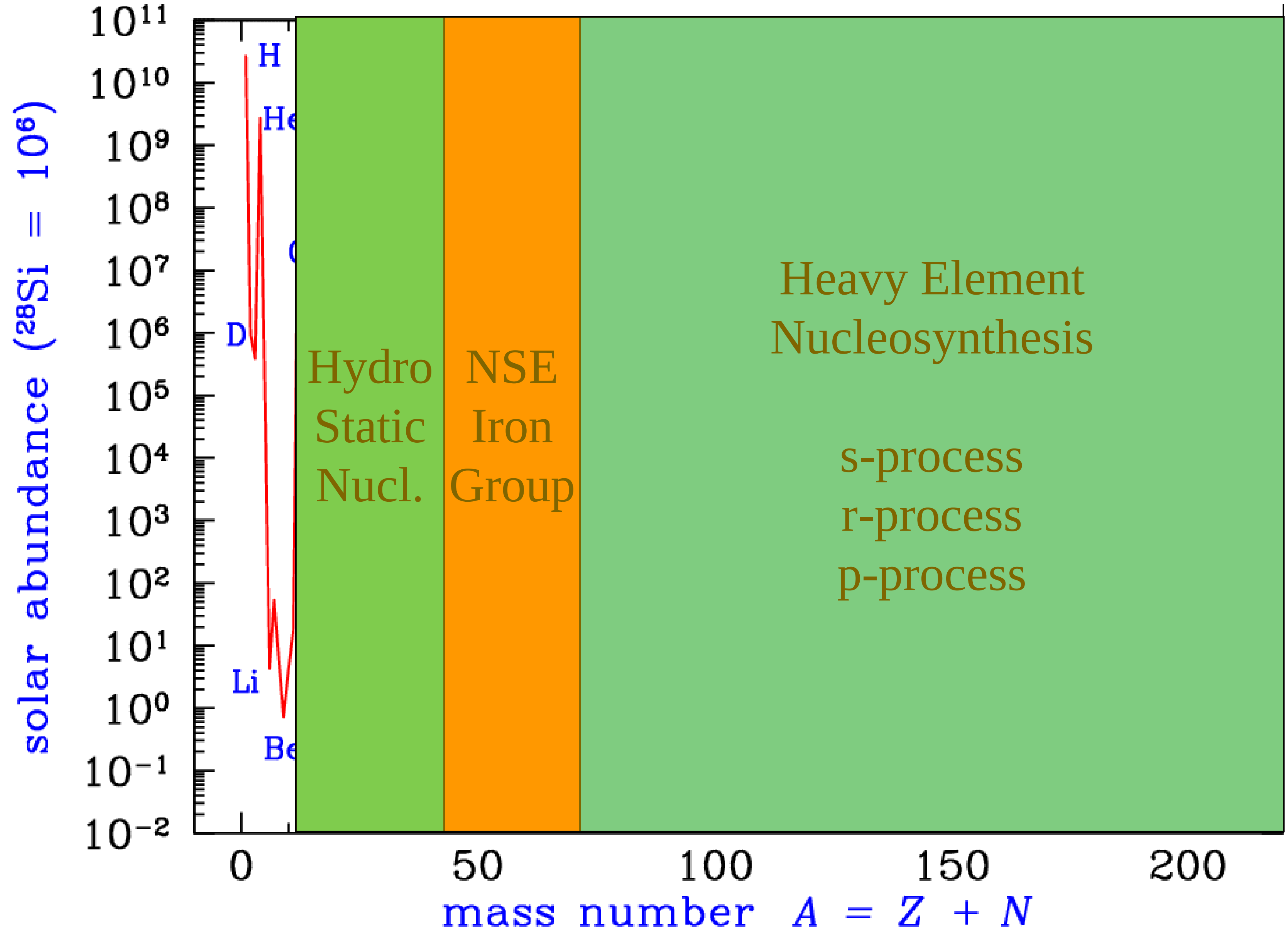


solar abundance (^{28}Si = 10^6)
10^{11}
10^{10}
10^{9}
10^{8}
10^{7}
10^{6}
10^{5}
10^{4}
10^{3}
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
H
He
D
Li
Be
Hydro Static Nucl.
NSE Iron Group
Heavy Element Nucleosynthesis
s-process
r-process
p-process
0
50
100
150
200
mass number $A = Z + N$

How do we explain obs.?

- If universe ~14 Gyr old
  - Where'd we get so much H & He???
    - pp-chain is too slow
    - massive stars burn beyond He
  - Stars must have been born with that H & He
    - Big bang nucleosynthesis

Info for any nucleosynthesis calculation

- What building blocks are available?
  - n, p, nuclides, e, γ, ν, etc…
- What are the reaction time scales?
  - Related to rxn rates: $\tau = 1/\Gamma$
- What are the dynamical time scales?
  - Hydro-static EQ; no time scale
  - Free-fall time τ = finite

Cosmology

First published in Weltall and Menschheit (1907) edited by Hans Kraemer

Tenets of Modern Cosmology

- Cosmological Principle
  - Universe is homogeneous
    - looks the same anywhere we go
  - Universe is isotropic
    - looks the same any direction we look
  - Laws of physics are the same everywhere(when)

Tenets of Modern Cosmology

- General Relativity
  – theory of gravity

- Standard Model of Particle Physics
  – Constituents of normal matter
  – Interactions between them

Tenets of Modern Cosmology

Courtesy of George Lucas

Dark Side of Cosmology

- Dark Matter
- Dark Energy

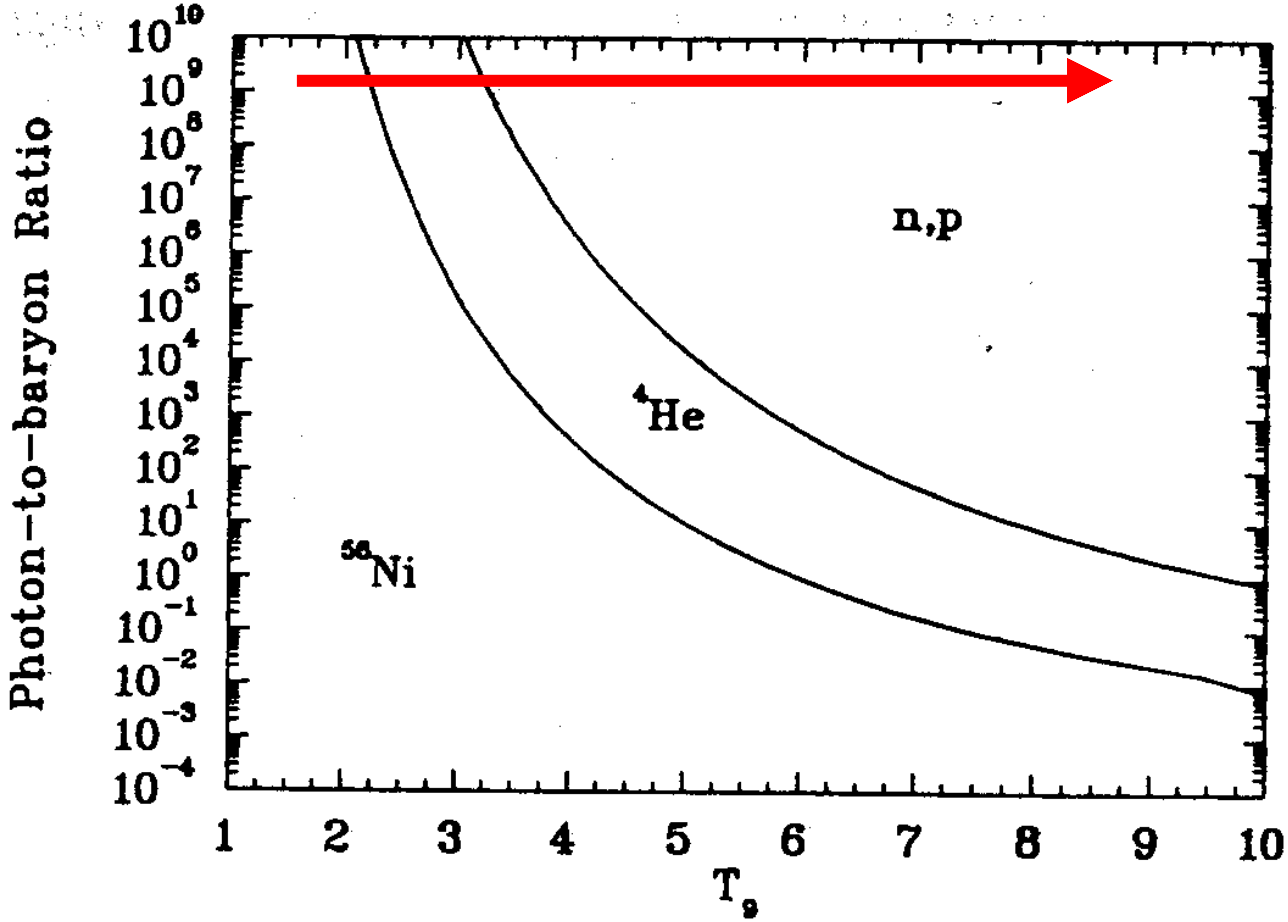
Working back to the big bang

- GR predicts universe is expanding
  - Einstein tried to fix this with Λ
  - Claims its his biggest mistake

- Hubble obs. recession of galaxies (1929)
  - First evidence for universal expansion
  - Subsequent obs. confirm this

Working back to the big bang

- If the universe is expanding….
  - What was it like in the past?
    - Smaller
    - Hotter
    - Denser
  - What happens to its constituents?
    - Baryons- n, p, nuclides



Photon-to-baryon Ratio
10^{10}
10^{9}
10^{8}
10^{7}
10^{6}
10^{5}
10^{4}
10^{3}
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
n,p
^{4}He
^{56}Ni
1
2
3
4
5
6
7
8
9
10
T_9

Initial Conditions

- At kT>1 MeV
  - Thermal equilibrium
  - Chemical equilibrium
  - Main constitients
    - Photons
    - Neutrinos
    - Electrons/positrons
    - Small number of baryons (n & p)

} NSE

Relevant timescales

- Dynamical timescale
  - Hubble expansion rate $H \sim T^2/M_P$
- Reaction timescales
  - Weak interaction $\Gamma_W \sim T^5/M_W^4$
  - Rxn rates $\Gamma_{rxn} \sim \rho_B \lambda_{rxn}$

Big bang nucleosynthesis

- When T~1 MeV
  - Γ_W~H weak rates become slow
    - ν's stop interacting
  - Electrons/positrons become NR
    - $e^+ + e^- \longrightarrow 2\gamma$
    - energy goes into all but ν's
      - $T_\gamma > T_\nu$

Big bang nucleosynthesis

- n,p would like to fuse into d
- But $N_\gamma(E>B_d) >> N_B$
  - So as soon as d is made, it is destroyed
  - $\Gamma_{diss} >> \Gamma_{fus}$
  - So we must wait…..
- Called the D bottleneck
- while we wait, n's decay

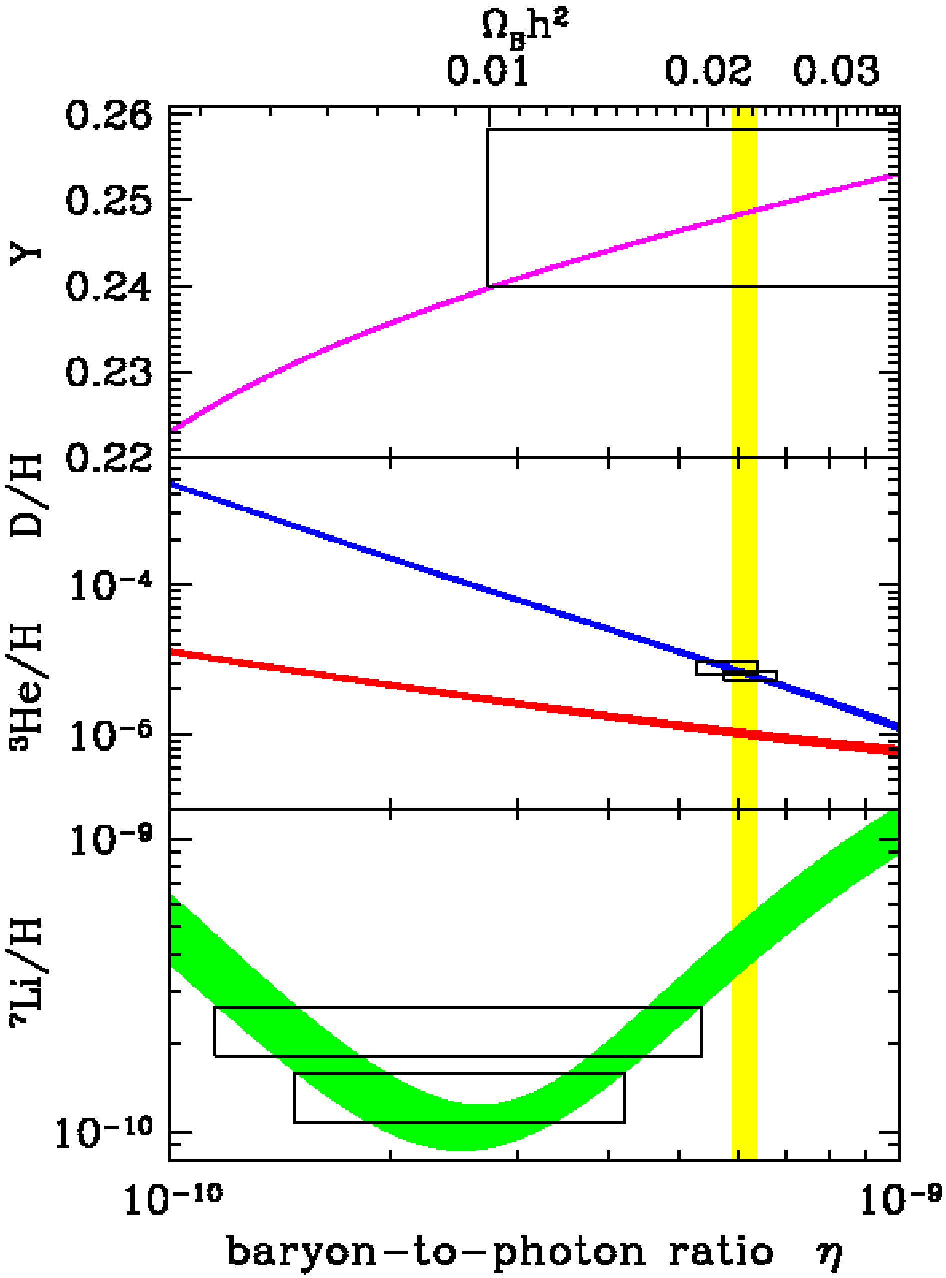
Big bang nucleosynthesis

- T~70 keV, d not efficiently destroyed
- So…….

$$p(n,\gamma)d(p,\gamma)^{3}He(d,p)^{4}He$$

- We convert H into ^{4}He (all n's go into ^{4}He)
- Sometimes we even $^{3}He(\alpha,\gamma)^{7}Be$

- T~40 keV, Coulomb barrier halts nucl.



Light Element Abundances

- ^4He: known syst.

Olive & Skillman 2004

- D: few obs. systems

Burles, Kirkman, O'Meara

- ^3He: extrap. error

Bania *et al*, Vangioni-Flam *et al*

- ^7Li: add. syst.?

Spite & Spite, Ryan *et al*, Bonifacio *et al*

- WMAP CMB $\Omega_B h^2$

Bennet et al, Spergel et al