Hydrogen Burning in Stars

Hydrogen in induced reaction have lowest Coulomb barrier $\Rightarrow$ highest reaction rate

Hydrogen burning provides energy production in "Main Sequence Stars" in the HR Diagram (sun) until hydrogen fuel is depleted $\Rightarrow$ the life time of main sequence star depends on the reaction rates

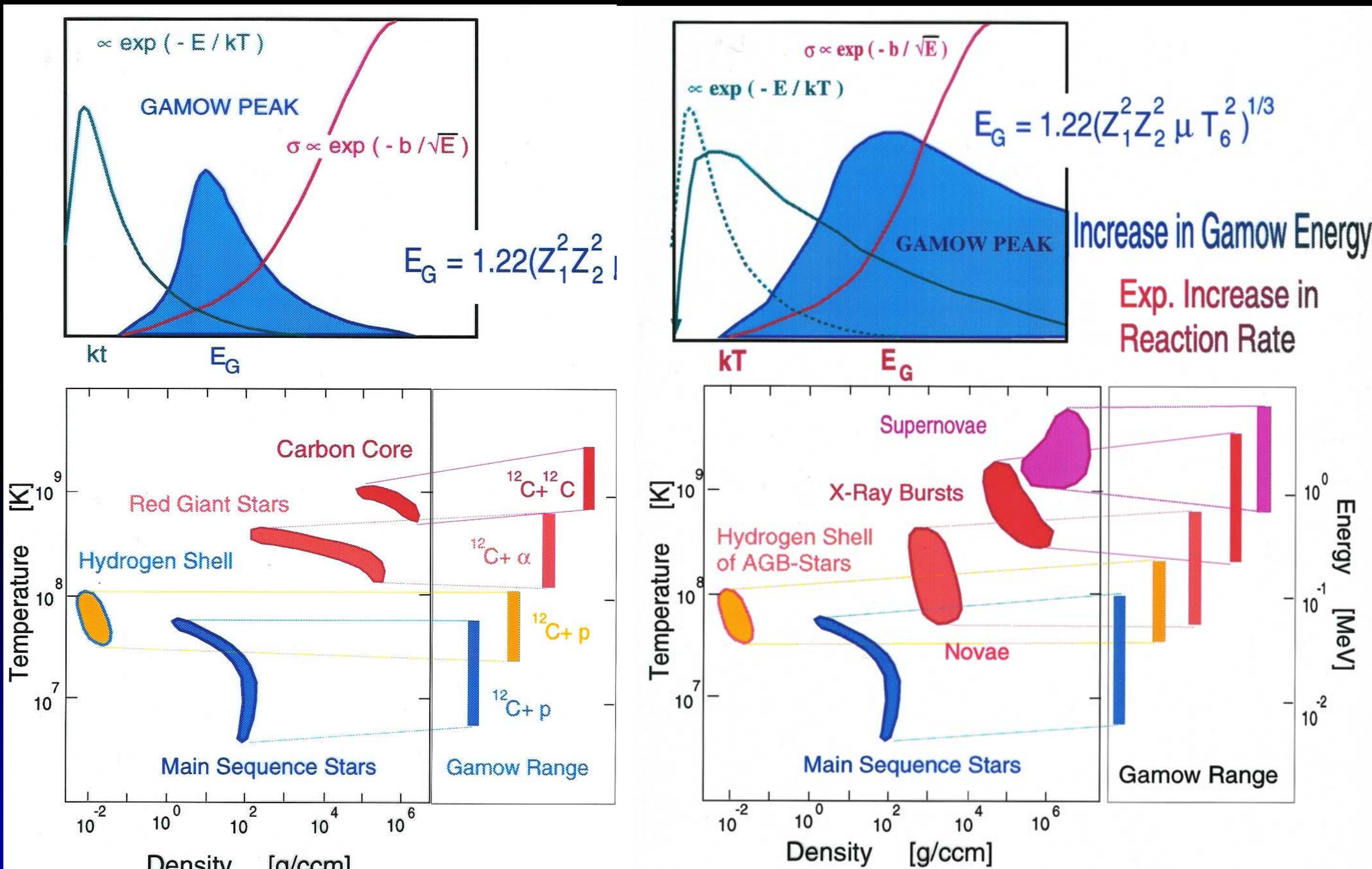
The stellar evolution, or subsequent evolutionary stages depend on the subsequent nucleosynthesis mechanisms or their nuclear fuel processing!

Topics in Nuclear Astrophysics III

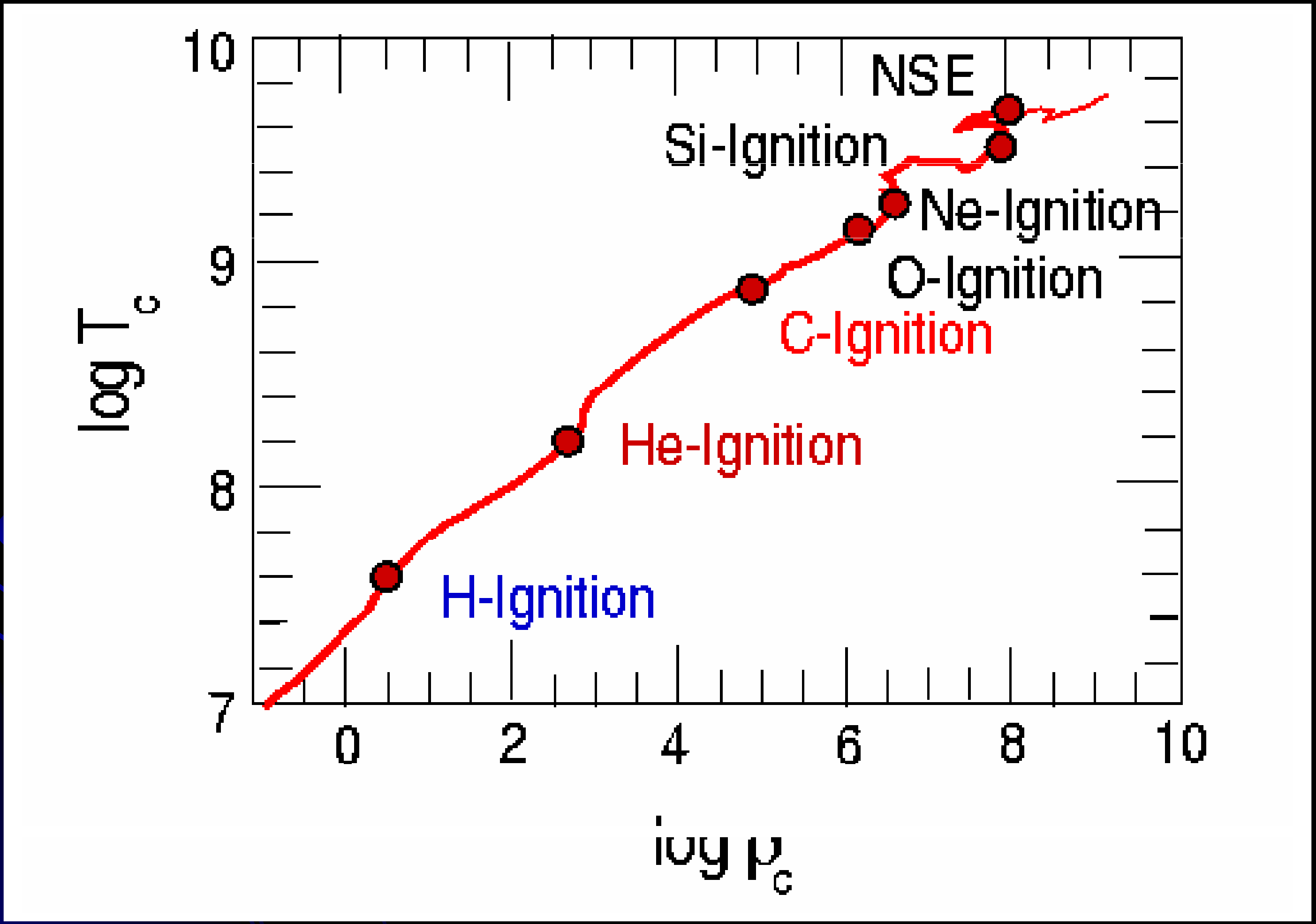
Stellar Hydrogen burning

- ❑ nuclear reactions in the pp-chains
  - ➢ pp-nucleosynthesis and energy production
  - ➢ neutrino origin & neutrino signals
  - ➢ pp-experiments underground
- ❑ nuclear reactions in the CNO cycles
  - ➢ the CNO cycles
  - ➢ CNO nucleosynthesis and energy production
  - ➢ CNO experimental questions

Nucleosynthesis Sites and Conditions

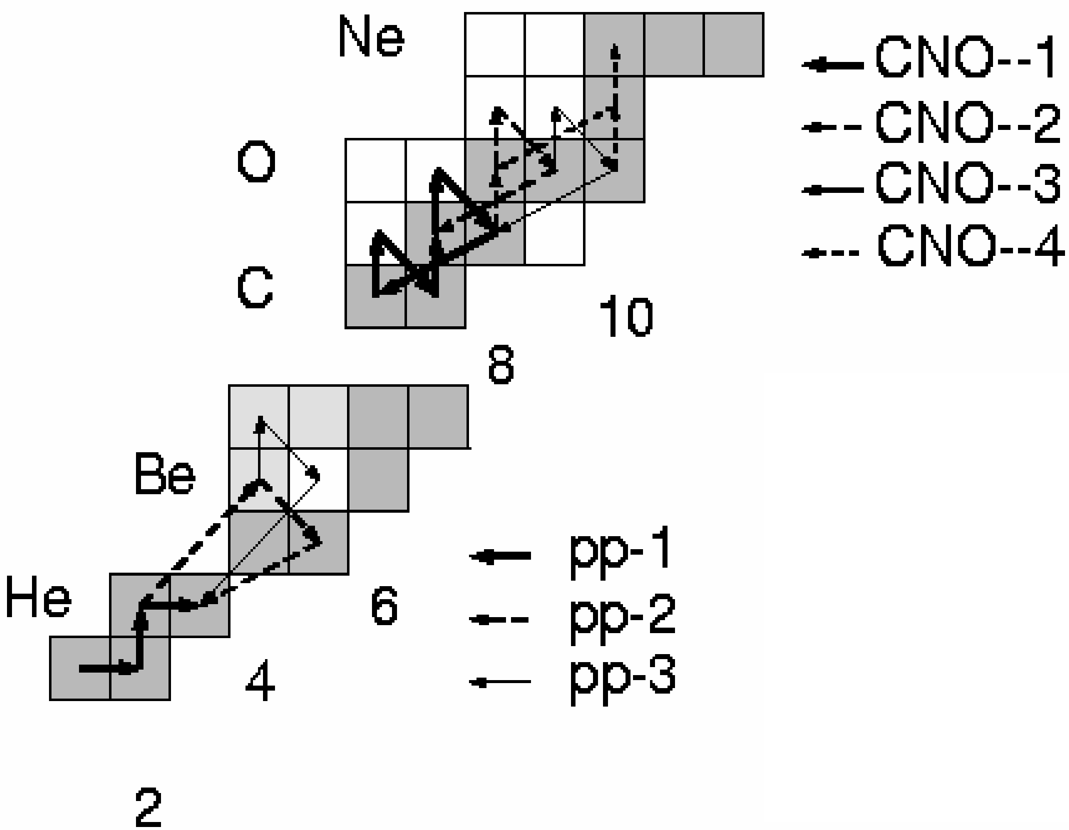


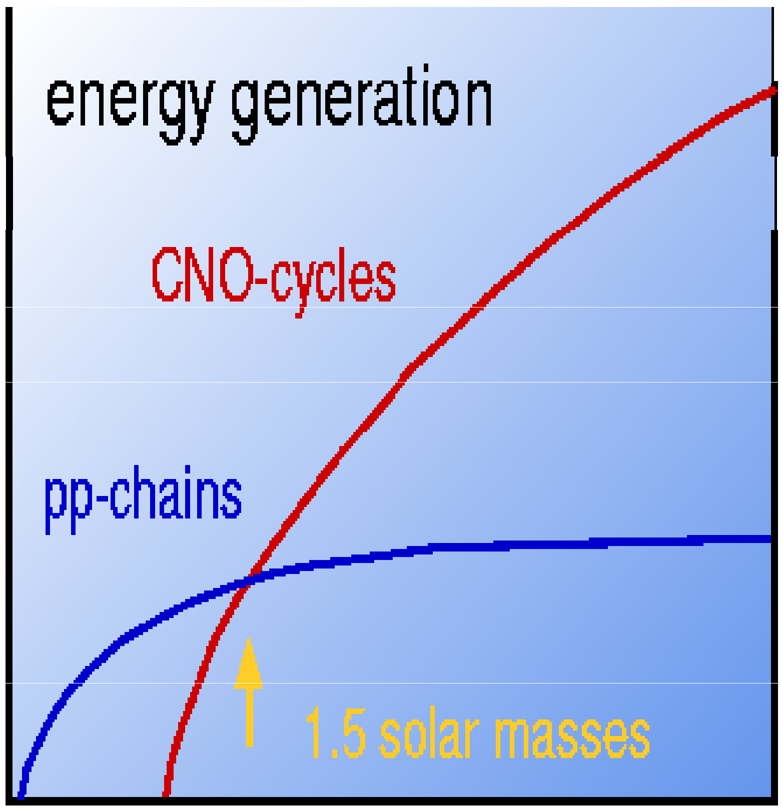
Temperature and Density Evolution in Stellar Core



Hydrogen Burning Stage of Stellar Evolution

Stars with $M>1.5M_o$





Stars with $M<1.5M_o$

The pp-chains

pp-1:	$^{1}H(p,e^{+}\nu)^{2}H$	
	$^{2}H(p,\gamma)^{3}He$	
	$^{3}He(^{3}He,2p)^{4}He$	84.7%
pp-2:	$^{3}He(\alpha,\gamma)^{7}Be$	13.8%
	$^{7}Be(e^{-},\nu)^{7}Li$	13.78%
	$^{7}Li(p,\alpha)^{4}He$	
pp-3:	$^{7}Be(p,\gamma)^{8}B$	0.02%
	$^{8}B(\beta^{+}\nu)2^{4}He$	

fusion of $4\ ^{1}H \rightarrow 4He + 2e+ + 2\nu e + 26.7$ MeV energy release

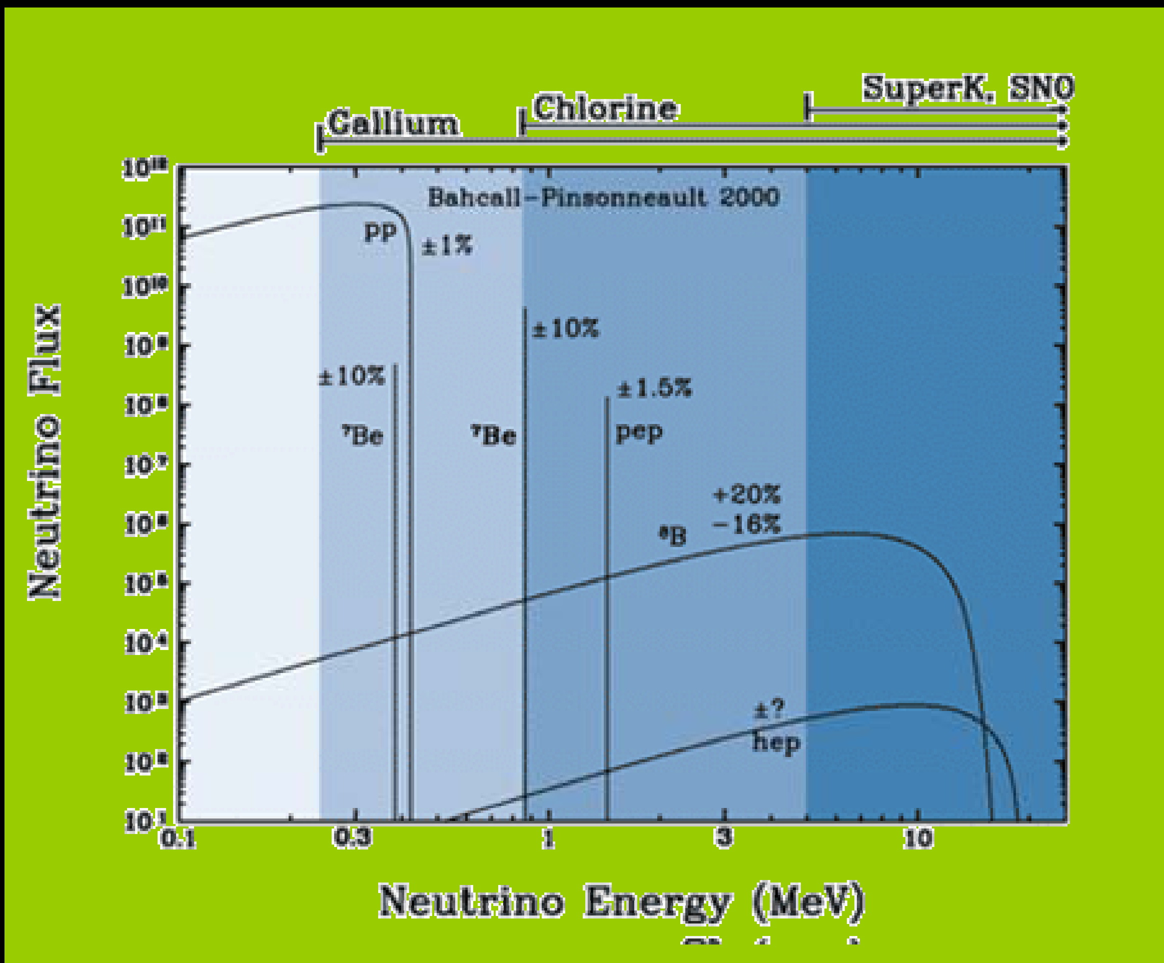
neutrino production

contributions from different reactions in the pp-chains. The branching point of $^3He(^3He,2p)^4He/^3He(\alpha,\gamma)^7Be$ is extremely important for generation of high energy neutrinos (accessible to Homestake Chlorine detector)

REACTION	TERM (%)	ν ENERGY (MeV)
$p + p \to {}^2H + e^+ + \nu_e$	(99.96)	≤ 0.423
or		
$p + e^- + p \to {}^2H + \nu_e$	(0.44)	1.445
${}^2H + p \to {}^3He + \gamma$	(100)	
${}^3He + {}^3He \to \alpha + 2p$	(85)	
or		
${}^3He + {}^4He \to {}^7Be + \gamma$	(15)	
${}^7Be + e^- \to {}^7Li + \nu_e$	(15)	0.863 90%; 0.385 10%
${}^7Li + p \to 2\alpha$		
or		
${}^7Be + p \to {}^8B + \gamma$	(0.02)	
${}^8B \to {}^8Be^* + e^+ + \nu_e$		< 15
${}^8Be^* \to 2\alpha$		
or		
${}^3He + p \to {}^4He + e^+ + \nu_e$	(0.00003)	< 18.8

Neutrino terminations from BP2000 solar model. Neutrino energies include solar corrections: J. Bahcall, Phys. Rev. C, 56, 3391(1997).

Impact of pp-chain reaction rates on ν production



High precision (<5%) measurements for the interpretation of solar ν flux at ν detectors & ν oscillation analysis!

For summary and details: Adelberger et al. Rev.Mod.Phys. 70, 1265 (1998)

Network for the pp-chain I

$$\frac{d^1H}{dt} = -2 \cdot \frac{1}{2} \cdot Y_{^1H} \cdot Y_{^1H} \cdot \rho \cdot N_A \langle \sigma \upsilon \rangle_{^1H(p,e^- \nu)} + 2 \cdot \frac{1}{2} \cdot Y_{^3He} \cdot Y_{^3He} \cdot \rho \cdot N_A \langle \sigma \upsilon \rangle_{^3He(^3He,2p)}$$

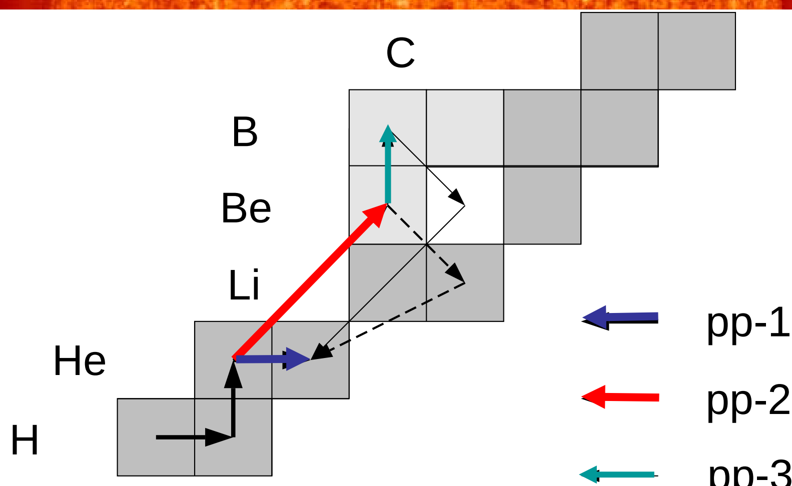
$$\frac{d^2H}{dt} = -Y_{^2H} \cdot Y_{^1H} \cdot \rho \cdot N_A \langle \sigma \upsilon \rangle_{^2H(p,\gamma)} + \frac{1}{2} \cdot Y_{^1H} \cdot Y_{^1H} \cdot \rho \cdot N_A \langle \sigma \upsilon \rangle_{^1H(p,e^- \nu)}$$

$$\frac{d^3He}{dt} = -2 \cdot \frac{1}{2} Y_{^3He} \cdot Y_{^3He} \cdot \rho \cdot N_A \langle \sigma \upsilon \rangle_{^3He(^3He,2p)} + Y_{^2H} \cdot Y_{^1H} \cdot \rho \cdot N_A \langle \sigma \upsilon \rangle_{^2H(p,\gamma)}$$

$$\frac{d^4He}{dt} = \frac{1}{2} Y_{^3He} \cdot Y_{^3He} \cdot \rho \cdot N_A \langle \sigma \upsilon \rangle_{^3He(^3He,2p)}$$

Hydrogen is depleted under release of neutrinos!
Helium is being produced + energy release $4H \Rightarrow 1\,^4He$!

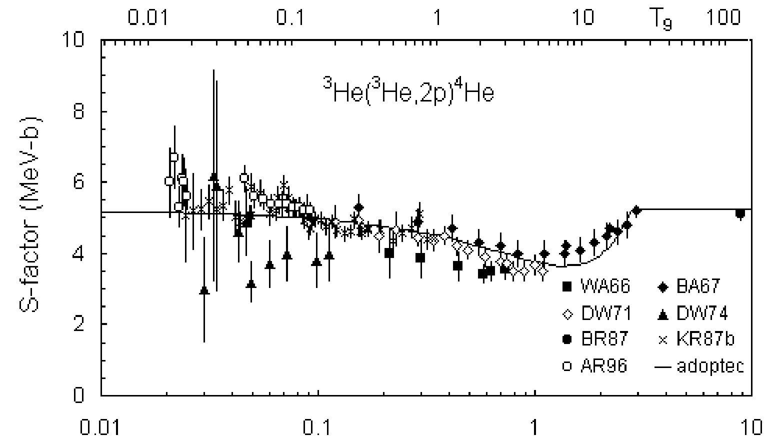
pp-chains in the sun

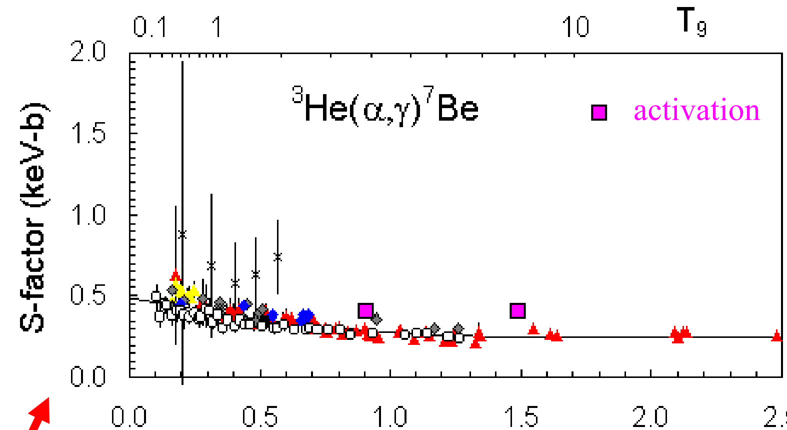


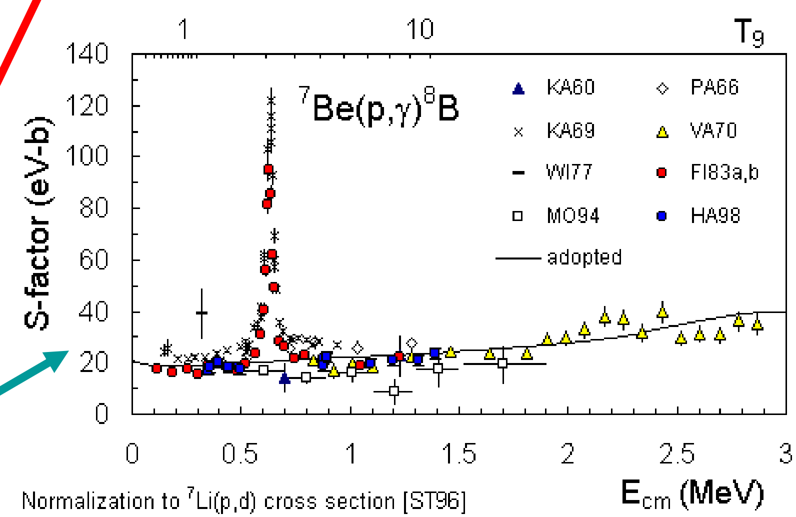
Impact on neutrino detection

Borexino

SNO & Superkamiokande







life time characteristics

Enormous differences in S-factors due to nuclear interaction

S_{p+p}	$= 5\ 10^{-25}$ MeV-barn	weak interaction
$S_{7Be(p,\gamma)}$	$= 2\ 10^{-5}$ MeV-barn	electromagnetic interaction
$S_{3He(\alpha,\gamma)}$	$= 5\ 10^{-4}$ MeV-barn	electromagnetic interaction
$S_{2H(p,\gamma)}$	$= 2\ 10^{-4}$ MeV-barn	electromagnetic interaction
$S_{3He(3He,2p)}$	$= 5$ MeV-barn	strong interaction

Differences translate into differences in reaction rate and life times some nuclei will be processed extremely fast, others will be processed extremely slow.

Slowest process in the fusion sequence determines life time of burning phase and energy production in the sun!!!

lifetime of sun!

slowest reaction rate: $^1H(p,e^+\nu)^2H$

$$\lambda_{pp} = \frac{\rho}{2}\cdot\frac{X_H}{A_H}\cdot N_A\langle\sigma\upsilon\rangle_{pp} =$$

$$= \frac{\rho}{2}\cdot\frac{X_H}{A_H}\cdot 3.9\cdot 10^9\left(\frac{Z_H\cdot Z_H}{\mu}\right)^{1/3} T_9^{-2/3}\cdot S[MeV-Barn]\cdot e^{\left(-4.248\left(\frac{Z_H^2 Z_H^2\mu}{T_9}\right)^{1/3}\right)}$$

$$= \rho\cdot X_H\cdot 4.93\cdot 10^9\cdot T_9^{-2/3}\cdot S[MeV-Barn]\cdot e^{\left(-\frac{3.37}{T_9^{1/3}}\right)}$$

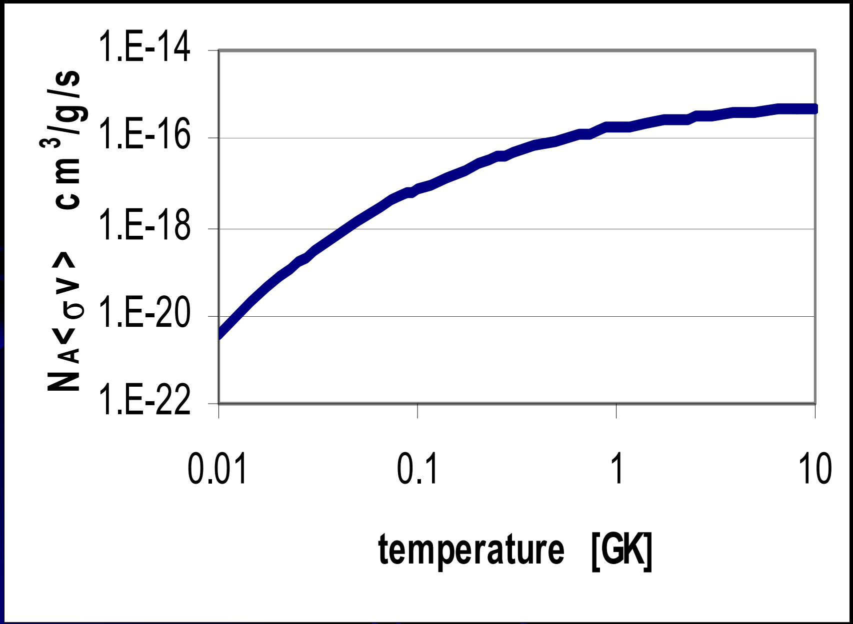
with ρ=10 g/cm^3; X_H=0.5; T_9=0.015; S=5 10^{-25} MeV barn

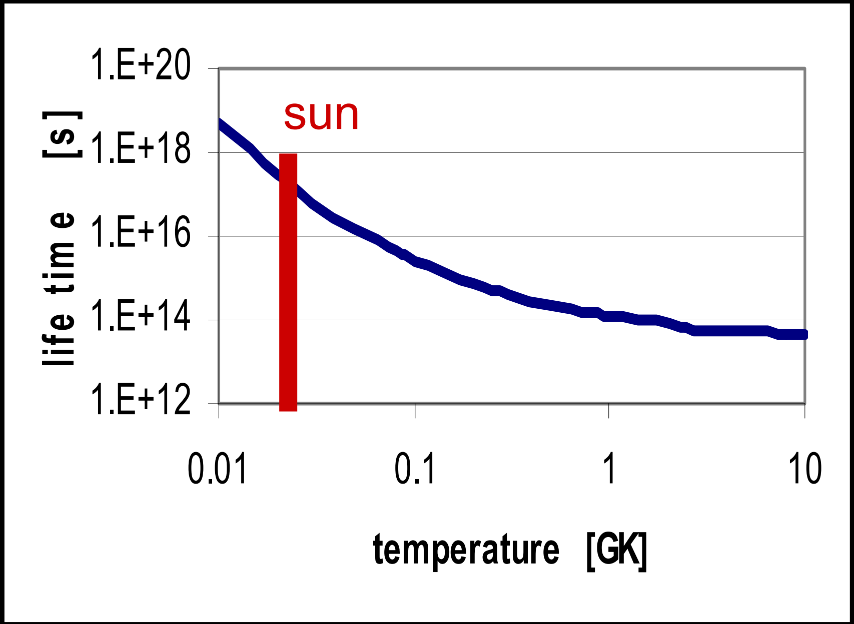
$\Rightarrow \lambda_{pp}=2.34\cdot 10^{-19}$ [1/s]; $\Rightarrow$ $\tau_{pp}=1/\lambda_{pp}=4.5\cdot 10^{18}$ [s]

The p+p reaction

$^1H(p,e^+\nu)^2H$ is a reaction based on weak interaction mechanism

the S-factor is calculated: $S=5\ 10^{-25}$ MeV-barn





What would be the life time of hydrogen with strong interaction $S=5\ 10^{-5}$ MeV-barn?

Speculation in hydrogen burning

$S_{weak}=5\cdot 10^{-25}$ MeV-barn $\Rightarrow$ $S_{strong}=5\cdot 10^{-5}$ MeV-barn

$$\tau_{\odot} \approx 4\cdot 10^{18}\,\mathrm{s} \approx 1.3\cdot 10^{11}\,\mathrm{y}$$

$$\Rightarrow \tau_{strong} \approx 4\cdot 10^{-2}\,\mathrm{s} \approx 1.3\cdot 10^{-9}\,\mathrm{y}$$

The nature of the nuclear reaction mechanism controls the lifetime of stars in general and our sun specifically.

energy production

$$\varepsilon_{pp} = Q \cdot \frac{r_{pp}}{\rho} = 9.65 \cdot 10^{17} \, \frac{X_H}{A_H} \cdot \lambda_{pp} \cdot Q_6 \quad \left[\frac{erg}{g\ s}\right]$$

$$= \rho \cdot X_H^2 \cdot 4.76 \cdot 10^{27} \cdot T_9^{-2/3} \cdot Q_6 \cdot S[MeV - Barn] \cdot e^{\left(-\frac{3.37}{T_9^{1/3}}\right)}$$

$$\varepsilon = 2.96 \left[\frac{erg}{g\ s}\right]$$

$$M_\Theta = 2 \cdot 10^{33} \quad [g]$$

$$\varepsilon_\Theta = 5.92 \cdot 10^{33} \quad \left[\frac{erg}{s}\right]$$

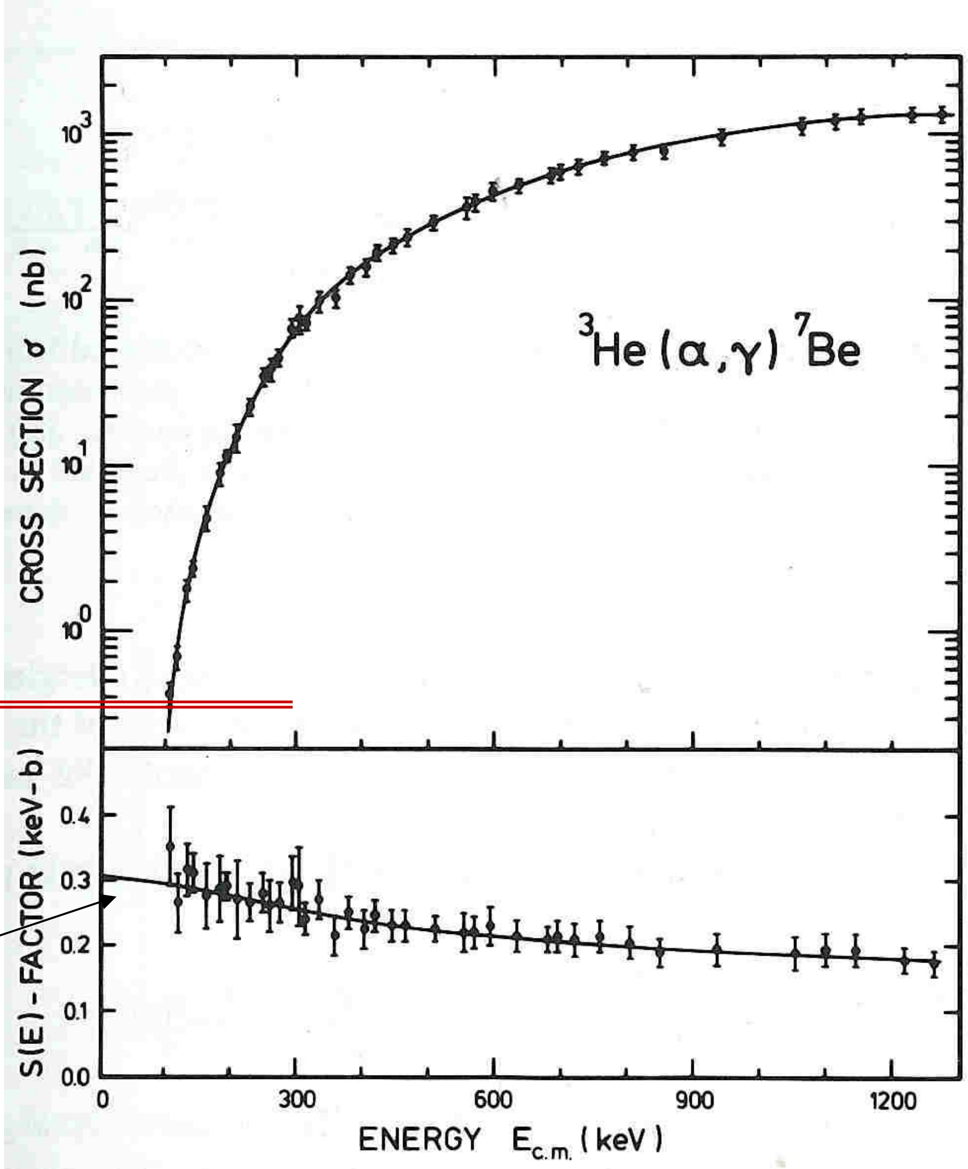
with Q_6=26 MeV

$$\varepsilon_{obs} = 4 \cdot 10^{33} \quad \left[\frac{erg}{s}\right]$$

Experimental difficulties!

Background level from cosmic ray & natural activities

Extrapolation (something missing?)



Reaction Yield as function of energy

$$Y(E) = \int_{E-\Delta E}^{E} \frac{\sigma(E)}{\varepsilon(E)} \cdot dE$$

$$\varepsilon(E) = \frac{1}{n} \cdot \frac{dE}{dx}$$

Yield is experimental observable product between actual reaction probability (cross section) and the atomic interaction between beam particles & target material.

Two energy dependent functions *σ(E)* and *ε(E)*

ΔE ≡ energy loss in target
E ≡ beam energy
n ≡ number density of active target atoms

reminder ....

$$n = \nu\,\rho\,\frac{N_A}{A}$$

solid: $N_A = 6.022 \cdot 10^{23}$ atoms/mole

$$n = \nu\,L$$

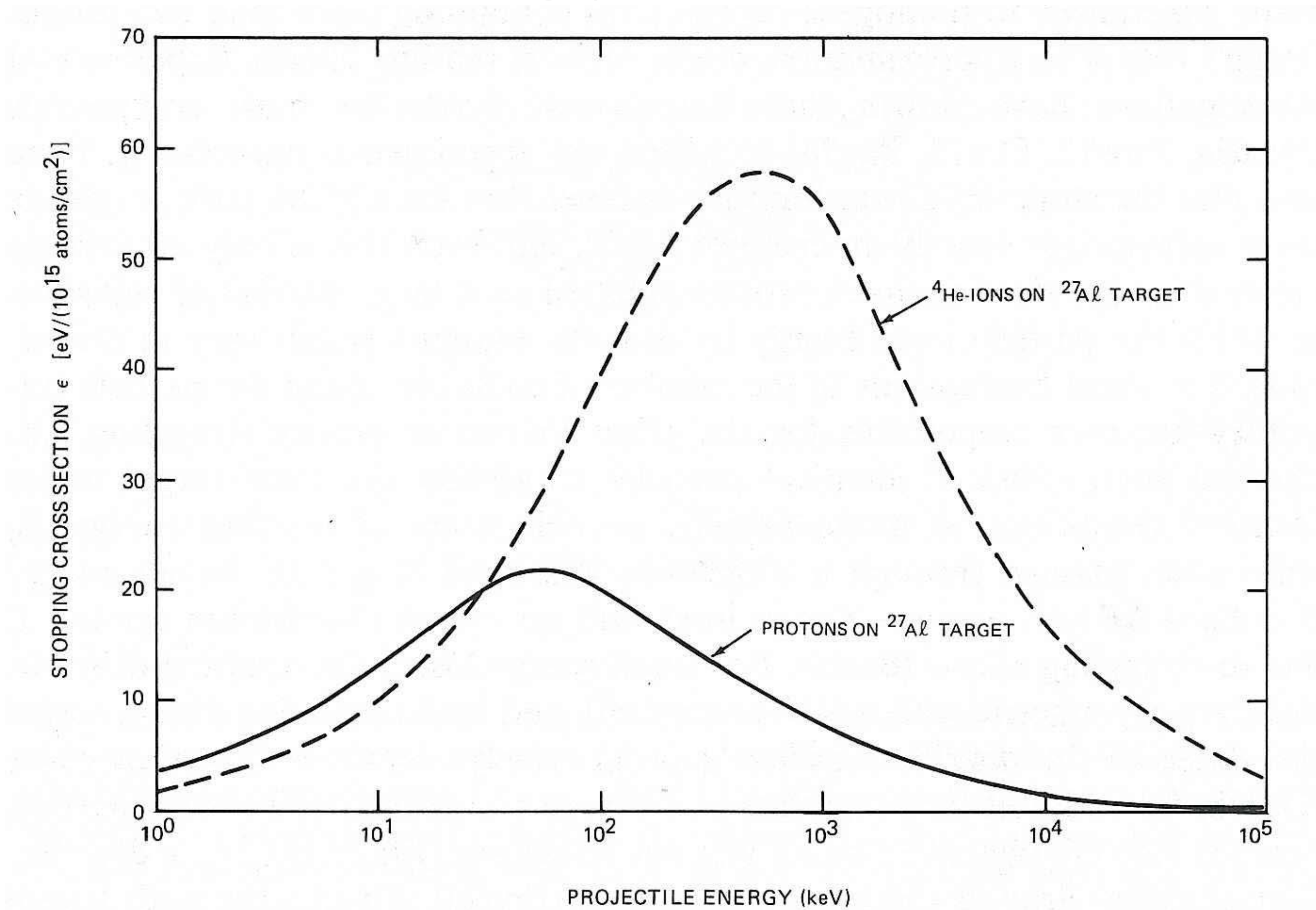
gas: $L = 2.69 \cdot 10^{19}$ atoms/cm^3

ν: number of atoms/molecule

example: N_2 gas $\nu=2 \;\Rightarrow\; n=5.48 \cdot 10^{19}$ atoms/cm^3

Al solid $\nu=1$, $\rho=2.69$ g/cm^3, $A=27 \;\Rightarrow\; n=6 \cdot 10^{19}$ atoms/cm^3

energy loss dE/dx



significant changes in ε over the critical energy range of astrophysical measurements

Thin Target Yield

no significant change in σ or ε over energy loss range ΔE

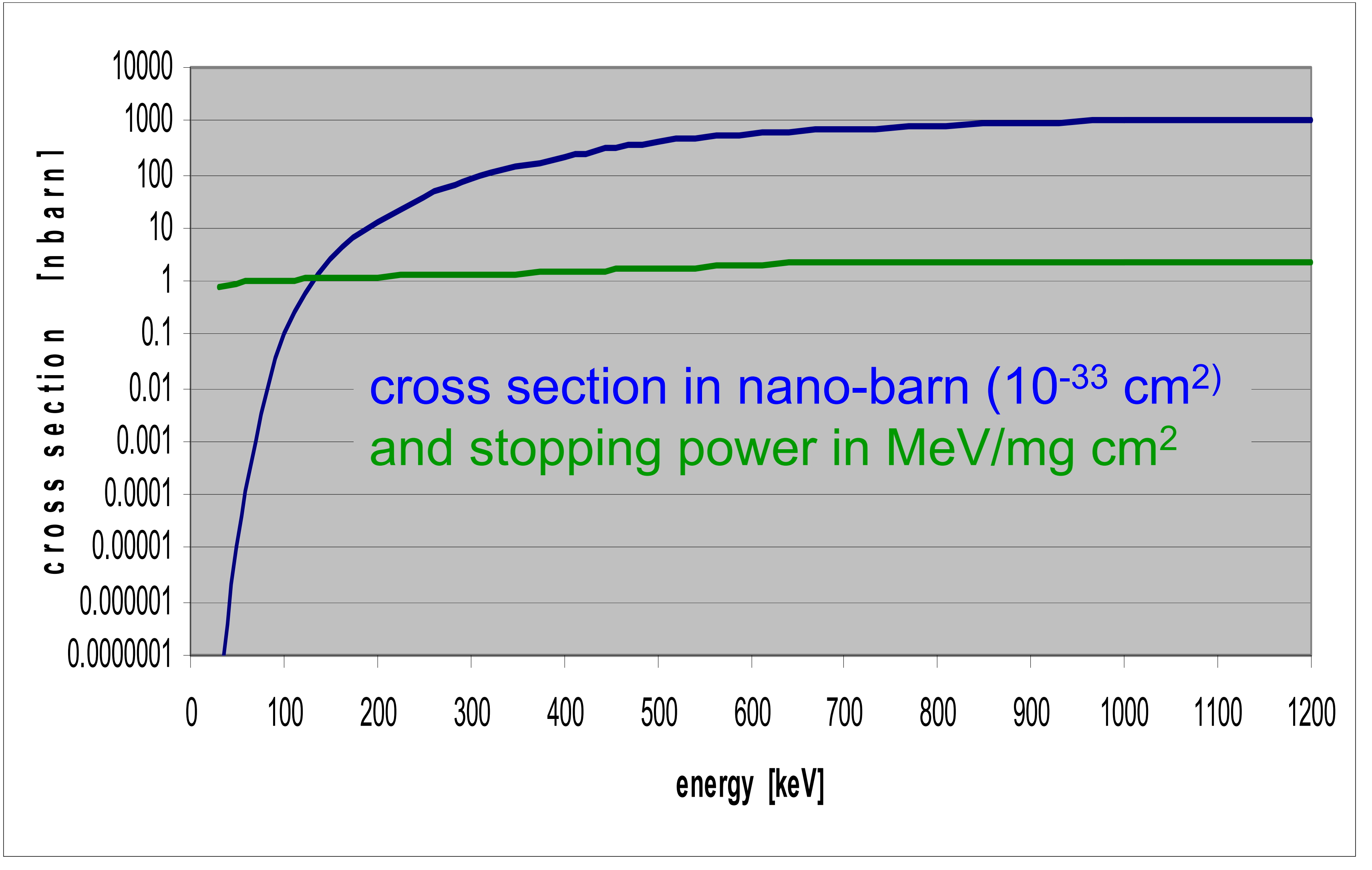
$$Y = \int_{E-\Delta E}^{E} \frac{\sigma(E)}{\varepsilon(E)} dE \approx \frac{\sigma}{\varepsilon} \cdot \int_{E-\Delta E}^{E} dE = \sigma \cdot \frac{dE}{\varepsilon} = \sigma \cdot \frac{\Delta E}{\varepsilon} = \sigma \cdot \frac{\Delta E}{\frac{dE}{n \cdot dx}} \approx \sigma \cdot n \cdot \Delta x$$

if molecular target with $N_a = n_a \Delta x$ active atoms/cm^2
and several $N_i = n_i \Delta_x$ inactive atoms/cm^2

$$\Delta E = N_a \cdot \varepsilon_a + \sum_i N_i \cdot \varepsilon_i; \qquad \varepsilon = \varepsilon_a + \frac{\sum_i N_i}{N_a} \cdot \varepsilon_i$$

Ta_2O_5 $\quad \varepsilon_{Ta_2O_5} = \varepsilon_O + \frac{2}{5} \cdot \varepsilon_{Ta}$

Example: $^3He + ^4He$



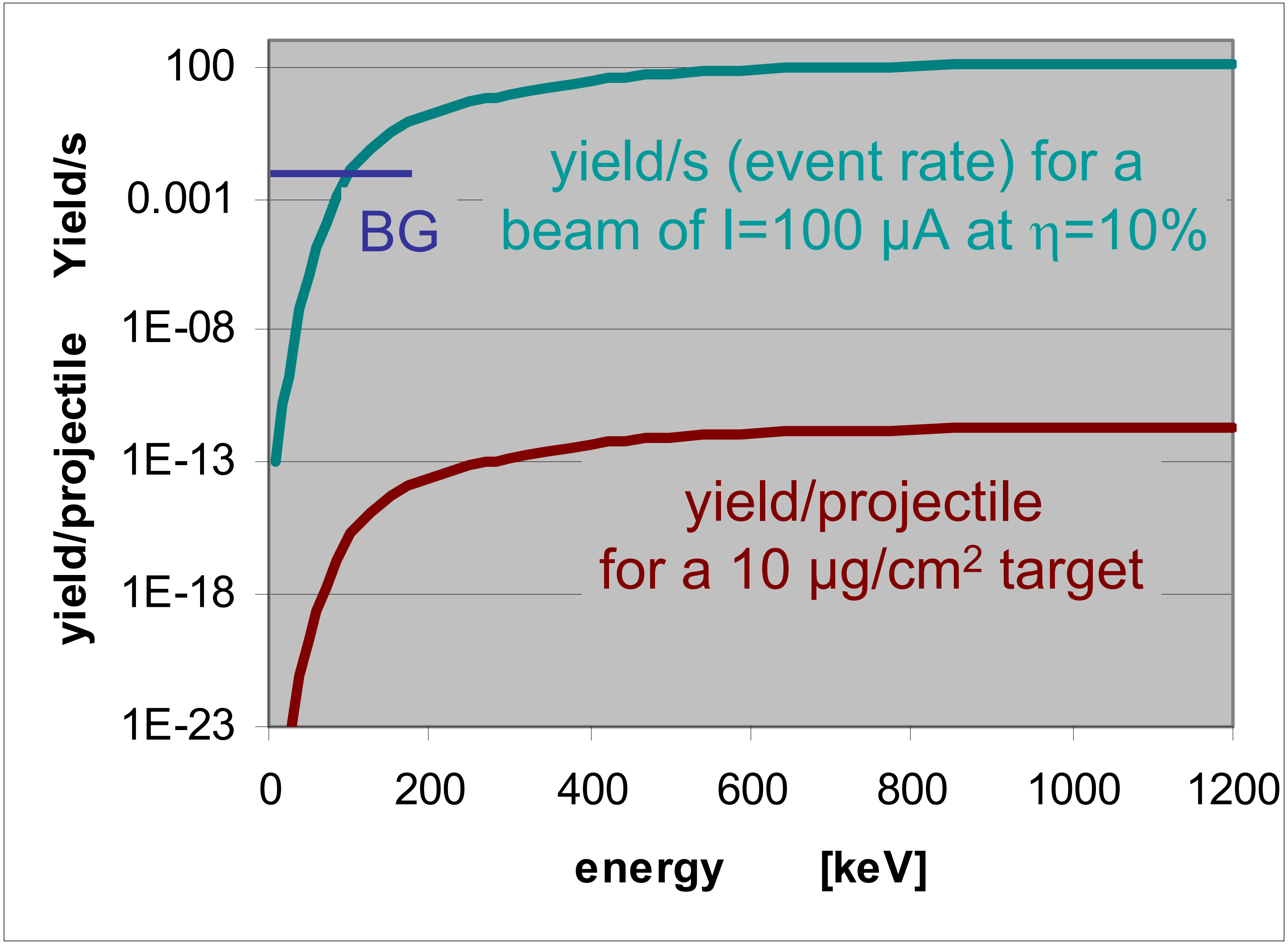
Detection count rate

yield Y is number of reactions/incoming particle to determine count rate you need to correct for detection efficiency η and number of incoming beam projectiles N_p.

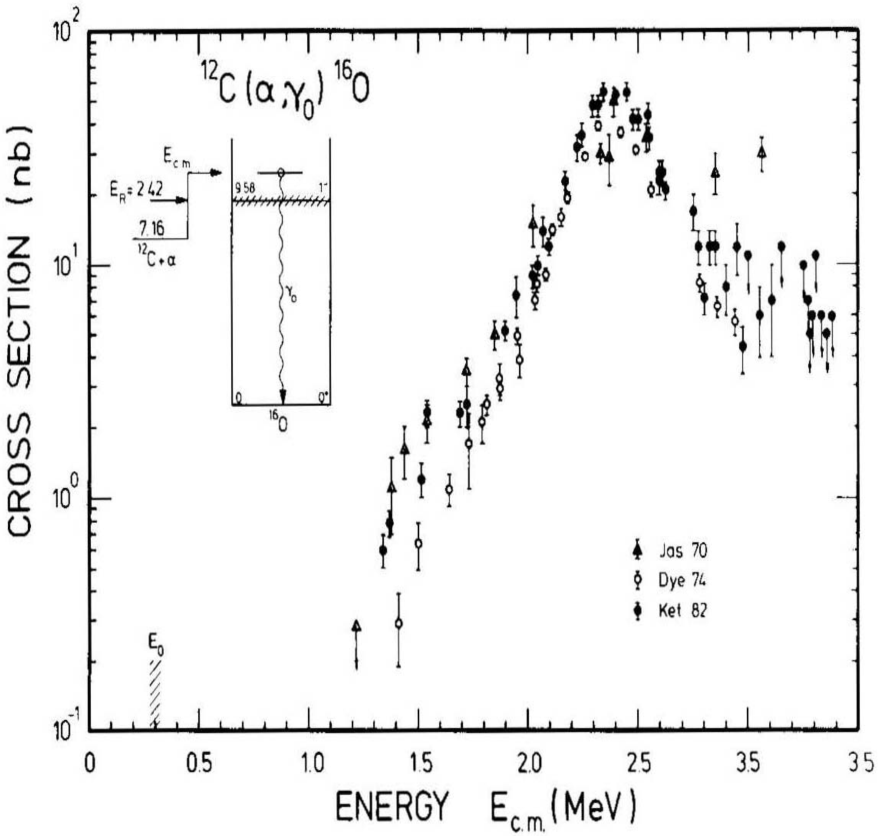
$$\boxed{I = Y \cdot \eta \cdot N_p \,[1/s] = Y \cdot \eta \cdot \frac{I[A]}{1.6 \cdot 10^{19}}\,[1/s]}$$

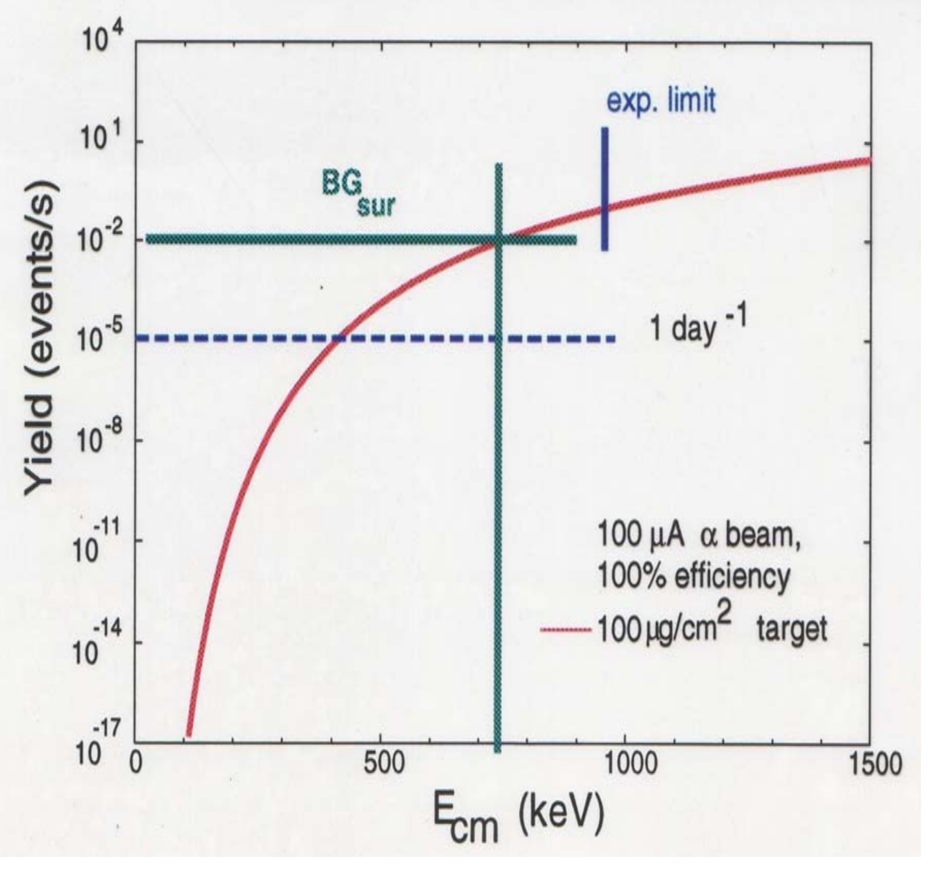
detection efficiency η depends on interaction probability between radiation and detector material

Yield and event rate



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

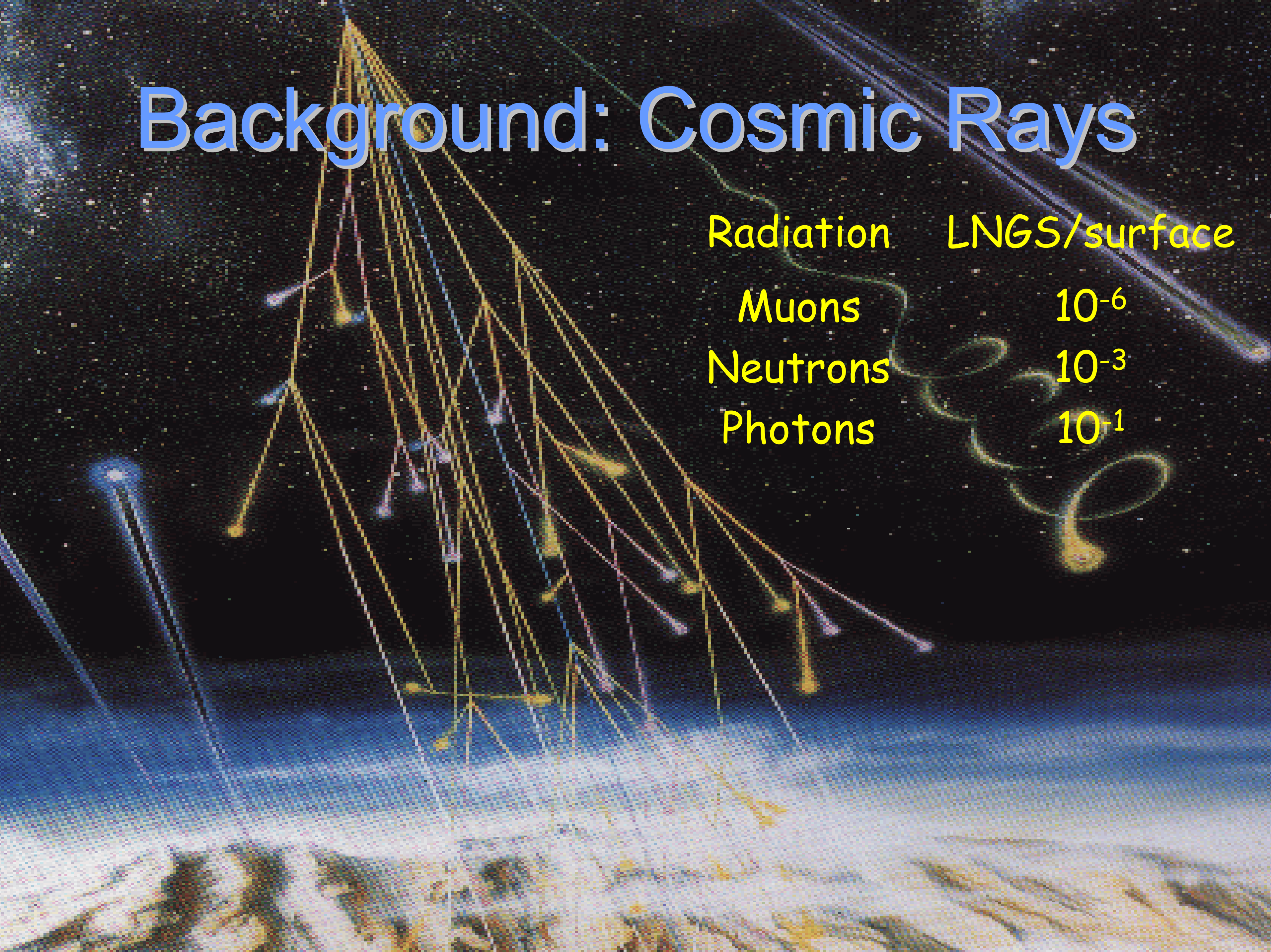




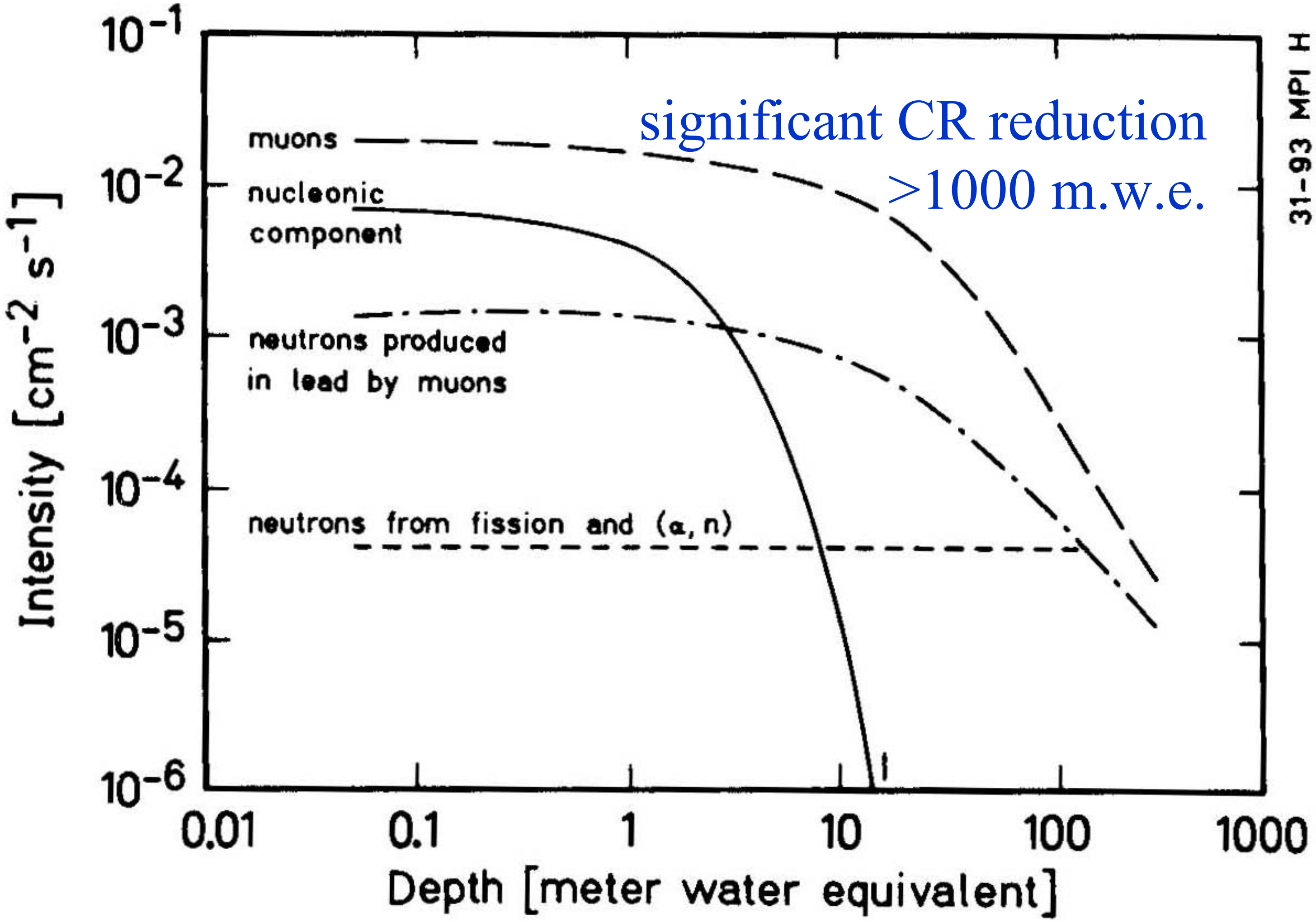
low energy measurements
limited by background rate

Background: Cosmic Rays

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



Underground Laboratory



physics underground: http://www.sns.ias.edu/~jnb/

LUNA @ Gran Sasso

Rock as passive shielding
cosmic ray background
Reduction $\approx 10^{-4}$

4-50 keV Accelerator
p-, α-beams $\leq$ 1 mA

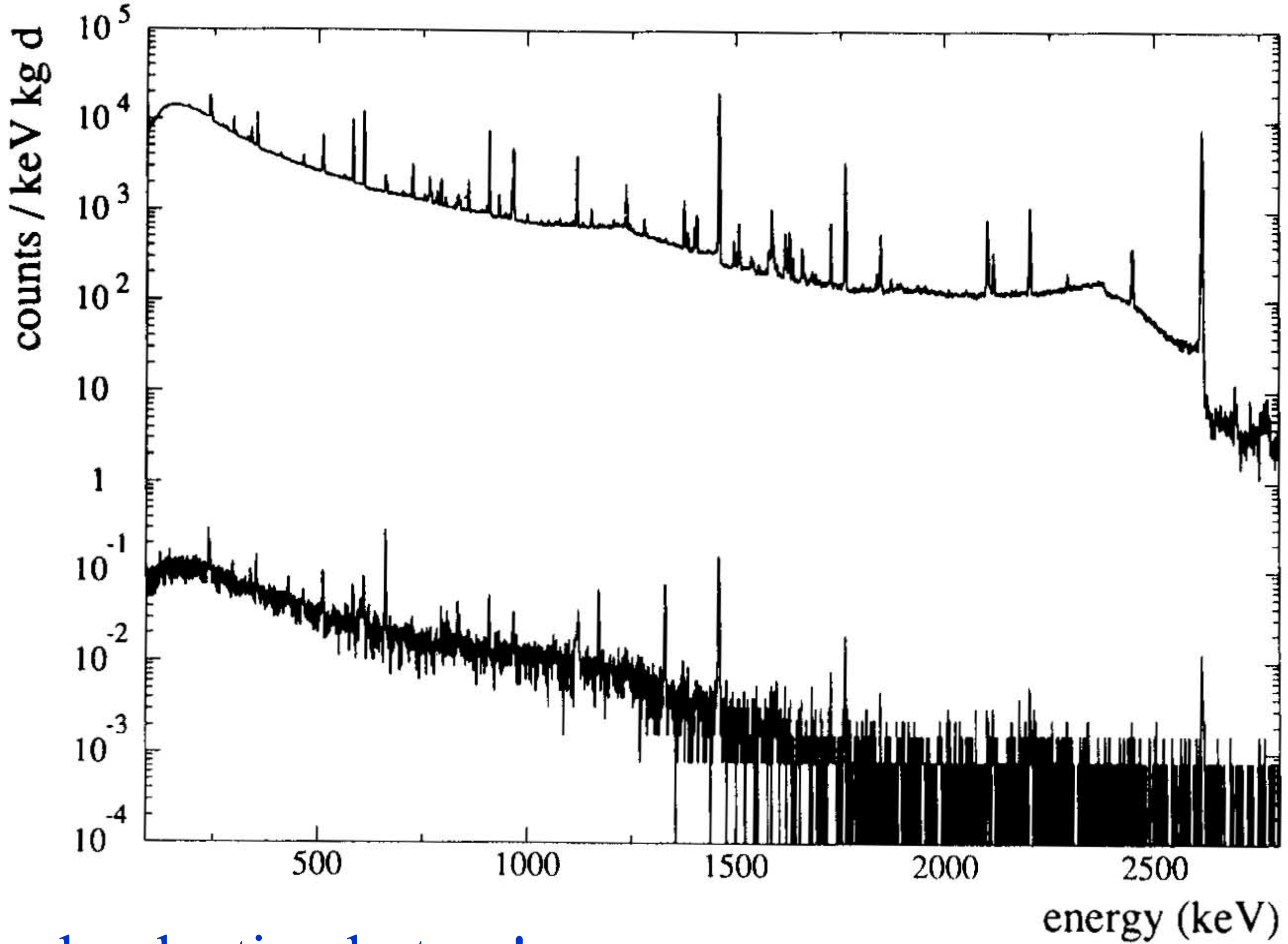
Study of pp-chains
e.g. $^{3}He + ^{3}He$

Passive Background Reduction

Ge-detector background spectrum

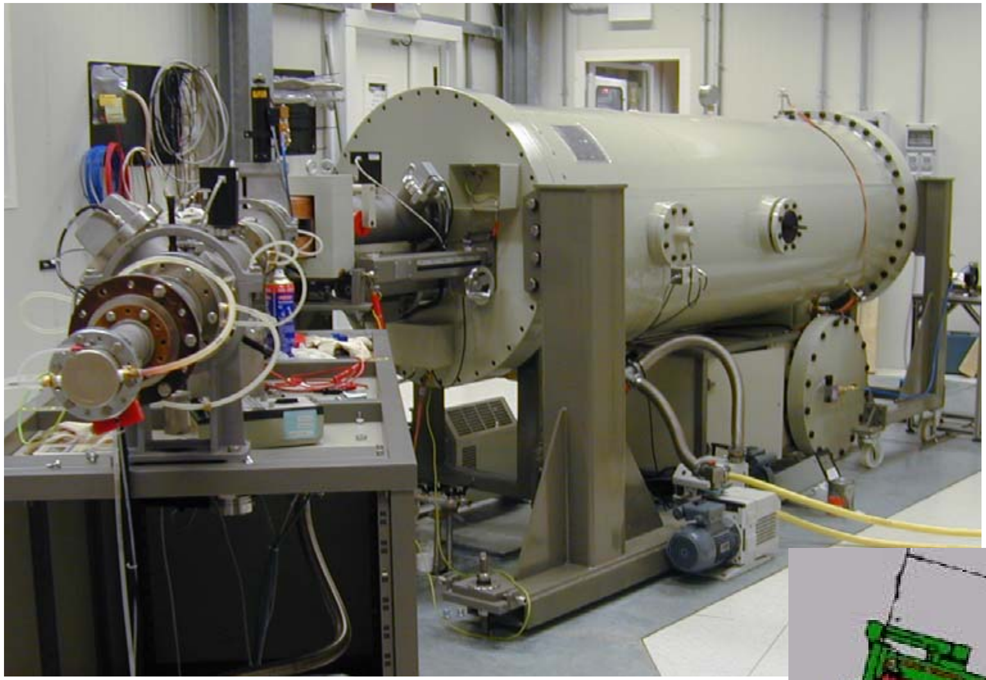
15 m.w.e.
unshielded

3400 m.w.e.
40cm Pb shield



Significant background reduction but …!

LUNA-II upgrade

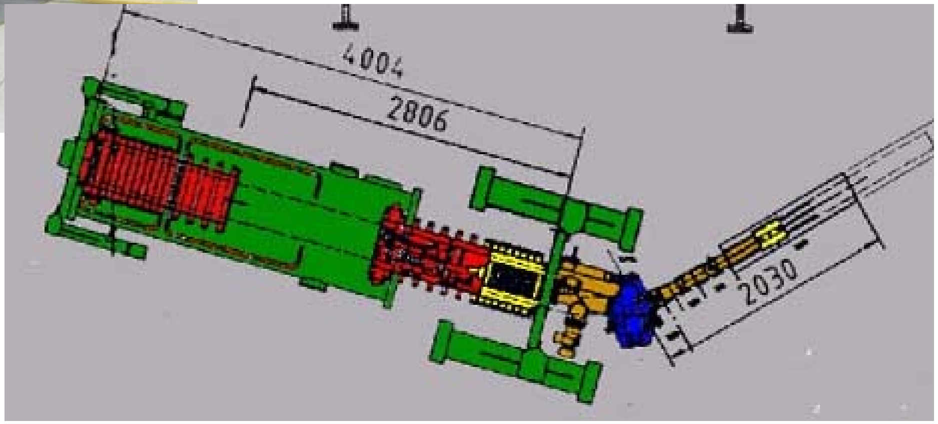


50-400 keV VdG

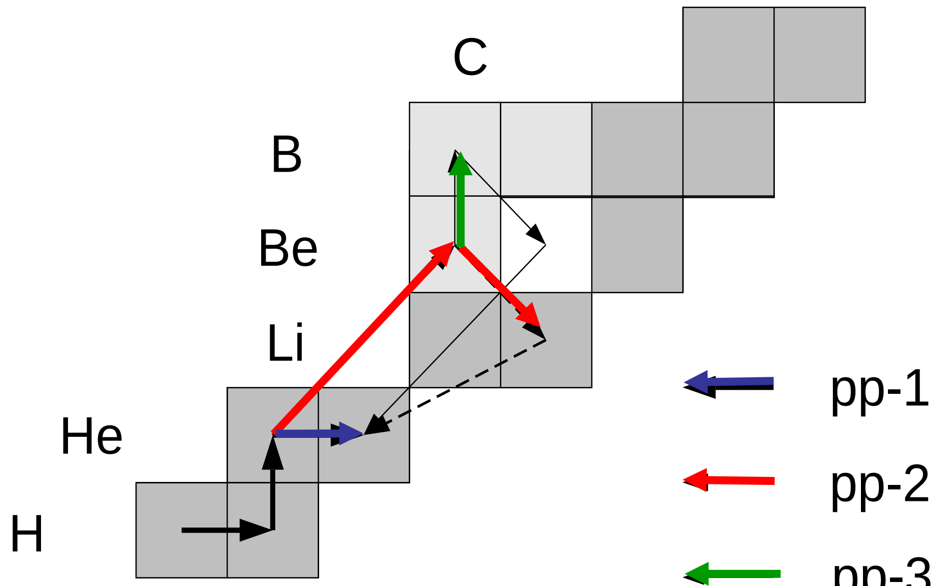
Accelerator Laboratory

p-, α-beams ≤ 0.5 mA

Study of p-capture on CNO nuclei (CNO-cycles) and α capture on light nuclei

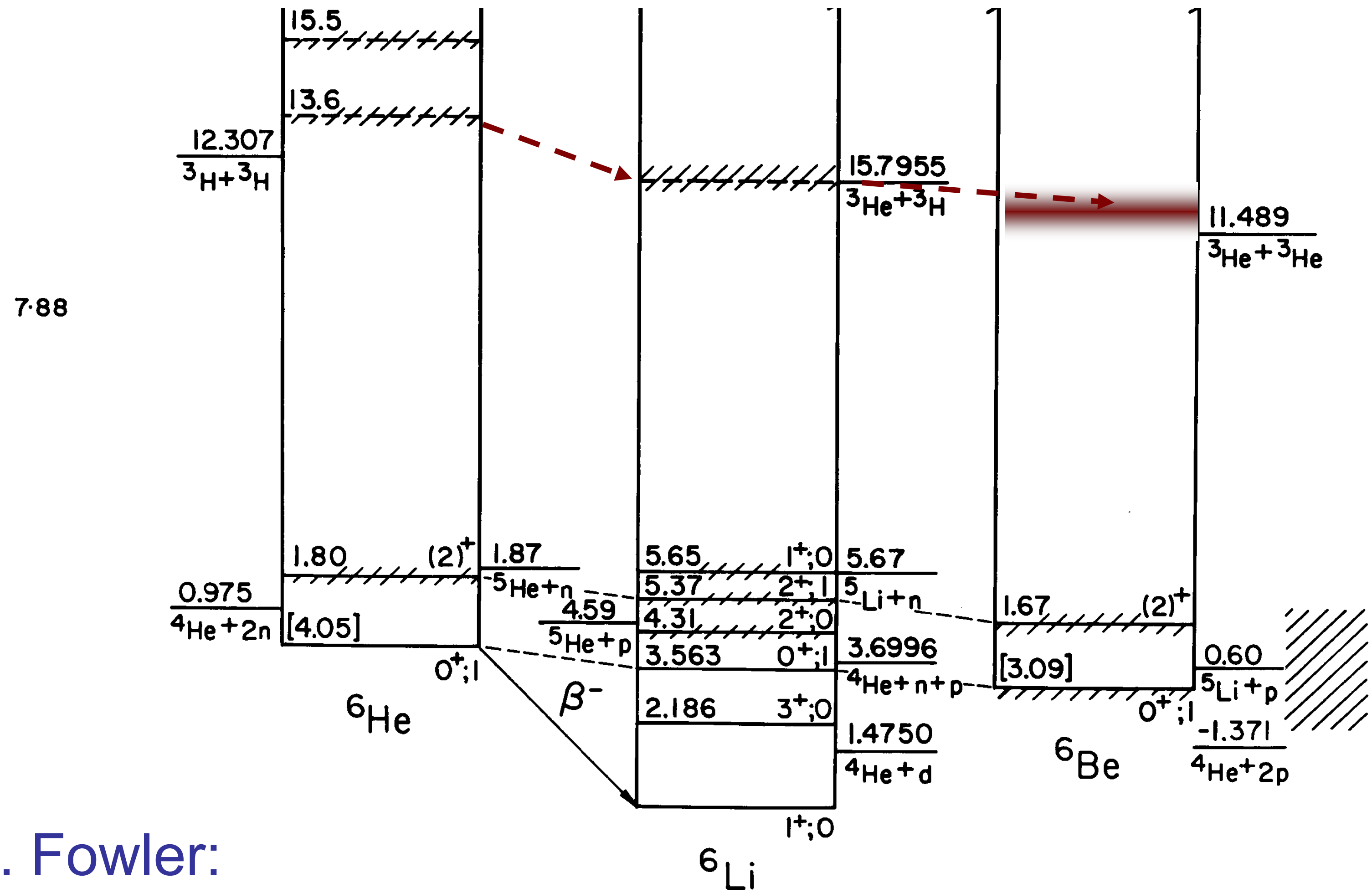


Branching and Neutrino Flux



increase in the $^3He+^3He$ reaction rate by factor X would reduce the neutrino flux from the $^7Be(e^-,\nu)$, $^8B(\beta^+\nu)$ significantly!
The resonance possibility appeared at its time as potential solution for solar neutrino problem! $\Rightarrow$ Search for resonance!

Example: $^3He+^3He$ for pp-I/pp-II branching

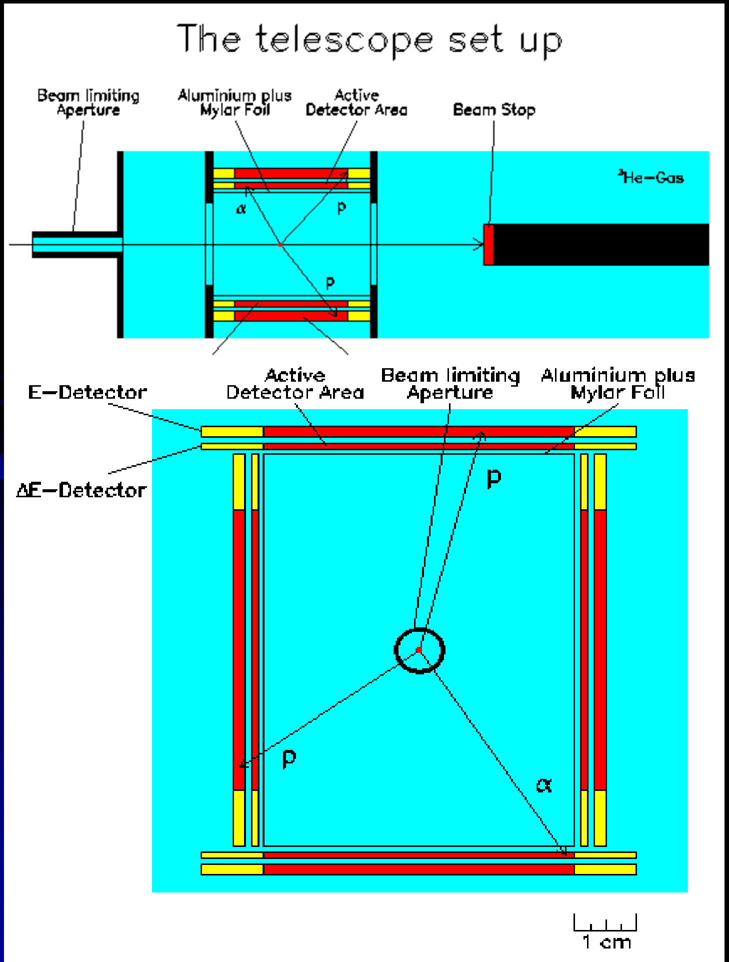


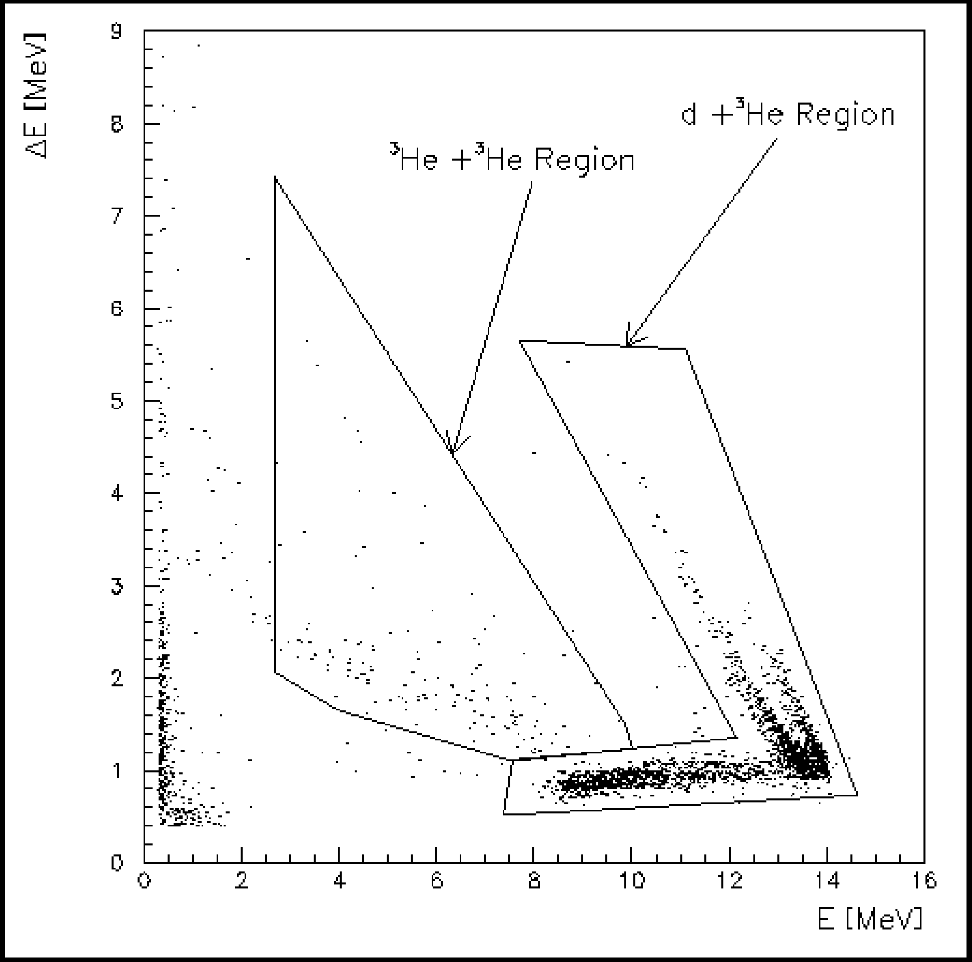
W.A. Fowler:

Is there a broad resonance in the $^3He+^3He$ system????

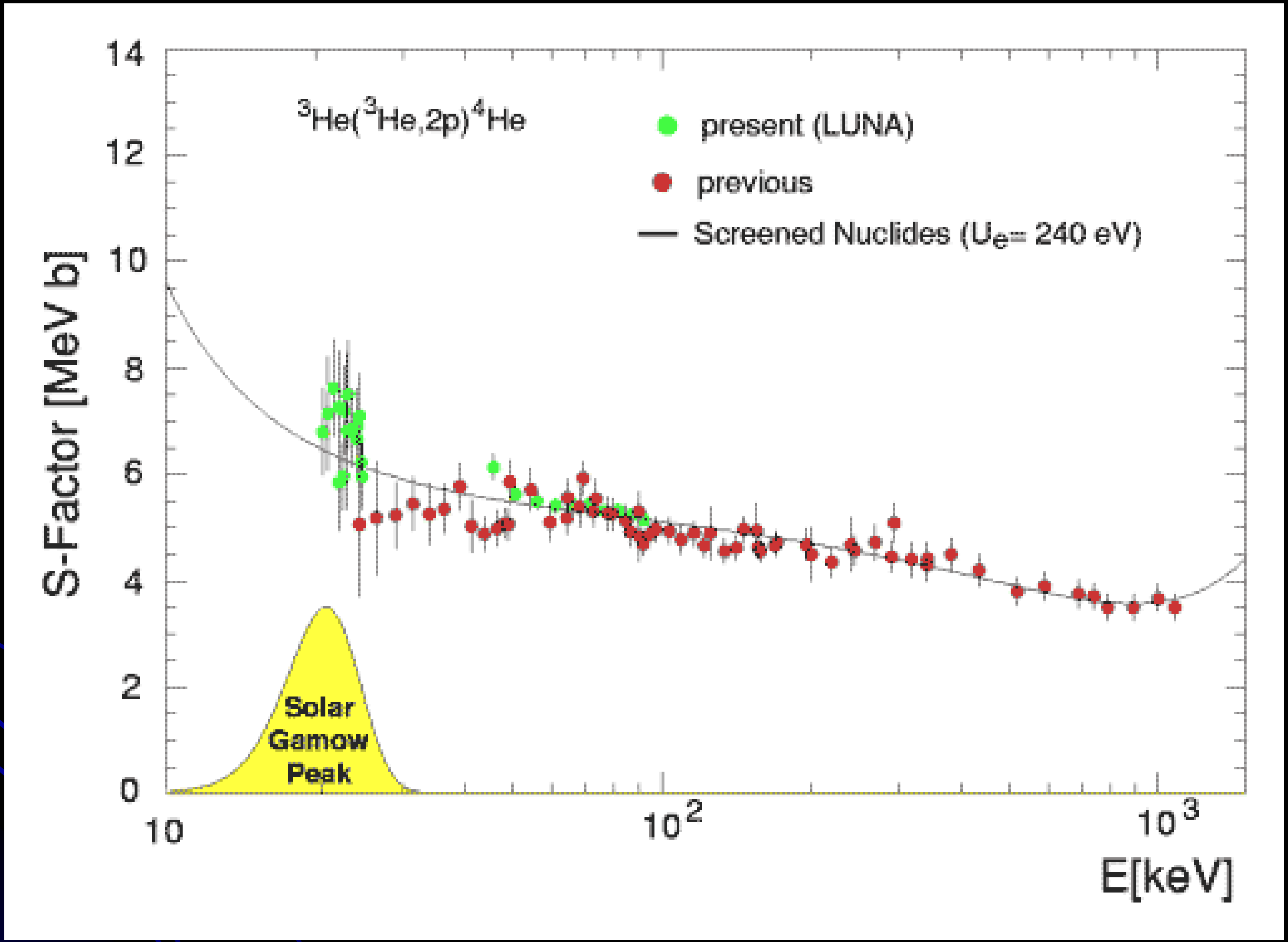
Background Reduction

- background reduction by underground location
- event identification by p-p coincidence requirement



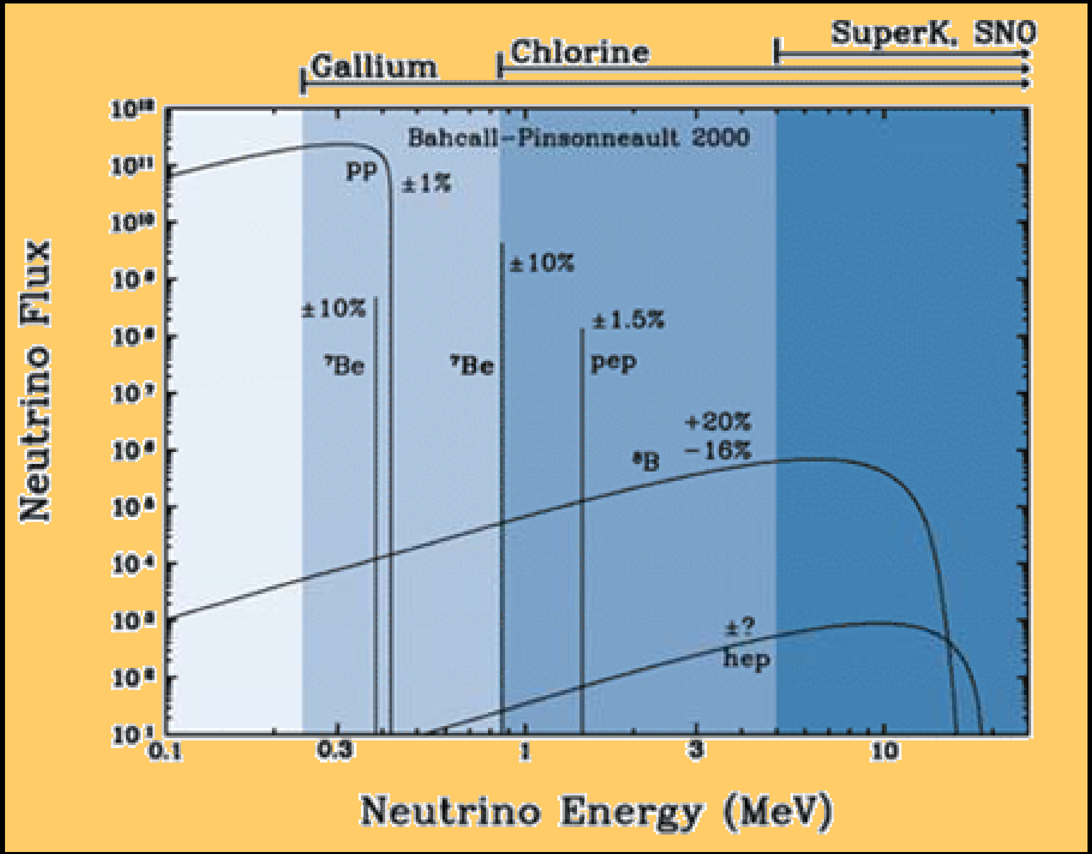


Present status on $^3He(^3He,2p)^4He$



extensive search towards low energies
but no evidence was found

$^{7}Be(p,\gamma)^{8}B$



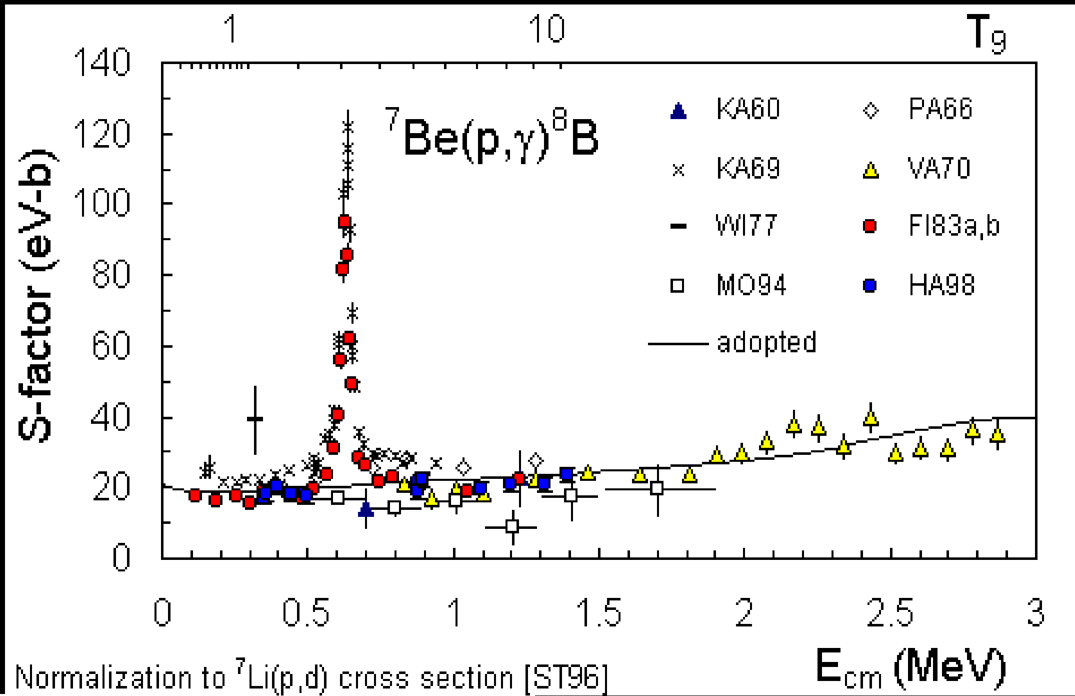
impact on ν detectors and interpretation of ν flux measurements

reaction determines the branch between pp-II and pp-III:

pp-II feeds the $^{7}Be(e-,\nu)^{7}Li$ neutrino source
pp-III feeds the $^{8}B(\beta+\nu)2^{4}He$ neutrino source

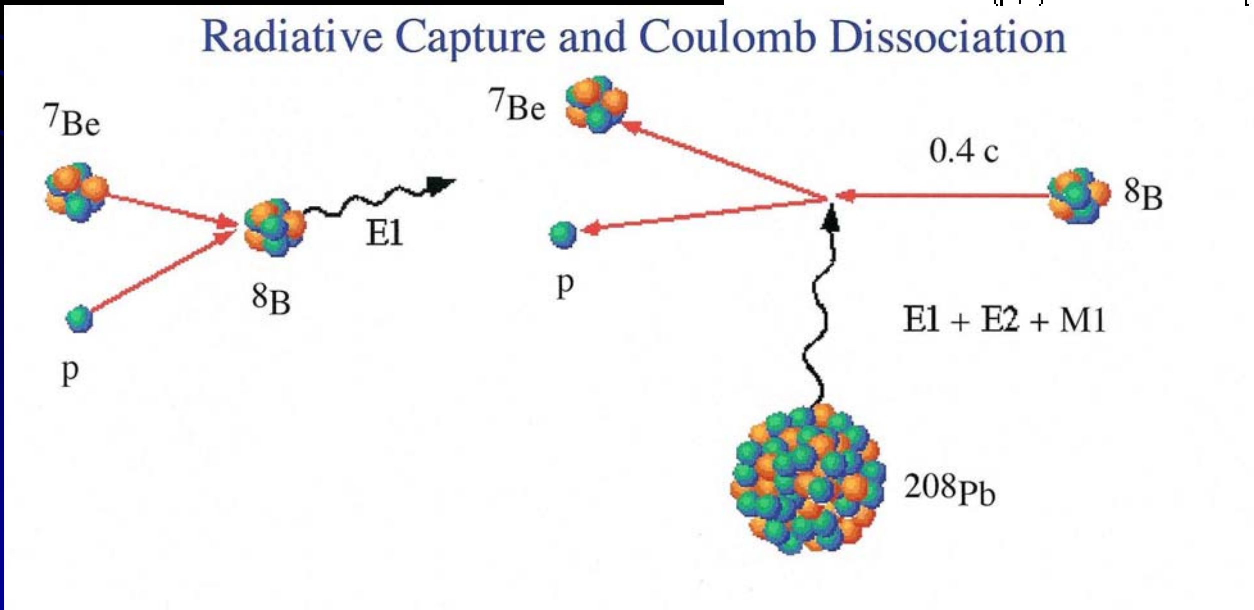
impacts Chlorine, SuperK and SNO experiments

Coulomb break-up techniques e.g. $^{7}Be(p,\gamma)^{8}B$



$^{7}Be(p,\gamma)^{8}B$

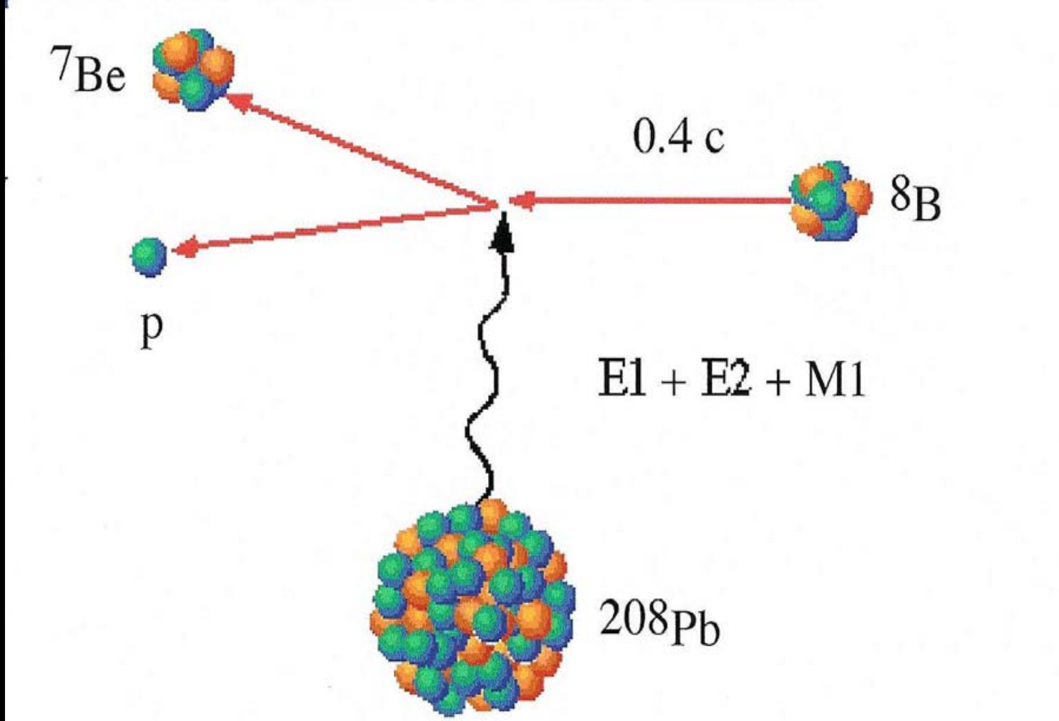
through capture reaction techniques



$^{8}B(\gamma,^{8}B)p$

reaction with real or virtual photons Coulomb break-up

Coulomb dissociation method



$^8B + {}^{208}Pb \to {}^7Be + p + {}^{208}Pb$

virtual photon theory

$^8B(\gamma,p)^7Be$ (abs.)

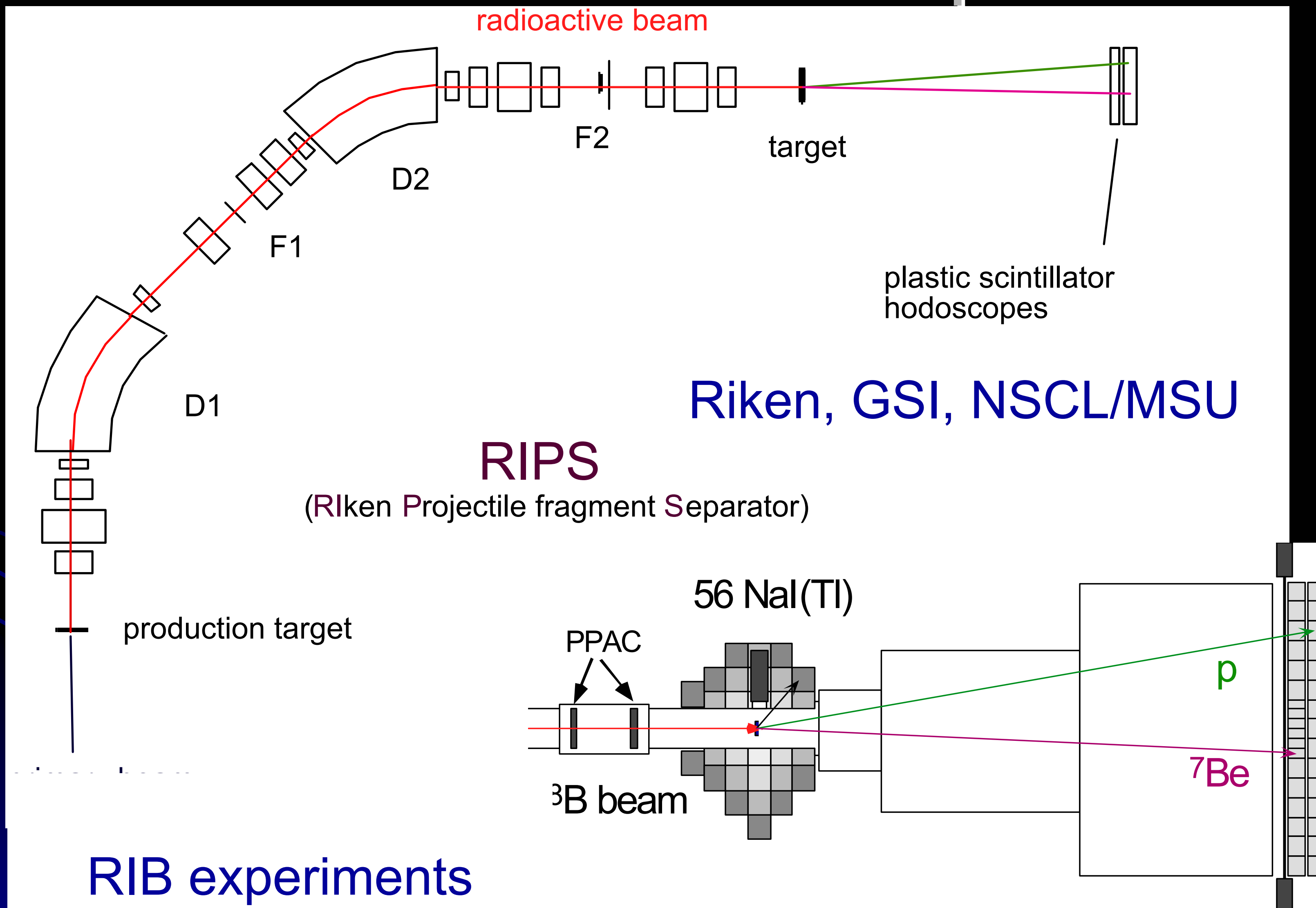
detailed balance

$^7Be(p,\gamma)^8B$ (capt.

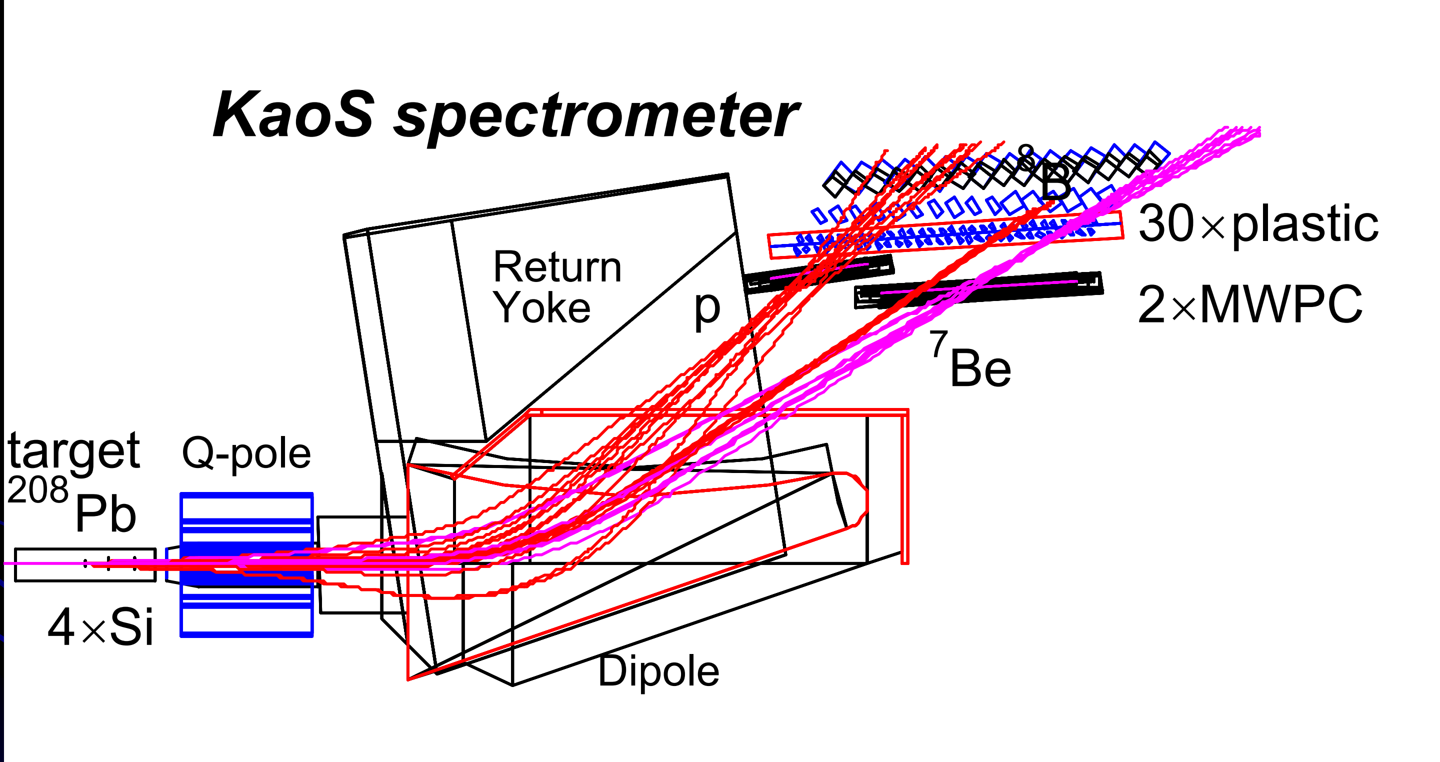
$$\sigma_{(\gamma,p)} = \frac{(2j_7+1)(2j_1+1)}{2(2j_8+1)} \frac{k_{17}^2}{k_\gamma^2} \sigma_{(p,\gamma)}$$

virtual photon number: $\left(\frac{d\sigma}{dE_\gamma}\right)_{C.D.} = \frac{n}{E_\gamma}\sigma_{(\gamma,p)}$ *E2>>E1>>M1*

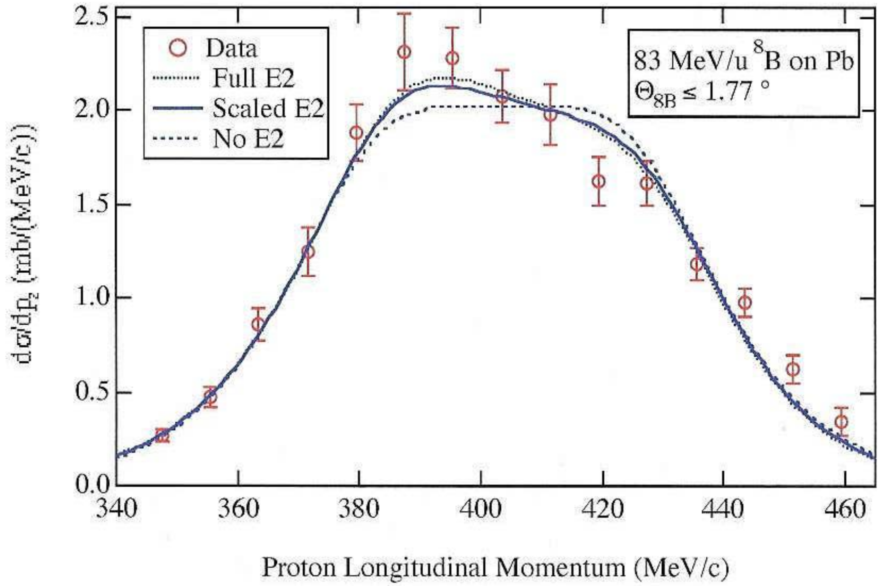
Coulomb Dissociation Experiment



GSI version


KaoS spectrometer
^{8}B
30×plastic
Return
Yoke
p
2×MWPC
^{7}Be
target
^{208}Pb
Q-pole
4×Si
Dipole

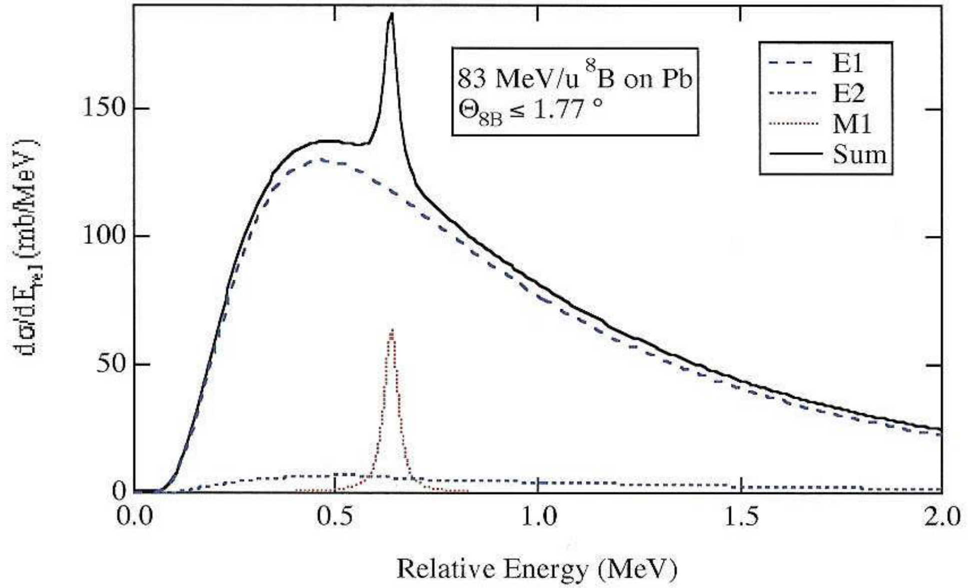
Experimental Results (NSCL/MSU)



First-order perturbation theory calculations

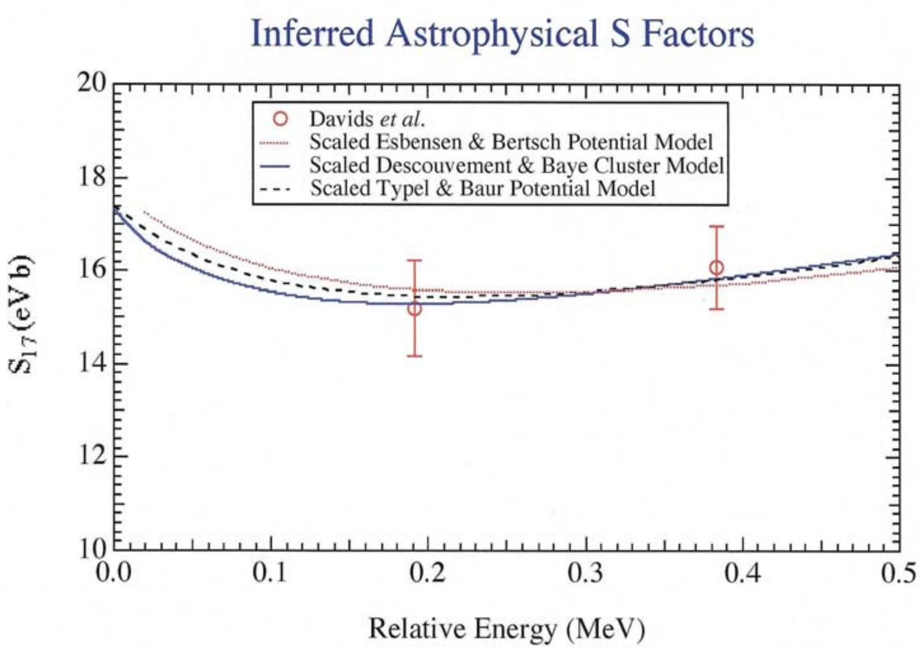
Asymmetry complementary to that of ^{7}Be fragments observed

Presence of E2 component confirmed

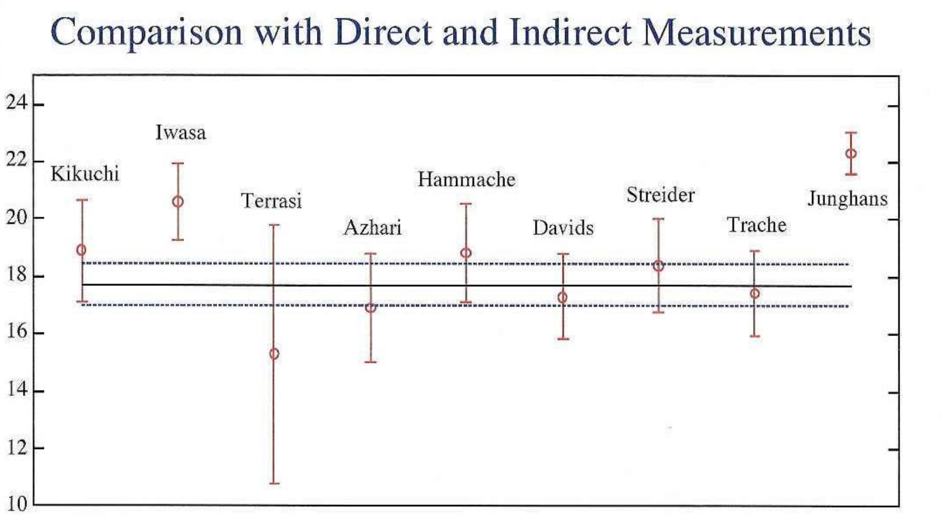


E2 terms are the main observables!

Results and comparison



$S_{17}(0) = 17.3 \pm 1.4$ eV b



ighted average of 6 direct and indirect measurements published since 2001 yields

$\langle S_{17}(0)\rangle = 17.7 \pm 0.7$ eV b

useful method if conditions (E2 transitions, ground state transitions) are guaranteed!

Network simulations at low temperature conditions of 10^7 K