第1回 NOP/Φ研/KMI分野横断セミナー
2014年5月26日（月）、名古屋大学 ES総合館

超新星元素合成とニュートリノ振動の物理

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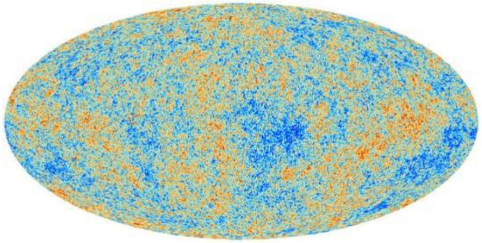
Challenge of the Century

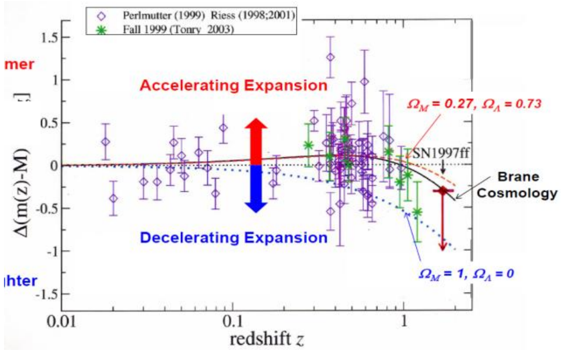
Universal expansion is most likely accelerating and flat !

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

CMB – Planck 2013



SN Ia magnitude-redshift relation
1998



- What is CDM (Ω_{CDM} = 0.27) and DE (Ω_Λ = 0.68) ?

CMB including ν-mass

- Is BARYON sector (Ω_B = 0.05) well understood ?

Big-Bang Nucleosynthesis

with Axions + **SUSY to solve DM & Li Problems**:

SUSY-DM ⇒ “beyond the Standard Model”

⇒ $m_\nu \neq 0$ is the unique signal !

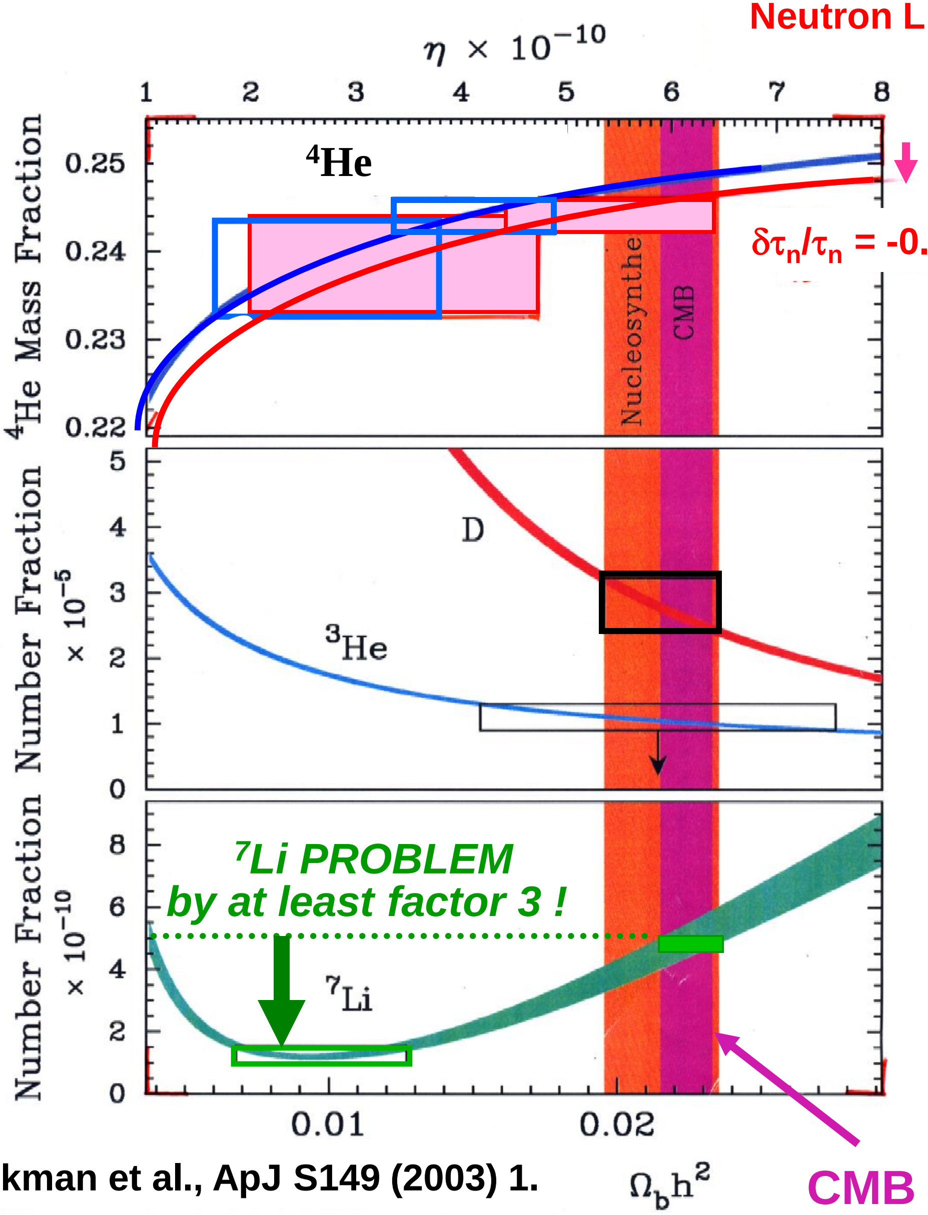
Key Particles

Neutrons (n’s) & Neutrinos (ν’s).

Big-Bang Nucleosynthesis is now a Precise Science ~1%

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

Neutron Life



$\delta\tau_n/\tau_n$ = -0.01

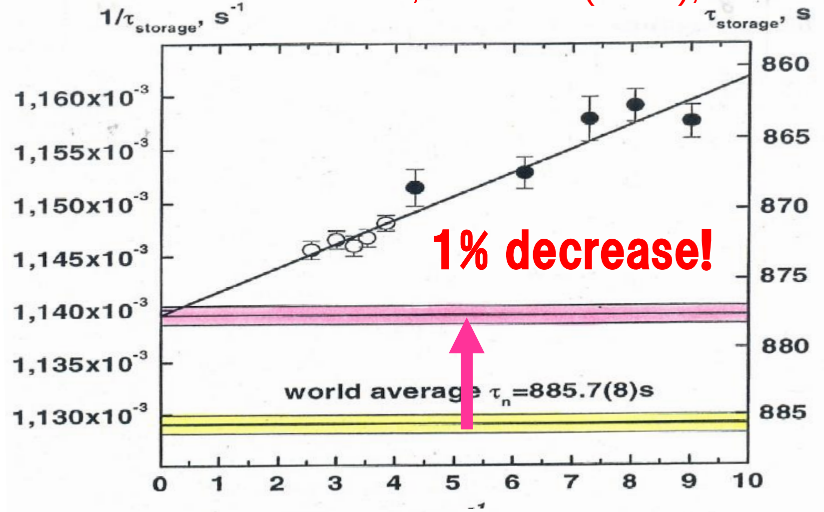
^{7}Li PROBLEM
by at least factor 3 !

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

CMB - WMAP

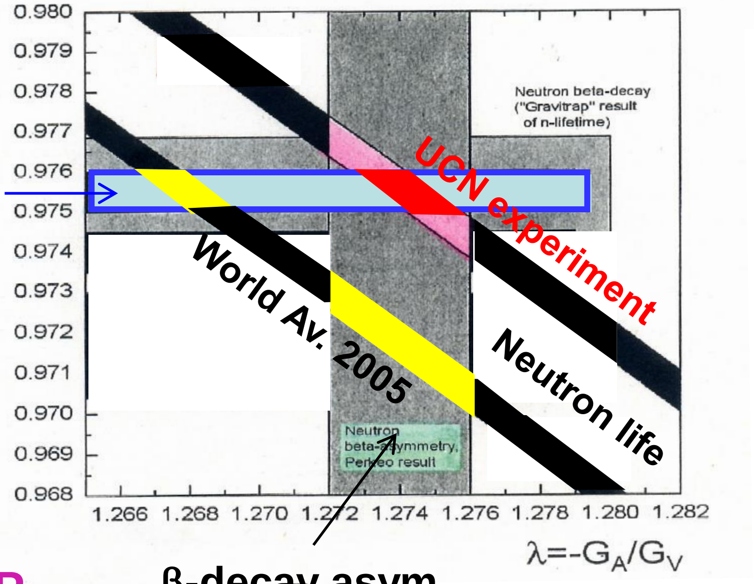
New UCN Experiment

Serevlov et al., PL B605 (2005), 72.



1% decrease!

CKM
Matrix
V_{ud}



UCN experiment

World Av. 2005

Neutron life

β-decay asym.

Cosmological Implication for ^{4}He-^{6}Li-^{7}Li PROBLEM

New measurements using Inverse-Compton γ-rays !

Shima et al. PR C72 (2005) 44004
Naito et al. PR C73 (2006) 34003
+ New Experiment (2008 —)

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

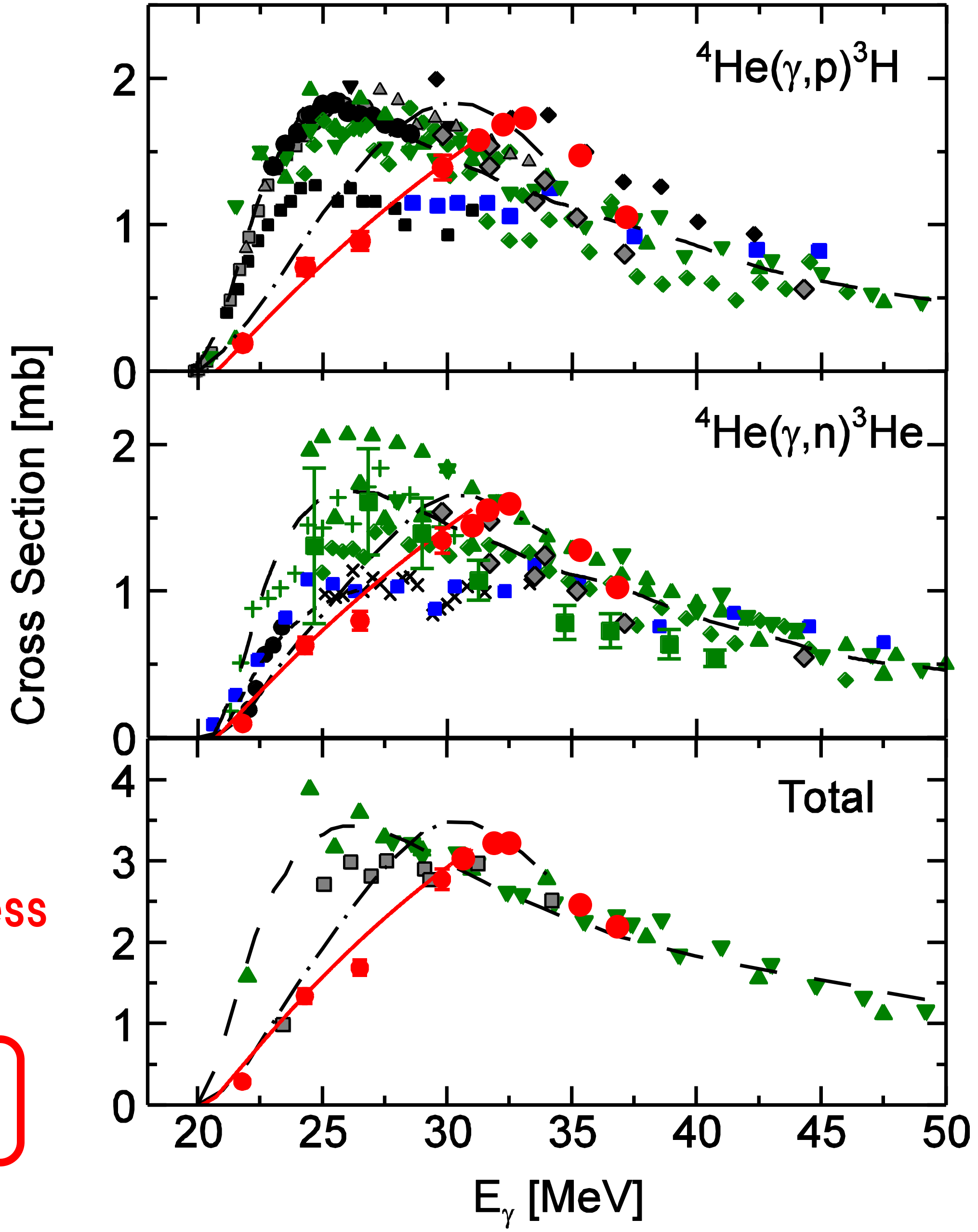
$^4He(\gamma_{NT},p)^3H(^4He,n)^6Li$

Decaying DM (i.e. SUSY) BBN for solving ^{6}Li problem:

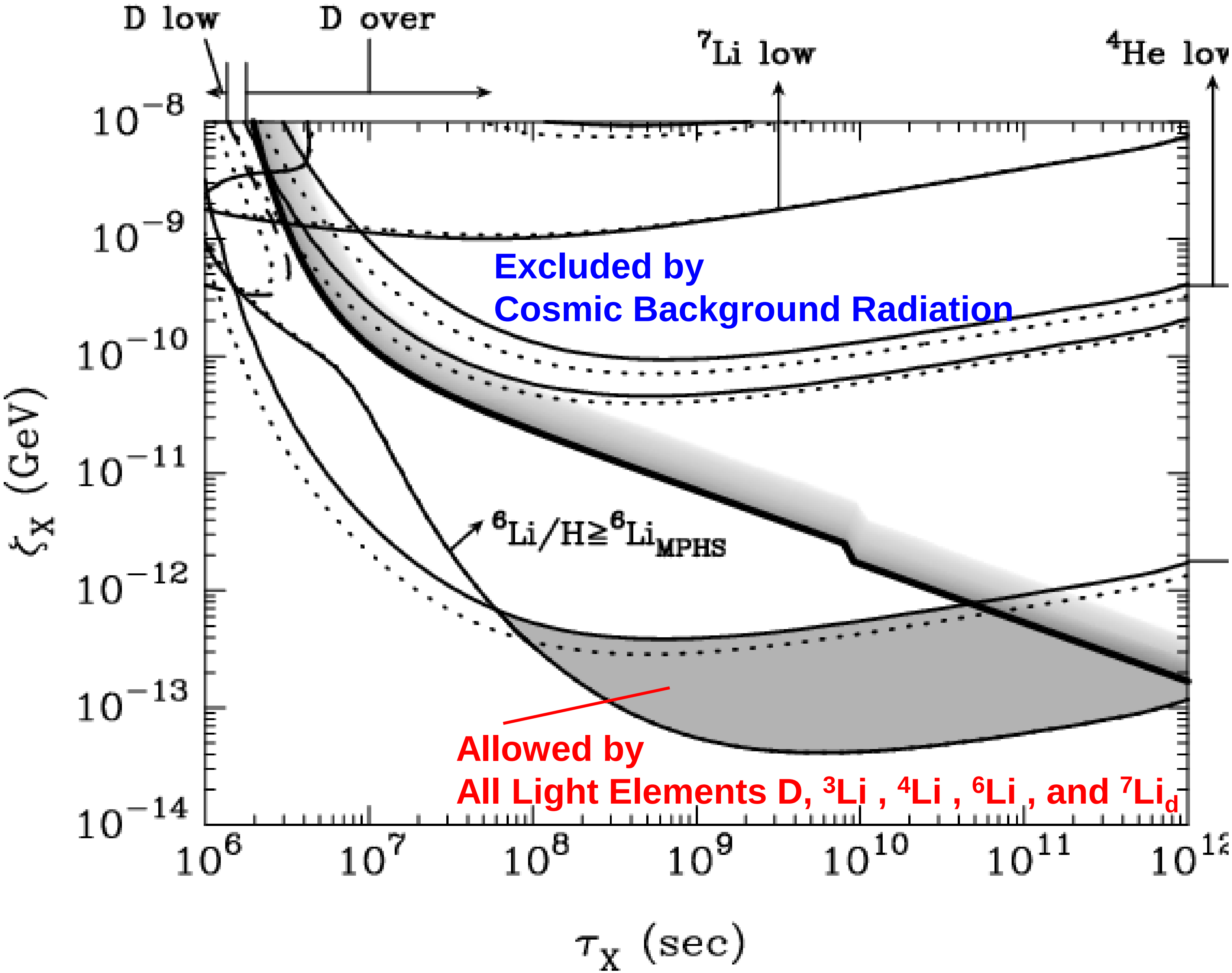
Kusakabe Kajino, Shima et al.,
PR D79 (2009) 123513.

Supernova ν−Process

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



Kusakabe, Kajino, Yoshida, Shima, Nagai, and Kii (2007-2014).



Excluded by
Cosmic Background Radiation

Allowed by
All Light Elements D, ^{3}Li , ^{4}Li , ^{6}Li , and ^{7}Li$_{d}$

BBN Constraint on Magnetic Moment of Massive Neutrinos

M. Kusakabe, A. B. Balantekin, T. Kajino & Y. Pehlivan, PR D87 (2013), 085045.

Cosmological: $\nu \longrightarrow \nu' + \gamma$ non-therm

sterile ($m_\nu \neq 0$, $\mu_\nu \neq 0$) sterile/active

Current Constraints

Laboratory: $\mu_\nu < 2.9 \times 10^{-11} \mu_B$

Astrophysical: $\mu_\nu < 3 \times 10^{-12} \mu_B$

Magnetic Moment of massive neutrino X

$$|\mu_{\rm eff}|^2 = |\mu_{ij}|^2 + |\epsilon_{ij}|^2.$$

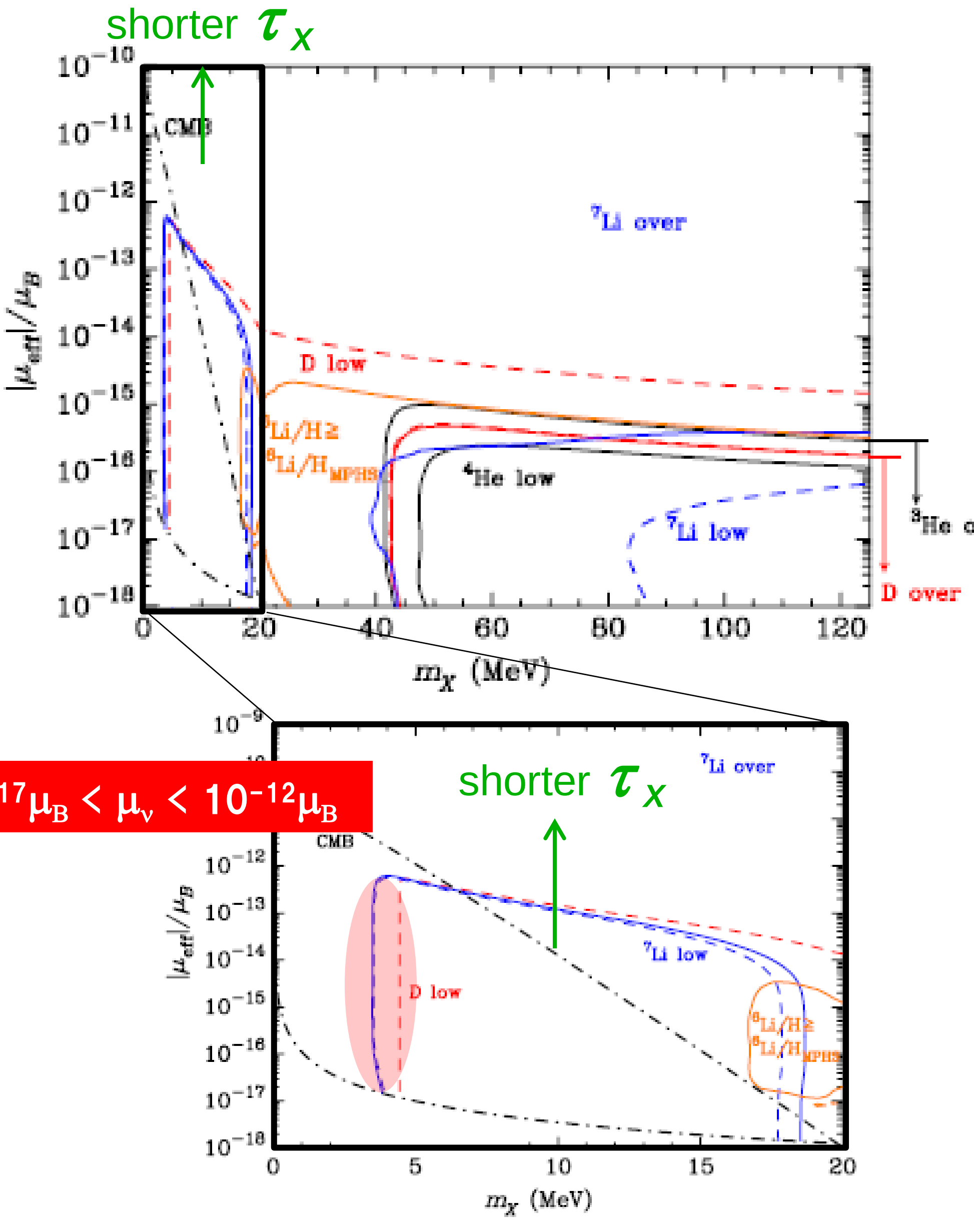
$$\boxed{\tau_X^{-1}} = \frac{|\mu_{ij}|^2 + |\epsilon_{ij}|^2}{8\pi}\left(\frac{m_i^2 - m_j^2}{m_i}\right)^3$$

$$= 5.308\ {\rm s}^{-1}\left(\frac{\mu_{\rm eff}}{\mu_B}\right)^2\left(\frac{m_i^2 - m_j^2}{m_i^2}\right)^3\left(\frac{m_i}{\rm eV}\right)^3$$

Decoupling Temp. is Max [1MeV, m_X/20]

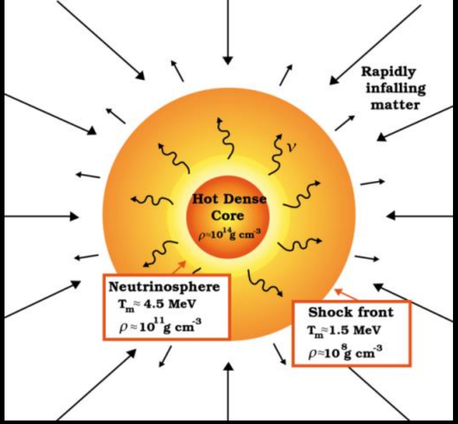
$$\boxed{\frac{n_X}{n_\gamma}} = \frac{4}{11}\frac{n_{{\rm d}X}(m_X)}{n_\gamma(T_{\rm d})} = \frac{2\pi^2}{11\zeta(3)}\frac{n_{{\rm d}X}(m_X)}{T_{\rm d}^3}.$$

$$n_{{\rm d}X}(m_X) = \frac{g_X}{2\pi^2}\int_0^\infty dp\frac{p^2}{\exp\left[\sqrt{p^2 + m_X^2}/T_{\rm d}(m_X)\right] + 1}$$



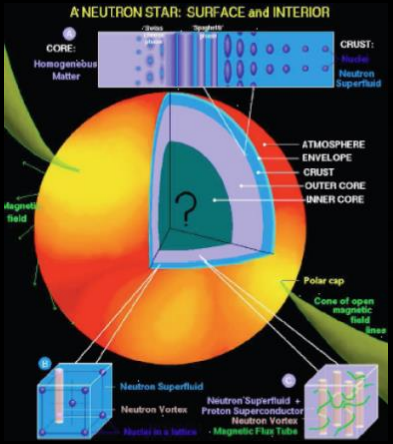
$10^{-17}\mu_B < \mu_\nu < 10^{-12}\mu_B$

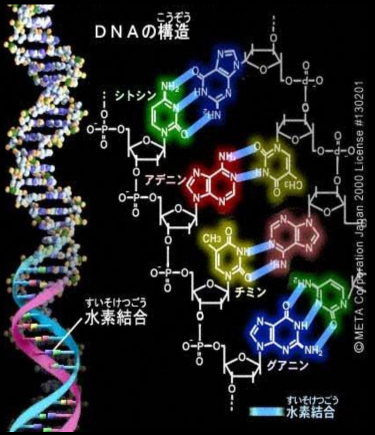
What happens as neutrinos flow through the SN outer layers ?



Neutrino induced nucleosynthesis to constrain ν-mass hierarchy.

Astrophysical sites for r-process including SNe, GRBs and neutron star mergers..

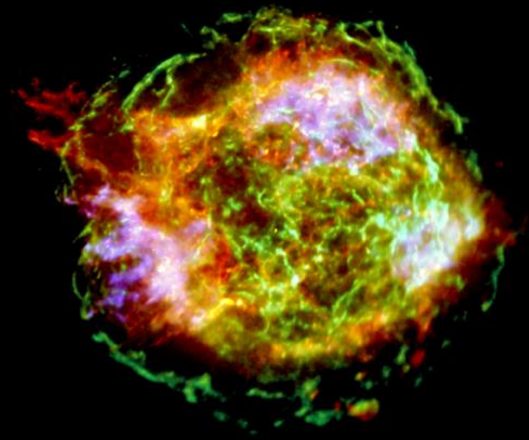




Pulsar kick from ν-baryon int. in magnetized neutron stars.

Origin of life – chirality of amino acids.

What happens to neutrinos once they leave the supernova?



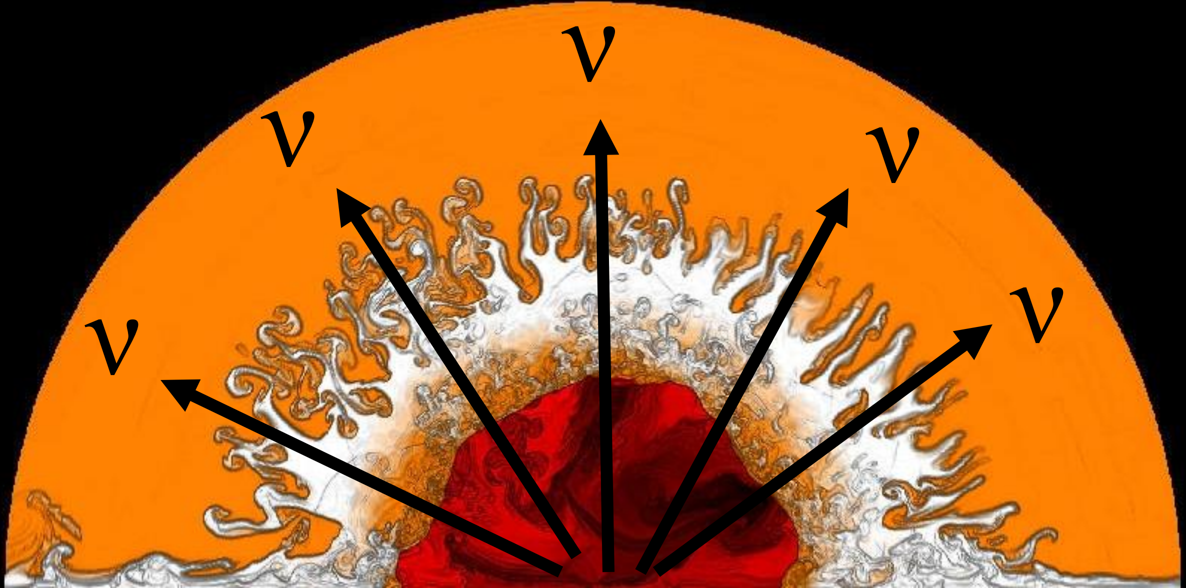
Supernova Relic Neutrinos (SRNs) to probe EoS of proto-neutron stars.

What happens as neutrinos flow through the SN outer layers ?

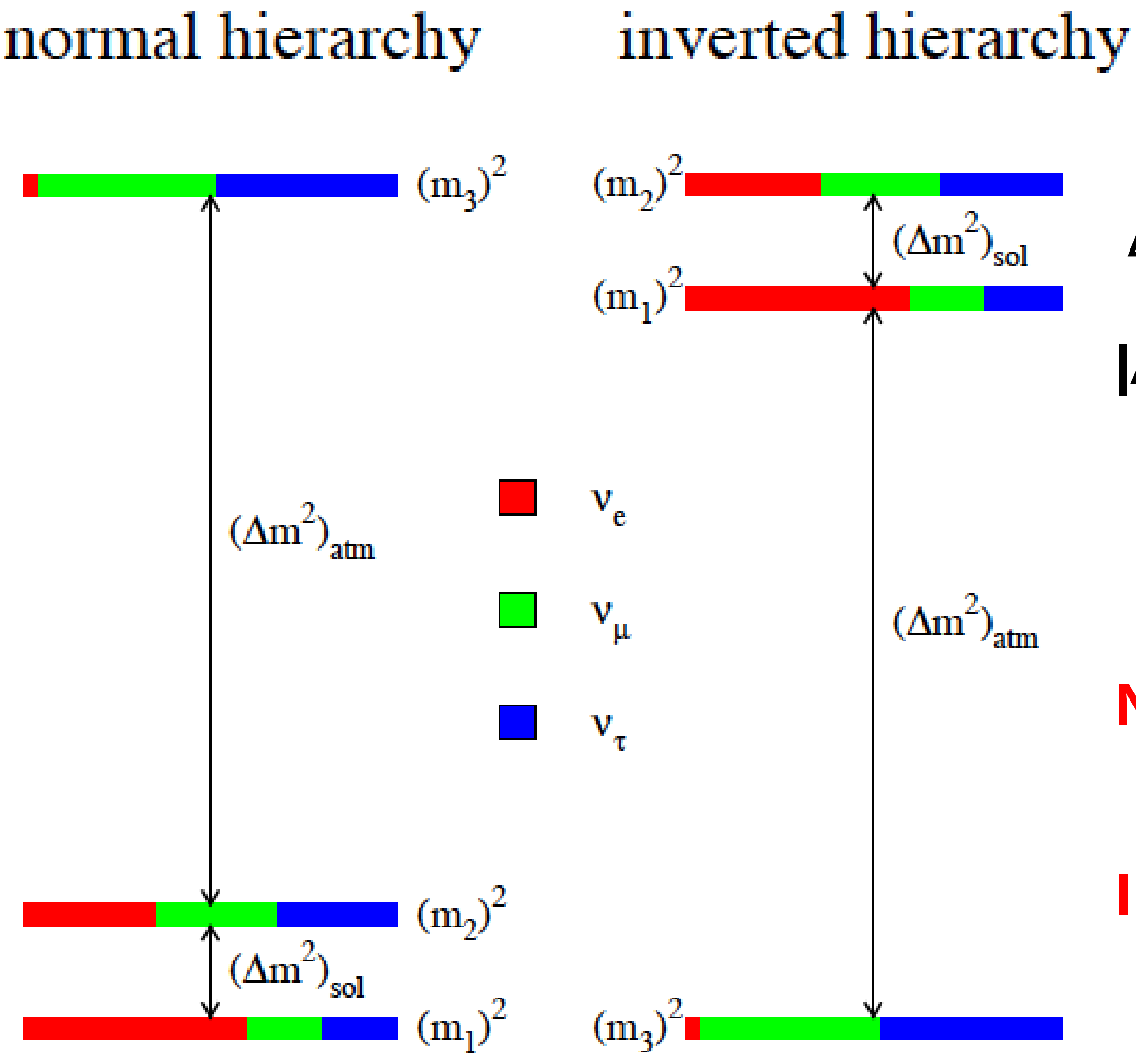
Pulsar Kick from ν-baryon int. in Magnetized Neutron Star.

ν-induced nucleosynthesis and Mass Hierarchy.

R-process nucleosynthesis in GRBs.



Mass Hierarchy?



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

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

$$= (0.05\ \mathrm{eV})^2$$

Normal:

$\Sigma\, m_\nu \sim 0.05$ eV !

Inverted:

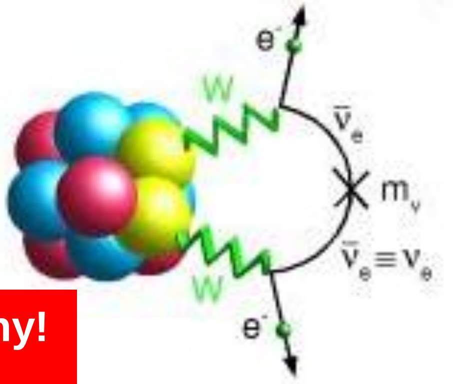
$\Sigma\, m_\nu \sim 0.1$ eV !

Total ν-Mass, constrained from Nuclear Physics and Cosmology

- **0νββ in COUORE, NEMO3, EXO, KamLAND Zen**

→ 0.05～0.1 eV in the future

$|\sum U^2_{e\beta} m_\beta| < 0.3$ eV: COUORE, NEMO3, EXO, KamLAND Zen (2012)



Neutrinoless ββ

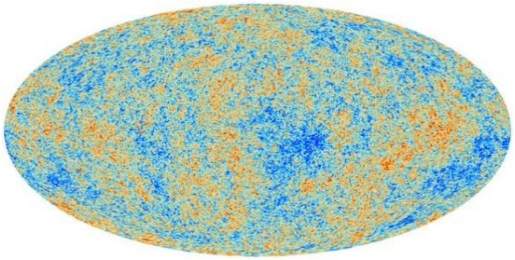
Strongly constrains mass hierarchy!
→ 0.1 eV in the future

- **CMB Anisotropies + LSS**

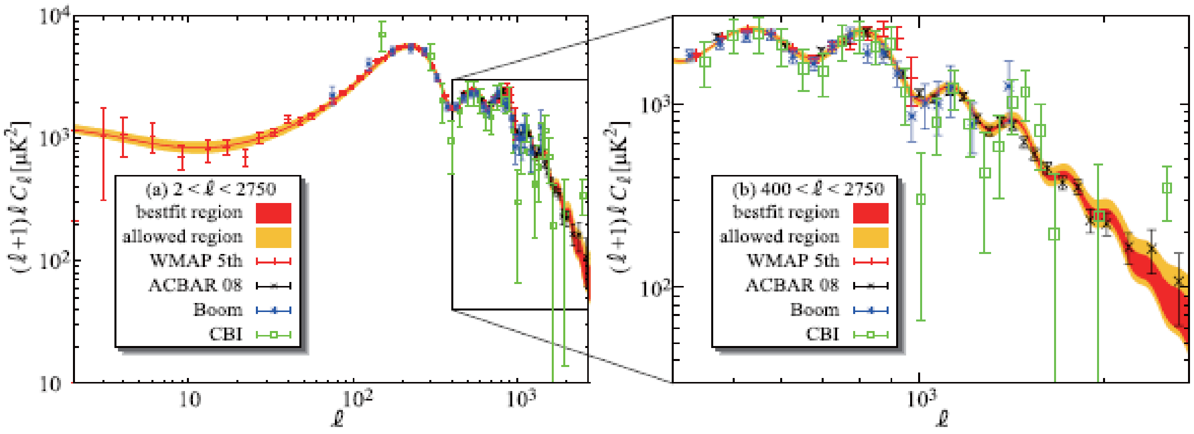
$\sum m_\nu < 0.36$ eV (95%C.L.): WMAP-7yr + HST + CMASS (Putter et al. arXiv:1201.1909)

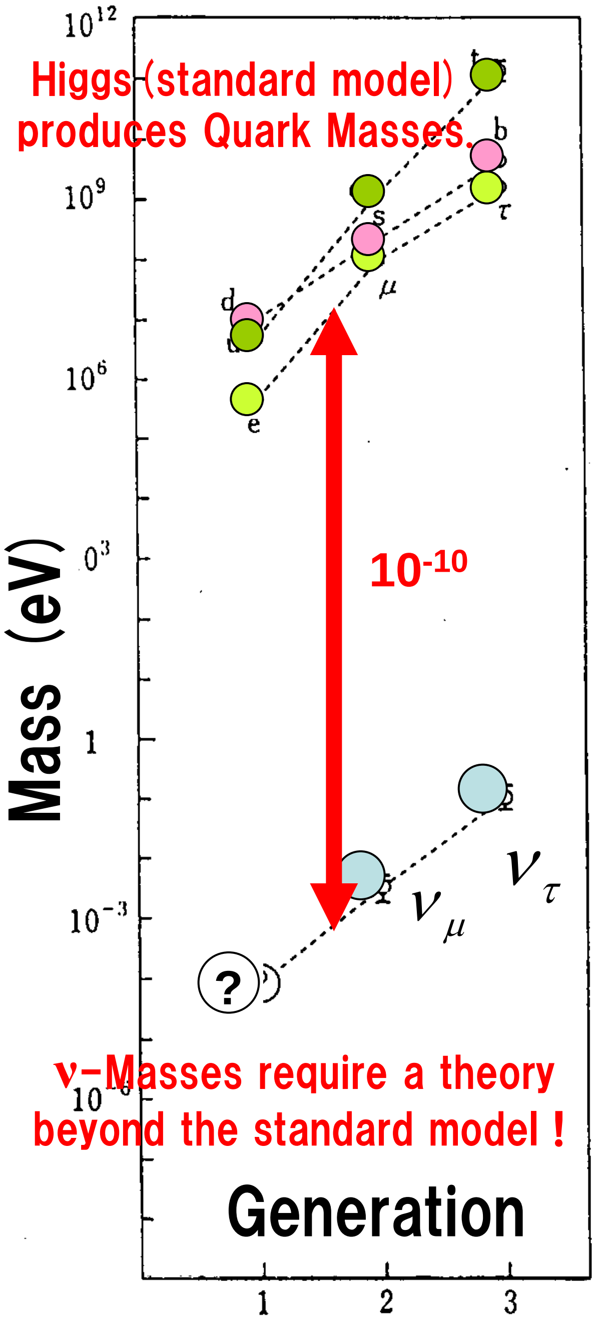
CMB Anisotropies & Polarization including Cosmic Magnetic Field

$\sum m_\nu < 0.2$ eV (2σ, B_λ<2nG): with Magnetic Field; Ymazaki, Kajino, Mathews & Ichiki, Phys. Rep. 517 (2012), 141; Phys. Rev. D81 (2010), 103519.



www.esa.int/Our_Activities/Space_Science/Planck/Planck_reveals_an_almost_perfect_Universe





Higgs (standard model) produces Quark Masses.

ν–Masses require a theory beyond the standard model !

$m_\nu \neq 0$ is the unique SIGNAL indicating a Model beyond the Standard Model !

Key Cosmology = beyond the standard model

What is Dark Matter, axion or SUSY ?

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

Why is cosmic expansion accelerating ?

Why 10^{-10} ?

Key Physics = beyond the standard model

Unification of elementary forces ?

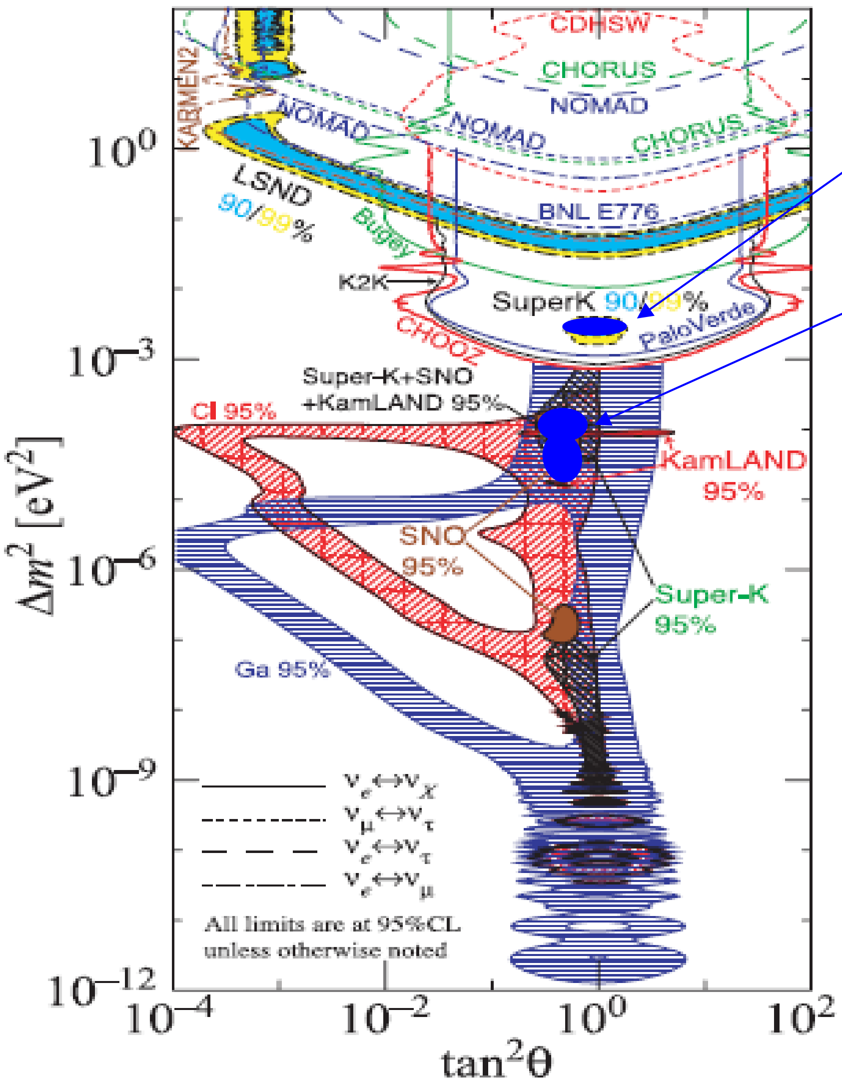
CP violation and Lepto– & Baryo–genesis ?

Why left–handed neutrinos, Majorana or Dirac ?

Explosion Mechanism of Supernovae ?

The "KNOWN" in Neutrino Oscillations

KAMIOKANDE, SK, KamLand (reactor ν), SNO determined $\varDelta m_{12}^2$ and θ_{12} uniquely: SK (atmospheric ν) determined $\varDelta m_{23}^2$ and θ_{23} uniquely.



23－mixing

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

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

12－mixing Cabibbo angle

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

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

"4 UNKNOWN"

1 2 3 4

~~13-mixing,~~ hierarchy, ~~δ_{CP}, mass~~

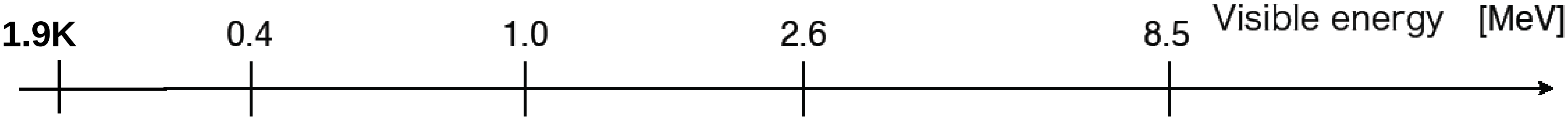
- $\sin^2 2\theta_{13} = 0.1 \pm 0.02$

T2K, MINOS, RENO, Dava Bay, Double Chooz

- $\varDelta m_{13}^2 = \pm 2.4 \times 10^{-3}\ \mathrm{eV}^2$?
- ~~δ－CP violation phase~~
- ~~Absolute Mass~~ 0νββ, cosmology

$E(\nu_\mu)=E(\nu_\tau)$: Yokomakura et al., PLB544, 286.

Various Neutrino-Sources in Nature/Culture



neutrino electron elastic scattering

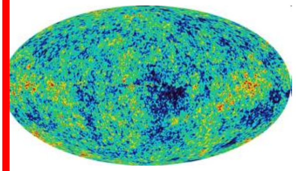
$\nu + e^- \rightarrow \nu + e^-$

inverse beta decay

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

CMB

Cosmic Background



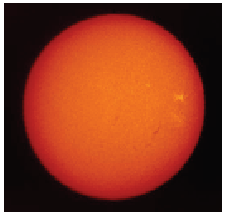
Neutrino Cosmology

verification
of particle model

ν_e, ν_μ, ν_τ

$\bar{\nu}_e, \bar{\nu}_\mu, \bar{\nu}_\tau$

^{7}Be solar neutrino

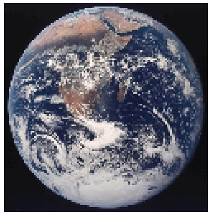


Neutrino Astrophysics

verification of SSM

ν_e

atmospheric neutrino
geo-neutrino



Neutrino Geophysics

verification of earth
evolution model

$\bar{\nu}_e$ or $\nu_e\ \nu_\mu\ \bar{\nu}_e\ \bar{\nu}_\mu$

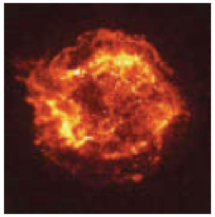
reactor neutrino

Neutrino Physics

Precision measurement
of oscillation parameters

$\bar{\nu}_e$

supernova relic neutrino
etc.



Neutrino Cosmology

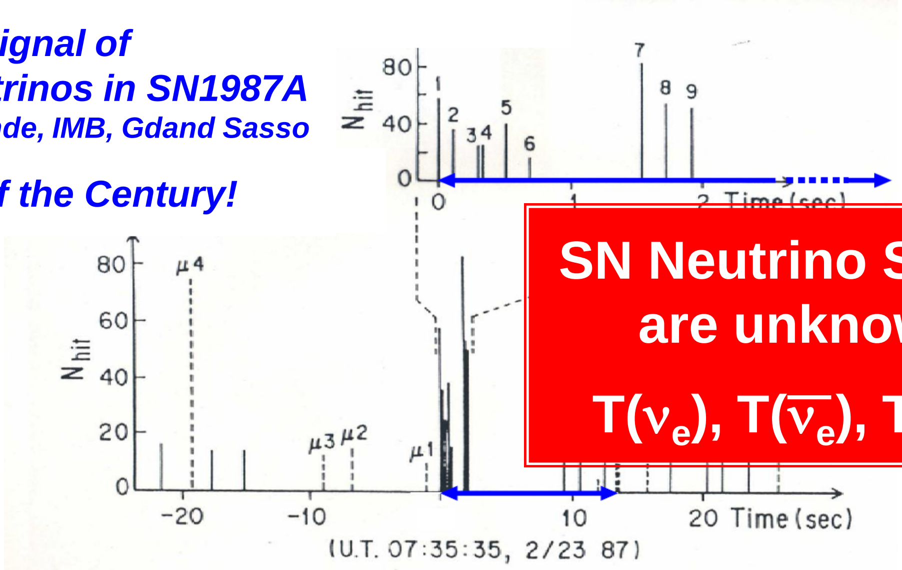
verification of
universe evolution

ν_e, ν_μ, ν_τ

$\bar{\nu}_e, \bar{\nu}_\mu, \bar{\nu}_\tau$

Direct signal of
SN neutrinos in SN1987A
Kamiokande, IMB, Gdand Sasso

Event of the Century!



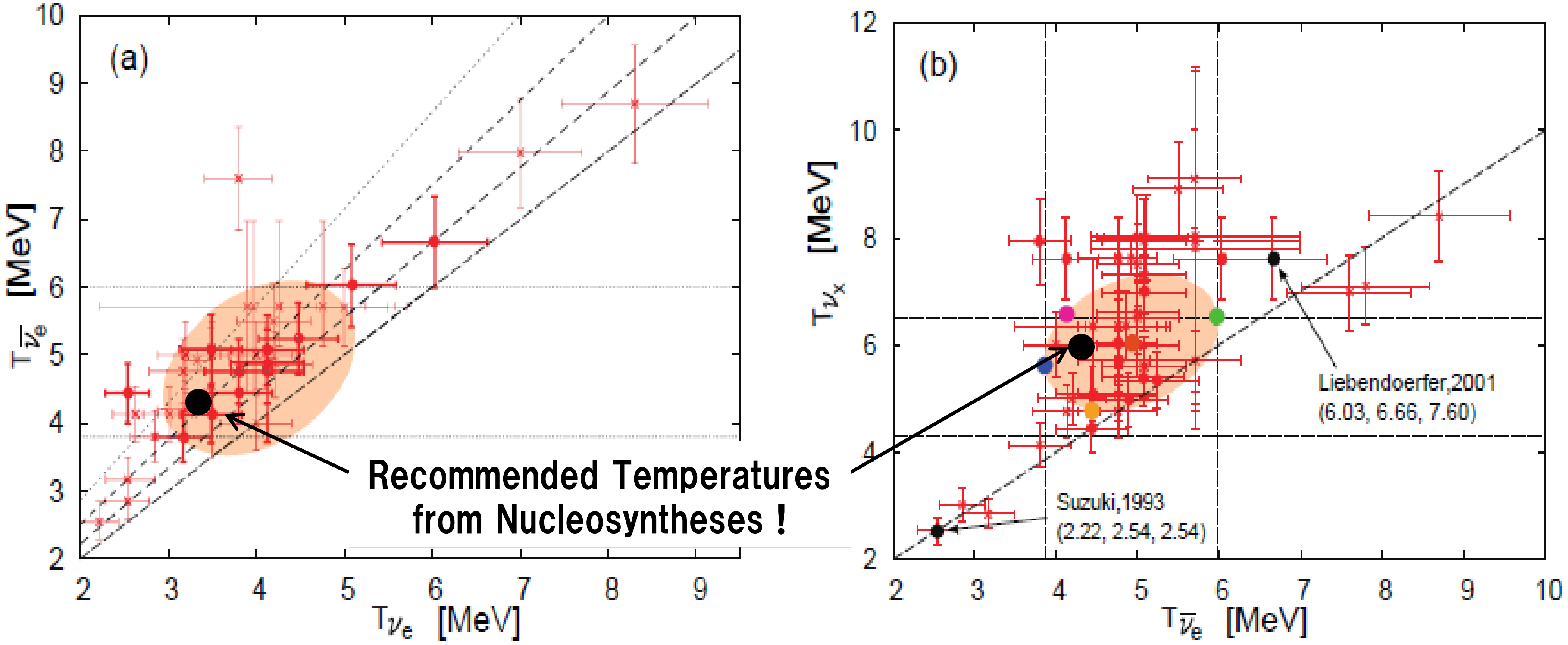
SN Neutrino Spectra
are unknown !

T(ν_e), T($\bar{\nu}_e$), T(ν_x) ?

By courtesy of K. Inoue

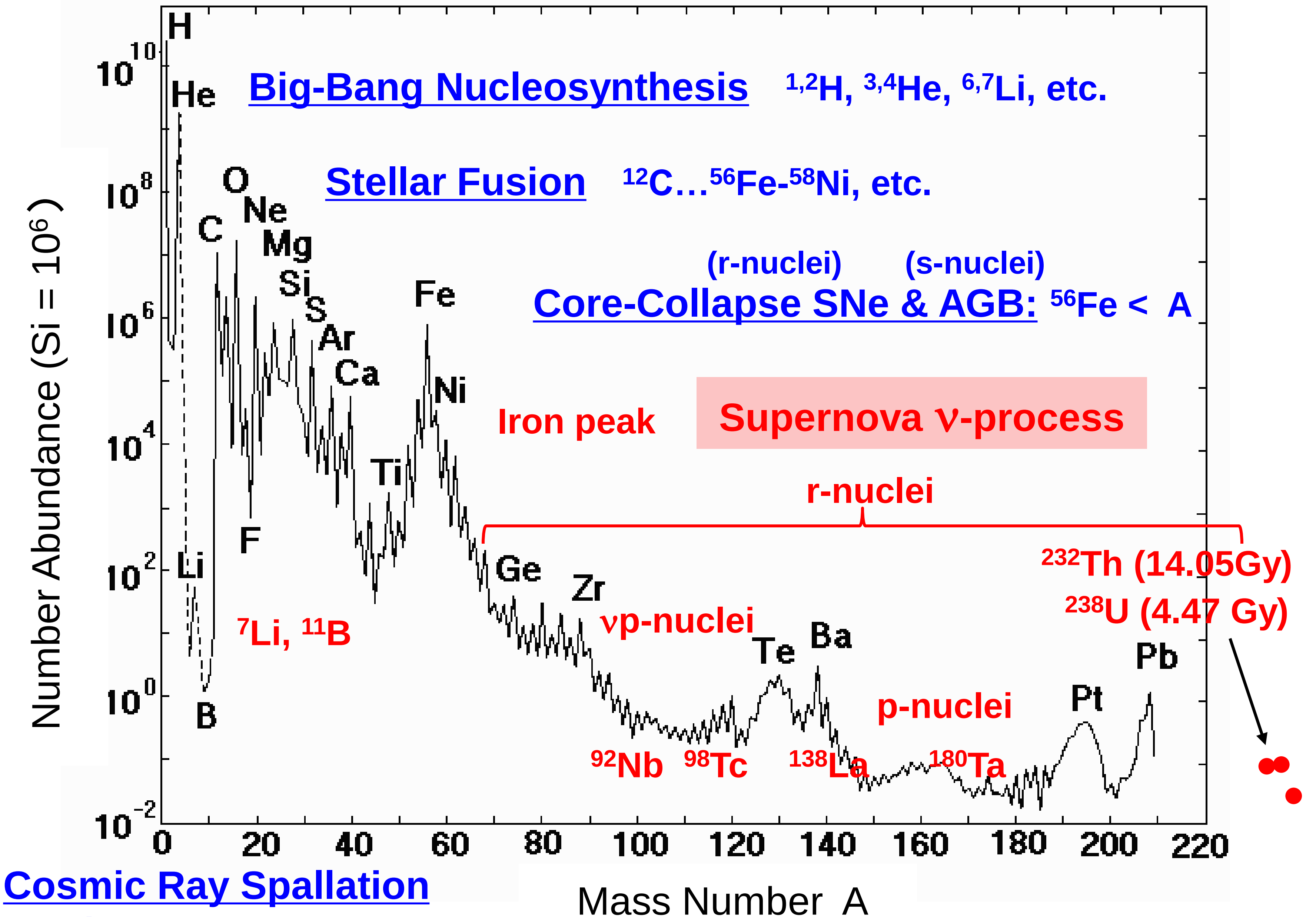
	Electron-capture SN (Faint SnNe)	Normal CC-SNe (Neutron Star fromation)	Failed Sne (Black Hole formation)		Pair-ν heated SNe (BH + Acc. Disk)
detail	ONeMg SN	CC-SN	fSN(SH EOS)	fSN(LS EOS)	GRB
mass($M_\odot$)	(8 ∼ 10)	8 ∼ 25(10∼25)	25 ∼ 125 (99.96%)	25 ∼ 125 (99.96%)	25 ∼ 125 (0.04%)
Remnant	Neutron Star	Neutron Star	Black Hole	Black Hole	Black Hole
Phenomenon	Supernova	Supernova	Failed Supernova	Failed Supernova	Gamma-Ray Burst
T_{ν_e}(MeV)	3.0	3.2	5.5	7.9	3.2
$T_{\bar{\nu}_e}$(MeV)	3.6	4.0	5.6	8.0	5.3
T_{ν_x}(MeV)	3.6	6.0	6.5	11.3	4.4
$E^{total}_{\nu_e}$(erg)	3.3×10^{52}	5.0×10^{52}	5.5×10^{52}	8.4×10^{52}	1.7×10^{53}
$E^{total}_{\bar{\nu}_e}$(erg)	2.7×10^{52}	5.0×10^{52}	4.7×10^{52}	7.5×10^{52}	3.2×10^{53}
$E^{total}_{\nu_x}$(erg)	1.1×10^{53}	5.0×10^{52}	2.3×10^{52}	2.7×10^{52}	1.9×10^{52}
△ t	few s	few s	$\sim 0.5s$	$\sim 0.5s$	$\sim 10s$

■ CC-SNe: Yoshida, et al., ApJ 686 (2008), 448; Suzuki & Kajino, J. Phys. G40 (2013) 83101 +



Recommended Temperatures
from Nucleosyntheses !

Solar System Abundance



Big-Bang Nucleosynthesis ^{1,2}H, ^{3,4}He, ^{6,7}Li, etc.

Stellar Fusion ^{12}C…^{56}Fe-^{58}Ni, etc.

(r-nuclei) (s-nuclei)

Core-Collapse SNe & AGB: $^{56}\mathrm{Fe} < A$

Iron peak

Supernova ν-process

r-nuclei

^{232}Th (14.05Gy)

^{238}U (4.47 Gy)

^{7}Li, ^{11}B

νp-nuclei

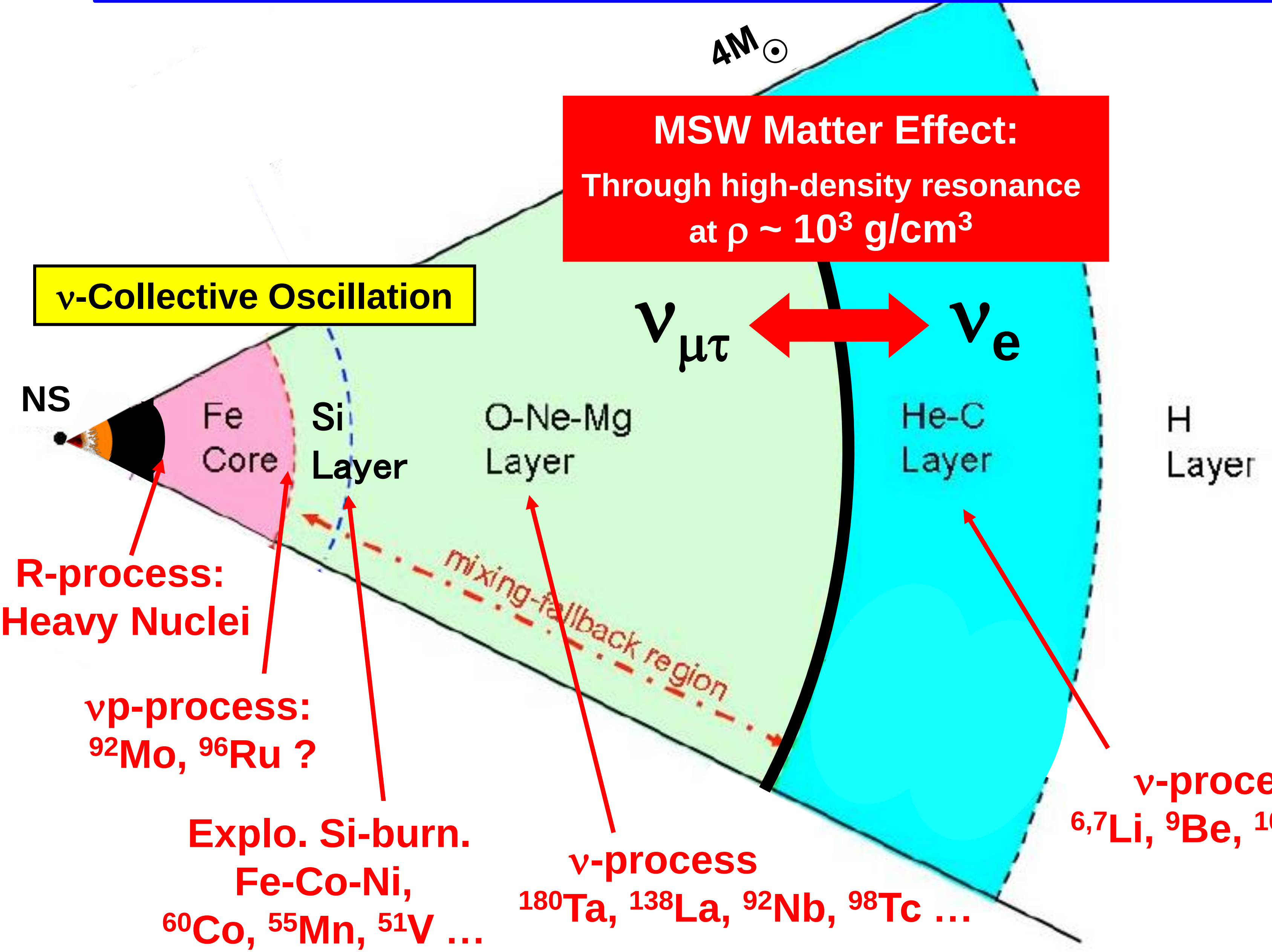
p-nuclei

^{92}Nb ^{98}Tc ^{138}La ^{180}Ta

Cosmic Ray Spallation

Li-Be-B, F, Na, etc.

Various roles of ν’s in SN-nucleosynthesis



MSW Matter Effect:

Through high-density resonance at $\rho \sim 10^3$ g/cm^3

ν-Collective Oscillation

R-process: Heavy Nuclei

νp-process: ^{92}Mo, ^{96}Ru ?

Explo. Si-burn. Fe-Co-Ni, ^{60}Co, ^{55}Mn, ^{51}V …

ν-process ^{180}Ta, ^{138}La, ^{92}Nb, ^{98}Tc …

ν-process: ^{6,7}Li, ^{9}Be, ^{10,11}B …

^{92}Nb also has SN-ν Origin !

Hayakawa et al., ApJ 778 (2013) L1.

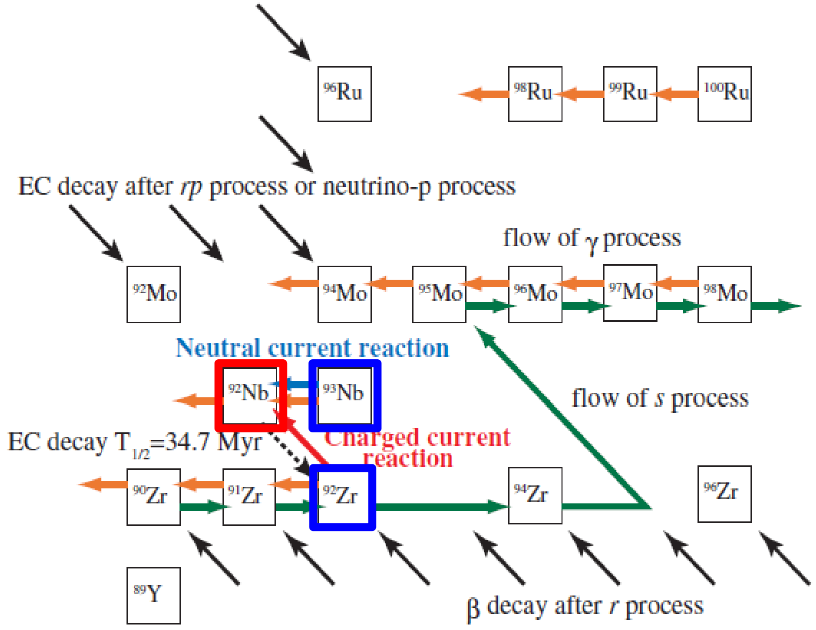
^{92}Nb ($\tau_{1/2}$=3.47x10^{7} y): Unique Chronometer of SN ν-Process

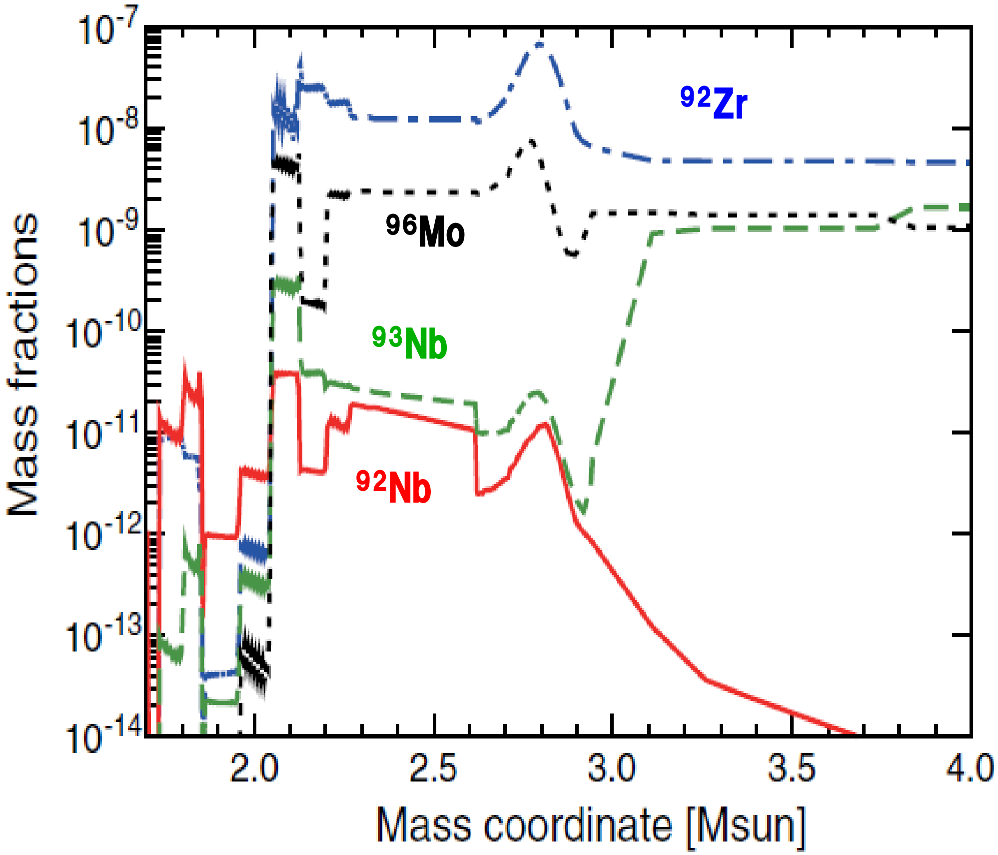
Isotopic anomaly in meteoritic ^{92}Zr/^{93}Nb:

Δ = 1x10^{6}—3x10^{7} y

Time duration after the last nearby Supernova to the Solar-System (protosolar cloud) formation

$T_{\nu e} = T_{\bar{\nu}e} = 4$ MeV





Tantalum (^{180,181}Ta)

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

The rarest isotope on the Earth & Universe !

Origin of ^{180}Ta was unknown since 1957.

S-process cannot explain both ^{180}Ta & ^{138}La !

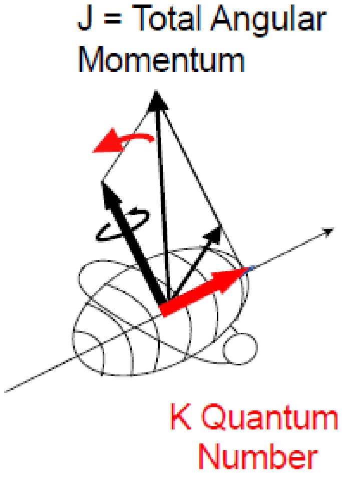
SN ν-process for overproduced ^{180}Ta/^{138}La ?

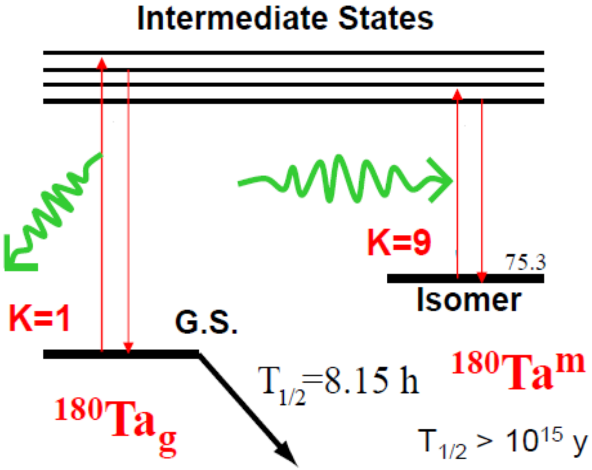
Solved by
$T_{\nu e}$ = 3.2 MeV,
$T_{\overline{\nu e}}$ = 4 MeV !

We solved dynamical "explosive SN-nucleosynthesis" coupled with "quantum transitions" simultaneously.

(Hayakawa, et al. 2010, PR C81, 052801®;
PR C82, 058801)

Bur





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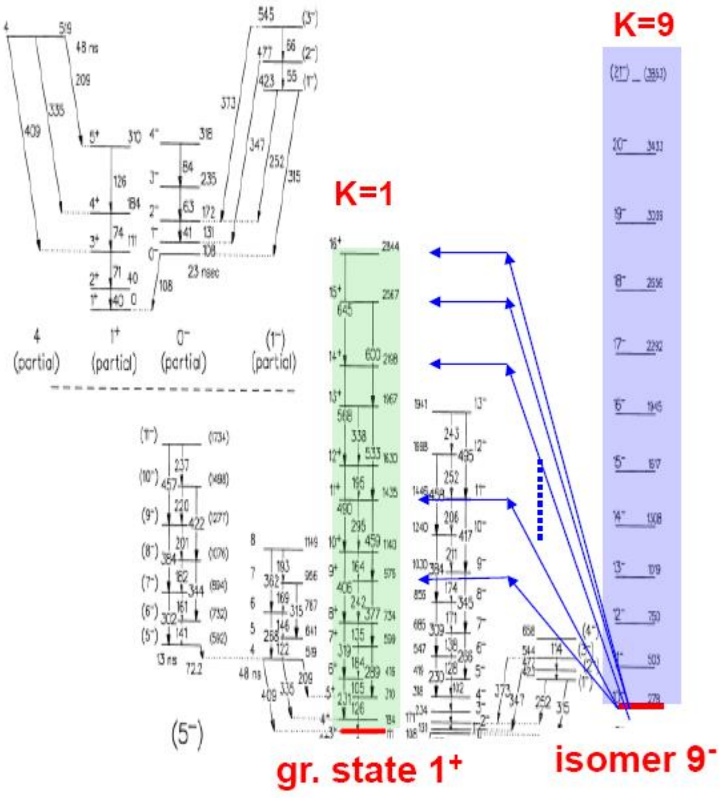
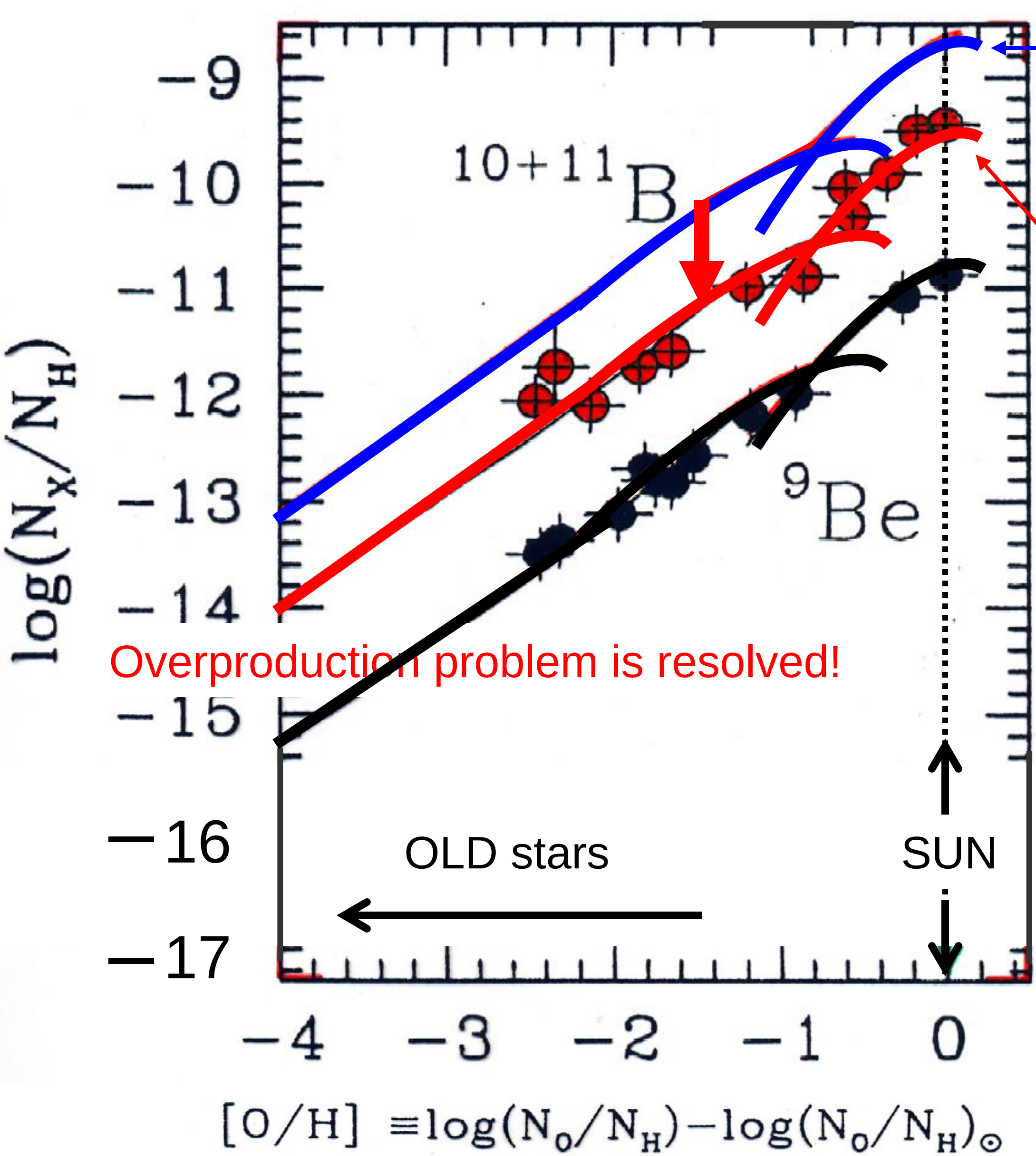


e

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



Overproduction problem is resolved!

Livermore Model

$T_{\nu_{\mu,\tau}}$ = 8 MeV

Woosley -Weaver 1995, ApJS 101, 181.

$\sigma \propto E_\nu^2$

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

Consistent with SN1987A

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

Consistent with SN1987A

^{9}Be:

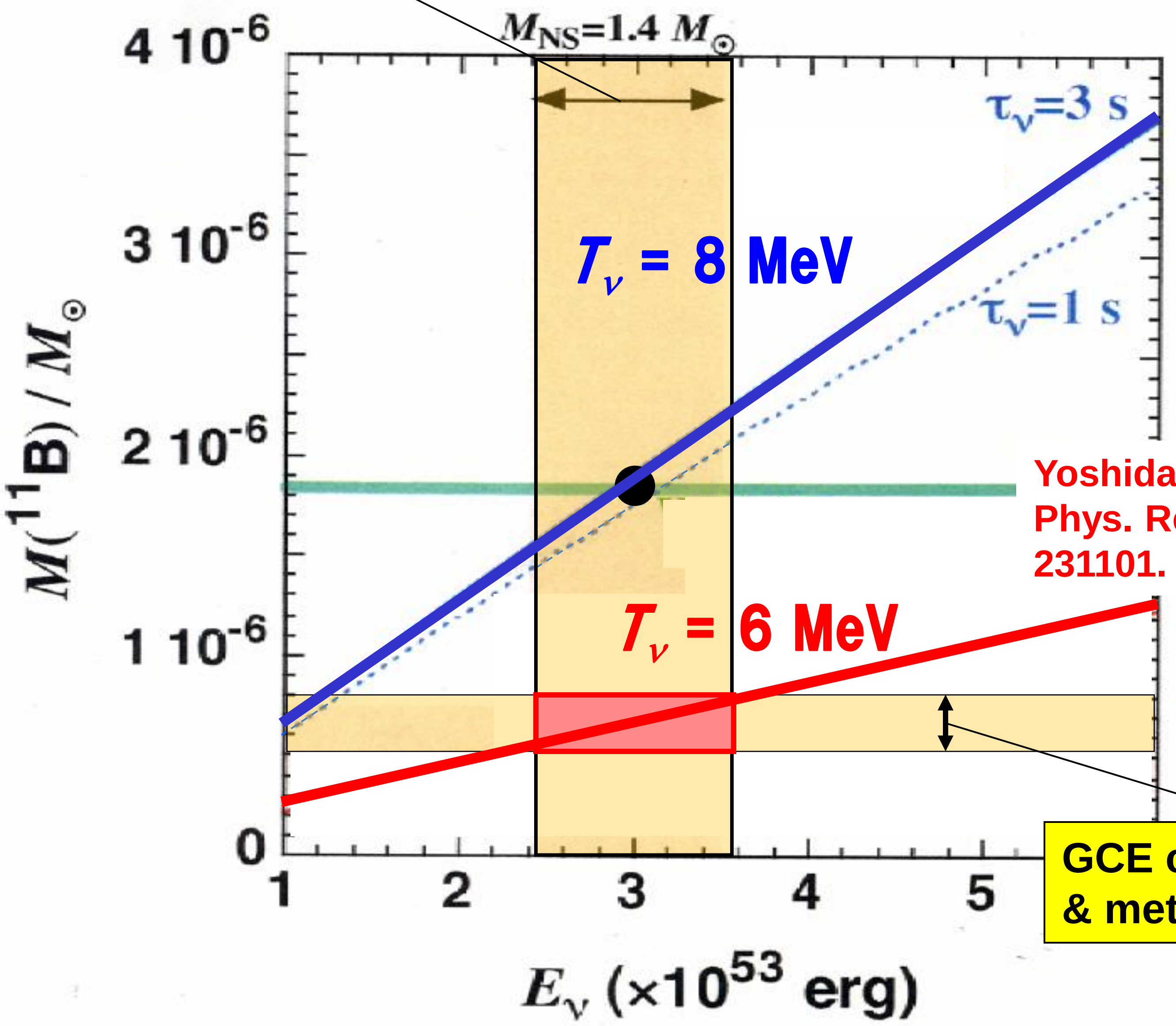
- Galactic Cosmic Rays

$^{10+11}$B + ^{11}B:

- Galactic Cosmic Rays
- Supernova ν–process

Yoshii, Kajino, Ryan, 1997, ApJ 486, 605.
Ryan, Kajino, Suzuki, 2001, ApJ549, 55.

SN-Boron calculations and constraints on SN- ν



SN1987A constraint on $E_{\nu,tot}$ & Grav. Energy

Woosley & Weaver ApJS 101 (1995), 181.

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

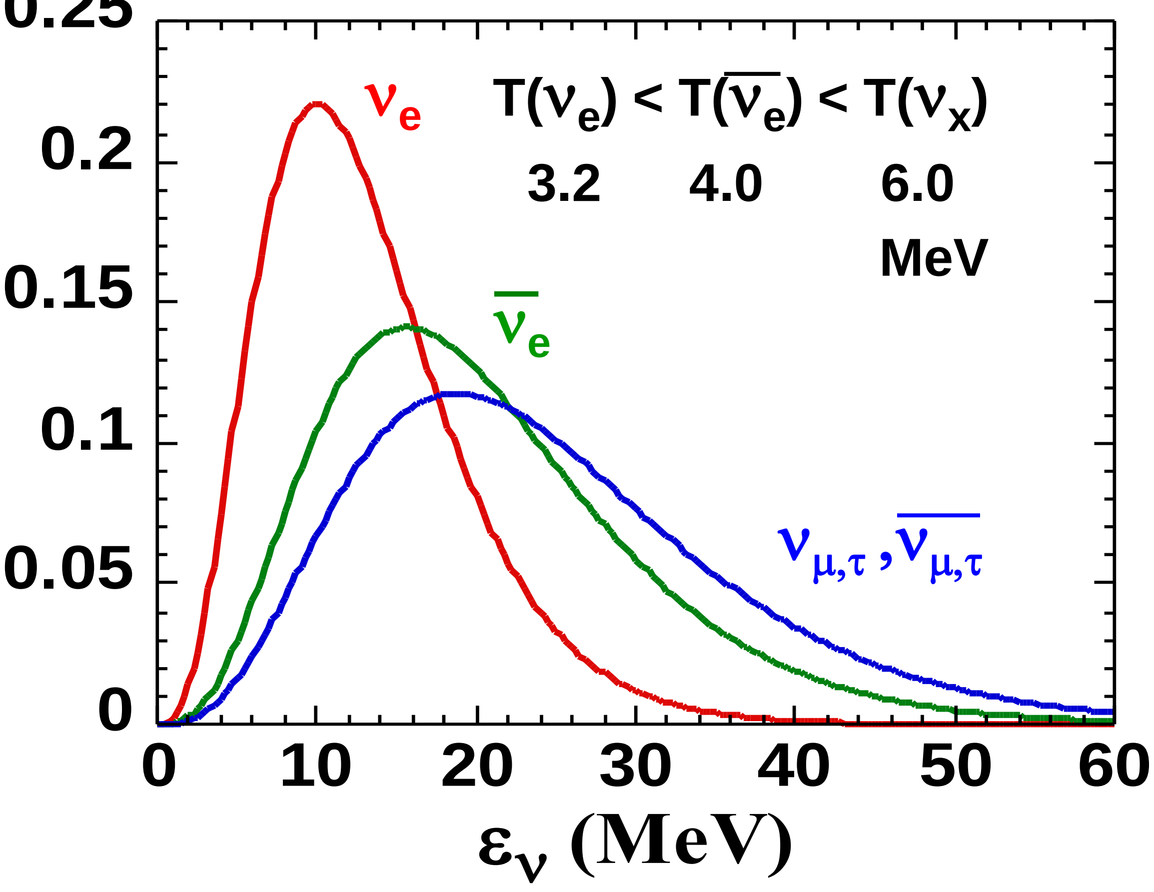
Consistent with SN simulation (MPA group) 2004-2013.

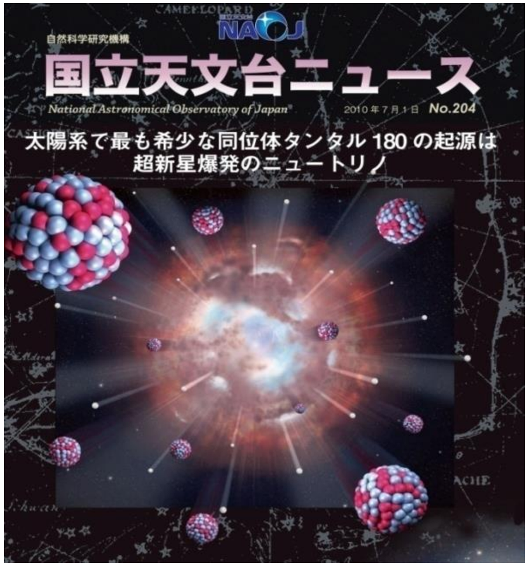
GCE constraints on ^{11}B & meteoritic ^{11}B/^{10}B

Mean ν-temperatures are known!

- R-process Elements & ^{180}Ta/^{138}La ➡ $T\nu_e = 3.2$ MeV, $T\overline{\nu}_e = 4$ MeV
- Astron. GCE of Light Elements & ^{11}B ➡ $T\nu_{\mu,} = T\nu_\tau = 6$ MeV

We can now study the "EOS" and "Neutrino Oscillation" !





自然科学研究機構
国立天文台ニュース
National Astronomical Observatory of Japan
2010年7月1日 No.204

太陽系で最も希少な同位体タンタル 180 の起源は
超新星爆発のニュートリノ

The Science News 科 学 新 聞 2010年（平成22年）5月28日（金曜日） 第3293号

太陽系で最も希少な同位体 タンタル180

超新星爆発のニュートリノで生成

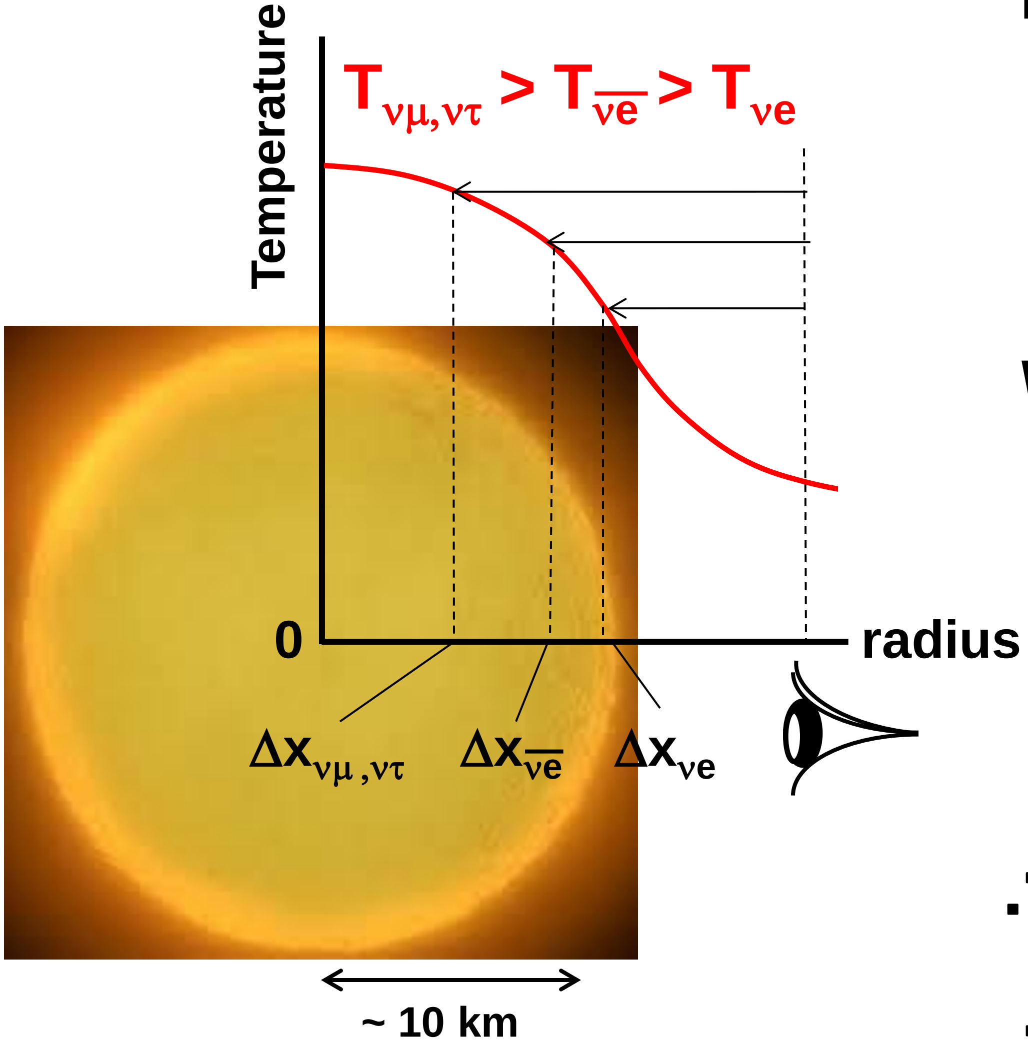
原子力機構 国立天文台

起源の謎を理論的に解明

科学新聞

電波の日・情報通信月間特集 5面

Temperature Hierarchy of Supernova− ν



Proto-Neutron Star

Neutrino diffusion process

$$\Delta x_\nu^2 = 2 D_\nu \tau_\nu$$

$$D_\nu = \lambda_\nu c/3$$

$$\lambda_\nu = (n_T\, \sigma_\nu)^{-1}$$

Weak interactions

$$\nu_e + n \rightarrow p + e^- \text{ (CC)}$$

$$\overline{\nu}_e + p \rightarrow n + e^+ \text{ (CC)}$$

$$\nu_i + p,n \rightarrow p,n + \nu_i \text{ (NC)}$$

$(i = e, \mu, \tau)$

$$\therefore\ \lambda_{\nu e} < \lambda_{\overline{\nu e}} < \lambda_{\nu\mu,\nu\tau}$$

$$\therefore\ \Delta x_{\nu e}^2 < \Delta x_{\overline{\nu e}}^2 < \Delta x_{\nu\mu,\nu\tau}^{\ 2}$$

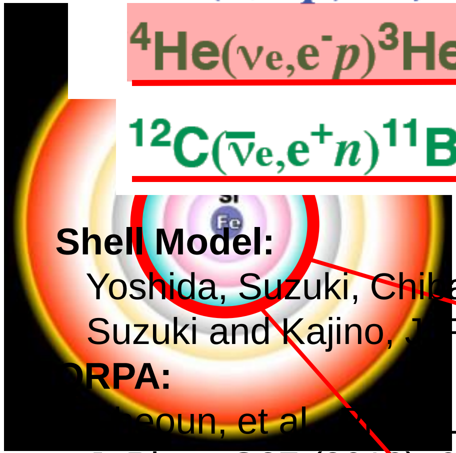
Supernova ν−Process: ^{7}Li, ^{11}B, ^{92}Nb, ^{138}La, ^{180}Ta

^{4}He(ν,ν'*p*)^{3}H, ^{4}He

$|\Delta m^2_{13}| = |\Delta m^2_{23}| = 2.4 \times 10^{-3}\ \mathrm{eV}^2$

^{4}He(νe,e$^-$*p*)^{3}He, ^{4}He($\overline{\nu}$e,e$^+$*n*)^{3}H, ^{12}C(νe,e$^-$*p*)^{11}C,

^{12}C($\overline{\nu}$e,e$^+$*n*)^{11}B



$$2\sqrt{2}G_F(\hbar c)^3\varepsilon_\nu$$

$$= 6.55 \times 10^6 \left(\frac{\Delta m^2_{ji}}{1\ \mathrm{eV}^2}\right)\left(\frac{1\ \mathrm{MeV}}{\varepsilon_\nu}\right)\cos 2\theta_{ij}$$

Shell Model:

Yoshida, Suzuki, Chiba, Kajino, et al., ApJ 686 (2008), 448:

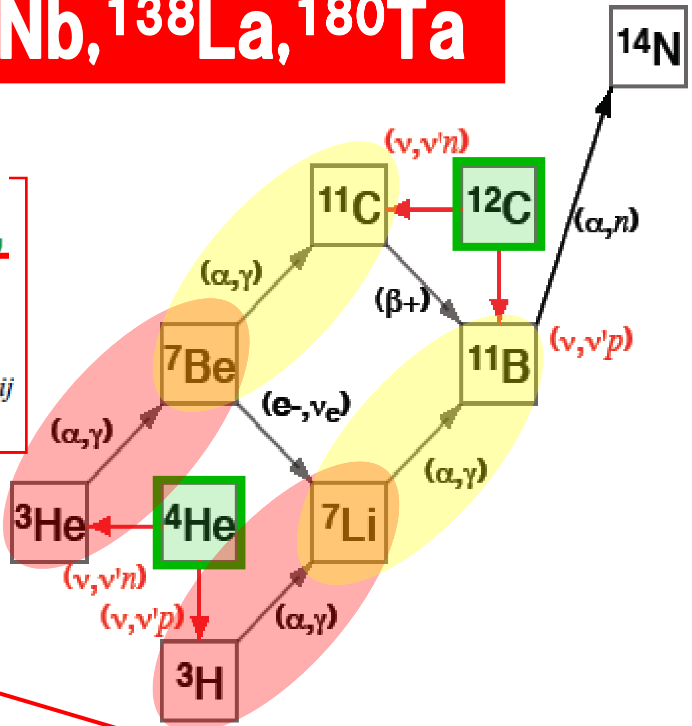
Suzuki and Kajino, J. Phys. G40 (2013), 083101:

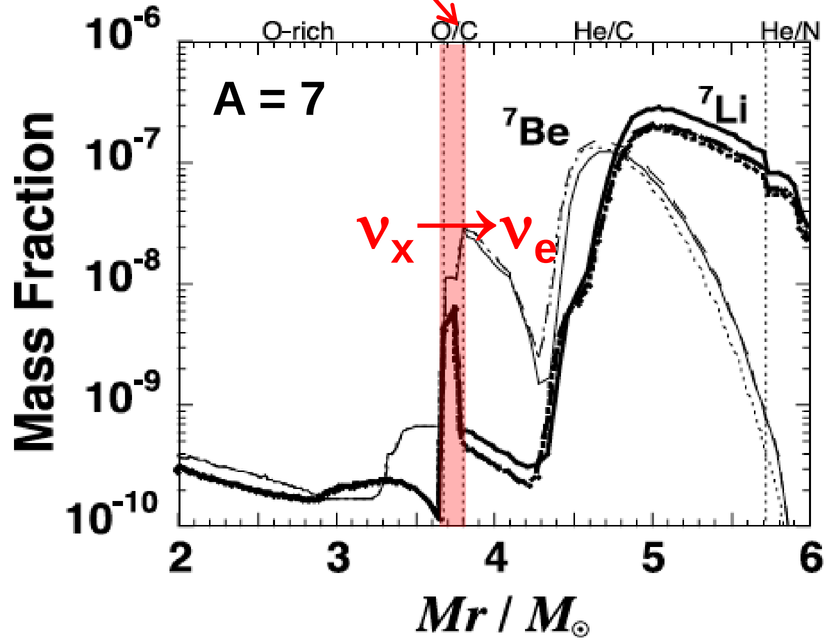
RPA:

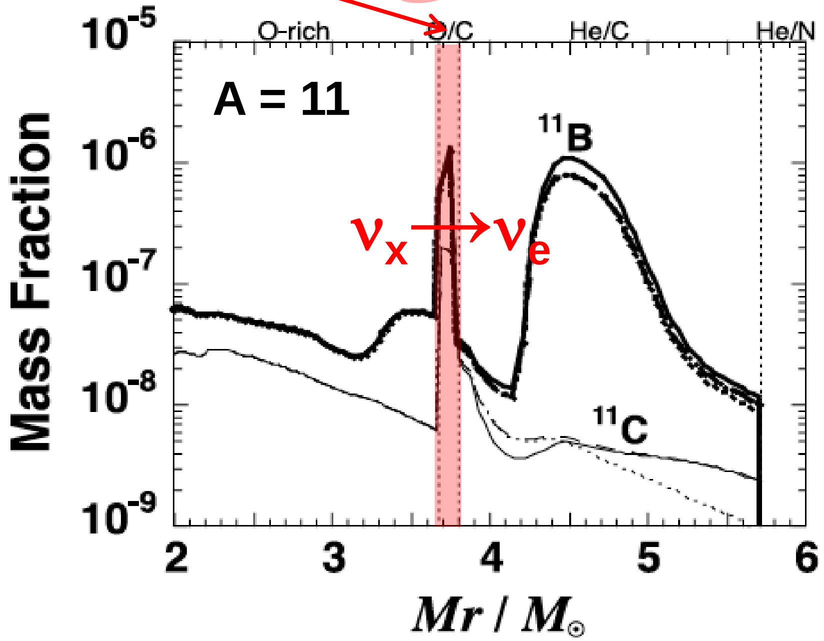
eoun, et al. 1 (2010), 028501; PRC82 (2010), 035504;

J. Phys. G37 (2010), 055101; PRC 83 (2011), 028801

MSW high-density resonance is located at the bottom of He/C shell at ρ ~ 10^3—10^4 g/cm^3.







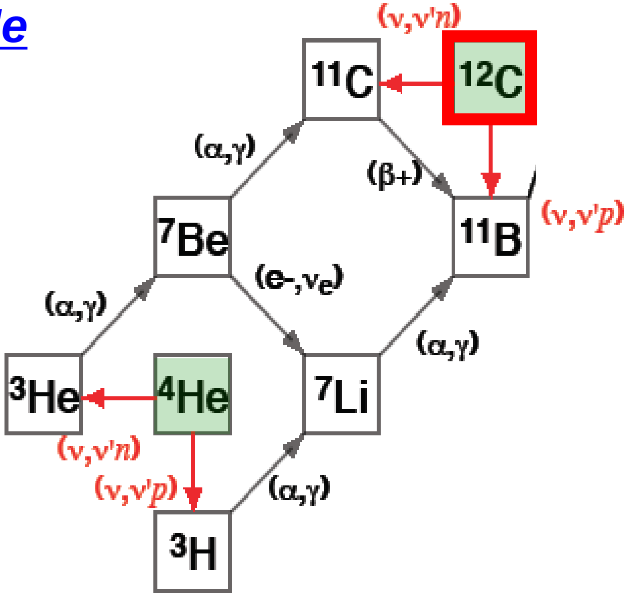
Role of Nucl. Phys. for ν–Nucleus X-Sections

New Shell Model cal. with NEW Hamiltonian: *ν -^{12}C, ^{4}He*

Suzuki, Chiba, Yoshida, Kajino & Otsuka, PR C74 (2006), 034307.
Suzuki, Fujimoto & Otsuka, PR C67, 044302 (2003)

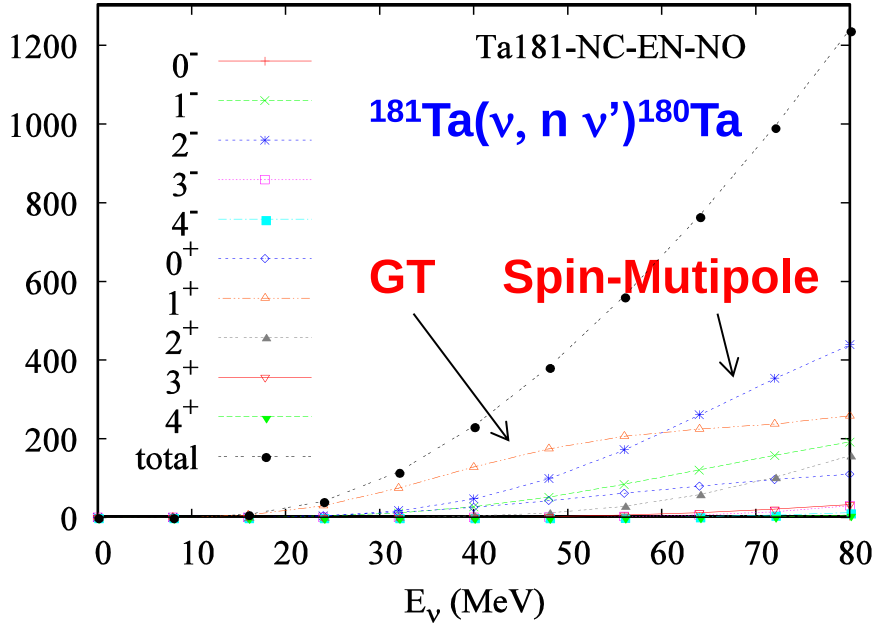
^{12}C: New Hamiltonian = Spin-isospin flip int. with tensor force to explain neutron-rich exotic nuclei.

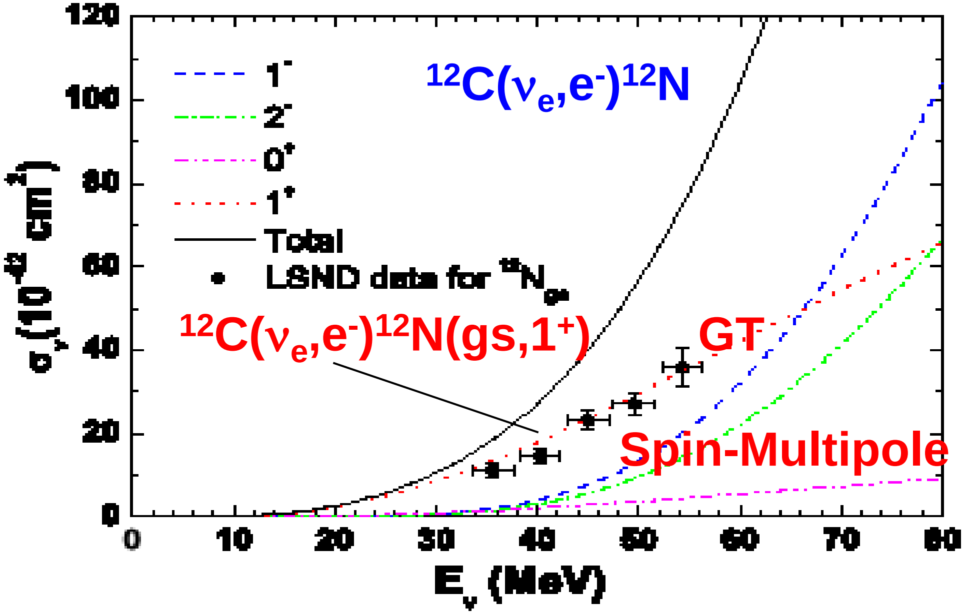
- μ-moments of p-shell nuclei
- GT strength for $^{12}C \rightarrow ^{12}N$, $^{14}C \rightarrow ^{14}N$, etc. (GT)
- DAR (ν,ν'), (ν,e-) cross sections



QRPA cal.: *ν -^{180}Ta, ^{138}La, ^{98}Tc, ^{92}Nb, ^{42}Ca, ^{12}C, ^{4}He…*

Cheoun, et al., PRC81 (2010), 028501; PRC82 (2010), 035504:
J. Phys. G37 (2010), 055101; PRC 83 (2011), 028801





Double β decay – ν mass – Astro-Cosmology Connection

K. Yako et al., PRL 103 (2009) 012503.

B(GT$^{+/-}$) distribution

Shell model …

with quenched operator

Spectra agree qualitatively up to …

(p,n) : E_x = 15 MeV

(n,p) : 8 MeV

Strengths beyond … underestimated.

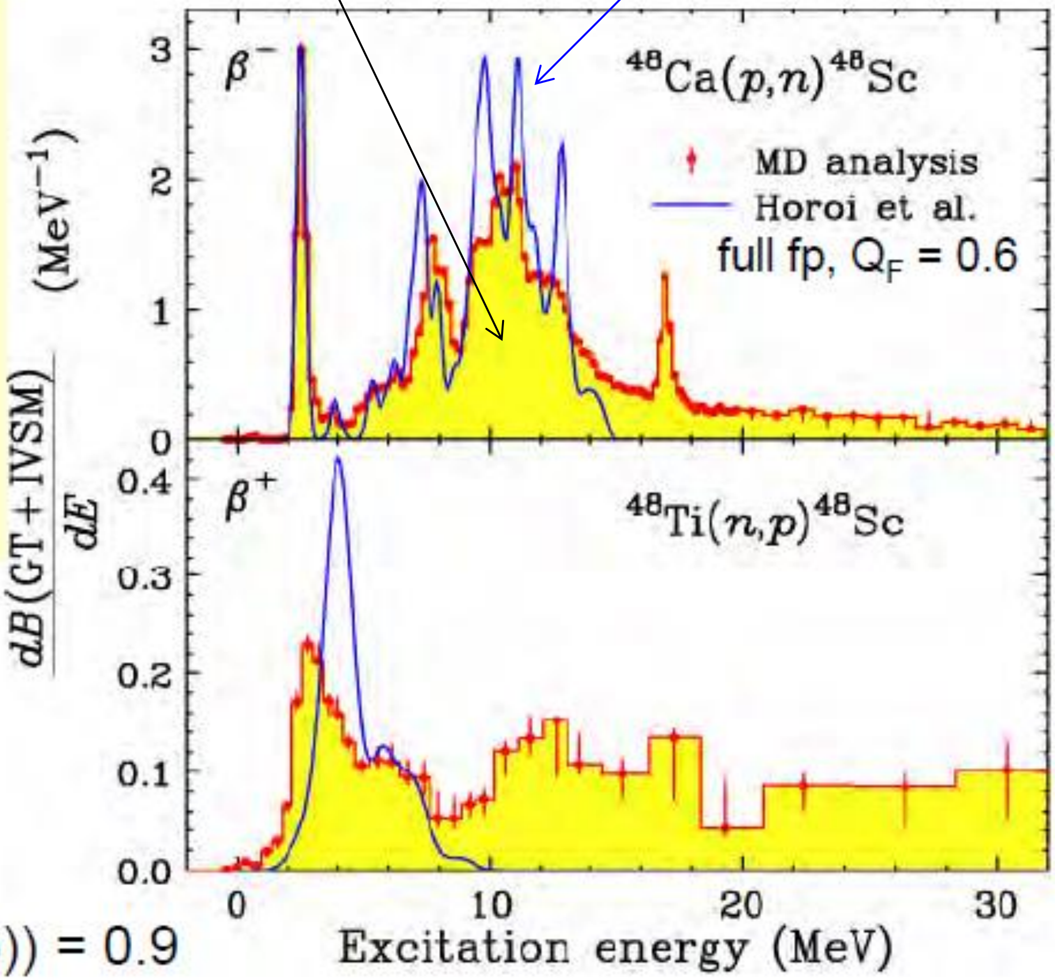
(n,p) channel :

$\Sigma B(GT^+;exp) = 1.9 \pm 0.3$…

(w subtraction of IVSM)

↕

$\Sigma B(GT^+;ShellModel(Q_F=0.6)) = 0.9$



Experiment (RCNP, Osaka)

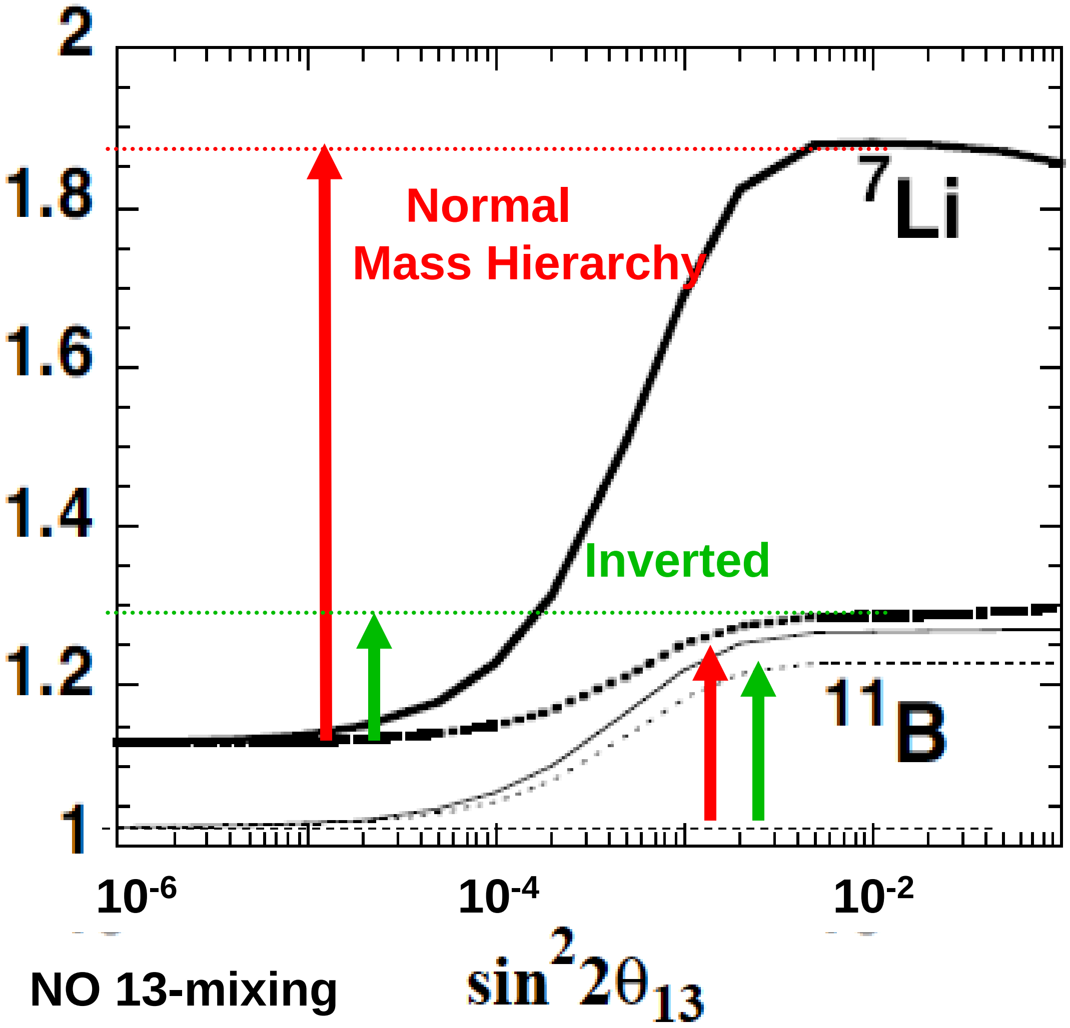
Shell model (theory)

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

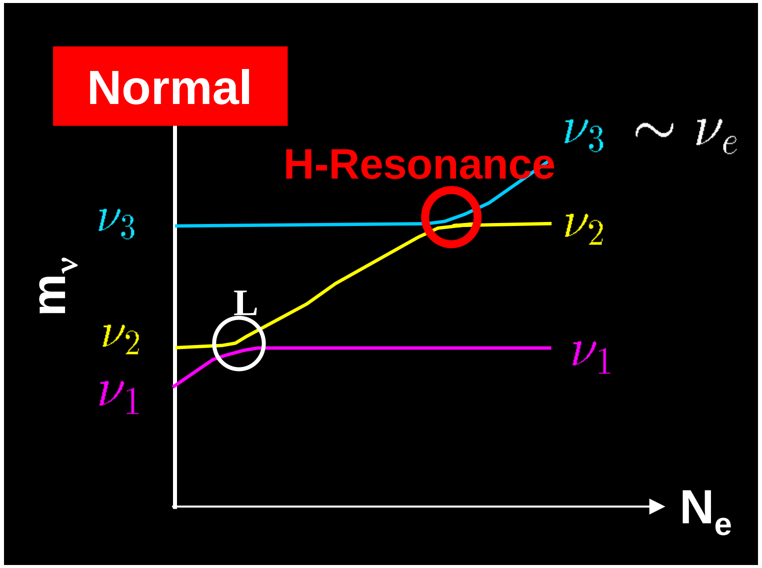
larger effect !

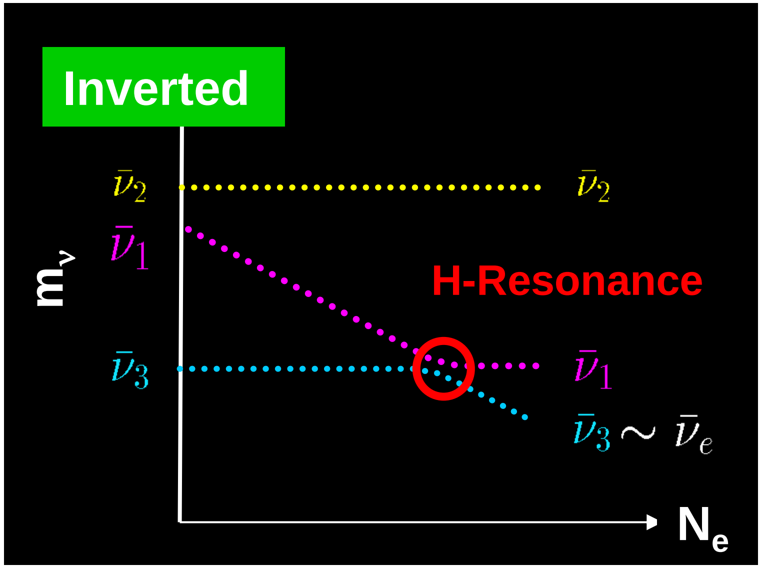
$T_{\nu e} < T_{\overline{\nu e}} < T_{\nu\mu\tau,\ \overline{\nu\mu\tau}}$

smaller effect !



NO 13-mixing





PHYSICAL REVIEW D 85, 105023 (2012)

Exploring the neutrino mass hierarchy probability with meteoritic supernova material, ν-process nucleosynthesis, and θ_{13} mixing

G. J. Mathews,[1,2] T. Kajino,[2,3] W. Aoki,[2] W. Fujiya,[4] and J. B. Pitts[5]

Bayesian Analysis, including astrophysical model dependence on SN progenitor masses, ν-temps. ($T_{\nu e}$,$T_{\nu e}$,$T_{\nu\mu\tau, \overline{\nu\mu\tau}}$) and nuclear input data.

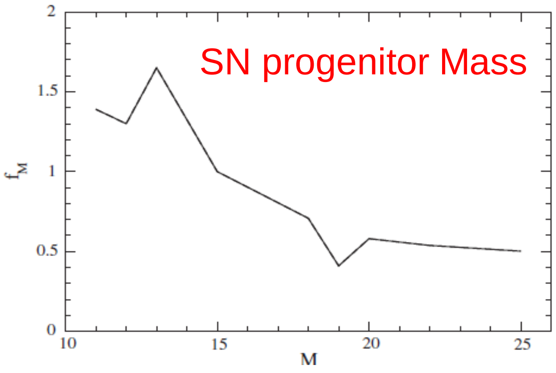
$$P(M_i|D) = \frac{P(D|M_i)P(M_i)}{\sum_j P(D|M_j)P(M_j)}$$

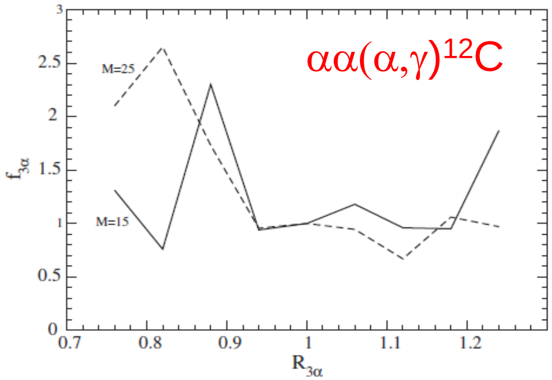
$$P(D|M_i) = \int dEdZda_k P(E,Z,D|M_i,a_k)P(a_k|M_i)$$

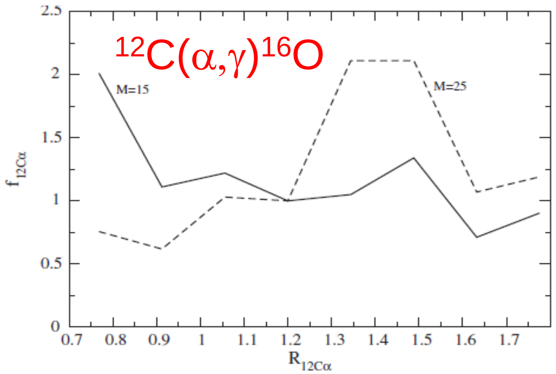
$$= \int dEdZda_k P(D|M_i,a_k,E,Z)P(Z,E|M_i,a_k)P(a|M_i)$$

TABLE I: Parameter likelihood functions $P(a_k|M_i)$.

Parameter a_k	prior			reference
$\sin^2 2\theta_{13}$	$e^{-(x-x_0)/2\sigma_x^2}$	$x_0 = 0.92$	$\sigma_x = 0.017$	[7]
$R_{3\alpha}$	$e^{-(x-x_0)/2\sigma_x^2}$	$x_0 = 1.0$	$\sigma_x = 0.12$	[35]
$R_{12C\alpha}$	$e^{-(x-x_0)/2\sigma_x^2}$	$x_0 = 1.2$	$\sigma_x = 0.25$	[36]
$M_{prog}(M_\odot)$	$m^{-2.65}$	$m_{min} = 10$	$m_{max} = 25$	[37]
T_ν(MeV)	Top hat	$T_\nu = 3.2 - 6.5$	(see text)	[15]

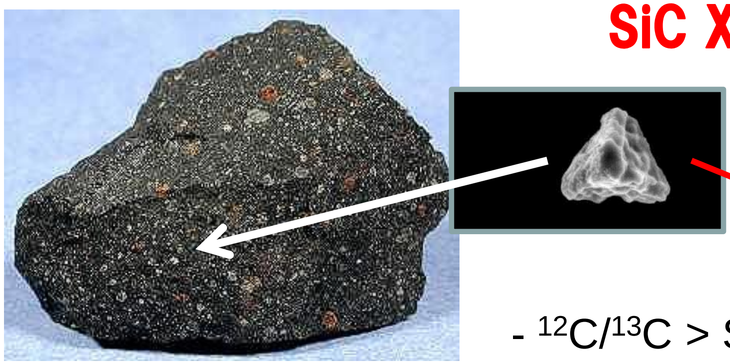




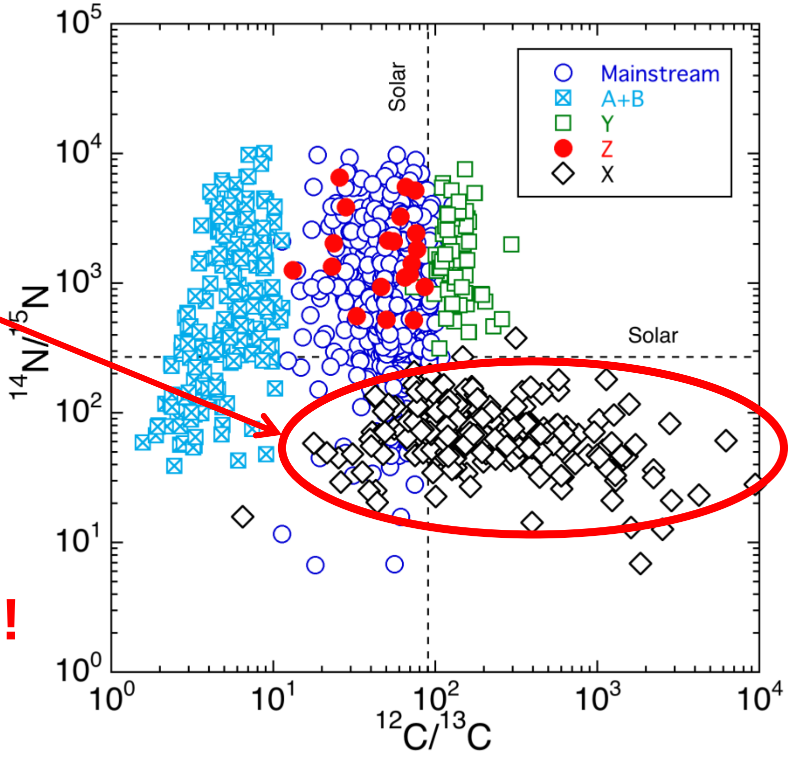


Murchison Meteorite

By courtesy of S. Amari



SiC X-grains



- $^{12}C/^{13}C$ > Solar
- $^{14}N/^{15}N$ < Solar

- Enhanced ^{28}Si
- Decay of ^{26}Al ($t_{1/2}=7\times10^5$yr), ^{44}Ti ($t_{1/2}$=60yr)

SiC X-grains are made of cc-SN Dust !

Fujiya, Hoppe and Ott (2011, ApJ 730, L7) discovered ^{11}B and ^{7}Li isotopes in 13 SiC X-grains.

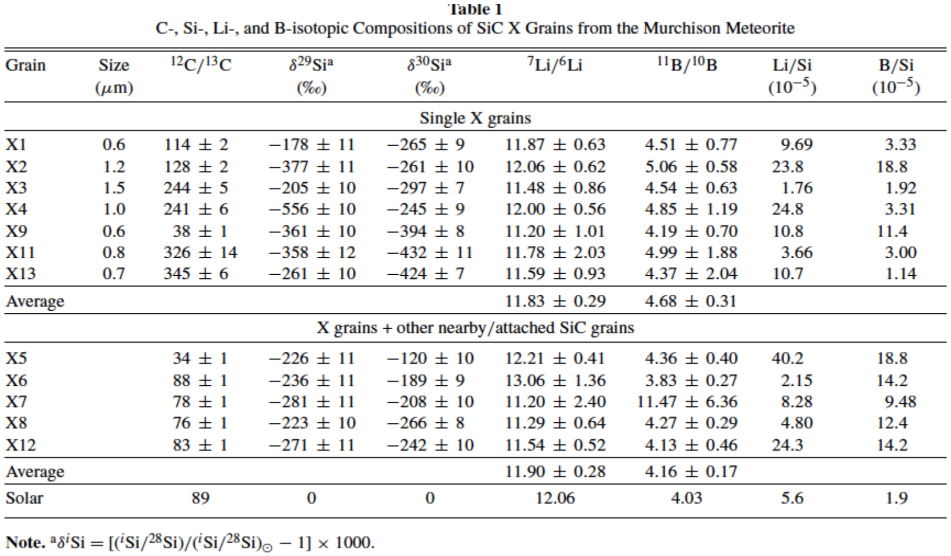
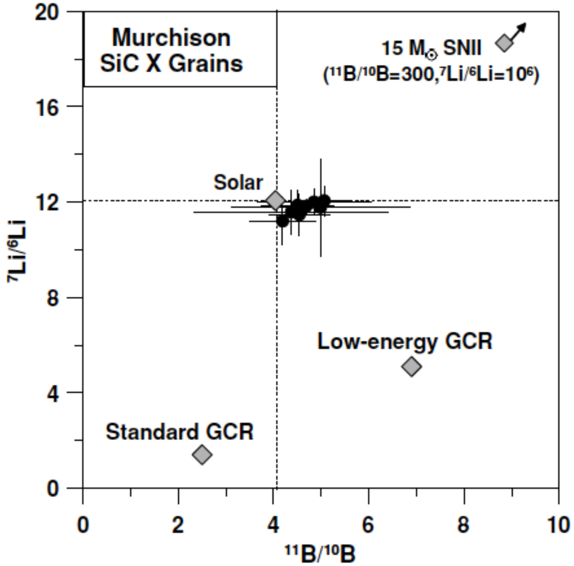


Table 1

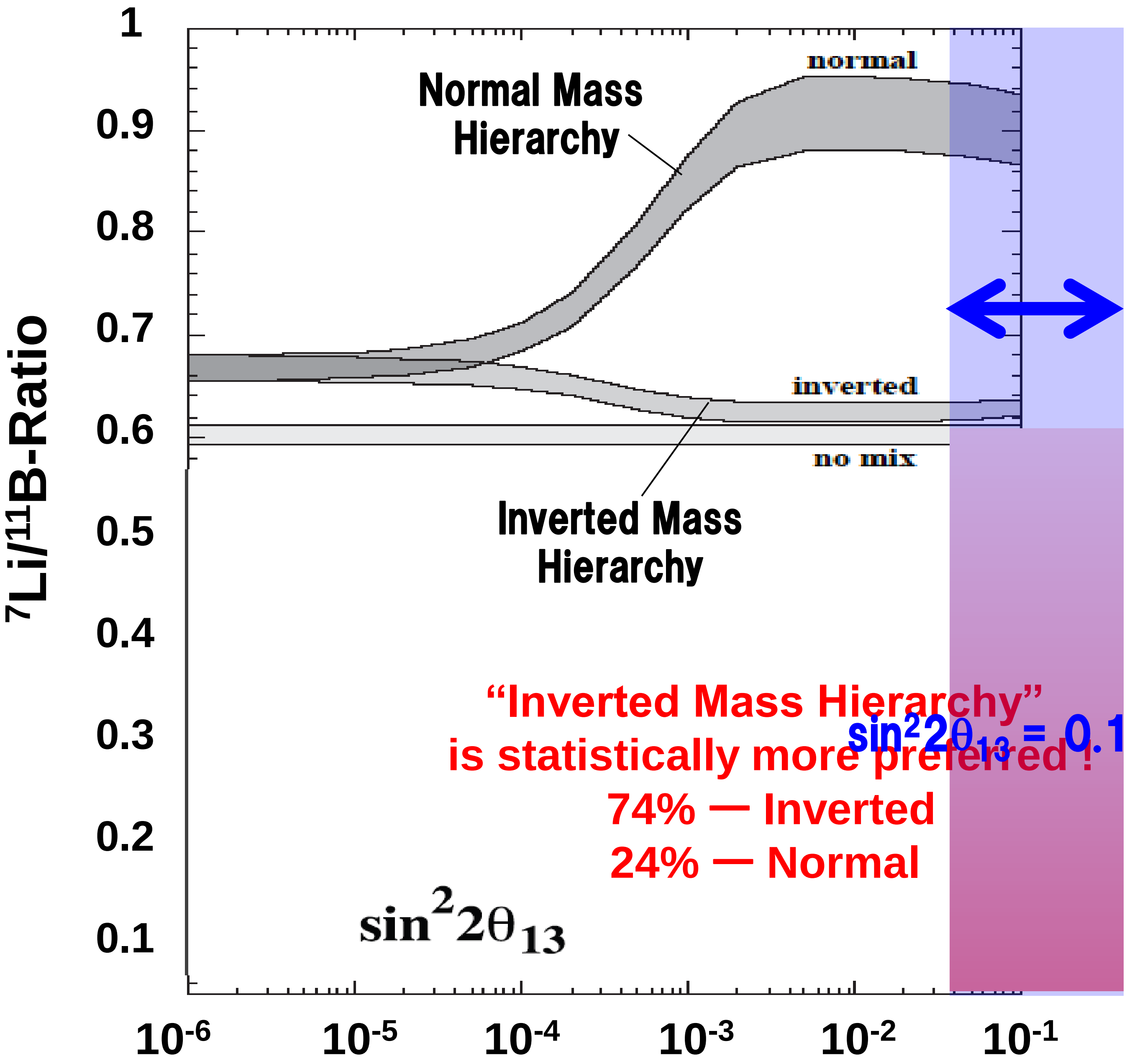
C-, Si-, Li-, and B-isotopic Compositions of SiC X Grains from the Murchison Meteorite

Grain	Size (μm)	$^{12}C/^{13}C$	$\delta^{29}Si^a$ (‰)	$\delta^{30}Si^a$ (‰)	$^7Li/^6Li$	$^{11}B/^{10}B$	Li/Si (10^{-5})	B/Si (10^{-5})
Single X grains								
X1	0.6	114 ± 2	−178 ± 11	−265 ± 9	11.87 ± 0.63	4.51 ± 0.77	9.69	3.33
X2	1.2	128 ± 2	−377 ± 11	−261 ± 10	12.06 ± 0.62	5.06 ± 0.58	23.8	18.8
X3	1.5	244 ± 5	−205 ± 10	−297 ± 7	11.48 ± 0.86	4.54 ± 0.63	1.76	1.92
X4	1.0	241 ± 6	−556 ± 10	−245 ± 9	12.00 ± 0.56	4.85 ± 1.19	24.8	3.31
X9	0.6	38 ± 1	−361 ± 10	−394 ± 8	11.20 ± 1.01	4.19 ± 0.70	10.8	11.4
X11	0.8	326 ± 14	−358 ± 12	−432 ± 11	11.78 ± 2.03	4.99 ± 1.88	3.66	3.00
X13	0.7	345 ± 6	−261 ± 10	−424 ± 7	11.59 ± 0.93	4.37 ± 2.04	10.7	1.14
Average					11.83 ± 0.29	4.68 ± 0.31		
X grains + other nearby/attached SiC grains								
X5		34 ± 1	−226 ± 11	−120 ± 10	12.21 ± 0.41	4.36 ± 0.40	40.2	18.8
X6		88 ± 1	−236 ± 11	−189 ± 9	13.06 ± 1.36	3.83 ± 0.27	2.15	14.2
X7		78 ± 1	−281 ± 11	−208 ± 10	11.20 ± 2.40	11.47 ± 6.36	8.28	9.48
X8		76 ± 1	−223 ± 10	−266 ± 8	11.29 ± 0.64	4.27 ± 0.29	4.80	12.4
X12		83 ± 1	−271 ± 11	−242 ± 10	11.54 ± 0.52	4.13 ± 0.46	24.3	14.2
Average					11.90 ± 0.28	4.16 ± 0.17		
Solar		89	0	0	12.06	4.03	5.6	1.9

Note. [a] $\delta^iSi = [(^iSi/^{28}Si)/(^iSi/^{28}Si)_\odot - 1] \times 1000$.



MSW Effect & ν Mass Hierarchy



"Inverted Mass Hierarchy"
is statistically more preferred !
74% — Inverted
24% — Normal

$\sin^2 2\theta_{13} = 0.1$

Mathews, Kajino, Aoki & Fujiya, PR D85, 105023 (2012);

Suzuki and Kajino, J. Phys. G40 (2013), 083101

First Detection of ^{7}Li/^{11}B in SN-grains

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

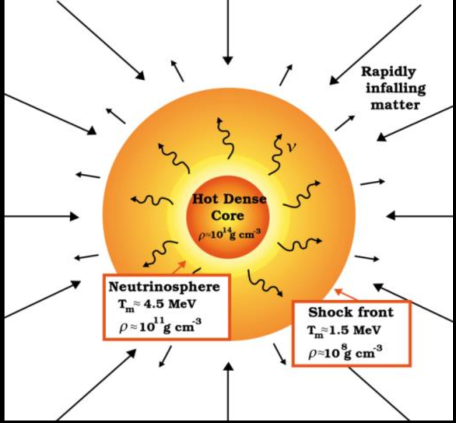
Long Baseline Exp. in 2011:

- T2K (Kamioka)
- MINOS

Reactor Exp. in2012:

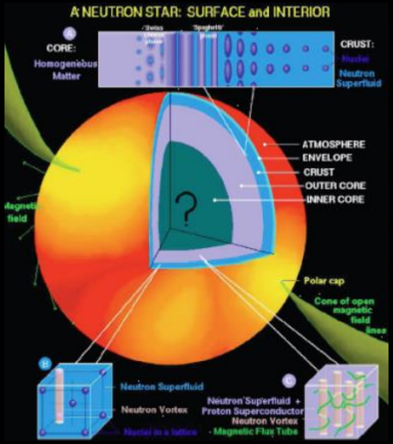
- Double CHOOZ
- Daya Bay
- RENO (KOREA)

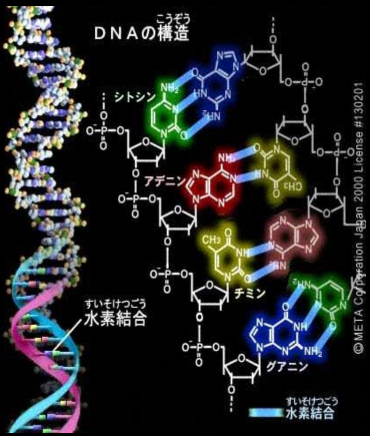
What happens as neutrinos flow through the SN outer layers ?



Neutrino induced nucleosynthesis to constrain ν-mass hierarchy.

Astrophysical sites for r-process including SNe, GRBs and neutron star mergers..

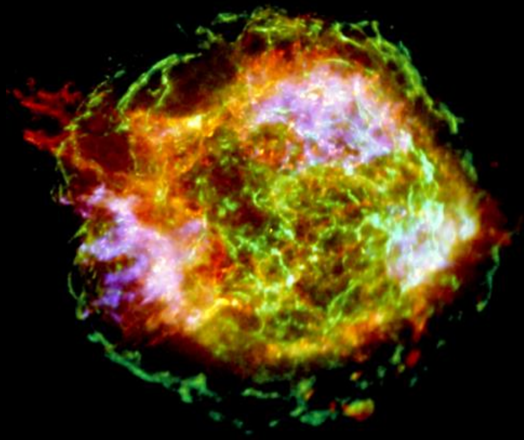




Pulsar kick from ν-baryon int. in magnetized neutron stars.

Origin of life – chirality of amino acids.

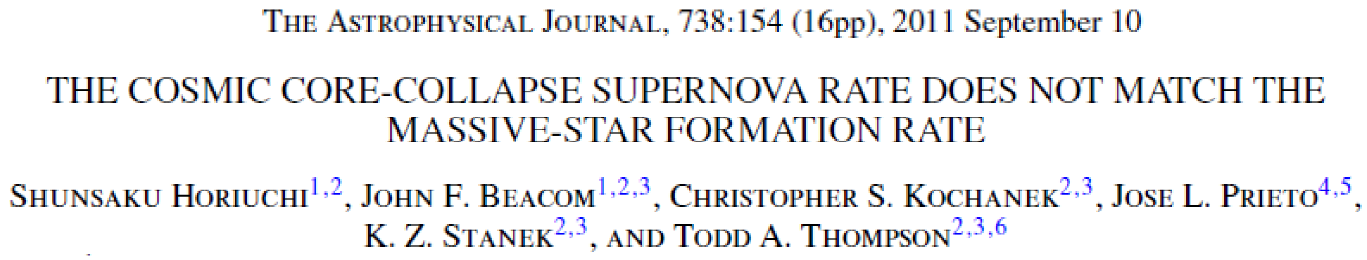
What happens to neutrinos once they leave the supernova?



Supernova Relic Neutrinos (SRNs) to probe EoS of proto-neutron stars.

A New Method to constrain EOS & ν-Osclation

G.J. Mathews, J. Hidaka, T. Kajino & J. Suzuki, ApJ（2014）, submitted.



The Astrophysical Journal, 738:154 (16pp), 2011 September 10

THE COSMIC CORE-COLLAPSE SUPERNOVA RATE DOES NOT MATCH THE MASSIVE-STAR FORMATION RATE

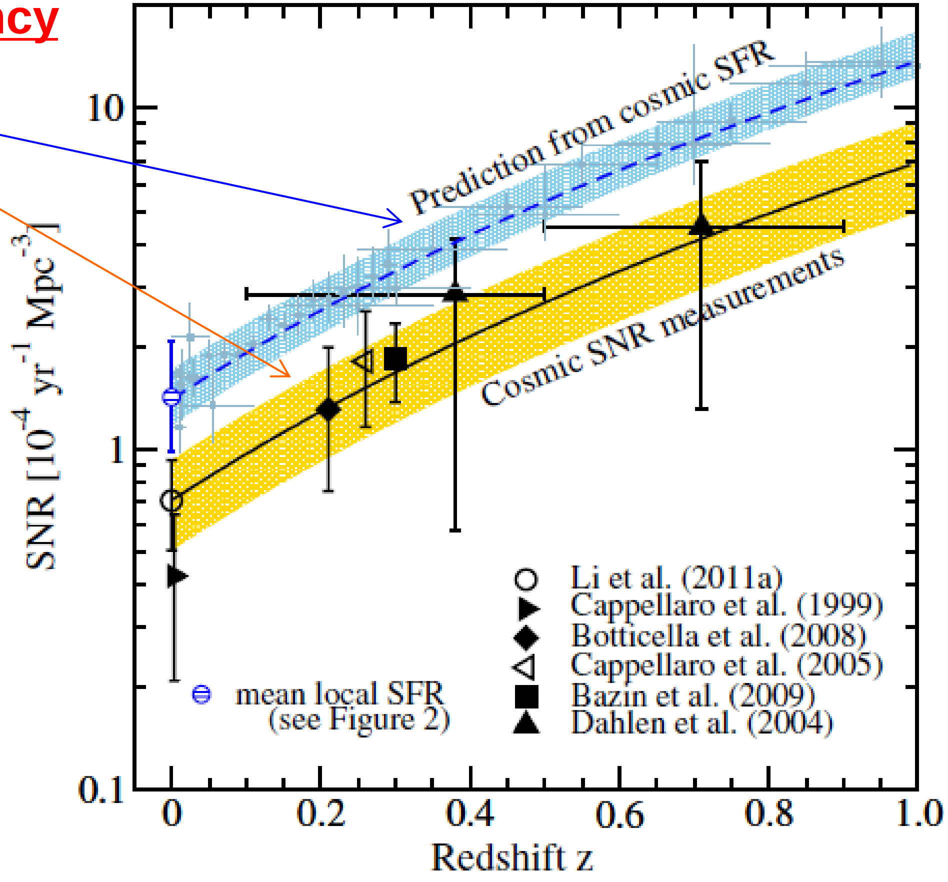
Shunsaku Horiuchi[1,2], John F. Beacom[1,2,3], Christopher S. Kochanek[2,3], Jose L. Prieto[4,5],
K. Z. Stanek[2,3], and Todd A. Thompson[2,3,6]

Supernova Rate Problem/Discrepancy

SFR of Massive Stars at birth

SNR: Supernova Explosions at death !

50% Massive Stars, missing !



Expected Reasons:

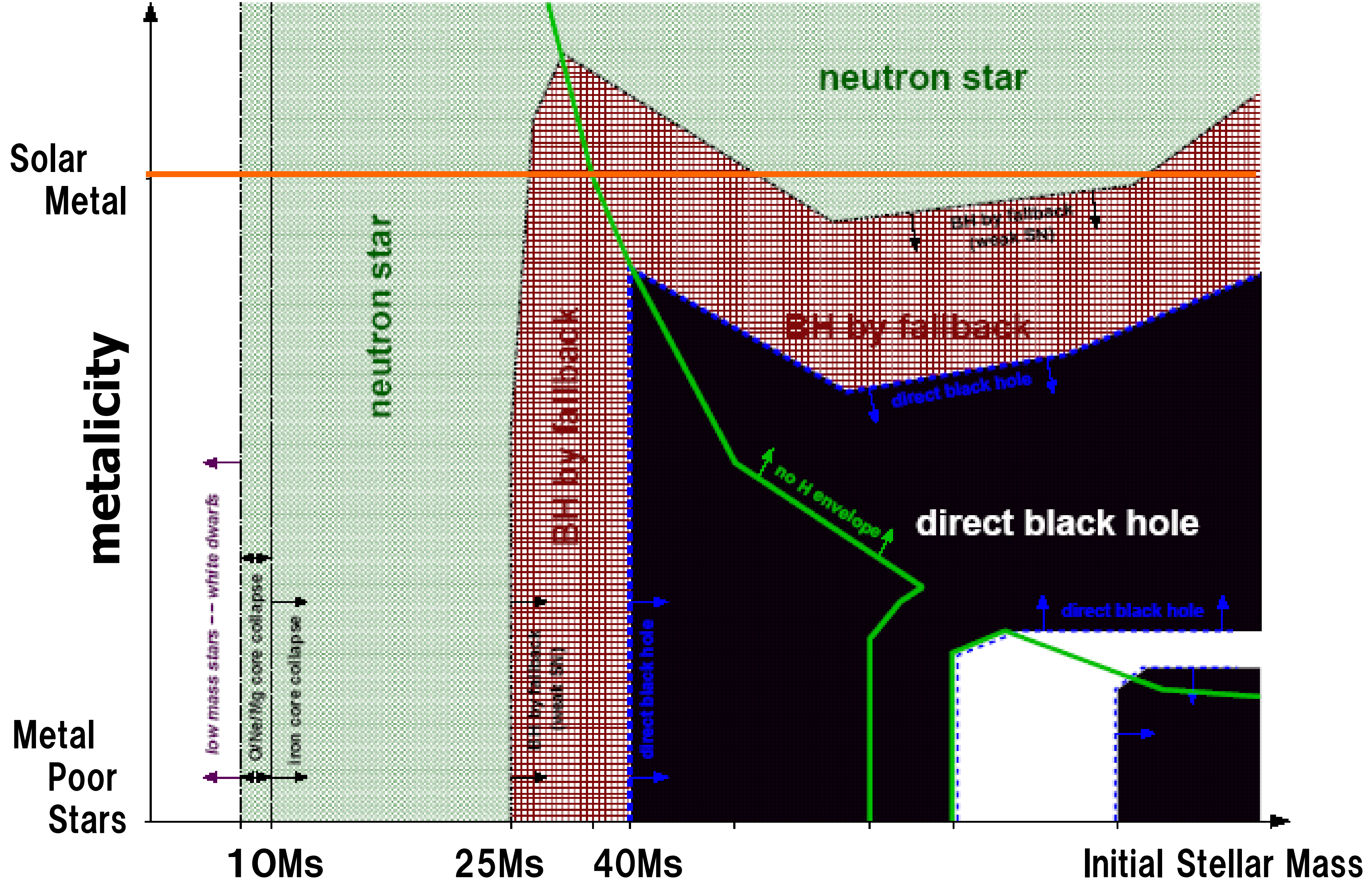
Half was evolved into too dark SNe to detect!

1. Failed SNe (<25M⊙ BH formation)
2. Faint ONeMg-SNe (8-10 M⊙)

or the mass function changed!

Fate of Massive Star

A. Heger et al. (2003)



Electron-capture SNe
(Faint SnNe)

Normal CC-SNe
(Neutron Star fromation)

Failed SNe
(Black Hole formation)

Pair-ν heated SNe
(BH + Acc. Disk)

detail	ONeMg SN	CC-SN	fSN(SH EOS)	fSN(LS EOS)	GRB
mass($M_\odot$)	(8 ∼ 10)	8 ∼ 25(10∼25)	25 ∼ 125 (99.96%)	25 ∼ 125 (99.96%)	25 ∼ 125 (0.04%)
Remnant	Neutron Star	Neutron Star	Black Hole	Black Hole	Black Hole
Phenomenon	Supernova	4.0 Supernova	Failed Supernova	Failed Supernova	Gamma-Ray Burst
T_{ν_e} (MeV)	3.0	3.2	5.5	7.9	3.2
$T_{\bar{\nu}_e}$ (MeV)	3.6	5.0	5.6	8.0	5.3
T_{ν_x} (MeV)	3.6	6.0	6.5	11.3	4.4
$E^{total}_{\nu_e}$ (erg)	3.3×10^{52}	5.0×10^{52}	5.5×10^{52}	8.4×10^{52}	1.7×10^{53}
$E^{total}_{\bar{\nu}_e}$ (erg)	2.7×10^{52}	5.0×10^{52}	4.7×10^{52}	7.5×10^{52}	3.2×10^{53}
$E^{total}_{\nu_x}$ (erg)	1.1×10^{53}	5.0×10^{52}	2.3×10^{52}	2.7×10^{52}	1.9×10^{52}
△ t	few s	few s	∼ 0.5s	∼ 0.5s	∼ 10s

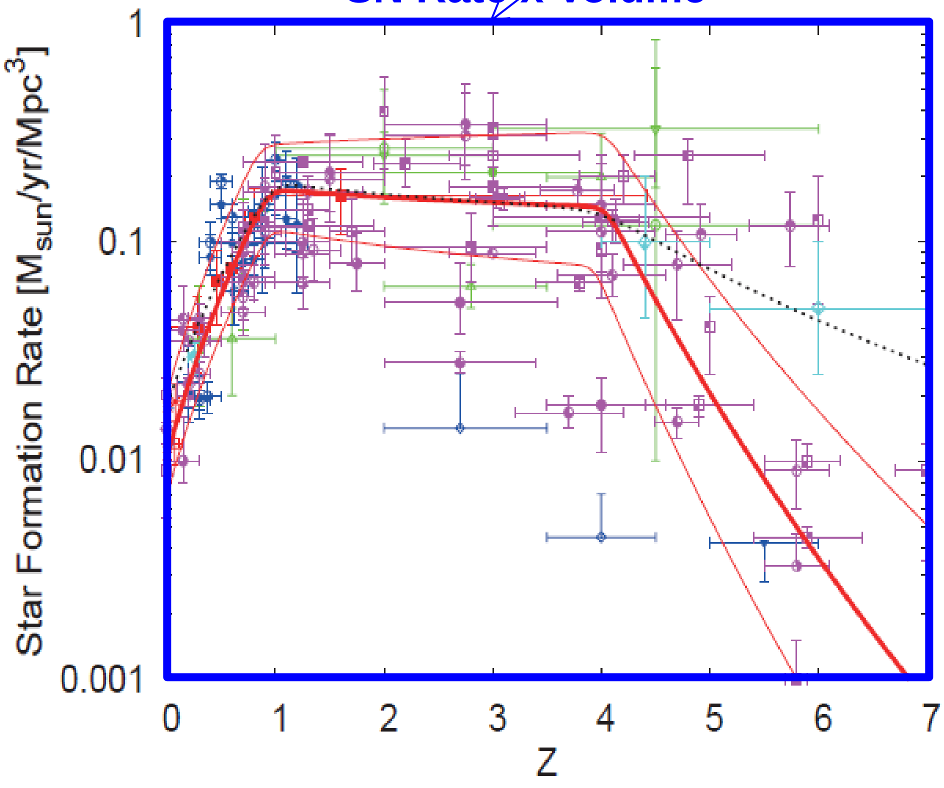
- **CC-Sne:** Yoshida, et al., ApJ **686** (2008), 448;
  Suzuki & Kajino, J. Phys. **G40** (2013) 83101.
- **fSN (failed SNe):** Sumiyoshi, et al., ApJ **688** (2008) 1176.
  - * **Shen-EOS:** Shen et al. Nucl. Phys. **A637** (1998) 435.
  - * **LS-EOS:** Lattimer & Swesty, Nucl. Phys. **A535** (1991) 331.
- **ONeMg SNe:** Hudepohl, et al., PRL 104 (2010).
- **GRBs:** Nakamura, Kajino, Mathews, Sato & Harikae, *Int. J. Mod. Phys*. E 22 (2013) 1330022; Kajino, Mathews & Hayakawa, J. Phys. **G41** (2014) 044007.

Spectrum of Relic Supernova Neutrinos (RSNs)

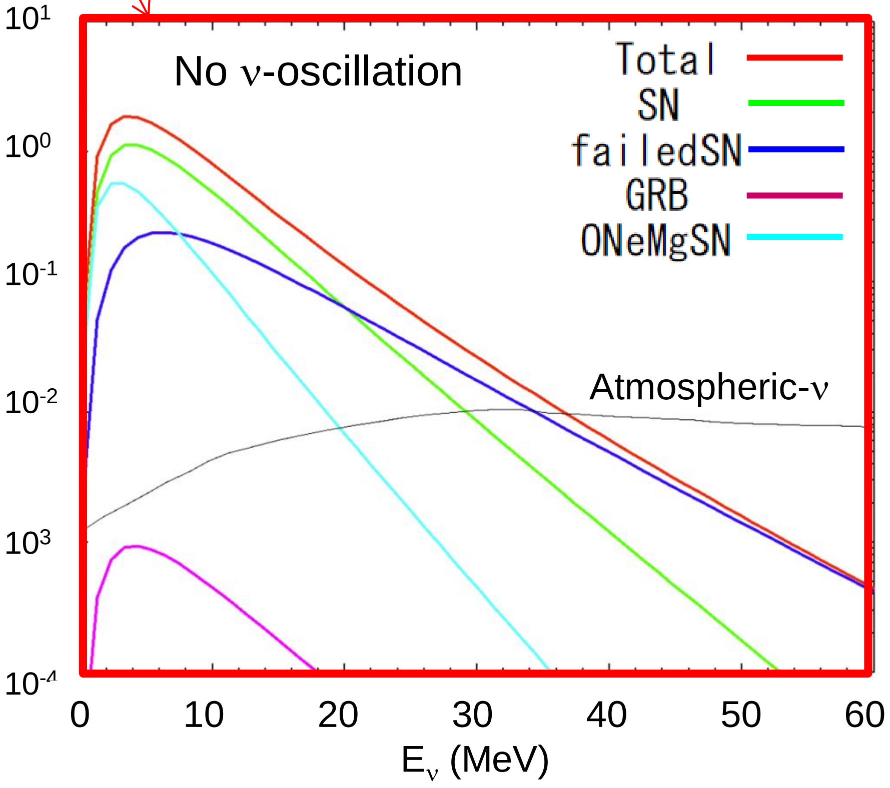
for Hyper-Kamiokande (Mega-ton): Water Cherenkov $\bar{\nu}_e + p \rightarrow e^+ + n$

$$\frac{dN_\nu}{dE_\nu} = \frac{c}{H_0}\int_0^{z_{max}} \boxed{R_{SN}(z)}\,\boxed{\frac{dN_\nu(E'_\nu)}{dE'_\nu}} \times \boxed{\frac{dz}{\sqrt{(\Omega_m)(1+z)^3+\Omega_\Lambda}}}$$

SN Rate x Volume



ν-spectrum at Various SNe & GRB



Spectrum of Relic Supernova Neutrinos (RSNs)

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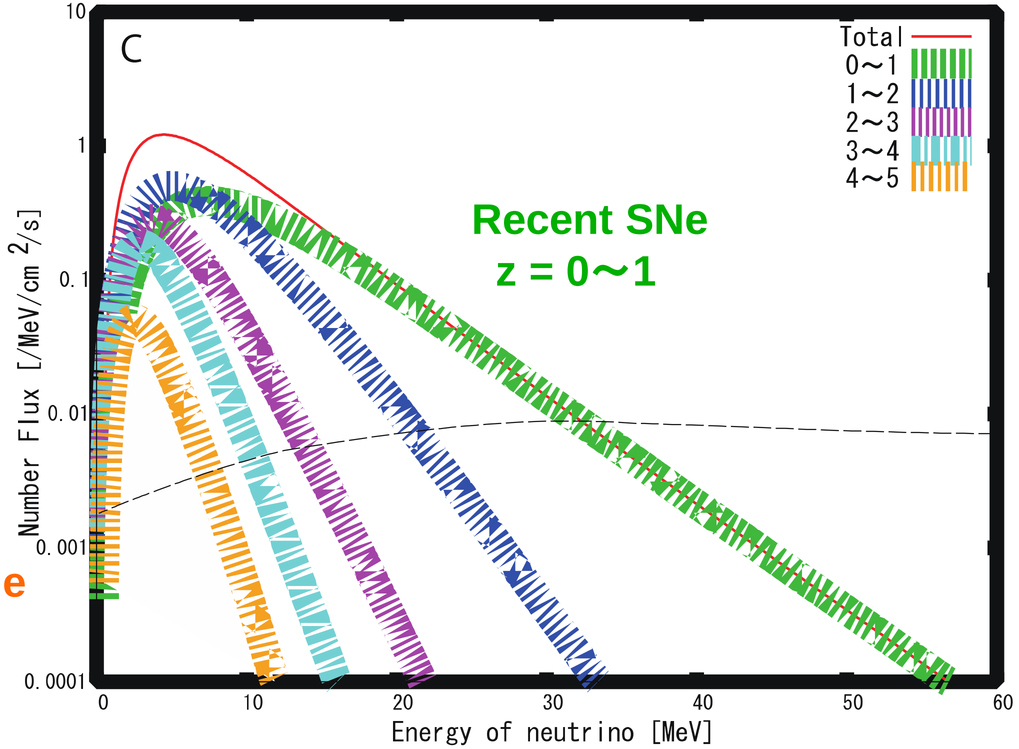


Recent SNe
z = 0～1

Cosmologically Old SNe
z = 4～5

Relic Supernova Neutrinos

Hyper-Kamiokande (Mega-ton, 10y), Gd-loaded Water Cherenkov Detector

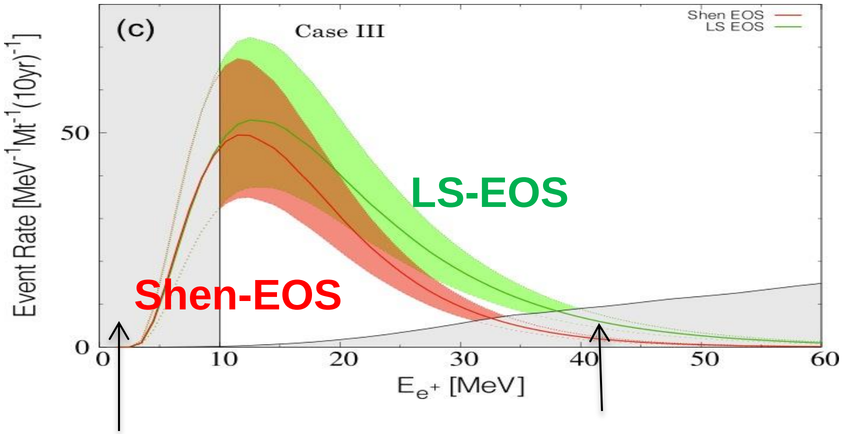
$\bar{\nu}_e + p \rightarrow e^+ + n$ G. J. Mathews, J. Hidaka, T. Kajino, and J. Suzuki, ApJ (2014), in press.

SN rate problem is resolved by assuming 2 x failed SNe for BH formation!

Same assumption as Horiuchi, Beacom (2011)

SN rate problem still remains.

No ν-Oscillation

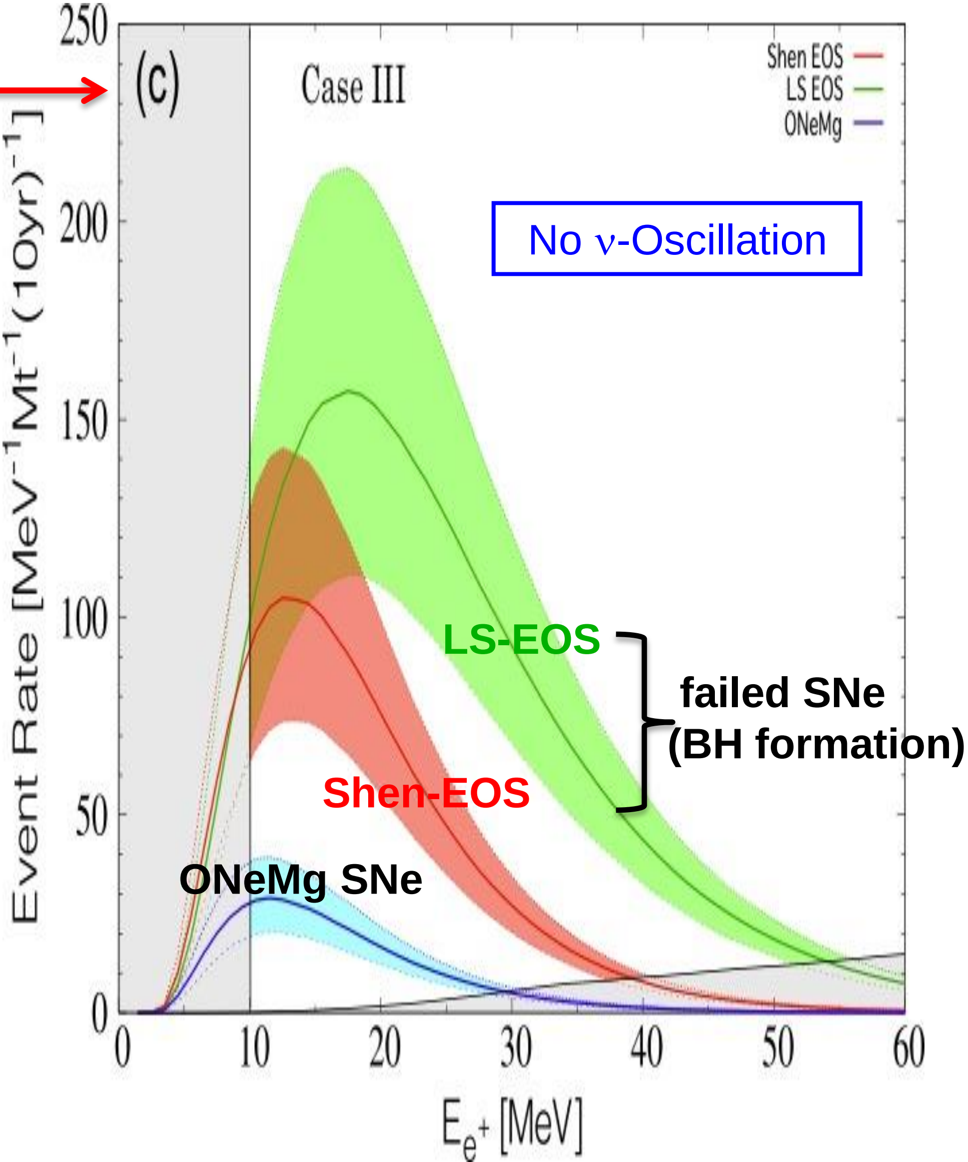


LS-EOS

Shen-EOS

Reactor-ν BG

Atmospheric-ν BG



No ν-Oscillation

LS-EOS

failed SNe (BH formation)

Shen-EOS

ONeMg SNe

Relic Supernova Neutrinos (RSNs)

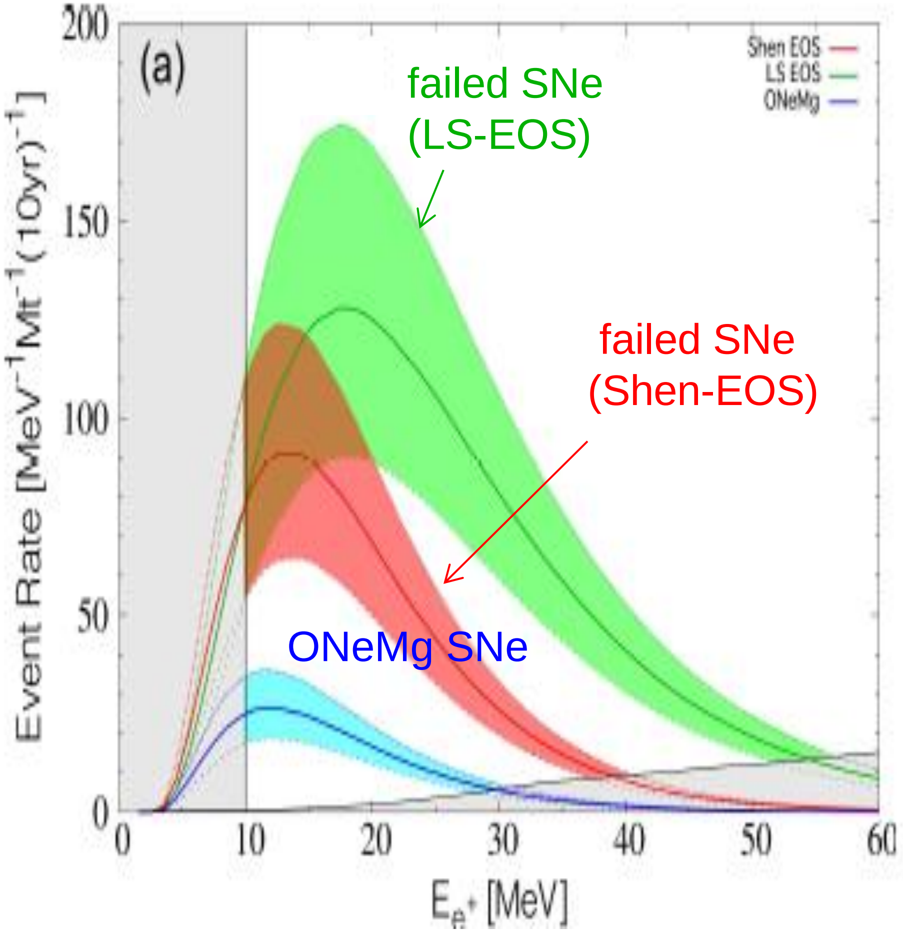
Hyper-Kamiokande（Mega-ton, 10y）, Gd-loaded Water Cherenkov Detector

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

G. J. Mathews, J. Hidaka, T. Kajino, and J. Suzuki, ApJ (2014), in press.

Assuming 2 x failed SNe for BH formation!

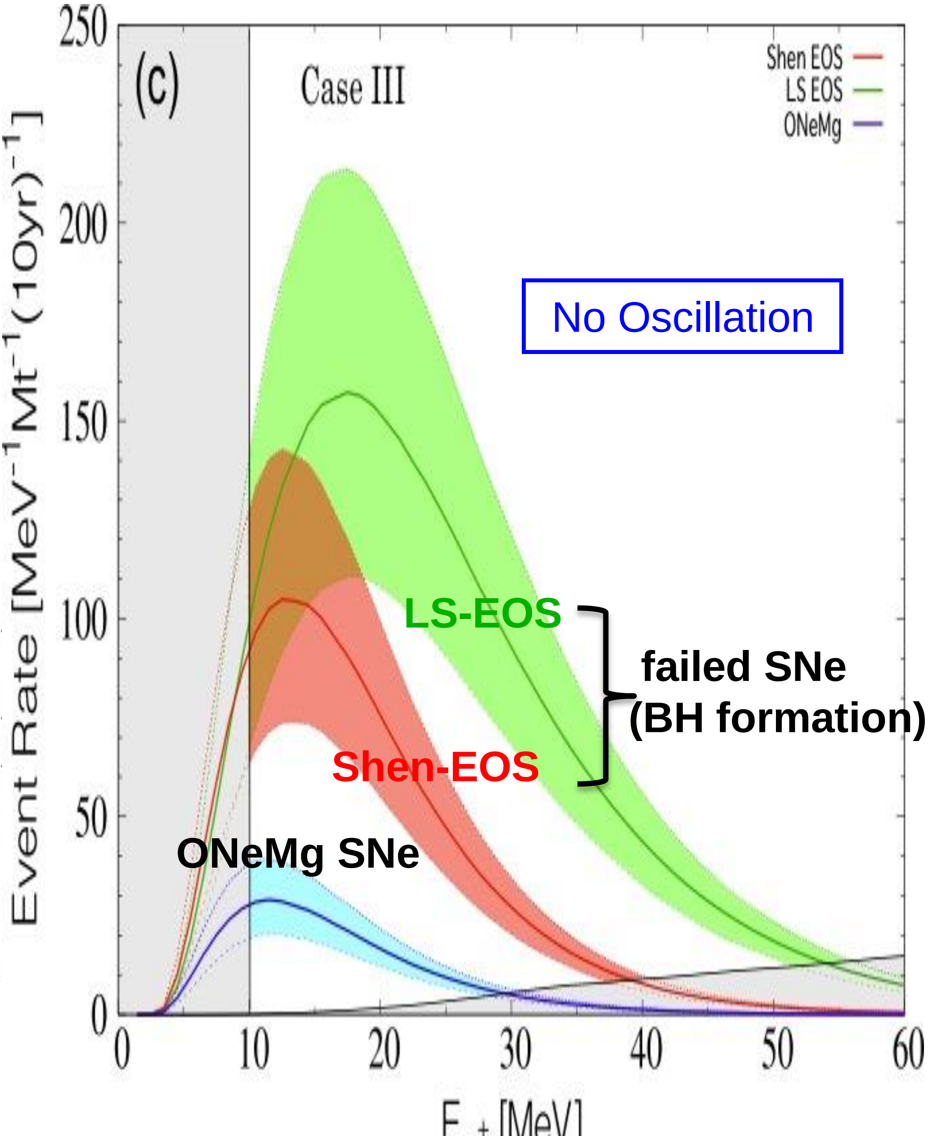
Non-Adiabatic MSW Oscillation



failed SNe (LS-EOS)

failed SNe (Shen-EOS)

ONeMg SNe



No Oscillation

LS-EOS

Shen-EOS

failed SNe (BH formation)

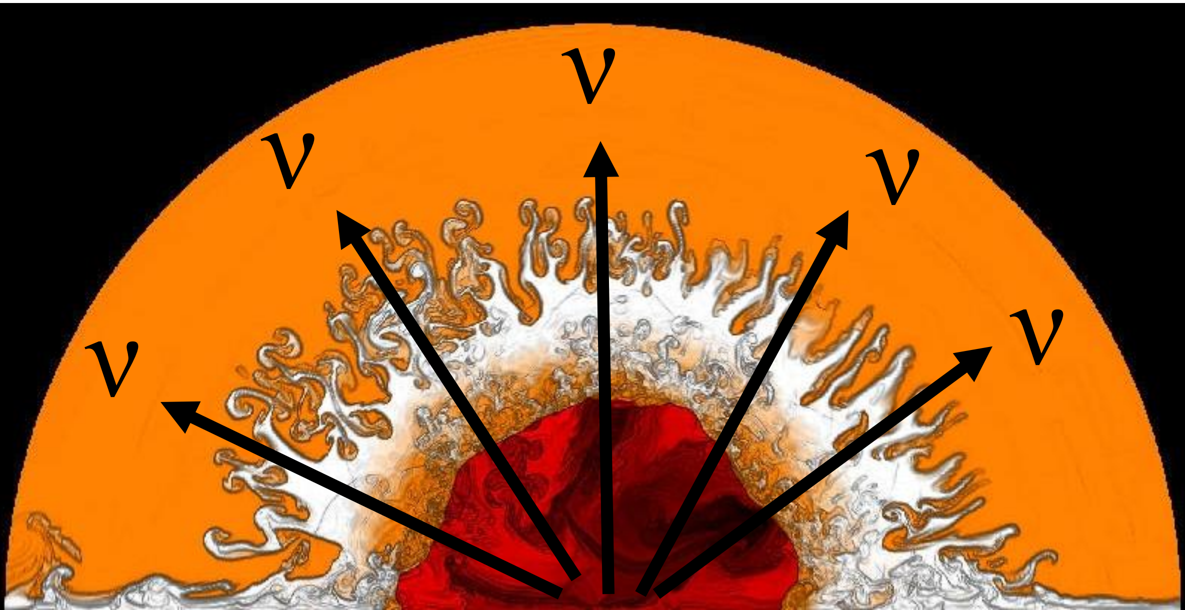
ONeMg SNe

What happens as neutrinos flow through the SN outer layers ?

Pulsar Kick from ν-baryon int. in Magnetized Neutron Star.

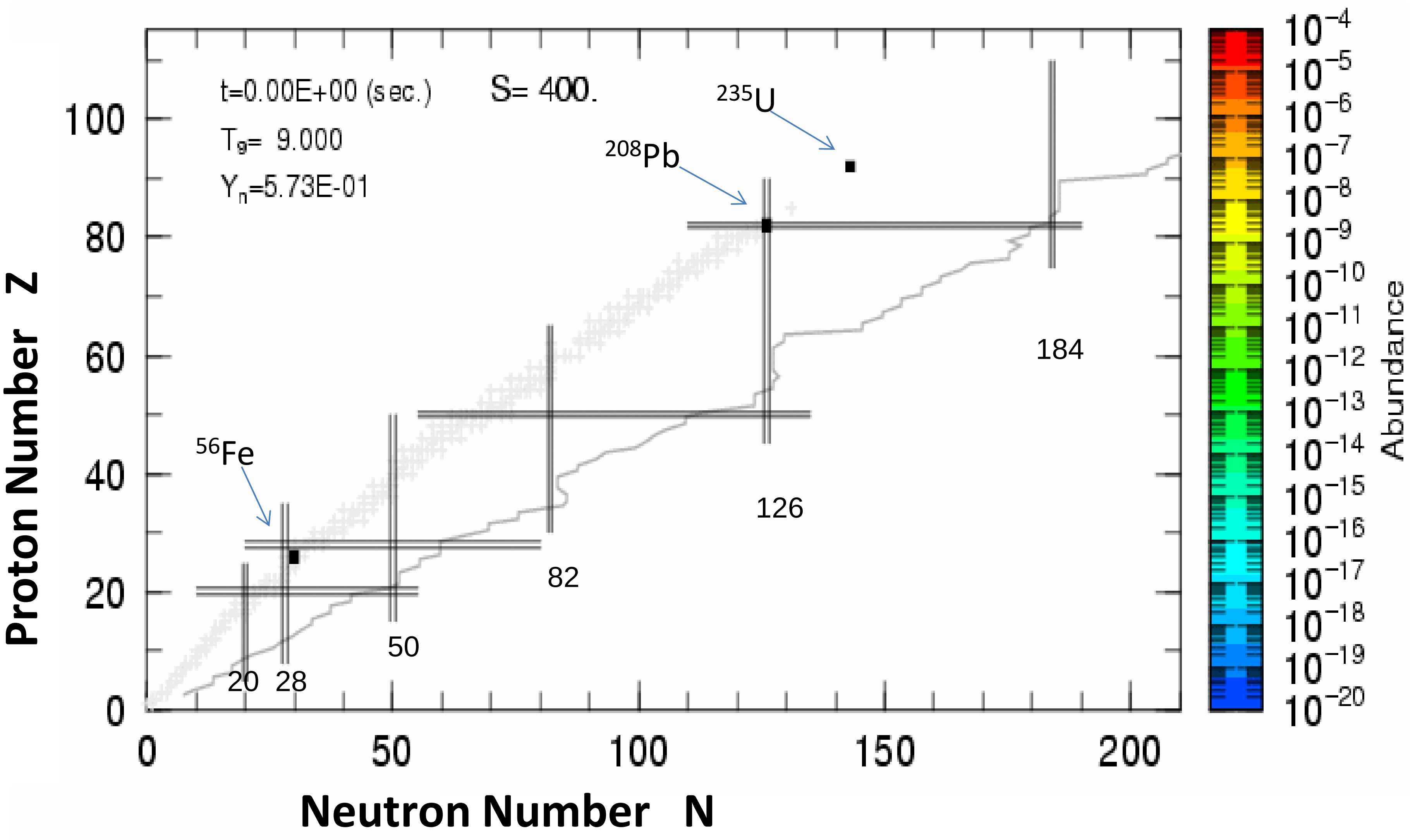
ν-induced nucleosynthesis and Mass Hierarchy.

R-process nucleosynthesis in GRBs.



Supernova Nucleosynthesis Simulation

T. Kajino & S. Chiba



R-process Nucleosynthesis

Otsuki, Tagoshi, Kajino and Wanajo, ApJ 533 (2000) ,424; Wanajo, Kajino, Mathews and Otsuki, ApJ 554 (2001) ,578.

Neutron-rich condition for successful r-process: $0.1 < Y_e < 0.5$

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

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

$$Y_e = \frac{p}{n+p} \approx \left(1 + \frac{L_{\bar{\nu}_e}}{L_{\nu_e}} \times \frac{\boxed{\epsilon_{\bar{\nu}_e}} - 2\Delta + 1.2\Delta^2/\epsilon_{\bar{\nu}_e}}{\boxed{\epsilon_{\nu_e}} + 2\Delta + 1.2\Delta^2/\epsilon_{\nu_e}}\right)^{-1}$$

$\varepsilon_\nu = 3.15\, T_\nu$

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

Theoretical Challenge:

1) Astrophysical Sites ?

- ν-wind SNe
- MHD jet SNe
- NS mergers (short GRB)
- long GRBs

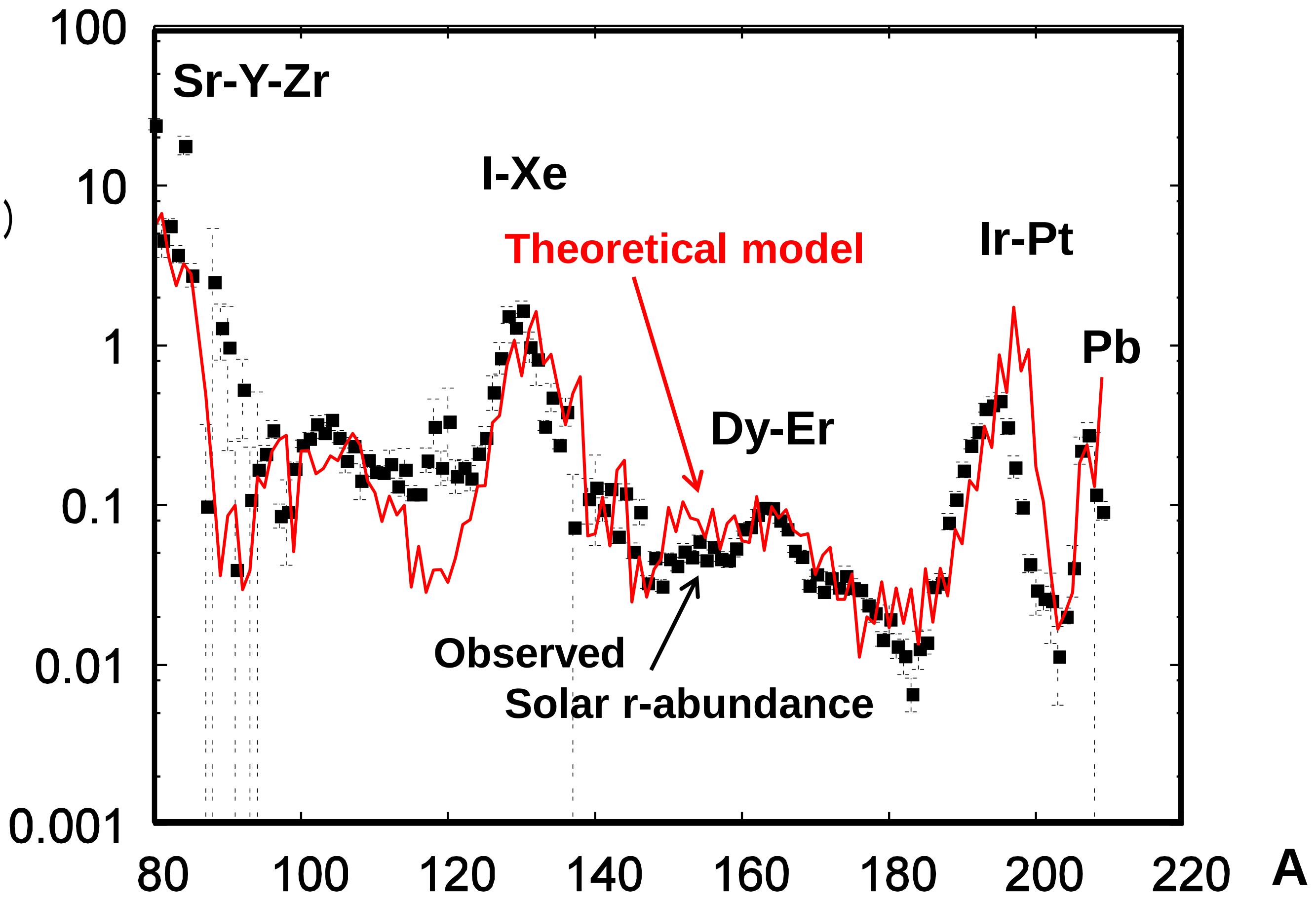
2) Neutrino effects ?

$Y_e > 0.5$?

Roberts, Reddy and Shen (PR C86, 065803, 2012) pointed out

$Y_e < 0.5$!

for nucleon potential and Pauli blocking effects.



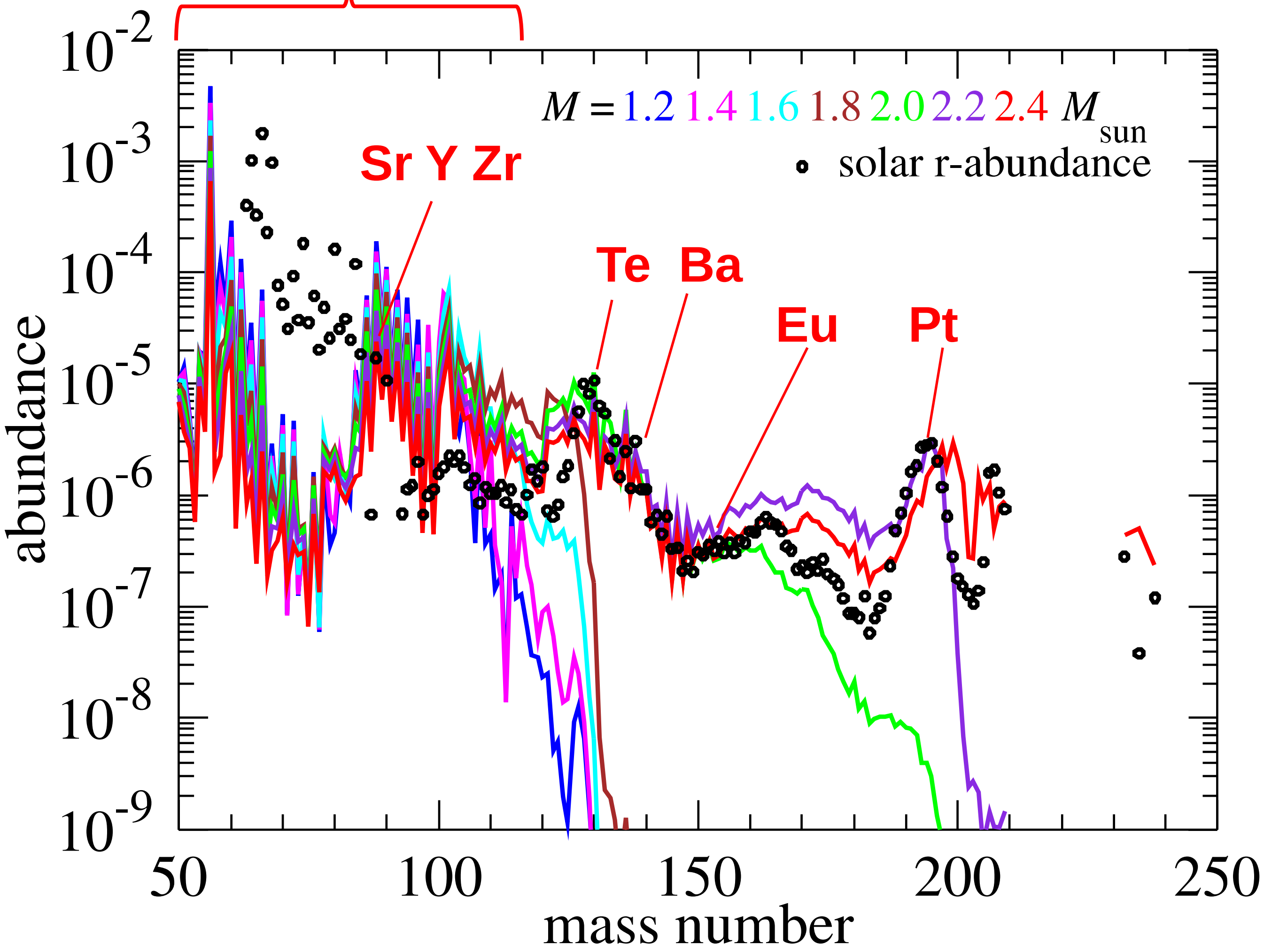
Lighter Mass End (10-13 $M_\odot$) of ν-Driven SNe;

not enough neutrons for the heaviest *r*-process nuclides.

➔ **Heavy Mass (15-25 $M_\odot$) CCSNe, wanted !?**

Only weak r-process?

S. Wanajo, ApJL, L22 (2013)



Alternative Models for the *r*-Process

Ejection of neutronized core material in MHD jet:

Moderate entropy: S>15,

Neutron rich: $Y_e \sim 0.2$.

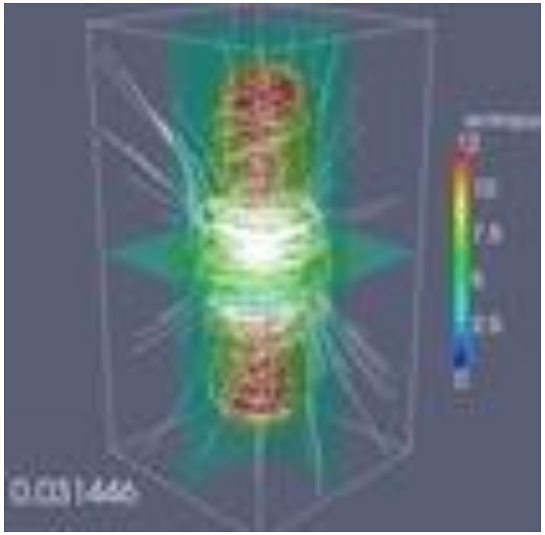
Neutron star mergers:

Low Entropy S ~ 1,
Extremely neutron rich: $Y_e \sim 0.02$.

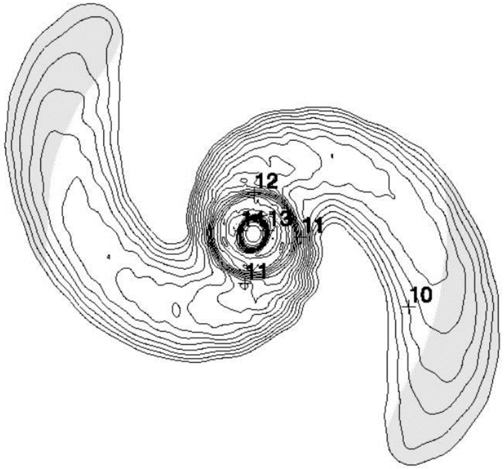
:- can contribute to the s.s. and recent generations of stars.

:- cannot contribute to the early generations of stars.

Nishimura, Nishimura, Kajino & Mathews (2012)



Freiburghaus et al (1999), Korobkin et al. (2012), Shibagaki, Kajino (2014)



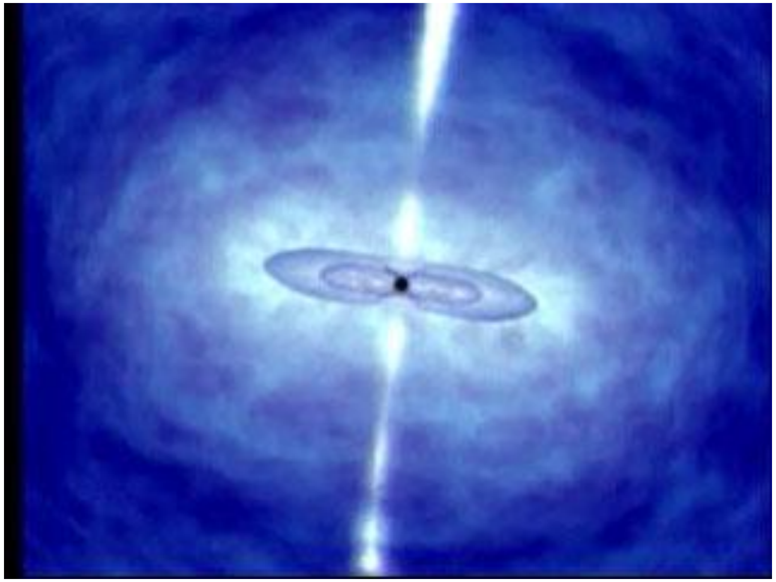
Is there another possibility?

Yes!

R-Process nucleosynthesis in collapsar jets:

Surman et al. 2008, Fujimoto et al. 2008, Ono et al. 2012, Nakamura et al. 2013.

- Model for long duration gamma-ray bursts (GRB).
- A failed supernova.
- Produces a black hole and a high temperature accretion disk.
- MHD + neutrino heating produces an energetic jet.

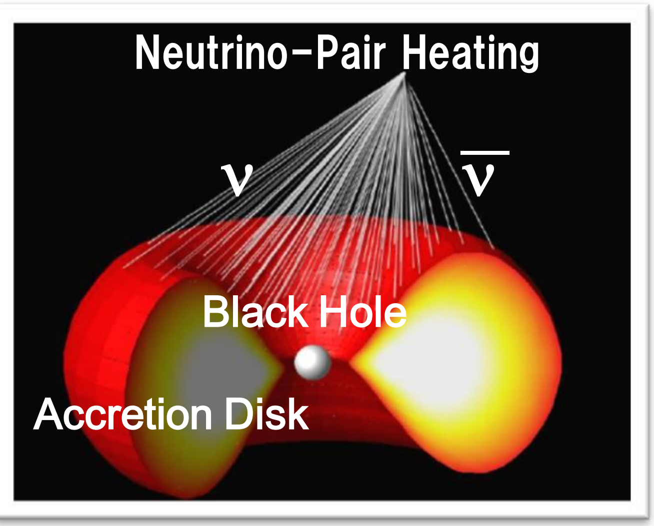


However, no fully successful numerical hydrodynamic model !

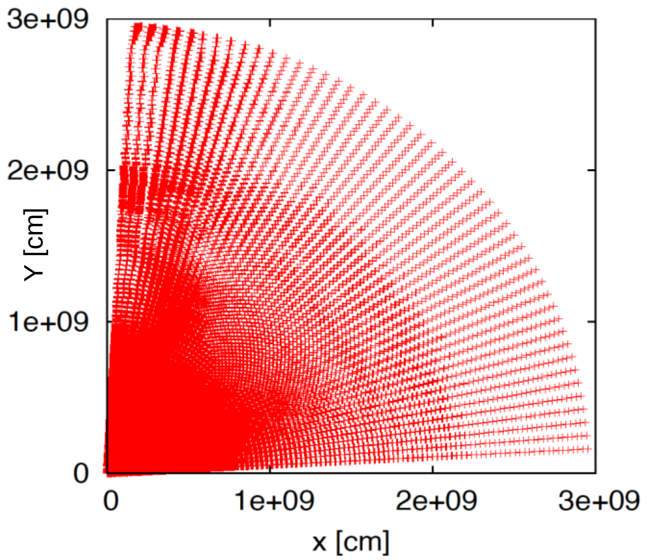
Woosley 1999, McFadyan & Woosley 2003 → Harikae et al. 2009 - 2014

Collapsar Model for Long Gamma-Ray Bursts

Harikae et al., ApJ 704 (2009), 354; 713 (2010) 304.
Nakamura, Kajino, Mathews, Sato & Harikae, IJMP 22 (2013), 1330022.



20,000 tracer particles



1208 trajectories with positive energy to be ejected outside.

Stages of a Collapsar

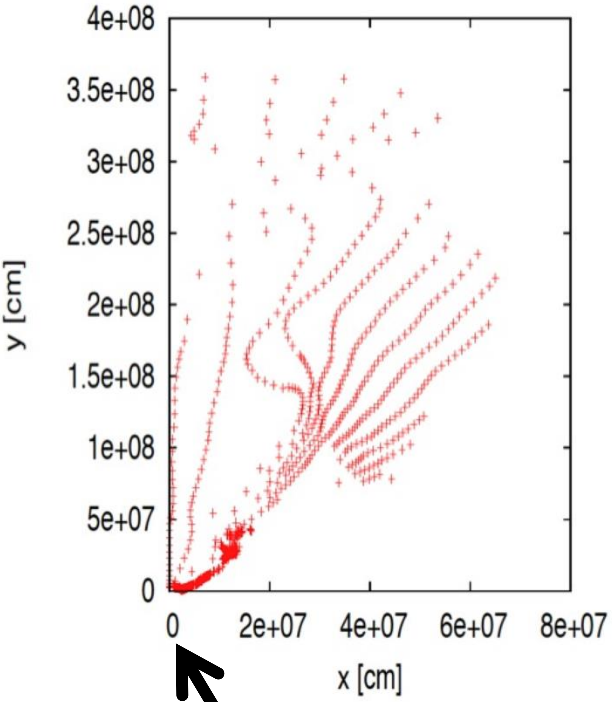
1. Initial Collapse of 25–40 $M_{\odot}$ progenitors.
2. Accretion disk heats up and a funnel region above the black hole is heated by neutrino pair-annihilation and magnetic fields.
3. Causes launch of a relativistic jet; $\Gamma \sim 5$.

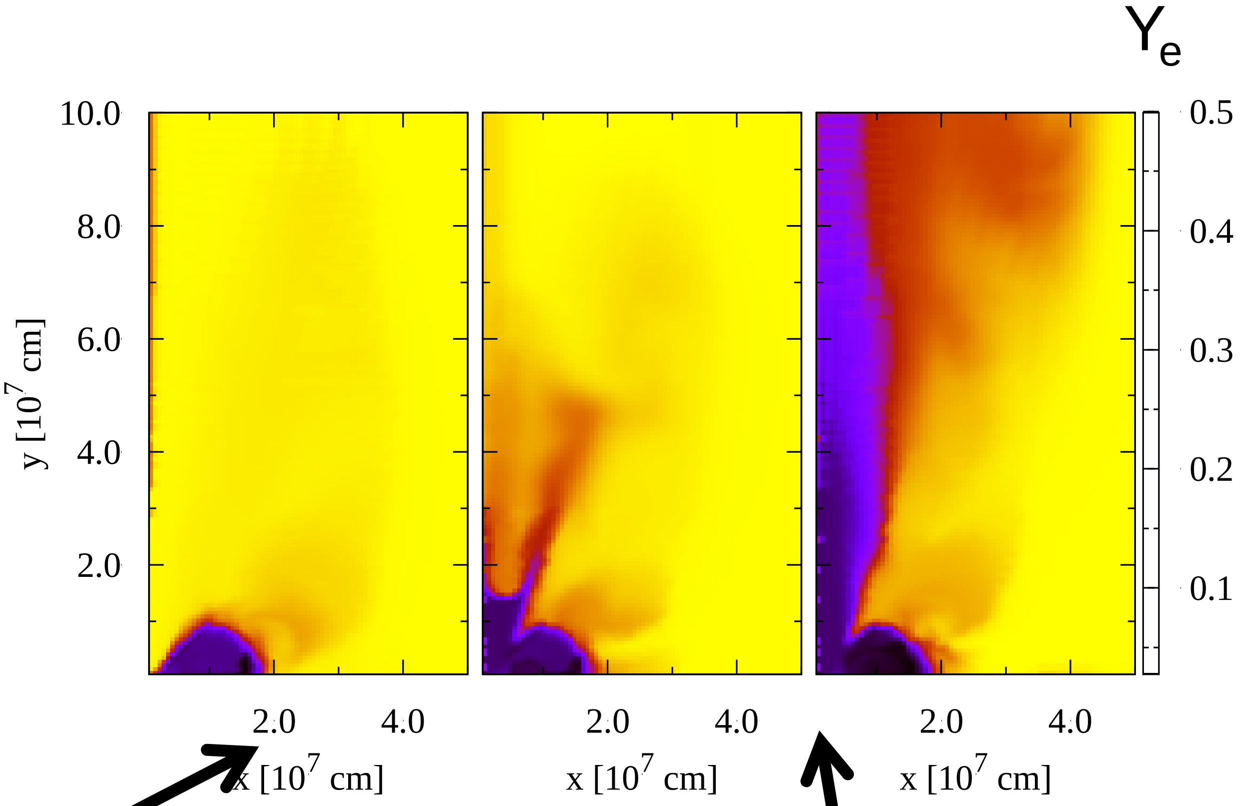
Modeling R-Process

1. Extend the jet beyond the MHD+neutrino pair-annihilation heating using 2D hydo.
2. Attach tracer particles to evolve the flow of material into the accretion disk and out into jet.

Evolution of low-Y_e neutron-rich material

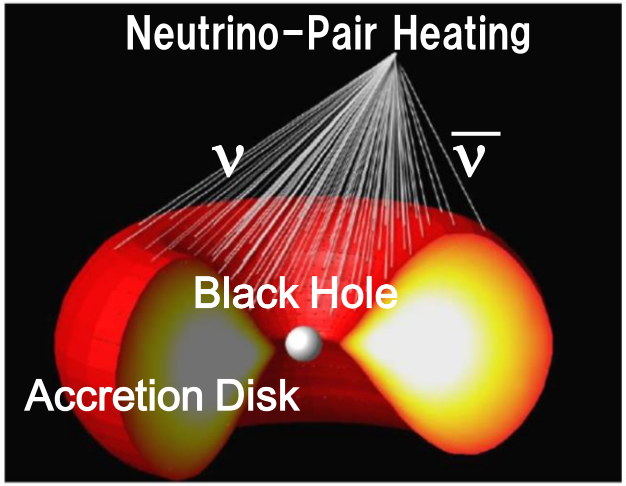
Nakamura, Kajino, Mathews, Sato & Harikae, Int. J. Mod. Phys. 22 (2013), 1330022.





Neutronized accretion-disk material

Flows into the jet



Collapsar Model for Long Gamma-Ray Bursts

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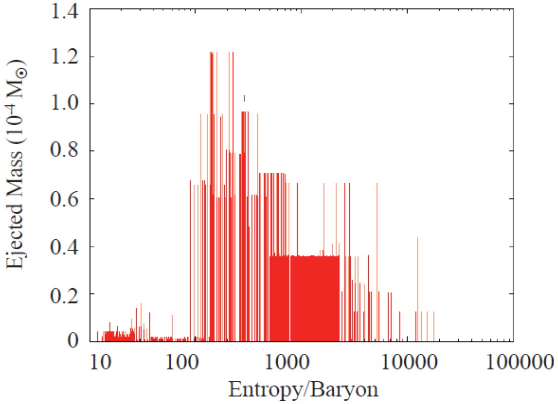
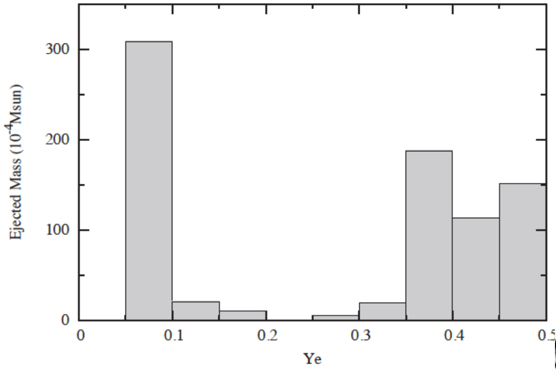
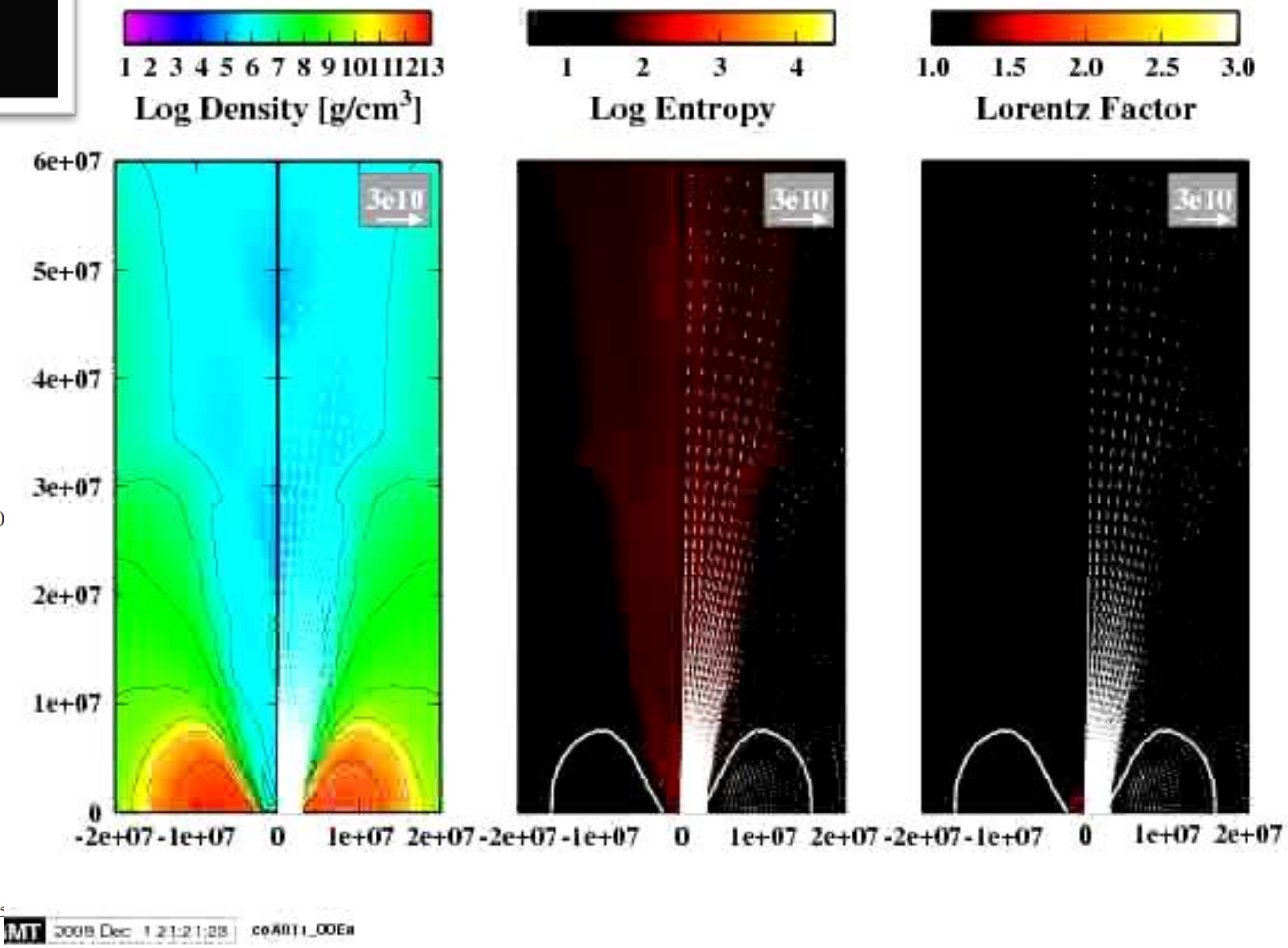
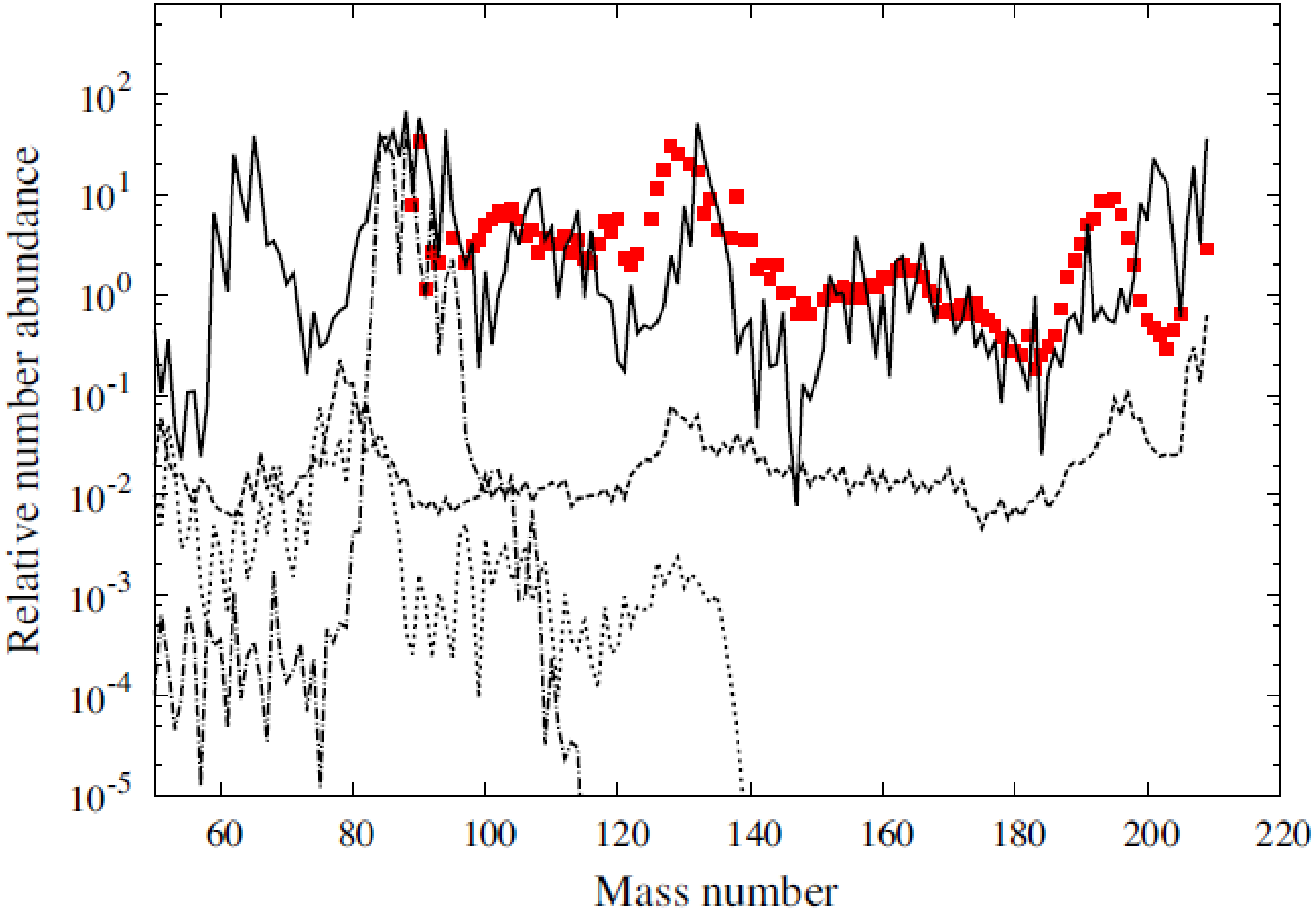






R-Process Nucleosynthesis in Gamma-Ray Bursts

Nakamura, Kajino, Mathews, Sato & Harikae, IJMP 22 (2013), 1330022.



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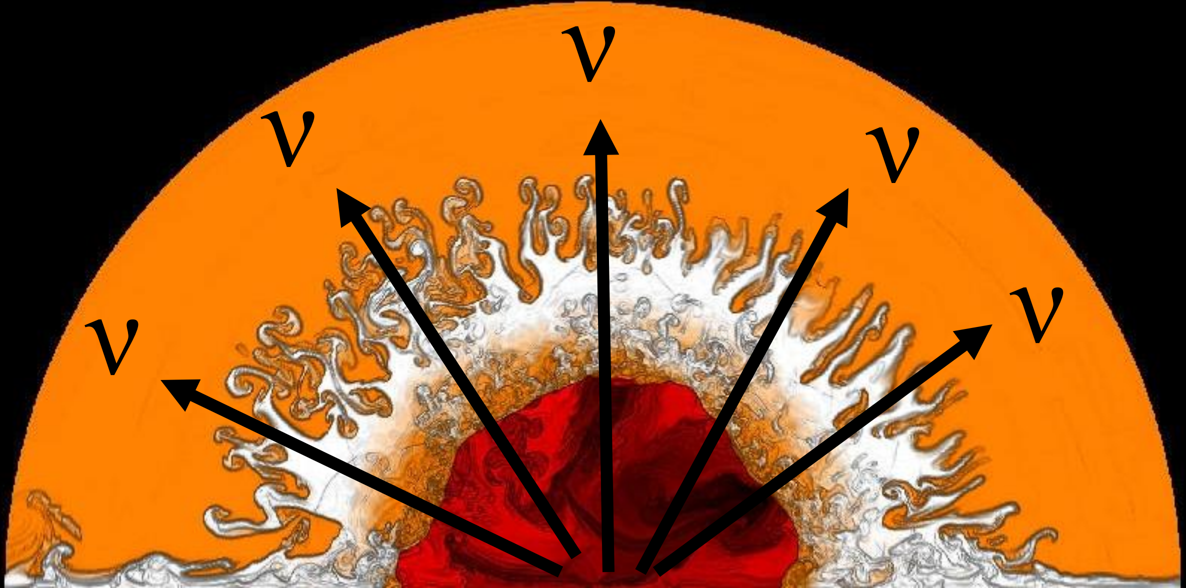
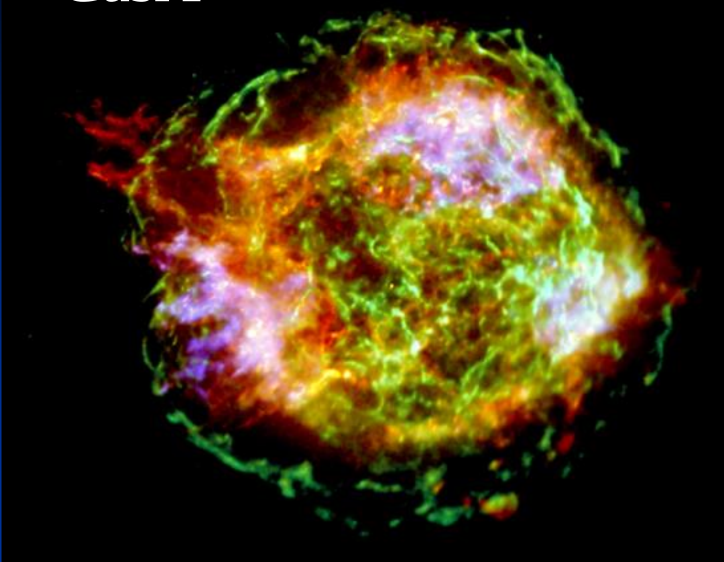


Estimating Pulsar Kick Velocities of Proto-Neutron Star

CasA



http://chandra.harvard.edu/photo/
2004/casa/casa_xray.jpg

A.G.Lyne, D.R.Lomier, Nature 369, 127 (94)

Kick Velocity:

Average … 400km/s,

Highest … 1500km/s

99% of Explosion Energy ~ 10^{53} erg is taken by Neutrinos!

***Even 1% Asymmetry* is sufficient to explain the Pulsar Kick.**

Lai & Qian, Astrophys.J. 495 (1998) L103.

Relativistic Mean Field Theory:

Maruyama, Kajino, Cheoun et al., PR D83, 081303(R), (2011); D86, 123003 (2012).

Estimating Kick Velocity of PNS with T = 20 MeV and $B = 2\times 10^{17}$G

Poloidal Magnetic Field 2 - 3% Asymmetry

$$v_{kick} = \frac{\langle p_z \rangle}{M} \approx 600\,[\mathrm{km/s}]$$

The Cross-Section of ν-B (Mg. Field) in Rel. MFT

$$\frac{d^2\sigma}{dk' d\Omega'_k} = \frac{G_F^2}{8\pi^2}\boldsymbol{k}'^2 \sum_{s_i,s_f}\int \frac{d^3p}{(2\pi)^3}\tilde{W}_{BL}(2\pi)\delta(|\boldsymbol{k}|-|\boldsymbol{k}'|+e_i(\boldsymbol{p})-e_f(\boldsymbol{k}+\boldsymbol{p}-\boldsymbol{k}'))$$

$$\times [1-f'_l(\boldsymbol{k}')]n_B(e_i)[1-n_{B'}(e_f)]$$

$$\tilde{W}_{BL} = \mathrm{Tr}\left\{\frac{(\not{k}'+m_f)(1+\gamma_5\not{a}_{l'})}{4|\boldsymbol{k}'|}\gamma^\mu(1-\gamma_5)\frac{\not{k}'}{2|\boldsymbol{k}|}\gamma^\nu(1-\gamma_5)\right\}$$

$$\times\ \mathrm{Tr}\left\{\frac{(\not{p}'+M_f^*)(1+\gamma_5\not{a}_f(p'))}{4E_f^*(\boldsymbol{p}')}\gamma_\mu(c_V-c_A\gamma_5)\frac{(\not{p}+M_i^*)(1+\gamma_5\not{a}_i(p))}{4E_i^*(\boldsymbol{p})}\gamma_\nu(c_V-c_A\gamma_5)\right\}$$

$m_f = 0$ when $l_f = \nu$ $\quad m_f = m_e$ when $l_f = e$

$$n(e(\boldsymbol{p}),s) \approx n(\varepsilon(\boldsymbol{p},s)) + n'(\varepsilon(\boldsymbol{p},s))\frac{\sqrt{p_T^2+M^{*2}}}{E_p^*}\mu B s.$$

Deformed Distribution

Perturbative Treatment ⟹

$$\sigma = \sigma_0 + \Delta\sigma \qquad \Delta\sigma \propto B$$

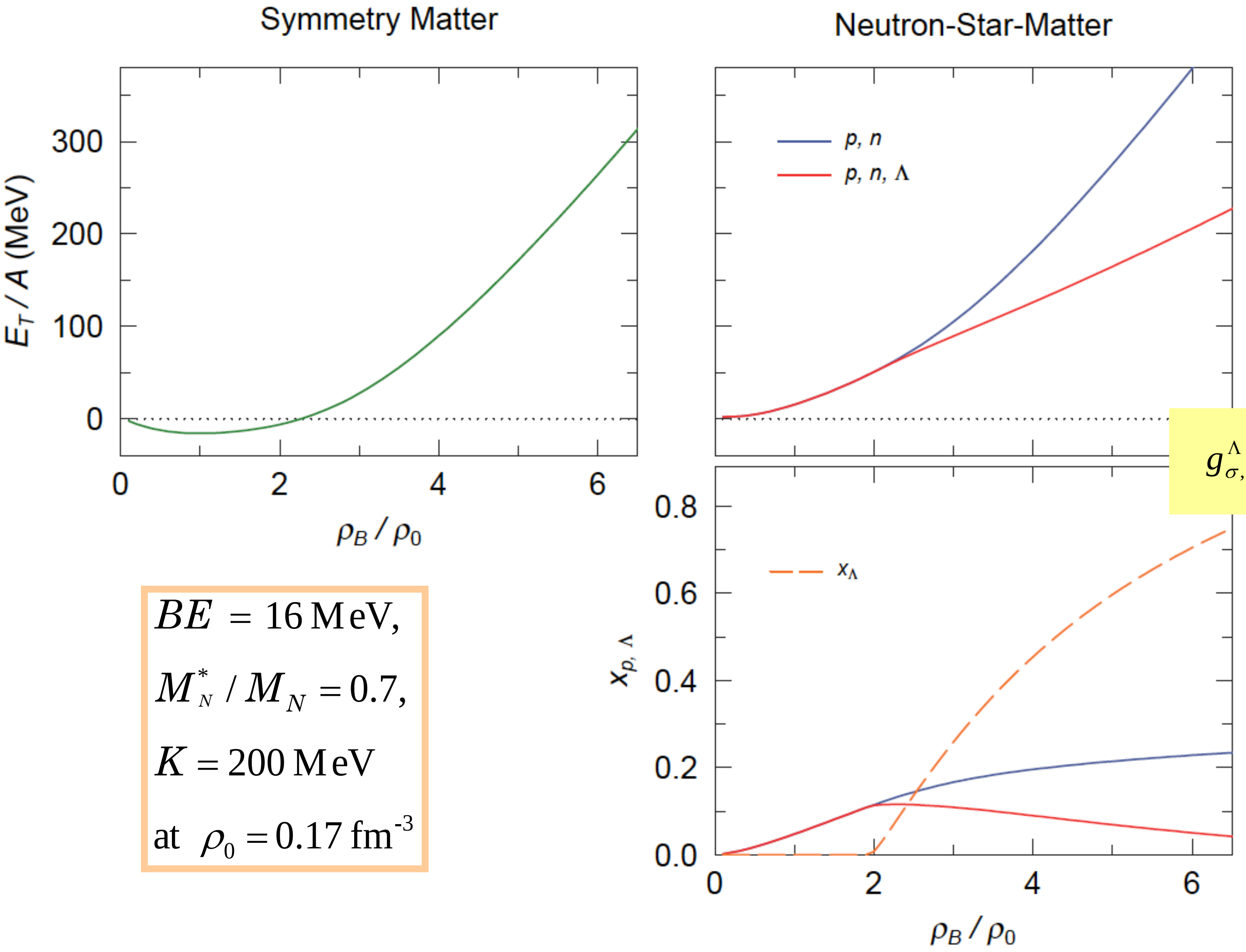
Non-Magnetic Part

Magnetic Part

EOS of Proto Neutron-Star-Matter in RMF

N, Λ, σ, ω, ρ

PM1-L1



$BE = 16\,\mathrm{MeV}$,

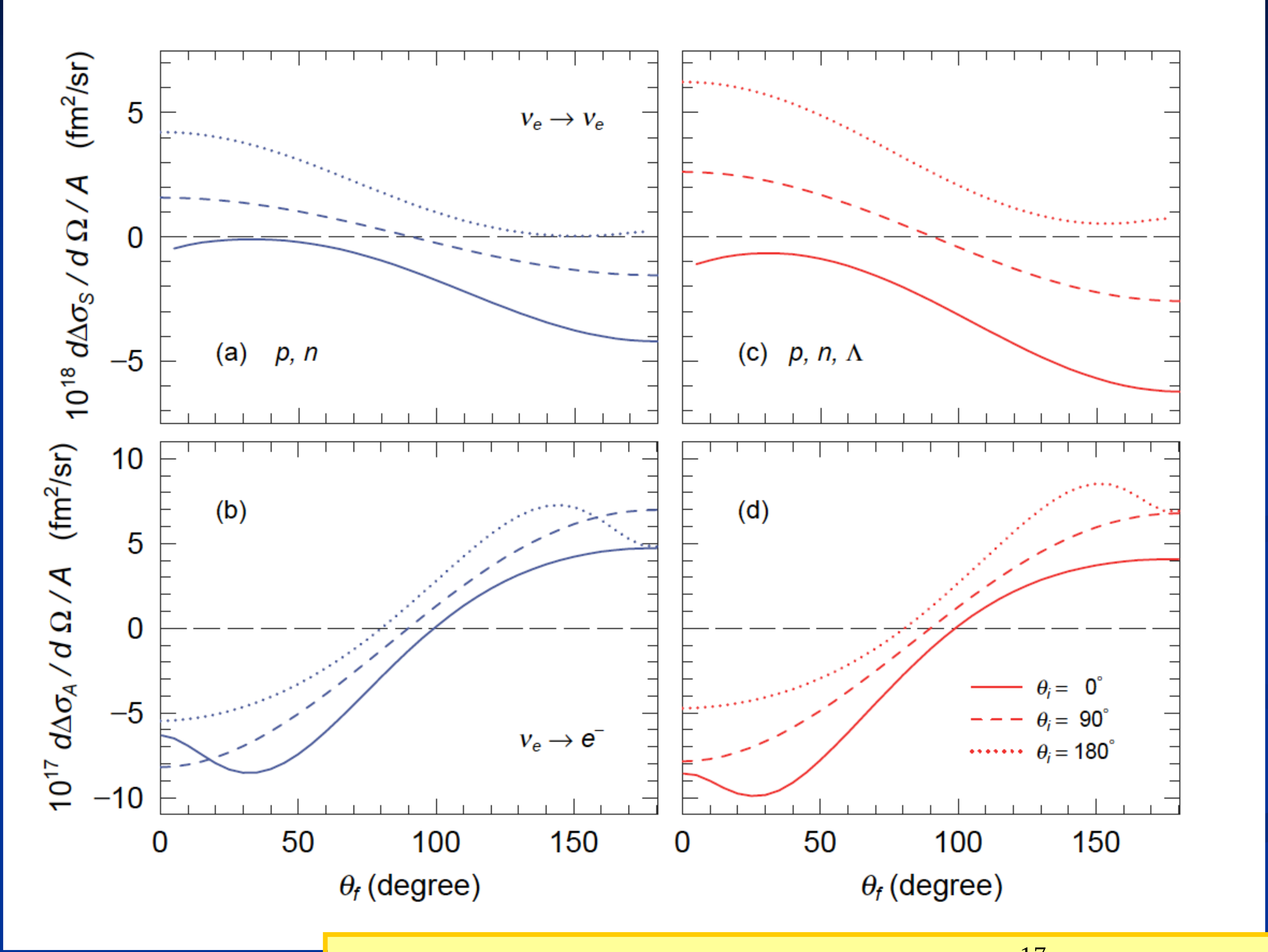
$M_N^* / M_N = 0.7$,

$K = 200\,\mathrm{MeV}$

at $\rho_0 = 0.17\,\mathrm{fm}^{-3}$

$g_{\sigma,\omega}^{\Lambda} = \frac{2}{3} g_{\sigma,\omega}$ **SU(3)**

Initial Angle-Dependence



$k_i = \varepsilon_\nu$ (neutrino chem. pot.), $B = 2\times10^{17}$G and $\theta_{\rm i} = 0^\circ$

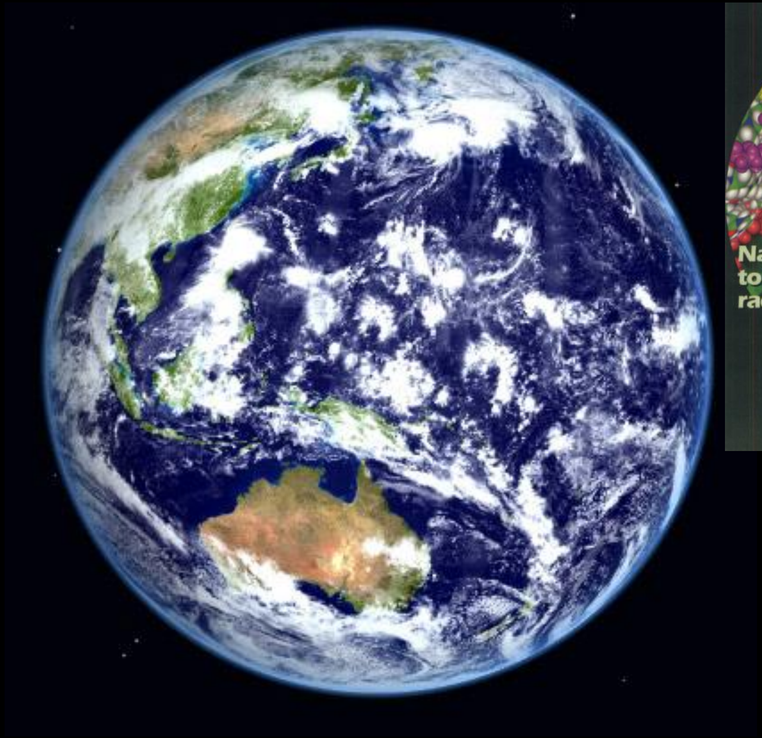
生命の起源？

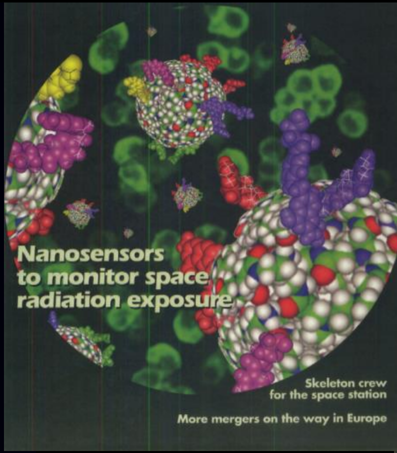
地球上で発生？

爆発的(暴走？)な進化を
遂げた多様な地球上生命

DNAは宇宙から？

生命が宇宙に起源を持つとすれば・・・
太陽系外のアミノ酸も同じ構造を持っている筈。

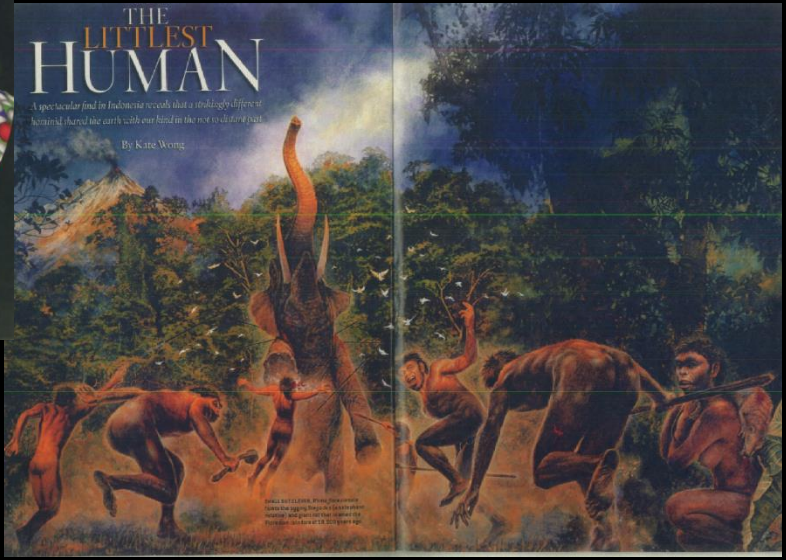




Nanosensors to monitor space radiation exposure

Skeleton crew for the space station

More mergers on the way in Europe



THE LITTLEST HUMAN

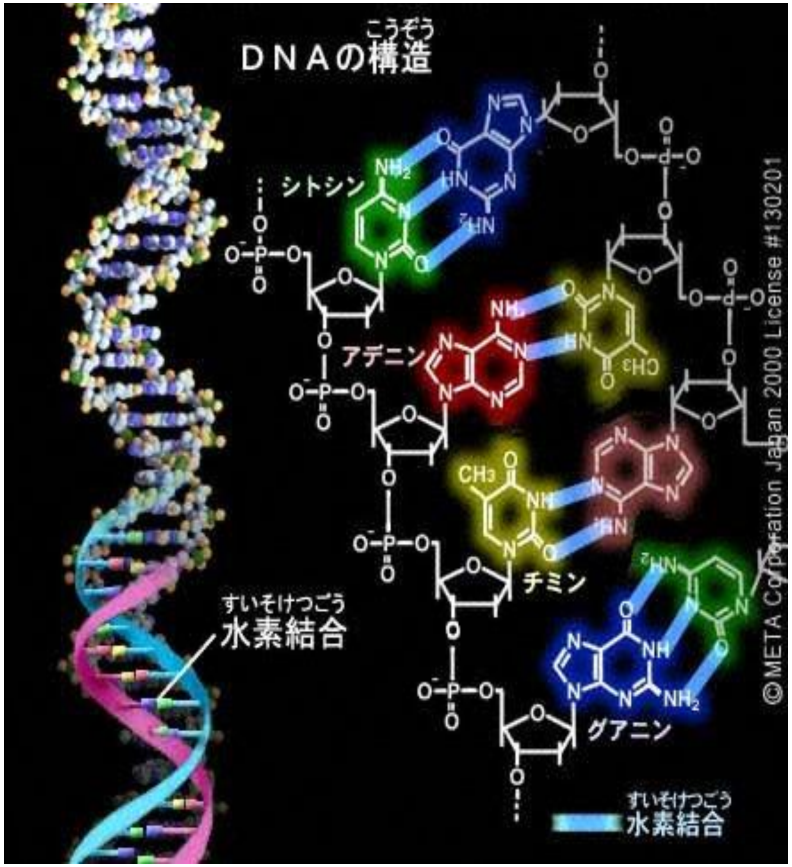
A spectacular find in Indonesia reveals that a strikingly different hominid shared the earth with our kind in the not so distant past

By Kate Wong

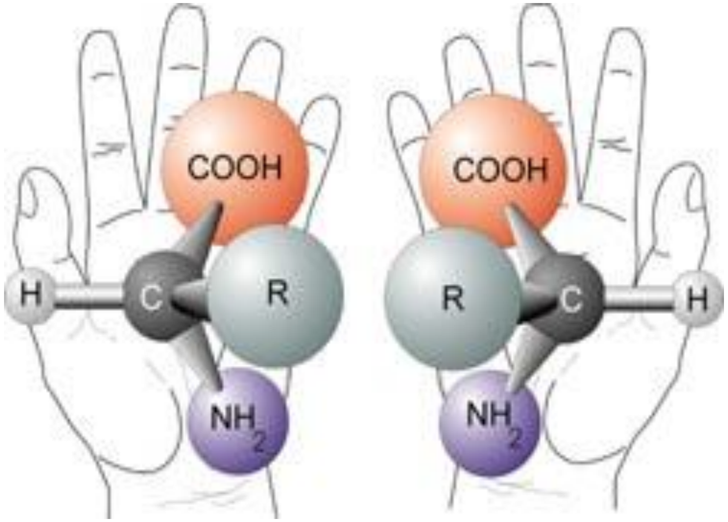
生命の起源を解く鍵

地球上のアミノ酸はすべて左巻き（Ｌ型）

左巻きキラリティーは地球だけの偶然（地球・太陽系起源説）？
それとも宇宙に共通（宇宙起源説）？



光学異性体

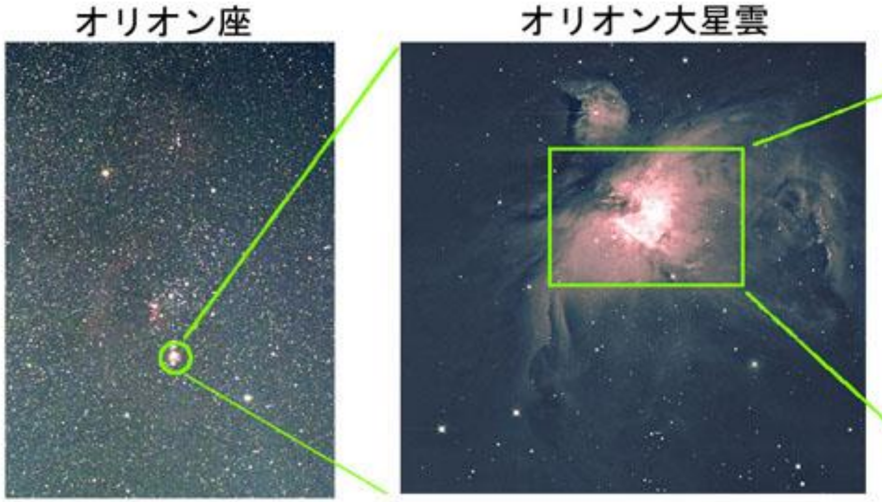


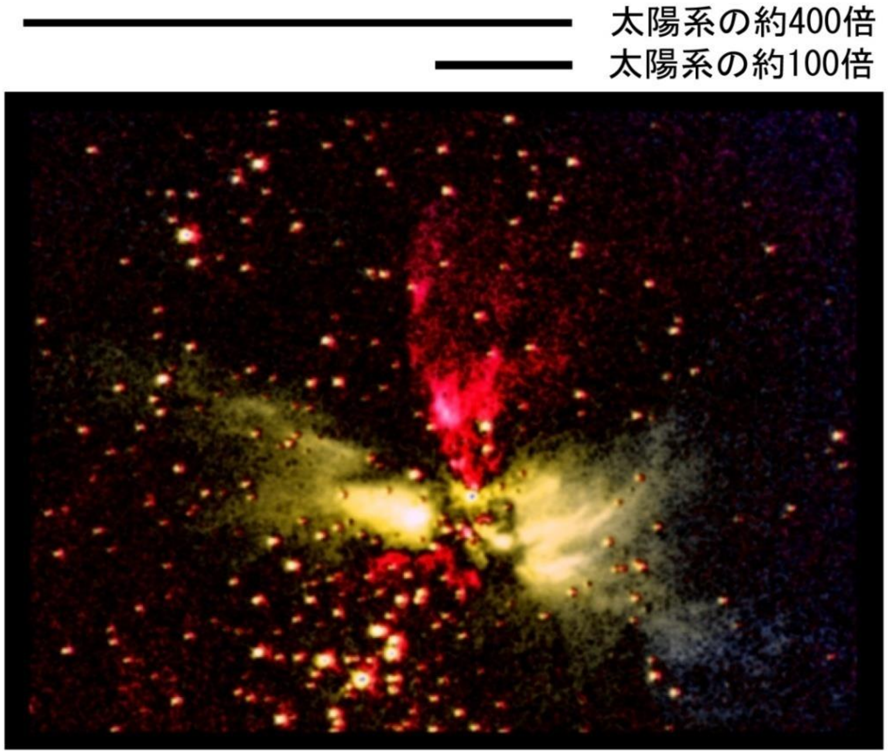
左（L）型と右（D）型は互いに鏡像関係にあり、
左型を回転させても右型には一致しない。

http://www.nao.ac.jp/releaselist/archive/20100406/index_j.html

円偏光をとらえたすばる望遠鏡観測装置

すばる望遠鏡、オリオン星雲中心部
の星形成領域に円偏光モード観測！
黄色部分が光が左回り(反時計回り)、
赤色部分が右回りの円偏光の領域。





地球(太陽系)起源説:

大規模な円偏光に原始太陽系が飲み込まれて誕生。
円偏光の照射で左巻きアミノ酸が選択され、その後隕石で地球に持ち込まれた。

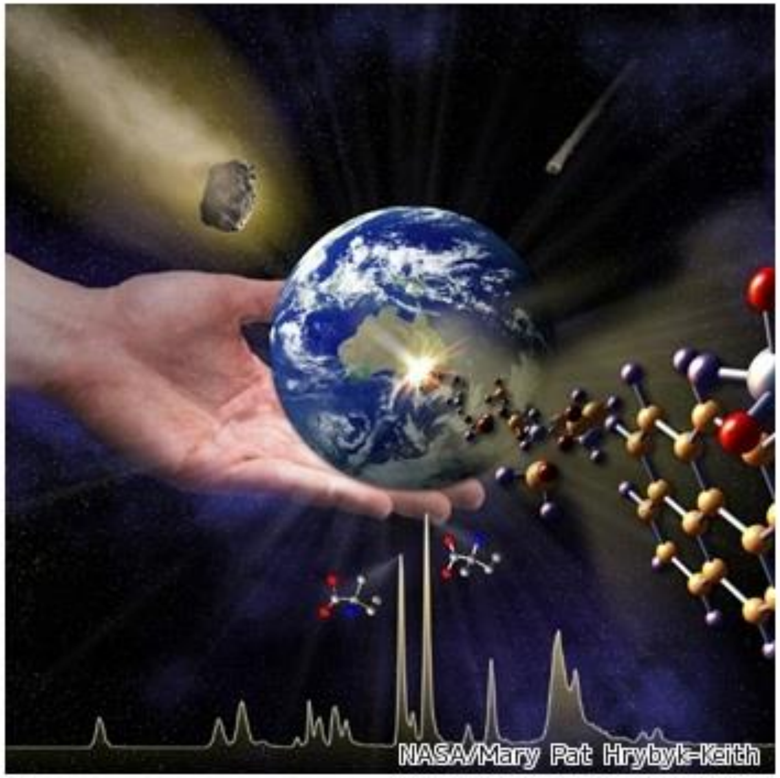
実験室の偏光実験で否定

第2、第3の地球では、左巻き、右巻き両方のアミノ酸が存在しえる。

マーチソン隕石:アミノ酸は人類と同じ左型！

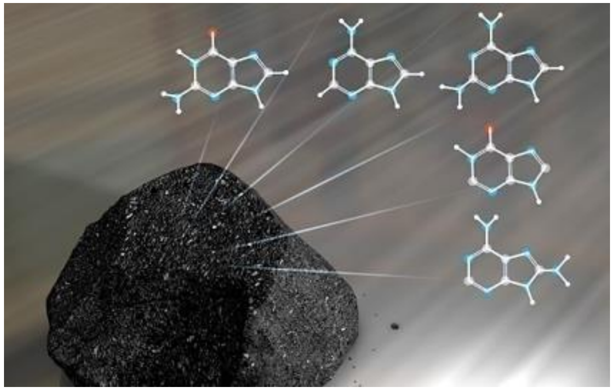
ＮＡＳＡ発表（２００９年３月１６日）

http://tokyo.secret.jp/80s/come/amino-acid.html



NASA/Mary Pat Hrybyk-Keith

アミノ酸のように、構成要素が同じでも鏡に映したような2つの立体構造を取り得る物質を鏡像体(光学異性体)という。同じアミノ酸でも右型と左型では性質が大きく変わり、右型アミノ酸は体に害をなすことも多い。なぜ生命は左型アミノ酸を選んだのか、その理由は宇宙にある…とするのがGlavin氏らの考え。今後のさらなる研究が期待される



はやぶさ、奇跡の生還！

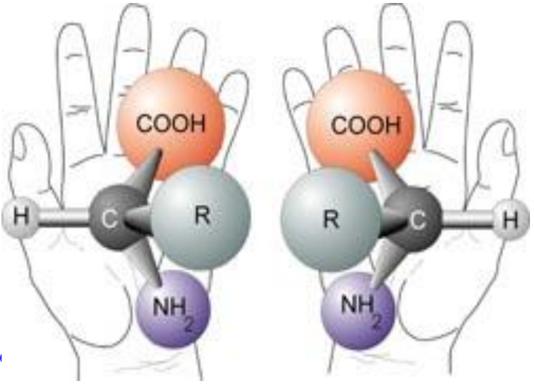
小惑星イトカワからの
サンプルリターンに成功。

はやぶさⅡに期待！

アミノ酸は全宇宙で左巻き＝宇宙起源説

ボイド・梶野・ファミアーノ・尾中 論文, Astrobiology 10 (2010), 561-568; Int. J. Mol. Sci. 12 (2011) 3432; Astrobiology (2014), submitted.

強磁場を持つ超新星（原始中性子星）周辺でのニュートリノ・原子核相互作用



★ 左右非対称が完全に破れた素粒子は宇宙でニュートリノだけ

Mann and Primakoff, Origins of Life, 11 (1981), 255；
14Cのベータ崩壊！ 5730年の半減期は、あまりにゆっくり過ぎる！

★ 超新星から多量（~10^{58} 個）のニュートリノが放射される。

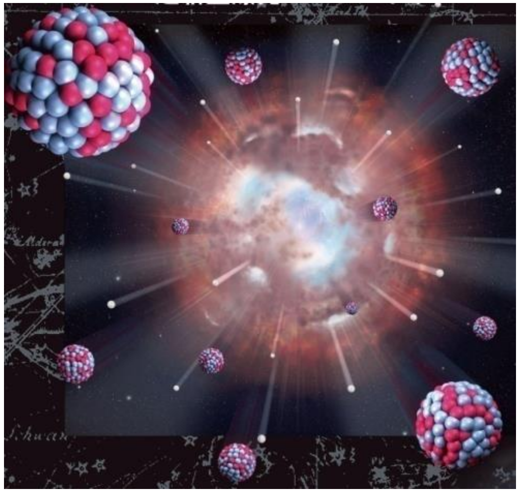
銀河中心で起きたとすると、10兆個/秒/cm^2

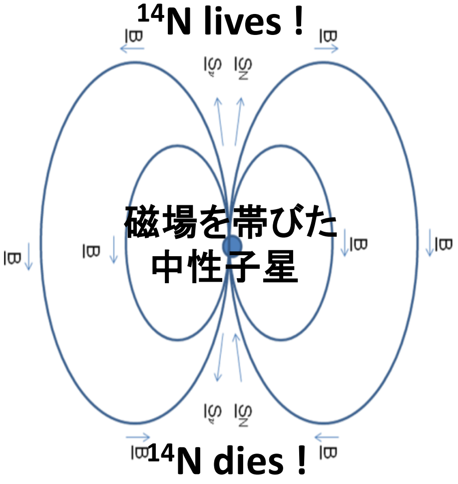
★ 生命元素（炭素、窒素、酸素など）は超新星爆発で合成される。

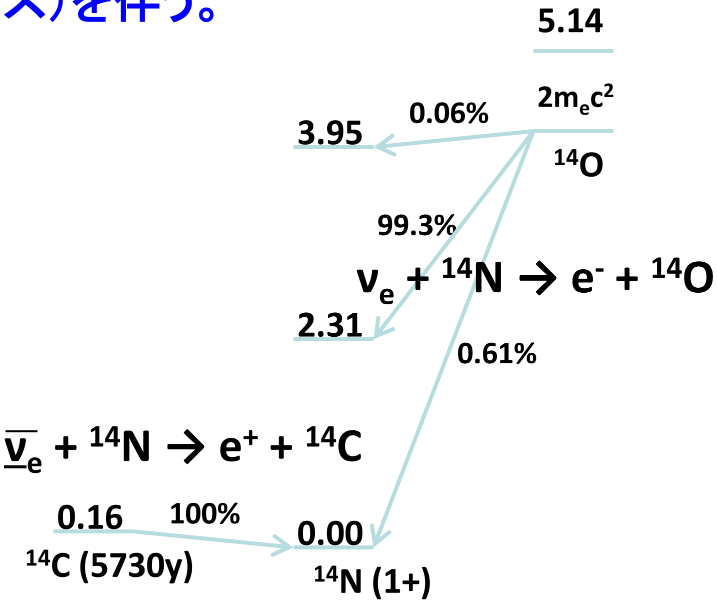
天の川で約50年に一回の頻度で繰り返し起きる。

★ 原始中性子星/ブラックホールは強磁場（~10^{14} ガウス）を伴う。

スピン：ニュートリノ＝1/2、炭素・酸素＝0、窒素＝1。



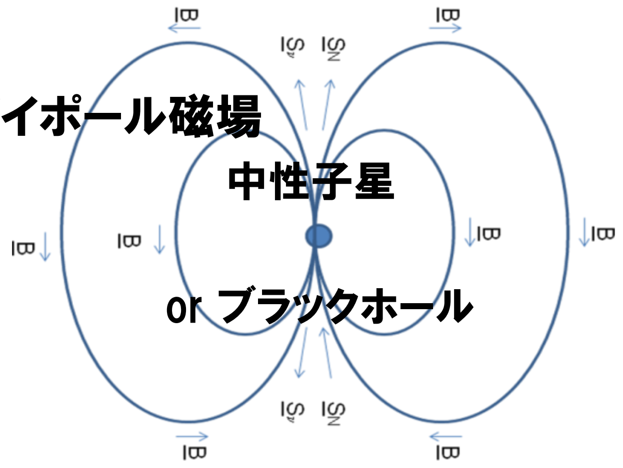




$\nu_e + {}^{14}N \rightarrow e^- + {}^{14}O$

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

強磁場を持つ超新星（原始中性子星）周辺でのニュートリノ・原子核相互作用



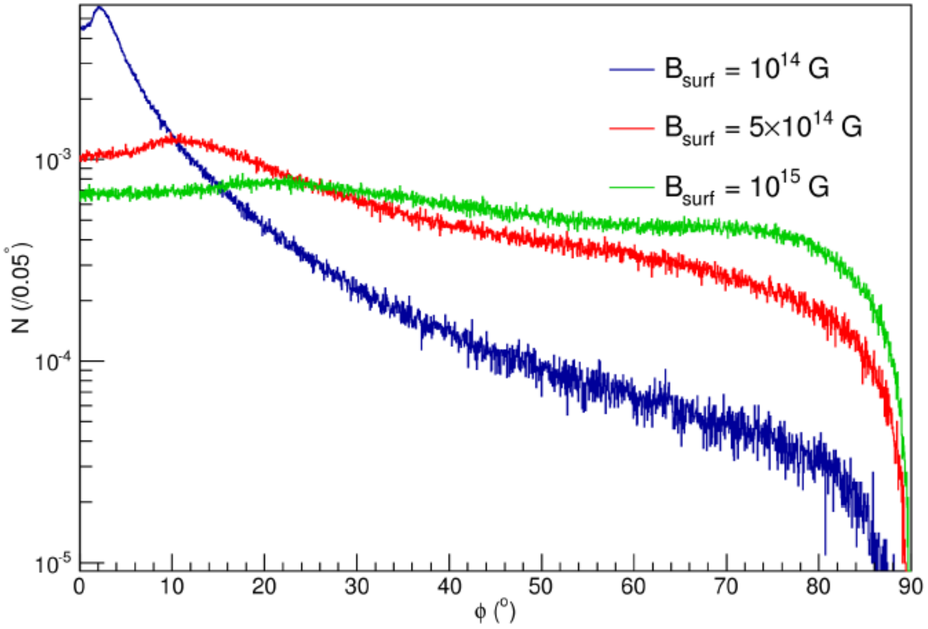
ダイポール磁場

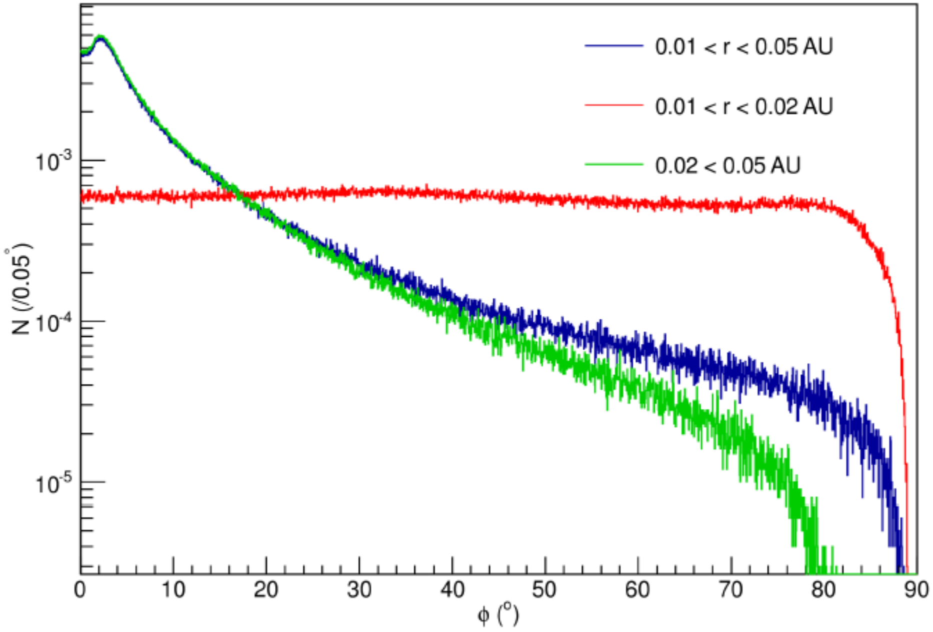
中性子星

or ブラックホール

Boyd, Famiano, Kajino & Onaka 2014,
Astrobiology, submitted.

強い磁場を帯びた中心星（中性子星、ブラックホール）からどれくらいの距離まで、磁場による偏極を保てるか？





SUMMARY

Relic Supernova-ν:

Future observation of Relic Supernova ν's in megaton Hyper-Kamiokande (i.e. Gd-loaded Water Cherenkov detector in 10y run) could solve the SN rate problem and also discriminate EoS and neutrino oscillation pattern.

ν-Mass hierarchy & Total Mass:

Supernova ν-process nucleosynthesis could determine the mass hierarchy Δm_{13}^2 and $\sin^2\theta_{13} \sim 0.1$ simultaneously. Inverted hierarchy is statistically more preferred. Total ν-mass, if $\Sigma m_\nu < 0.1$eV or 0.05eV, strongly constrain the mass hierarchy.

Origin of r-process:

GRB could be a viable site for r-process (+ CCSN, MHD-jet, NSM).

Origin of Chirality of Amino Acids on Earth:

Breaking Chirality of neutrinos may be the universal origin.

Origin of Pulsar Kick:

Parity violation in magnetized neutron star triggers asymmetric ν-baryon reactions to likely explain the observed pulsar kick.