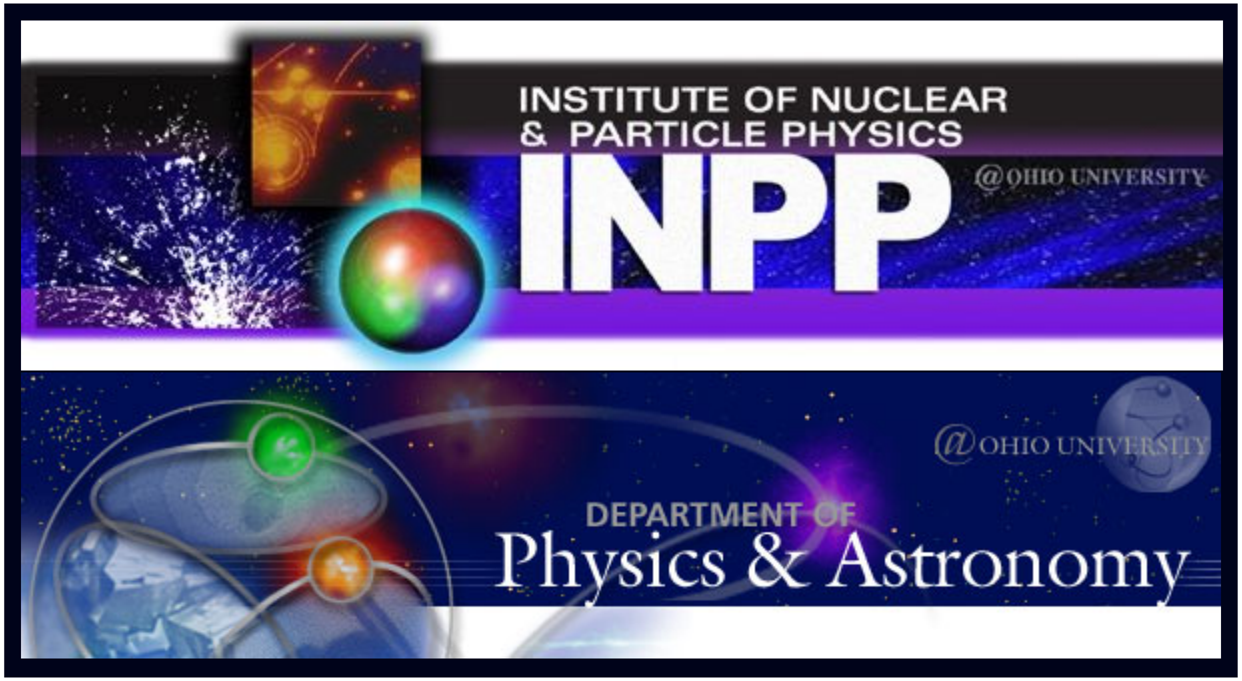
Nuclear Astrophysics - I

Carl Brune
Ohio University, Athens Ohio



Astrophysics and Cosmology

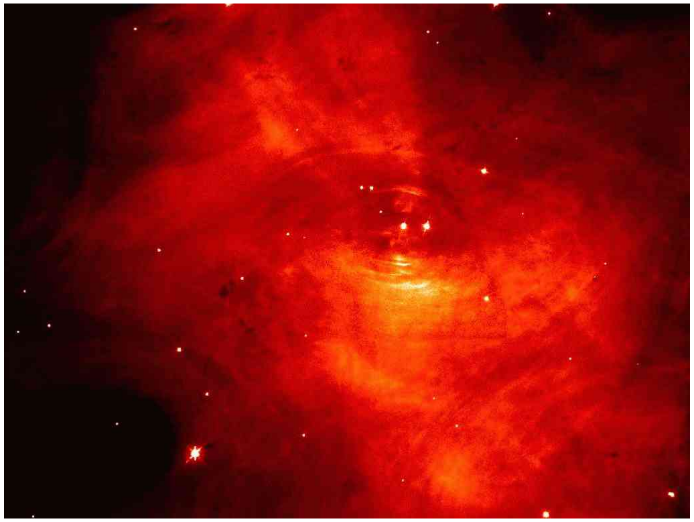
Observations

- Electromagnetic Spectrum: radio, microwave, IR, optical, UV, x-rays, γ-rays
- Neutrinos
- Cosmic Rays
- Meteorites
- Terrestrial Abundances
- Gravitational Waves

↔

Underlying Physics

- Atomic Physics
- Nuclear Physics
- Particle Physics
- Statistical Mechanics
- Hydrodynamics
- Gravity (General Relativity)
- …..



Nuclear Astrophysics

Nuclear Physics plays a very important role in astrophysics because:

- **Nuclear reactions can provide a tremendous amount of energy e.g. $^{3}He + ^{3}He \rightarrow 2p + ^{4}He + 13\ \text{MeV}$**
- **Nuclei are created and destroyed via nuclear reactions (aka nucleosynthesis) – Origin of the Elements**

Scenarios include:

- Stellar processes
- Big Bang
- Cosmic-ray induced processes
- Neutron star structure
- …

Origin of the Elements

- Age of Universe: 13.7 Gyr
- Age of Solar System: 4.5 Gyr

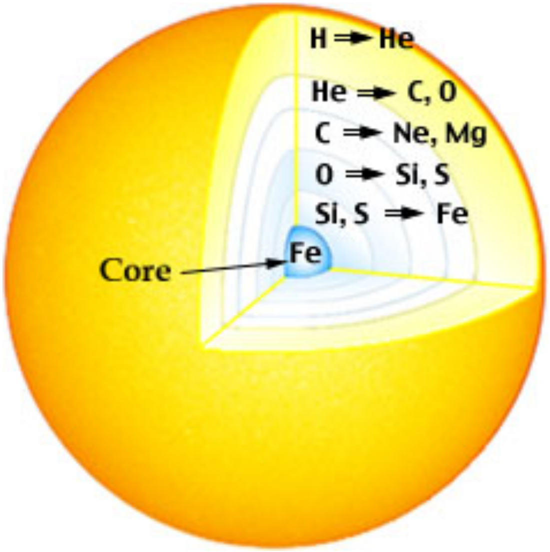
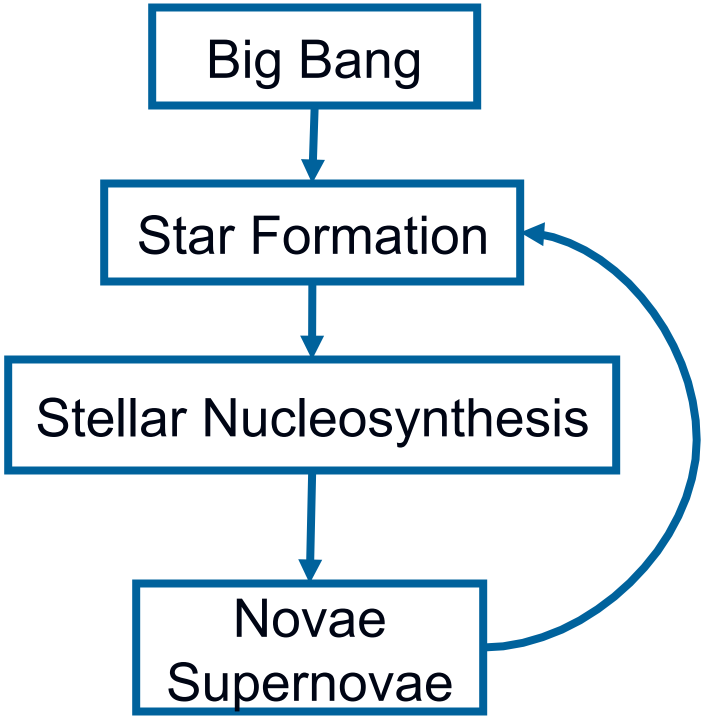


Image credit: NASA


Big Bang

Star Formation

Stellar Nucleosynthesis

Novae
Supernovae

“Laundry List” of Processes

Big Bang Nucleosynthesis	Light Elements ($A<10$)
Hydrogen Burning	Main sequence of stellar evolution ($A<60$)
Helium Burning	Red giants ($A<60$, especially ^{12}C and ^{16}O)
“Heavy Ion” Burning	Late stages of massive star evolution (terminates at Fe)
S Process	“Slow” neutron capture ($A>60$)
R Process	“Rapid” neutron capture ($A>60$)
RP Process	Rapid proton capture: novae and x-ray bursts
γ (or P) Process	γ-, p- and α- induced
Cosmic-Ray Spallation	Li and Be
ν–induced reactions	?
Neutron Stars	R-Process site?

Life of a Massive Star (25 solar-mass)

Hydrogen burning	5 x 10^7 K	10^7 years
Helium burning	10^8 K	10^6 years
C, O burning	10^9 K	500 years
Si burning (➔ Fe)	4 x 10^9 K	1 day
Supernova (type II)		

Si Burning

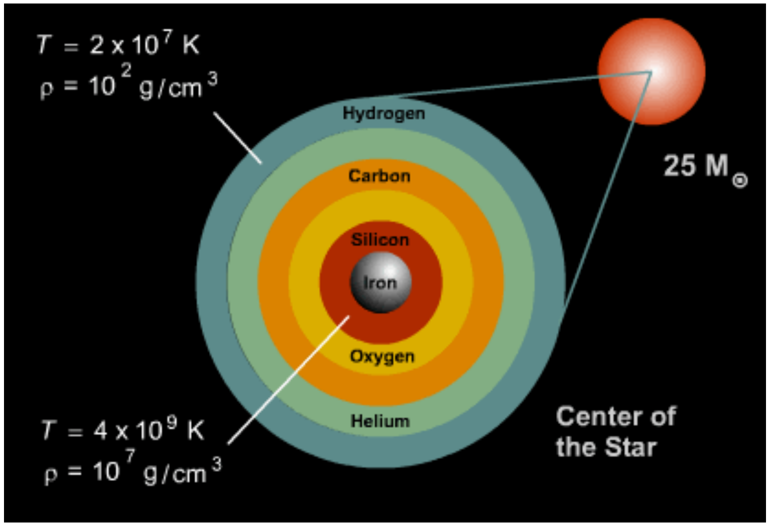
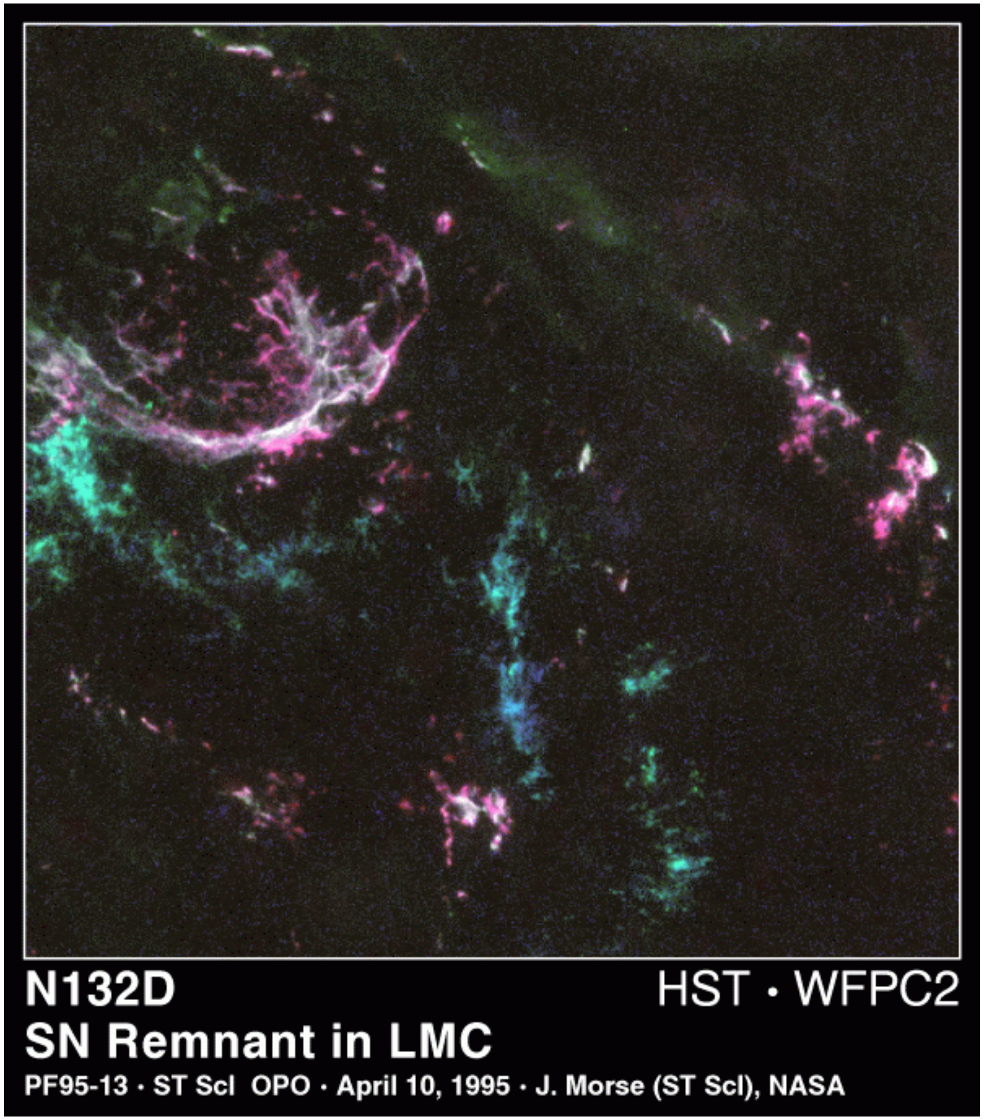


Image credit: Brooks/Cole Thompson Learning

Supernova Remnant N132D

- **Exploded 3,000 years ago**
- **169,000 light-years away**
- **Blue: O^+**
- **Green: O^{2+}**
- **Pink: S^+**



N132D
HST • WFPC2
SN Remnant in LMC
PF95-13 • ST ScI OPO • April 10, 1995 • J. Morse (ST ScI), NASA

What is the needed Nuclear Physics?

- **Nuclear masses, Q values**
- **Half lives, decay modes**
- **Resonance energies, partial widths**
- **Reaction cross sections**

Breit-Wigner Formula

$$\sigma(E) = \frac{2J+1}{(2J_1+1)(2J_2+1)}\frac{\pi}{k^2}\frac{\Gamma_1\Gamma_3}{(E-E_R)^2+\Gamma^2/4}$$

Reaction Rate Formalism:
T = temperature
k = Boltzmann constant
μ = reduced mass
σ = cross section
E = c.m. energy

consider the process: $1+2\rightarrow 3+4$

where n_i = number density of species i

$$\begin{aligned}\frac{\mathrm{d}n_3}{\mathrm{d}t} &= n_1 n_2 \langle\sigma v\rangle \\ \langle\sigma v\rangle &= \sqrt{\frac{8}{\pi\mu}}(kT)^{-3/2}\int_0^\infty E\,\sigma(E)\,\exp(-E/kT)\,\mathrm{d}E\end{aligned}$$

More Nuclear Physics

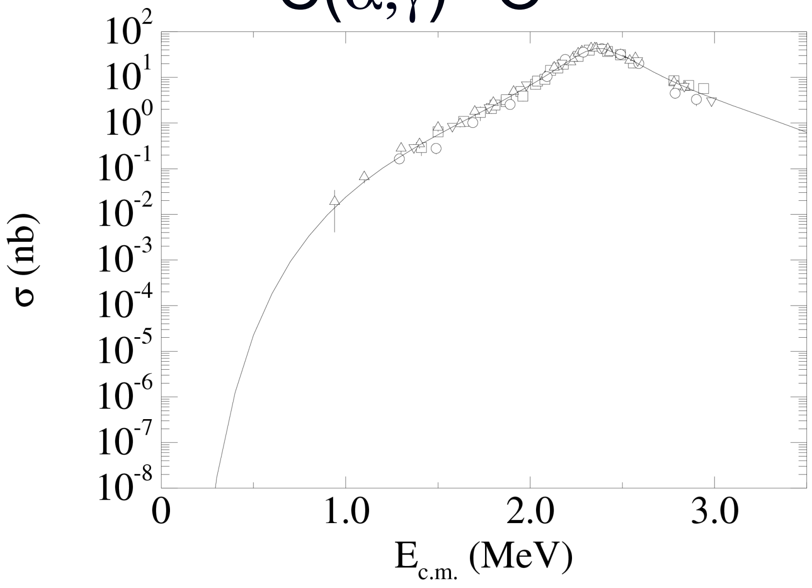
Charged Particles

Coulomb barrier:
S = “astrophysical S factor”

$$\boxed{\sigma = \frac{S}{E}\exp\left(-\sqrt{\frac{E_G}{E}}\right)}$$

E_G is a constant - “Gamow Energy”

$^{12}C(\alpha,\gamma)^{16}O$



Neutron-induced Reactions

No Coulomb barrier
$\sigma \sim E^{-1/2}$

Statistical Reactions (roughly A>30)

- Reaction rate determined by many resonances
- Rates can be computed using statistical methods
- Requires systematic information: level densities, optical potentials,…

Example S-factor

An example from my thesis:

The $^3H(\alpha,\gamma)^7Li$ reaction

85

σ

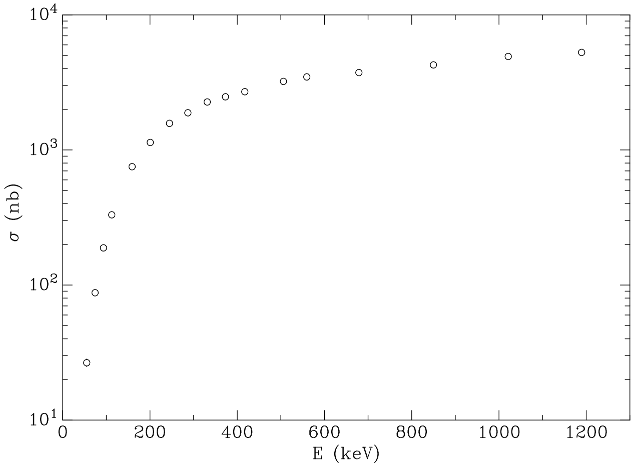


Figure 5.2: The final result for σ, found by combining data sets shown in Figure 5.1.

S

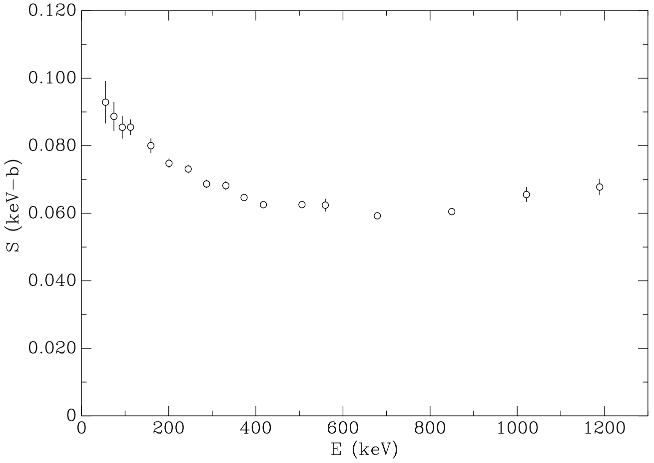


Figure 5.3: The final result for S, found by combining data sets shown in Figure 5.1. The error bars do not include the additional systematic error of 6%.

At High Temperatures
above (a few)x10^9 K

- Reaction rates tend to be “fast” – faster than dynamical timescales
- Production and destruction rates of a given nucleus are nearly balanced
- Abundances are determined by equilibrium considerations
- Q-values (masses) are most important
- Reaction *rates* are less important

Important Temperatures for various Processes

Big Bang Nucleosynthesis	(1-10)x10^8 K
Hydrogen Burning (non-explosive)	(1-10)x10^7 K
Helium Burning	(1-4)x10^8 K
“Heavy Ion” Burning	(1-4)x10^9 K
S Process	(1.5-4)x10^8 K
R Process	(several➔0)x10^9 K
Explosive hydrogen burning	(1-10)x10^8 K

Temperature and Energy Scales

- For $T=10^9$ K, kT=86 keV – a pretty low energy!
- Coulomb and/or angular momentum barriers are important
- Neutrons: Energies ~ kT most important for determining reaction rate
- Charged particles: Energies significantly higher than kT needed due to Coulomb barrier (Gamow Energy / Gamow Window)
  - Example: $\alpha+^{12}C$ @ $T=2x10^8$ K ➔ $E_0=0.3$ MeV

Big Bang Nucleosynthesis

- Standard Model of Particle Physics
- General Relativity
- Homogeneity and Isotropy
- Nuclear Cross Sections

→ Light Elements

single free parameter: Baryon Density
(or η = baryon-to-photon ratio)

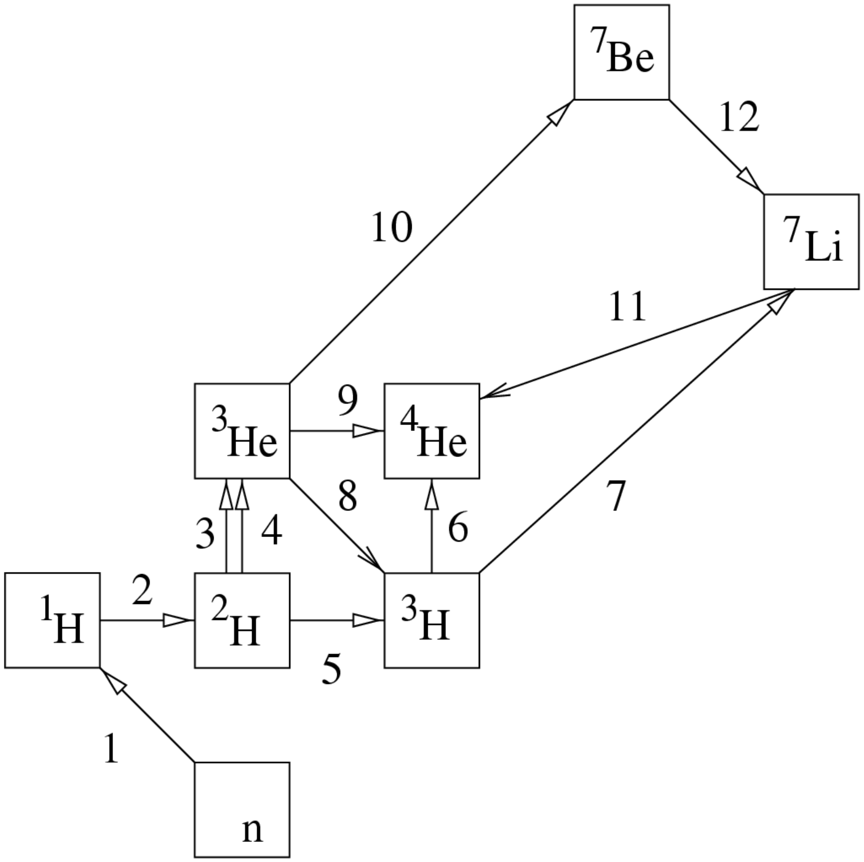
Goals:

- Determine **η**
- Compare to astronomical observations
- Test physics input, e.g.
    - 3 neutrino generations
    - extra particles
    - phase transitions?

Nuclear Physics

- 11 cross sections
- neutron lifetime
- E ~ 100 keV

Measure in the lab!



1. $p \longleftrightarrow n$
2. $p(n,\gamma)d$
3. $d(p,\gamma)^3\mathrm{He}$
4. $d(d,n)^3\mathrm{He}$
5. $d(d,p)t$
6. $t(d,n)^4\mathrm{He}$
7. $t(\alpha,\gamma)^7\mathrm{Li}$
8. $^3\mathrm{He}(n,p)t$
9. $^3\mathrm{He}(d,p)^4\mathrm{He}$
10. $^3\mathrm{He}(\alpha,\gamma)^7\mathrm{Be}$
11. $^7\mathrm{Li}(p,\alpha)^4\mathrm{He}$
12. $^7\mathrm{Be}(n,p)^7\mathrm{Li}$

Inverse reactions also included

Evolution of the Elements

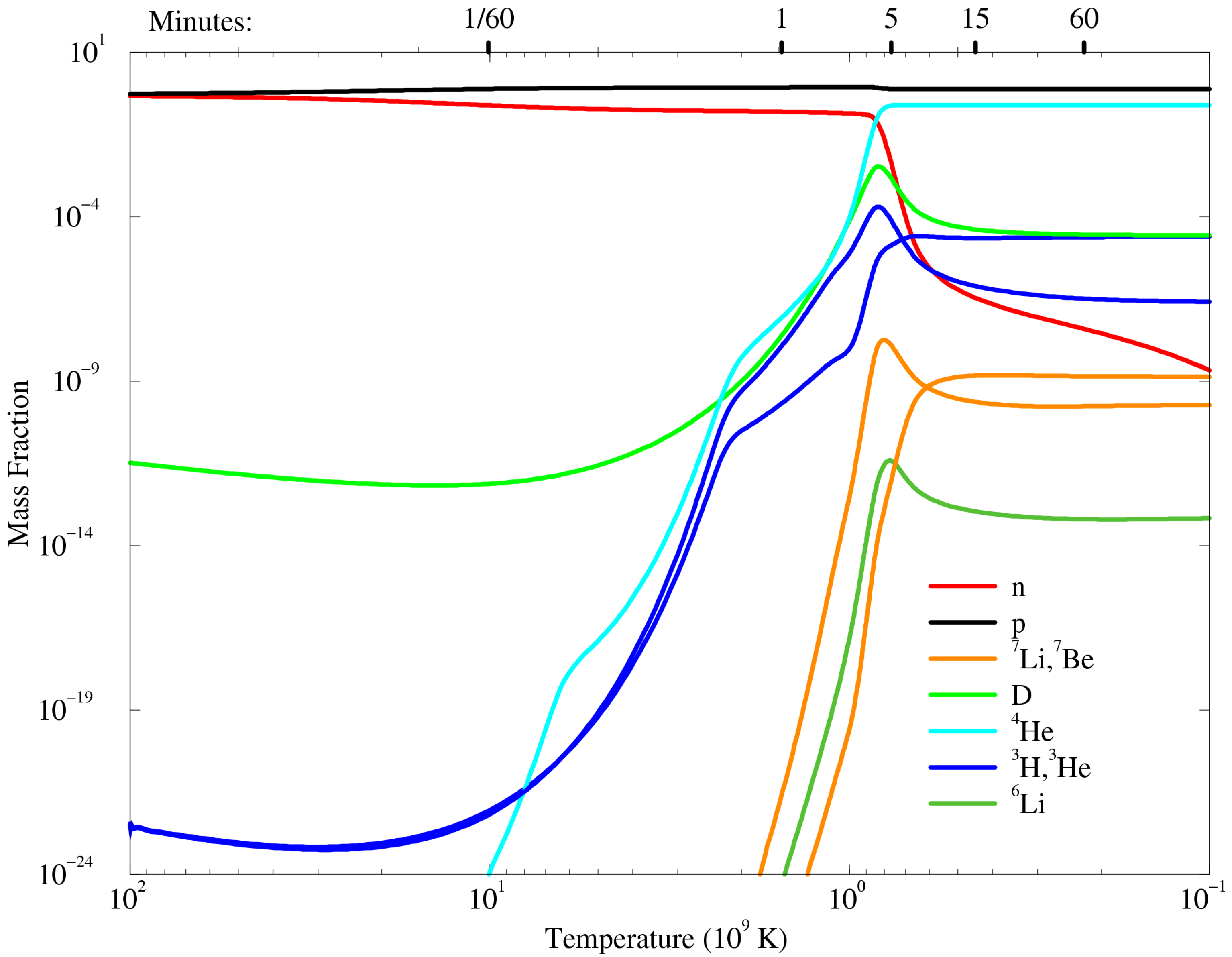
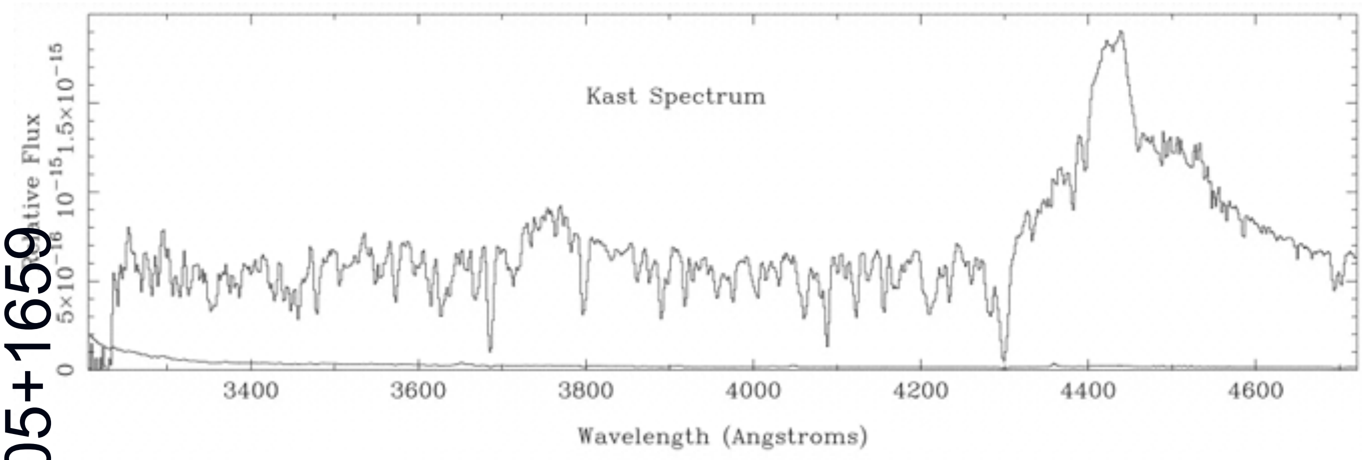


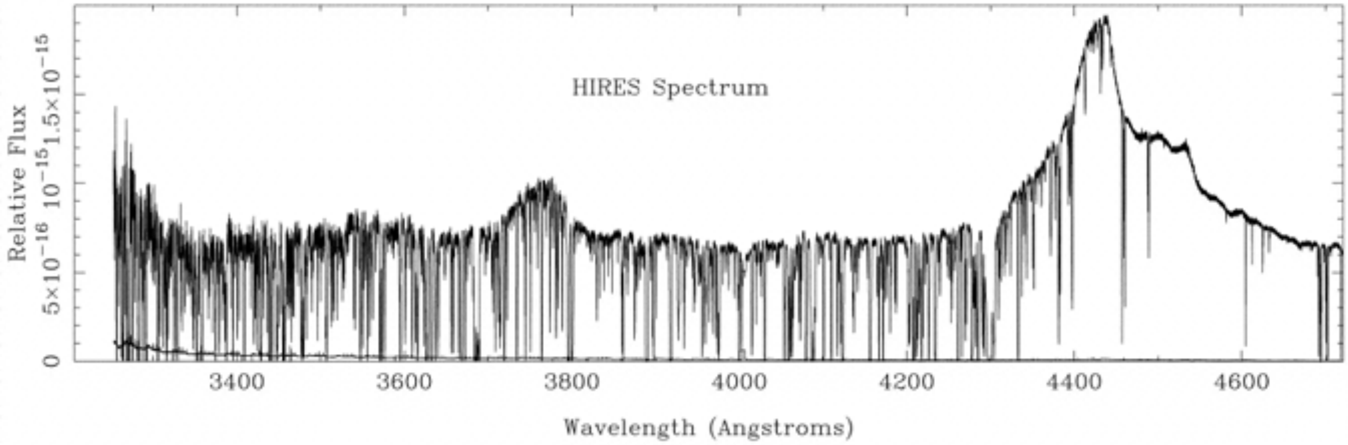
Figure: Ken Nollett

Observing ^{2}H with QSOs

HS 0105+1659

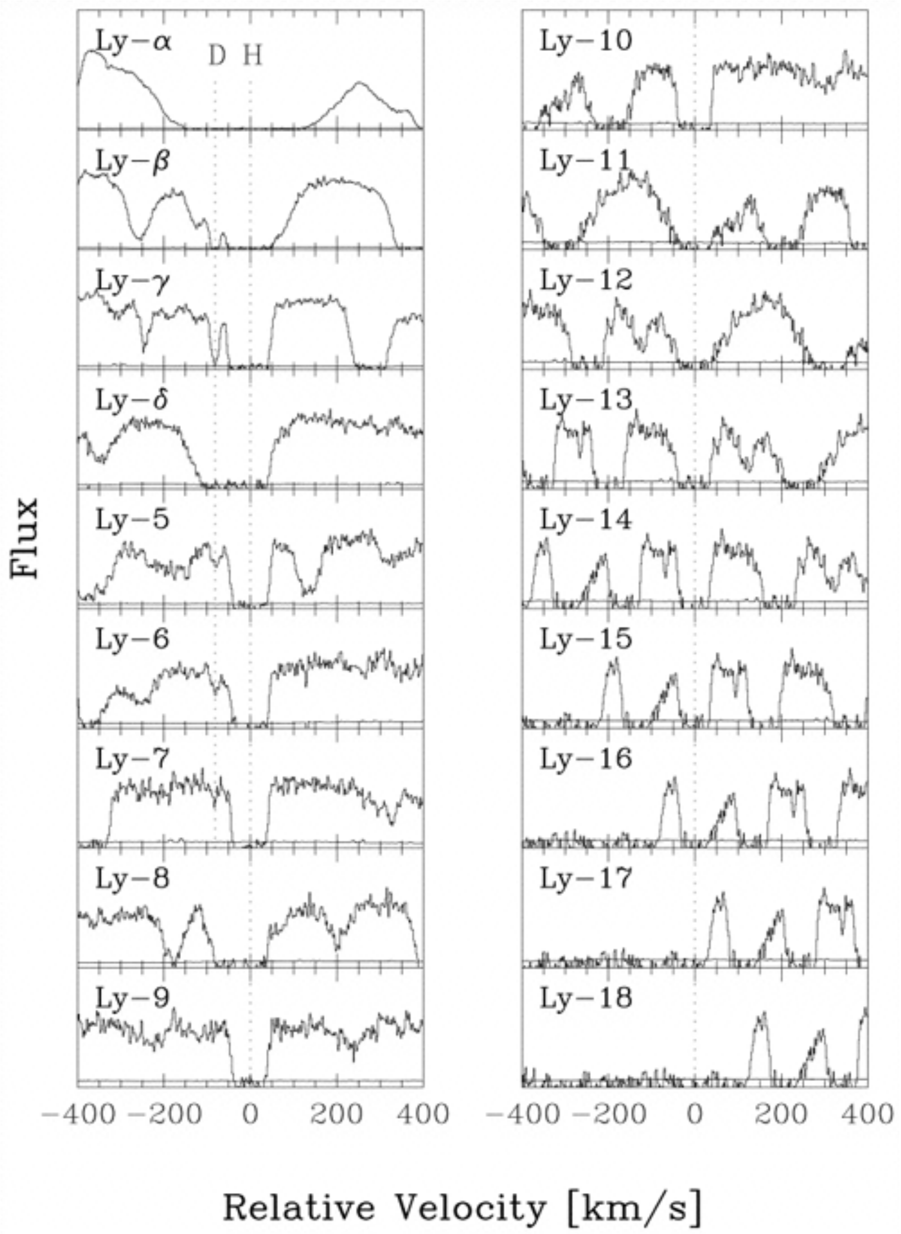


Older data



Keck Data

HS 0105+1619



D/H can be extracted:

QSO	$\log_{10}$D/H
PKS 1937-1009	-4.49(4)
Q1009+2956	-4.40(7)
Q0130-4021	< -4.17
HS 0105+1619	-4.60(4)

It would appear that we know the primordial Deuterium abundance within ~5%!

We have observations for D, ^{3}He, ^{4}He, and ^{7}Li which are thought to represent primordial abundances.

Big Bang Nucleosynthesis:
η = 5.1(6) x 10^{-10}

The lithium data are not in good agreement.

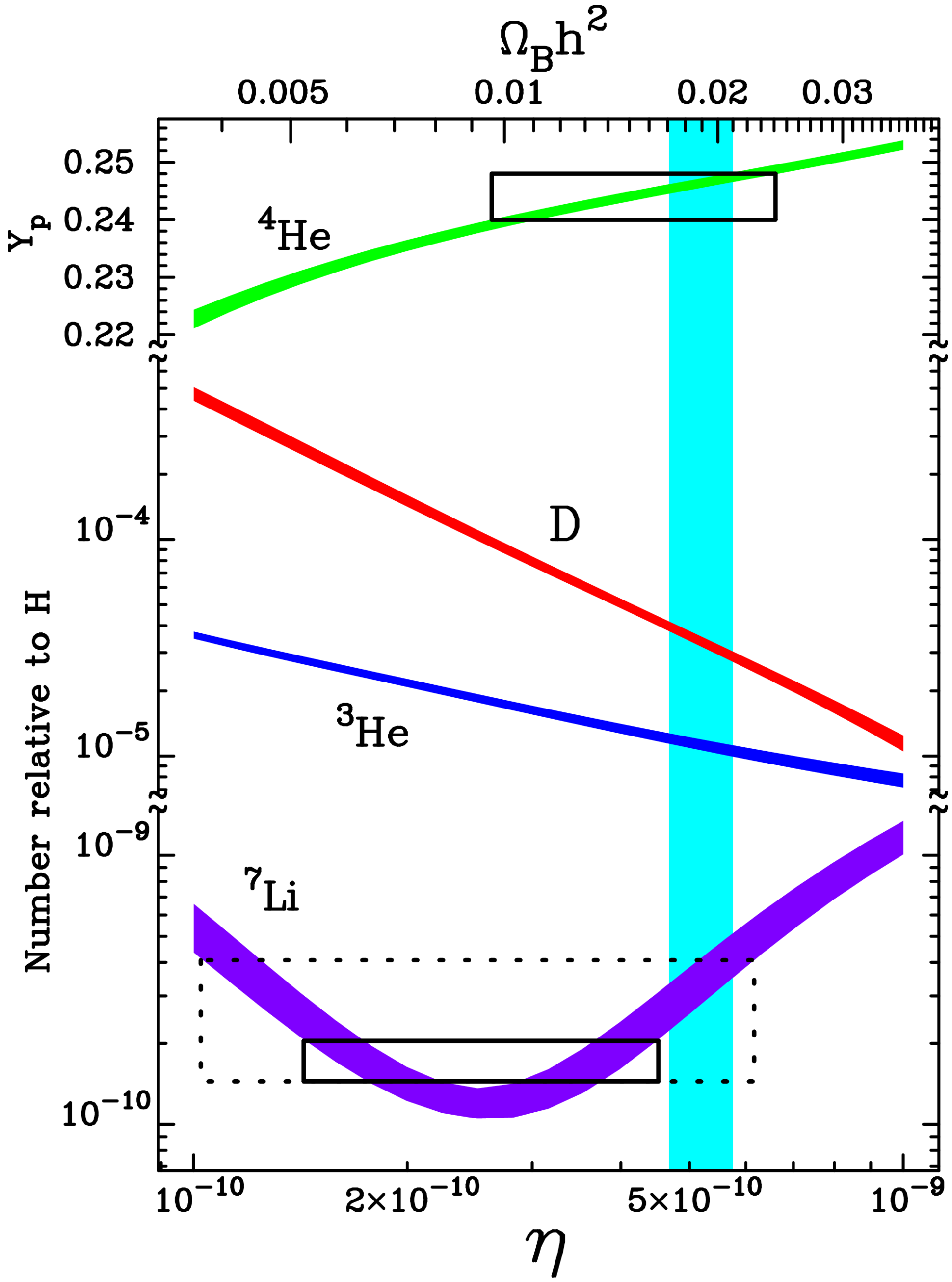
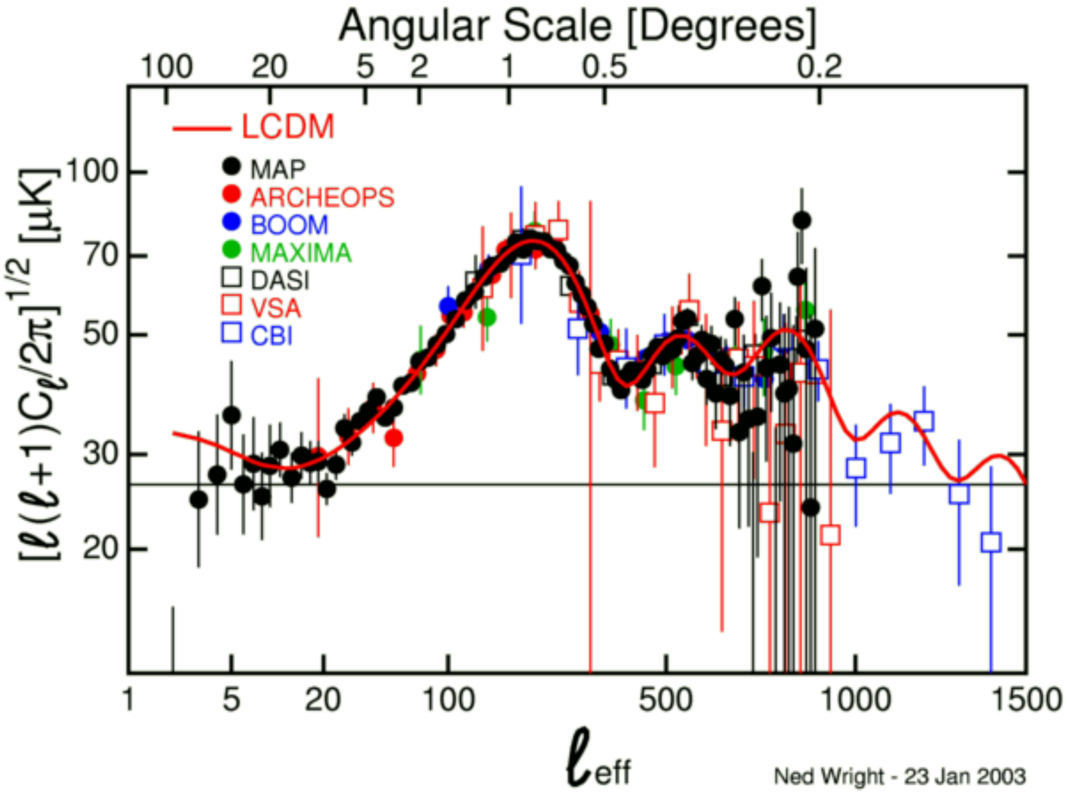
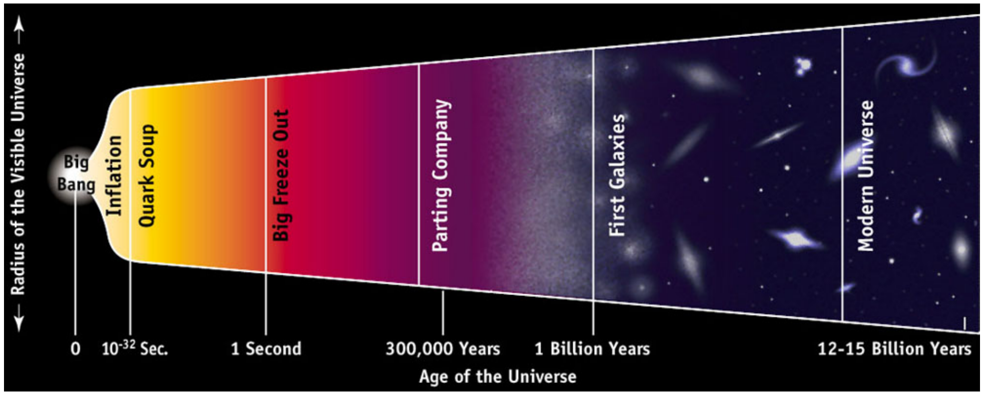


Figure: Ken Nollett and Scott Burles

Cosmic Microwave Background





Cosmic Microwave Background: Inferences

WMAP 15 January 2010 release

quantity	value
Ω_Λ (dark energy density)	0.734(29)
Ω_m (matter density)	0.266(29)
Ω_b (baryon density)	0.0449(28)
t_0 (age of universe)	13.75(13) Gyr
η (baryon-to-photon ratio)	$6.18(16) \times 10^{-10}$

↕ Consistent (sort of…)

Big Bang Nucleosynthesis: $\boldsymbol{\eta} = 5.1(6) \times 10^{-10}$

Present Status of BBN

- Exciting developments in observations of the CMB, light elements, and distant supernovae.
- Agreement is reasonable but not perfect. Lithium?
  - Reactions on ^{7}Be ???
- From a nuclear physics point of view the field is mature, but higher-accuracy data are needed for reactions involving Deuterium.

Reaction Rate for a Narrow Resonance

Breit-Wigner Formula

$$\sigma(E) = \frac{2J+1}{(2J_1+1)(2J_2+1)} \frac{\pi}{k^2} \frac{\Gamma_1\Gamma_3}{(E-E_R)^2+\Gamma^2/4}$$

consider the process: $1 + 2 \rightarrow 3 + 4$

where n_i = number density of species i

$$\begin{aligned} \frac{\mathrm{d}n_3}{\mathrm{d}t} &= n_1 n_2 \langle\sigma v\rangle \\ \langle\sigma v\rangle &= \sqrt{\frac{8}{\pi\mu}}(kT)^{-3/2} \int_0^\infty E\,\sigma(E)\,\exp(-E/kT)\,\mathrm{d}E \end{aligned}$$

For $\Gamma \ll E_R$, $\langle\sigma v\rangle = (\mathrm{const}) \times T^{-3/2} \times \Gamma_1\Gamma_3/\Gamma \times \exp(-E_R/kT)$

Very useful formula!

Focus on Helium Burning

Hydrogen burning	5 x 10^7 K	10^7 years
Helium burning	10^8 K	10^6 years
C, O burning	10^9 K	500 years
Si burning (➔ Fe)	4 x 10^9 K	1 day
Supernova (type II)		

(For a 25 solar mass star)

Si Burning

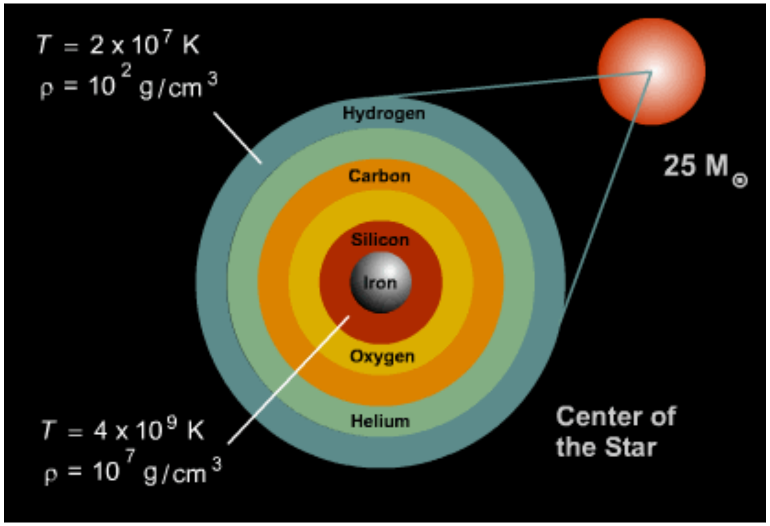
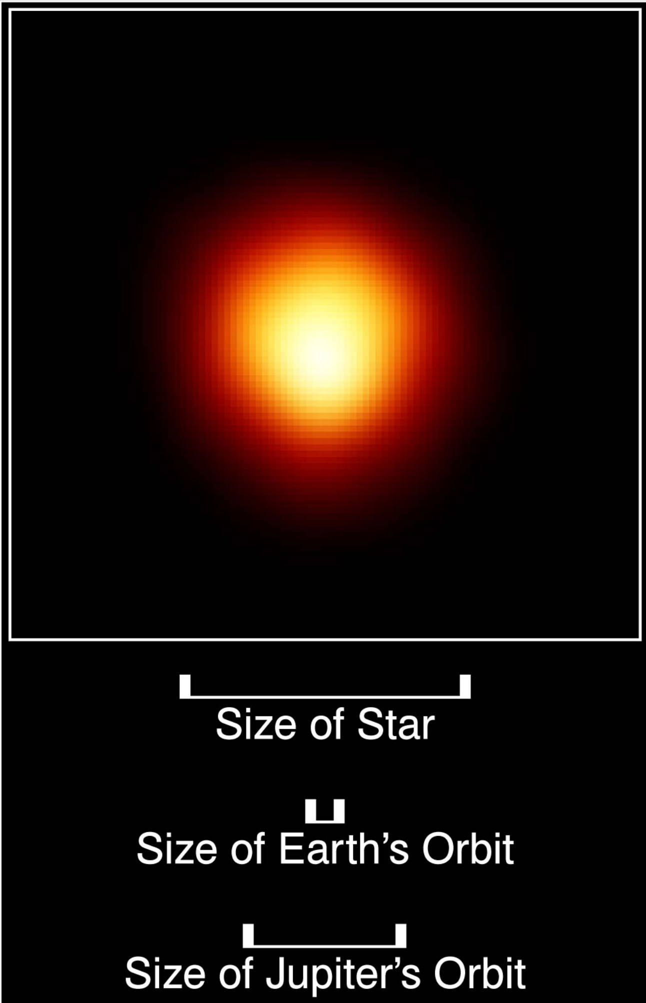


Image credit: Brooks/Cole Thompson Learning

Helium Burning Reactions

- $3\alpha \rightarrow {}^{12}C$
  - -- $\alpha + \alpha \leftrightarrow {}^{8}Be$ (${}^{8}Be$ ground state is just unboud)
  - -- ${}^{8}Be + \alpha \rightarrow {}^{12}C + \gamma$ (via the 7.6-MeV "Hoyle" state)
    rate known with ~10%, but still under intense scrutiny
    ~ electron scattering measurement [TU Darmstadt, Chernykh et al., PRL 98, 032501 (2007)]
- ${}^{12}C(\alpha,\gamma){}^{16}O$
  - -- rate only known within 30-50%
- Rates of these reactions are roughly equal
- Further α captures are hindered by the Coulomb barrier and absence of resonances



Atmosphere of Betelgeuse • Alpha Orionis

Hubble Space Telescope • Faint Object Camera

PRC96-04 • ST ScI OPO • January 15, 1996 • A. Dupree (CfA), NASA, ESA

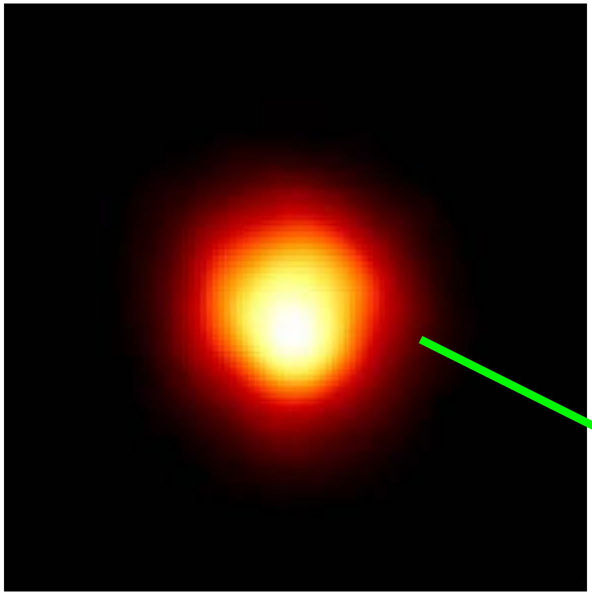
Helium Burning Reactions *Matter*

They determine:

- The $^{12}C/^{16}O$ ratio in massive stars (and hence for the Universe)
- Nucleosynthesis of heavier elements
- The remnant mass after the supernova explosion (black hole versus neutron star)
- See recent studies:
  Tur, Heger, and Austin, ApJ 671, 821 (2007)
  Tur, Heger, and Austin, ApJ 702, 1068 (2009)

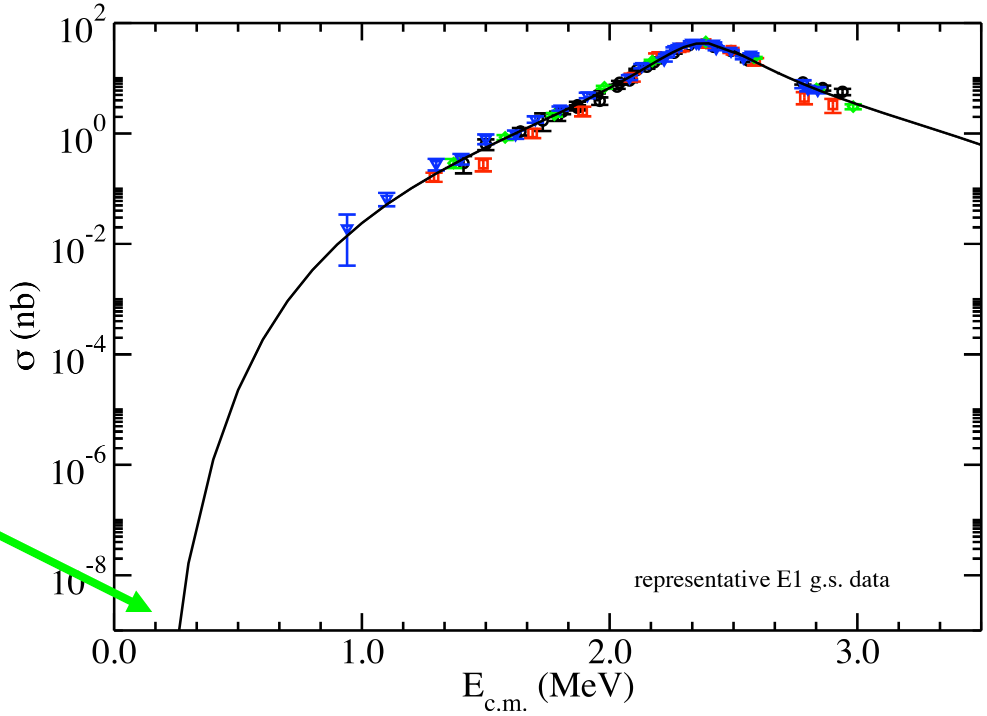
The Problem:

Red Giant



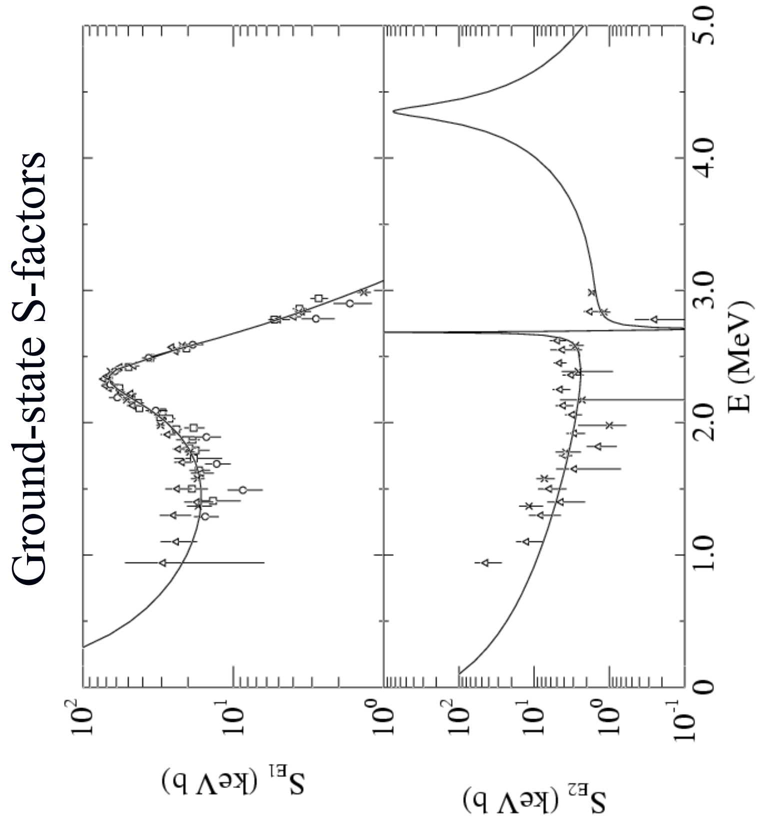
T=(1-3)x10^8 K

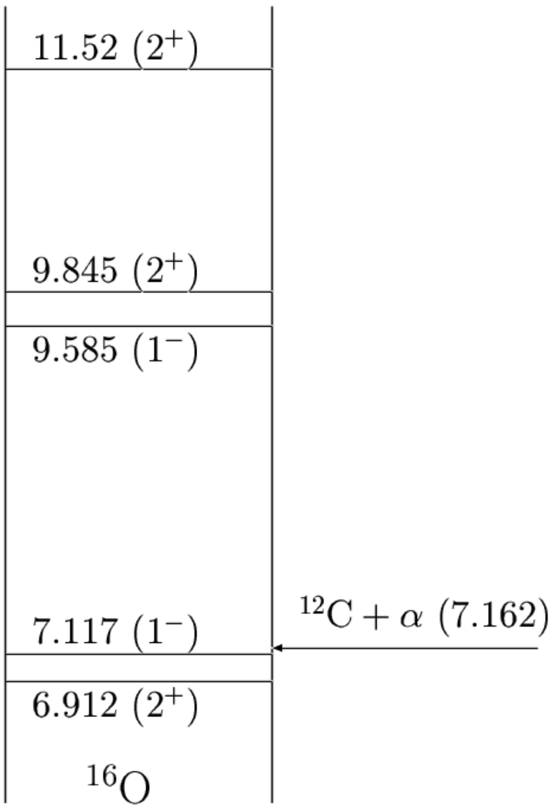
The Lab



- cross section is abnormally small (E1 is isospin-forbidden)
- subthreshold resonances

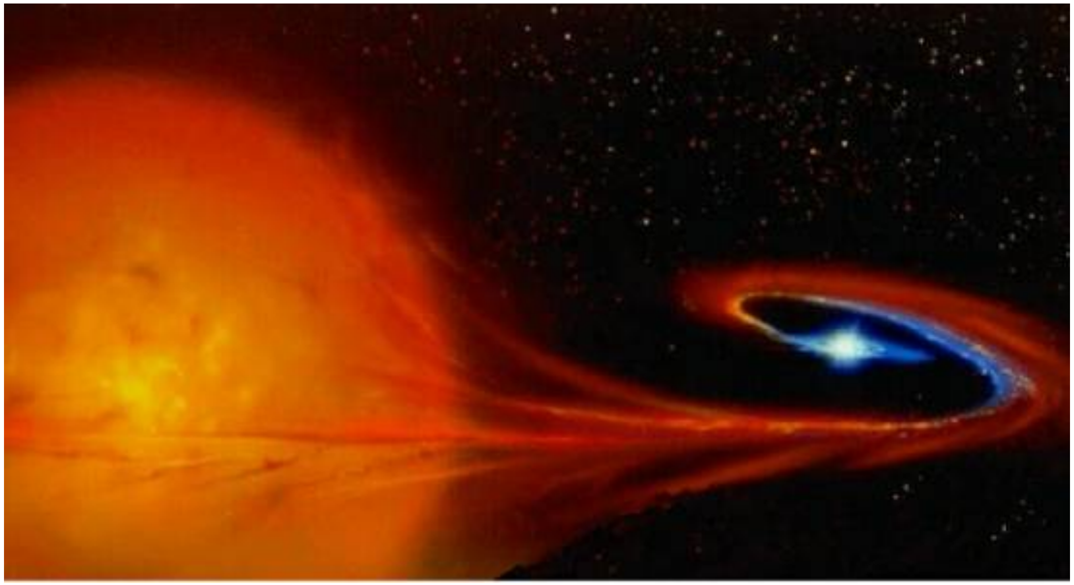
1^- and 2^+ states of ^{16}O





Resonances correspond to nuclear excited states!
Sub-threshold resonances… Ugh…

Classical Novae



- 2-3 / month in our Galaxy
- Binary star systems
- Mass transferred from less massive star (red giant) to white dwarf companion
- Hydrogen gas burns explosively with CNO nuclei
  → thermonuclear explosion

- Elements as heavy as calcium may be synthesized
- Primary target for gamma-ray telescopes (^{7}Be, ^{18}F, ^{22}Na, ^{26}Al)

Charged Particle Reactions A = 15 - 40

Key Features:

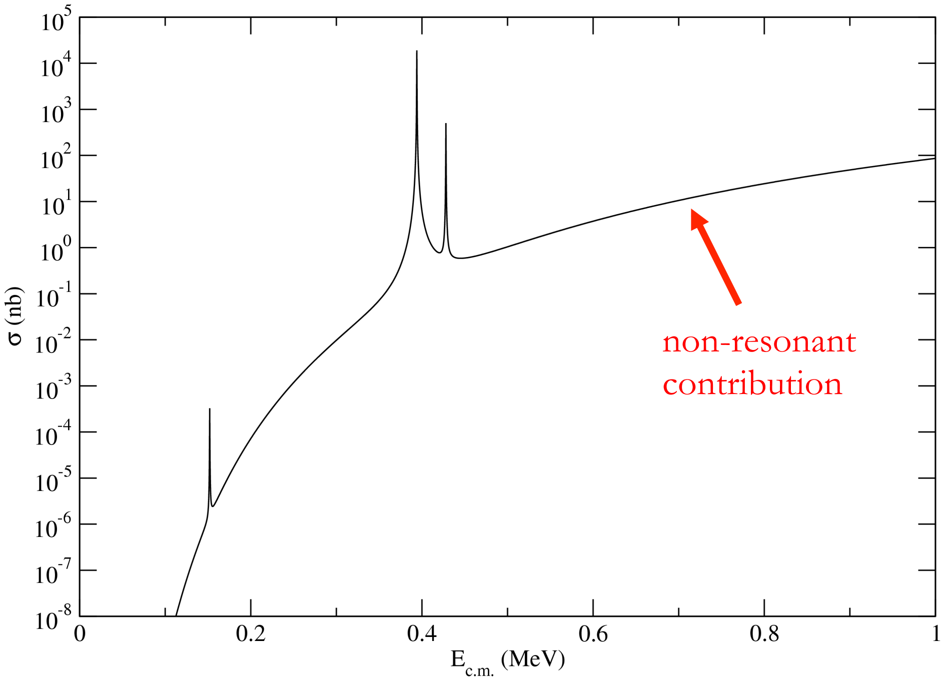
- Resonant contributions (usually dominant)
- Non-resonant contributions
- Coulomb barrier

Resonance Properties:

- Energy
- Partial Widths
- Spin and Parity

All properties are important!

Typical Cross Section



Experimental Approaches for Novae

- **Direct measurements (Si arrays, recoil separators)**
- **Indirect measurements (transfer reactions)**
- **Mirror nuclei**
- **Measurements of individual resonances is required**

To Summarize

TODAY:

- **Introduction**
- **BBN, He burning, Novae**

NEXT:

- **Heavier nuclei**
- **Higher temperatures**