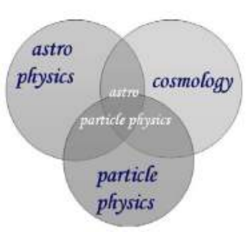
ASTROPARTICLE PHYSICS



Hilary 2021

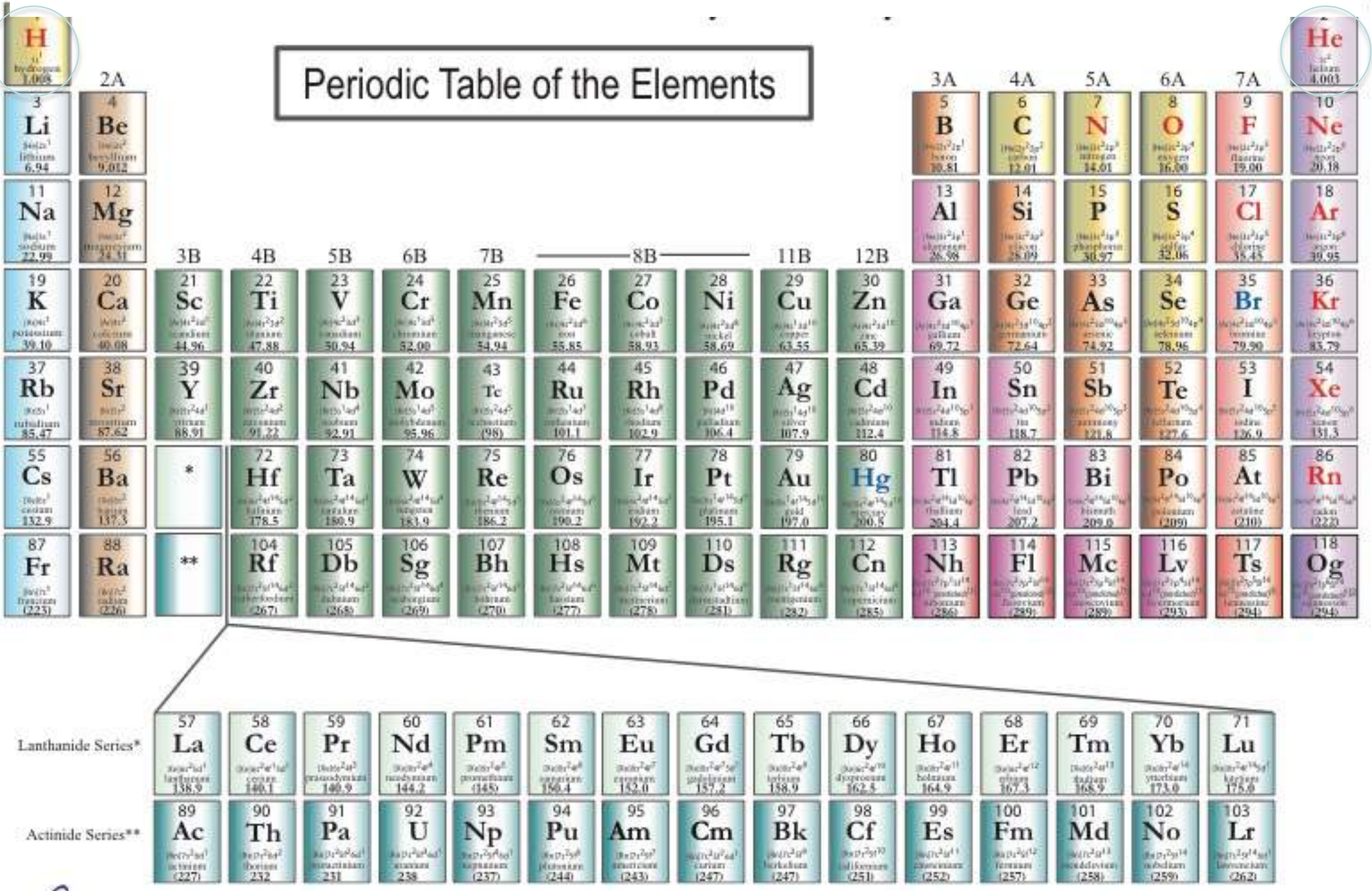
Oxford Master Course in Mathematical and Theoretical Physics

Oxford Physics

- The universe observed
- Relativistic world models
- Reconstructing the thermal history
- Big bang nucleosynthesis
- Dark matter: astrophysical observations
- Dark matter: relic particles
- Dark matter: direct detection
- Dark matter: indirect detection
- Cosmic rays in the Galaxy
- Antimatter in cosmic rays
- Ultrahigh energy cosmic rays
- High energy cosmic neutrinos
- The early universe: constraints on new physics
- The early universe: baryo/leptogenesis
- The early universe: inflation & the primordial density perturbation
- Cosmic microwave background & large-scale structure

http://www-thphys.physics.ox.ac.uk/user/SubirSarkar/astropartphys.html

The universe is made mainly of hydrogen (~75%) and helium (~25%) + traces of heavier elements



Periodic Table of the Elements

	2A	3B	4B	5B	6B	7B	8B			11B	12B	3A	4A	5A	6A	7A	
H 1.008																	He 4.003
3 Li 6.94	4 Be 9.012											5 B 10.81	6 C 12.01	7 N 14.01	8 O 16.00	9 F 19.00	10 Ne 20.18
11 Na 22.99	12 Mg 24.31											13 Al 26.98	14 Si 28.09	15 P 30.97	16 S 32.06	17 Cl 35.45	18 Ar 39.95
19 K 39.10	20 Ca 40.08	21 Sc 44.96	22 Ti 47.88	23 V 50.94	24 Cr 52.00	25 Mn 54.94	26 Fe 55.85	27 Co 58.93	28 Ni 58.69	29 Cu 63.55	30 Zn 65.39	31 Ga 69.72	32 Ge 72.64	33 As 74.92	34 Se 78.96	35 Br 79.90	36 Kr 83.79
37 Rb 85.47	38 Sr 87.62	39 Y 88.91	40 Zr 91.22	41 Nb 92.91	42 Mo 95.96	43 Tc (98)	44 Ru 101.1	45 Rh 102.9	46 Pd 106.4	47 Ag 107.9	48 Cd 112.4	49 In 114.8	50 Sn 118.7	51 Sb 121.8	52 Te 127.6	53 I 126.9	54 Xe 131.3
55 Cs 132.9	56 Ba 137.3	*	72 Hf 178.5	73 Ta 180.9	74 W 183.9	75 Re 186.2	76 Os 190.2	77 Ir 192.2	78 Pt 195.1	79 Au 197.0	80 Hg 200.5	81 Tl 204.4	82 Pb 207.2	83 Bi 209.0	84 Po (209)	85 At (210)	86 Rn (222)
87 Fr (223)	88 Ra (226)	**	104 Rf (267)	105 Db (268)	106 Sg (269)	107 Bh (270)	108 Hs (277)	109 Mt (278)	110 Ds (281)	111 Rg (282)	112 Cn (285)	113 Nh (286)	114 Fl (289)	115 Mc (289)	116 Lv (293)	117 Ts (294)	118 Og (294)

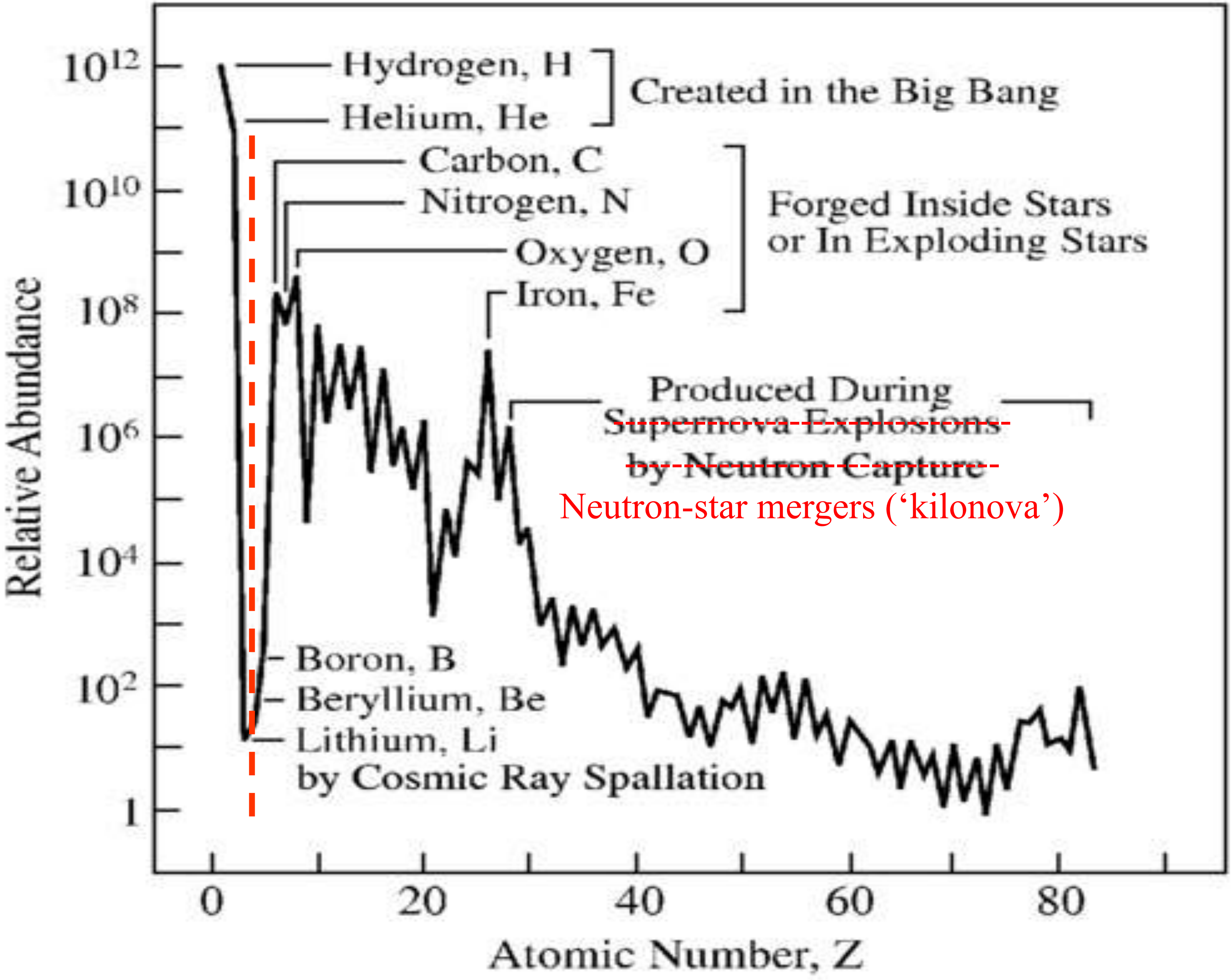
Lanthanide Series*	57 La 138.9	58 Ce 140.1	59 Pr 140.9	60 Nd 144.2	61 Pm (145)	62 Sm 150.4	63 Eu 152.0	64 Gd 157.2	65 Tb 158.9	66 Dy 162.5	67 Ho 164.9	68 Er 167.3	69 Tm 168.9	70 Yb 173.0	71 Lu 175.0
Actinide Series**	89 Ac (227)	90 Th 232	91 Pa 231	92 U 238	93 Np (237)	94 Pu (244)	95 Am (243)	96 Cm (247)	97 Bk (247)	98 Cf (251)	99 Es (252)	100 Fm (257)	101 Md (258)	102 No (259)	103 Lr (262)

Los Alamos NATIONAL LABORATORY

CHEMISTRY

element names in blue are liquids at room temperature
element names in red are gases at room temperature
element names in black are solids at room temperature

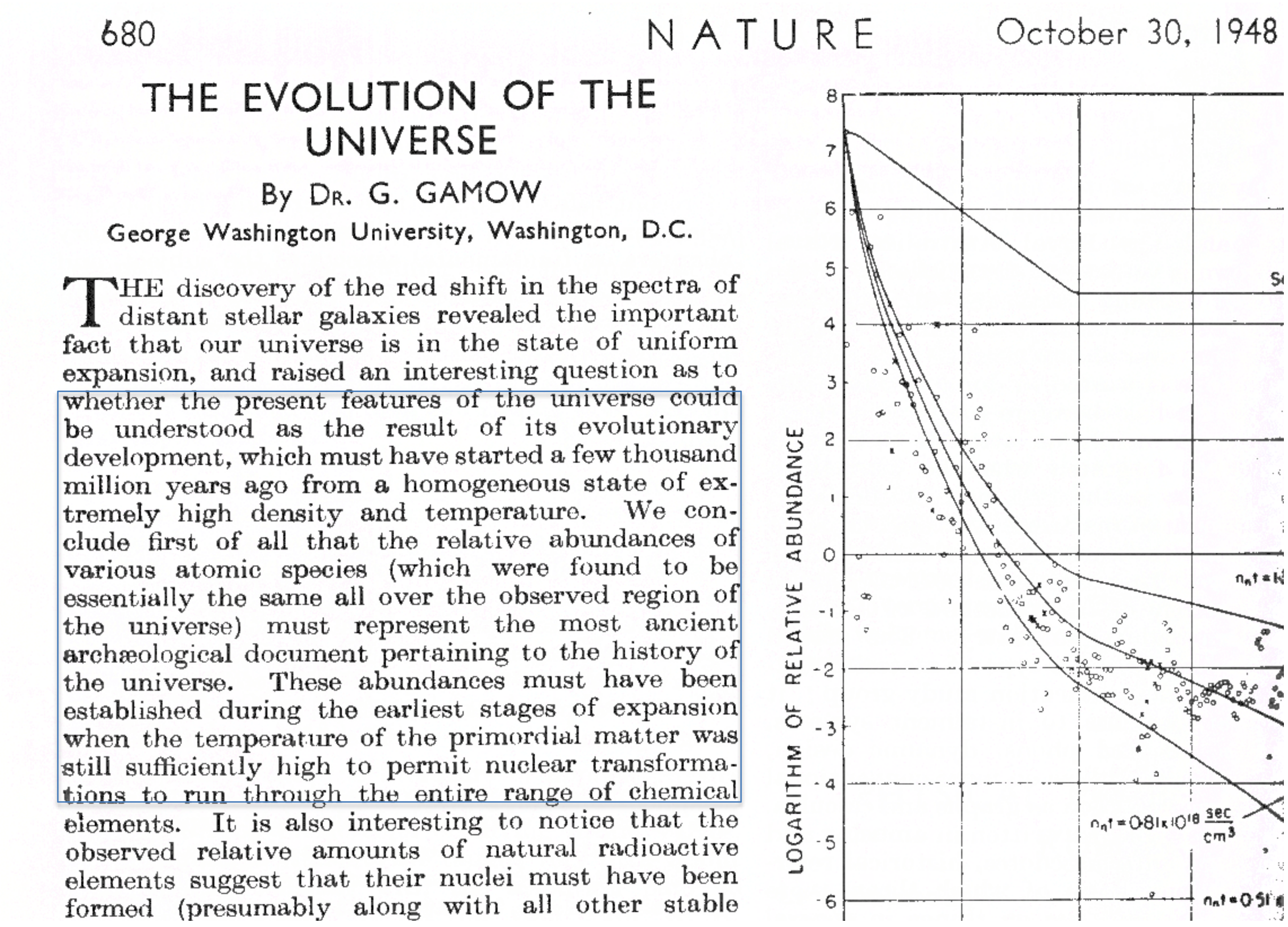
WHERE DID ALL THE ELEMENTS COME FROM?



Neutron-star mergers (‘kilonova’)

Burbidge, Burbidge, Fowler & Hoyle, RMP **29**:547,1957

George Gamow is generally credited with having founded the theory of primordial nucleosynthesis and, as a corollary, predicted the temperature of the relic radiation



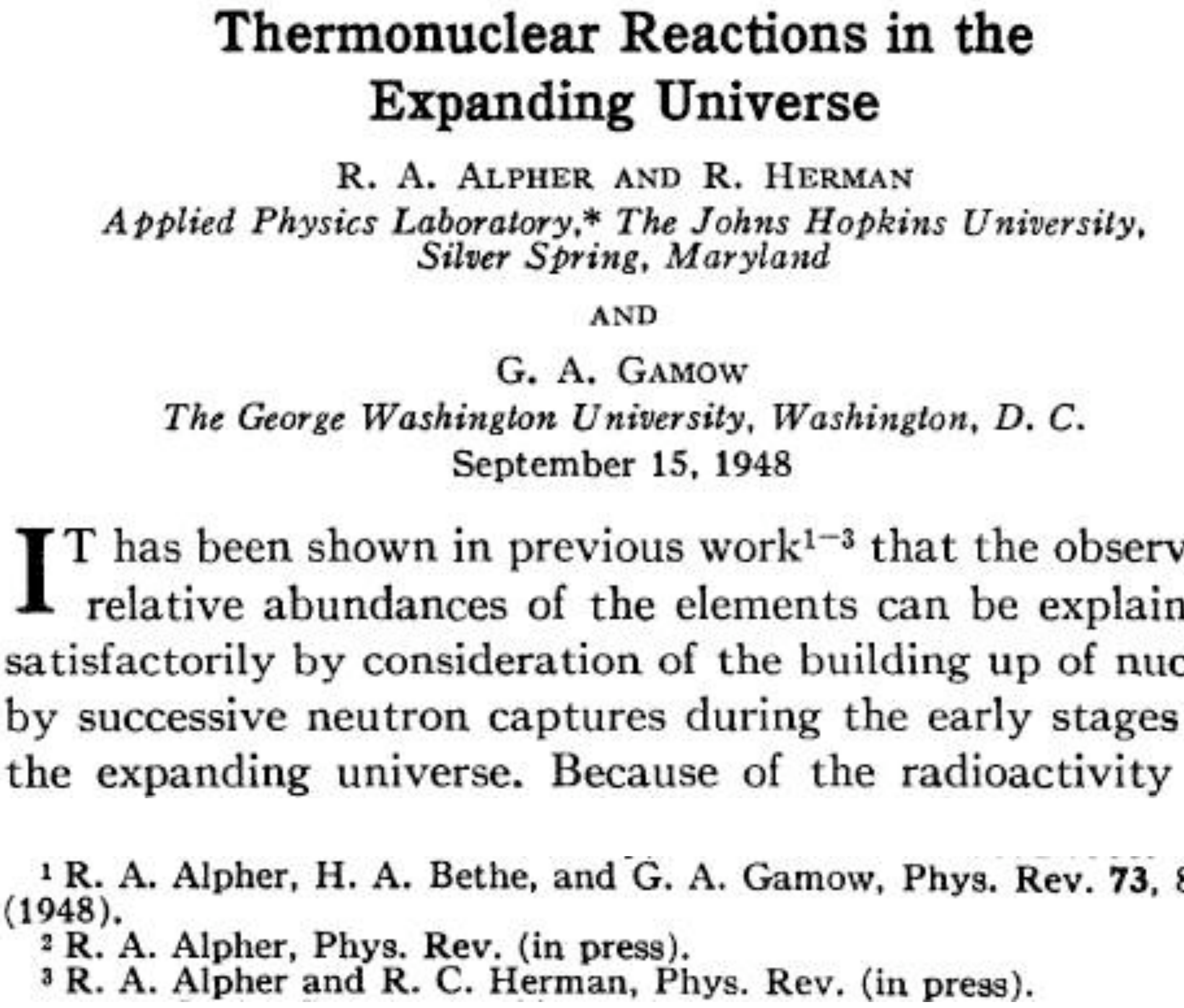
680 NATURE October 30, 1948

THE EVOLUTION OF THE UNIVERSE

By Dr. G. GAMOW
George Washington University, Washington, D.C.

THE discovery of the red shift in the spectra of distant stellar galaxies revealed the important fact that our universe is in the state of uniform expansion, and raised an interesting question as to whether the present features of the universe could be understood as the result of its evolutionary development, which must have started a few thousand million years ago from a homogeneous state of extremely high density and temperature. We conclude first of all that the relative abundances of various atomic species (which were found to be essentially the same all over the observed region of the universe) must represent the most ancient archæological document pertaining to the history of the universe. These abundances must have been established during the earliest stages of expansion when the temperature of the primordial matter was still sufficiently high to permit nuclear transformations to run through the entire range of chemical elements. It is also interesting to notice that the observed relative amounts of natural radioactive elements suggest that their nuclei must have been formed (presumably along with all other stable

The real story is that while Gamow had brilliant ideas, he could not calculate too well, so enlisted the help of graduate student Ralph Alpher and posdoc Robert Herman



Thermonuclear Reactions in the Expanding Universe

R. A. ALPHER AND R. HERMAN
Applied Physics Laboratory, The Johns Hopkins University, Silver Spring, Maryland*

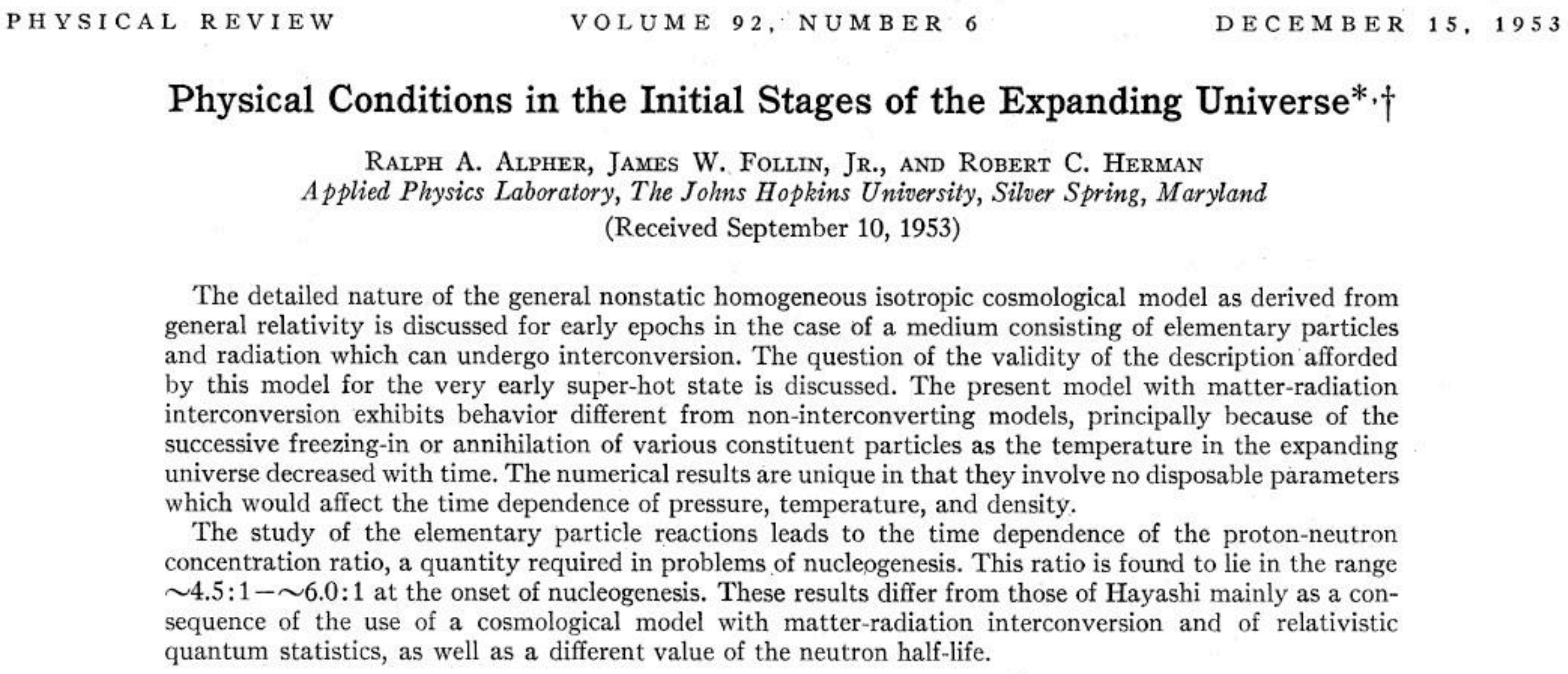
AND

G. A. GAMOW
The George Washington University, Washington, D. C.
September 15, 1948

IT has been shown in previous work[1-3] that the observed relative abundances of the elements can be explained satisfactorily by consideration of the building up of nuclei by successive neutron captures during the early stages of the expanding universe. Because of the radioactivity of

[1] R. A. Alpher, H. A. Bethe, and G. A. Gamow, Phys. Rev. **73**, 803 (1948).
[2] R. A. Alpher, Phys. Rev. (in press).
[3] R. A. Alpher and R. C. Herman, Phys. Rev. (in press).

1) was published on 1 April 1948 … including Bethe (who had nothing to do with it) - but leaving out Herman because he "*stubbornly refused to change his name to Delter*"!



PHYSICAL REVIEW VOLUME 92, NUMBER 6 DECEMBER 15, 1953

Physical Conditions in the Initial Stages of the Expanding Universe*,†

RALPH A. ALPHER, JAMES W. FOLLIN, JR., AND ROBERT C. HERMAN
Applied Physics Laboratory, The Johns Hopkins University, Silver Spring, Maryland

(Received September 10, 1953)

The detailed nature of the general nonstatic homogeneous isotropic cosmological model as derived from general relativity is discussed for early epochs in the case of a medium consisting of elementary particles and radiation which can undergo interconversion. The question of the validity of the description afforded by this model for the very early super-hot state is discussed. The present model with matter-radiation interconversion exhibits behavior different from non-interconverting models, principally because of the successive freezing-in or annihilation of various constituent particles as the temperature in the expanding universe decreased with time. The numerical results are unique in that they involve no disposable parameters which would affect the time dependence of pressure, temperature, and density.

The study of the elementary particle reactions leads to the time dependence of the proton-neutron concentration ratio, a quantity required in problems of nucleogenesis. This ratio is found to lie in the range $\sim$4.5:1—$\sim$6.0:1 at the onset of nucleogenesis. These results differ from those of Hayashi mainly as a consequence of the use of a cosmological model with matter-radiation interconversion and of relativistic quantum statistics, as well as a different value of the neutron half-life.

The modern theory of primordial nucleosynthesis is based essentially on this paper … which followed the crucial observation by Hayashi (Prog.Theoret.Phys.**5:**224,1950) that **neutrons and protons were in chemical equilibrium in the hot early universe**

Alpher's achievement was recognised belatedly when he was awarded the US National Medal of Science in 2005:

"For his unprecedented work in the areas of nucleosynthesis, for the prediction that universe expansion leaves behind background radiation, and for providing the model for the Big Bang theory"

WEAK INTERACTIONS AND NUCLEAR REACTIONS IN EXPANDING, COOLING UNIVERSE

(Hayashi 1950, Alpher, Follin & Herman 1953, Peebles 1966, Wagoner, Fowler & Hoyle 1967)

Dramatis personae:

Radiation (dominates) $\gamma, e^{\pm}, 3\nu\bar{\nu}$

Matter n, p

baryon-to-photon ratio (only free parameter) $n_B/n_\gamma \equiv \eta \simeq 2.74 \times 10^{-8}\Omega_B h^2$

Initial conditions: $T >> 1$ MeV, $t << 1$ s

n-*p* weak equilibrium: $n + \nu_e \leftrightarrow p + e^-$

neutron-to-proton ratio: $p + \nu_e \leftrightarrow n + e^+$

$$\tau_{\text{weak}}(n \leftrightarrow p) \geq t_{\text{universe}} \Rightarrow T_{\text{freeze-out}} \sim \left(G_N / G_F^2\right)^{1/3}$$

Weak freeze-out: $T_f \sim 1$ MeV, $t_f \sim 1$ s

which fixes: $n/p = e^{-(m_n - m_p)/T_f} \approx 1/6$

Deuterium bottleneck: $T \sim 1 \rightarrow 0.07$ MeV

D created by $np \rightarrow D\gamma$

but destroyed by high-E photon tail: $D\gamma \rightarrow np$

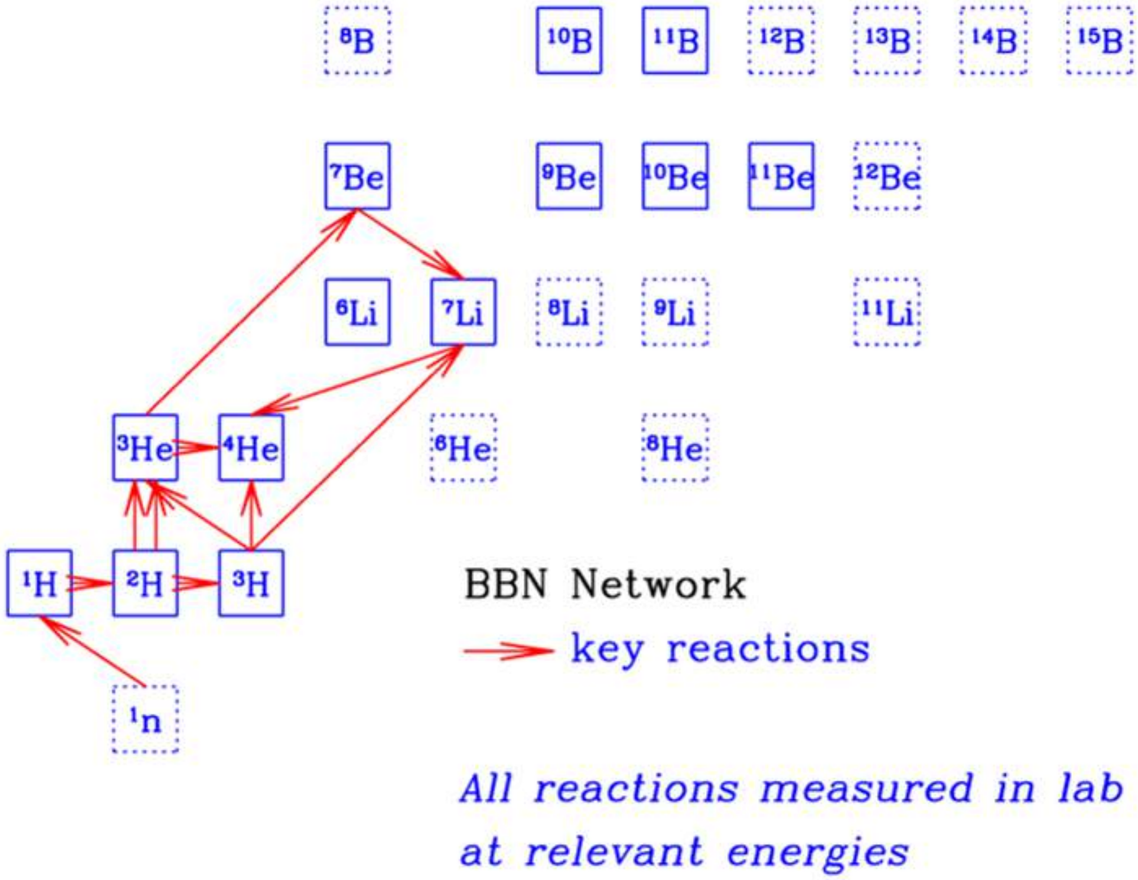
so nucleosynthesis halted until: $T_{\text{nuc}} \sim \Delta_D/-\ln(\eta)$

Element synthesis: $T_{\text{nuc}} \sim 0.07$ MeV, $t_{\text{nuc}} \sim 3$ min

(meanwhile $n/p \rightarrow 1/7$ through neutron β-decay)

nearly all $n \rightarrow {}^4$He ($Y_P \sim 25\%$ by mass) + left-over traces of D, ^{3}He, ^{7}Li (with ^{6}Li/^{7}Li $\sim 10^{-5}$)

No heavier nuclei formed in standard, homogeneous hot Big Bang … must wait for stars to form after a ~billion years and synthesise all the other nuclei in the universe (s-process, r-process, …)

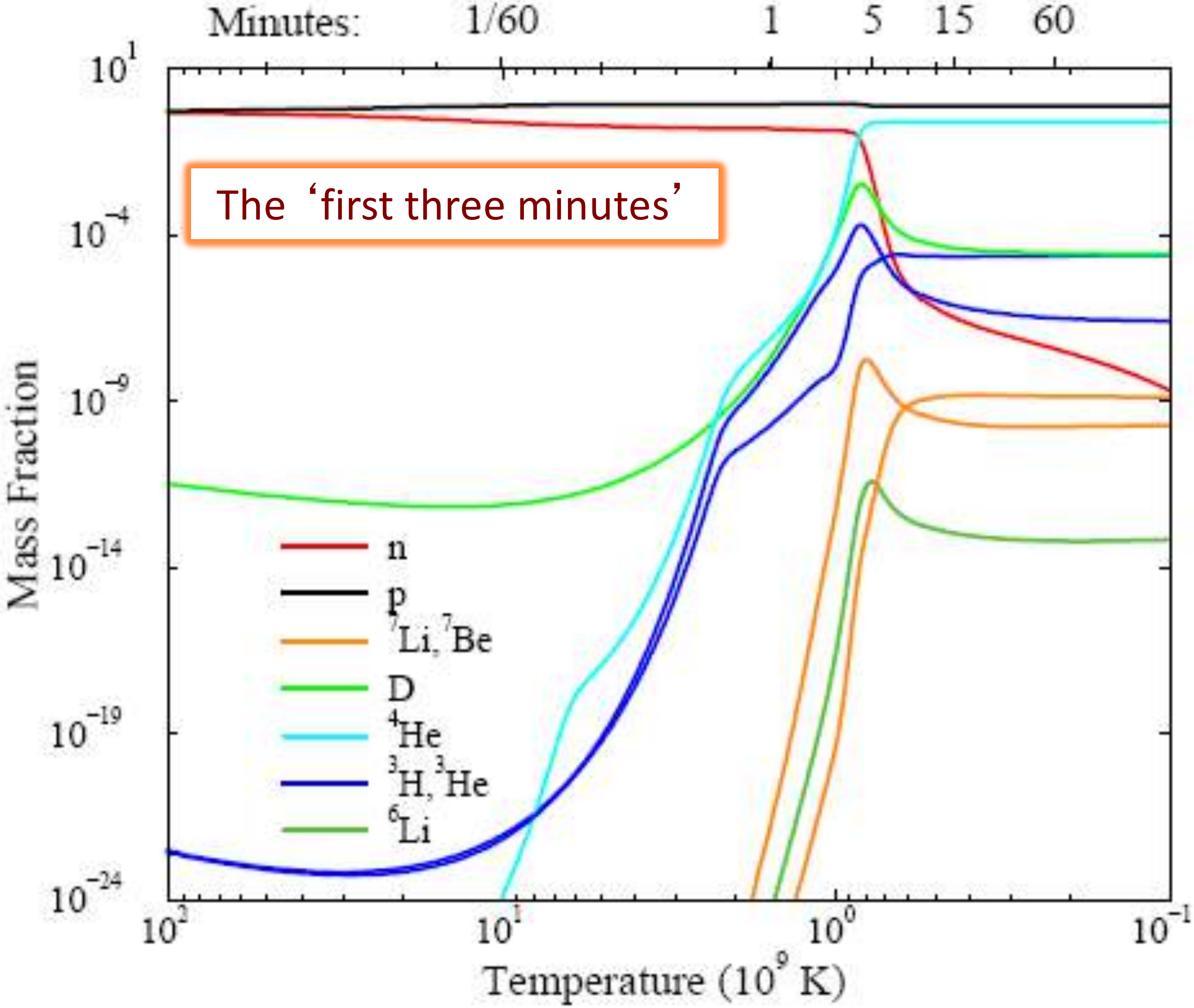


BBN Network

⟶ key reactions

All reactions measured in lab at relevant energies

- Computer code by Wagoner (1969, 1973) .. updated by Kawano (1992)
- Coulomb & radiative corrections, ν heating et cetera (Dicus *et al* 1982)
- Nucleon recoil corrections (Seckel 1993)
- Covariance matrix of correlated uncertainties (Fiorentini *et al* 1998)



The ‘first three minutes’

- **Time < 15 s, Temperature > 3 x 10^9 K**
  - universe is soup of protons, electrons and other particles … so hot that nuclei are blasted apart by high energy photons as soon as they form

- **Time = 15 s, Temperature = 3 x 10^9 K**
  - Still too hot for Deuterium to survive
  - Cool enough for Helium to survive, but too few building blocks

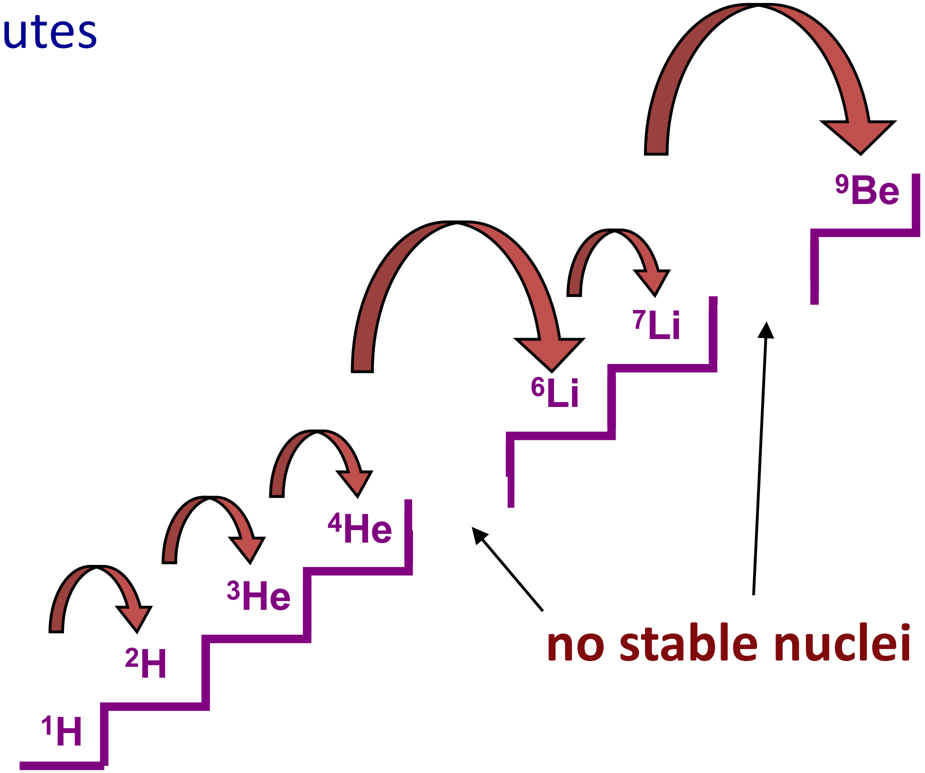
- **Time = 3 min, Temperature = 10^9 K**
  - Deuterium survives and is quickly fused into He
  - no stable nuclei with 5 or 8 nucleons, and this restricts formation of elements heavier than Helium
  - trace amounts of Lithium are formed

- **Time = 35 min, Temperature = 3 x 10^7 K**
  - nucleosynthesis essentially complet (still hot enough to fuse He, but density too low for appreciable fusion)

Model makes predictions about the relative abundances of the light elements ^{2}H, ^{3}He, ^{4}He and ^{7}Li, as a function of the nucleon density

PRIMODIAL VERSUS STELLAR NUCLEOSYNTHESIS

- **Timescale**
  - Stellar Nucleosynthesis (SN): billions of years
  - Primordial Nucleosynthesis (PN): minutes
- **Temperature evolution**
  - SN: slow increase over time
  - PN: rapid cooling
- **Density**
  - SN: 100 g/cm^3
  - PN: 10^{-5} g/cm^3 (like air!)
- **Photon to baryon ratio**
  - SN: less than 1 photon per baryon
  - PN: billions of photons per baryon



The lack of stable elements with masses 5 and 8 make it hard for BBN (2-body processes, short time-scale) to synthesise elements beyond helium

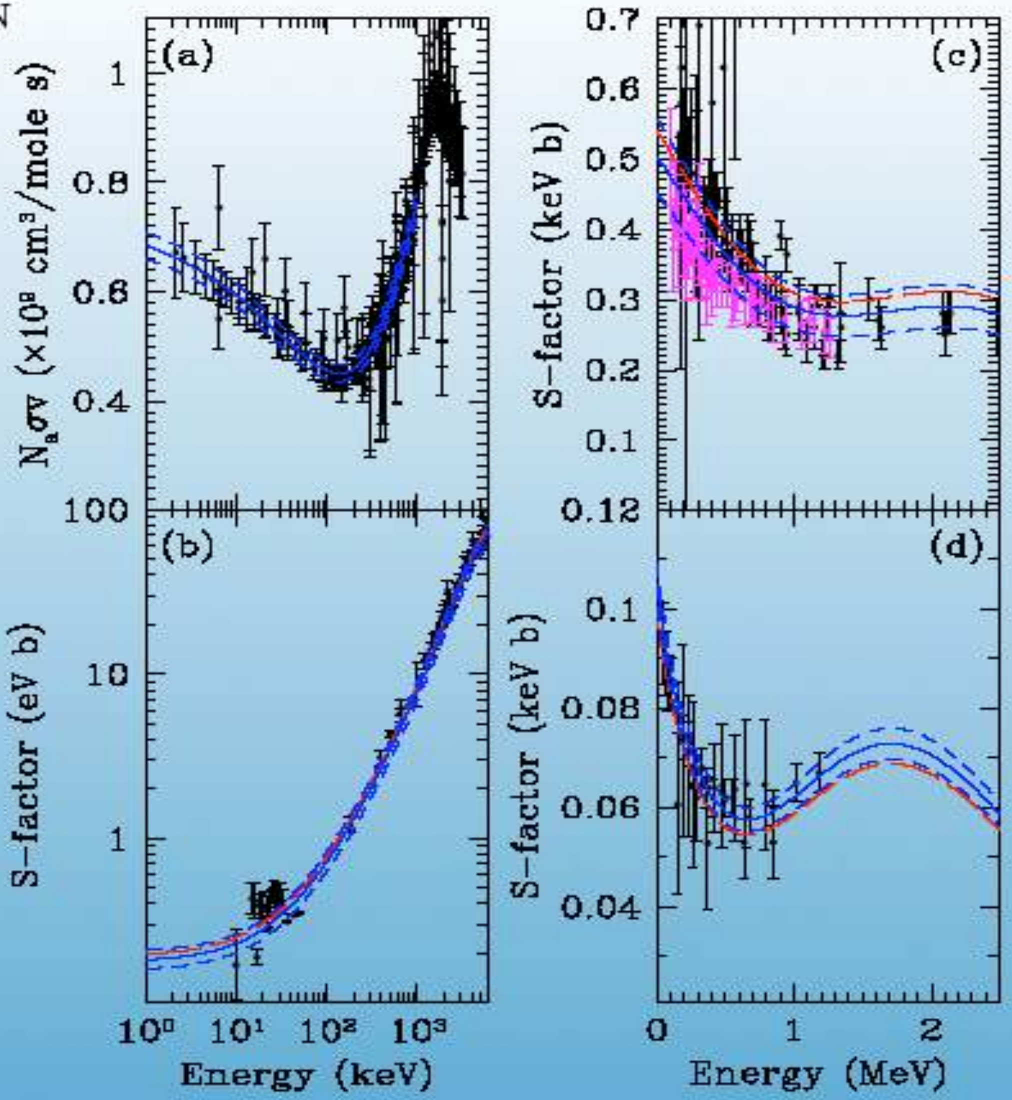
… this can be happen only in stars, on a (much) longer timescale

The neutron lifetime normalises the “weak” interaction rate: τ_n = 880.0 ± 0.9 s
(has recently dropped in value by ~**5σ** because of *one* new measurement!)

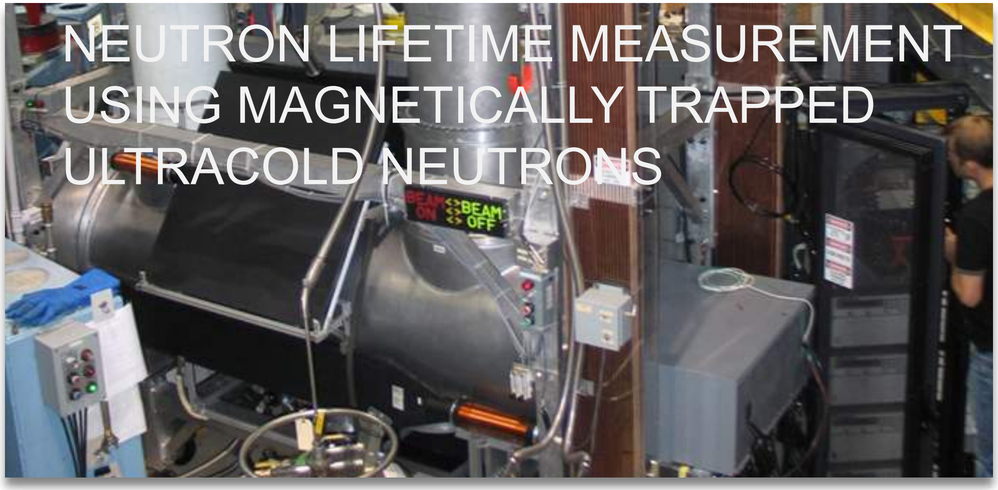
Table 1: Key Nuclear Reactions for BBN

Source	Reactions	
NACRE	$d(p,\gamma)^3$He	(b)
	$d(d,n)^3$He	
	$d(d,p)t$	
	$t(d,n)^4$He	
	$t(\alpha,\gamma)^7$Li	(d)
	^{3}He$(\alpha,\gamma)^7$Be	(c)
	^{7}Li$(p,\alpha)^4$He	
SKM	$p(n,\gamma)d$	
	^{3}He$(d,p)^4$He	
	^{7}Be$(n,p)^7$Li	
This work	^{3}He$(n,p)t$	(a)
PDG	τ_n	

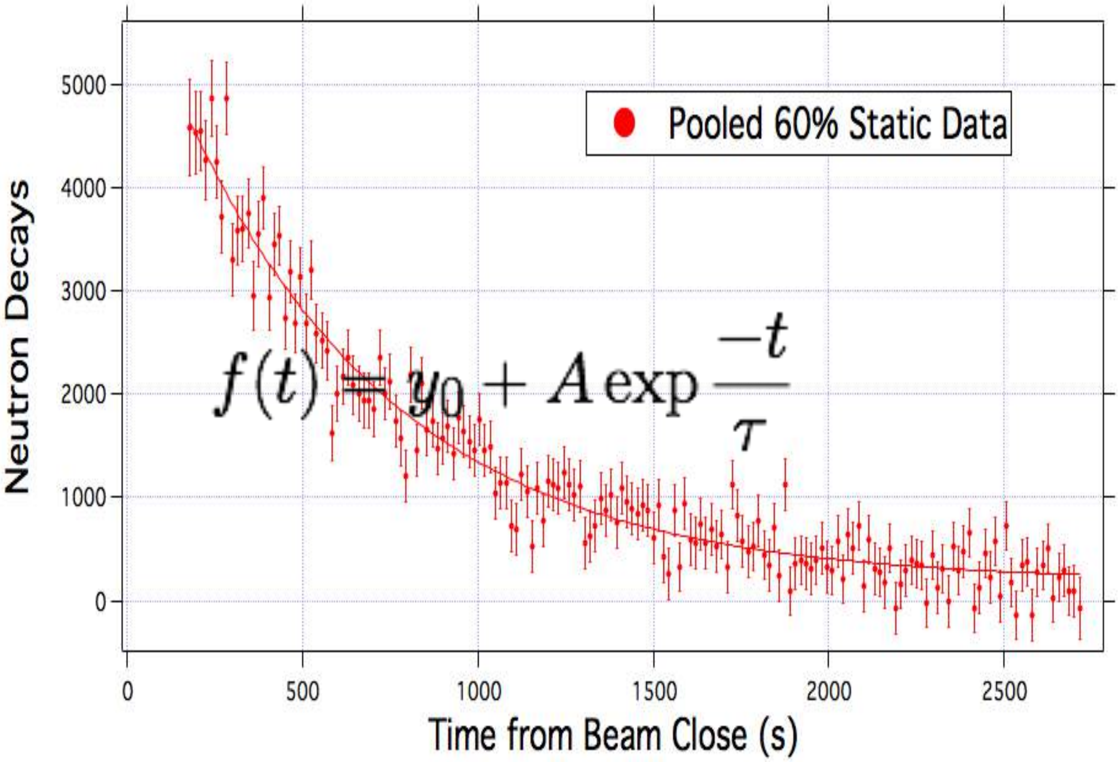
NACRE
Cyburt, Fields, KAO
Nollett & Burles
Coc et al.

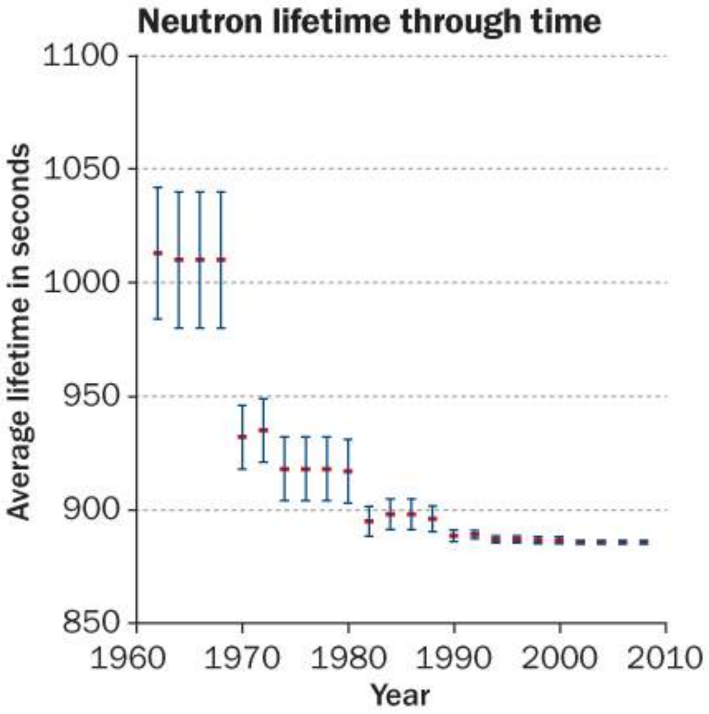


Uncertainties in synthesized abundances are *correlated* … estimate using Monte Carlo
(Smith, Kawano, Malaney 1993; Krauss, Kernan 1994; Cyburt, Fields, Olive 2004)



The neutron lifetime cannot be accurately computed theoretically (even knowing the weak interaction coupling G_F *very* well) because there are corrections due to the strong interactions (which alter g_A/g_V away from unity) .. so it has to be measured experimentally

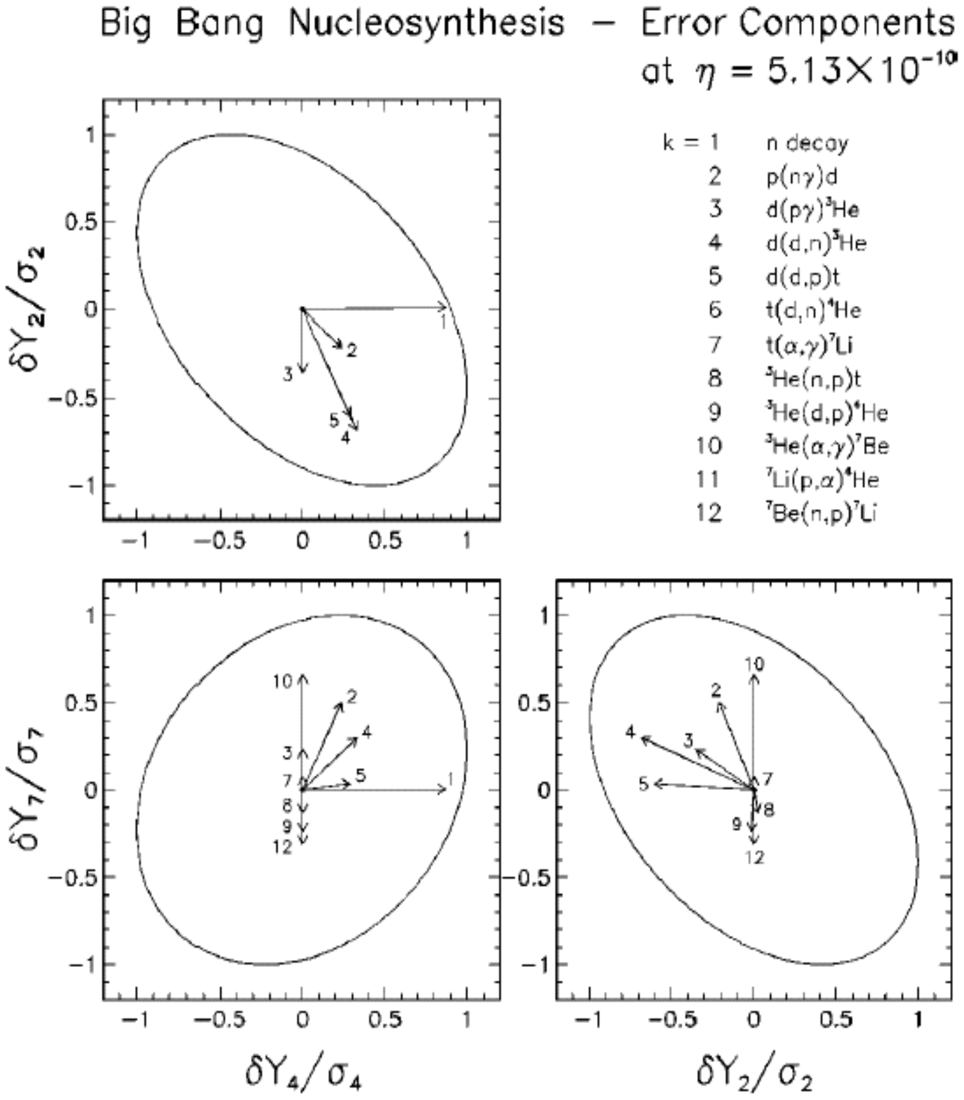




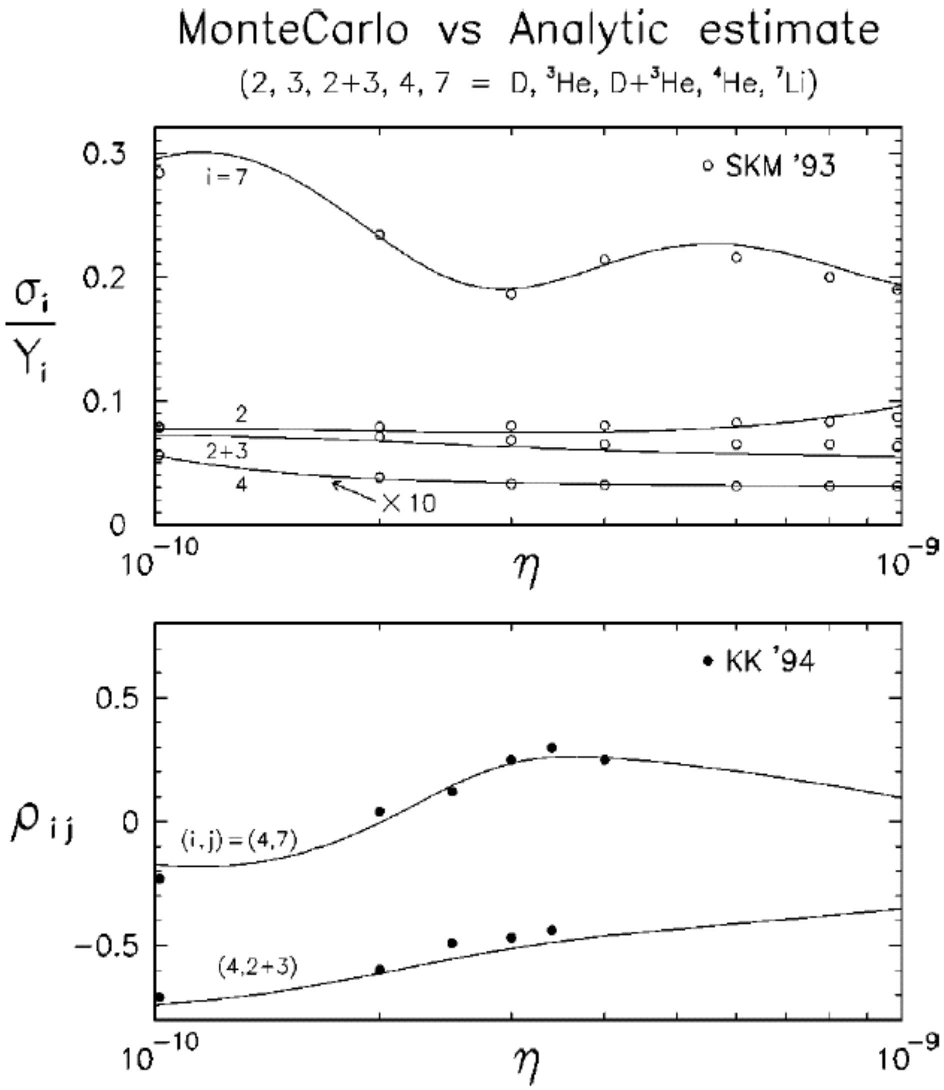
Linear propagation of errors → **covariance matrix** (in *agreement* with Monte Carlo results)

$$Y_i = Y_i(\eta) \pm \sigma_i(\eta) \Rightarrow \delta Y_i(\eta) = Y_i(\eta) \sum_k \lambda_{ik}(\eta) \frac{\delta R_k}{R_k}, \quad \lambda_{ik}(\eta) = \frac{\partial \ln Y_i(\eta)}{\partial \ln R_k(\eta)}$$

$$\sigma^2_{ij}(\eta) = Y_i(\eta) Y_j(\eta) \sum_k \lambda_{ik}(\eta) \lambda_{jk}(\eta) \left(\frac{\Delta R_k}{R_k} \right)^2 \Rightarrow \sigma_i(\eta) = \sqrt{\sigma^2_{ii}(\eta)}, \quad \rho_{ij}(\eta) = \frac{\sigma^2_{ij}(\eta)}{\sigma_i(\eta)\sigma_j(\eta)}$$



Big Bang Nucleosynthesis – Error Components at $\eta = 5.13 \times 10^{-10}$



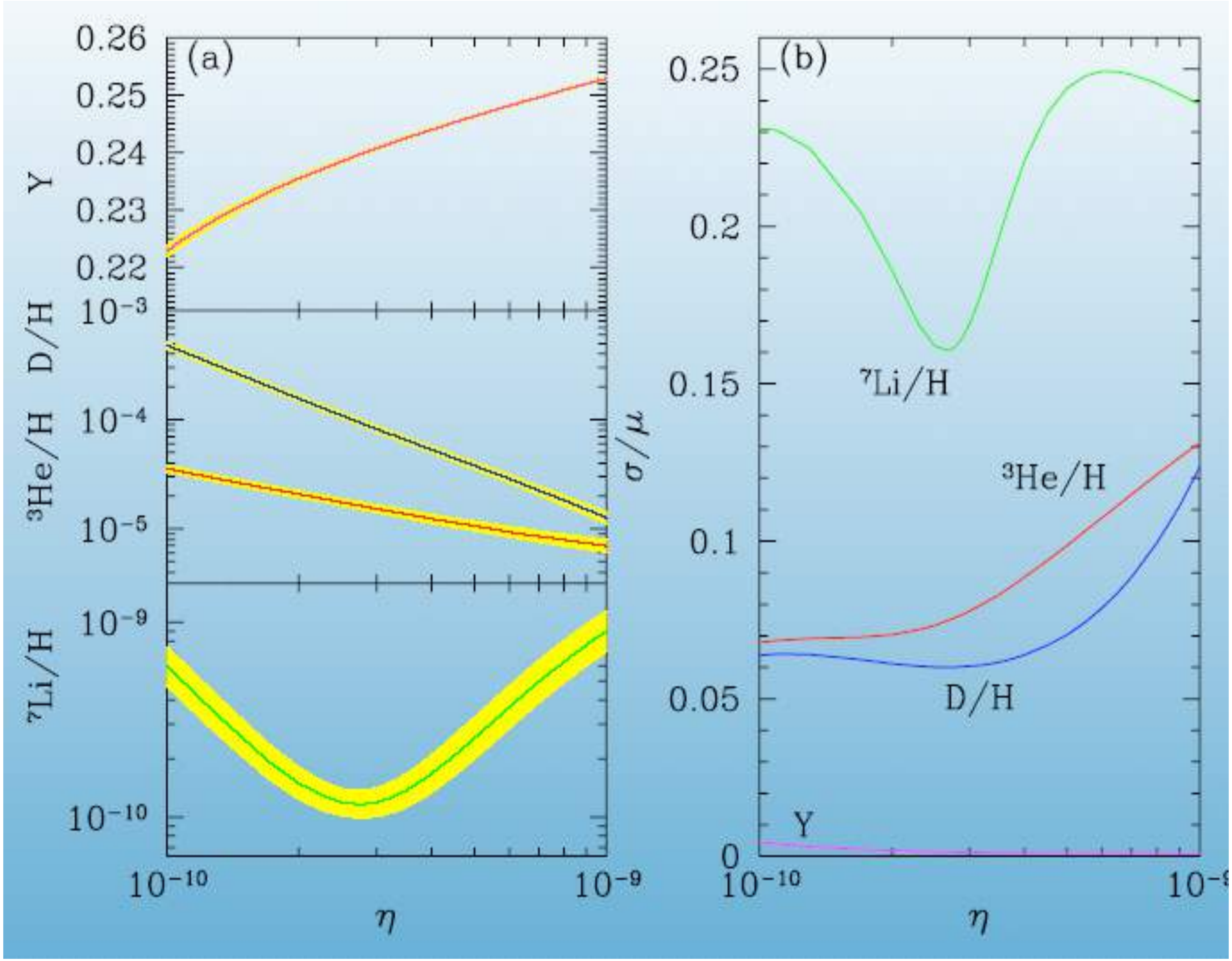
MonteCarlo vs Analytic estimate

(2, 3, 2+3, 4, 7 = D, ³He, D+³He, ⁴He, ⁷Li)

Fiorentini, Lisi, Sarkar, Villante, Phys.Rev.D58:063506,1998

BBN PREDICTIONS

line widths ⇒ theoretical uncertainties (neutron lifetime, nuclear #-sections)



NUCLEOSYNTHESIS *WITHOUT* A COMPUTER

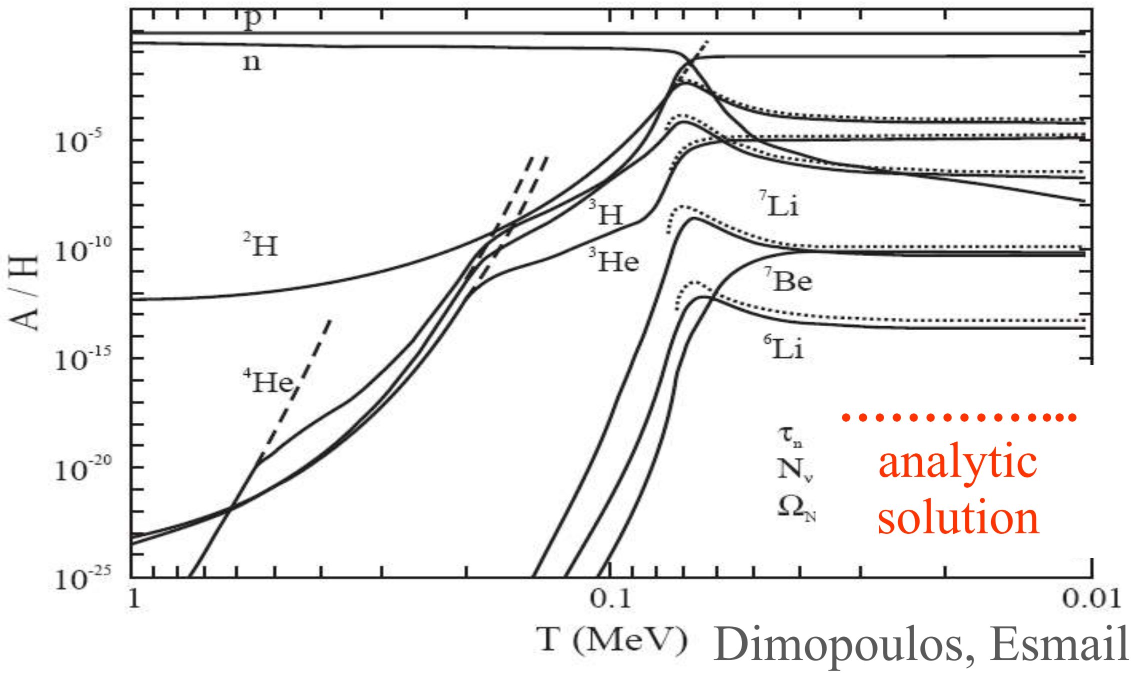
$$\frac{\mathrm{d}X}{\mathrm{d}t} = \underset{\text{source}}{J(t)} - \underset{\text{sink}}{\Gamma(t)X} \qquad \Rightarrow \qquad X^{\mathrm{eq}} = \frac{J(t)}{\Gamma(t)}$$

… but general solution is:

$$X(t) = \exp\left(-\int_{t_i}^{t} \mathrm{d}t'\ \Gamma(t')\right)\left[X(t_i) + \int_{t_i}^{t} \mathrm{d}t'\ J(t')\ \exp\left(-\int_{t_i}^{t} \mathrm{d}t''\ \Gamma(t'')\right)\right]$$

If $\left|\frac{\dot{J}}{J} - \frac{\dot{\Gamma}}{\Gamma}\right| \ll \Gamma$ … then abundances approach equilibrium values

Freeze-out occurs when: $\Gamma \simeq H \quad \Rightarrow \quad X(t\to\infty) \simeq X^{\mathrm{eq}}(t_{\mathrm{fr}}) = \frac{J(t_{\mathrm{fr}})}{\Gamma(t_{\mathrm{fr}})}$



Dimopoulos, Esmailzadeh, Hall, Starkman, ApJ **378**:504,1991

Examine reaction network to identify the largest 'source' and 'sink' terms

obtain D, ^{3}He and ^{7}Li to within a factor of ~2 of exact numerical solution, and ^{4}He to within a few %

… can use this formalism to determine *joint* dependence of abundances on expansion rate as well as baryon-to-photon ratio

$$\frac{\mathrm{d}Y_i}{\mathrm{d}t} \propto \eta \sum_{+,-} Y \times Y \times \langle \sigma v \rangle_T \quad \text{and} \quad dT/dt \propto -T^3 \sqrt{g_\star} \quad \text{so:}$$

$$\frac{\mathrm{d}Y_i}{\mathrm{d}T} \propto -\frac{\eta}{g_\star^{1/2}} T^{-3} \sum_{+,-} Y \times Y \times \langle \sigma v \rangle_T \Rightarrow \log \eta - \frac{1}{2} \log g_\star = \mathrm{const}$$

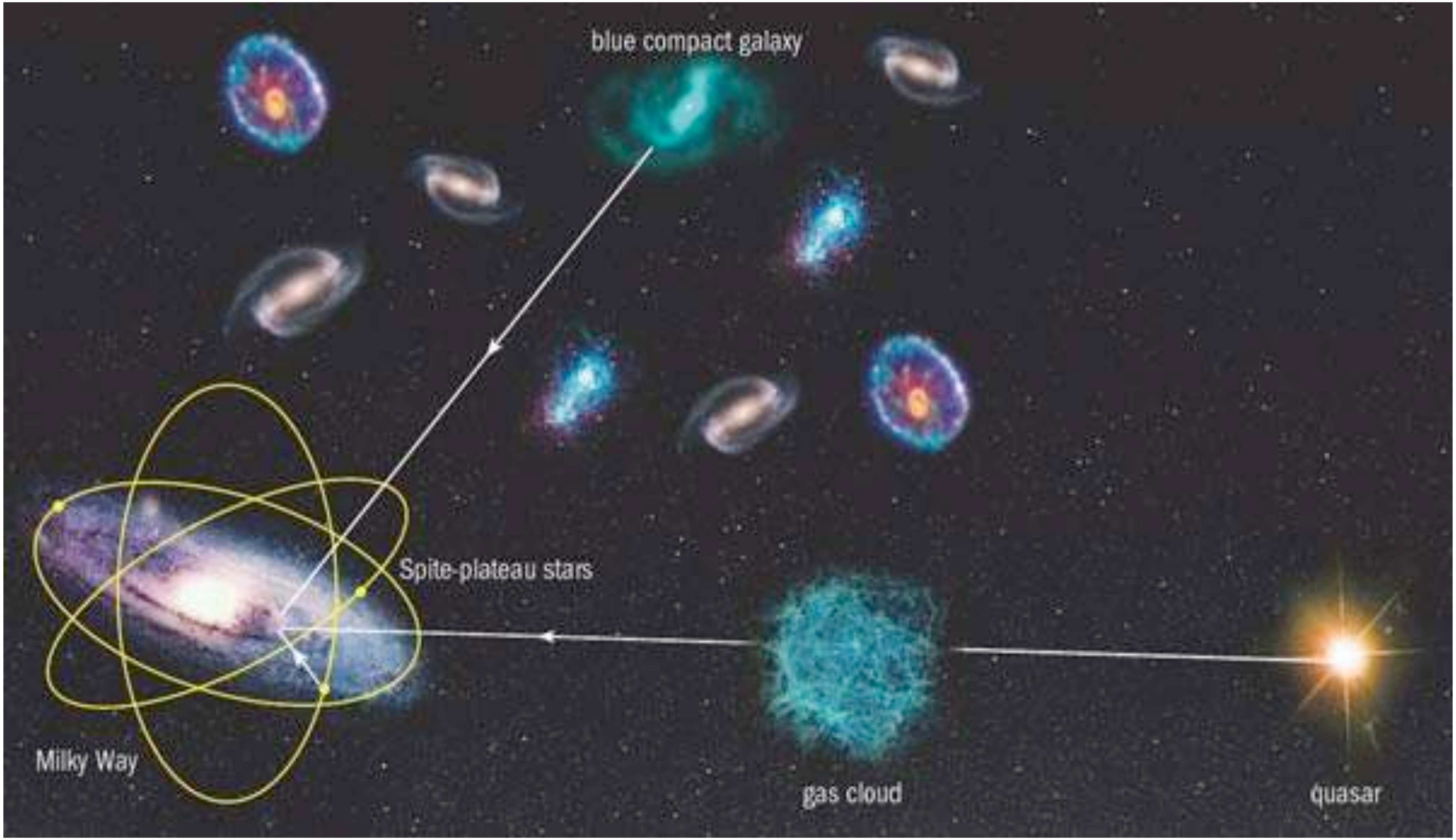
… can therefore employ simple χ^2 statistics to determine best-fit values and uncertainties (*faster* than Monte Carlo + Maximum Likelihood)

$$S_{ij}^2(\eta) = \sigma_{ij}^2(\eta) + \overline{\sigma_{ij}^2} \qquad \overline{\sigma_{ij}^2} = \delta_{ij} \overline{\sigma}_i \overline{\sigma}_j \qquad W_{ij}(\eta) = [S_{ij}^2(\eta)]^{-1}$$

$$\chi^2(\eta) = \sum_{ij} [Y_i(\eta) - \overline{Y}_i] W_{ij}(\eta) [Y_j(\eta) - \overline{Y}_j]$$

Lisi, Sarkar, Villante, Phys.Rev.D**59**:123520,1999

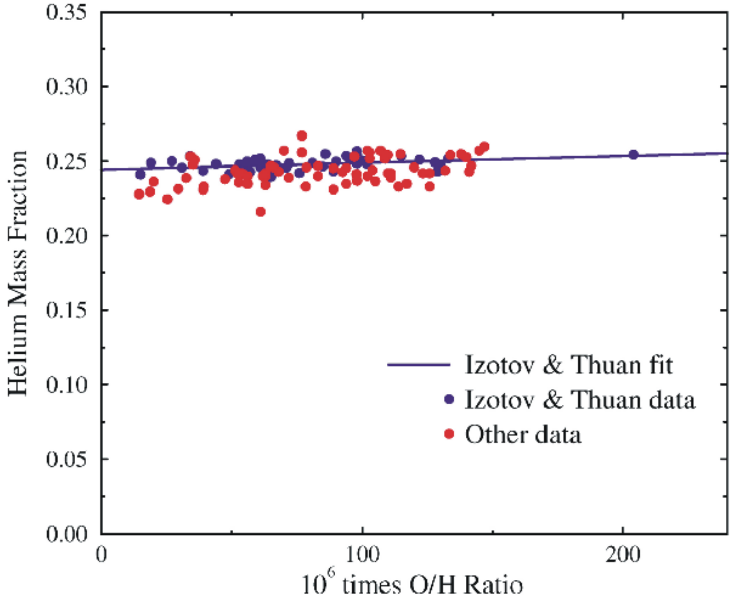
INFERRING PRIMORDIAL ABUNDANCES



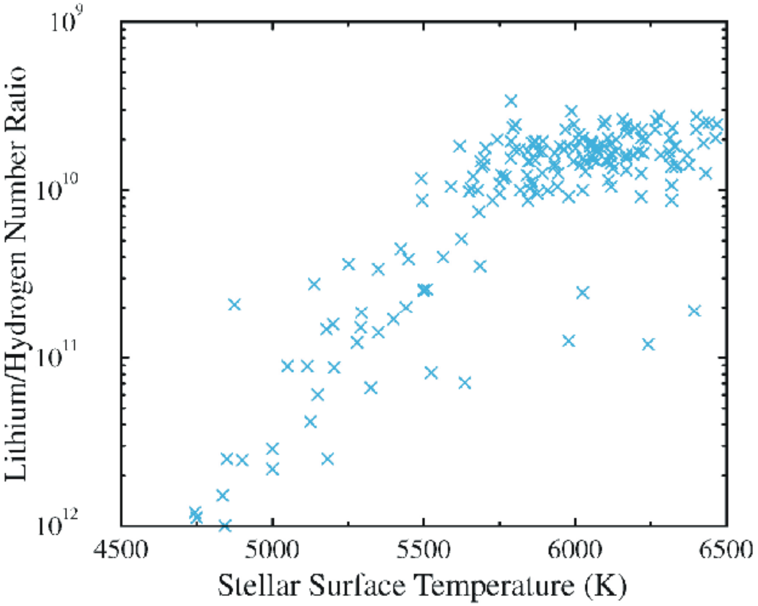
OBSERVATIONS OF THE LIGHT ELEMENTS HE AND LI

- **Helium Abundance**
  - measured in extragalactic HII regions with lowest observed abundances of heavier elements such as Oxygen and Nitrogen

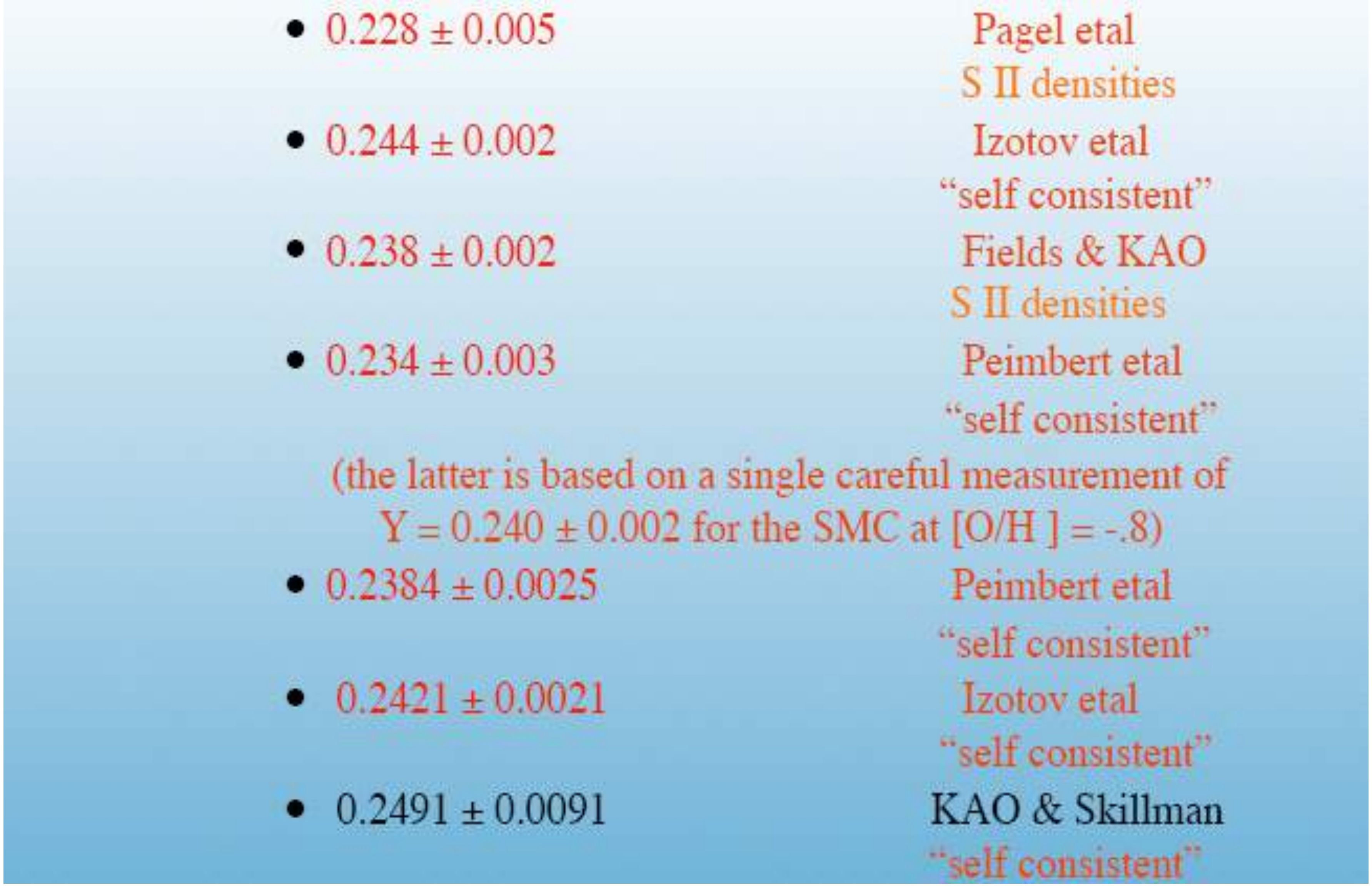
  (i.e. smallest levels of contamination from stellar nucleosynthesis)



- **Lithium Abundance**
  - measured in halo Pop II stars
  - Lithium is easily destroyed hence observe the transition from low mass stars (low surface temp) whose core material is well mixed by convection, to higher mass stars (higher surface temp) where mixing of core is not efficient



For a quantity of such fundamental cosmological importance, relatively *little* effort has been spent on measuring the primordial helium abundance



•	0.228 ± 0.005	Pagel etal S II densities
•	0.244 ± 0.002	Izotov etal “self consistent”
•	0.238 ± 0.002	Fields & KAO S II densities
•	0.234 ± 0.003	Peimbert etal “self consistent”

(the latter is based on a single careful measurement of $Y = 0.240 \pm 0.002$ for the SMC at [O/H] = -.8)

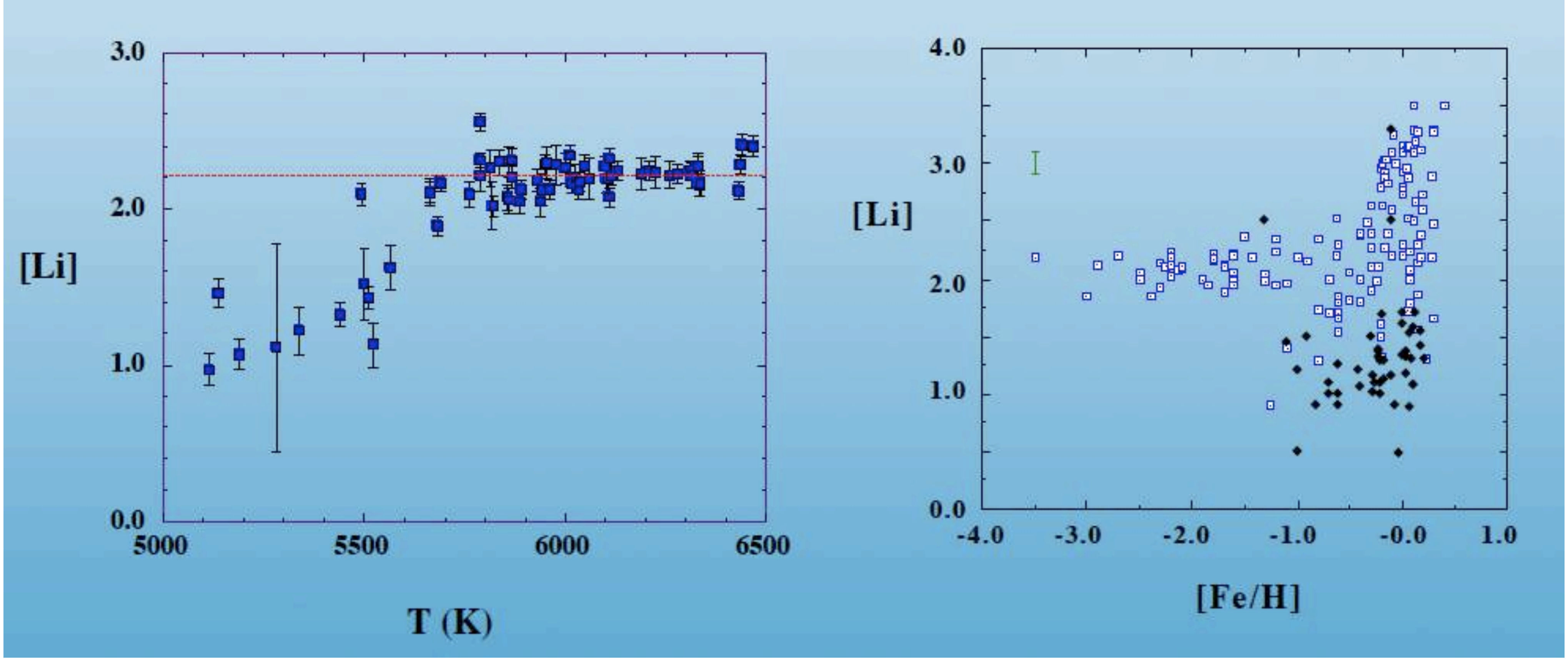
•	0.2384 ± 0.0025	Peimbert etal “self consistent”
•	0.2421 ± 0.0021	Izotov etal “self consistent”
•	0.2491 ± 0.0091	KAO & Skillman “self consistent”

Recent reevaluations (e.g. Aver *et al*, JCAP 07:011,2015, Izotov *et al*, MNRAS **445**:778,2014) are consistent with **$Y_P = 0.245 \pm 0.003$**

PRIMORDIAL LITHIUM

Observe in primitive (Pop II) stars: (most abundant isotope is ^{7}Li)

- Li-Fe correlation ⇒ mild evolution
- Transition from low mass/surface temp stars (core well mixed by convection) to higher mass/temp stars (mixing of core is not efficient)



'Plateau' at low Fe (high T) ⇒ constant abundance at early epochs
… so *infer* observed '^{7}Li plateau' is primordial (Spite & Spite 1982)

PRIMORDIAL DEUTERIUM?

Look in **Q**uasar **A**bsorption**S**ystems - low density clouds of gas seen in absorption along the lines of sight to distant quasars (when universe was only ~10% of its present age)

The difference between H and D nuclei causes a *small* change in the energies of electron transitions, shifting their absorption lines apart and enabling D/H to be measured

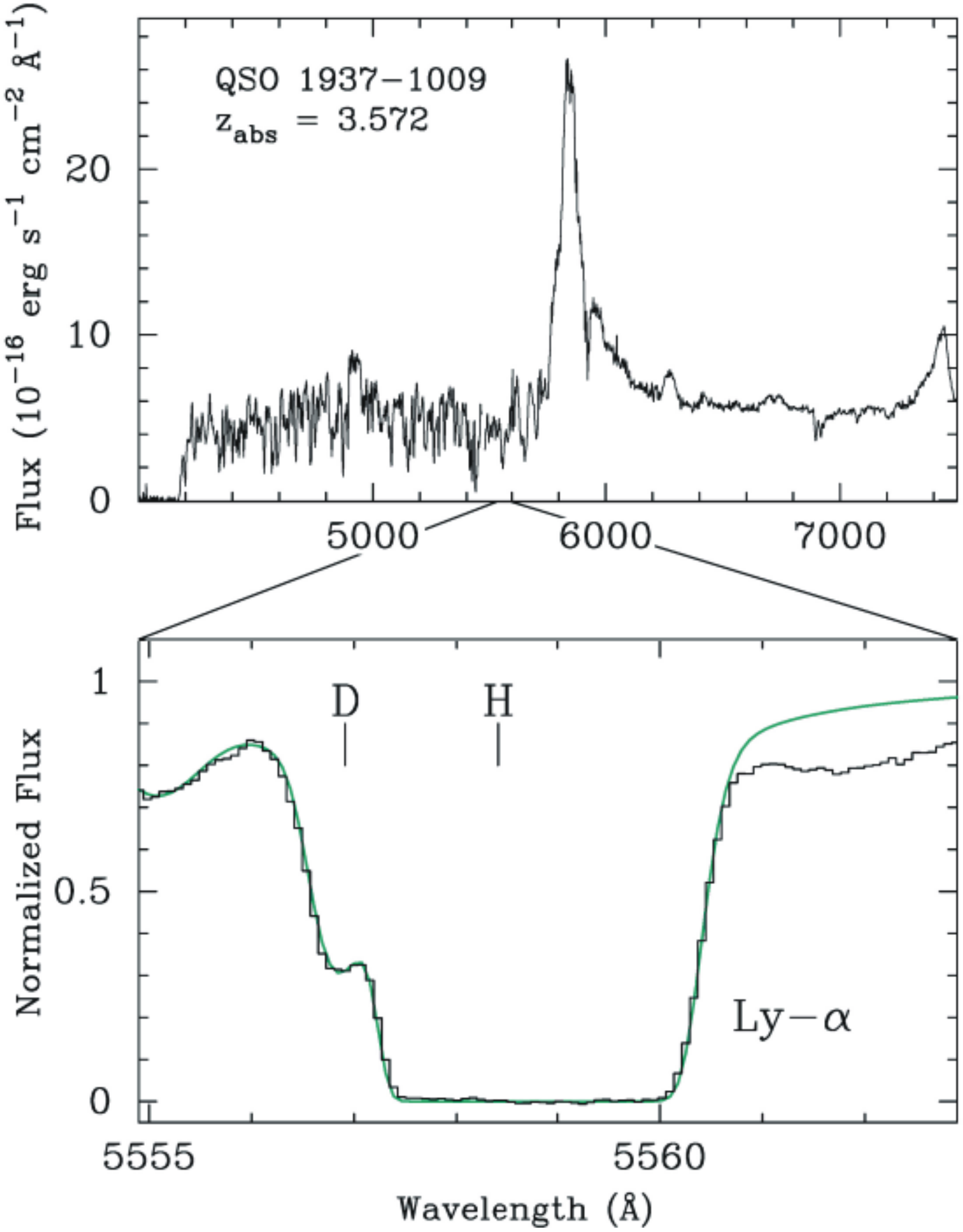
$$E_{\mathrm{Ly}-\alpha} \sim \alpha^2 \mu_{\mathrm{reduced}}$$

$$\frac{\delta\lambda_{\mathrm{D}}}{\lambda_{\mathrm{H}}} = -\frac{\delta\mu_{\mathrm{D}}}{\mu_{\mathrm{H}}} = -\frac{m_e}{2m_p}$$

$$c\delta z = 82 \;\; \mathrm{km/s}$$

But:

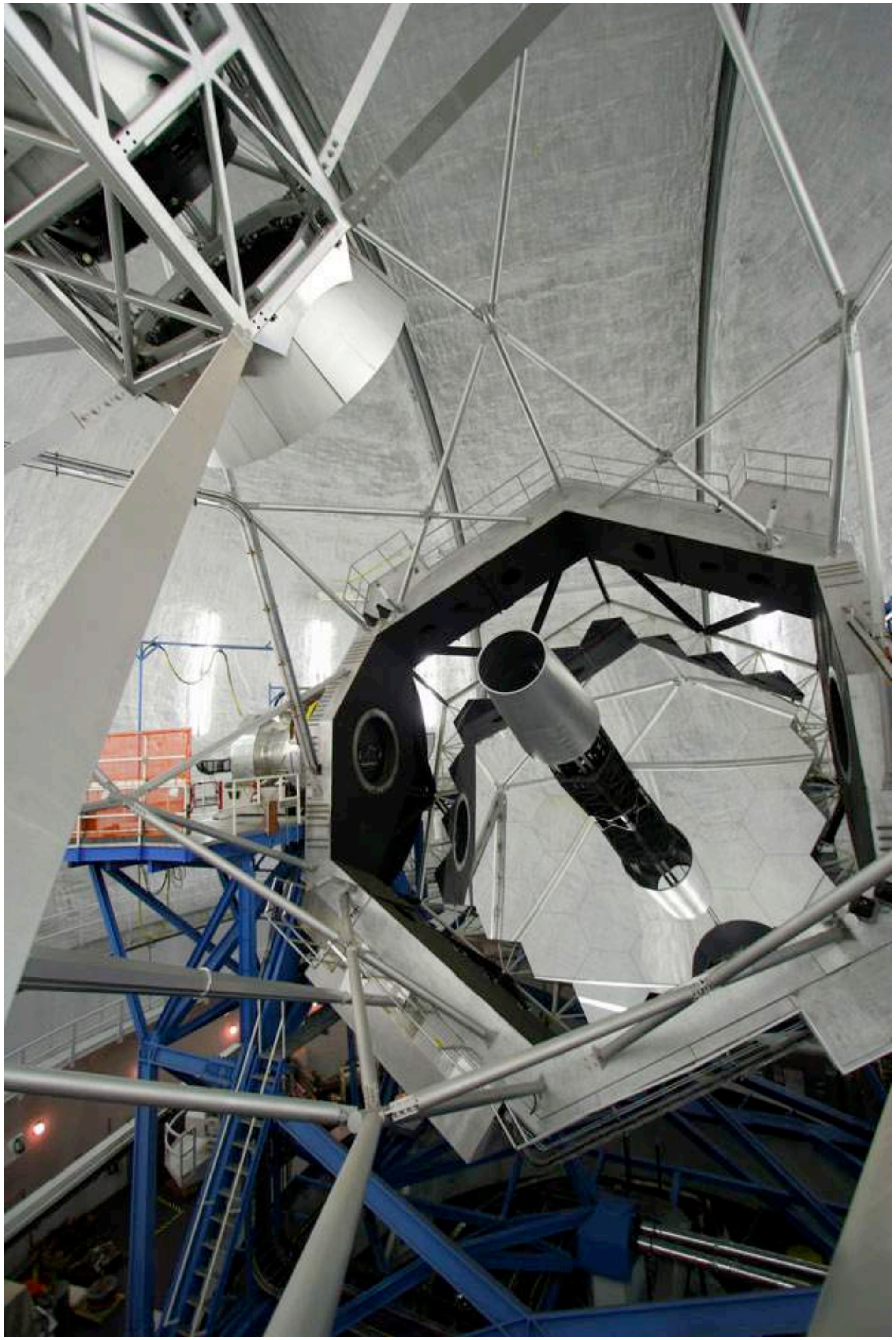
- Hard to find clean systems
- Do not resolve clouds
- Dispersion/systematics?



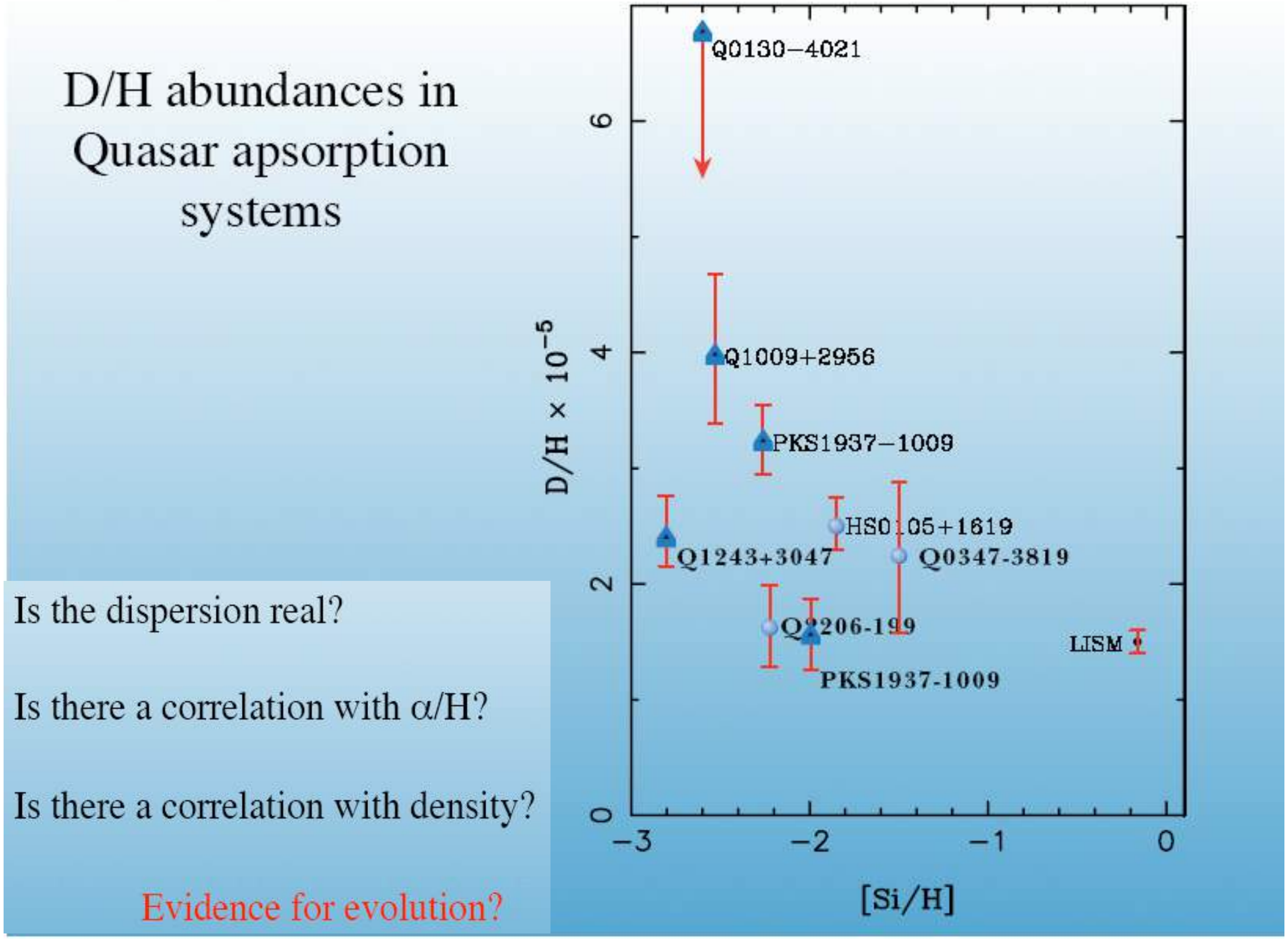
Kirkman, Tytler, Suzuki, O'Meara, Lubin, ApJS 149:1,2003

W. M. KECK OBSERVATORY

Spectra with the necessary resolution for such distant objects *can* be obtained with 10 m class telescopes … this has revolutionised the determination of the primordial D abundance



The observed scatter is *not* consistent with fluctuations about an average value!



D/H abundances in Quasar apsorption systems

Is the dispersion real?

Is there a correlation with α/H?

Is there a correlation with density?

Evidence for evolution?

Progress made by looking at ‘damped Ly-*a*’ systems in which the H column density can be precisely measured and *many* resolved D absorption lines are seen – leading to a determination of log(D/H) = −4.597±0.006 (Cooke & Pettini, MNRAS **425**:1244,2012)

INFERRED PRIMORDIAL ABUNDANCES

^{4}He observed in extragalactic HII regions:

$$Y_P = 0.245 \pm 0.003$$

^{2}H observed in quasar absorption systems (and ISM):

$$D/H|_P = (2.569 \pm 0.027) \times 10^{-5}$$

^{7}Li observed in atmospheres of dwarf halo stars:

$$Li/H|_P = (1.6 \pm 0.3) \times 10^{-10}$$

(^{3}He can be both created & destroyed in stars … so primordial abundance *cannot* be reliably estimated)

Systematic errors have been re-evaluated based on scatter in data

(Particle Data Group, Phys.Rev.D**98**:030001,2018)

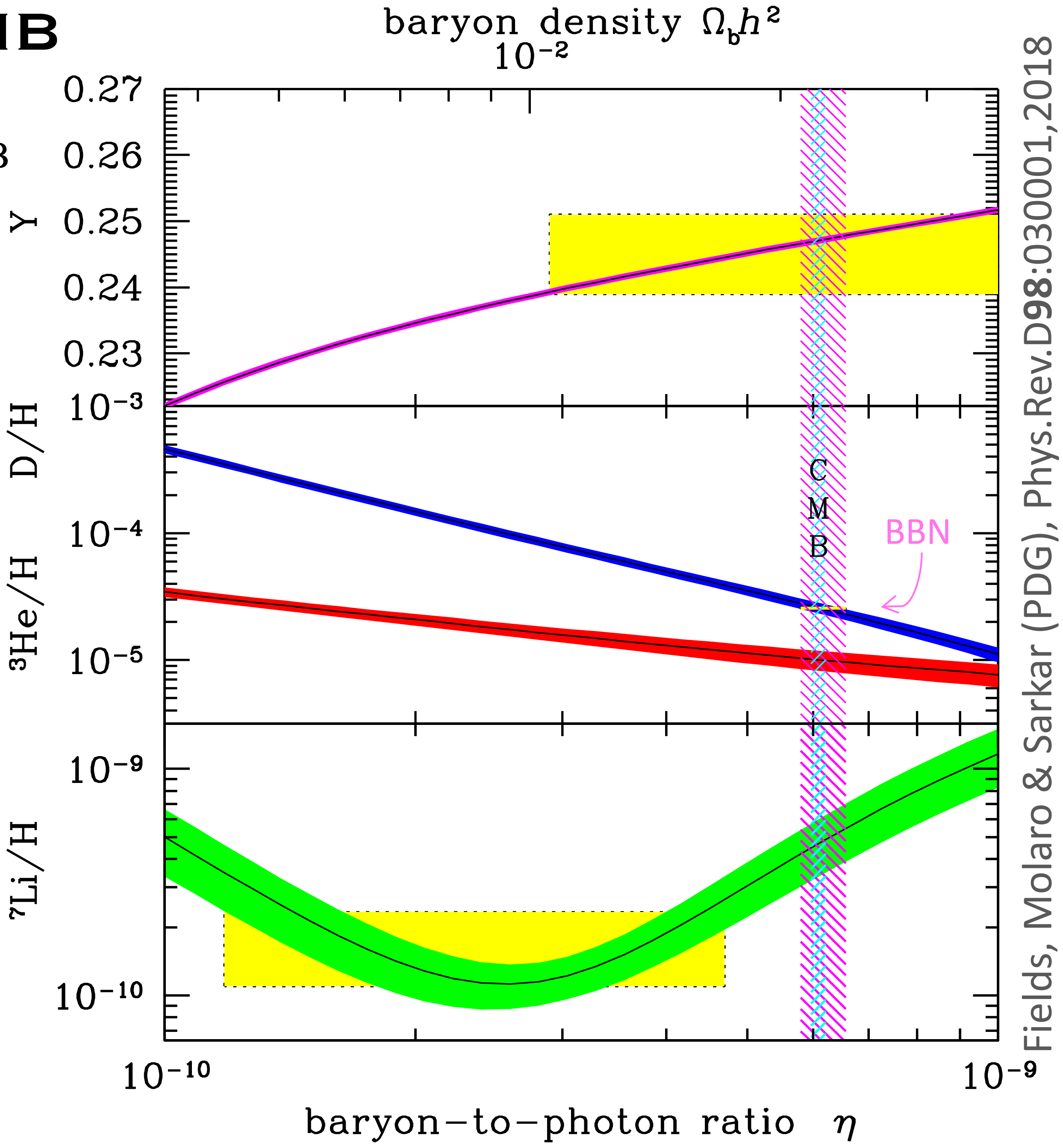
BBN VERSUS CMB

η_{BBN} is in agreement with η_{CMB}
allowing for large uncertainties
in the *inferred* abundances
$5.8 < \eta_{10} < 6.6$ (95% CL)

Confirms and sharpens the
case for (two kinds of)
dark matter

Baryonic Dark Matter:
warm-hot IGM, Ly-α , X-ray gas
+
Non-baryonic dark matter: ?

Constrains the Hubble
expansion rate at $t \sim 1$ s
⇒ bounds on new particles



Fields, Molaro & Sarkar (PDG), Phys.Rev.D**98**:030001,2018

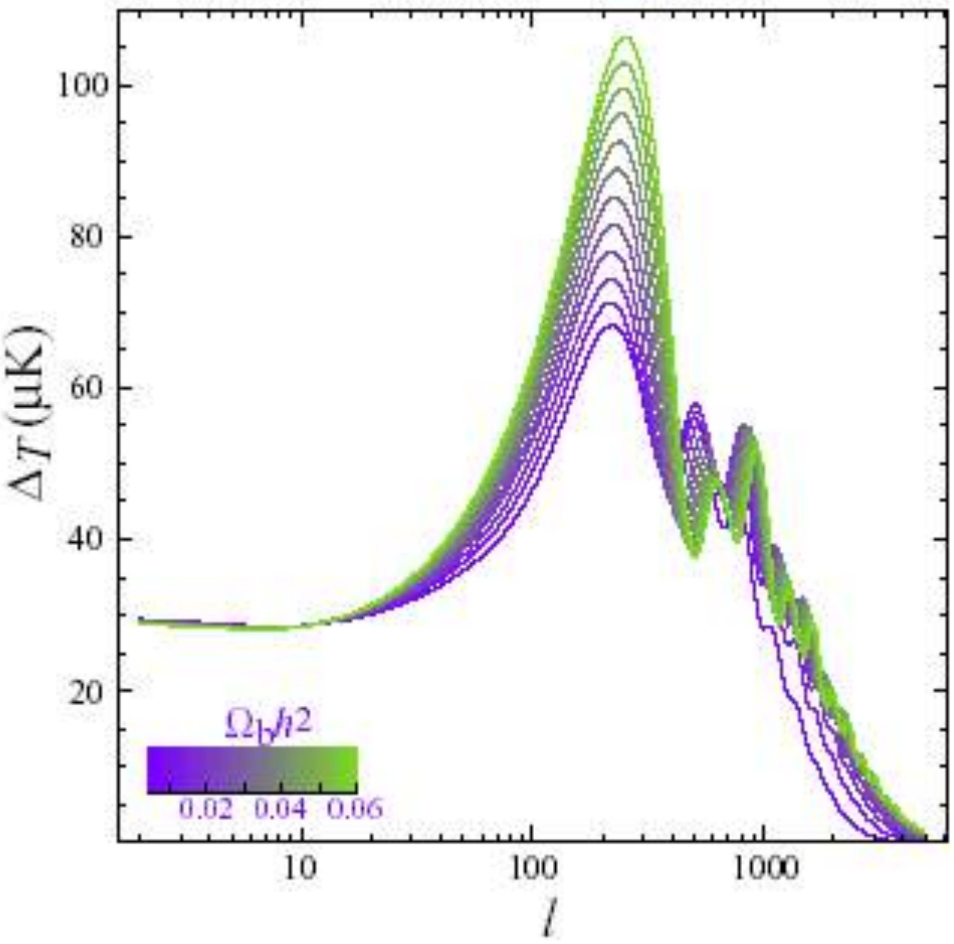
There is a “lithium problem” *possibly* indicative of non-standard physics

THE COSMIC MICROWAVE BACKGROUND

ΔT_ℓ provide *independent* measure of $\Omega_b h^2$

Acoustic oscillations in (coupled) photon-baryon fluids imprint features at small angles (< 1°) in CMB angular power spectrum

Detailed peak positions, heights, … sensitive to cosmological parameters
e.g. 2nd/1st peak ratio ⇒ baryon density



e.g. Planck best-fit:

$\Omega_b h^2 = 0.0223 \pm 0.0002$

$\Rightarrow \eta_{10} = 6.09 \pm 0.06$

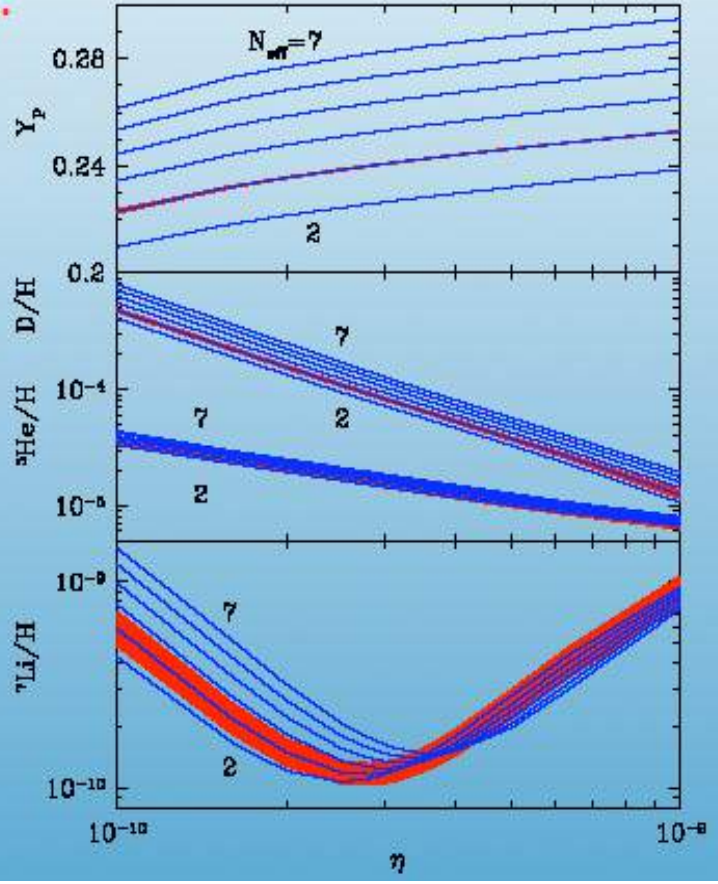
(NB: degeneracies with e.g. n_s, τ …)

Bond & Efstathiou, ApJ **285**:L45,1984
Dodelson & Hu, ARAA **40**:171,2002

NB: The CMB measure of the baryon-to-photon ratio is at *t*~400,000 yr, *cf*. *t*~1 s for BBN, so the two should agree only if there has been no dissipation of energy in between ….

Limits on Particle Properties

- BBN Concordance rests on balance between interaction rates and expansion rate.
- Allows one to set constraints on:
  - Particle Types
  - Particle Interactions
  - Particle Masses
  - Fundamental Parameters



EXAMPLE: "NEUTRINO" COUNTING

Element abundances sensitive to expansion history during BBN

⇒ observed values constrain relativistic energy density

$$\boxed{H^2 \sim G\rho_{\rm rel}} \qquad \rho_{\rm rel} \equiv \rho_{\rm EM} + N_{\nu,{\rm eff}}\,\rho_{\nu\bar{\nu}}$$

(Hoyle & Taylor 1964, Peebles 1966; Shvartsman 1969; Steigman *et al* 1977)

Pre-CMB:

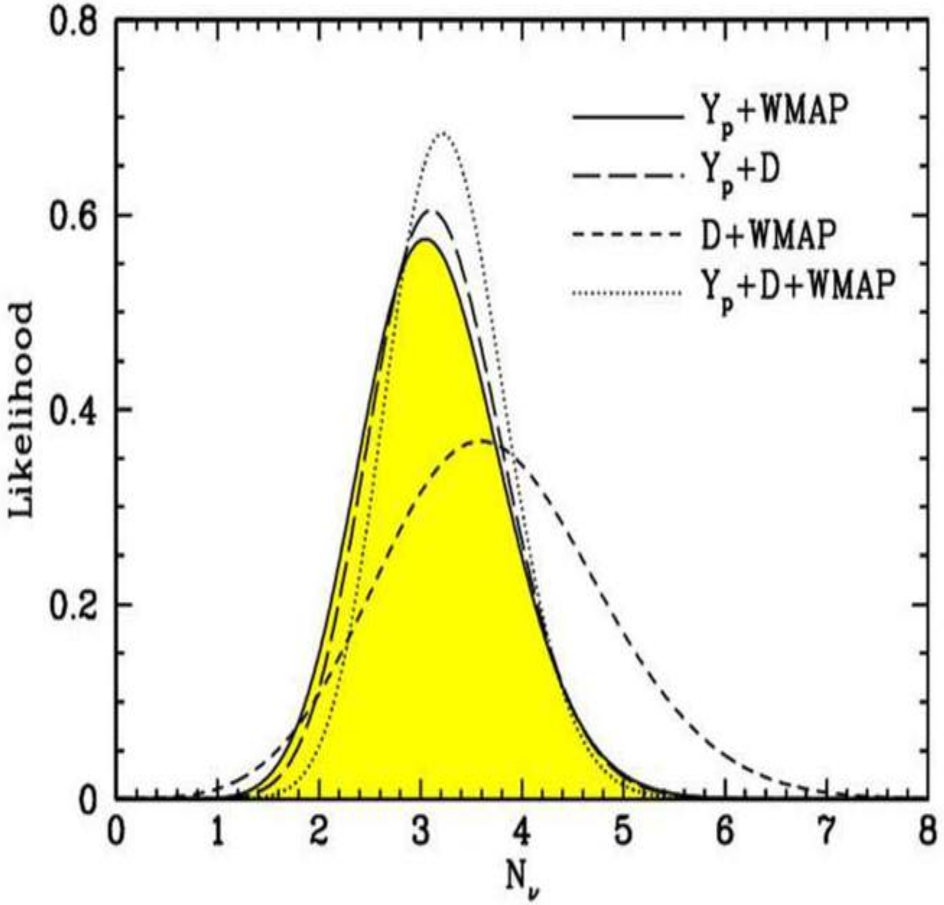
^{4}He as probe, other elements give η

$$2.3 < N_\nu < 3.4$$

With η from CMB:

- All abundances can be used
- ^{4}He still sharpest probe

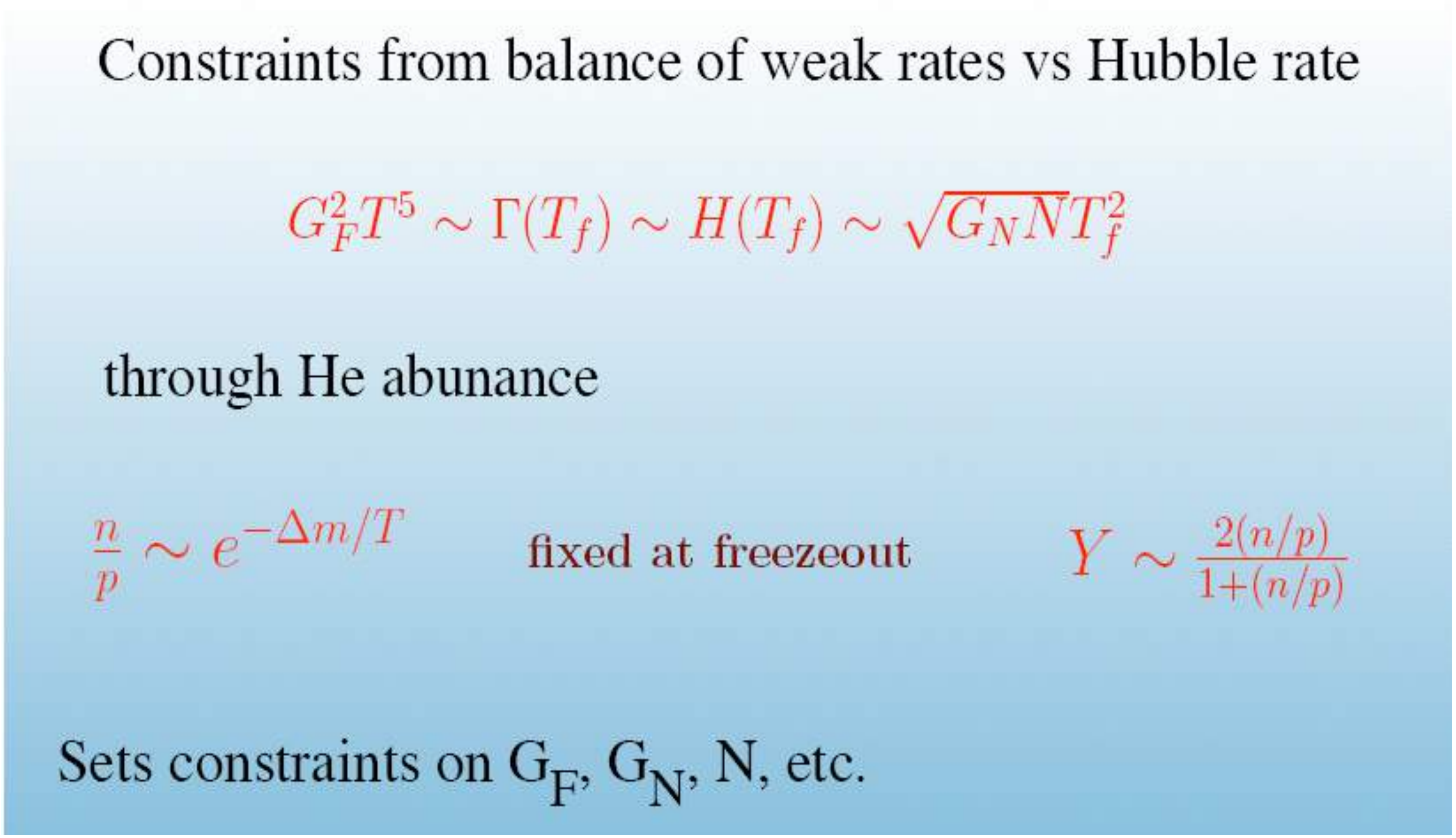
$$N_\nu = 2.88 \pm 0.16$$



Cyburt *et al,* Rev.Mod.Phys.**88**:015004,2016

…. so a singlet neutrino (*cf.* LSND) is *allowed*

Example: Fundamental couplings



Constraints from balance of weak rates vs Hubble rate

$$G_F^2 T^5 \sim \Gamma(T_f) \sim H(T_f) \sim \sqrt{G_N N} T_f^2$$

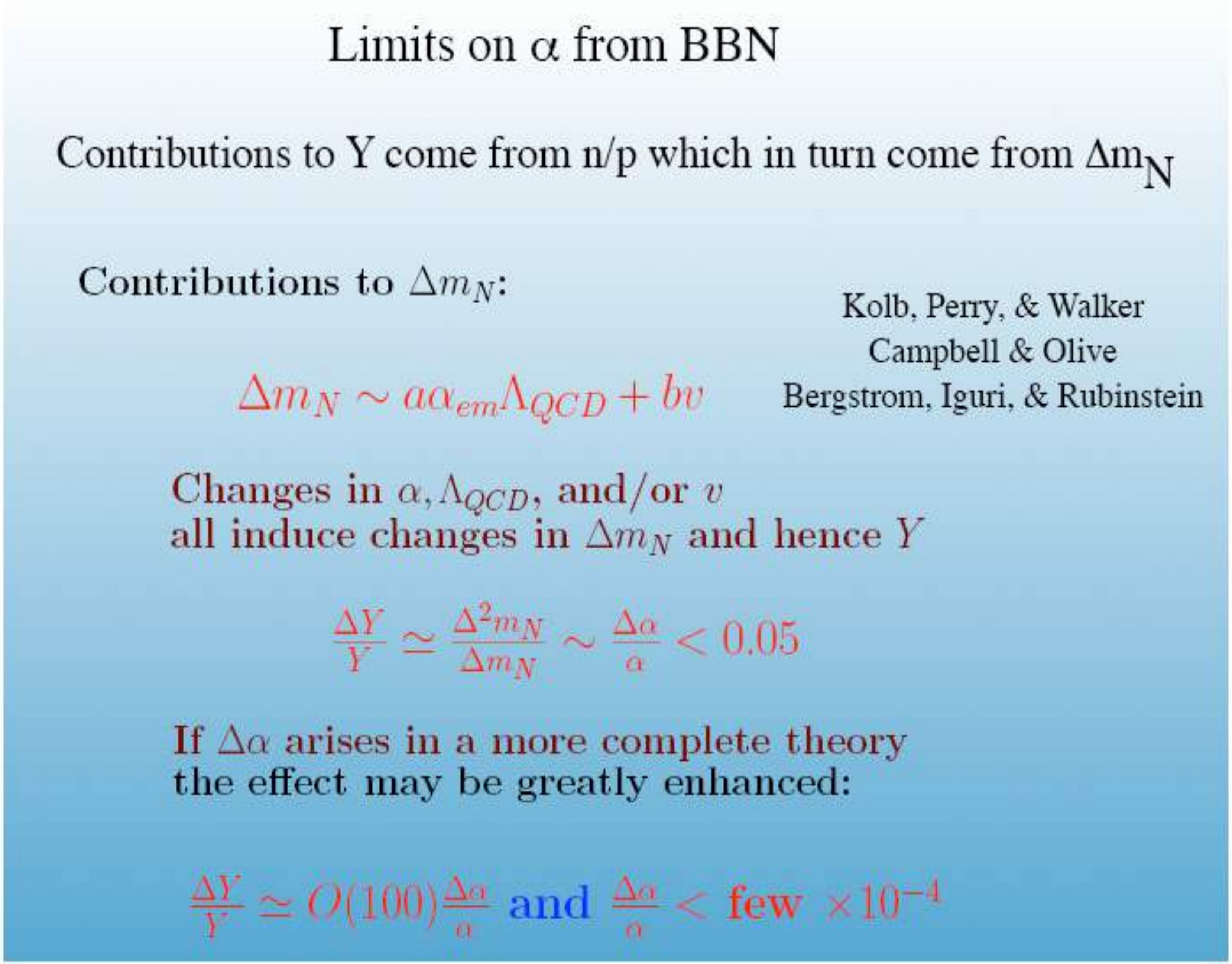
through He abunance

$\frac{n}{p} \sim e^{-\Delta m/T}$ fixed at freezeout $Y \sim \frac{2(n/p)}{1+(n/p)}$

Sets constraints on G_F, G_N, N, etc.

Note *n-p* mass difference is sensitive to both em and strong interactions, while freeze-out temp is sensitive to weak interactions and gravity, hence ^{4}He abundance is *exponentially* sensitive to *all* coupling strengths

Conversely obtain bound of < few % on any additional contribution to energy density driving expansion … e.g. rules out Λ of $O(H^2)$ *always* (since this would correspond to a large ‘renormalisation’ of G_N)



Limits on α from BBN

Contributions to Y come from n/p which in turn come from Δm_N

Contributions to Δm_N:

Kolb, Perry, & Walker
Campbell & Olive
Bergstrom, Iguri, & Rubinstein

$$\Delta m_N \sim a\alpha_{em}\Lambda_{QCD} + bv$$

Changes in α, Λ_{QCD}, and/or v
all induce changes in Δm_N and hence Y

$$\frac{\Delta Y}{Y} \simeq \frac{\Delta^2 m_N}{\Delta m_N} \sim \frac{\Delta\alpha}{\alpha} < 0.05$$

If $\Delta\alpha$ arises in a more complete theory
the effect may be greatly enhanced:

$$\frac{\Delta Y}{Y} \simeq O(100)\frac{\Delta\alpha}{\alpha} \text{ and } \frac{\Delta\alpha}{\alpha} < \text{few } \times 10^{-4}$$

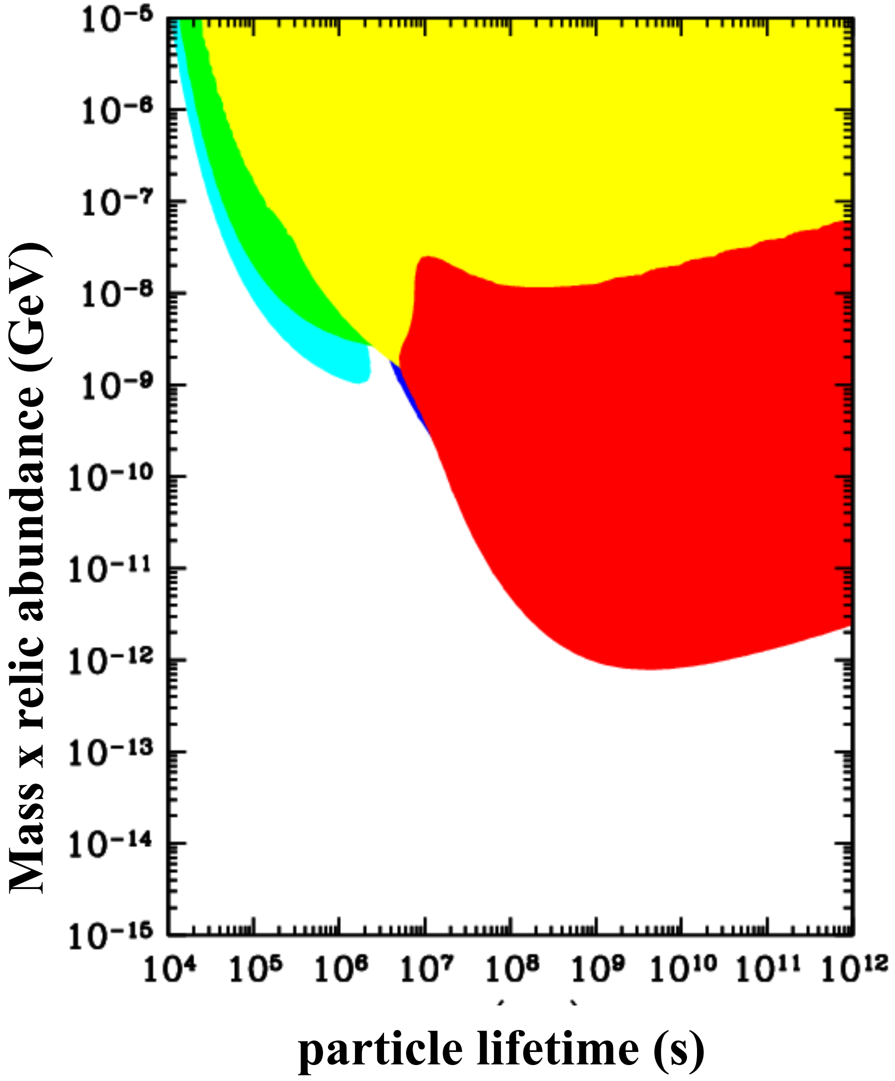
In fundamental theories e.g. string theory, the physical “constants” do vary with time … but the BBN constraint says that this must have stopped before t ~ 0.1 s

Example: BBN and decaying particles

Extensions of the Standard Model predict new (typically) *unstable* particles, which would have been created (thermally) in the early Universe, e.g. TeV mass gravitinos in supergravity

$$\widetilde{G} \to \gamma\gamma \qquad \tau_{3/2} \approx 4\times10^{5}\ \mathrm{s}\left(\frac{m_{3/2}}{1\ \mathrm{TeV}}\right)^{-3}$$

(Weinberg 1982; Khlopov & Linde 1983; Ellis, Nanopoulos & Sarkar 1985; Reno & Seckel 1988)



Ellis *et al*, Nucl.Phys.B**373**:399 1992,
Cyburt *et al*, Phys.Rev.D**67**:103521,2003

The high energy photons would have photo-dissociated the synthesized elements ⇒ *severe* limits on the decaying particle abundance

This requires that *highest* temperature reached in our past (after inflation) was $< 10^{8}$ GeV … constraint on baryogenesis!

SUMMARY

Observational inferences about the primordially synthesised abundances of D, ^{4}He and ^{7}Li presently provide the *deepest* probe of the Big Bang, based on an *established* physical theory

The overall concordance between the inferred primordial abundances of D and ^{4}He with the predictions of the standard cosmology requires most of the matter in the universe to be *non*-baryonic, and places constraints on any deviations from the usual expansion history (e.g. new neutrinos)

Nucleosynthesis marked the beginning of the development of modern physical cosmology … and it is still the final observational frontier as we 'look back' to the Big Bang