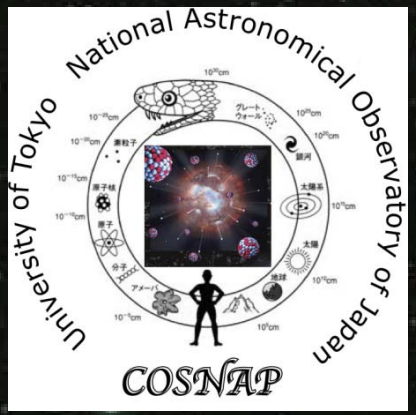
Meeting on “Unification of Particle Physics, Nuclear Physics and Astrophysics”, Ise-Shima, December 3-5, 2011

Nucleosynthesis in Supernovae and GRBs and Neutrino Oscillation

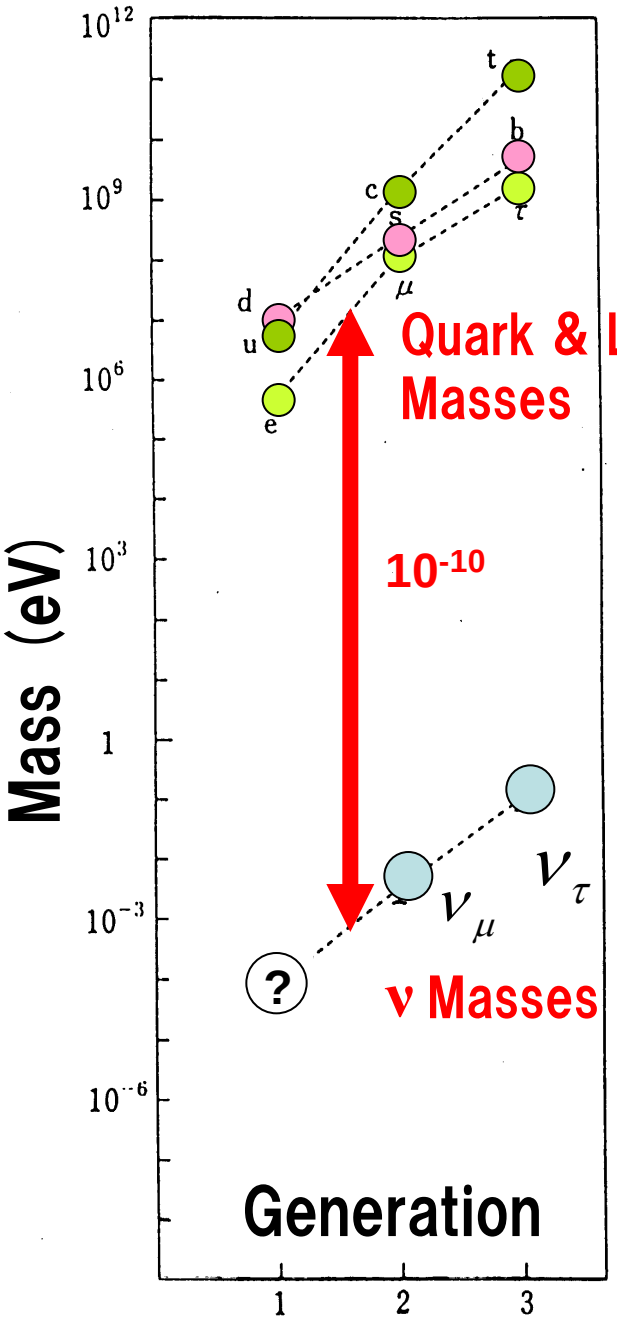
Taka KAJINO

National Astronomical Observatory (NAOJ)
Department of Astronomy, University of Tokyo (UT)



COSNAP-Collaboration

NAOJ: W. Aoki, K. Nakamura, J. Hidaka, T. Kuroda, T. Yamazaki,
Tokyo: T. Yoshida, W. Fujiya, S. Sato, K. Shaku, M. Kusakabe, T. Otsuka, K. Nomoto, H. Umeda, S. Kawagoe, N. Yasutake
JAEA: T. Hayakawa, S. Chiba, N. Iwamoto,
Nihon: T. Suzuki, T. Maruyama,
Nagoya: H. Yokomakura, K. Kimura, A. Takamura,
Visi. Profs.: K. Cheoun (Soongsil), Y. Pehlivan (Turky), G. Mathews (Notre Dame), A. Balantekin (Wisconsin), M. Famiano (W.Michigan)



Neutrino Masses / Quark & Lepton Masses $\approx$ 1 / 10,000,000,000

Why 10^{-10} ?

$E = mc^2$

This could be a signature of new physics at 10^{10} times higher energy scale than the ordinary scale.

$$\nu_i + \overline{\nu}_i \rightleftharpoons e^+ + e^- \rightleftharpoons 2\gamma\,(T)$$

Key Physics suggested by FINITE mass neutrinos:

Unification of elementary forces beyond the standard model ?

CP violation and Lepto- & Baryo-genesis ?

Why left-handed neutrinos, Majorana or Dirac ?

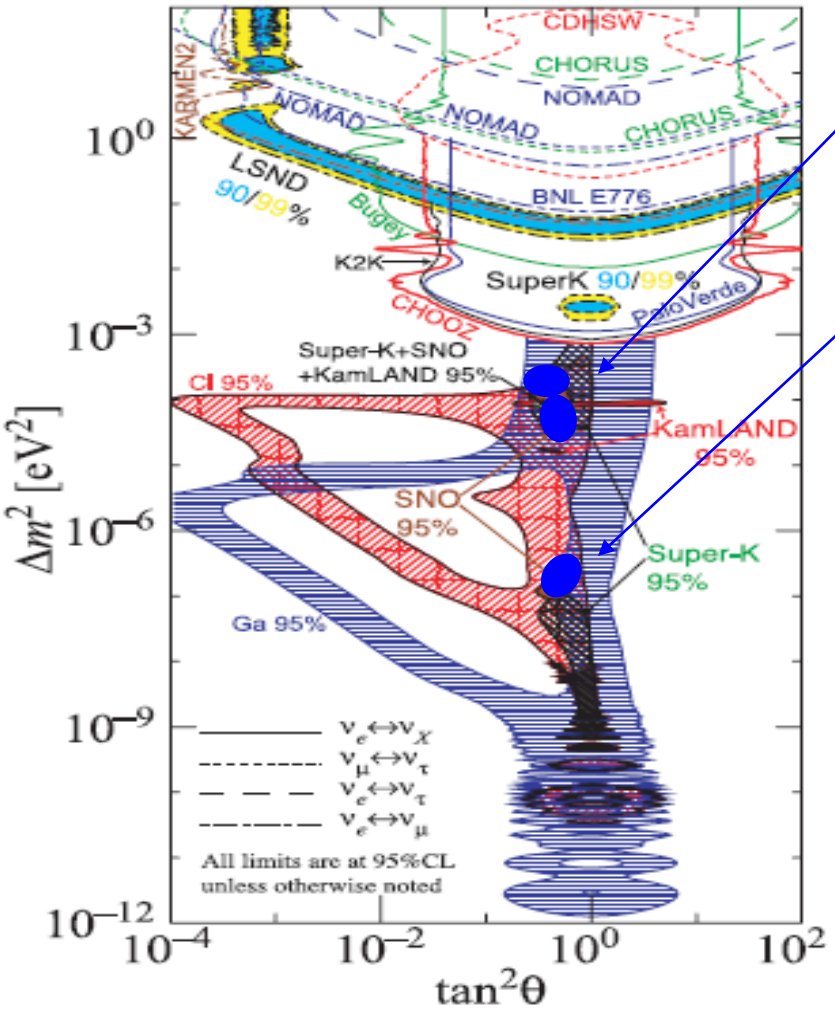
Explosion Mechanism of cc-SNe & Neutron Stars ?

Neutrino Oscillations

$|\Delta m_{23}^2|$ and θ_{23} —— SK (atmospheric ν)

Δm_{12}^2 and θ_{12} —— KAMIOKANDE, SK, KamLand (reactor ν), SNO

"KNOWN"



23—mixing

$\sin^2 2\theta_{23} = 1.0$

$|\Delta m^2_{23}| = 2.4 \times 10^{-3}$ eV^2

12—mixing Cabibbo angle

$\sin^2 2\theta_{12} = 0.816$ $(\theta_{12}+\theta_C=\pi/2)$

$\Delta m^2_{12} = 7.9 \times 10^{-5}$ eV^2

"UNKNOWN"

13—mixing

- $\sin^2 2\theta_{13}$ (< 0.1)
  T2K, June 14, 2011
- $\Delta m_{13}^2 = \pm 2.4 \times 10^{-3}$ eV^2
- ~~δ=CP-phase~~
- ~~Absolute Mass~~

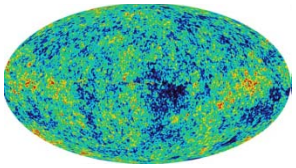
E(νμ)=E(ντ): Kobayashi-Masukawa, PTP (1973)
Yokomakura et al., PL B (1986)

Various Neutrino-Sources in Nature

1.9K | 0.4 | 1.0 | 2.6 | 8.5 Visible energy [MeV]

CMB

Cosmic Background



Neutrino Cosmology

verification of particle model

ν_e, ν_μ, ν_τ

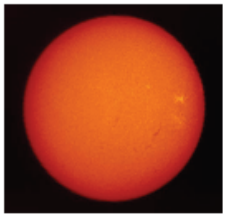
neutrino electron elastic scattering

$\nu + e^- \rightarrow \nu + e^-$

inverse beta decay

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

^{7}Be solar neutrino



Neutrino Astrophysics

verification of SSM

geo-neutrino

Neutrino Geophysics

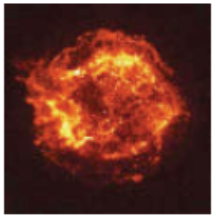
verification of earth evolution model

reactor neutrino

Neutrino Physics

Precision measurement of oscillation parameters

supernova relic neutrino etc.



Neutrino Cosmology

verification of universe evolution

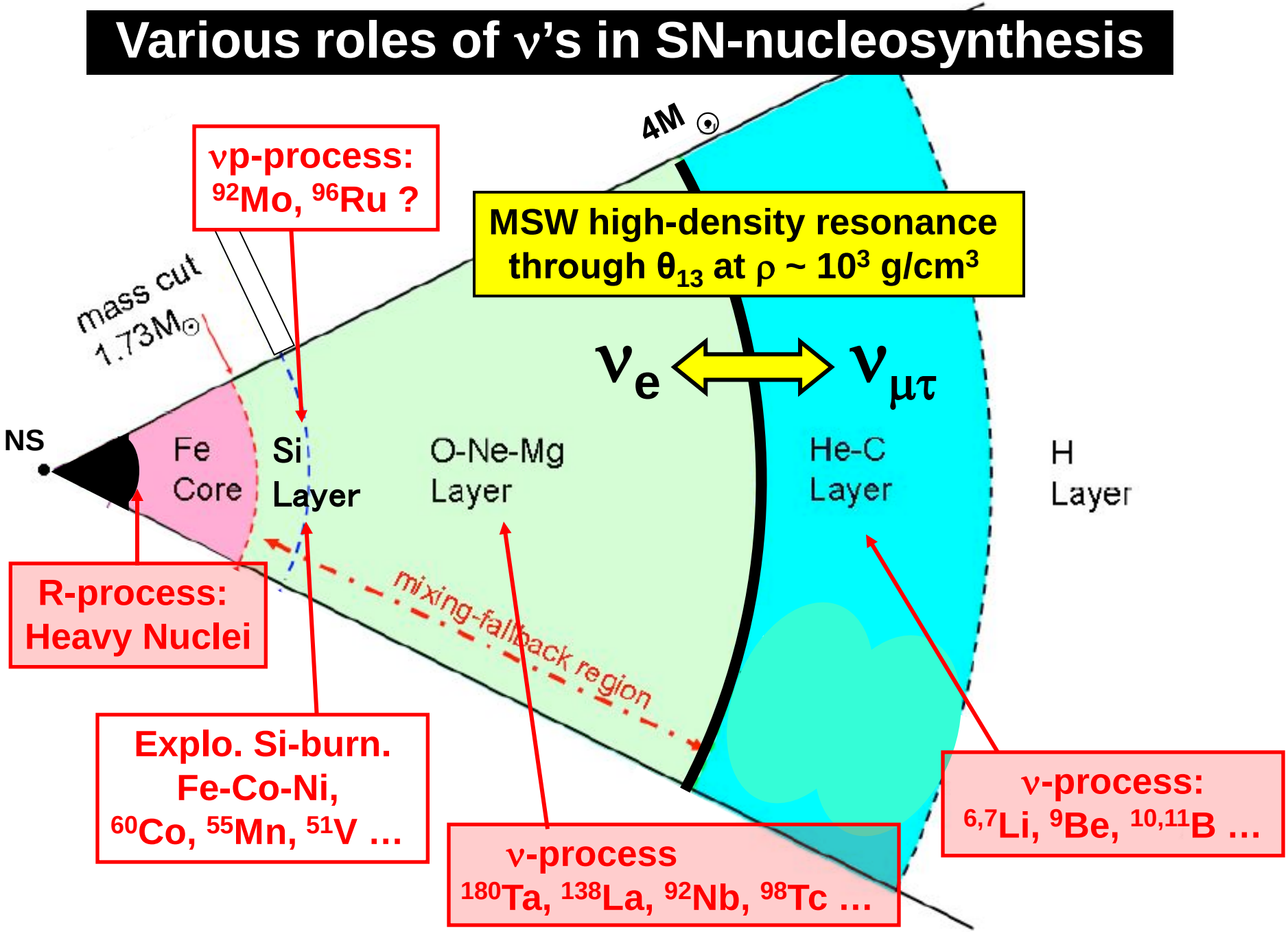
ν_e, ν_μ, ν_τ

PURPOSE

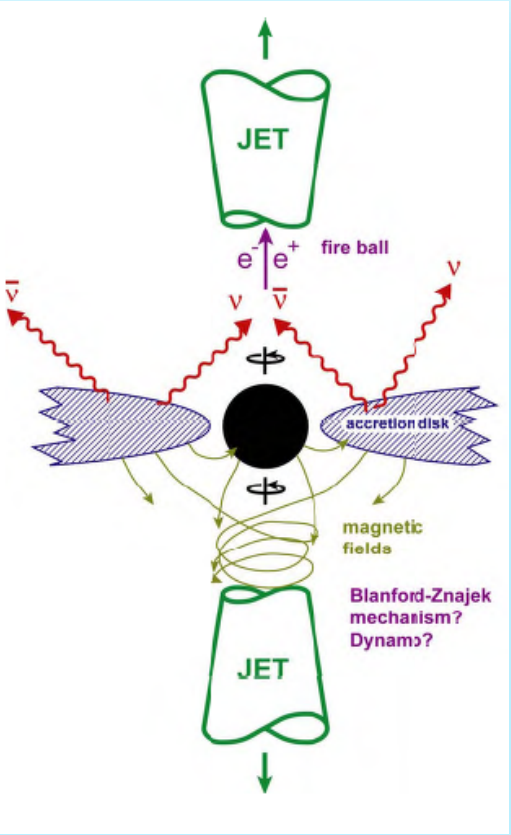
Study SUPERNOVA-ν and CMB-Anisotropies:

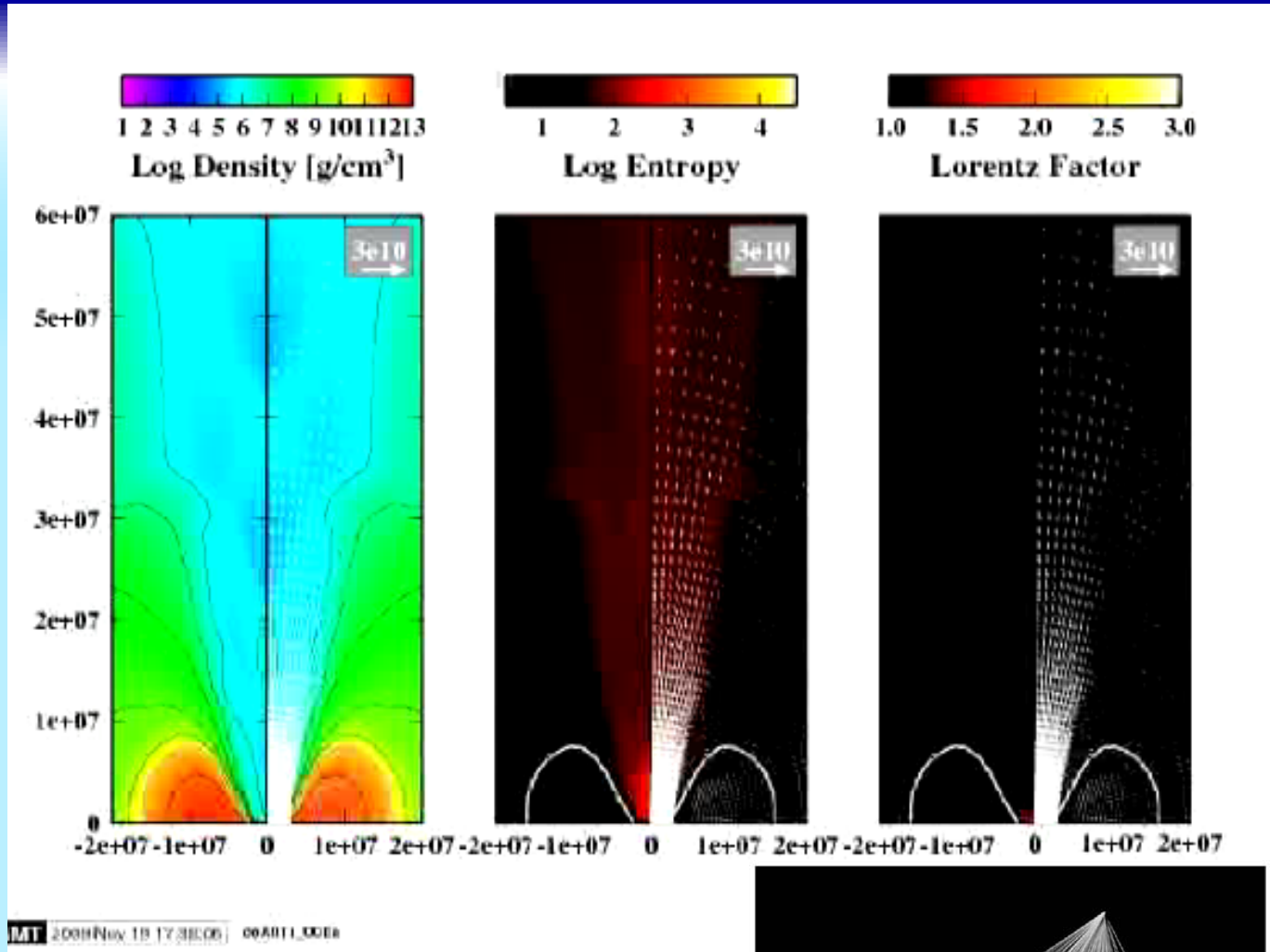
1. to constrain the ν–oscillation parameters θ_{13} and Δm_{13}^2.
2. to constrain the ν–total mass.

Various roles of ν's in SN-nucleosynthesis

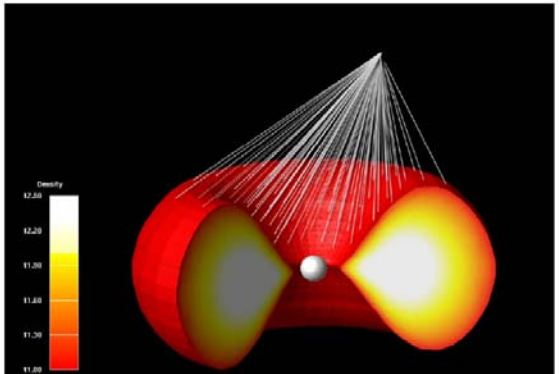


Neutrino-driven relativistic jet (Harikae + ’09, ‘10





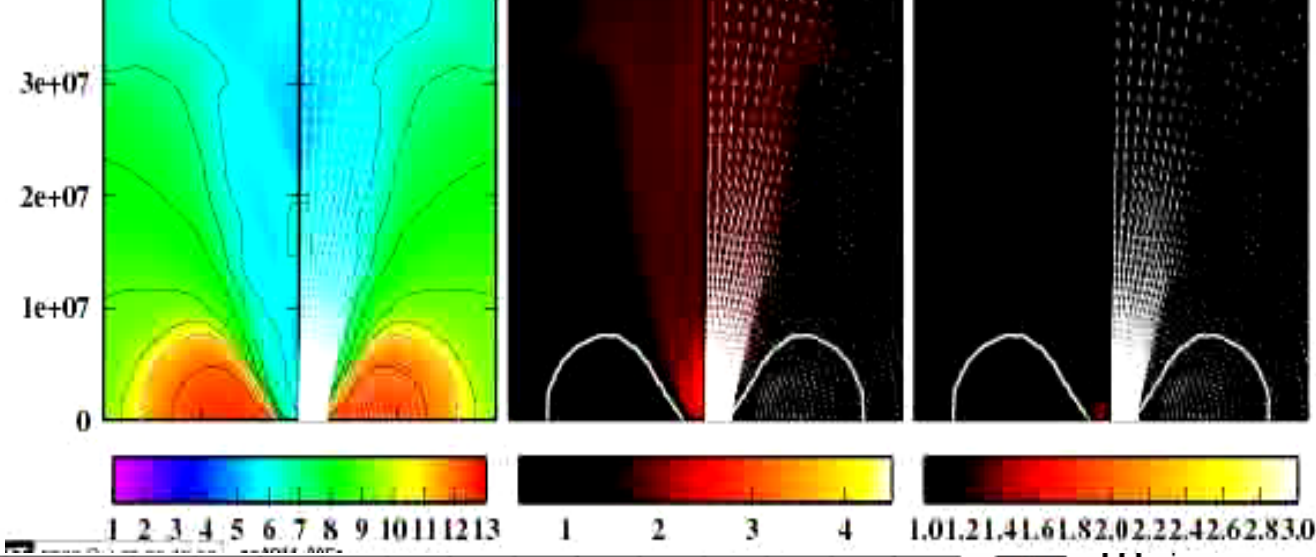
- Special relativistic MHD code (Takiwaki et al 2009)
- Neutrino heating is calculated by ray-tracing in flat timespace.
- Realistic EOS of Shen et al (1998) is implemented.
- Initial data is taken from 35OC model (Woosley&Heger 2006)

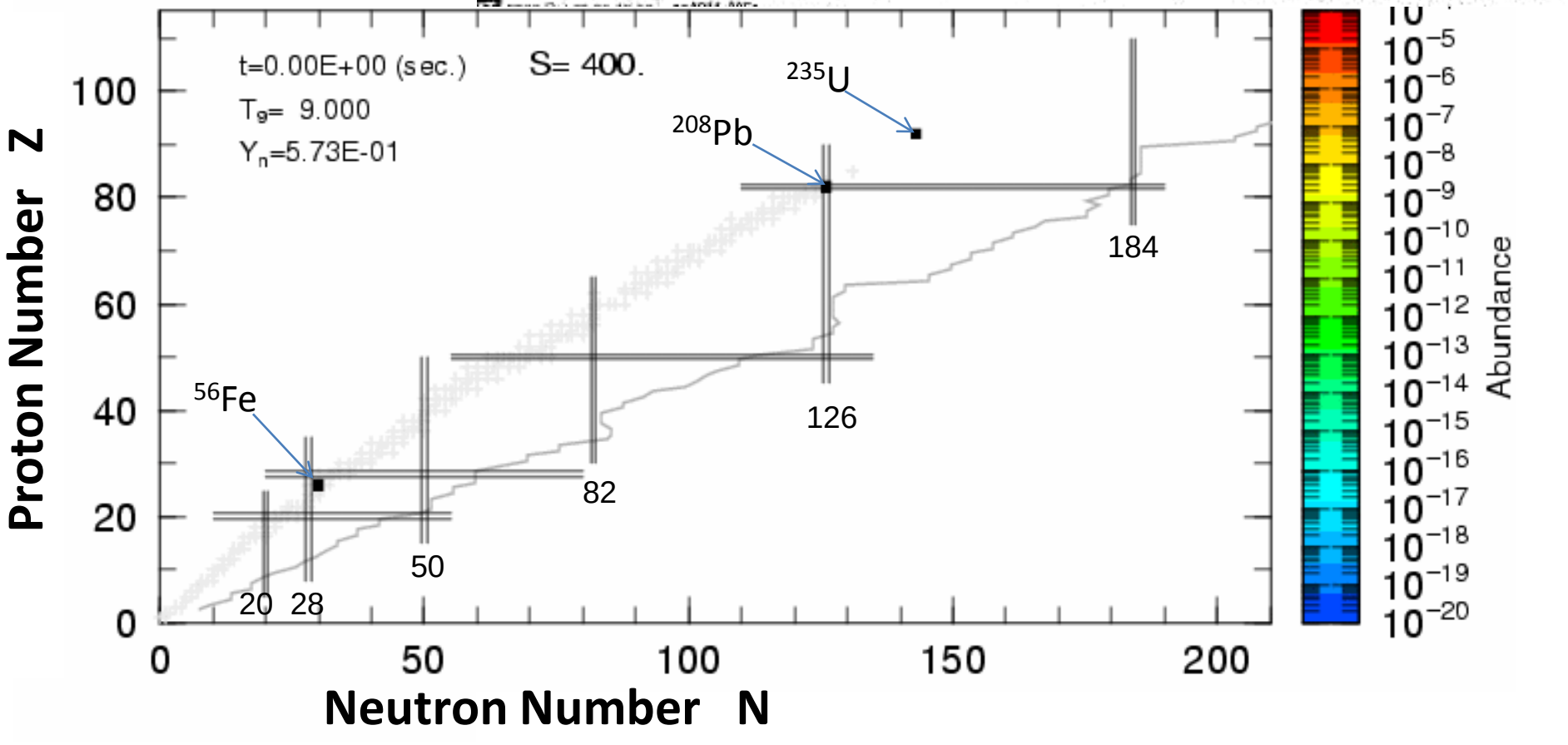


Supernova Nucleosynthesis Simulation

T. Kajino & S. Chiba

ν-Pair Heated Collapsar Model
K. Nakamura, et al. ApJ (2011).

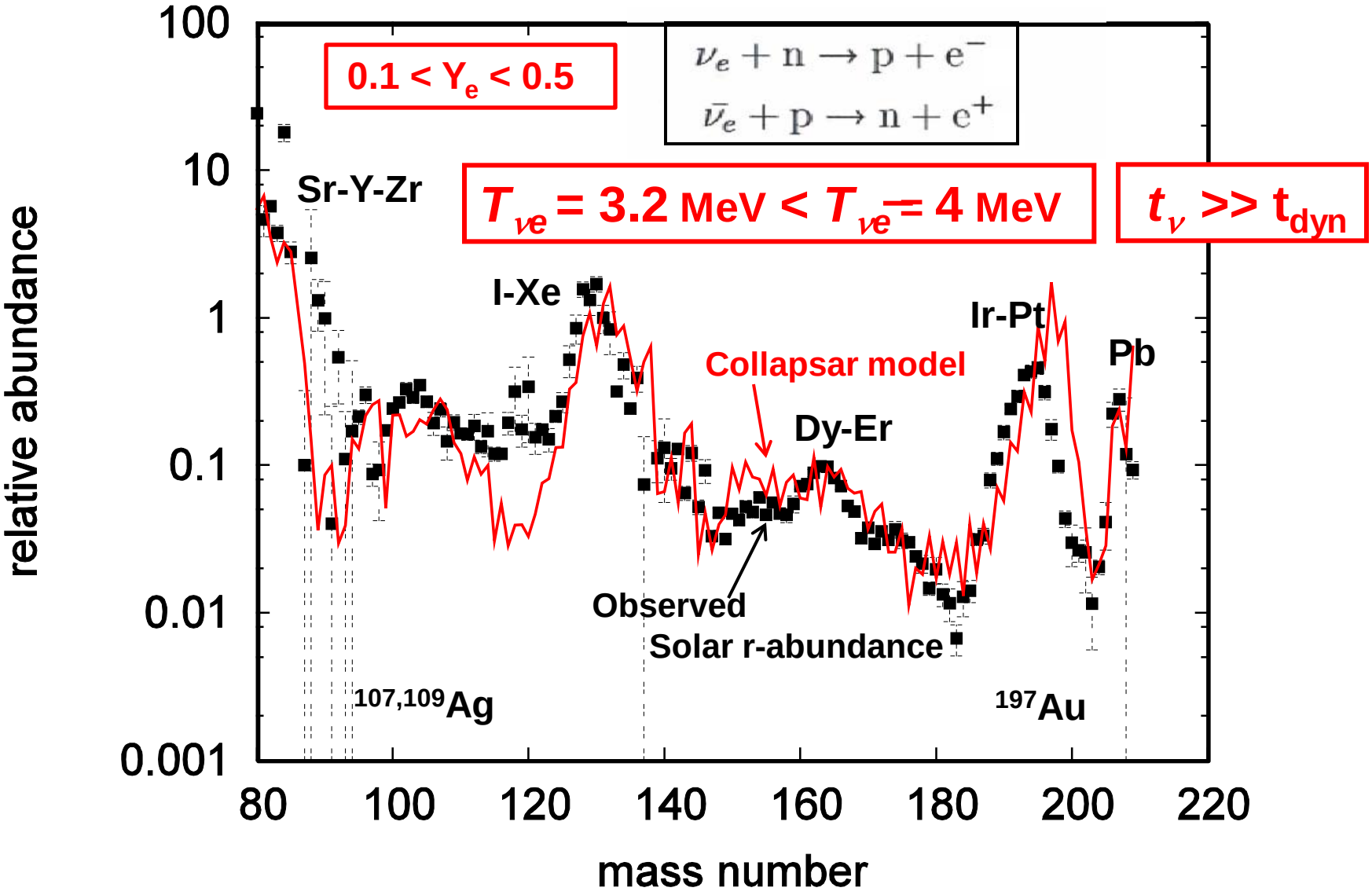




R-process in Pair ν-Heated Collapsar Model for GRB

K. Nakamura, S. Sato, S. Harikae, T. Kajino and G.J. Mathews (2011), submitted to ApJ.

Neutron-rich condition for successful r-process:



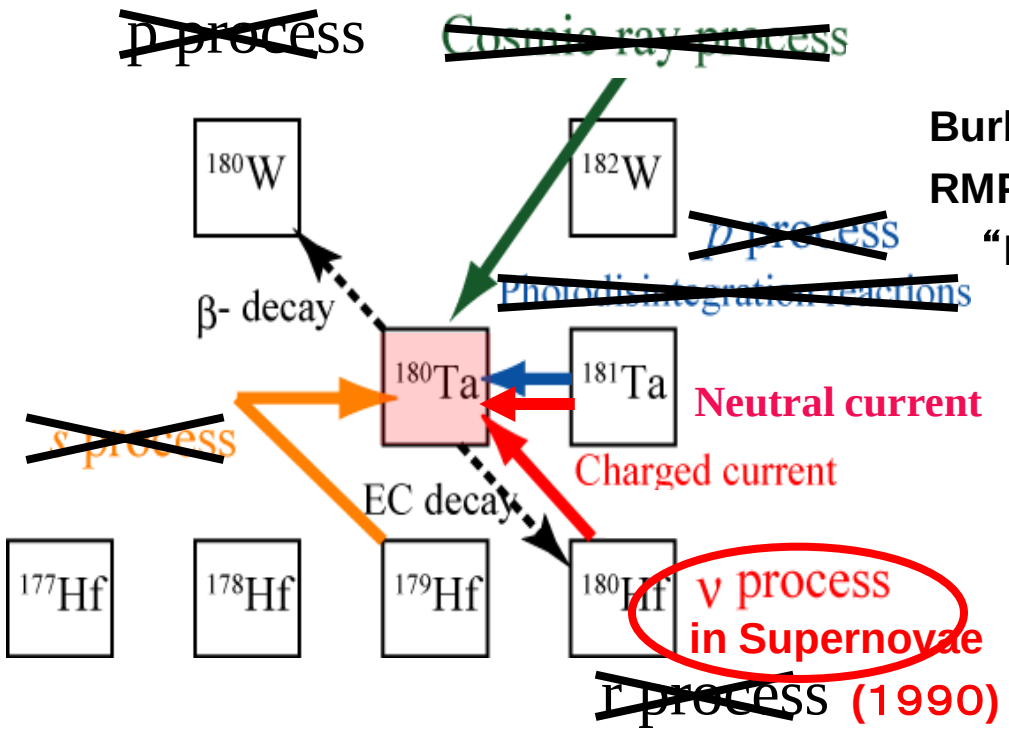
Tantalum (^{180,181}Ta)

^{138}La

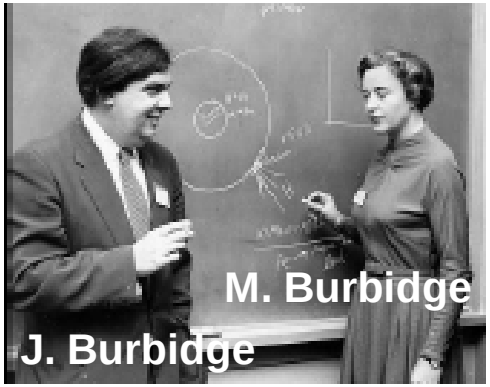
$^{181}Ta_g$ (stable), $^{180}Ta_g$ (unstable, $\tau_{1/2}$ = 8h), $^{180}Ta^m$ (isomer, $\tau_{1/2} > 10^{15}$y)

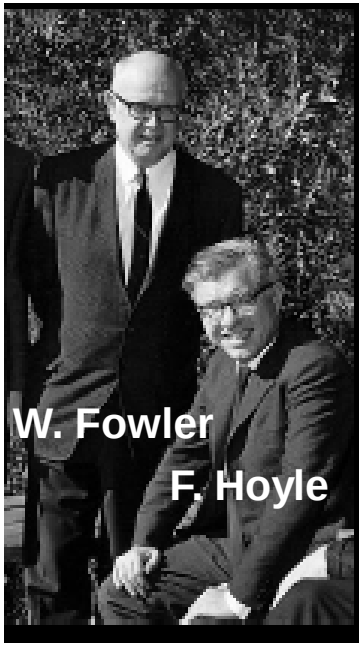
^{180}Ta is the rarest isotope in the Solar-Systerm and even in the Universe!

Where was ^{180}Ta synthesized ?



Burbidge[2]–Fowler-Hoyle, RMP 29 (1957), 547-650.
"Element Genesis"



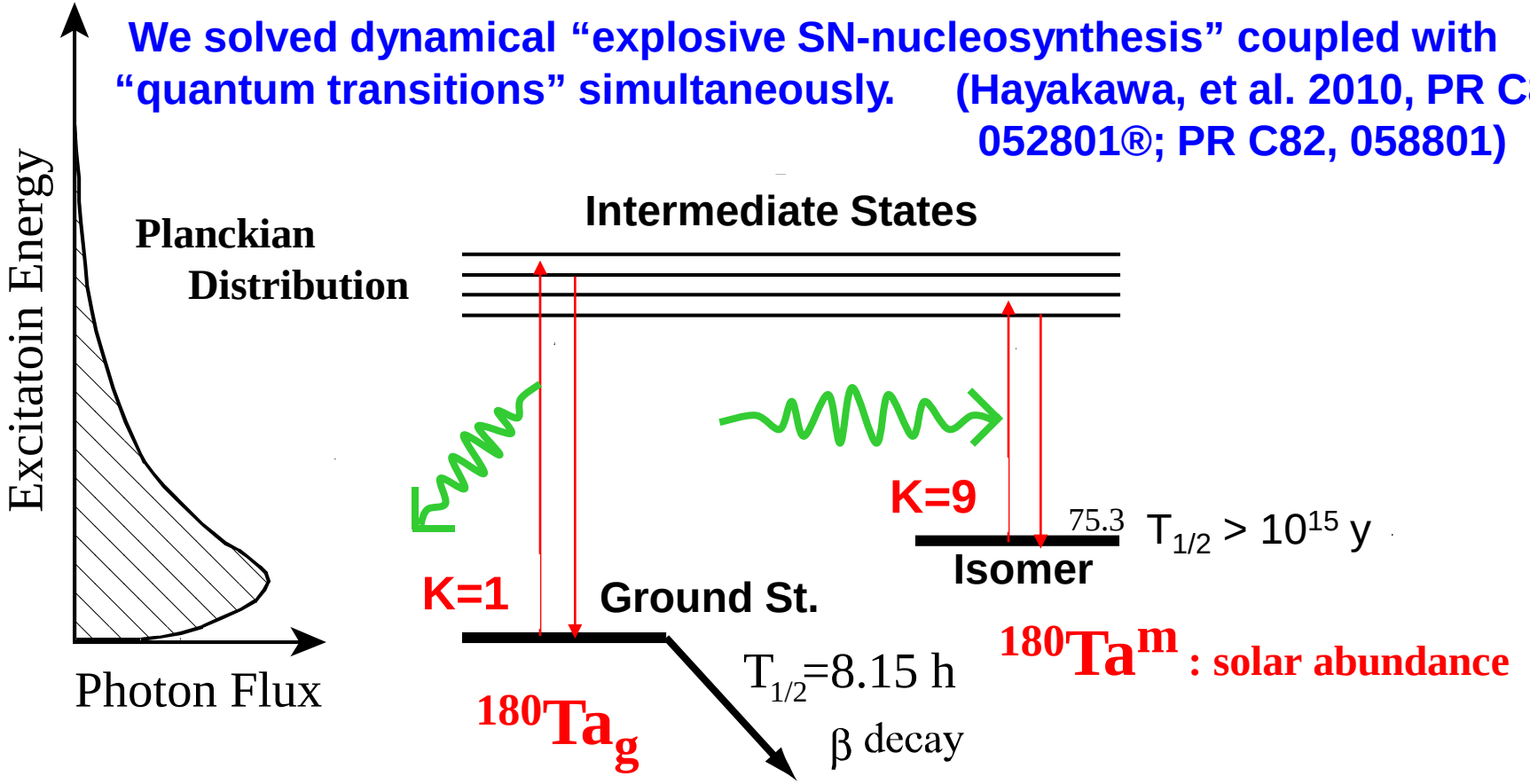


^{180}Ta-genesis needs Quantum Phys. + SN Hydro-dyn.

Solar-^{180}Ta is all "ISOMER" with $T_{1/2} > 10^{15}$ y!

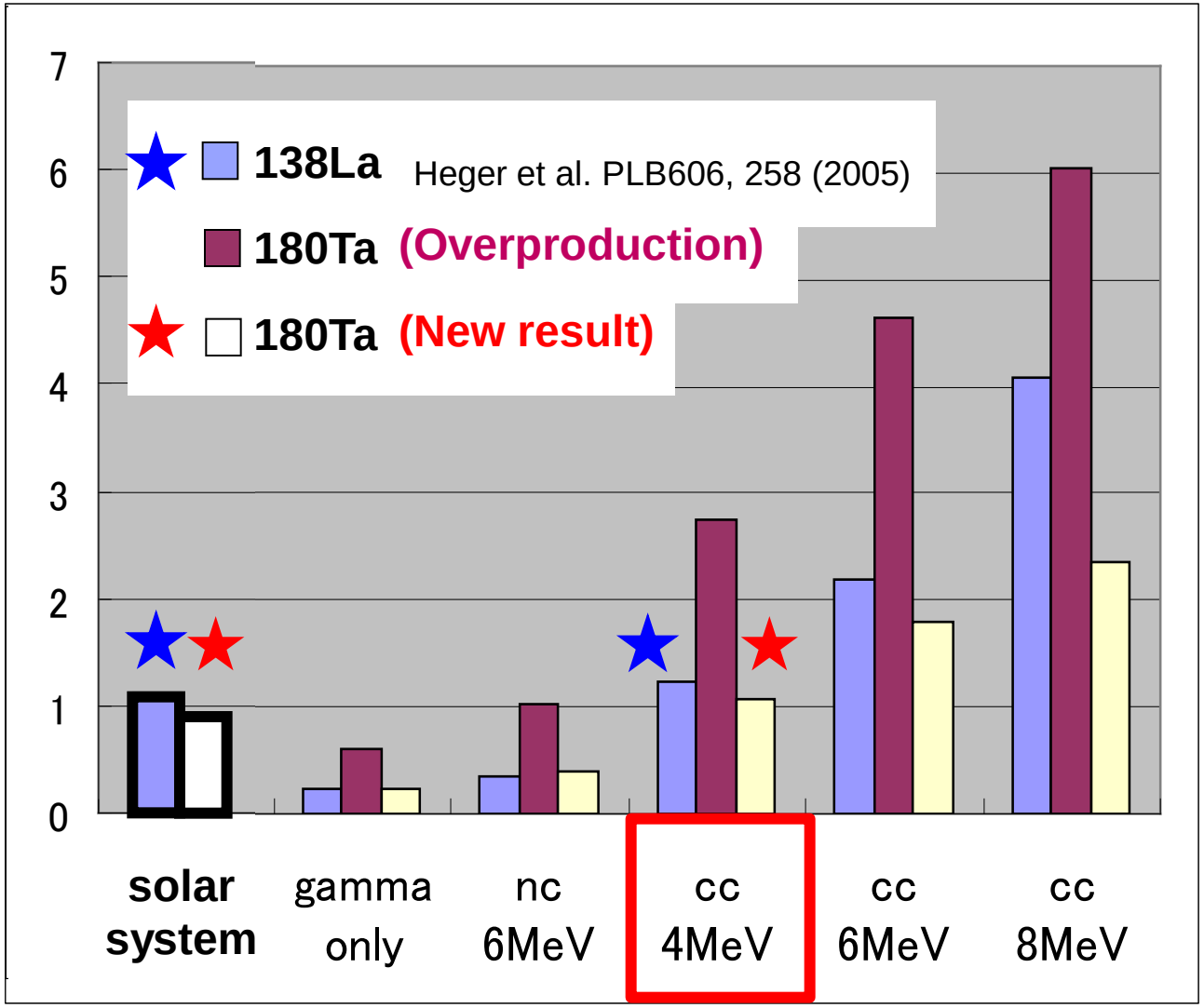
- **Long lived ^{180}Ta^{m} is excited in hot SN-photon bath.**
- **Intermediate states are depopulated to the ground state, which decays in 8 hours.**

We solved dynamical "explosive SN-nucleosynthesis" coupled with "quantum transitions" simultaneously. (Hayakawa, et al. 2010, PR C81, 052801®; PR C82, 058801)



Result from ν-Nucleosynthesis

T. Hayakawa, T. Kajino, S. Chiba, and G.J. Mathews, Phys. Rev. C81 (2010), 052801®



About 40% $^{180}Ta^{m}$ survives in supernova explosion.

Then, both ^{138}La and ^{180}Ta abundances can be consistently reproduced by the CC-int. of ν_e and $\overline{\nu_e}$ of

$$T_{\nu e} = 3.2 \text{ MeV},$$
$$T_{\overline{\nu e}} = 4 \text{ MeV}.$$

⇕

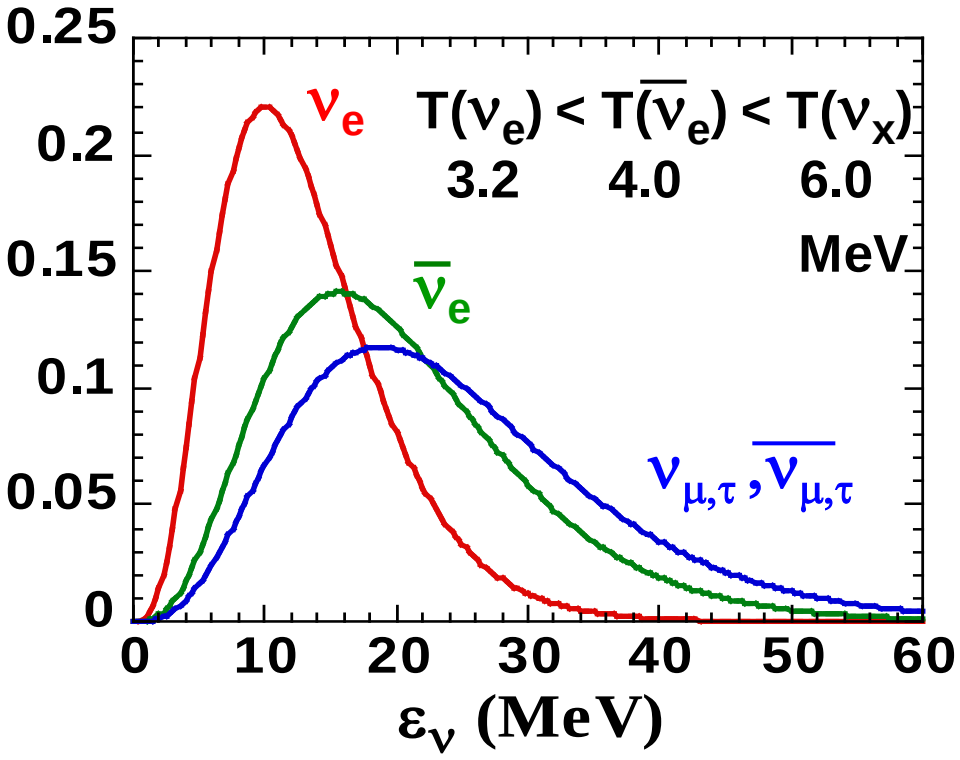
Consistent with the r-process !

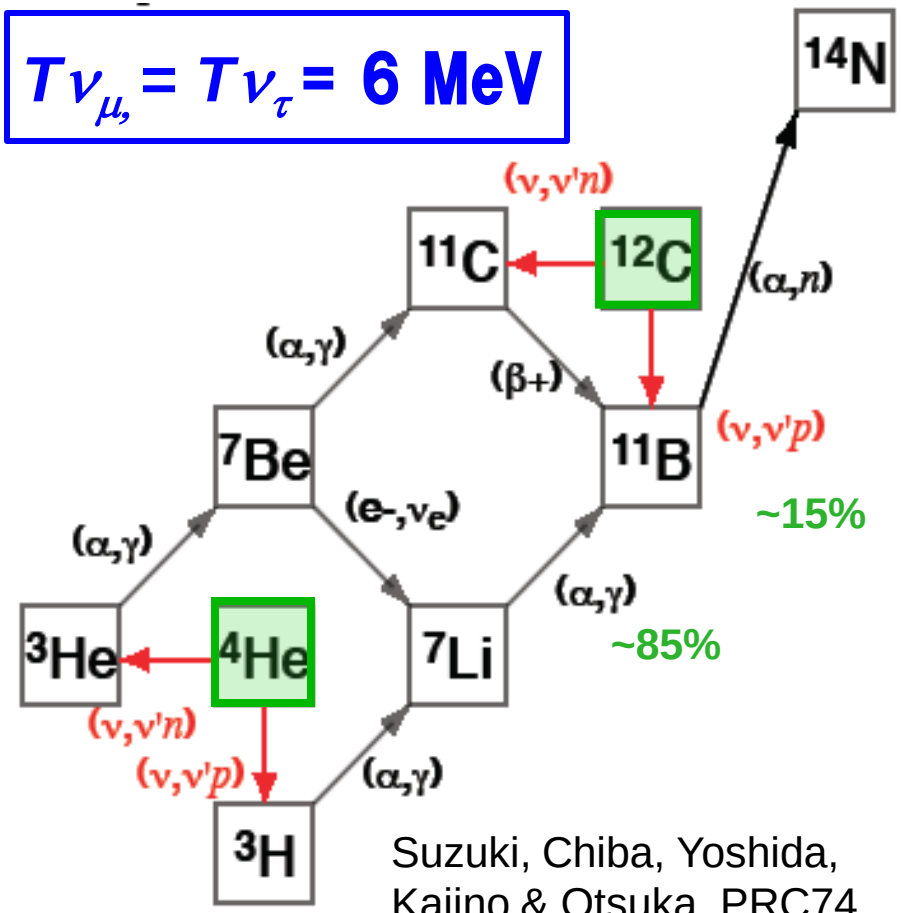
Oscillation (MSW) Effect on Supernova ν-Process

SN II: Yoshida, Kajino & Hartman, Phys. Rev. Lett. 94 (2005), 231101.
SNIc + II: Nakamura, Yoshida, Shigeyama, Kajino, ApJL 718 (2010), L137.

GCE of ^{11}B & ^{11}B/^{10}B ⇨ $T\nu_{\mu,} = T\nu_{\tau} = 6$ MeV

ν-temperatures are known!



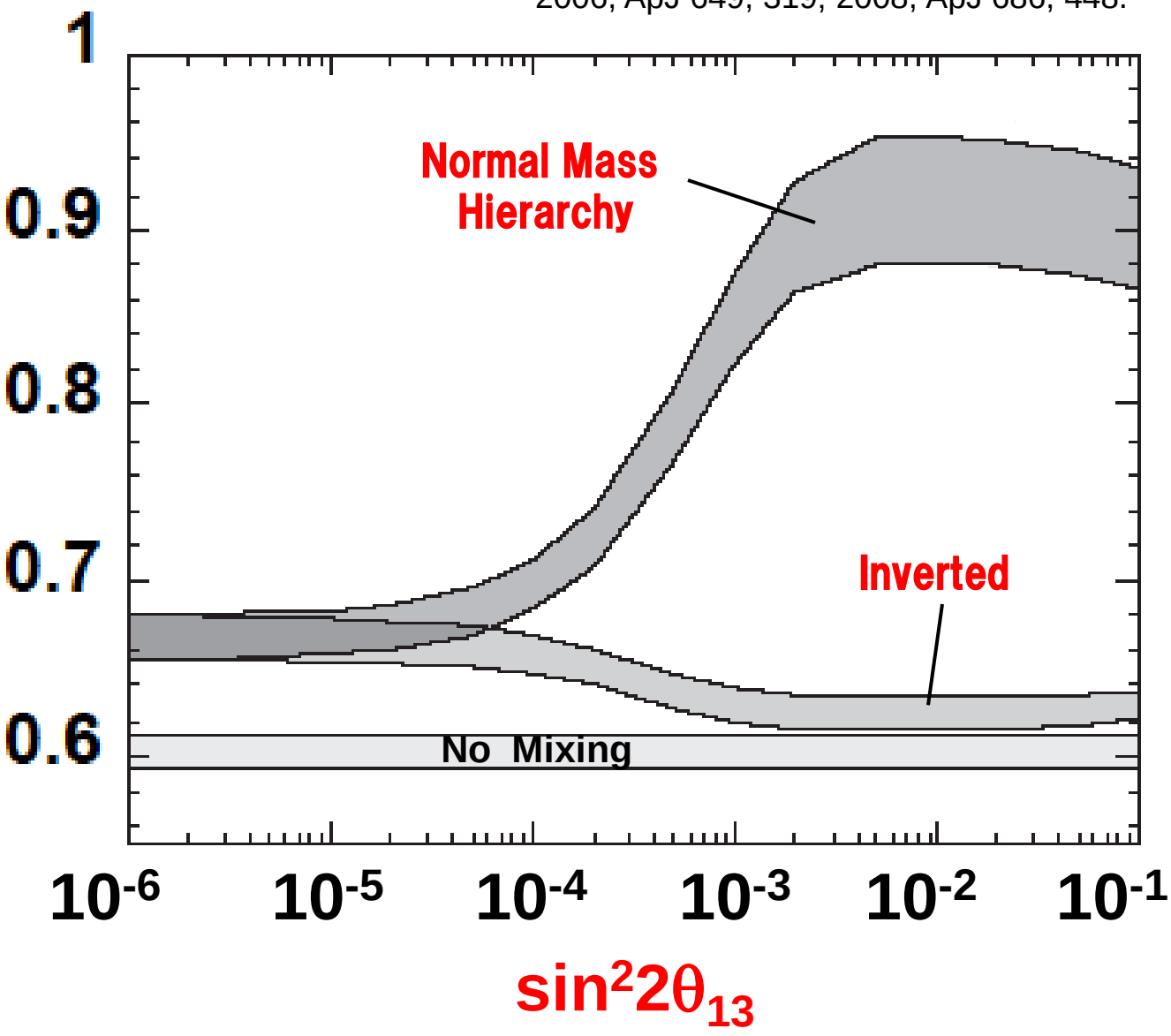


Suzuki, Chiba, Yoshida, Kajino & Otsuka, PRC74 (2006), 034307

Our Theoretical Prediction

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

Yoshida, Kajino et al . 2005, PRL94, 231101; 2006, PRL 96, 091101; 2006, ApJ 649, 319; 2008, ApJ 686, 448.



Astrophysics:

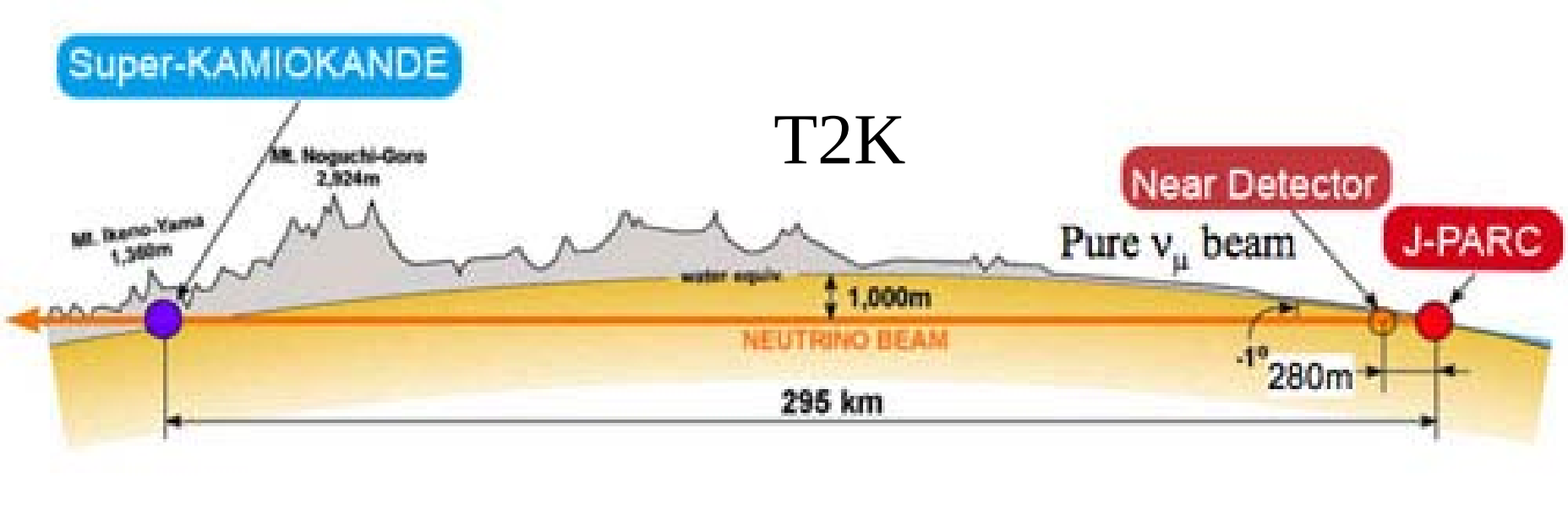
Mass Hierarchy
Δm_{13}^2

13-Mixing Angle
θ_{13}

Long Baseline Exp:

- **T2K (Kamioka)**
  June 14, 2011
- **MINOS**
  July 29, 2011
- **RENO (KOREA)**
- **Double CHOOZ**
- **Daya Bay**

What is the lower limit to $\sin^2 2\theta_{13}$?



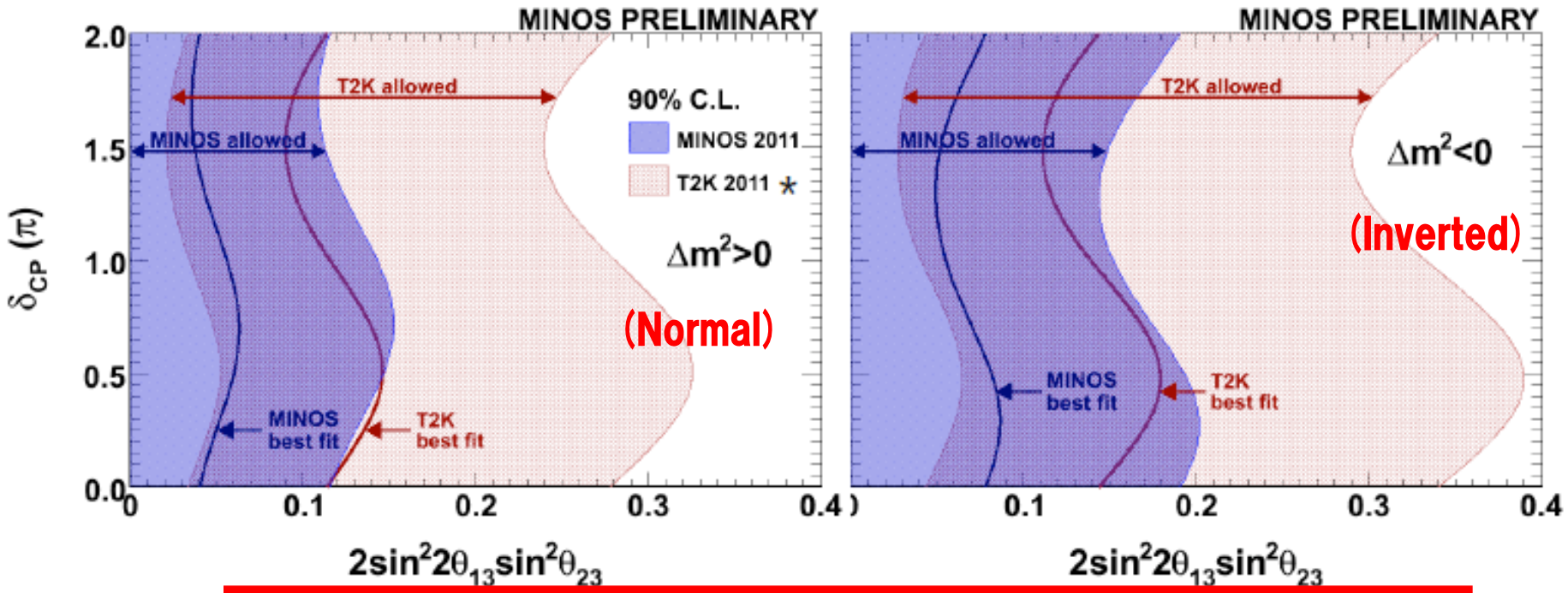
PRL 107, 041801 (2011)

Selected for a Viewpoint in *Physics*
PHYSICAL REVIEW LETTERS

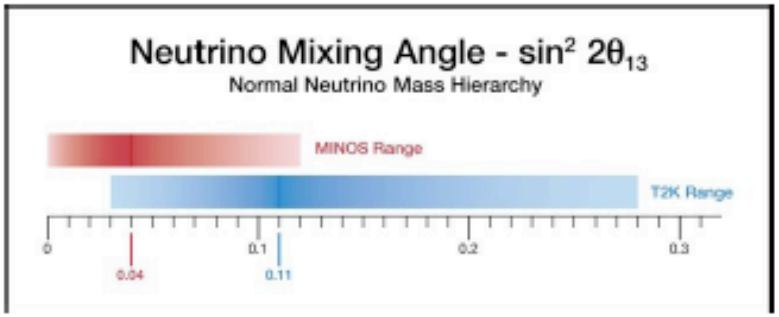
week ending
22 JULY 2011

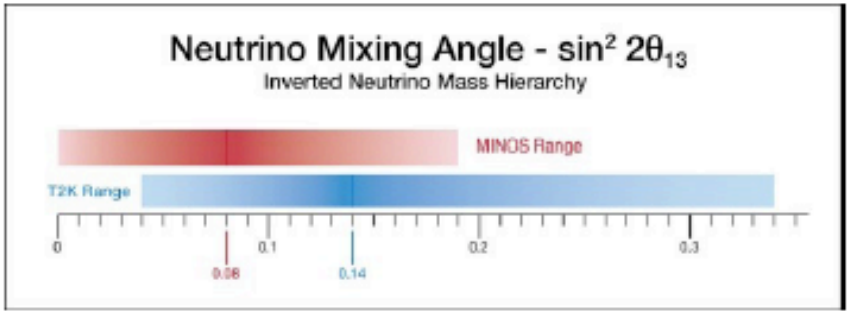
Indication of Electron Neutrino Appearance from an Accelerator-Produced Off-Axis Muon Neutrino Beam

Compasrison between MINOS and T2K



Mass hierarchy is still unknown !

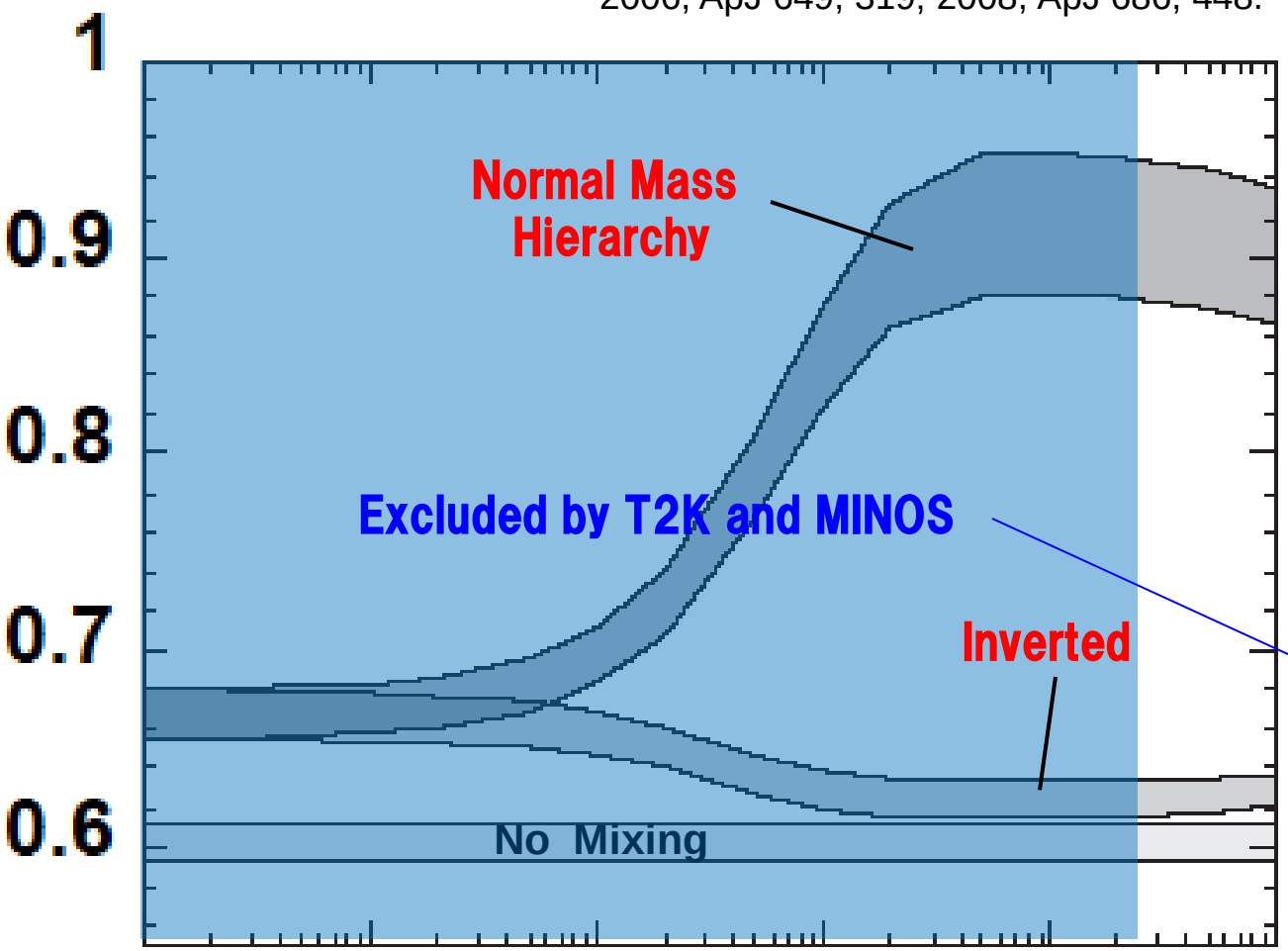




Our Theoretical Prediction

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

Yoshida, Kajino et al . 2005, PRL94, 231101; 2006, PRL 96, 091101; 2006, ApJ 649, 319; 2008, ApJ 686, 448.



10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1}

$\sin^2 2\theta_{13}$

ALLOWED !

Astrophysics:

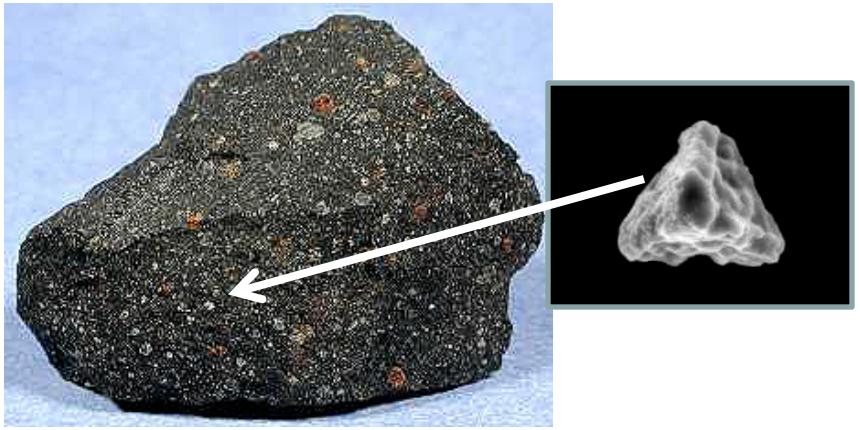
Mass Hierarchy
Δm_{13}^2

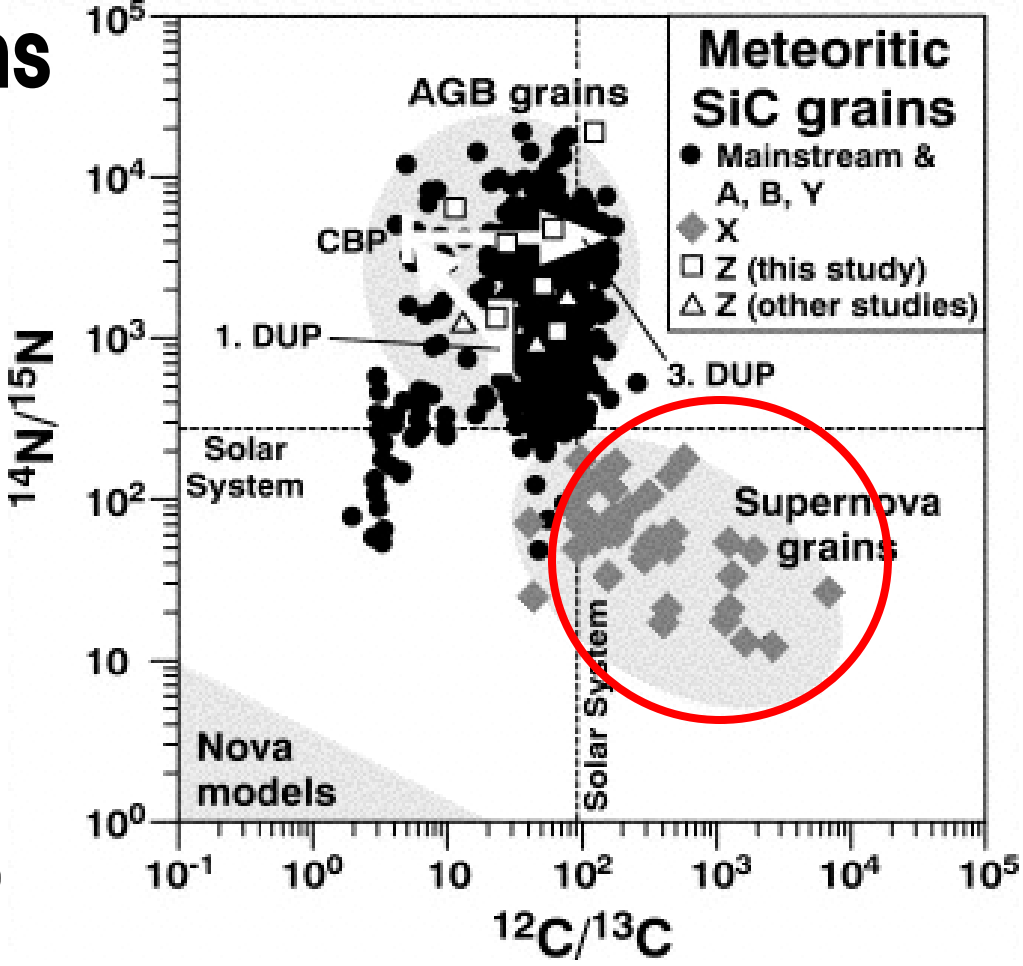
13-Mixing Angle
θ_{13}

Long Baseline Exp:

- **T2K (Kamioka)**
  June 14, 2011
- **MINOS**
  July 29, 2011

Murchison SiC X-grains





SiC X grains exhibit

- $^{12}C/^{13}C$ > Solar
- $^{14}N/^{15}N$ < Solar
- Enhanced ^{28}Si
- Decay of ^{26}Al ($t_{1/2}$ = 7x10^5 yr) & ^{44}Ti ($t_{1/2}$ = 60 yr)

⇨ **Origin in Core Collapse Supernovae**

THE ASTROPHYSICAL JOURNAL LETTERS, 730:L7 (5pp), 2011 March 20

HINTS FOR NEUTRINO-PROCESS BORON IN PRESOLAR SILICON CARBIDE GRAINS FROM SUPERNOVAE

WATARU FUJIYA[1], PETER HOPPE[2], AND ULRICH OTT[2]

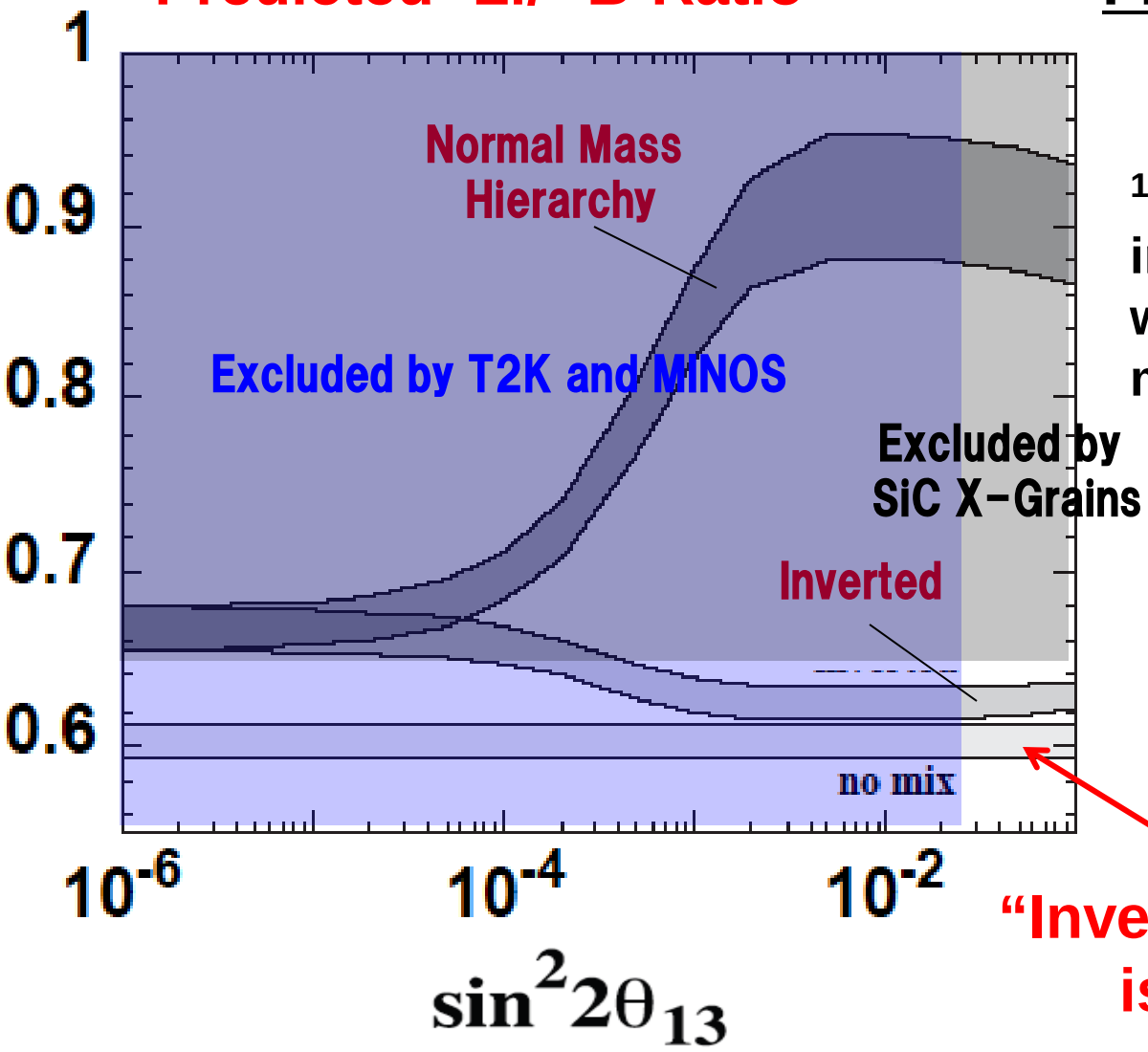
[1] Department of Earth and Planetary Science, University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033, Japan;
[2] Max Planck Institute for Chemistry, J.-J.-Becher-Weg 27, 55128 Mainz, Germany

Received 2010 December 20; accepted 2011 February 10; published 2011 February 25

Mass Hierarchy, Normal or Inverted ?

Mathews, Kajino, Aoki and Fujiya, arXiv:1108.0725 (2011).

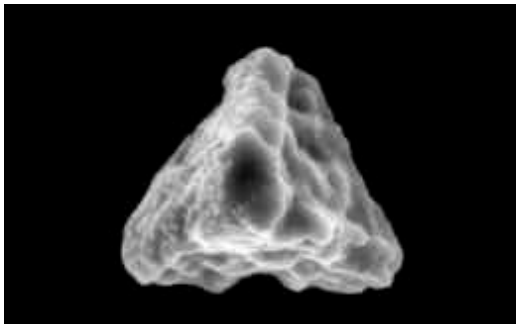
Predicted $^{7}Li/^{11}B$-Ratio



First Detection of $^{7}Li/^{11}B$

W. Fujiya, P. Hoppe, and U. Ott, ApJ 730, L7 (2011).

^{11}B and ^{7}Li were measured in SiC presolar X-grains which are known to be made of Supernova dusts.

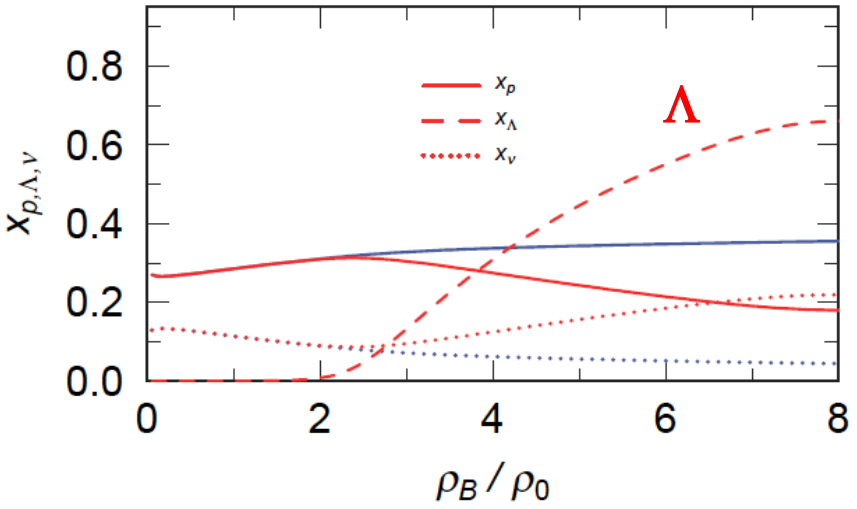


"Inverted mass hierarchy" is more preferred !

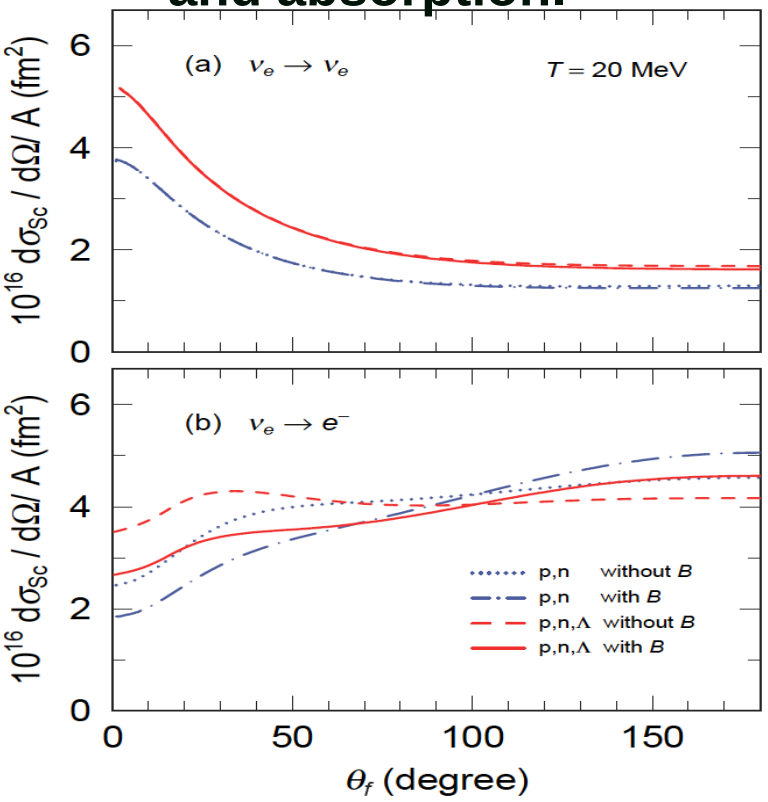
ν-Asymmetry under the Strong Dipole (Poroidal) Magnetic Field

Fundamental Interactions among Hadrons (p, n, Λ, Σ …) and Lepton (e,ν…) at High-ρ and High-T in Relativistic Field Theory and QCD

Maruyama, Kajino, Yasutake, Cheoun, & Ryu, PRD83 (2011), 081302 (R).



Asymmetric ν-scattering and absorption.



Neutrino scattering and absorption process inside the magnetized Neutron star (10^{15}G) is asymmetric.

⇒ ~ 2 % asymmetric ν-abs. (drift)

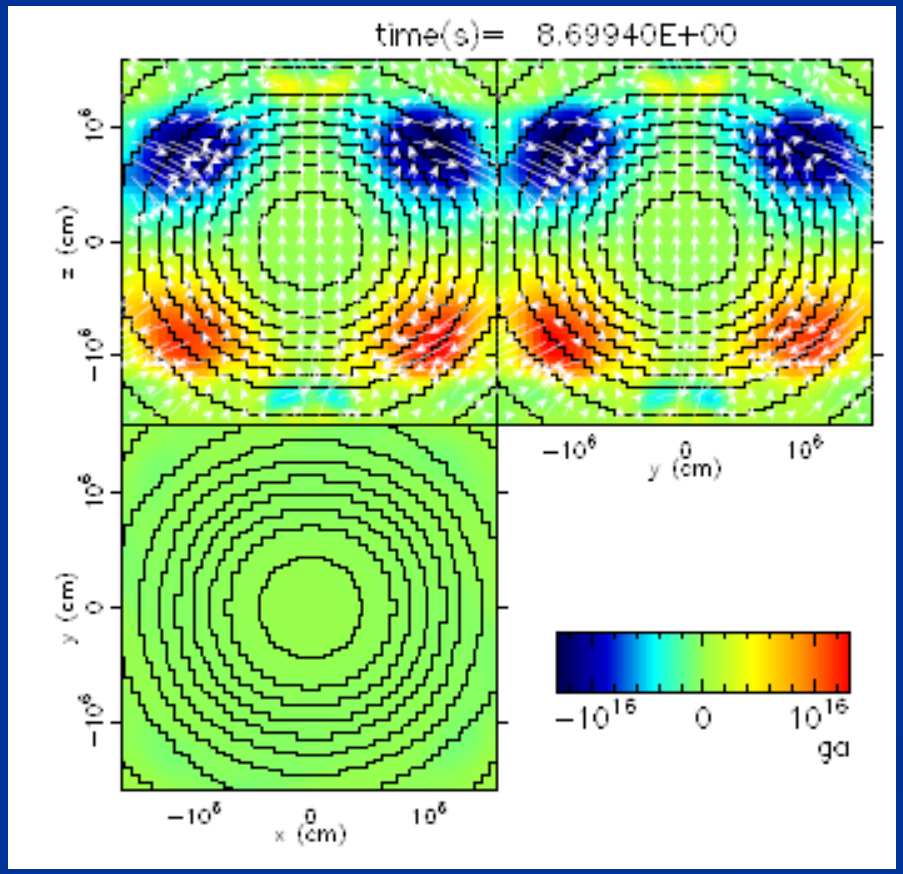
⇒ Enough for Pulsar-Kick ~500km/s !

Magnetic Field and ν-interactions

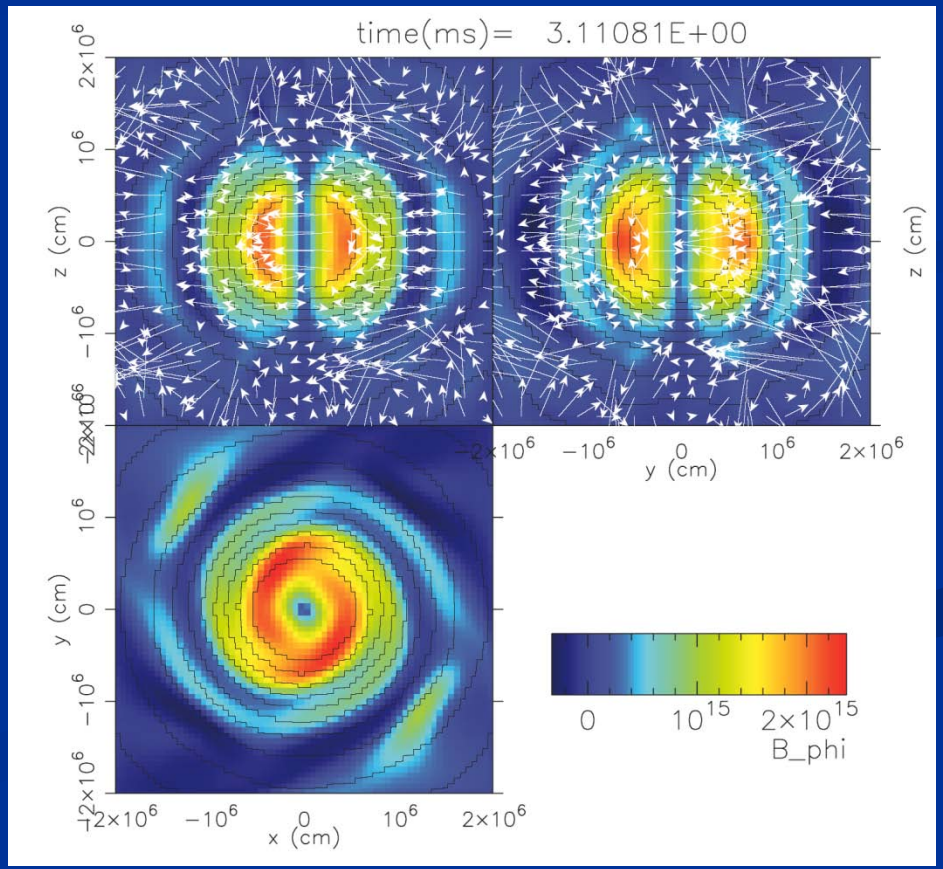
★ Poroidal → Pulsar Kick
★ Toroidal → Twist Mode → Spin down & growth of intsability

T. Kuroda, with Yasutake, Maruyama, Hidaka & Kajino

Initially dipole → Double Toroidals

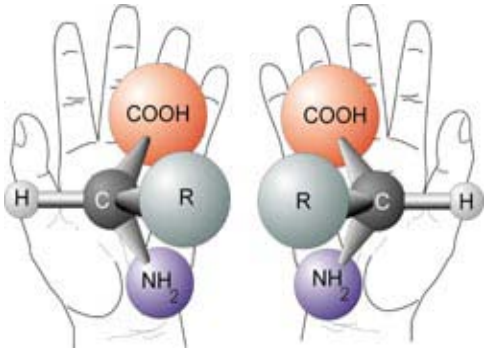


Initially no dipole → Single Toroidal



Why Amino Acids on the Earth, All Left-Handed?

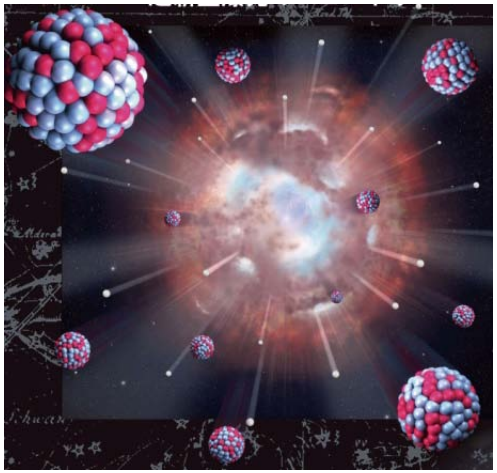
Chitrality, earth origin or universal ?



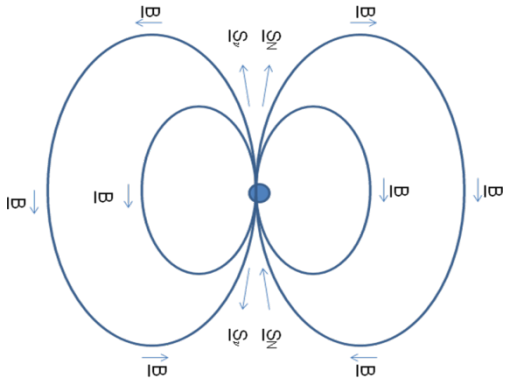
- ★ **Neutrinos are all left-handed!**
- ★ **Supernovae with strongly magnetized neutron star or BH emit intensive flux of neutrinos over 10^{10} yrs!**
- ★ **SN ejecta including ^{14}N interact with neutrino under strong magnetic field!**
- ★ **Neutrino-^{14}N coupling is asymmetric & chiral selective!**

Boyd, Kajino, & Onaka suggested that the L-handed chirality of amino acids is UNIVERSAL! (Astrobio. 10 (2010), 561-568; Int. J. Mol. Sci. 12 (2011), 3432)

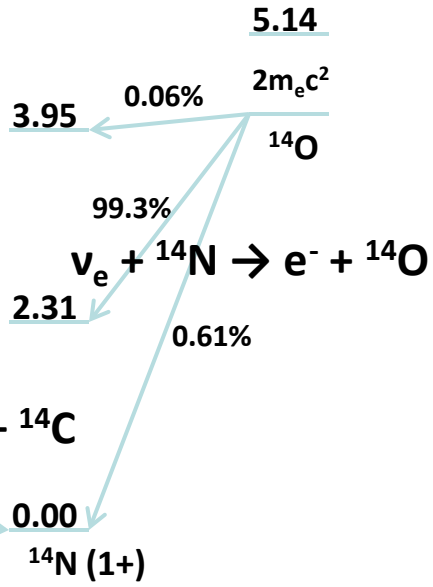
Magnetized Supernovae



^{14}N lives !



^{14}N dies !



$\overline{\nu}_e + {}^{14}N \rightarrow e^+ + {}^{14}C$

Mann and Primakoff (Origins of Life, 11 (1981), 255) suggested β-decay of 14C, but it's too SLOW!

CONCLUSION

We propose a new astrophysical method to determine the unknown ν-oscillation parameters, θ_{13} and mass hierarchy Δm_{13}^2, simultaneously in terms of the supernova ν-process nucleosynthesis of ^{180}Ta, ^{138}La, ^{7}Li and ^{11}B By taking account of the MSW effects.

Combining the recent detection of ^{7}Li/^{11}B isotopic ratio in presolar X-grains and the T2K + MINOS results of long-baseline neutrino oscillation experiments on θ_{13}, we can conclude that the "inverted mass hierarchy" is more preferred.

Collaboration、highly desirable in Theory plus Exp/Obs. as required/demoinstrated in SN-neutrino project!

Nucleosynthesis—c.c. SNe—ν—Magnetic Field—Life