Galactic and cosmic chemical evolution, and their connection to neutrino astronomy

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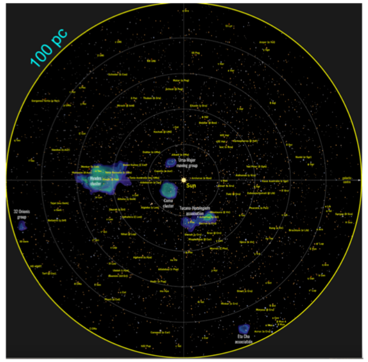
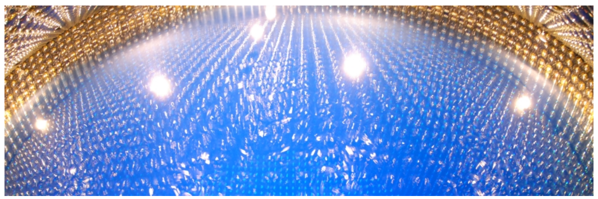
I. Chemical evolution in the solar vicinity



II. Chemical evolution of the Milky Way

III. Cosmic star formation/supernova rate in the Universe

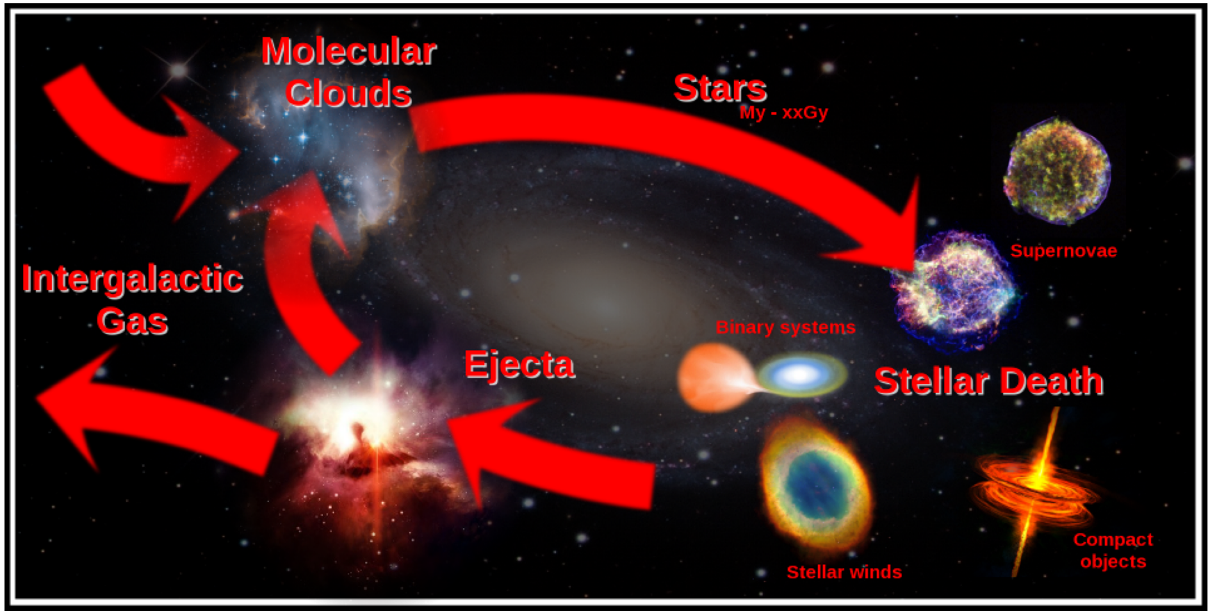


Neutrino astronomy

March. 6th 2024 at UGAP2024 workshop

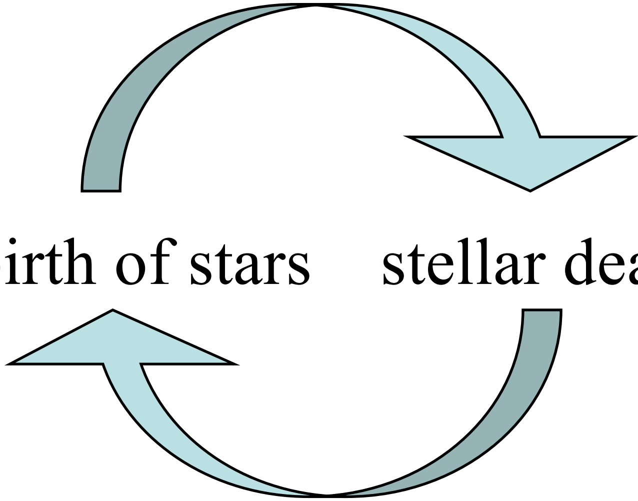
Chemical Evolution

Calculation of the evolutionary change in the mass fraction, Z_i, of each heavy element, i, in gas



@Longland

creation of elements



a birth of stars

stellar death

ejection of elements into gas

Each time's Z_i of **gas** can be recorded as **stellar Z_i** at each time (at a stellar surface)

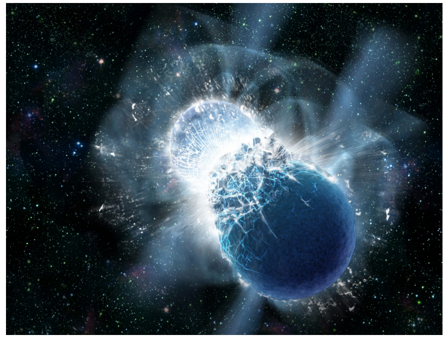
can be compared with the **observed Z_i of long-lived stars** ($M<0.8\ M_\odot$)

Chemical evolution is a powerful tool to discuss/identify the production sites of heavy elements

- A good example: r-process elements -

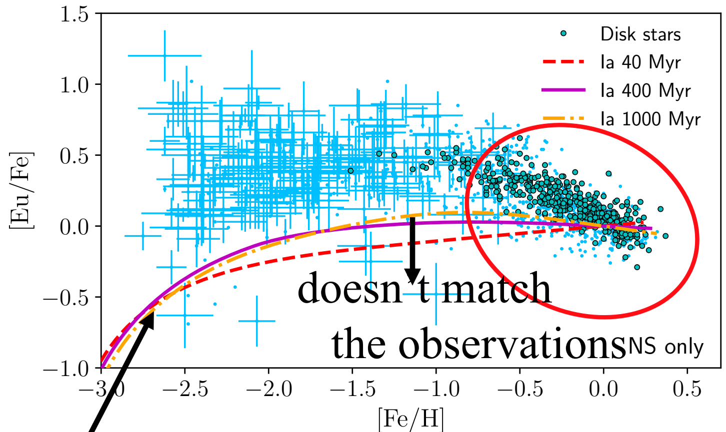
Now, we surely know they are synthesized by neutron star mergers (NSMs) via GW170817

(!!Latest JWST results strengthen this!!: Levan+ 2024)



But, chemical evolution suggests NSMs are NOT the sole *r*-process site

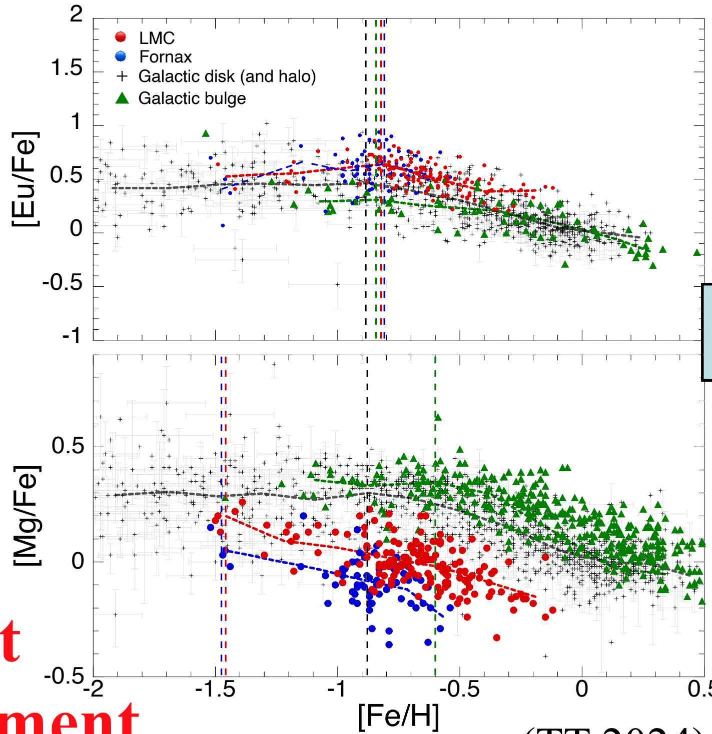
Milky Way



the path by NSM only

(Siegel+ 2019)

Milky Way vs. dwarf galaxies



(TT 2024)

I. Both NSMs and specific SNe must exist as *r*-process sites.

II. Specific SNe strongly favor a low-metallicity environment.

Short-lived massive stars must contribute to *r*-process enrichment

$$\frac{df_g}{dt} = -\psi(t) + \int_{\max(m_l,m_t)}^{m_u} dm\phi(m)r(m)\psi(t-t_m) + A(t)$$

$$\frac{d(Z_i f_g)}{dt} = -Z_i(t)\psi(t) + \int_{\max(m_l,m_t)}^{m_u} dmA\psi(m)y_{\mathrm{Ia},i} \times \int_0^t dt_{\mathrm{Ia}} g(t_{\mathrm{Ia}})\psi(t-t_{\mathrm{Ia}}) + \int_{\max(m_l,m_t)}^{m_u} dm(1-A)\phi(m)[y_{\mathrm{cc},i} + Z_i(t-t_m) r_w(m)]\psi(t-t_m) + Z_{A,i}(t)A(t) \ ,$$

Based on detailed modeling of chemical evolution,

we discuss

✓the progenitor star's mass range for canonical core-collapse supernovae (CCSNe)

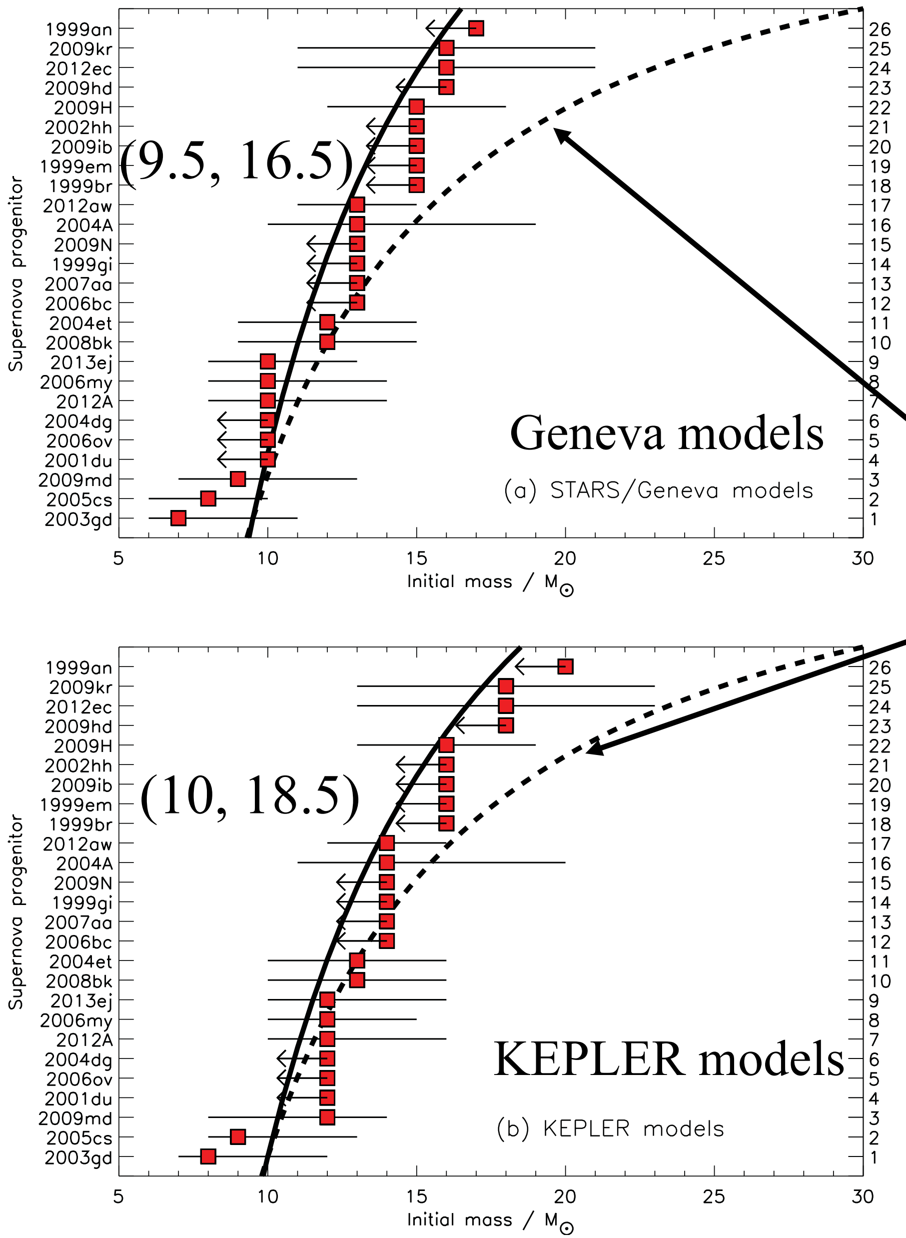
Where is its upper mass bound??

✓the initial mass function (IMF)

the universality or non-universality??

The observational evidence for the missing high-mass CCSN progenitors

Cumulative frequency of the progenitor masses with the Salpeter IMF



(Smart+ 2009; Smartt 2015)

Here, M_{max} means a high-mass end for CCSN progenitors

m_{max}=30 $M_\odot$

,suggesting

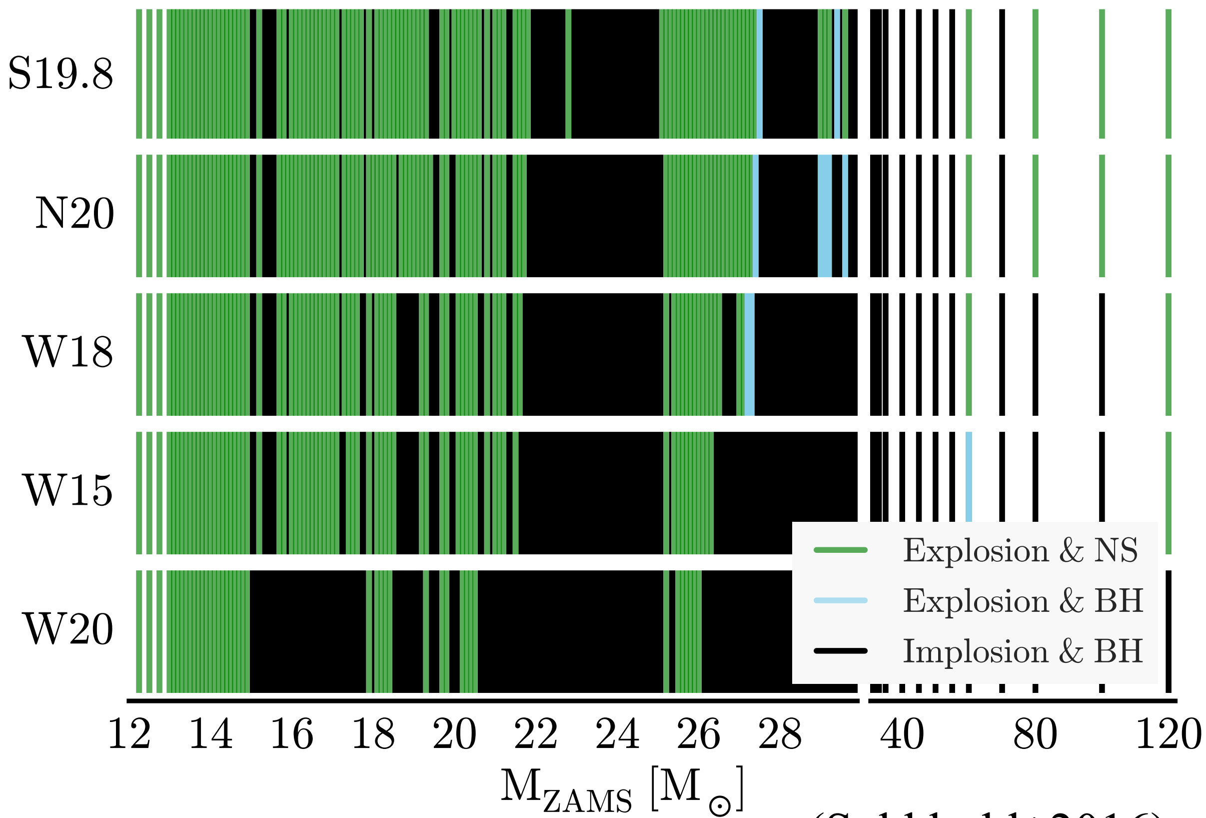
m_{max}≈18 $M_\odot$

with

m_{min}≈ 8 $M_\odot$

The theoretical modeling of CCSNe supports a low m_{max}

the complex explosion/BH landscape



(Sukhbold+2016)

an increase in the number of CCSNe, compared to a single mass range:8-18$M_\odot$

13% (m_{max}=22.6 $M_\odot$)

11% (m_{max}=21.2 $M_\odot$)

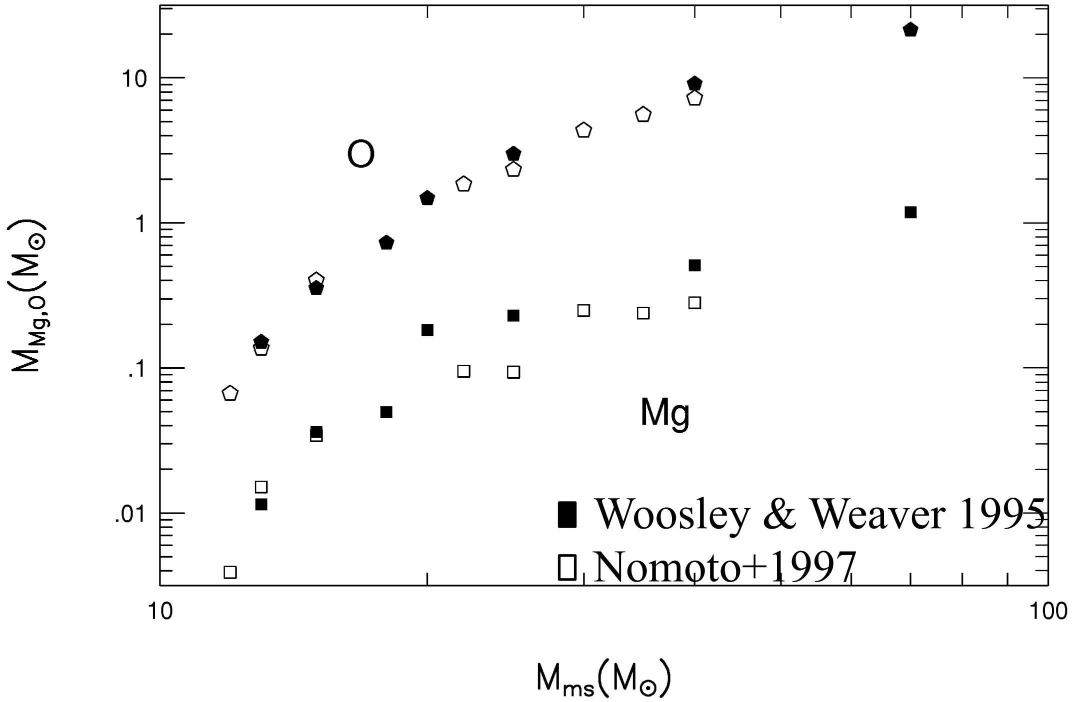
If a single mass range is assumed

It may be reasonable to assume the CCSN mass range≈8-18$M_\odot$

(Stars with m > 18$M_\odot$ end with black hole formation: failed supernovae)

The conventional Galactic chemical evolution scheme adopts a high $m_{\rm max}$ such as 50 $M_\odot$ or 100 $M_\odot$

(Shigeyama & TT 1998)



More heavy elements are generally ejected from CCSNe whose progenitor stars are more massive with a larger core mass

If $m_{\rm max}$=18 $M_\odot$,

The CCSN number **reduces to ~70%**

The reduction in the total amount of heavy element is more serious

$m_{\rm star}$ ↗ $m_{\rm element}$ ↗

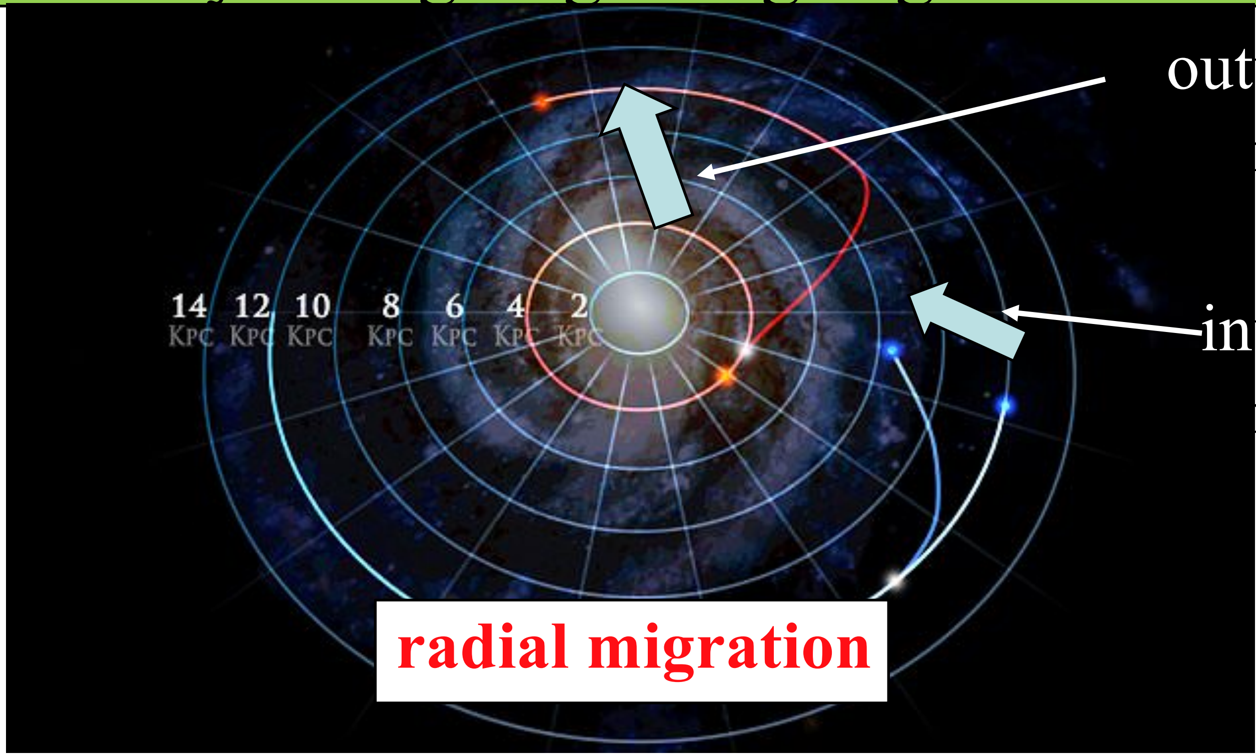
reduces to ~50%

Can the predictions of Galactic chemical evolution models with m_{max}=18 $M_{\odot}$ match the observed chemical abundances ?

The difficulty of addressing this issue is alleviated by the renewed view regarding Galactic chemodynamical evolution.

Stars radially move on the disk via a gravitational interaction with spiral arms by losing or gaining angular momentum.

e.g. Sellwood & Binney 2002; Roškar+ 2008; Schönrich & Binney 2009; Minchev & Famaey 2010; Grand+ 2015 etc

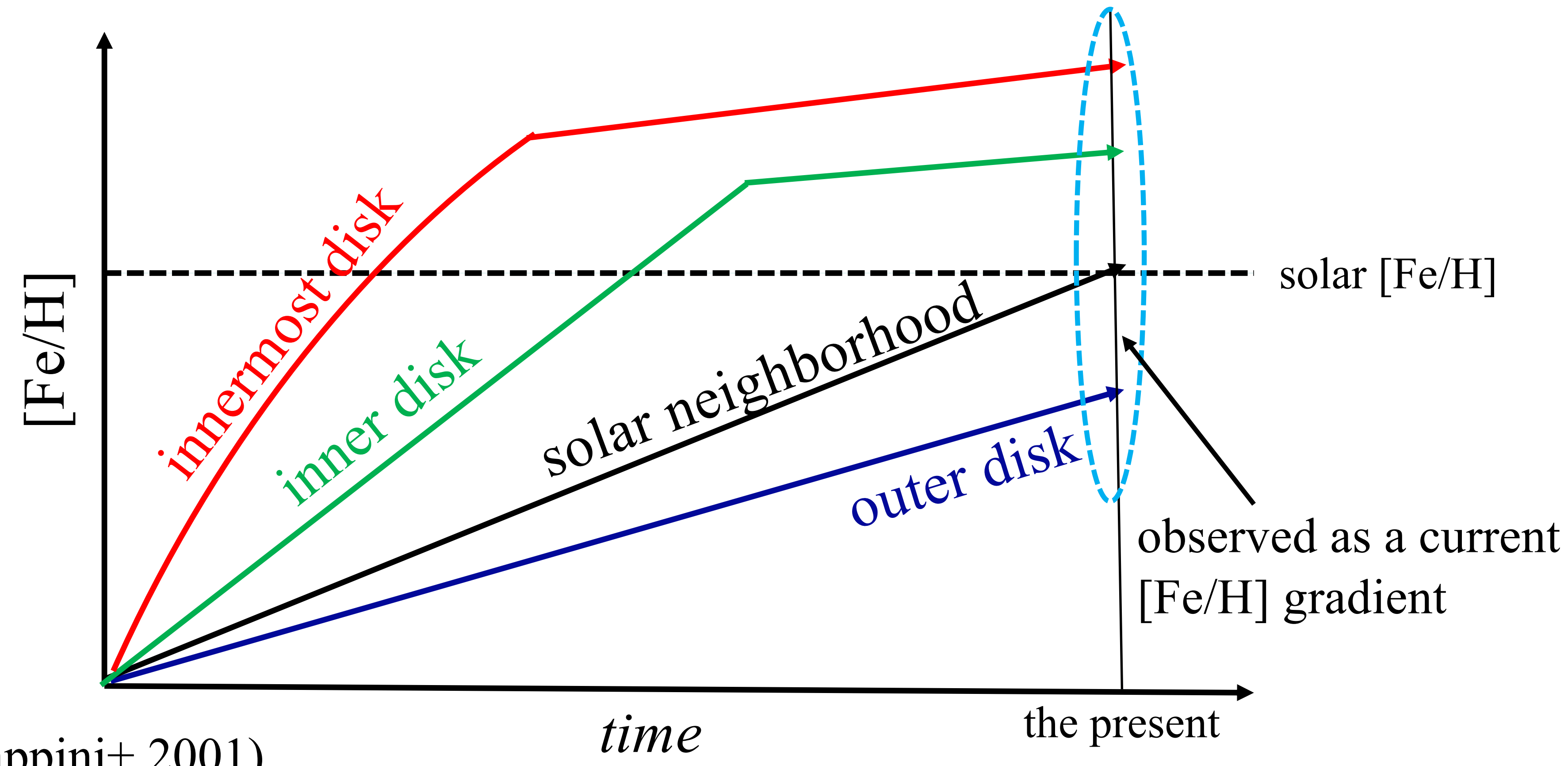


outward migration

inward migration

This theory predicts :

the stars in the solar vicinity represent the mixture of stars born at various Galactocentric distances over the disk



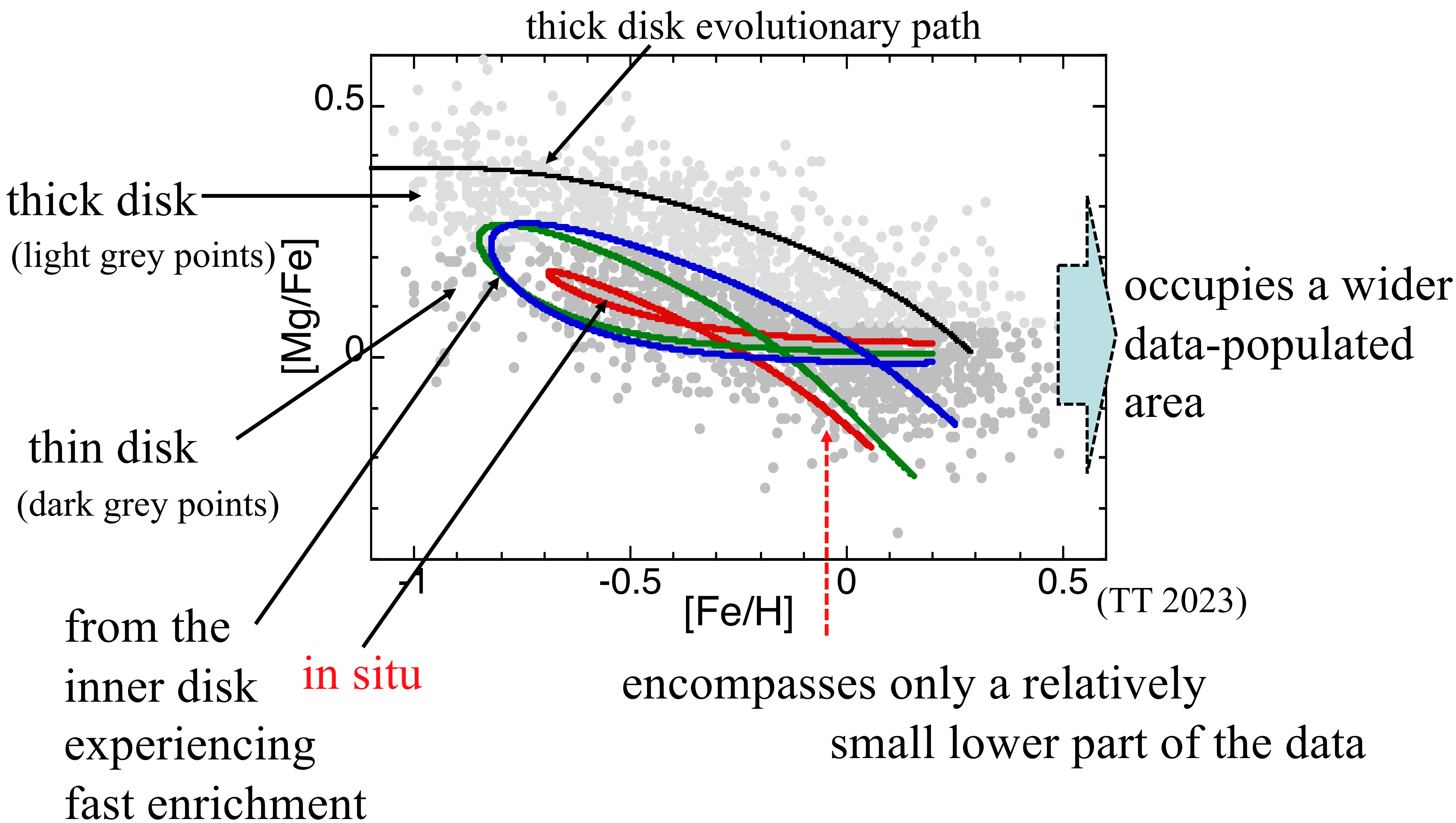
(e.g., Chiappini+ 2001)

Expectations from radial migration

- Stars born under **less efficient CCSN enrichment than previously thought owing to a low high mass end** contribute to only a part of the local Galactic chemistry

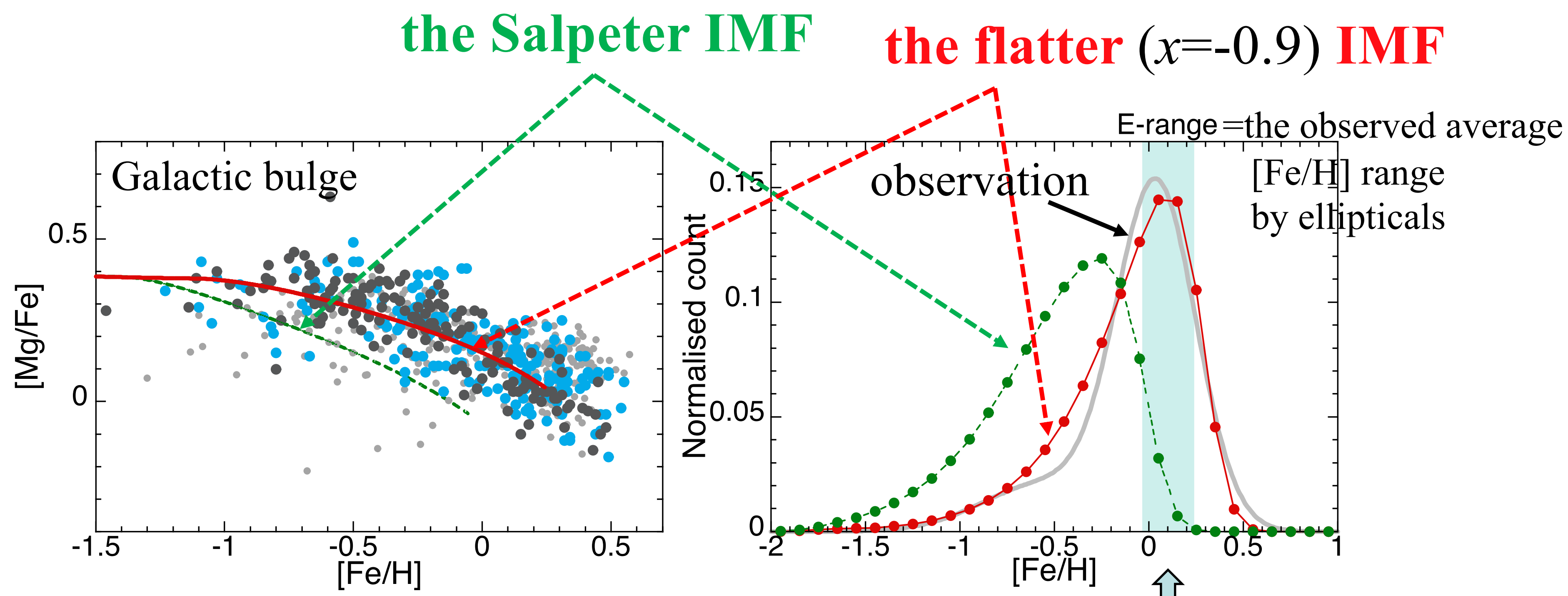
- The remaining composition is due to more efficient enrichment trajectories by inner disk stars than an in situ one.

Yes, Galactic chemical evolution accepts a 8-18 $M_\odot$ mass range for CCSN progenitors



On the other hand,

The Galactic bulge demands more CCSNe than that expected from a 8-18 $M_\odot$ mass range with the Salpeter (x=-1.35) IMF



(e.g., Matteucci & Brocato 1990; Ballero+ 2007)

This argument for **a flat IMF** in the Galactic bulge can be extended to an insight into the form of **the IMFs in elliptical galaxies**.

→ **a flat IMF**

(e.g., Arimoto & Yoshii 1987; Matteucci & Tornambe 1987)

Galactic chemical evolution for the disk and the bulge suggests ***the variable IMF in the Universe***

How star formation proceeds?

moderate mode

bursting mode

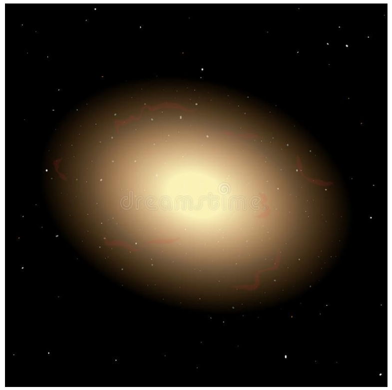
||

||

(e.g., Pouteau+2022)

late-type galaxies

early-type galaxies



the IMF

the Salpeter

(x=-1.35)

the one generating more numerous CCSNe

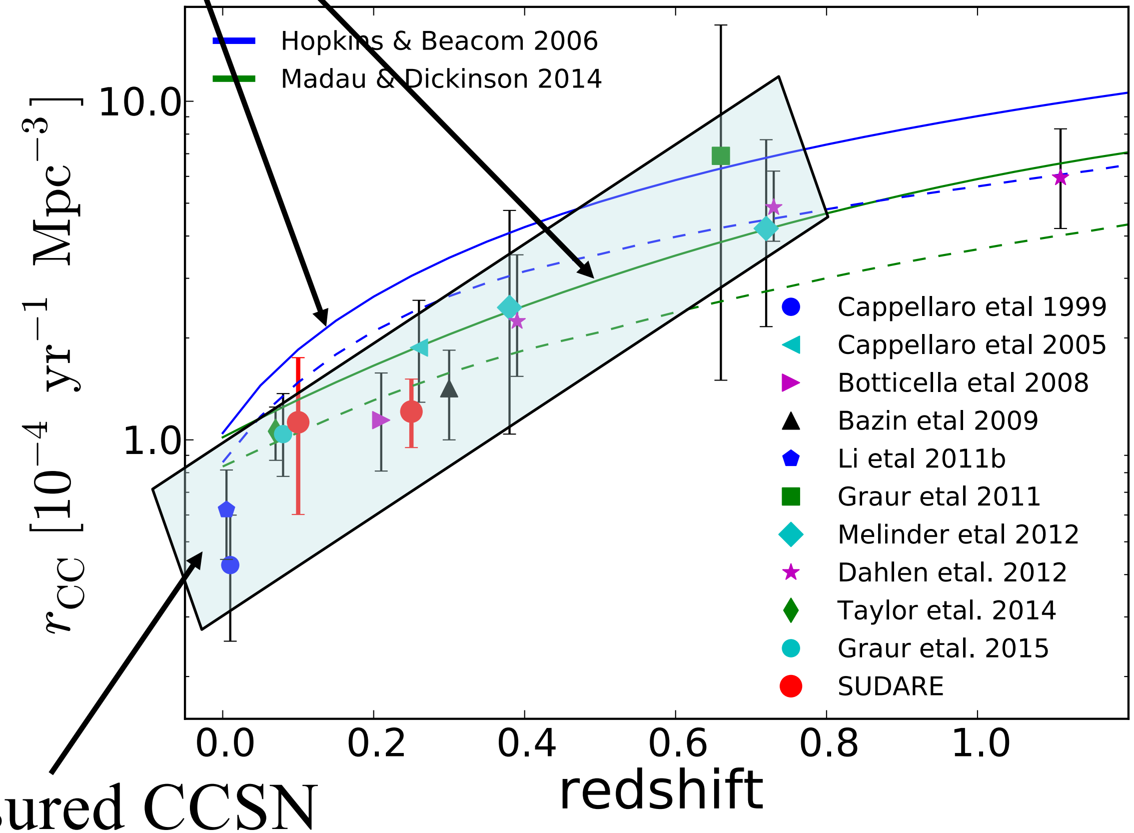
(x=-0.9)

The observed CCSN rate's slope is steeper than the predictions from the observed cosmic star formation rate **with the universal IMF**

$$r_{\rm cc}(z) = k_{\rm cc}\, h^2\, \Psi(z)$$

$k_{\rm cc}$ = a scale factor of massive stars that explode as CCSNe per unit mass of the IMF

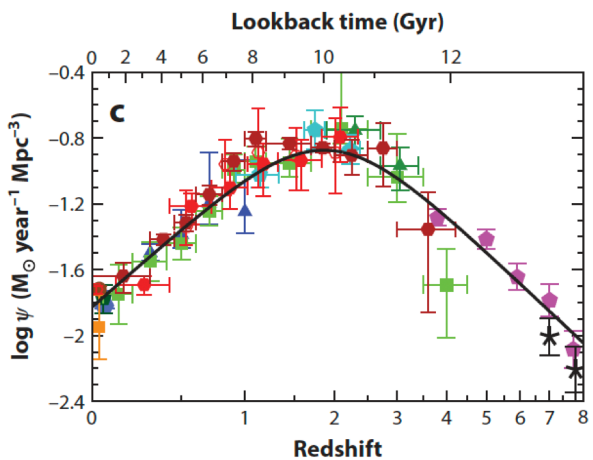
assuming $k_{\rm cc} = \text{const.}$



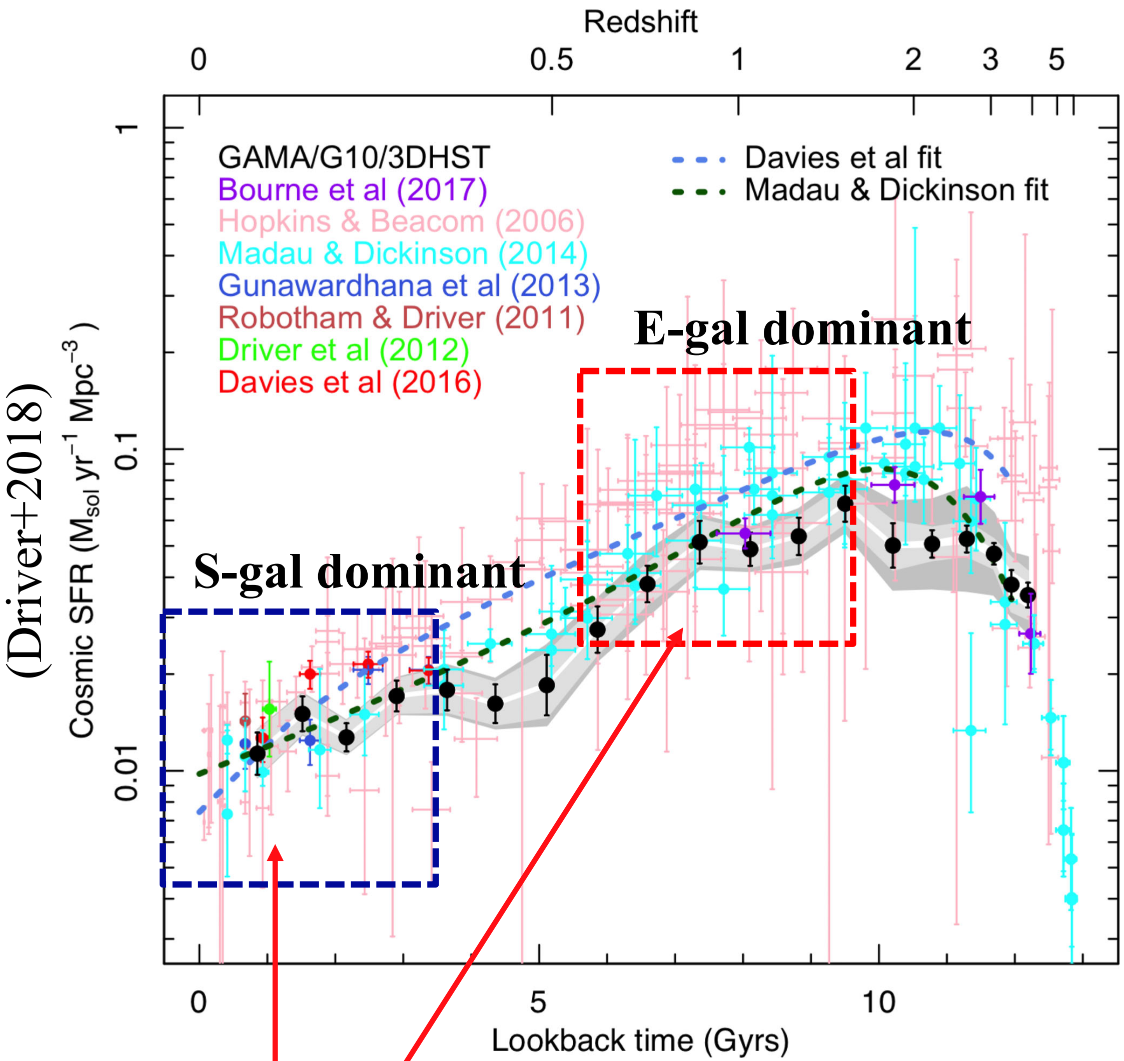
the measured CCSN rate trend

(Cappellaro+2015)

cosmic star formation: $\Psi(z)$



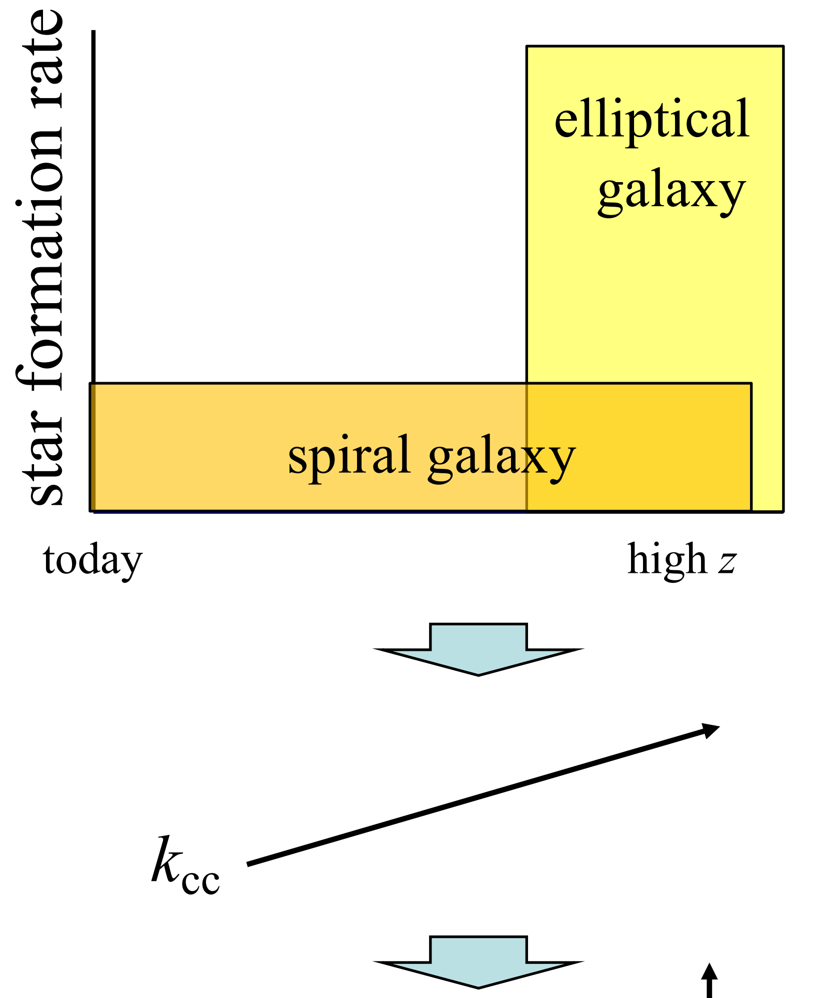
Cosmic star formation history



The contributing fraction in cosmic star formation from individual types of galaxies varies in accordance with redshift

Star formation history of galaxies

Ellipticals vs. Spirals

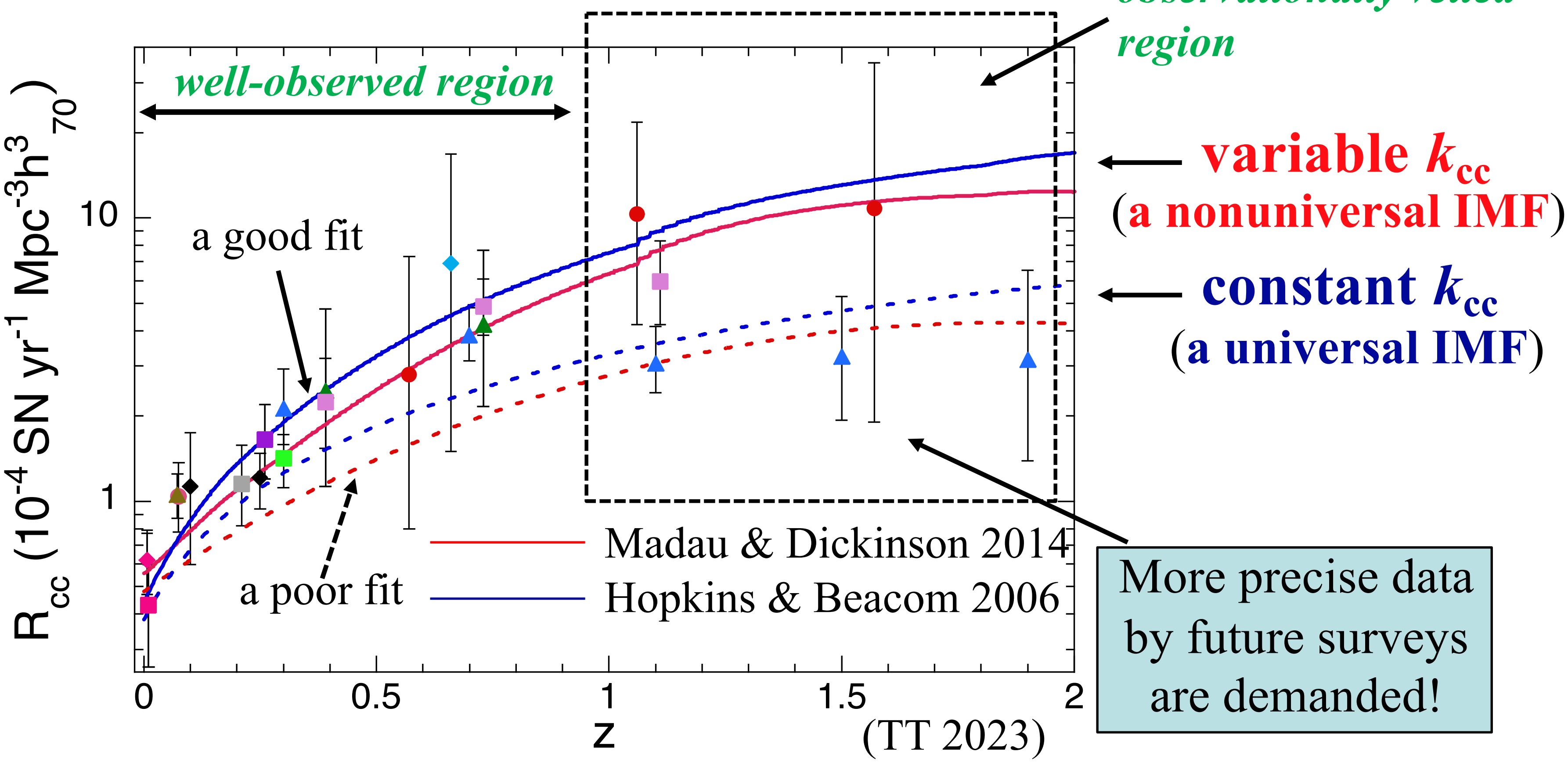


CCSN rate contrast ↑

between low and high z

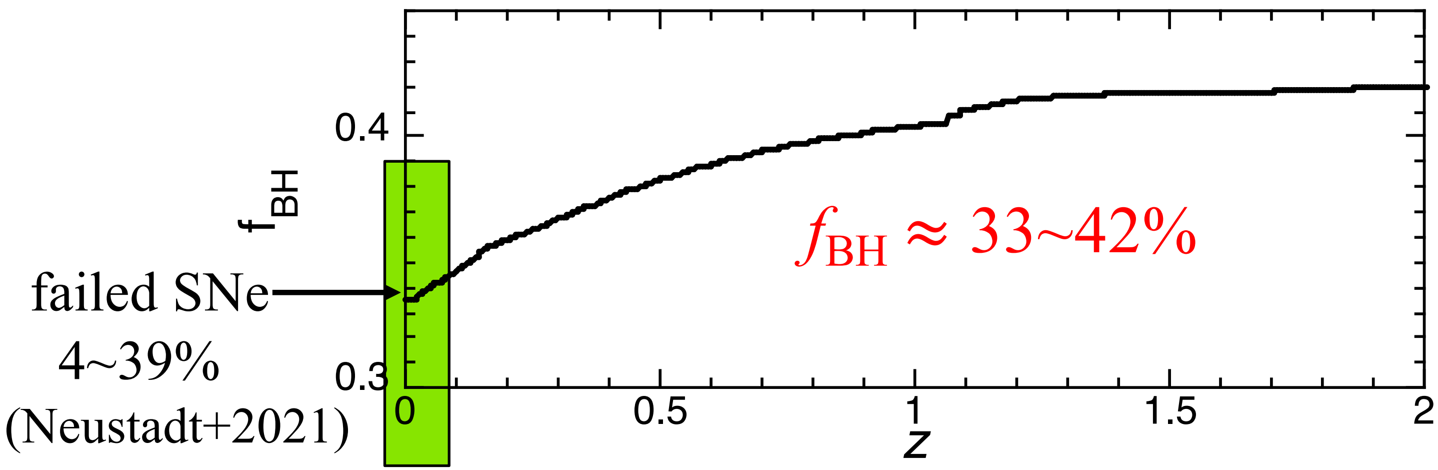
The redshift evolution of cosmic CCSN rate

The relative contribution to ψ(z) from each type of galaxy is calculated by weighting with its relative proportion and mass-to-luminosity ratio.

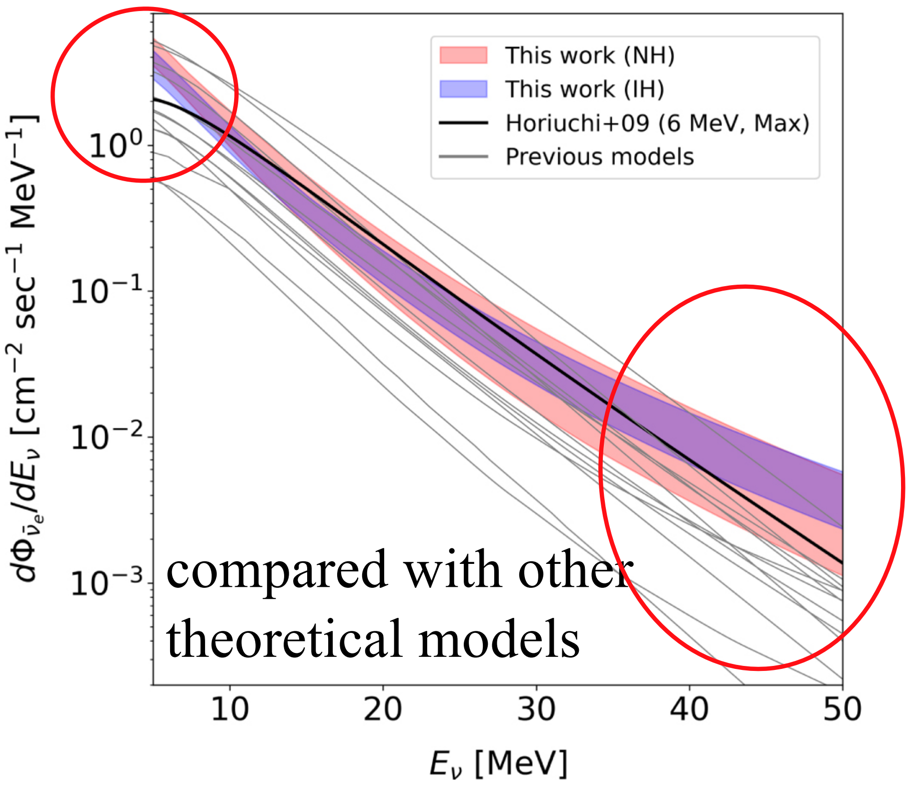


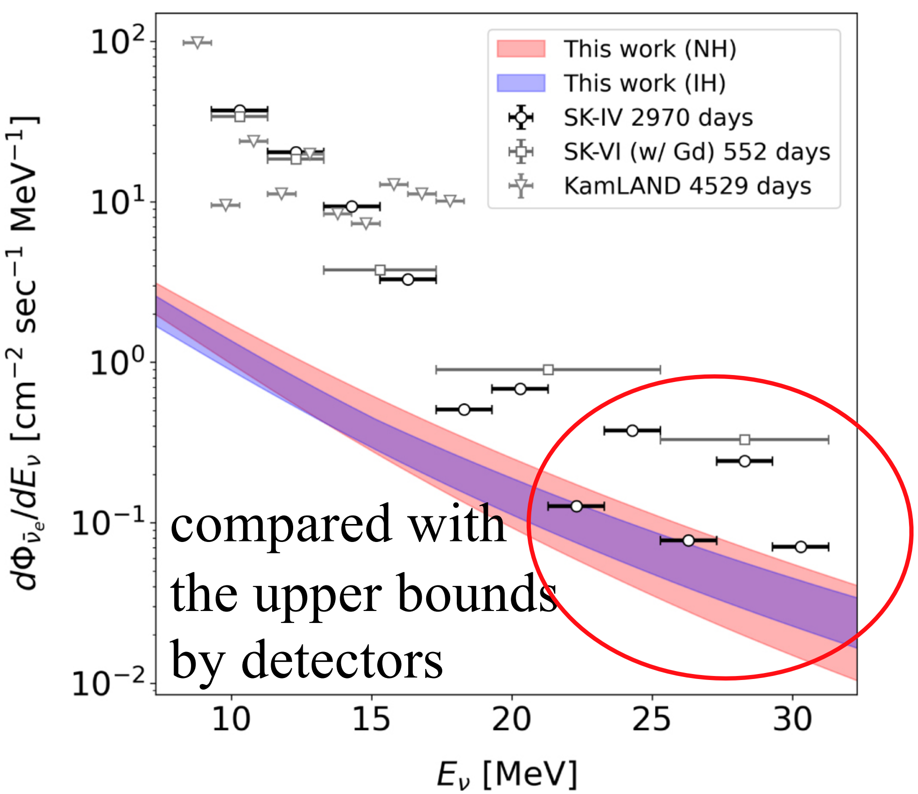
The variation in the IMF is favored by the cosmic CCSN rate evolution, at least, for $0<z<1$.

A high rate of BH formation is predicted:



Predicted diffuse supernova neutrino flux (Ashida, Nakazato & TT 2023)





Summary

- The narrow mass range (8-18 $M_{\odot}$) for CCSN progenitors
  is found to be accepted by Galactic chemical evolution

- This narrow mass range strongly supports a variable IMF
  among different type of galaxies

- This variable IMF well explains an observed large contrast
  in the cosmic CCSN rates for $z<1$

- Diffuse supernova neutrino background is calculated, and
  its enhancement at both low and high energy ranges are predicted

  $\lesssim$ 10 Mev $\gtrsim$ 30 Mev