Laboratory
Underground
Nuclear
Astrophysics

The LUNA project

an underground facility for the study of nuclear reactions of astrophysical interest

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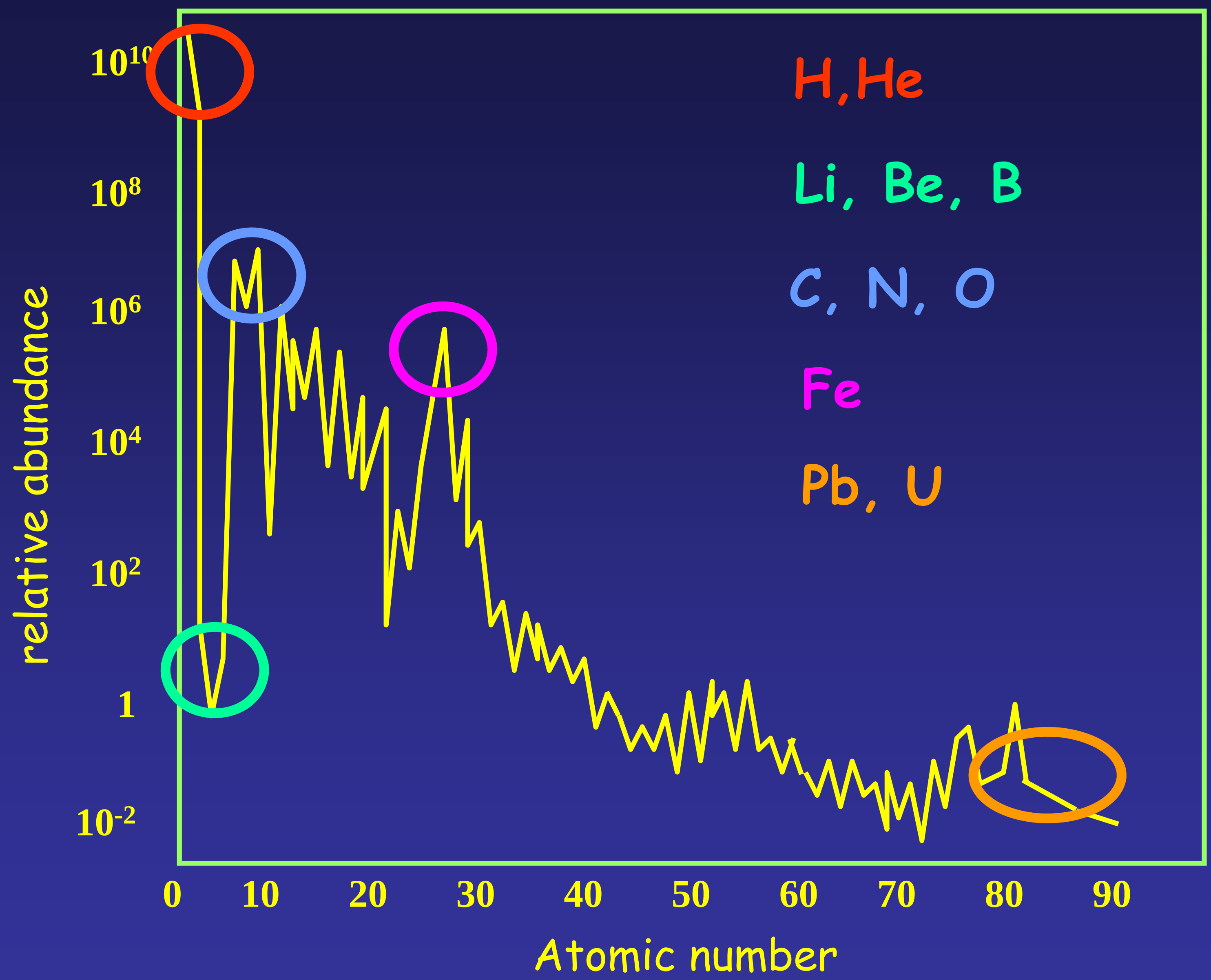
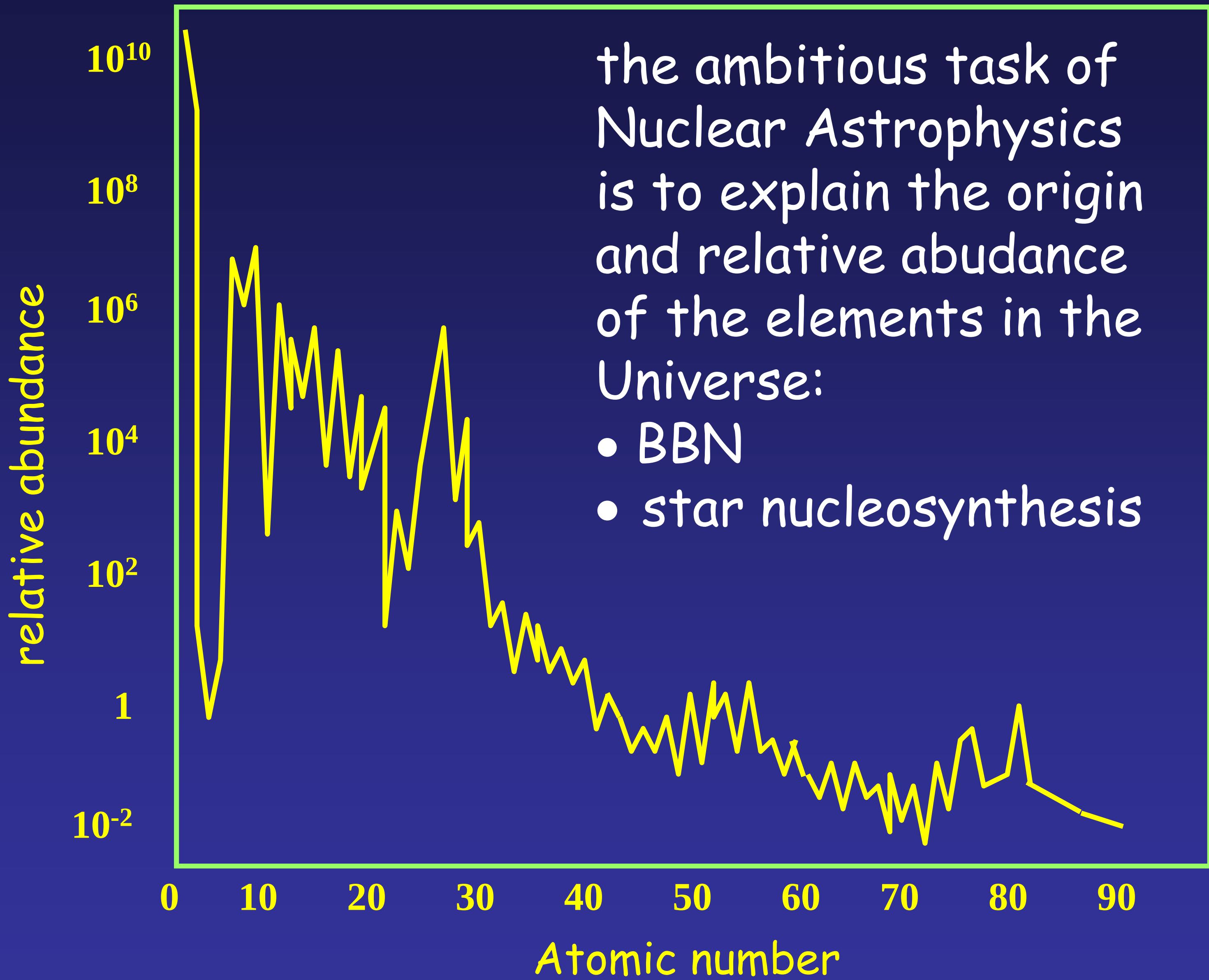
the abundance of the elements in the Universe



elements are produced inside stars during their life

the abundance of the elements in the Universe



elements are produced inside stars during their life

known Universe

- consists of $\approx 10^{10} \div 10^{11}$ §
- each of them contains $\approx 10^{10} \div 10^{11}$ ★
- there are $\approx 10^{21}$ ★
- very different in mass, size, luminosity, density

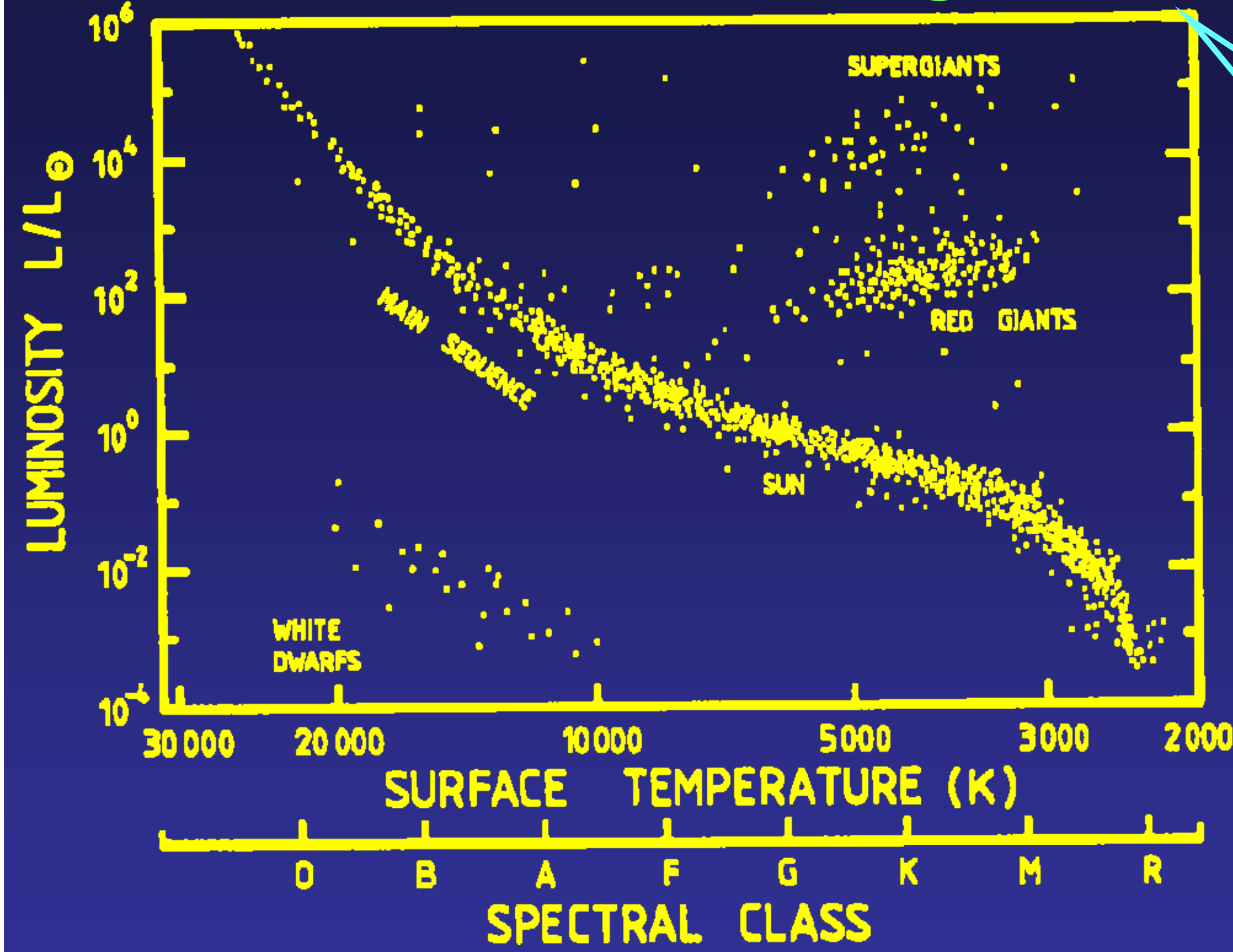
$$\begin{cases} 10^{-4} < L/L_\odot < 10^{4} \\ 10^{-1} < M/M_\odot < 10^{2} \\ 10^{-2} < r/r_\odot < 10^{3} \\ 10^{-6} < \rho/\rho_\odot < 10^{4} \end{cases}$$

$M_\odot = 2 \cdot 10^{33}$ g
$R_\odot = 1.39 \cdot 10^{11}$ cm
$\rho_\odot = 1.4$ g/cm^3
$T_\odot = 5.800$ K
$L_\odot = 3.83 \cdot 10^{33}$ erg/s

Are they randomly distributed ?

Are they governed by some general laws ?

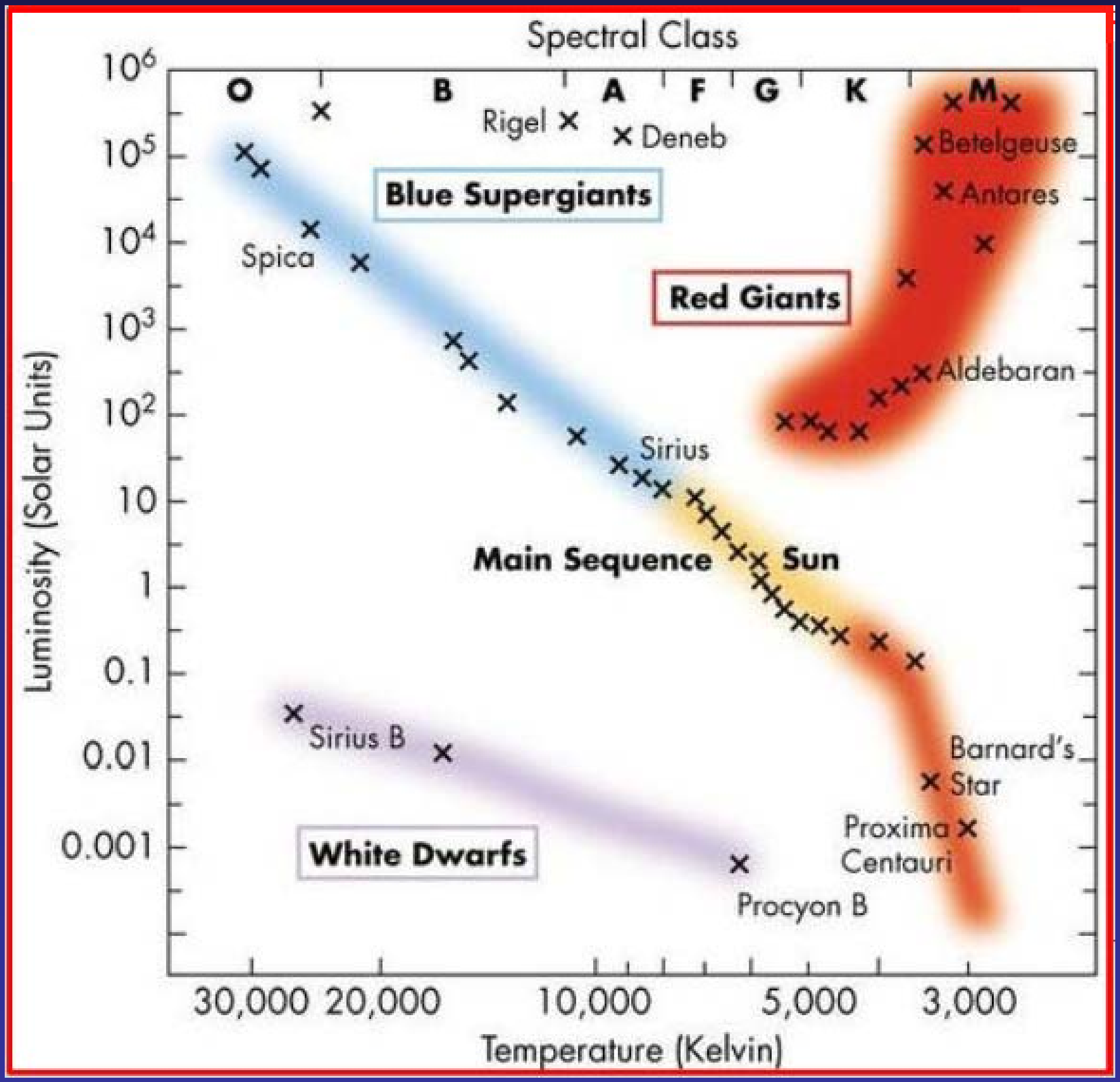
HR diagram

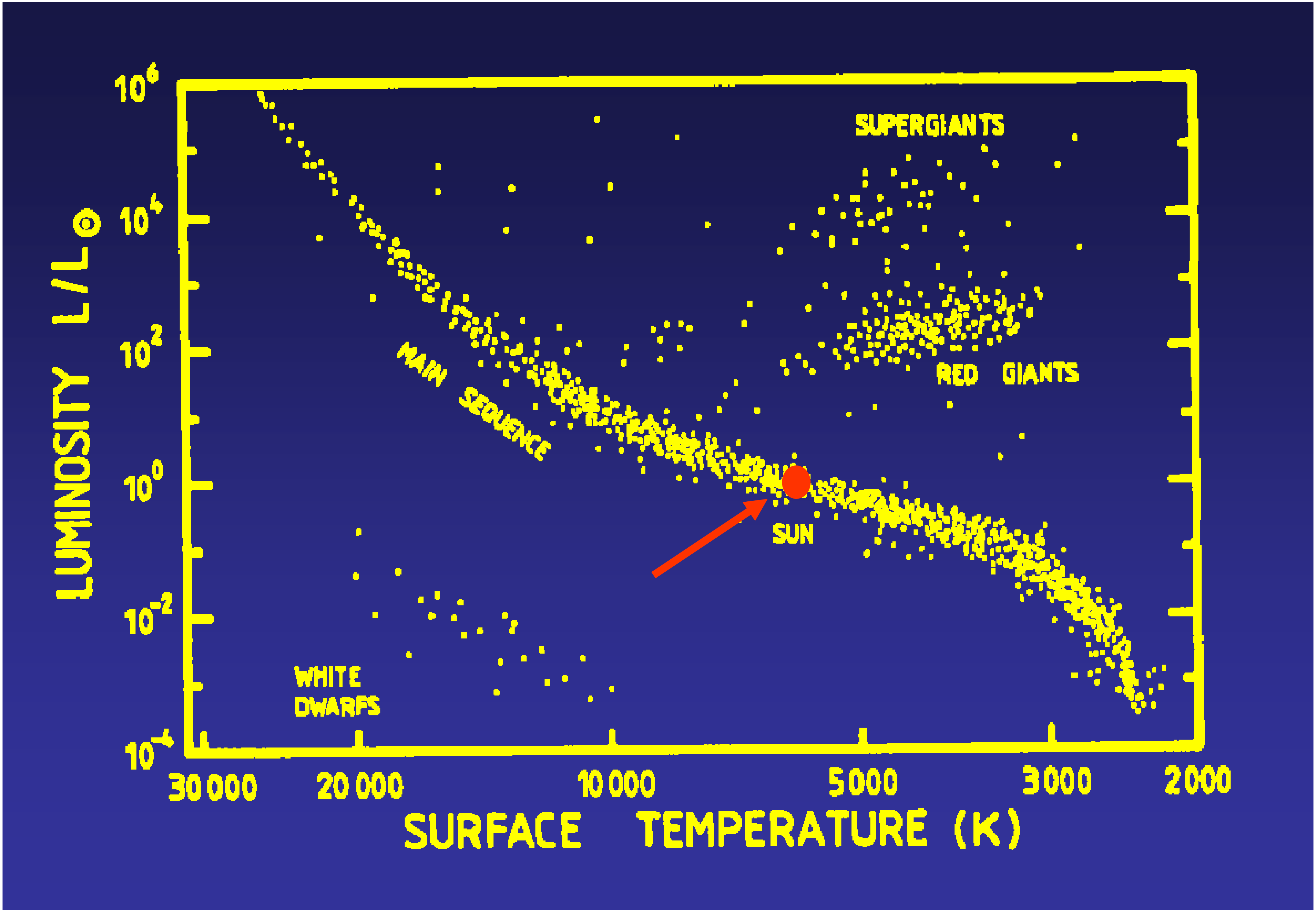


star evolution
is governed
by physical laws

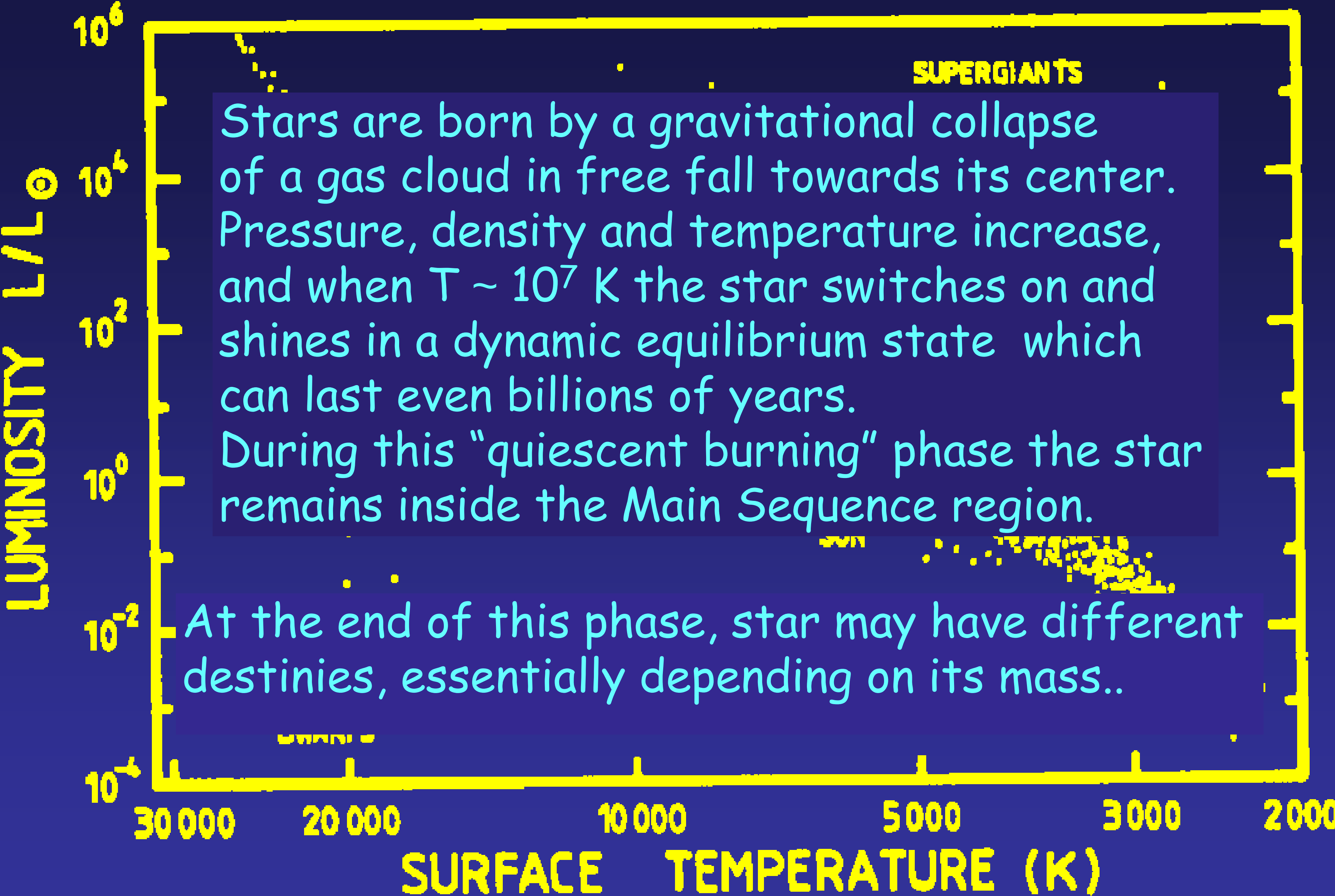
nuclear reactions are responsible
for birth, life and death of the stars

some known stars…





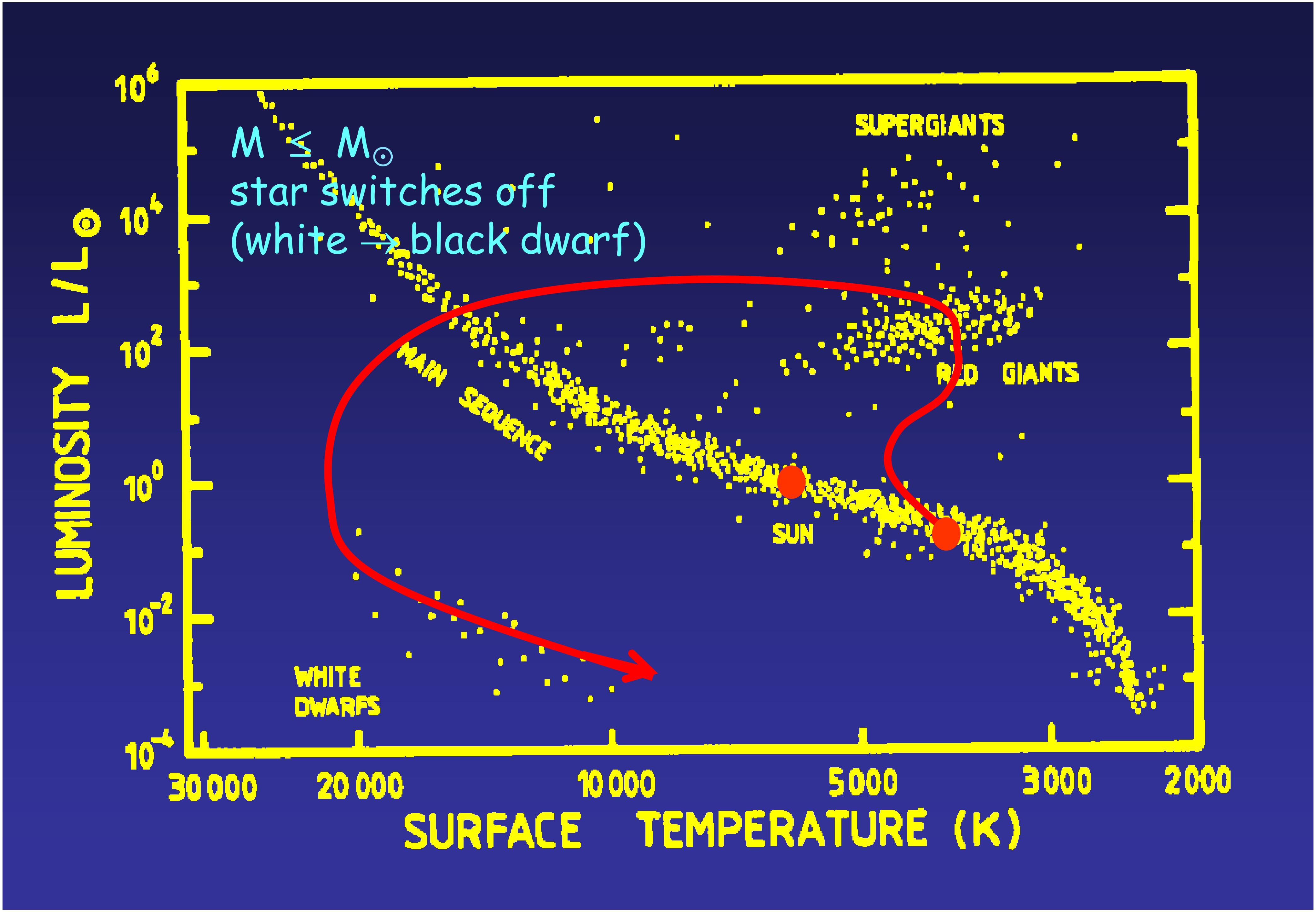
LUMINOSITY L/L⊙
10^6
10^4
10^2
10^0
10^-2
10^-4
SUPERGIANTS
RED GIANTS
MAIN SEQUENCE
SUN
WHITE DWARFS
30 000
20 000
10 000
5000
3000
2000
SURFACE TEMPERATURE (K)



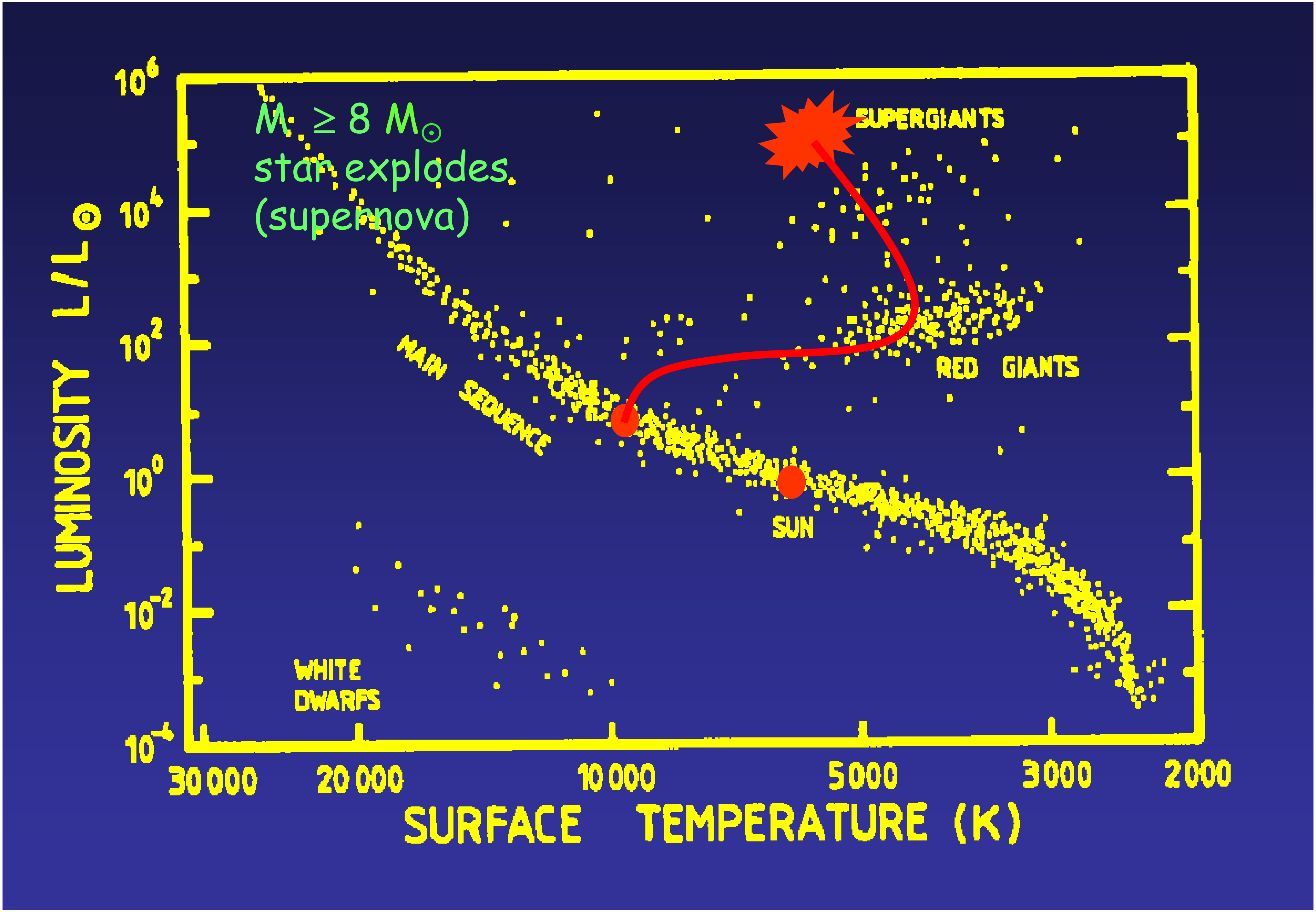
Stars are born by a gravitational collapse of a gas cloud in free fall towards its center. Pressure, density and temperature increase, and when T ~ 10^7 K the star switches on and shines in a dynamic equilibrium state which can last even billions of years.

During this "quiescent burning" phase the star remains inside the Main Sequence region.

At the end of this phase, star may have different destinies, essentially depending on its mass..

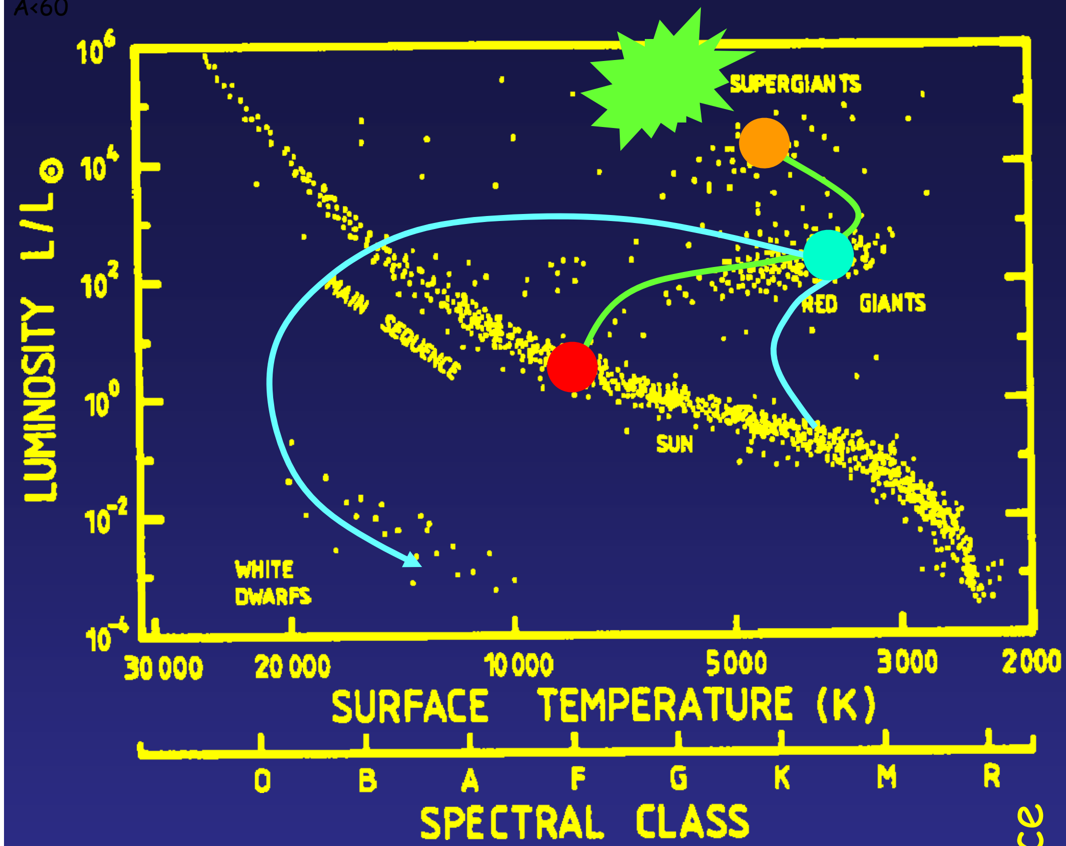


M ≲ M⊙
star switches off
(white → black dwarf)
SUPERGIANTS
RED GIANTS
MAIN SEQUENCE
SUN
WHITE DWARFS
LUMINOSITY L/L⊙
10^6
10^4
10^2
10^0
10^-2
10^-4
30 000
20 000
10 000
5000
3000
2000
SURFACE TEMPERATURE (K)



M ≥ 8 M⊙
star explodes
(supernova)
SUPERGIANTS
RED GIANTS
MAIN SEQUENCE
SUN
WHITE DWARFS
LUMINOSITY L/L⊙
10^6
10^4
10^2
10^0
10^-2
10^-4
30 000
20 000
10 000
5000
3000
2000
SURFACE TEMPERATURE (K)

A<60



M < 8 M¤
star switches off
(white → black dwarf)

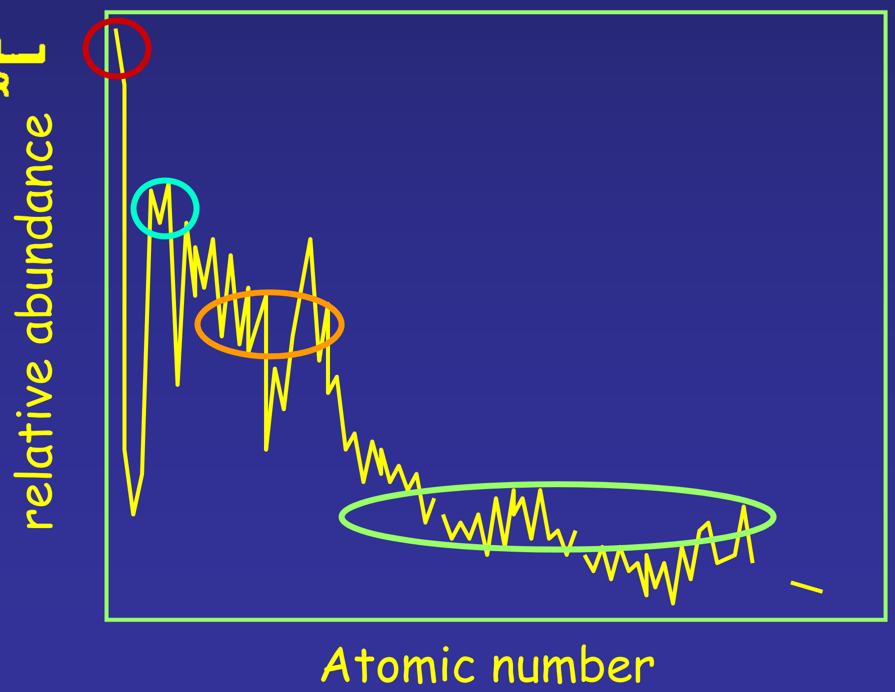
M > 8 M¤
star explodes
(supernova)

H burning → He

He burning → C, O, Ne

C/O … Si burning → Fe

explosive burning



Hydrogen burning

produces energy for most of the life of the star

pp chain

$p + p \rightarrow d + e^+ + \nu_e$

$d + p \rightarrow {}^3He + \gamma$

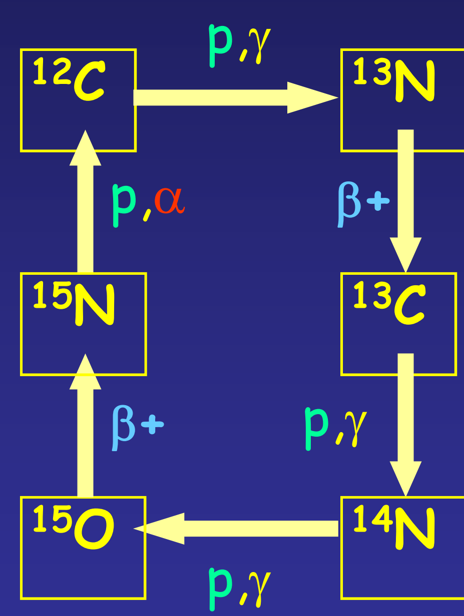
84.7 %: $^3He + {}^3He \rightarrow \alpha + 2p$

13.8 %: $^3He + {}^4He \rightarrow {}^7Be + \gamma$

13.78 %: $^7Be + e^- \rightarrow {}^7Li + \gamma + \nu_e$, then $^7Li + p \rightarrow \alpha + \alpha$

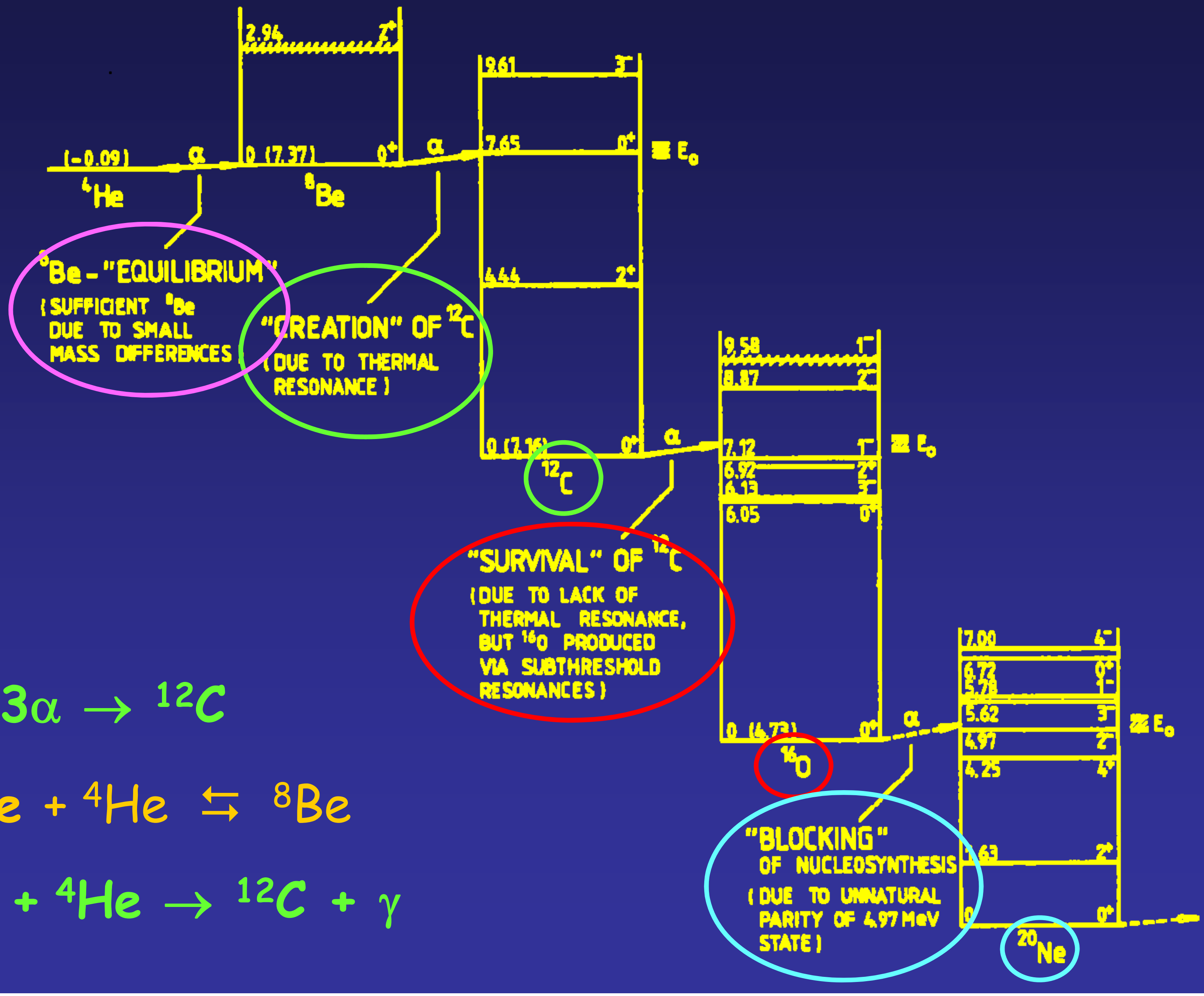
0.02 %: $^7Be + p \rightarrow {}^8B + \gamma$, then $^8B \rightarrow 2\alpha + e^+ + \nu_e$

CNO cycle



$$4p \rightarrow {}^4He + 2e^+ + 2\nu_e + 26.73\ MeV$$

He burning   nucleosynthesis of the elements of life..

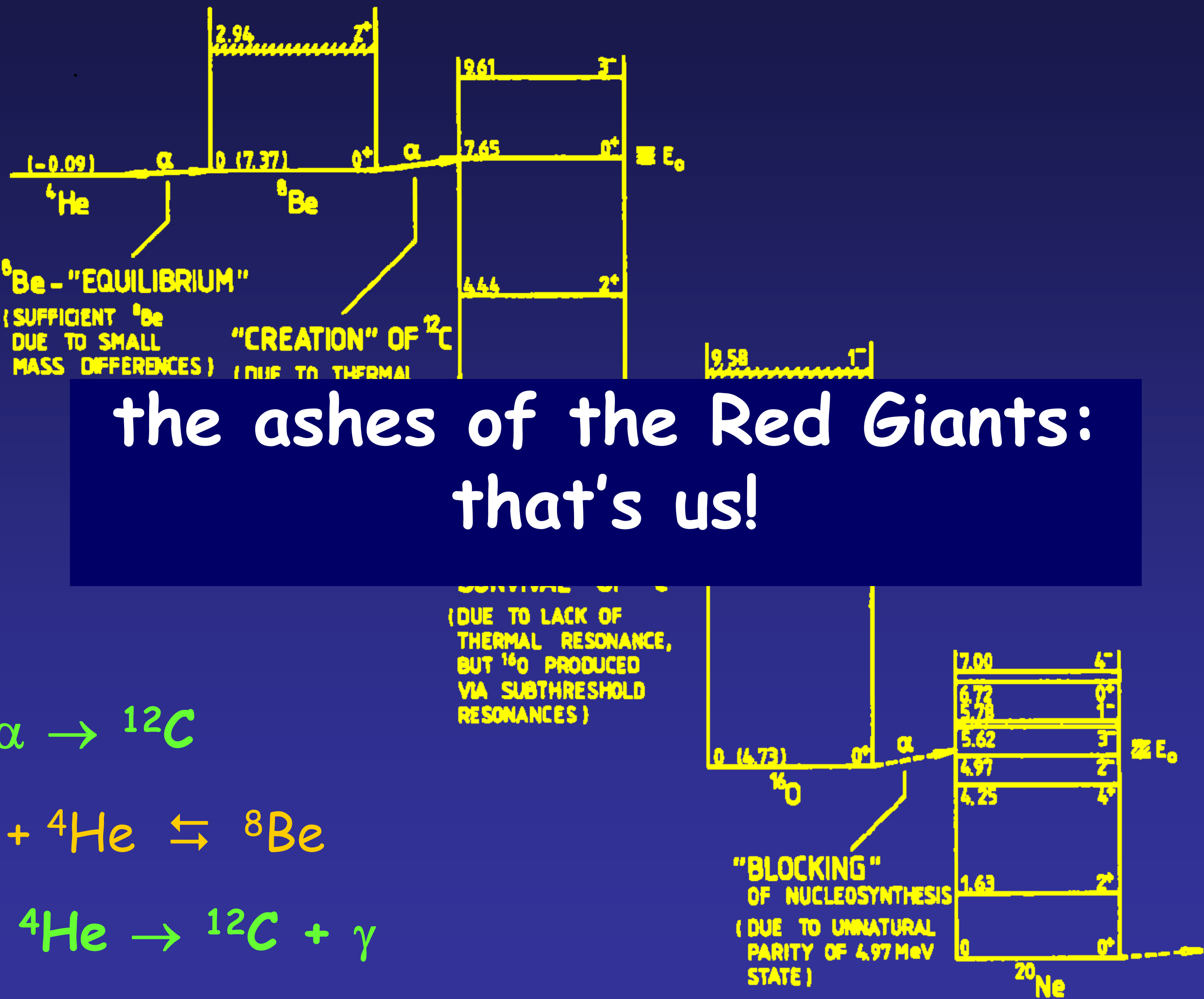


$3\alpha \rightarrow {}^{12}C$

${}^{4}He + {}^{4}He \leftrightarrows {}^{8}Be$

${}^{8}Be + {}^{4}He \rightarrow {}^{12}C + \gamma$

He burning   nucleosynthesis of the elements of life..

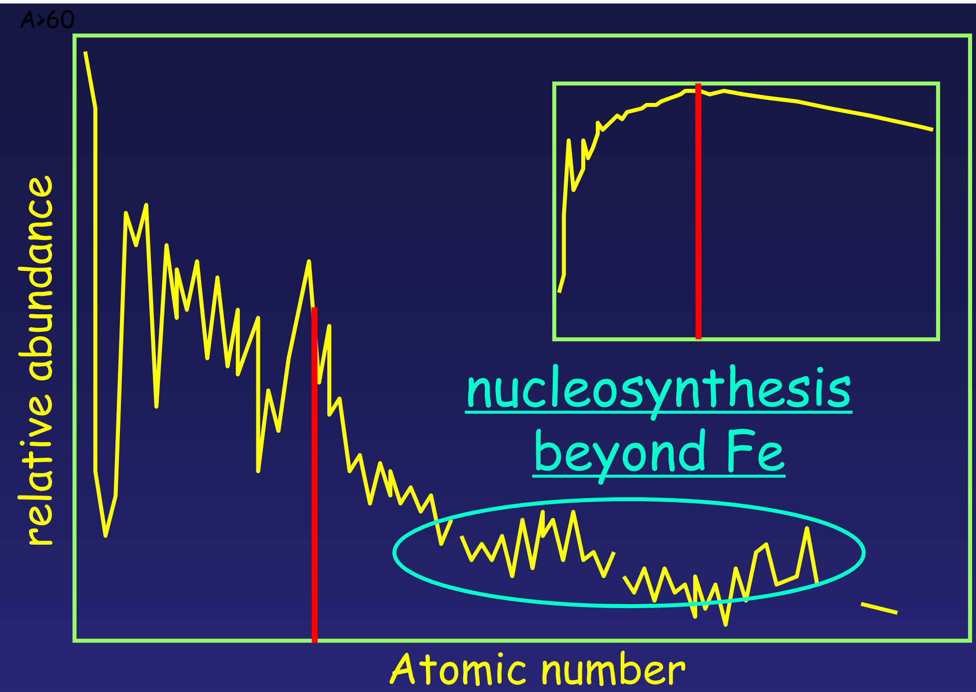


the ashes of the Red Giants: that's us!

$3\alpha \rightarrow {}^{12}C$

${}^{4}He + {}^{4}He \leftrightarrows {}^{8}Be$

${}^{8}Be + {}^{4}He \rightarrow {}^{12}C + \gamma$



neutron (α,n) production:

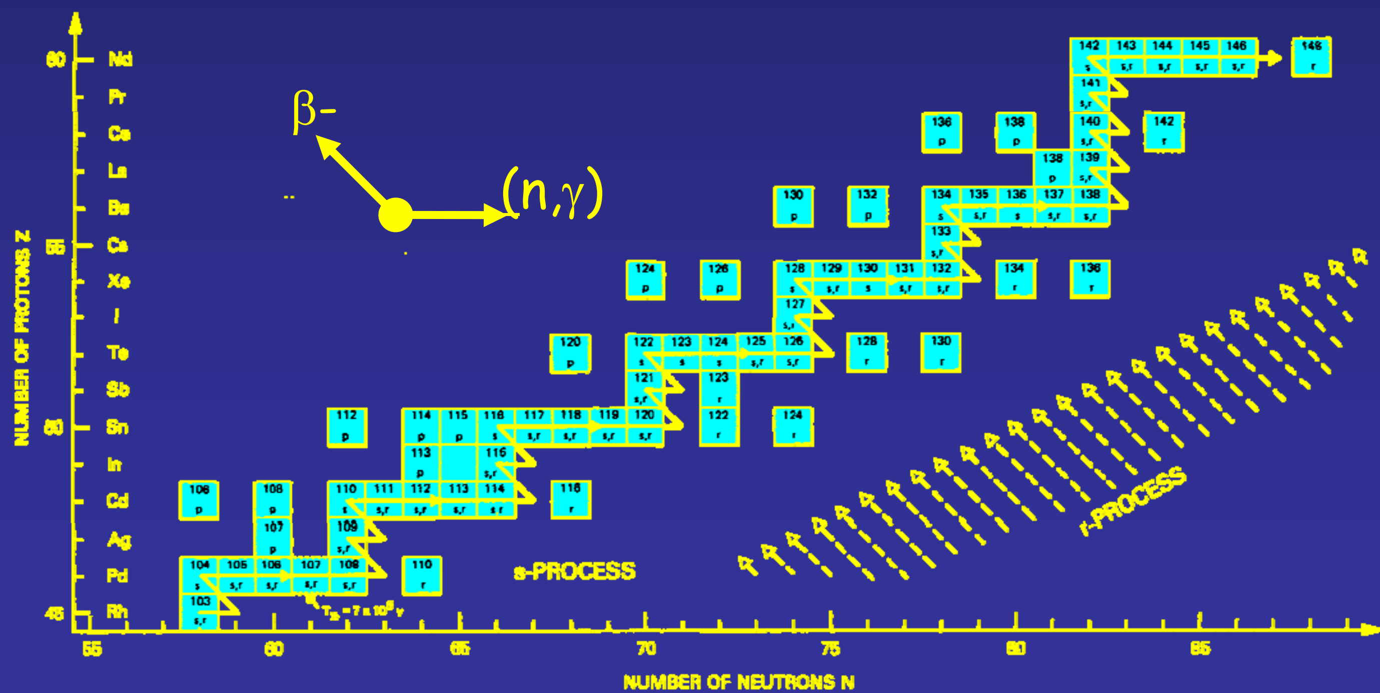
$^{13}C(\alpha,n)^{16}O$

$^{18}O(\alpha,n)^{21}Ne$

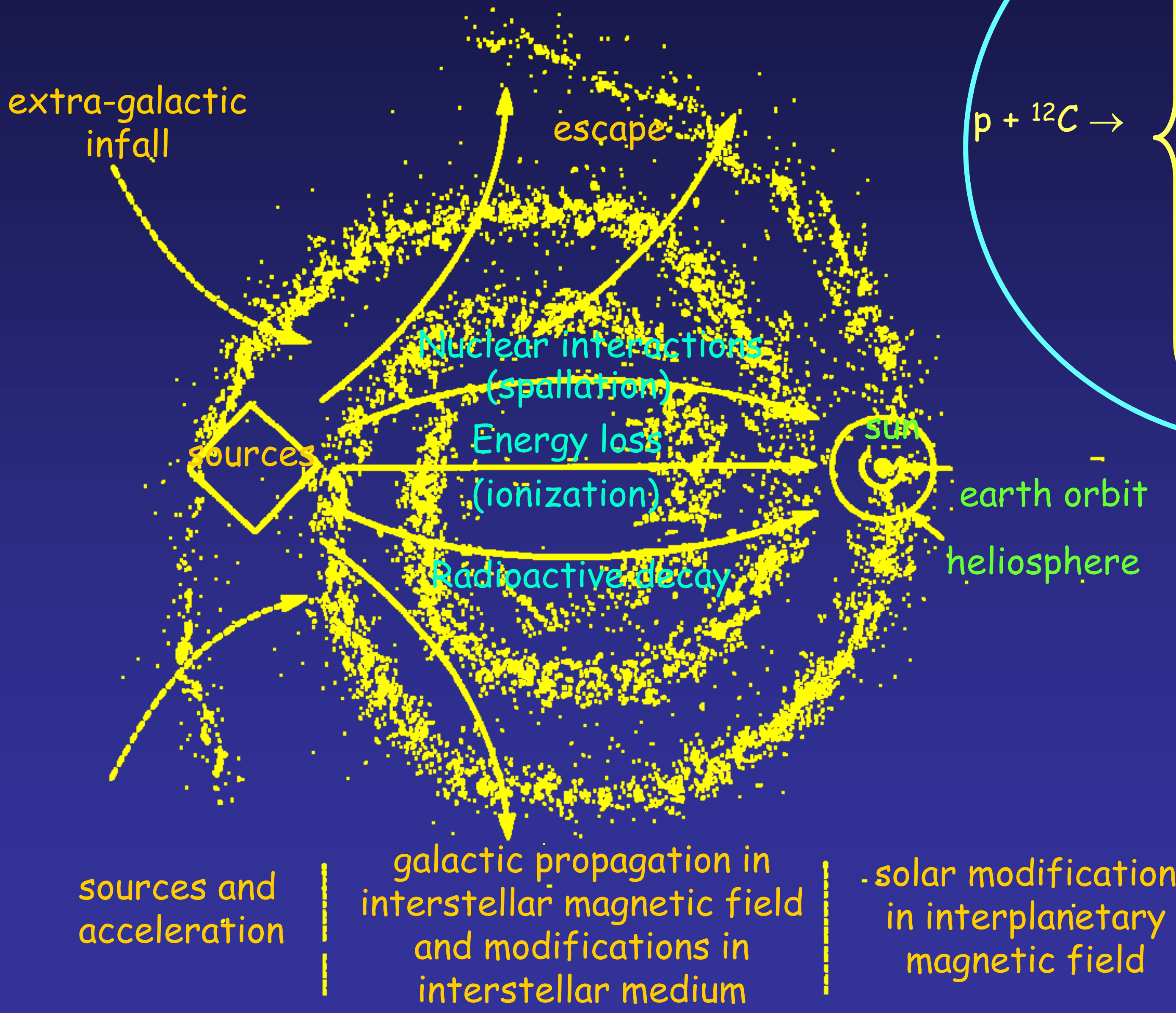
$^{22}Ne(\alpha,n)^{25}Mg$

$$^{A}X_{Z} + n \rightarrow {}^{A+1}X_{Z} + \gamma$$

$$^{A+1}X_{Z} \rightarrow {}^{A+1}Y_{Z+1} + \beta^{-} + \nu$$

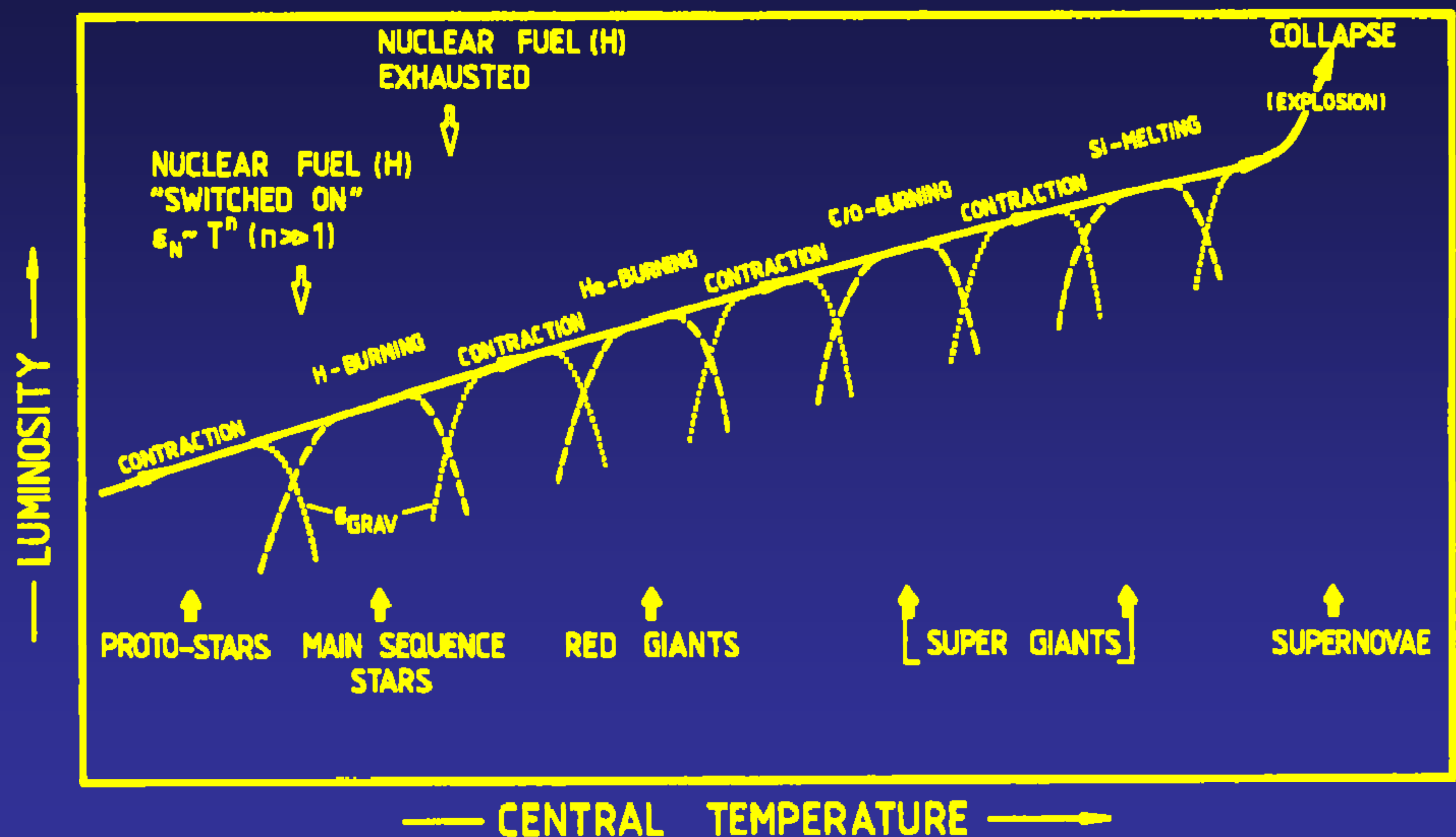


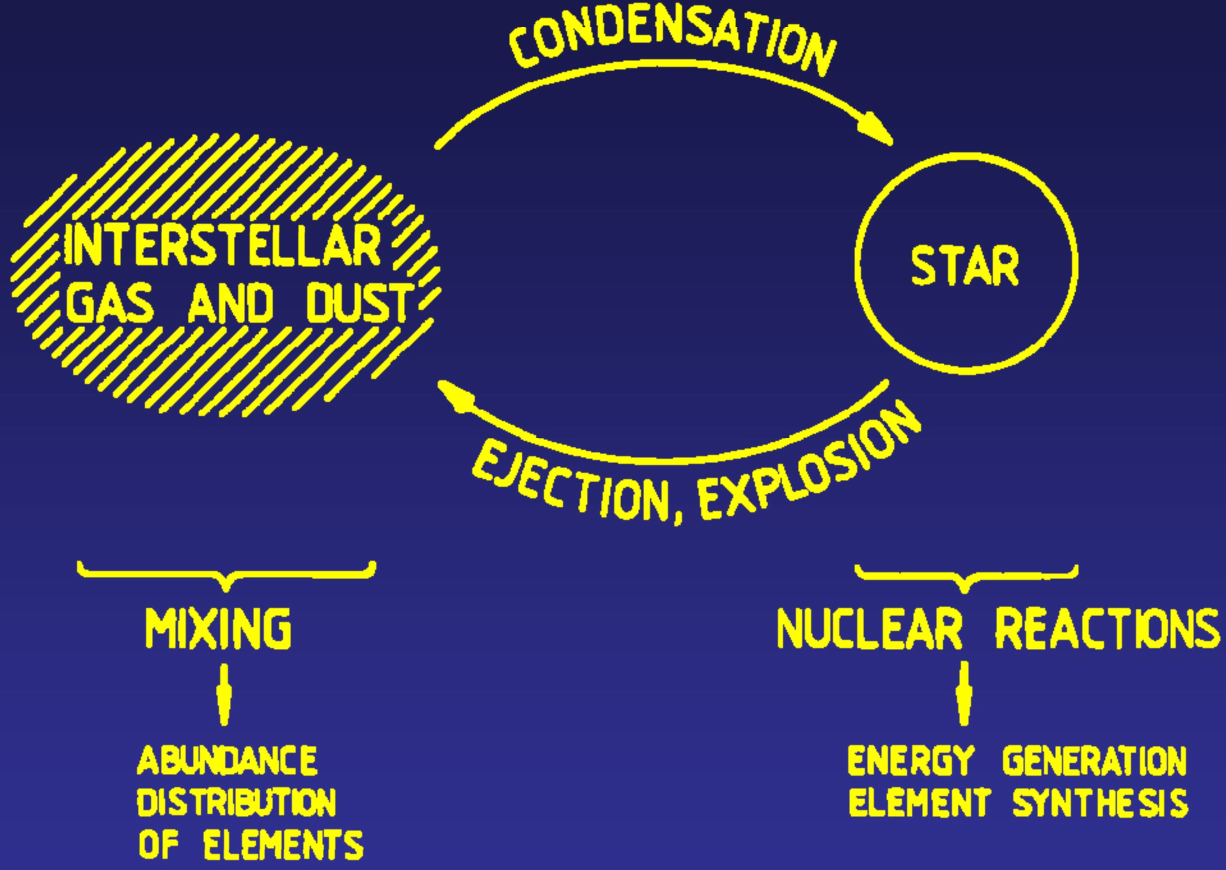
why do Li, Be, B exist ?



$p + {}^{12}C \rightarrow$
- ${}^{11}B + 2p$
- ${}^{10}B + 2p + n$
- ${}^{10}B + {}^{3}He$
- ${}^{9}Be + 3p + n$
- ${}^{9}Be + {}^{3}He + p$
- ${}^{7}Li + 4p + 2n$
- ${}^{7}Li + {}^{4}He + 2p$
- ${}^{6}Li + 4p + 3n$
- ${}^{6}Li + {}^{4}He + 2p + n$
- ${}^{6}Li + {}^{4}He + {}^{3}He$

the life of massive stars





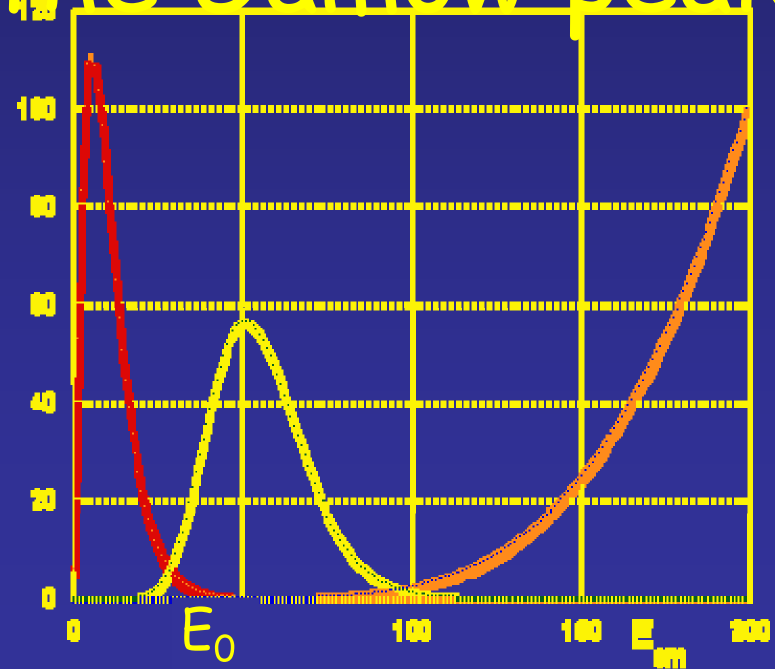
stars are … "cauldrons in the cosmos"

Maxw. energy distribution function (KT ~ keV)

$KT \ll \frac{Z_1 Z_2 e^2}{R_N} \Rightarrow$ tunneling probability

$$\langle \sigma v \rangle = \sqrt{\frac{8}{\pi\mu}} \frac{1}{(KT)^{3/2}} \int_0^\infty S(E) \exp\left(-\frac{E}{KT} - \frac{b}{E^{1/2}} \right) dE$$

the Gamow peak....



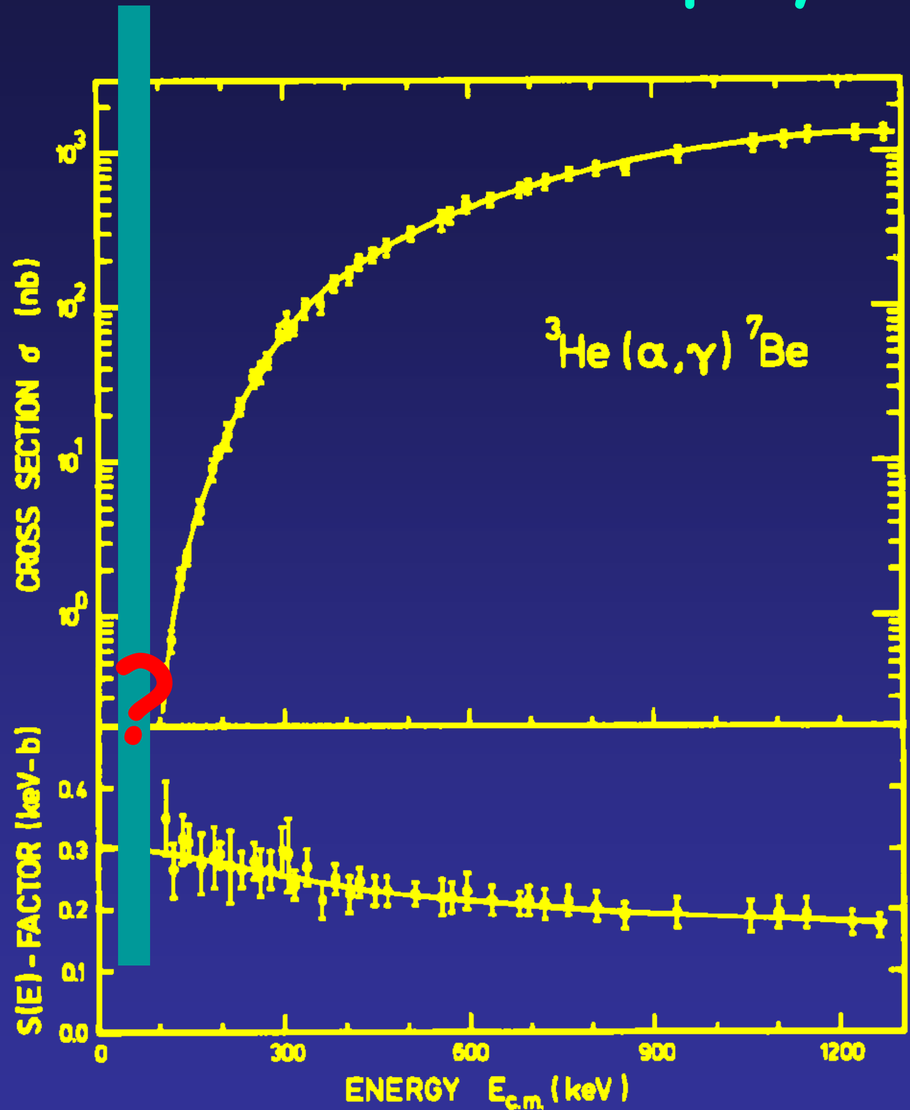
$^3He(^3He,2p)^4He$

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

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

$20 < E_0 < 26$ keV

The astrophysical S-factor...



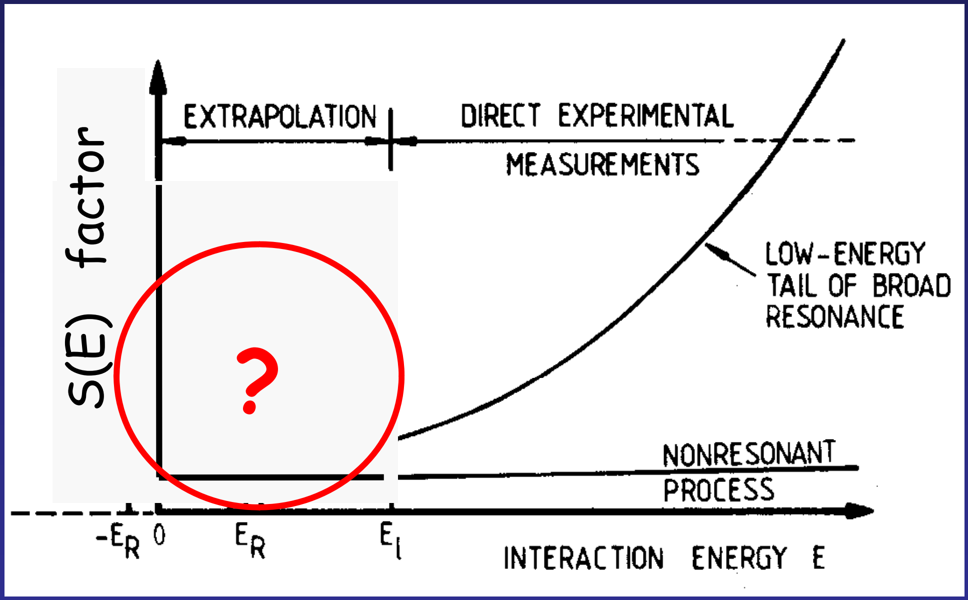
$$\sigma(E) = S(E) \cdot \exp(-2\pi\eta) / E$$

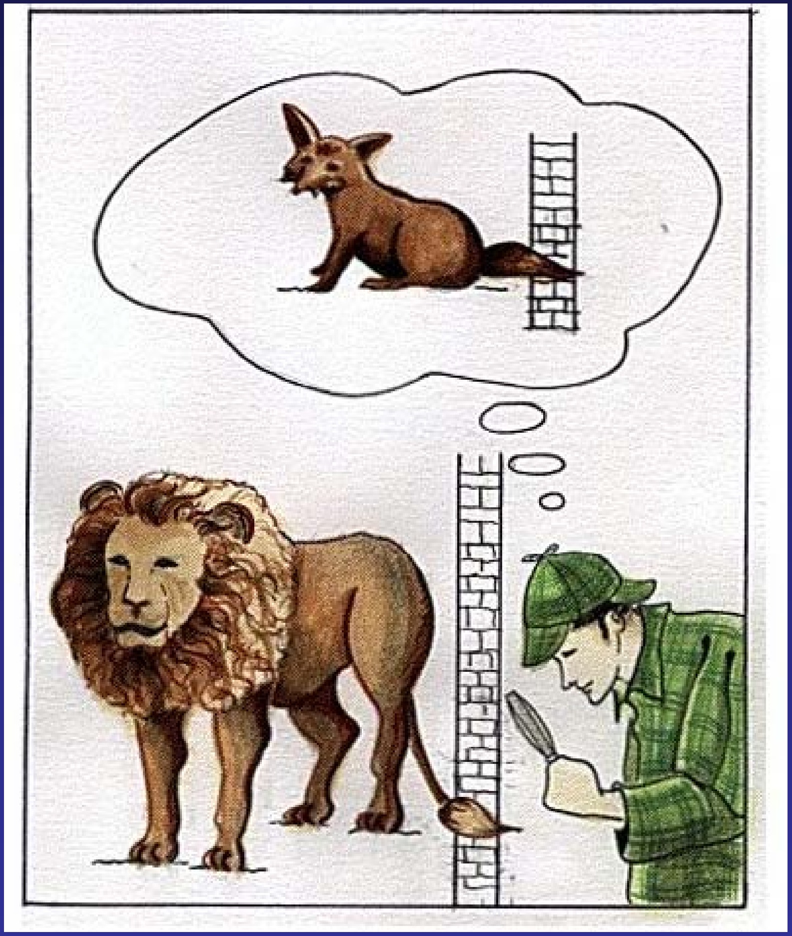
$$S(E) = E \cdot \sigma(E) \cdot \exp(2\pi\eta)$$

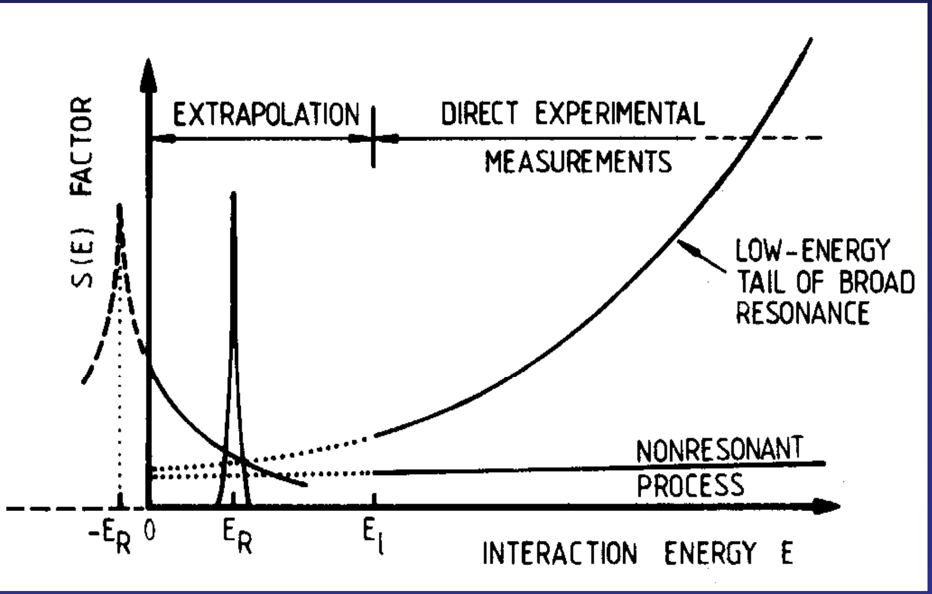
$$2\pi\eta = 31.29\ Z_1 Z_2 (\mu/E)^{0.5}$$

extrapolation is needed....

but…


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

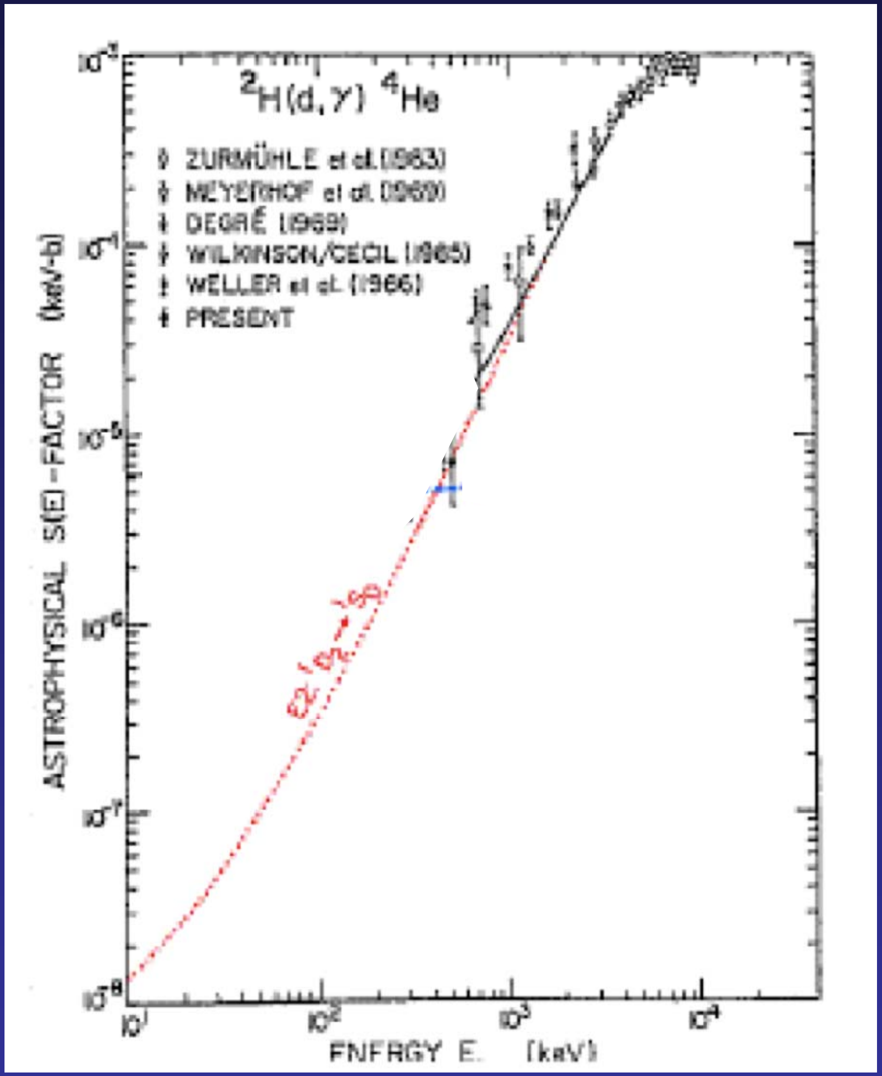




sometimes extrapolation fails !!

An emblematic case:

$d + d \rightarrow {}^4He + \gamma$

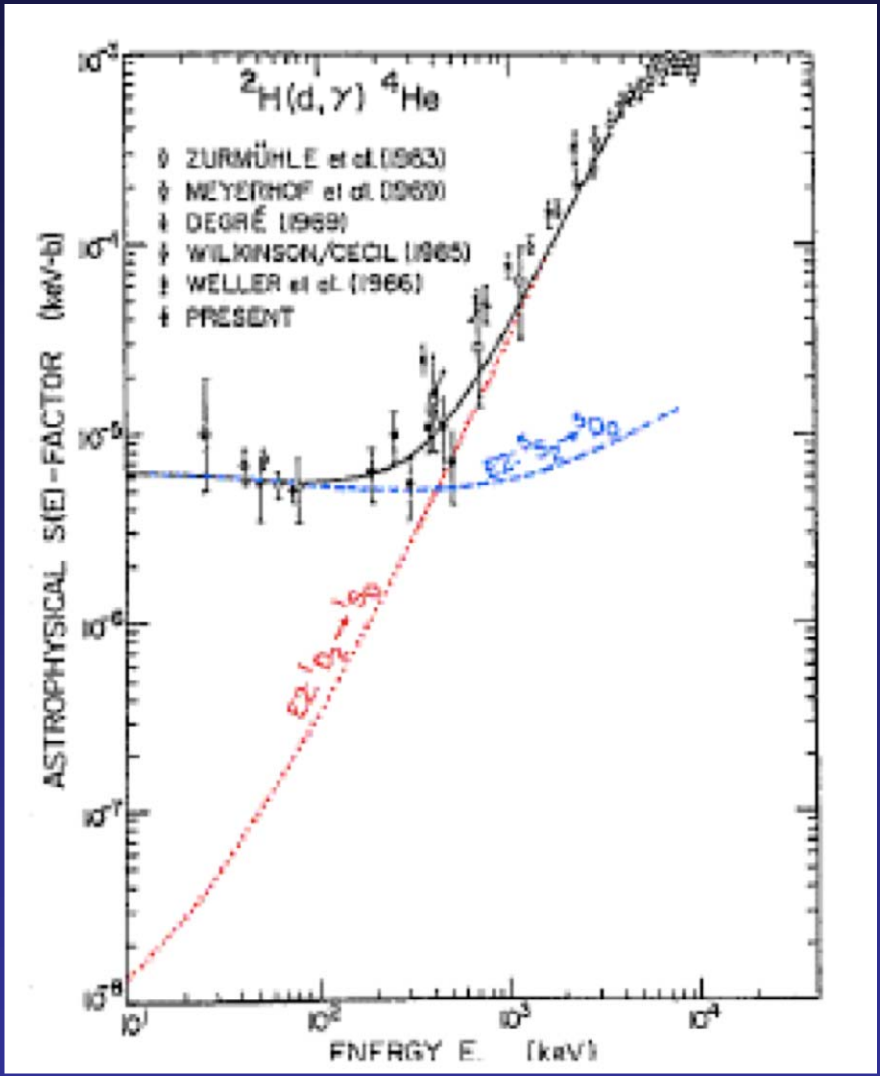


the experiment was done, and…

An emblematic case:

$d + d \rightarrow {}^4He + \gamma$

?!?



the experiment was done, and…

identical T= 0 bosons ⇒ L + S even

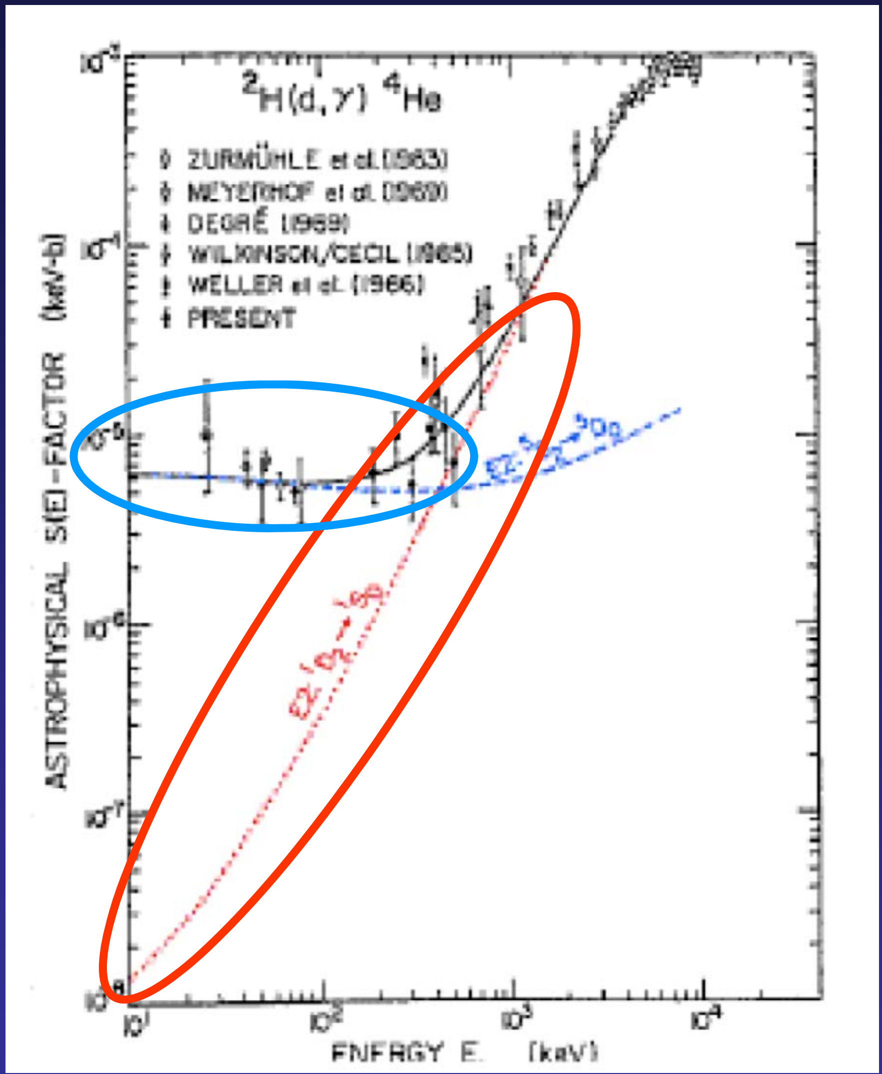
- E_1 and M_1 strongly depressed
- pure E_2 transition

D-wave capt. to the S ^{4}He g.s.
$^1D_2 \rightarrow {}^1S_0$
strongly depressed by
the centrifugal barrier

But.. ^{4}He g.s. has also
a (≈%) D-component…

At low energy: S-wave capture
$^5S_2 \rightarrow {}^5D_0$ dominates on $^1D_2 \rightarrow {}^1S_0$

≈% ^{4}He D-state component
strongly enhanced by
the centrifugal barrier !!



don't trust 100% extrapolation !

don't trust 100% theoreticians !

a "direct" measurement is desirable...

reaction rates

<u>inside the sun:</u>

Luminosity $L_\odot = 2 \cdot 10^{39}$ MeV/s

Q-value $Q = 26.73$ MeV

$$R_\odot = \frac{L_\odot}{Q} = 10^{38}\ s^{-1}$$

<u>in the Lab:</u> $R_{lab} = \sigma \cdot \varepsilon \cdot I_p \cdot \tau \cdot N_{av} / A$

$\varepsilon \sim 10\ \%$

$I_p \sim$ mA

$\tau \sim \mu g/cm^2$

fb $< \sigma <$ pb

event/month $< R_{lab} <$ event/day

<u>but…</u>

cosmic ray flux at sea level $\approx 2 \cdot 10^{-2}\ cm^{-2}\ s^{-1}$

on a 10 cm^2 detector $\approx$ 2000 events/day !!!

reaction rates

inside the sun:

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$\tau \sim \mu g/cm^2$
fb < σ < pb

event/month < R_{lab} < event/day ???

but...

cosmic ray flux at sea level ≈ $2\cdot10^{-2}\ cm^{-2}\ s^{-1}$

on a 10 cm^2 detector ≈ 2000 events/day !!!

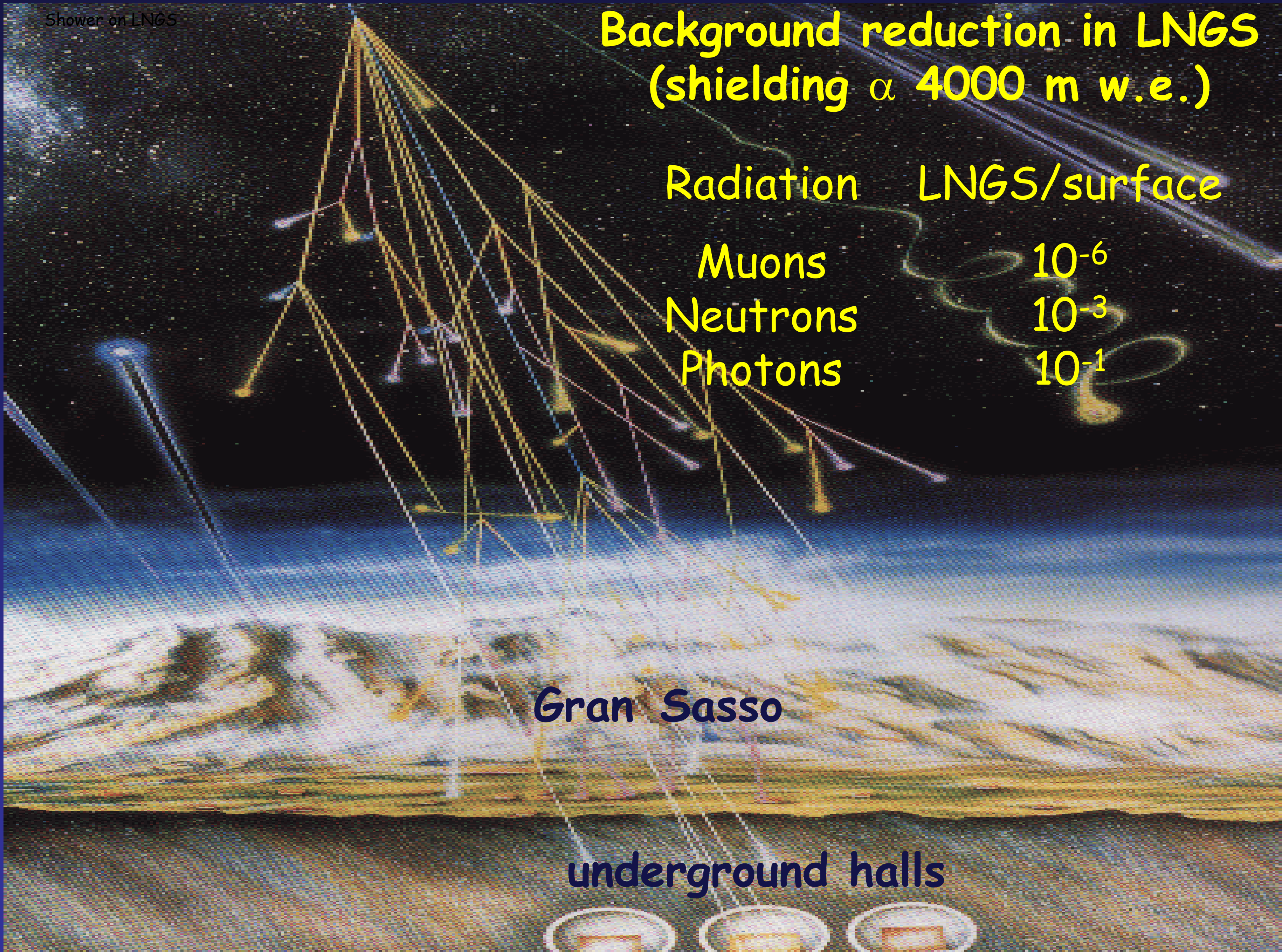
background rate >> signal rate !!

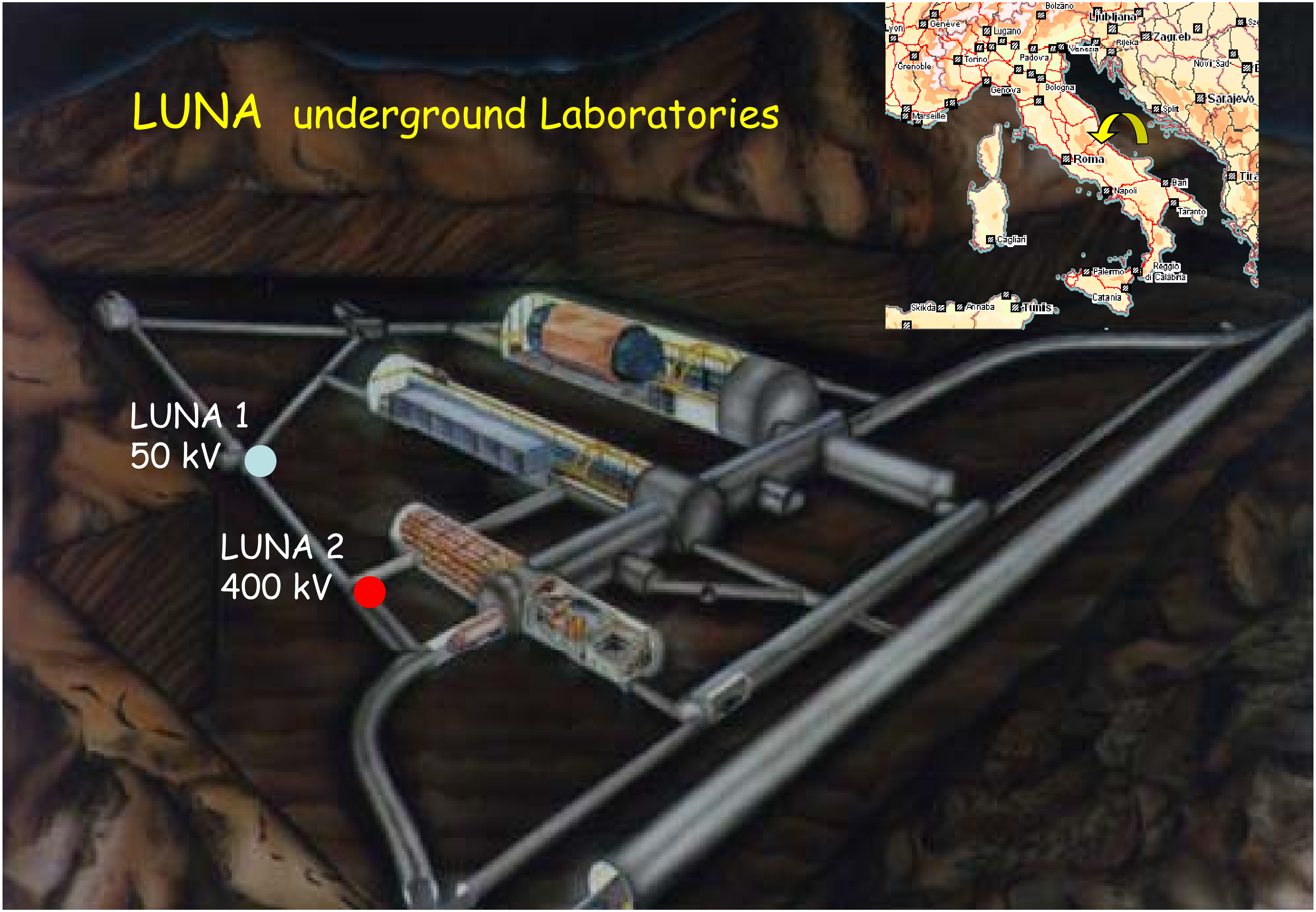
how to overcome
these
experimental
problems
??

go underground

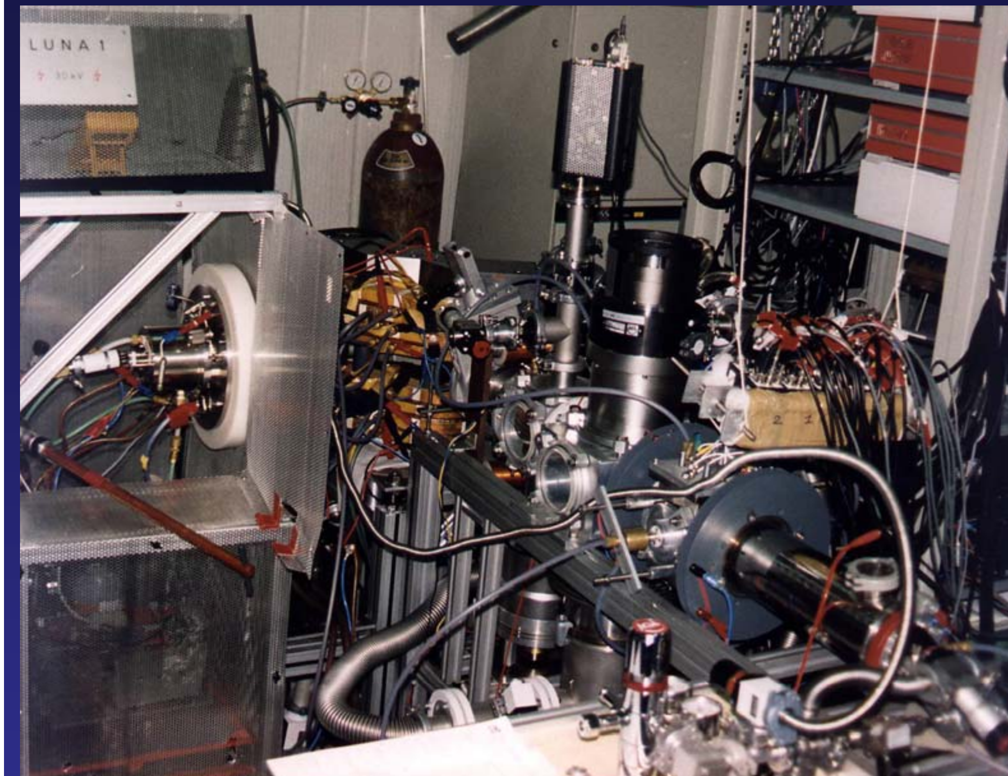
Background reduction in LNGS (shielding α 4000 m w.e.)

Radiation	LNGS/surface
Muons	10^{-6}
Neutrons	10^{-3}
Photons	10^{-1}



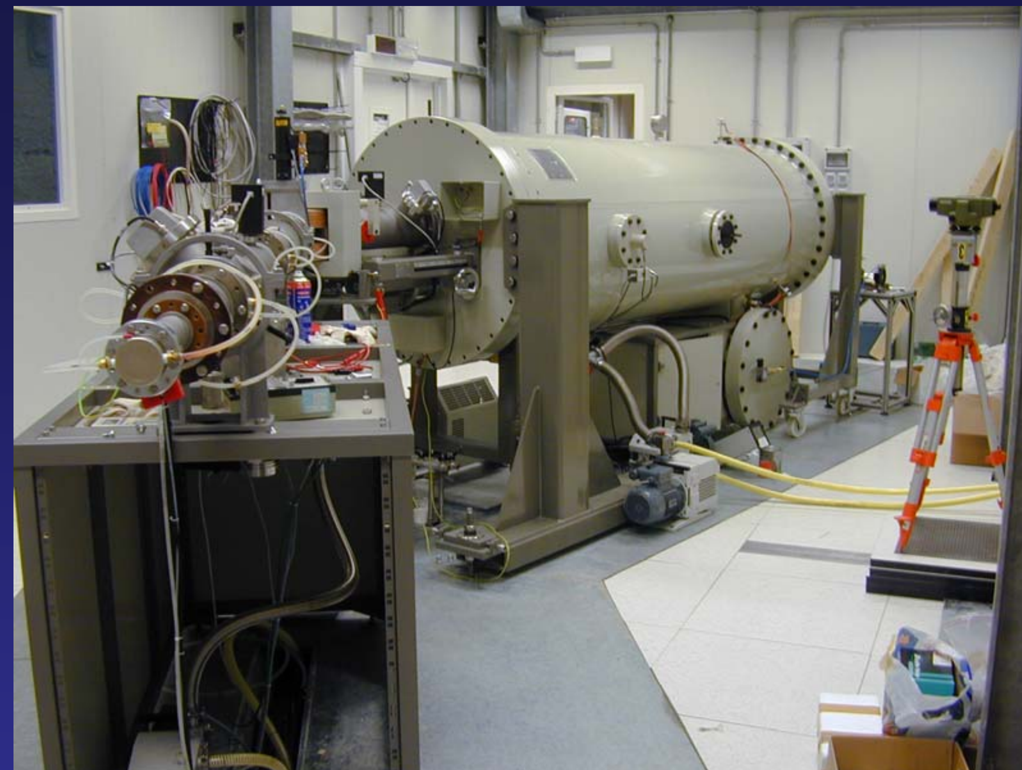

LUNA underground Laboratories
LUNA 1
50 kV
LUNA 2
400 kV
Bolzano
Ljubljana
Genève
Lugano
Zagreb
Lyon
Torino
Padova
Venezia
Rijeka
Grenoble
Novi Sad
Genova
Bologna
Sarajevo
Split
Marseille
Roma
Bari
Napoli
Taranto
Cagliari
Reggio di Calabria
Palermo
Catania
Skikda
Annaba
Tunis

LUNA1 (50 kV)



Voltage Range : 1 - 50 kV
Output Current: 1 mA
Beam energy spread: 20 eV
Long term stability (8h): 10^{-4}
Terminal Voltage ripple:5 10^{-5}

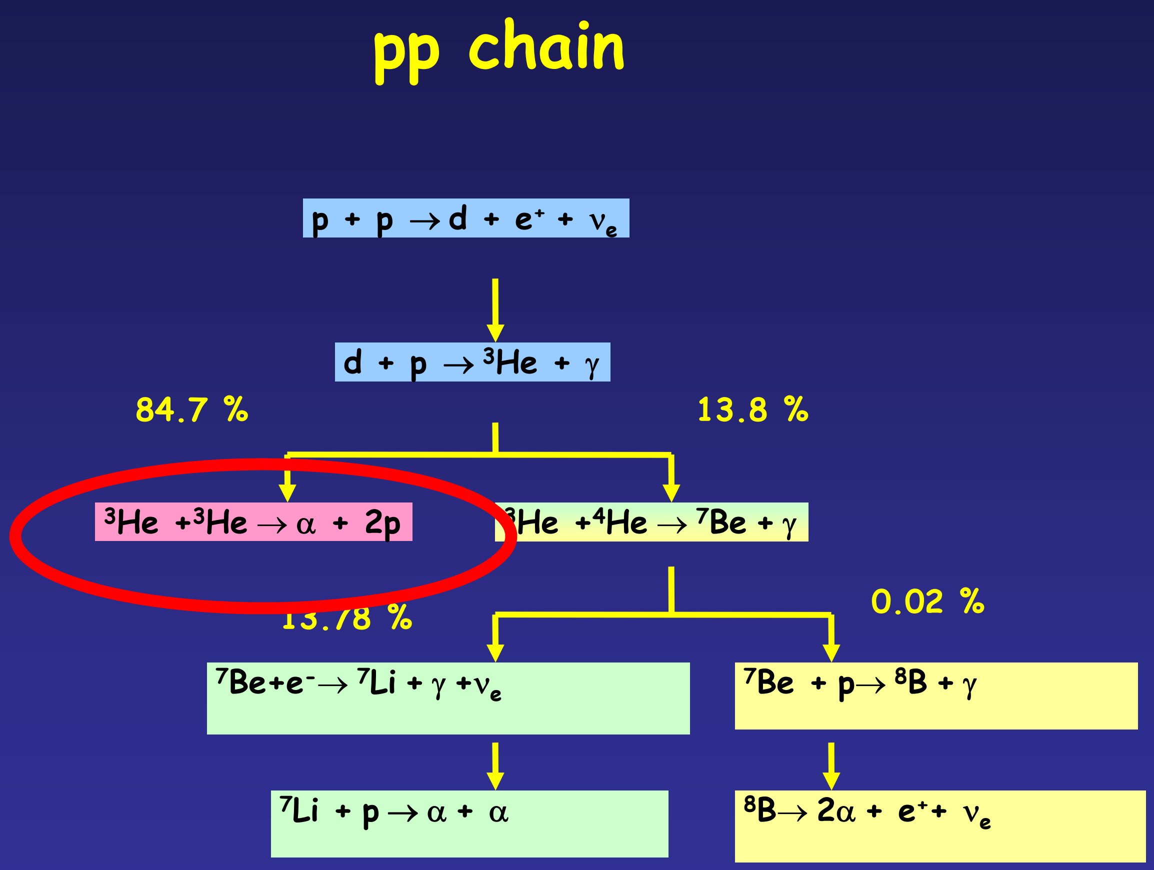
LUNA2 (400 kV)



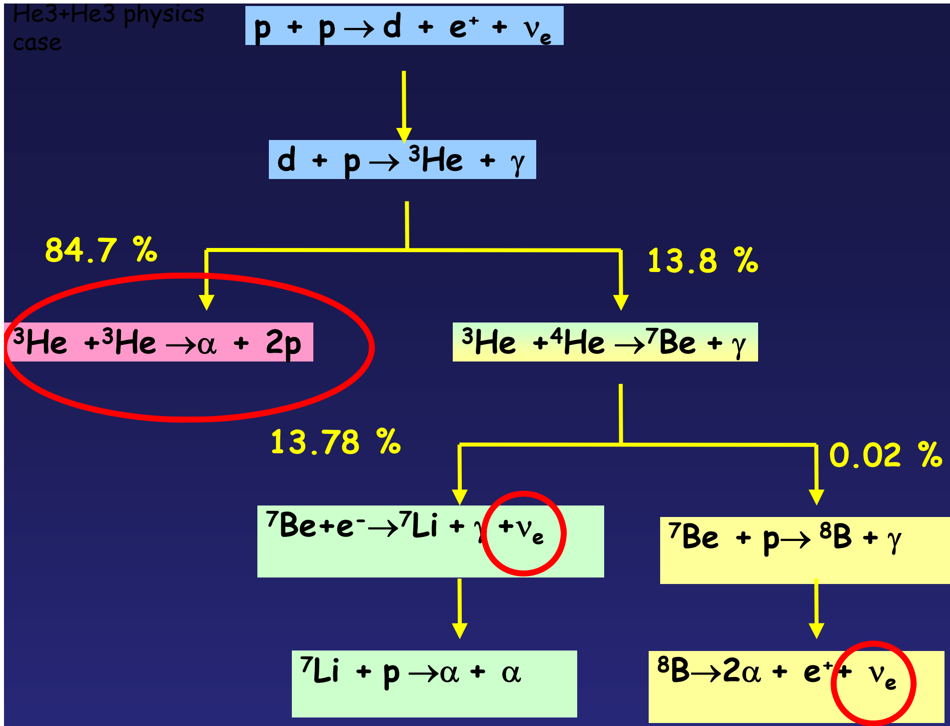
Voltage Range : 50-400 kV
Output Current: 1 mA (@ 400 kV)
Absolute Energy error: ±300 eV
Beam energy spread: <100 eV
Long term stability (1 h) : 5 eV
Terminal Voltage ripple:5 Vpp Ge det




LUNA results



He3+He3 physics case



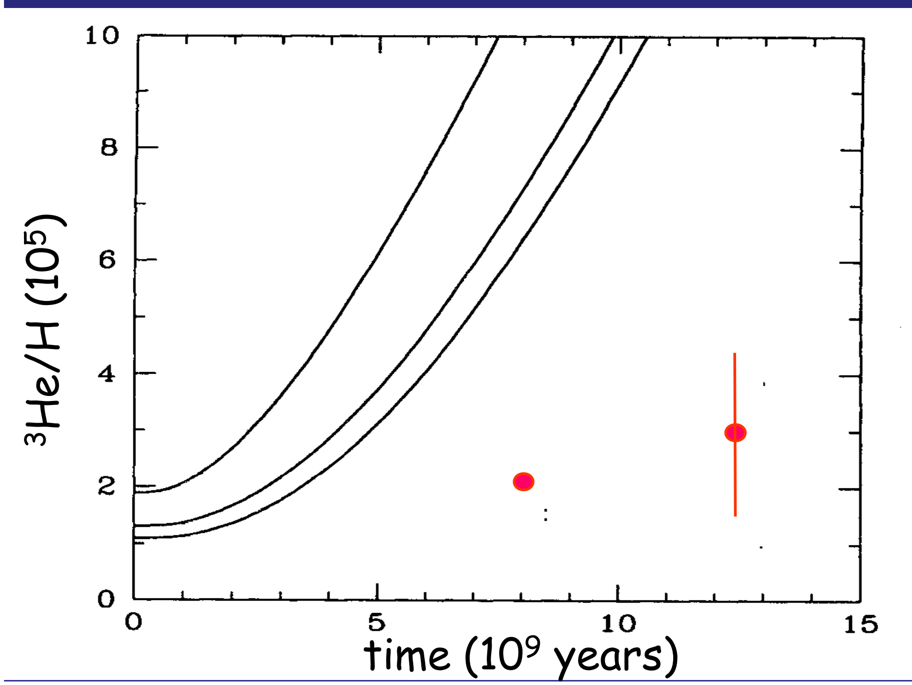
the physics case:
a resonance in the ${}^3He+{}^3He$ channel (Fowler, 1972) might have accounted for:

- solar neutrino problem
- ${}^3He$ galactic abundance

higher cross section

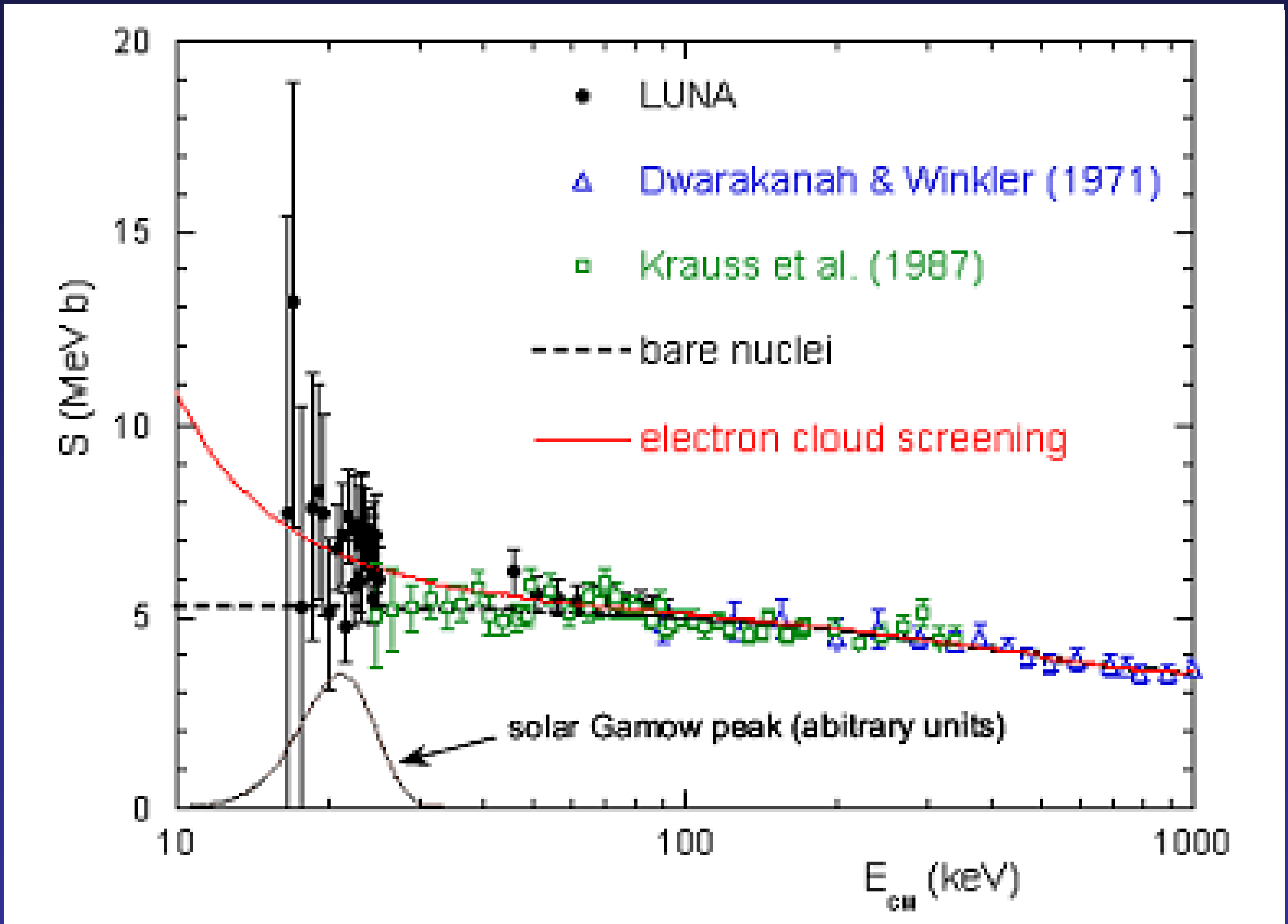
⇓

- Lower ν fluxes from ${}^7Be$ and ${}^8B$
- Lower ${}^3He$ galactic abundance

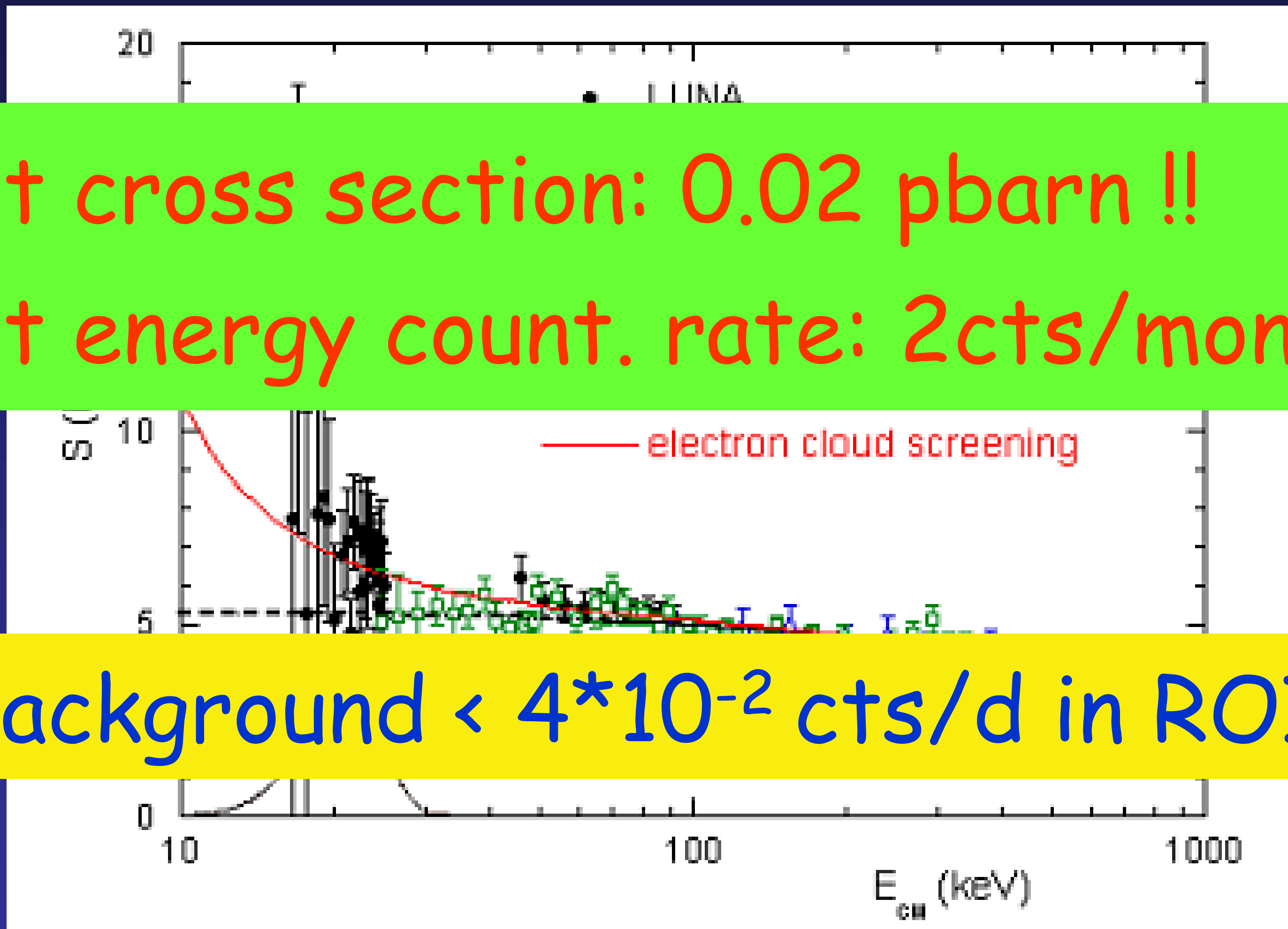


no resonance has been found...
But:
no more extrapolations are needed for this reaction

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



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

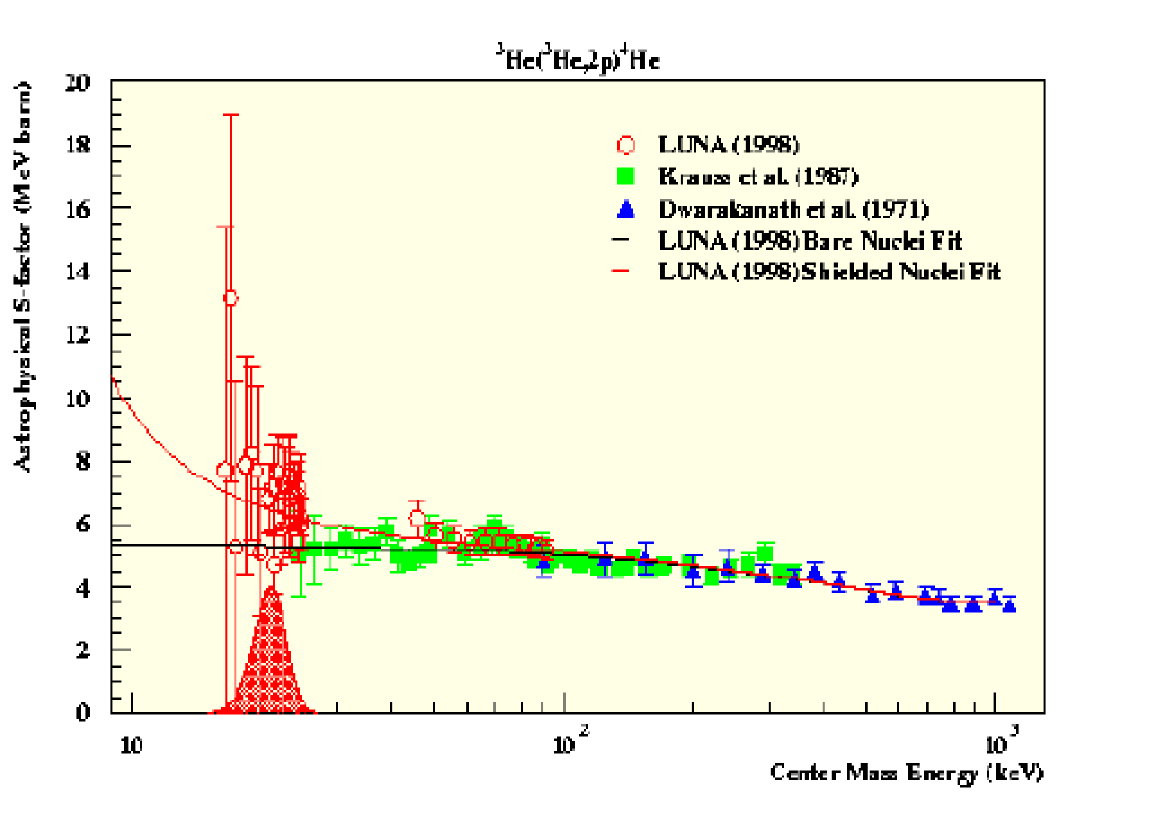


- Lowest cross section: 0.02 pbarn !!
- Lowest energy count. rate: 2cts/month !!

Background < $4*10^{-2}$ cts/d in ROI

*PRL 82(1999) 5205

S(0)=5.32 (1± 6%)MeVb

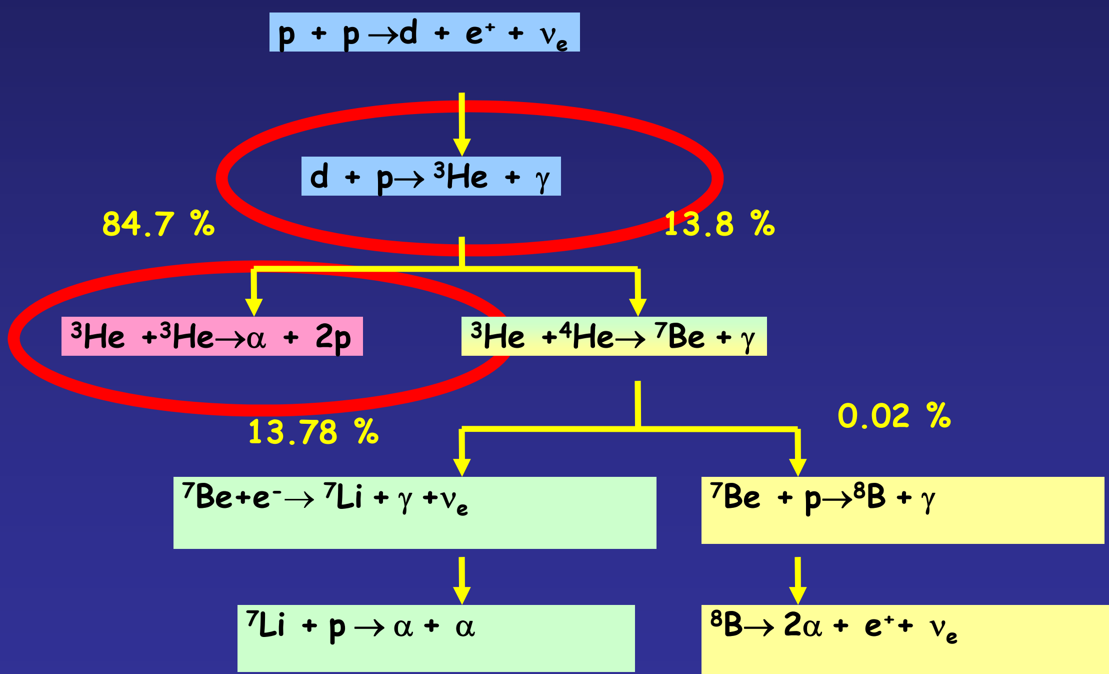


J. Bachall: "Historical breakthrough"

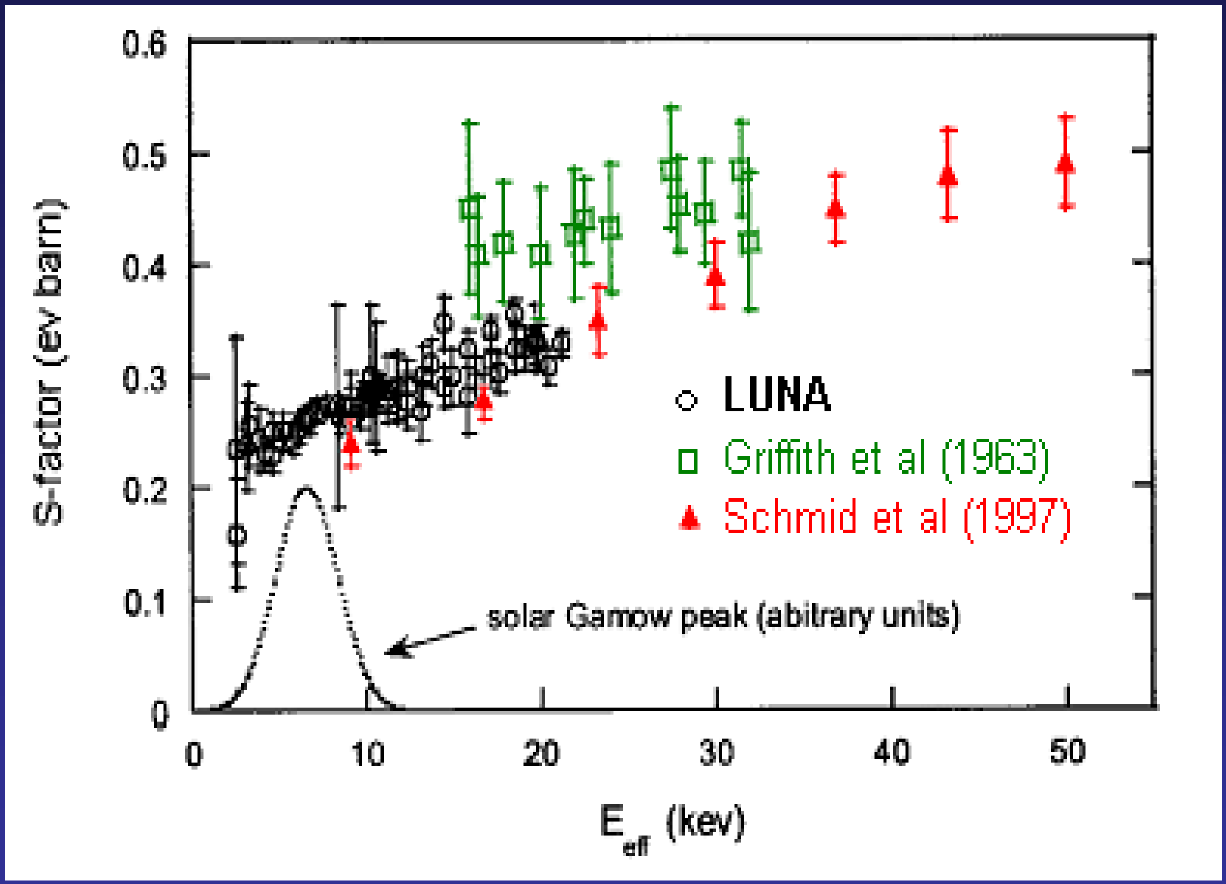
I am writing to you about a historic opportunity of which I first became aware at the recent meeting on Solar Fusion Reactions at the Institute of Nuclear Theory, Washington University. At this meeting, I had the opportunity to see for the first time the results of the LUNA measurements of the important $3He - 3He$ 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.

LUNA results

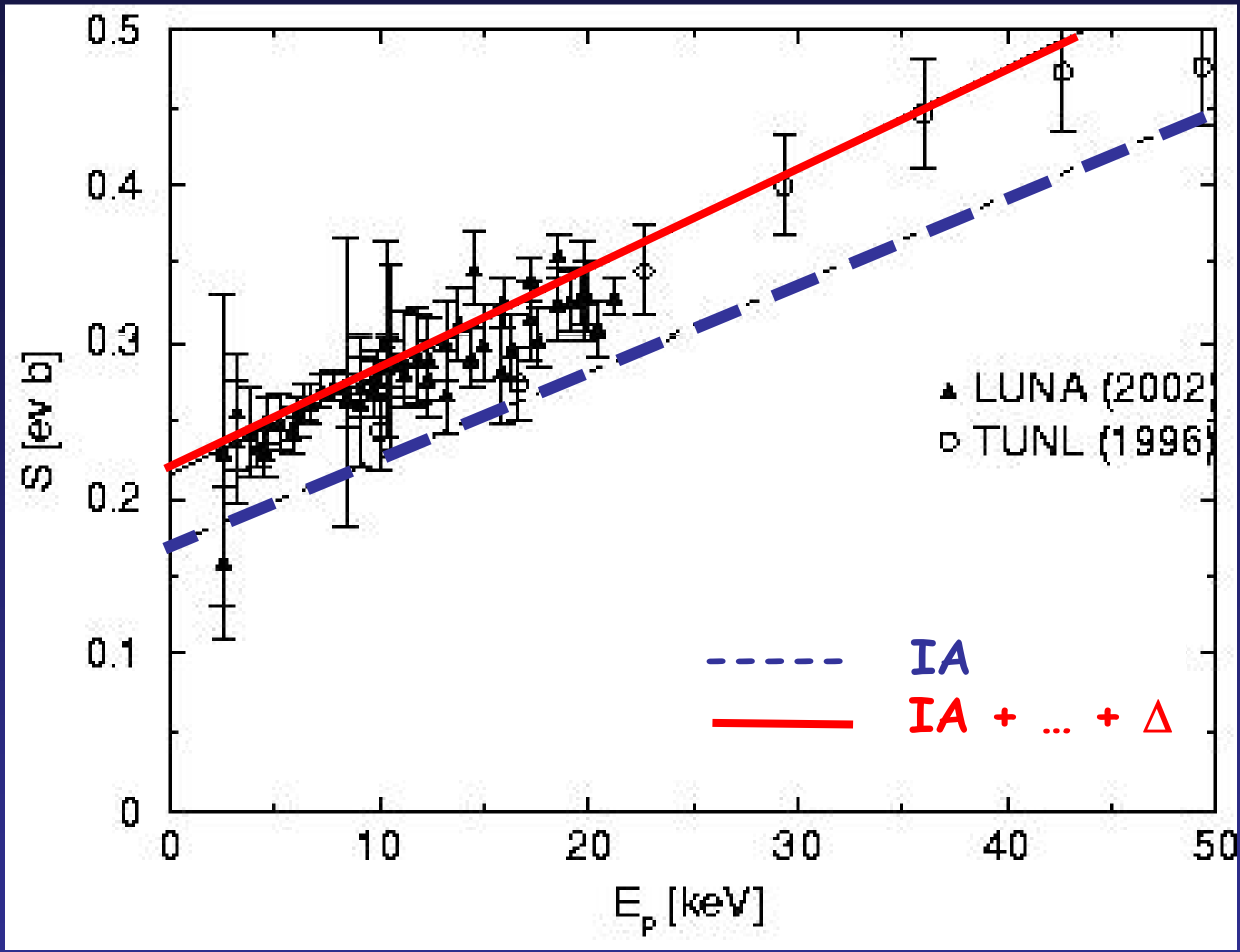
pp chain



$d(p,\gamma)^3He$

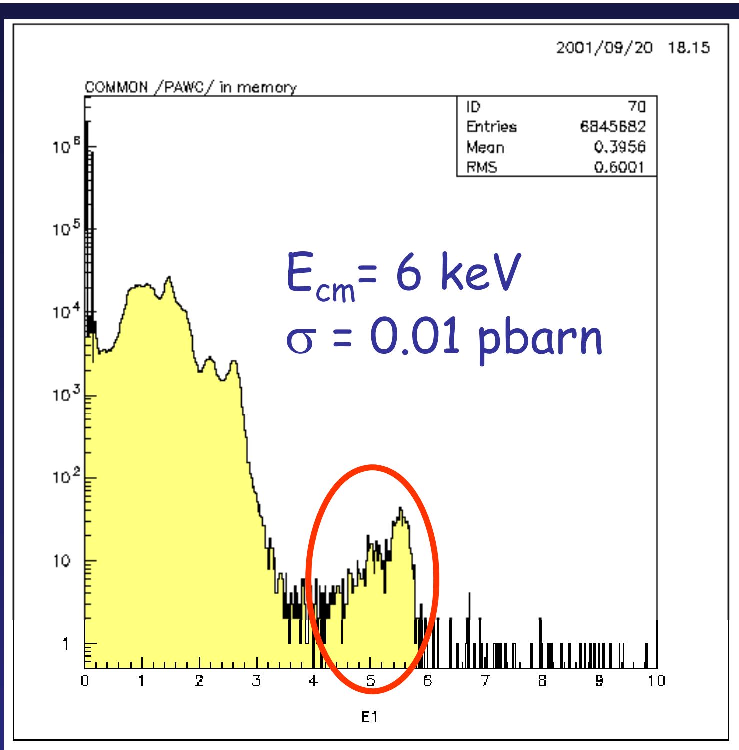


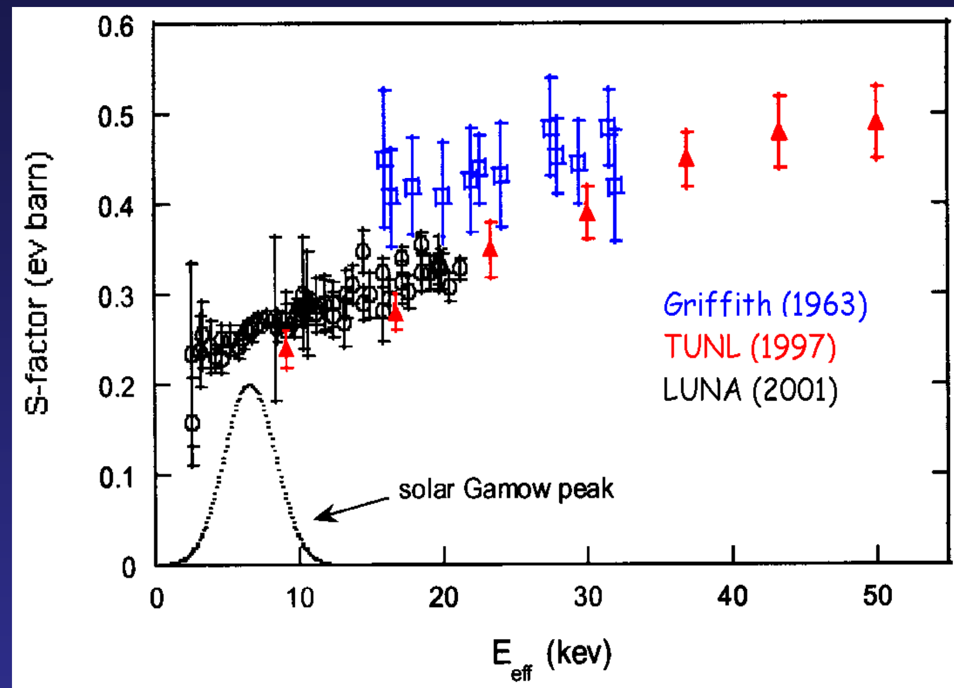
0.6
0.5
0.4
0.3
0.2
0.1
0
S-factor (ev barn)
0
10
20
30
40
50
E_eff (kev)
LUNA
Griffith et al (1963)
Schmid et al (1997)
solar Gamow peak (abitrary units)

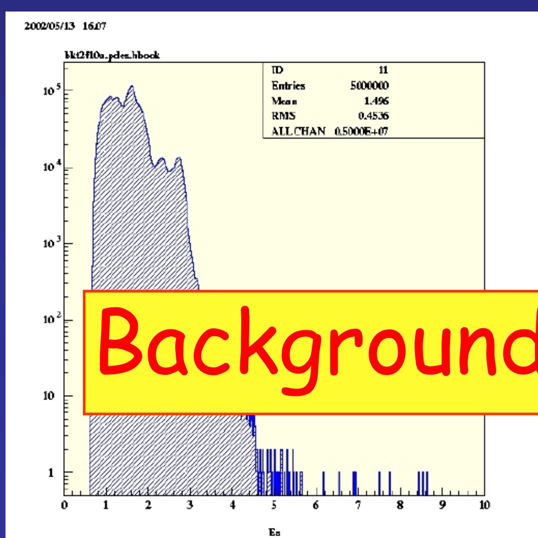


sizeable effect of non nucleonic degrees of freedom

Viviani et al.: PRC61 (2000) 064001



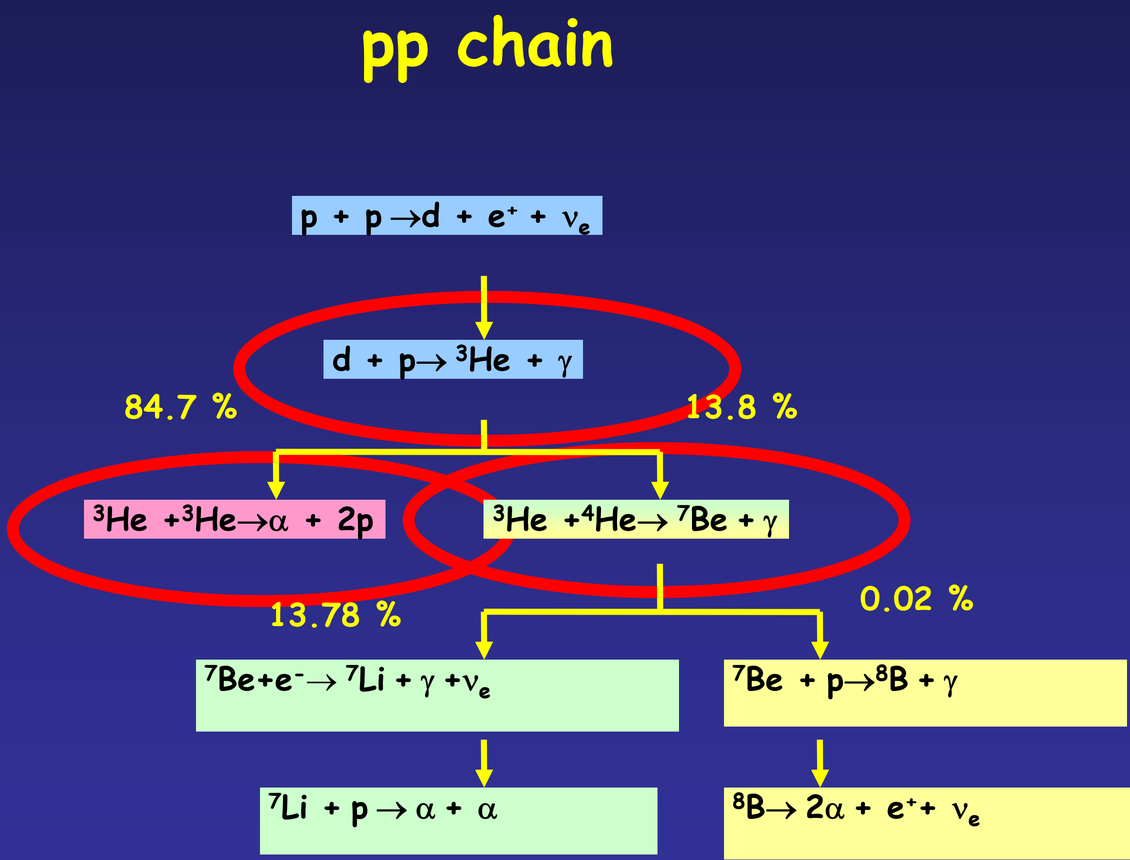




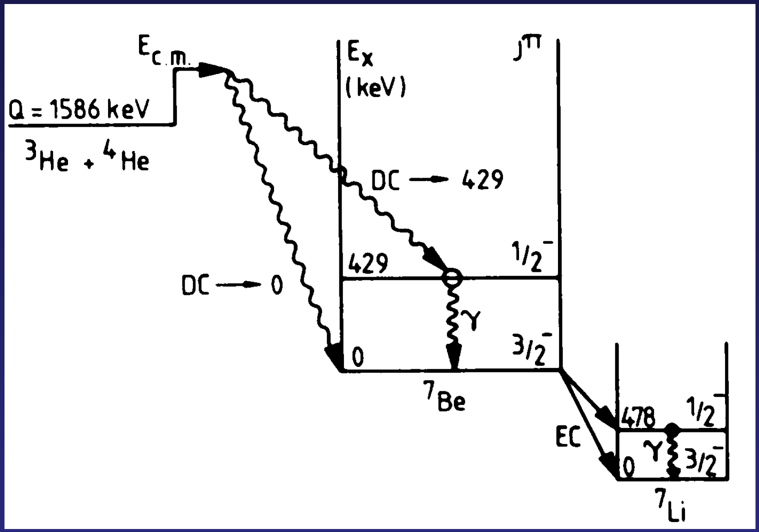
below the Gamow peak !

Background (E > 5 MeV) ~ 4 counts/MeV/day

LUNA results



$^3He(\alpha,\gamma)^7Be$ 　 $^7Be+e \rightarrow {}^7Li^*(\gamma)$



$E\gamma$ = 478 keV

$E\gamma$ = 1586 keV + E_{cm} (DC → 0)

$E\gamma$ = 1157 keV + E_{cm} (DC → 0.429)

$E\gamma$ = 429 keV

- Cross section of **direct decay** down to 90 keV (CM energy) using ^4He beam on ^3He target
- Reaction Yield via off-line **radioactive decay** measurements of the recoils collected in the beam catcher
- All with a final error < 5 %

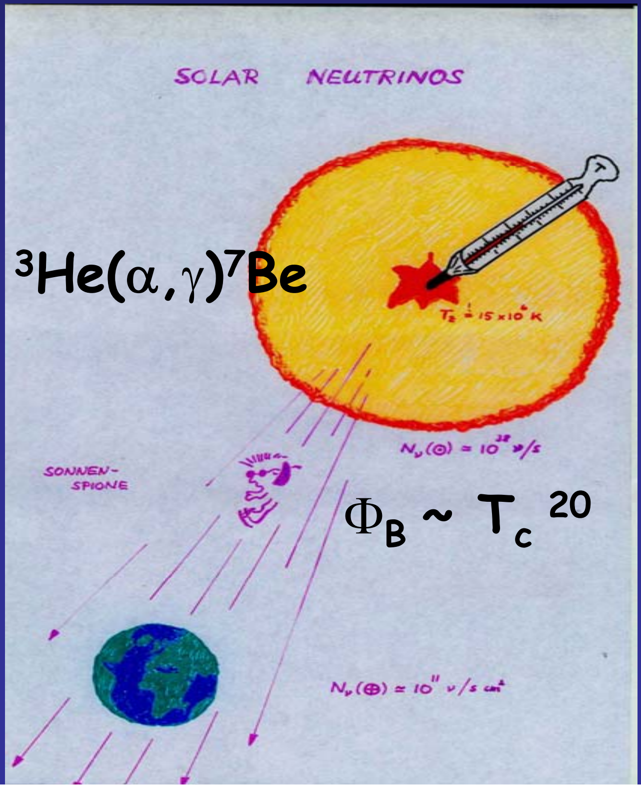
Low Q-value, angular distribution effects, no resonances

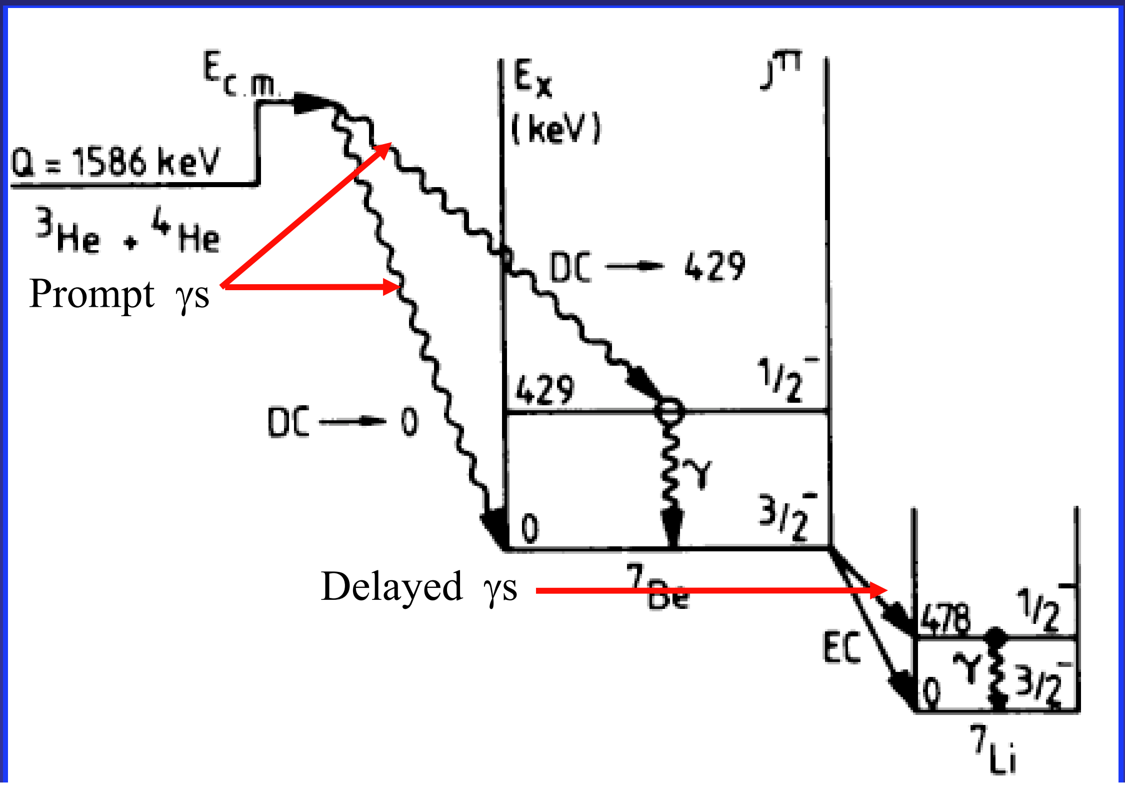
$^3He(^4He,\gamma)^7Be$

After the discovery of ν oscillation, the solar neutrinos are back to study the Solar interior.

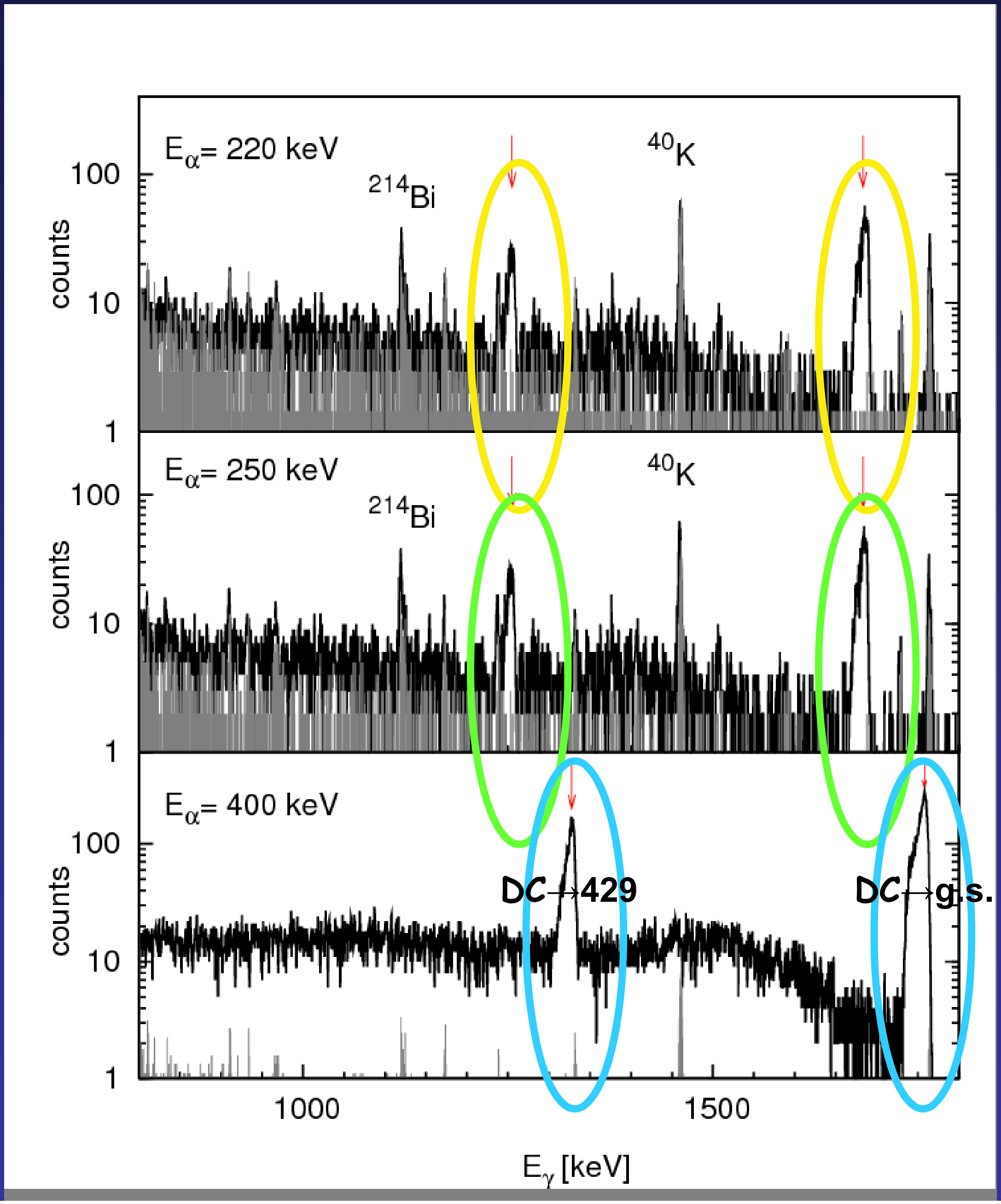
Three objectives for the LUNA measurement:

- Lowest energy never reached (90 keV)
- Lowest uncertainty (4%)
- Simultaneous measurement of prompt and delayed γs (systematic discrepancy of previous measurements)





Prompt-γ: experimental spectra



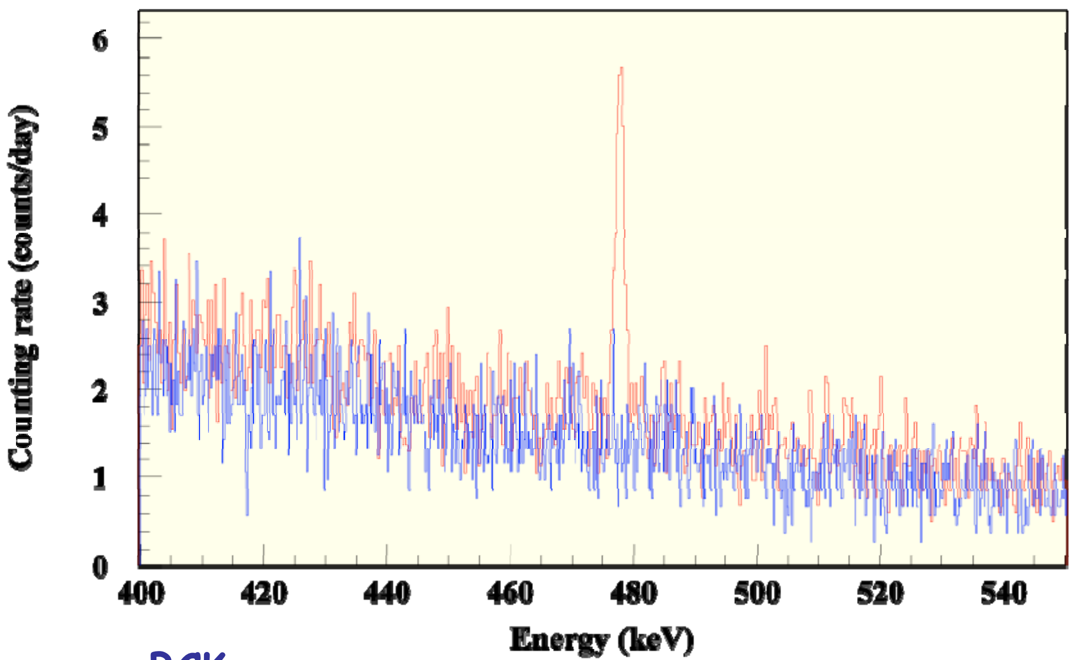
E_{cm} = 93.3 keV
T = 30.1 d
C = 637 C

E_{cm} = 106.1 keV
T = 20.8 d
C = 407 C

E_{cm} = 170.1 keV
T = 4.35 d
C = 112.7 C

Activation measurement

E_{lab}=220 keV   Q= 637 C   T = 11.58 d

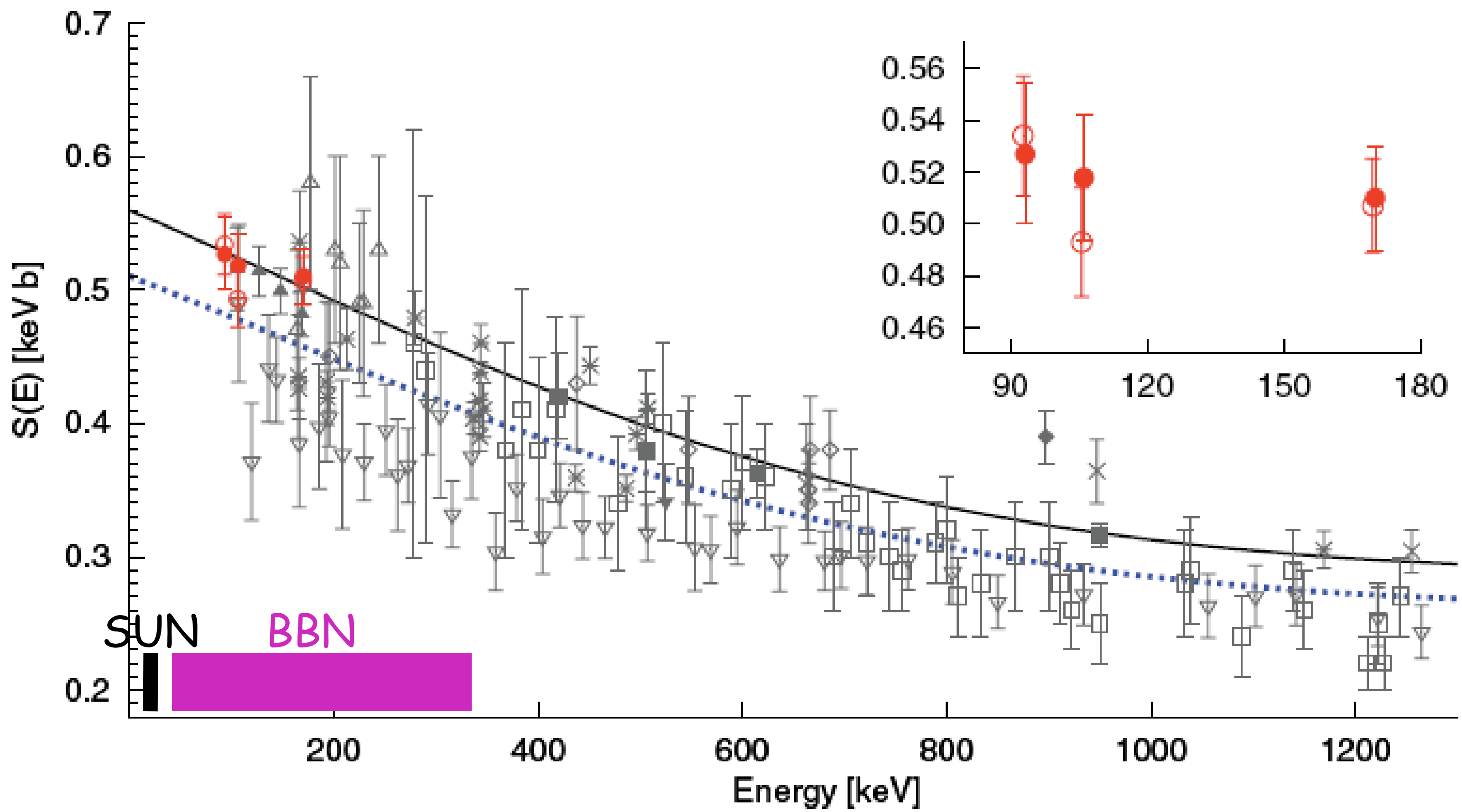


(D. Bemmerer et al, Phys. Rev. Lett. 97, 122502 (2006))

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

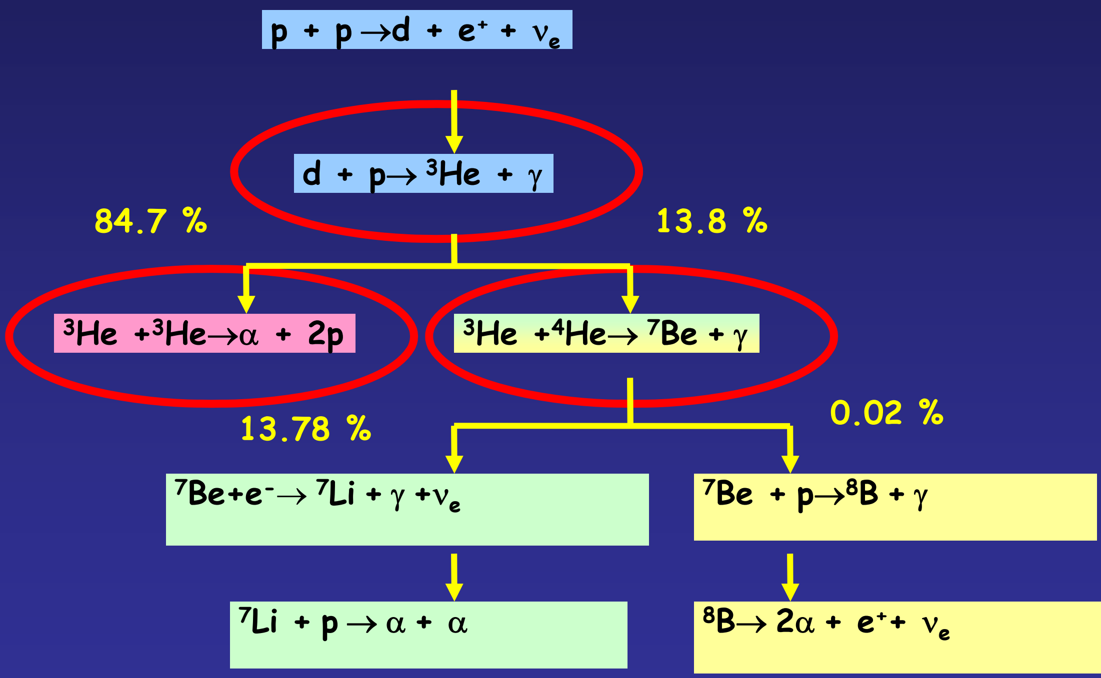
The uncertainty on the predicted ^{8}B neutrino flux due to S_{34} is now reduced from 7.5% to 2.4% and the total uncertainty, including astrophysical parameters, goes from 12% to 10% [37]. Similarly, the uncertainty on ^{7}Be predicted flux goes from 9.4% to 5.5%, being the contribution of S_{34} error reduced from 8% to 2.5% [37].

F.Confortola et al., PRC 75,065803(2007)



H burning

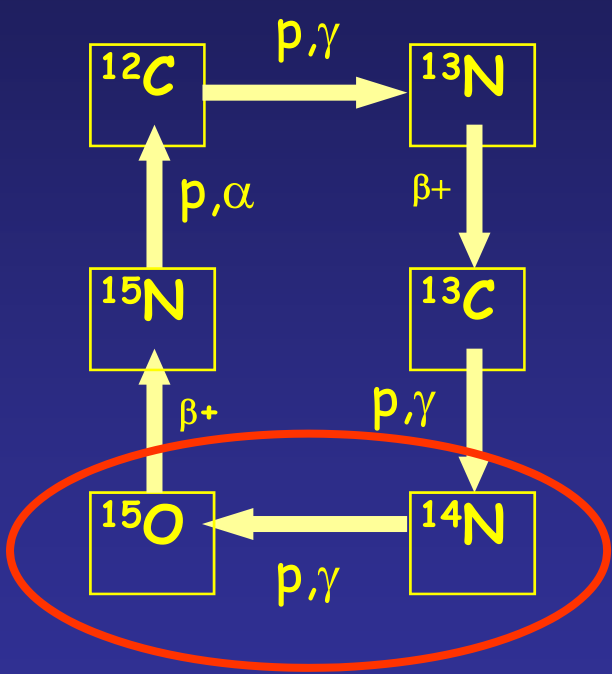
pp chain



$$4p \rightarrow {}^4He + 2e^+ + 2\nu_e + 26.73\ MeV$$

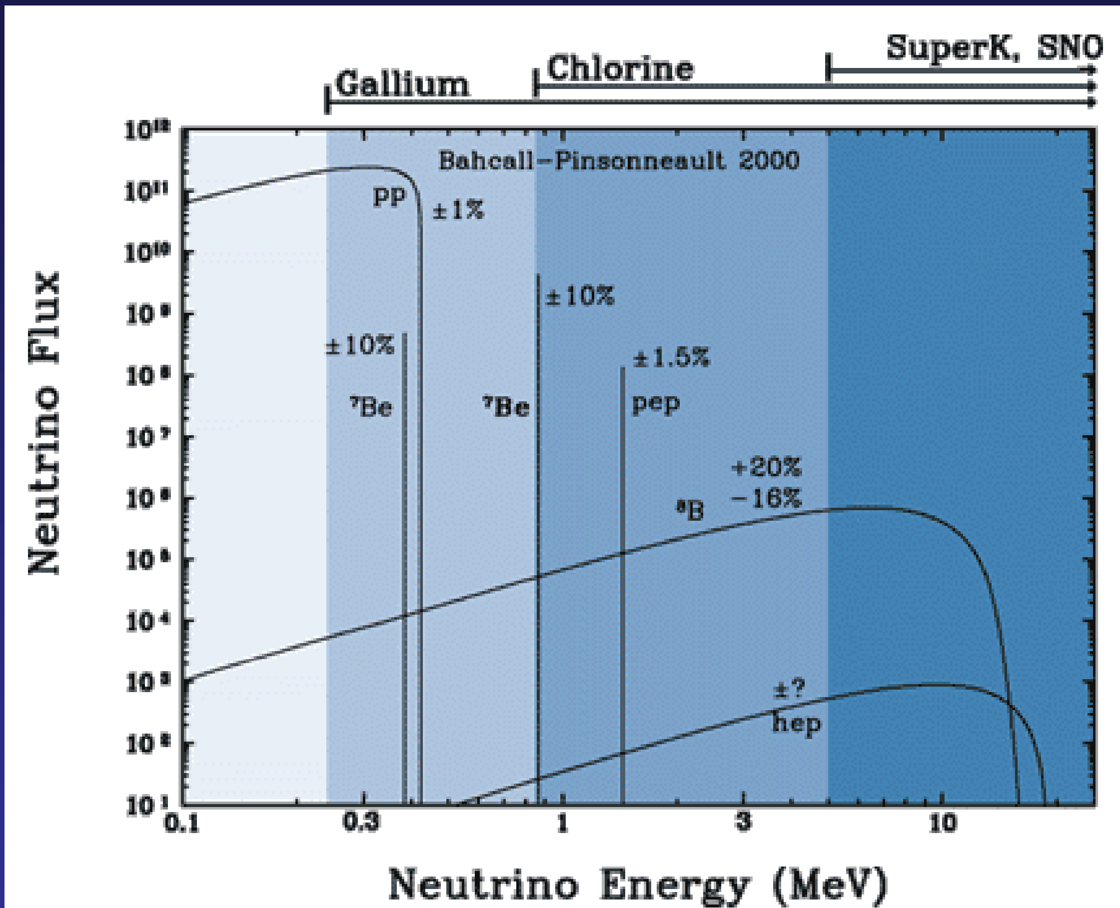
H burning

CNO cycle

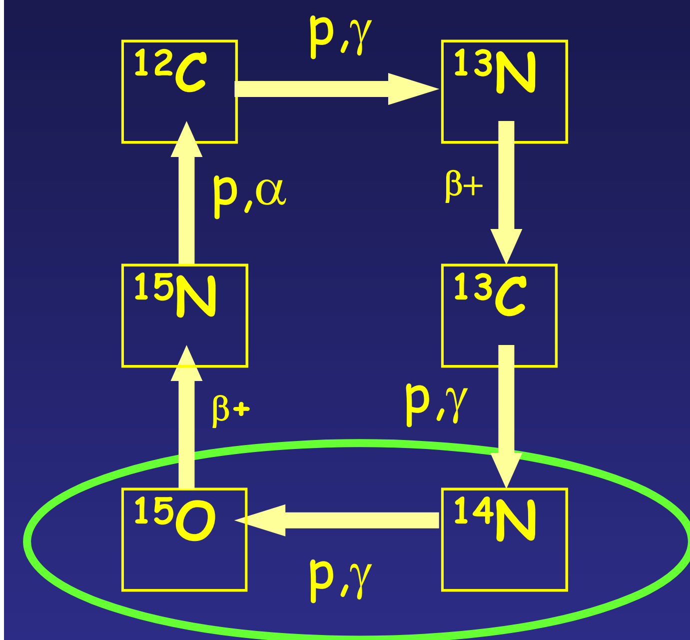


$$4p \rightarrow {}^{4}He + 2e^{+} + 2\nu_e + 26.73\ MeV$$

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



CNO cycle



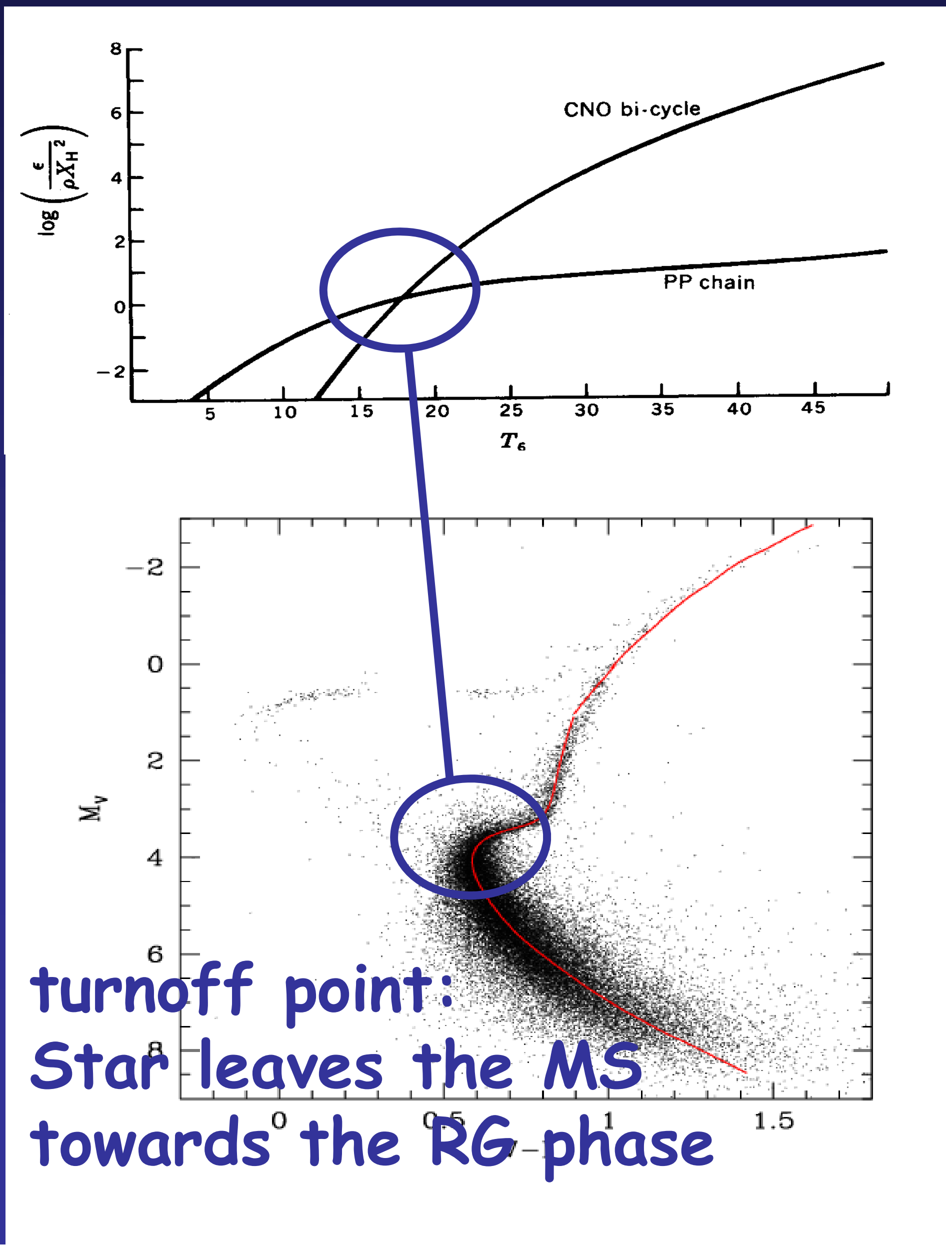
$\Phi_\nu(^{15}O) \propto \sigma_{1,14}{}^{1}$

$\Phi_\nu(^{13}N) \propto \sigma_{1,14}{}^{0.85}$

slowest reaction of CNO cycle

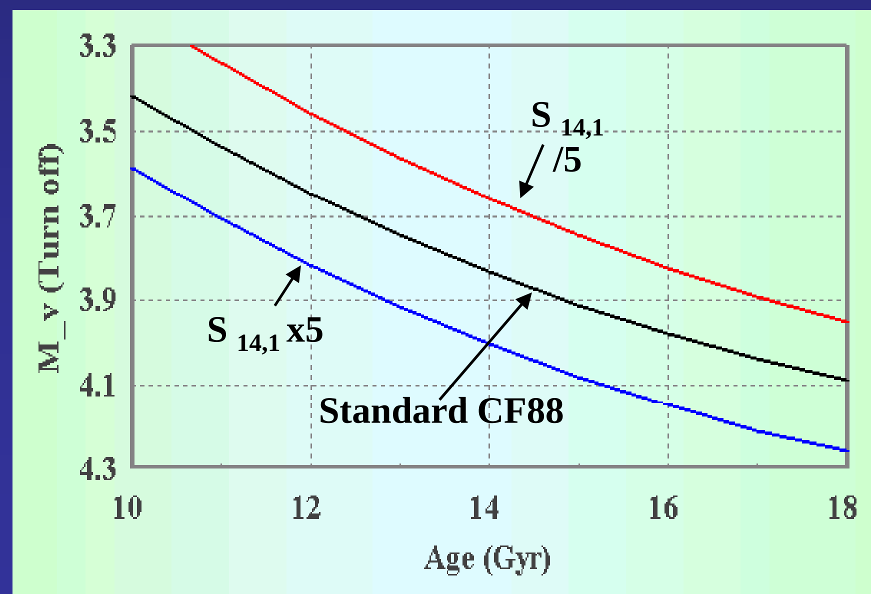
determines neutrino flux from CNO cycle

$^{14}N(p,\gamma)^{15}O$ and globular clusters age



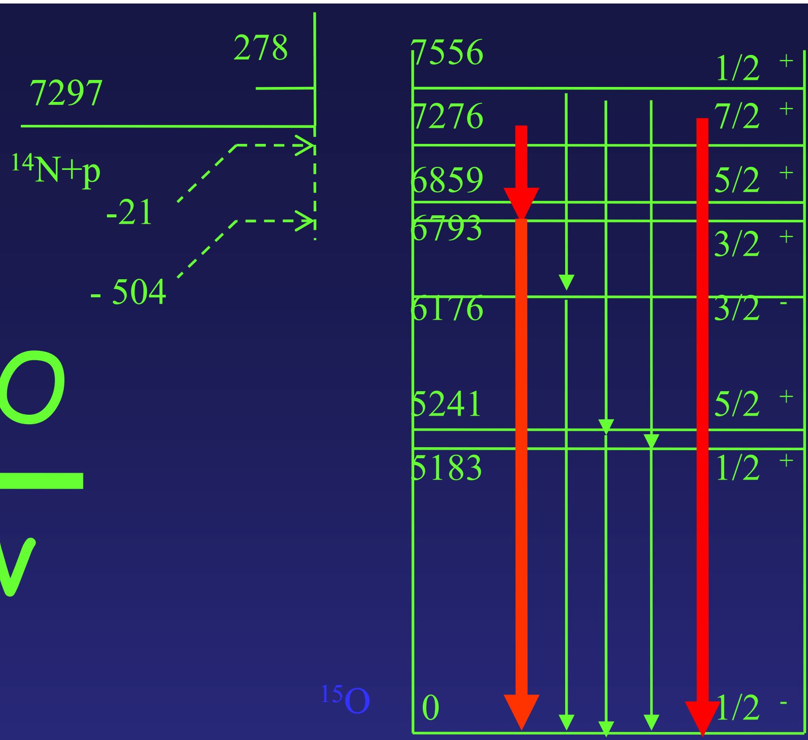
turnoff point:
Star leaves the MS towards the RG phase

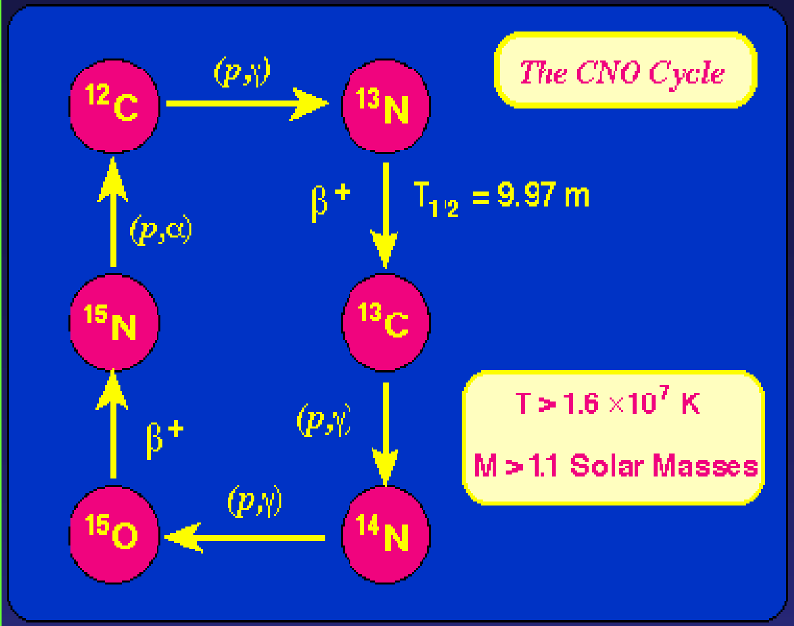
Chronometer of the Universe age

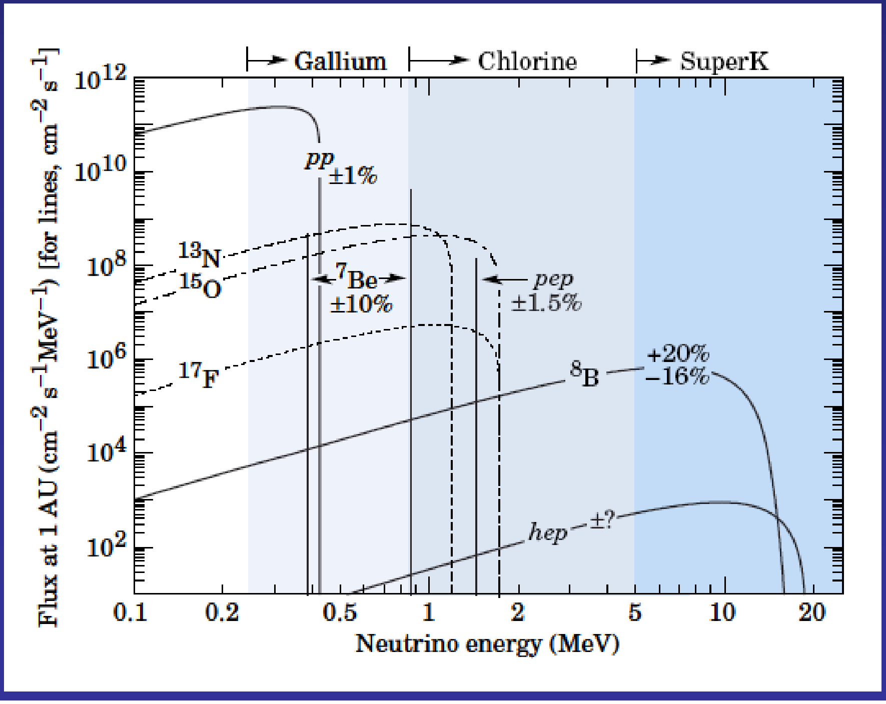


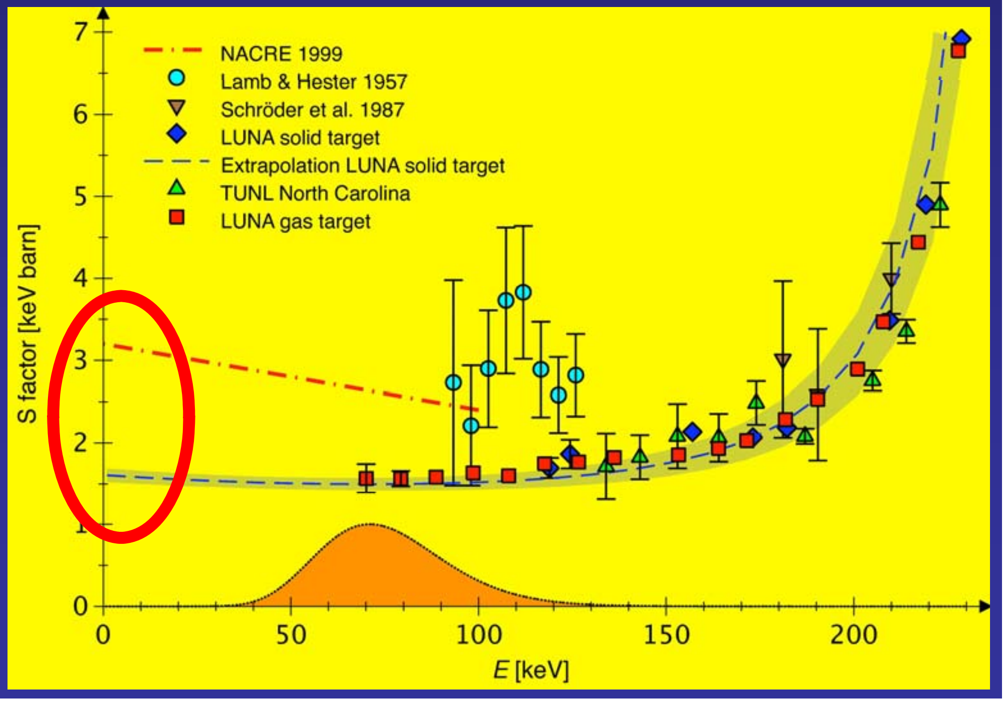
$^{14}N(p,\gamma)^{15}O$

Q=7.3 MeV









Main consequences:

GC age estimation increases by 0.7 Gyr

CNO neutrino flux decreases by a factor ≈ 2

Laboratory
Underground
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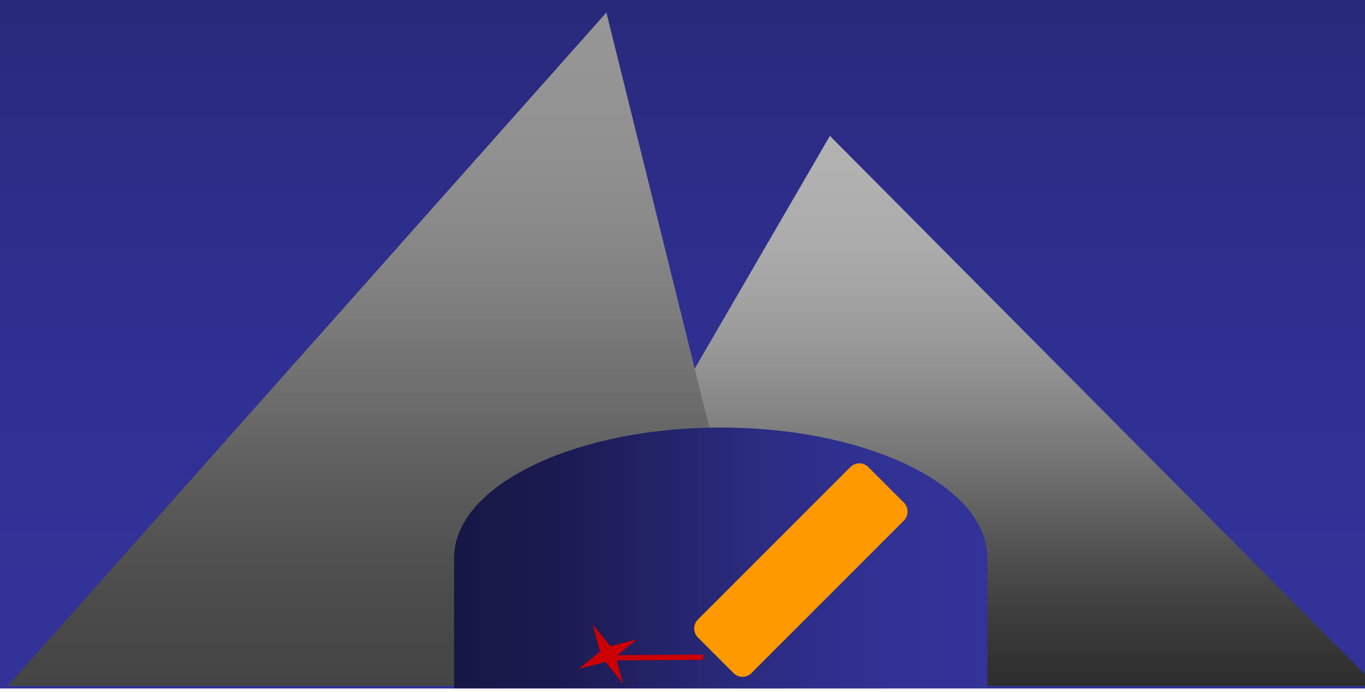
$D(\alpha,\gamma)^6Li$



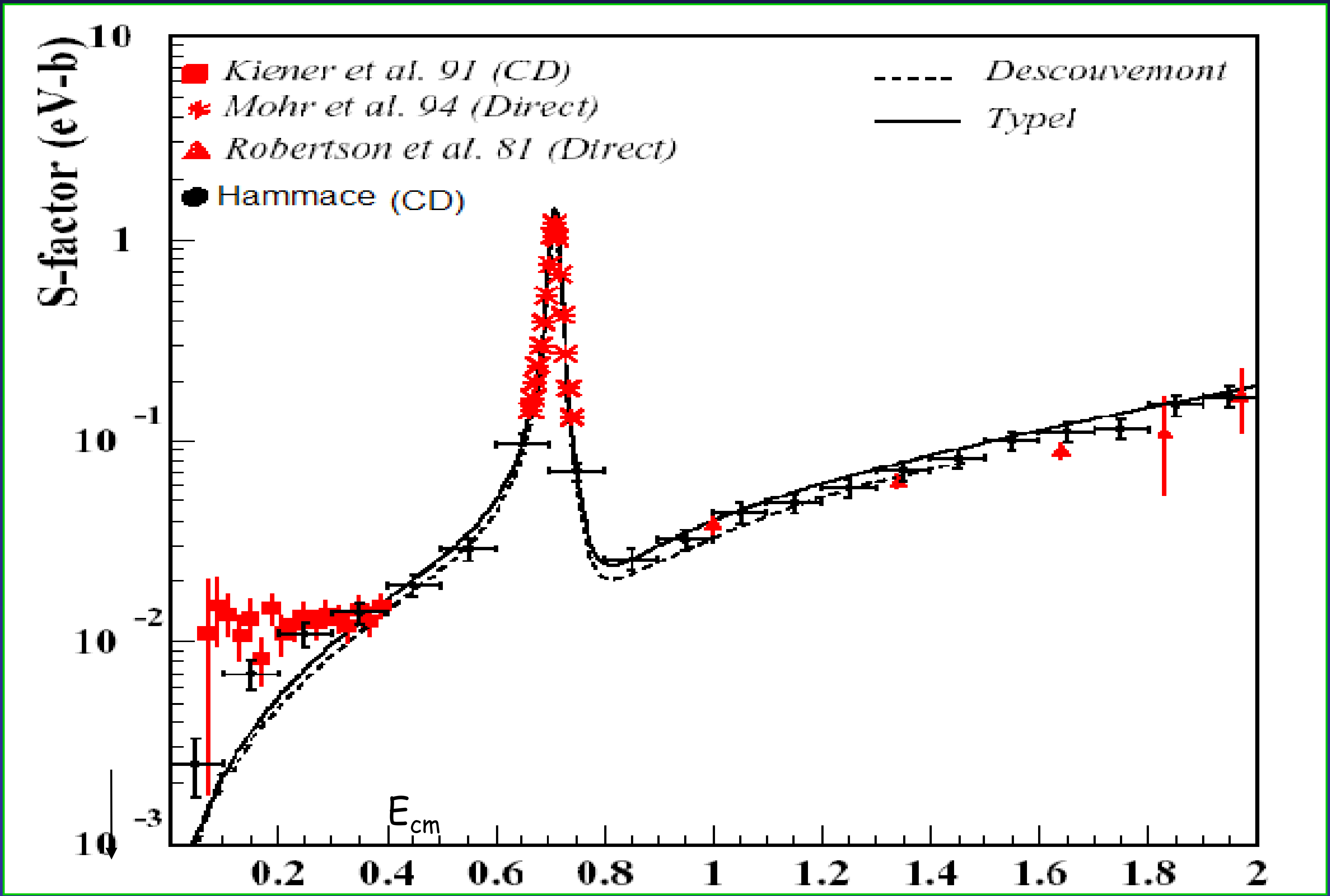
Key reaction for ^{6}Li BBN production

No direct measurements in the BBN region

Large discrepancies among exp. data
(indirect meas. only)

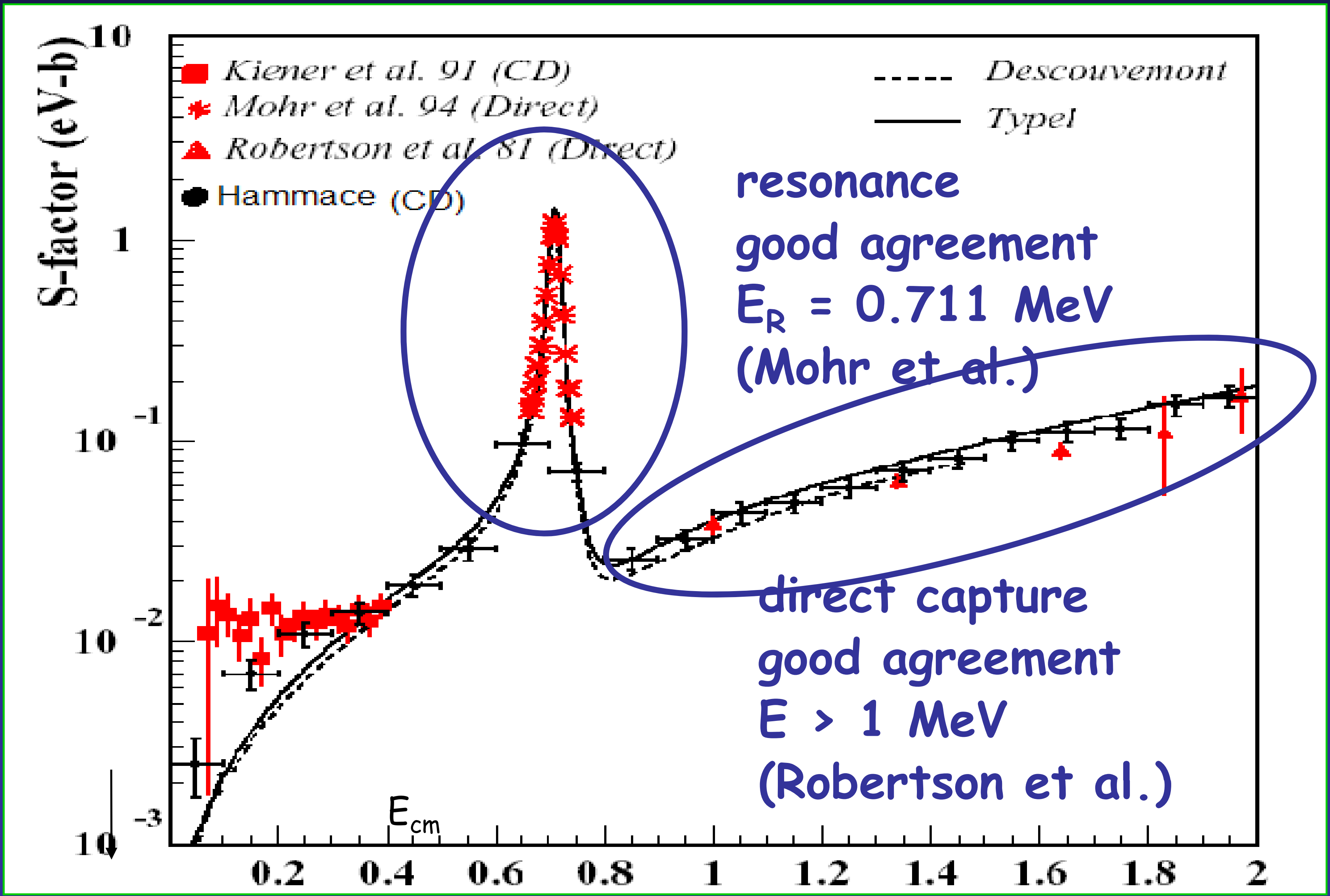
Theoretical calculations differ by
more than 1 order of magnitude.

D(α,γ)⁶Li



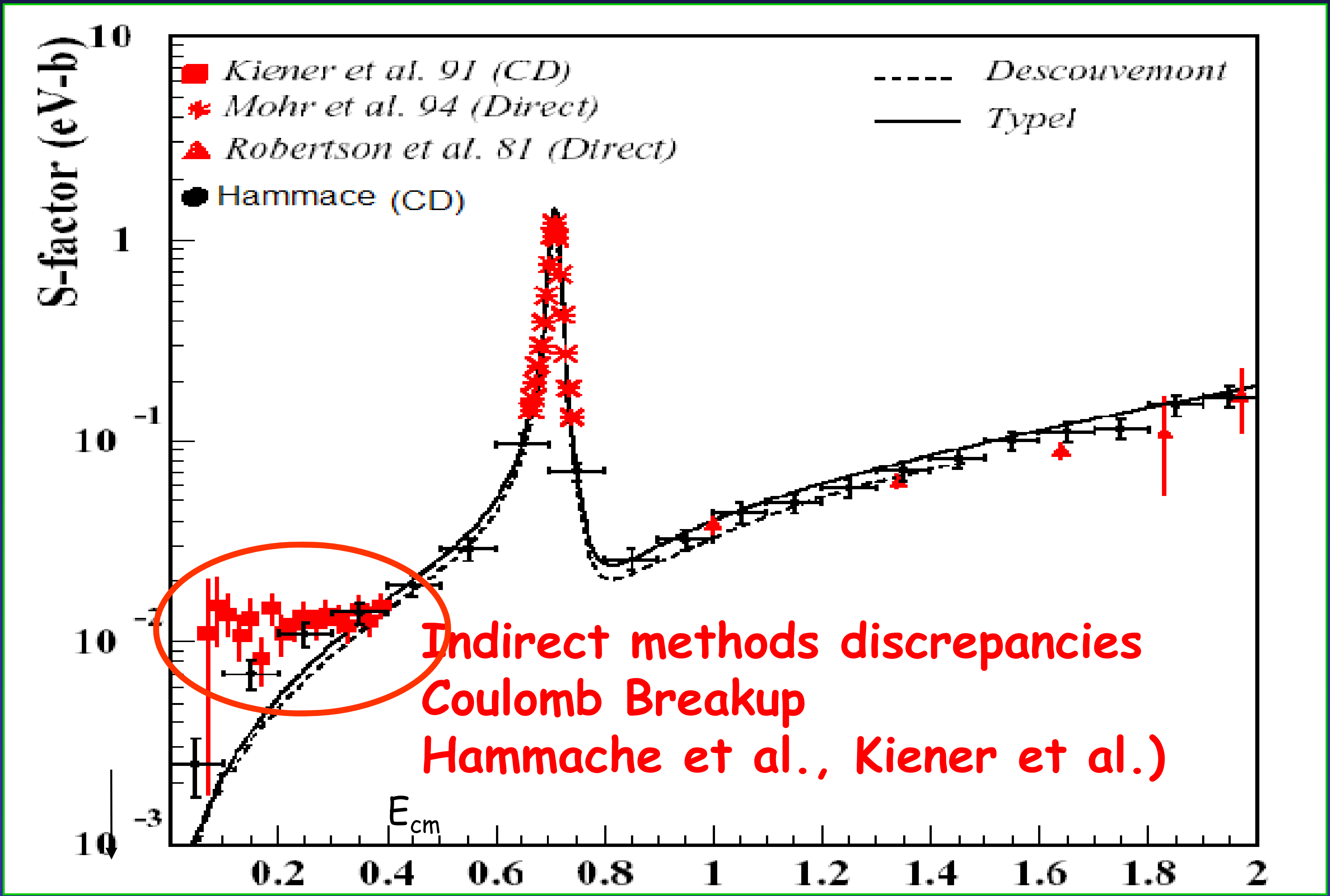
S-factor (eV-b)
10
1
10⁻¹
10⁻²
10⁻³
Kiener et al. 91 (CD)
Mohr et al. 94 (Direct)
Robertson et al. 81 (Direct)
Hammace (CD)
Descouvemont
Typel
E_cm
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2

D(α,γ)^{6}Li



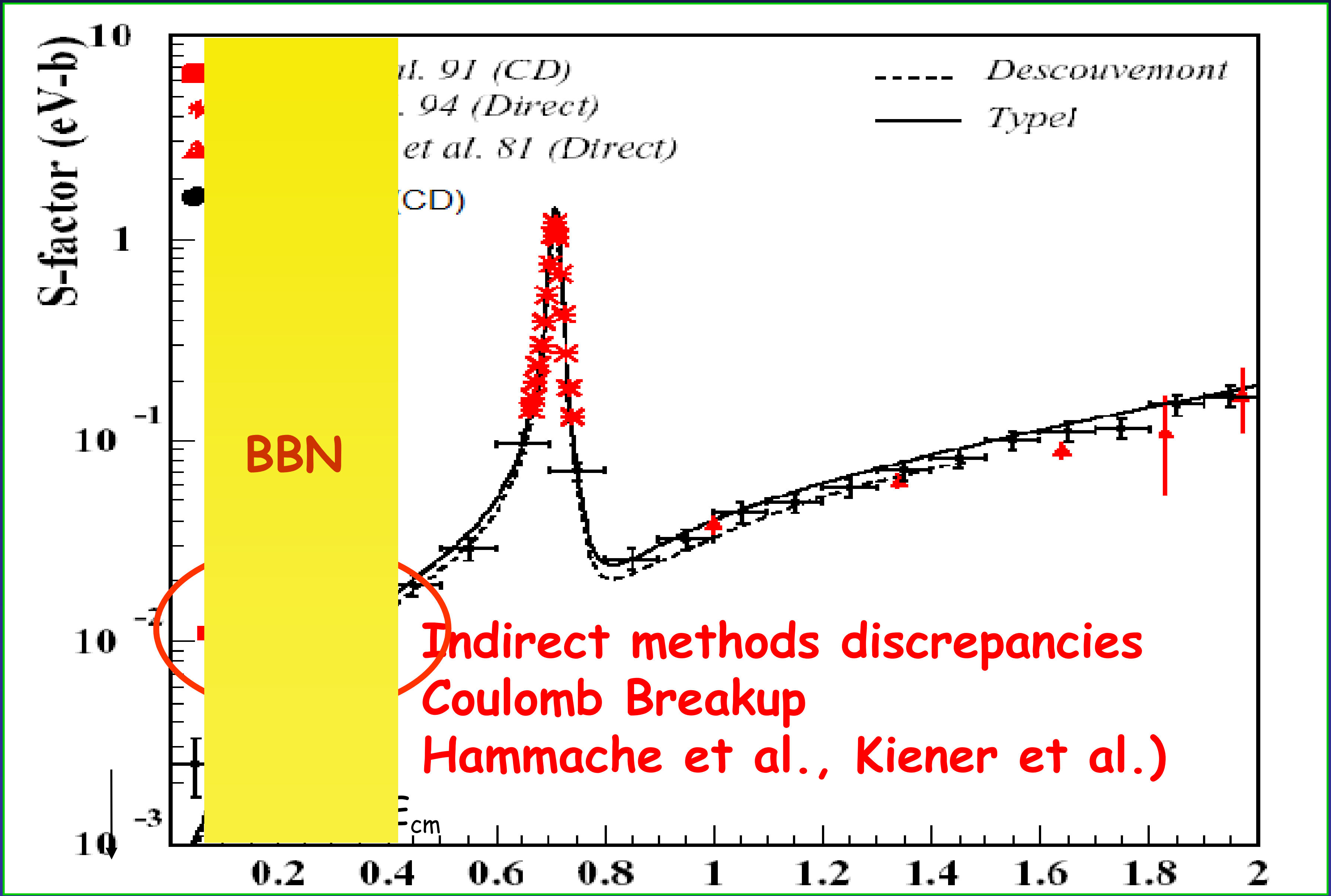
S-factor (eV-b)
Kiener et al. 91 (CD)
Mohr et al. 94 (Direct)
Robertson et al. 81 (Direct)
Hammace (CD)
Descouvemont
Typel
resonance
good agreement
E_R = 0.711 MeV
(Mohr et al.)
direct capture
good agreement
E > 1 MeV
(Robertson et al.)
E_cm
10
1
10^-1
10^-2
10^-3
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2

D(α,γ)^{6}Li

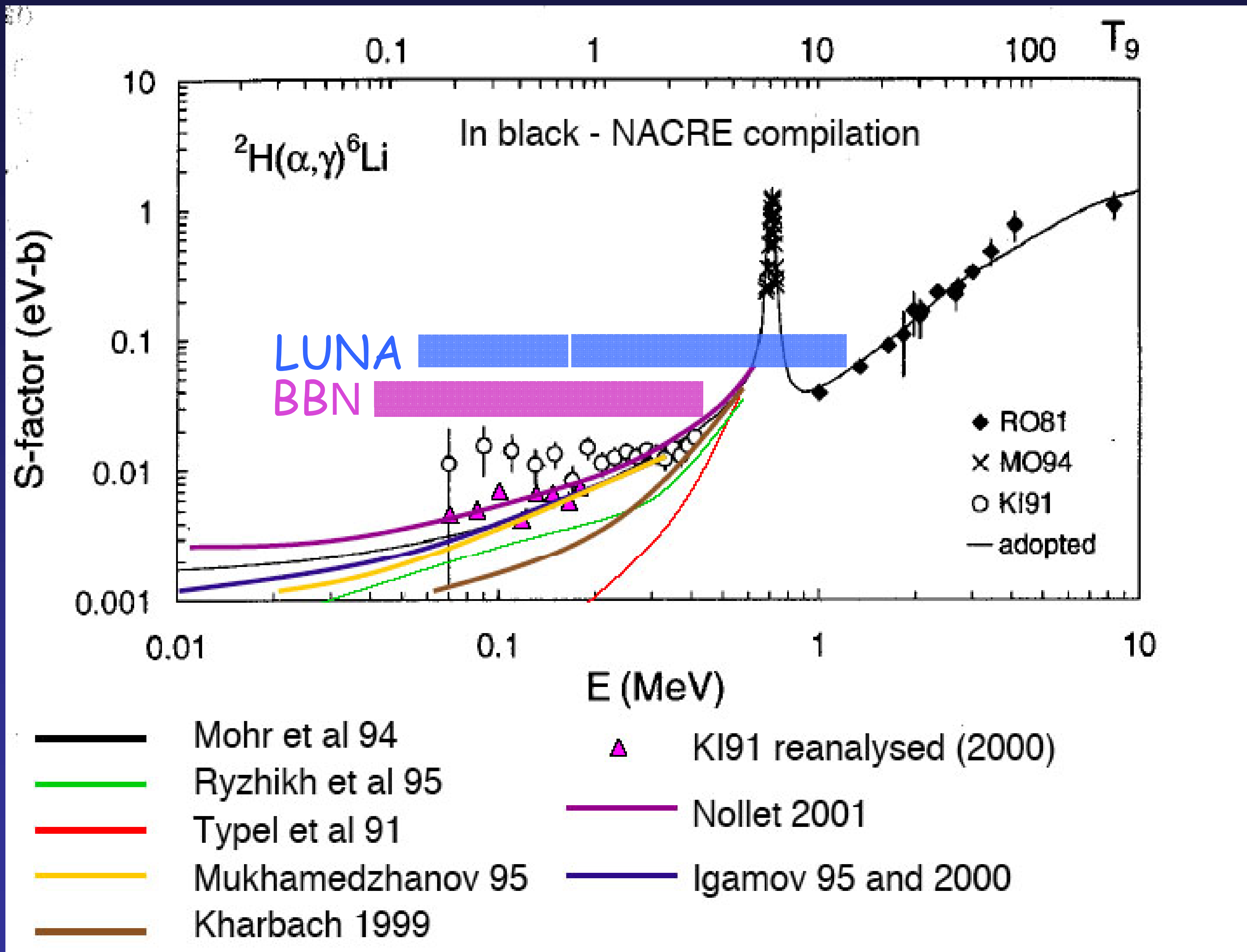


S-factor (eV-b)
10
1
10 -1
10 -2
10 -3
Kiener et al. 91 (CD)
Mohr et al. 94 (Direct)
Robertson et al. 81 (Direct)
Hammace (CD)
Descouvemont
Typel
Indirect methods discrepancies
Coulomb Breakup
Hammache et al., Kiener et al.)
E cm
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2

D(α,γ)^{6}Li



S-factor (eV-b)
10
1
10 -1
10 -2
10 -3
al. 91 (CD)
. 94 (Direct)
et al. 81 (Direct)
(CD)
Descouvemont
Typel
BBN
Indirect methods discrepancies
Coulomb Breakup
Hammache et al., Kiener et al.)
E cm
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2



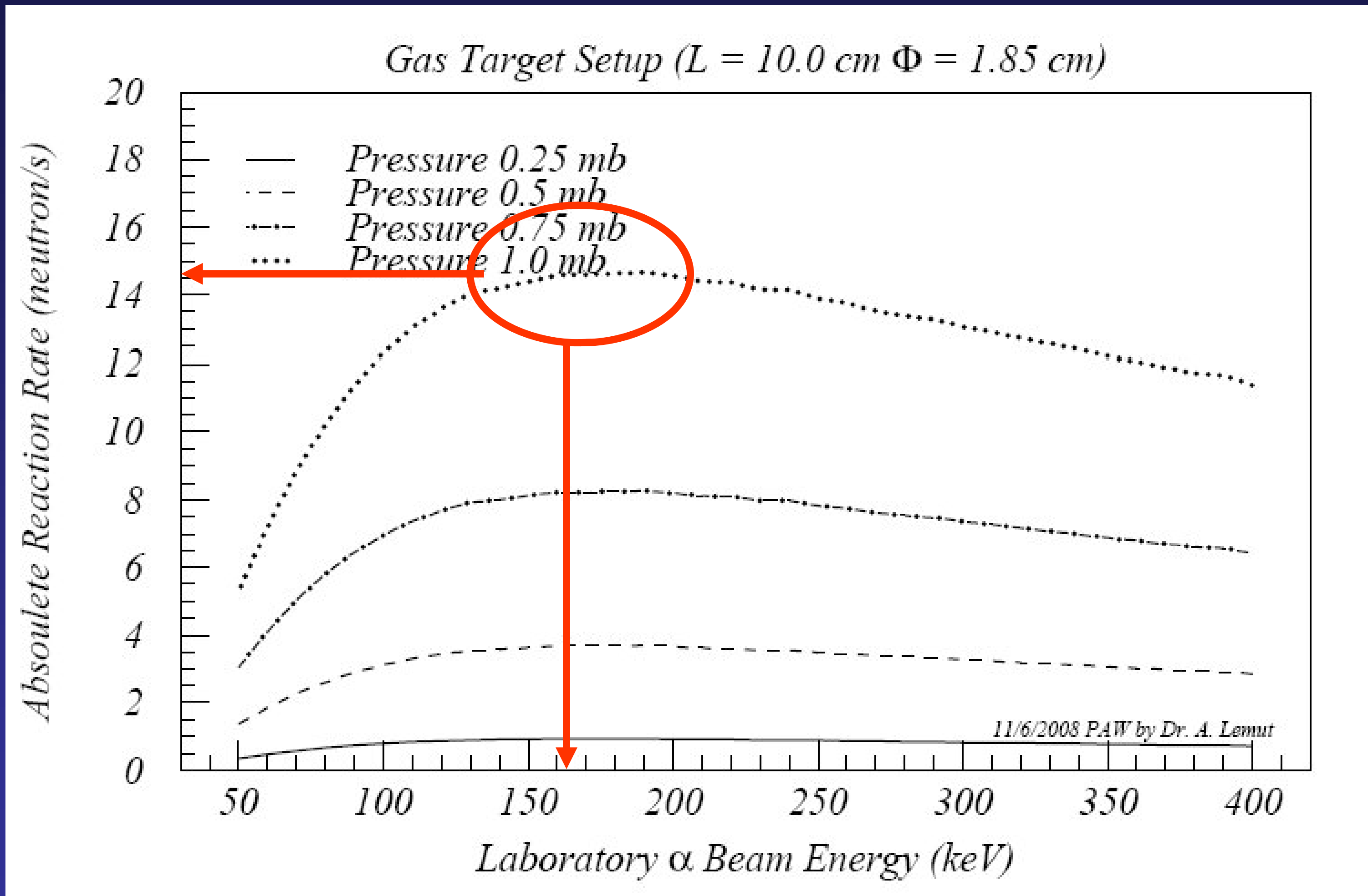
0.1
1
10
100
T_9
10
1
0.1
0.01
0.001
$^2H(\alpha,\gamma)^6Li$
In black - NACRE compilation
LUNA
BBN
RO81
MO94
KI91
adopted
S-factor (eV-b)
0.01
0.1
1
10
E (MeV)
Mohr et al 94
Ryzhikh et al 95
Typel et al 91
Mukhamedzhanov 95
Kharbach 1999
KI91 reanalysed (2000)
Nollet 2001
Igamov 95 and 2000

Data taking is still in stand-by

problem

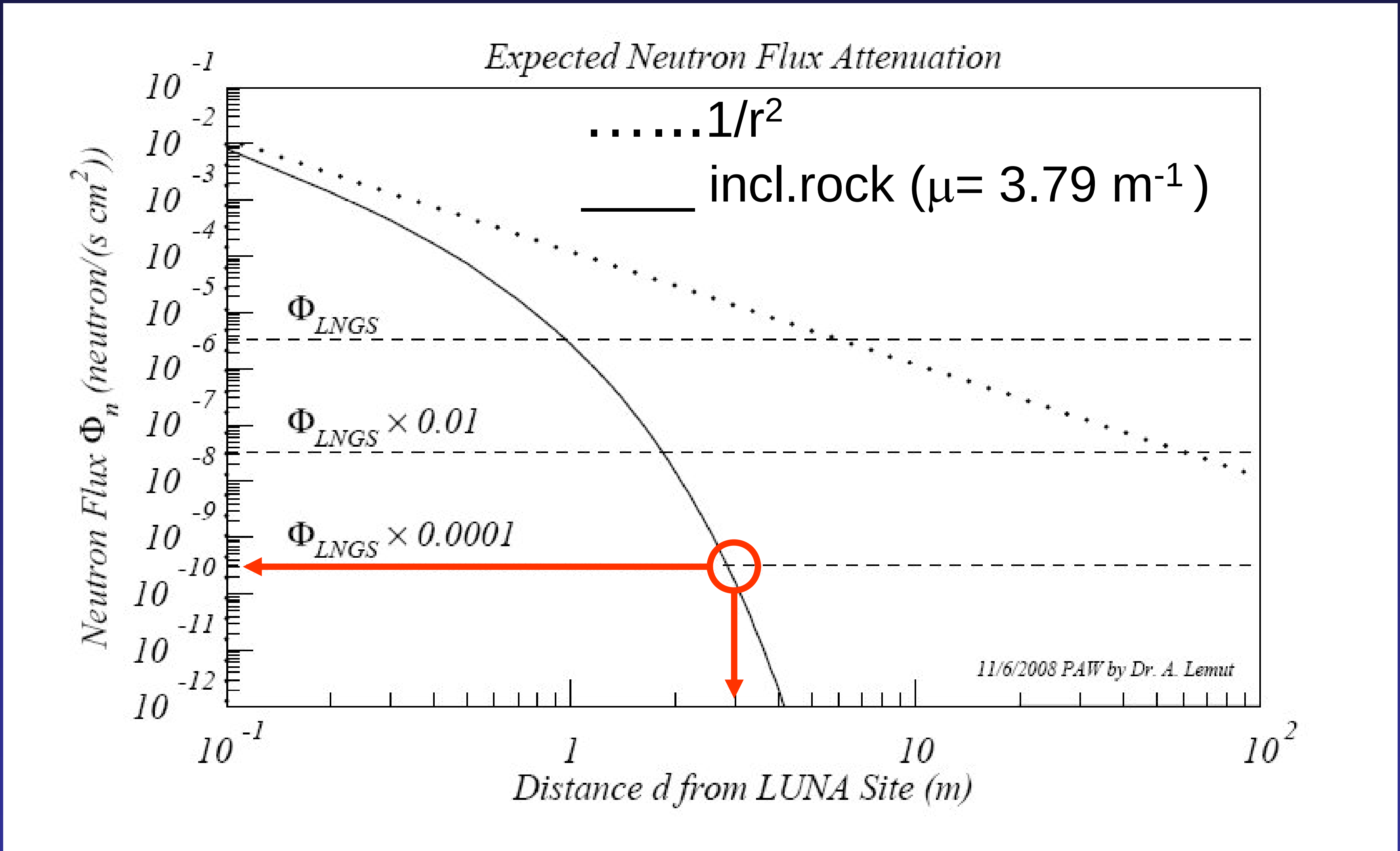
A small amount of neutrons can be produced by D(d,n)3He reaction due to D(α,α)D Rutherford scattered deuterons by the alpha beam.

neutron yield estimation



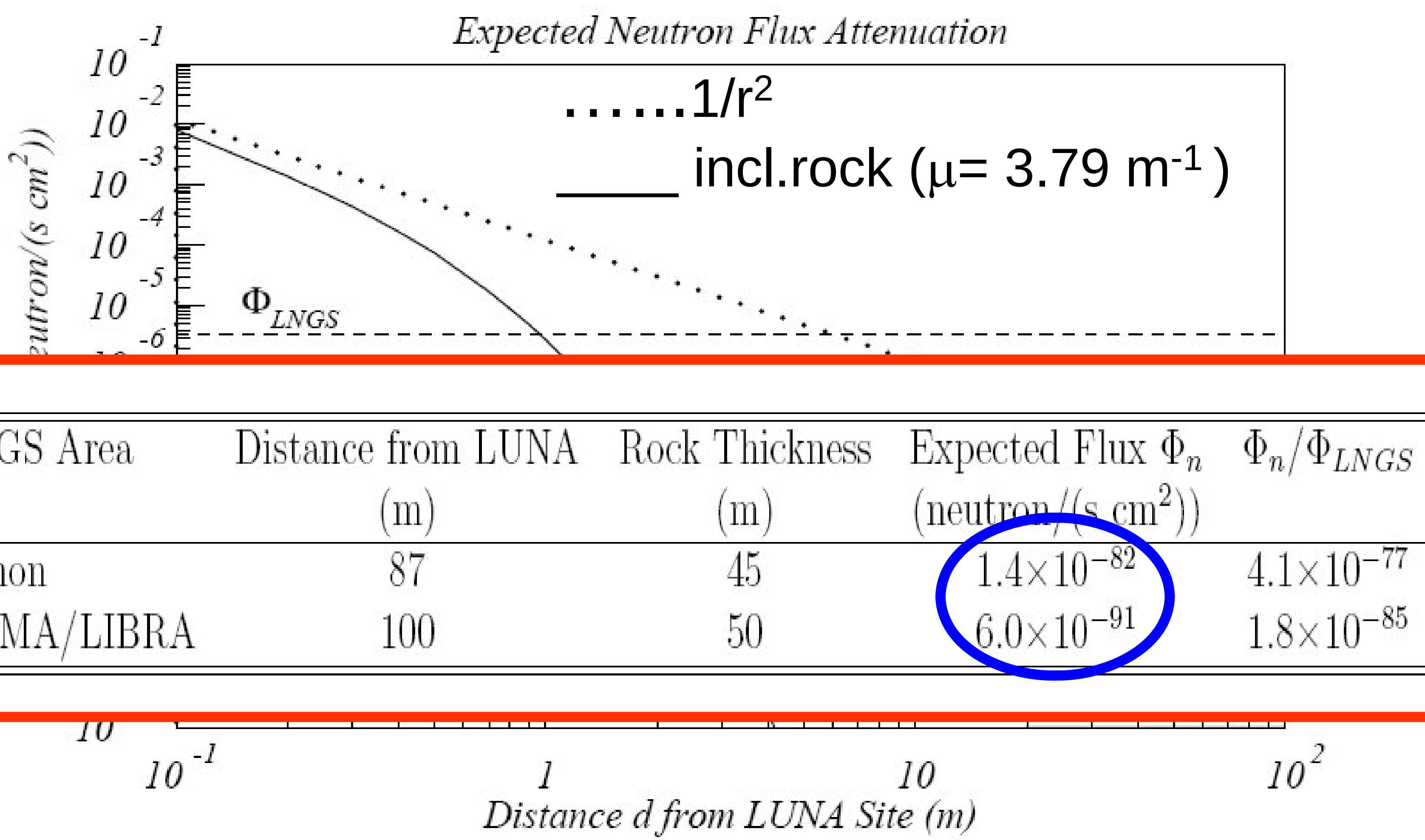
Max. count. rate: 15 neutrons/s

neutron flux estimation



@3m: $\Phi_n = 10^{-4}\Phi_{LNGS}$

neutron flux estimation



LNGS Area	Distance from LUNA (m)	Rock Thickness (m)	Expected Flux Φ_n (neutron/(s cm^2))	Φ_n/Φ_{LNGS}
Xenon	87	45	1.4×10^{-82}	4.1×10^{-77}
DAMA/LIBRA	100	50	6.0×10^{-91}	1.8×10^{-85}

@3m: $\Phi_n = 10^{-4}\Phi_{LNGS}$

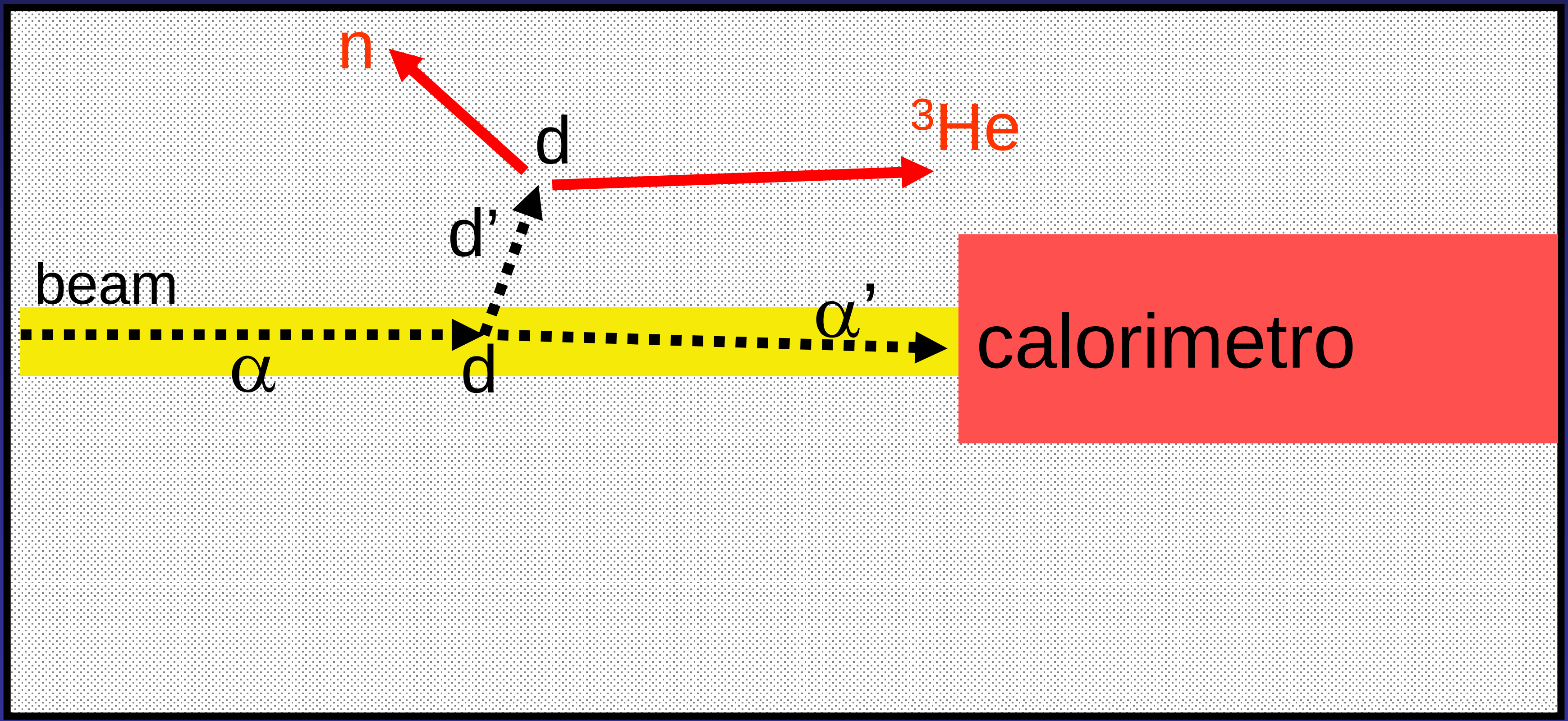
We ask the permission to do a test run

A report with neutron rate calculation has been submitted to the LNGS Committee in charge to fix the rules for the use of calibration neutron sources.

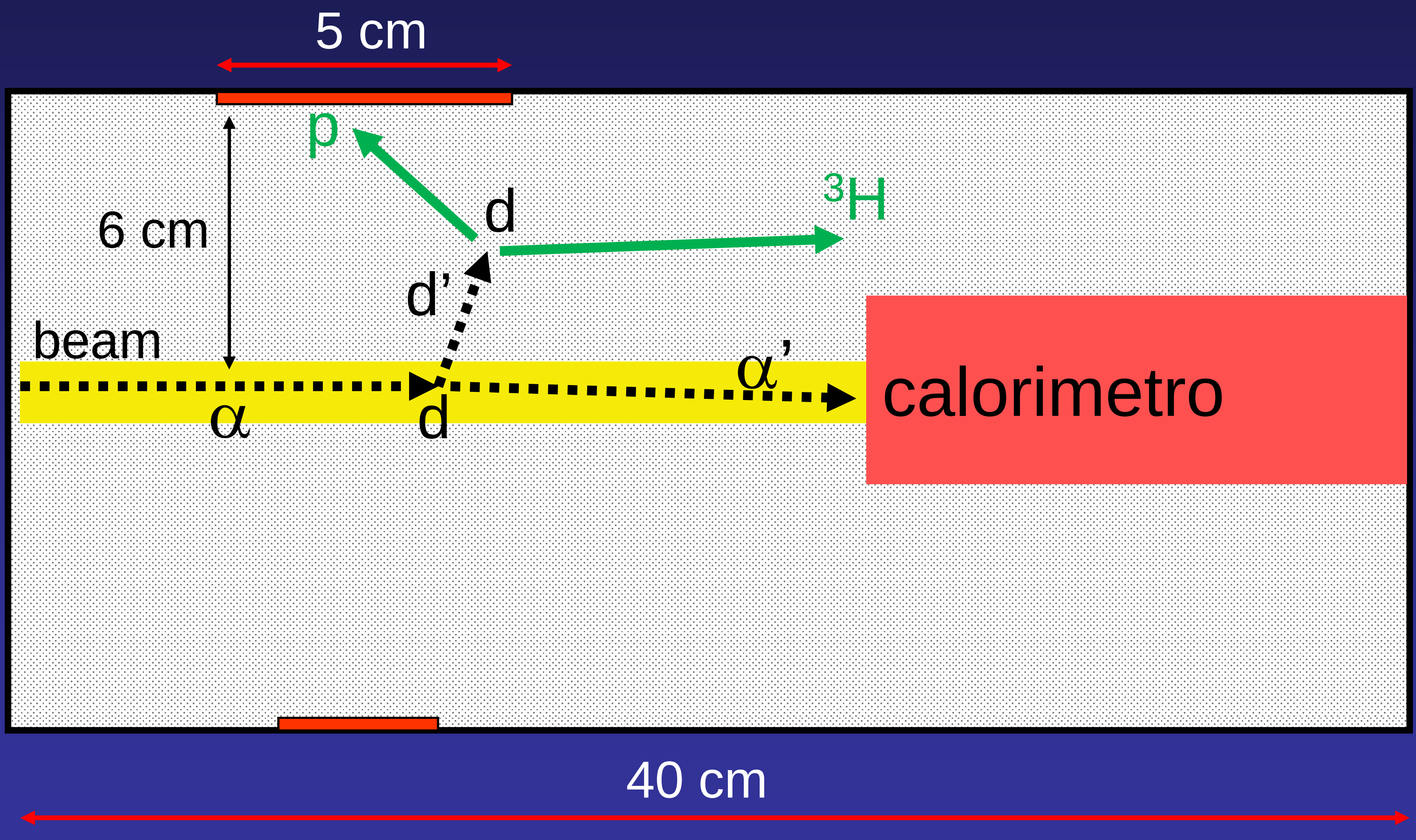
26 March 2009: test started

14 September 2010: experiment started

$$\sigma_{dd\to n\,^3He} = \sigma_{dd\to p\,^3H}$$

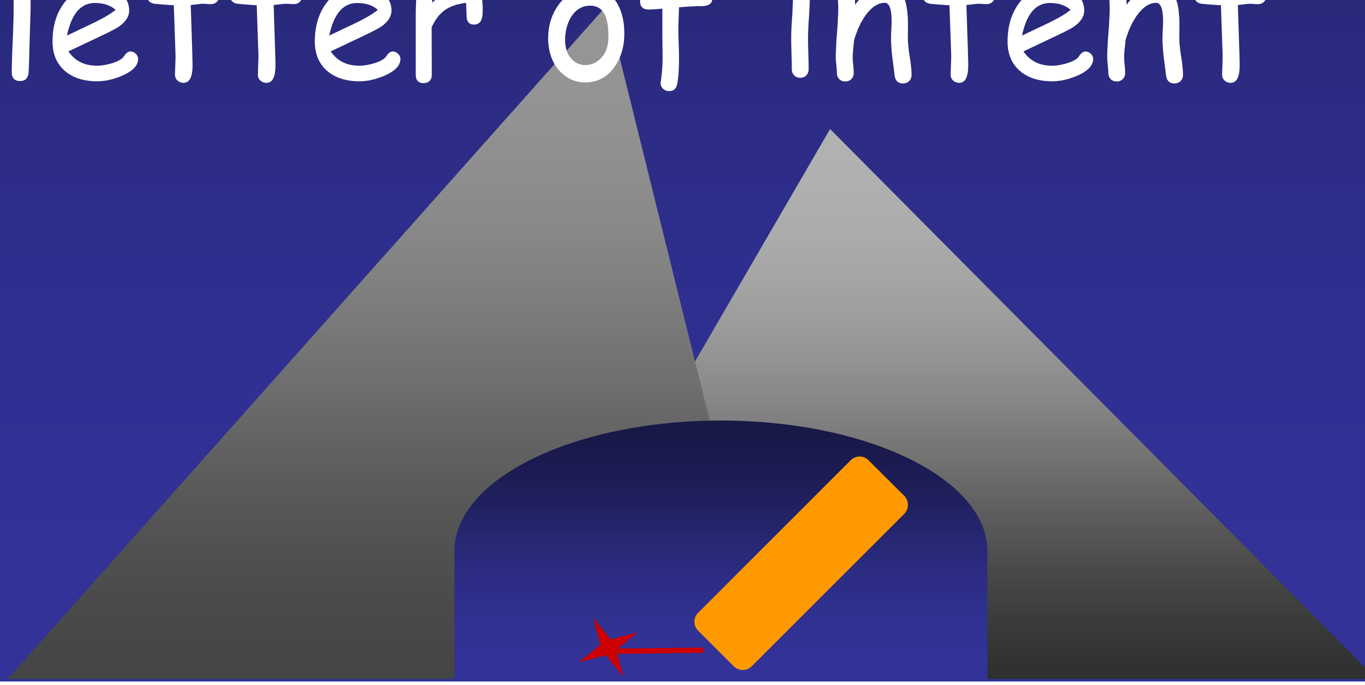


$$\sigma_{dd \rightarrow n\,^3He} = \sigma_{dd \rightarrow p\,^3H}$$



Laboratory
Underground
Nuclear
Astrophysics

LUNA - MV letter of intent



what else might be studied underground?

$^{12}C(\alpha,\gamma)$, $^{16}O(\alpha,\gamma)$ *Supernovae ~ He burning*

$^{13}C(\alpha,n)$, $^{22}Ne(\alpha,n)$ *s process ~ n production*

$^{14}N(\alpha,\gamma)$
$^{18}O(\alpha,\gamma)$
$^{22}Ne(\alpha,\gamma)$
} *AGB stars ~ s process*

$^{14}N(p,\gamma)$
$^{17}O(p,\gamma)$
$^{17}O(p,\alpha)$
} *Red giants ~ CNO cycle*

$^{22}Ne(p,\gamma)$
$^{23}Na(p,\alpha)$
$^{24}Mg(p,\gamma)$
} *Globular clusters ~ Ne/Mg/Na cycles*

^{20}Ne, ^{24}Mg, ^{28}Si, ^{32}S, ^{36}Ar, $^{40}Ca(\alpha,\gamma)$ *Supernova nucleosynthesis*

what else might be studied underground?

$^{12}C(\alpha,\gamma)$, $^{16}O(\alpha,\gamma)$ *Supernovae ~ He burning*

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$^{14}N(\alpha,\gamma)$
$^{18}O(\alpha,\gamma)$
$^{22}Ne(\alpha,\gamma)$
} *AGB stars ~ s process*

$^{14}N(p,\gamma)$
$^{17}O(p,\gamma)$
$^{17}O(p,\alpha)$
} *Red giants ~ CNO cycle*

$^{22}Ne(p,\gamma)$
$^{23}Na(p,\alpha)$
$^{24}Mg(p,\gamma)$
} *Globular clusters ~ Ne/Mg/Na cycles*

^{20}Ne, ^{24}Mg, ^{28}Si, ^{32}S, ^{36}Ar, $^{40}Ca(\alpha,\gamma)$ *Supernova nucleosynthesis*

In april 2007 + november 2007 (addendum) we presented to the XXVIII S.C. a LOI for a 3.5 MV accelerator to be installed @ LNGS for the study of the reactions:

$^{12}C(\alpha,\gamma)^{16}O$ $D(\alpha,\gamma)^{6}Li$

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

.. plus other "minor" reactions...

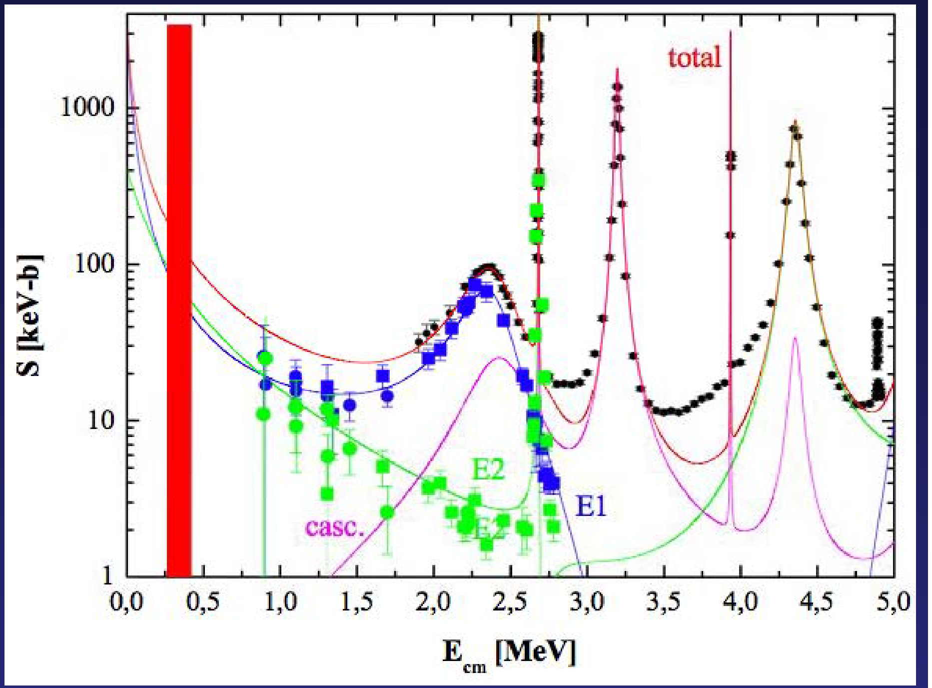
the answer was:

Gran Sasso Scientific Committee Report on LUNA MV Proposal

The SC analyzed the LUNA-MV Letter of Intent (LNGS-LOI 42/07), together with the addendum presented at the last meeting (XXVIII – October 2007), concerning the construction of a new LUNA accelerator in the underground Laboratory. The SC recognizes the important physics programme of the proposal, a natural development of the current experiment which gave outstanding results. Nevertheless, the SC noted that the LUNA-MV project has a non-negligible impact on the whole Laboratory's activity, mainly under two respects: (i) the underground space needed and (ii) the possible radio-activity pollution. The space needed by LUNA-MV can be evaluated to be approximately 1/5 of a main experimental hall. This space, if allocated, will definitively saturate the total available space underground for a substantial time. This scenario has important consequences for the Laboratory, preventing any further development of the approved experiments as well as any new experiment proposal. The second issue concerns the neutron and gamma activity connected with a 3 MV accelerator. This activity, even if properly shielded as discussed in the LOI/addendum, could still seriously increase the Laboratory background, the low level of which is a major advantage of the Gran Sasso Laboratory. Based on these two important points the SC was not able to recommend approval of LUNA-MV to proceed to a full proposal for deployment at Gran Sasso. Nevertheless, the SC reiterates its view that the science of the LUNA-MV project is very important and hopes the collaboration will be successful in finding an alternative location.

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

- MV-accelerator
- ^{12}C-enriched targets
- Beam intensity: 500 ⌠A
- Detection efficiency: 50% total
  2.5% single segment (angular distributions)
- Detection set-up: scintillator-crystal ball



- We would have the possibility to measure angular distributions down to 600 keV and total S-factor down to 500 keV with 10% accuracy
- Theoreticians ask for 10% uncertainty on $S_{tot}(300)$

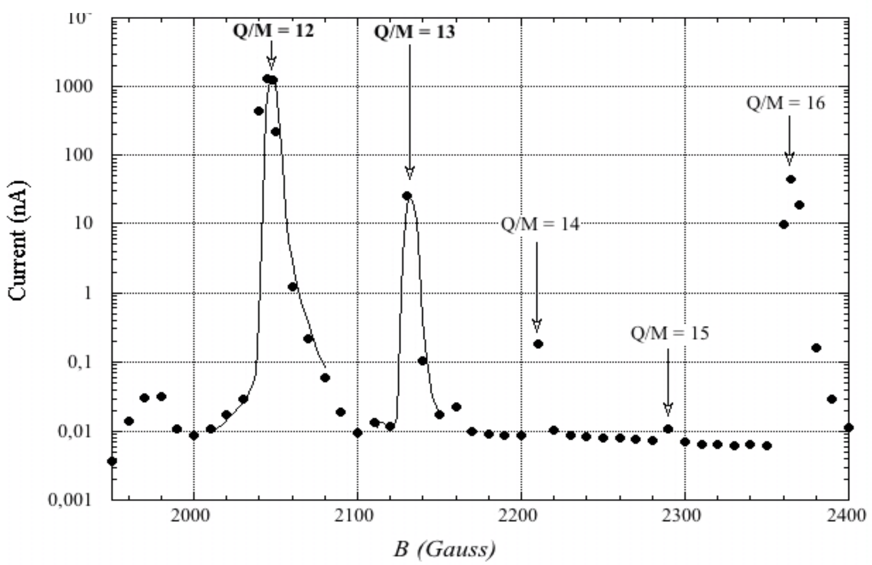
Great step forward: so far, 10% accuracy only over 1.5 MeV

Target preparation

$$\frac{^{13}C}{^{12}C} \approx 10^{-2} \qquad \frac{\sigma\left(^{13}C(\alpha,n)^{16}O\right)}{\sigma\left(^{12}C(\alpha,\gamma)^{16}O\right)} \approx 10^{7}$$

goal: reduce ^{13}C content to $10^{-7} \div 10^{-6}$

Implantation facility @ LNL



magnet resolving power seems ok

How to measure?

sharp resonance of $^{13}C(p,\gamma)^{14}N$ @ 1.75 MeV

Reactions powering the astrophysical s-process

Neutron source reactions: **$^{13}C(a,n)^{16}O$** and **$^{22}Ne(a,n)^{25}Mg$**

- Important for nucleosynthesis of elements heavier than iron

-Take place in helium- and carbon-burning reactions in massive and AGB stars

-For $^{13}C(a,n)^{16}O$ data above 270 keV are available
(Gamow peak ~170 keV, LUNA ~200 keV)

- For $^{22}Ne(a,n)^{25}Mg$ data above 850 keV are available
(Gamow peak ~470-700 keV, LUNA ~630 keV)

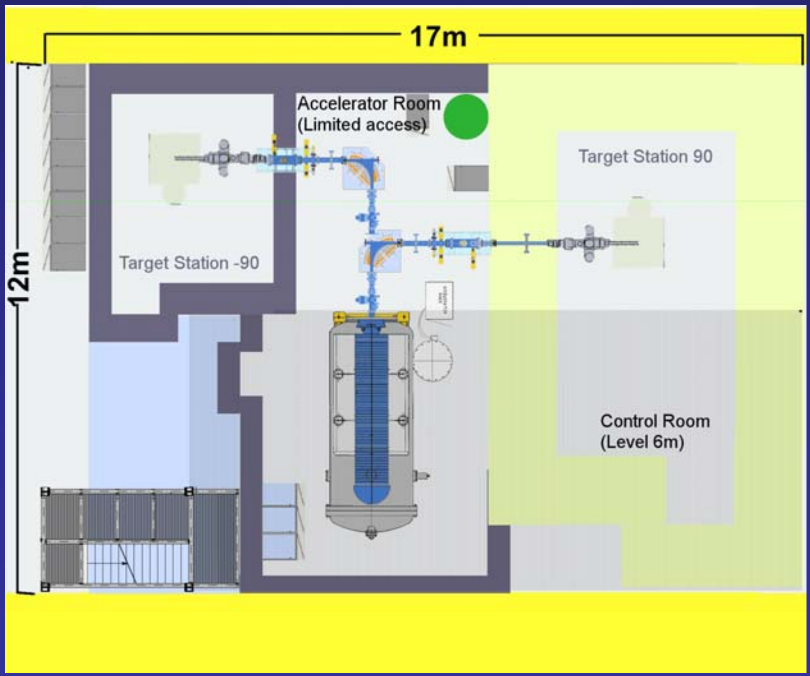
⇒ **MV accelerator**

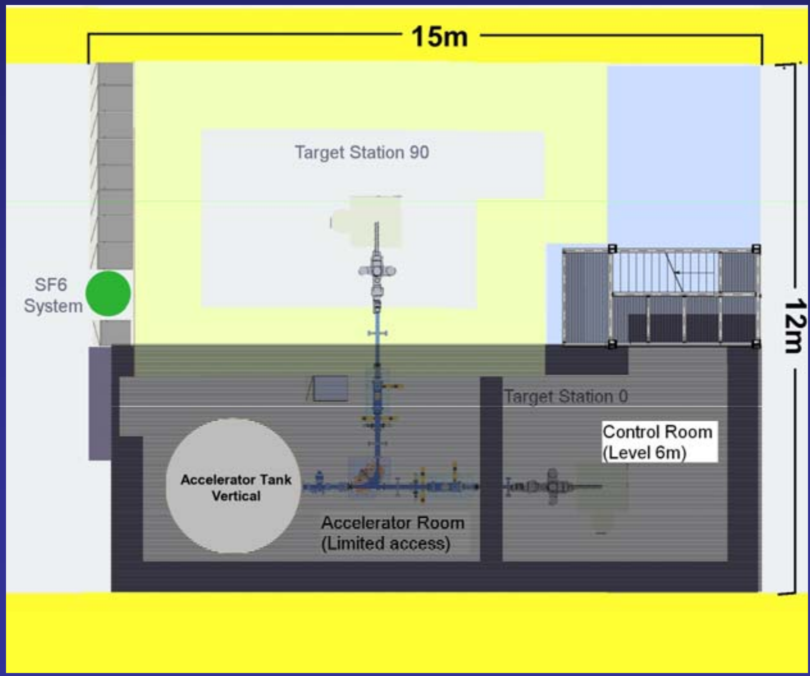
Accelerator

Accelerator requirements:

- MV electrostatic accelerator
- Option 1: HVEE + conventional RF ion source
- Option 2: NEC + ECR high charge state ion source

Two possible layouts:

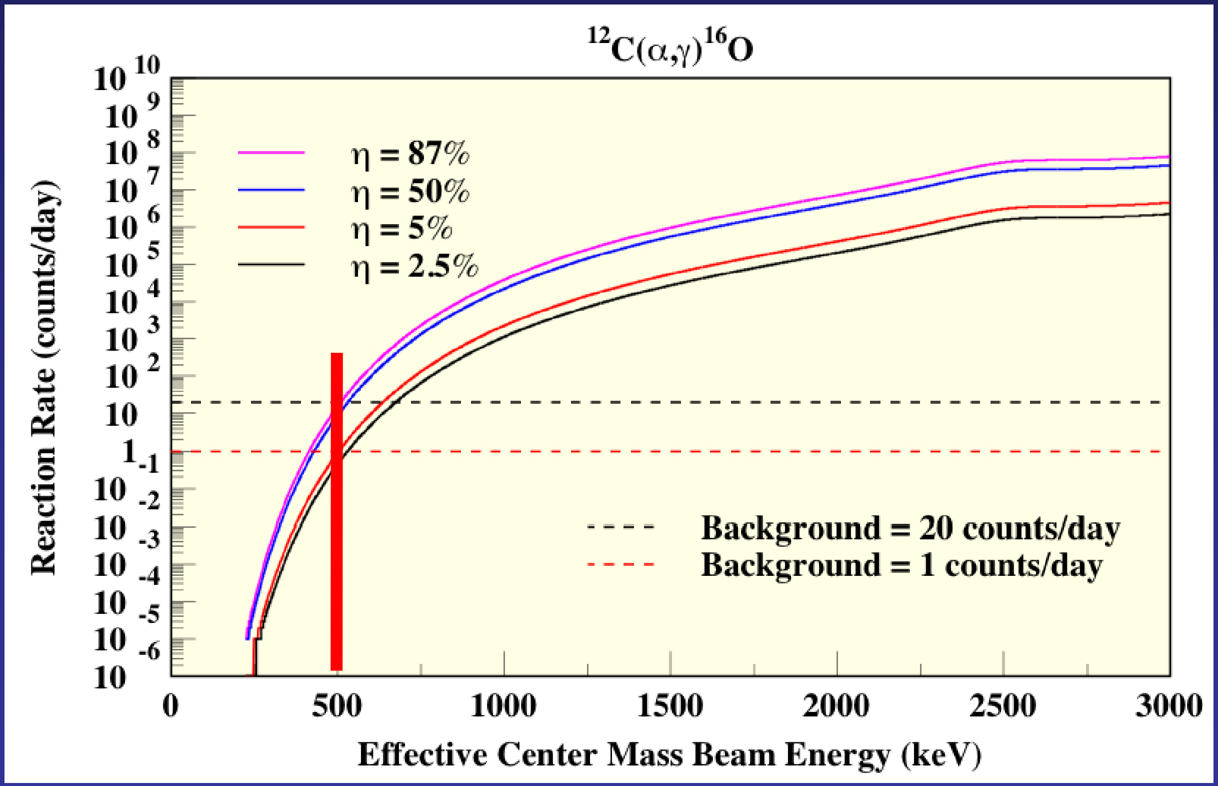




letter of intent submitted to LNGS

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

counting rate



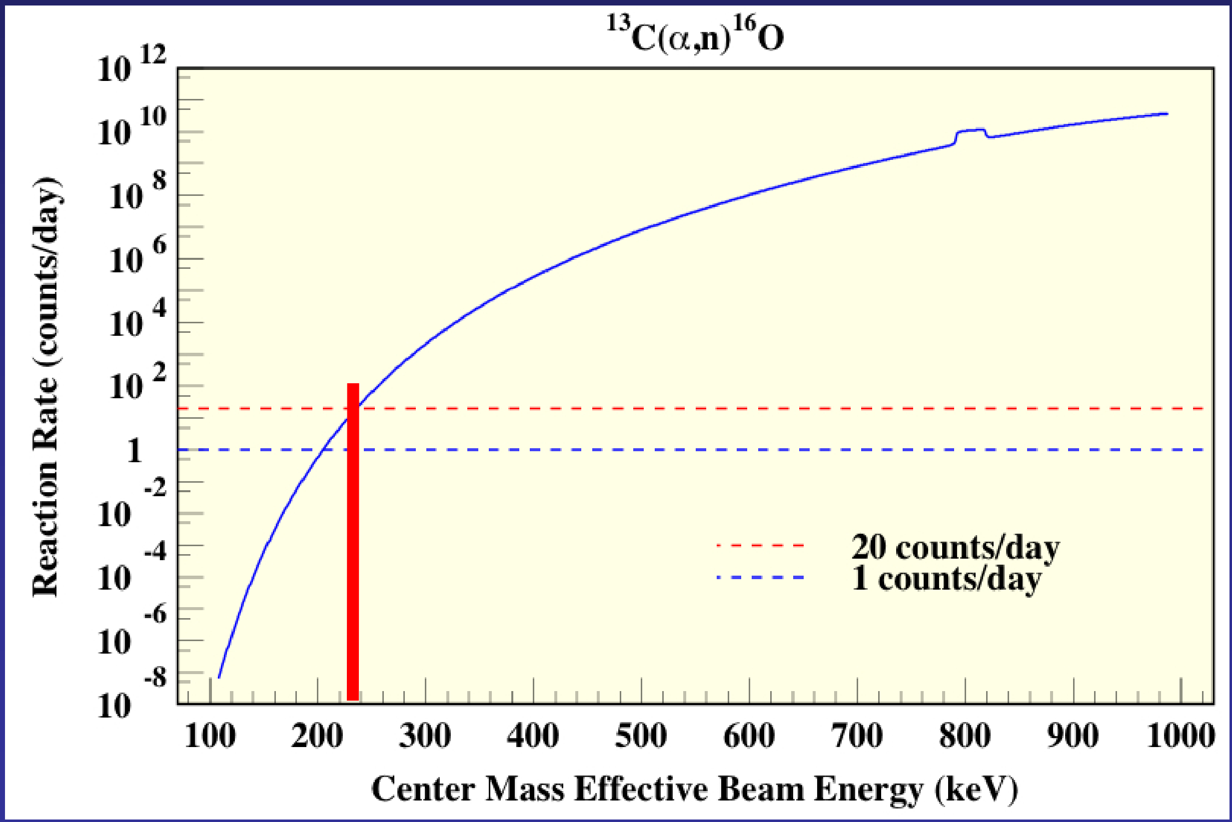
50% effic.

400 μA

solid target
$2 \cdot 10^{18}$ atoms/cm2

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

counting rate



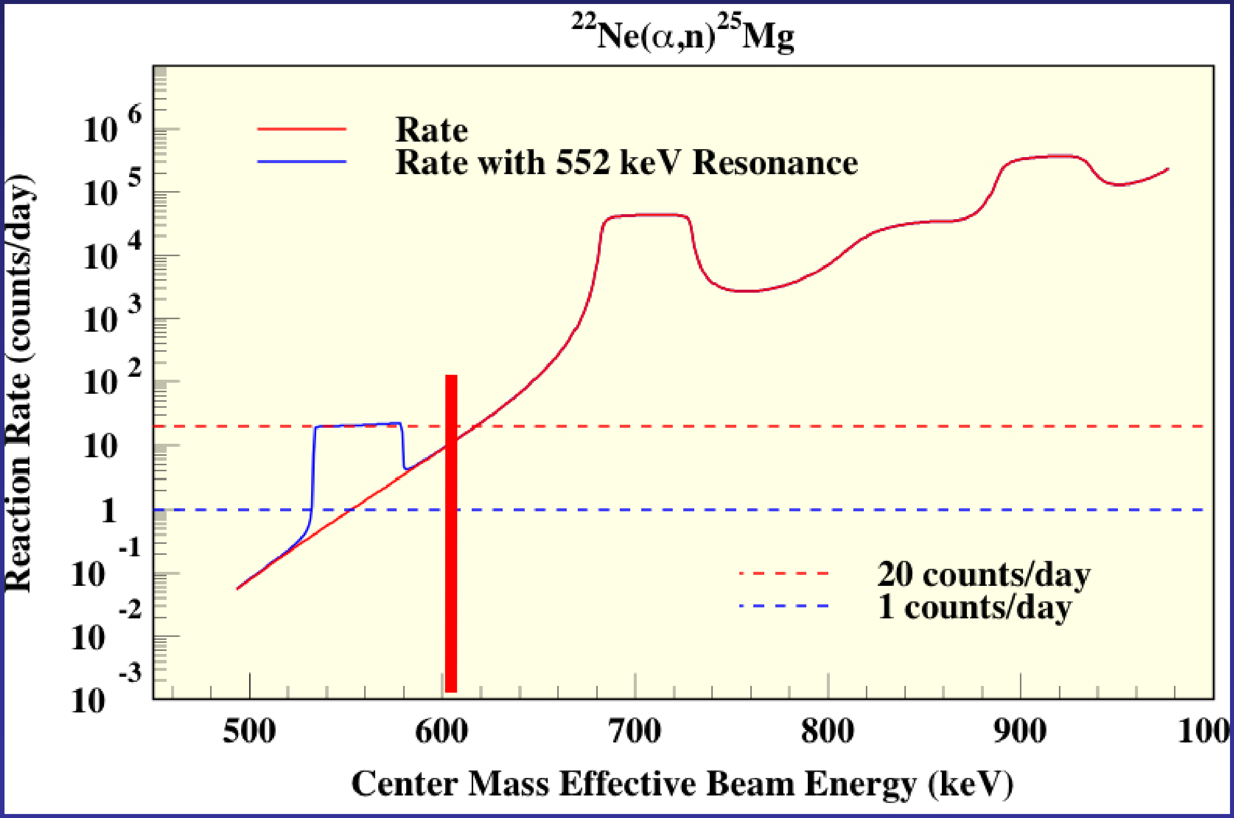
10% effic.

100 μA

solid target
$5 \cdot 10^{18}$ atoms/cm2

$^{22}Ne(\alpha,n)^{24}Mg$

counting rate



10% effic.

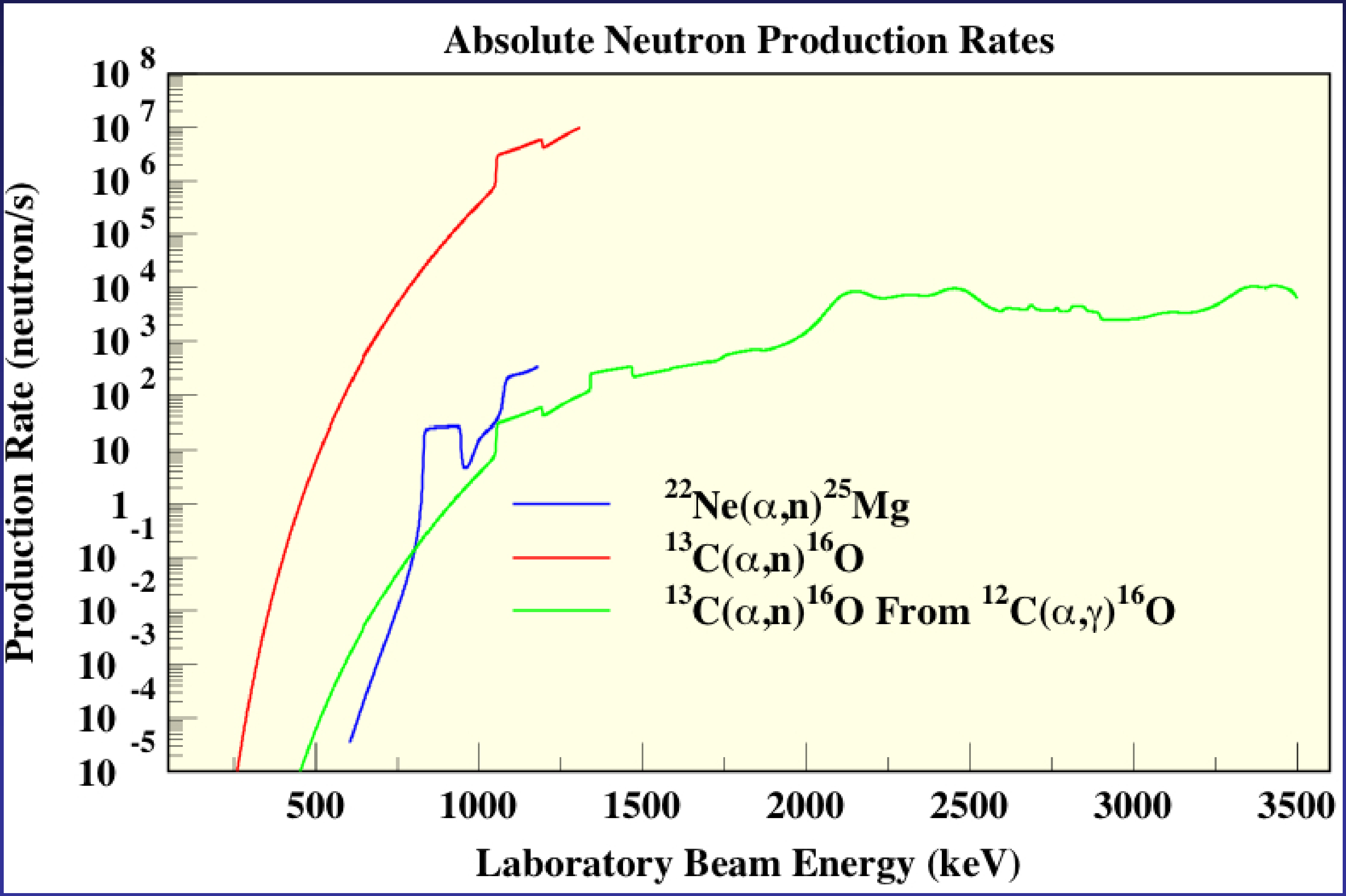
100 µA

5 mbar

10^{18} atoms/cm2

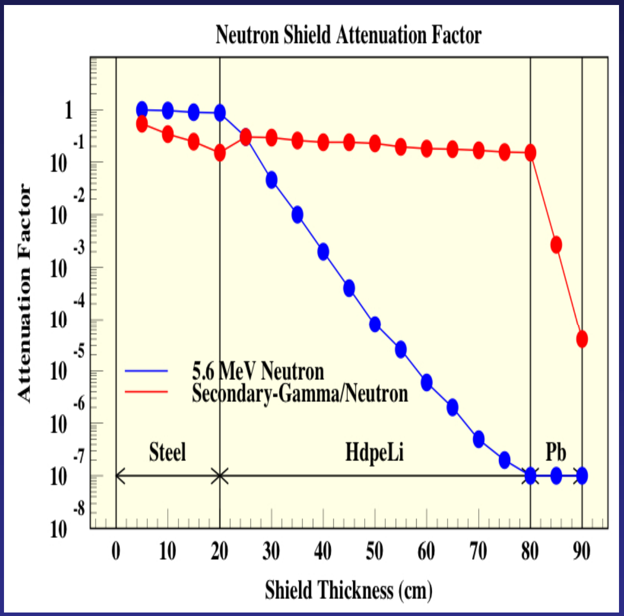
Neutron shielding

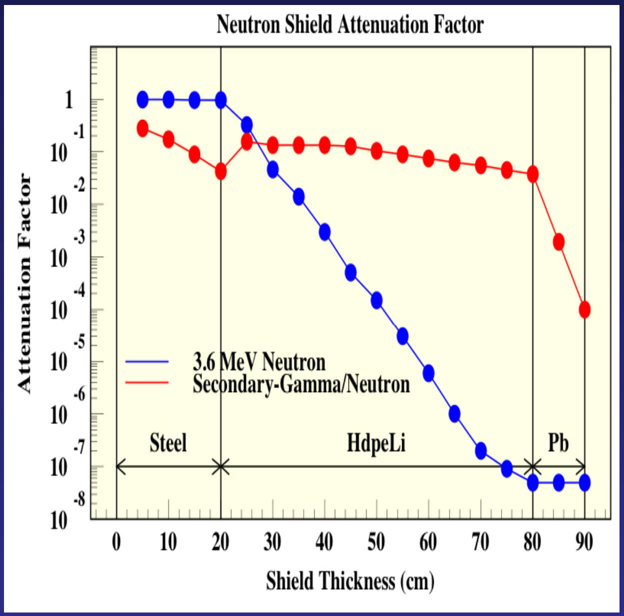
neutron production rate

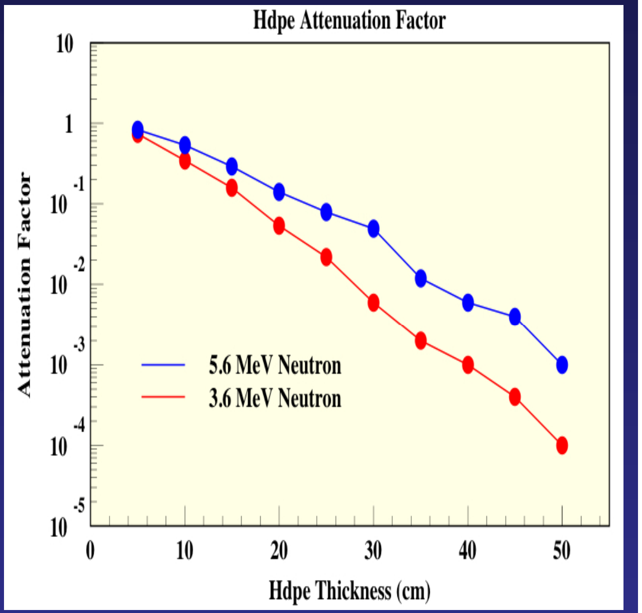


Neutron shielding

GEANT4 simulation – Fluka simulation







20 cm steel
60 cm HD poliethylene(Li)
10 cm lead

$\Phi_{nat}=3.78\cdot 10^{-6}$ neutrons/($m^2\cdot d$)

LUNA COLLABORATION

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