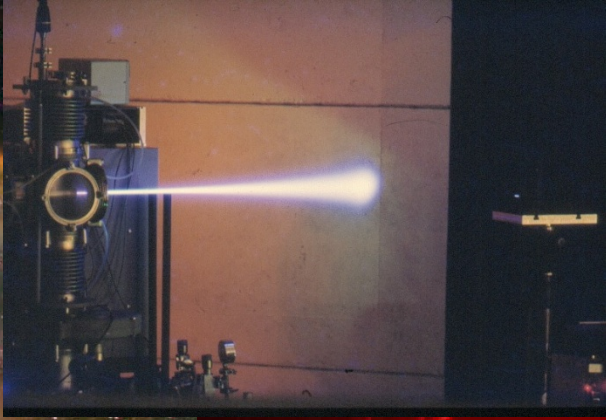
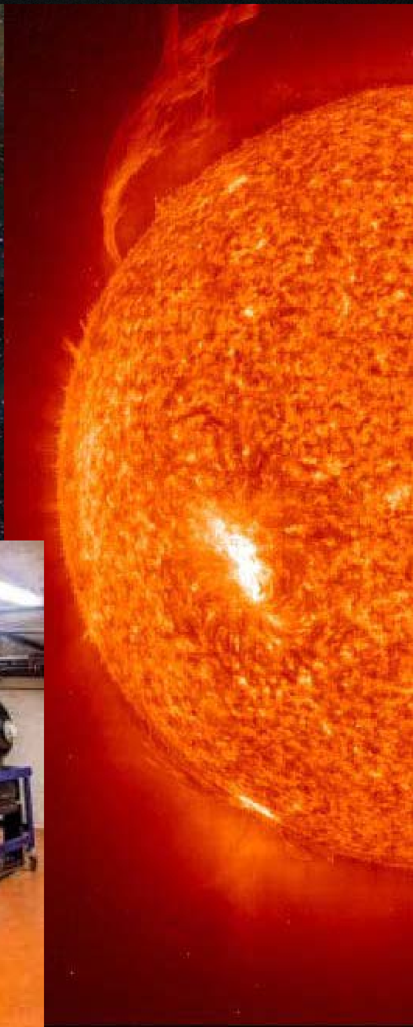
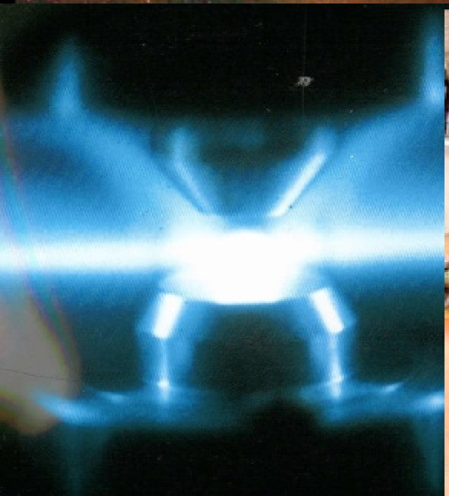
# *Nuclear Astrophysics Underground*
# *Status & Future*



*Frank Strieder*
South Dakota School of Mines & Technology



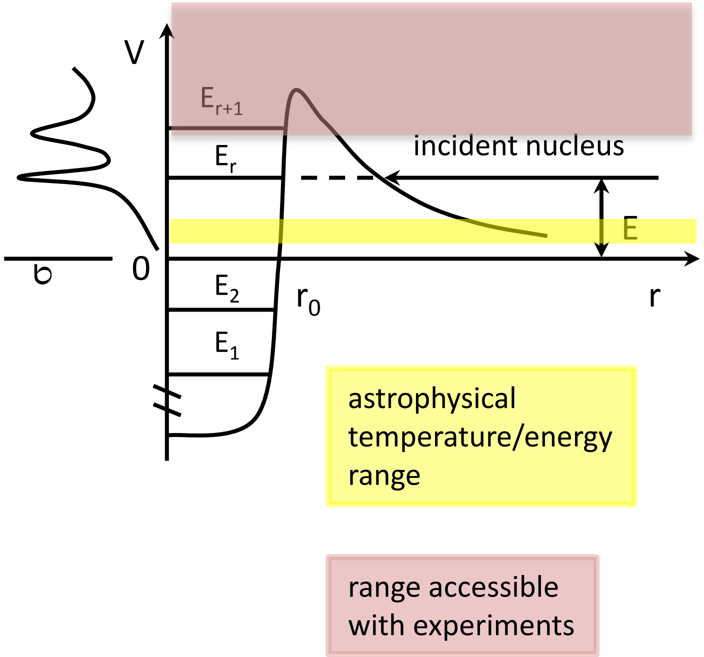
Conference on the Intersection of Particle and Nuclear Physics
Indian Wells, California, USA
May 30th, 2018



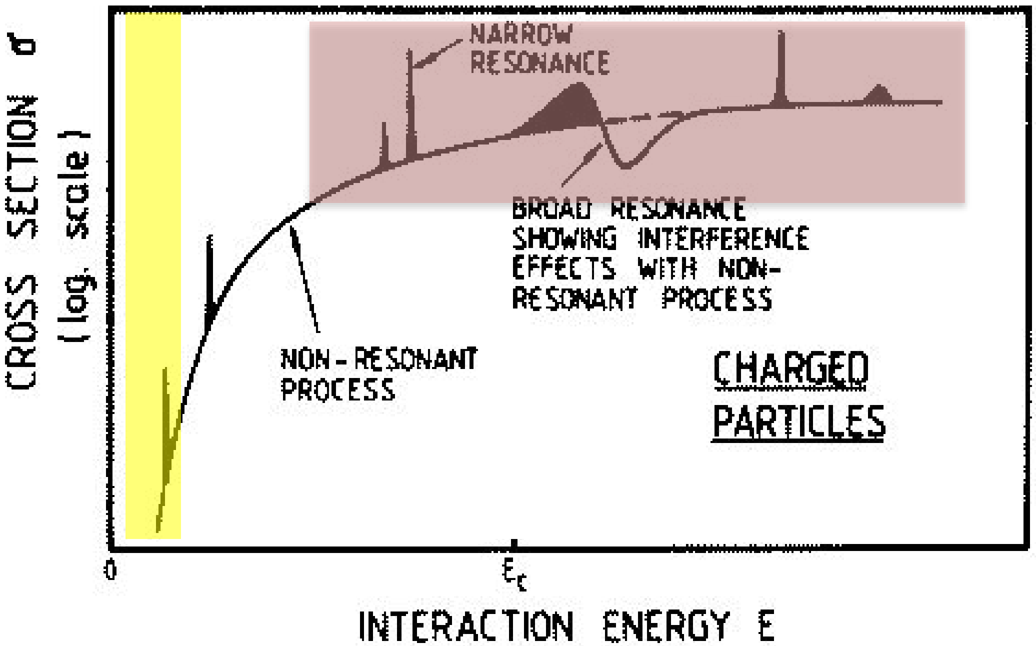
# Nuclear reactions at astrophysical energies

nuclear reactions important to provide energy and the neutrons for nucleosynthesis

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

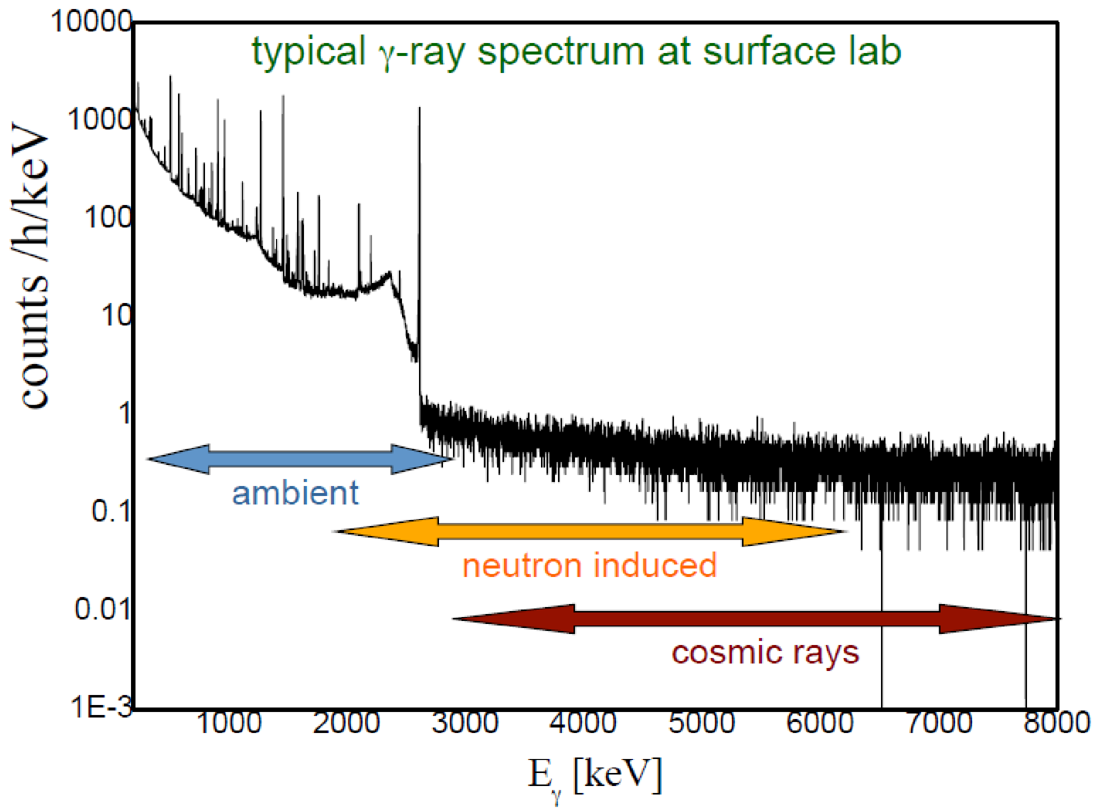


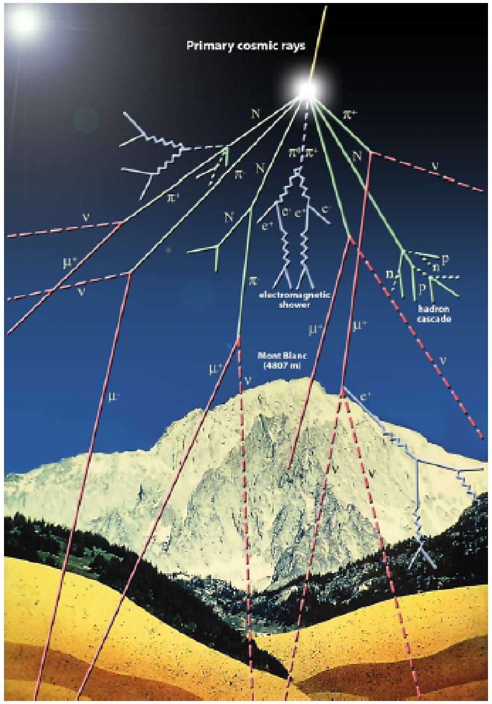

- occurs at specific energies
- cross section has STRONG energy dependence



# 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

# Underground Accelerator: The Beginning

LUNA – Laboratory for Underground Nuclear Astrophysics

initiated: 1$^{st}$ Nuclei in the Cosmos Conference (Baden, Austria, 1990)

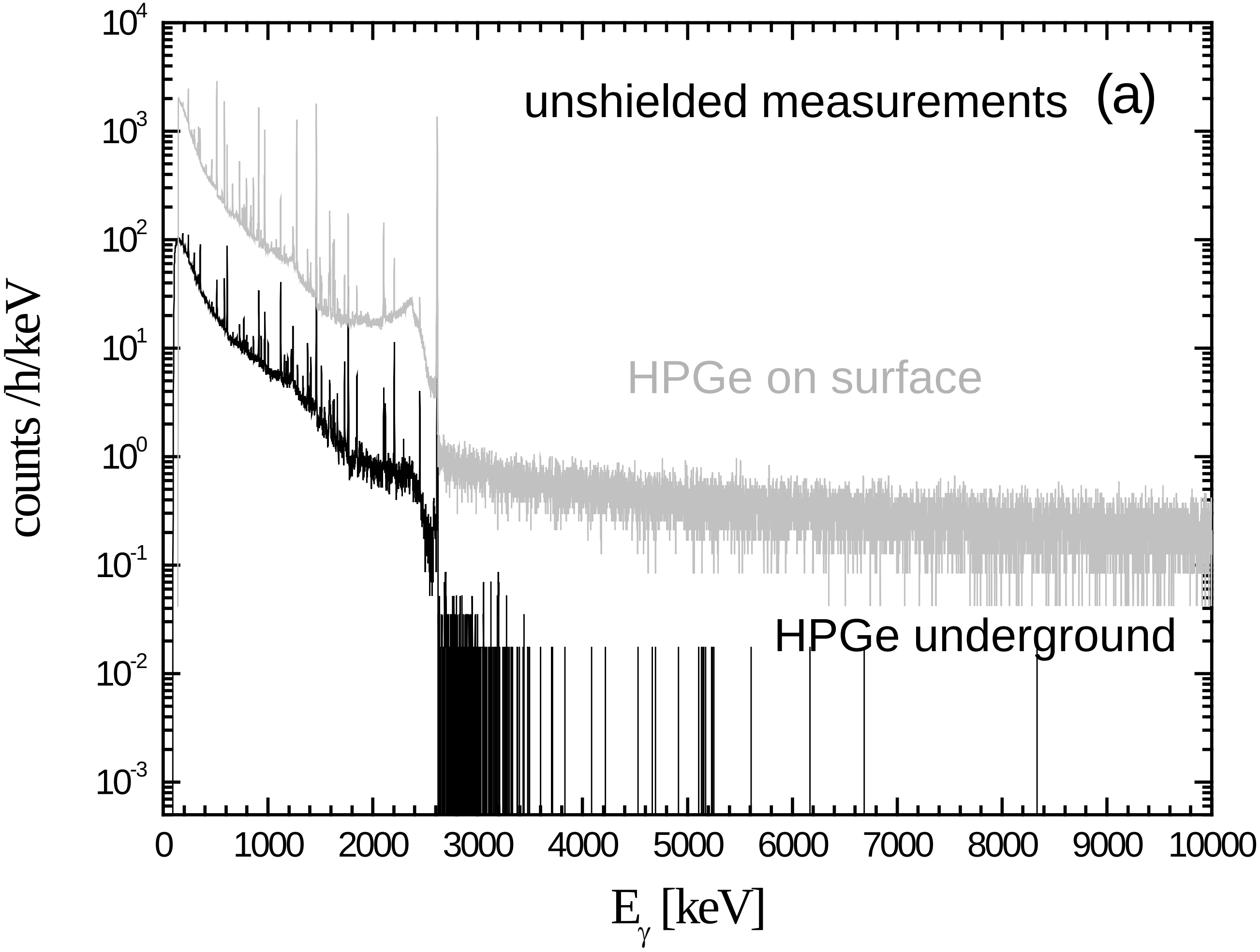
Giani Fiorentini
INFN Ferrara
Italy

Claus Rolfs
Ruhr-Universität Bochum
Germany

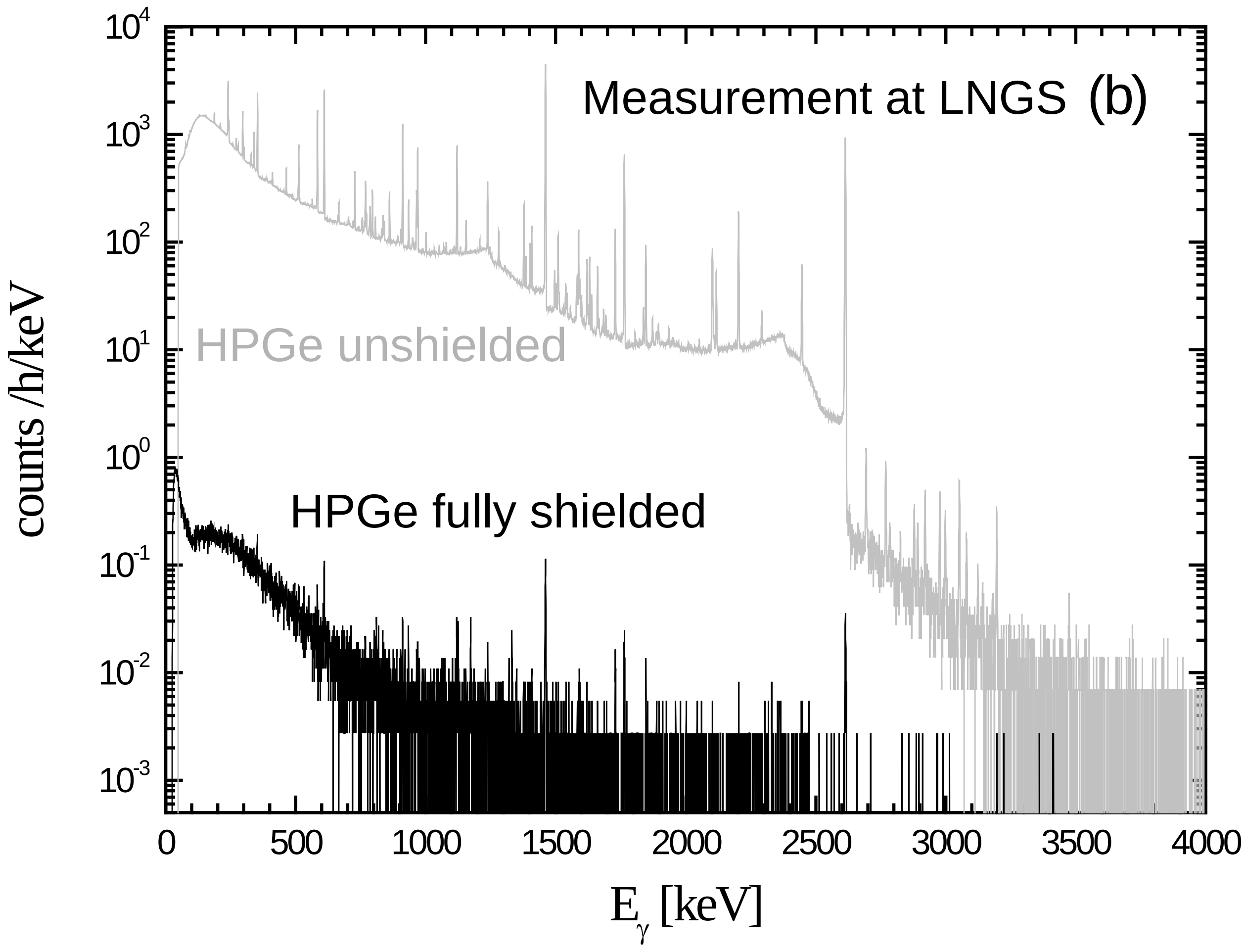
**Why are we not going into the Gran Sasso Lab?**

# Benefit of an Underground Laboratory

## in $\gamma$-ray spectroscopy

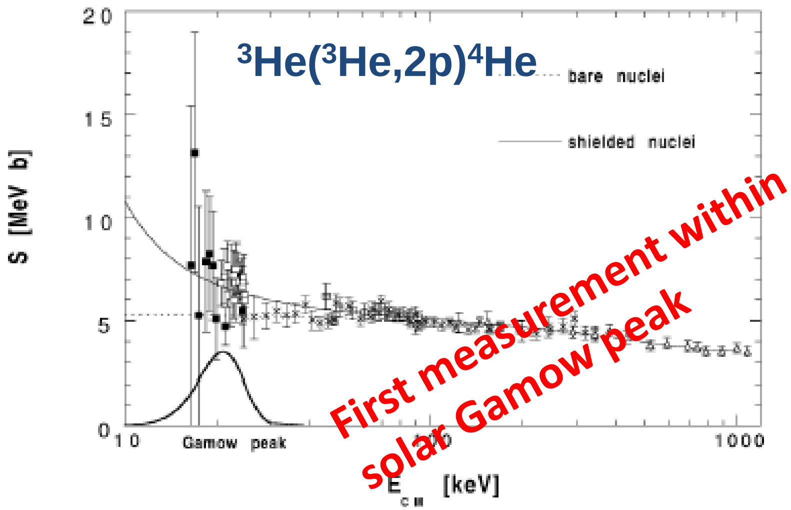


# Benefit of an Underground Laboratory
## in γ-ray spectroscopy

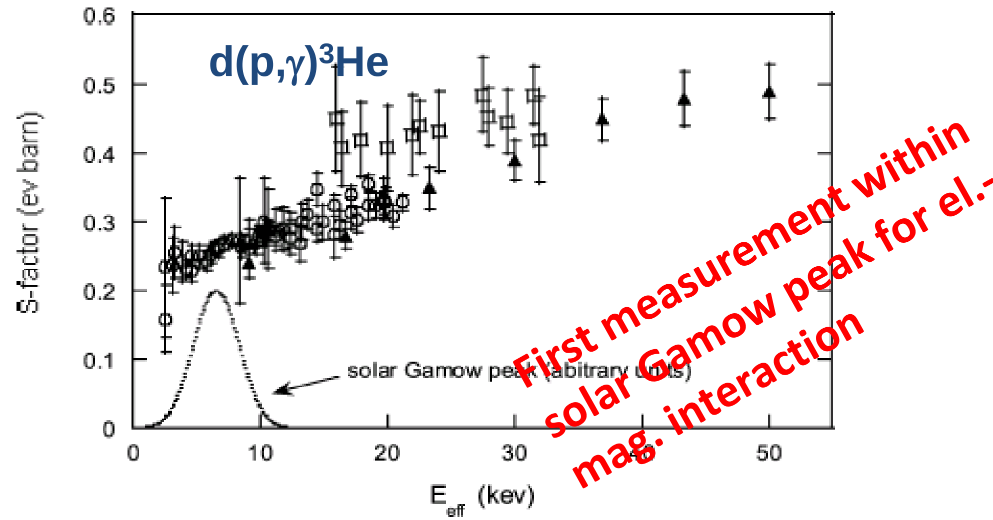


# LUNA I – Achievements Underground

**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

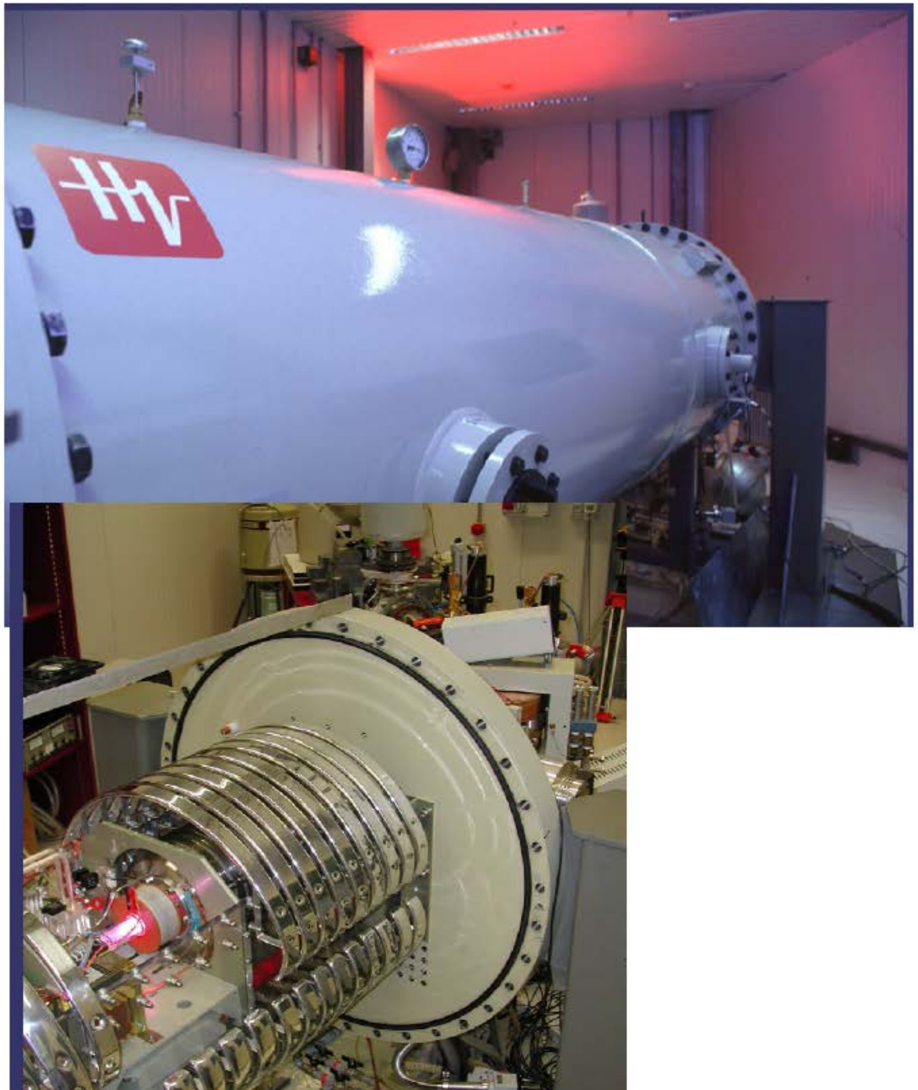



at lowest energy: σ ~ 9 pb → 50 counts/day
C. Casella et al.: Nucl. Phys. A706 (2002) 203

Definition of astrophysical S factor

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

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

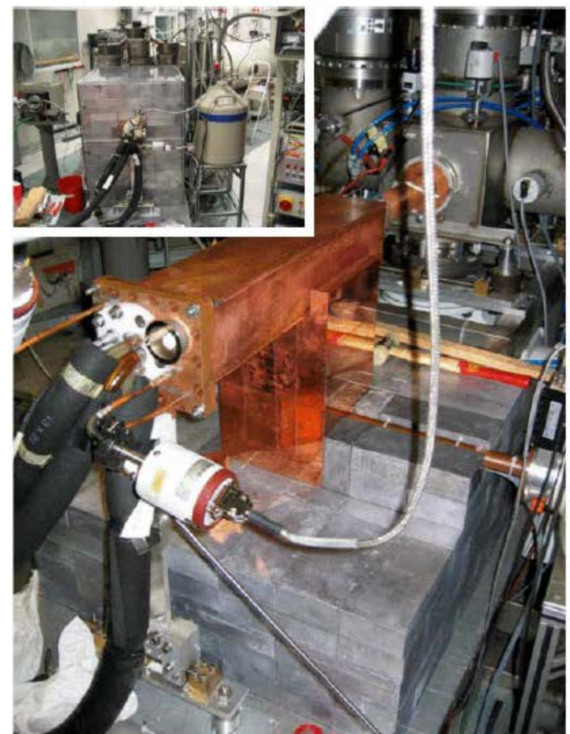


$U_{terminal}$ = 50 – 400kV

$I_{max}$ = 500μA (on target)

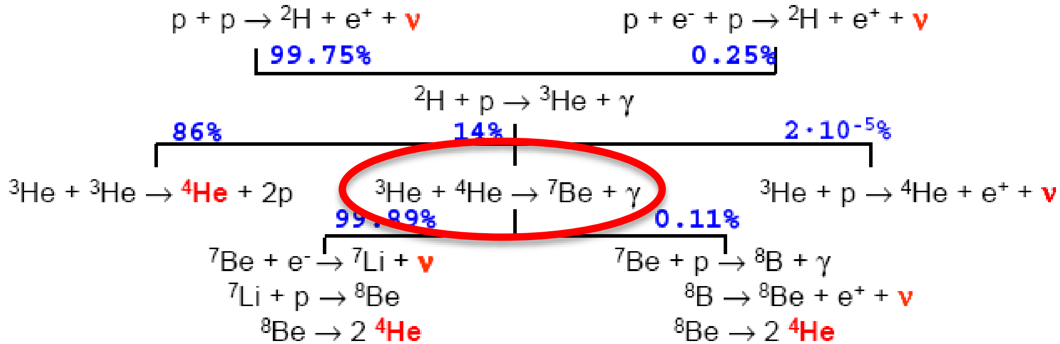
ΔE = 0.07keV

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

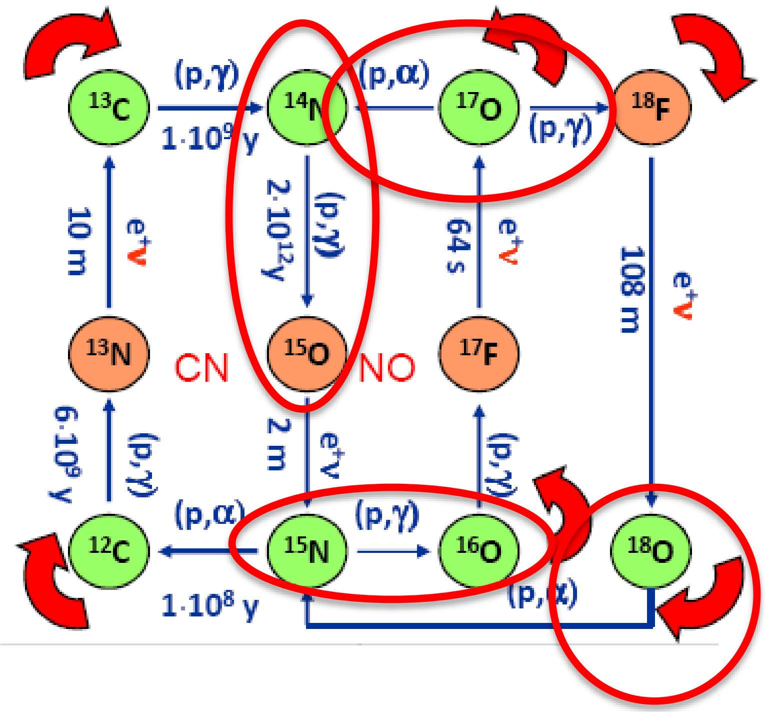


# LUNA II – Key Studies

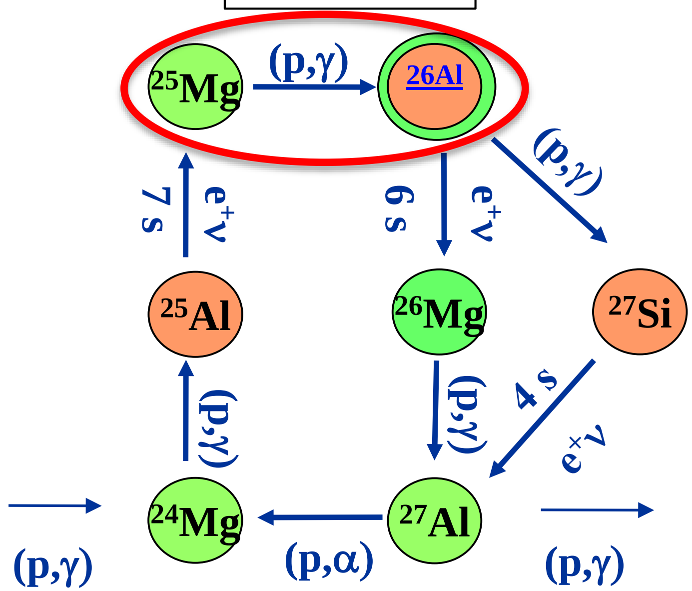
pp chain



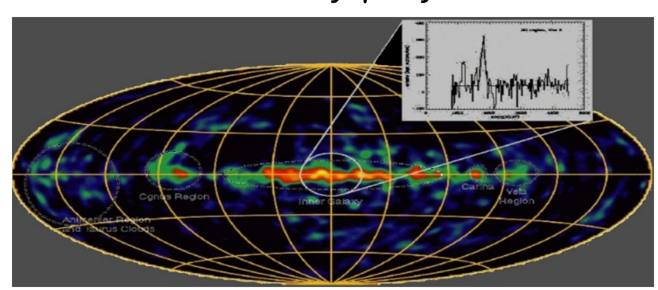

CNO cycle



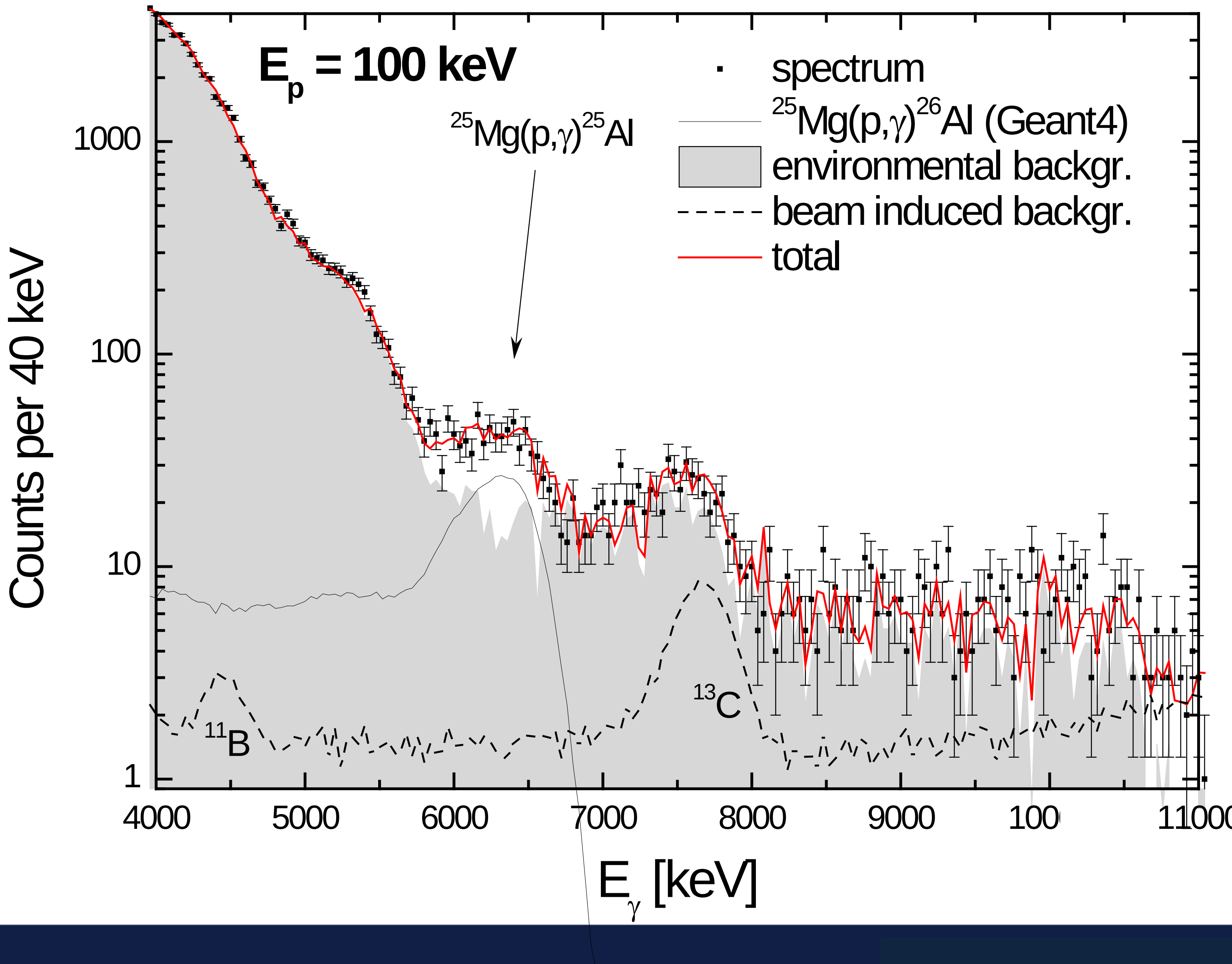

MgAl cycle




1.8 MeV $^{26}$Al decay γ-ray line



# LUNAII Measurement of $^{25}Mg(p,\gamma)^{26}Al$



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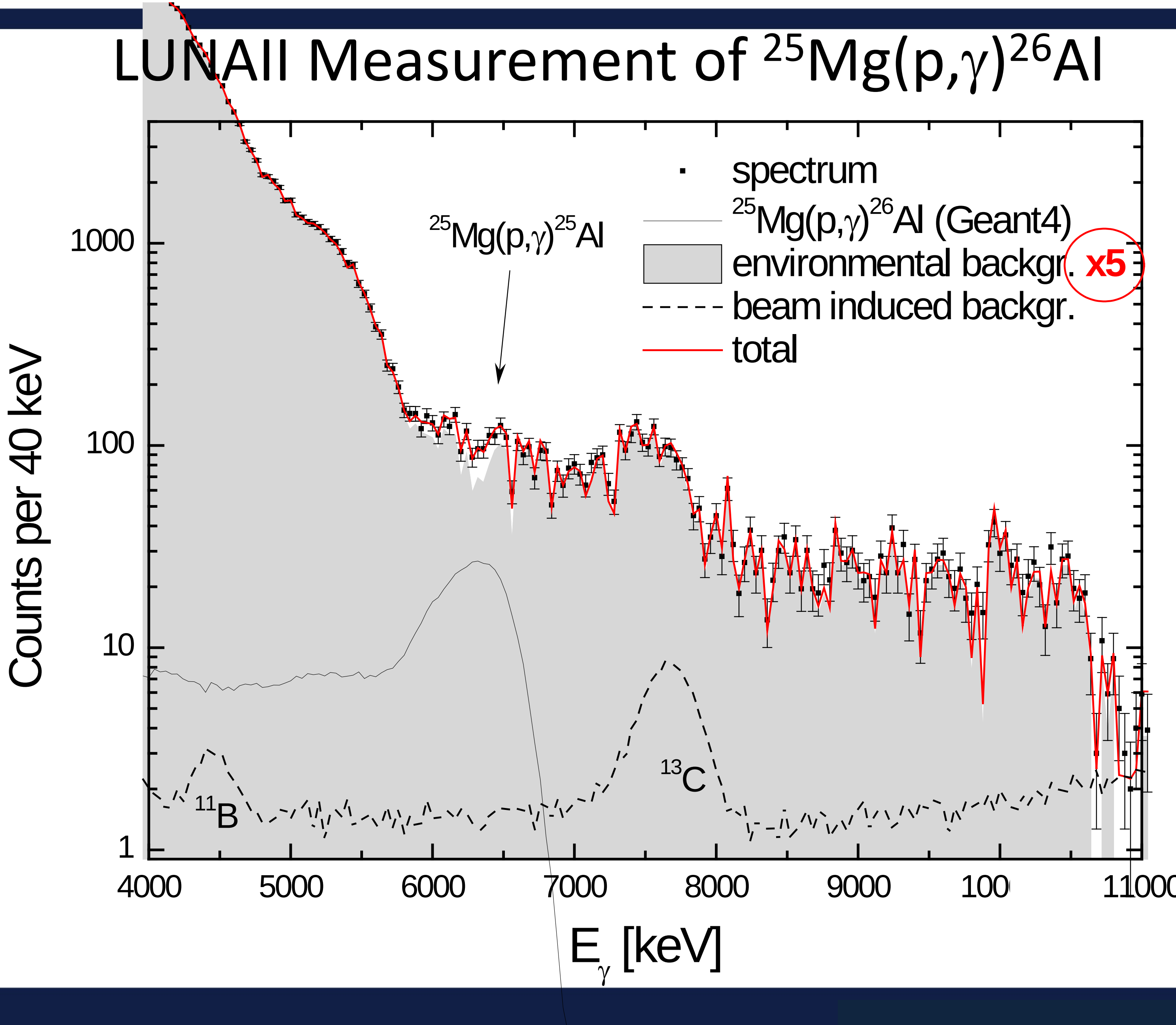


# **C**ompact **A**ccelerator **S**ystem for **P**erforming **A**strophysical **R**esearch

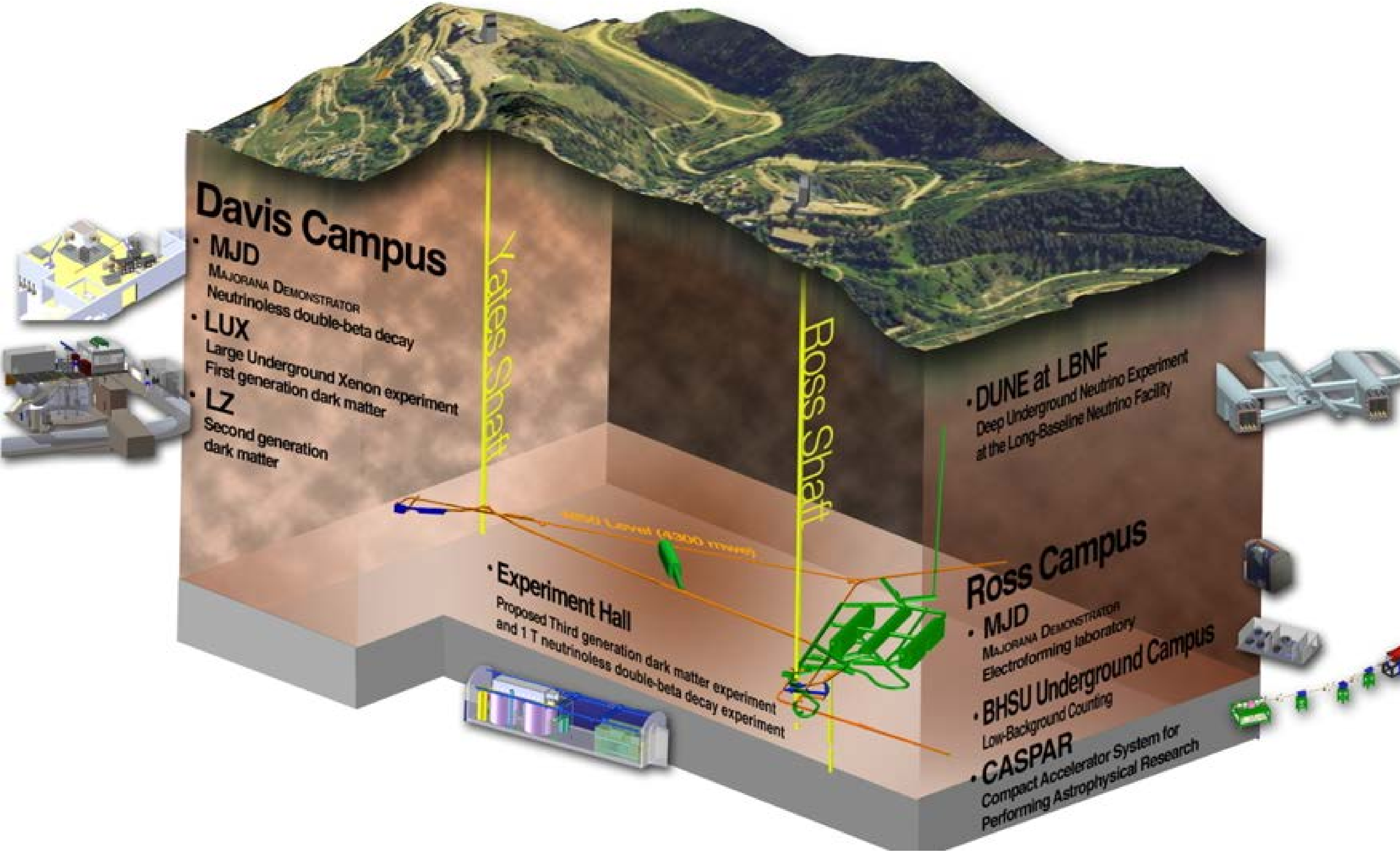
Frank Strieder (PI)
Tyler Borgwardt
Mark Hanhardt
Thomas Kadleczek
Chamaka Senarath
Brandon DeVries
Drew Powers

Dan Robertson (TC)
Manoel Couder
Michael Wiescher
Joachim Goerres
Axel Boeltzig
Bryce Frentz

Uwe Greife

# Sanford Underground Research Facility

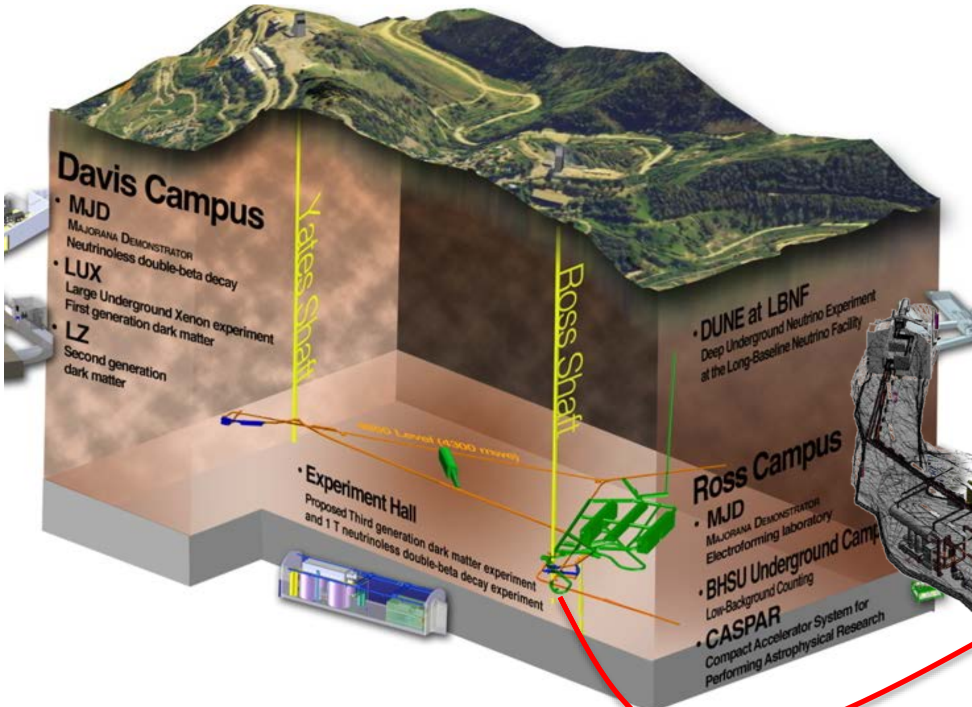

# Sanford Underground Research Facility

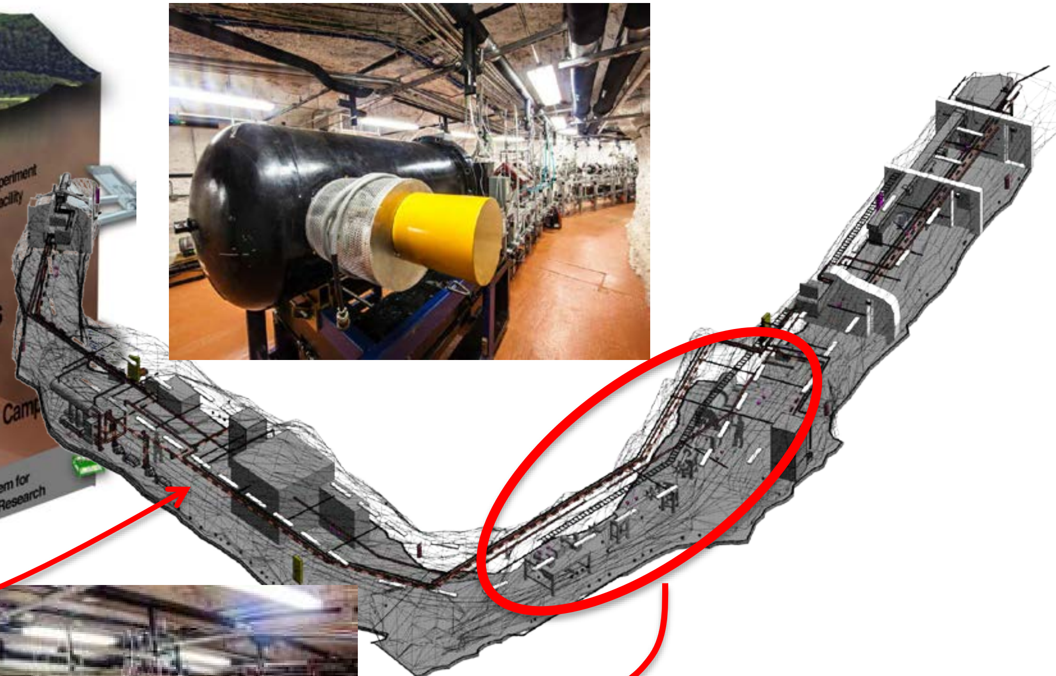


# Compact Accelerator System for Performing Astrophysical Research

First US Underground Accelerator

at Sanford Underground Research Facility



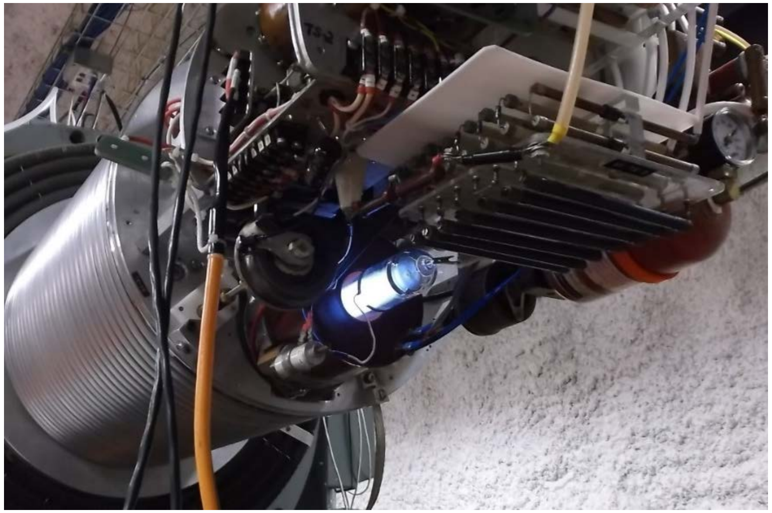



**Studies of stellar neutron sources in the Laboratory**
**→ Understanding of Origin of the Elements**

# Accelerator - Model JN 1 MV van-de-Graaff with RF ion source

1 MV electrostatic accelerator:
Belt driven charging system
Single stage acceleration of positive ions
Particle intensity ~150μA

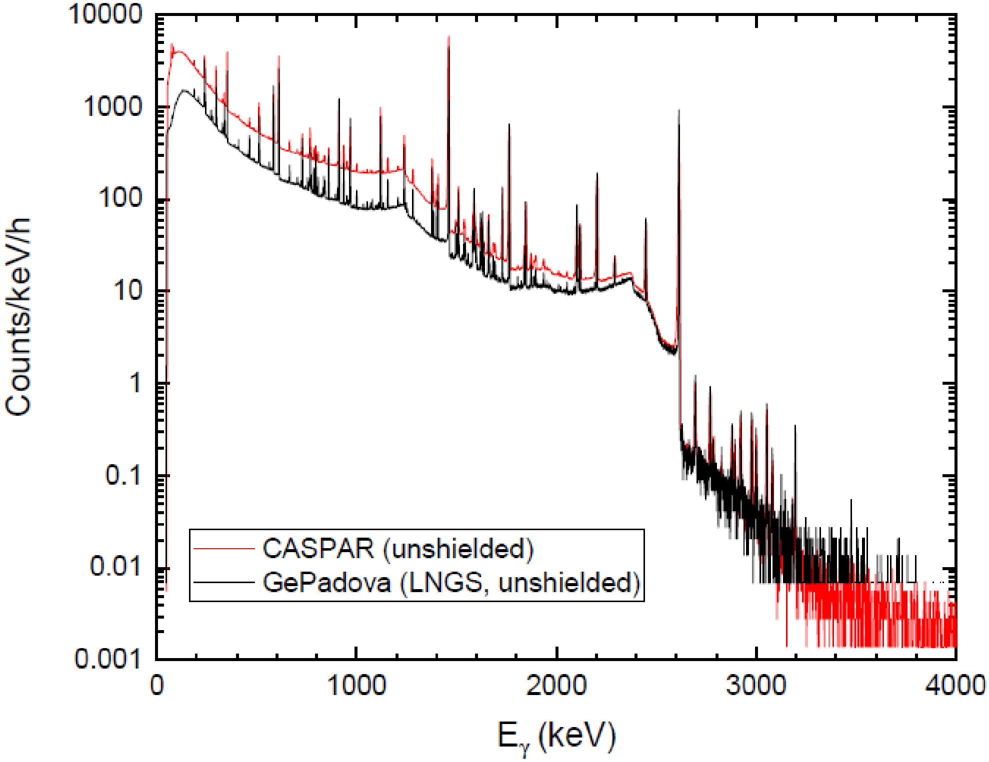
Exchangeable solid target
and windowless extended gas target
Roots blowers oil free pumps
& turbo molecular pumps



RF ion source with helium plasma
(usually closed in tank)

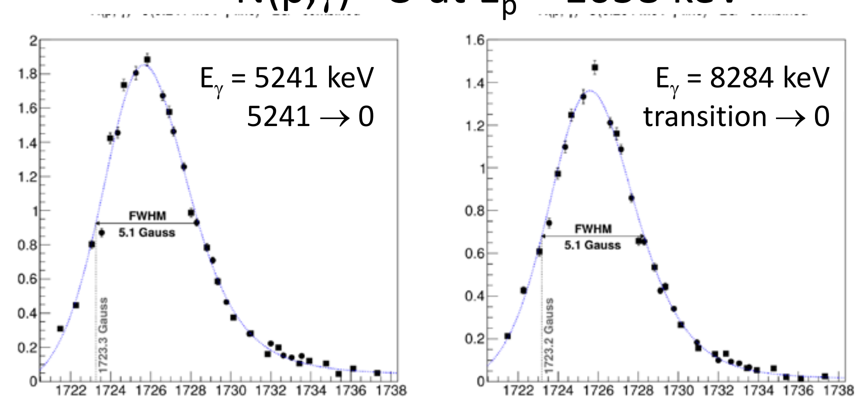
# First Science at CASPAR

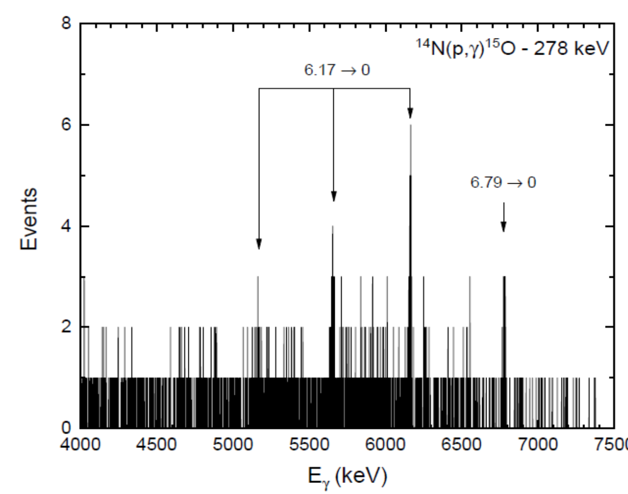
## γ-ray background at CASPAR



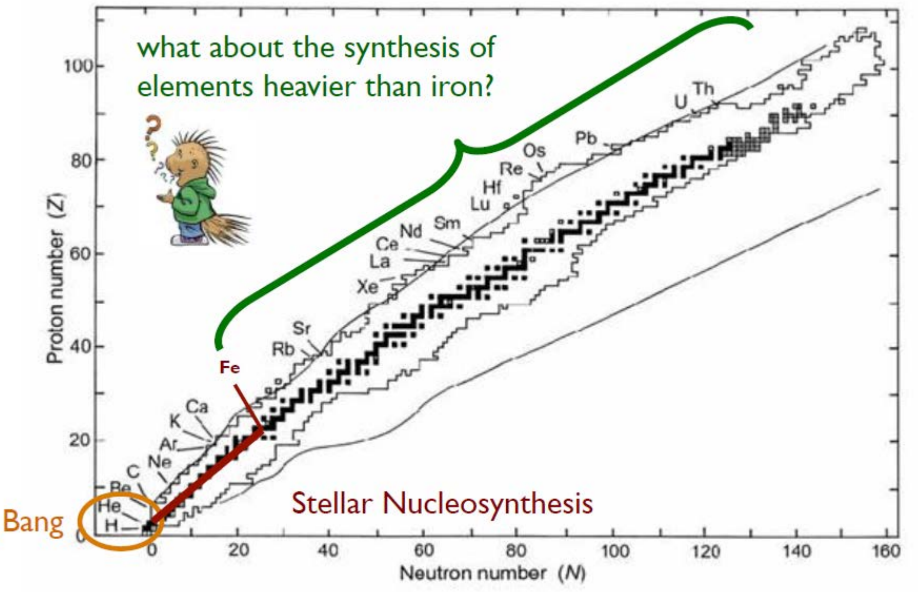

## commissioning experiment

$^{14}N(p,\gamma)^{15}O$ at $E_p$ = 1058 keV



# How were Elements from Iron to Uranium made?




"The 11 Greatest Unanswered Questions of Physics"
from: National Academy of Science Report, 2002

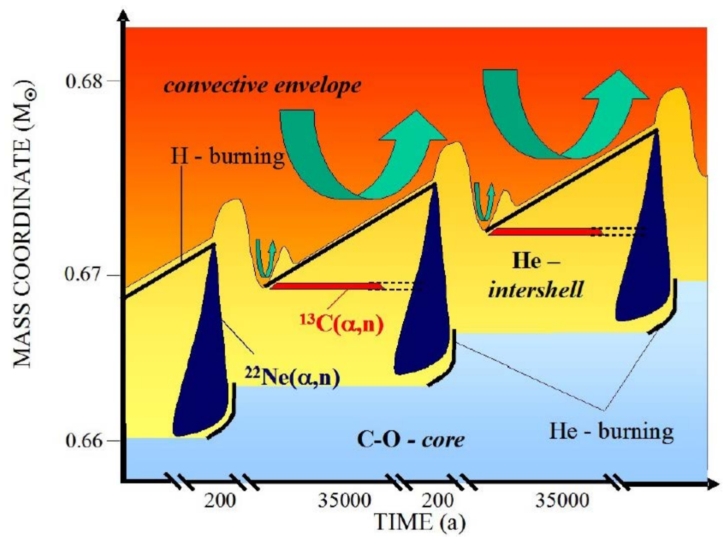
## s- and r-process

→ different astrophysical sites

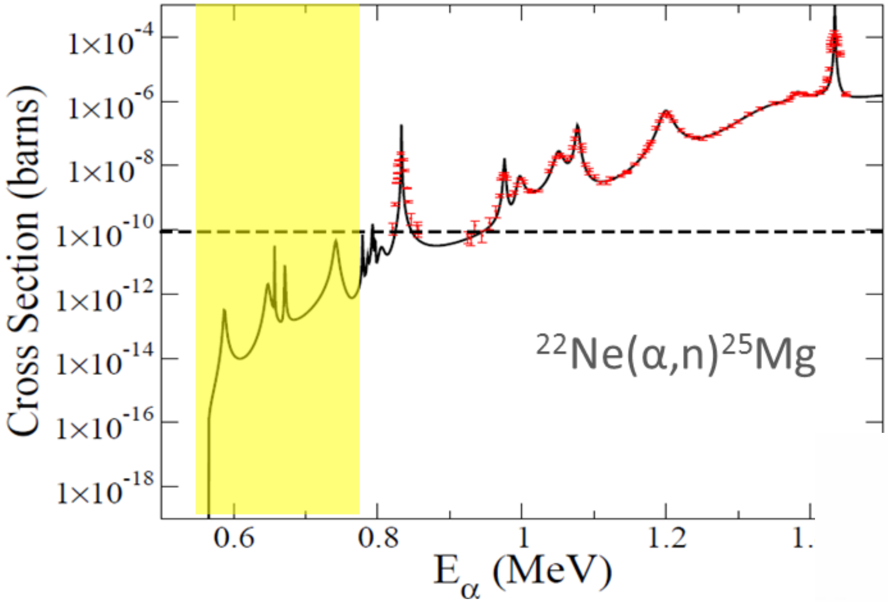
## Main s-process: Thermally Pulsing AGB Stars

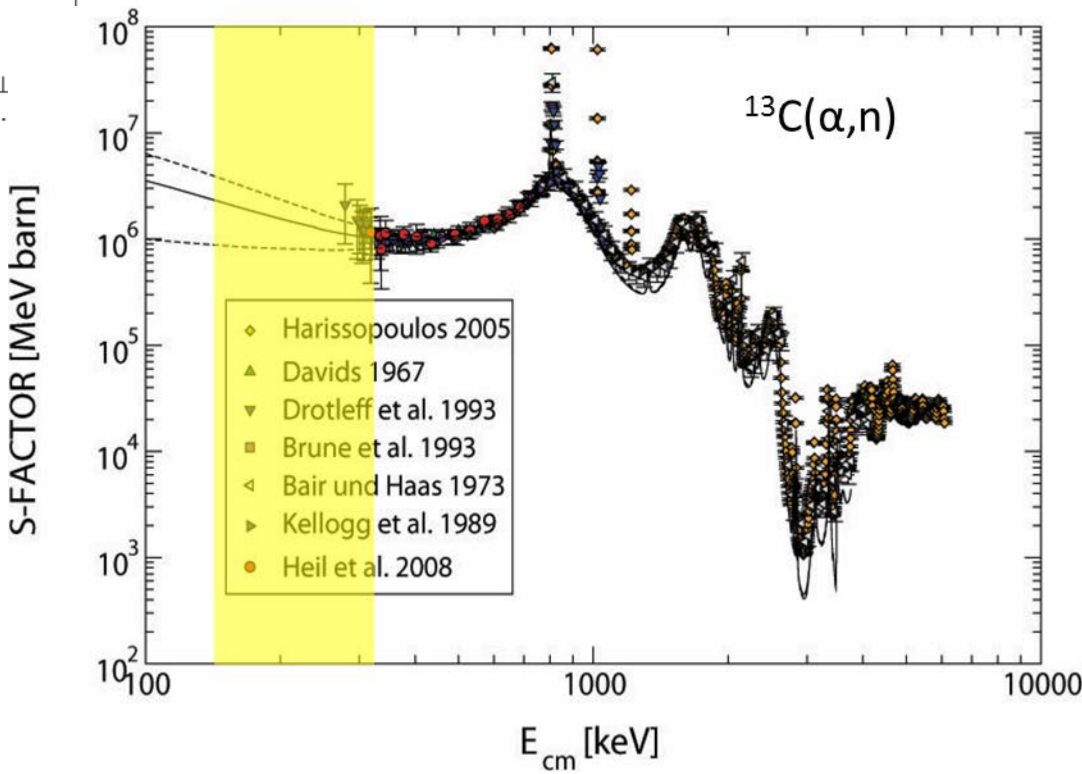
AGB star = Asymptotic Giant Branch star
= evolved star after central He burning

- neutron flux of $10^8 - 10^{11}$ n/cm$^3$ during different phases of pulsing
- neutron source strength critical



# Seeds for the s-process

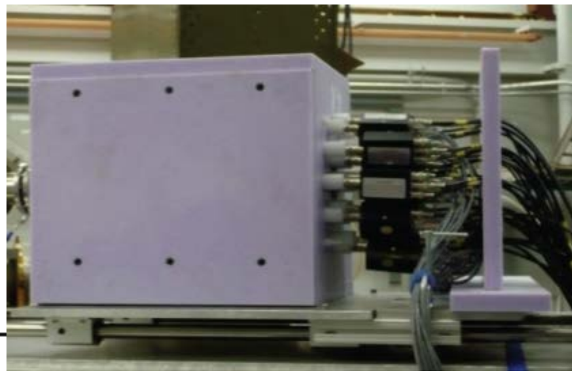


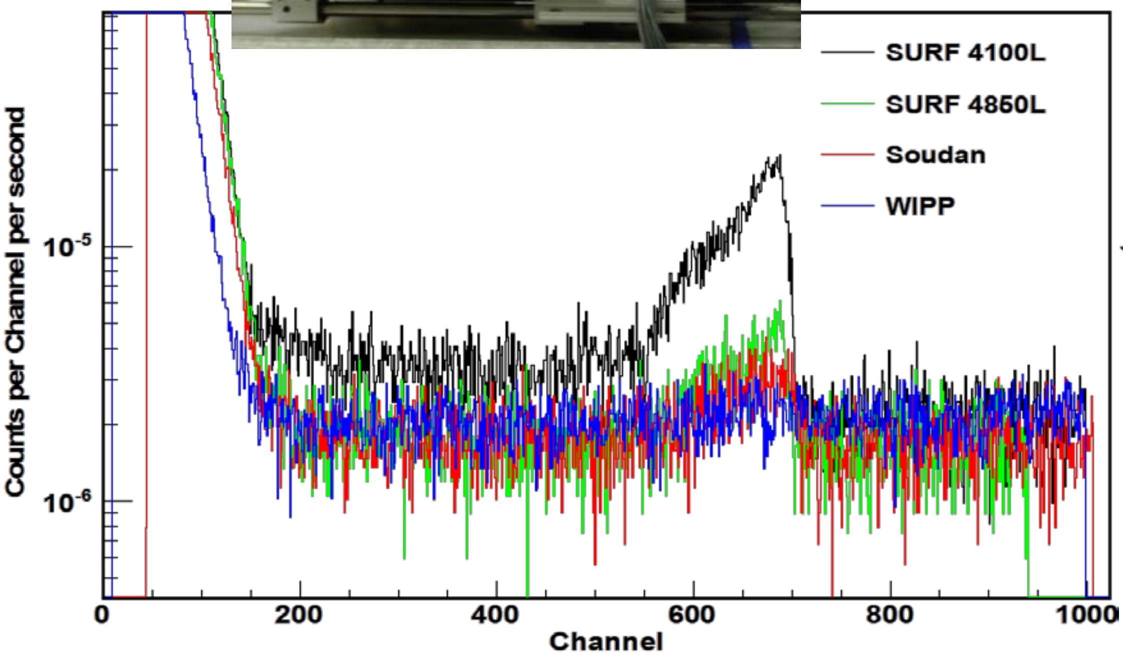



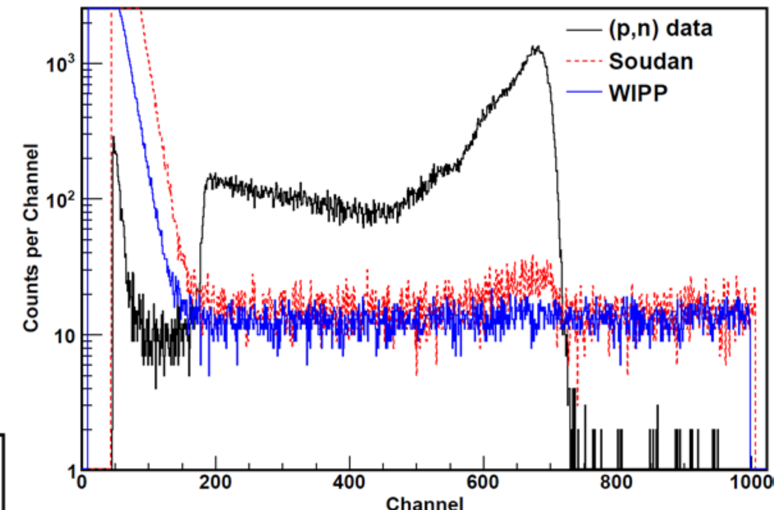

- $^{22}$Ne(α,n)$^{25}$Mg and $^{13}$C(α,n)$^{16}$O
- Neutron sources for the s-process
- Large Uncertainties in astrophysical energy region
- Measurements limited by cosmic-ray induced background

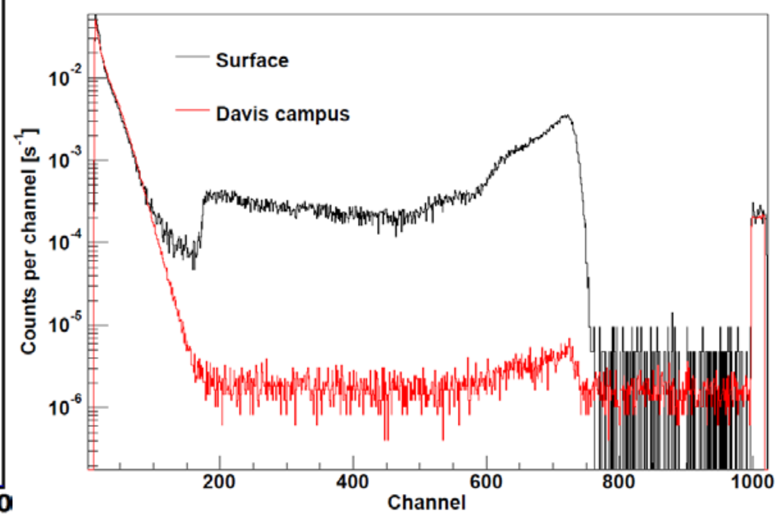
# Neutron Background Reduction

$^3$He proportional counter in
a polyethylene moderator matrix





# CASPAR Program: Currently 5-8 years

Some reactions of interest:

- $^{22}Ne(\alpha,n)^{25}Mg$
- $^{13}C(\alpha,n)^{16}O$

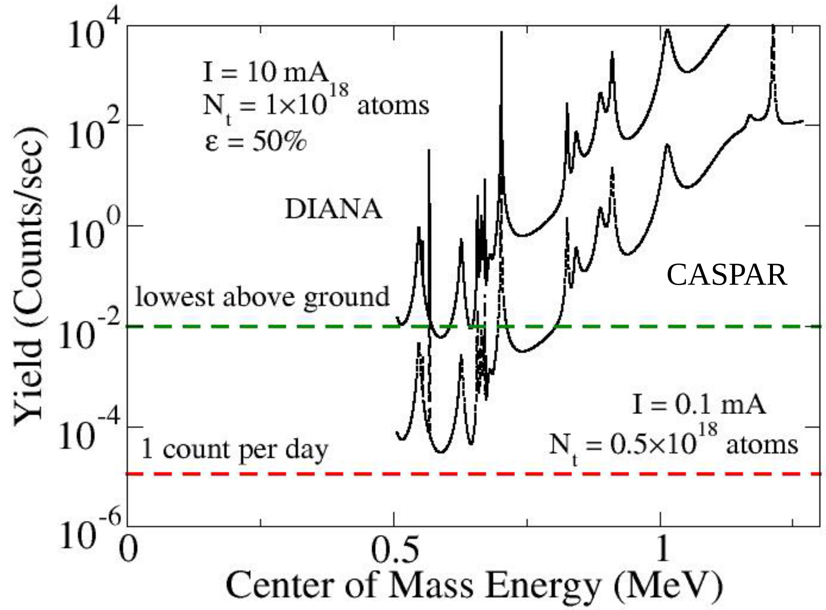
**Priority**

- $^{22}Ne(\alpha,\gamma)^{26}Mg$
- $^{14}N(p,\gamma)^{15}O$
- $^{3}He(\alpha,\gamma)^{7}Be$

**γ-ray spectroscopy**

- $^{26}Al(p,\gamma)^{27}Si$

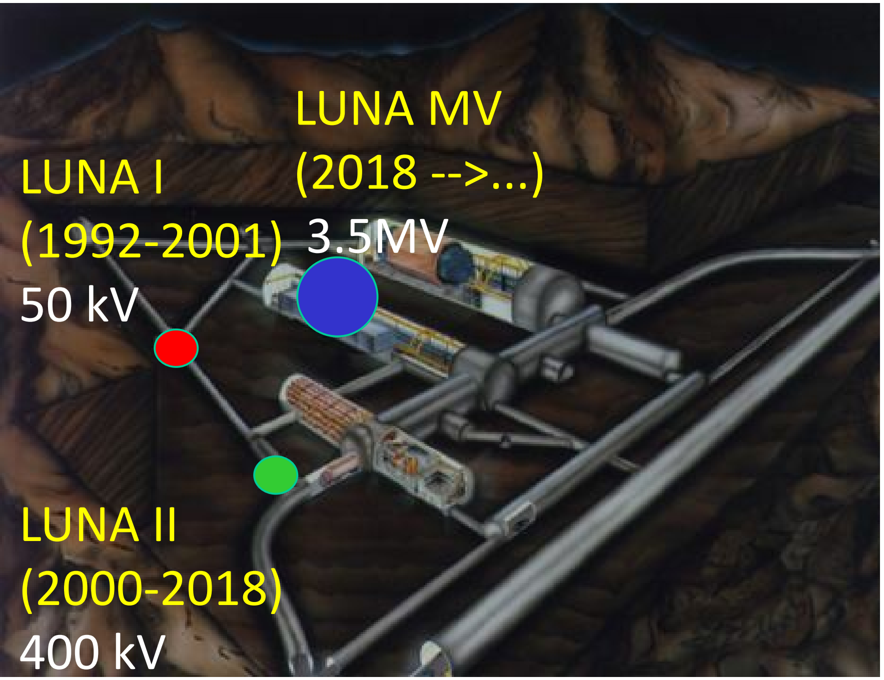
**future challenges**

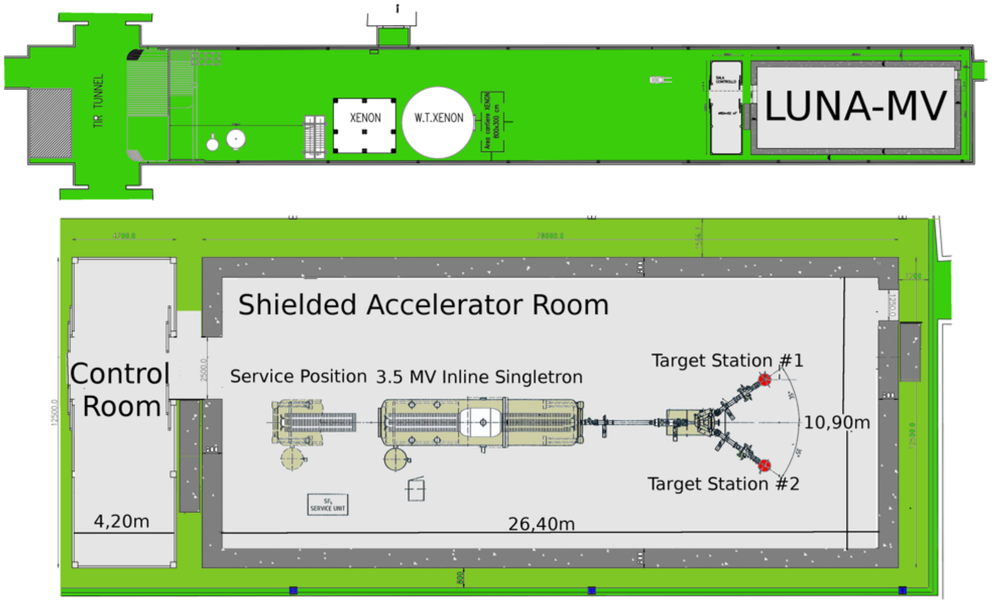



- Cavity rehabilitation and preparation completed
- Beneficial occupancy of accelerator vault August 2015
- First beam on target summer 2017
- First scientific results in 2018

# LUNA MV project

LUNA MV will be installed in the North part of Hall B of LNGS



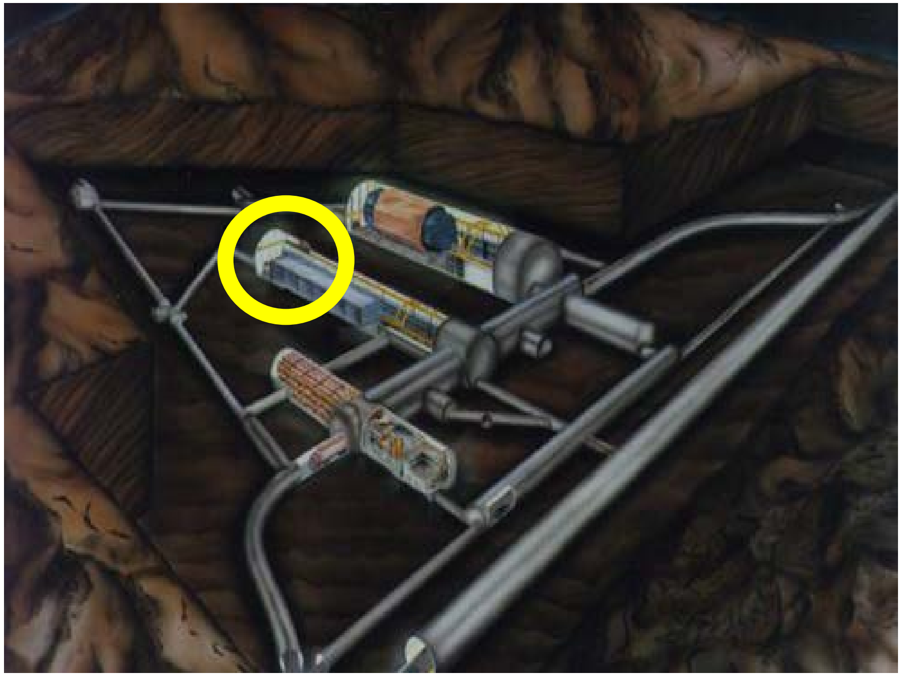

Funded by the Italian Department of Science as a “premium project”,
HVEE has been selected through a public tender as provider of the new accelerator (0.3 < TV < 3.5 MV) able to deliver intense H, He and C beams.

Expected installation at LNGS in 2019

courtesy Alba Formicola

# LUNA MV project

LUNA MV will be installed in the North part of Hall B of LNGS



Hall B

(ICARUS decommissioning almost complete – some areas used for OPERA decommissioning storage)

LUNA
Laboratory for Underground Nuclear Astrophysics

courtesy Alba Formicola

# LUNA MV- scientific program (2019 ….)

$^{12}C+^{12}C$: solid state target: gamma and particle detectors

$^{13}C(\alpha,n)^{16}O$: enriched $^{13}C$ solid or gas target. Neutron detector
(data taking at LUNA 400 kV)

$^{22}Ne(\alpha,n)^{25}Mg$: enriched $^{22}Ne$ gas target. Neutron detector.

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

high scientific interest for revised data covering a wide energy range (400 keV - 3.5 MeV).

LUNA MV is open to new collaborations on the whole program or even on single experiments (please refer for any information SP: prati@ge.infn.it)

courtesy Alba Formicola

# ECR ion source Model SO-201

1. **Gas type:** **HELIUM**
   Purity level: 99.999% (grade 5)
   Bottle: Lecture bottle type LB including outlet valve CGA 180, capacity 0.4 liters, dimensions 51 mm OD x 375 mm OAL
   Charging pressure: 150 bar

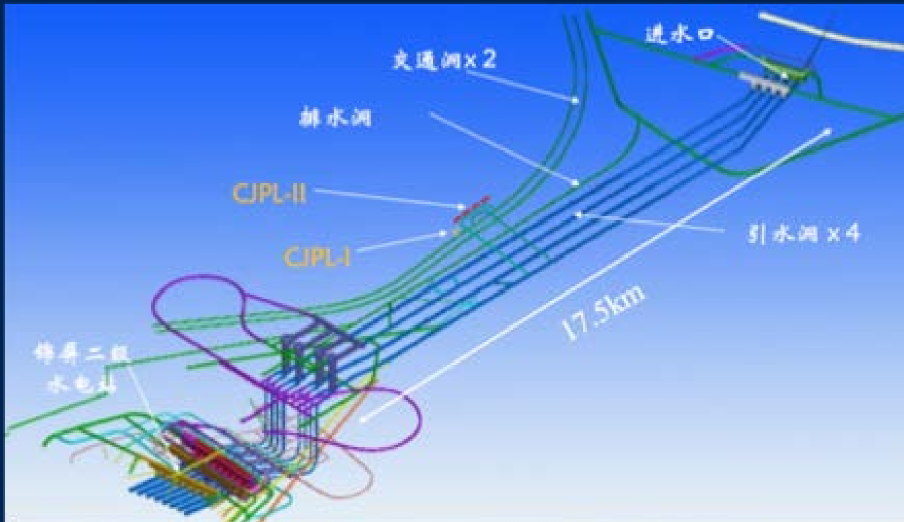
2. **Gas type:** **HYDROGEN**
   Purity level: 99.999% (grade 5)
   Bottle: Lecture bottle type LB including outlet valve CGA 180, capacity 0.4 liters, dimensions 51 mm OD x 375 mm OAL
   Charging pressure: 150 bar

3. **Gas type:** **CARBON DIOXIDE**
   Purity level: 99.995% (grade 4.5)
   Bottle: Lecture bottle type LB including outlet valve CGA 180, capacity 0.4 liters, dimensions 51 mm OD x 375 mm OAL
   Charging pressure: 120 bar

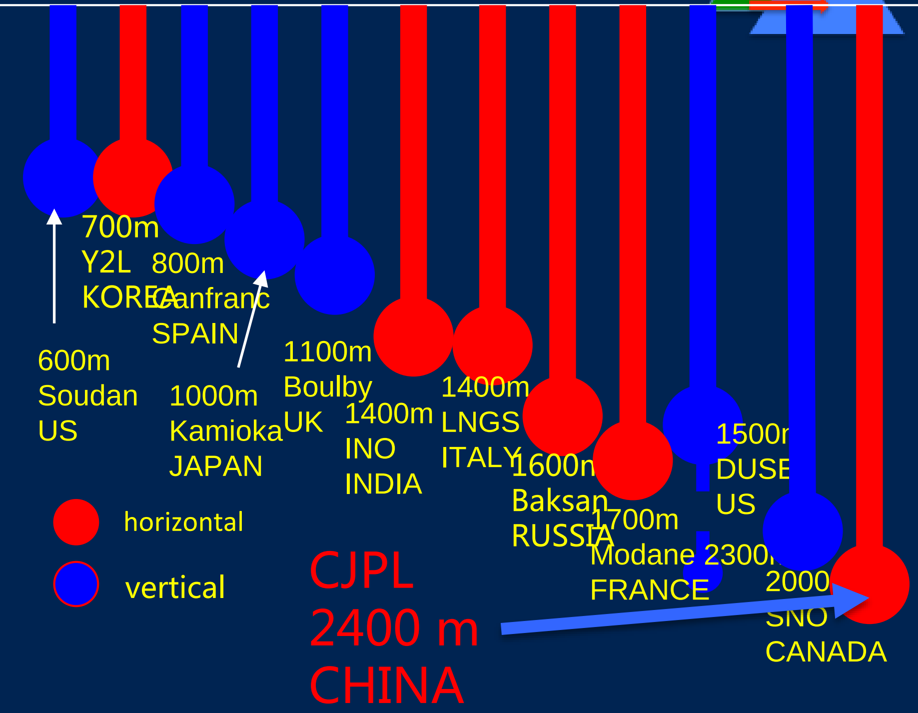
→ **with the C beam, experiments in inverse kinematic will be possible**

courtesy Alba Formicola

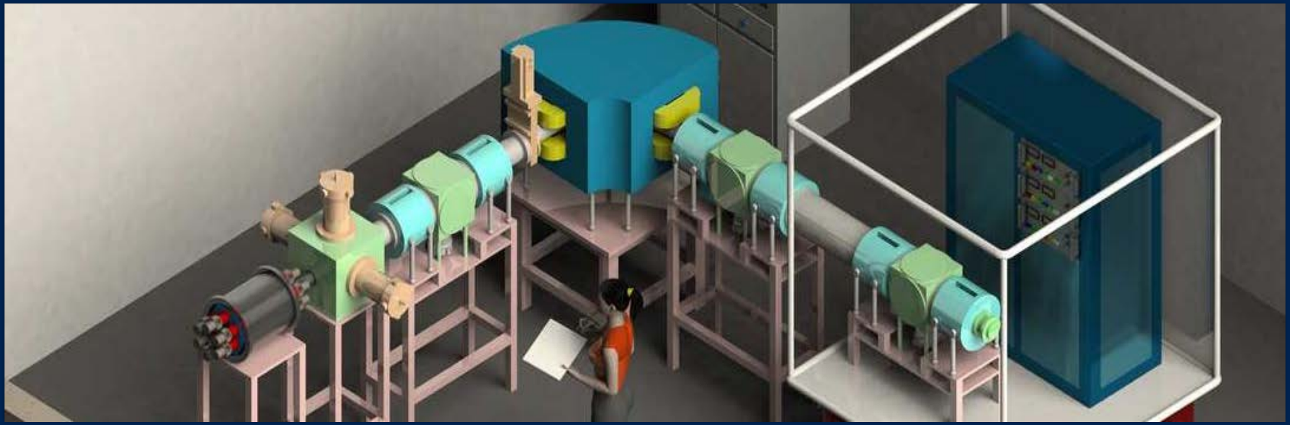
# CJPL underground laboratory








# JUNA-I plan

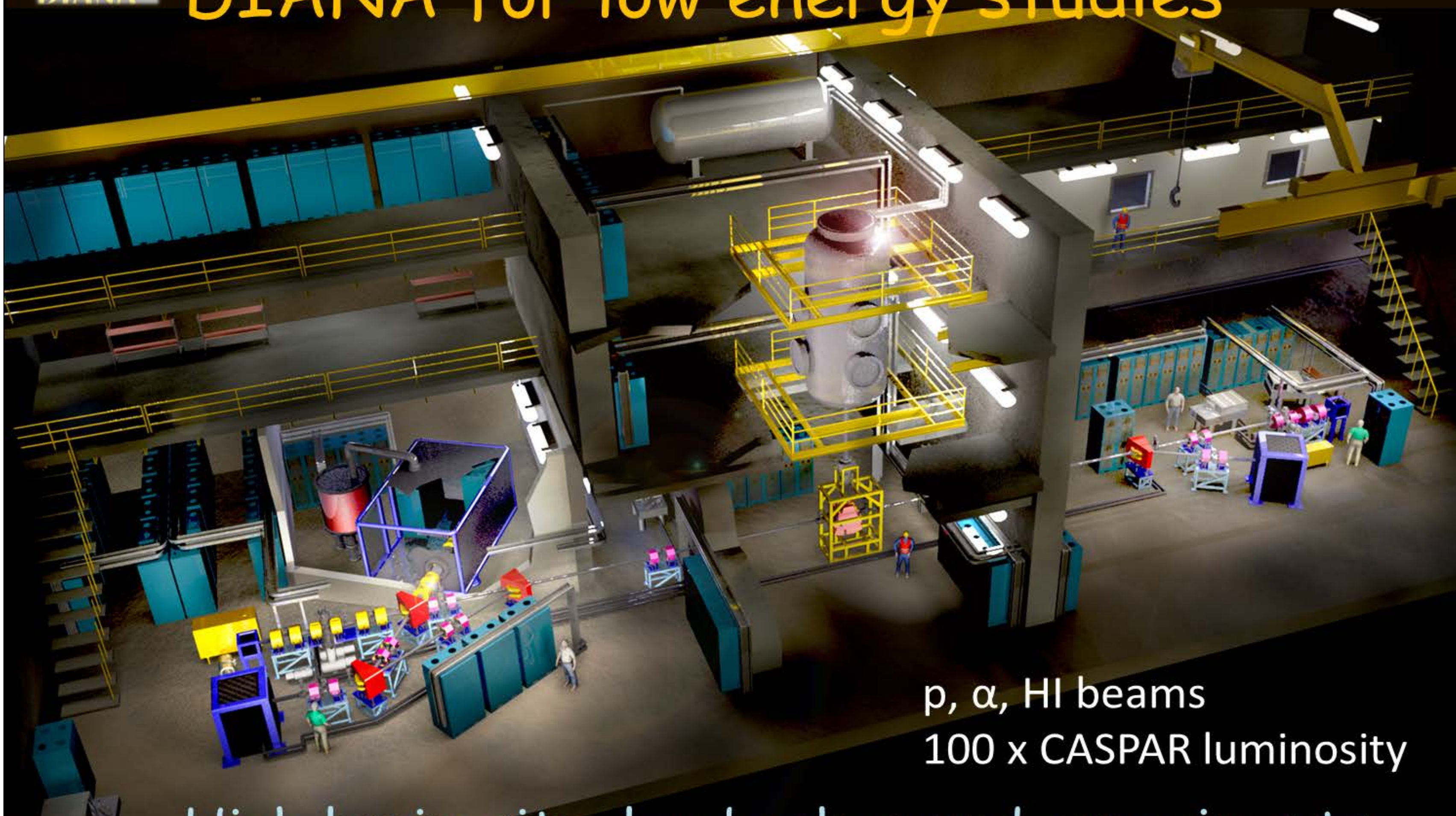


## JUNA-I

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

courtesy Weiping Liu

# Underground accelerator project DIANA for low energy studies




High luminosity, low background experiments


Thank you for your attention!