The 4th CCAST Workshop on the JUNO related theory and phenomenology: Astrophysical Neutrinos, CCAST, April 28-29, 2024

Neutrinos in the Universe from Big-Bang to Supernova and Origin of Life

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Cosmic Evolution of Elements & Roles of Neutrinos

Multi-messenger Era with GW, γ, ν, Nuclei

Gravity, EM, Weak, Strong — 4 fundamental forces

Dark Age

Big-Bang Nucleosynthesis

Galaxies

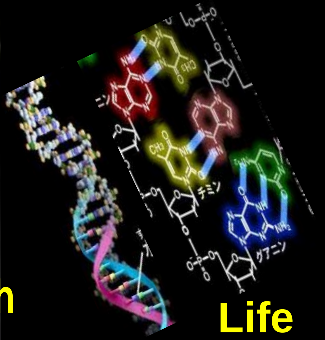
Inflation

Cosmic Age13.8 Gy ~10^{10} y

Earth

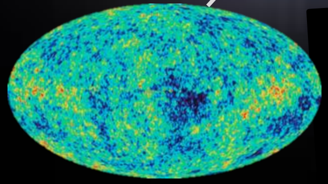
Quantum Fluct. of Space-Time

First Stars → Stellar & Galactic Eviolution

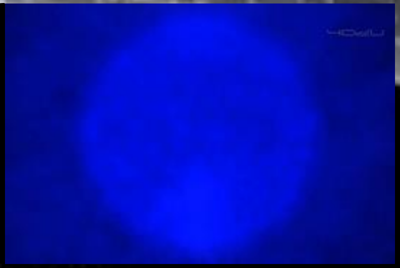


Life

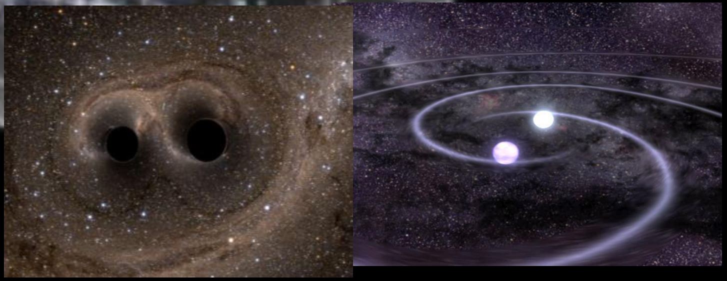
Sun



CMB Fluctuation
$3.8\mathrm{x}10^5$ y

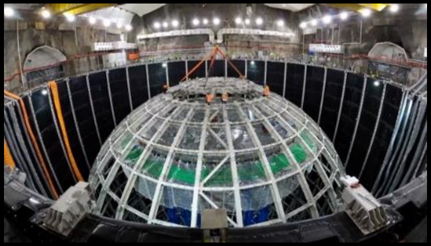


Collapsar & Supernova
~ 10^6 y



Binary BH/Neutron-Star Merger
~ 10^8—10^9 y

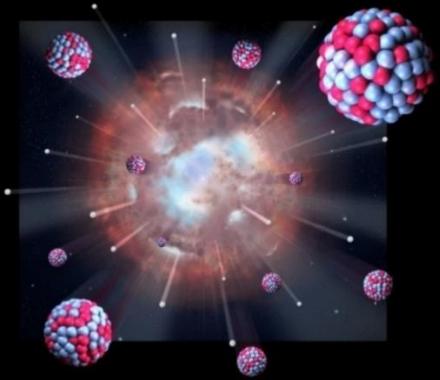
Purpose



Nuclear & Particle Physics

JUNO, SK/HK … ν-facilities will determine the ν-nature in vacuum at high precision of 3-5σ C.L.

HI accelerators at HIAF, RIKEN, RCNP, FRIB, FAIR, RAON… are/will be in operation.



Nuclear Astrophys. & Cosmology

Clarify the challenging unsolved questions, i.e. origin of elements & ν-matter interactions, to ultimately constrain ν-mass hierarchy.

Today's Goal

We elucidate the roles of ν-matter interactions in nucleosyntheses from the Big-Bang to Sun-Supernova-Life.

SUCCESS in Big-Bang Cosmology, based on;

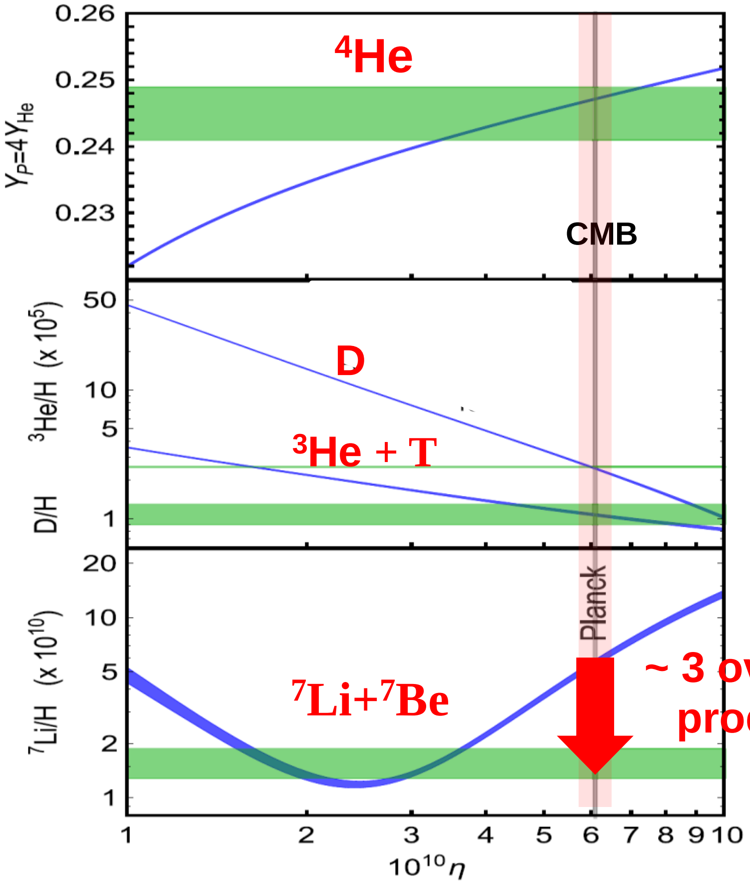
1. Cosmic Microwave Background Anisotropies
2. Big-Bang/Primordial Nucleosynthesis

Cosmological “Lithium” Problem !

Consistency among Light Elements?

Possible Solutions?

1. Cosmology
   - CMB + ν + Mag. Fluct.
2. New Physics
   - ν mag. moment ($m_\nu \neq 0$)
   - Decay of Particles
3. Nuclear Physics
   - Reaction cross sections
4. Astron. Observation
   - ^{4}He in metal-poor galaxies



~ 3 over-produced!

The Power of Quantum Mechanics and Relativity

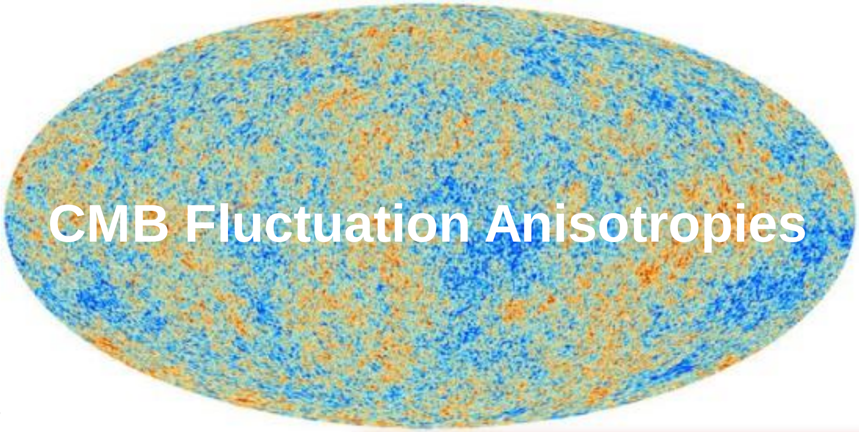
Quantum Systems of Particles and Nuclei

- Elementary Particles; Relativistic
- Atomic Nuclei; Non-relativistic
- Fermi vs. Bose Statistics
  Planckian
  Maxwell-Boltzmann

$$n_i(p)dp = \frac{1}{2\pi^2} g_i\, p^2 \left[\exp\left(\frac{E_i(p) - \mu_i}{kT}\right) \pm 1\right]^{-1} dp$$

$$\rho_i = \int p\,[n_i(p) + n_{\bar{i}}(p)]\,dp$$

$$\rho_\gamma = \frac{\pi^2}{15}(kT_\gamma)^4 \quad , \quad \rho_{\nu_i} = \frac{7}{8}\frac{\pi^2}{15}(kT_\nu)^4$$



CMB Fluctuation Anisotropies

Expansion Dynamics

- Einstein Eq.
- Fluid Dynamic. Eq.

$$H^2(t) = \left(\frac{}{R}\frac{}{dt}\right) = \frac{}{3}\rho + \frac{}{3} - \frac{}{R^2}$$

Numerical simulation for

Flucuations of Primordial Magnetic Field ?

Reaction Network

$$dn_i/dt = \sum_{kl\,j} <\sigma_{kl\rightarrow ij}\,\upsilon> n_k n_l \;-\; \sum_{j\,kl} <\sigma_{ij\rightarrow kl}\,\upsilon> n_i n_j \;-\; n_i/\tau_i$$

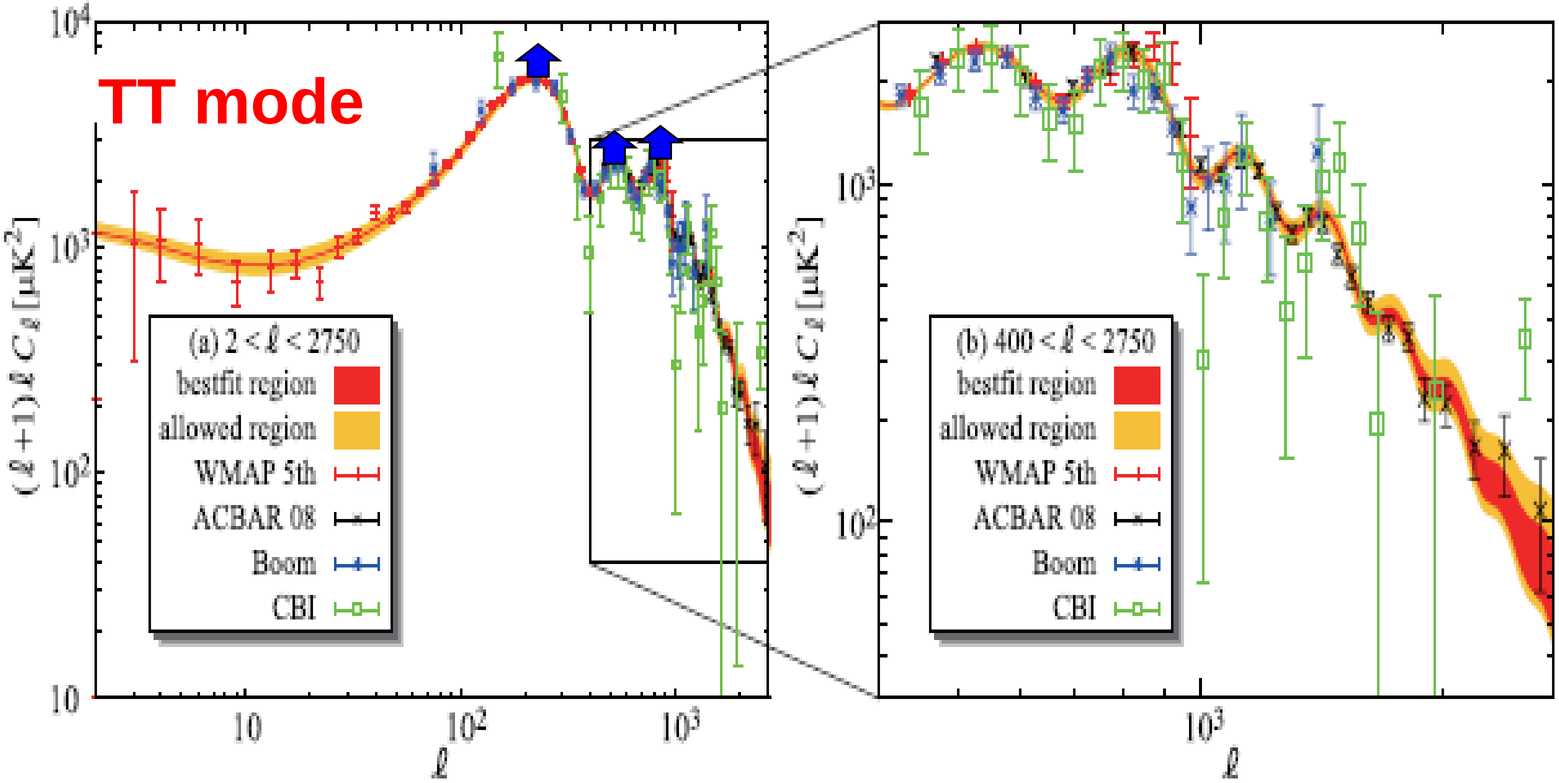
- Nuclear (strong), Electro-magnetic, and Weak interactions

CMB Anisotropy and Polarization exhibit a signal of ν mass and Primordial Magnetic Field (PMF) !

Yamazaki, Kajino, Mathews & Ichiki, Phys. Rep. 517 (2012), 141; PR D81 (2010), 023008; PR D81 (2010), 103519; PRD, 77, 043005 (2008); ApJ 825 (2006), L1.

Integrated Sachs-Wolfe Effect, similarly to CDM

Free Streaming Effect of Finite Mass Neutrinos



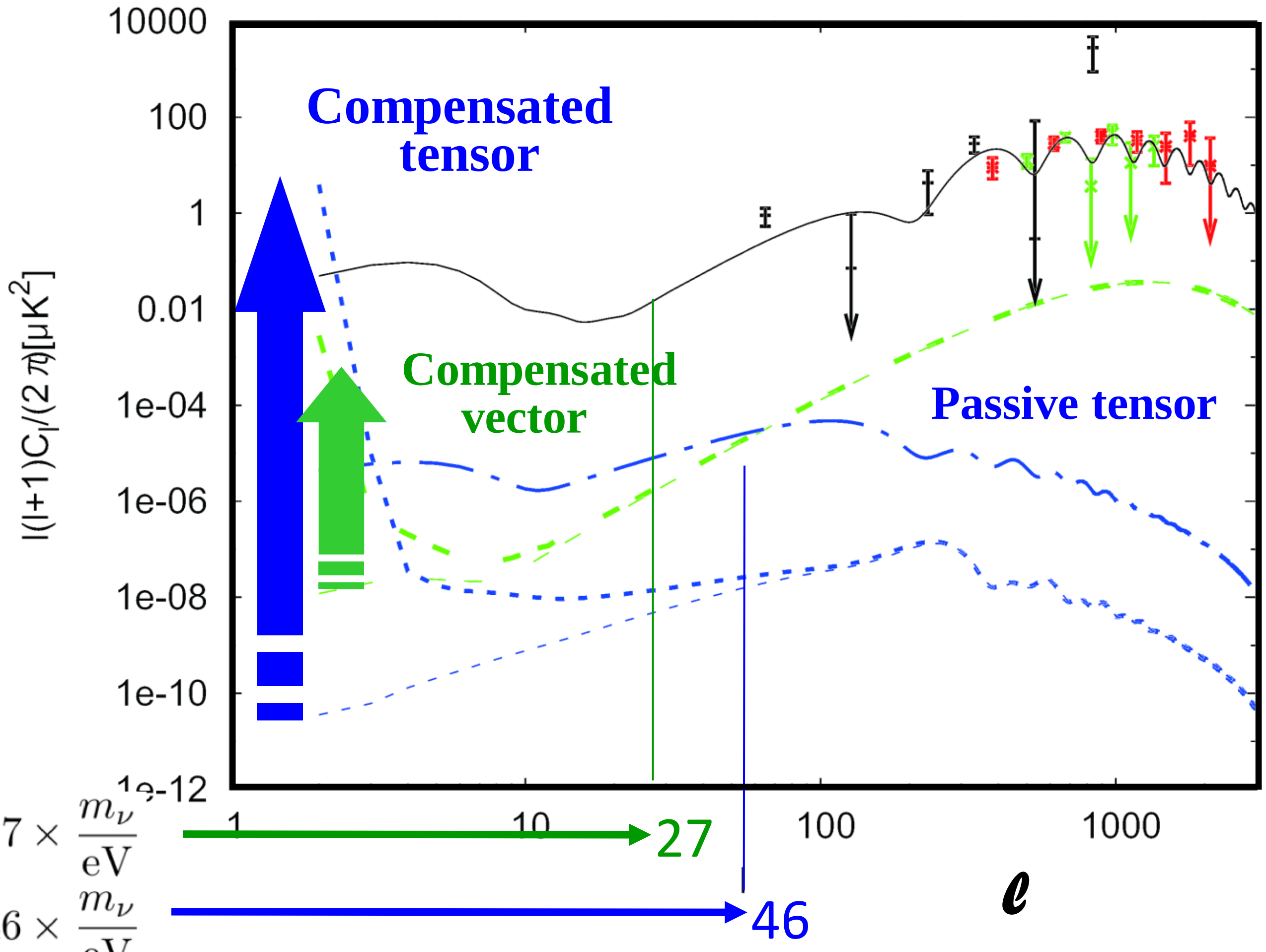
Signal of ν mass

Yamazaki, Kajino, Mathews & Ichiki, Phys. Rep. 517 (2012), 141;
Kojima, Ichiki, Yamazaki, Kajino & Mathews, Phys. Rev. D78 (2008), 045010.

At larger (angular) scales !

m_ν= 1eV

EE Mode



B=3nG

n_B=-2.9

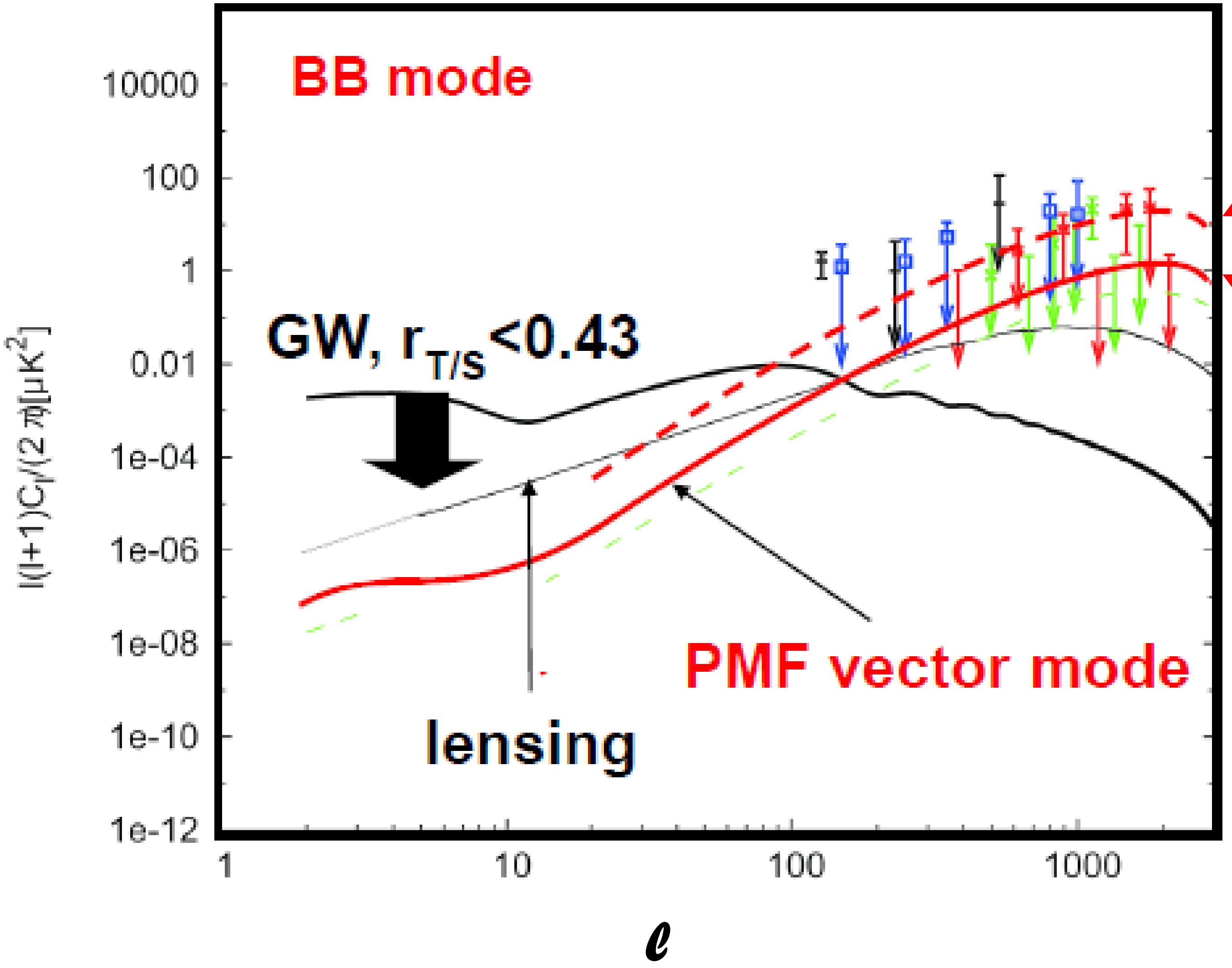
$$\ell_m^{(1)} \sim 27 \times \frac{m_\nu}{\mathrm{eV}}$$

$$\ell_m^{(2)} \sim 46 \times \frac{m_\nu}{\mathrm{eV}}$$

Signal of Primordial Magnetic Field

$m_\nu = 0$

At smaller (angular) scales !



Upper limit:

B = 7.7nG

n_B=-2.9

B=5nG

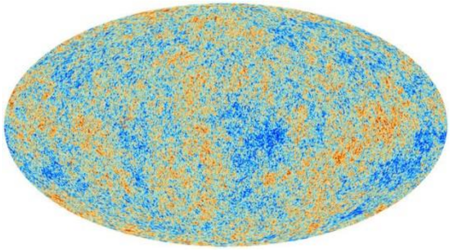
$$k^3P(k) \propto B^4 \cdot k^{2n+6}$$

$n = n_B = -3$

Scale invariant.

1. Cosmological Solution ?

PMF (B-field) & T-fluctuation



$$\rho_\lambda = \frac{\langle B^2\rangle}{8\pi} = \frac{1}{8\pi}\int_{k_{[min]}}^{k_{[max]}} \frac{dk}{k}\,\frac{k^3}{2\pi^2}P_{[PMF]}(k)$$

$B^2 \propto P_{[PMF]} = Ak^{n_B}$ *CMB power law spectrum*

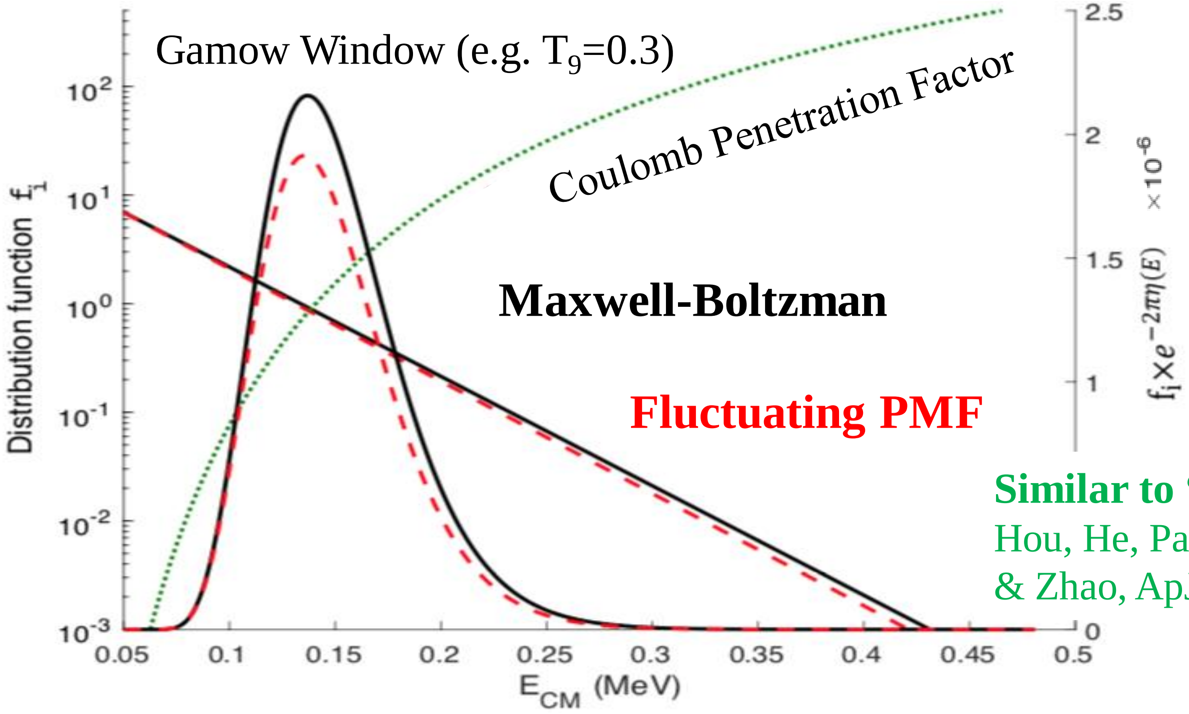
Thermonuclear Reaction Rate: $$\langle\sigma\nu\rangle(T) = \left(\frac{\mu}{2\pi kT}\right)^{3/2}\int_0^\infty v\cdot\sigma(v)\cdot\underline{P(v)}\cdot 4\pi v^2 dv$$

$$f(\beta) = \frac{1}{\sqrt{2\pi}\sigma}\exp\left[-\frac{\left(\frac{\pi g}{30}\cdot(T_{eff}^4-\beta^{-4})-\rho_\lambda\right)^2}{2\sigma^2}\right]\cdot\frac{2\pi g}{15}\beta^{-5}$$

$$\boxed{P(v) = \int d\beta\, p(v|\beta) f(\beta)}$$

Temp. Fluctuation

→ various T=β^{-1}



Yudon Luo, T. Kajino, et al., ApJ 872 (2019), 172.

Only ~ 50% reduction of factor ~3 over-poduction of Big-Bang Li problem!

Similar to "Tsallis Distrib. (1<q)"

Hou, He, Parikh, Kahl, Bertulani, Kajino, Mathews & Zhao, ApJ. 834 (2017), 165.

2. New Physics ? : BBN constraint on neutrino magnetic moment

李英英 Ying-Ying Li

Cosmological: $\nu_S \longrightarrow \nu + \gamma_{NT}$ γ_{NT} photodisintegrates nuclei.

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

active/sterile

Magnetic Moment of massive neutrino X

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

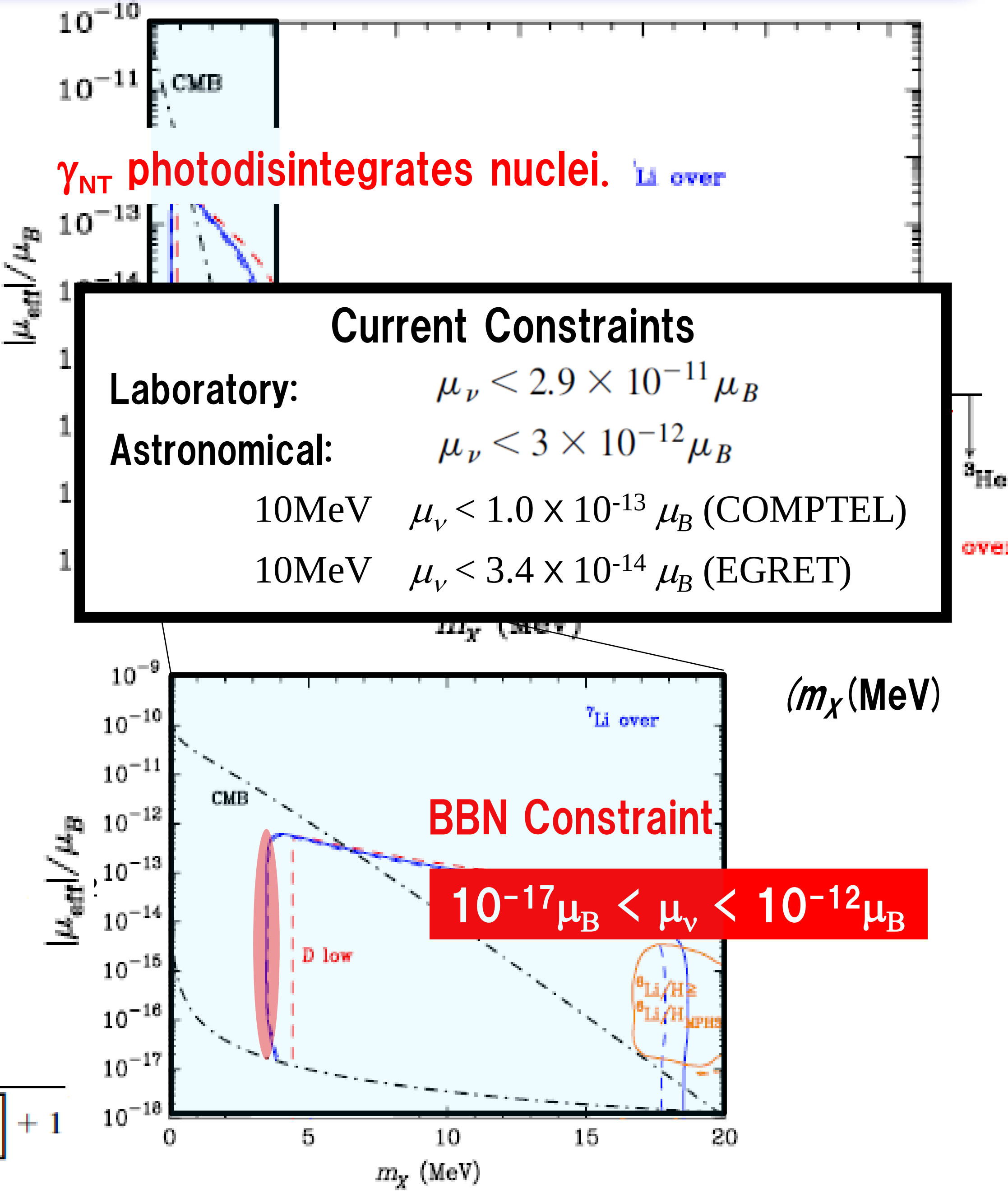
$$\boxed{\tau_X^{-1}} = \frac{|\mu_{ij}|^2 + |\epsilon_{ij}|^2}{8\pi}\left(\frac{m_i^2 - m_j^2}{m_i}\right)^3$$

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

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

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

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



Current Constraints

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

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

10MeV $\mu_\nu < 1.0 \times 10^{-13}\ \mu_B$ (COMPTEL)

10MeV $\mu_\nu < 3.4 \times 10^{-14}\ \mu_B$ (EGRET)

(m_X(MeV)

BBN Constraint

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

3. Nuclear Physics Solution ?

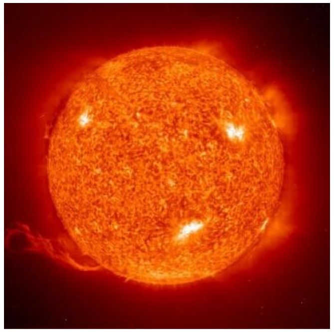
Big-Bang Nucleosynthesis

First 3 min

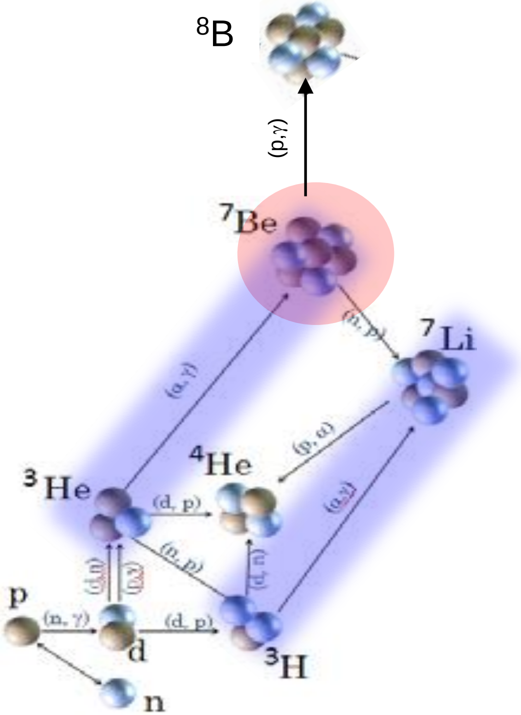
G. Gamow predicted nucleosynthesis. (1948)
Spite & Spite observed ^{7}Li. ('1980ー)

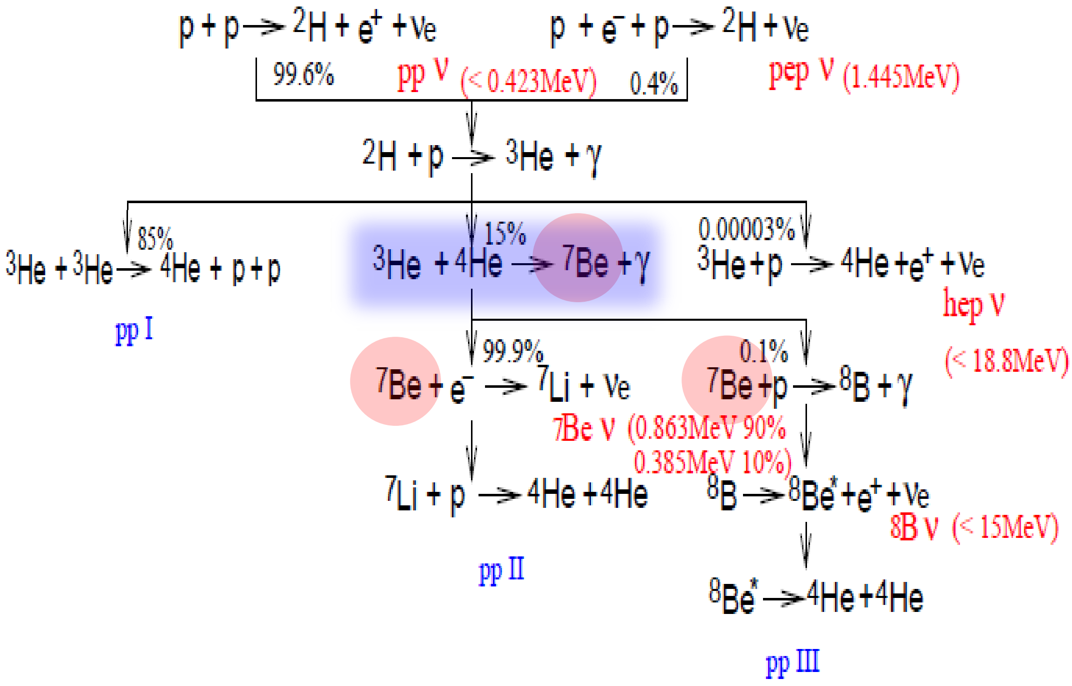
Solar Fusion

Sun
Today



W. Fowler predicted solar ν-flux. (1958)
R. Davis detected. (1969ー)





$p + p \rightarrow {}^{2}H + e^{+} + \nu_e$ 99.6% pp ν (< 0.423MeV)

$p + e^{-} + p \rightarrow {}^{2}H + \nu_e$ 0.4% pep ν (1.445MeV)

${}^{2}H + p \rightarrow {}^{3}He + \gamma$

85%: ${}^{3}He + {}^{3}He \rightarrow {}^{4}He + p + p$

pp I

15%: ${}^{3}He + {}^{4}He \rightarrow {}^{7}Be + \gamma$

0.00003%: ${}^{3}He + p \rightarrow {}^{4}He + e^{+} + \nu_e$ hep ν (< 18.8MeV)

99.9%: ${}^{7}Be + e^{-} \rightarrow {}^{7}Li + \nu_e$ 7Be ν (0.863MeV 90% 0.385MeV 10%)

${}^{7}Li + p \rightarrow {}^{4}He + {}^{4}He$

pp II

0.1%: ${}^{7}Be + p \rightarrow {}^{8}B + \gamma$

${}^{8}B \rightarrow {}^{8}Be^{*} + e^{+} + \nu_e$ 8B ν (< 15MeV)

${}^{8}Be^{*} \rightarrow {}^{4}He + {}^{4}He$

pp III

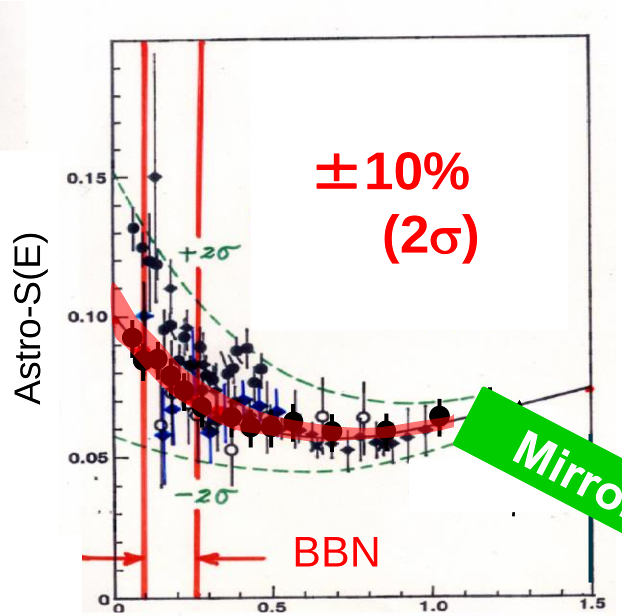
$^{4}\mathrm{He}(^{3}\mathrm{H},\gamma)^{7}\mathrm{Li}$ ← **Mirror** **$^{4}\mathrm{He}(^{3}\mathrm{He},\gamma)^{7}\mathrm{Be}$**

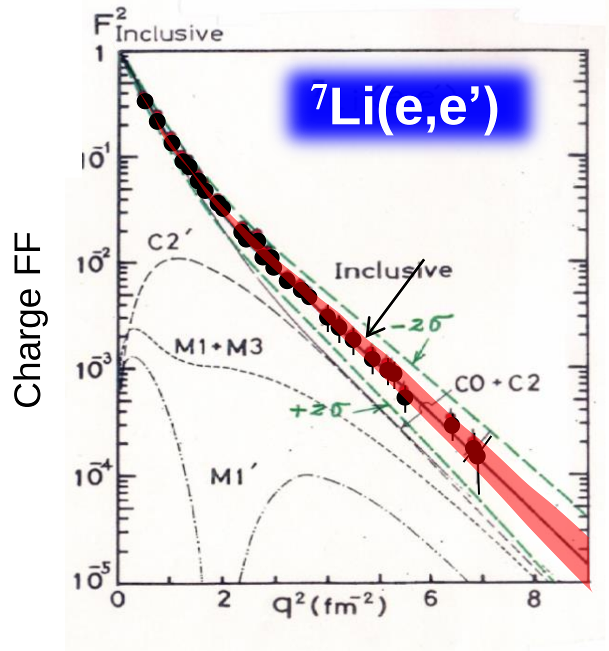
Kajino, He, Yao et al. (2024), World Scientific, in press.

Adelberger et al., RMP 83 (2011),195; Haxton et al., RMO (2024), in press.

±5% (1σ) ? → **±40% (2σ) !**

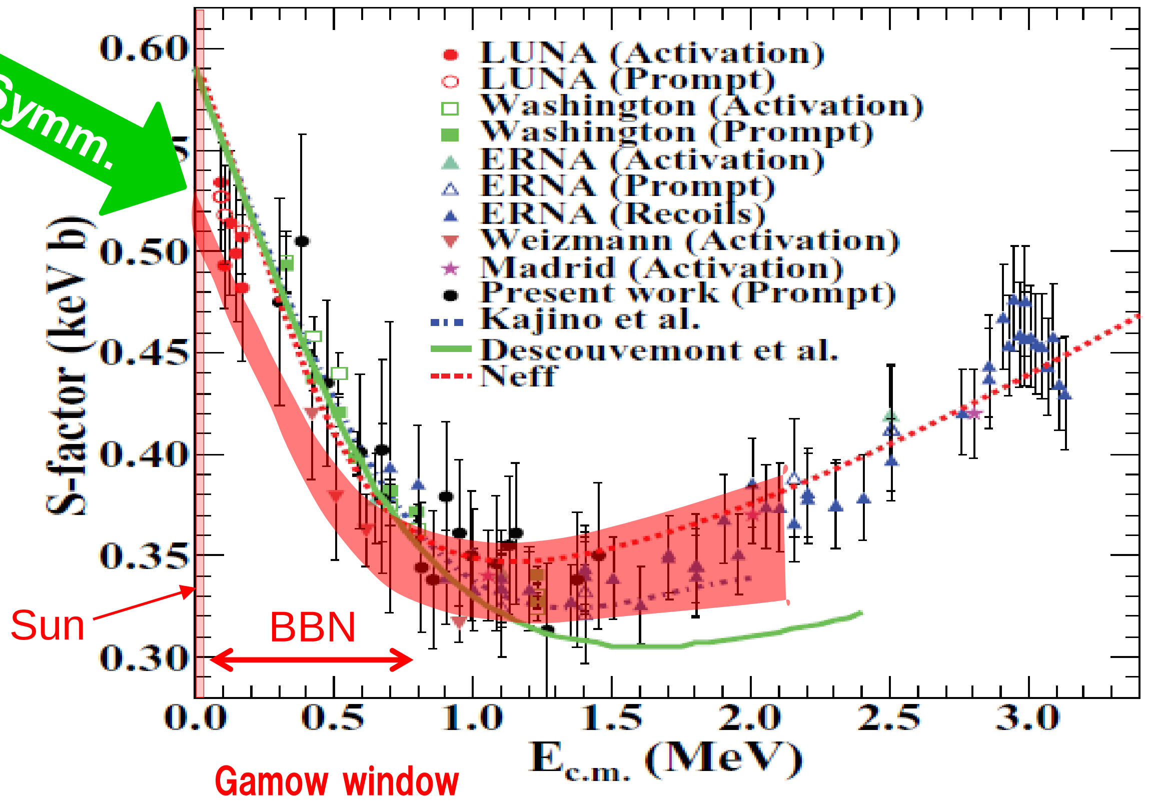
Kajino & Arima, PRL 52 (1984), 739; NP A413 (1084), 323; NP A460 (1986), 559; ApJ 319 (1987), 531, Neff, PRL 106 (2011), 042502, Dohet-Early et al., PL B757 (2016), 430; Vorabbi et al., PR C100 (2019), 024304; Kiss et al., PL B807 (2020), 135606 +





Mirror Symm.

$^{4}\mathrm{He}(^{3}\mathrm{He},\gamma)^{7}\mathrm{Be}$



Li problem in Red-Clump Stars

Kumar et al. (2020), Nature Astron.

Mori, Kusakabe, Balantekin, Kajino, Famiano (2021), MNRAS 503, 2746.

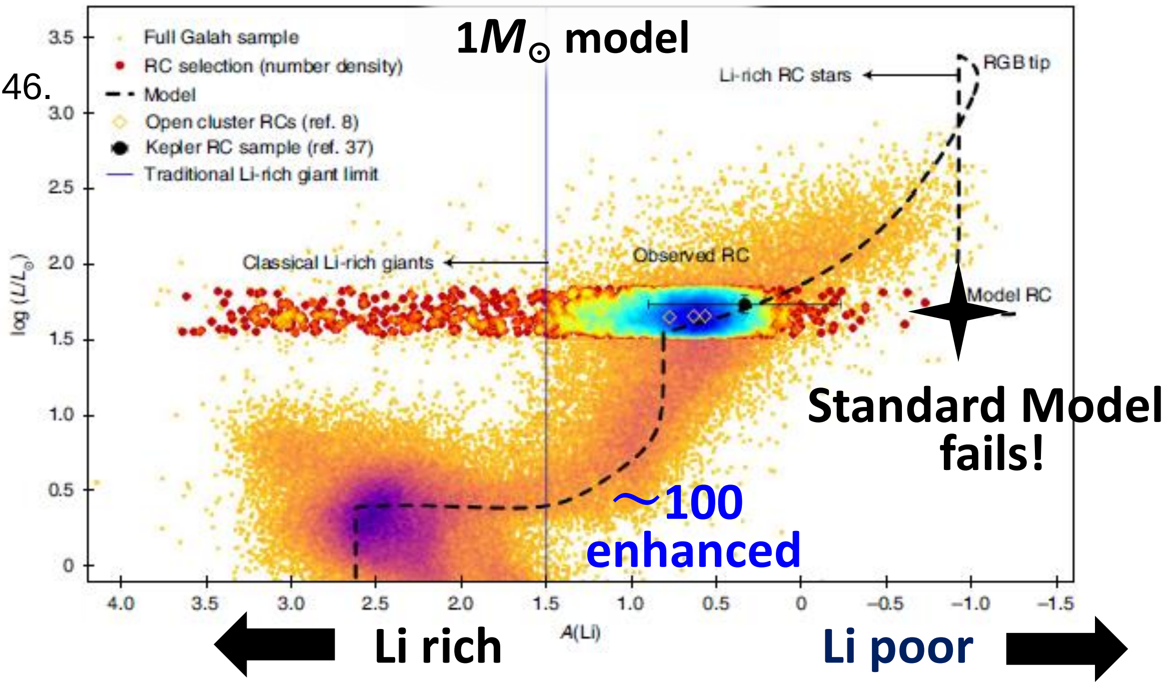
Fowler-Cameron mechanism

$^4He(^3He,\gamma)^7Be(e^-,\nu_e)^7Li$

Additional energy loss induced by neutrino magnetic moment

$\mu_{12} = \mu/10^{-12}\mu_B = 2 - 5$

- → Activates thermohaline mixing
- → heavier ^4He core
- → more ^7Be → ^7Li !

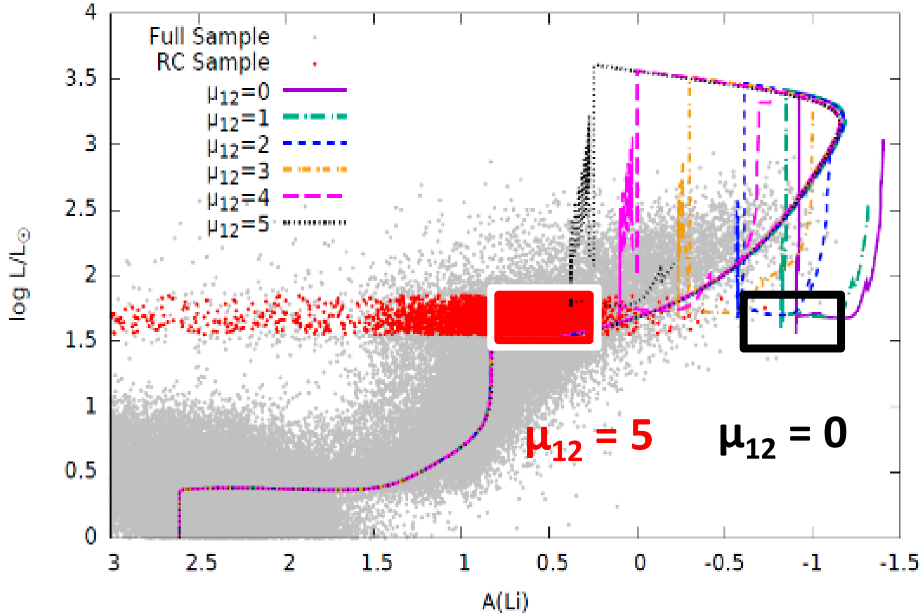


$1M_\odot$ model

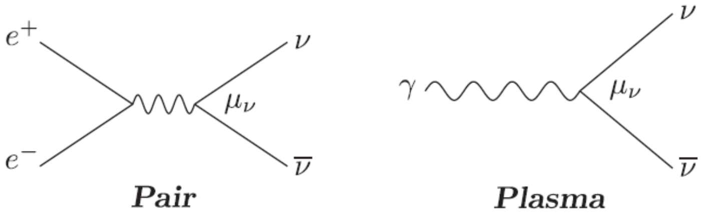
Standard Model fails!

∼100 enhanced

Li rich **Li poor**



$\mu_{12} = 5$ $\mu_{12} = 0$



Heger et al., ApJ 696 (2009), 608.

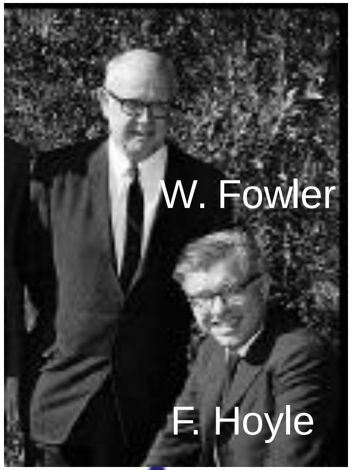
Standard parameter of efficiency of internal mixing : $\alpha_{thm}=100$

亚洲宇宙核物理进展

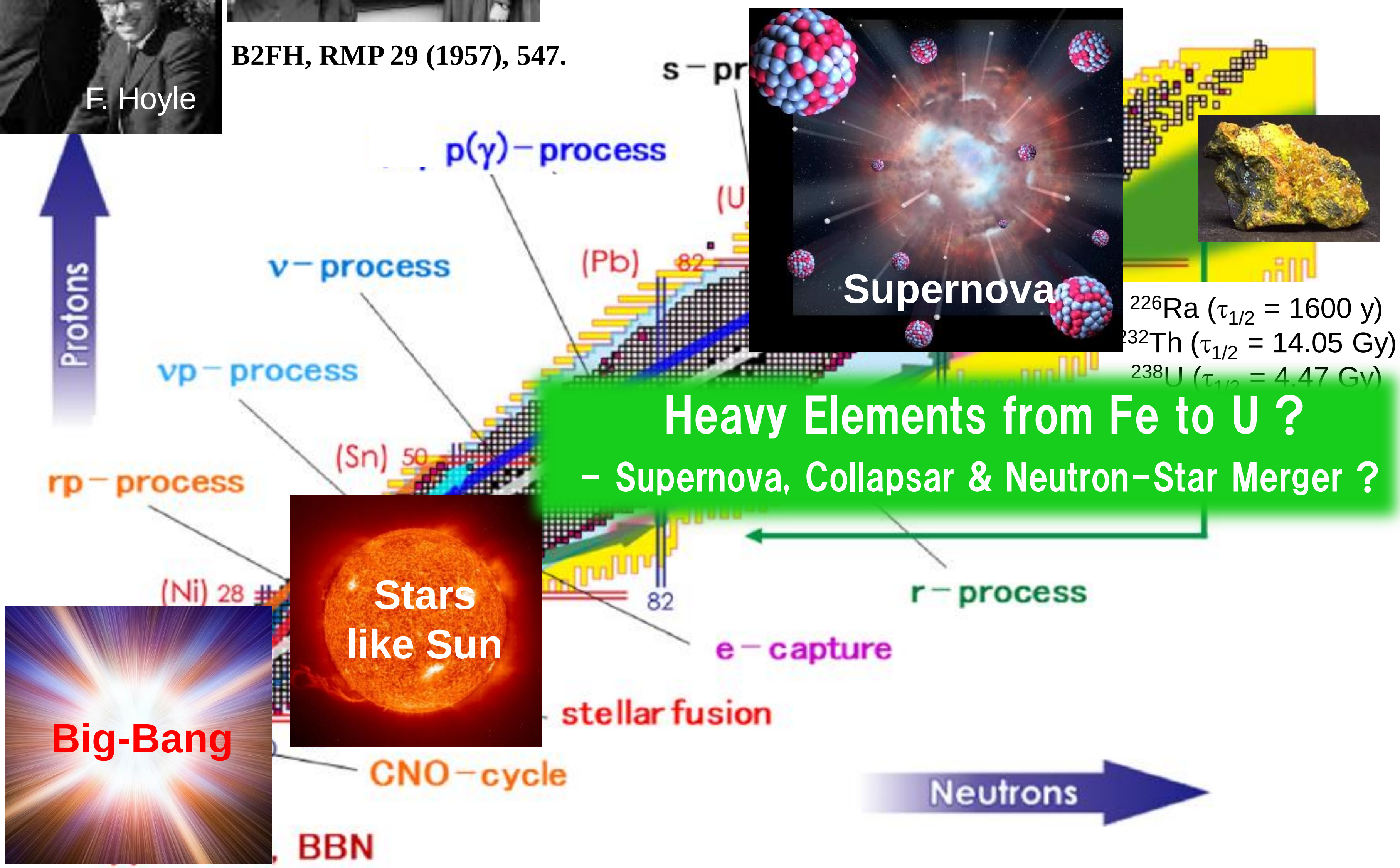
Ahmad, Ahn, Aoki, Aziz, Bhuyan, Chen, Guo, Hahn, Kajino, [illegible] Motob[illegible] Yusof, AAPPS Bulletin 31 (2021), 18.

Origin of Atomic Nuclei in Stars

B2FH, Rev. Mod. Phys. 29 (1957), 547.



B2FH, RMP 29 (1957), 547.



^{226}Ra ($\tau_{1/2}$ = 1600 y)

^{232}Th ($\tau_{1/2}$ = 14.05 Gy)

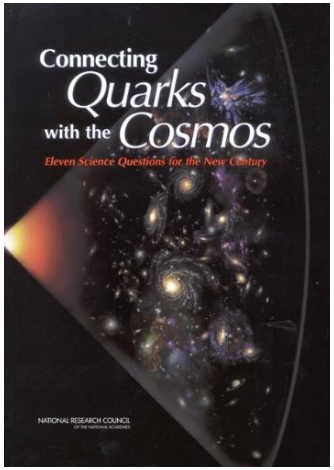
^{238}U ($\tau_{1/2}$ = 4.47 Gy)

Heavy Elements from Fe to U ?

- Supernova, Collapsar & Neutron-Star Merger ?

二十一世纪末解物理之谜

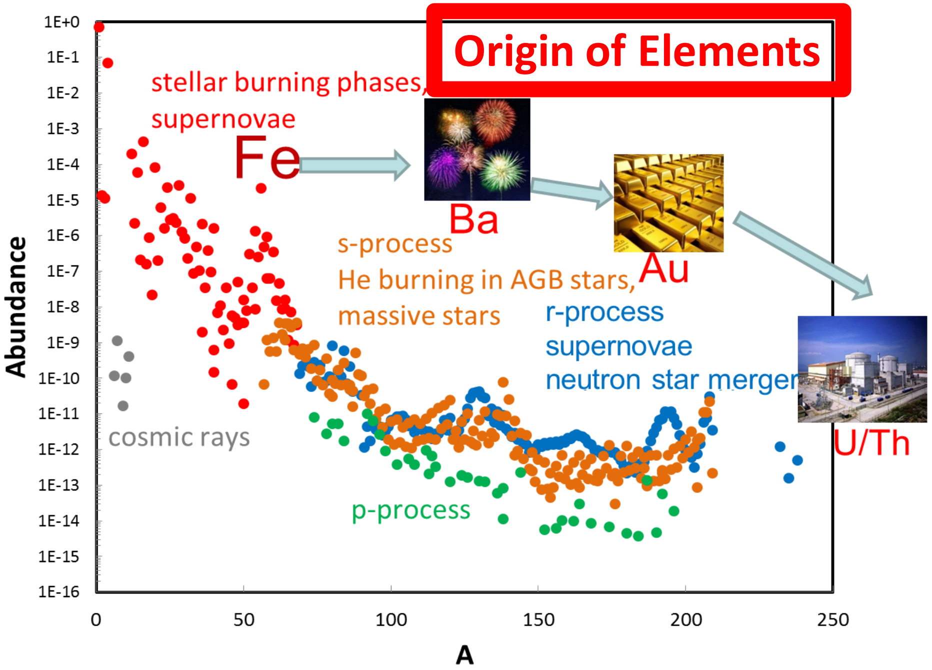
Unsolved Mysteries of Physics in the 21st Century



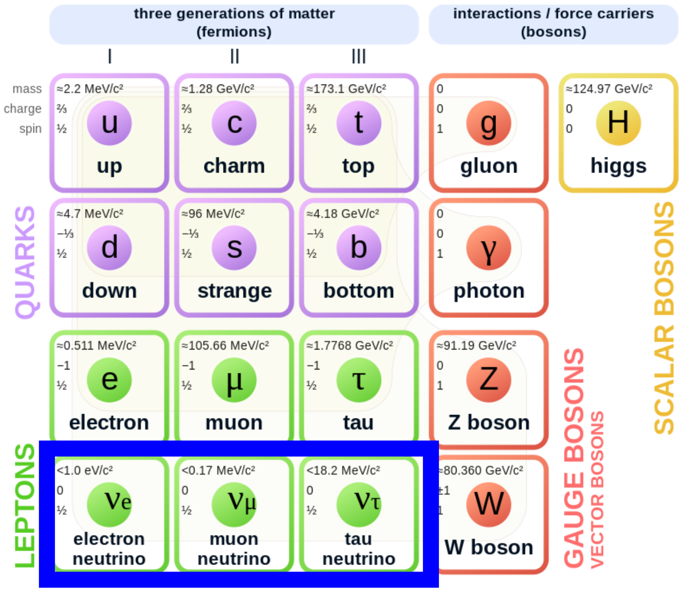
US Academy of Science selected 11 greatest unanswered questions in modern physics:

- **比铁重的元素是如何产生的? How were the heavy elements made?**
- **为什么中微子有质量? Why do neutrinos have mass?**
  Mass hierarchy constrains total ν-mass
  (beyond the standard model).

11个将夸克与宇宙联系起来的世纪难题



Standard Model of Elementary Particles



Cosmic Evolution & Origin of Matter (Elements & Life)

Multi-messenger Era with GW, γ, ν, Nuclei

Gravity, EM, Weak, Strong — 4 fundamental forces

Dark Age

Big-Bang Nucleosynthesis

Galaxies

Inflation

Cosmic Age13.8 Gy ~10^{10} y

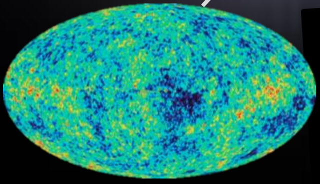
Earth

Life

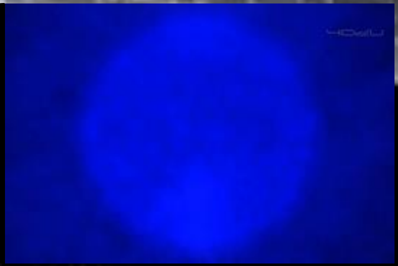
Quantum Fluct. of Space-Time

First Stars → Stellar & Galactic Eviolution

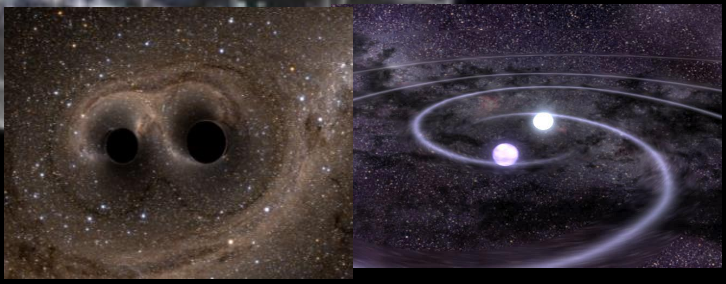
Sun



CMB Fluctuation
$3.8\text{x}10^5$ y



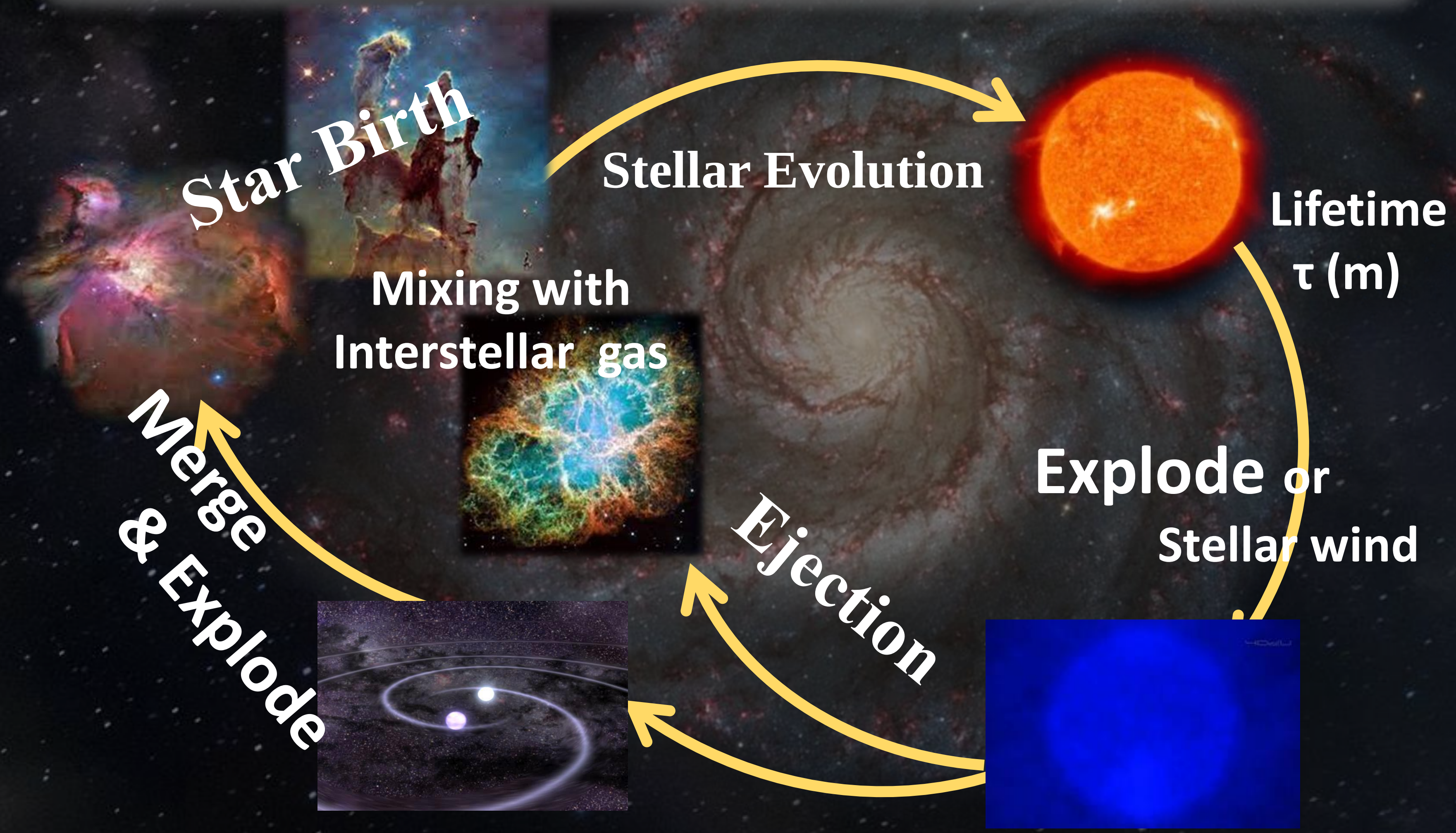
Collapsar & Supernova
～ 10^6 y



Binary BH/Neutron-Star Merger
～ 10^8ー10^9 y

Cosmic & Galactic Evolution Model

Big-Bang → 1st stars form in the galaxies
→ SNe explode and stellar winds eject elements and heat
→ next generations of stars form …



Star Birth

Stellar Evolution

Lifetime
τ (m)

Explode or
Stellar wind

Ejection

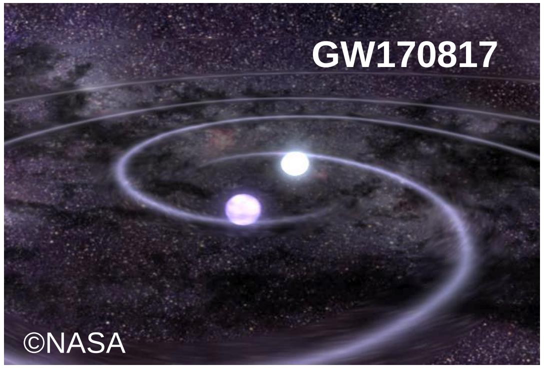
Mixing with
Interstellar gas

Merge
& Explode

Astrophysical Candidates for R-Process

BINARY Stars

Neutron Star Merger



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Time Delay : 100 My < τ < 10 Ty

Lorimer, Living Rev. Rel. 11(2008), 8.
Beniamini+ (2019), Timmes+ (1995)

Failed SN → Collapsar

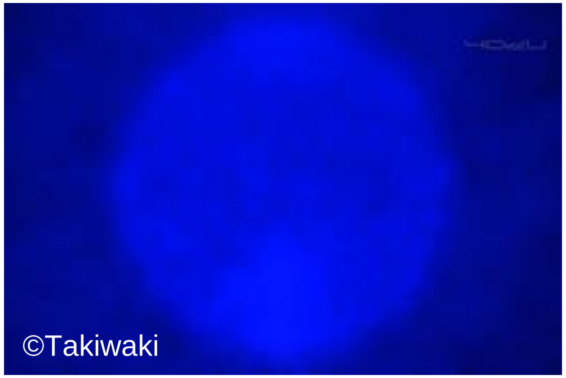
MacFadyen, Woosley, ApJ 524 (1999), 262;
Nakamura, Kajino, Mathews, Sato & Harikae,
A&Ap 582 (2015), A34; Yamazaki, et al. (2022).

Super-Luminous SN/Hypernova

Siegel, Barnes & Metzger, Nature 569 (2019), 243.

SINGLE Star

CCSN II : ν-DW & MHD Jet



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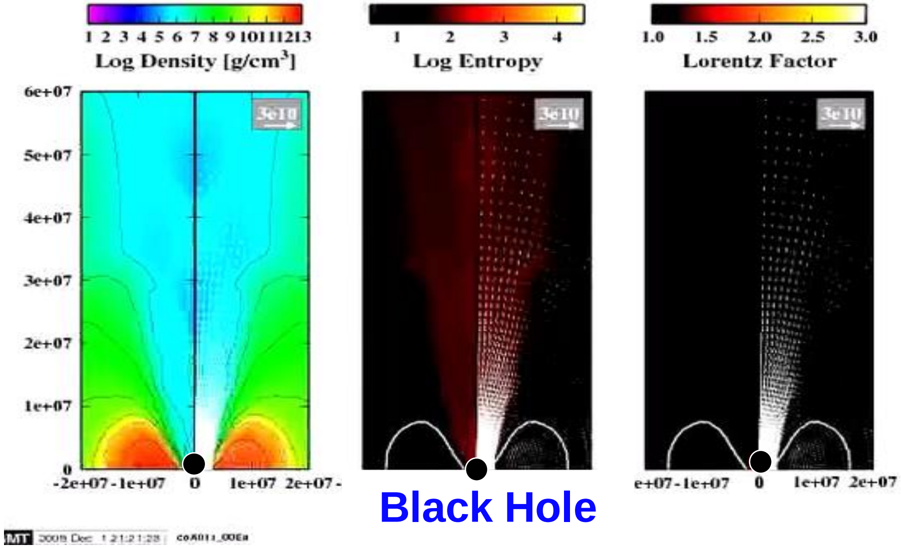
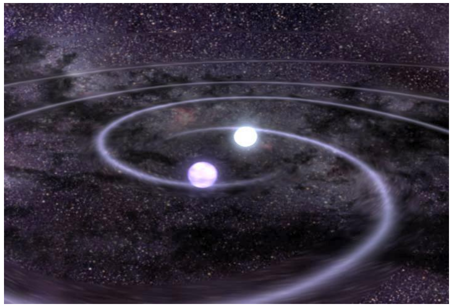
Neutron Star

Collapsar Jet



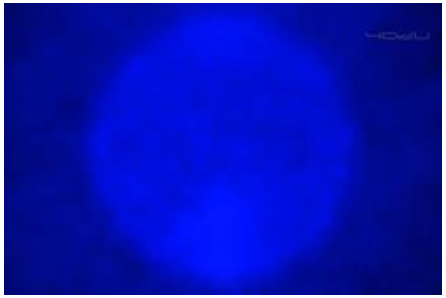
Black Hole

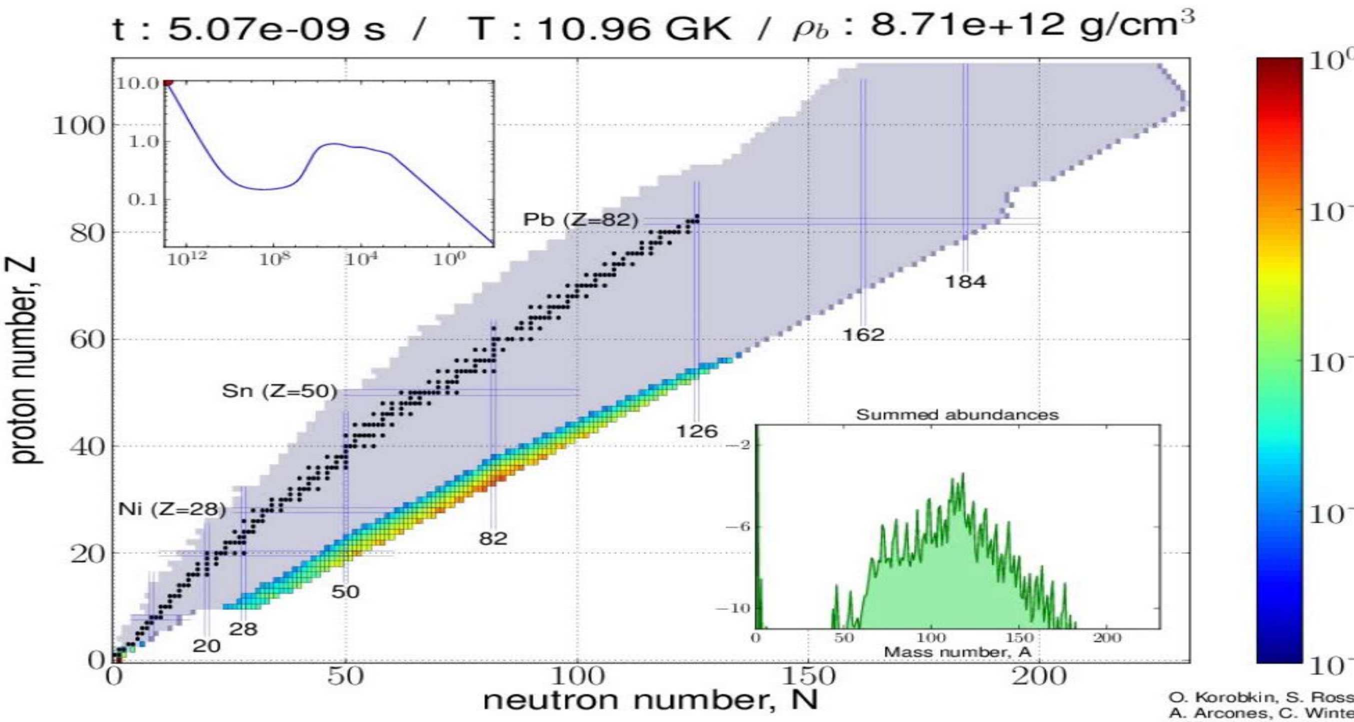
Neutron Star Merger



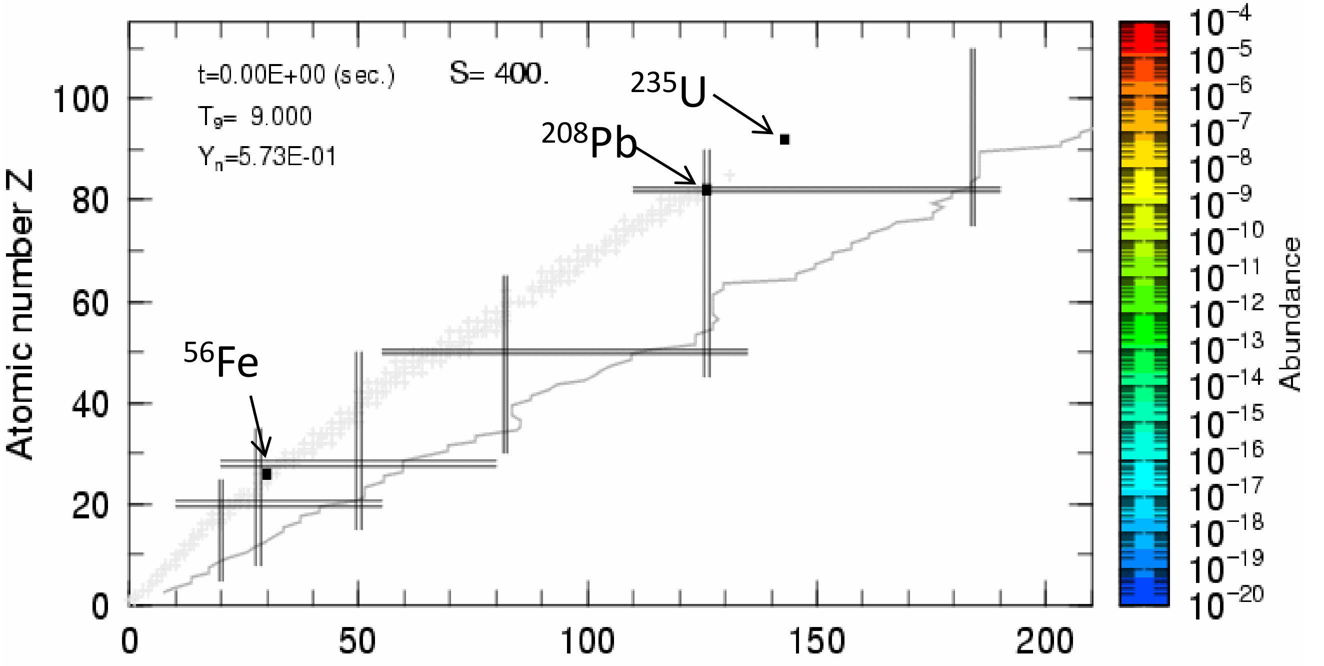
Kajino, Aoki, Balantekin, Diehl, Famiano, Mathews, Prog. Part. Nucl. Phys. 107 (2019) 109-166.

Supernova & Collapsar



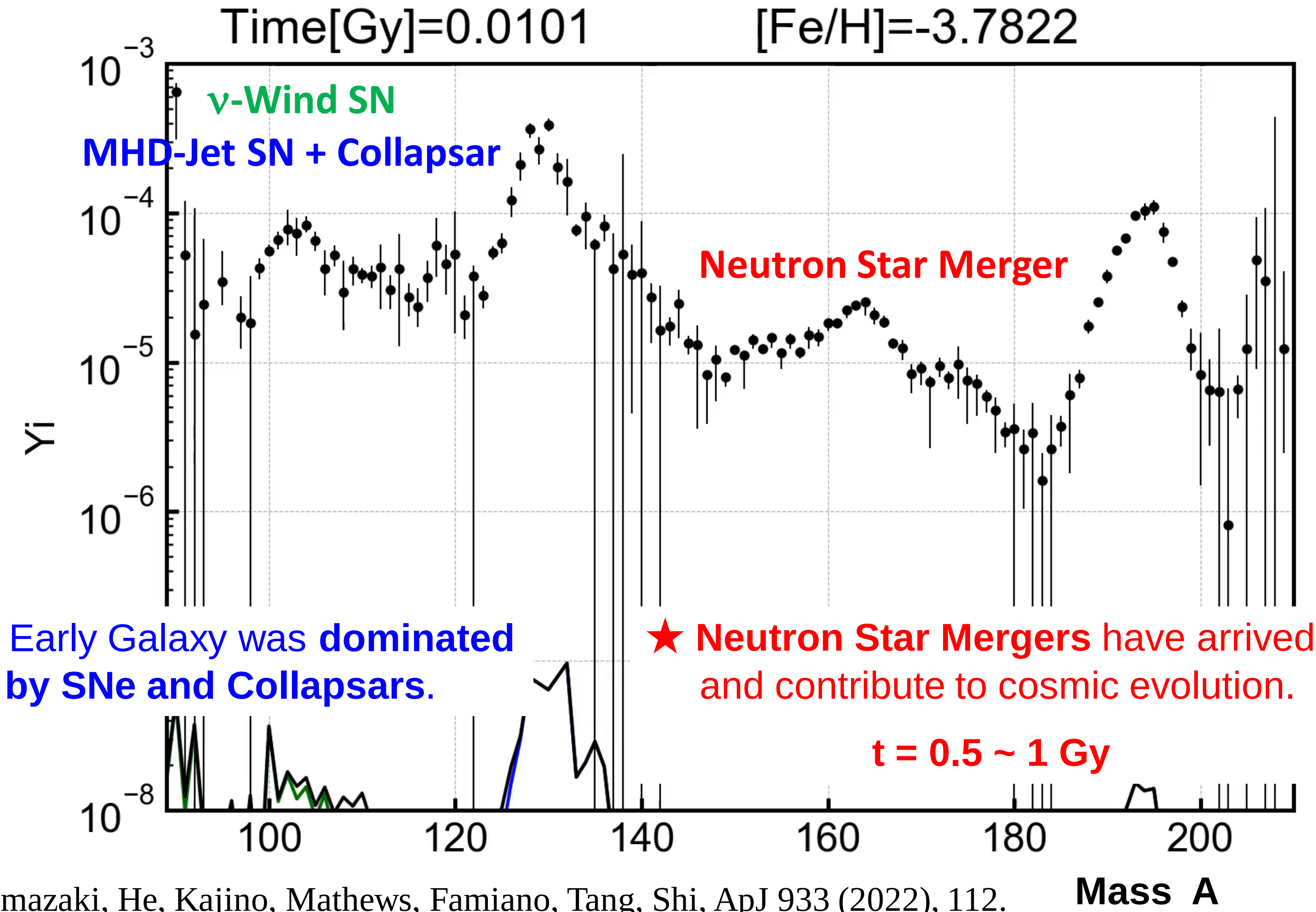


O. Korobkin, S. Ross
A. Arcones, C. Winte
arXiv:1206.2379



Cosmic & Galactic Evolution : CCSNe, NSMs, Collapsars

$t\ (\mathrm{Gy}) = 10^{[\mathrm{Fe/H}]}$ ↔ $[\mathrm{Fe/H}] = \log(N_{Fe}/N_H)_{☆} - \log(N_{Fe}/N_H)_{\odot}$



★ Early Galaxy was **dominated by SNe and Collapsars.**

★ **Neutron Star Mergers** have arrived later and contribute to cosmic evolution.

t = 0.5 ~ 1 Gy

Yamazaki, He, Kajino, Mathews, Famiano, Tang, Shi, ApJ 933 (2022), 112.

Observed EVENT RATES

Contribution = Ejected Mass [$M_\odot$] x Event Rate [/Galaxy/Century]

νSNe (Weak r) = 7.4×10^{-4} x $(1.3\pm0.6)^{a}$

MHD Jet SNe = 0.6×10^{-2} x $((0.03\pm0.02) \times (1.3\pm0.6))^{b}$

* Binary NSMs (Short-GRB) = $(2\pm1) \times 10^{-2}$ x $(1\text{-}28)\times10^{-3\ c}$

* Collapsars (Failed SN) = Assuming to be the same as MHD Jet SNe

---

Observations a 1.9±1.1* Diehl, et al., Nature 439, 45 (2006). *1.3±0.6 (2018)

b 0.03±0.02 Winteler, et al., ApJ 750, L22 (2012).

Obs. Est. c $(1\text{-}28) \times 10^{-3}$ Kalogera, et al., ApJ 614, L137 (2004).

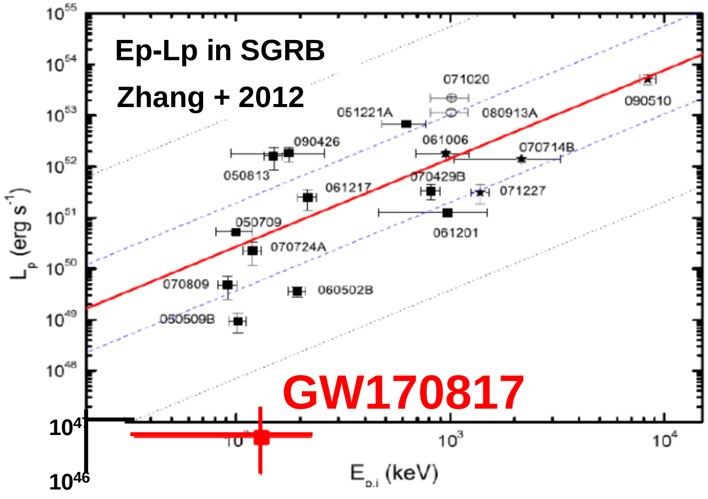
*** Binary NSM ← Central engine of Short-GRB**

- GW170817: Why faint
- Jet inclination and beaming < 5°

*** Collapsar (BH) ←Failed Supernovae, Long-GRB**

Yamazaki et al. (2022); Harikae et al. (2009, 2010);
Nakamura et al. (2015)

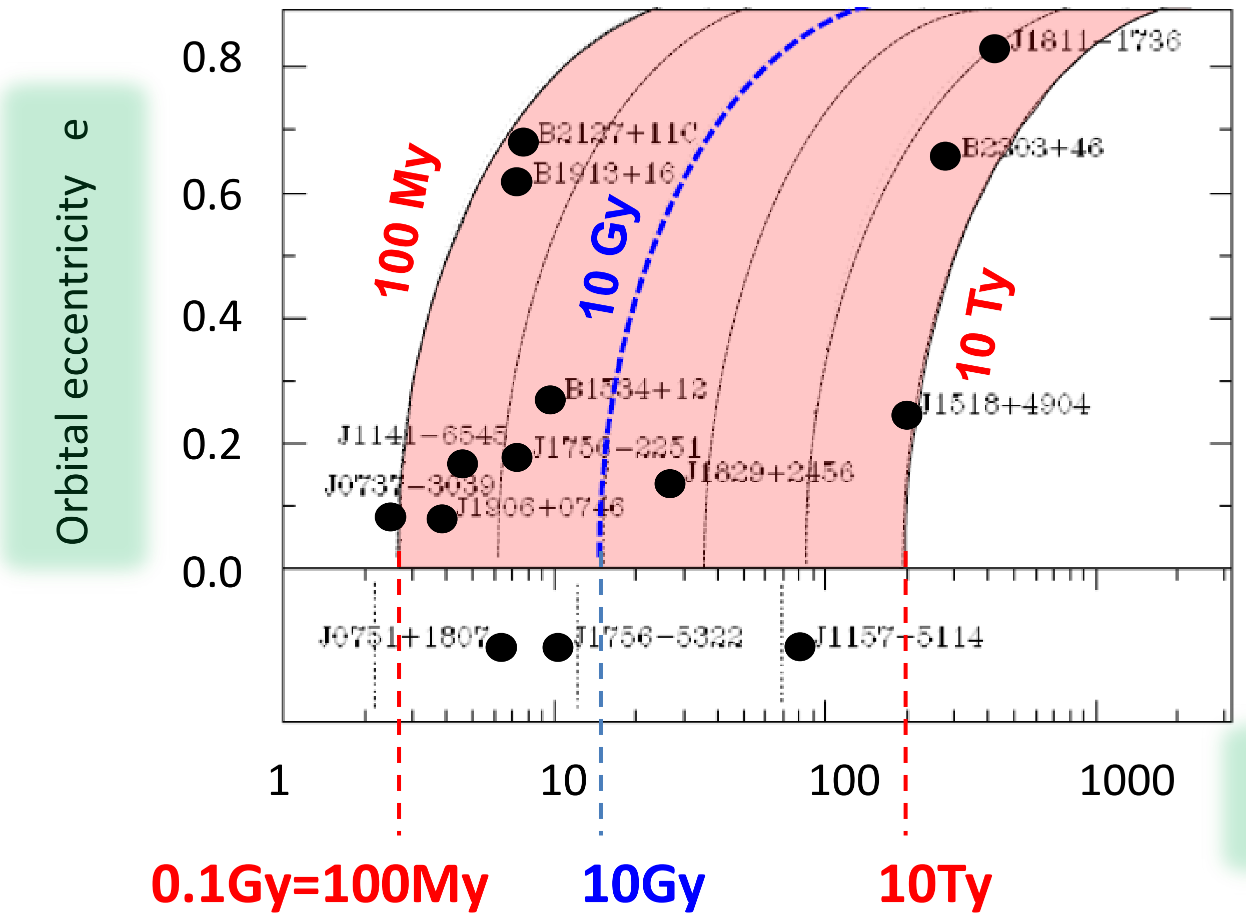
c.f. Siegel et al. (2019) assumed: Super-Luminous SN
Hypernova



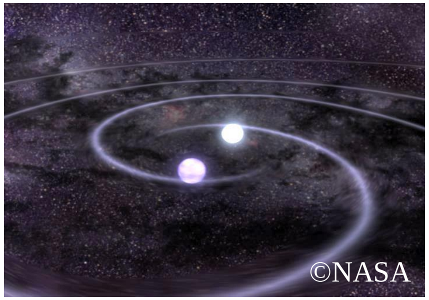
Binary Pulsars : Expected Coalescence Time-Delay

General Relativity : $\tau_C = 9.83\ \mathrm{Myr} \times \left(\frac{P_b}{\mathrm{hr}}\right)^{8/3} \times \left(\frac{m_1+m_2}{M_\odot}\right)^{-2/3} \left(\frac{\mu}{M_\odot}\right)^{-1} (1-e^2)^{7/2}$

BINARY PULSARS : Lorimer, Living Rev. Rel. 11(2008), 8; Beniamini+ (2019).



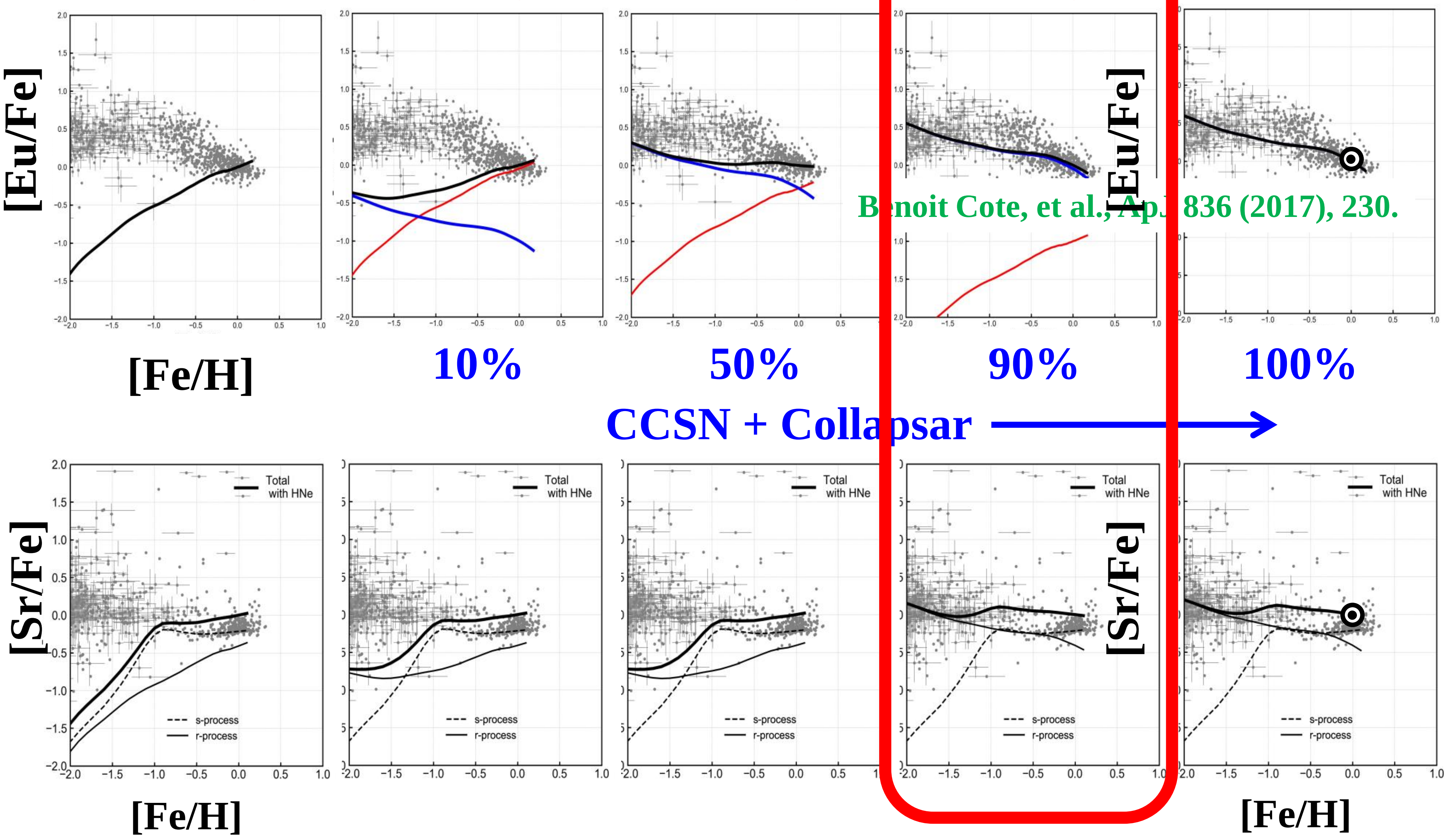
Orbital period P_b (hours)


©NASA

Coalescence Time Delay of NSM

$[\mathrm{Fe/H}] = \log(N_{Fe}/N_H)_\star - \log(N_{Fe}/N_H)_\odot$

Yamazaki, He, Kajino, Mathews, Famiano, Tang, Shi, ApJ 933 (2022), 112.



NSM (τ_C=0.1 Gy)

100% 90% 50% 10% 0%

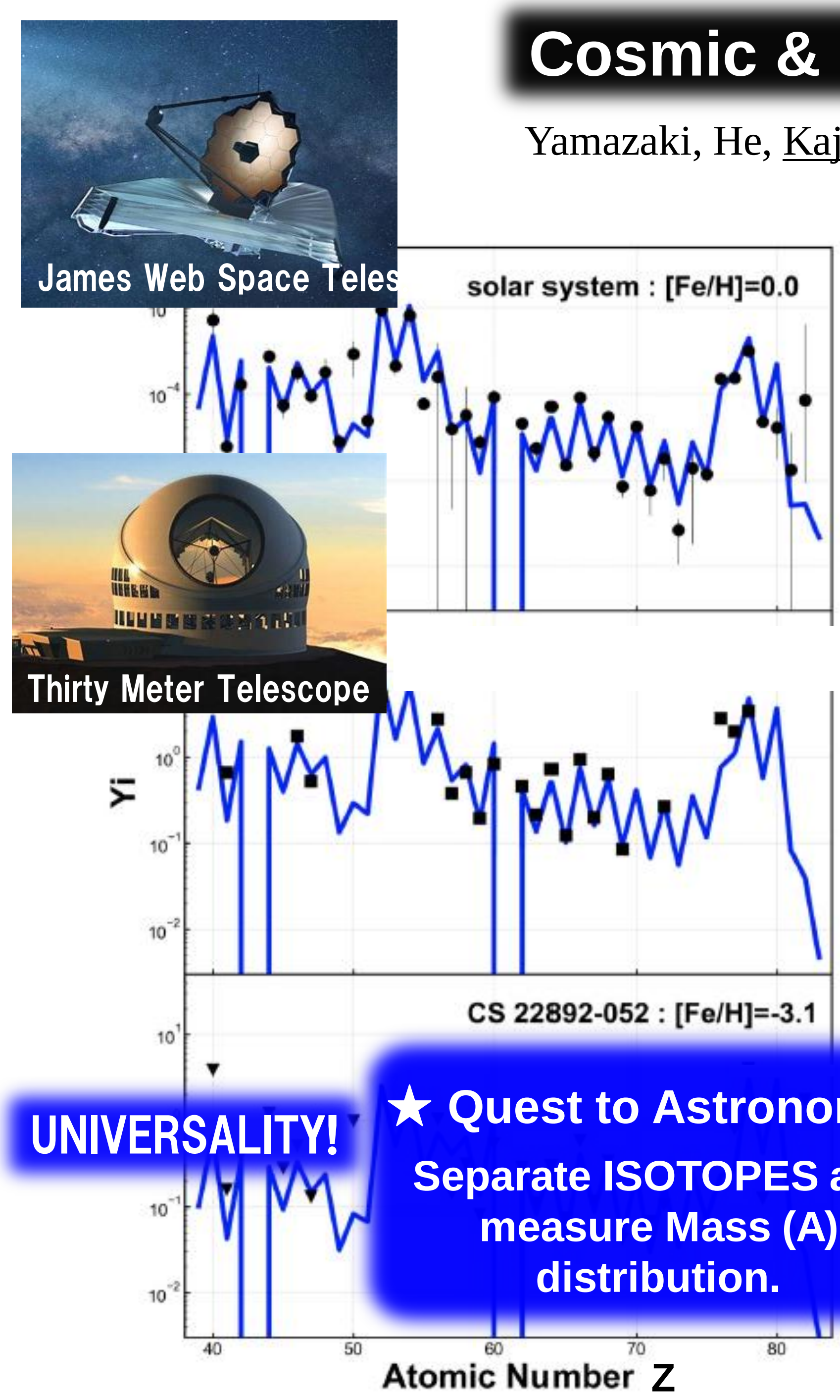
10% 50% 90% 100%

CCSN + Collapsar

Benoit Cote, et al., ApJ 836 (2017), 230.

Cosmic & Galactic Chemical Evolution

Yamazaki, He, Kajino, Mathews, Famiano, Tang, Shi, ApJ 933 (2022), 112.

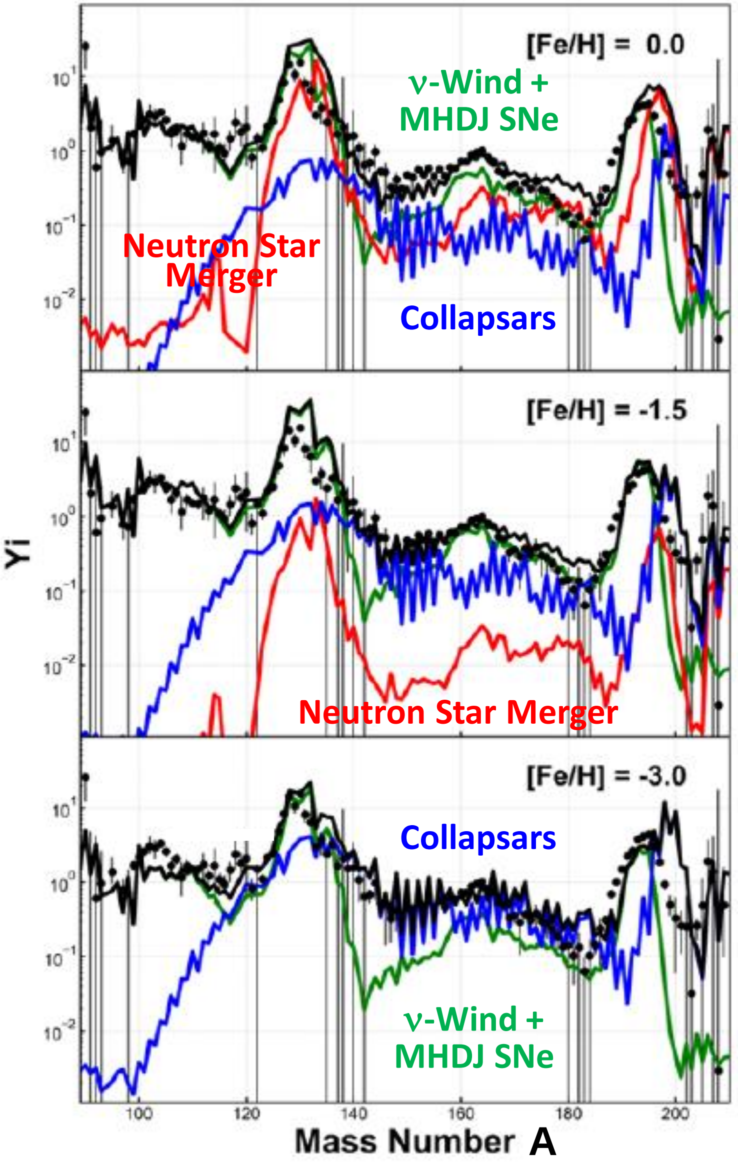


UNIVERSALITY!

★ Quest to Astronomy

Separate ISOTOPES and measure Mass (A) distribution.

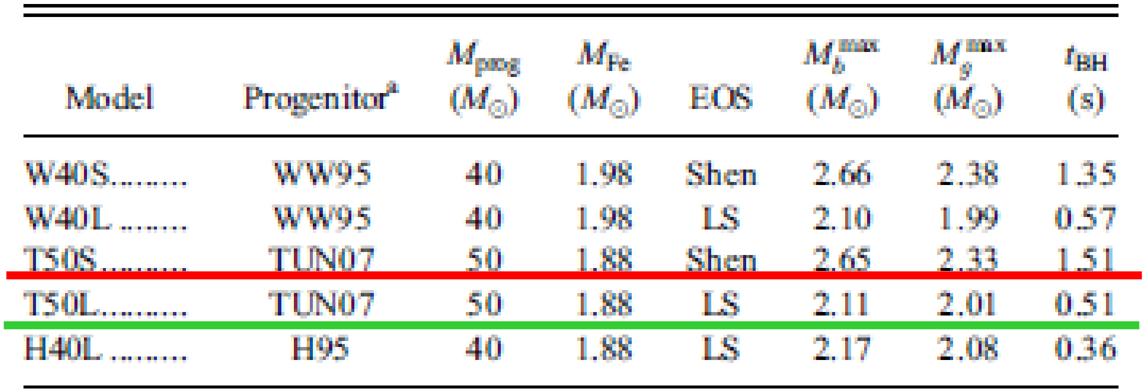
Symm. fission



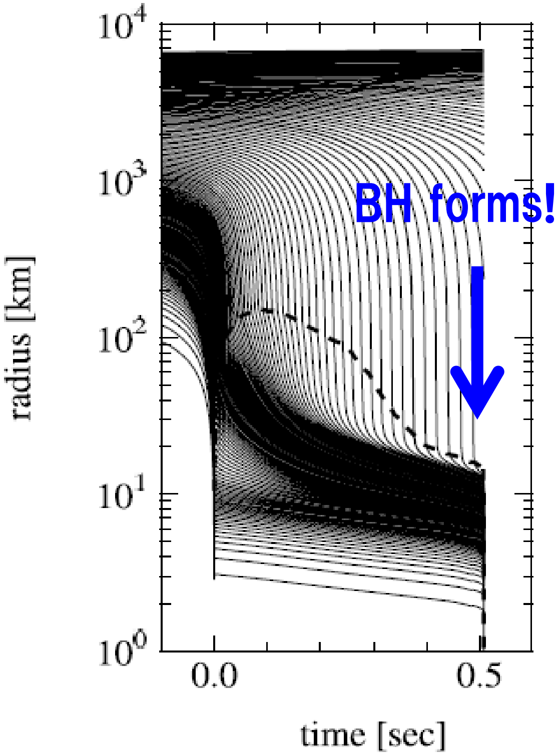
Cosmic Time

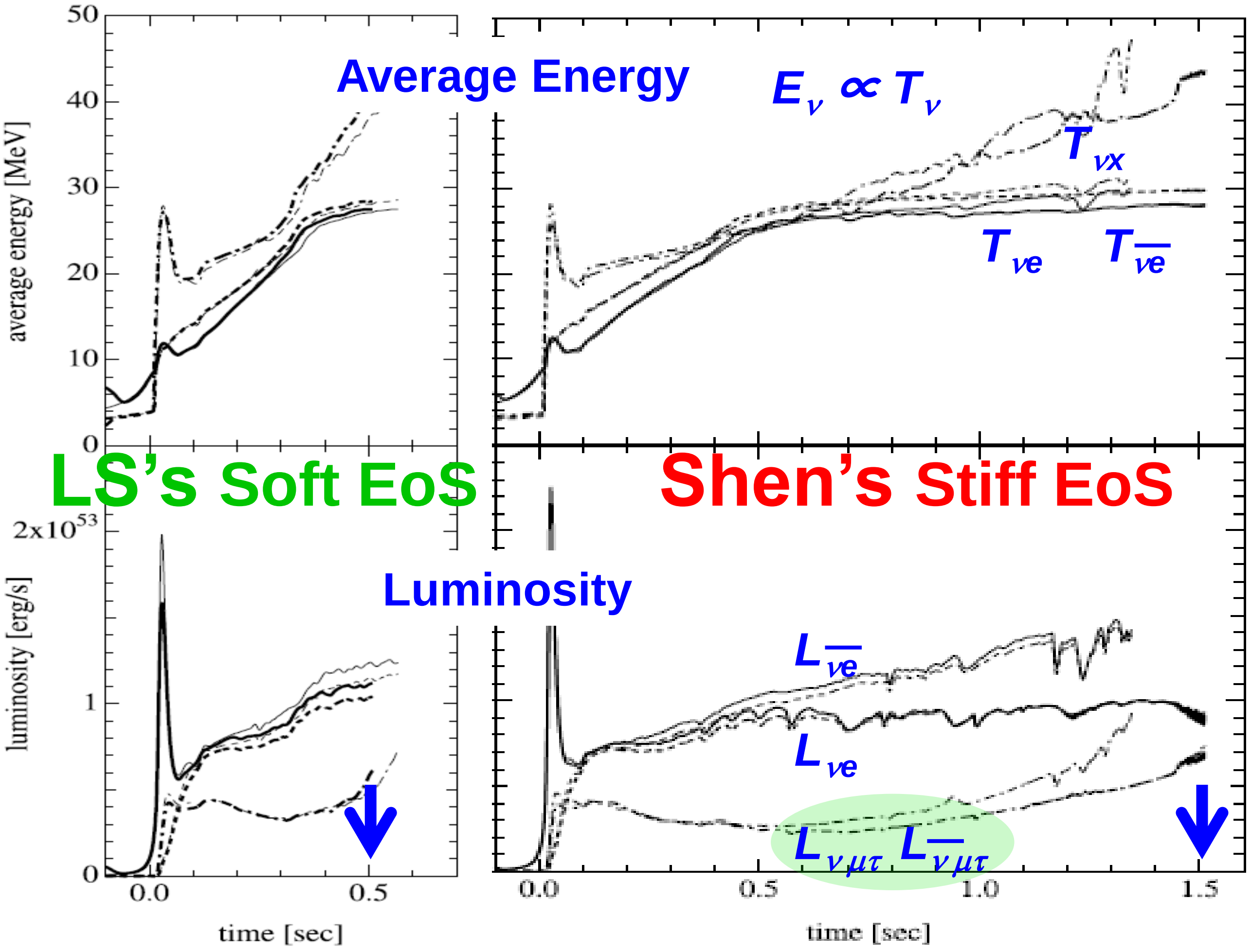
Neutrino Signal from Collapsars

Sumiyoshi, Yamada,
& Suzuki
ApJ **688** (2008)1176.



Model	Progenitor[a]	$M_{\rm prog}$ ($M_\odot$)	$M_{\rm Fe}$ ($M_\odot$)	EOS	$M_b^{\rm max}$ ($M_\odot$)	$M_g^{\rm max}$ ($M_\odot$)	$t_{\rm BH}$ (s)
W40S.........	WW95	40	1.98	Shen	2.66	2.38	1.35
W40L	WW95	40	1.98	LS	2.10	1.99	0.57
T50S.........	TUN07	50	1.88	Shen	2.65	2.33	1.51
T50L.........	TUN07	50	1.88	LS	2.11	2.01	0.51
H40L	H95	40	1.88	LS	2.17	2.08	0.36





Galactic Diffuse (BG) SN-ν Spectrum

+ Collective Oscillation

- JUNO: 20 kilo-ton Water Cherenkov Detector
- Hyper-K: 188 kilo-ton Gd-loaded Water Cherenkov Detector

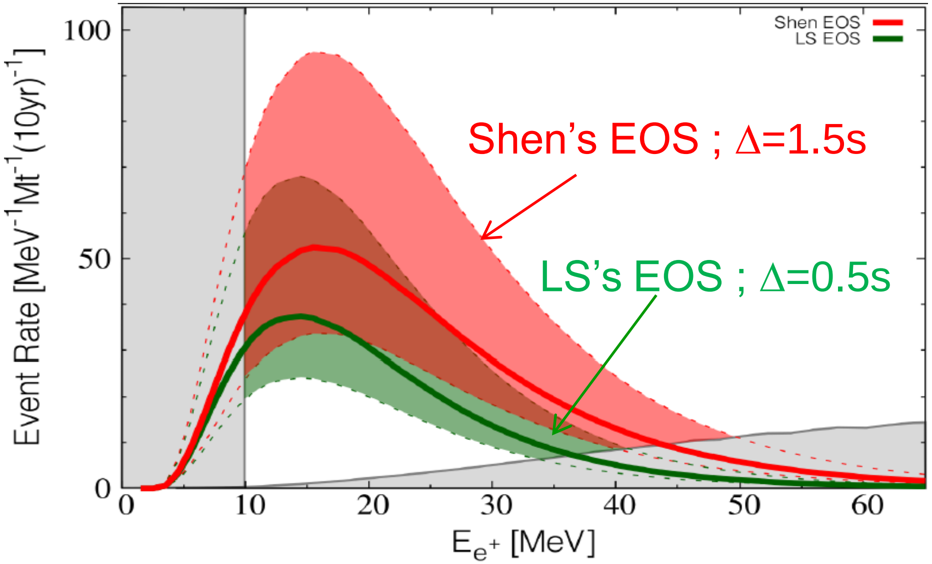
$$\overline{\nu}_e + p \to e^+ + n$$

Hidaka, Kajino & Mathews, ApJ 869 (2018), 31, 11pp;
ApJ 790 (2014), 115.

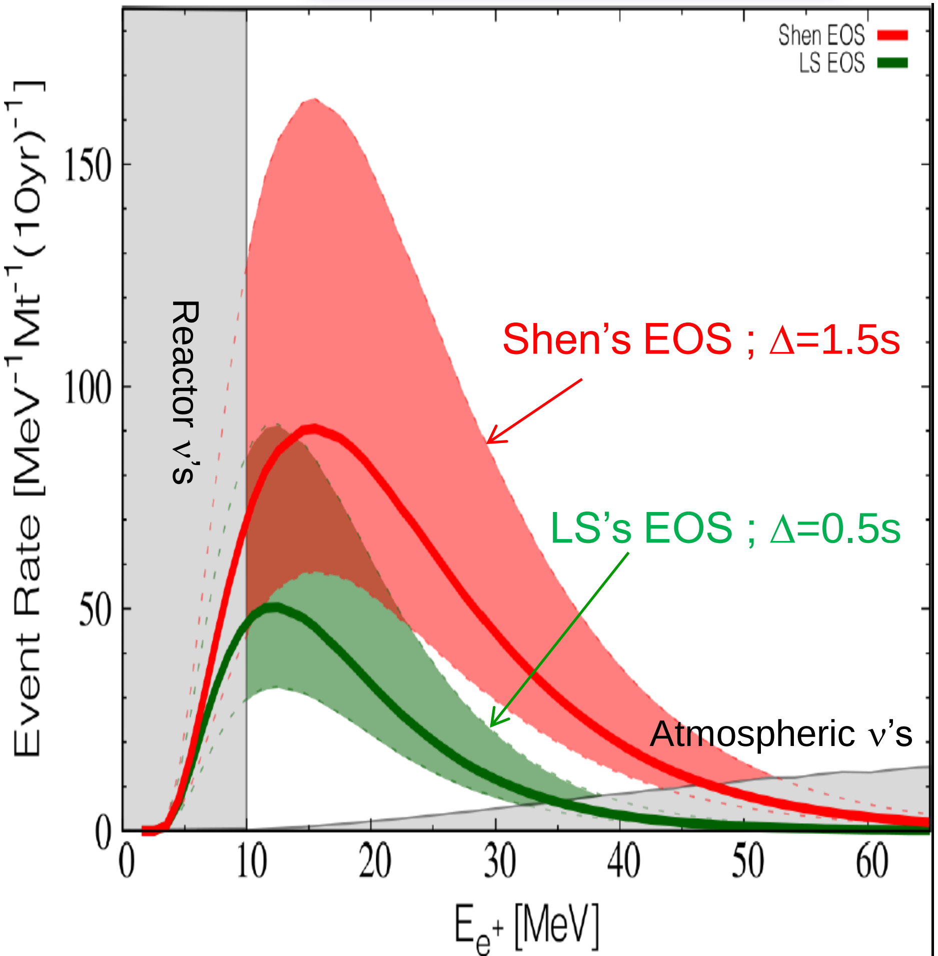
Relic SN Neutrinos probe EOS and Mass Hierarchy !

MSW-HD Res. ; $L_{\nu e} = L_{\overline{\nu e}} >> L_{\overline{\nu \mu,\tau}}$)

Inverted Hierarchy - HK

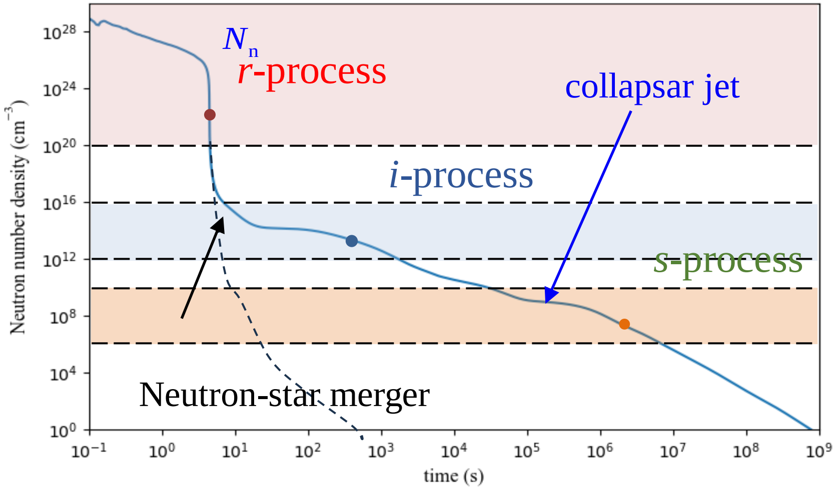


Normal Hierarchy - HK



r-, i-, s-processes in Collapsar Jet Nucleosynthesis

Zhenyu He, Kajino, Zhou et al., ApJ Lett (2024), in press.



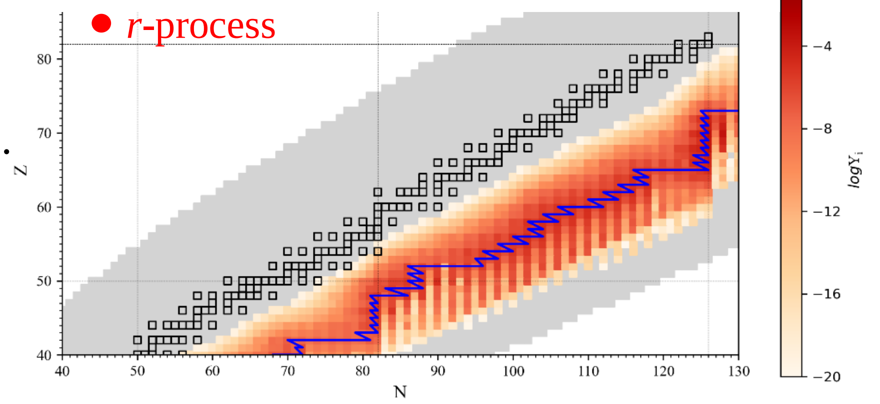
Trans-uranium fissions → neutrons

	$N_n\left(\mathrm{cm}^{-3}\right)$
r-process:	$>10^{20}$
i-process:	$10^{12} \sim 10^{16}$
s-process:	$10^{6} \sim 10^{10}$

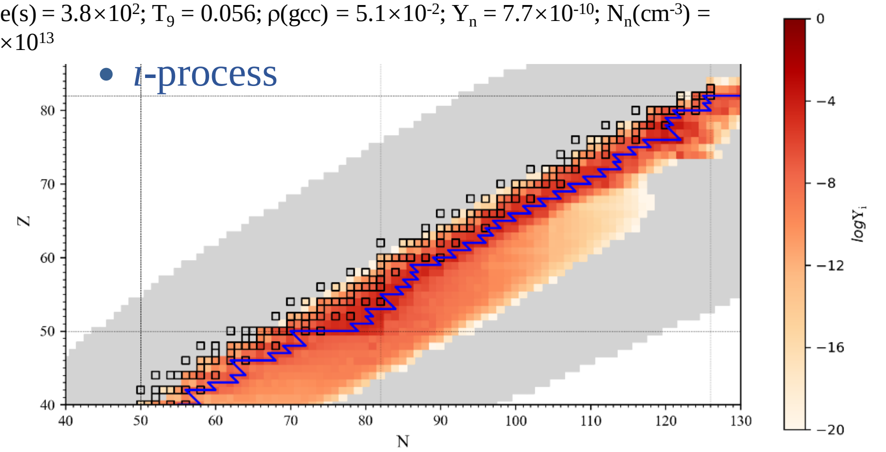
Time scales

$$\tau_{(n,\gamma)} = \frac{1}{\rho Y_n N_A \langle \sigma v \rangle} < \tau_{dyn} = -\left(\frac{d \ln T_9}{dt}\right)^{-1}$$

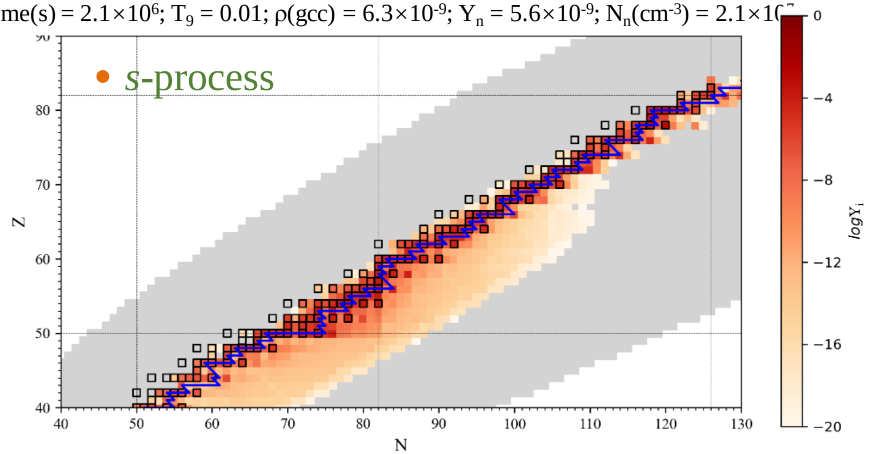
time(s) = 4.5; T_9 = 0.86; ρ(gcc) = 1.8×10^2; Y_n = 1.6×10^{-6}; N_n(cm^{-3}) = 1.8×10^{20}



time(s) = 3.8×10^2; T_9 = 0.056; ρ(gcc) = 5.1×10^{-2}; Y_n = 7.7×10^{-10}; N_n(cm^{-3}) = 2.4×10^{13}

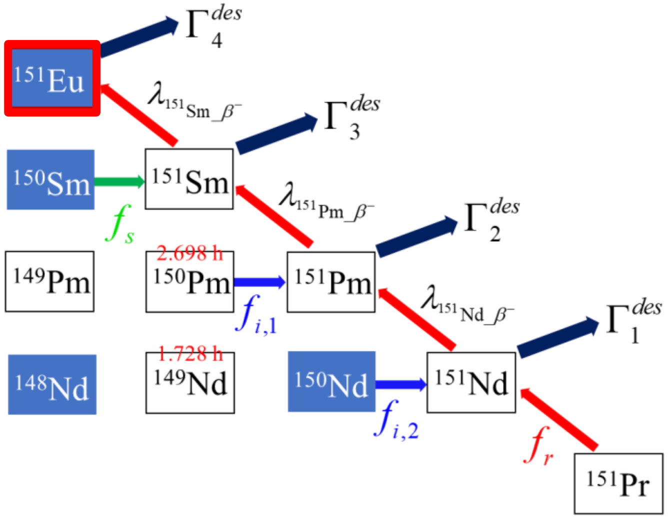


time(s) = 2.1×10^6; T_9 = 0.01; ρ(gcc) = 6.3×10^{-9}; Y_n = 5.6×10^{-9}; N_n(cm^{-3}) = 2.1×1

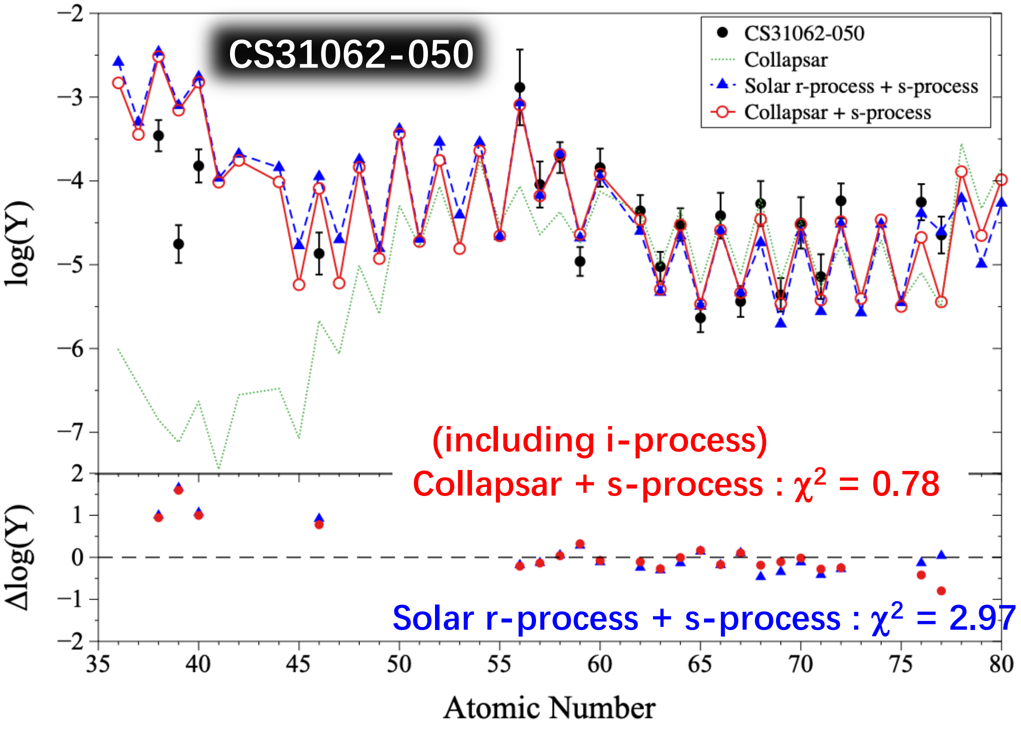


Each contribution from *i*- & *s*-process to the *r*-only nuclei and Observational Signature (e.g. ^{151}Eu)

Zhenyu He, Kajino, Zhou et al.,
ApJ Lett (2024), in press.



CEMP r-/s-star (Hampel et al. 2016)



(including i-process)
Collapsar + s-process : χ^2 = 0.78

Solar r-process + s-process : χ^2 = 2.97

Theoretical Formulae:

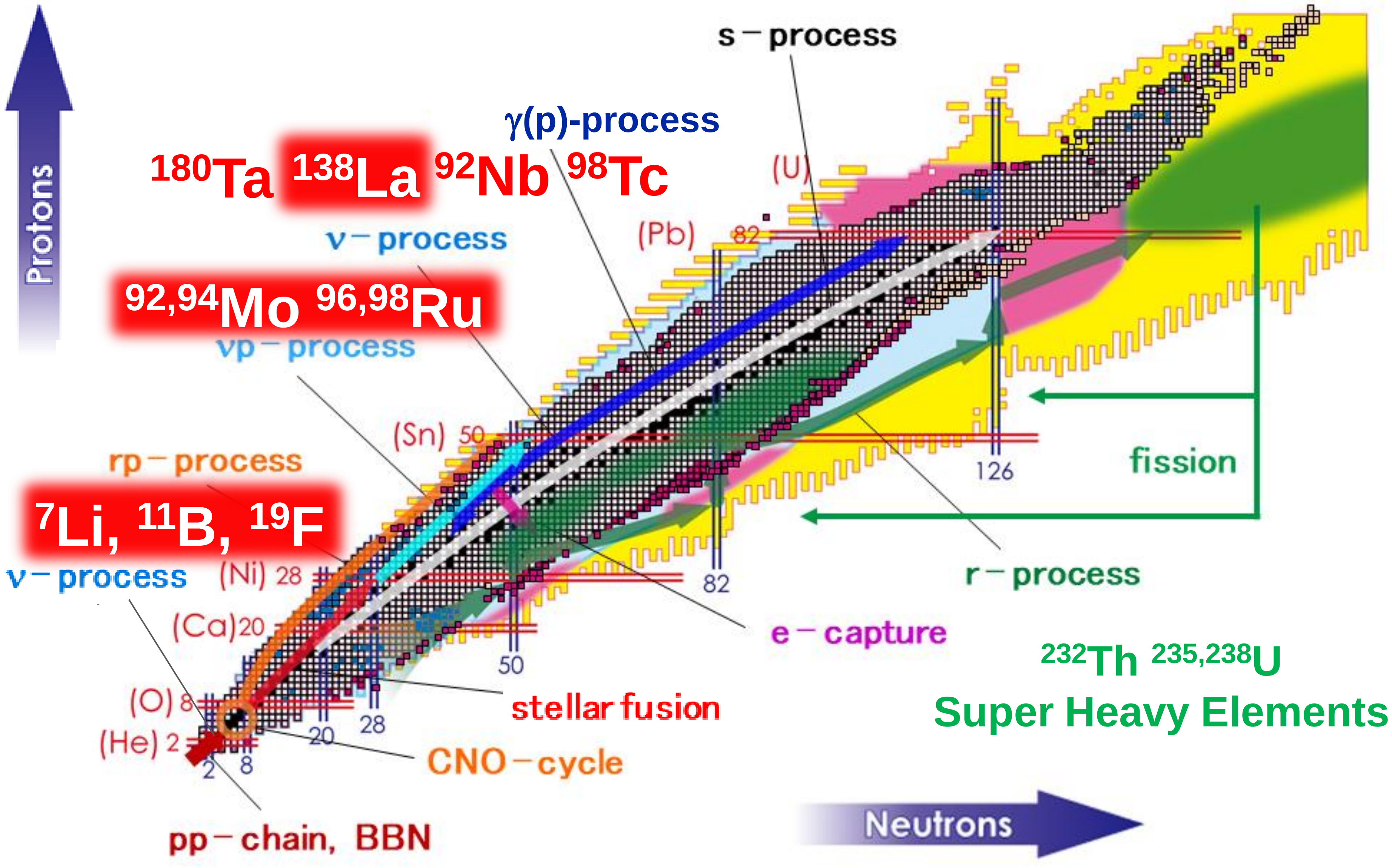
$$Y_s = \int_0^T dt P_4^{sur}(t;T)\left[\lambda_{^{151}\mathrm{Sm}\_\beta^-}\int_0^t d\tau\, f_s(\tau) P_3^{sur}(\tau;t)\right] \quad \text{where,} \quad P_k^{sur}(\tau;t) = \exp\left[-\int_\tau^t dt'\,\Gamma_k^{des}(t')\right]$$

$$Y_i = \int_0^T dt_3 P_4^{sur}(t_3;T)\left\{\lambda_{^{151}\mathrm{Sm}\_\beta^-}\int_0^{t_3} dt_2\left[\lambda_{^{151}\mathrm{Pm}\_\beta^-}\int_0^{t_2} dt_1\left(f_{i,2}(t_1) + \lambda_{^{151}\mathrm{Nd}\_\beta^-}\int_0^{t_1} d\tau\, f_{i,2}(\tau) P_1^{sur}(\tau;t_1)\right) P_2^{sur}(t_1;t_2)\right] P_3^{sur}(t_2;t_3)\right\}$$

$$Y_r = \int_0^T dt_3 P_4^{sur}(t_3;T)\left\{\lambda_{^{151}\mathrm{Sm}\_\beta^-}\int_0^{t_3} dt_2\left[\lambda_{^{151}\mathrm{Pm}\_\beta^-}\int_0^{t_2} dt_1\left(\lambda_{^{151}\mathrm{Nd}\_\beta^-}\int_0^{t_1} d\tau\, f_r(\tau) P_1^{sur}(\tau;t_1)\right) P_2^{sur}(t_1;t_2)\right] P_3^{sur}(t_2;t_3)\right\}$$

ν-processes in SNe/HNe

Ahmad, Ahn, Aoki, Aziz, Bhuyan, Chen, Guo,
Hahn, Kajino, Kassim, Kim, Kubono, Kusakabe,
Li, Li, Li, Liu, Liu, Motobayashi, Pan, Park, Shi,
Tang, Wang, Wen, Wu, Yan and Yusof,
AAPPS Bulletin 31 (2021), 18.



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

^{92,94}Mo ^{96,98}Ru

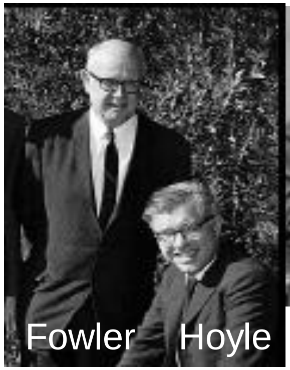
^{7}Li, ^{11}B, ^{19}F

^{232}Th ^{235,238}U

Super Heavy Elements

Origin of ^{92,94}Mo & ^{96,98}Ru ?

— Long-standing Unsolved Question —



Fowler Hoyle

J. & M. Burbidge

Synthesis of the Elements in Stars

Sasaki, Kajino, Yamazaki et al., ApJ 924 (2022), 29; PL B851 (2024), 138581.

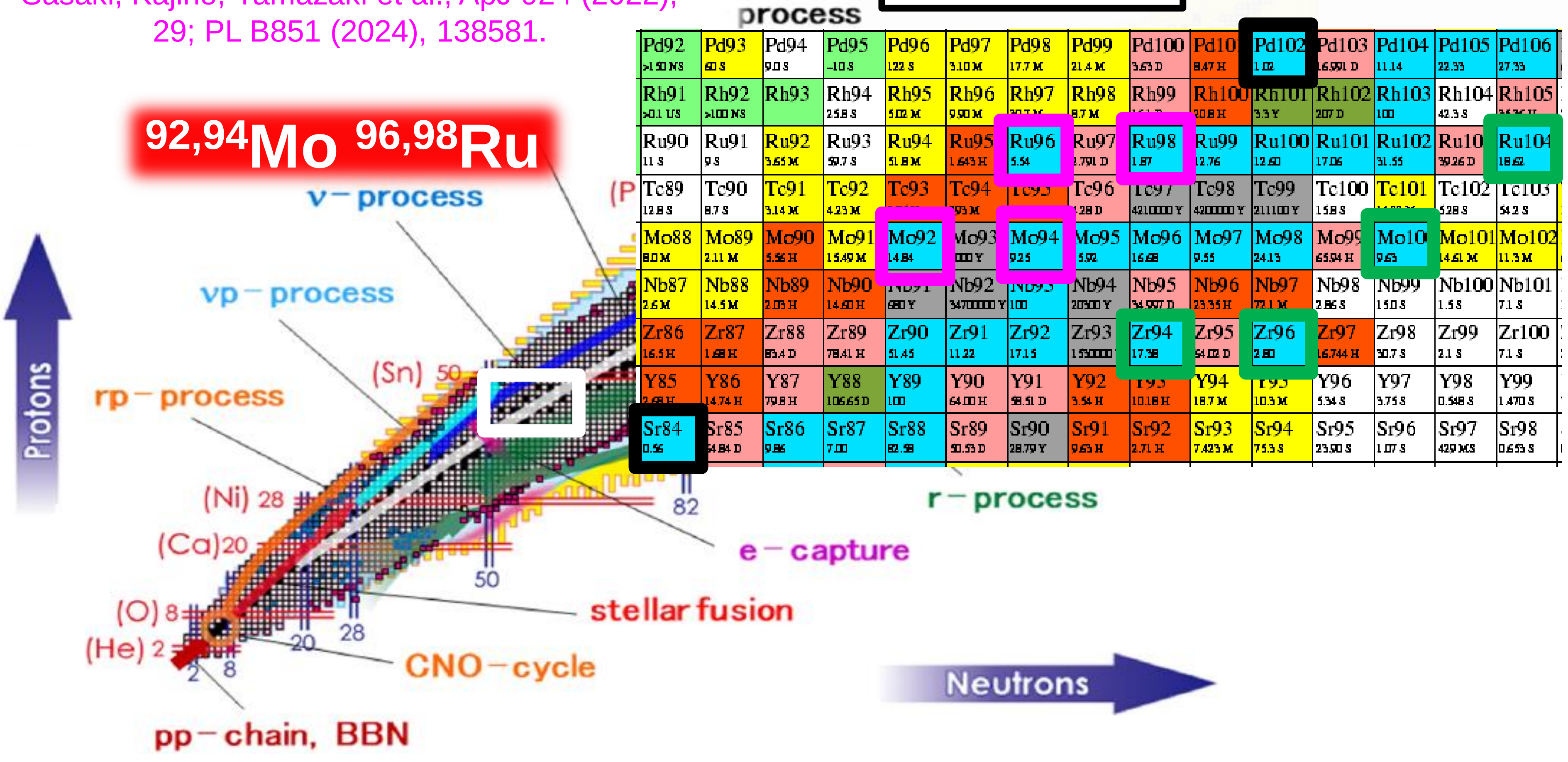
νp-process in Hypernova

^{92}Mo	14.53%
^{94}Mo	9.15%
^{96}Ru	5.54%
^{98}Ru	1.87%

All other p-nuclei ~ 0.1-1%

~~γ-process~~

^{92,94}Mo ^{96,98}Ru



Pd92 >1.50 NS	Pd93 60 S	Pd94 9.0 S	Pd95 ~10 S	Pd96 122 S	Pd97 3.10 M	Pd98 17.7 M	Pd99 21.4 M	Pd100 3.63 D	Pd10 8.47 H	Pd102 1.02	Pd103 16.991 D	Pd104 11.14	Pd105 22.33	Pd106 27.33
Rh91 >0.1 US	Rh92 >1.00 NS	Rh93	Rh94 25.8 S	Rh95 5.02 M	Rh96 9.90 M	Rh97	Rh98 8.7 M	Rh99	Rh100 20.8 H	Rh101 3.3 Y	Rh102 207 D	Rh103 100	Rh104 42.3 S	Rh105
Ru90 11 S	Ru91 9 S	Ru92 3.65 M	Ru93 59.7 S	Ru94 51.8 M	Ru95 1.643 H	Ru96 5.54	Ru97 2.791 D	Ru98 1.87	Ru99 12.76	Ru100 12.60	Ru101 17.06	Ru102 31.55	Ru10 39.26 D	Ru104 18.62
Tc89 12.8 S	Tc90 8.7 S	Tc91 3.14 M	Tc92 4.23 M	Tc93	Tc94 293 M	Tc95	Tc96 4.28 D	Tc97 4210000 Y	Tc98 4200000 Y	Tc99 211100 Y	Tc100 15.8 S	Tc101	Tc102 5.28 S	Tc103 54.2 S
Mo88 8.0 M	Mo89 2.11 M	Mo90 5.56 H	Mo91 15.49 M	Mo92 14.84	Mo93 000 Y	Mo94 9.25	Mo95 15.92	Mo96 16.68	Mo97 9.55	Mo98 24.13	Mo99 65.94 H	Mo10 9.63	Mo101 14.61 M	Mo102 11.3 M
Nb87 2.6 M	Nb88 14.5 M	Nb89 2.03 H	Nb90 14.60 H	Nb91 680 Y	Nb92 34700000 Y	Nb93 100	Nb94 20300 Y	Nb95 34.997 D	Nb96 23.35 H	Nb97 72.1 M	Nb98 2.86 S	Nb99 15.0 S	Nb100 1.5 S	Nb101 7.1 S
Zr86 16.5 H	Zr87 1.68 H	Zr88 83.4 D	Zr89 78.41 H	Zr90 51.45	Zr91 11.22	Zr92 17.15	Zr93 1530000	Zr94 17.38	Zr95 64.02 D	Zr96 2.80	Zr97 16.744 H	Zr98 30.7 S	Zr99 2.1 S	Zr100 7.1 S
Y85 2.68 H	Y86 14.74 H	Y87 79.8 H	Y88 106.65 D	Y89 100	Y90 64.00 H	Y91 58.51 D	Y92 3.54 H	Y93 10.18 H	Y94 18.7 M	Y95 10.3 M	Y96 5.34 S	Y97 3.75 S	Y98 0.548 S	Y99 1.470 S
Sr84 0.56	Sr85 64.84 D	Sr86 9.86	Sr87 7.00	Sr88 82.58	Sr89 50.53 D	Sr90 28.79 Y	Sr91 9.63 H	Sr92 2.71 H	Sr93 7.423 M	Sr94 75.3 S	Sr95 23.90 S	Sr96 1.07 S	Sr97 429 MS	Sr98 0.653 S

Mo is a valuable element to study all nucleosynthetic processes in the solar-system.

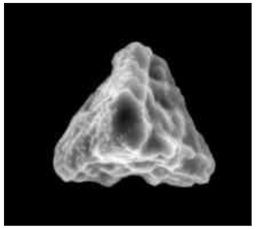
Isotopic fraction in %

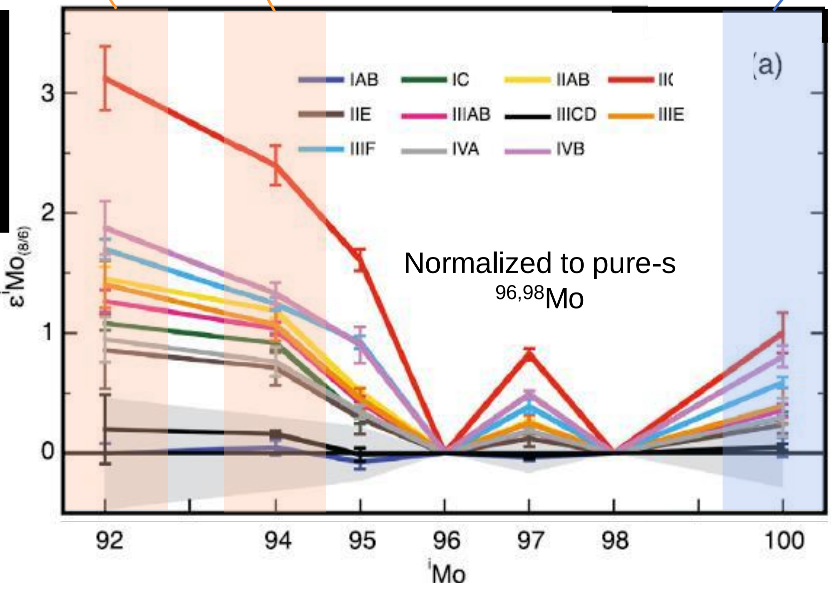
^{92}Mo	^{94}Mo	^{95}Mo	^{96}Mo	^{97}Mo	^{98}Mo	^{100}Mo
14.53	9.15	15.84	16.67	9.6	24.39	9.82
100	99.1	0	0	0	0	0
0	0.9	69.6	100 (over)	63.7	82.2	4.5
0	0	30.4	0	36.3	17.8	95.5

Bisterzo et al.,
MNRAS 418, 284 (2011);
ApJ. 787, 10 (2014).

Red = p-process
Green = s-process
Blue = r-process

Isotopic Anomaly





Normalized to pure-s ^{96,98}Mo

Poole,
EPSL, 473,
215 (2017).

Mo isotopes

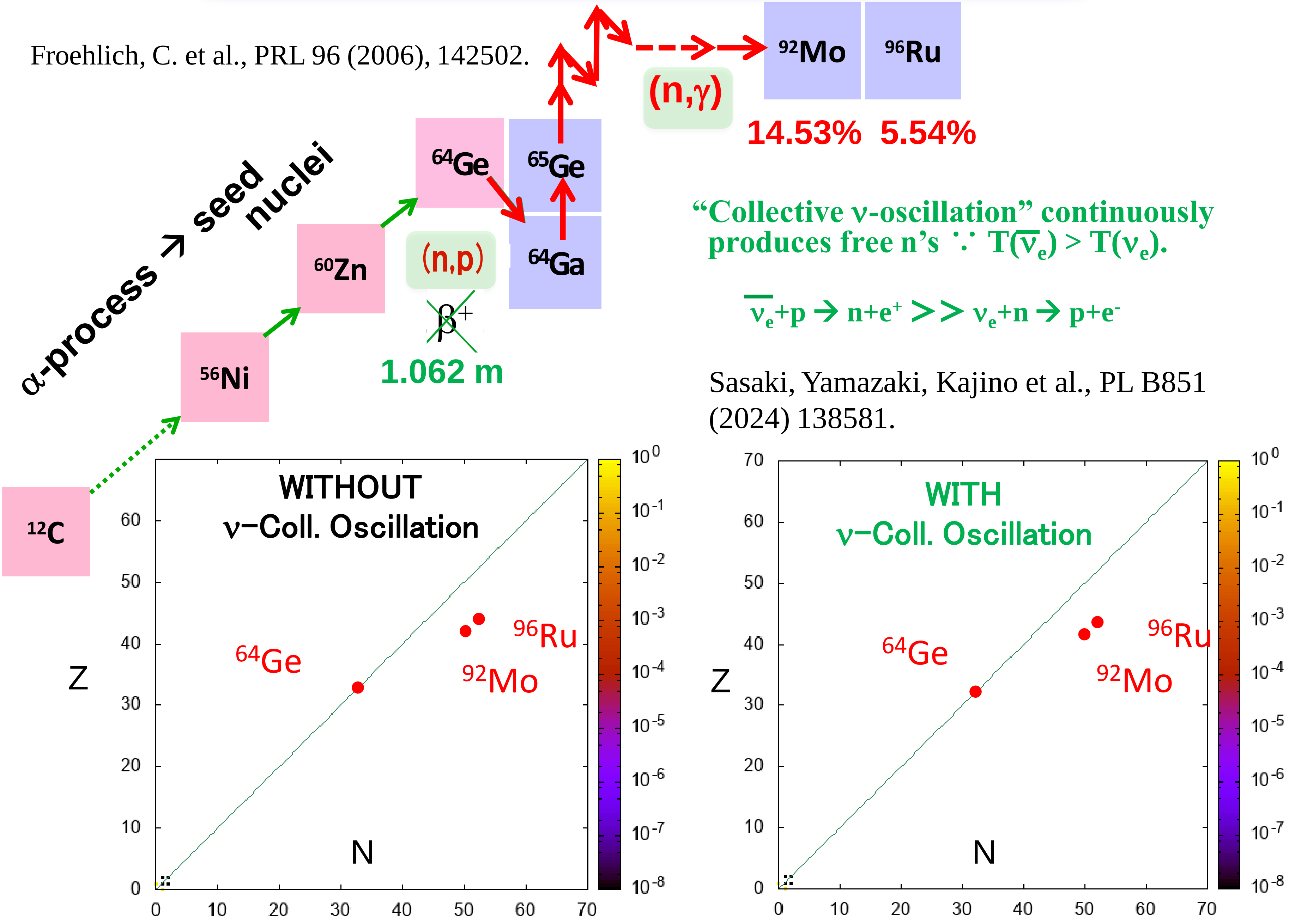
Correlated Anomaly in Meteorites between ^{92,94}Mo & ^{100}Mo

pure-p **pure-r**

Origin is in
the same astrophysical site.

ν-p processeswith Collective Oscillation

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



“Collective ν-oscillation” continuously produces free n’s ∵ T($\overline{\nu}_e$) > T(ν_e).

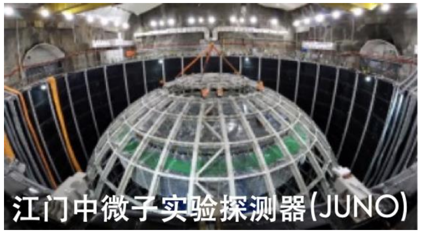
$$\overline{\nu}_e + p \rightarrow n + e^+ >> \nu_e + n \rightarrow p + e^-$$

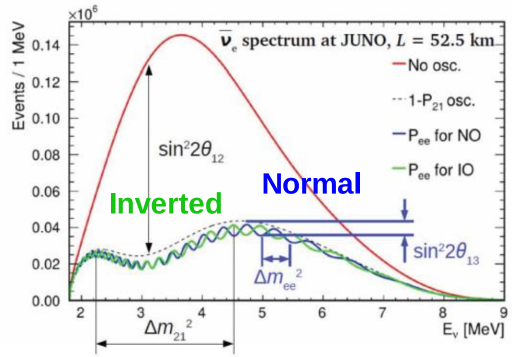
Sasaki, Yamazaki, Kajino et al., PL B851 (2024) 138581.

元素的起源与超越标准模型的新物理：中微子质量是关键

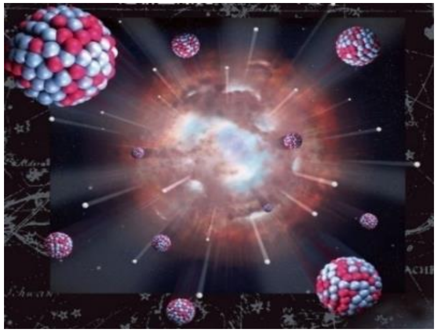
Origin of Heavy Elements & New Physics beyond the Standard Model: Neutrino mass takes the key.

Vacuum



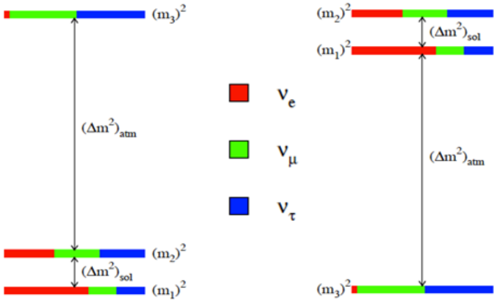


High density



Hierarchy, still unknown !

Normal **Inverted**



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

$$|\Delta m^2_{23}| = 2.4 \times 10^{-3} = (0.05\ \mathrm{eV})^2$$

- **JUNO将确定在真空条件下的中微子质量排序**
  JUNO will determine the neutrino mass hierarchy in vacuum.

- **超新星中的中微子核合成可研究高密度环境中的中微子振荡，为中微子质量排序提供新的约束**
  Supernova neutrino nucleosynthesis offers another opportunity to study the neutrino mass hierarchy in a high density environment.

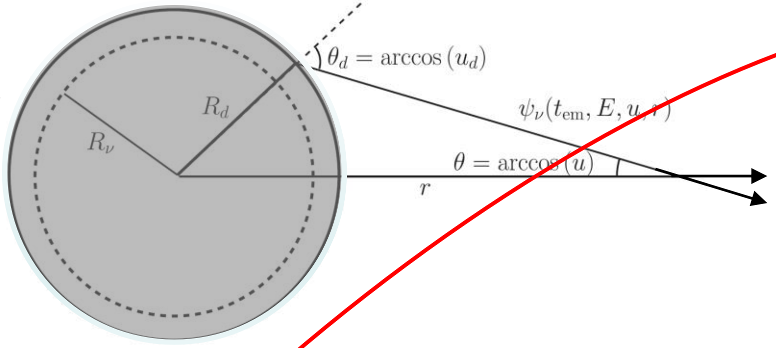
Collective + MSW ν Oscillations — Many Body Quantum Effect

Balantekin, Pehlivan & Kajino, PR D84 (2011), 065008; PR D90 (2014), 065011; PR D98 (2018), 083002
Duan, Fuller, Carlson & Qian, PRL 97 (2006), 241101; Fogli, Lisi, Marrone & Mirizzi, JCAP 12 (2007) 010;
Sasaki, Kajino, Takiwaki, Hayakawa, Balantekin, Pehlivan, PR D96 (2017), 043013.

ν–sphere

proto-neutron Star

~10km



GWS standard model

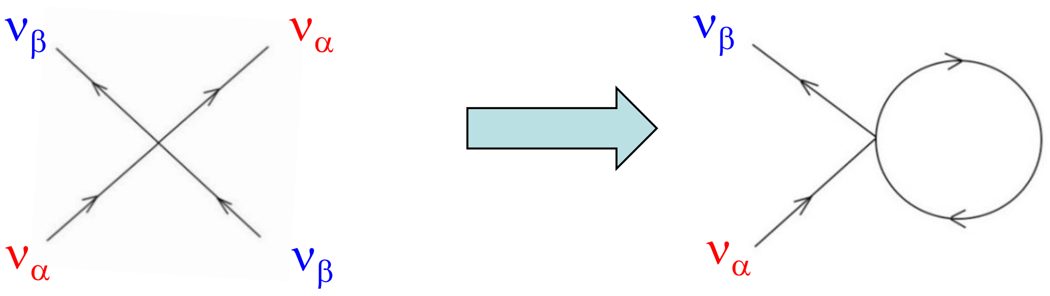
$$\begin{cases} i\dfrac{d\psi_\nu}{dt} = (H_{\rm v} + H_e + H_\nu)\,\psi_\nu(t_{\rm em}, E, u, r), \\ H_{\rm v} = U\dfrac{M^2}{2E}U^\dagger, \\ H_e = \sqrt{2}G_F n_e(r)\,{\rm diag}(1,0,0), \end{cases}$$

Vacuum

MSW

Collective flavor oscillation in coherent ν-ν scattering

$$H_\nu = \sqrt{2}G_F\sum_\alpha\int \underbrace{dE'd\Omega'(1-uu')}_{\nu\text{ angle dep !}}\left[\frac{d^2n_{\nu_\alpha}}{dE'd\Omega'}\rho_{\nu_\alpha}(t'_{\rm em},E',u',r) - \frac{d^2n_{\bar\nu_\alpha}}{dE'd\Omega'}\rho^*_{\bar\nu_\alpha}(t'_{\rm em},E',u',r)\right].$$



α, β = e, μ, τ

10^{44} ν's with 3-flavors & multi-angles ! → Mean Field Approx.

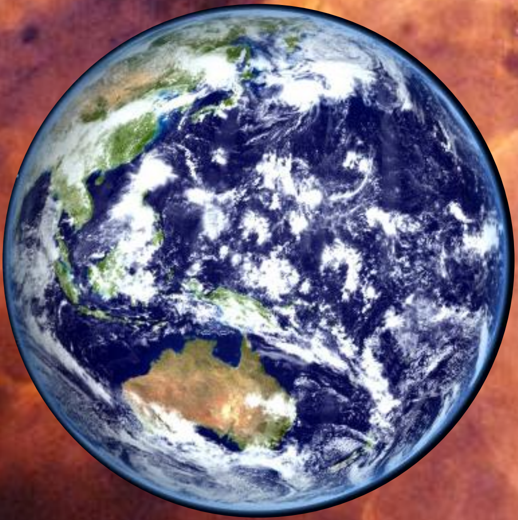
Origin of Life ?

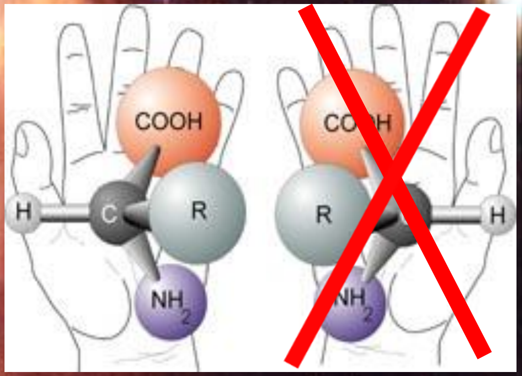
Where was life (amino acid) born?

Universal origin?

Happen to be born on the Earth?

Amino acids on the Earth are all L-handed !



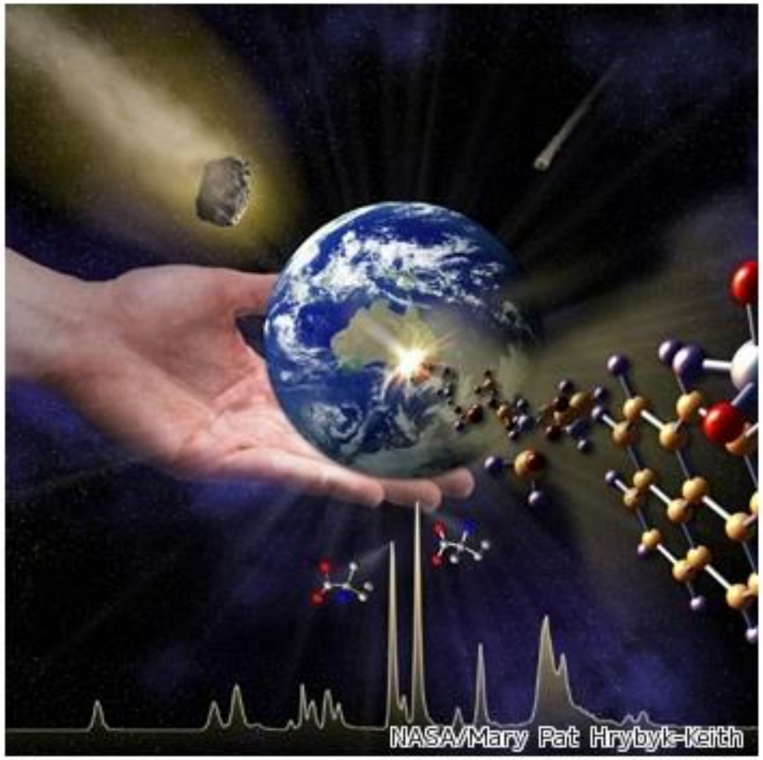


We are made of star dust.

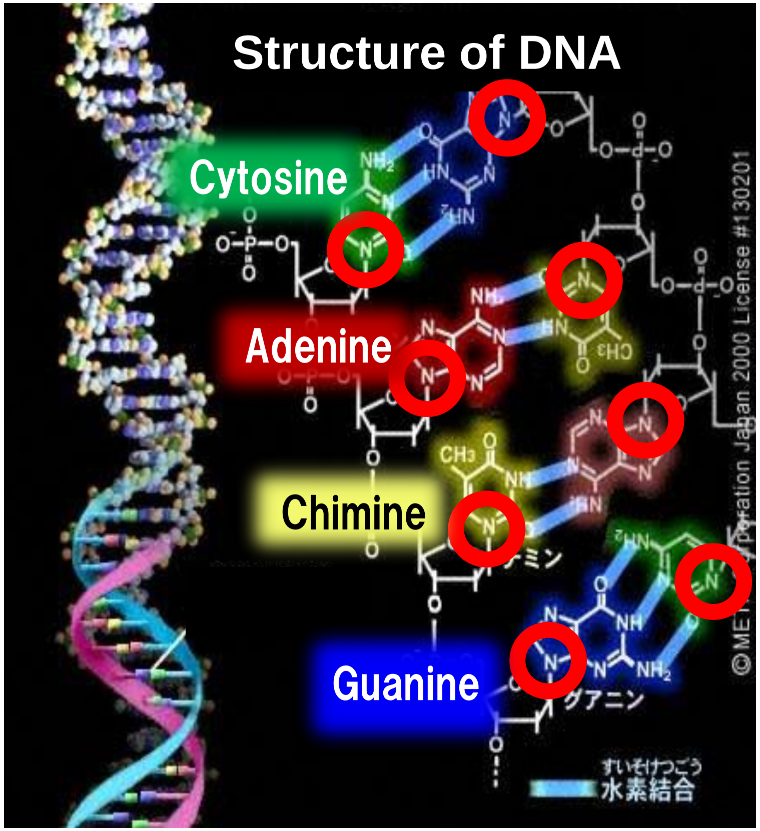
Murchison Meteorite exhibits EXCESS of L-handed Amino Acids!

NASA (2009, March 16)

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

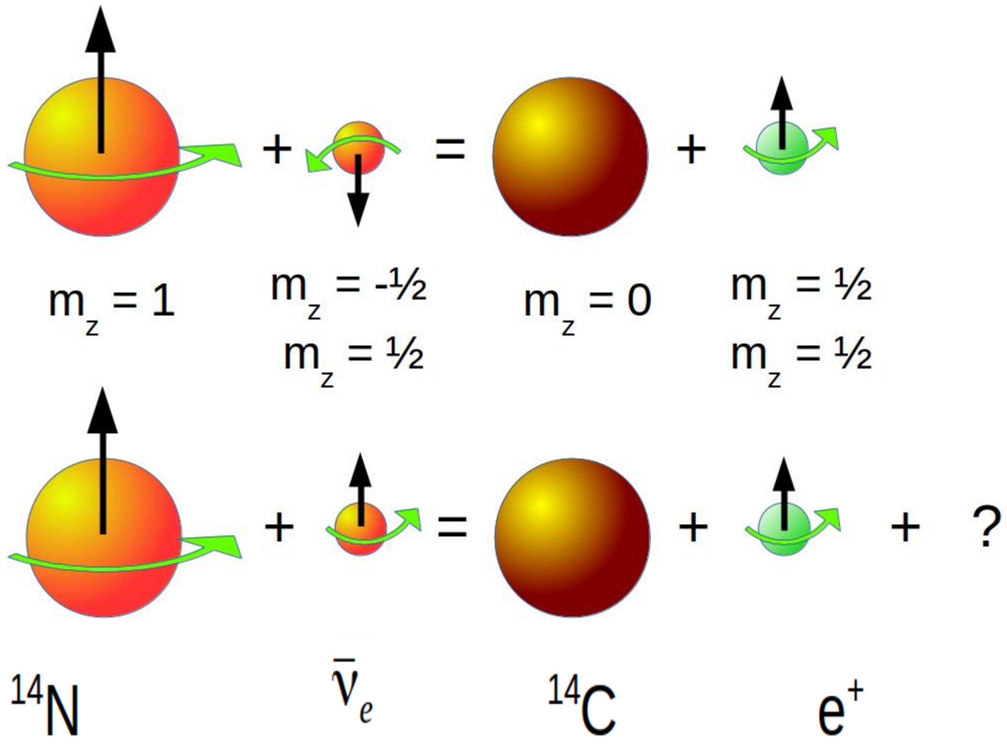


アミノ酸のように、構成要素が同じでも鏡に映したような2つの立体構造を取り得る物質を鏡像体(光学異性体)という。同じアミノ酸でも右型と左型では性質が大きく変わり、右型アミノ酸は体に害をなすことも多い。なぜ生命は左型アミノ酸を選んだのか、その理由は宇宙にある…とするのがGlavin氏らの考え。今後のさらなる研究が期待される



All connections bridging the double helix are occupied by $^{14}N(1+)$.

Effect of ^{14}N and Antineutrino Spin



Cross section for destroying spin-aligned ^{14}N is less than for anti-aligned ^{14}N by an order of magnitude (or two).

Excess of L-Chirality in Amino Acids !

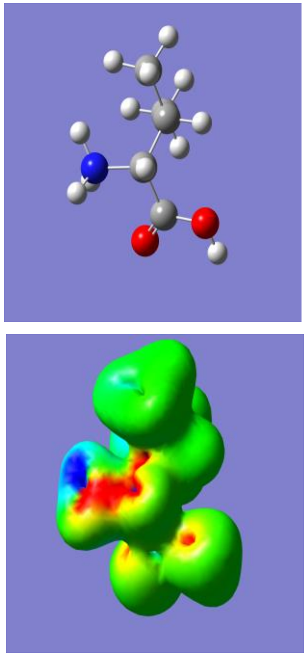
Famiano, Boyd, Kajino, Onaka, et al. Astrobio. 10 (2010), 561; Int. J. Mol. Sci. 12 (2011), 3432; Symm. 6 (2014), 909; Astrobio. 18 (2018) 190; ApJ 856 (2018) 26 ; Sci. Rep. 8 (2018), 8833; Symm. 11 (2019) 23; Astrobio. 20 (2020), 964.

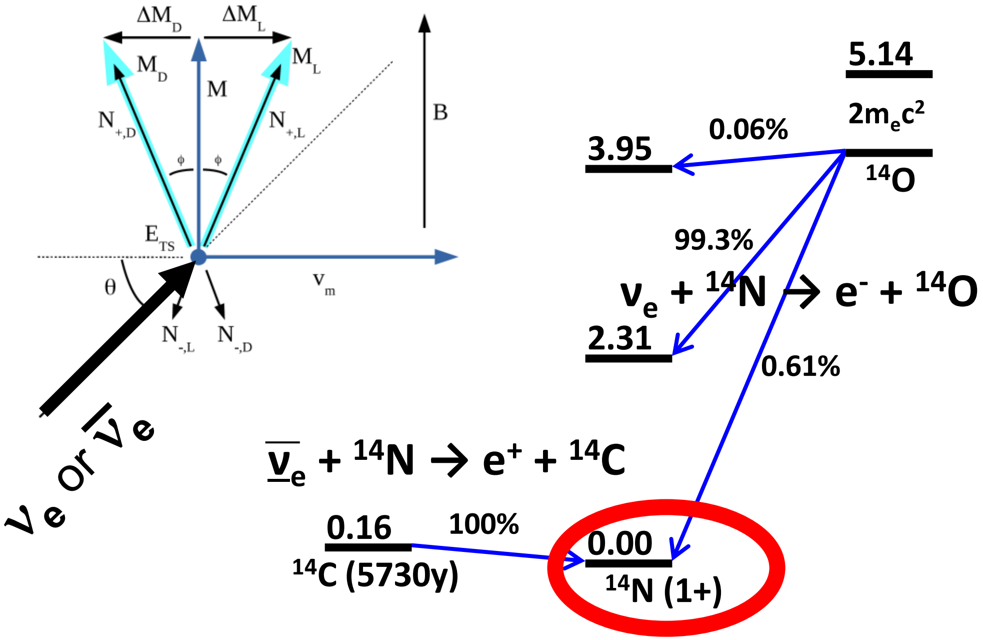
EW Coupling of Nuclei & Molecules under B-Field → Chiral Selection

- Magnetic B-field of NS, BH, NSM orients $^{14}N(s=1)$ via *nuclear* magnetic dipole moment.
- Meteoroid & amino acids are exposed to B-field & induced E-field.
- E-field shifts the electrons, so affects the *molecular* electric dipole moment.

Quantum molecular calculations for Valine

→ ***These operate opposite for two chiralities.***





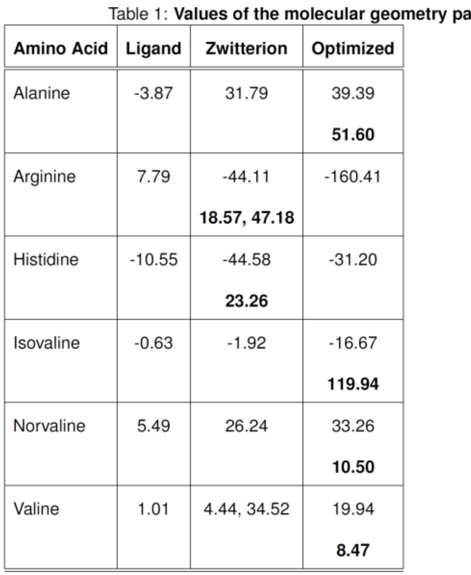


Table 1: **Values of the molecular geometry pa**

Amino Acid	Ligand	Zwitterion	Optimized
Alanine	-3.87	31.79	39.39 **51.60**
Arginine	7.79	-44.11 **18.57, 47.18**	-160.41
Histidine	-10.55	-44.58 **23.26**	-31.20
Isovaline	-0.63	-1.92	-16.67 **119.94**
Norvaline	5.49	26.24	33.26 **10.50**
Valine	1.01	4.44, 34.52	19.94 **8.47**

Summary of Research Targets

Quest No. 1 : Cosmological ν in CMB fluctuations and BBN Li problem

Quest No. 2 : Solar ν problem and Li problem in red-clump stars

Quest No. 3 : SN/HN/Collapsar ν's in the origin of heavy elements,
ν-mass hierarchy/ordering effects at high-density

Quest No. 4 : ν-chirarity and cosmological origin of amino acids

Final Goal

Elucidate the roles of ν-matter interactions in nucleosyntheses at high density from the Big-Bang to Supernova;

Seek for the consistency with particle & nuclear physics.