νSTEP 2025, Beijing, Nov. 24-27 2025

Neutrinos and Nucleosynthesis in the Universe

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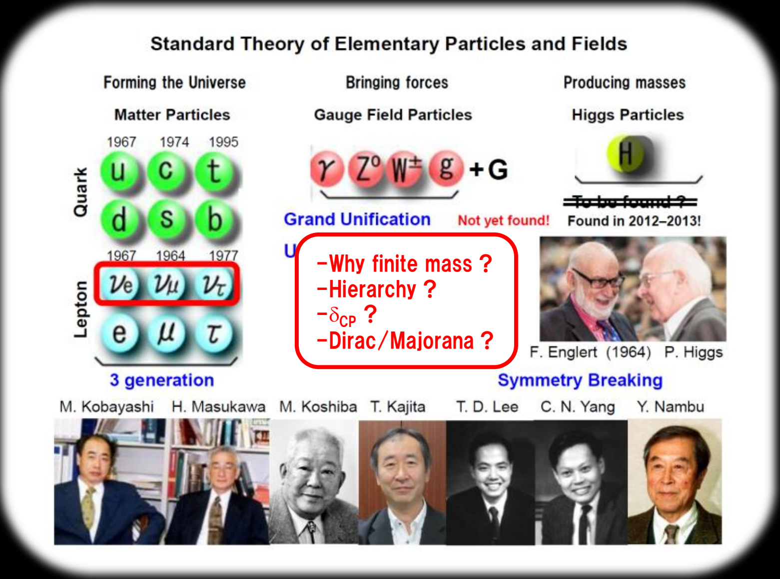
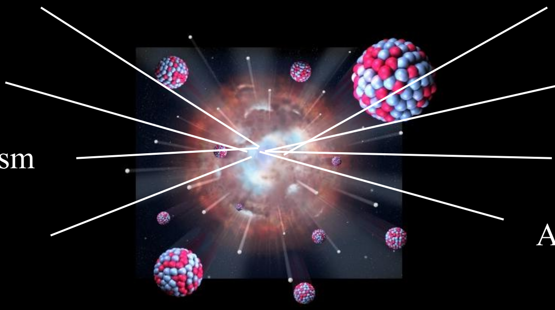
LOC’s request: Talk on Cosmic Background Neutrinos



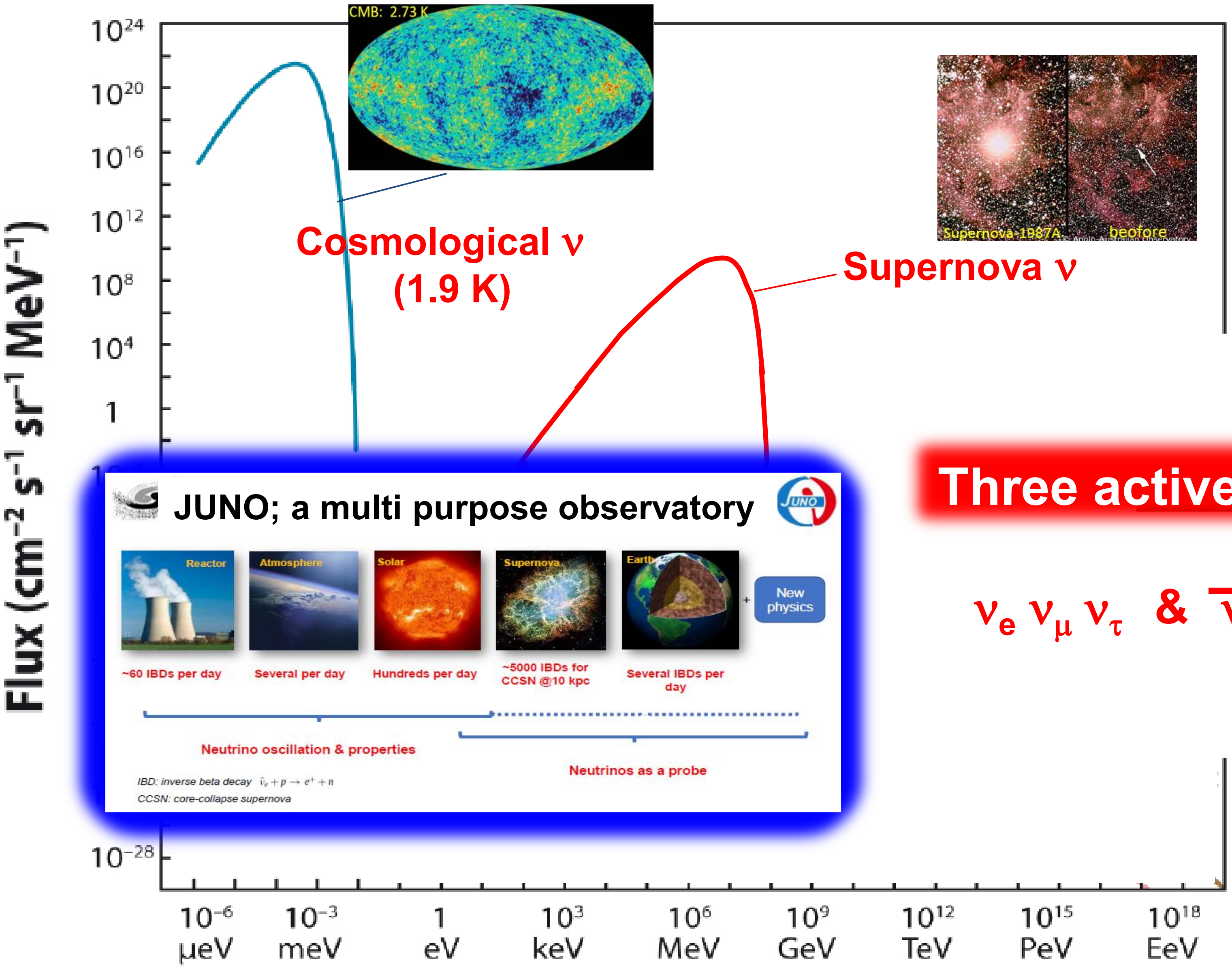
Universe is the Laboratory for
Fundamental Physics at Multi-messenger Era



Weak force
Gravity
Electromagnetism
Strong force

Neutrinos ν
GW
Photons γ
Atomic Nuclei

Among Various Neutrino-Sources in Nature/Culture ···



JUNO; a multi purpose observatory

Reactor	Atmosphere	Solar	Supernova	Earth	New physics
~60 IBDs per day	Several per day	Hundreds per day	~5000 IBDs for CCSN @10 kpc	Several IBDs per day	

Neutrino oscillation & properties

Neutrinos as a probe

IBD: inverse beta decay $\bar{\nu}_e + p \rightarrow e^+ + n$

CCSN: core-collapse supernova

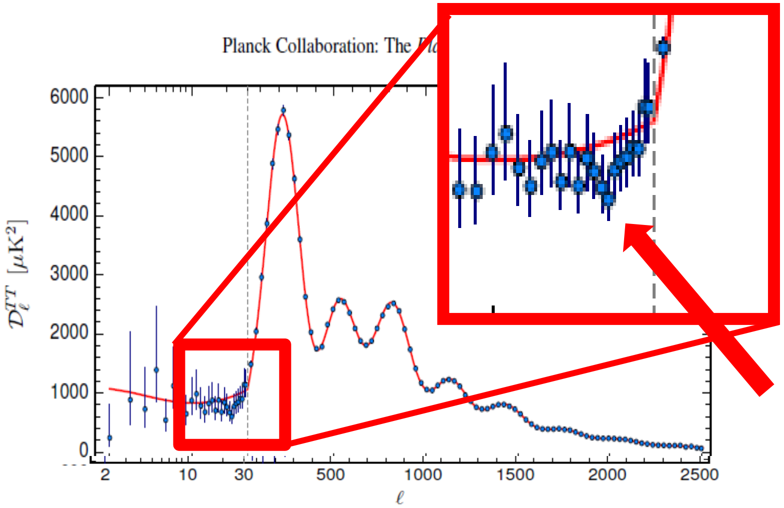
Three active ν & $\overline{\nu}$!

$\nu_e\ \nu_\mu\ \nu_\tau$ & $\overline{\nu_e}\ \overline{\nu_\mu}\ \overline{\nu_\tau}$

Physical Review D92, 123519 (2015)

Possible evidence for Planck-scale resonant particle production during inflation from the CMB power spectrum

G. J. Mathews,[1,2] M. R. Gangopadhyay,[1] K. Ichiki,[3] and T. Kajino[2,4]



- Planck-mass Fermion creation coupled to inflation
- Cosmic Variance:
  Planck XX arXiv:1502.02114
- Modified inflation effective potential
  - Harza, et al. arXiv:1405.2012,
  - Kitazawa and Sagnotti 1411.6396v2,
  - Yang and Ma arXiv:1501.00282

$\ell = 25 \sim \theta = 10^o$ (Planck & WMAP)

Astrophysical Journal Letters, 951 (2023), L8

Cosmic Background GW ! → Why not ν ?

The NANOGrav 15 yr Data Set: Evidence for a Gravitational-wave Background

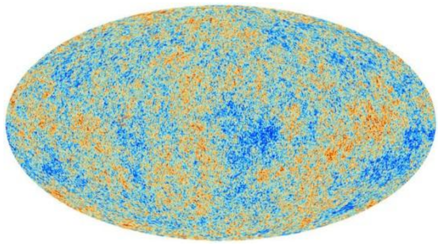
Gabriella Agazie, et al. (The NANOGrav Collaboration) ← Pulsar Timing Array Collabs.

Journal of High Energy Astrophysics 47 (2025) 100358

Is the NANOGrav detection evidence of resonant particle creation during inflation?

M.R. Gangopadhyay[a], V.V. Godithi[b,a], R. Inui[c], K. Ichiki[c], T. Kajino[d,e,f], A. Manusankar[g,a],
G.J. Mathews[h], Yogesh[i,*]

PBH formation enhances Background GW !



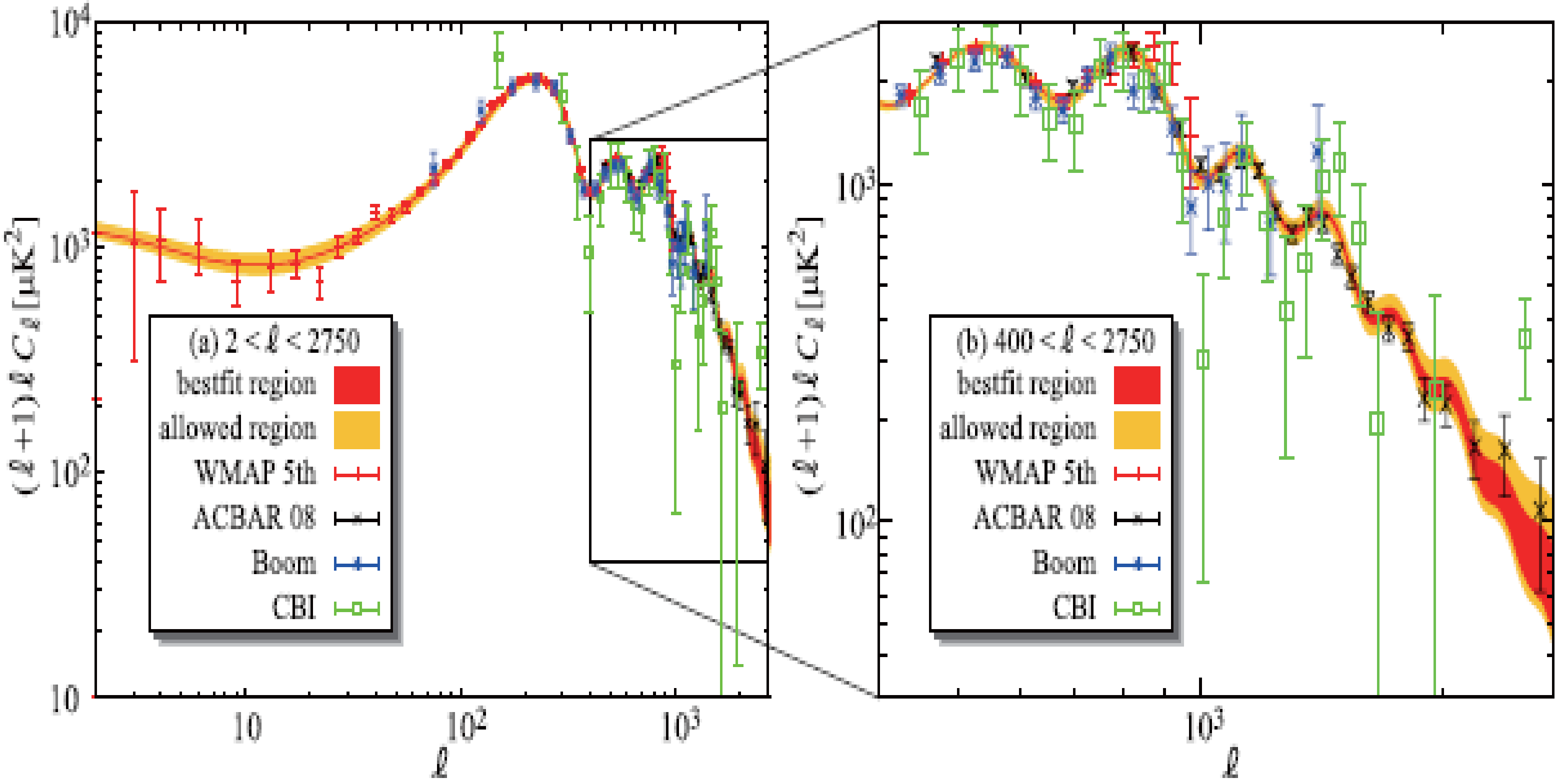
CMB Anisotropy and Polarization exhibit a signal of ν mass and Primordial Magnetic Field (PMF) !

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

Anisotropic stress : **$\Sigma m_\nu = 10^{-2}$ eV,** **B = 3 nG (comoving)**

Finite mass neutrinos :
Free streaming & integrated Sachs-Wolfe effects, similarly to CDM

TT mode



Basic Equations for Metric Perturbation

Isotropic & Homogeneous BG

$$\left(\frac{a'}{a}\right)^2 = \frac{8\pi G}{3}\rho - \frac{K}{a^2}$$

Friedmann Eq.

$$k\frac{1}{a^2}\frac{a'}{a}\mathcal{Z} = 4\pi G\delta\rho + k^2\frac{H_T}{a^2}$$

Linear Metric Perturbation

Perturbed Einstein Equation of “Super-Horizon Scale (kτ<<1)”

$$\boxed{\ddot{H}_T} + 2\frac{\dot{a}}{a}\dot{H}_T = 8\pi G a^2 (p_\nu \boxed{\pi_\nu} + p_\gamma \boxed{\pi_{ext}})$$

Metric perturbation

ν-anisotropic stress

anisotropic stress due to **Megnetic Field**

Effective wave number
for finite neutrino mass

$$k_{\mathrm{eff}}^2 = k^2 + k_{\mathrm{m}}^2$$

$$k_{\mathrm{m}} = \sqrt{\frac{1}{2}\frac{5}{7\pi^2}H_0^2\Omega_R\frac{4R_\nu + 15}{c}\boxed{m_\nu^2}}$$

ν-mass

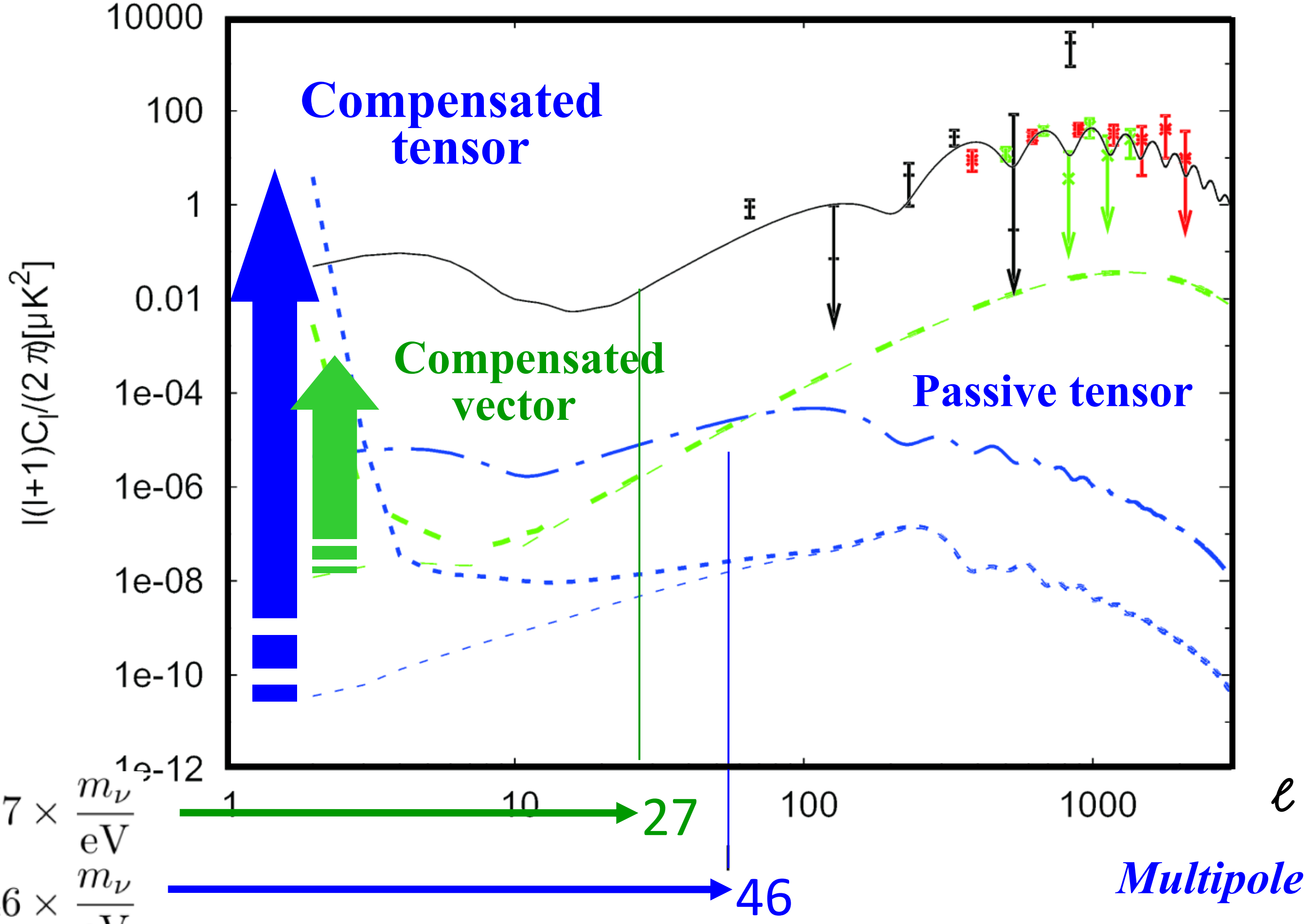
Signal of ν mass

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

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

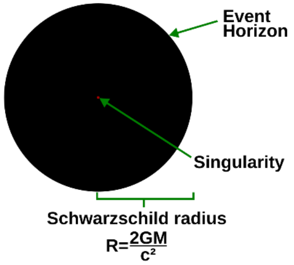
$$\ell_m^{(2)} \sim 46 \times \frac{m_\nu}{\mathrm{eV}}$$

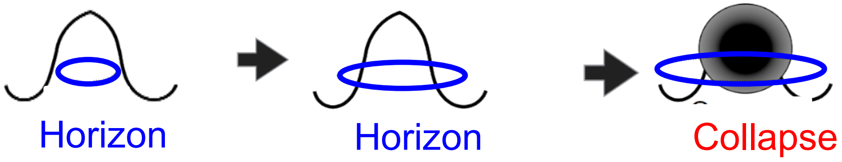
Multipole ℓ ~ π/θ

Primordial Black Holes

PBH is a type of black hole which forms from sufficiently high-density perturbation in the early Universe. (It is not formed through the gravitational collapse of a star.)

➢ Collapse of overdense regions within Event horizon





➢ Threshold

$R_H \sim R > R_J$

Hubble radius

Jeans length

Overdense region $\delta = \delta\rho/\rho$

$$t_{\rm sound} = \frac{R}{c_s} \approx 0.5\,{\rm Myr} \cdot \frac{R}{0.1\,{\rm pc}} \cdot \left(\frac{c_s}{0.2\,{\rm km\,s^{-1}}}\right)^{-1}$$

$$t_{\rm ff} = \frac{1}{(G\rho)^{\frac{1}{2}}} \approx 2\,{\rm Myr} \cdot \left(\frac{n}{10^3\,{\rm cm^{-3}}}\right)^{-\frac{1}{2}}$$

$$\boxed{t_{\rm ff} < t_{\rm sound}}$$

$$R_J = \frac{c_s}{(G\rho)^{\frac{1}{2}}} \approx 0.4\,{\rm pc} \cdot \frac{c_s}{0.2\,{\rm km\,s^{-1}}} \cdot \left(\frac{n}{10^3\,{\rm cm^{-3}}}\right)^{-\frac{1}{2}}$$

➢ Mass range

$\rho \sim T^4/G \sim 1/Gt^2$, $H \sim t^{-1}$

$$M_{\rm PBH} \sim M_H \sim \frac{c^3 t}{G} \sim 10^{15} \left(\frac{t}{10^{-23}{\rm s}}\right) {\rm g}$$

Horizon-mass approximation

Planck scale	$\sim 10^{-43} s$	→	$10^{-5} g$
EW scale	$\sim 10^{-10} s$	→	$10^{28} g$
QCD scale	$\sim 10^{-6} s$	→	$10^{32} g$
Neutrino decoupling	$\sim 1 s$	→	$10^5 M_\odot$

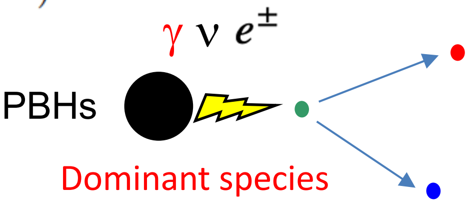
➢ Mass function

Monochromatic (δ-func.) vs. Critical collapse (ours)

- **Hawking radiation:** $$\frac{d^2N}{dtdE} = \frac{1}{2\pi}\frac{\Gamma_s(E,M)}{e^{8\pi GME}-(-1)^{2s}};$$

$$\frac{d\dot{N}_\gamma}{dE_\gamma}(E_\gamma,M) = \frac{d\dot{N}_\gamma^{\rm pri}}{dE_\gamma}(E_\gamma,M) + \frac{d\dot{N}_\gamma^{\rm sec}}{dE_\gamma}(E_\gamma,M),$$

QCD jet



γ ν $e^{\pm}$

PBHs

Dominant species

Electromagnetic cascade

$$\gamma+\gamma_{bg}\to e^{\pm},$$
$$\gamma+\gamma_{bg}\to\gamma+\gamma,$$
$$\gamma+e^{\pm}_{bg}\to\gamma+e^{\pm},$$
$$e^{\pm}+\gamma_{bg}\to e^{\pm}+\gamma,$$
$$\gamma+N_{bg}\to e^{\pm}+N.$$

- **Non-thermal photons interact with Light Elements:**

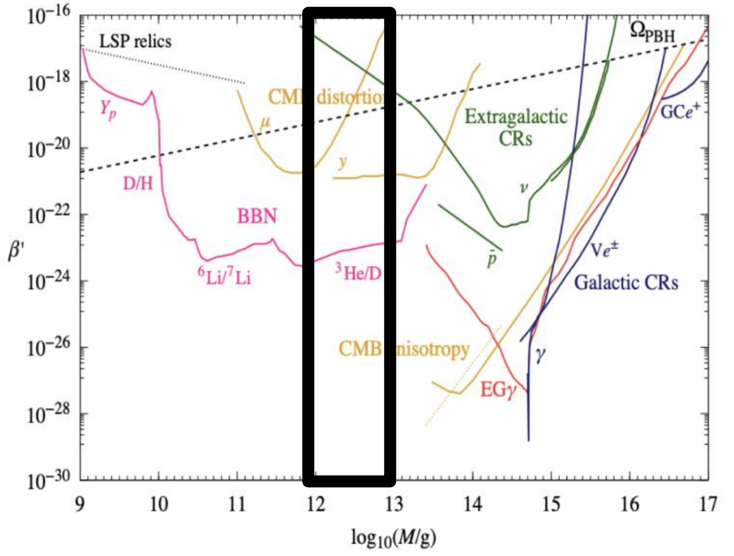
- **Observatoinal constraints on Big-Bang/Primordial Elements !**

$$\beta(M)\equiv\frac{\rho_{\rm PBH}}{\rho_{\rm tot}}$$

$$\beta'(M)\equiv\gamma^{-1/2}\left(\frac{g_{*,\rm form}}{106.75}\right)^{1/4}\left(\frac{h}{0.67}\right)^{-2}\beta(M)$$

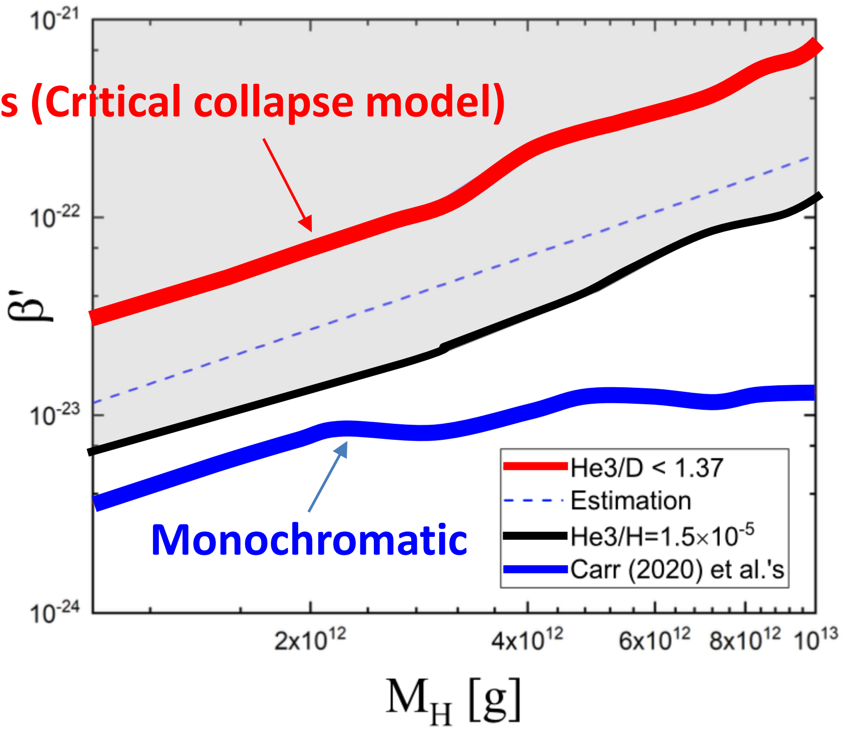
Y. Luo, C. Chen, M. Kusakabe and T. Kajino (2021), JCAP 05, 042.

Carr et al., PRD 81, 104019 (2010).



Ours (Critical collapse model)

Monochromatic



Success of Big-Bang Cosmology

1. BBN
2. CMB Fluctuations

GUTs Baryo-Lepto genesis model

Broken L_e-symmetry ?

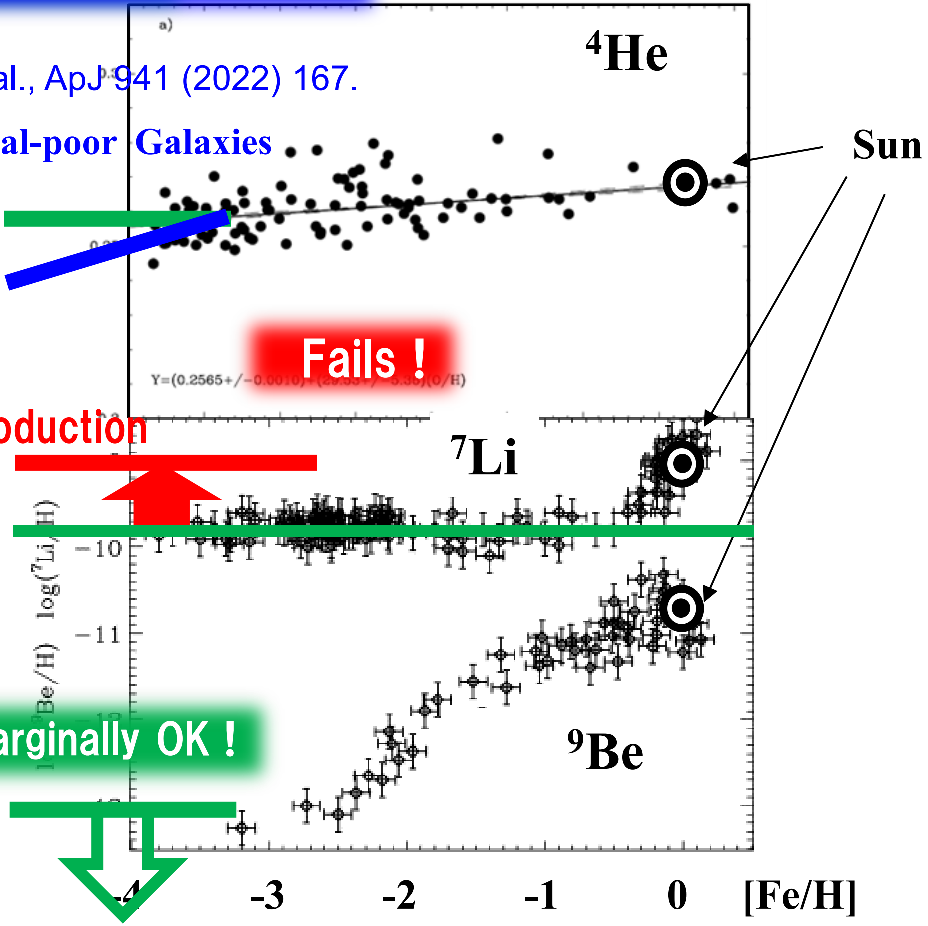
$\eta_L \sim 10^{-2}$ too large!

$\eta_B \sim 10^{-10}$

New observation !

EMPRESS:
Matsumoto et al., ApJ 941 (2022) 167.

Extremely metal-poor Galaxies



Crisis of
Unified Theor.?

Fails !

Theor. ~3 overproduction
Cosmological
Li−problem !

Marginally OK !

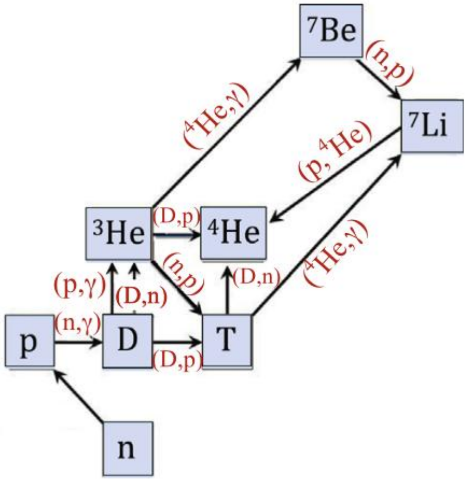
Possible Solutions?

1. Astro-Cosmo.
   - Astration of ^{7}Li
   - Extra Galaxy of ^{4}He

   → B-L Asymmetry
   → Fluct. IBBN
2. New Physics
   - Nature of DM
   - ν-mag. moment
3. Nucl.-Part. Phys.
   - Reaction X-sect.

Big-Bang: t = 0 → **Time**

Big Bang Nucleosynthesis (BBN)



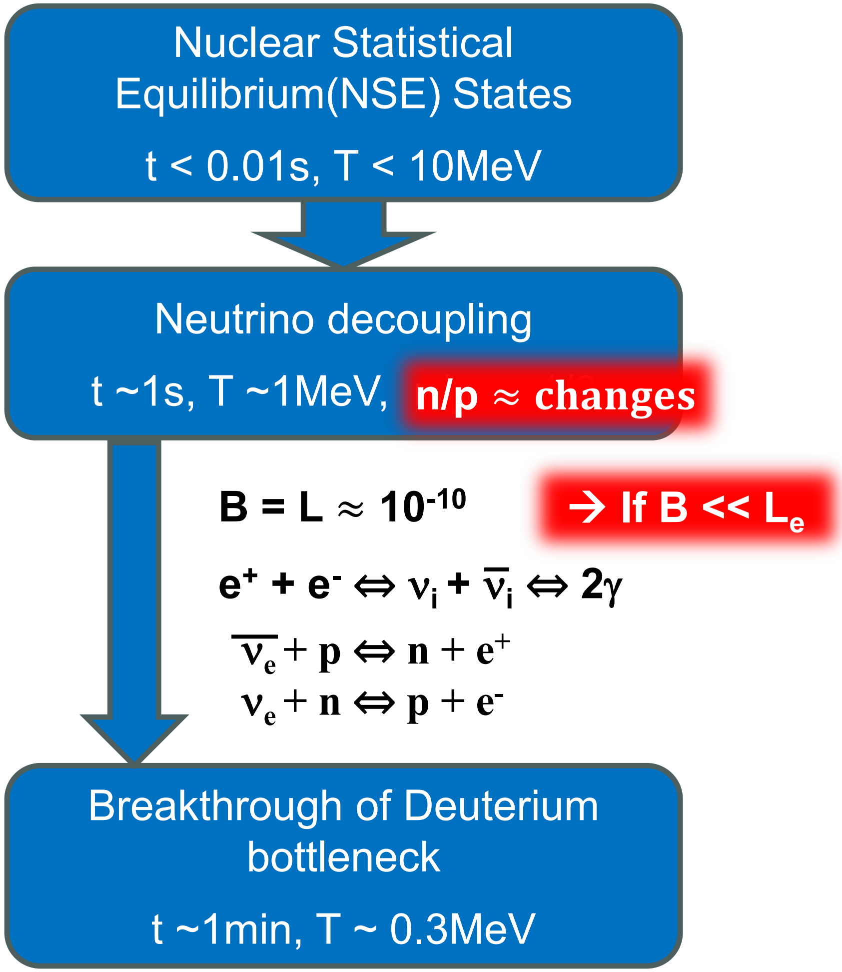
Dynamical evolution: - Friedmann Eq.
(Standard model):

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho$$

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}\left(\rho + \frac{3p}{c^2}\right)$$

Abundance changes of the nuclei i:

$$\frac{\mathrm{d}Y_i}{\mathrm{d}t} = \sum_{j,k,l} N_i \left(-\frac{Y_i^{N_i} Y_j^{N_j}}{N_i!\,N_j!}[ij]_k + \frac{Y_l^{N_l} Y_k^{N_k}}{N_l!\,N_k!}[lk]_j \right)$$



Nuclear Statistical Equilibrium(NSE) States

t < 0.01s, T < 10MeV

Neutrino decoupling

t ~1s, T ~1MeV, **n/p ≈ changes**

B = L ≈ 10^{-10}

→ If B << L_e

$e^+ + e^- \Leftrightarrow \nu_i + \bar{\nu}_i \Leftrightarrow 2\gamma$

$$\overline{\nu_e} + p \Leftrightarrow n + e^+$$

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

Breakthrough of Deuterium bottleneck

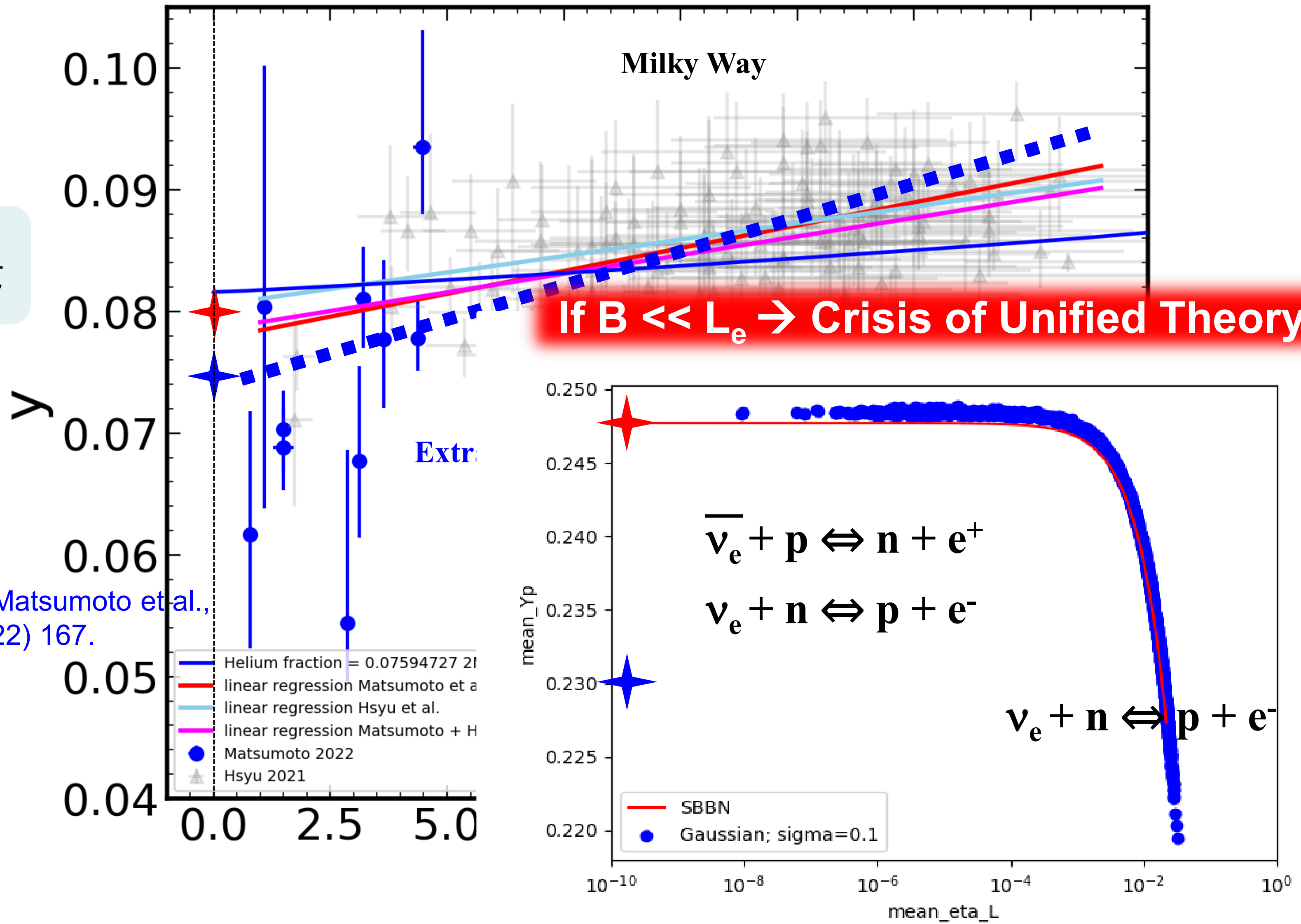
t ~1min, T ~ 0.3MeV

C. Bertulani and T. Kajino,
Prog. Part. Nucl. Phys., 89, 56 (2016).

Galactic Chemical Evolution

S. Choi, E. Gjergo, T. Kajino, Y. Kim, T. Shima, ApJ, to be submitted (2025).

$$Y_P = \frac{4y}{1+4y}$$



If B << L_e → Crisis of Unified Theory

$\overline{\nu_e} + p \Leftrightarrow n + e^+$

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

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

EMPRESS: Matsumoto et al.,
ApJ 941 (2022) 167.

Cosmological solution of BBN-Li ?

CMB-B Fluctuation !

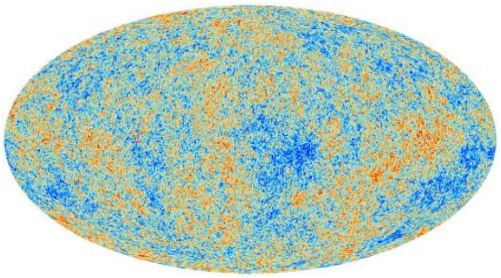
Luo, Kajino, Kusakabe, Mathews, Astrophys. J.872 (2019),172
Yamazaki, Kajino, Mathews, Ichiki, Phys. Rep. 517 (2012), 141.

Magnetic Field Energy Density:

$$B^2 \propto P_{[PMF]} = Ak^{n_B}$$

(CMB power law spectrum)

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


Planck

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

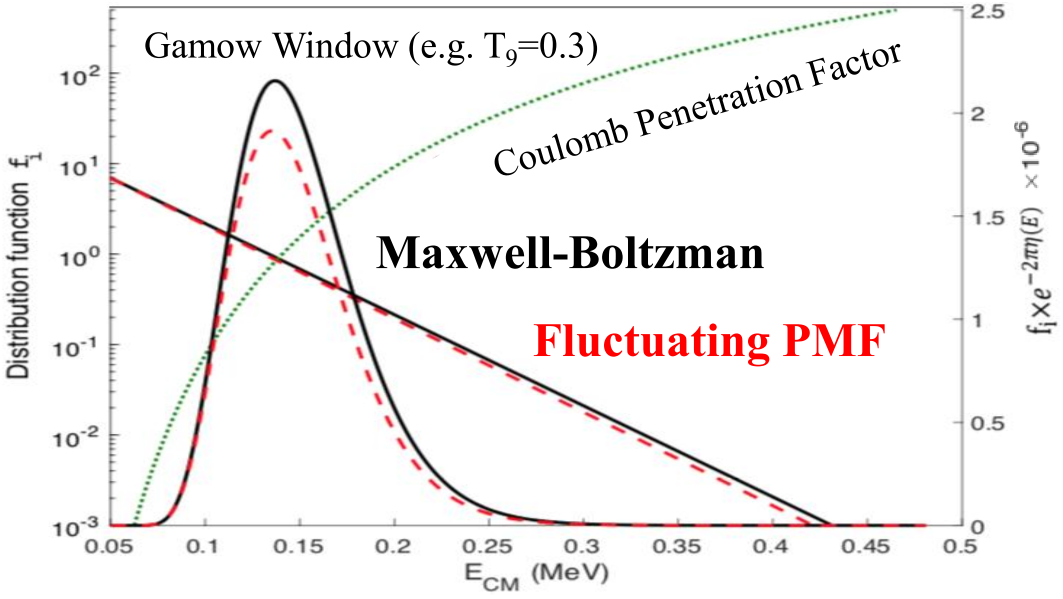
$$f(\beta) = \frac{1}{\sqrt{2\pi}\sigma}\exp\left[-\frac{\left(\frac{\pi g}{30}\cdot(T_{eff}^4-\beta^{-4})-\rho_\lambda\right)^2}{2\sigma^2}\right]\cdot\frac{2\pi g}{15}\beta^{-5}$$

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

Temp. Fluctuation

→ various Temp.

$T=\beta^{-1}$



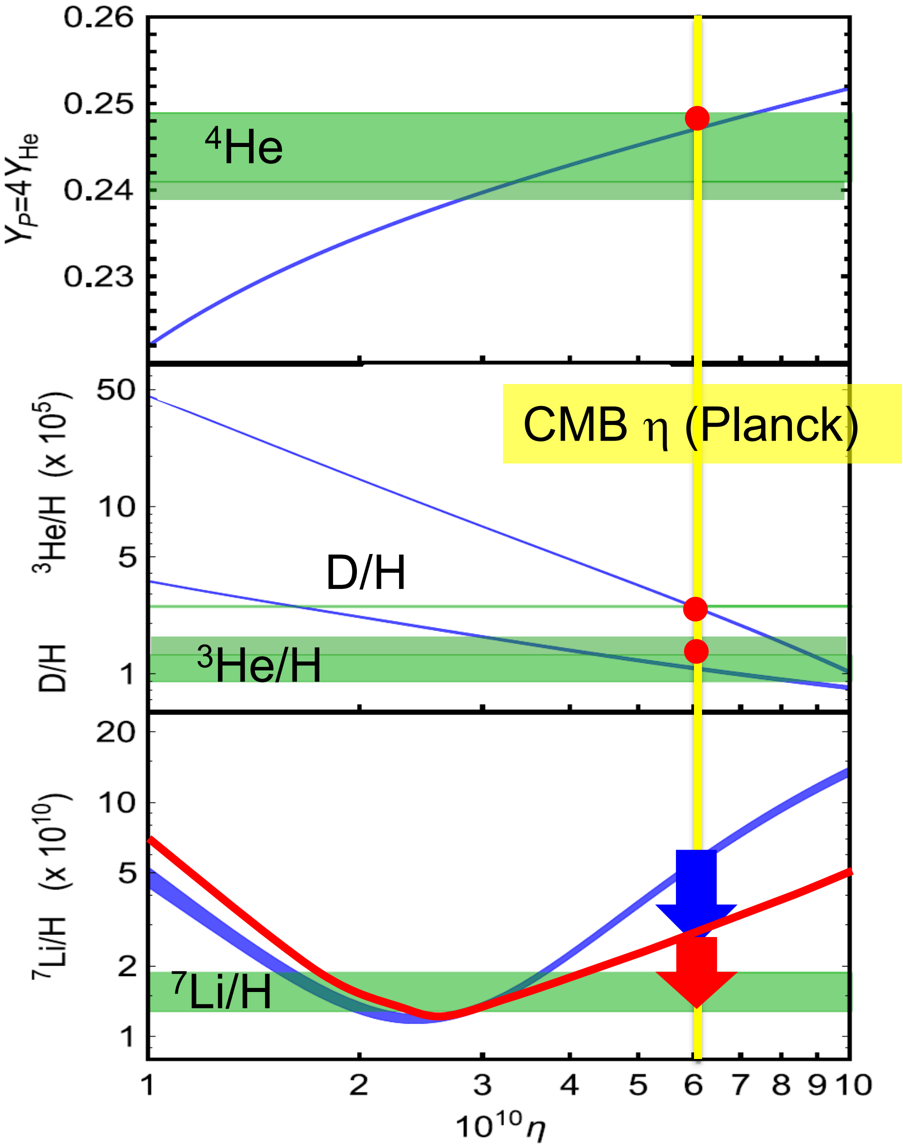
INHOMOGENEOUS Primordial Magnetic Field Fluctuations

Y. Luo, T. Kajino, M. Kusakabe, G. J. Mathews, Astrophys. J. 872 (2019),172.

^{7}Li-problem, remarkably relaxed !

Needs
The Other Effects such as:

Stellar/Astration Effect, PMF dissipation, DM particle decay, or Nucl. React.



Mass of W Boson : $\varepsilon = 0.06\%$ **excess** $M_W = M_{W0}\,(1+\varepsilon)$

$M_W = 80.385\ \mathrm{GeV}/c^2 \rightarrow M_W = 80{,}433.5 \pm 9.4\ \mathrm{MeV}/c^2 \neq \mathrm{SM}$ → **Too large ?**

(CDF Collaboration, Science 376 (2022), 170–176.)

Neutron Lifetime : **0.24% increase** $\tau = \tau_0\,(1+\varepsilon)^4 \sim \tau_0\,(1+4\varepsilon) \quad \because \quad \tau \propto M_W{}^4$

$$\frac{1}{\tau} = \int_{m_e c^2}^{E_0} \frac{dW}{dE_e}\,dE_e = \int_{m_e c^2}^{E_0} \frac{2\pi}{\hbar}\,|\mathcal{M}_{fi}|^2\,\frac{d\varrho_f(E_0, E_e)}{dE_e}\,dE_e$$

$$|\mathcal{M}_{fi}|_{\mathrm{F}} = \frac{G_{\mathrm{F}}}{V} c_{\mathrm{V}} \left|\langle \mathrm{uud}| \sum^{3} T_{i,+} |\mathrm{udd}\rangle\right| \qquad \propto g_V{}^2$$

$$|\mathcal{M}_{fi}|_{\mathrm{GT}} = \frac{G_{\mathrm{F}}}{V} c_{\mathrm{A}} \left|\langle \mathrm{uud}| \sum_{i=1}^{3} T_{i,+}\boldsymbol{\sigma} |\mathrm{udd}\rangle\right| \qquad \propto 3g_A{}^2$$

$$\frac{G_F}{\sqrt{2}} = \frac{\pi\alpha}{2} \cdot \frac{g^2}{e^2} \cdot \frac{(\hbar c)^3}{M_{\mathrm{W}}^2 c^4} \quad \propto \quad (M_W/g)^{-2}$$

Standard Model

(Glashow-Weinberg-Salam)

$G_F = v^2/\sqrt{2}$ (← μ-life!)

$M_W = gv/2$

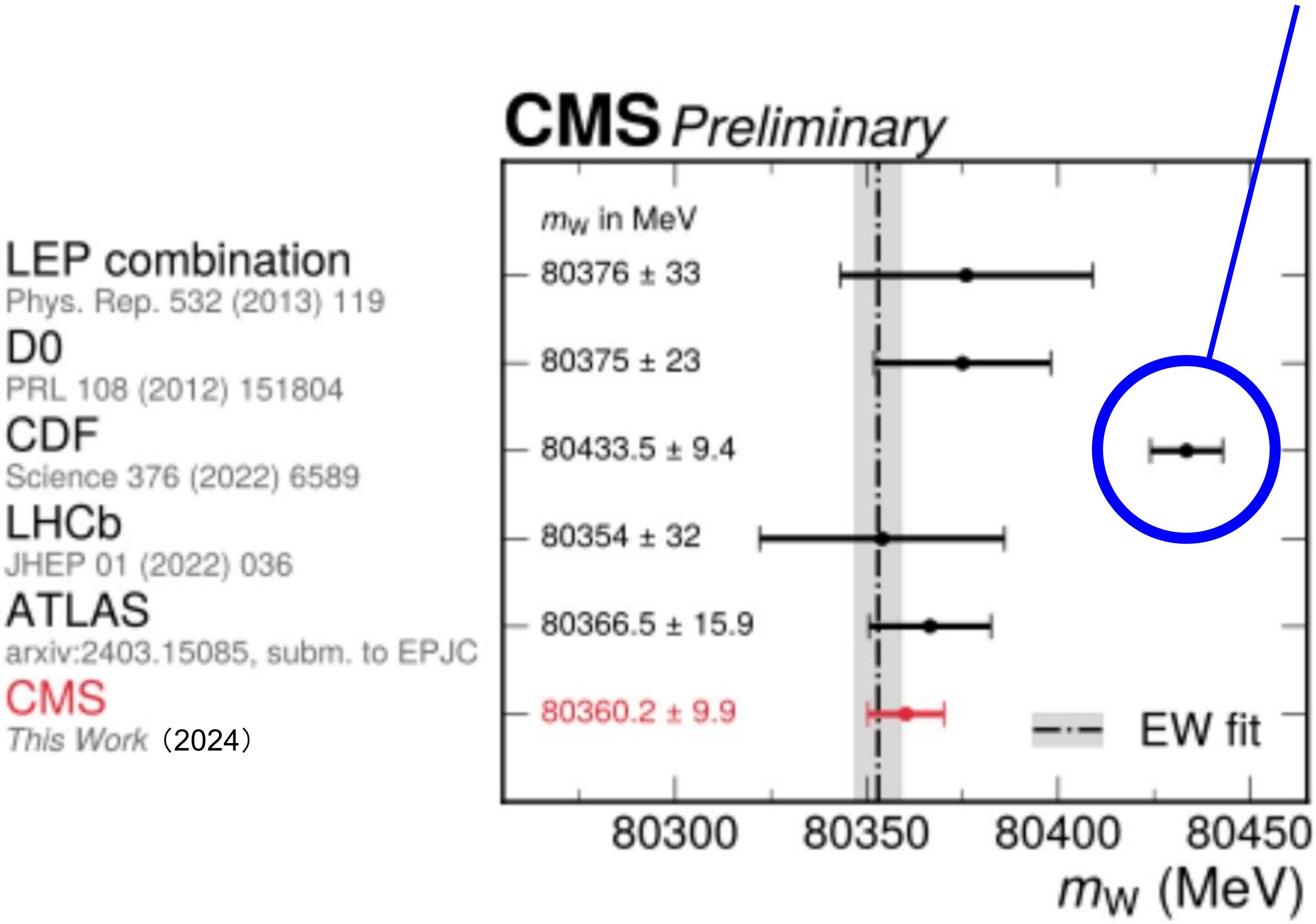
$v = \langle 0|\phi|0\rangle$: Higgs field

g = SU(2) gauge x Fermion coupl. const.

Cabbibo-Kobayashi-Masukawa matrix elemernts

$$\begin{pmatrix} \boxed{V_{ud}} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} \boxed{0.9745 \cdots 0.9760} & 0.217 \cdots 0.224 & 0.0018 \cdots 0.0045 \\ 0.217 \cdots 0.224 & 0.9737 \cdots 0.9753 & 0.036 \cdots 0.042 \\ 0.004 \cdots 0.013 & 0.035 \cdots 0.042 & 0.9991 \cdots 0.9994 \end{pmatrix}$$

Measurement of the W bson mass in proton-proton collisions at √s= 13 TeV

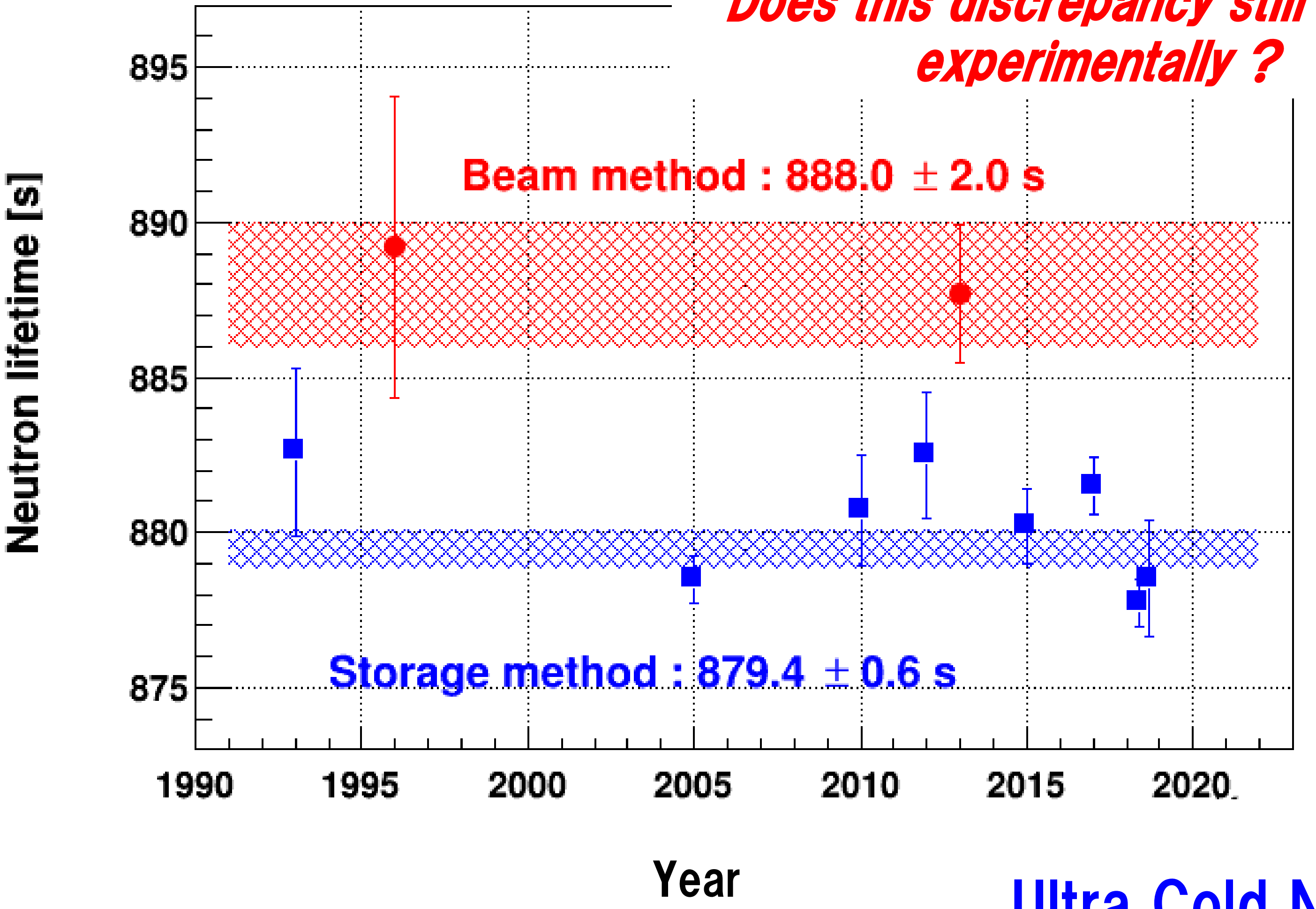


Too large ?

Neutron Lifetime Measurements $n \rightarrow p + e^{-} + \overline{\nu}_e$

Sasha!

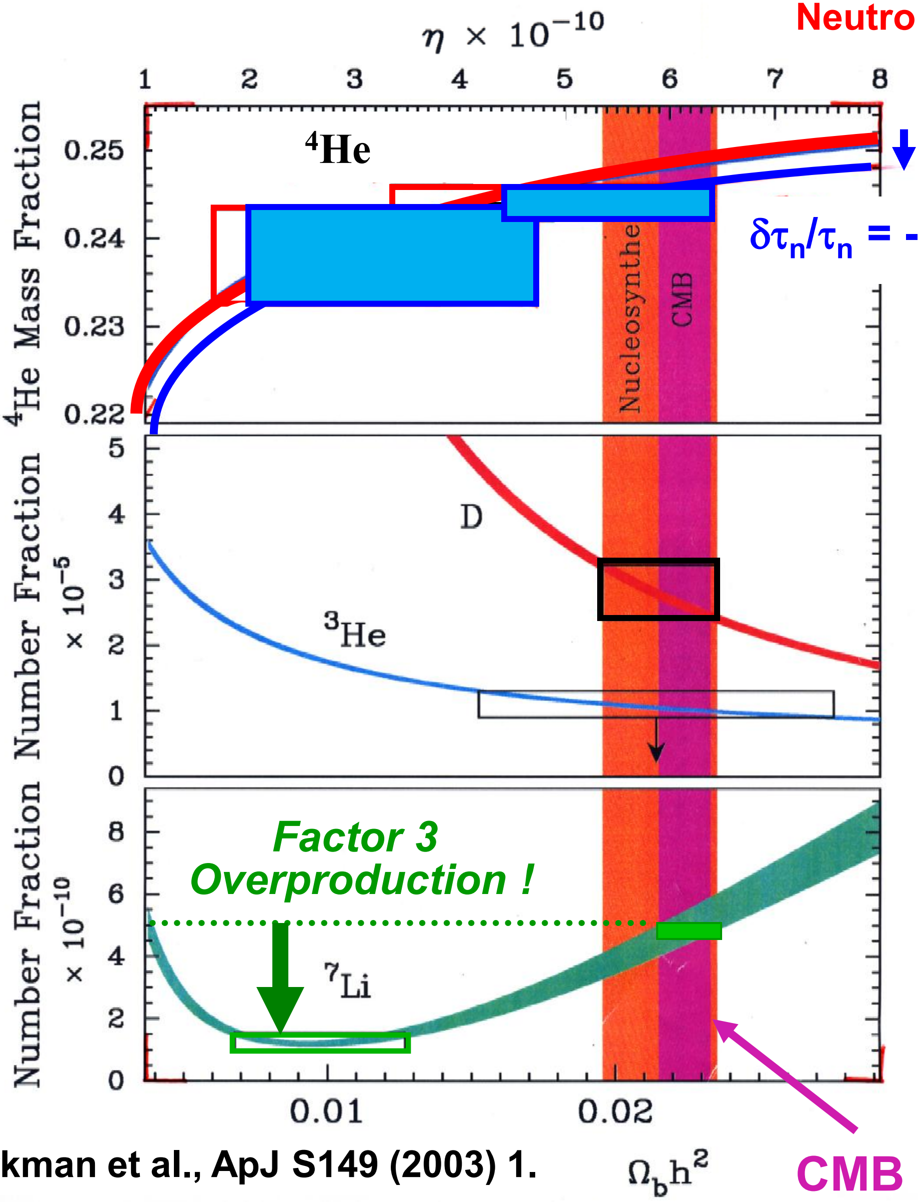
Does this discrepancy still remain experimentally ?



Ultra Cold Neutron

Big-Bang Nucleosynthesis, 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

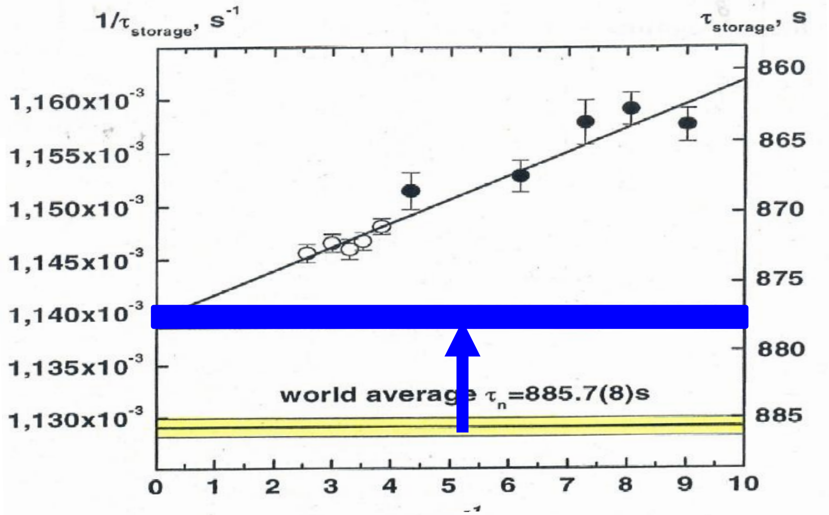
Factor 3 Overproduction !

CMB

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

UCN Experiment

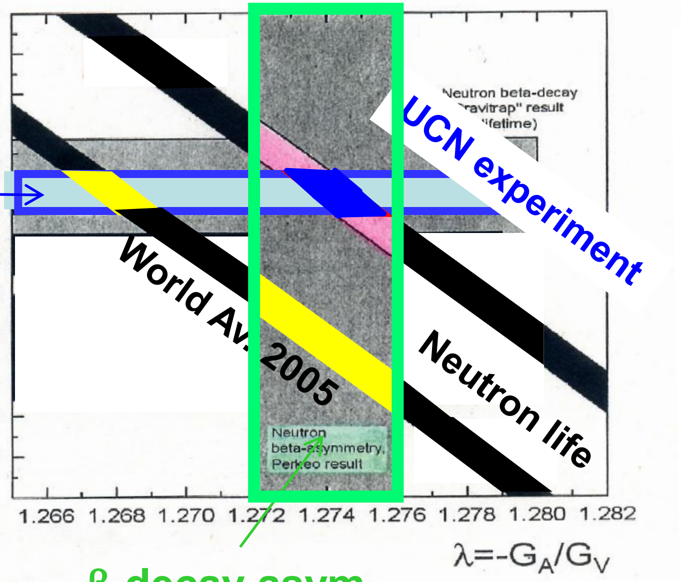
Serevlov et al., PL B605 (2005), 72.



CKM Matrix V_{ud}

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

$u \rightarrow d$



β-decay asym.

New Physics ? : BBN constraint on neutrino magnetic moment

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

Cosmological: $\nu_S \longrightarrow \nu + \gamma_{NT}$ ➡ **Photodisintegration of BBN nuclei**

$D + \gamma_{NT} \rightarrow p + n$

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

active/sterile

Magnetic Moment of massive neutrino X

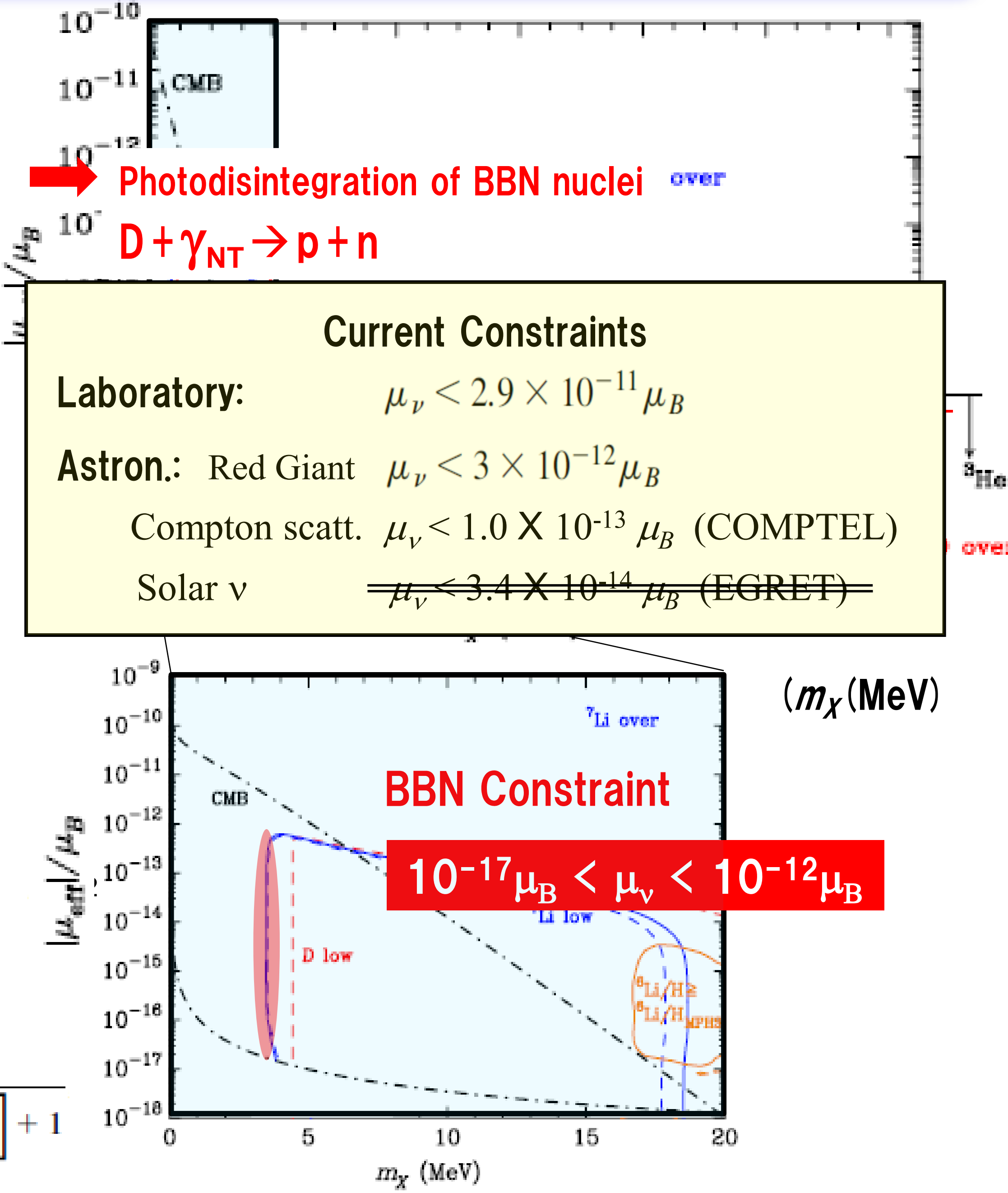
$$|\mu_{\rm eff}|^2 = |\mu_{ij}|^2 + |\epsilon_{ij}|^2.$$

$$\boxed{\tau_X^{-1}} = \frac{|\mu_{ij}|^2 + |\epsilon_{ij}|^2}{8\pi}\left(\frac{m_i^2 - m_j^2}{m_i}\right)^3 = 5.308\ {\rm s}^{-1}\left(\frac{\mu_{\rm eff}}{\mu_B}\right)^2\left(\frac{m_i^2 - m_j^2}{m_i^2}\right)^3\left(\frac{m_i}{\rm eV}\right)^3$$

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

$$\boxed{\frac{n_X}{n_\gamma}} = \frac{4}{11}\frac{n_{dX}(m_X)}{n_\gamma(T_d)} = \frac{2\pi^2}{11\zeta(3)}\frac{n_{dX}(m_X)}{T_d^3}.$$

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



Current Constraints

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

Astron.: Red Giant $\mu_\nu < 3 \times 10^{-12}\mu_B$

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

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

BBN Constraint

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

Li problem in Red-Clump Stars

Kumar et al. (2020),
Nature Astron.

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

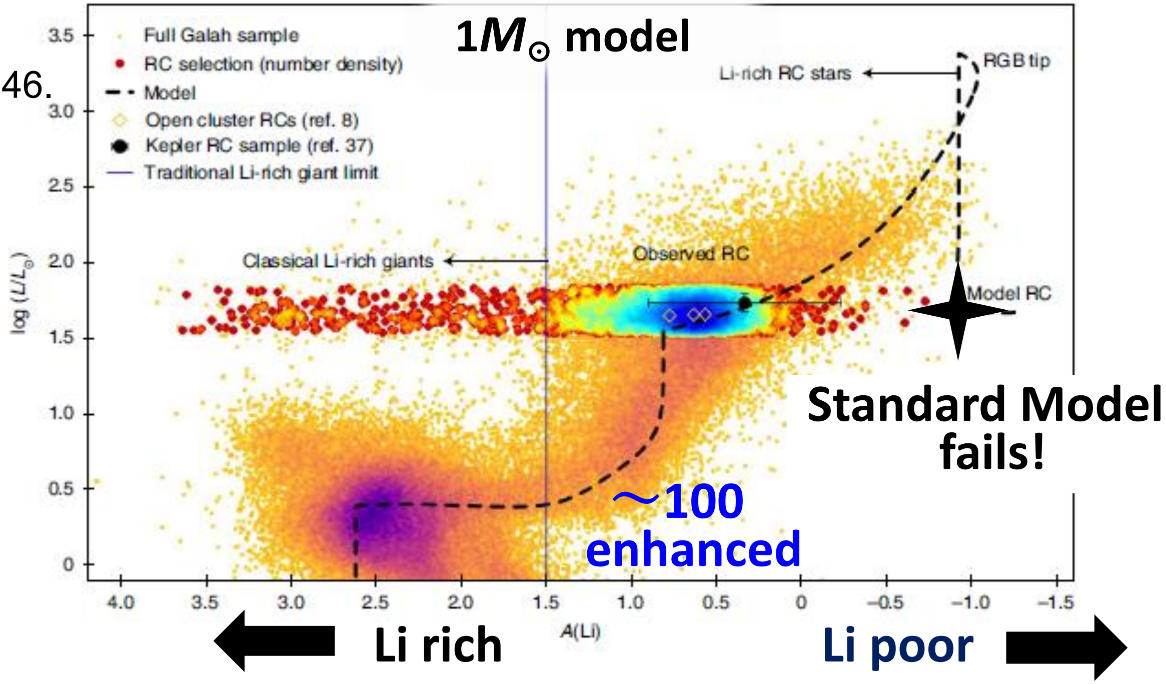
Fowler-Cameron mechanism

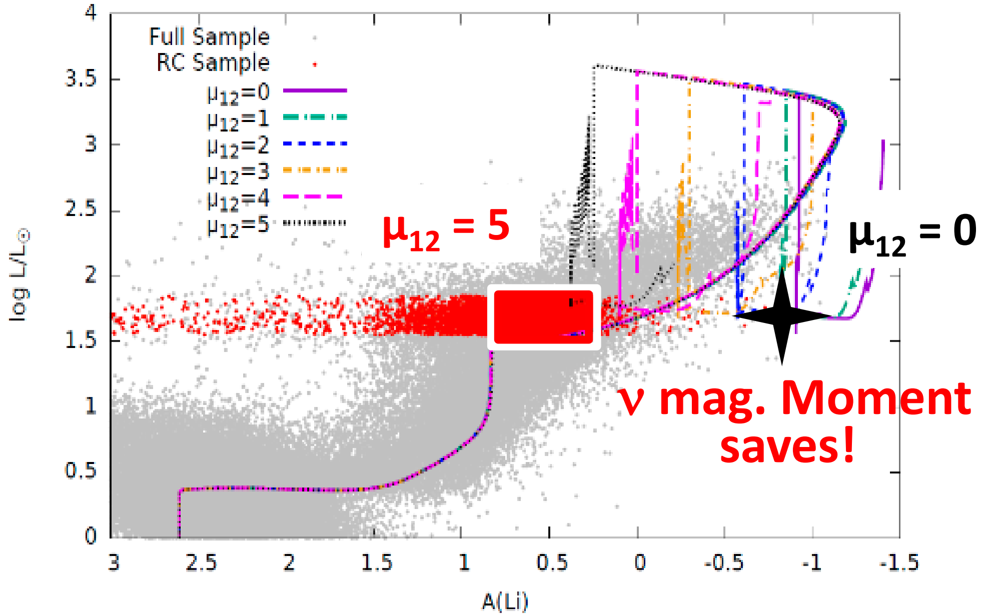
$^4He(^3He,\gamma)^7Be(e^-,\nu_e)^7Li$

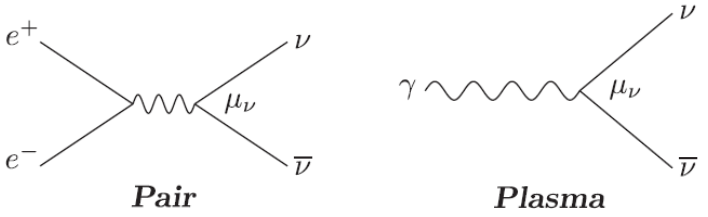
Additional energy loss induced by neutrino magnetic moment

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

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







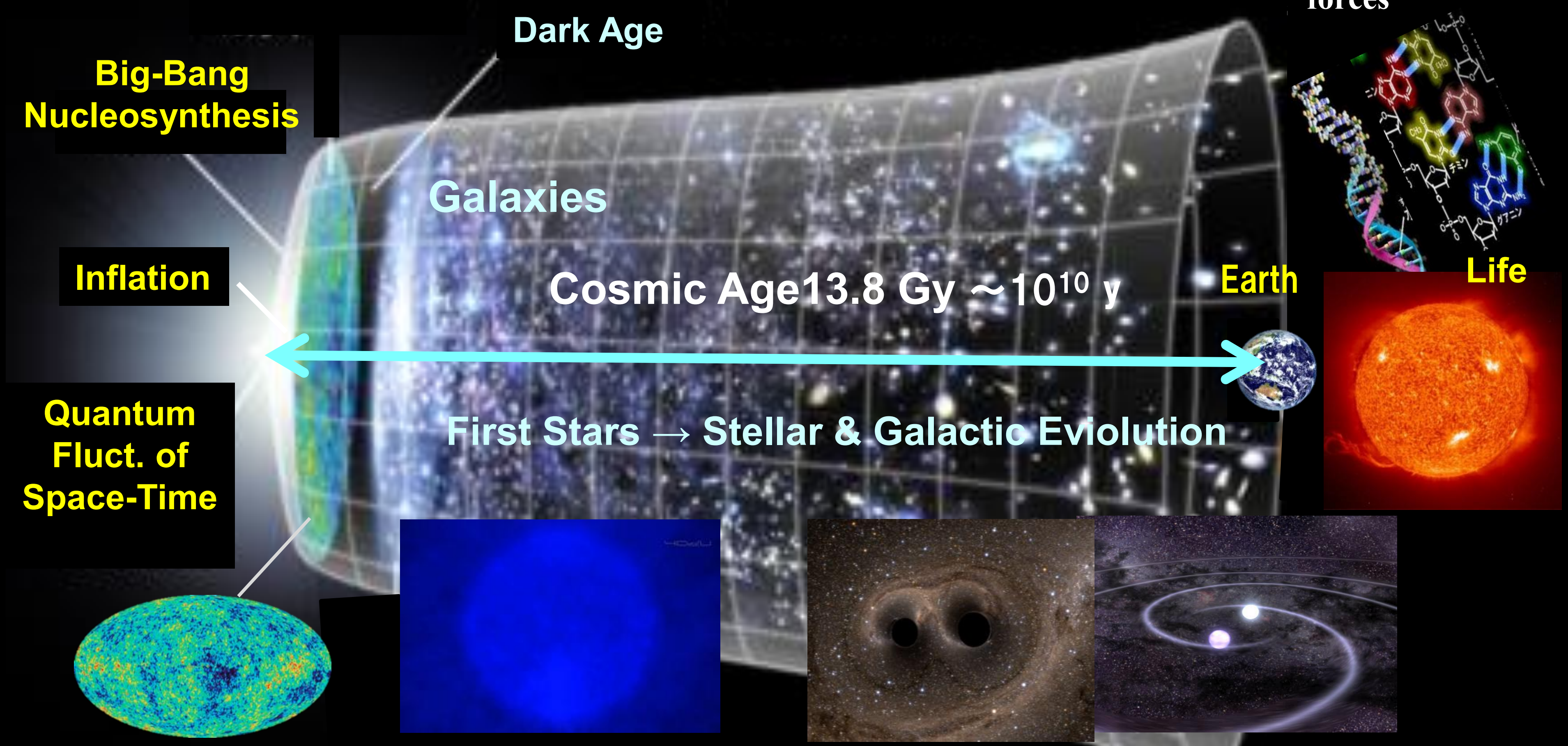
Heger et al., ApJ 696 (2009), 608.

Standard parameter of efficiency of
internal mixing : α_{thm}=100

Origin of Elements and Roles of Neutrinos in Cosmic Evolution

— 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

CMB Fluctuation
3.8×10^5 y

Collapsar & Supernova

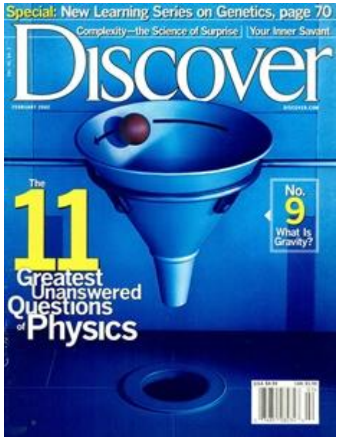
$\tau \sim 1$ My Long-GRB

GRB090423 (z=8.2) ~ 13.1 Gly

Binary BH or Neutron-Star Merger

100 My < τ Short-GRB

GW170817 ~ 0.13 Gly



11 Unsolved Mysteries of Physics in the 21st Century

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

Q3 How were the heavy elements made?

Q4 Why do neutrinos have mass?

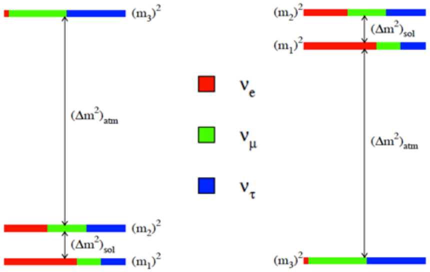
Finite ν-mass, the only unique evidence to go "beyond the standard model".

Why Neutrinos and Element Genesis?

(1) ~~Mass~~, (2) Hierarchy, (3) ~~δ_{CP}~~ (4) Dirac/Majorana ?

Hierarchy, still unknown !

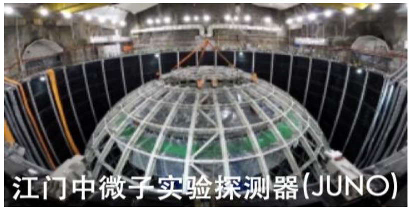
Normal ~ 0.05 eV **Inverted** ~ 0.1 eV

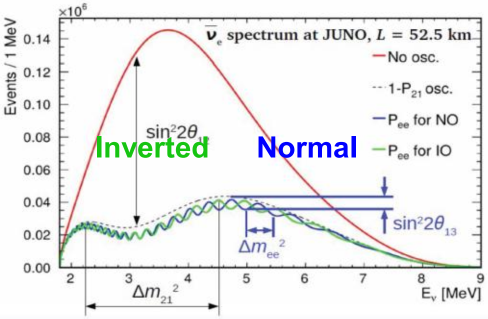


$$\Delta m^2_{12} = 7.9 \times 10^{-5} eV^2$$

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

Vacuum



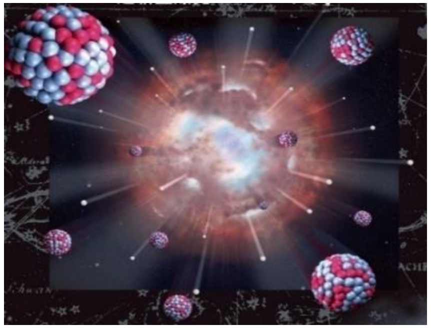


< a few % precision is required!

Any observables in flavor oscillations do not depend on δ_{CP} when

(Yokomakura et al., Phys. Lett. B544, 286)

ν-oscil. @ high density



Supernova : $E\nu_e < E\bar{\nu}_e < E\nu_\mu = E\nu_\tau$

Factor ~ 3 (300%) sensitivity !

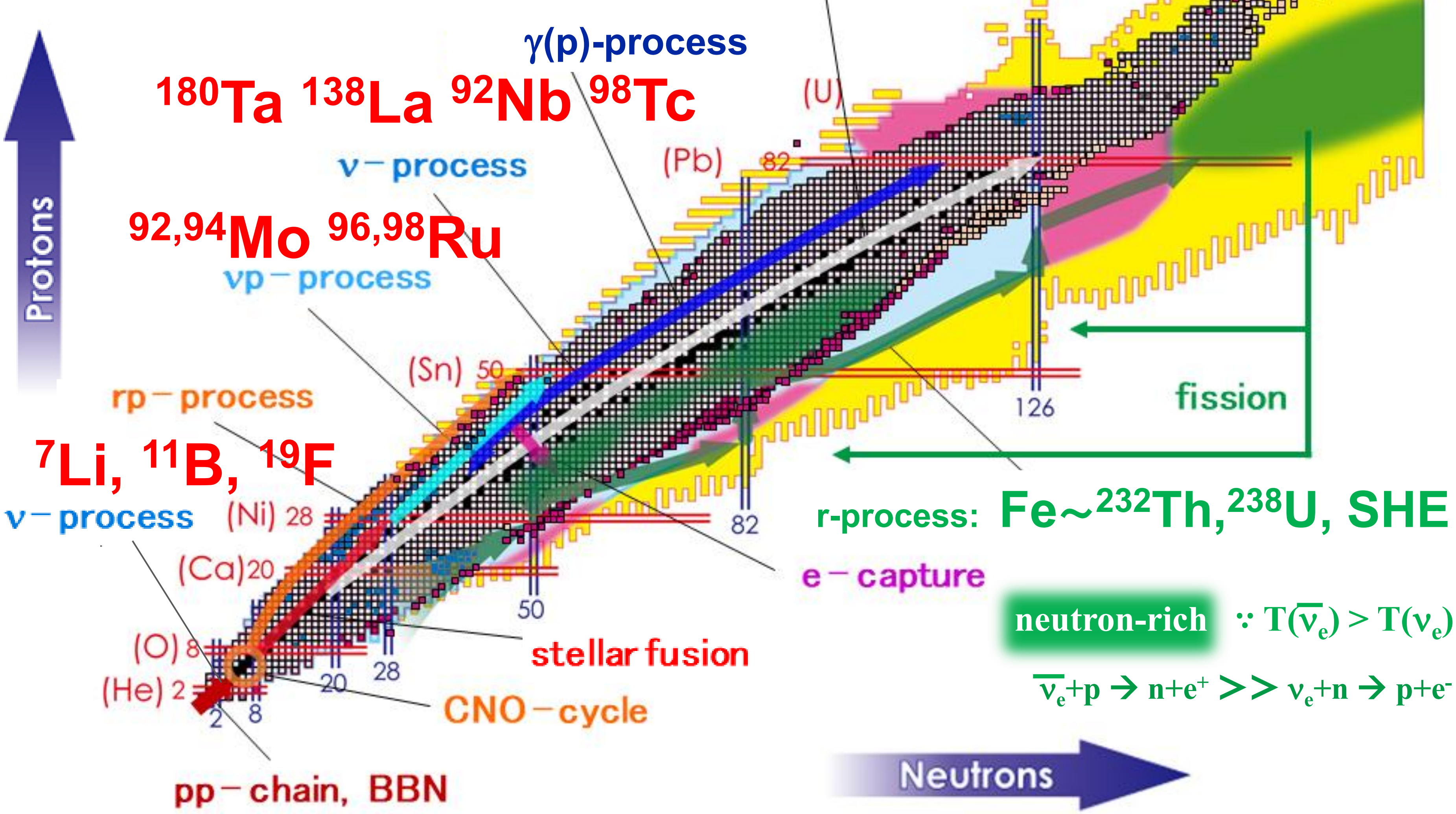

Fowler Hoyle


J. & M. Burbidge

Origin of r-process Elements ?

— Long-standing Question —

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



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

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

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

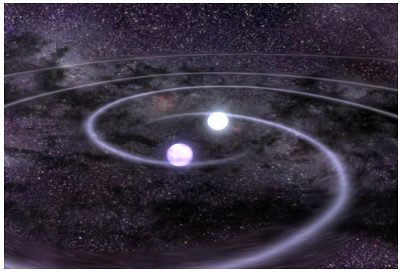
r-process: Fe~^{232}Th,^{238}U, SHE

neutron-rich $\because T(\overline{\nu}_e) > T(\nu_e)$

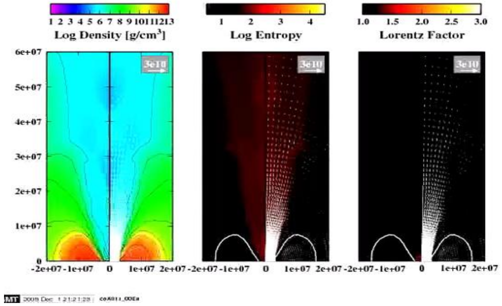
$\overline{\nu}_e + p \rightarrow n + e^+ >> \nu_e + n \rightarrow p + e^-$

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

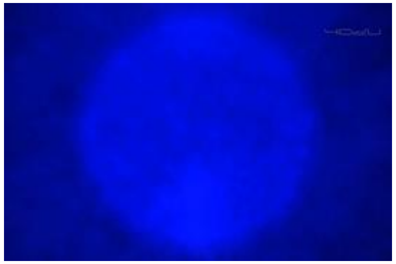
Neutron Star Merger

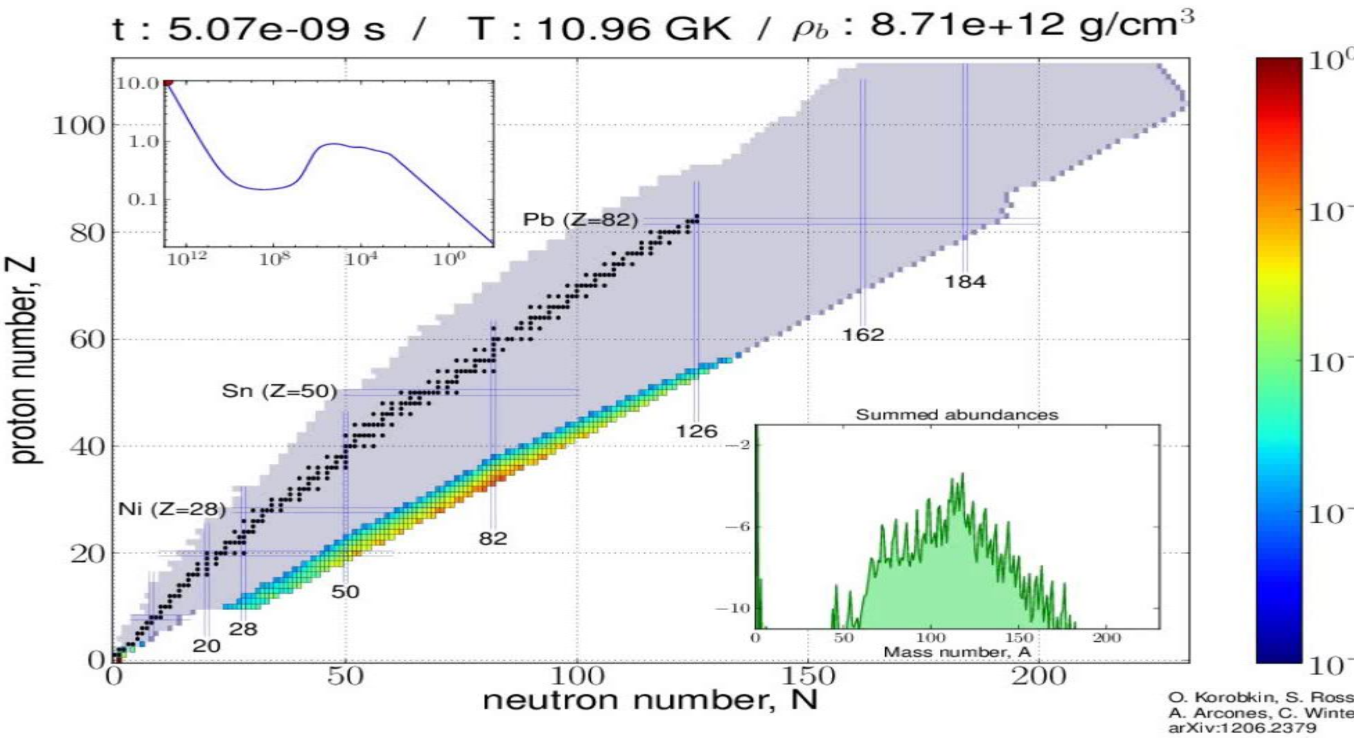


Collapsar Jet

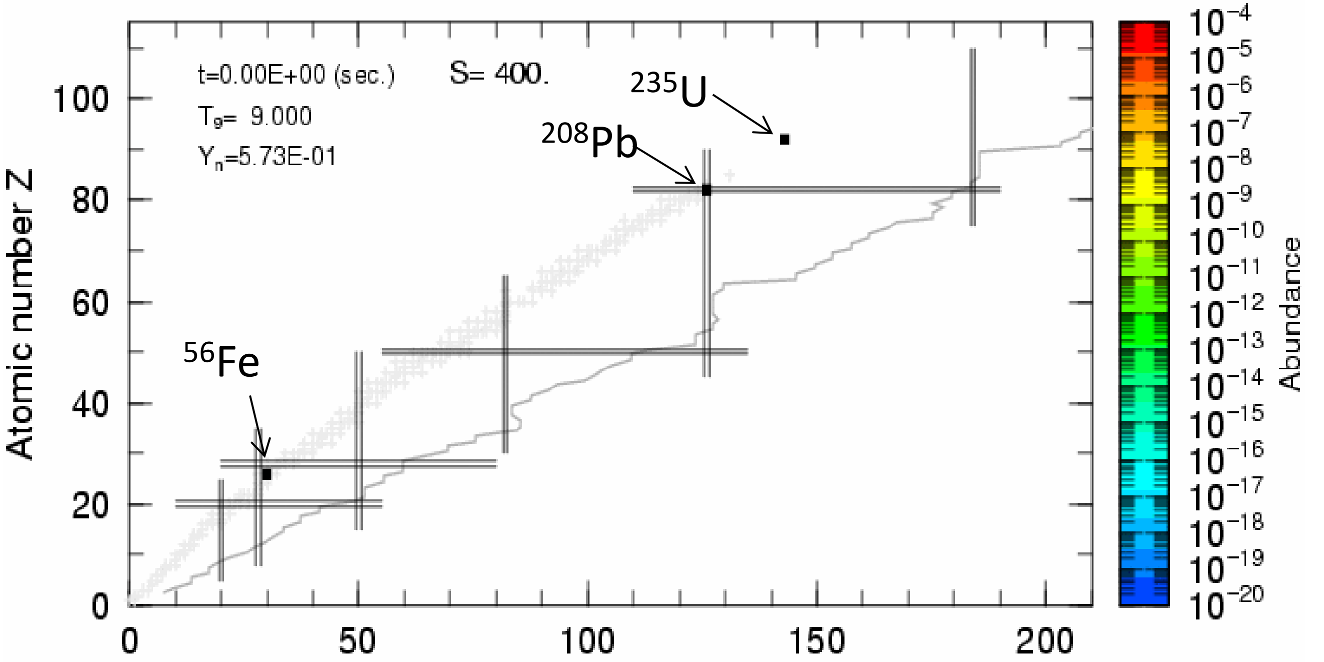


MHD Jet Supernova



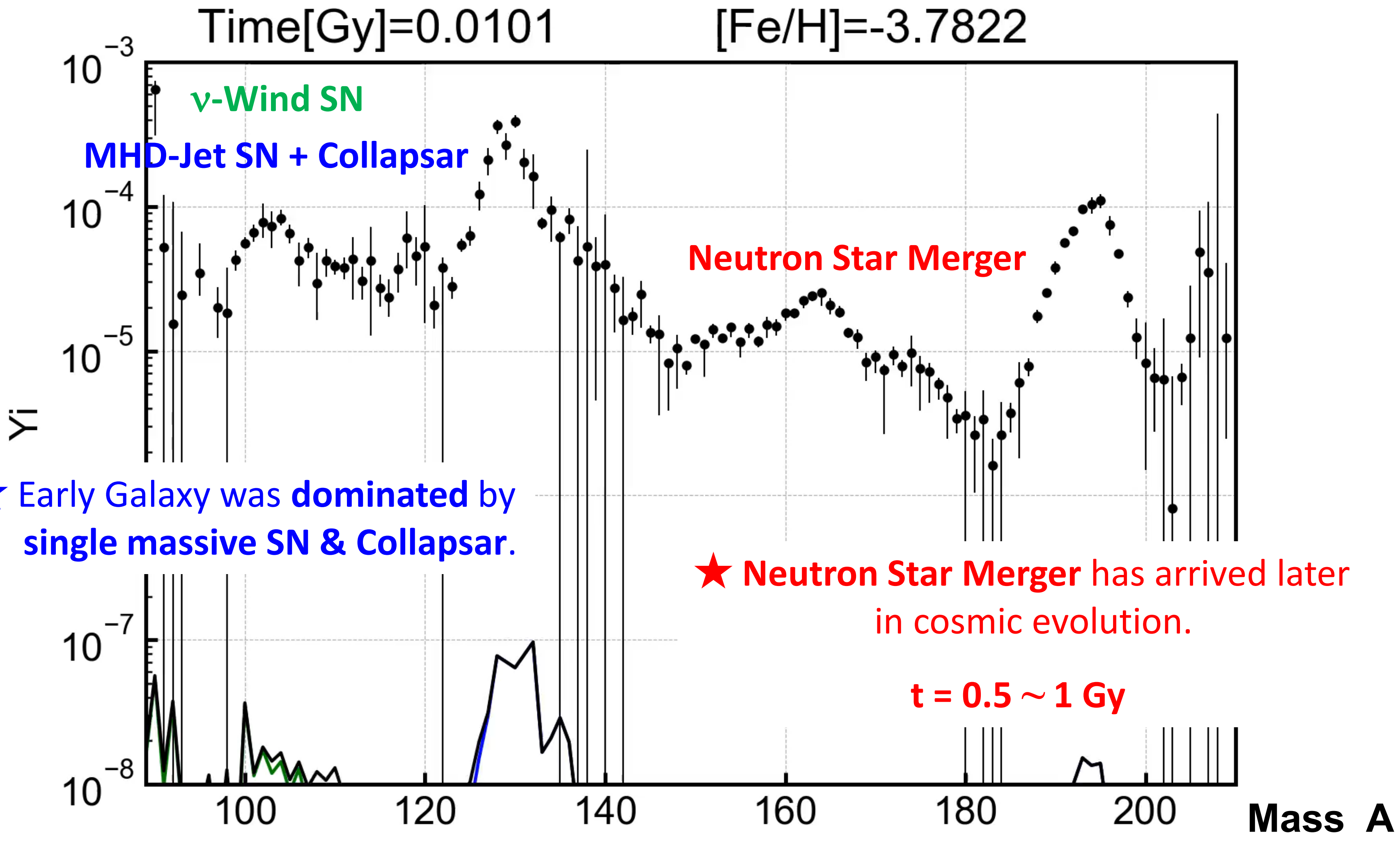


O. Korobkin, S. Ross
A. Arcones, C. Winte
arXiv:1206.2379



Cosmic & Galactic Evolution, based on F. Timmes model

$t/10\text{Gy} = 10^{[\text{Fe/H}]}$ ⟷ $[\text{Fe/H}] = \log(N_{\text{Fe}}/N_{\text{H}})_{\star} - \log(N_{\text{Fe}}/N_{\text{H}})_{\odot}$



★ Early Galaxy was **dominated** by **single massive SN & Collapsar**.

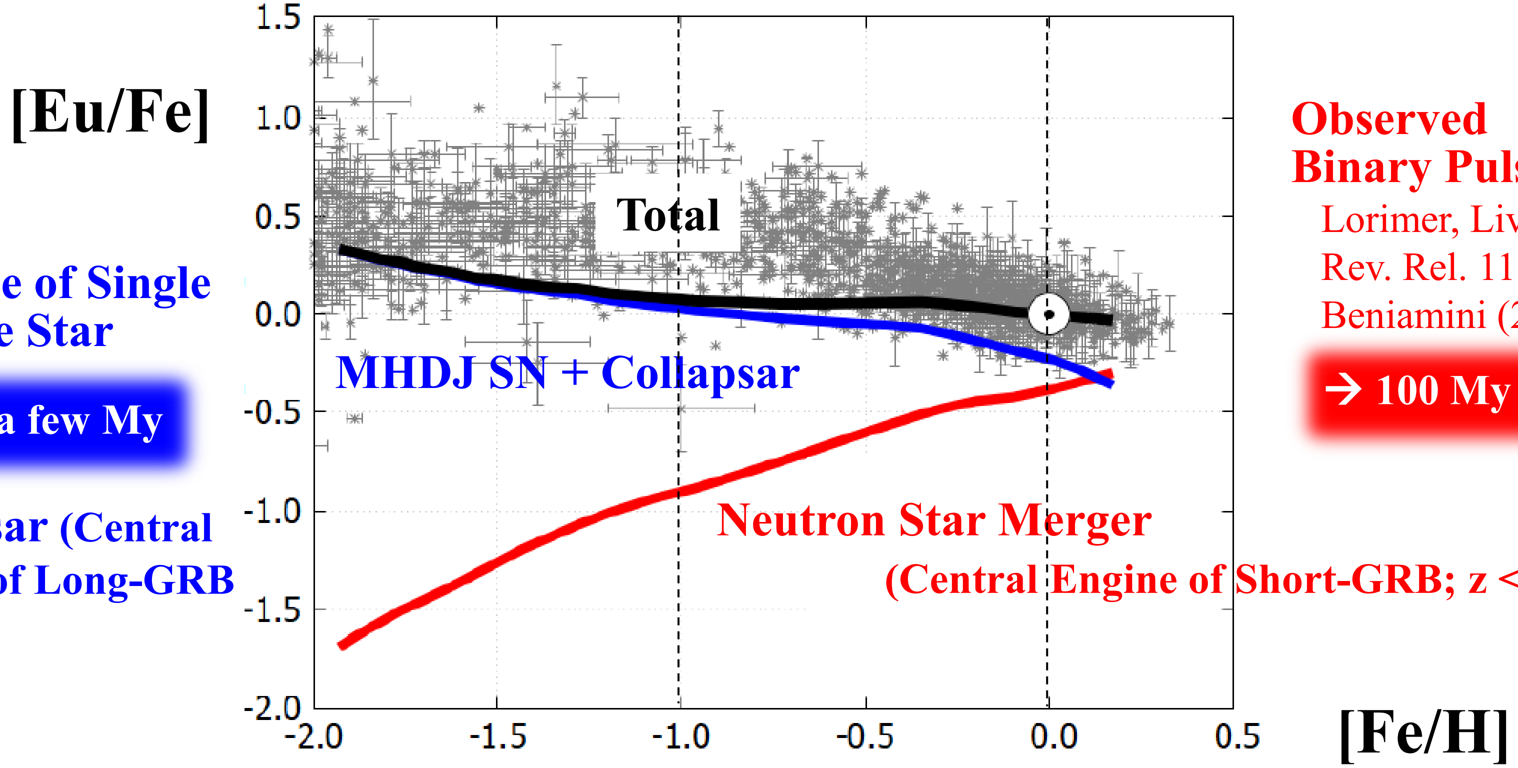
★ **Neutron Star Merger** has arrived later in cosmic evolution.

t = 0.5 ~ 1 Gy

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

Coalescence Time Delay of of Neutron Star Merger (NSM)

Yamazaki, He, Kajino, et al., ApJ 933 (2022), 112 ; Zhenyu He, Kajino, et al., ApJ Lett 966 (2024), L34 ;
Kobayashi, Karakas & Lugaro, ApJ 900 (2020), 179.



Lifetime of Single Massive Star

τ_{life} ~ a few My

Collapsar (Central Engine of Long-GRB ; z < 8)

Observed Binary Pulsars

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

→ 100 My < τ_{delay}

(Central Engine of Short-GRB; z < 1)

BB

100 My

1 Gy

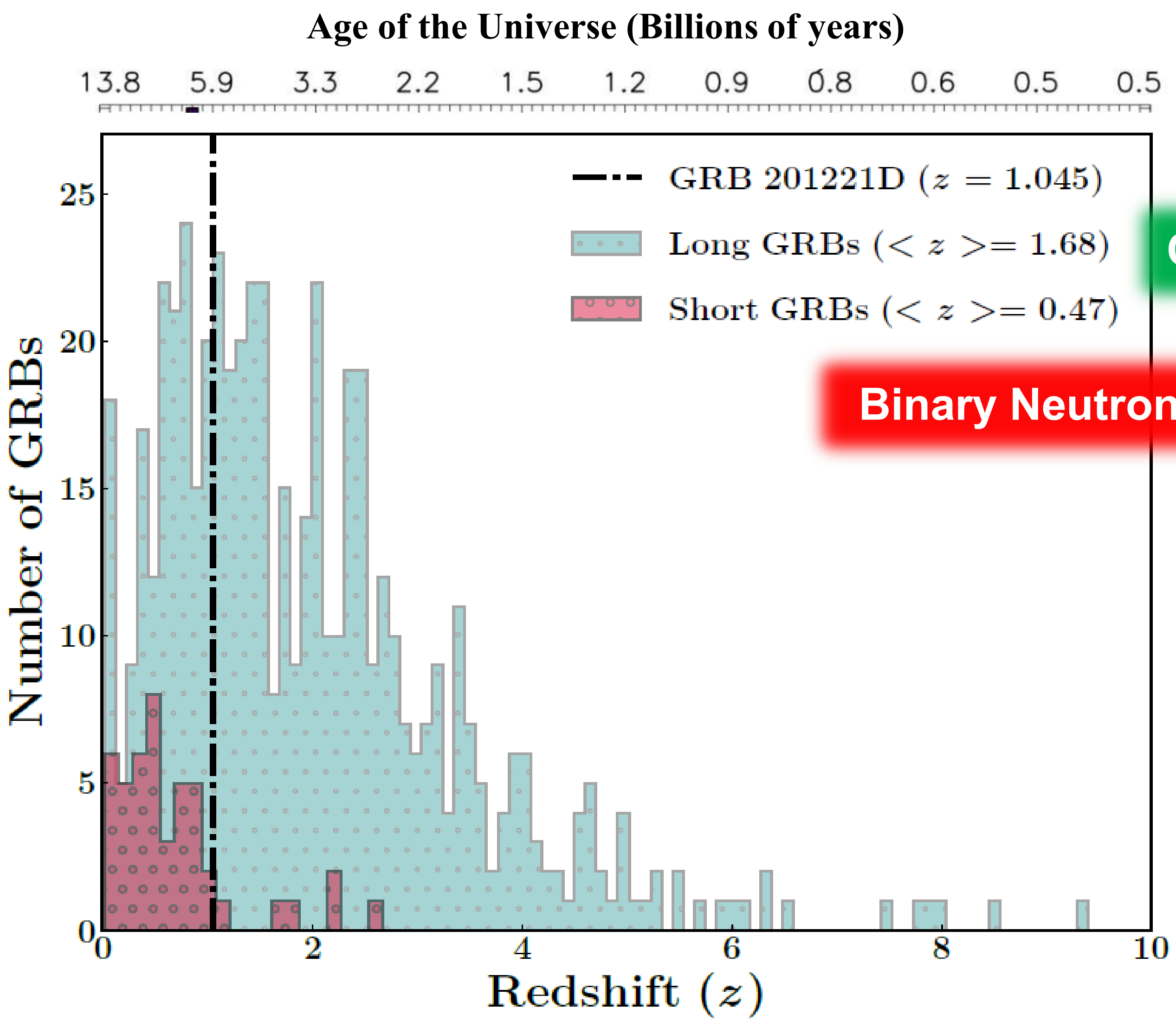
10 Gy

Now =13.8 Gy

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

Redshift – Age relation of Gamma-Ray Bursts

Dimple, et al., MNRAS (2022) 516, Issue 1, pp.1-12



Collapsar

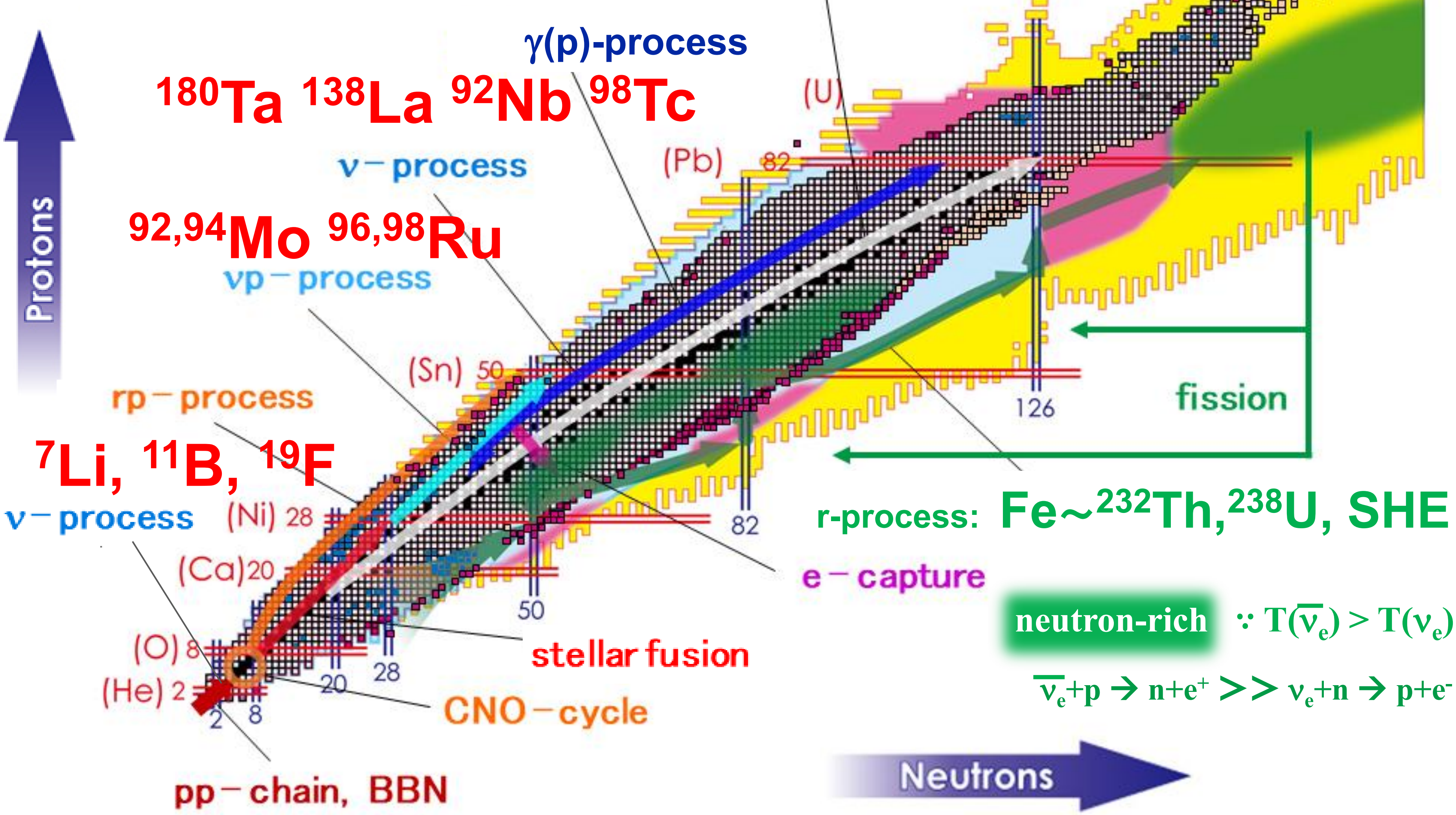
Binary Neutron-Star Merger

Origin of Li-B ~ Rare p-Isotopes ?

— Long-standing Question —

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

J. & M. Burbidge



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

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

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

r-process: Fe~^{232}Th,^{238}U, SHE

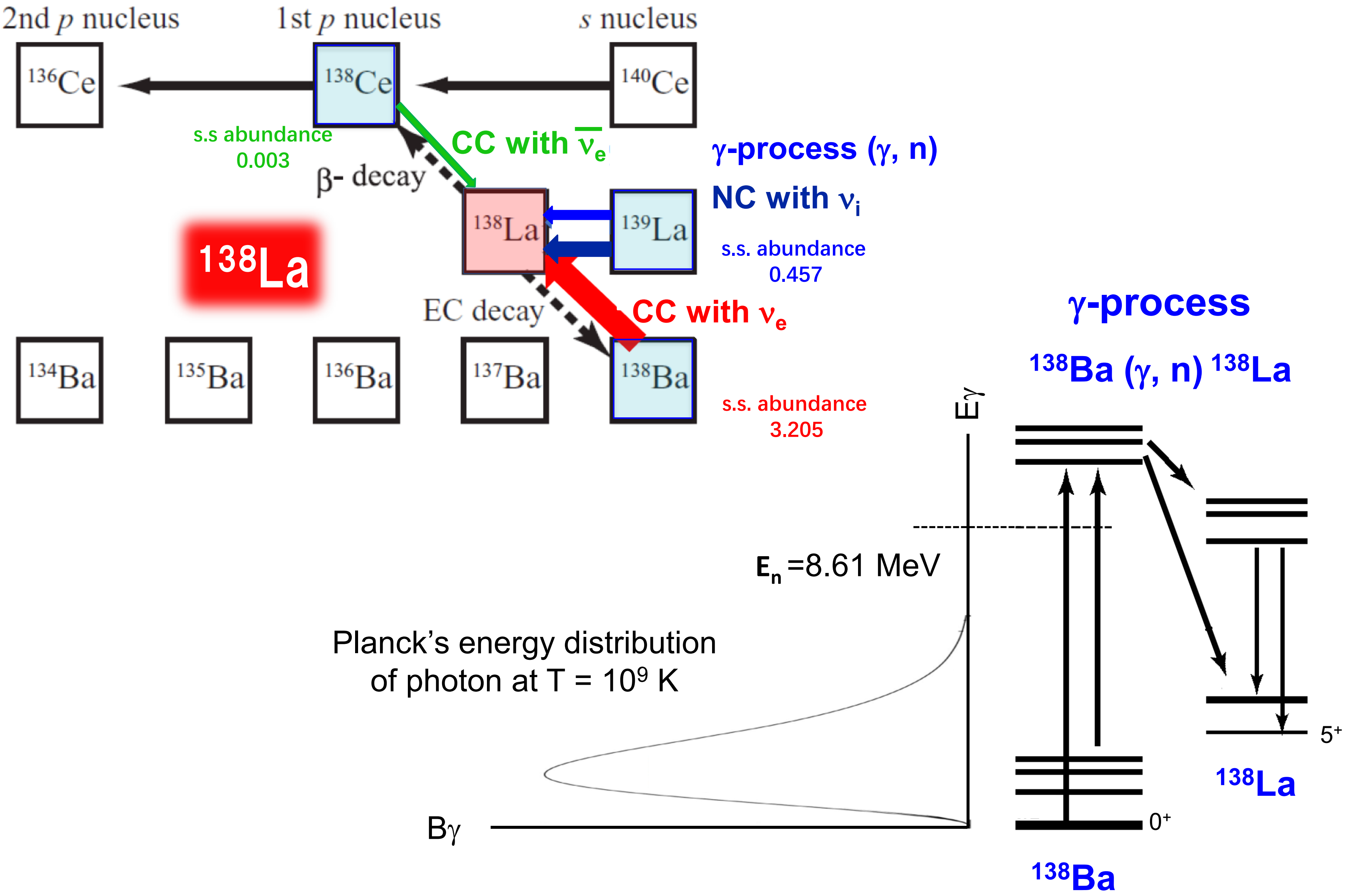
neutron-rich $\because T(\overline{\nu}_e) > T(\nu_e)$

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

Why ^{138}Ba(ν, e$^-$)^{138}La dominates over ^{139}La(γ, n)^{138}La ?

Weak - process

EM - process



2nd *p* nucleus

1st *p* nucleus

s nucleus

^{136}Ce

^{138}Ce

^{140}Ce

s.s abundance
0.003

CC with $\overline{\nu}_e$

β- decay

γ-process (γ, n)

NC with ν_i

^{138}La

^{139}La

s.s. abundance
0.457

^{138}La

EC decay

CC with ν_e

^{134}Ba

^{135}Ba

^{136}Ba

^{137}Ba

^{138}Ba

s.s. abundance
3.205

γ-process

^{138}Ba (γ, n) ^{138}La

Eγ

E_n =8.61 MeV

Planck's energy distribution
of photon at T = 10^9 K

Bγ

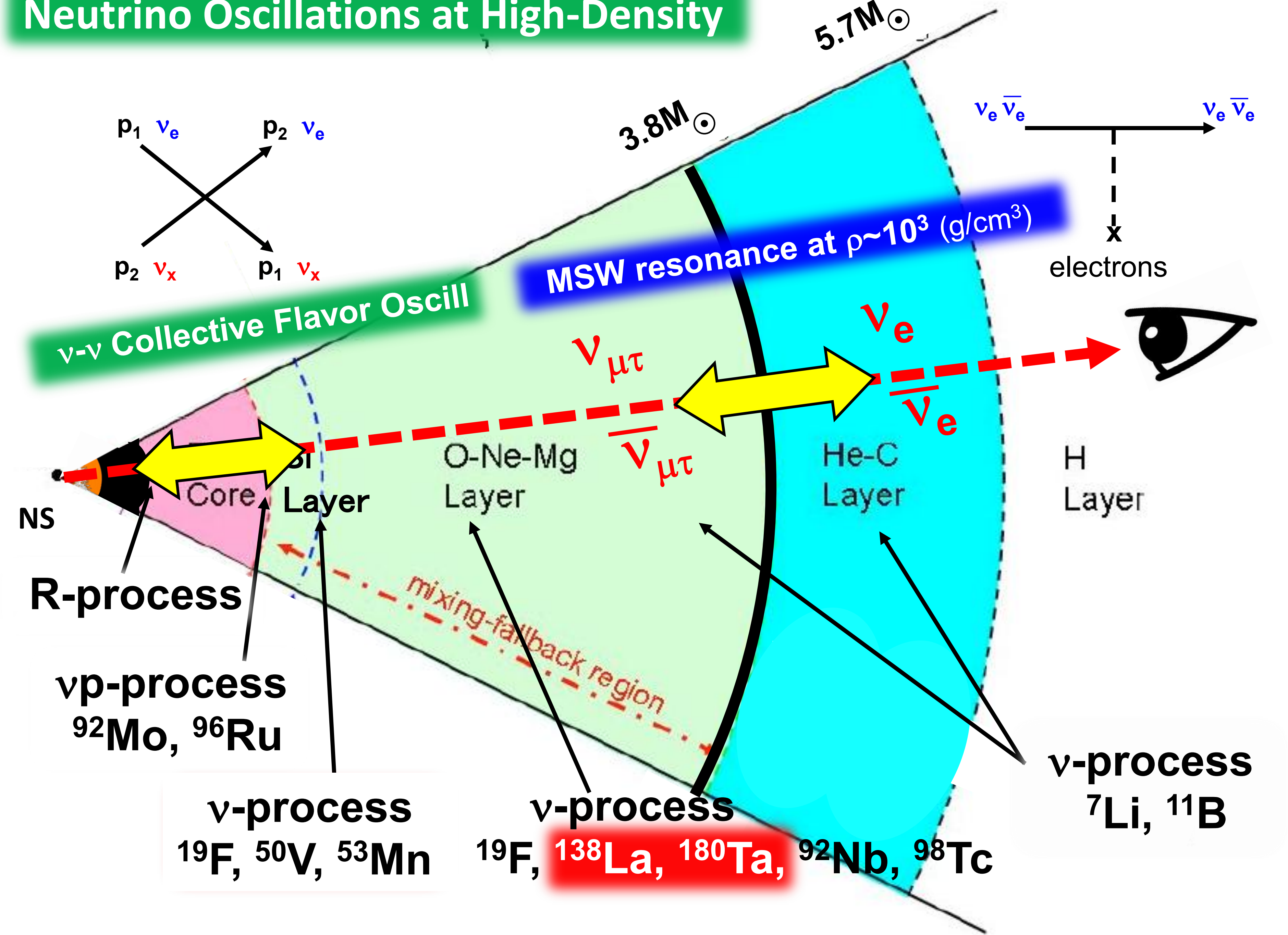
0^+

5^+

^{138}La

^{138}Ba

Neutrino Oscillations at High-Density



ν-ν Collective Flavor Oscill

MSW resonance at $\rho \sim 10^3$ (g/cm^3)

R-process

νp-process
^{92}Mo, ^{96}Ru

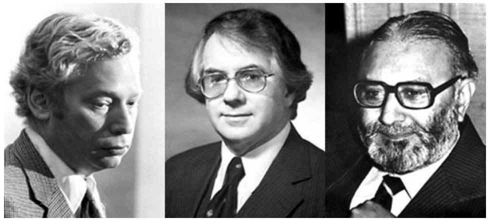
ν-process
^{19}F, ^{50}V, ^{53}Mn

ν-process
^{19}F, ^{138}La, ^{180}Ta, ^{92}Nb, ^{98}Tc

ν-process
^{7}Li, ^{11}B

ν-flavor Oscill. due to MSW + νν-Quantum Coll. Many-Body Effect

Unified Electroweak Theory,
Nobel Prize 1979



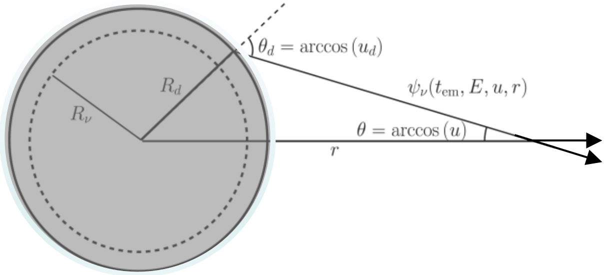
S. Weinberg S. Glashow A. Salam

A. B. Balantekin

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; Yao, Kajino, Luo et al. (2025), ApJ 980, 247.

proto-
Neutron Star

ν-sphere ~10km



GWS standard model

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

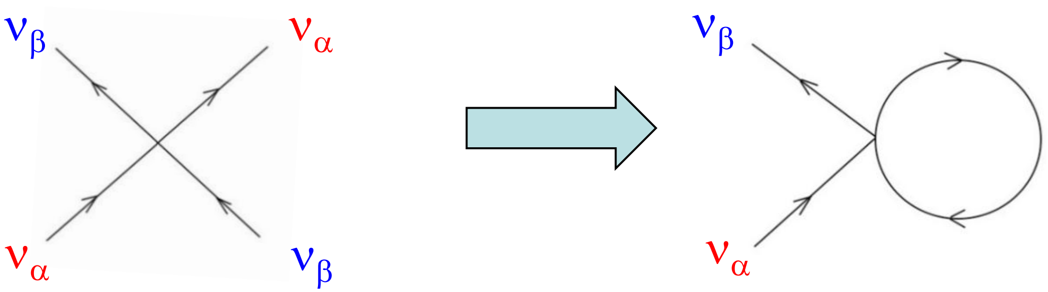
Vacuum

MSW

Collective flavor oscillation in coherent ν-ν scattering

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

ν angle dep !



α, β = e, μ, τ

10^{58} ν' s with 3-flavors & multi-angles ! → Mean Field Approx.

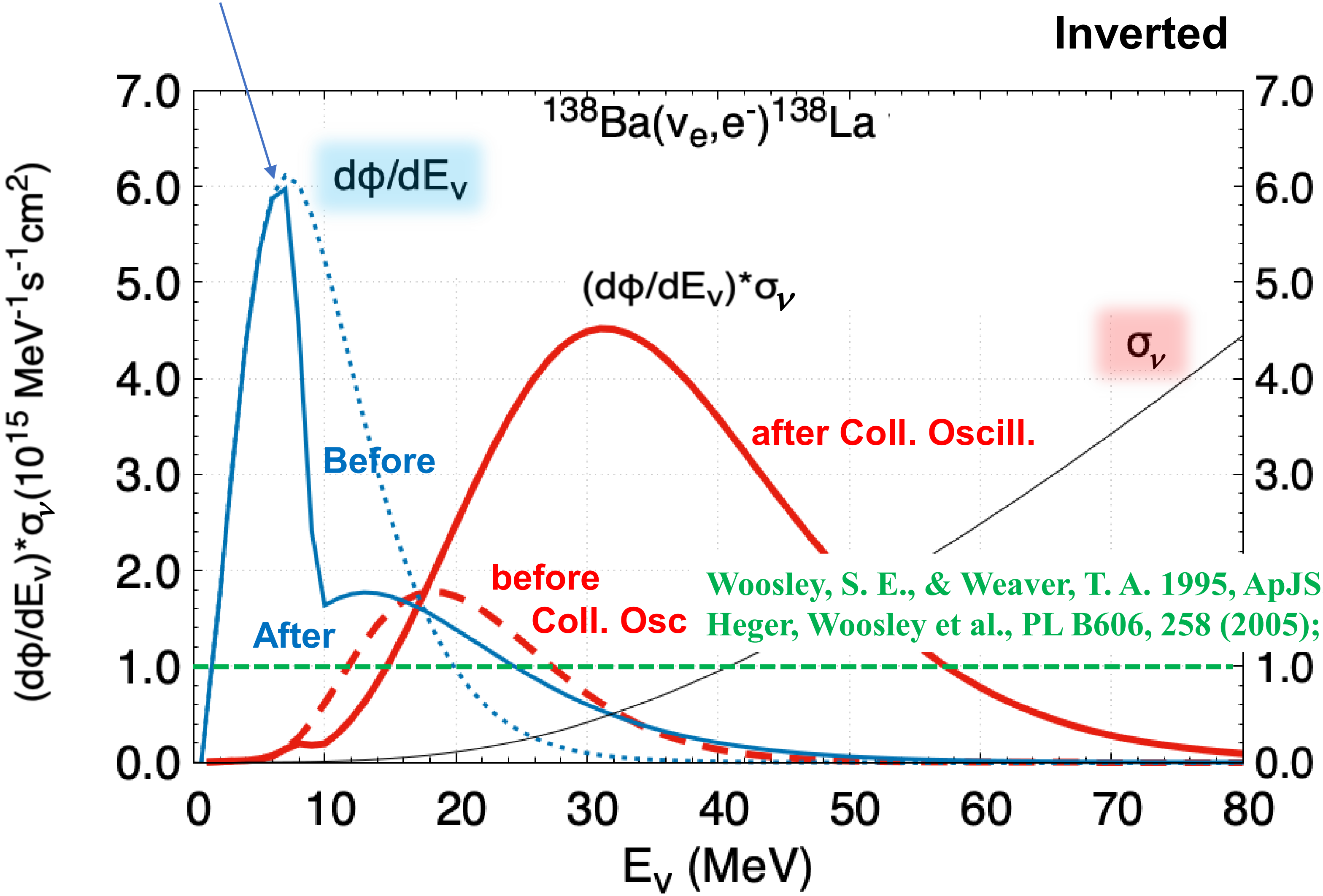
$^{138}\mathrm{Ba}(\nu_e, e^-)^{138}\mathrm{La}$

$$dn_{^{138}\mathrm{La}}/dt = \langle d\phi_\nu/dE_\nu\,\sigma_\nu c\rangle_R\, n_{^{138}\mathrm{Ba}}$$

$d\phi_\nu/dE_\nu \propto \nu$–spectrum

$\sigma_\nu \propto E_\nu{}^2$

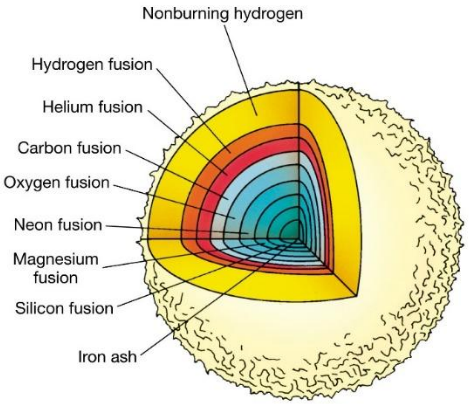
ν-Energy Spectral Change due to Collective Oscill. (Mean-field approx.)



Woosley, S. E., & Weaver, T. A. 1995, ApJS, 101, 181;
Heger, Woosley et al., PL B606, 258 (2005);

Calculated Result

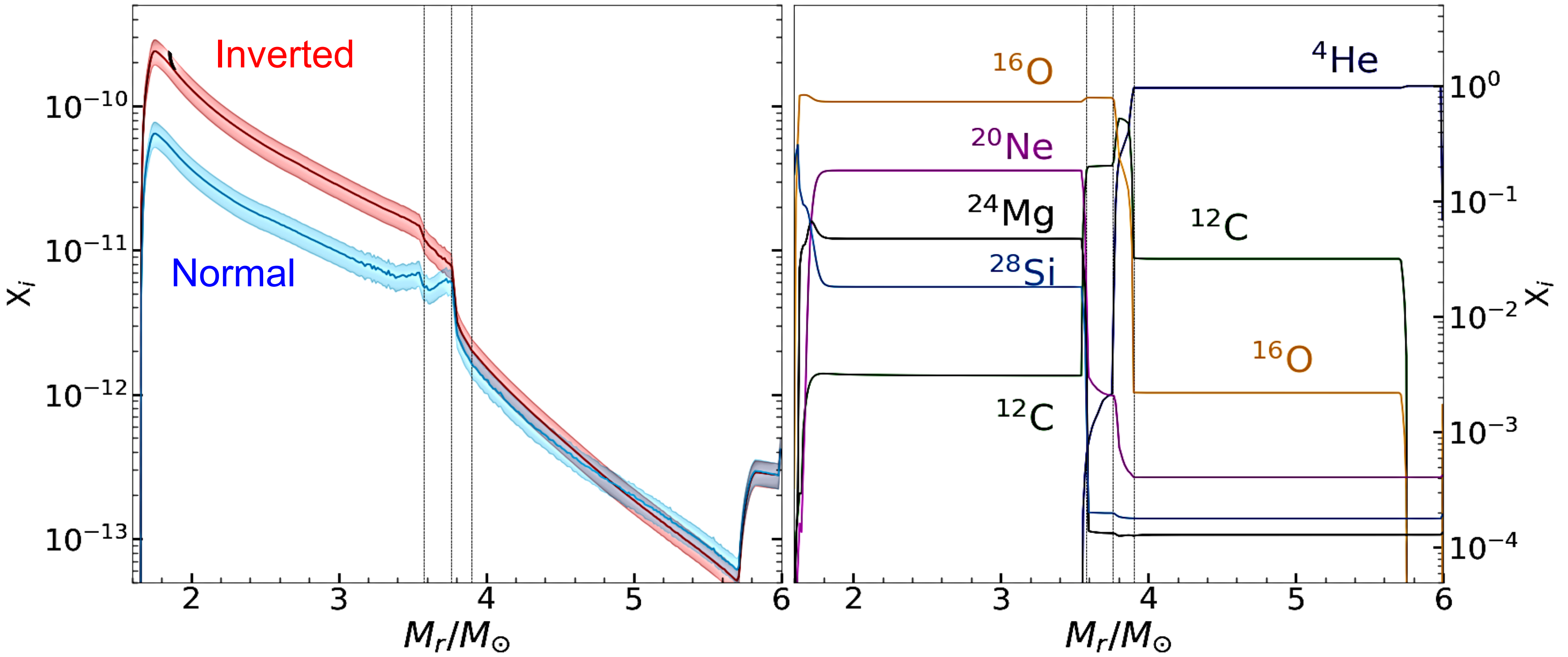
Yao, Kajino, Luo et al. (2025), ApJ 980, 247.
Yao, Luo, Kajino et al. (2025), CPC 49, v9.
Luo, Yao, Kajino et al. (2025), to be submitted.



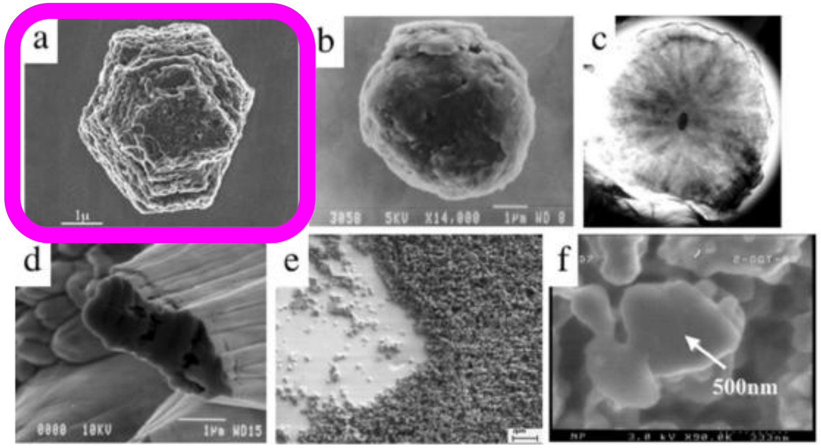
The effect of collective ν-oscillation at high-density inside exploding SN!

^{138}La from ν-process manifests very large difference between normal and inverted hierarchy by more than **factor of 3 (> 300%)!**

^{138}La



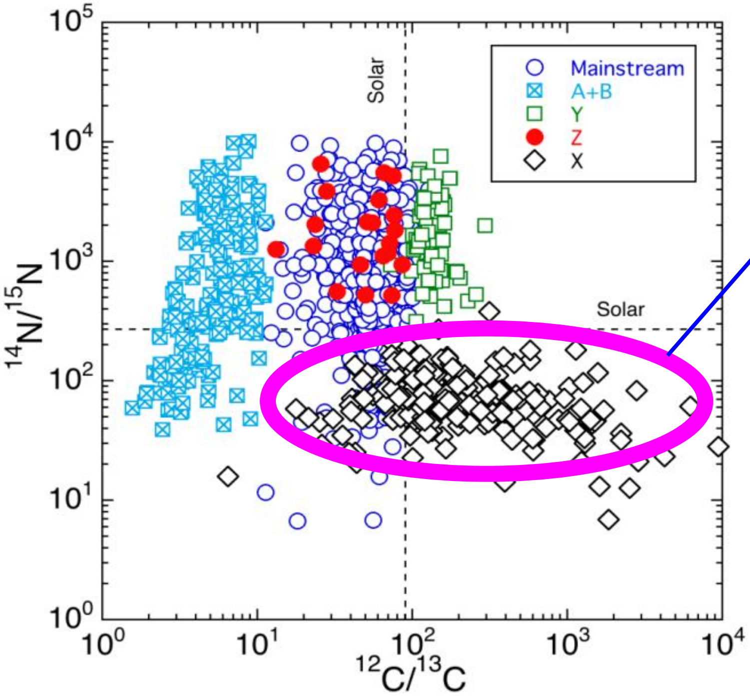
Nucleosynthesis constrains ν-Hierarchy with SUPERNOVA Grains



Pre-solar dust grains scanning e-micrographs

E. Zinner (2008), **Meteorite** Scientist

(a) Silicon-carbide
(b) Graphite,
(c) Graphite slice with inner TiC grain,
(d) Aluminum oxide, (e) Spinel, (f) Silicate



Characteristics of SiC X-Grains

- Enhanced ^{12}C ($^{12}C/^{13}C$ > Solar)
- Enhanced ^{28}Si ($^{28}Si/^{29,30}Si$ > Solar)
- Decay of ^{26}Al ($t_{1/2}=7\times10^5$yr), ^{44}Ti ($t_{1/2}$=60yr)
- Deficient ^{14}N ($^{14}N/^{15}N$ < Solar)

Probe of SN ν−Flavor Oscillations

MSW effect:

Mathews, Kajino, Aoki & Fujiya, PR D85, 105023 (2012),
Kajino, Mathews, Hayakawa, J. Phys. G41 (2014), 044007

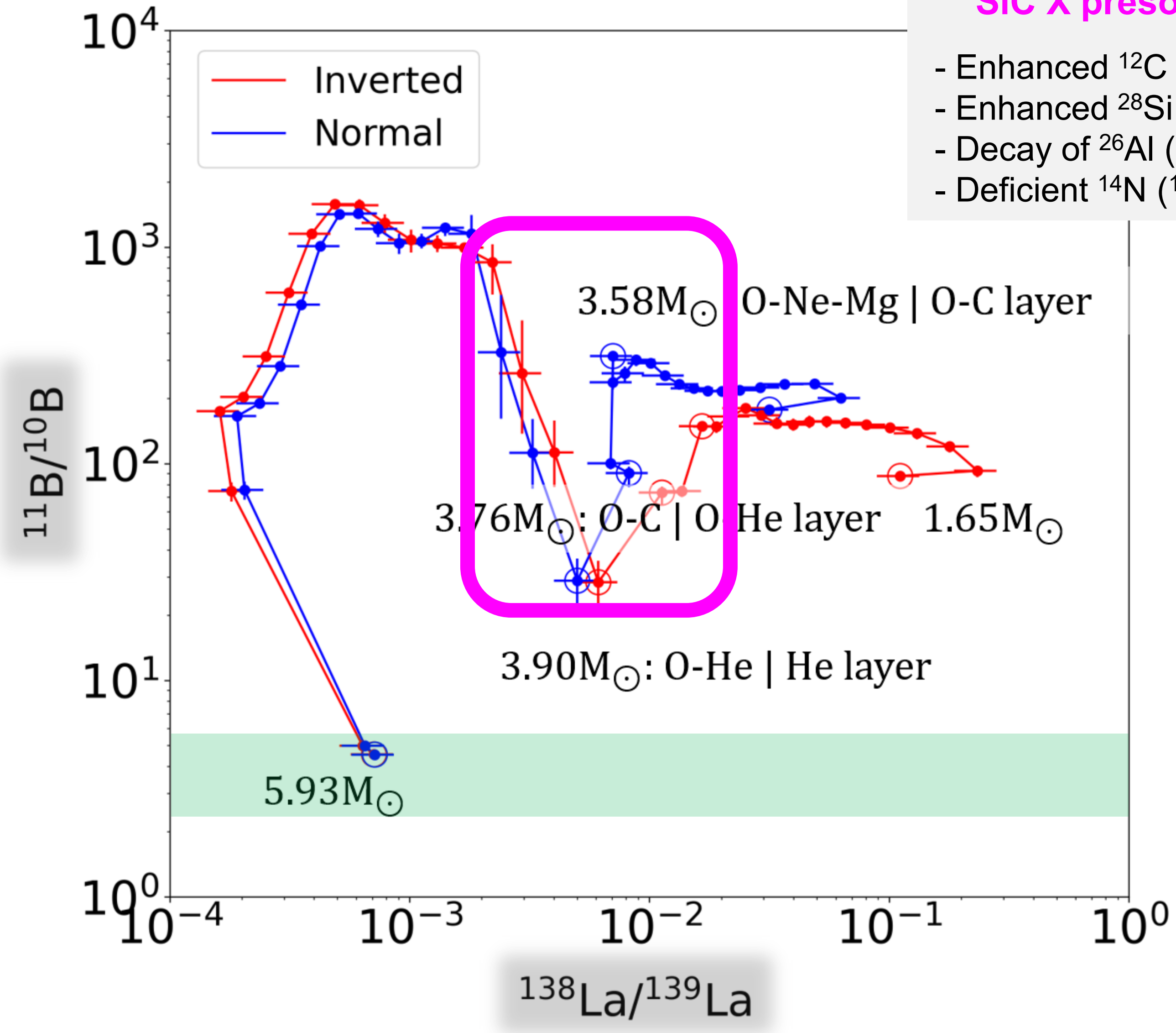
Collective + MSW effects:

Yao, Kajino, Luo, et al., ApJ 980, 247 (2025)

Obs. Test No. 1 – SiC X grain

Yao, Kajino, Luo et al. (2025), ApJ 980, 247.
Yao, Luo, Kajino et al. (2025), CPC 49, v9.

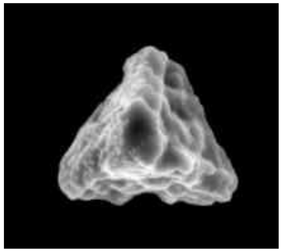
Isotopic Correlation $^{138}La/^{139}La$ vs. $^{11}B/^{10}B$



SiC X presolar grains → SN grain

- Enhanced ^{12}C ($^{12}C/^{13}C$ > Solar)
- Enhanced ^{28}Si ($^{28}Si/^{29,30}Si$ > Solar)
- Decay of ^{26}Al ($t_{1/2}=7 \times 10^5$yr), ^{44}Ti ($t_{1/2}$=60yr)
- Deficient ^{14}N ($^{14}N/^{15}N$ < Solar)

SiC-X grains (SN grains),
largely mixed with
ISM (~ solar composition)



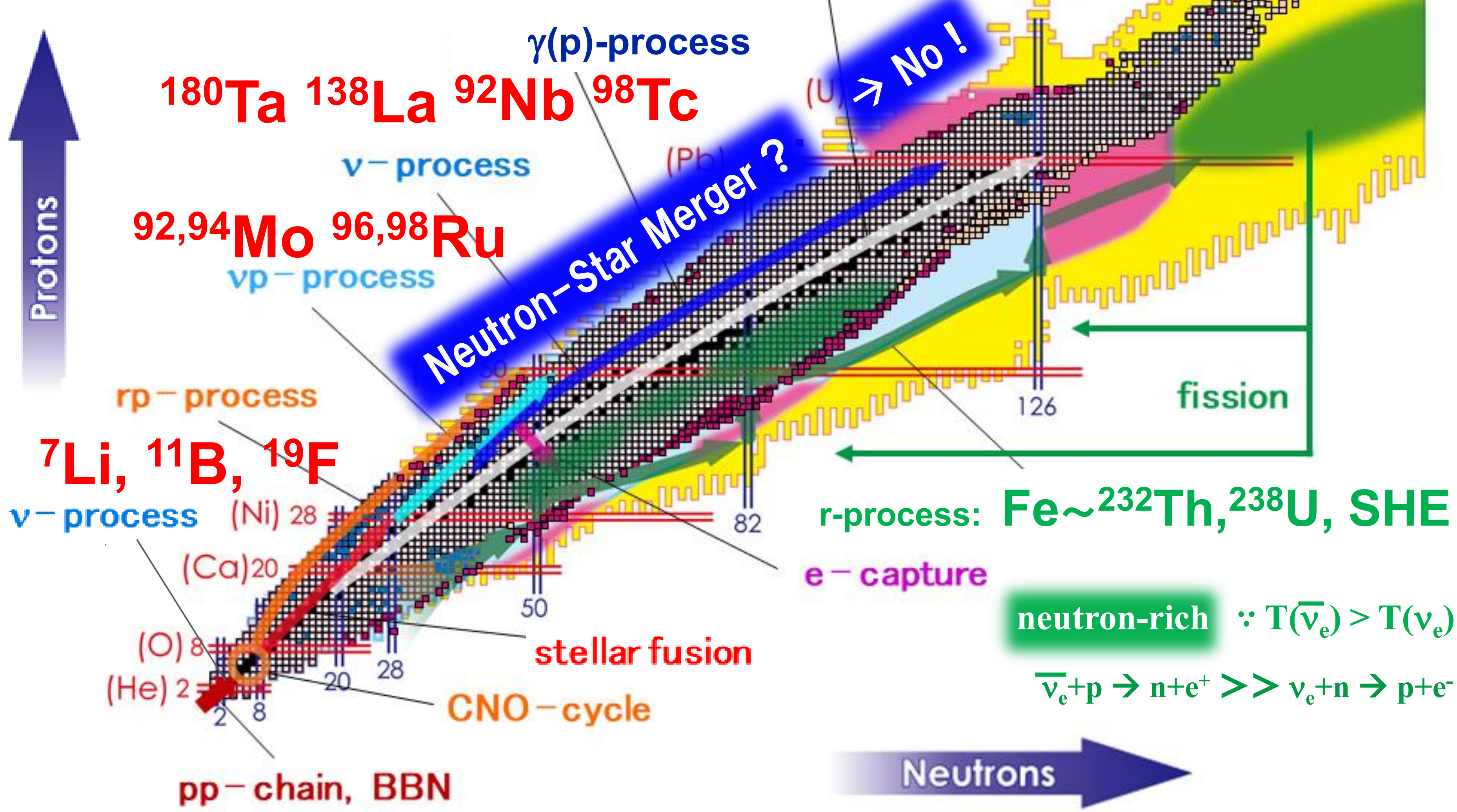
Fujiya, Hoppe, Ott, ApJ 730 (2011), L7; Hoppe, Lodders, Strebel, et al., ApJ 551 (2001), 478.

Origin of Li-B ~ Rare p-Isotopes ?

— Long-standing Question —

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

J. & M. Burbidge



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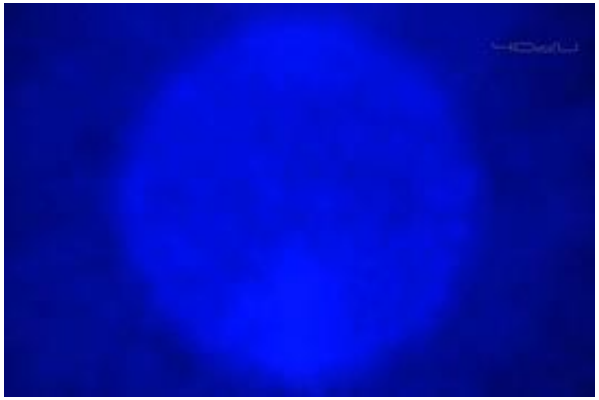
neutron-rich $\because T(\overline{\nu}_e) > T(\nu_e)$

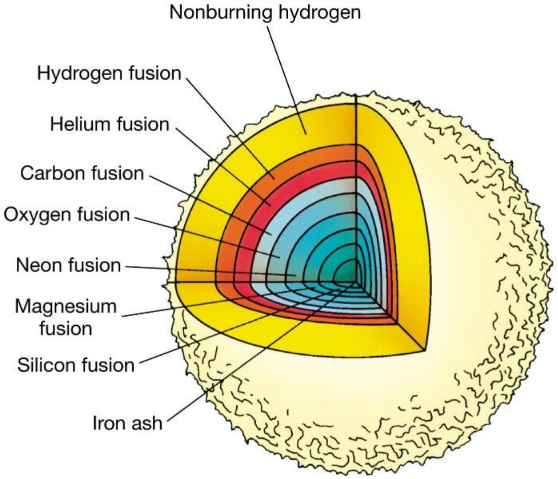
$\overline{\nu}_e + p \rightarrow n + e^+ >> \nu_e + n \rightarrow p + e^-$

Roles of ν-A Interactions for ν-process Nucleosynthesis

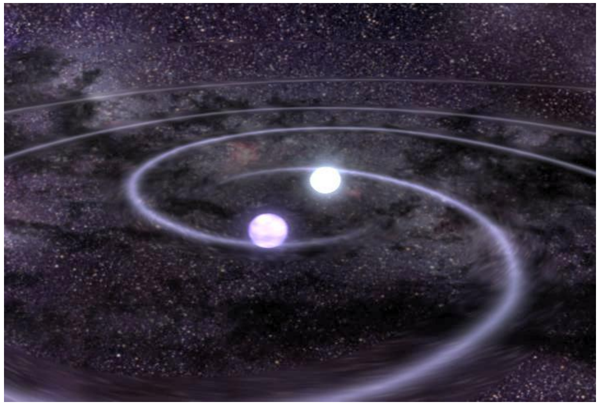
Single Massive Stars

SNe, Hne, Collapsars



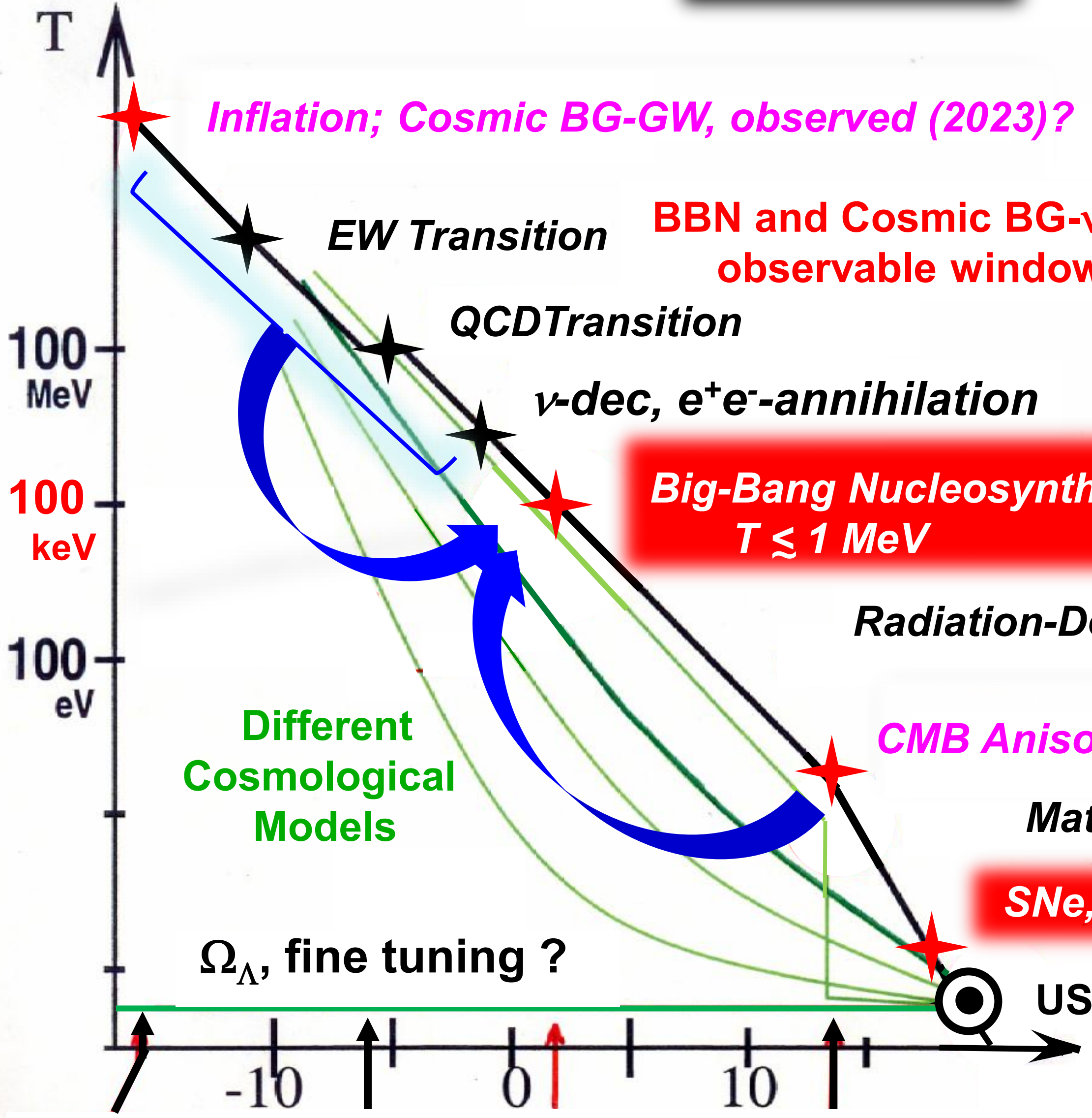


Neutron-Star Mergers



Cosmic Evolution History

Summary



Inflation; Cosmic BG-GW, observed (2023)?

EW Transition

QCDTransition

ν-dec, e^+e^--annihilation

Big-Bang Nucleosynthesis $T \lesssim 1$ MeV

Radiation-Dom. Era

CMB Anisotropies

Matter-Dom. Era

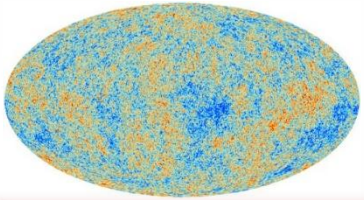
SNe, Collapsars, Neutron-Star-Mergrs

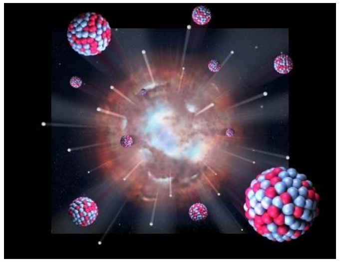
Different Cosmological Models

Ω_Λ, fine tuning ?

BBN and Cosmic BG-ν are unique cosmological observable window to the early Universe!

Primordial Black Hole





Supernova is a unique astrophysical observable window to ν mass hierarchy!