Michael Hass
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The Weizmann Institute

Recent News on Solar Fusion Reactions
-
The Never-Ending Saga…

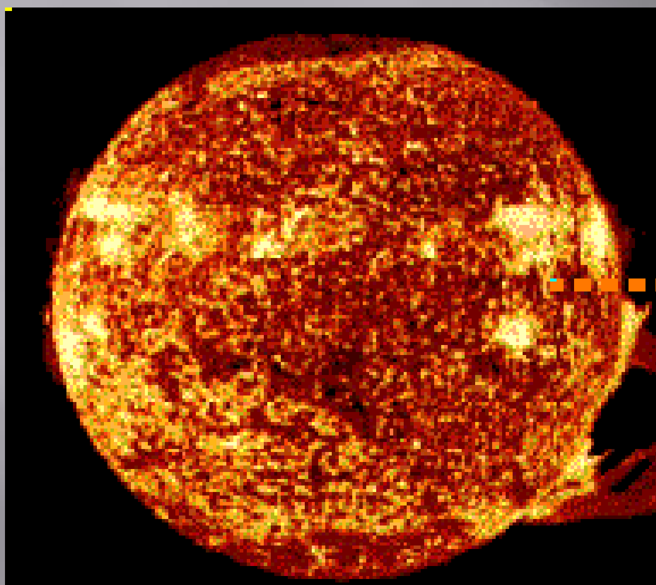
It is imperative to understand the Sun, our nearest and best-studied astrophysical object

At This Conference:

- **Aldo Ianni**
- **Carlo Brogggini**
- **Filippo Terrasi**
- **Hans Feldmeier**
- **Tohru Motobayashi**
- **Claus Rolfs**
- **MH….**

Fusion Reactions in the Sun:

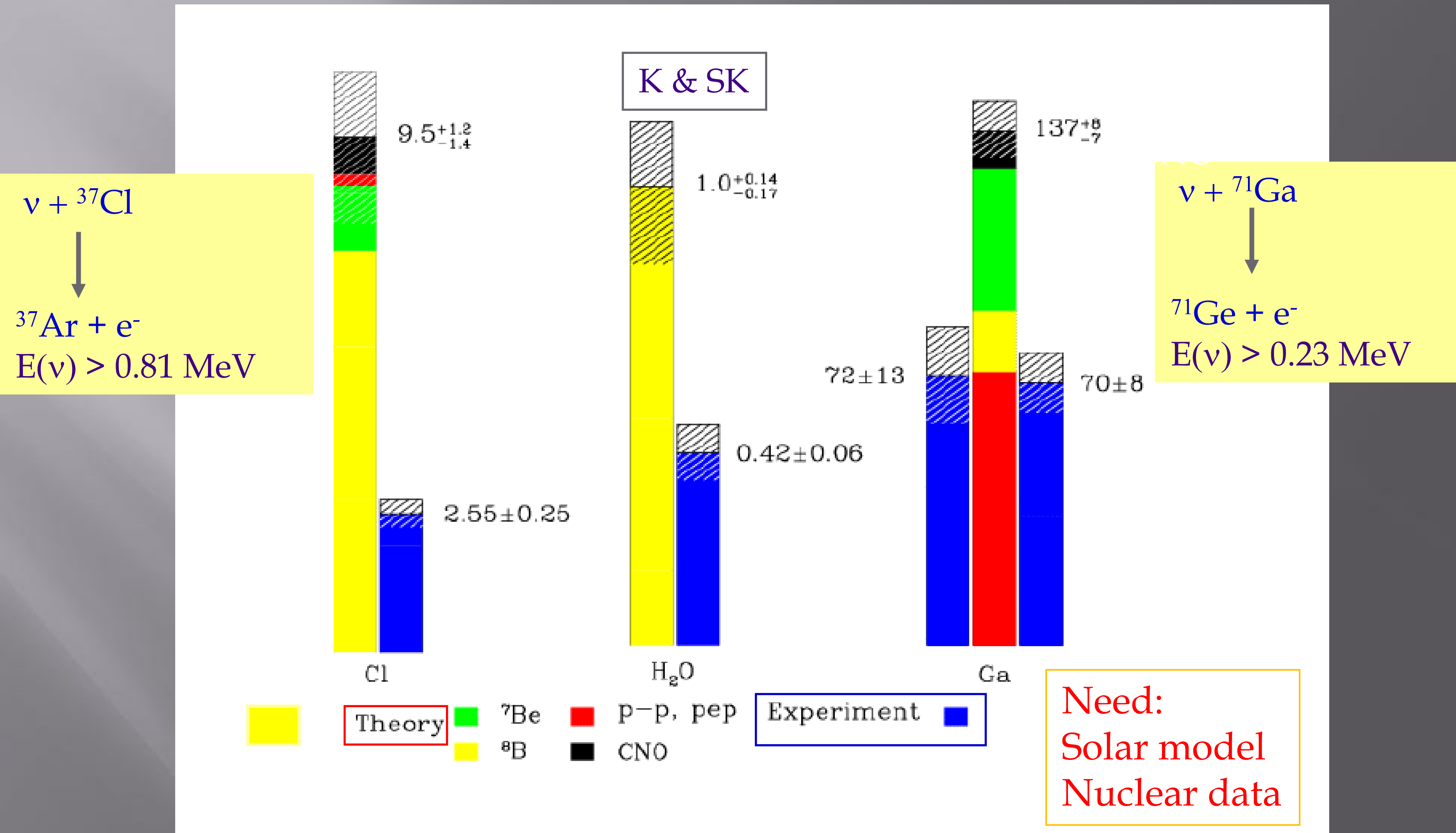
The main p-p chain



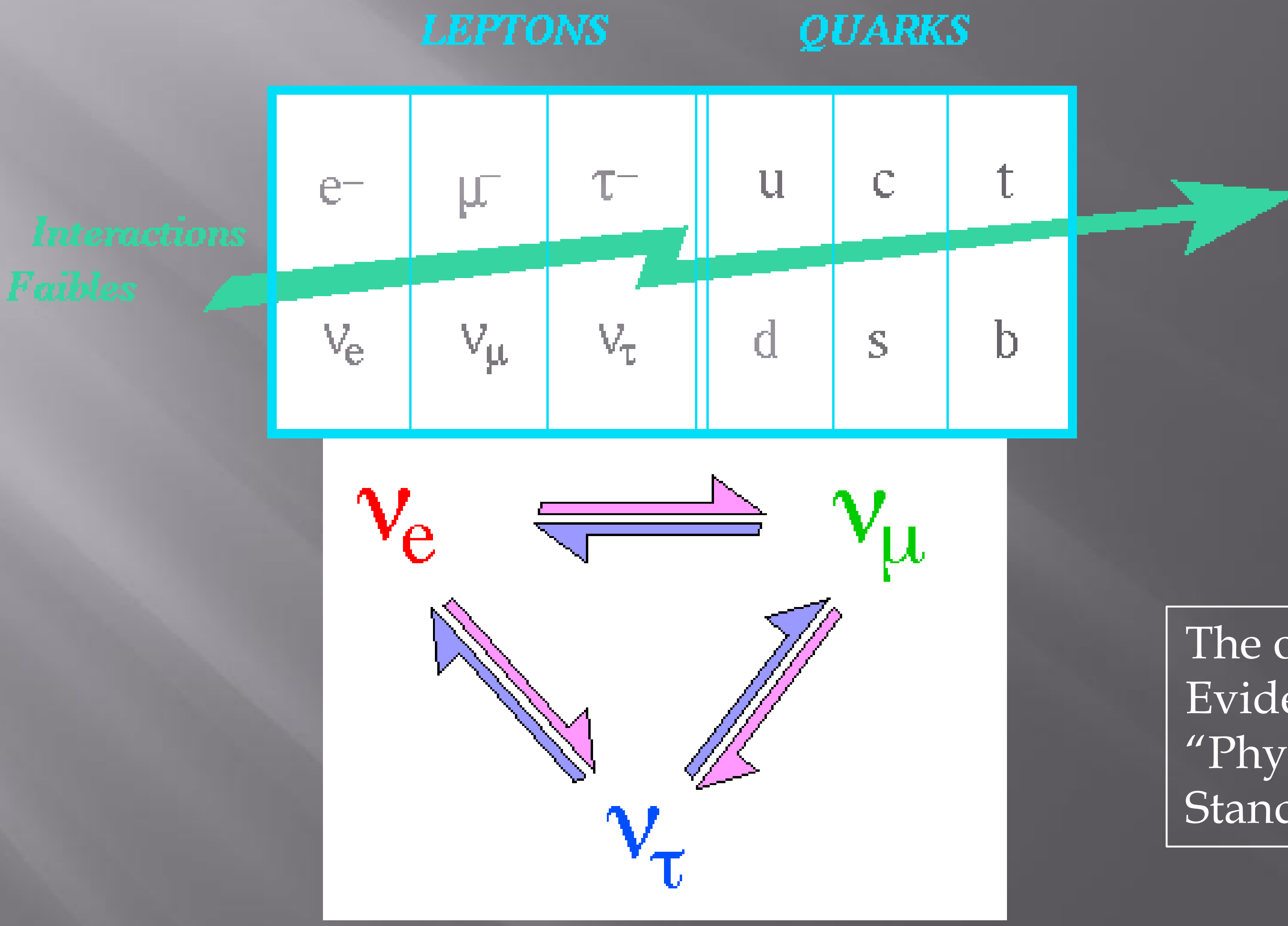
REACTION	TERM. (%)	ν ENERGY (MeV)
$p + p \rightarrow {}^2H + e^+ + \nu_e$	(99.96)	≤ 0.420
or		
$p + e^- + p \rightarrow {}^2H + \nu_e$	(0.44)	1.442
${}^2H + p \rightarrow {}^3He + \gamma$	(100)	
${}^3He + {}^3He \rightarrow \alpha + 2p$	(85)	
or		
${}^3He + {}^4He \rightarrow {}^7Be + \gamma$	(15)	
${}^7Be + e^- \rightarrow {}^7Li + \nu_e$	(15)	0.861 90%; 0.383 10%
${}^7Li + p \rightarrow 2\alpha$		
or		
${}^7Be + p \rightarrow {}^8B + \gamma$	(0.02)	
${}^8B \rightarrow {}^8Be^* + e^+ + \nu_e$		< 15
${}^8Be^* \rightarrow 2\alpha$		
or		
${}^3He + p \rightarrow {}^4He + e^+ + \nu_e$	(0.000004)	18.8

WI

Theory vs. Experiment for the 3 solar-neutrino experiments

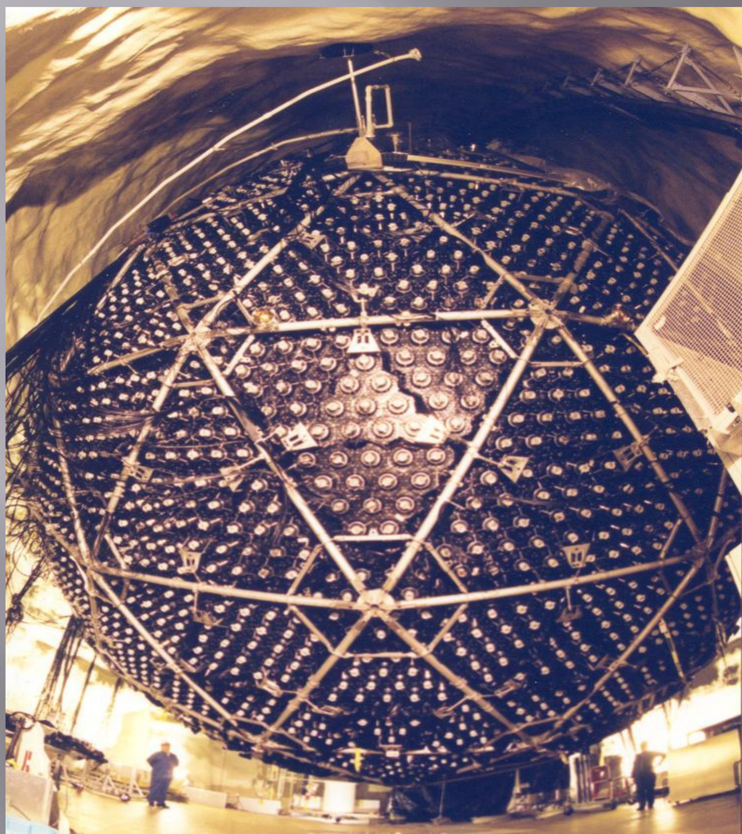


The “Standard Model” of Particle Physics



The only (!!??) REAL Evidence of “Physics beyond the Standard model”

The SNO (Sudbury Neutrino Observatory) Experiment



A D_2O Detector

$\nu_x + e^- \longrightarrow \nu_x + e^-$

Elastic
Mostly ν_e

$\nu_e + d \longrightarrow p + p + e^-$

charge current

Only ν_e

$\nu_x + d \longrightarrow p + n + \nu_x$

neutral current

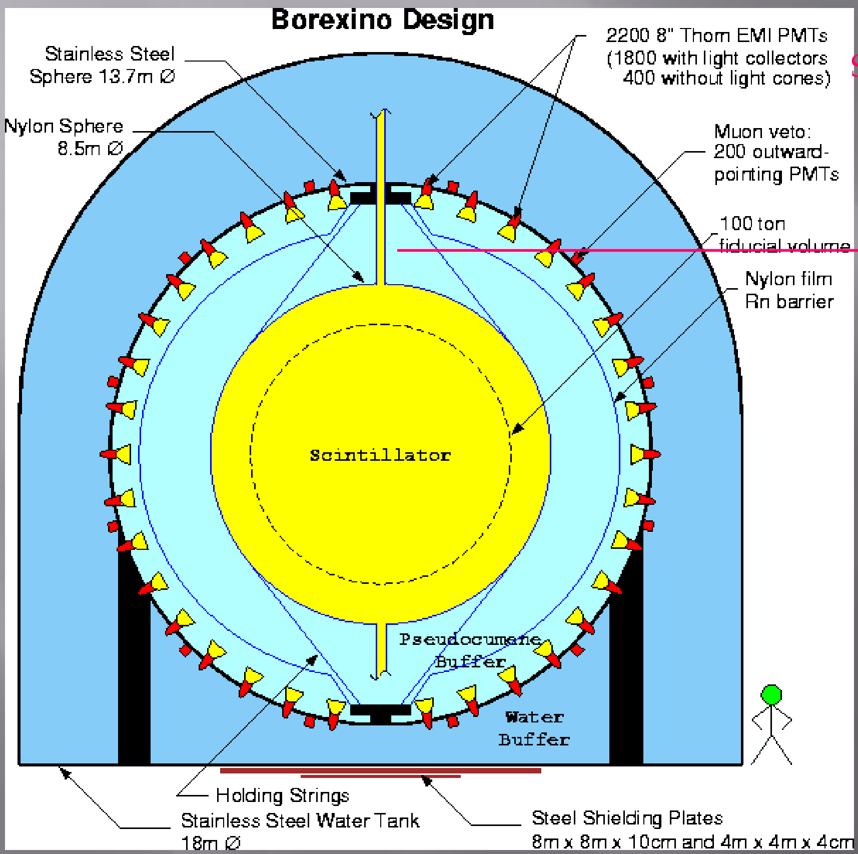
All flavors

YES!!
PRL 87, 071301 (2001)
PRL 89, 011301 (2002)
PRL 92, 181301 (2004)

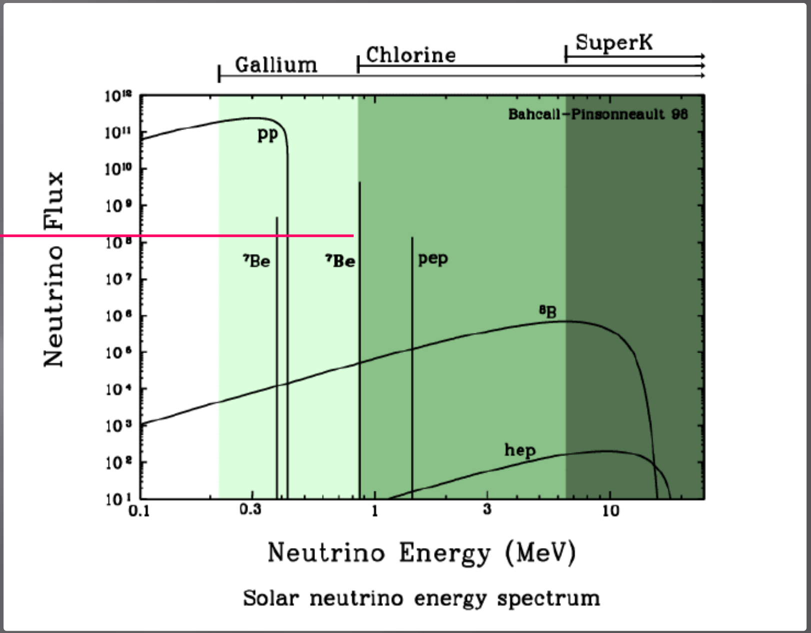
Also, Atmospheric and reactor neutrinos

"SMOKING GUN"!!

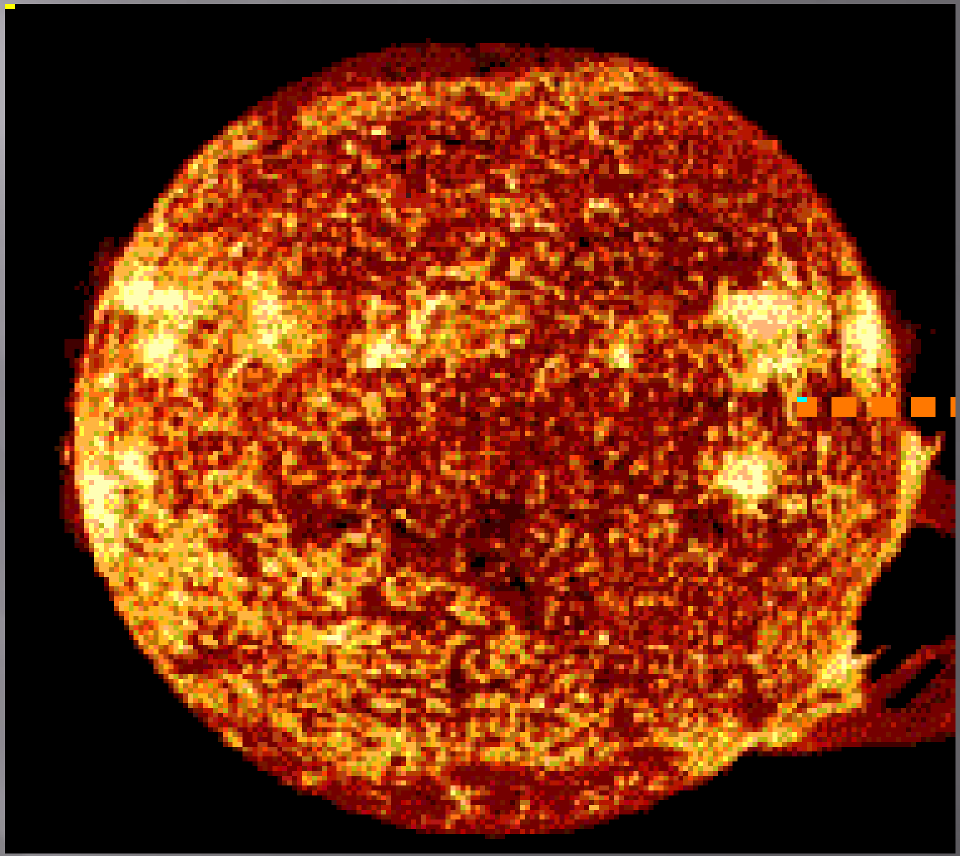
Dedicated experiments to measure the ^{7}Be EC lines: Borexino etc…



SNO



The Sun has its say….

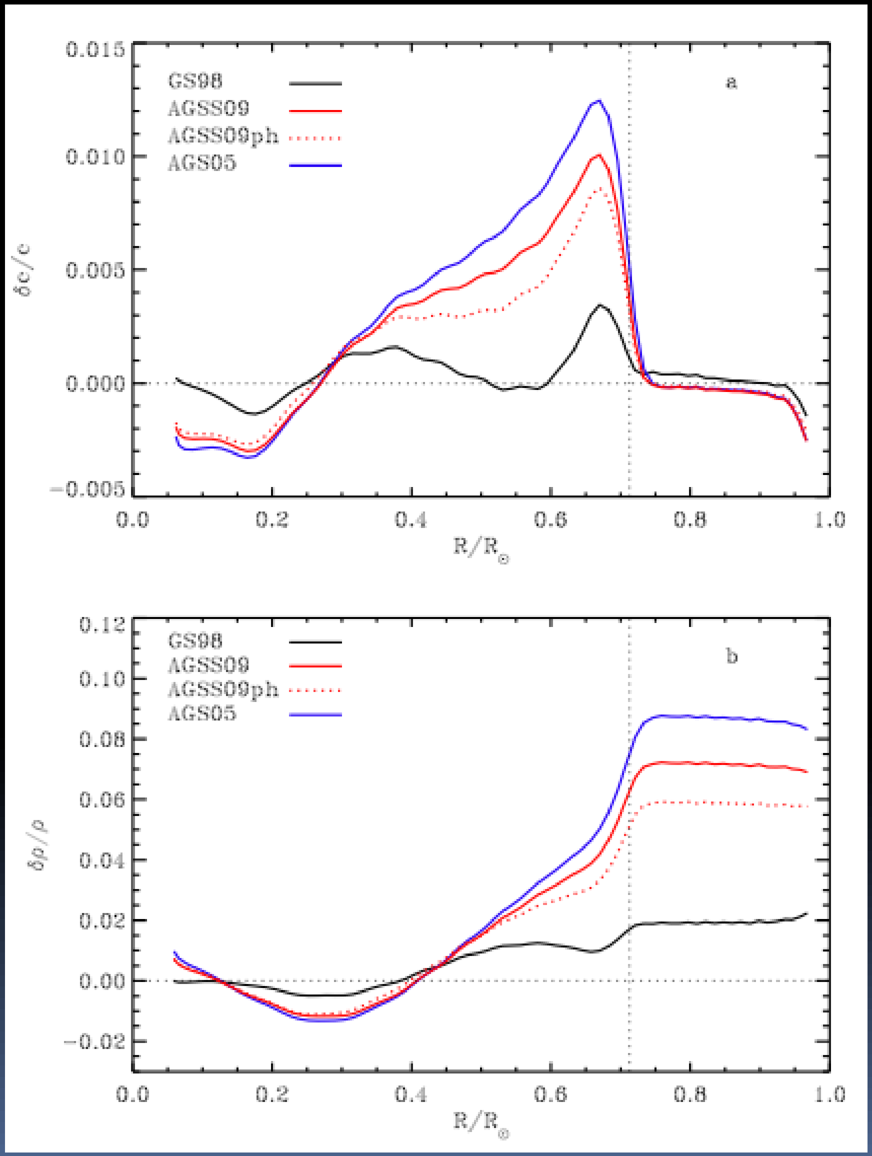


"what's new?…"
With the (model) Sun?…

STATUS OF THE STANDARD SOLAR MODEL

Carlos Peña Garay
IFIC, Valencia

BPS10 Helioseismology: GS vs AGSS



Sound speed

Density profile

R_{CZ}=0.713 – 0.728 (0.001)

Solar Fusion Reactions – A Status report 2010

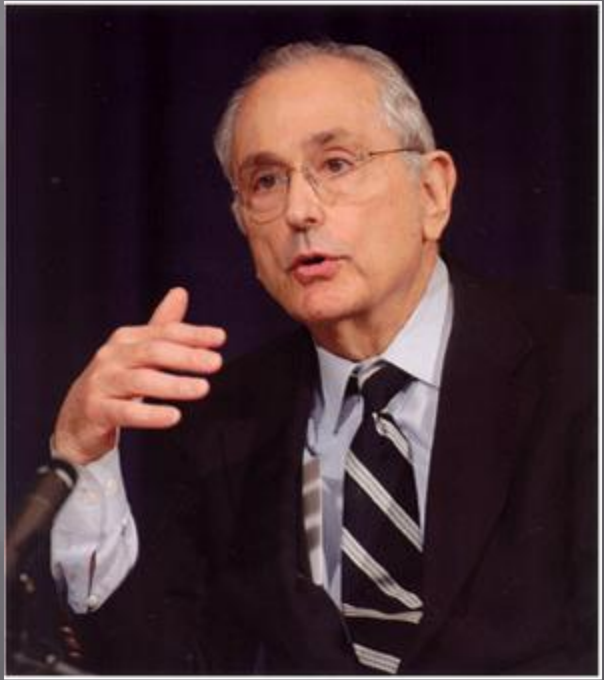
arXive:1004.23182 [nucl-ex] 18 April 2010

Solar fusion cross sections II: the pp chain and CNO bi-cycle

Wick Haxton – Editor – RMP
(In press)

Title: Solar fusion cross sections
Author(s): Adelberger, EG; Austin, SM; Bahcall, JN, et al.
Source: REVIEWS OF MODERN PHYSICS Volume: 70 Issue: 4
Pages: 1265-1291 Published: 1998
Times Cited: 364

….dedicate Solar Fusion II to John Bahcall, who proposed and led the effort on Solar Fusion I. John's advocacy for laboratory astrophysics and his appreciation of its importance to solar neutrinos paved the way for many advances in our field.



Solar fusion reactions and the mythological Hydra monster…

For example, see S_{34} …S_{17}

- However, many advances in experiment and theory!!
- Breakthroughs in detection of solar neutrinos: **SNO, Borexino,…**
- **Problems with Solar Model…**

“what’s new?...”
With Solar Fusion Reactions

What's New
By Bob Park

“Opinions are the author's and are not necessarily shared by the University ----- but they should be…..”

My (Personal) Motivation and Summary

- Present status, Direct and Indirect
- Precision, accuracy, compatibility ; ERRORS
  (Intrinsic and cross-methods)
- What is (or, is there?..) **THE** adopted value?
- **Does the Community need a better value? Why?**
- How to go about achieving this goal?
  Repeat? New methods?

X. THE SPECTRUM OF ^{8}B NEUTRINOS

XI. THE CNO BI-CYCLE

→ XII. INDIRECT METHODS AND THEIR VALIDATION

- A. The asymptotic normalization coefficient method
- B. The Coulomb dissociation method
- C. The Trojan Horse method
- D. Summary

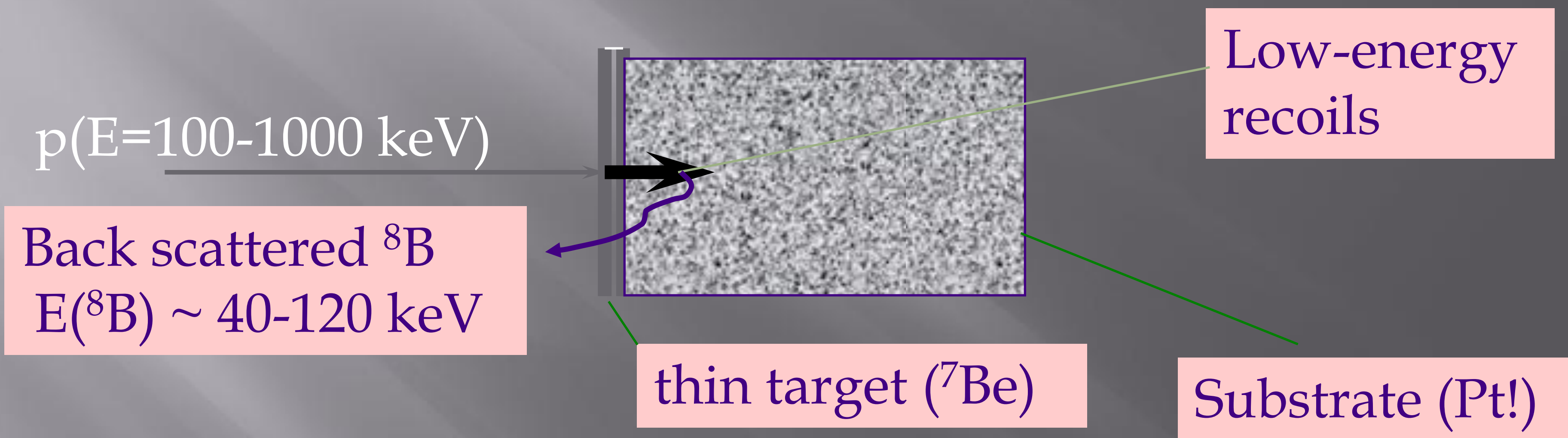
→ XIII. FUTURE FACILITIES AND CURRENT CAPABILITIES

→ Appendix: Treating Uncertainties

Example: New Advances in S_{17}

- Backscattering
- Raster Scanning of Beam - homogeneity
- Target characterization
- Theoretical work [Extrapolation for S(0)]
- Treatment of Errors

The issue of back scattering of ^{8}B



Back scattered nuclei can be an appreciable factor (~10%) at low energies and are lost to the counting cycle.

Weissman et al. NP A630, 678 (1998)

Confirmation by: Strieder et al., E. Phys. J A3, 1(1998)

SRIM 2000

Comparison of recent direct-capture measurements

$\sigma = 1/E \exp(-2\pi\eta)\, S(E)$

η --- Sommerfeld Parameter.

$2\pi\eta = 32.29\, Z_1 Z_2 (\mu/E)^{1/2} \quad \mu = A_1 A_2/(A_1+A_2)$

Exponentially smaller and smaller cross sections at low E

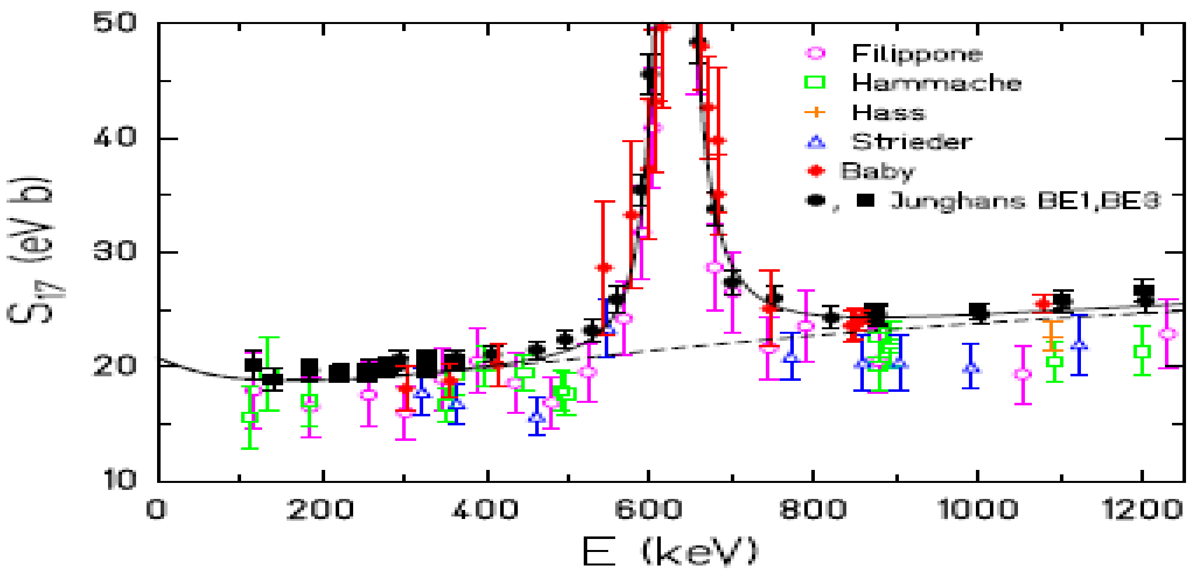


FIG. 9 (Color online) $S_{17}(E)$ vs. center-of-mass energy E, for $E \leq 1250$ keV. Data points are shown with total errors, including systematic errors. Dashed line: scaled Descouvemont (2004) curve with $S_{17}(0) = 20.8$ eV b; solid line: including a fitted 1^+ resonance shape. Note the suppressed zero.

Current status of S_{17} - direct capture - determinations

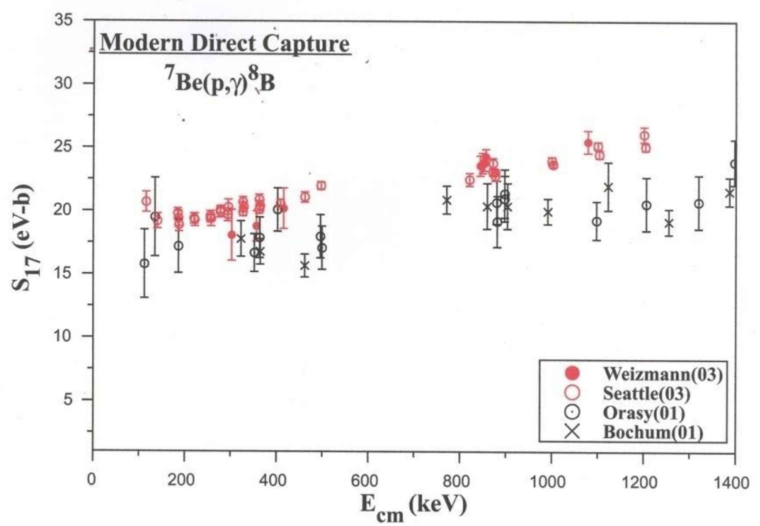
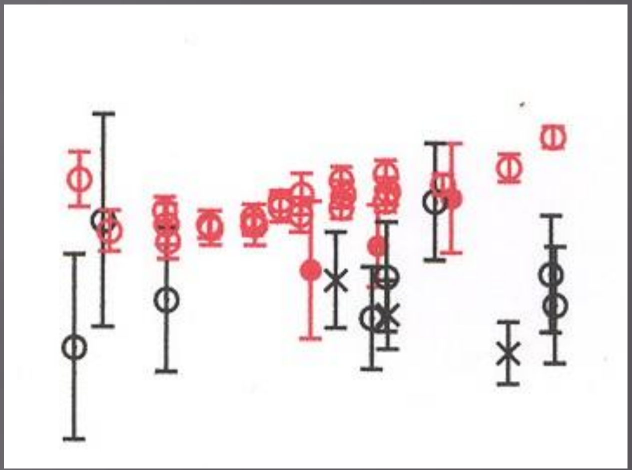


FIG. 1: Modern Direct Capture world data on S_{17} (excluding data around the 632 keV resonance) exhibiting marked systematical deviations by up to five sigma.



New measurement at low energy…? WI (Implanted ^{7}Be target)? Inverse Kinematics?

Adopted New Value

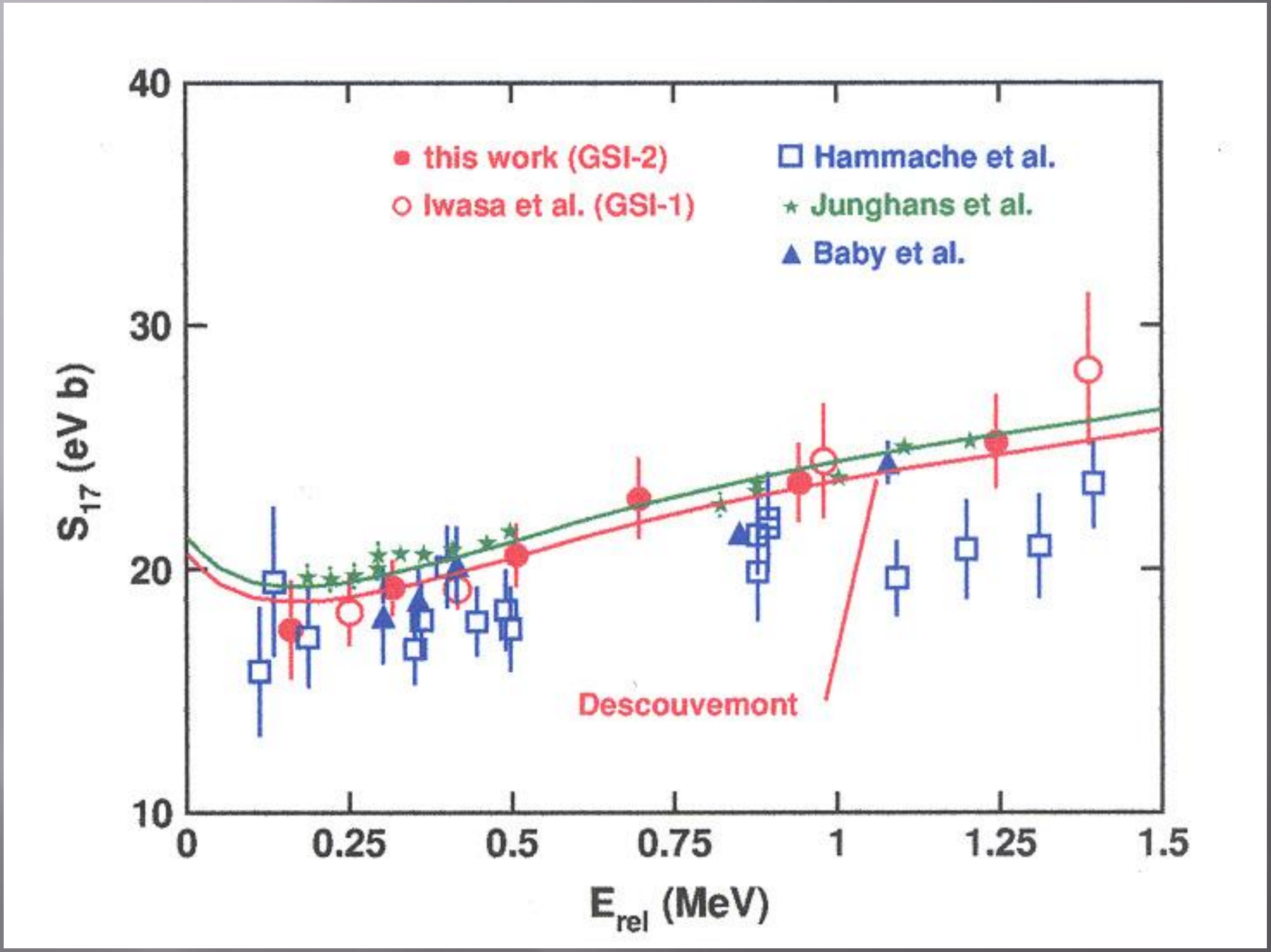
From a fit to the $E \leq 475$ keV

S_{17} = 20.8 ± 0.7(expt) ± 1.4 (theo) eV b

But, also, STABLE with respect to other possibilities – like $E \leq 1250$ keV

In Solar Fusion I:
S_{17} = 19 (+4) (-2) eV b

Coulomb Dissociation – A "special case" for S_{17}



- MSU data Still lower
- RIKEN

S_{17} astrophysical factor - ANC and other Indirect Methods

$$S_{17}(0) = \frac{38.6 \text{ eV b}}{\text{fm}^{-1}} \left(C^2_{p_{3/2}} + C^2_{p_{1/2}}\right)$$

Determine C^2 by three approaches

^{8}B breakup

- **JLM S_{17}=17.4±2.1 eVb**
- **"standard" S_{17}=19.6±1.2 eVb**
- **Ray S_{17}=20.0±1.6 eVb**

Average: S_{17}=18.7±1.9 eVb PRC '04

Transfer

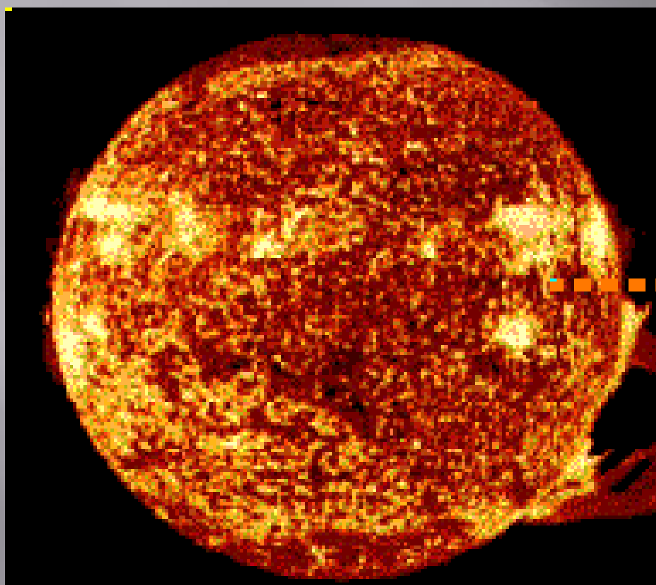
- (^{7}Be,^{8}B) proton transfer at 12 MeV/u two targets:
  - ^{10}B: $S_{17}(0)$ = 18.4 ± 2.5 eVb (PRL '99)
  - ^{14}N: $S_{17}(0)$ = 18.0 ± 1.8 eVb (PRC '99; PRC '06)

Average: S_{17} = **18.2 ± 1.7 eV•b**

- ^{13}C(^{7}Li,^{8}Li)^{12}C at 9 MeV/u using mirror symmetry (PRC '03)
  $S_{17}(0)$ = 17.6 ± 1.7 eVb

Fusion Reactions in the Sun:

The main p-p chain



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WI

S_{34}

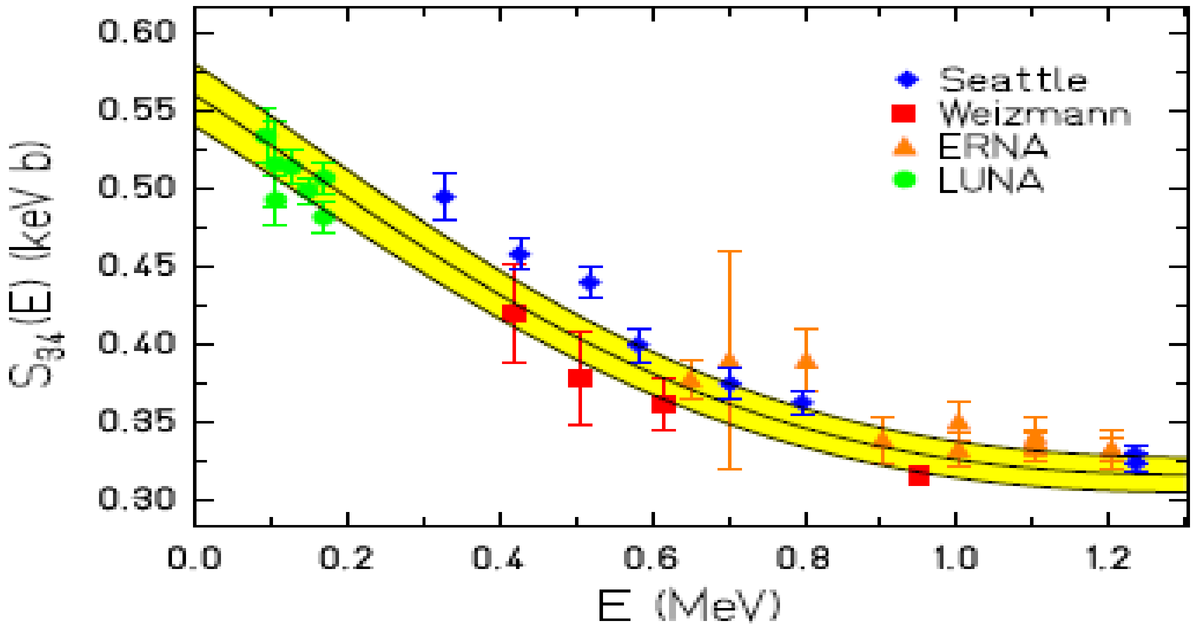


FIG. 5 (Color online) $S_{34}(E)$ vs. E. Data points: LUNA - green circles; Weizmann - red squares; UW-Seattle - blue diamonds; ERNA - brown triangles. Solid curve - best fit scaled Nollett theory to the data with $E \leq 1.002$ MeV. The yellow band indicates the ± 1-σ error band. Data are shown with statistical-plus-varying-systematic errors only; overall systematic errors are not included.

Adopted New Value

S_{34} = 0.56 ± 0.02(expt) ± 0.02(theo) keV b

In Solar Fusion I:
S_{34} = 0.53 ± 0.05 keV b

Also needed for Big Bang Nucleo-synthesis –^{7}Li production
not S(0) but rather S(~100)

b.- Primordial ^{7}Li –SBBN (A. Coc, Orsay)

The 12 reactions of standard BBN

Origin of reaction rates

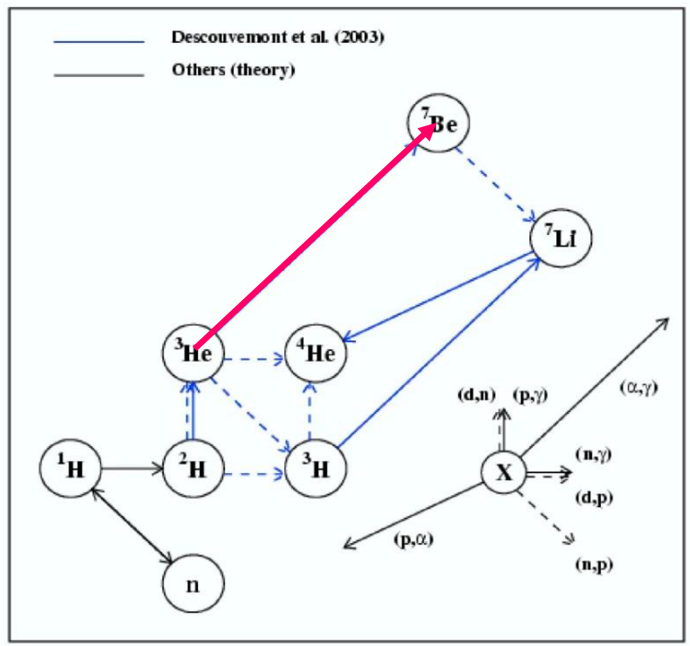
Theoretical:

•n↔p : with τ_n=886.7±1.9 s *[PDG 2000]*, very small uncertainty *[Brown & Sawyer (2001)]*

•$^1H(n,\gamma)^2H$: Two nucleons effective field theory *[Chen & Savage (1999)]*

New compilation:

[Descouvemont, Adahchour, Angulo, Coc & Vangioni-Flam (2004), submitted]

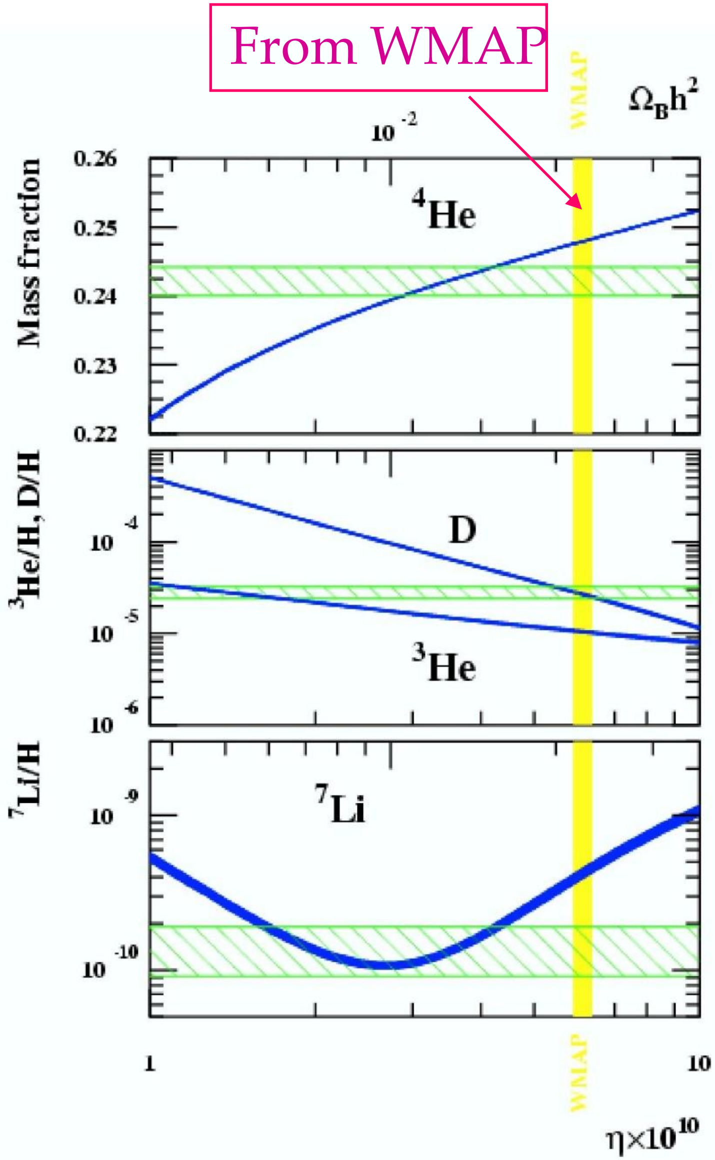


Comparison between observed and calculated abundances

Limits (1-σ) obtained by Monte-Carlo from *DAACV* reaction rate uncertainties.

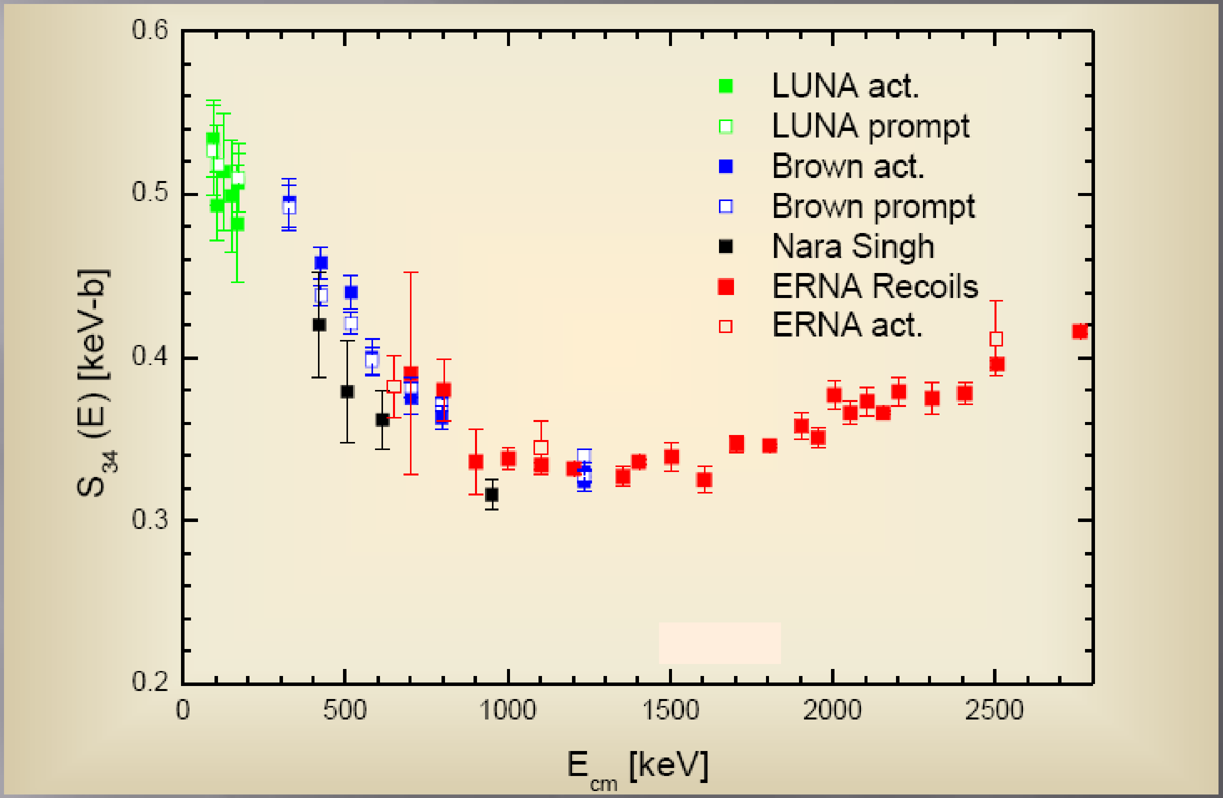
Primordial abundances

- ^{4}He : $Y_p = 0.2421 \pm 0.0021$ *[Izotov et al. (2003)]*
- D : $D/H = (2.78^{+0.44}_{-0.38}) \times 10^{-5}$ (1σ) *[Kirkman et al. (2003)]*
- ^{7}Li : $Li/H = (1.23^{+0.68}_{-0.32}) \times 10^{-10}$ (2σ) *[Ryan et al. (2000)]*
- $\Omega_B h^2 = 0.0224 \pm 0.0009$, *[WMAP: Spergel et al. (2003)]*



Look for another resolution to ^{7}Li discrepancy

S_{34}



- 2009/10 – New experimental activity
- Madrid - Activity
- TRIUMF – DRAGON (as we speak..)
- Others?
- Angular Distribution of prompt γ rays at high energy

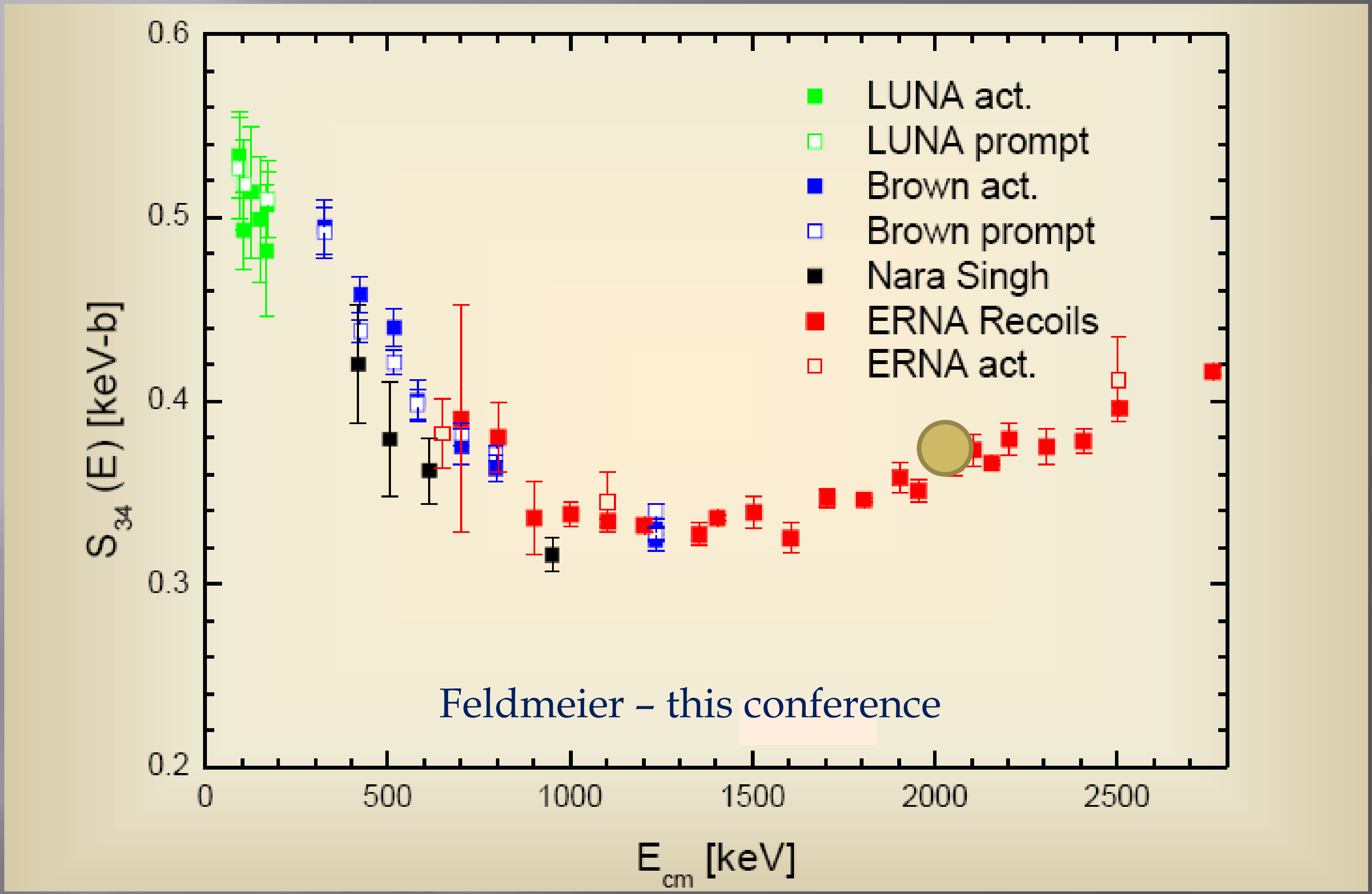
^{3}He(^{4}He, gamma)^{7}Be direct-capture cross-section measurements close to $E_{cm} = 2$ MeV

University of York: B.S. Nara Singh, B.R. Fulton, J. McGrath, R.Wadsworth
Instituto de Estructura de la Materia-CSIC: M. Carmona, A. Perea, O. Tengblad
Centro de Microanalisis de Materiales (CMAM): A. Muñoz
The Weizmann Institute: M. Hass
Soreq Research Centre: Y. Nir-El, G. Haquin, Z.Yungreiss.

New Run in Madrid:

1. Few energies
2. Catchers collected and measured
3. Full analysis in progress

Previous Data



XIII. FUTURE FACILITIES AND CURRENT CAPABILITIES

- Inverse kinematics measurements

- Underground Facilities:
  Europe - Gran Sasso (proposed "LUNA-MV")
  others (UK, Spain)
  USA

- Indirect methods (complementary)

- Theoretical progress

Conclusions

In the recent Adelberger et al. II (RMP – in press, 2010) one can find **44** Phys. Rev. Lett. papers!...

And they'll keep coming…

European Physical Society - 24th Nuclear Physics Divisional Conference

Nuclear Physics in Astrophysics V

April 3-8, 2011 | Eilat, Israel

Topics

- Nuclear Structure - Theory and Experiment
- Big-Bang Nucleosynthesis and Formation of First Stars
- Stellar Reactions and Solar Neutrinos
- Explosive Nucleosynthesis
- Radioactive Beams and Exotic Nuclei – New Facilities and Future Possibilities for Astrophysics
- Neutrino Physics - the Low - and High-Energy Frontiers
- Rare Events, Dark Matter, Double β-decay, Symmetries

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A. Leviatan (Jerusalem)
H. Schatz (MSU)
M. Wiescher (Notre Dame)

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T. Aumann (GSI)
N. Bahcall (Princeton)
B. Balantekin (Wisconsin)
M. Block (GSI)
A. Brown (NSCL)
A. Coc (Orsay)
T. Duguet (Saclay)
A. Faessler (Tubingen)
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Uncertainties: Partial contributions

Source	No composition % (S_{33}, S_{34}, S_{17}, S_{114}, Op, Diff)	Composition %
^{7}Be	7 (2.5,4.2,0.0,0.0,3.2,2.0)	2
^{8}B	13 (2.6,4.1,7.6,0.0,6.8,4.2)	5
^{13}N	8 (0.2,0.3,0.0,6.0,3.6,5.1)	13
^{15}O	11 (0.2,0.3,0.0,8.3,5.2,5.9)	12

Recommendations:

- Reduce $S_{1,7}$,$S_{1,14}$ uncertainties to be below 5%
- Reduce uncertainty in Fe (to 0.02 dex)
- Reduce uncertaintiy in C (to 0.02 dex)

Conclusions

BPS10 neutrino fluxes: dominant error sources identified (S_{34}, $S_{1,7}$, $S_{1,14}$, Op, Diff, Z_i/X). Work needed.

Improvements in solar surface composition lead to wrong beating Sun in all regions.

Solar neutrinos: Best θ_{12} (10% in $\tan^2\theta_{12}$) and test MSW
Neutrino fluxes determined (pp/pep, ^7Be, ^8B) and CNO luminosity constrain

Ongoing and future neutrino experiments will probe the solar composition:
- test BPS10(GS) & BPS10(AGSS) solutions
- test core CN abundances