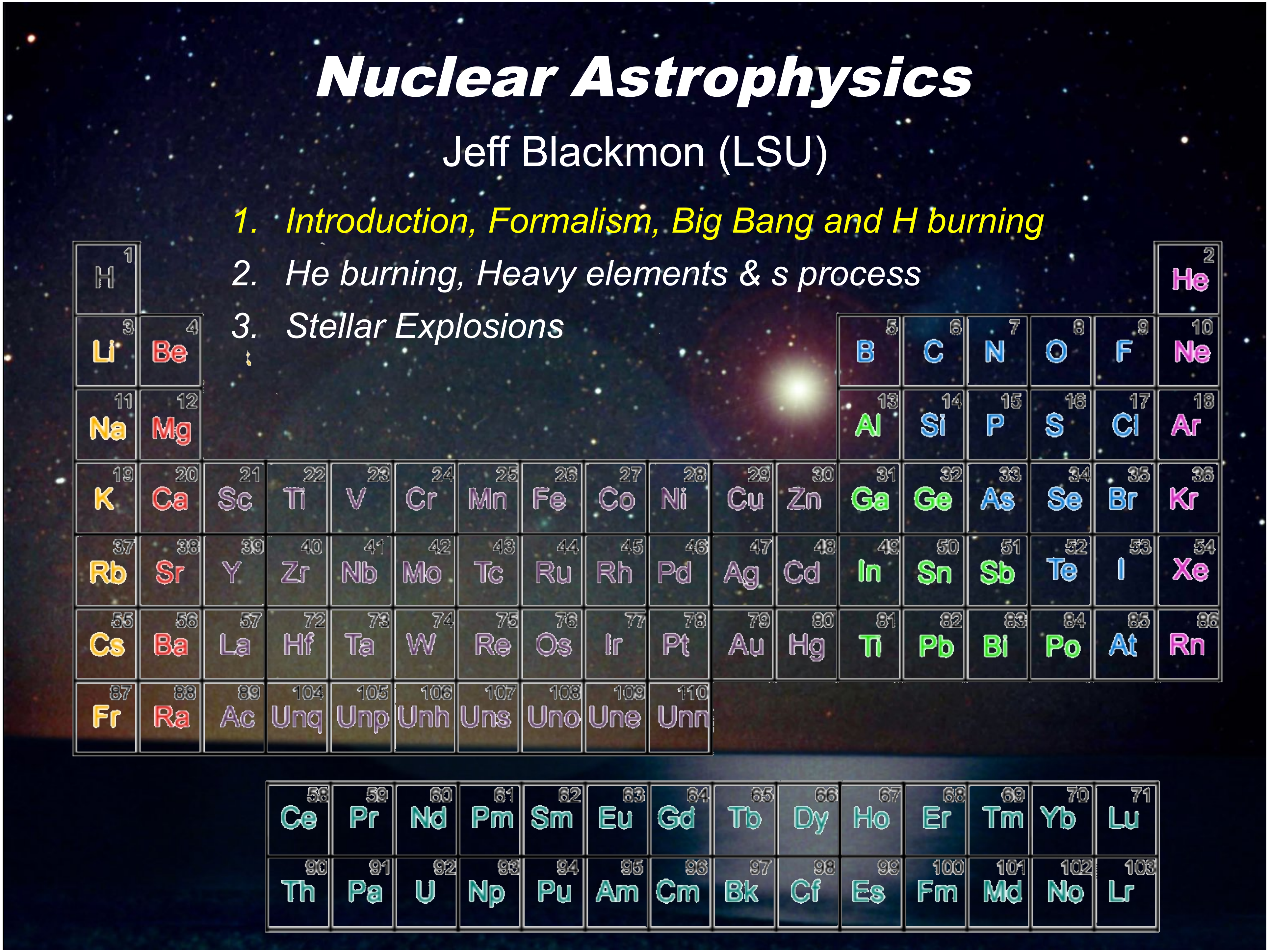
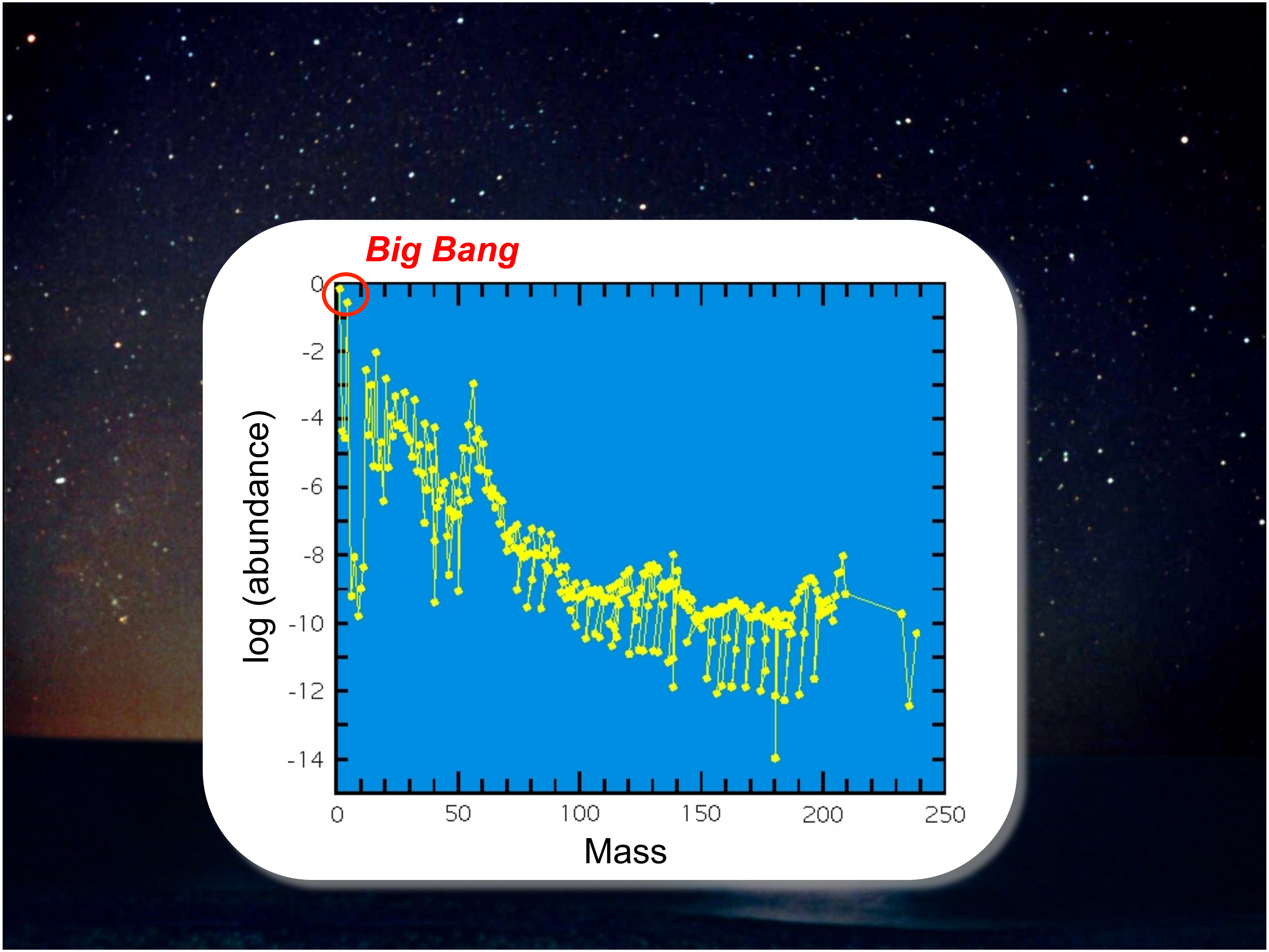


Nuclear Astrophysics

Jeff Blackmon (LSU)

1. *Introduction, Formalism, Big Bang and H burning*
2. *He burning, Heavy elements & s process*
3. *Stellar Explosions*

1 H																	2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba	57 La	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra	89 Ac	104 Unq	105 Unp	106 Unh	107 Uns	108 Uno	109 Une	110 Unn								
			58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu	
			90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr	


Big Bang
0
-2
-4
-6
-8
-10
-12
-14
log (abundance)
0
50
100
150
200
250
Mass

In the beginning. . . .

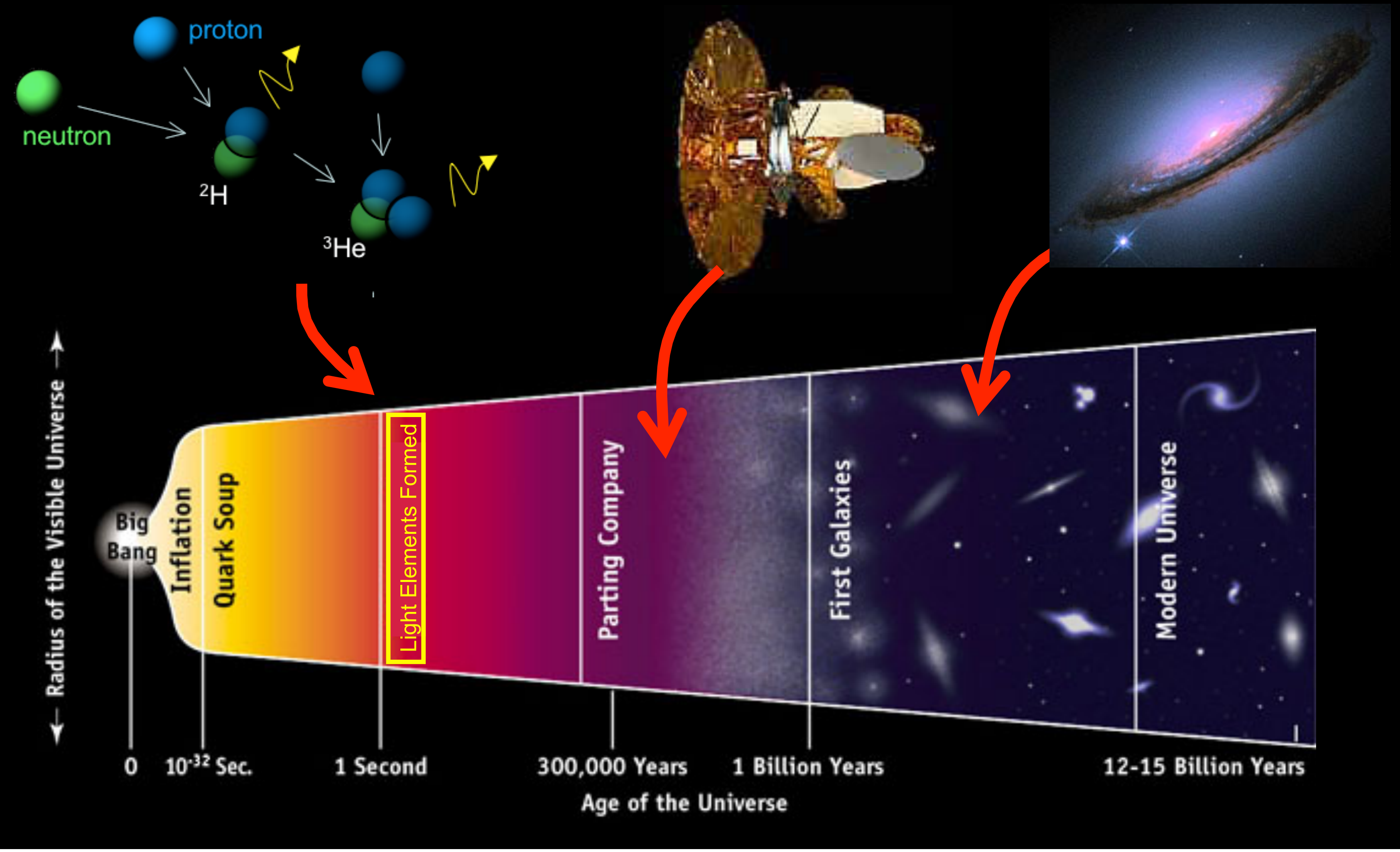
Space, time, matter, & energy began with the Big Bang

Observations in 3 very different epochs probe the Big Bang

Nucleosynthesis

CMB -The afterglow

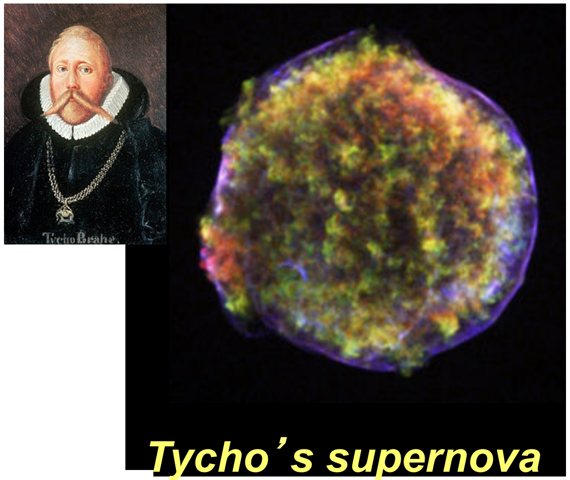
Stellar observations



Optical Observations: Type Ia Supernova

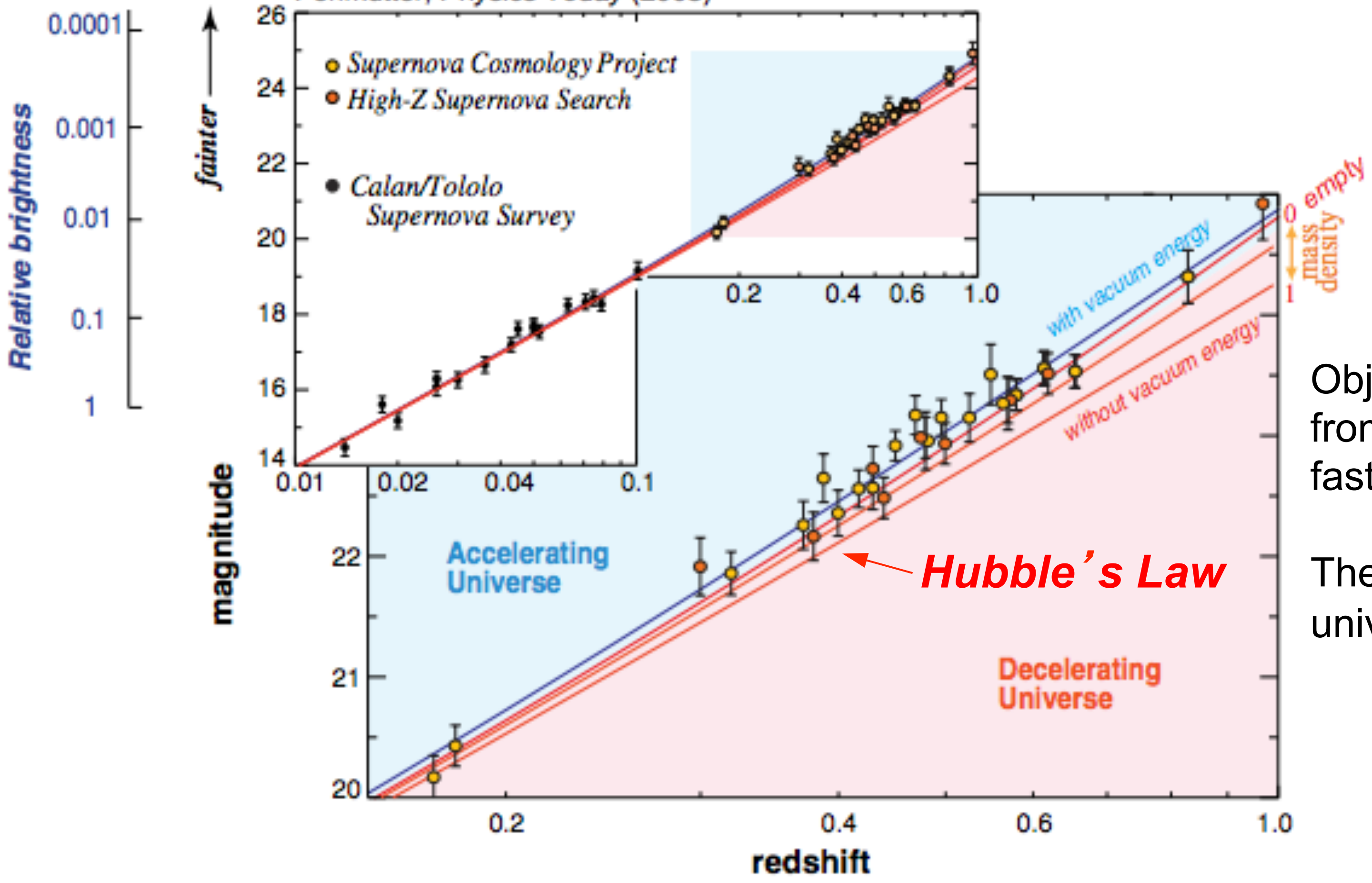
Type Ia: very bright thermonuclear explosions resulting in the total destruction of a star

- Shape of light curve → true brightness
- Observed brightness → distance from earth
- Doppler shift → velocity relative to earth

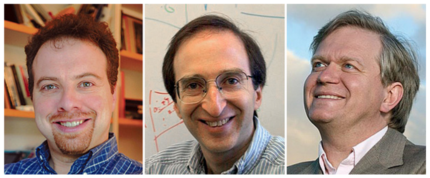


Tycho's supernova

Perlmutter, *Physics Today* (2003)



2011 Nobel Prize

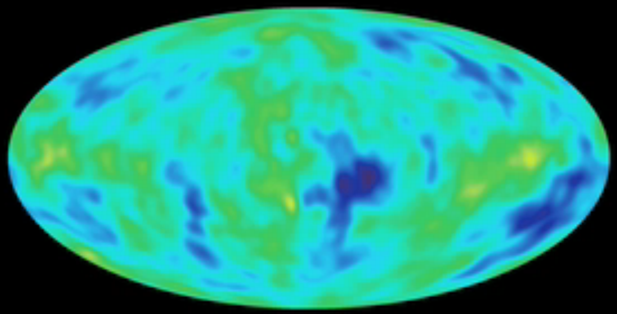


Riess Perlmutter Schmidt

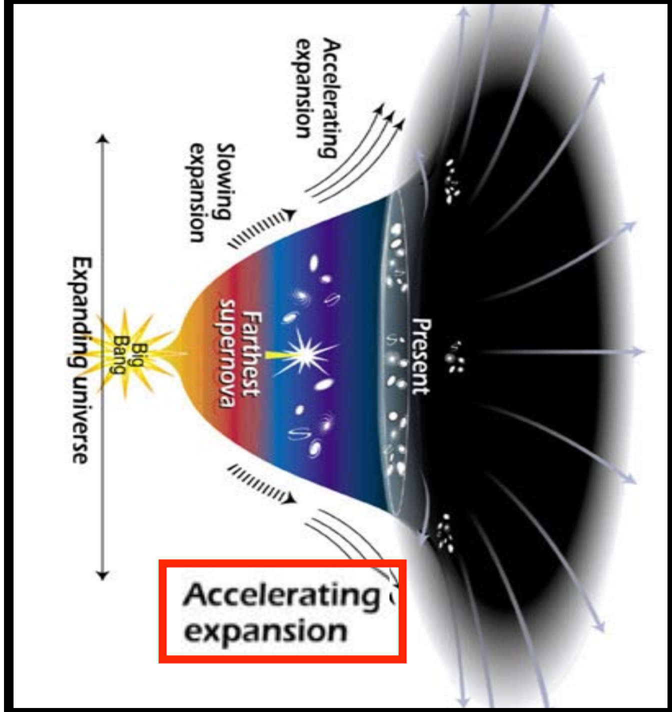
Objects are moving away from earth with velocity faster than Hubble's Law

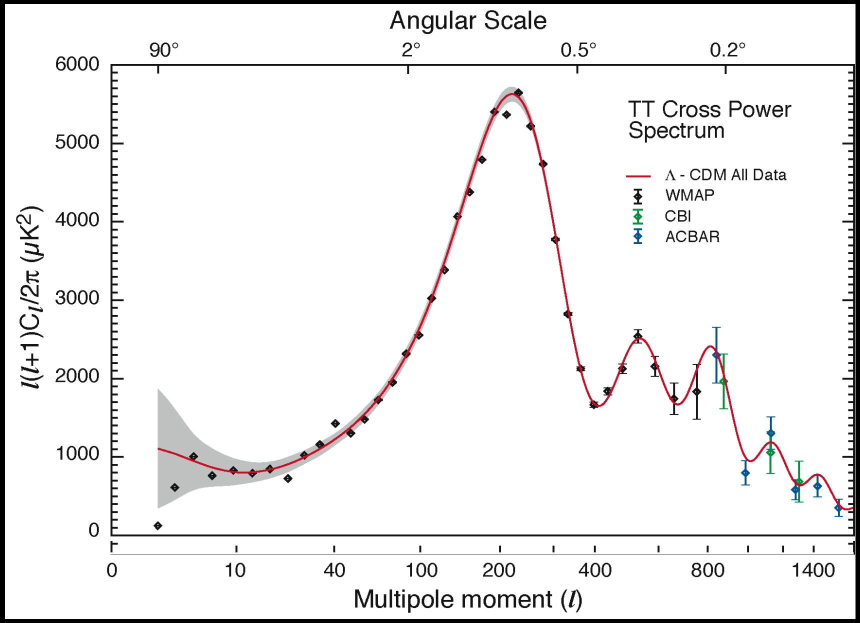
The expansion of the universe is ***accelerating***

Cosmic Microwave Background



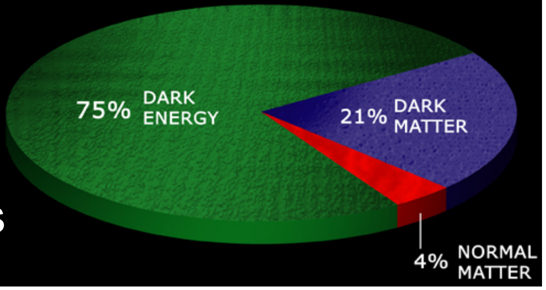
WMAP: CMB Observations
Photons left over from Big Bang
From instant when atoms/molecules form
Matter and energy composition is imprinted on
variations in temperature with position



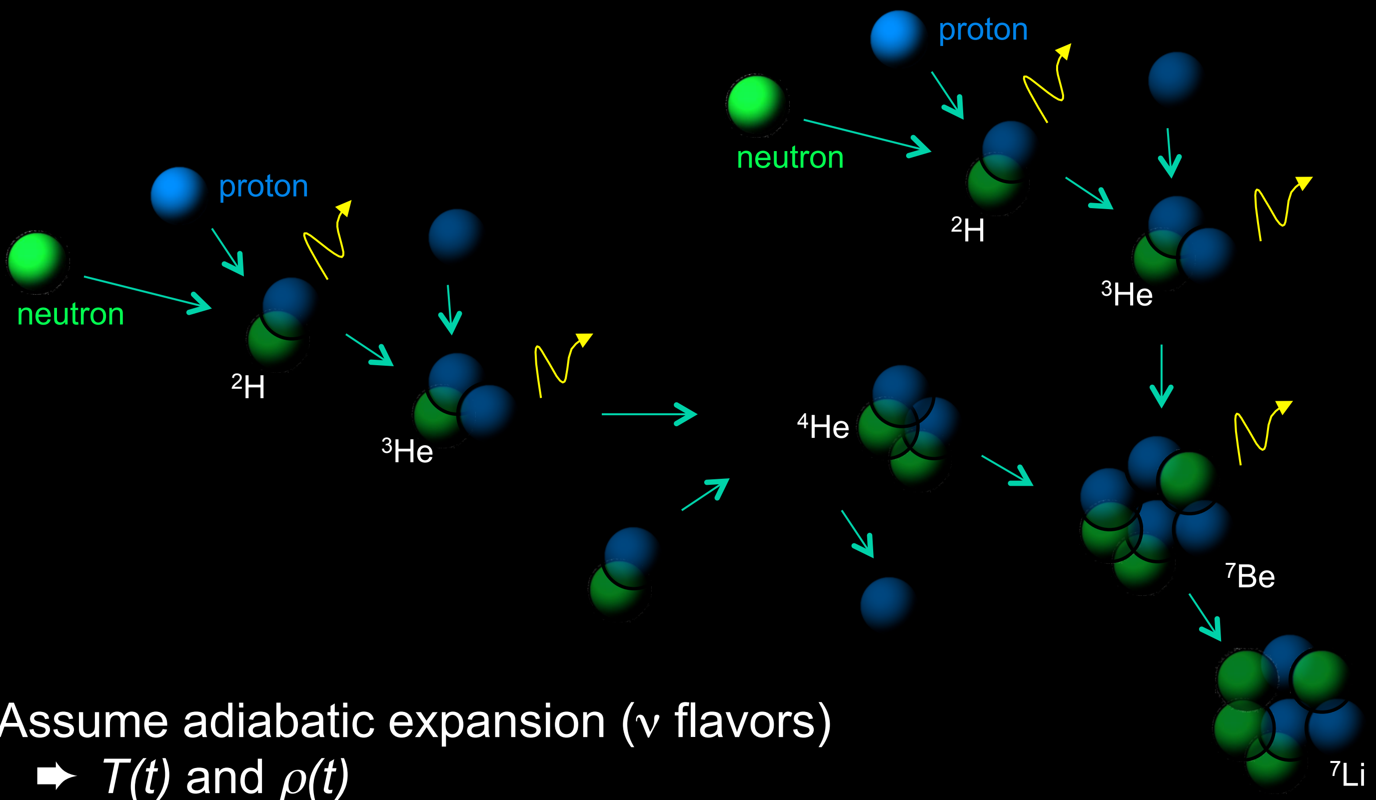


DARK ENERGY (e.g. cosmological constant) exerts a
“negative pressure” causing the acceleration

4.5 ± 0.3% of universe is baryonic → test with nucleosynthesis



The Homogeneous BBN Model



- Assume adiabatic expansion (ν flavors)
  - ➡ $T(t)$ and $\rho(t)$
- n/p ratio set by weak strength (n half-life)
- ***Only*** free parameter is baryon/photon ratio

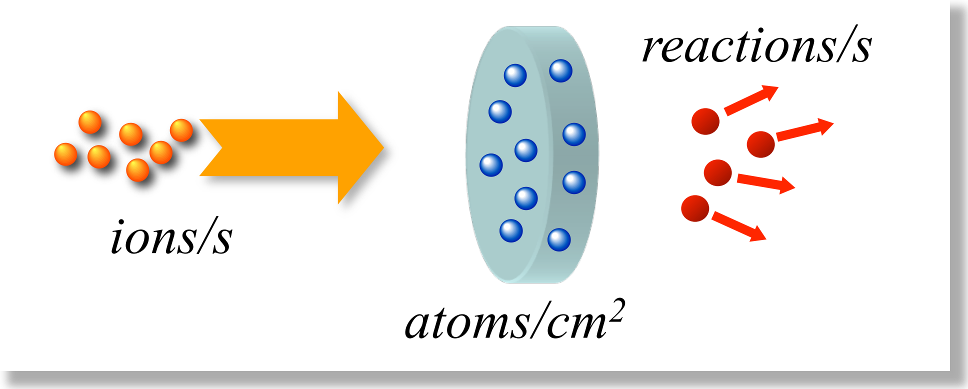
~All free neutrons into ^{4}He
Mass 5 & 8 gaps inhibit formation of heavy elements

➡

p ~75%
^{4}He ~25%
^{2}H,^{3}He ~ 10^{-5}
^{7}Li ~ 10^{-10}

Nuclear reactions in the lab & in space

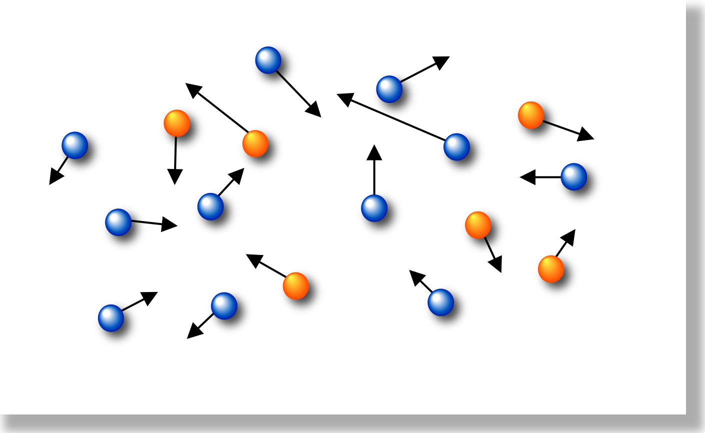
In the lab:



cross section

$$\frac{\text{reactions}}{s} = \frac{\text{ions}}{s}\,\frac{\text{atoms}}{cm^2}\,\sigma$$

In astrophysical events:



reaction rate

$$\frac{\text{reactions}}{cm^3 s} = \int \frac{n_x}{cm^3}\,\frac{n_y}{cm^3}\,v\sigma(v)\phi(v)\,dv$$

$$\phi(v) = 4\pi v^2\left(\frac{\mu}{2\pi kT}\right)^{3/2}\exp\left(-\frac{\mu v^2}{2kT}\right)$$

$$\frac{\text{reactions}}{cm^3 s} = \frac{n_x}{cm^3}\,\frac{n_y}{cm^3}\langle\sigma v\rangle$$

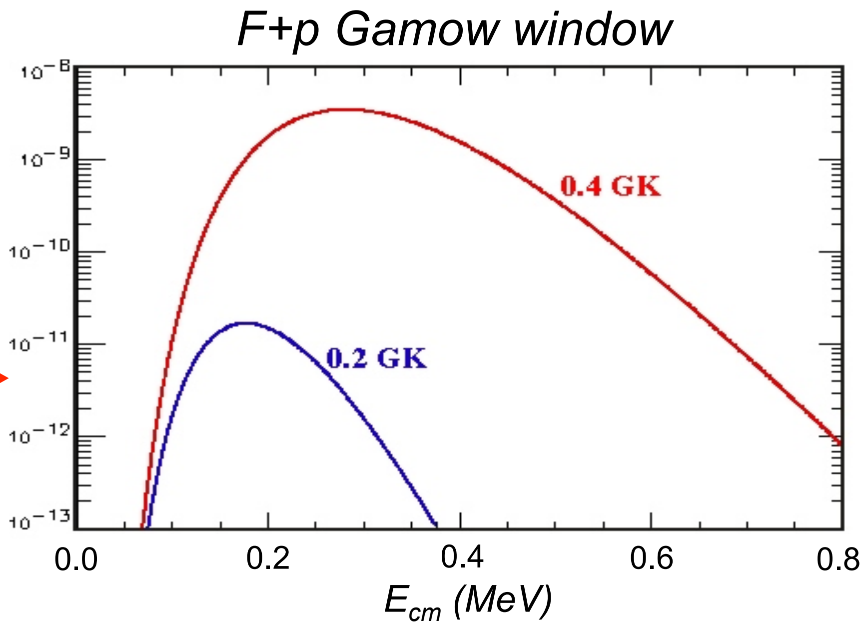
$$\langle\sigma v\rangle = \sqrt{\frac{8}{\pi\mu}}\,(kT)^{3/2}\int_0^\infty \sigma E e^{-E/(kT)}\,dE$$

The Gamow window

$$\langle \sigma v \rangle = \sqrt{\frac{8}{\pi\mu}}(kT)^{3/2}\int_0^\infty \sigma E e^{-E/(kT)}dE$$

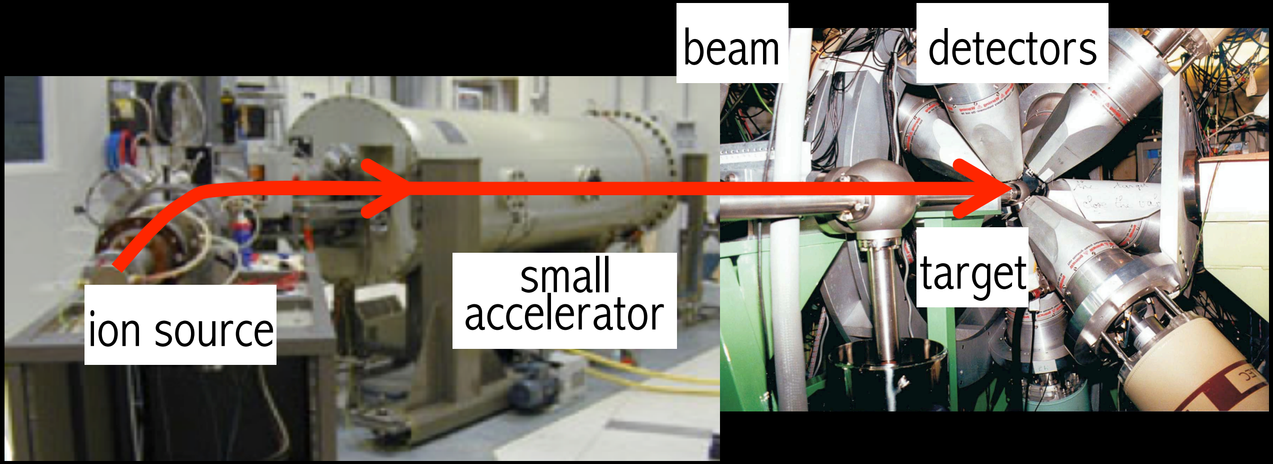
$$\sigma \equiv \frac{S}{E}e^{-\sqrt{E_G/E}} \qquad E_G \equiv \frac{2\mu}{\hbar^2}\left(\pi Z_1 Z_2 e^2\right)^2$$

$$\langle \sigma v \rangle = \sqrt{\frac{8}{\pi\mu}}(kT)^{3/2}\int_0^\infty \overbrace{S e^{-\sqrt{E_G/E}}e^{-E/(kT)}}\,dE$$



Reaction	*site*	*T* (10^6 *K*)	*kT (keV)*	r_{turn} *(fm)*	*r (fm)*	E_0 *(keV)*
p+p	sun	15	1.3	1100	2.5	6
p+N	CNO	30	2.6	3900	4.3	42
α+C	red giant	190	16	1060	4.8	300
p+F	nova	300	26	500	4.5	230
α+S	x-ray burst	1000	86	500	5.9	1800
He+He	big bang	2000	***170***	33	3.8	***580***

Direct Laboratory Measurements



Directly measure cross sections in the lab at the lowest possible energies

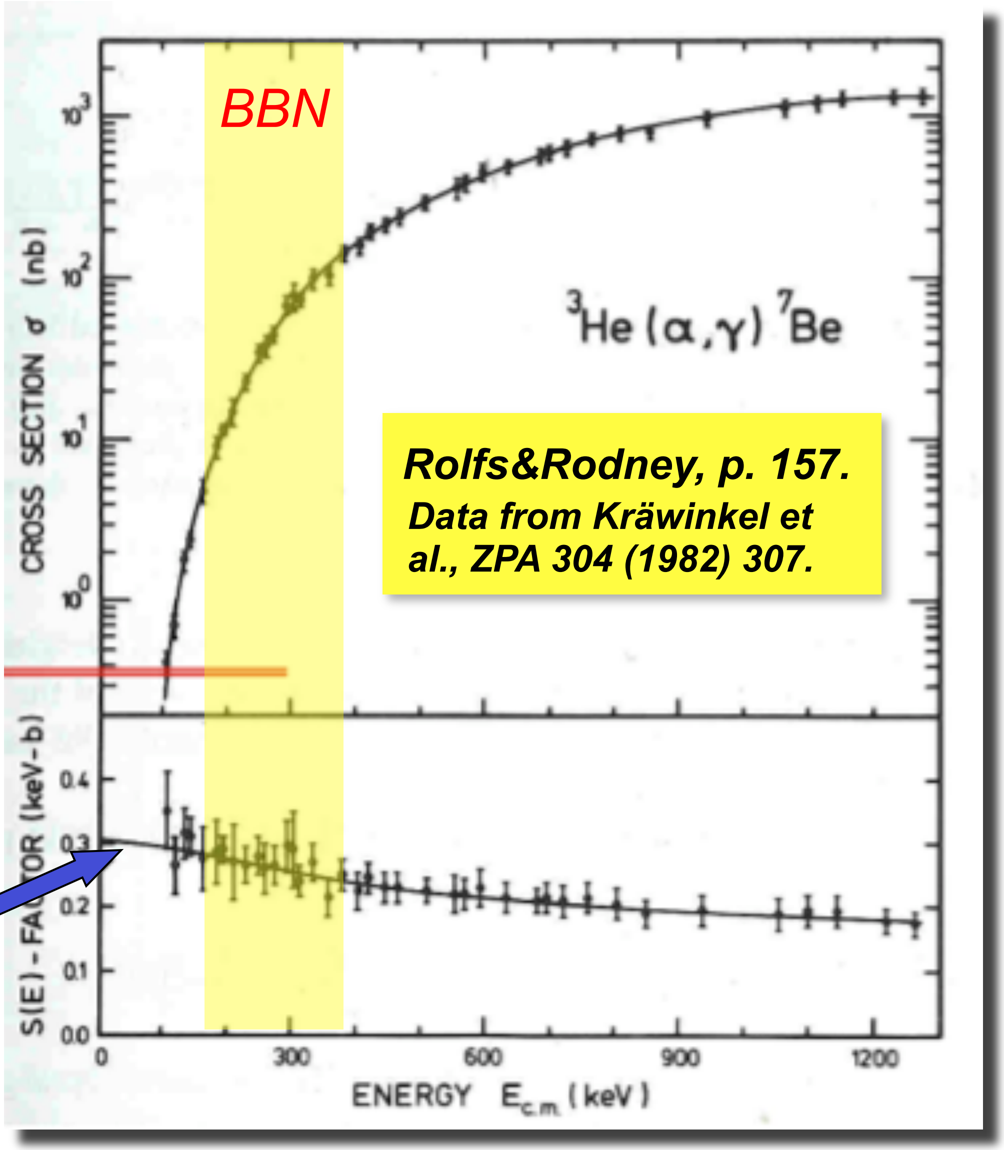
Bombarding energy range ~ 10 keV to ~MeV

High currents (~ mA)
Long run times
Efficient detectors to obtain high statistics
Pure, stable targets
Absolute cross section measurements
    Good normalization & careful control of systematic uncertainties
Background suppression crucial

Textbook example

$$S \equiv \sigma E e^{\sqrt{E_G/E}}$$

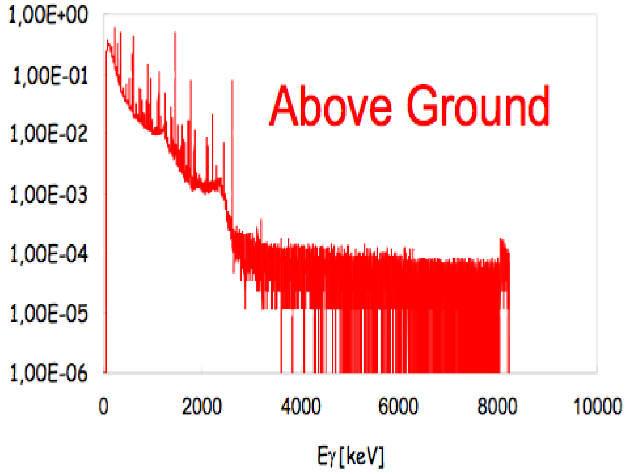
$$E_G \equiv \frac{2\mu}{\hbar^2}\left(\pi Z_1 Z_2 e^2\right)^2$$

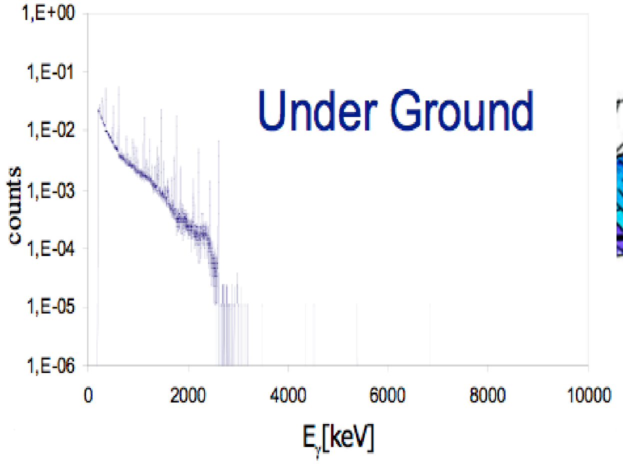


Rolfs&Rodney, p. 157.
Data from Kräwinkel et al., ZPA 304 (1982) 307.

Previous experimental limit

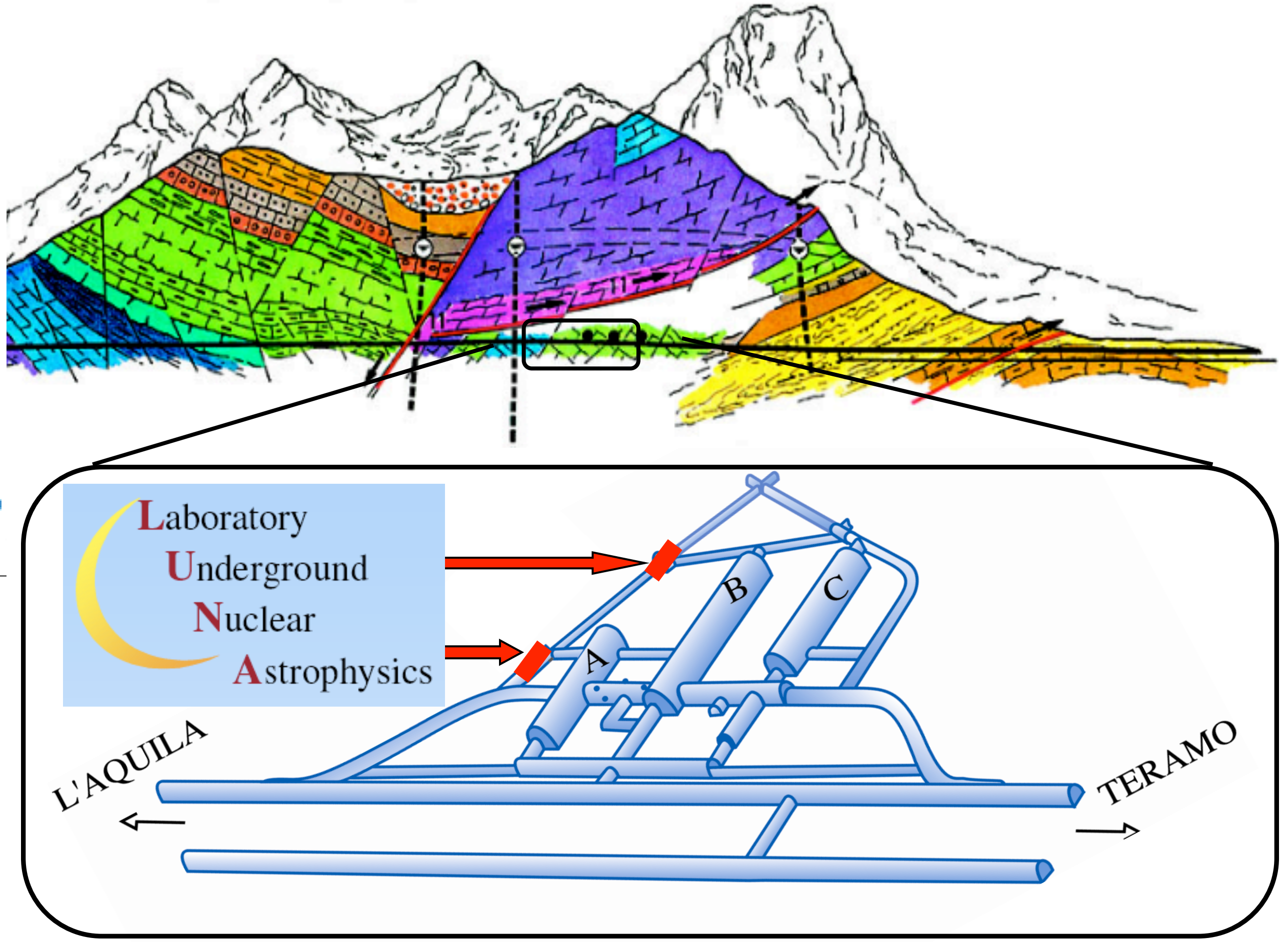
Need σ here for sun





INFN Istituto Nazionale di Fisica Nucleare

Laboratori Nazionali del Gran Sasso



1400 m rock coverage

cosmic μ reduction= 10^{-6}

muon rate ~ 1 (/m^2 h)

$^3He(\alpha,\gamma)^7Be$

Laboratory
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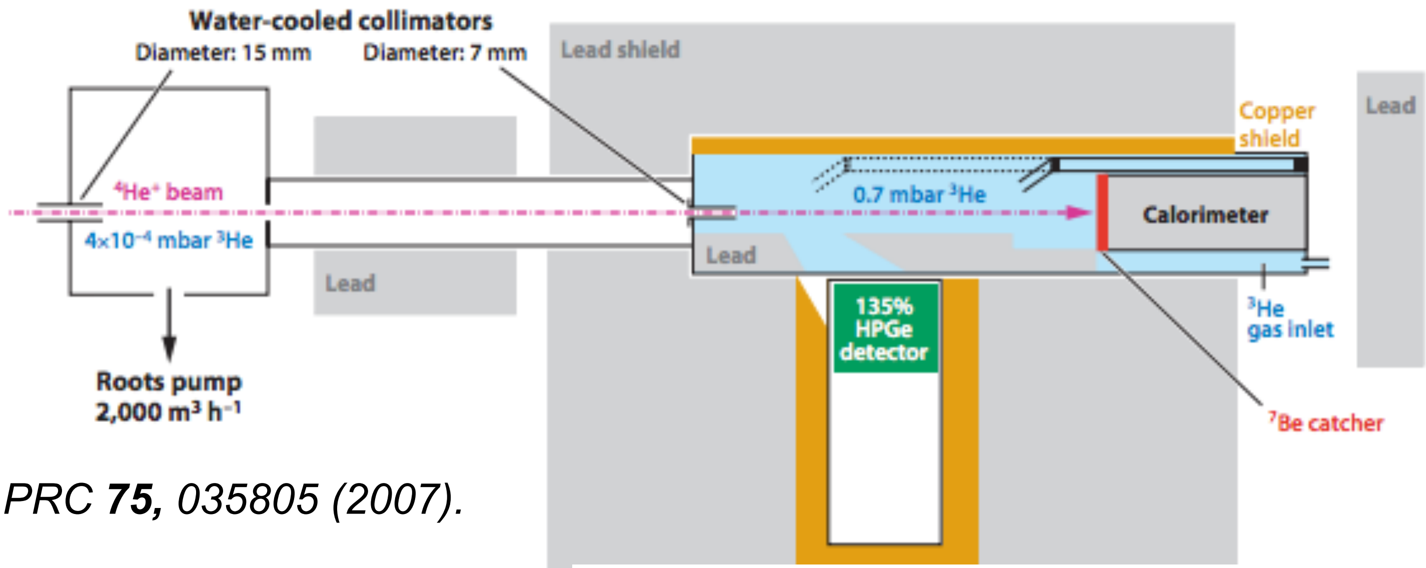
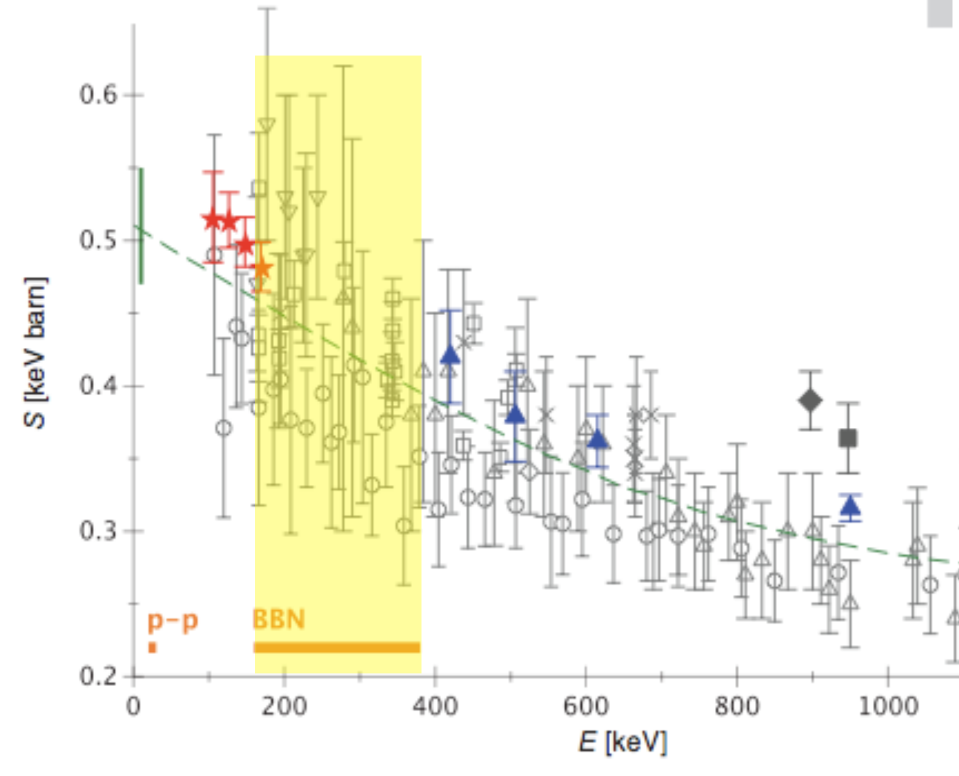
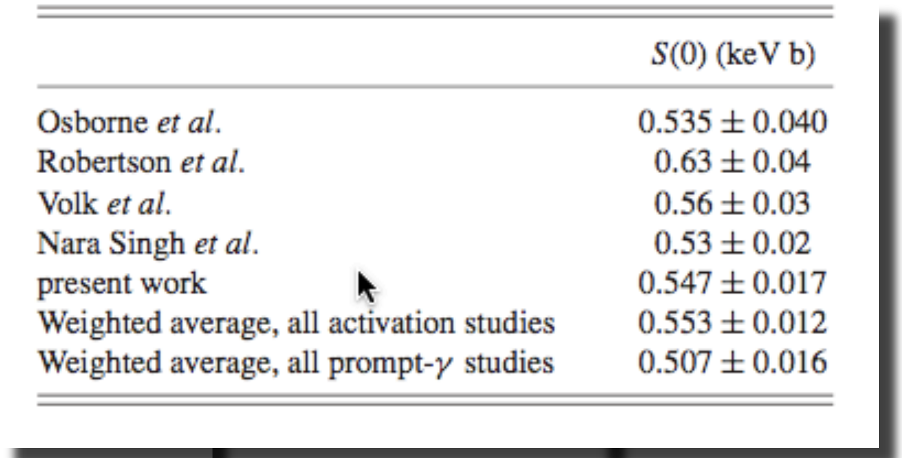


*Gyürky et al., PRC **75,** 035805 (2007).*

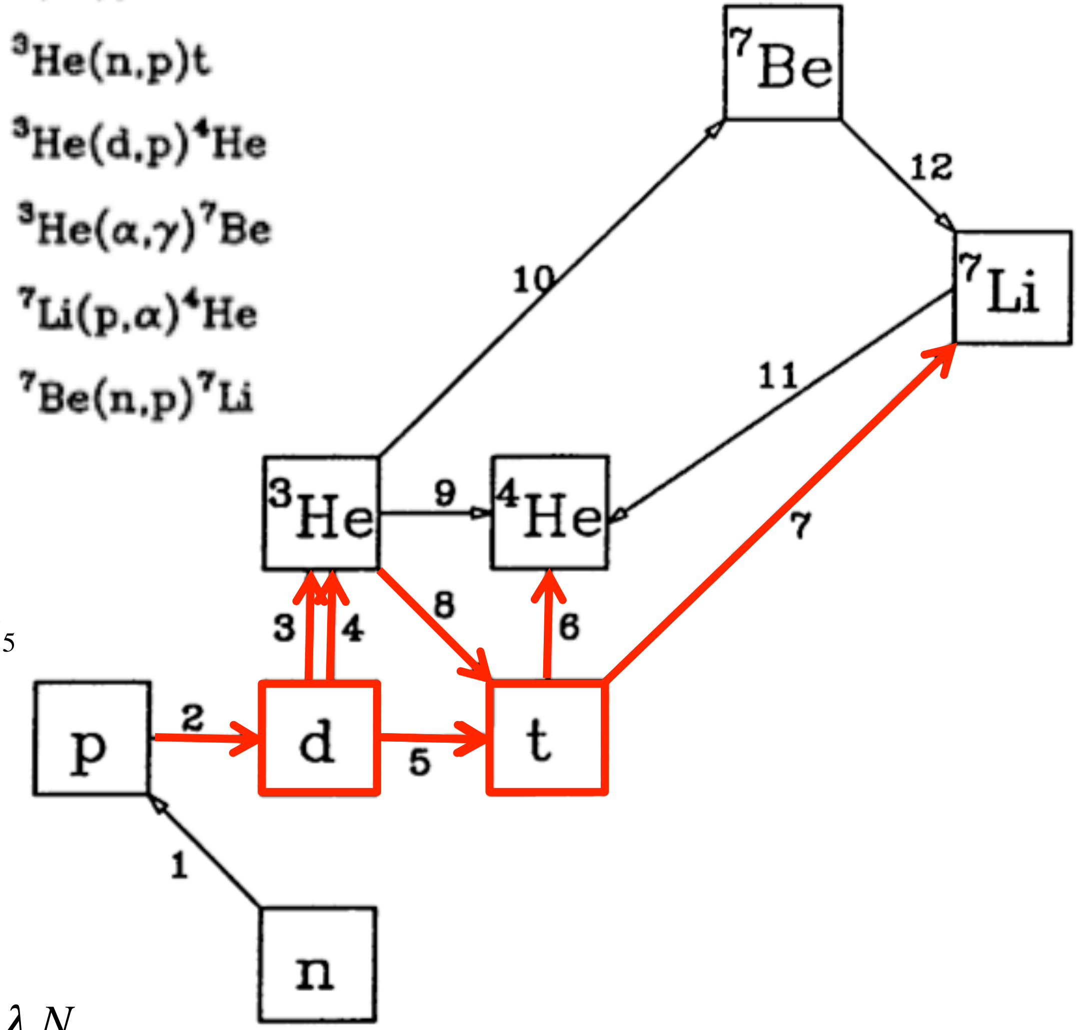




	$S(0)$ (keV b)
Osborne *et al.*	0.535 ± 0.040
Robertson *et al.*	0.63 ± 0.04
Volk *et al.*	0.56 ± 0.03
Nara Singh *et al.*	0.53 ± 0.02
present work	0.547 ± 0.017
Weighted average, all activation studies	0.553 ± 0.012
Weighted average, all prompt-γ studies	0.507 ± 0.016

Simple Big Bang Reaction Network

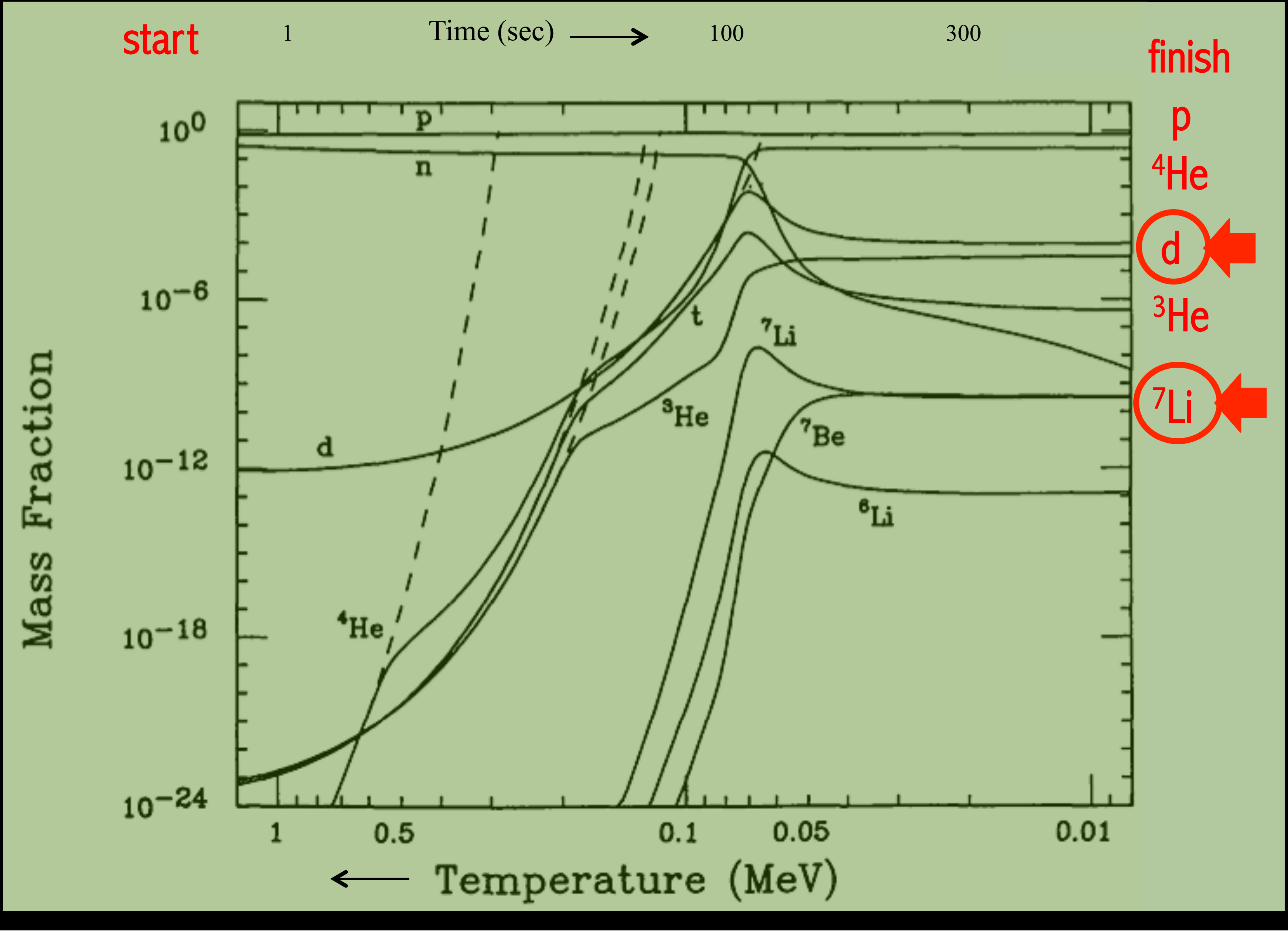
1. n <-> p
2. p(n,γ)d
3. d(p,γ)^{3}He
4. d(d,n)^{3}He
5. d(d,p)t
6. t(d,n)^{4}He
7. t(α,γ)^{7}Li
8. ^{3}He(n,p)t
9. ^{3}He(d,p)^{4}He
10. ^{3}He(α,γ)^{7}Be
11. ^{7}Li(p,α)^{4}He
12. ^{7}Be(n,p)^{7}Li



$$\frac{dN_d}{dt} = N_p N_n \langle \sigma v \rangle_2 - N_d N_p \langle \sigma v \rangle_3 - N_d N_d \langle \sigma v \rangle_4 - N_d N_d \langle \sigma v \rangle_5$$

$$\frac{dN_t}{dt} = N_d N_d \langle \sigma v \rangle_5 + N_{3He} N_n \langle \sigma v \rangle_8 - N_t N_d \langle \sigma v \rangle_6 - N_t N_\alpha \langle \sigma v \rangle_7 - \lambda_t N_t$$

Solve the reaction rate network



start

finish

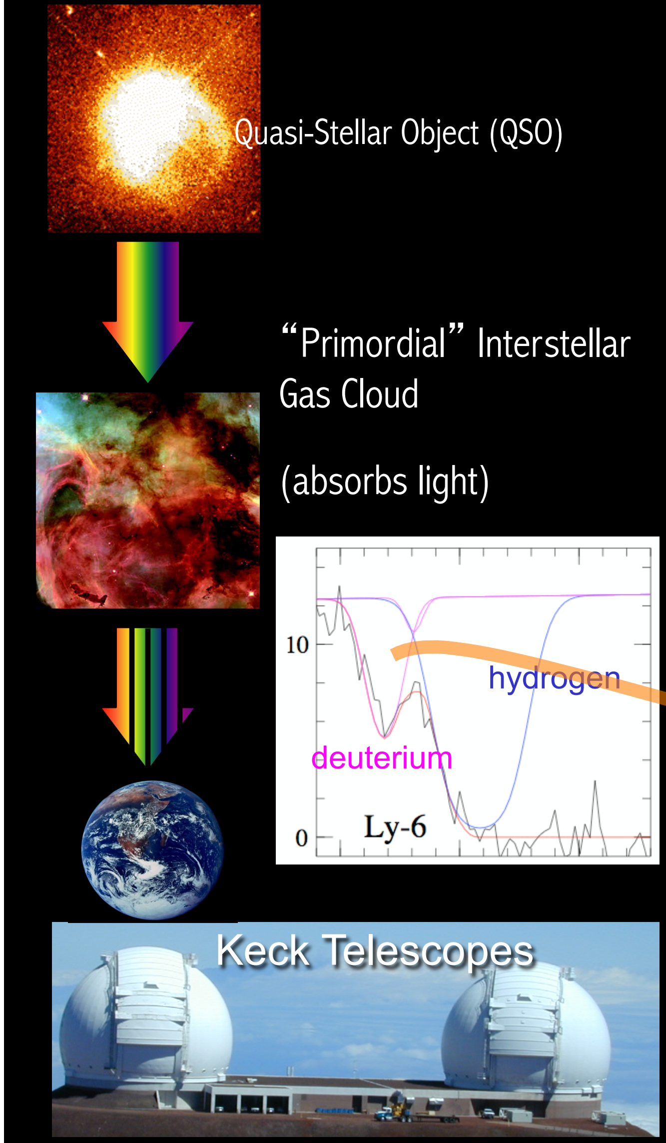
p

^{4}He

d

^{3}He

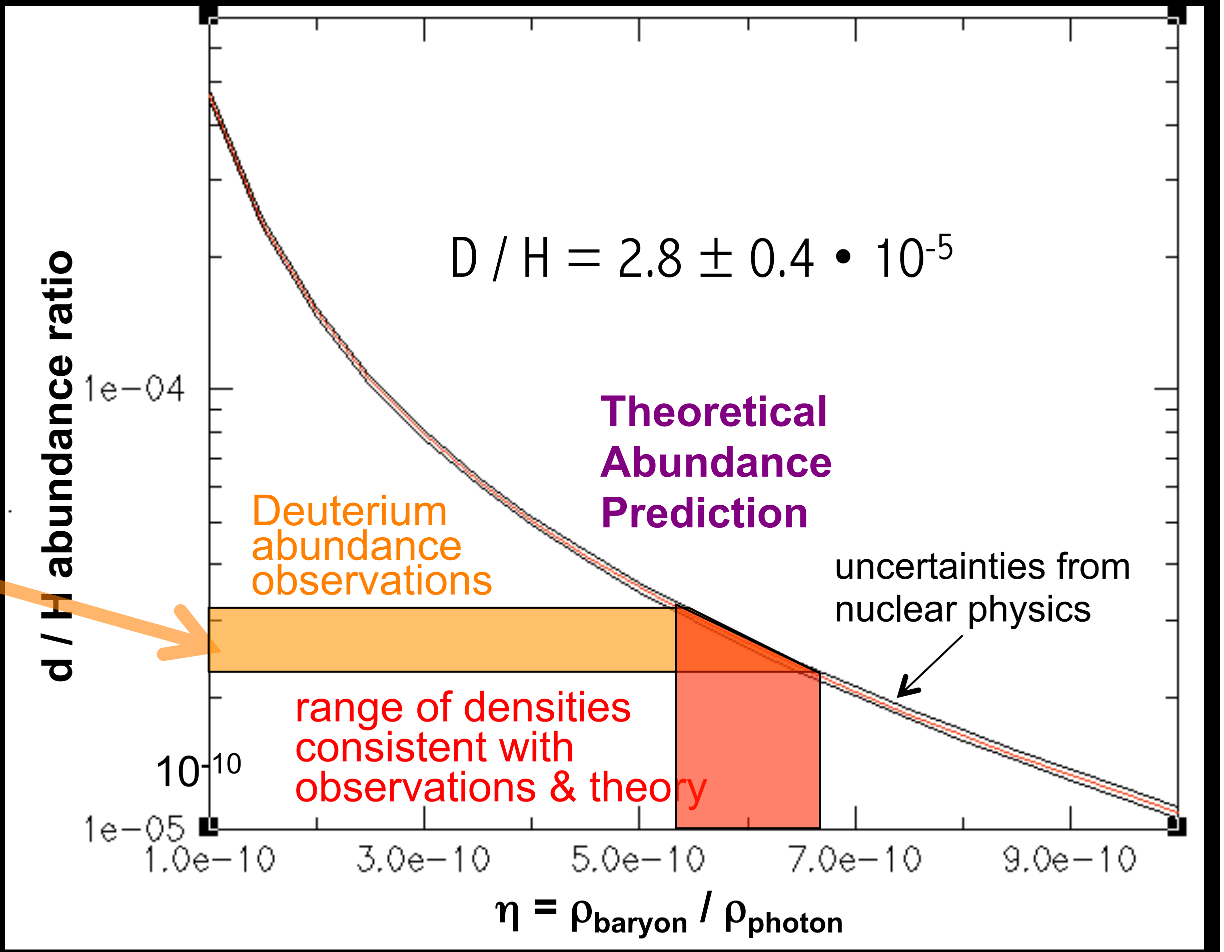
^{7}Li



Quasi-Stellar Object (QSO)

“Primordial” Interstellar Gas Cloud

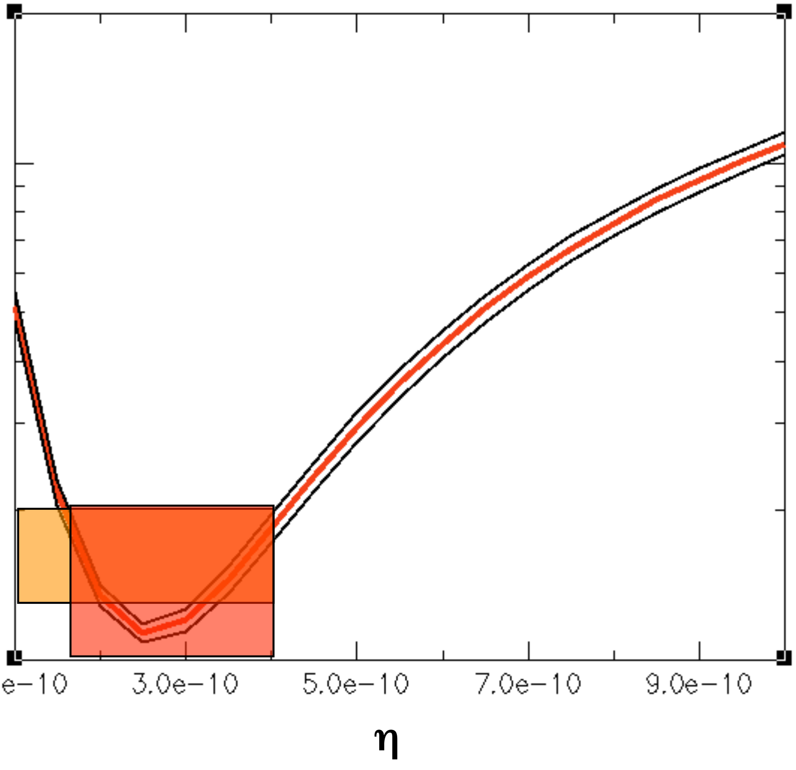
(absorbs light)

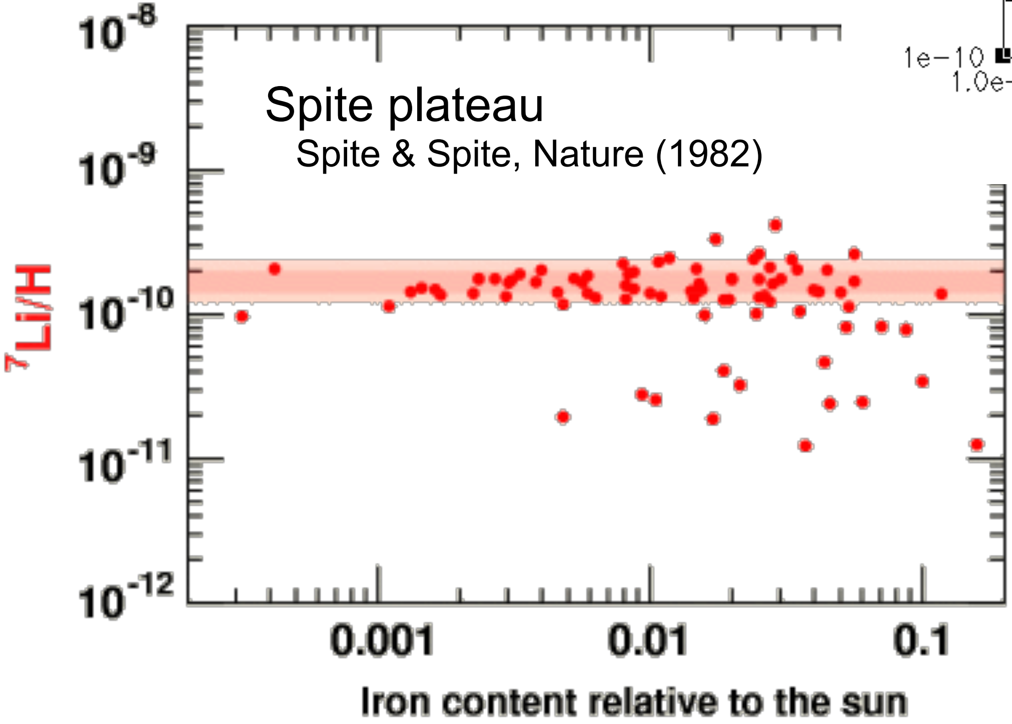


$D / H = 2.8 \pm 0.4 \bullet 10^{-5}$

Abundance Observations can be used to constrain matter density - *the only free parameter* - independent of WMAP

- ^{7}Li production is particularly sensitive to matter density
- Certain low mass stars may preserve the ^{7}Li abudnance they were formed with





Spite plateau

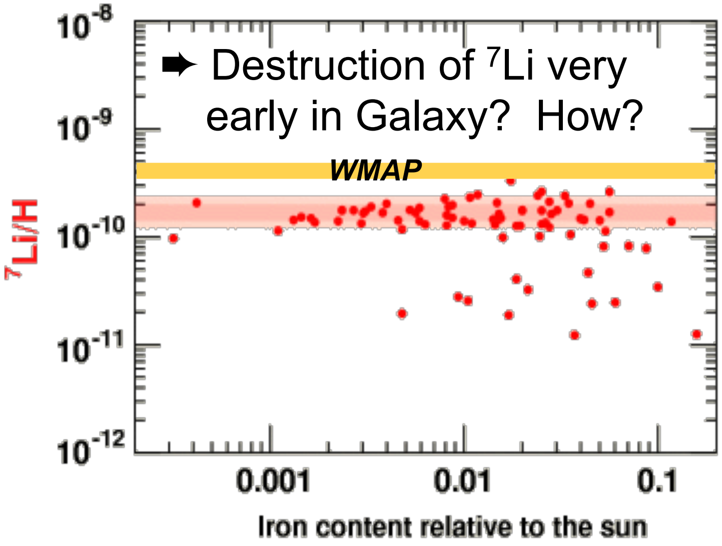
Spite & Spite, Nature (1982)

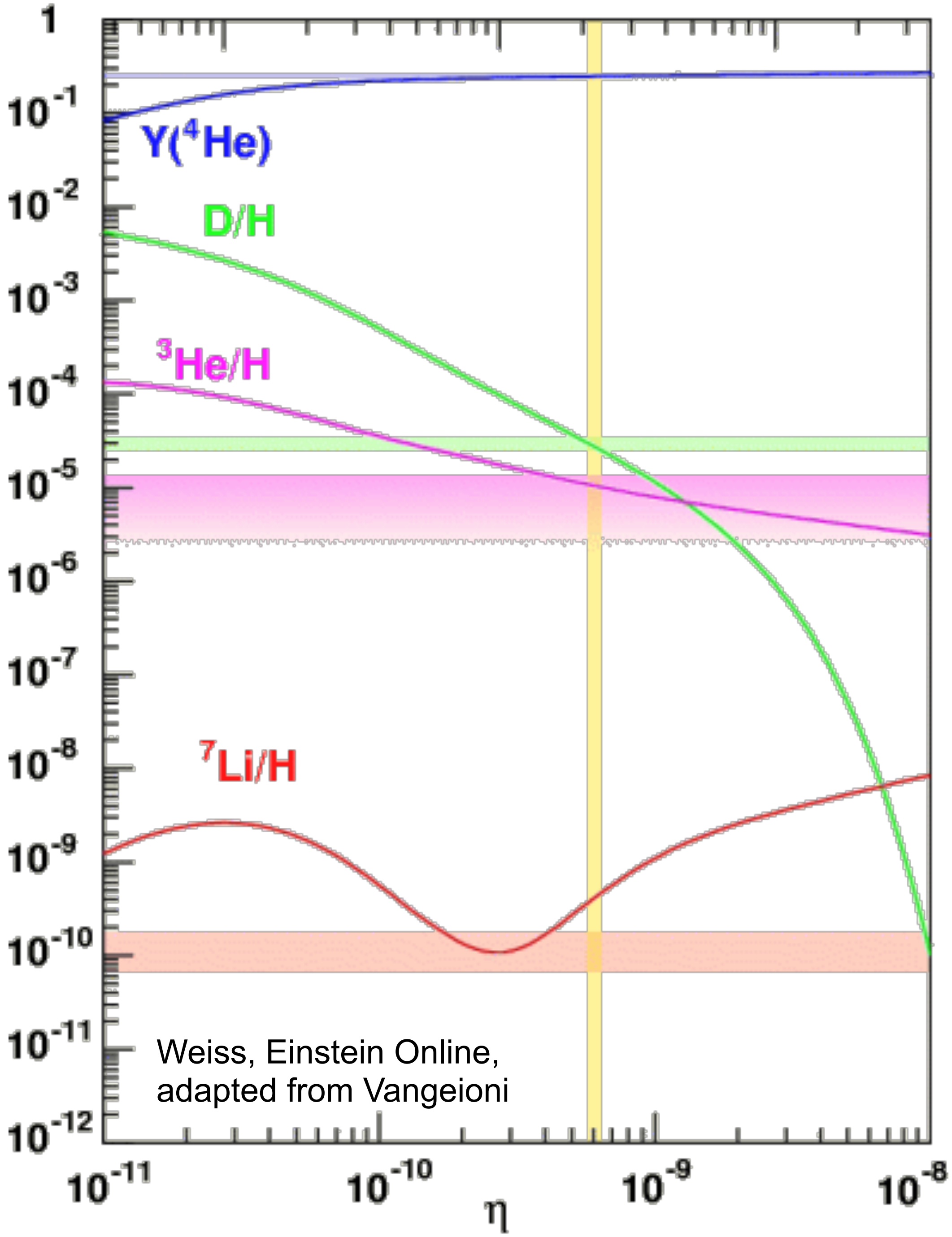
$$^7\text{Li} / \text{H} = 1.\,3 - 2.0 \bullet 10^{-10}$$

- Most abundances agree with BBN calculations using WMAP η
- One problem: ^{7}Li

Cosmological Li problem

- Direct σ measurements have seemingly ruled out any nuclear solution
- Is Spite plateau really reflective of primoridal abundances?


➨ Destruction of ^{7}Li very early in Galaxy? How?


Weiss, Einstein Online, adapted from Vangeioni

Hydrogen burning in stars

Inner 70% of sun's radius is dominated by radiative heat transport

Large T,P gradient

Opacity: photons absorbed and emitted at shorter λ

Hydrostatic equilibrium

$$\frac{dP(r)}{dr} = -\frac{GM_{in}(r)\rho(r)}{r^2}$$

Energy conservation

$$\frac{dL(r)}{dr} = \frac{\varepsilon(r)\rho(r)}{4\pi r^2}$$

Pressure

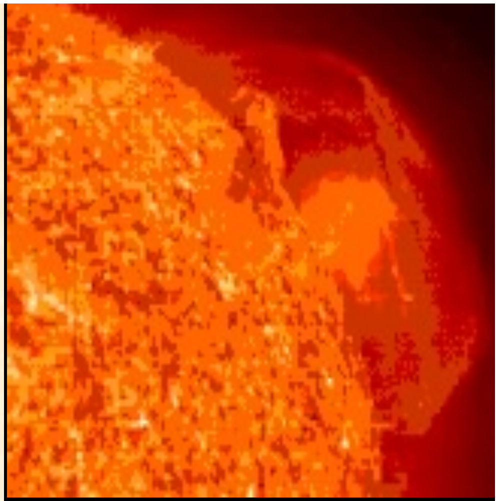
$$P(r) = P_{gas}(r) + P_{rad}(r)$$

For sun (non-degenerate)

$$P_{gas}(r) = \frac{k}{\langle m \rangle}\rho(r)T(r)$$

$$P_{rad}(r) = \frac{1}{3}aT^4(r) << P_{gas}(r)$$

Luminosity/opacity/T relationship ➡ $L \propto M^4$



The sun

M=2x10^{30} kg

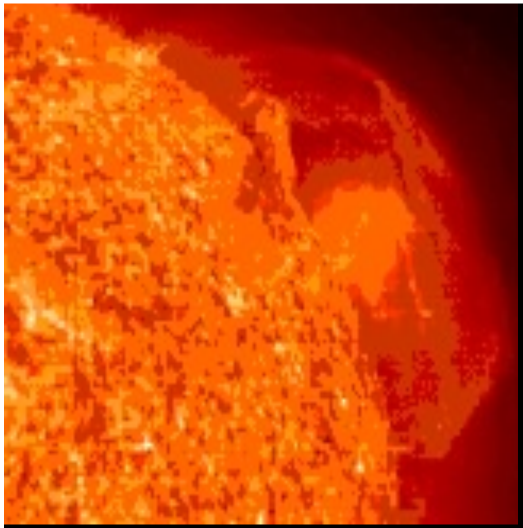
$\rho(0)$=150 g/cm^3

T(0)=1.5x10^7 K

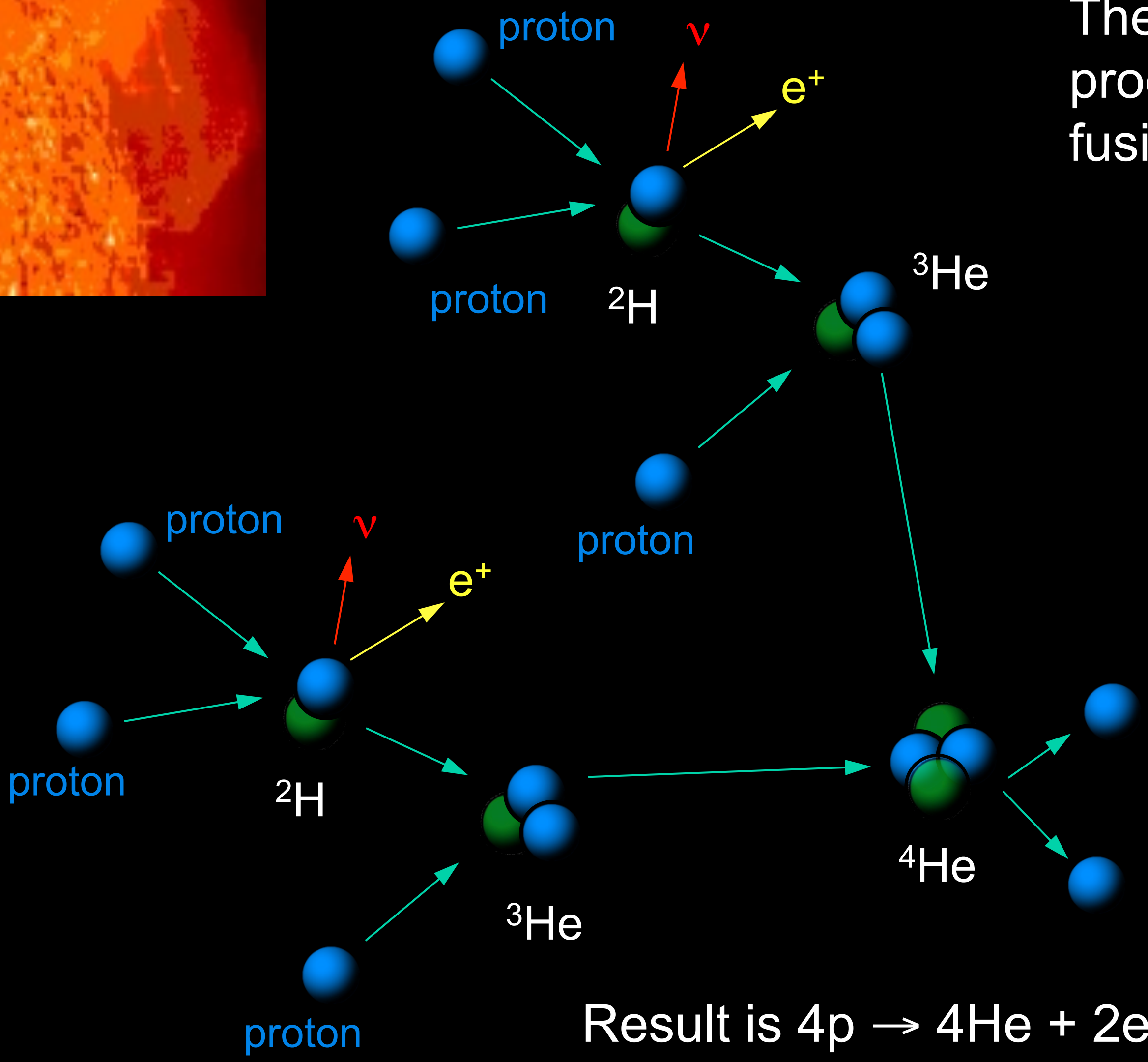
T(surf)=5800 K

L=3.8x10^{26} W

5x10^4 yr for energy produced in sun's core to be reach surface



Solar fusion



The sun's energy is produced by nuclear fusion in its core

T(core)=15 MK

T(surf)=5800 K

Result is $4p \rightarrow 4He + 2e^+ + 2\nu + 27$ MeV

27 MeV = 4×10^{-12} J   * 10^{38} fusions/s = 4×10^{26} Watts

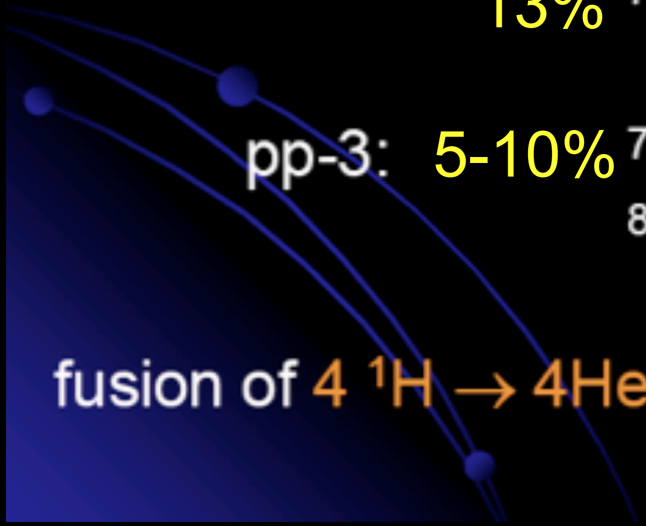
Solar fusion: The pp-chains

Thanks to substantial efforts in experiment, theory & evaluation

pp-1:	5%	$^1H(p,e^+\nu)^2H$	
	5%	$^2H(p,\gamma)^3He$	
	7%	$^3He(^3He,2p)^4He$	84.7%
pp-2:	3%	$^3He(\alpha,\gamma)^7Be$	13.8%
		$^7Be(e^-,\nu)^7Li$	13.78%
	13%	$^7Li(p,\alpha)^4He$	
pp-3:	5-10%	$^7Be(p,\gamma)^8B$	0.02%
		$^8B(\beta^+\nu)2\,^4He$	

Only ν most experiments measure

fusion of $4\ ^1H \rightarrow 4He + 2e^+ + 2\nu_e + 26.7$ MeV energy release



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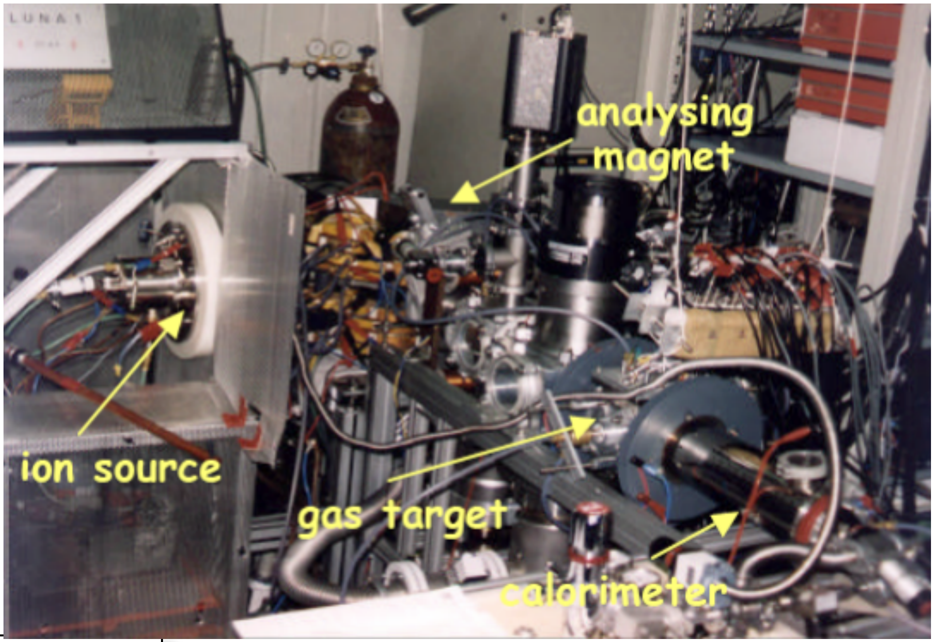
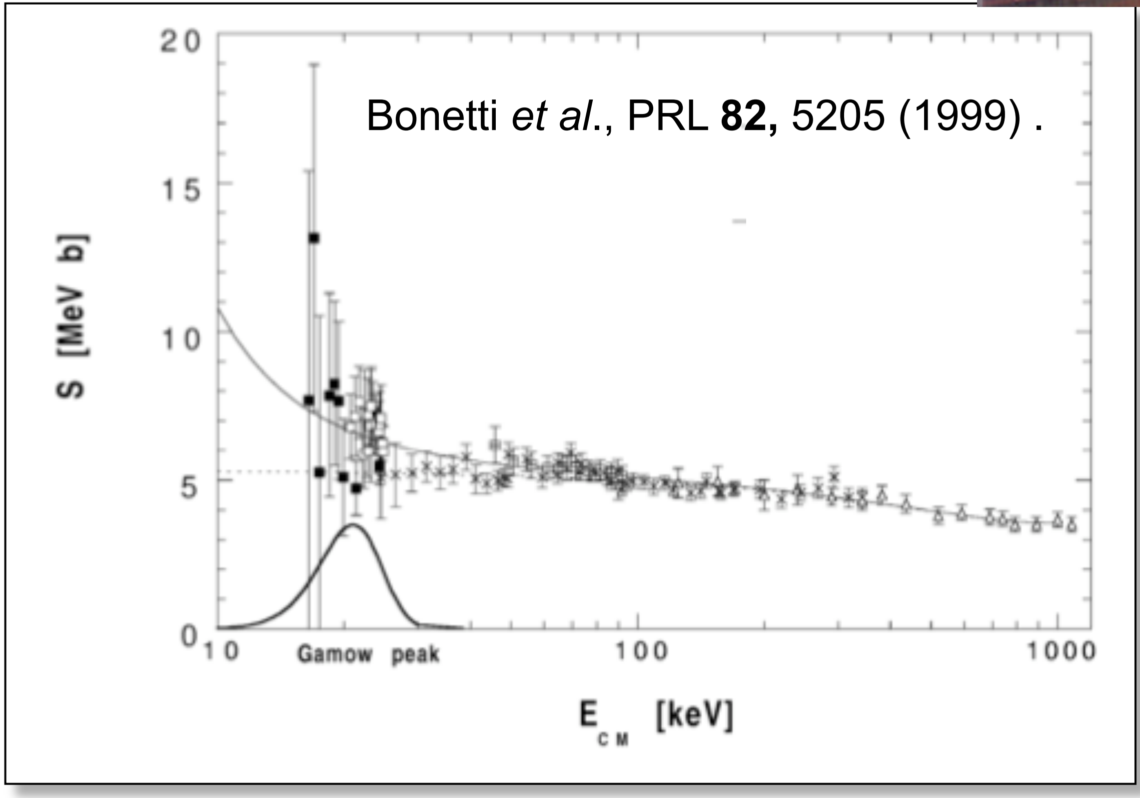
$^3He(^3He,2p)^4He$

- 1999 – First measurement of a pp reaction σ at the ***solar*** Gamow widow
- Somewhat unique situation
  - ➨ 2 protons with $E_p > 6$ MeV

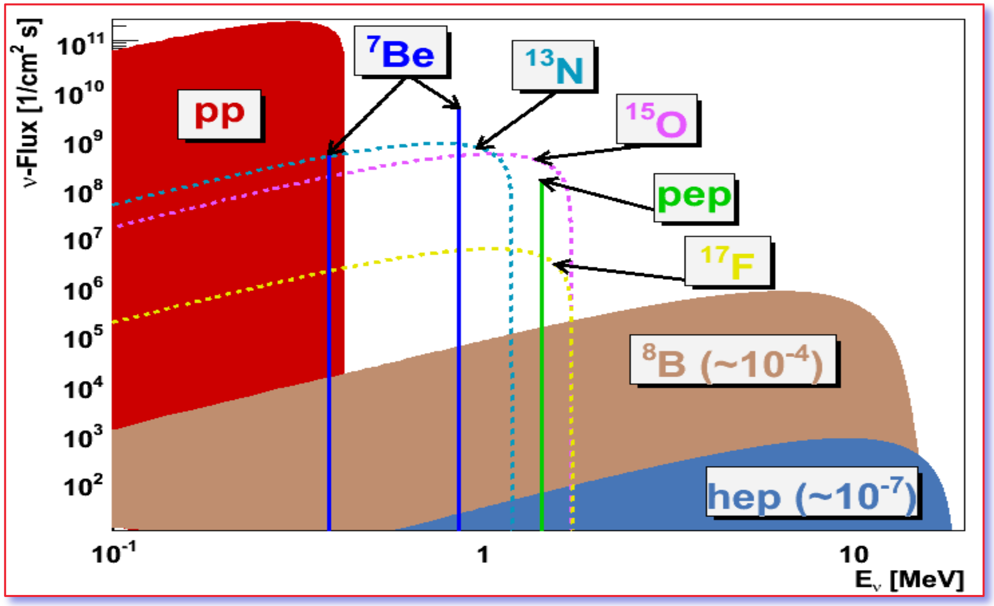



Bonetti *et al.*, PRL **82,** 5205 (1999) .

$$I \approx 1\ mA$$

- Windowless ^{3}He gas target
- 2 events/month at lowest energy (E_{cm}= 16 keV)
- Effect of electron screening has been largely resolved
- About 7% uncertainty at solar energies

Why *still* measure solar neutrinos?



- ^{8}B flux ~4% precision
  - →Super-K, SNO, Borexino, . . .
- ^{7}Be flux ~5% precision
  - →Borexino
- Others
  - →Radiochemical (integral)

- Neutrino flavor oscillation
  - →Neutrinos have mass
  - →Mass ≠ Flavor eigenstates

- But weak constraints on photospheric luminosity (pp neutrino flux)
- What is contribution of CNO cycle to solar energy generation?
- Is photospheric composition reflective of solar core?

Need precise measure of pp & CNO solar ν flux

Borexino Collab, PRL 107 (2011)