Astrophysics & reactions of light nuclei, and some quantum Monte Carlo

Kenneth Nollett
Ohio University

Electroweak Properties of Light Nuclei
Institute for Nuclear Theory
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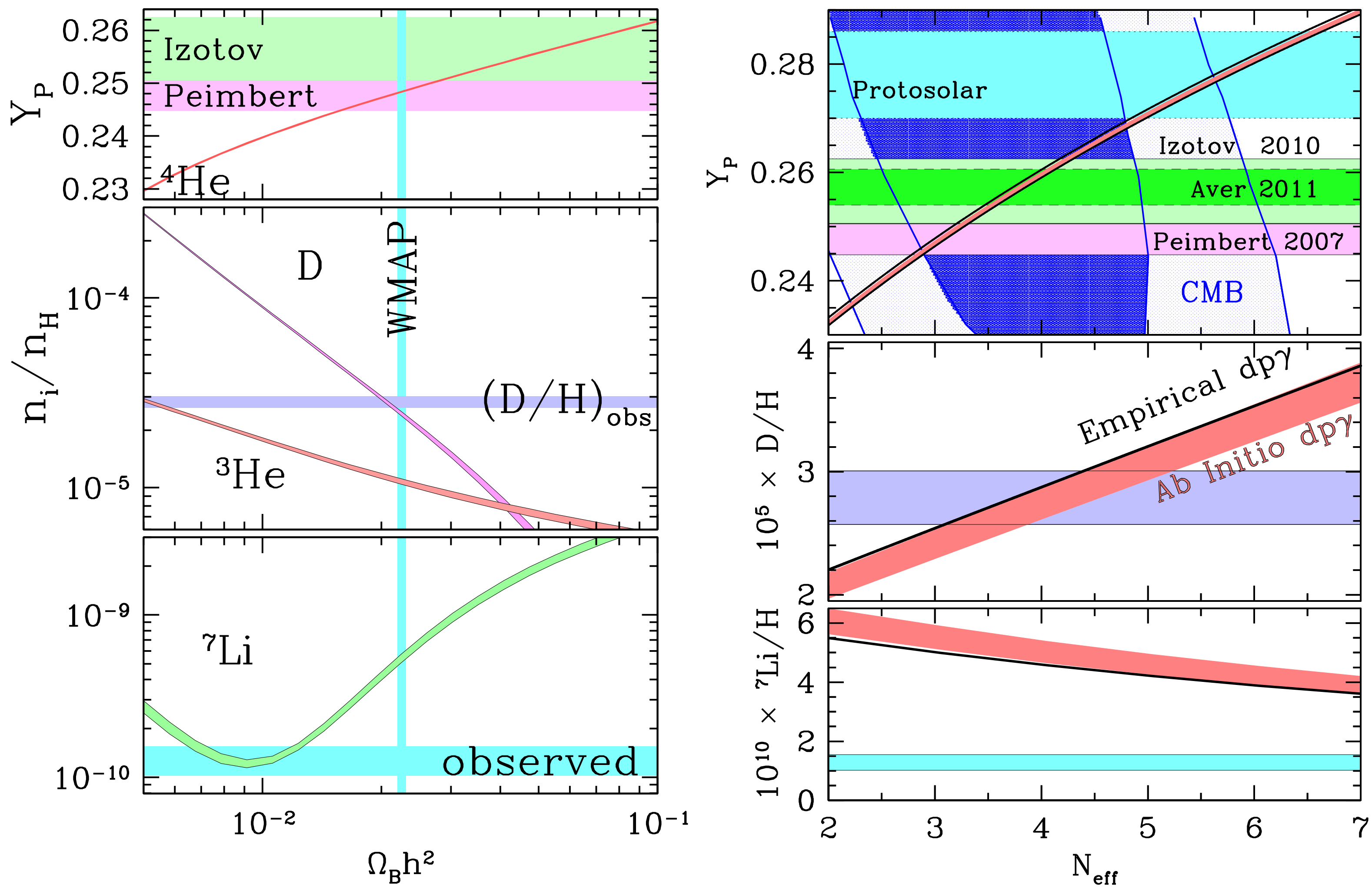
Radiative capture in the big bang and the Sun

What we can (still) learn from big-bang nucleosynthesis (BBN)

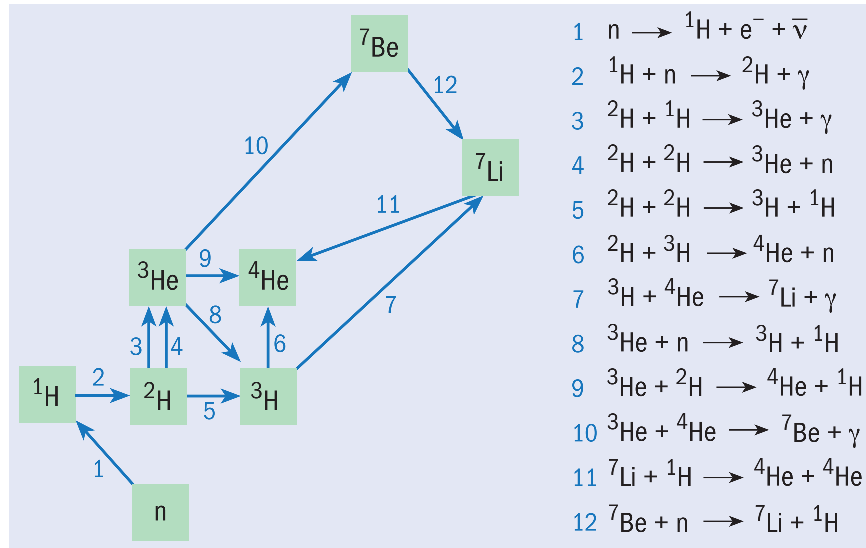


Are the primordial abundances consistent with the weird but well-verified "concordance" cosmology?

With 2% precise $\Omega_B h^2$ from cosmic microwave background, BBN gives very precise predictions – deviations probe conditions in the early universe

BBN and rates: overview

Abundance evolution in BBN proceeds through nuclear collisions



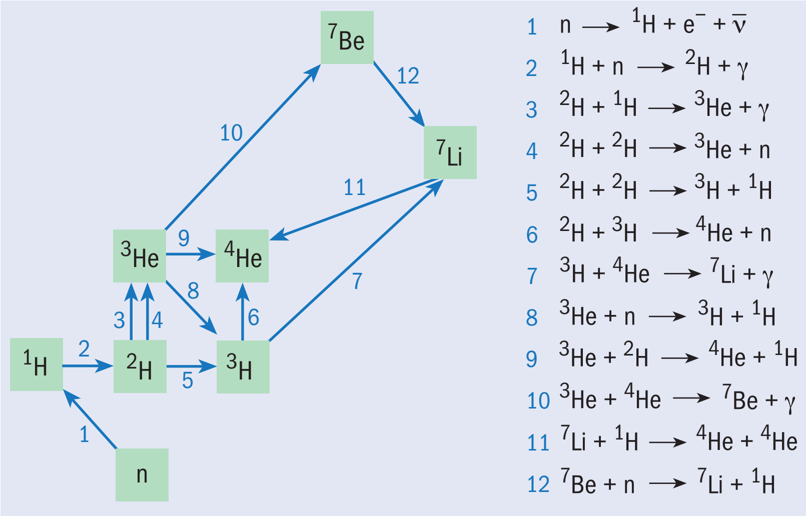
Cross sections are almost all empirical & don't require extrapolation (50 to 500 keV)

Only 12 processes matter*, enumerated by Smith, Kawano, Malaney (1993)

Calculations with huge reaction networks and nuclei into CNO region have been done

Weak $p+l \leftrightarrow n+l'$ processes are all normalized to neutron lifetime (toublesome, but at finer level than BBN) & computed from weak-interaction physics

BBN post-WMAP: Precise D/H predictions

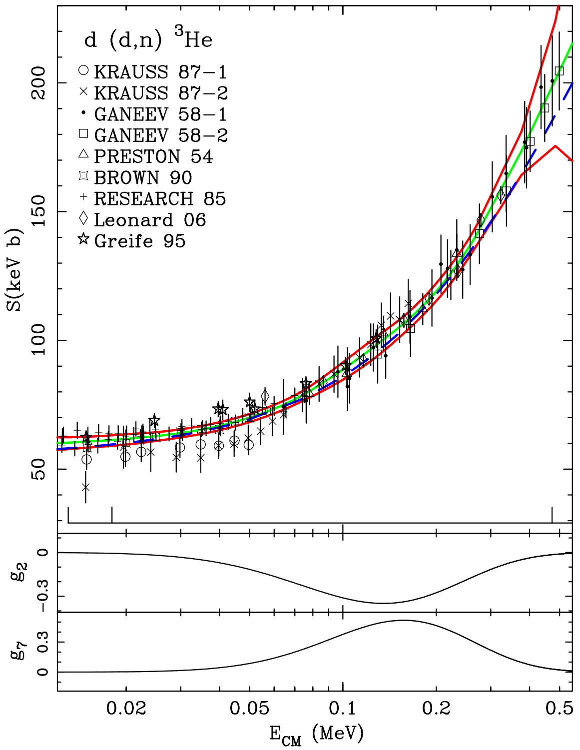


Deuterium is a remnant of ^{4}He production

At the end of BBN:

$p(n,\gamma)d$ competes with
$d(p,\gamma)^3$He, $d(d,n)^3$He & $d(d,p)^3$H

Much progress has been made in 12 years since Nollett & Burles rates

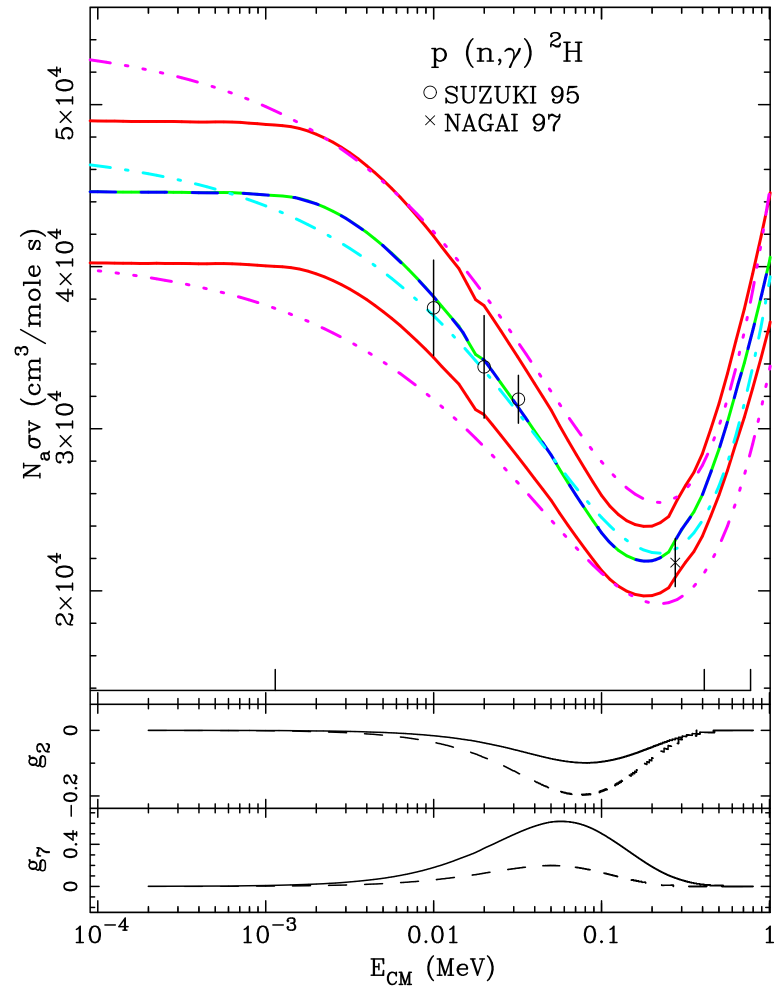


Until 2006, the only $d+d$ data at 200 $< E <$ 500 were very old (1950s) & poorly documented

Doug Leonard & collaborators at TUNL measured $d+d$ cross sections to $\sim$ 2% – huge improvement

BBN post-WMAP: Precise D/H predictions

Graph shows $p(n,\gamma)d$ from year 2000
(There are more data now)



This case needs theory input: model curve & 5% error came from a dispersion-model fit

But the nucleon-nucleon force is well-known: better precision is possible

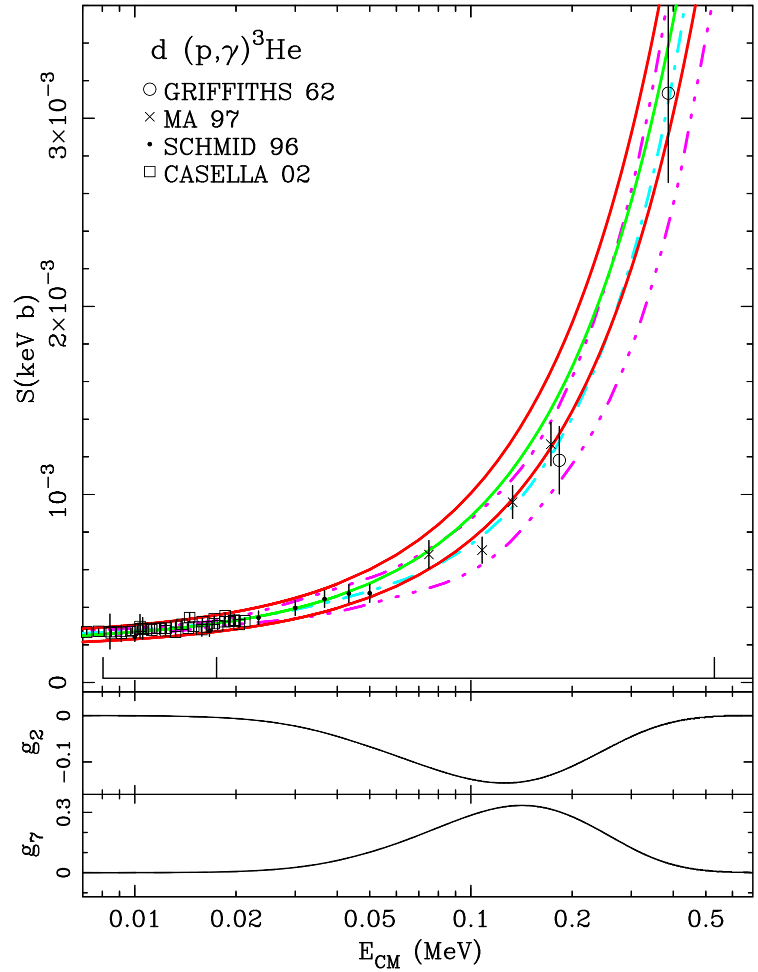
Effective field theory (EFT) produces an accurate low-E cross section from a few measured numbers (effective-range, σ_{th}, etc.)

EFT gives a *quantified* error of $< 1\%$

"Traditional" potential-model nuclear physics with meson exchange currents gives the same curve (so did the old fit!)

BBN post-WMAP: Precise D/H predictions

$d(p,\gamma)^3$He also has sparse data at BBN energies – just one modern experiment



There are now very nice data at lower E, solar & just above

But modern nuclear theory can handle this reaction quite well

The Pisa group used correlated hyperspherical harmonics: Argonne v_{18} + Urbana IX potential & consistent EM currents

Curve shape is p-wave vs. s-wave competition – also probed by good $d\sigma/d\Omega$ and polarization measurements – scale confirmed at lower E

This *ab initio* rate is probably better than the empirical rate, I've assigned 7% error from low-E data

BBN post-WMAP: Precise D/H predictions

So all four rates affecting D/H have improved significantly

Nuclear error is 2.5%

D$/$H $\propto (\Omega_B h^2)^{-1.6}$ so error from WMAP value of $\Omega_B h^2$ is 4%

Predicted D/H is then $(2.42 \pm 0.11) \times 10^{-5}$, vs. $(2.78 \pm 0.22) \times 10^{-5}$ observed [More recently $(2.54 \pm 0.05) \times 10^{-5}$]

Beating down systematics is important for cosmological limits on neutrino & other beyond-standard-model physics

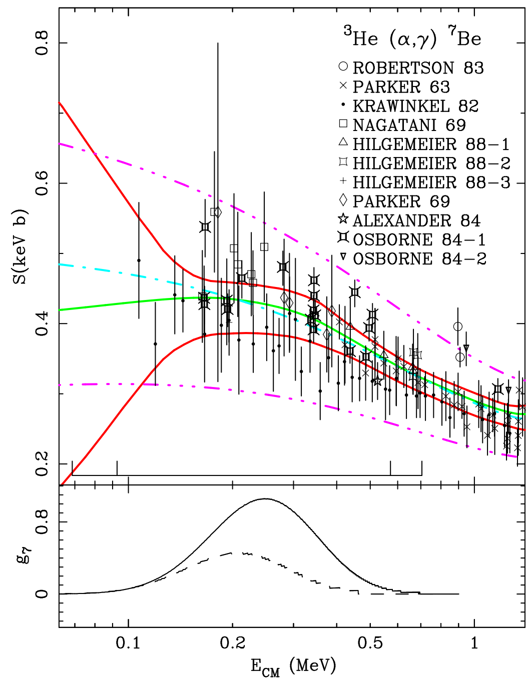
The biggest lever for improvement is now $d(p, \gamma)^3$He

BBN post-WMAP: Precise Li/H predictions

The lithium prediction has also improved recently – all goes through ${}^3\mathrm{He}(\alpha,\gamma)^7\mathrm{Be}$

Some inconsistency remains, but overall precision went from $\sim 10\%$ to 7% in Adelberger et al. (2011) Solar Fusion recommendations

From



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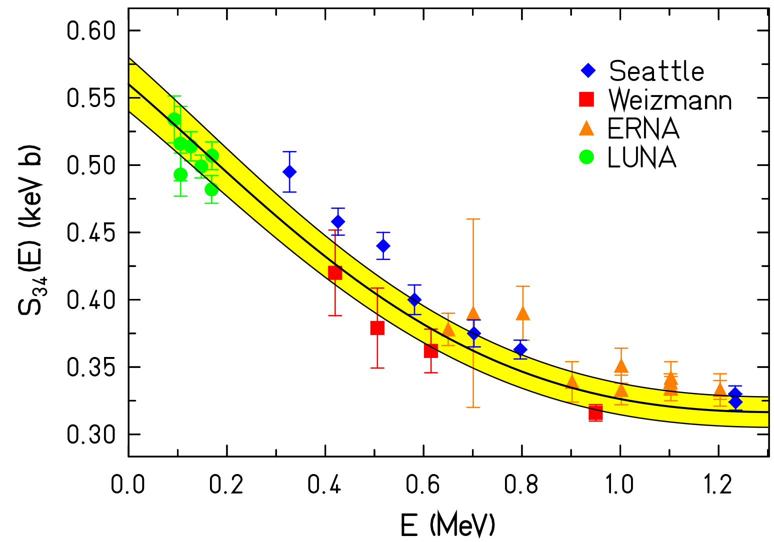


Prediction is $\mathrm{Li/H} = (5.5 \pm 0.4) \times 10^{-10}$, only 2% from $\Omega_B h^2$

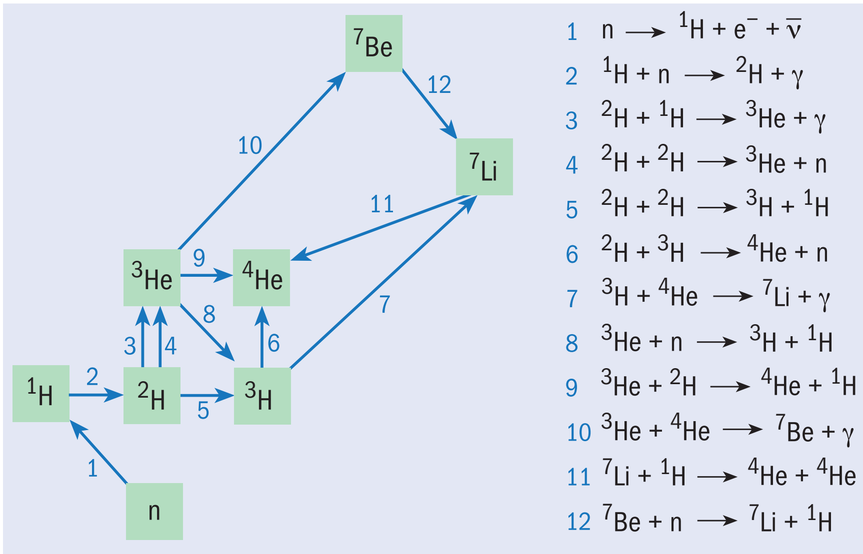
But that comes from Nollett/Burles estimation – probably better to use Adelberger fit of norm to Nollett (2001) *ab initio* curve (or re-analyse with Neff curve)

BBN post-WMAP: Room for improvement in Li/H

Only one of the 12 known important rates destroys ^{7}Li at $\Omega_B h^2 = 0.0226$

Actually ^{7}Be is destroyed via $^7\mathrm{Be}(n,p)^7\mathrm{Li}(p,\alpha)^4\mathrm{He}$

That rate is pretty well known & doesn't dominate the BBN error budget



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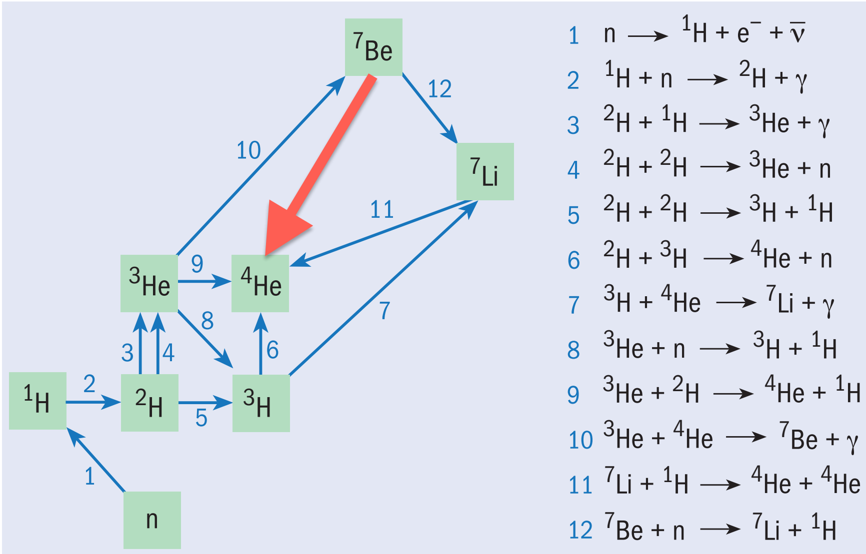

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But there is another rate that biases Li/H by 1% & is assigned no error in most studies

Moshe Gai is proposing to measure $^7\text{Be}(n,\alpha)^4\text{He}$ and $^7\text{Be}(n,\gamma\alpha)^4\text{He}$ at SARAF (I'm the theory guy)

Current rate is p-wave ($\sigma \propto v$) extrapolation of a very old upper limit σ_{th}

Dividends could be large...

^{7}Li: A puzzle in the oldest stars

Charbonnel & Primas mean of many metal-poor stars:

$Li/H = (1.6^{+0.4}_{-0.3}) \times 10^{-10}$

(fairly stable over 30 years)

Theory gave $(5.5 \pm 0.4) \times 10^{-10}$

Factor of 3.4 (5σ) mismatch

So what gives?

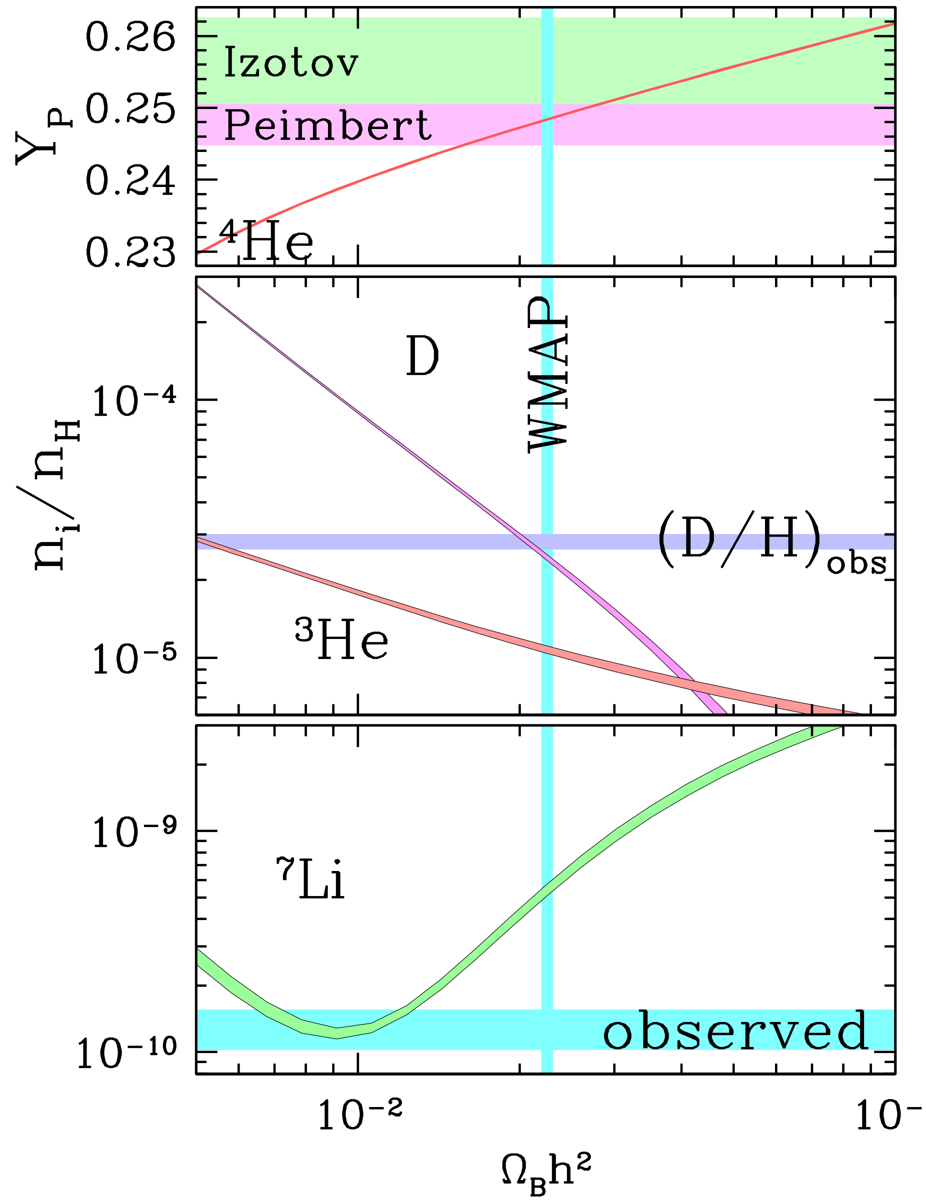
Bad cross sections? Unlikely

Missing cross sections? Unlikely

Misinterpreted spectra? Unlikely

Exotic particle physics? Possible

Deep mixing in the stars? Maybe



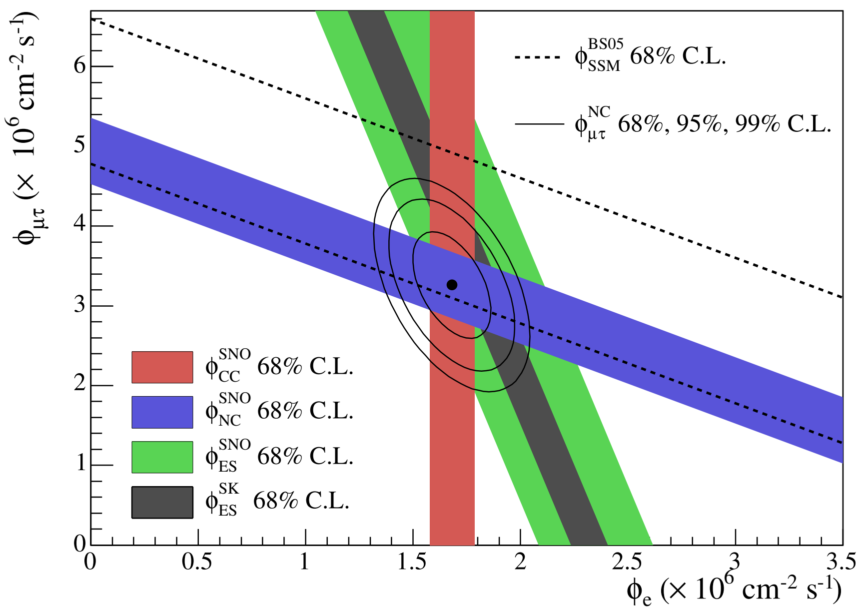
Solar neutrinos: Another place for percent-level precision

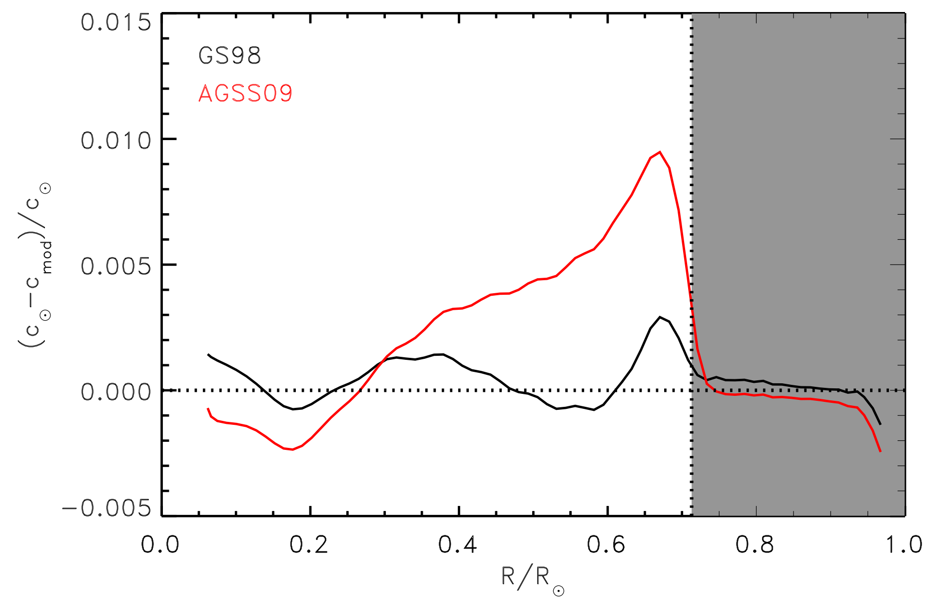
Solar-neutrino experiments also require percent-level nuclear rates

The solar neutrino problem has been solved in that we can see ν_e that became ν_μ & ν_τ

However, there are lingering problems with the solar model: agreement with helioseismology was broken $\sim$ 10 years ago (by revised composition)

Precision in the model inputs is needed for ν properties & the remaining model difficulties





Radiative capture in the heart of the Sun

There are three radiative captures in the pp-chain:

$d(p,\gamma)^3$He processes everything but is downstream from the slower pp capture: its rate doesn't matter

^{3}He$(\alpha,\gamma)^7$Be competes with ^{3}He$(^3$He$,pp)^4$He to affect whether there are neutrinos

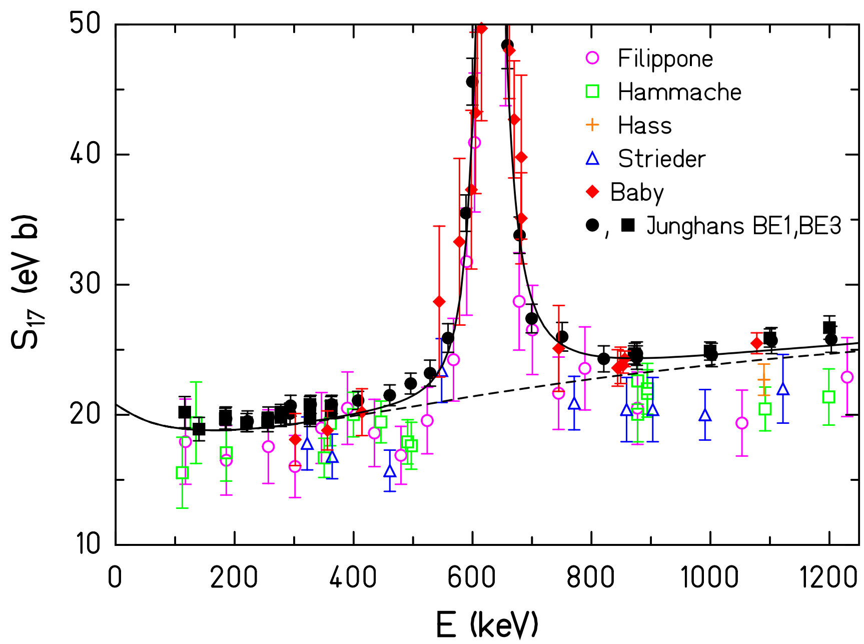
^{7}Be$(p,\gamma)^8$B competes with ^{7}Be decay to affect neutrino spectrum

$$
\begin{array}{rcl}
p + p & \longrightarrow & {}^2\mathrm{H} + e^+ + \nu_e \\
 & \downarrow & \\
{}^2\mathrm{H} + p & \longrightarrow & {}^3\mathrm{He} + \gamma \longrightarrow {}^3\mathrm{He} + {}^3\,\mathrm{He} \longrightarrow {}^4\mathrm{He} + 2p \;(86\%) \\
 & \downarrow & \\
{}^3\mathrm{He} + {}^4\mathrm{He} & \longrightarrow & {}^7\mathrm{Be} + \gamma \longrightarrow {}^7\mathrm{Be} + e^- \longrightarrow {}^7\mathrm{Li} + \nu_e \\
 & & \qquad\qquad {}^7\mathrm{Li} + p \longrightarrow 2\,{}^4\mathrm{He} \;(14\%) \\
 & \downarrow & \\
{}^7\mathrm{Be} + p & \longrightarrow & {}^8\mathrm{B} + \gamma \\
{}^8\mathrm{B} & \longrightarrow & 2\,{}^4\mathrm{He} + e^+ + \nu_e \;(0.02\%)
\end{array}
$$

Radiative capture rates for the Sun

Unlike BBN, solar reactions do require low-energy extrapolation from the data (alleviated a bit by Gran Sasso measurements at or near the solar Gamow peak; higher-E information is still useful)

Like $^{3}\mathrm{He}(\alpha,\gamma)^{7}\mathrm{Be}$, $^{7}\mathrm{Be}(p,\gamma)^{8}\mathrm{B}$ has also seen great improvements in experiments this last decade



"Officially:" $S_{17}(0) =$ $20.8 \pm 0.7(\mathrm{expt}) \pm 1.4(\mathrm{theor})\ \mathrm{eV}\cdot\mathrm{b}$

For both reactions, experimental error is mainly in systematic differences between experiments

The range of plausible theoretical models is a significant source of the quoted error in both reactions

Modeling captures

The two reactions are very similar: $E1$ transitions from s- to p-wave states, d becoming more important as E increases

^{7}Be$(p, \gamma)^8$B is more peripheral, since ^{8}B has a 138 keV p-separation energy (1.1 & 1.6 MeV for $^7\text{Be} \to \alpha\, ^3\text{He}$)

So how do you model these?

1. Pure external capture (but temptation is to make places too close to $r = 0$ "external"; source of confusion to experimentalists with ^{3}He$(\alpha, \gamma)^7$Be right now)

2. Potential models (Woods-Saxon or Gaussian, more convincing with phase shift information)

2$'$. R-matrix or EFT (Fit same data as potential models, similar physics, hard to prove that they're better)

How to model captures

3. Microscopic (RGM or semi-*ab-initio*; mainly good antisymmetry, but scale of $\sigma(E)$ often bad)

RGM with crude (no-tensor) interactions seems good on E dependence but not overall scale (mainly ANC?)

Semi-*ab-initio* models (Nollett '01 & Navratil '06) had "real" bound states but potential model for the scattering

Short-range stuff there is wrong at some level, maybe worse for $^7\mathrm{Be}(p,\gamma)^8\mathrm{B}$ because scattering constraints lacking

How to model captures

4. Real *ab initio* models: Realistic NN interaction with tensor, plus minor fudging for separation energy

These look good – Neff '11 ^{3}He$(\alpha, \gamma)^7$Be Fermionic Molecular Dyanamics & Navratil '11 ^{7}Be$(p, \gamma)^8$B from NCSM/RGM

Neff calculation shows non-asymptotic states (initial & final) out to $\sim$ 10 fm

An interesting puzzle in the $A = 7$ systems:

Both Nollett & Neff find E dependences that match both ^{3}He$(\alpha, \gamma)^7$Be & ^{3}H$(\alpha, \gamma)^7$Li data

Nollett matches scale of ^{3}H$(\alpha, \gamma)^7$Li data, 20% too low on ^{3}He$(\alpha, \gamma)^7$Be

Neff matches scale of ^{3}He$(\alpha, \gamma)^7$Be data, 20% too high on ^{3}H$(\alpha, \gamma)^7$Li

Hints that consistency requires ^{3}H$(\alpha, \gamma)^7$Li data to be wrong? There's less of it (disagreement is with "definitive" experiment of Brune)

Quantum Monte Carlo

I can't speak to what lies ahead in most many-body methods, but I can say a bit about quantum Monte Carlo

We've done semi-*ab initio* calculations of $d(\alpha,\gamma)^6$Li, ^{3}H$(\alpha,\gamma)^7$Li, ^{3}He$(\alpha,\gamma)^7$Be (faked our way through scattering)

We've done a fair amount of electroweak transitions in particle-stable states (i.e., Saori's talk)

We've also done some actual scattering (^{4}He $+ n$ published, some preliminary probing of ^{3}H $+ n$)

It would be good to combine these last two developments for electroweak reactions

QMC developments for electroweak reactions

I expect particle-in-box treatment of scattering to be harder for us with extended nuclei (^{2}H, ^{7}Be), but there's no in-principle problem

The ^{3}H $+ n$ scattering benchmark is important for us – compare with Pisa, Lisbon for same interaction

Each of these scattering calculations is a labor-intensive endeavour

Useful approximations may come from recent work on integral relations for ANCs, decay widths, phase shifts (Kievsky '10, '12; Romero-Redondo '11, Suzuki '09, '10, Nollett '11, '12)

ANCs are useful in themselves for some unmeasured cross sections

Integral relations (essentially Pinkston-Satchler overlaps) might provide a path to generate accurate "potential models" from microscopic variational wave functions

Summary

There is a need for interaction between astrophysics & the physics of light nuclei

We need to try to do things that actually are improvements:
Reproducing potential-model results with fancier methods doesn't count

The main need for theory is in data-fitting & *maybe* data-weeding – theory that demonstrably beats all data will be hard to generate

Truly *ab initio* models have finally arrived, but:

Neff α-captures may be one-offs (helped a lot that ^{4}He is 0^+)

It will be much better when we have multiple computational methods to check against each other (not much to check NCSM/RGM now)

QMC methods would have complementary strengths & weaknesses (e.g., three-body forces easier, but calculations generally more labor)