Nuclear reactions in the early universe II

Mark Paris – Los Alamos Nat'l Lab
Theoretical Division
ISSAC 2014 UCSD

Organization

Nuclear reactions in the early universe

- Lectures (Paris/E. Grohs)
  I. Overview of cosmology/Kinetic theory/Big bang nucleosynthesis (BBN)
  II. Scattering & reaction formalism/Neutrino energy transport
- Workshop sessions (E. Grohs/Paris)
  I. BBN exercises: compute Nuclear Statistical Equilibrium/electron fraction
  II. Compute primordial abundances vs $\Omega_b h^2$: code parallelization
- Lecture notes
  - Will be available online (URL TBA)

Outline

Lecture I

- Overview
- Cosmological dynamics in GR
- Big bang nucleosynthesis (BBN)
- Boltzmann equation
  - Flat & curved spacetime

Lecture II

- Unitary reaction network (URN) of light nuclei
- Neutrino energy transport
- Evan Grohs: observations of primordial abundances

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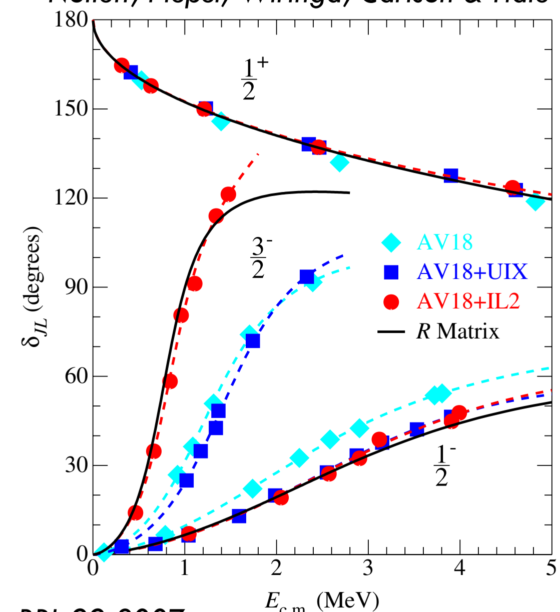
Light nuclear reaction program @ LANL

- Motivation
  - Data sets: σ, σ(θ), $A_i(\theta)$, $C_{i,j}$, $K_i^{i'}$, Σ(γ),…→ T matrix → resonance spectrum
  - ***Unitary*** parametrization of compound nuclear system
  - Applications: astrophysical, nuclear security, inertial confinement fusion, criticality safety, charge-particle transport, nuclear data (ENDF, ENSDF)
- Ab initio
  - Variational MC; Green's function MC
  - GFMC [PRL **99**, 022502 (2007)]
    - n-^{4}He phase shifts
    - comparison GFMC/R-matrix
  - challenge: multichannel
    - eg. nα→nα, nα→dt & dt→dt
- Phenomenology
  - R matrix (2→2 body scatt/reacs)
  - 3–body channels being incorporated

Nollett, Pieper, Wiringa, Carlson & Hale



PRL 99 2007

EDA Analyses of Light Systems

A	System	Channels	Energy Range (MeV)
2	N-N	p+p; n+p, γ+d	0-30 0-40
3	N-d	p+d; n+d	0-4
4	^{4}H ^{4}Li	n+t p+^{3}He	0-20
	^{4}He	p+t n+^{3}He d+d	0-11 0-10 0-10
5	^{5}He	n+α d+t ^{5}He+γ	0-28 0-10
	^{5}Li	p+α d+^{3}He	0-24 0-1.4

Analyses of Light Systems, Cont.

A	System (Channels)
6	^{6}He (^{5}He+n, t+t); ^{6}Li (d+^{4}He, t+^{3}He); ^{6}Be (^{5}Li+p, ^{3}He+^{3}He)
7	^{7}Li (t+^{4}He, n+^{6}Li); ^{7}Be (γ+^{7}Be, ^{3}He+^{4}He, p+^{6}Li)
8	^{8}Be (^{4}He+^{4}He, p+^{7}Li, n+^{7}Be, p+^{7}Li*, n+^{7}Be*, d+^{6}Li)
9	^{9}Be (^{8}Be+n, d+^{7}Li, t+^{6}Li); ^{9}B (γ+^{9}B, ^{8}Be+p, d+^{7}Be, ^{3}He+^{6}Li)
10	^{10}Be (n+^{9}Be, ^{6}He+α, ^{8}Be+nn, t+^{7}Li); ^{10}B (α+^{6}Li, p+^{9}Be, ^{3}He+^{7}Li)
11	^{11}B (α+^{7}Li, α+^{7}Li*, ^{8}Be+t, n+^{10}B); ^{11}C (α+^{7}Be, p+^{10}B)
12	^{12}C (^{8}Be+α, p+^{11}B)
13	^{13}C (n+^{12}C, n+^{12}C*)
14	^{14}C (n+^{13}C)
15	^{15}N (p+^{14}C, n+^{14}N, α+^{11}B)
16	^{16}O (γ+^{16}O, α+^{12}C)
17	^{17}O (n+^{16}O, α+^{13}C)
18	^{18}Ne (p+^{17}F, p+^{17}F*, α+^{14}O)

26 tabulated analyses

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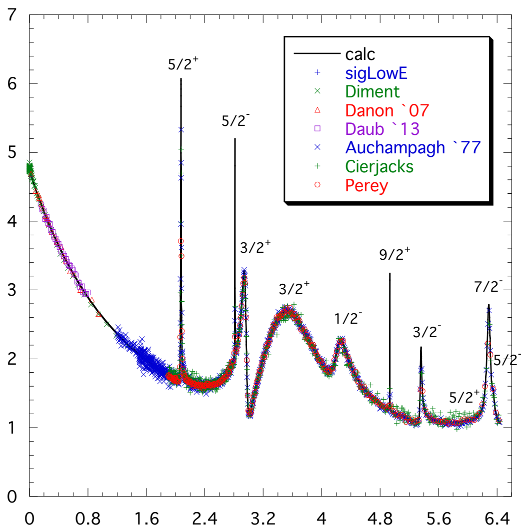
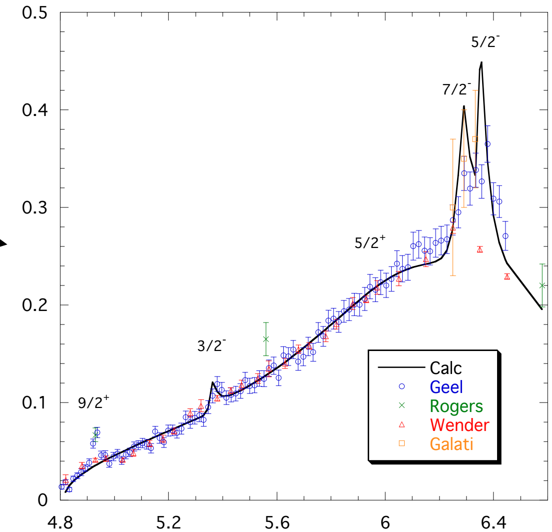
^{13,14}C system analyses: σ_T (b) vs. E_n (MeV)

n+^{12}C Total Cross Section

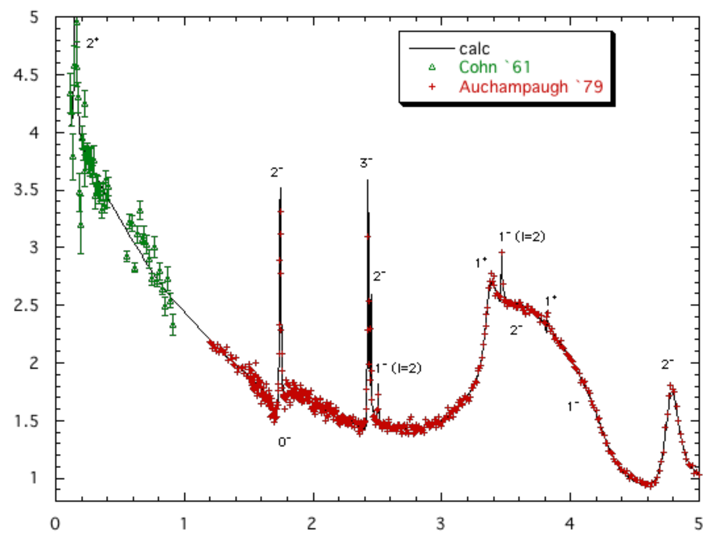


Two-channel analysis

^{12}C(n,n') Cross Section



n+^{13}C Total Cross Section



Analyses by GMH/MWP

Single-channel analysis

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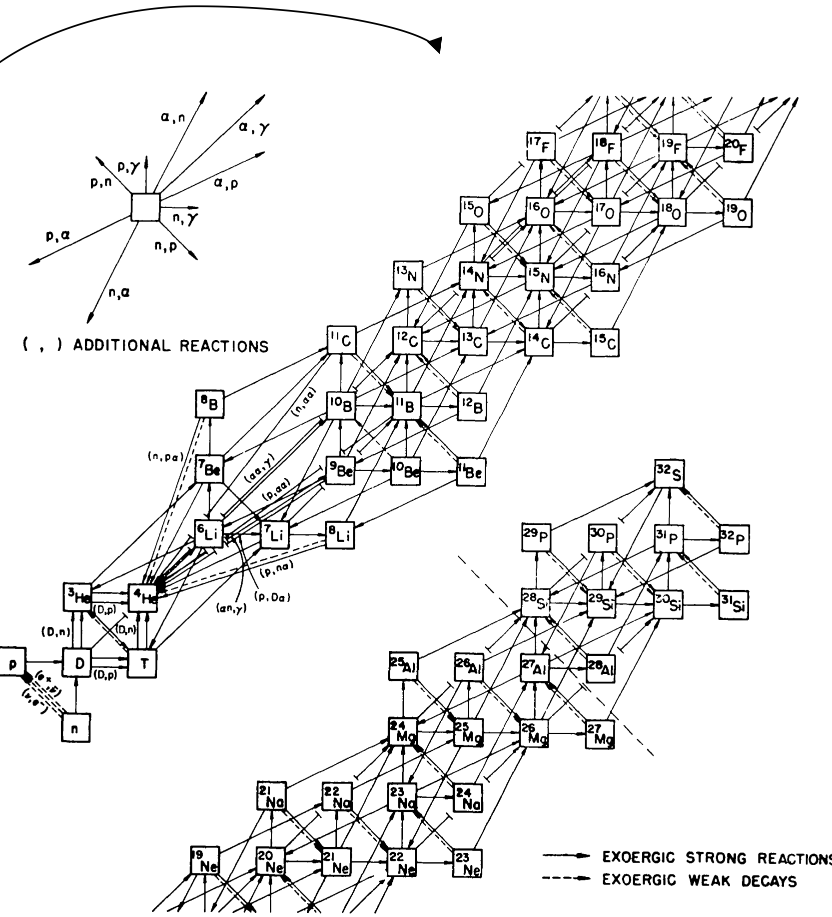
Unitary, self-consistent primordial nucleosynthesis

- State of standard big-bang nucleosynthesis (BBN)
  - d & ^{4}He abundances: signature success cosmology+nucl astro+astroparticle
    - but there's at least one Lithium (^{7}Li) Problem [^{6}Li too? See: *Lind et.al. 2013*]
  - coming *precision* observations of d, ^{4}He, η , N_{eff} demand new BBN capabilities
  - resolution of ^{7}Li problem:
    - observational/stellar astrophysics?
    - ^{7}Li controversial anomaly: nuclear physics solution?
    - new physics?
- Advance BBN as a tool for precision cosmology
  - incorporate unitarity into strong & electroweak interactions (next slide)
  - couple unitary reaction network (URN) to full Boltzmann transport code
    - neutrino energy distribution function evolution/transport code
    - fully coupled to nuclear reaction network
    - calculate light primordial element abundance for non-standard BBN
      - active-sterile ν mixing
      - massive particle out-of-equilibrium decays→energetic active SM particles
  - Produce tools/codes for nuc-astro-particle community: test new physics w/BBN
    - existing codes are based on Wagoner's (1969) code

Nuclear reaction network

- Single-process (non-unitary) analysis
  - $\sigma_{\alpha\beta}(E) \pm \delta\sigma_{\alpha\beta}(E)$ from expt
  - fit form (non-res+narrow res) to $\sigma_{\alpha\beta}(E)$
  - compute $\langle \sigma v \rangle(T)$ →reactivity→network
  - NB: norm. systematics can be large
    - ^{17}O case (below)
- Multi-channel (unitary) analysis
  - Construct unitary parametrization
    - R-matrix (Wigner-Eisenbud '47)
  - simultaneous fit of unpolarized/pol'd scatt/reac data→determine *T*(or *S*)matrix
  - determines a unitary reaction network (URN) for analyzed compound systems



Wagoner ApJSuppl '69

Boltzmann eq., cross sections, thermal averages

- Boltzmann equation
  - Toy model, single reaction → $\frac{1}{a^3}\frac{d(n_1 a^3)}{dt} = -\langle\sigma v\rangle \left\{ n_1 n_2 - n_3 n_4 \frac{n_1^{(0)} n_2^{(0)}}{n_3^{(0)} n_4^{(0)}} \right\}$
    - Full code has 144 reactions
  - Thermal (Maxwellian) averaged flux(v)*cross section

$$\langle\sigma v\rangle = \left(\frac{8}{\pi\mu}\right)^{1/2} \left(\frac{1}{kT}\right)^{3/2} \int_0^\infty dE\, E\, \sigma_{12\to 34}(E)\, e^{-E/kT}$$

- Energy dependent, angle-integrated cross section is determined from data; Ranking worst → best:
  - Guess: sometimes necessary when no data/calc. (e.g. TALYS)
  - Parametrize resonance data: undesirable since res/non-res related by unitarity; results in model dependent reaction cross section
  - Fit to experimental cross section: can be OK; normalization often problematic; subject to sometimes large systematic uncertainty
  - Unitary theory: multichannel R-matrix: sure-fire; downside: need multichannel data

Observables from transition (T) matrix

- Scattering matrix: QM amplitude for (i)nitial → (f)inal

$$\langle \mathrm{f}|S(E)|\mathrm{i}\rangle = \delta_{fi} + 2iT_{fi}(E)$$

- All observables ~ T matrix bilinears
  - unpolarized differential cross section

$$\frac{d\sigma_{fi}}{d\Omega} = \frac{4\pi}{k^2}\frac{1}{N_{spins,i}}\sum_{spins,f}|T_{fi}|^2$$

  - polarization asymmetry

$$P = \frac{\sigma_{\uparrow\uparrow} - \sigma_{\downarrow\uparrow}}{\sigma_{\uparrow\uparrow} + \sigma_{\downarrow\uparrow}}$$

- Diff cross section → int'd cross section → thermal averaged

$$\sigma(E) = \int d\Omega \, \frac{d\sigma}{d\Omega} \rightarrow \langle \sigma v\rangle$$

Unitarity: consequences on T matrix

$$\left.\begin{array}{ll}\delta_{fi} & = \sum_n S^\dagger_{fn} S_{ni} \\ S_{fi} & = \delta_{fi} + 2i\rho_f T_{fi} \\ \rho_n & = \delta(H_0 - E_n)\end{array}\right\}$$

$$T_{fi} - T^\dagger_{fi} = 2i \sum_n T^\dagger_{fn} \rho_n T_{ni}$$

NB: unitarity implies *optical theorem* $\sigma_{\text{tot}} = \frac{4\pi}{k} \text{Im } f(0)$; but *not only* the O.T.

- **Implications of unitarity constraint on transition matrix**
  1. Doesn't uniquely determine T_{ij}; highly restrictive, however

     Elastic: $\text{Im } T^{-1}_{11} = -\rho_1$ (assuming T & P invariance)

     Multichannel: $\text{Im } \mathbf{T}^{-1} = -\boldsymbol{\rho}$
  2. Unitarity violating transformations
     - cannot scale ***any*** set: $T_{ij} \to \alpha_{ij} T_{ij} \qquad \alpha_{ij} \in \mathbb{R}$
     - cannot rotate ***any*** set: $T_{ij} \to e^{i\theta_{ij}} T_{ij} \qquad \theta_{ij} \in \mathbb{R}$

     ★ consequence of linear 'LHS' $\propto$ quadratic 'RHS'
  3. Unitary parametrizations constrain the experimental data itself

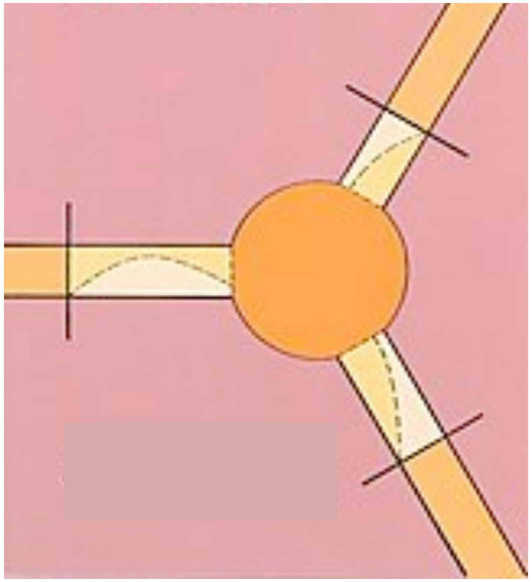
     ★ *normalization*, in particular

     ★ case studies: ^{17}O & ^{9}B compound system

Most important feature: linear ~ quadratic

Basics of R-matrix (data ⇨ amplitudes)

- Assumptions (cf. Lane & Thomas RMP ‘58)
  a) Non-relativistic QM (L&T58); LANL-EDA uses rel.
  b) Two-body channels only (‘c’); aux. spectra code
  c) Conservation of N, Z
  d) Finite radius a_c beyond V_{pol}≈0; sharp boundaries
- Separated pairs, “channels”
  - A nucleons → (A_1,A_2)
  - $c=\{\alpha s_1 m_1 s_2 m_2\} \to \{\alpha(s_1 s_2) s m_s \ell m_\ell\} \to \{\alpha(s_1 s_2) s\ell, JM\}$
  - Assume $a_c = a_\alpha$ ➔ many c have same channel in configuration space
- Channel surface
  - Consider configuration space of 3A dimensions
  - Set of points: $\cup_c r_{\alpha(c)} = a_{\alpha(c)}$
  - Surfaces coincide but assumed to have negl. prob.
  - Channels are cylinders normal to channel surf.



Example: ^{8}Be compound system

$$\mathrm{Li}^7+p \to \mathrm{Be}^{8*} \to \begin{cases} \mathrm{Li}^7+p \text{ (elastic scattering)} \\ \mathrm{Li}^{7*}+p' \text{ (inelastic scattering)} \\ \mathrm{Be}^7+n \\ \mathrm{Li}^6+d \\ \mathrm{He}^4+\mathrm{He}^4 \\ \mathrm{Be}^8+\text{photon, etc. (capture)} \end{cases}$$

R-matrix formalism

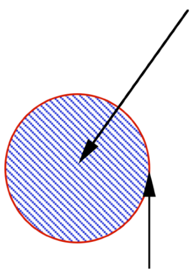
INTERIOR (Many-Body) REGION
(Microscopic Calculations)

ASYMPTOTIC REGION
(S-matrix, phase shifts, etc.)

$$H + \mathcal{L}_B$$

compact, hermitian operator with real, discrete spectrum; eigenfunctions in Hilbert space

$$(r_{c'}|\psi_c^+\rangle = -I_{c'}(r_{c'})\delta_{c'c} + O_{c'}(r_{c'})S_{c'c}$$



$$|\psi^+) = (H + \mathcal{L}_B - E)^{-1}\mathcal{L}_B|\psi^+)$$

Measurements

SURFACE

$$\mathcal{L}_B = \sum_c |c)(c|\left(\frac{\partial}{\partial r_c} r_c - B_c\right),$$

$$(\mathbf{r}_c|c) = \frac{\hbar}{\sqrt{2\mu_c a_c}}\frac{\delta(r_c - a_c)}{r_c}[(\phi_{s_1}^{\mu_1} \otimes \phi_{s_2}^{\mu_2})_s^{\mu} \otimes Y_l^m(\hat{\mathbf{r}}_c)]_J^M$$

$$R_{c'c} = (c'|(H + \mathcal{L}_B - E)^{-1}|c) = \sum_\lambda \frac{(c'|\lambda)(\lambda|c)}{E_\lambda - E}$$

Bloch operator $\mathcal{L}_B = \sum_c |c)(c|\left[\frac{\partial}{\partial r_c} r_c - B_c\right]$ ensures Hermiticity of Hamiltonian restricted to internal region

- R-matrix theory: unitary, multichannel parametrization of (not just resonance) data
- Interior/Exterior regions
  - Interior: strong interactions
  - Exterior: Coulomb/non-polarizing interactions
  - Channel surface

$$\mathcal{S}_c : r_c = a_c \qquad \mathcal{S} = \sum_c \mathcal{S}_c$$

- R-matrix elements
  - Projections on channel surface functions $(\mathbf{r}_c|c)$ of Green's function
    $$G_B = [H + \mathcal{L}_B - E]^{-1}$$
  - Boundary conditions
    $$B_c = \frac{1}{u_c(a_c)}\frac{du_c}{dr_c}\bigg|_{r_c=a_c}$$

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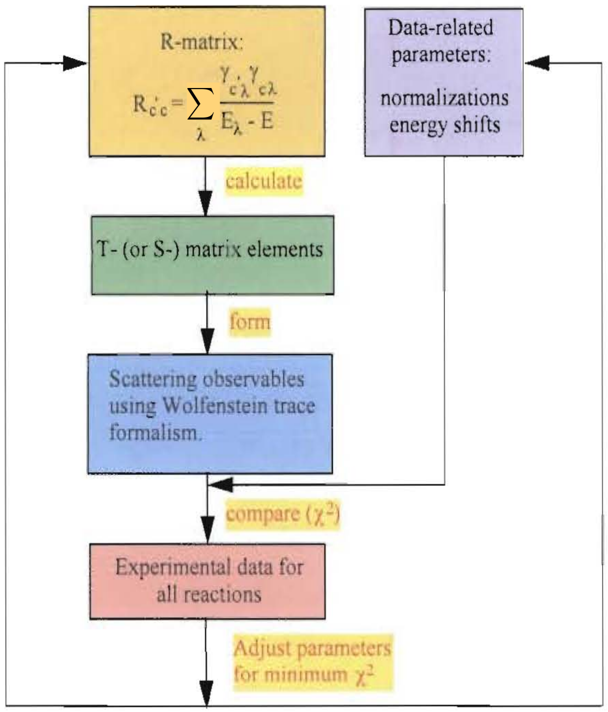
R-matrix implementation in EDA

- EDA = Energy Dependent Analysis
  - Adjust E_λ & $\gamma_{c\lambda}$
- Any number of two-body channels
  - Arbitrary spins, masses, charges (zero mass)
- Scattering observables
  - Wolfenstein trace formalism
- Data
  - Normalization
  - Energy shifts
  - Energy resolution/spread
- Fit (rank-1 var. metric) solution

$$\chi^2_{EDA} = \sum_i \left[\frac{nX_i(\mathbf{p}) - R_i}{\delta R_i}\right]^2 + \left[\frac{nS-1}{\delta S/S}\right]^2$$

- *Covariance determined*



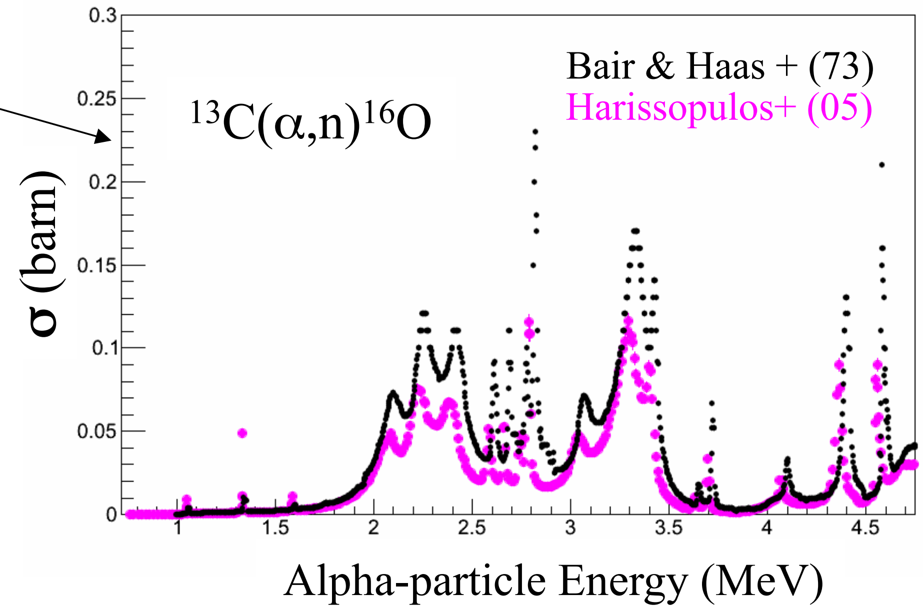
^{17}O analysis configuration

Channel	a_c (fm)	l_{max}
$n+^{16}O$	4.3	4
$\alpha+^{13}C$	5.4	5

Reaction	Energies (MeV)	# data points	Data types
$^{16}O(n,n)^{16}O$	$E_n = 0 – 7$	2718	σ_T, $\sigma(\theta)$, $P_n(\theta)$
$^{16}O(n,\alpha)^{13}C$	$E_n = 2.35 – 5$	850	σ_{int}, $\sigma(\theta)$, $A_n(\theta)$
$^{13}C(\alpha,n)^{16}O$	$E_\alpha = 0 – 5.4$	874	σ_{int}
$^{13}C(\alpha,\alpha)^{13}C$	$E_\alpha = 2 – 5.7$	1296	$\sigma(\theta)$
total		5738	8

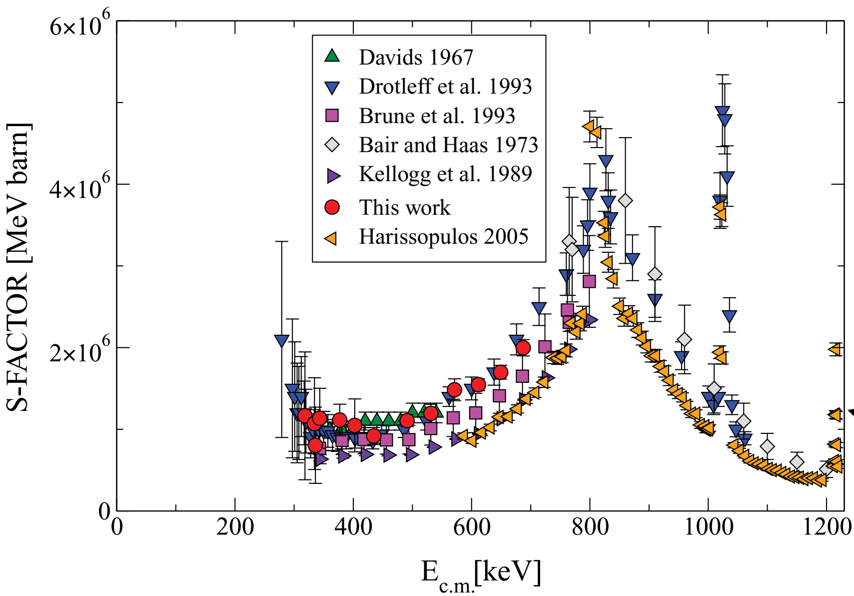
^{17}O compound system: experimental status

Recent (Harissopulos '05) measurement $^{13}C(\alpha,n)^{16}O$ vs. older (Bair & Haas '73)



Credit: S. Kunieda

Heil et.al. PRC **78** 025803 ('08)



Harissopulos(05) data 2/3*B&H(73)
Heil(08) data consistent with B&H

Tempting to conclude that B&H73 was right all along!

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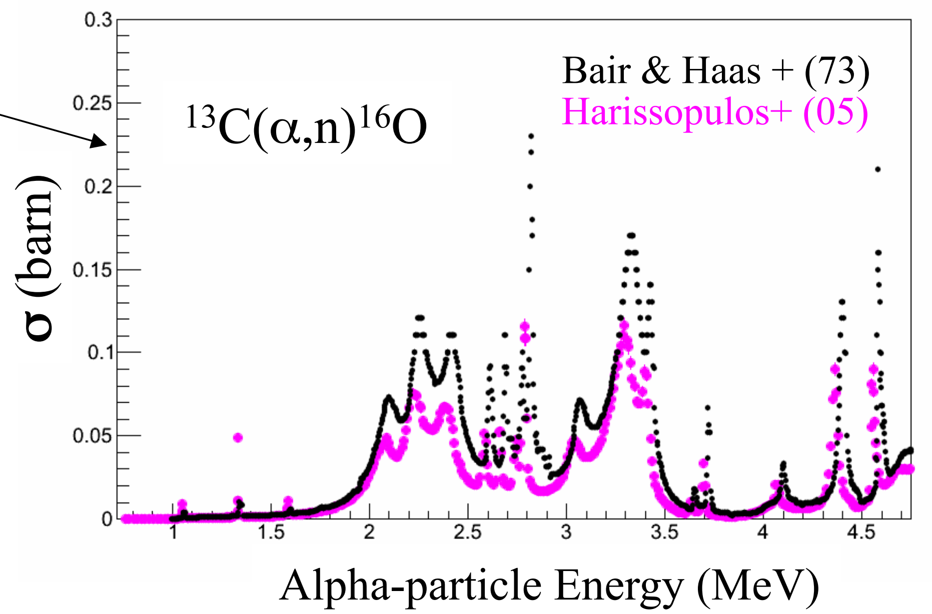
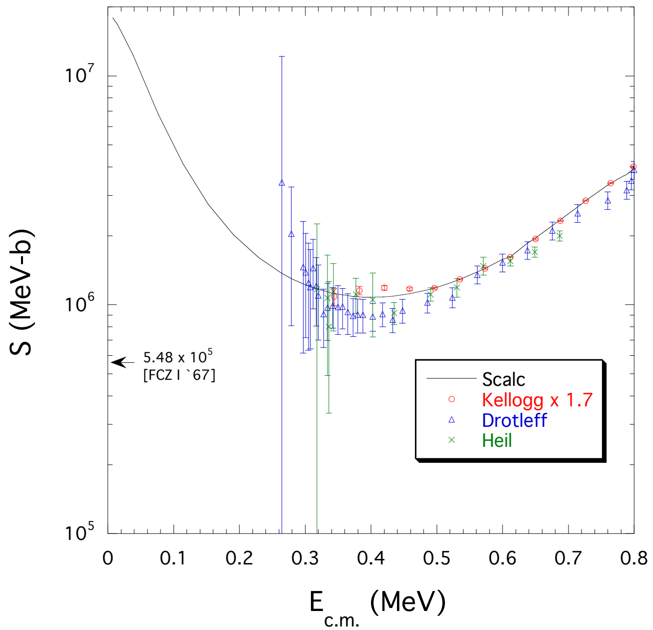


Credit: S. Kunieda

Hale (2013, unpublished)



Subthreshold ½$^+$

deep min in σ_T

$S(0) >> S_{FCZ67}(0)$

Tempting to conclude that B&H73 was right all along!

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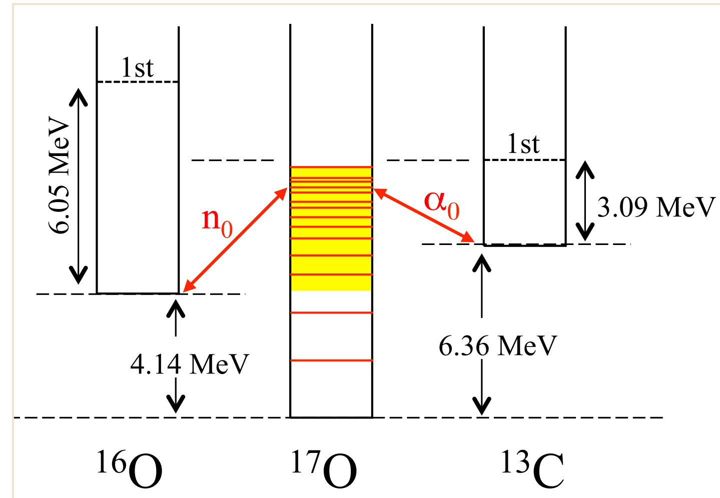
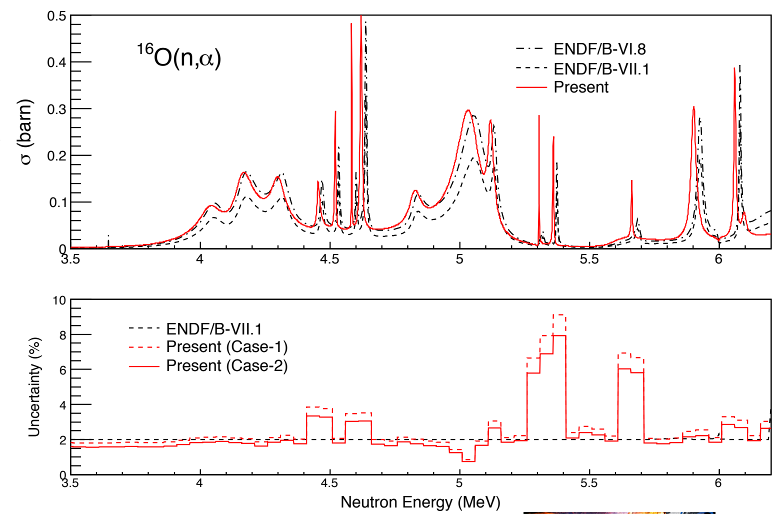
R-matrix analyses support B&H73/Heil08

- LANL R-matrix fit to Bair&Haas73
  - two-channel fit: (^{16}O,n) & (^{13}C, α)
    - $\ell_n = 0, \ldots, 4; \quad \ell_\alpha = 0, \ldots, 5$
  - data included: $\sigma_T(E)$
    - ^{16}O(n,n), ^{16}O(n, α), ^{13}C(α ,n)
      - $\sigma_{el}, d\sigma/d\Omega, A_y$
    - χ^2 min: normalizations float
  - Test Hariss05 data
    - remove B&H73/Heil08 data
    - fix Hariss05 norm to unity
      - unable to obtain fit χ^2 (< 2.0)
    - now allow Hariss05 norm to float
      - requires scale factor of ~1.5, consistent with B&H73
- Kunieda/Kawano analysis [2013]
  - cf. LANL R-matrix(EDA)/ENDF/B-VI.8
  - with independent R-matrix code
  - ***Right to conclude B&H73 data correct on the basis of unitarity!***

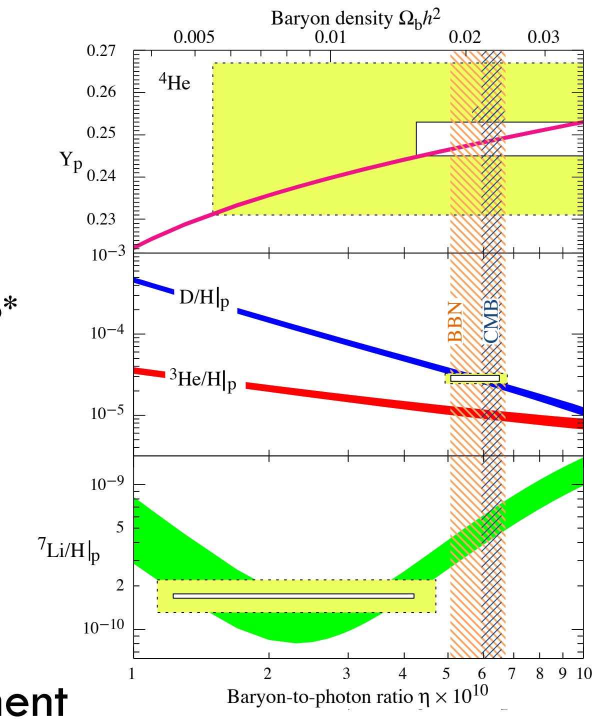


Credit: S. Kunieda



Toward a unitary reaction network for BBN

- Primordial nucleosynthesis
  - *Can unitarity play a role in precision BBN?*
  - D,^{4}He abund. agree with theo/expl uncertainties
  - At η_{wmap} (CMB) ^{7}Li/H$|_{BBN}$ ~ (2.2–4.2)*^{7}Li/H$|_{halo*}$
  - Discrepancy ~ 4.5–5.5 σ → the "Li problem"
- Resonant destruction ^{7}Li
  - Prod. mass 7 "well understood"; destruction not
  - Cyburt & Pospelov *arXiv:0906.4373; IJMPE, 21(2012)*
    - ^{7}Be(d,p)$\alpha\alpha$ & ^{7}Be(d,γ)^{9}B resonant enhancement
    - Identify ^{9}B $E_{5/2+}$≃16.7 MeV≃E_{thr}(d+^{7}Be)+200 keV
      - *Near threshold*
    - (E_r,Γ_d)≃(170–220,10–40) keV solve Li problem
  - 'Large' widths
    - Conclude "large channel radius" required



NB: both approaches assume validity of TUNL-NDG tables

^{9}B analysis: included data

- ^{6}Li+^{3}He elastic *Buzhinski et.al., Izv. Rossiiskoi Akademii Nauk, Ser.Fiz., Vol.43, p.158 (1979)*
  - Differential cross section
  - 1.30 MeV < E(^{3}He) < 1.97 MeV
- ^{6}Li+^{3}He $\rightarrow$ p+^{8}Be* *Elwyn et.al., Phys. Rev. C 22, 1406 (1980)*
  - Integrated cross section
  - Quasi-two-body, excited-state, summed final channel
  - 0.66 MeV < E(^{3}He) < 5.00 MeV
- ^{6}Li+^{3}He $\rightarrow$ d+^{7}Be *D.W. Barr & J.S. Gilmore, unpublished (1965)*
  - Integrated cross section
  - 0.42 MeV < E(^{3}He) < 4.94 MeV
- ^{6}Li+^{3}He $\rightarrow \gamma$ +^{9}B *Aleksic & Popic, Fizika 10, 273-278 (1978)*
  - Integrated cross section
  - 0.7 MeV < E(^{3}He) < 0.825 MeV
  - New to ^{9}B analysis
- New evaluation
  - Separate ^{8}Be* states
    - 2^{+}@200 keV [16.9 MeV], 1^{+}@650 keV [17.6 MeV], 1^{+}@1.1 MeV[18.2 MeV]
  - n+^{8}B: E_{thresh}(^{3}He) = 3 MeV
  - Simultaneous analysis with ^{9}Be mirror system

Data accessed via EXFOR/CSISRS database (C4 format)

R-matrix configuration in EDA code

Hadronic channels (in blue, not included)

$A_1A_2{}^{\pi}$	$^3\mathrm{He}^6\mathrm{Li}^+$(1)		$p^8\mathrm{Be}^{*+}$(2)		$d^7\mathrm{Be}^-$(3)		
ℓ \ S	$\frac{3}{2}$	$\frac{1}{2}$	$\frac{5}{2}$	$\frac{3}{2}$	$\frac{5}{2}$	$\frac{3}{2}$	$\frac{1}{2}$
0	$^4S_{3/2}$	$^2S_{1/2}$	$^6S_{5/2}$	$^4S_{3/2}$	$^6S_{5/2}$	$^4S_{3/2}$	$^2S_{1/2}$
1	$^4P_{5/2,3/2,1/2}$	$^2P_{3/2,1/2}$	$^6P_{7/2,5/2,3/2}$	$^4P_{5/2,3/2,1/2}$	$^6P_{7/2,5/2,3/2}$	$^4P_{5/2,3/2,1/2}$	$^2P_{3/2,1/2}$
2	$^4D_{7/2,5/2,3/2,1/2}$	$^2D_{5/2,3/2}$	$^6D_{9/2,7/2,5/2,3/2,1/2}$	$^4D_{7/2,5/2,3/2,1/2}$	$^6D_{9/2,7/2,5/2,3/2,1/2}$	$^4D_{7/2,5/2,3/2,1/2}$	$^2D_{5/2,3/2}$
E_{thr}(CM, MeV)	16.6		16.7		16.5		

Electromagnetic channel: $\gamma + {}^9B \rightarrow E_1^{3/2}, M_1^{5/2}, M_1^{3/2}, M_1^{1/2}, E_1^{5/2}, E_1^{1/2}$

Full model space:
state number;
channel pair;
LS; J; channel
radius [fm]

1	1	4s	3/2	7.50000000f	20	1	4p	1/2	7.50000000f
2	1	4d	3/2	7.50000000f	21	1	2p	1/2	7.50000000f
3	1	2d	3/2	7.50000000f	22	2	4p	1/2	5.50000000f
4	2	4s	3/2	5.50000000f	23	3	2s	1/2	7.00000000f
5	3	6p	3/2	7.00000000f	24	4	M1	1/2	50.00000000f
6	3	4p	3/2	7.00000000f	25	1	4d	7/2	7.50000000f
7	3	2p	3/2	7.00000000f	26	3	6p	7/2	7.00000000f
8	4	E1	3/2	50.00000000f	27	1	4d	5/2	7.50000000f
9	1	4p	5/2	7.50000000f	28	1	2d	5/2	7.50000000f
10	2	6p	5/2	5.50000000f	29	2	6s	5/2	5.50000000f
11	2	4p	5/2	5.50000000f	30	3	6p	5/2	7.00000000f
12	3	6s	5/2	7.00000000f	31	3	4p	5/2	7.00000000f
13	4	M1	5/2	50.00000000f	32	4	E1	5/2	50.00000000f
14	1	4p	3/2	7.50000000f	33	1	4d	1/2	7.50000000f
15	1	2p	3/2	7.50000000f	34	1	2s	1/2	7.50000000f
16	2	6p	3/2	5.50000000f	35	3	4p	1/2	7.00000000f
17	2	4p	3/2	5.50000000f	36	3	2p	1/2	7.00000000f
18	3	4s	3/2	7.00000000f	37	4	E1	1/2	50.00000000f
19	4	M1	3/2	50.00000000f	38	2	6p	7/2	5.50000000f

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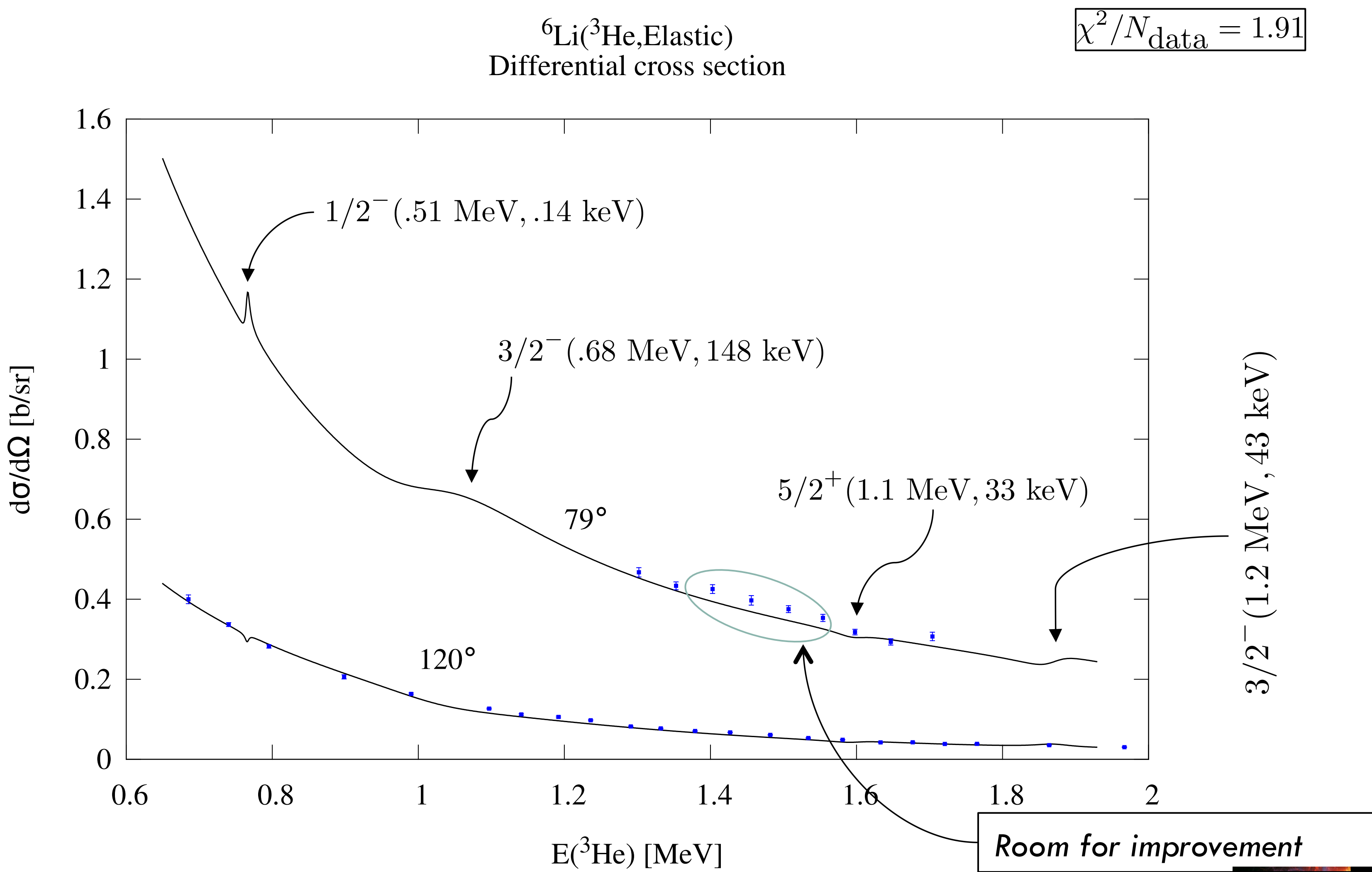
Observable fit: ^{3}He+^{6}Li elastic DCS



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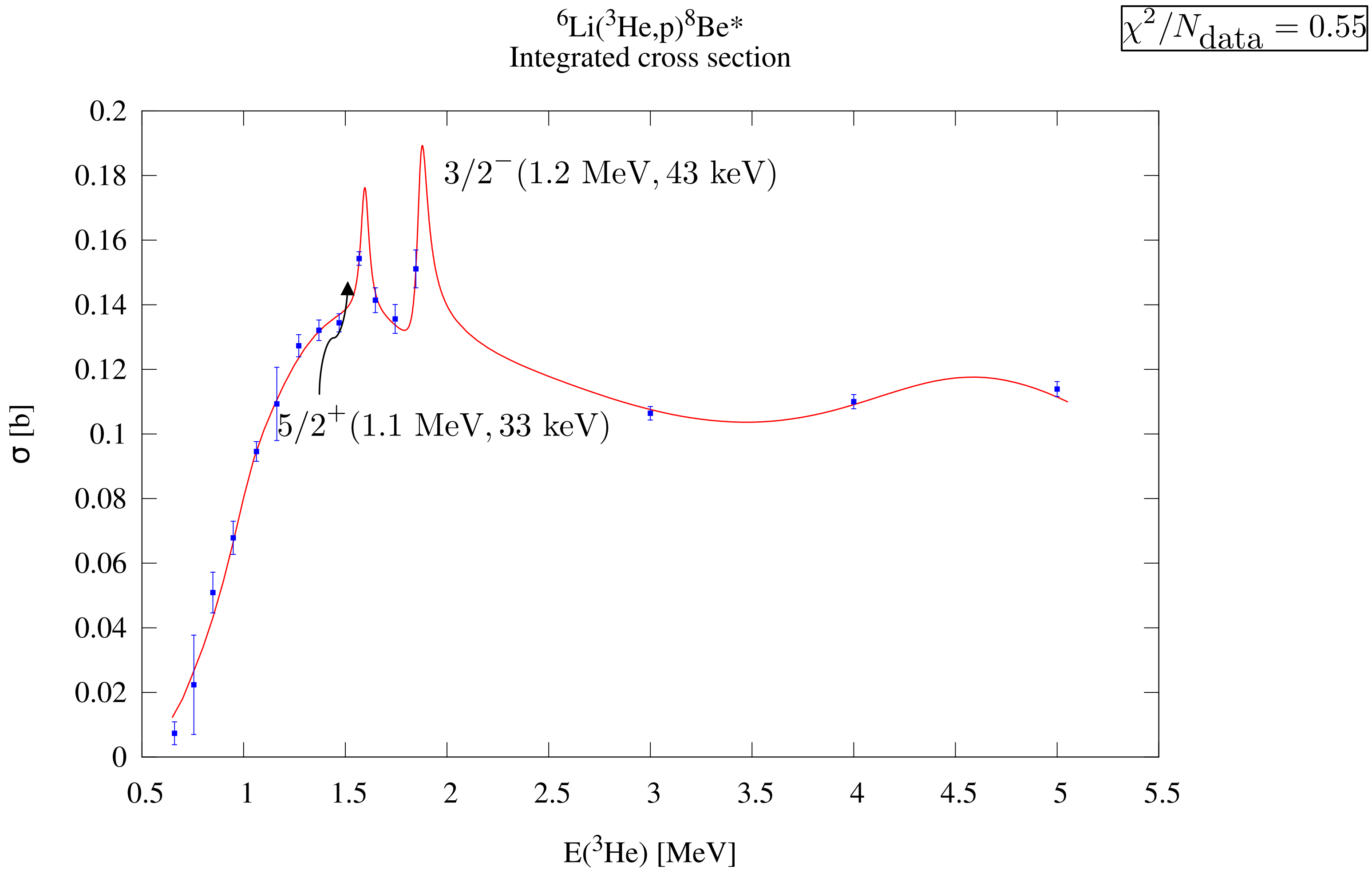
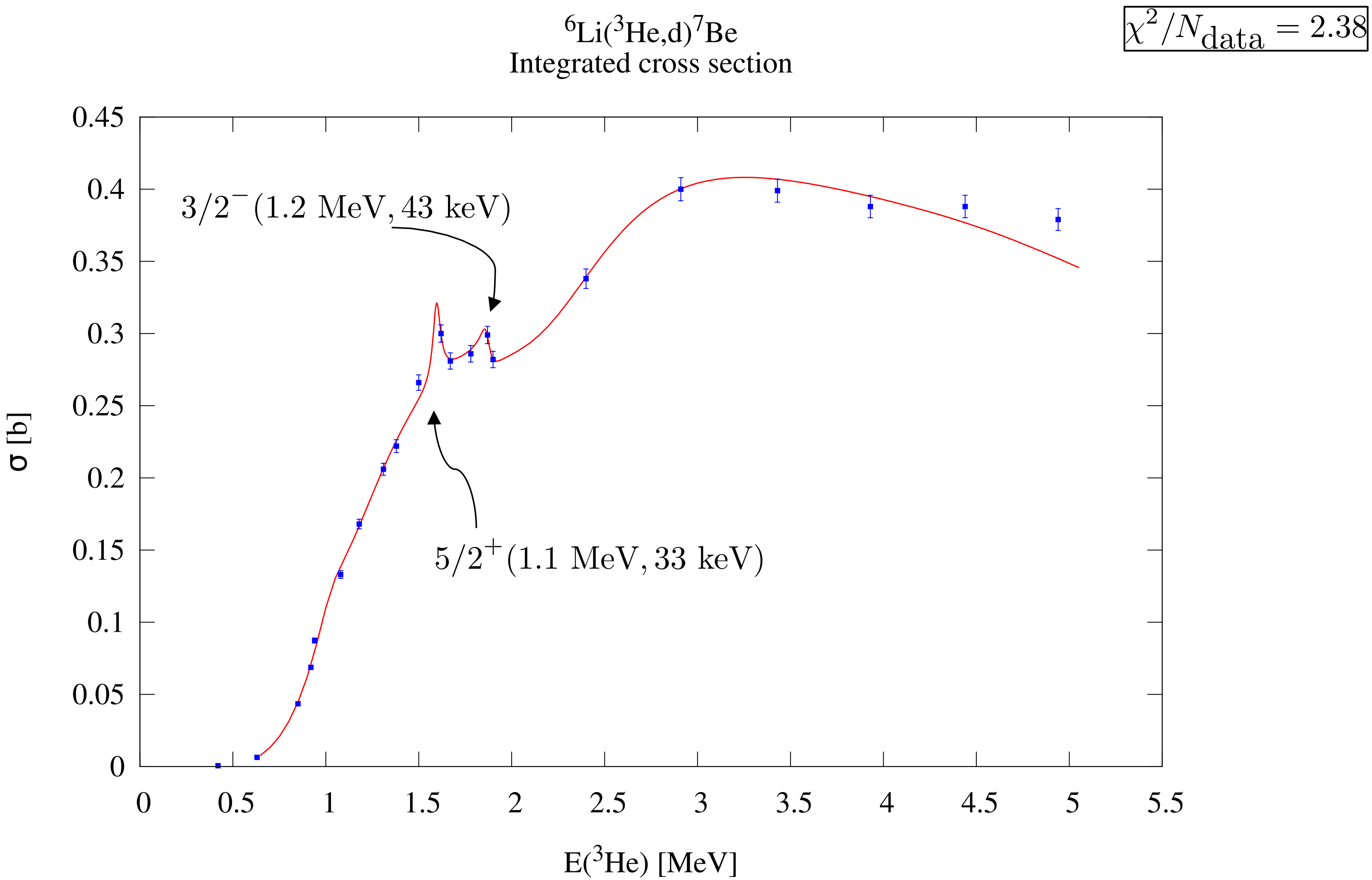
Observable fit: ^{6}Li(^{3}He,p)^{8}Be* integrated x-sec

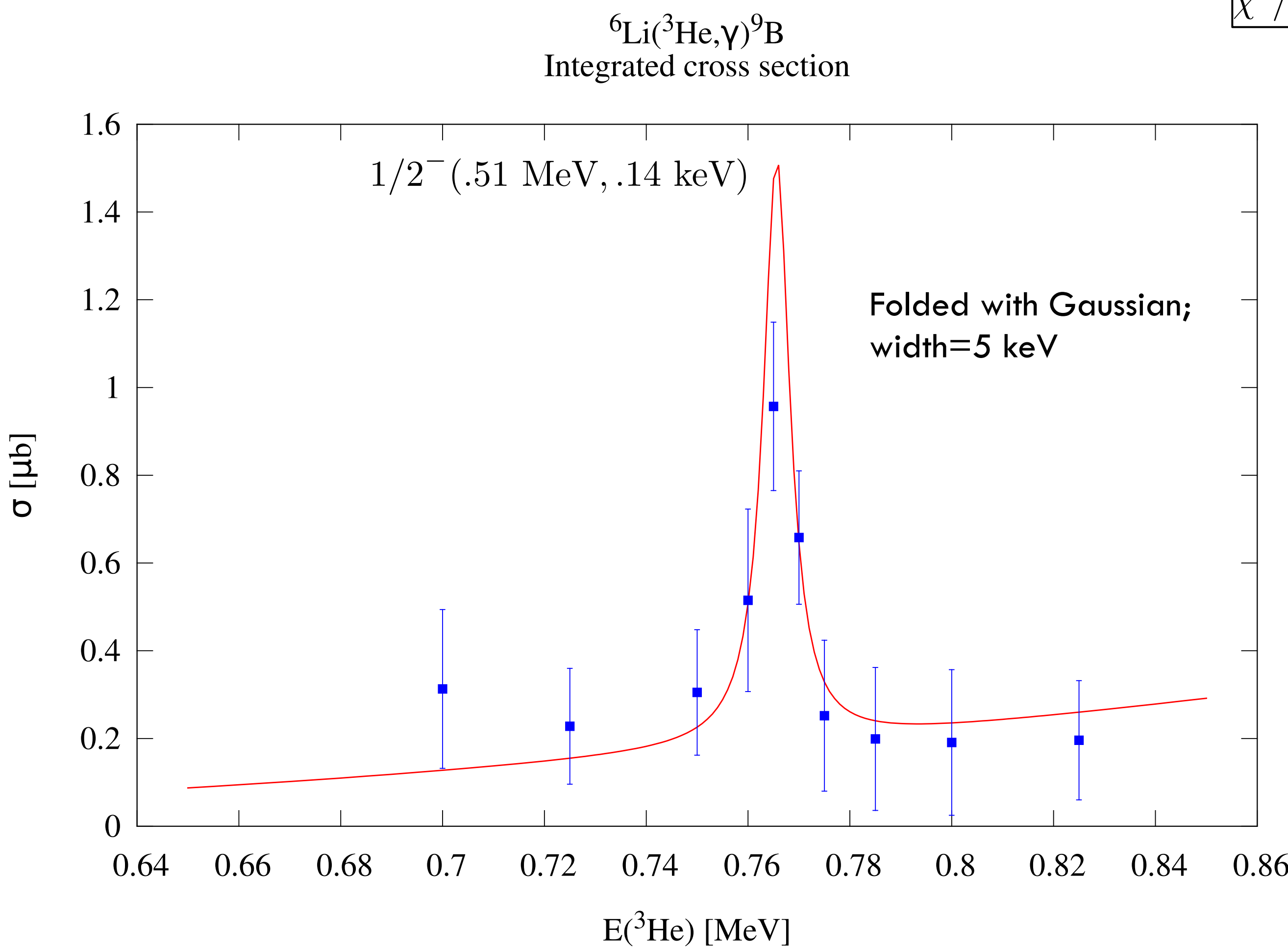


Observable fit: ^{6}Li(^{3}He,d)^{7}Be integrated x-sec



Observable fit: $^6Li(^3He, \gamma)^9B$ integrated x-sec

$\chi^2/N_{\mathrm{data}} = 0.37$



^9B analysis result: resonance structure

Ex(MeV)	Jpi	Gamma(keV)	Er(MeV)	ImEr(MeV)	E(3He)	Strength
16.46539	1/2-	768.46	-.1369	-0.3842	-0.2054	0.06 weak
17.11317	1/2-	0.14	0.5109	-0.6771E-04	0.7664	1.00 strong
17.20115	5/2-	871.63	0.5989	-0.4358	0.8984	0.40 weak
17.28086	3/2-	147.78	0.6785	-0.0739	1.0178	0.77 strong
17.66538	5/2+	33.33	1.0631	-0.0167	1.5947	0.98 strong
17.83619	7/2+	2036.21	1.2339	-1.0181	1.8509	0.15 weak
17.84773	3/2-	42.52	1.2454	-0.0213	1.8681	0.97 strong
18.04821	3/2+	767.11	1.4459	-0.3836	2.1689	0.54 weak
18.42292	1/2+	5446.32	1.8206	-2.7232	2.7309	0.03 weak
18.67716	1/2-	10278.41	2.0749	-5.1392	3.1124	0.15 weak
19.60923	3/2-	1478.22	3.0069	-0.7391	4.5104	0.52 weak

TUNL-NDG/ENSDF parameters

E_x [a] (MeV ± keV)	$J^\pi; T$	$\Gamma_{c.m.}$ (keV)	Decay
16.024 ± 25	$T = (\frac{1}{2})$	180 ± 16	
16.71 ± 100 [h]	$(\frac{5}{2}^+); (\frac{1}{2})$		
17.076 ± 4	$\frac{1}{2}^-; \frac{3}{2}$	22 ± 5	$(\gamma, {}^3He)$
17.190 ± 25		120 ± 40	p, d, ^3He
17.54 ± 100 [h,i]	$(\frac{7}{2}^+); (\frac{1}{2})$		
17.637 ± 10 [i]		71 ± 8	p, d, ^3He, α

NB: no strong resonance seen ~100 keV of $^3He+^6Li$ threshold

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Summary

- Provided overview of current work in the LANL light nuclear reaction program
- Emphasize the utility of multichannel, unitary parametrization of light nuc data
  - ^{17}O norm issue: are Bair & Haas '73 data conclusive?
  - ^{9}B resonance spectrum:
    - no resonances in ^{9}B that reside within ~200 (~100) keV of the d+^{7}Be (^{3}He+^{6}Li) threshold with 'large' widths 10—40 keV
  - Appears to rule out scenarios considered by *Cyburt & Pospelov (2009)* that low-lying, robust resonance in ^{9}B could explain the "Li problem"

End Lecture II

BSMs scenarios

- New particles: WIMPs, Axion, SUSY, …
- GR modifications: new propagating DsOF; scalar-tensor
- Modifications of Cosmological SM: non-zero ν chem. pot.; non-equil. phenomena
- Variation of fundamental couplings
- Cosmic variance
- Neutrino sector
  - solar, atmospheric & reactor neutrinos oscillation experiment prove at least two neutrinos have mass
  - "sterile neutrinos": mass → neutrinos have left- & right-hand spin states
    - only left-hand neutrinos interact in SM
  - Massless neutrinos (recall)
    - have only one spin state

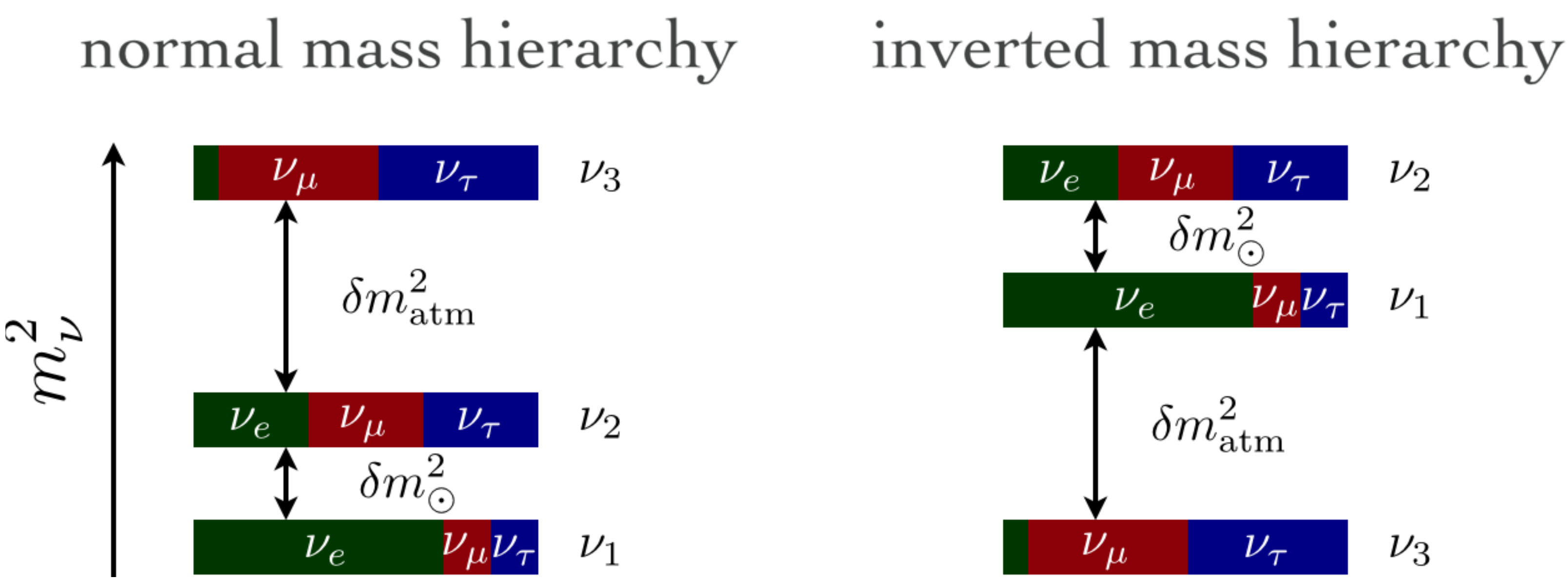
Neutrino Mass: what we know and don't know

We know the *mass-squared* differences:

$$\begin{cases} \delta m_{\odot}^2 \approx 7.6 \times 10^{-5}\,\mathrm{eV}^2 \\ \delta m_{\mathrm{atm}}^2 \approx 2.4 \times 10^{-3}\,\mathrm{eV}^2 \end{cases}$$

$$e.g., \quad \delta m_{21}^2 \equiv m_2^2 - m_1^2$$

We *do not* know the *absolute masses* or the *mass hierarchy*:



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Neutrino mass mixing 101

- Take-away message from experiments: "neutrinos have mass"
  - neutrino flavor eigenstates $|\nu_e\rangle, |\nu_\mu\rangle, |\nu_\tau\rangle$
    - interact via left-hand (L) components $\bar{\psi}_e \gamma_\mu \frac{1}{2}(1-\gamma_5)\psi_{\nu_e} = \bar{\psi}_{e,L}\gamma_\mu \psi_{e,L}$
    - Mass term, however, mixes L & R: $\bar{\psi}_e \psi_e = \bar{\psi}_{e,R}\psi_{e,L} + \bar{\psi}_{e,L}\psi_{e,R}$

$$\begin{pmatrix} |\nu_e\rangle \\ |\nu_\mu\rangle \\ |\nu_\tau\rangle \end{pmatrix} = U_m \begin{pmatrix} |\nu_1\rangle \\ |\nu_2\rangle \\ |\nu_3\rangle \end{pmatrix} \qquad U_m = U_{23}\, U_{13}\, U_{12}\, M$$

- Mass mixing matrix
  - Pontecorvo-Maki-Nakagawa-Sakata
  - neutrino flavor oscillation: confirmed!

$$U_{23} \equiv \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix}$$

$$U_{13} \equiv \begin{pmatrix} \cos\theta_{13} & 0 & e^{i\delta}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{-i\delta}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix}$$

$$U_{12} \equiv \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$\theta_{12}, \theta_{23}, \theta_{13}, \delta$

$$\theta_{12} \approx 0.59^{+0.02}_{-0.015}$$

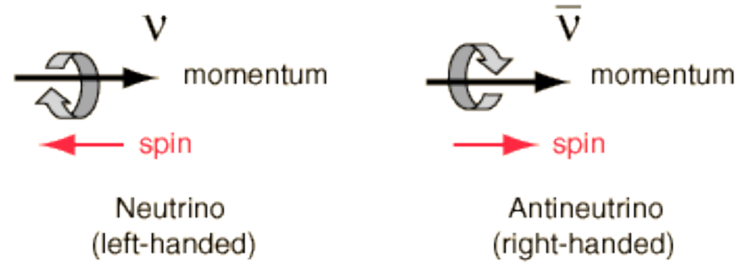
$$\theta_{23} \approx 0.785^{+0.124}_{-0.124} \approx \frac{\pi}{4}$$

$$\theta_{13} \approx 0.154^{+0.065}_{-0.065}$$

$\delta = CP$ violating phase $=?$

Sterile* neutrinos

- What are they?
  - Related to right-handed components



- Wherefore?
  - Mass → right-handed neutrinos → must exist by Lorentz invariance
    - but may have mass modified by interactions
  - Non-interacting(?!): only example of particles that interact solely via GR
  - Interactions → necessarily beyond SM physics
- What (if anything) do they do?
  - perhaps they mix with active (e, μ , τ) neutrinos?
  - then they're not really "sterile"

$$
\begin{aligned}
|\nu_e\rangle &= \cos\theta|\nu_1\rangle + \sin\theta|\nu_2\rangle \\
|\nu_s\rangle &= -\sin\theta|\nu_1\rangle + \cos\theta|\nu_2\rangle
\end{aligned}
$$

- Why would we want (need?) them?
  - leptogenesis; baryogenesis
  - BBN & N_{eff}

*Coined by Bruno Pontecorvo '67;
"infertile" or "aseptic"?

Hints for light sterile neutrinos?

- mini-BooNE
  - neutrino oscillation experiment $\nu_e \to \nu_s \to \nu_\mu$
  - appearance with $\delta m^2 \sim 1 \text{ eV}^2$
  - result inconsistent with flavor oscillation alone
- Neutrino reactor anomaly
  - 3σ deficit neutrinos detected in short-baseline (<100m) reactor ν experiments

    $\bar{\nu}_e$ deficit from $\bar{\nu}_e \to \bar{\nu}_s$ (???) – a disappearance experiment
  - A. Hayes et al. (2013) find "large corrections"
- Extra radiation at photon-decoupling (Neff) ??
  - CMB observations (PolarBear, ACT, SPT, Planck, CMBPol,…)
  - 'extra' RED could reconcile H_0 and σ_8 inferred from CMB and astronomical observation

Dark radiation

- γ -decoupling (last scattering) T ~ 0.2 eV (z~1000)
- N_{eff}: "effective number of neutrino degrees of freedom"
  - A misnomer; it refers to any/all relativistic particles at decoupling
  - 'Baby' formula: $\rho_{\rm rad} = 2\left[1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{\rm eff}\right] \frac{\pi^2}{30} T_\gamma^4$
    - We've done this better…
- CSM+SMPP → predicts N_{eff} = 3.046 [Dicus et. al. '83; Dolgov, Hansen, Semikoz '97, '99; Gnedin^2 '98,…]
  - annihilation of neutrinos-antineutrinos at weak decoupling
  - QED corrections
- Measurements
  - WMAP9 (2012): 3.26(35); Planck (2013): 3.30(50); ACT(2013): 2.79(56); SPT-SZ (2012): 3.71(35)
- Sterile neutrinos can affect the physics of dark radiation

CMB as a probe of steriles: caveats

- Sterile neutrinos can decay *out-of-equilibrium*
  - "dilution": steriles are "sub-weakly" interacting
  - non-thermal energy spectra/number densities
- Care must be applied when
  - computing N_{eff}: non-equilibrium effects; relativistic vs. non-relativistic kinematics
  - determining N_{eff} and Y_P (mass fraction ^{4}He)
    - current Planck collab. procedure is inconsistent w.r.t. N_{eff} and Y_P
    - in preparation: "Neutrino physics in the era of precision cosmology"
- neutron/proton ratio (and therefore ^{4}He)
  - competing weak reaction rates determine Y_P(^{4}He)
  - ***very sensitive to neutrino energy spectra***

$$\nu_e + n \leftrightarrow p + e^-$$

$$\bar{\nu}_e + p \leftrightarrow n + e^+$$

$$n \leftrightarrow p + e^- + \bar{\nu}_e$$

Dilution physics (I)

- Consider the presence of ν_s
  - heavy (~100 MeV), unstable (~10 s)
- Thermal effects
  - Assume interaction of steriles sufficiently strong at T~few GeV to maintain thermal equilibrium with e, ν, γ,…
  - Further, the sterile decouples at T~few MeV

$$s = \frac{\rho + p}{T} = g_*(a)\frac{2\pi^2}{45}T^3$$

    - *assume* relativistic kinematics throughout
    - proper entropy is conserved: s a^3 = constant (FLRW)
    - sterile neutrino temperature distribution cooled or "diluted"

$$\frac{T_{\nu_s}(a_{wdc})}{T_\gamma(a_{wdc})} = \left(\frac{g_*(a_{wdc})}{g_*(a_{\nu_s dc})}\right)^{1/3} = \left(\frac{10.75}{61.75}\right)^{1/3} \approx \frac{1}{1.8}$$

    - number density comparable to photons (since lifetime chosen 10's secs)
      - n(ν_s) ~ 0.1 n(γ)
- NB: ν_s is *out-of-equilibrium* with $e\mu\nu\gamma$

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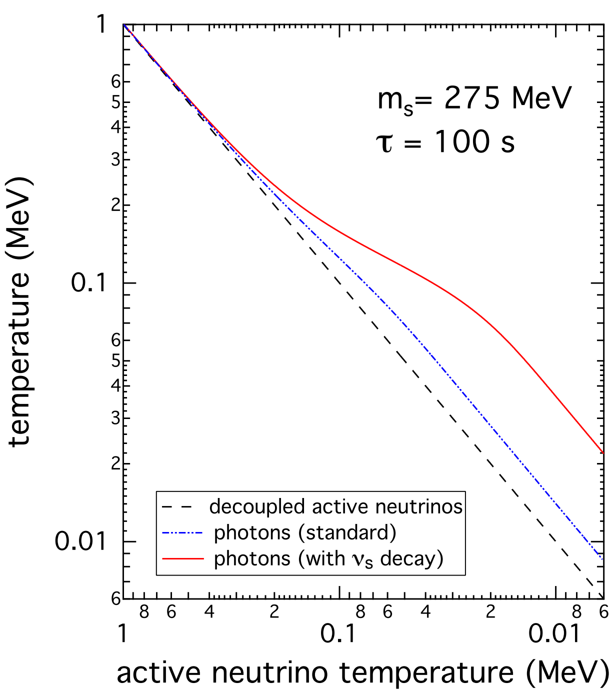
Dilution physics (II)

- Heavy particle decay during/after weak decoupling
  - Interactions

Exothermic	Endothermic	
$\nu_s \to 3\nu_i$	$\nu_s \to \nu_i + e^- + e^+$	$\nu_s \to \nu + \pi^0$
$\nu_s \to \nu_i + \gamma$	$\nu_s \to \nu + \mu^+ + \mu^-$	$\nu_s \to \pi^\pm + e^\mp$
		$\nu_s \to \pi^\pm + \mu^\mp$



- Entropy production
  - due to out-of-equilibrium decay
  - plasma cools slower than decoupled actives
- Dilution
  - decoupled actives diluted down
  - Two effects
    - coupling to plasma → reduction in N_{eff}
    - coupling to actives → increase N_{eff}

Dilution phyiscs (III)

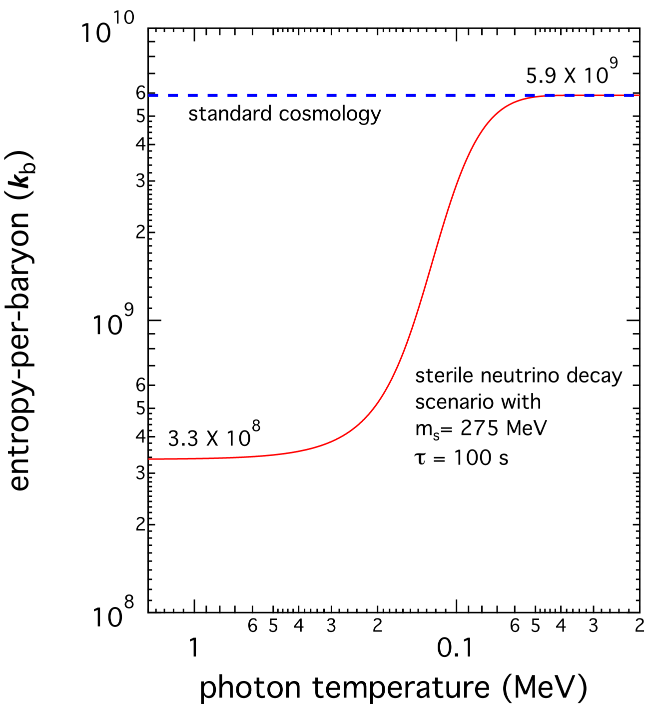
- Photons thermalize
  - sterile neutrino decay (m_s< few GeV)
- But active neutrinos may not
  - energy/decay-epoch dependent

$$\nu_s \to \pi^0 + \nu_{e,\mu,\tau} \to 2\gamma + \nu_{e,\mu,\tau}$$

$$\nu_s \to \pi^+ + e^- \to 2\gamma + 3\nu$$

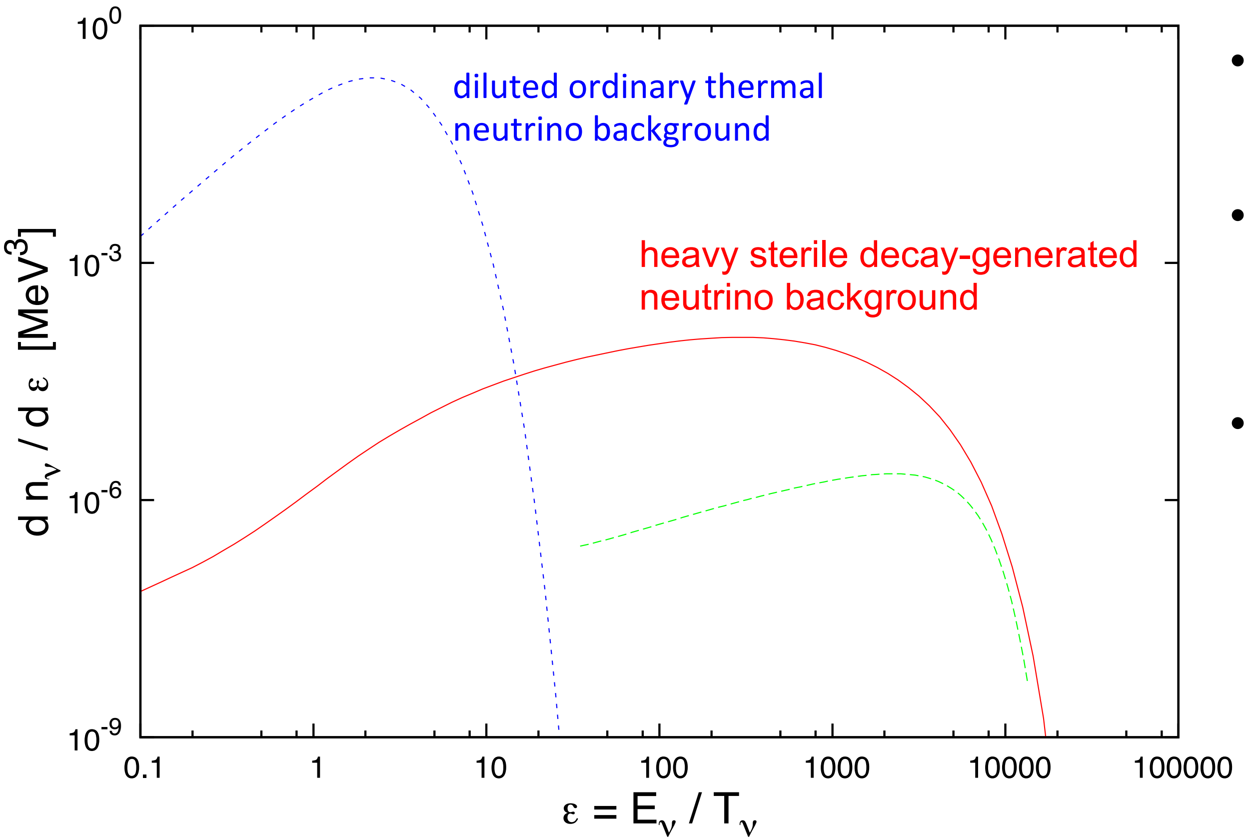
$$\pi^+ \to \mu^+ + \nu_\mu, \quad \mu^+ \to e^+ + \bar{\nu}_\mu + \nu_e$$

$$\nu_s \to \pi^+ + \mu^- \to 2\gamma + 5\nu$$



- Heavy sterile neutrino decay
  - dilution of background (CνB)
  - generation of radiation energy density: N_{eff}
  - prodigious entropy production

Non-equilibrium distribution of CνB



- Heavy sterile dilutes the normal background neutrino spectrum
- decay-generated spectrum $\sim 10^3$ times more energetic than standard; never non-relativistic
- can't detect neutrino rest mass cosmologically

The Big Question: what effect on BBN? Y_P

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Code capabilities & design

- Capabilities
  - Boltzmann equation solver: two classes of Boltzmann equations
    - Nucleosynthesis: Unitary Reaction Network for BBN (previous slides)
    - Neutrino energy transport: **new capability – never before achieved**

$$\frac{Df_1}{Dt} = \int \frac{s}{2E_1}\frac{d^3p_2}{(2\pi)^3(2E_2)}\frac{d^3p_3}{(2\pi)^3(2E_3)}\frac{d^3p_4}{(2\pi)^3(2E_4)} \times \langle|\mathcal{M}|^2\rangle(2\pi)^4\delta^4(P_1+P_2-P_3-P_4)F(p_1,p_2,p_3,p_4)$$

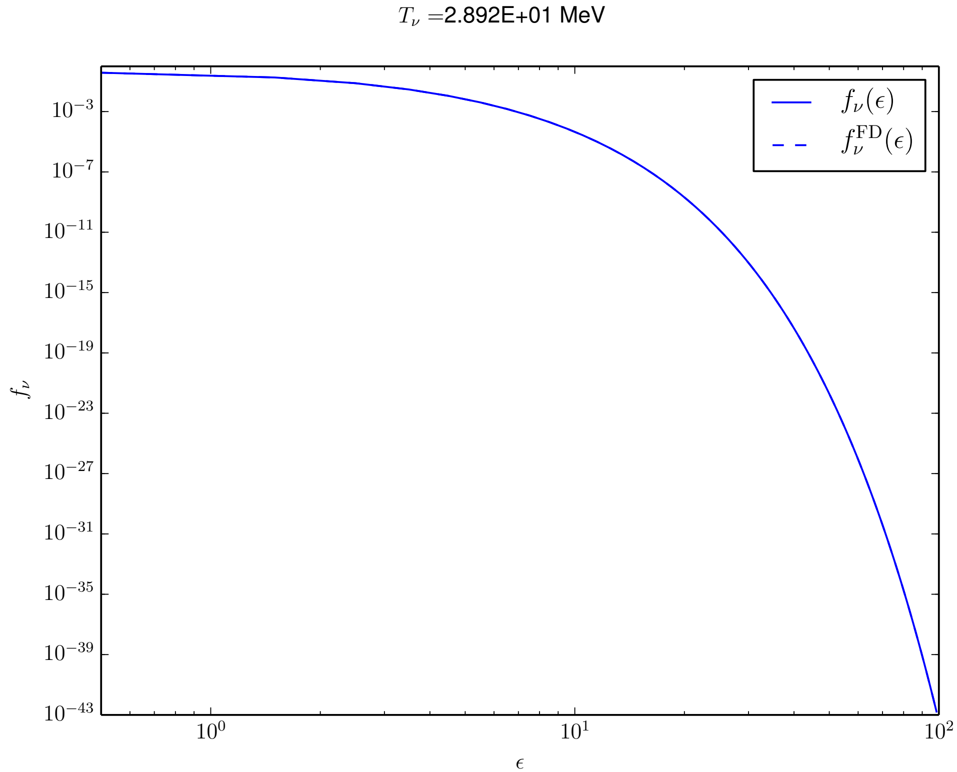
$$\frac{Df_1}{Dt} = \frac{\kappa}{32(2\pi)^3}\int_0^\infty p_1p_2^3\,dp_2\int_{-1}^{1}dx\,\frac{(1-x)^2}{\sqrt{p_1^2+p_2^2+2p_1p_2x}}\int_{E_{\rm min}}^{E_{\rm max}}dp_3F(p_1,p_2,p_3,p_1+p_2-p_3).$$

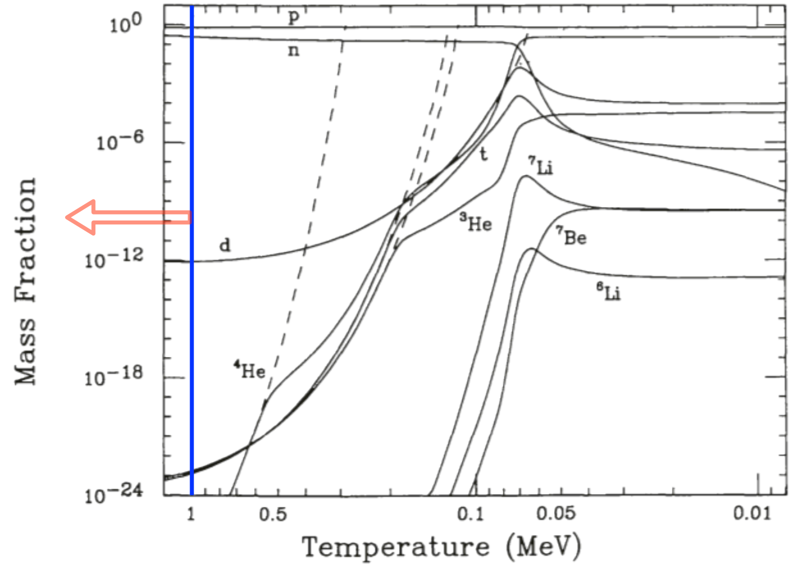
    - Various reactions result in seven evaluations of this **triple** integral
    - **Achieved short turn-around time by parallelization**
- Design
  - Modular code design for adaptability for ***public code release***
  - Allow insertion of "physics packages" to test BSM (not just sterile ν's)

Code testing/preliminary results

- Evolve assuming equilibrium from 30 MeV → 3 MeV
- Then turn-on only elastic ν-lepton scattering

$$\nu_i + e^{\pm} \to \nu_i + e^{\pm} \qquad i = e, \mu, \tau$$





- since the ν & anti-ν are cooler than the $e^{\pm}$ anticipate upscattering

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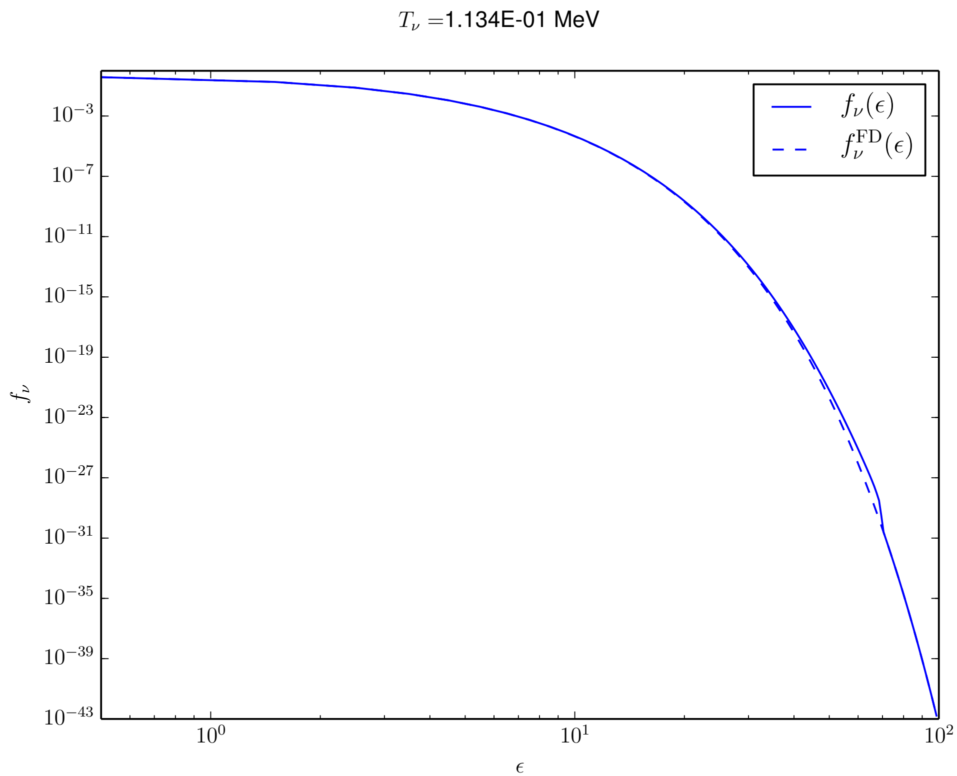

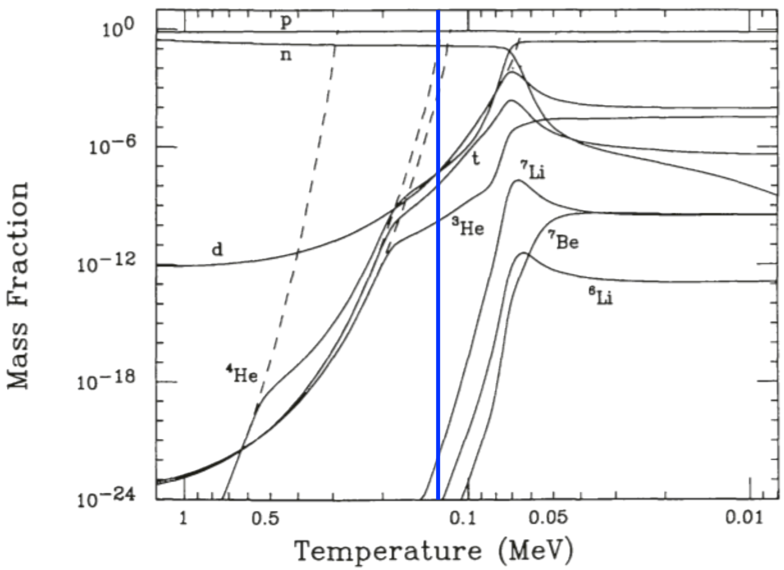

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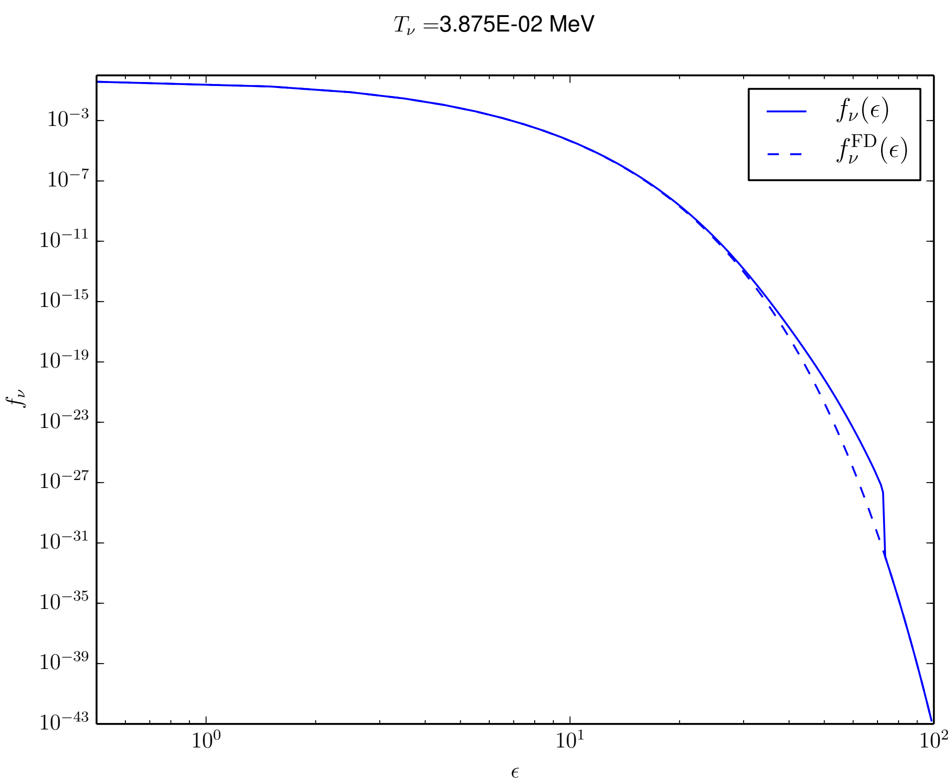

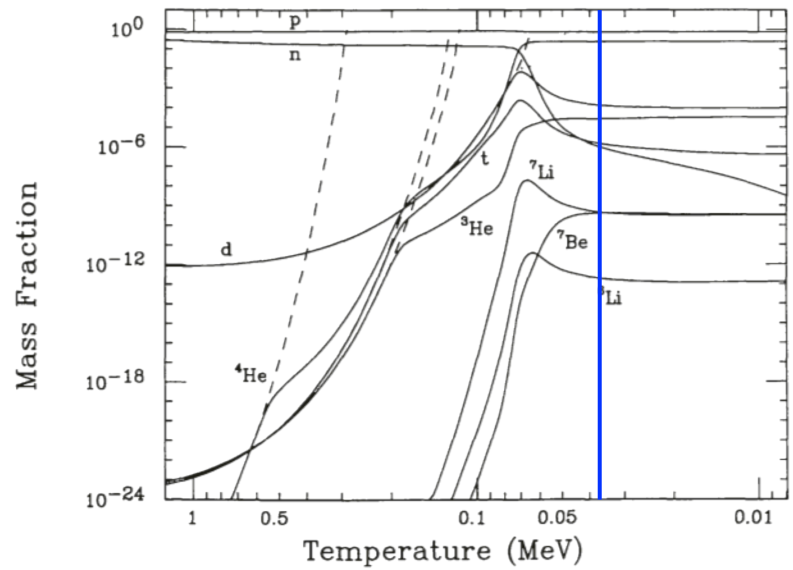

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Code testing/preliminary results

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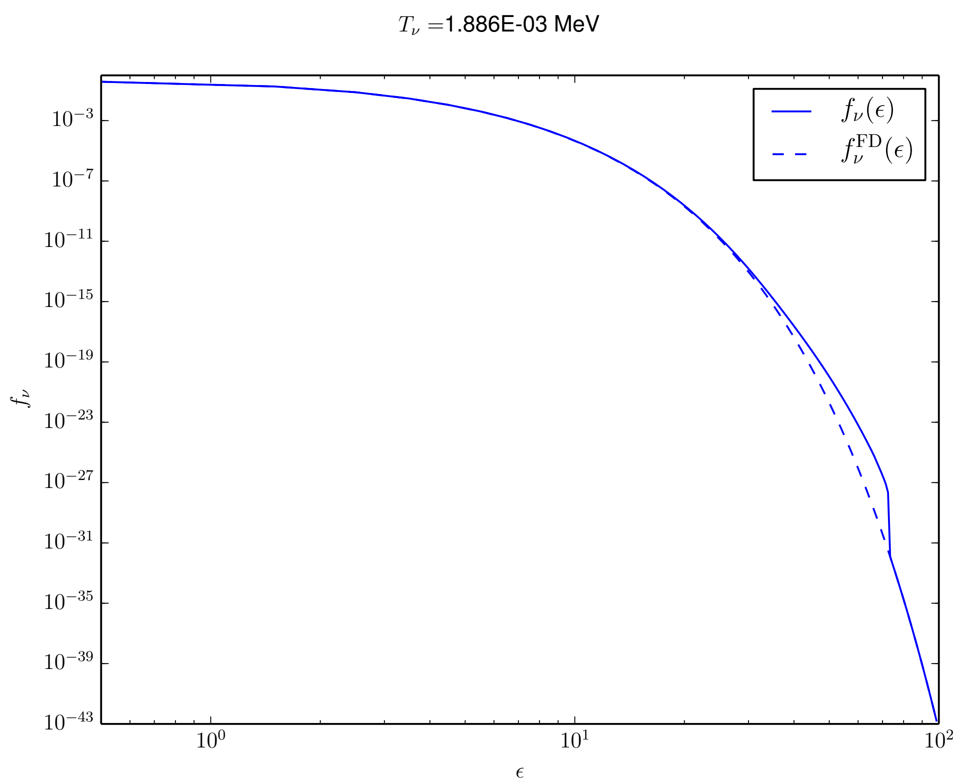

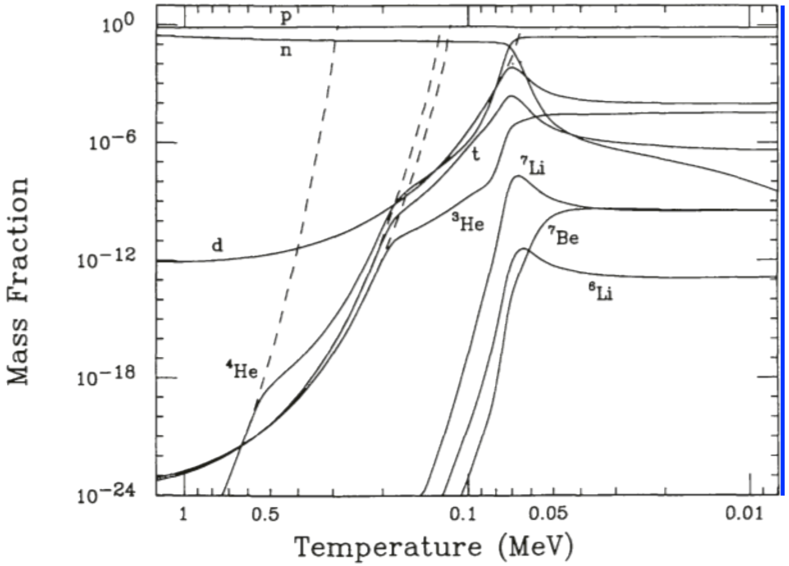

- since the ν & anti-ν are cooler than the $e^{\pm}$ anticipate upscattering
- INTERESTING: because "ν decoup. complete by e^+e^- annihilation"

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N_{eff}

Elastic scattering

Initial transport temperature [keV]	N_{eff}
20	3.0055
40	3.0055
100	3.005666
200	3.005936
400	3.006555
1000	3.008414
3000	3.013428

$e^{\pm}$ annihilation

Initial transport temperature [keV]	N_{eff}
20	3.005584
40	3.005590
100	3.005682
200	3.005985
400	3.006604
1000	3.008309
3000	3.xxxxxx

These preliminary/test results give a nice demonstration that the fundamentals of the neutrino energy transport are working.