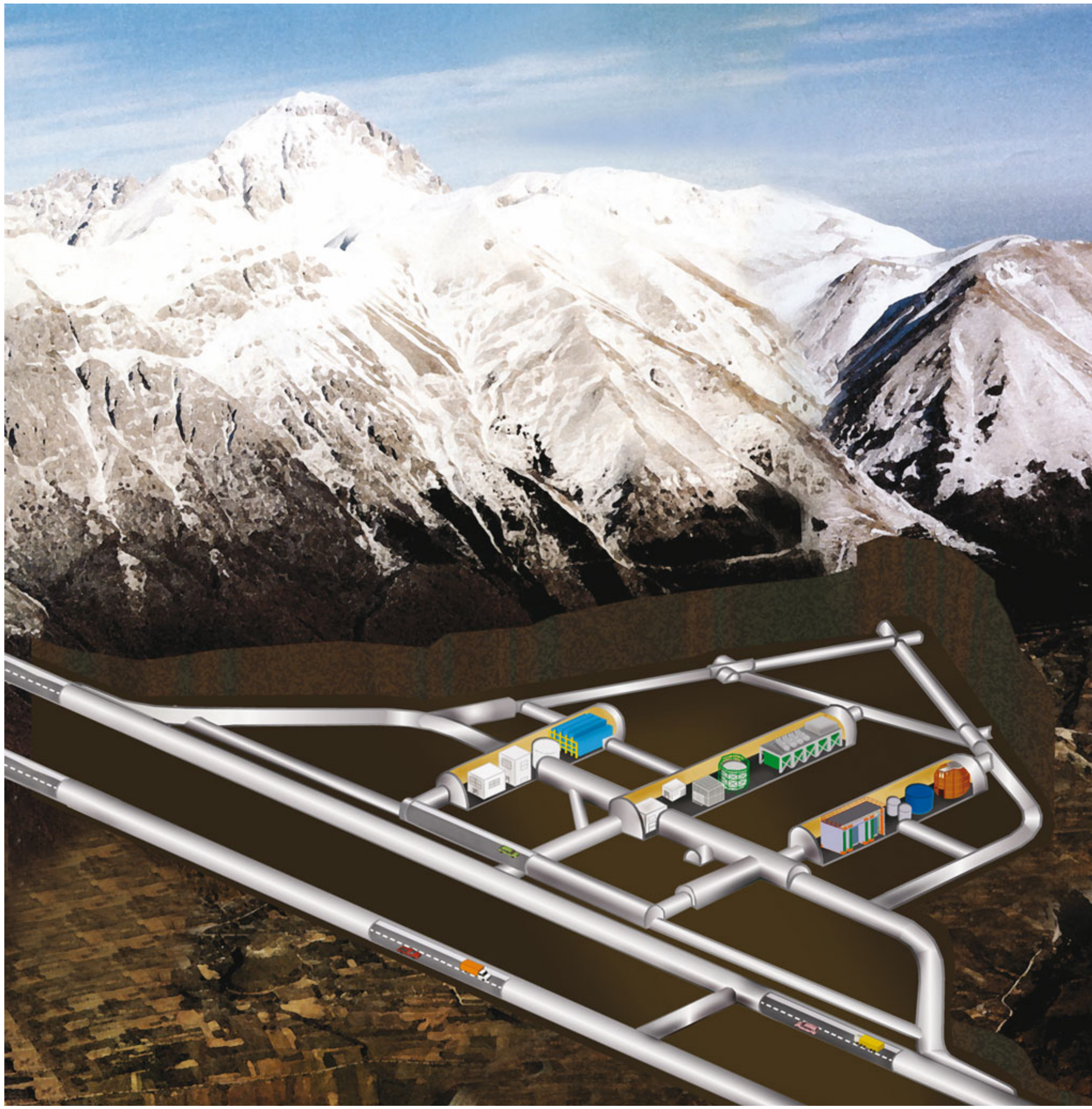
The impact of LUNA on Nuclear Astrophysics

P. Corvisiero

LNGS, 1-2 Dec. 2016
Silver Moon: the first and the next twentyfive years of Nuclear Astrophysics at Gran Sasso

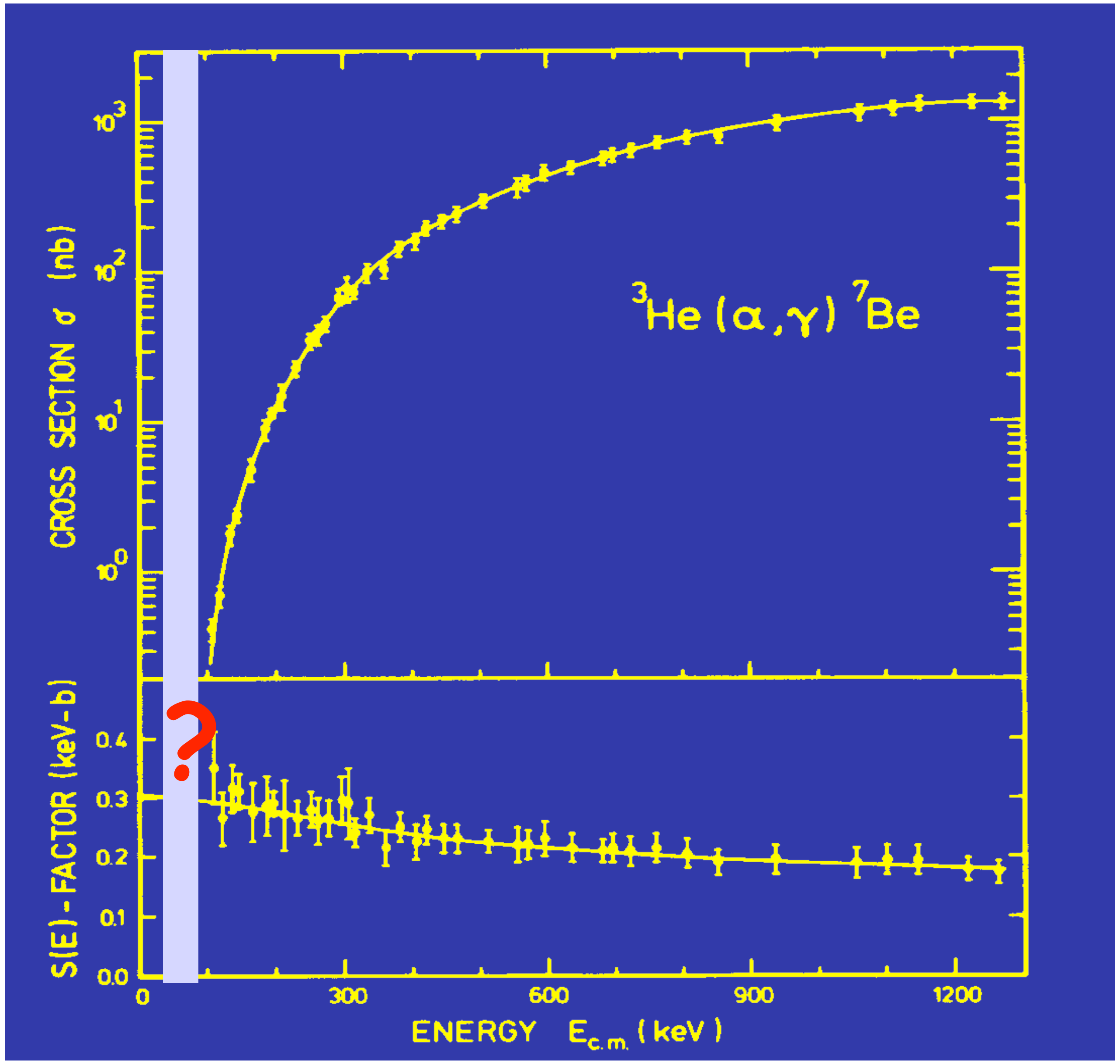
Once upon a time...

Nuclei in the Cosmos I
1990 Baden/Vienna, Austria




Puccio Bellotti

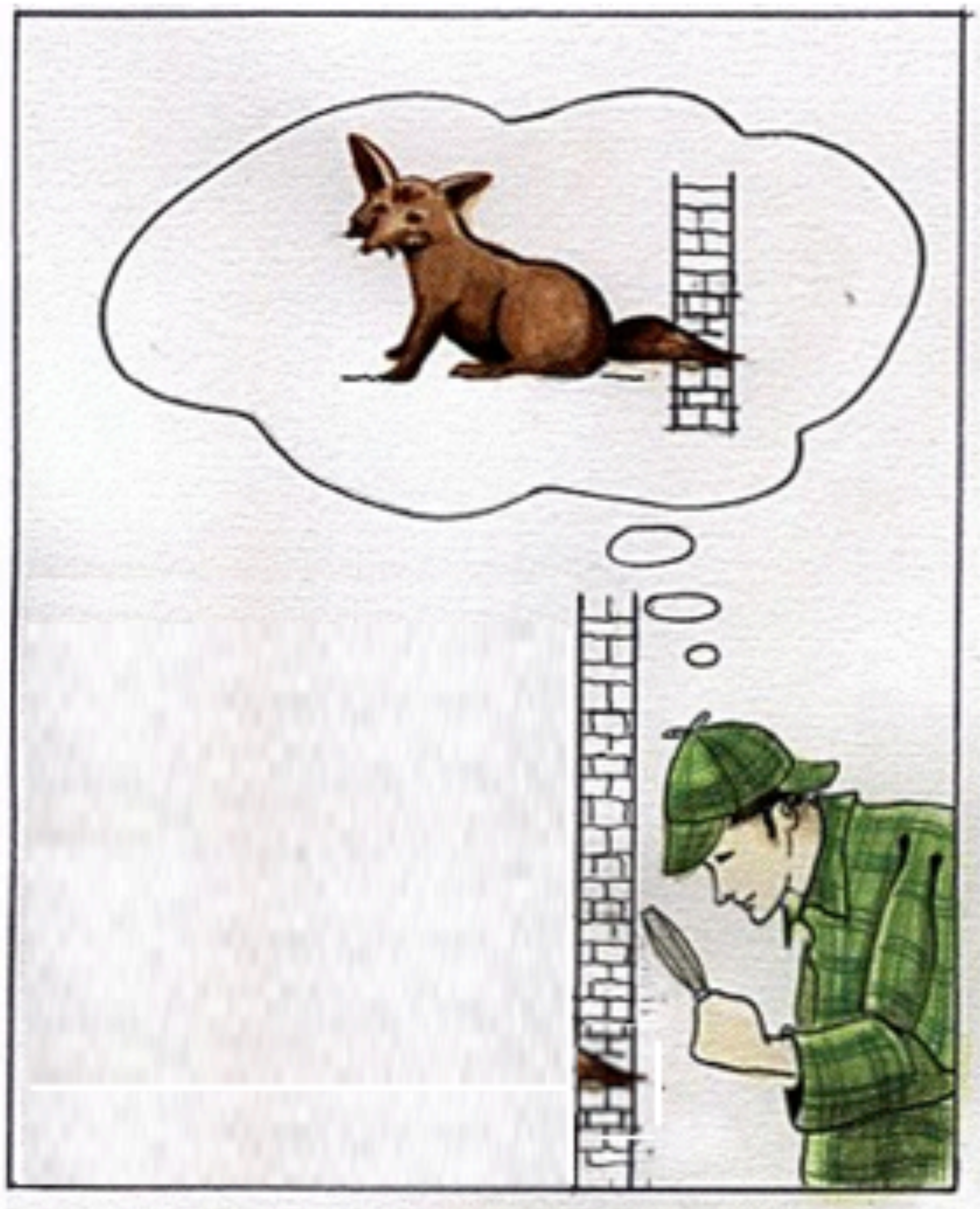
The astrophysical S-factor

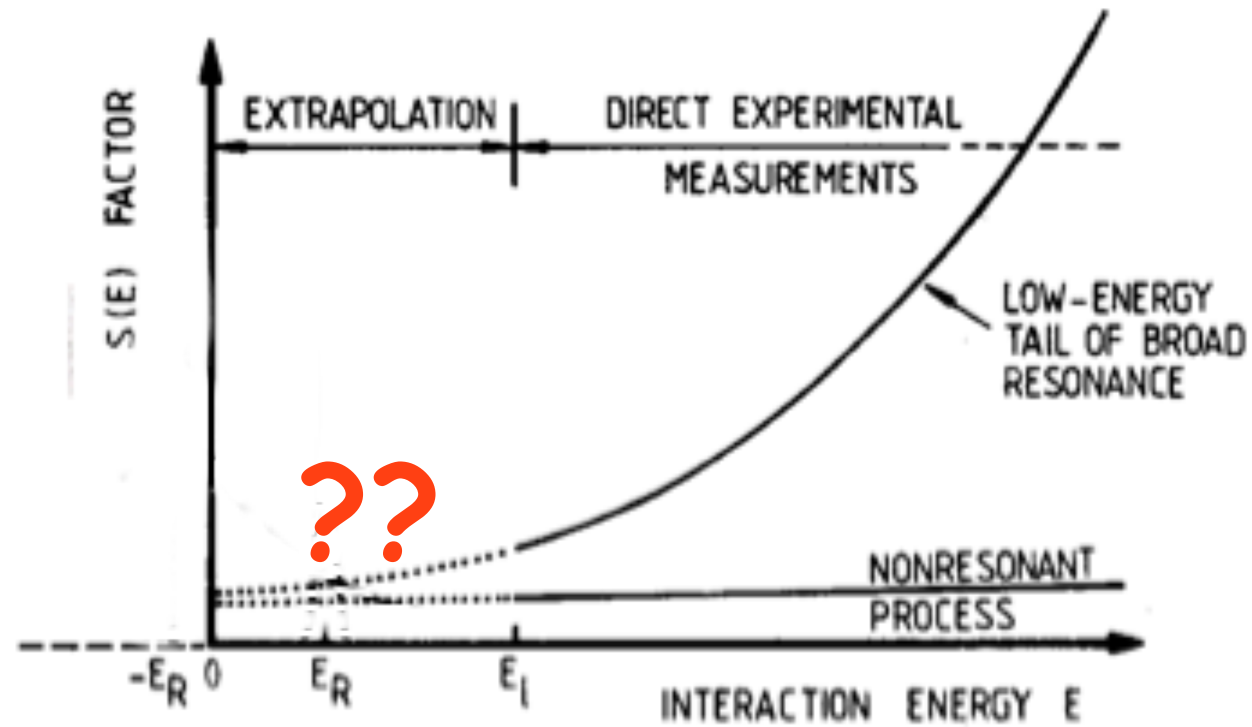


$$\sigma(E) = \frac{1}{E} S(E) e^{-\frac{2\pi\eta}{E}}$$

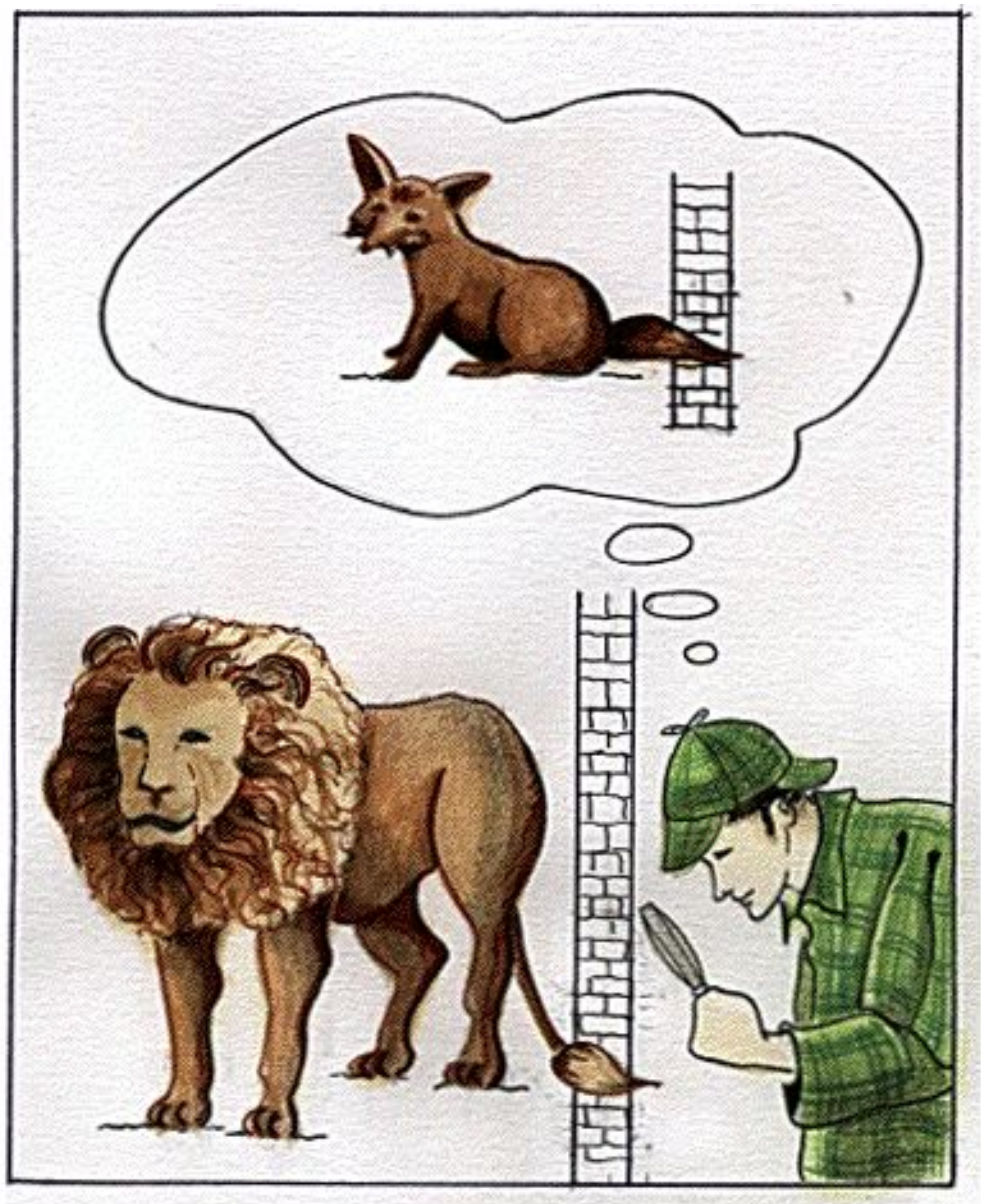
$$S(E) = E\sigma(E) e^{\frac{2\pi\eta}{E}}$$

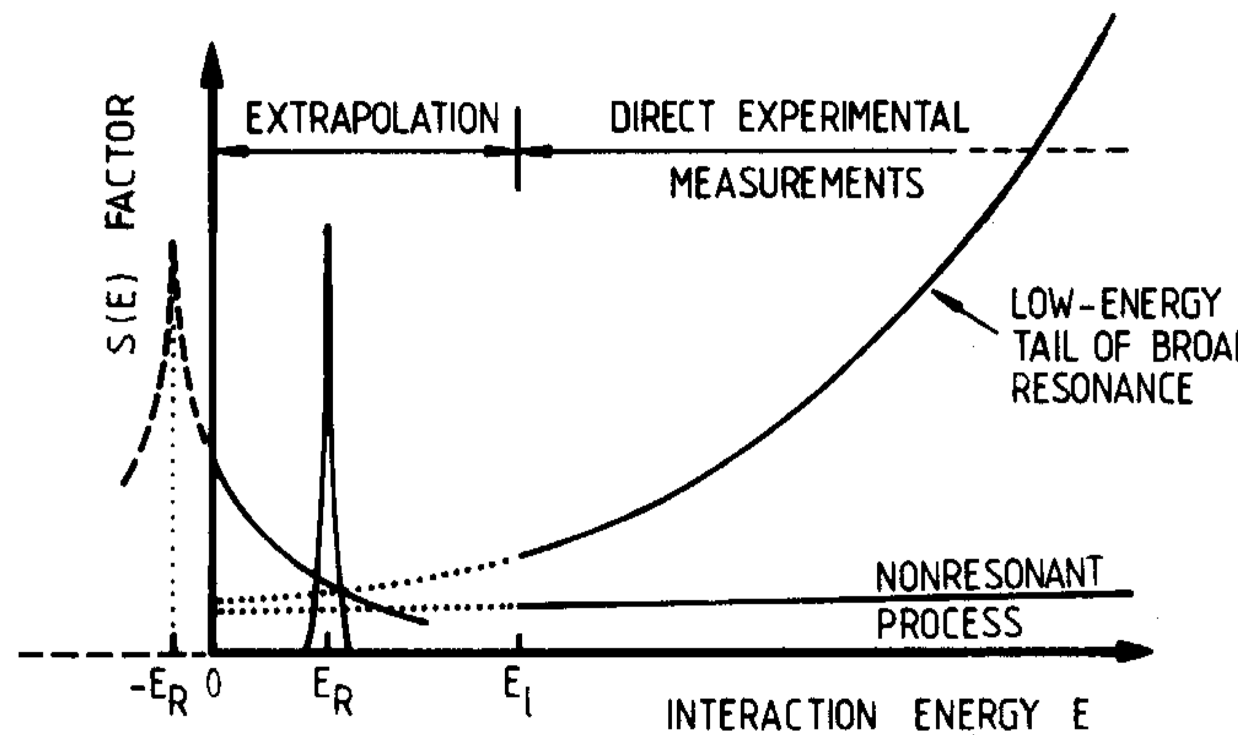
$$2\pi\eta = 31.29\, Z_1 Z_2 \sqrt{\frac{\mu}{E}}$$





S(E) FACTOR
EXTRAPOLATION
DIRECT EXPERIMENTAL
MEASUREMENTS
LOW-ENERGY
TAIL OF BROAD
RESONANCE
??
NONRESONANT
PROCESS
$-E_R$
0
E_R
E_l
INTERACTION ENERGY E





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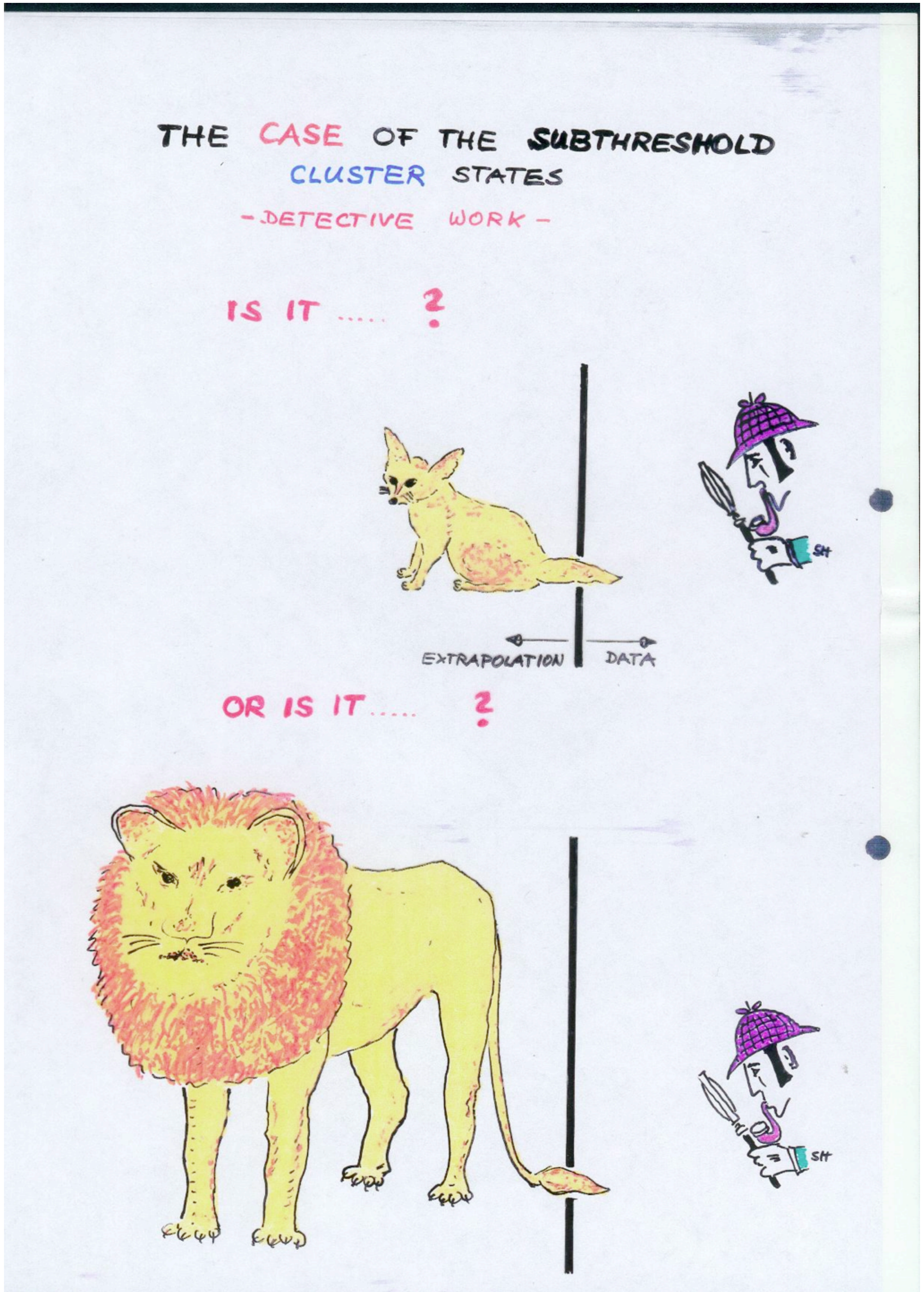
LUNA

from Claus

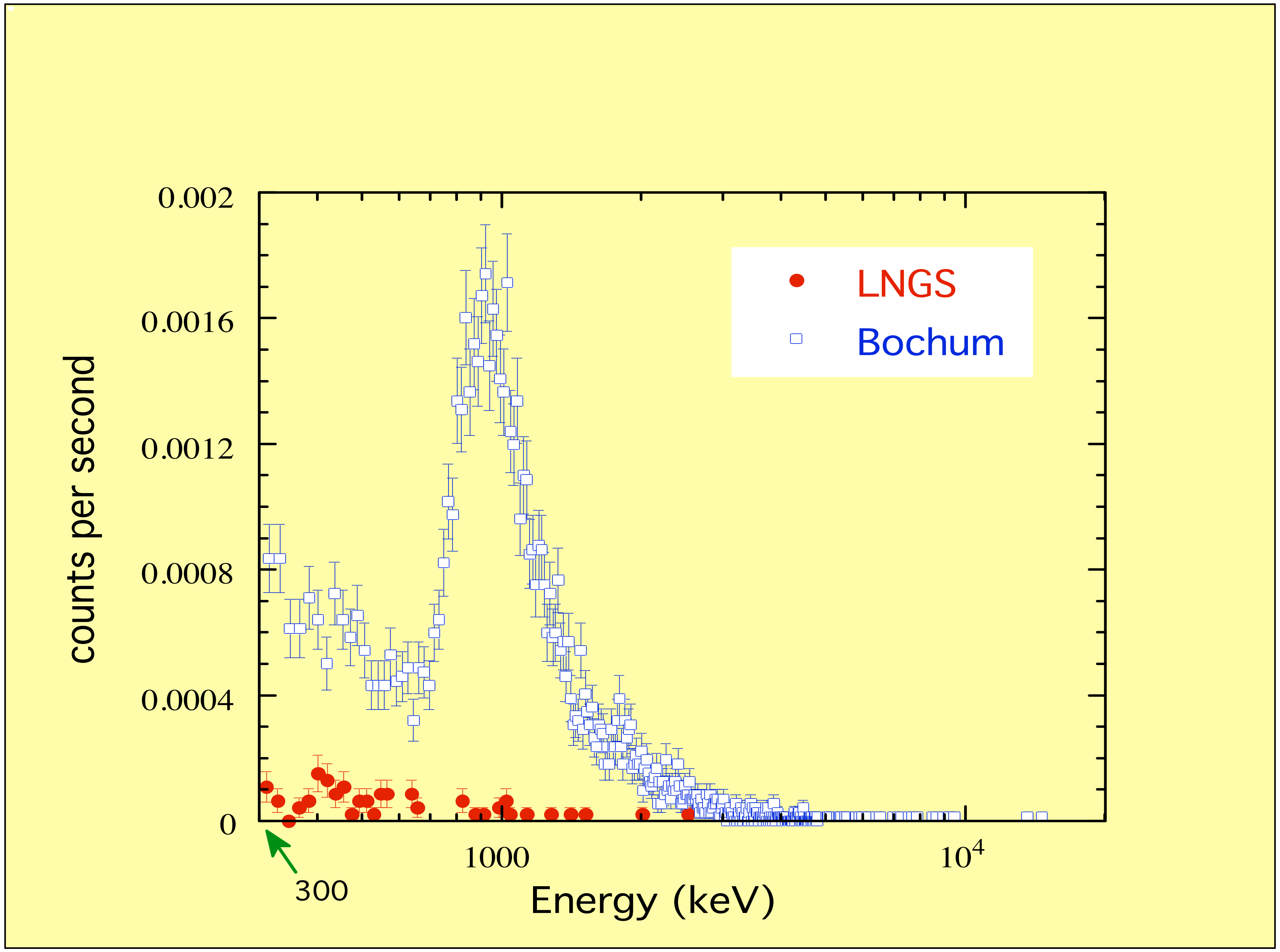


..as many other things...

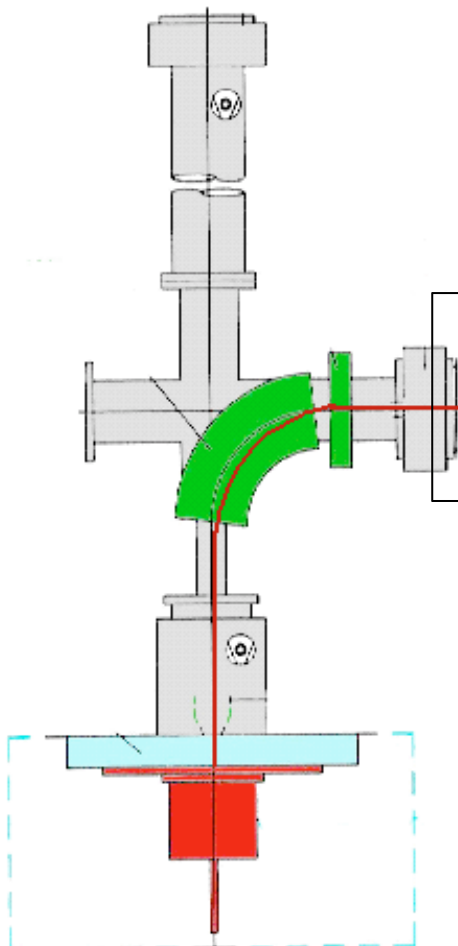
1991: First Background Test in LNGS

surface-barrier silicon detector

thickness = 2 mm



LUNA - 50 kV accelerator

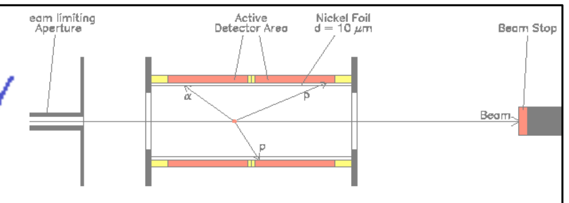


Energy Range for Protons:
50keV - 3 keV

Energy Stability
$\leq 10^{-4}$

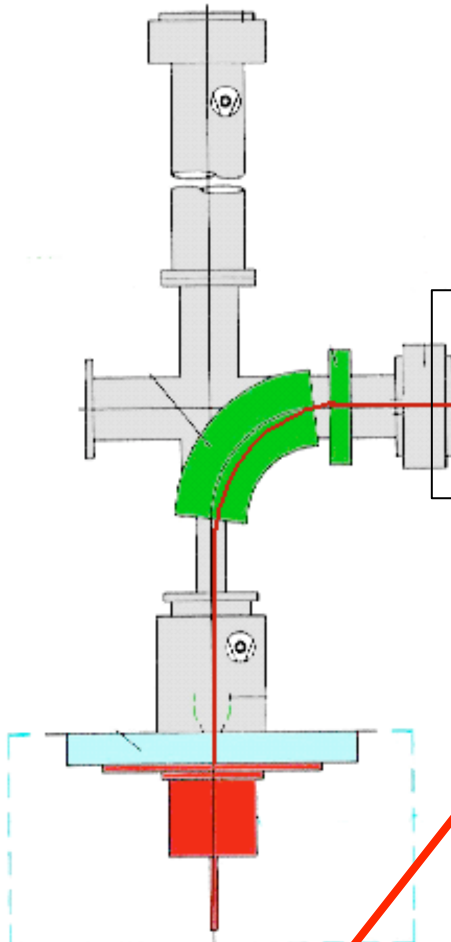
Ions:
p, ^{3}He, ^{4}He

Current:
50- 500 μA



detectors

LUNA - 50 kV accelerator



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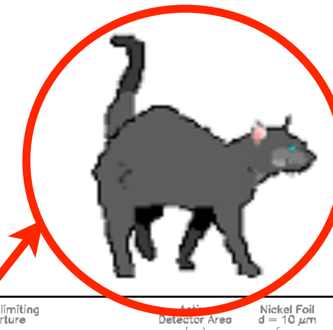
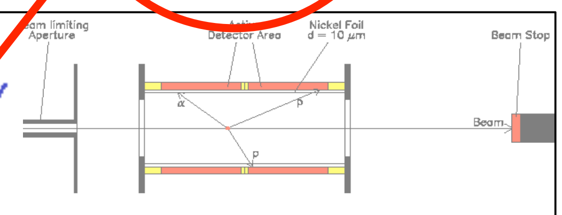
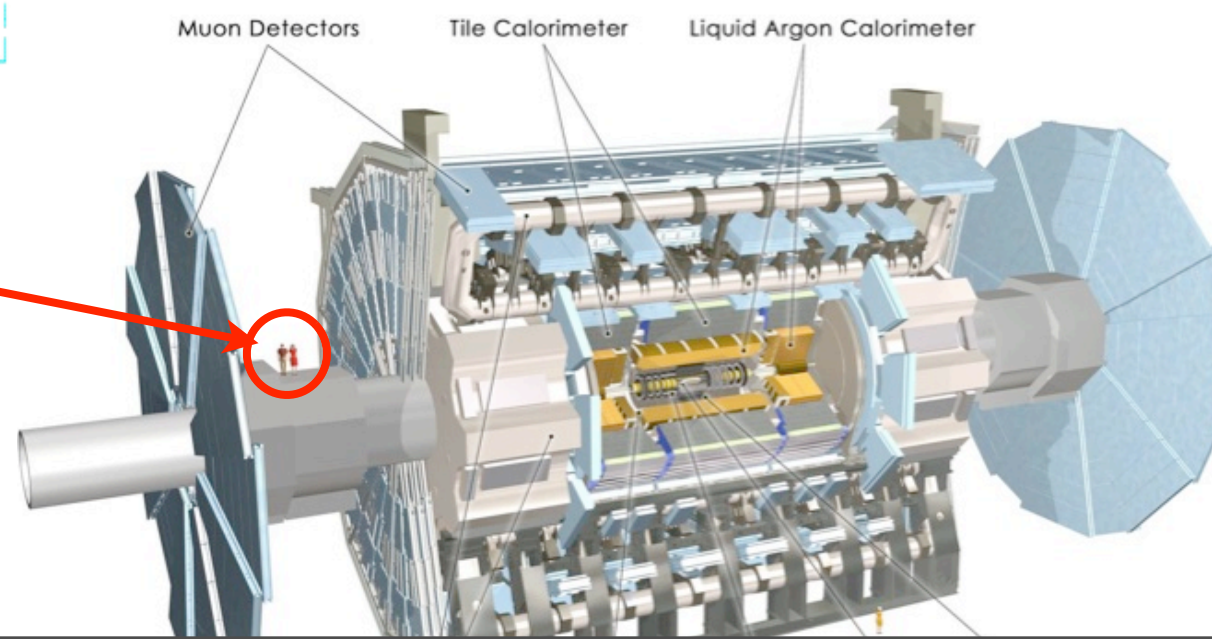


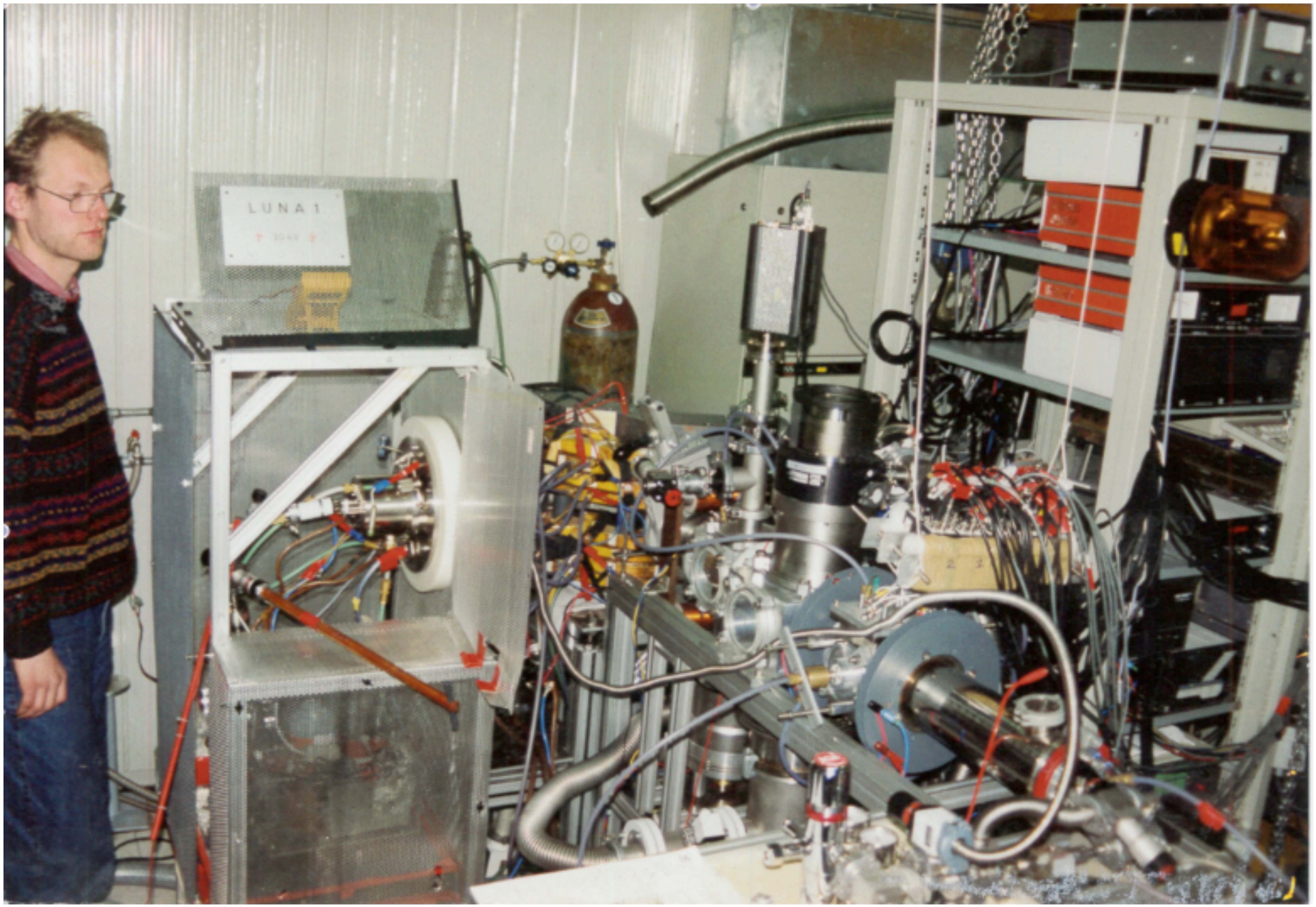


detectors

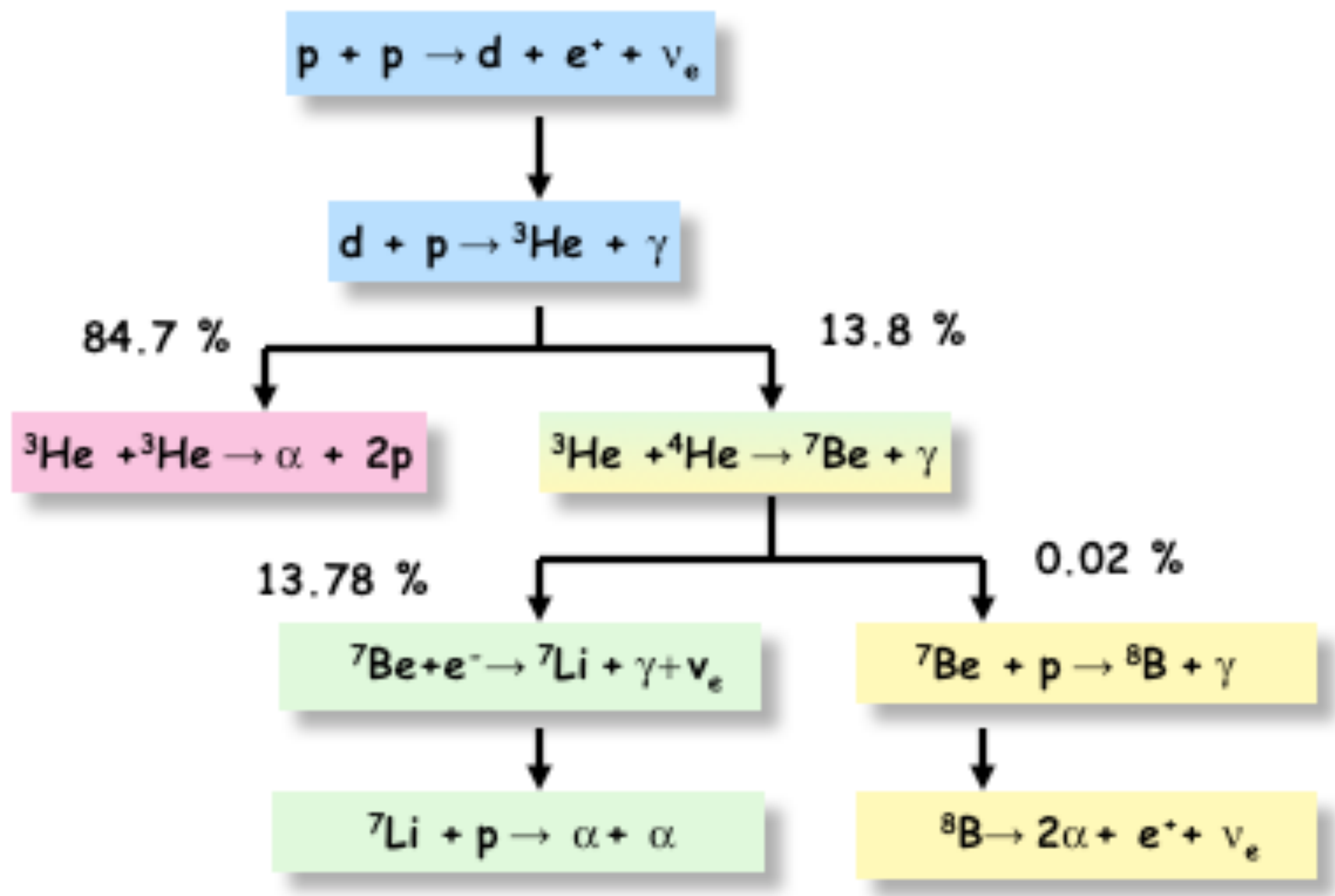


cat and men
are in scale

LUNA - 50 kV accelerator

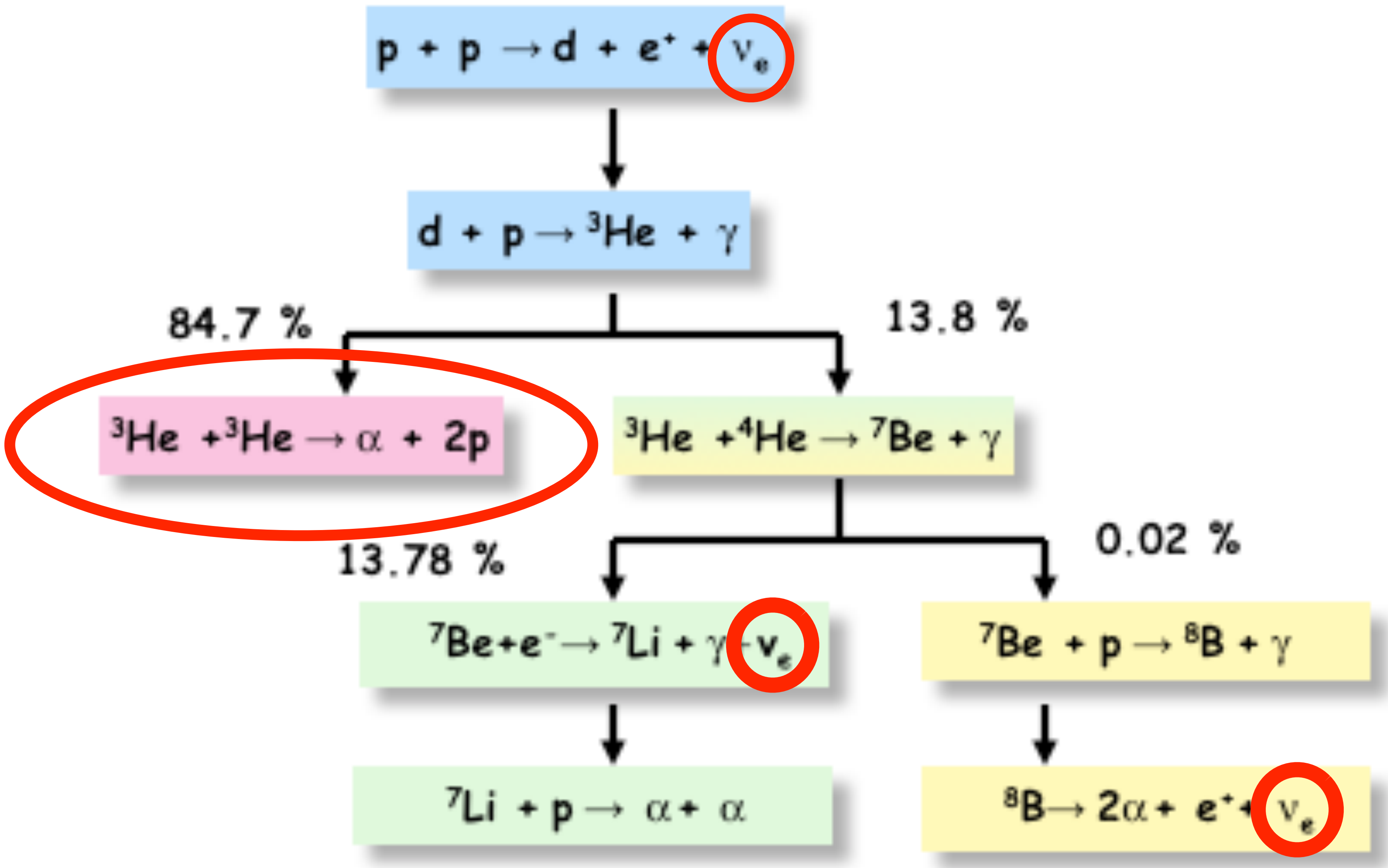


pp chain



p + p → d + e⁺ + ν_e
d + p → ³He + γ
84.7 %
13.8 %
³He + ³He → α + 2p
³He + ⁴He → ⁷Be + γ
13.78 %
0.02 %
⁷Be + e⁻ → ⁷Li + γ + ν_e
⁷Be + p → ⁸B + γ
⁷Li + p → α + α
⁸B → 2α + e⁺ + ν_e

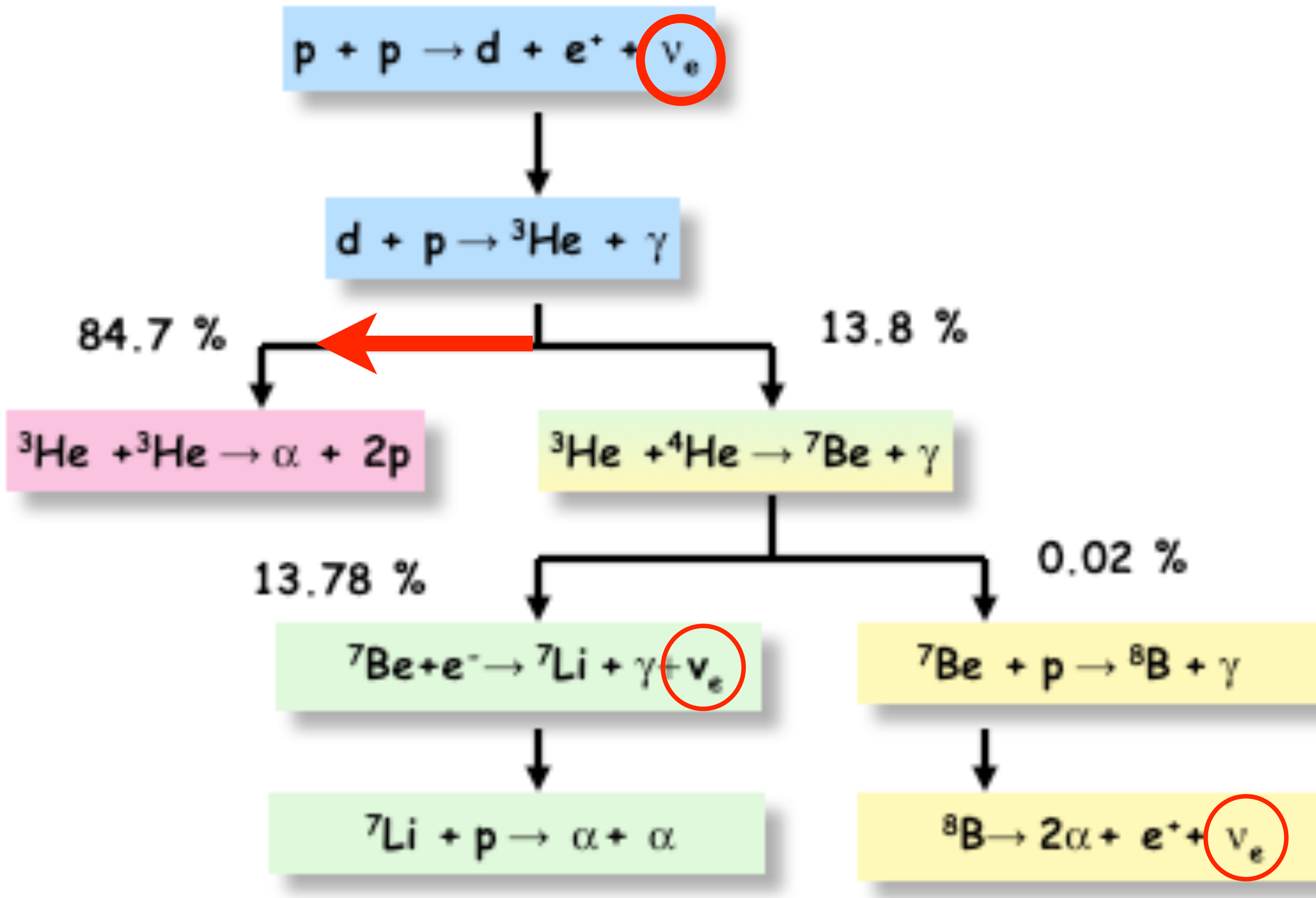
$^3He(^3He,2p)^4He$



$Q = 12.86$ MeV $E_p^{max} = 10.7$ MeV

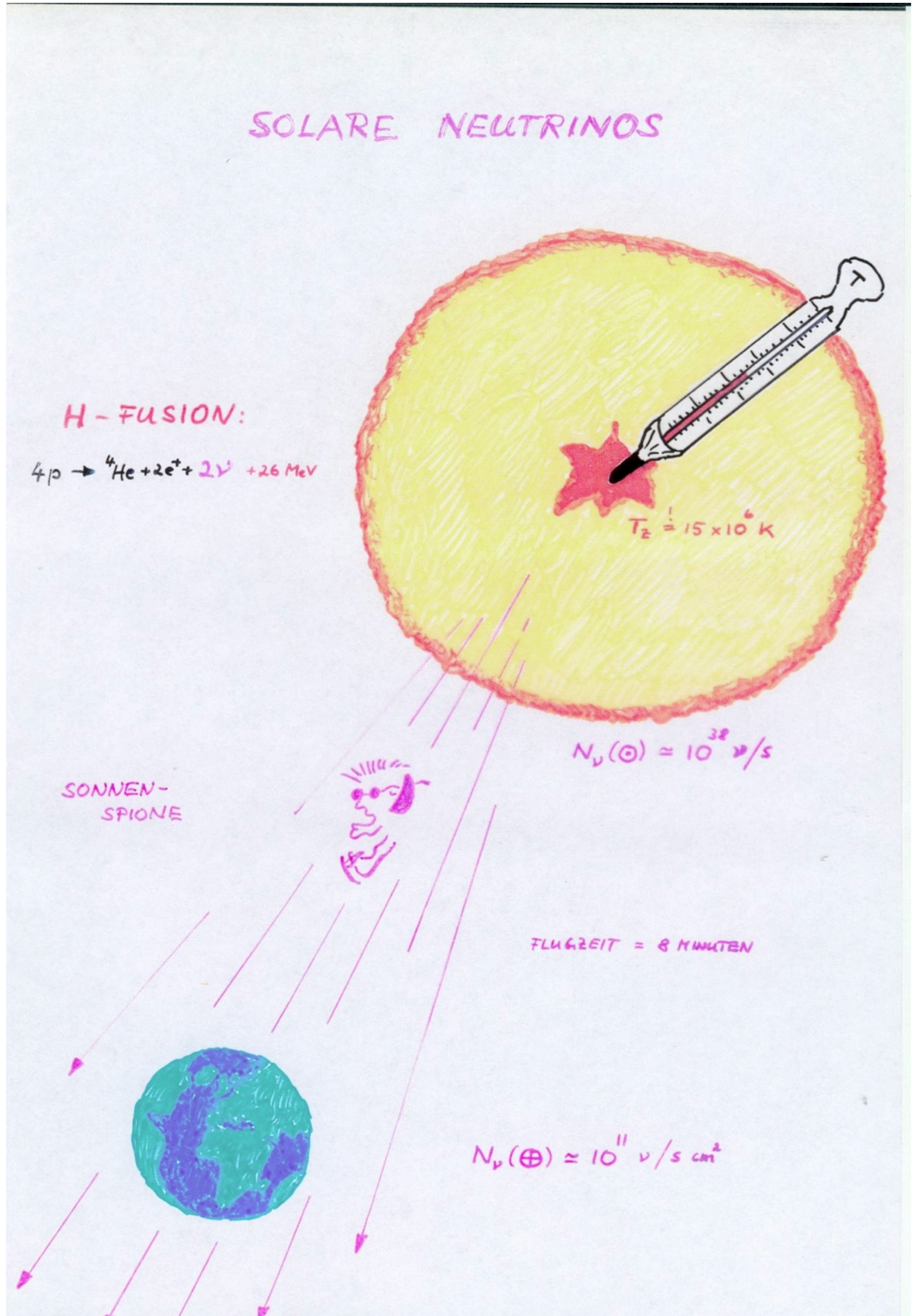
neutrinoless branch

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



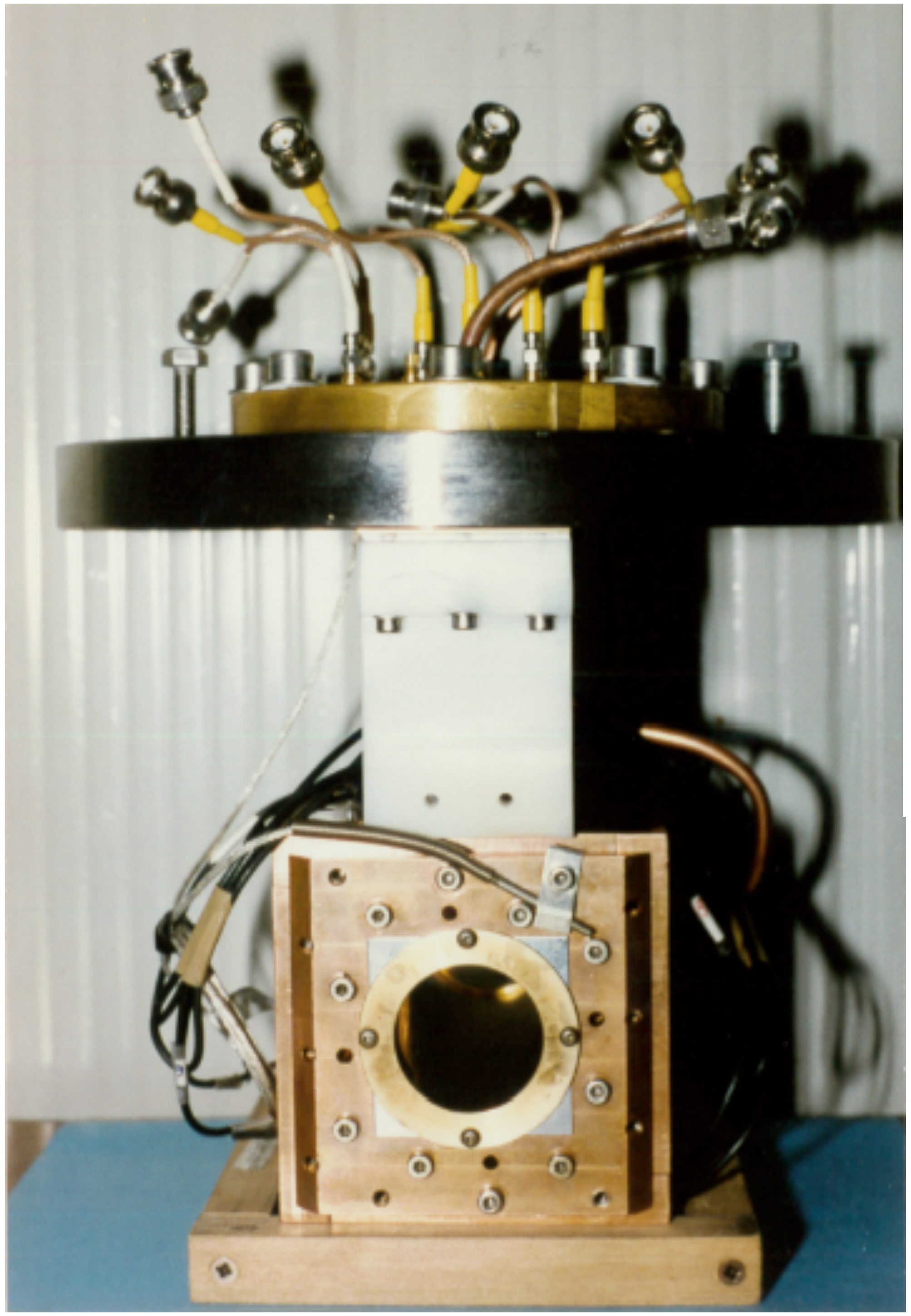
suppression of ^7Be and ^8B ν_e due to a resonance?

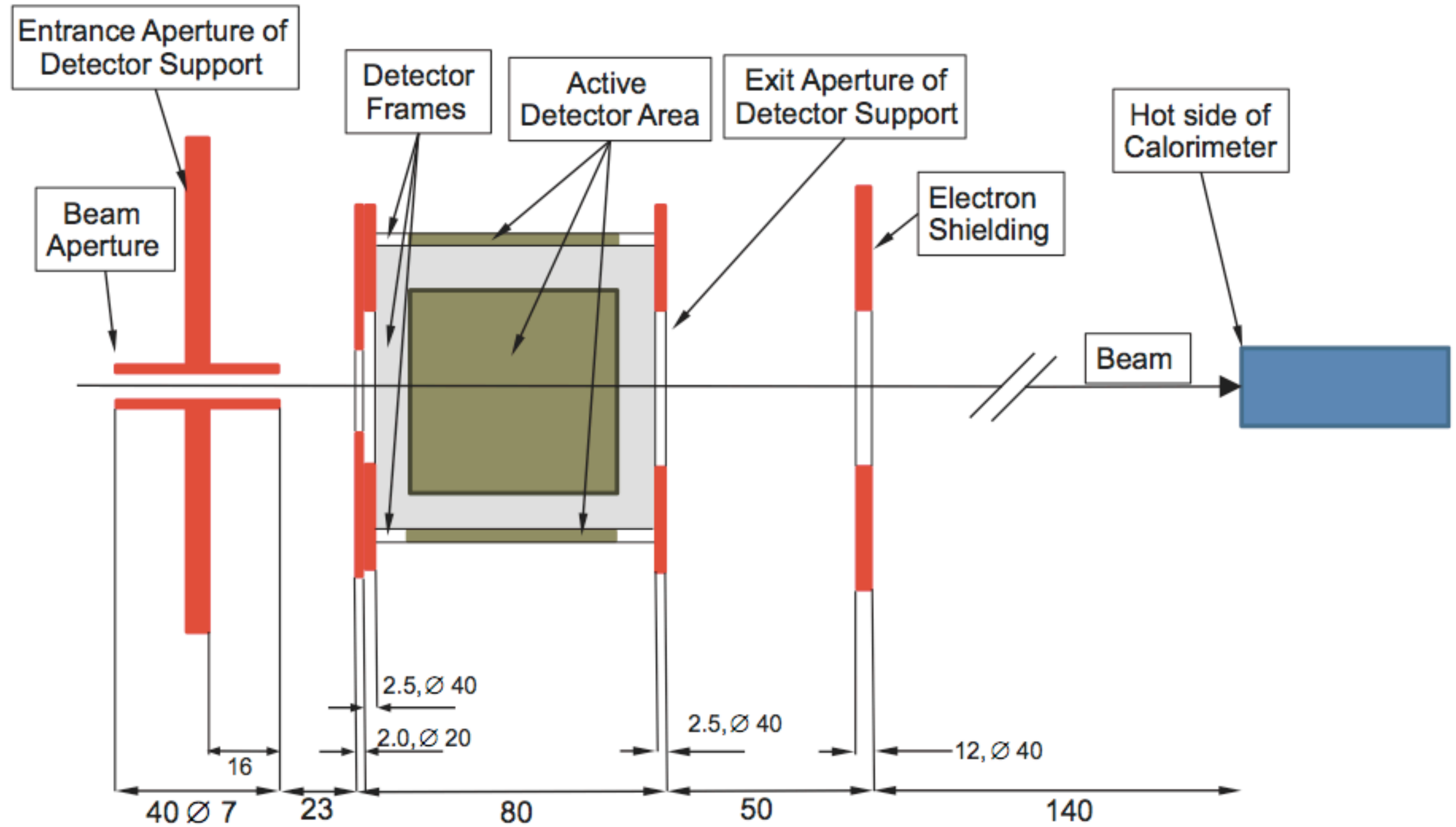
from Claus

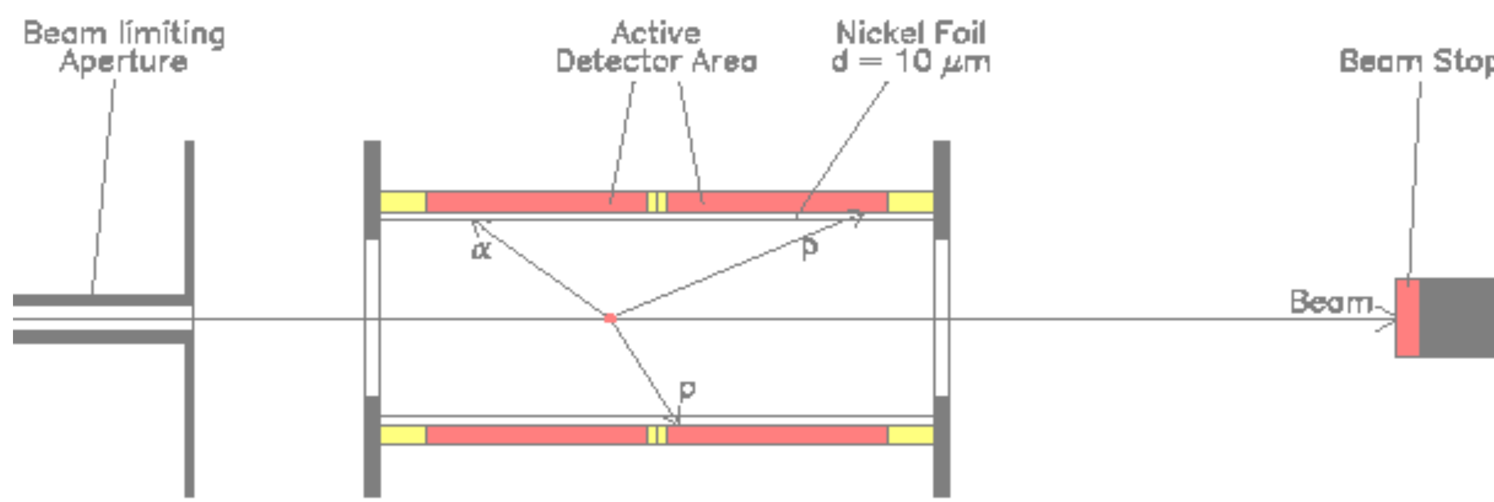


..as many other things...

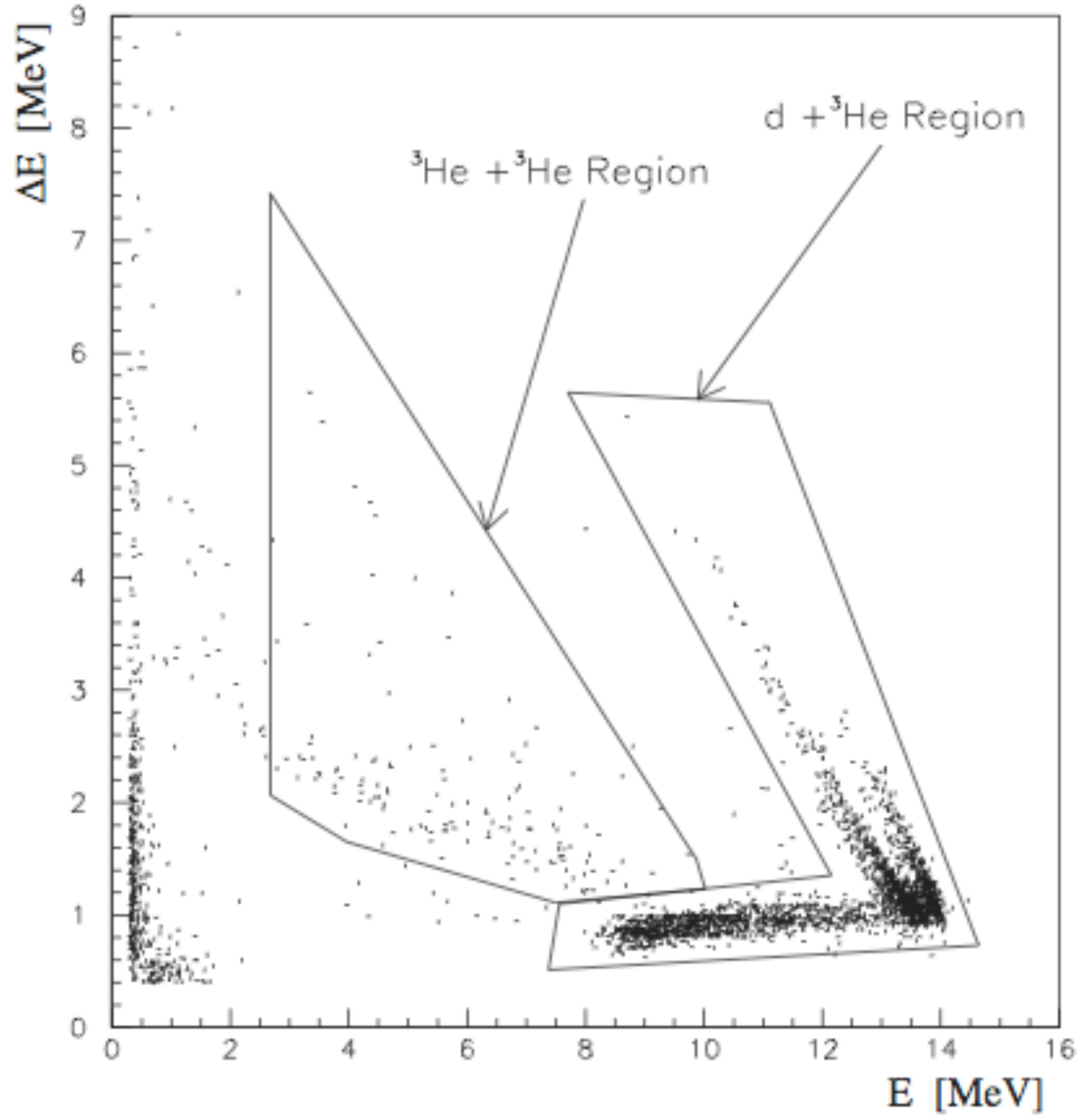
$^{3}He(^{3}He,2p)^{4}He$





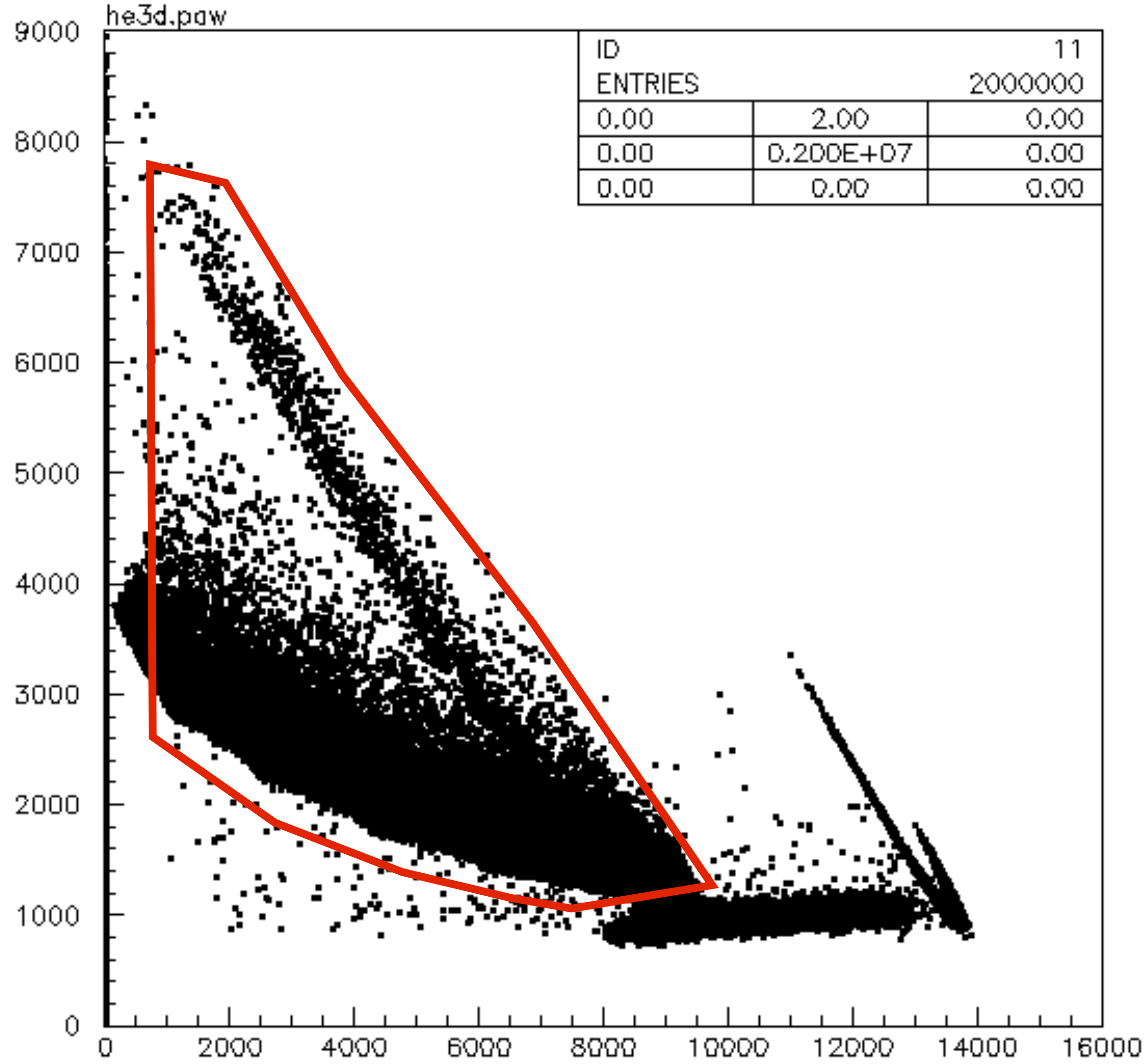


^3He (^3He,2p)^4He



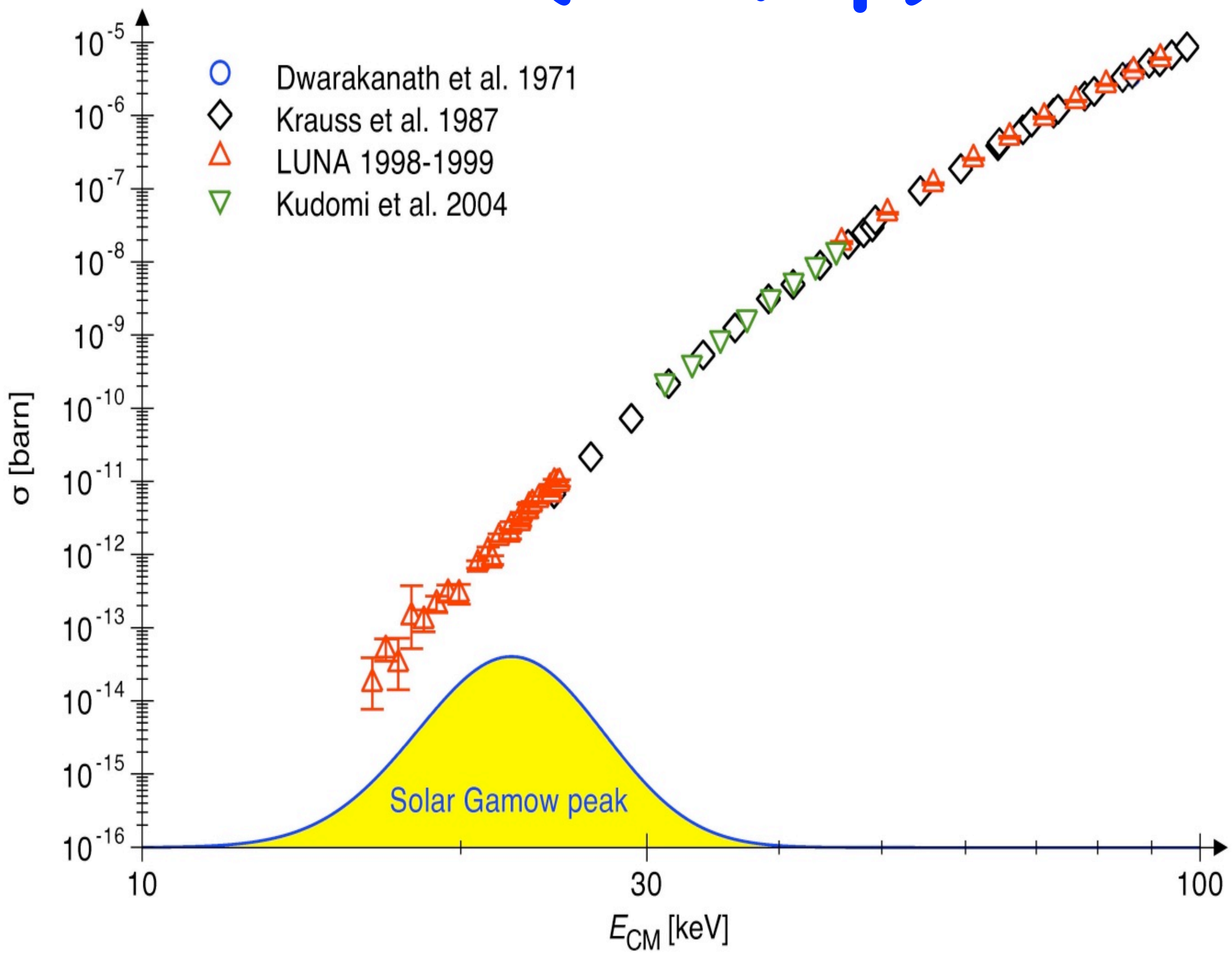
HD$^+$ ions in beam $\rightarrow$ D(^{3}He,p)^{4}He

$^{3}He\ (^{3}He,2p)^{4}He$



first Geant3 simulation..

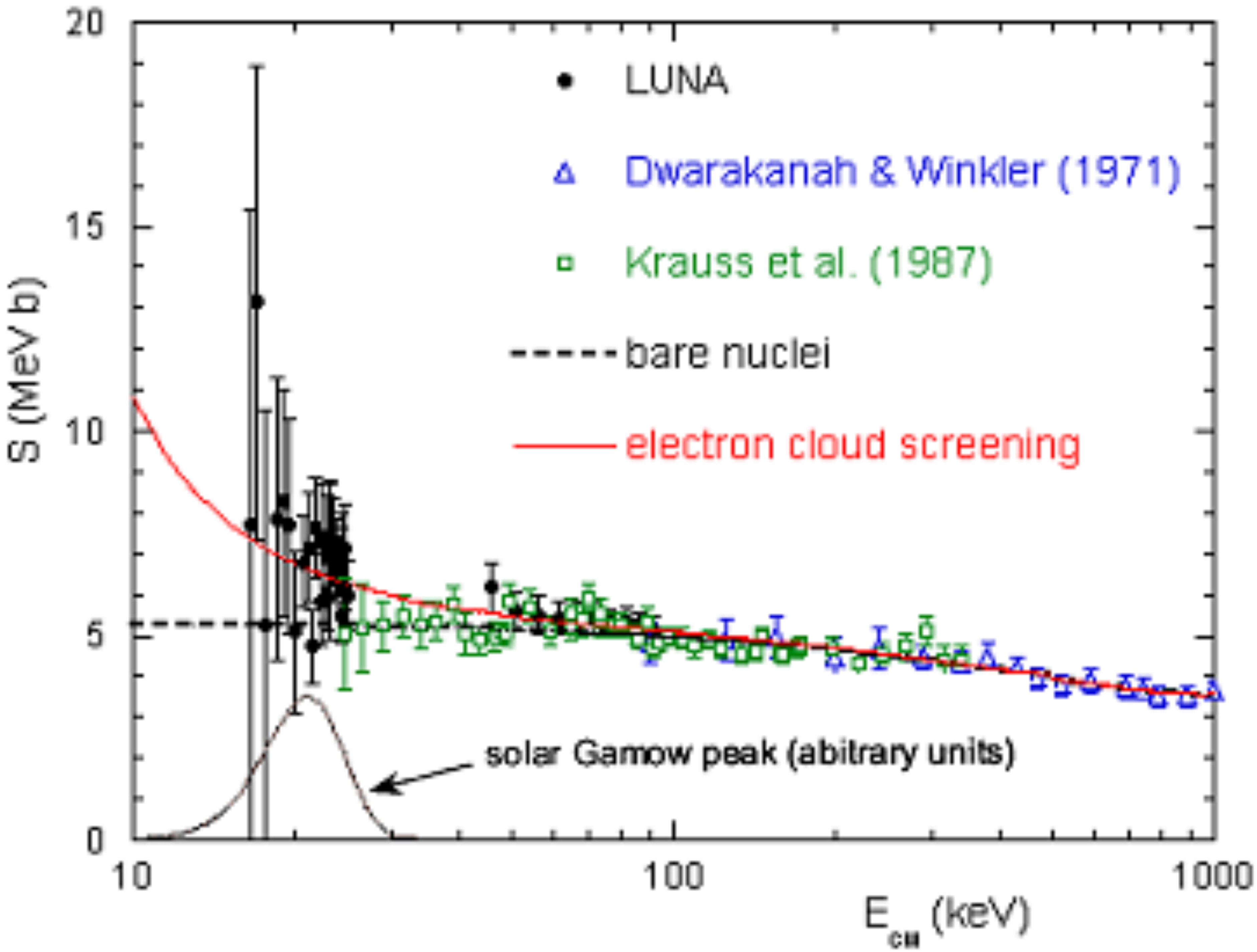
$^3He(^3He,2p)^4He$



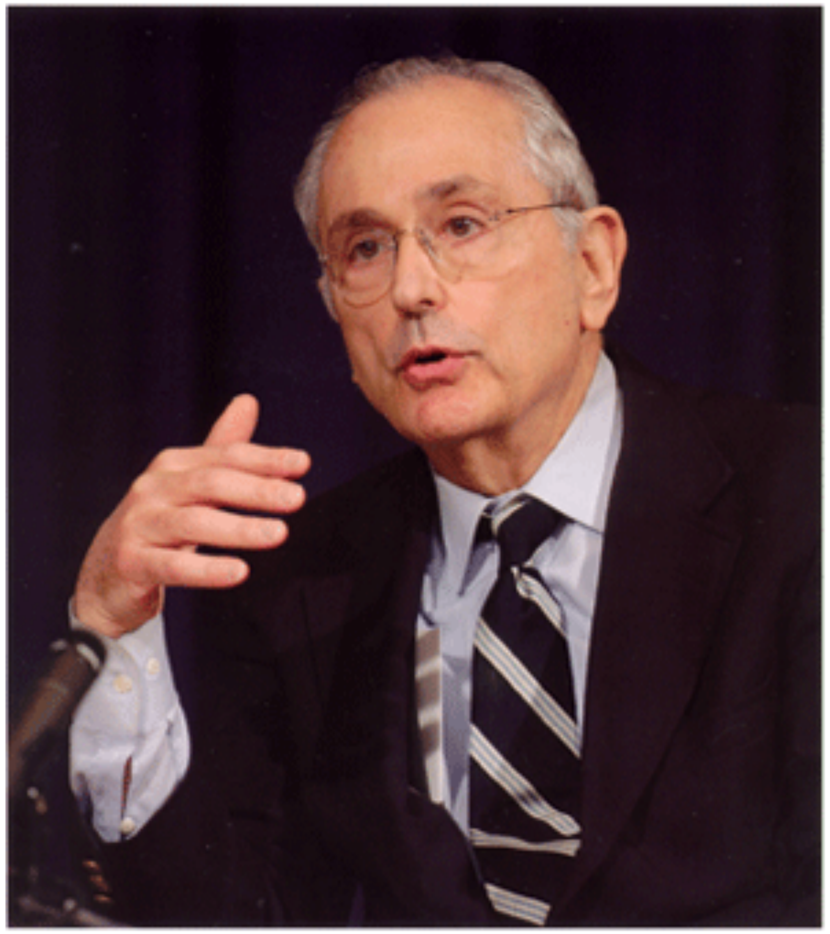
σ_{min}=20 fb (2 events/month)

No resonance at the Gamow peak

$^{3}He\,(^{3}He,2p)^{4}He$



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



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SCHOOL OF NATURAL SCIENCES — JOHN N. BAHCALL

28 May 1997

Professor P. Corvisiero
Professor C. Rolfs
Spokesmen for the LUNA-Collaboration

Dear Professors Corvisiero and Rolfs:

I am writing to you about a historic opportunity of which I first became aware at the recent meeting on Solar Fusion Reactions at the Institute of Nuclear Theory, Washington University. At this meeting, I had the opportunity to see for the first time the results of the LUNA measurements of the important $3He - 3He$ reaction in a region that covers a significant part of the Gamow energy peak for solar fusion. This was a thrill that I had never believed possible. These measurements signal the most important advance in nuclear astrophysics in three decades.

With the LUNA results, debates on the validity of nuclear physics extrapolations to low energy that were ignited by the differences between standard predictions and observations of solar neutrinos can now be resolved experimentally. At least for the important $^{3}He(^{3}He,2p)^{4}He$ reaction, it is becoming clear that no major discrepancy can be attributed to our nuclear physics understanding. (Additional measurements are needed in order to clarify some systematic uncertainties and to extend the results to the lower energy part of the Gamow peak.)

There are a number of other reactions that are crucial for our understanding of solar neutrino experiments and for the evolution of main sequence stars. These include: $^{3}He(\alpha,\gamma)^{7}Be$, $^{7}Be(p,\gamma)^{8}B$, and $^{14}N(p,\gamma)^{15}O$. We need to know the rates for these reactions at or near the energies at which fusion occurs in the sun and other main sequence stars.

The LUNA collaboration is superbly qualified to carry out the required studies provided an improved facility, a 200 kV high current machine, is installed in the unique environment of the Gran Sasso Underground National Laboratory.

I have had some experience in helping to set priorities for research in physics and in astronomy, most recently as Chair of the Decade Survey for Astronomy and Astrophysics of the National Academy of the United States and as President (now emeritus) of the American Astronomical Society. I can say, with the perspective provided by these previous assignments, that the work of the LUNA collaboration is unique and essential for further progress in solar neutrino studies and for understanding how main sequence stars evolve. I personally would rank the LUNA project among the highest priorities internationally for research in nuclear astrophysics, in stellar evolution, in solar neutrinos, and in particle phenomenology.

To Professor P. Corvisiero — 28 May 1997 — Page 2

Please inform the individuals responsible for making the crucial budgetary decisions regarding the 200 kV high current machine of my eagerness to be personally available for more detailed discussions.

Sincerely yours,

John N. Bahcall
Professor of Natural Science

JNB:jnb

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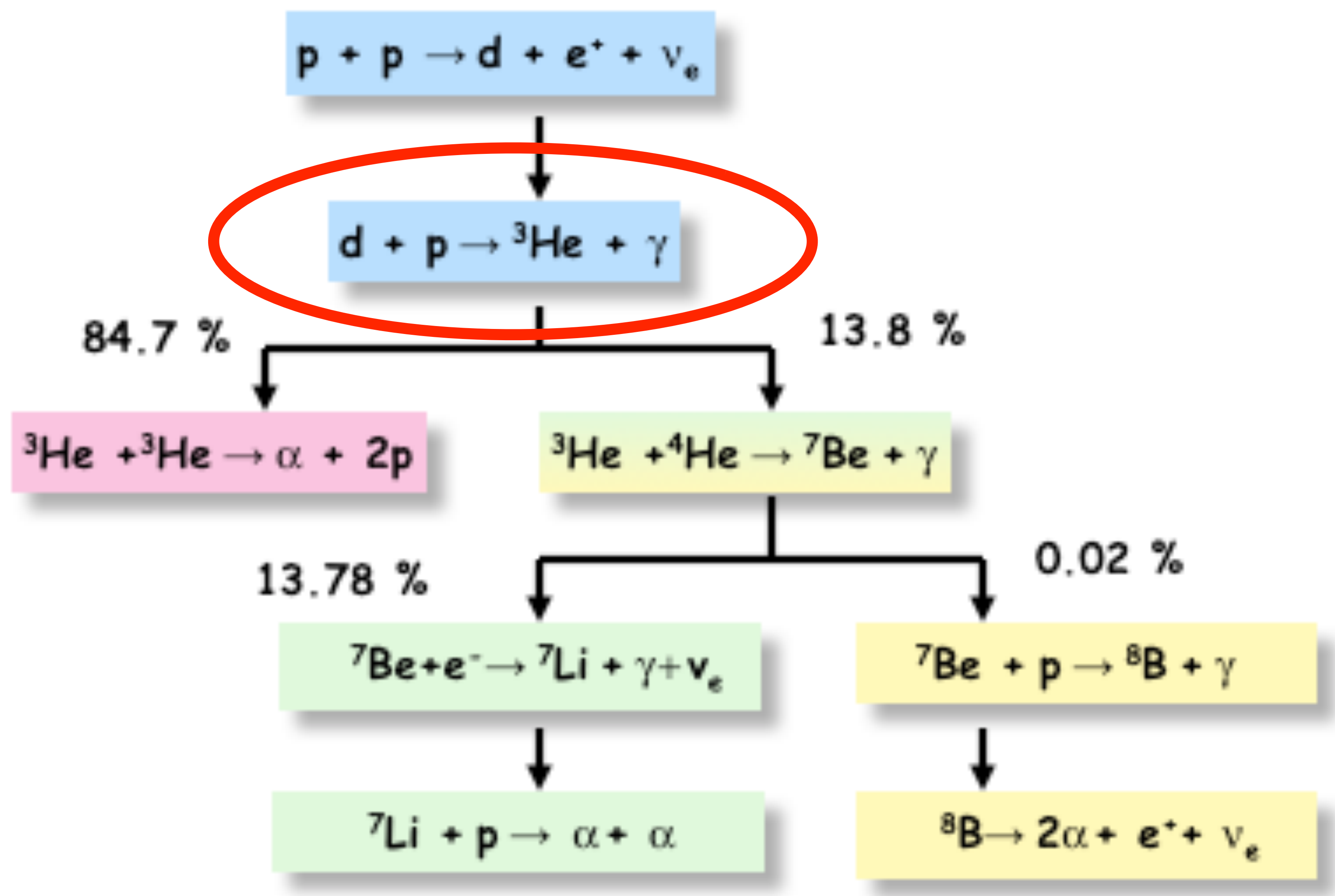
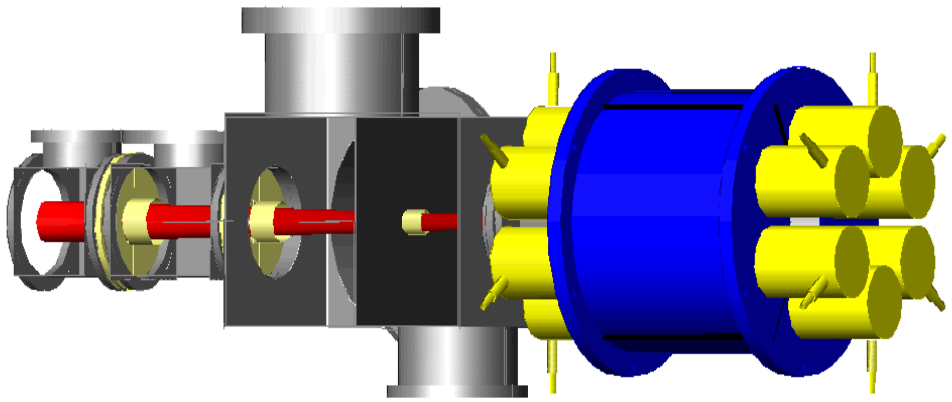
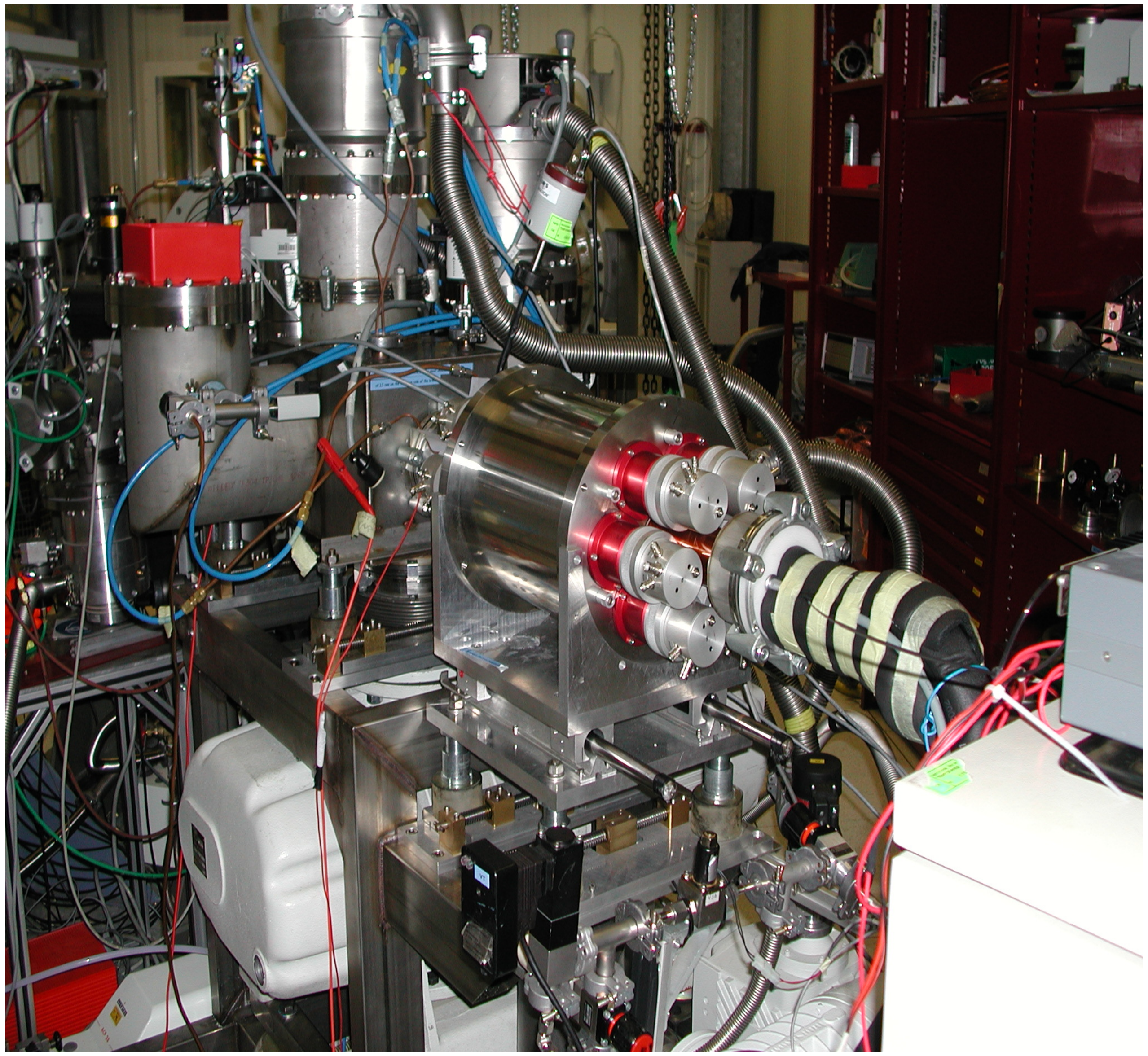
pp chain



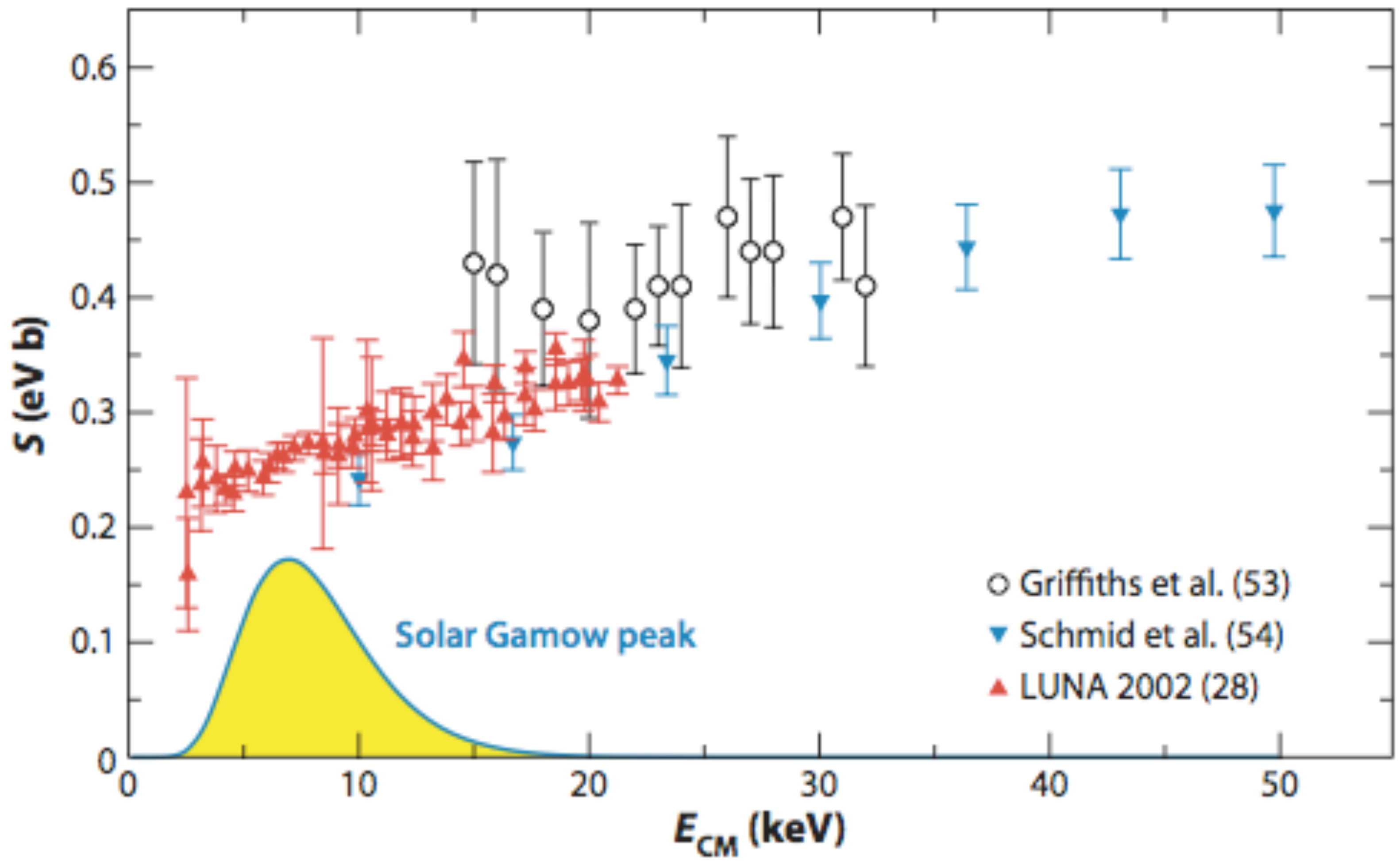
$p + p \rightarrow d + e^+ + \nu_e$
$d + p \rightarrow {}^3He + \gamma$
84.7 %
13.8 %
${}^3He + {}^3He \rightarrow \alpha + 2p$
${}^3He + {}^4He \rightarrow {}^7Be + \gamma$
13.78 %
0.02 %
${}^7Be + e^- \rightarrow {}^7Li + \gamma + \nu_e$
${}^7Be + p \rightarrow {}^8B + \gamma$
${}^7Li + p \rightarrow \alpha + \alpha$
${}^8B \rightarrow 2\alpha + e^+ + \nu_e$

$^{2}H\ (p,\gamma)^{3}He$





$^2H(p,\gamma)^3He$

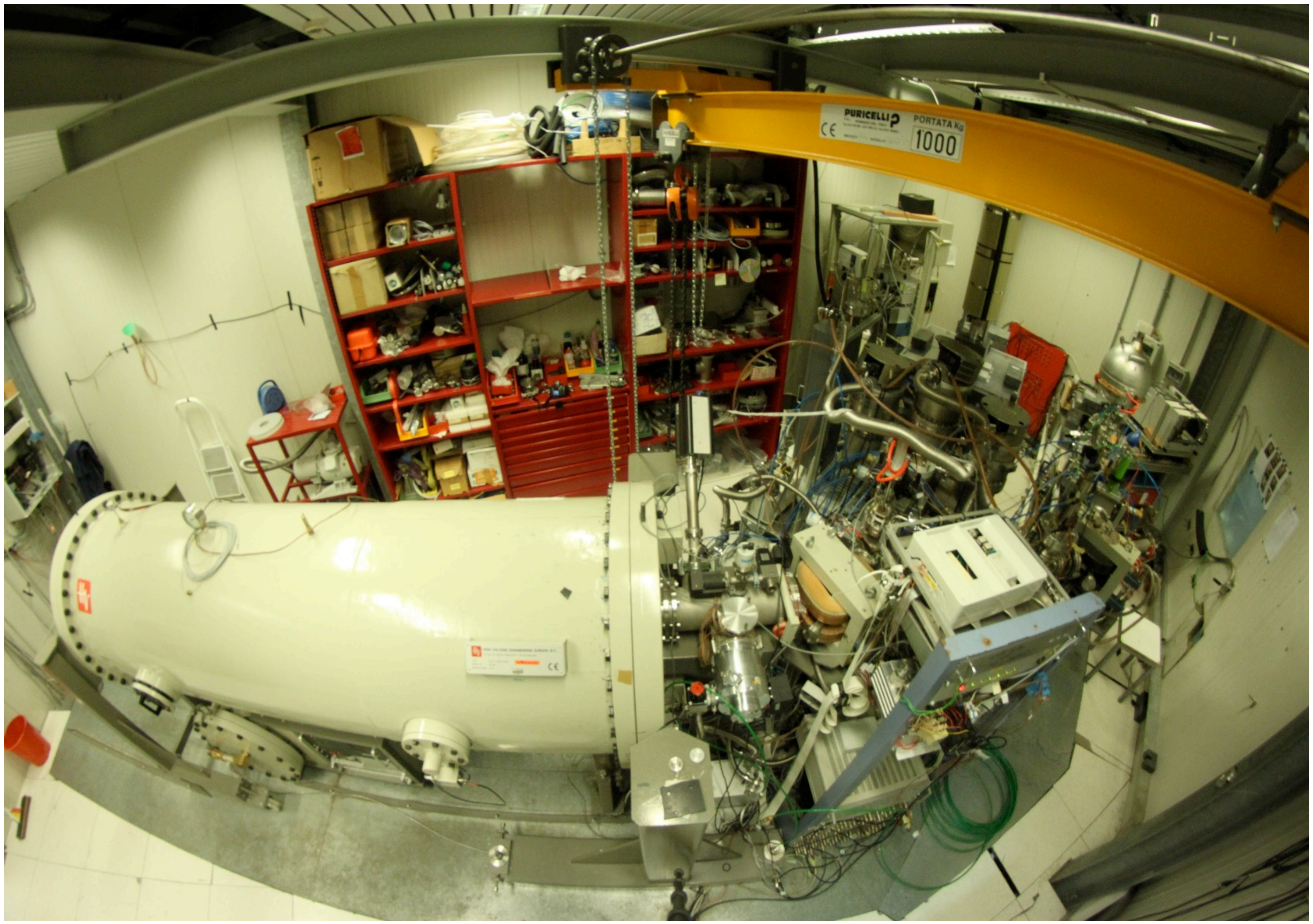


Gamow peak fully covered

Important results for "ab-initio" few body calculations

this reaction is presently remeasured in the BBN energy region

LUNA 400kV accelerator (summer 2000)



$E_{beam} \approx$ 50 – 400 keV

$I_{max} \approx$ 500 μA protons

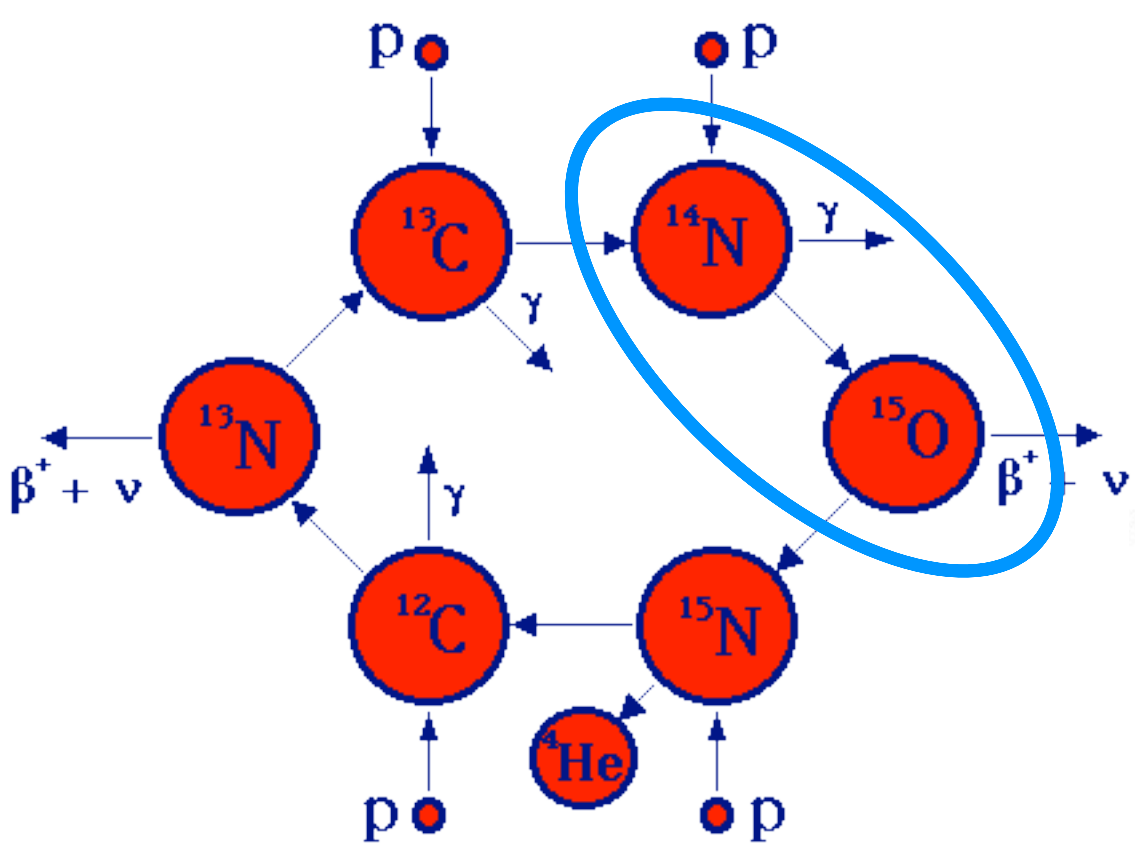
$I_{max} \approx$ 250 μA alphas

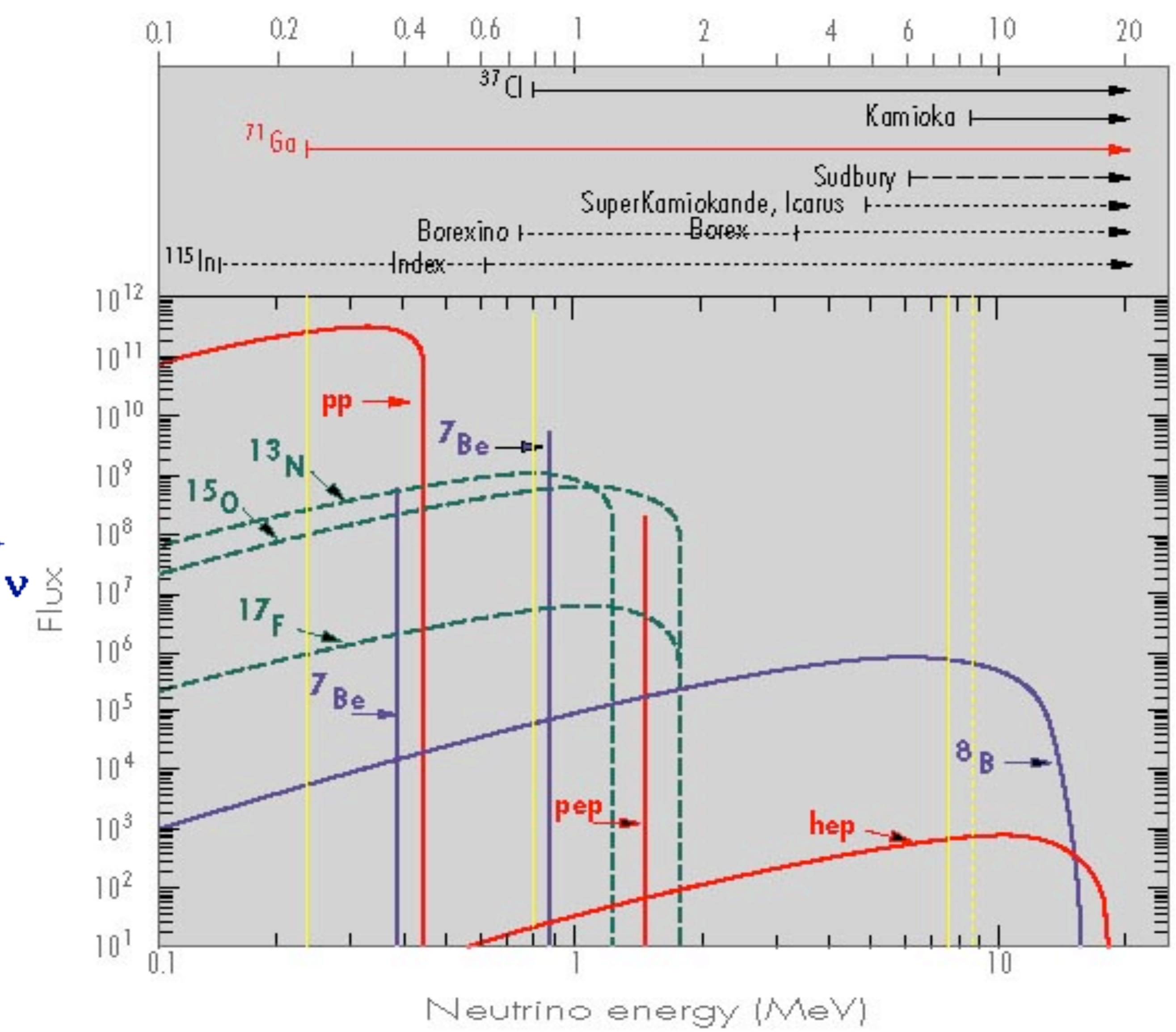
Energy spread ≈ 70 eV

Long term stability ≈ 5eV/h

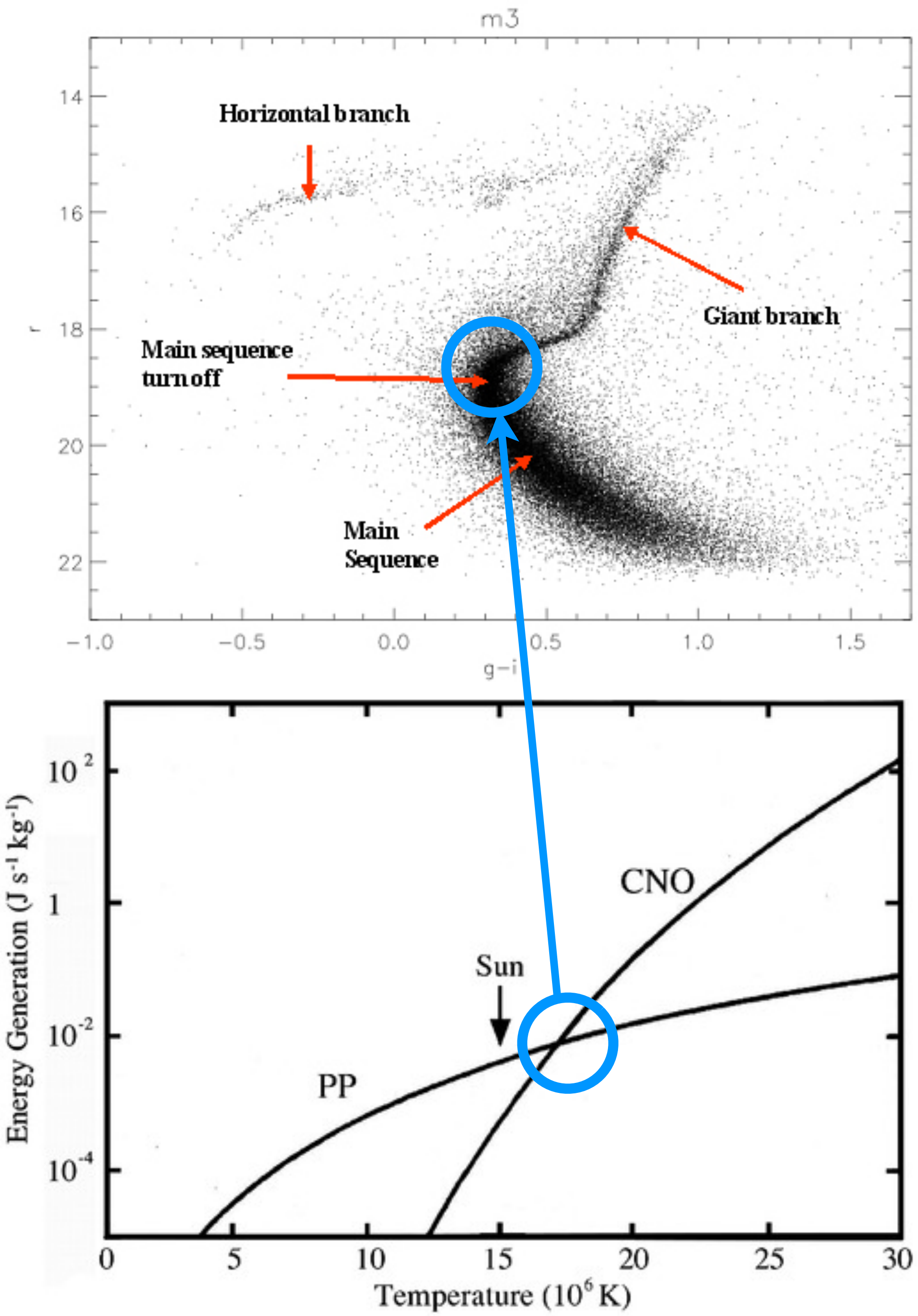
$^{14}N(p,\gamma)^{15}O$

Bottle neck of CNO cycle



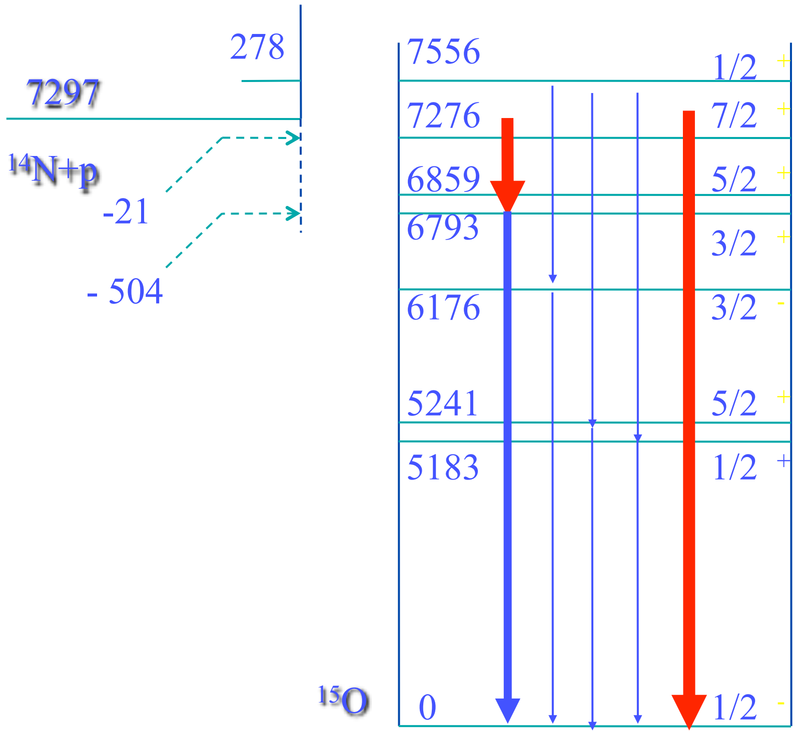


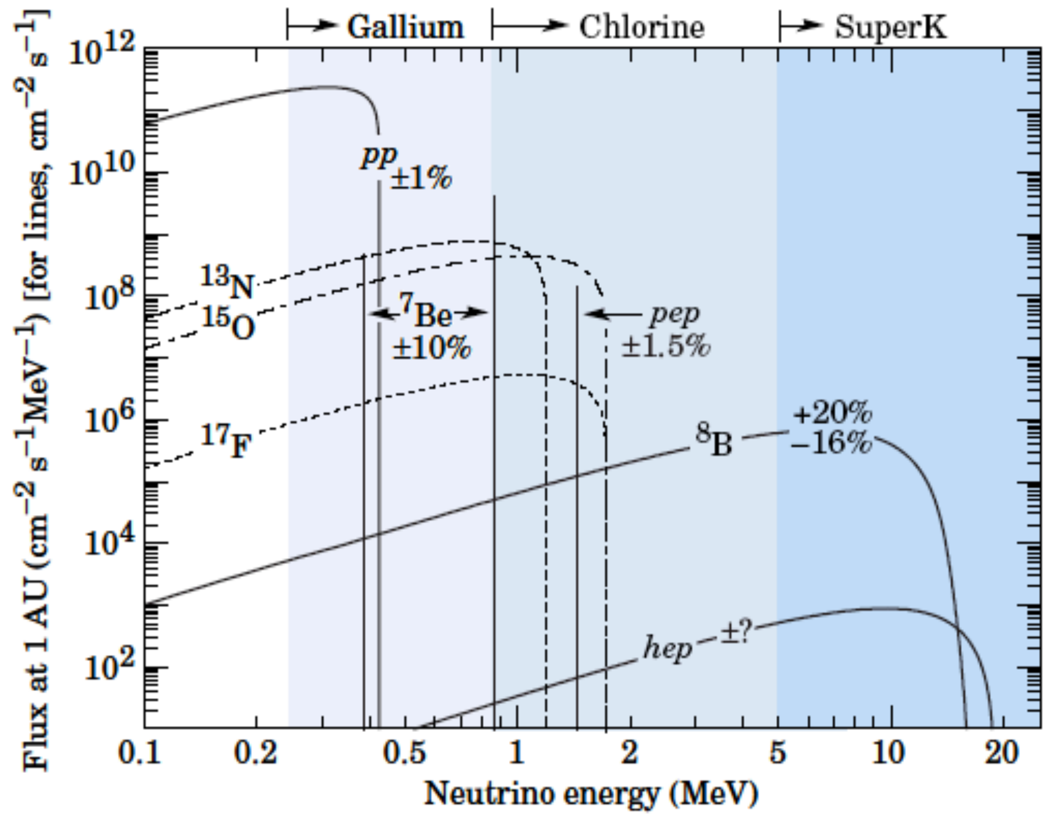
$^{14}N(p,\gamma)^{15}O$

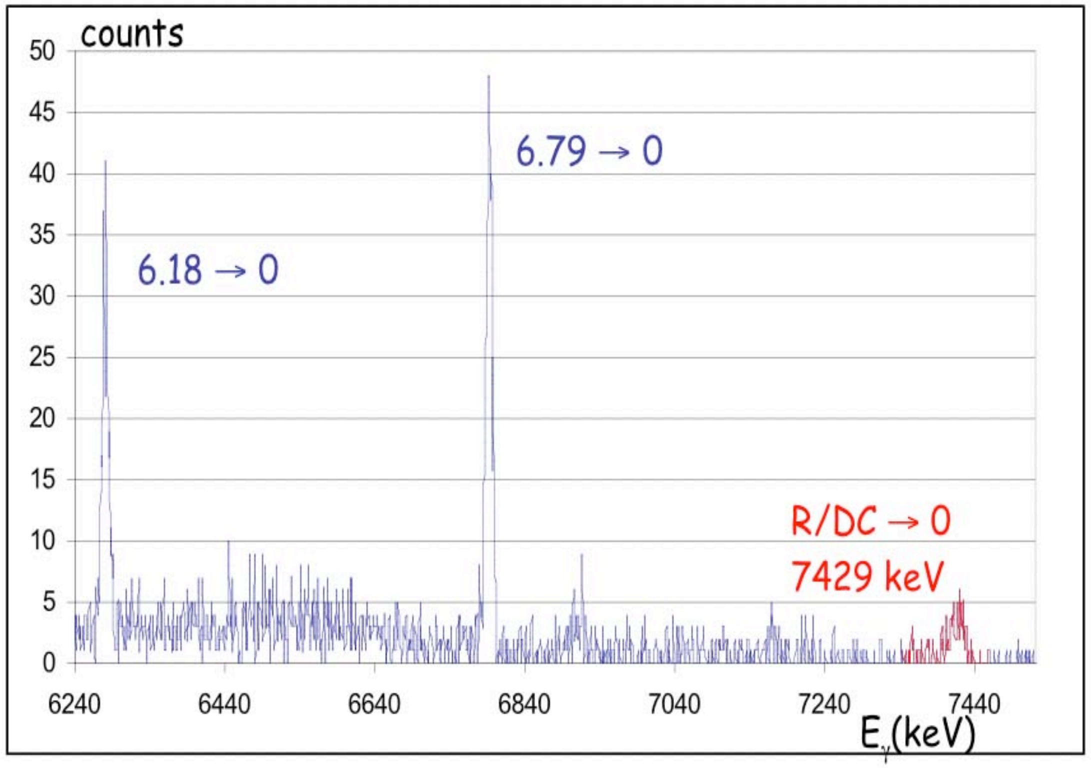


"High" energy: solid target + HpGe

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





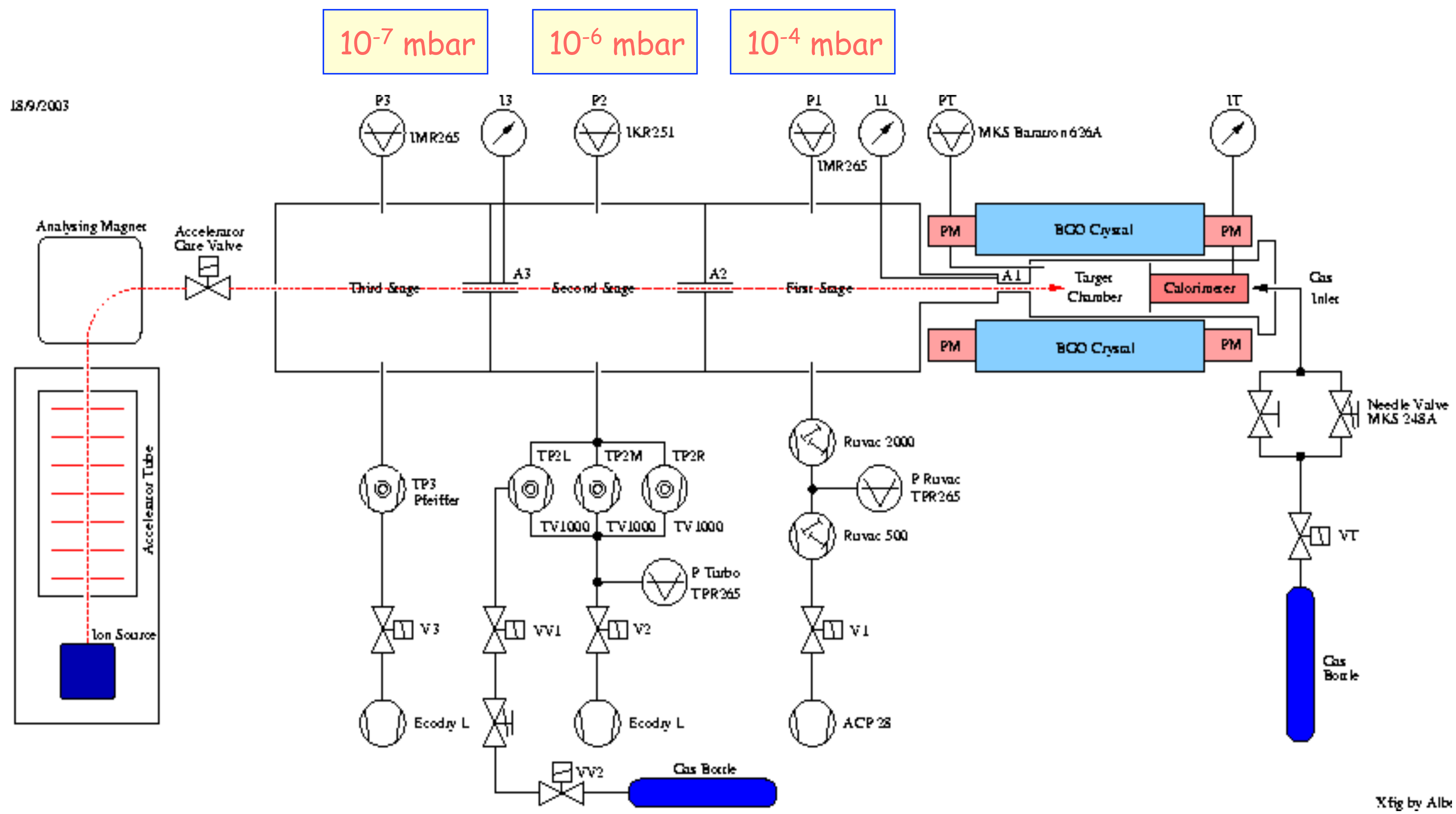


gamma spectrum of $^{14}N(p,\gamma)^{15}O$ at Ep=140 keV

LUNA

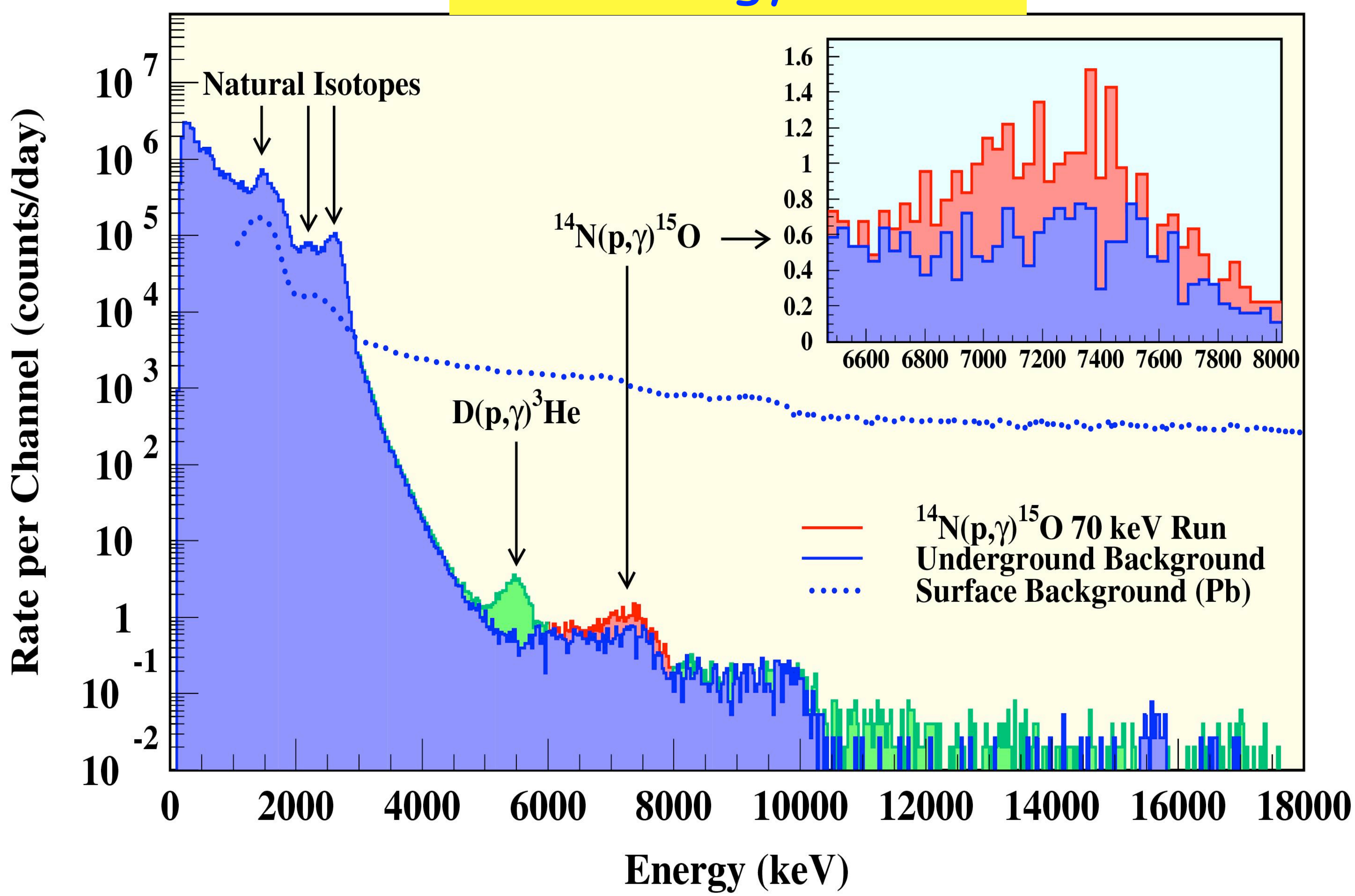
$^{14}N(p,\gamma)^{15}O$

Low energy: gas target + BGO



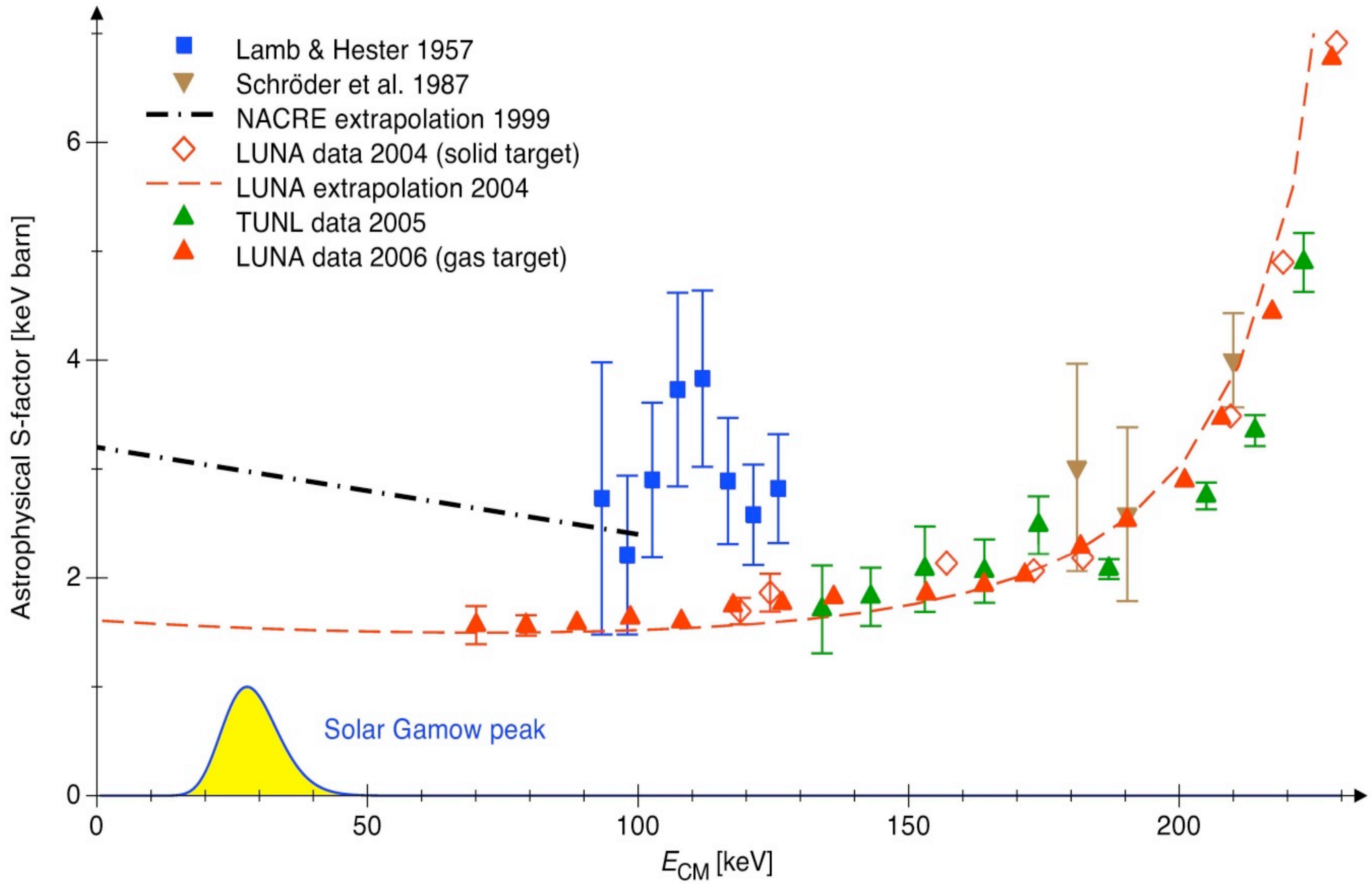
$^{14}N(p,\gamma)^{15}O$

beam energy: 80 keV



Reaction Rate = 10.95 ± 0.83 counts/day
Background rate = 21.14 ± 0.75 counts/day

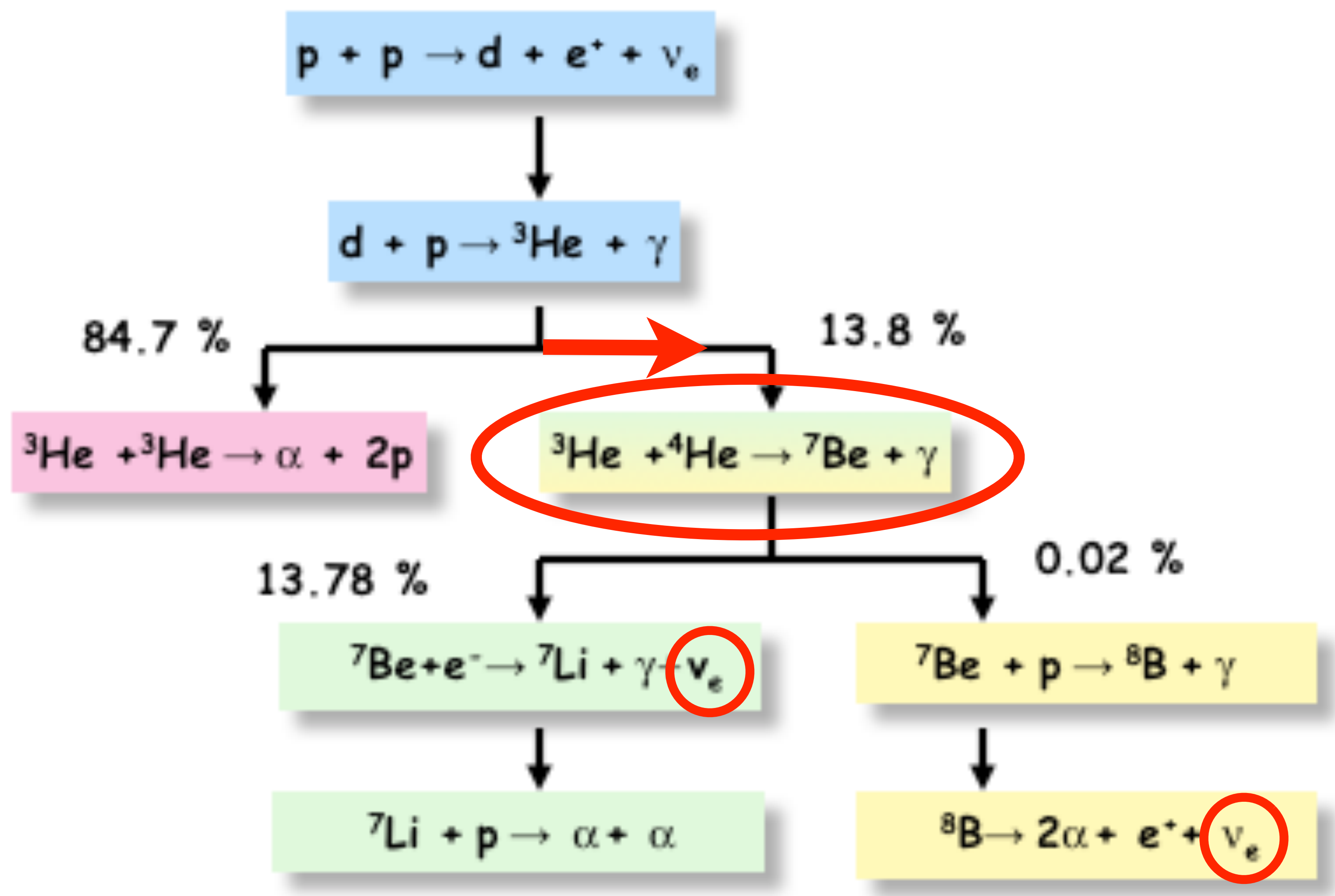
$^{14}N(p,\gamma)^{15}O$



$S_t(0)=1.57\pm0.13$ keV b

* $\frac{1}{2}\nu_{cno}$ from the Sun
* Globular Cluster age +1Gy

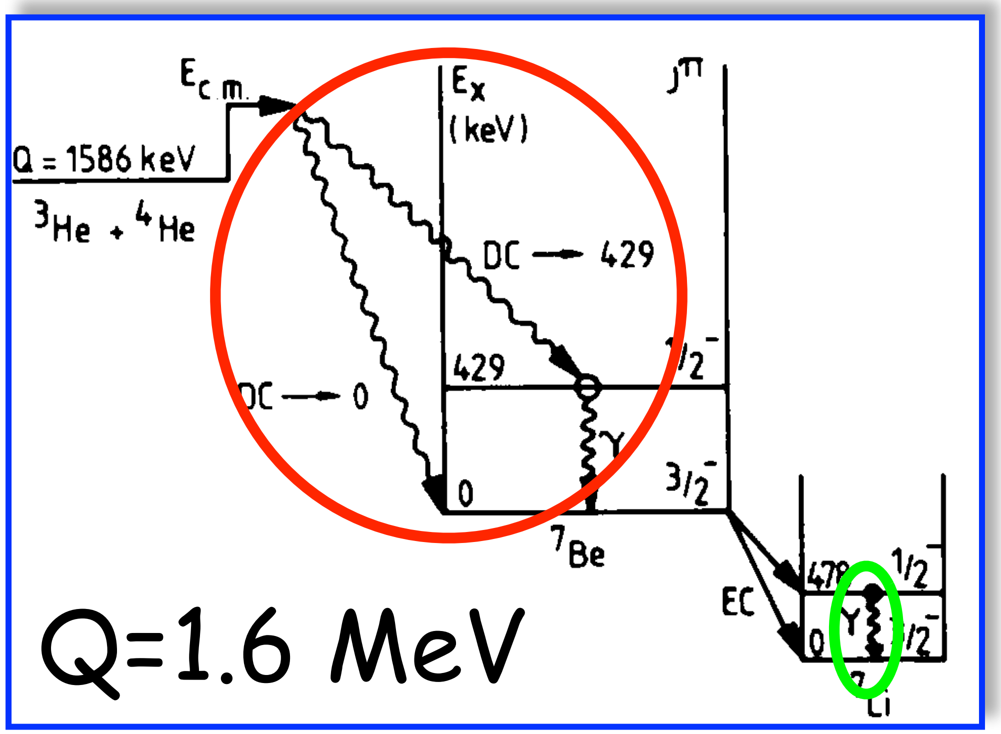
$^{3}He(^{4}He,\gamma)^{7}Be$



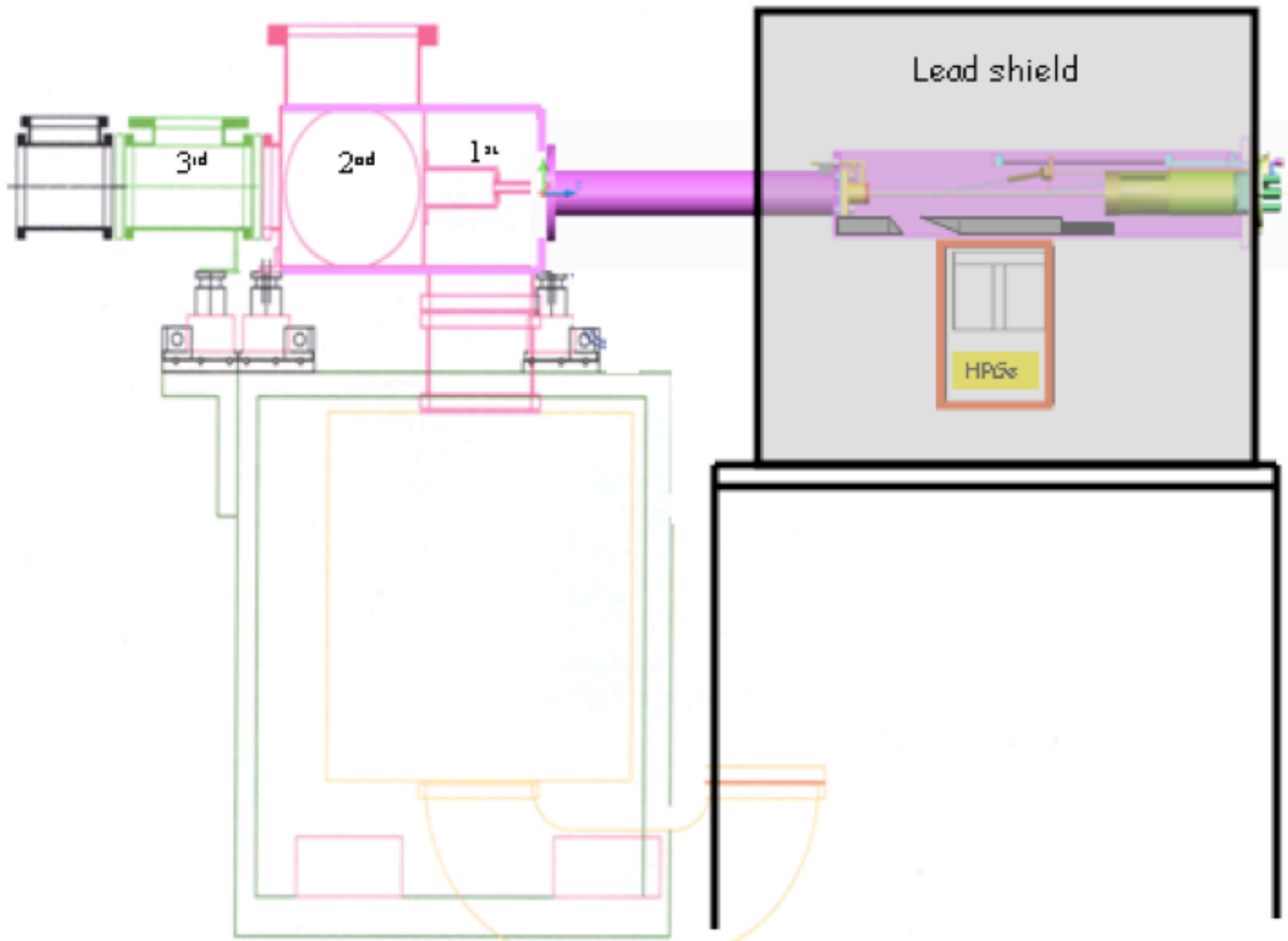
$^{3}He\ (^{4}He,\gamma)^{7}Be$

- solar neutrinos: ^{7}Be, ^{8}B
- BBN ^{7}Li

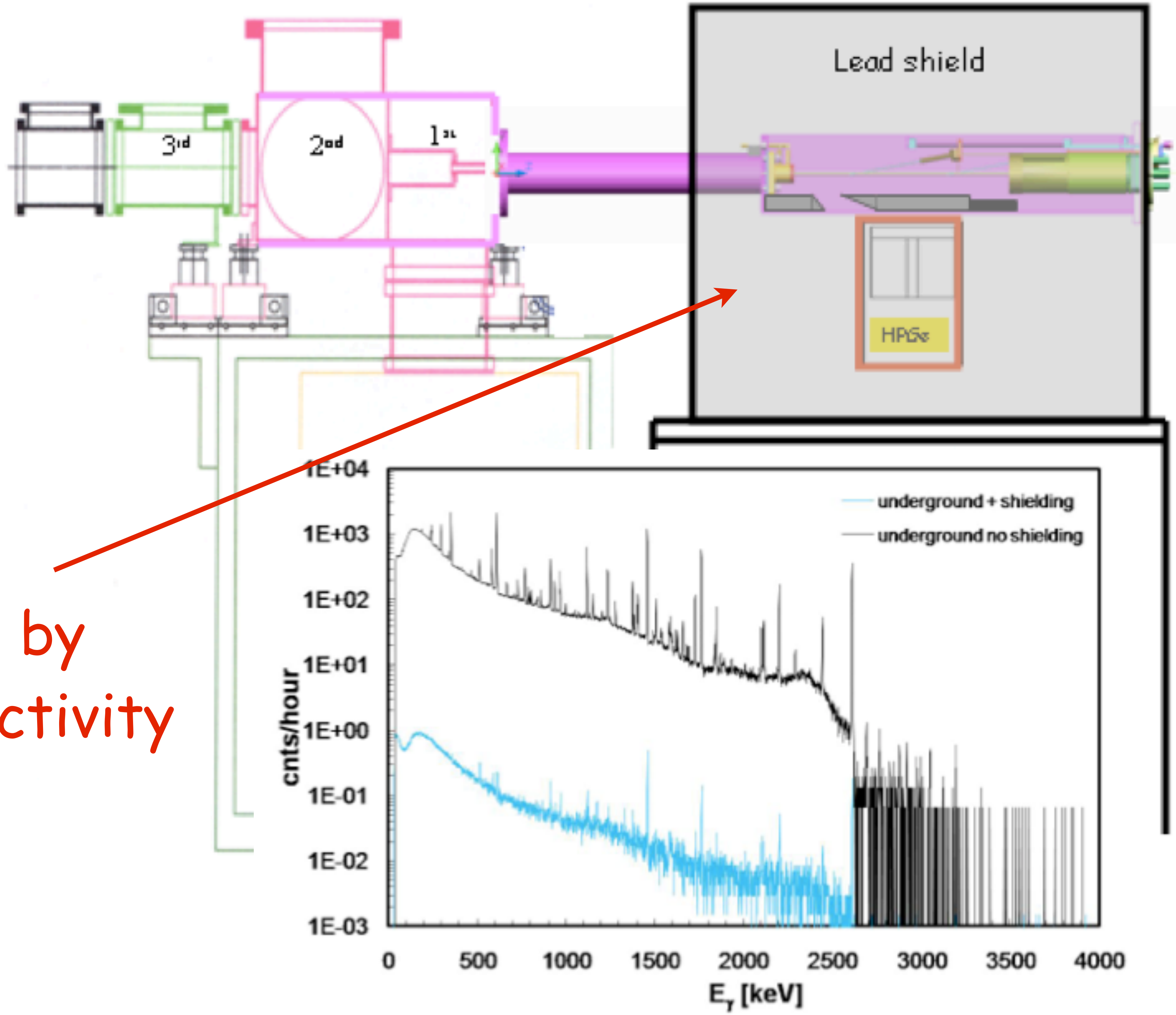
•Cross section from **prompt gamma** down to **90** keV (CM energy) using ^{4}He beam on ^{3}He target
•Activation via off-line **radioactive decay** measurements of the ^{7}Be atoms collected in the beam catcher
•All with a final error < 5 %



$^3He(^4He,\gamma)^7Be$



$^3He(^4He,\gamma)^7Be$



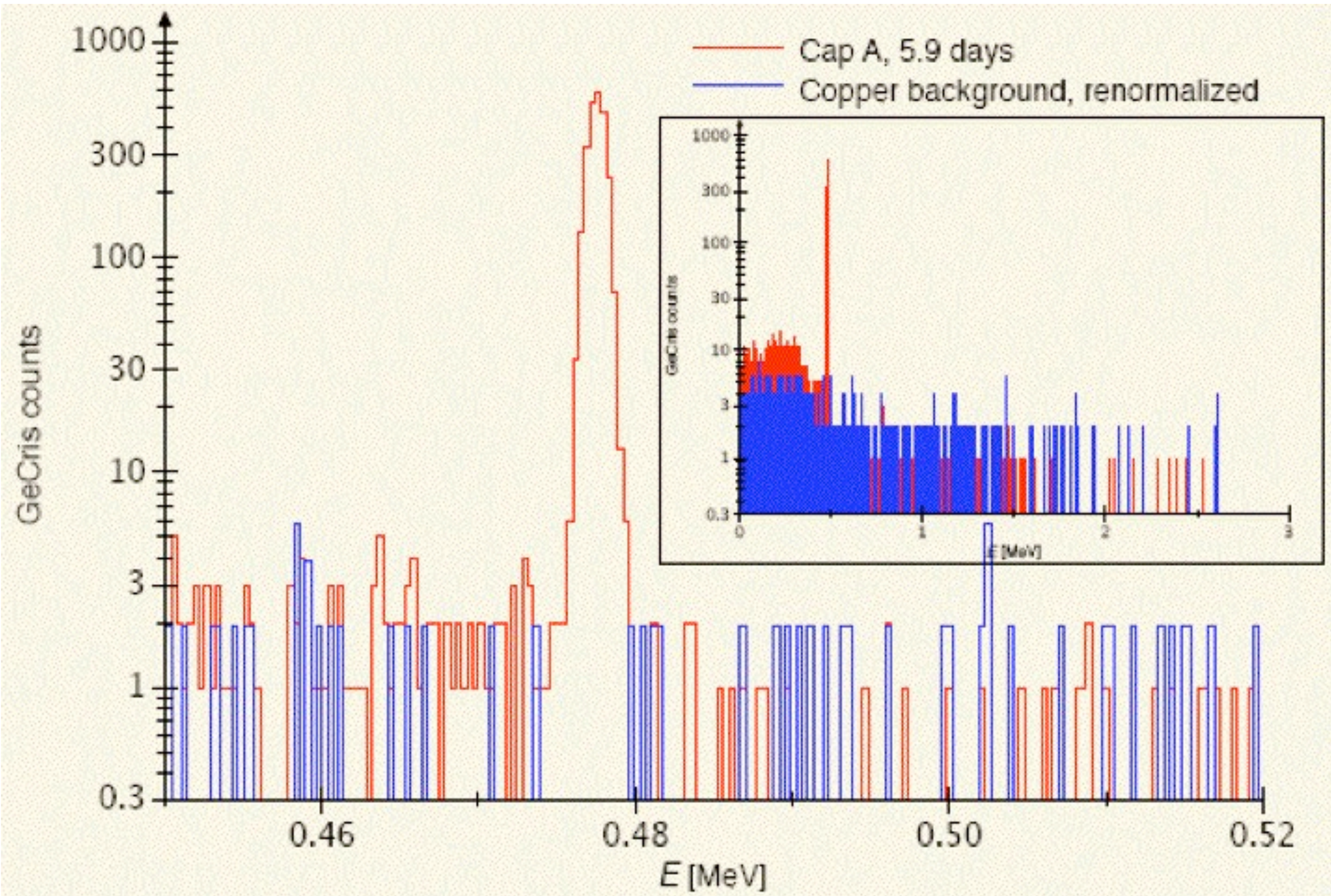
Q=1.6 MeV

signal covered by natural radioactivity

LUNA

$^{3}He\ (^{4}He,\gamma)^{7}Be$

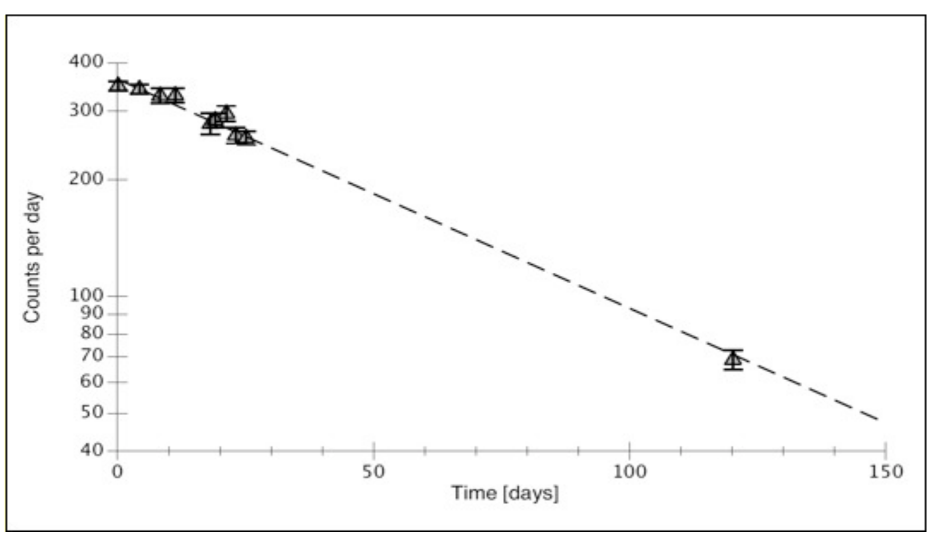
Activation measurement



^{4}He beam @ 350 keV

<I> ~ 230 μA

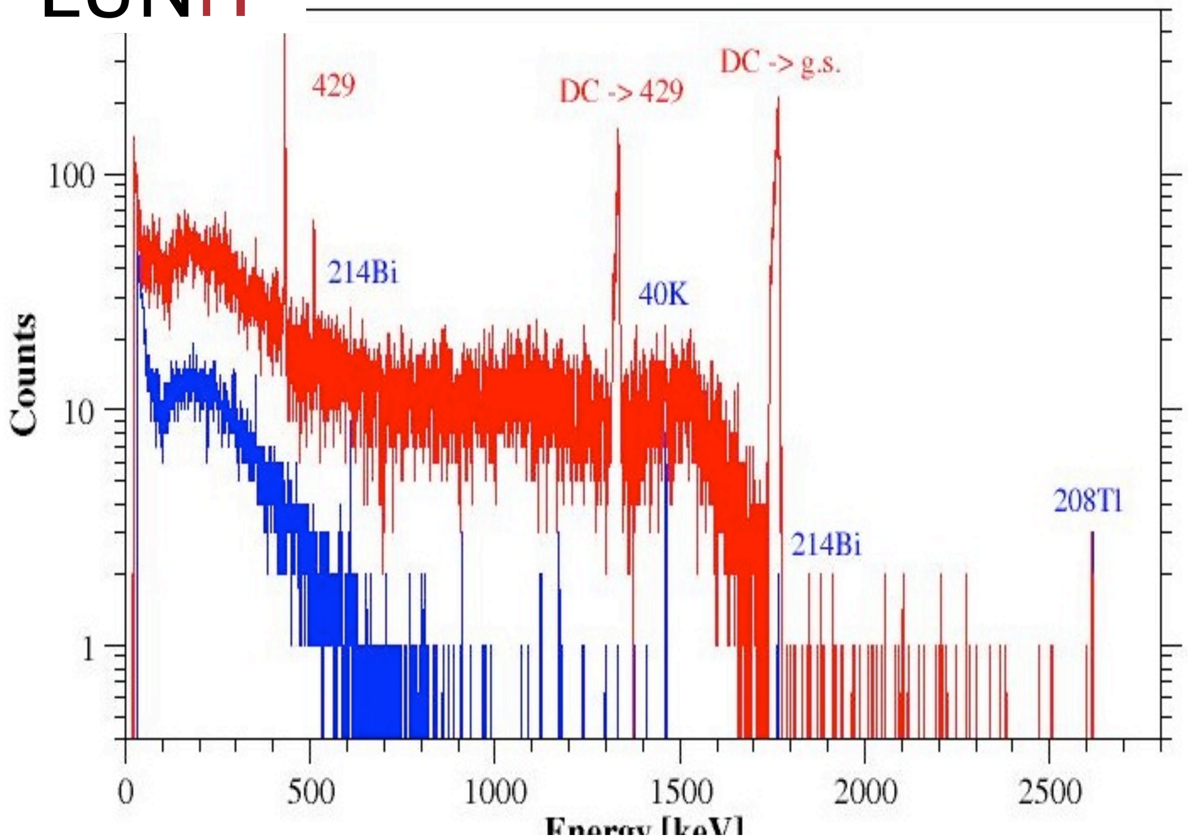
recirc. ^{3}He @ 0.7 mbar



$T_{\frac{1}{2}}$ =52.2±1.5 d

$^{3}He\ (^{4}He,\gamma)^{7}Be$

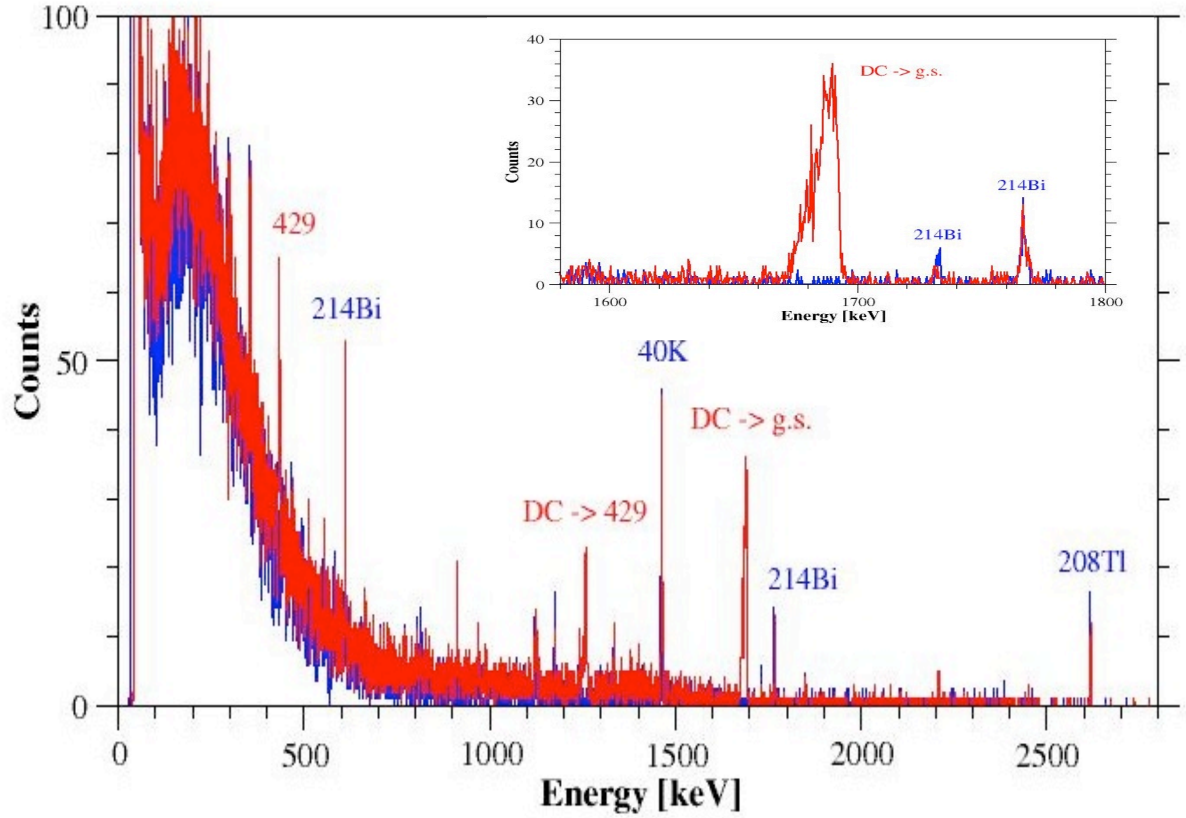
Prompt γ-spectra



^{4}He beam @ 400 keV

<I> ~ 300 μA

Irradiation time: 4.4d

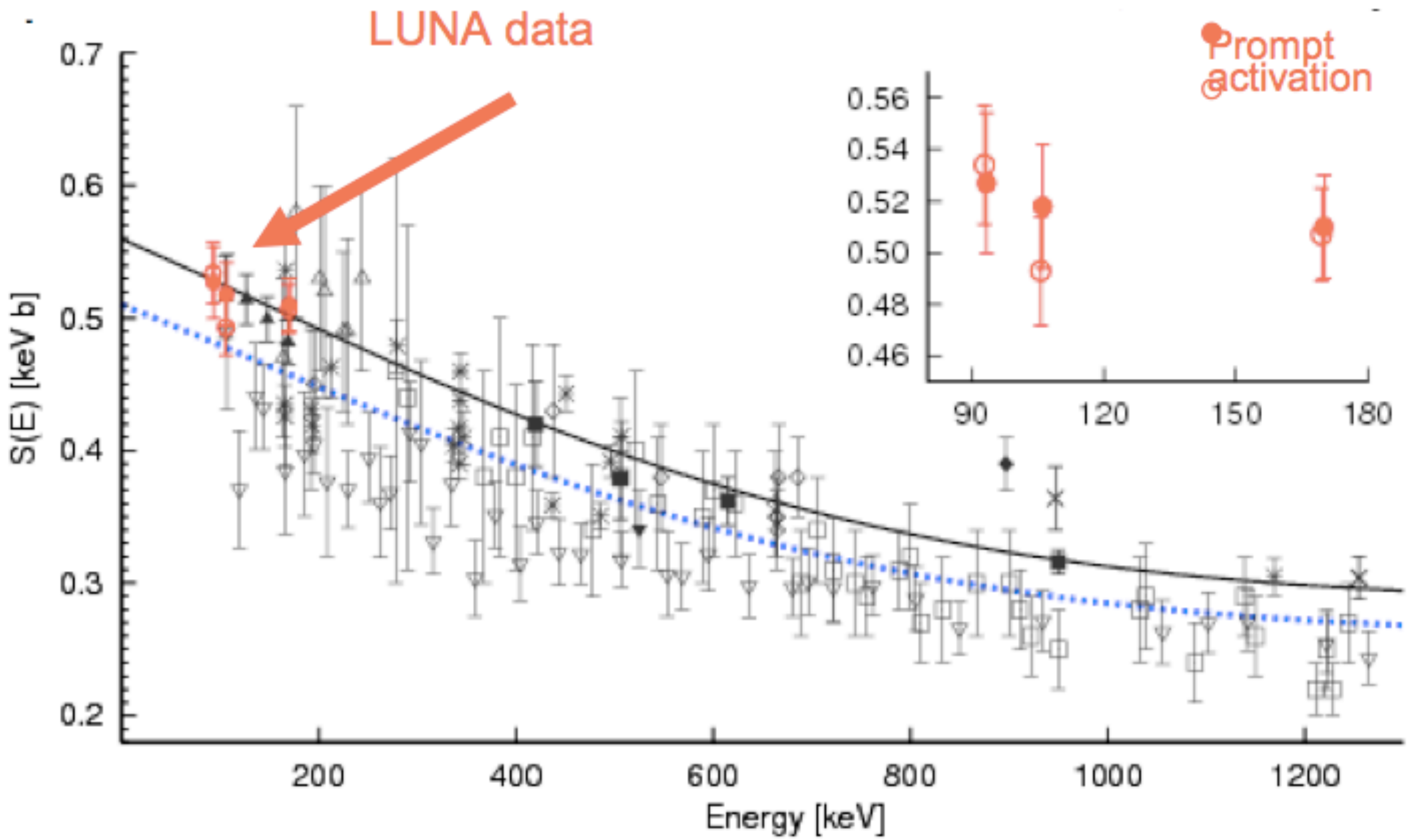


^{4}He beam @ 220 keV

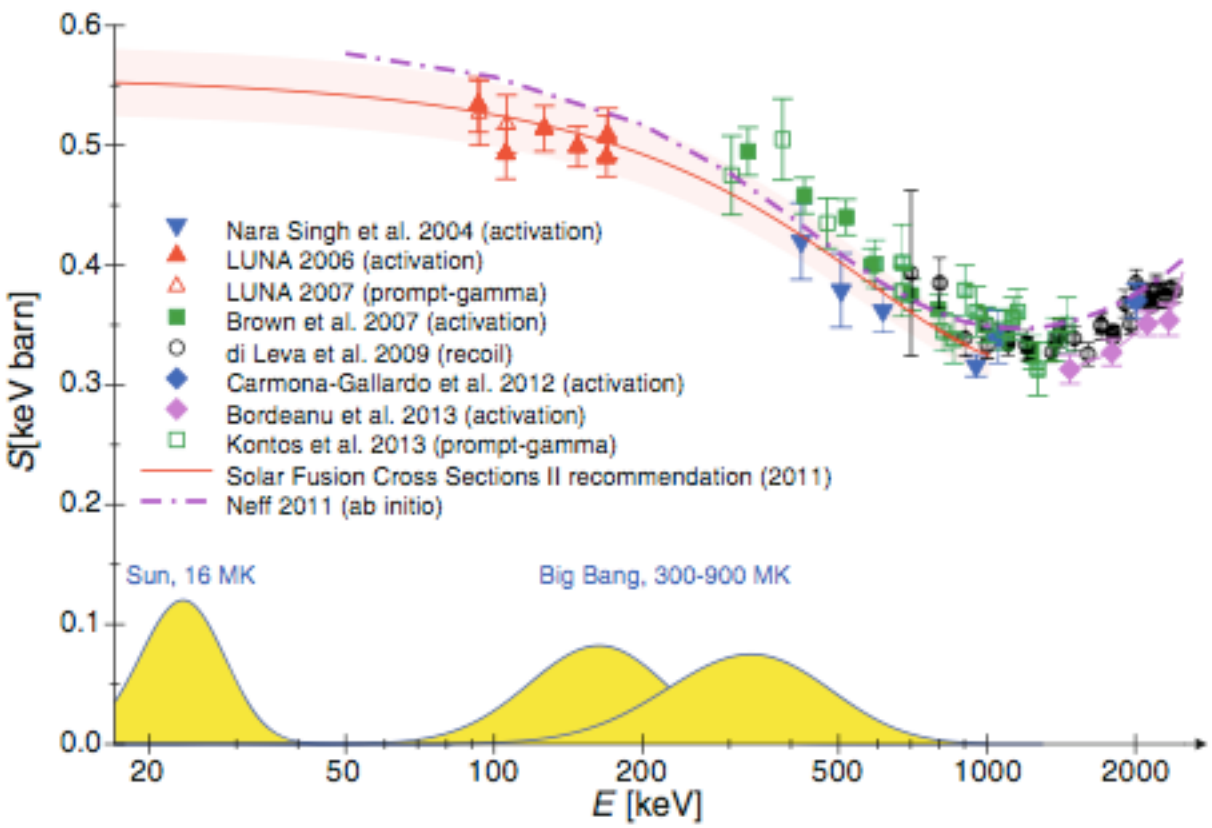
<I> ~ 240 μA

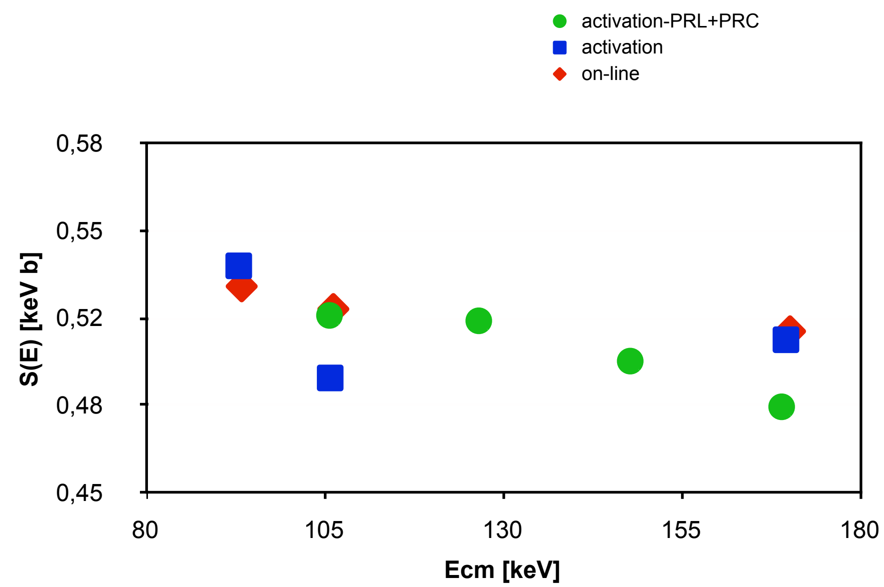
Irradiation time: 24.4d

$^{3}He\ (^{4}He,\gamma)^{7}Be$



$^{3}He\ (^{4}He,\gamma)^{7}Be$





σ down to 93 keV

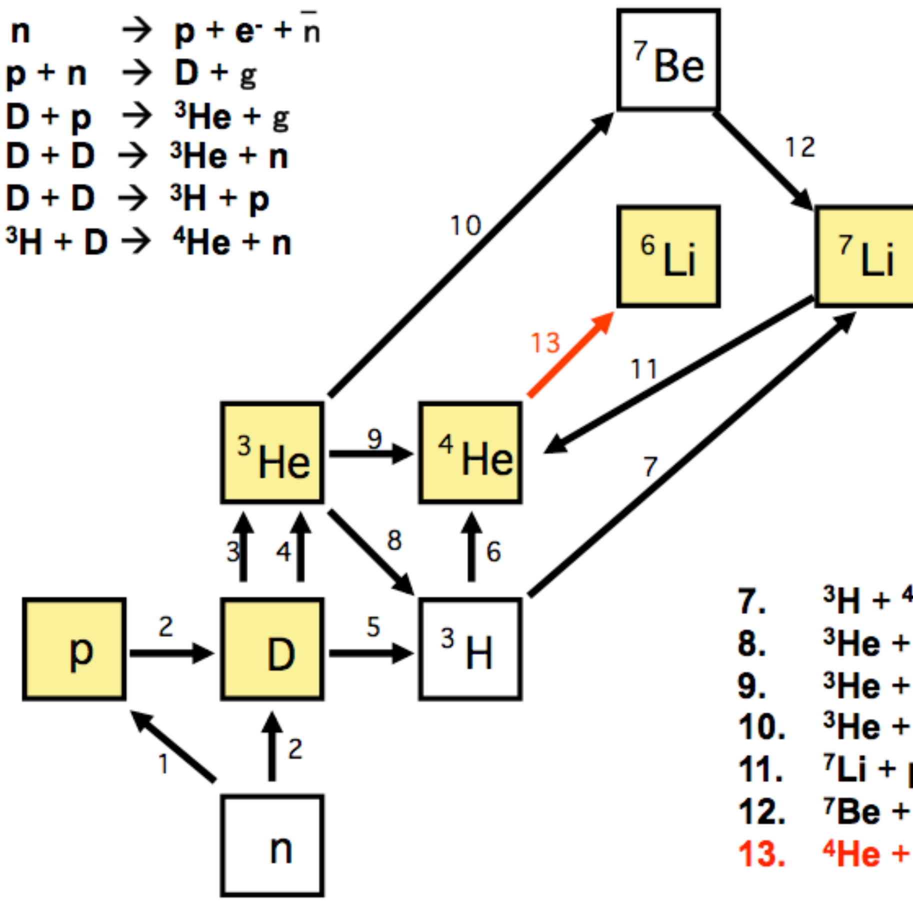
$S_{34}(0) = 0.567 \pm 0.018$ keV b

recommended value 0.56 ± 0.02 (expt) ± 0.02 (theory)

$^2H(\alpha,\gamma)^6Li$

BBN reaction network

1. n → $p + e^- + \bar{n}$
2. p + n → D + g
3. D + p → ^3He + g
4. D + D → ^3He + n
5. D + D → ^3H + p
6. ^3H + D → ^4He + n

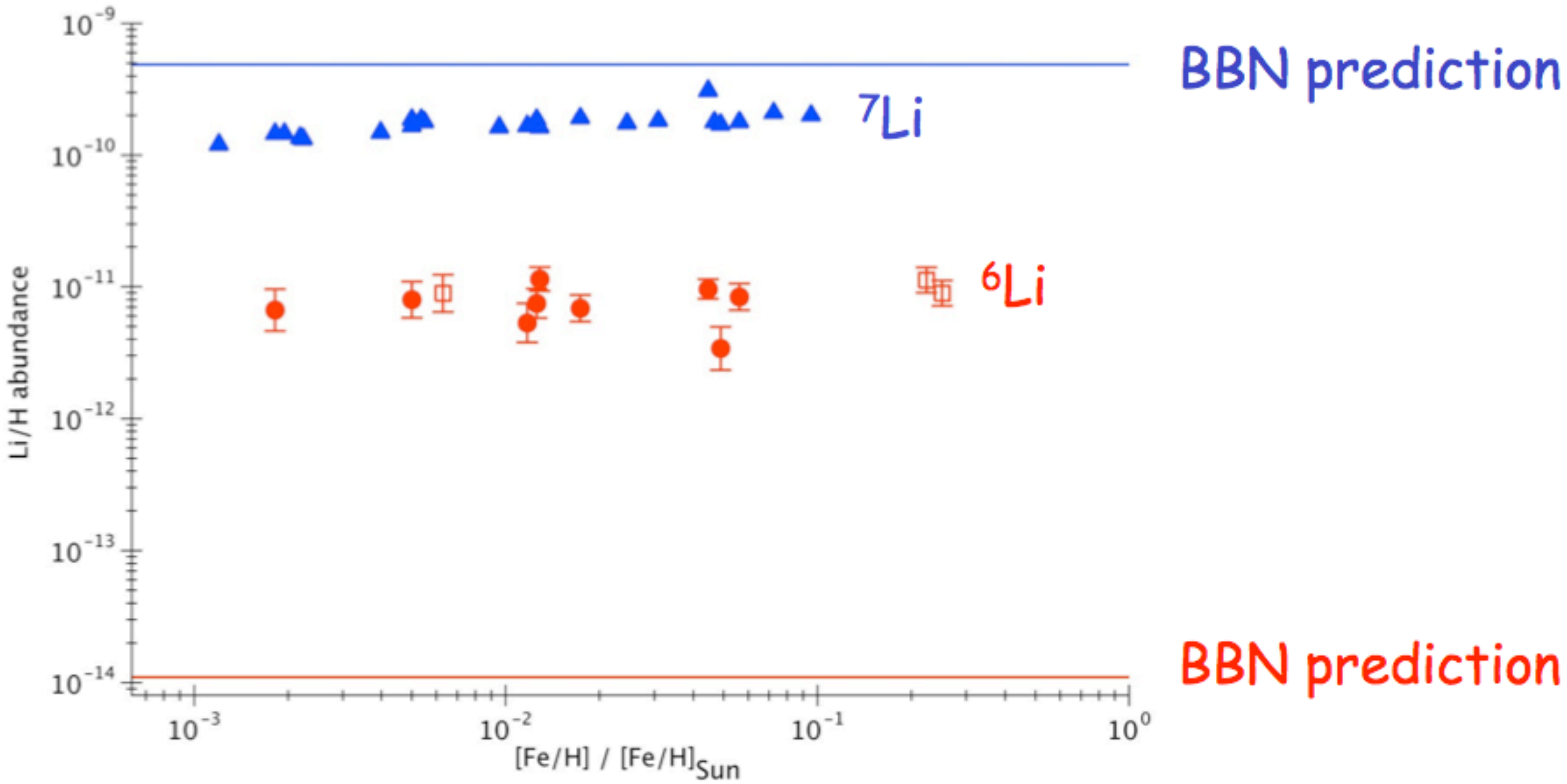


7. ^3H + ^4H → ^7Li + g
8. ^3He + n → ^3H + p
9. ^3He + D → ^4He + p
10. ^3He + ^4He → ^7Be + g
11. ^7Li + p → ^4He + ^4He
12. ^7Be + n → ^7Li + p
13. ^4He + D → ^6Li + g

$^{2}H(\alpha,\gamma)^{6}Li$

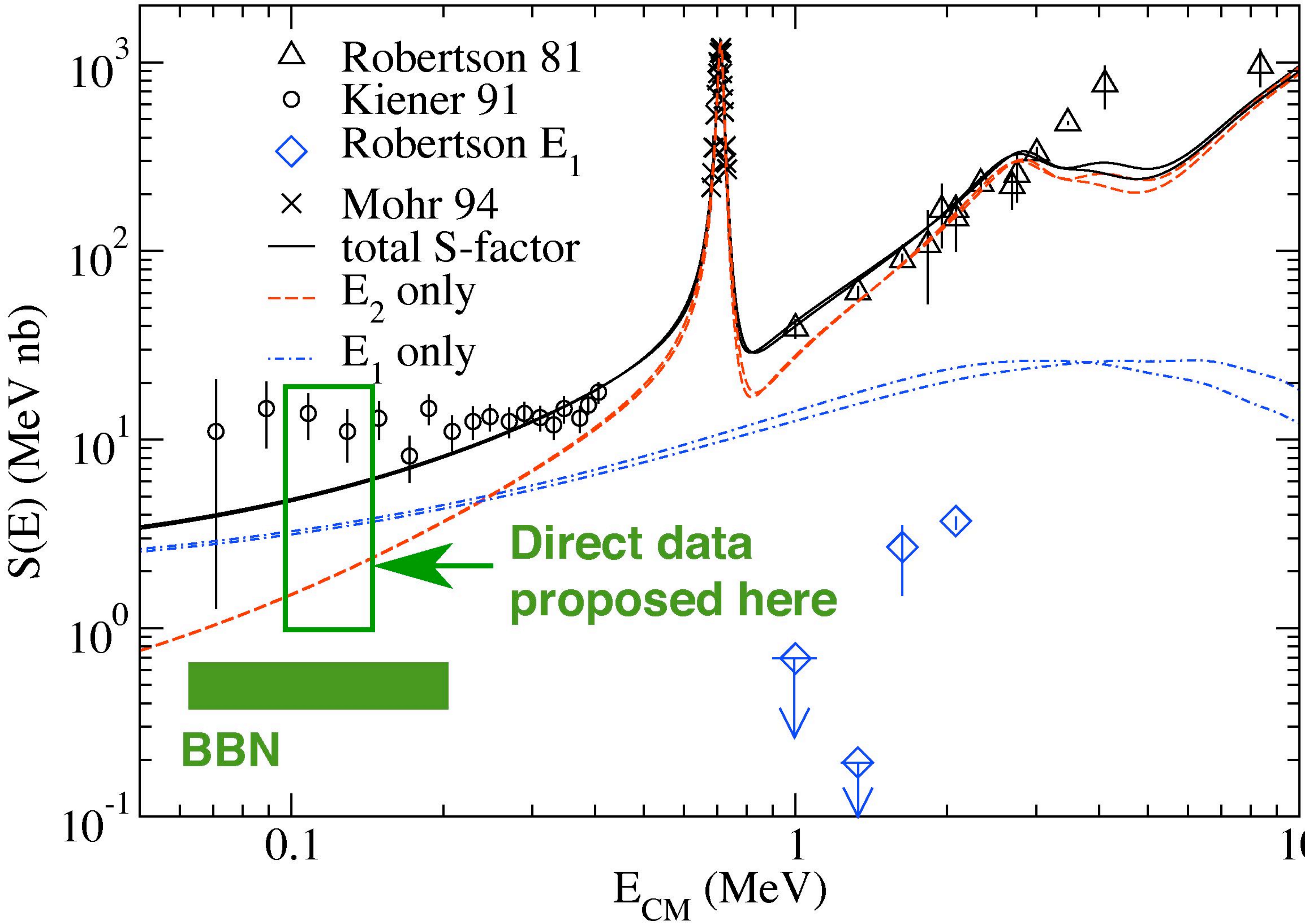
The ^{6}Li case

Constant amount in stars of different metallicity (→age)
2-3 orders of magnitude higher than predicted with the BBN network (NACRE)
(Asplund 2006, now debated since convective motions on the stellar surface can give an asymmetry in the absorption line mimicking the presence of ^{6}Li)

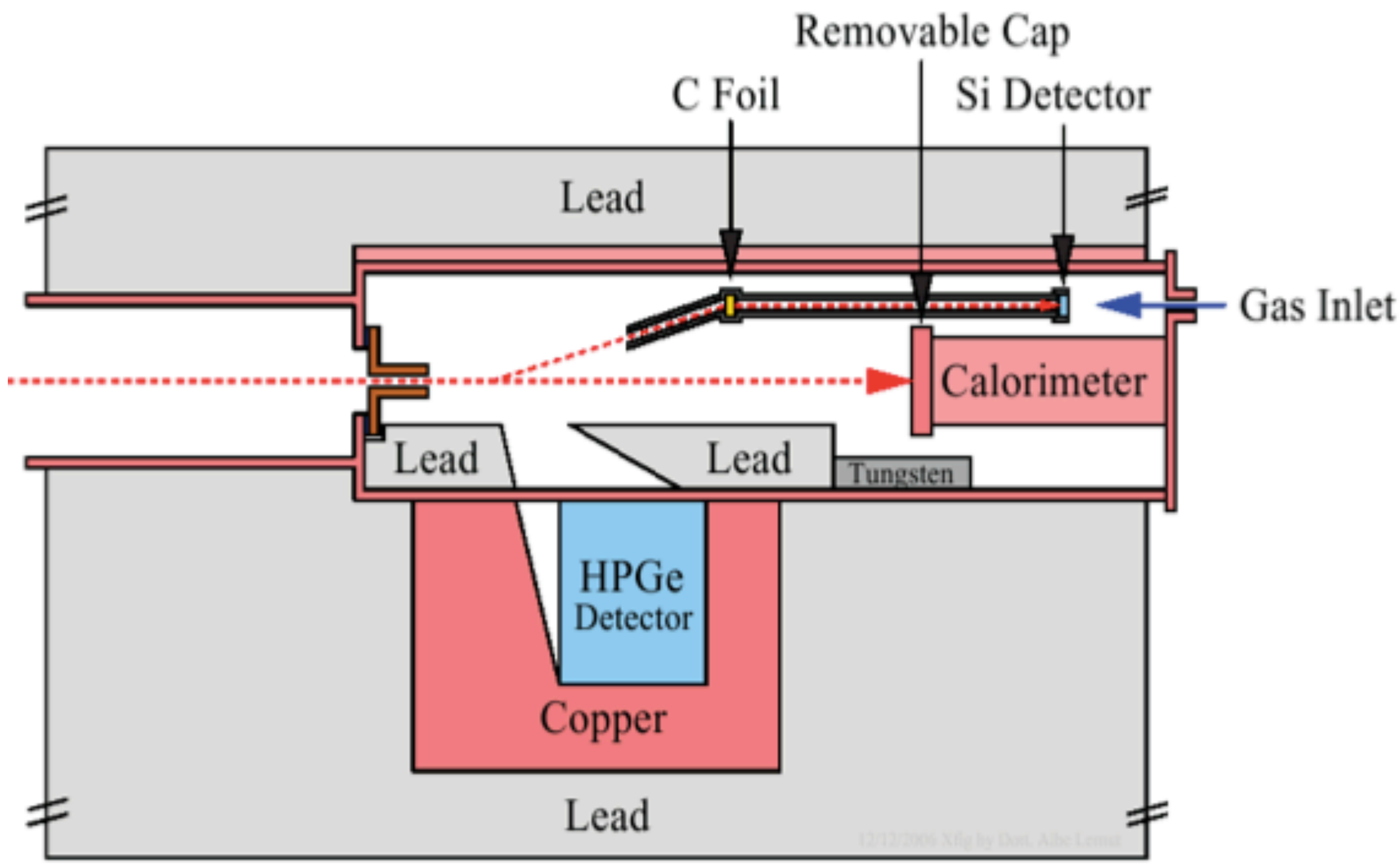


The primordial abundance is determined by:
$^{2}H(\alpha,\gamma)^{6}Li$ producing almost all the ^{6}Li
$^{6}Li(p,\alpha)^{3}He$ destroying ^{6}Li → well known

$^2H(\alpha,\gamma)^6Li$



$^{2}H(\alpha,\gamma)^{6}Li$



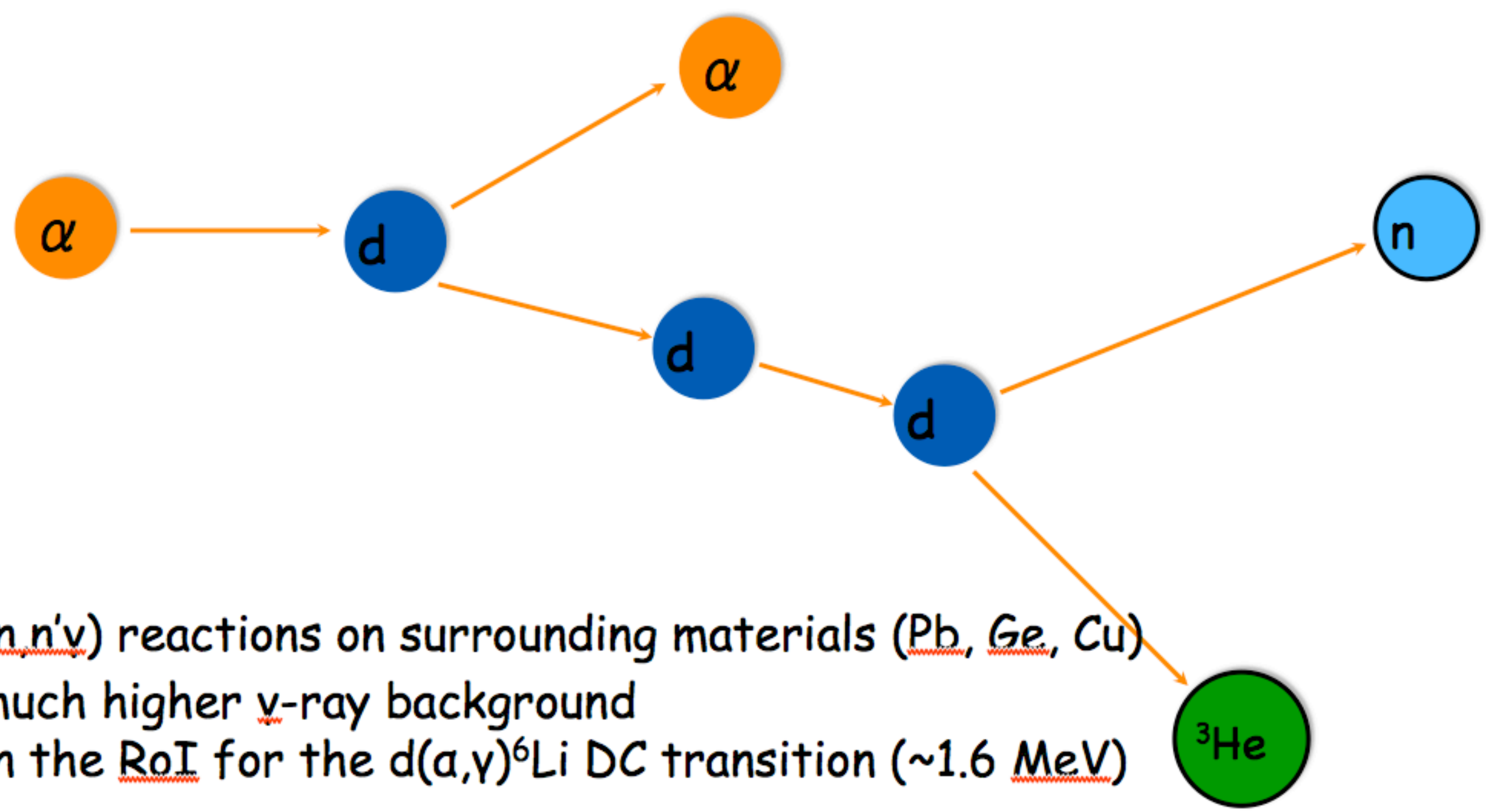
same setup used for $^{3}He\ (^{4}He,\gamma)^{7}Be$ reaction

but....

$^{2}H(\alpha,\gamma)^{6}Li$

The beam-induced background

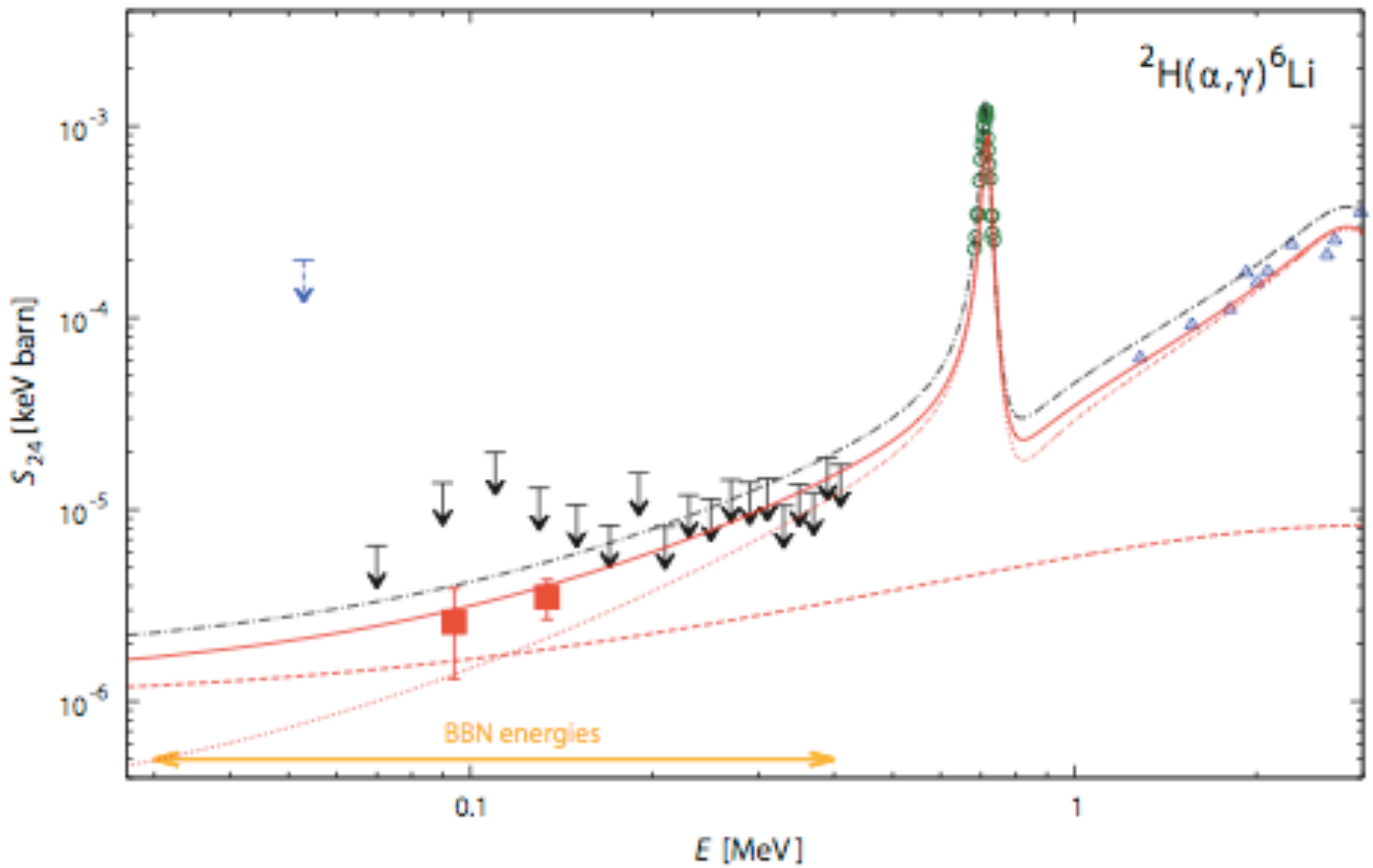
- neutron background generated by d(α,α)d Rutherford scattering followed by $d(d,n)^{3}He$ reactions



-> (n,n'γ) reactions on surrounding materials (Pb, Ge, Cu)

-> much higher γ-ray background in the RoI for the $d(\alpha,\gamma)^{6}Li$ DC transition (~1.6 MeV)

$^2H(\alpha,\gamma)^6Li$



first direct measurement at BBN energies

(σ = 60 pbarn @ E_{cm} = 133 keV)

Shell and explosive hydrogen burning

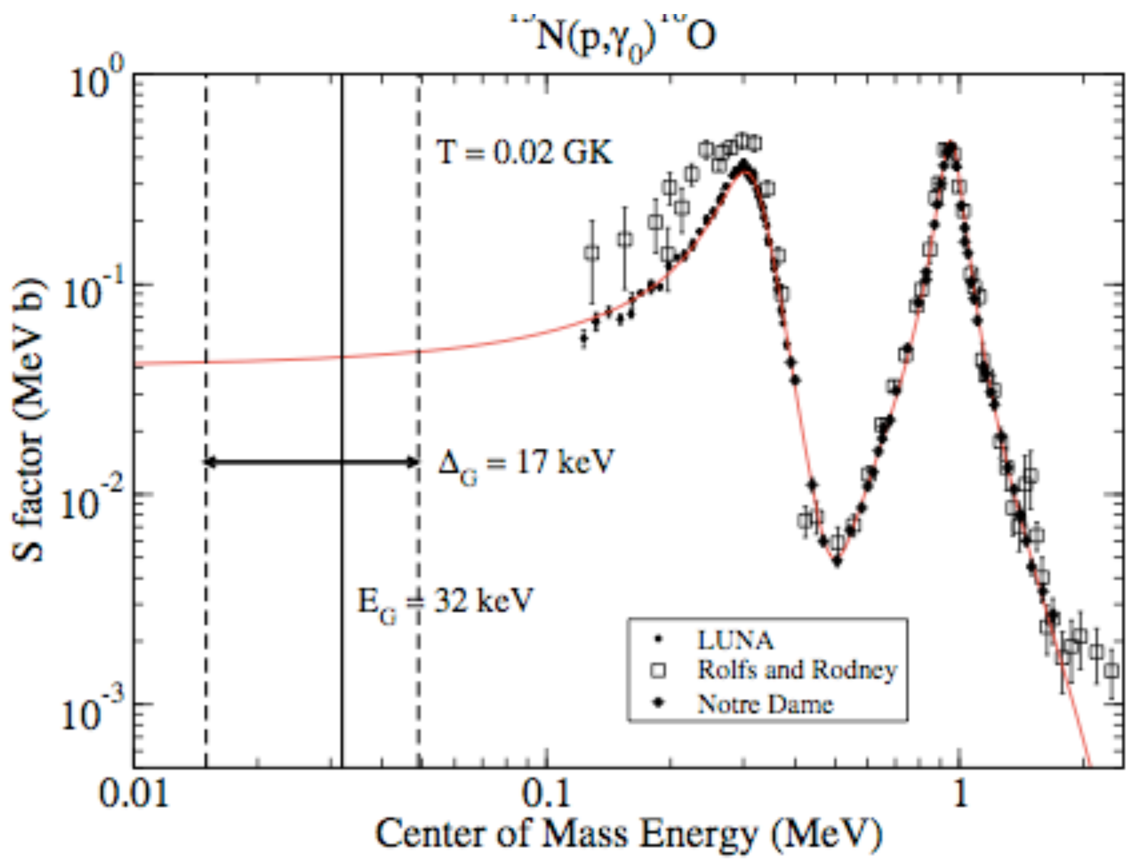
$^{15}N(p,\gamma)^{16}O$

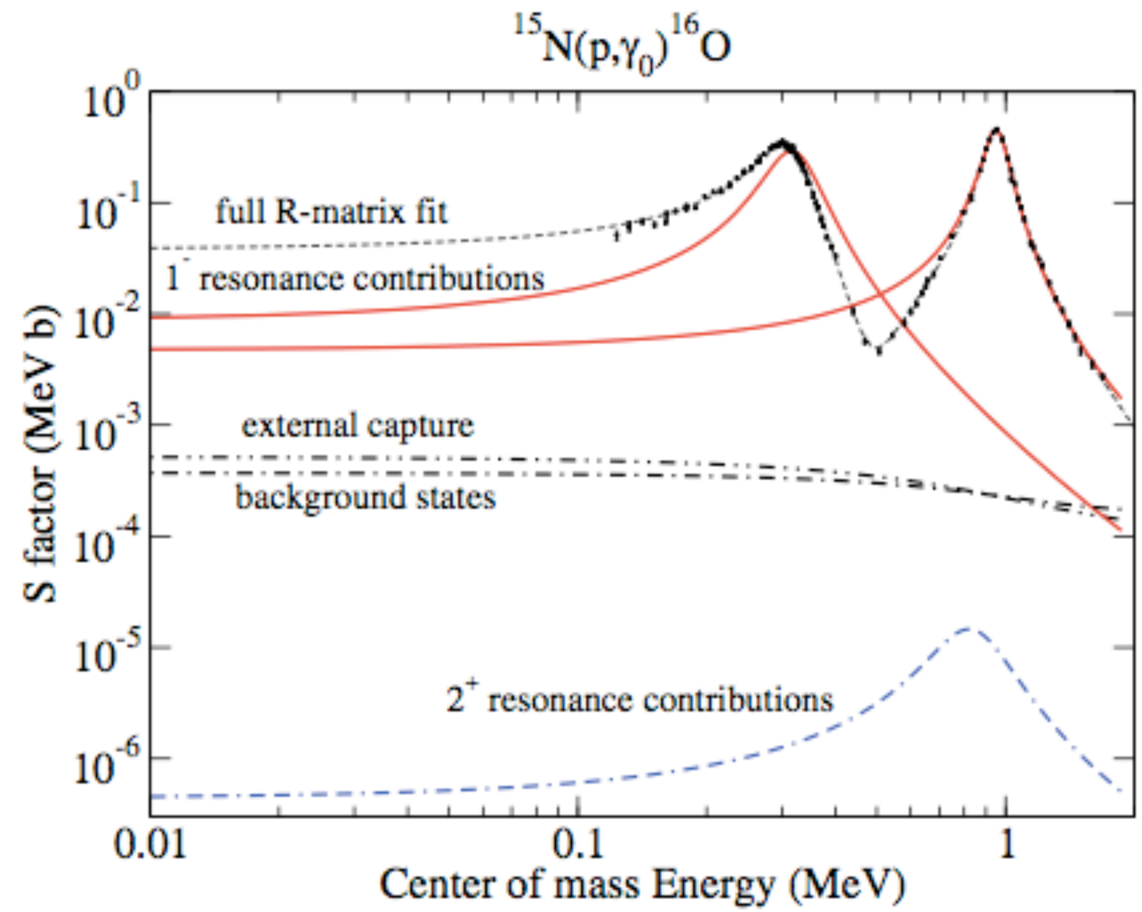
$^{17}O(p,\gamma)^{18}F$

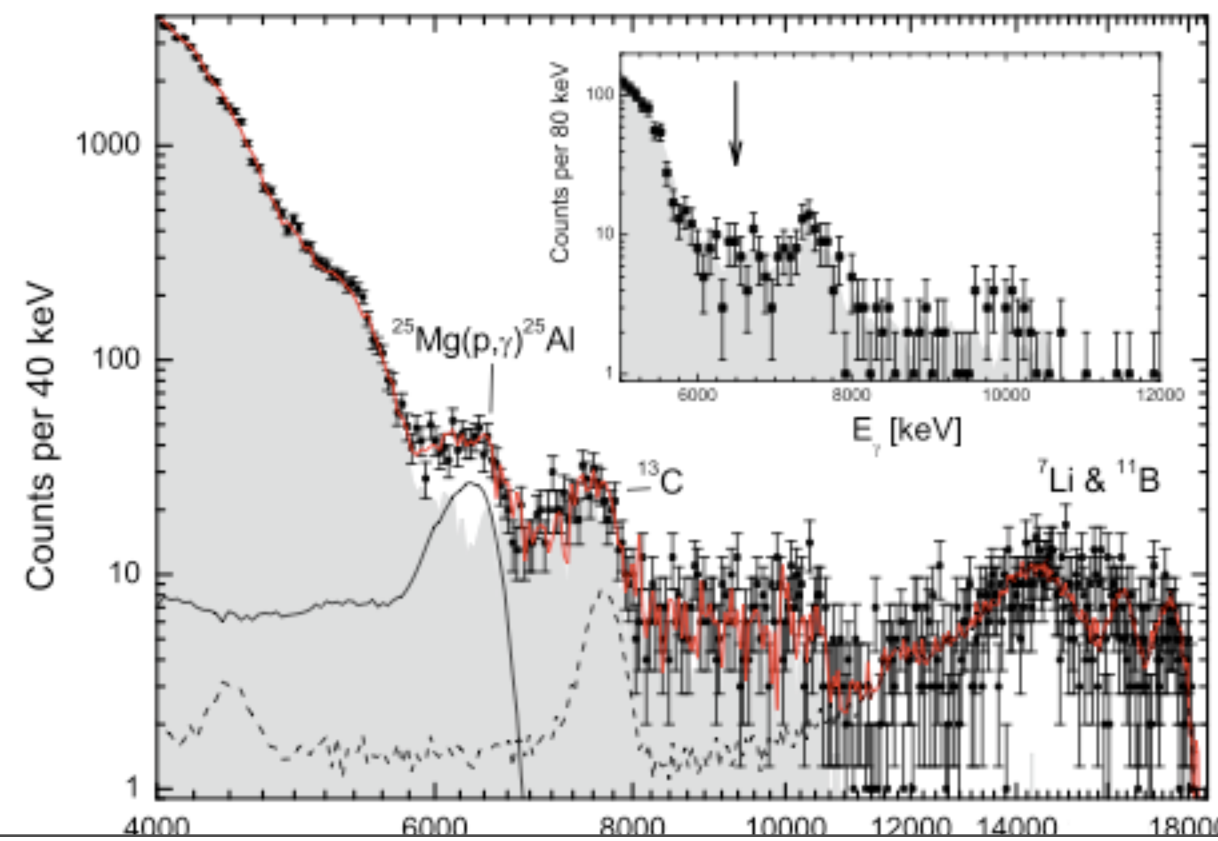
$^{17}O(p,\alpha)^{14}N$

$^{22}Ne(p,\gamma)^{23}Na$

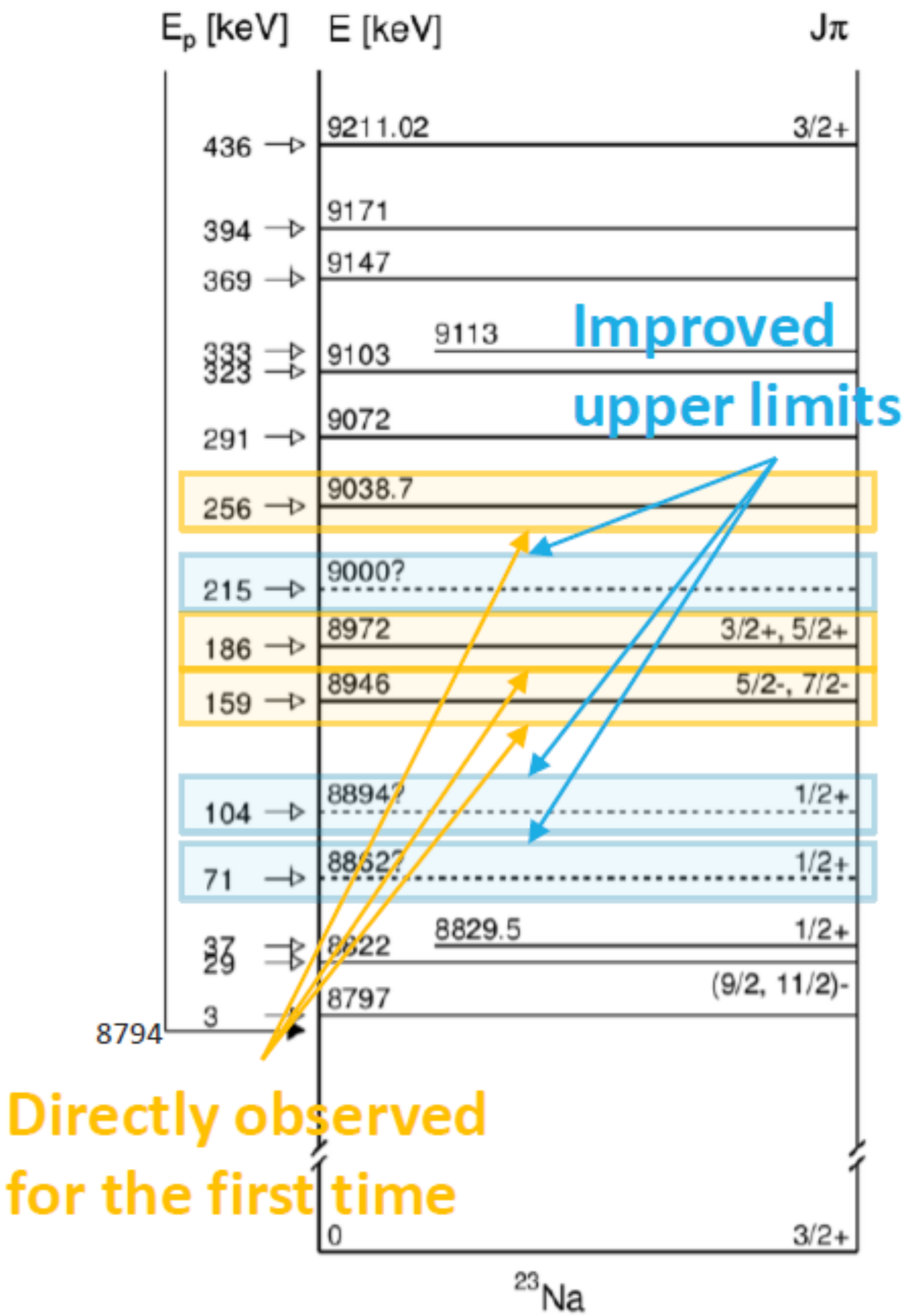
$^{25}Mg(p,\gamma)^{26}Al$

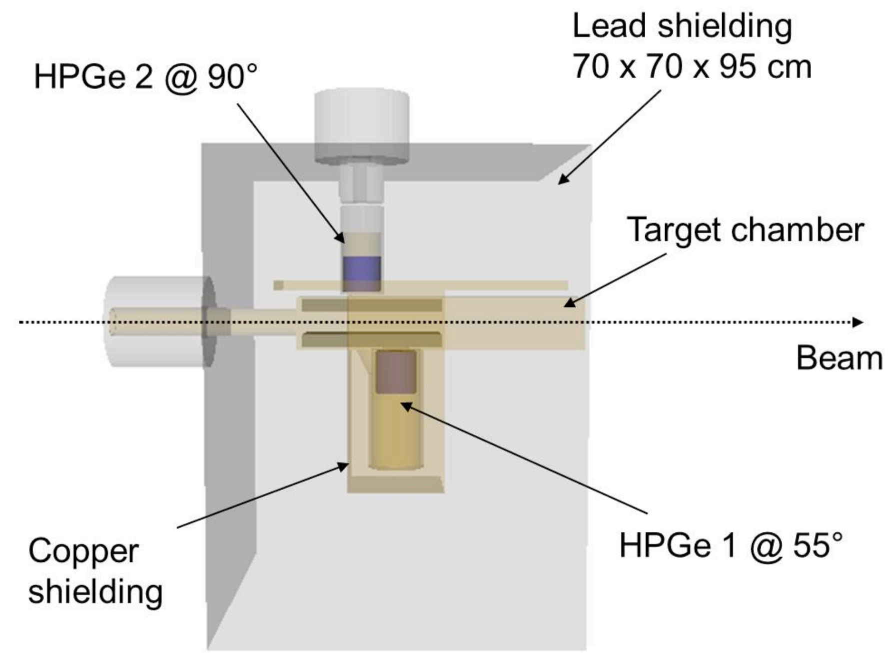

N(p,γ0)O
T = 0.02 GK
ΔG = 17 keV
EG = 32 keV
LUNA
Rolfs and Rodney
Notre Dame
S factor (MeV b)
Center of Mass Energy (MeV)


15N(p,γ0)16O
full R-matrix fit
1- resonance contributions
external capture
background states
2+ resonance contributions
S factor (MeV b)
Center of mass Energy (MeV)


25Mg(p,γ)25Al
13C
7Li & 11B
Counts per 40 keV
Counts per 80 keV
Eγ [keV]

$^{22}Ne(p,\gamma)^{23}Na$ (HPGe results)





3 resonances observed for the first time

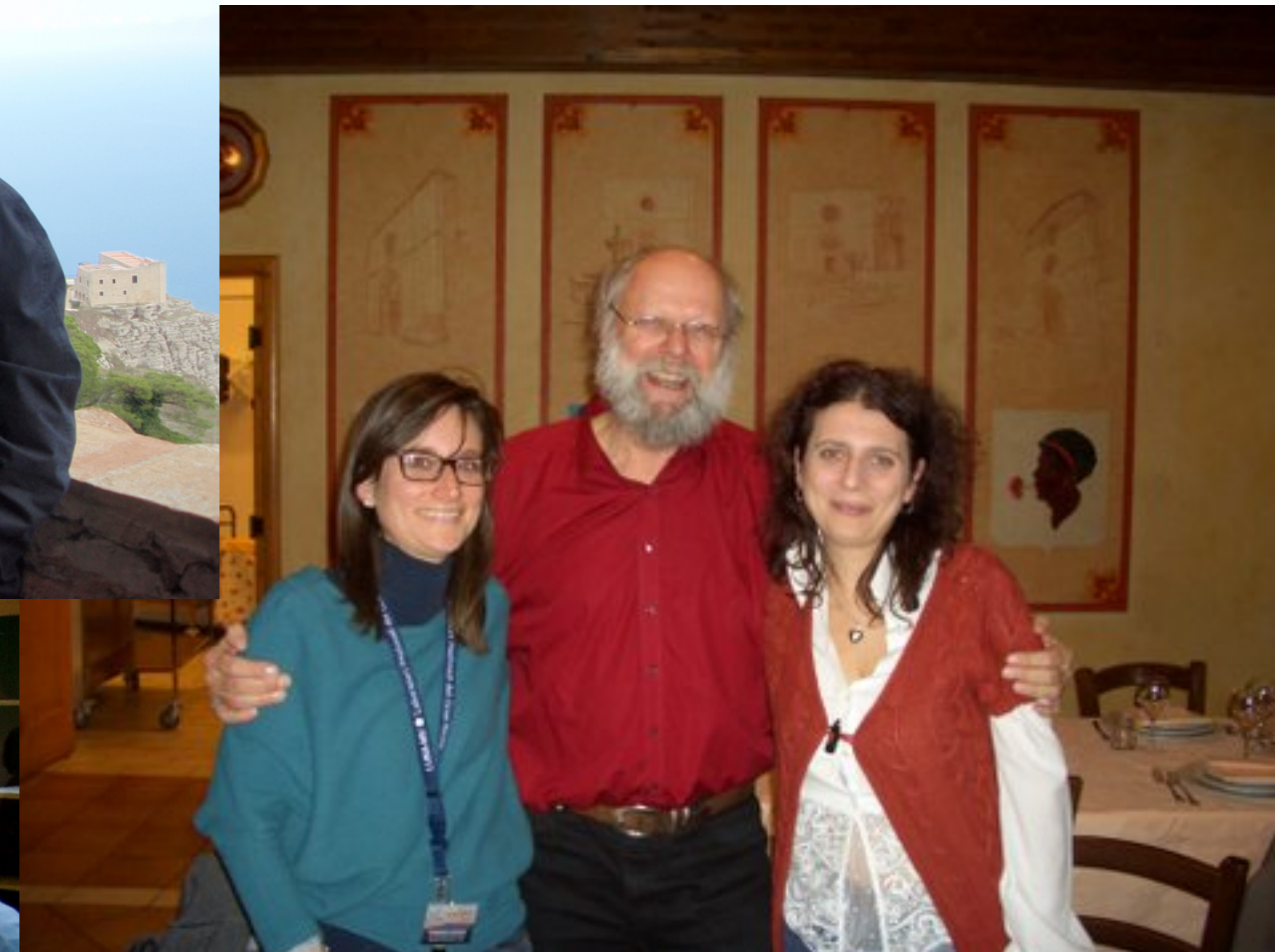
new upper limits are two order of magnitude lower

F. Cavanna et al., First observation of low-energy resonances in the $^{22}Ne(p,\gamma)^{23}Na$ reaction, PRL, 115 (2015)

from Matthias Junker

LUNA

from Marialuisa Aliotta



from Marialuisa Aliotta

LUNA

from Hanns Peter..

Thanks to all for
these wonderful 25 years !!

Enjoy the next 25 !!


"That's all Folks!"