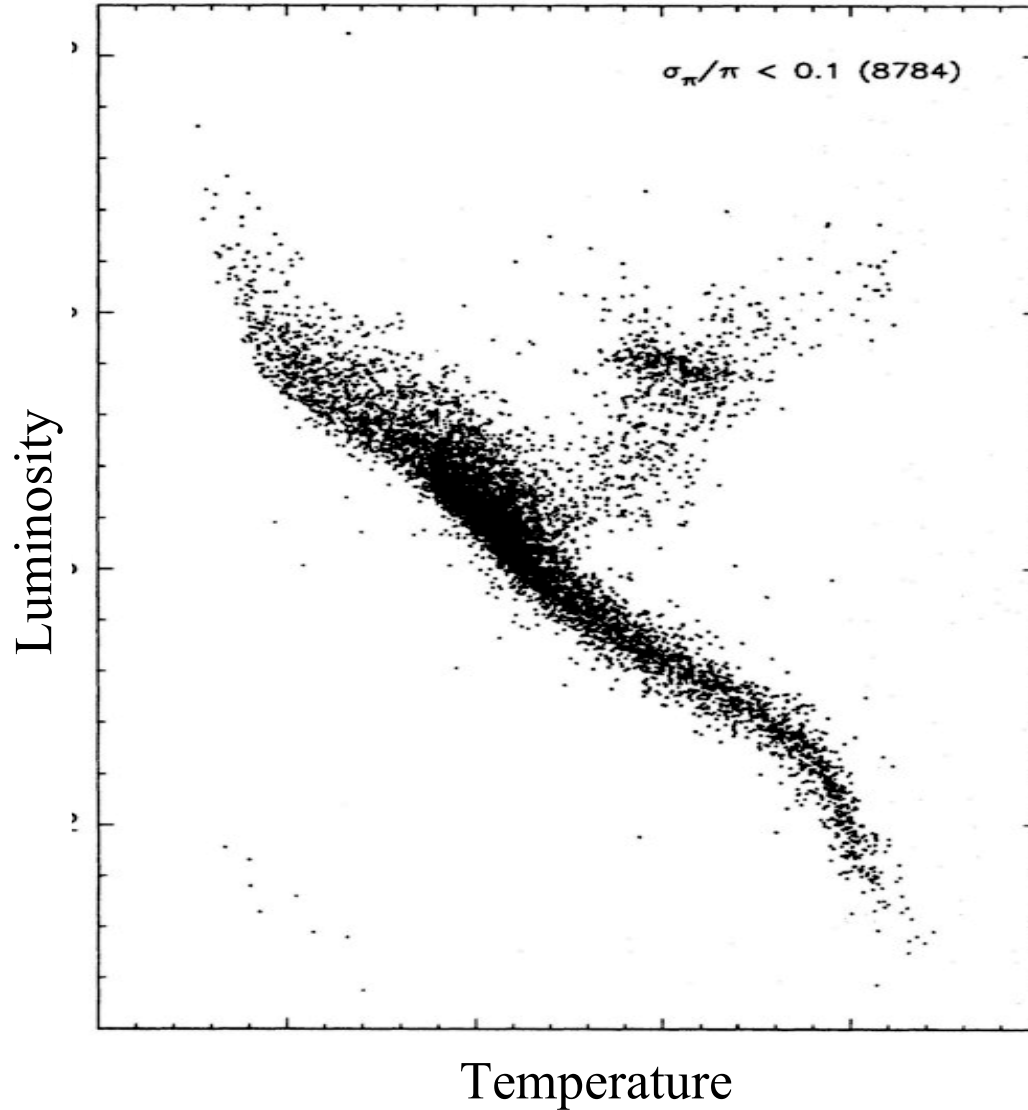


# The Main Sequence: Hydrogen Burning

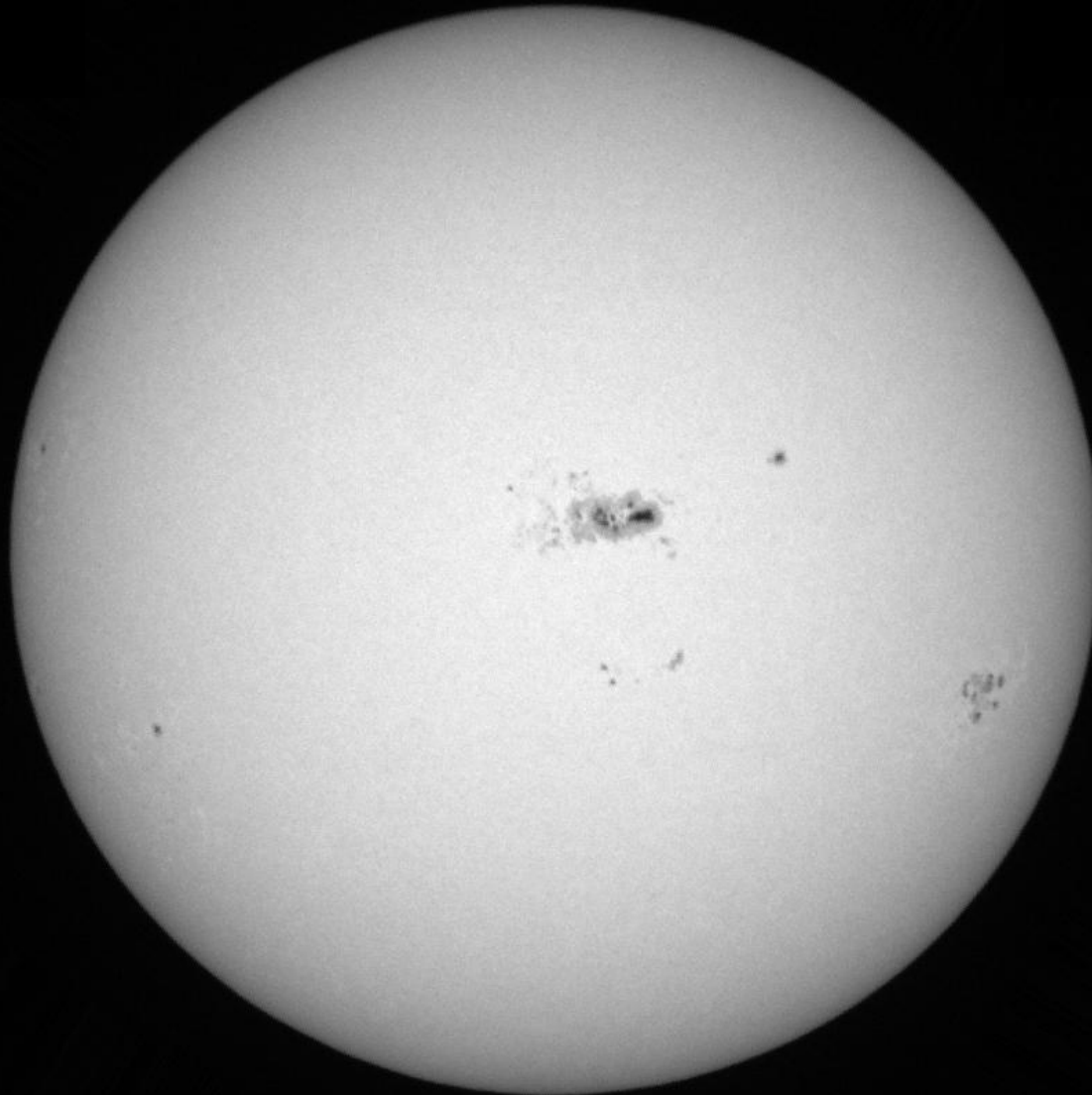
- Concept of steady flow in nuclear reactions
- the pp-chain(s)
- CNO-cycle(s)

Literature: Iliadis: Chap. 5.1 - 5.2

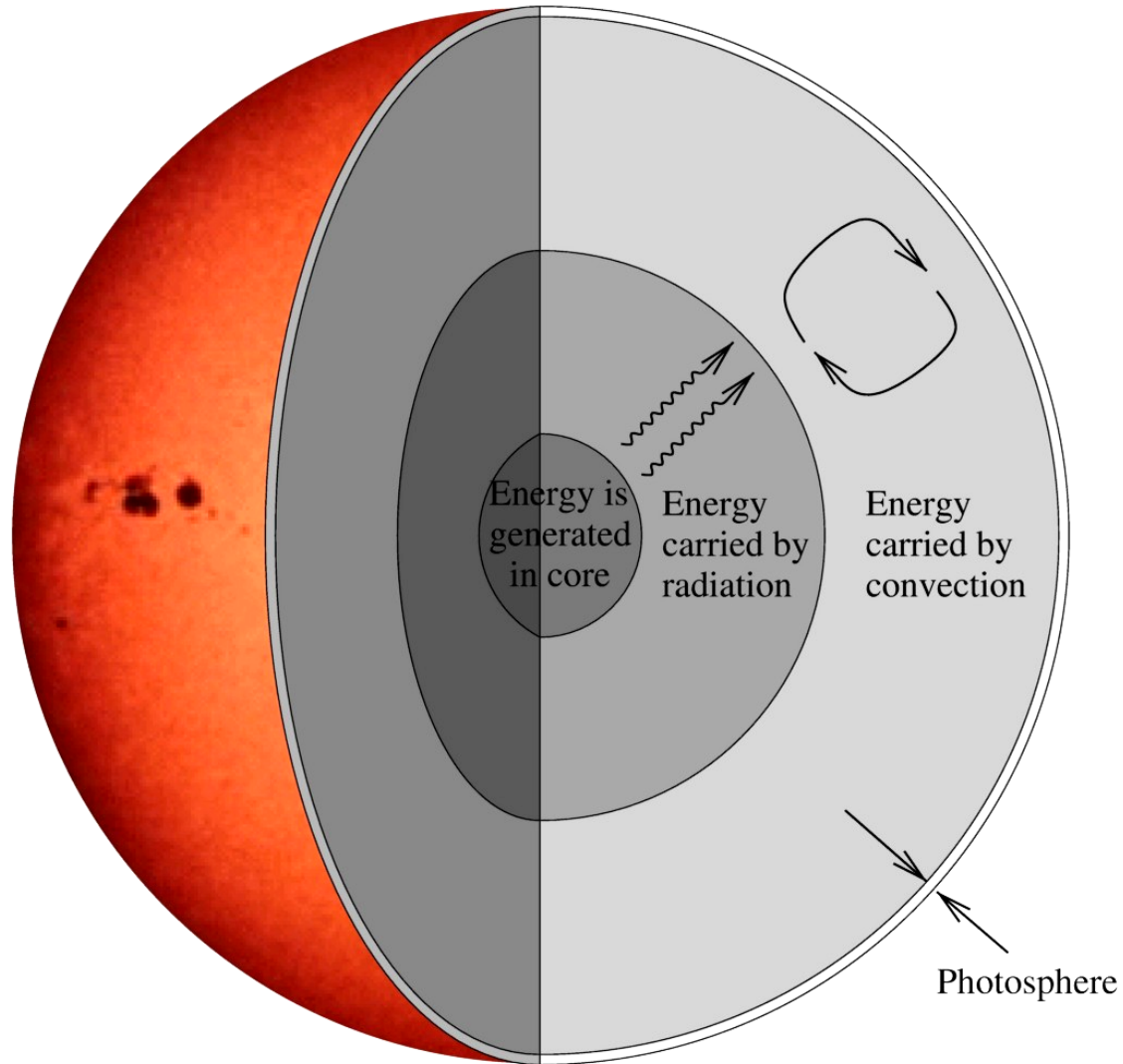
# The Real H-R Diagram for Stars near the Sun



# The Sun at Visible Wavelengths



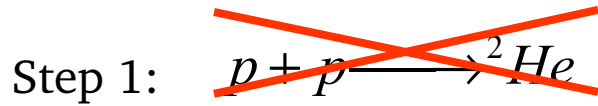
# The Interior of the Sun



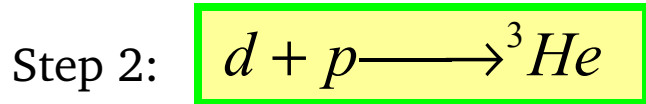
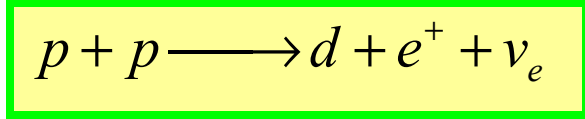
**Remark:** Nuclear processes proceed along two body reactions if possible



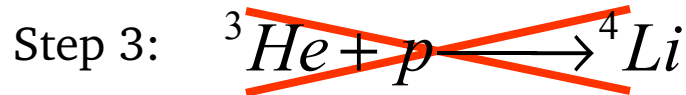
# The ppI chain



${}^2\text{He}$  is unstable



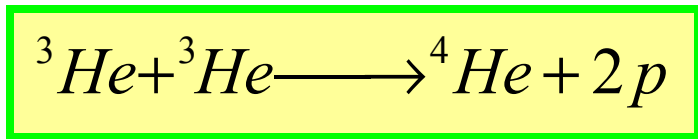
d abundance is too low



${}^4\text{Li}$  is unstable



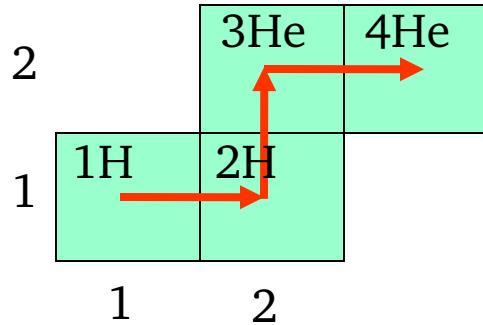
d abundance is too low



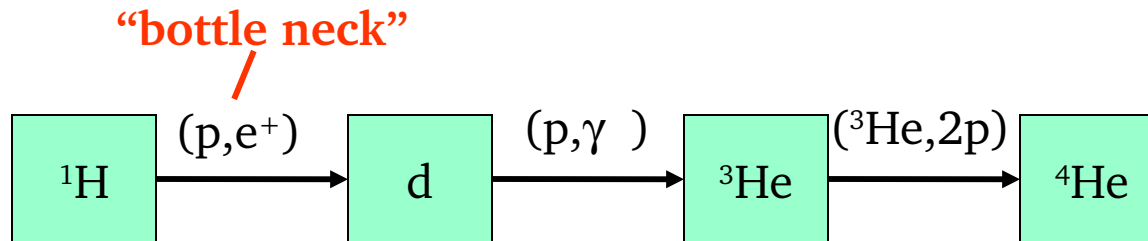
d+d not going because  $Y_d$  is small as d+p leads to rapid destruction

${}^3\text{He} + {}^3\text{He}$  goes because  $Y_{{}^3\text{He}}$  gets large as there is no other rapid destruction

On chart of nuclides:



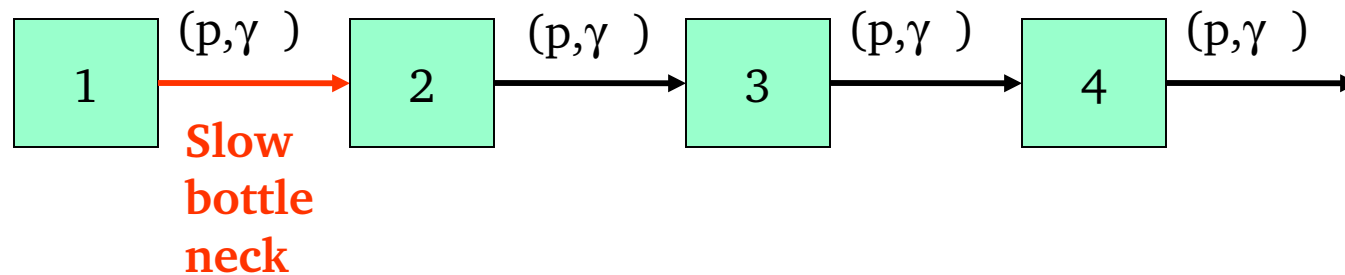
Or as a chain of reactions:



# Steady Flow: A chain of reactions after a “bottle neck”

## Example

For simplicity consider chain of proton captures:



Assumptions:

- $Y_1$  const as depletion is very slow because of “bottle neck”
- Capture rates constant ( $Y_p \sim$  const because of large “reservoir”, conditions constant as well)

Abundance of nucleus 2 evolves according to:

$$\frac{dY_2}{dt} = \underbrace{Y_1 \lambda_{12}}_{\text{production}} - \underbrace{Y_2 \lambda_{23}}_{\text{destruction}}$$

$$\lambda_{12} = \frac{1}{1 + \delta_{p1}} Y_p \rho N_A \langle \sigma v \rangle_{1 \rightarrow 2}$$



For our assumptions  $Y_1 \sim \text{const}$  and  $Y_p \sim \text{const}$ ,  $Y_2$  will then, after some time reach an equilibrium value regardless of its initial abundance:

In equilibrium:

$$\frac{dY_2}{dt} = Y_1 \lambda_{12} - Y_2 \lambda_{23} = 0 \quad \text{and} \quad Y_2 \lambda_{23} = Y_1 \lambda_{12}$$

(this equilibrium is called steady flow)

Same for  $Y_3$  (after some longer time)

$$\frac{dY_3}{dt} = Y_2 \lambda_{23} - Y_3 \lambda_{34} = 0$$

$$\text{and } Y_3 \lambda_{34} = Y_2 \lambda_{23} \quad \text{with result for } Y_2: \quad Y_3 \lambda_{34} = Y_1 \lambda_{12}$$

and so on ...

So in steady flow:  $Y_i \lambda_{i,i+1} = \text{const} = Y_1 \lambda_{12}$  or  $Y_i \propto \tau_i$

# Timescale to achieve steady flow equilibrium

for  $\lambda \sim \text{const}$

$$\frac{dY_2}{dt} = Y_1\lambda_{12} - Y_2\lambda_{23}$$

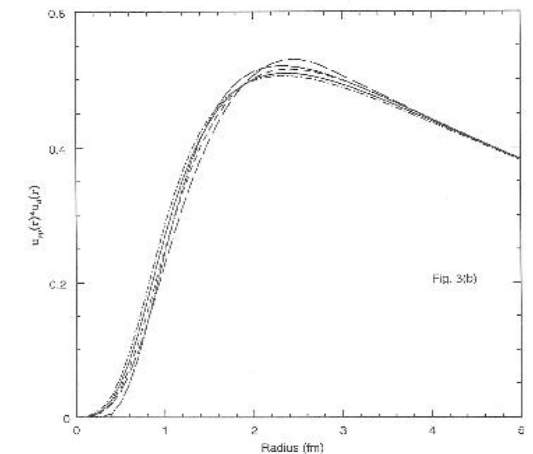
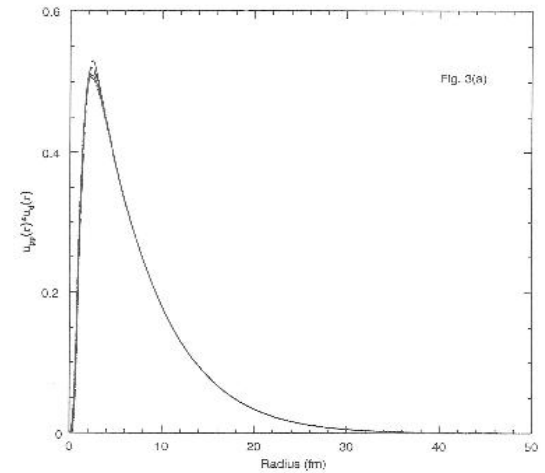
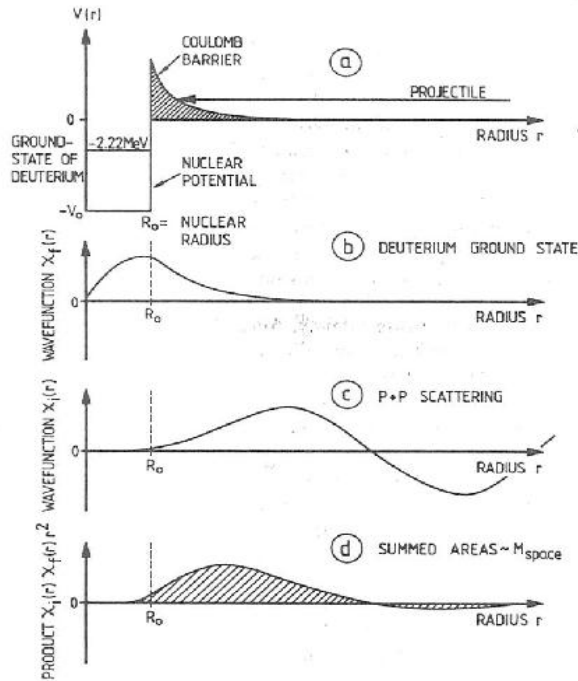
has the solution:

$$Y_2(t) = \bar{Y}_2 - (\bar{Y}_2 - Y_{2\text{initial}}) e^{-t/\tau_2}$$

with  $\bar{Y}_2$  equilibrium abundance  
 $Y_{2\text{initial}}$  initial abundance

so independently of the initial abundance, the equilibrium is approached on a exponential timescale equal to the lifetime of the nucleus.

# The Proton Proton Reaction $p(p, n)d$



- s/d wave ratio
- only 'sensitive' to small distances
- different NN forces give same results

# S factor for the p p reaction

The S factor at zero energy for the pp reaction can be written as, (Adelberger *et al.*, *Rev. Mod. Phys.* **70**, 1265 (1998)).

$$S_{11}(0) = 6\pi^2 m_p c \alpha (\ln 2) \frac{\Lambda^2}{(2\mu E_d)^{3/2}} \left( \frac{G_A}{G_V} \right)^2 \frac{f_{pp}}{(ft)_{0^+ \rightarrow 0^+}} (1 + \delta)^2$$

Here  $E_d$  is the deuteron binding energy and the weak coupling constants have been introduced via the  $ft$ -value for superallowed Fermi transitions ( $0^+ \rightarrow 0^+$ ) which are experimentally wellknown ( $ft = 3073.1 \pm 3.1$  s).  $f_{pp} = 0.144$  is the proton-proton phase space factor.

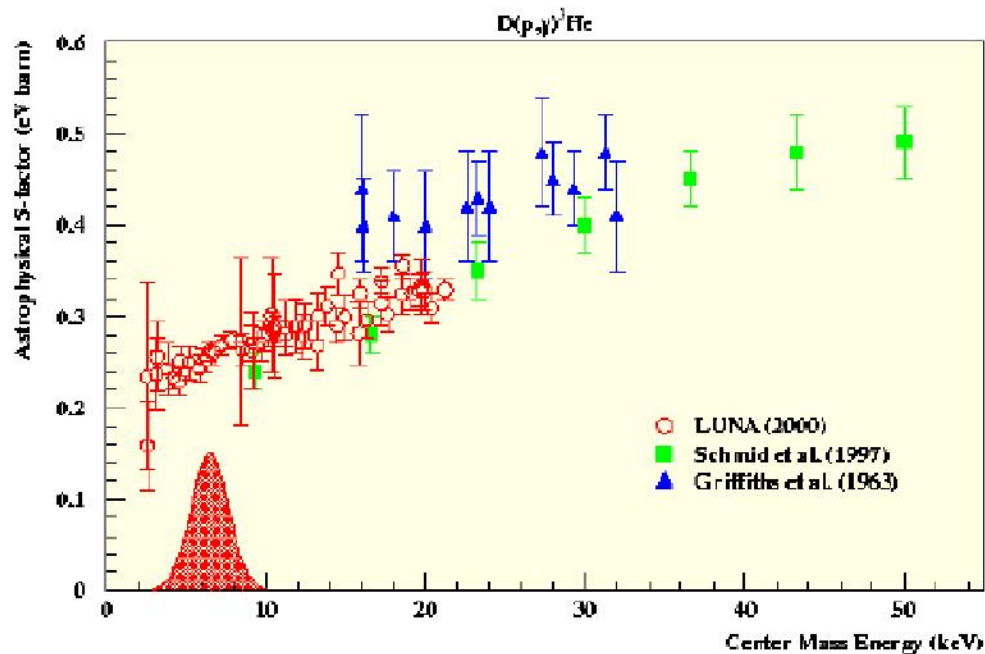
One finds

$$S_{11}(0) = (4.00 \pm 0.05) \times 10^{-25} \text{ MeVb}$$

This corresponds to  $\langle \sigma v \rangle_{11} = 1.2 \times 10^{-43} \text{ cm}^3/\text{s}$  at  $T_6 = 15$ .

# The $d(p,\gamma)^3\text{He}$ Cross Section

The LUNA collaboration has measured the  $d(p,\gamma)^3\text{He}$  cross section at the solar Gamow energies.



$$S_{12}(0) = 2.5 \times 10^{-4} \text{ keVb}$$

# The $d(p, \gamma)^3\text{He}$ Reaction

Deuterons are burnt by the reaction  $d(p, \gamma)^3\text{He}$ :

$$\begin{aligned}\frac{dD}{dt} &= r_{11} - r_{12} \\ &= \frac{H^2}{2} \langle \sigma v \rangle_{11} - HD \langle \sigma v \rangle_{12}\end{aligned}$$

In equilibrium ( $\frac{dD}{dt} = 0$ ) one has

$$\left(\frac{D}{H}\right)_e = \frac{\langle \sigma v \rangle_{11}}{2 \langle \sigma v \rangle_{12}}$$

$$(D/H)_e = 5.6 \times 10^{-18} \text{ for } T_6 = 5$$

# The Lifetime of Deuterium in the Sun

Consider the reaction  $1 + 2 \rightarrow 3 + 4$ , then the lifetime of the nucleus  $a$  against destruction by  $b$  in some environment is given by

$$\tau_b(a) = \frac{1}{N_b \langle \sigma v \rangle_{ab}}$$

If we assume a density  $\rho = 100 \text{ g/cm}^3$  and an equal mixture by mass of hydrogen and helium ( $X_H = X_{He} = 0.5$ ), one finds

$$\tau_p(p) = 0.9 \times 10^{10} \text{ y} ; \tau_p(d) = 1.6 \text{ s}$$

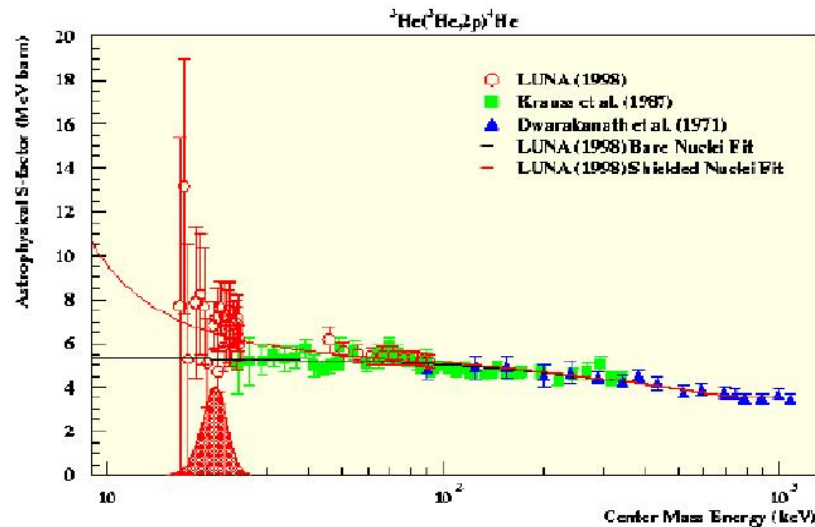
If one assumes a constant  $H$  abundance, one finds for the time evolution of  $D/H$

$$D = \frac{H^2}{2} \langle \sigma v \rangle_{11} + e^{-t/\tau_p(d)} \left( Y_{D,\text{initial}} - \frac{H^2}{2} \langle \sigma v \rangle_{11} \right)$$

Equilibrium is reached in about  $\tau_p(d) = 1.6 \text{ s}$ !

# The $^3\text{He}(^3\text{He},2p)^4\text{He}$ cross section

The LUNA collaboration has measured the  $^3\text{He}(^3\text{He},2p)^4\text{He}$  at solar Gamow energies. This was the first time that a nuclear reaction has been determined at the most effective stellar energies.



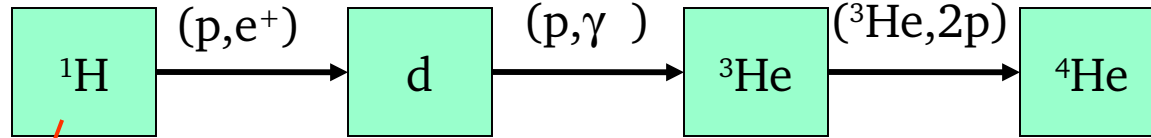
$$S_{33}(0) = 5.4 \times \text{MeVb}$$

Much larger than  $S_{12}(0)$  as resonant and mediated by strong



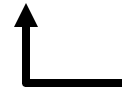
# The ppI chain:

“bottle neck”



large reservoir  
( $Y \sim \text{const}$  ok for

$\tau$   
some time)



d steady flow abundance ?

$$Y_d \lambda_{d+p} = \text{const} = Y_p \lambda_{p+p}$$

$$\frac{Y_d}{Y_p} = \frac{\lambda_{p+p}}{\lambda_{d+p}} = \frac{Y_p \frac{1}{2} \rho N_A \langle \sigma v \rangle_{p+p}}{Y_p \rho N_A \langle \sigma v \rangle_{d+p}}$$

$$\frac{Y_d}{Y_p} = \frac{\langle \sigma v \rangle_{p+p}}{2 \langle \sigma v \rangle_{d+p}}$$

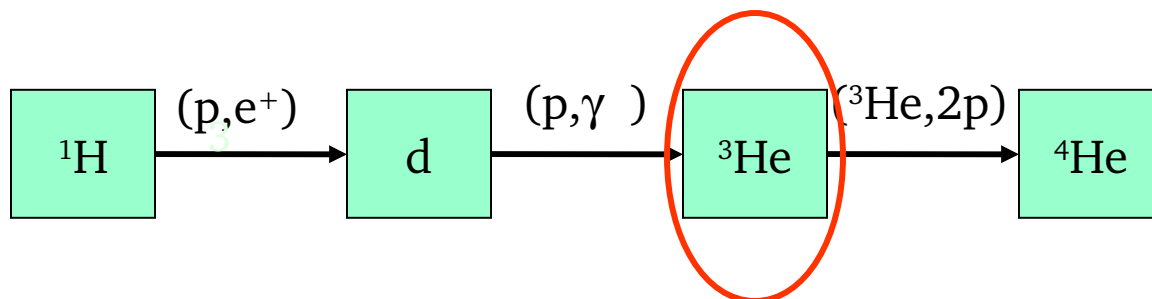
$\leftarrow S = 3.8 \times 10^{-22} \text{ keV barn}$   
 $\leftarrow S = 2.5 \times 10^{-4} \text{ keV barn}$

therefore, equilibrium d-abundance extremely small (of the order of  $4 \times 10^{-18}$  in the sun)

equilibrium reached within lifetime of d in the sun:

$$N_A \langle \sigma v \rangle_{pd} = 1 \times 10^{-2} \text{ cm}^3/\text{s}/\text{mole} \quad \tau_d = 1 / (Y_p \rho N_A \langle \sigma v \rangle_{p+d}) = 2 \text{ s}$$

# He equilibrium abundance

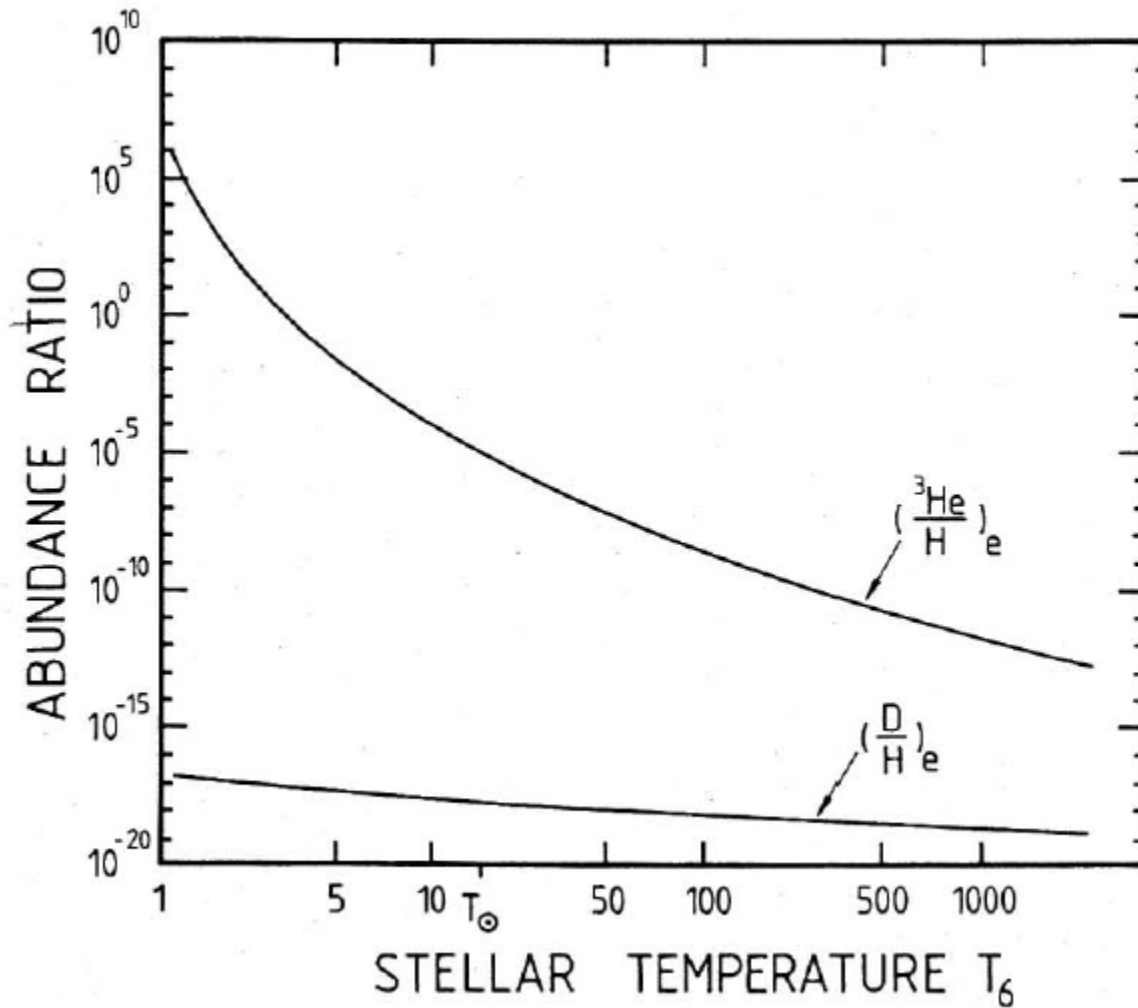


different because two identical particles fuse  
therefore destruction rate  $\lambda_{^3\text{He}+^3\text{He}}$  obviously NOT constant:

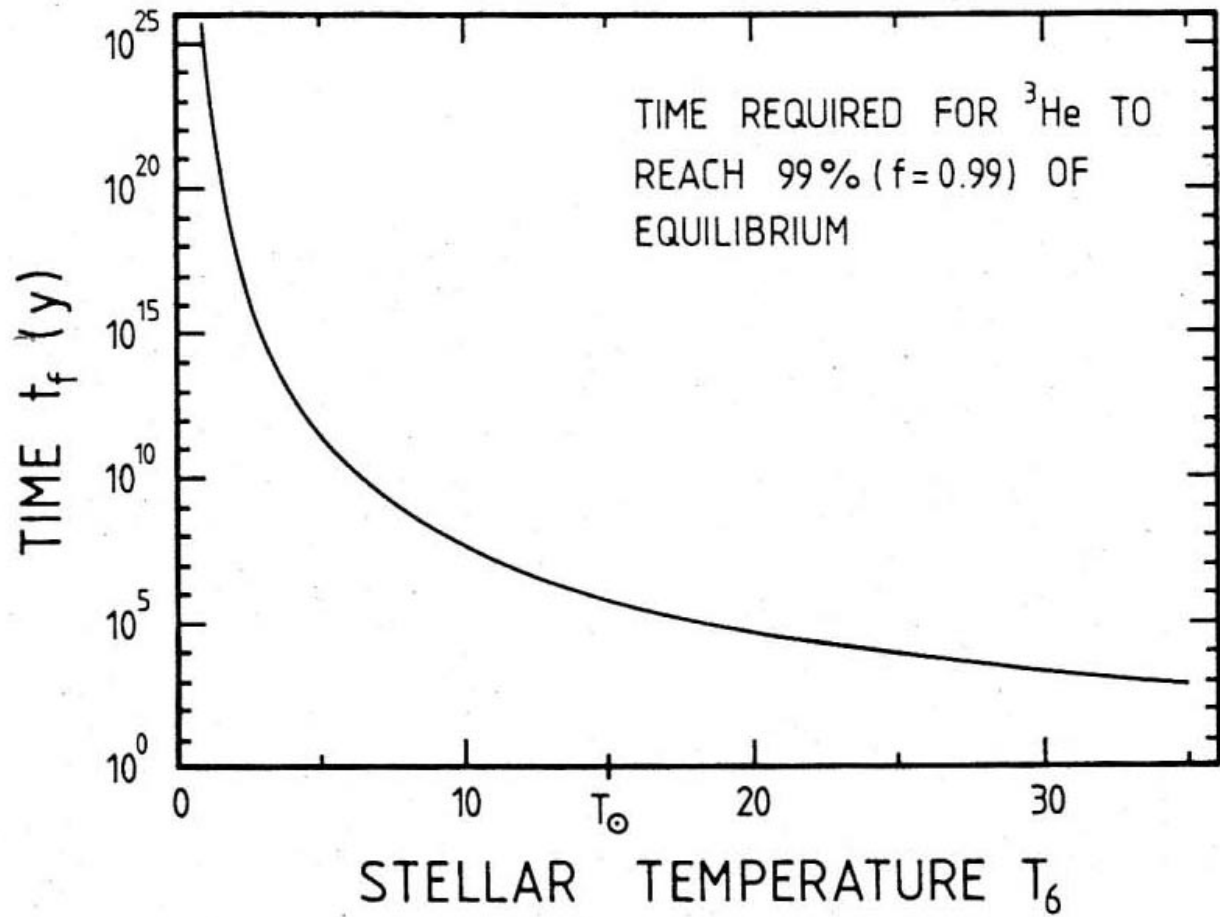
$$\lambda_{^3\text{He}+^3\text{He}} = \frac{1}{2} Y_{^3\text{He}} \rho N_A \langle \sigma v \rangle_{^3\text{He}+^3\text{He}}$$

but depends strongly on  $Y(^3\text{He})$  itself

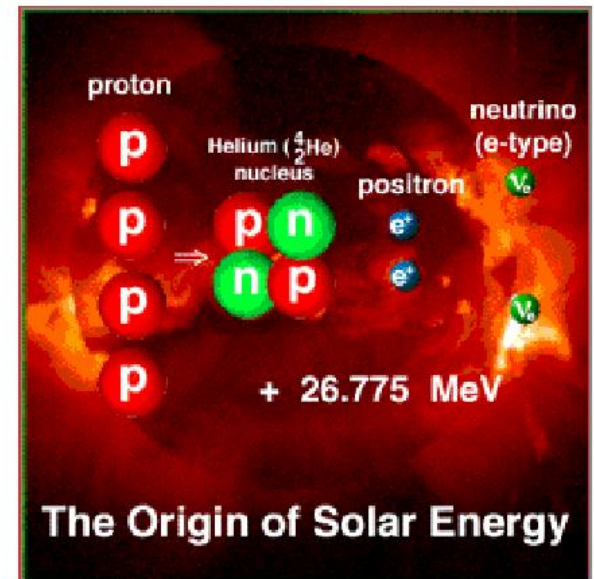
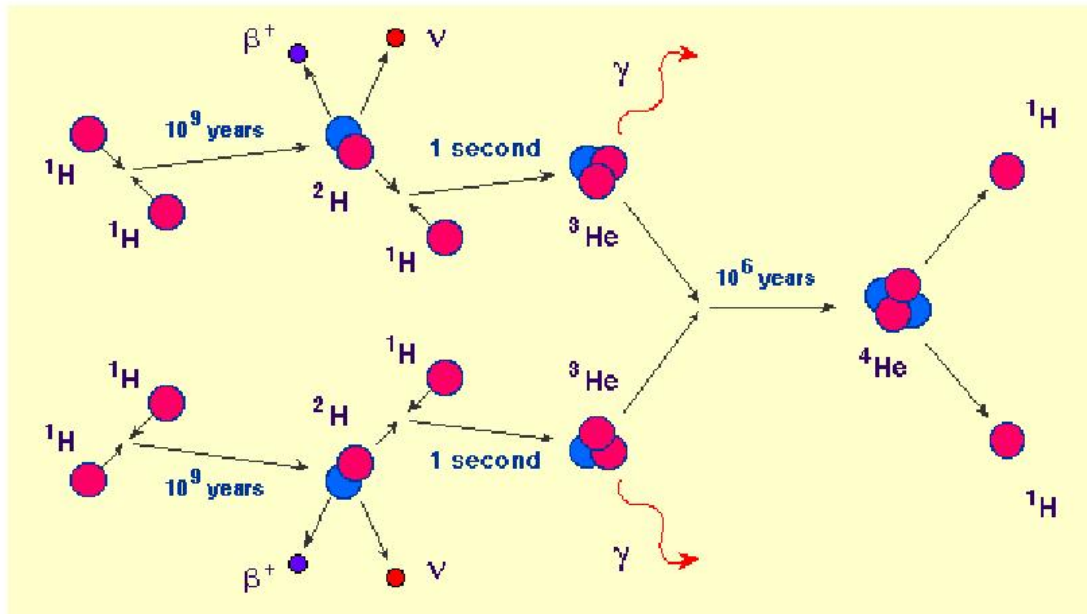
But equations can be solved again



${}^3\text{He}$  has a much higher equilibrium abundance than  $\text{d}$   
 - therefore  ${}^3\text{He} + {}^3\text{He}$  possible ...



# The PP I Chain

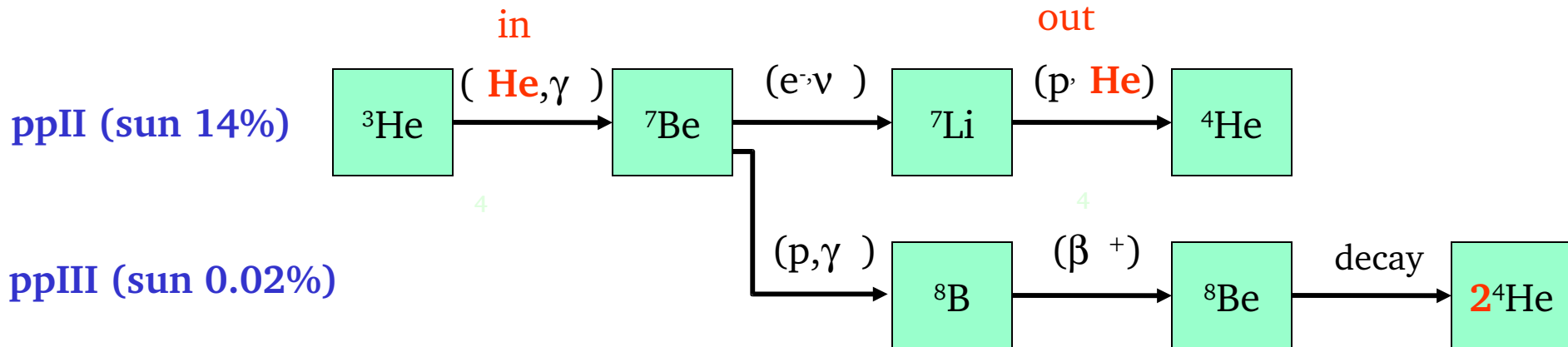


# Hydrogen burning with catalysts

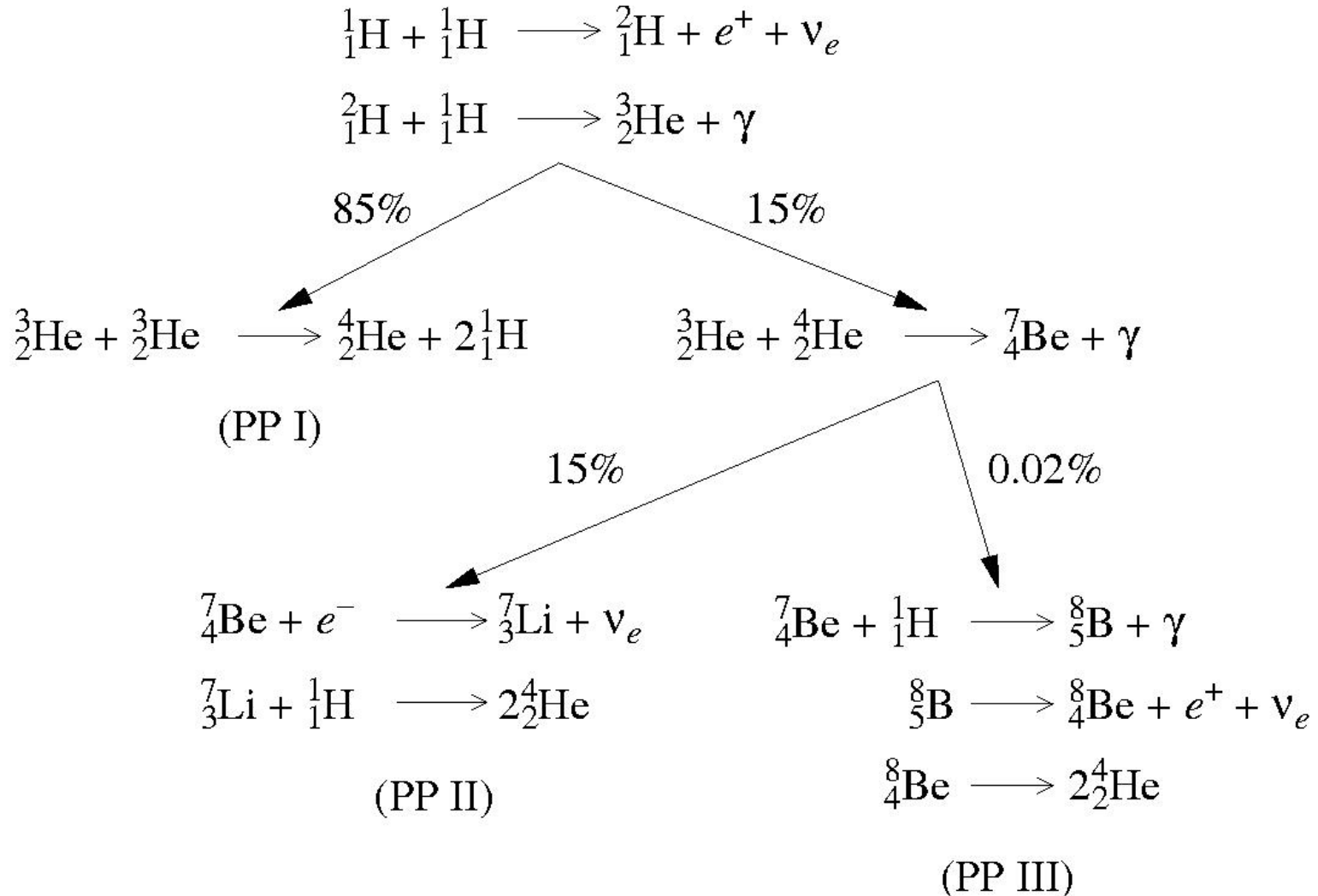
1. ppII chain
2. ppIII chain
3. CNO cycle

## 1. ppII and ppIII:

once  $^4\text{He}$  has been produced it can serve as catalyst of the ppII and ppIII chains to synthesize more  $^4\text{He}$ :

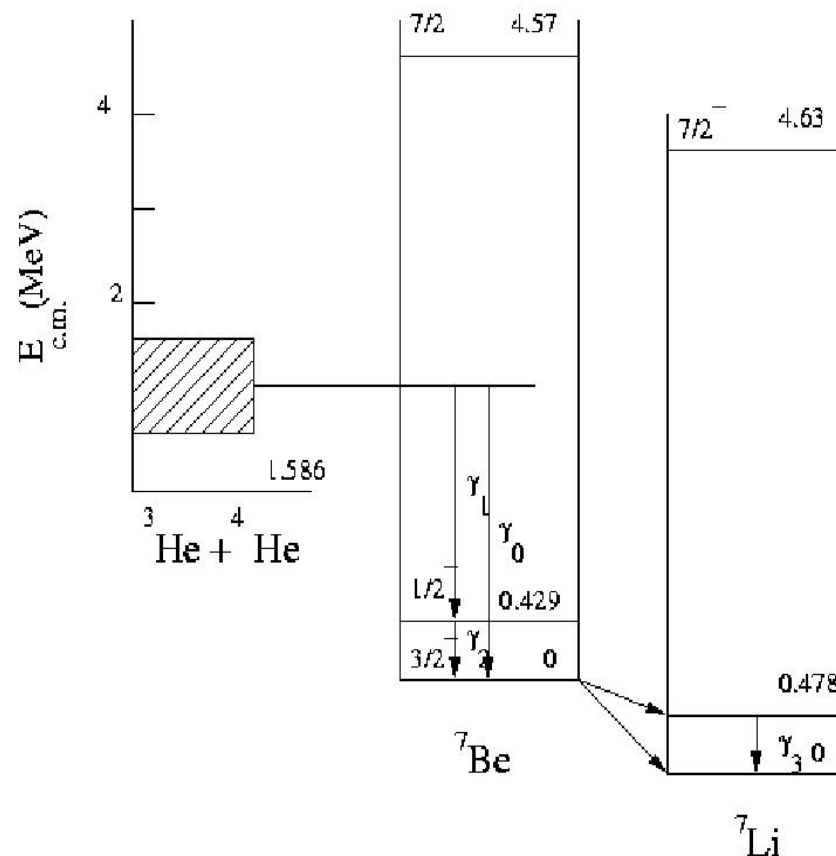


# The PP Chain(s) in the Sun/He as Catalyst



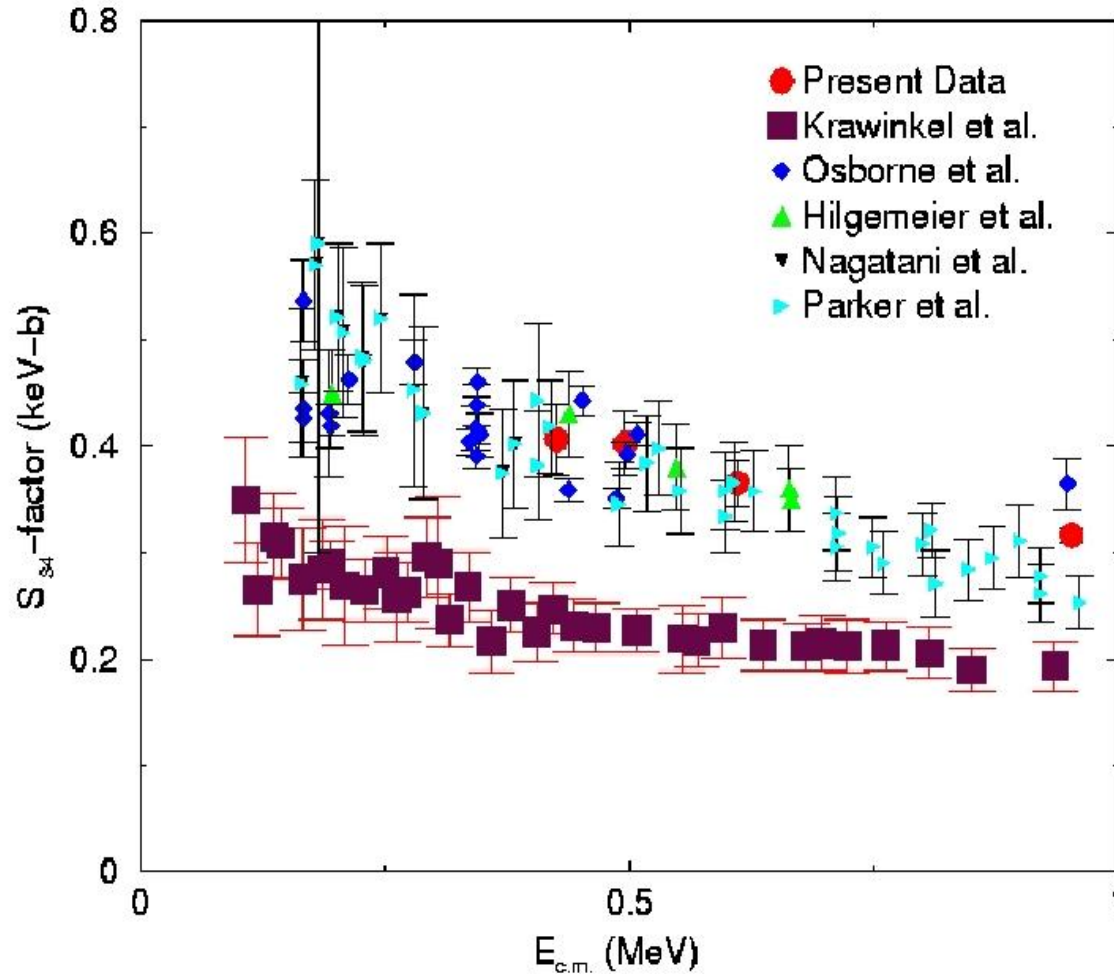
# The $3\text{He} + 4\text{He}$ Fusion Reaction: PP2/3

In 1958 Holmgren and Johnston measured the  ${}^3\text{He}({}^4\text{He}, \gamma){}^7\text{Be}$  cross section and found it 1000 times larger than expected. Willy Fowler immediately realized the possibility of a break-out from the ppI chain.





# The $3\text{He}-4\text{He}$ Fusion Data



# Electron capture decay of Be

Why electron capture:

$$Q_{EC} = 862 \text{ keV}$$

$$Q_{\beta^+} = Q_{EC} - 1022 = -160 \text{ keV}$$

only possible decay mode

7

Earth: • Capture of bound K-electron

**T = 77 days**

Sun: • Ionized fraction: Capture of continuum electrons  
 → depends on density and temperature

$$\tau_{7Be} = 4.72e8 \frac{T_6^{1/2}}{\rho(1 + X_H)} \text{ s}$$

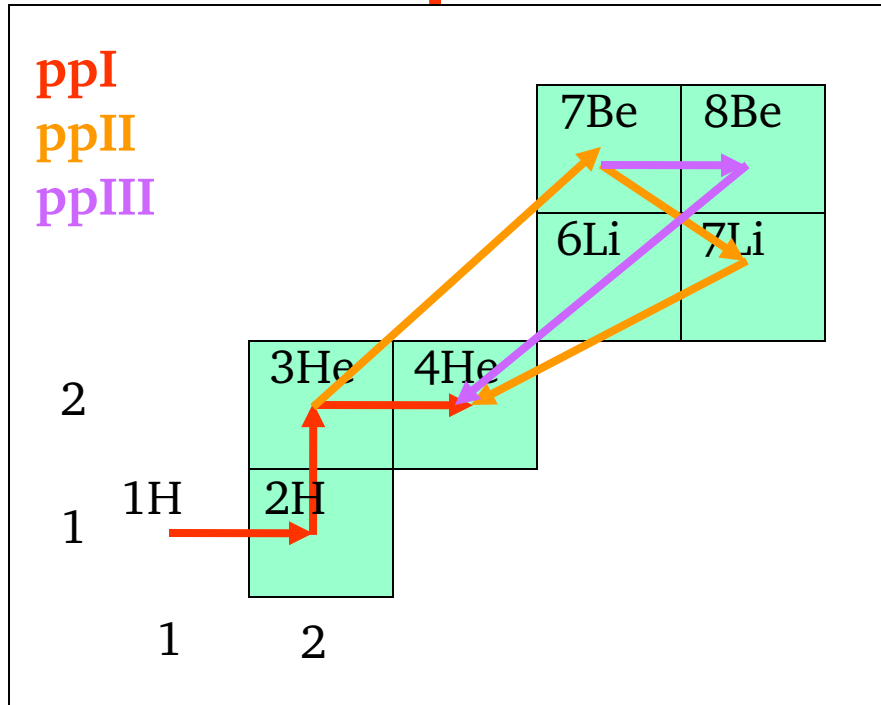
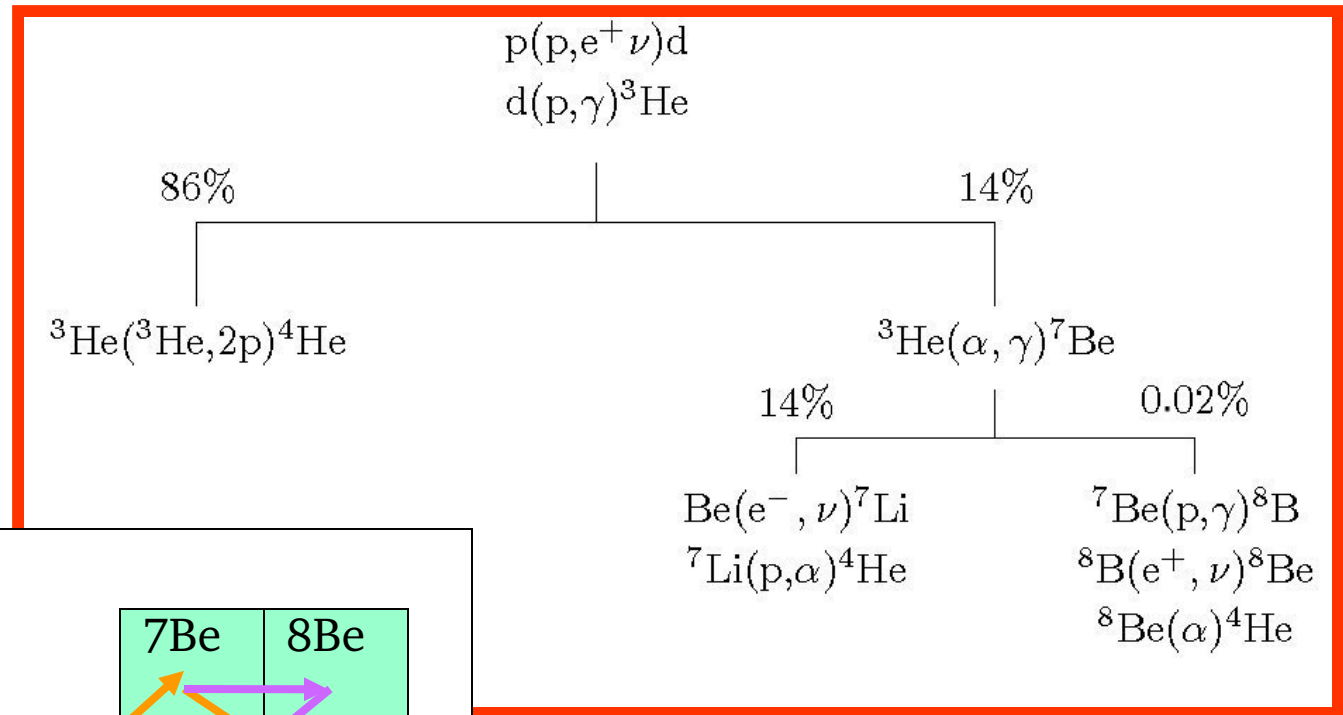
• Not completely ionized fraction: capture of bound K-electron  
 (21% correction in sun)

1/2

**T = 120 days**

1/2

# Summary pp-chains:



Why do additional pp chains matter ?

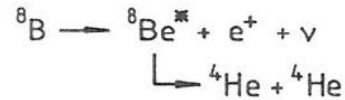
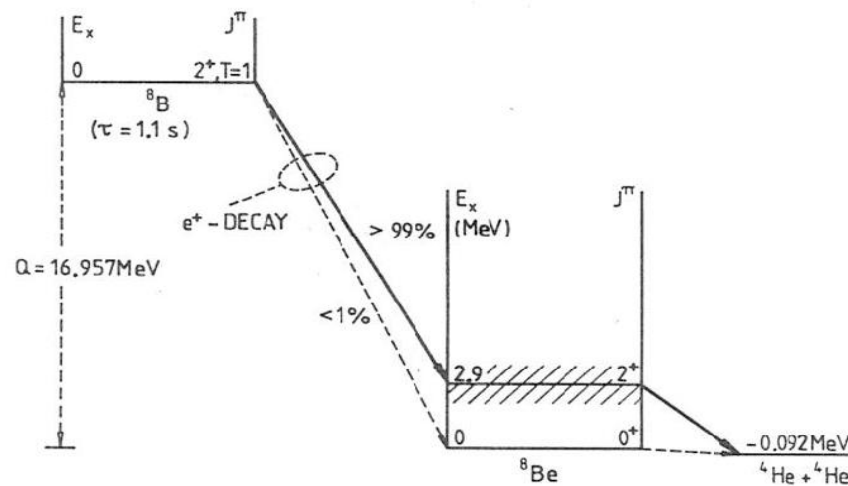
p+p dominates timescale BUT

ppI produces 1/2  ${}^4\text{He}$  per p+p reaction

ppI+II+III produces 1  ${}^4\text{He}$  per p+p reaction

→ **double burning rate**

# The Proton Capture on ${}^7\text{Be}$



- ${}^8\text{B}$  binding energy is only 137 keV

(Rolfs and Rodney)

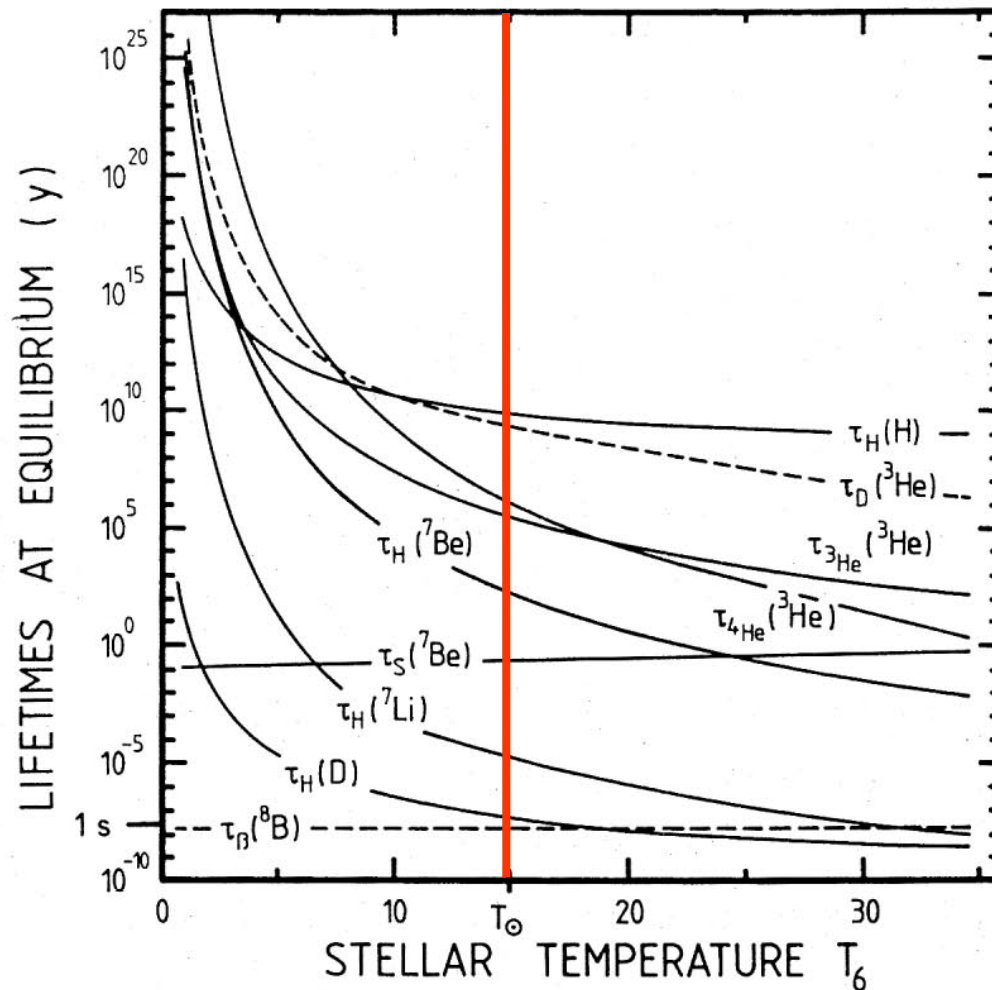


FIGURE 6.7. Plotted are the equilibrium lifetimes of  $^3\text{He}$  resulting from different burning processes (Table 6.2). The  $^3\text{He}(\alpha, \gamma)^7\text{Be}$  reaction leading to the  $\tau_{4\text{He}}(^3\text{He})$ -curve is important only in stars which have an appreciable amount of  $^4\text{He}$ . Shown for comparison is the lifetime of hydrogen against destruction via the  $p + p$  reaction and those of D,  $^7\text{Li}$ , and  $^7\text{Be}$  against destruction via hydrogen-burning interactions. The electron-capture lifetime of  $^7\text{Be}$  in stars,  $\tau_s(^7\text{Be})$ , and the laboratory lifetime of the positron decay for  $^8\text{B}$  are also shown. All curves assume conditions of  $\rho = 100 \text{ g cm}^{-3}$ ,  $X_{\text{H}} = X_{\text{He}} = 0.5$ .

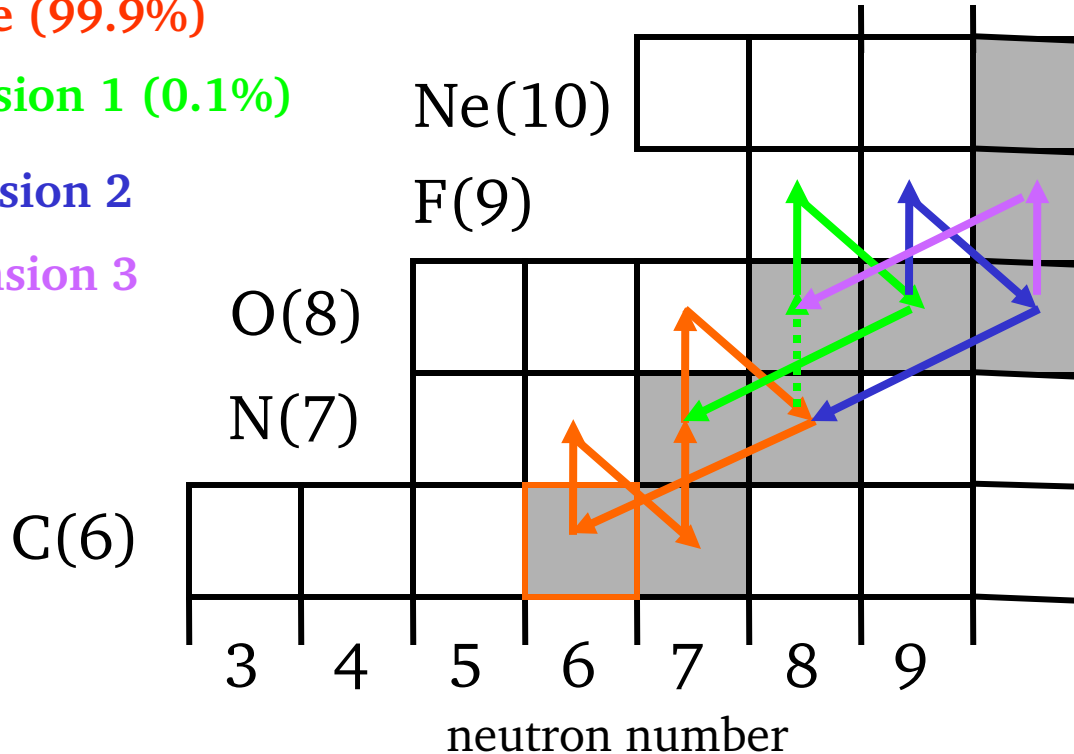
# The Alternative H-Burning: CNO cycle. CNO as Catalysator

CN cycle (99.9%)

O Extension 1 (0.1%)

O Extension 2

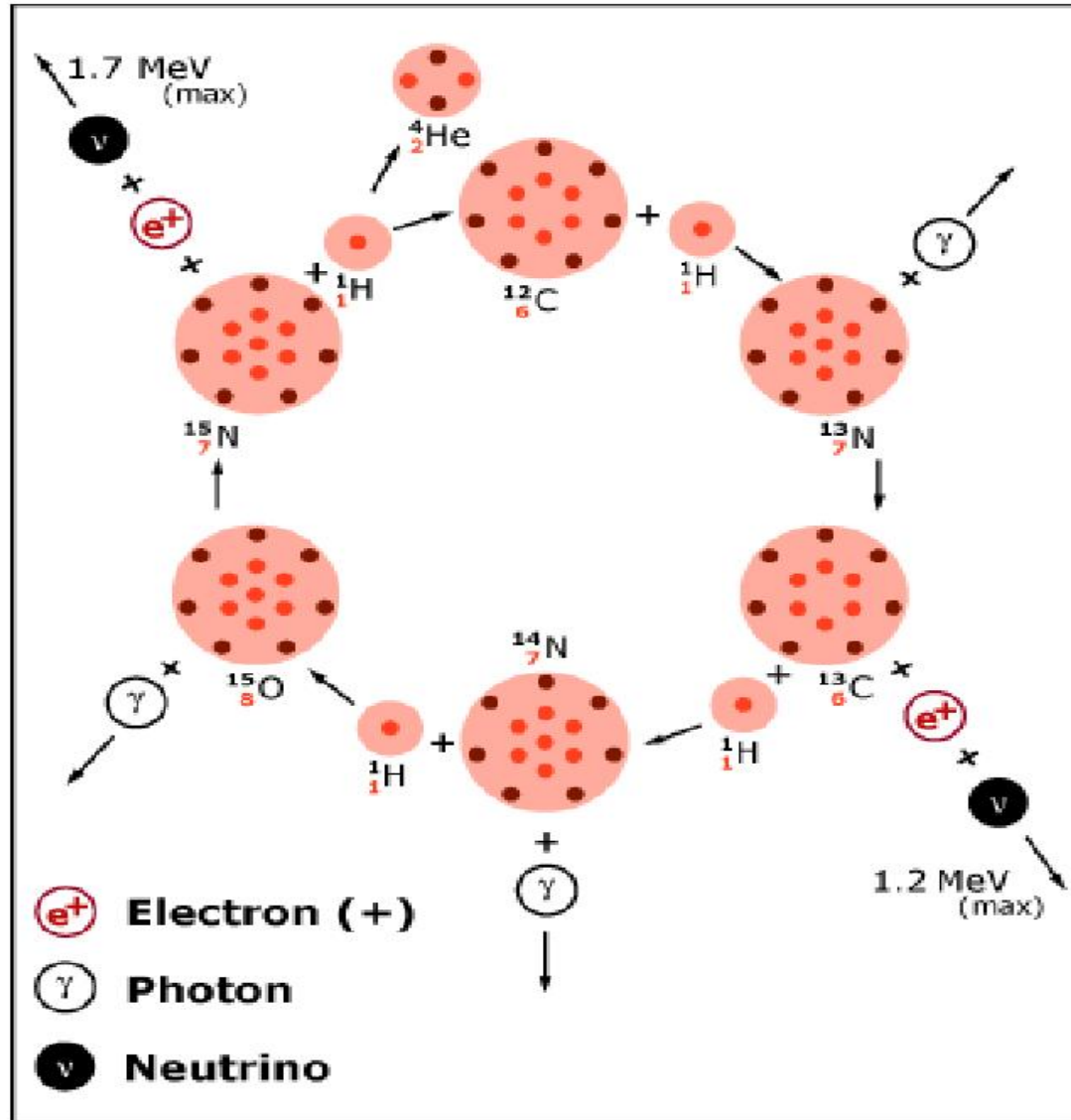
O Extension 3



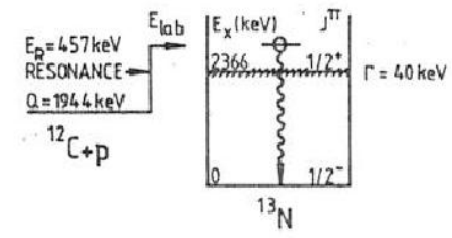
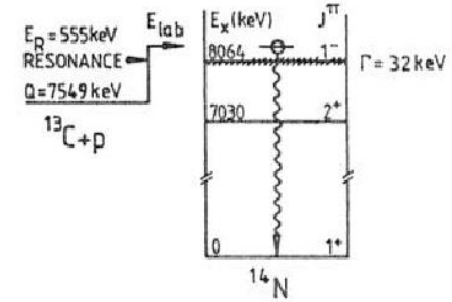
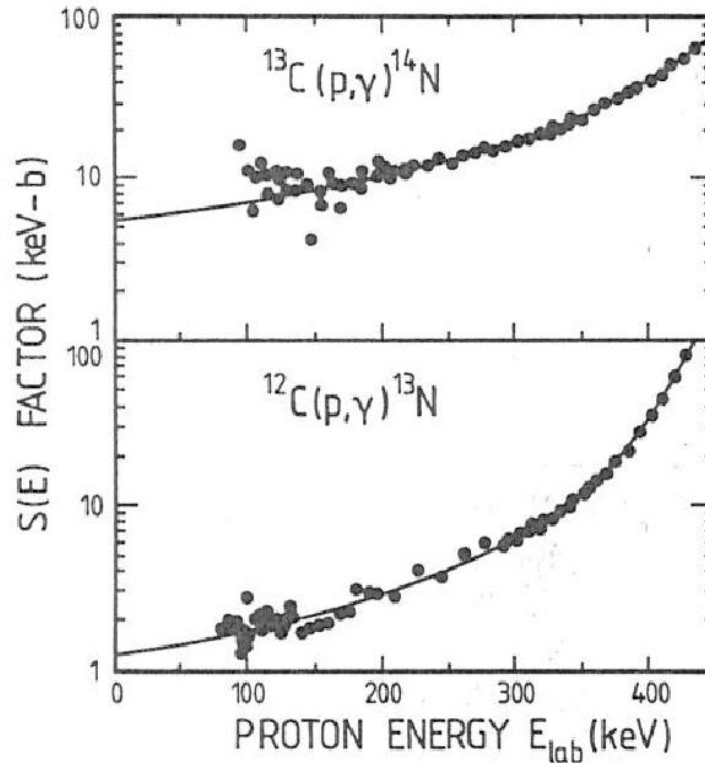
All initial abundances within a cycle serve as catalysts and accumulate at largest  $\tau$

Extended cycles introduce outside material into CN cycle (Oxygen, ...)

# The CNO Cycle:



# Proton Capture on Carbon



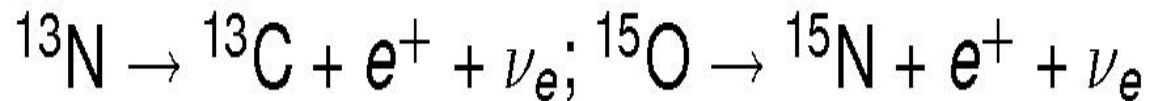
Dipole transition, dominated by  $\frac{1}{2}^+$  resonance.

$^{12}\text{C}+p$ :  $S(0)=1.34\pm 0.21$  keV b;  $^{13}\text{C}+p$ :  $S(0)=8.2$  keV b.



## Beta+ decay of $^{13}\text{N}$ and $^{15}\text{O}$

$\beta^+$  decays:

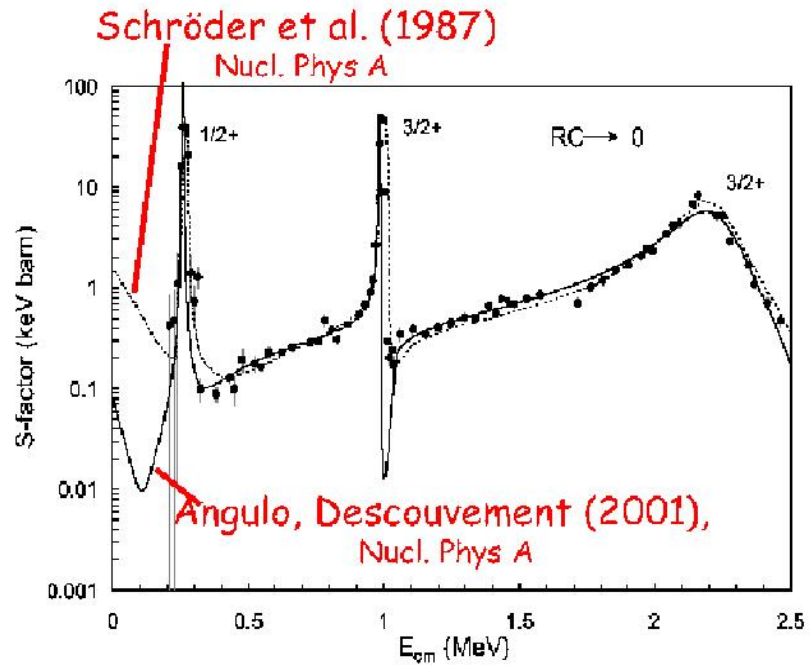
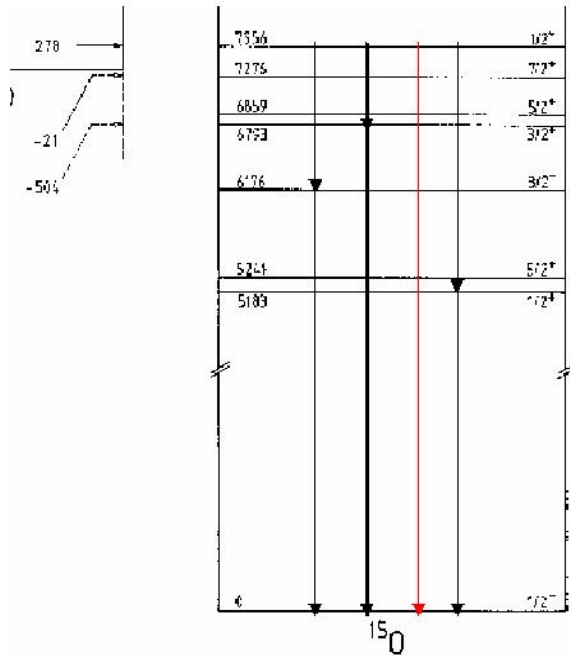


the lifetimes of the decays are experimentally wellknown

the Sun (or stars during hydrogen burning) is not dense enough to alter the laboratory lifetimes

$$\tau(^{13}\text{N}) = 863 \text{ s}; \quad \tau(^{15}\text{O}) = 176 \text{ s}$$

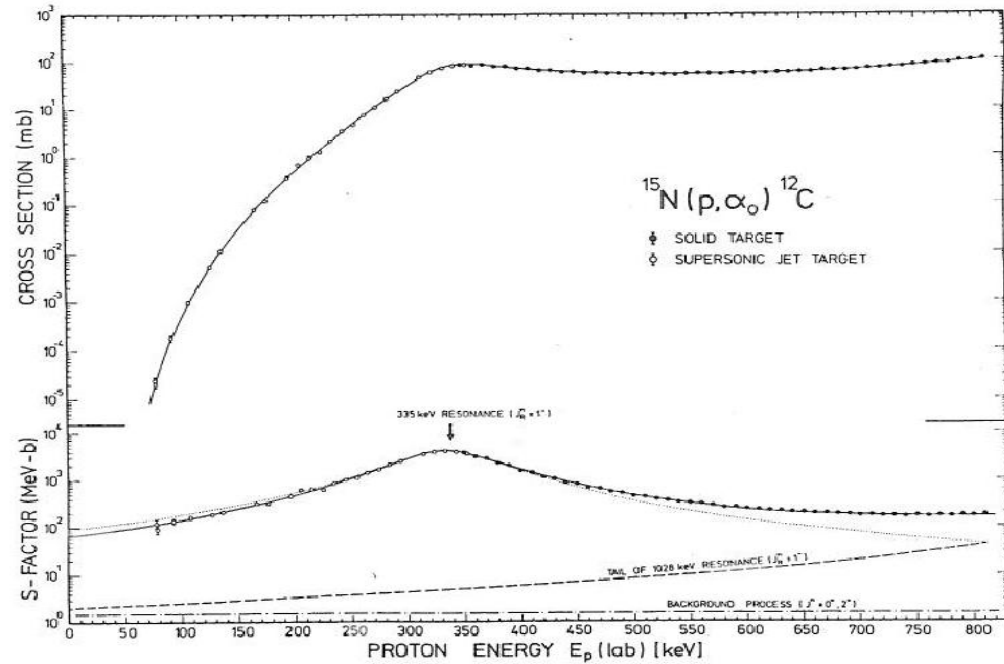
# Proton Capture on $^{14}\text{N}$



$$R/DC \rightarrow 0 \left\{ \begin{array}{l} S(0) = 1.55 \pm 0.34 \text{ keV-b (Schröder)} \\ S(0) = 0.08 \pm 0.06 \text{ keV-b (Angulo)} \end{array} \right.$$

# Proton Capture on $^{15}\text{N}(p,\alpha)$

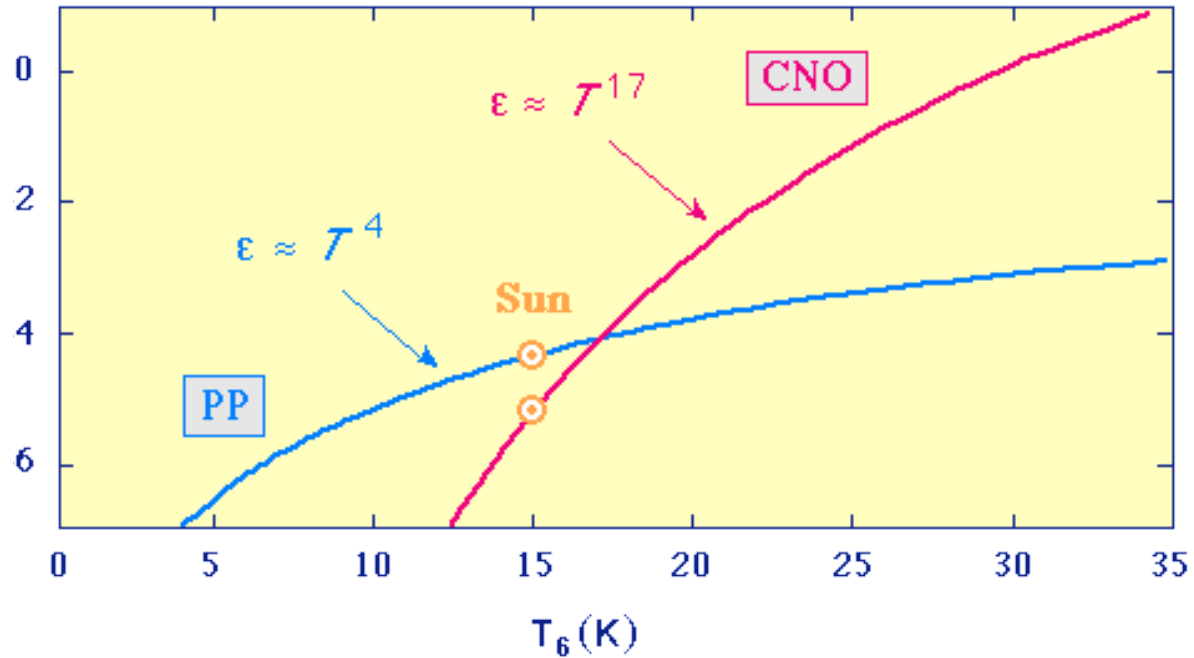
158 DETERMINATION OF STELLAR REACTION RATES



$$S(0) = 65 \pm 4 \text{ MeV b}$$



# Competition between the p-p chain and the CNO Cycle



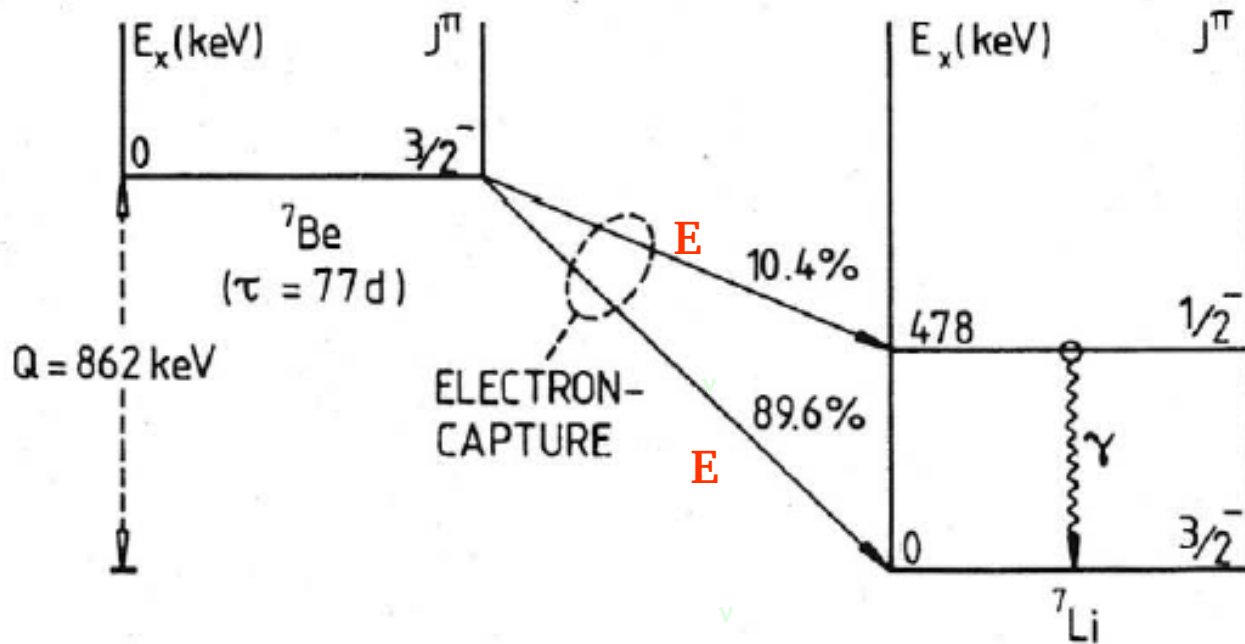
# Consequences (see Kippenhahn, 1970)

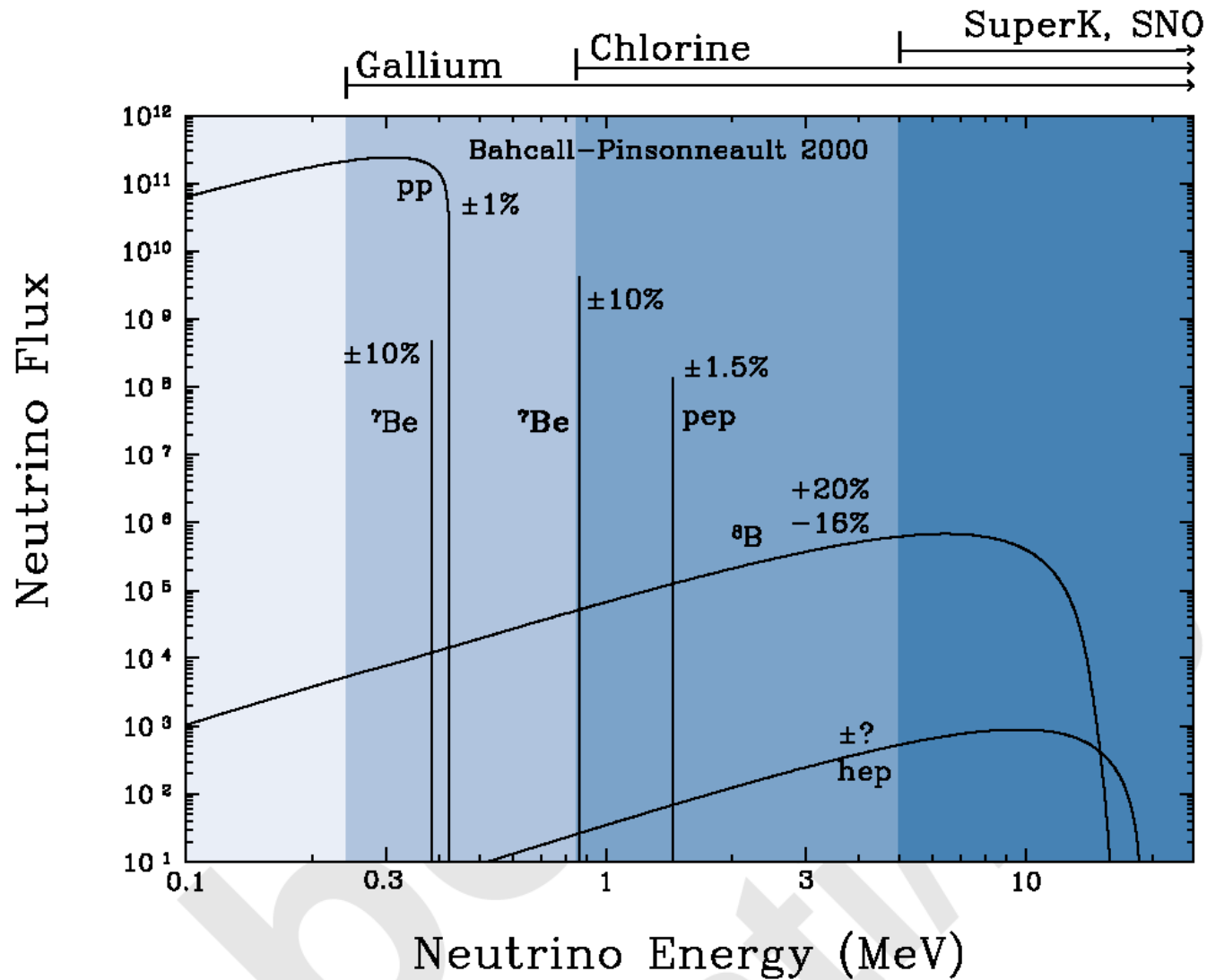
mass [ $M_{\odot}$ ]	timescale [y]
0.4	$2 \times 10^{11}$
0.8	$1.4 \times 10^{10}$
1.0	$1 \times 10^{10}$
1.1	$9 \times 10^9$
1.7	$2.7 \times 10^9$
3.0	$2.2 \times 10^8$
5.0	$6 \times 10^7$
9.0	$2 \times 10^7$
16.0	$1 \times 10^7$
25.0	$7 \times 10^6$
40.0	$1 \times 10^6$

- stars with more than 3 $M_{\odot}$  go CNO

- stars without CNO do pp (early universe)

2 neutrino energies from  ${}^7\text{Be}$  electron capture ?





Continuous fluxes in  $/\text{cm}^2/\text{s}/\text{MeV}$

Discrete fluxes in  $/\text{cm}^2/\text{s}$

# The Sun & Neutrino Astrophysics

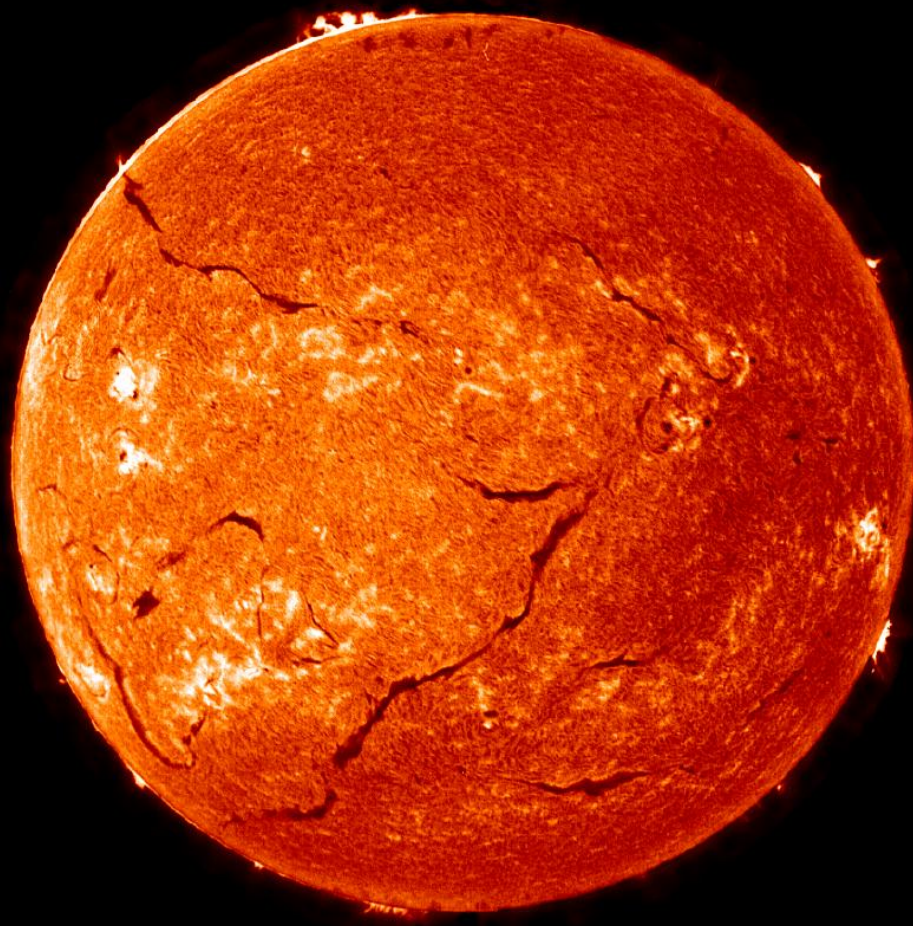
- Properties of the solar Neutrinos
- The Solar Neutrino Problem
- Properties of Neutrinos

Literature: Iliadis, Chapter 5



# The Surface the Sun

11 Aug



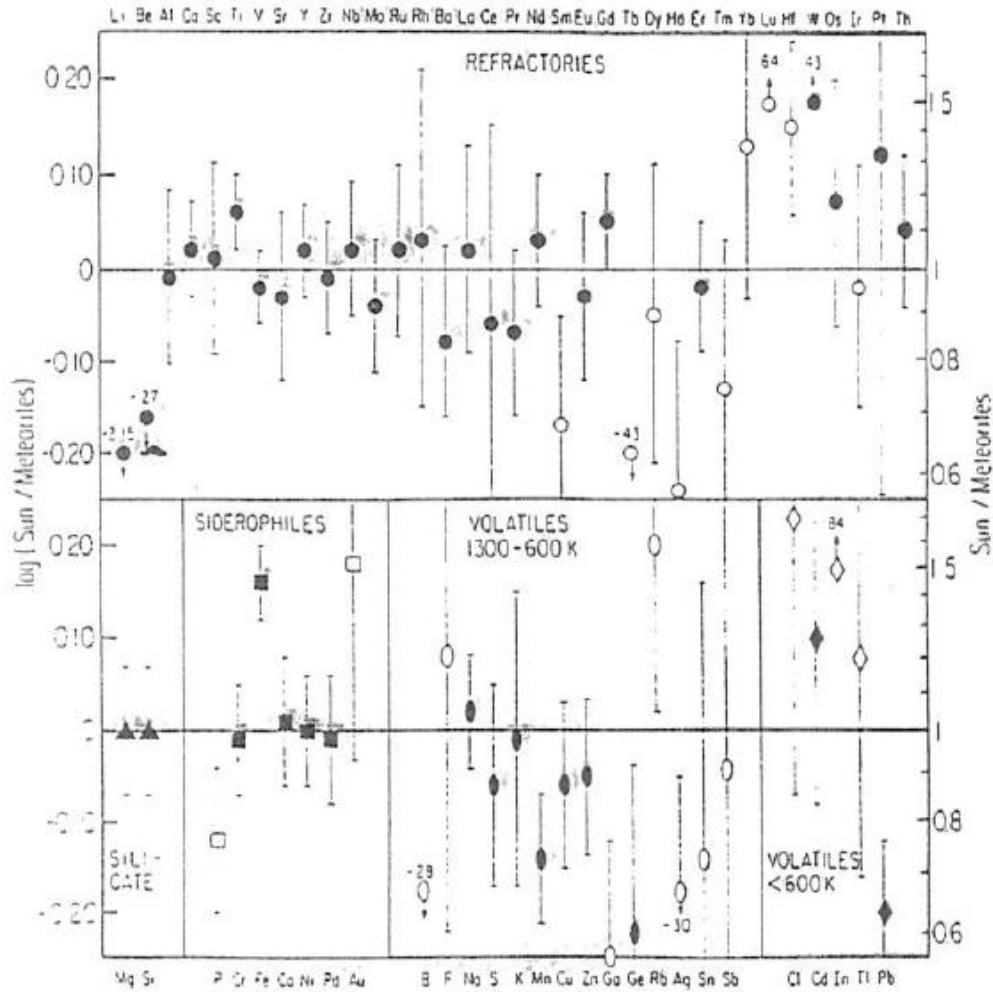
Source

HAO A-005

# Basic Properties of the Sun

Parameter	Value
Photon luminosity ( $L_{\odot}$ )	$3.86 \times 10^{33} \text{ erg s}^{-1}$
Neutrino luminosity	$0.023L_{\odot}$
Mass ( $M_{\odot}$ )	$1.99 \times 10^{33} \text{ g}$
Radius ( $R_{\odot}$ )	$6.96 \times 10^{10} \text{ cm}$
Oblateness [[ $R_{\text{equatorial}}/R_{\text{polar}}$ ] - 1]	$\leq 2 \times 10^{-5}$
Effective (surface) temperature	$5.78 \times 10^3 \text{ K}$
Moment of inertia	$7.00 \times 10^{53} \text{ g cm}^2$
Age	$\approx 4.55 \times 10^9 \text{ yr}$
Initial helium abundance by mass	0.27
Initial heavy element abundance by mass	0.020
Depth of convective zone	$0.26R_{\odot} (0.015M_{\odot})$
Central density	$148 \text{ g cm}^{-3}$
Central temperature	$15.6 \times 10^6 \text{ K}$
Central hydrogen abundance by mass	0.34
Neutrino flux from pp reaction	$6.0 \times 10^{10} \text{ cm}^{-2} \text{ s}^{-1}$
Neutrino flux from $^8\text{B}$ decay	$6 \times 10^6 \text{ cm}^{-2} \text{ s}^{-1}$
Fraction of energy from pp chain	0.984
Fraction of energy from CNO cycle	0.016

# Solar Composition:



Element	Number fraction [Grevesse (1984)]	Number fraction [Aller (1986)]
C	0.29661	0.27983
N	0.05918	0.05846
O	0.49226	0.49761
Ne	0.06056	0.06869
Na	0.00129	0.00125
Mg	0.02302	0.02552
Al	0.00179	0.00198
Si	0.02149	0.02672
P	0.00017	0.00018
S	0.00982	0.01040
Cl	0.00019	0.00019
Ar	0.00230	0.00227
Ca	0.00139	0.00134
Ti	0.00006	0.00007
Cr	0.00028	0.00035
Mn	0.00017	0.00016
Fe	0.02833	0.02382
Ni	0.00108	0.00114
Total	1.000	1.000

# The Equations of Stellar Structure

## 1. Four structure equations

(a) Pressure equilibrium

$$\frac{dP_r}{dr} = -\rho_r \frac{GM_r}{r^2}$$

(c) Energy generation

$$\frac{dL_r}{dr} = 4\pi r^2 \rho_r \varepsilon$$

(b) Conservation of mass

$$\frac{dM_r}{dr} = 4\pi r^2 \rho_r$$

(d) Energy transport (convection)

$$\frac{dT_r}{dr} = \left(1 - \frac{1}{\gamma}\right) \frac{T_r}{P_r} \frac{dP_r}{dr}$$
$$\frac{dT}{dr} = -\frac{3}{32\pi\sigma c} \frac{\kappa\rho L}{r^2 T^3}$$

with L: luminosity,  $\sigma$  Stephan-Boltzman constant

## 2. Subsidiary equations, such Equation of State for gas

Ideal Boltzmann:      Fermi:

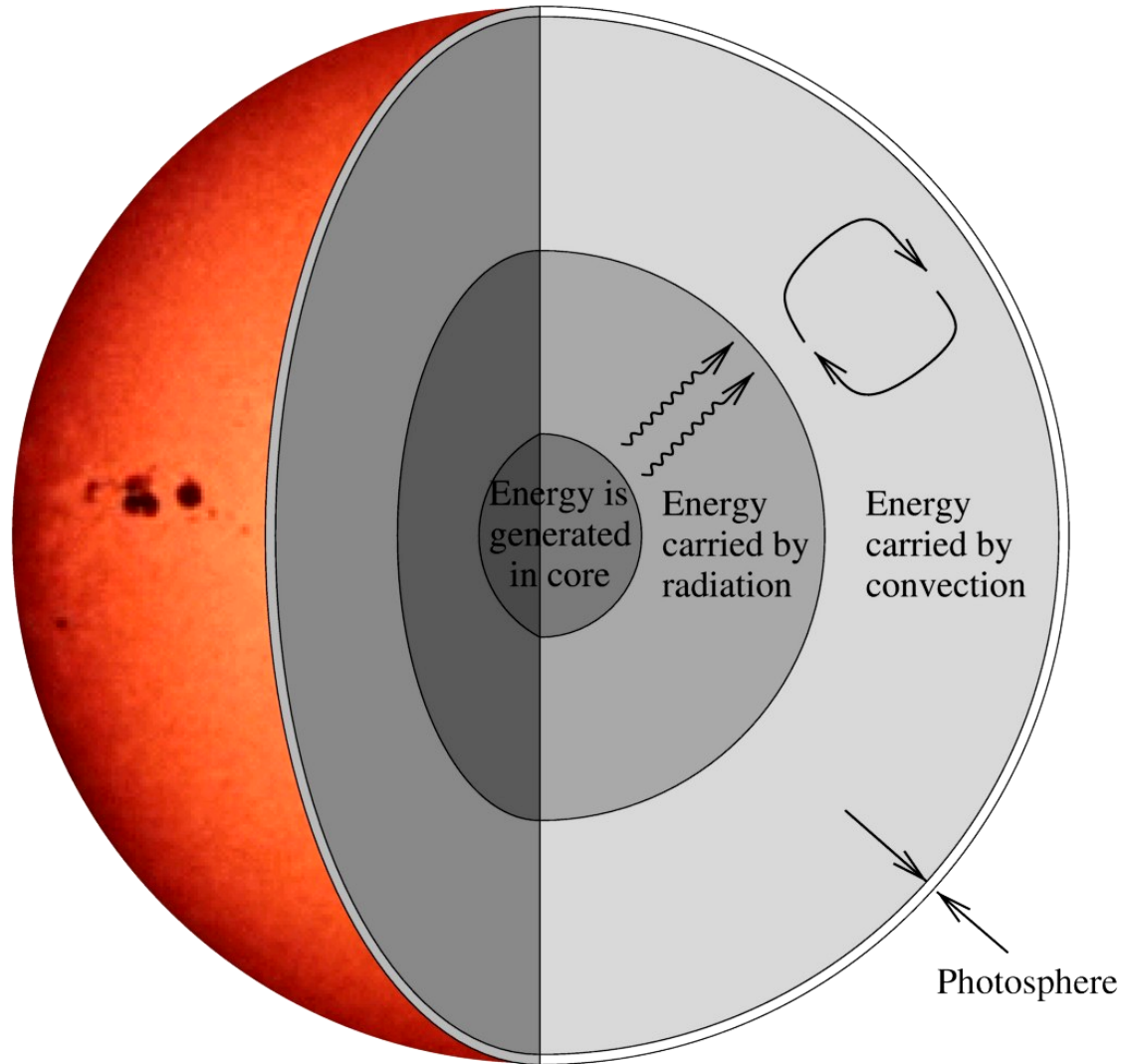
$$P = \frac{\rho k T}{\mu m_H}$$

$$P = \rho^\gamma$$

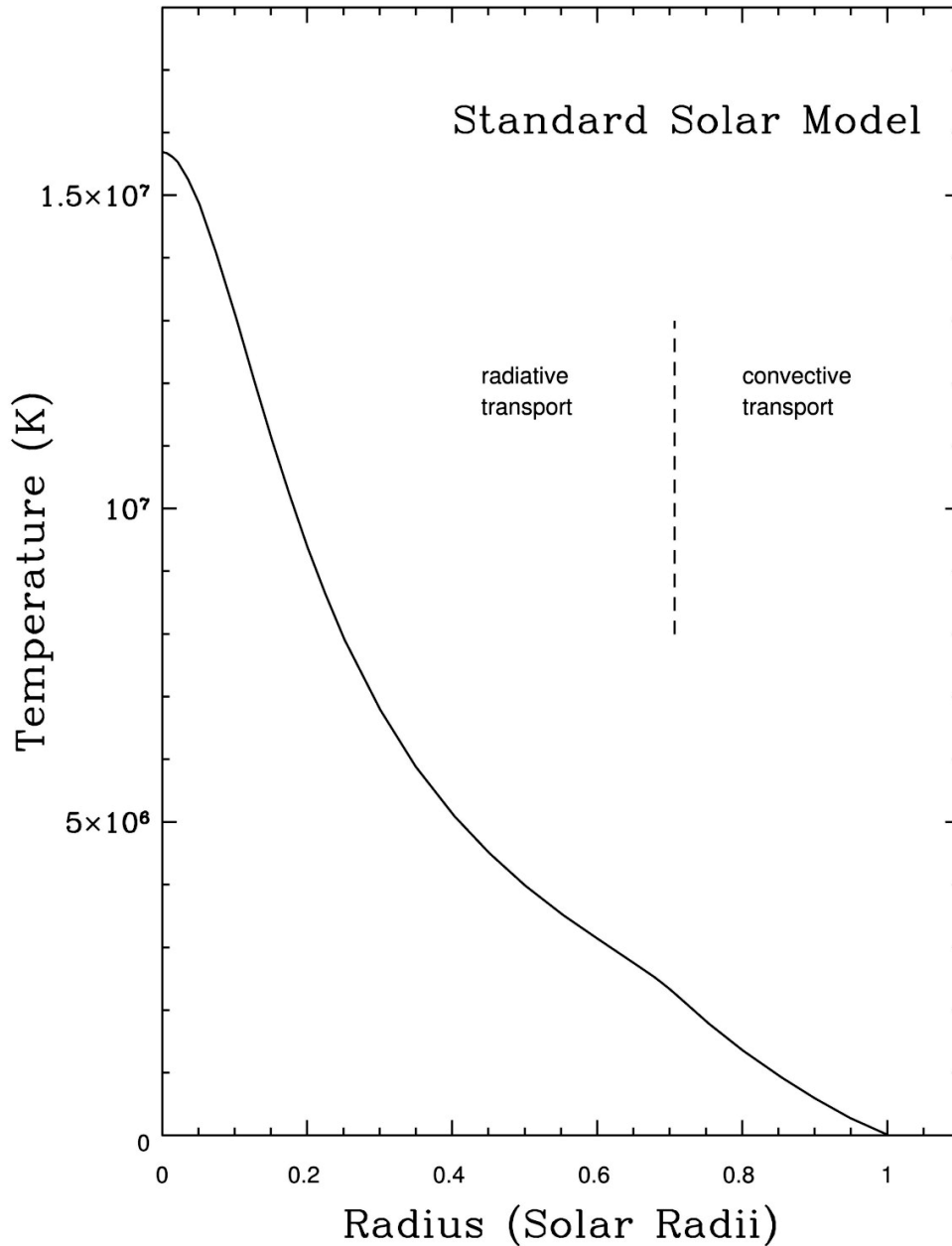
with  $\gamma = 5/3$  in the limit of non-relativistic degenerate gas

with  $\gamma = 4/3$  in the limit of relativistic degenerate gas

# The Interior of the Sun

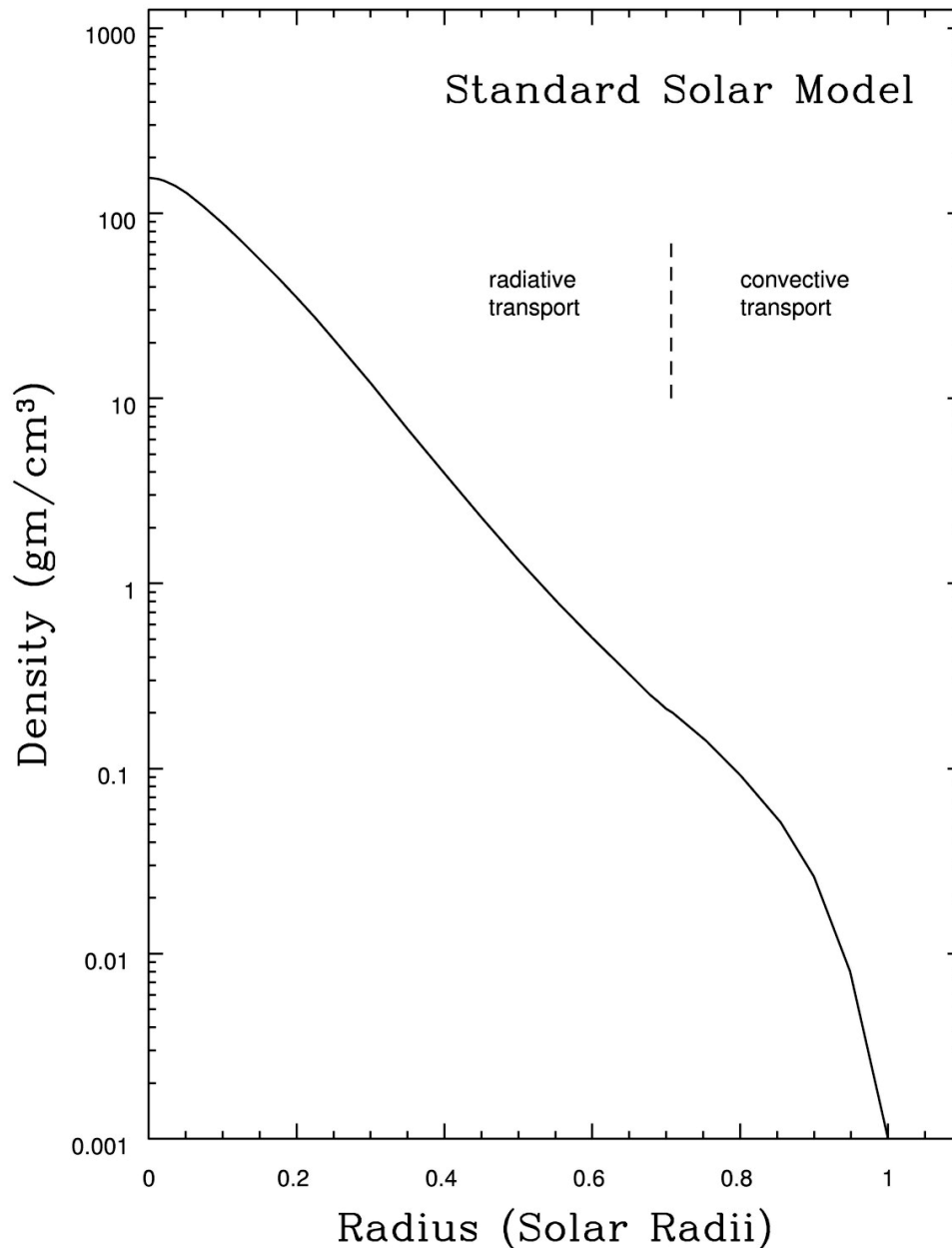


# The Temperature Inside the Sun



The temperature at the center of the sun is a bit more than 15 million K.

# The Density Inside the Sun



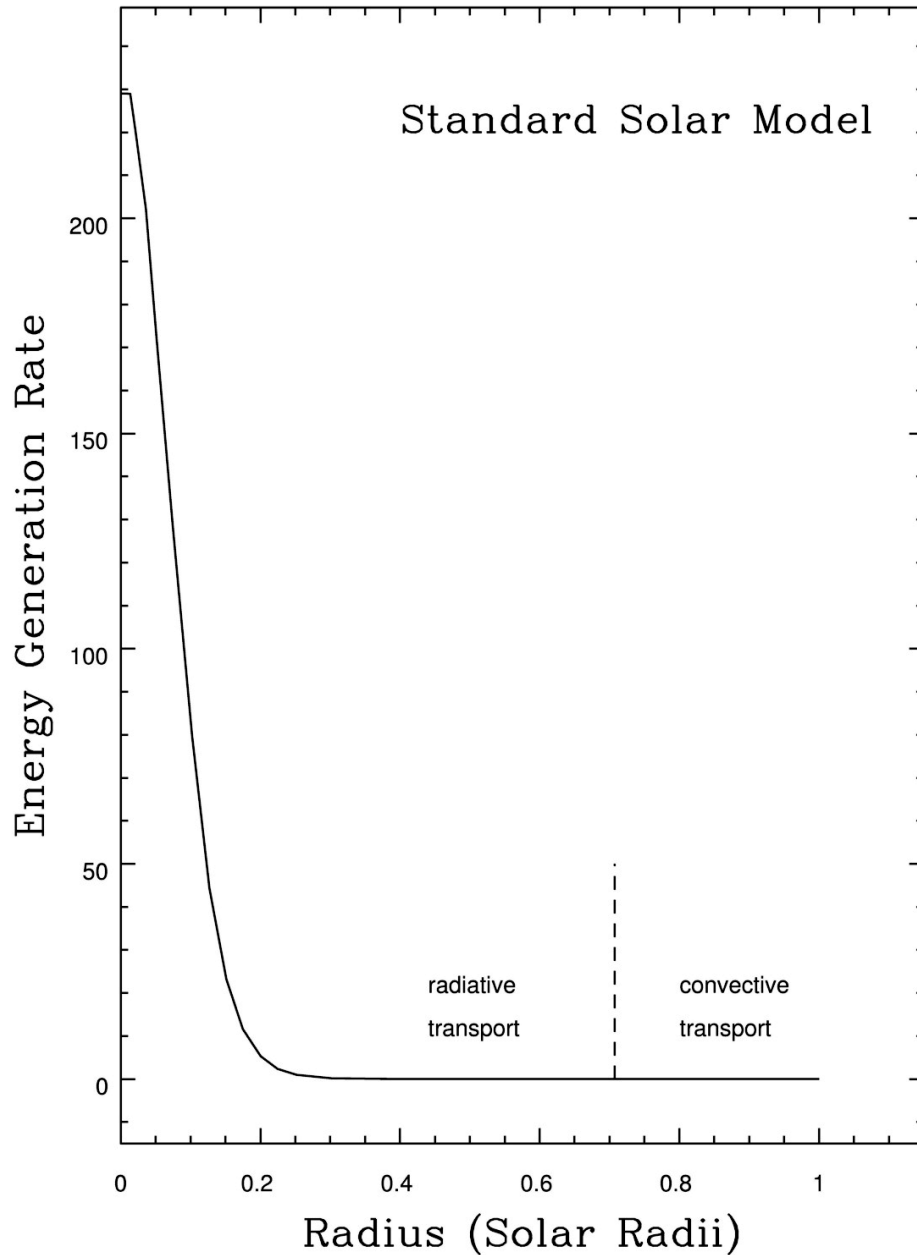
- The density at the center of the sun is a bit more than  $150 \text{ gm}/\text{cm}^3$ .

3

This is about 10 times denser than lead!

- At its visible surface the density of the sun is 10,000 times lower than the Earth's atmosphere.

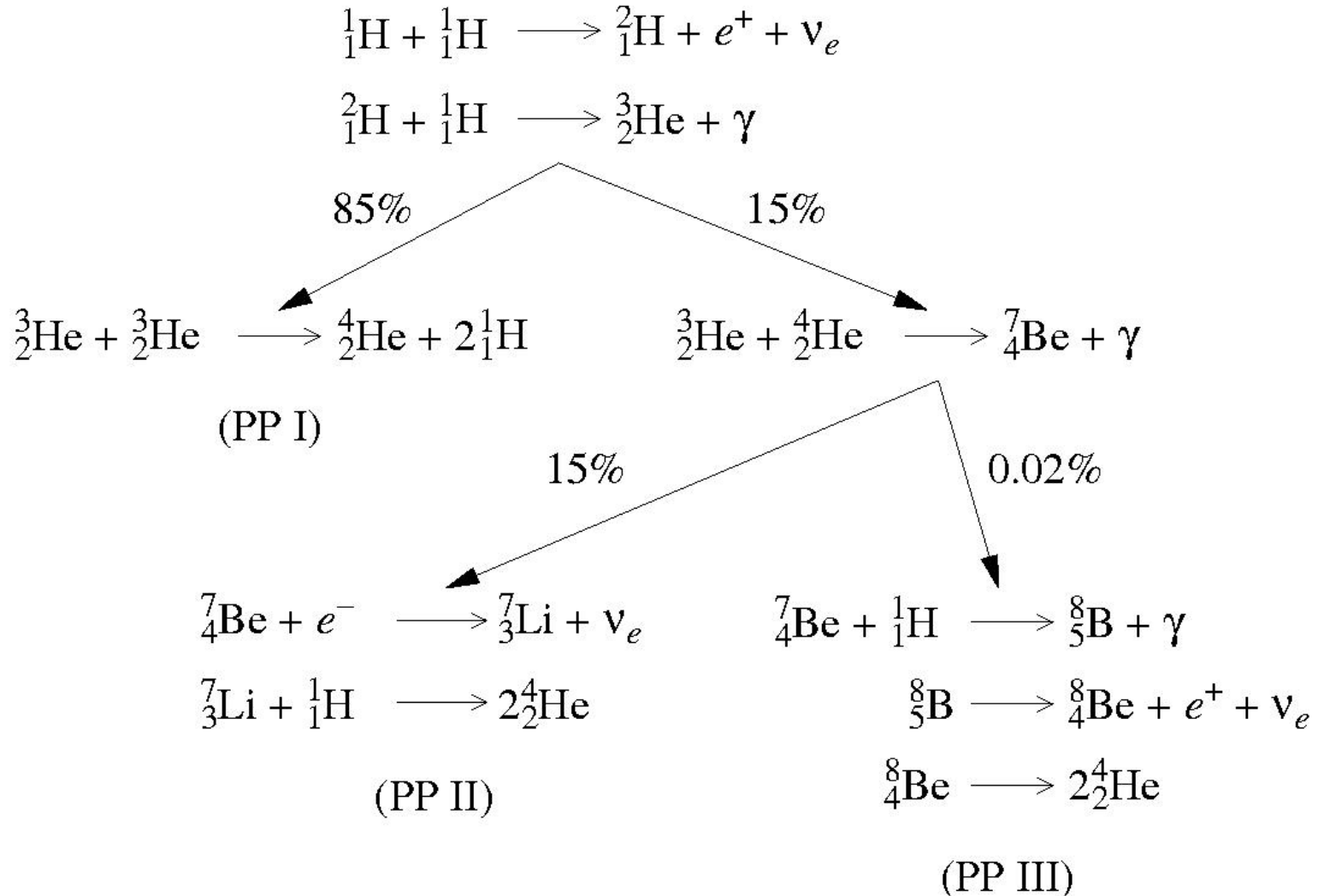
# The Energy Generation Rate Inside the Sun



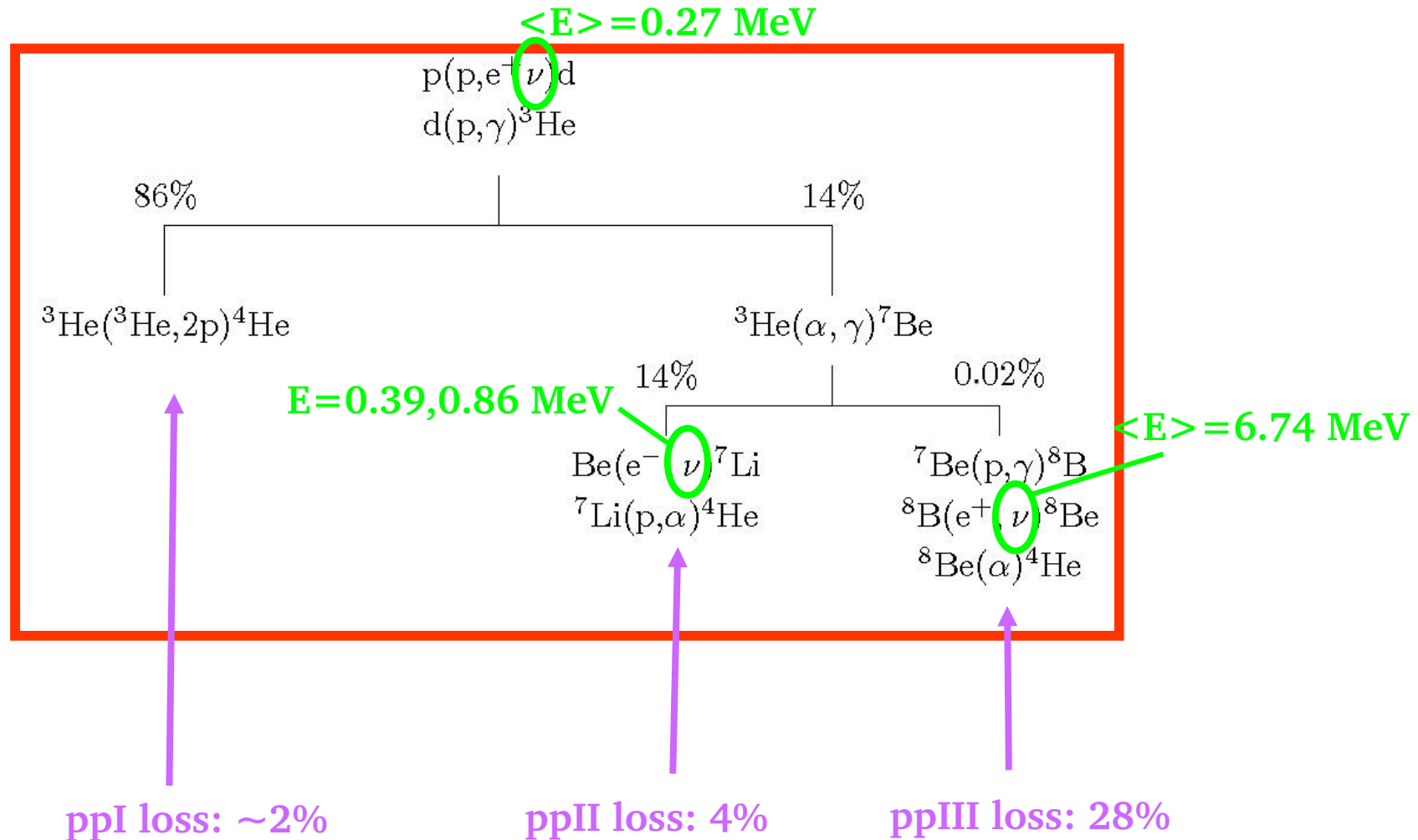
All the nuclear energy in the sun is produced inside  $0.2 R$ .



# H-Burning in the Sun



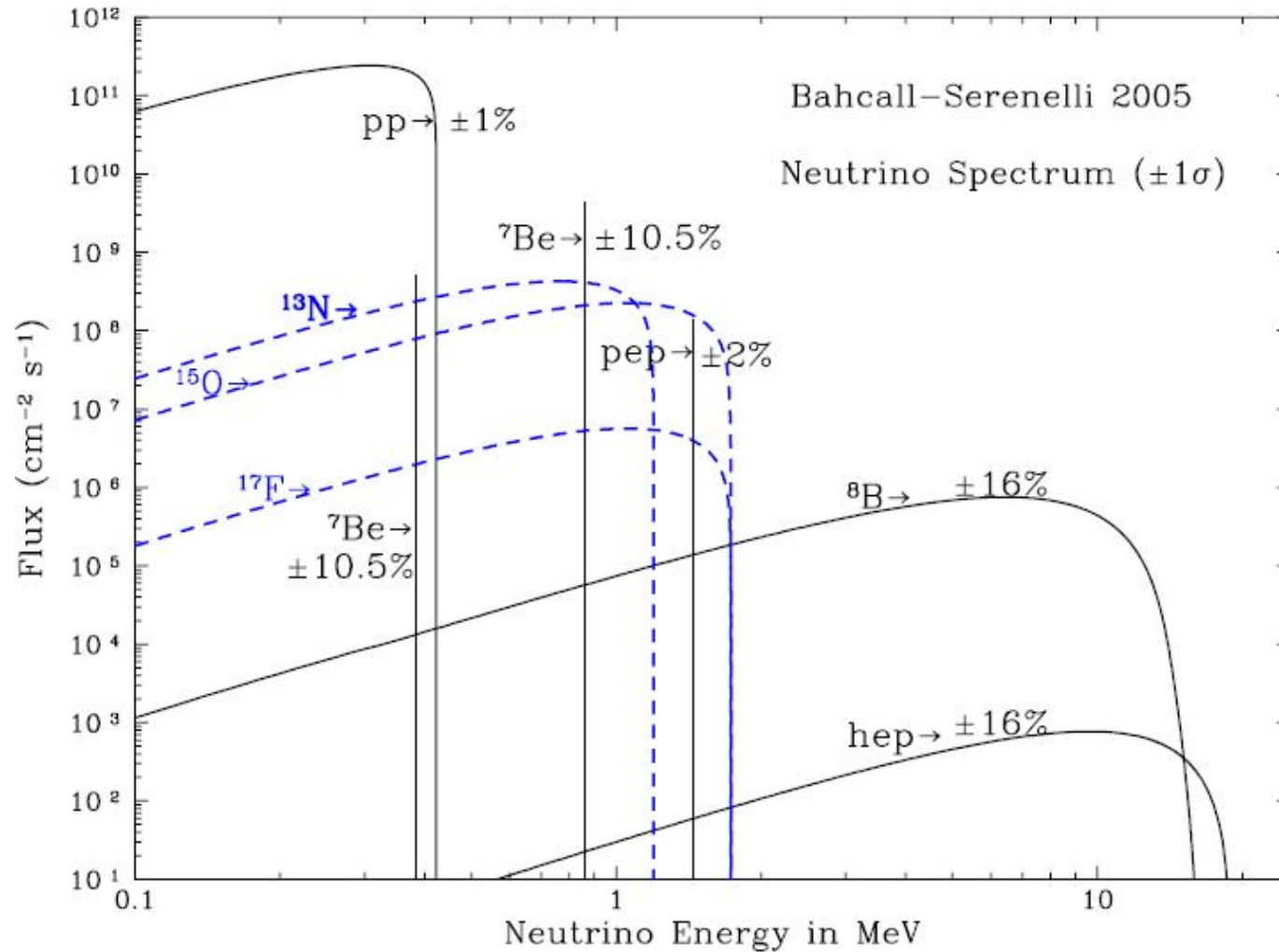
# Neutrino emission



note:  $\langle E \rangle / Q =$   
 $0.27 / 26.73 = 1\%$

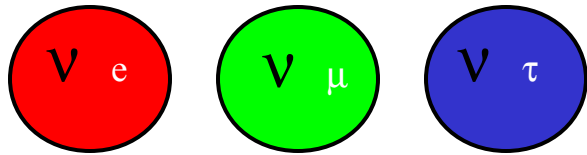
**Total loss: 2.3%**

# Solar Neutrino Production in the Standard Model

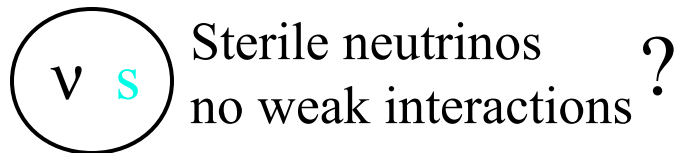


# Neutrino Properties: Flavors and Masses

Flavor states:

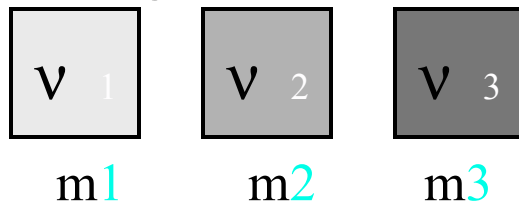


Eigenstates of the CC weak interactions

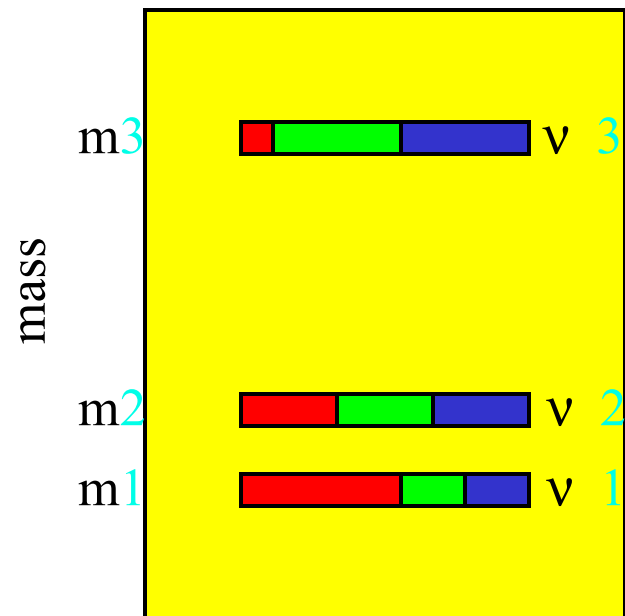
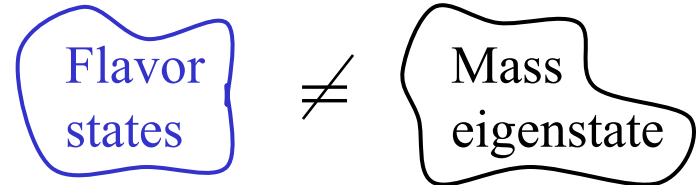


Sterile neutrinos  
no weak interactions ?

Mass eigenstates:



Mixing:



Neutrino mass and flavor spectrum

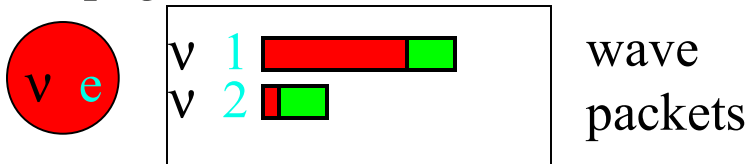
# Mixing and oscillations

$$\begin{aligned}
 \begin{array}{|c|c|} \hline \color{red}{\blacksquare} & \color{green}{\blacksquare} \\ \hline \end{array} &= \sin\theta \quad \nu_e + \cos\theta \quad \nu_\mu \\
 \begin{array}{|c|c|} \hline \color{red}{\blacksquare} & \color{green}{\blacksquare} \\ \hline \end{array} &= \cos\theta \quad \nu_e - \sin\theta \quad \nu_\mu
 \end{aligned}$$

$\theta$  is the vacuum mixing angle

$\nu_e = \cos\theta \nu_1 + \sin\theta \nu_2$  coherent mixture of mass eigenstates

Propagation:



$$\Delta \nu_{\text{phase}} = \frac{\Delta m^2}{2E}$$

$$\Delta m = m_2 - m_1$$

$$\Delta \phi = \Delta \nu_{\text{phase}} t$$

Oscillations: effects of the phase difference increase which changes the interference pattern

Interference of the parts of wave packets with the same flavor depends on the phase difference  $\Delta \phi$  between  $\nu_1$  and  $\nu_2$

# Matter effect

Elastic forward scattering

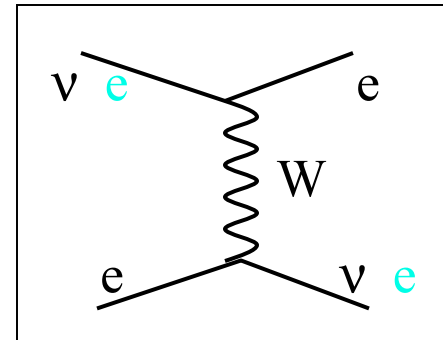


Potentials  
 $V_e, V_\mu$

Difference of potentials is important



for  $\nu_e \nu_\mu$  :



$$V_e - V_\mu = \sqrt{2} G_F n_e$$

Matter changes

- mixing angle

$$-\theta \rightarrow \theta_m(\nu_e, E) \quad (\text{mixing angle in matter})$$

- eigenstates

$$\nu_1, \nu_2 \rightarrow \nu_{1m}, \nu_{2m}(\nu_e, E)$$

- effective masses

$$m_1, m_2 \rightarrow m_{1m}, m_{2m}(\nu_e, E)$$

- modifies oscillations in the case of uniform medium
- leads to qualitatively new effects in media with varying densities

# MSW conversion

Resonance condition:

$$V(n) = \cos 2\theta \frac{\Delta m^2}{2E}$$

Matter  
frequency

Eigenfrequency  
of neutrino system

Density,  $n$ , (energy,  $E$ ) which satisfies the resonance condition

is called the resonance density (energy)

If density changes slowly enough (typical scale of density change is larger than the oscillation length) the adiabaticity condition is fulfilled

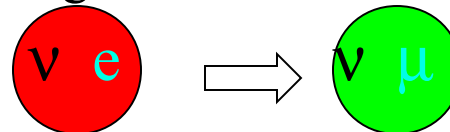
Adiabatic  
propagation

Flavor of neutrino state  
follows density change:

$$\text{Flavor} = F(\text{density})$$

If density, e.g., decreases from  
 $n \gg n_R$  down to  $n \ll n_R$

Strong transformation of flavor:



# Vacuum Oscillation solutions

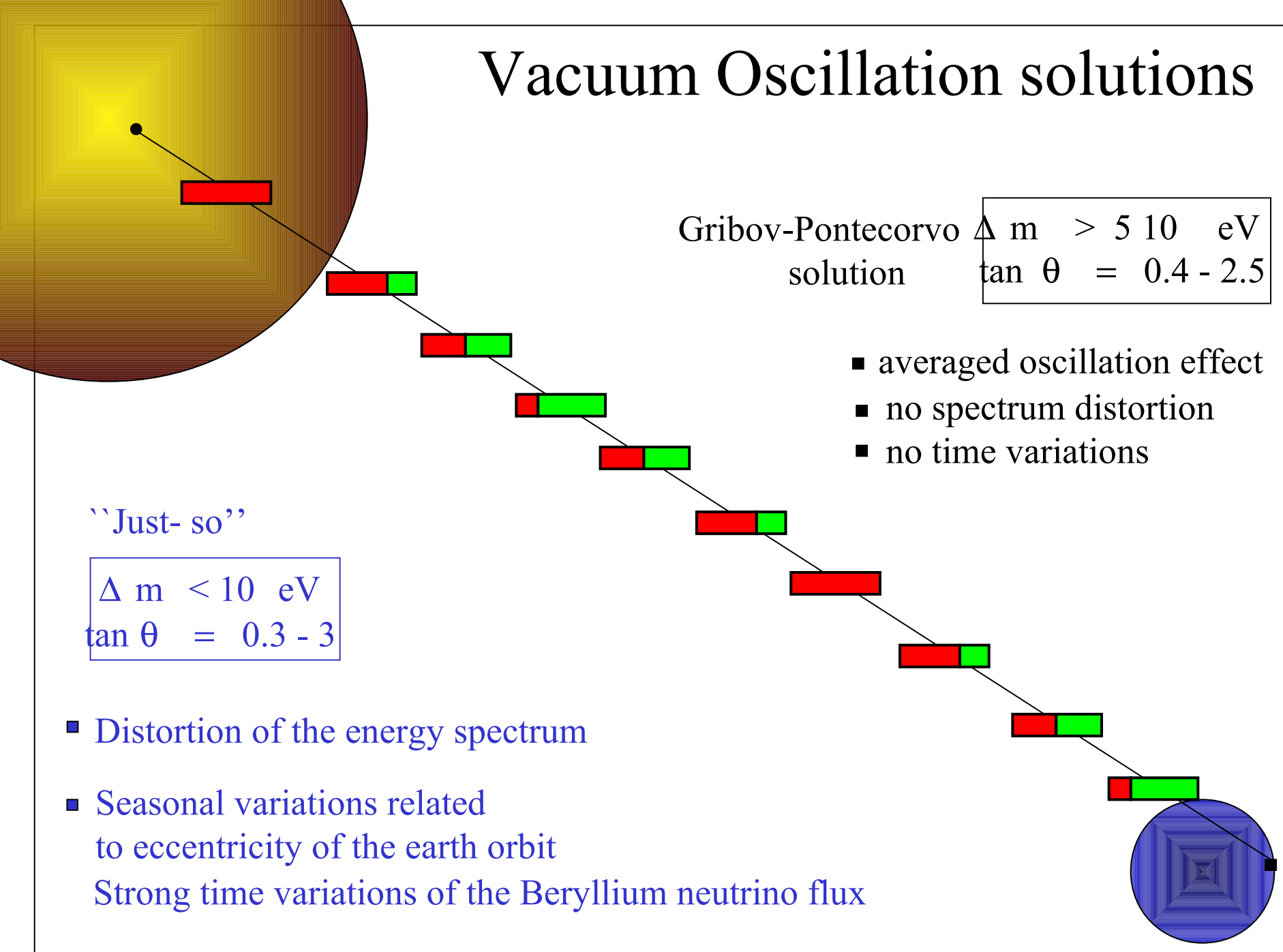
Gribov-Pontecorvo solution  $\Delta m > 5 \cdot 10 \text{ eV}$   
 $\tan \theta = 0.4 - 2.5$

- averaged oscillation effect
- no spectrum distortion
- no time variations

“Just- so”

$\Delta m < 10 \text{ eV}$   
 $\tan \theta = 0.3 - 3$

- Distortion of the energy spectrum
- Seasonal variations related to eccentricity of the earth orbit  
Strong time variations of the Beryllium neutrino flux





# MSW conversion

Inside the Sun

LMA, LOW

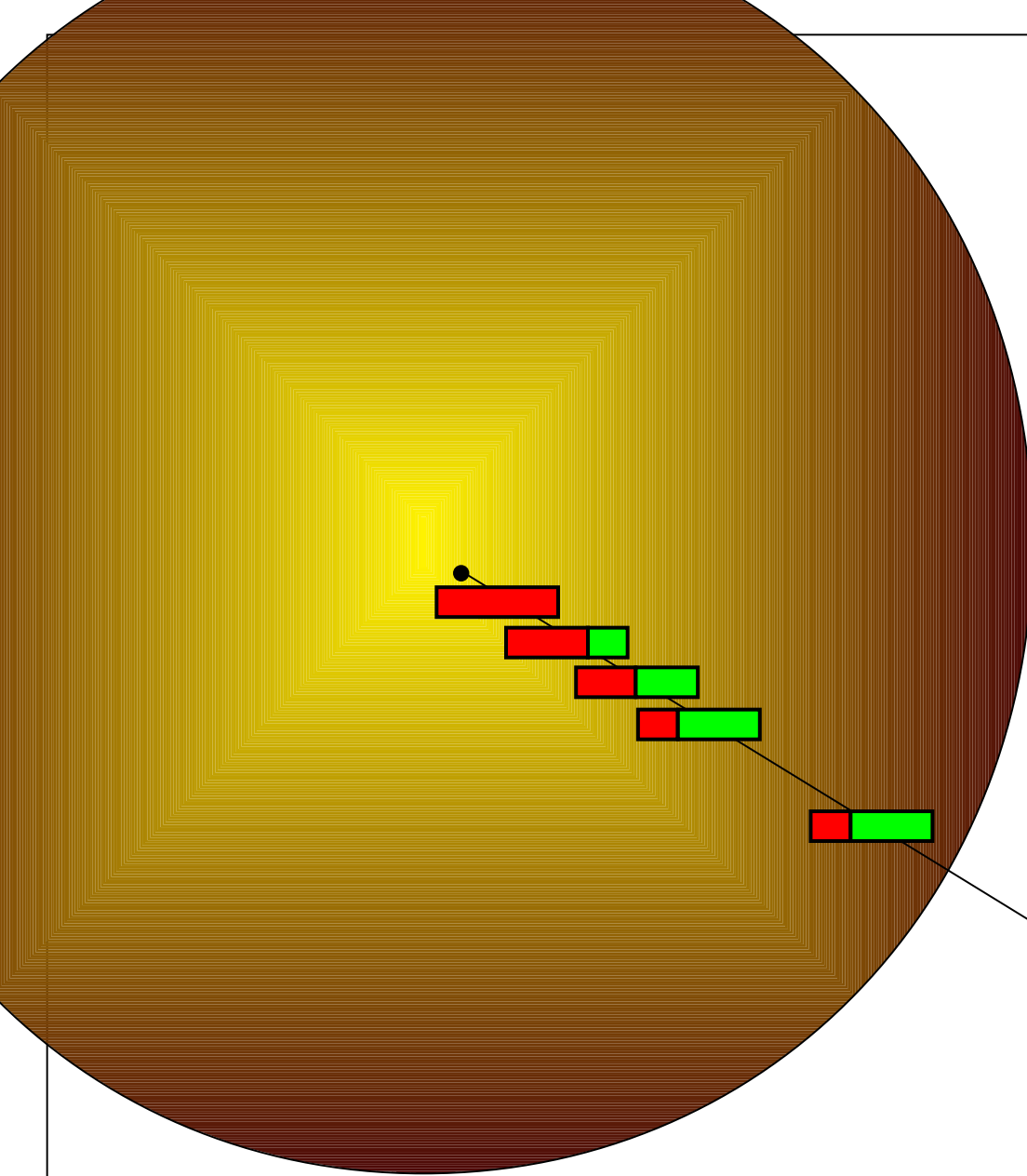
$$\Delta m^2 = (3 - 5) \times 10^6 \text{ eV}^2$$
$$\tan \theta = 0.2 - 1$$

- Weak spectrum distortion
- time variations due to earth matter effect

SMA

$$\Delta m^2 = (3 - 9) \times 10^7 \text{ eV}^2$$
$$\tan \theta \sim 10$$

Flavor of neutrino state follows density change



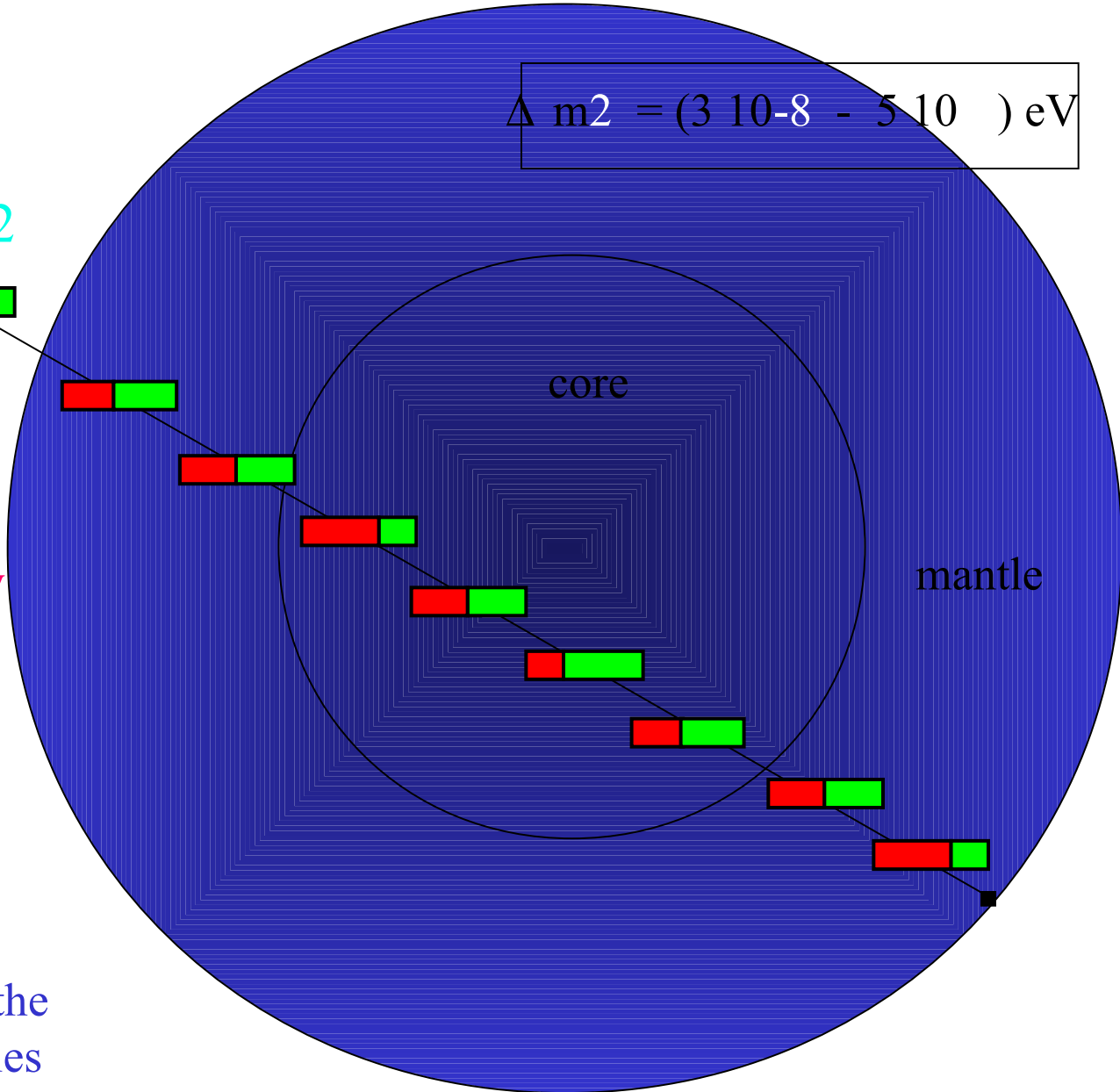
# Inside the Earth. Regeneration

Oscillations  
in the matter  
of the Earth

Regeneration of  
the  $\nu_e$  flux

- Day - Night asymmetry
- Variations of signal during nights (zenith angle dependence),
- Seasonal variations
- Spectrum distortion
- Parametric effects for the core crossing trajectories

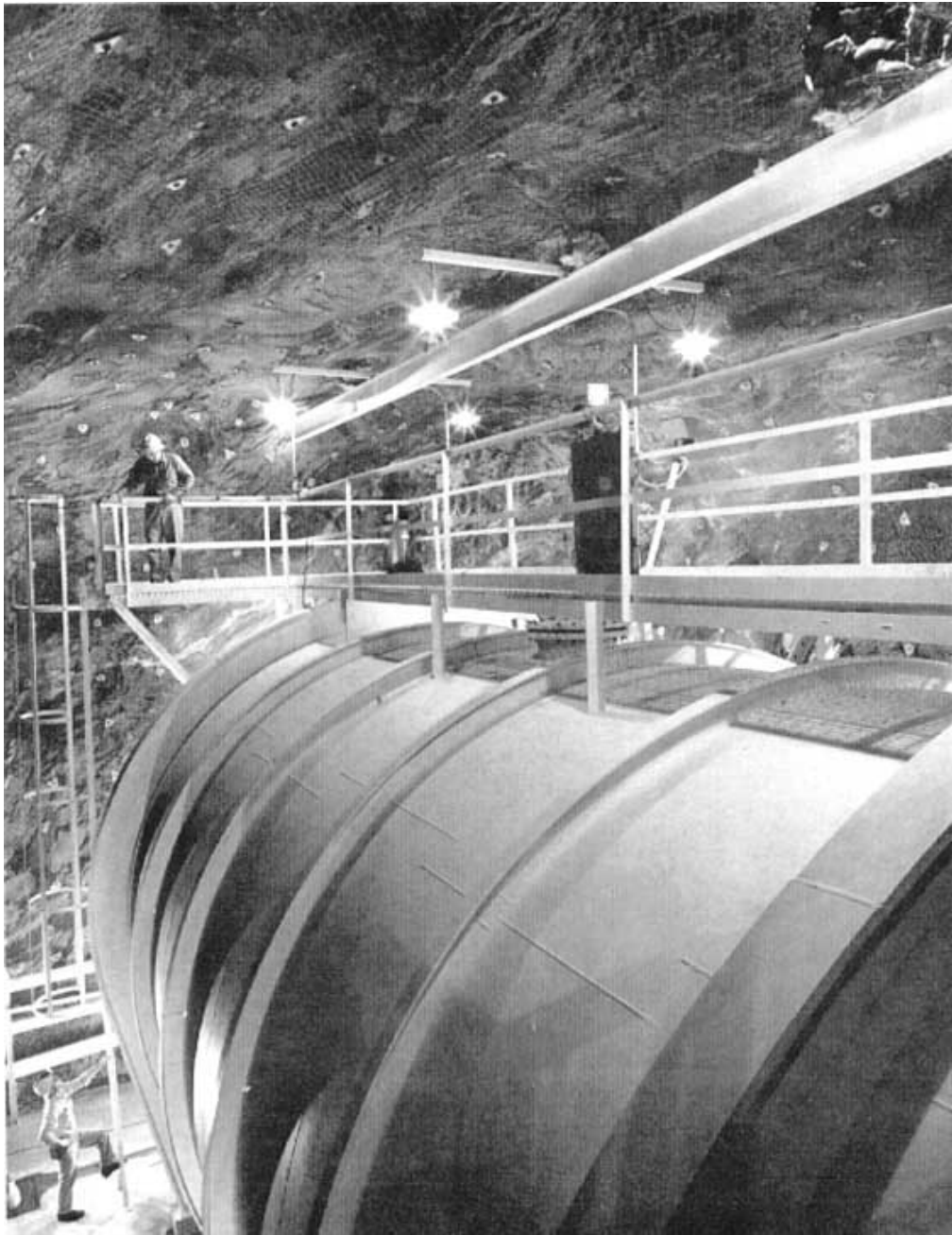
$\nu_e$



$$\Delta m^2 = (3 \cdot 10^{-8} - 5 \cdot 10^{-7}) \text{ eV}^2$$

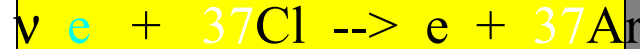
core

mantle



# Homestake experiment

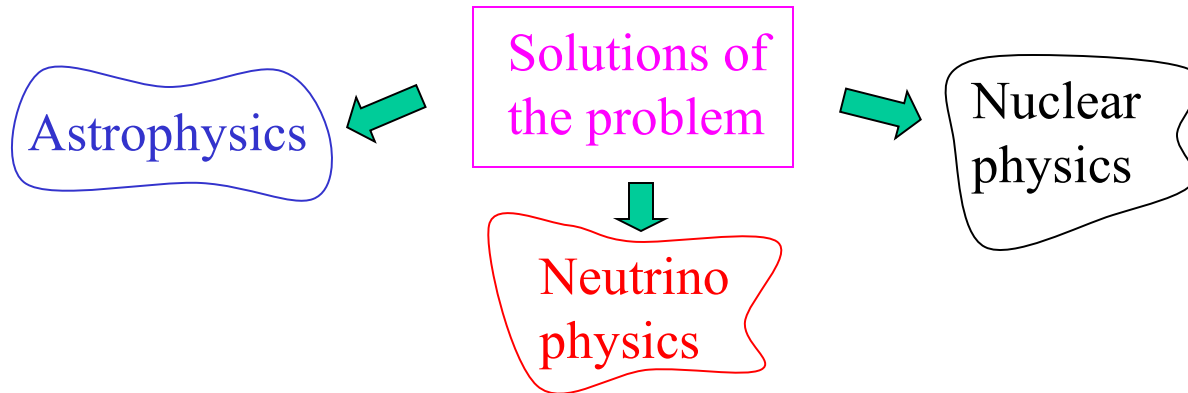
R. Davis Jr. et al  
Establishing the problem



$E_{\text{th}} = 0.814 \text{ MeV}$   
Sensitive to  $\nu_e$  only

Deficit of the Argon  
production rate:

$$R_{\text{Ar}} = 0.298 \pm 0.049$$



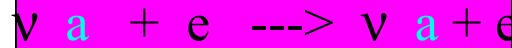
For about 20 years the only experimental result  
Practically all solutions have been suggested during this period

Time variations of the signal: 11 years/ 2 years/1 month?  
**Favored solution: Spin flip in the magnetic field**

# Kamiokande

Water Cerenkov detector

1987 - 1995



$a = e, \mu, \tau$

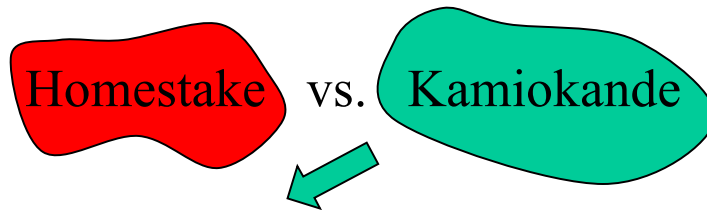
$E_{th} = 7.5 \text{ MeV}$

sensitive to all active neutrinos  
detects the Boron and hep- neutrino fluxes

Deficit of the boron  
neutrino flux

$$R_K = \frac{FB}{FB_{SSM}} = 0.47 \pm 0.06$$

No time  
variations



Barabanov  
Bahcall  
Bethe

$$FB \Rightarrow Q_{Ar} \Rightarrow Q_{Ar}^B > Q_{Ar}^{\text{Homestake}}$$

Distortion of the energy spectrum  
Beryllium neutrino flux should be  
strongly suppressed

or/and

The fluxes of  $\nu_\mu$ ,  $\nu_\tau$  from  
the Sun exist which contribute to  
Kamiokande but not to Homestake

- Hint: astrophysics and nuclear physics solutions do not work
- SMA MSW -- favorite solution

# SAGE, GALLEX, GNO

1990, 1991, 1998



$$E_{\text{th}} = 0.233 \text{ MeV}$$

sensitive to all components of the solar neutrino spectrum

Deficit of signal  
time variations ?

$$R_{\text{Ga}} \frac{Q_{\text{Ge}}}{Q_{\text{GeSSM}}} = 0.581 \pm 0.055$$

“Just at the edge”

Contribution from the pp neutrino  
flux (reliably predicted)

$$Q_{\text{Ge}} = 70 \text{ SNU}$$

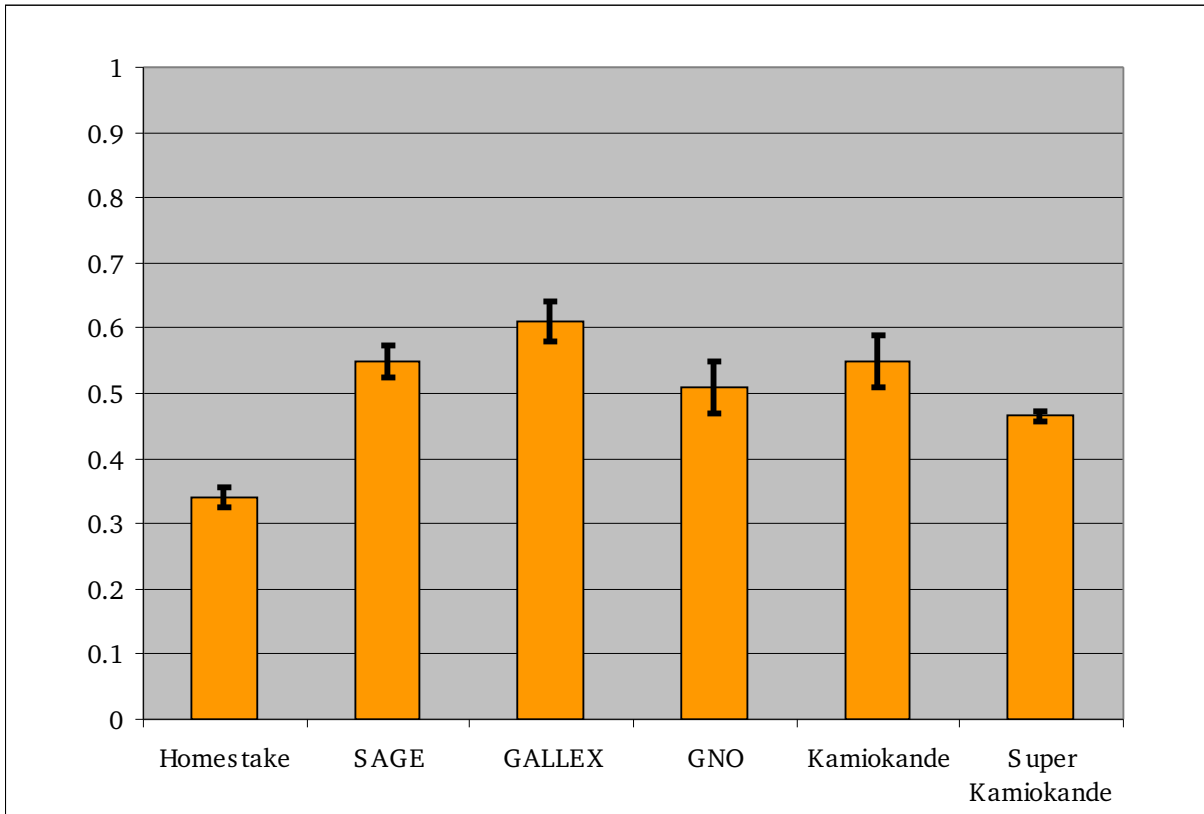
$Q_{\text{Ge}} < 70 \text{ SNU}$  would exclude astrophysical solutions

Observations:

$$Q_{\text{Ge}} = (75 \pm 5) \text{ SNU}$$

- Confirm deficit and inferences from Homastake-Kamiokande comparison
- Strong suppression of the Beryllium neutrino flux or/and the pp-neutrino flux
- SMA MSW -- favorite solution

many more experiments over the years with very different energy thresholds:



all show deficit to standard solar model

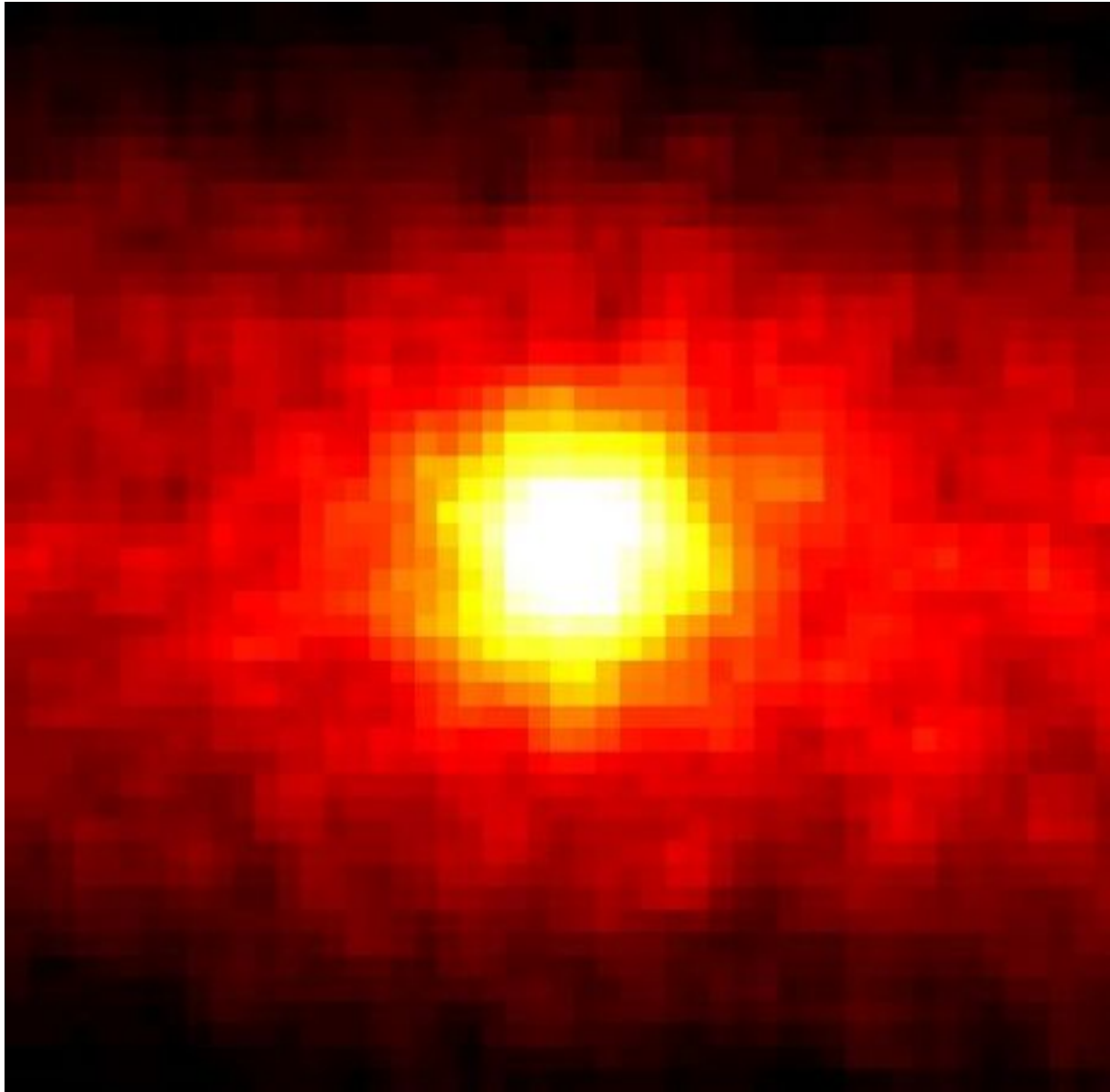


$\nu_e$  only



all flavors, but  $\nu_\tau, \nu_\mu$  only 16% of  $\nu_e$  cross section because no CC, only NC

Astronomy Picture of the Day June 5, 1998



Neutrino image of the sun by Super-Kamiokande – next step in neutrino astronomy 64



# SuperKamiokande

Water Cerenkov detector

1996

$$\nu_a + e \rightarrow \nu_a + e$$

$a = e, \mu, \tau$

$E_{th} = 5 \text{ MeV}$

## ■ Deficit

$$R_{SK} = \frac{FB}{FB_{SSM}} = 0.391 \pm 0.060$$

## ■ No spectrum distortion.

Excess of events in the high energy bins?

## ■ No time variations of the flux apart from seasonal variations related to the eccentricity of the Earth orbit

Day- Night asymmetry:  $2.5 \sigma \rightarrow 1 \sigma$

Zenith angle distribution of events: no enhancement in the deepest night bin expected for SMA solution, flat distribution...

Signatures disappear

## ■ Change of favorites: SMA MSW is disfavored by SK data

SMA MSW

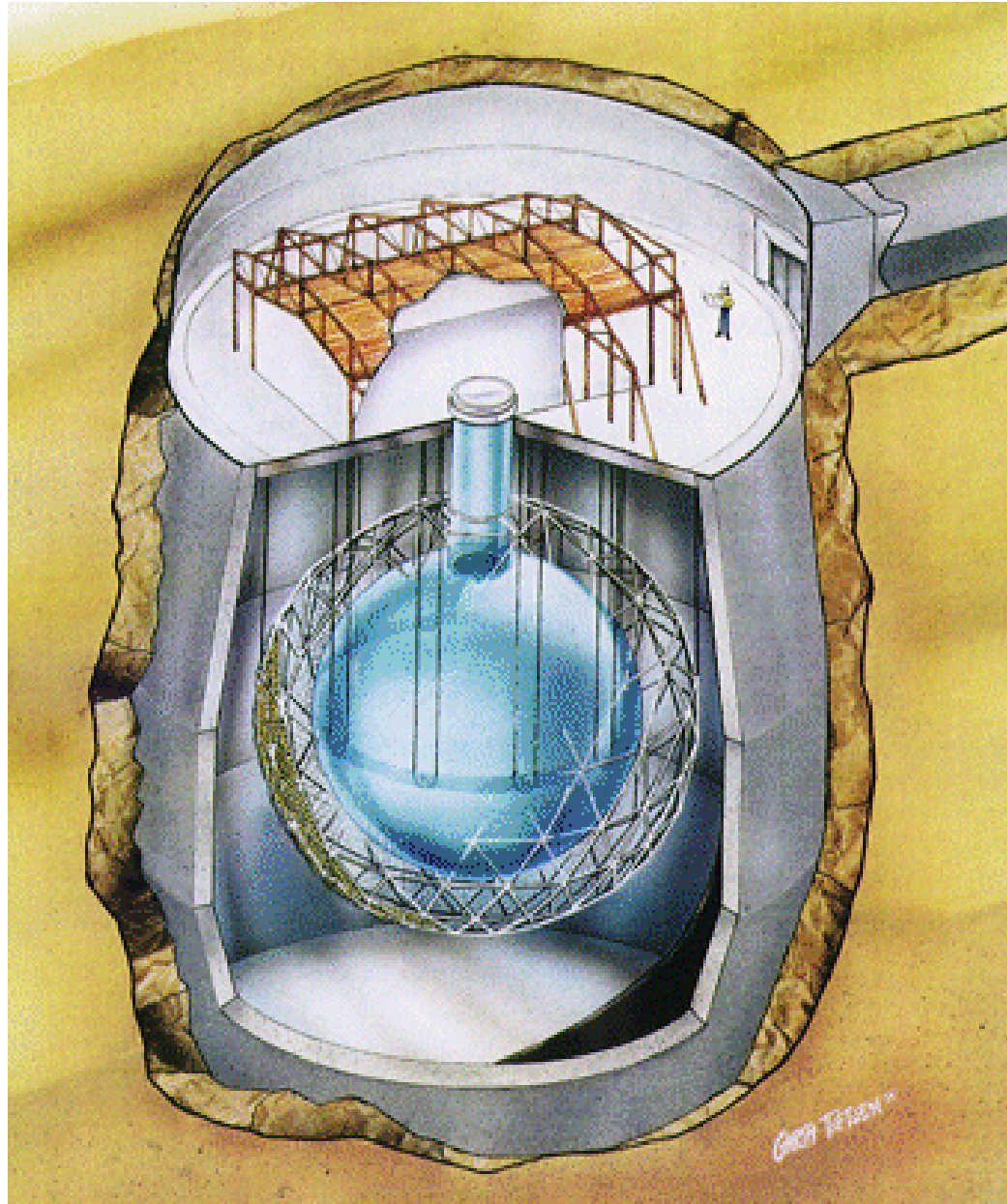


Vacuum oscillations



LMA MSW

# Sudbury Neutrino Observatory

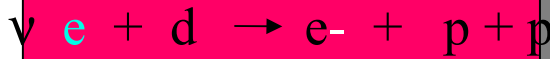


# SNO

1000 tons of heavy water

1999

CC



$E_{th} = 6.75 \text{ MeV}$

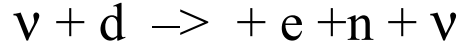
Sudbury  
Neutrino

ES



Observatory

NC



■ Deficit:

$$R_{SNO} = \frac{F_{B}}{F_{BSSM}} = 0.295 \pm 0.051$$

First strong  
evidence of  
solar neutrino  
flavor conversion

■ SNO vs. SuperKamiokande

$$F_{\nu_e} = 1.75 \pm 0.15$$

$\nu_e$  contribute only

$$F_{\text{all}} = 2.32 \pm 0.085$$

all active neutrinos contribute

units  
10 cm s

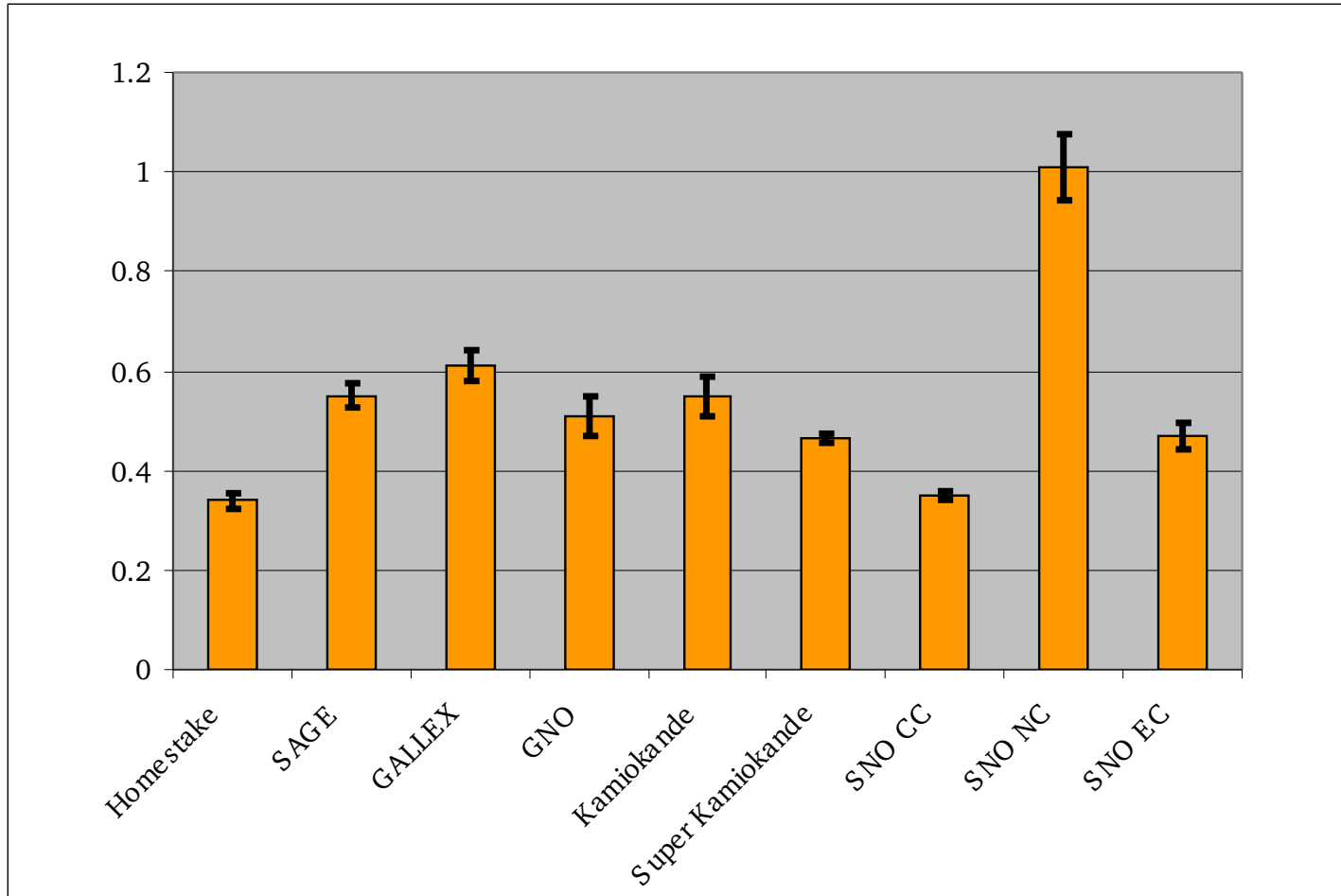
$$\frac{F_{ES,SK}}{F_{BCC,SNO}} = 3\sigma$$

■ Implied appearance of  $\nu_\mu/\nu_\tau$  flux from the Sun (which contributes to SK)

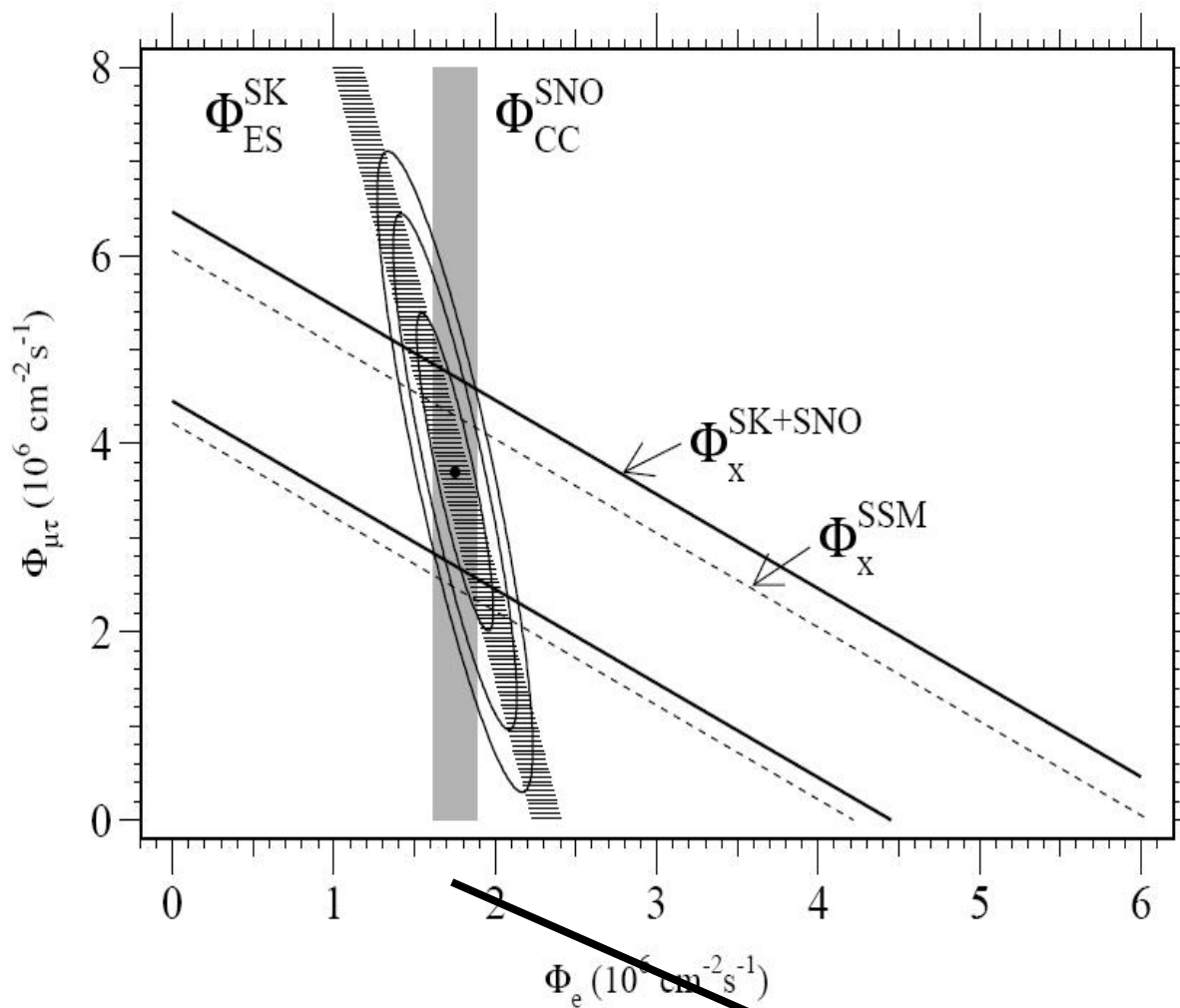
■ LMA is further favored, SMA -- disfavored

■ "sterile" solutions are also disfavored

With SNO results:



# SNO proof of Neutrino Oscillations

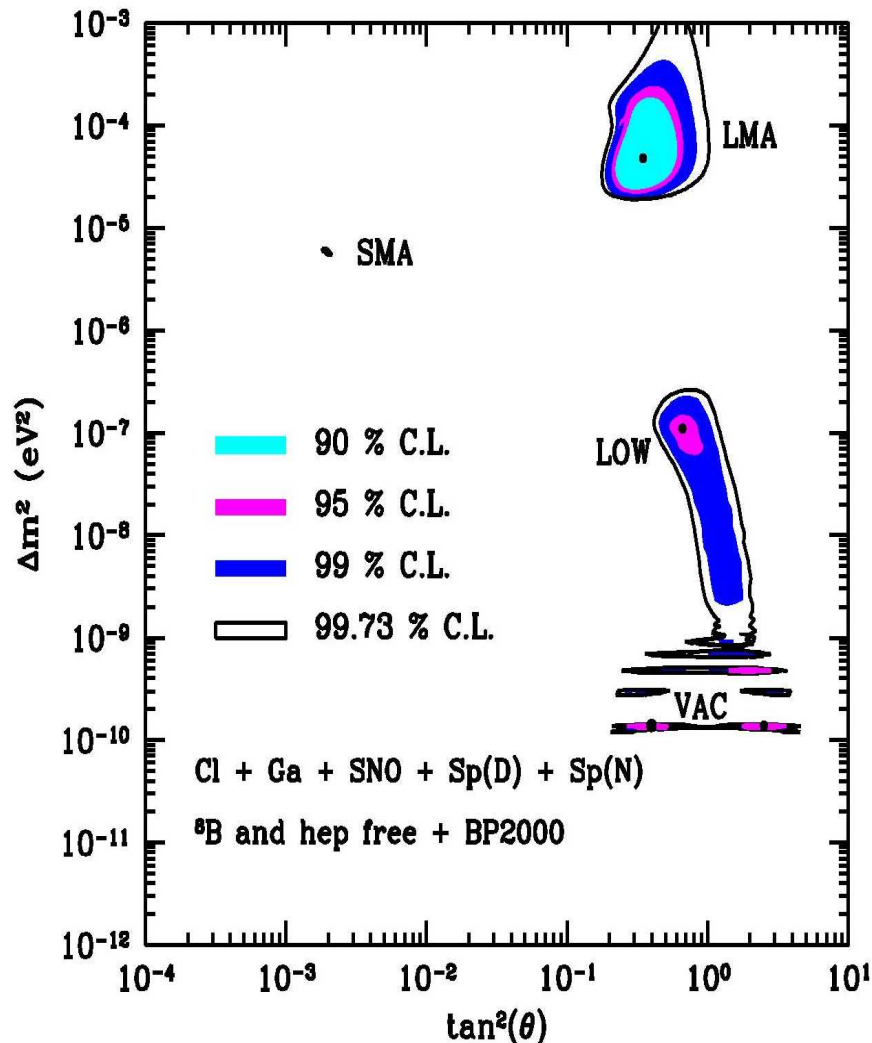
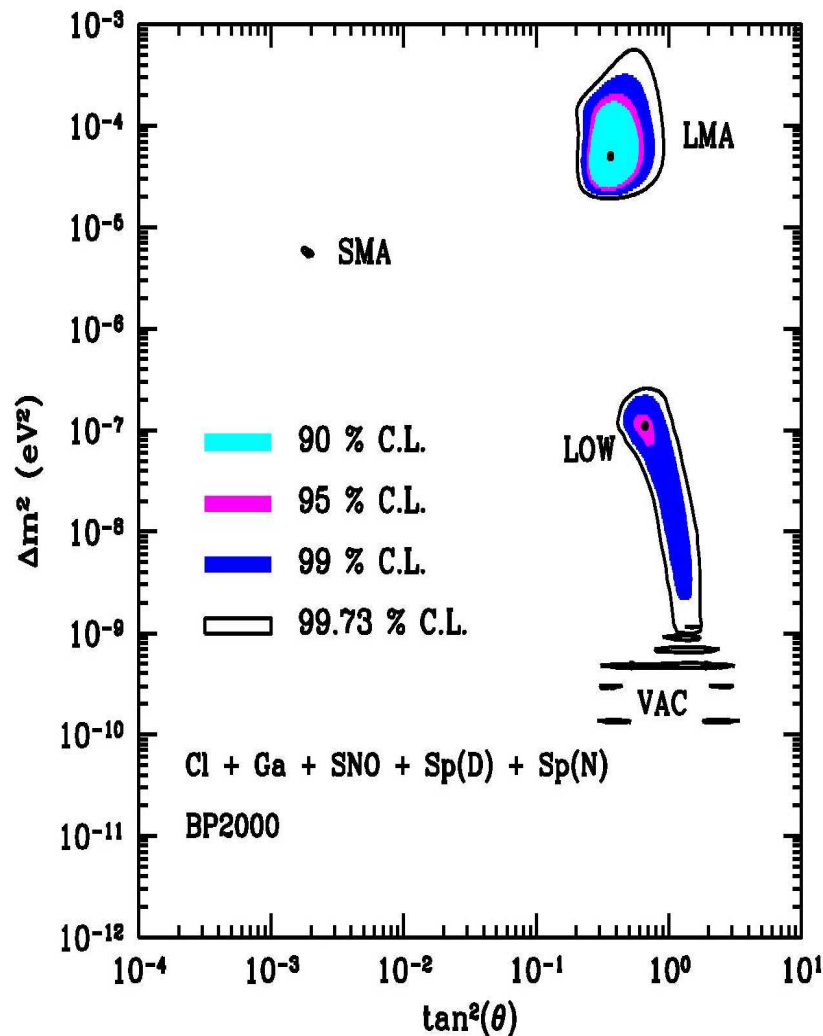


Observed total flux agrees with solar value

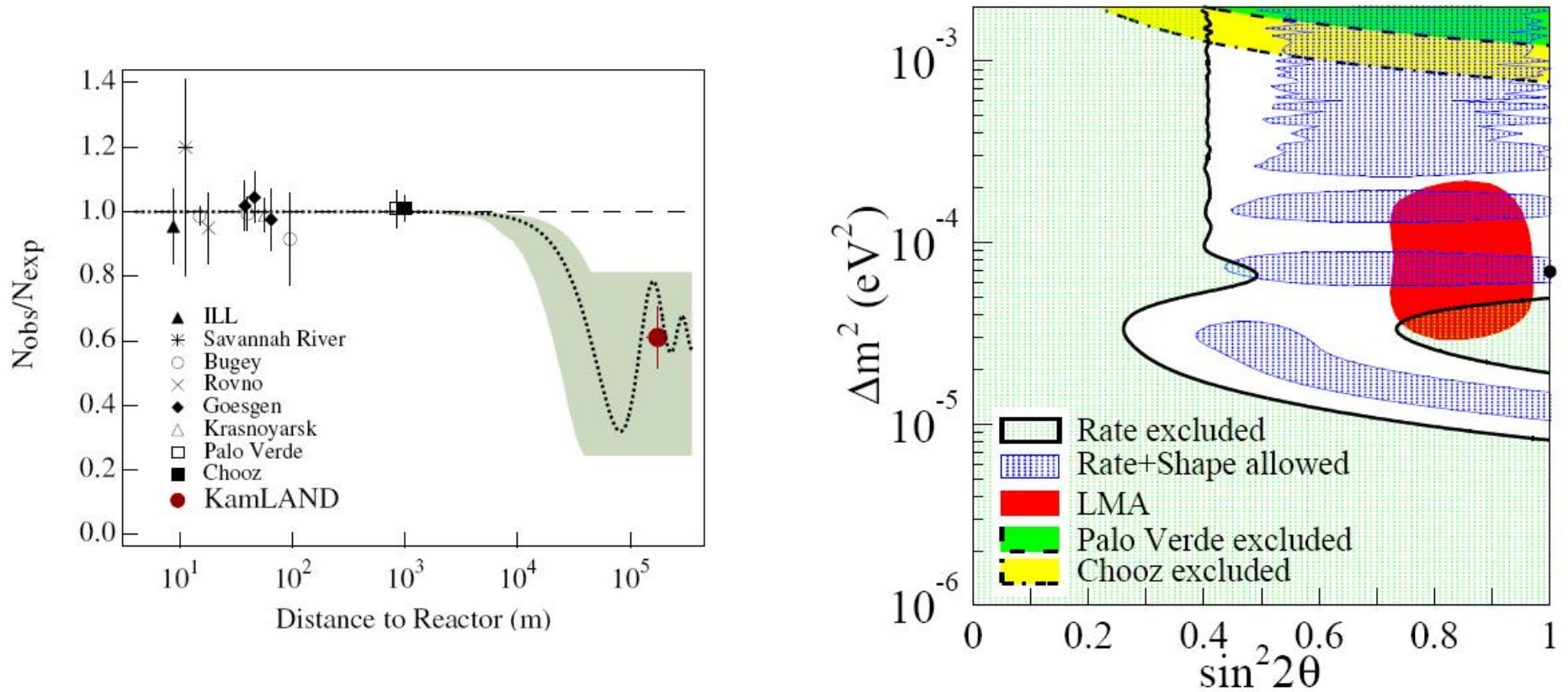
# Global Fit after SNOW

Allowed regions of the oscillation parameters

P Krastev, A.S



# KamLAND confirmed Oscillations





# Current Status (from Raffelt)

## Three-Flavor Neutrino Parameters

Atmospheric/K2K  
 $41^\circ < \theta_{23} < 49^\circ$

CHOOZ  
 $\theta_{13} < 8^\circ$

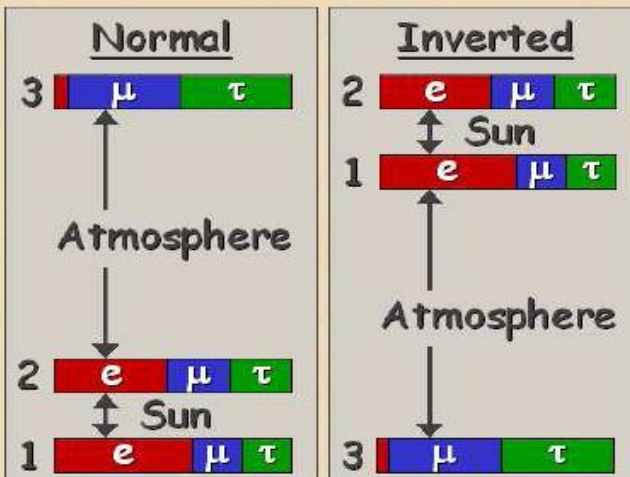
Solar/KamLAND  
 $32^\circ < \theta_{12} < 36^\circ$

$1\sigma$  ranges  
 hep-ph/0306001

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & & e^{-i\delta} s_{13} \\ & 1 & \\ -e^{i\delta} s_{13} & & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} \\ -s_{12} & c_{12} \\ & & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$c_{12} = \cos \theta_{12}$  etc.,  $\delta$  CP-violating phase

Solar  
 67 – 77  
 Atmospheric  
 2200 – 3000  
 $\Delta m^2 / \text{meV}^2$



### Tasks and Open Questions

- Precision for  $\theta_{12}$  and  $\theta_{23}$  ( $\theta_{12} < 45^\circ$  and  $\theta_{23} = 45^\circ$ ?)
- How large is  $\theta_{13}$ ?
- CP-violating phase?
- Mass ordering? (normal vs inverted)
- Absolute masses? (hierarchical vs degenerate)
- Dirac or Majorana?