Solar Neutrinos I: Solar Modeling and Neutrino Detection

- The Cl experiment and the standard solar model
- Some nuclear physics of ν production and detection
- SAGE, GALLEX/GNO, and Kamioka

Hertzsprung-Russell diagram

- $L \sim 10^{-4} - 10^{6} L_{\odot}$ and $T \sim 2000 - 50000K$

- Simplest possible model might be a radiating blackbody

$$L = 4\pi R^2 \sigma T_s^4 \Rightarrow \frac{L}{L\odot} = (\frac{R}{R_{\odot}})^2 (\frac{T_s}{T_{\odot}})^4$$

- Suggests a 1D path in the (L, T_s) plane following the parameter $R/R_{\odot}$

- HR diagram dominated by one such path corresponding to the 80% of "main sequence" stars powered by H burning

pp chain, CNO cycle

- Sun is a test case of our understanding of main-sequence evolution: know L, R, surface composition, γ and ν luminosity, helioseismology

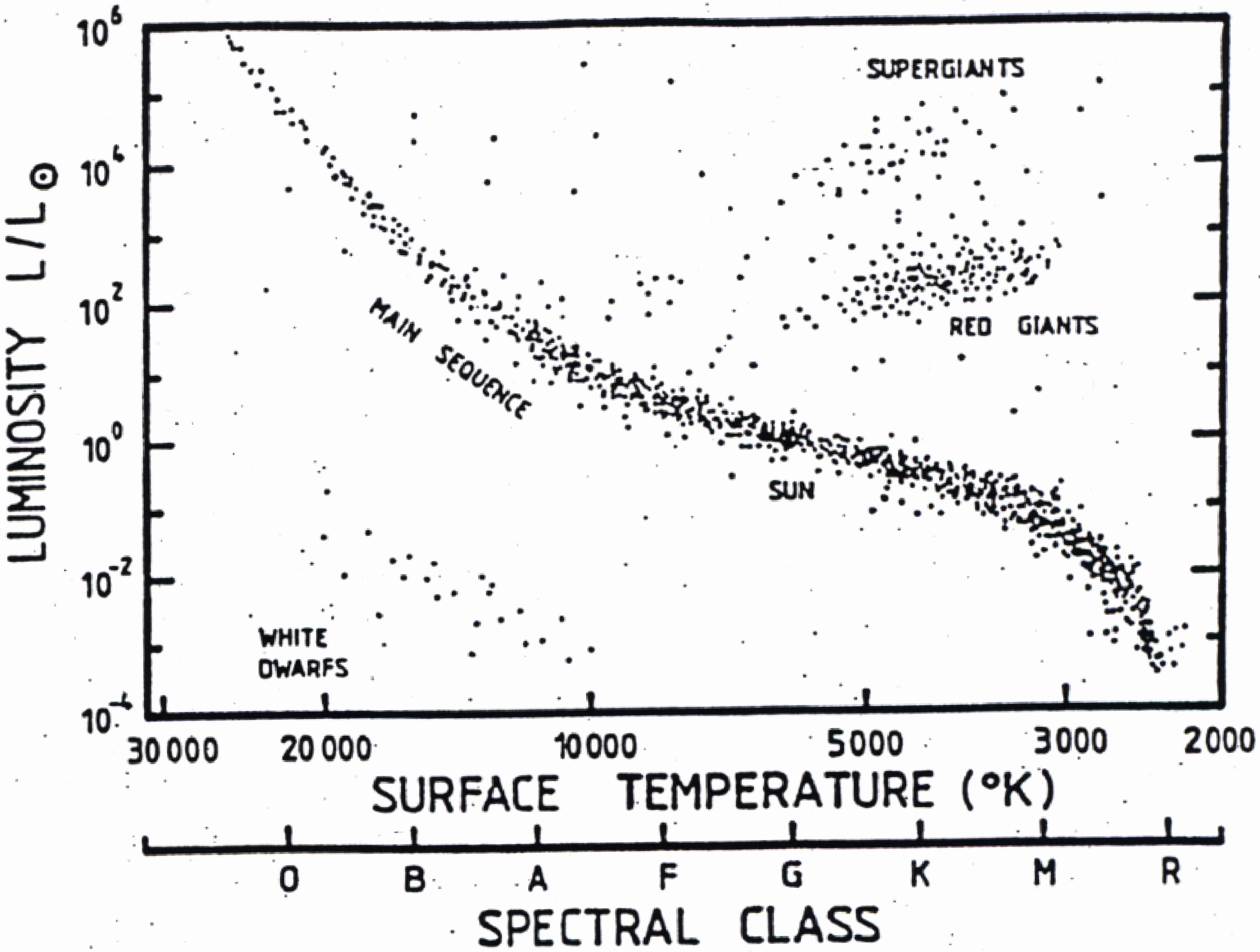


FIGURE 1.24. The Hertzsprung-Russell (H-R) diagram is shown schematically. Most of the sta (including the sun) are grouped along a band called the main sequence. As one goes from tl upper left-hand corner to the lower right-hand corner along the main sequence, the temperatur mass, size, and luminosity decrease, while the mean density increases. The diagram represents snapshot in the history of the stars' lives. The wide variety of stellar masses and the resultir variety of evolutionary tracks reflect the diversity of stellar objects. Note that only a small fractic of low-mass main-sequence stars is shown.

The Standard Solar Model

- Origin of solar neutrino physics: desire to test a rather simple model of low-mass, main-sequence stellar evolution
    - ◇ local hydrostatic equilibrium: gas pressure gradient counteracting gravitational force
    - ◇ hydrogen burning, dominated by the pp chain
    - ◇ energy transport by radiation (interior) and convection (envelope)
    - ◇ boundary conditions: today's mass, radius, luminosity; the ZAMS abundance ratios H:He:Z needed

- The implementation of this physics requires
    - ◇ electron gas EOS, which under solar conditions is quite close to that of an ideal gas
    - ◇ low-energy S-factors for the pp chain and CN-cycle
    - ◇ an understanding of solar metalicity: the opacity is dominated by free-bound transitions
    - ◇ some means of fixing the composition at ZAMS

Nuclear and weak reactions in a plasma: basic observations

- Atoms in the interior of the sun are almost entirely ionized

$$\frac{3}{2}kT \sim 2 \text{ keV} >> 13.6 \text{ eV}$$

- Charges are free: electrons can adjust to fields to screen reactions

- Electron momenta are large compared to inverse Bohr radius

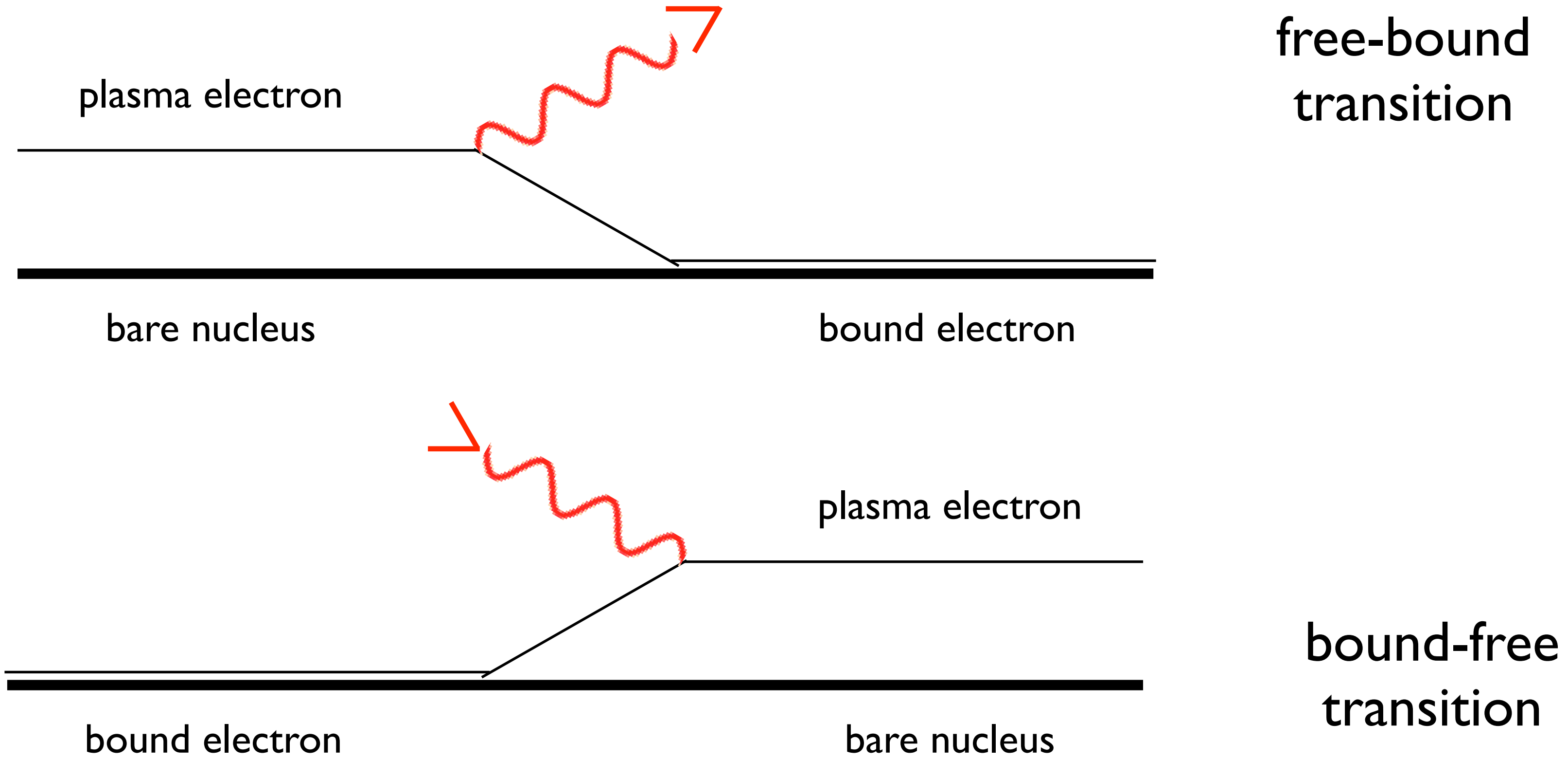
$$p \sim \sqrt{2m_e E} \sim 45 \text{ keV} >> 1/a_o \quad a_0 \sim 0.53A$$

- Center-of-mass energies of colliding ions are small compared to the height of Coulomb barriers

$$^3\text{He} +^3 \text{He} \Rightarrow \alpha \frac{Z_1 Z_2}{r_{nuclear}} \sim \frac{1}{137}\frac{4}{10 \text{ f}} 197 \text{ MeV f} \sim 575 \text{ keV}$$

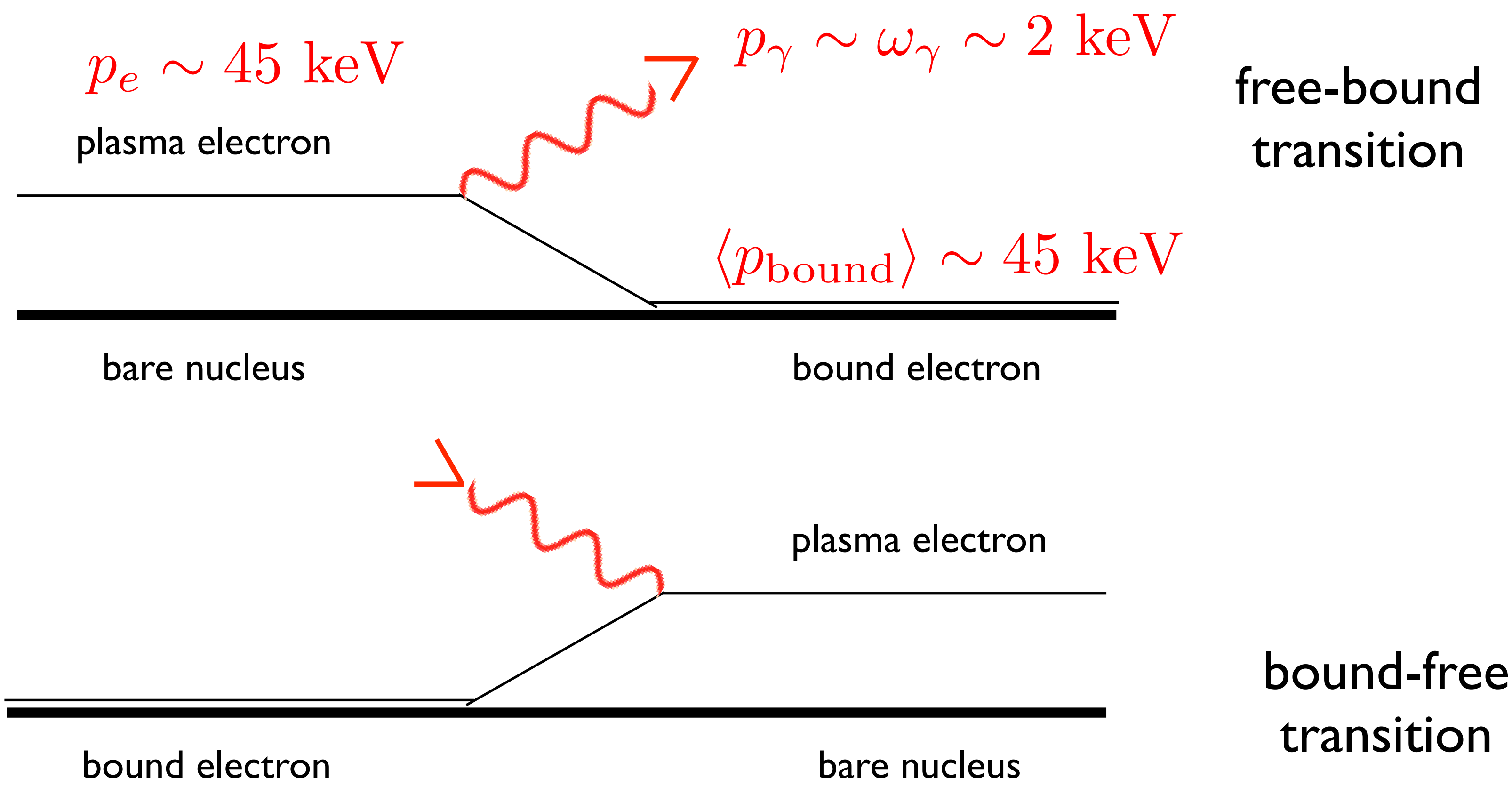
so reactions require tunneling and are correspondingly exponentially suppressed (Gamow first pointed out that QM would then allow stellar nuclear reactions)

Simple conclusions follow from such dimensional arguments

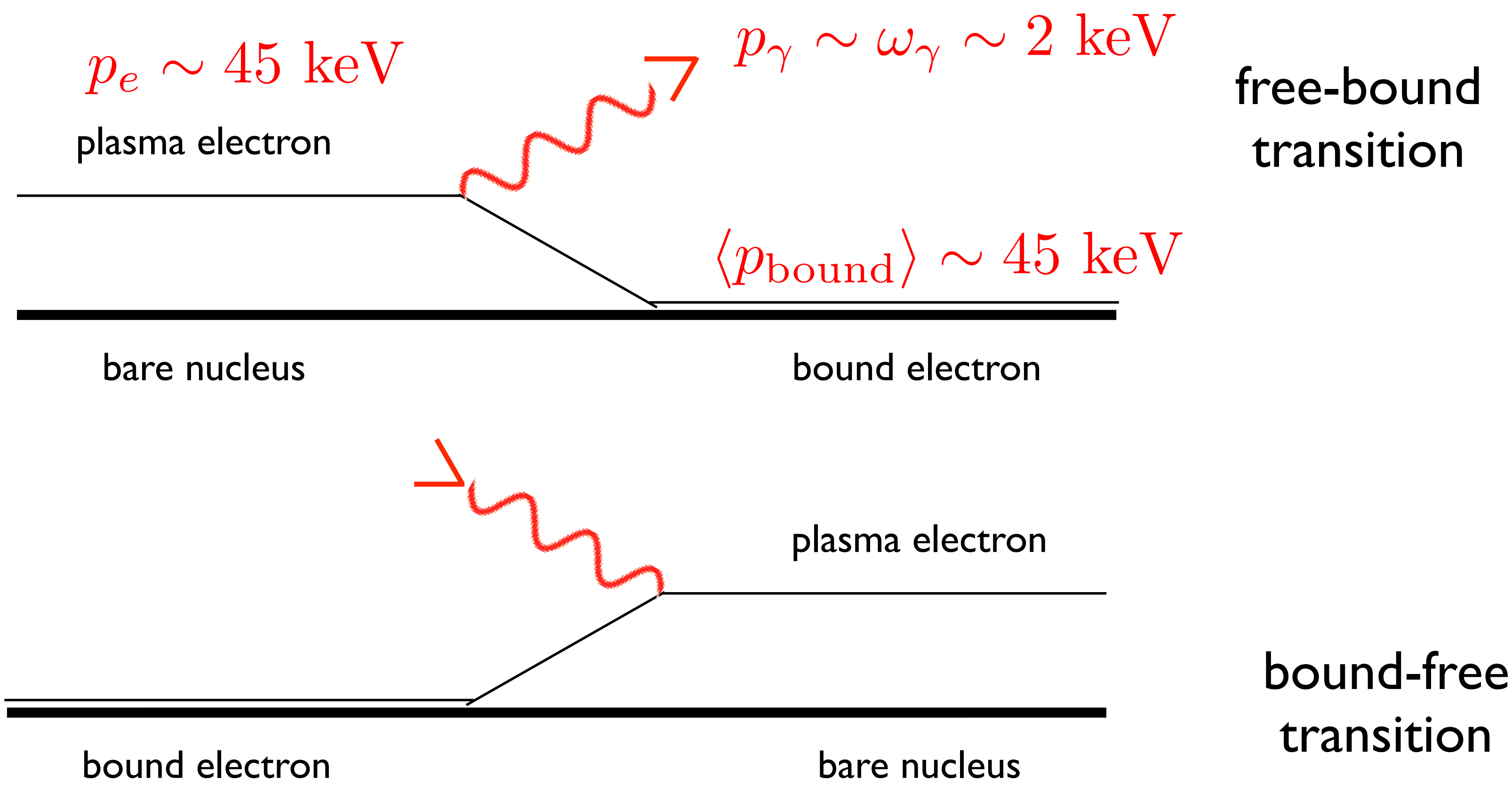


what are the important nuclei for these processes
(which dominate the opacity/transport)?

Simple conclusions follow from such dimensional arguments



Simple conclusions follow from such dimensional arguments



$$\Rightarrow 1/a_{\rm nucleus} \sim Z/a_0 \sim Z/0.53A(1.97 \text{ keV A}) \sim 45 \text{ keV} \Rightarrow Z \sim 12$$

metals such as Fe, O, Ne play a major role in the opacity

One can do more: envision a numerical model of the Sun

- Equation of state: relationship between p, ρ, T
  - ◇ dilute electron gas, well described by an ideal gas EOS
  - ◇ corrections one could envision include very small adjustments to account for incomplete ionization, relativity $(\delta c \sim 0.002c)$

- Energy transport
  - ◇ radiative or convective?
  - ◇ radiative over 98% of the sun by mass (70% by radius)
  - ◇ radiative transport: cross sections by which photons scattered, or are absorbed/emitted
  - ◇ thus some means of fixing the composition at ZAMS -- which then evolves in the core as nuclear fusion proceeds

- Dimensionality/initial conditions
  - ◇ calculations generally done in 1D

- Energy production by nuclear reactions: critically dependent on T

Historically νs provided the motivation to build such a model

- In 1956 Cowan and Reines succeeding in measuring reactor $\bar{\nu}_e s$

$$\bar{\nu}_e + p \to n + e^+ \Rightarrow \text{ pair produce}$$
$$n +^{108}\text{Cd} \to^{109}\text{Cd} \to^{109}\text{Cd} + \gamma$$

- 10 years earlier Pontecorvo had discussed another possibility

$$\nu_e + {}^{37}\text{Cl} \to {}^{37}\text{Ar} + e^-$$

$$\text{then } e^-_{1s} + {}^{37}\text{Ar} \to {}^{37}\text{Cl} + \nu_e, \quad \tau_{1/2} \sim 35 \text{ d}$$

- ${}^{37}\text{Cl}$ is a major isotope of chlorine (24%), available within organic fluids such as C_2Cl_4, and argon is a noble gas, a few atoms of which can be purged from large volumes of organic fluid

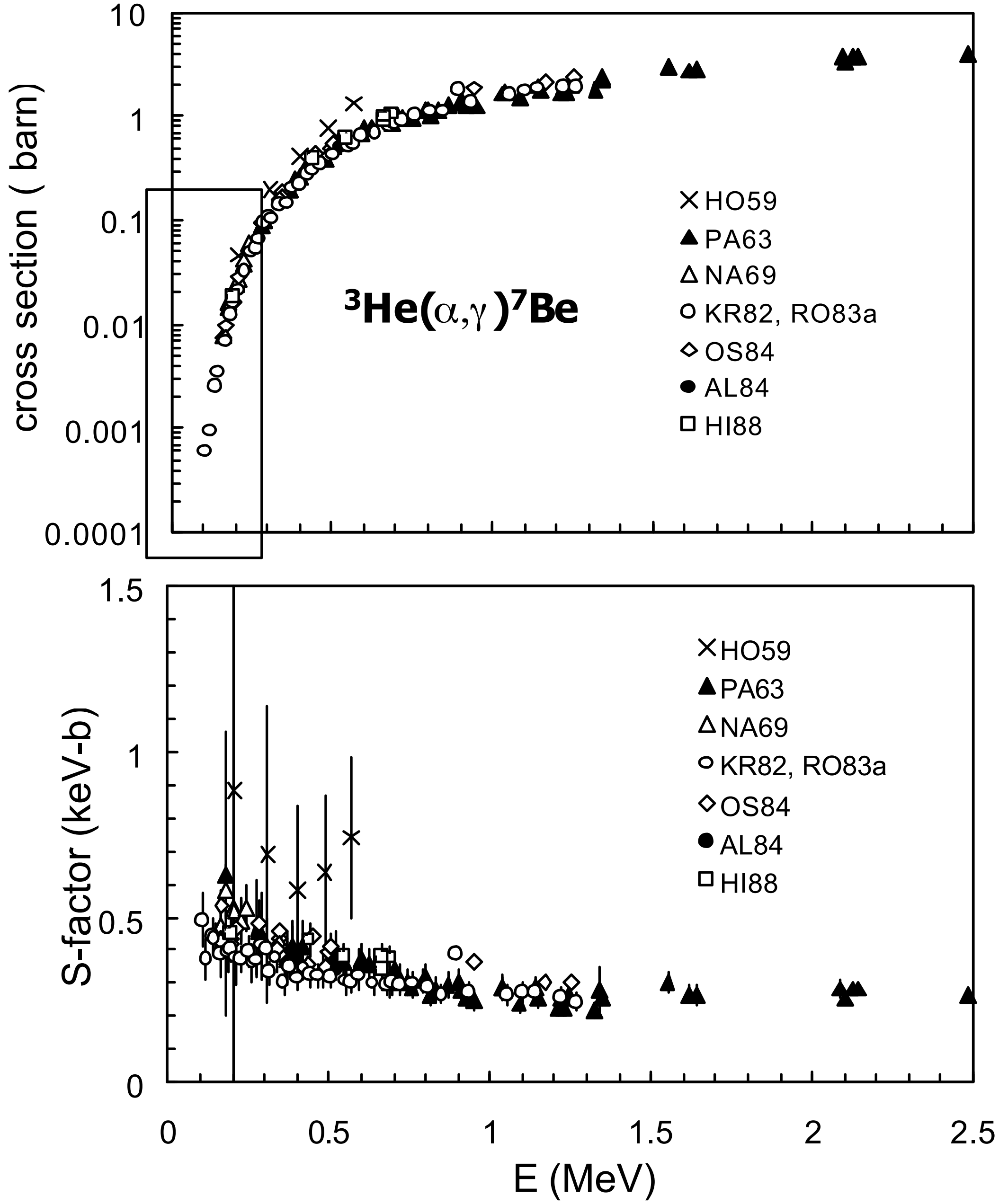
- Alvarez carefully studied associated background issues in 1949, and considered a reactor experiment, but did not pursue the idea, as he anticipated that $\bar{\nu}_e^{\text{reactor}} \perp \nu_e$

- Pontecorvo had dismissed the Sun as a solar neutrino source because of the ν energy: the Cl; reaction threshold is 810 keV, while

$$p + p \to {}^2\mathrm{H} + e^+ + \nu_e \qquad E_\nu^{\max} \sim 420 \text{ keV}$$
$$\downarrow$$
$${}^2\mathrm{H} + p \to {}^3\mathrm{He} + \gamma$$
$$\downarrow$$
$${}^3\mathrm{He} + {}^3\mathrm{He} \to {}^4\mathrm{He} + 2p$$

- but in the early 1950s Davis began to develop the Cl detector, placing a 3800 liter tank 19 feet below ground at Brookhaven, establishing a limit of 40,000 SNU on the flux of CNO neutrinos from the Sun

Referee: "Any experiment such as this, which does not have the requisite sensitivity, really has no bearing on the question of the existence of neutrinos. To illustrate my point, one would not write a scientific paper describing an experiment in which an experimenter stood on a mountain and reached for the moon, and concluded that the moon was more than 8 feet from the top of the mountain"



But two details changed the game

In1959 Holmgren & Johnston measured the cross section for ^{3}He(α,γ)^{7}Be, finding it was ~1000 times larger than expected

This reaction opens two new pathways for the Sun to synthesize He, both producing νs sufficiently energetic to excite Cl

$p + p \rightarrow {}^{2}H + e^{+} + \nu$

$p + p + e^{-} \rightarrow {}^{2}H + \nu$

99.75%

0.25%

${}^{2}H + p \rightarrow {}^{3}He + \gamma$

86%

14%

${}^{3}He + {}^{3}He \rightarrow {}^{4}He + 2p$

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

99.89%

0.11%

${}^{7}Be + e^{-} \rightarrow {}^{7}Li + \nu$

${}^{7}Be + p \rightarrow {}^{8}B + \gamma$

${}^{7}Li + p \rightarrow 2\,{}^{4}He$

${}^{8}B \rightarrow {}^{8}Be^{*} + e^{+} + \nu$

ppI

ppII

ppIII

$p + p \rightarrow {}^2H + e^+ + \nu$ $\qquad$ $p + p + e^- \rightarrow {}^2H + \nu$

99.75% $\qquad$ 0.25%

$${}^2H + p \rightarrow {}^3He + \gamma$$

86% $\qquad$ 14%

$${}^3He + {}^3He \rightarrow {}^4He + 2p \qquad {}^3He + {}^4He \rightarrow {}^7Be + \gamma$$

99.89% $\qquad$ 0.11%

$${}^7Be + e^- \rightarrow {}^7Li + \nu \qquad {}^7Be + p \rightarrow {}^8B + \gamma$$

$${}^7Li + p \rightarrow 2\,{}^4He \qquad {}^8B \rightarrow {}^8Be^* + e^+ + \nu$$

ppI $\qquad$ ppII $\qquad$ ppIII

$\sim T^{-1.1}$ $\qquad$ $E_\nu \sim 861$ keV, $\sim T^{10}$ $\qquad$ $E_\nu \leq 15$ MeV, $\sim T^{22}$

- Holmgen/Johnston: ppII and ppIII fluxes opened up the possibility that a deeper, larger version of the Davis's experiment could see solar νs
  - ◇ Davis estimated that, were the ppIII cycle dominant, an experiment similar to that at BNL would record 7 events/day

- The very different T-dependences of the ppI, ppII, and ppIII cycles became a critical attribute of the standard solar model (SSM)

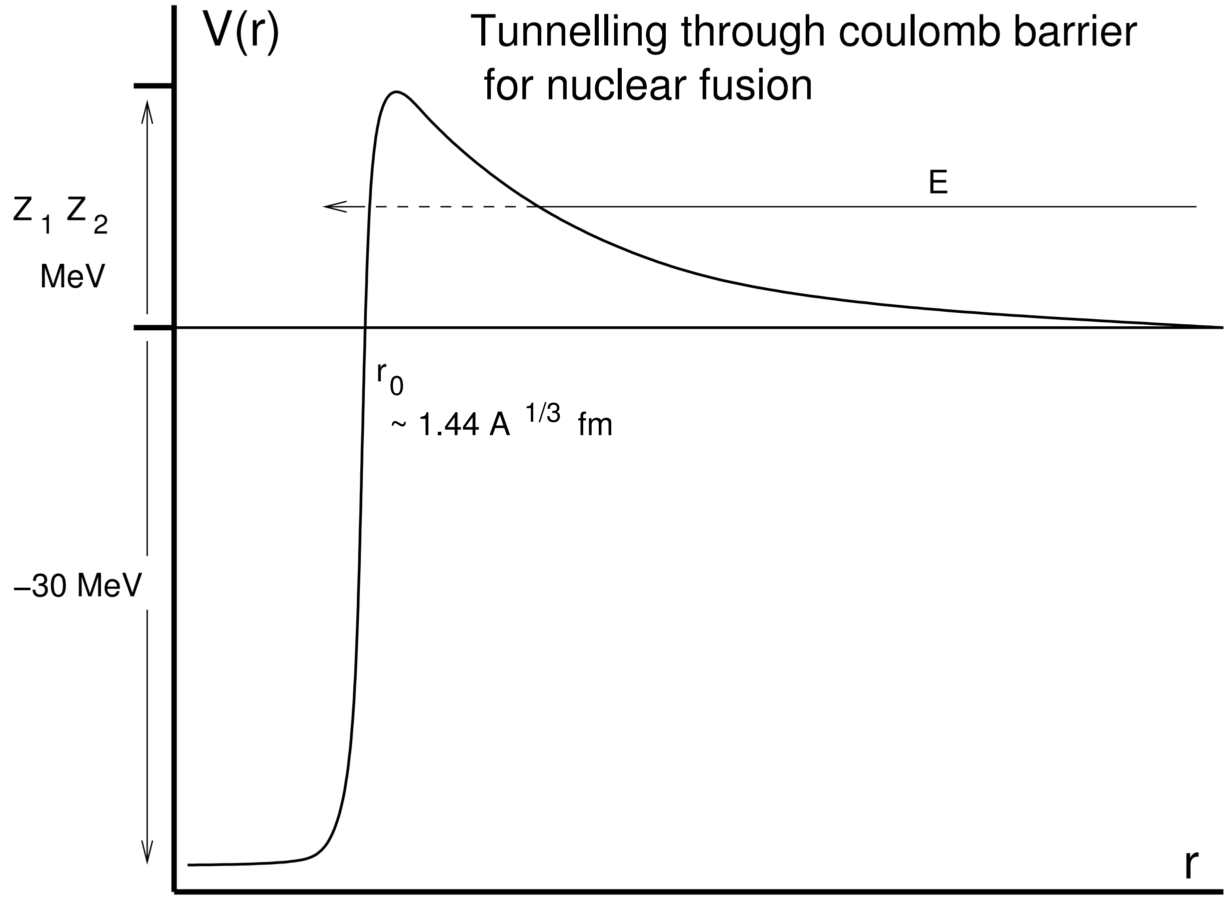
- 1962: a quantitative model of the Sun, capable of predicting T_{core} at the % level -- would be needed to predict the Cl counting rate
  - ◇ Willy Fowler brought Iben, Sears, Bahcall together at Caltech to build such a model, and to make the first flux predictions

- For the next 40 years: neutrino fluxes became a tool to
  - ◇ determine T_{core} at 1%, and thus precisely test the SSM
  - ◇ look for deviations for the SSM T-dependence, as a signature of new physics

The most difficult challenge in the SSM is the solar microphysics

- The solar fusion reactor is a cold one, producing the required energy only because of the core's enormous mass
  - ◇ the rate of energy production, averaged over the solar core, is ~ 15 W/m^3 -- comparable to a bike light

- Most pp-chain cross sections needed at energies where they cannot be directly measured



$$r = \frac{N_1 N_2}{1+\delta_{12}} \int d\vec{v}_1 d\vec{v}_2 \left(\frac{m_1}{2\pi kT}\right)^{3/2} e^{-\frac{m_1 v_1^2}{2kT}} \left(\frac{m_2}{2\pi kT}\right)^{3/2} e^{-\frac{m_2 v_2^2}{2kT}} \sigma_{12}(|\vec{v}_1 - \vec{v}_2|)|(\vec{v}_1 - \vec{v}_2|)$$

$$= \frac{N_1 N_2}{1+\delta_{12}} \left(\frac{\mu}{2\pi kT}\right)^{3/2} \int d\vec{v} e^{-\mu v^2/2kT} \sigma_{12}(v) v$$

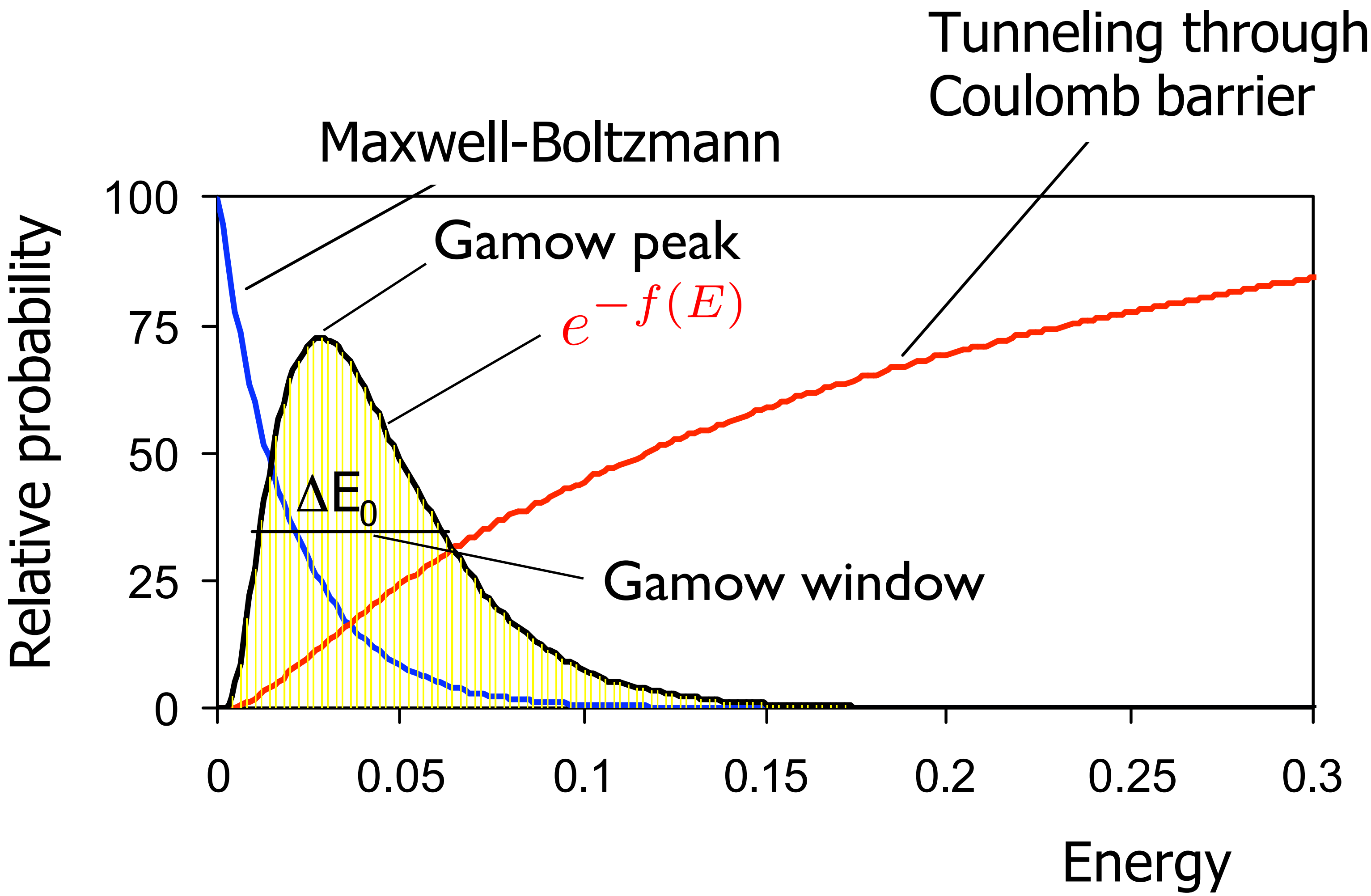
(The relative velocity distribution in a Maxwellian gas is a Maxwell distribution in the reduced mass)

$$= \frac{N_1 N_2}{1+\delta_{12}} \sqrt{\frac{8}{\pi\mu}} \left(\frac{1}{kT}\right)^{3/2} \int_0^\infty E dE e^{-E/kT} \sigma_{12}(E)$$

Remove the rapidly varying point-charge s-wave Coulomb behavior

$$\sigma_{12}(E) \equiv \frac{1}{E} e^{-2\pi\alpha Z_1 Z_2 \sqrt{\mu/2E}} S(E) \Rightarrow$$

$$r = \frac{N_1 N_2}{1+\delta_{12}} \sqrt{\frac{8}{\pi\mu}} \left(\frac{1}{kT}\right)^{3/2} \int_0^\infty dE \underbrace{e^{-(E/kT + 2\pi\alpha Z_1 Z_2 \sqrt{\mu/2E})}}_{\equiv f(E)} S(E)$$



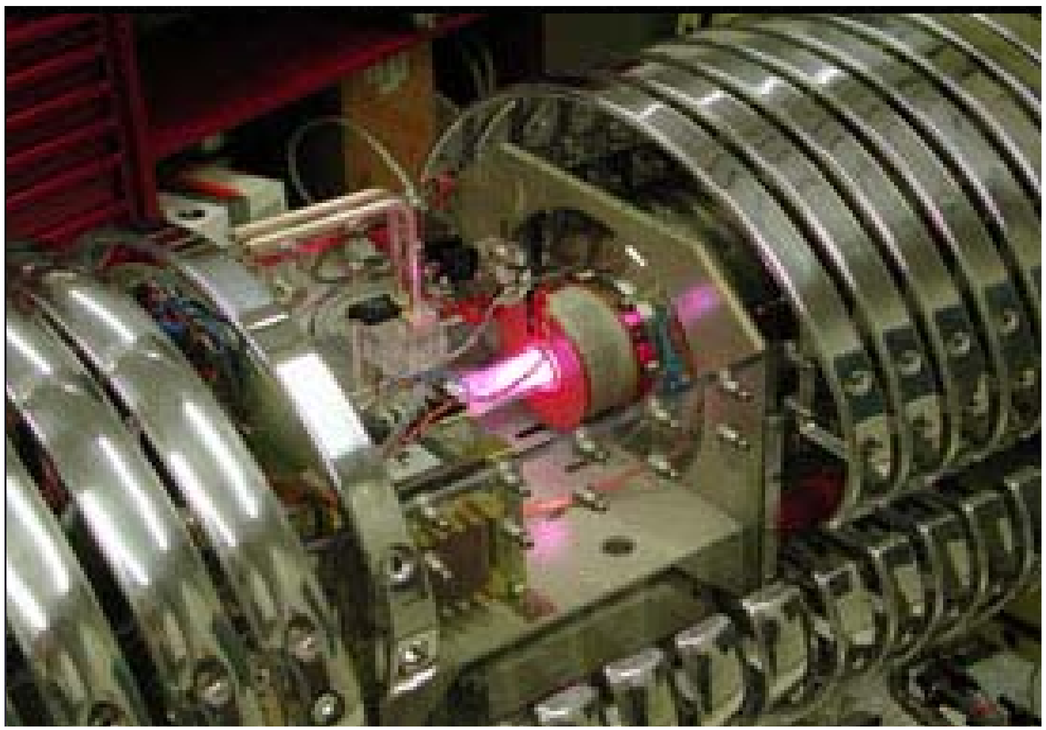
$$f(E) = f(E_0) + \cancel{f'(E_0)(E - E_0)} + \frac{1}{2} f''(E_0)(E - E_0)^2 + \ldots$$

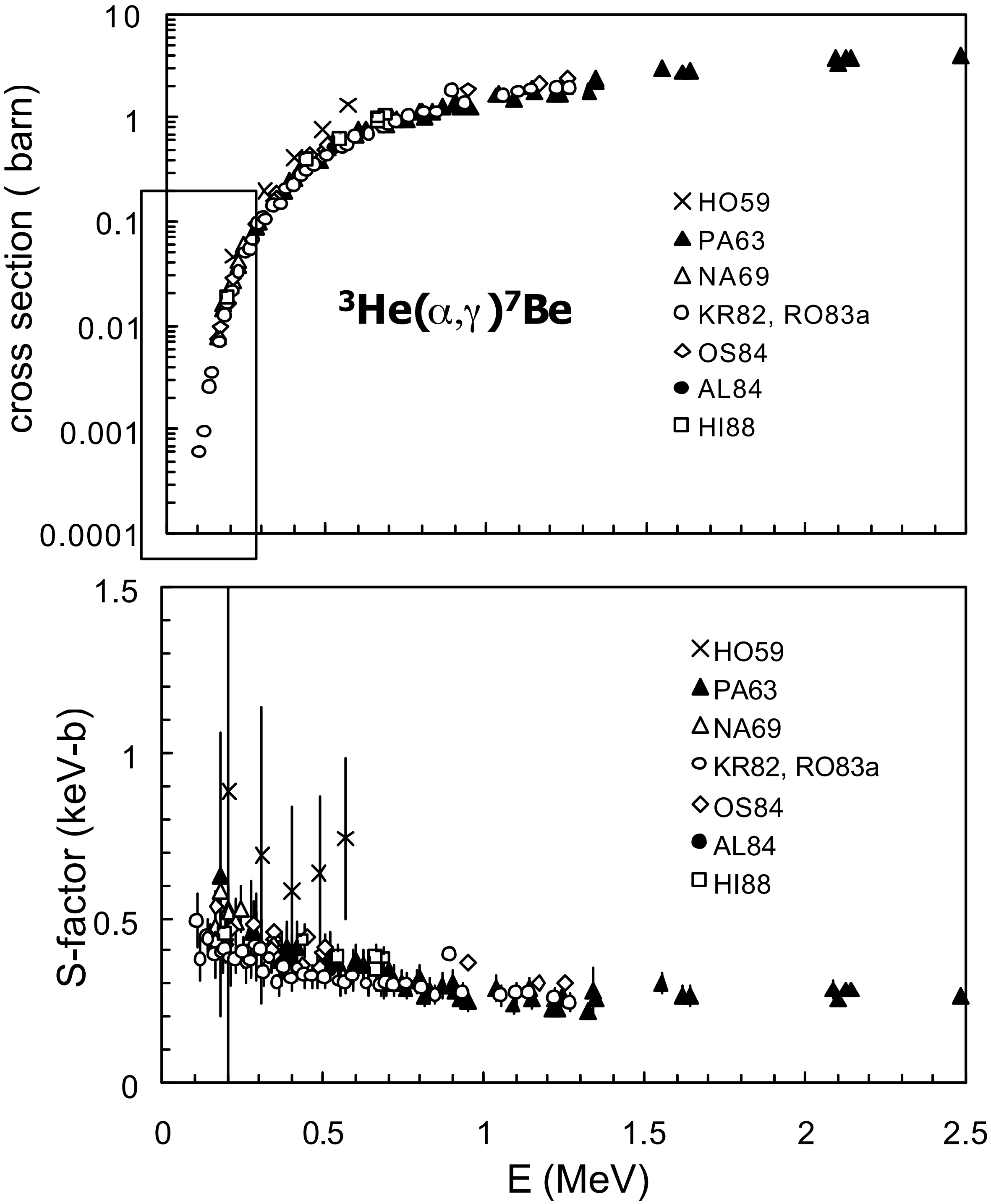
$$\text{Gamow energy}: \frac{E_0}{kT} = \left(\frac{\pi\alpha Z_1 Z_2}{\sqrt{2}}\right)^{2/3} \left(\frac{\mu c^2}{kT}\right)^{1/3}$$

$$\boxed{r = \frac{N_1 N_2}{1+\delta_{12}} (7.2 \cdot 10^{-19} \mathrm{cm}^3/\mathrm{s}) \frac{A_1 + A_2}{A_1 A_2 Z_1 Z_2} \frac{S(E_0)}{\mathrm{keV\ b}} e^{-3E_0/kT} \left(\frac{3E_0}{kT}\right)^2}$$

Solar modeler: the ion number densities N_i(r) and T(r)

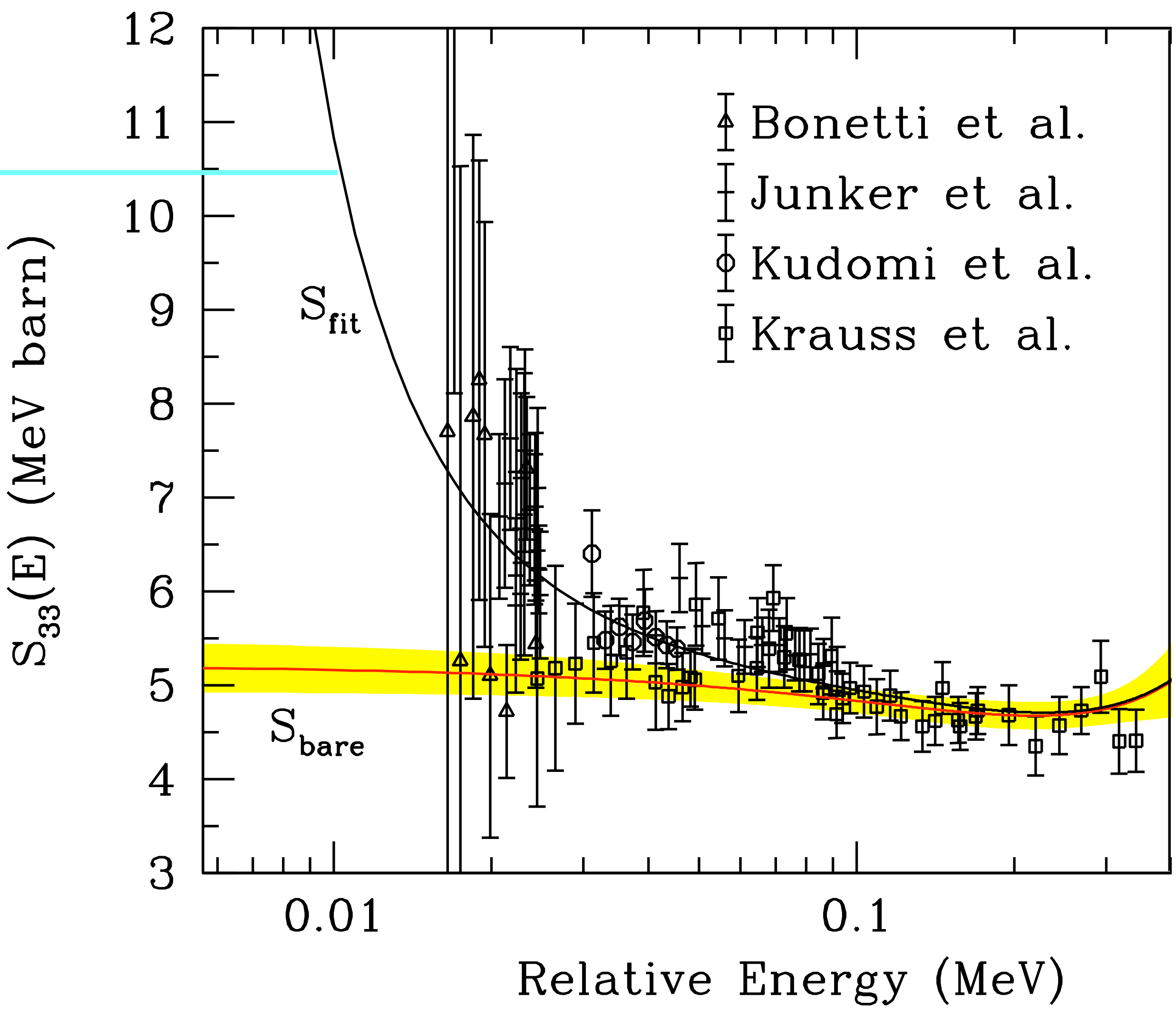
Lab nuclear astrophysicist: $S(E_0)$





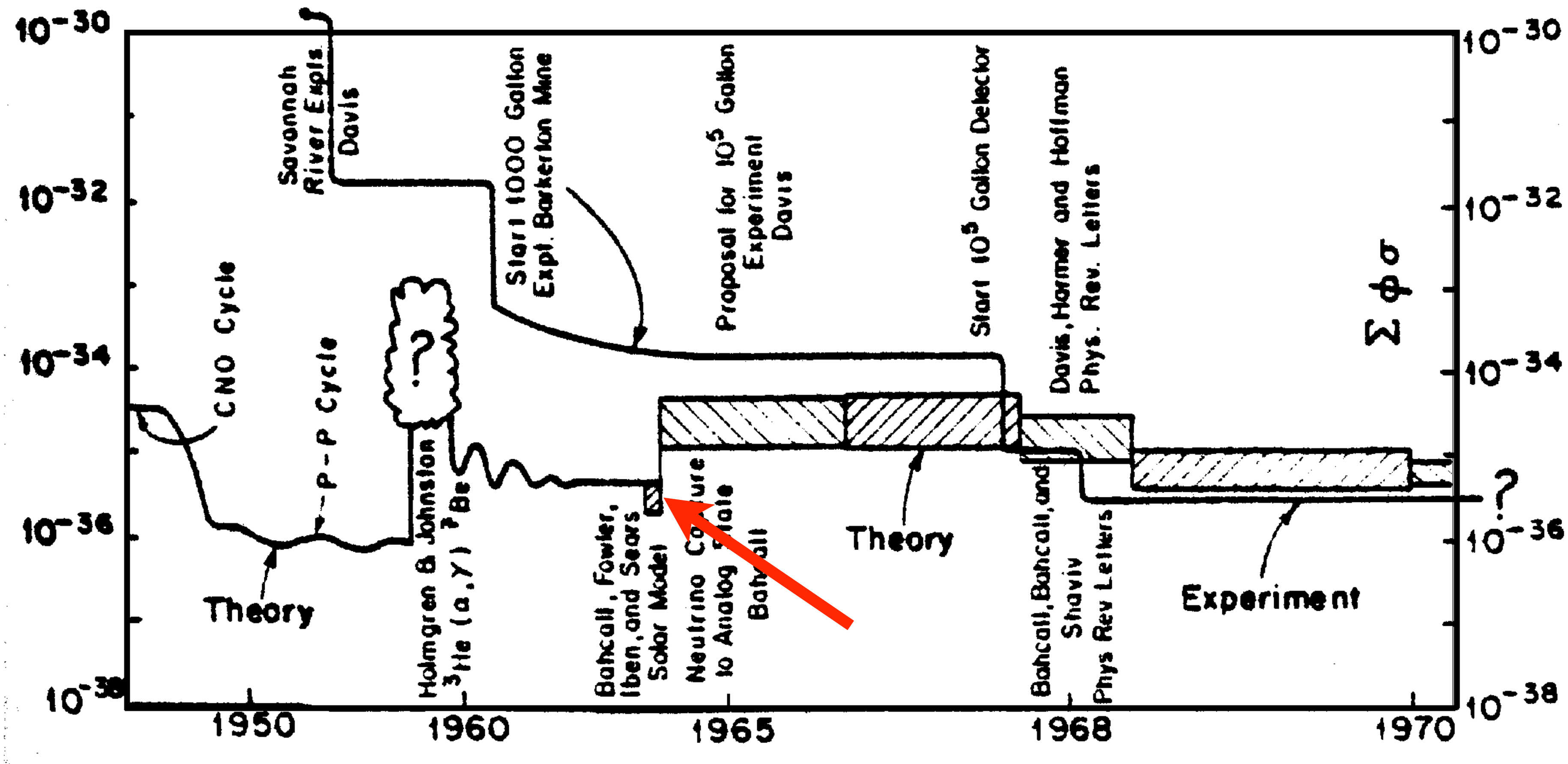
HJ cross section again, showing the advantages of the S-factor:

much easier extrapolation to solar energies ~ 0.02 MeV theory tells us the form of the screening potential, but not the value of the low-energy parameter (the adiabatic screening potential)



Modern LUNA measurement of S(3He+3He) down to Gamow energy of 16 keV: Even then a nontrivial problem remains, correcting the terrestrial cross section for screening, to obtain bare ion S

Early days: Caltech's Bahcall, Iben, and Sears in summer 1962 developed a model to estimate the central temperature of the sun -- despite large uncertainties, ppIII cycle was not dominant



Davis's sketch: the Cl experiment's "reach" vs solar model predictions

Cl detector cross section (the second detail)

- Most neutrino detection experiments involve nuclear targets

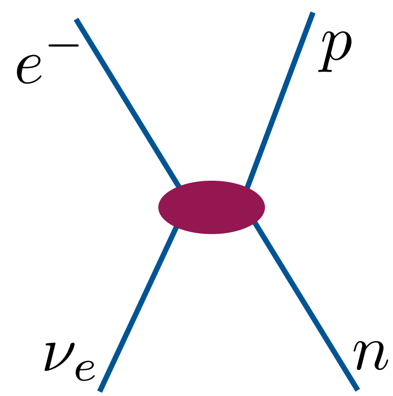
- Precise experiments require a precise understanding of the nuclear response, which is seldom simple

threshold ➙ quasielastic ➙ resonance production ➙ deep inelastic

- With solar neutrinos, one is better positioned than in most other cases (e.g., compared to the LB program today)

$$\frac{p^2}{M^2} \sim 0.01$$

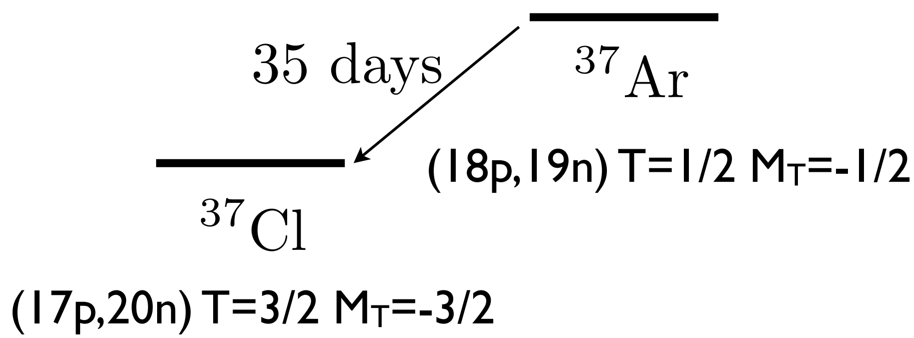
$$(qR)^2 \sim \left(\frac{10\ \mathrm{MeV}\ \ 1.2A^{1/3} f}{197\ \mathrm{MeV}\ \ f}\right)^2 < 0.01$$



so the only operators that can be constructed are extensive: $\vec{\sigma}, \tau_\pm$

$$\sigma \sim G_F^2 \cos\theta_c{}^2 \left[g_A^2 |\langle J_f || \sum_{i=1}^{A} \sigma(i)\tau_+(i) || J_i \rangle|^2 + |\langle J_f || \sum_{i=1}^{A} \tau_+(i) || J_i \rangle|^2 \right]$$

What Bahcall and Davis knew - what they based their ν absorption cross section on - was



$$e^-_{1s} + {}^{37}\mathrm{Ar} \to {}^{37}\mathrm{Cl} + \nu_e$$

Summer 63 @ Bahcall seminar at the Niels Bohr Institute, Mottelson asked "what about the excited states [in Ar]?"

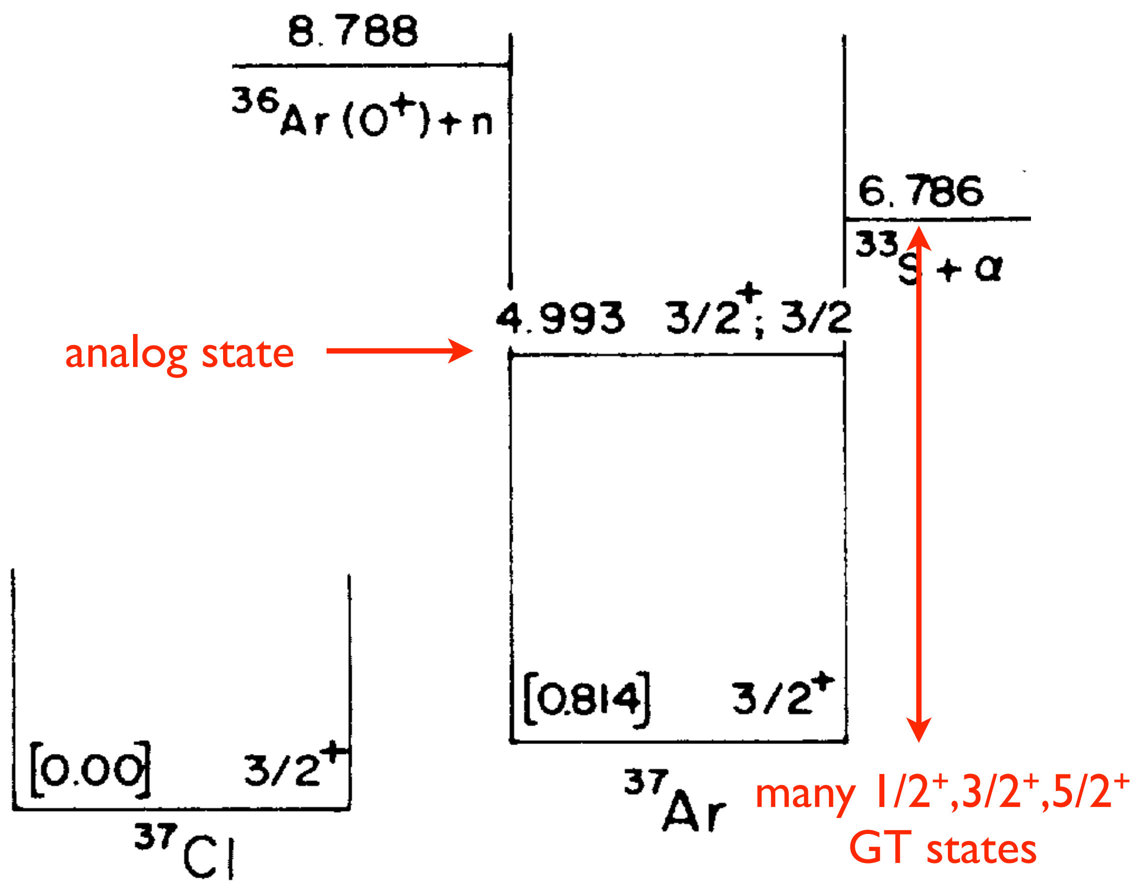
$$\sum_f |\langle J_f || \sum_{i=1}^{A} \tau_+(i) || J_i \rangle|^2 \sim |\langle J_i T_i = 3/2 M_{T_f} = -1/2 || T_+ || J_i T_i = 3/2 M_{T_i} = -3/2 \rangle|^2 \sim (N-Z)$$

$$\sum_f |\langle J_f T_f M_{T_f} = -1/2 || \sum_{i=1}^{A} \sigma(i)\tau_+(i) || J_i T_i = 3/2 M_{T_i} = -3/2 \rangle|^2 \sim 3(N-Z)$$

Isospin a good approximate symmetry in nuclei, broken at the few % level by Coulomb effects, pion mass (current quark mass) differences, etc.

Bahcall built a model, of the F and GT transitions, found a cross section 20 times larger than before

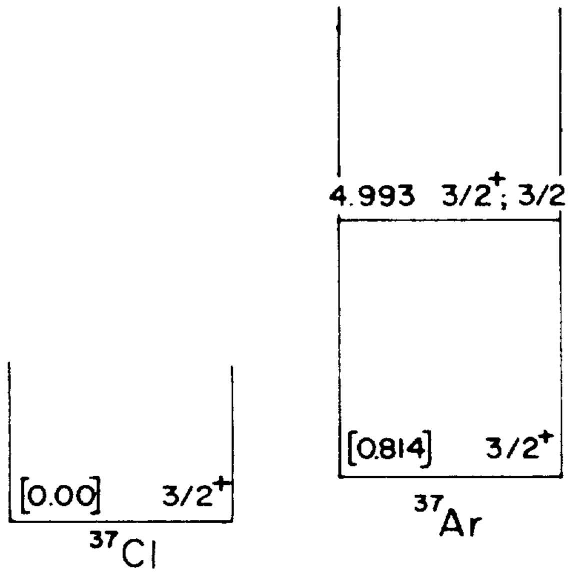
A 100,000-gallon, deep Cl experiment might see solar νs

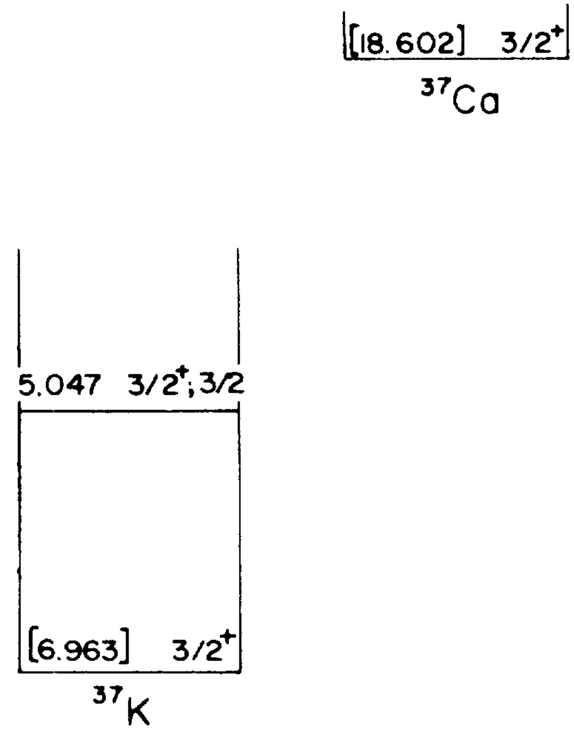


JNB recognized that there was an experimental test of the predicted cross section increase, the isospin mirror decay

$$^{37}\mathrm{Ca}(20p, 17n) \rightarrow {}^{37}\mathrm{K}(19p, 18n) + e^+ + \nu_e$$

$$\nu_e + {}^{37}\mathrm{Cl} \rightarrow e^- + {}^{37}\mathrm{Ar}$$





$$ {}^{37}\mathrm{Ca} \rightarrow e^+ + \nu_e + {}^{37}\mathrm{K}$$

(N,Z): (20,17) ⇨ (19,18) (18,19) ⇦ (17,20)

isospin invariance:

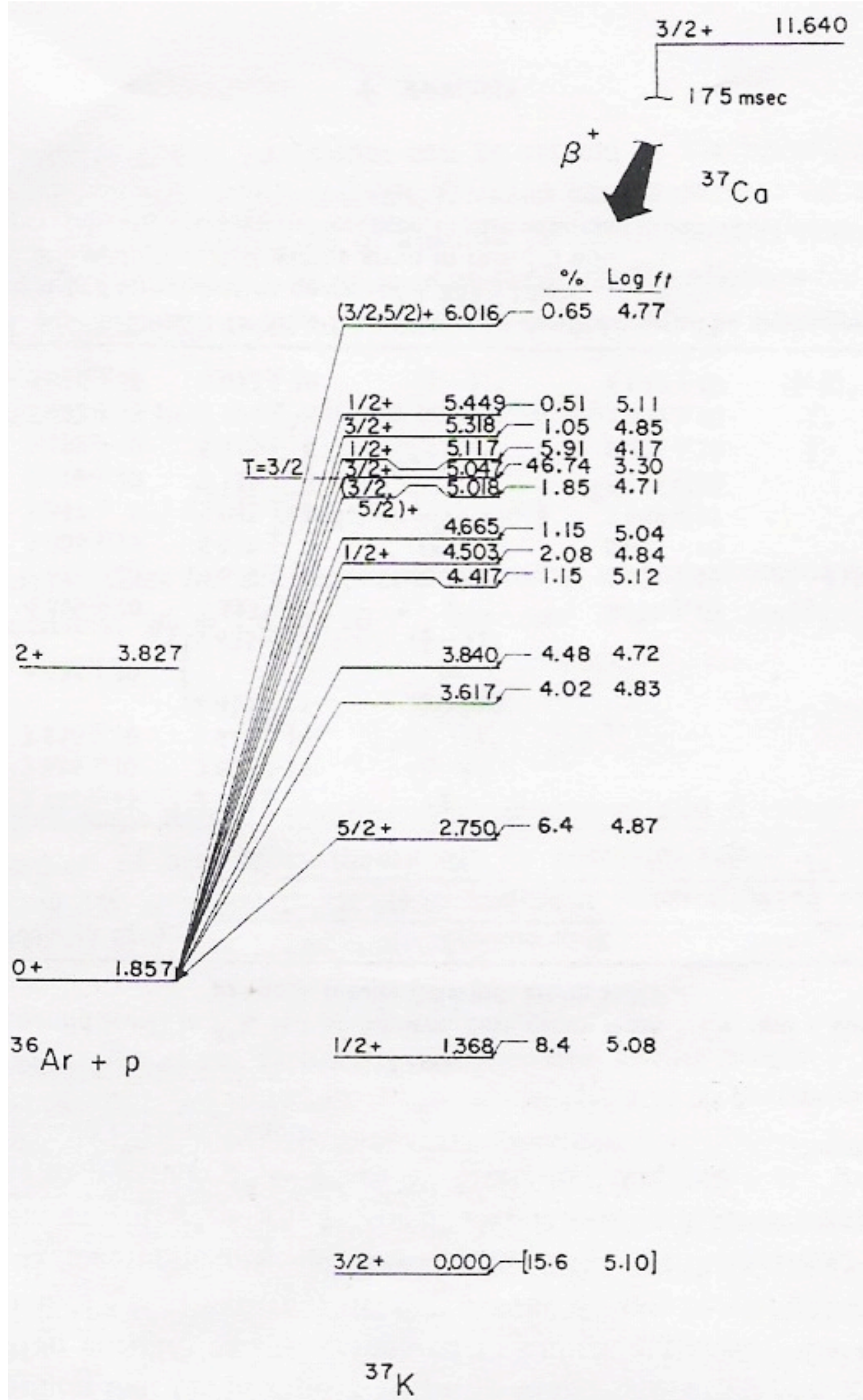
Ca beta decay tests same weak rates that govern neutrino absorption in Cl

- $^{37}\mathrm{Ca}$ was produced and found to decay rapidly

- strong, nuclear-physics-independent Fermi transition meant that the Cl experiment would be primarily sensitive to $^{8}\mathrm{B}\ \nu s\ (\propto T^{22})$

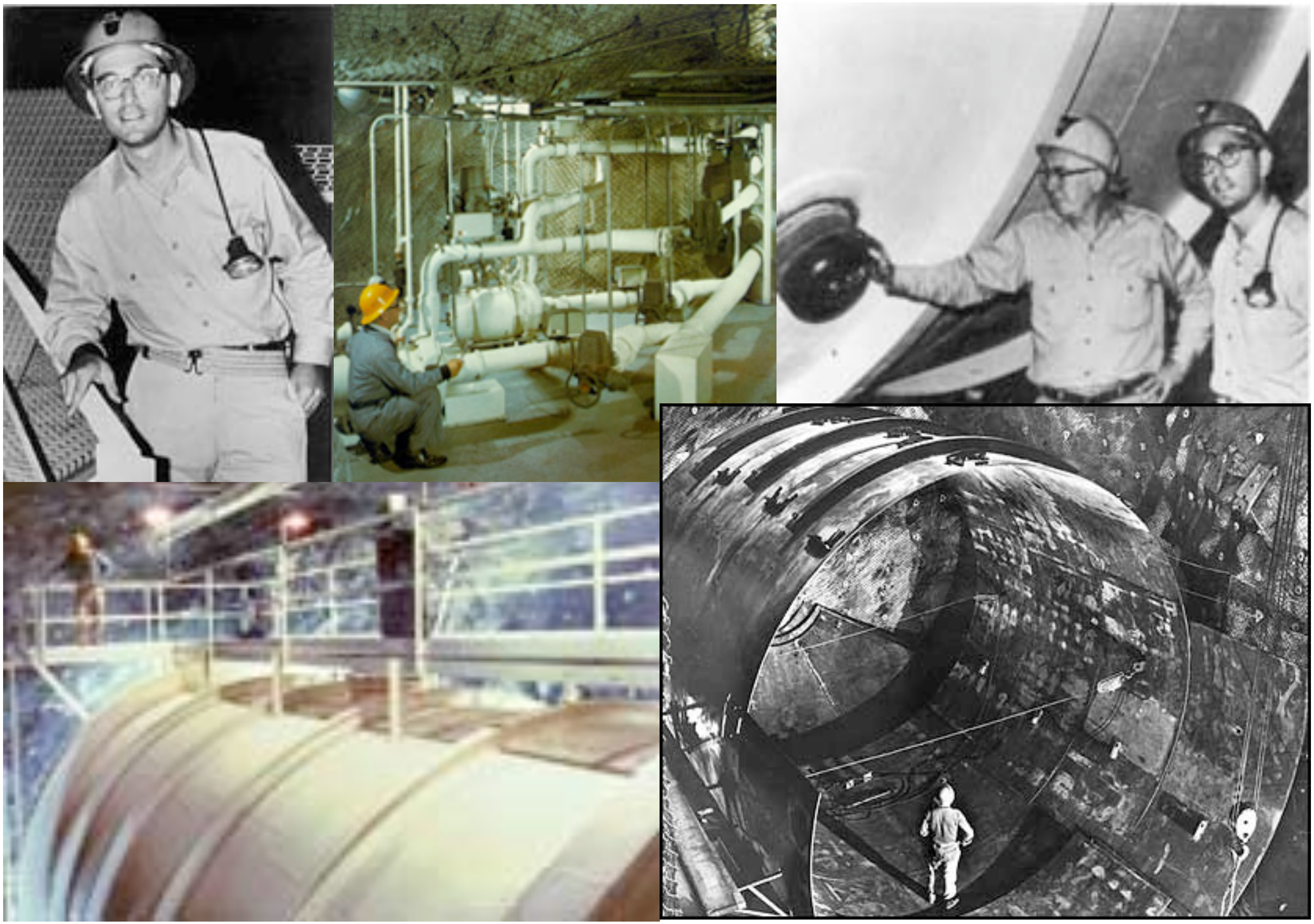
- the mirror isospin symmetry was further exploited to measure the full set of nuclear-physics-dependent GT transitions

- for two decades errors in the analysis of this experiment went undiscovered -- errors that fortunately largely cancelled



The order-of-magnitude increase in the capture cross section changed perceptions about the feasibility of the Cl experiment

- Davis and Bahcall companion papers in PRL, March 1964, arguing the feasibility and adequacy of a 100,000g detector
- SSM developments coupled with measurements of the key pp chain S-factors
- The excavation of the Homestake cavity in summer 1965, the completion and filling of the tank a year later
- The announcement of first results by Davis, Harmer, Hoffman -- a bound on the neutrino flux of about 1/3 SSM
- The observation by a miner that summer '68 had been cloudy, and Davis should not give up!



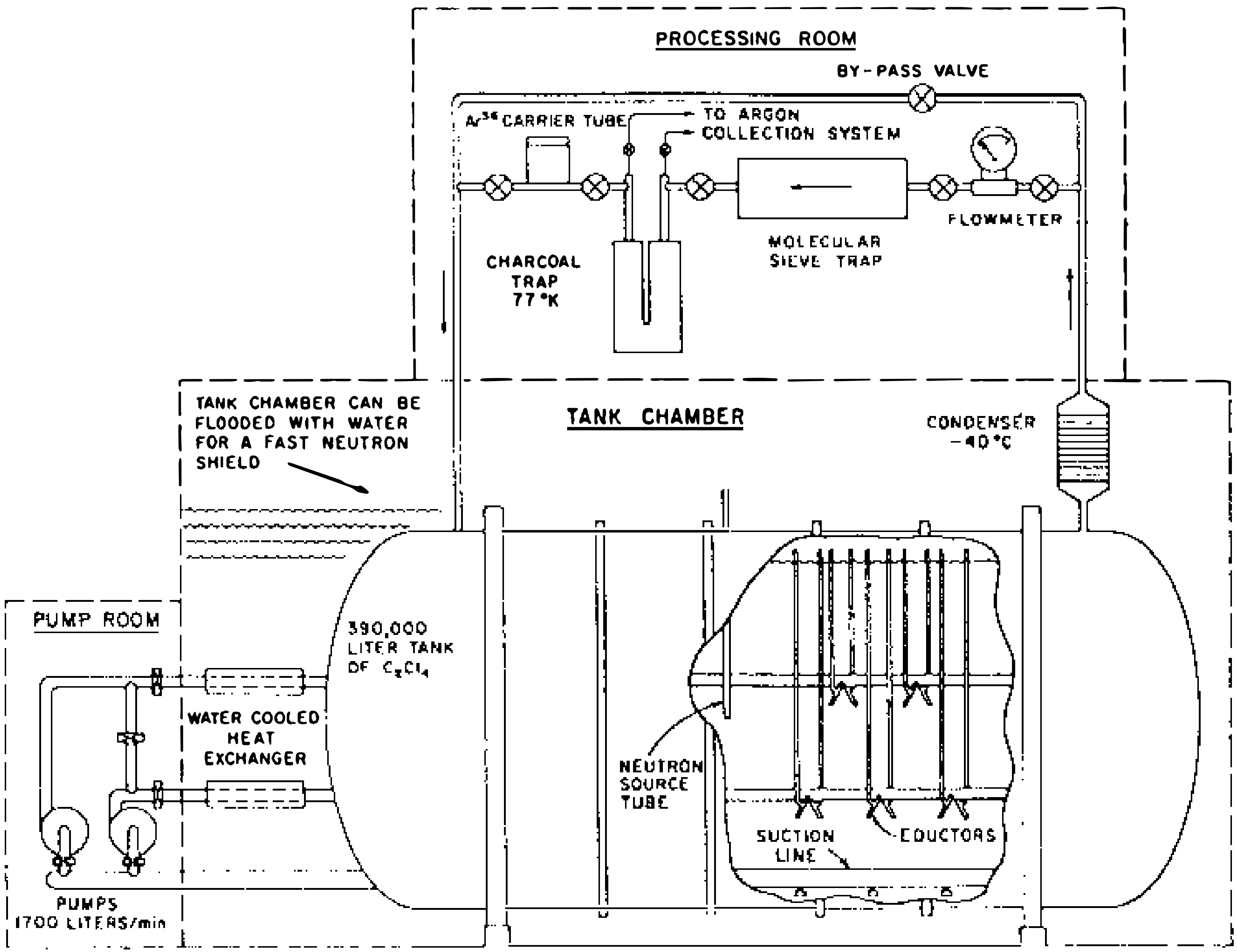


Figure 7 The Homestake ^{37}Cl solar neutrino experiment. This schematic is from the Davis, Harmer & Hoffman (1968) paper reporting the first results from their experiment.

How did Davis measure the few Ar atoms he extracted?

$$e^-_{1s} + {}^{37}\mathrm{Ar(g.s.)} \to {}^{37}\mathrm{Cl(g.s.)} + \nu_e$$

The EC produces a 1s-electron hole in the atomic cloud of Ar, while the nuclear charge is suddenly changed from 18 to 17

Total atomic rearrangement energy ~ 3 keV

Davis developed miniaturized gas proportional counters to measure the energy deposited by the 2.62 keV Auger electrons, with a range of about 0.02 mm

30-year rate: 2.56 ± 0.16 ± 0.16 SNU

SSM prediction: 8.1 ± 1.3 SNU (SNU = captures/10^{36} atoms/s)

The Standard Solar Model

- One-dimensional integration that begins at zero-age, with an assumed initial composition, and integrated to today, 4.6 b.y. later

- Designed to reproduce properties of the core and radiative interior, not the more complicated physics of the convective zone

- In addition to its physical approximations, the model depends on some 19 parameters that must be supplied, along with their assigned uncertainties: pp chain (99%) and CN cycle (1%) cross sections, key metallicities (C, N, O, Ne, Mg, Si, S, Ar, Fe), the luminosity, opacity, age, and diffusion coefficient

- The metal abundances (A>5) are determined from a combination of meteoritic (refractory) and photospheric (volatile) data; the mass fraction in metals is Z

Fixing the zero-age composition

- Standard picture of pre-solar contraction, evolution
  - ◇ sun forms from a primordial gas cloud: pre-ZAMS Hayashi phase: cool, highly opaque, large internal temperature gradients, slowly contracting -- conditions where transport is convective
  - ◇ radiative transport becomes more efficient at star's center: radiative core grows, convection dominates a surface envelope, core and surface no longer mix -- Henyey phase
  - ◇ ZAMS: thermonuclear energy generation compensates emissions

- The SSM assumes that the Hayashi phase fully mixes the sun and thus that the radiative and convective zones will be chemically identical
  - ◇ as H+He+Z=1, two conditions needed to fix ZAMS composition
  - ◇ Z fixed to contemporary abundances: volatile elements from photospheric absorption lines; others from meteoritic abundances, assumed representative the primordial gas
  - ◇ H/He fixed by condition that luminosity reproduced at 4.6 b.y.

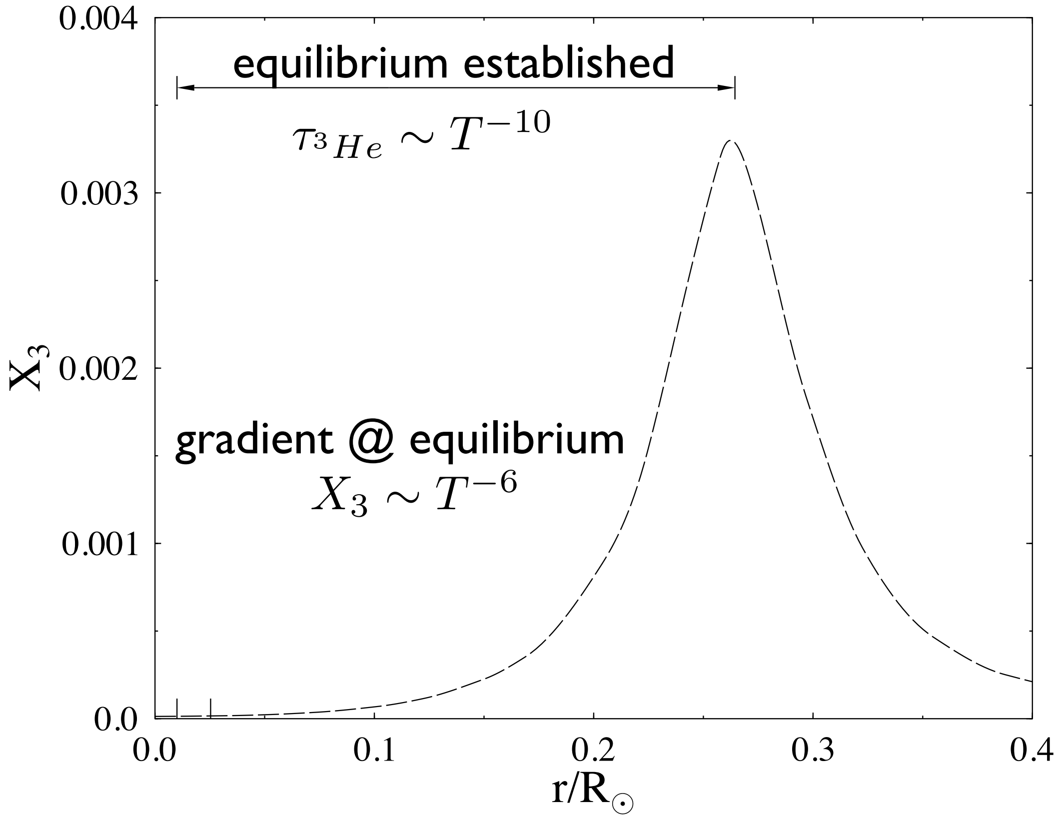
Model attributes:

- dynamic sun: 44% luminosity growth over 4.6 b.y.
  - ◇ an interesting issue for paleo-climatic modeling

- significant high-energy neutrino luminosity is recent
  - ◇ $\phi(^8\mathrm{B}) \sim \phi_0 e^{-\tau/\tau_0}, \qquad \tau_0 \sim 0.9 b.y.$

- apart from diffusion, *induced* chemical gradients assumed static

most interesting is ^{3}He
a fuel that in principle
could drive convection
(solar spoon, etc.):
relevant to recent work
on convection in
3D red giant simulations



- origin of the diffusion is the local electric fields that are microscopically the mechanism by which hydrostatic equilibrium is maintained
  - ◇ thus elements with larger A/Z ratios will tend to settle
  - ◇ this effect alters local sound speed at a level that affects helioseismology

- chemistry of the core adjusts at the onset of nuclear burning
  - ◇ inherits C, N abundances from primordial gas cloud
  - ◇ lifetime of $^{12}\mathrm{C}$ -- determined by rate for $^{12}\mathrm{C}(p,\gamma)$ for an initial core temperature of $T \sim 1.34 \cdot 10^7 K$ -- is about $2 \cdot 10^7$ y
  - ◇ thus burning of C to N in initial Sun is complete and rapid
  - ◇ creates a temperature gradient sufficient to drive convection in the core over this time

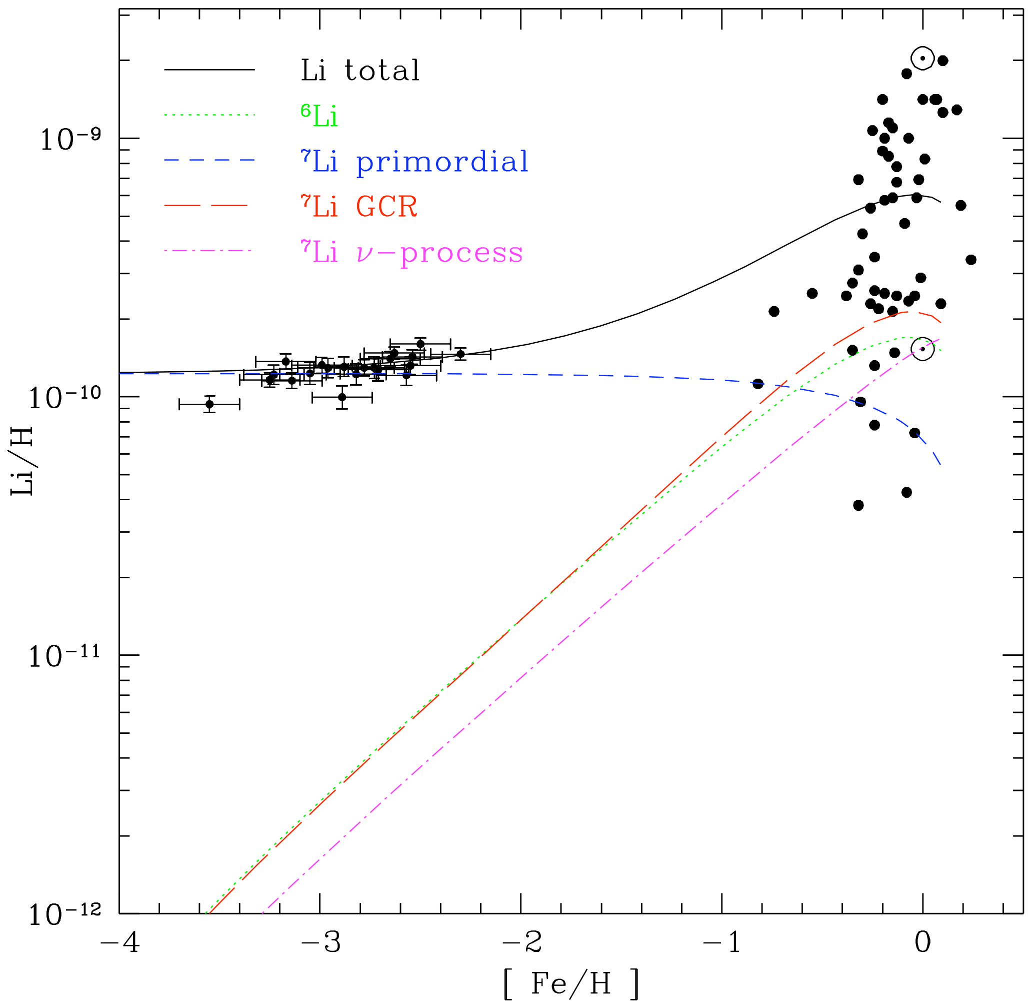
Some of the successes:

- resulting ^{4}He abundance near surface (0.247) in excellent agreement with value determined from helioseismology (0.242)

- depth of the convective zone consistent with acoustic mode eigenfrequencies

And some properties not explained

- surface Li is significantly depleted, but SSM does not transport Li to a depth where it could be burned



← expected solar

← observed solar surface

Model tests:

- Solar neutrinos: direct measure of core temperature to ~ 1%

- Helioseismology: inversions map out the local sound speed
  - ◇ prior to 2000, the SSM - helioseismology concordance was considered a significant confirmation on the model
  - ◇ acoustic modes sensitive to the depth of the convective zone and surface He abundance

Solar neutrino tests: basically probes SSM 1) nuclear cross sections; 2) core temperature; 3) temperature profile

$$p + p \rightarrow {}^{2}H + e^{+} + \boxed{\nu_e} \qquad p + e^{-} + p \rightarrow {}^{2}H + \nu_e$$

99.76% 0.24%

$${}^{2}H + p \rightarrow {}^{3}He + \gamma$$

83.2% 16.7%

$${}^{3}He + {}^{3}He \rightarrow {}^{4}He + 2p \qquad {}^{3}He + {}^{4}He \rightarrow {}^{7}Be + \gamma$$

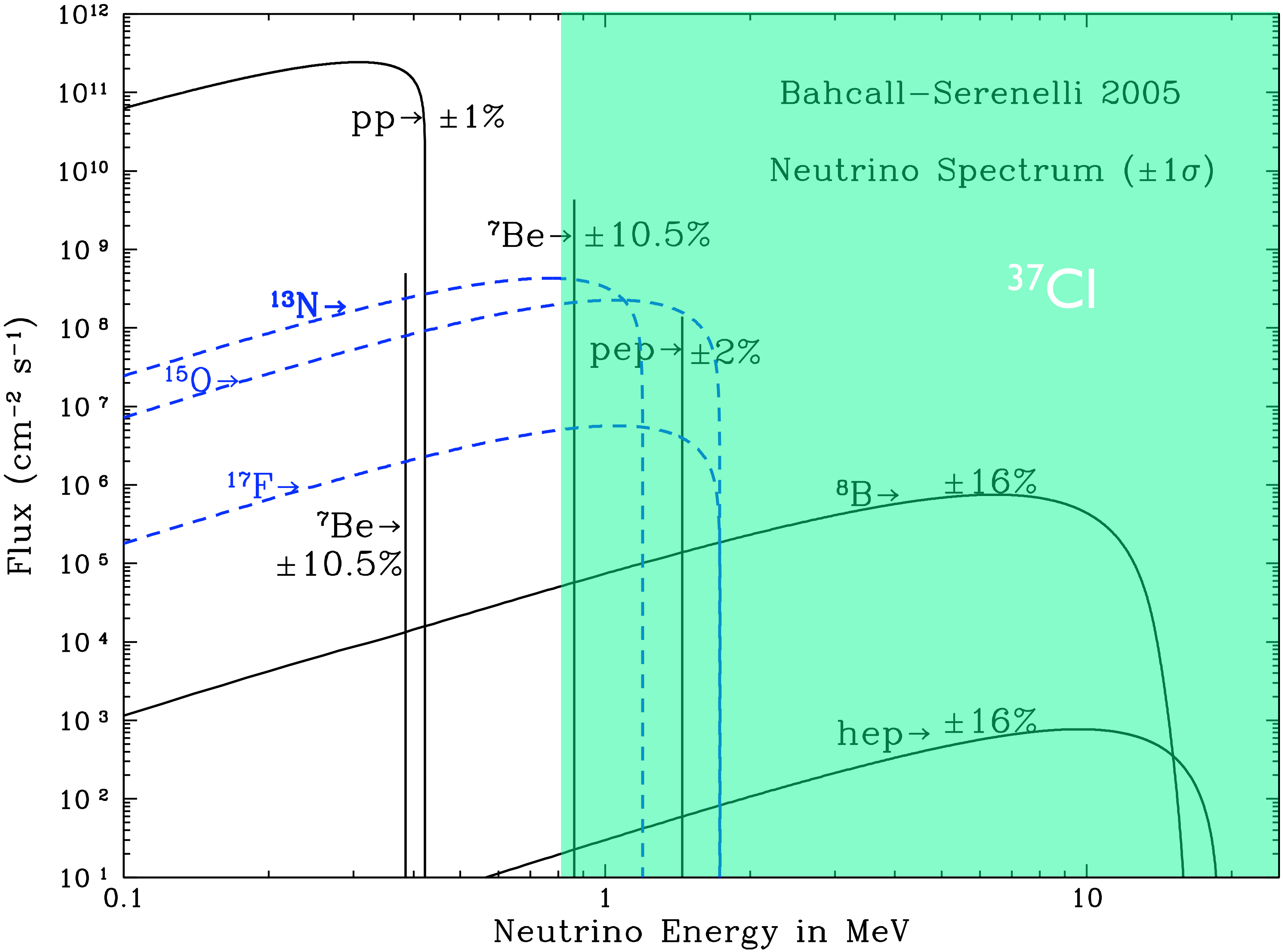
99.88% 0.12%

$${}^{7}Be + e^{-} \rightarrow {}^{7}Li + \boxed{\nu_e} \qquad {}^{7}Be + p \rightarrow {}^{8}B + \gamma$$

$${}^{7}Li + p \rightarrow 2\,{}^{4}He \qquad {}^{8}B \rightarrow {}^{8}Be^{*} + e^{+} + \boxed{\nu_e}$$

ppI ppII ppIII

a neutrino source tags each cycle


Bahcall−Serenelli 2005
Neutrino Spectrum (±1σ)
pp→ ±1%
⁷Be→ ±10.5%
³⁷Cl
¹³N→
¹⁵O→
pep→ ±2%
¹⁷F→
⁷Be→
±10.5%
⁸B→ ±16%
hep→ ±16%
Flux (cm⁻² s⁻¹)
Neutrino Energy in MeV
10¹²
10¹¹
10¹⁰
10⁹
10⁸
10⁷
10⁶
10⁵
10⁴
10³
10²
10¹
0.1
1
10

- Under the assumption that the SSM burns in equilibrium, the neutrino flux and surface luminosity are coupled -- despite the Sun's Kelvin time of about 10^6 years: the luminosity is then a SSM constraint

- Allows one to calculate, for example, the pp flux in a pure ppI Sun

$$2\left[\frac{2.4 \cdot 10^{39}\ \mathrm{MeV/s}}{25\ \mathrm{MeV}\ 4\pi(1.5 \cdot 10^{13}\ \mathrm{cm})^2}\right] \sim 6.8 \cdot 10^{10}/\mathrm{cm}^2\mathrm{s}$$

  which compares to the SSM prediction of $6.06 \cdot 10^{10}\ /\mathrm{cm}^2\mathrm{s}$ [BS05(AGS,OP)]

- Davis's ^{8}B νs (about 80% of his counting rate) are quite different: they comprise only 0.01% of the flux and, were the solar core temperature reduced by 5%, can be effectively turned off

- There are SSM modifications that could accomplish this, e.g., a lowering of the core Z from ~0.02 to ~0.002 (and also nuclear solutions)

- Alternatively, there was the possibility of new physics: ν decay, oscillations, ...

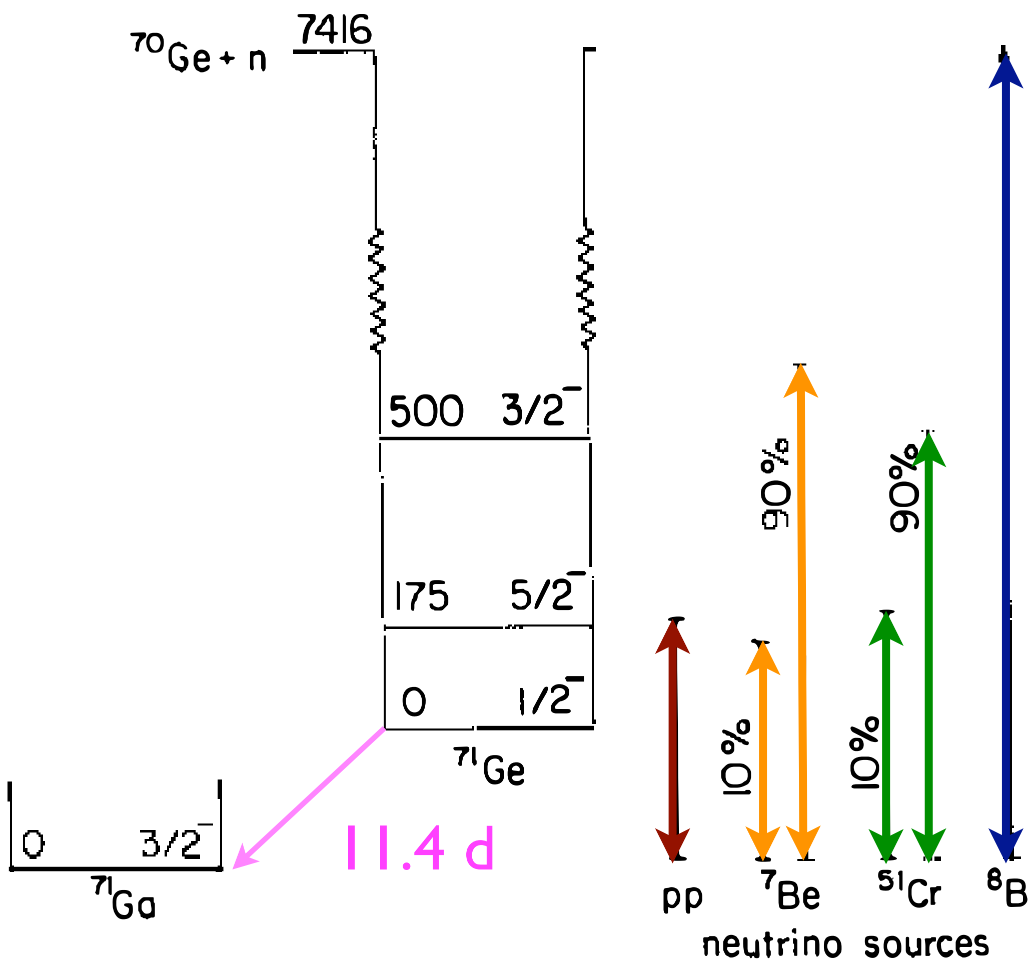
- New experiments: One possibility for distinguishing between SM and particle physics solutions was to measure additional fluxes: it was assumed that ν oscillations, for example, would affect all species

- Kuzmin (1966) suggested

$$\nu_e + {}^{71}\mathrm{Ga} \rightarrow {}^{71}\mathrm{Ge} + e^-$$

threshold of 233 keV

- Davis and collaborators developed the chemistry for extracting Ge from both metal and acid solutions, mounted a BNL pilot exp.



Gallex/GNO experiment
Gran Sasso Laboratory
$GaCl_2$ + HCl

SAGE experiment
Baksan Laboratory
Ga metal

- There is a "minimum astronomical value" for any steady-state solar model, obtained by generating all energy through the ppI cycle: 79 SNU

- Mitigating the more complicated chemistry was the possibility of calibrating the detector with a ~ megaCurie neutrino source
  - ◇ ^{51}Cr, ^{37}Ar calibration sources were produced, used

- There was US funding agency resistance to these experiments, due to the cost (~$50M) of the requisite Ga (>25 tons)

- First results for both experiments were reported in 1992

SAGE	$75 \pm 7 \pm 3$
GALLEX	$78 \pm 6 \pm 5$
GNO	$66 \pm 10 \pm 3$

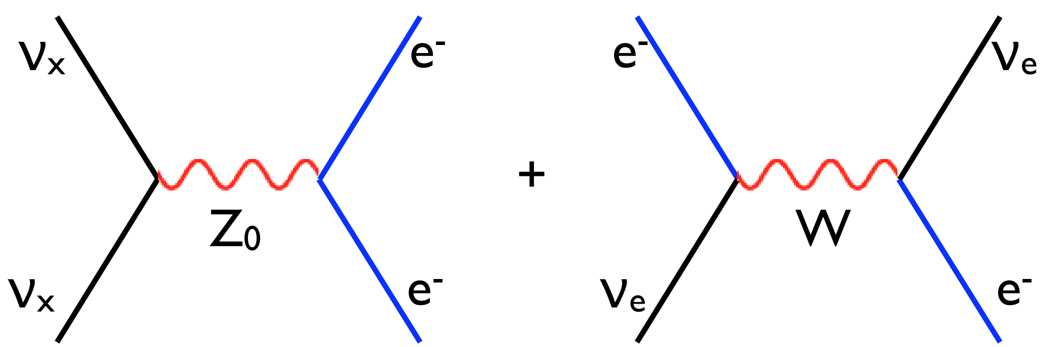
  or 50-60% of the SSM prediction but not inconsistent with the minimum astronomical value

Kamiokande II

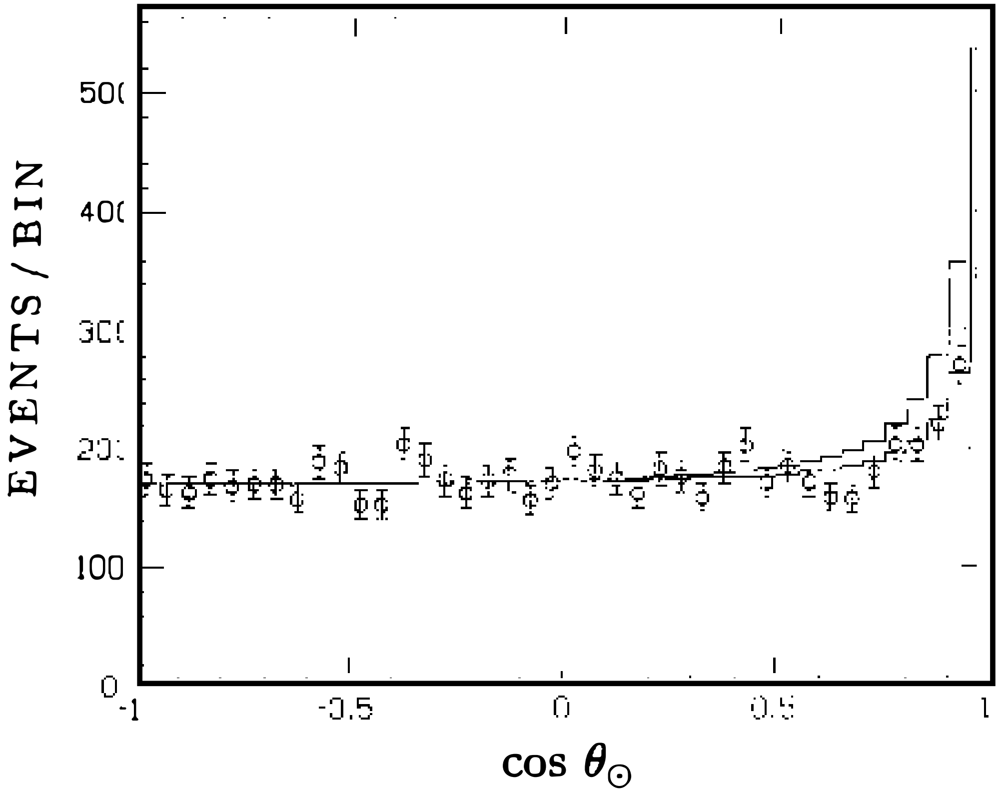
- 4.5 kton water Cerenkov detector constructed for proton decay: light produced by relativistic electrons recorded in surrounding phototubes

- modified to enable detection of low-energy electron recoils from 8B solar neutrino interactions: water purification system (radon), new electronics to improve timing, cavity expansion and installation of an outer detector

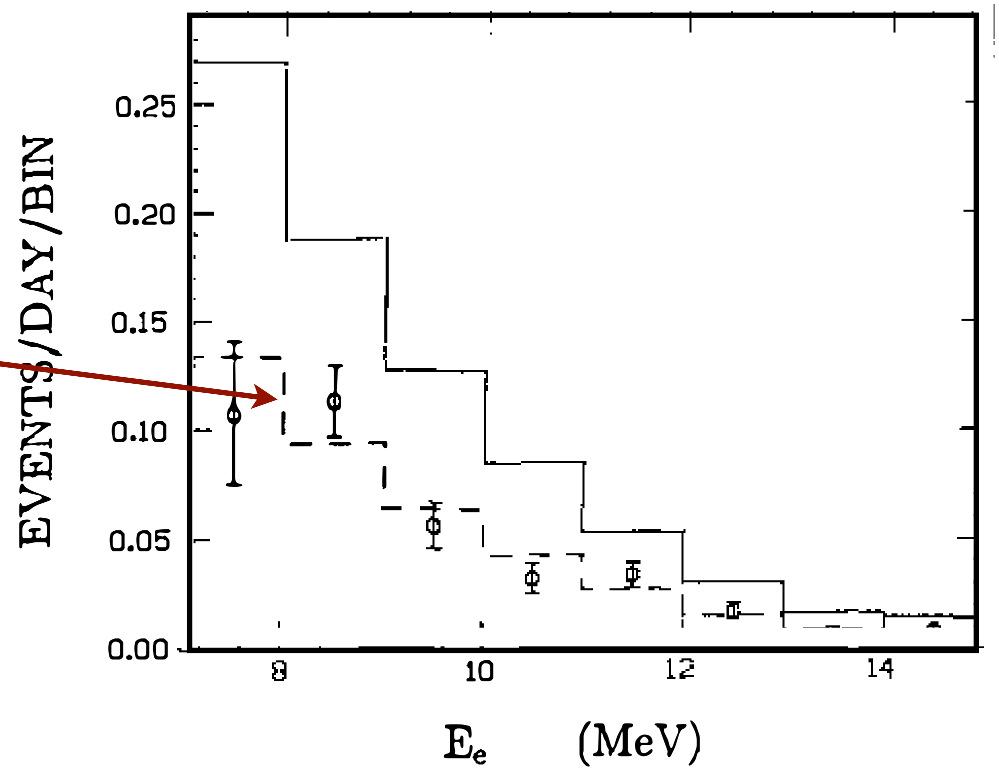
- Kamiokande II began taking data in 1985: electrons scattered into a forward cone with a width that is largely governed by the angular resolution of the detector



$$\Rightarrow \quad \sigma(\nu_{\text{heavy flavor}}) \sim \frac{1}{7}\sigma(\nu_e)$$

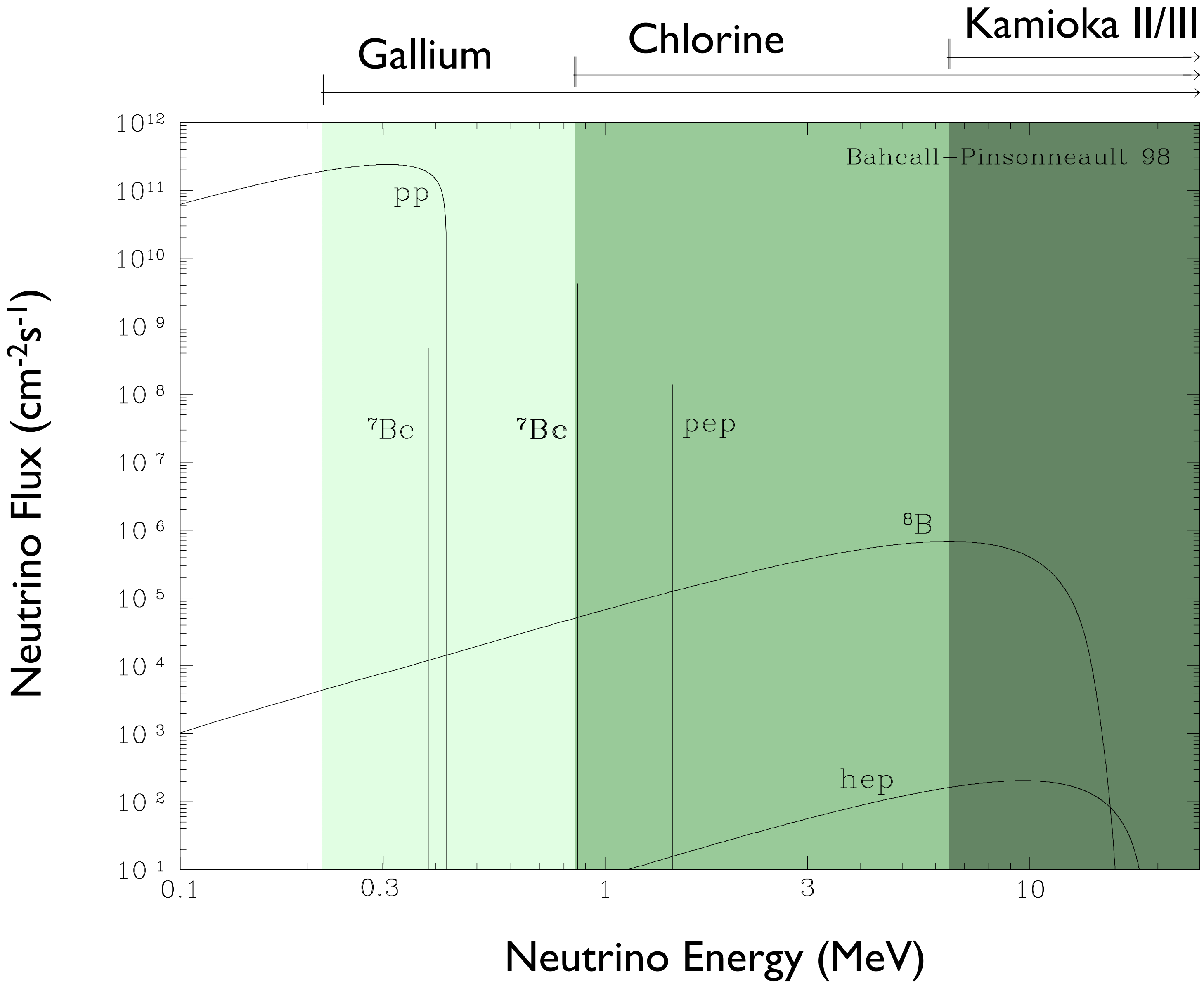


Signal correlated with Sun's position

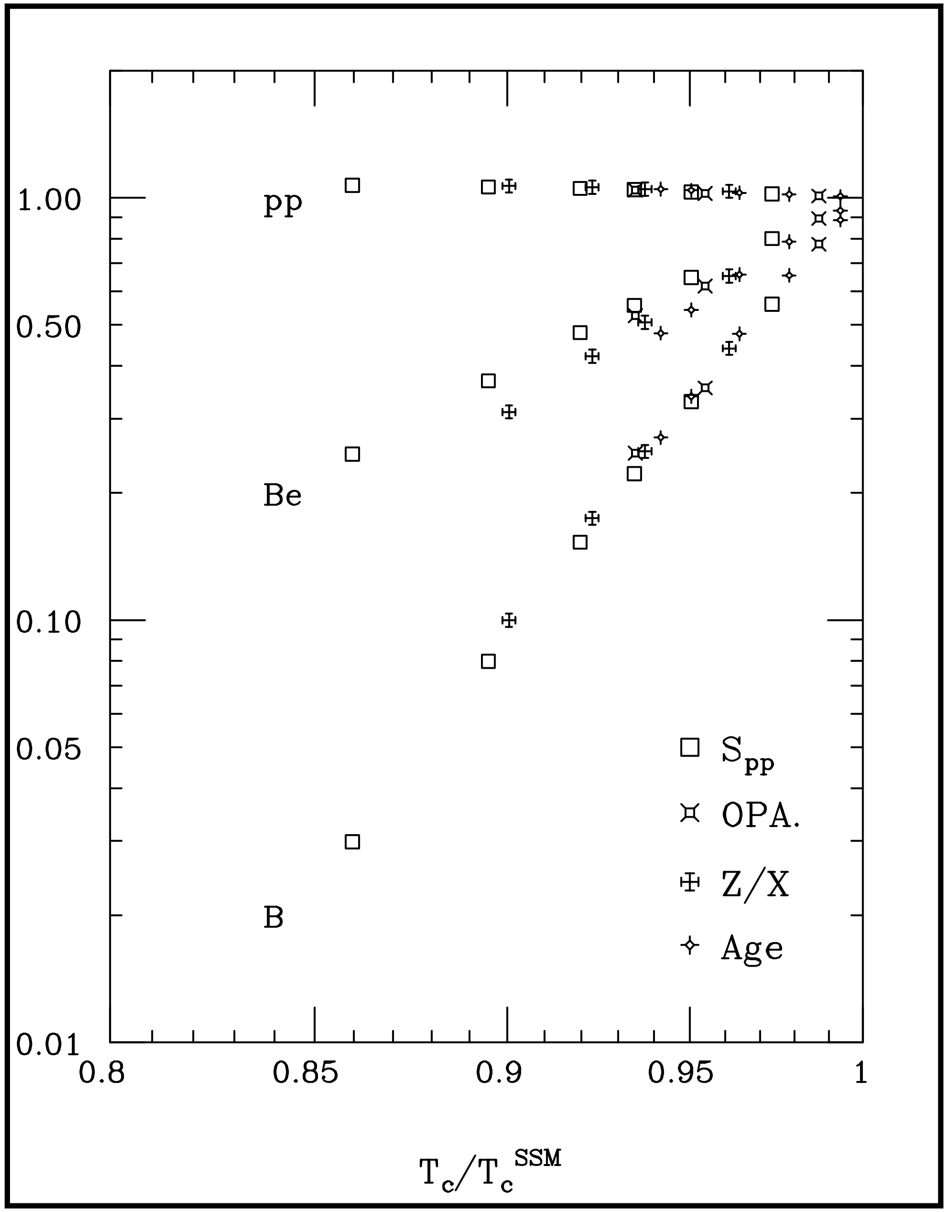


Fit to 0.5 * SSM 8B flux

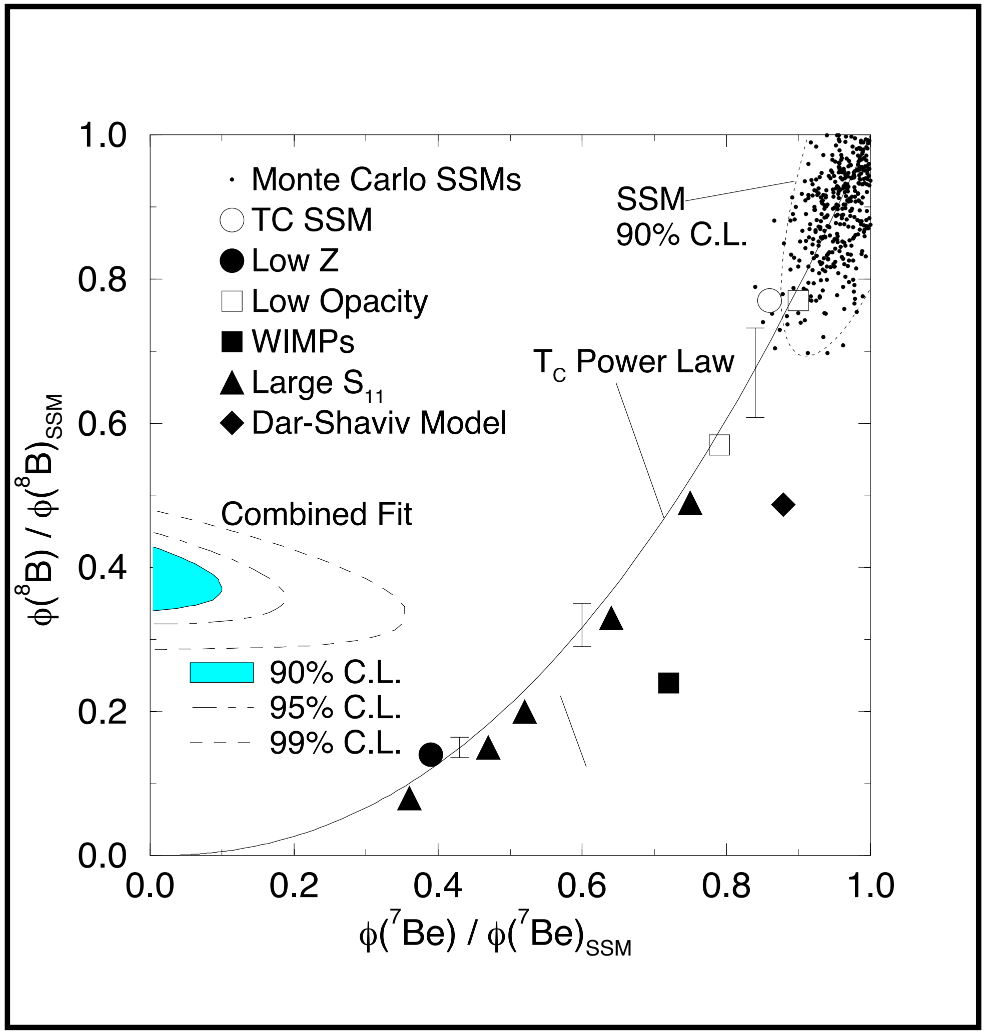
so one had, at this point, first-generation experiments sensitive in differing ways to the three key pp-chain neutrino fluxes



SSM fluxes track with core T -- regardless of the kind of SSM perturbation -- but the measured fluxes did not follow this pattern



Castellani et al.



Hata et al.

(and Heeger and Robertson)

Thus some began to suspect that there would not be a SSM solution -- at least not one consistent with a steady-state sun

Two other developments helped to strengthen the case

- precision helioseismology, which demonstrated that the SSM sound speed was in excellent agreement with measurement (~0.2%)
- the recognition that neutrino oscillations in matter could account for the missing flux, even of mixing angles are small