IV International Summer School 2005
Center for Nuclear Study, University of Tokyo
August 18 – 23, 2005

Nucleosynthesis in Supernovae and the Big-Bang (II)

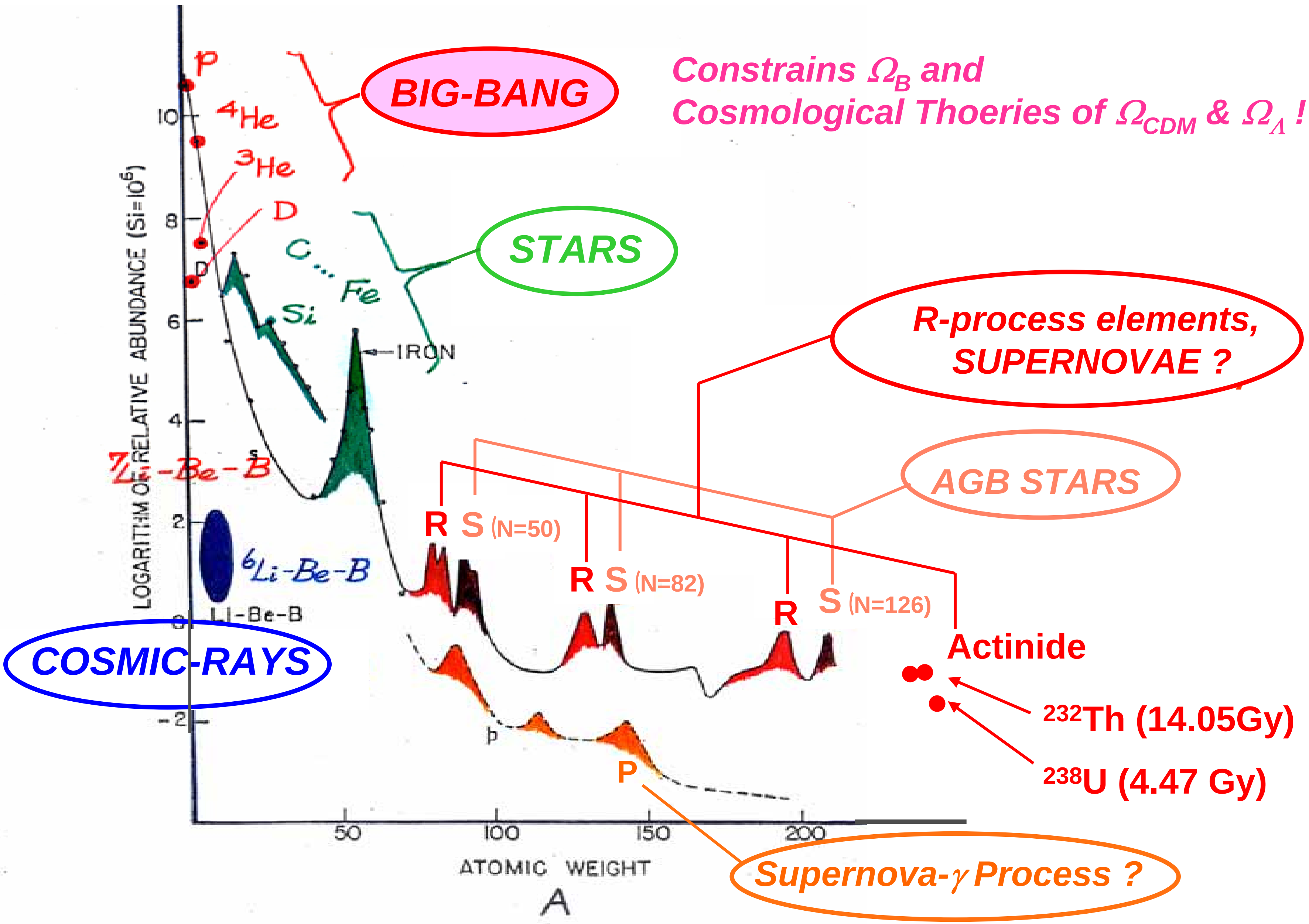
Taka Kajino

National Astronomical Observatory

Department of Astronomy, University of Tokyo

Solar System Abundance

Constrains Ω_B and
Cosmological Thoeries of Ω_{CDM} & Ω_Λ !



OUTLINE

Universe is likely flat and accelerating!
$\Omega_B + \Omega_{CDM} + \Omega_\Lambda = 1$

Six (eleven) Parameters !

- **Is BARYON, $\Omega_B = 0.04$, consistent with Big-Bang Cosmology and Nucleosynthesis (as a CANDLE of dark side of the Universe) ?**

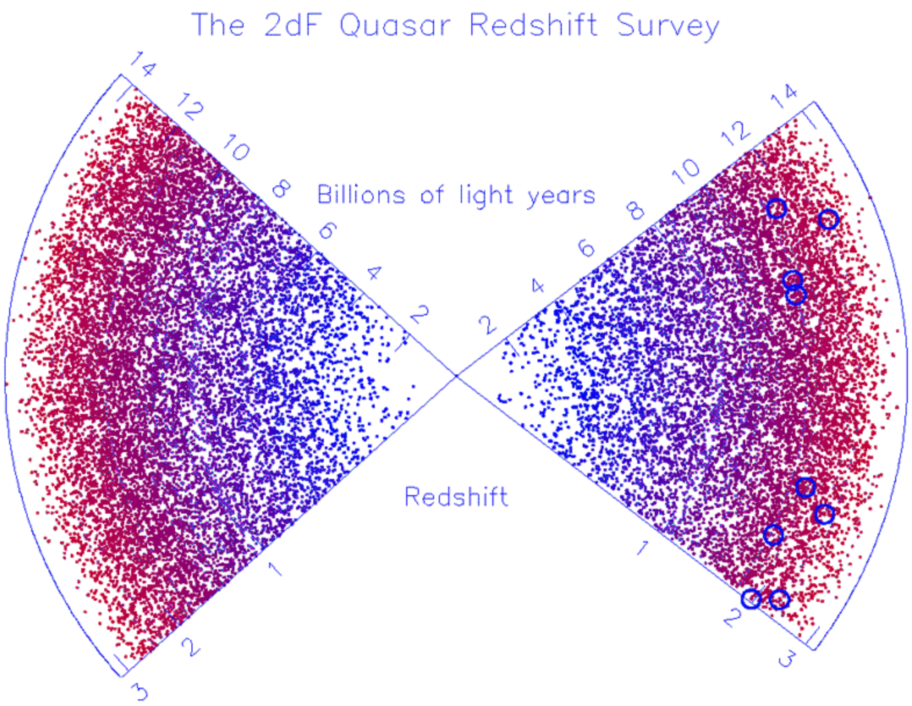
BBN constrains Brane Cosmology !

- **What is the nature of CDM, $\Omega_{CDM} = 0.26$?**
  Disappearing CDM Model in Brane World Cosmology !
  Ichiki, Garnavich, Kajino, Mathews & Yahiro, PRD 68 (2003) 083518

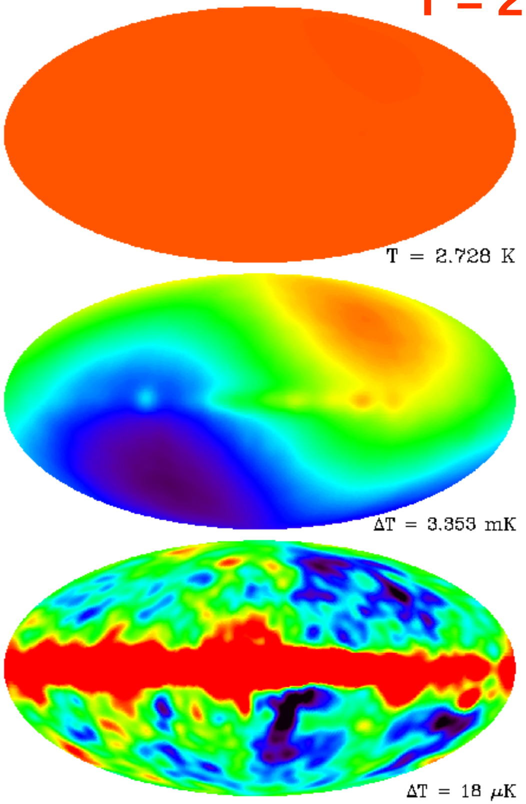
- **What is DARK ENERGY, $\Omega_\Lambda = 0.7$?**
  Growing CDM Model in Brane World Cosmology !
  Umezu, Ichiki, Kajino, Mathews Nakamura & Yahiro,(2005)
  (astro-ph/0507227)

- **COSMIC AGE (13.7 +- 0.2 Gy), strongly model-dependent ?**
  Supernova R-Process & Origin of ^{232}Th, ^{235,238}U ! --- Model independent !
  Sasaqui, Kajino & Balantekin, ApJ (2005), in press. (astro-ph/0506100)

The Universe is homogeneous and isotropic in a large enough scale.



T = 2.728 K



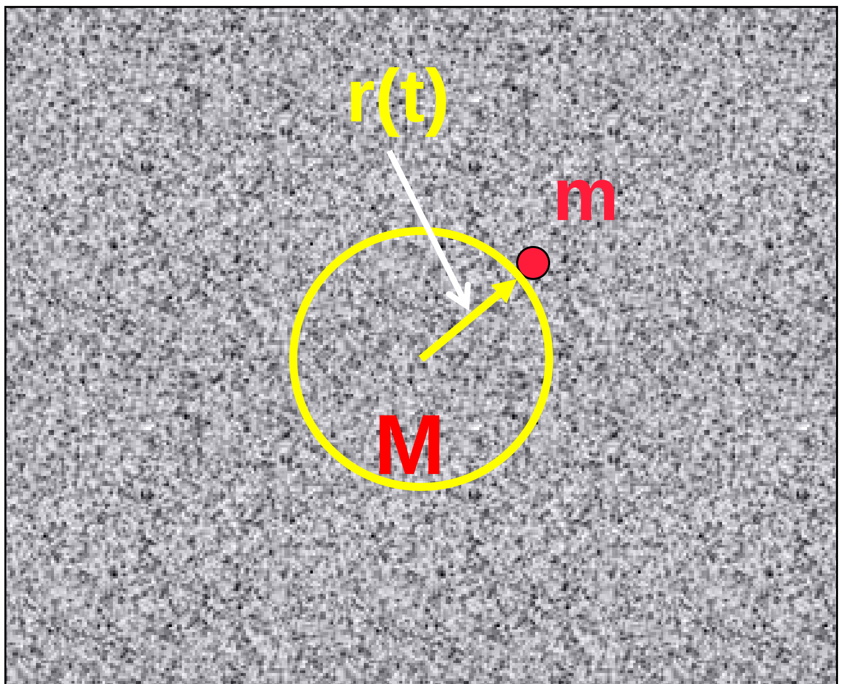
$\delta T < 18\ \mu K$

2dF Quasar (Matter) Distribution:
Homogeneous

Cobe Sky Maps of CMB;
Isotropic

Newtonian Equation

Birkoff's Theorem:
Gravity due to mass interior to an arbitrary sphere.



$M = 4/3\pi\rho r^3$

$$E = \frac{1}{2} m\dot{r}^2 - \frac{GmM}{r}$$

$$\frac{1}{2} m\dot{r}^2 = \frac{Gm[(4/3)\pi\rho r^3]}{r} + E$$

x $\boldsymbol{1/2mr^2}$

$$\left(\frac{\dot{r}}{r}\right)^2 = \frac{8}{3}\pi G\rho + \frac{2E}{mr^2}$$

General Relativity

$$G^{\mu\nu} = R^{\mu\nu} - \frac{1}{2} R g^{\mu\nu} = 8\pi\, G T^{\mu\nu} + \Lambda g^{\mu\nu}$$

$$R_{\mu\nu} = R^{\lambda}{}_{\mu\lambda\nu} = \partial_{\lambda}\Gamma^{\lambda}_{\mu\nu} - \partial_{\nu}\Gamma^{\lambda}_{\mu\lambda} + \Gamma^{\lambda}_{\eta\lambda}\Gamma^{\eta}_{\mu\nu} - \Gamma^{\lambda}_{\eta\nu}\Gamma^{\eta}_{\mu\lambda}$$

$$\Gamma^{\lambda}_{\mu\nu} = \frac{1}{2} g^{\lambda\beta}\left\{\partial_{\nu} g_{\beta\mu} + \partial_{\mu} g_{\beta\nu} - \partial_{\beta} g_{\mu\nu}\right\}$$

$$g_{\mu\nu} = \begin{bmatrix} -1 & & & \\ & \frac{a^2(t)}{1-kr^2} & & \\ & & a^2(t) r^2 & \\ & & & a^2(t) r^2 \sin^2\theta \end{bmatrix}$$

$$T^{\mu}{}_{\nu} = \begin{bmatrix} -\rho & & & \\ & p & & \\ & & p & \\ & & & p \end{bmatrix}$$

Einstein Equation

Space-space component

$$G^{00} = 8\pi\, G T^{00} + \Lambda g^{00}$$

Friedmann Eq.

Cosmological Constant

$$H^2 = \frac{8}{3}\pi G\rho - \frac{k}{a^2} + \frac{\Lambda}{3}$$

$$H^2 = H_0^2\left(\frac{\Omega_\gamma}{a^4} + \frac{\Omega_M}{a^3} - \frac{\Omega_k}{a^2} + \Omega_\Lambda\right)$$

Newtonian Equation

$H^2 = (v/r)^2$

$- k = E/m$

$$\left(\frac{\dot r}{r}\right)^2 = \frac{8}{3}\pi G\rho + \frac{E}{mr^2}$$

$\Omega_\alpha = \rho_\alpha/\rho_C$

$\rho_C = 3H_0^2/8\pi G$

$a = a(t) =$ scale factor $= r$

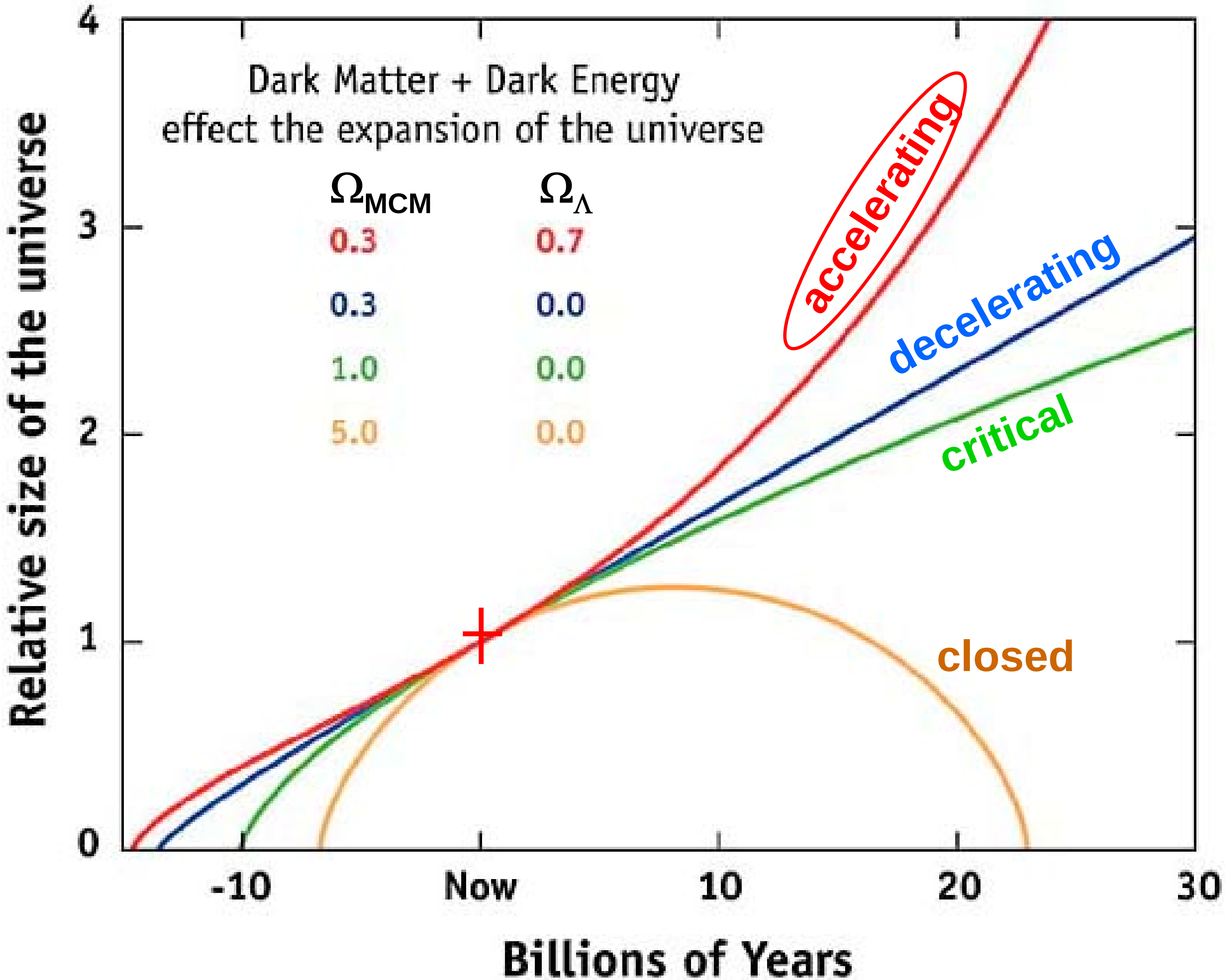
Deceleration parameter

$$q_0 = -(d^2r/dt^2)/rH^2 = [\Omega_{CDM}/2 - \Omega_\Lambda]$$

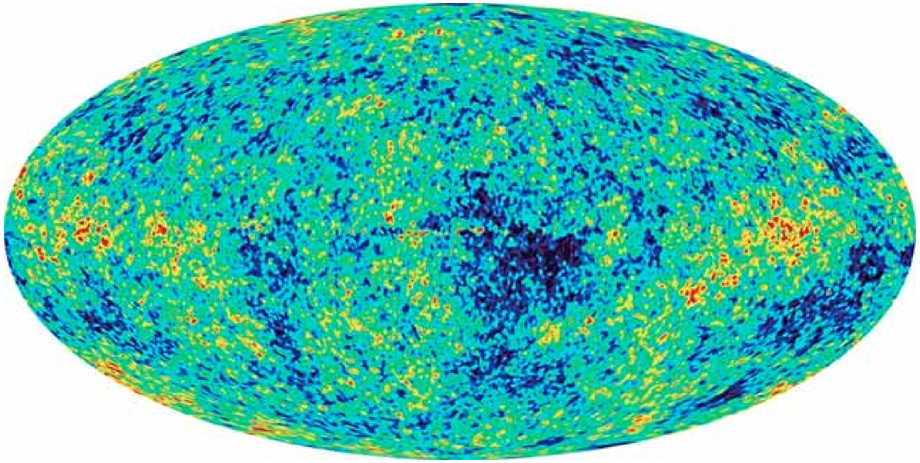
$\Omega_{CDM}/2 < \Omega_\Lambda$

acceleration !

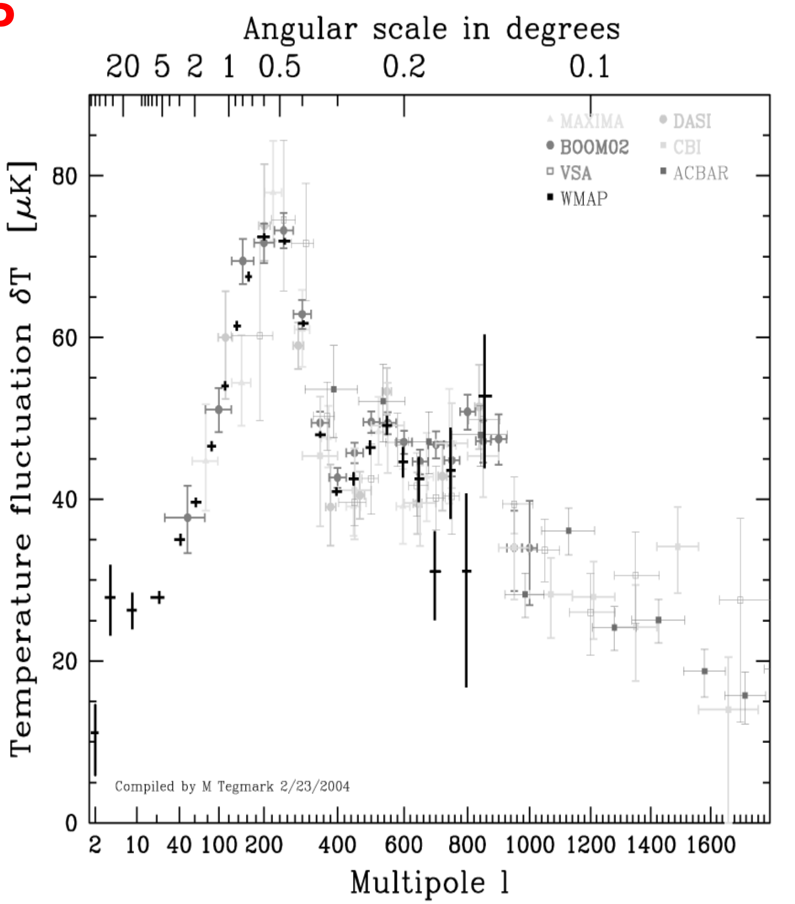
Cosmic Expansion History



Cosmic Microwave Background Anisotropies



WMAP

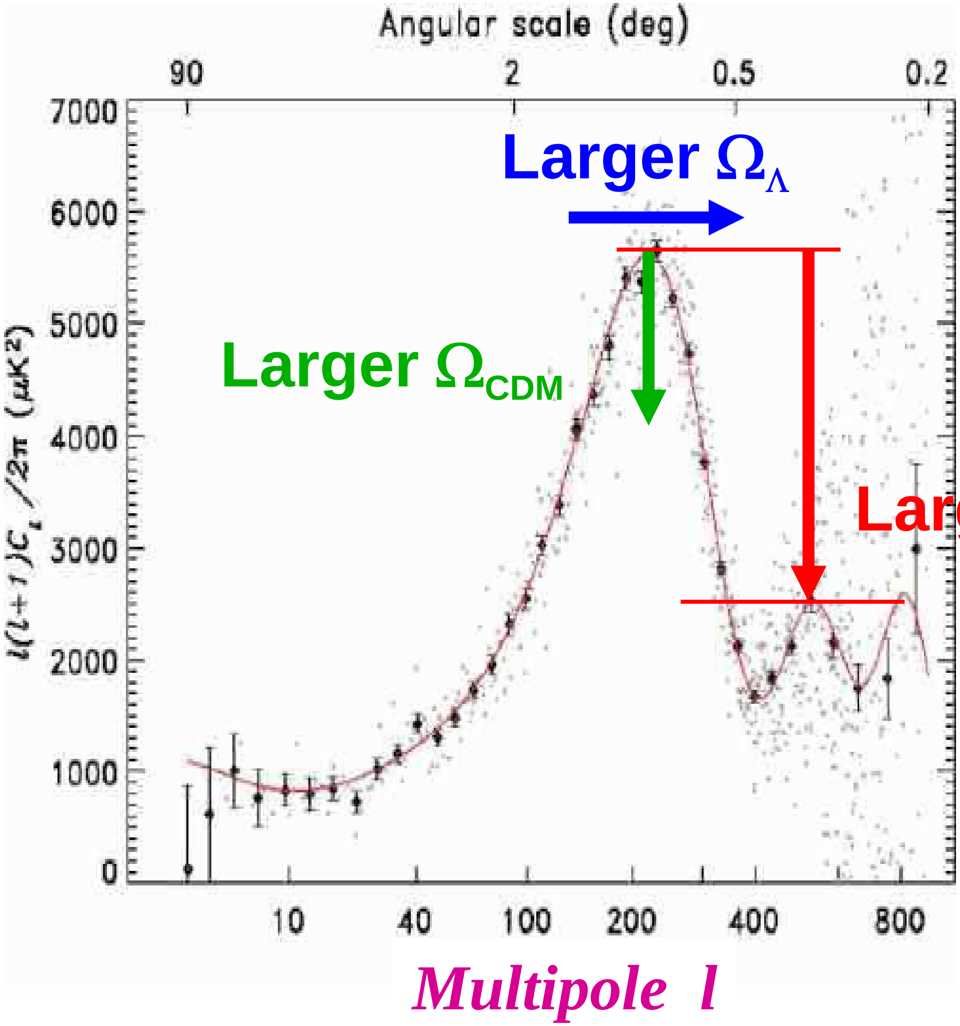


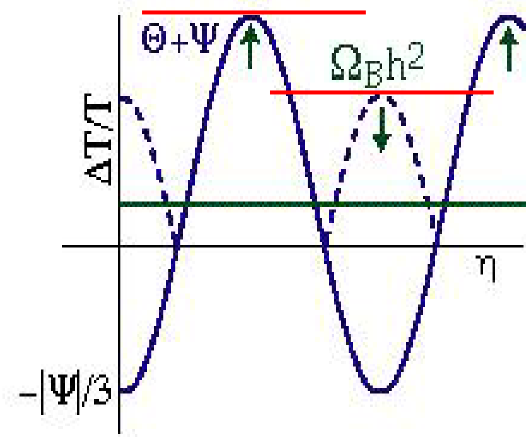
$$\frac{\delta T}{T} = \sum_{l} \sum_{m} a_{lm} Y_{lm}(\theta,\phi)$$

$$C_l \equiv \left\langle \left| a_{lm} \right|^2 \right\rangle$$

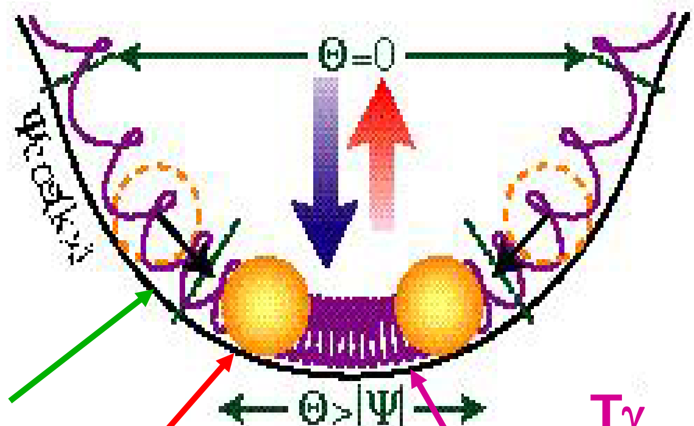
$$C_l = \left\langle \delta T/T(\mathbf{n}) \cdot \delta T/T(\mathbf{n}+\theta) \right\rangle$$

Cosmological Parameter Dependence





Baryon Drag

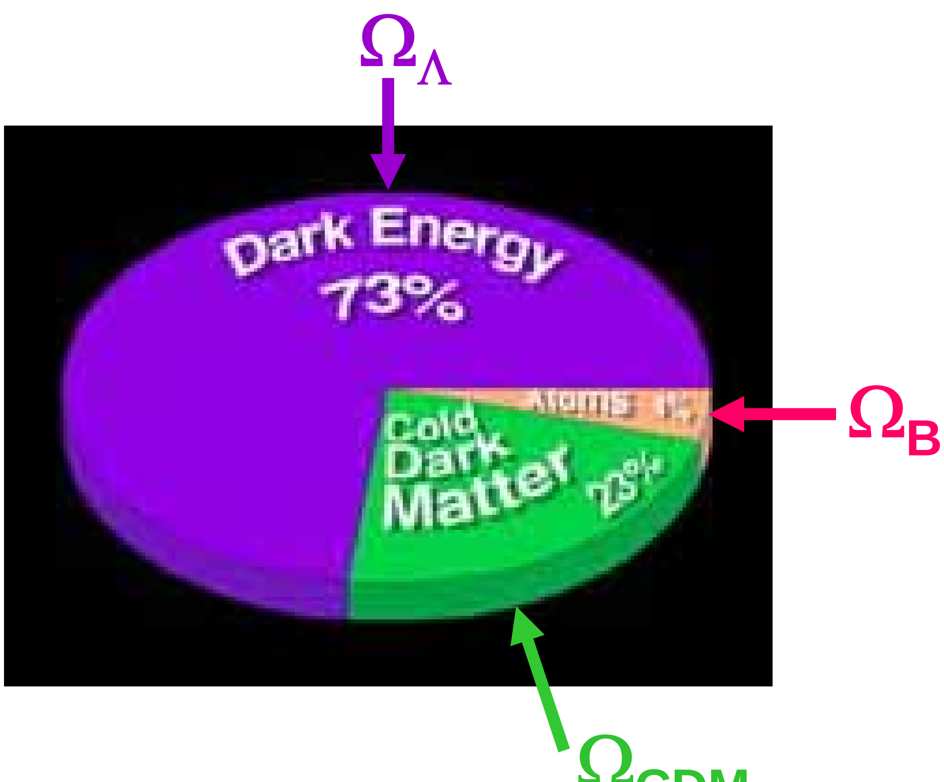


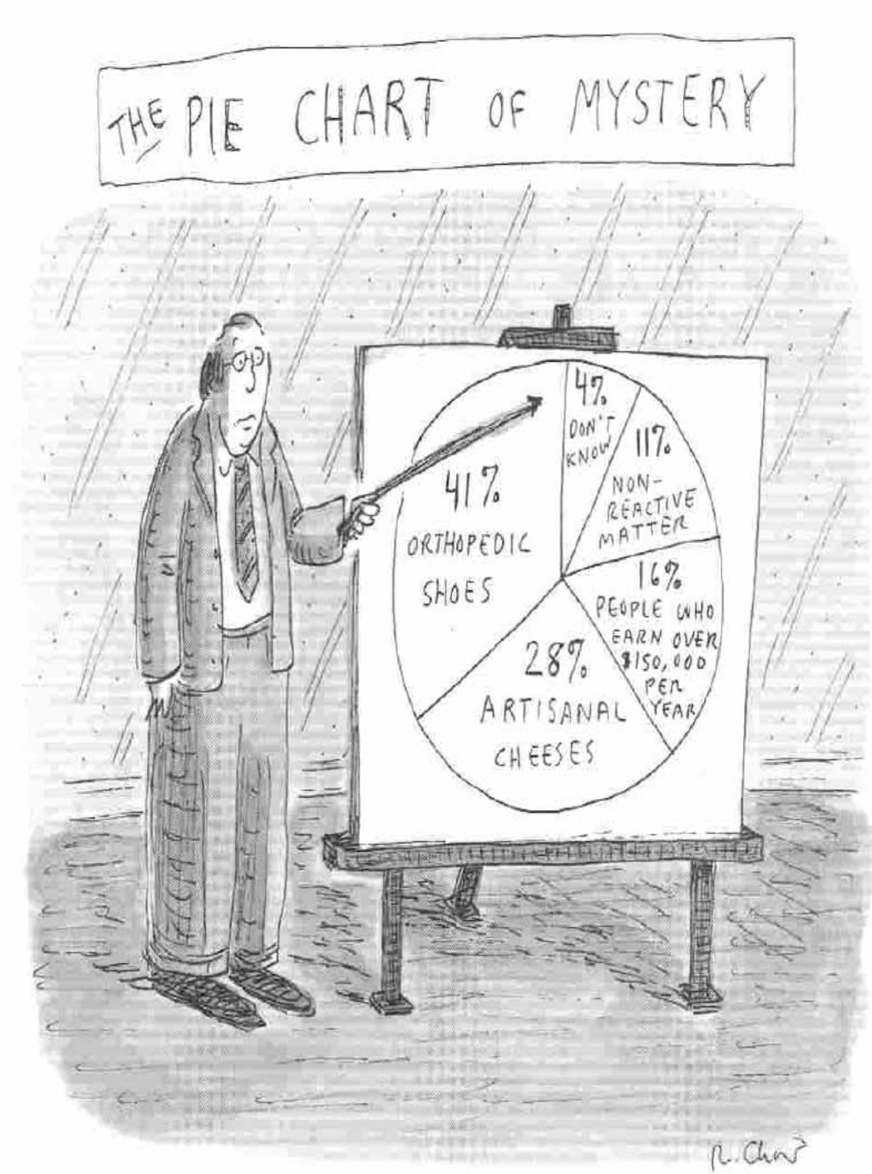
Pie Chart of Cosmic Mystery

$t = 3 \times 10^5$ yr

Ordinary matter makes up a small fraction of mass/energy.

Dark matter and dark energy dominate.





The Power of BBN is that the Physics is Accessible

Thermodynamic Equilibrium of Particles and Nuclei

$$n_i(p)dp = \frac{1}{2\pi^2} g_i\, p^2 \left[\exp\left(\frac{E_i(p)-\mu_i}{kT}\right) \pm 1\right]^{-1} dp$$

$$\rho_i = \int p\,[n_i(p) + n_{\bar{i}}(p)]\, dp$$

$$\rho_\gamma = \frac{\pi^2}{15}(kT_\gamma)^4 \quad , \quad \rho_{\nu_i} = \frac{7}{8}\frac{\pi^2}{15}(kT_\nu)^4$$

$$\rho = \rho_\gamma + \rho_{\nu_i} + \rho_i = \frac{\pi^2}{30} g_{eff}(kT)^4$$

$$g_{\text{eff}}(T) = \sum_{\text{bose}} g_{\text{bose}} + \frac{7}{8}\sum_{\text{fermi}} g_{\text{fermi}}$$

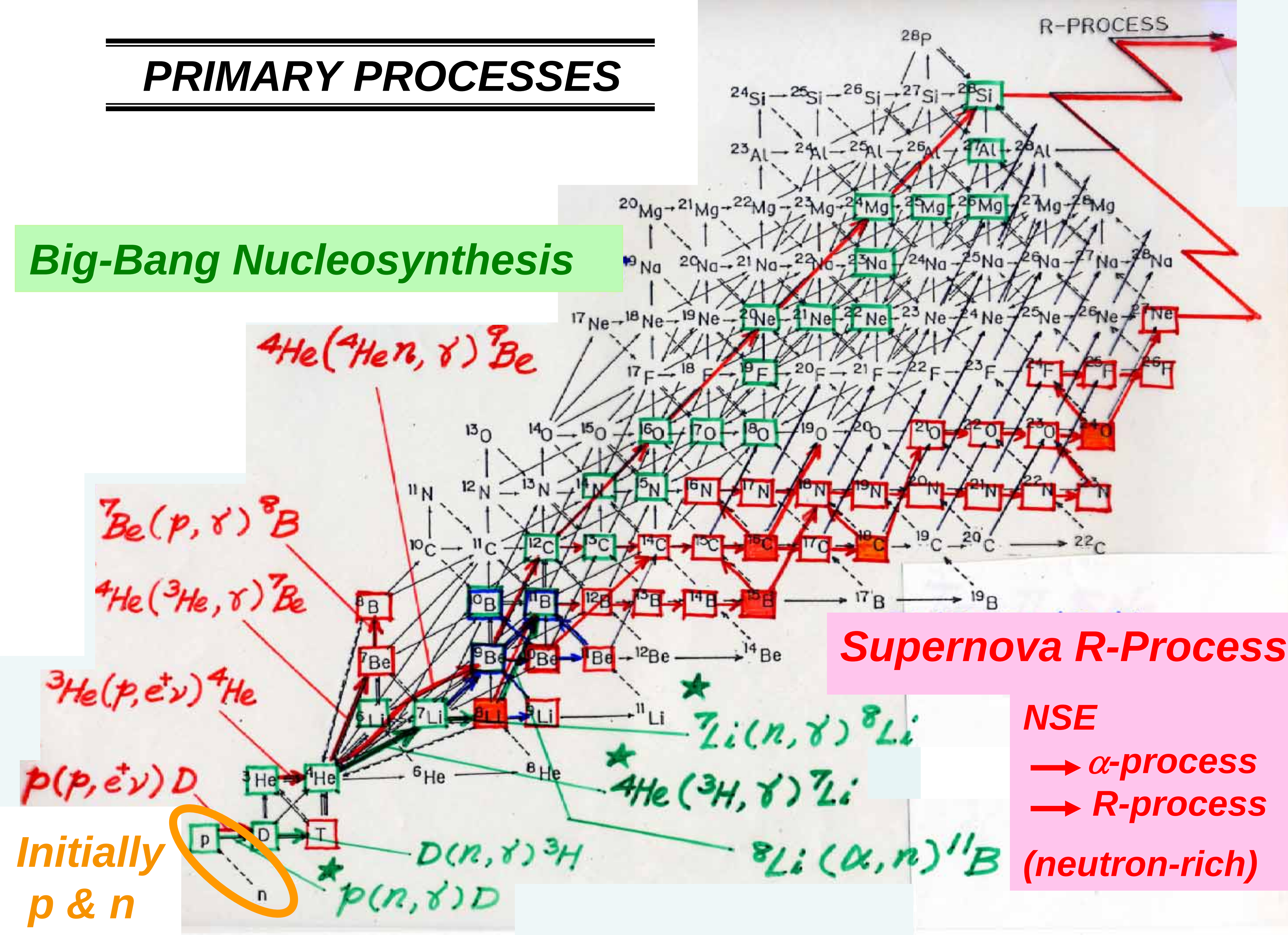
Cosmic Expansion

$$H^2(t) = \left(\frac{1}{R}\frac{dR}{dt}\right)^2 = \frac{8\pi G}{3}\rho + \frac{\Lambda}{3} - \frac{k}{R^2}$$

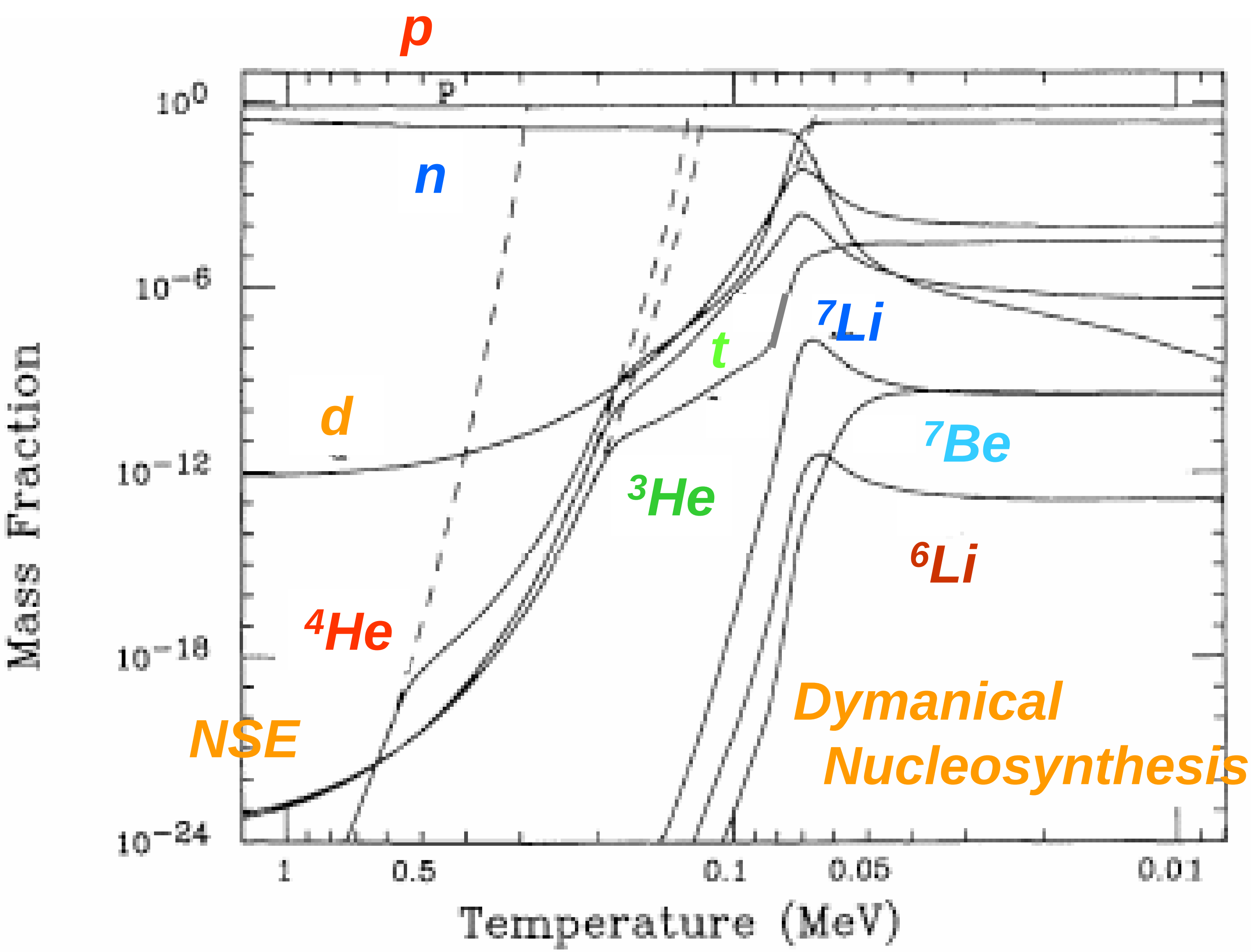
Nuclear Reactions

$$\frac{dY_i}{dt} = \sum_{ijk} N_i \left(\frac{Y_l^{N_l} Y_k^{N_k}}{N_l! N_k!} \langle n_k \sigma_{lk} v \rangle - \frac{Y_i^{N_i} Y_j^{N_j}}{N_i! N_k!} \langle n_j \sigma_{ij} v \rangle \right)$$

PRIMARY PROCESSES



Evolution of Abundances



Big-Bang Nucleosynthesis (BBN) Diagram

t = 3 min

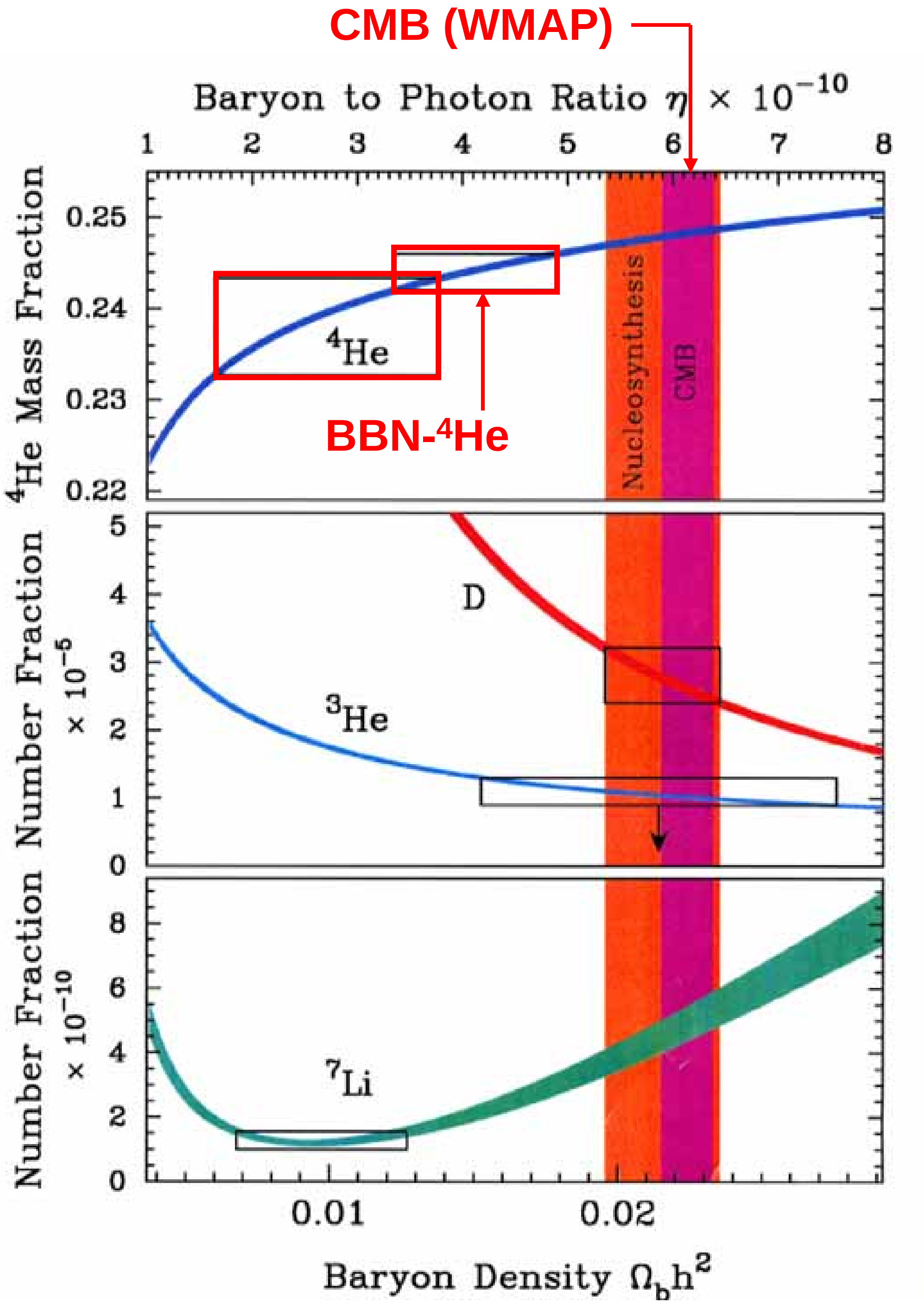
Big-Bang Nucleosynthesis Constraints

↓

Cosmic Baryon Density

Ω_B

Ω_B's from ***BBN and CMB are inconsistent !***

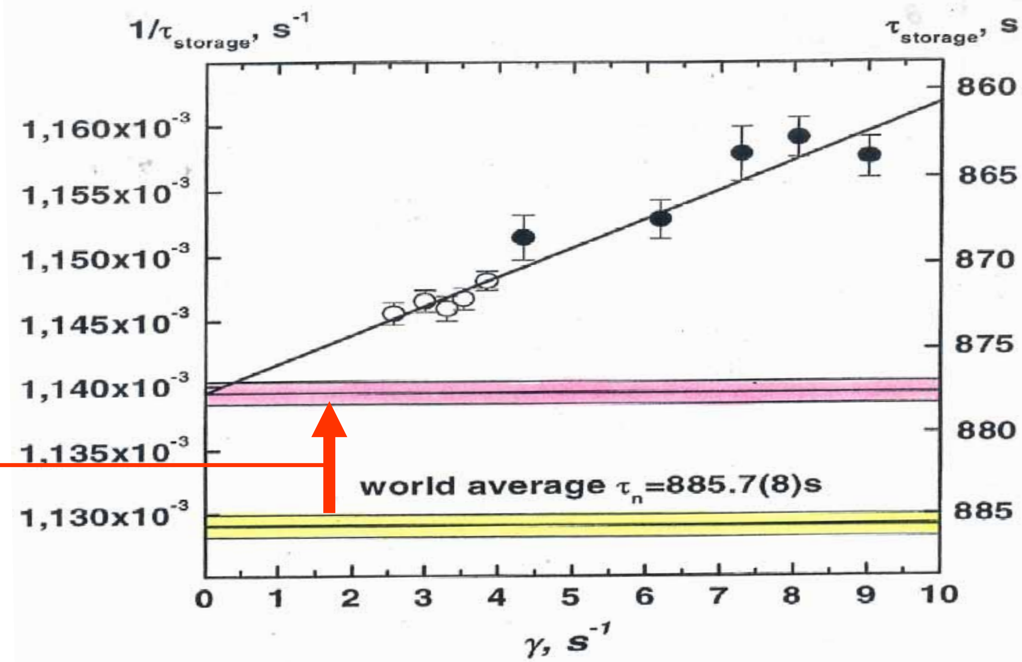


NEW MEASUREMENT OF NEUTRON LIFE

Serevlov et al., Phys. Lett. B605 (2005), 72

ULTRA-COLD NEUTRON

$\delta\tau_n/\tau_n = -1\ \%$

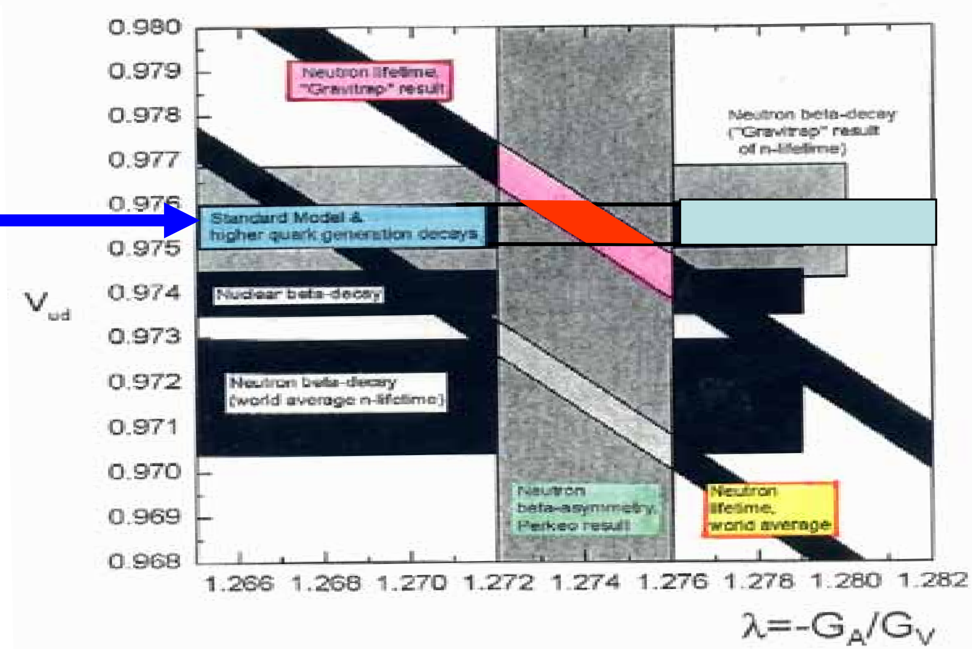


STANDARD QUARK MODEL

KMS (Kobayashi-Masukawa-Cabbibo) MATRIX

N $\longrightarrow$ P

d $\longrightarrow$ u : V_{ud}



Effect of Neutro-Life on BBN-^{4}He : 2p + 2n $\longrightarrow$ ^{4}He

Boltzmann distribution

$$n_A = g_A \left(\frac{m_A T}{2\pi}\right)^{3/2} \exp\left(\frac{\mu_A - m_A}{T}\right)$$

Weak Equilibrium until $T \gtrsim T_d$ (Decoupling Temp.)

$$p + e^- \rightleftarrows n + \nu_e$$

$$\mu_p + \underset{\simeq 0}{\mu_e} = \mu_n + \mu_{\nu_e}$$

$$\boxed{r \equiv \frac{n_n}{n_p} = \left(\frac{m_n}{m_p}\right)^{3/2} \exp\left(-\frac{\Delta m}{T_d} - \frac{\mu_{\nu_e}}{T_d}\right) < 1.} \quad \text{— (1)}$$

^{4}He Synthesis ($2p + 2n \rightarrow {}^4He$)

Approximation : All neutrons ($n_n < n_p$) are interconverted to ^{4}He, and nucleosynthesis quits suddenly when $n_n \approx 0$.

$$\boxed{Y_p \equiv \frac{4n_n}{2n_p + 2n_n} = \frac{2r}{1+r}.} \quad \text{—— (2)}$$

Weak Decoupling Temperature

$$\boxed{T_d^3 = \frac{1.66}{M_{pl}} \times \frac{\sqrt{g_*}}{G_F^2}.} \quad \text{—— (3)}$$

$$\begin{cases} M_{pl} = 1/\sqrt{G} \\ g_* = \sum_b g_b + \frac{7}{8}\sum_f g_f \end{cases}$$

$$= \underset{\gamma}{2} + \frac{7}{8}\left(\underset{e^\pm,\, s}{2\times 2} + \underset{\nu_x\ \nu,\bar\nu,\ h}{3\times 2\times 1}\right) = \frac{43}{4}$$

STANDARD

1st effect: $\delta\tau_n \rightarrow \delta T_d \rightarrow \delta(n/p) \longrightarrow \delta(^4He)$

(1) ; $\delta r = \frac{\Delta m}{T_d^2} e^{-\frac{\Delta m}{T_d}} \delta T_d = \frac{\Delta m}{T_d^2} r\, \delta T_d$

(2) ; $\delta Y_p = \frac{2}{1+r}\delta r - \frac{2r}{(1+r)^2}\delta r = \frac{Y_p}{r}\left(1 - \frac{Y_p}{2}\right)\delta r$

$$\therefore \boxed{\delta Y_p = Y_p\left(1 - \frac{Y_p}{2}\right)\left(\frac{\Delta m}{T_d}\right)\left(\frac{\delta T_d}{T_d}\right).} \quad \text{—— (4)}$$

$$\tau_n^{-1} = \Gamma_{n\to p e \bar\nu} = \frac{G_F^2}{2\pi^3}(1 + 3g_A^2)\, m_e^5 \underbrace{\int_1^q d\epsilon\ \epsilon(\epsilon - q)^2(\epsilon^2 - 1)^{1/2}}_{\approx 1.636}$$

($g_A \approx 1.26$ Axial-vector coupl.

$\tau_n \propto G_F^{-2}$

$\frac{\delta\tau_n}{\tau_n} = (-2)\frac{\delta G_F}{G_F}$

(3) ; $3\frac{\delta T_d}{T_d} = (-2)\frac{\delta G_F}{G_F} = \frac{\delta \tau_n}{\tau_n}$

(4) ; $\delta Y_p = \frac{1}{3} Y_p\left(1 - \frac{Y_p}{2}\right)\left(\frac{\Delta m}{T_d}\right)\left(\frac{\delta\tau_n}{\tau_n}\right) \rightarrow \boxed{\frac{\left(\frac{\delta Y_p}{Y_p}\right)}{\left(\frac{\delta\tau_n}{\tau_n}\right)} \approx 0.3 \ !}$

2nd effect: $\delta\tau_n \rightarrow \delta n \longrightarrow \delta(^4He)$

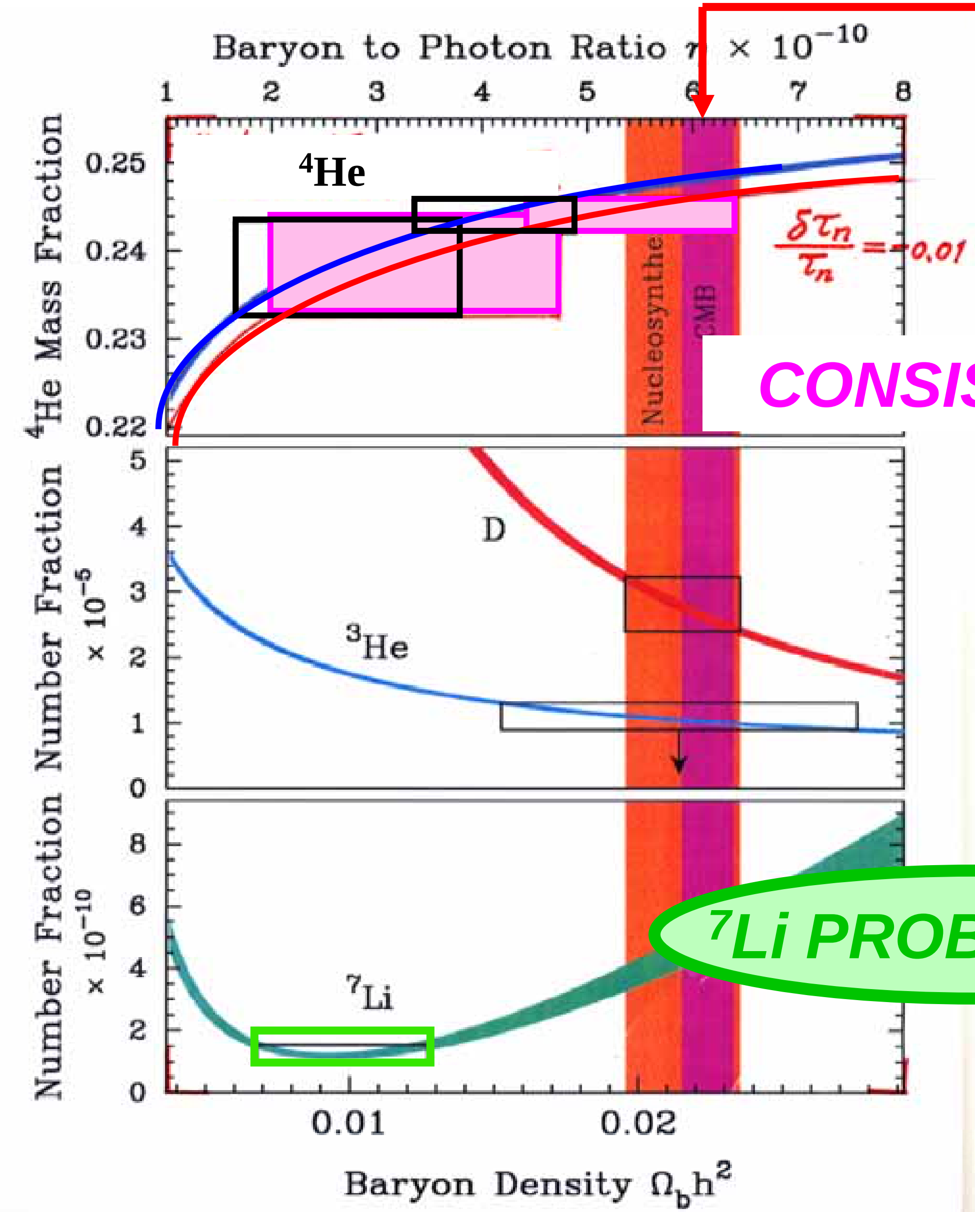
Freezeout time of $p + n \rightleftarrows D + \gamma$ changes.

NET EFFECT:

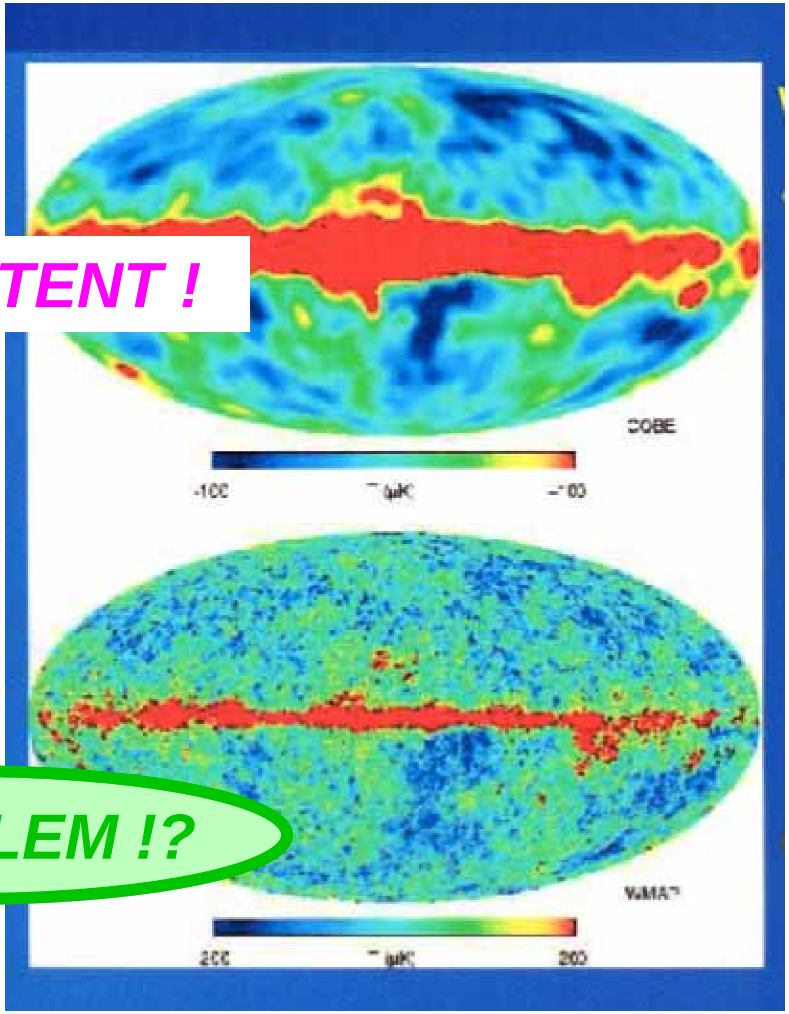
$$\boxed{\delta\tau_n < 0 \longrightarrow \delta(^4He) < 0}$$

Big-Bang Nucleosynthesis vs. CMB

Mathews, Kajino & Shima, PRD71 (2005) 021302 (R)



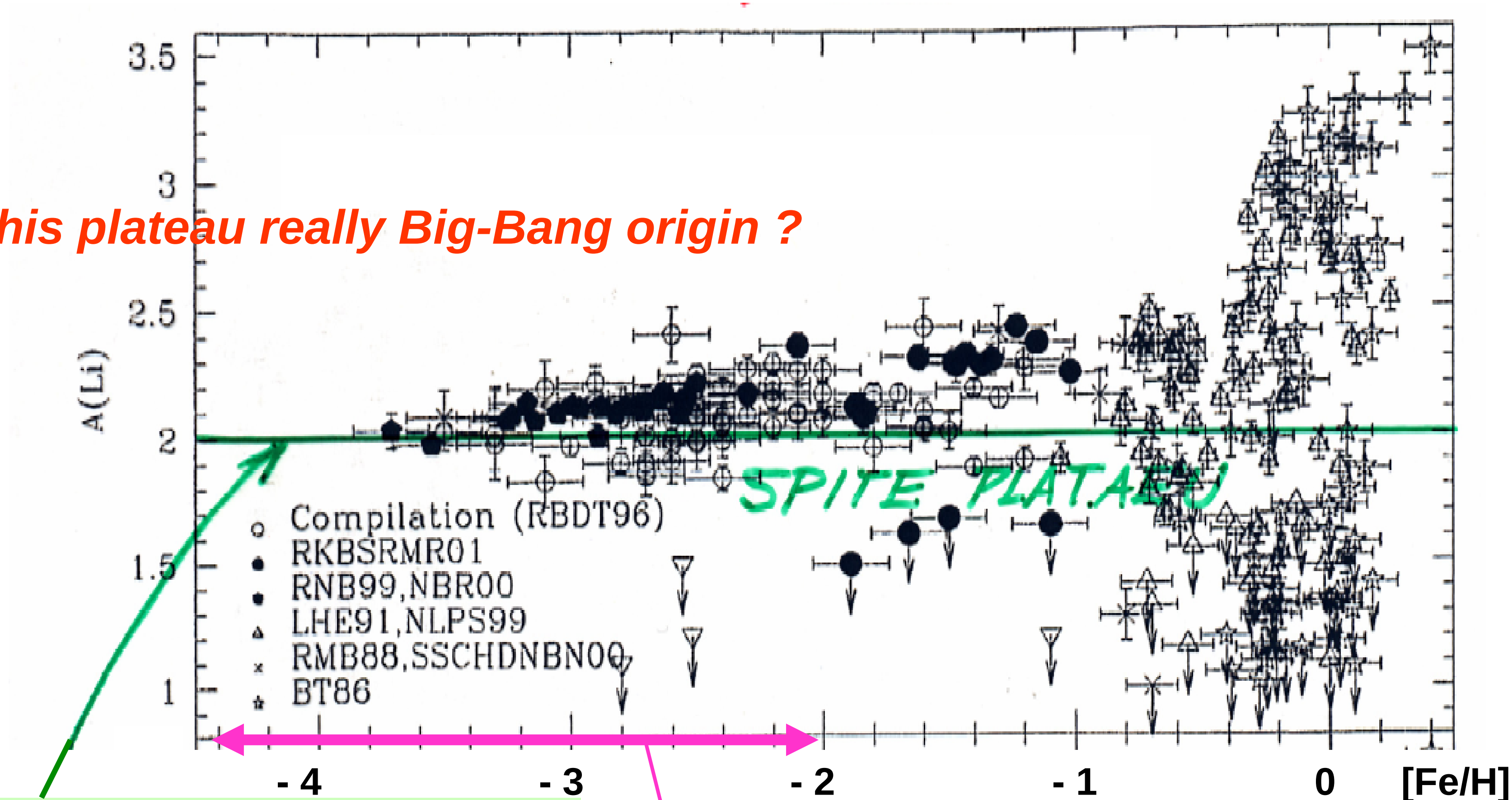
CMB - WMAP



^7Li Abundance in Halo Dwarf Stars

Ryan, Kajino, Beers, Suzuki, Romano,
Matteucci & Rosolankova 2001, ApJ 549, 55.

Is this plateau really Big-Bang origin ?



Affected by SN ν-process ?

SN II Nucleosynthesis contributes !

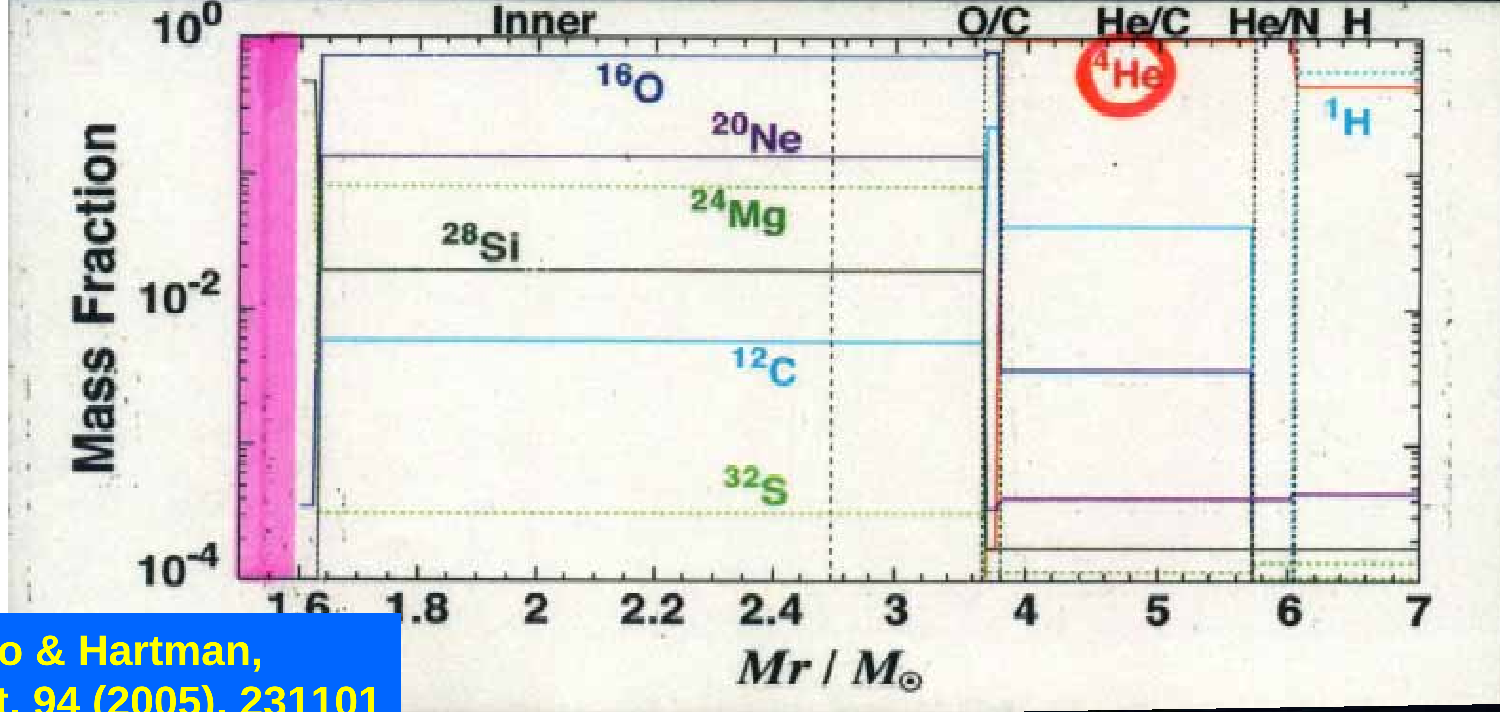
SN1987A

SNe II Nucleosynthesis can produce ^{7}Li and ^{11}B as the BBN does in the early Universe !

Supernova ν - process !

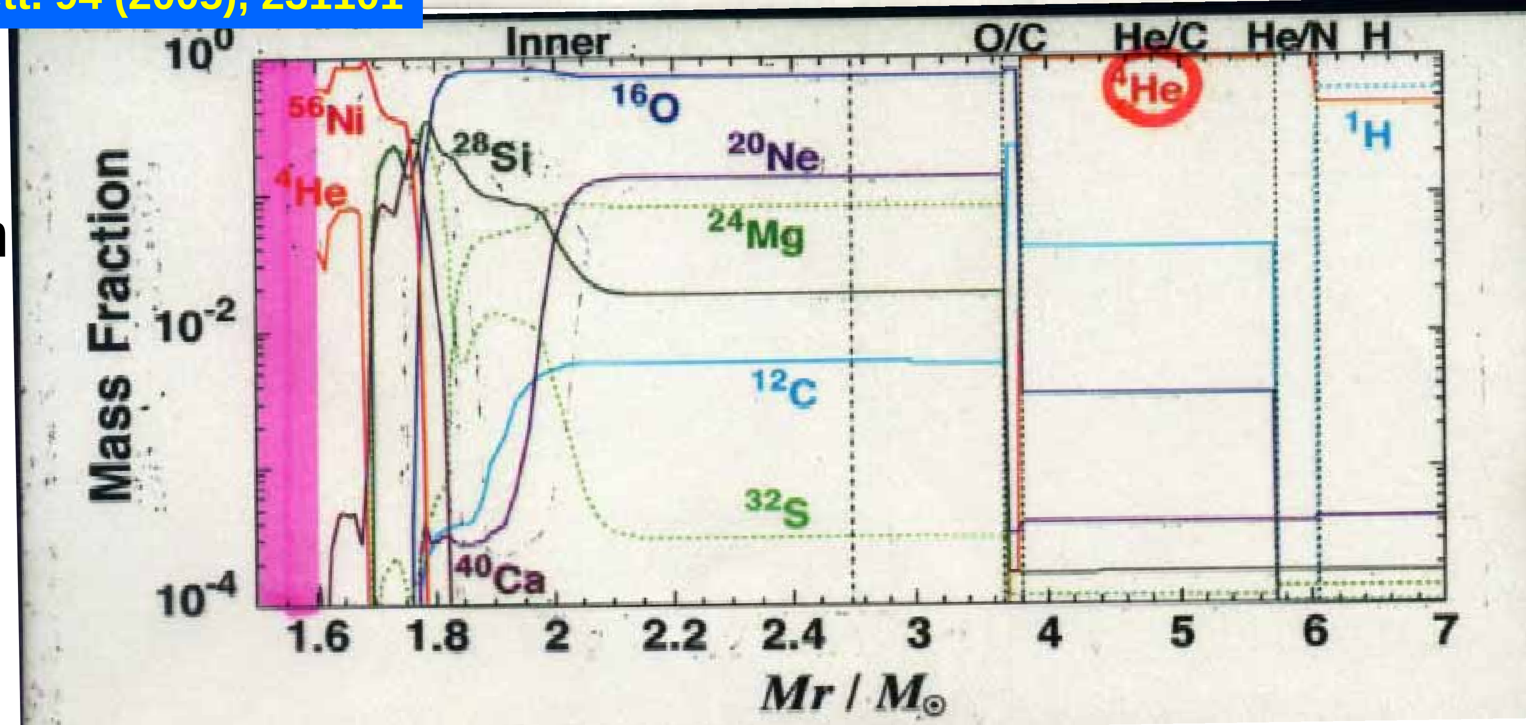
Supernova 1987A. These two photographs show the same star field in the Large Magellanic Cloud, near the Tarantula Nebula (30 Doradus), before and after the explosion. The star Sanduleak-69 202 is marked by an arrow. (D. Malin, Anglo-Australian Telescope Board)

Before Explosion

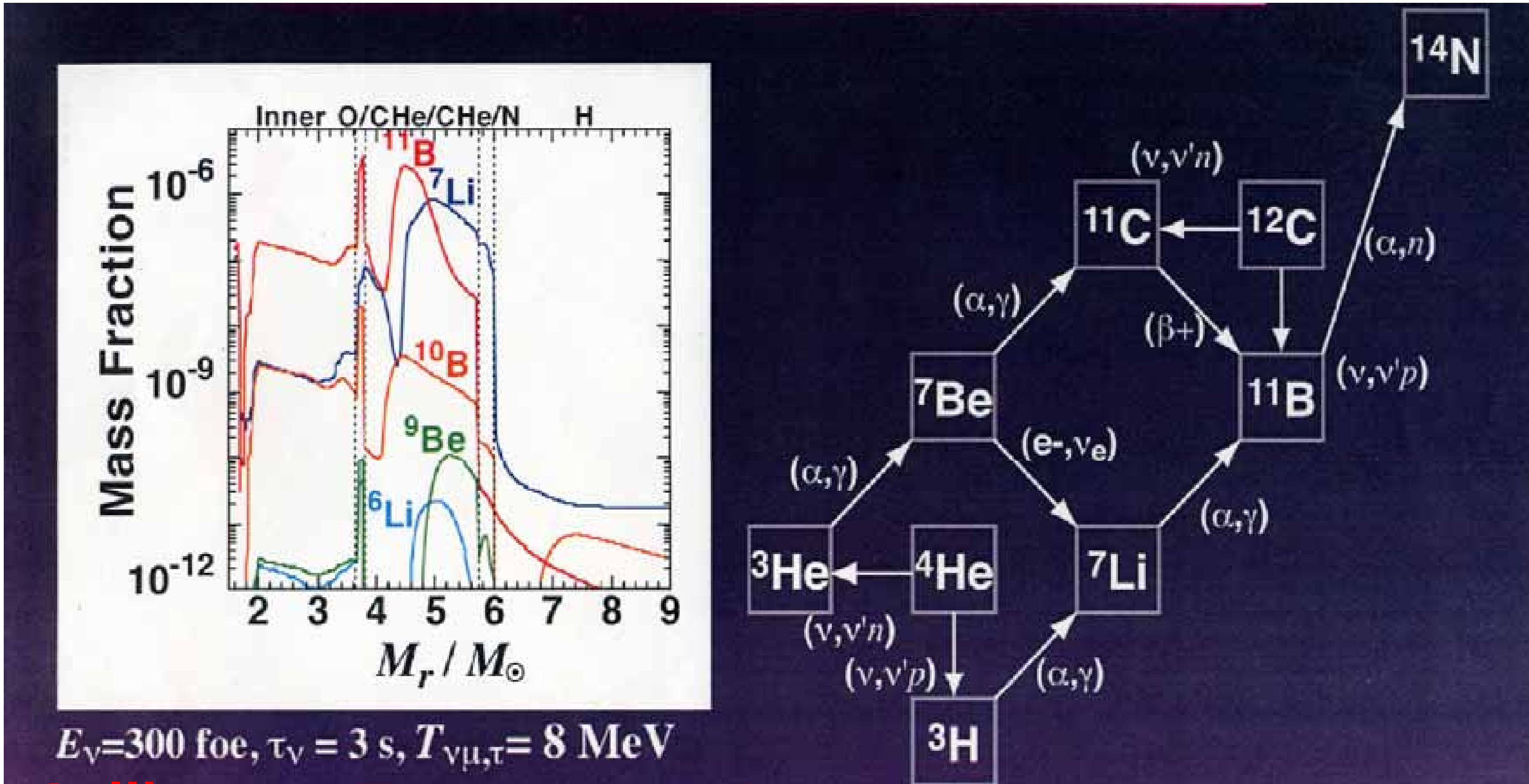


Yoshida, Kajino & Hartman,
Phys. Rev. Lett. 94 (2005), 231101

After Explosion



Yoshida, Terasawa, Kajino & Sumiyoshi, Astrophys. J. 600 (2004), 204.
Yoshida, Kajino & Hartman, Phys. Rev. Lett. 94 (2005), 231101.



★ **Calibrate ν-Temperature !**

★ **Constrain ν-Oscillation ?**

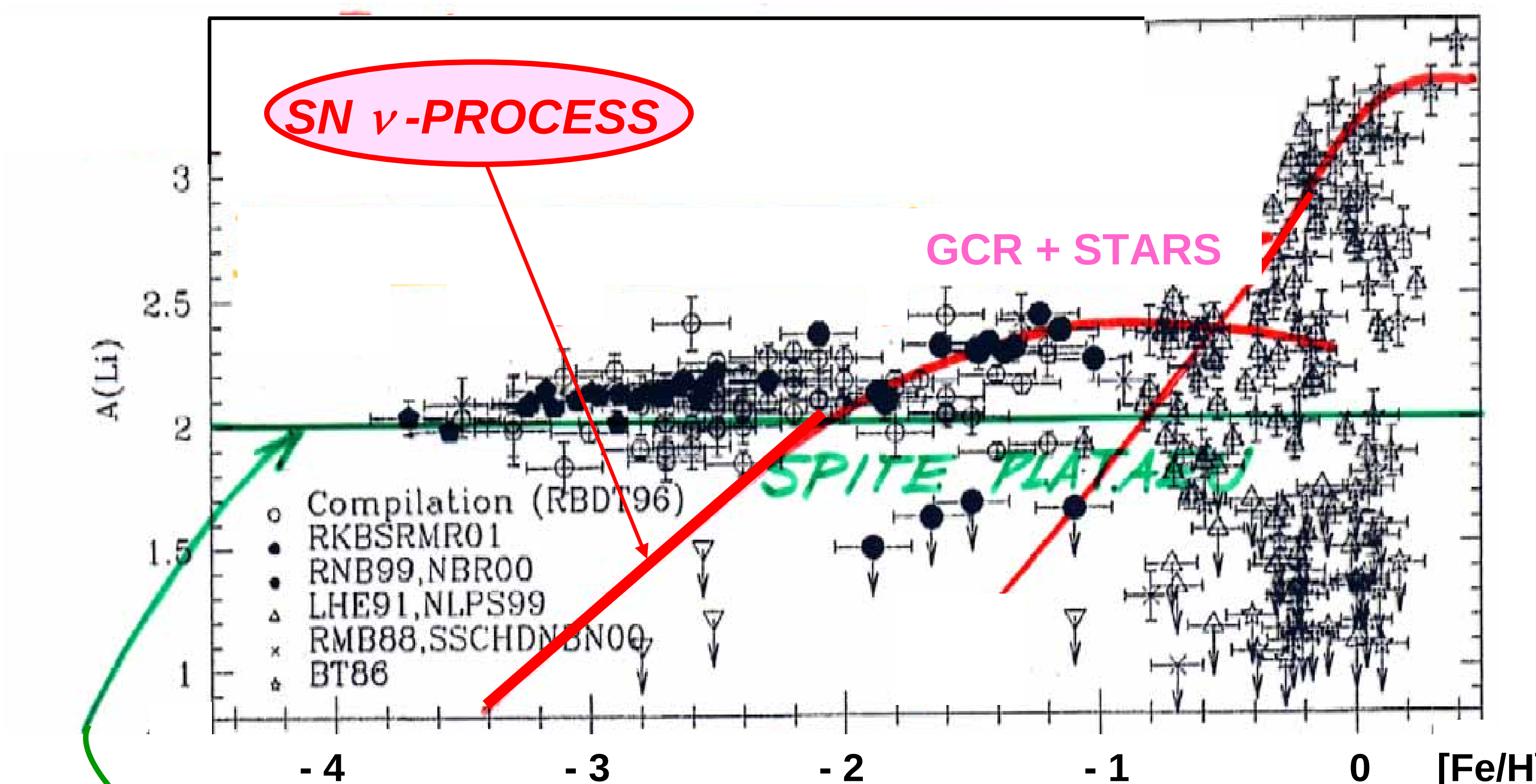
^{7}Li & ^{11}B production in He/C layer

^{4}He$(\nu,\nu'p)^{3}$H, ^{4}He$(\nu,\nu'n)^{3}$He, ^{12}C$(\nu,\nu'p)^{11}$B

^{4}He$(\nu_e,e^-p)^{3}$He, ^{4}He$(\bar{\nu}_e,e^+n)^{3}$H, ^{12}C$(\nu_e,e^-p)^{11}$C, ^{12}C$(\bar{\nu}_e,e^+n)^{11}$B

Primordial ^{7}Li Abundance, observed ?

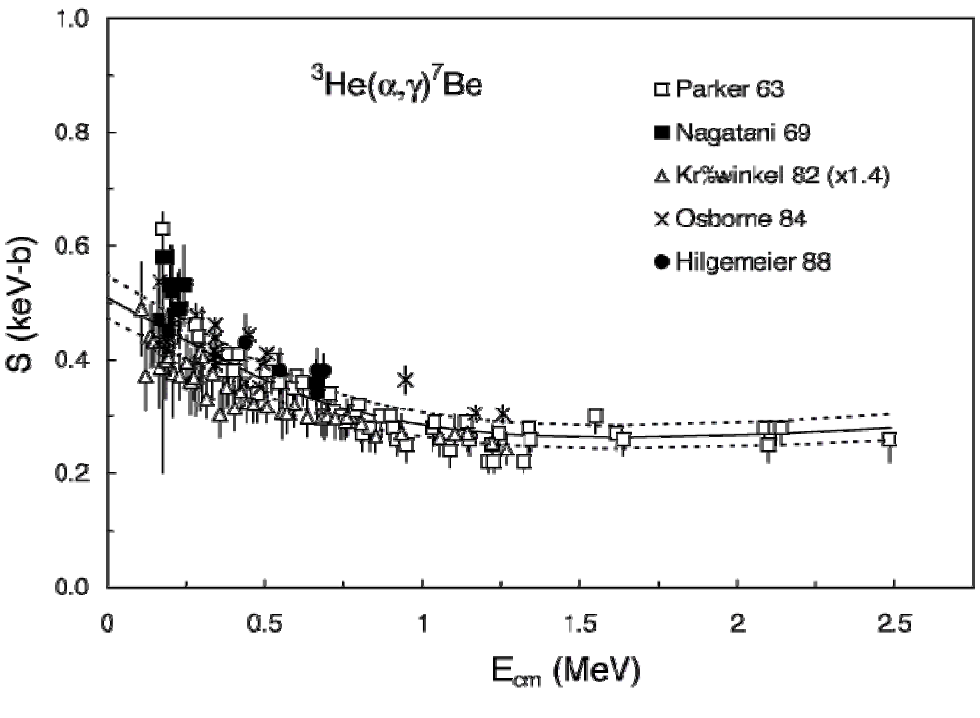
Ryan, Kajino, Beers, Suzuki, Romano,
Matteucci & Rosolankova 2001, ApJ 549, 55.



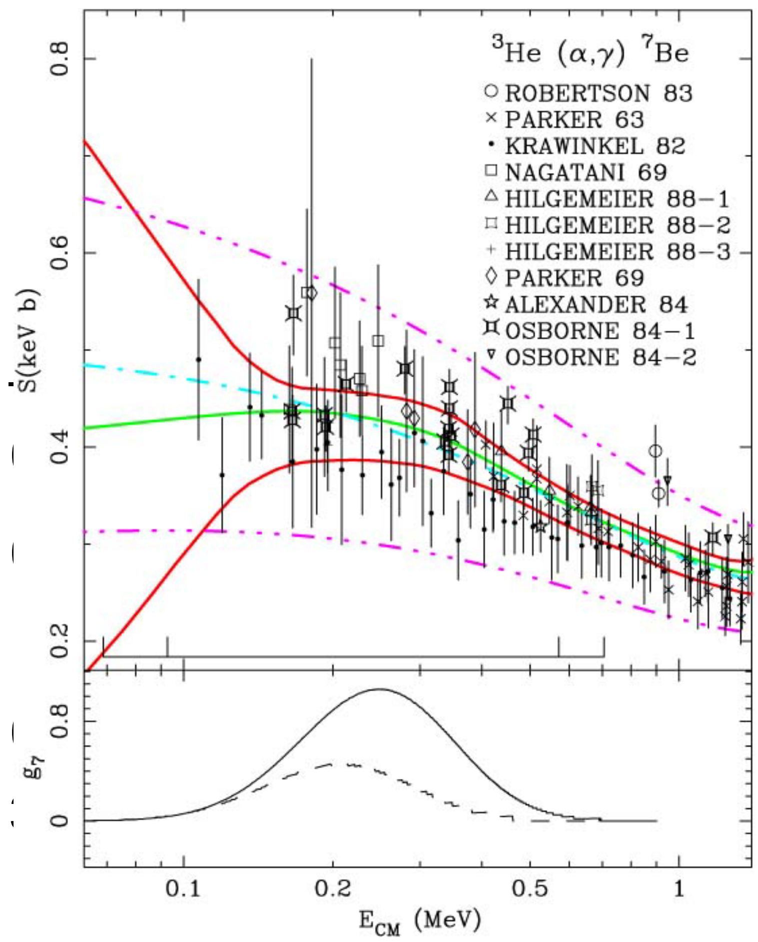
Primordial ^{7}Li is NOT affected by the SN ν-PROCESS !

Nuclear Physics can solve ^{7}Li PROBLEM ?

BBN Nuclear Uncertainties are Improving



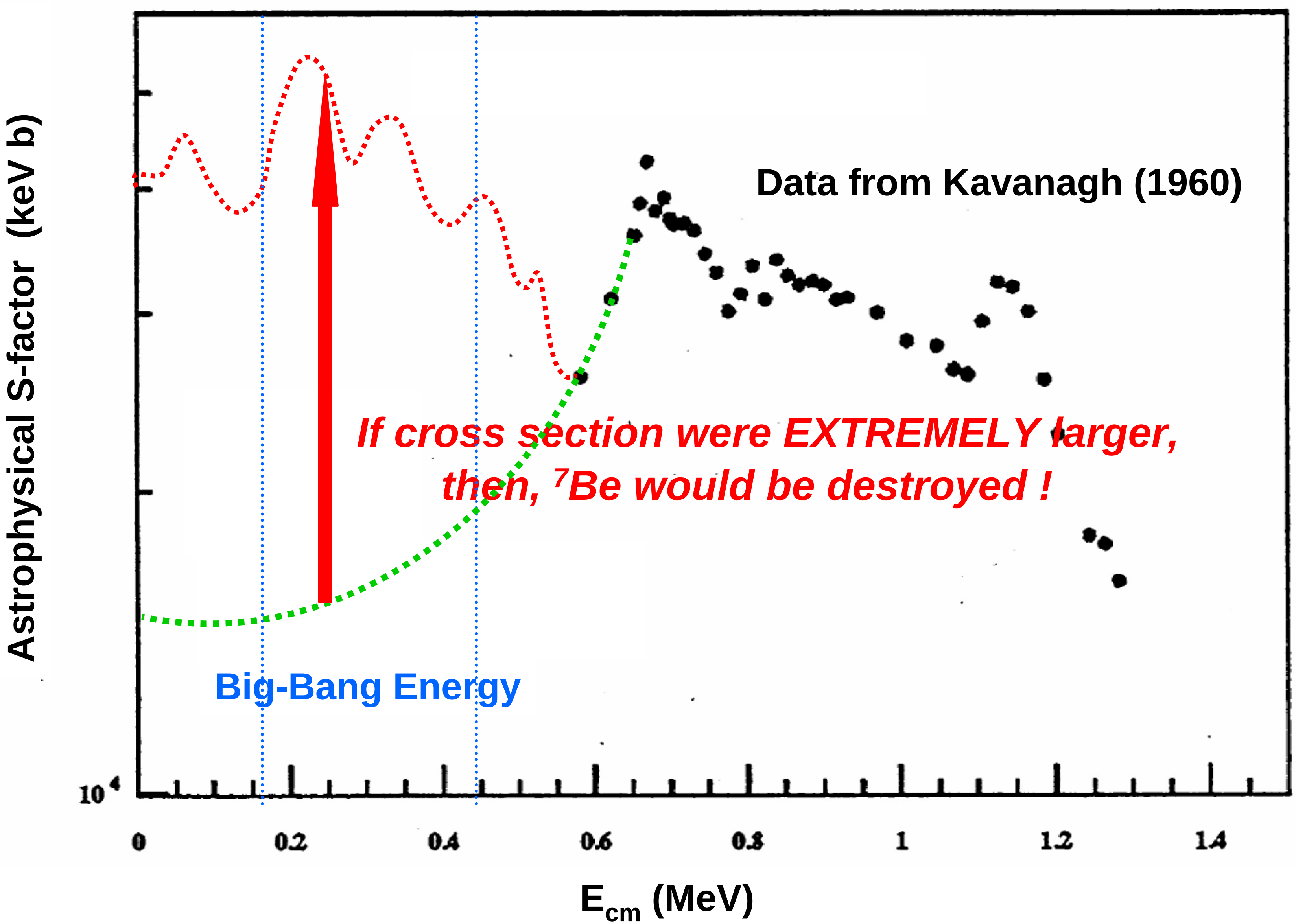
Descouvemont, Adahchour, Angulo, Coc, Vangioni-Flam. ApJ, (2004)



Nollett & Burles, PRD, 61, 123505 (2000)

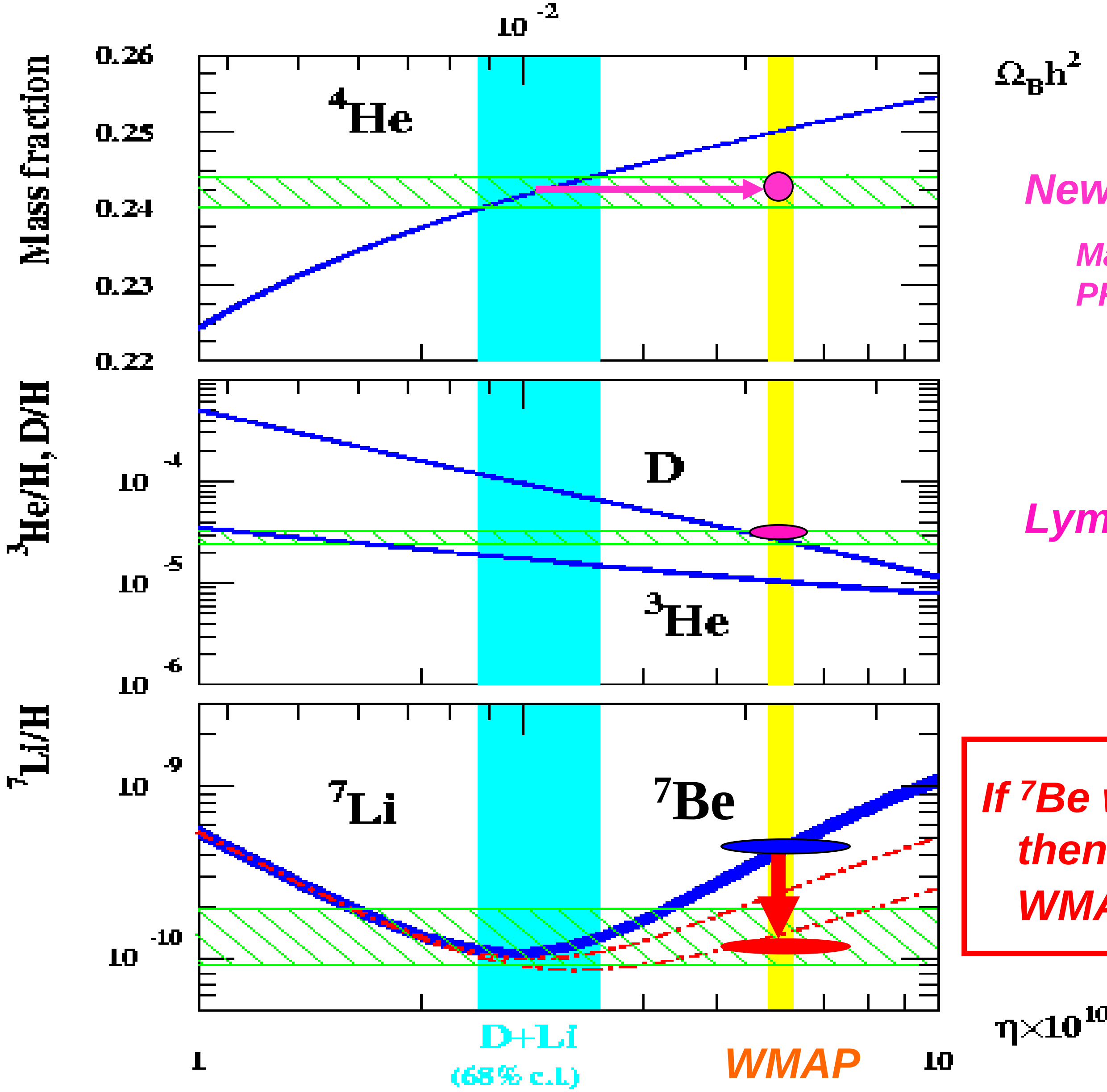
^7Be (d, p) 2α

PRPROSAL of Coc et al. (2003)



Big-Bang Nucleosynthesis

Coc, Vangioni-Flam, Descouvement, Adahchour & Angulo, ApJ 600 (2004) 544.



New neutron life !

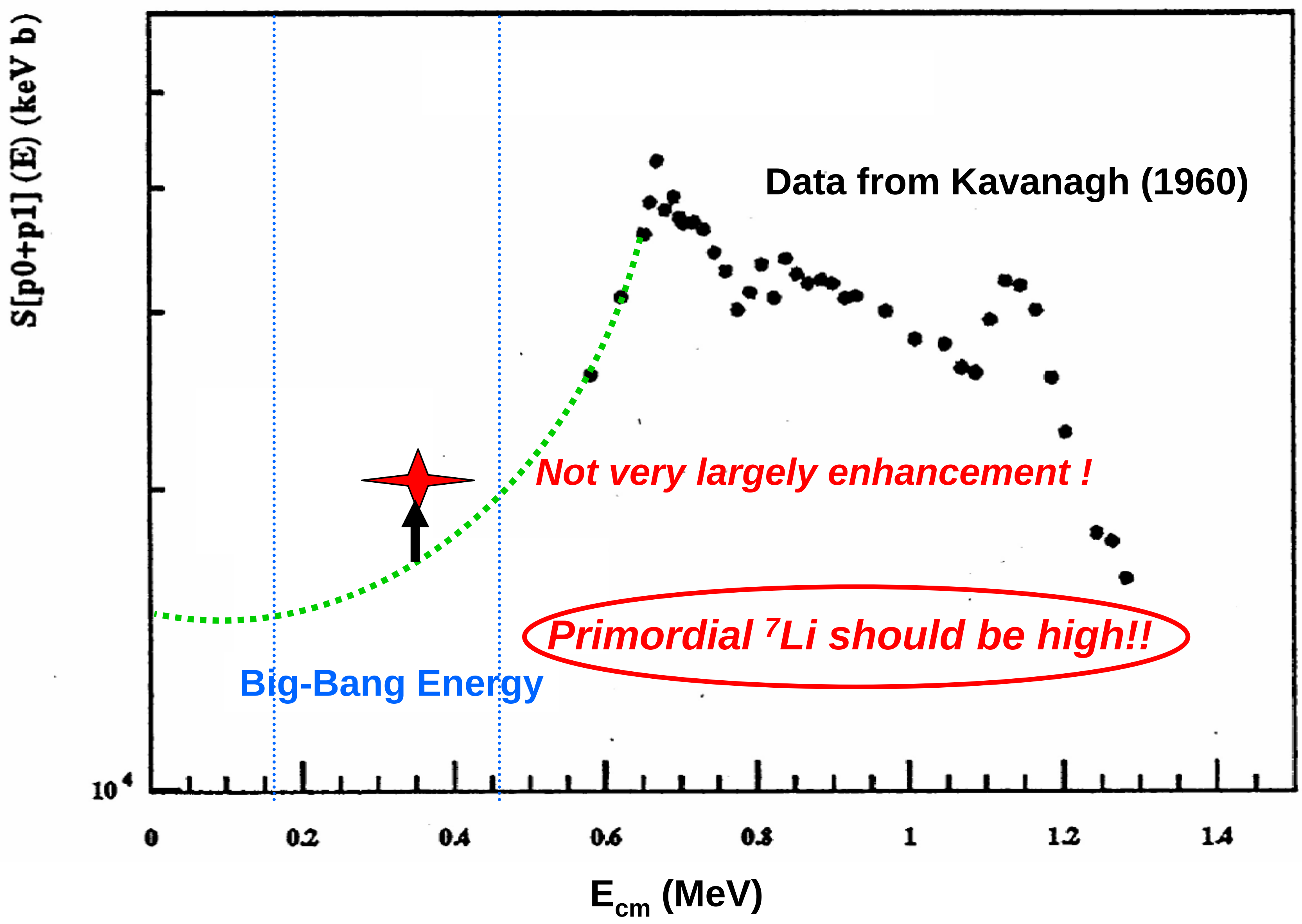
Mathews, Kajino and Shima, PRD71 (2005) 021302 (R)

Lyman-α !

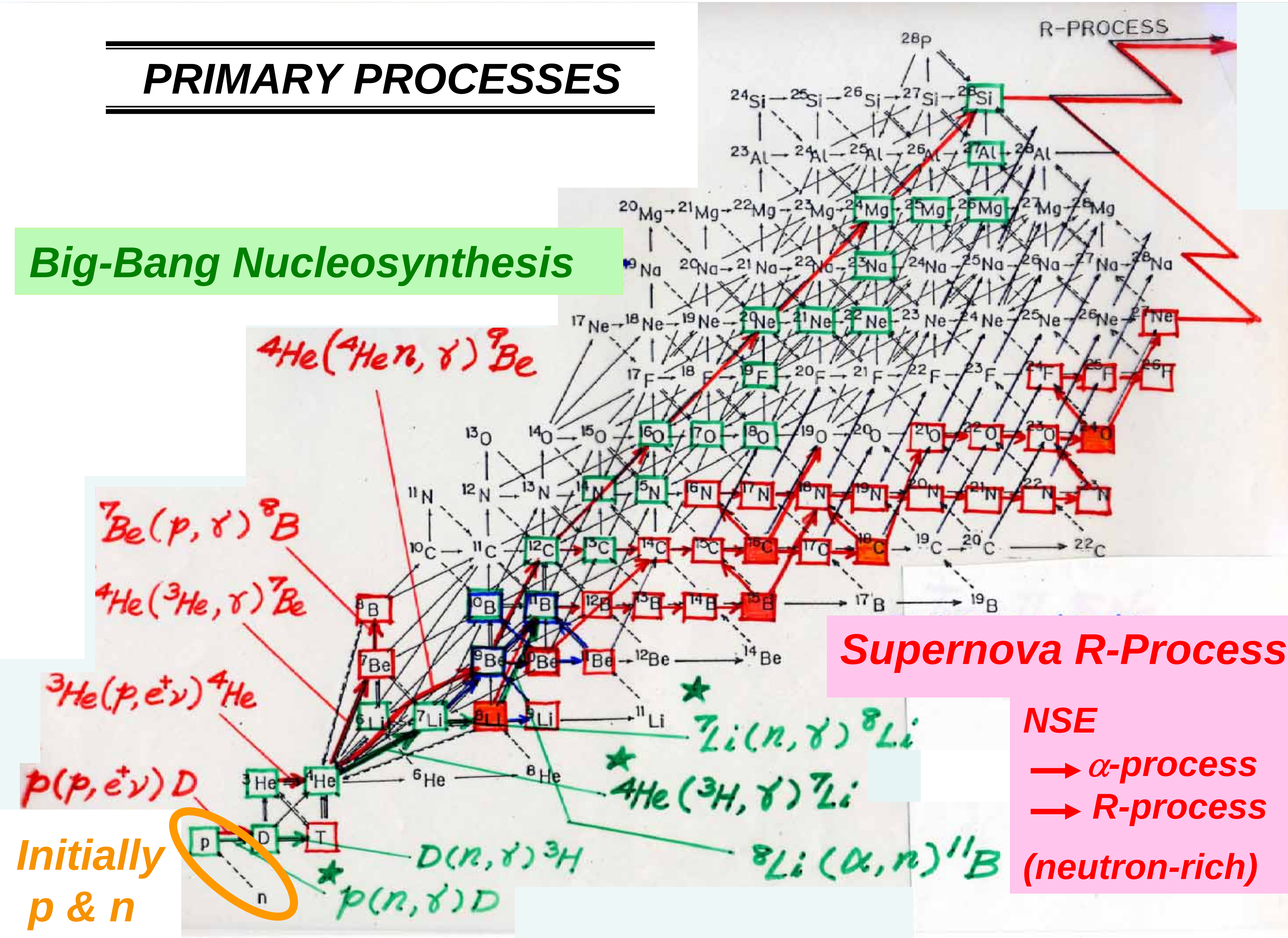
If ^{7}Be would be destroyed, then Ω_B's from BBN and WMAP could be consistent !

^7Be (d, p) 2α

Angulo et al. (2005) EXPERIMENT

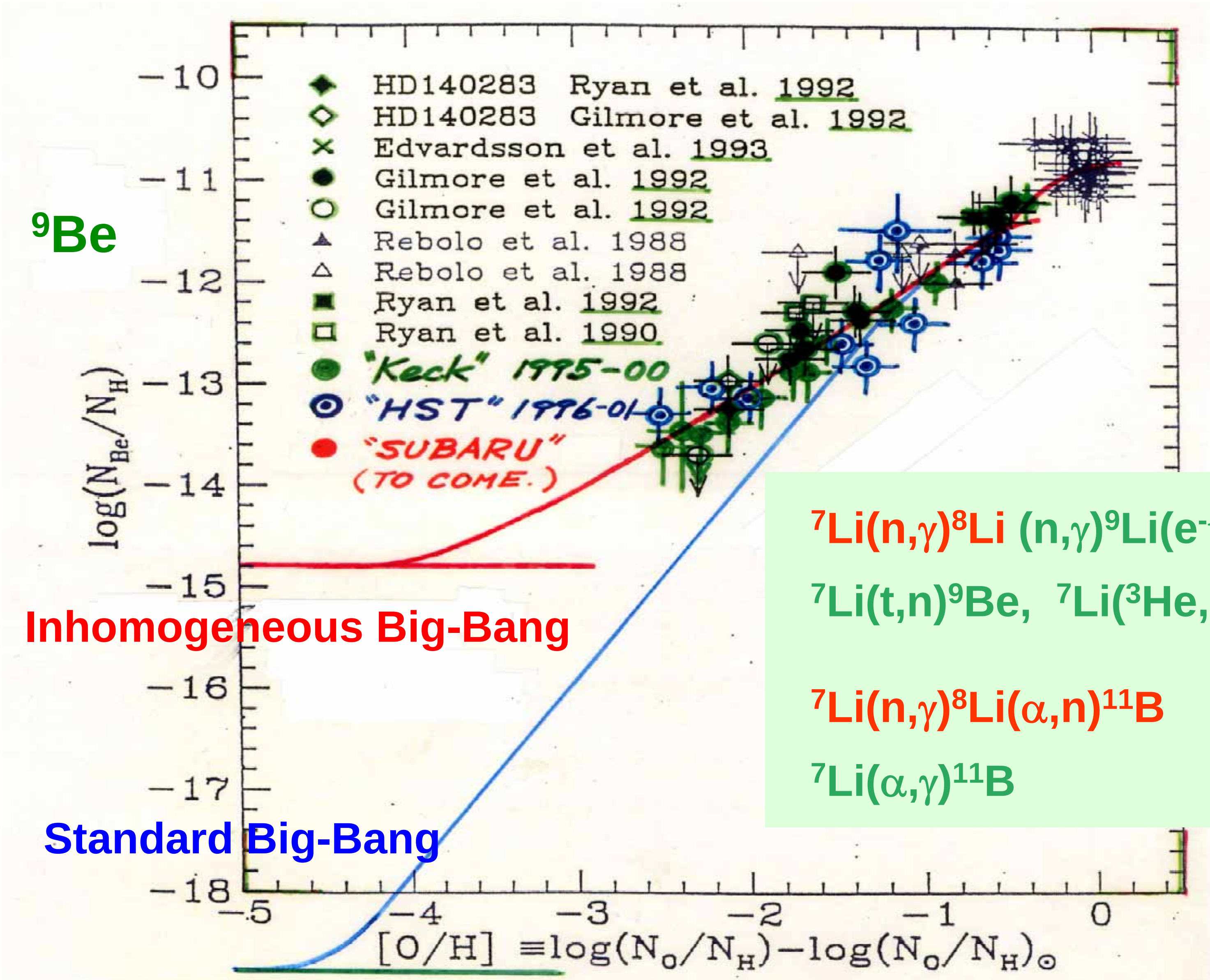


PRIMARY PROCESSES



INHOMOGENEOUS BIG-BANG NUCLEOSYNTHESIS

Kajino and Boyd, ApJ 359 (1990) 267; Orito, Kajino, Boyd & Mathews, ApJ 488 (1997) 515.



^{7}Li(n,γ)^{8}Li (n,γ)^{9}Li(e$^{-}\nu$)^{9}Be,

^{7}Li(t,n)^{9}Be, ^{7}Li(^{3}He,p)^{9}Be

^{7}Li(n,γ)^{8}Li(α,n)^{11}B

^{7}Li(α,γ)^{11}B

OUTLINE

Universe is likely flat and accelerating!
$\Omega_B + \Omega_{CDM} + \Omega_\Lambda = 1$

Six (eleven) Parameters !

- **Is BARYON, $\Omega_B = 0.04$, consistent with Big-Bang Cosmology and Nucleosynthesis (as a CANDLE of dark side of the Universe) ?**

BBN constrains Brane Cosmology !

- **What is the nature of CDM, $\Omega_{CDM} = 0.26$?**

  Disappearing CDM Model in Brane World Cosmology !
  Ichiki, Garnavich, Kajino, Mathews & Yahiro, PRD 68 (2003) 083518

- **What is DARK ENERGY, $\Omega_\Lambda = 0.7$?**

  Growing CDM Model in Brane World Cosmology !
  Umezu, Ichiki, Kajino, Mathews Nakamura & Yahiro,(2005) (astro-ph/0507227)

- **COSMIC AGE (13.7 +- 0.2 Gy), strongly model-dependent ?**

  Supernova R-Process & Origin of ^{232}Th, ^{235,238}U ! --- Model independent !
  Sasaqui, Kajino & Balantekin, ApJ (2005), in press. (astro-ph/0506100)

Brane World Cosmology

Motivated by the D-brane solution in 10 dim STRING THEORY

Randall-Sundrum II; PRL 83 (1999)

Quantized matter fields in AdS_5 leads to quasilocalized eigenstates on the 4 dim brane.

CDM Particle   ***SUSY !?***

5–th dimension, compactified.

Massive particle can tunnel into z !

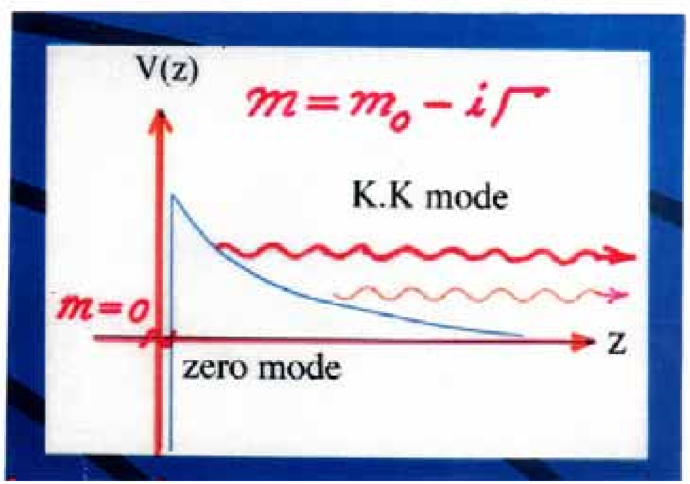
The Universe is embedded in a 5 dim spacetime AdS_5.

Brane

||

4D-Einstein Universe

Dubovsky, Rubakov, & Tinyakov (2000)



Disappearing LSP (Lightest SUSY Particle) CDM Model Is a likely possibility !

LSP = Lightest Supersymmetric Particle

$m_0 \sim 1$ TeV **vs.** $\mathbf{m_B \sim 1}$ **GeV**

Fermion:

$$\Gamma = m_0 (m_0/2k)^{2gv/k-1}\, \pi/\Gamma_f(gv/k+1/2)^2$$

v = vacuum expectation value

g = coupling const.

Scalar Particles (Bosons):

$$\Gamma = (\pi/16)\, m_0^{\,3}/k^2$$

$$k = (-\Lambda_5/6)^{-1/2}$$

- ***LSPs (CDM) disappear at cosmological time !***
- ***BARYONS do not !***

Largest Γ for largest m_0

Modified Friedmann Equation

$$H^2 = \frac{8\pi G_N}{3}\rho - \frac{k}{a^2} + \frac{\Lambda_4}{3} + \cancel{\frac{\kappa_5^4}{36}\rho^2} + E$$

$$\rho = \rho_M + \rho_R + \rho_{DM}$$

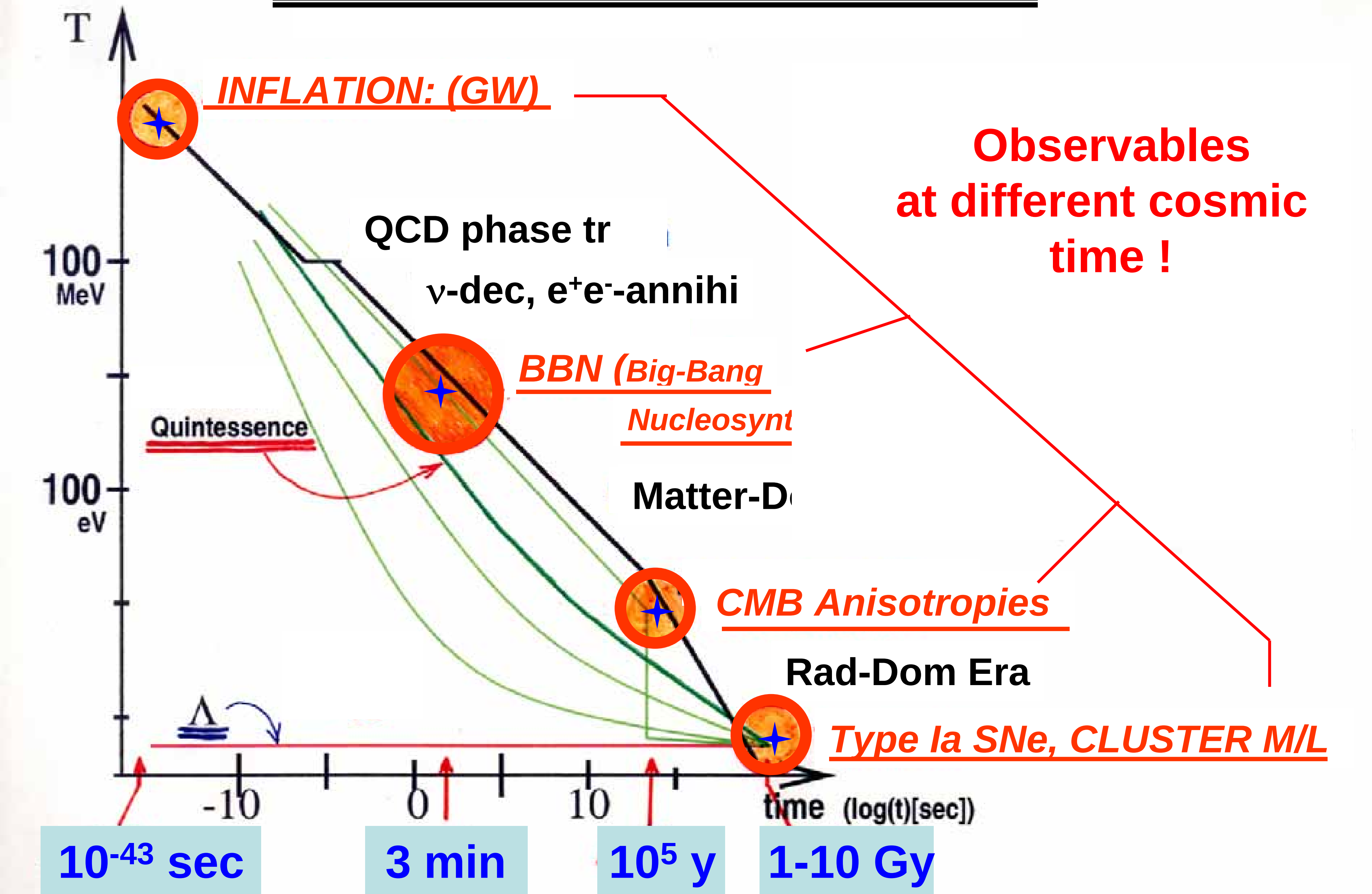
$$\boxed{\rho_{DM} = Ce^{-\Gamma t} / a^3}$$

E = Dark Radiation or Electric part of the bulk Weyle tensor

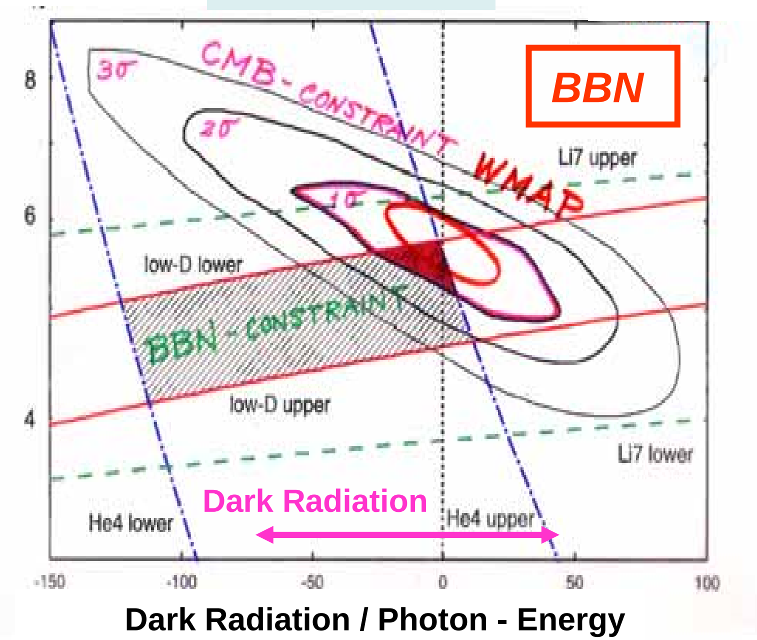
$$\boxed{\frac{dE}{dt} + 4HE = \Gamma \rho_{DM}}$$

Ichiki, Garnavich, Kajino, Mathews & Yahiro
PRD 68 (2003), 083518

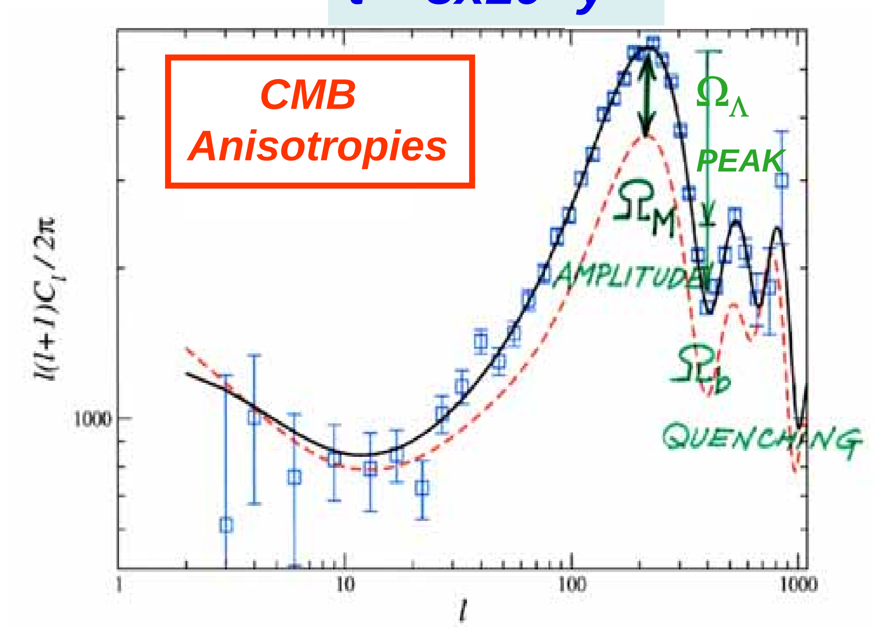
Thermal History of the Universe



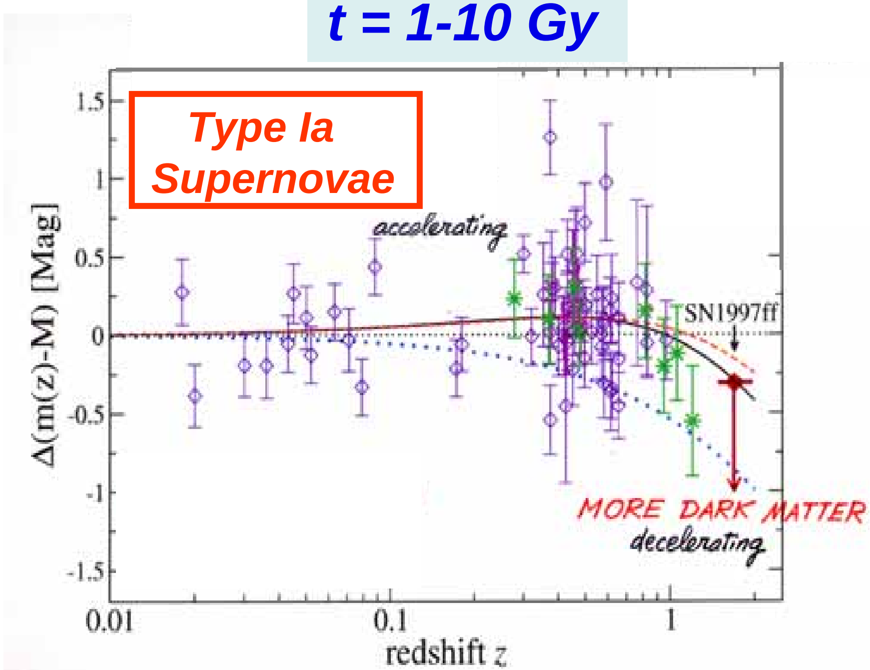
t = 3 min



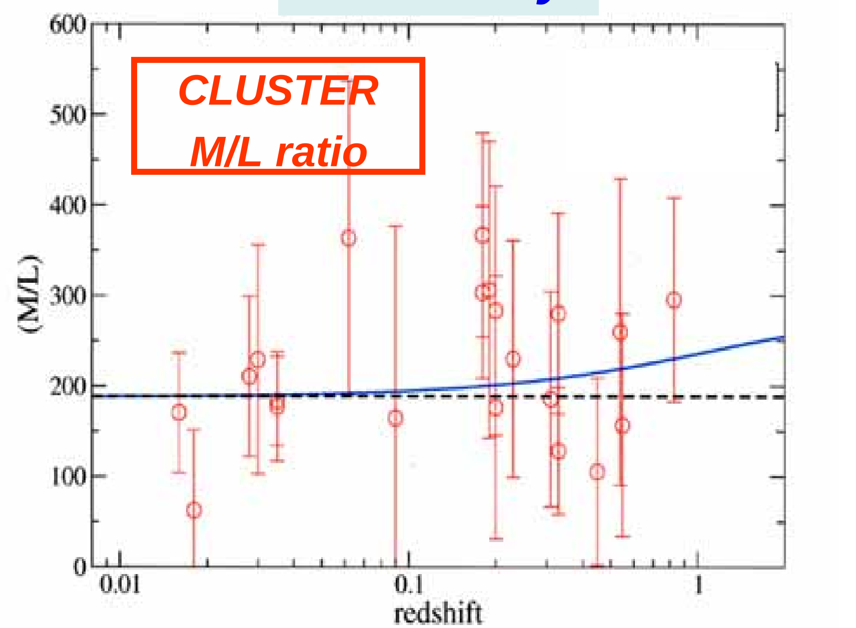
t = 3x10^5 y



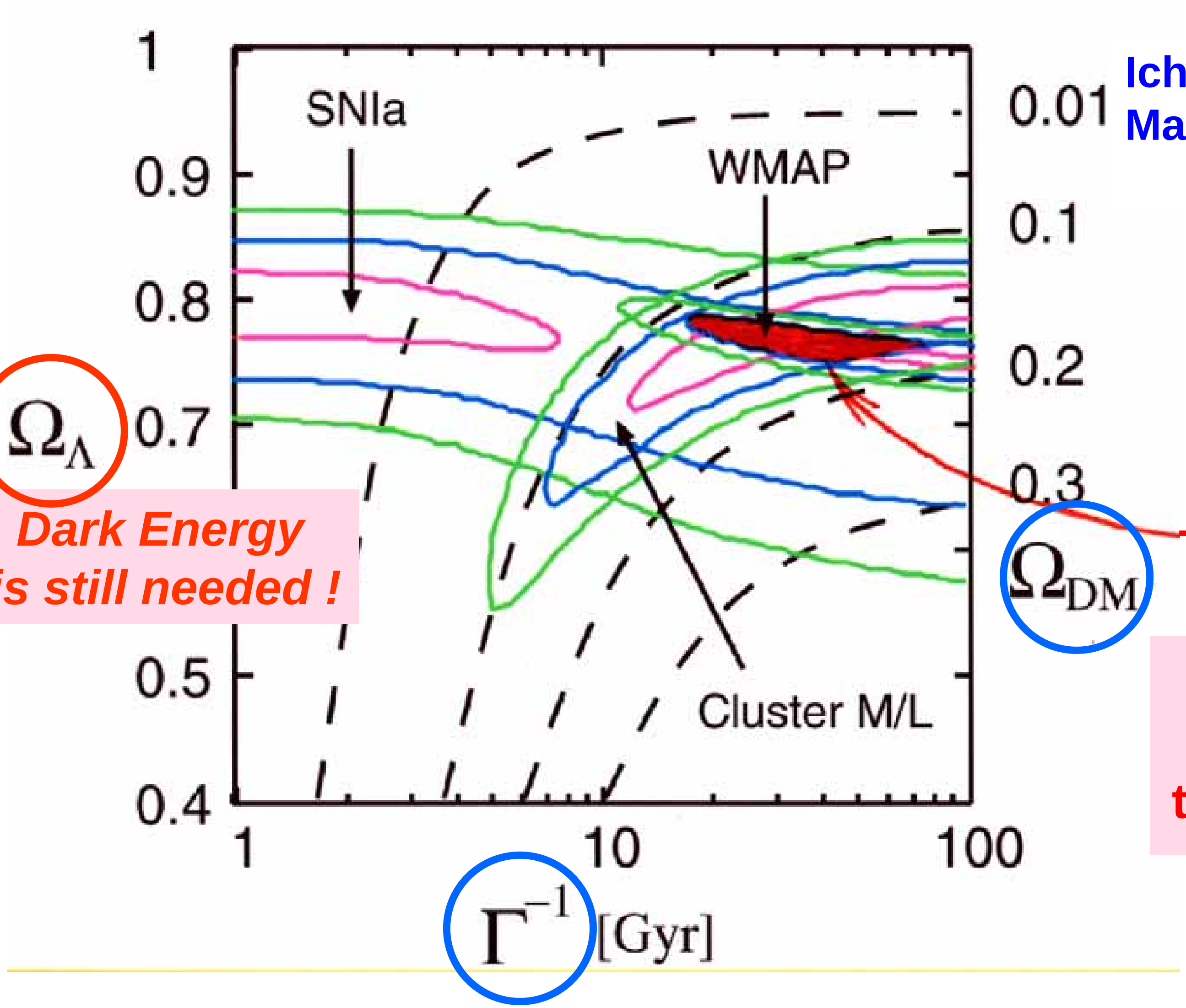
t = 1-10 Gy



t = 1-10 Gy



Constraints on SUSY-Brane Cosmology (Disappearing CDM) Model

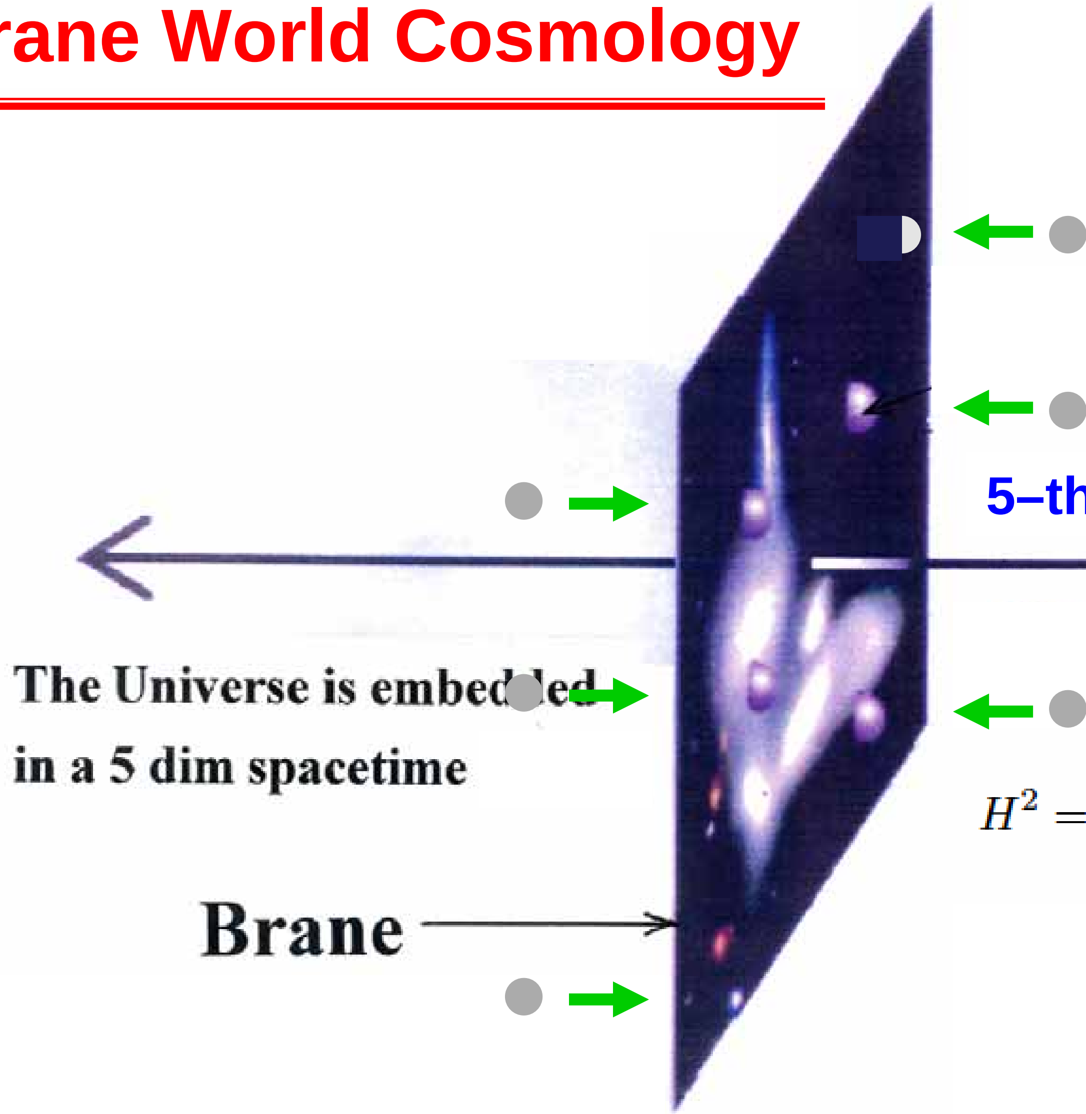


Ichiki, Garnavich, Kajino, Mathews & Yahiro, PRD 68 (2003) 083518

Dark Energy is still needed !

Our Model is as good as the standard model.

Brane World Cosmology



CDM particles can exist in the bulk.

Then, they can FLOW IN from the bulk !

5–th dimension, compactified.

$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}(\bar{\rho} + \rho + \rho_\chi) + \frac{k}{a^2}$$

Dark Enerfy term:

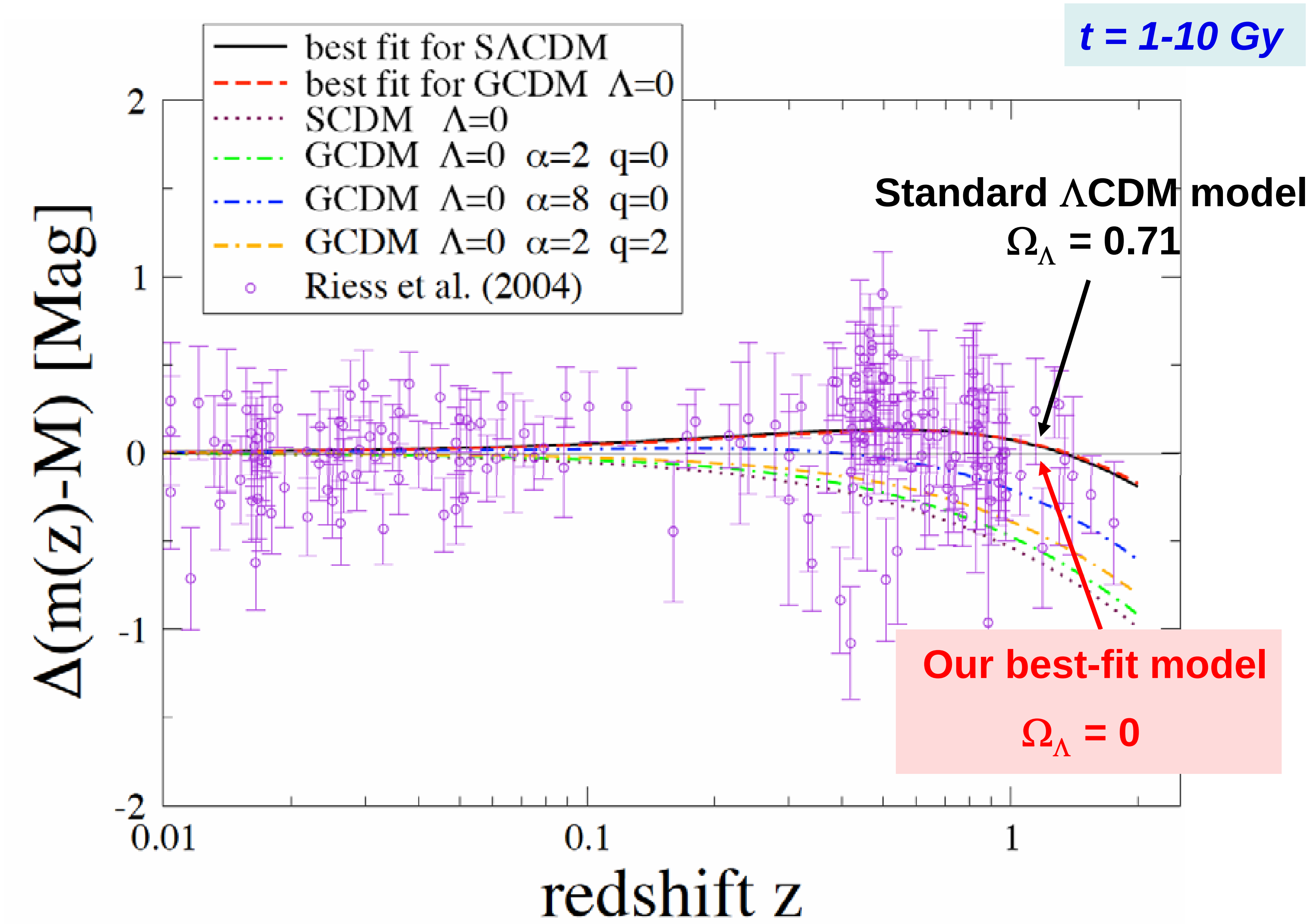
$$\dot{\rho}_\chi + 4H\rho_\chi = -\alpha/a^q \times \rho_{cr} H$$

q* = *adjustable parameter

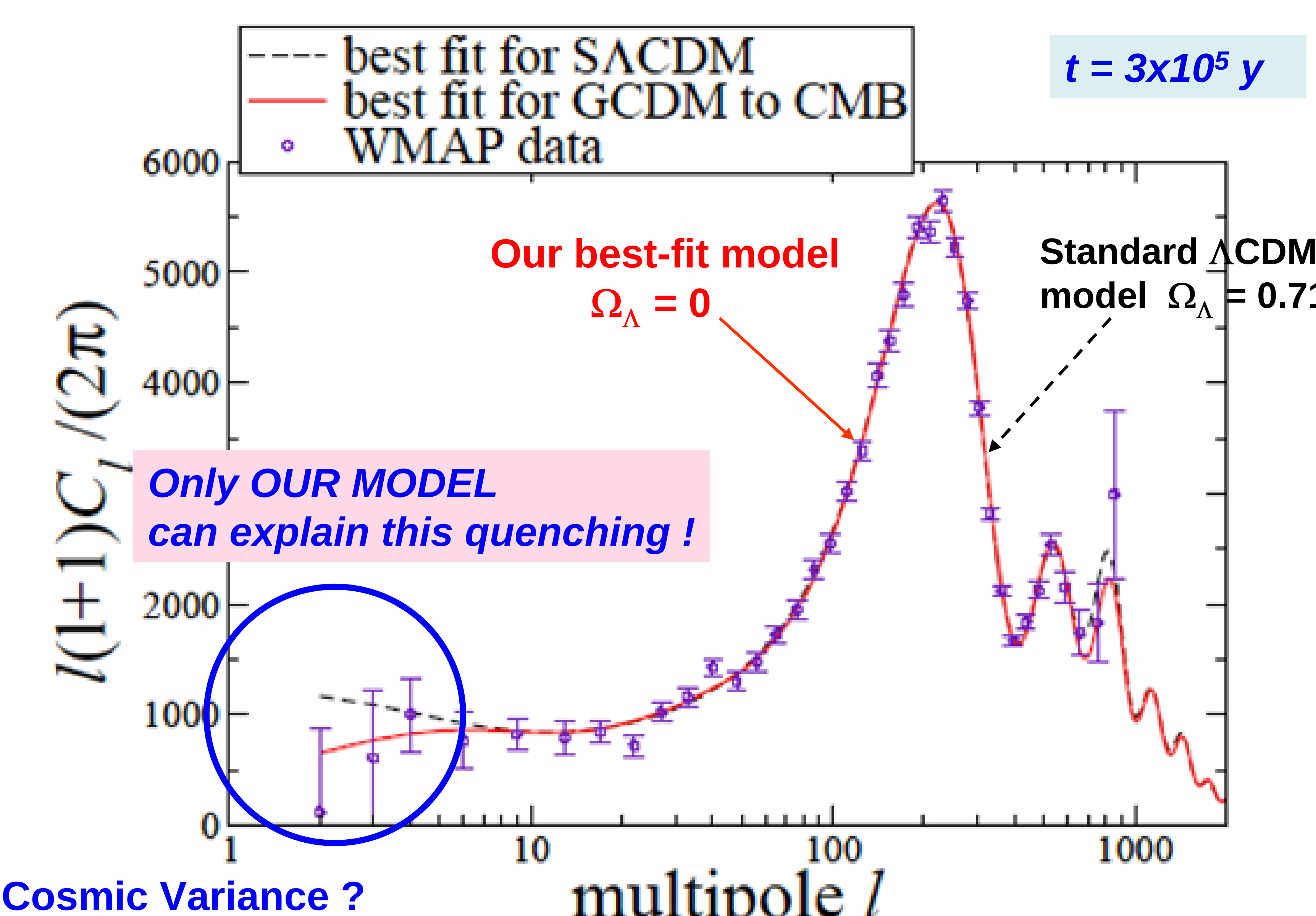
We propose Growing-CDM Model for DARK ENERGY !

Ω_Λ = 0 model !

Supernova z vs. m-M Relation



CMB Anisotropies

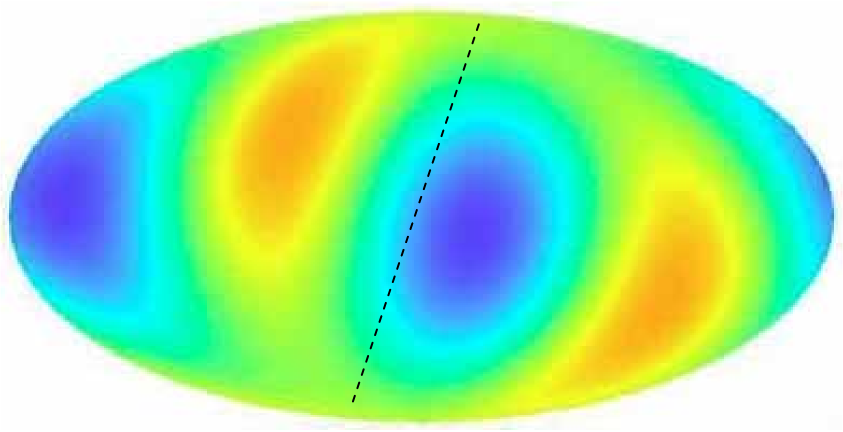
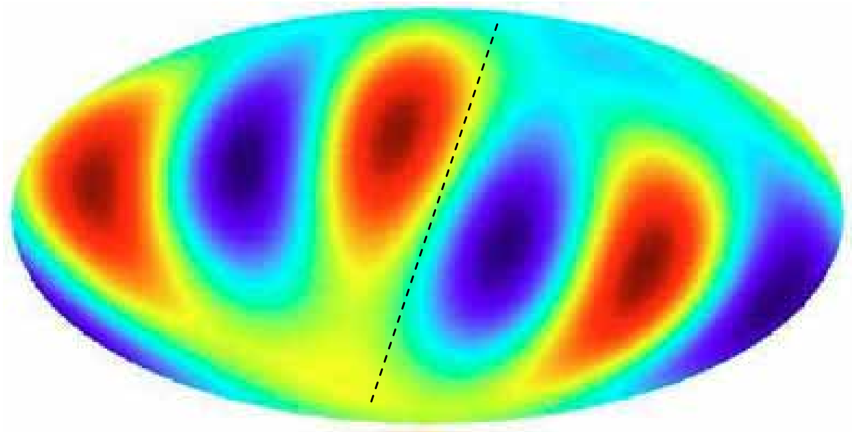


$t = 3x10^5$ y

Only OUR MODEL can explain this quenching !

Cosmic Variance ?

Cosmic Microwave Background

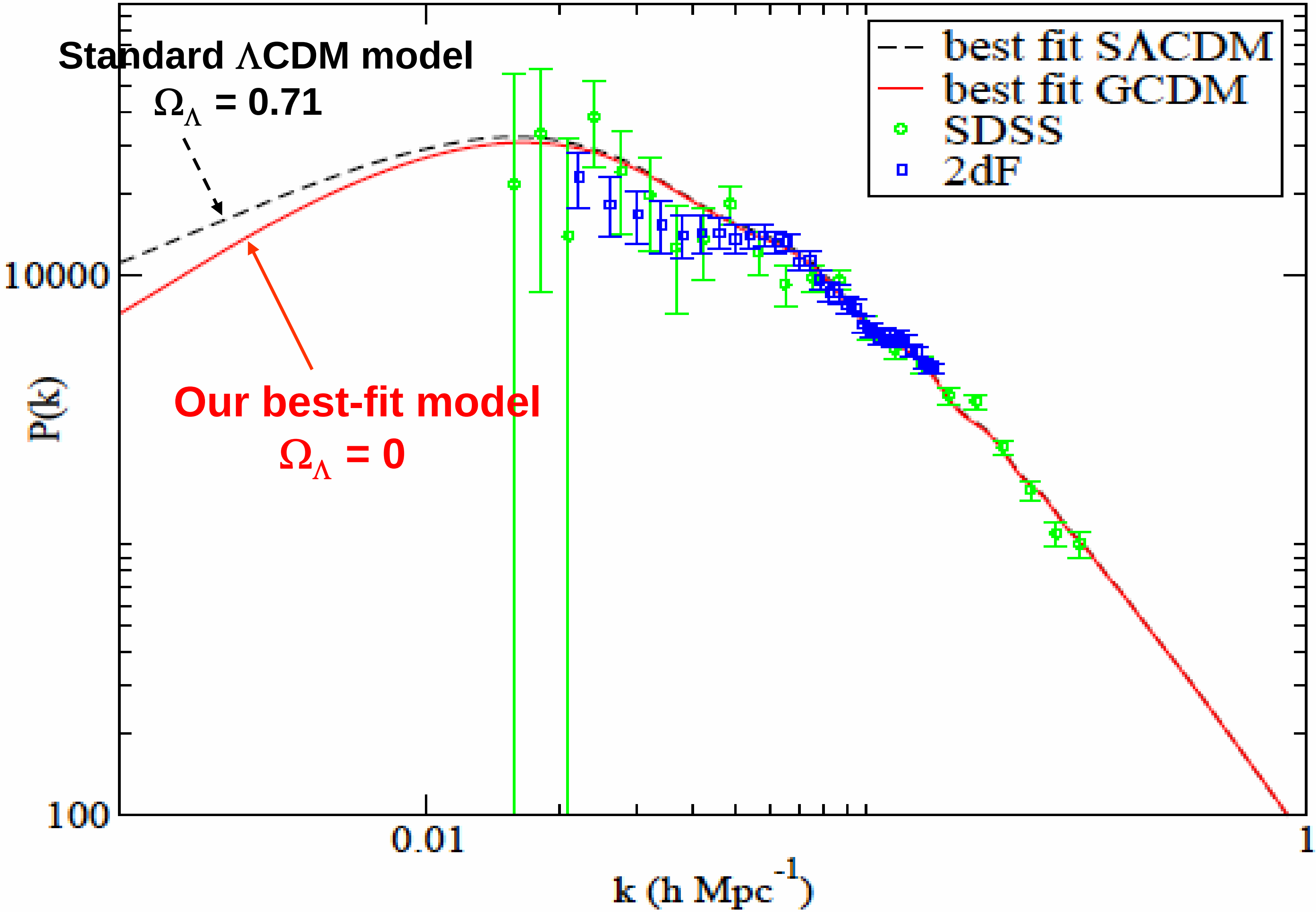
 

WMAP shows evidence for suppression of quadrupole and octopole moments.

- **Aligned in the direction of Virgo:** **Tegmark et al (2003)**
- **This could suggest a compact cosmology**
- **Use axis to guide search (l,b) ~ (-80°,60°)**

Matter Power Spectrum P(k)

t = 1-10 Gy



Conclusion

Big-Bang Nucleosynthsis is one of the Pillars of very precise Particle-Nuclear Theory and Modern Cosmology.

Standard Quark Model --- KMC Matrix !
Dark Matter --- SUSY Particles in Brane Cosmology
Dark Energy --- Flowing in of CDM in Brane Cosmology

Acceleration, due to CDM inflow without Ω_Λ !
Quenching of low multipoles in CMB, due to late ISW effect !

^{7}Li problem still remains ??

Core-Collapse Supernovae are Viable Astrophysical Sites for R-Process.

New Role of R-Process Elements ^{232}Th & ^{235,238}U
--- Cosmochronology for Metal-Deficient Stars, hopeful but needs more precision?
--- Sensitivity of Neutrino Cutoff to BH vs. NS Formation !