The Primordial Lithium Problem

Can We Avoid New Physics ?

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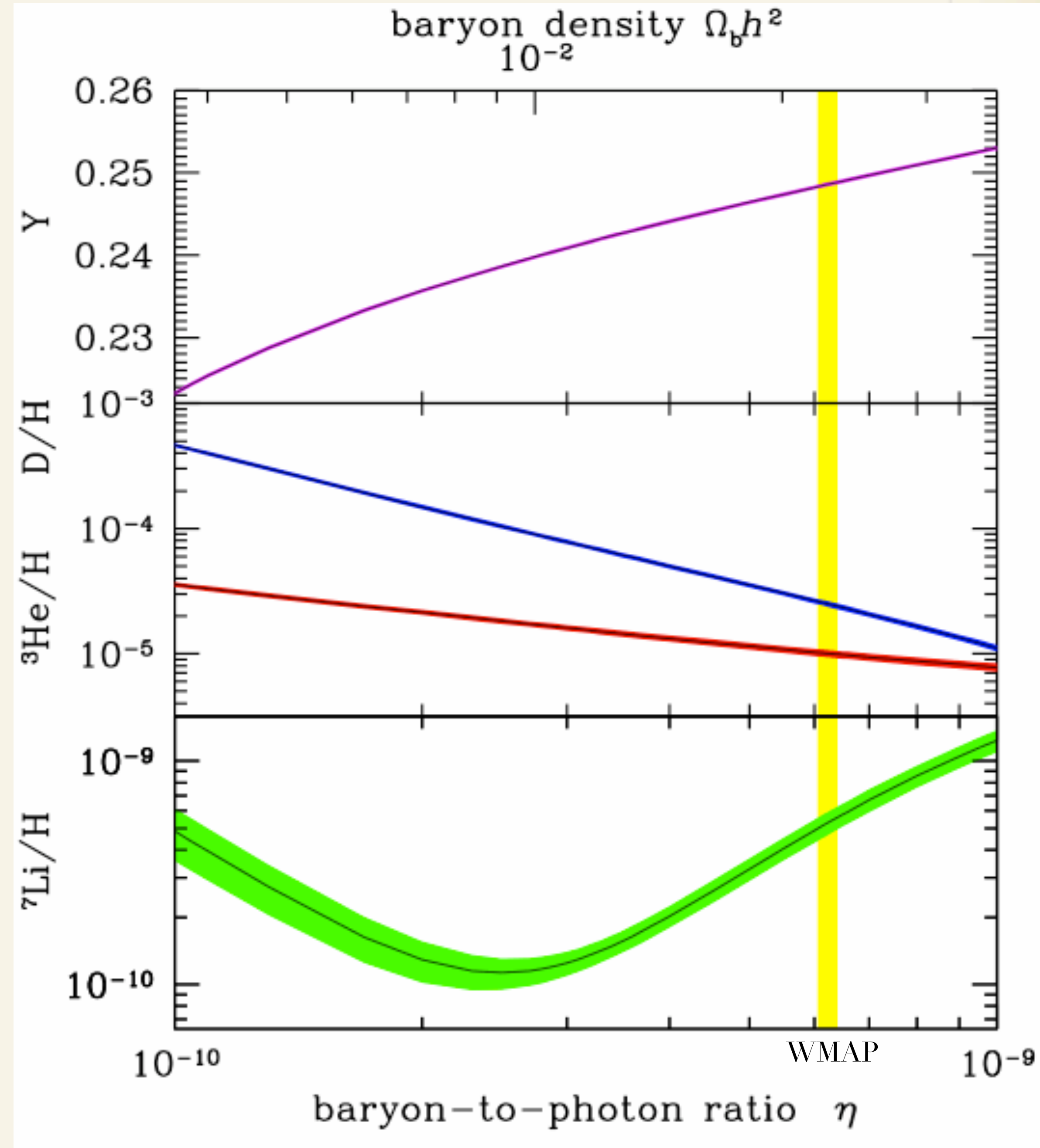
New Perspectives 2011

What's the problem ?

- Light elemental abundances constrain Big Bang cosmology (Wagoner, Fowler and Hoyle, 1967 ; Steigman, Schramm and Gunn, 1977 ; Schramm and Turner, 1998)
- Abundances set by

  $n_b/n_\gamma = \eta \propto \Omega_b$

- WMAP gives η
- Discrepancy between theory (Cyburt, Fields and Olive, 2008) and observation of ^{7}Li (Spite and Spite, 1982 ; Smith et al., 1998)
- "Law of trichotomy"
  - Theory wrong
  - Observation wrong (Richards et al., 2005 ; Melendez et al., 2010)
  - Both wrong



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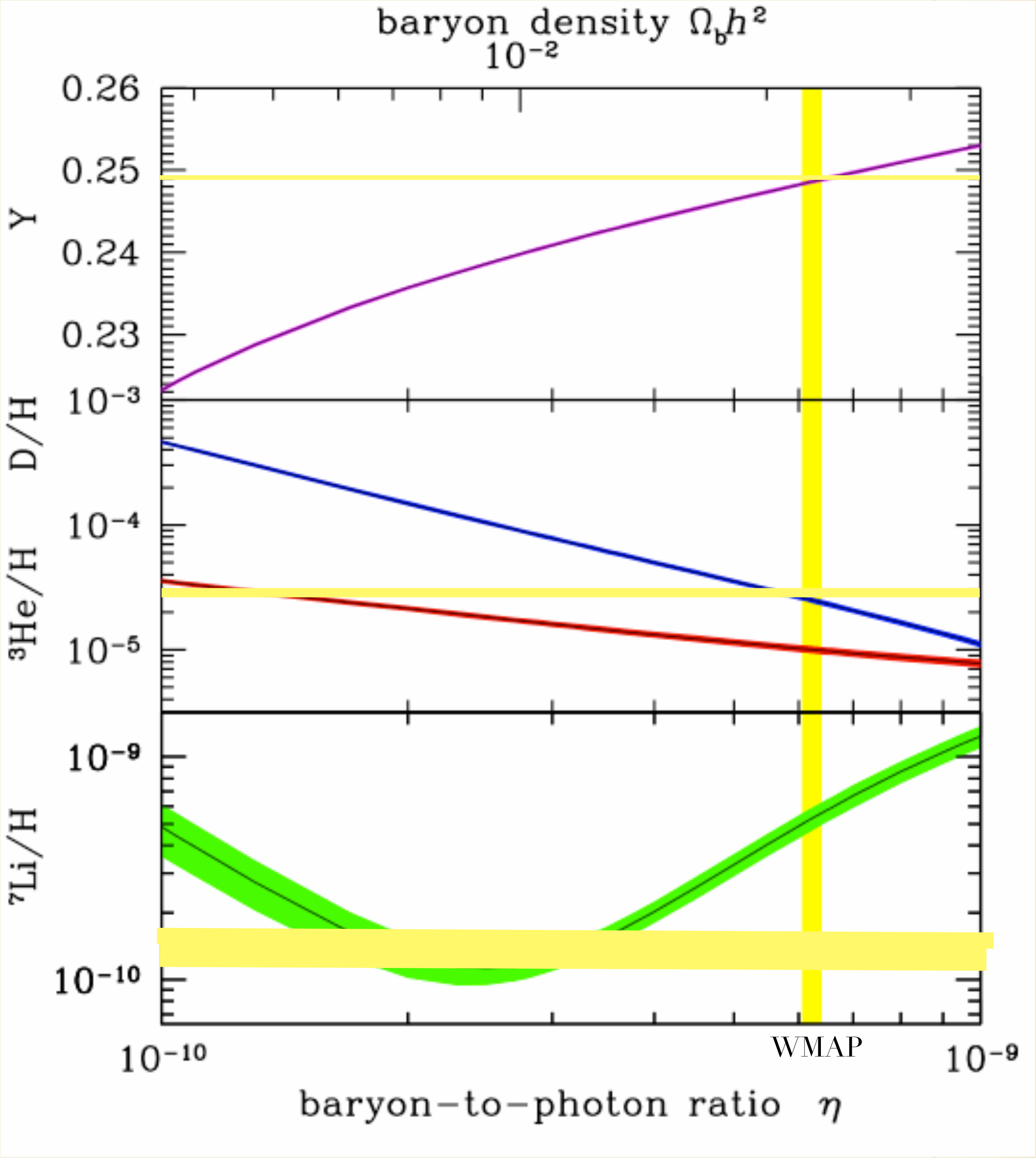

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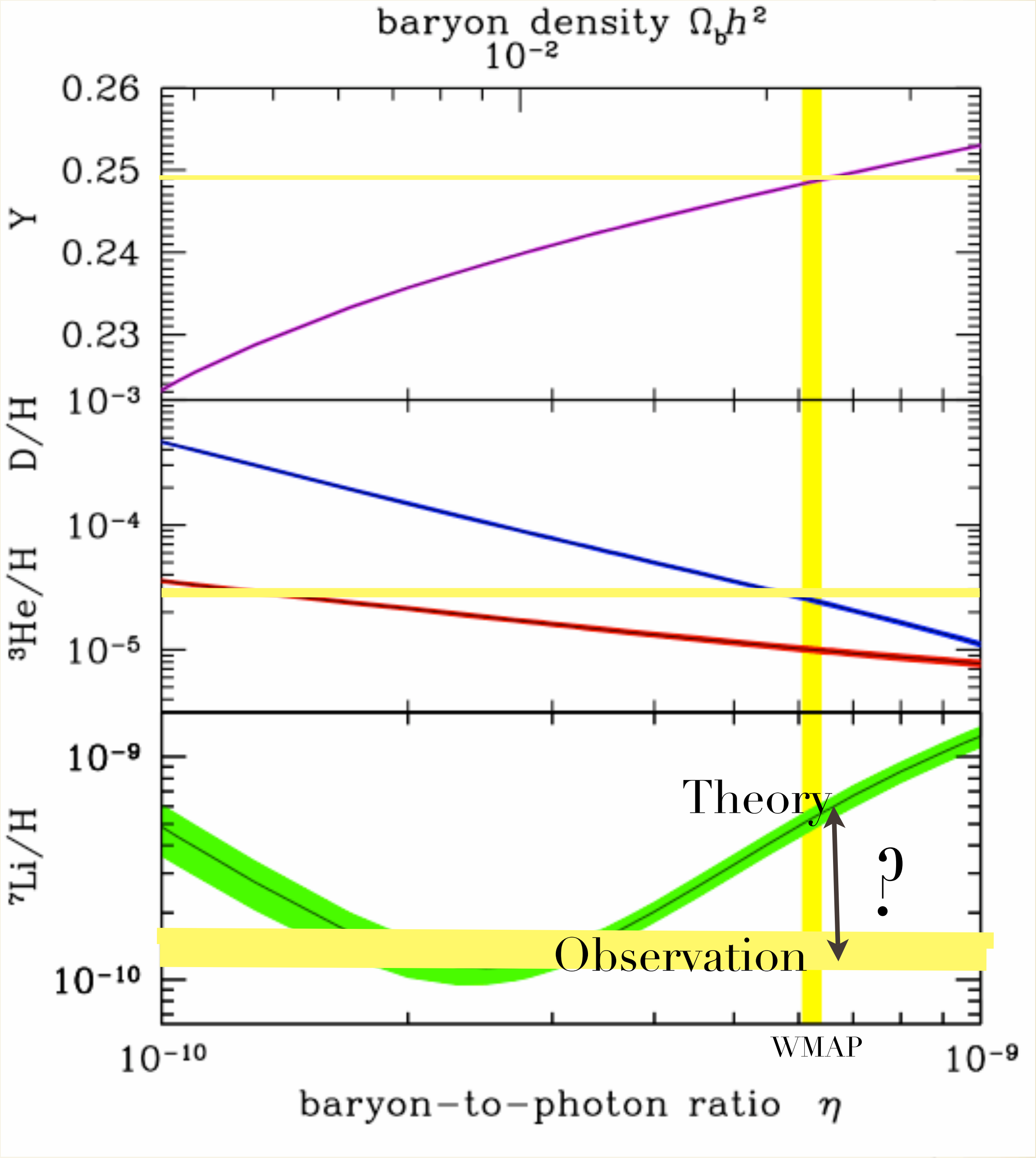

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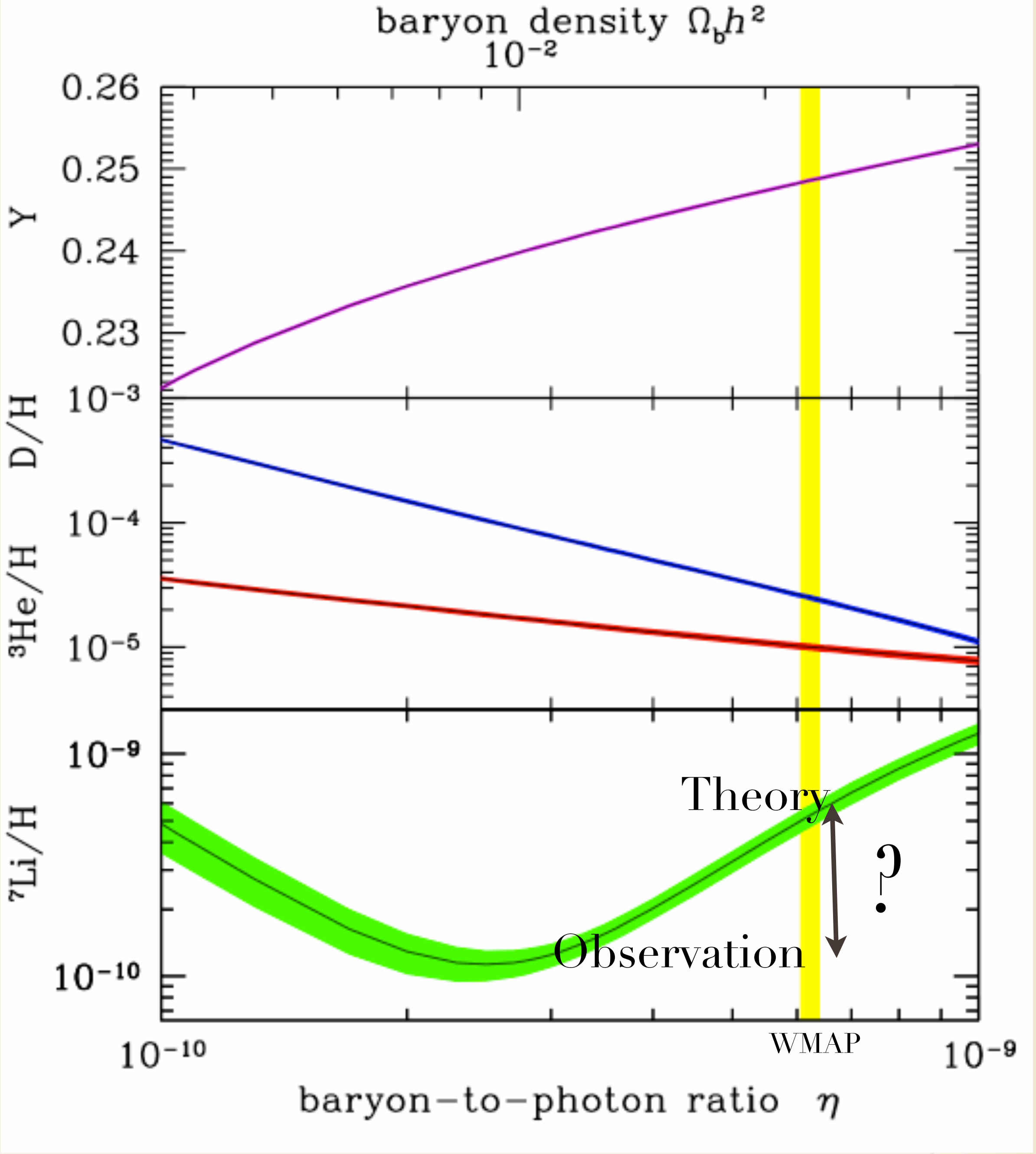

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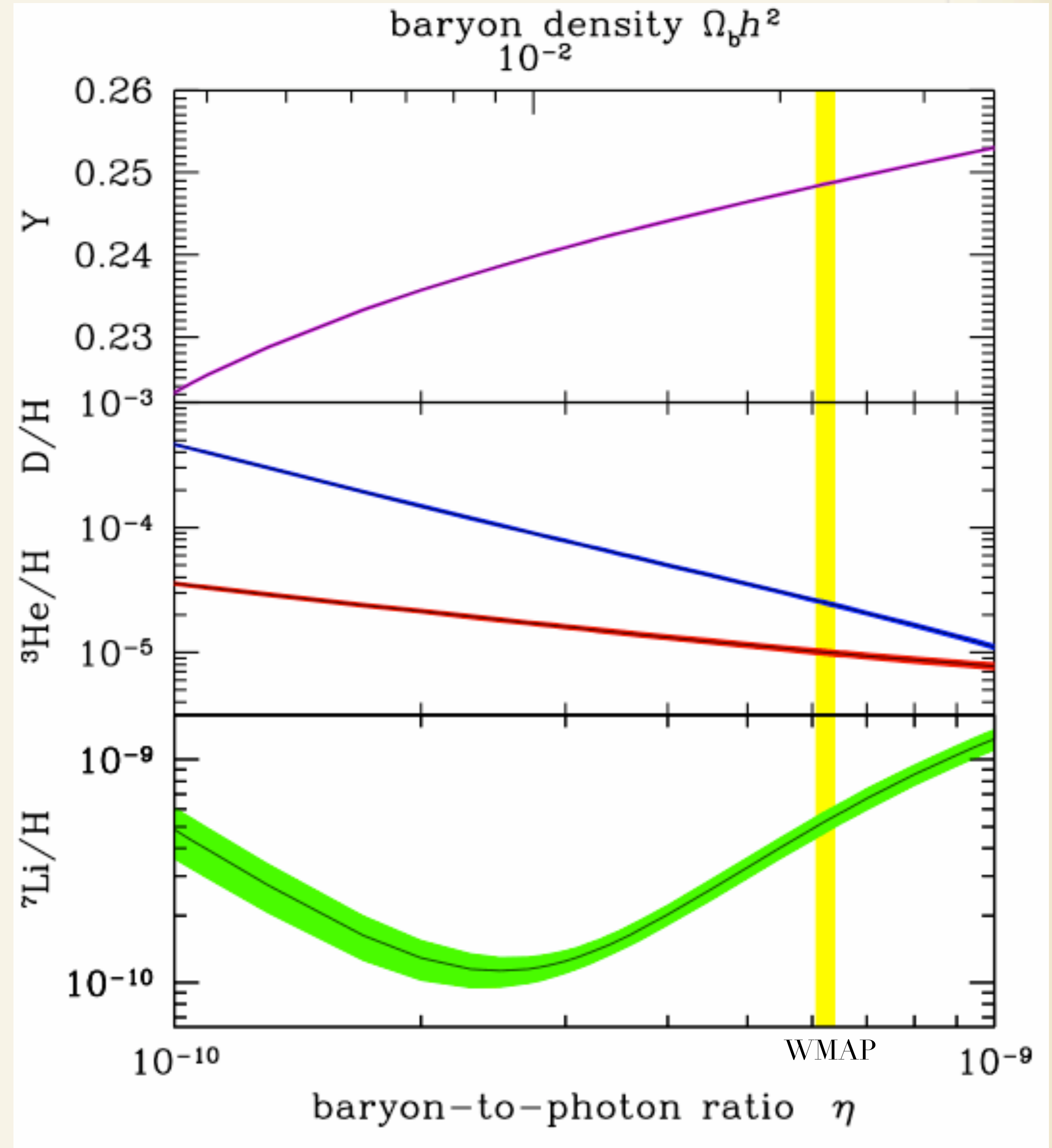

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Theory Solutions

- Assume observations right
  $\Rightarrow$ Reduce ^{7}Li or ^{7}Be
- Beyond Standard Model
  - Dark matter decay (Bailly et al., 2009 and others)
  - Bound states (Jittoh et al., 2010, Cyburt et al., 2006 and others)
  - Varying fundamental constants (Berengut et al.,2010),....) etc.

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CERN

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Fermilab

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OR

- Within Standard Model
  - Enhance nuclear reactions
  (Cyburt and Pospelov, 2009), Chakraborty, Fields and Olive (2011)

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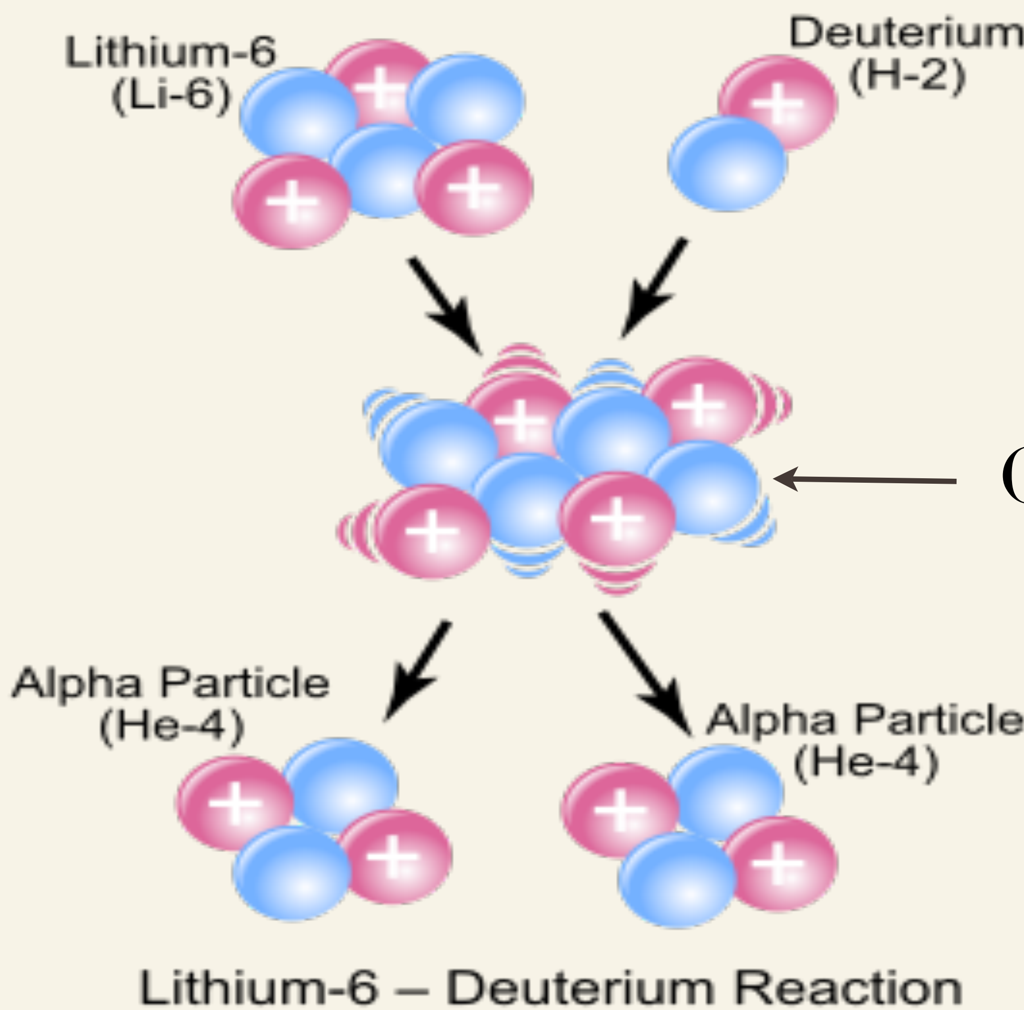
Fermilab

Resonances

Resonances



Compound nucleus

- A + B --> C + D vs A + B --> X* --> C + D

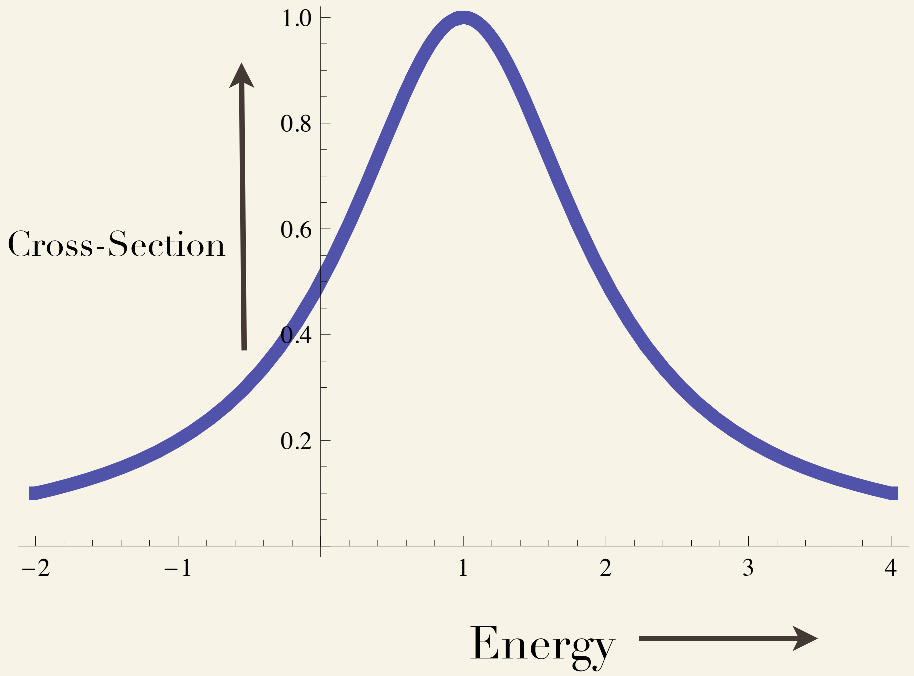
Resonance parameters

Resonance parameters

Cross-Section

Energy

Resonance parameters



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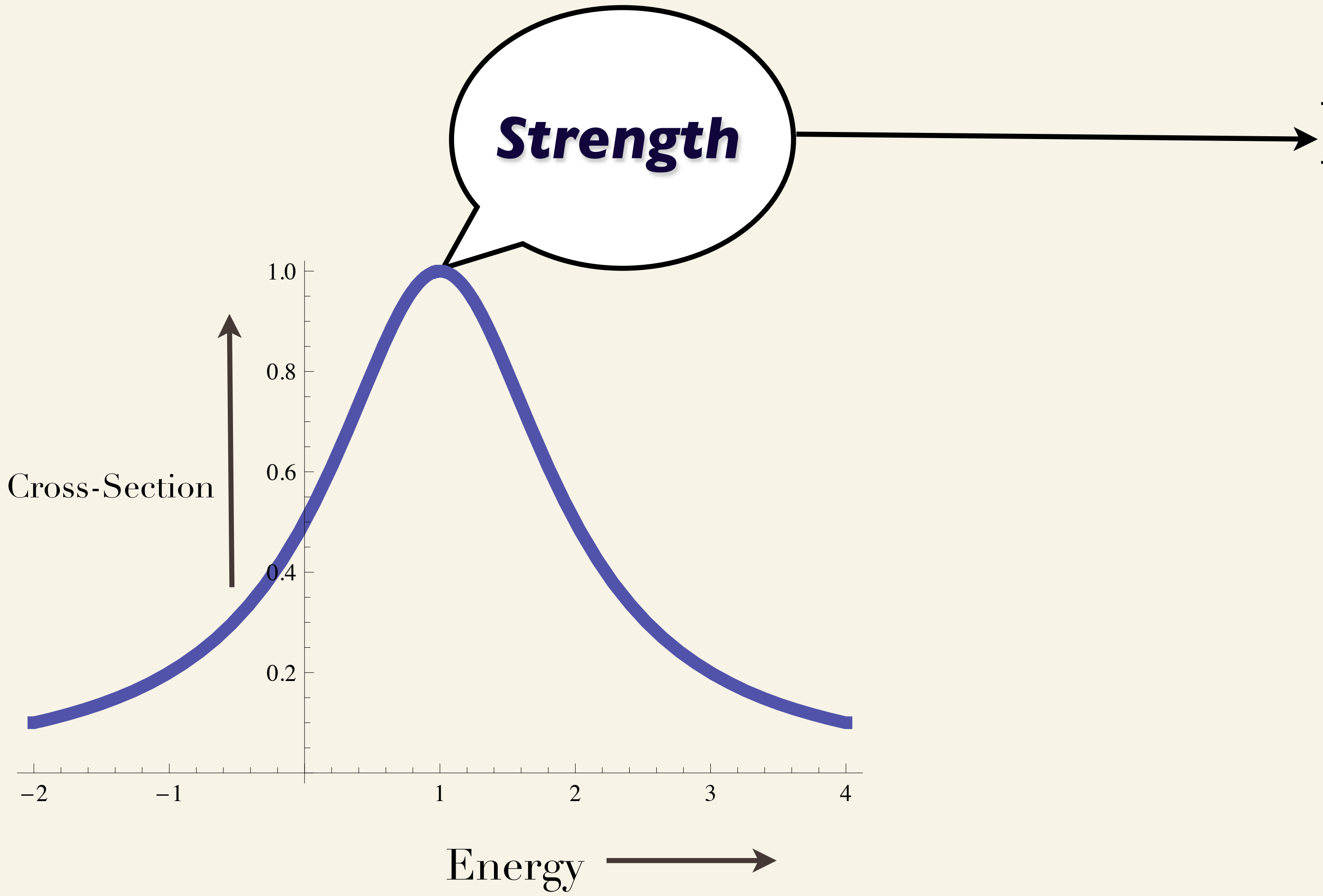
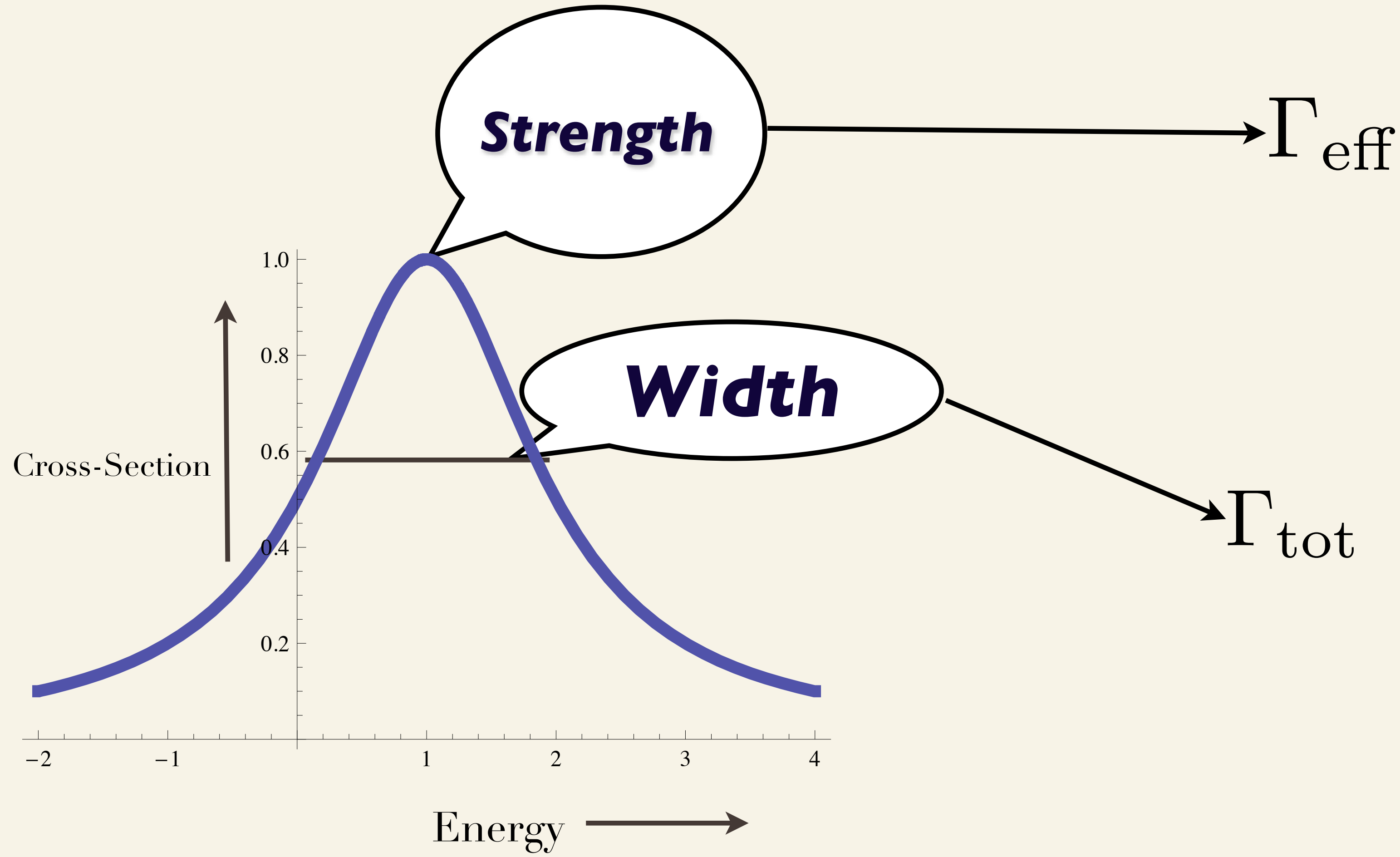


Γ_{eff}

Resonance parameters



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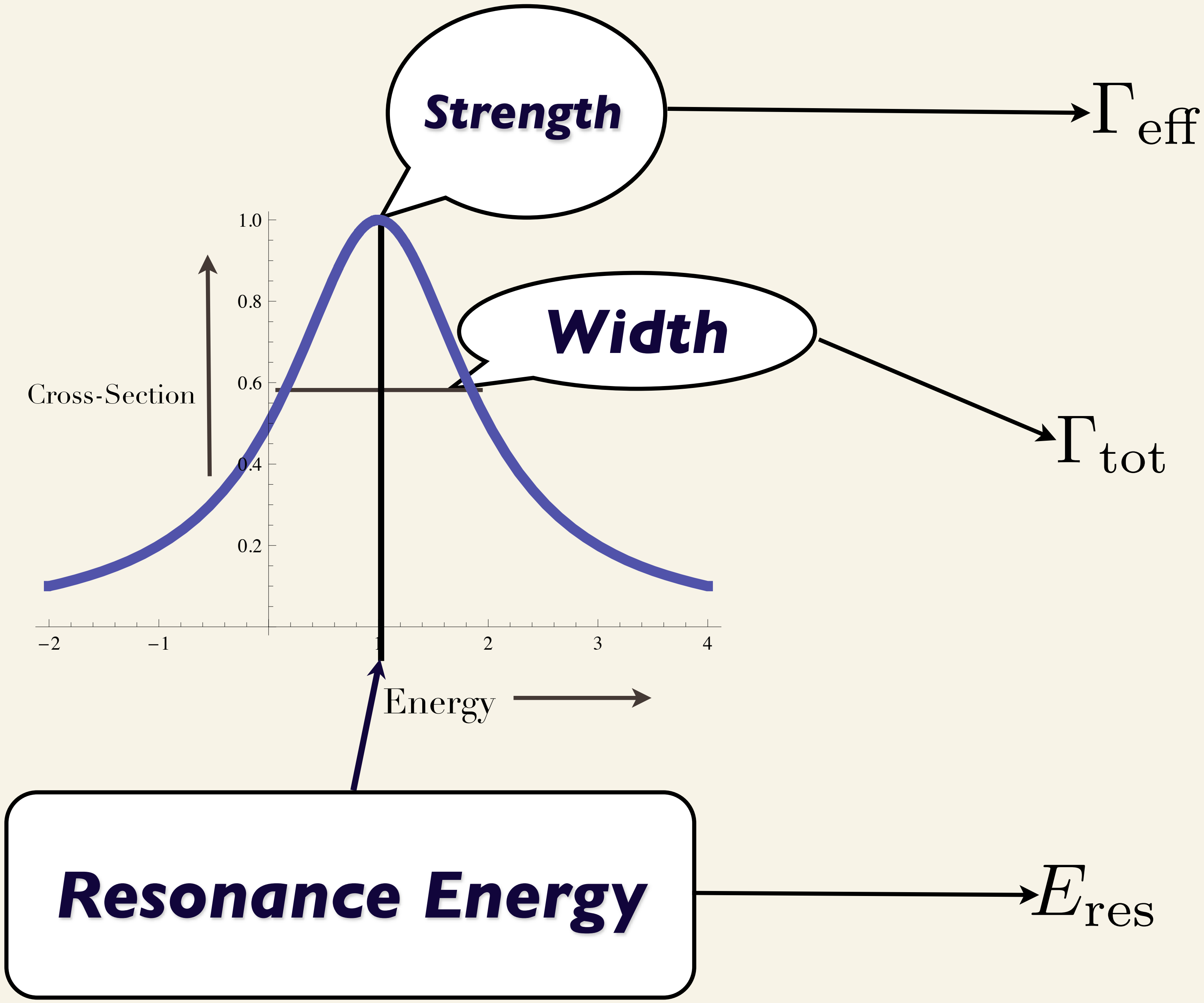

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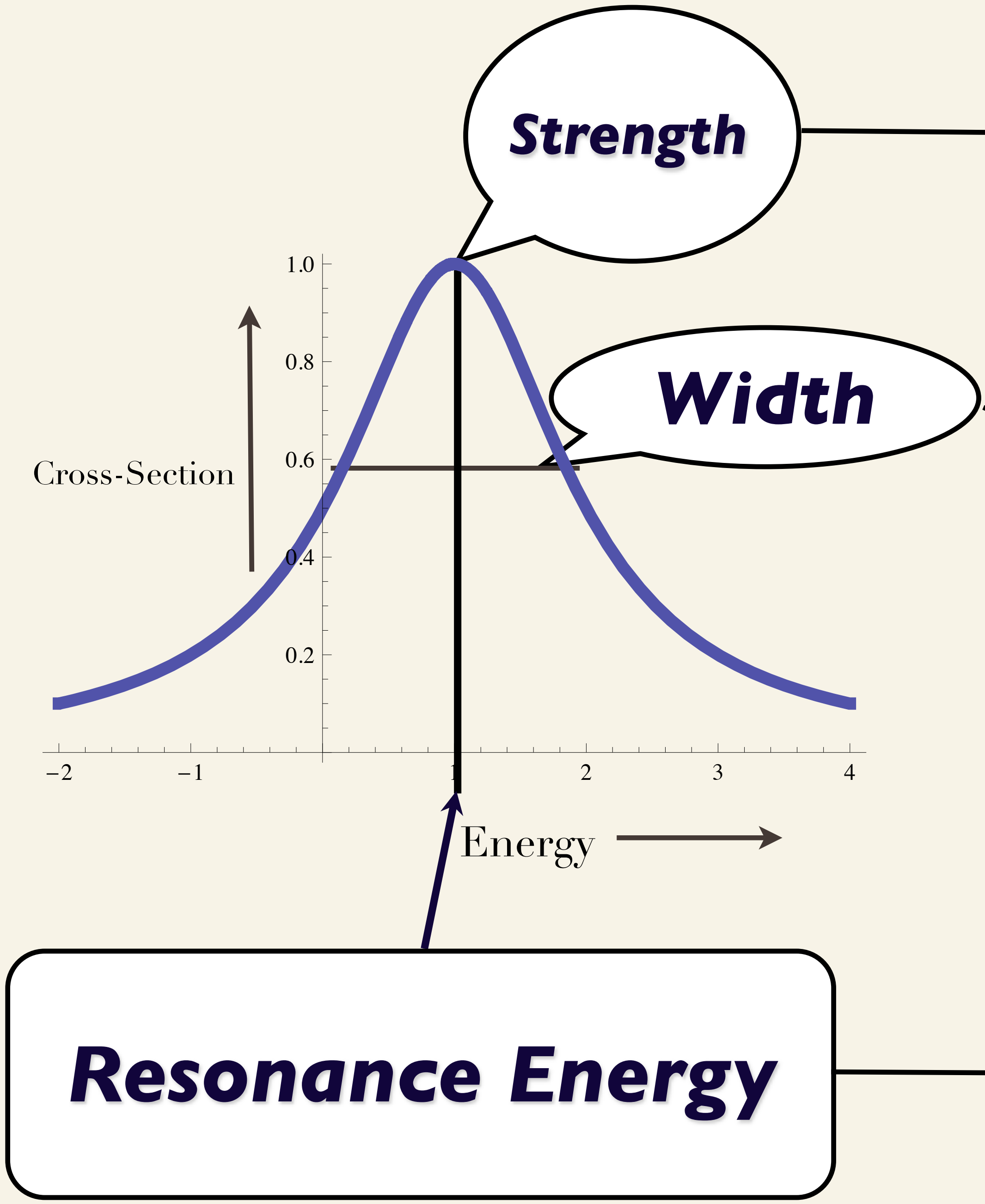

$$\sigma \propto \frac{\Gamma_1 \Gamma_2}{(E - E_R)^2 + (\Gamma_{tot}/2)^2}$$

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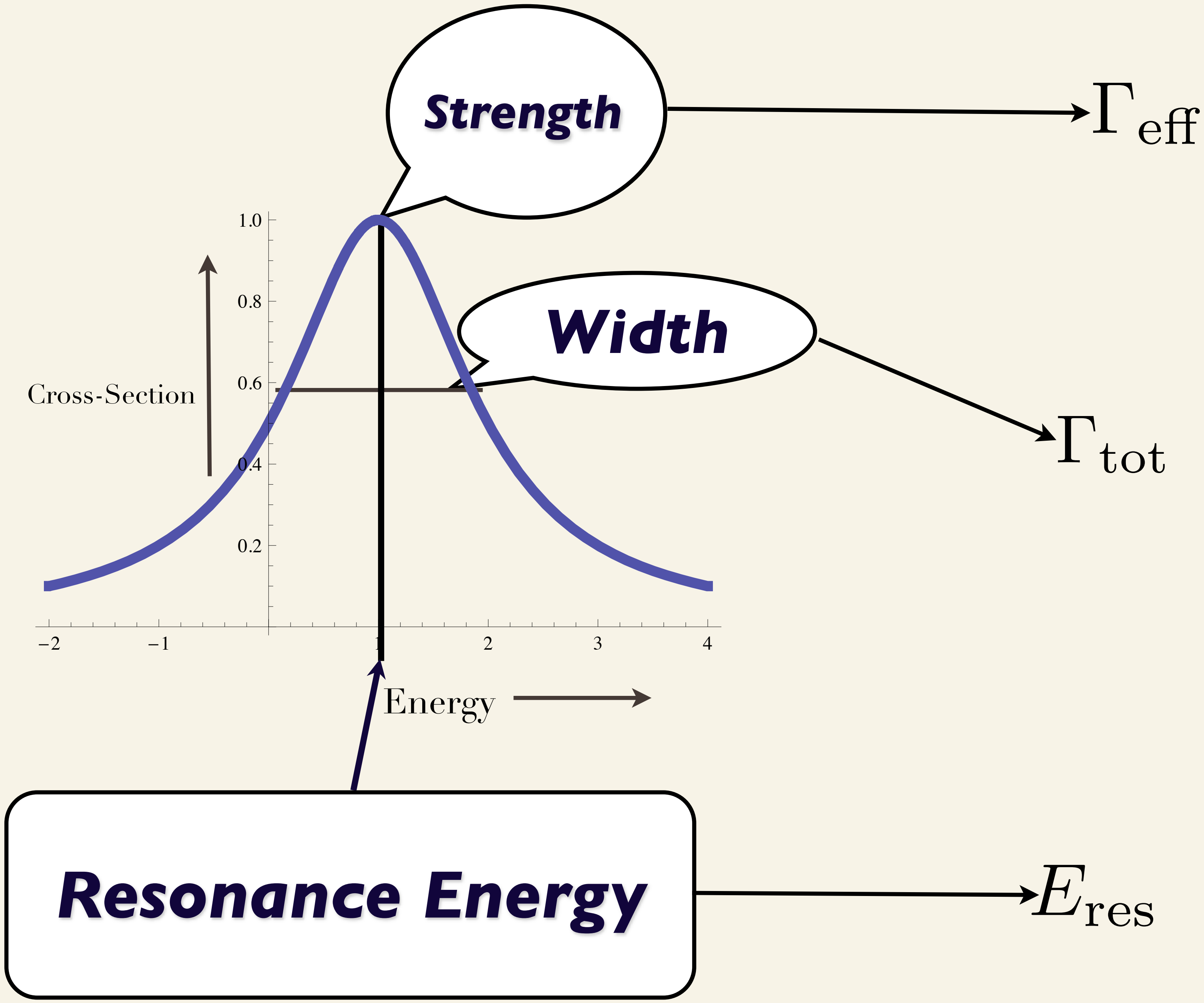

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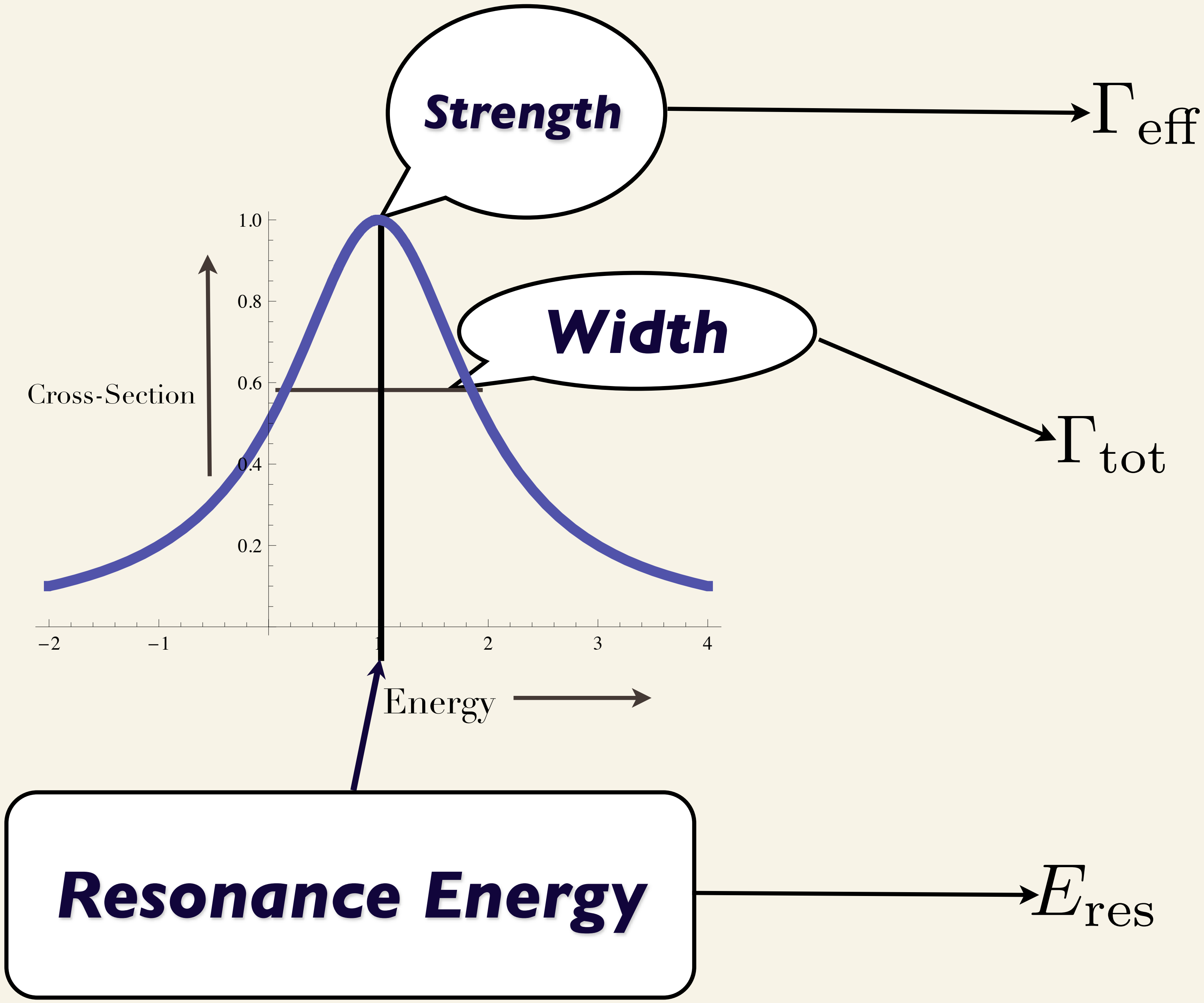

Narrow Resonance Approximation

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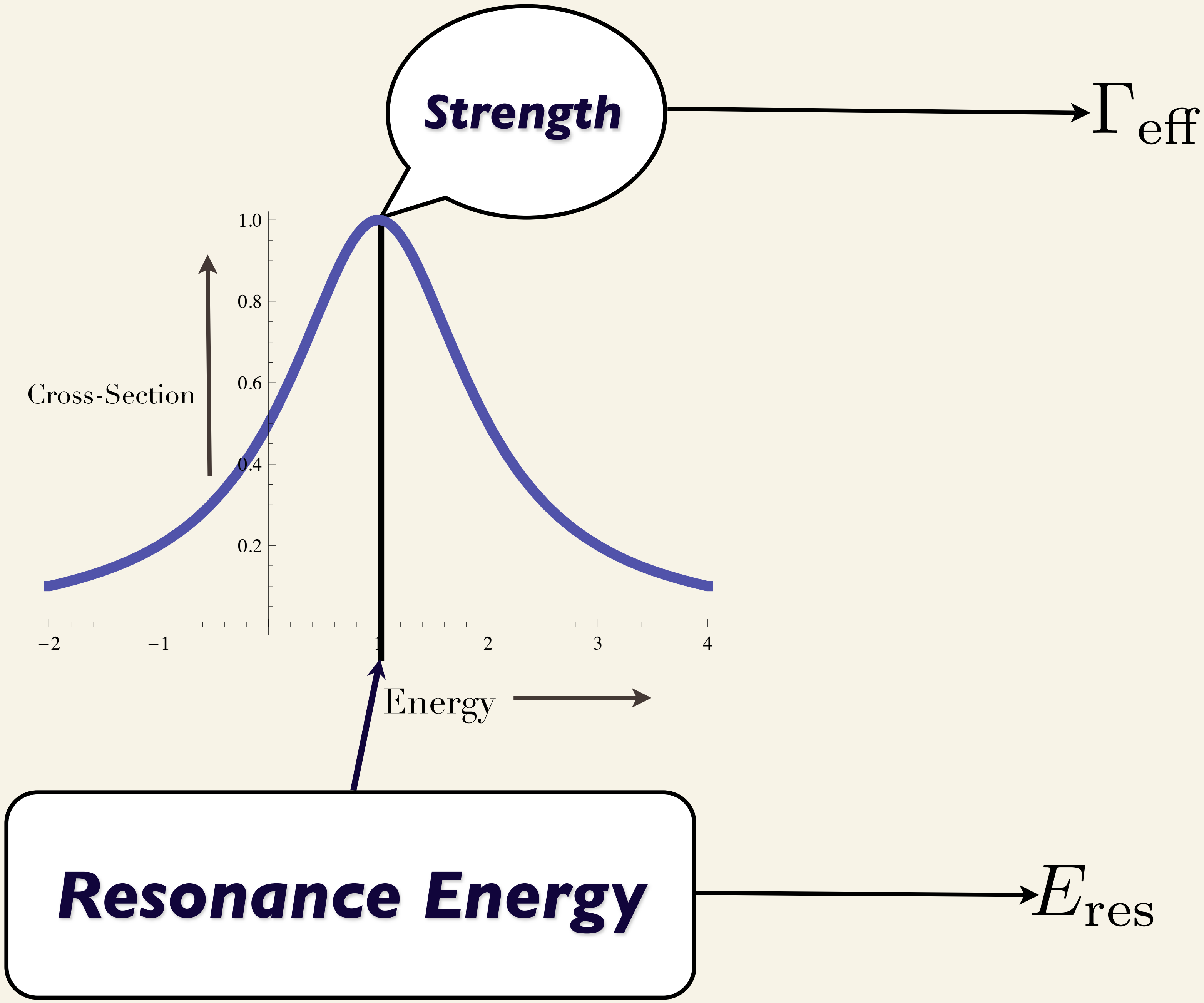

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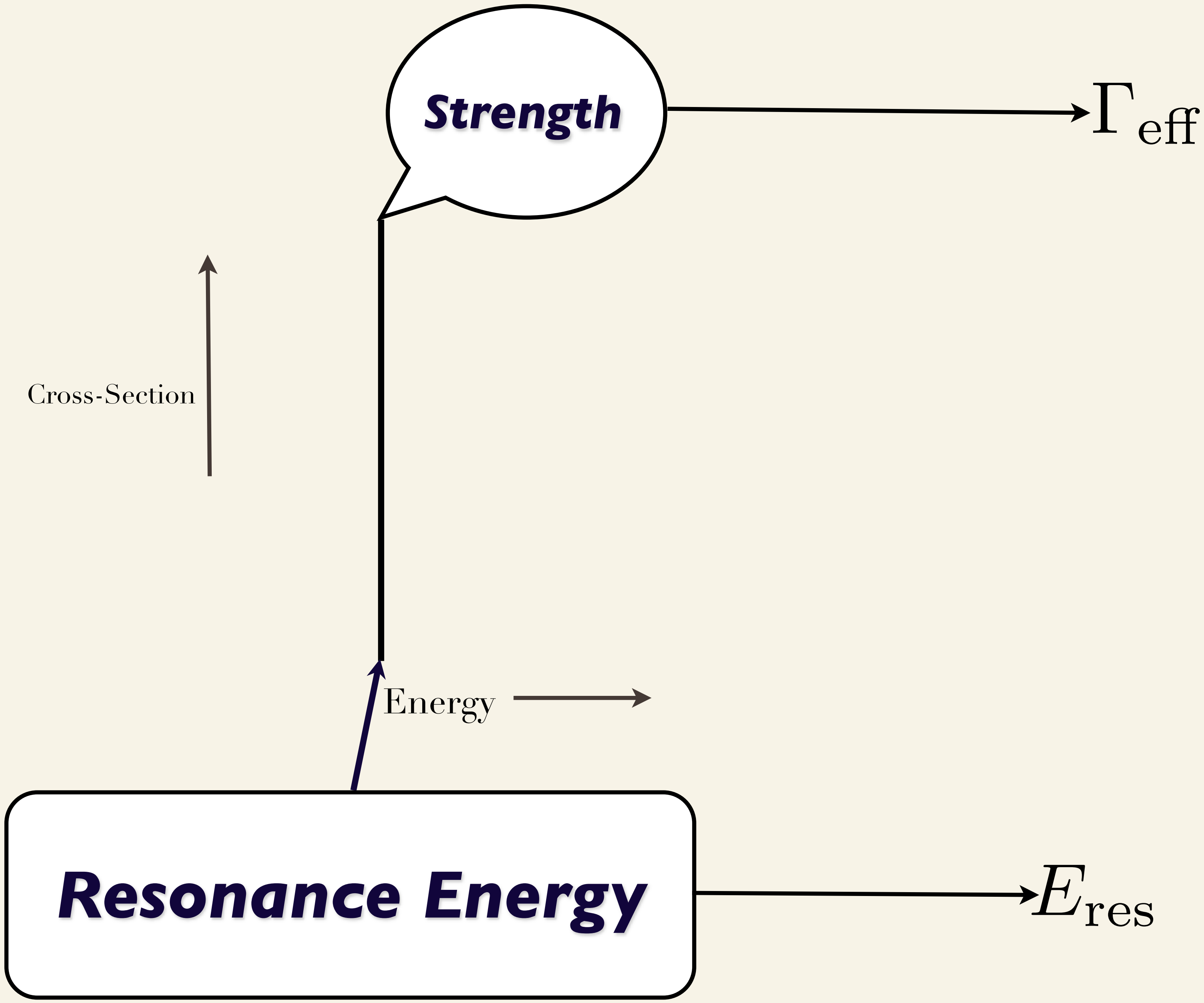

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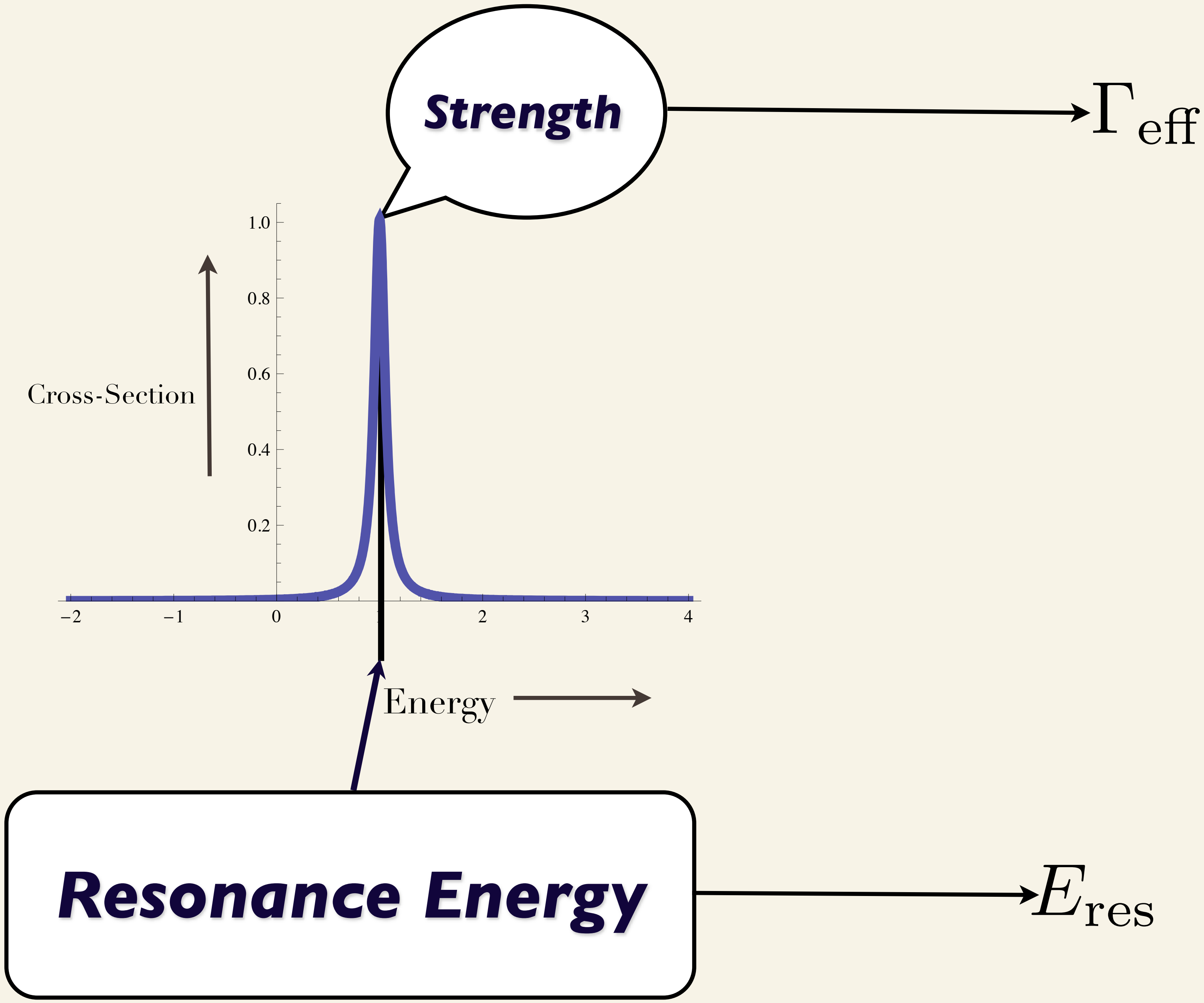
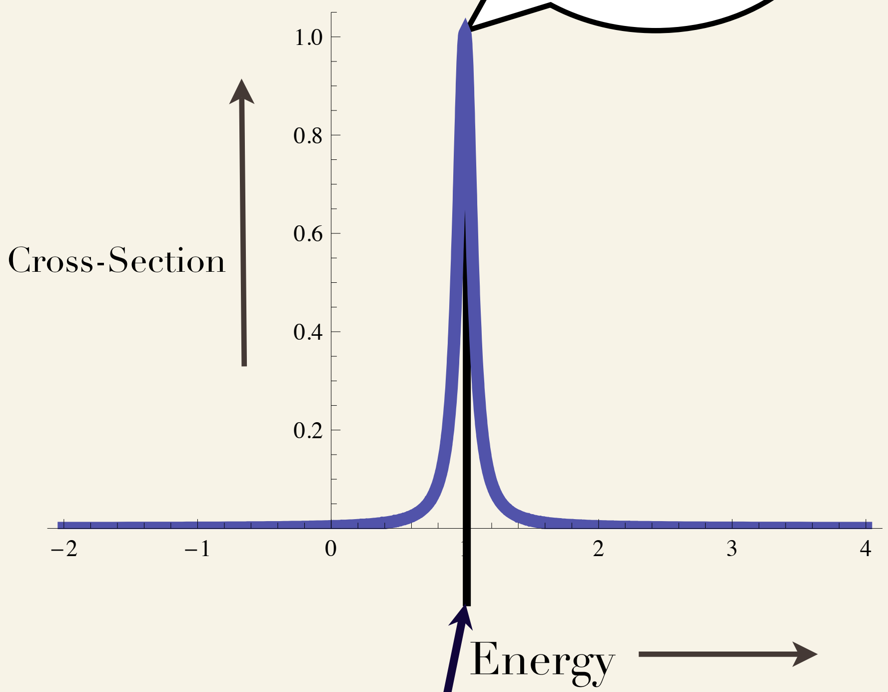


Narrow Resonance Approximation

Resonance parameters

Strength → Γ_{eff} ↔ a (channel radius)



Resonance Energy → E_{res}

Narrow Resonance Approximation

Cyburt and Pospelov

- Cyburt and Pospelov, (2009)

  - Recognised existing level (16.7 MeV in ^{9}B)
  - $^{7}Be + d \rightarrow p + 2\alpha$
  - Strength unknown
  - Big error bars in E_{res}
  - Potential solution ?
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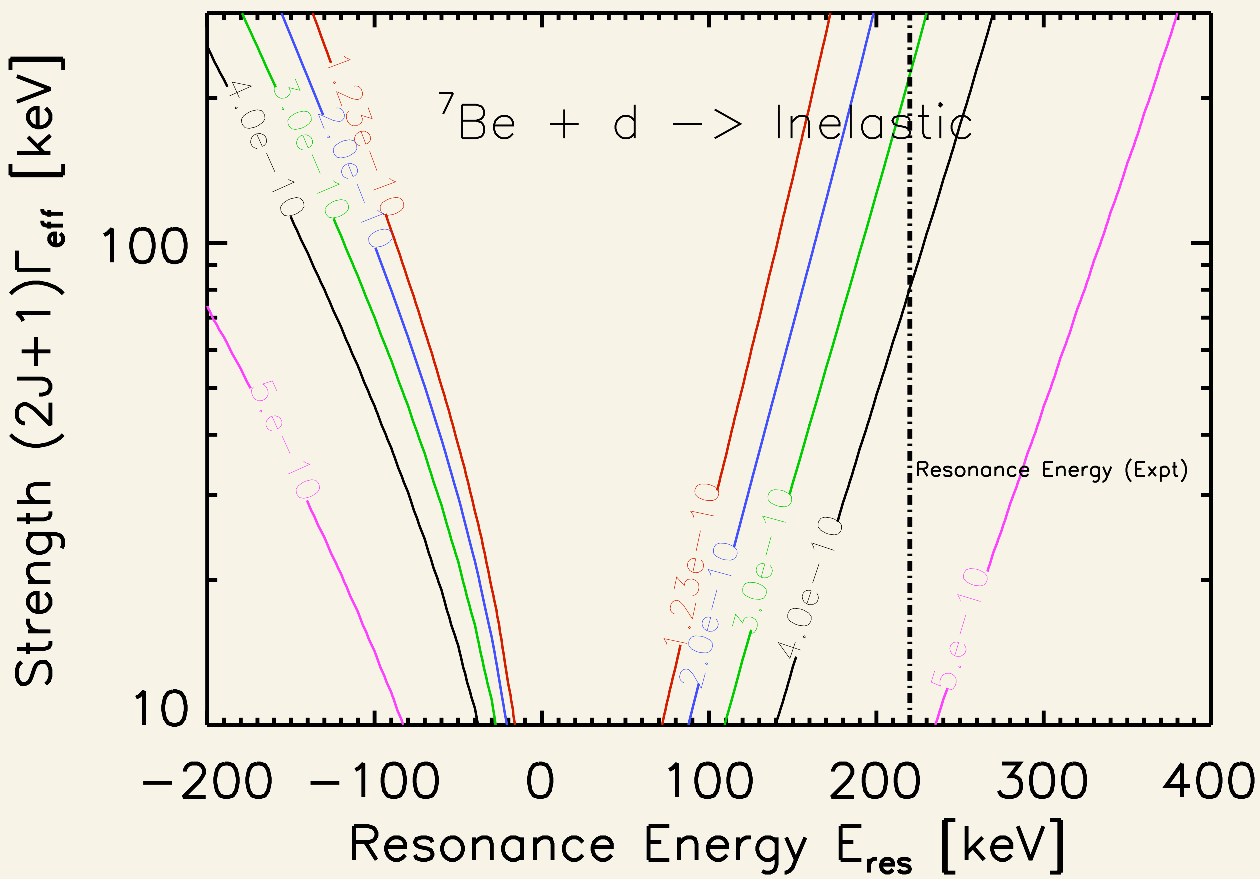

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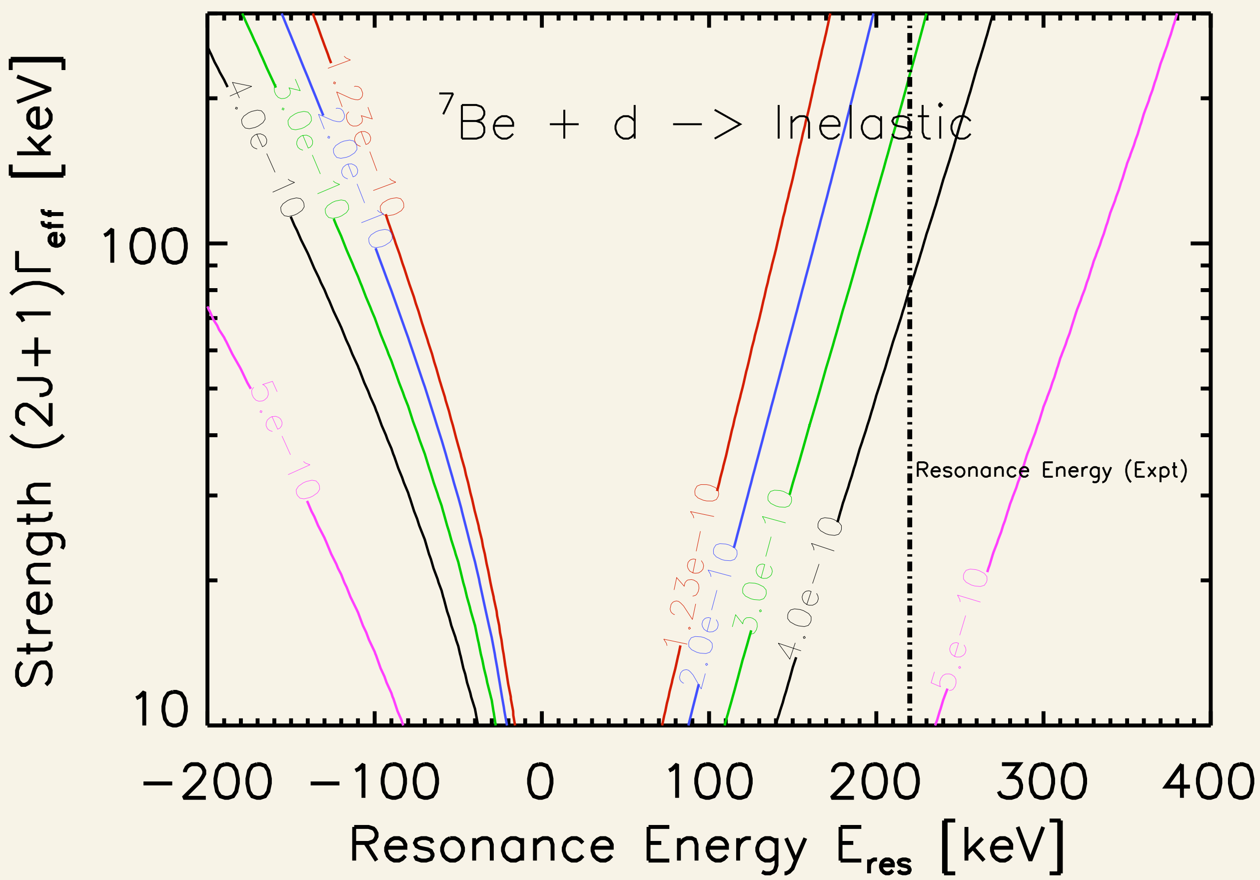

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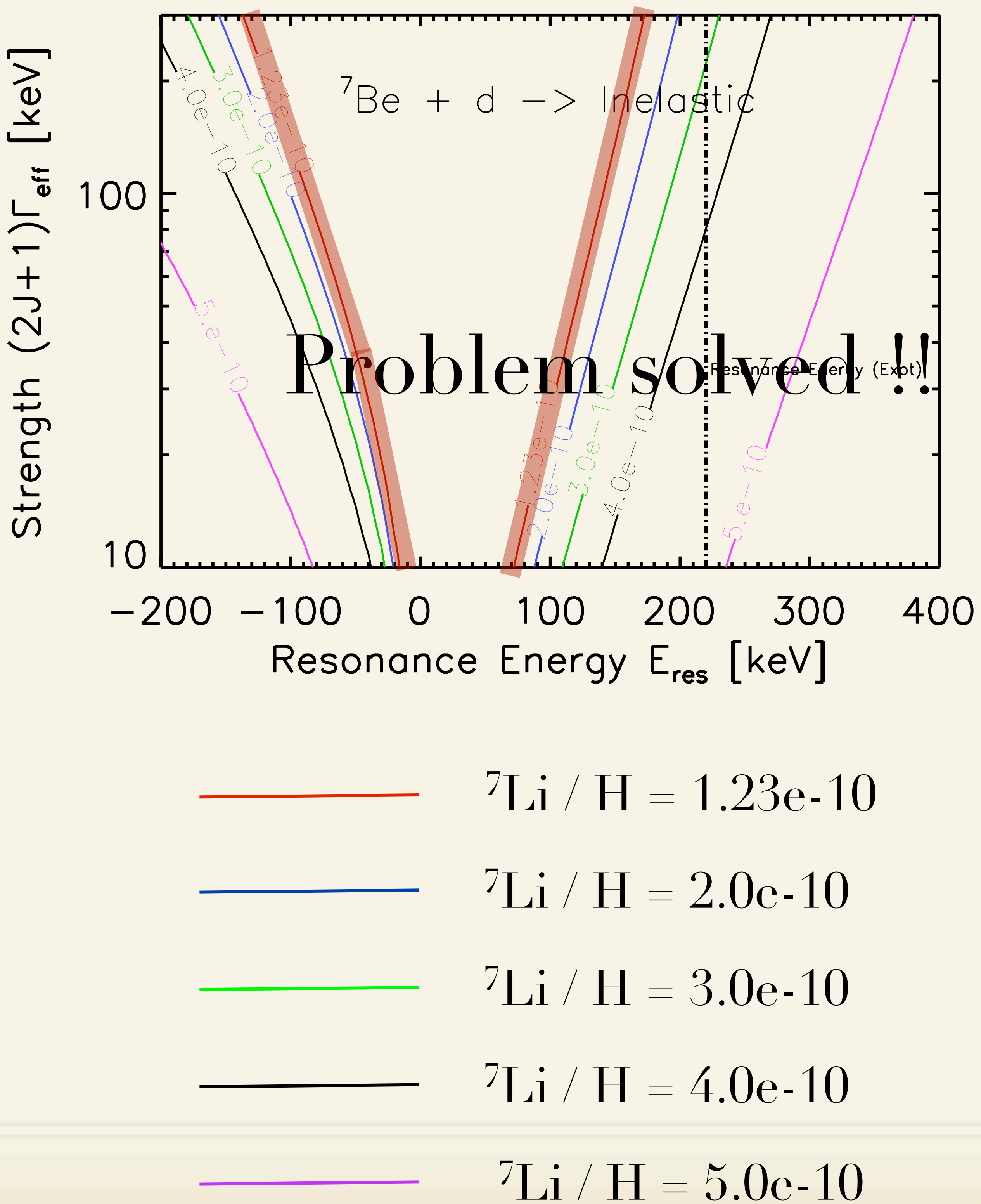

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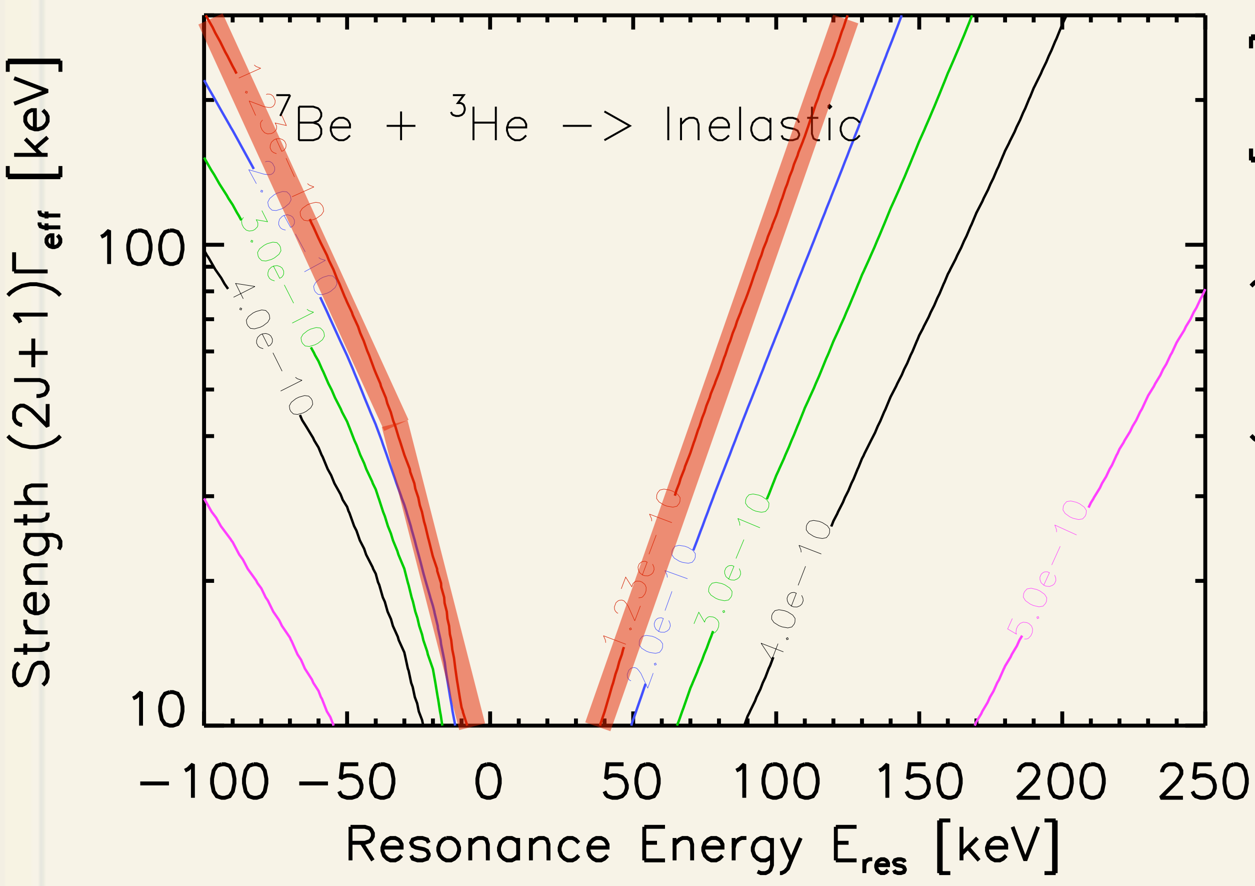

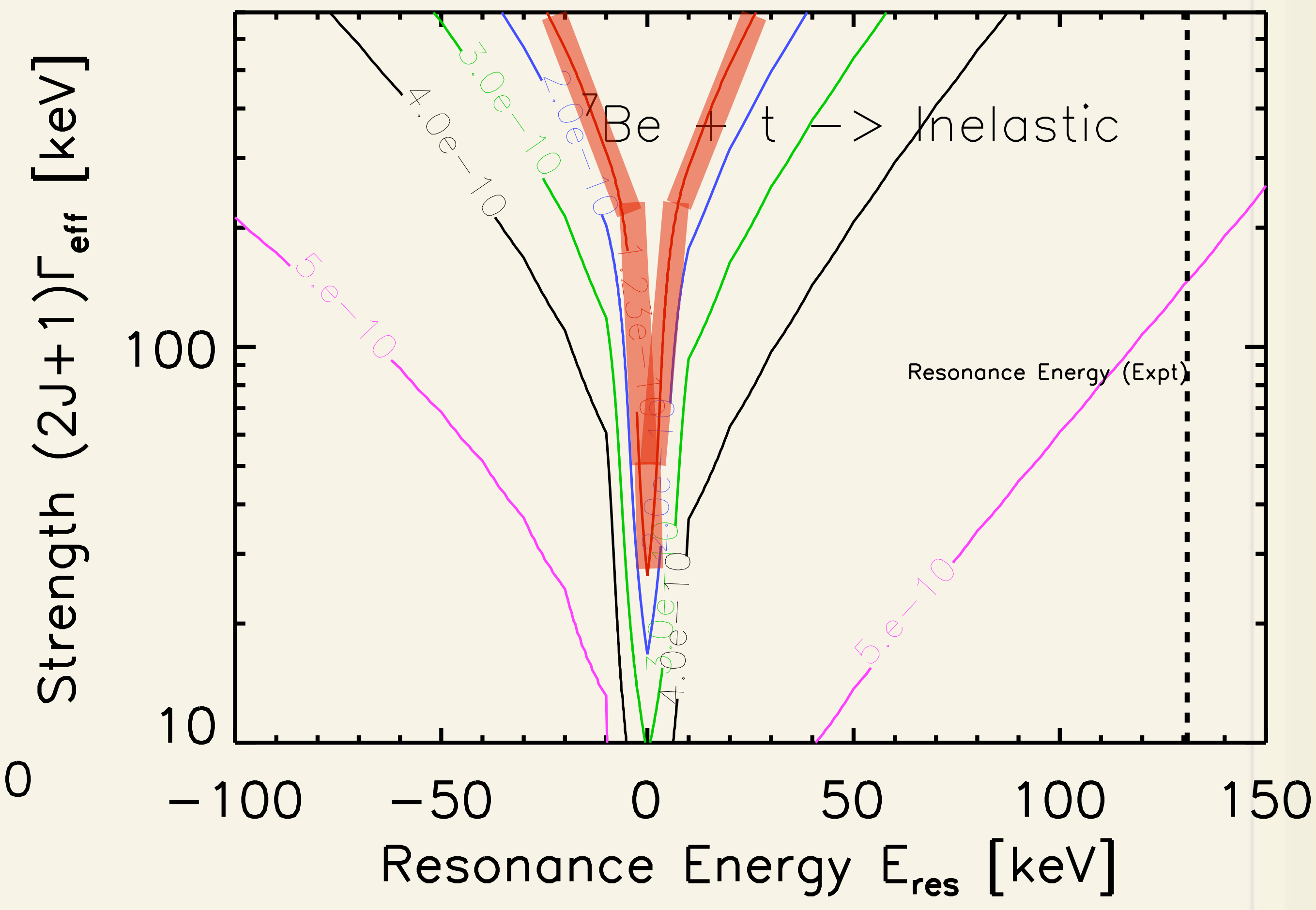

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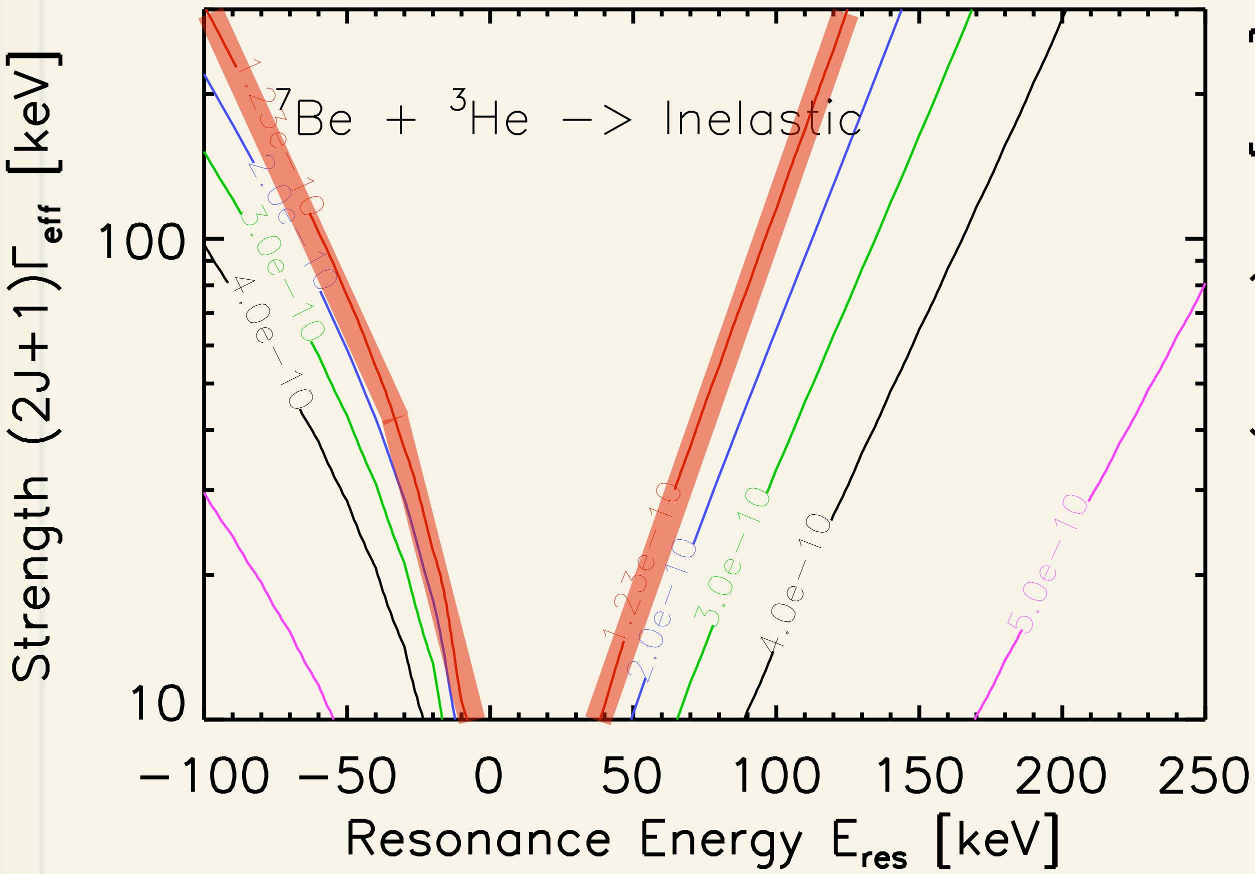

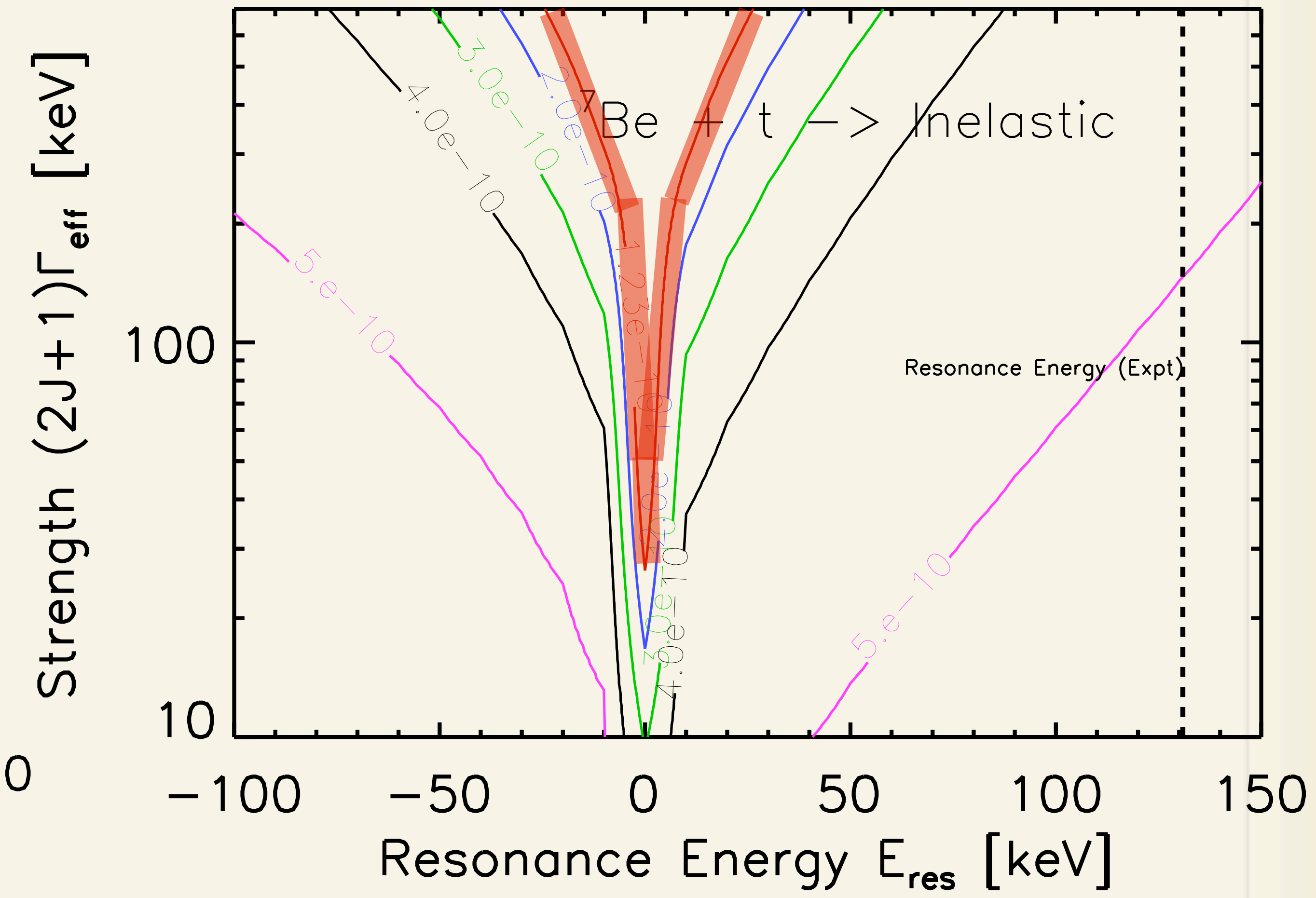

Problem solved ??

We may be able to avoid new physics

- Potentially yes → But nuclear resonances with **large** channel radii (a > 10 fm)
- Fat nuclei or SUSY - take a pick
- Testable by current nuclear experiments
- Complete or partial match
  - ^{7}Be + d → p + 2 α (Cyburt and Pospelov, (2009) and competing channels)
  - ^{7}Be + t → Inelastic (Chakraborty, Fields and Olive, (2011)
  - ^{7}Be + ^{3}He → Inelastic (Chakraborty, Fields and Olive, (2011)
  - Missed resonances / levels

Thank you !!!

Acknowledgments

http://www.tunl.duke.edu/nucldata/
http://www.nndc.bnl.gov/chart/

Nuclear Physics Solution

- Two main checks
  1. Completeness of nuclear database or missing reactions
  2. Improved reaction rates
- Can't decrease production rates - well studied and constrained
- Increase destruction
- Resonances ?

Let's try resonances

http://pntpm3.ulb.ac.be/Nacre/barre_database.htm

- http://en.wikipedia.org/wiki/Nuclear_reaction

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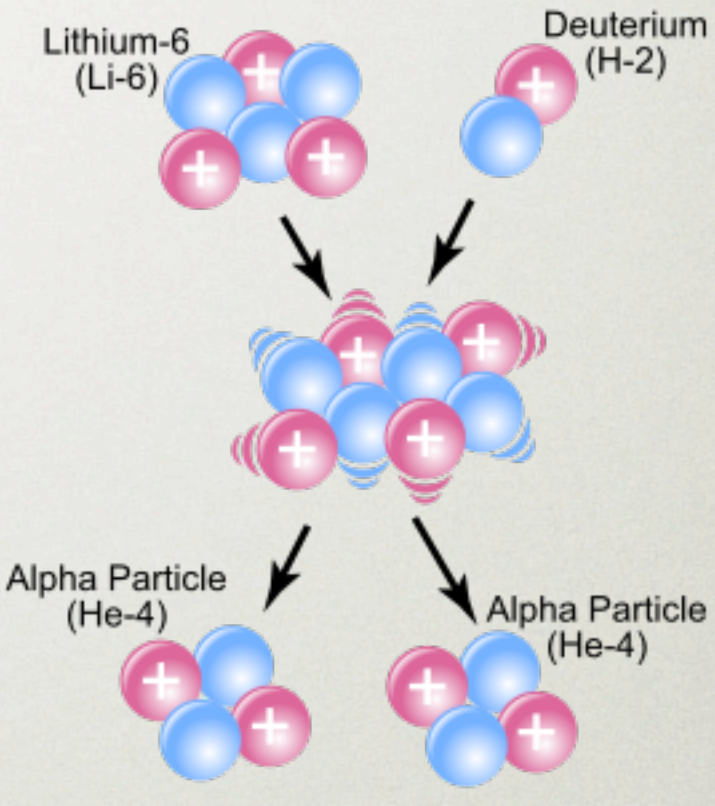

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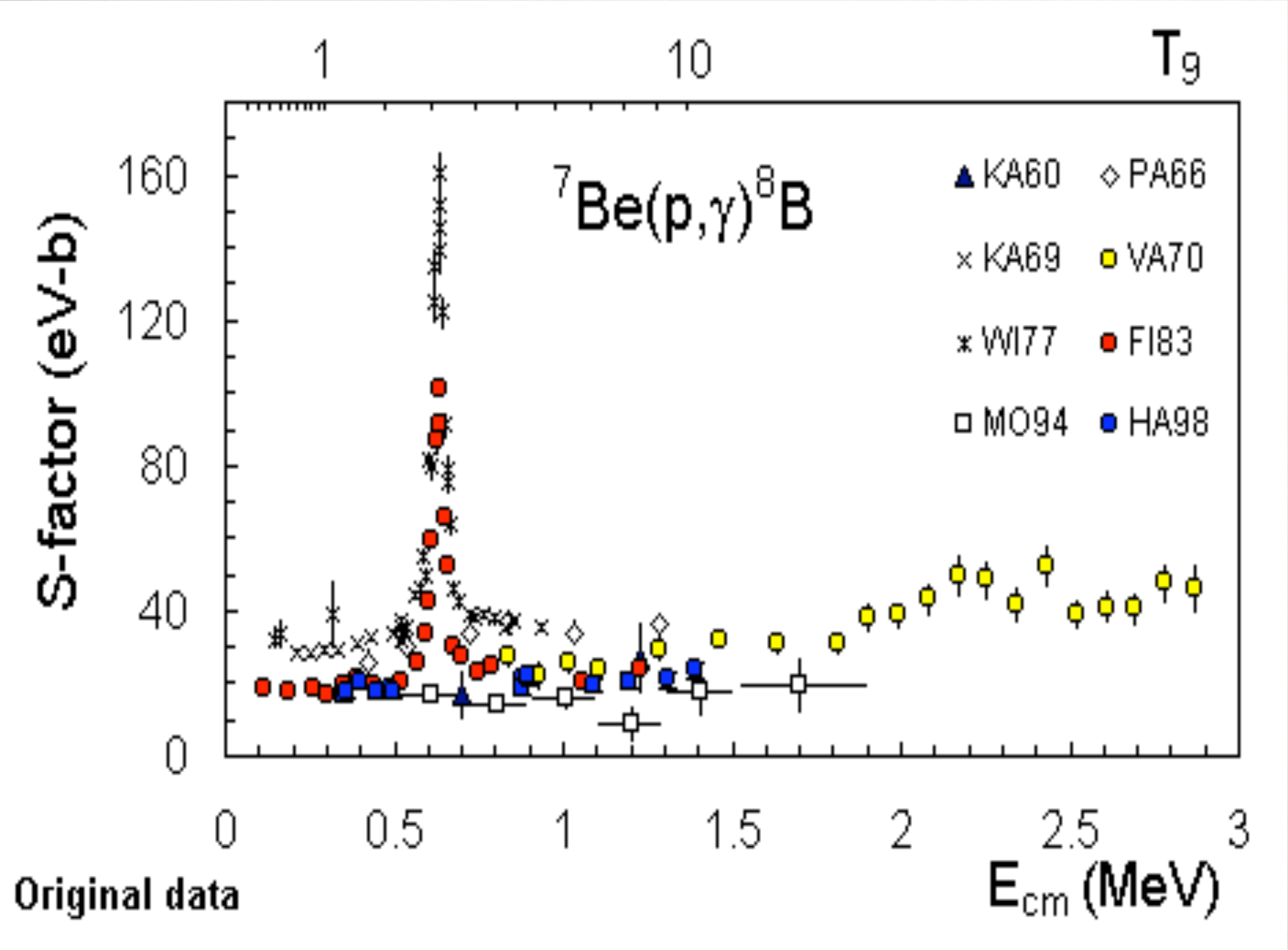

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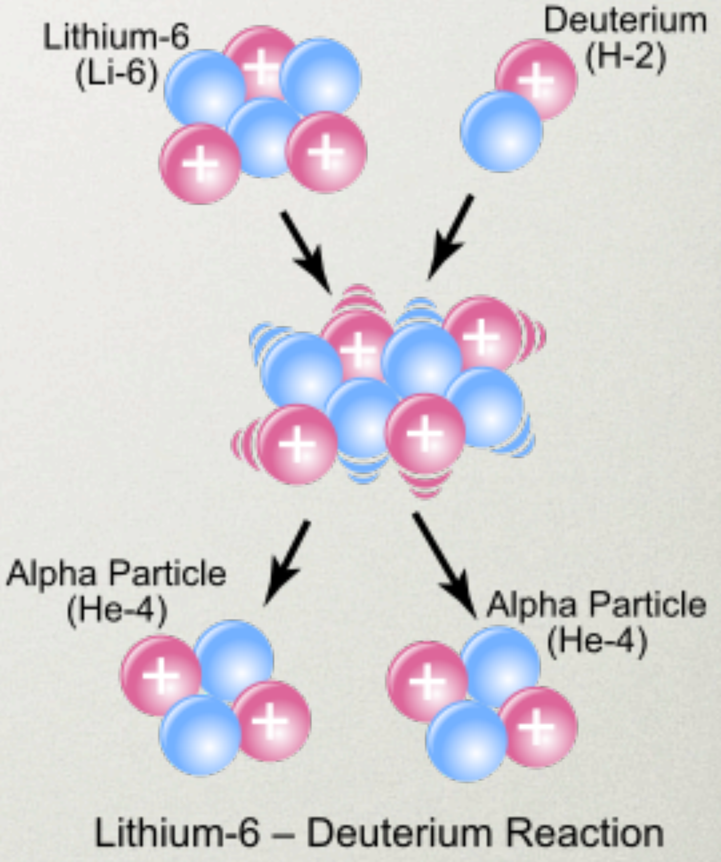

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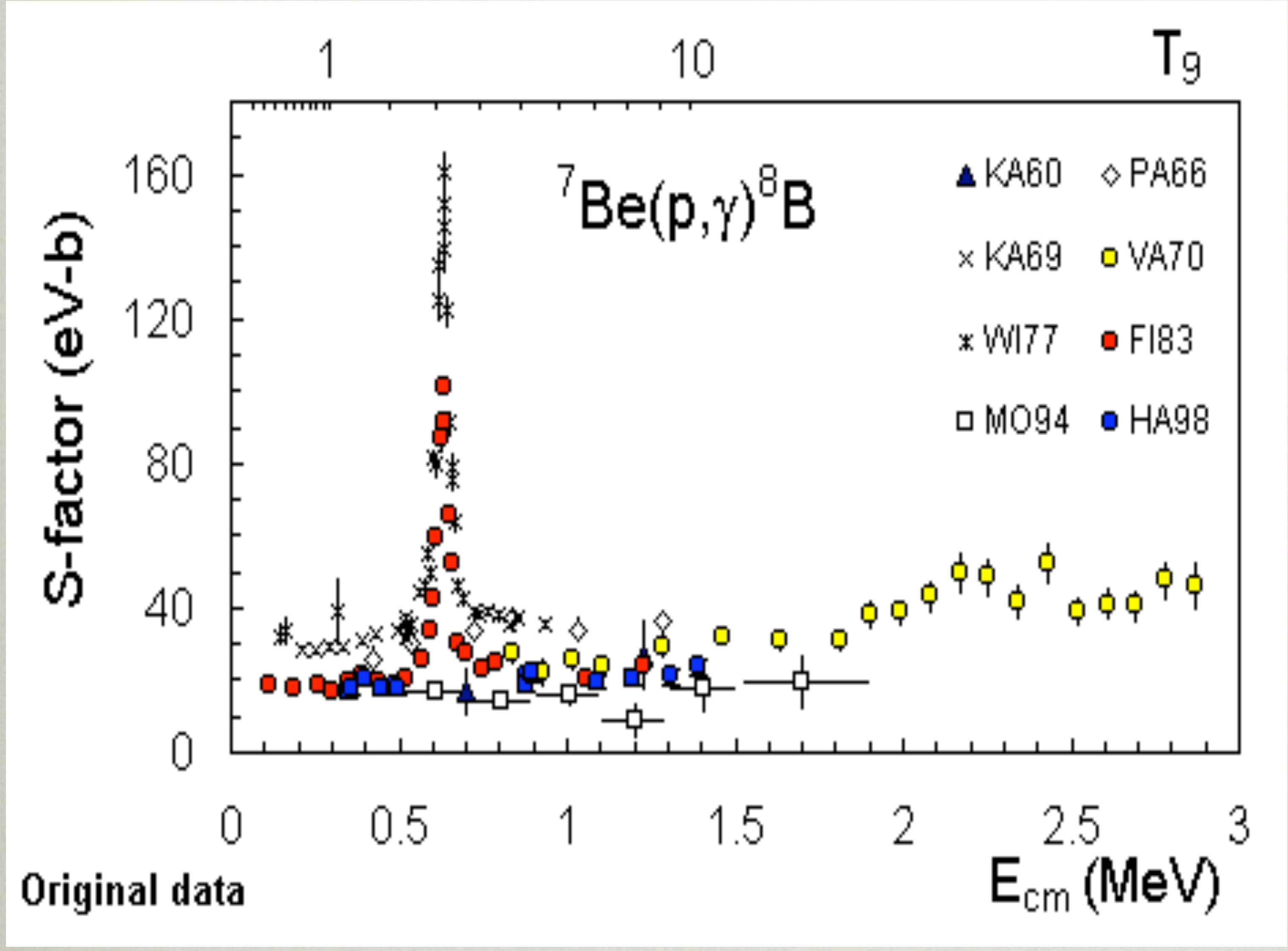

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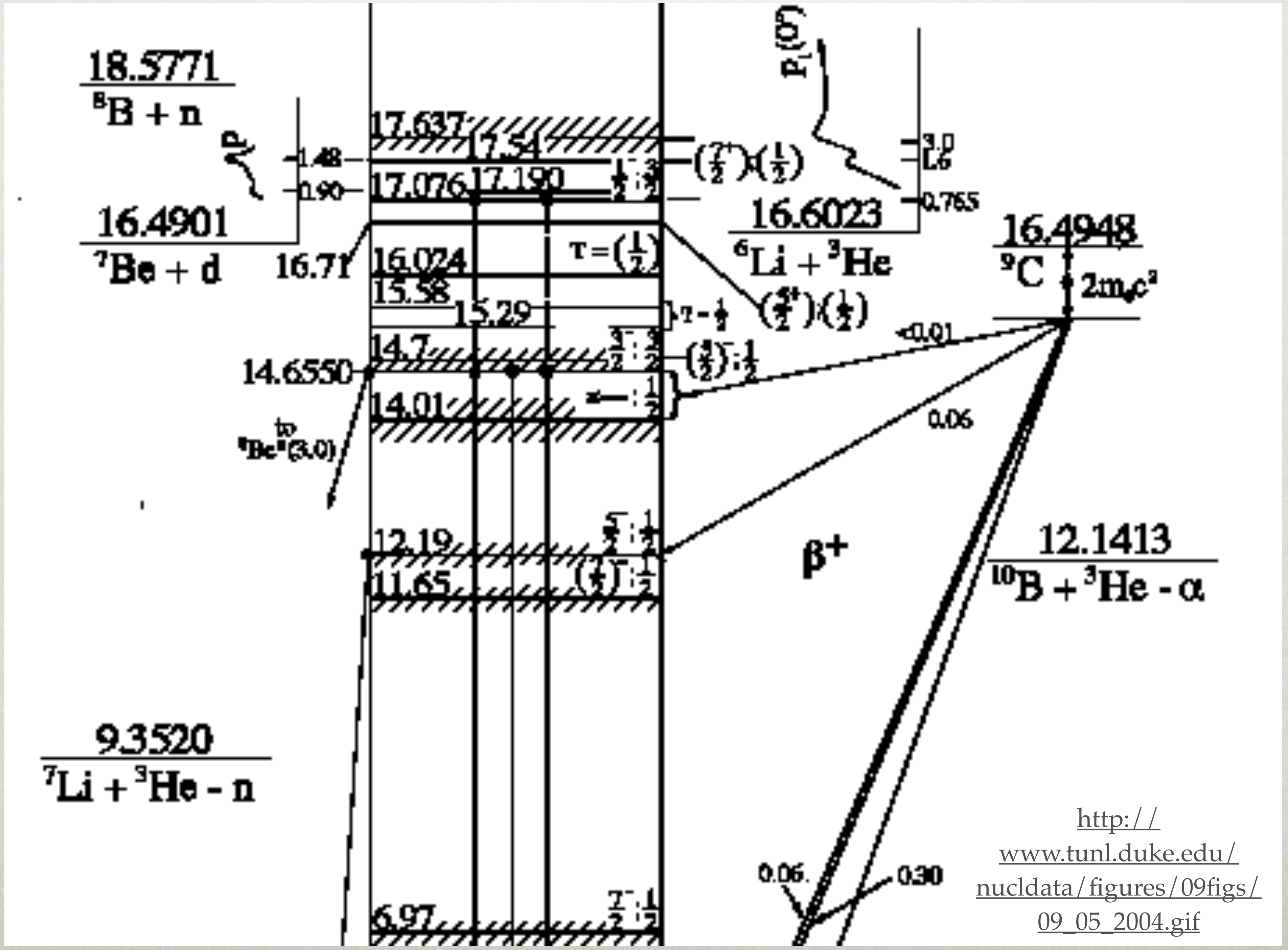

http://www.tunl.duke.edu/nucldata/figures/09figs/09_05_2004.gif

Resonant Cross-section

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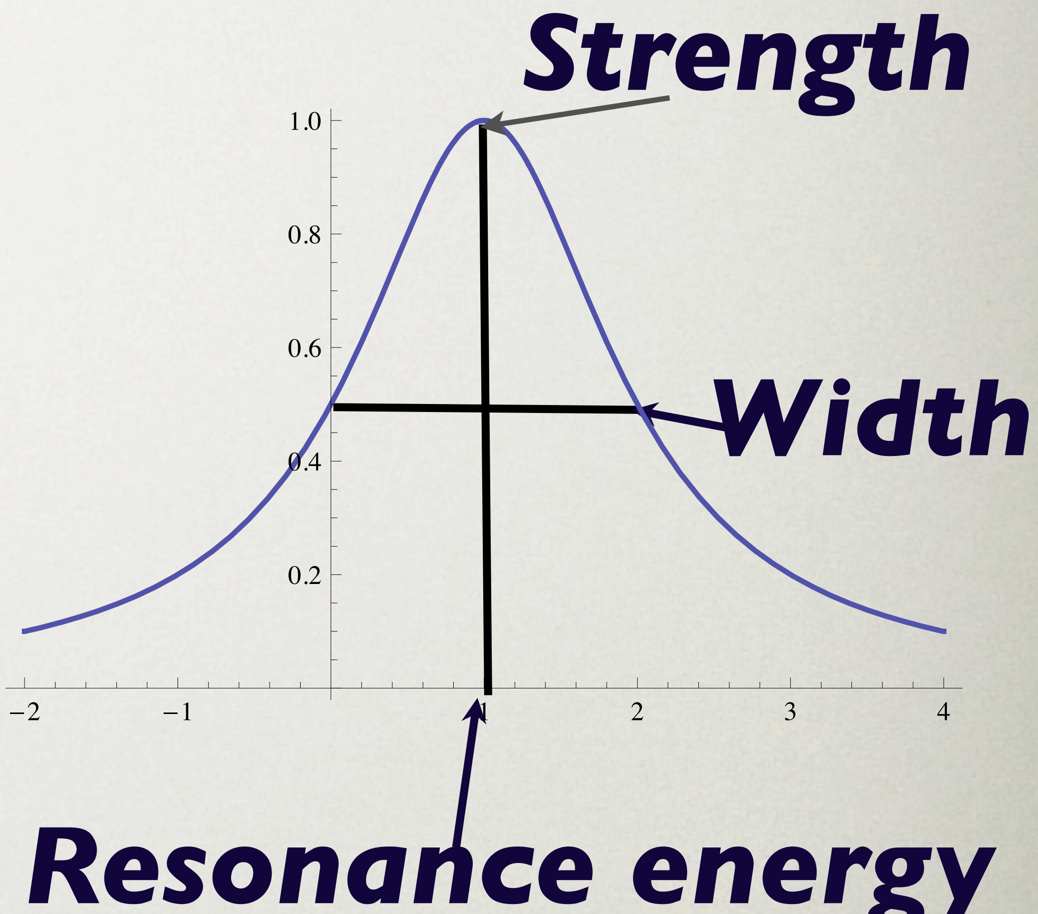
$$\sigma \propto \frac{\Gamma_1 \Gamma_2}{(E - E_R)^2 + (\Gamma_{tot}/2)^2}$$

- (Breit-Wigner single level formula)



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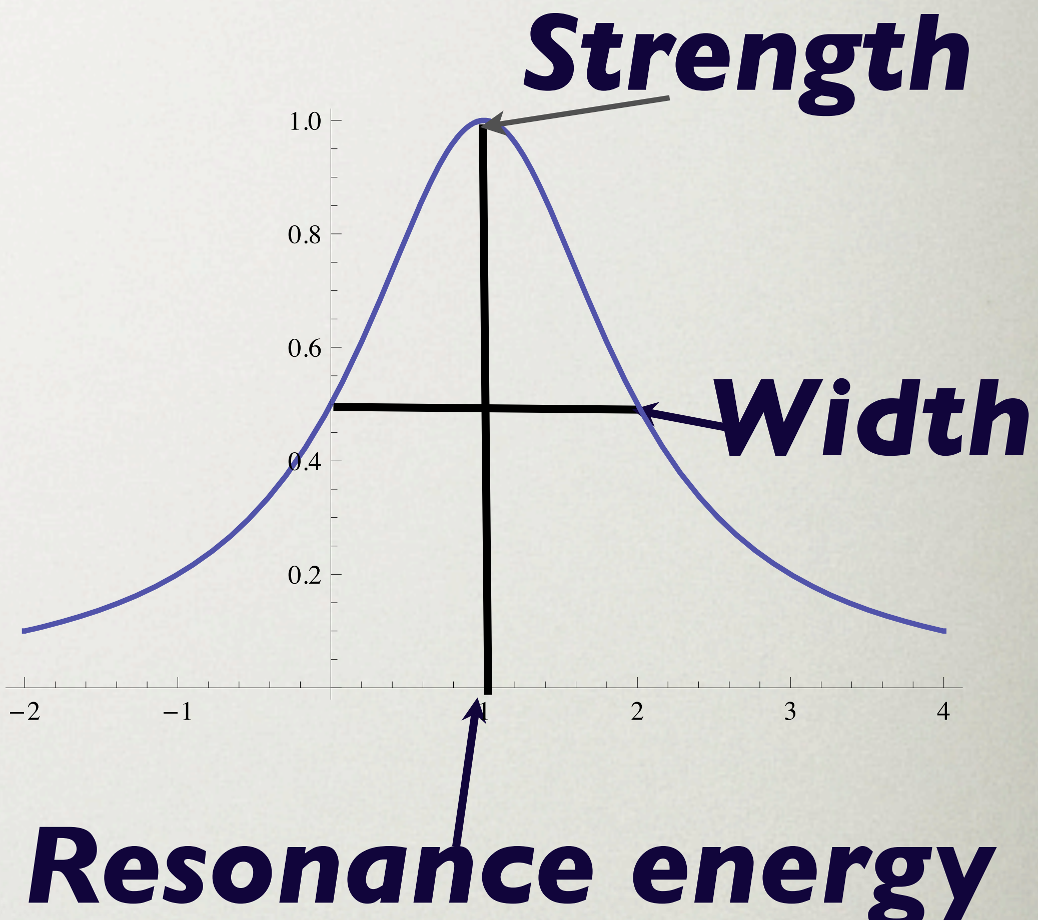

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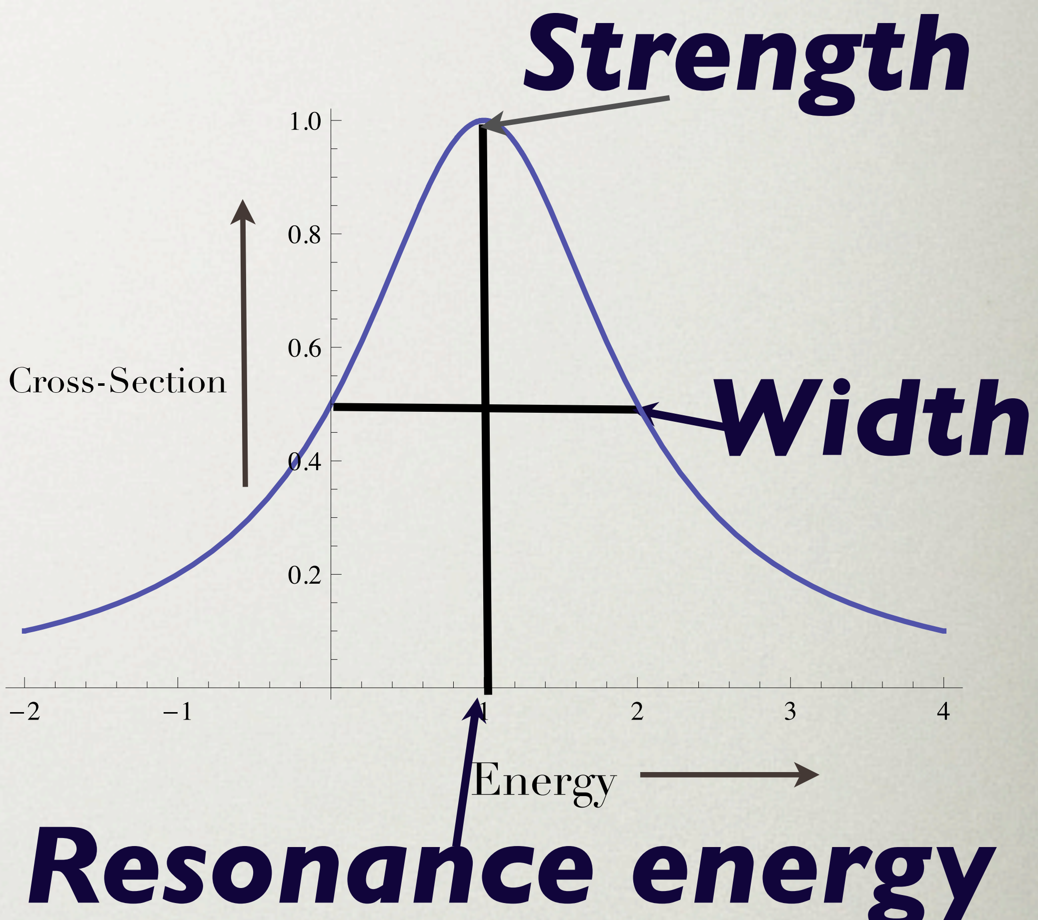

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Equilibrium Rates

- The rate eqn for abundances

$$\frac{dY_i}{dt} = n_b \Sigma (Y_k Y_l \langle \sigma v \rangle_{kl} - Y_i Y_j \langle \sigma v \rangle_{ij}) \quad Y_i = \frac{n_i}{n_H}$$

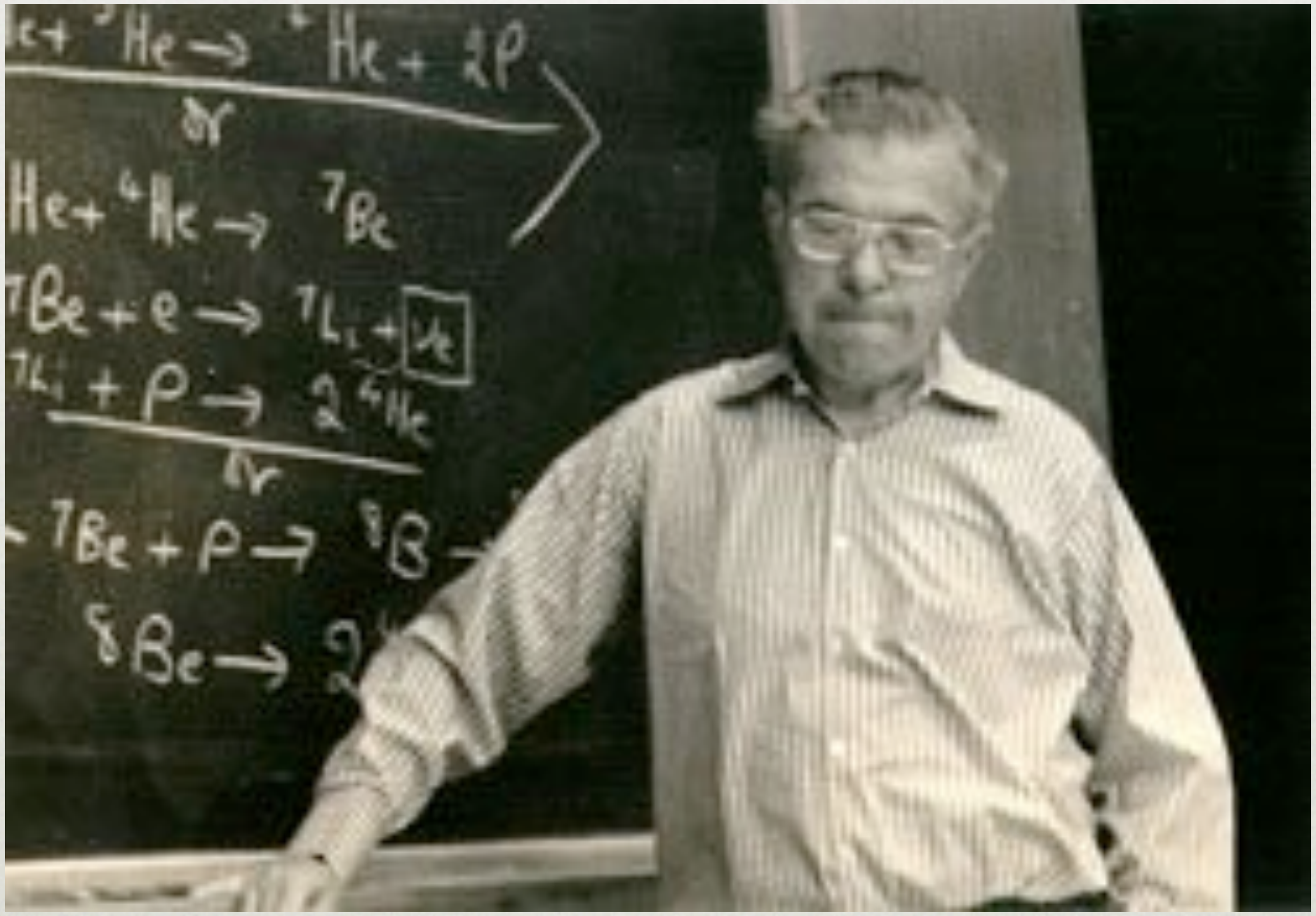
- At equilibrium, production = destruction

$$\Sigma Y_k Y_l \langle \sigma v \rangle_{kl} = \Sigma Y_i Y_j \langle \sigma v \rangle_{ij}$$

- New rates must compare with old important rates

$$Y_i = \frac{\Sigma Y_k Y_l \langle \sigma v \rangle_{kl}}{(\Sigma Y_j \langle \sigma v \rangle_{ij})_{old} + (Y_p \langle \sigma v \rangle_{ip})_{new}} = \frac{(Y_i)_{old}}{1 + \frac{Y_p \langle \Box v \rangle_{ip})_{new}}{(\Sigma Y_j \langle \Box v \rangle_{ij})_{old}}}$$

Fred Hoyle set a famous precedent



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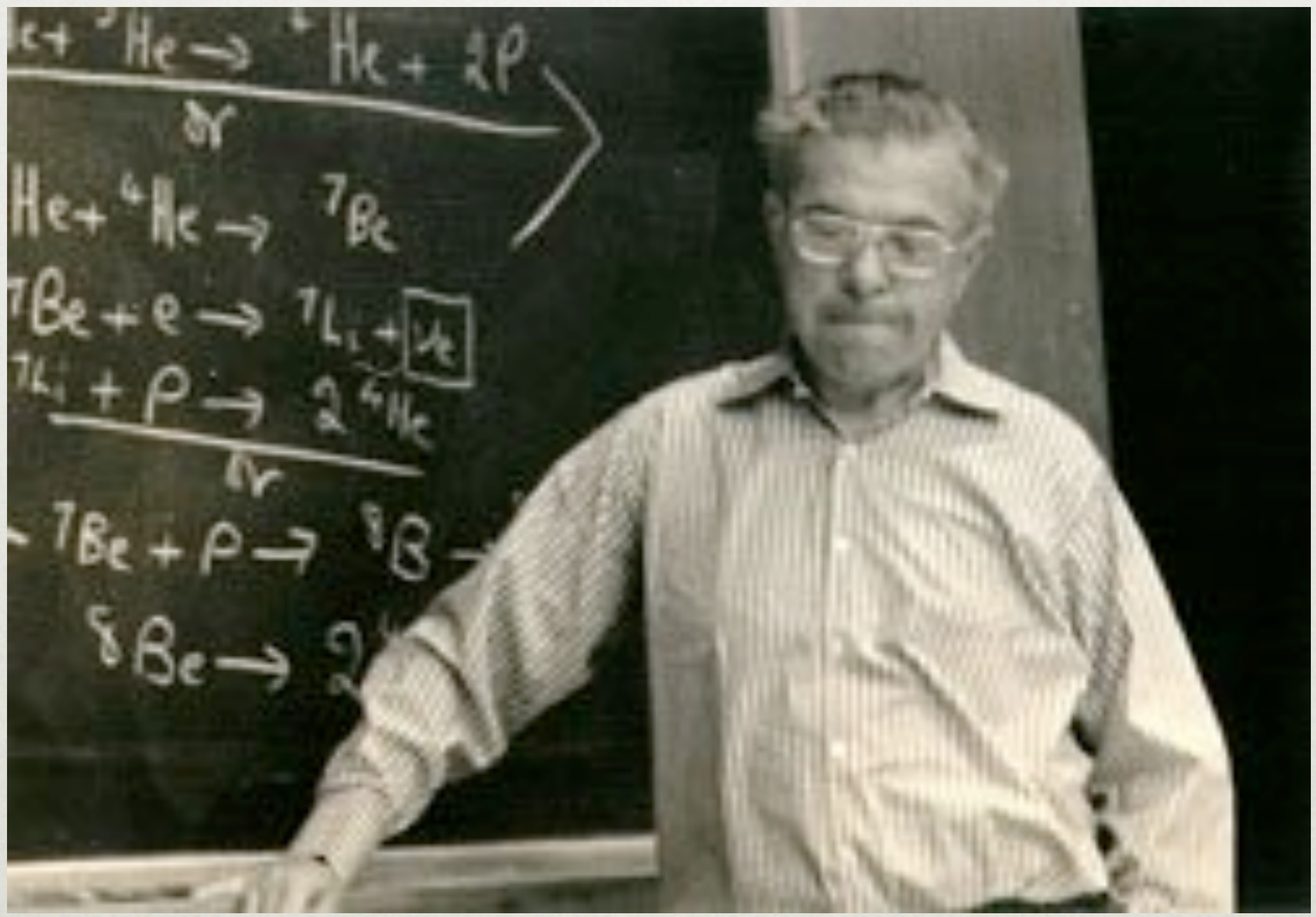

4He + 4He -> 8Be
8Be + 4He -> 12C

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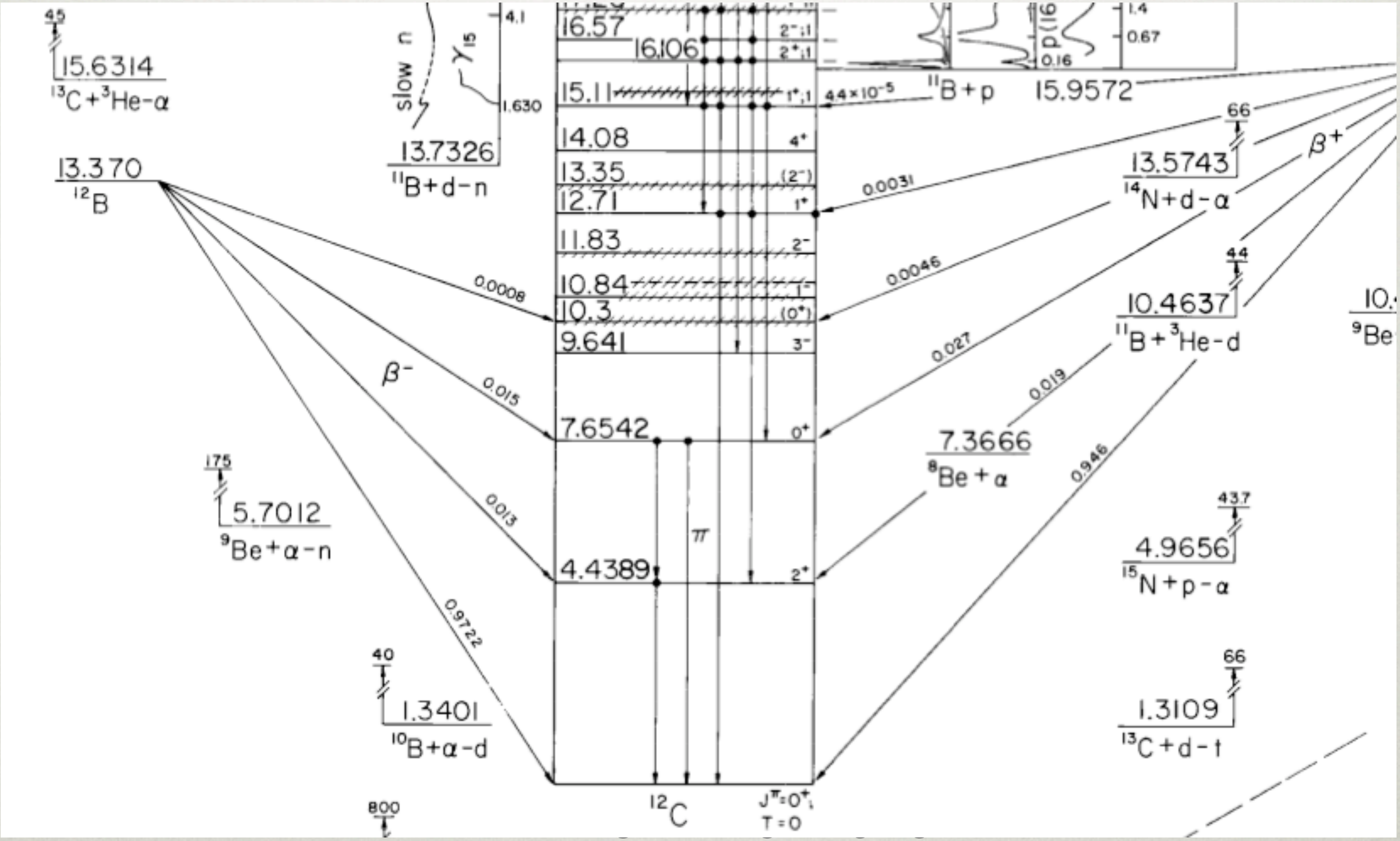

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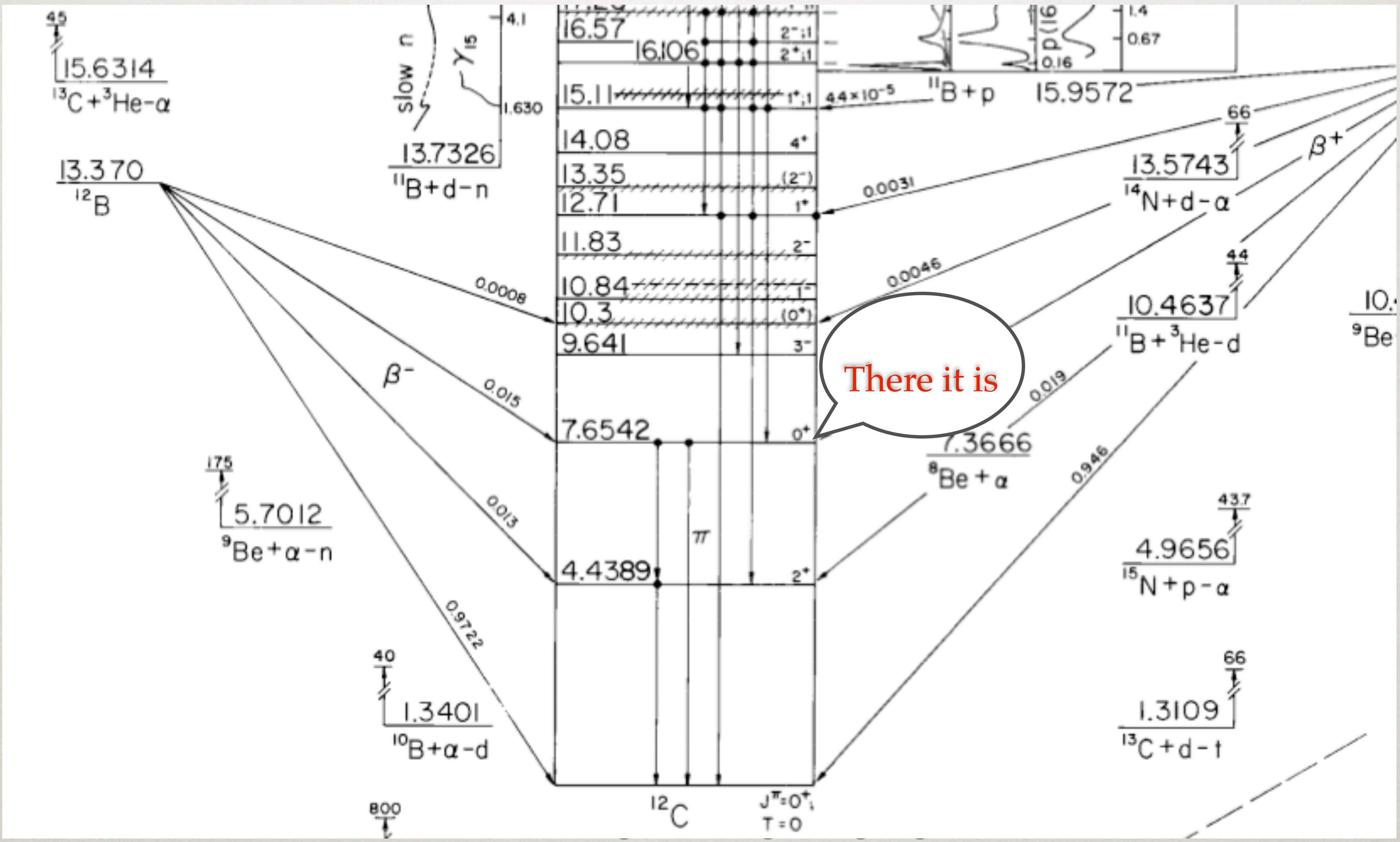

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- Width of energy level unknown
- Enhancement of reaction $^{7}Be(d,\gamma)^{9}B$ and $^{7}Be(d,p)\alpha\alpha$
- $(E_R, \Gamma_d) \sim (170\text{-}220, 10\text{-}40)$ keV ,
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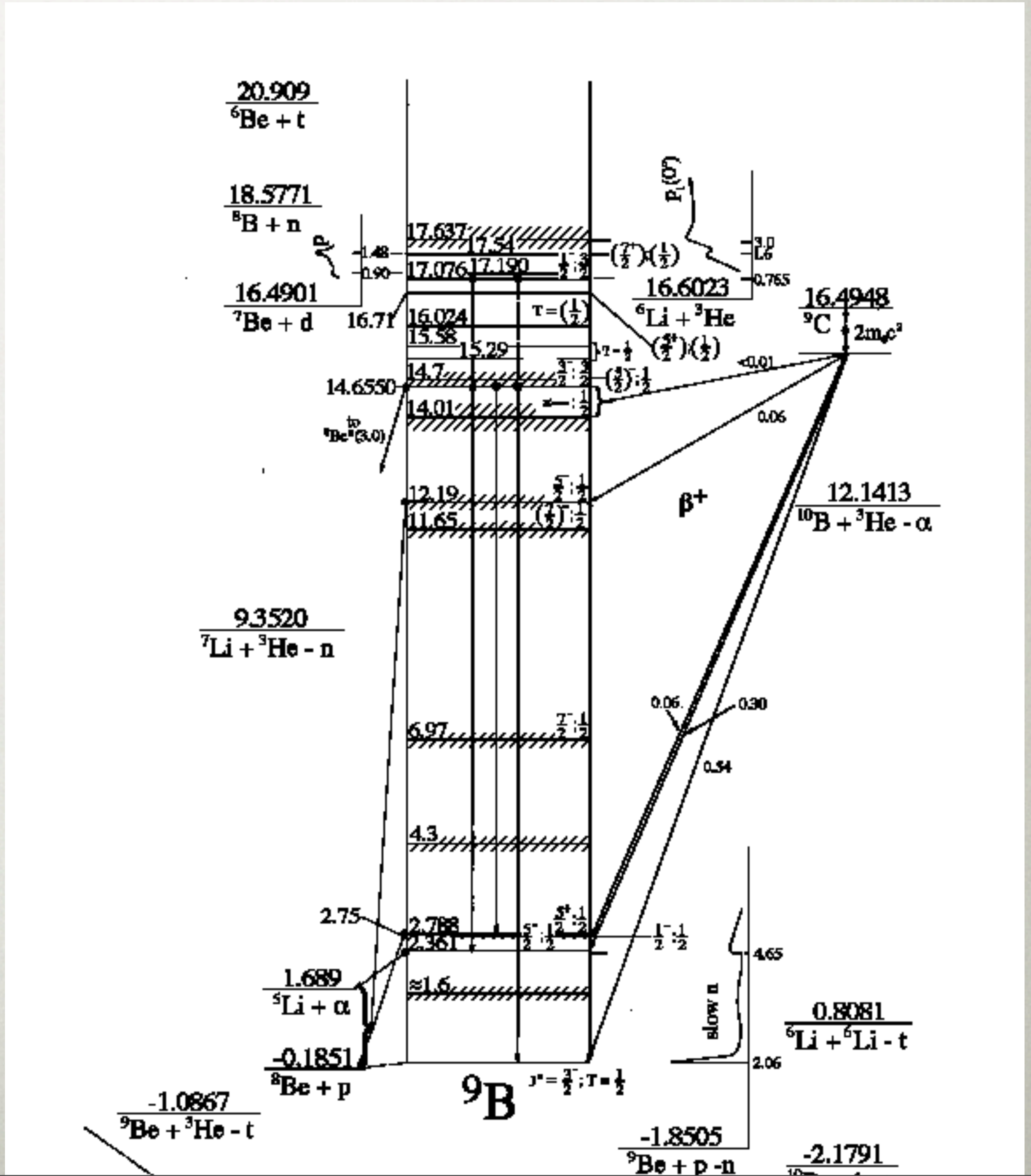

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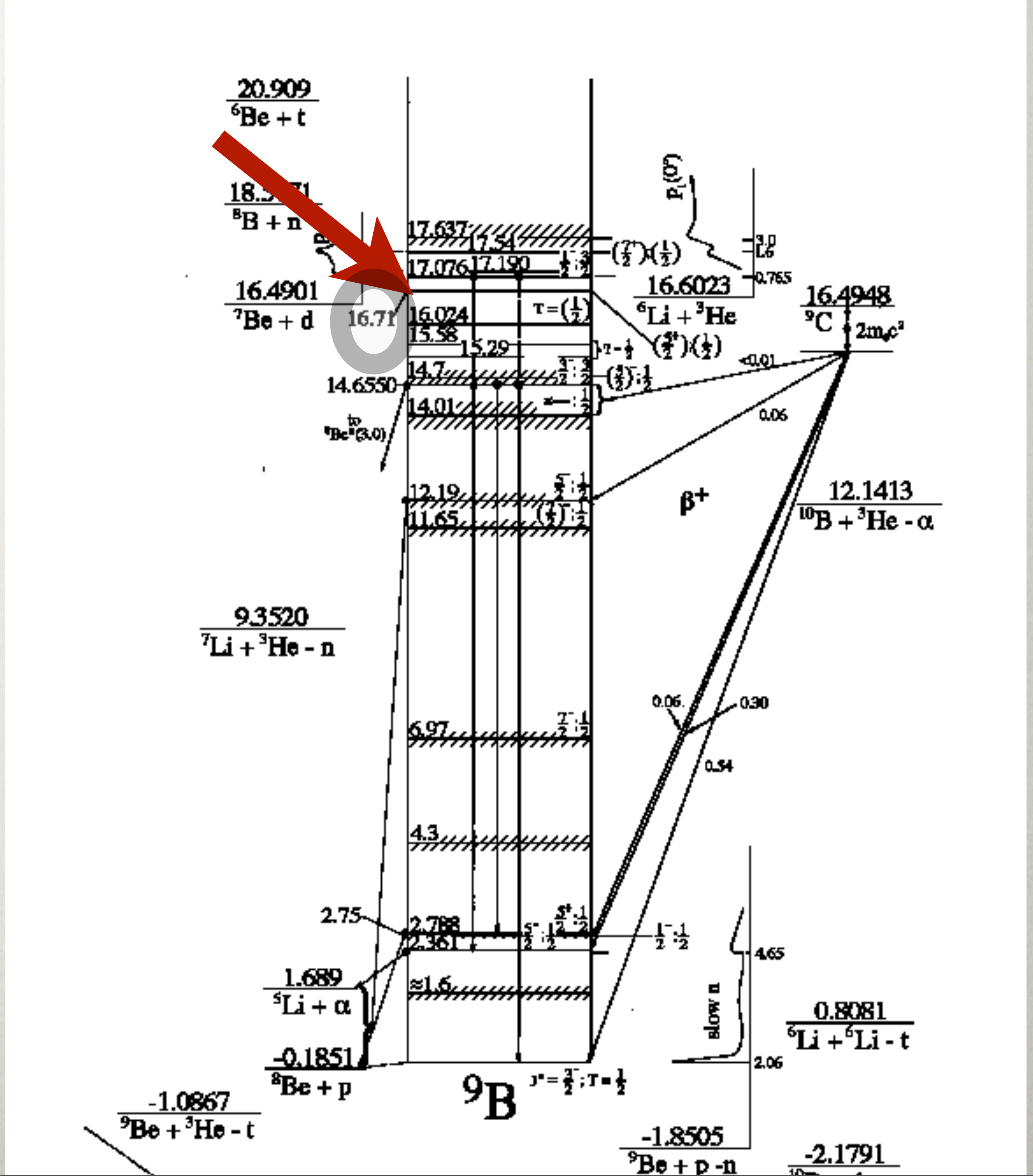

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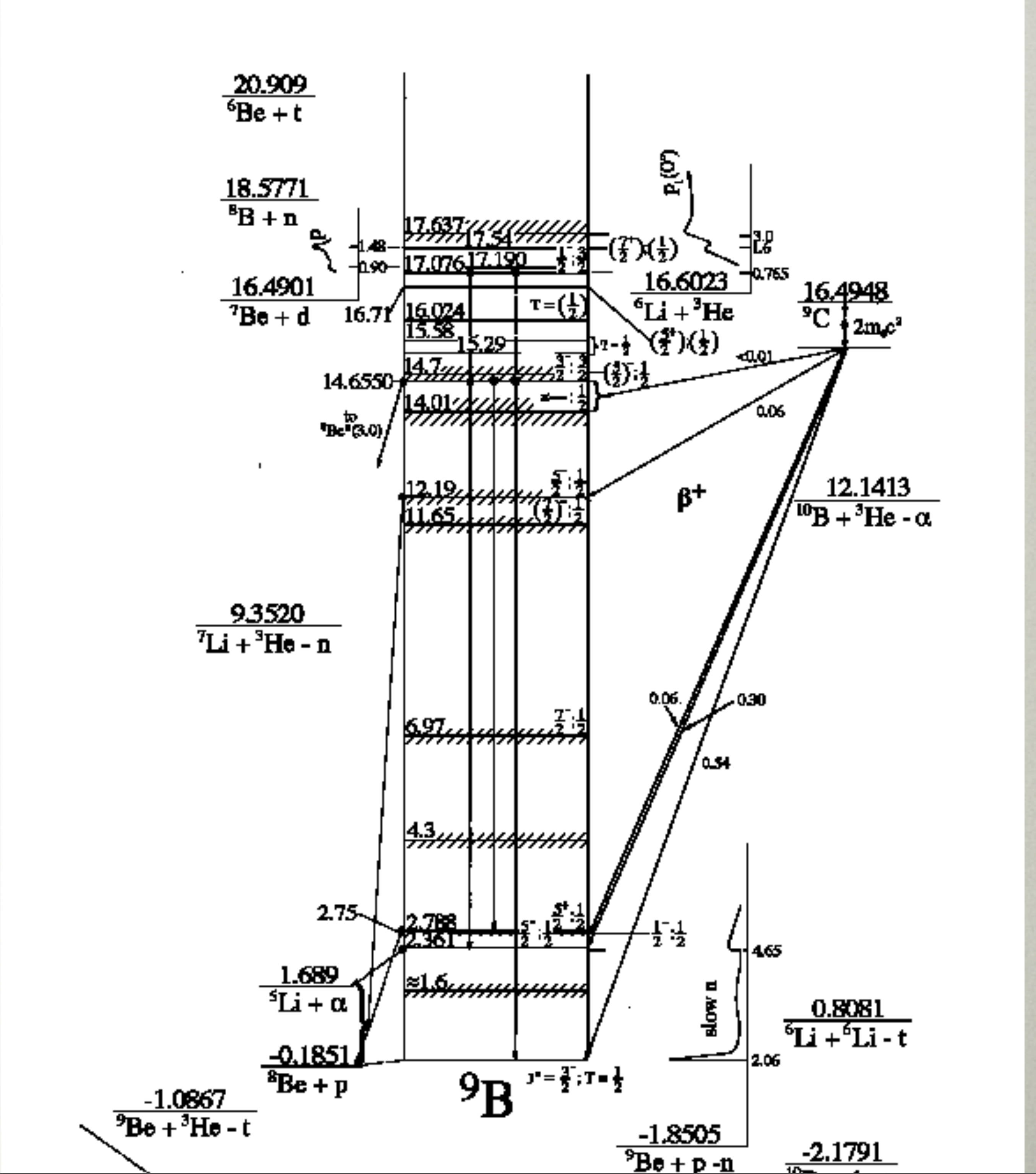

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- Identified a narrow level in ^{9}B at 16.7 MeV
- Width of energy level unknown
- Enhancement of reaction $^{7}Be(d,\gamma)^{9}B$ and $^{7}Be(d,p)\alpha\alpha$
- $(E_R,\Gamma_d) \sim (170\text{-}220, 10\text{-}40)$ keV ,
  $^{7}Li/H = (2.5 - 6) \times 10^{-10}$
- Needs experimental verification

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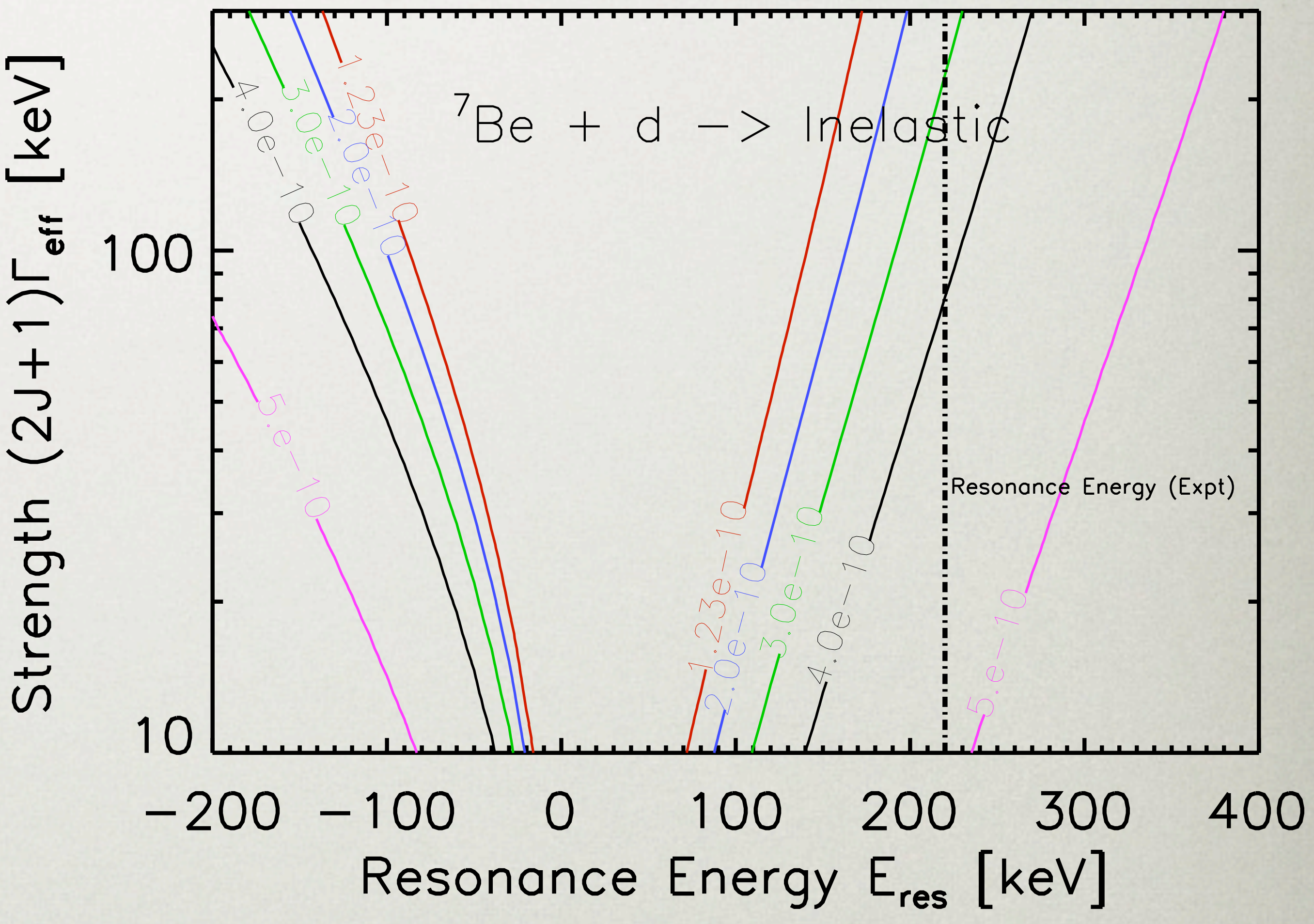

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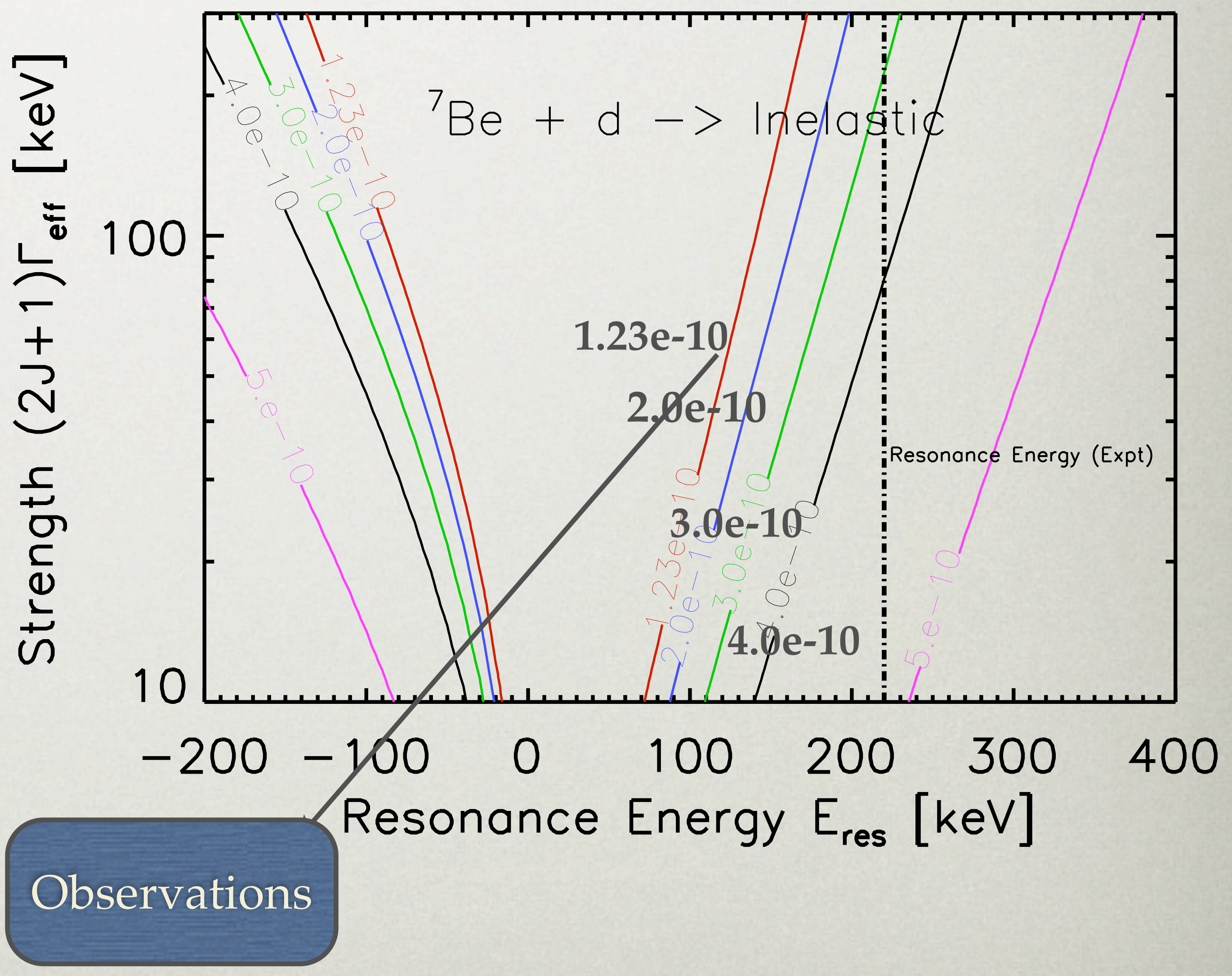


Systematic Search for the "Hoyle" State

- Need other options ready
- Want to try all conceivable resonances
- Not infinite choices !!
- Lock on to our targets
  - ^{7}Li, ^{7}Be
- Ready our projectiles
  - n,p,t, ^{3}He, ^{4}He, and photons
- Destroy !!!

Candidate resonance selection

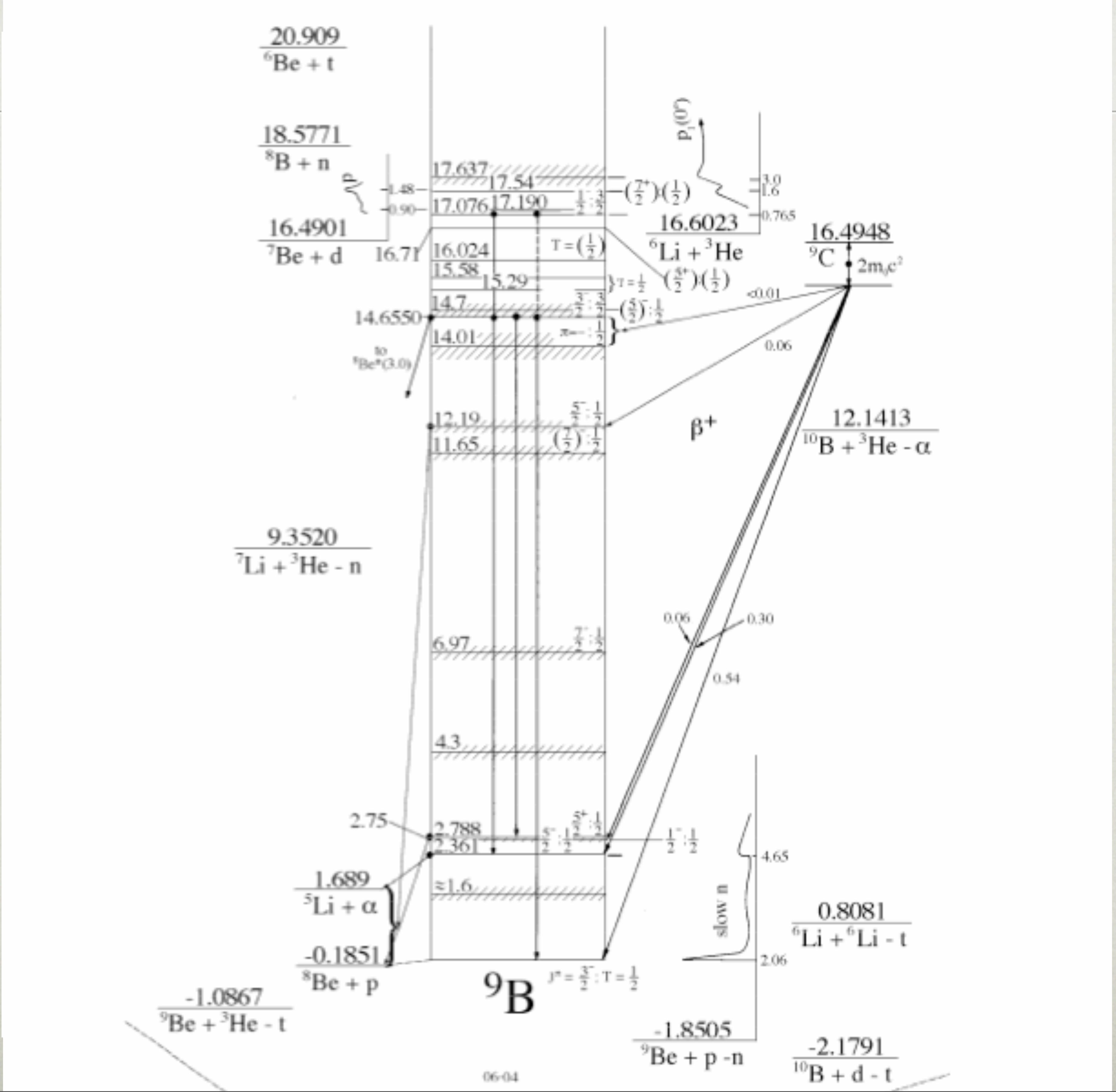
- Compound nuclei of masses 8 to 11
- Obey selection rules
- 2 body - 2 body reactions
- Existing resonances not included in BBN estimates
- New or missed resonances

DATA MINING

DATA MINING

E_x [a] (MeV ± keV)	$J^\pi; T$	$\Gamma_{c.m.}$ (keV)	Decay	Reactions
g.s.	$\frac{3}{2}^-; \frac{1}{2}$	0.54 ± 0.21	p	1, 2, 3, 4, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17
≈ 1.6 [b]			p, (α)	3, 4, 8, 13
2.361 ± 5	$\frac{5}{2}^-; \frac{1}{2}$	81 ± 5	p, α	1, 2, 4, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17
2.75 ± 300 [c]	$\frac{1}{2}^-; \frac{1}{2}$	3130 ± 200	p	3, 7, 10
2.788 ± 30	$\frac{5}{2}^+; \frac{1}{2}$	550 ± 40	p, α	4, 7, 10, 11, 13, 15, 16
4.3 ± 200 [d]		1600 ± 200		7
6.97 ± 60	$\frac{7}{2}^-; \frac{1}{2}$	2000 ± 200	p	4, 7, 11, 14, 15, 16
11.65 ± 60 [e]	$(\frac{7}{2})^-; \frac{1}{2}$	800 ± 50	p	11, 13, 15, 16
12.19 ± 40 [f]	$\frac{5}{2}^-; \frac{1}{2}$	450 ± 20	p, α	4, 7, 10, 14
14.01 ± 70	$\pi = -; \frac{1}{2}$	390 ± 110	p, α	4, 7, 10, 14
14.6550 ± 2.5	$\frac{3}{2}^-; \frac{3}{2}$	0.395 ± 0.042	γ, p	4, 7, 8, 10, 14
14.7 ± 200 [g]	$(\frac{5}{2})^-; \frac{1}{2}$	1350 ± 200		11
15.29 ± 40	$T = \frac{1}{2}$			14
15.58 ± 40	$T = \frac{1}{2}$			14
16.024 ± 25	$T = (\frac{1}{2})$	180 ± 16		4, 14
16.71 ± 100 [h]	$(\frac{5}{2}^+); (\frac{1}{2})$			7
17.076 ± 4	$\frac{1}{2}^-; \frac{3}{2}$	22 ± 5	(γ, ^{3}He)	1, 14
17.190 ± 25		120 ± 40	p, d, ^{3}He	4, 5, 14
17.54 ± 100 [h,i]	$(\frac{7}{2}^+); (\frac{1}{2})$			7
17.637 ± 10 [i]		71 ± 8	p, d, ^{3}He, α	1, 4, 5, 14

DATA MINING



20.909
6Be + t
18.5771
8B + n
16.4901
7Be + d
9.3520
7Li + 3He - n
1.689
5Li + α
-0.1851
8Be + p
-1.0867
9Be + 3He - t
16.6023
6Li + 3He
16.4948
9C
2m0c2
12.1413
10B + 3He - α
0.8081
6Li + 6Li - t
-1.8505
9Be + p -n
-2.1791
10B + d - t
17.637
17.54
17.076
17.190
16.71
16.024
15.58
15.29
14.7
14.6550
14.01
12.19
11.65
6.97
4.3
2.75
2.788
2.361
≈1.6
β+
<0.01
0.06
0.30
0.54
4.65
2.06
slow n
9B

LIST(S) OF CANDIDATES

Compound Nucleus, J^π, E_{ex}	Initial State	L_{init}	L_{fin}	E_{res}	Γ_{tot}	Exit Channels	Exit Channel Width
^{8}Li, 3^+, 2.255 MeV (Included)	$^7\mathrm{Li}+n$	1	1	222.71 keV	33 ± 6 keV	γ(ground state)	$7.0 \pm 3.0 \times 10^{-2}$ eV
			1			n (elastic) ≈100%	33 ± 6 keV
^{8}Be, 2^+, 16.922 MeV	$^7\mathrm{Li}+p$	1	2	-333.1 keV	74.0 ± 0.4 keV	γ(ground state)	$8.4 \pm 1.4 \times 10^{-2}$ eV
			1			γ(3.04 MeV)	$< 2.80 \pm 0.18$ eV
			2			$\alpha \approx 100\%$	≈ 74.0 keV
			1			p (elastic)	unknown
^{8}Be, 1^+, 17.640 MeV	$^7\mathrm{Li}+p$	1	1	384.9 keV	10.7 keV	γ(ground state)	16.7 eV
			1			γ(3.04 MeV)	6.7 ± 1.3 eV
			2			γ(3.04 MeV)	0.12 ± 0.05 eV
			1			γ(16.63 MeV)	$(3.2 \pm 0.3) \times 10^{-2}$ eV
			1			γ(16.92 MeV)	$(1.3 \pm 0.3) \times 10^{-3}$ eV
			1			p (elastic) 98.8%	10.57 keV
^{8}Be, 2^-, 18.91 MeV (Included)	$^7\mathrm{Be}+n$	0	1	10.3 keV	122 keV*	γ(16.922 MeV)	$9.9 \pm 4.3 \times 10^{-2}$ eV
			1			γ (16.626 MeV)	0.17 ± 0.07 eV
			0			p	< 105.1 keV*
			2			$p + {}^7\mathrm{Li}^*$ (0.4776 MeV)	< 105.1 keV*
			0			n (elastic)	16.65 keV*
^{8}Be, 3^+, 19.07 MeV (Included)	$^7\mathrm{Be}+n$	1	1	170.3 keV	270 ± 20 keV	p ≈ 100%	< 270 keV
			3			$p + {}^7\mathrm{Li}^*$ (0.4776 MeV)	< 270 keV
			1			γ(3.03 MeV)	10.5 eV
			1			n (elastic)	unknown
^{8}Be, 3^+, 19.235 MeV (Included)	$^7\mathrm{Be}+n$	1	1	335.3 keV	227 ± 16 keV	p ≈ 50%	≈ 113.5 keV
			1			γ(3.03 MeV)	10.5 eV
			1			n (elastic) ≈ 50%	≈ 113.5 keV
^{8}Be, 1^-, 19.40 MeV	$^7\mathrm{Be}+n$	0	0	500.3 keV	645 keV	p	unknown
			0			$p + {}^7\mathrm{Li}^*$ (0.4776 MeV)	unknown
			0			n (elastic)	unknown
			1			α	unknown
$^8\mathrm{B}^{g.s.}$, 2^+, 0 MeV	$^7\mathrm{Be}+p$	1	1	-0.1375 MeV	unknown	p (elastic)	unknown
			0			EC→ ^{8}Be	8.5×10^{-19} eV
^{8}B, 1^+, 0.7695 MeV (Included)	$^7\mathrm{Be}+p$	1	1	630 ±3 keV	35.7 ± 0.6 keV	γ (ground state)	25.2 ± 1.1 meV
			1			p (elastic) 100%	35.7 ± 0.6 keV

SOME MORE

Compound Nucleus, J^π, E_{ex}	Initial State	L_{init}	L_{fin}	E_{res}	Γ_{tot}	Exit Channels	Exit Channel Width
^{9}Be, (5/2$^+$), 16.671 MeV	^{7}Li + d	1	unknown	-24.9 keV	41 ± 4 keV	γ	unknown
			2			$n + {}^8$Be	unknown
			0			$n + {}^8$Be* (3.03 MeV)	unknown
			2			$n + {}^8$Be* (11.35 MeV)	unknown
			0			p	unknown
			1			α	unknown
			1			d (elastic)	unknown
^{9}Be, 1/2$^-$, 16.9752 MeV	^{7}Li + d	0	1	279.3 keV	389 ± 10 eV	γ (ground state)	16.9 ± 1.0 eV
			1			γ (1.68 MeV)	1.99 ± 0.15 eV
			2			γ (2.43 MeV)	0.56 ± 0.12 eV
			1			γ (2.78 MeV)	2.2 ± 0.7 eV
			unknown			γ (Unknown level TUNL)	< 0.8 eV
			1			γ (4.70 MeV)	2.2 ± 0.3 eV
			1			p	12^{+12}_{-6} eV
			1			n	< 288 eV
			1			$n + {}^8$Be* (3.03 MeV)	< 288 eV
			3			$n + {}^8$Be* (11.35 MeV)	< 288 eV
			2			α	< 241 eV
			0			d (elastic)	62 ± 10 eV
^{9}Be, (5/2)$^-$, 17.298 MeV (Included)	^{7}Li + d	0	unknown	602.1 keV	200 keV	γ (ground state)	unknown
			1			p	194.4 keV
			3			$n + {}^8$Be	unknown
			1			$n + {}^8$Be* (3.03 MeV)	unknown
			1			$n + {}^8$Be* (11.35 MeV)	unknown
			2			α	unknown
			0			d (elastic)	unknown

And more

Compound Nucleus, J^π, E_{ex}	Initial State	L_{init}	L_{fin}	E_{res}	Γ_{tot}	Exit Channels	Exit Channel Width
^{9}B, (5/2$^+$), 16.71 MeV	^{7}Be + d	1	2	219.9 keV	unknown	$p + ^8$Be	unknown
			0			$p + ^8$Be* (3.03 MeV)	unknown
			2			$p + ^8$Be* (11.35 MeV)	unknown
			0			$p + ^8$Be* (16.626 MeV)	unknown
			0			$p + ^8$Be* (16.922 MeV)	unknown
			2			^{3}He	unknown
			1			$\alpha + ^5$Li	unknown
			3			$\alpha + ^5$Li* (1.49 MeV)	unknown
			1			d (elastic)	unknown
^{9}B, (1/2$^-$), 17.076 MeV	^{7}Be + d	0	1	585.9 keV	22 keV	$p + ^8$Be	unknown
			1			$p + ^8$Be* (3.03 MeV)	unknown
			3			$p + ^8$Be* (11.35 MeV)	unknown
			1			$p + ^8$Be* (16.626 MeV)	unknown
			1			^{3}He	unknown
			2			$\alpha + ^5$Li	unknown
			0			$\alpha + ^5$Li* (1.49 MeV)	unknown
			0			d (elastic)	unknown

Compound Nucleus, J^π, E_{ex}	Initial State	L_{init}	L_{fin}	E_{res}	Γ_{tot}	Exit Channels	Exit Channel Width
^{10}Be, (2$^-$), 17.12 MeV	^{7}Li + t	0	0	-130.9 keV	$\approx$ 150 keV	$n + ^9$Be	unknown
			1			$n + ^9$Be* (1.684 MeV)	unknown
			0			$n + ^9$Be* (2.4294 MeV)	unknown
			2			$n + ^9$Be* (2.78 MeV)	unknown
			1			$n + ^9$Be* (3.049 MeV)	unknown
			1			$n + ^9$Be* (4.704 MeV)	unknown
			0			$n + ^9$Be* (5.59 MeV)	unknown
			2			$n + ^9$Be* (6.38 MeV)	unknown
			3			$n + ^9$Be* (6.76 MeV)	unknown
			0			$n + ^9$Be* (7.94 MeV)	unknown
			0			t (elastic)	unknown
^{10}Be, unknown, 17.79 MeV	^{7}Li + t	unknown	unknown	539.1 keV	112 $\pm$ 35 keV	γ	3 + 2 eV
			unknown			$n + ^9$Be	< 77 keV
			unknown			$n + ^9$Be* (1.684 MeV)	< 77 keV
			unknown			$n + ^9$Be* (2.4294 MeV)	< 77 keV
			unknown			$n + ^9$Be* (2.78 MeV)	< 77 keV
			unknown			$n + ^9$Be* (3.049 MeV)	< 77 keV
			unknown			$n + ^9$Be* (4.704 MeV)	< 77 keV
			unknown			$n + ^9$Be* (5.59 MeV)	< 77 keV
			unknown			$n + ^9$Be* (6.38 MeV)	< 77 keV
			unknown			$n + ^9$Be* (6.76 MeV)	< 77 keV
			unknown			$n + ^9$Be* (7.94 MeV)	< 77 keV

You get the point !!!

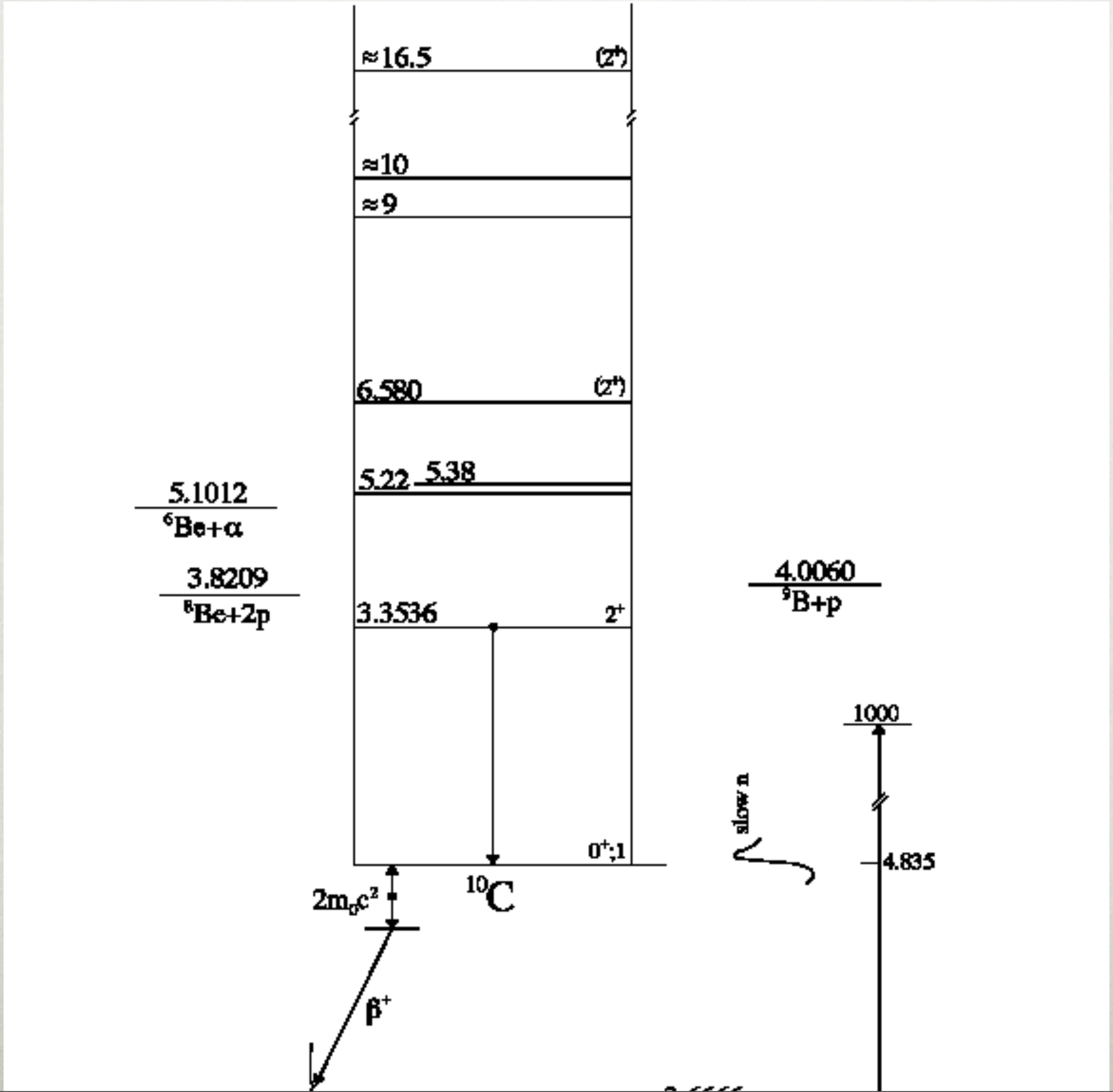
Final Candidates

Final Candidates

Compound Nucleus, J^π, E_{ex}	Initial State	L_{init}	L_{fin}	E_{res}	Γ_{tot}	Exit Channels	Exit Channel Width
^{9}B, $(5/2^+)$, 16.71 MeV	^{7}Be + d	1	0	219.9 keV	unknown	$p + {}^8$Be* (16.63 MeV)	unknown
			1			$\alpha + {}^5$Li	unknown
^{10}B, 2^+, 18.80 MeV	^{7}Be + t	1	1	130.9 keV	< 600 keV	$p + {}^9$Be* (11.81 MeV)	unknown
			1			^{3}He	unknown
			2			α	unknown
^{10}C, unknown	^{7}Be + ^{3}He	unknown	unknown	unknown	unknown	p	unknown
			unknown	($Q = 15.003$ MeV)		α	unknown
						^{3}He (elastic)	unknown

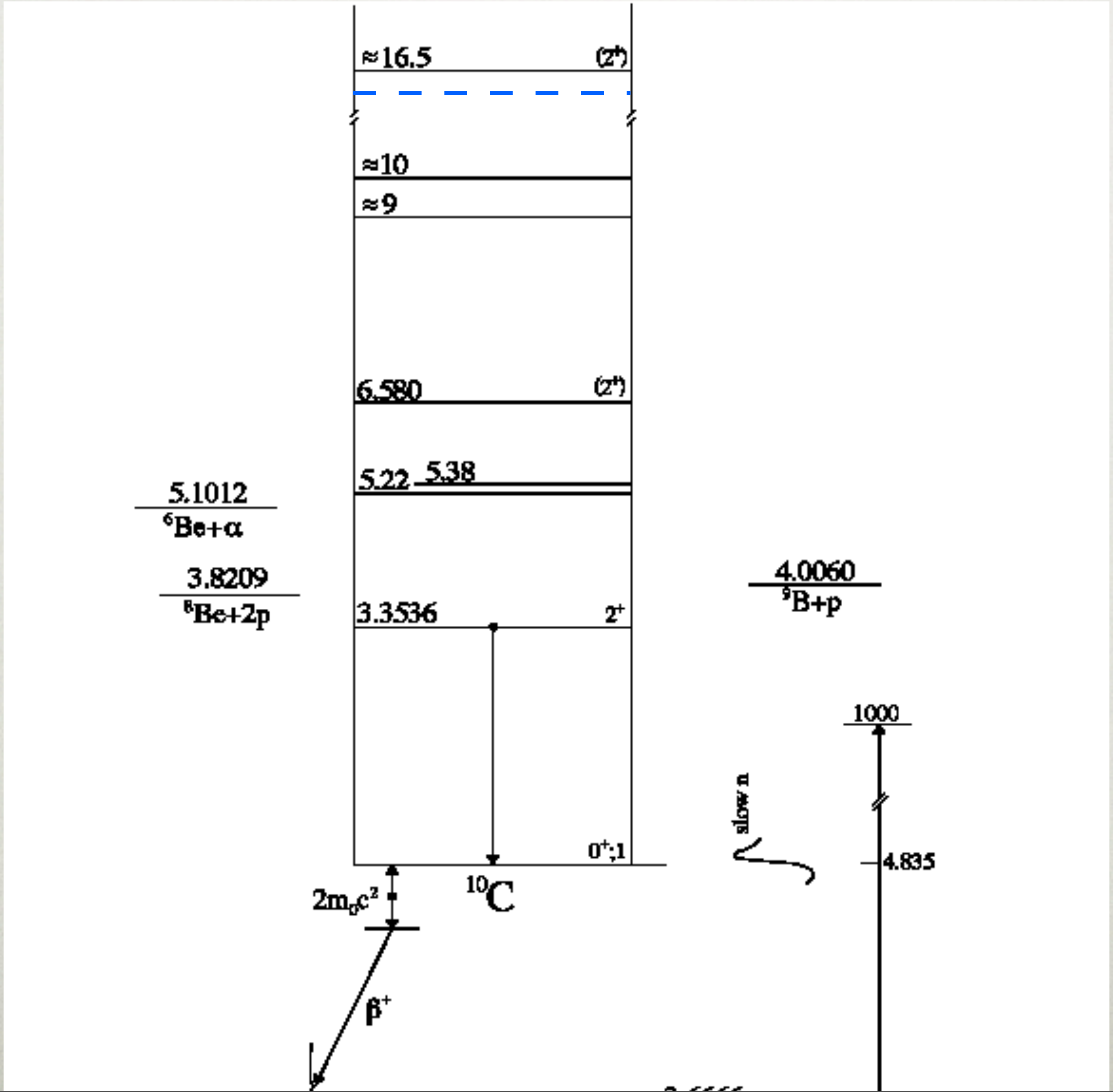
Final Candidates

Final Candidates



http://www.tunl.duke.edu/nucldata/figures/10figs/

Final Candidates



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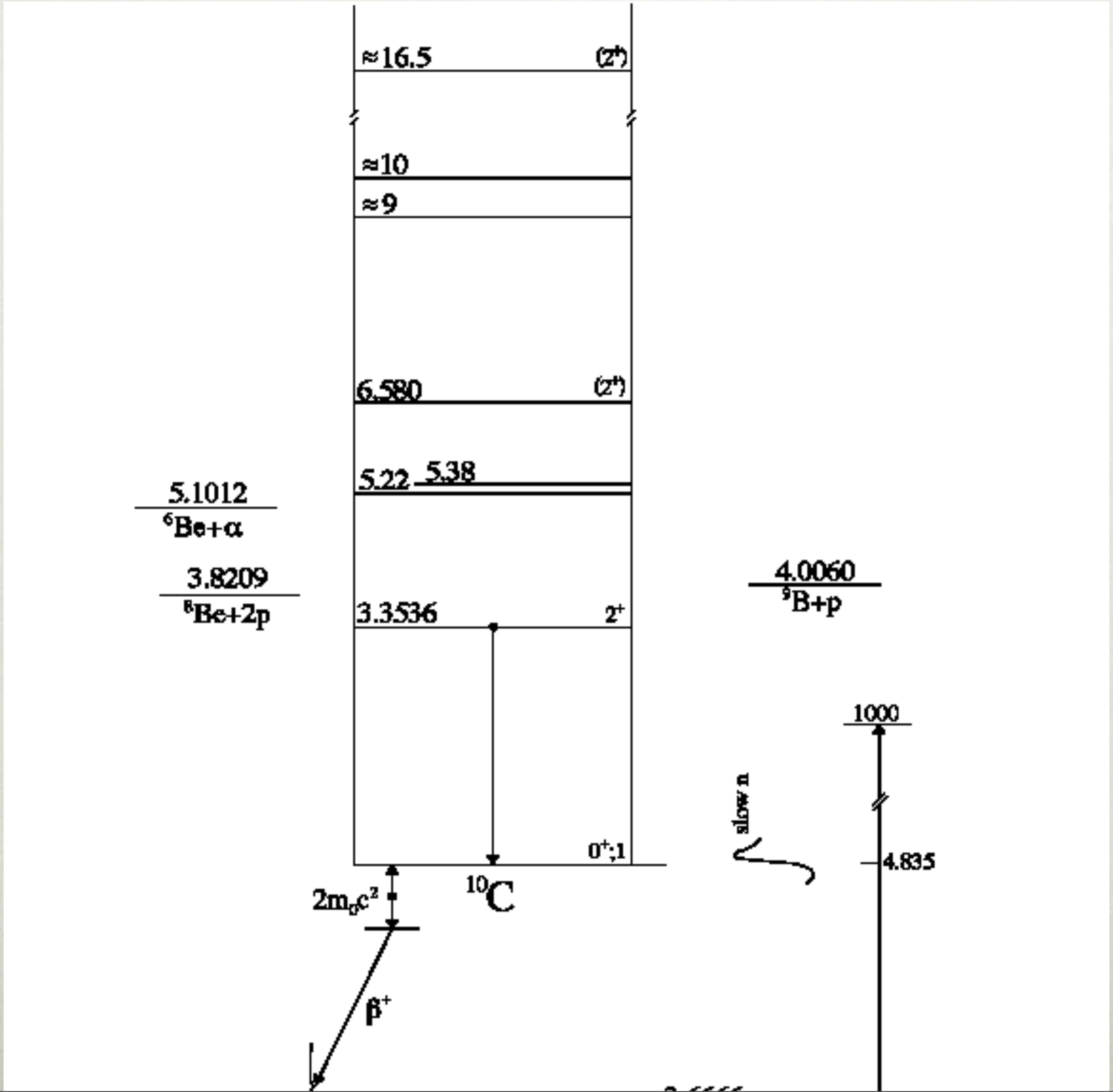

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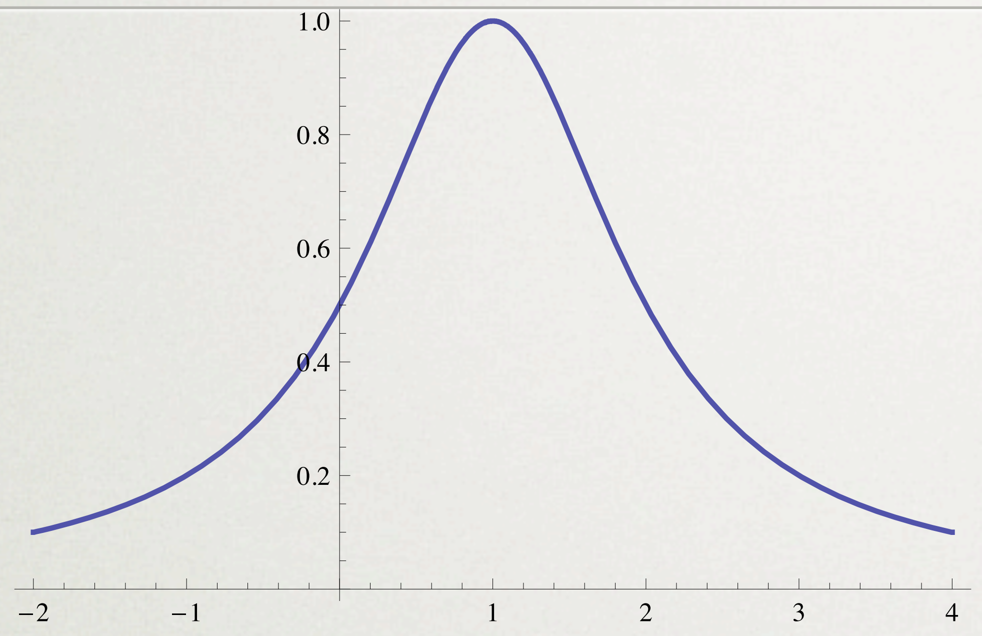
Resonance parameters

Resonance parameters



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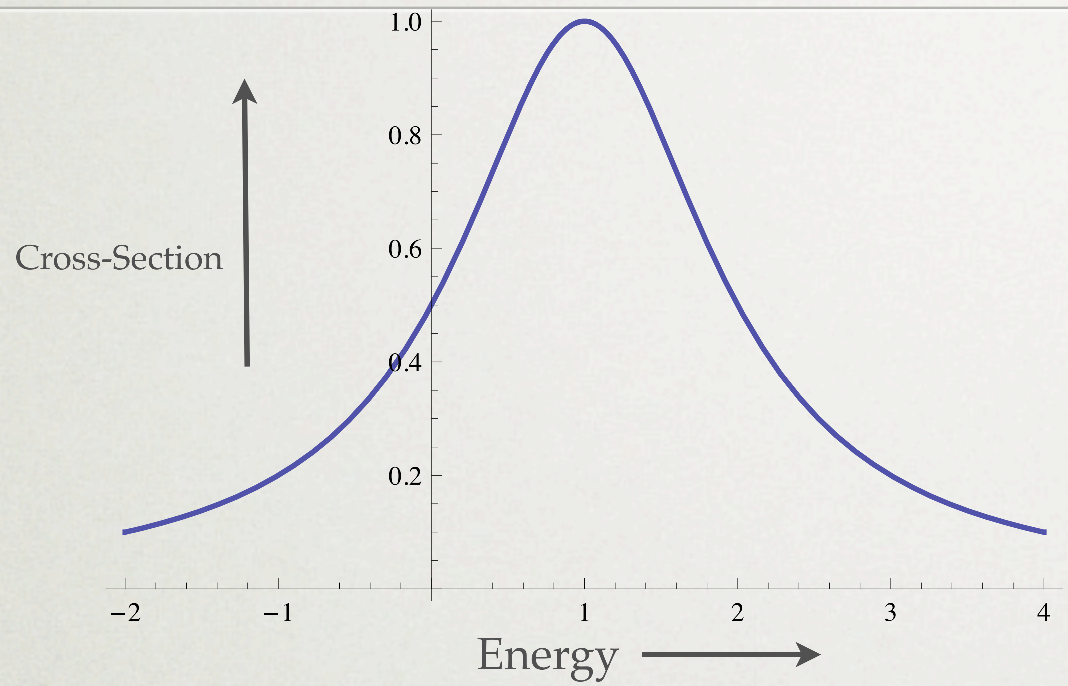

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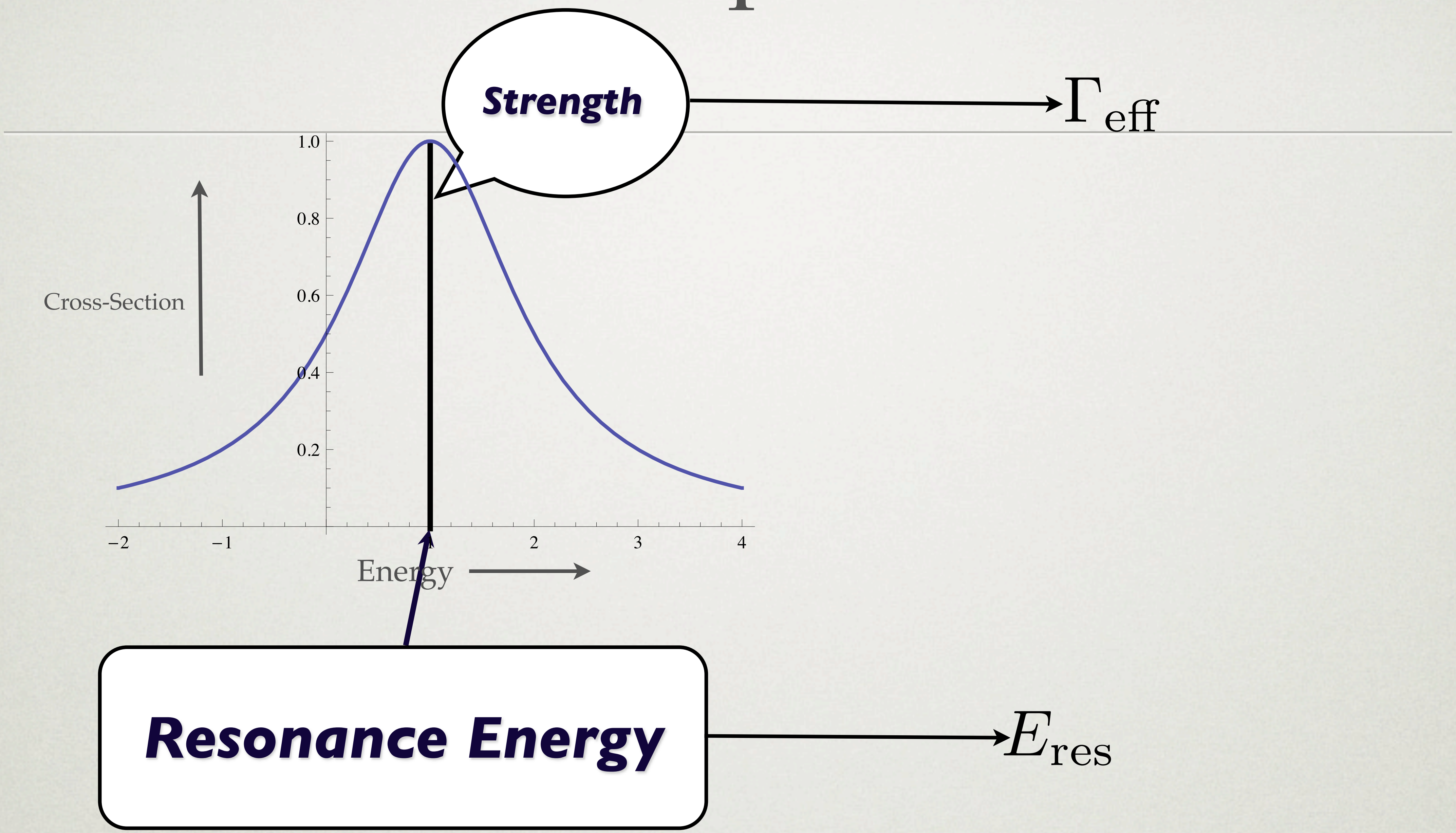

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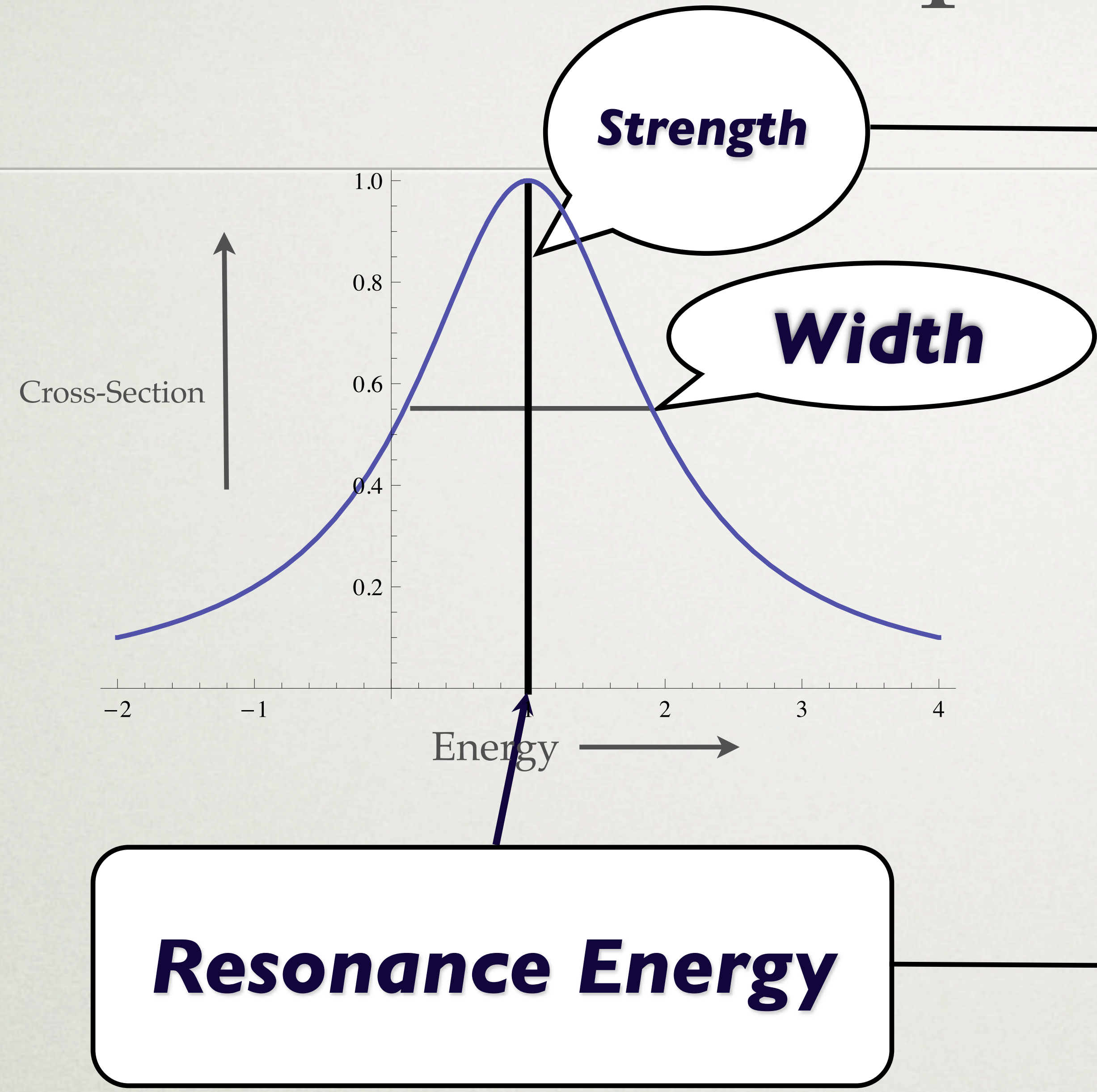
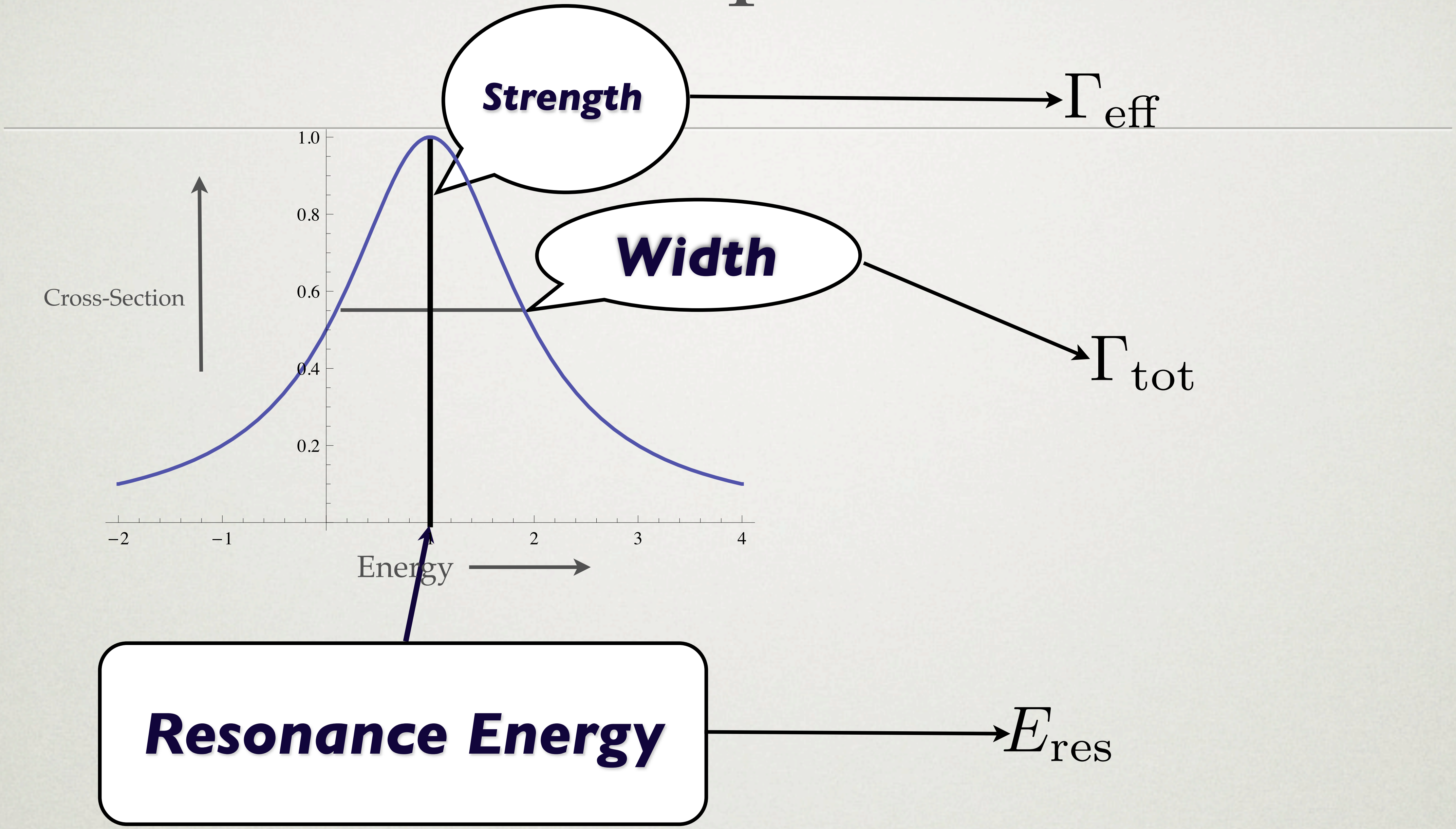


Γ_{eff}

Γ_{tot}

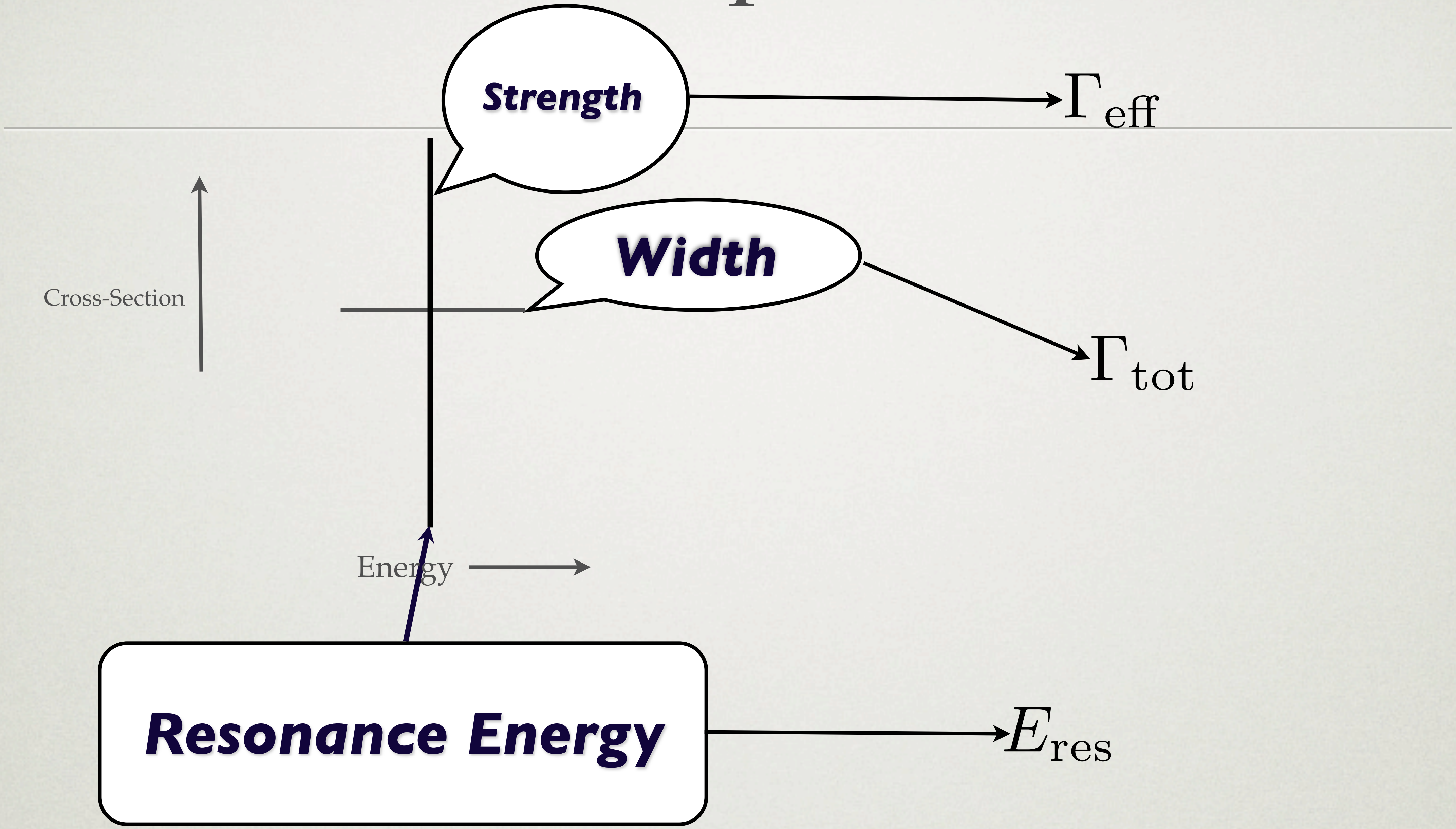
E_{res}

Resonance parameters



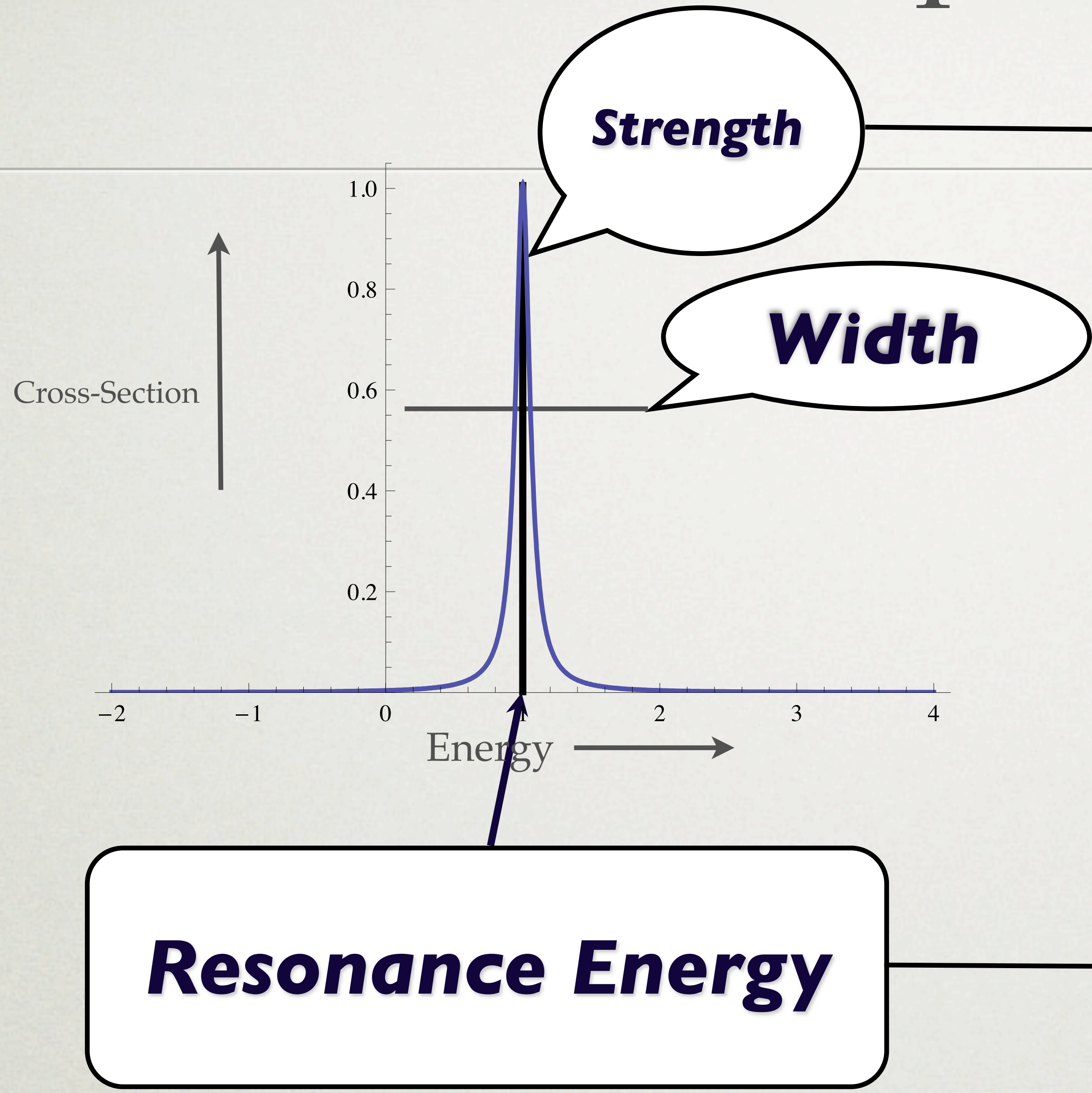
Narrow Resonance Approximation

Resonance parameters



Narrow Resonance Approximation

Resonance parameters



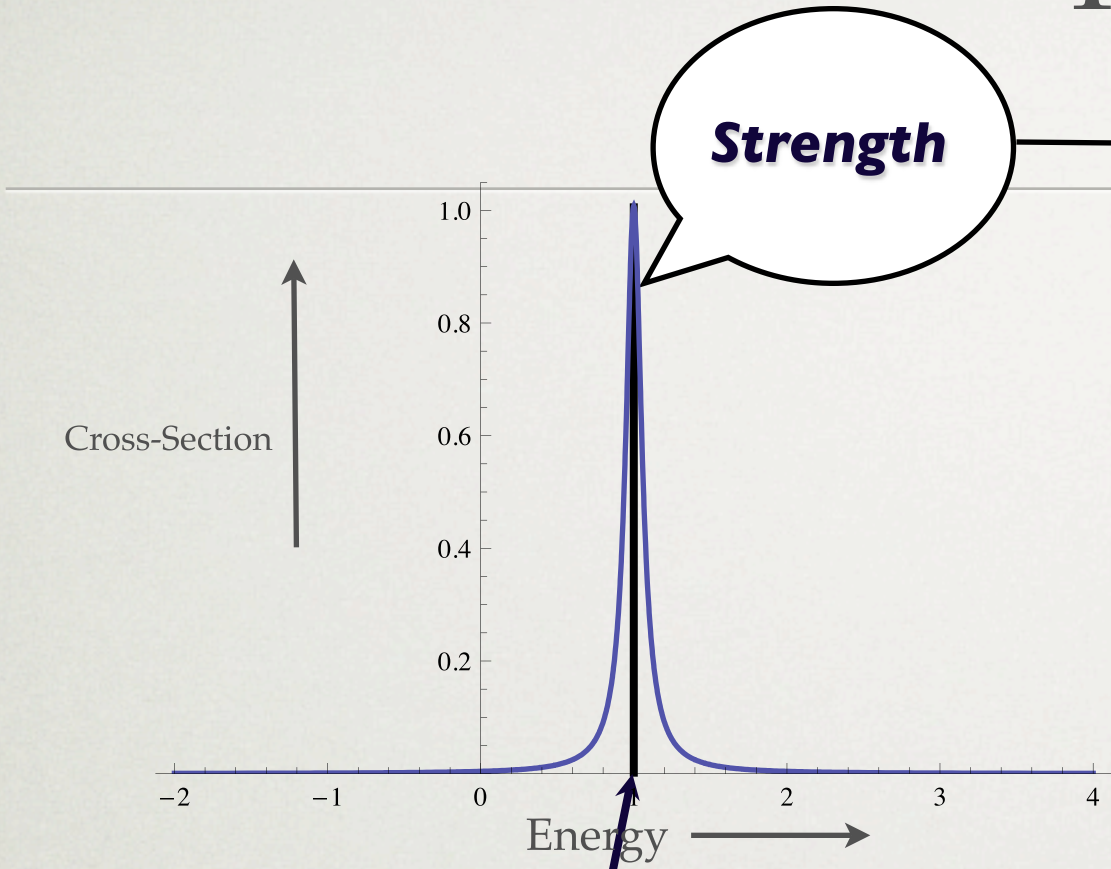
Γ_{eff}

Γ_{tot}

E_{res}

Narrow Resonance Approximation

Resonance parameters

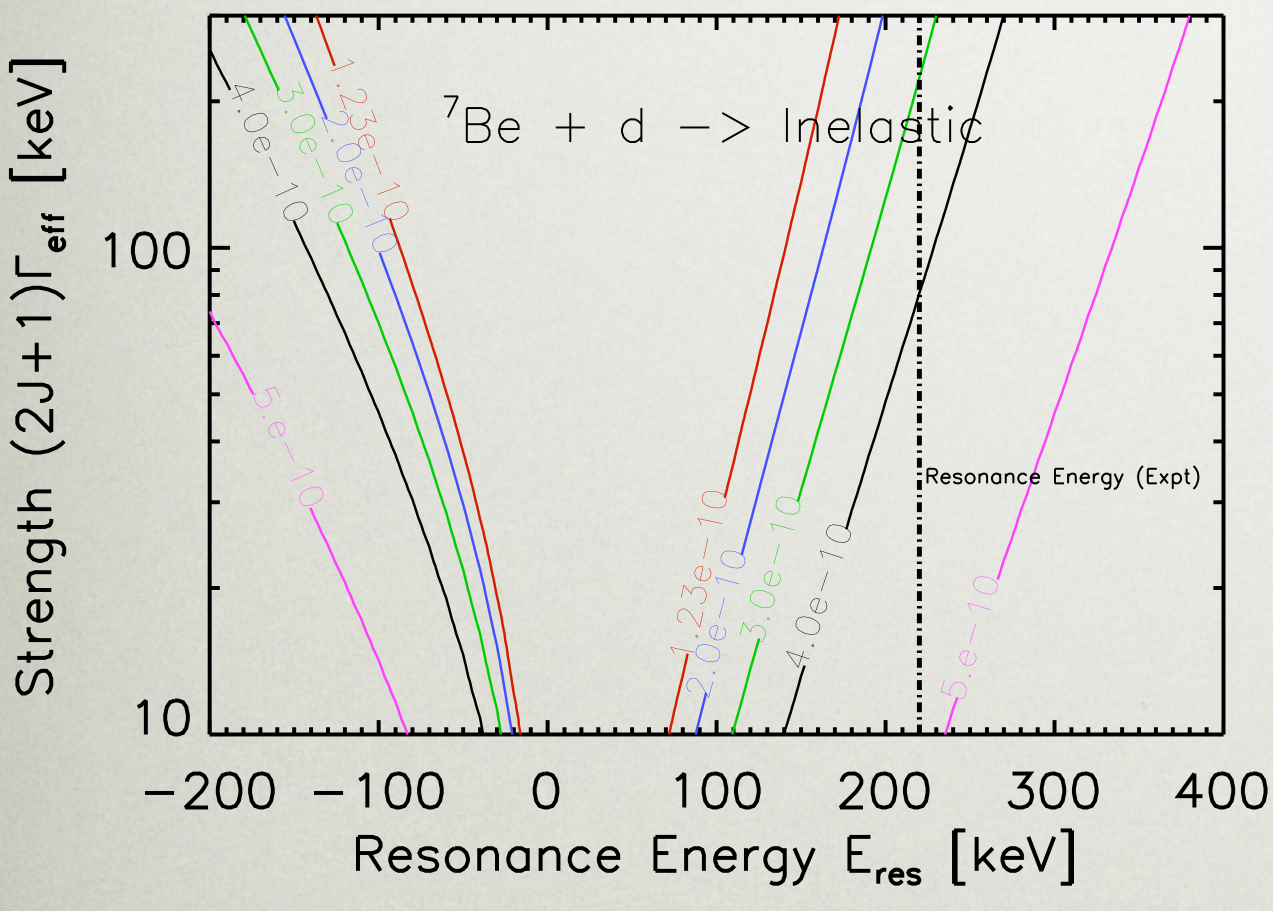


Strength → Γ_{eff}

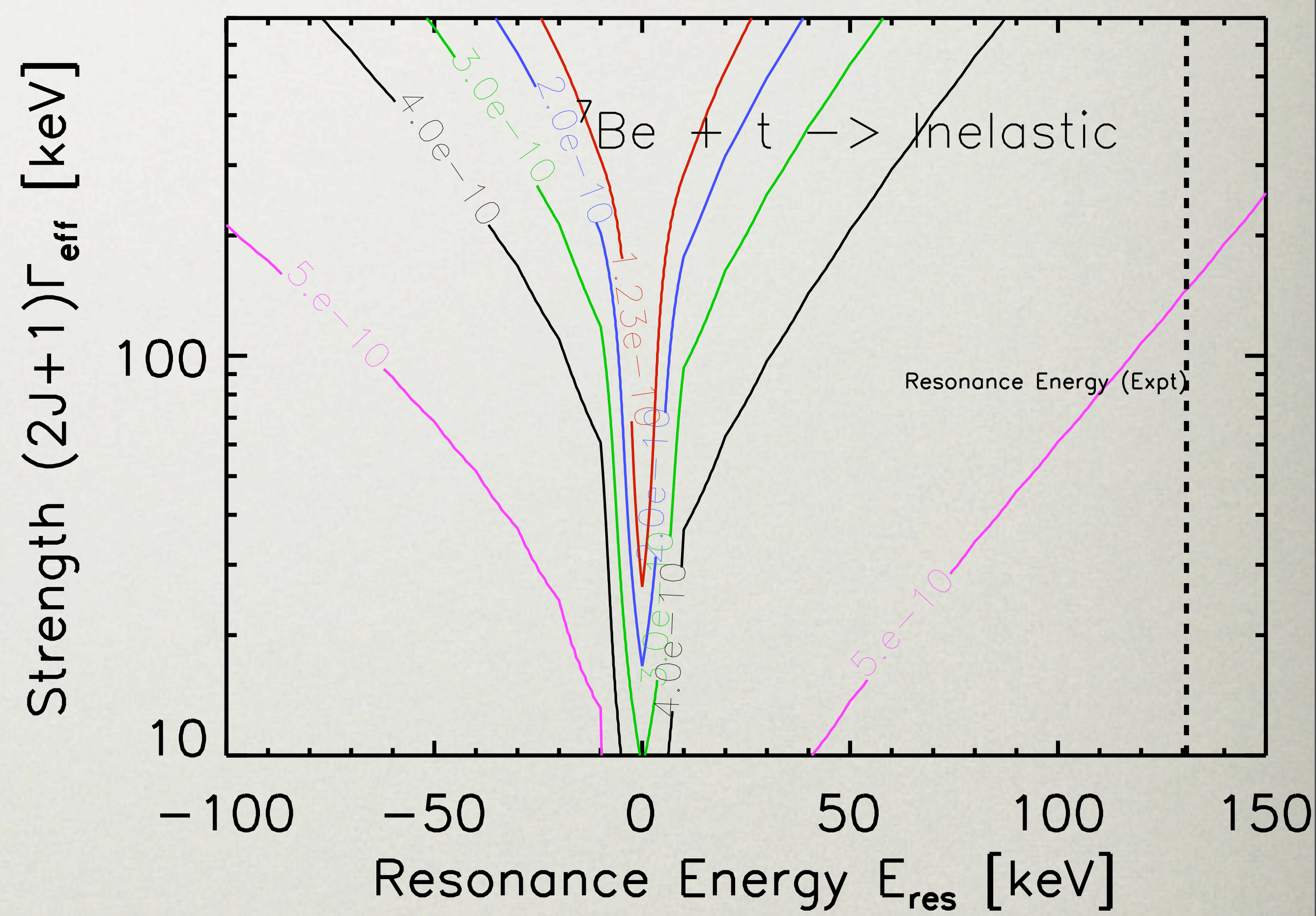
Resonance Energy → E_{res}

Narrow Resonance Approximation

Our bets

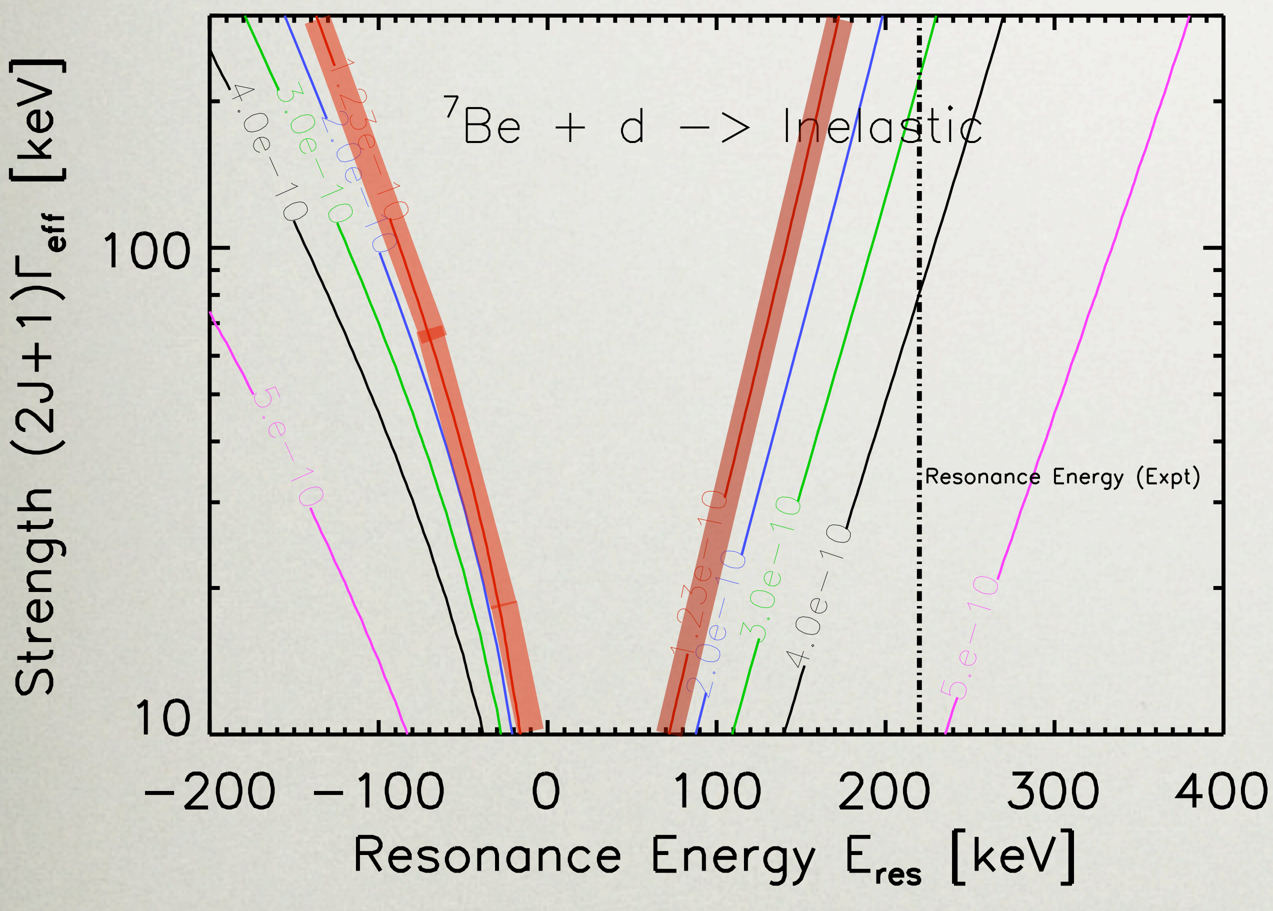


^{7}Be + d -> Inelastic
Resonance Energy (Expt)
1.23e-10
2.0e-10
3.0e-10
4.0e-10
5.e-10
Strength (2J+1)Γ$_{eff}$ [keV]
Resonance Energy E$_{res}$ [keV]
10
100
−200
−100
0
100
200
300
400

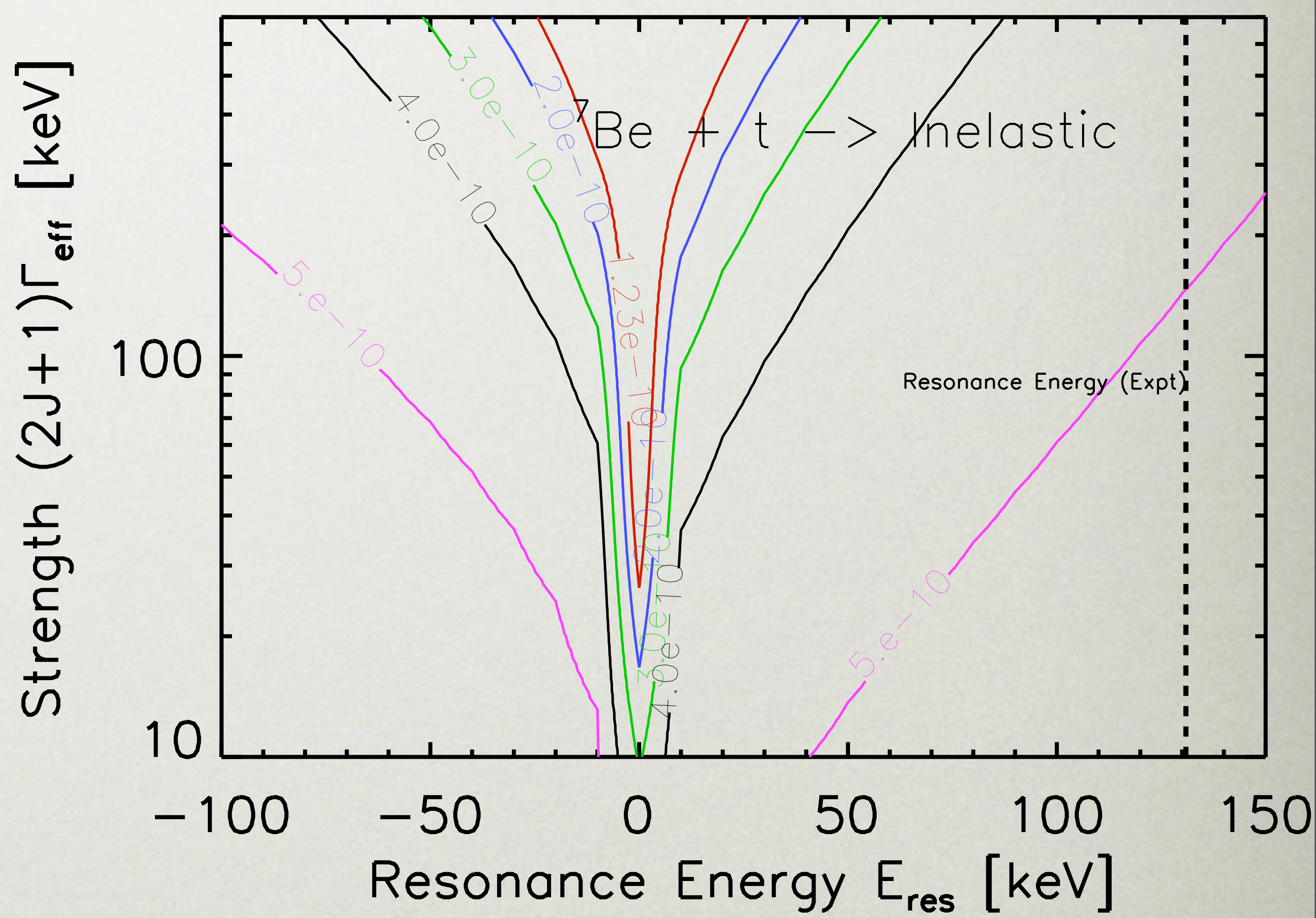


^{7}Be + t -> Inelastic
Resonance Energy (Expt)
1.23e-10
2.0e-10
3.0e-10
4.0e-10
5.e-10
Strength (2J+1)Γ$_{eff}$ [keV]
Resonance Energy E$_{res}$ [keV]
10
100
−100
−50
0
50
100
150

Our bets



^{7}Be + d -> Inelastic
Resonance Energy (Expt)
1.23e-10
2.0e-10
3.0e-10
4.0e-10
5.e-10
Strength (2J+1)Γ_{eff} [keV]
Resonance Energy E_{res} [keV]



^{7}Be + t -> Inelastic
Resonance Energy (Expt)
1.23e-10
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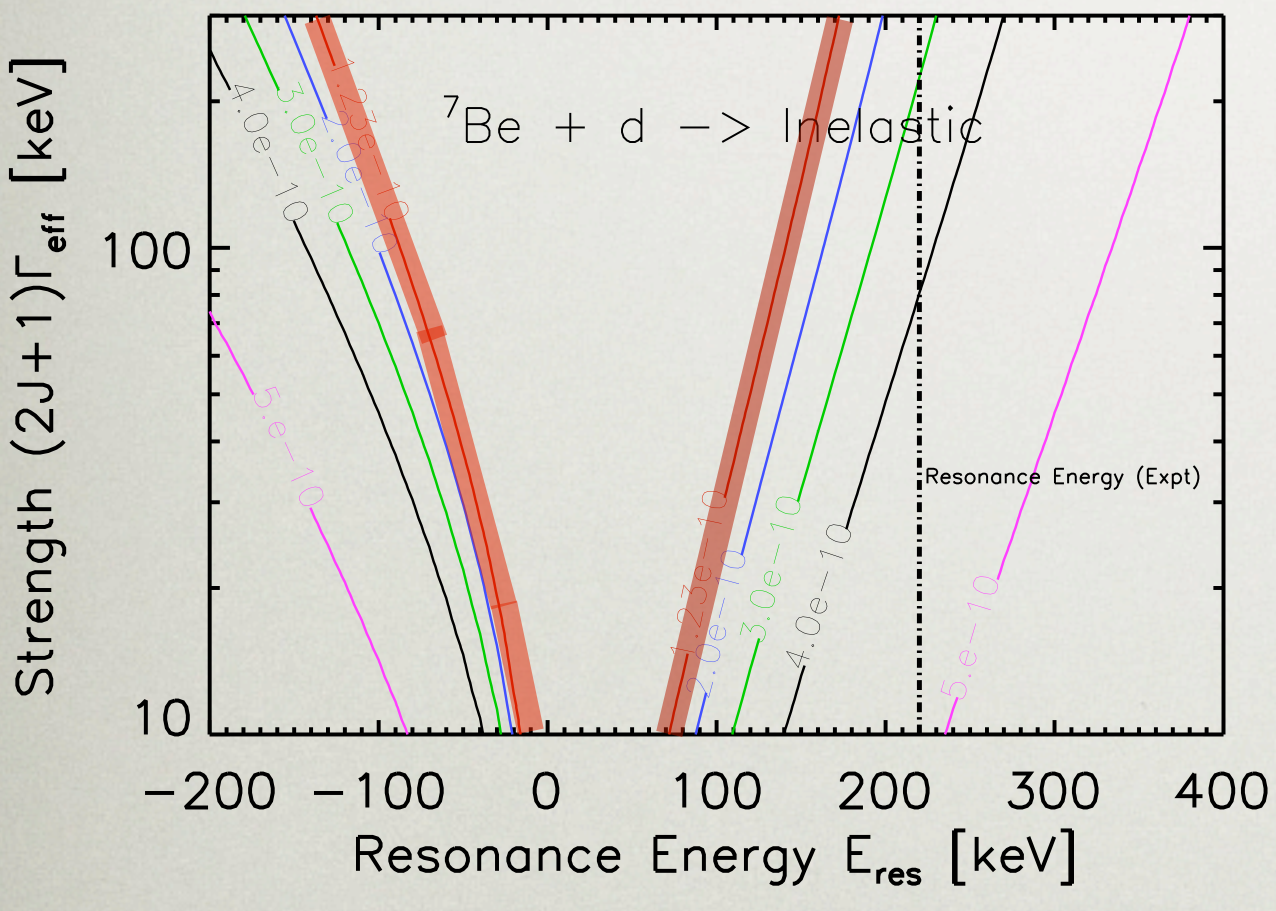
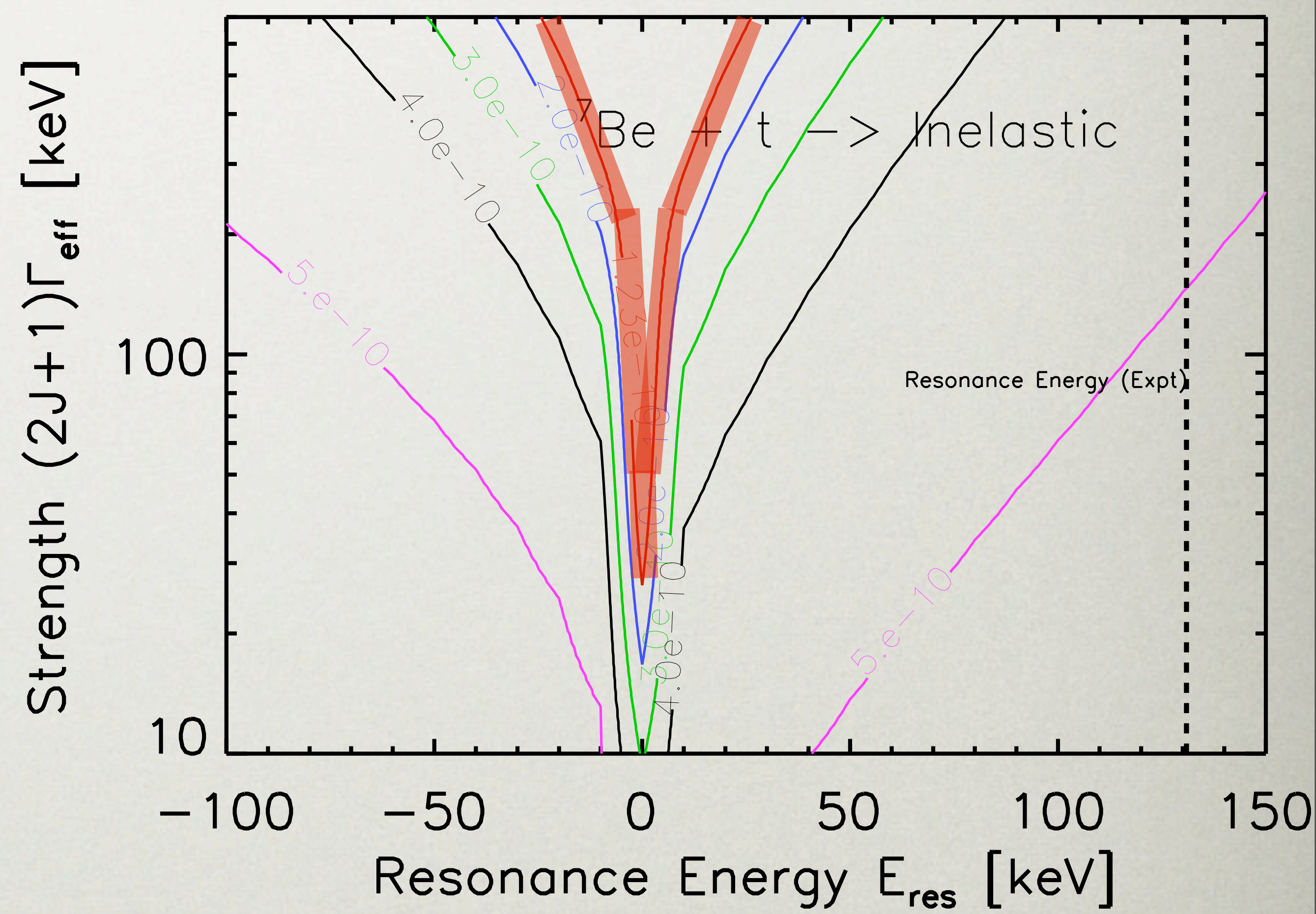
3.0e-10
4.0e-10
5.e-10
Strength (2J+1)Γ_{eff} [keV]
Resonance Energy E_{res} [keV]

Our bets

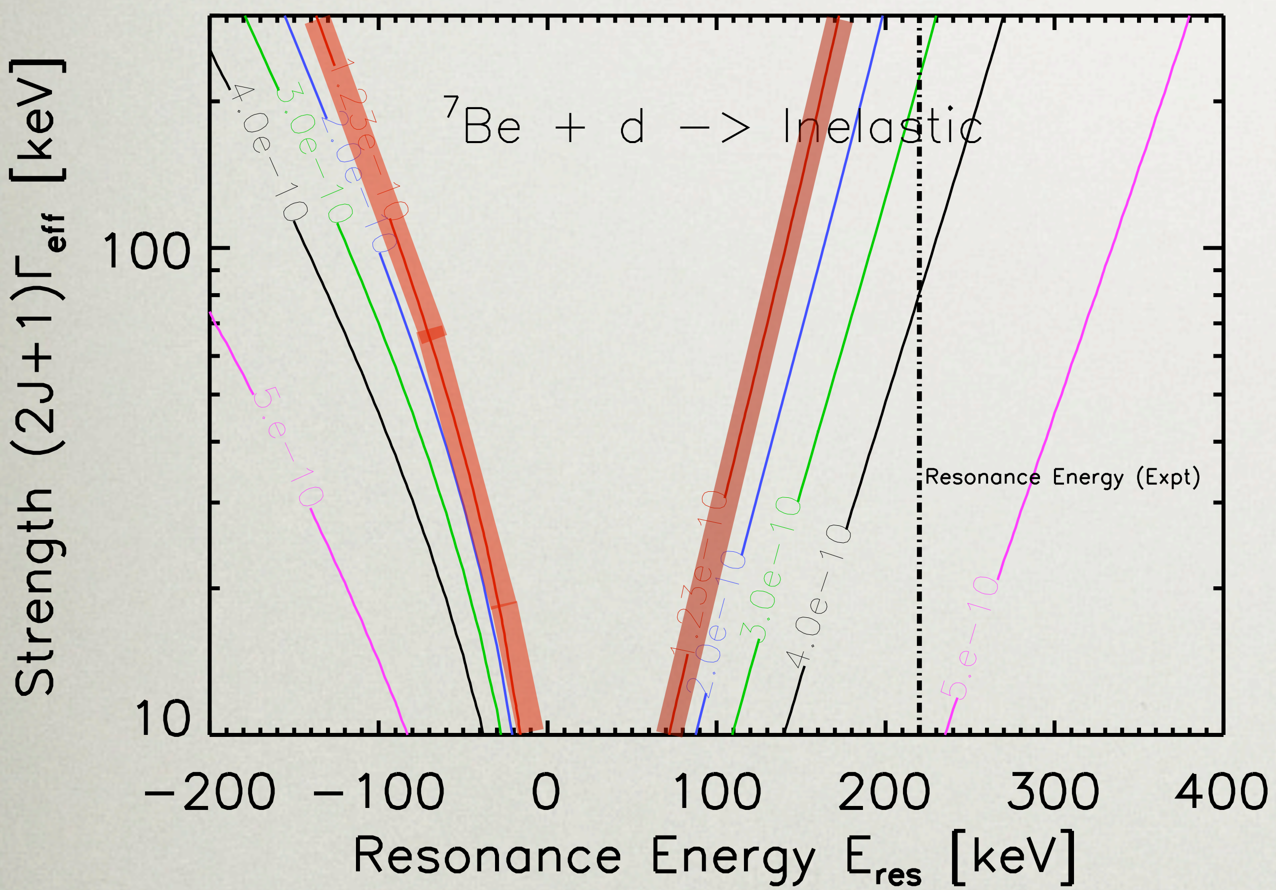


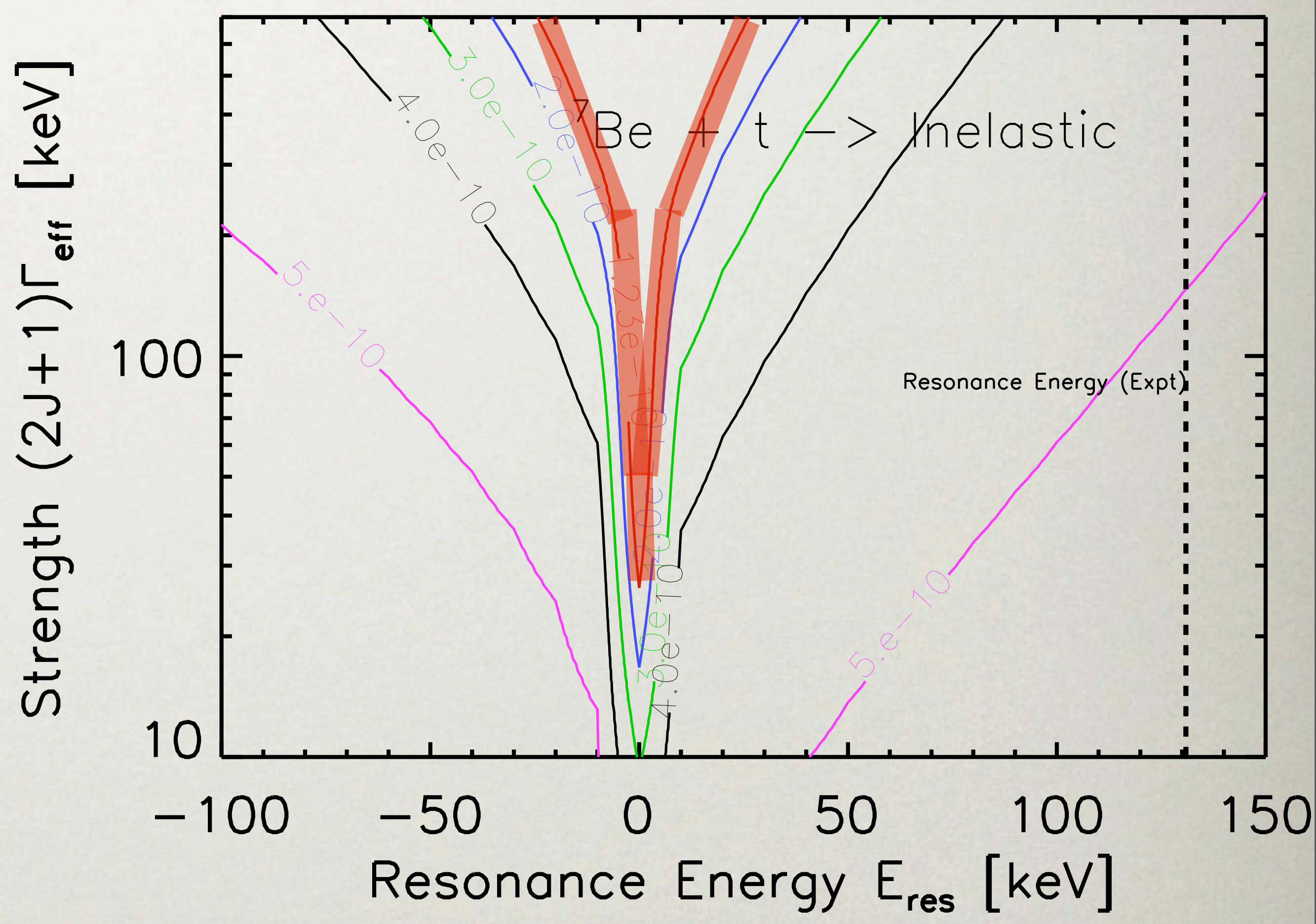
^{7}Be + d -> Inelastic
Resonance Energy (Expt)
Strength $(2J+1)\Gamma_{eff}$ [keV]
Resonance Energy E_{res} [keV]
1.23e-10
2.0e-10
3.0e-10
4.0e-10
5.e-10



^{7}Be + t -> Inelastic
Resonance Energy (Expt)
Strength $(2J+1)\Gamma_{eff}$ [keV]
Resonance Energy E_{res} [keV]
2.0e-10
3.0e-10
4.0e-10
5.e-10

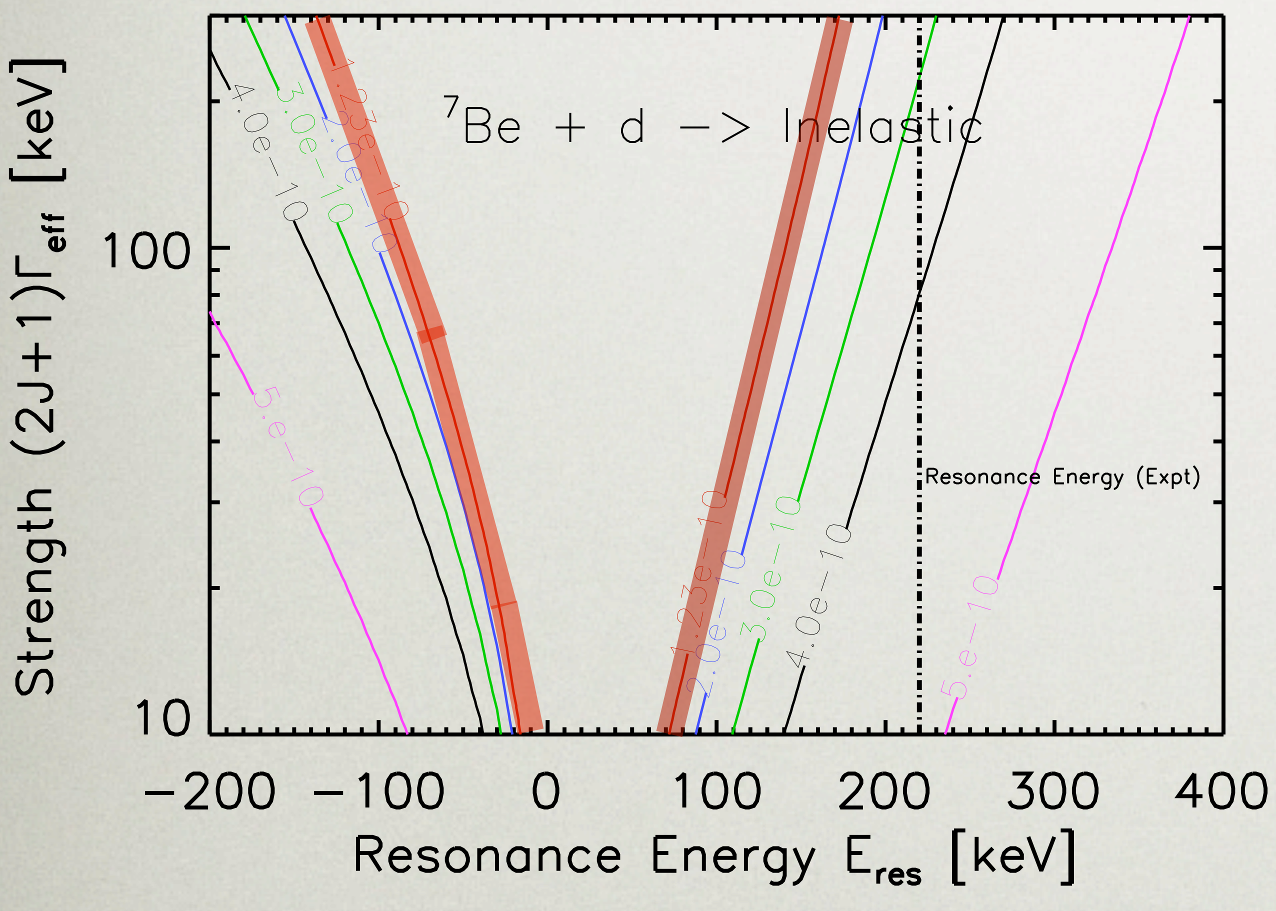
Our bets



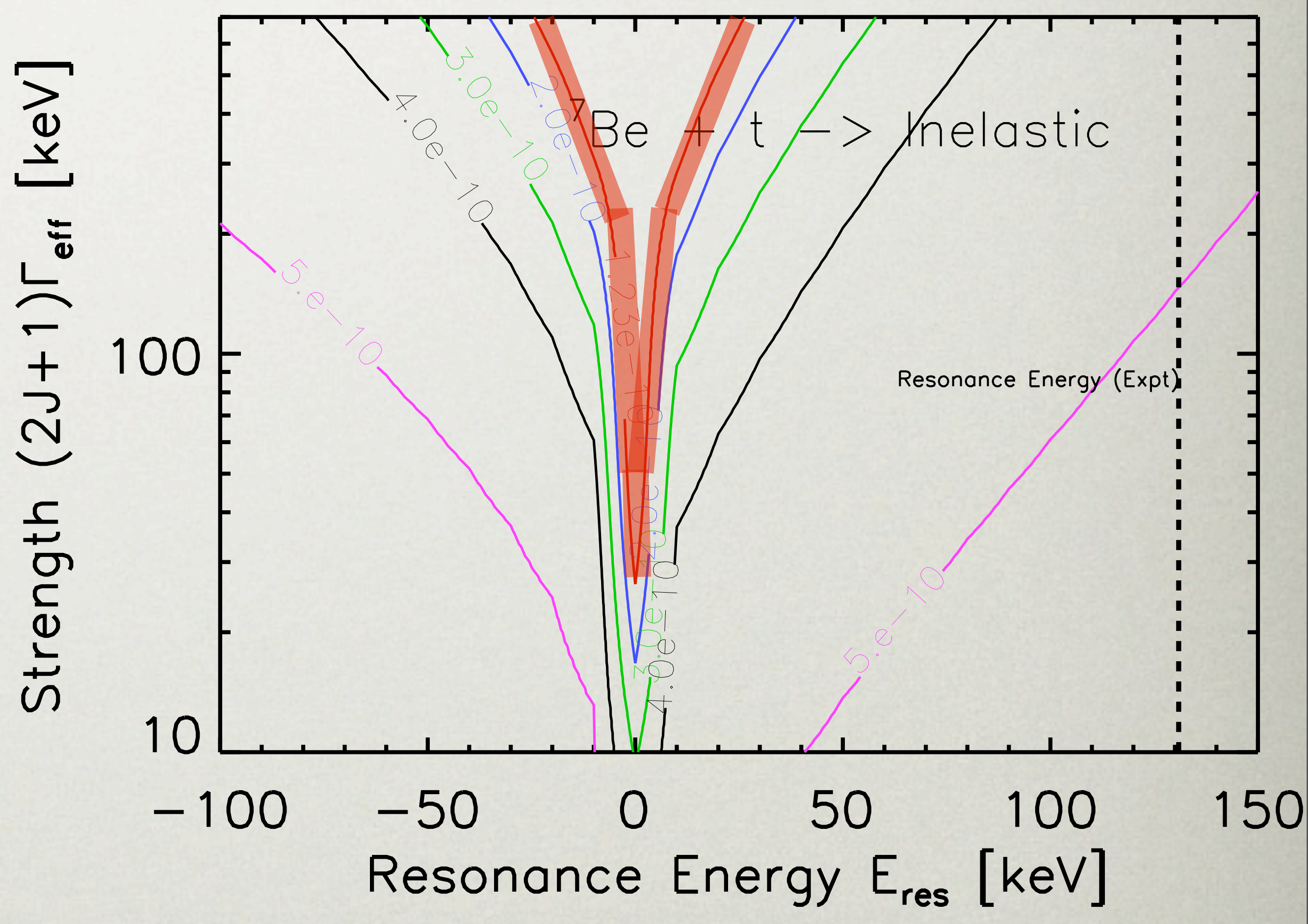


Problem solved !!

Our bets

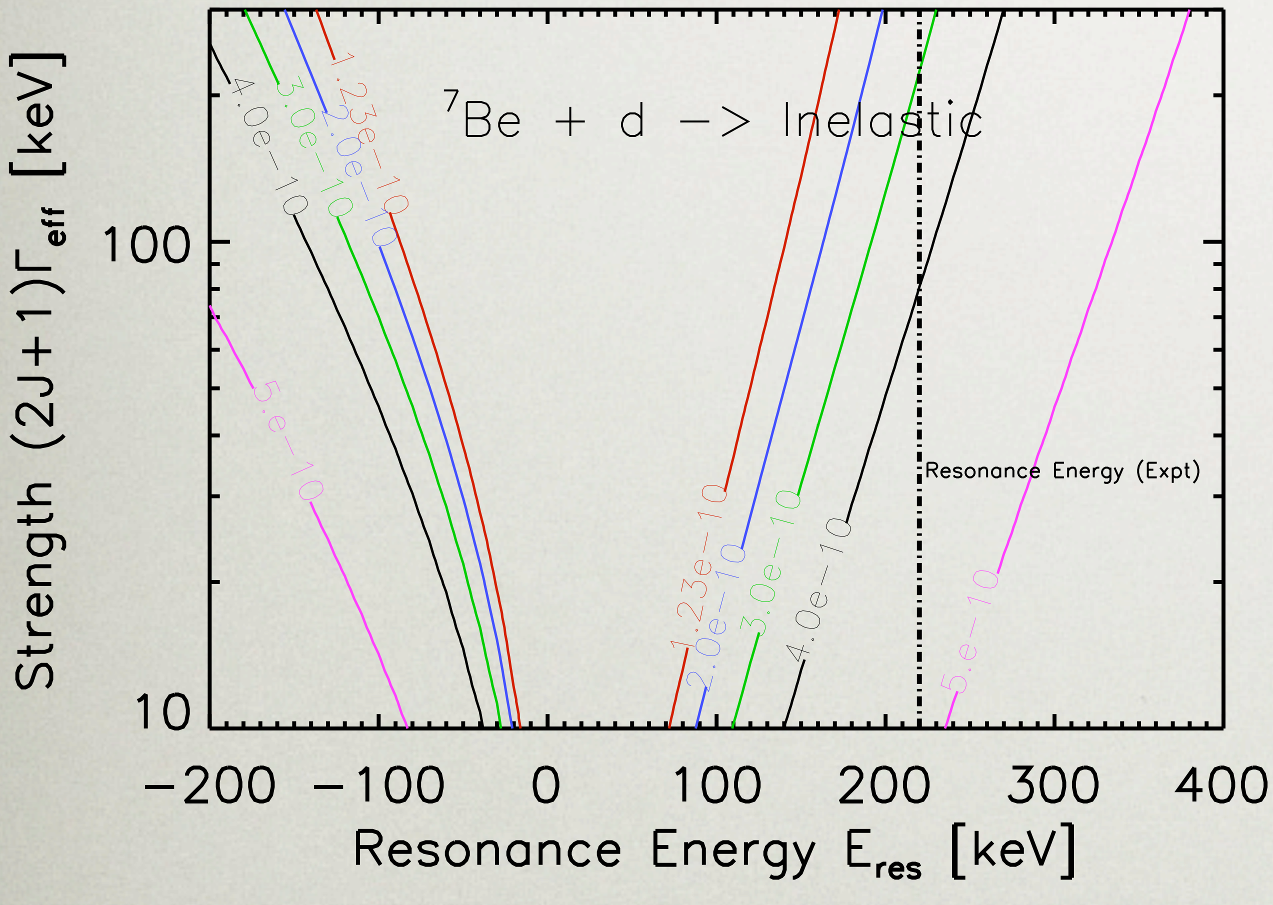


^{7}Be + d -> Inelastic
Resonance Energy (Expt)
Strength $(2J+1)\Gamma_{eff}$ [keV]
Resonance Energy E_{res} [keV]

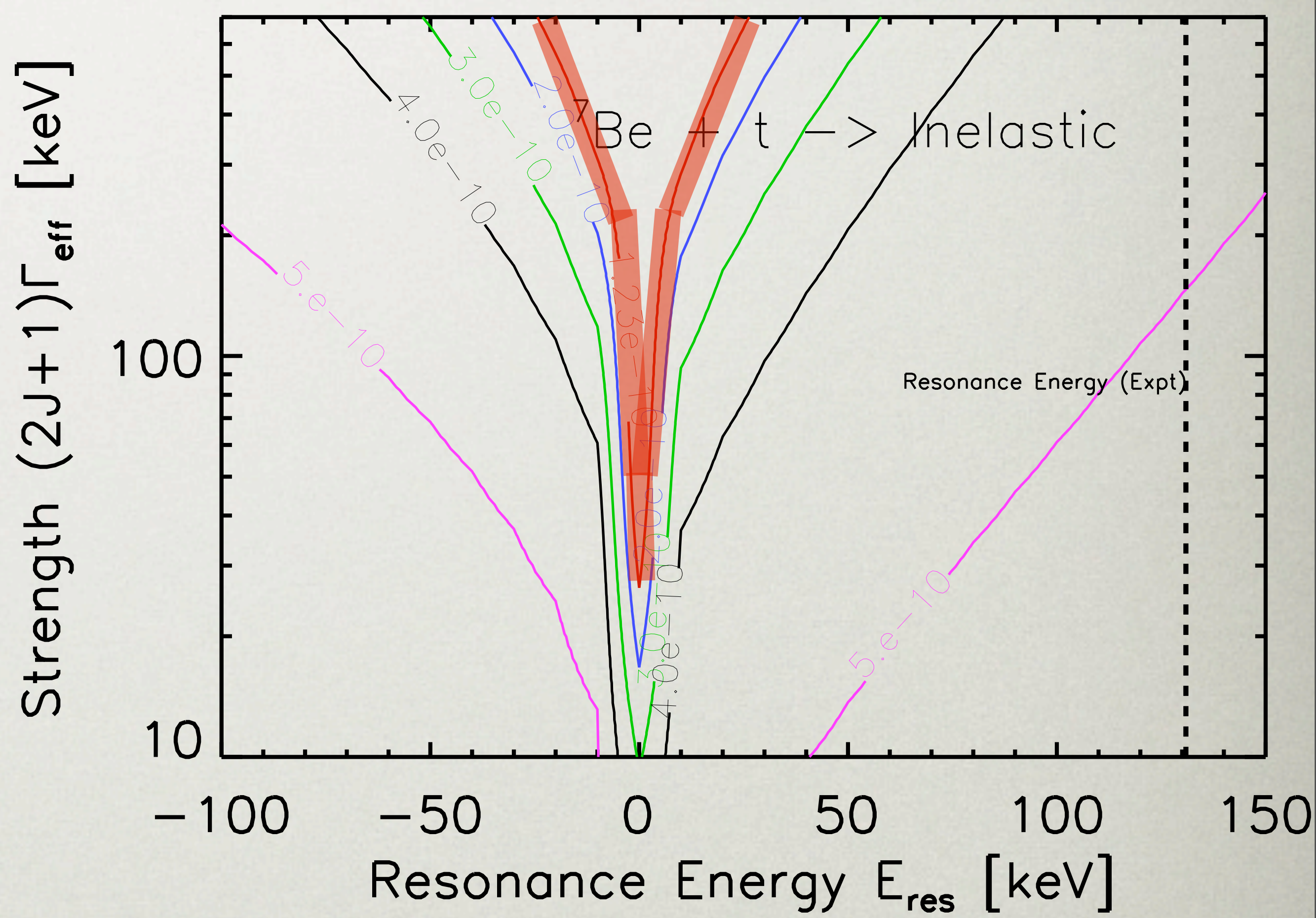


^{7}Be + t -> Inelastic
Resonance Energy (Expt)
Strength $(2J+1)\Gamma_{eff}$ [keV]
Resonance Energy E_{res} [keV]

Our bets

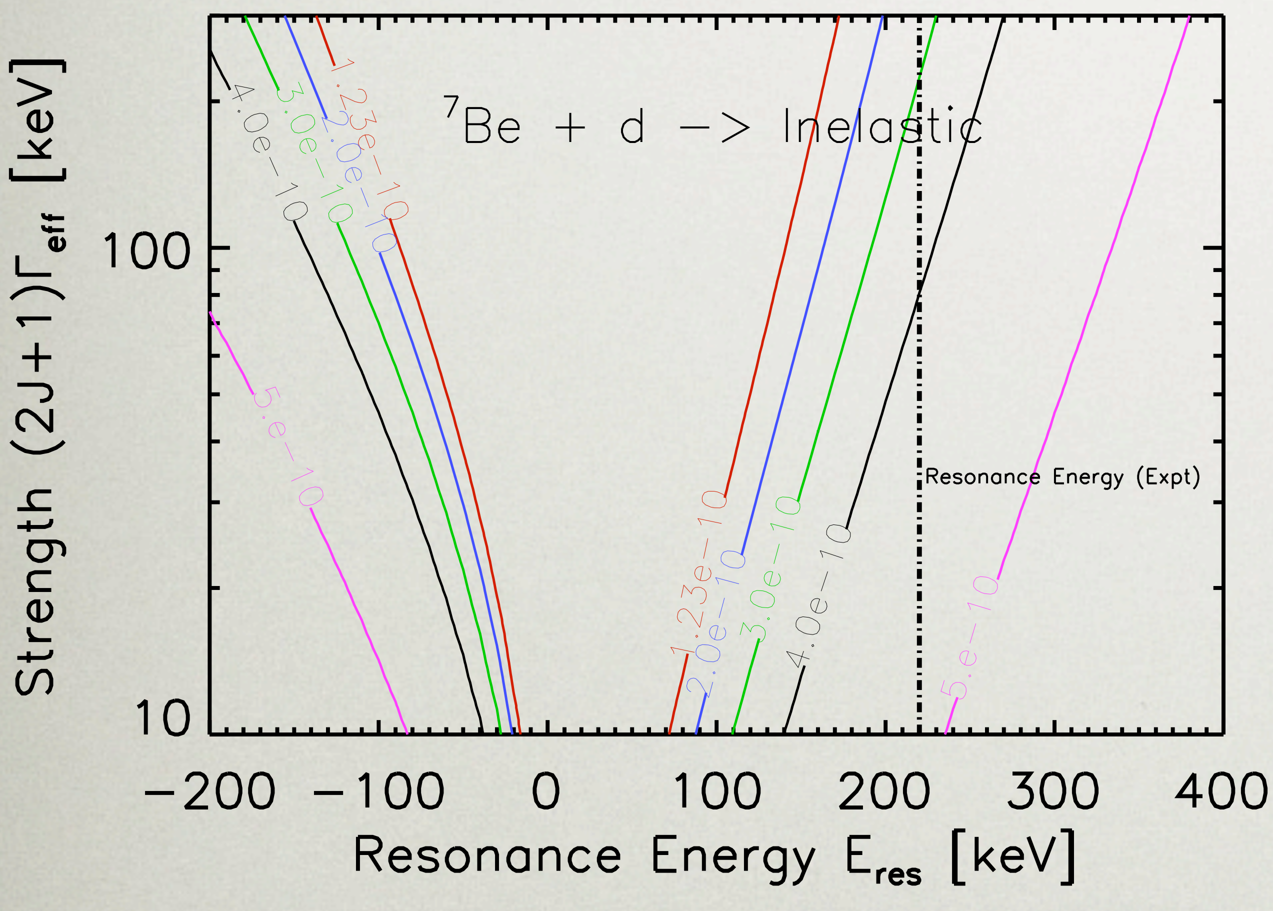


^{7}Be + d –> Inelastic
Resonance Energy (Expt)
1.23e–10
2.0e–10
3.0e–10
4.0e–10
5.e–10
Strength (2J+1)Γ_{eff} [keV]
Resonance Energy E_{res} [keV]
10
100
–200
–100
0
100
200
300
400

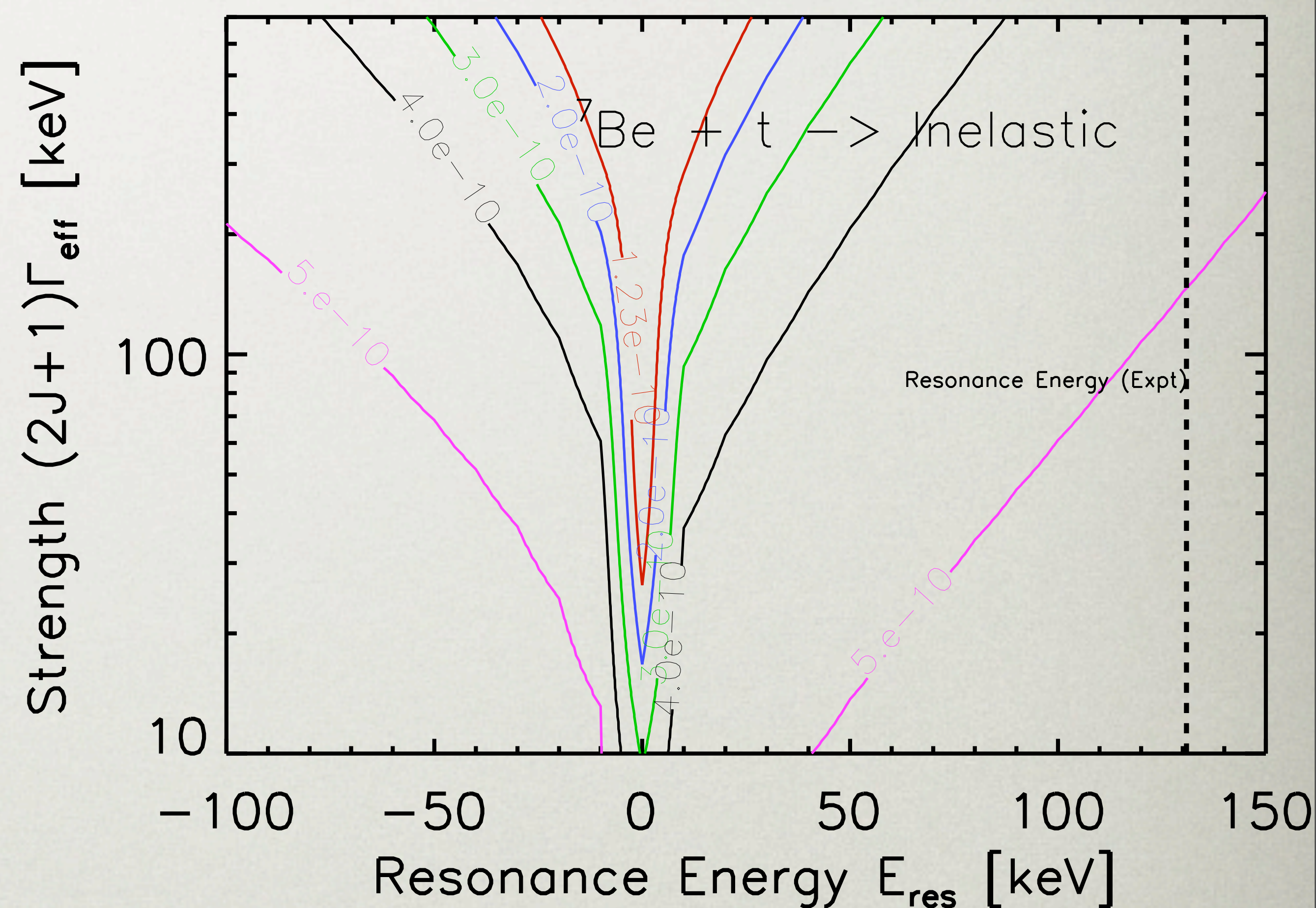


^{7}Be + t –> Inelastic
Resonance Energy (Expt)
4.0e–10
3.0e–10
2.0e–10
5.e–10
Strength (2J+1)Γ_{eff} [keV]
Resonance Energy E_{res} [keV]
10
100
–100
–50
0
50
100
150

Our bets



^{7}Be + d −> Inelastic
Resonance Energy (Expt)
1.23e−10
2.0e−10
3.0e−10
4.0e−10
5.e−10
Strength (2J+1)Γ$_{eff}$ [keV]
100
10
−200 −100 0 100 200 300 400
Resonance Energy E$_{res}$ [keV]



^{7}Be + t −> Inelastic
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Strength (2J+1)Γ$_{eff}$ [keV]
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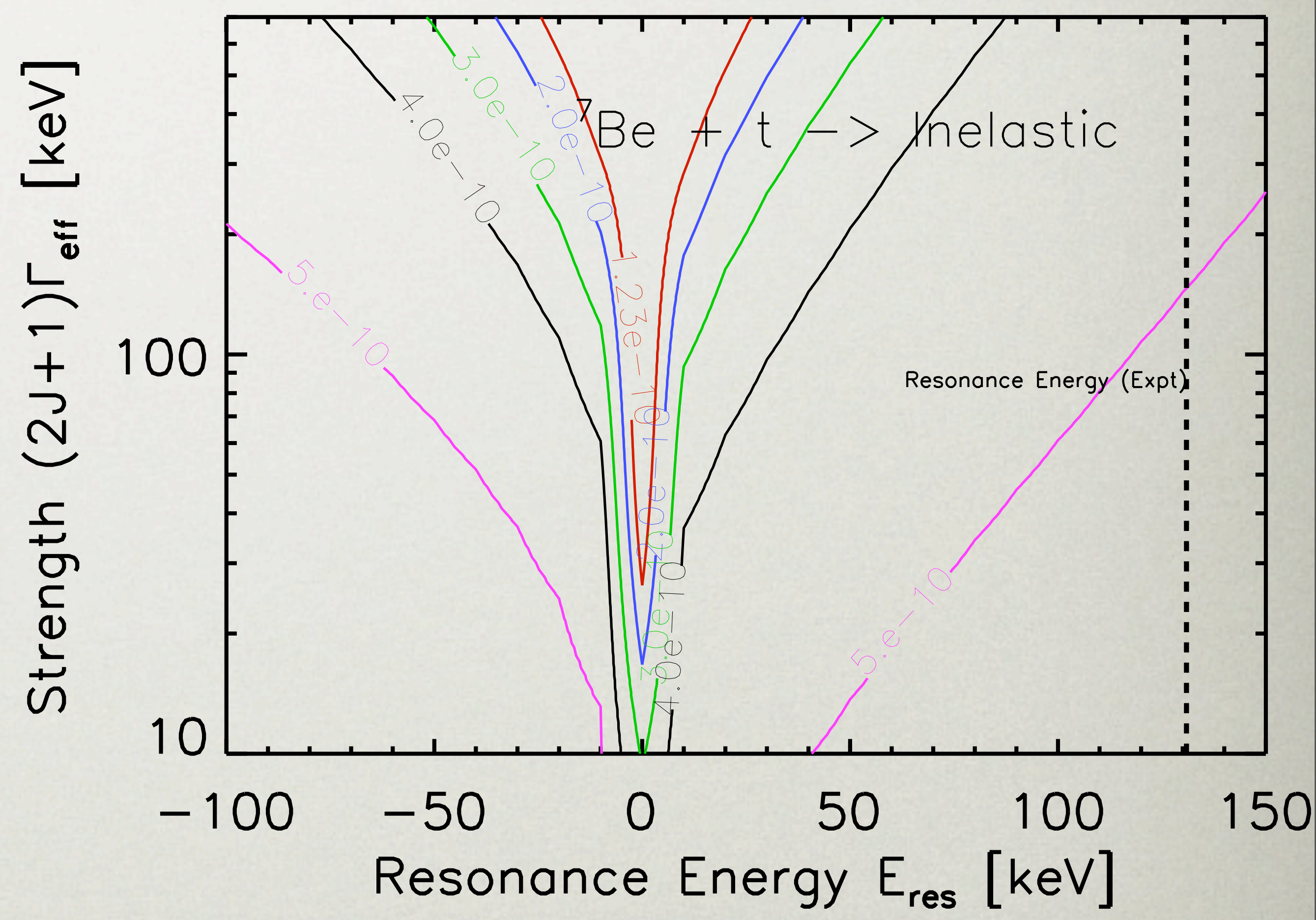
10
−100 −50 0 50 100 150
Resonance Energy E$_{res}$ [keV]

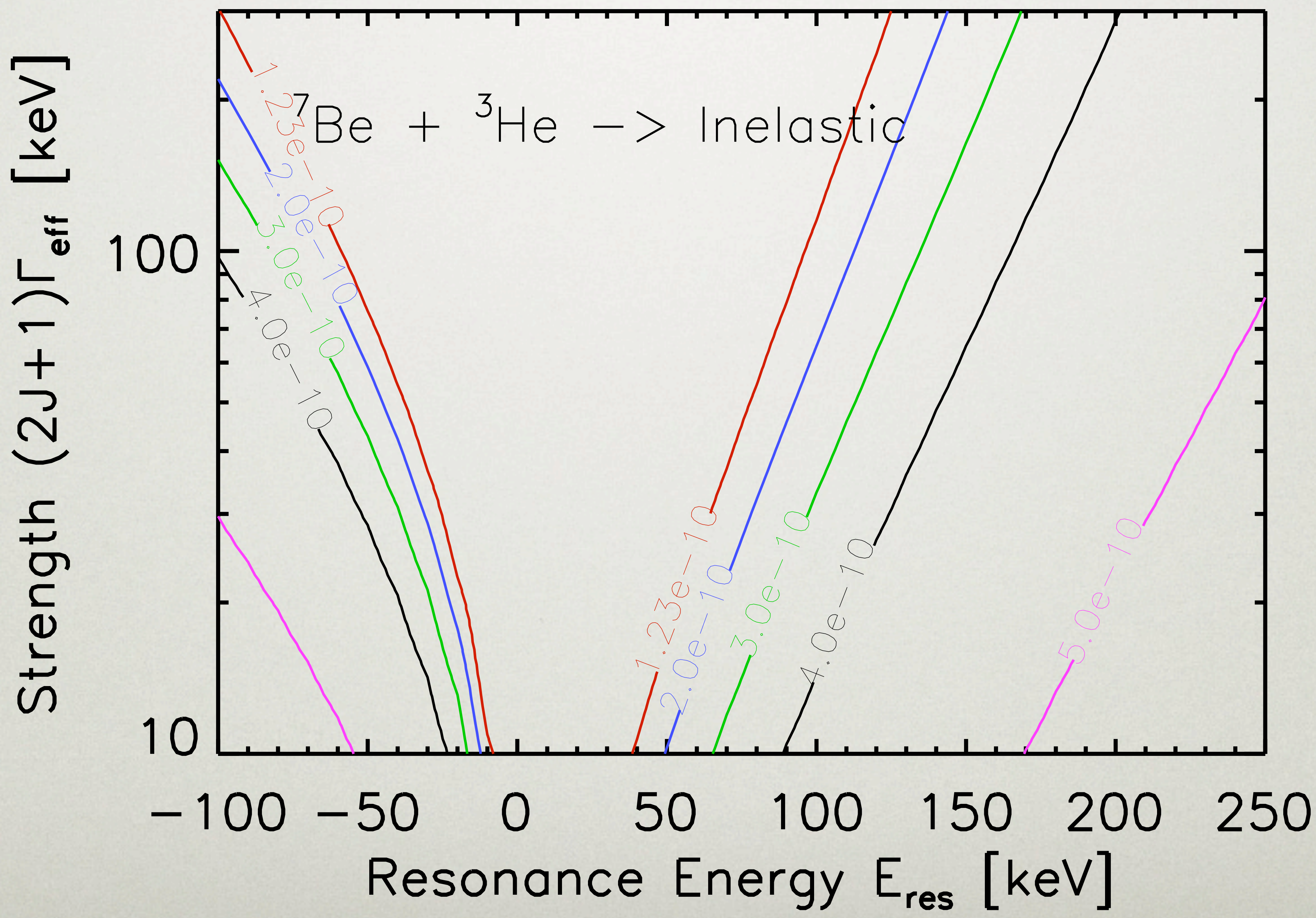
Our bets



^{7}Be + t -> Inelastic
Resonance Energy (Expt)
4.0e-10
3.0e-10
2.0e-10
1.23e-10
5.e-10
100
10
-100
-50
0
50
100
150
Strength (2J+1)Γ_{eff} [keV]
Resonance Energy E_{res} [keV]

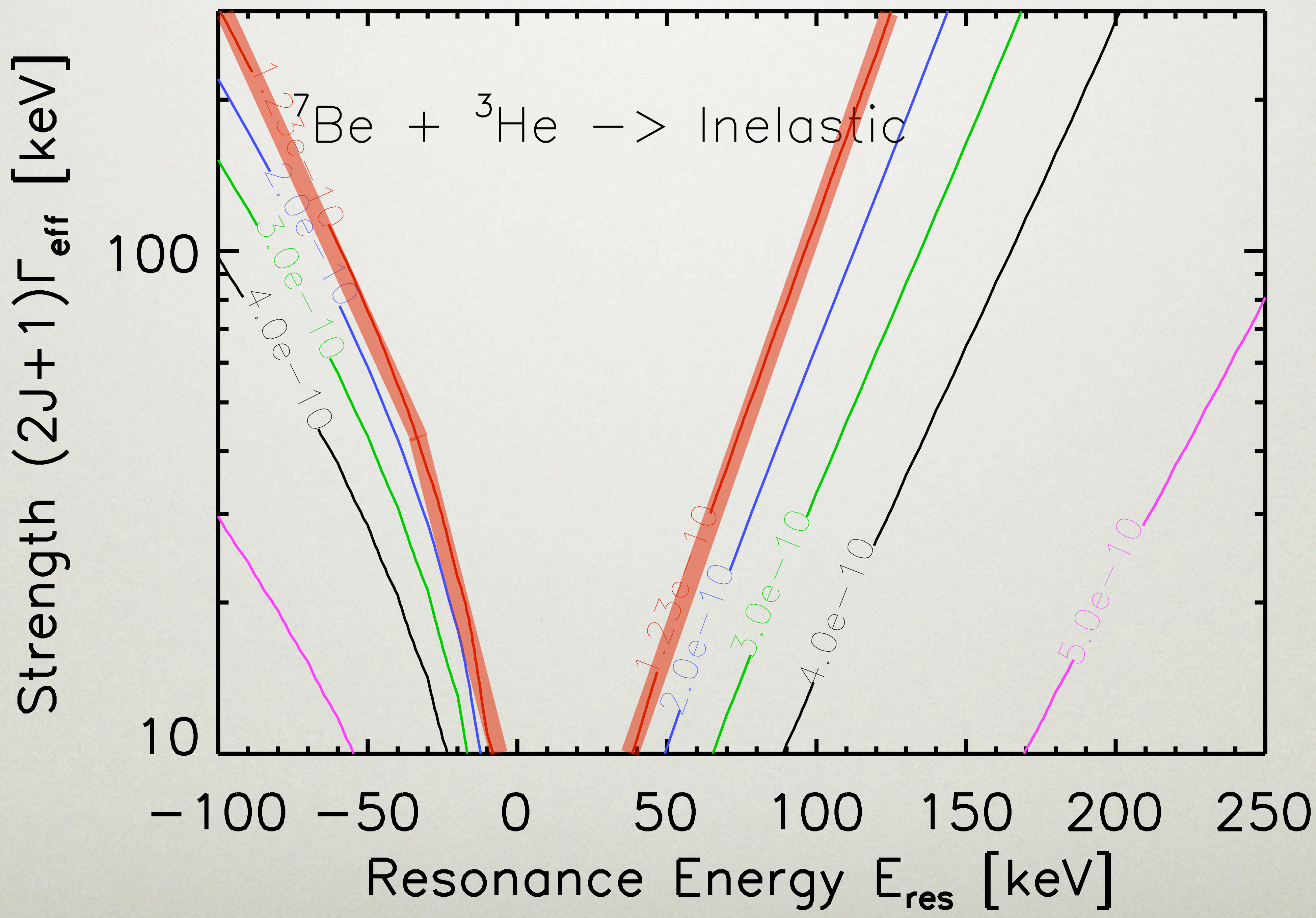
Our bets

Our bets



^{7}Be + ^{3}He -> Inelastic
1.23e-10
2.0e-10
3.0e-10
4.0e-10
5.0e-10
100
10
−100
−50
0
50
100
150
200
250
Resonance Energy E_{res} [keV]
Strength $(2J+1)\Gamma_{eff}$ [keV]

Our bets



^{7}Be + ^{3}He -> Inelastic
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Resonance Energy E_{res} [keV]
100
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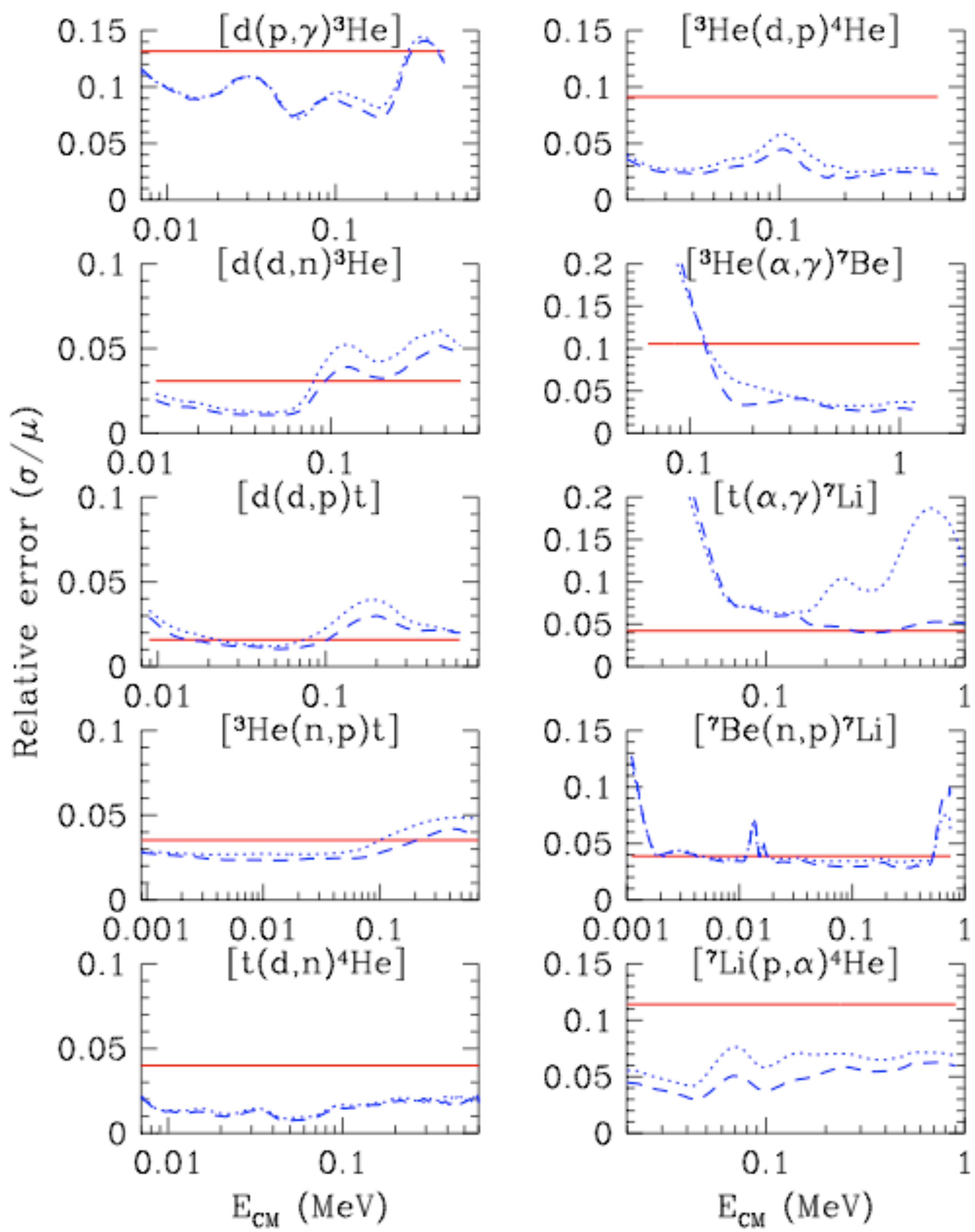
200
250
1.23e−10
2.0e−10
3.0e−10
4.0e−10
5.0e−10

Do we have any Standard Model solutions ?

- Potentially yes → Nuclear resonances
- Complete or partial match
  - ^{7}Be + d → p + 2 α (Cyburt and Pospelov, (2009) and competing channels)
  - ^{7}Be + t → Inelastic (Chakraborty, Fields and Olive, 2010)
  - ^{7}Be + ^{3}He → Inelastic (Chakraborty, Fields and Olive, 2010)
  - Missed resonances / levels
- Testable by current nuclear experiments
- We may be able to avoid new physics

We know reactions pretty well



Cyburt, Fields and Olive (2008)

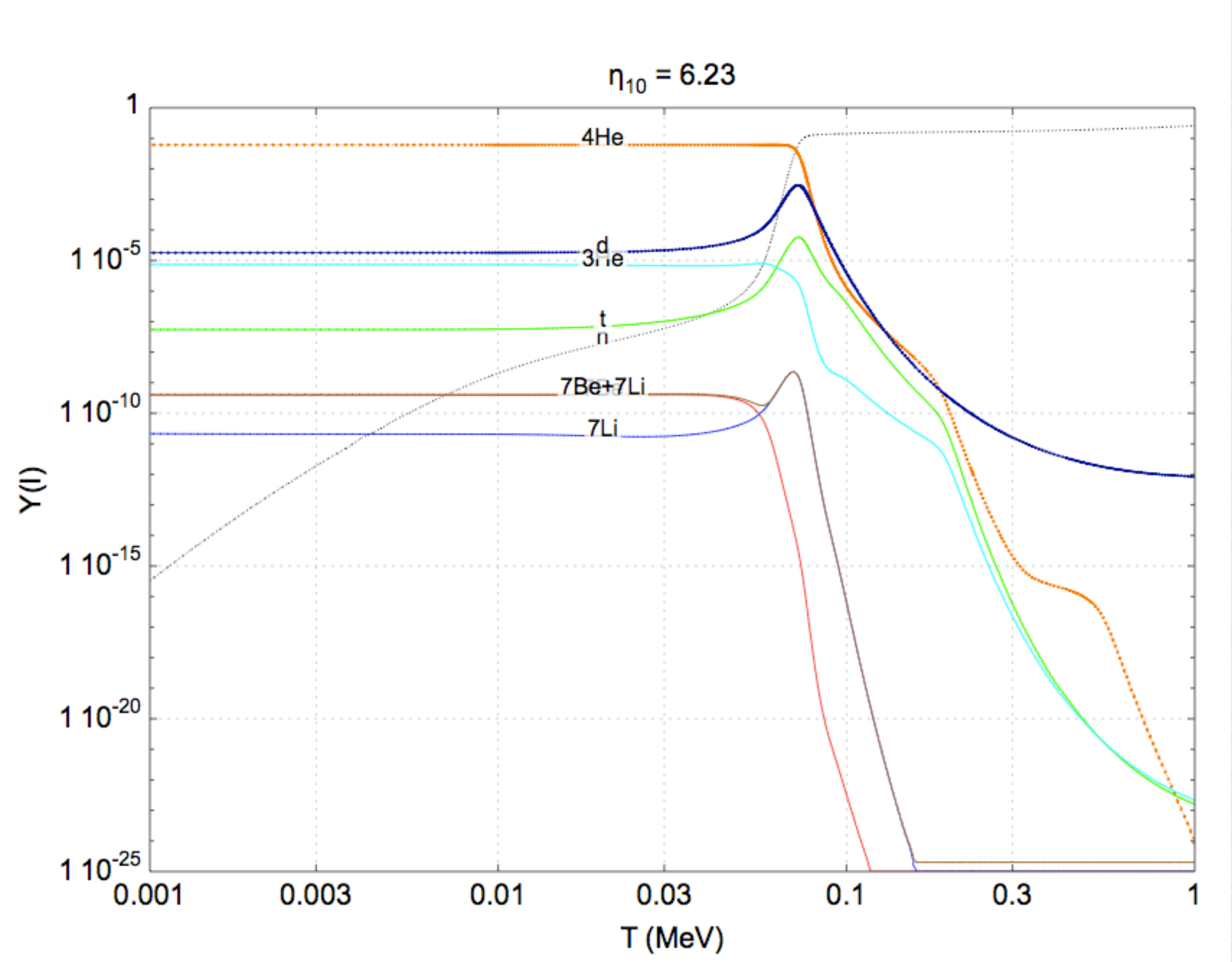
Resonant rate

$$\lambda = N_A \frac{2\pi}{\mu K} \hbar^2 \omega \; \frac{\Gamma_1 \Gamma_2}{\Gamma_{\rm tot}} \; T^{-3/2} \exp(-E_R/KT)$$

History of the elements

- $t \propto T^{-2}$ Radiation dominated

History of the elements



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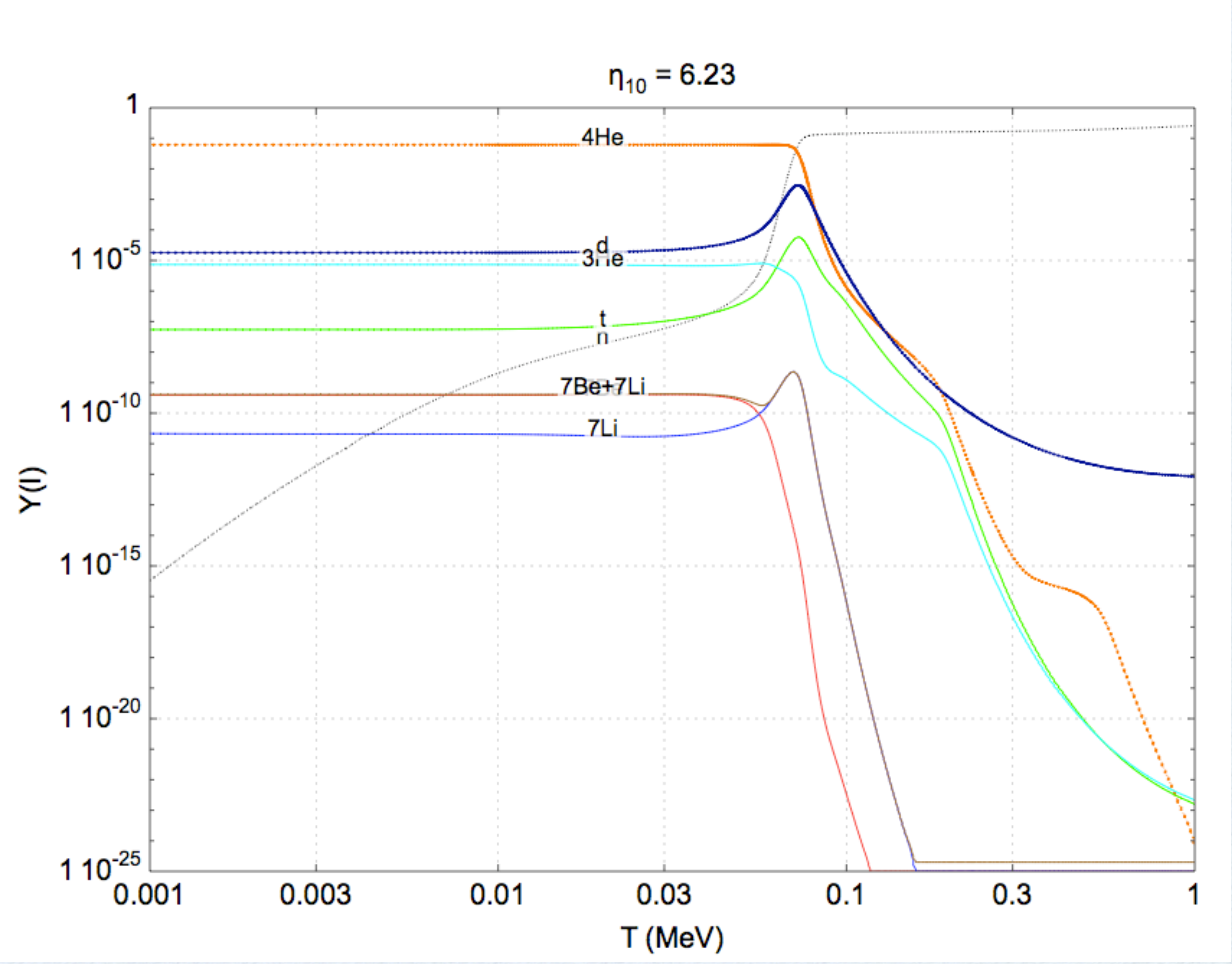
History of the elements



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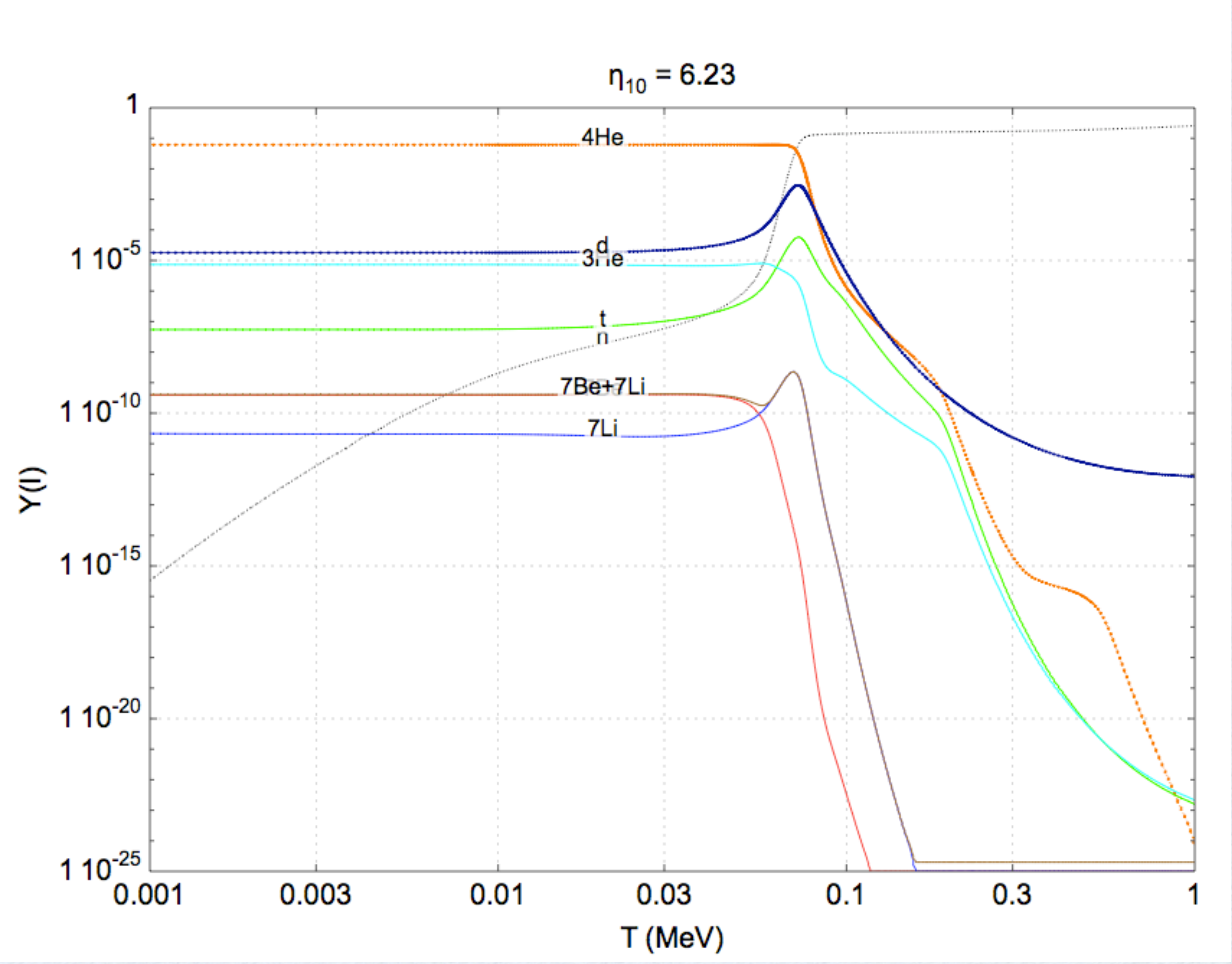
History of the elements



t

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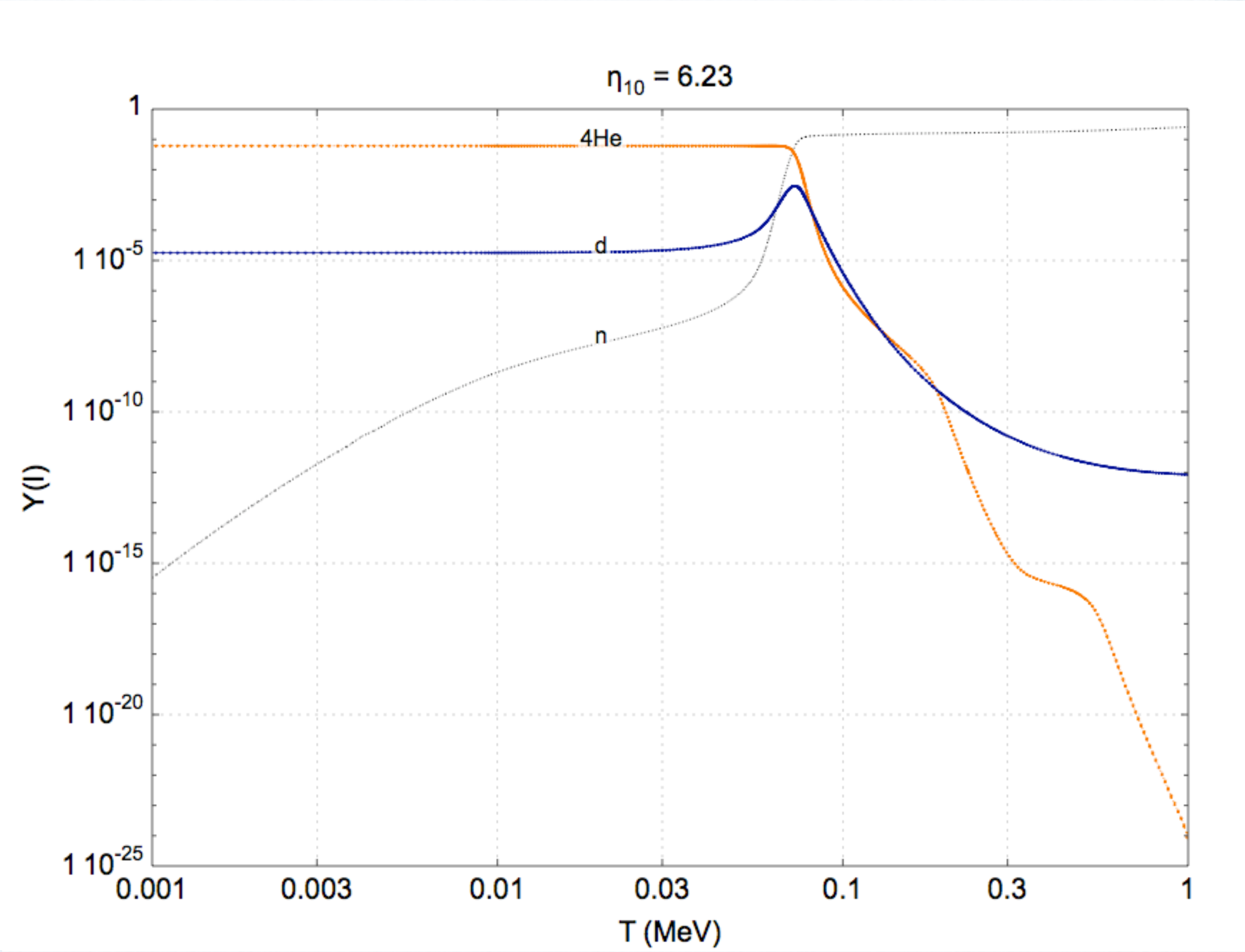
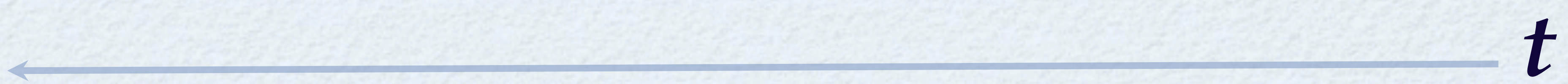
History of the elements





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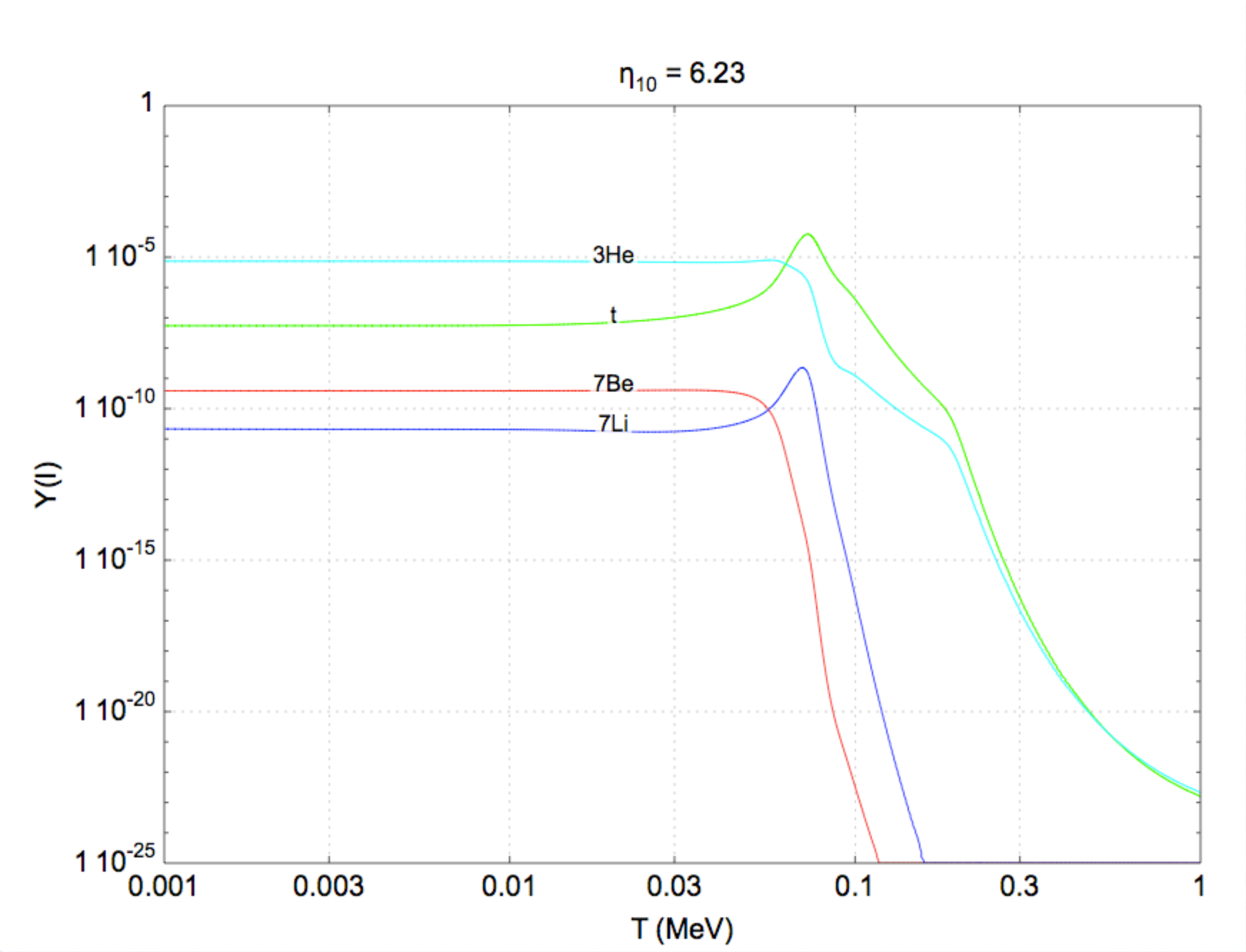
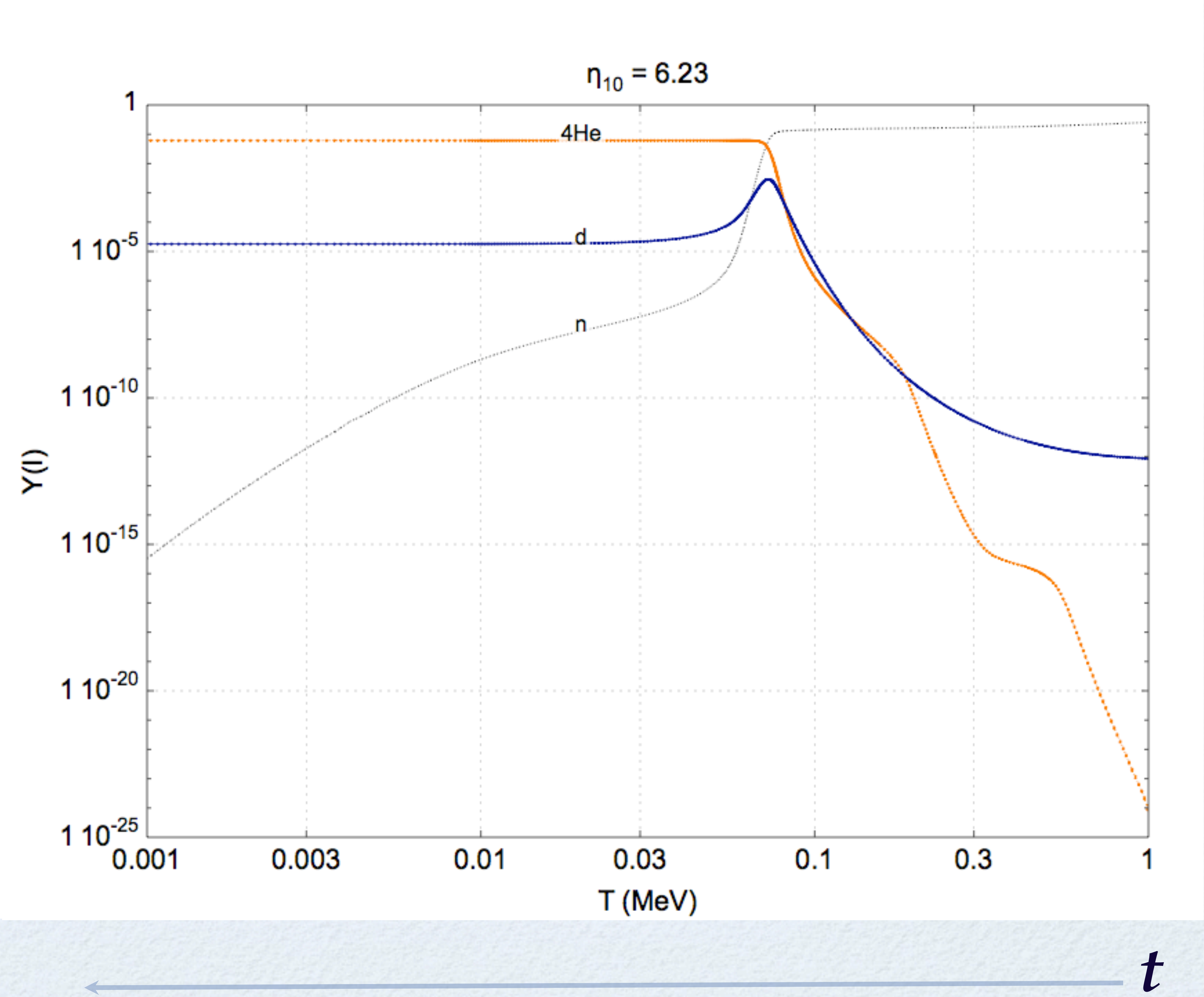
History of the elements



t

- $t \propto T^{-2}$ Radiation dominated

History of the elements



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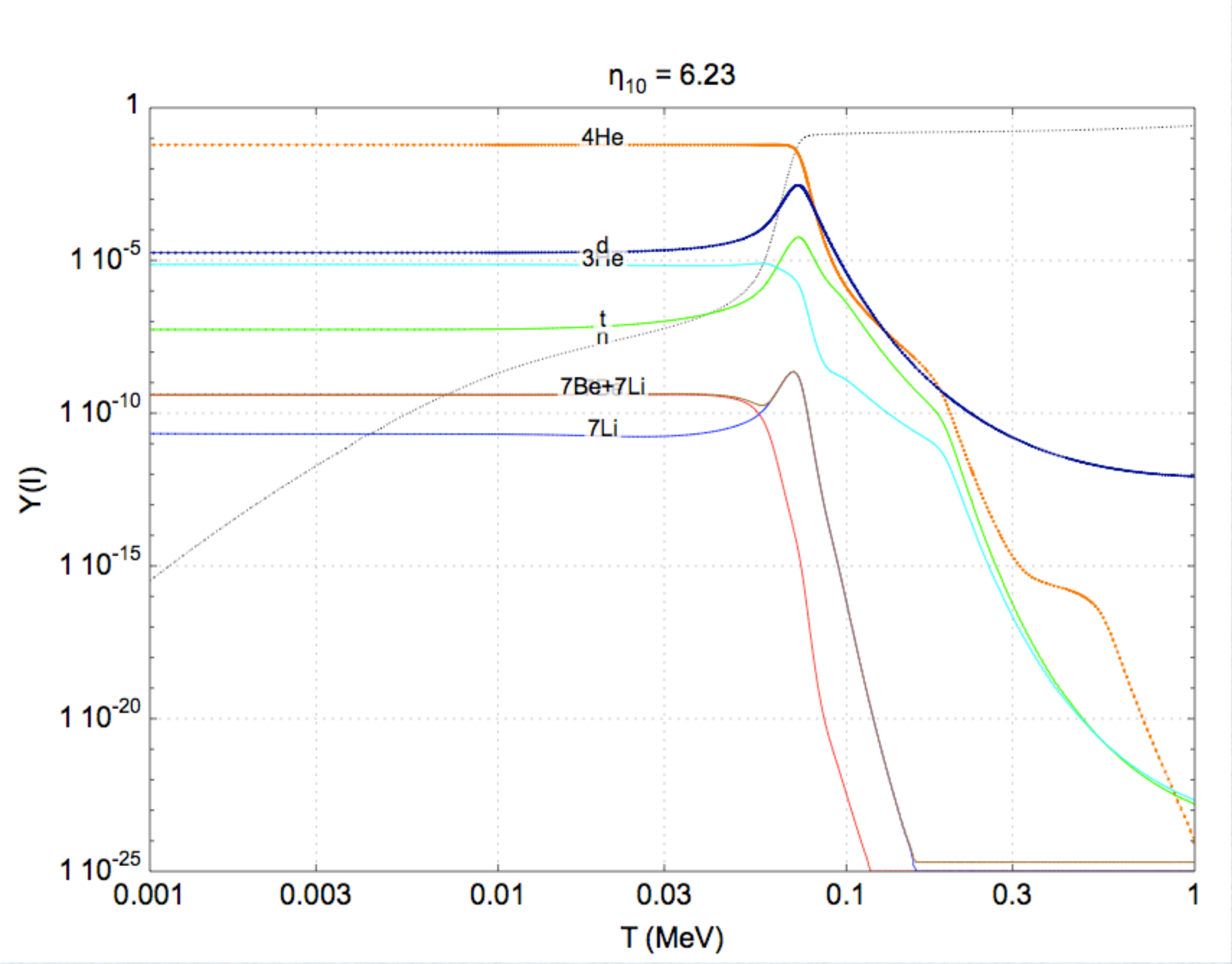
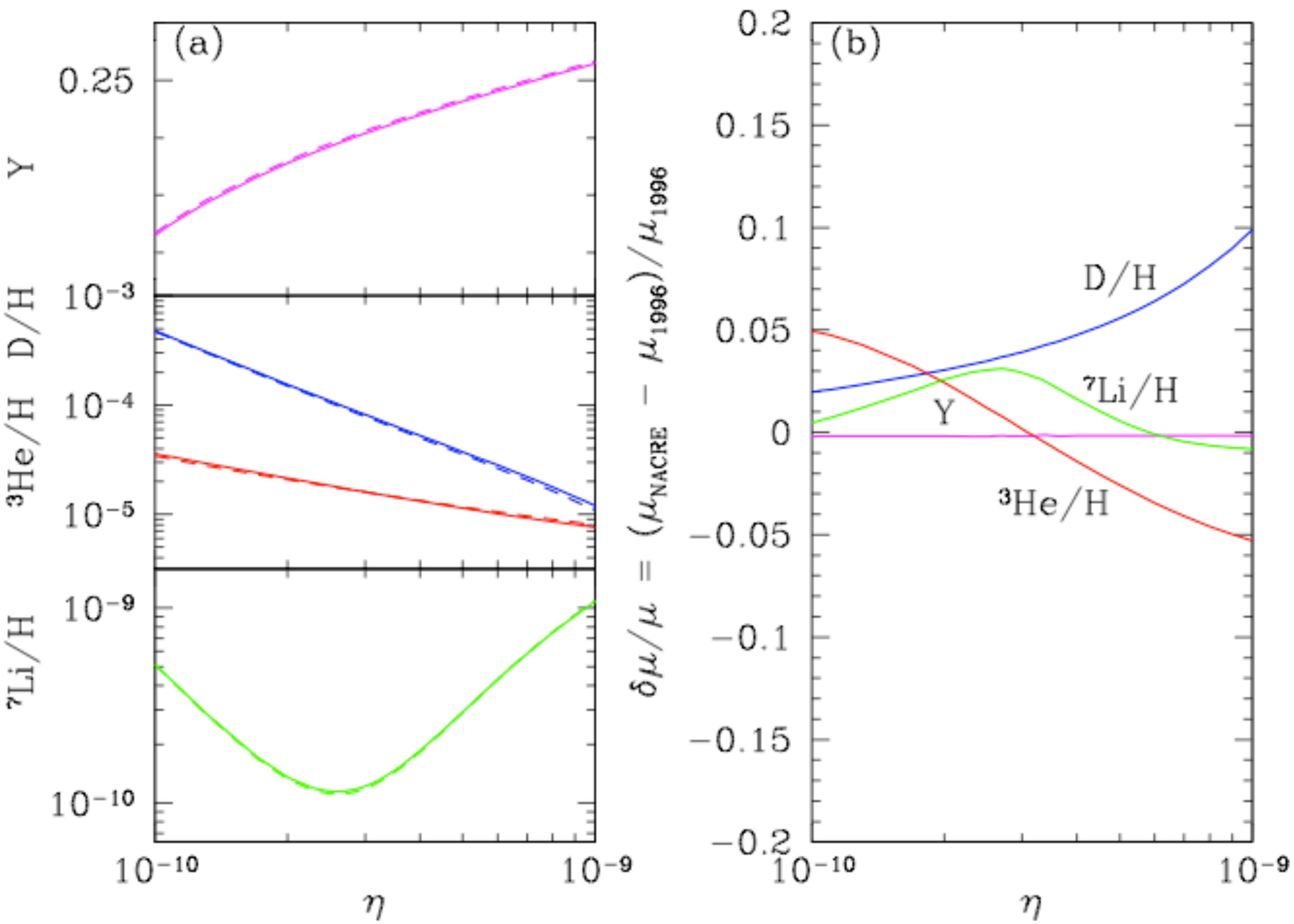
History of the elements



t

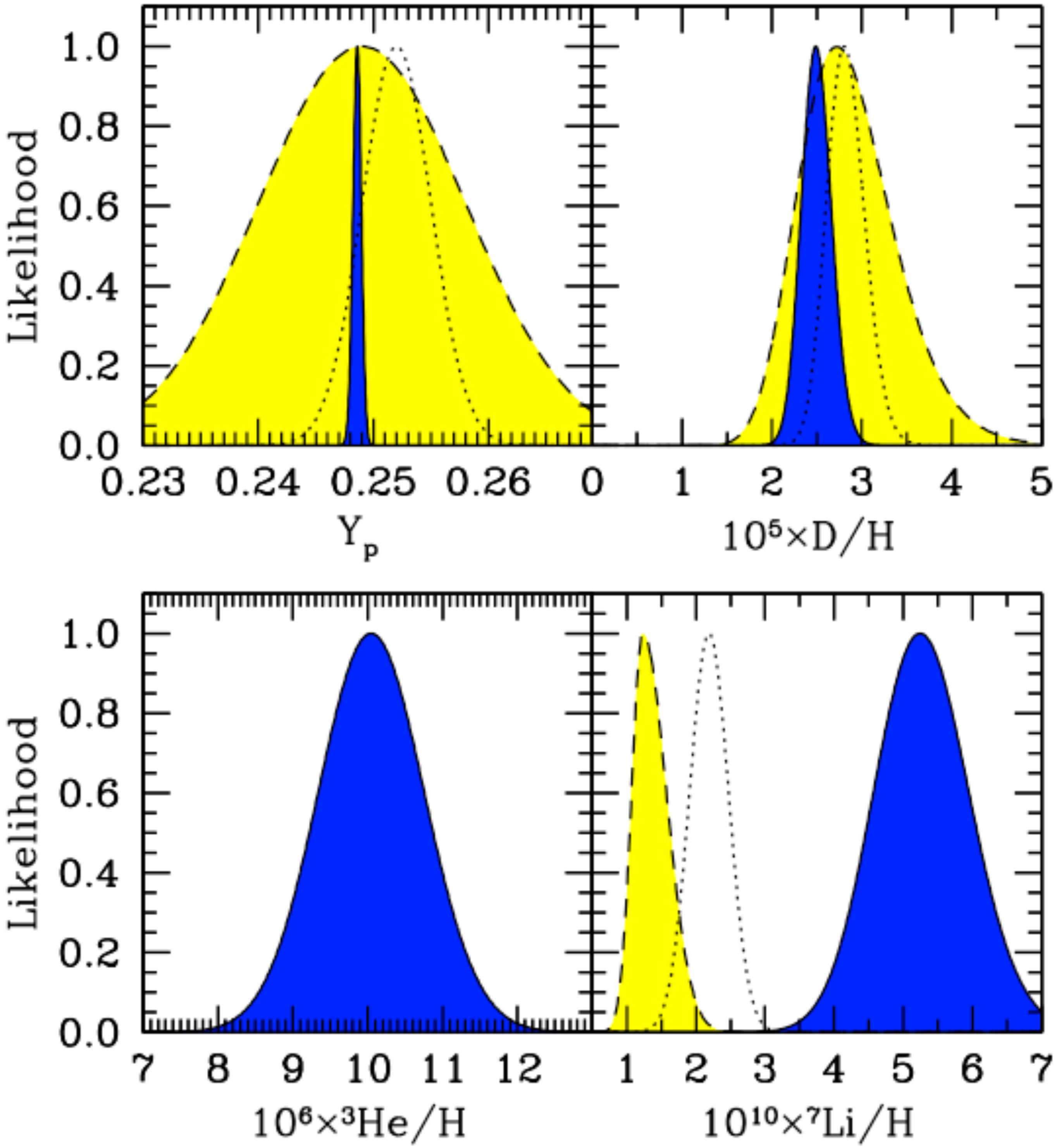
- $t \propto T^{-2}$ Radiation dominated

Effect on abundances



CFO (2008)

Theory vs Observations - The Lithium problem



Observations (yellow)

Observations (dotted line)

Theory (blue)

Cyburt, Fields and Olive, 2008

New physics

- Decays of NLSP => 7Li destruction
- Hadronic showers due to longer lifetime of NLSP
- Formation of bound states reducing Coloumb barrier
- Quark mass variation -> Changes in BE

Lithium Observations

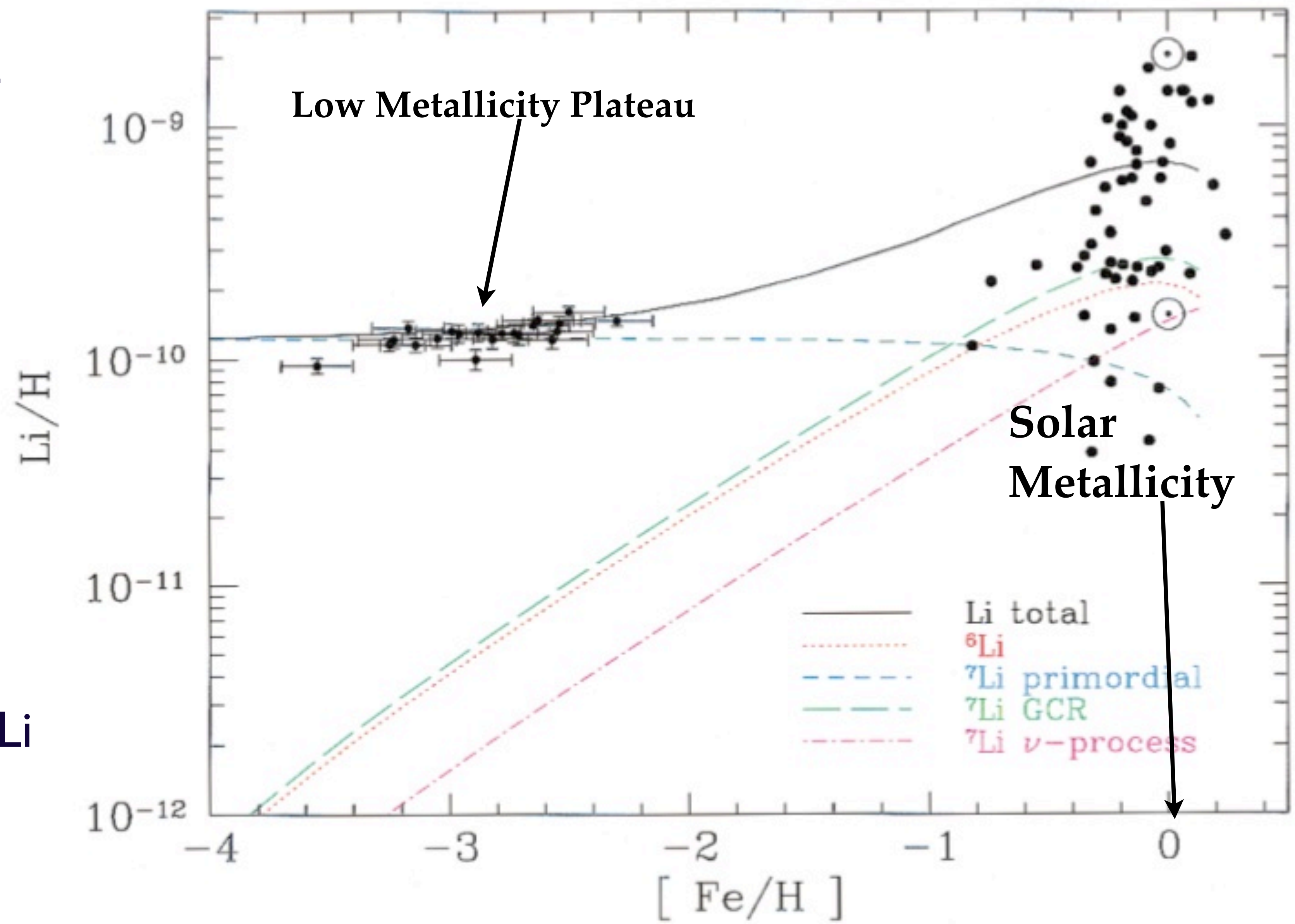
Observed in metal-poor, halo stars (Spite and Spite, 1982 ; Bonifacio and Molaro, 1997 ; Pinsonnealt et al., 1992)

The resonance line at 6707 A° is observed.

Equivalent widths -> primordial abundance

Sources of uncertainty include
1. Galactic chemical evolution of Li
2. Depletion of initial surface abundance
3. Derivation of abundance
4. Stellar scatter

Most promising - Stellar transport (Melendez et al.,2010 and others)



Ryan et al., (2000)

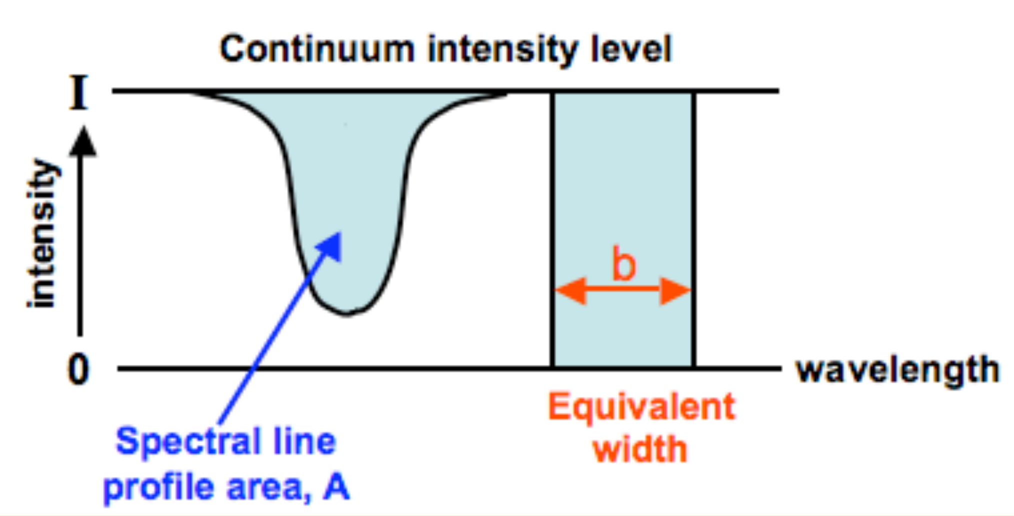
Caveats to Li depletion

- Low metallicities stars -> Lower opacity -> Reduction in Convection -> Harder to convect 7Li to places where T > 2*10^6
- Lithium - Small scatter, within error bars
- There is 6Li which is much more fragile

Equivalent width

- The shape of an absorption line depends on the number of photons that are absorbed at a particular wavelength. In order to compare the strengths of different absorption lines from a source, or the same absorption line from several different sources, we can use the equivalent width.
- To obtain the equivalent width, first we measure the area, A, of the spectral line below the continuum intensity level, as shown in the diagram below:
- The area, A, of a spectral line measured below the continuum level is related to a rectangular line profile with the same area, and equivalent width, b.
- We then replace the spectral line profile by a rectangle with the same area such that

where *I* is the intensity level of the continuum and *b* is the equivalent width of the absorption line.



Solar Abundances

Rank	Name	Z	N	A	Abundance (Si = 10^6)	Fractional Abundances	Mass Fraction
1	^{1}H	1	0	1	2.79E+10	9.098126E-01	7.057277E-01
2	^{2}H	1	1	2	9.49E+05	3.094667E-05	4.800972E-05
3	^{3}He	2	1	3	3.86E+05	1.258737E-05	2.92915E-05
4	^{4}He	2	2	4	2.72E+09	8.869858E-02	2.752085E-01
5	^{6}Li	3	3	6	4.28E+00	1.395698E-10	6.495731E-10
6	^{7}Li	3	4	7	5.282E+01	1.722448E-09	9.352537E-09
7	^{9}Be	4	5	9	7.3E-01	2.380513E-11	1.661875E-10
8	^{10}B	5	5	10	4.22E+00	1.376132E-10	1.067445E-09
9	^{11}B	5	6	11	1.698E+01	5.537139E-10	4.724582E-09
10	^{12}C	6	6	12	9.99E+06	3.257716E-04	3.032353E-03
11	^{13}C	6	7	13	1.11E+05	3.619685E-06	3.650054E-05
12	^{14}N	7	7	14	3.12E+06	1.017425E-04	1.104881E-03
13	^{15}N	7	8	15	1.15E+04	3.750124E-07	4.36337E-06
14	^{16}O	8	8	16	2.37E+07	7.728516E-04	9.591827E-03