CNNP2017, Catania Italy, Oct. 15-21, 2017

Neutrino Collective Oscillation & Hierarchy

— Impact of Nucleosynthesis on ν-physics in Neutron Star Mergers & Supernovae —

GW170817 : Binary Neutron Star Merger
LIGO and Virgo discovered 1st cosmic event observed in both GW and light !

From LIGO Home Page

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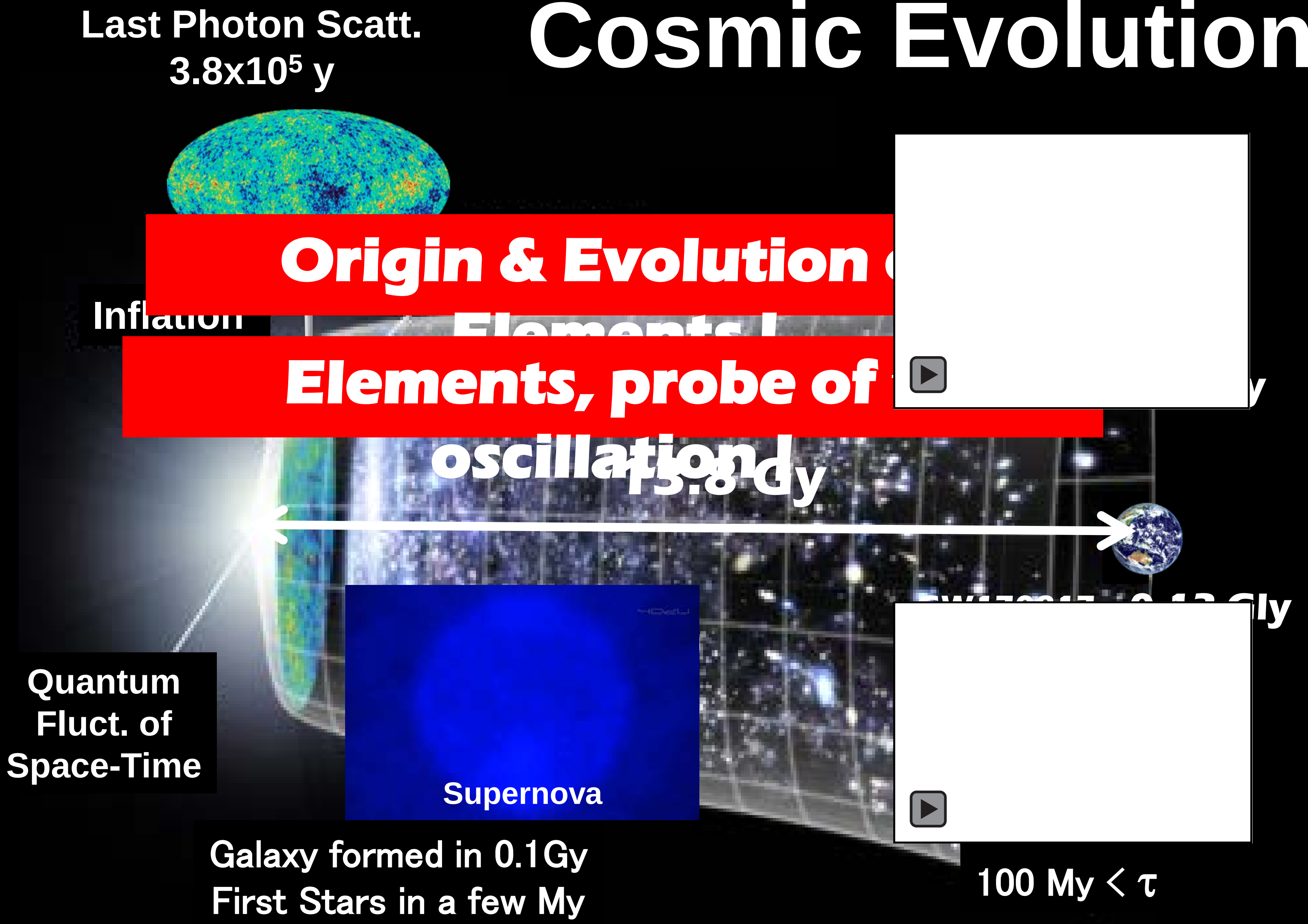
Cosmic Evolution

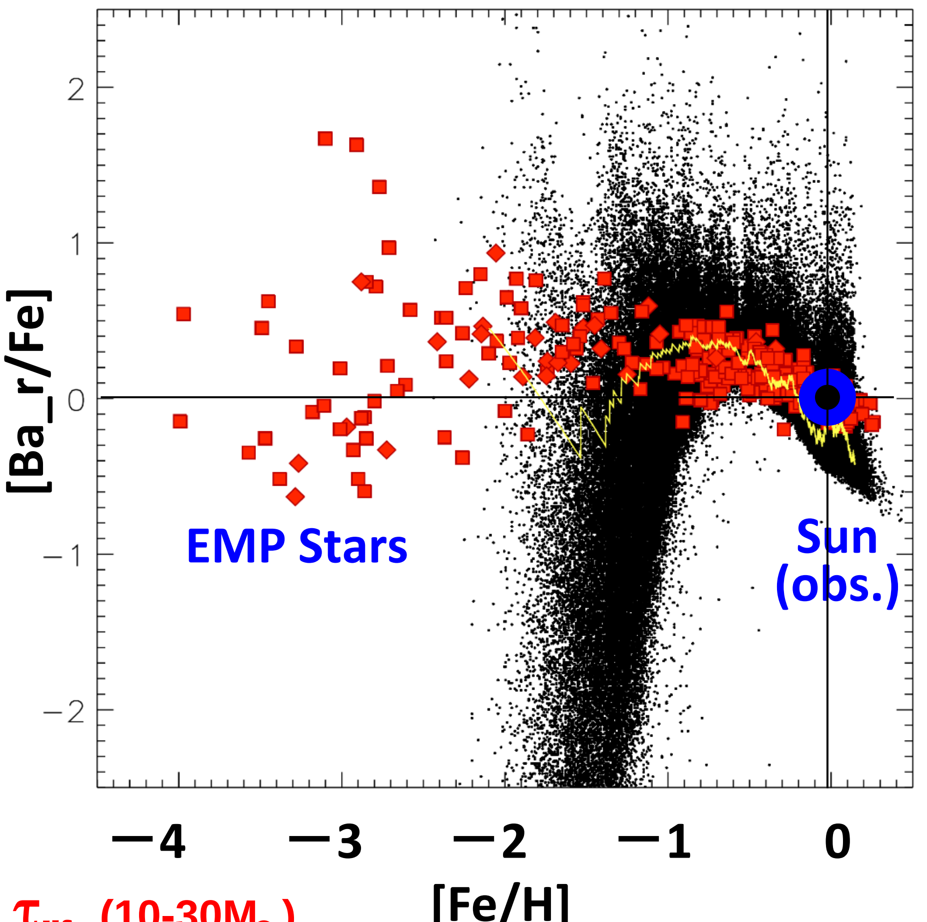


Galactic Chemo-Dynamical Evolution

Time Scale Problem

Argast, et al., A&A 416 (2004), 997,
Wehmeyer et al., MNRAS, 452 (2015), 1970.

τ_c = 100 My **Merger R-Process (Theory)**



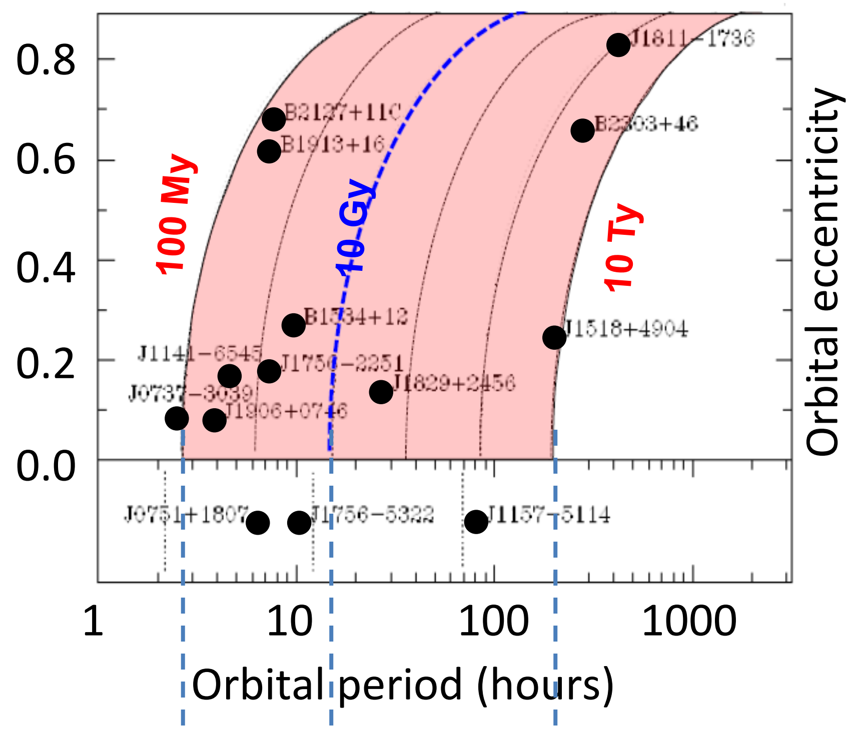
τ_{life} (10-30$M_\odot$)

1My 10My 100My ··· 10Gy

Binary merger process, too slow for GW radiation: 100My<τ_c

$$\tau_c \simeq 9.83 \times 10^6 \text{ yr} \left(\frac{P_b}{\text{hr}}\right)^{8/3} \times \left(\frac{m_1+m_2}{M_\odot}\right)^{-2/3} \left(\frac{\mu}{M_\odot}\right)^{-1} (1-e^2)^{7/2}$$

Lorimer, Living Rev. Rel. 11(2008), 8.



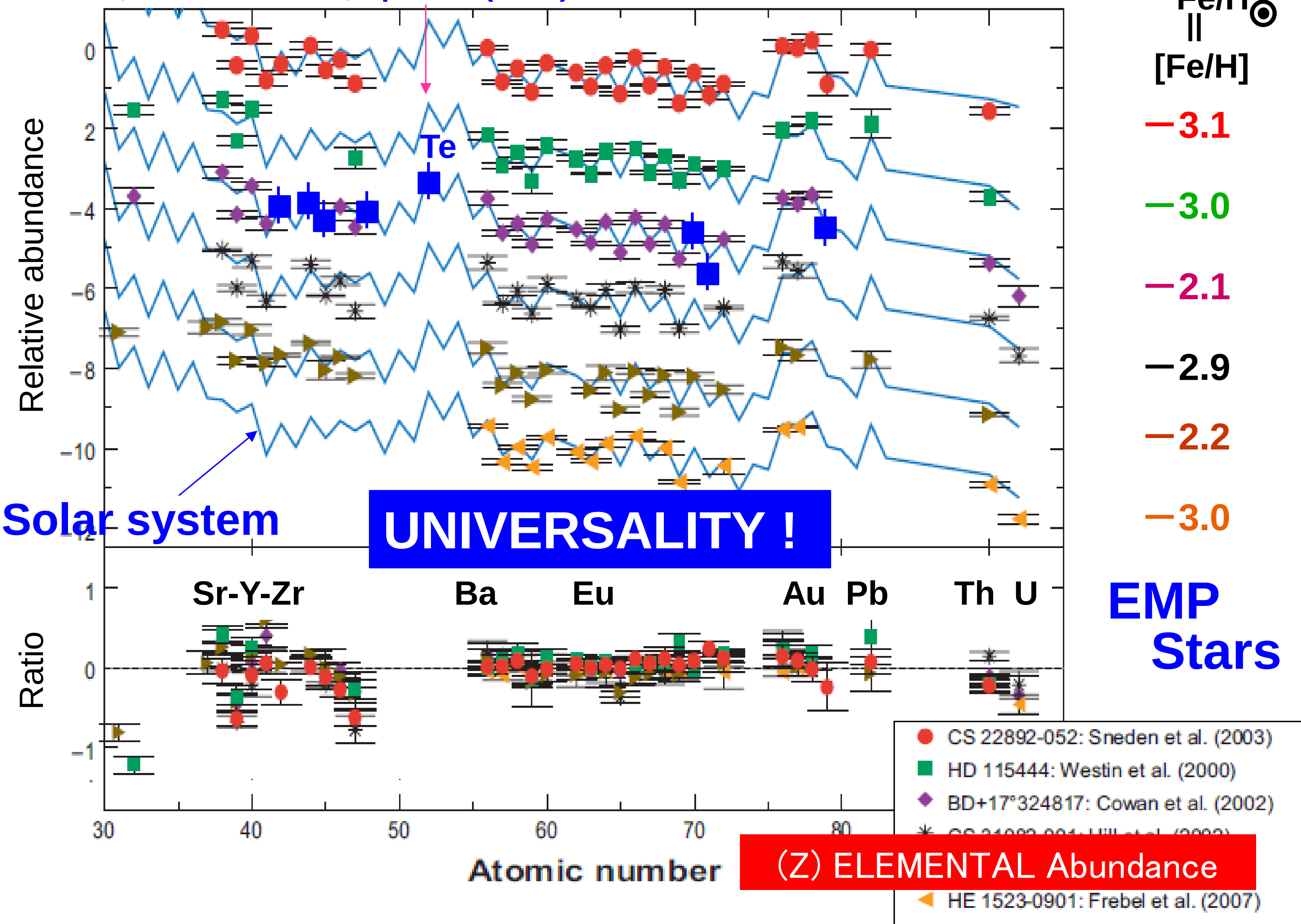
100My 10Gy 10Ty

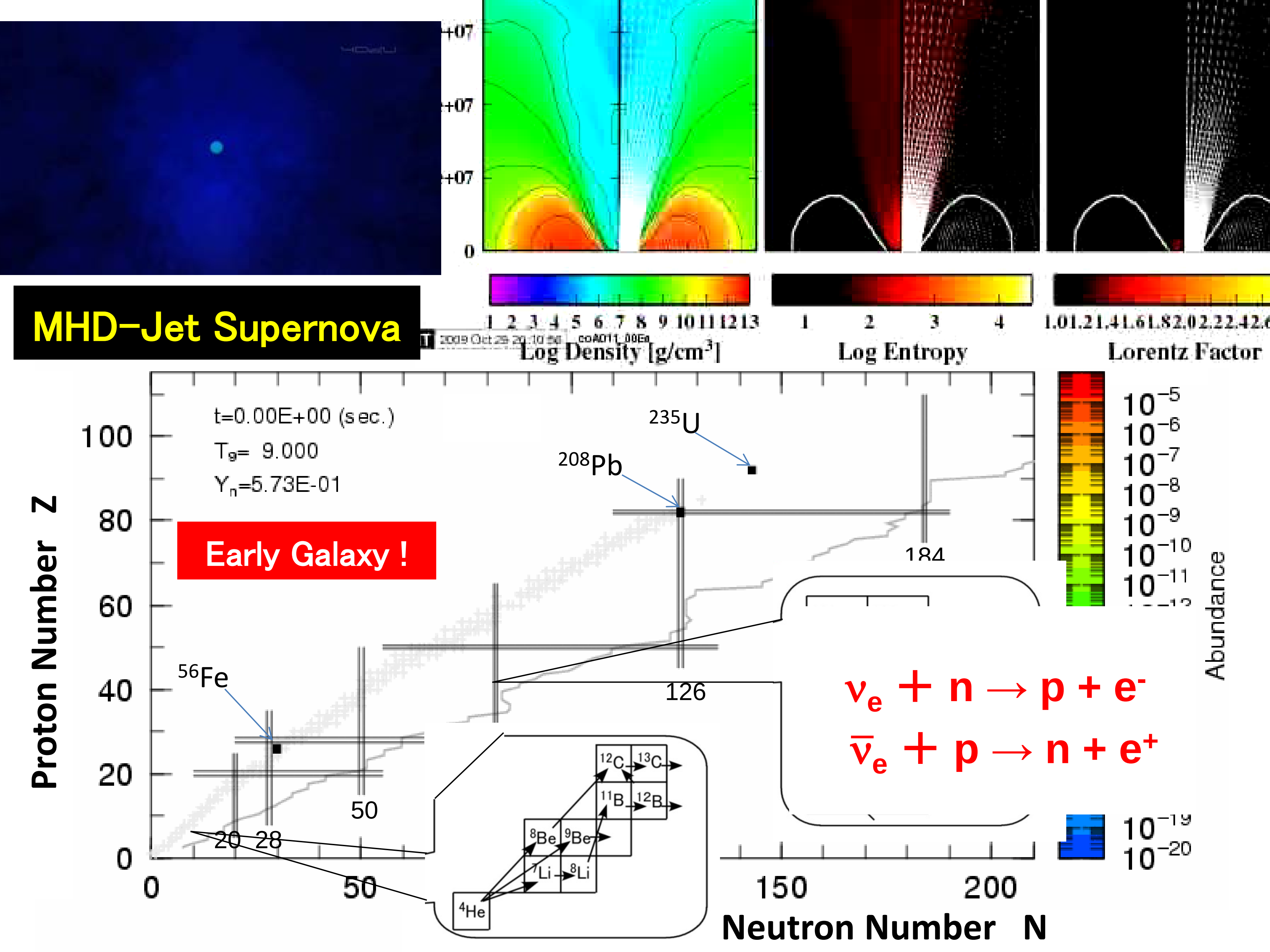
Sneden, Cowan, Gallino, ARAA 46 (2008) 241.

HST-obs., Roederer et al., ApJ 747 (2012) L8.

$$\frac{t}{10^{10}y} \fallingdotseq 10^{[Fe/H]}$$

$$\mathrm{Log}\ \frac{Fe/H_{\star}}{Fe/H_{\odot}} = [Fe/H]$$



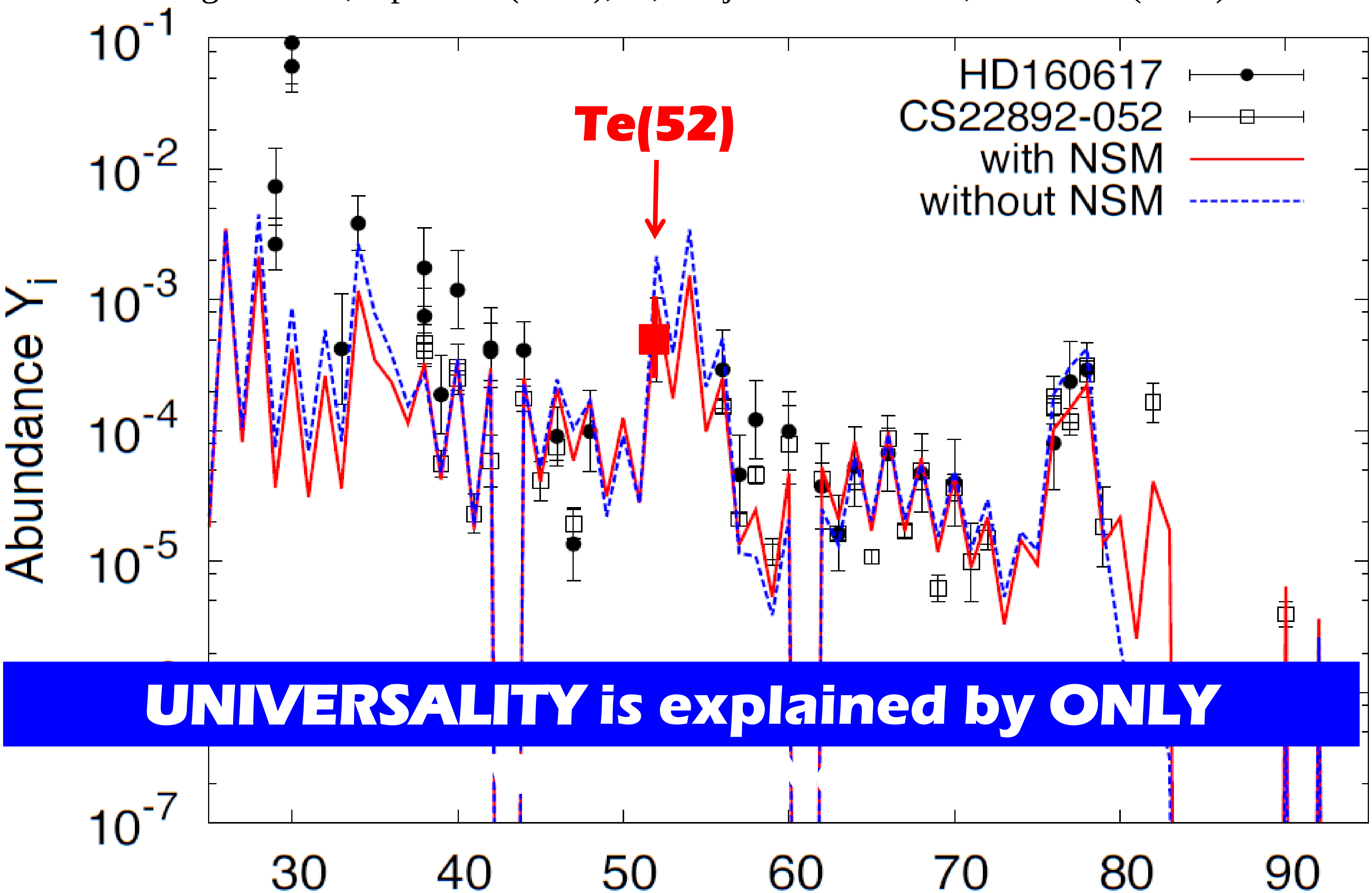


MHD-Jet Supernova
Log Density [g/cm^3]
Log Entropy
Lorentz Factor
t=0.00E+00 (sec.)
T_9= 9.000
Y_n=5.73E-01
Early Galaxy !
^{235}U
^{208}Pb
^{56}Fe
184
126
50
20
28
^{4}He
^{7}Li
^{8}Li
^{8}Be
^{9}Be
^{11}B
^{12}B
^{12}C
^{13}C
$\nu_e + n \rightarrow p + e^-$
$\bar{\nu}_e + p \rightarrow n + e^+$
Abundance
Proton Number Z
Neutron Number N

UNIVERSALITY !

Early Galaxy !

Shibagaki et al., ApJ. 816 (2016),79; Kajino & Mathews, ROPP **80** (2017) 08490.



UNIVERSALITY is explained by ONLY

Atomic Number Z

Astron. Obs. cannot separate ISOTOPES !

ELEMENTAL (Z)

Binary Neutron … ers

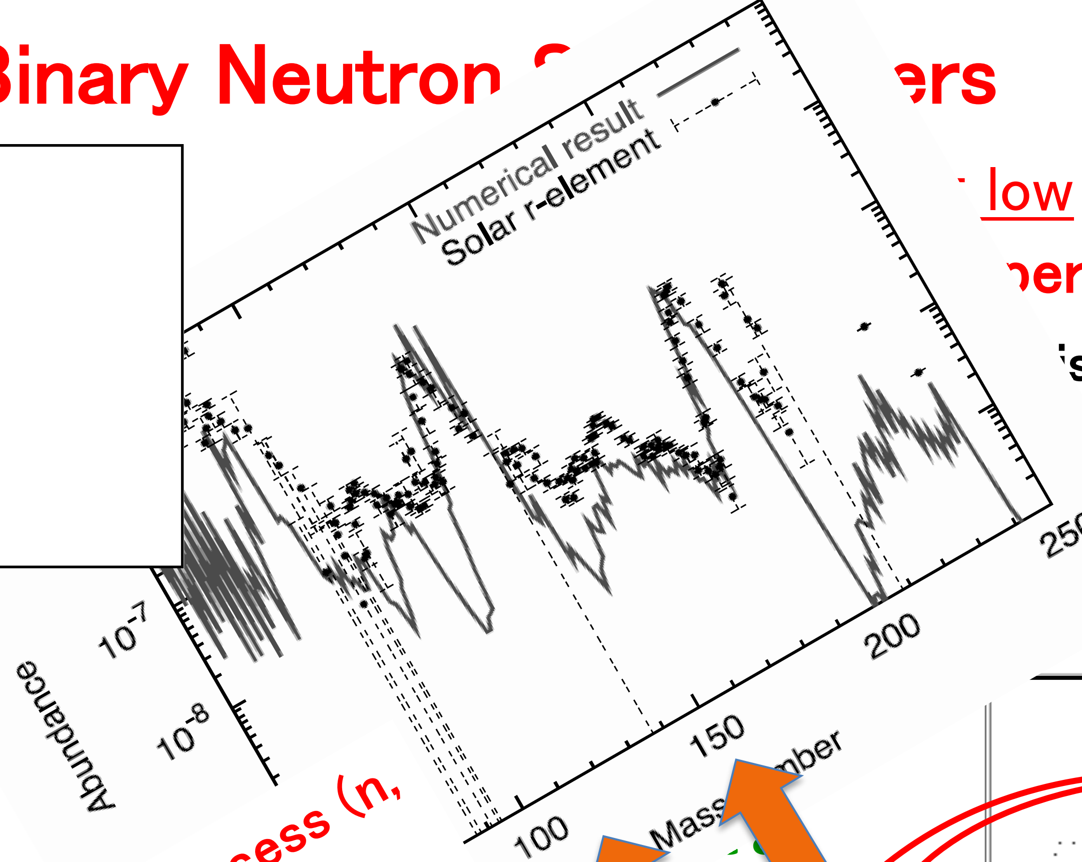
low

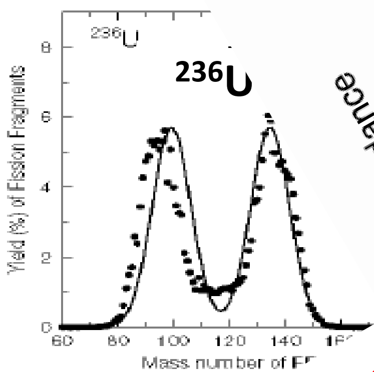
erates!

istribution

e, France, (2007)

8).





Bimordial or T

$f(A, A$ … 2σ

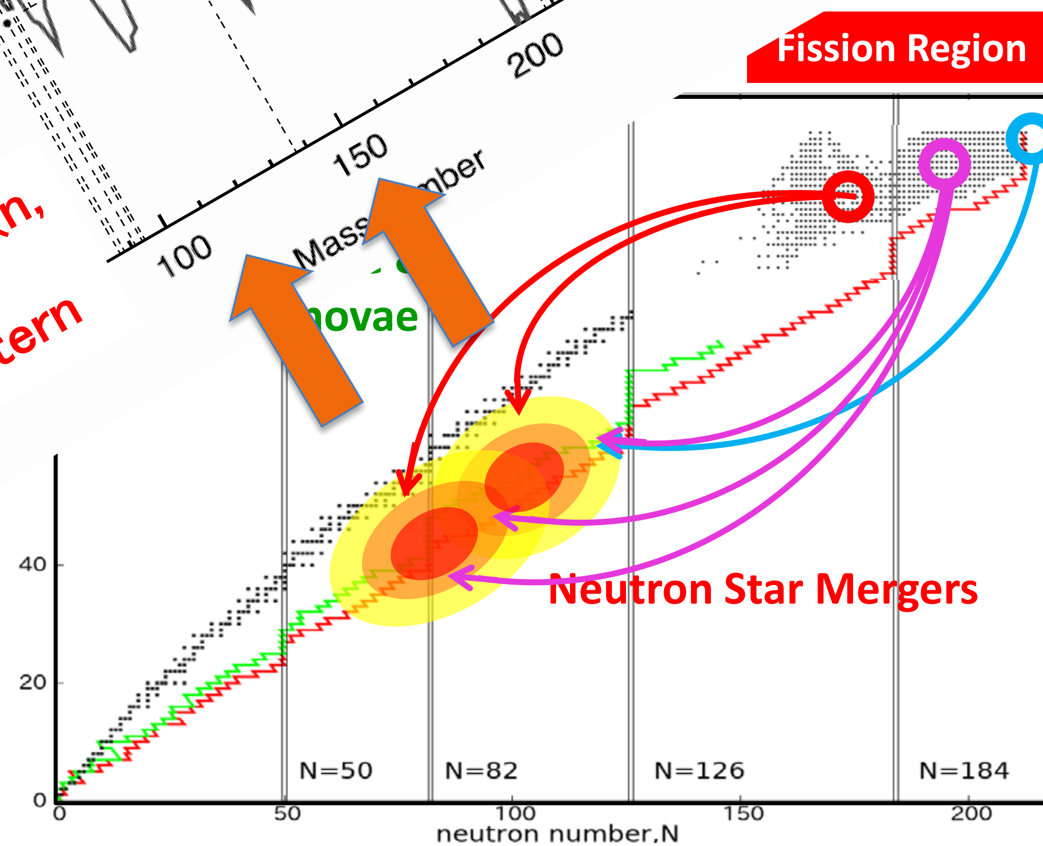
$N_{loss})/2$

$-\alpha)(A_p - N_{loss})/2$

$A_M = (A_H + A_L)/2.$

Fission recycling and r-process (n, γ) & β-decay for smoothing abundance pattern

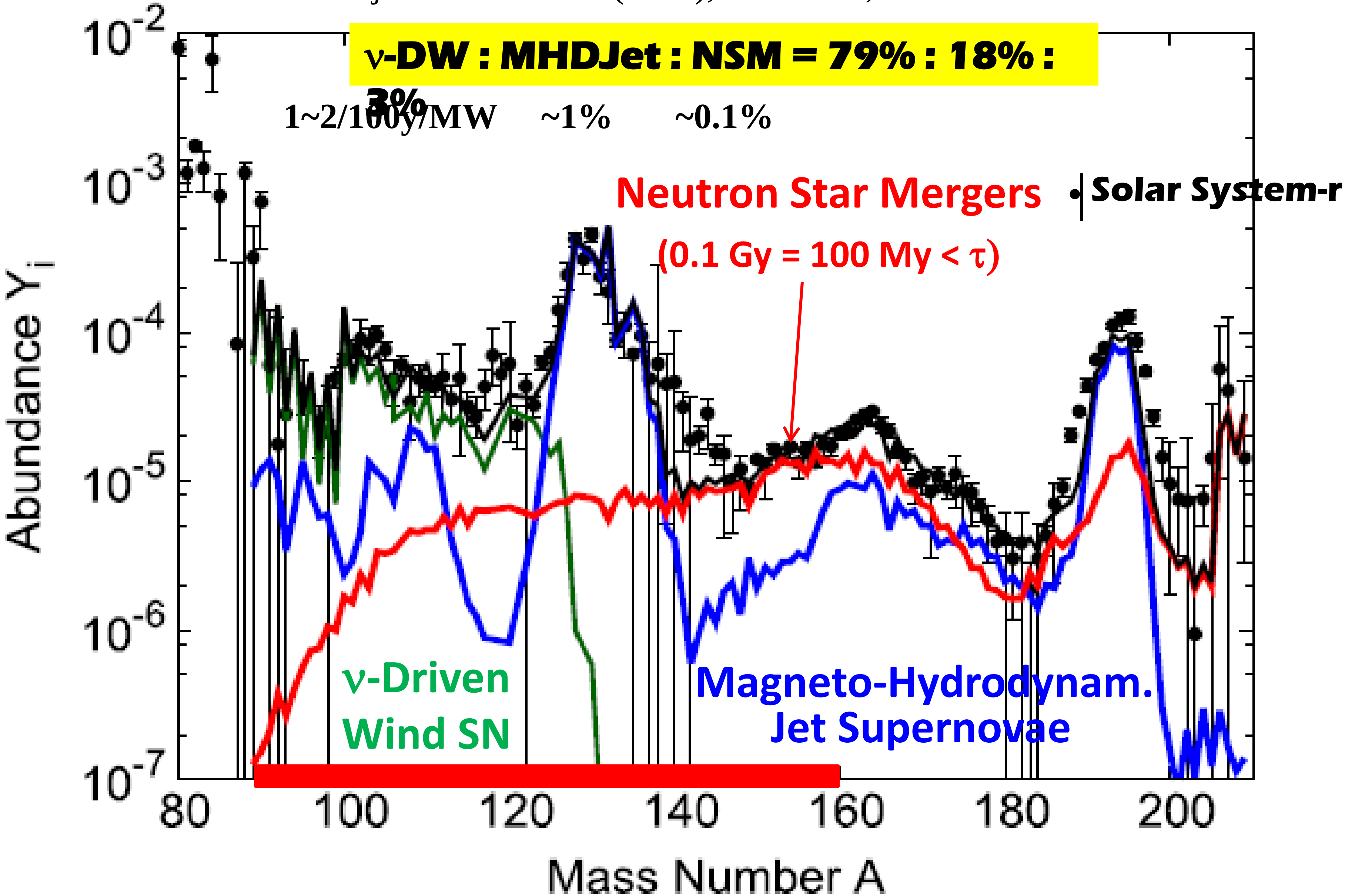
novae



Solar System r-Process Abundance

Present time: t =

Shibagaki, Kajino, Chiba, Mathews, Nishimura & Lorusso (2016), ApJ 816, 79; ApJ (2017); Kajino & Mathews (2017), ROPP 80 , 084901.



Observed Galactic event rates !

Ejected Mass [Msun] x Event Rate [/Galaxy/Century]

νSN (Weak r)	=	7.4×10^{-4}	x	(1.9±1.1) [a]
MHD Jet SNe	=	0.6×10^{-2}	x	((0.03±0.02) x (1.9±1.1)) [b]
Binary NSMs	=	$(2\pm1) \times 10^{-2}$	x	$(1\text{-}28)\times10^{-3}$ [c]

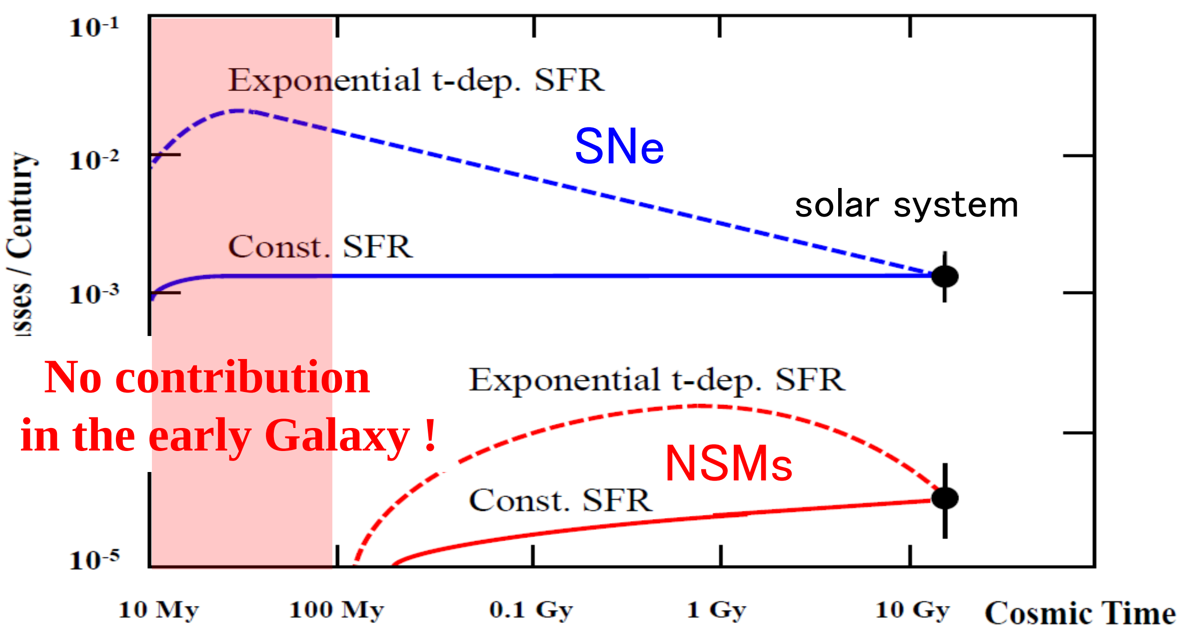
Observations	a	1.9±1.1	Diehl, et al., Nature 439, 45 (2006).
	b	0.03±0.02	Winteler, et al., ApJ 750, L22 (2012).
Obs. Estimate	c	$(1\text{-}28) \times 10^{-3}$	Kalogera, et al., ApJ 614, L137 (2004).

Event rates
including Binary Evolution

Kajino & Mathews, Rep. Prog. Phys. **80** (2017) 08490;
Mathews & Kajino, (1987).

Time Scale Problem in

Neutron Star Mergers

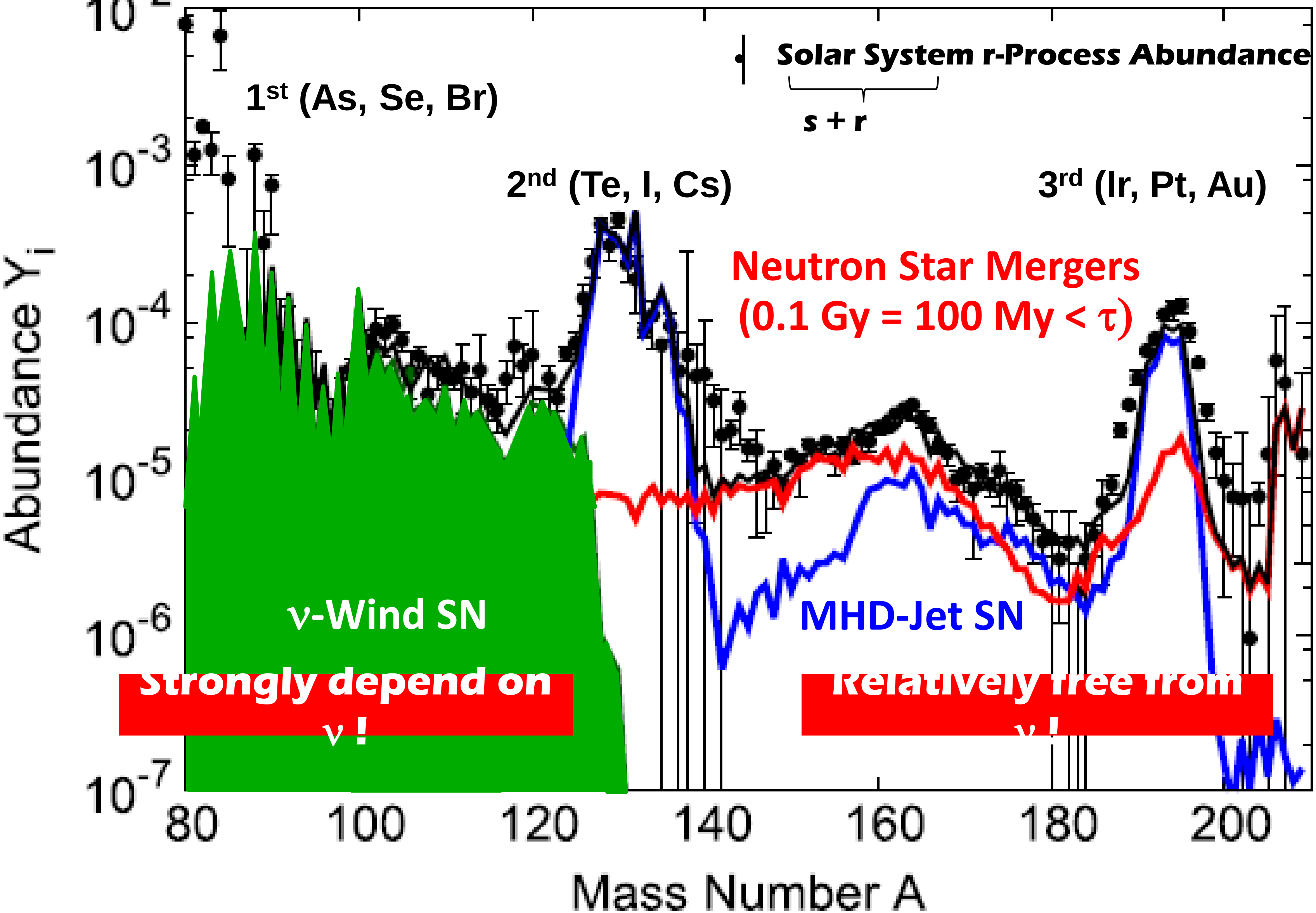


Solar System r-Process Abundance

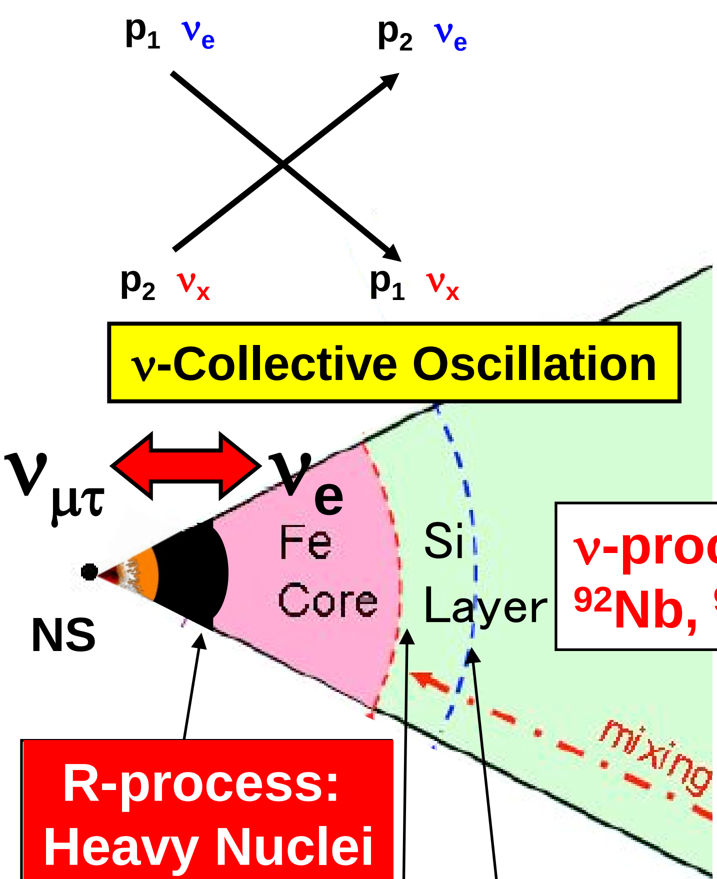
Present time: t =

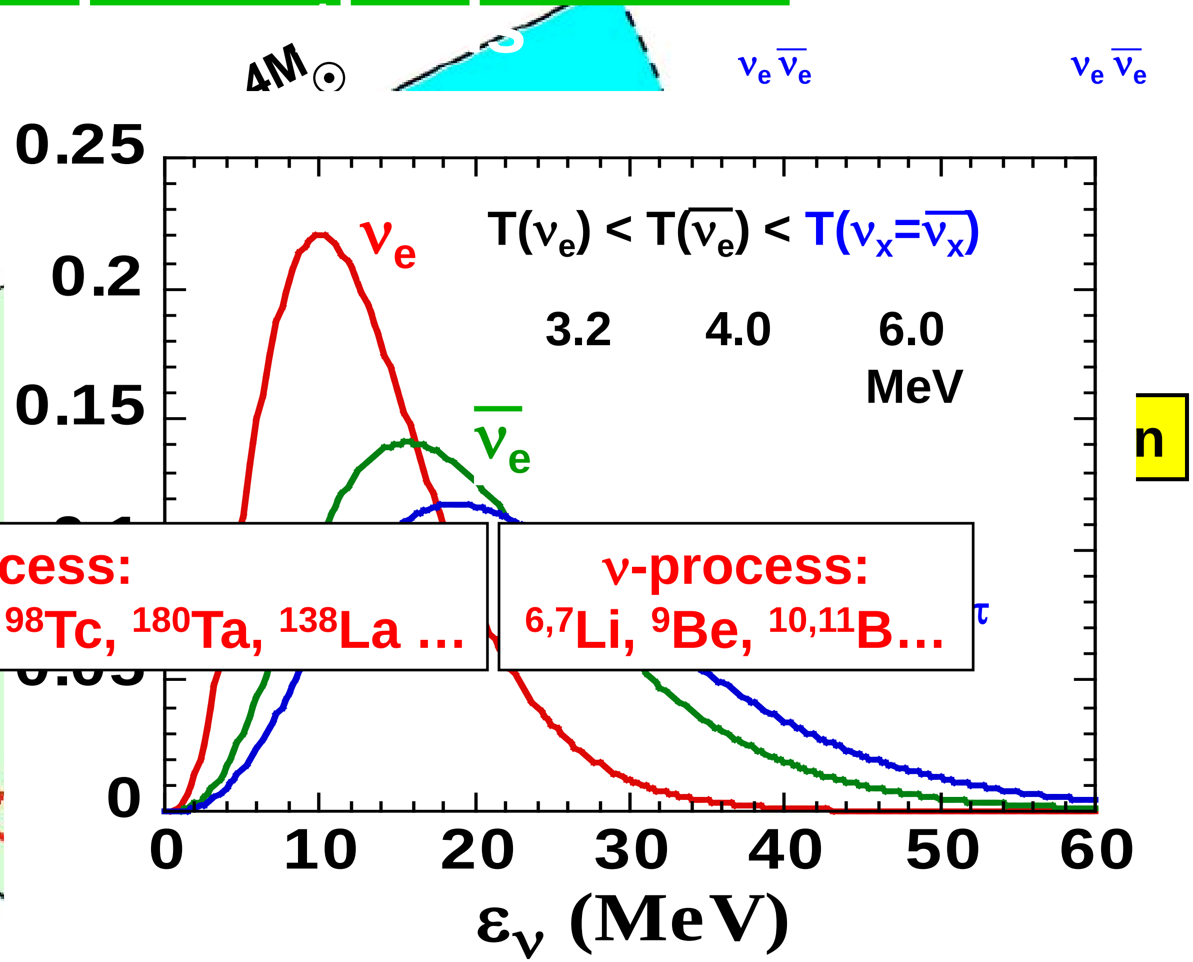
Shibagaki, Kajino, Chiba, Mathews, Nishimura & Lorusso (2016), ApJ 816, 79; ApJ (2017);
Kajino & Mathews (2017), ROPP 80, 084901.

New process, required ?



ν-Oscillation and





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

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

R-process: Heavy Nuclei

νp-process: ^{92}Mo, ^{96}Ru ?

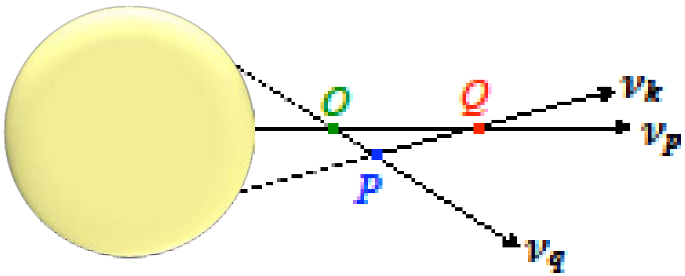
Explo. Si-burn.: Fe-Co-N ^{60}Co, ^{55}Mn, ^{51}V …

$\nu_{x=\mu,\tau}$ $\quad \nu_e + n \rightarrow p + e^-$ **proton-rich!**

$\bar{\nu}_{x=\mu,\tau}$ $\quad \bar{\nu}_e + p \rightarrow n + e^+$

Collective ν Oscillation — Many-Body Effect

Proto Neutron Star

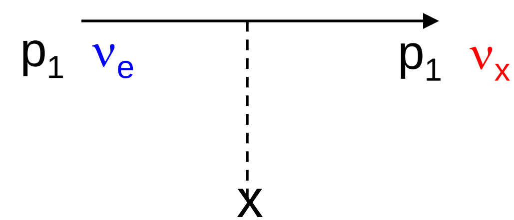


Duan, Fuller, Carlson & Qian, PRL 97 (2006), 241101.
Fogli, Lisi, Marrone & Mirizzi, JCAP 12, (2007) 010.
Balantekin, Pehlivan & Kajino, PR D84, (2011), 065008
PR D90, (2014), 065011.

H_ν = Mixing and Int. with Background Electrons

MSW (Matter) Effect

$$H_\nu = \frac{1}{2}\int d^3p \left(\frac{\delta m^2}{2p}\cos 2\theta - \sqrt{2}G_F N_e\right)\left(a_x^\dagger(p)a_x(p) - a_e^\dagger(p)a_e(p)\right) + \frac{1}{2}\int d^3p \frac{\delta m^2}{2p}\sin 2\theta\left(a_x^\dagger(p)a_e(p) + a_e^\dagger(p)a_x(p)\right).$$

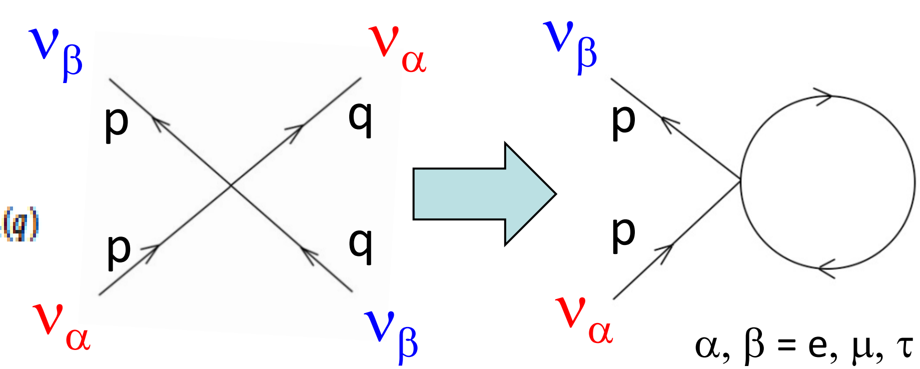


N_e = electron density

$H_{\nu\nu}$ = Self-Interactions

Collective Effect for νν-scatt.

$$H_{\nu\nu} = \frac{G_F}{\sqrt{2}V}\int d^3p\, d^3q\, R_{pq}\left[a_e^\dagger(p)a_e(p)a_e^\dagger(q)a_e(q) + a_x^\dagger(p)a_x(p)a_x^\dagger(q)a_x(q) + a_x^\dagger(p)a_e(p)a_e^\dagger(q)a_x(q) + a_e^\dagger(p)a_x(p)a_x^\dagger(q)a_e(q)\right].$$



α, β = e, μ, τ

10^{49} ν's with 3-flavors & multi-angles (3 x 3r x 3p /ν) !

→ **Mean Field Approx.**

Theoretical Method

3 x 3 density matrices

$\rho(t,\mathbf{p})$ for ν, $\bar{\rho}(t,\mathbf{p})$ for $\bar{\nu}$.

$$\bar{\rho}(t,\mathbf{p}) = \begin{pmatrix} \bar{\rho}_{ee} & \bar{\rho}_{e\mu} & \bar{\rho}_{e\tau} \\ \bar{\rho}_{\mu e} & \bar{\rho}_{\mu\mu} & \bar{\rho}_{\mu\tau} \\ \bar{\rho}_{\tau e} & \bar{\rho}_{\tau\mu} & \bar{\rho}_{\tau\tau} \end{pmatrix}$$

$$\langle a^\dagger_\alpha(\mathbf{p}) a_\beta(\mathbf{q})\rangle = (2\pi)^3\delta^{(3)}(\mathbf{p}-\mathbf{q}) f(t,\mathbf{p})\rho(t,\mathbf{p})_{\beta\alpha}$$

$$\langle b^\dagger_\alpha(\mathbf{p}) b_\beta(\mathbf{q})\rangle = (2\pi)^3\delta^{(3)}(\mathbf{p}-\mathbf{q}) g(t,\mathbf{p})\bar{\rho}(t,\mathbf{p})_{\alpha\beta}$$

$$\mathrm{Tr}\rho(t,\mathbf{p}) = \mathrm{Tr}\bar{\rho}(t,\mathbf{p}) = 1$$

G. Sigl and G. Rafflet,Nucl. Phys. B 406, 423, 1993

Diagonal components $\bar{\rho}_{\alpha\alpha}$ represents the probability of finding $\bar{\nu}_\alpha$.

Solving dynamical eqs.

$$\frac{d}{dt}\rho_{\alpha\beta}(t,\mathbf{p}) = -i\left[\rho(t,\mathbf{p}), \Omega(\mathbf{p}) + V(t,\mathbf{p})\right]_{\alpha\beta}$$

$$\frac{d}{dt}\bar{\rho}_{\alpha\beta}(t,\mathbf{p}) = -i\left[\bar{\rho}(t,\mathbf{p}), -\Omega(\mathbf{p}) + V(t,\mathbf{p})\right]_{\alpha\beta}$$

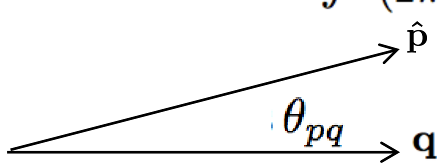
$\Omega(\mathbf{p})$ ……Vacuum Hamiltonian

$V(t,\mathbf{p}) = V_{\mathrm{MSW}} + V_{\mathrm{self}}$

…… Potential in flavor space

Mean field ν-ν coherent scattering term

$$V_{\mathrm{self}\,\alpha\beta} = \sqrt{2}G_F \int \frac{\mathrm{d}^3 q}{(2\pi)^3}(1-\cos\theta_{pq})\{f(t,\mathbf{q})\rho_{\alpha\beta}(t,\mathbf{q}) - g(t,\mathbf{q})\bar{\rho}_{\alpha\beta}(t,\mathbf{q})\}$$



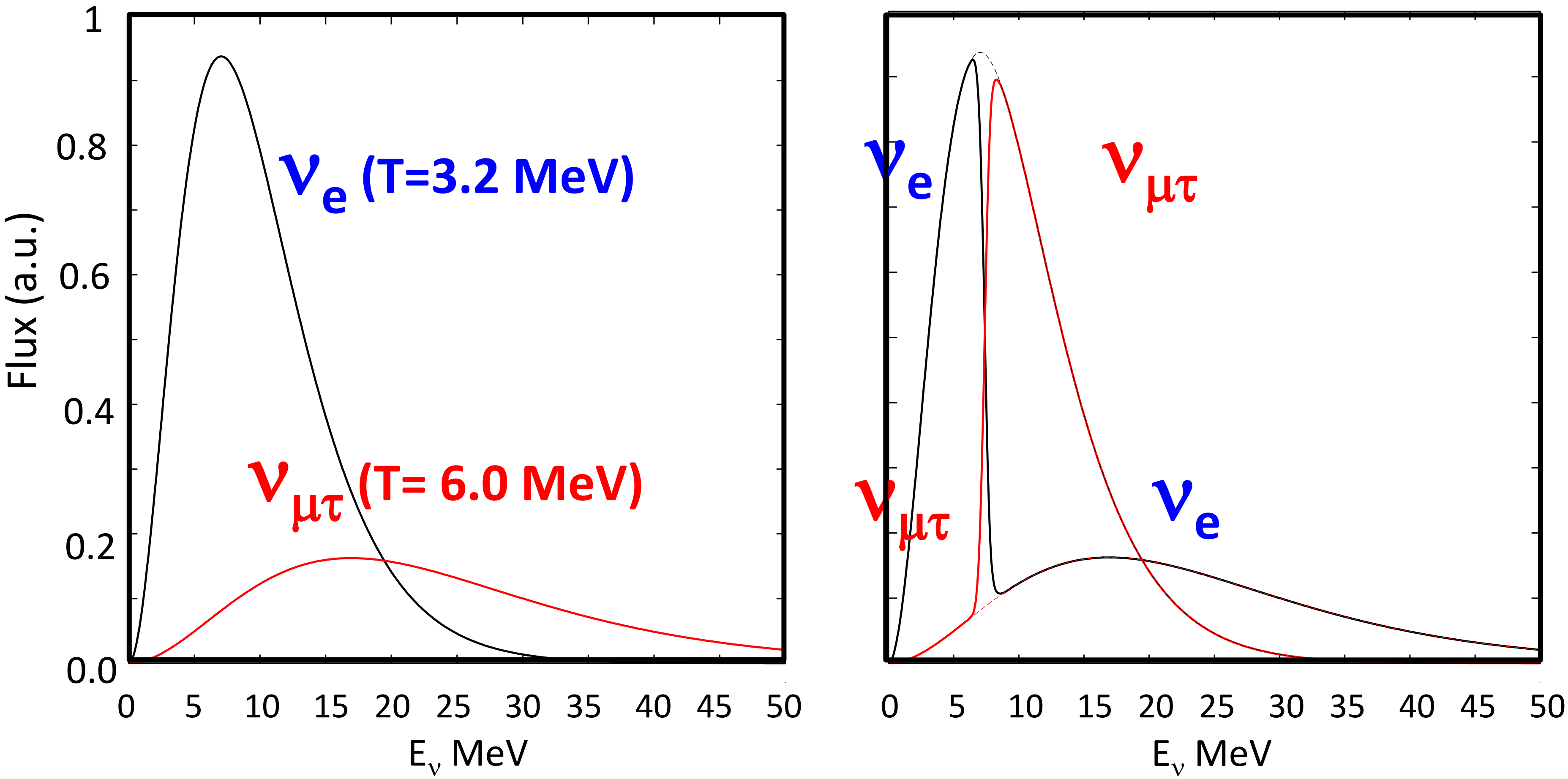
$$\int \frac{\mathrm{d}^3 p}{(2\pi)^3} f(p) = n_\nu \qquad \int \frac{\mathrm{d}^3 p}{(2\pi)^3} g(p) = \bar{n}_\nu$$

Swapped ν Energy Spectra

Sasaki et al. PR **D96** (2017), 043013.

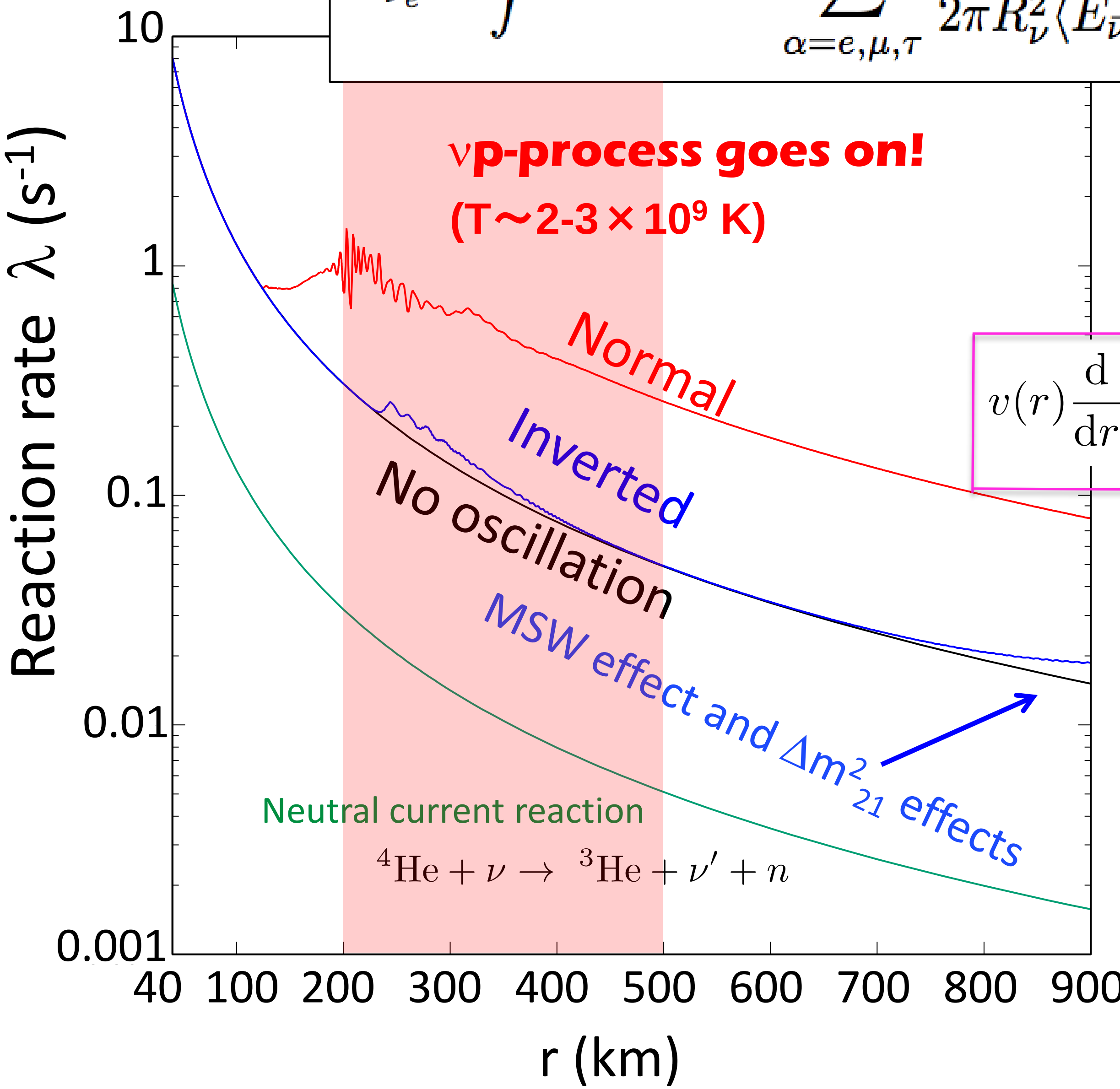
Both Normal & Inverted hierarchy, Observed θ_{13} & Δm^2

r = 10km (ν-sphere) → r=250km



Continuous Collective ν-Oscillation Effect at 200 km < r

$$\lambda_{\bar{\nu}_e} = \int dE \, d\cos\theta \sum_{\alpha=e,\mu,\tau} \frac{L_{\bar{\nu}_\alpha}}{2\pi R_\nu^2 \langle E_{\bar{\nu}_\alpha} \rangle} f_{\bar{\nu}_\alpha}(E) \bar{\rho}_{ee}(E, \theta_R) \sigma_{\bar{\nu}_e}(E)$$



Charged current reaction

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

$$v(r) \frac{d}{dr} Y_n = \lambda_{\bar{\nu}_e} Y_p + \lambda_{\nu\nu'} Y_{^4\mathrm{He}} + \mathrm{Other}$$

Y_n ... neutron abundance

Y_p ... proton abundance

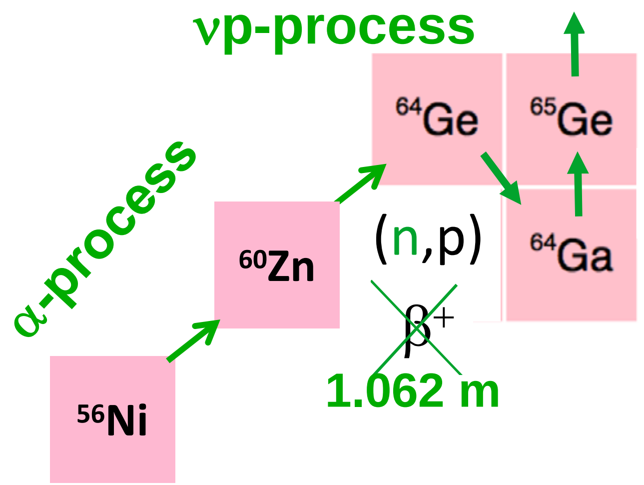
$Y_{^4\mathrm{He}}$ ... helium4 abundance

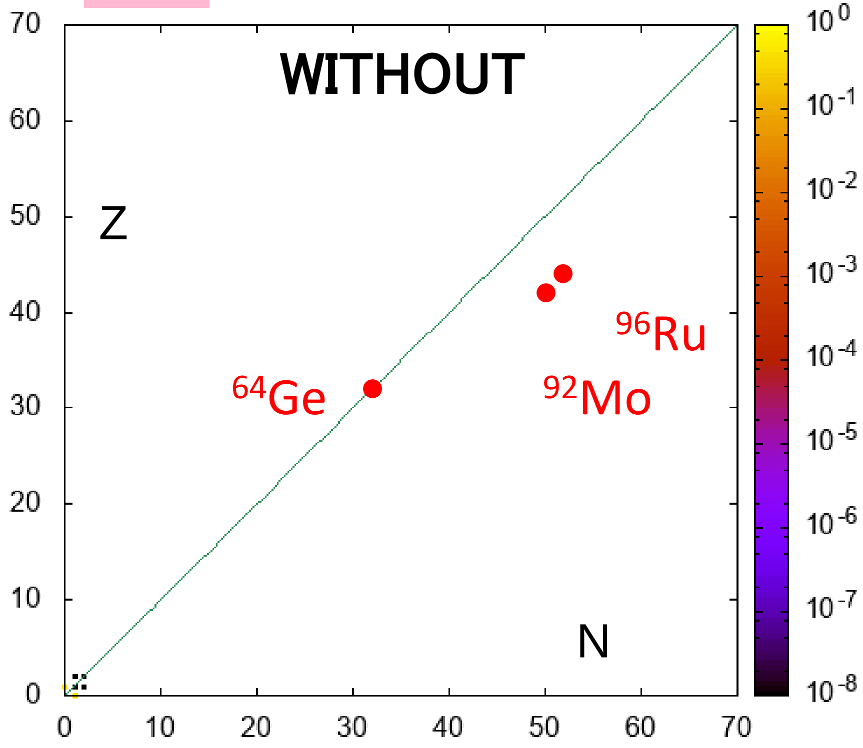
$v(r)$ ... gas velocity

Ordinary νp-process

C. Freohlich, et al., PRL 96 (2006), 142502.

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





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C. Freohlich, et al., PRL 96 (2006), 142502.

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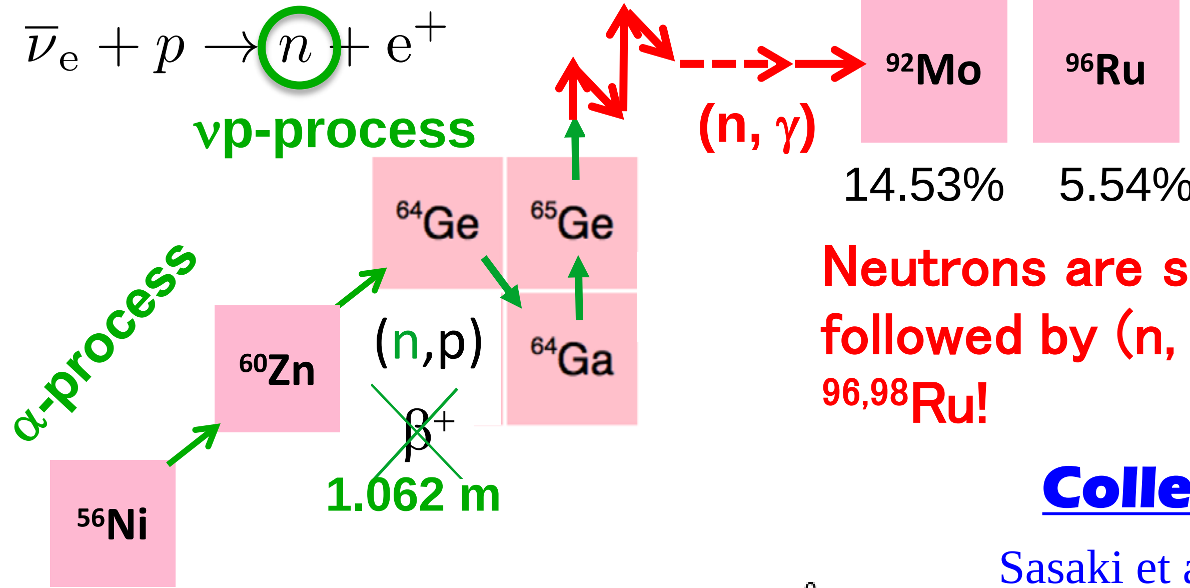
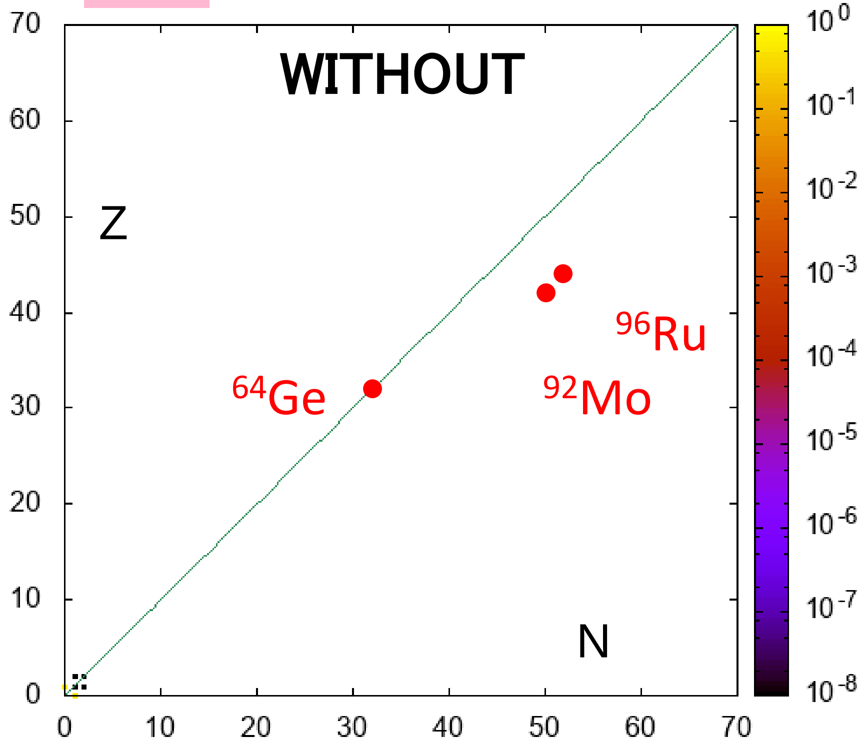


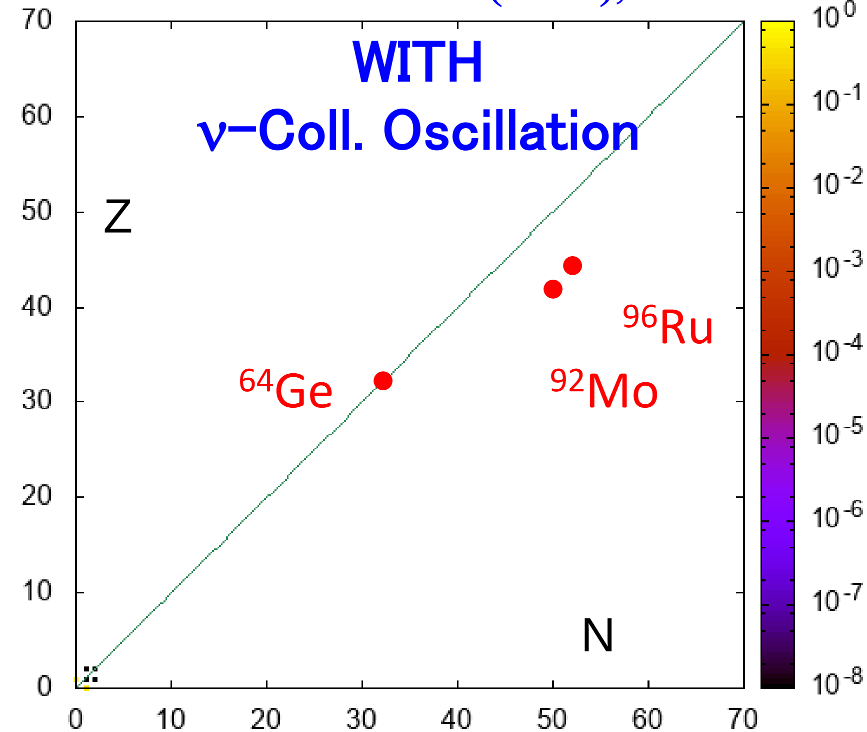
Isotopic ratio of p-nuclei ~ 0.1-1%

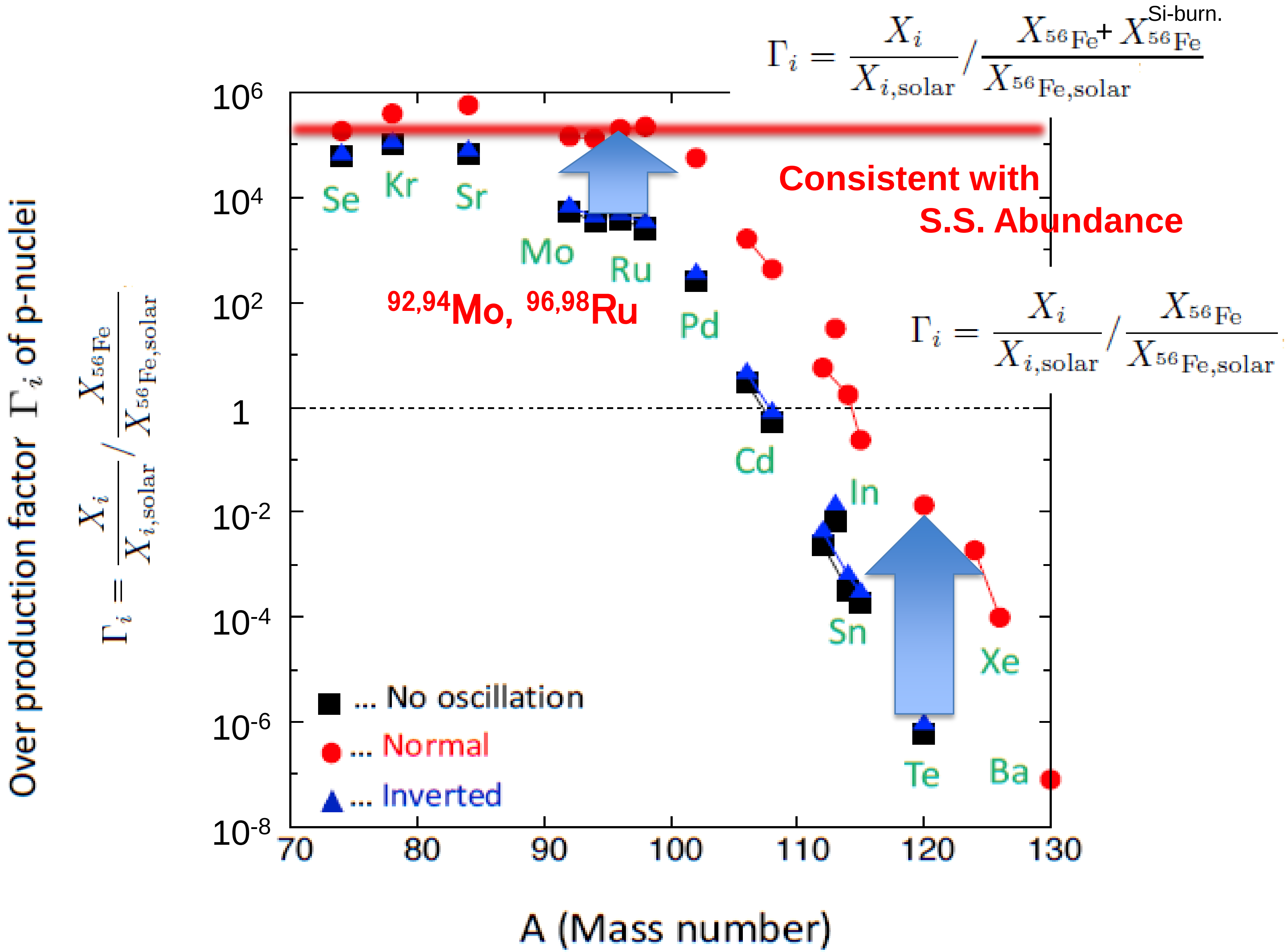
Neutrons are supplied continuously, followed by (n, γ) to produce ^{92,94}Mo, ^{96,98}Ru!

Collective νpn-process

Sasaki et al. PR **D96** (2017), 043013.

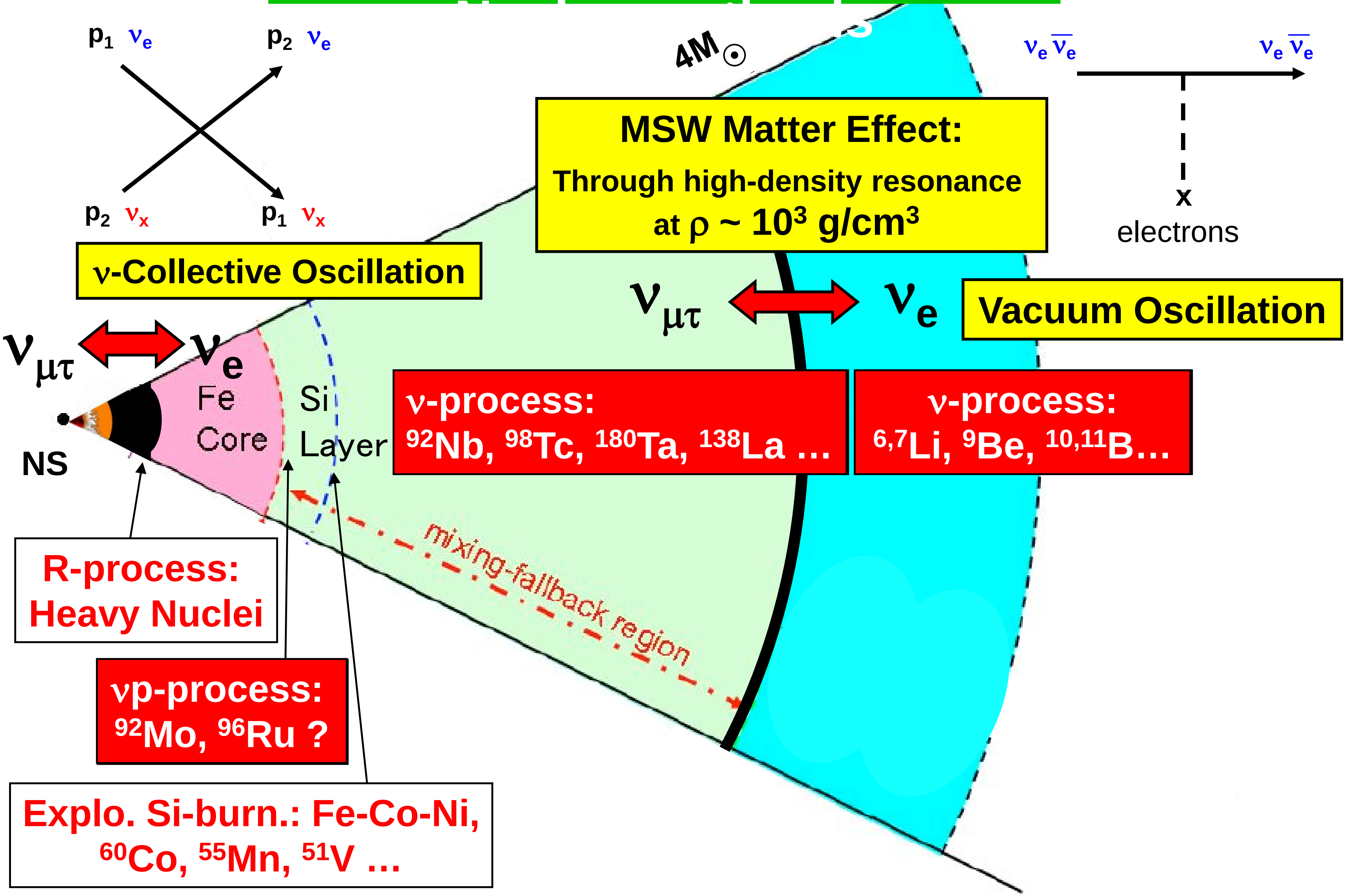






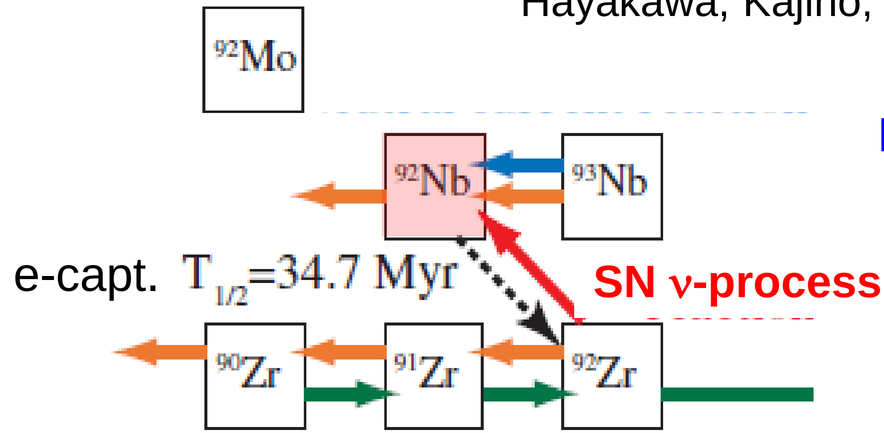
Si-burn.
$\Gamma_i = \frac{X_i}{X_{i,\mathrm{solar}}} / \frac{X_{^{56}\mathrm{Fe}} + X_{^{56}\mathrm{Fe}}^{\mathrm{Si\text{-}burn.}}}{X_{^{56}\mathrm{Fe,solar}}}$
Consistent with
S.S. Abundance
^{92,94}Mo, ^{96,98}Ru
$\Gamma_i = \frac{X_i}{X_{i,\mathrm{solar}}} / \frac{X_{^{56}\mathrm{Fe}}}{X_{^{56}\mathrm{Fe,solar}}}$
Over production factor Γ_i of p-nuclei
$\Gamma_i = \frac{X_i}{X_{i,\mathrm{solar}}} / \frac{X_{^{56}\mathrm{Fe}}}{X_{^{56}\mathrm{Fe,solar}}}$
10^6
10^4
10^2
1
10^{-2}
10^{-4}
10^{-6}
10^{-8}
Se
Kr
Sr
Mo
Ru
Pd
Cd
In
Sn
Te
Xe
Ba
... No oscillation
... Normal
... Inverted
70
80
90
100
110
120
130
A (Mass number)

ν-Oscillation and

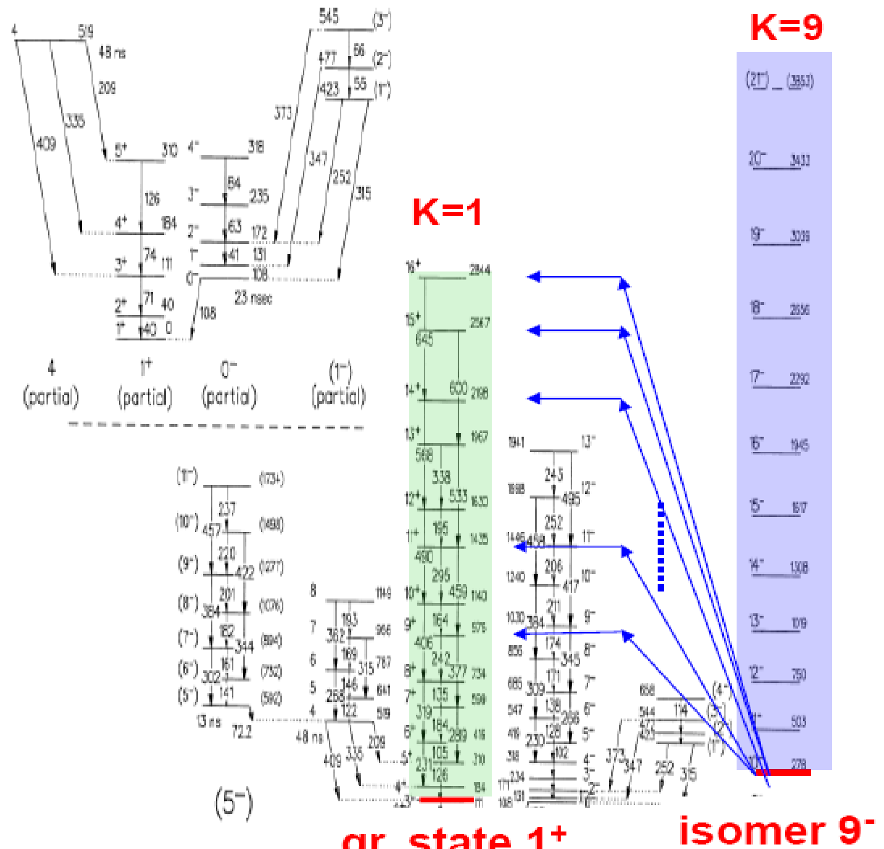


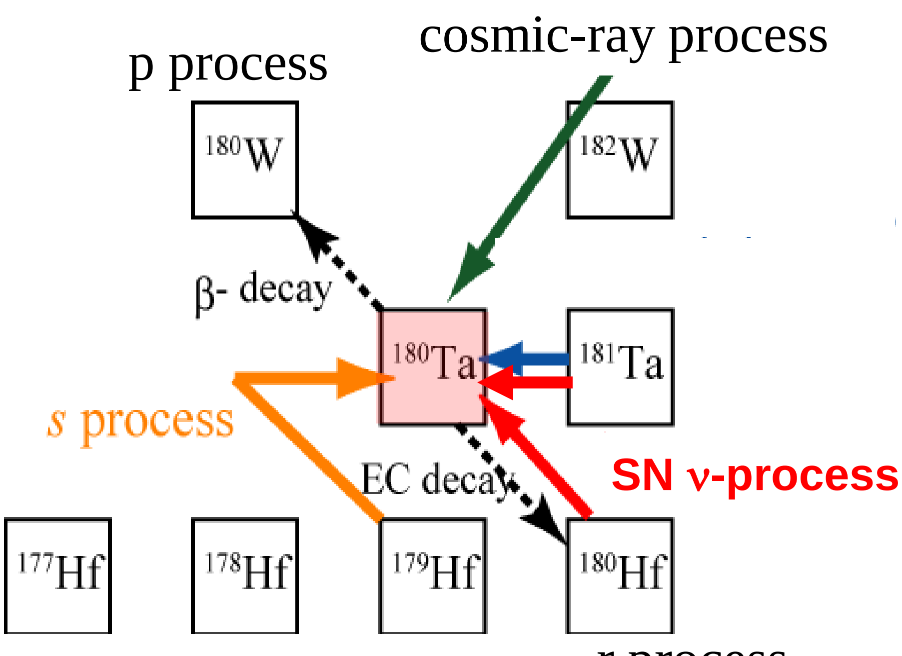
ν-Isotopes: ^{180}Ta, ^{138}La, ^{92}Nb, ^{98}Tc …

Hayakawa, Kajino, Mohr, Chiba & Mathews, PR C81 (2010), 052801®;
PR C82 (2010), 058801; ApJL 779 (2013), L1.



Einstein AB theory + SN Nucleosynthesis



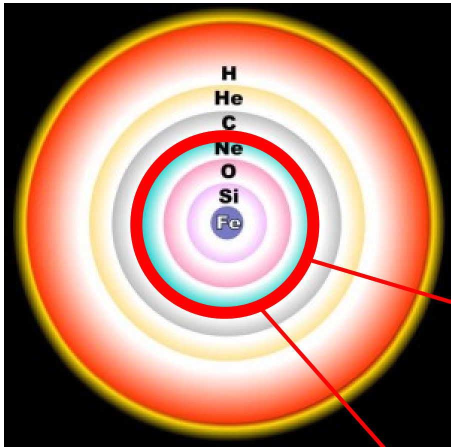


$^{180}Ta_g(\tau_{1/2} = 8h)$, $^{180}Ta^m(\tau_{1/2} > 10^{15}y)$

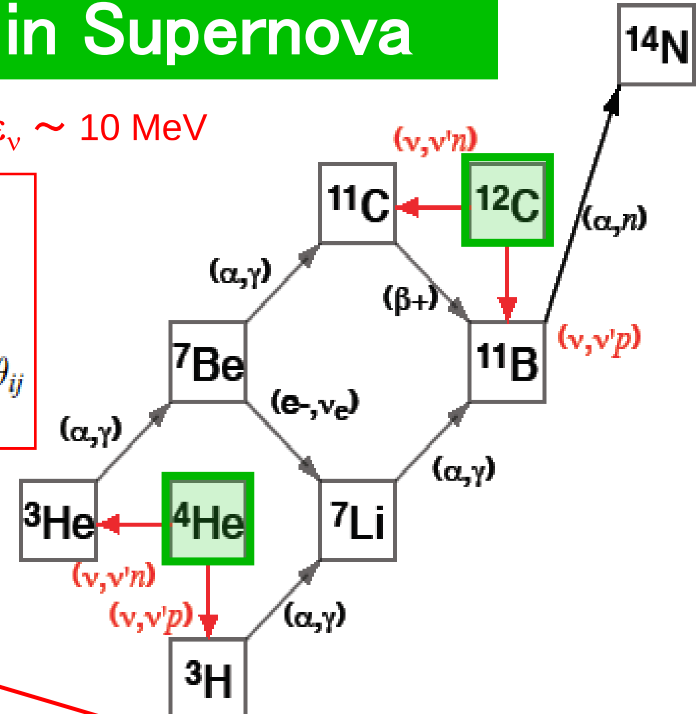
The rarest isotope on the Earth & Universe !

^{6,7}Li–^{9}Be–^{10,11}B : Outer Layer in Supernova

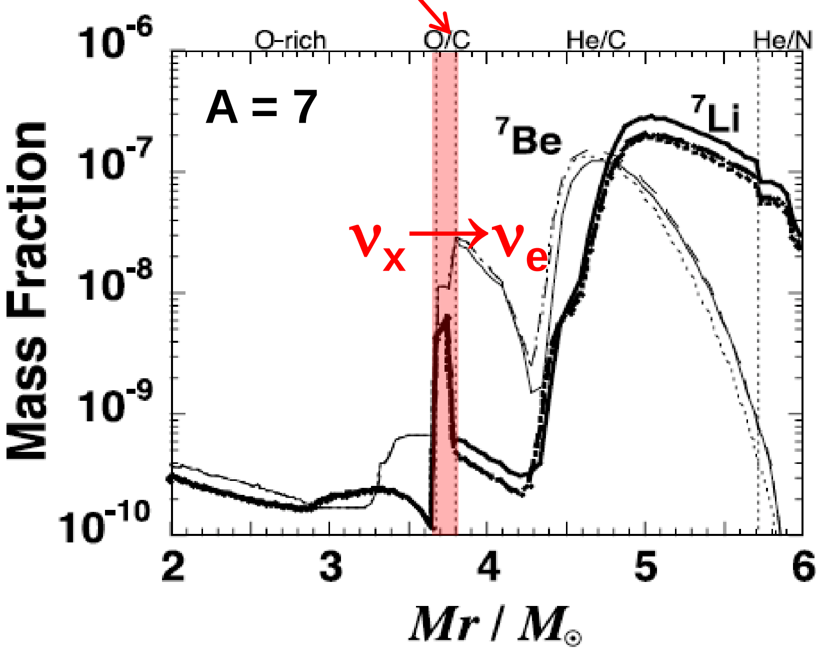
$|\Delta m^2_{13}| = |\Delta m^2_{23}| = 2.4 \times 10^{-3}$ eV^2, $\varepsilon_\nu \sim 10$ MeV

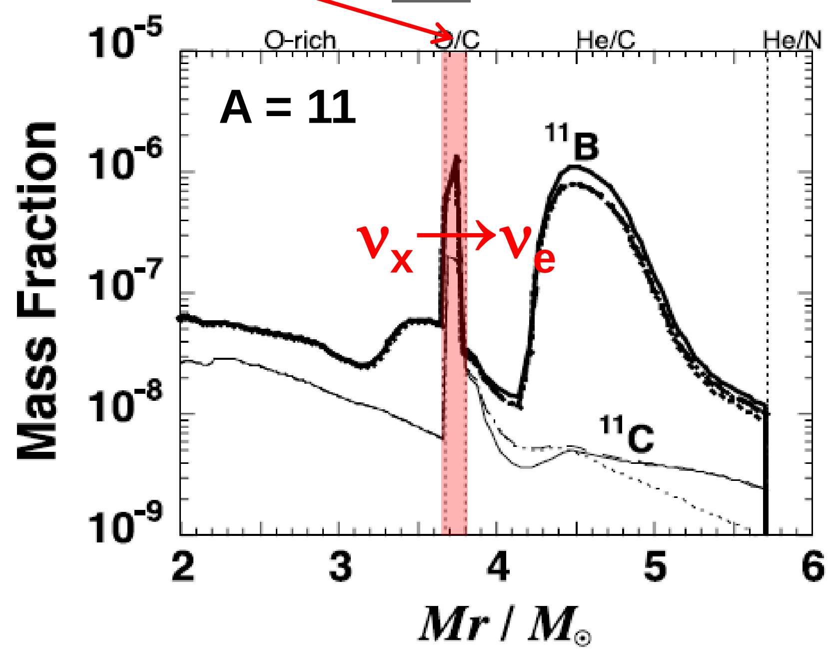


$$\rho_{\text{res}} Y_e = \frac{m_u \Delta m^2_{ji} c^4 \cos 2\theta_{ij}}{2\sqrt{2} G_F (\hbar c)^3 \varepsilon_\nu} \quad [\text{ g cm}^{-3}]$$
$$= 6.55 \times 10^6 \left(\frac{\Delta m^2_{ji}}{1\ \text{eV}^2}\right)\left(\frac{1\ \text{MeV}}{\varepsilon_\nu}\right) \cos 2\theta_{ij}$$

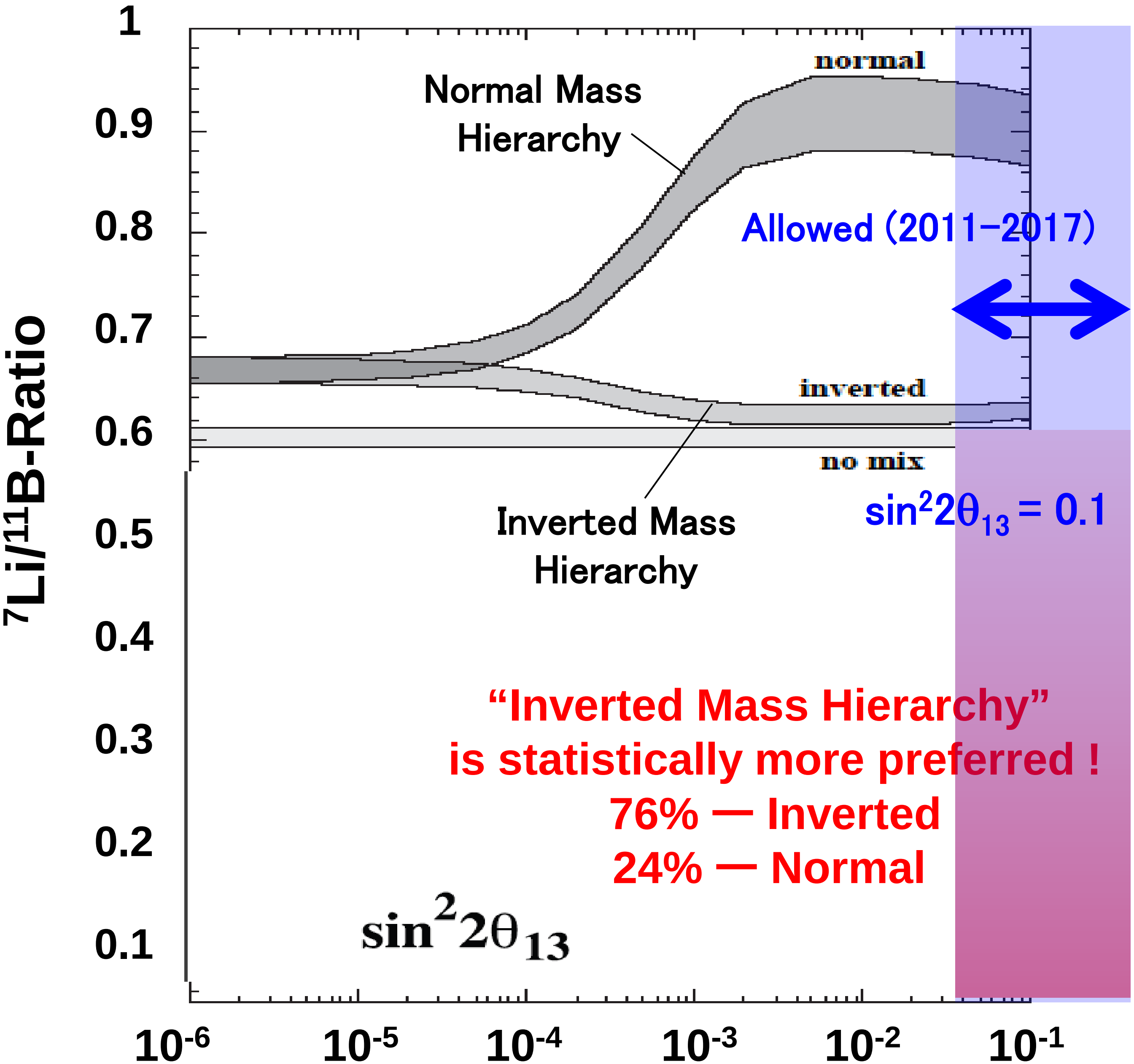


MSW high-density resonance is located at O/C - He/C shell at $\rho \sim 10^3$ g/cm^3.





New Method to constrain Mixing Angle θ_{13} & Mass Hierarchy



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

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

Kajino, Mathews & Hayakawa, J. Phys.G41 (2014), 044007.

Long BaselineExp. from 2011-:

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

・T2K (Kamioka)
・MINOS

Reactor Exp. from2012-:

・RENO (KOREA)
・Double CHOOZ
・Daya Bay

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

Kajino, Mathews & Hayakawa, J. Phys. G41, 044007 (2014).

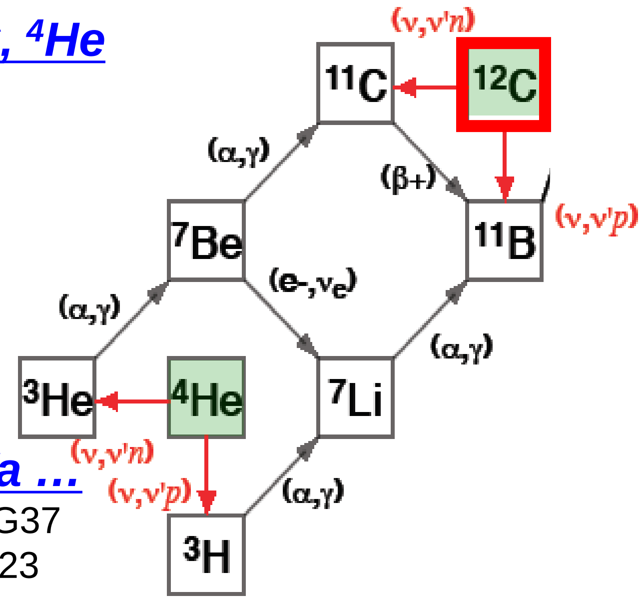
Theoretical Calculation for ν-Nucleus Cross Secti

New generation SM cal. with NEW Hamiltonian: ν-^{12}C, ^{4}He

Suzuki, Chiba, Yoshida, Kajino & Otsuka, PR C74 (2006), 034307;
Suzuki & Kajino, J. Phys. G40 (2013), 083101; +

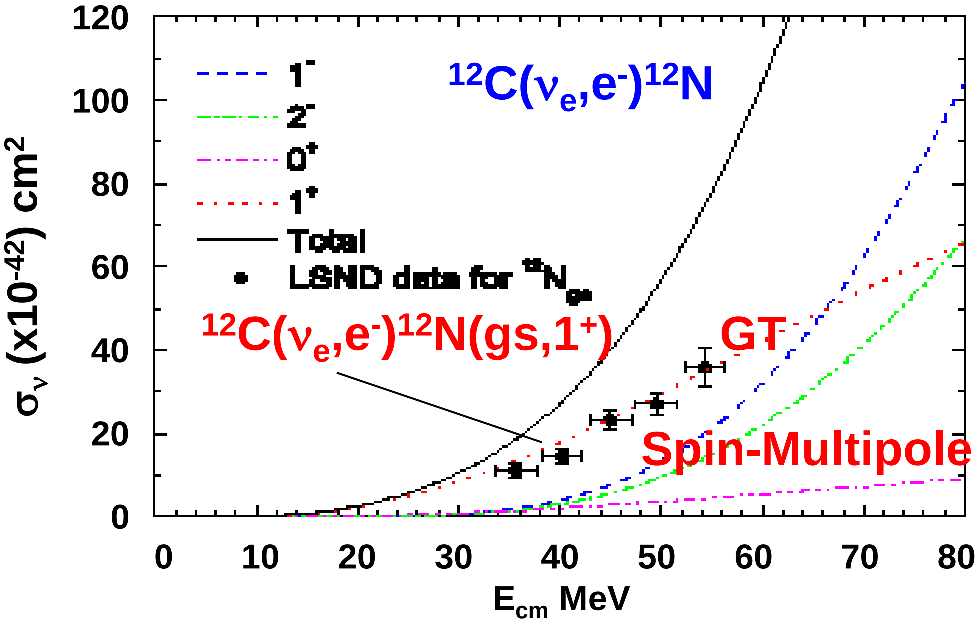
^{12}C: New Hamiltonian = Spin-isospin flip int. with tensor force to explain neutron-rich exotic nuclei.

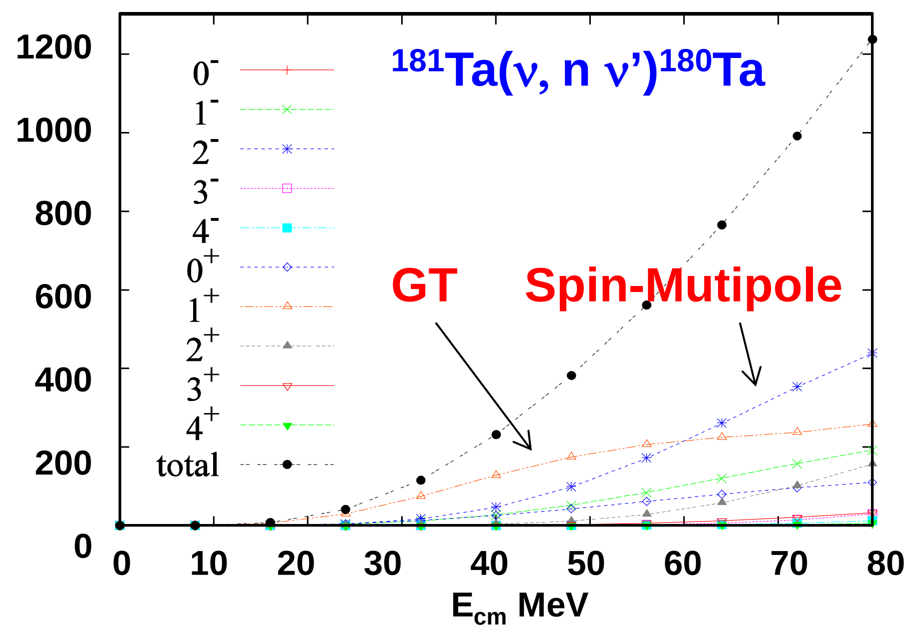
- μ-moments of p-shell nuclei
- GT strength for $^{12}C \rightarrow {}^{12}N$, $^{14}C \rightarrow {}^{14}N$, etc. (GT)
- DAR (ν,ν'), (ν,e-) cross sections



QRPA cal.: ν-^{4}He, ^{12}C, ^{40}Ar, ^{42}Ca, ^{98}Tc, ^{92}Nb, ^{138}La, ^{180}Ta …

Cheoun, et al., PRC81 (2010), 028501; PRC82 (2010), 035504: J. Phys. G37 (2010), 055101; PRC 83 (2011), 028801; PRC 85 (2013), 065807; PLB 723 (2013), 464; J. Phys. G42 (2015), 045102; +





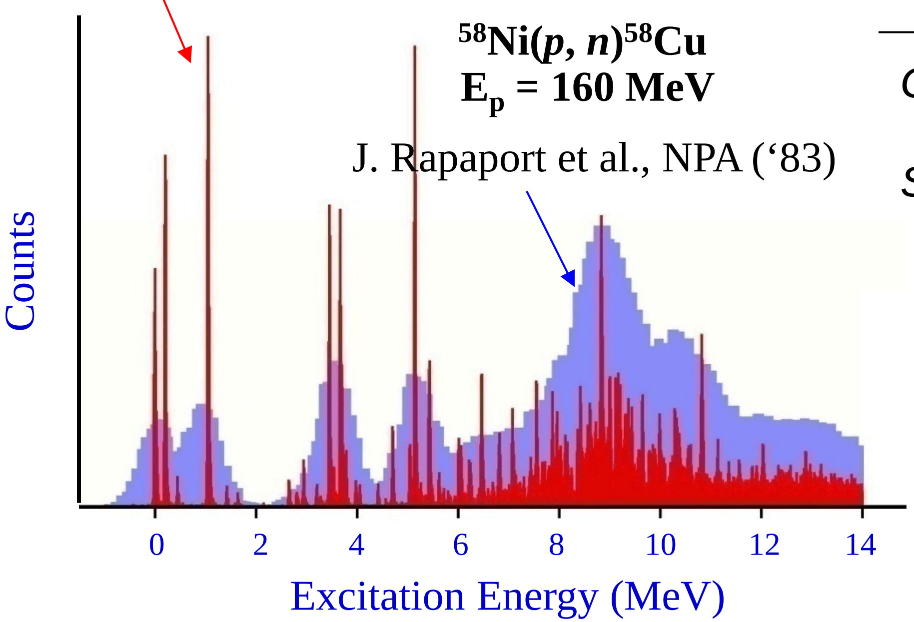
ν−BEAM spectro. Exp., still difficult at E<100 MeV.

Hadronic CEX, charg. lepton (e μ), photon (γ) !

Similarity between Electro-Magnetic & Weak Interactions

^{58}Ni(^{3}He, *t*)^{58}Cu
E = 140 MeV/u

Y. Fujita et al., EPJ A 13 ('02) 411.
Y. Fujita et al., PRC 75 ('07)



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-Teller operator = $\vec{\sigma}\tau_{\pm}$

Spin-Multipole operator = $[\vec{\sigma} \times Y^{(L)}]^{J} \tau_{\pm}$

Cosmology – ν mass – 0νββ
– ν mass hierarchy
– Astro Connection

c.f. Ymazaki, Kajino, Mathews & Ichiki, Phys. Rep. 517 (2012), 141;
PR D81 (2010), 103519

Conclusion

R–process elements in the early Galaxy are predicted to be dominated by MHDJ– & ν–SNe, and NSMs have arrived later in the solar–system.

- **Multi-messenger astrophysics has opened.: GW, light, elements & ν. NSM & MHDJ-SN are relatively free from ν, while ν-wind SN is not ?**
- Nuclear masses and fission–fragment distribution take the keys to NSM r–process as well as β–life,(n,γ) measurements.

ν–wind SNe are the probe of ν physics and 1st r–process peak. Abundant p–nuclei (^{92,94}Mo, ^{96,98}Ru) could be produced in proton–rich ν–wind SNe with collective oscillation, being sensitive to ν–mass hierarchy.

- ν–collective oscillation in 3 flavor multi–angle Hamiltonian should be solved EXACTLT to verify this new νnp–process.
- (n,γ) and (n,p)reactions on proton–rich side of nuclei take the keys.

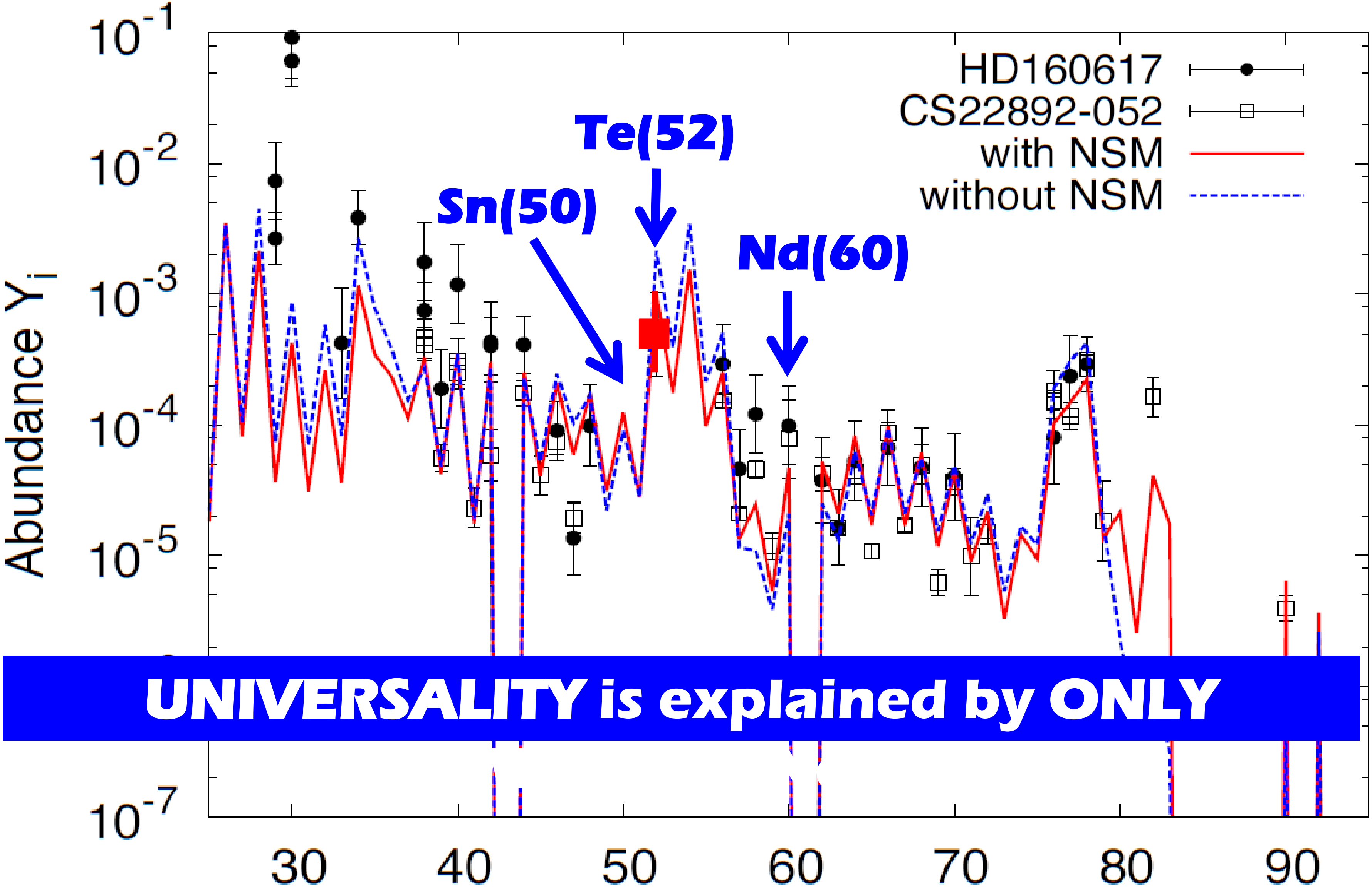
CEX reactions are highly desirable to know weak transitions relevant to SN ν–process in order to determine ν–mass hierarchy.

- **ν -^{4}He, ^{12}C, ^{40}Ar, ^{42}Ca, ^{92}Nb, ^{98}Tc, ^{138}La, ^{180}Ta**

UNIVERSALITY !

Early Galaxy !

Shibagaki et al., ApJ. 816 (2016),79; Kajino & Mathews, ROPP **80** (2017) 08490.

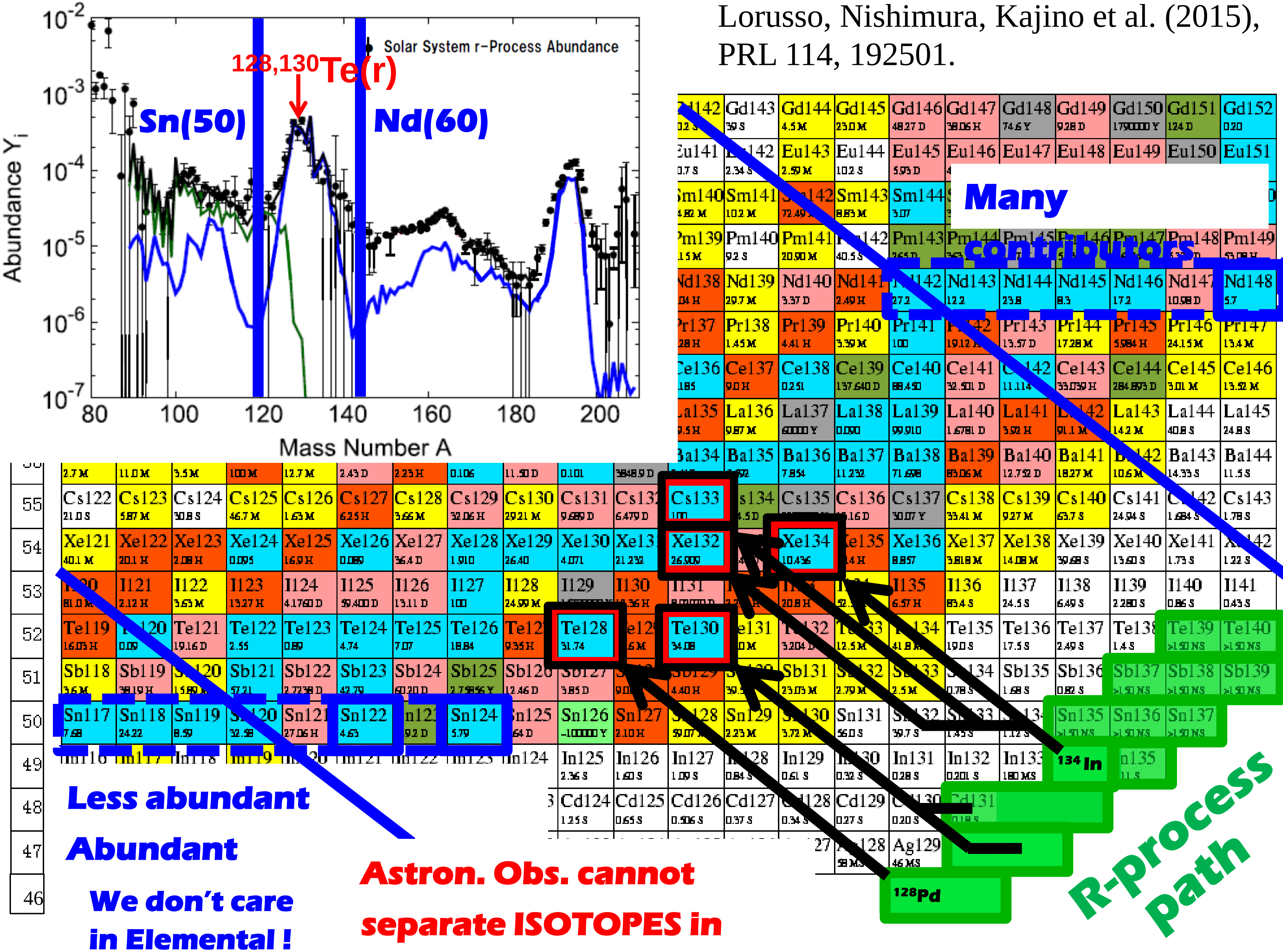


UNIVERSALITY is explained by ONLY

Astron. Obs. cannot separate ISOTOPES !

ELEMENTAL (Z)

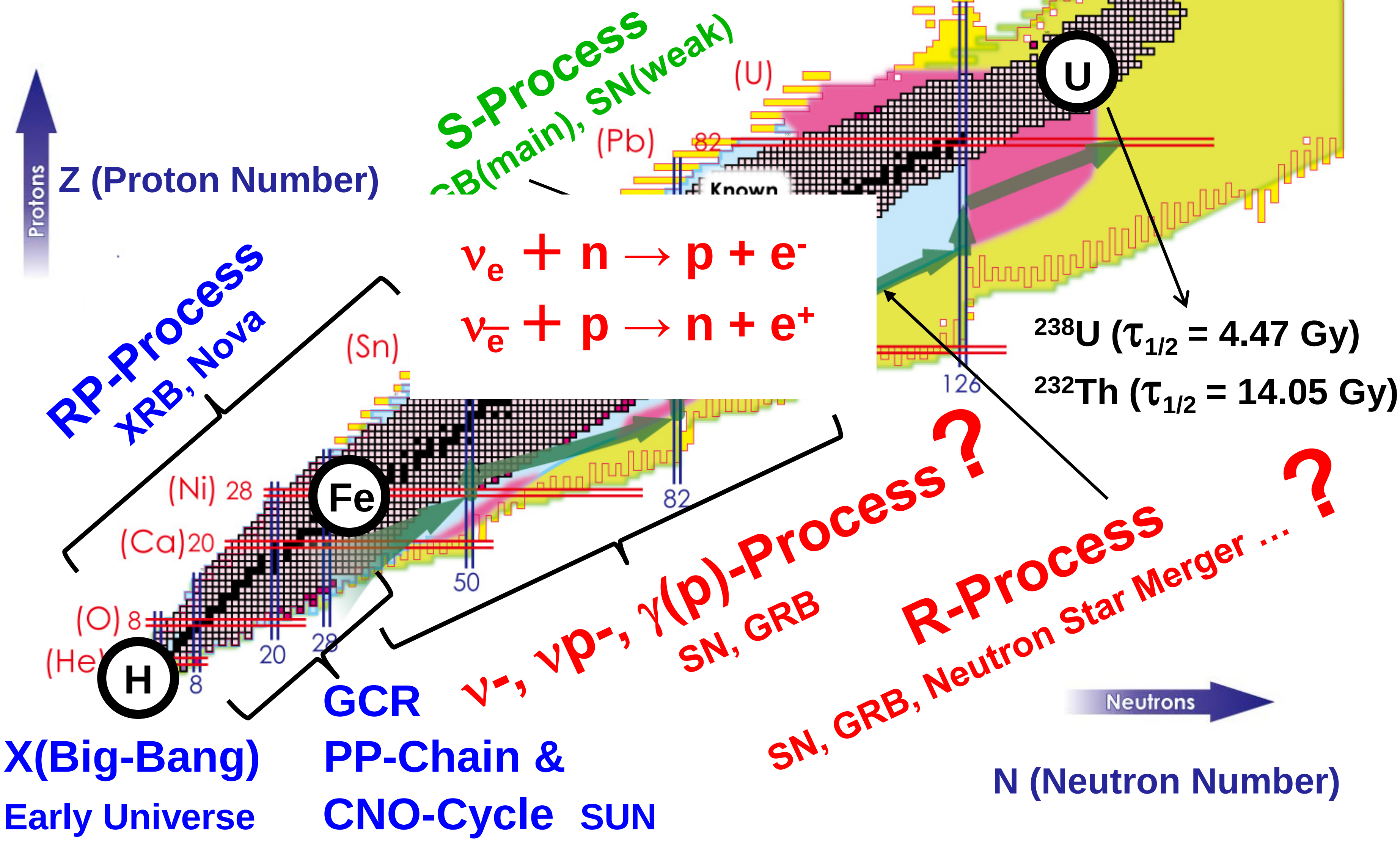
Lorusso, Nishimura, Kajino et al. (2015), PRL 114, 192501.



Element Genesis from Nuclear Processes in Cosmos

Burbidge[2], Fowler & Hoyle, Rev. Mod. Phys. 29 (1957), 547-650.

Alpher, Bethe & Gamow, Phys. Rev. 73 (1958), 803.

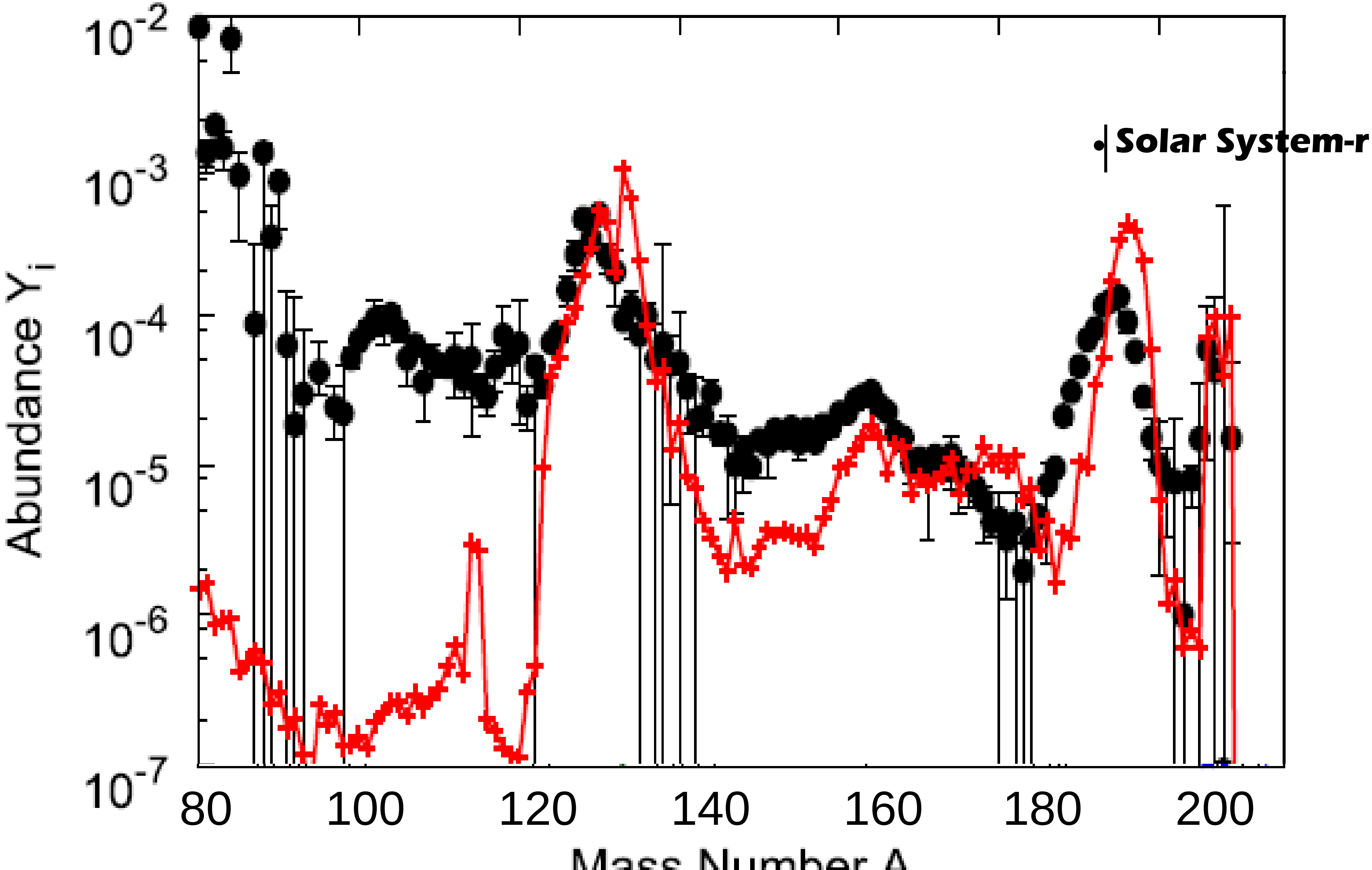


$$\nu_e + n \rightarrow p + e^-$$

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

Challenge of Nucear Physics — Fission & Mass Formula

Mass Formula: FRDM (Moeller & Kratz)



SUPERCOMPUTING of Galactic Chemo-Dynamical Evolution

Evolution of Single Dwarf Galaxy

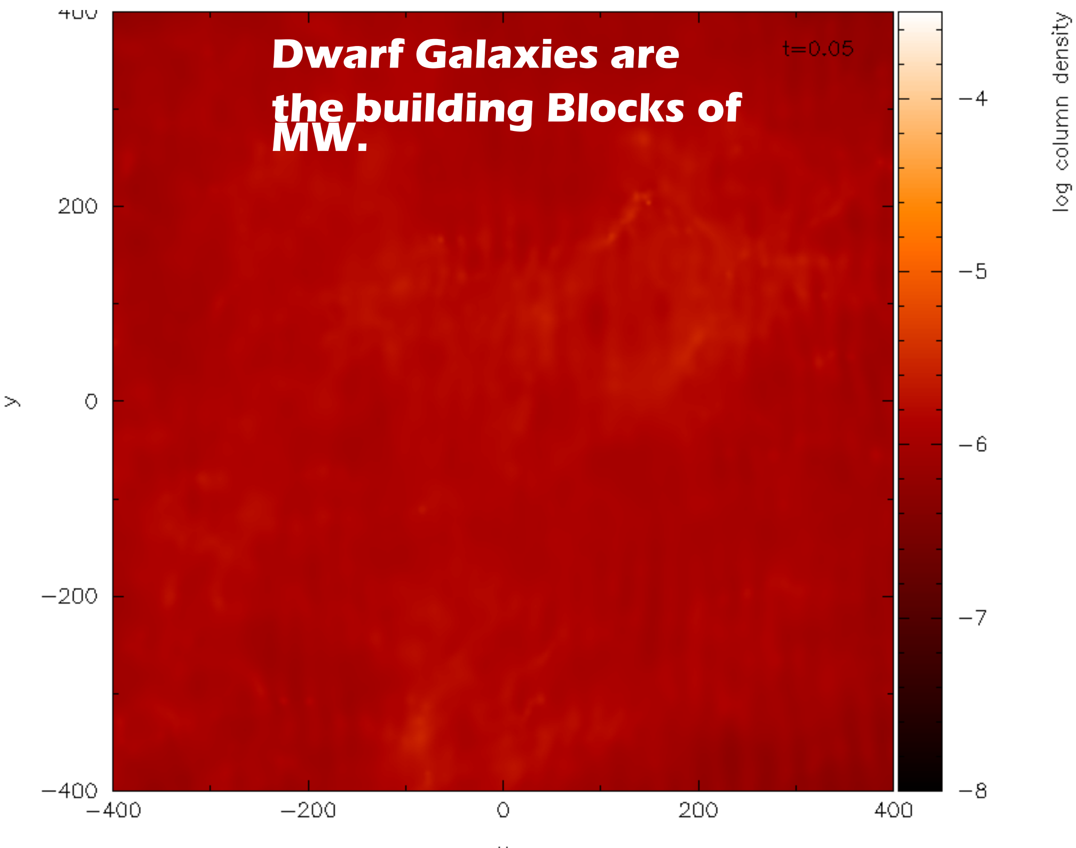
Komiya & Shigeyama, ApJ 830, 10 (2016).

Mixing of r-elements between neighboring Dwarf Galaxies is limited to only 0.001-0.1% for[Fe/H] < -3.5.

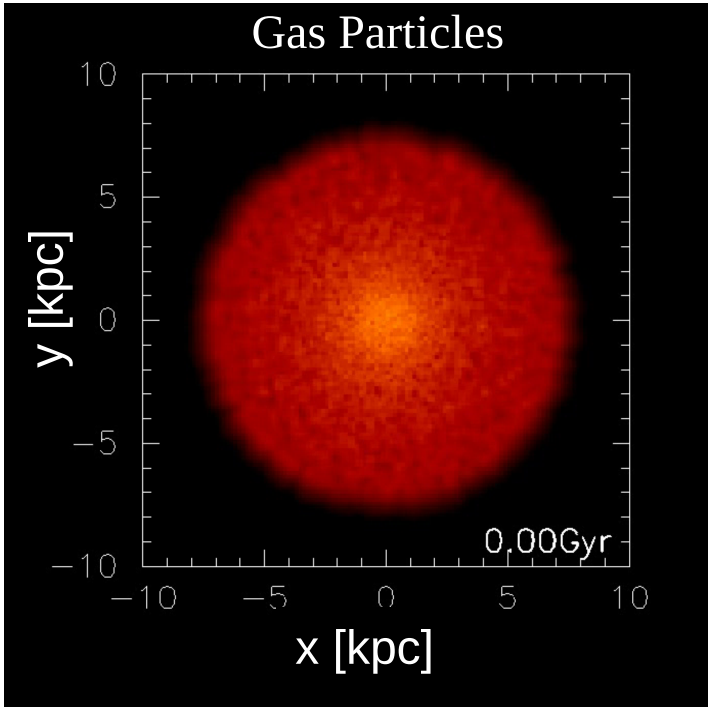
N-Body/SPH Simulation DM + GAS + Star Particles with GAS-MIXING in the star forming region.

Hirai et al., ApJ 814 (2015), 41; MNRAS 466 (2017) 2474.

Mathews et al., MPL A29 (2014), 1430012-118.



$M_{tot} = 7x10^8 M_{sun}$, $N_i = 5x10^5$ particles, $M_\bigstar = 100 M_{sun}$



SUPERCOMPUTING of Galactic Chemo-Dynamical Evolution of Dwarf Galaxies

N-Body/SPH Simulation of DM+GAS+Star Particles with GAS MIXING in star forming region.

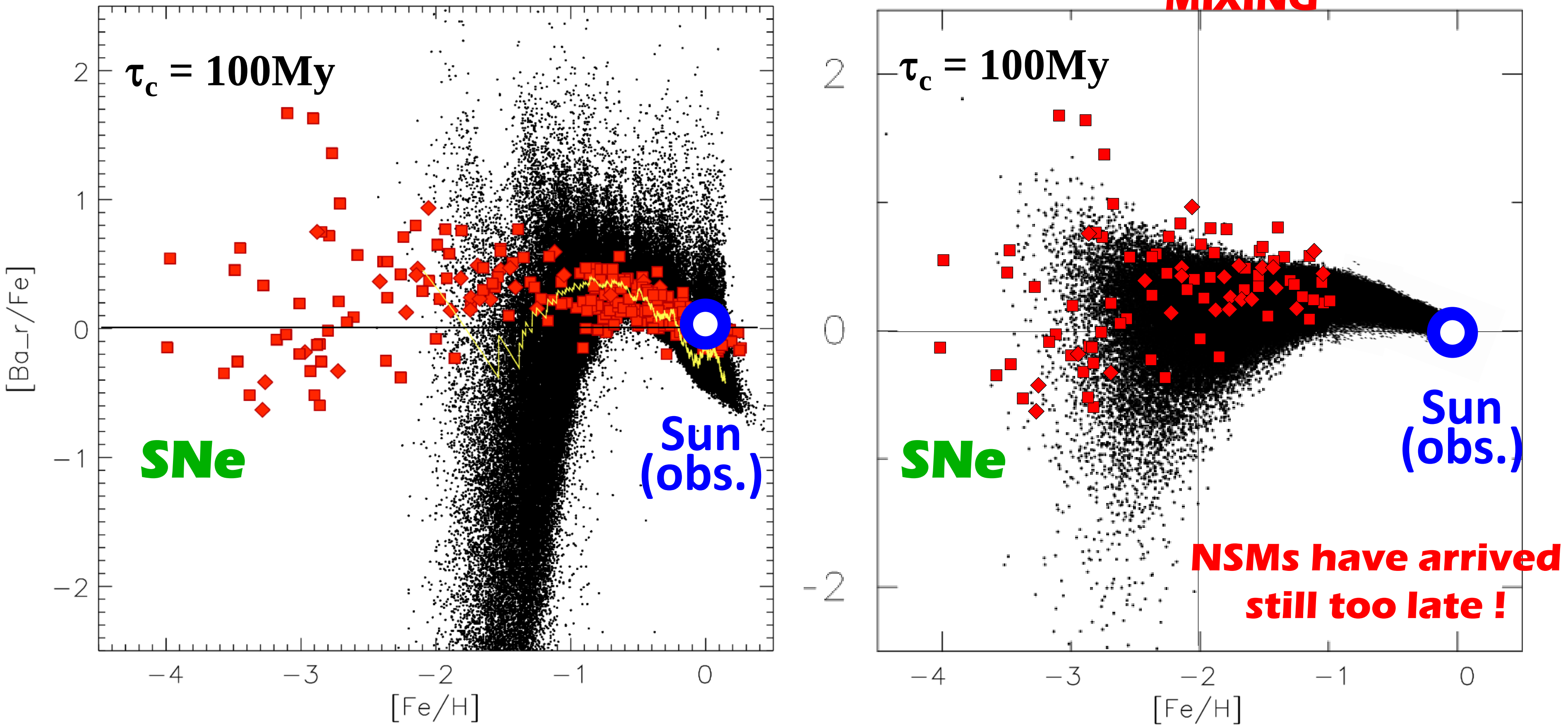
SNe = Metals ; NSM(τ_c=100My)= r-process elements. (n_H >100 cm^{-3} → ～10-100pc)

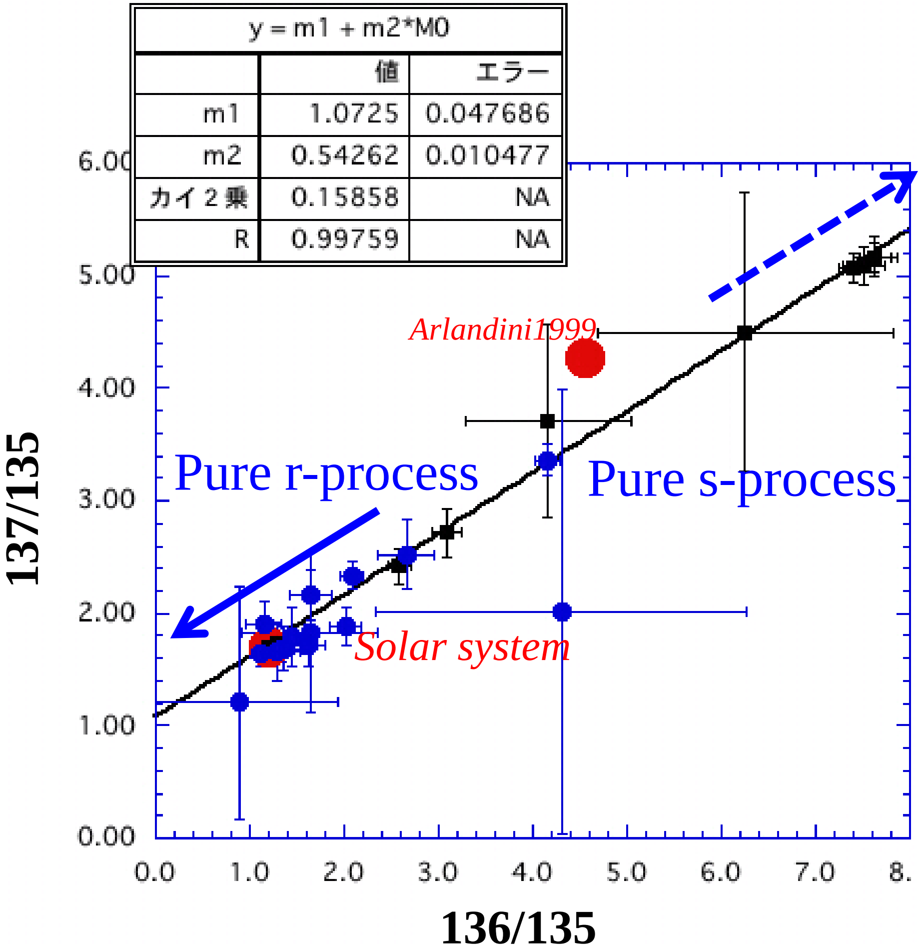
Argast, Samland, Thielemann, Qian, A&A 416 (2004), 997.

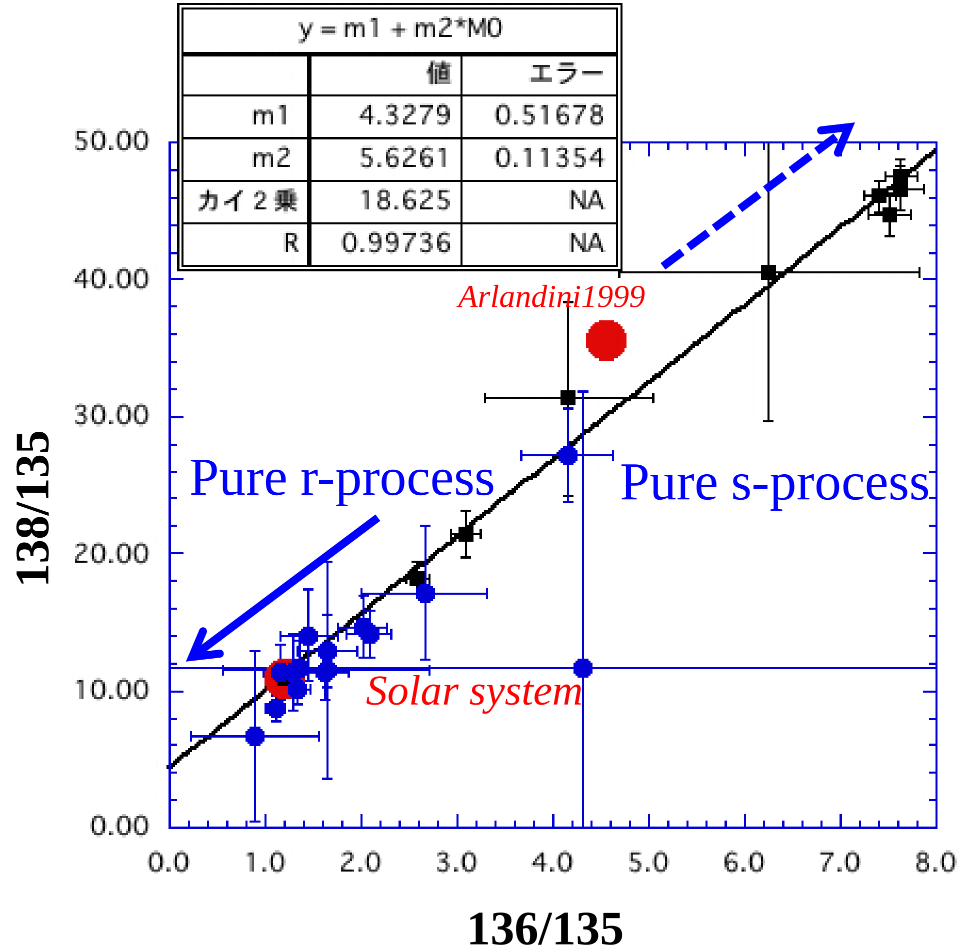
Hirai, Ishimaru, Saitoh, Fujii, Hidaka and Kajino, ApJ 814 (2015), 41; MNRAS 466 (2017), 2474.

Without Dynamics & GAS MIXING

With Dynamics & GAS MIXING





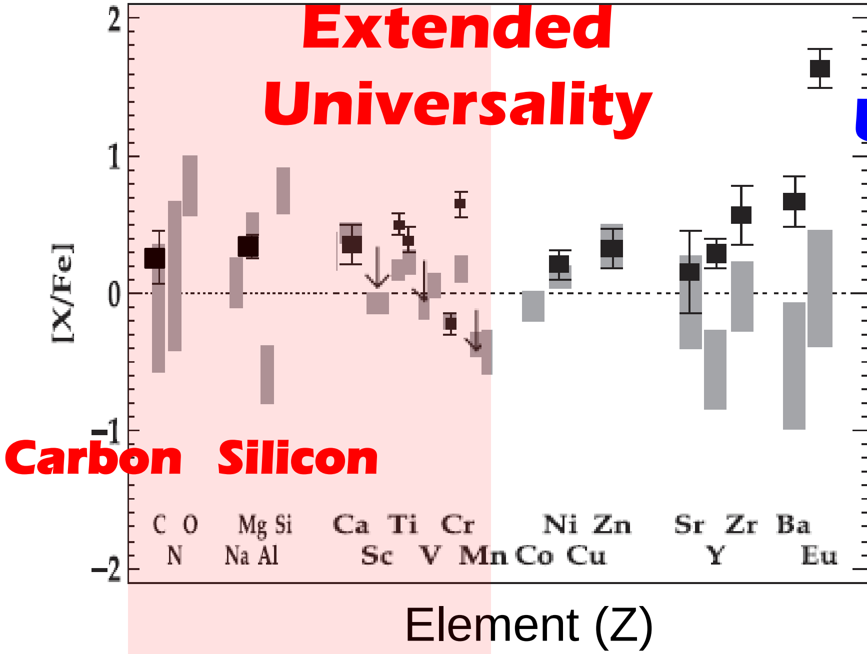


Meteorite (Terada et al. 2017)

^{136}Ba=s-only: In the limit of ^{136}Ba→0, pure r-component is extracted.

Isotopic ratios	Wanajo et al et al. (2014) **NSM**	Giuseppe et al. (2015) **ν–DW**	Shibagaki et al. (2016) **NSM**	**MHD-jet**
137/135=1.07 ± 0.05	**0.218**	**2.23**	**1.0**	**0.2**
138/135=4.33 ± 0.52	**0.294**	**3.46**	**1.1**	**0.18**

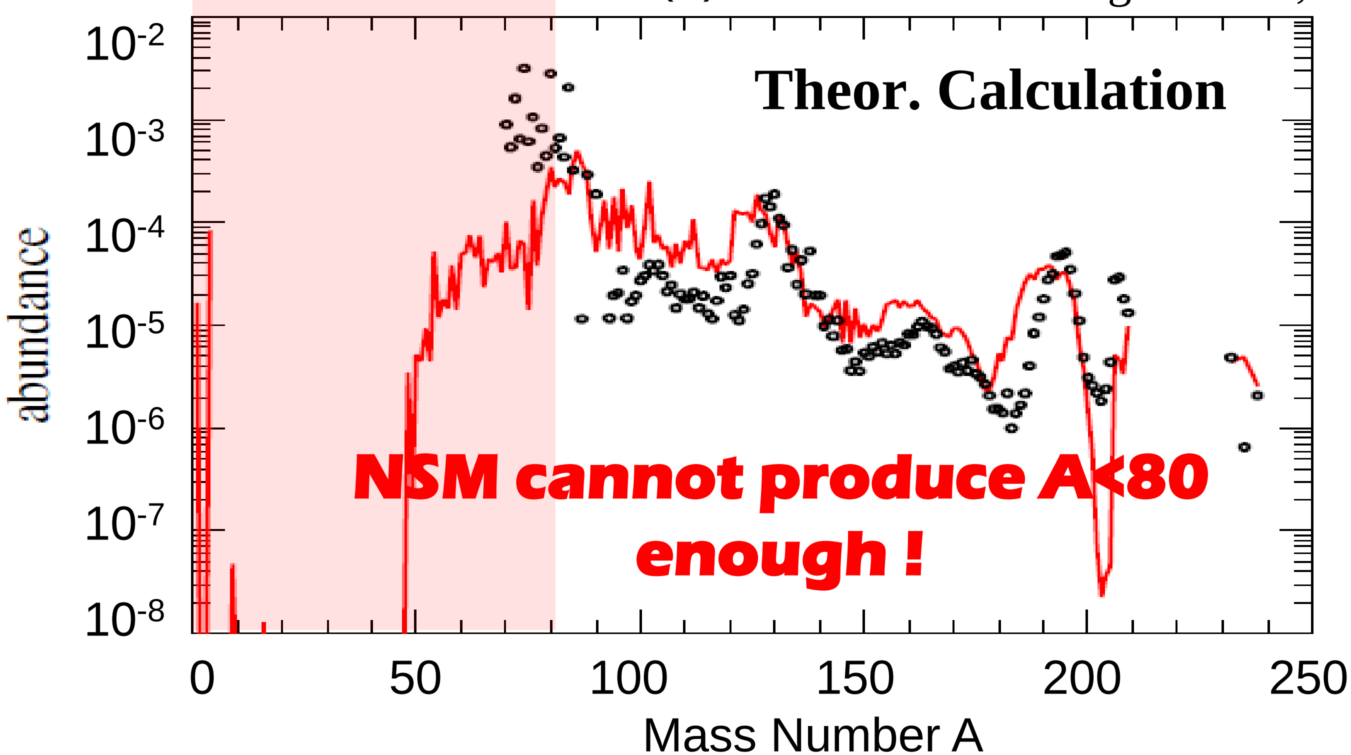
Ultra-Faint warf Galaxy: Ret. II



Astron. Observation

Ian U. Roederer et al., ApJ. 151 (2016), 82;
P. Ji Alexander, Anna Frebel, Anirudh Chiti, Joshua D. Simon, Nature 531 (2016), 610.

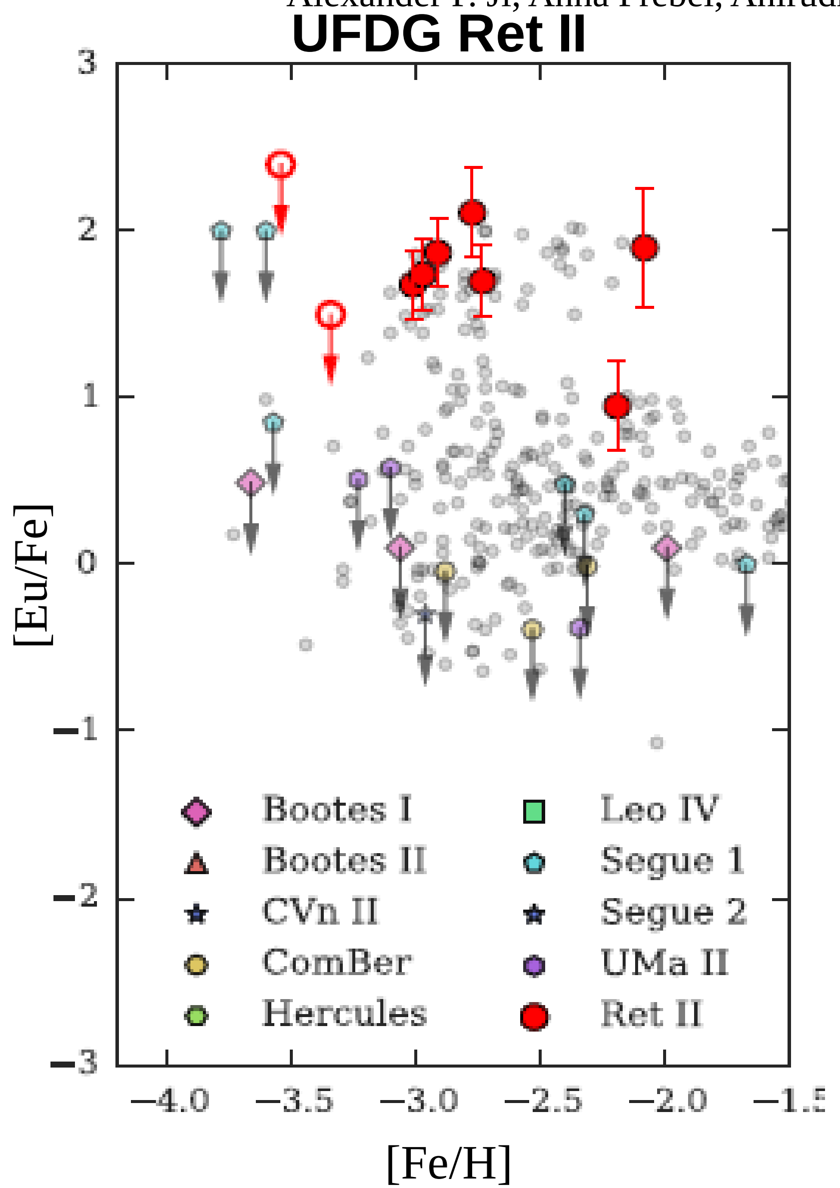
Wanajo et al., ApJ. 789 (2014), L39.
Shibagaki et al., ApJ. 816 (2016), 79; (2017)



Goriely, et al., ApJ 738, L32 (2011); Korobkin, et al., MNRAS 426, 1940 (2012); Bauswein, et al., ApJ 773, 78 (2013); Rosswog, et al., MNRAS 430, 2585 (2013); Goriely, et al., PRL 111, 242502 (2013), (2015): Piran, et al., MNRAS 430, 2121 (2013).

Strong Universality in Ultra-Faint Dwarf Ret. II

Ian U. Roederer et al., AJ 151 (2016), 82
Alexander P. Ji, Anna Frebel, Anirudh C...



Which is likely r-process site, MHD-Jet SN or Binary NSM?

Product. Yield ~ 10^{-2} $M_\odot$ /event

1. **Event Rate, too small?**

   (2.6 +/- 0.2)x$10^3 M_\odot$ Ret. II baryon mass

   → **~10 SNe** IMF

   → **~(0.01-0.3)x10** NSM/SN (0.1%) MHDJ/SN (1-3%)

   SN ! NSM !

2. **Very old ?**

   SN ! NSM !

3. **Extended Universality ?**
   Dust forms ?

   SN ! NSM ?

4. **Ejecta escape from shallow pot. ?**

   SN ! NSM ?

Evidence for r-Process in Neutron Star Mergers?

My Score Sheet (cont')

5. Kilonova ?

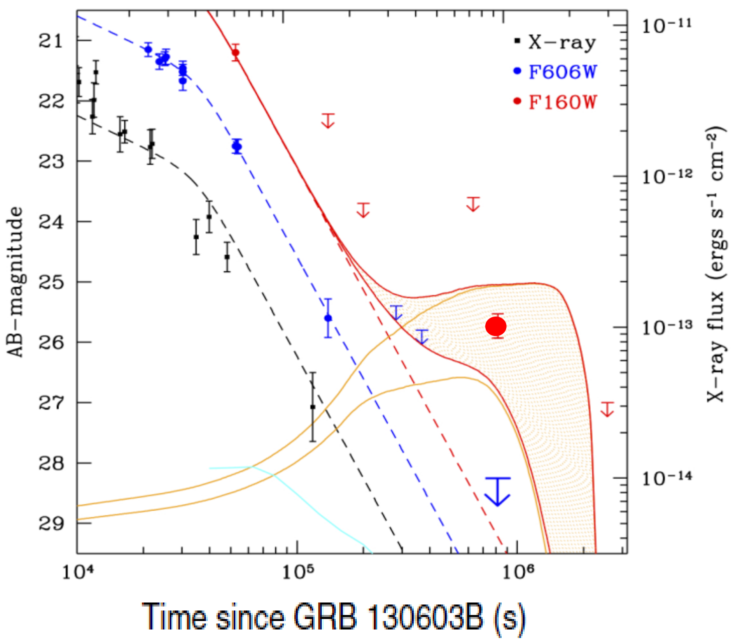
SN ! **NSM ?**

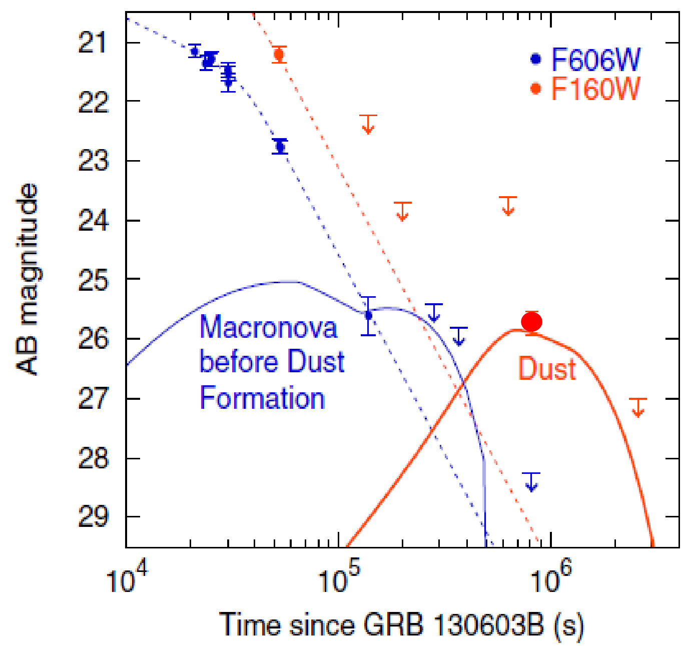
Macronova (Kilonova)

Tanvir, Levan, Fruchter, et al., Nature 500, 547 (2013)

Dust is hard to form for deficient Carbon and other lighter elements.

Takami, Nozawa & Ioka, ApJ 786, L5 (2014).





Dust formation becomes even more difficult when one includes more complete opacity table for heavy actinide elements.

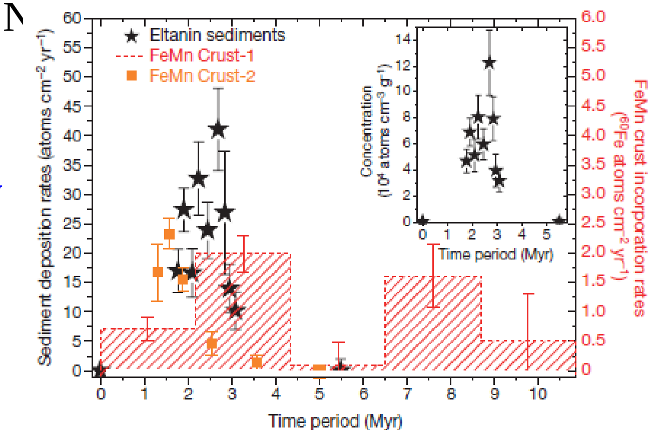
Deep Sea Sediments & EMPS points DUALITY of SN & NSM

^{244}Pu/^{60}Fe in Earth's Deep Sea Sediments → NSM/MHDJ : SNe = 1 : 100

NSM, ~~MHDJ~~ — ^{244}Pu(80.8 My): Wallner et al., Nature Comm. 6 (2015), 1-9; NPA8 (2017)

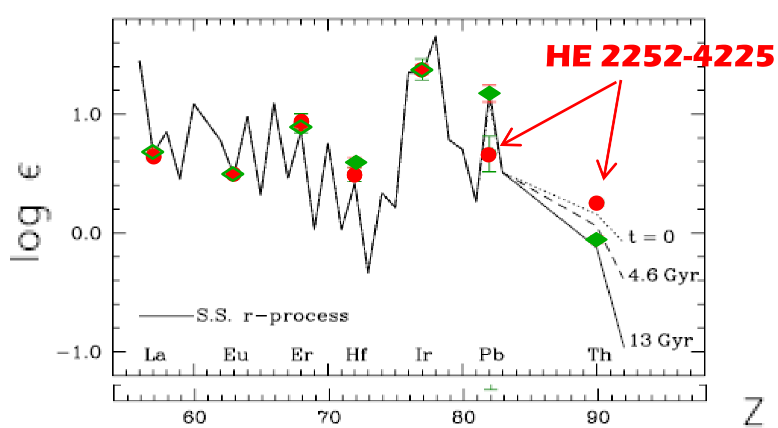
ν-DW — ^{60}Fe(2.62 My): Wallner et al. N

Over 25 My

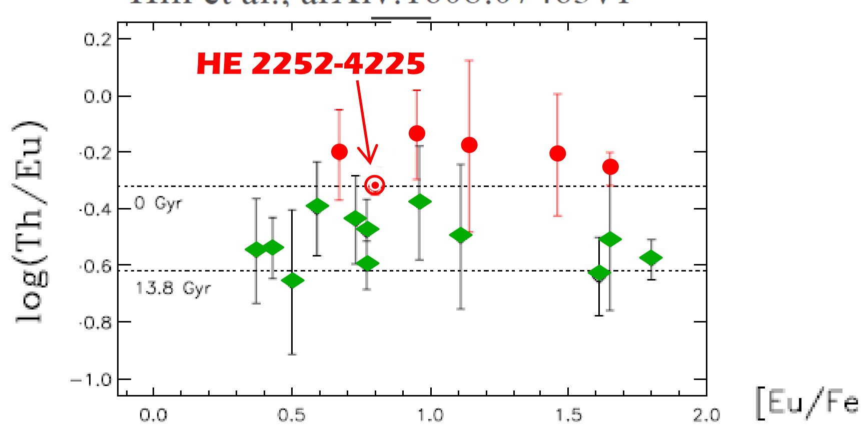


Actinide Boost EMP Stars needs "Fission-Recycling R-process in NSMs".

Mashonkina et al. A&A 569, A43 (2014)



Roederer et al. ApJ 698, 1963 (2009)
Hill et al., arXiv:1608.07463v1

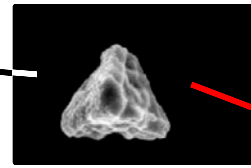


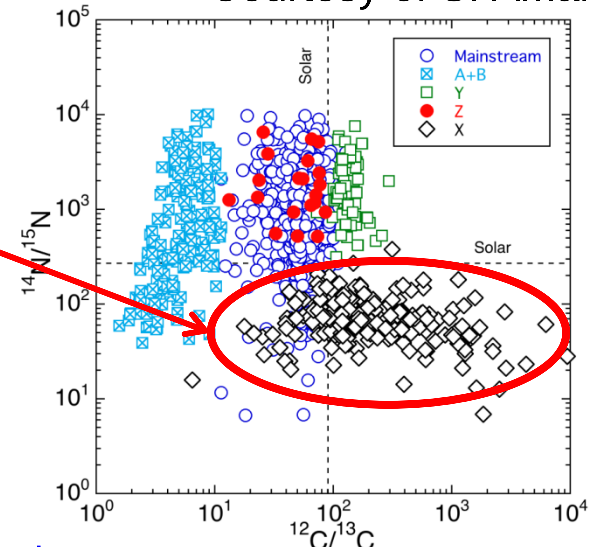
SiC X–Grain including heavy "r–process" elements, HARD to form from NSM Ejecta !

◎ Supernova Grains   e.g. Murchison Meteorite

Courtesy of S. Amari

SiC X–grains





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

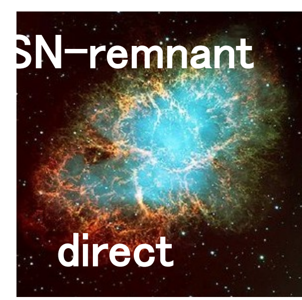
Pre–solar X–grains condense and form in SN ejecta.

- ■ SiC X–grain including r–elements → NSM ?   SN !
- ■ If extended Universality manifests in [r/C–Si–Fe]=0 → SN !

◎ Spectr. Astron. Obs.

Direct detection of C, Si & r-elements simultaneously !

+



RIKEN-RIBF : Decay Spectroscopy around A = 100-145

G. Lorusso et al., PRL **114 (2015), 192501**.

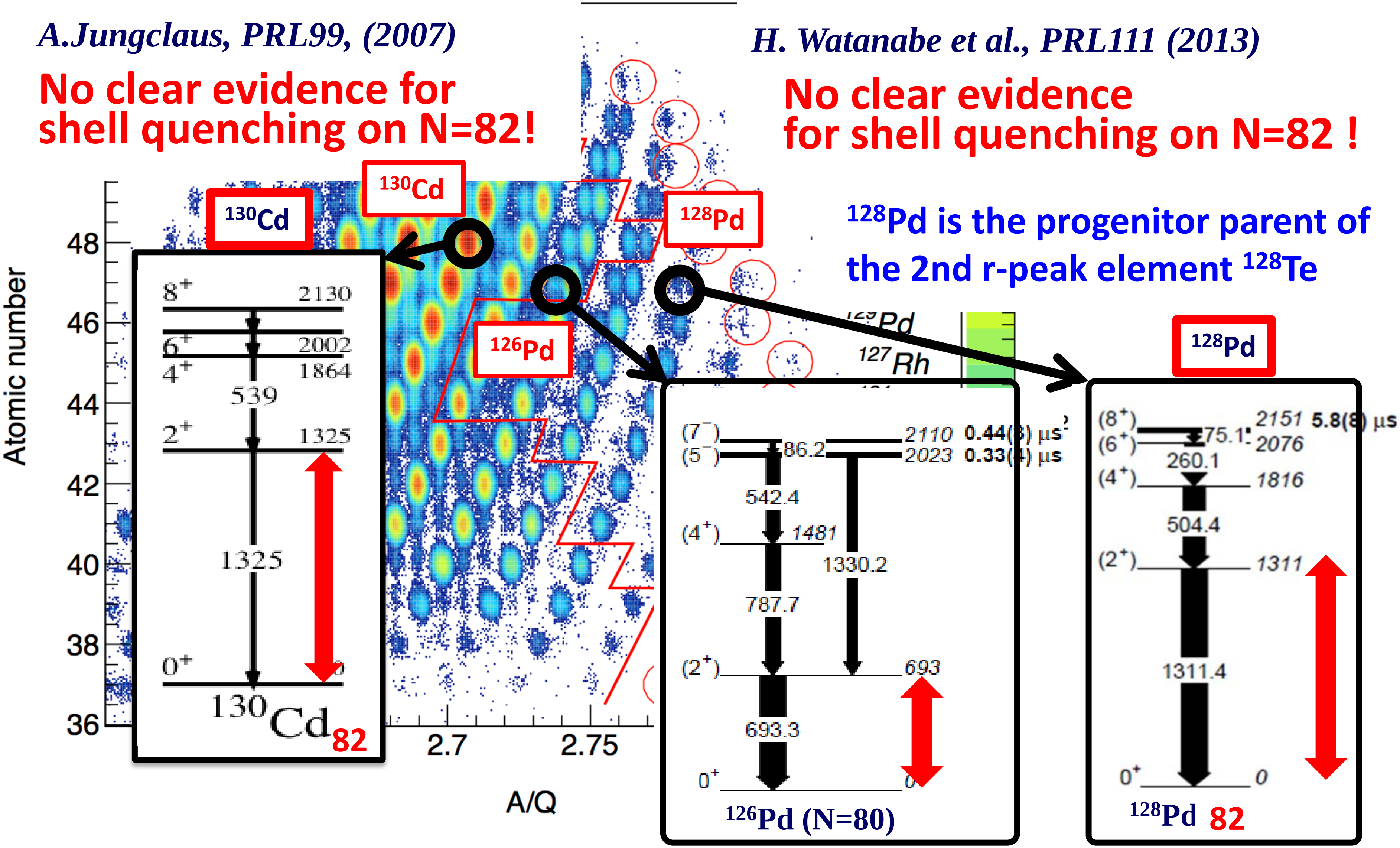
A.Jungclaus, PRL99, (2007)

No clear evidence for shell quenching on N=82!

H. Watanabe et al., PRL111 (2013)

No clear evidence for shell quenching on N=82 !

^{128}Pd is the progenitor parent of the 2nd r-peak element ^{128}Te



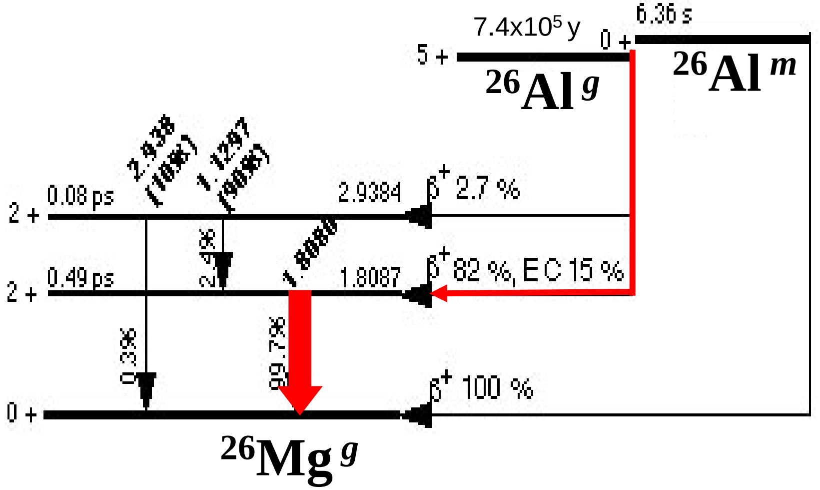
Skymap of γ-ray line Satellites (COMPTEL & INTEGRAL)

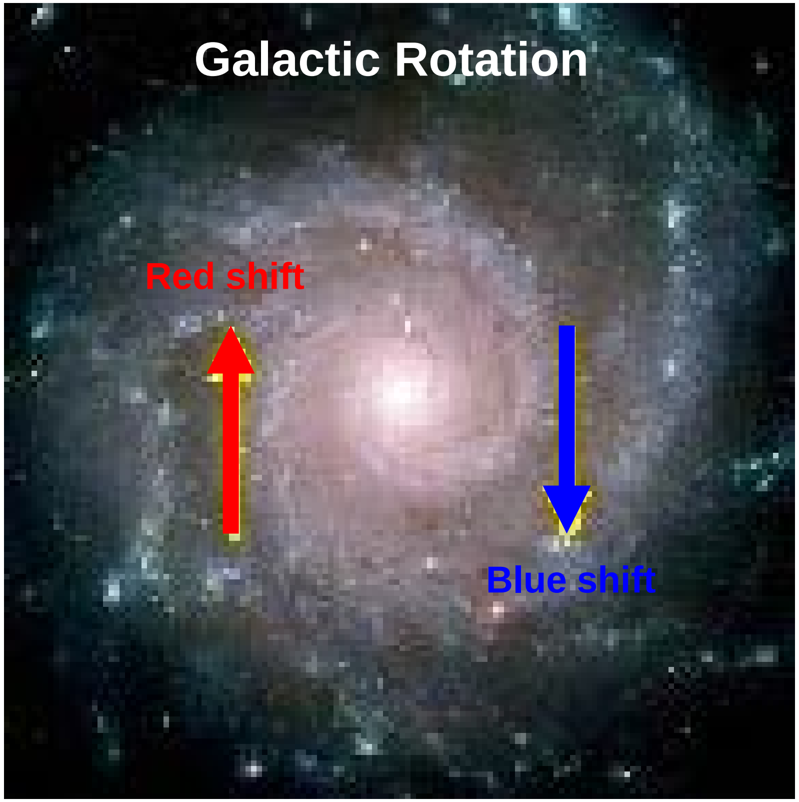
R. Diehl et al., Nature 439 (2006), 45.

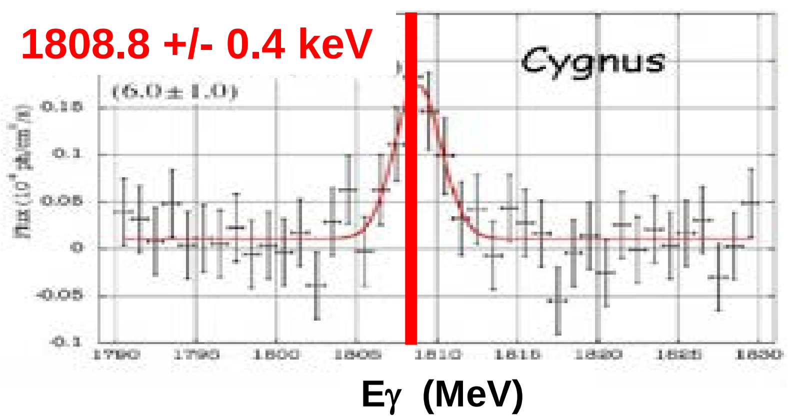
^{26}Al (5^+,0.72MeV; 7.4x10^5 y)

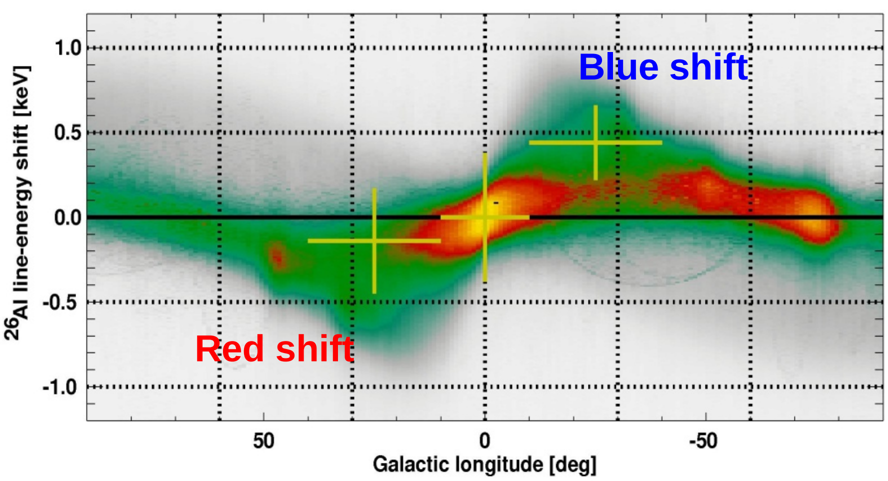
→ ^{26}Mg (2^+)

→ ^{26}Mg(0^+) + 1.809MeV









Astrophysical Implication

The total "OBSERVED" ^{26}Al gamma-ray flux in model 3D spatial distribution turns out to be 3.3(±0.4) × 10^{-4} ph $cm^{-2}s^{-1}$.

➡ Equilibrium ^{26}Al mass = 2.8 ±0.8 Msun

"THEORETICAL" nucleosynthesis yields in core-collapse supernovae and the preceding Wolf-Rayet phase stars:

Rauscher, T., Heger, A., Hoffman, R.D., Woosley S.E., ApJ, 576, 323 (2002)
Limongi, M., & Chieffi, A., Nucl.Phys.A, 758, 11c (2005)
Palacios, A., Meynet, G., Vuissoz, C., et al., A&A., 429, 613 (2005)
Woosley, S. E., Heger, A., Hoffman, R. D., ApJ. (2005)

➡ Average ejected ^{26}Al/massive star = 1.4 × 10^{-4} Msun

"SN Event Rate": Stellar yields + IMF -> independent estimate of the Galactic SFR. IMF; Scalo IMF ($\xi \sim m^{-2.7}$, m=10-120Msun)

Galactic CCSN Rate

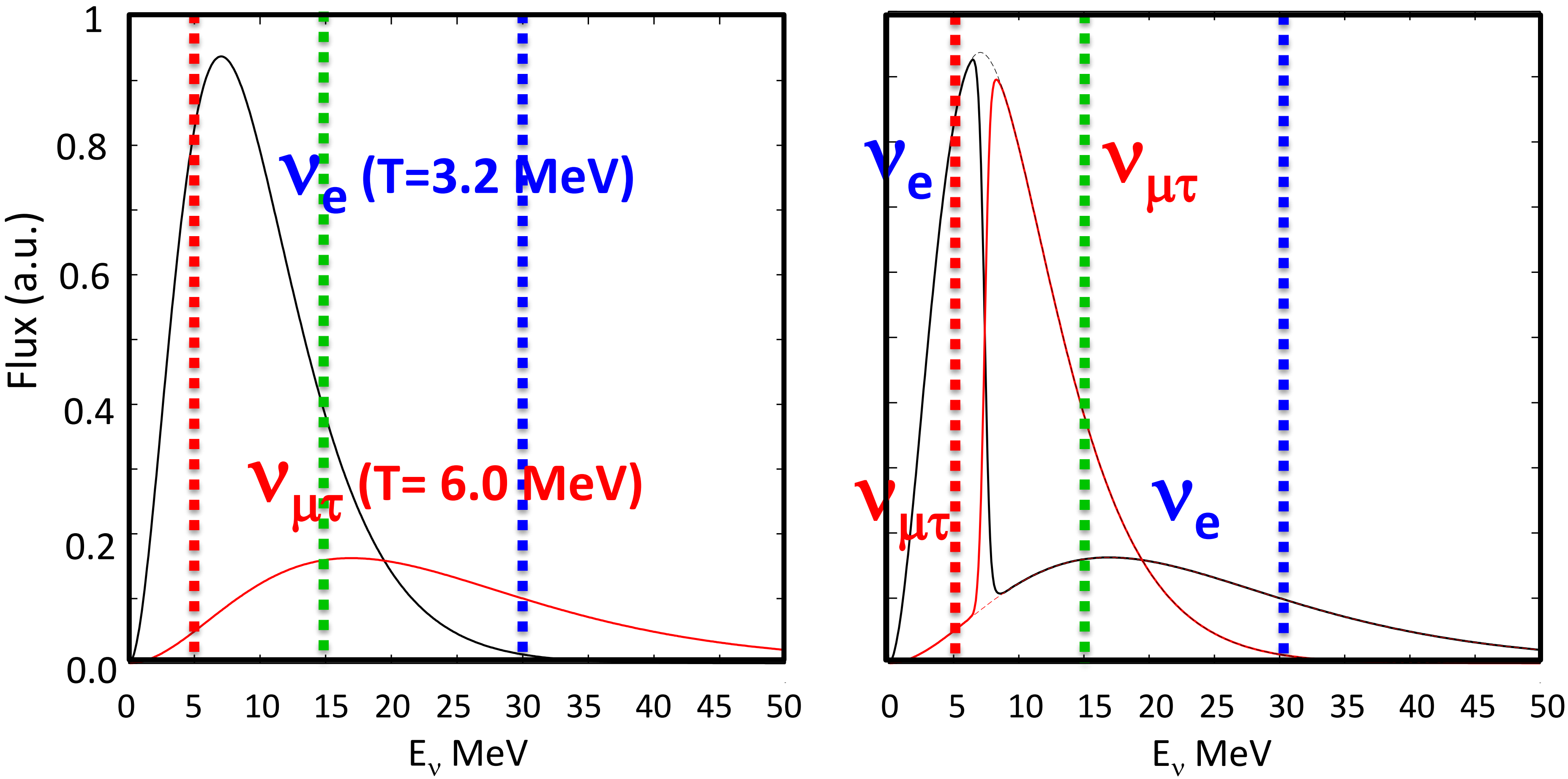
1.9 ± 1.1 /century/Milky Way

Swapped ν Energy Spectra

Sasaki et al. PR **D96** (2017), 043013.

Inverted hierarchy(m_1>m_3), Observed θ_{13} & Δm^2

r = 10km (ν-sphere) → r=250km



Calculated ν Flavor Oscillation

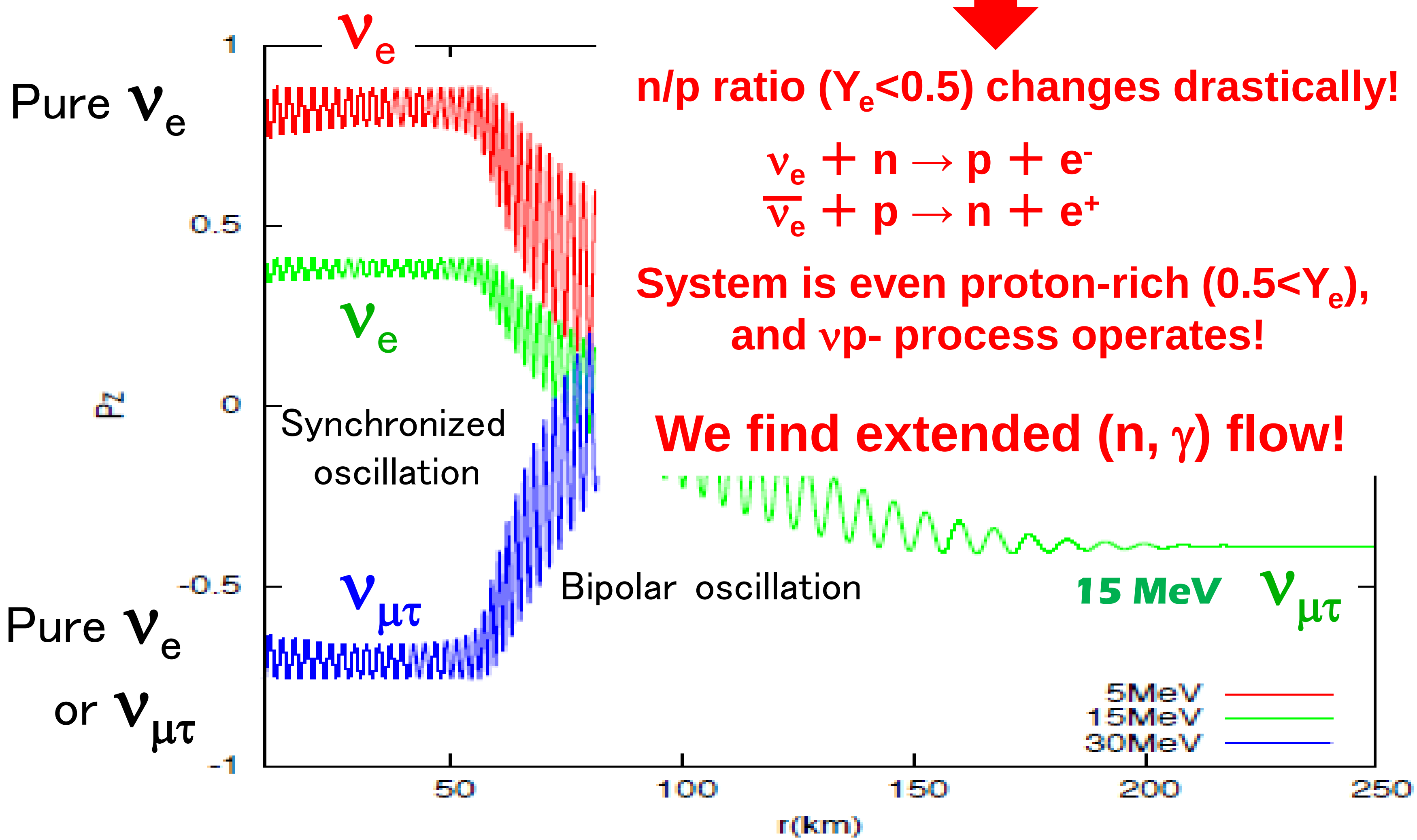
Energy spectra swap!

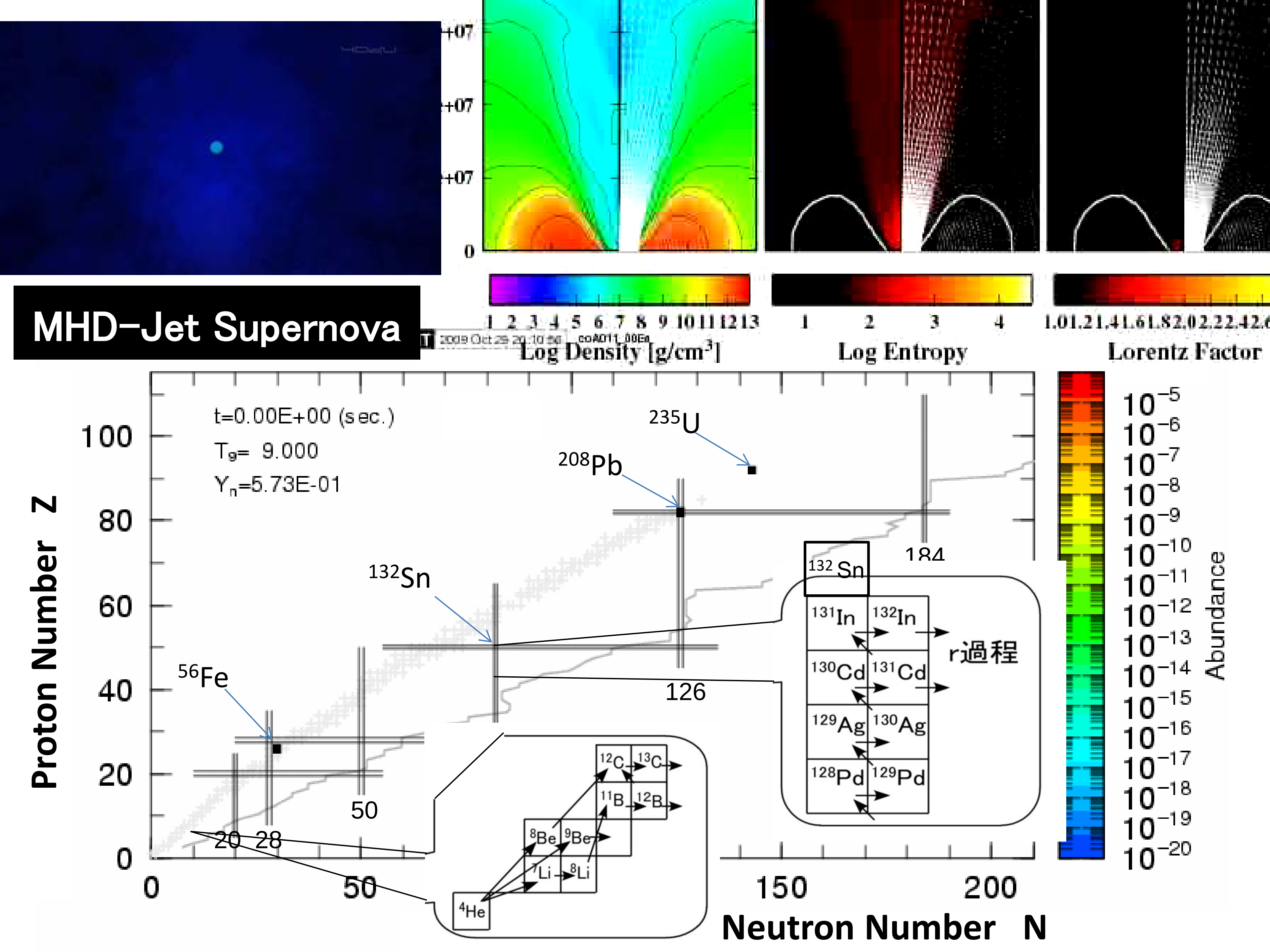
n/p ratio (Y_e<0.5) changes drastically!

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

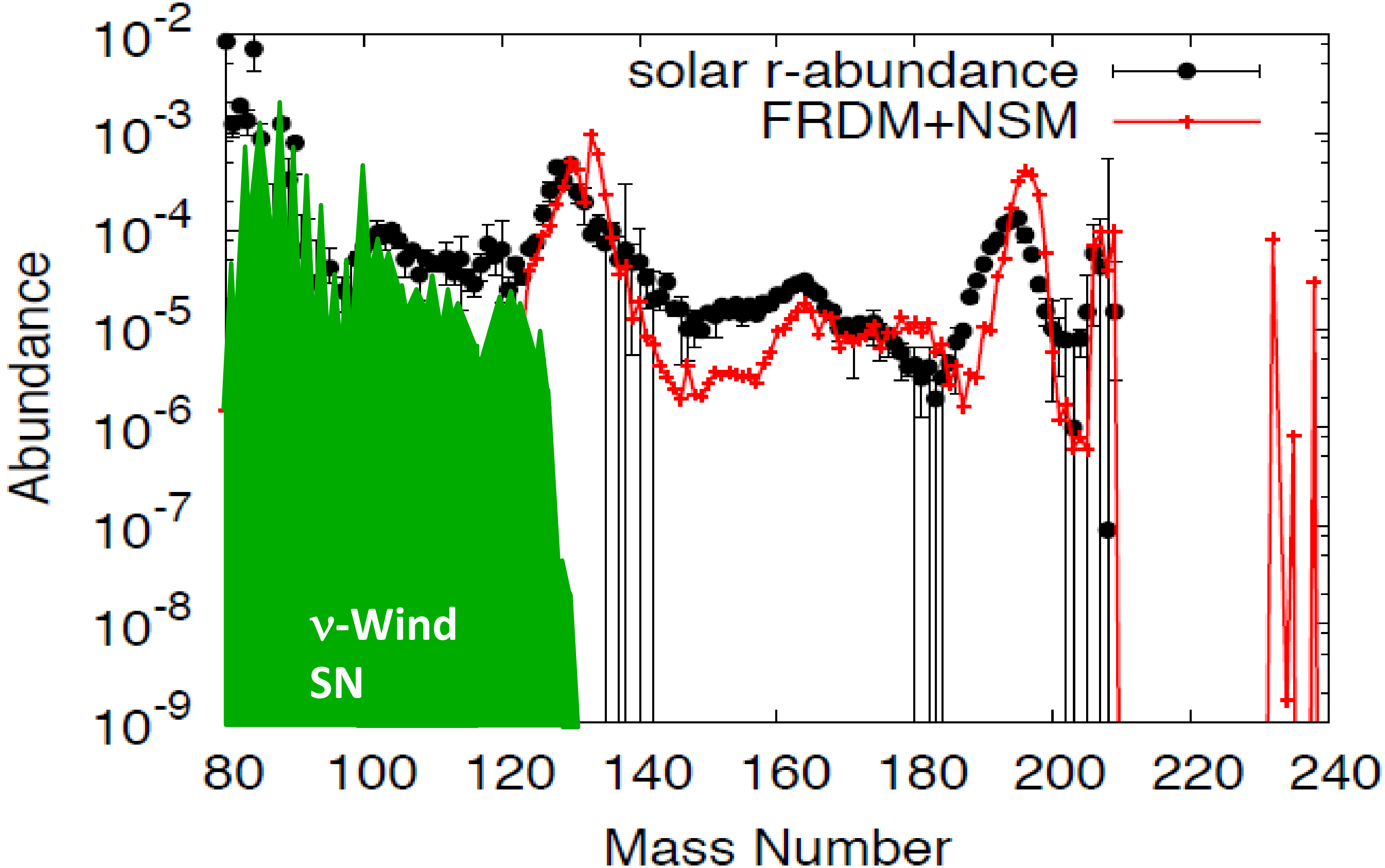
System is even proton-rich (0.5<Y_e), and νp- process operates!

We find extended (n, γ) flow!

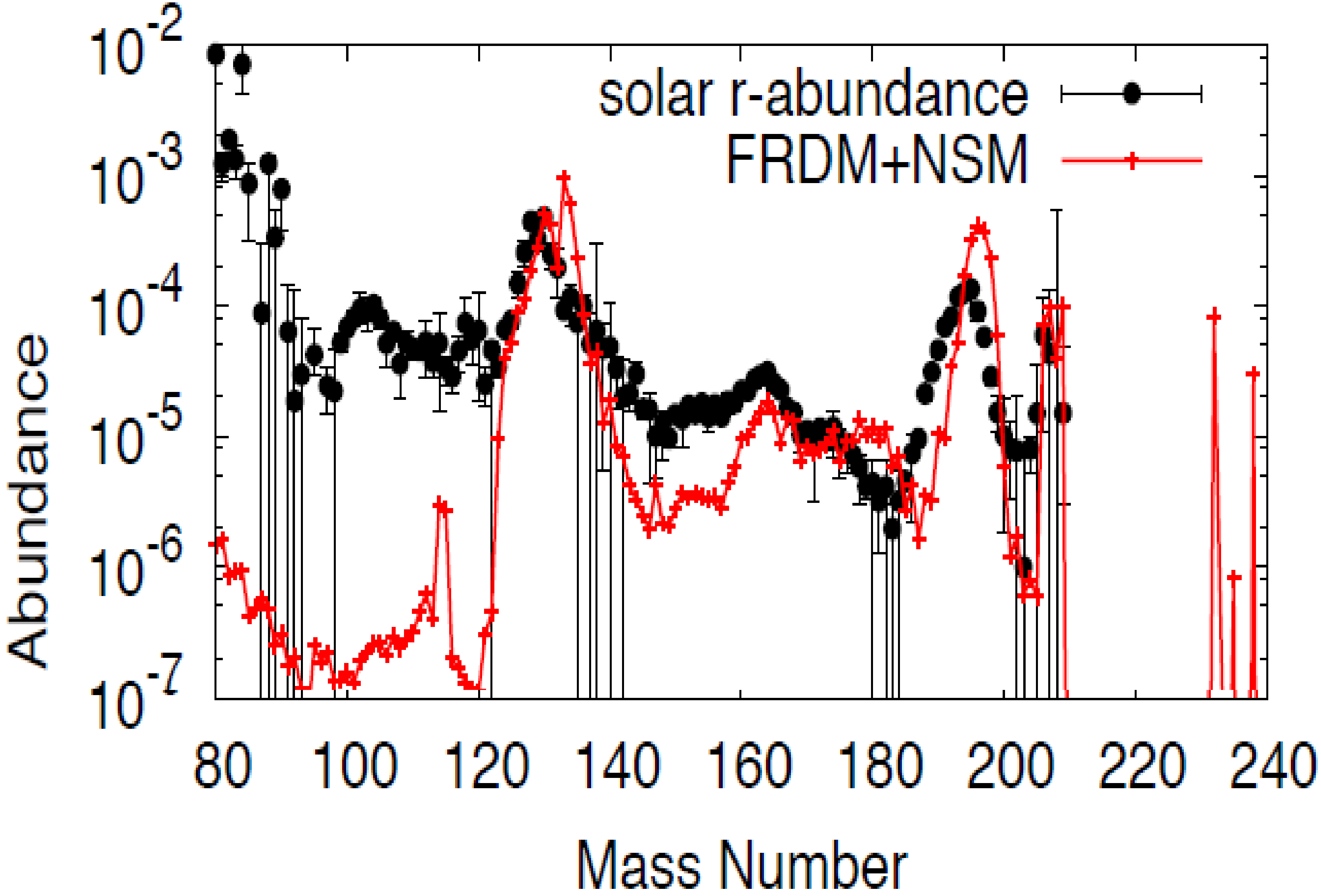




MHD-Jet Supernova
Log Density [g/cm³]
Log Entropy
Lorentz Factor
t=0.00E+00 (sec.)
T9= 9.000
Yn=5.73E-01
235U
208Pb
132Sn
56Fe
20
28
50
126
184
132 Sn
131In
132In
130Cd
131Cd
129Ag
130Ag
128Pd
129Pd
r過程
4He
7Li
8Li
8Be
9Be
11B
12B
12C
13C
Proton Number Z
Neutron Number N
Abundance



Abundance
Mass Number
solar r-abundance
FRDM+NSM
ν-Wind
SN
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
80
100
120
140
160
180
200
220
240



solar r-abundance
FRDM+NSM
Abundance
Mass Number
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
80
100
120
140
160
180
200
220
240

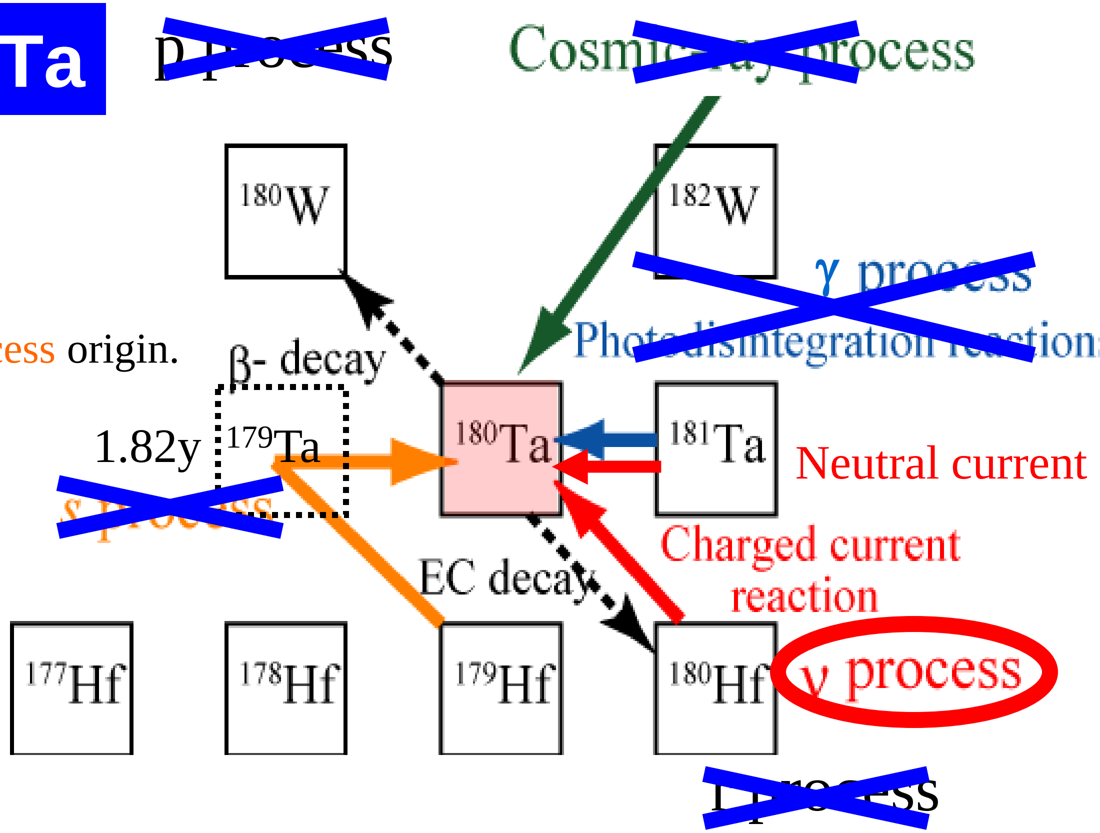
Missing Origin of ^{180}Ta

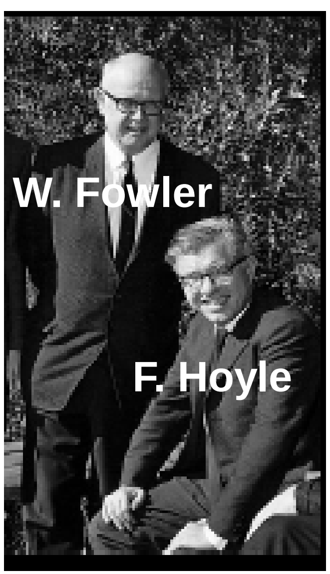
^{138}La = spherical
^{180}Ta = deformed

K.Yokoi, Nature (1983) proposal of s-process origin.

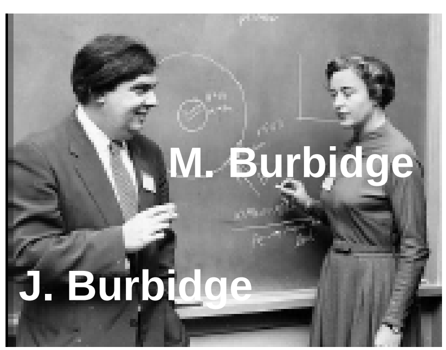
Belic et al., Phys. Rev. Lett. (1999)
Wisshak, Phys. Rev. Lett. (2001)

S-process can NOT produce both ^{138}La & ^{180}Ta consystently with s.s. abundance.





B^{2}FH,
RMP. 29 (1957), 547-650.
"Element Genesis in Stars"



Supernova neutrino-process:

Nucleosynthesis Theory
Woosley, Hartmann, Hoffman, & Haxton, ApJ 356 (1990), 272.
Heger et al., Phys. Lett. B 606, 258 (2005)

Nucleo-Cosmochronology:
Hayakawa, Shimizu, Kajino, Ogawa, & Nakada, PRC 77 (2008), 065802; 79 (2009) 059802.

Origin of HEAVY Atomic Nuclei (r–elements)?

CC–Supernovae?

ν–DW ? Woosley, et al., ApJ 433, 229 (1994). +
Nishimura, et al., ApJ 642, 410 (2006).

MHD–Jet Fujimoto, et al., ApJ 680, 1350 (2008).
Winteler, et al., ApJ 750, L22 (2012).
Nishimura et al., ApJ, 810, 109 (2015)

Long–GRB Nakamura, et al, A&Ap 582 A34 (2015)

τ =1My

Explosion Condition(Ω, B) !

1st, 2nd, 3rd peaks ?

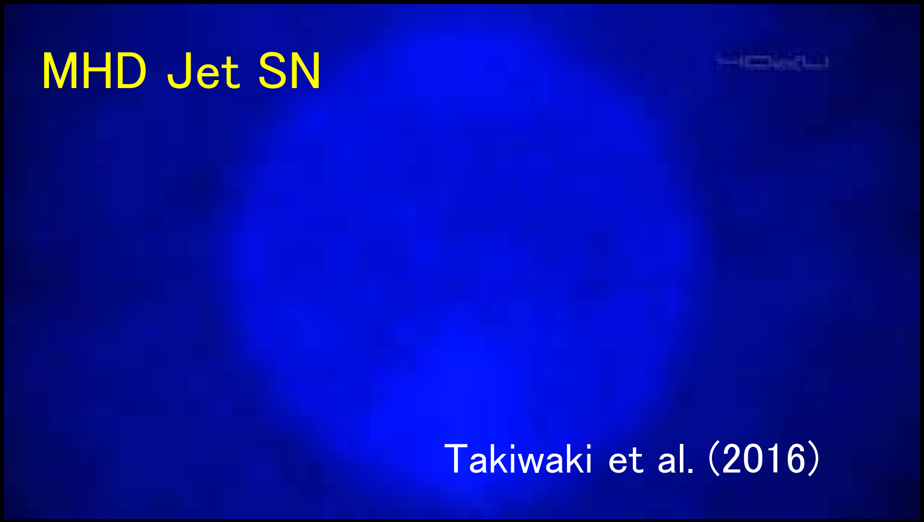
Binary Neutron–Star Mergers?

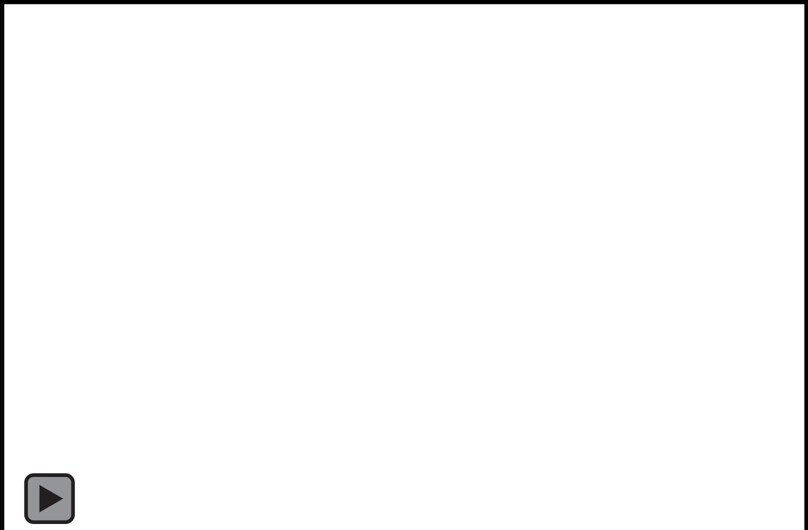
Goriely, et al., ApJ 738, L32 (2011).
Korobkin, et al., MNRAS 426, 1940 (2012).
Rosswog, et al., MNRAS 430, 2585 (2013).
Goriely, et al., PRL 111, 242502 (2013), (2015).
Piran, et al., MNRAS 430, 2121 (2013).
Wanajo, et al., ApJ 789, L39 (2014).

100My $\leq \tau \leq$ 10Ty

Merging time, too long !

Time Scale Problem ?





Tantalum ^{180}Ta

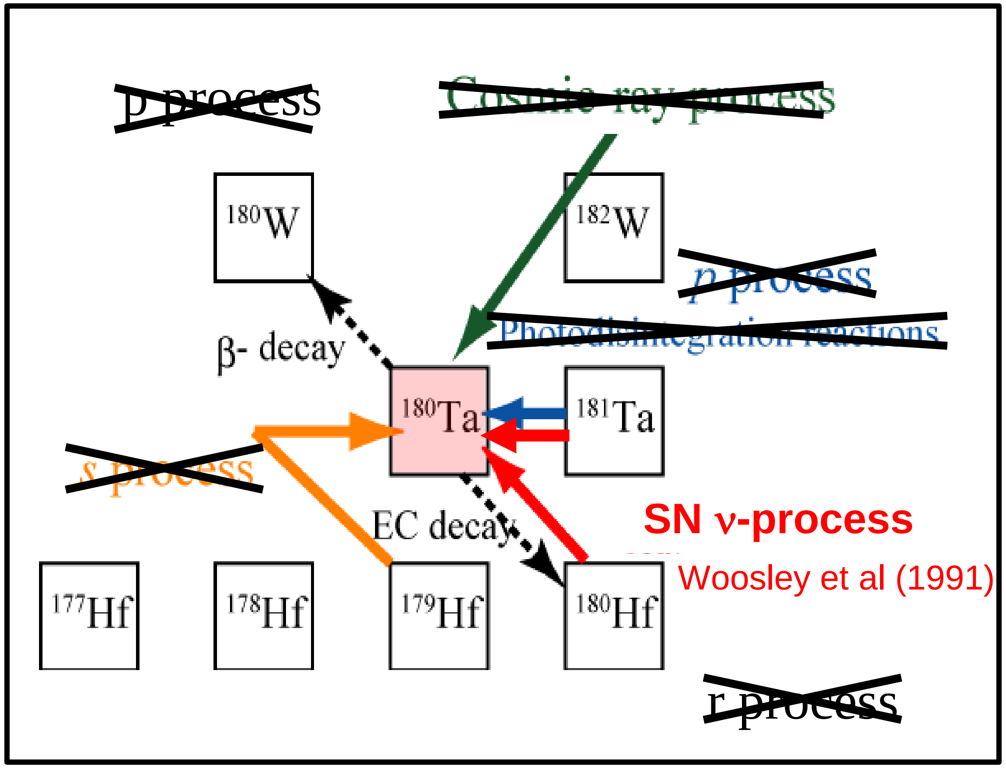
Explosive SN nucleosynthesis coupled with quantum transitions can reproduce both ^{180}Ta and ^{138}La simultaneously.

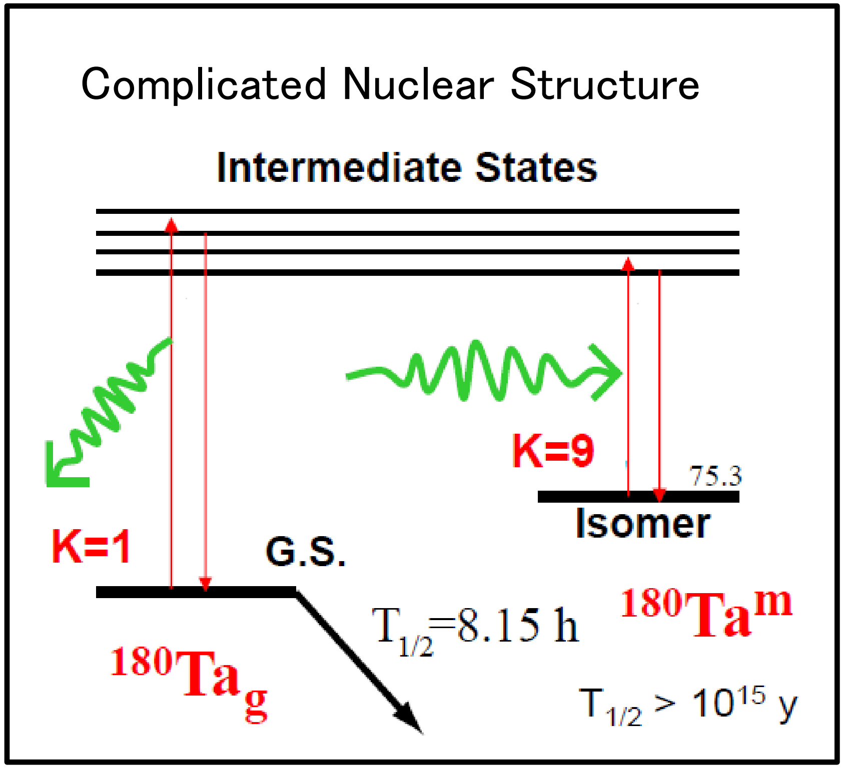
Hayakawa et al. (2010) PRC81, 052801®; (2010) PR C82, 058801.

Overproduction problem, solved!

$(^{180}Ta/^{138}La)_{theory} = 1$

→ ***Only when $T_{\nu e}$ = 3.2MeV, $T_{\overline{\nu e}}$ = 4-5MeV !***





SN ν−Process : Origin of ^{92}Nb !

Hayakawa, Nakamura, Kajino, Chiba, Iwamoto, Cheoun, Mathews,
Astrophys. J. Lett. **779** (2013), L1.

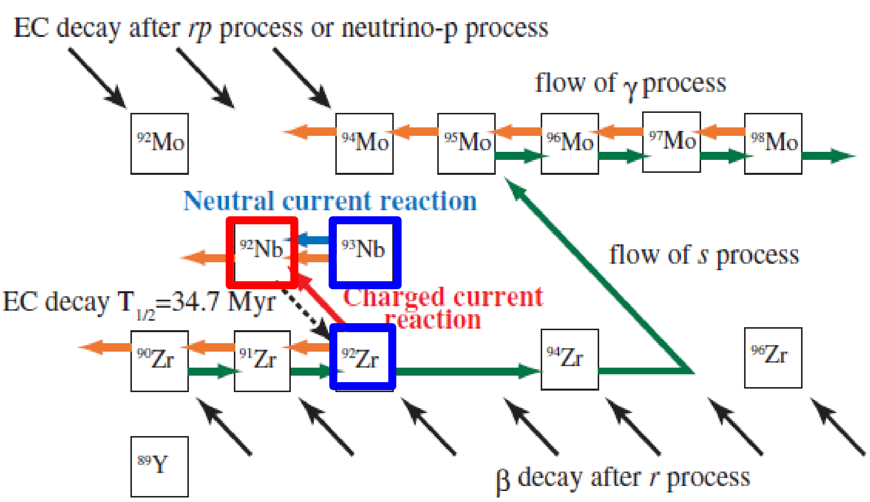
★ ^{92}Nb($\tau_{1/2}$=3.47x10^{7} y) existed at the s.s. formation (4.56 Gy ago)!

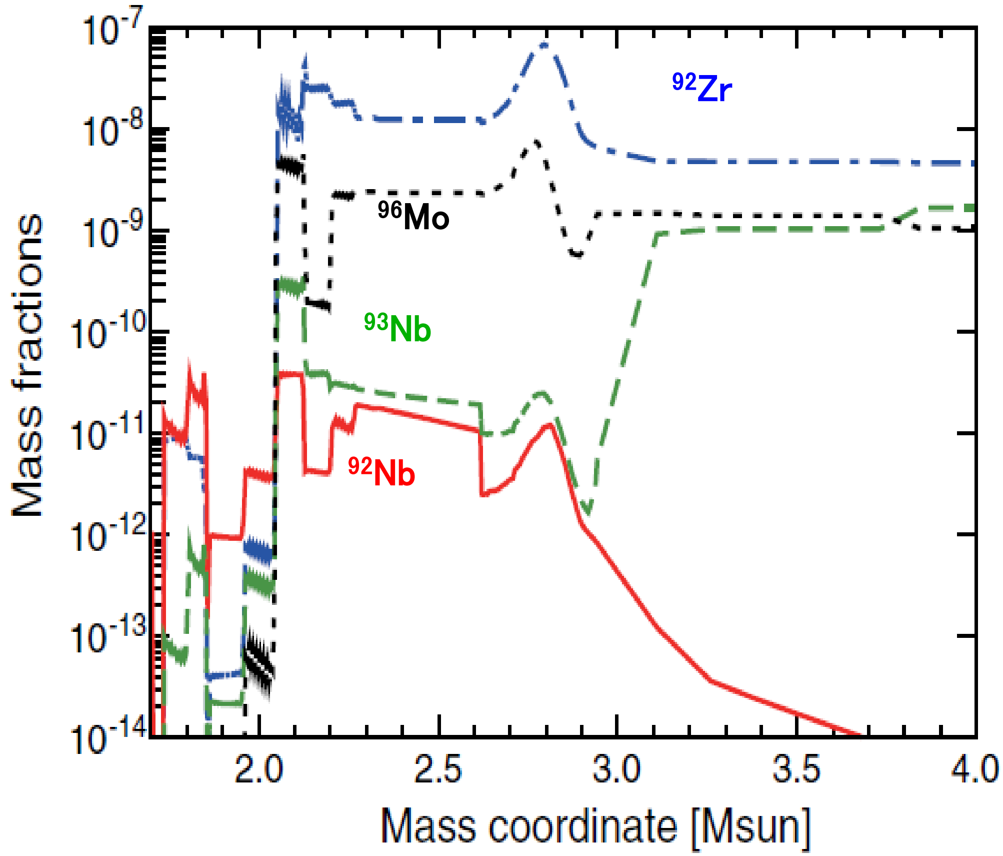
★ Isotopic anomaly in meteoritic, found;

^{92}Zr/^{93}Nb ∼ 10^{-3}

$T_{\nu e}$ = 3.2 MeV, $T_{\overline{\nu e}}$ = 4.0 MeV, $T_{\nu x}$ = 6.0 MeV

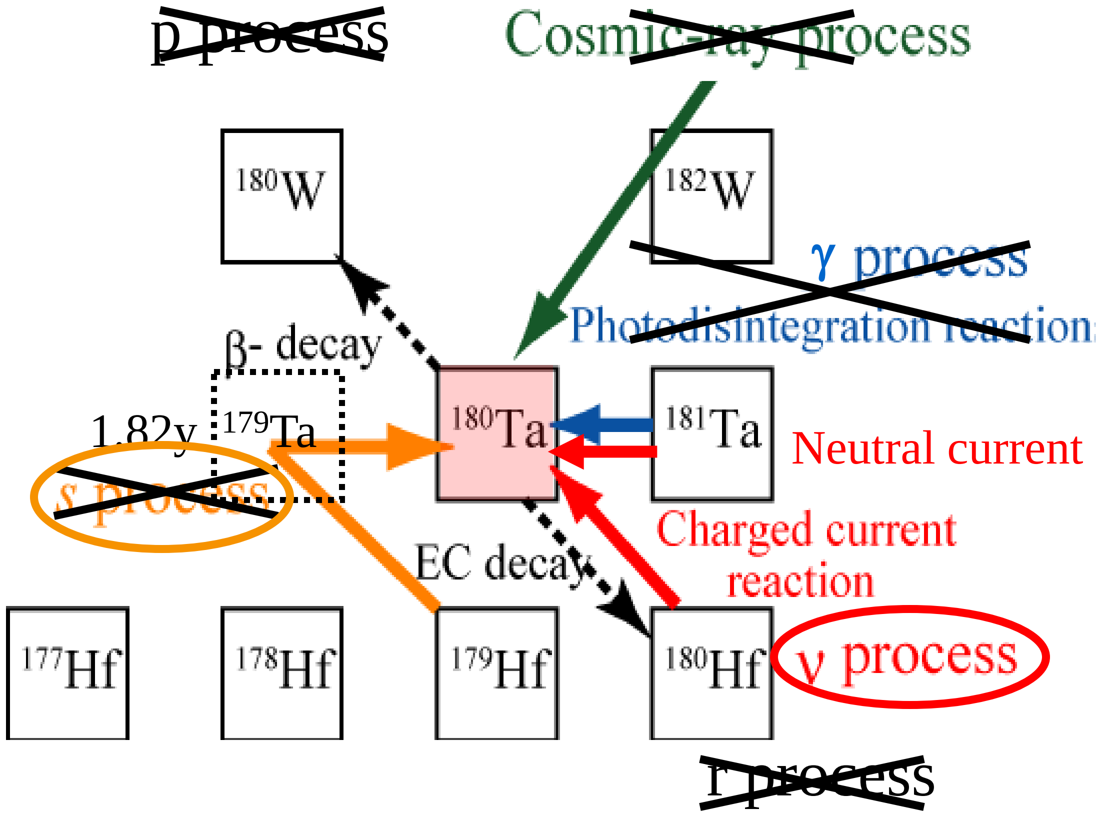
When did the last nearby SN exploded before the solar sytem formation ?





Origin of ^{180}Ta

^{138}La = spherical
^{180}Ta = deformed



K.Yokoi, Nature (1983)
proposal of s-process origin.

Belic et al., Phys. Rev. Lett. (1999)
Wisshak, Phys. Rev. Lett. (2001)

S-process cannot produce both ^{138}La & ^{180}Ta.

Supernova neutrino-process:

Nuclear Experiment & Theory

Goko, Phys. Rev. Lett. (2007)
Byelilov , Phys. Rev. Lett. (2007)
Cheoun et al., (2010), in preparation.

Nucleosynthesis Theory

Woosley, Hartmann, Hoffman, & Haxton, ApJ 356 (1990), 272.
Heger et al., Phys. Lett. B 606, 258 (2005)

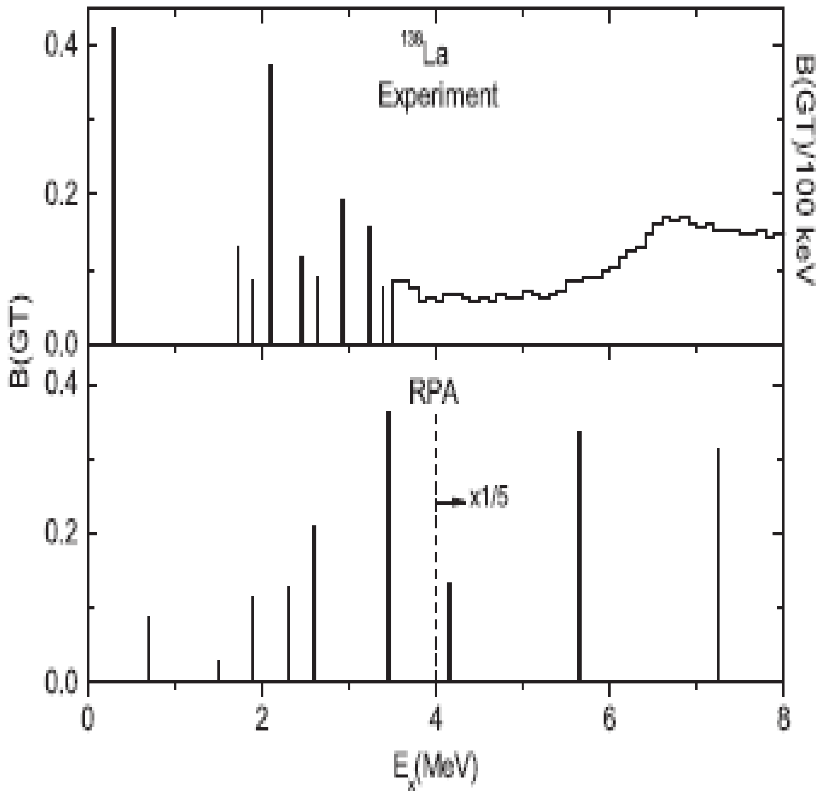
Nucleo-Cosmochronology:

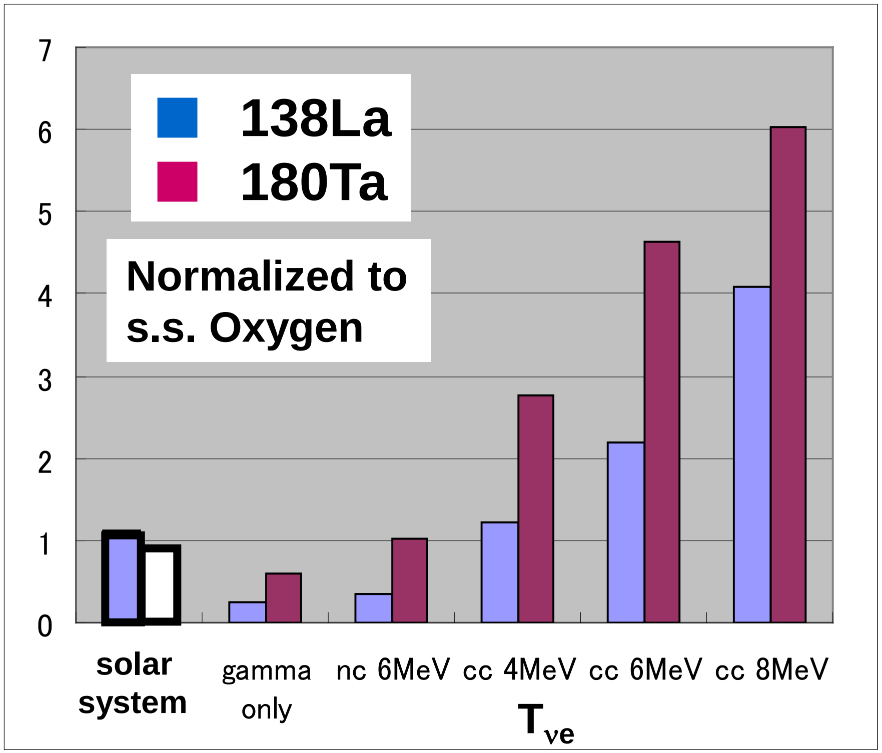
Hayakawa, Shimizu, Kajino, Ogawa, & Nakada, PRC 77 (2008), 065802; 79 (2009) 059802.

Impact of CEX Reaction on ν-Process

Byelikov + Fujita et al., PRL (2007), RCNP measurement of GT strength.

A. Heger, Phys. Lett. B 606, 258 (2005)





(1) Forbidden transitions + as well as GT contribute!

Eν = 0 ~ 80 MeV

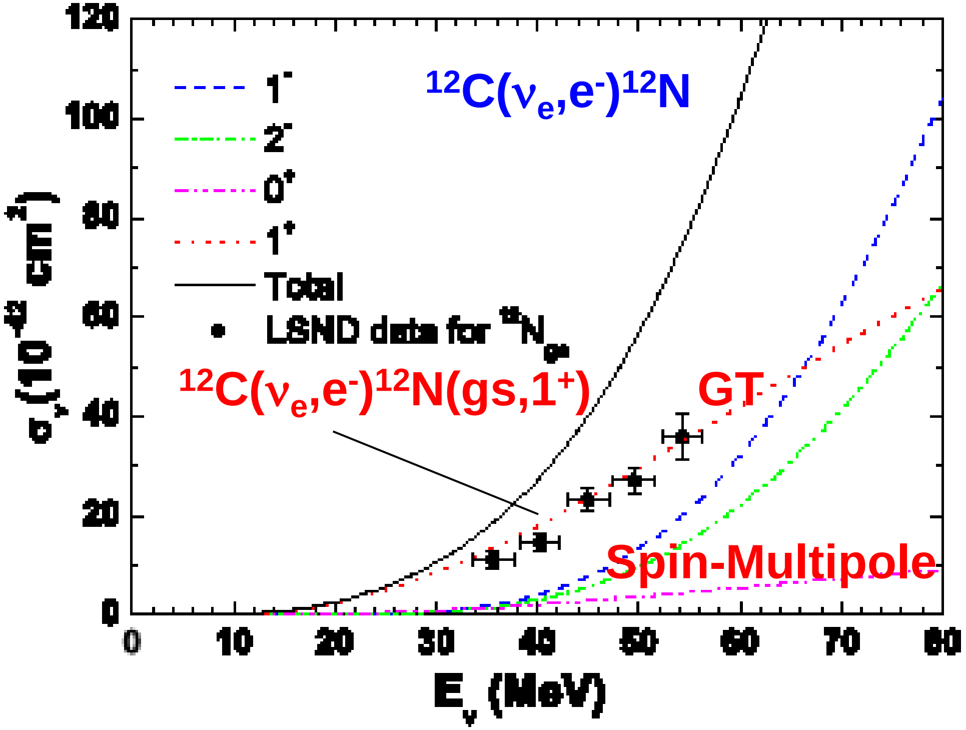
(2) Overproduction of ^{180}Ta relative to ^{138}La!

(1) Neutrino-^{138}La, ^{180}Ta cross section calculations in Quasi-particle Random Phase Approximation

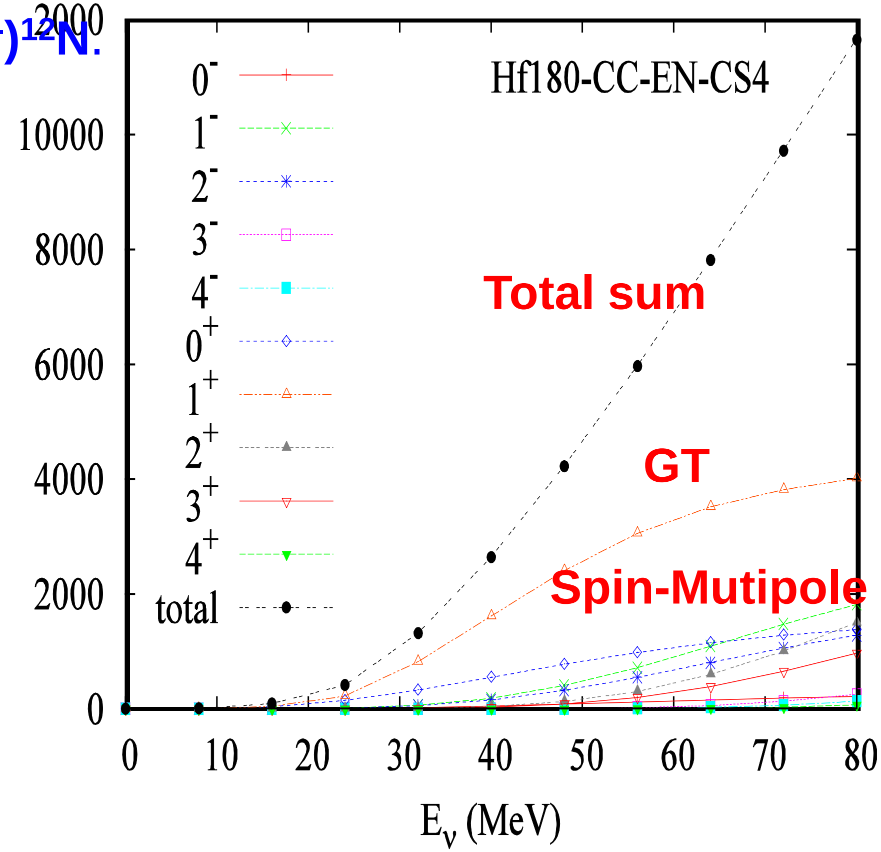
Cheoun, et al., PRC81 (2010), 028501; PRC82 (2010), 035504: J. Phys. G37 (2010), 055101; PRC 83 (2011), 028801: Suzuki, et al., PR C74 (2006), 034307; PR C67, 044302 (2003).

GT and Forbidden Transitions, equally importa

Calibrated by unique data on $^{12}C(\nu_e,e^-)^{12}N$.



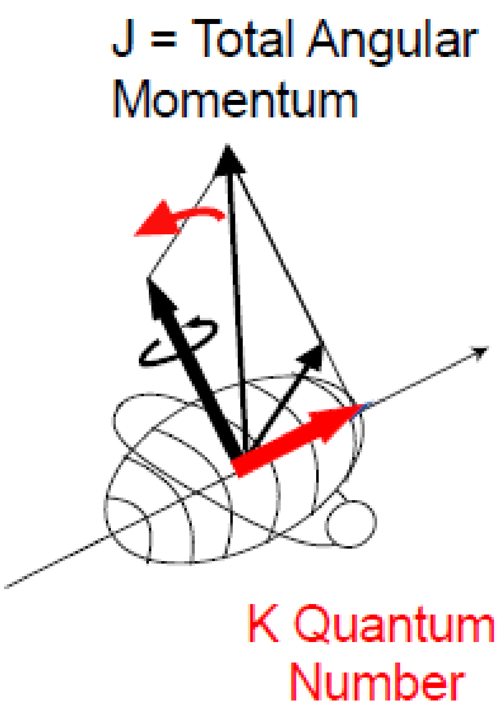
$^{180}Hf + \nu \rightarrow {}^{180}Ta + e^-$ (CC)

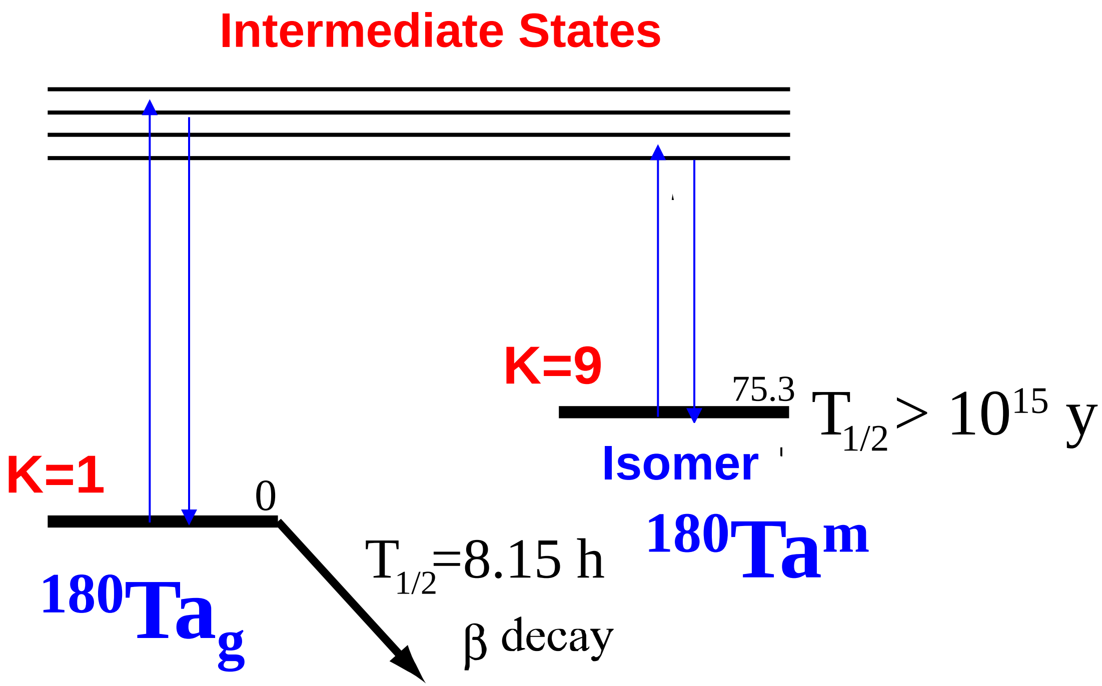


(2) OVEREPRODUCTION of Isomer state ^{180}Ta

How robust is $^{180}Ta^m$ ($T_{1/2} > 10^{15}$ y) in SN explosion dynamics at very high temperature?

★ $^{180}Ta_g$ and $^{180}Ta^m$ can couple with each other through intermediate linking transitions in hot SN explosions.





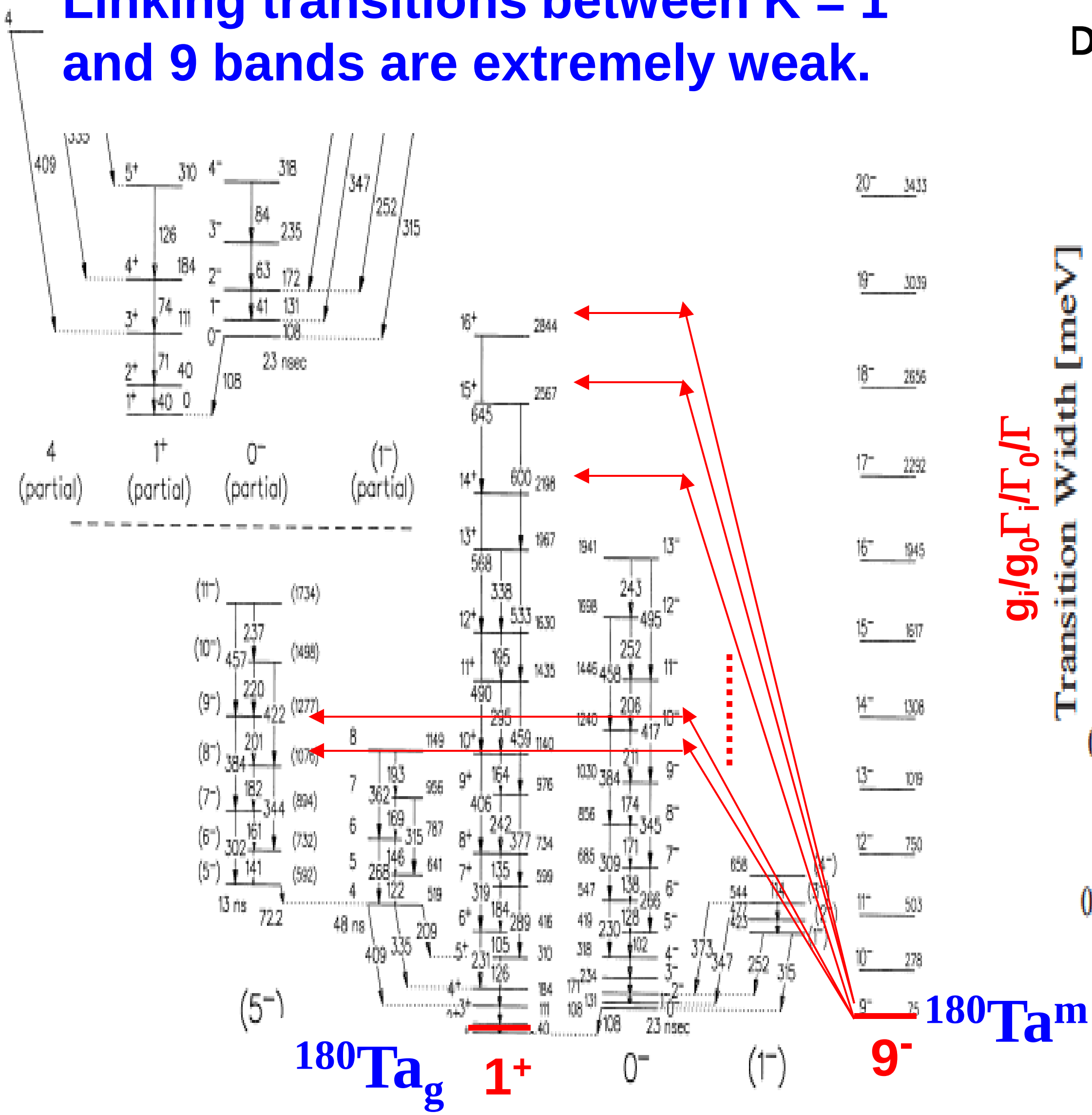
Measurement of Gamma-Decay Widths of Excited States

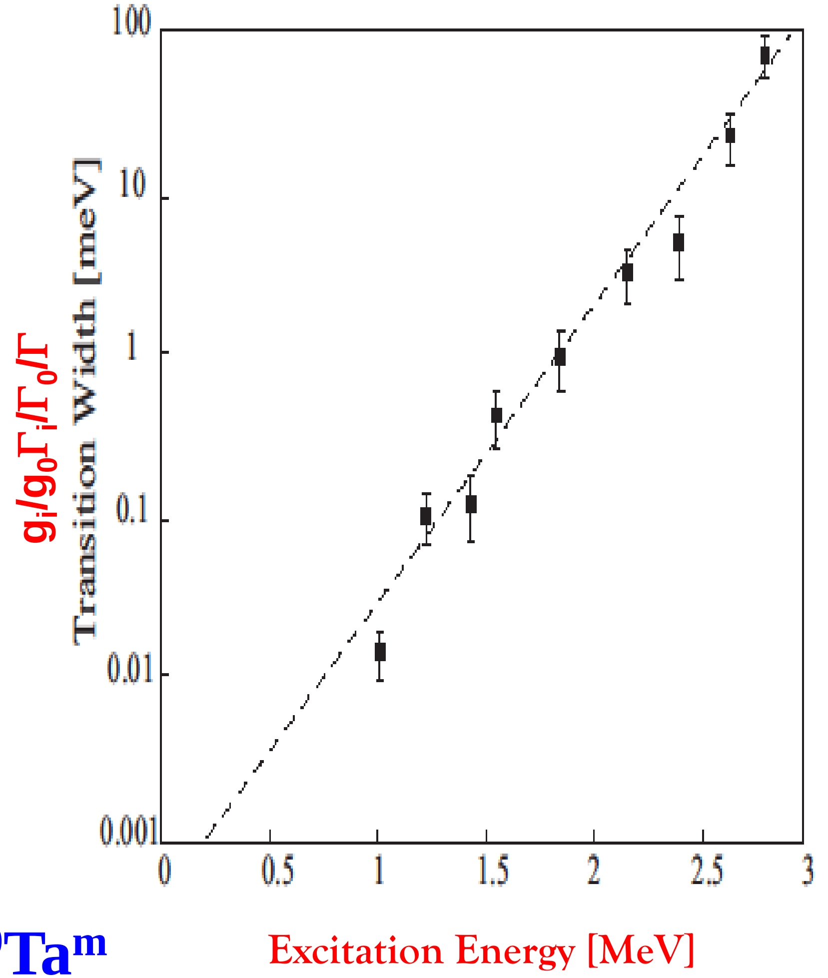
Saitoh et al. (NBI group), NPA 1999 +
Dracoulis et al. (ANU group), PRC 1998 +

Very small total decay width

Linking transitions between K = 1 and 9 bands are extremely weak.

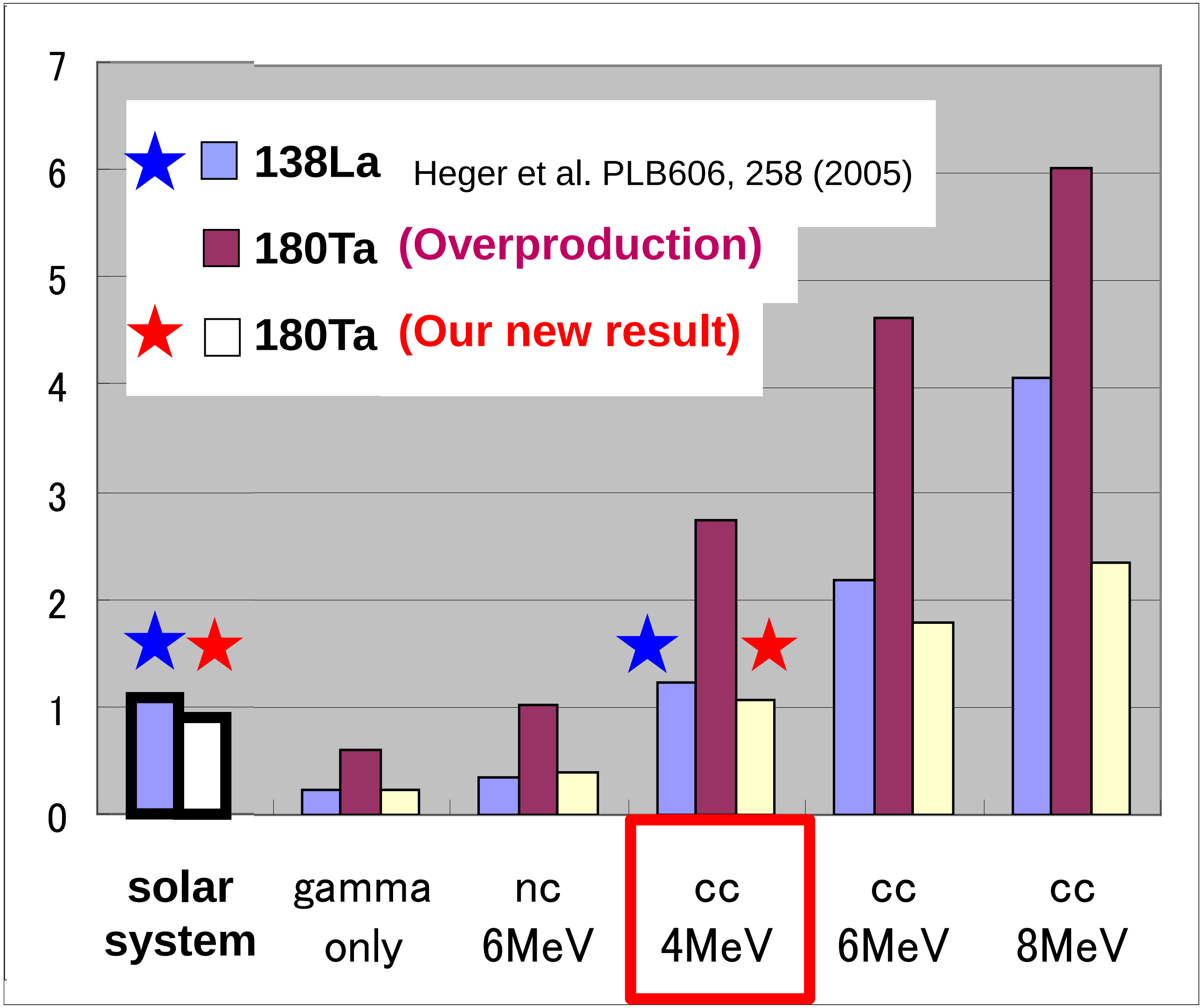
D. Belic et al., PR C65 (2002), 035801.





Result from our ν-Nucleosynthesis

T. Hayakawa, P. Mohr, T. Kajino, S. Chiba, and G.J. Mathews, Phys. Rev. C81 (2010), 052801®; Phys. Rev. C82 (2010), 058801.



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

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

Consistent with r-process in ν-DW SN !

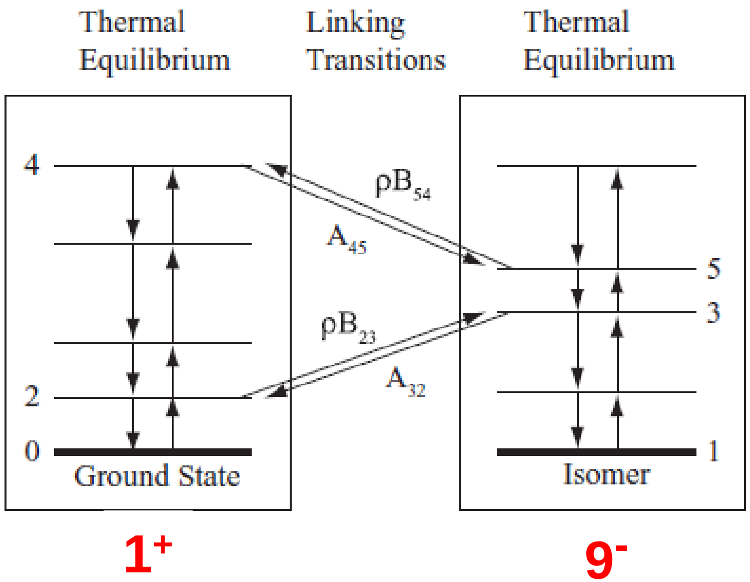
Formula to calculate time-dept linking transitions

Hayakawa, Kajino, Mohr, Chiba & Mathews, PR C81 (2010), 052801®; PR C82 (2010), 058801

★ General formula (Einstein AB theory) for $kT \ll \Delta E_{ij}$:

$$\frac{dN_0}{dt} = -\sum_{iP} P_i^g A_{ip} N_0 + \sum_{ip} P_i^m \rho B_{pi}(1-N_0), -\sum_{jq} P_j^g \rho B_{qj} N_0 + \sum_{jq} P_j^m A_{jq}(1-N_0)$$

$$= -\sum_{i\,p} P_0^g \frac{g_i}{g_0} exp(-(E_i - E_0)/kT) A_{ip} N_0 + \sum_{ip} P_1^m \frac{g_i}{g_1} exp(-(E_i - E_1)/kT) A_{ip}(1-N_0),$$



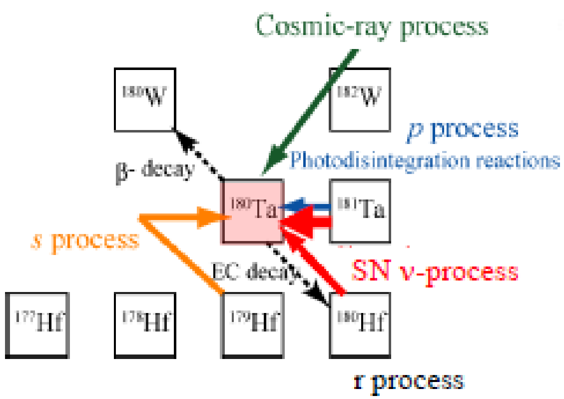
$$m_i/m_j = (2J_i+1)/(2J_j+1) exp(-(E_i - E_j)/kT),$$

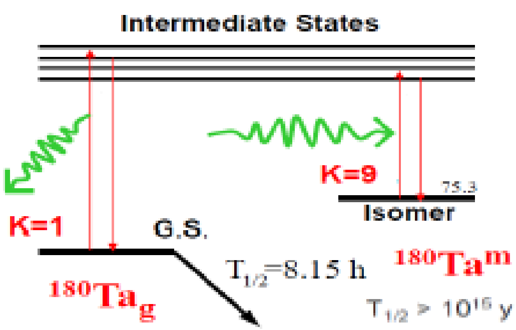
$$P_i \equiv m_i/m_{total} = \frac{m_i/m_0}{\sum(m_i/m_0)}.$$

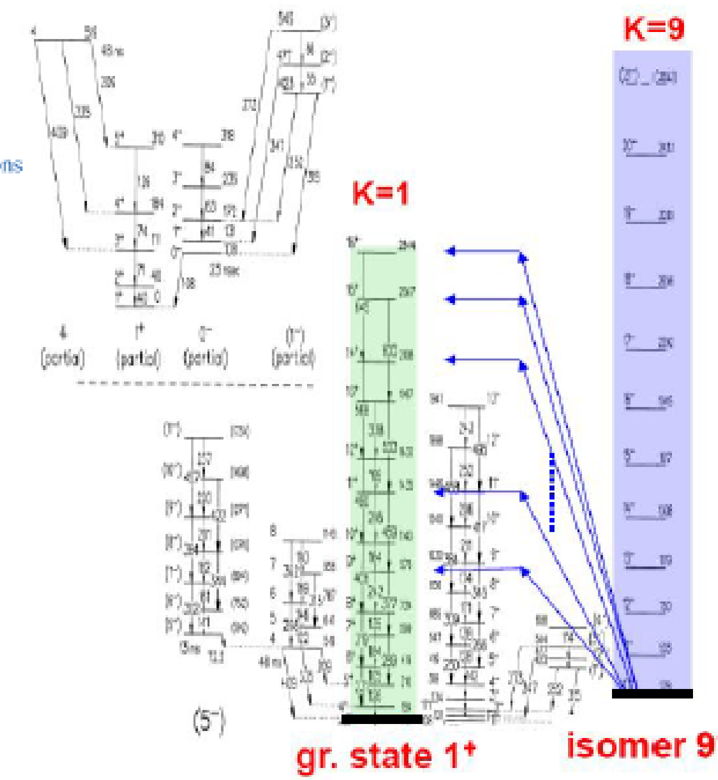
★ In the SPECIFIC case of ^{180}Ta:

Transition prob. $\Sigma_p A_{ip} = \Gamma_i / \hbar$ ⟵ Exp.

$$\frac{dN_0}{dt} = -\sum_i P_0^g \frac{g_1}{g_0} exp(-(E_i - E_0)/kT) \frac{g_i}{g_1}\frac{\Gamma_i}{\hbar} N_0 + \sum_i P_1^m exp(-(E_i - E_1)/kT) \frac{g_i}{g_1}\frac{\Gamma_i}{\hbar}(1-N_0).$$


Cosmic-ray process
180W
182W
p process
Photodisintegration reactions
β- decay
180Ta
181Ta
s process
EC decay
SN ν-process
177Hf
178Hf
179Hf
180Hf
r process


Intermediate States
K=9
75.3
Isomer
K=1
G.S.
$T_{1/2}$=8.15 h
180Tam
180Tag
$T_{1/2}$ > 10^15 y


K=9
K=1
(5⁻)
gr. state 1+
isomer 9-