Nuclear reactions in the early universe II

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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

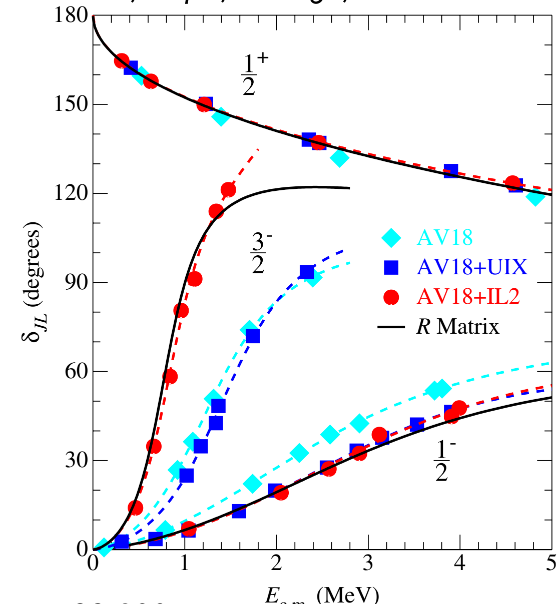
Lecture II

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

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

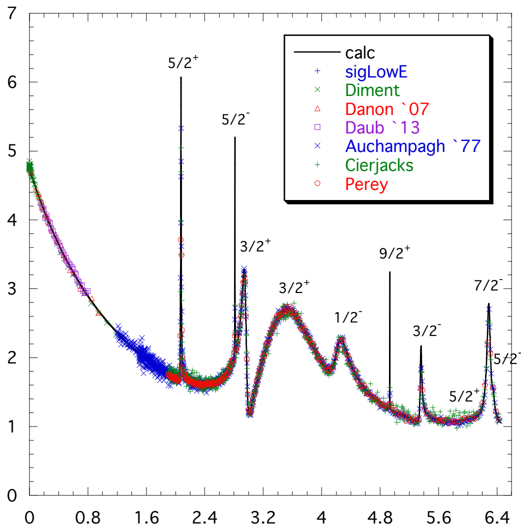
Analyses of Light Systems, Cont.

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

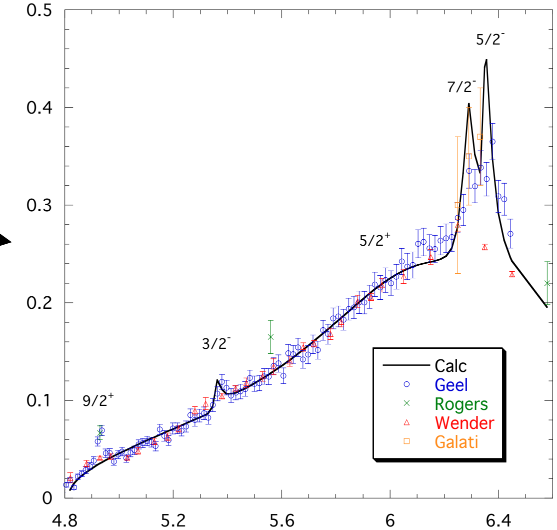
^{13,14}C system analyses: σ_T (b) vs. E_n (MeV)

n+^{12}C Total Cross Section

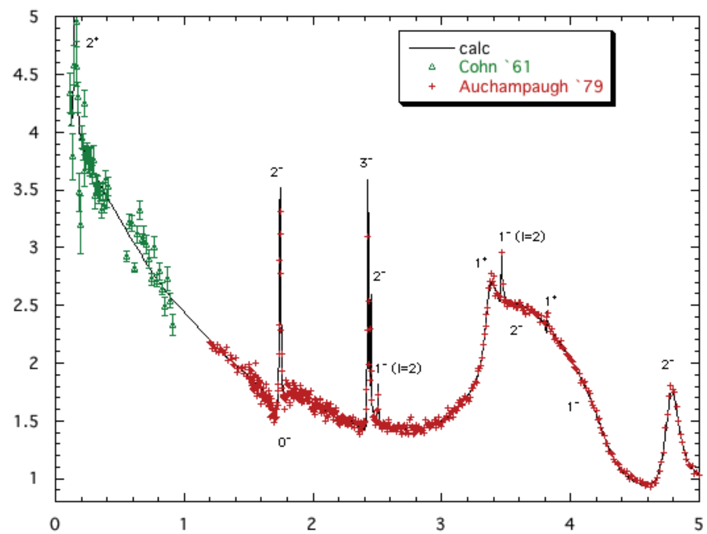


Two-channel analysis

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



n+^{13}C Total Cross Section



Analyses by GMH/MWP

Single-channel analysis

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

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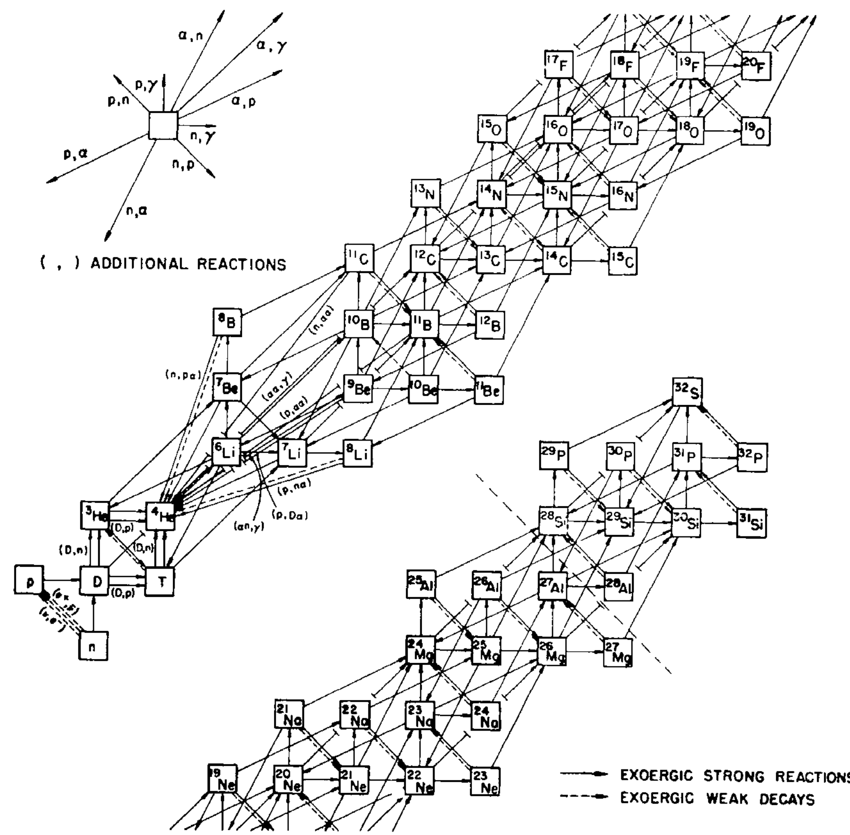
Nuclear reaction network

- 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

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

Unitarity: consequences on T matrix

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

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

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

- **Implications of unitarity constraint on transition matrix**

1. Doesn't uniquely determine T_{ij}; highly restrictive, however

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

   Multichannel: $\mathrm{Im}\ \mathbf{T}^{-1} = -\boldsymbol{\rho}$

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

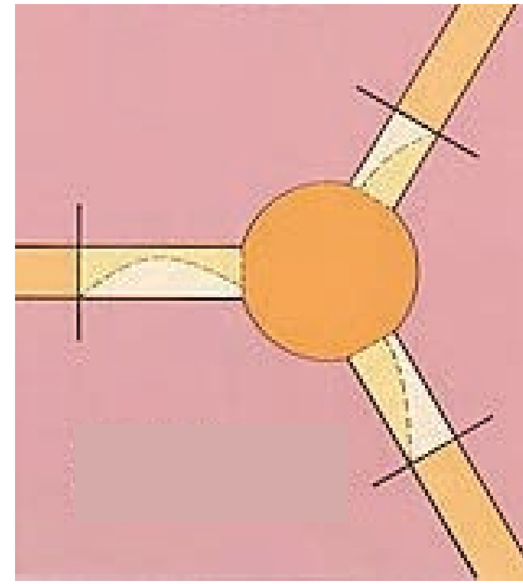
   ★ *normalization*, in particular

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

Most important feature:
linear ~ quadratic

Basics of R-matrix (data ⇨ amplitudes)

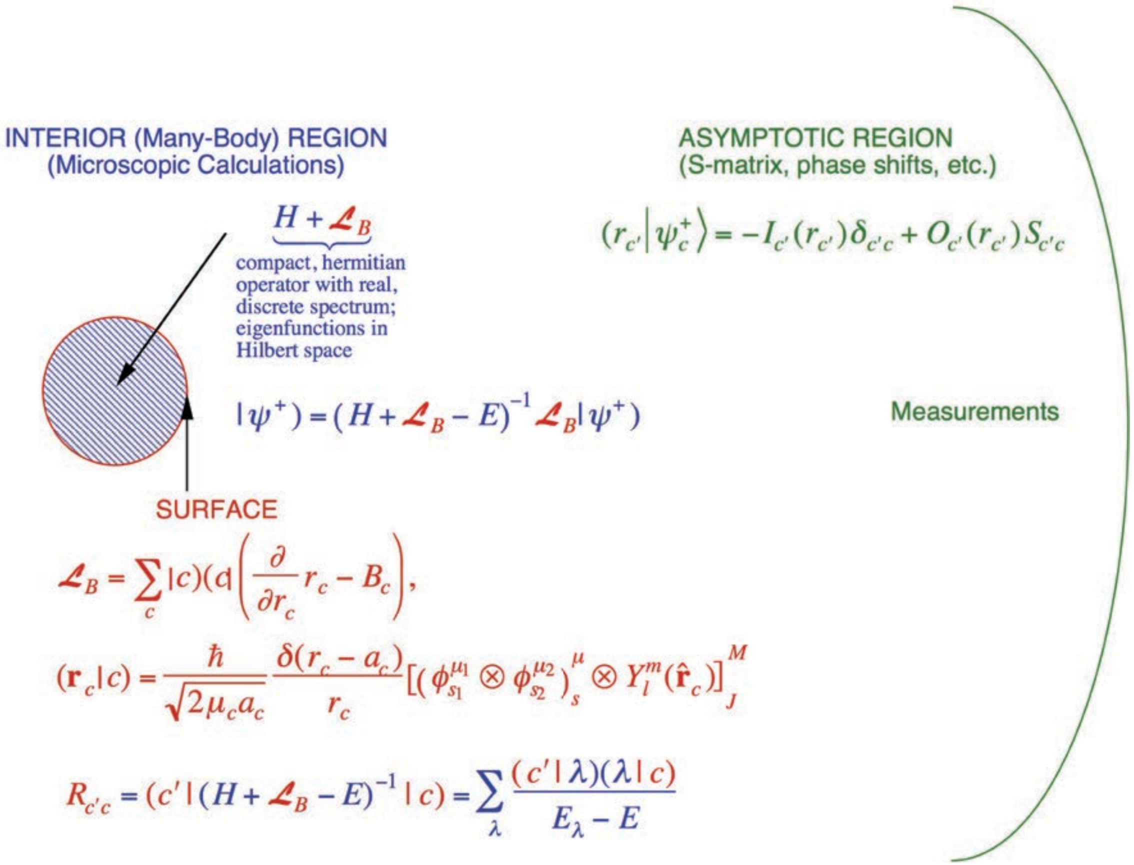
- Assumptions (cf. Lane & Thomas RMP '58)
  - a) Non-relativistic QM (L&T58); LANL-EDA uses rel.
  - b) Two-body channels only ('c'); aux. spectra code
  - c) Conservation of N, Z
  - d) Finite radius a_c beyond $V_{pol}\approx 0$; sharp boundaries
- Separated pairs, "channels"
  - A nucleons → (A_1,A_2)
  - $c = \{\alpha s_1 m_1 s_2 m_2\} \to \{\alpha(s_1 s_2) s m_s \ell m_\ell\} \to \{\alpha(s_1 s_2) s\ell, JM\}$
  - 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



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

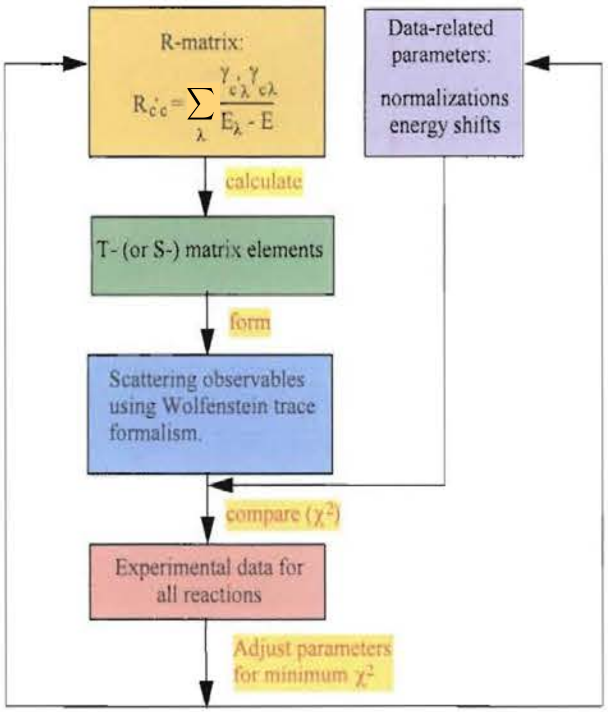
$$B_c = \frac{1}{u_c(a_c)} \frac{du_c}{dr_c}\bigg|_{r_c=a_c}$$

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*



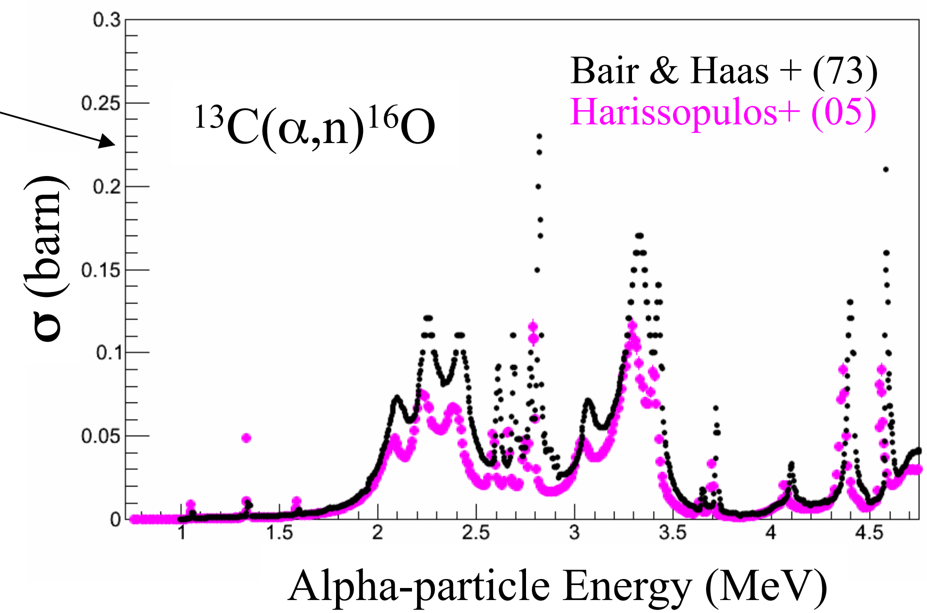
^{17}O analysis configuration

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

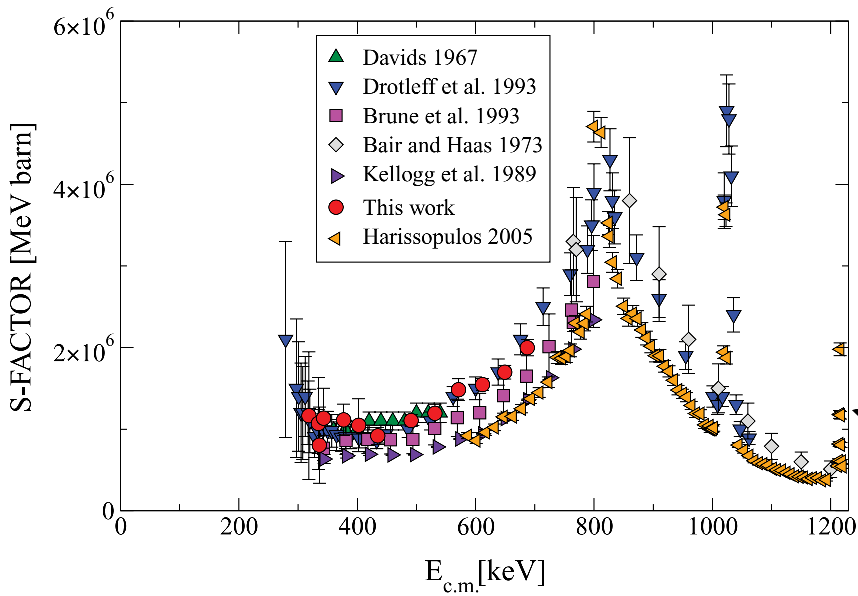
^{17}O compound system: experimental status

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)

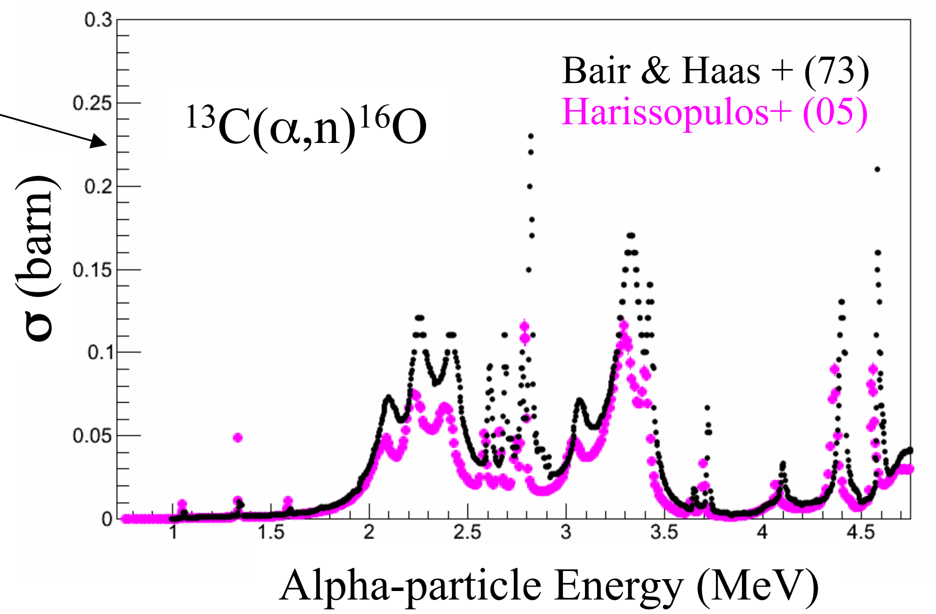


Harissopulos(05) data 2/3*B&H(73)
Heil(08) data consistent with B&H

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

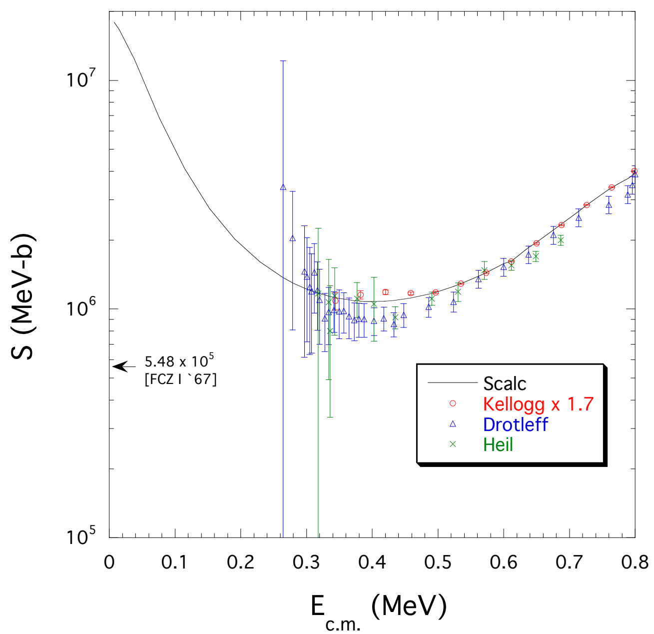
^{17}O compound system: experimental status

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



Credit: S. Kunieda

Hale (2013, unpublished)

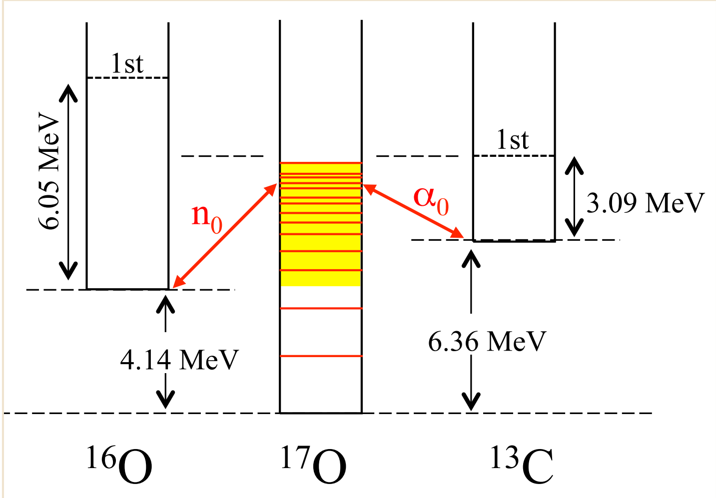


Subthreshold ½$^+$
deep min in σ_T
$S(0) >> S_{FCZ67}(0)$

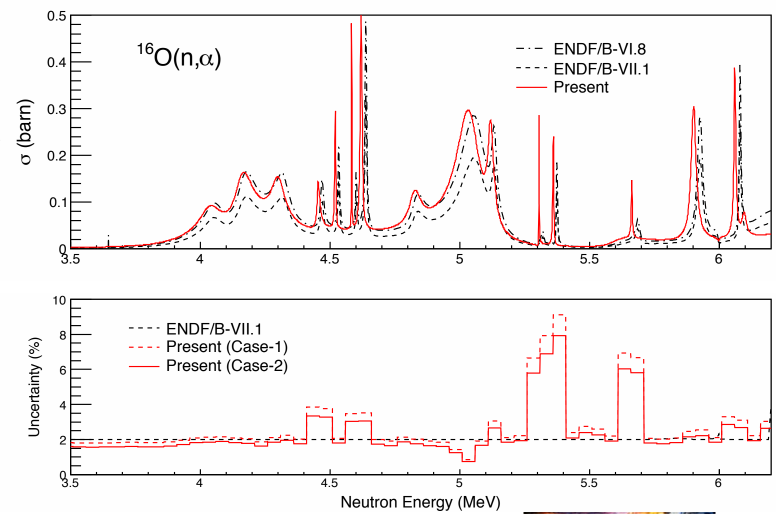
Tempting to conclude that B&H73 was right all along!

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!***

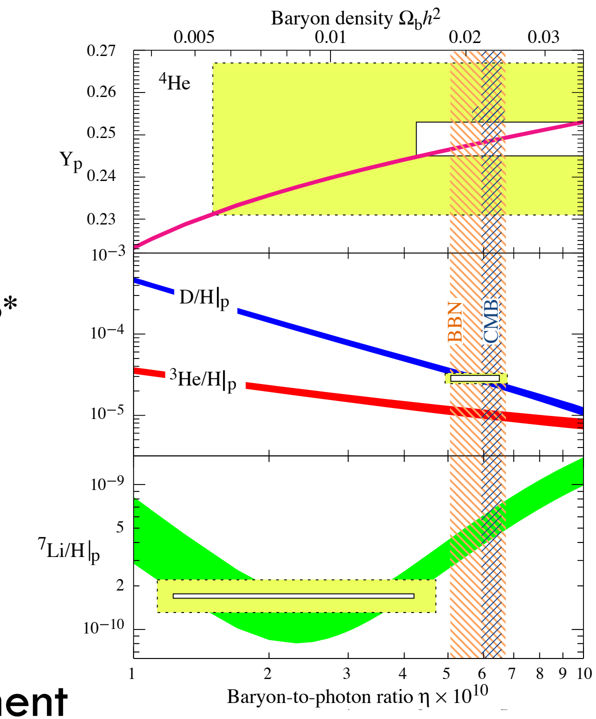


Credit: S. Kunieda



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 $\eta_{\rm wmap}$ (CMB) ^{7}Li/H$|_{\rm BBN}$ ~ (2.2–4.2)*^{7}Li/H$|_{\rm halo*}$
  - 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: $\gamma + {}^9B \rightarrow E_1^{3/2}, M_1^{5/2}, M_1^{3/2}, M_1^{1/2}, E_1^{5/2}, E_1^{1/2}$

<u>Full model space</u>:
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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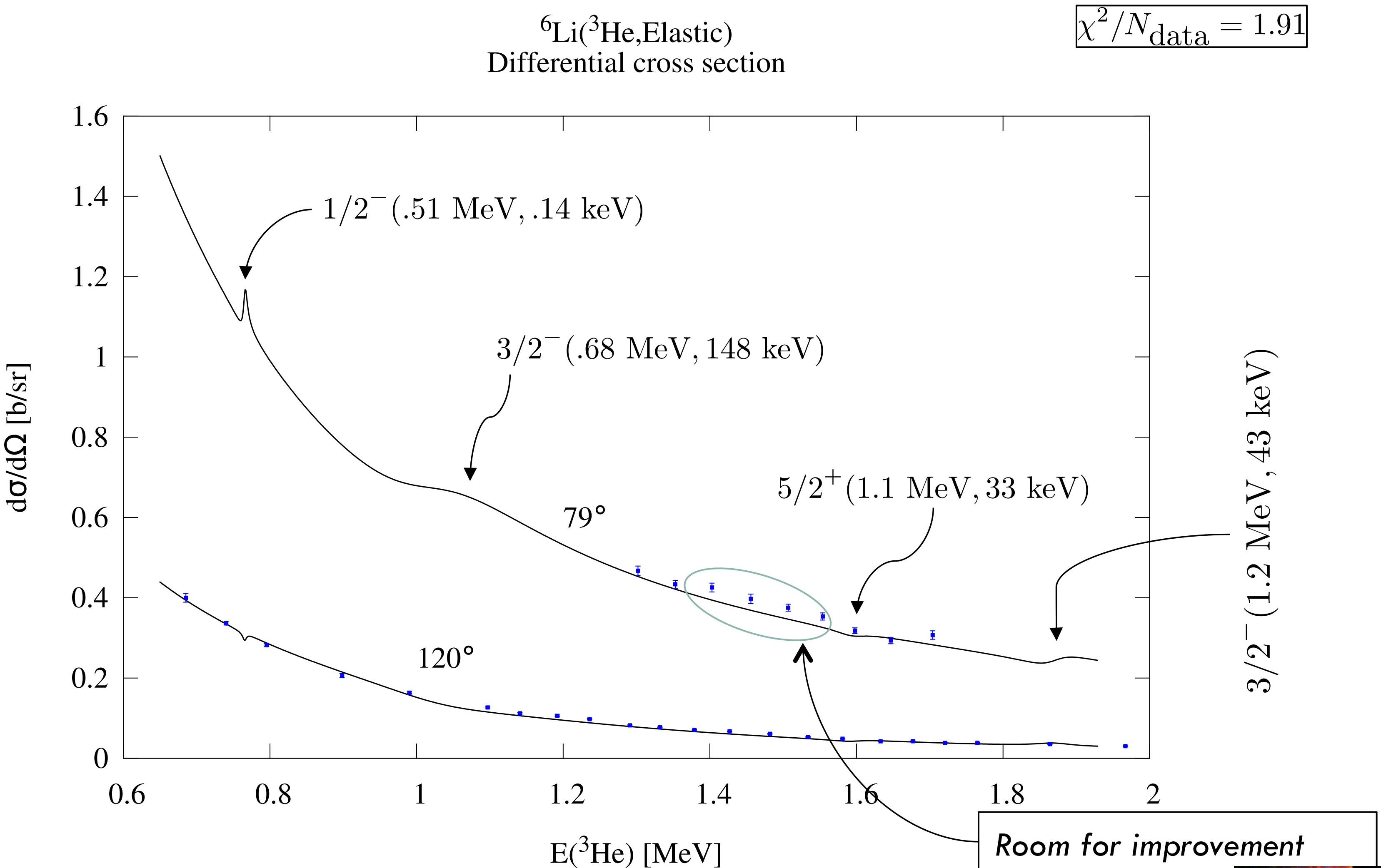
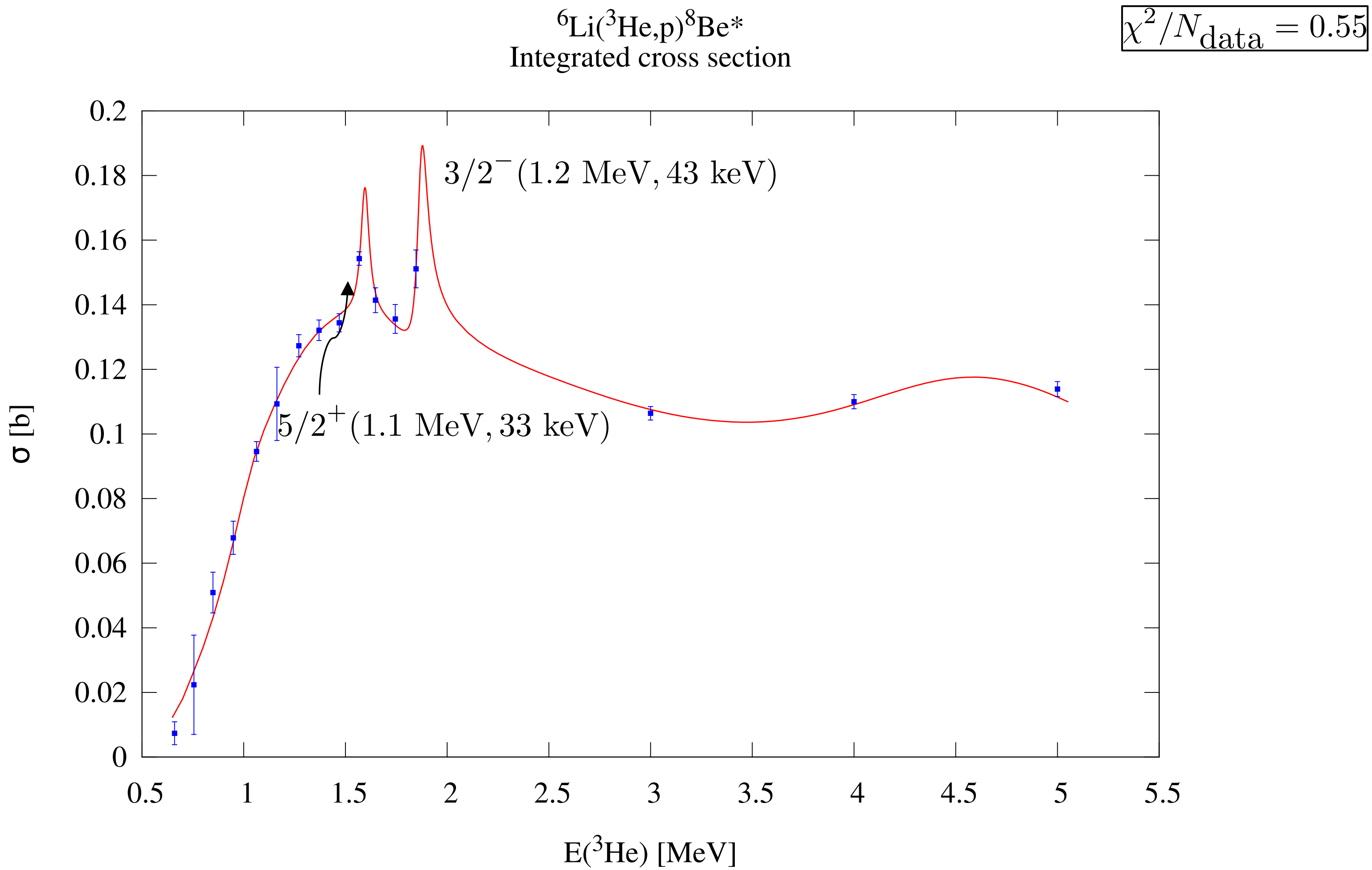
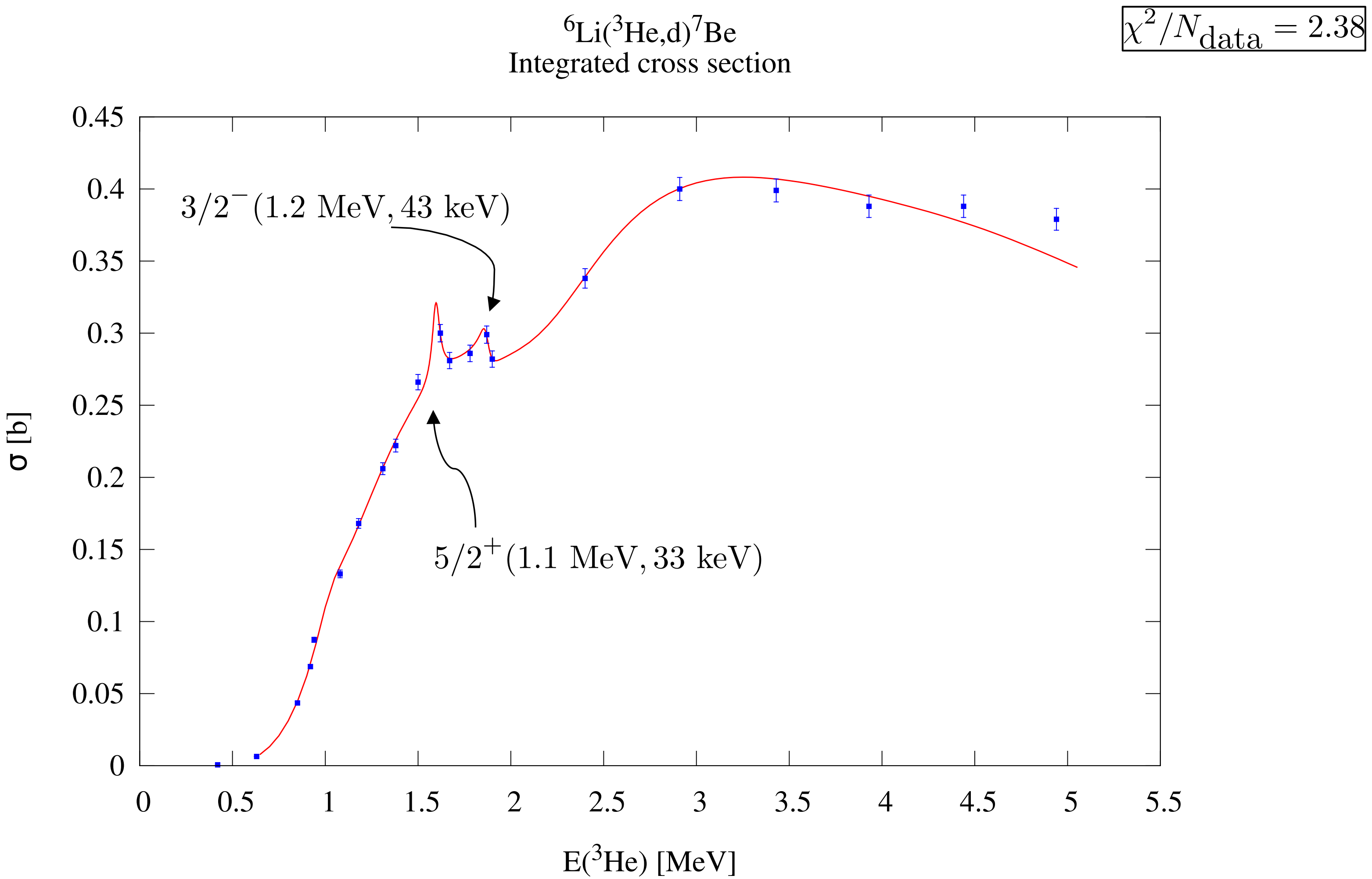
Observable fit: $^3He+^6Li$ elastic DCS



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

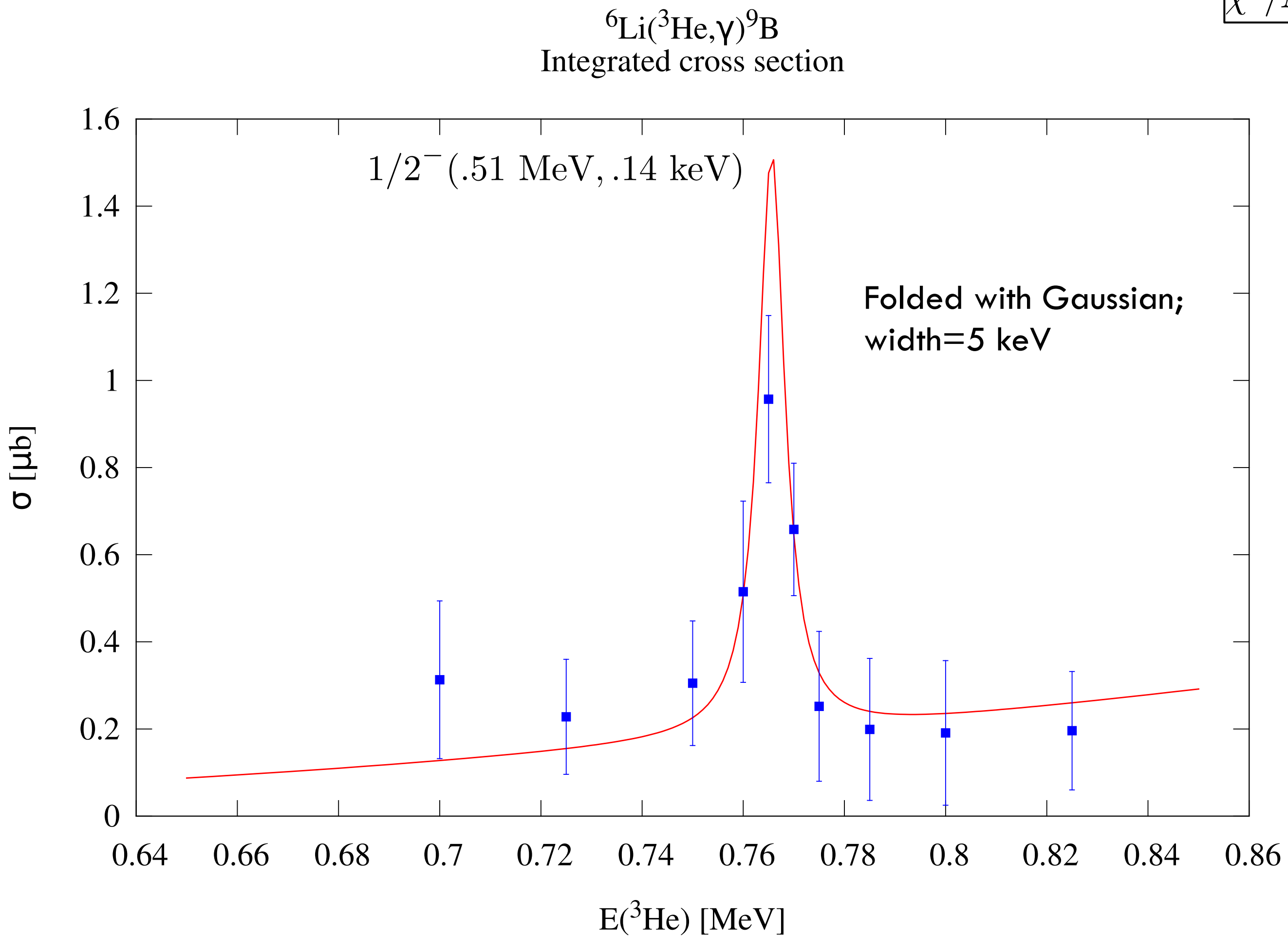


Observable fit: ^{6}Li(^{3}He,d)^{7}Be integrated x-sec



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

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



^{9}B 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	$(\gamma, {}^3\mathrm{He})$
17 190	25		120	40	$\mathrm{p, d, {}^3He}$
17 54	100 [h i]	$(\frac{7}{2}^+); (\frac{1}{2})$			
17 637	10 [i]		71	8	$\mathrm{p, d, {}^3He}, \alpha$

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

Summary

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

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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

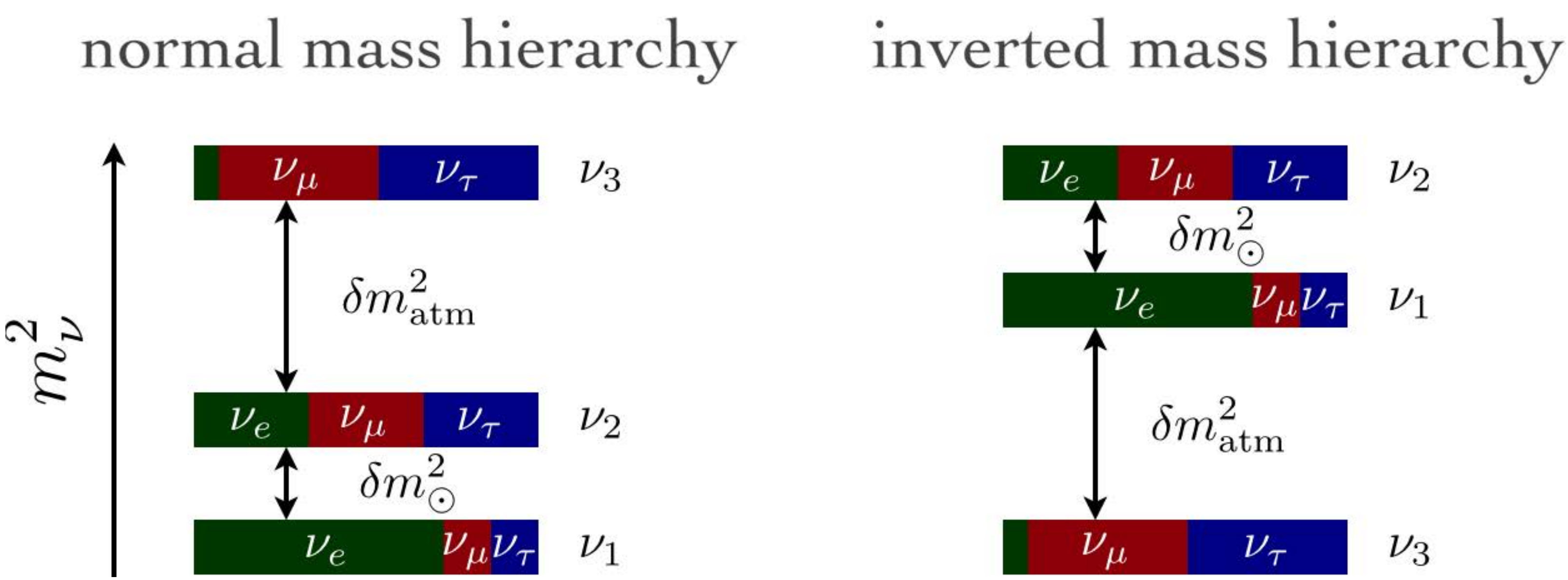
Neutrino Mass: what we know and don't know

We know the *mass-squared* differences:

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

$$\boxed{e.g., \quad \delta m^2_{21} \equiv m^2_2 - m^2_1}$$

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



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!

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

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

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

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

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

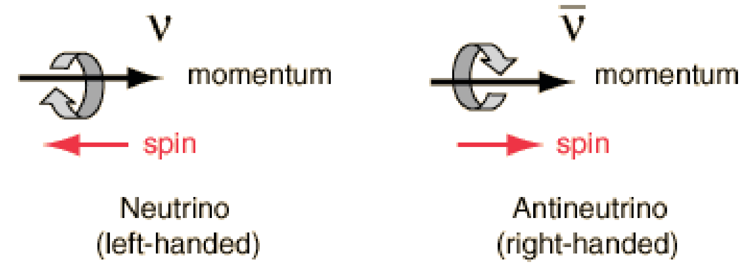
$$\theta_{23} \approx 0.785^{+0.124}_{-0.124} \approx \frac{\pi}{4}$$

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

$$\delta = CP \text{ violating phase } =?$$

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"

$$|\nu_e\rangle = \cos\theta|\nu_1\rangle + \sin\theta|\nu_2\rangle$$
$$|\nu_s\rangle = -\sin\theta|\nu_1\rangle + \cos\theta|\nu_2\rangle$$

- 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 $\delta m^2 \sim 1\ \mathrm{eV}^2$
  - 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 $Y_P(^4\text{He})$
  - ***very sensitive to neutrino energy spectra***

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

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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"

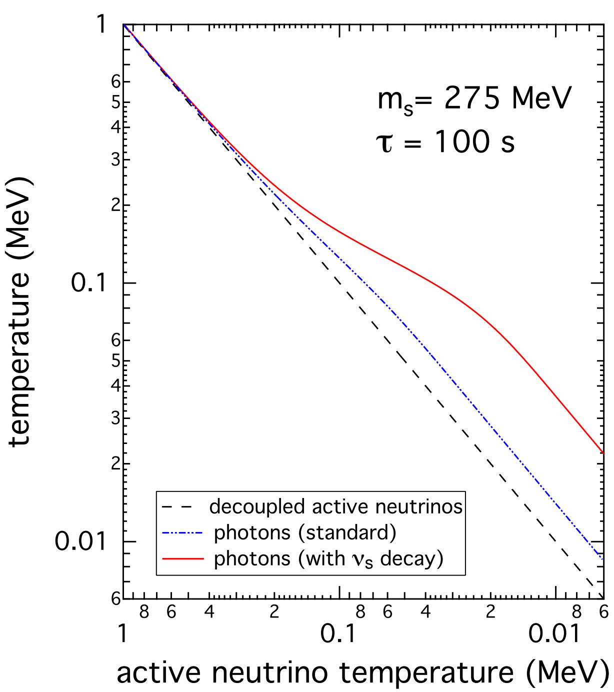
$$\frac{T_{\nu_s}(a_{wdc})}{T_\gamma(a_{wdc})} = \left(\frac{g_*(a_{wdc})}{g_*(a_{\nu_s dc})}\right)^{1/3} = \left(\frac{10.75}{61.75}\right)^{1/3} \approx \frac{1}{1.8}$$

    - 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 $e\mu\nu\gamma$

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}

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Dilution phyiscs (III)

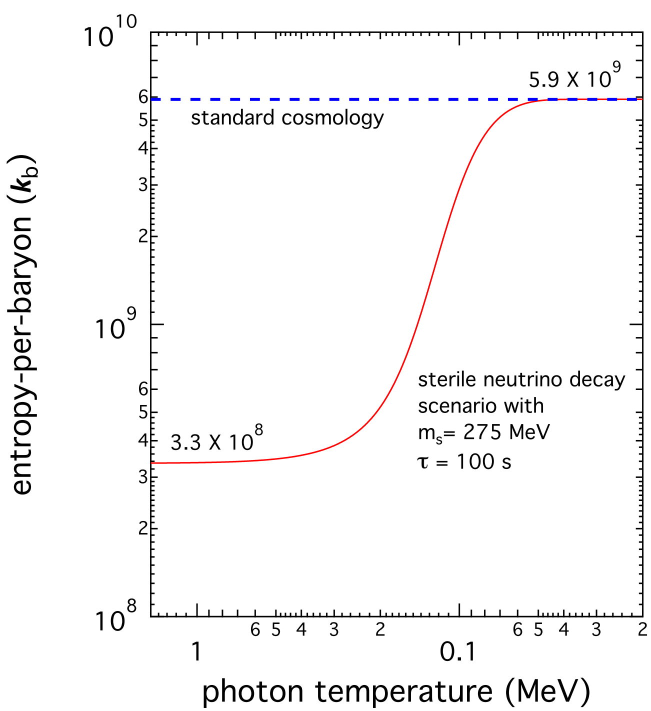
- Photons thermalize
  - sterile neutrino decay (m_s< few GeV)
- But active neutrinos may not
  - energy/decay-epoch dependent

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

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

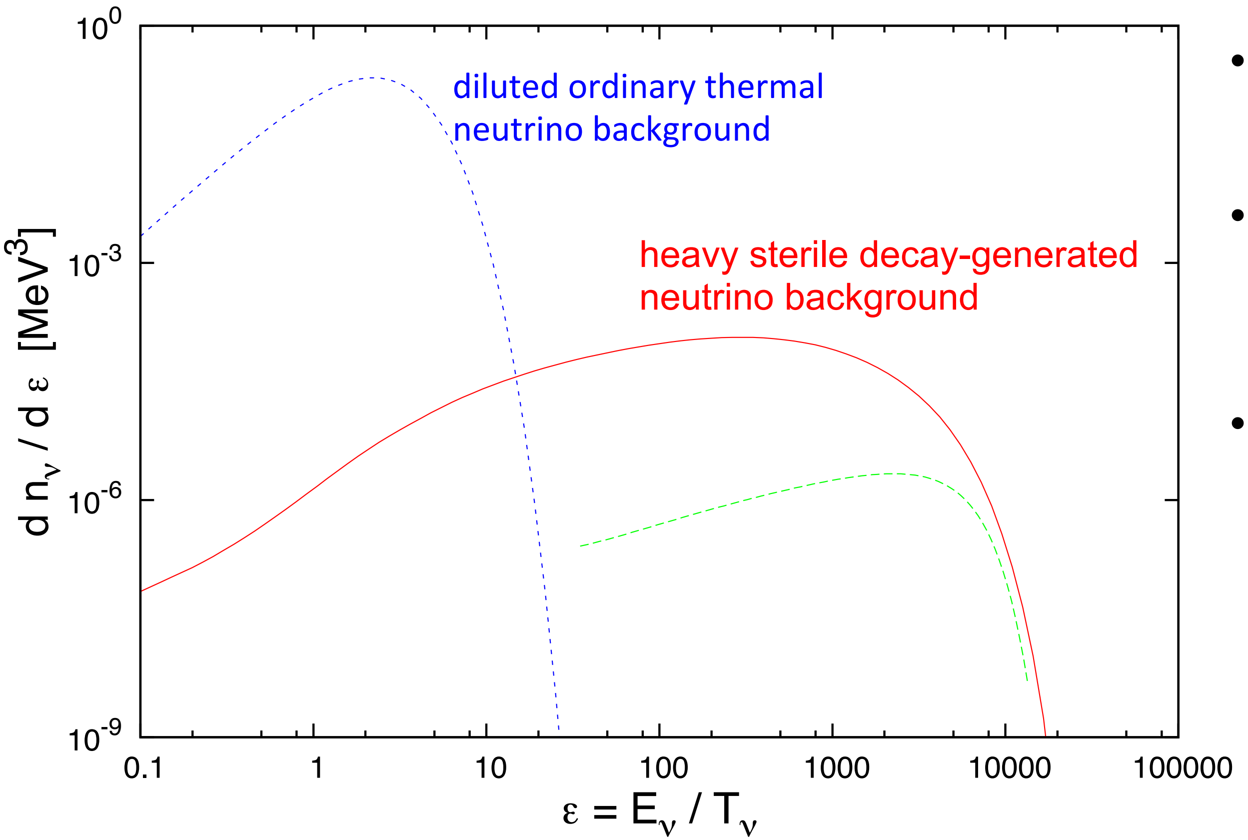
$$\pi^+ \to \mu^+ + \nu_\mu, \quad \mu^+ \to e^+ + \bar{\nu}_\mu + \nu_e$$

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



- 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 ~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

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**

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

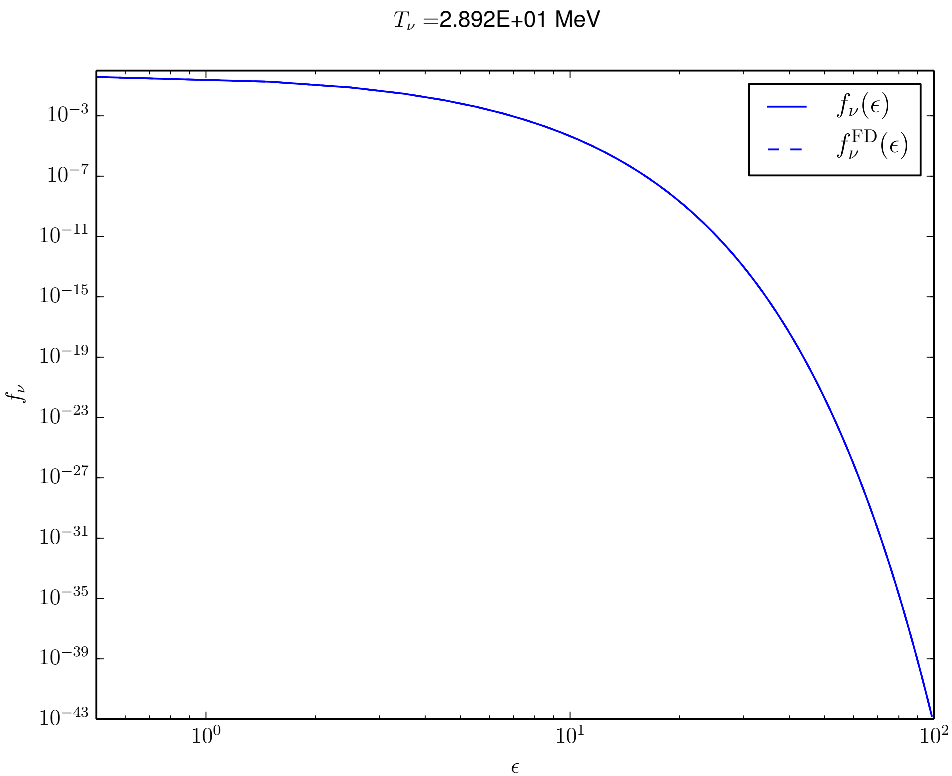
$$\frac{Df_1}{Dt} = \frac{\kappa}{32(2\pi)^3} \int_0^\infty p_1 p_2^3\, dp_2 \int_{-1}^{1} dx \frac{(1-x)^2}{\sqrt{p_1^2 + p_2^2 + 2p_1p_2x}} \int_{E_{\rm min}}^{E_{\rm max}} dp_3 F(p_1, p_2, p_3, p_1 + p_2 - p_3).$$

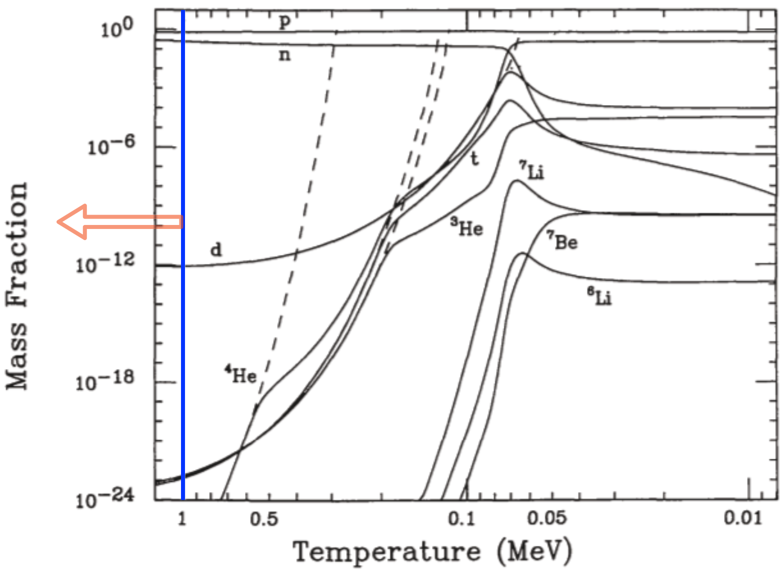
    - Various reactions result in seven evaluations of this **triple** integral
    - **Achieved short turn-around time by parallelization**
- Design
  - Modular code design for adaptability for ***public code release***
  - Allow insertion of "physics packages" to test BSM (not just sterile ν's)

Code testing/preliminary results

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

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





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

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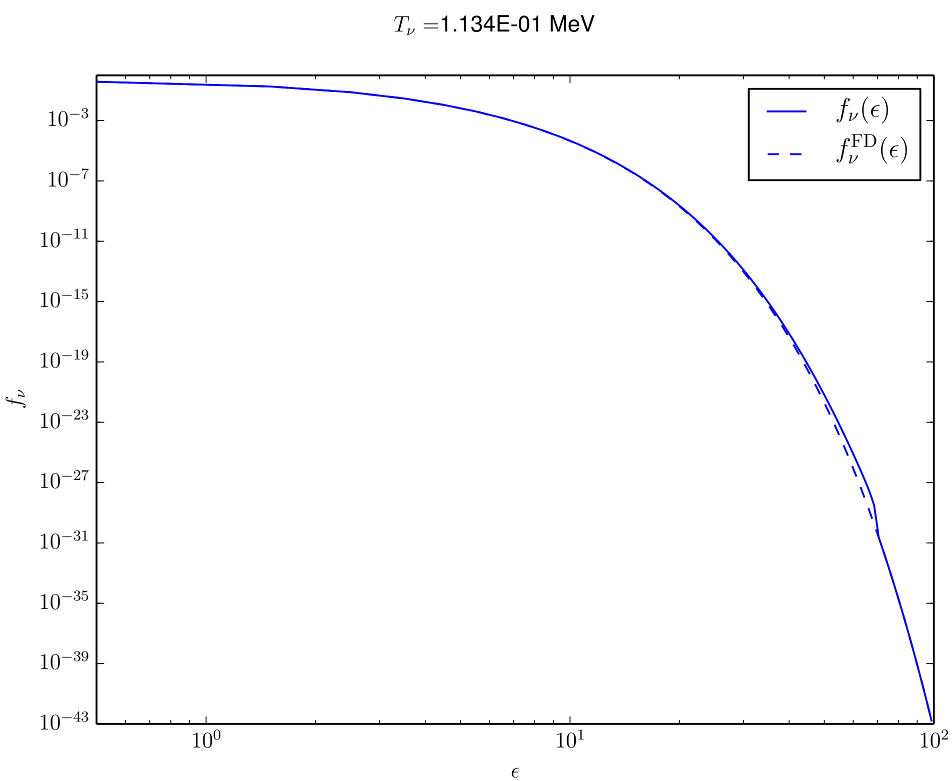

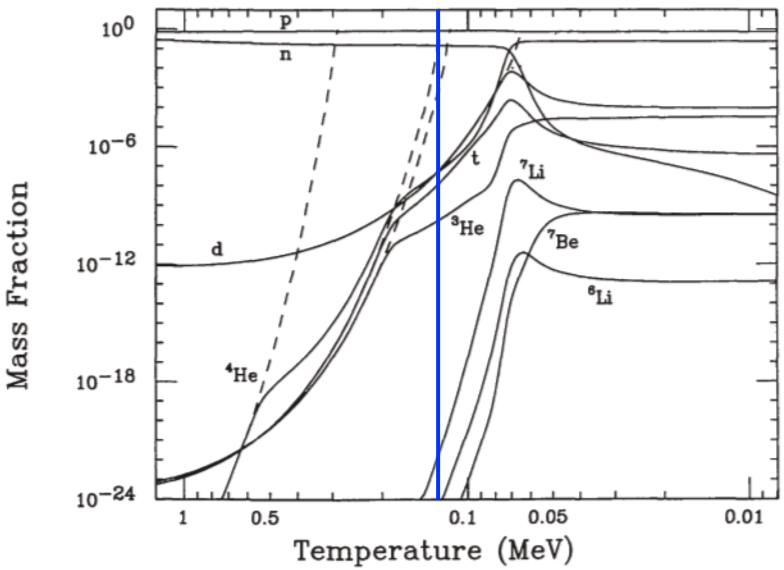

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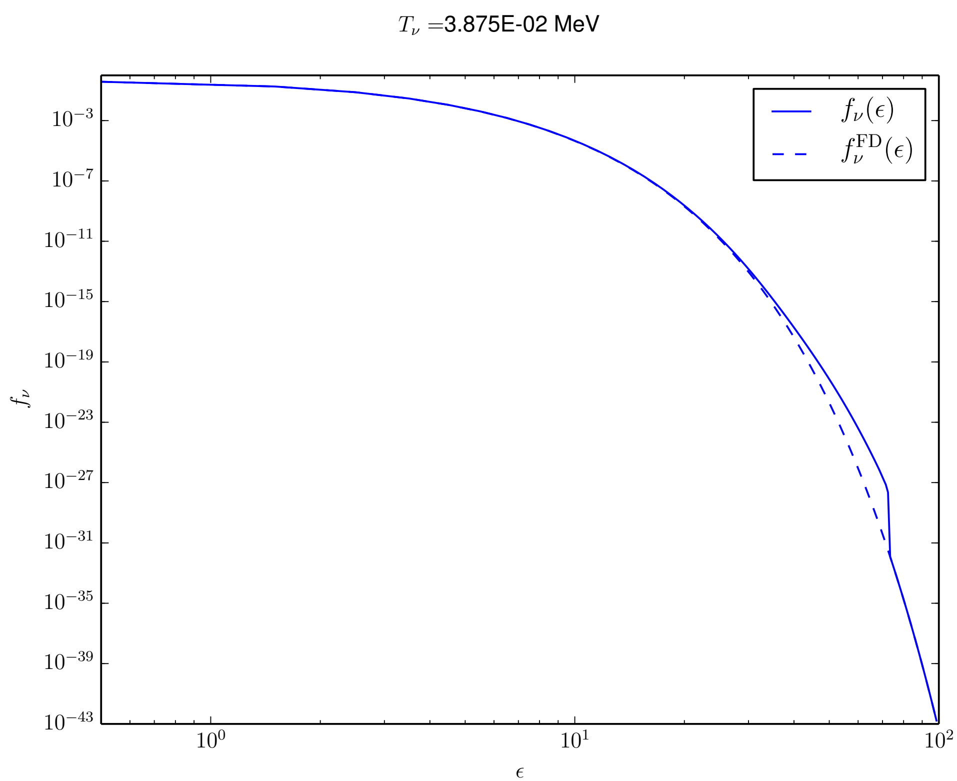

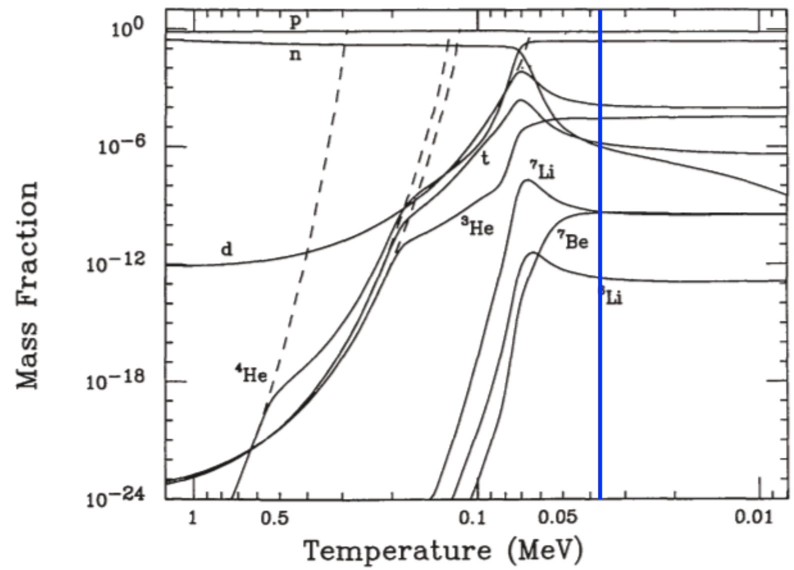

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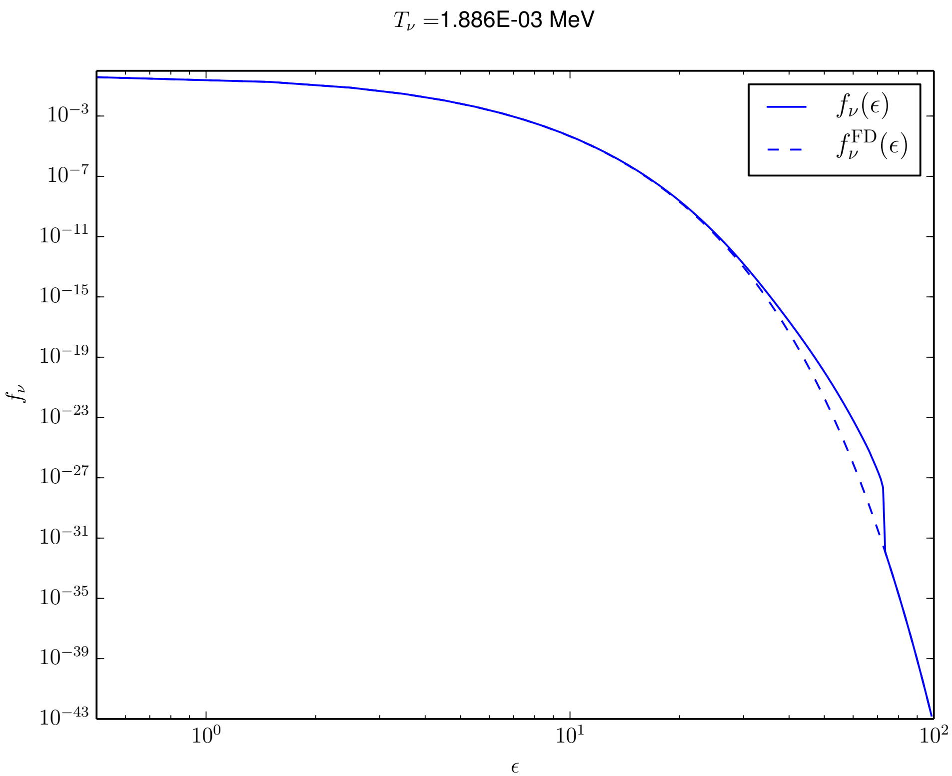
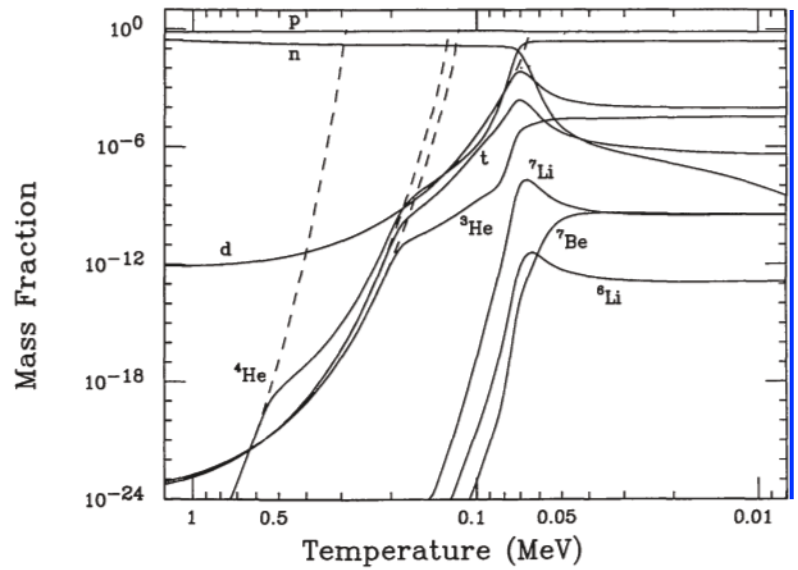
Code testing/preliminary results

- 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
- 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.