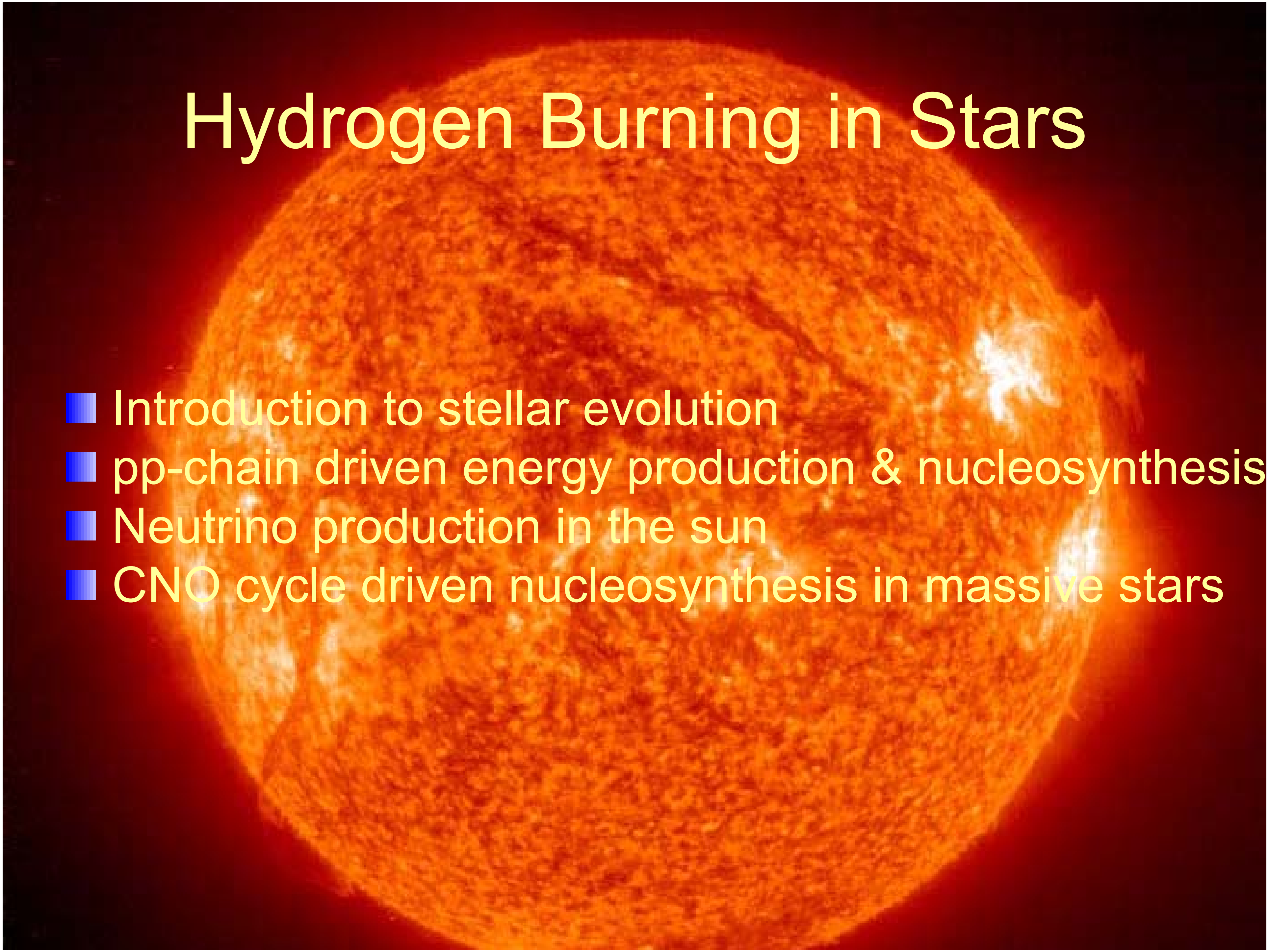


Hydrogen Burning in Stars

- Introduction to stellar evolution
- pp-chain driven energy production & nucleosynthesis
- Neutrino production in the sun
- CNO cycle driven nucleosynthesis in massive stars

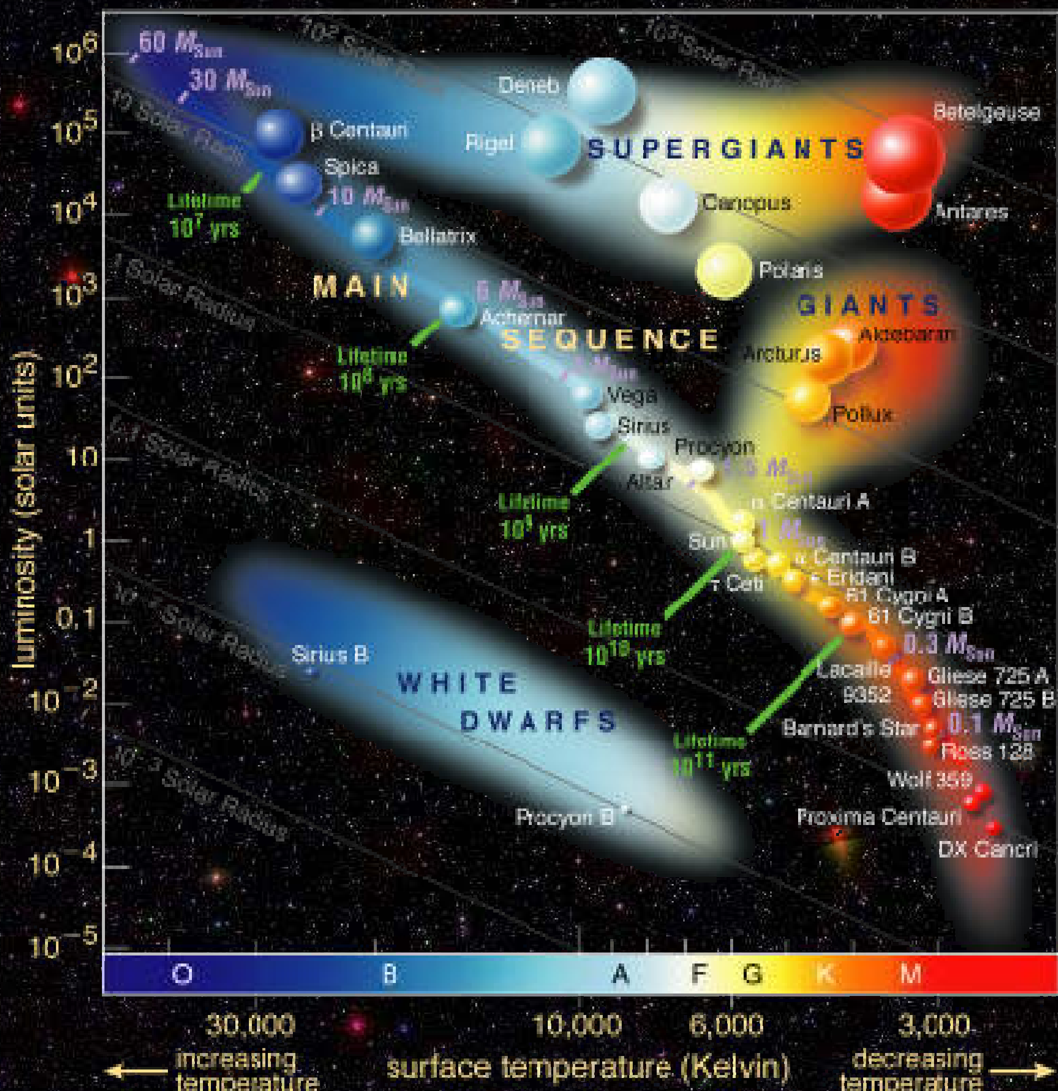
Fundamentals in nucleosynthesis driven stellar evolution

Hydrogen 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

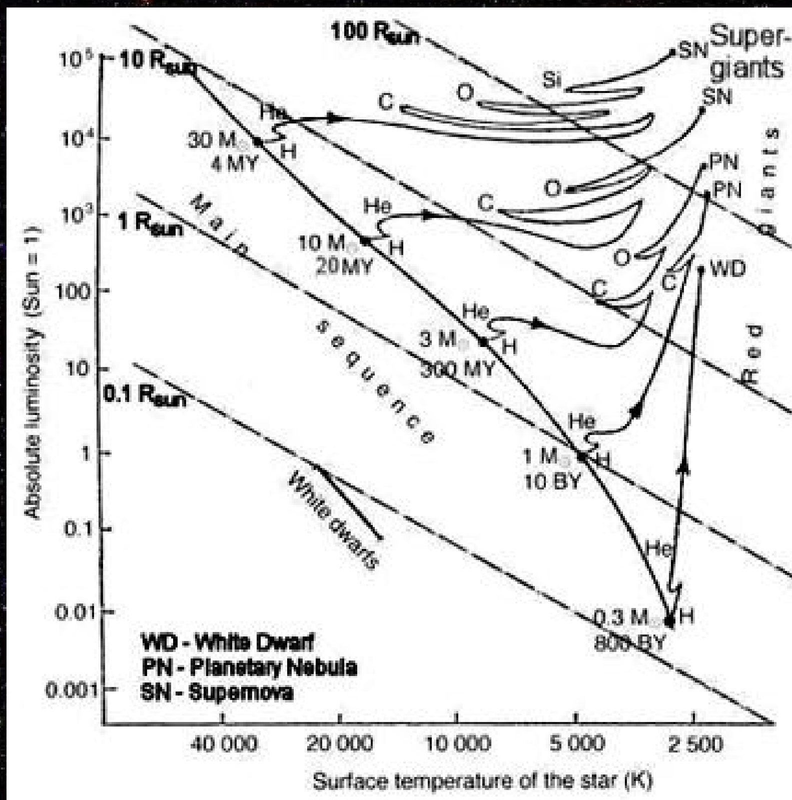
The stellar evolution, or subsequent evolutionary stages depend on the subsequent nucleosynthesis mechanisms or their nuclear fuel processing!

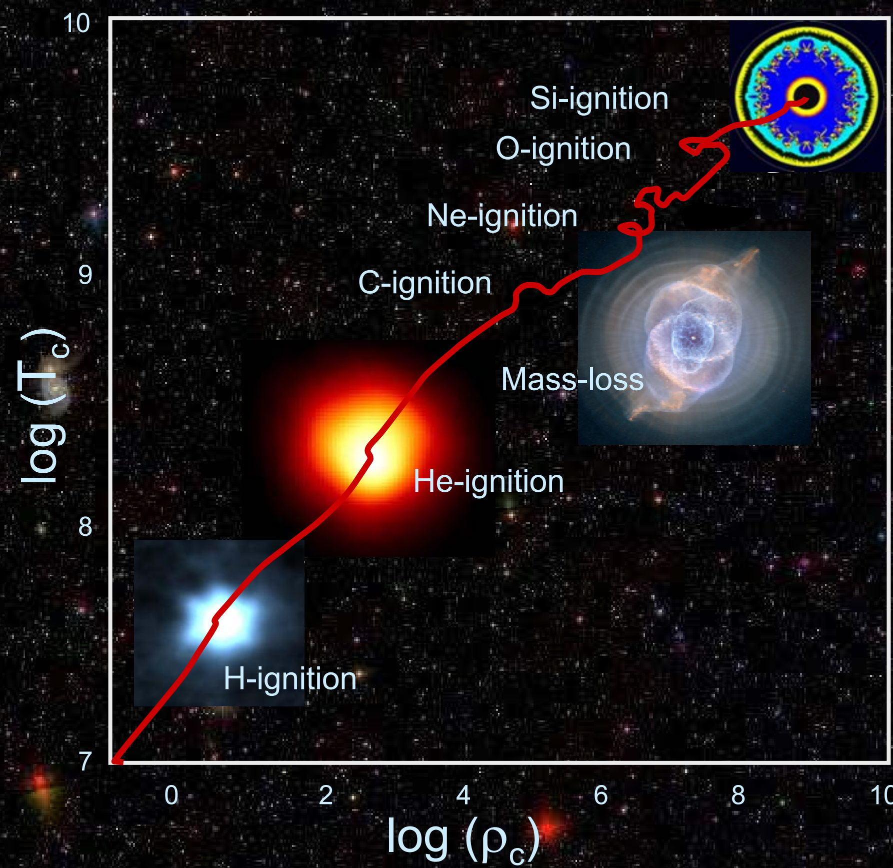
Hertzsprung Russell Diagram



Main Sequence Stars are identified as stars in their hydrogen burning stage. As more massive the star is as larger is its size, its energy production (temperature), and its luminosity.

Temperature and Density Evolution in Stellar Core

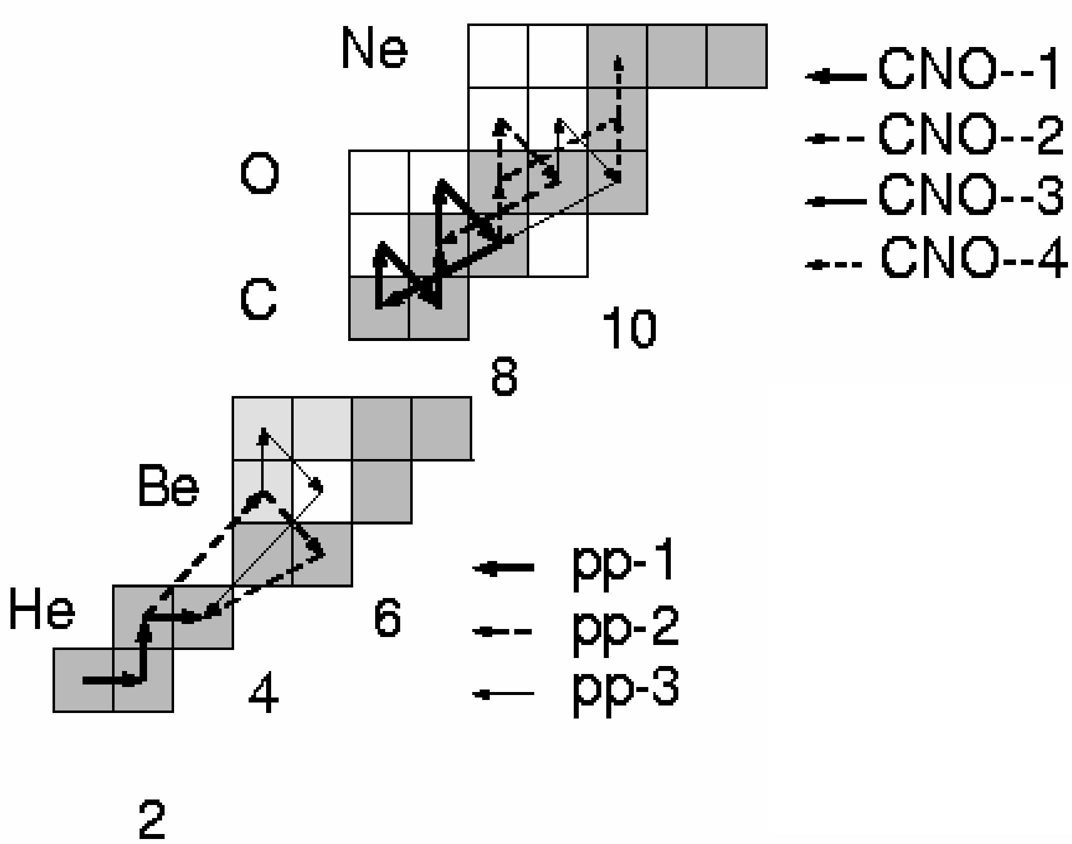


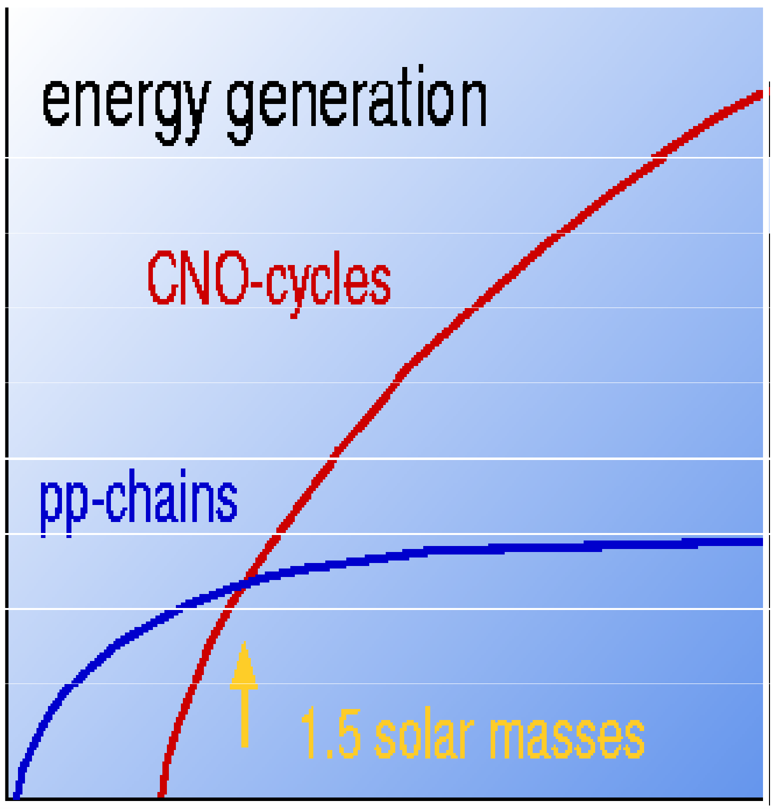


Graphical presentations of stellar evolution

Hydrogen Burning Stage of Stellar Evolution

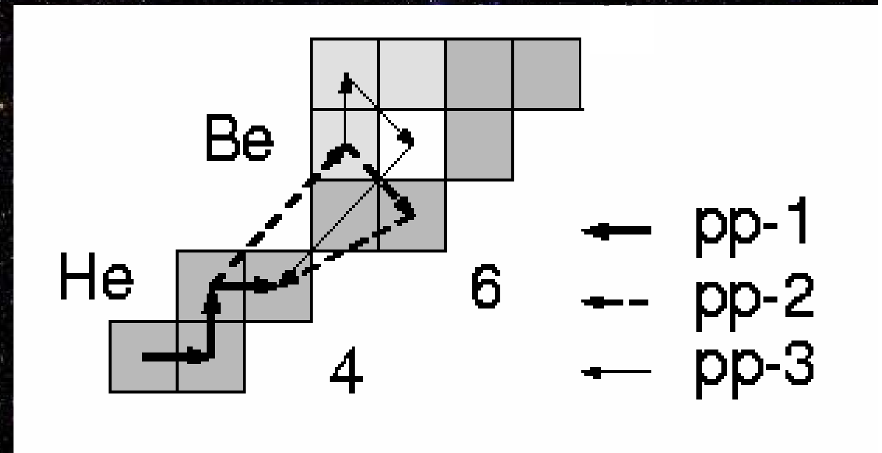
Stars with $M>1.5M_o$





Stars with $M<1.5M_o$

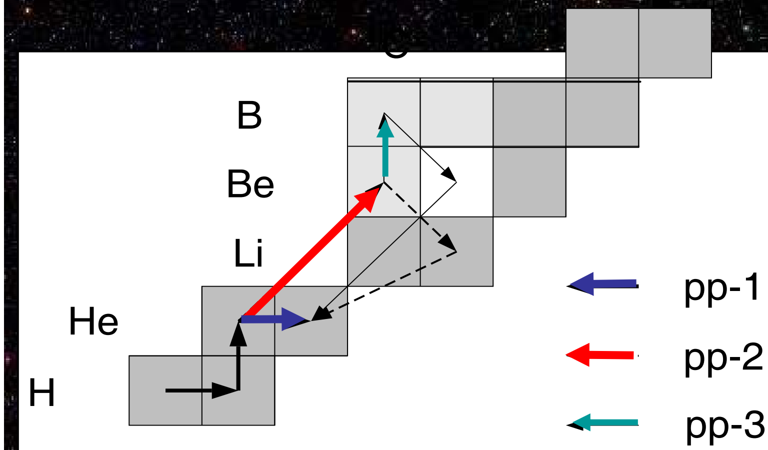
The pp-Chains



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

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

Neutrino production & neutrino energy



Neutrino production reaction

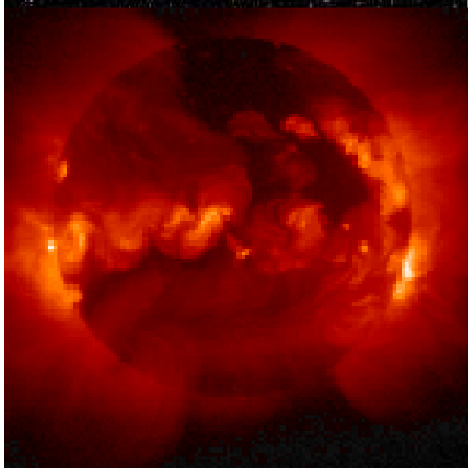
$p + p \Rightarrow {}^2H + e^+ + \nu_e$	E= 0.0 to 0.4 MeV
$p + e^- + p \Rightarrow {}^2H + \nu_e$	E= 1.4 MeV
$e^- + {}^7Be \Rightarrow {}^7Li + \nu_e$	E= 0.86, 0.38 MeV
${}^8B \Rightarrow {}^8Be + e^+ + \nu_e$	E= 0.0 to 15 MeV

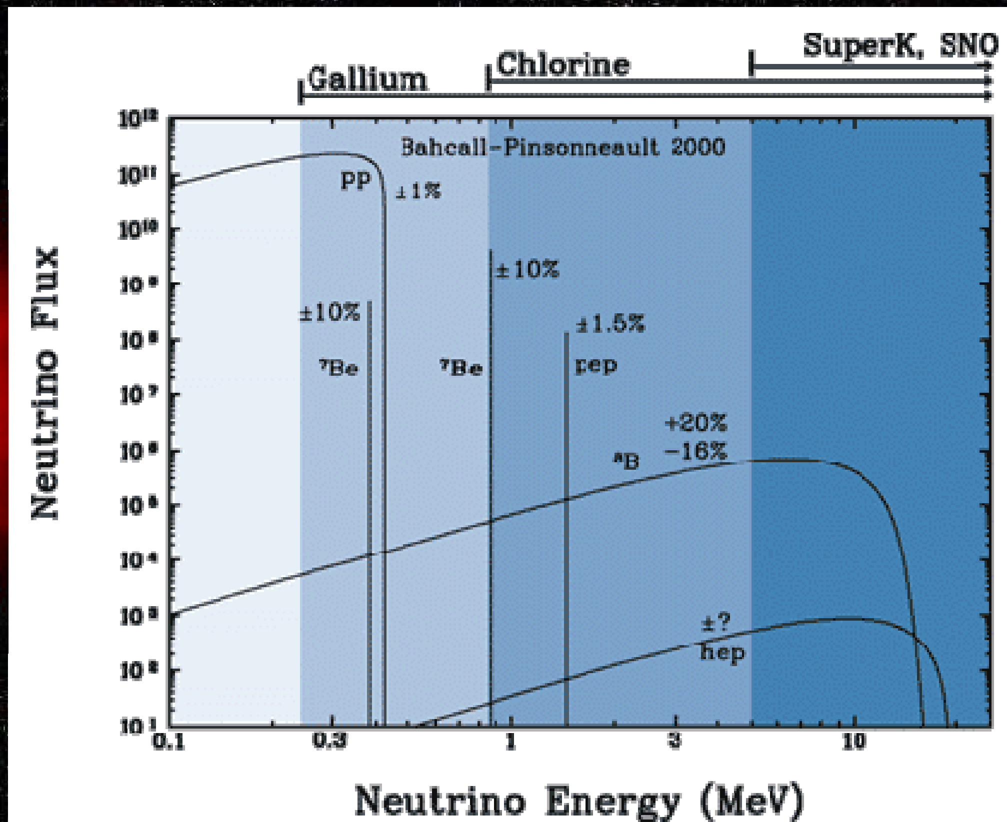
Neutrino flux in different energies depends on pp-chain branchings determined by the associated reaction rates:

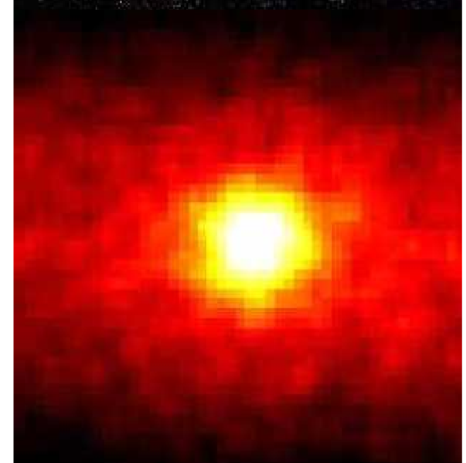
- ${}^1H + {}^1H$ versus ${}^1H + e^-$ determines neutrino flux at 1.4 MeV
- ${}^3He + {}^3He$ versus ${}^3He + {}^4He$ determines neutrino flux above 0.4 MeV
- ${}^7Be + p$ versus ${}^7Be + e^-$ determines neutrino flux above 0.9 MeV

Reaction rates are equivalent to neutrino production rates!

Solar Neutrino Production







Neutrinos as signature for probing the solar core
With neutrino detectors with sensitivity to specific neutrino energies: SNO, Borexino, Kamiokande …

Network for the pp-chain I

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

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

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

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

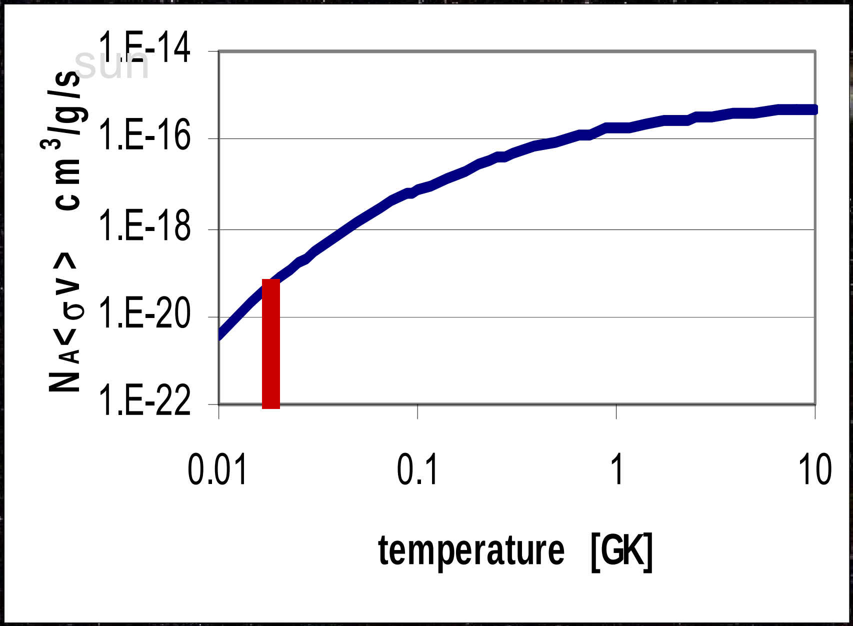
Hydrogen is depleted under release of neutrinos!
Helium is being produced + energy release 4H$\Rightarrow$1^{4}He!

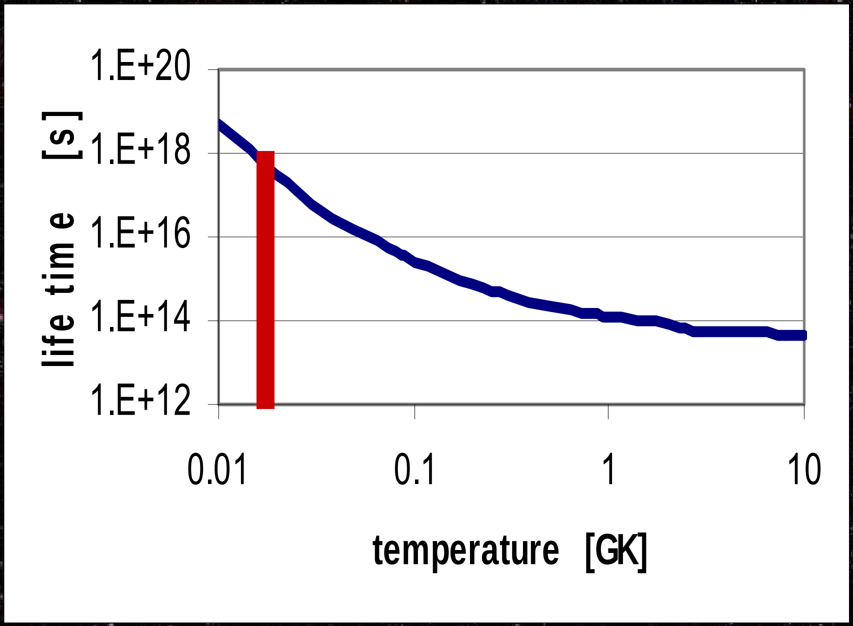
http://www.cococubed.com/talk_pages/jina.shtml

The p+p reaction

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

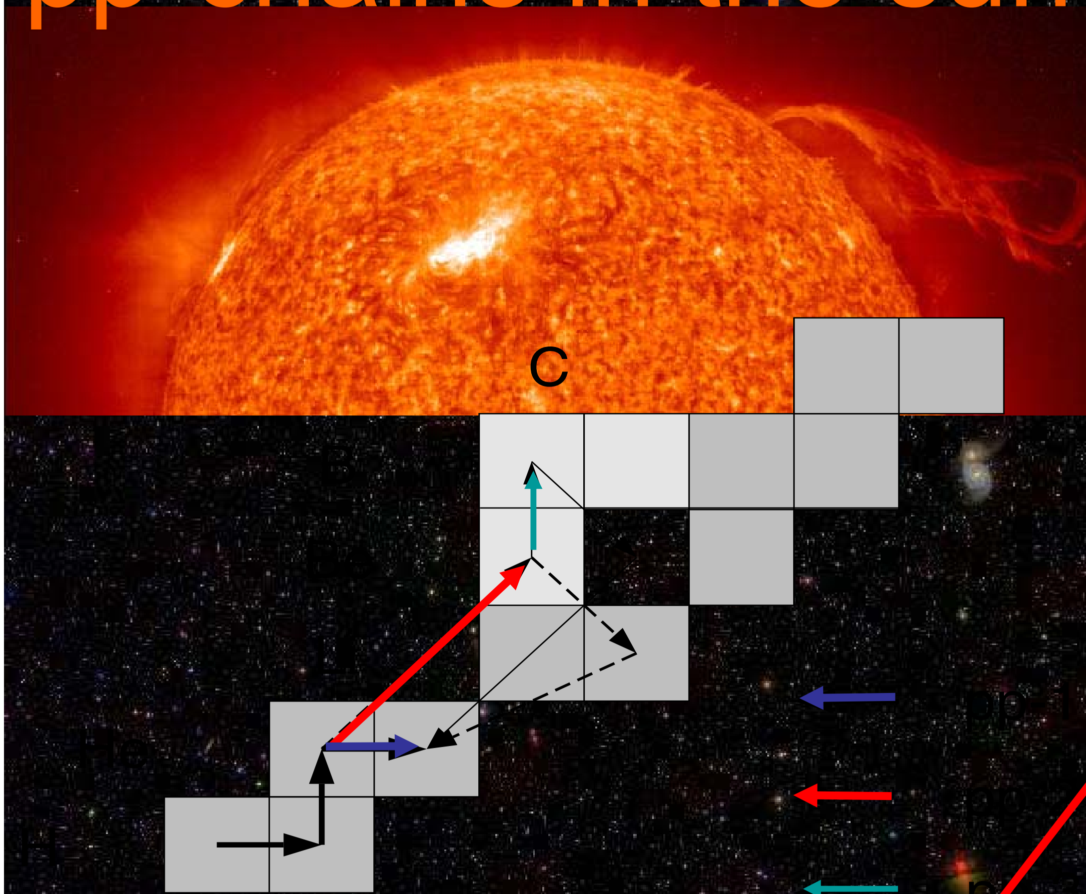
the S-factor is calculated: $S=5\cdot10^{-25}$ MeV-barn

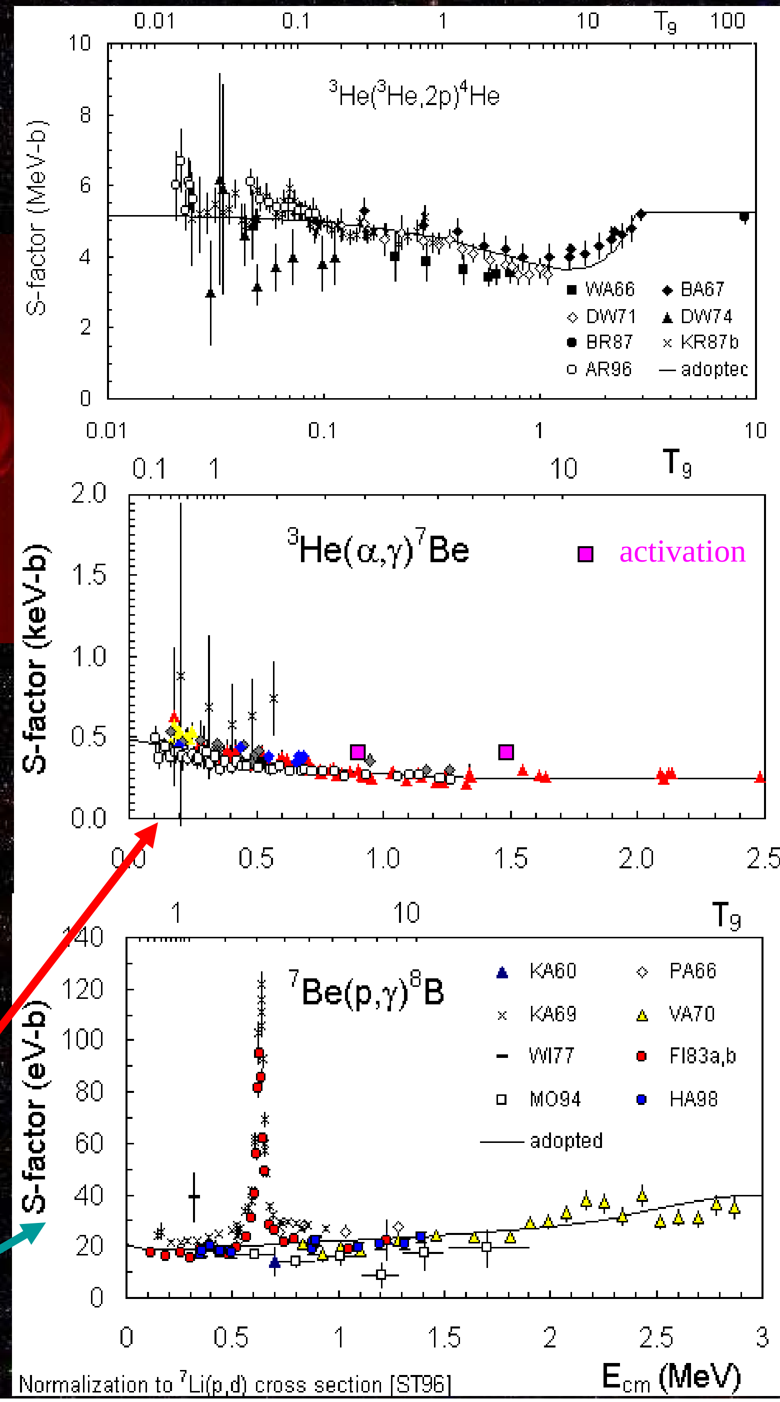




What would be the life time of hydrogen with strong interaction $S=5\cdot10^{-5}$ MeV-barn?

pp-chains in the sun





Impact on solar neutrino detectors

Borexino

SNO & Superkamiokande

Life Time Characteristics

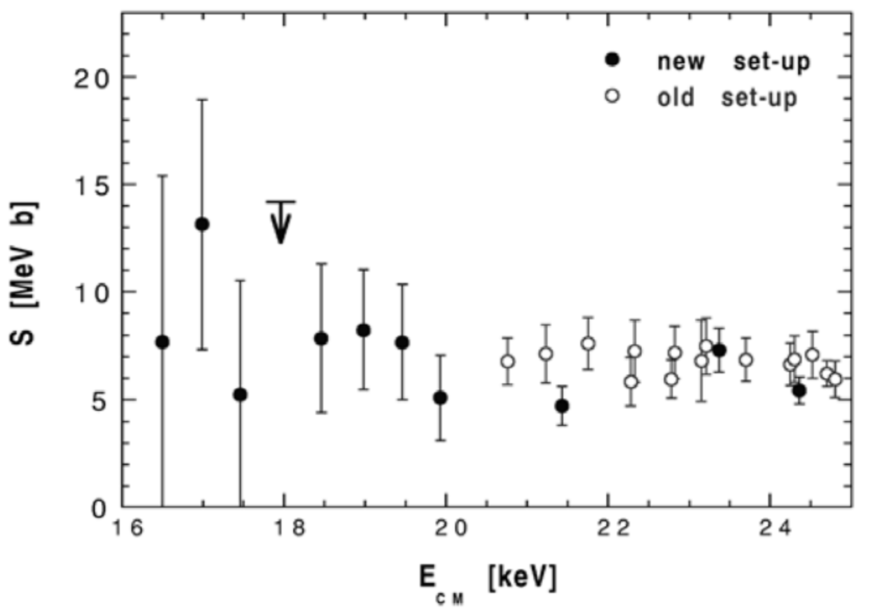
Enormous differences in S-factors due to nuclear interaction

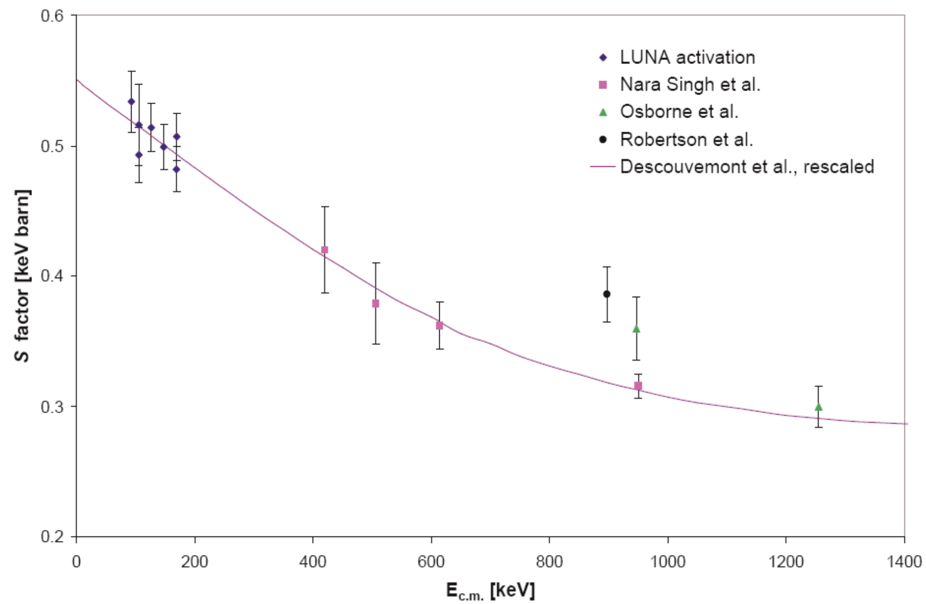
S_{p+p}	=	$5\ 10^{-25}$ MeV-barn	weak interaction
$S_{7Be(p,\gamma)}$	=	$2\ 10^{-5}$ MeV-barn	electromagnetic interaction
$S_{3He(\alpha,\gamma)}$	=	$5\ 10^{-4}$ MeV-barn	electromagnetic interaction
$S_{2H(p,\gamma)}$	=	$2\ 10^{-4}$ MeV-barn	electromagnetic interaction
$S_{3He(3He,2p)}$	=	5 MeV-barn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

Results and Improvements
through underground measurements
(with refined detector technology)





$^3He(^3He,2p)^4He$ S-factor increase by 20% to 6.0±xxx MeV-barn?

Bonetti et al. PRL 82, 5205 (1999)

$^3He(\alpha,\gamma)^7Be$ S-factor increase by 10% to $5.5 \cdot 10^{-4}$ MeV-barn

Confortola et al. PRC 75, 065803 (2007)

Nucleosynthesis product of pp-chains

$$\frac{d^1H}{dt} = -2\cdot\frac{1}{2}\cdot Y_{^1H}\cdot Y_{^1H}\cdot\rho\cdot N_A\langle\sigma\upsilon\rangle_{^1H(p,e^-\nu)} - Y_{^7Be}\cdot Y_{^1H}\cdot\rho\cdot N_A\langle\sigma\upsilon\rangle_{^7Be(p,\gamma)} + 2\cdot\frac{1}{2}\cdot Y_{^3He}\cdot Y_{^3He}\cdot\rho\cdot N_A\langle\sigma\upsilon\rangle_{^3He(^3He,2p)}$$

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

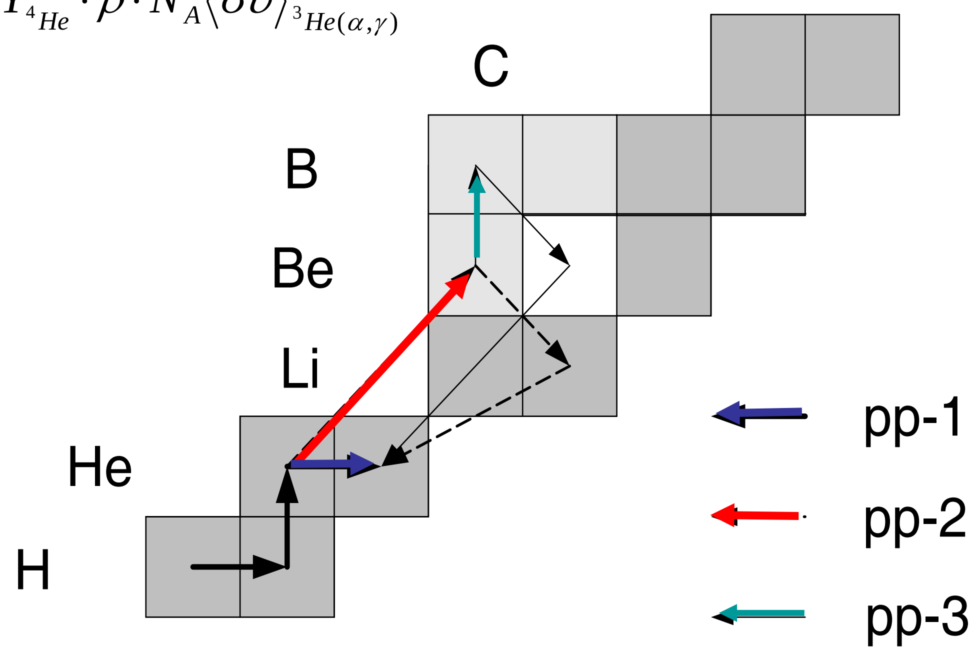
$$\frac{d^3He}{dt} = -2\cdot\frac{1}{2}\cdot Y_{^3He}\cdot Y_{^3He}\cdot\rho\cdot N_A\langle\sigma\upsilon\rangle_{^3He(^3He,2p)} - Y_{^3He}\cdot Y_{^4He}\cdot\rho\cdot N_A\langle\sigma\upsilon\rangle_{^3He(\alpha,\gamma)} + Y_{^2H}\cdot Y_{^1H}\cdot\rho\cdot N_A\langle\sigma\upsilon\rangle_{^2H(p,\gamma)}$$

$$\frac{d^7Be}{dt} = -\lambda_{ec}\cdot Y_{^7Be} - Y_{^7Be}\cdot Y_{^1H}\cdot\rho\cdot N_A\langle\sigma\upsilon\rangle_{^7Be(p,\gamma)} + Y_{^3He}\cdot Y_{^4He}\cdot\rho\cdot N_A\langle\sigma\upsilon\rangle_{^3He(\alpha,\gamma)}$$

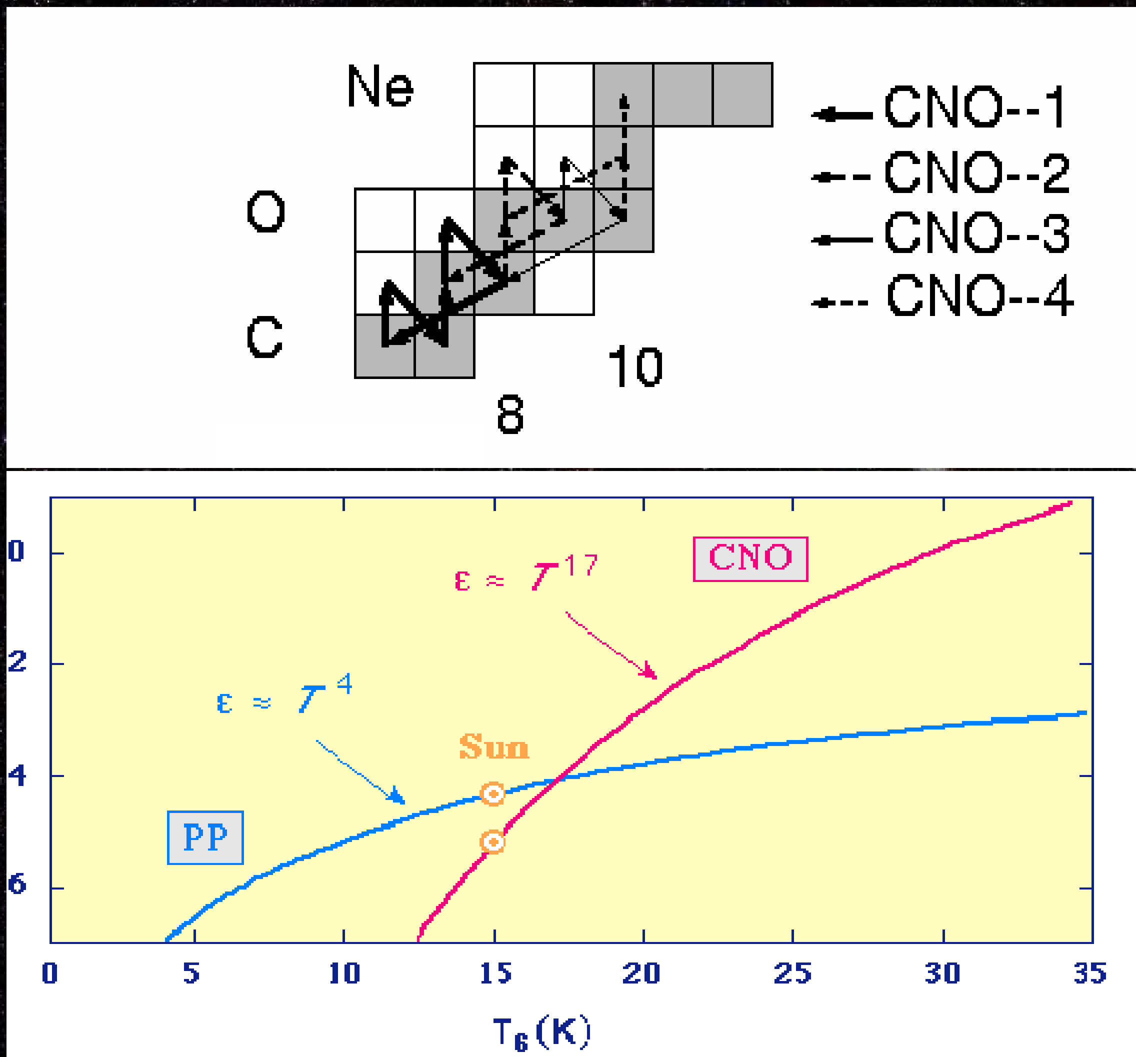
$$\frac{d^7Li}{dt} = -Y_{^7Li}\cdot Y_{^1H}\cdot\rho\cdot N_A\langle\sigma\upsilon\rangle_{^7Li(p,\alpha)} + \lambda_{ec}\cdot Y_{^7Be}$$

$$\frac{d^8B}{dt} = -\lambda_{(\beta,2\alpha)}\cdot Y_{^8B} + Y_{^7Be}\cdot Y_{^1H}\cdot\rho\cdot N_A\langle\sigma\upsilon\rangle_{^7Be(p,\gamma)}$$

$$\frac{d^4He}{dt} = 2\cdot\frac{1}{2}\cdot Y_{^3He}\cdot Y_{^3He}\cdot\rho\cdot N_A\langle\sigma\upsilon\rangle_{^3He(^3He,2p)} - Y_{^3He}\cdot Y_{^4He}\cdot\rho\cdot N_A\langle\sigma\upsilon\rangle_{^3He(\alpha,\gamma)} + Y_{^7Li}\cdot Y_{^1H}\cdot\rho\cdot N_A\langle\sigma\upsilon\rangle_{^7Li(p,\alpha)} + 2\cdot\lambda_{(\beta,2\alpha)}\cdot Y_{^8B}$$



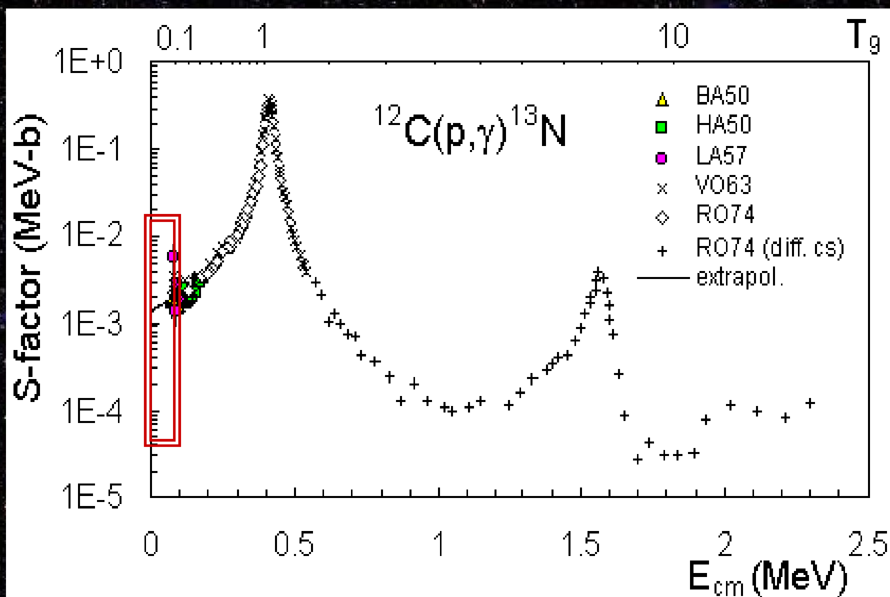
Hydrogen Burning in Massive Stars

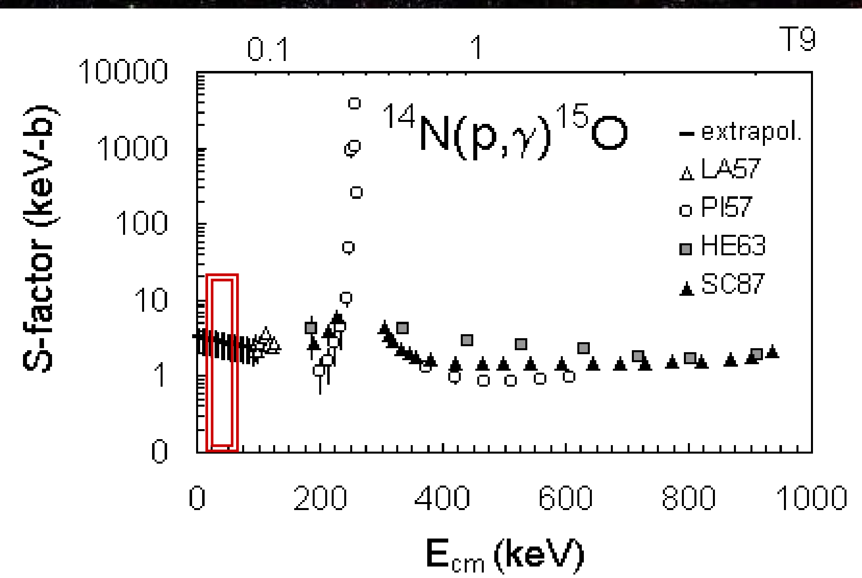


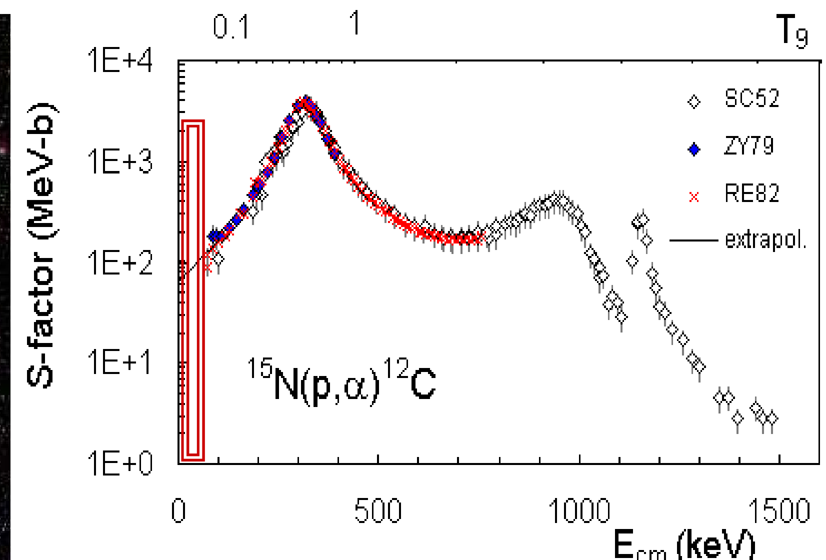
Requires pre-existing CNO abundances as catalyzing isotopes for the helium production through consecutive four proton capture and two beta-decay processes

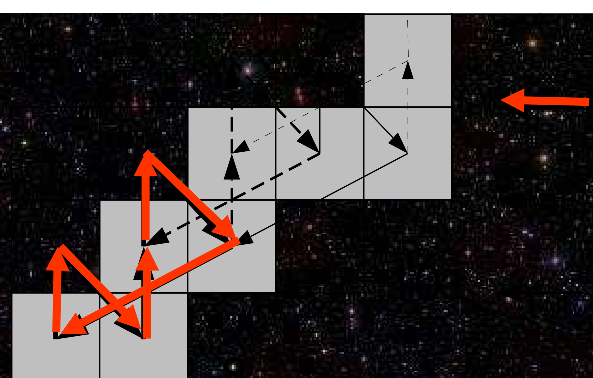
CNO burning is necessary for massive star evolution to stabilize the stellar core against its internal gravitational contraction!

The main CNO cycle









Reactions in the CNO cycles

CNO-1:

$^{12}C(p,\gamma)^{13}N$ $S_{12C(p,\gamma)}$=3 10^{-3} MeV-barn

$^{13}N(\beta^{+}\nu)^{13}C$

$^{13}C(p,\gamma)^{14}N$

$^{14}N(p,\gamma)^{15}O$ $S_{14N(p,\gamma)}$=2 10^{-3} MeV-barn

$^{15}O(\beta^{+}\nu)^{15}N$

$^{15}N(p,\alpha)^{12}C$ $S_{15N(p,\alpha)}$=1 10^{+2} MeV-barn

CNO-2:

$^{15}N(p,\gamma)^{16}O$ $S_{15N(p,\gamma)}$=5 10^{-2} MeV-barn

$^{16}O(p,\gamma)^{17}F$

$^{17}F(\beta^{+}\nu)^{17}O$

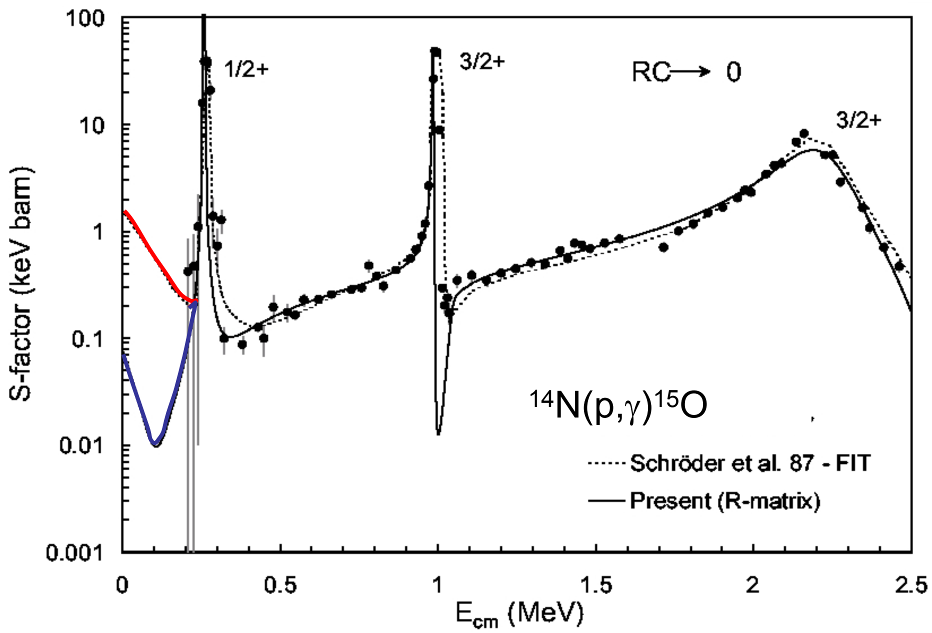
$^{17}O(p,\alpha)^{15}N$

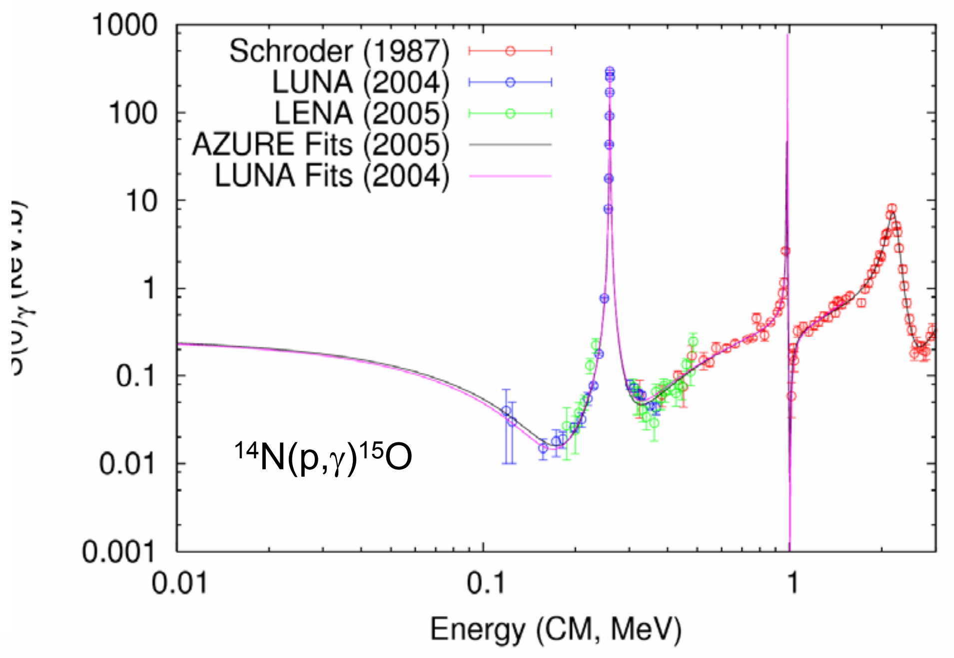
CNO-3:

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

$^{18}F(p,\alpha)^{15}O$

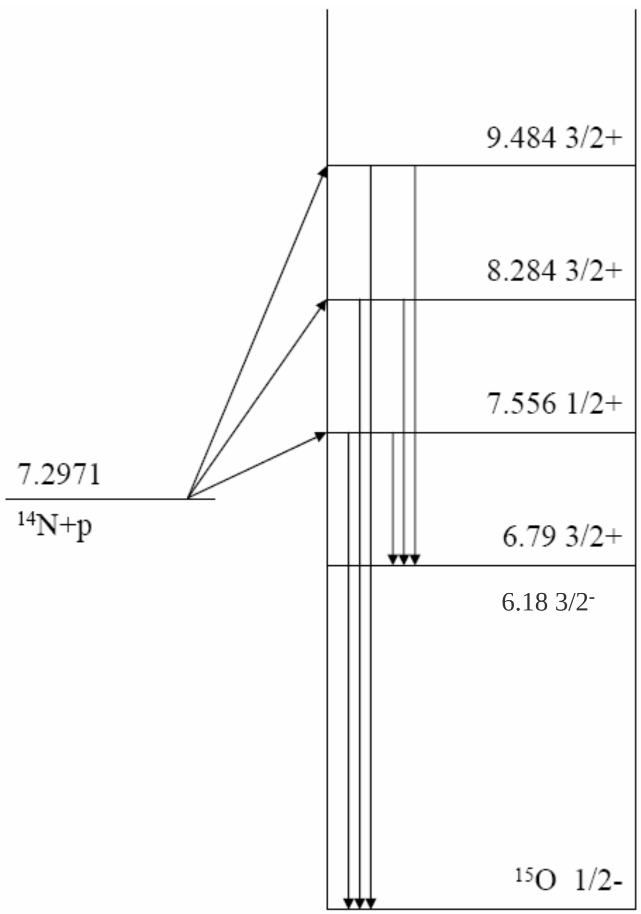
BUT: recent results & new questions

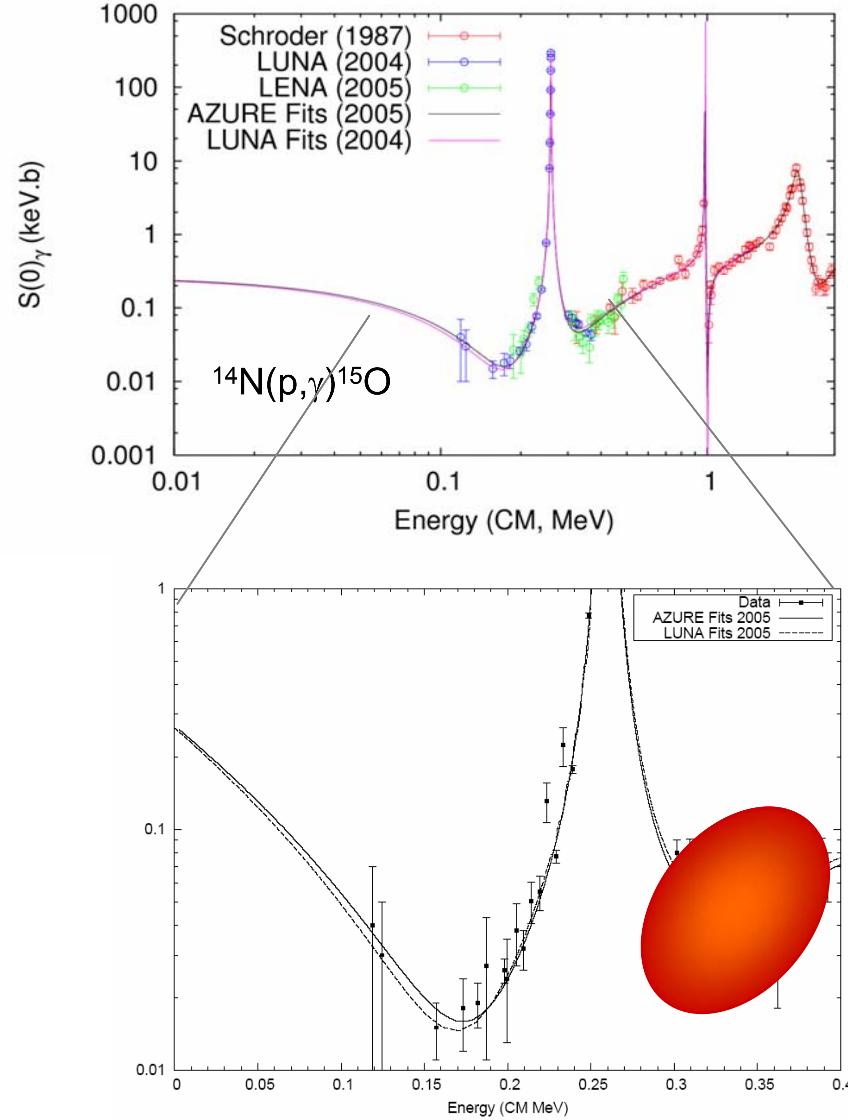




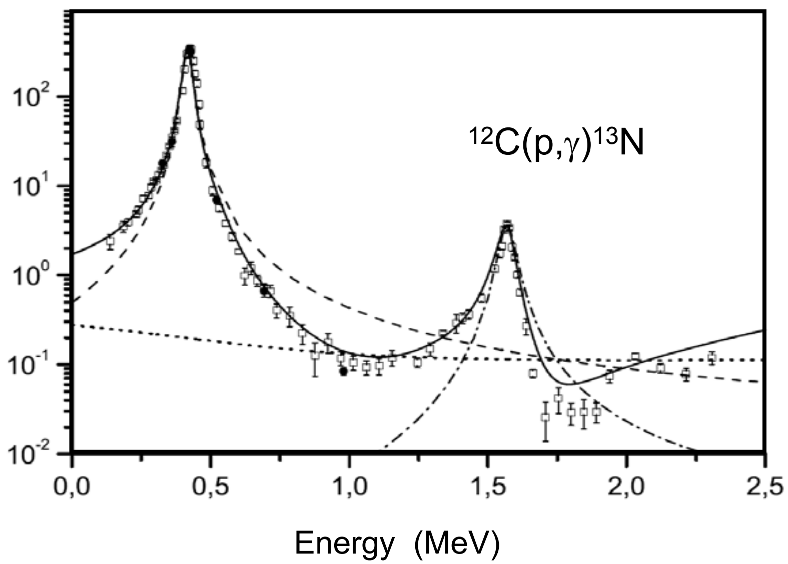
Uncertainties in the $^{14}N(p,\gamma)^{15}O$ rate caused considerable uncertainties, in age determination for Globular Clusters, CNO energy generation, and in neutrino flux of massive main sequence low metallicity stars!

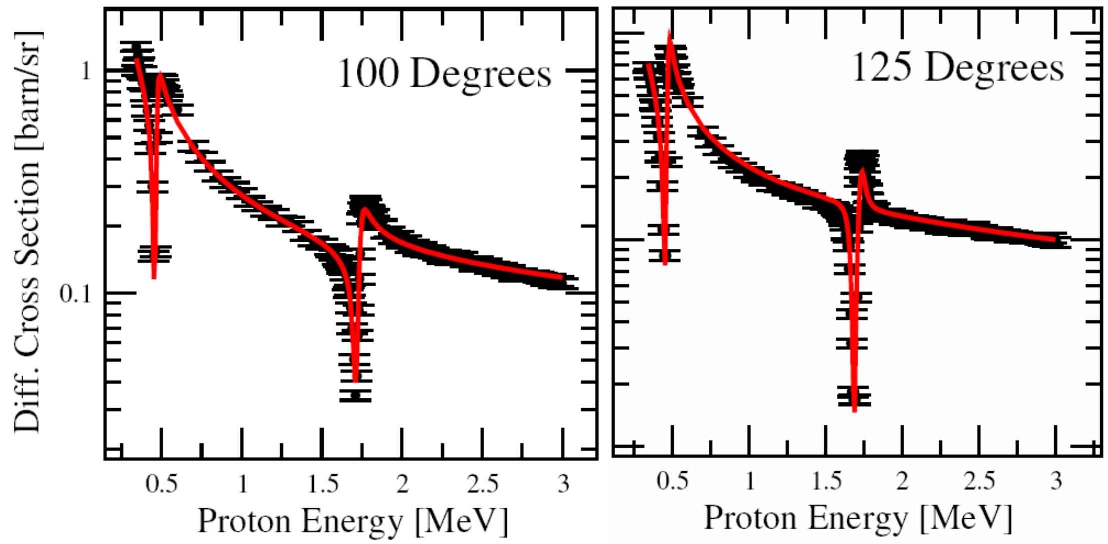
Relevance of higher energy data and channels in r-matrix analysis

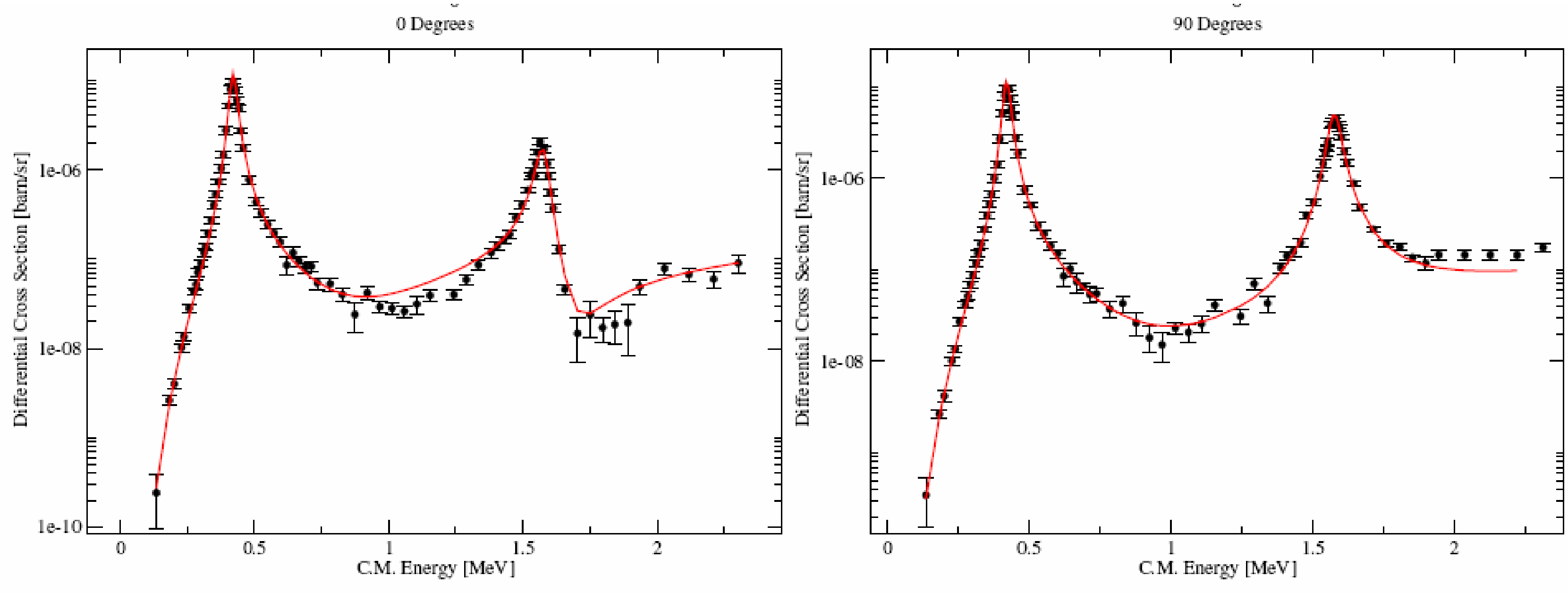




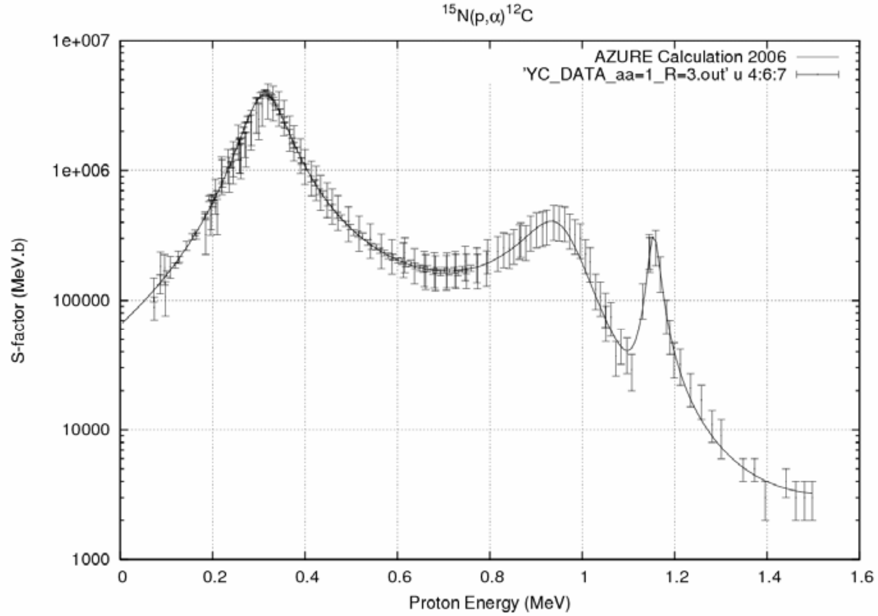
Inconsistencies in $^{12}C(p,\gamma)^{13}N$ extrapolation

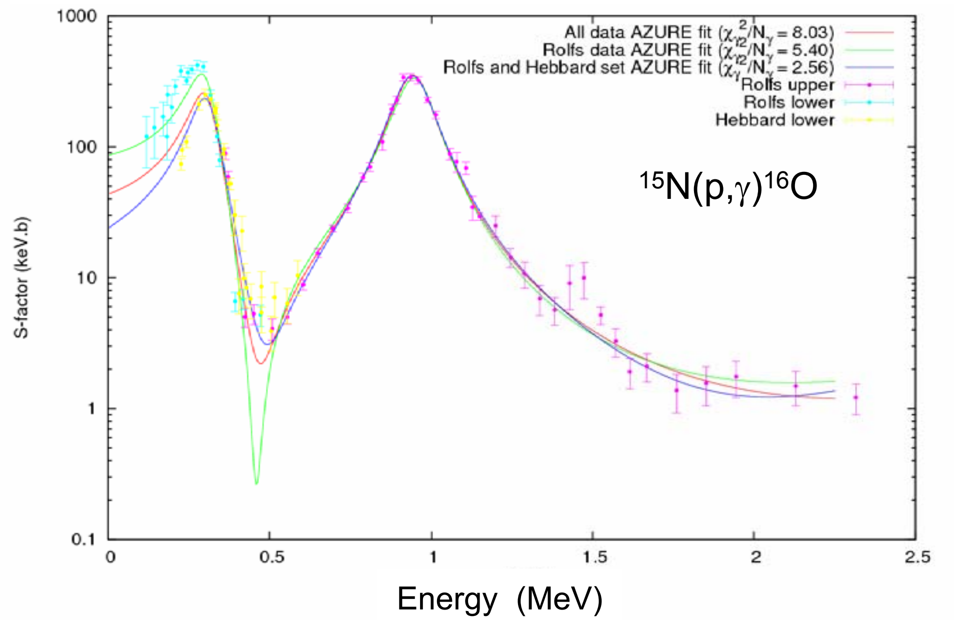


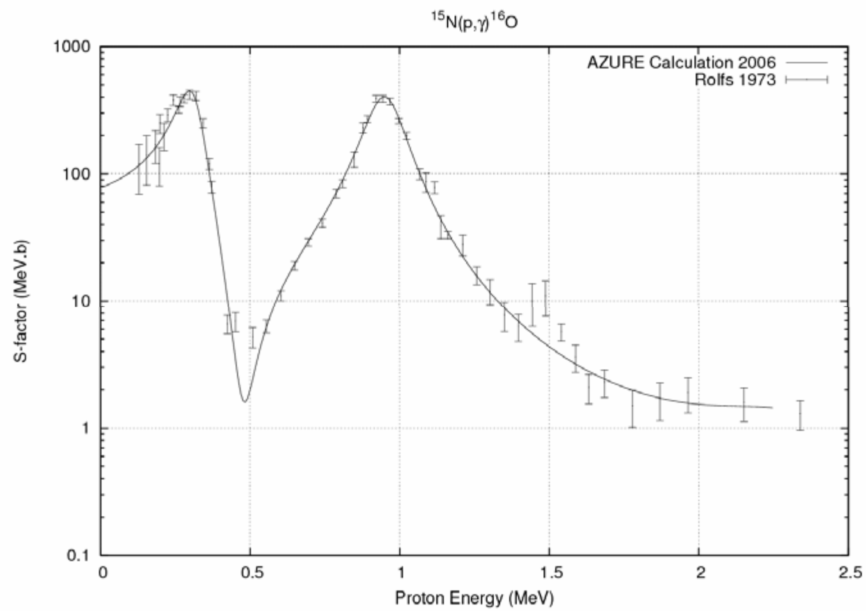


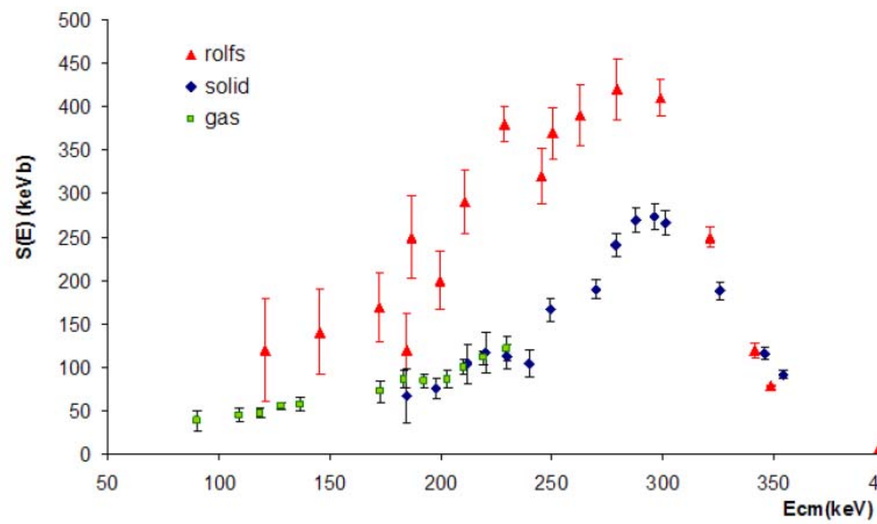


The first CNO branching

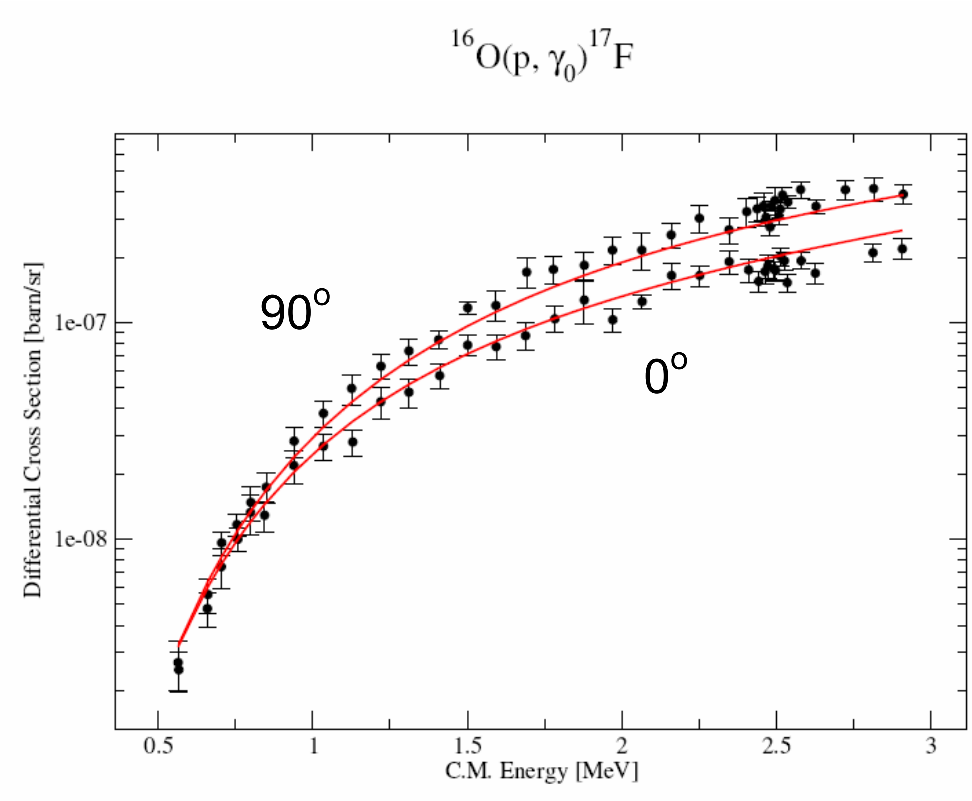


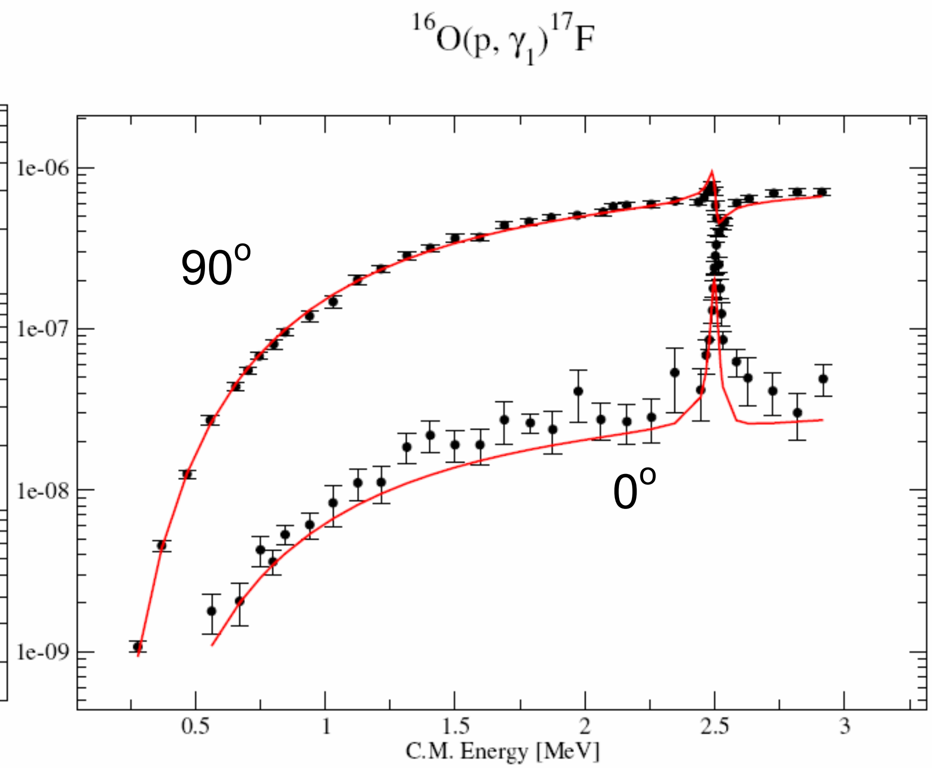






Non-resonant direct capture





Ground state transition is isotropic; deviations point towards deficiencies in set-up or efficiency corrections

Transition to 1st excited state shows $\sin^2\Theta$ distribution; similar deviations as for gs transition!

Network for CN cycle

$$\frac{dY_{^{12}C}}{dt} = -Y_{^{12}C} \cdot Y_{^{1}H} \cdot \rho \cdot N_A \langle \sigma \upsilon \rangle_{^{12}C(p,\gamma)} + Y_{^{15}N} \cdot Y_{^{1}H} \cdot \rho \cdot N_A \langle \sigma \upsilon \rangle_{^{15}N(p,\alpha)}$$

$$\frac{dY_{^{13}N}}{dt} = -Y_{^{13}N} \cdot \lambda_{^{13}N(\beta^+)} + Y_{^{12}C} \cdot Y_{^{1}H} \cdot \rho \cdot N_A \langle \sigma \upsilon \rangle_{^{12}C(p,\gamma)}$$

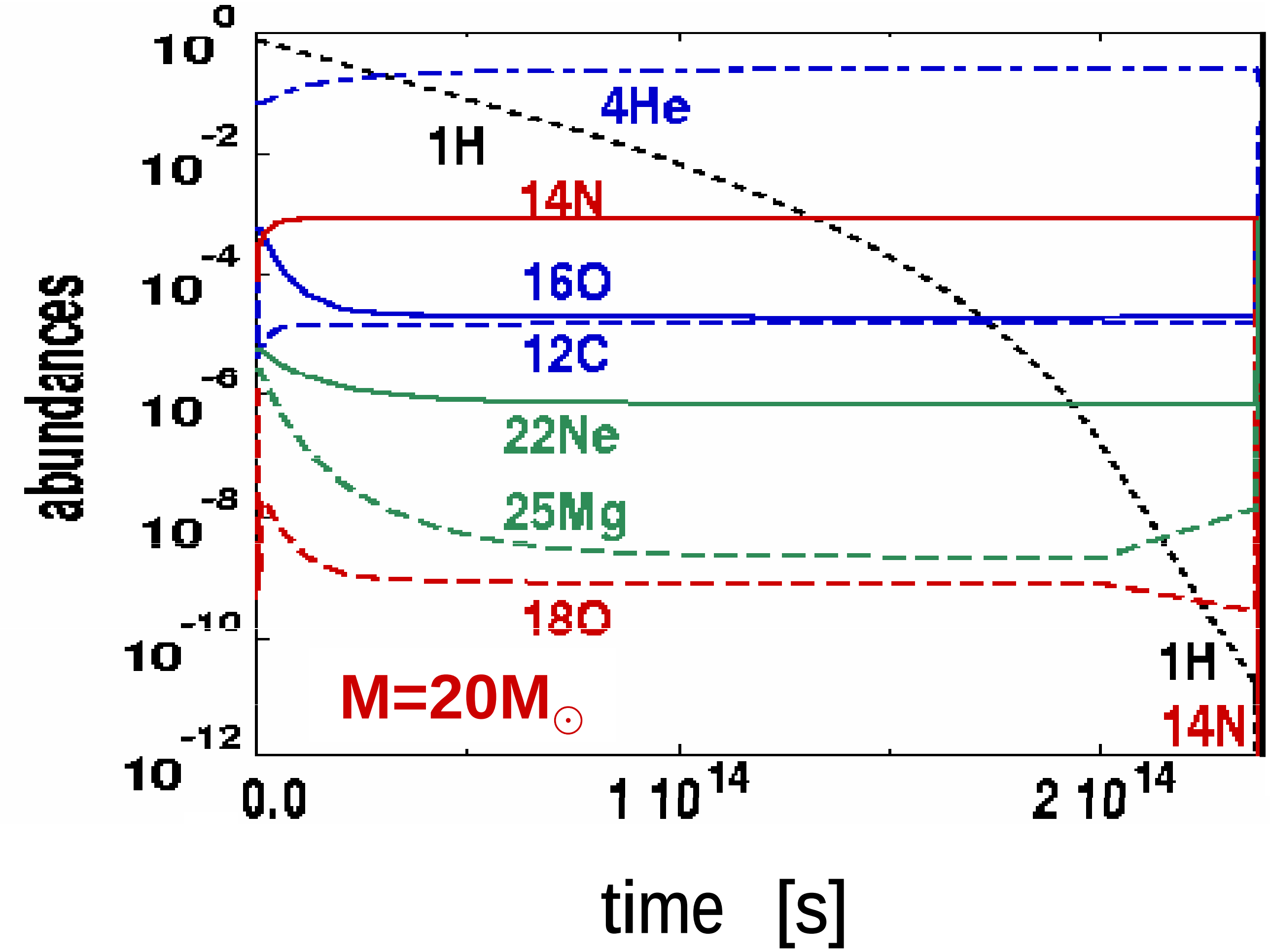
$$\frac{dY_{^{13}C}}{dt} = -Y_{^{13}C} \cdot Y_{^{1}H} \cdot \rho \cdot N_A \langle \sigma \upsilon \rangle_{^{13}C(p,\gamma)} + Y_{^{13}N} \cdot \lambda_{^{13}N(\beta^+)}$$

$$\frac{dY_{^{14}N}}{dt} = -Y_{^{14}N} \cdot Y_{^{1}H} \cdot \rho \cdot N_A \langle \sigma \upsilon \rangle_{^{14}N(p,\gamma)} + Y_{^{13}C} \cdot Y_{^{1}H} \cdot \rho \cdot N_A \langle \sigma \upsilon \rangle_{^{13}C(p,\gamma)}$$

$$\frac{dY_{^{15}O}}{dt} = -Y_{^{15}O} \cdot \lambda_{^{15}O(\beta^+)} + Y_{^{14}N} \cdot Y_{^{1}H} \cdot \rho \cdot N_A \langle \sigma \upsilon \rangle_{^{14}N(p,\gamma)}$$

$$\frac{dY_{^{15}N}}{dt} = -Y_{^{15}N} \cdot Y_{^{1}H} \cdot \rho \cdot N_A \langle \sigma \upsilon \rangle_{^{15}N(p,\alpha)} + Y_{^{15}O} \cdot \lambda_{^{15}O(\beta^+)}$$

Reaction network of CNO



Conversion of the initial

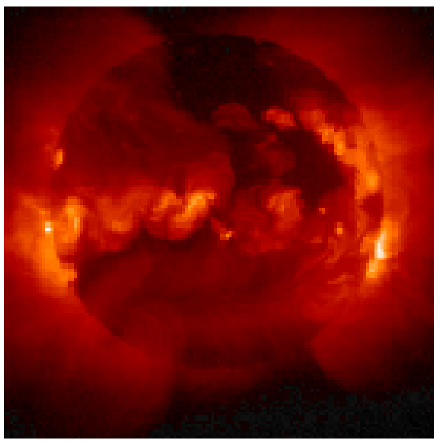
- ^{1}H to ^{4}He
- ^{12}C,^{16}O to ^{14}N

^{4}He and ^{14}N are the ashes of the CNO burning, the fuel and seed for the following He burning stage

Life Time of Main Sequence Stars

The life time of pp-burning stars is determined by the weak interaction based reaction rate of $^{1}H(p,e^{+}\nu)^{2}H$.

Life time of CNO burning stars is determined by the EM interaction based reaction rate of $^{14}N(p,\gamma)^{15}O$.

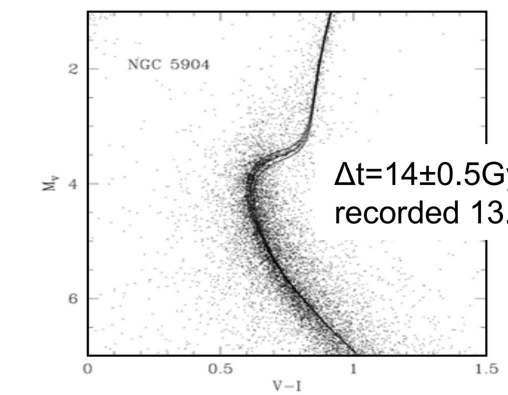


$$\tau = \frac{1}{r_{p,t}} = \frac{1}{N_p N_t \langle \sigma \upsilon \rangle}$$

$$\tau = \frac{1}{N_p N_t \int_0^{\infty} \phi(E) \cdot E \cdot \sigma(E) \cdot dE}$$

From 10^{9} years
To 10^{-9} seconds

Direct correlation with channel threshold effects in reaction cross section.



Subsequent Burning Phases