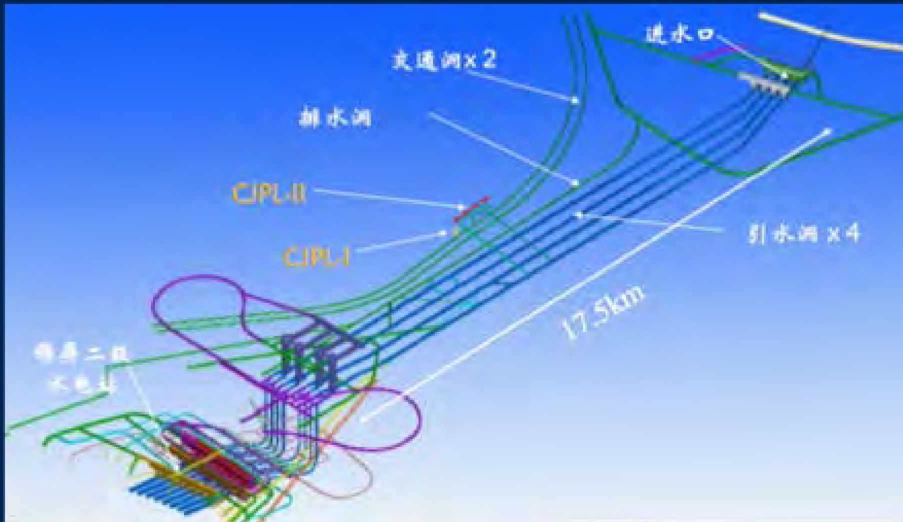
higher separation power

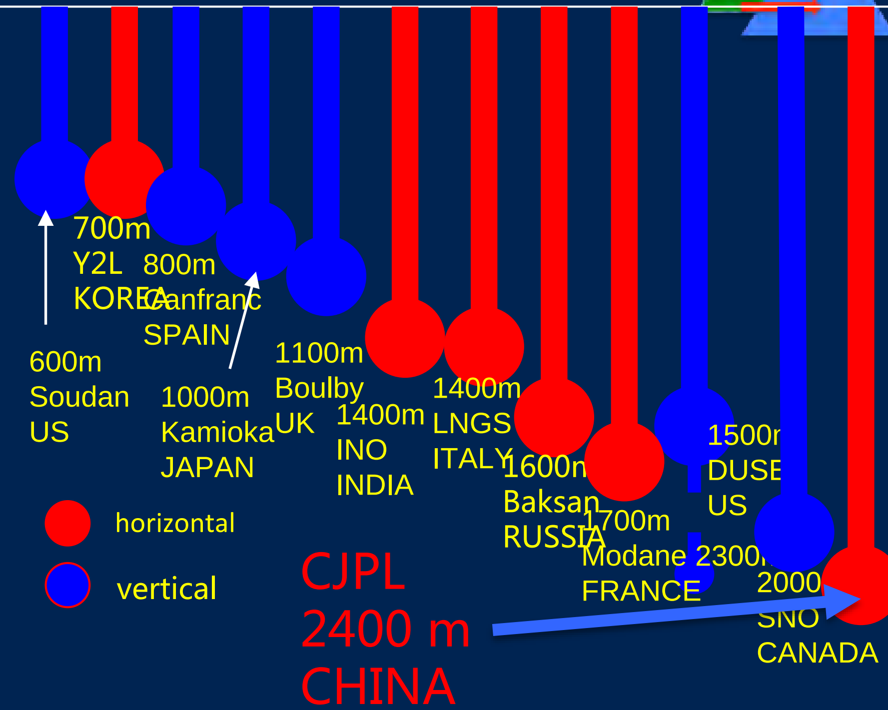
high homogeneity





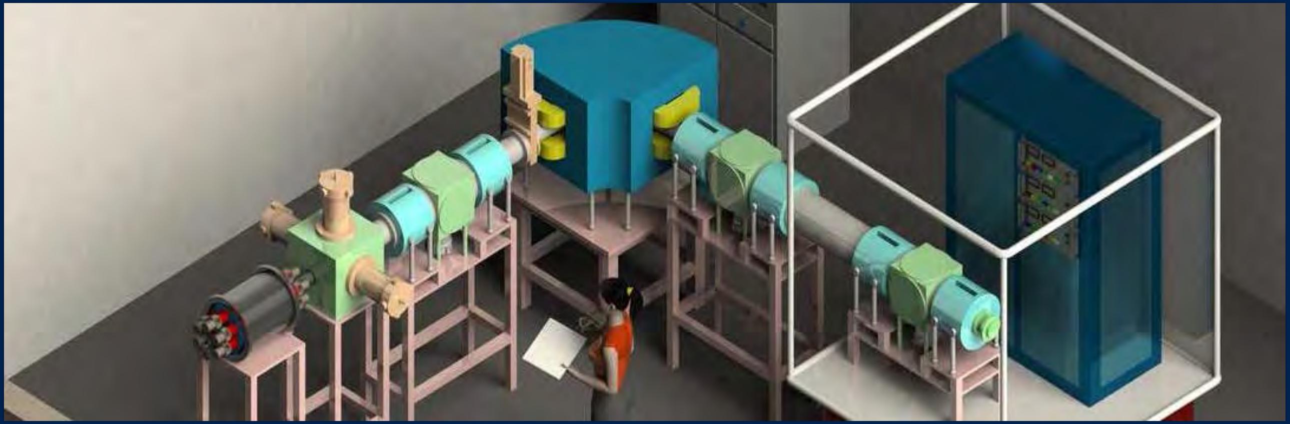
CJPL underground laboratory





courtesy Weiping Liu

JUNA-I plan

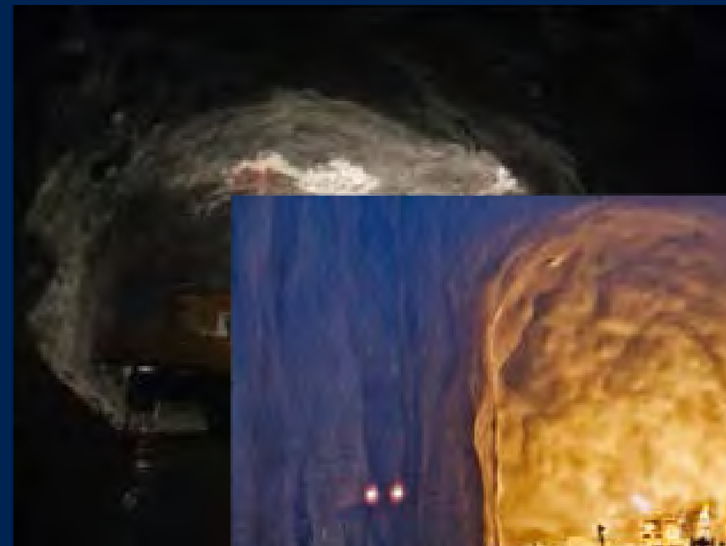


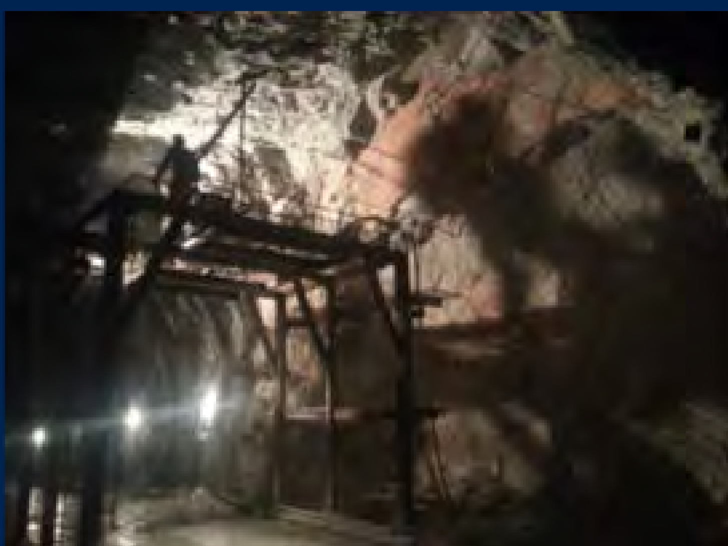
JUNA-I

Beam	***Intensity (mA)***	***Energy,keV***
H^+	***10***	***70-400***
He^+	***10***	***70-400***
He^{++}	***2-5***	***140-800***

courtesy Weiping Liu

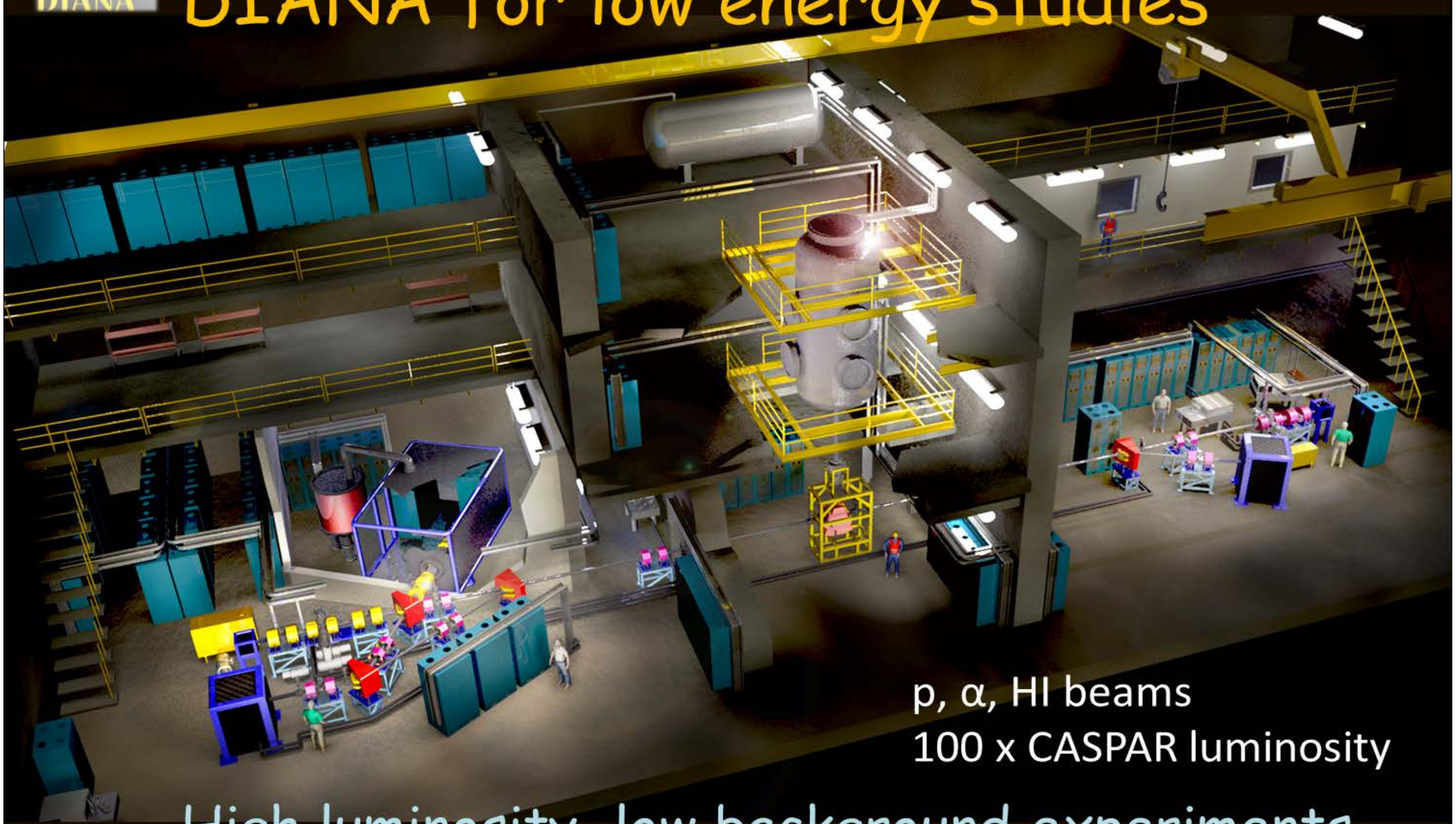
CJPL-II progress





courtesy Weiping Liu

Underground accelerator project DIANA for low energy studies



High luminosity, low background experiments