原子核物理でつむぐｒプロセス

r-process元素組成比の宇宙時間進化

Contribution from Supernovae and Neutron Star Merger

- r-process abundance
  - ✓ r-process sites
  - ✓ Event rate
- Evolution
  - ✓ Isotopic abundance
  - ✓ universality
- NSM delay time

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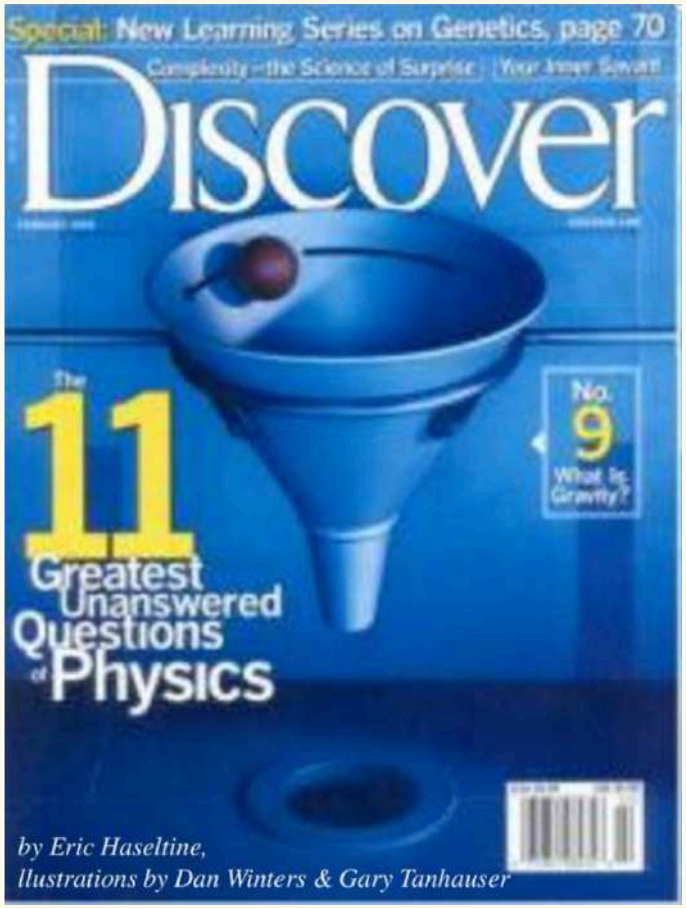
The origin of heavy elements

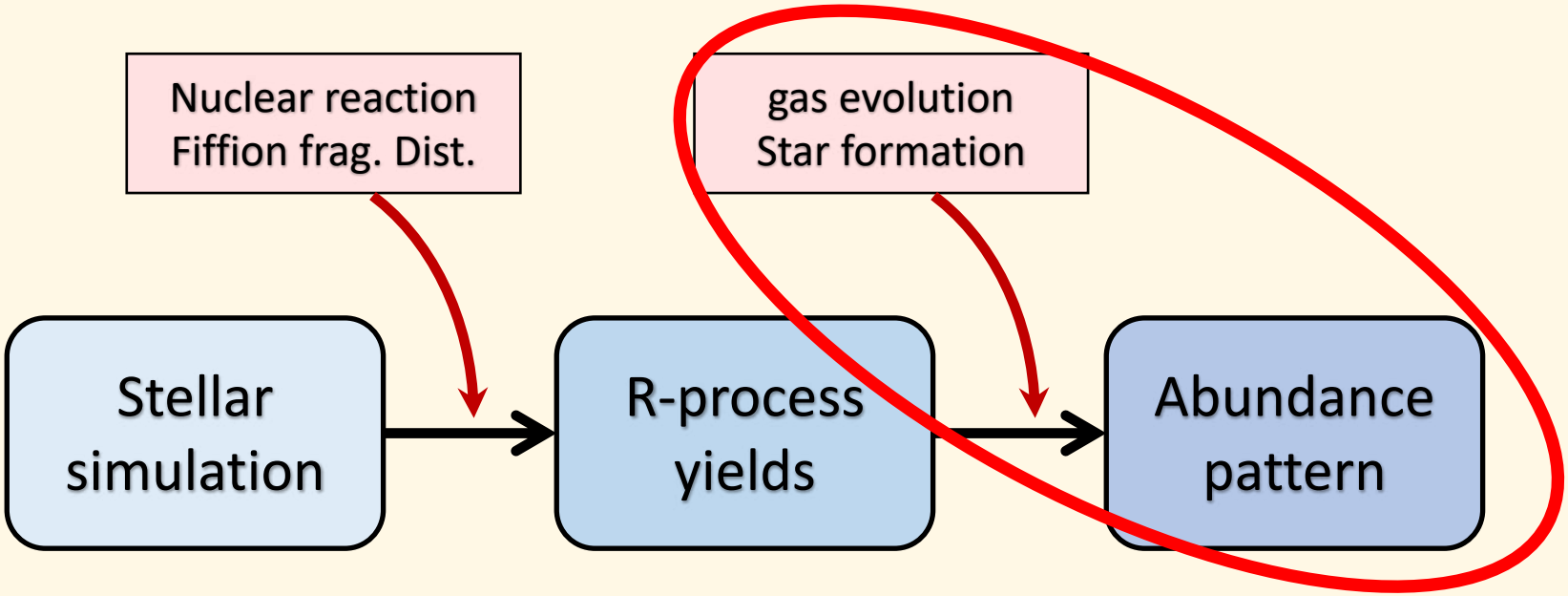


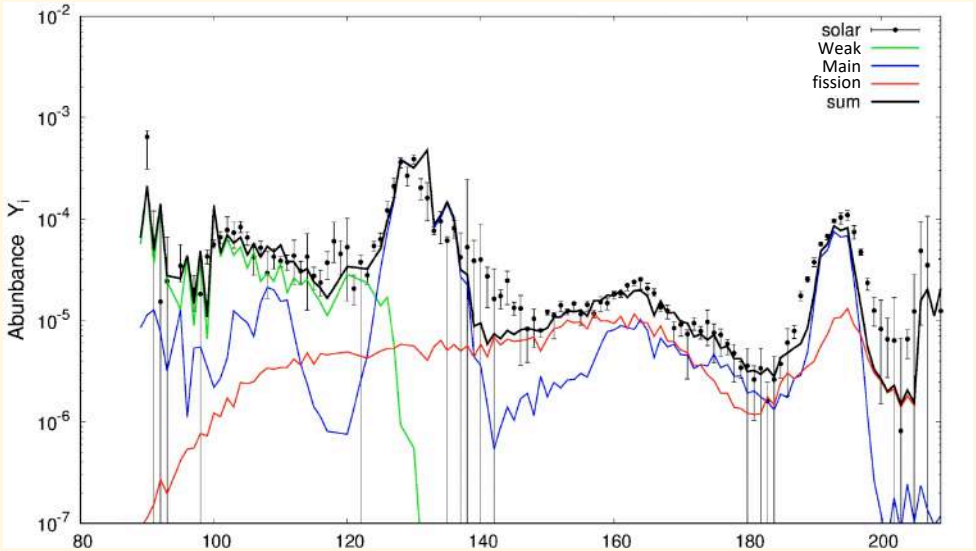
TOP 11 GREATEST UNANSWERED QUESTIONS OF PHYSICS[1]

1. What is dark matter?
2. What is dark energy?
3. How were the heavy elements from iron to uranium made?
4. Do neutrinos have mass?
5. Where do ultrahigh-energy particles come from?
6. New light and matter theory needed at ultra-high energies?
7. New states of matter at ultrahigh temperatures and densities?
8. Are protons unstable?
9. What is gravity?
10. Are there additional dimensions?
11. How did the universe begin?

[1] Discover Magazine, February 2002.

r-process study (in terms of astroph.)

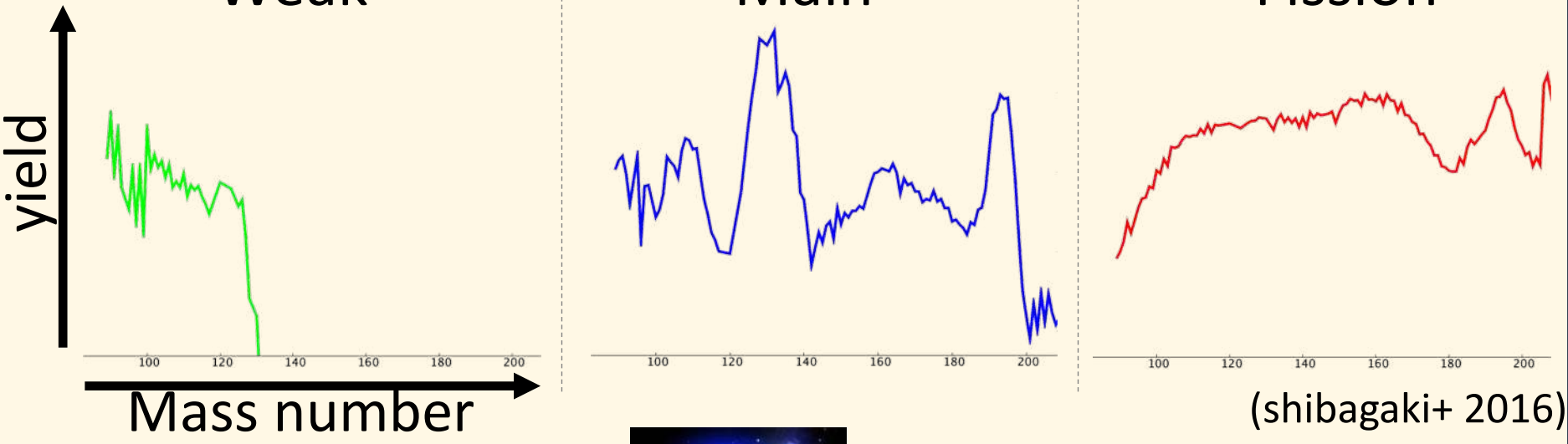




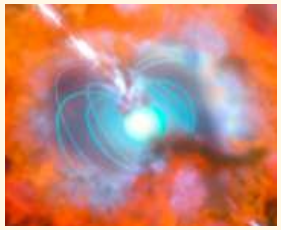
r-process yields from each site

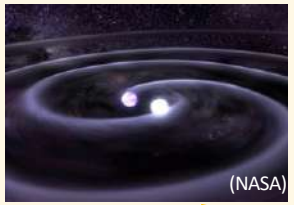
high — Ye — low

Weak | Main | Fission



(shibagaki+ 2016)





ν Driven Wind

MHD Jet

NS Merger

Event Rate

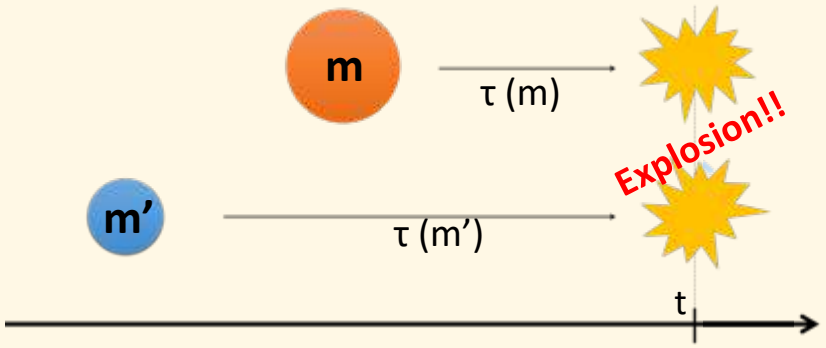
SN Rate :

$$R_{SNII} = \int_{m_l}^{m_h} \phi(m)\, B(t-\tau(m))\, dm$$

$\Phi(m)$: Initial mass function (kroupa 2001, MNRAS)

$B(t)$: Star Formation Rate

1. Exp(-t) (Miller&Scalo 1979, ApJ)
2. Schmidt's law (Schmidt 1959, ApJ)

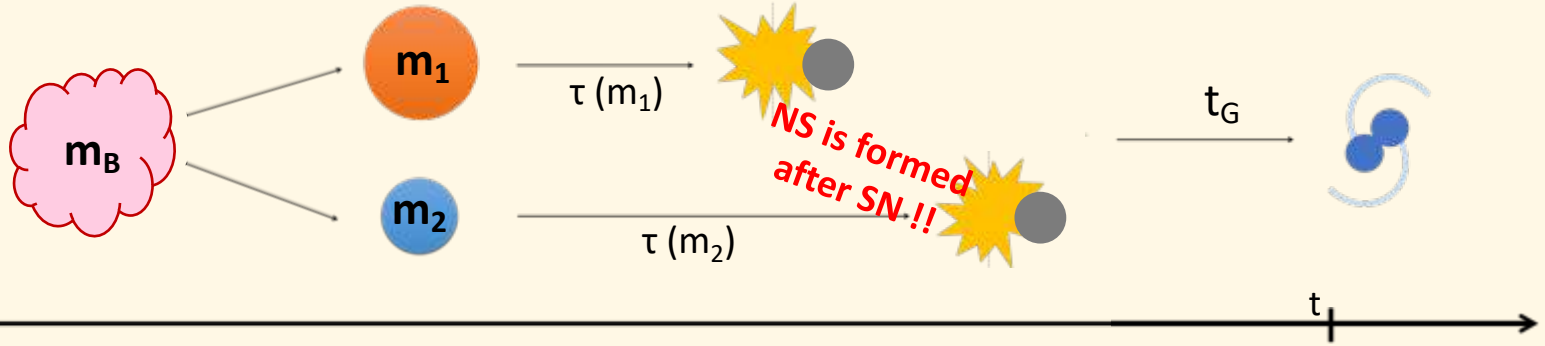


NSM Rate :

$$R_{NSM} = \epsilon_{NSM} \int_{m_l}^{m_h} dM_B\, \phi(M_B) \int_{q_l}^{1} dq\, f(q) \int_{a_l}^{a_h} da\, P(a)\, B(t-\tau(m_2)-t_G)$$

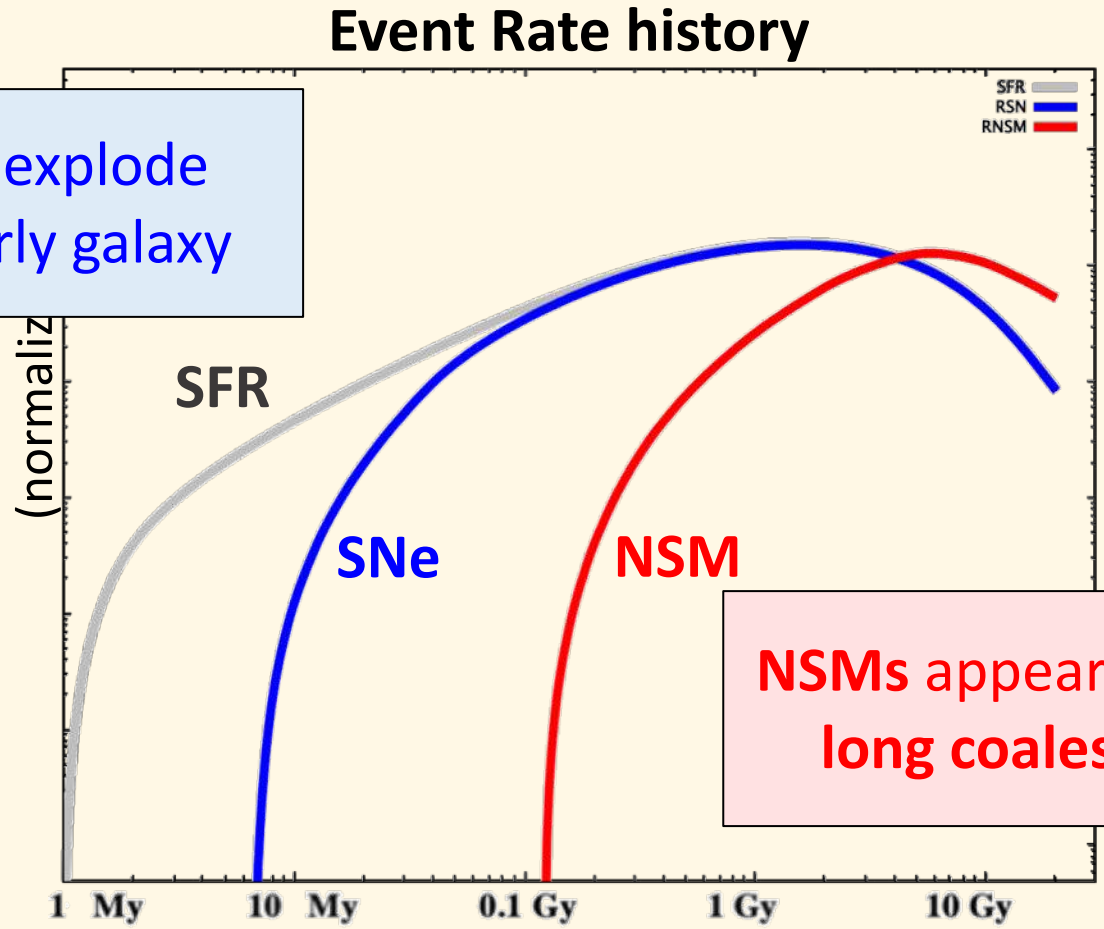
Coalescing time

f = m_2/m_1
a: separation of NS-binary



Event Rate

CCSNe can explode from the early galaxy



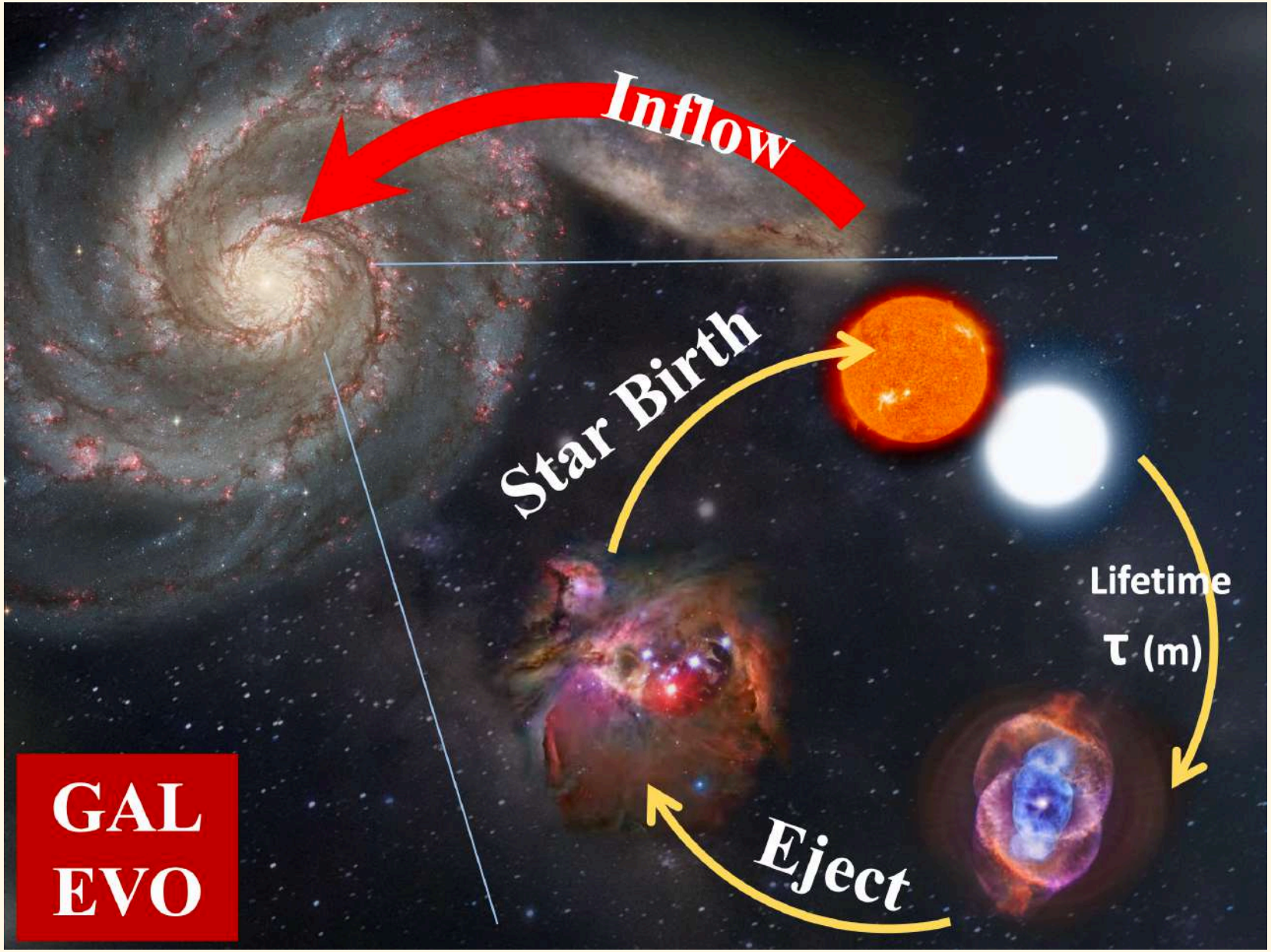
NSMs appear later due to **long coalescing time**

Massive star's life ~ a few Myr

τ_G : Coalescing time
a : binary separation

$$\tau_G \propto a^4$$

Galactic Chemical Evolution



Formulation

Gas Evolution

σ_X : density of X in gas (X = *gas, heavy element*)

$$\dot{\sigma}_X = Inflow \cdot \delta_{X,gas} - \frac{\sigma_X}{\sigma_{gas}} \cdot StarBirth + StellarEjection$$

$$= Inflow \cdot \delta_{X,gas} - \frac{\sigma_X}{\sigma_{gas}} \cdot B(\xi_{gas}) + \int B(t-\tau_*(m))\,\phi(m)\,E_X(m)\,dm$$

event number

Ejection of X From 1 Event

Contribution Ratio

normalized by MHDJ (main process)

$\sigma_{r,***}$: amount of r-process isotopes which originate from ***

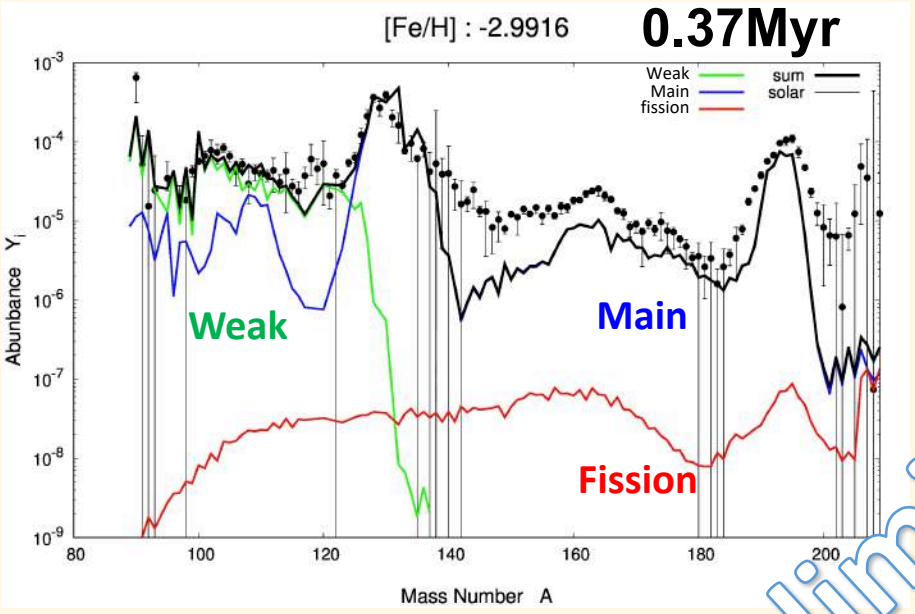
$$f_{NSM} = \frac{\sigma_{r,NSM}}{\sigma_{r,MHDJ}} \qquad f_{NDW} = \frac{\sigma_{r,NDW}}{\sigma_{r,MHDJ}}$$

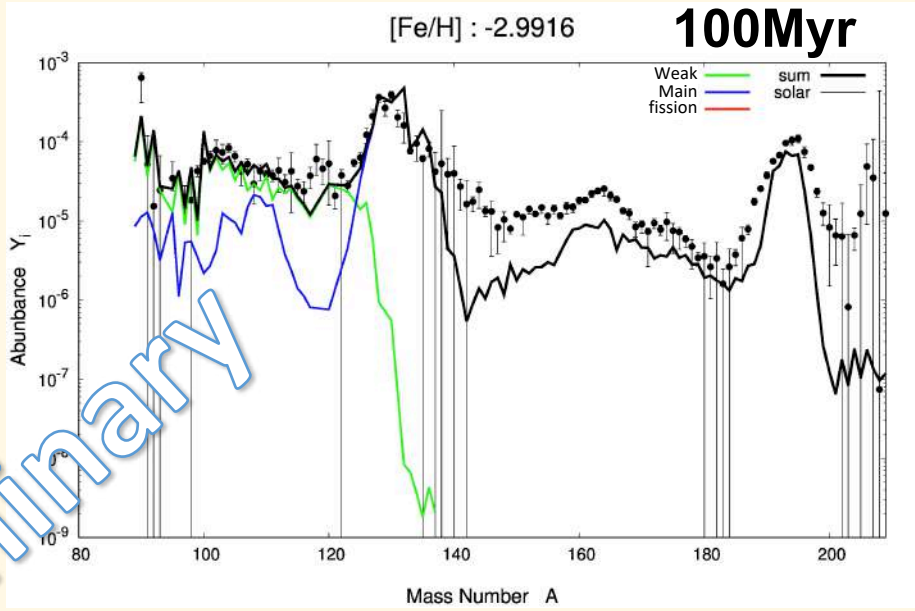
X = r-process nuclei

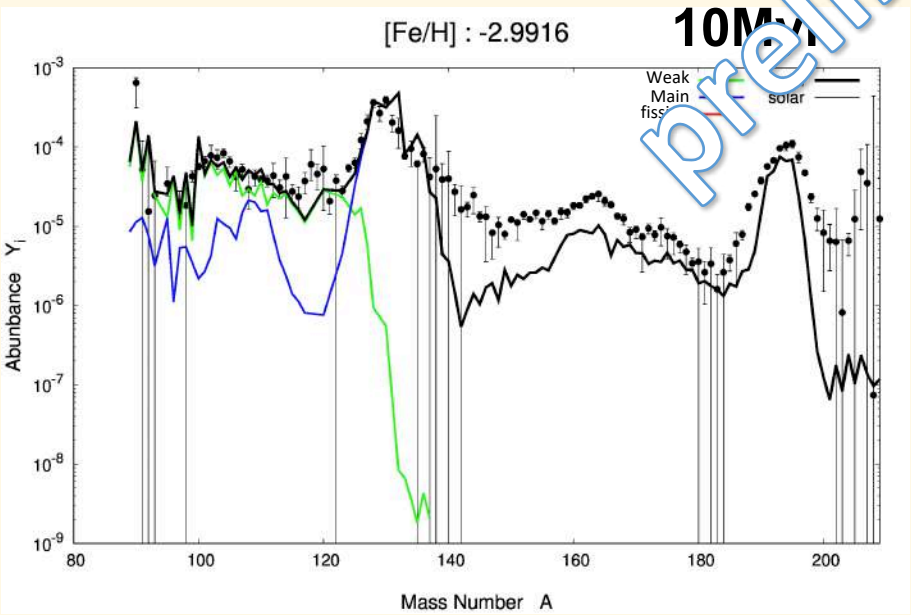
NDW	$2 \cdot 10^{-5}$	$M_\odot$ [1]
MHDJ	$6 \cdot 10^{-3}$	$M_\odot$ [2]
NSM	$2 \cdot 10^{-2}$	$M_\odot$ [3]

[1] (Wanajo 2013, ApJL)
[2] (Winteler+ 2012, ApJL)
[3] (Korobkin+ 2012, MNRAS)

Evolution of r-process abundance







preliminary

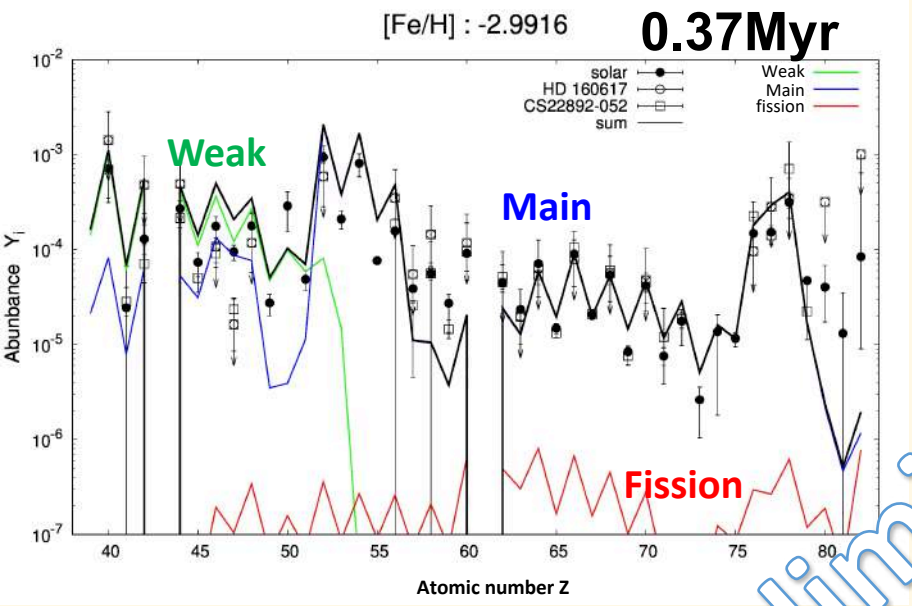
★ Early galaxy was dominated by **weak & main** and showed different isotopic abundance pattern from s.s. abundance.

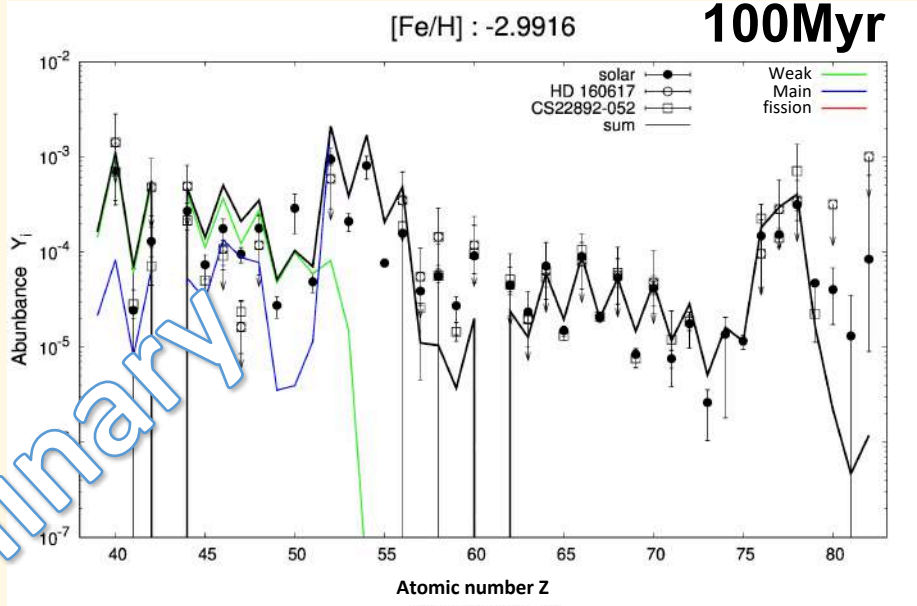
★ **Neutron Star Mergers** have arrived quite recently in cosmic evolution history.

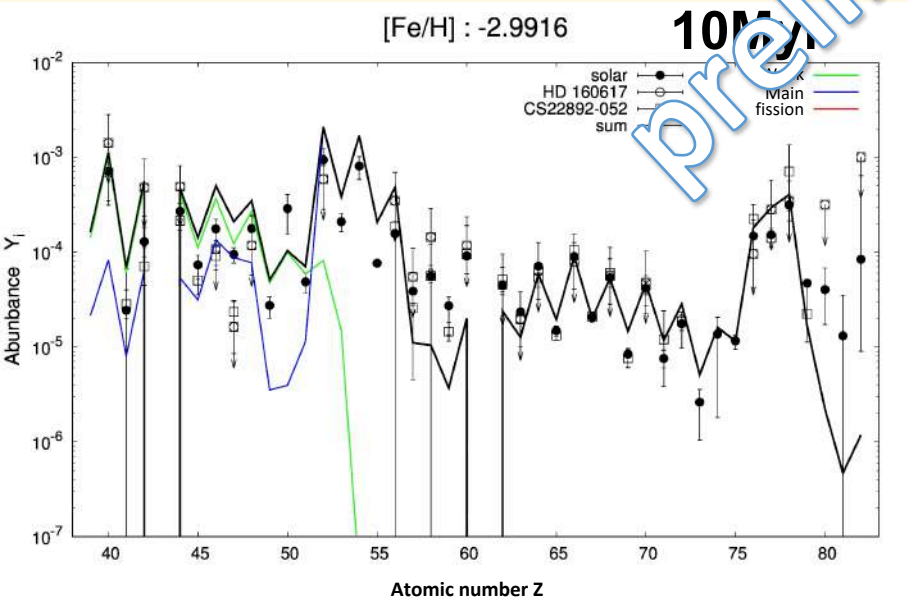
★ Can we check this contribution ratio?

also Depend on fission model!

Universality of r-Process Abundance







preliminary

★ Fission can violate universality
only in the case that its contribution is large

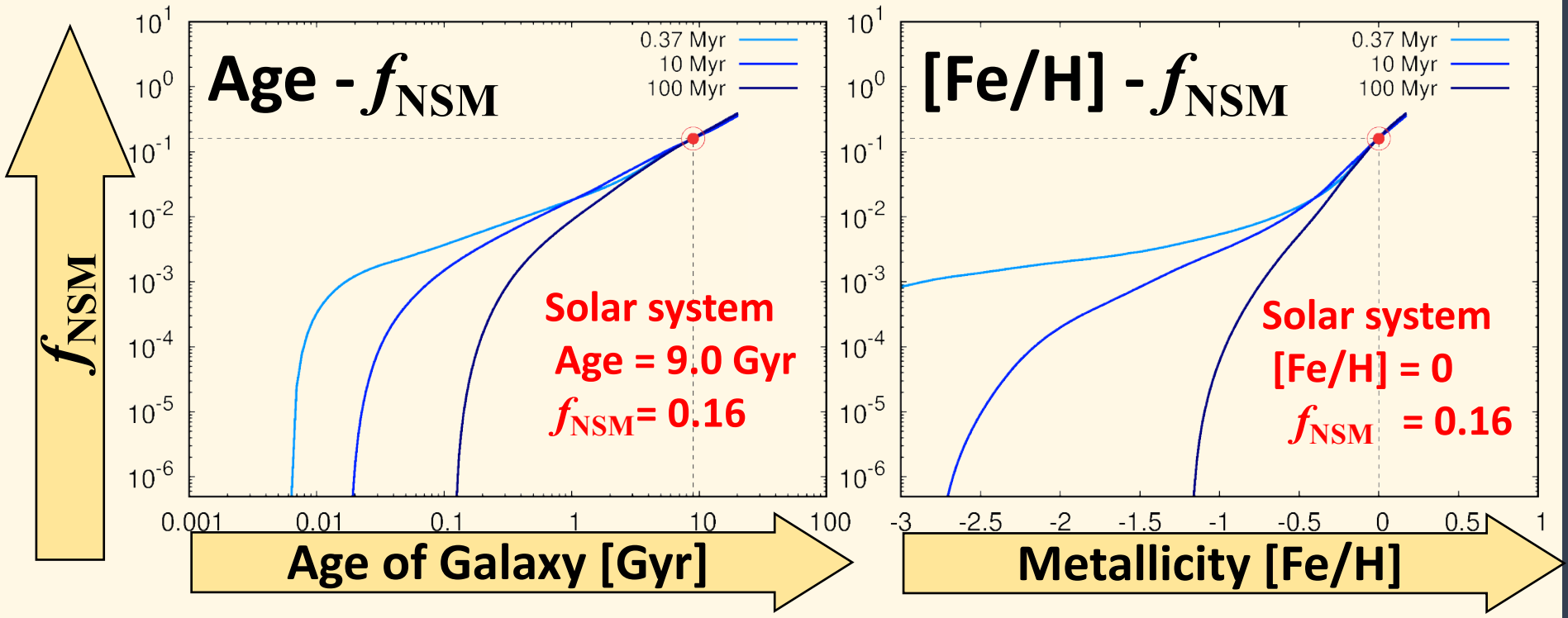
★ Observations of universality in more wide mass range are needed

‘universality’ is observed even in EMPS_

HD 160617	[Fe/H] ~ -1.8
CS22892-052	[Fe/H] ~ -3.1

Coalescing time delay

(this ‘ratio evolution‘ is independent from models of each sites)



For the shorter coalescing timescale,

f_{NSM} appear from earlier / more metal-poor region

f_{NSM} → 1/10 ; t = 0.5 — 1 Gyr, [Fe/H] = -1.0 — -0.5

Summary and Future Prospects

- r-process abundance is explained by 3 component
  - Weak, Main and Fission
- Abundance pattern have changed with ER of SN and NSM.
- Fission can change abundance pattern dramatically
- More accurate nuclear data is highly needed
  - Fission fragment distribution
  - Nuclear reaction @2^{nd} peak ~ hill for evaluating ‘universality’
- GW and ELT observations are really prospective


Thank you.