13th Lomonosov Conference on Elementary Particle Physics
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Big-Bang Cosmology, Nucleosynthesis and Neutrino Oscillation

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OUTLINE

Burbidge, Burbidge, Fowler & Hoyle (B^2FH, 1957) —— 50 yr

Pontecorvo (ν Oscillation, 1957~60) —— ~ 50 yr

Koshiba (SN ν, 1987) —— 20 yr

Smoot & Mathar (COBE, 1992) —— 15 yr

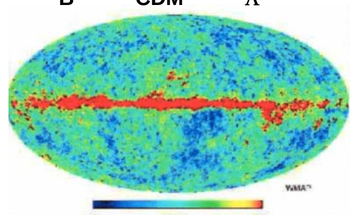
X-process is known today to be the Big-Bang Nucleosynthesis (BBN) !

Power of the BBN to constrain Cosmological Theories !

- DARK ENERGY (Ω_Λ = 0.74), CDM (Ω_{CDM} = 0.22) ?
- BARYON (Ω_B = 0.04) consistent with particle-nuclear theory ?
  → ^{6}Li, ^{7}Li problems

Universe is flat & accelerating !

$\Omega_B + \Omega_{CDM} + \Omega_\Lambda = 1$



COBE (1992), WMAP (2003, 2006)

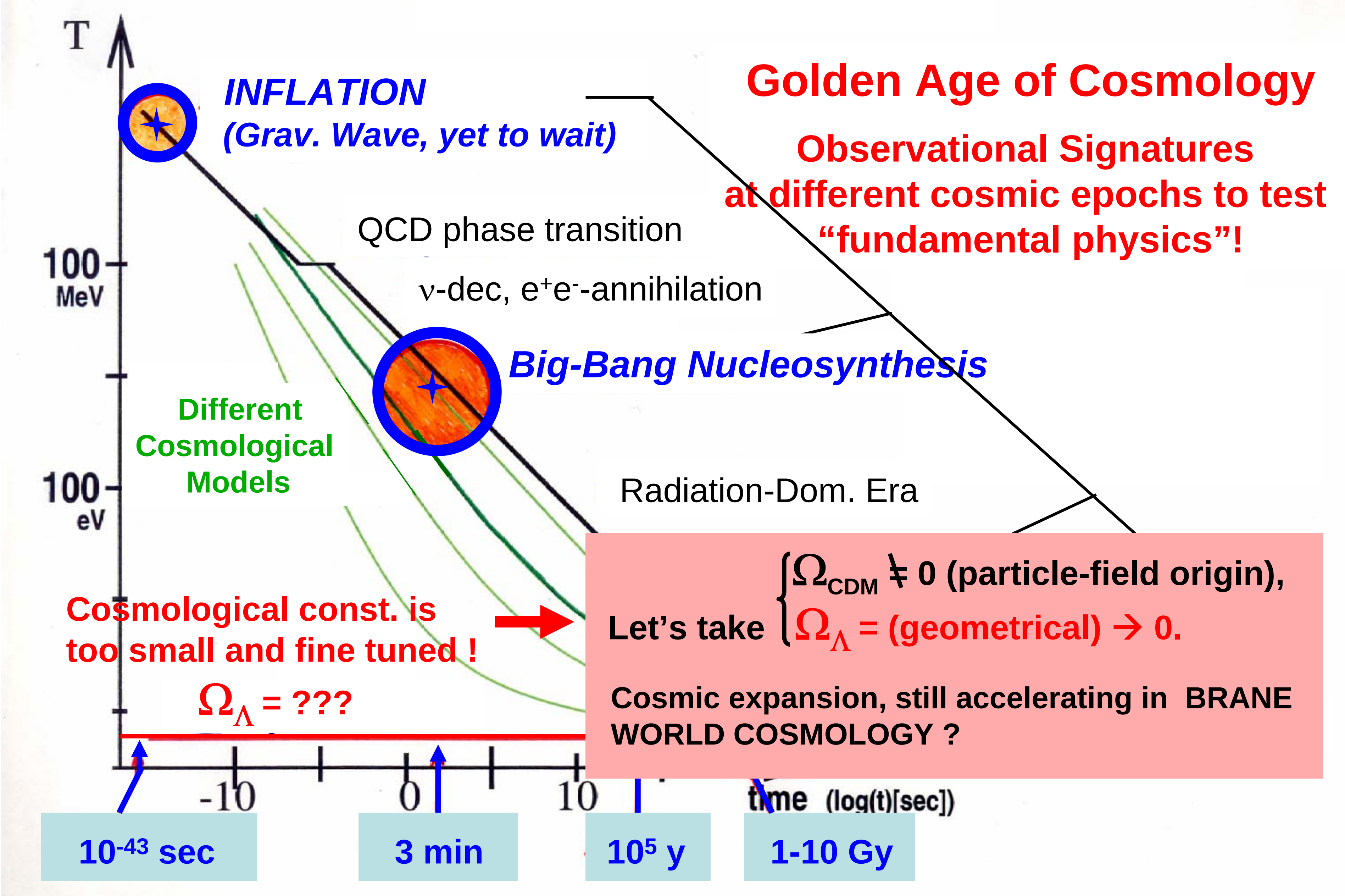
Supernova ν-oscillaion – MSW Effect !

X-process operates in SN ν-process, too !

- New Method using "MSW Effect" to determine θ_{13} and Mass Hierarchy !

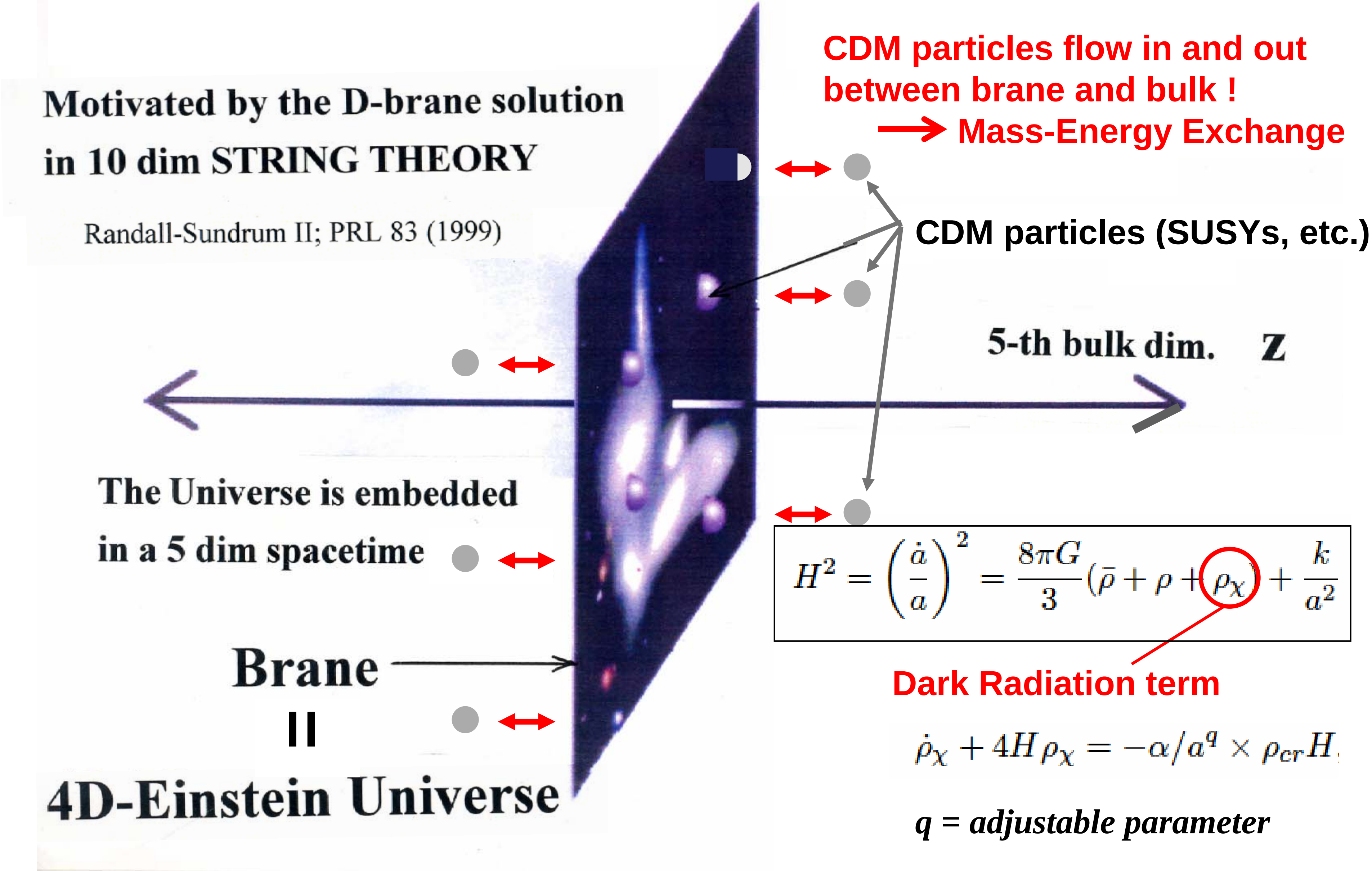
SN1987A

Thermal History of our Expansing Universe



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

—— A Model for Accelerating Universe ? ——



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

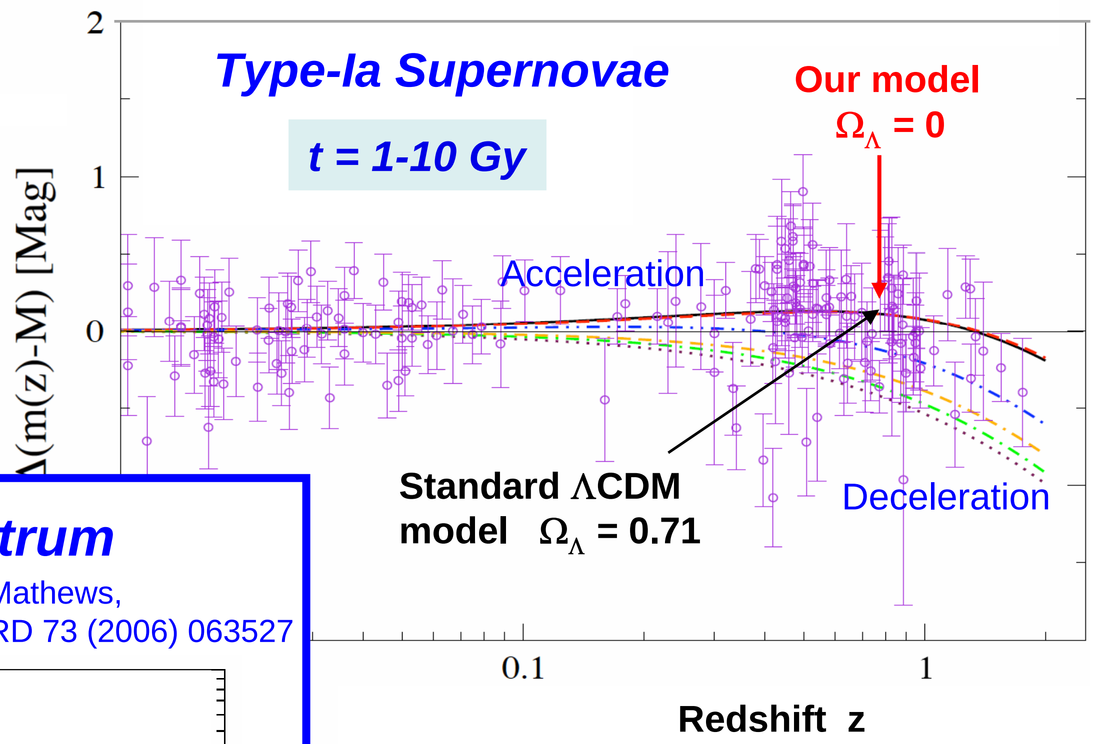
$$\dot{\rho}_\chi + 4H\rho_\chi = -\alpha/a^q \times \rho_{cr} H$$

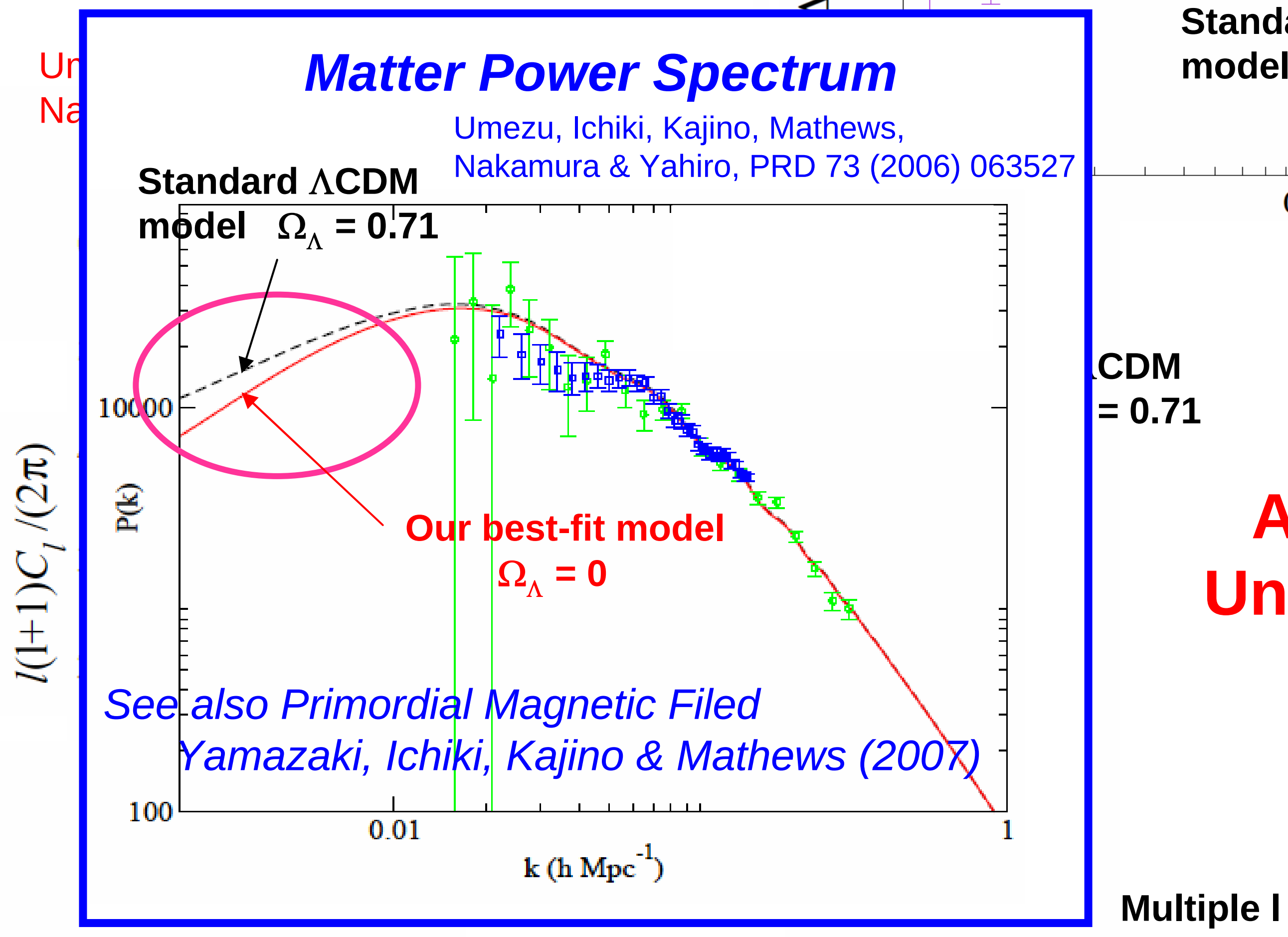
q = adjustable parameter

BRANE WORLD COSMOLOGY
with Ω_Λ=0

↕ ?

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





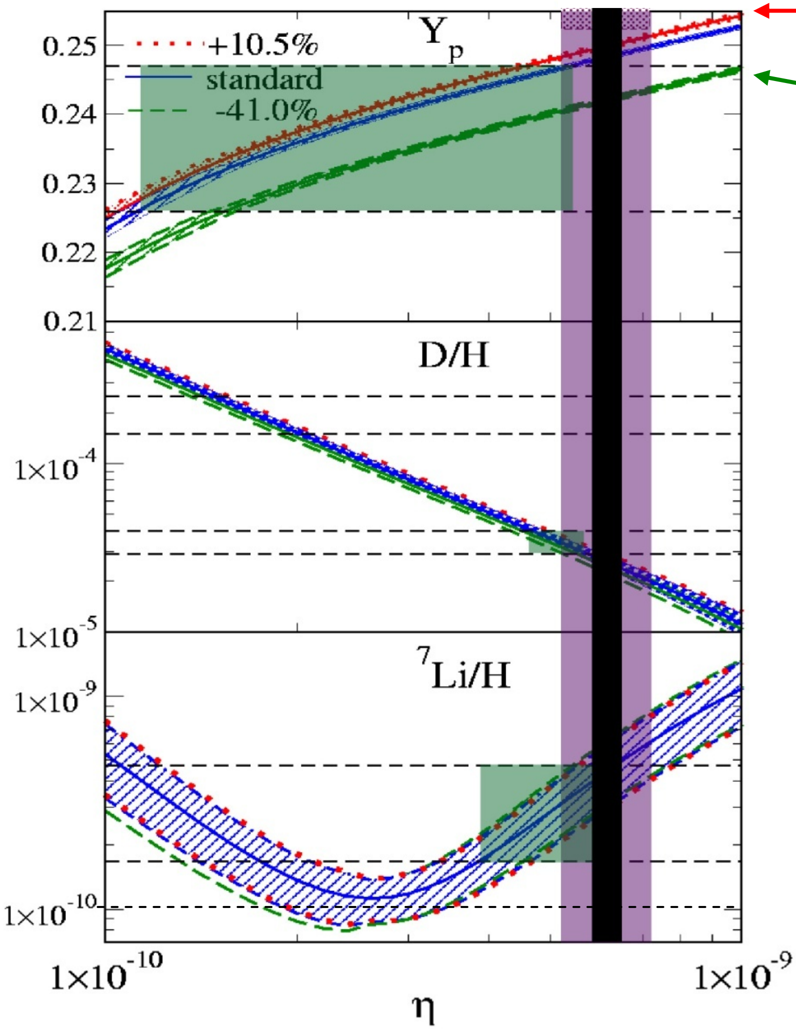
ACCELERATING
Universal expansion
without Ω_Λ !

BBN constrains Brane World Cosmology

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

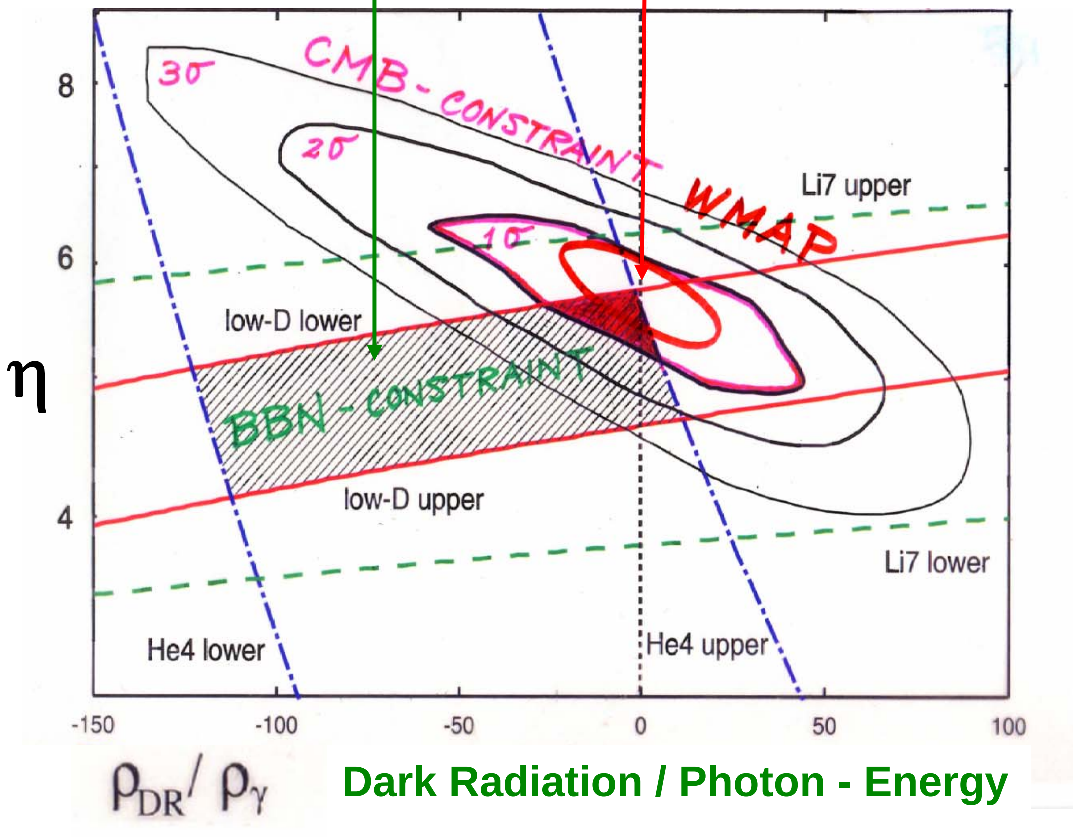
t = 3 min

CMB-WMAP



Standard BBN Model

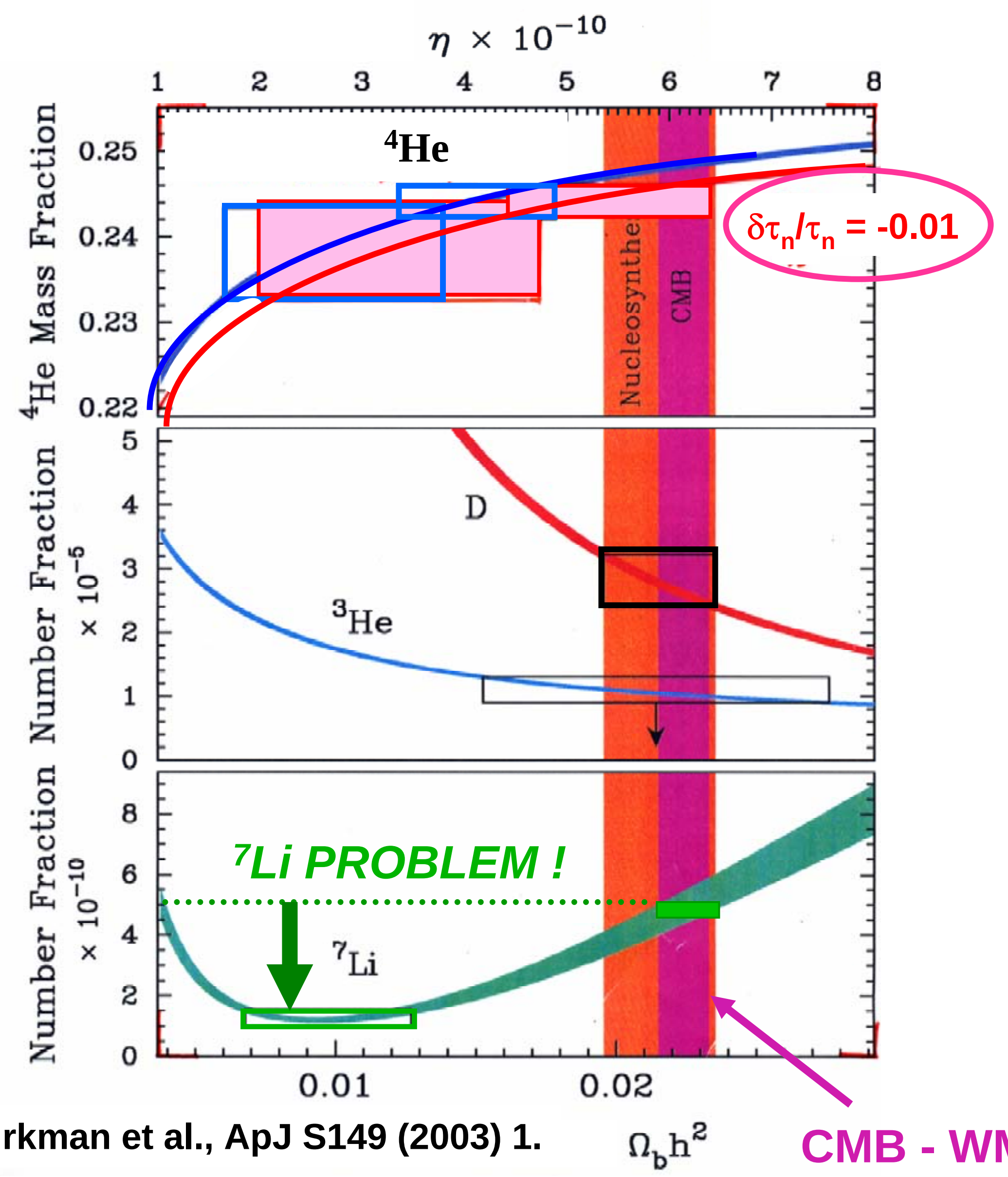
Dark Radiation relaxes the tension between the CMB+D/H and ^{4}He.



Dark Radiation / Photon - Energy

BBN and Particle Physics

Smith, Kawano & Malaney, ApJ S85(2003) 219; Mathews, Kajino & Shima, PRD71 (2005) 21302 (R).



Kirkman et al., ApJ S149 (2003) 1.

CMB - WMAP

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

Factor 2~4 stellar depletion ?
Abundance scatter is too small to accept DEPLETION !

Relic DM particles (SUSY, etc.) X's decay to non-thermal photons:

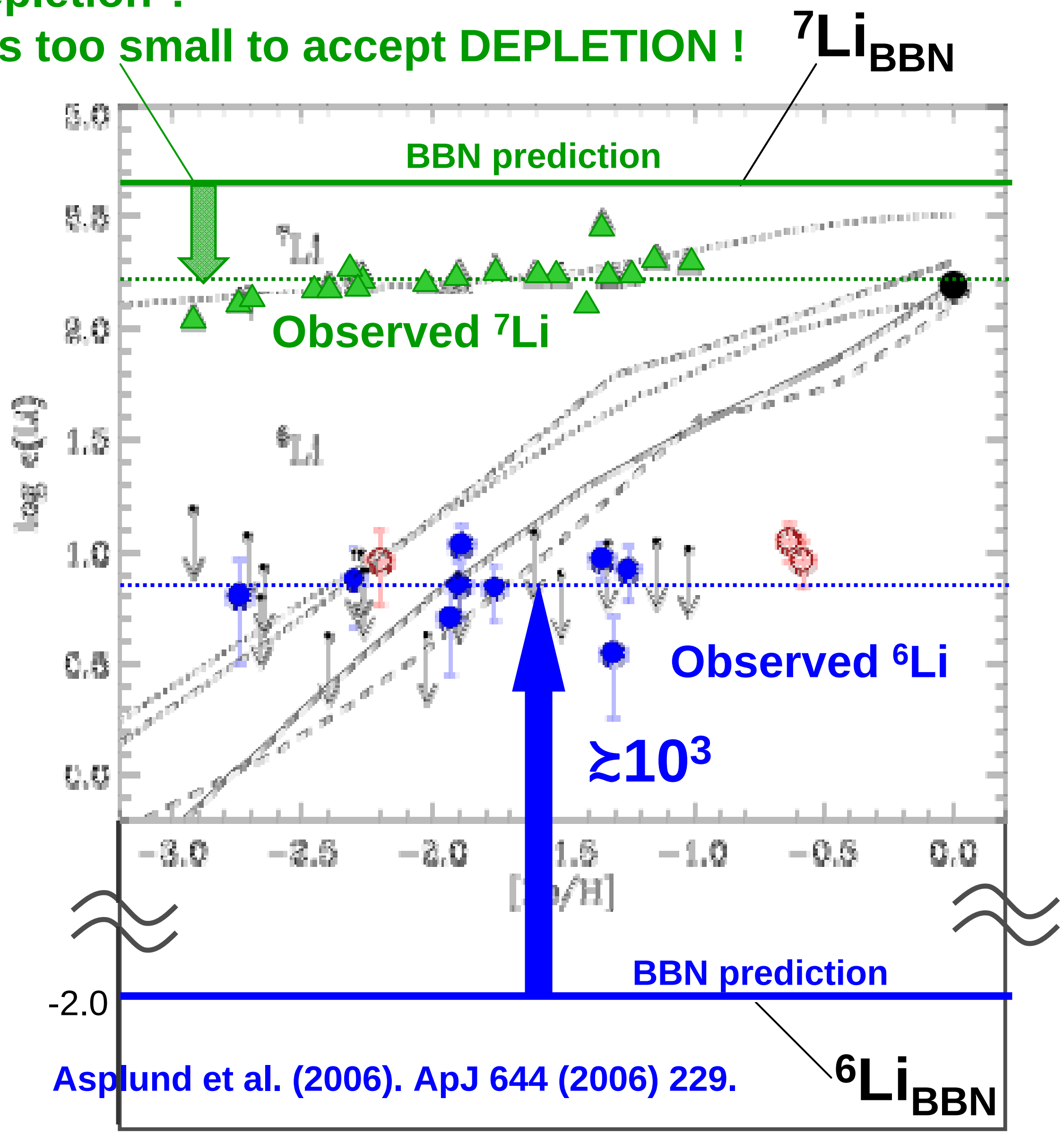
γ_{NT}.

Non-thermal photons spalt ^{4}He into ^{3}He, ^{3}H. New class of BBN occurs:

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

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

critical reactions !



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

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

Theoretical of X decay: X → γ_{NT}

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 τ_X

Number density * Eγ of X

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

Reaction process

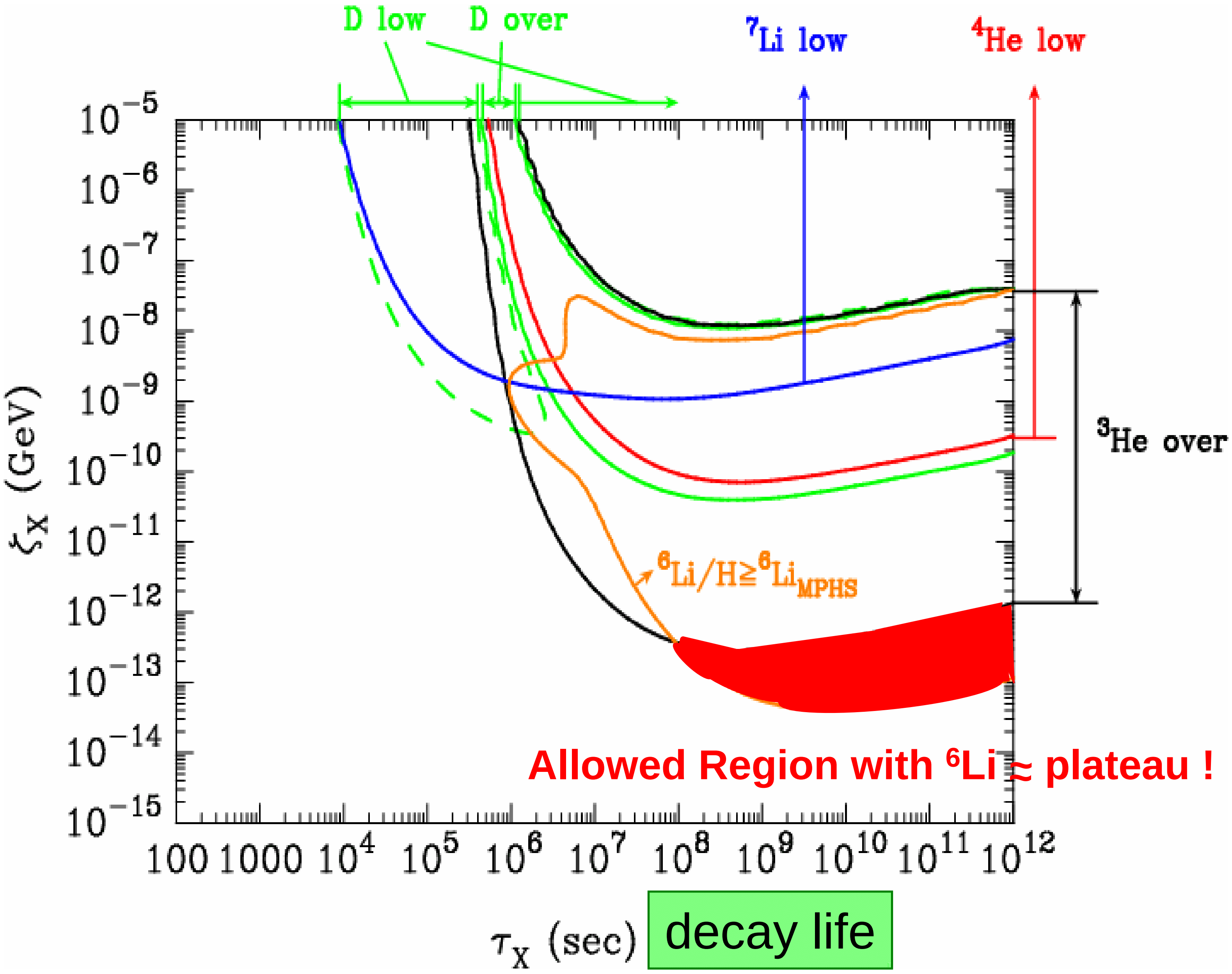
Rate equation
$$\frac{dY_A}{dt} = \sum_P N_A(P)\left(-\frac{Y_A}{N_A(P)!}[A\gamma]_P + \frac{Y_P}{N_P(P)!}[P\gamma]_A\right) \quad + \text{SBBN}$$

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

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 particle properties

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



abundance parameter

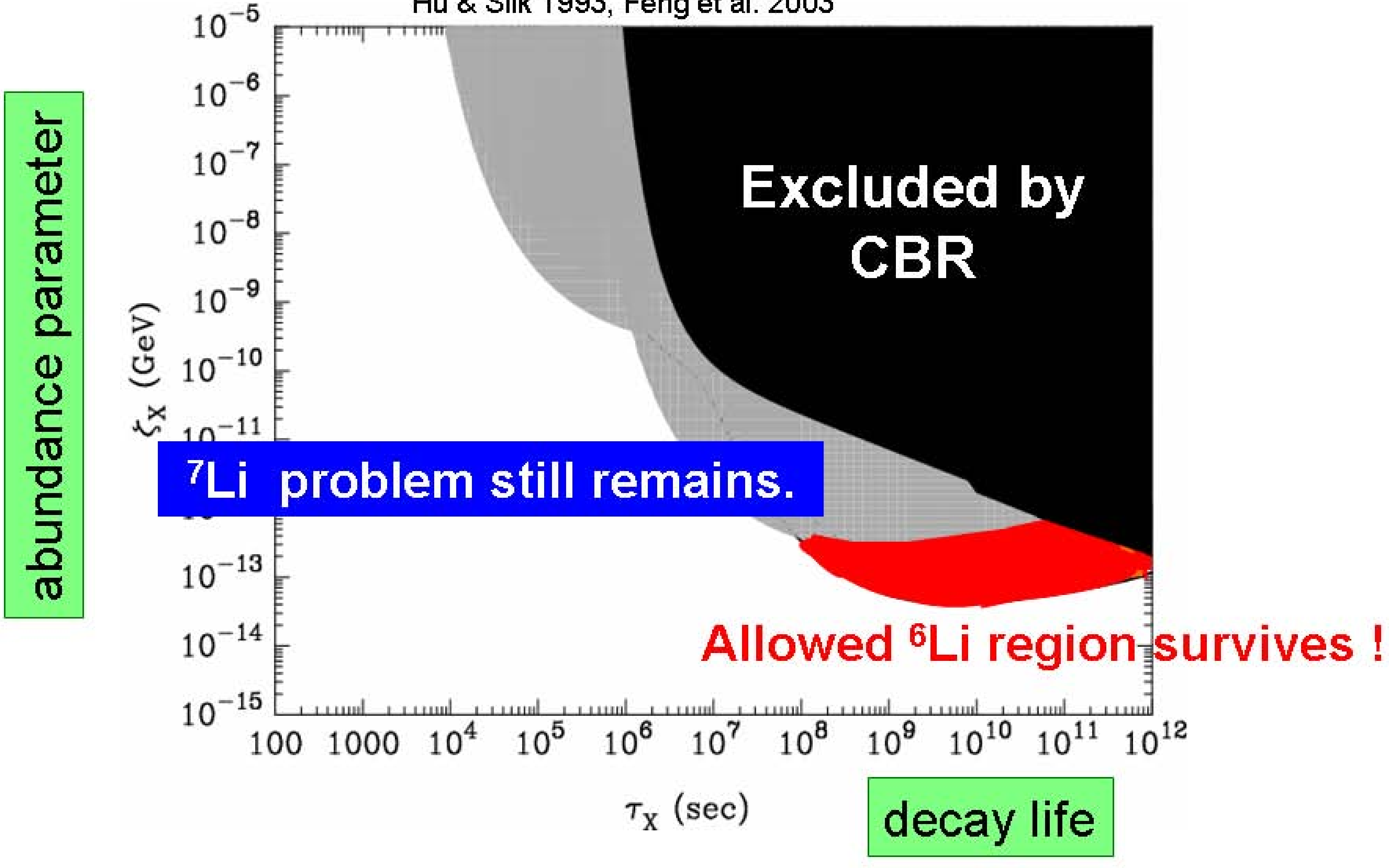
decay life

Allowed Region with ^{6}Li ≈ plateau !

Constraint from the CBR energy spectrum

Radiative decay causes CBR distortion from black-body distribution by $e^{\pm}\gamma_{BG} \rightarrow e^{\pm}\gamma$ ➡ **Another Constraint**

Hu & Silk 1993, Feng et al. 2003



Case of Leptonic X⁻

Kusakabe, Kajino, Boyd, Yoshida, and Mathews (2007)

If relic X⁻ particle is leptonic, X's form bound exotic nuclei like ^4He_X, ^7Be_X, $^4He_{XX}$, $^7Be_{XX}$, etc.

Recomination of X particles destroys normal nuclei, and new class of BBN proceeds:

$^4He_X + d \rightarrow {}^6Li + X$

Pospelov (2006), Hamaguchi et al. (2007)

$^7Be_X + p \rightarrow {}^8B^*_X \rightarrow {}^8B + \gamma$

$^8B^*_X$ = nuclear excitation

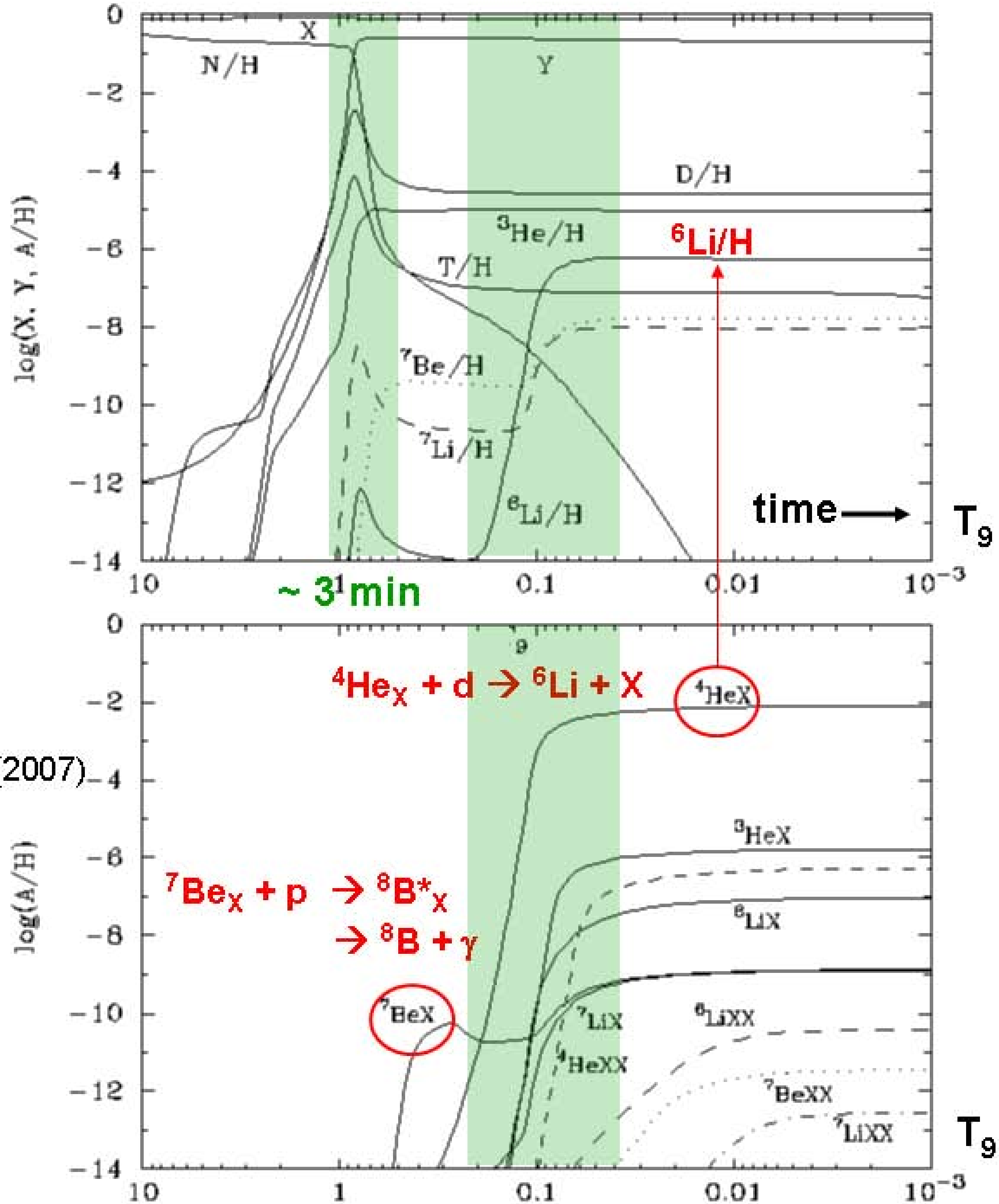
Kusakabe et al. (2007)

$^8B^*_X$ = atomic excitation

Bird et al. (2007)

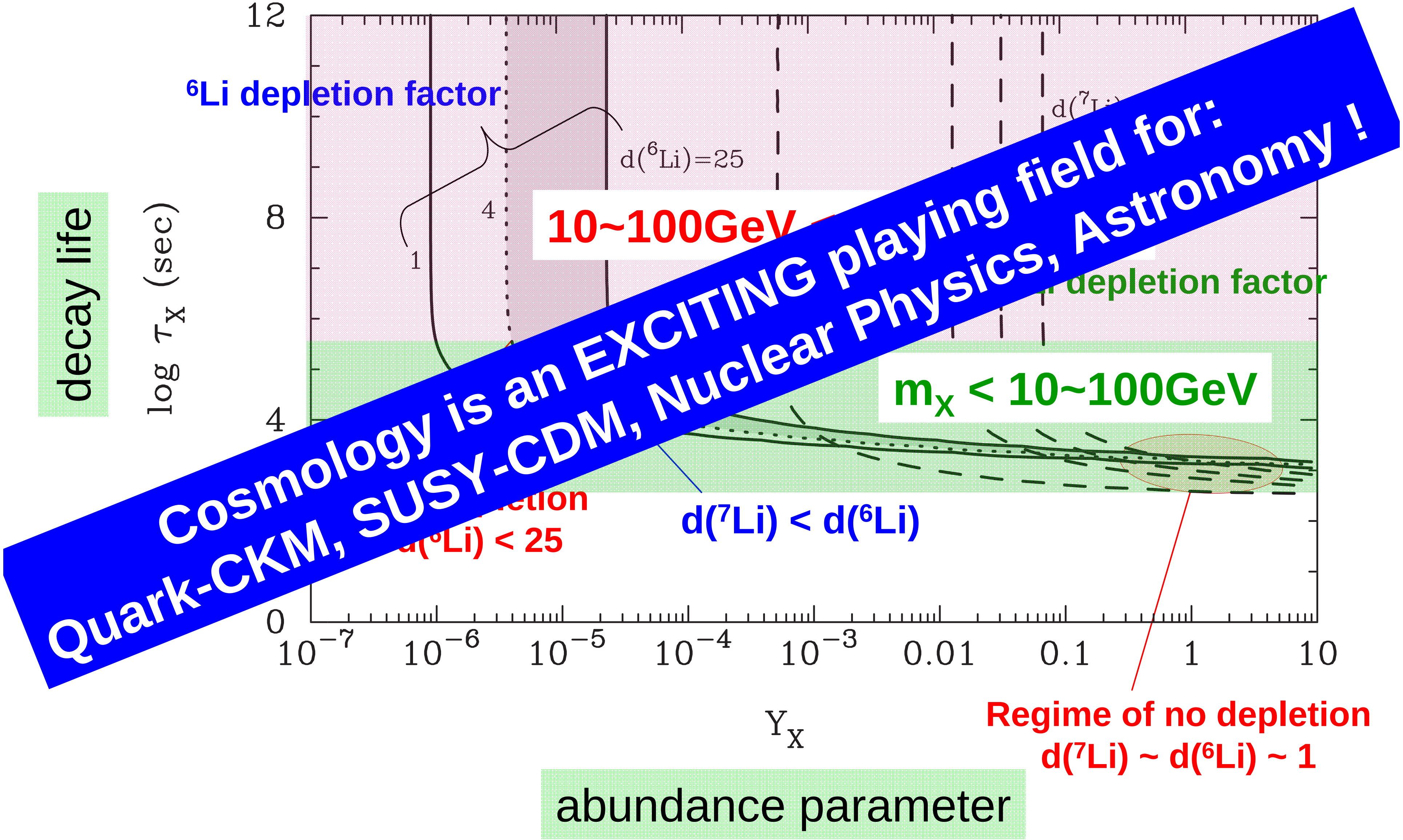
$^7Be_X \rightarrow {}^7Li + X^0$

Bird et al. (2007)



Depletion Factor of ^{6,7}Li/H ratio (Abundance normalized to MPHSs)

Kusakabe, Kajino, Boyd, Yoshida, and Mathews (2007)

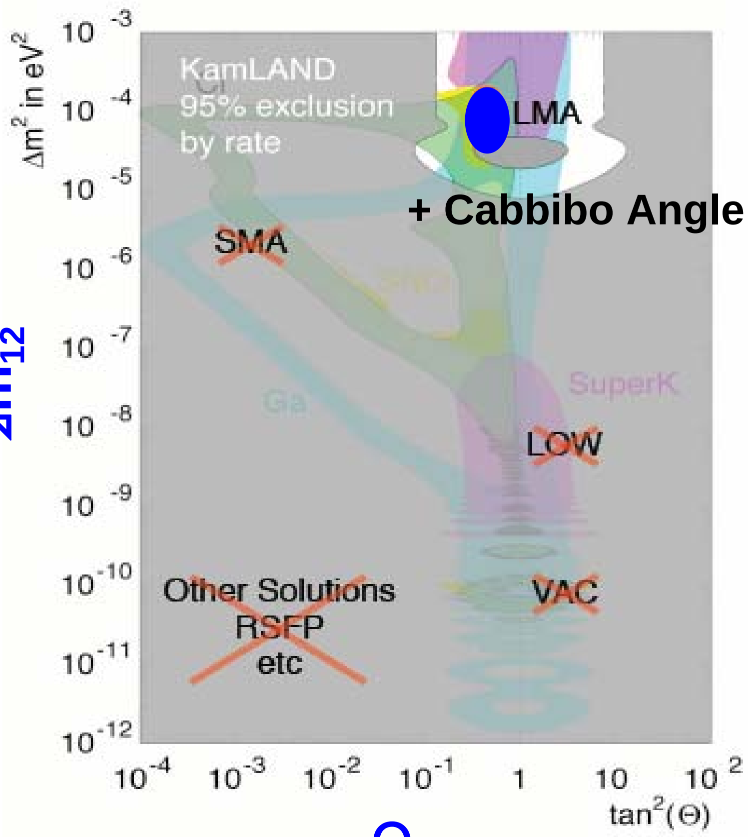


Neutrino Physics in Supernovae

ν–oscillation, proposed by Pontecorvo 1957, Sov. Phys. JETP 6, 429 ~ ibid. 1960, 37, 1236,

Super-K, SNO, KamLand (reactor ν) determined Δm_{12}^2 and θ_{12} uniquely.

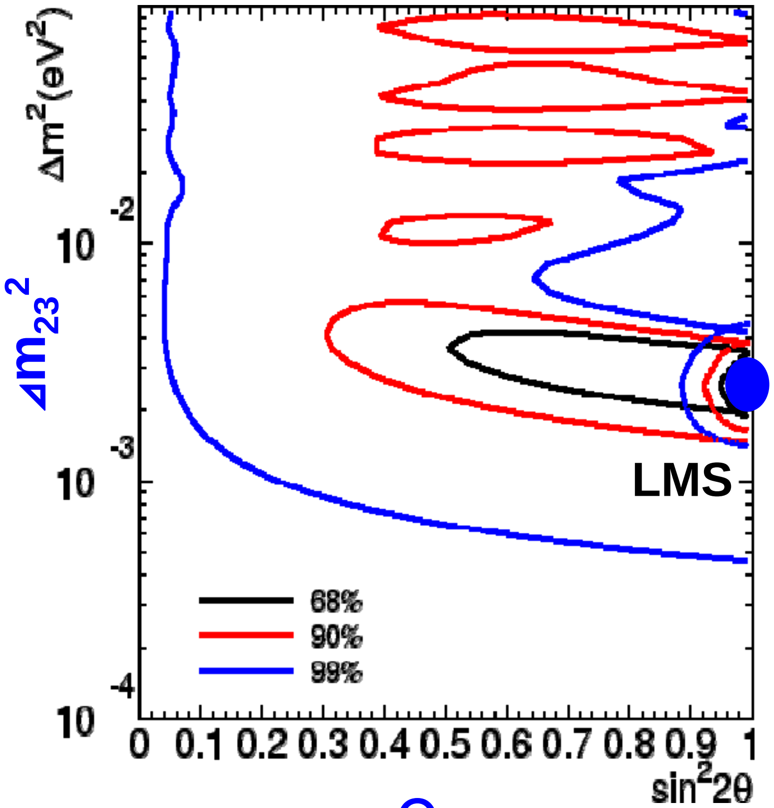
Δm_{12}^2



Θ_{12}

Super Kamiokande (atmospheric ν) determined Δm_{23}^2 and θ_{23} uniquely.

Δm_{23}^2



Θ_{23}

"UNKNOWN" Neutrino-Oscillation Parameters:
$\sin^2 2\theta_{13} < 0.1$, $|\Delta m_{13}^2| = 2.4\times10^{-3}$ eV^2, δ_{CP} = CP violation phase?

We propose a new method to determine θ_{13} and Δm_{13}^2 using the MSW-effect on SN ν-process nucleosynthesis.

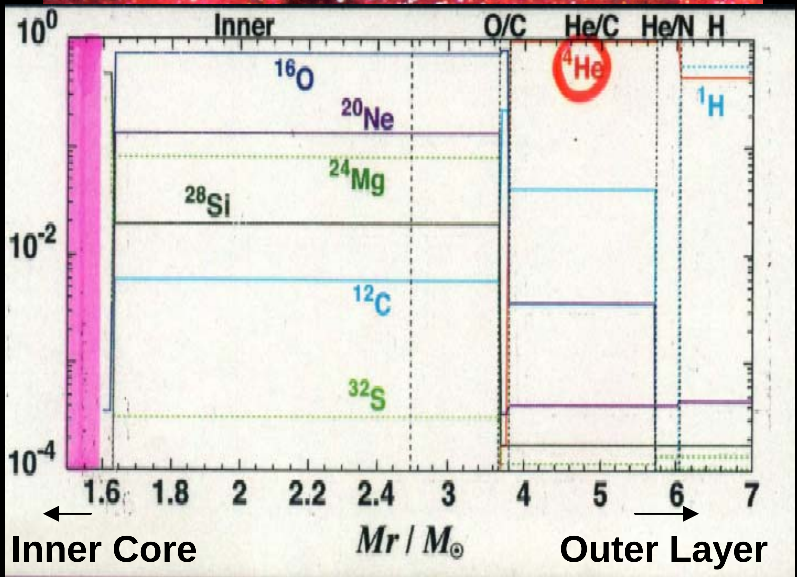
MSW: Wolfenstein 1978, PR D17, 2369; Mikheyev & Smirnov 1986, Sov. J. Nucl. Phys. 42, 913.

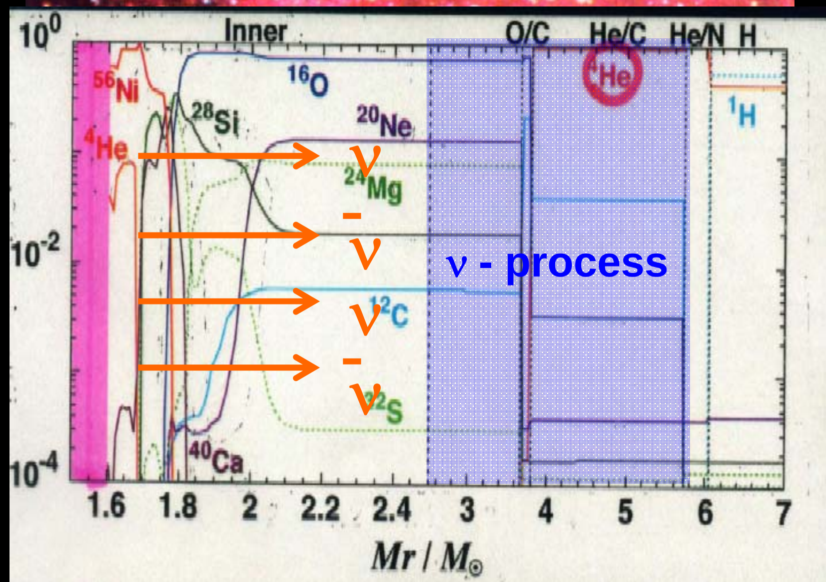
"KEY"

Energy Hierarchy due to neutron-rich SN matter !

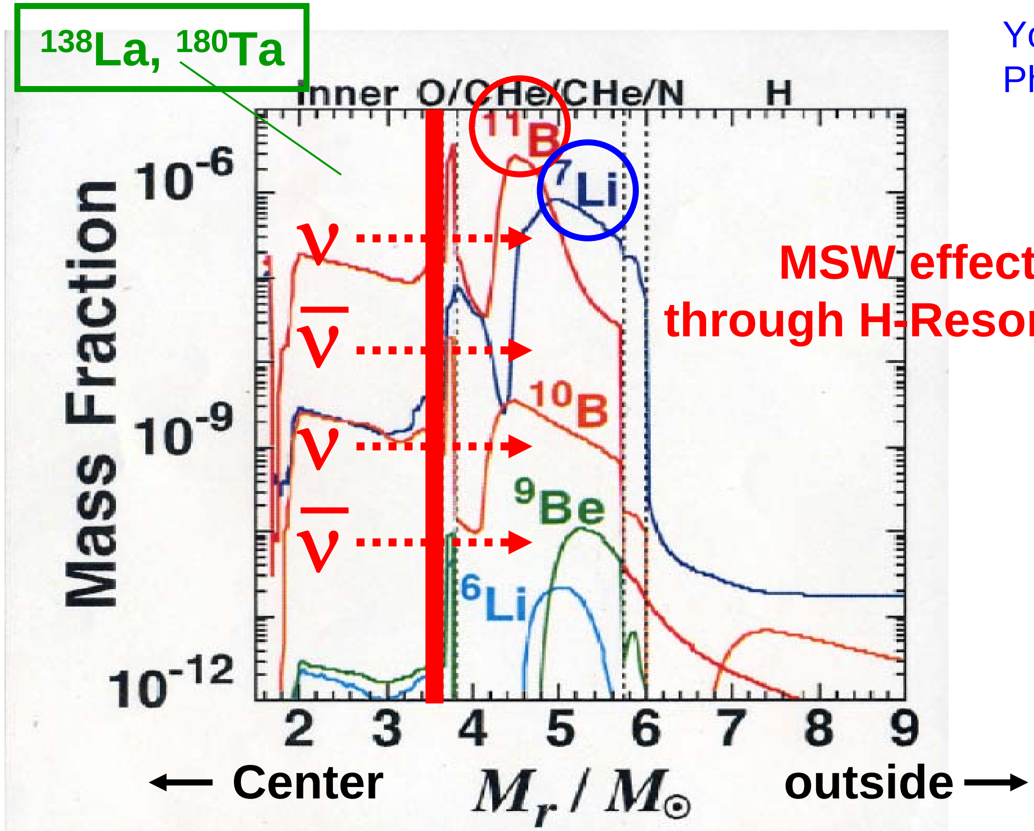
$$E_{\nu e} \le E_{\bar{\nu} e} \le E_{\nu\mu}\ \overline{\nu\mu\tau}$$

3.2 MeV   4.0 MeV   6.0 MeV



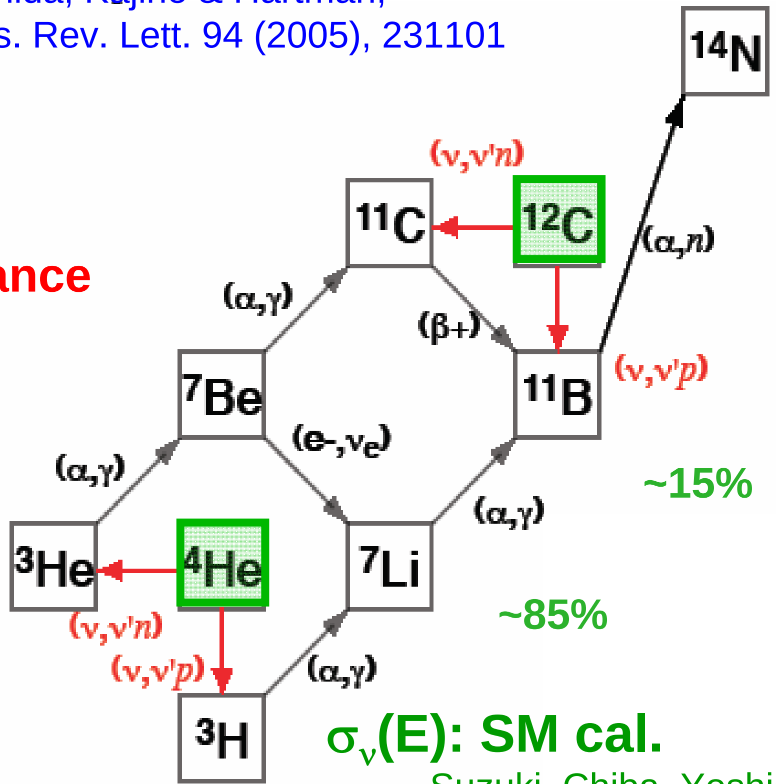


X-process operates in Supernova ν-Process !



MSW effect
through H-Resonance

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



$\sigma_\nu(E)$: SM cal.

Suzuki, Chiba, Yoshida,
Kajino & Otsuka,
PR C74 (2006), 034307

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

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

Additional Charged Current Int.

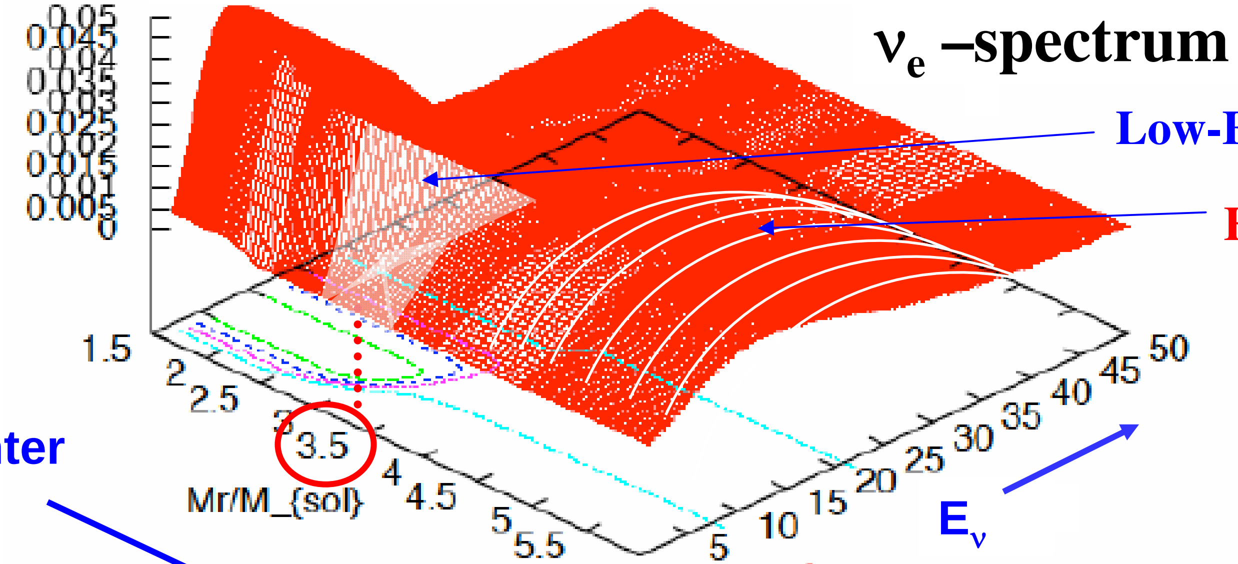
$\nu_{\mu\tau}(\bar{\nu}_{\mu\tau}) \longrightarrow \nu_e\ (\bar{\nu}_e)$

energetic

$^{4}\mathrm{He}(\nu_e,e^- p)^{3}\mathrm{He}$ & $^{4}\mathrm{He}(\bar{\nu}_e,e^+ n)^{3}\mathrm{H}$

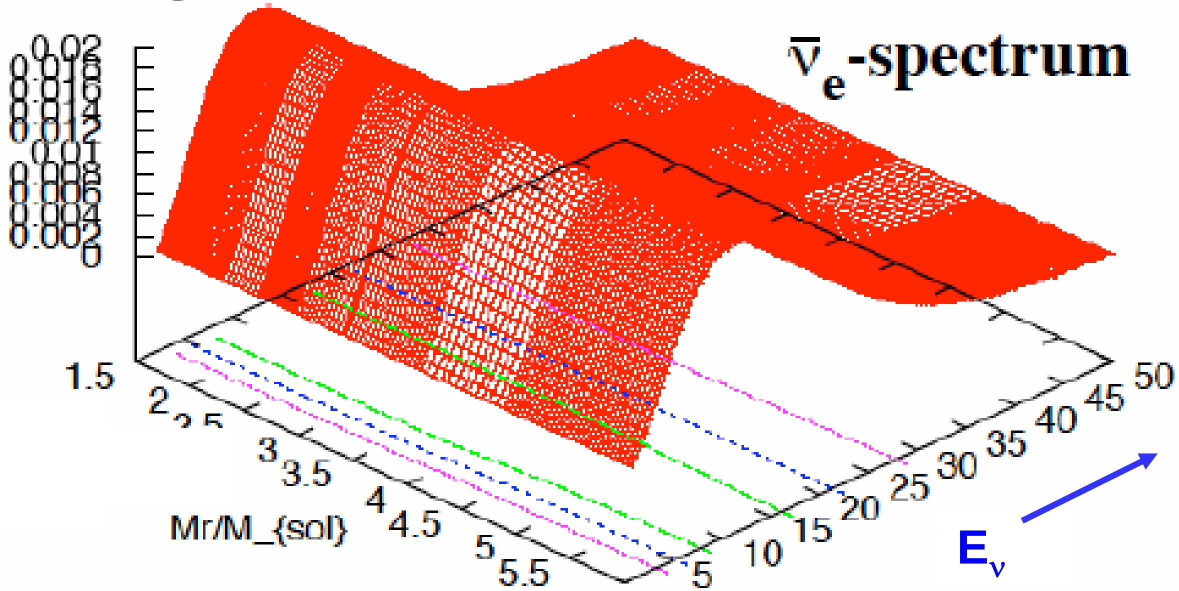
energetic energetic

Neutrino Oscillation (MSW Effect) through propagation



Center

outside

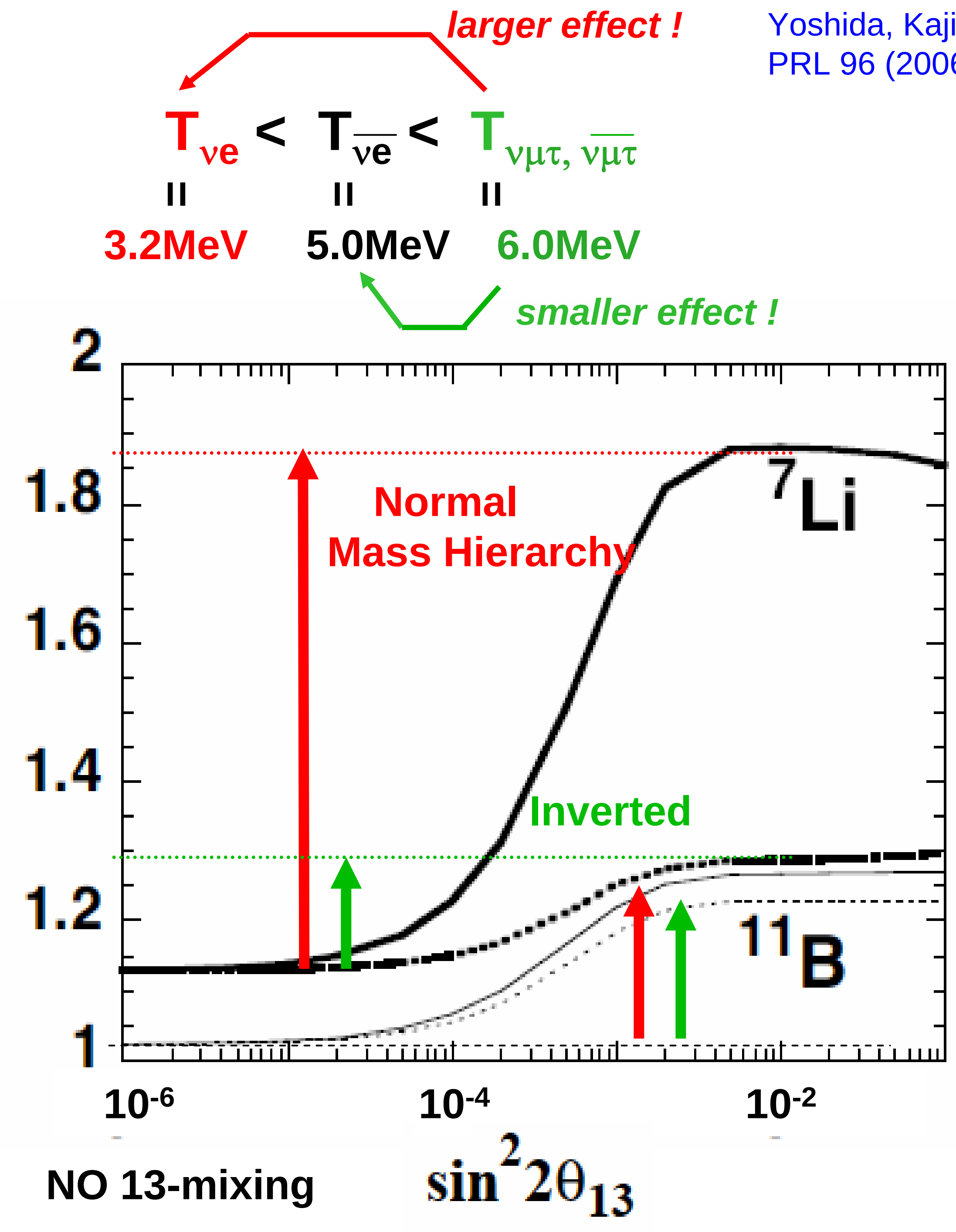


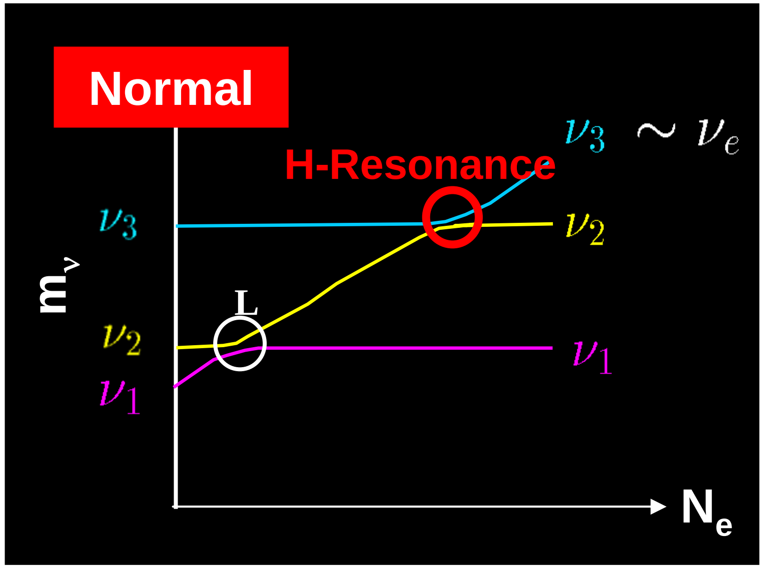
Parameters:

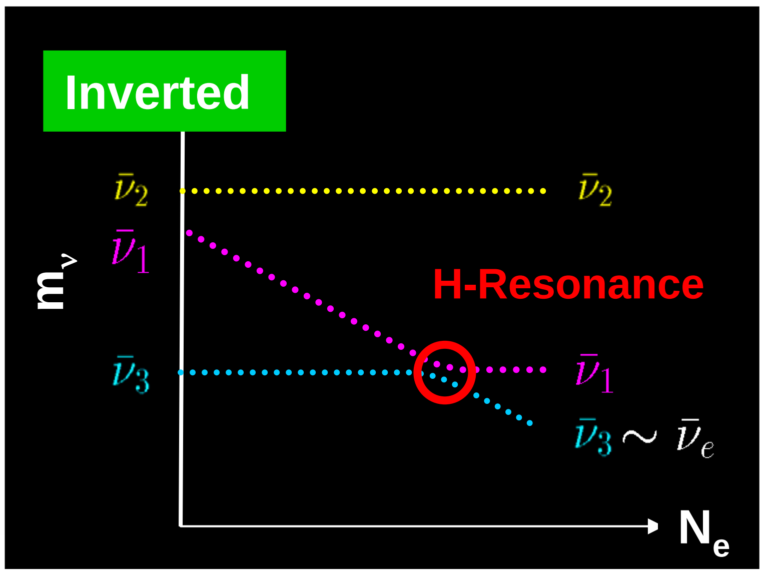
$25M_{solar}$ progenitor SN model
(Hashimoto & Nomoto 1999)

- $\sin^2 2\theta_{13} = 0.04$
- $\Delta m_{13}^2 = 2.4\times10^{-3}\ eV^2$
- $L_\nu = 3\times10^{53}$ erg, $\tau_\nu = 3$ sec
- $T_{\nu e}$=3.2MeV, $T_{\bar{\nu} e}$=5.0MeV, $T_{\nu\mu\tau}$=6.0MeV

Yoshida, Kajino, Yokomakura, Kimura,Takamura & Hartmann,
PRL 96 (2006) 09110; ApJ 649 (2006), 349.



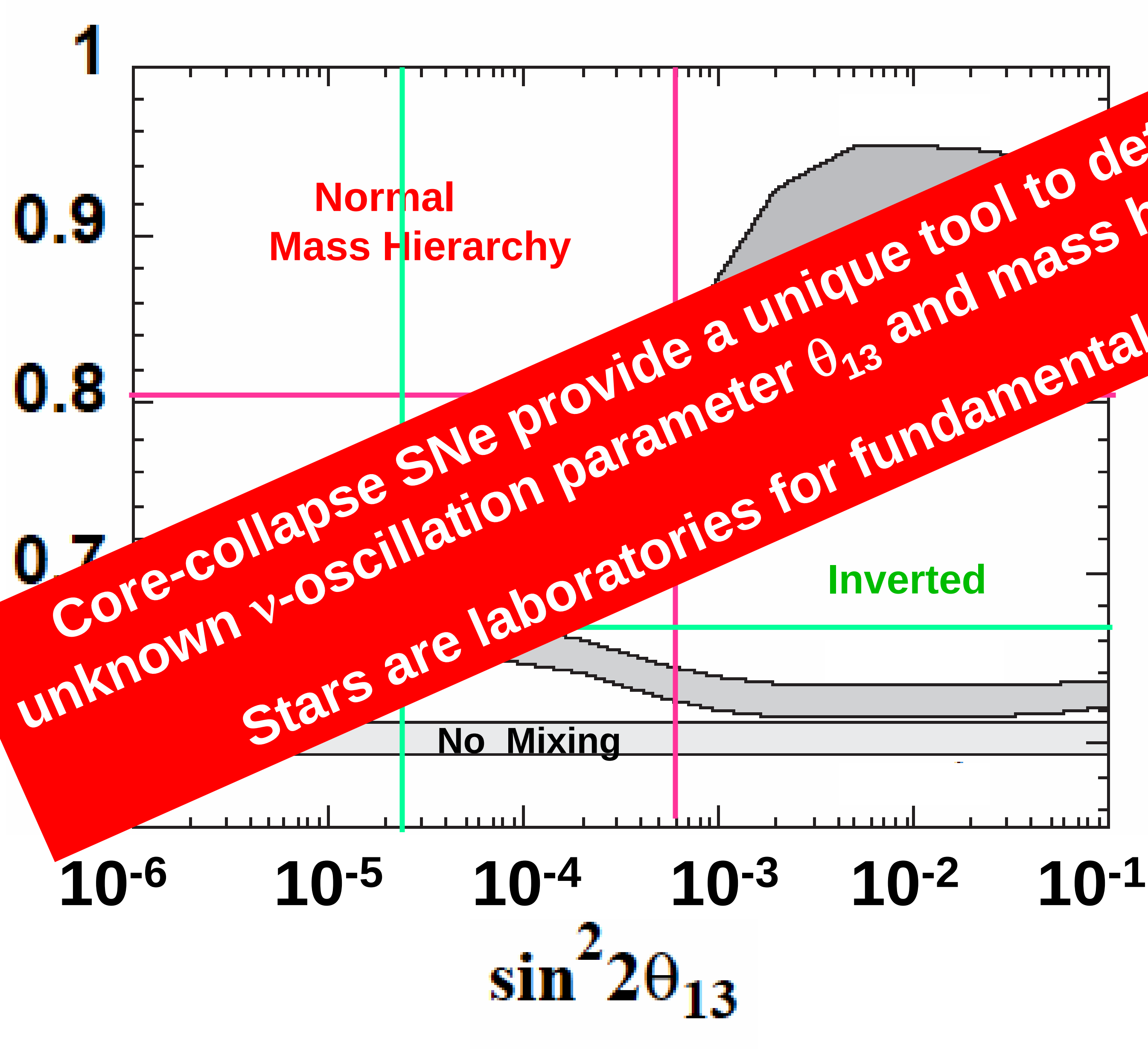




$^7Li/^{11}B$ - Ratio

Yoshida, Kajino, Yokomakura, Kimura,Takamura & Hartmann,
PRL 96 (2006) 09110; ApJ 649 (2006), 349.

Suzuki, Chiba, Yoshida, Kajino & Otsuka,
PR C74 (20…



Core-collapse SNe provide a unique tool to determine the unknown ν-oscillation parameter θ_{13} and mass hierarchy Δm_{13}.

Stars are laboratories for fundamental physics!

…-Mixing Angle
θ_{13}

Long Baseline Exp:

T2K (Kamioka)

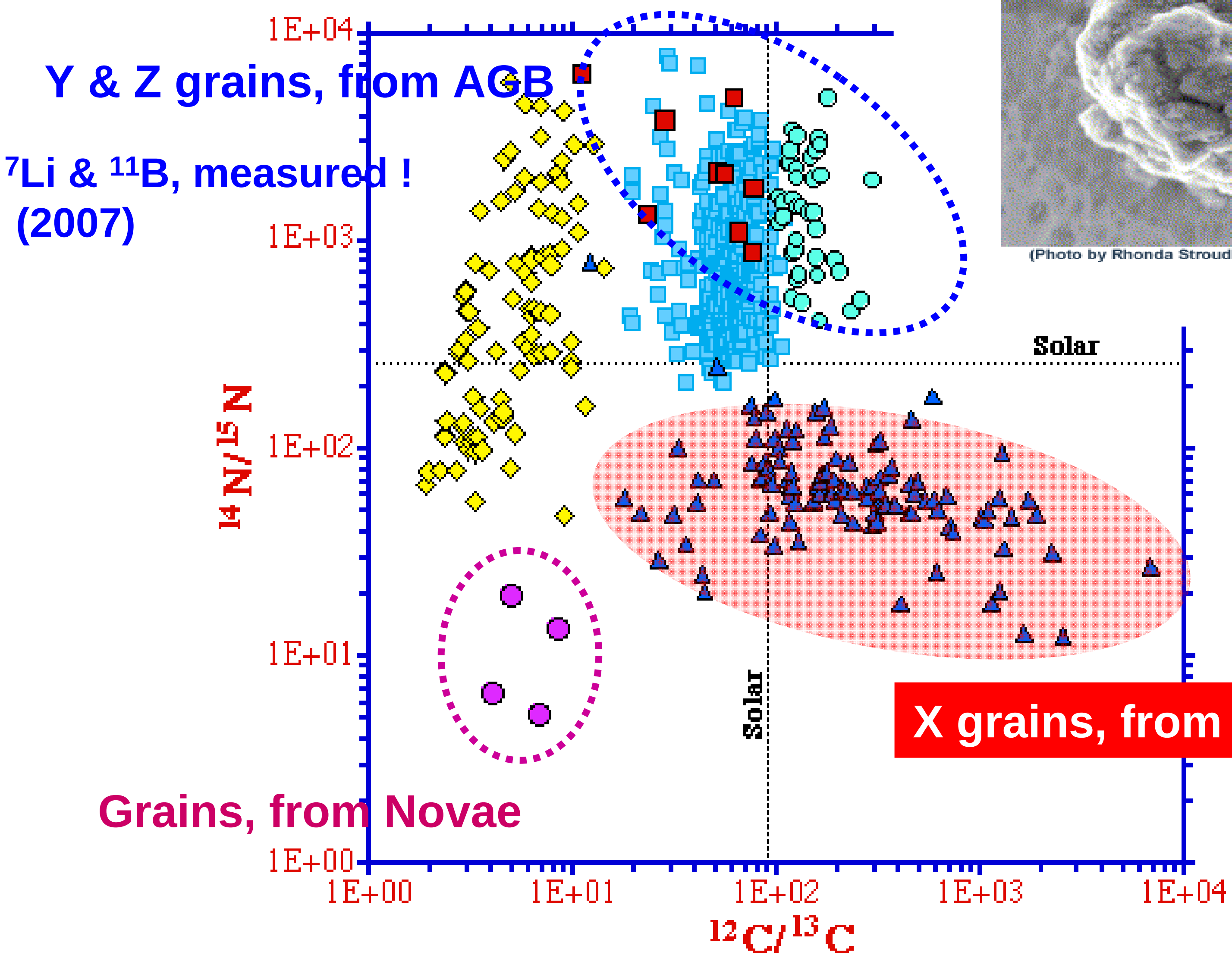
T2KK (KOREA)

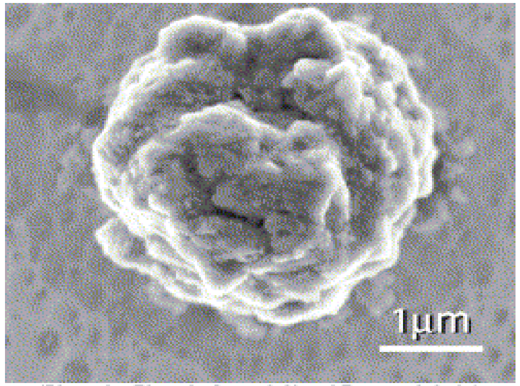
Double CHOOZ

Daya Bay

How to observe the $^{7}Li/^{11}B$ ratio ?

(1) Presolar SiC Grain





(Photo by Rhonda Stroud, Naval Research Lab.)

(2) SPECTROSCOPIC OBSERBATION

^{11}B absorption line ~ 2497 A (Space Telescope like HST)

$^{11}B/^{10}B$, observed in MPH Stars!

Rebull et al. ApJ 507 (1998) 387; Proc. (2000)

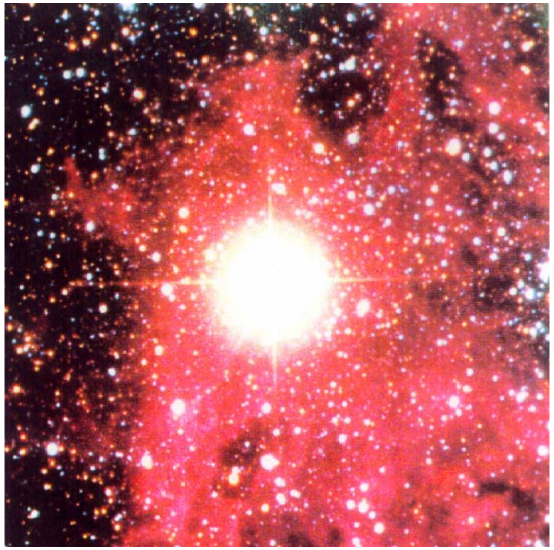
^{7}Li absorption line ~ 6708 A (Ground Base Telescope like SUBARU)

^{7}Li & $^{7}Li/^{6}Li$, observed in MPH Stars, but BBN-comp. dominates!

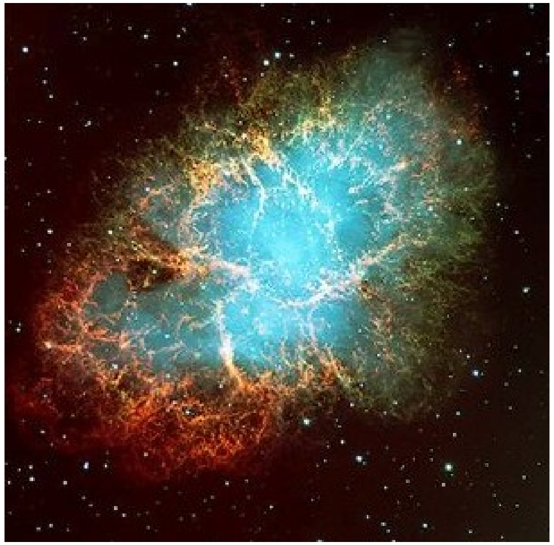
LMXB for both ^{7}Li & ^{11}B !

Many observations (1982 – present)

SN1987A Remnant



Crab Nebula

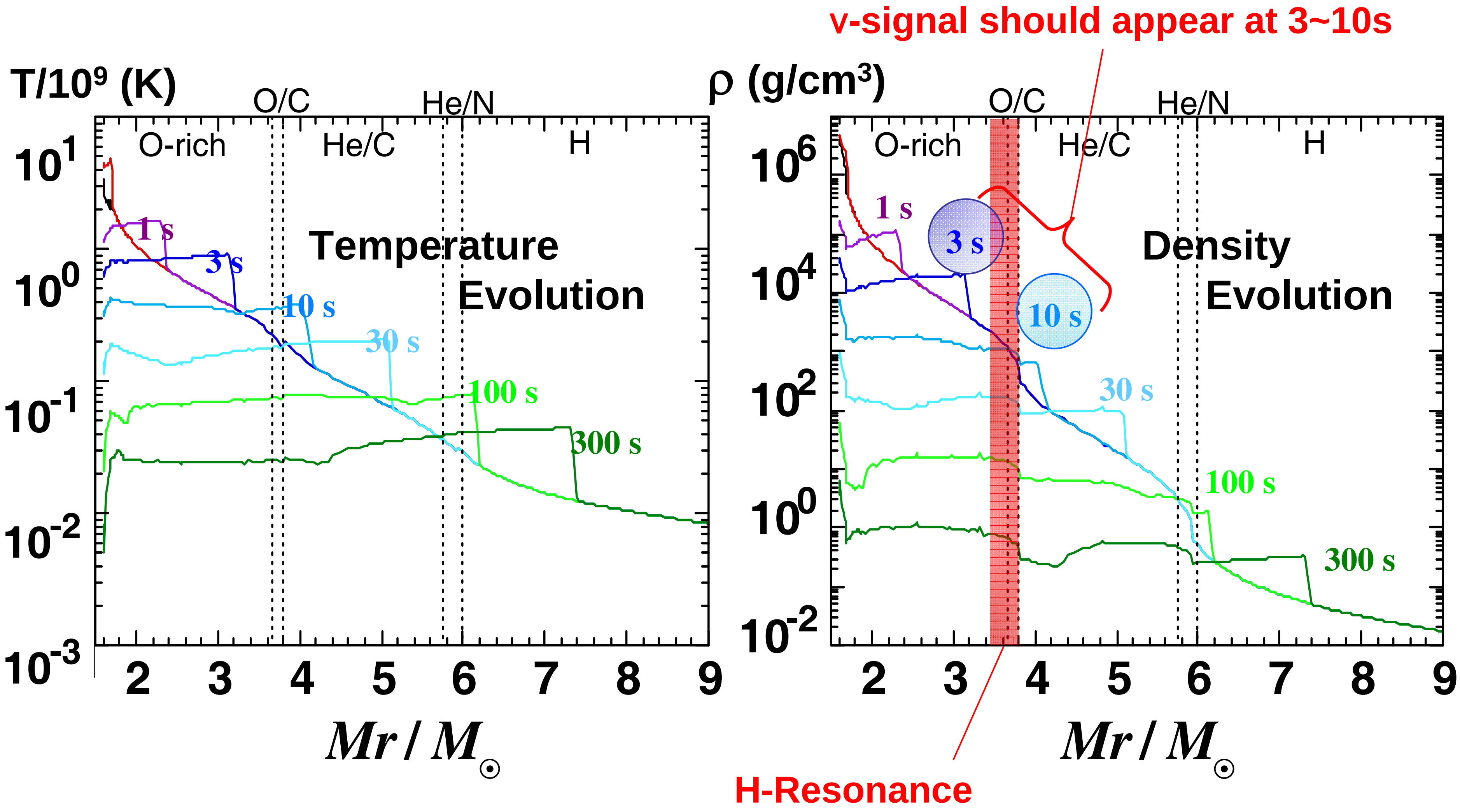


R-element enhanced Metal-Poor Halo Stars

Neutrino Signal in 16.2 $M_\odot$ - SN Model

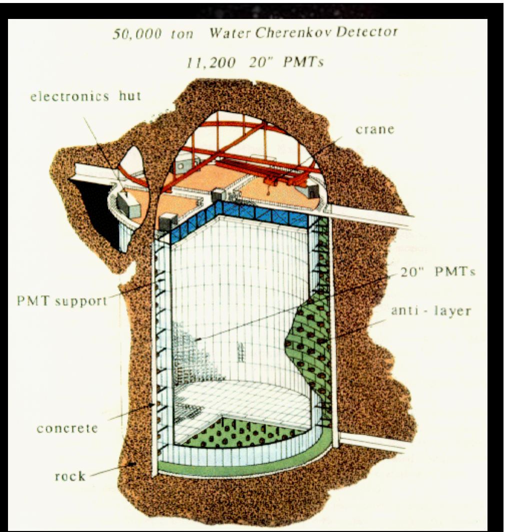
Shock Propagation Effect

Kawagoe, Kajino, Sumiyoshi, Suzuki, & Yamada (2007)



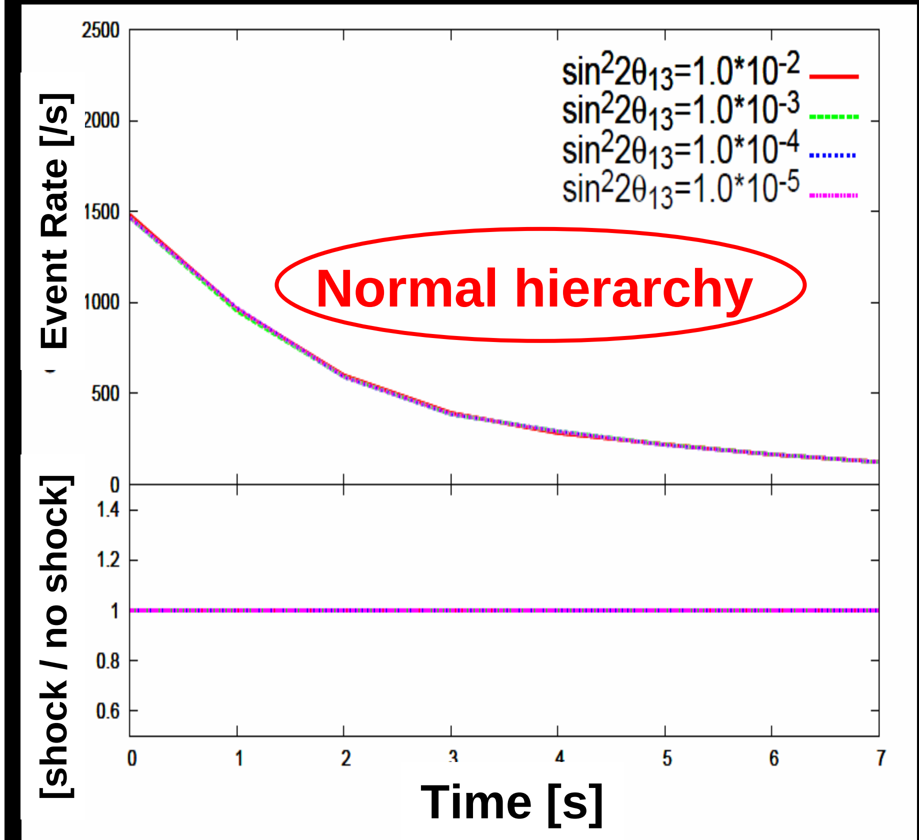
Event Rate in Super-Kamiokande

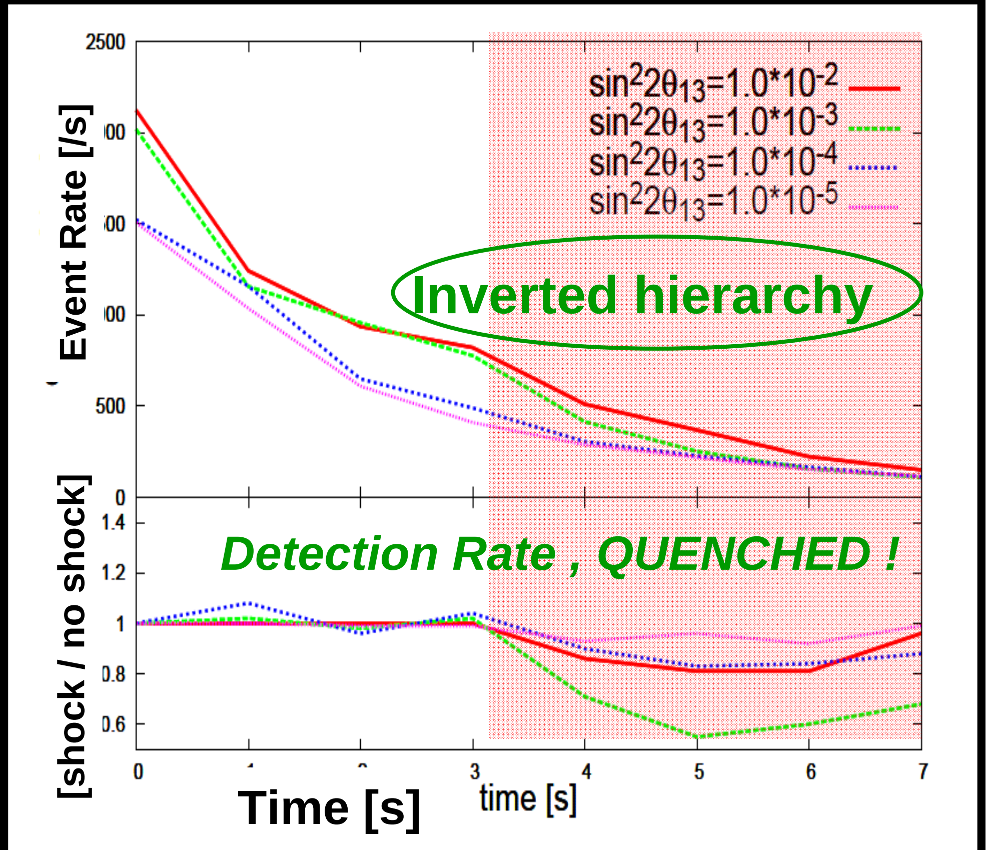
Kawagoe, Kajino, Sumyoshi, Suzuki & Yamada (2007)



☆target : pure water (32,000 t)

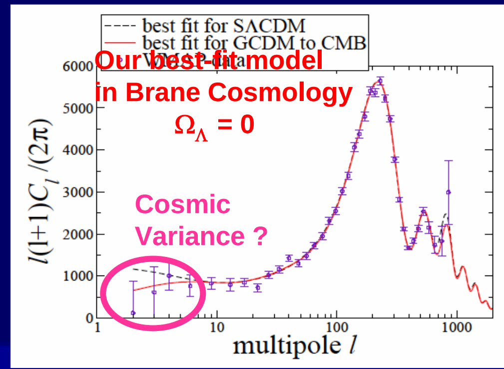
☆ $\bar{\nu}_e + p \rightarrow n + e^+$



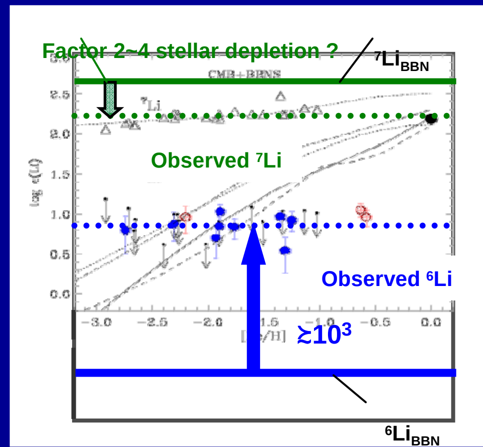


Summary

1 . Big-Bang Nucleosynthesis provides "critical test" for particle & nuclear theories and observational cosmology.

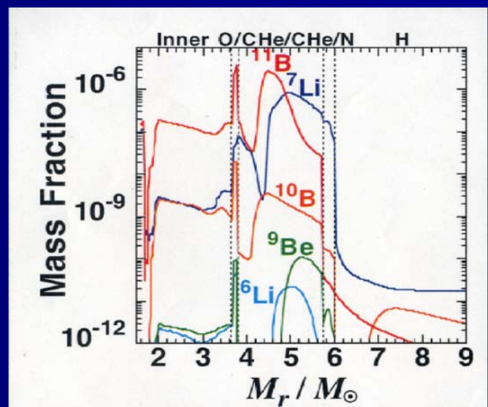


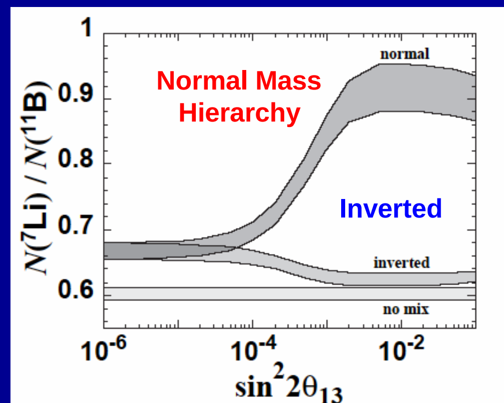
1a: Brane World Cosmology with mass-energy exchange between brane and bulk can describe accelarating cosmic expansion with $\Omega_\Lambda = 0$!



1b: Relic X- particle model (progenitor of CDM), if they are bound in normal nuclei or radiative decay to non-thermal photons, can solve both ^{6}Li and ^{7}Li problems.

2 The core-collapse SN ν-process provides a unique tool to determine the unknown ν-oscillation parameter θ_{13} and mass hierarchy Δm_{13} of active ν's in terms of ν-matter effect (MSW) in nucleosynthesis.





Theoretical Uncertainties ?

(1) Neutrino Energy Spectrum, well known?

Fermi-Dirac distr. of T_ν

How to determine T_ν ? ← from "SN1987A obs." & "GCE"

Yoshida, T., Kajino, T., & Hartmann, D. H., PRL 94 (2005), 231101

(2) Neutrino-Nucleus Cross Section $\sigma_\nu(E)$, well known?

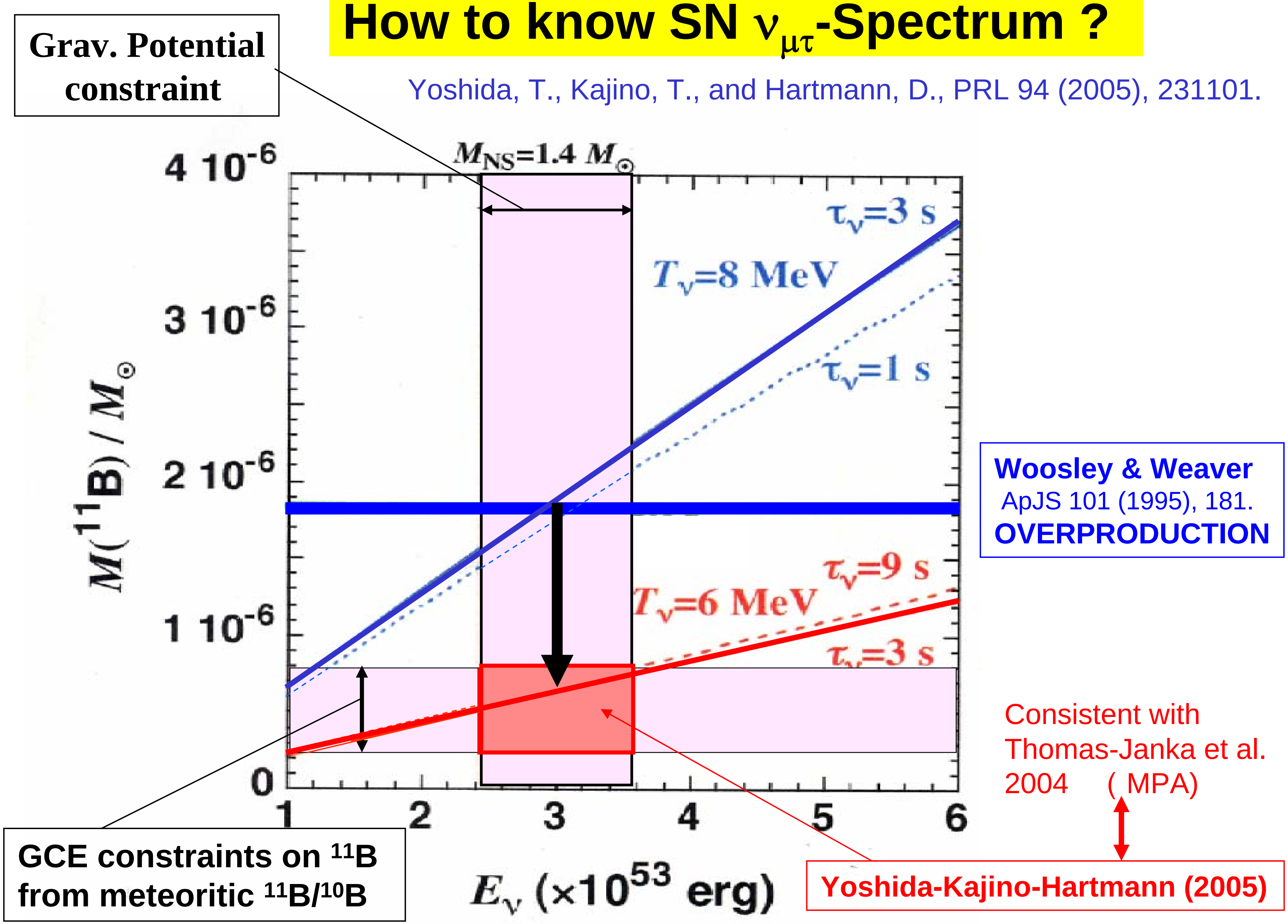
Previous SM cal. by W. Haxton (1990)

Precise SM cal. using better interactions, done (2006) !

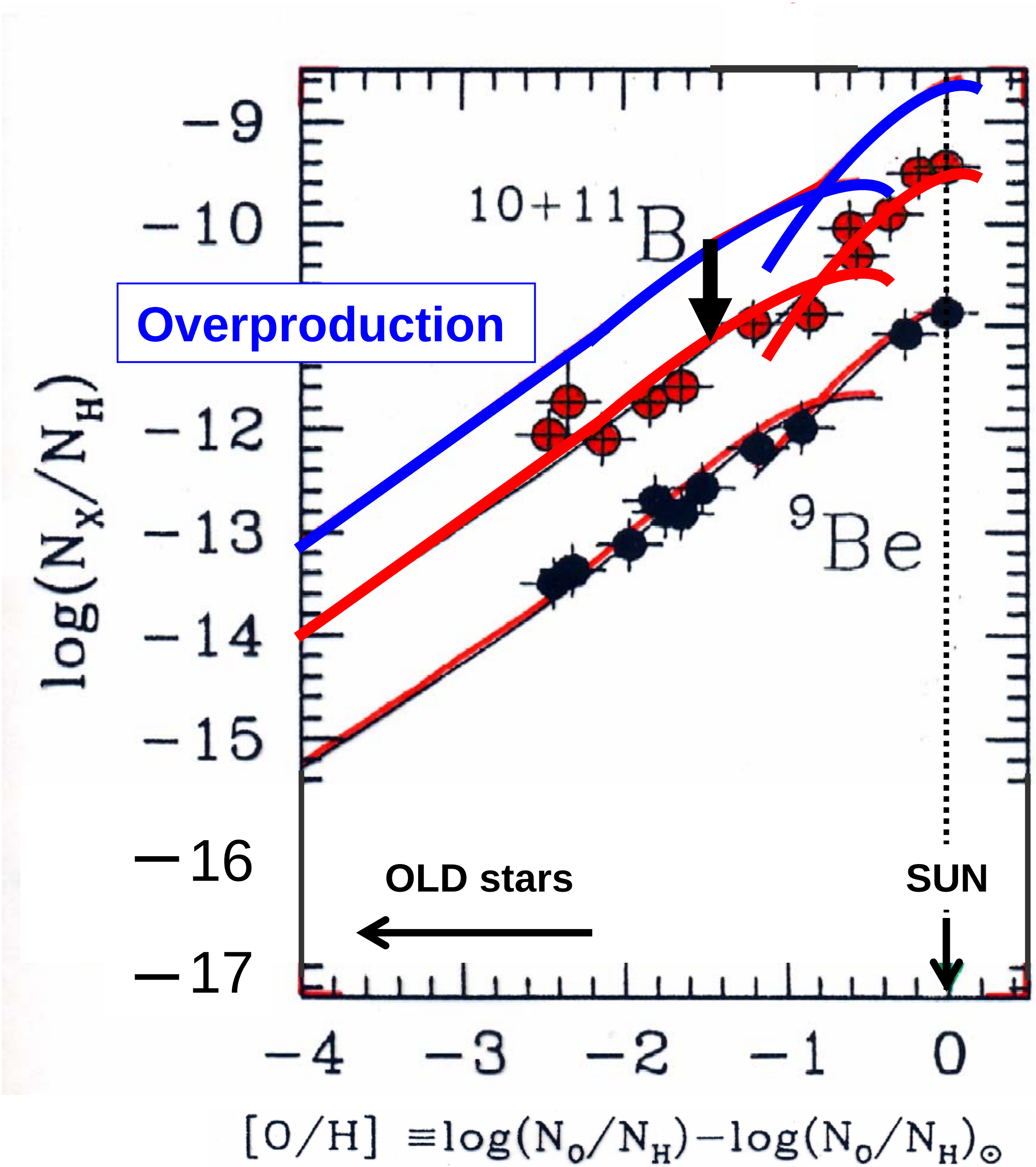
Suzuki, Chiba, Yoshida, Kajino & Otsuka, PR C74 (2006), 034307.

How to know SN $\nu_{\mu\tau}$-Spectrum ?

Yoshida, T., Kajino, T., and Hartmann, D., PRL 94 (2005), 231101.



Galactic Chemical Evolution of ^{9}Be & $^{10,11}B$



Livermore Model
Woosley and Weaver
ApJS 101 (1995) 181.
$T_{\nu_{\mu,\tau}}$ = 8 MeV

$T_{\nu_{\mu,\tau}}$ = 6 MeV

Yoshida, Kajino & Hartmann, PRL 94 (2005), 231101.

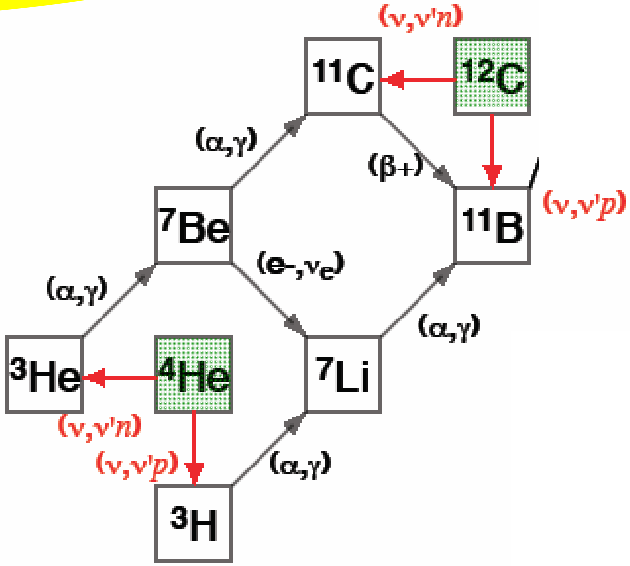
- **^{11}B has two origins:**

  Supernova ν–process
  Galactic Cosmic Rays

(GCR)

- **^{9}Be has pure GCR.**
- **$^{11}B >> ^{10}B$**

Theoretical Uncertainty?



Haxton's SM cal. (Woosley et al. ApJ. 356 (1990), 272)

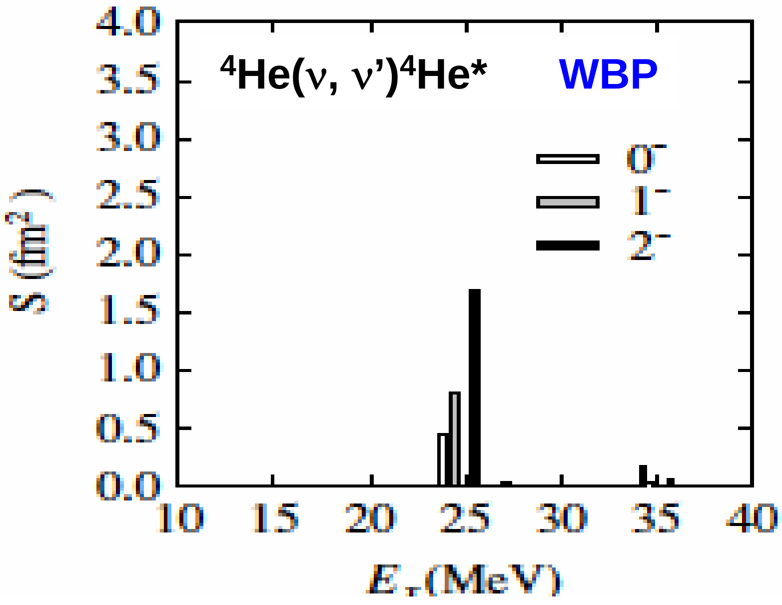
Suzuki's new SM cal. With new Hamiltonian

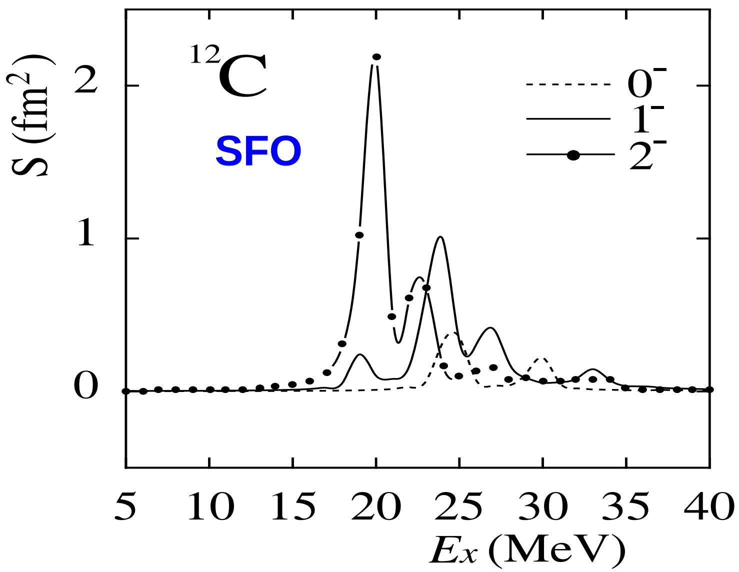
Suzuki, Chiba, Yoshida, Kajino & Otsuka, PR C74 (2006), 034307

^{4}He: WBP (Warburton-Brown) Hamiltonian = Similar to microscopic ab initio cal. of Gazit et al. PRC70 (2004) 048801

^{12}C: SFO Hamiltonian = Spin-isospin flip int. with enhanced $op_{1/2}$-$op_{3/2}$ separation from Cohen-Kurath

- μ-moments of p-shell nuclei
- GT strength for $^{12}C \to {}^{12}N$, $^{14}C \to {}^{14}N$, etc.
- proper tensor int.

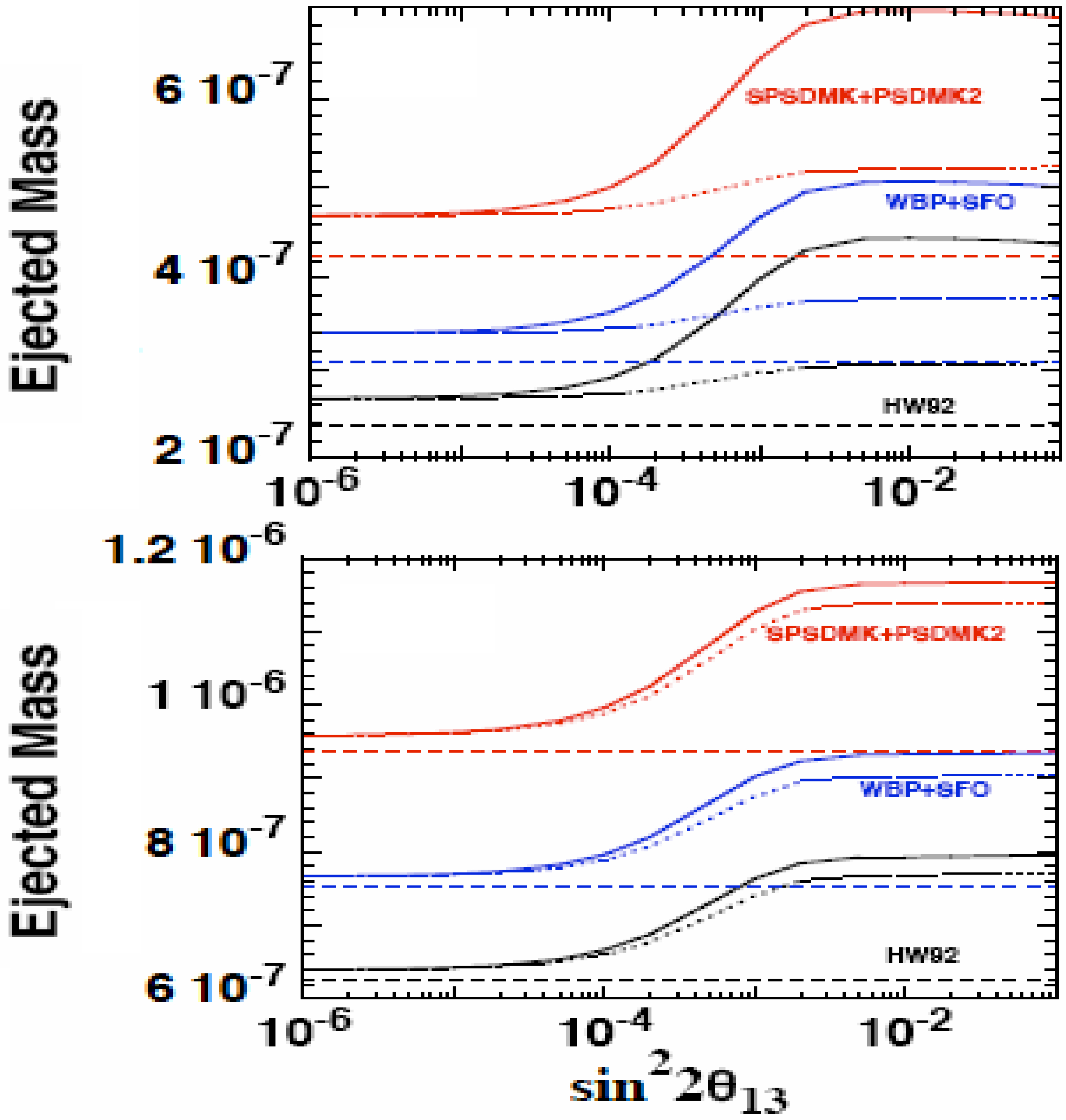




Neutrino Oscillation Matter (MSW) Effect

^7Li

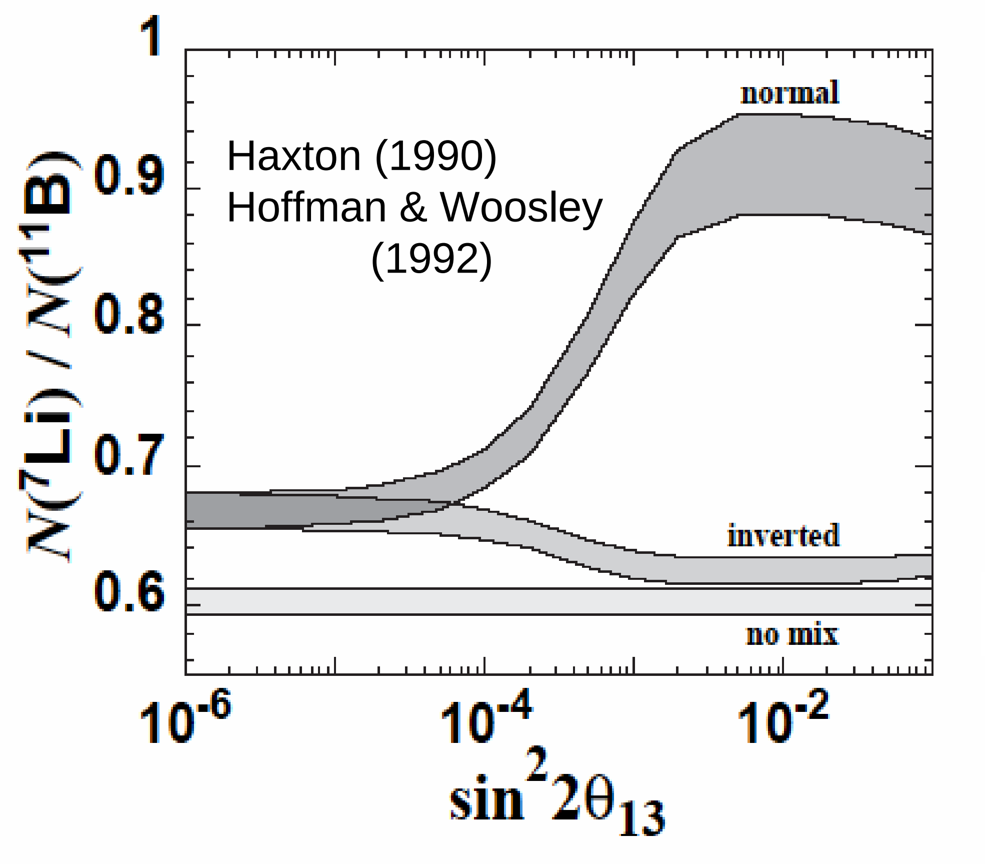
^{11}B



Neutrino Oscillation Effect on $^{7}Li/^{11}B$-ratio

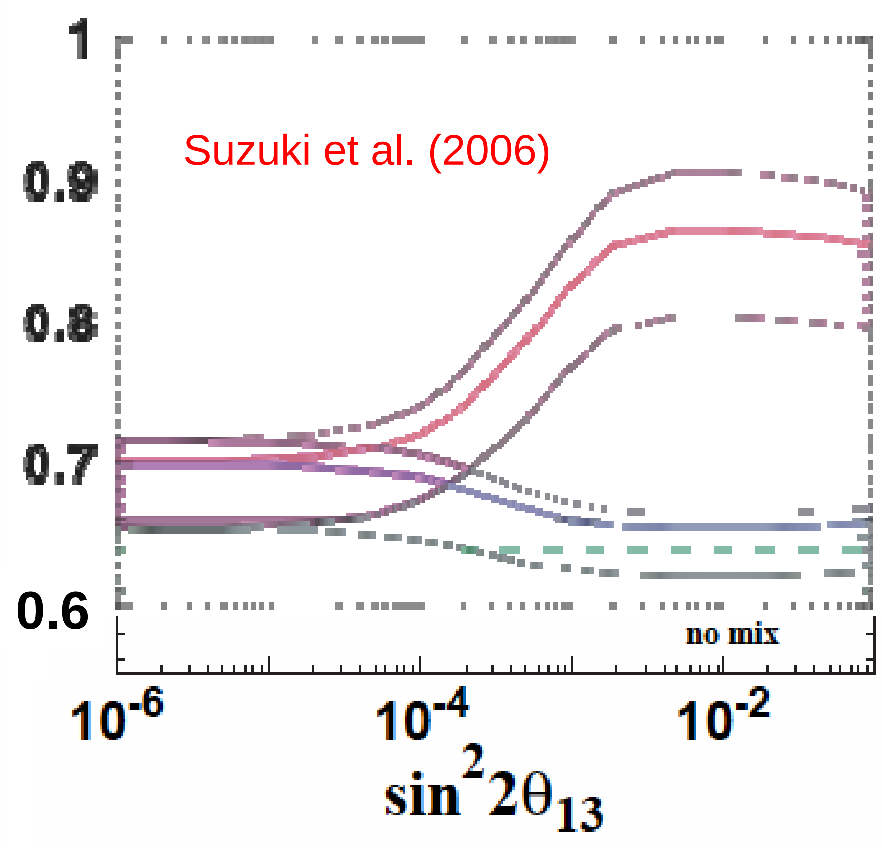
Previous SM-σ_ν(E) of Haxton

Woosley, Haxton, Hoffmann, Wilson, ApJ. (1990).
Hoffmann & Woosley, ApJ. (1992).



New SM-σ_ν(E) using WBP(^{4}He) & SFO(^{12}C) interactions

Suzuki, Chiba, Yoshida, Kajino & Otsuka, Phys. Review C74 (2006), 034307.

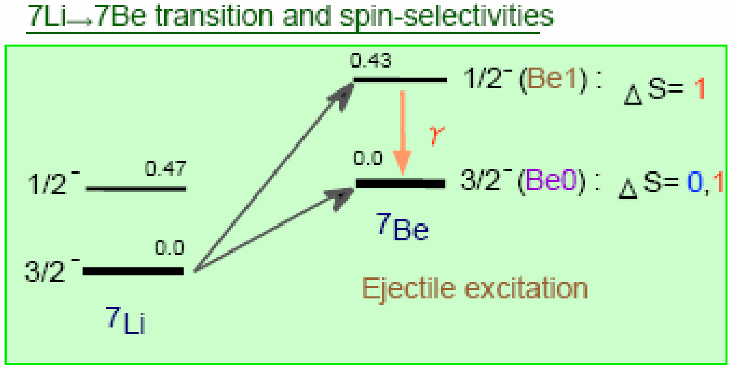


Almost the same result ! → $^{7}Li/^{11}B$-ratio is SM independent !

From S. Nakayama (Tokushima University)

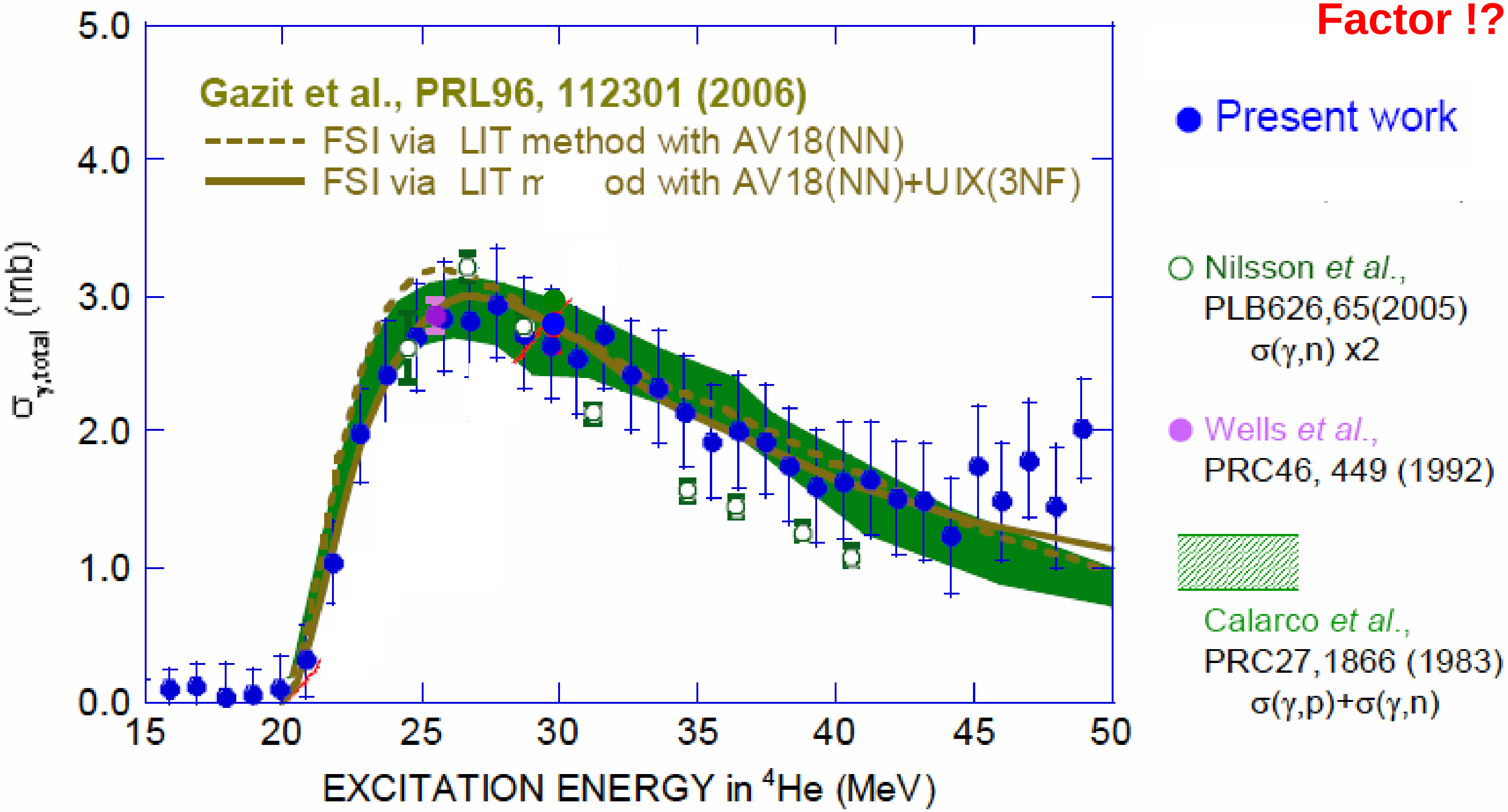
Charge Exchange (^{7}Li,^{7}Be) Reactions

⊿S=0 spectrum & σ_γ for ^{4}He(γ,n)



$$\sigma_{E1}(E_\gamma, 0^+ \to 1^-) = 4.0K_\tau \times E_\gamma \frac{d^2\sigma}{dEd\Omega}(\Delta S = 0, \Delta L = 1)\,,\quad K_\tau = 0.033$$

Renormalization Factor !?



Similarity between Electro-Magnetic & Weak Interactions

EM-current = $\vec{V}$, Weak-current = $\vec{V}$ - $\vec{A}$

$$\vec{V} \approx g_V^{IV} \frac{i}{2m} \vec{\sigma} \times \vec{q} + \frac{g_V}{2m} (\vec{p} + \vec{p}\,')$$

$$\vec{A} \approx g_A \vec{\sigma}$$

Weak operator in non-relativistic limit

Gamow-Tellar operator = $\vec{\sigma}\,\tau_{\pm}$

Spin-Dipole operator = $[\vec{\sigma} \times \vec{r}\,]^J \tau_{\pm}$

We still don't have the ν-beam !

However, we can use Electro-Magnetic PROBE:

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

⟶ $^4He(\nu, \nu')$, $^4He(\nu_e, e^-)$, $^4He(\bar{\nu}_e, e^+)$

Charge Exchange Reactions ⟶ B(GT)

Y. Fujita
足立竜也

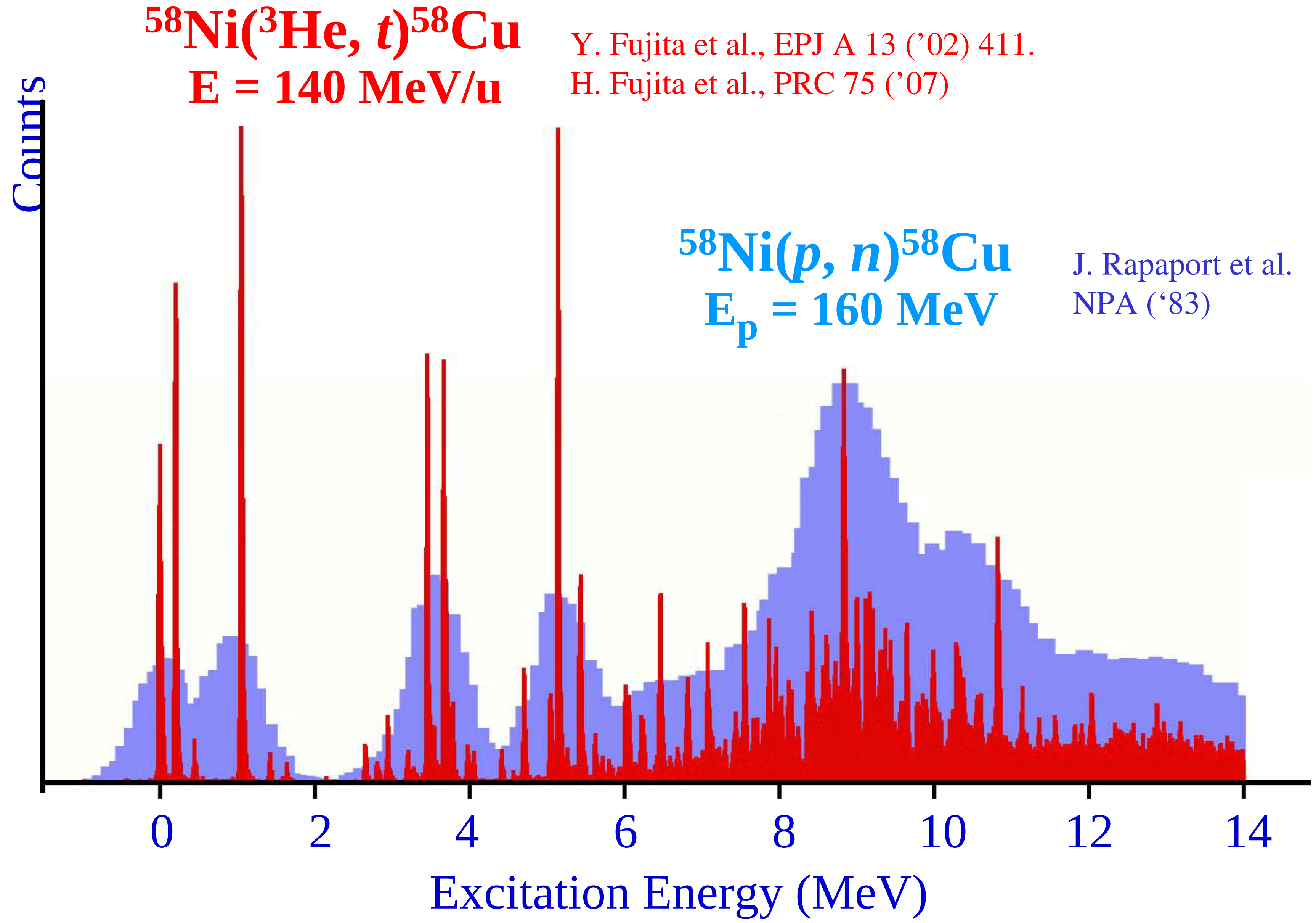
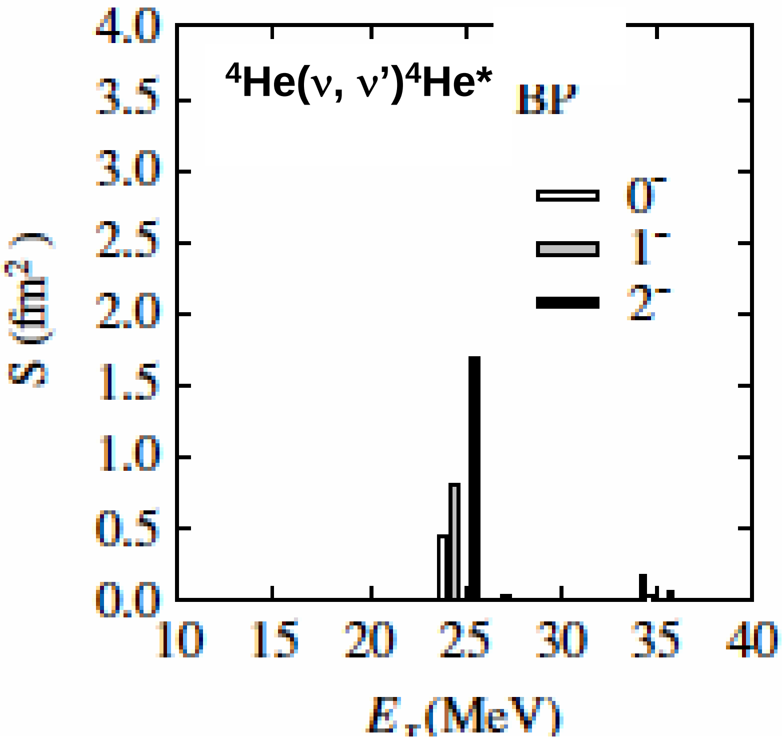


Photo-induced Reaction

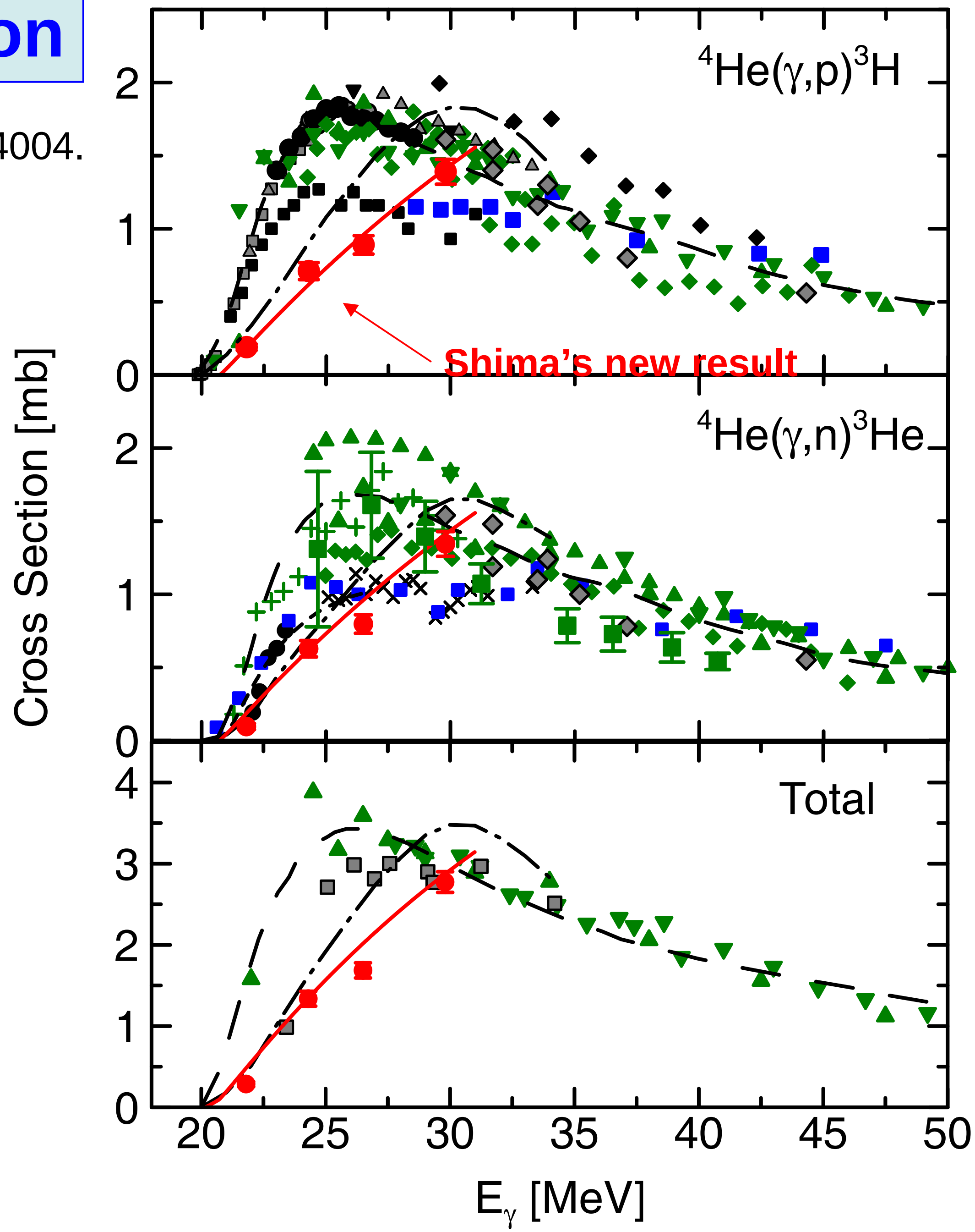
Shima et al. Phys. Rev. C72 (2005) 044004.

Experiment using real-γ !

→ **Absolute Yields !**



Suzuki et al. Phys. Rev. C74 (2006) 034307.

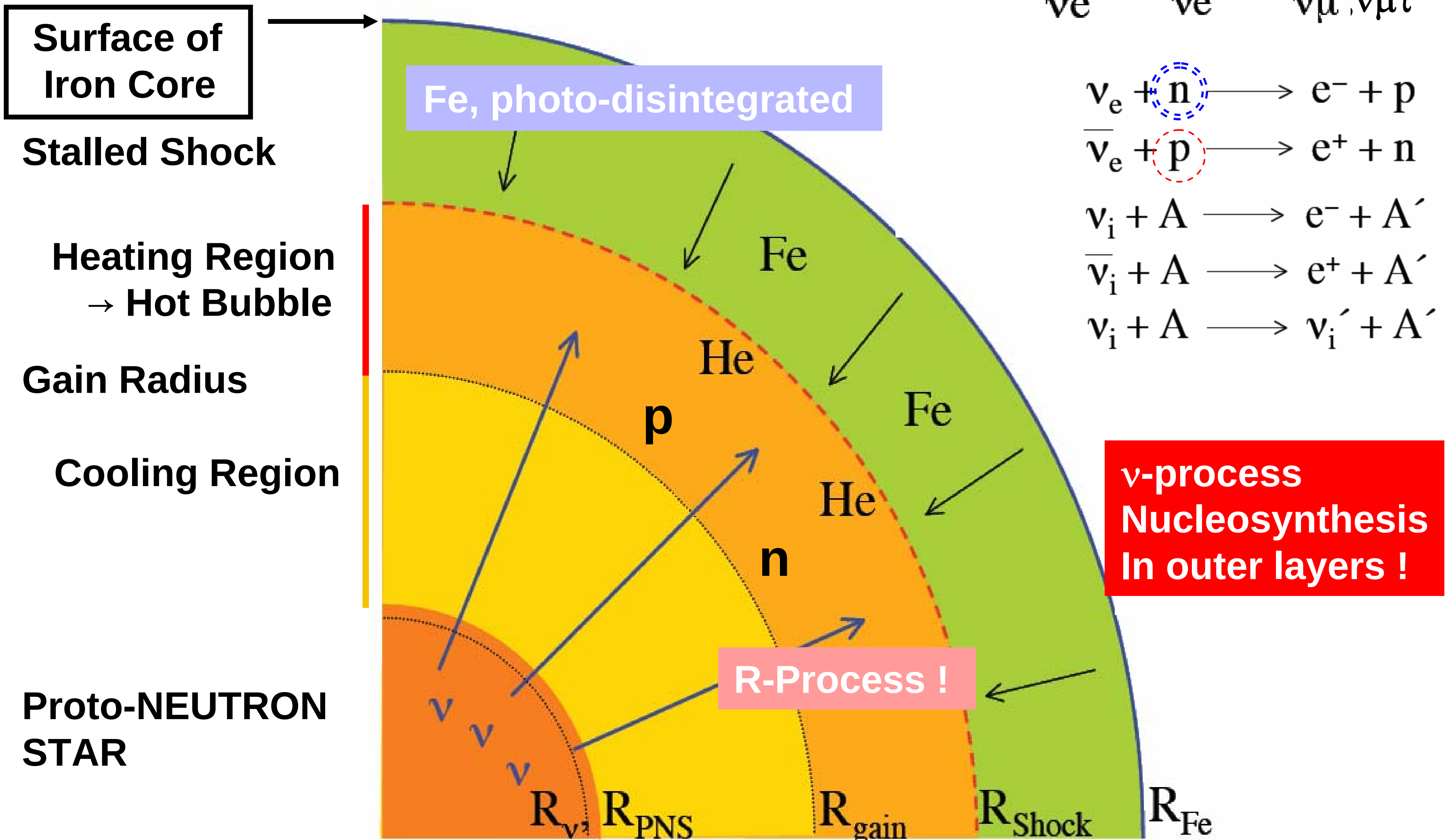


Core-Collapse, ν-Heating, Nucleosynthesis

Energy Hierarchy due to neutron-rich matter !

$$E_{\nu e} \le E_{\bar{\nu} e} \le E_{\nu\mu,\overline{\nu\mu\tau}}$$

$$\nu_e + n \longrightarrow e^- + p$$
$$\bar{\nu}_e + p \longrightarrow e^+ + n$$
$$\nu_i + A \longrightarrow e^- + A'$$
$$\bar{\nu}_i + A \longrightarrow e^+ + A'$$
$$\nu_i + A \longrightarrow \nu_i' + A'$$



ν–A int. help explosion ?
ν–ν int. & oscillation ?

~ 10km ~20—100km ~1000km