Basics of Theoretical Astronomy and Astrophysics – 5
November 28, 2016

Cosmic QCD Phase Transition and Dark Matter, Dark Enerygy

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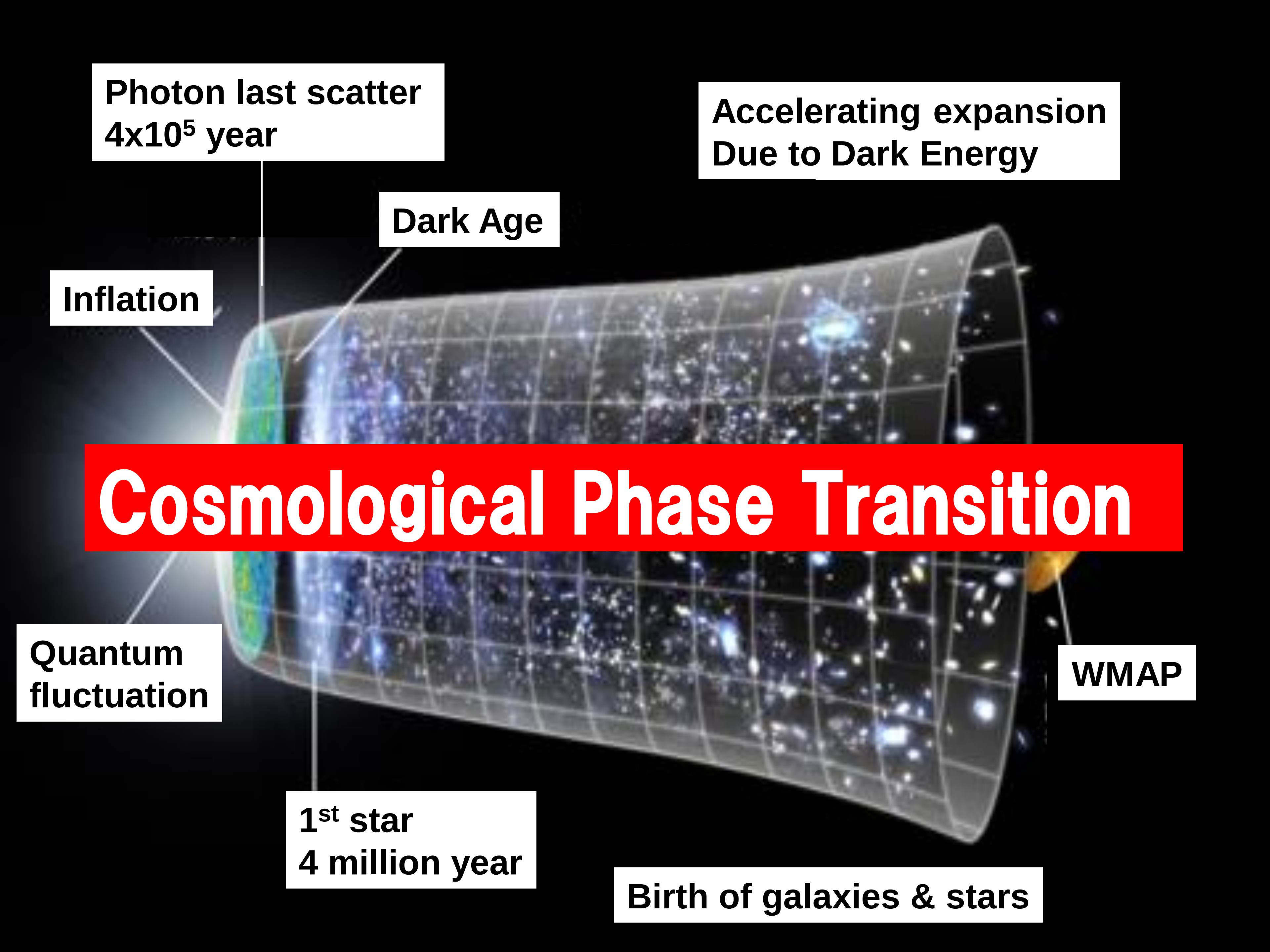
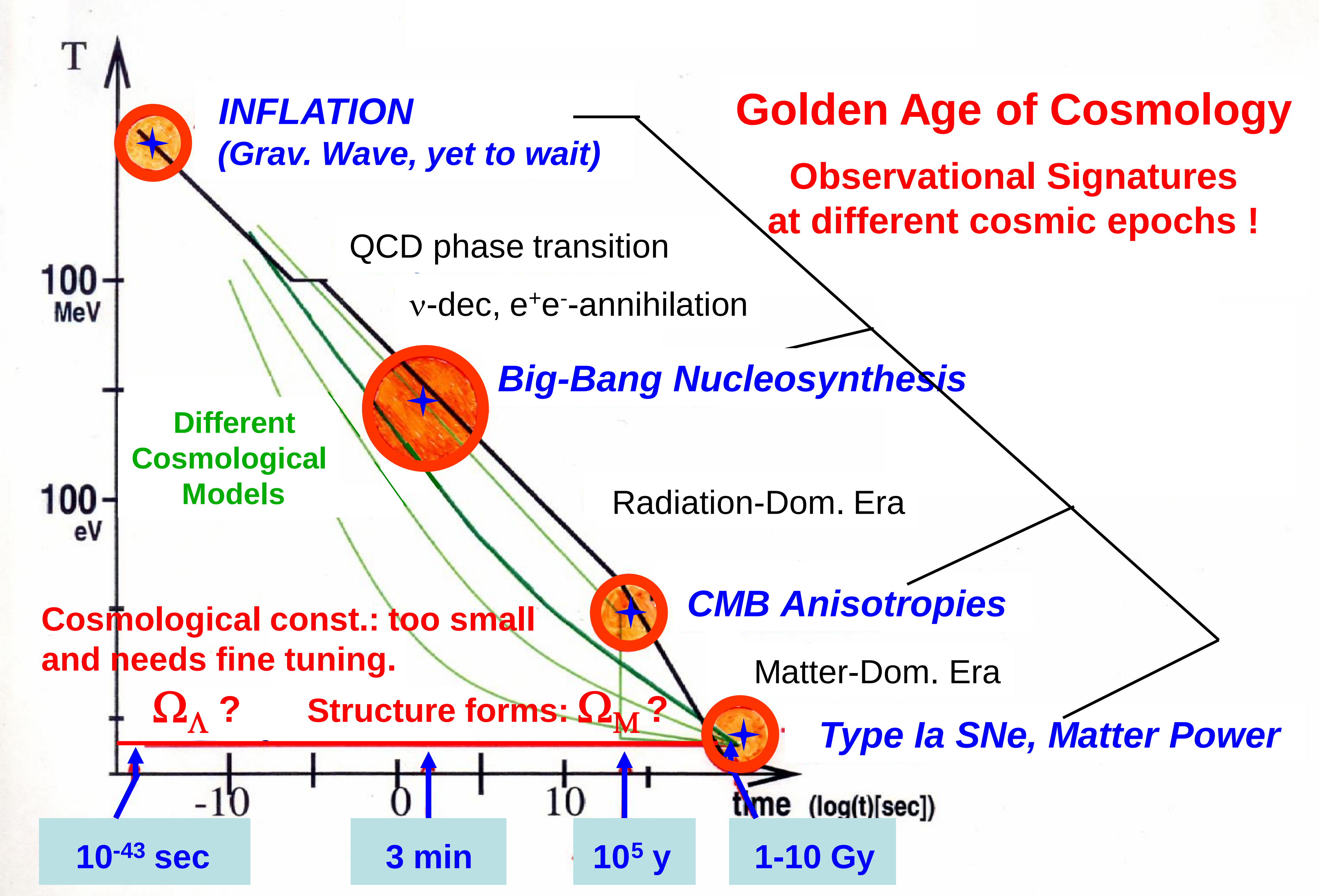

Photon last scatter
4x10⁵ year
Accelerating expansion
Due to Dark Energy
Dark Age
Inflation
Cosmological Phase Transition
WMAP
Quantum
fluctuation
1st star
4 million year
Birth of galaxies & stars

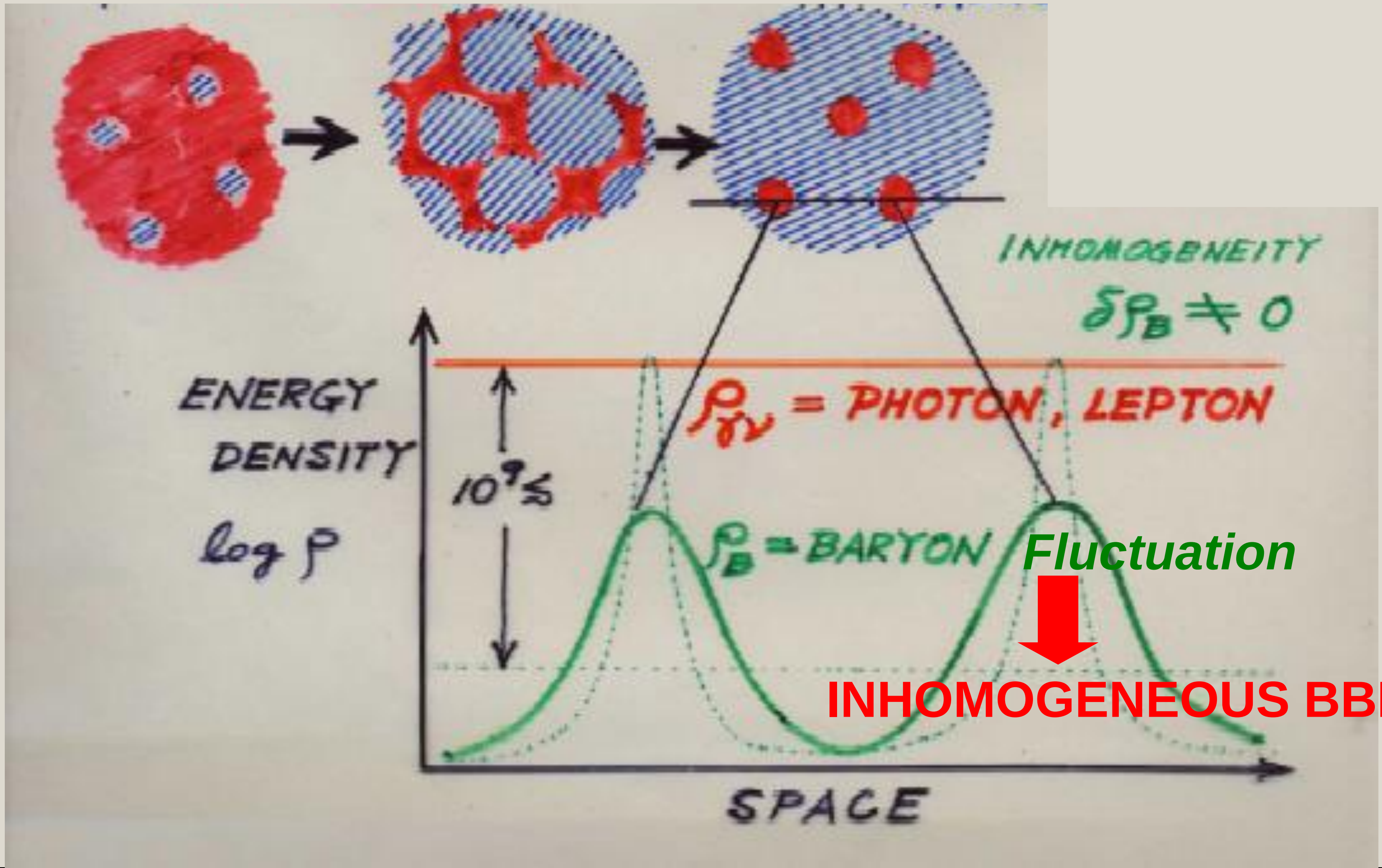
Thermal History of the Universe



Inhomogeneous Cosmology

due to Cosmic Phase Transition

High ρ-T phase **Low ρ-T hadron phase**



Fluctuation

INHOMOGENEOUS BBN

$V(t) = a(t)^3$

UNIVERSAL EXPANSION; $a(t)$, $f_V(t)$ ··· Einstein eq.

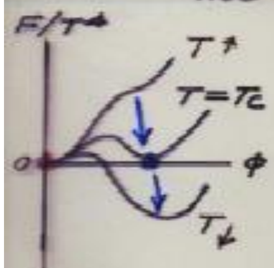
$$\begin{cases} \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\left\{\rho_q f_V + \rho_h (1-f_V)\right\} \\ \dot{p} a^3 = \frac{d}{dt}\left[a^3\left\{\rho_q f_V + \rho_h(1-f_V)\right\} + p a^3\right] \end{cases}$$

$\rho_{q,h}$, $p_q \approx p_h$; Free-Gas Approx. $\Leftarrow T_c$

NUCLEATION OF HADRONIC BUBBLES IN QGP

$$F(\phi,T) = V(\phi) - T^4 \frac{1}{2\pi^2}\sum_{i=1}^{117}\int_0^\infty k^2 dk\,(\pm)\log\left[1 \pm \exp\left(-\left\{k^2 + \frac{\lambda_i^2\phi^2}{T^2}\right\}^{1/2}\right)\right]$$

$$\Gamma_{Nuc}(T) = T^4\left(\frac{S}{2\pi T}\right)^{3/2}\left[\frac{\det'\left(-\nabla^2 + \frac{\partial^2 F}{\partial\phi^2}\right)}{\det\left(-\nabla^2 + \frac{\partial^2 F}{\partial\phi^2}\right)}\right]^{-1/2}\exp\left(-\frac{S}{T}\right)$$



$$\sim T^4 \exp\left(-\frac{\Delta F}{T}\right)$$

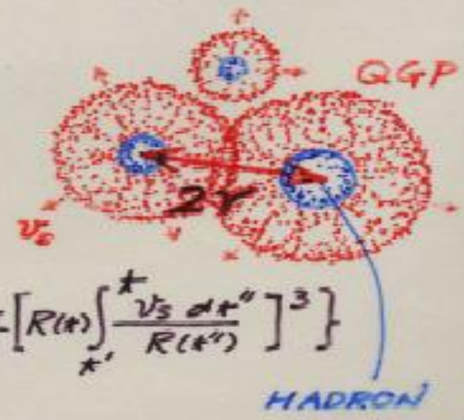
CLASSICAL ISOTHERMAL-FLUCTU.

$$\sim T_c^4 \exp\left(-\frac{16\pi}{3}\frac{\sigma^3}{T_c L^2 \eta^2}\right)$$

$\Leftarrow \sigma$, $L(T_c)$

$$\eta = \frac{T_c - T}{T_c}$$

WEAK SUPER-COOLING $\eta \ll 1$.



$$t T^2 = t_c T_c^2$$

$$f_{sc}(t) = \exp\left\{-\int_{t_c}^{t} f_{sc}(t')\,\Gamma_{Nuc}(T')\,dt'\,\frac{4\pi}{3}\left[R(t)\int_{t'}^{t}\frac{v_s\,dt''}{R(t'')}\right]^3\right\}$$

$$\langle l \rangle^{-3} \approx n_H = \int_{t_c}^{t_f}\Gamma_{Nuc}(T')\,f_{sc}(t')\,dt'$$

$\tau_B \sim 10$ fm QUANTUM EFFECT !

真空の相転移の量子論
Theory of Quantum (QCD) Phase Transition

⬇

等温度ゆらぎ（Isothermal Fluctuation）の
熱力学（Classical Thermodynamic Theory)で近似

過冷却(Supercooling)とハドロン相の核化（Nucleation）
Ref.: Inflation (A. Guth 1982）

NUCLEATION IN SUPERCOOLING EPOCH

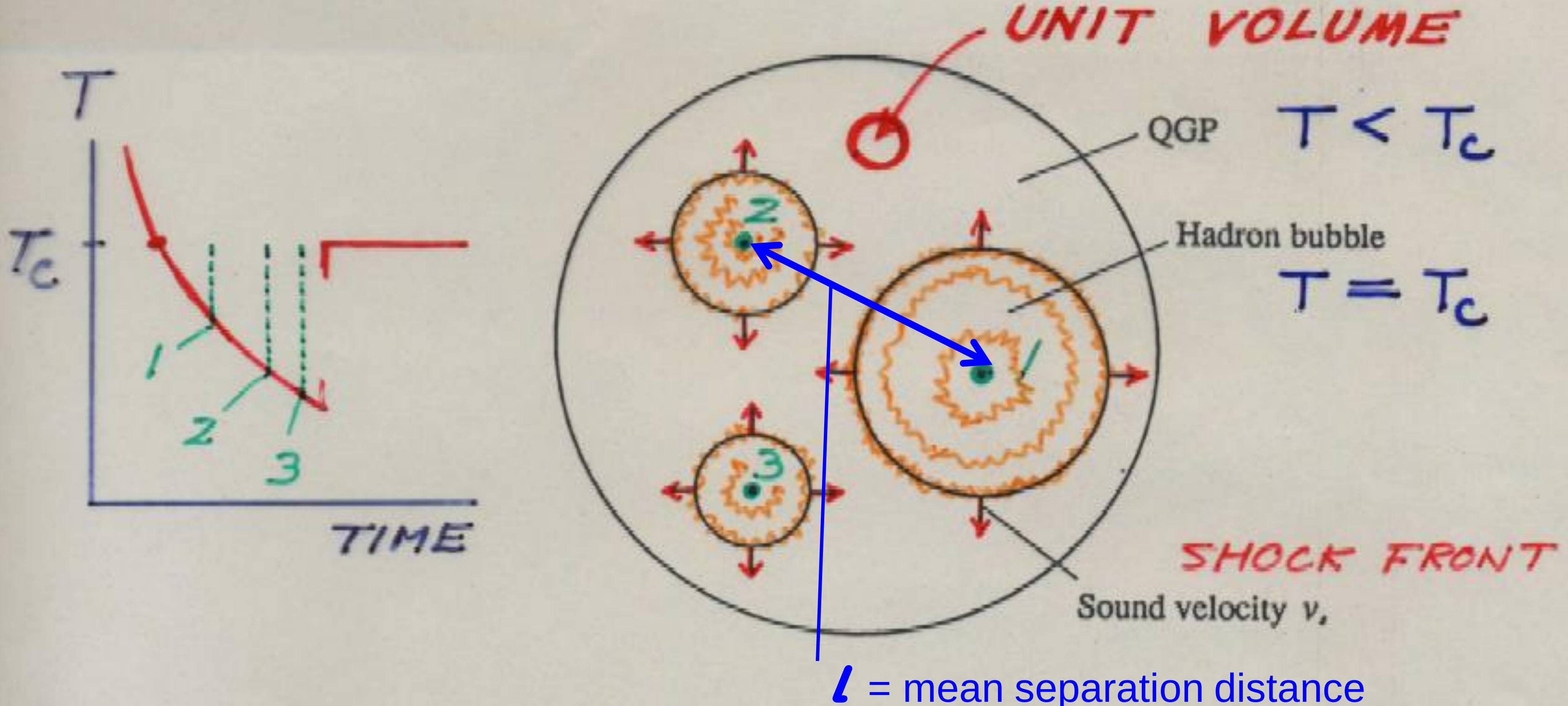
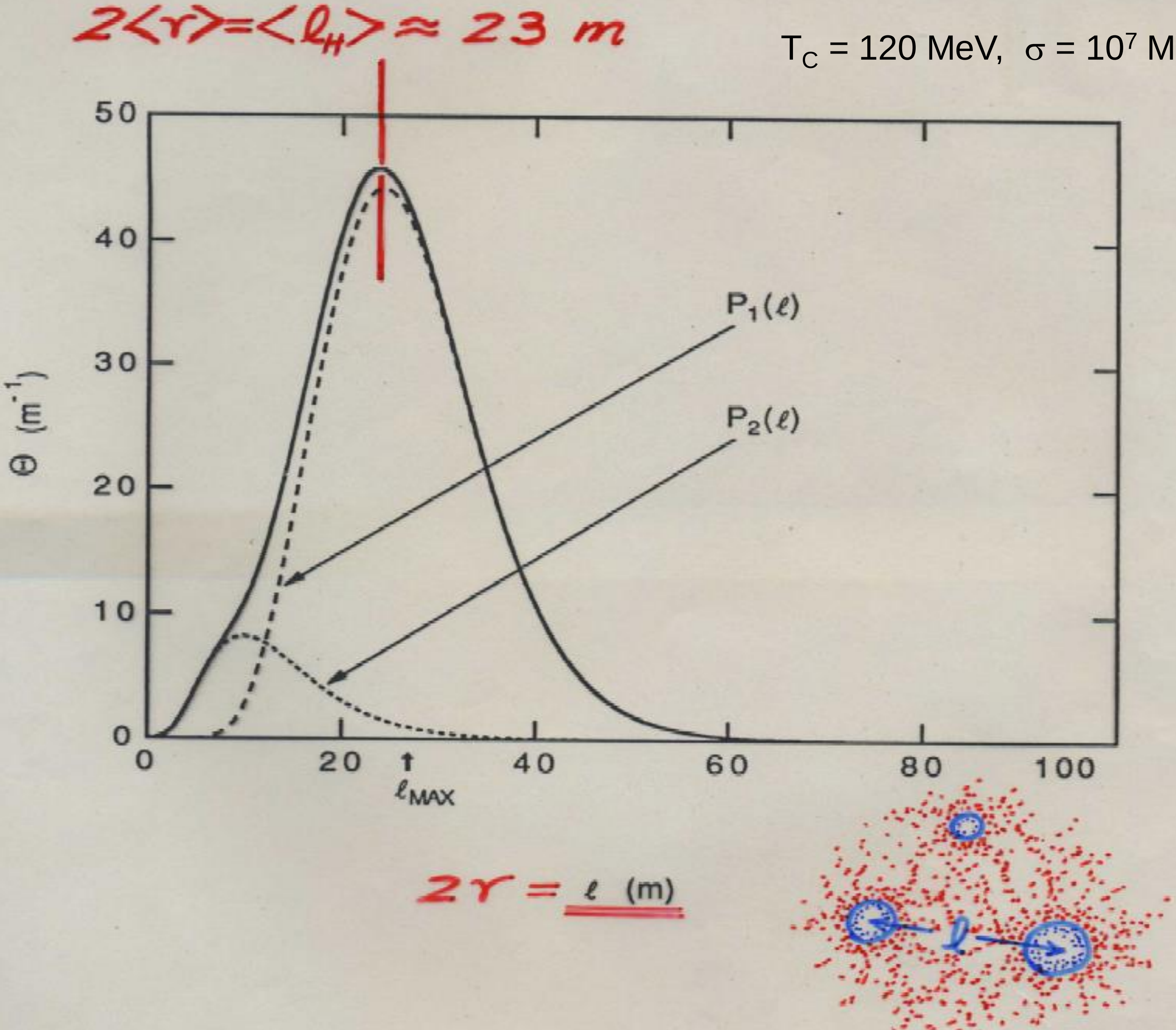


Fig.3.2.2 Once the hadron bubble nucleates, the shock wave propagates into the QGP phase at the sound velocity v_s of relativistic plasma. The hadron bubble also grows, but the velocity of the growth is smaller than v_s.

T_C = 120 MeV, $\sigma = 10^7$ MeV^3



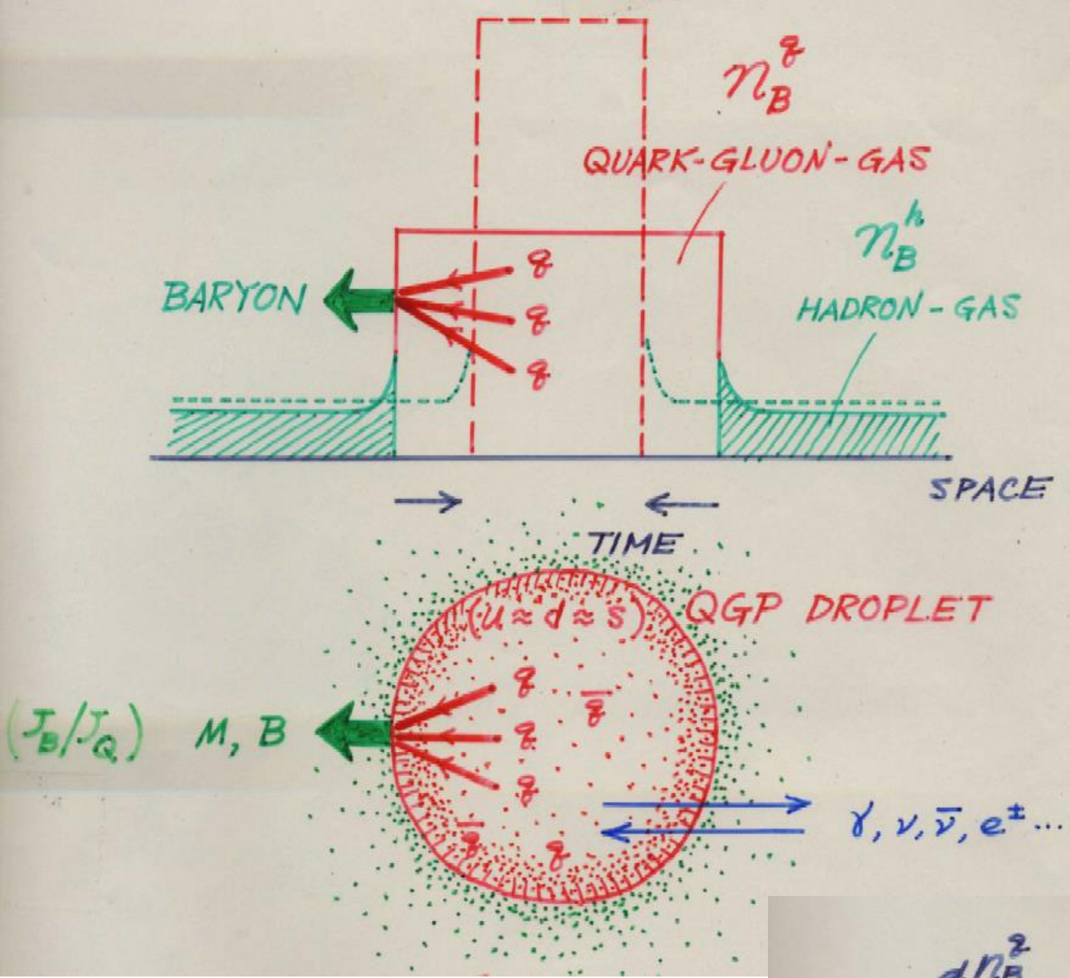
真空の相転移中の宇宙膨張
Cosmic Expansion during Phase Transition

Friedmann Equation
+ Entropy Transport Equation

相境界でのクォーク・グルーオン・ダイナミックス
Quark-Gluon ynamic near thePhase Boundary

漸近的自由性 → クォーク閉じ込め
Asymptotically Free → Quark Confinement

カイラル対称性の破れ、クォーク（ハドロン）の有限質量
Chiral Symmetry Breaking　Mass of Quarks (& Hadrons)



Phase Transition in Co-Existing Phase of QGP and Hadron Gas

Background: γ, ν, e^-, …

QGP: Quark, Gluon, …

Hadron: Baryon and Meson

Time-Variation of Quark-Number Densities:

$$\frac{dn_B^q}{dt} = -n_B^q \lambda_B + n_B^h \lambda'_B - n_B^q\left\{\frac{\mathring{V}}{V} + \frac{\mathring{f}_V}{f_V}\right\}$$

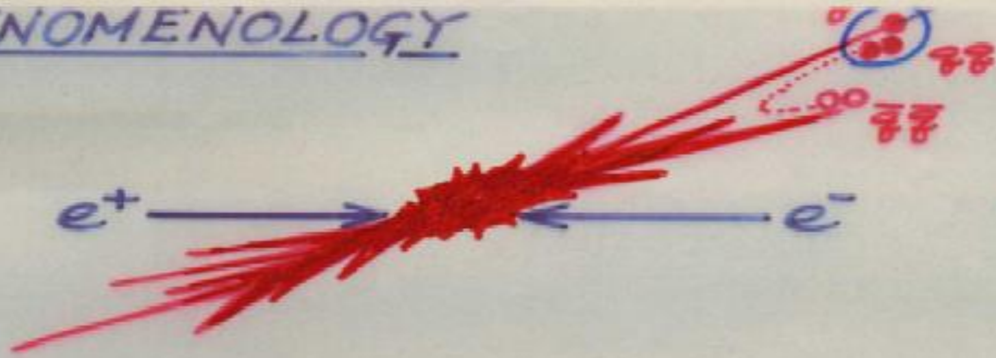
$$\frac{dn_B^h}{dt} = \frac{f_V}{1-f_V}\left\{-n_B^h\lambda'_B + n_B^q\lambda_B + n_B^h\frac{\mathring{f}_V}{f_V}\right\} - n_B^h\frac{\mathring{V}}{V}$$

→ $\lambda_B = \gamma J_B/3J_Q$

λ'_B = DETAILED BALANCE

$V(t)$, $f_V(t)$: Einstein eq.

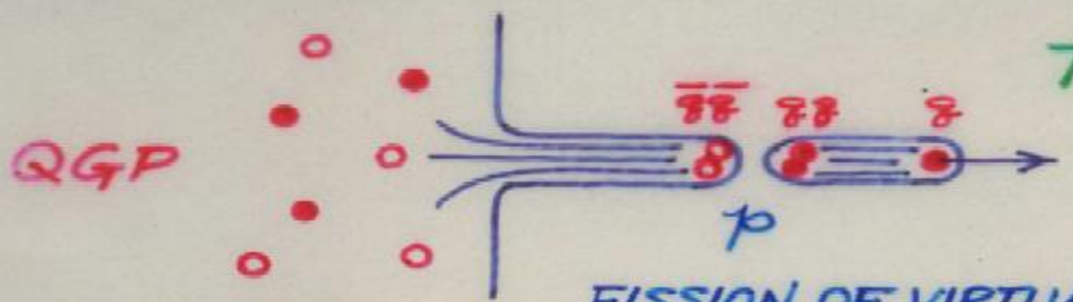
JET PHENOMENOLOGY



$T \approx 0$

CHROMO-ELECTRIC FLUX-TUBE MODEL

$T \approx 150$ MeV



FISSION OF VIRTUAL PAIR

$$J_H = \sum_q \frac{n_q}{Z_q} \int d^3k_q \exp\left(-\frac{E_q}{T}\right) \frac{k_{zq}}{E_q} \int dk_z^H \int dE^H$$

$$\times \frac{1}{k_c^2} \exp\left[-\frac{E_q}{k_c^2} \left\{ (k_{zq} - k_z^H) + \frac{1}{2E_{zq}} \left((k_z^H E_z - k_{zq} E_{zq}) + m_q^2 \ln \frac{k_z^H + E_z}{k_{zq} + E_{zq}} \right) \right\} \right]$$

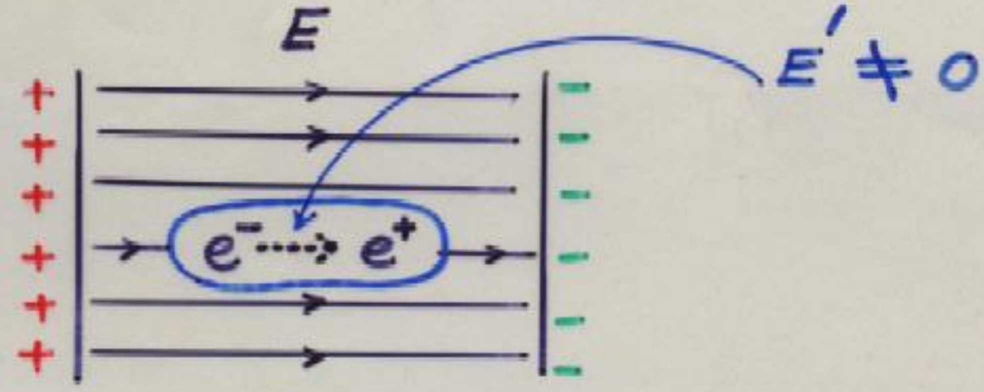
$$k_c = \sqrt{\frac{3\sigma_H^3}{2\pi \alpha_c p}}$$

$\sigma_H(T)$

$p(\bar{q}\bar{q} - qq)$: m_{qq}

CREATION OF HADRONS IN A CHROMOELECTRIC-FLUX-TUBE

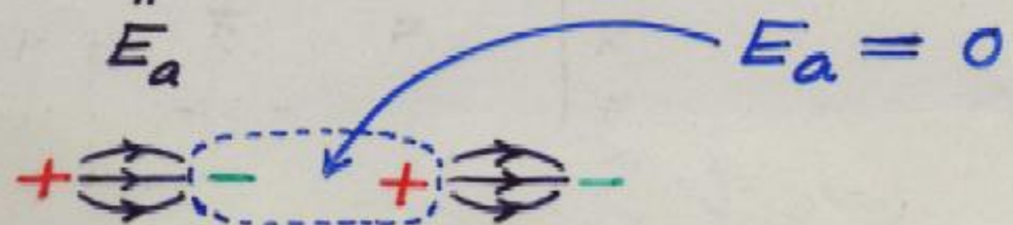
QED



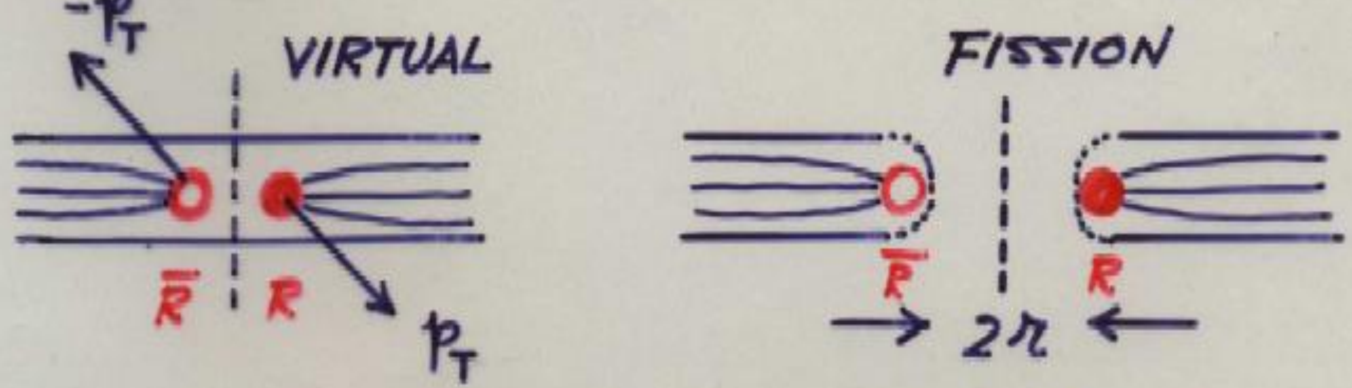
$$p(e^+e^-) = \frac{eE^2}{4\pi^3} \sum_{n=1}^{\infty} \frac{1}{n^2} \exp\left[-\pi m_e^2 n / eE^2\right]$$

QCD

$$E_1 \cdots E_8$$
$$\parallel$$
$$E_a$$

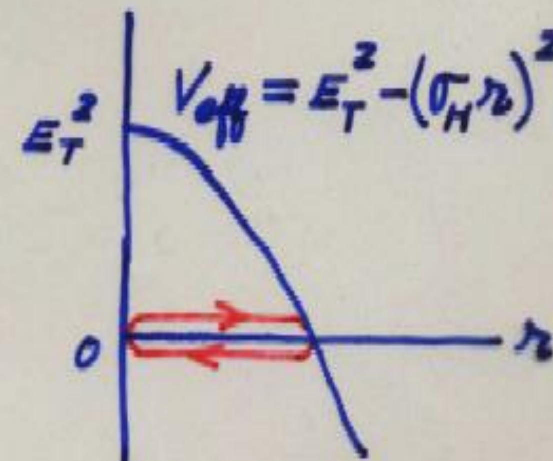


FISSION PROBABILITY OF VIRTUAL $q\bar{q}$ PAIR : p



$$2\sqrt{p_L^2(r) + p_T^2 + m_q^2} = 2\sigma_H r$$

$$p_L^2(r) + V_{eff}(r) = 0$$



$$\therefore \tilde{p}(p_T) = \exp\left\{2\oint |p_L(r)|\, dr\right\}$$

$$|\langle 0_+|0_-\rangle|^2 = \prod_{\xi} \prod_{s} \prod_{p_T} \prod_{r} \prod_{t} \left(1 - \tilde{p}(p_T)\right) = \exp\{-VTp\}$$

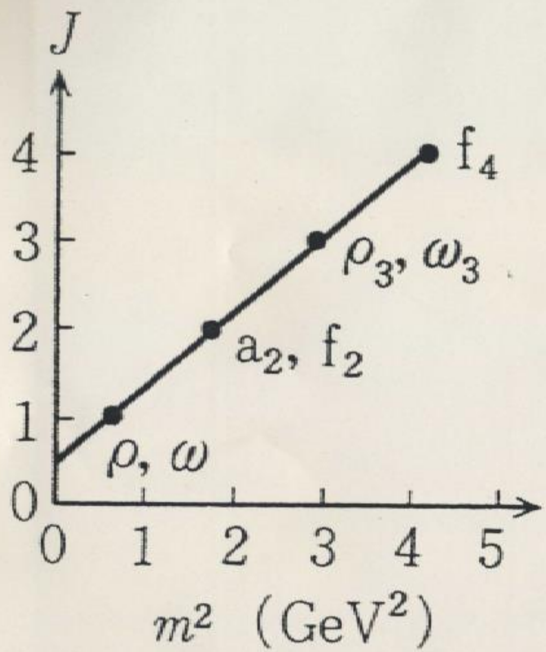
$$\therefore p(q\bar{q}) = \frac{\sigma_H'^2}{4\pi^3} \sum_{\substack{\xi \\ (q_i)}} \sum_{n} \frac{1}{n^2} \exp\left[-\pi m_q^2 n / \sigma_H'\right]$$

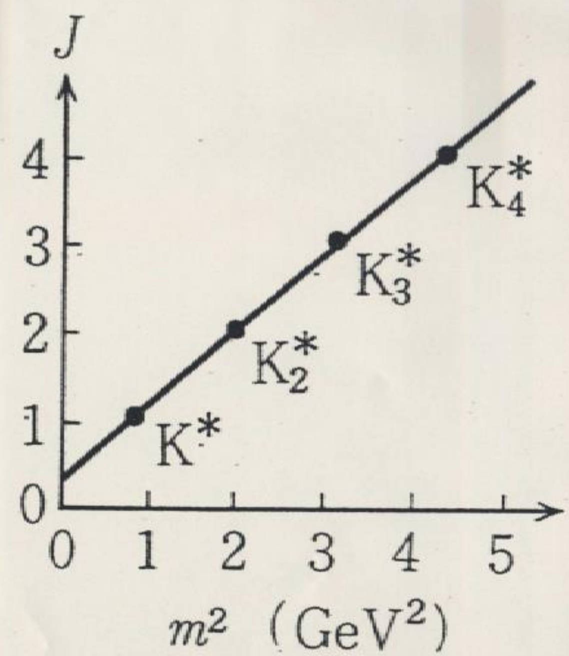
$$\begin{cases} p_{\bar{q}-q} = \dfrac{\sigma_H(T)^2}{4\pi^3} \sum_f \sum_{n=1}^{\infty} \dfrac{1}{n^2} \exp\left(-\pi m_{q_f}^2 n/\sigma_H(T)\right) \\ p_{\bar{q}\bar{q}-qq} = \dfrac{\sigma_H(T)^2}{4\pi^3} \sum_f \sum_{n=1}^{\infty} \dfrac{(-)^{n+1}}{n^2} \exp\left(-\pi m_{qq_f}^2 n/\sigma_H(T)\right) \end{cases}$$

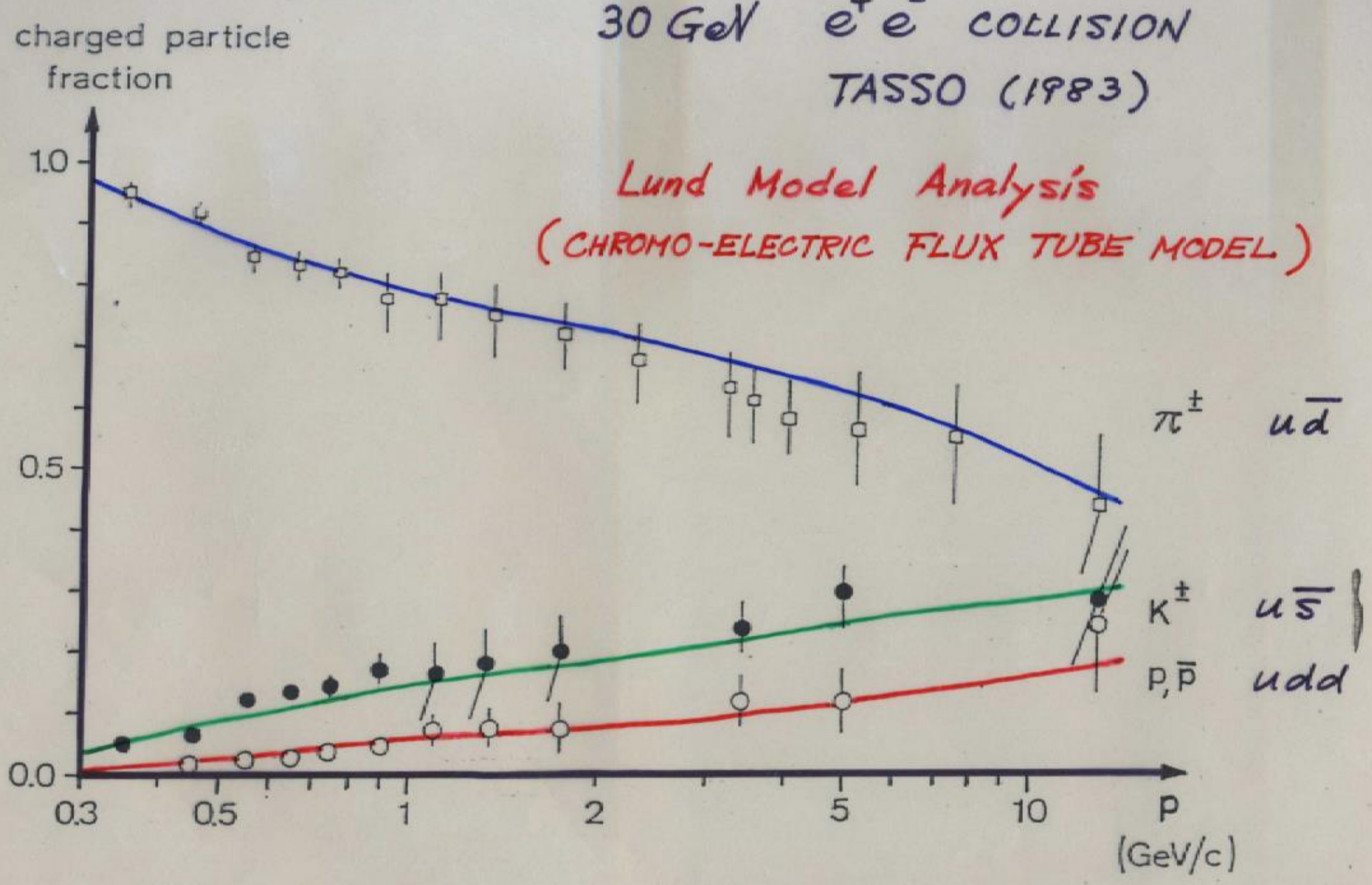
$m_u^0 \approx m_d^0 \approx 0,3$, $m_{qq}^0 = ?$ ← JET PHENOM.

STRING TENSION

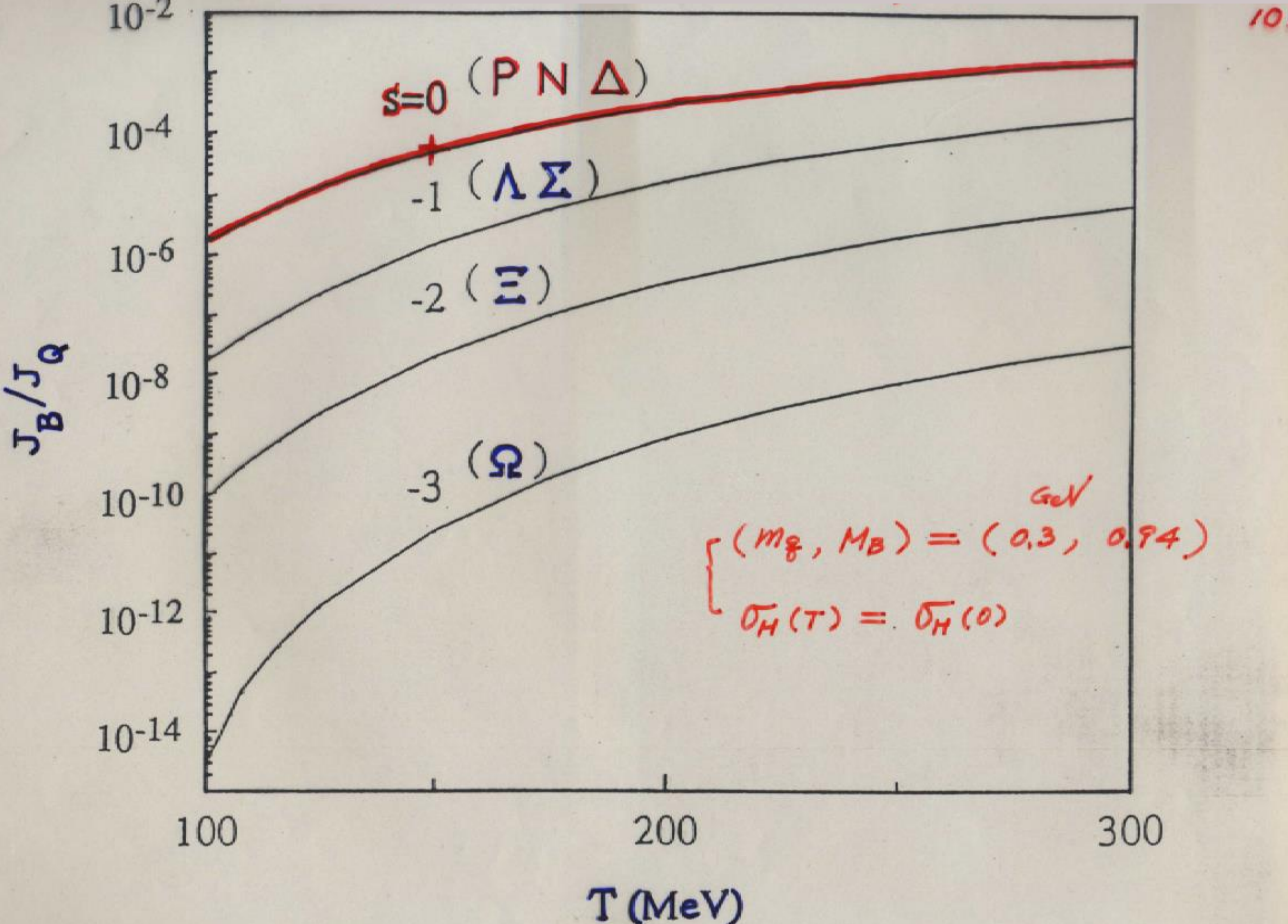
$\lim_{T \to T_c} \sigma_H(T) \approx 0{,}05\, \sigma_H(0)$ ← LATTICE



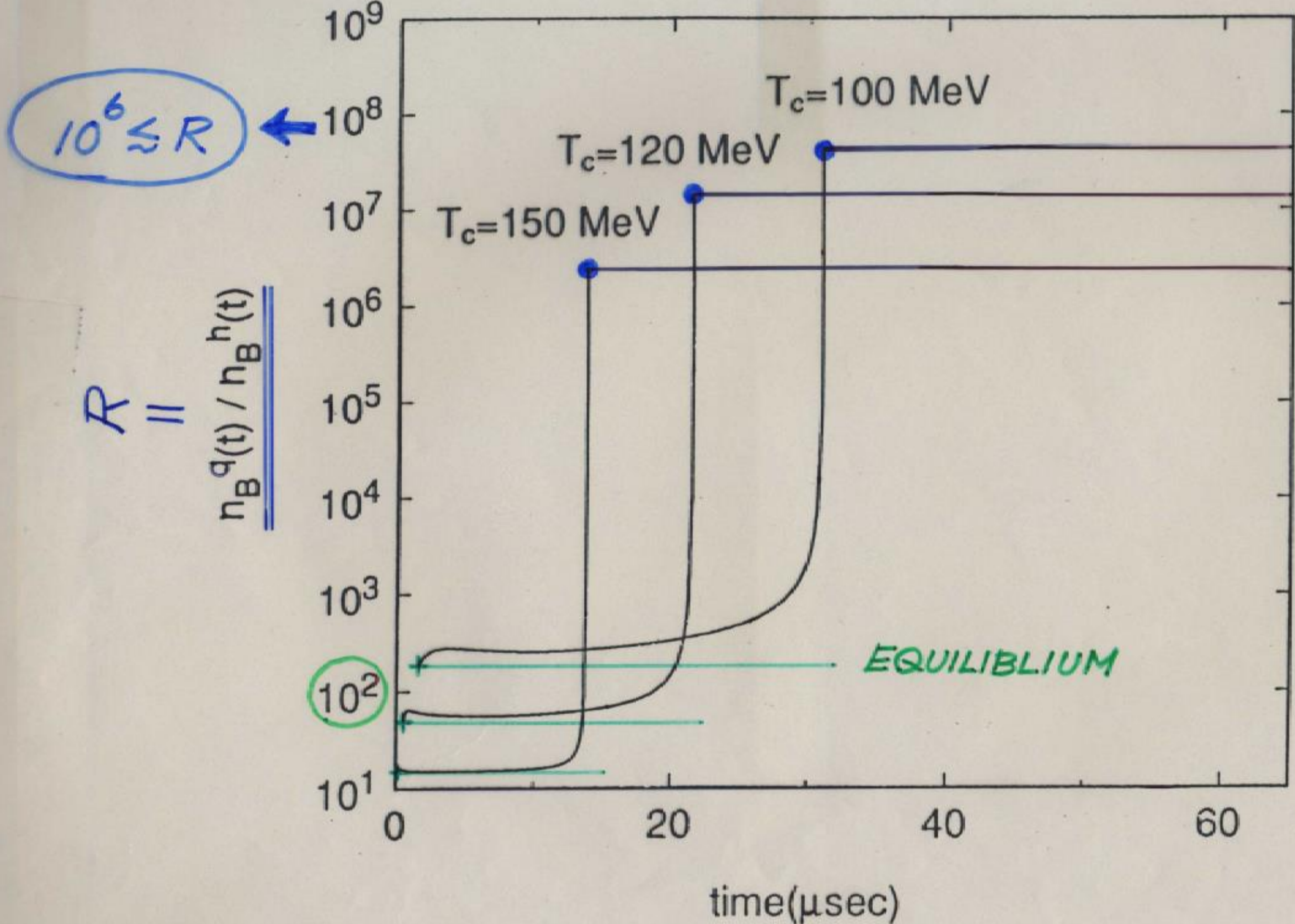


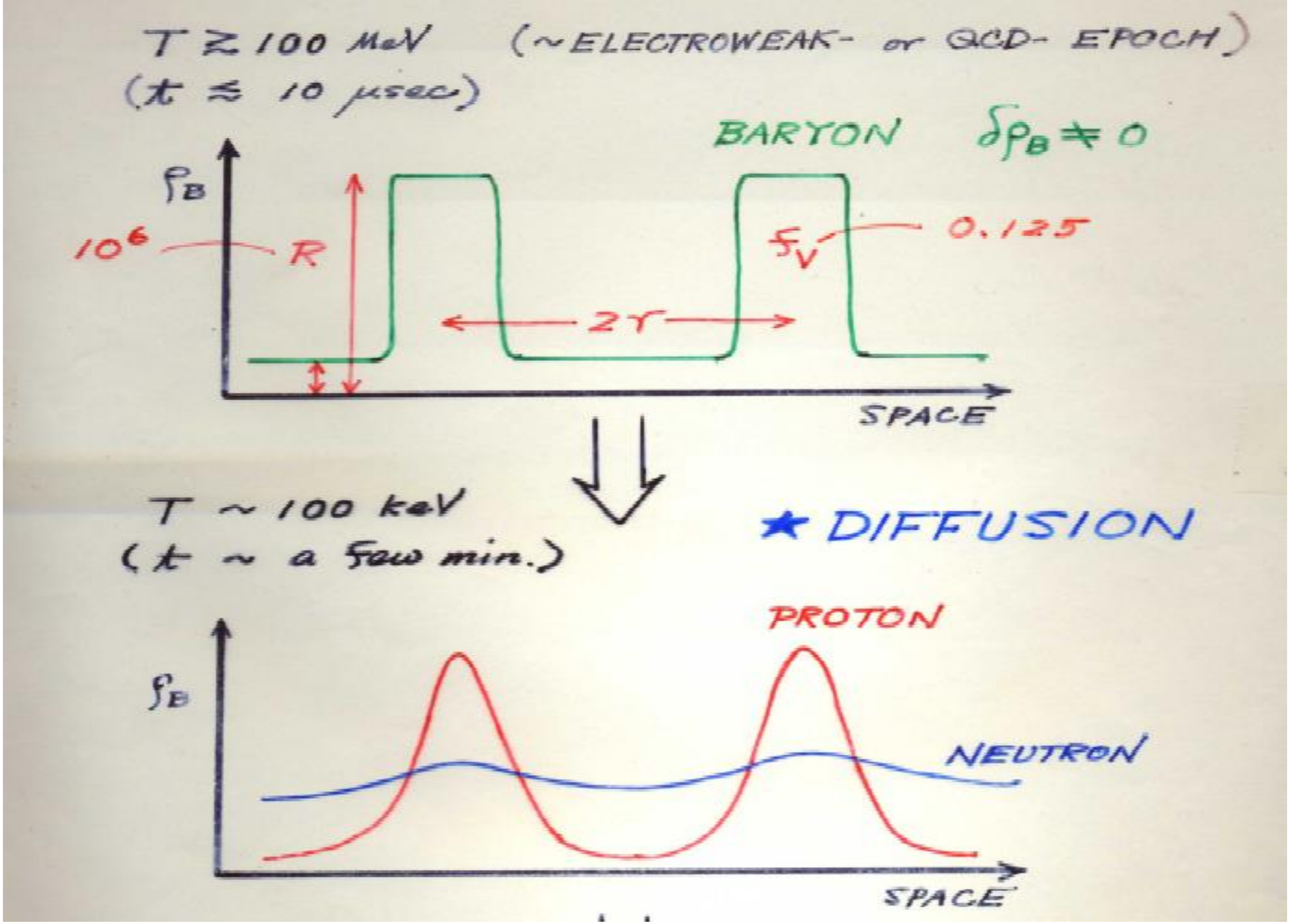


30 GeV e+e- COLLISION
TASSO (1983)
Lund Model Analysis
(CHROMO-ELECTRIC FLUX TUBE MODEL)
charged particle fraction
1.0
0.5
0.0
0.3
0.5
1
2
5
10
p (GeV/c)
π± ud̄
K± us̄
p, p̄ udd


10.
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-12}
10^{-14}
J_B/J_Q
s=0 (P N Δ)
-1 (Λ Σ)
-2 (Ξ)
-3 (Ω)
GeV
$(m_q, M_B) = (0.3, 0.94)$
$\sigma_H(T) = \sigma_H(0)$
100
200
300
T (MeV)

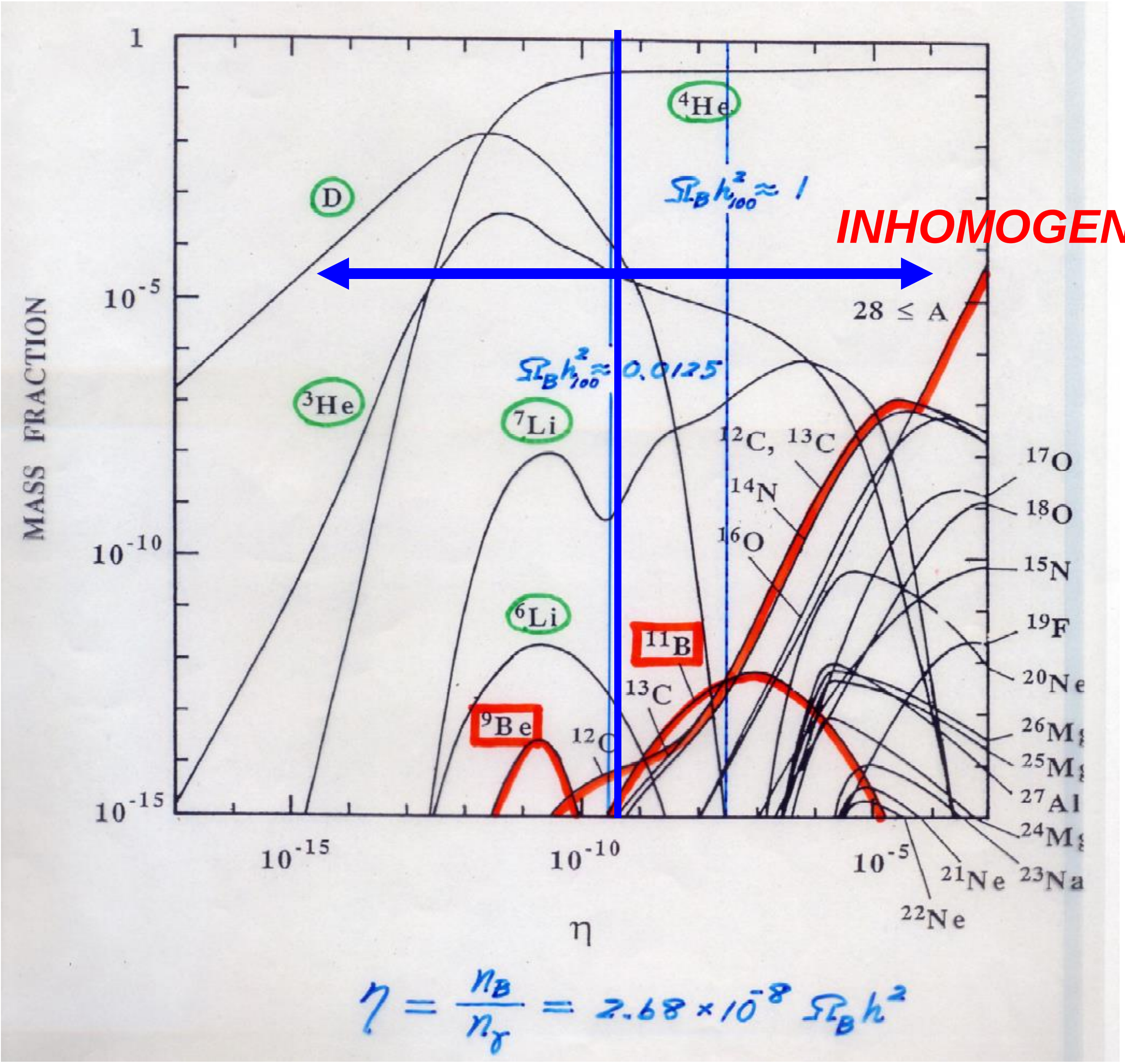
$\sigma = 10^6\ MeV^3$





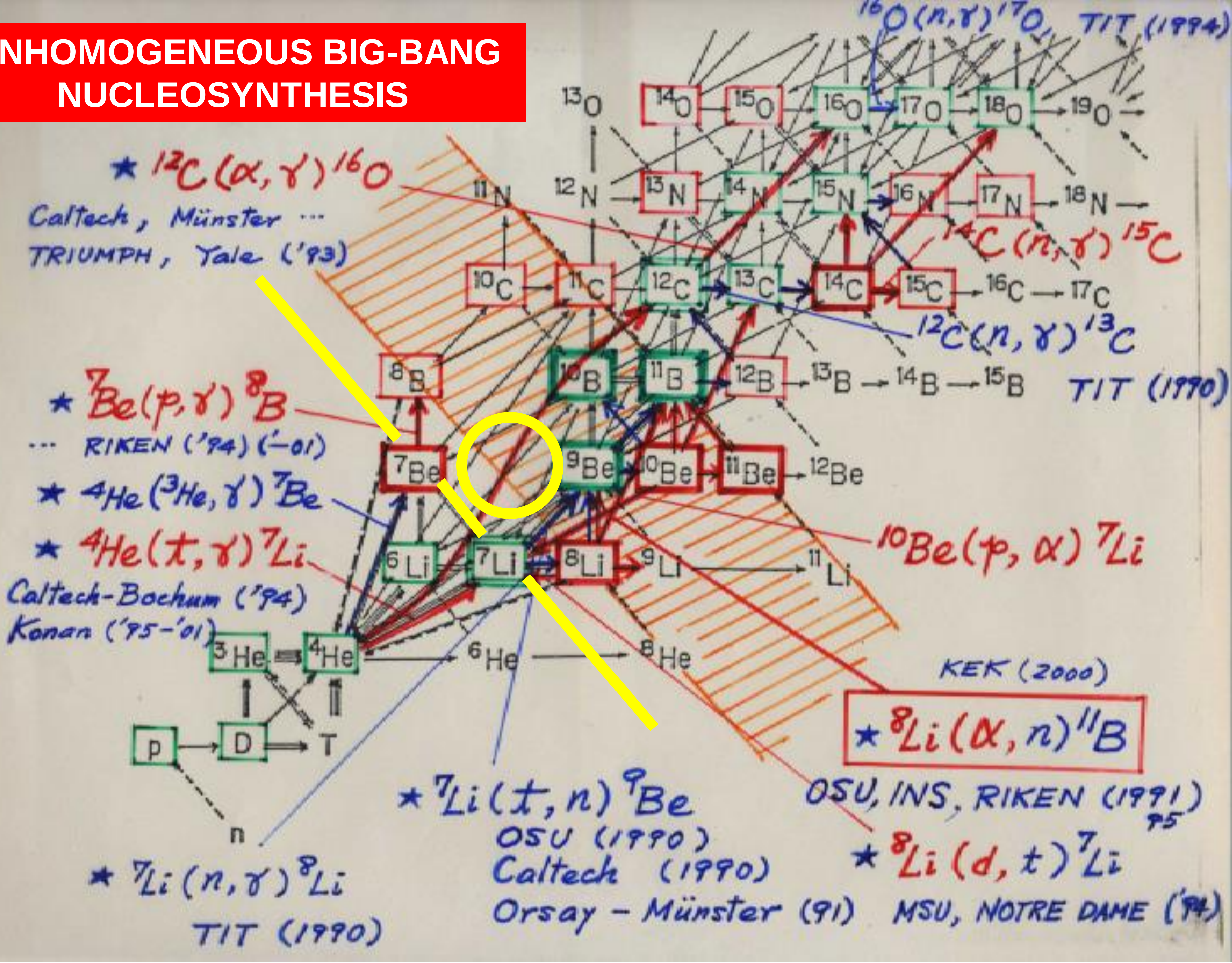
INHOMOGENEOUS Big-Bang Nucleosynthesis

Big-Bang (Primordial) Nucleosynthesis



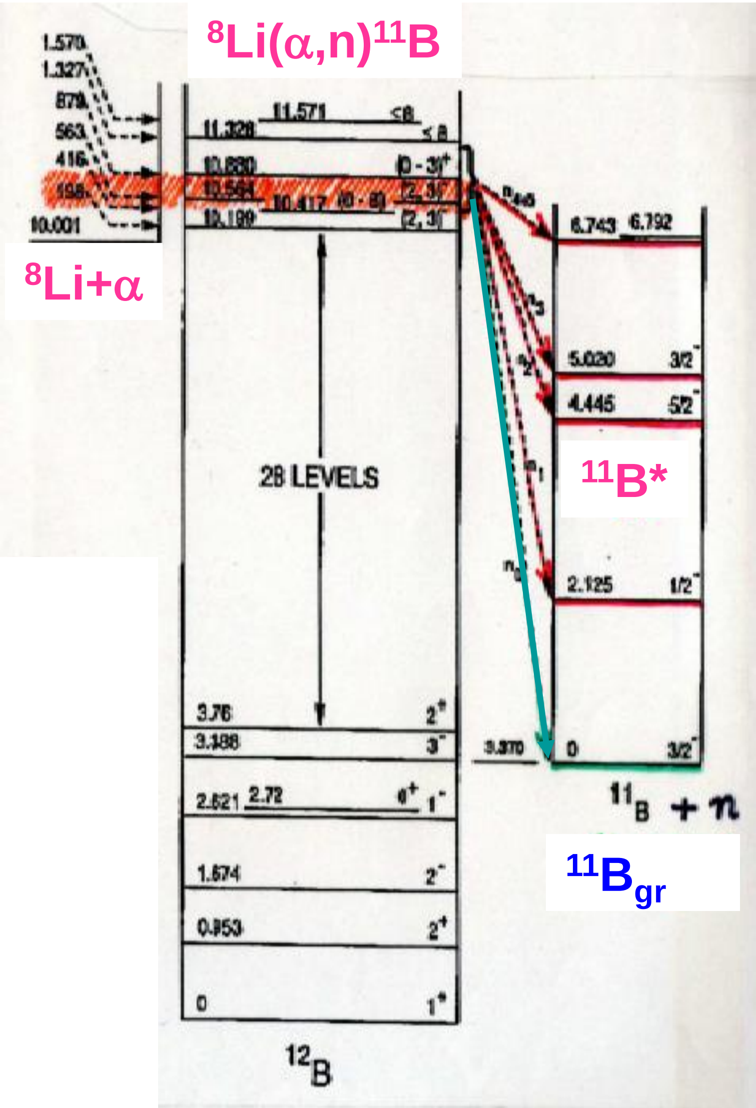
NUCLEAR REACTION + DIFFUSION

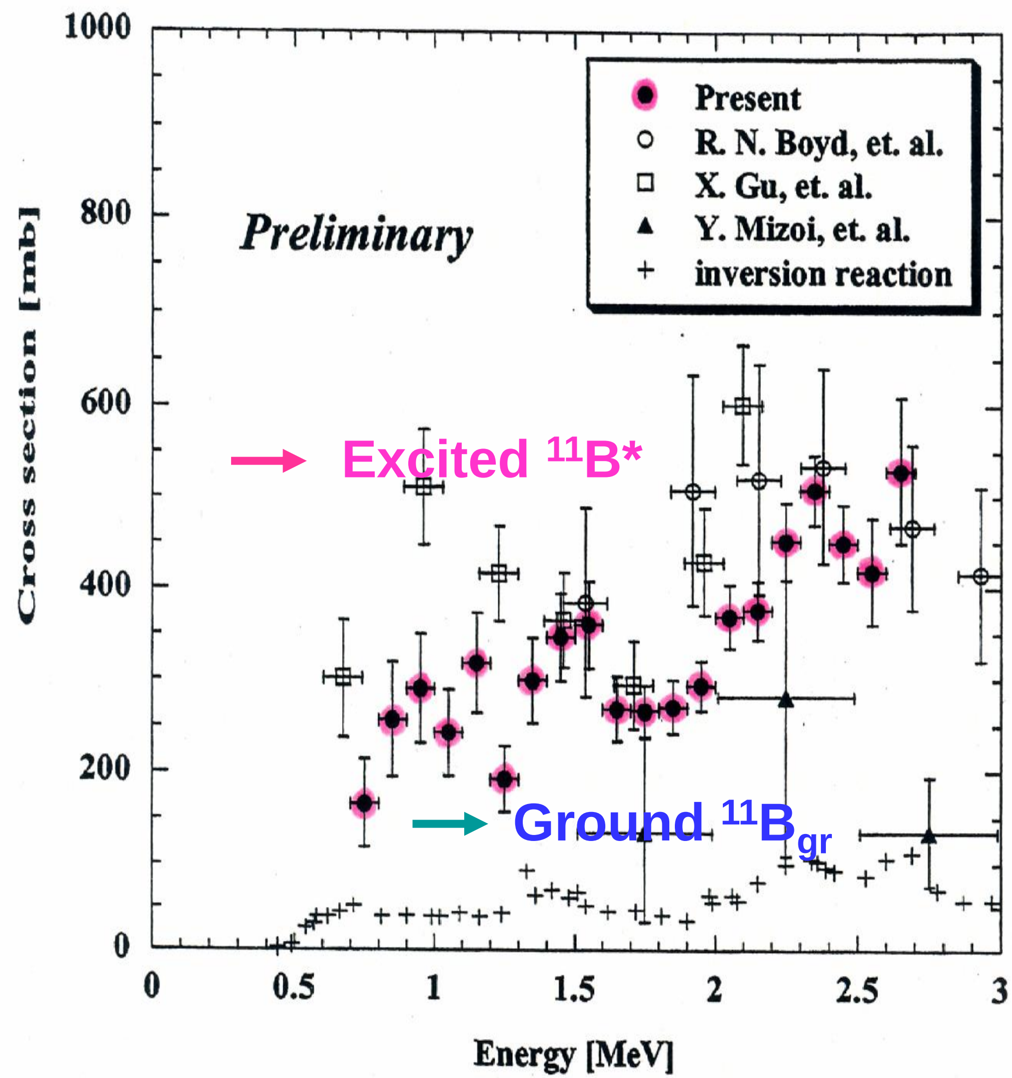
INHOMOGENEOUS BIG-BANG NUCLEOSYNTHESIS



$^{8}Li(\alpha,n)^{11}B$

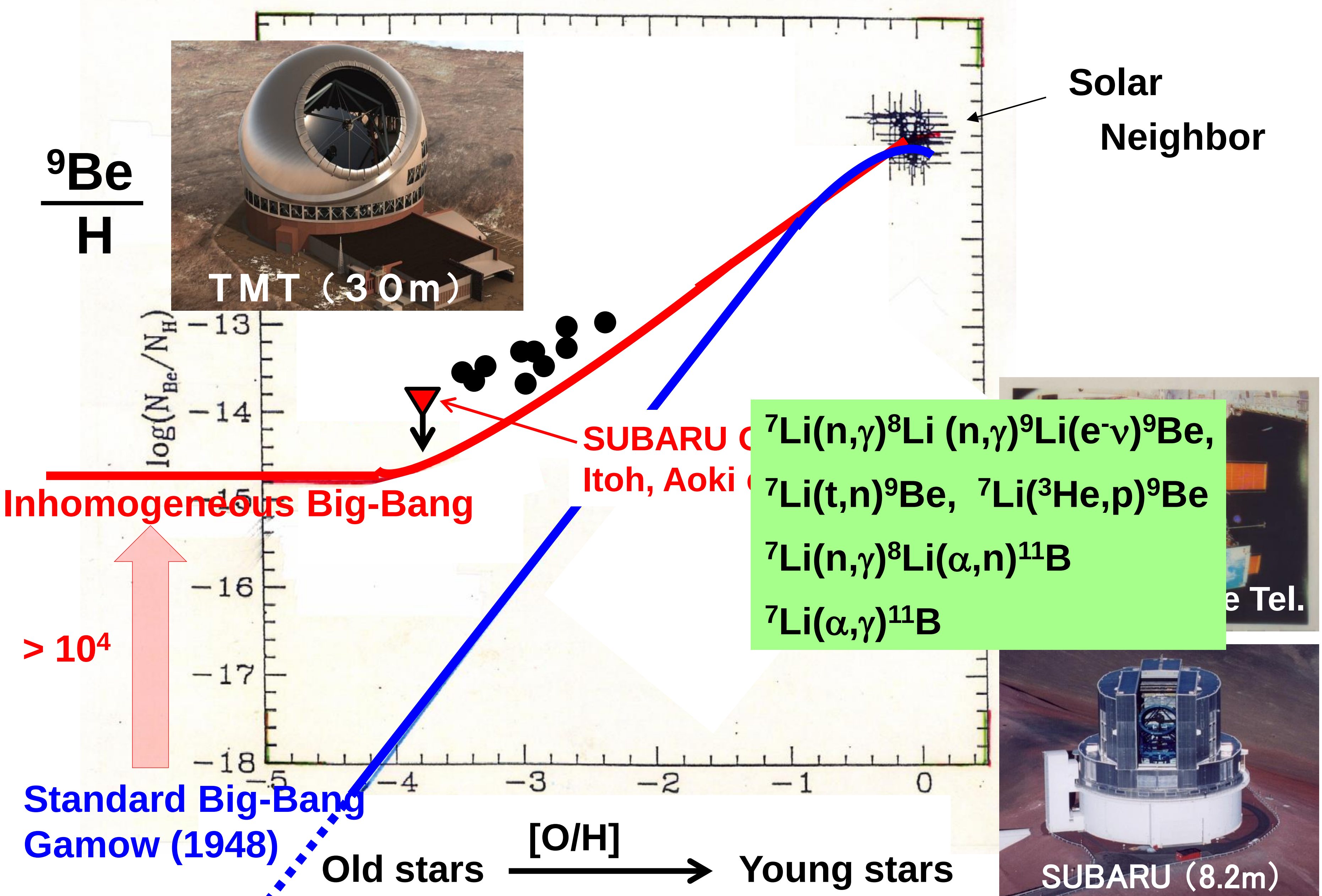
H. Ishiyama et al. AIP Conf. Proc. 704 (2004) 453.
T. Hashimoto et al. Phys. Lett. B 674 (2009) 276.



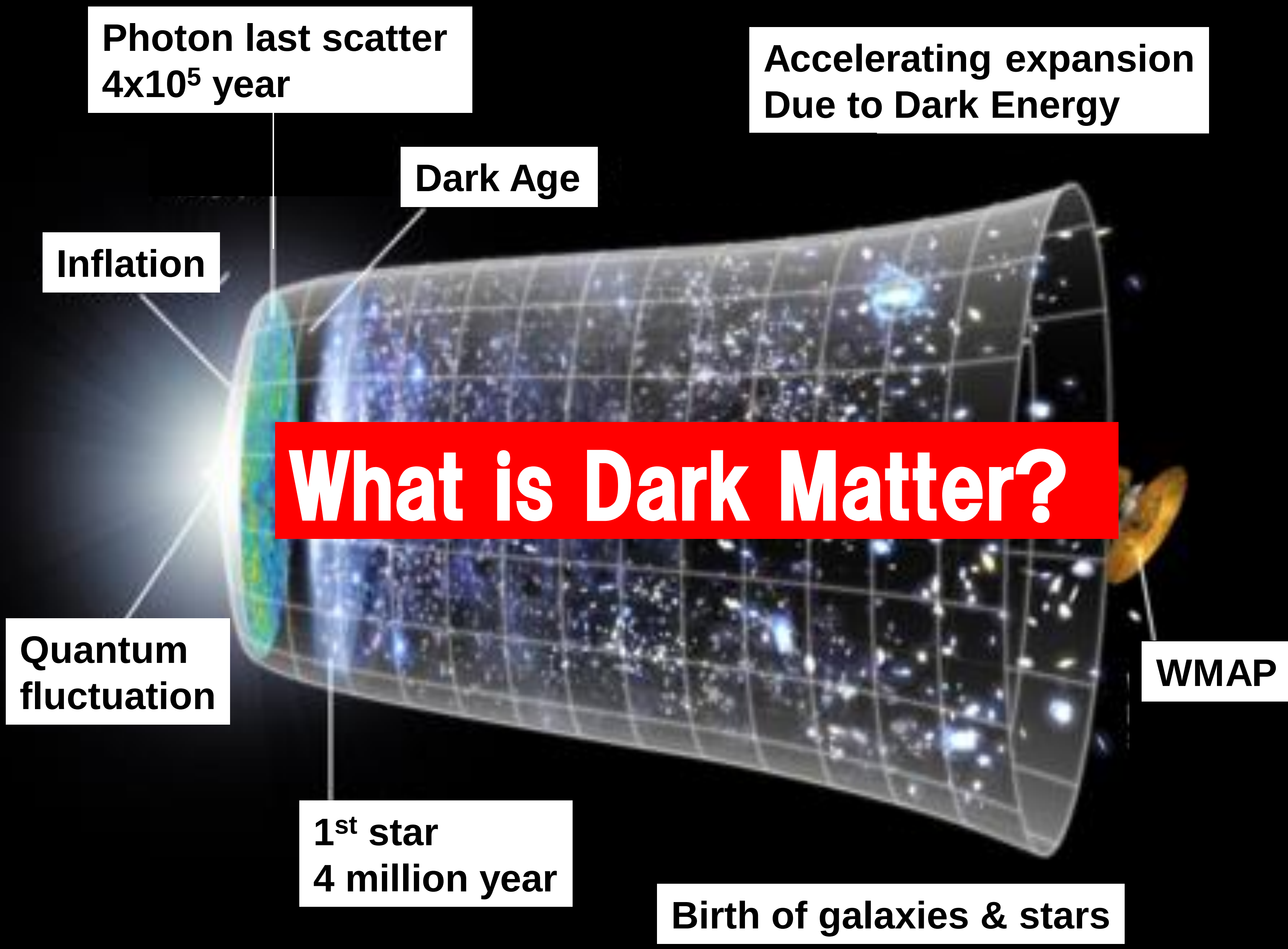


INHOMOGENEOUS BIG-BANG NUCLEOSYNTHESIS

Kajino and Boyd, ApJ 359 (1989, 1990) 267



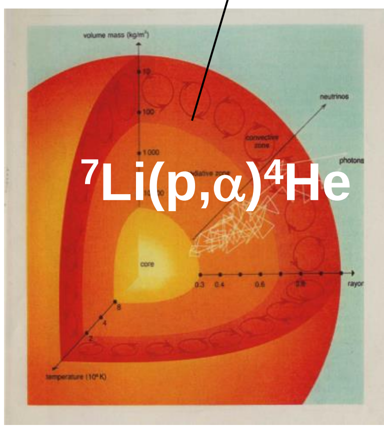
What is Dark Matter?

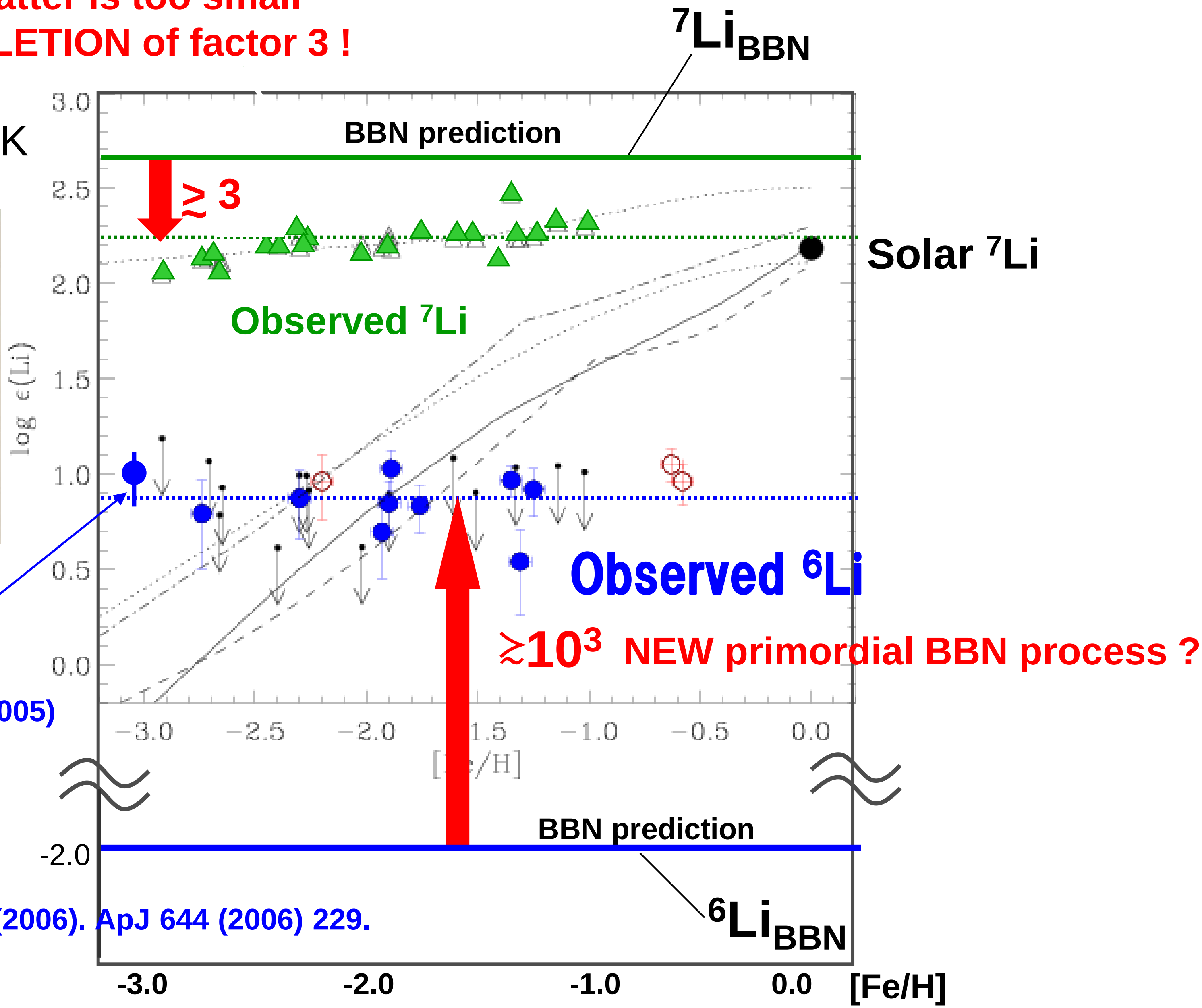


Plateau like HIGH ^{6,7}Li ABUNDANCE --- primordial ?

Abundance scatter is too small
to accept DEPLETION of factor 3 !

T = 1~3x10^6 K





SUBARU OBS.
Inoue, Aoki et al (2005)

Asplund et al. (2006). ApJ 644 (2006) 229.

How to solve HIGH ^{6}Li primordial abundance?

Ellis et al. (1986); Moroi and Kawasaki (1994); Jedamzik PRL 84 (2000) 3248; Cyburt et al., PRD 67 (2003) 103521; Ellis et al. PLB619 (2005) 30; Pospelov, PRL 98 (2007) 231301; Hamaguchi et al. PL B650 (2007) 208; Bird et al. PRD78 (2008), 083010; Kusakabe, Kajino & Mathews, D74 (2006), 023526 ++

Cosmological Solution !?

1st Scenario

Decaying massive relic DM particles : X^0 decays to non-thermal γ's:

$$^4He(\gamma_{NT},n)^3He(^4He,p)^6Li,$$

$$^4He(\gamma_{NT},p)^3H(^4He,n)^6Li.$$

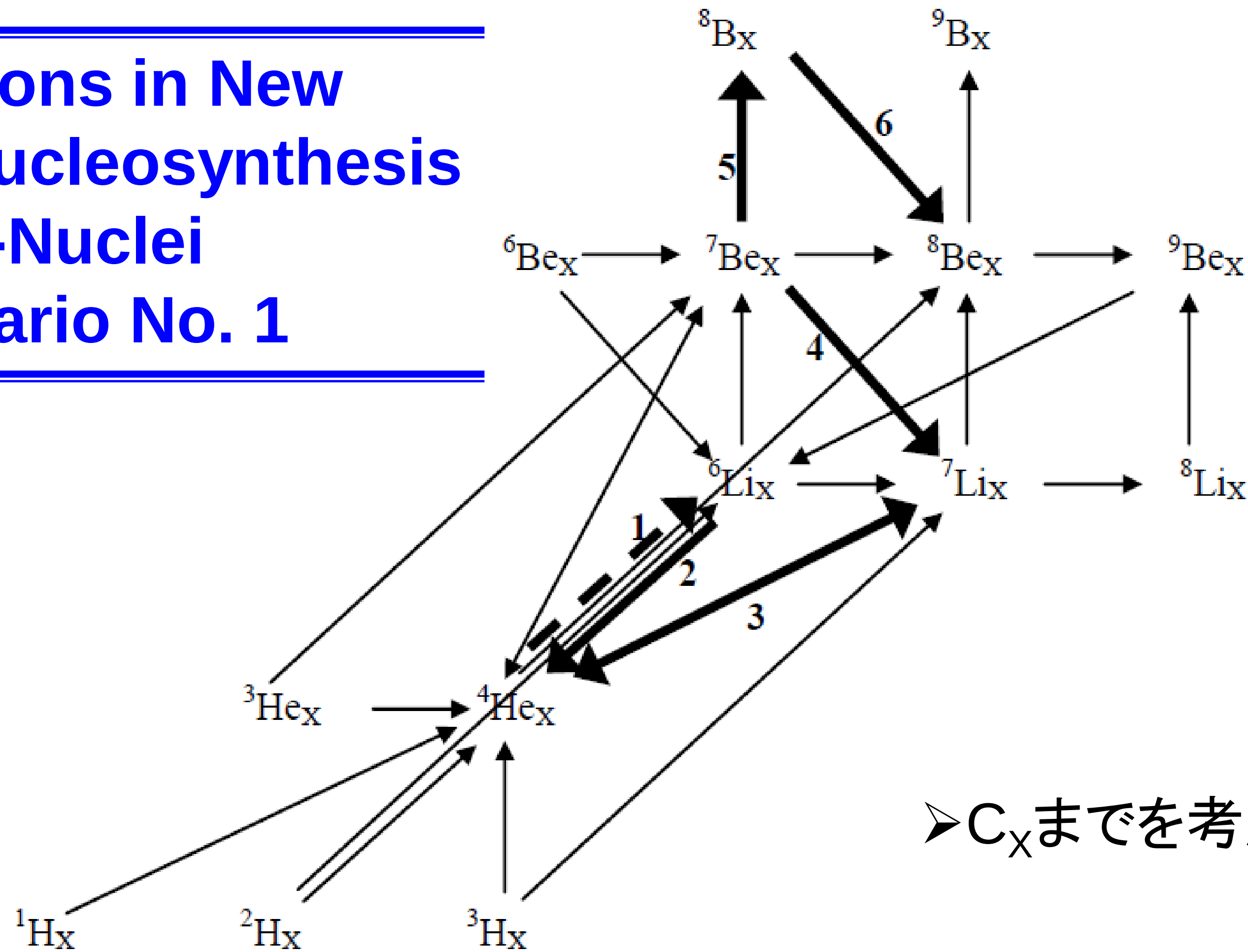
2nd Scenario

SUSY Leptonic "stau" (NLS-particle) with CDM = gravitino

X^- is bound to ^{4}He, ^{7}Li, ^{7}Be and catalizes 2nd burst of BBN:

$$^4He_X(d,X^-)^6Li, \qquad ^7Be_X(p,\gamma)^8B_X$$

Main Reactions in New Big-Bang Nucleosynthesis including X-Nuclei Scenario No. 1



➢C_Xまでを考慮

Main reactions

1. $^4He_X(d,X^-)^6Li$
2. $^6Li_X(p,{}^3He\ \alpha)X^-$
3. $^4He_X(t,\gamma)^7Li_X$ & $^7Li_X(p,2\alpha)X^-$
4. $^7Be_X(,X^0)^7Li$
5. $^7Be_X(p,\gamma)^8B_X$
6. $^8B_X(,e^+\nu_e)^8Be_X$

✓X^-再結合: 16
✓X核反応: 59
（含β崩壊: 2）
✓X^-荷電移行: 3
✓X-decay: 11

1st Scenario: Theory of X^0 decay: $X^0 \rightarrow \gamma_{NT}$

Ellis et al. (1986); Moroi and Kawasaki (1994);Jedamzik PRL 84 (2000) 3248; Kawasaki et al. PRD63 (2001), 103502; Cyburt et al., PRD 67 (2003) 103521; Ellis et al. PLB619 (2005) 30; Kusakabe, Kajino & Mathews, D74 (2006), 023526.

Spectrum of non-thermal γ_{NT} $p_\gamma(E_\gamma)$

Primary γ_{NT} interacts with CBRs

Pair creation ($\gamma\gamma_{bg} \rightarrow e^+e^-$)

Inverse Compton ($e^\pm + \gamma_{bg} \rightarrow e^\pm + \gamma$)

Then it degrades its energy by:

Compton scattering ($\gamma + e^\pm_{bg} \rightarrow \gamma + e^\pm$)

Bethe–Heitler process (γ+nuclus$_{bg} \rightarrow e^+ + e^-$+nucleus)

Photon–photon scattering ($\gamma\gamma_{bg} \rightarrow \gamma\gamma$)

Two Parameters

Life time of X^0 τ_X

Number density ∗ Eγ of X^0

$$\zeta_X = \frac{n_X^0}{n_\gamma^0} E_{\gamma 0}$$

Reaction process

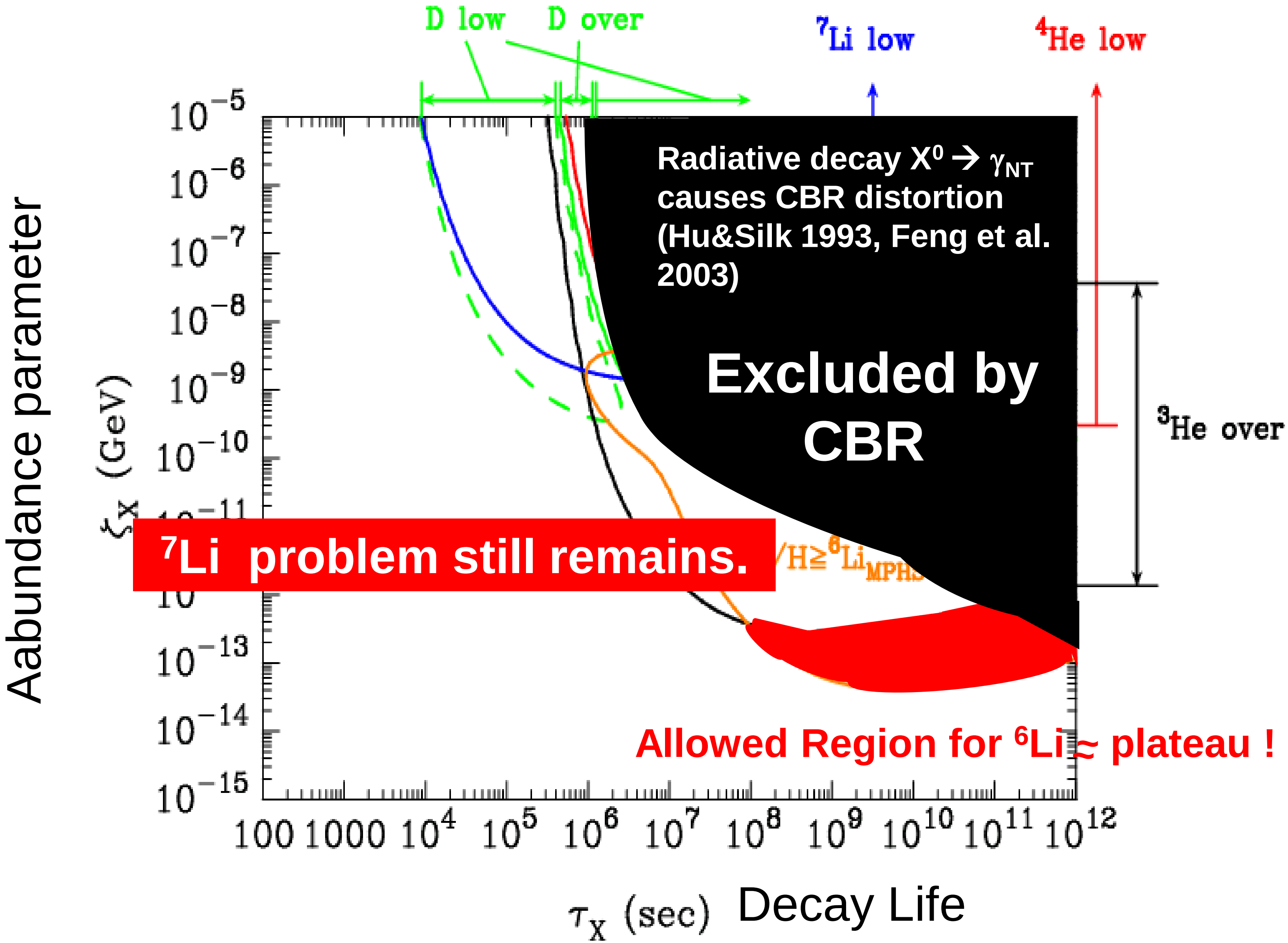
Rate equation
$$\frac{dY_A}{dt} = \sum_P N_A(P)\left(-\frac{Y_A}{N_A(P)!}[A\gamma]_P + \frac{Y_P}{N_P(P)!}[P\gamma]_A\right) \quad + \text{SBBN}$$

$$[A\gamma]_P \equiv \frac{n_\gamma^0 \zeta_X}{\tau_X}\left(\frac{1}{2H_r t}\right)^{3/2} \exp(-t/\tau_X) \int_0^\infty \left(\frac{\tau_X}{E_{\gamma 0} n_X} N_\gamma^{QSE}(E_\gamma)\right)\sigma_{\gamma + A \rightarrow P}(E_\gamma)$$

Photon # density
$$N_\gamma^{QSE}(E_\gamma) = \frac{n_X\, p_\gamma(E_\gamma)}{\Gamma_\gamma(E_\gamma)\tau_X} \qquad H_r = \sqrt{\frac{8\pi G \rho_{rad}^0}{3}}$$

BBN Light Elemental Abundance Constraints on X^0 properties

Kusakabe, Kajino & Mathews, Phys. Rev. D74 (2006), 023526.



2nd Scenario

#1: Decaying relic DM X

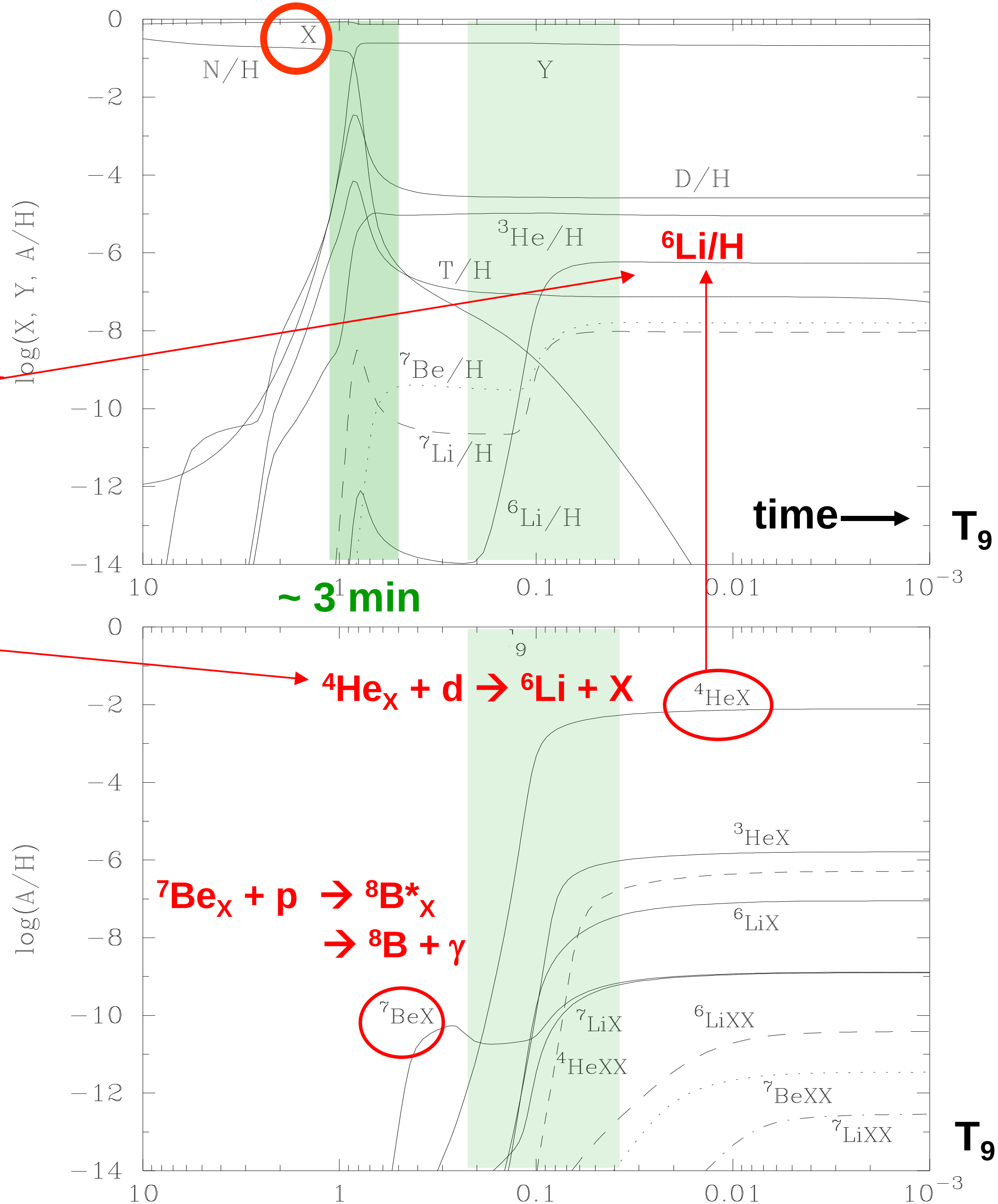
$^4He(\gamma_{NT},n)^3He(^4He,p)^6Li$

$^4He(\gamma_{NT},p)^3H(^4He,n)^6Li$

#2: SUSY Leptonic Stau

$^4He_X(d,X^-)^6Li$

$^7Be_X(p,\gamma)^8B_X$



Pospelov (2007)
Hamaguchi et al. (2007)
Bird et al. (2008)

Kusakabe, Kajino, Boyd, Yoshida, and Mathews, PRD74 (2006), 023526; PRD76 (2007), 121302(R); ApJ 680 (2008), 846; PRD79 (2009) 123513; PRD80 (2009), 103501; PRD81 (2010), 083521.

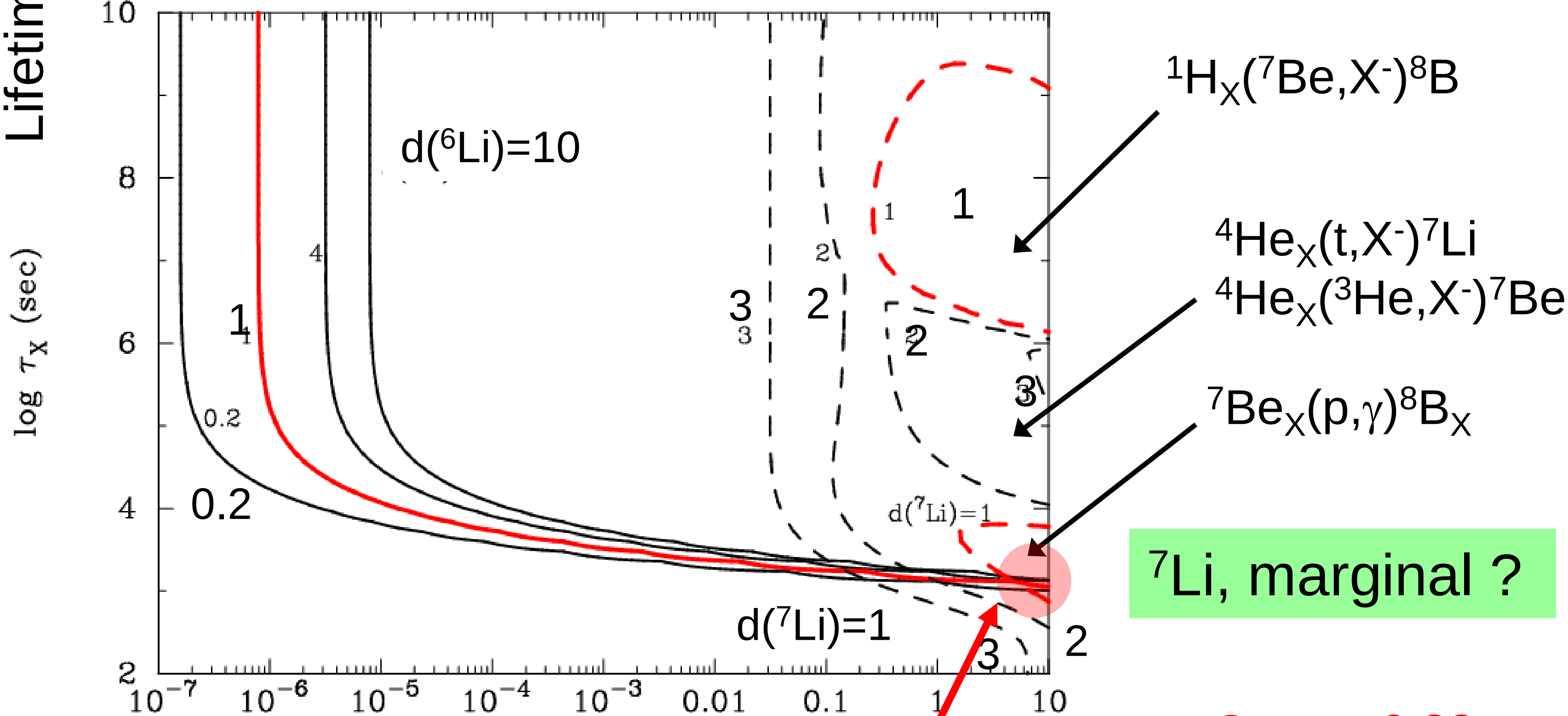
Cosmological Solution to both ^{6,7}Li problems

Kusakabe, Kajino, Boyd, Yoshida, and Mathews ApJ 680 (2007), 846; PRD81 (2010), 083521.

^{6}Li, solved !

$d(^{A}Li) = {}^{A}Li^{Calc} / {}^{A}Li^{Obs}$

$\eta = 6.1 \times 10^{-10}$



^{7}Li, marginal ?

X-abundance $Y_X = n_X/n_b$

SOLUTION !?

Ω_{CDM} = 0.23

$m_X \sim$ 10GeV

X's, too abundant ?

Too light mass ?

Axion Dark Matter Model

Erken, Sikivie, Tam & Yang,
PRL 108 (2012), 061304.

Dark matter "axions" Bose-Einstein condensate, and cool CBR-photons after the BBN epoch (3min) and before the photon last scattering epoch (3.8x10^5 yr).

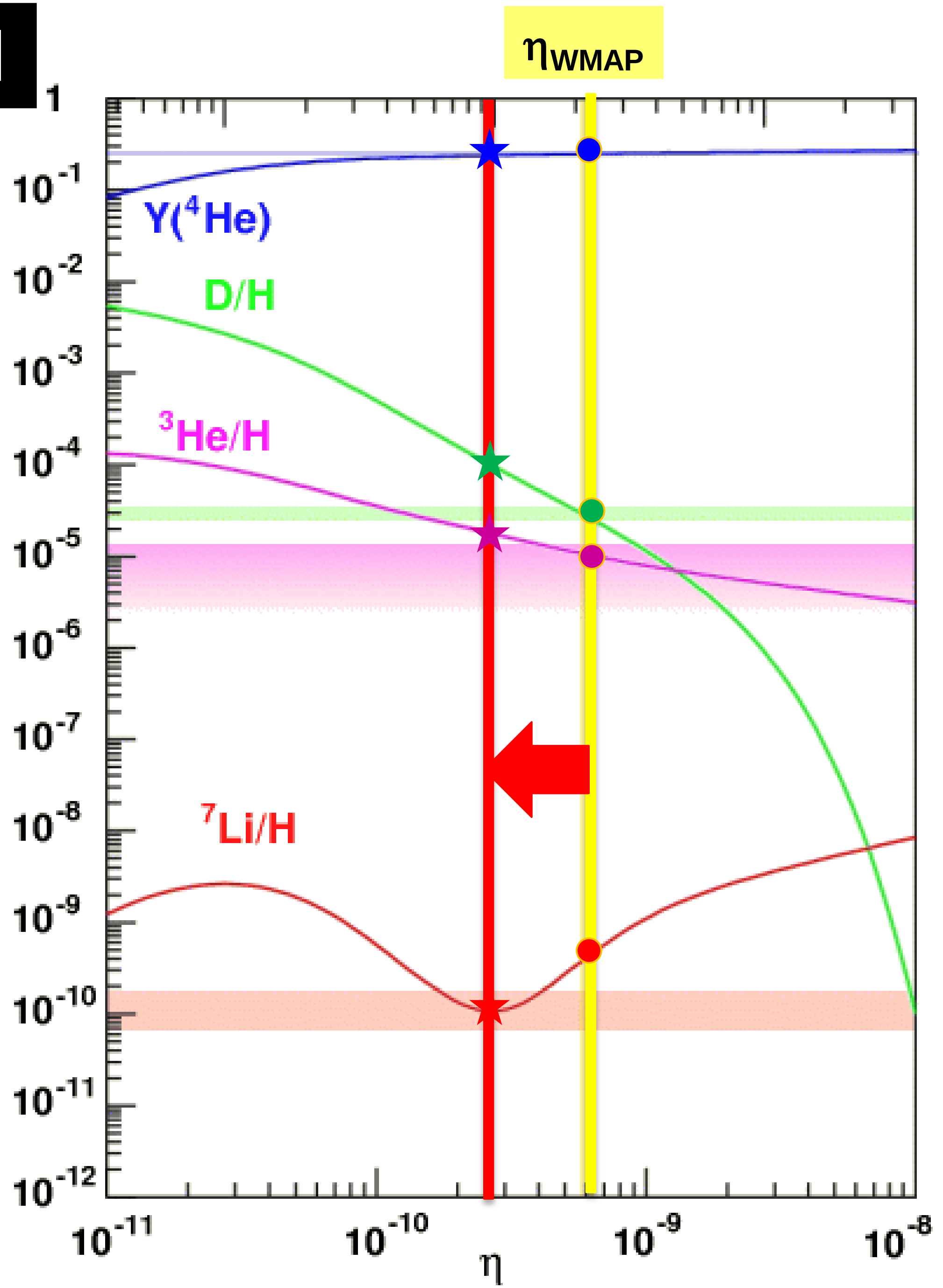
$$\eta = n_B/n_\gamma$$

$$n_\gamma \propto T_\gamma^{\;3}$$

$$\eta_{BBN} < \eta_{WMAP}$$

⇩

D overproduction !



アクシオン： アクシオンは非常に軽いが、熱的でないいわゆる傾斜 (misaligned) アクシオンは、極低温でボーズ・アインシュタイン縮退状態にあるので冷たい暗黒物質に分類される。アクシオンの存在は強い相互作用が CP を保存することの解決策として提案されたが、数々の実験や観測で存在可能範囲が非常に狭まっており、現在開いている窓は、ほぼ質量が $10^{-6}\sim10^{-3}$eV 程度に限られる。アクシオンは 2 個のフォトンに崩壊できるので、強い電磁場に通せば、アクシオン質量に等しいエネルギーを持つフォトンが放出される。マイクロ波技術を使った実験が進行中である。

QCD – Strong CP Problem（Standard Model）

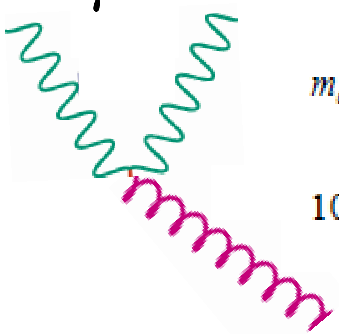
QCD Lagrangian breaks CP symmetry, but experimentally (n–dipole) it preserves very well!

⇒Peccei-Quinn (1977) : U(1) is dynamically broken to restore CP symm.

$$L = L_0 + \frac{\theta}{32\pi^2} F_{\mu\nu}\tilde{F}^{\mu\nu}$$

$$\mathcal{L}_{a\gamma} = -g_{a\gamma}\boldsymbol{E}\cdot\boldsymbol{B}a$$

CBR-γ CBR-ν

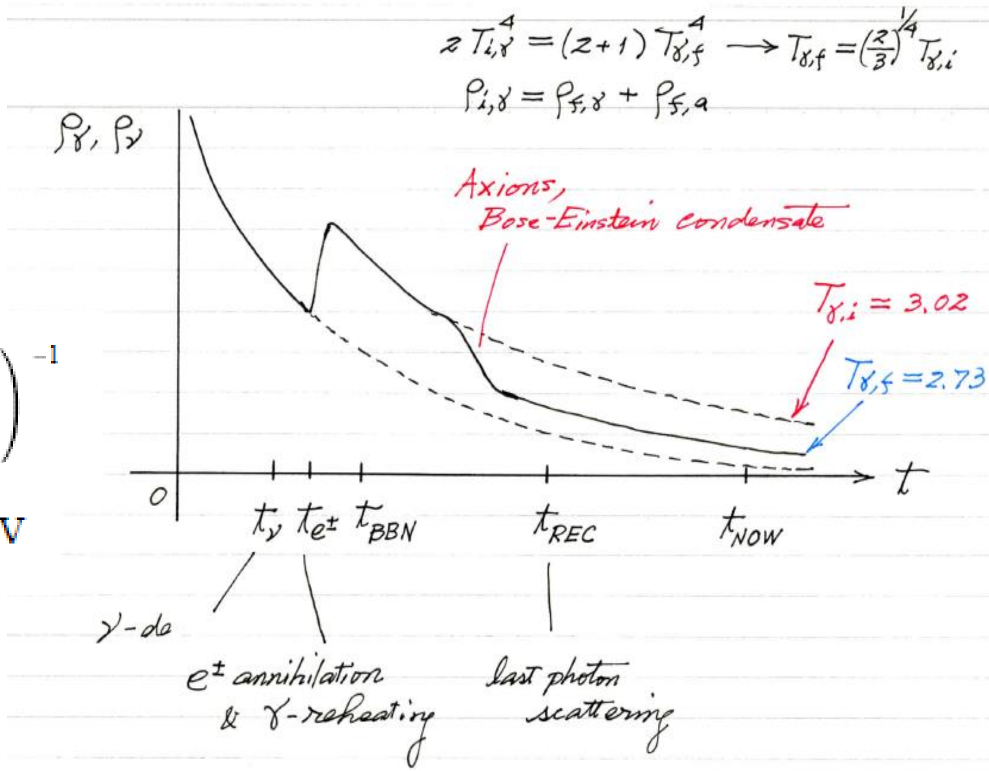


$$m_a = 0.62\times10^{-5}\,\mathrm{eV}\left(\frac{F_a}{10^{12}\,\mathrm{GeV}}\right)^{-1}$$

$$10^{9-10}\,\mathrm{GeV} \lesssim F_a \lesssim 10^{12-13}\,\mathrm{GeV}$$

a (Axion)

Nambu-Goldstone Boson

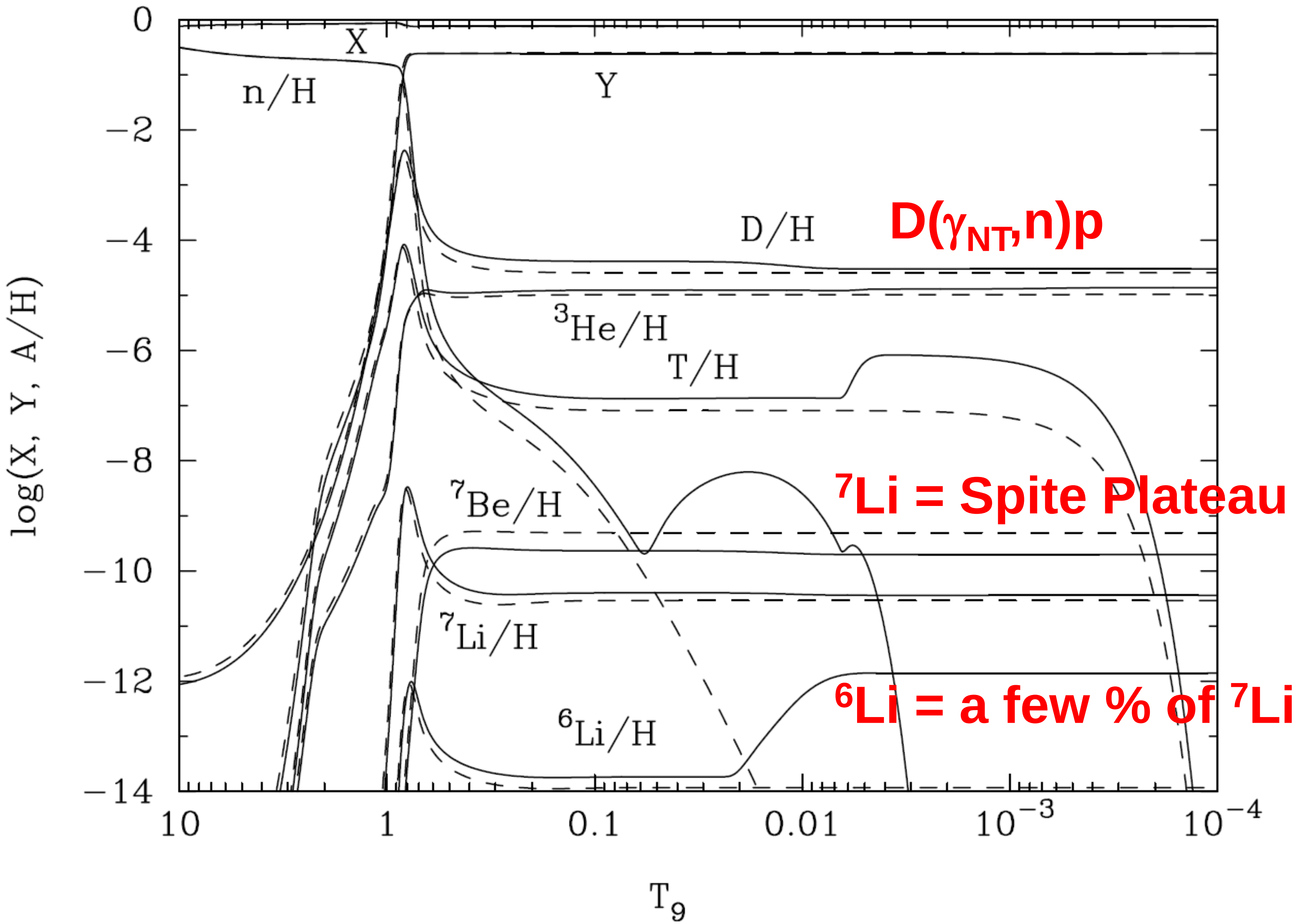


Hybrid Axion DM Model

Kusakabe, Balantekin, Kajino & Pehlivan (2013).

DM = Axions + Relic $X^0 \rightarrow \gamma_{NT}$

$\eta = 4.6 \times 10^{-10}$



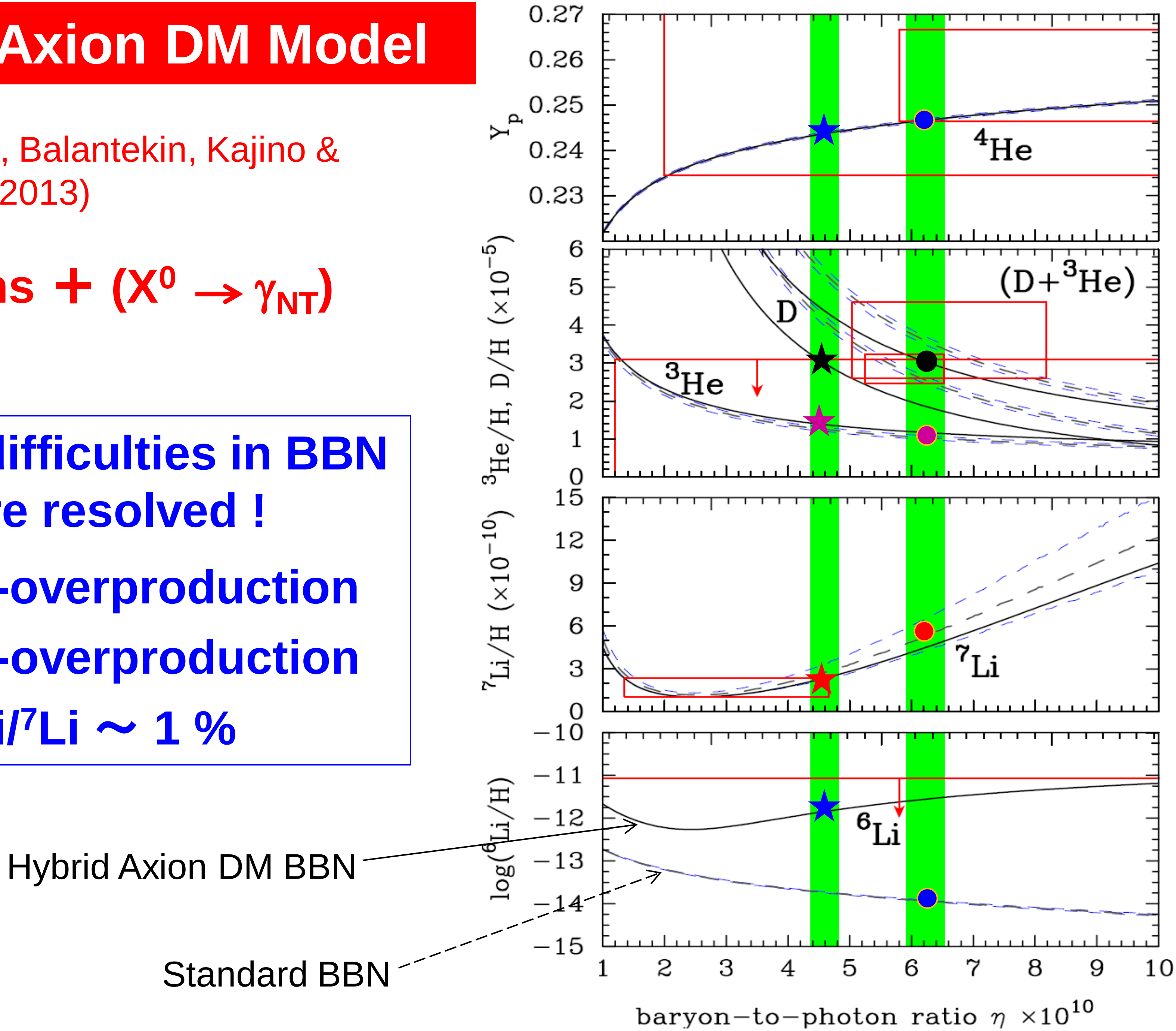
Hybrid Axion DM Model

Kusakabe, Balantekin, Kajino & Pehlivan (2013)

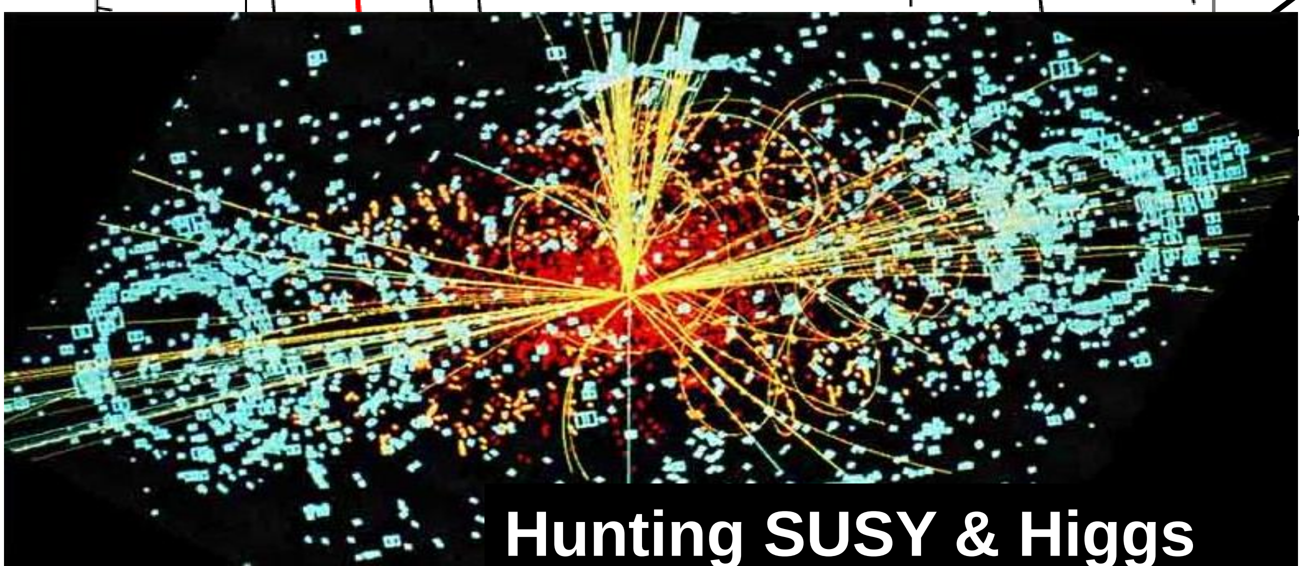
Axions + ($X^0 \rightarrow \gamma_{NT}$)

Three difficulties in BBN are resolved !

- **^{7}Li-overproduction**
- **D-overproduction**
- **^{6}Li/^{7}Li ~ 1 %**



Particle Physics Experiment tests Astronomical Prediction !



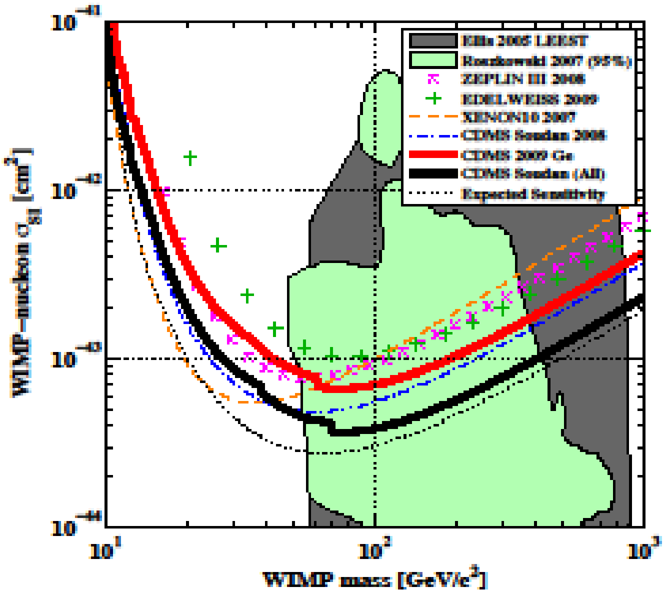
$\Omega_{CDM} = 0.2$

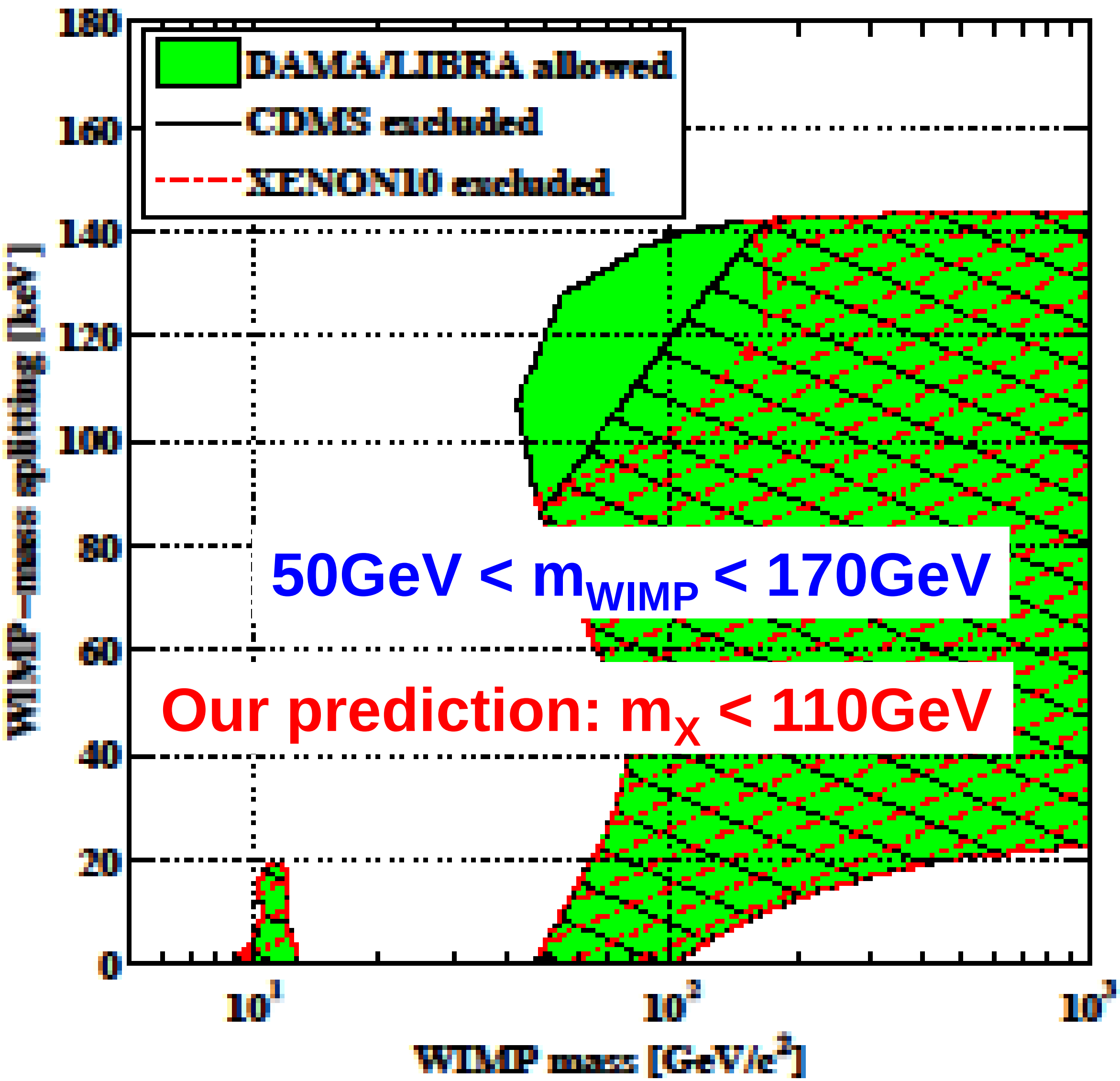
$m_X < 10\sim100 GeV$

Recent Result from CDMS II Experiment

Z. Ahmed et al.
(CDMS Collaboration)

arXiv:0912.3592v1





50GeV < m_{WIMP} < 170GeV

Our prediction: m_X < 110GeV

Variation of Fundamental Constants

Motivation

- Gravitational const. G could change in cosmic time: G(t) P. Dirac

- **Extra space dimensions** (Kaluza-Klein, Superstring and M-theories). Extra space dimensions is a common feature of theories unifying **gravity** with other interactions. Any change in size of these dimensions would manifest itself in the 3D world as variation of fundamental constants.

- **Scalar fields** . Fundamental constants depend on scalar fields which vary in space and time (variable vacuum dielectric constant ε_0). May be related to "dark energy" and accelerated expansion of the Universe..

Variation of the fundamental coupling const. provides natural explanation of the "fine tunung".

V. V. Flambaum

Variation of strong coupling const. α

Grand unification models

$$\Delta(m/\Lambda_{QCD})/(m/\Lambda_{QCD})=35\Delta\alpha/\alpha$$

1. Proton mass $M_p=3\Lambda_{QCD}$, measure m_e/M_p
2. Nuclear magnetic moments $\mu=g\ eh/4M_pc$
   $g=g(m_q/\ \Lambda_{QCD})$

3. Nuclear energy levels

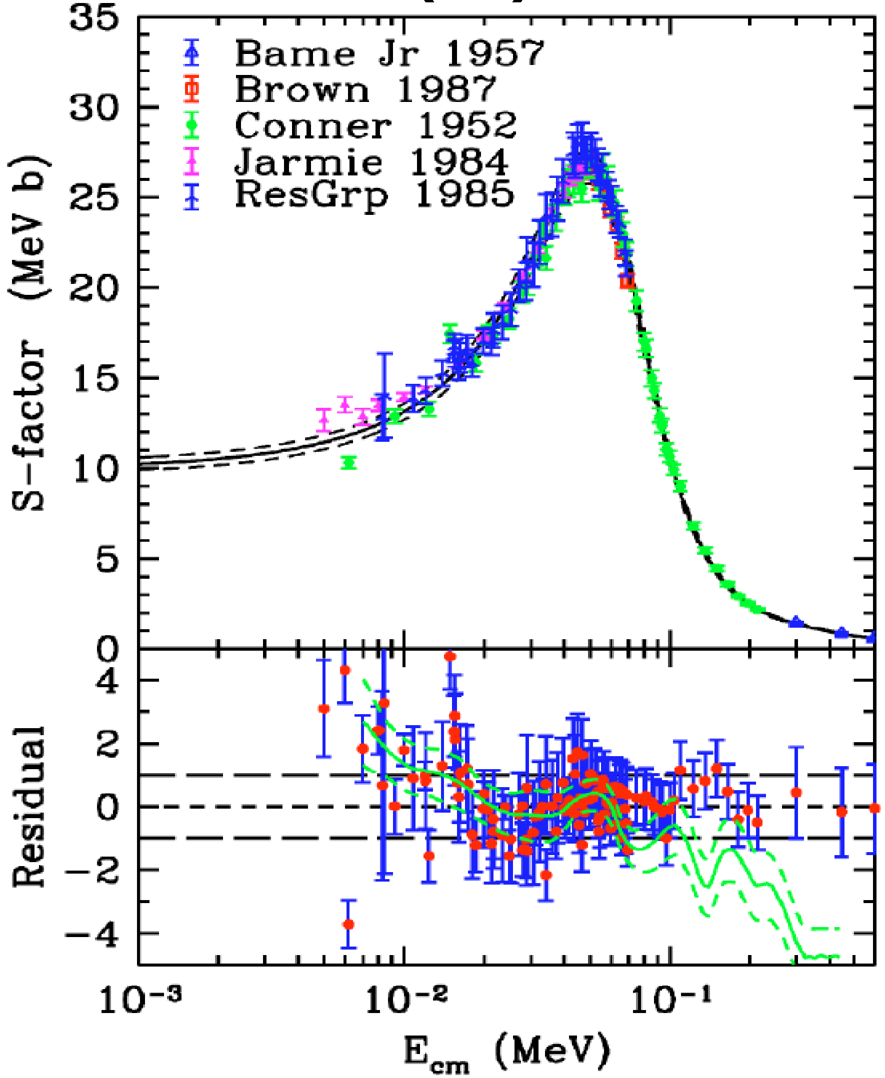
→ **Big-Bang Nucleosynthesis**

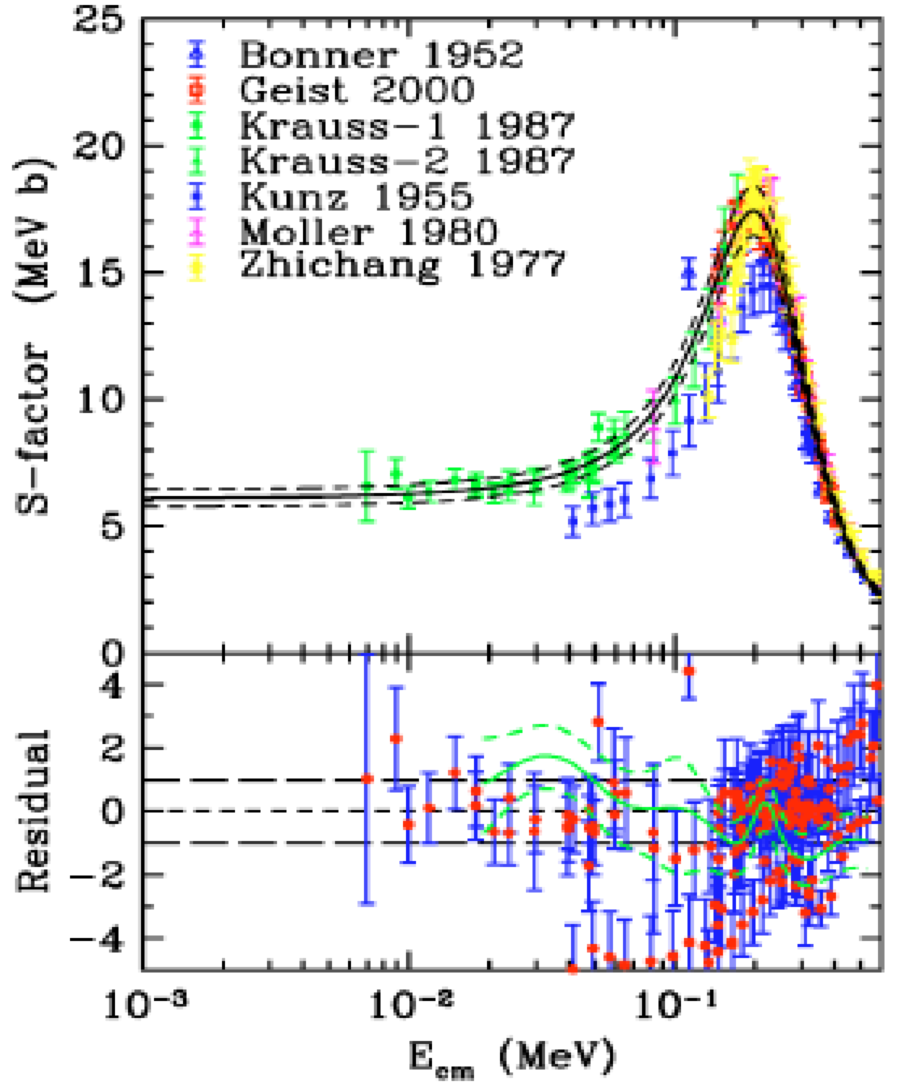
$$\delta E(A)/E(A) = K\ \delta(m_q/\Lambda_{QCD})/(m_q/\Lambda_{QCD})$$

K-values: V.V. Flambaum and R.B. Wiringa, PRC79, 034302 (2009)

Richard H. Cyburt

PHYSICAL REVIEW D 70, 023505 (2004)



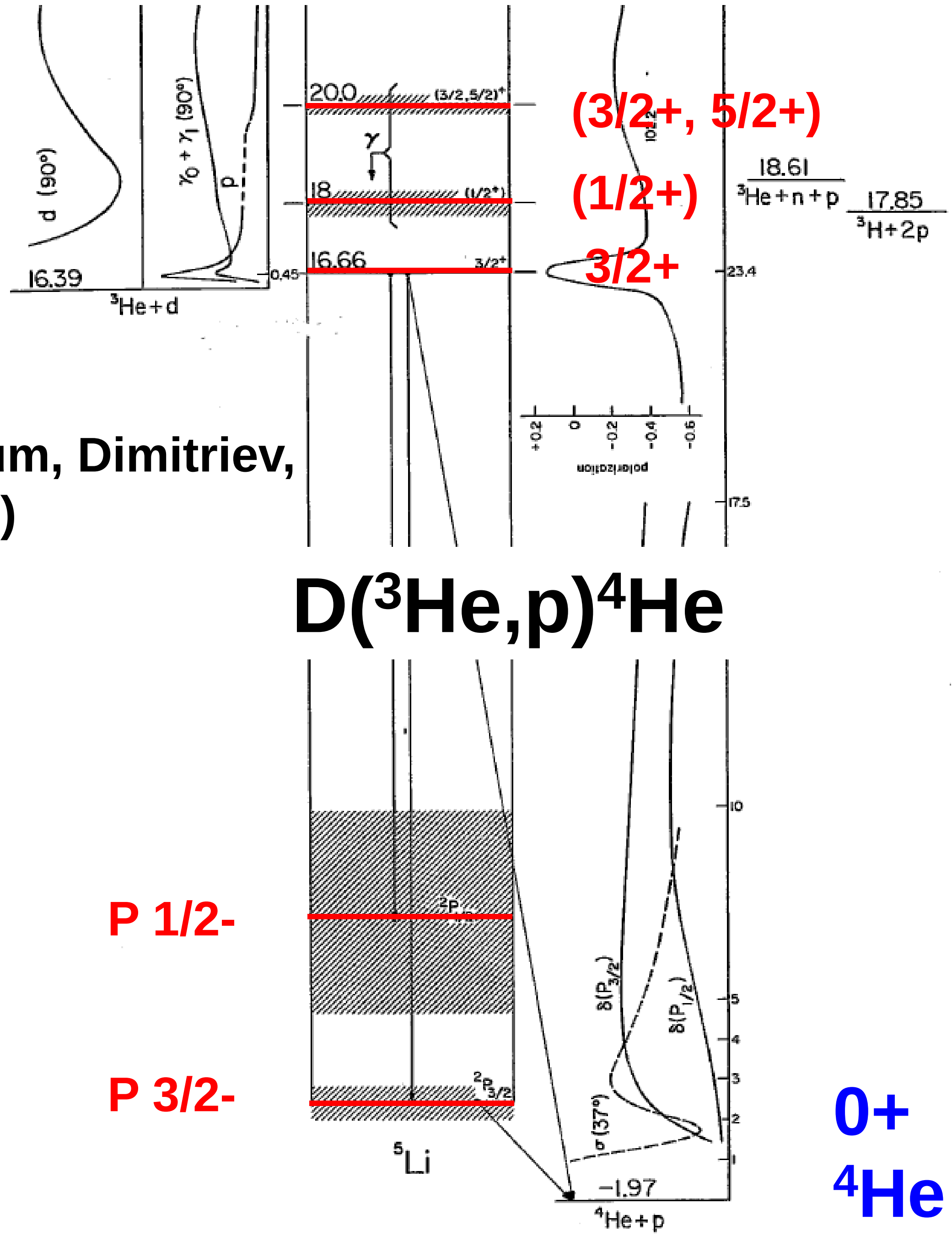


1s-wave

D + ^{3}He

1+ ½+

Berengut, Flambaum, Dimitriev, PL B683, 114 (2101)



D(^{3}He,p)^{4}He

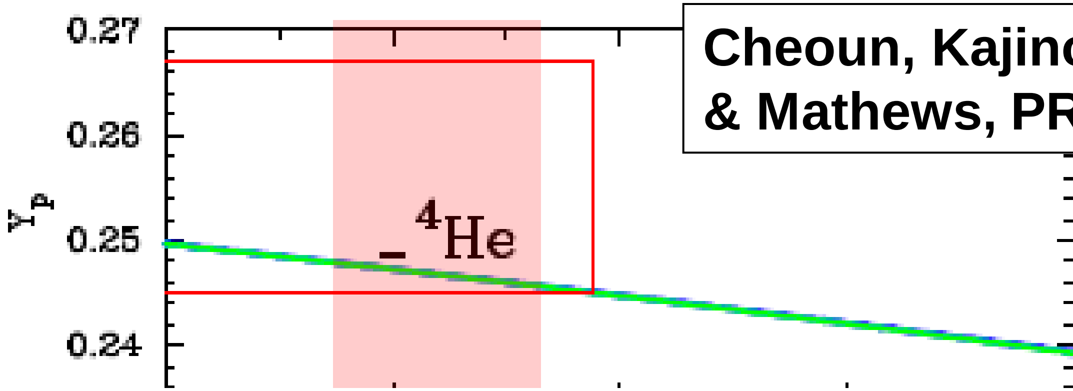
0d-wave

0p-wave

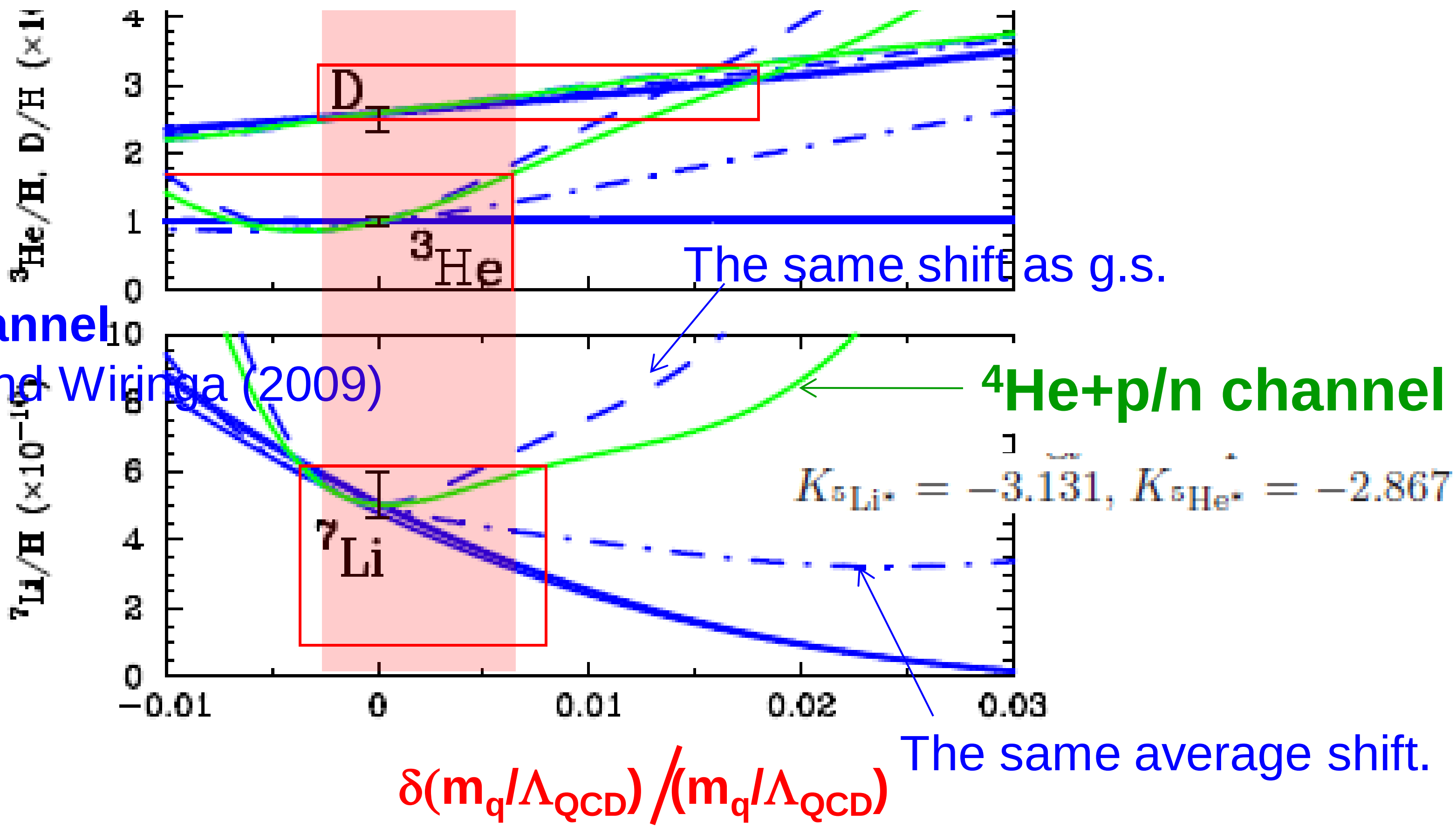
0+ ½+

^{4}He + p

Cheoun, Kajino, Kusakabe & Mathews, PRD (2012).



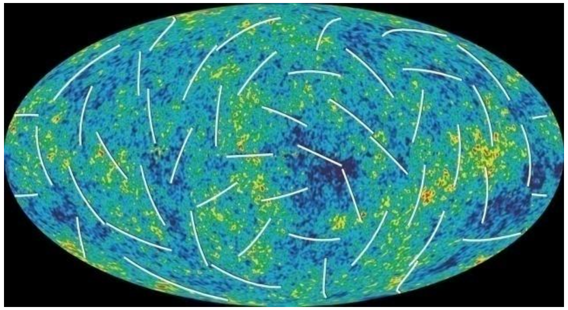
Consistent with no variation in 95% C.L. !



Neutrino Mass Constraint from Cosmology

CMB & LSS are strongly affected by:

- integrated Sachs-Wolfe
- neutrino free streaming
- compensation mode of anisotropic stress for neutrinos (π_ν) and cosmic magnetic field (π_B) or extra dimension (π_5).



http://lambda/gsfc.nasa.gov/

Total Neutrino Mass

Cosmology

CMB and LSS constraint from cosmological parameter-fit:

$\Sigma m_\nu < 1.3$ eV (2σ C.L.) ⟹ **$\Omega_\nu h^2 < 0.013$**

WMAP-5yr, 7yr: Komatsu et al. (2008, 2010)

New constraint: CMB + Magnetic Field + ν-mass :

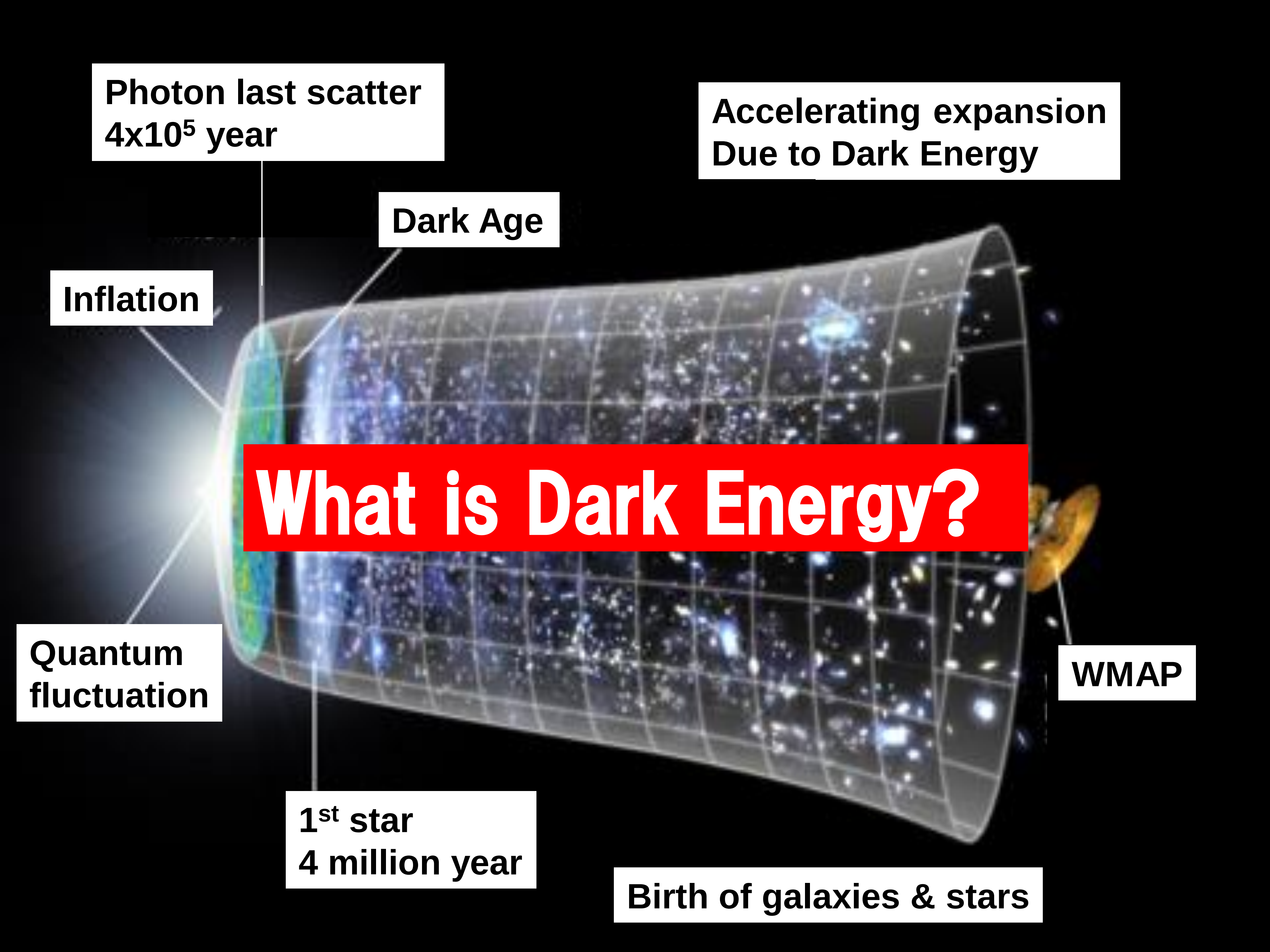
$\Sigma m_\nu < 0.8$ eV (1σ C.L.) ⟹ **$\Omega_\nu h^2 < 0.008$ (1σ)**

Yamazaki, Ichiki, Kajino & Mathews, PR D81 (2010), 103519.

Nuclear Physics

0ν-ββ : **$|\sum U^2_{e\beta} m_\beta| < 1\sim6$ eV** ⟹ **0.1~0.05 eV !? (future)**

Lesgourgues and Pastor (2006)

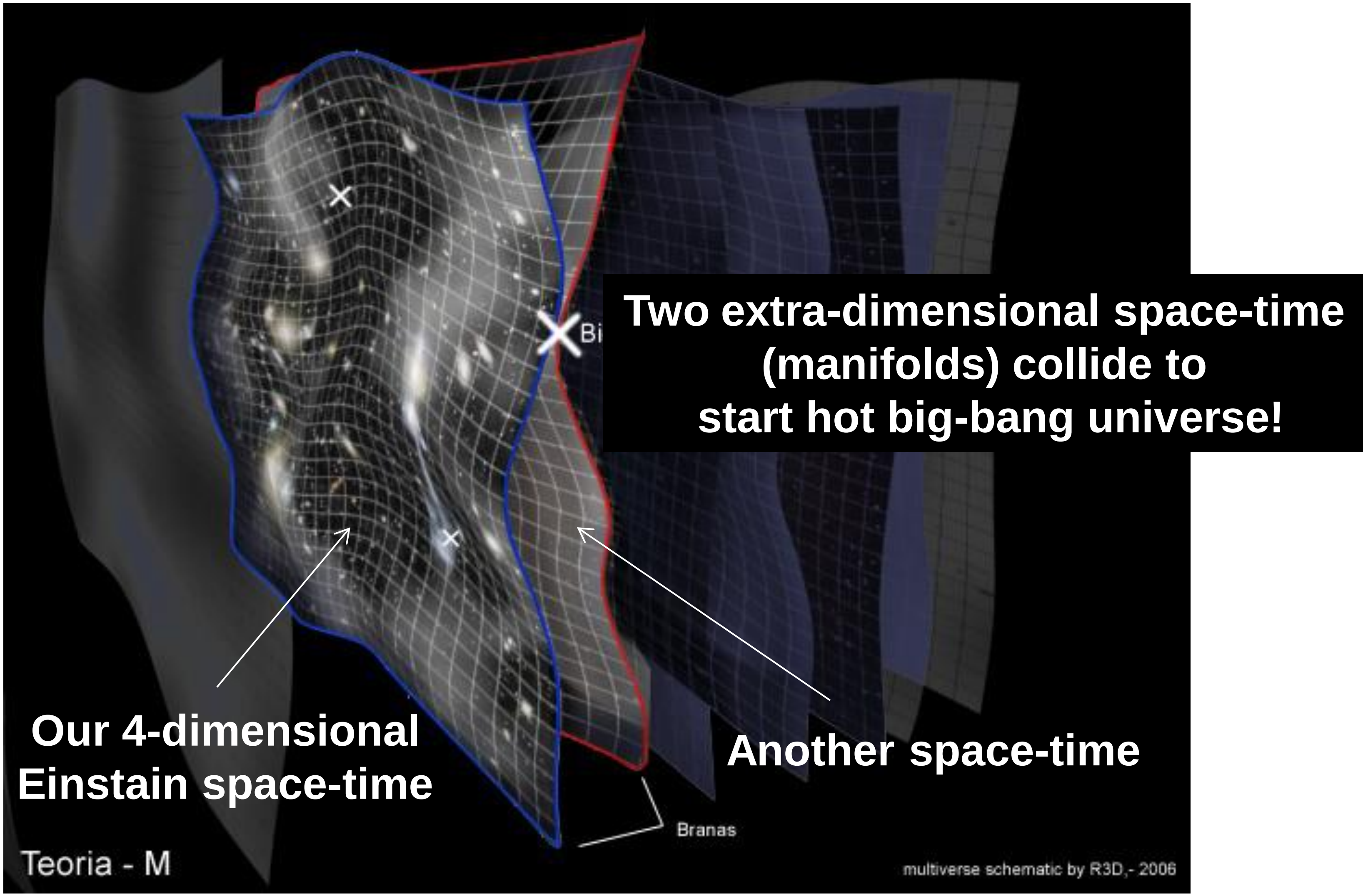


Photon last scatter
4x10^5 year
Accelerating expansion
Due to Dark Energy
Dark Age
Inflation
What is Dark Energy?
Quantum
fluctuation
WMAP
1st star
4 million year
Birth of galaxies & stars

Dark Energy in Extra-Dimension Universe

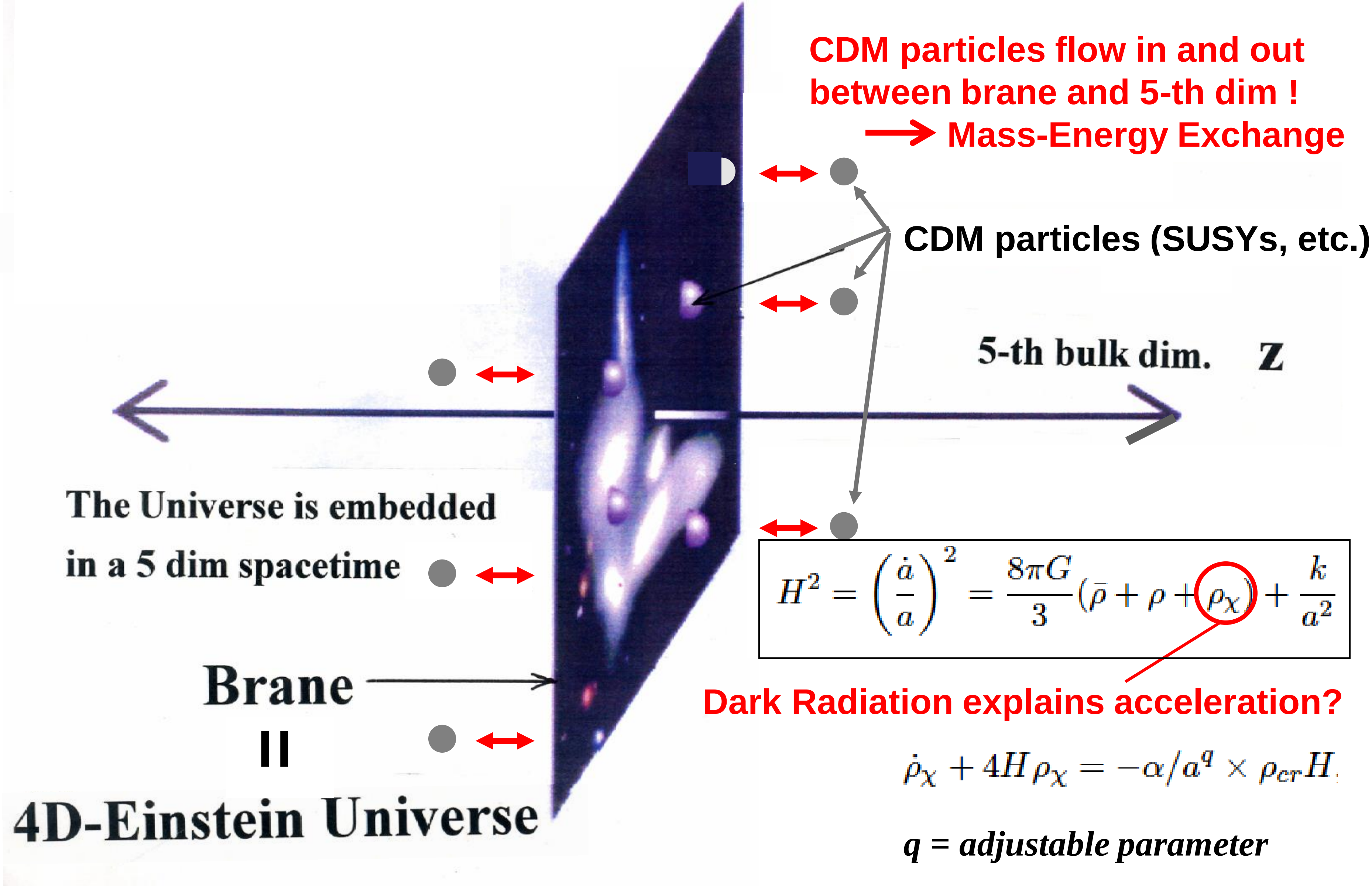
Randall and Sundrum, PRL 83 (1999) proposed brane world cosmology, motivated by 10 dim String Theory.

Brane World Cosmology
There is/are extra-dimension/s as manifolds.



5D Brane World Cosmology with $\Omega_\Lambda = 0$

—— A Model for Accelerating Universe ——



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

Dark Radiation explains acceleration?

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

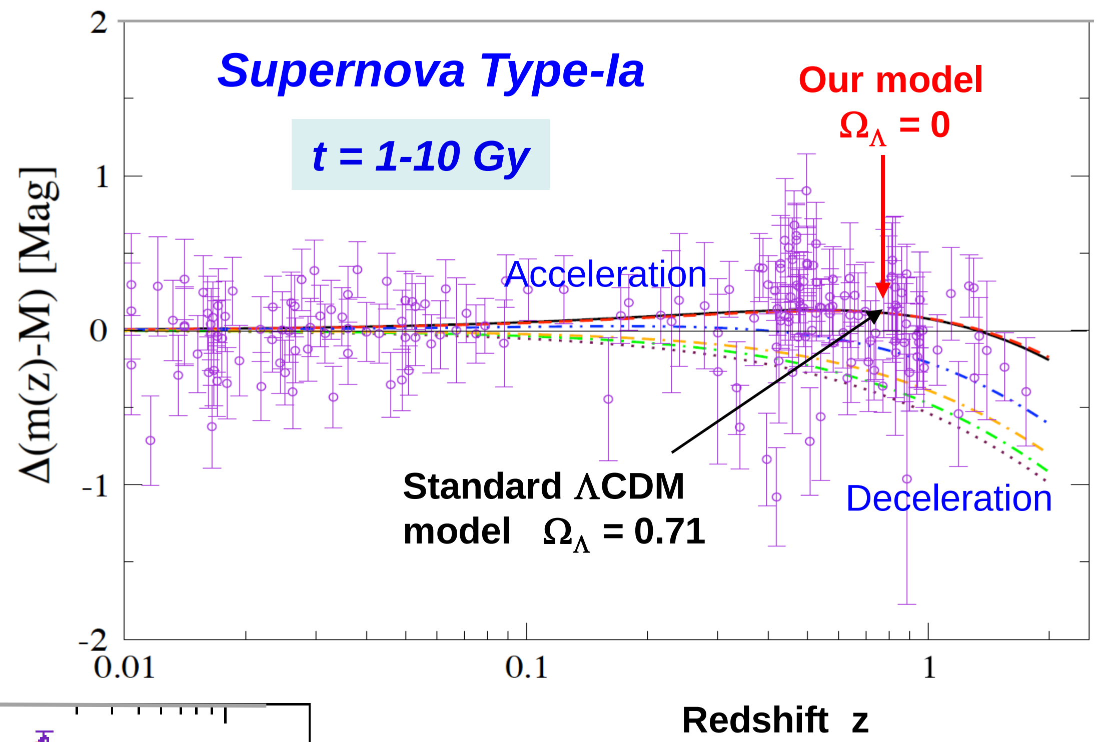
q = adjustable parameter

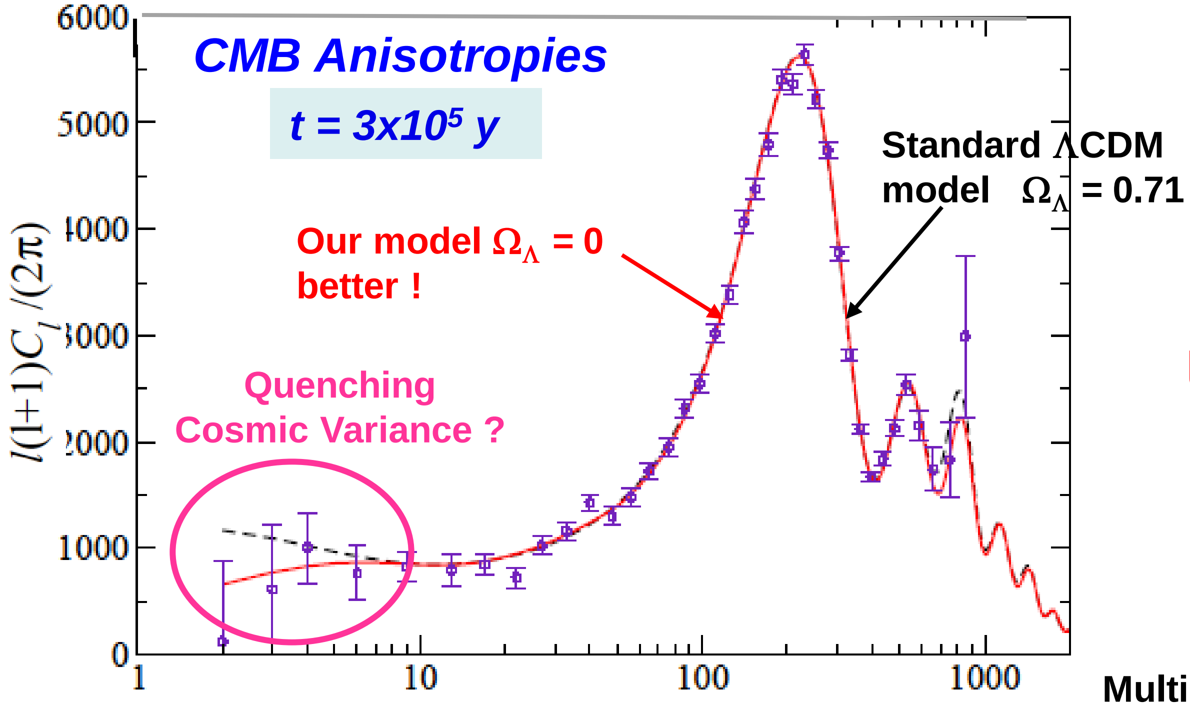
BRANE WORLD COSMOLOGY with $\Omega_\Lambda=0$

↕

Standard ΛCDM with $\Omega_\Lambda \neq 0$

Umezu, Ichiki, Kajino, Mathews, Nakamura & Yahiro, PRD 73 (2006), 063527

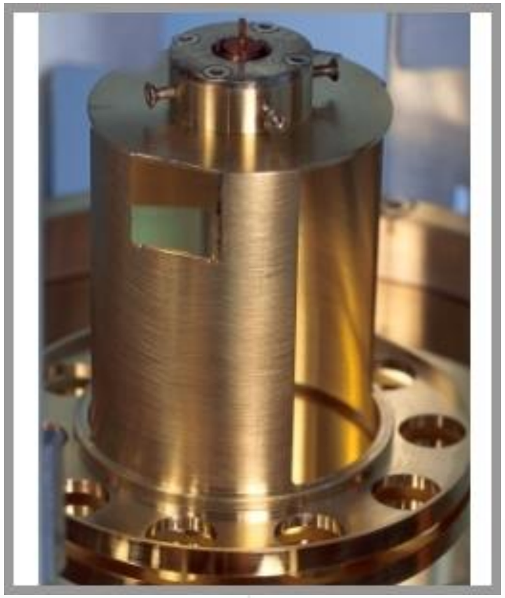




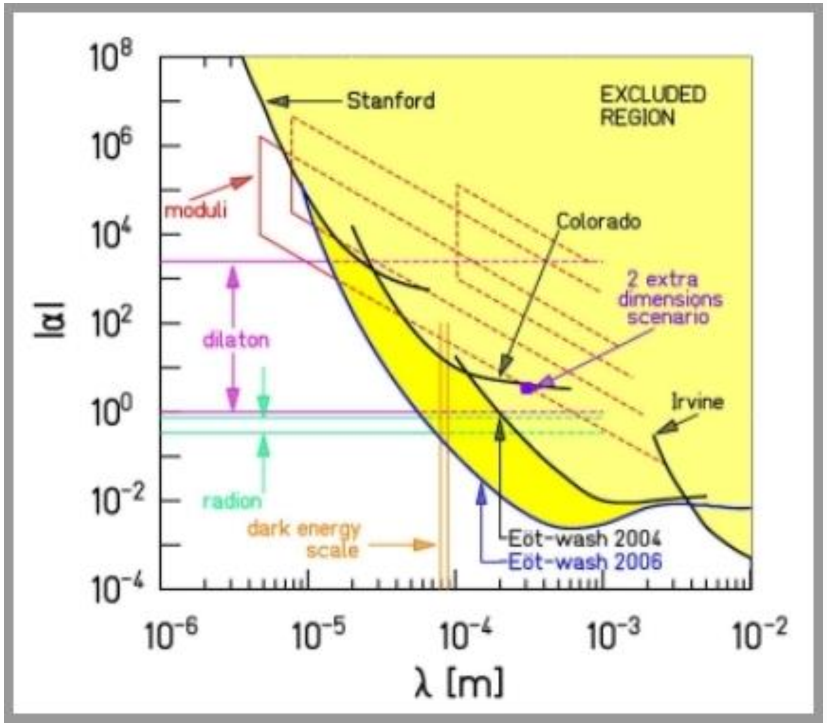
ACCELERATING Universal expansion even for $\Omega_\Lambda = 0$!

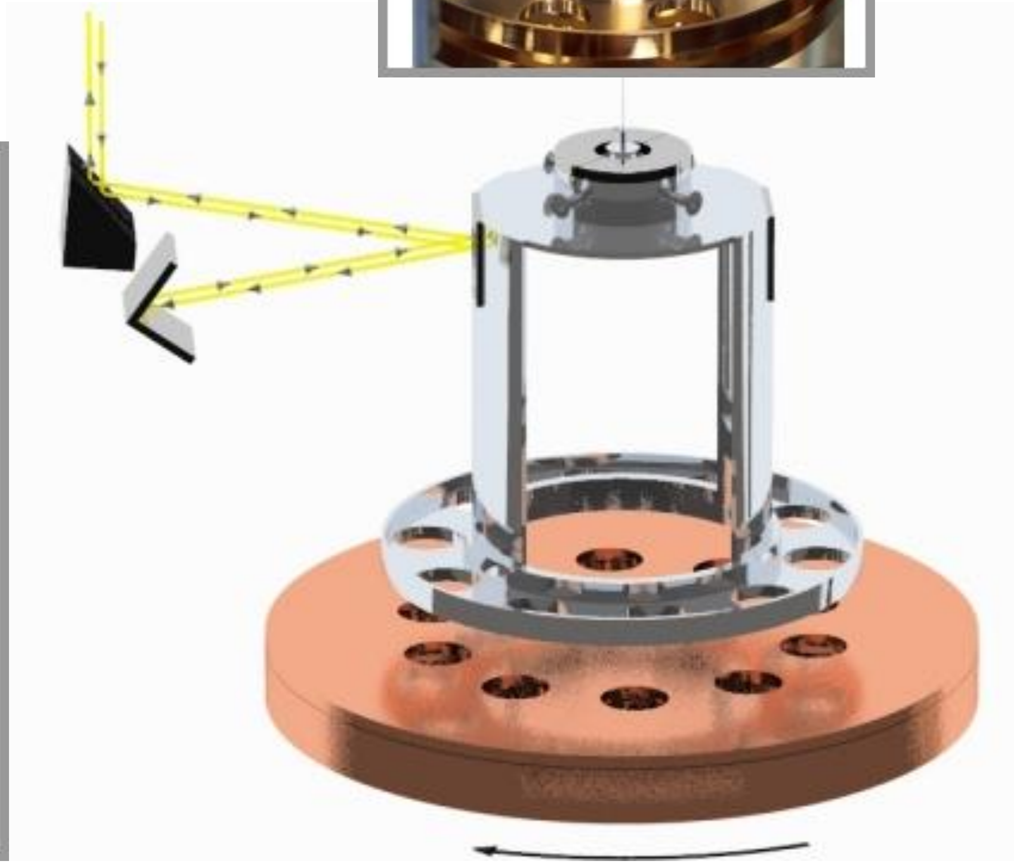
Laboratory experiments
To seek for extra-dimension

Prof. Adelberger's group
@ University of Washington



To test the breaking of Newtonian Inverse power law!

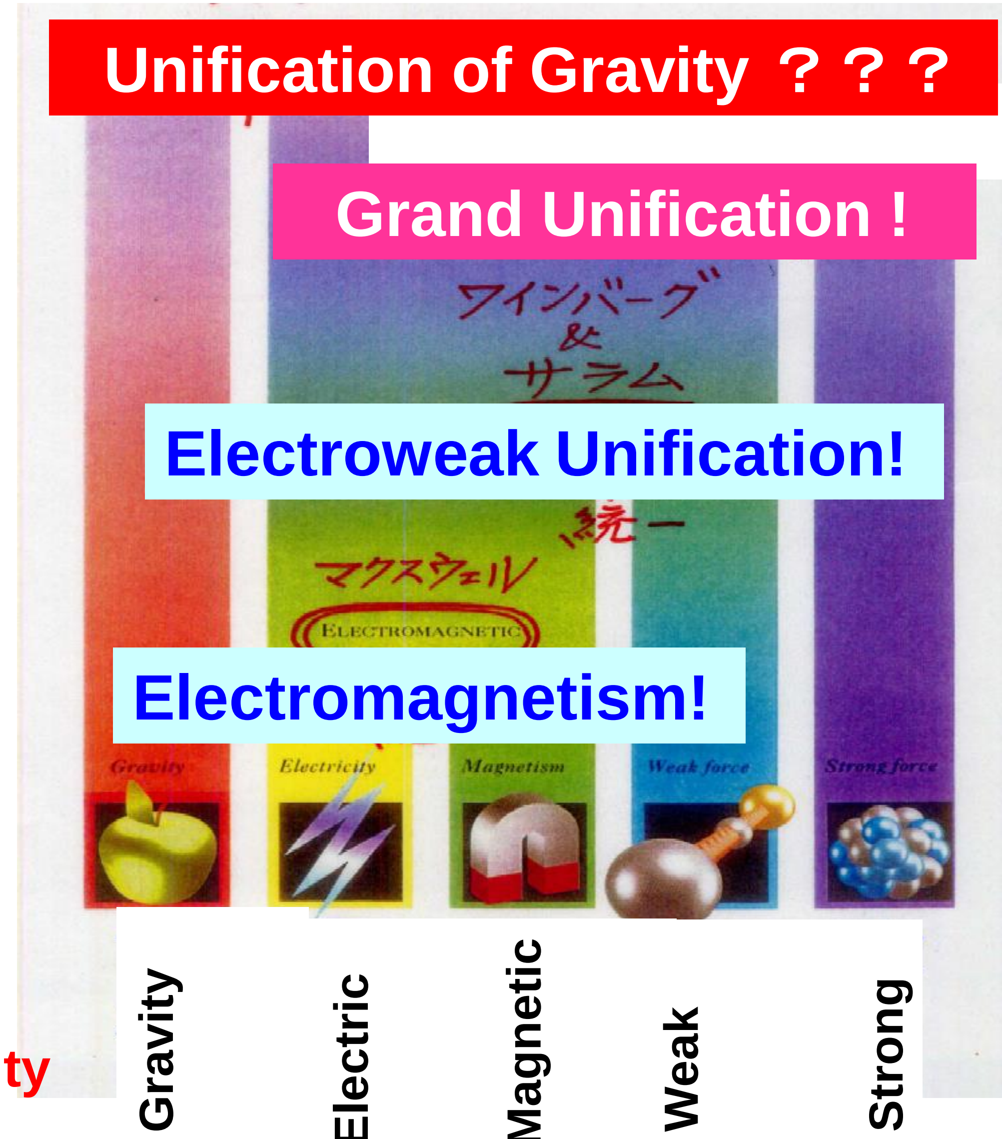




Ultimate Challenge of Modern Science !

:- is to construct Unified Theory of Fundamental Forces, and to resolve the mystery of the beginning and evolution of the Universe!

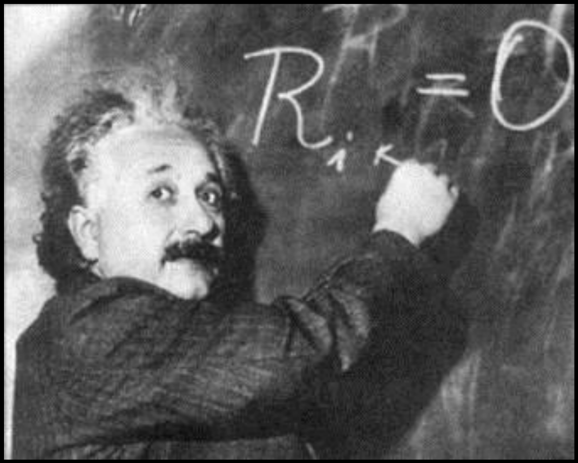
- **Electromagnetism**
  Maxwell (1864)
- **Electroweak Unification**
  Weinberg and Salam (1973)
- **Grand Unification !**
  Gauge Theory, unfinished !
- **Unification of Gravity ???**
  Superstring, SUSY, Supergravity



Need EXTRA DIMENSION ?

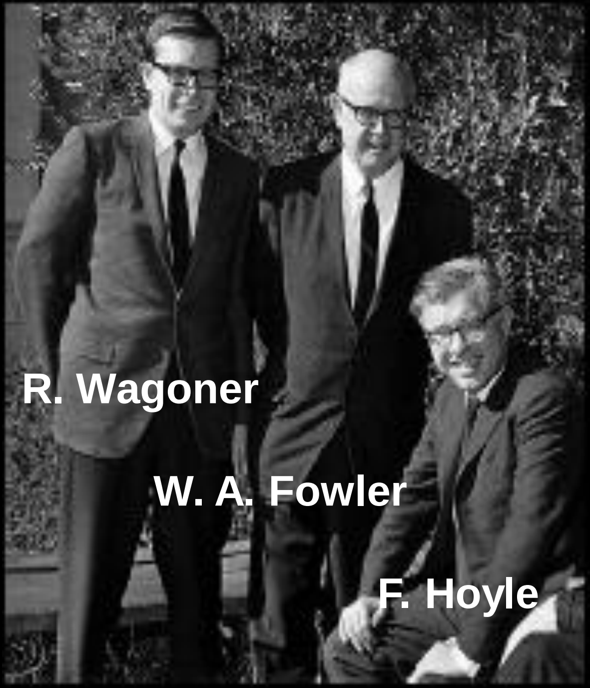
G. Gamow

The Universe is the "Laboratory" for the fundamental science!



A. Einstein

G. Smoot



R. Wagoner

W. A. Fowler

F. Hoyle