宇宙化学進化とニュートリノ天文学

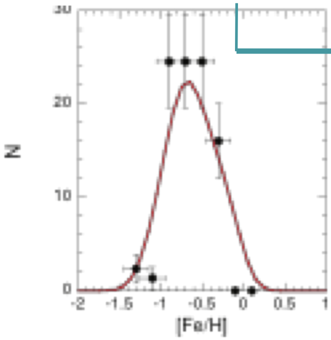
辻本拓司 (国立天文台)

- **<u>銀河系</u>**の化学進化（基本中の基本）
- **<u>近傍矮小銀河</u>**の化学進化
- **<u>*r*過程元素</u>**の化学進化
- 宇宙化学進化と**<u>ニュートリノ</u>**の接点

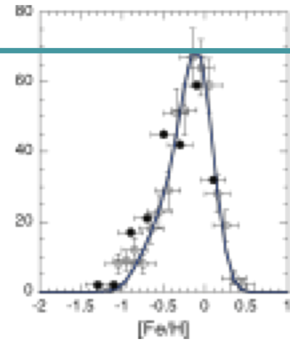
第5回超新星ニュートリノ研究会, 1月8日 at 国立天文台

	scale height	回転速度
薄い円盤	300 pc	220km/s
厚い円盤	1000 pc	180km/s

厚い円盤

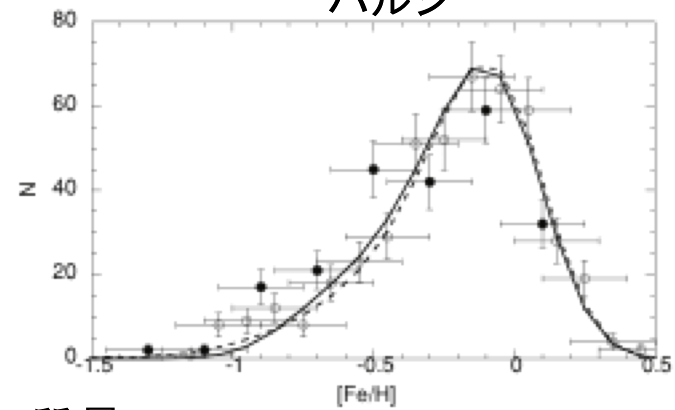


薄い円盤



質量$\sim 6\times10^{10}M_\odot$

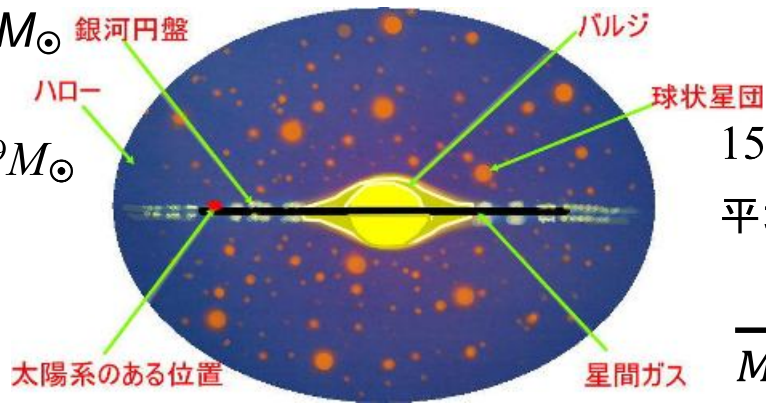
バルジ



質量$\sim 1\times10^{10}M_\odot$

銀河系の総質量

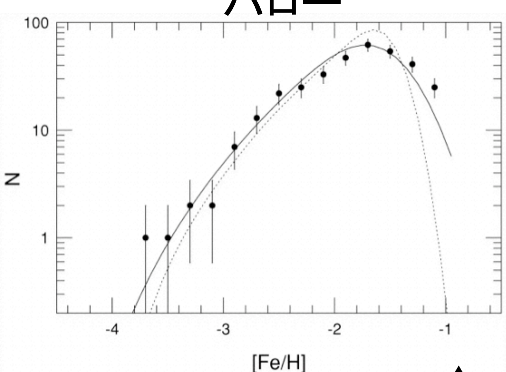
$\sim(0.7\text{-}1.5)\times10^{12}M_\odot$



中心から約8.5kpc

ハロー

質量$\sim10^{9}M_\odot$



157個

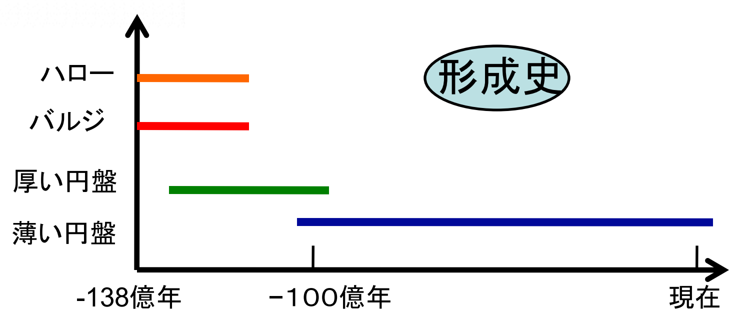
平均質量 $\sim10^{5}M_\odot$

$$\frac{M_{gas}}{M_{star}+M_{gas}} \sim 20\%$$

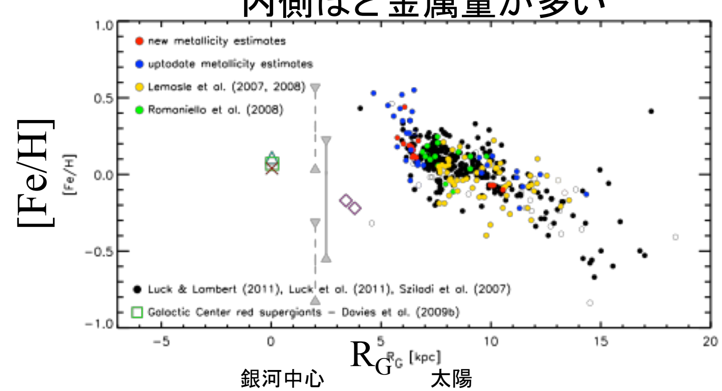
(太陽近傍)

現在の星形成率 $\sim 1.5\text{-}2\ M_\odot \mathrm{yr}^{-1}$

形成史



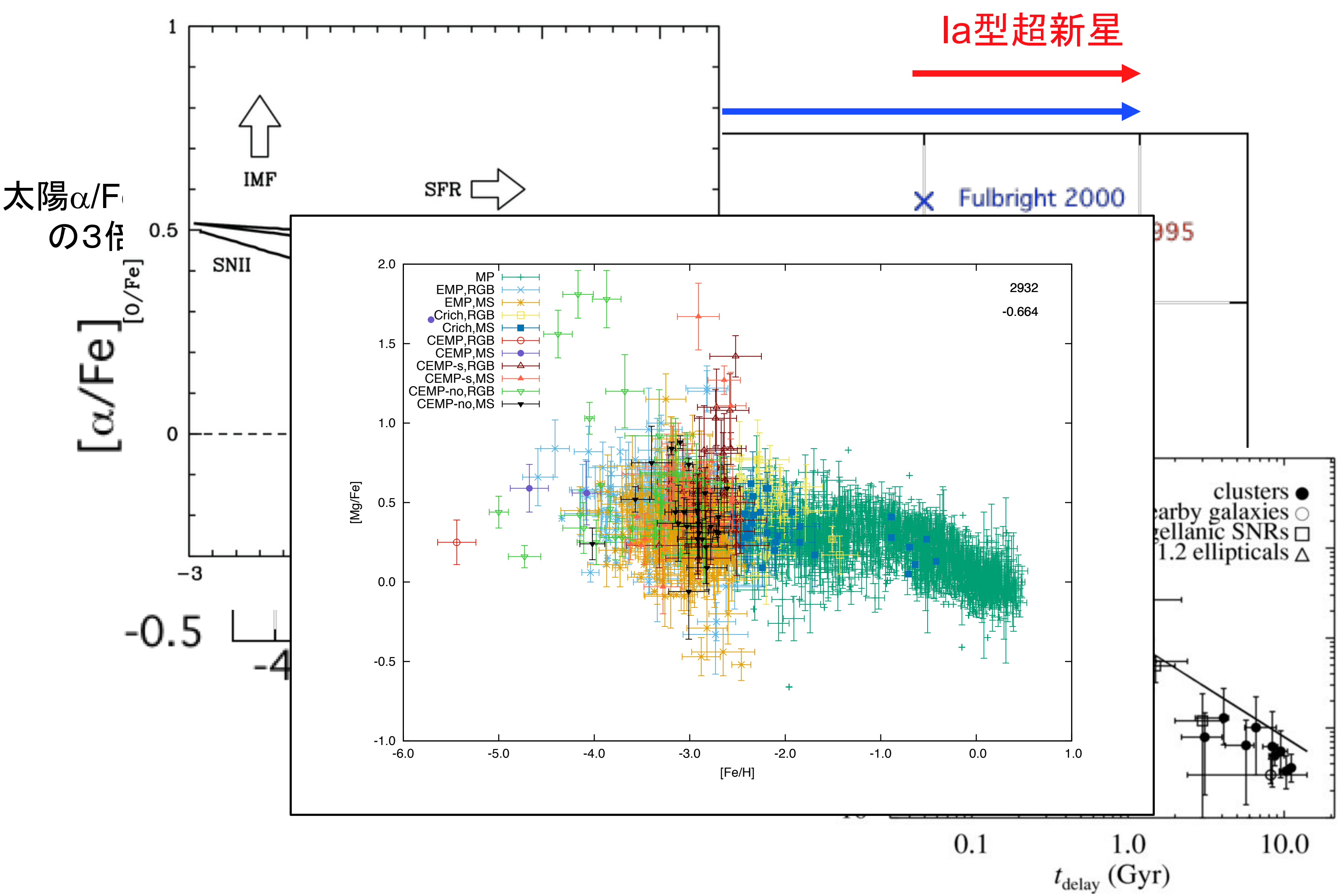
内側ほど金属量が多い



Note:

[Fe/H]=log (Fe/H)$_{星}$ - log (Fe/H)$_\odot$

太陽近傍星の**組成比**の化学進化

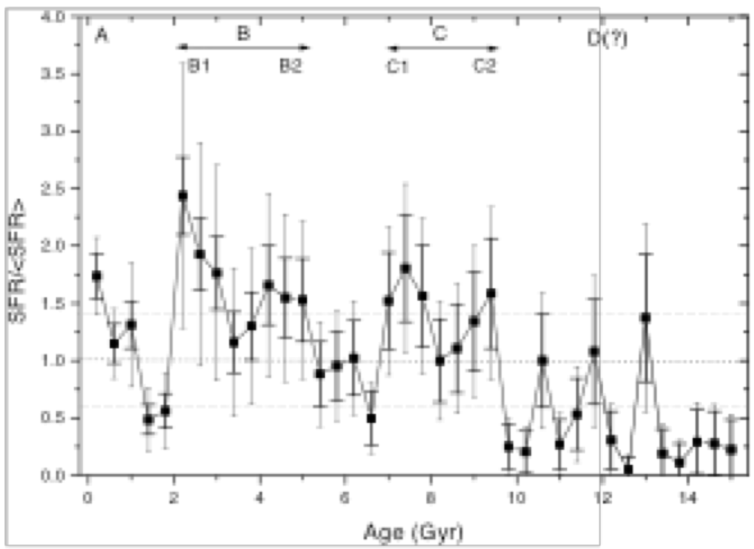


$$[Fe/H]=\log (Fe/H)_{星} - \log (Fe/H)_{\odot}$$

星形成史

銀河系の星形成史
(銀河円盤)

星形成率

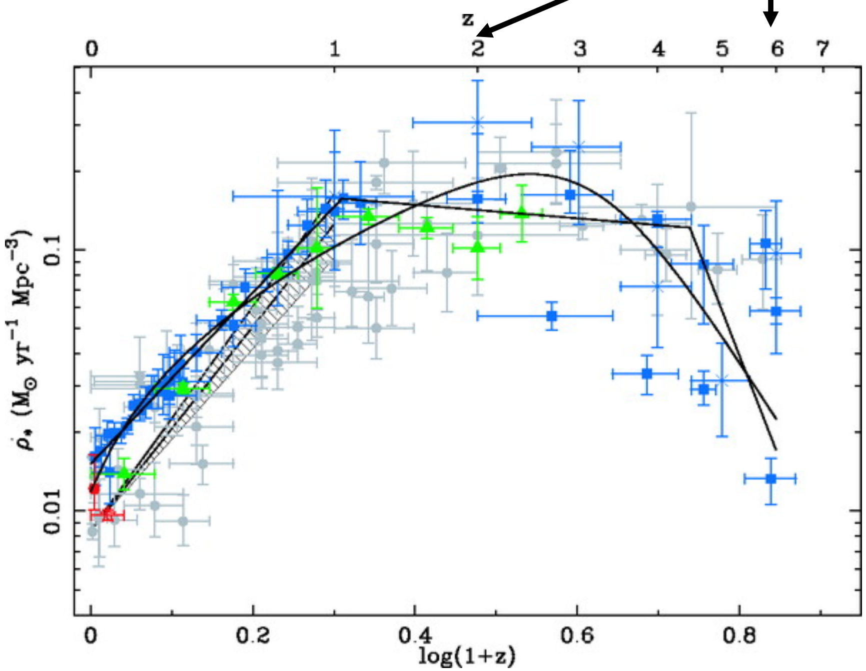


(Rocha-Pinto+ 2000)

≠

cosmic star formation

10Gyr ago 1Gyr ago



(Hopkins & Beacom 2006)

およそ100億年にわたりほぼ
定常的に星形成が続いた

星形成の素材は外からやって

銀河ディスクはハローからの低金属量
定常的な流入の中で作られてき

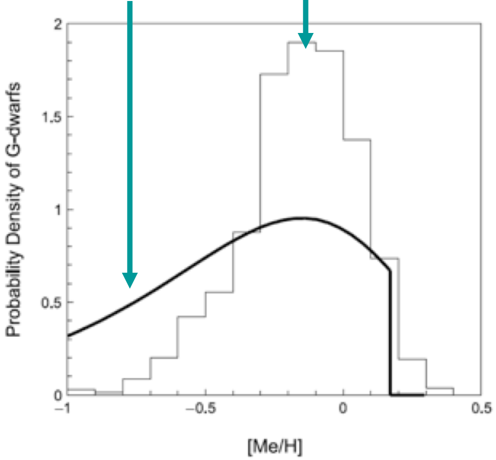
理論的示唆

G型矮小星問題を解決

閉鎖系モデル

観測データ

星の重元素量頻度分布

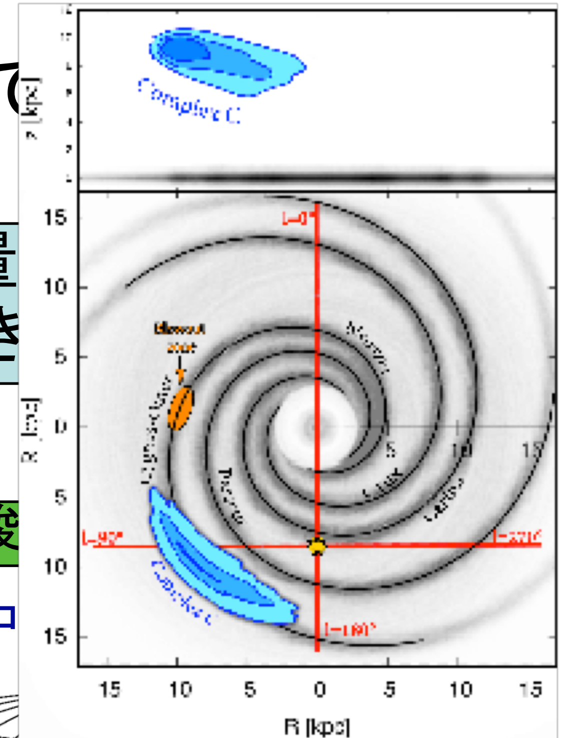


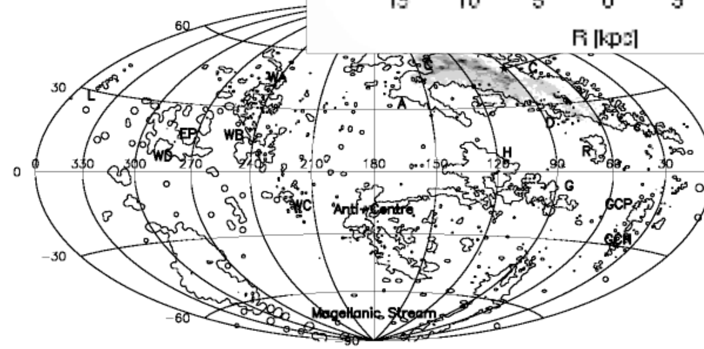
閉鎖系だと
低金属量星
を作り過ぎて
しまう

階層的銀河形成の描像ともマッチ

観測的示唆

高速度中





Complex C

質量:$8\times10^6\ M_\odot$, 距離: 10 kpc, サイズ: 3 × 15 kpc

Smith cloud

質量:$2\times10^6\ M_\odot$, 距離: 12 kpc, サイズ: >3 × 1 kpc

約3000万年後にディスクに衝突

銀河系はsmall systemが降着しながら、構造形成がなされ、そして現在まで進化してきた

✓ >100億年前に~$10^9\ M_\odot$のsmall galaxyが降着した

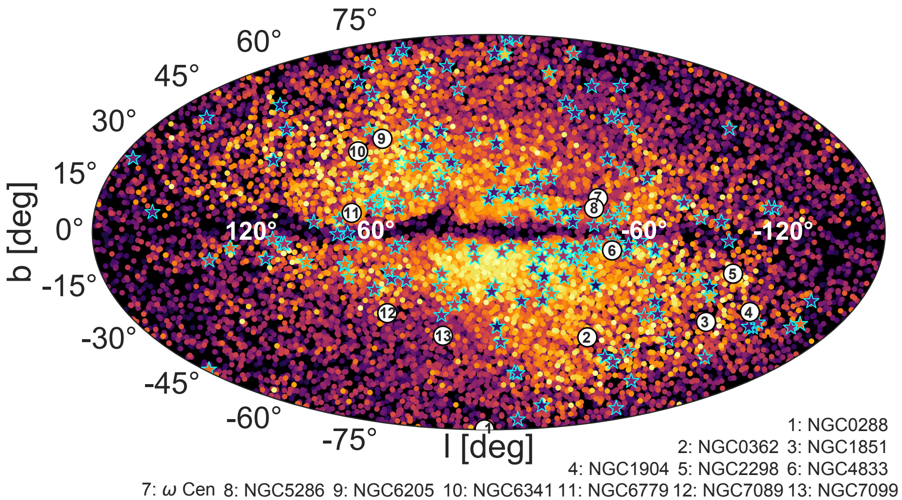
→ thick disk形成

✓ 現在Sagittarius galaxyが降着中

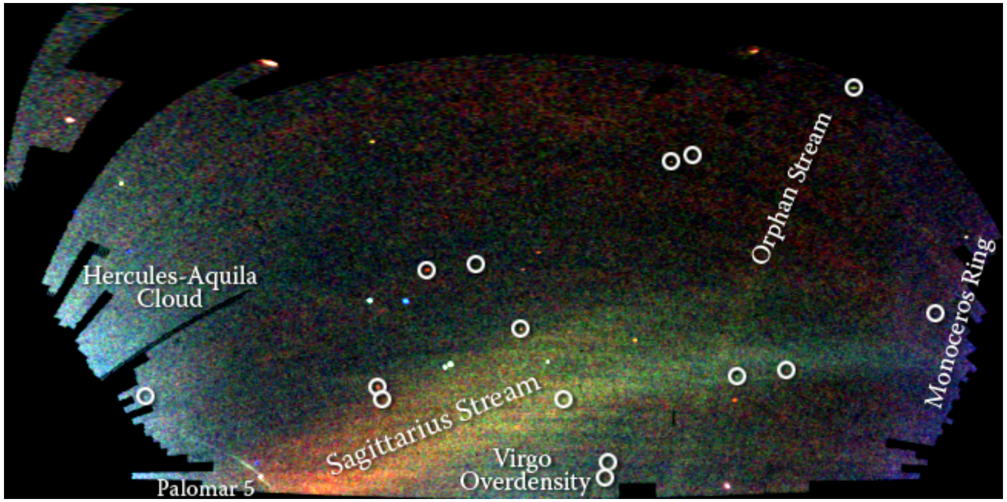
✓ 定常的にgas cloudが降着してきた

→ thin disk形成

accretion of satellite galaxies evidenced in the Galactic halo



Helmi+ 2018

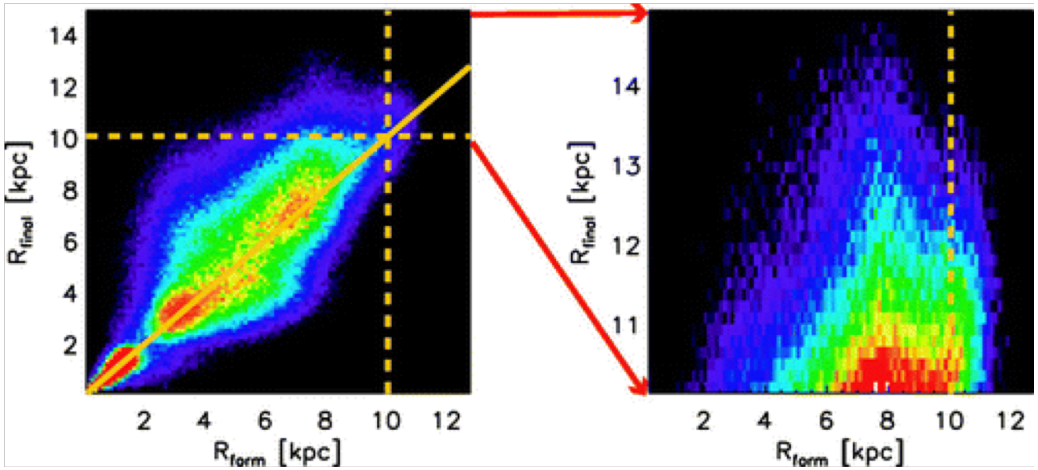


@SDSS

銀河円盤形成・進化に関する最新描像

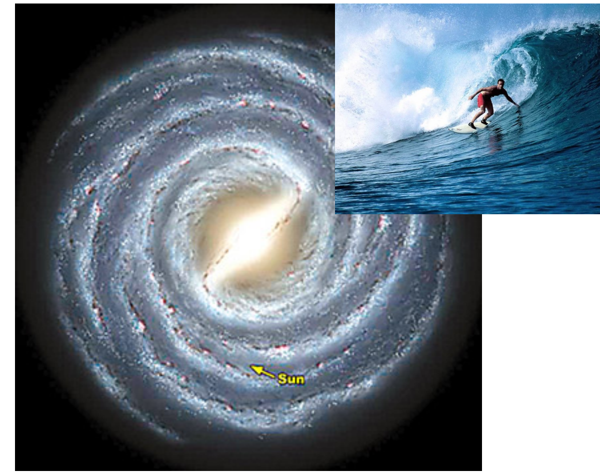
銀河円盤内を*波に乗*って星は大移動: radial migration

現在位置



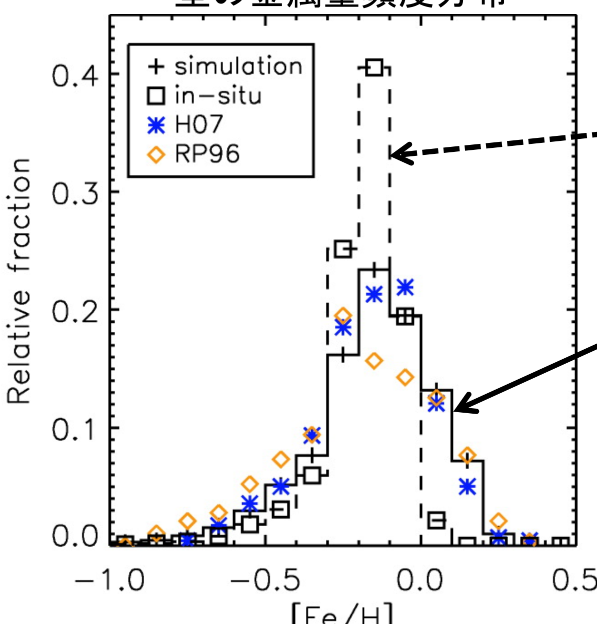
Roskar et al. 2008

生まれた位置



星が渦状腕（波）に遭遇すると角運動量の輸送が起こり動径方向に移動する

星の金属量頻度分布

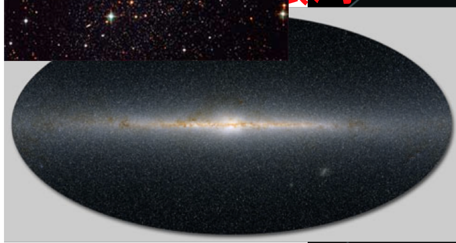


太陽近傍で生まれた星の分布

現在太陽近傍に存在する星の分布

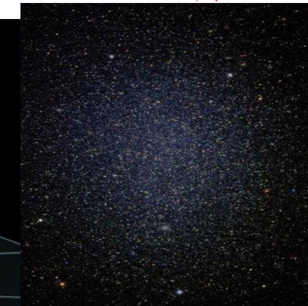
太陽も銀河のもっと内側で形成され、そして移動してきた可能性あり

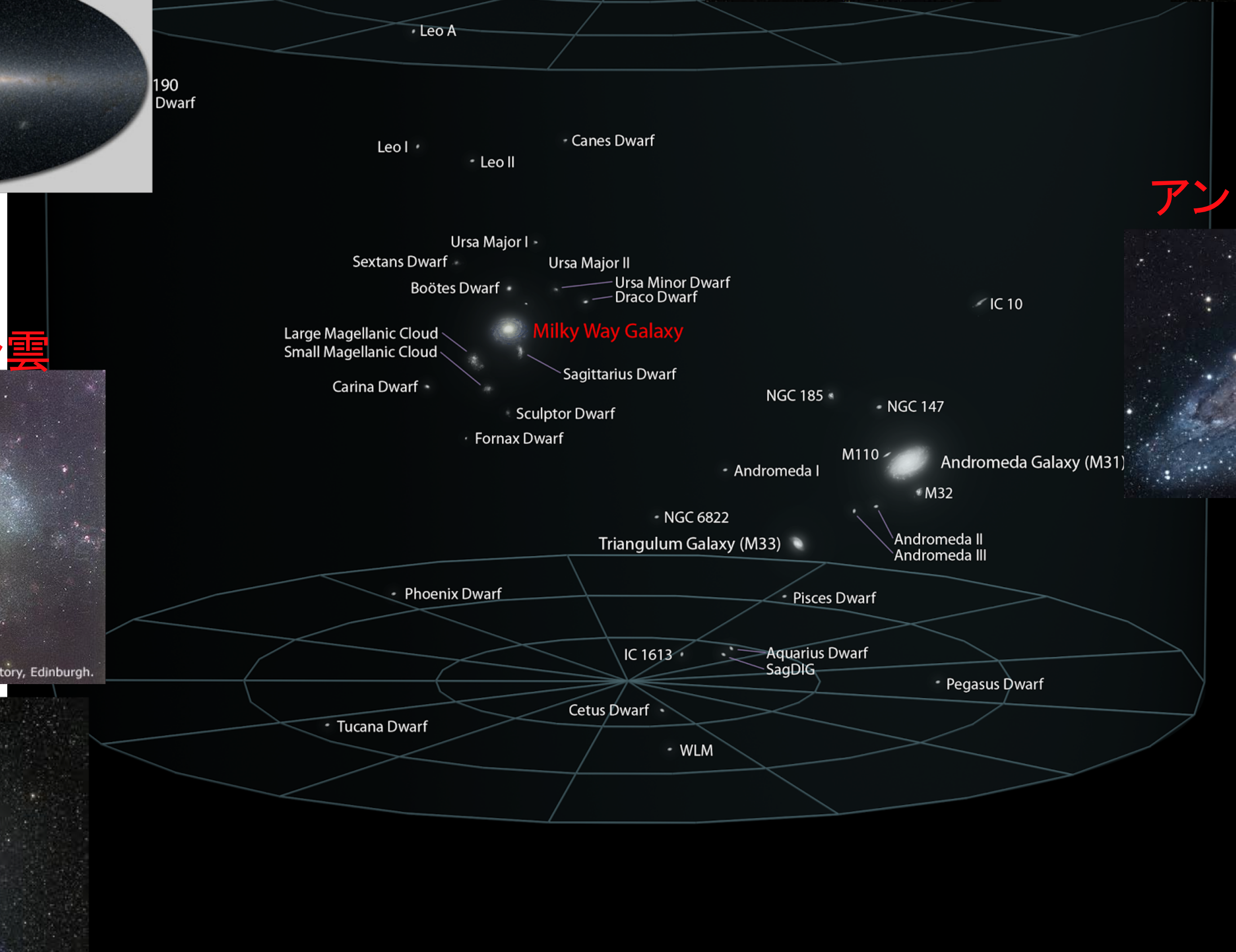
いて座銀河



ろ座銀河

しし座I銀河





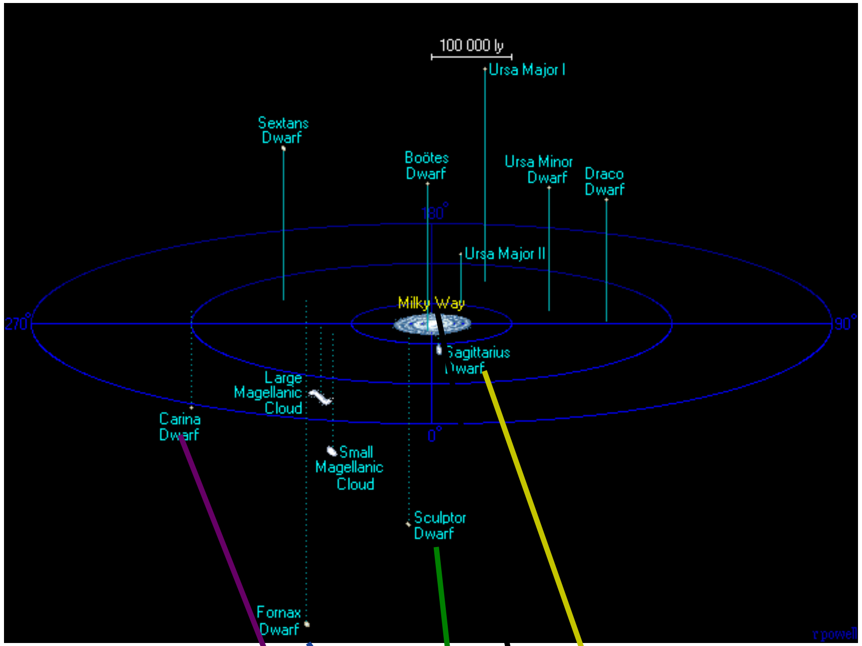
アンドロメダ銀河

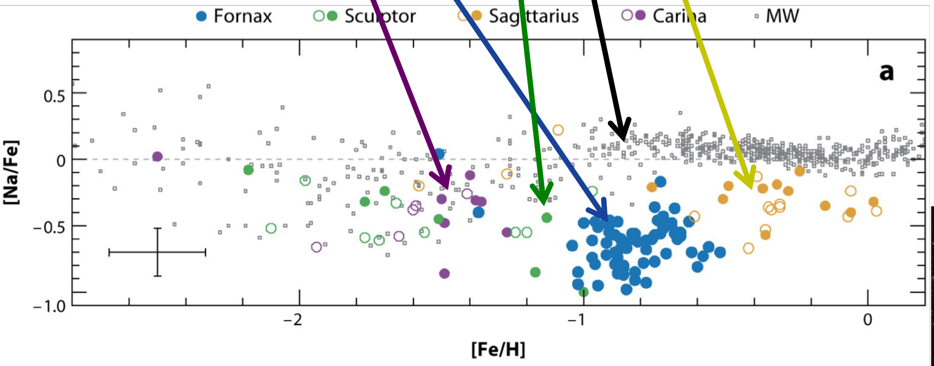
大マゼラン雲

小マゼラン雲

(1kpc=3x10^{21}cm
=2x10^{8} au)

星のスペクトル分光: <300 kpcが射程内





Tolstoy+ 2009

黒: 銀河系
カラー: 回転楕円体

矮小不規則銀河

ガスrich

星の質量
$M_* \sim 10^9\ M_\odot$ 大マゼラン星雲

50kpc

$10^8\ M_\odot$ 小マゼラン星雲

60kpc

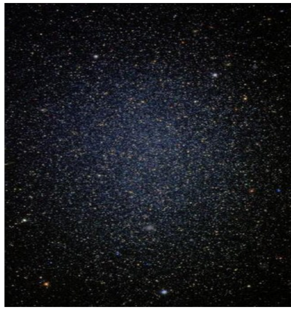
矮小回転楕円体銀河

ガスを含まない
$M_* \sim 10^3$ - $10^7\ M_\odot$
(因に球状星団は$10^5 M_\odot$, 銀河系は$10^{11} M_\odot$)

いて座 (20kpc)

ろ座 (138kpc)

しし座I (254kpc)

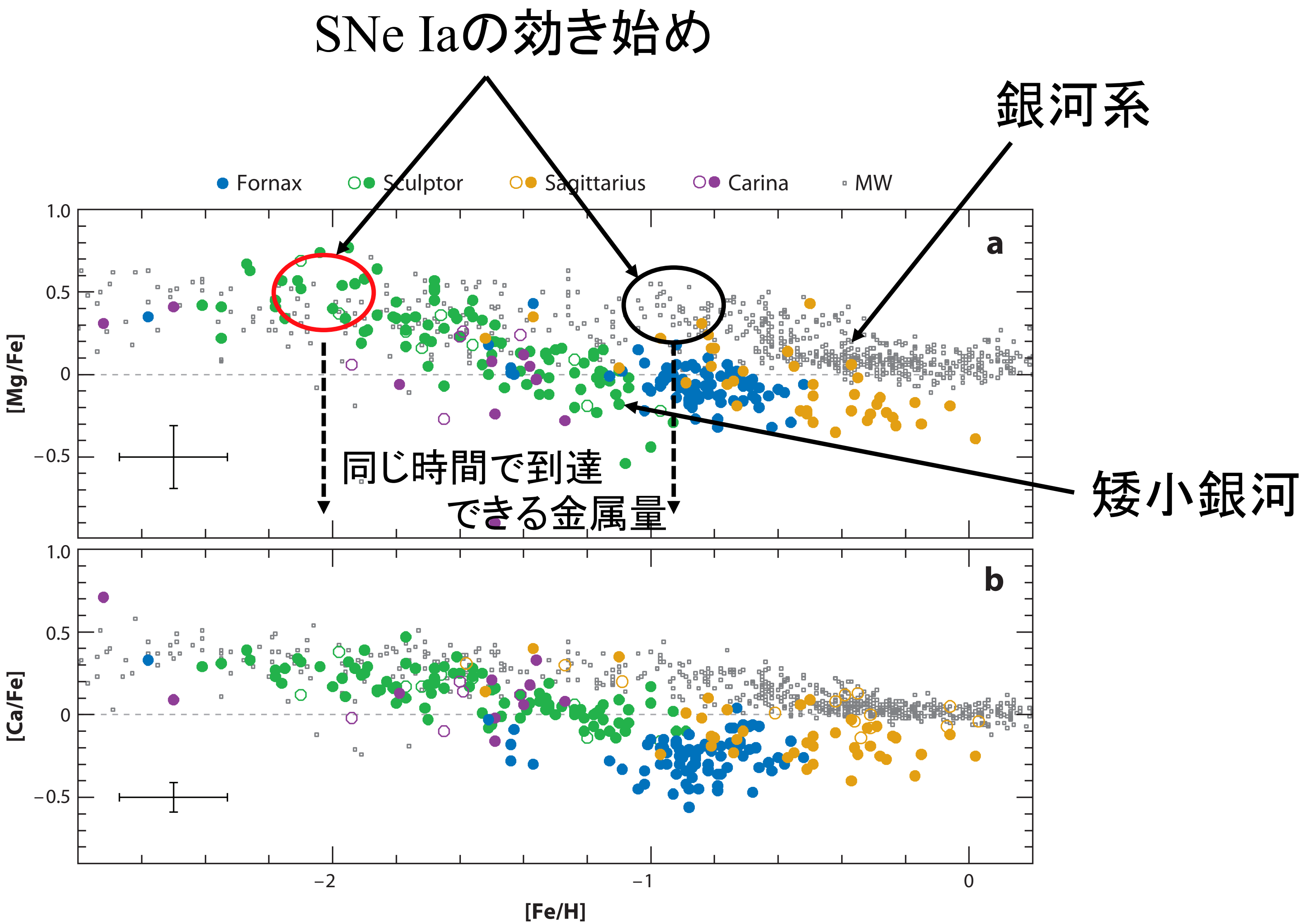


化学進化のfundamental parameters

✓ 星形成率 (star formation rate)

✓ 星の初期質量関数 (initial mass function)

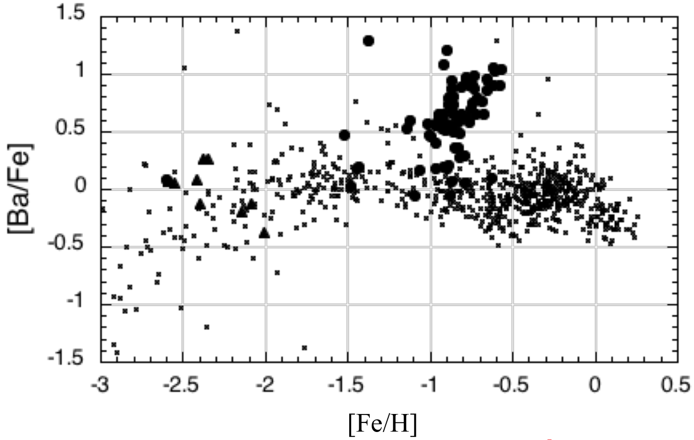
星形成はゆっくり


SNe Iaの効き始め
銀河系
Fornax
Sculptor
Sagittarius
Carina
MW
a
b
同じ時間で到達
できる金属量
矮小銀河
[Mg/Fe]
[Ca/Fe]
[Fe/H]
1.0
0.5
0
−0.5
−2
−1
0

大質量星の欠如（？）

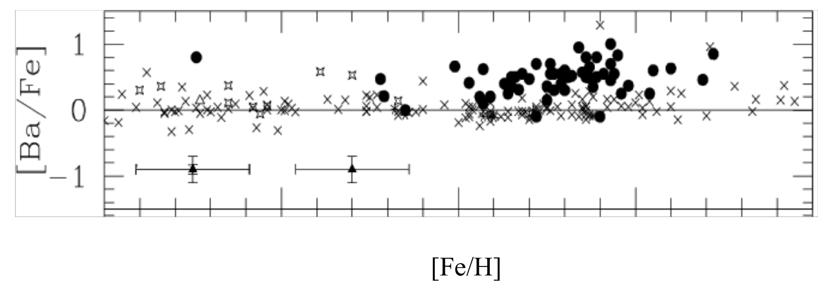
Fornax

Letarte+ 2010

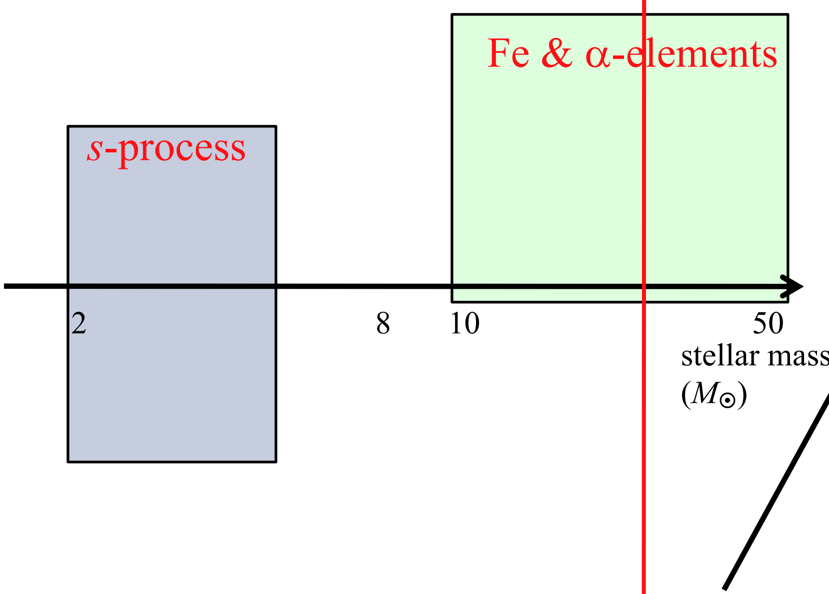


LMC

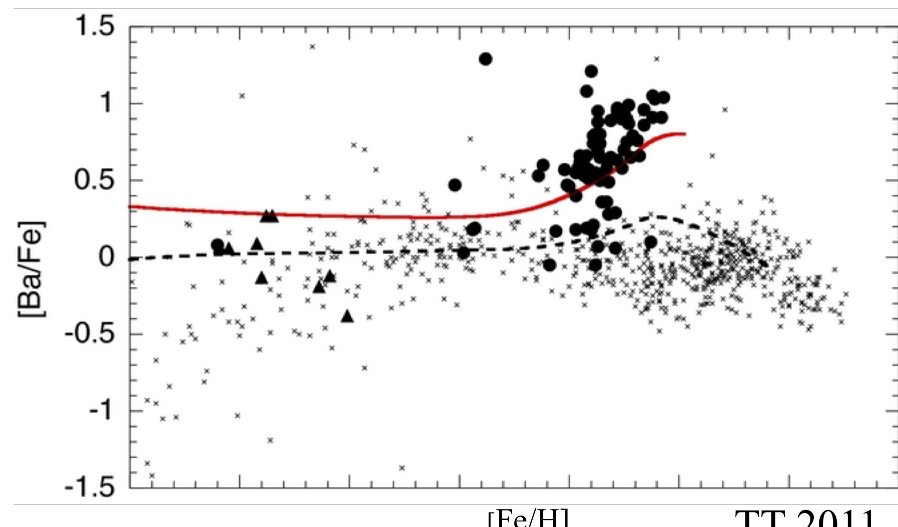
Pompeia+ 2008



$$\frac{s-process}{Fe\ \&\ alpha}$$

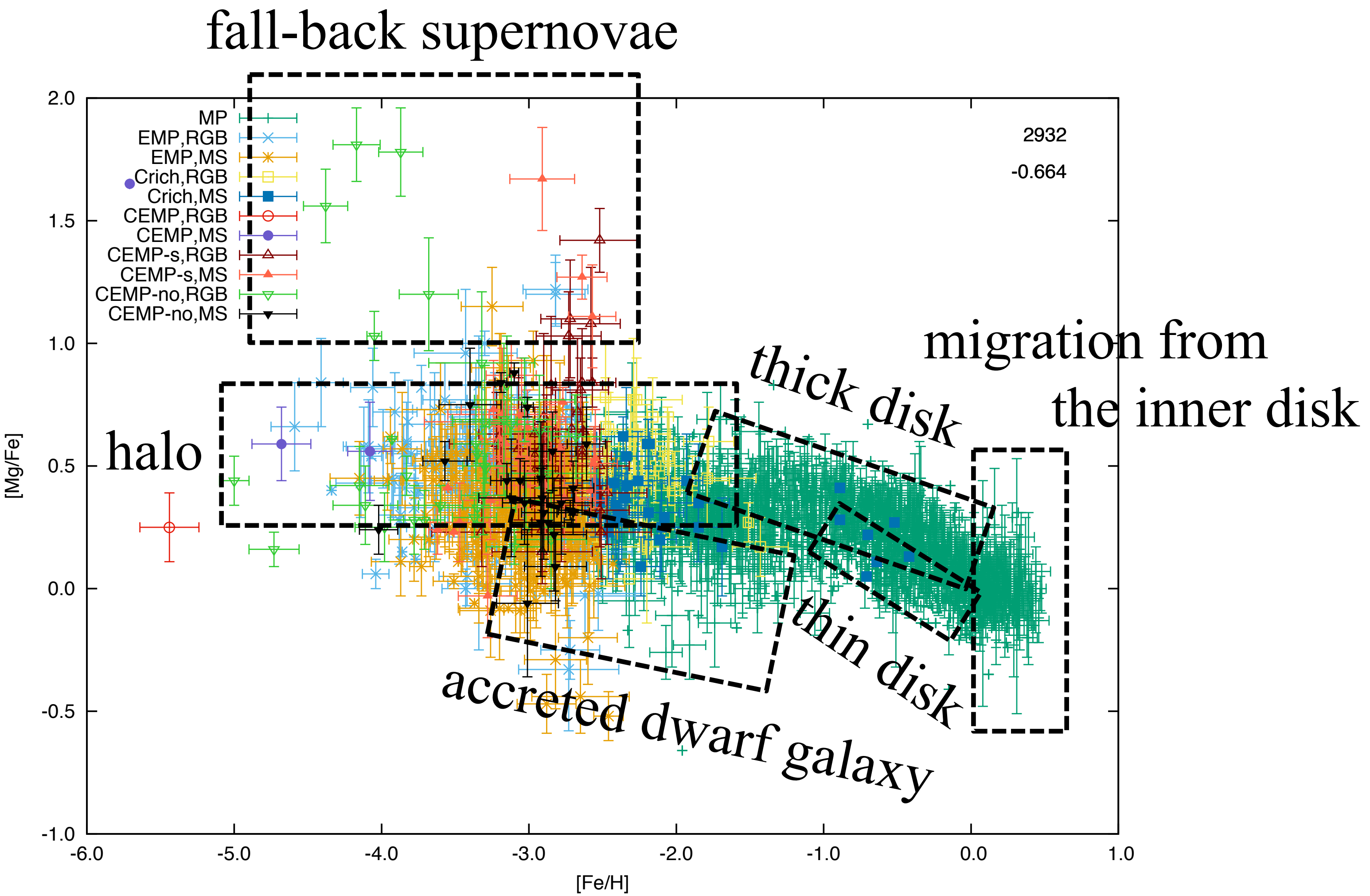


cut-off



TT 2011

太陽近傍星の化学組成分布の理解



矮小銀河とr過程元素

どうも中性子星合体が起源らしい

もしそうであるならば、r過程元素合成イベントの特徴は

1. 稀な現象
2. 一回当たりの合成量は多い

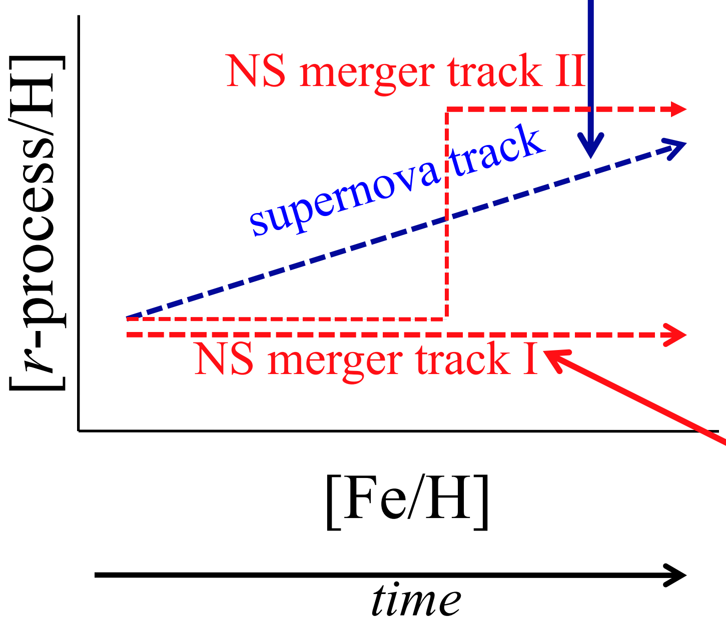
✓その痕跡、証拠を化学組成に捉えたい

✓中性子星合体の元素合成、頻度に関する情報の取得

Why dwarf galaxies?

supernovae vs. NS mergers

rarity



For instance, a dwarf galaxy with $10^5 M_\odot$

~500 CCSNe in total

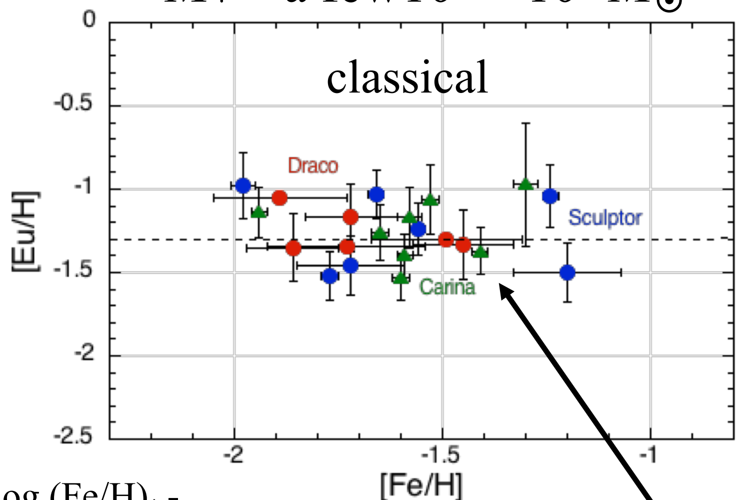
A few or no NS Merger events in such a galaxy are predicted.

Note! the Milky way experiences more than 2×10^5 NS mergers.

The rarity of *r*-process event is identified

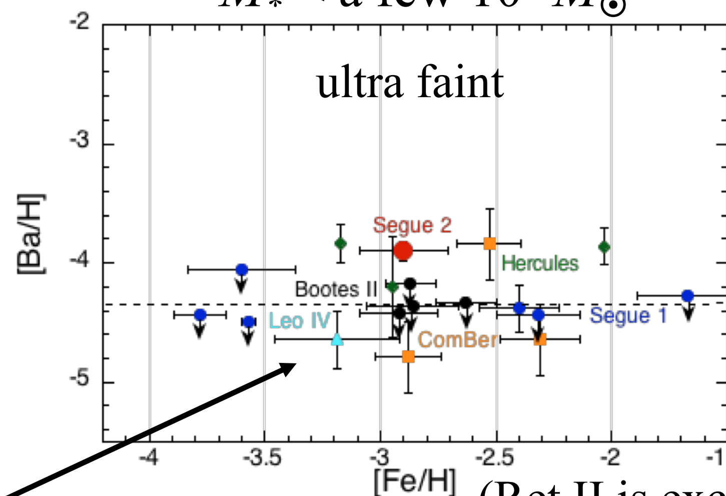
faint (small-mass) dwarf galaxies

stellar mass: $M_* \sim$ a few$10^5 - 10^6\ M_\odot$



([Fe/H]=log $(Fe/H)_*$ - log $(Fe/H)_\odot$)

$M_* <$ a few $10^4\ M_\odot$



(TT & Shigeyema 2014)

(Ret II is excluded)

a broadly constant r-process abundance with increasing [Fe/H]

r-process production events did not happen
while numerous CCSNe explode and increase Fe in the ISM.

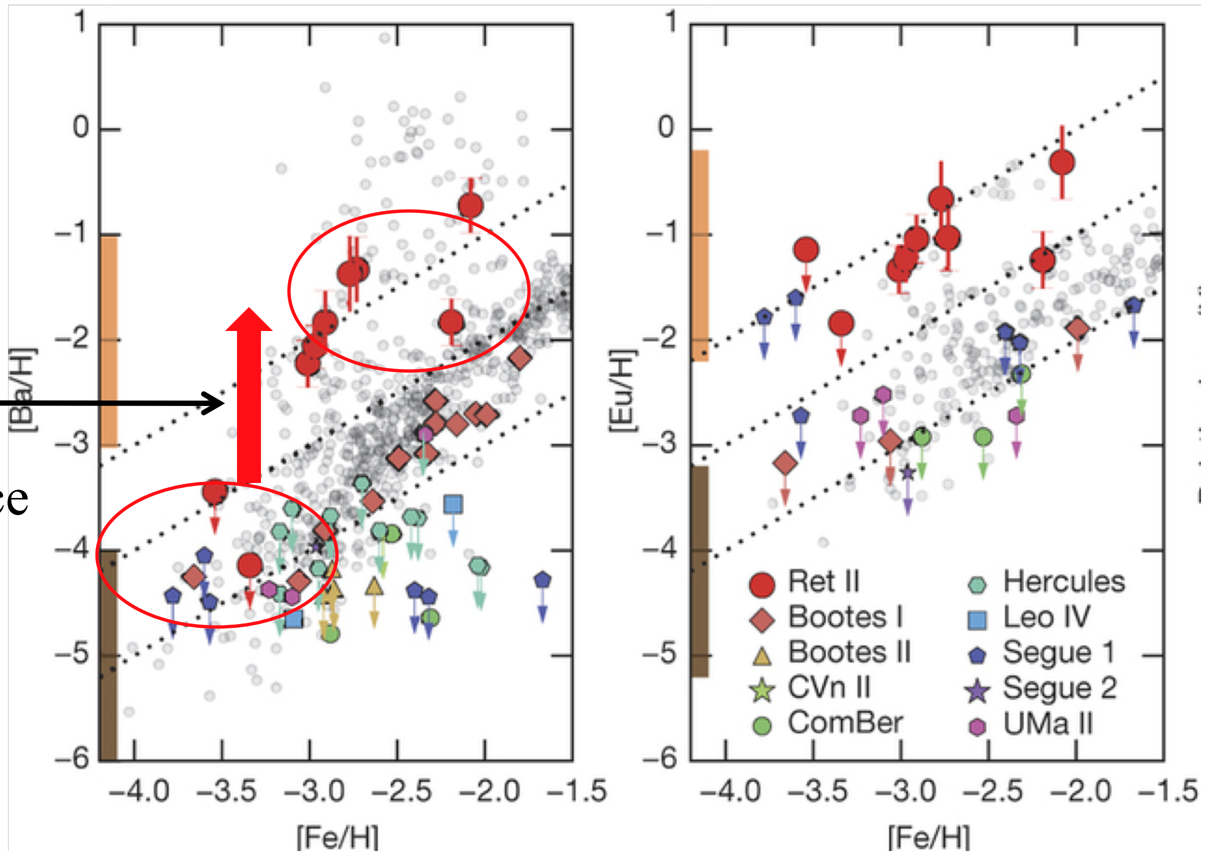
Such a rarity supports NS mergers as the site of r-process elements

ultra faint dwarf galaxy Reticulum II

"*r*-process galaxy"

stellar mass of $\sim 2400 M_\odot$

a jump by more than two orders of r-process abundance



Ji et al. 2016

identify **a rare event** and **a high r-process yield**

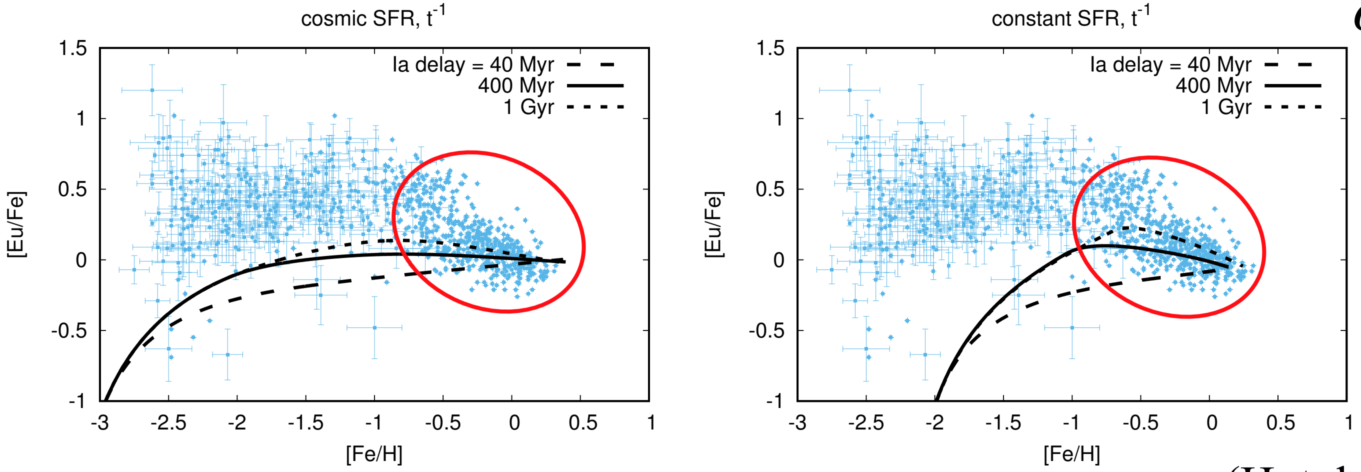
no counterparts in other UFDs

a big abundance jump

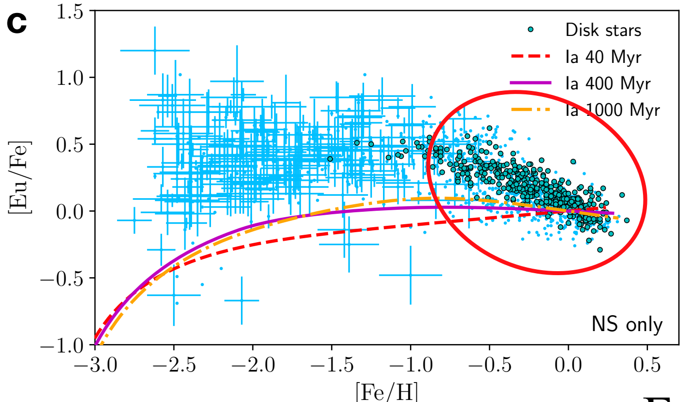
銀河系とr過程元素

r-process enrichment in the Galaxy

The prediction by NS mergers is not compatible with the observed feature of Galactic disk



(Hotokezaka+ 2018)



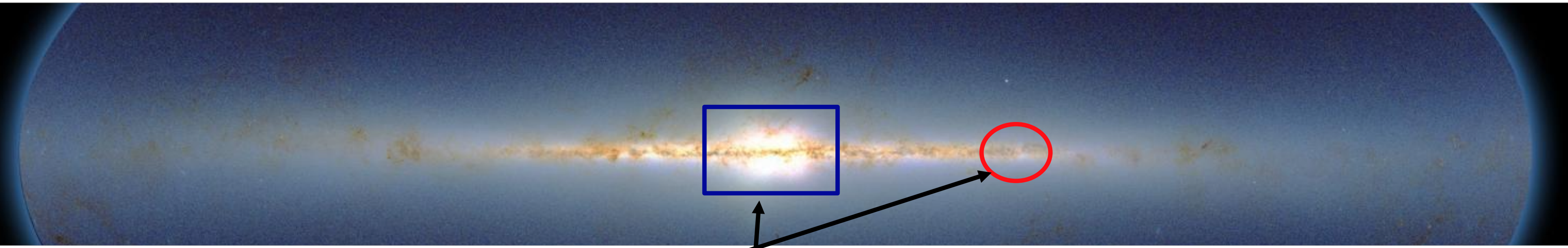
(Siegel+ 2018)

Short GRB rate = NS merger rate

delay time distribution (DTD) of NSM

$\approx$ DTD of sGRB $\propto t^{-1}$

Faster enrichment than the expectation from $\propto t^{-1}$ seems to be required such as a large contribution (~80%!) from collapsars (Siegel+2018).



However, **the Galactic disk** is a kind of messy component.

✓ a mixture of two components, i.e., thick disk and thin disk

Two disks experienced completely different star formation histories.

✓ Some fraction of nearby disk stars is not formed in-situ but migrate from the disk at different Galactocentric distances.

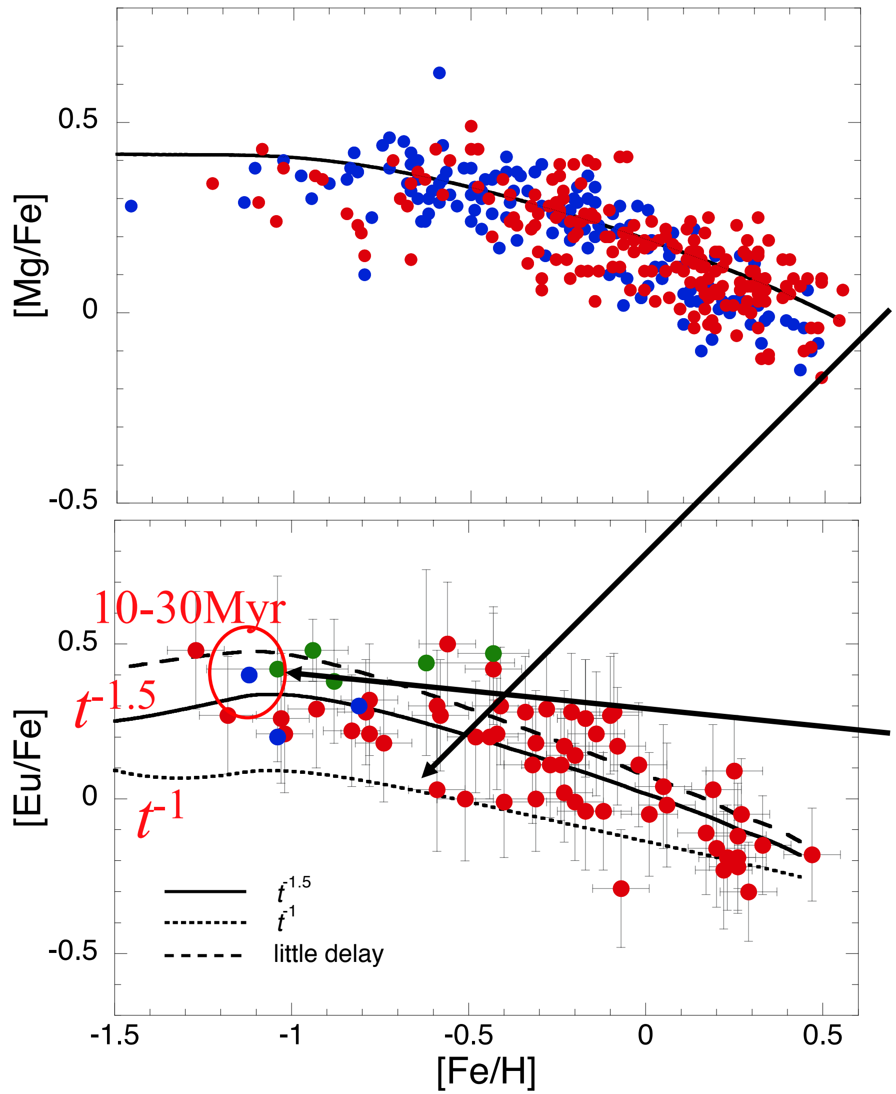
Chemical evolution of the disk differs according to the distance form the Galactic center.

On the other hand, **the Galactic bulge** is a simple component.

✓ a single component

✓ no contaminants from outside

r-process enrichment in the Galactic Bulge



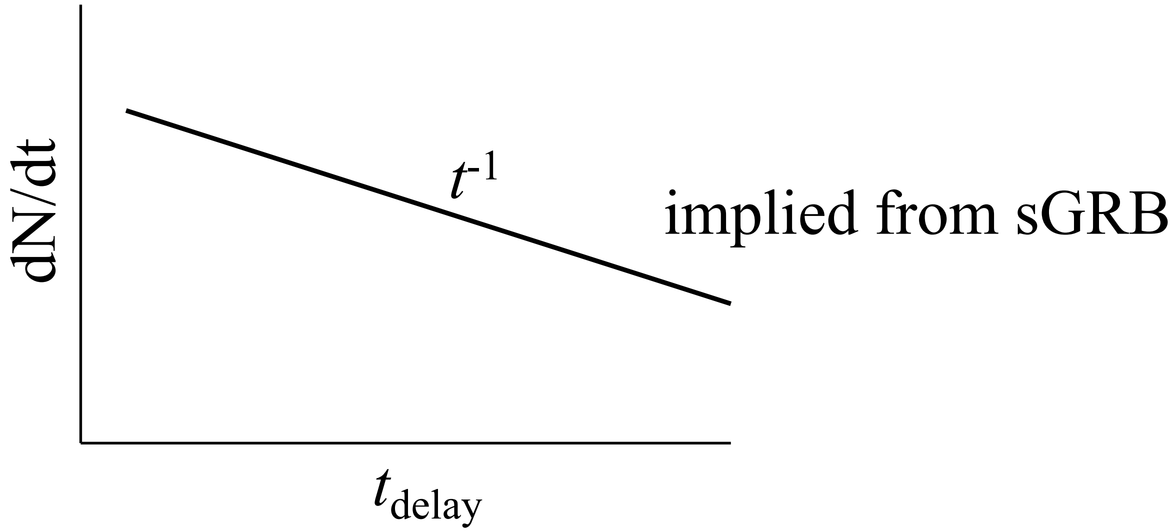
Study of the Galactic bulge confirms that *r*-process enrichment with DTD∝ t^{-1} is not consistent with the observations.

Faster enrichment such as the form of DTD∝ $t^{-1.5}$ is required.

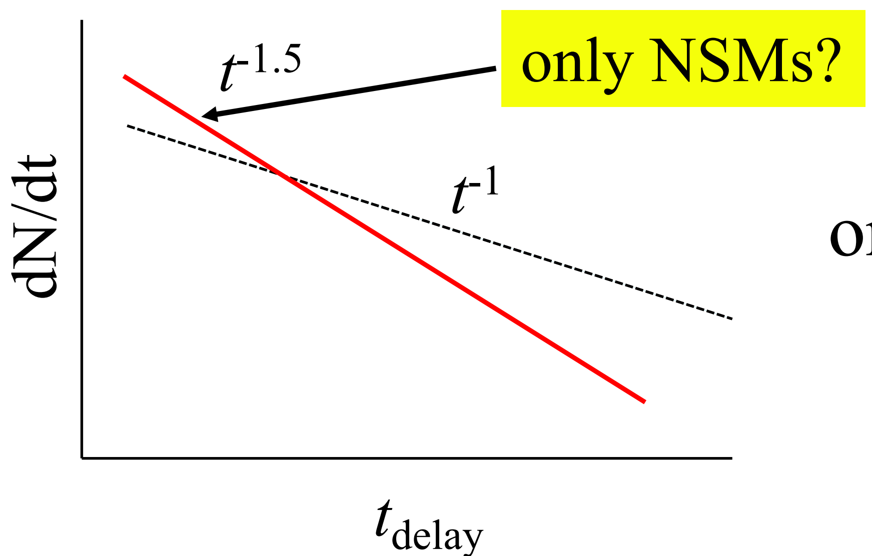
(TT & Baba, submitted)

Delay time distribution of r-process enrichment

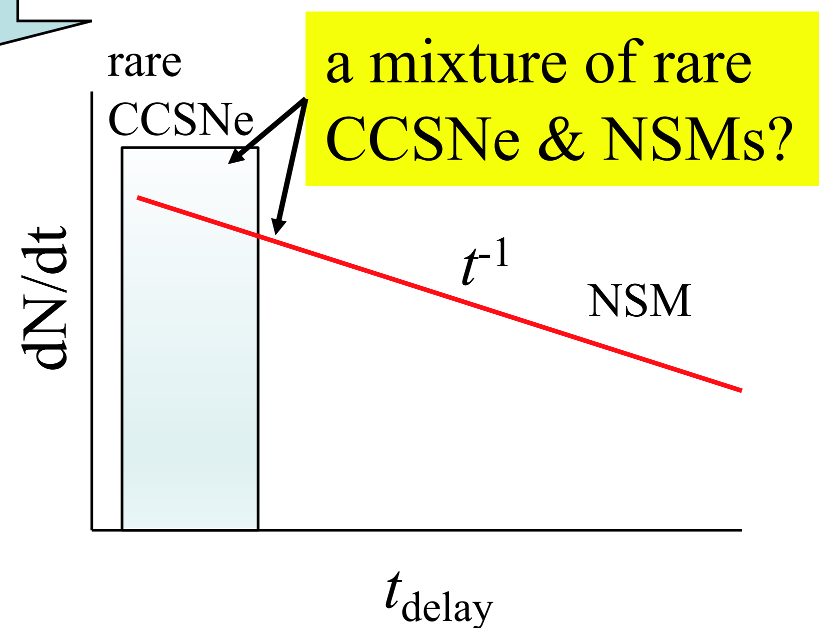
is not like



but should be like



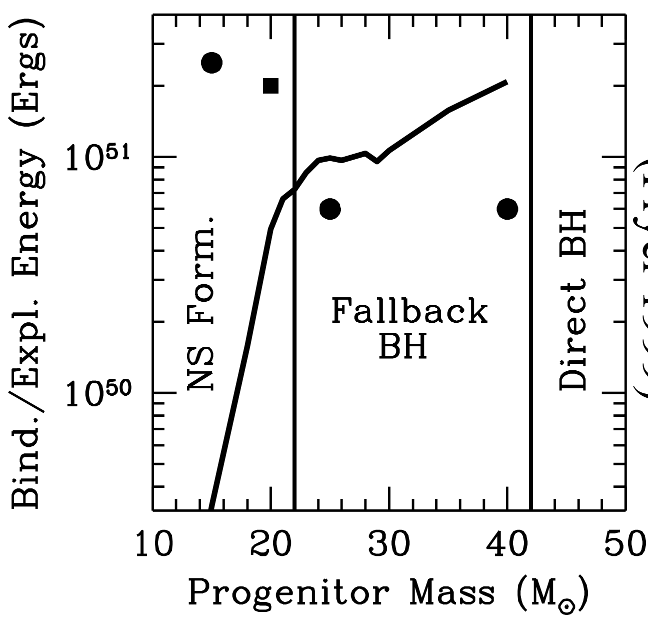
or



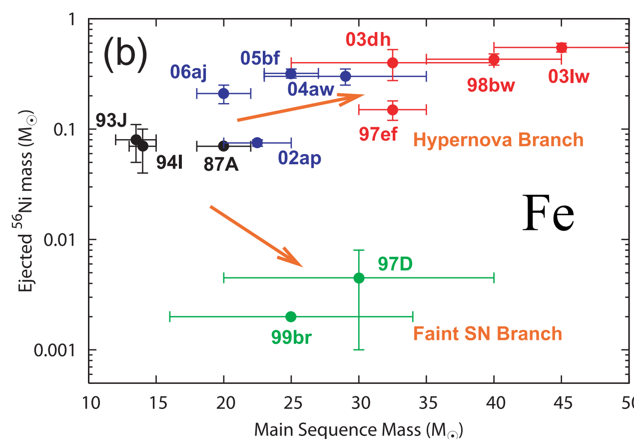
宇宙化学進化とニュートリノの接点

化学進化の原動力は超新星

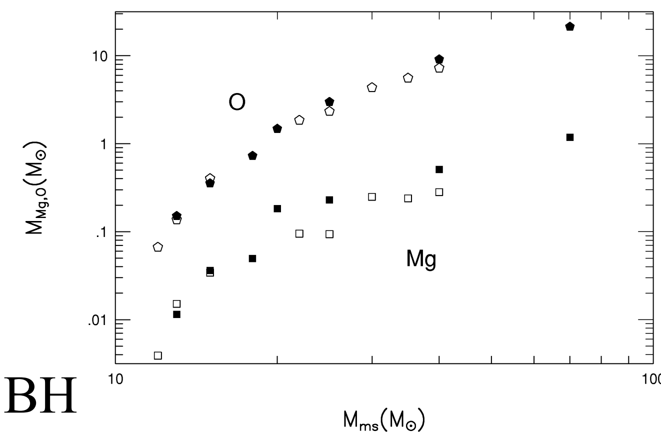
} ニュートリノ放射に違いがある(？)



(Fryer 1999)



(Tominaga+ 2007)



(Shigeyama & TT 1998)

*r*過程元素

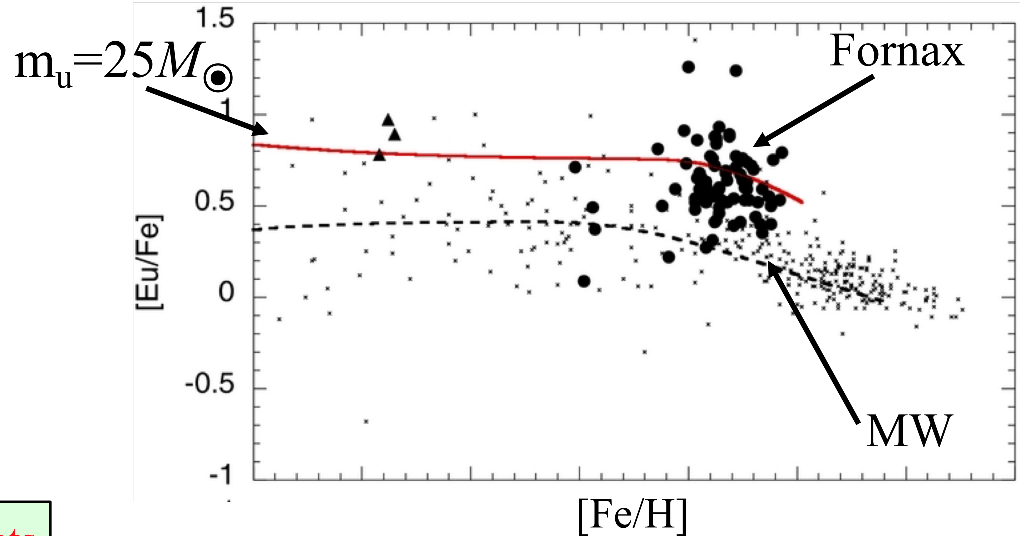
アルファ元素
／鉄属元素

~60-70% from SNe with BH

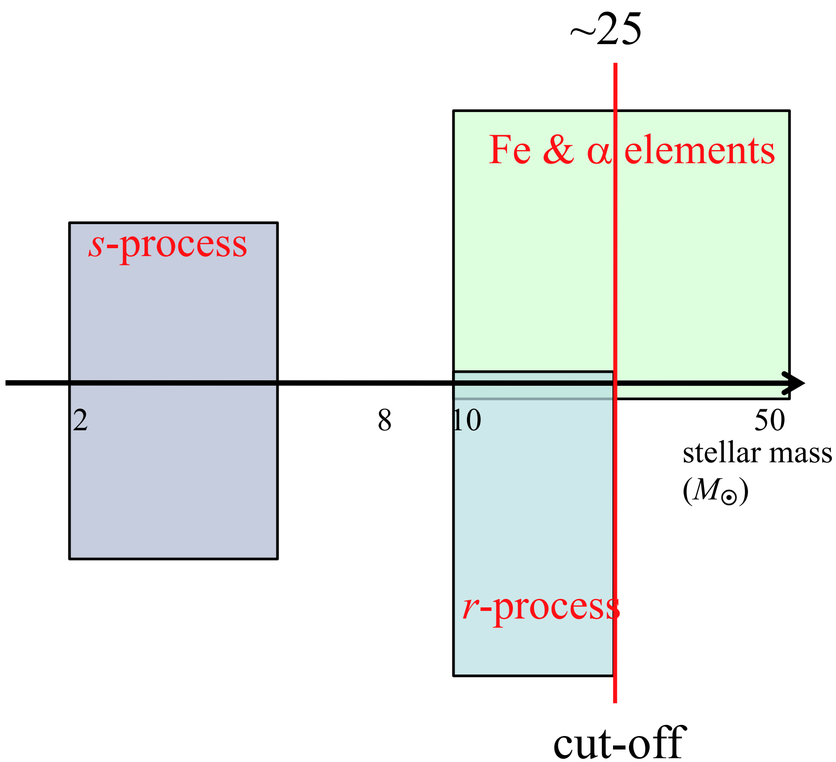
SNe with BH が矮小銀河では欠如？

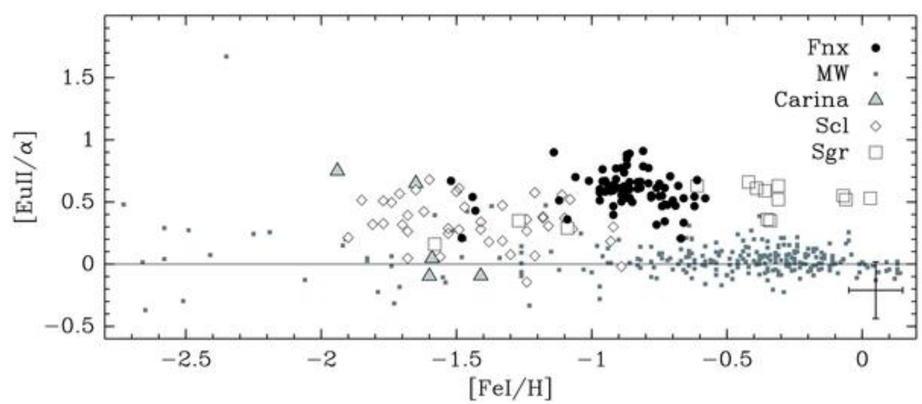
相対的に組成比がアップ

$$\frac{r-process}{Fe\ \&\ alpha} \nearrow$$



(TT 2011)





(Letarte+ 2010)

A truncated IMF in dwarf galaxies

observationally

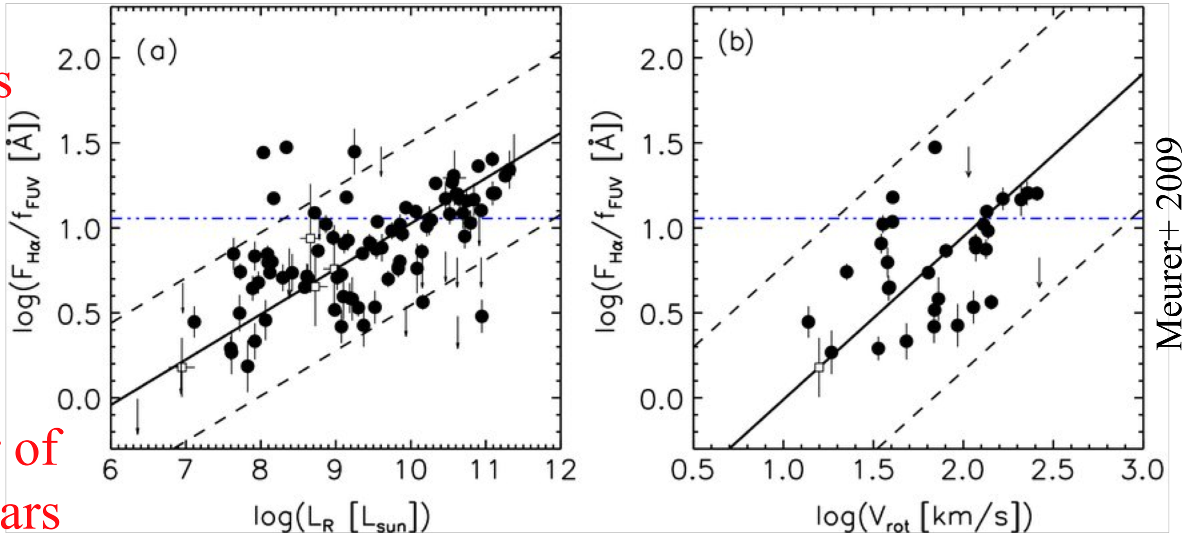
Low-surface brightness galaxies have

A low $\frac{F_{H\alpha}}{F_{FUV}}$ ratio

massive O-type stars

less massive stars

➡ a smaller number of very massive stars



Meurer+ 2009

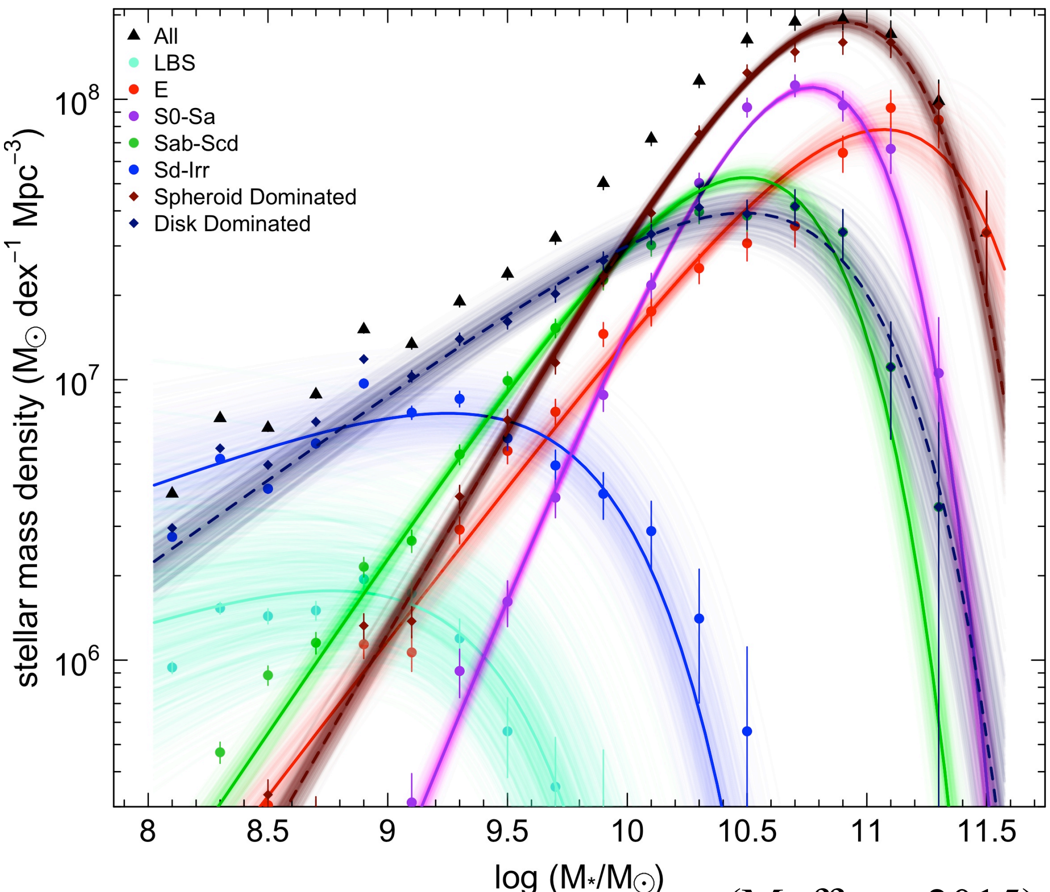
theoretically

A high mass end of the IMF depends on the mass of the star clusters.
In the low density environment, the formation of massive star clusters is suppressed.

(Kroupa & Weidner 2003, Pflamm-Altenburg & Kroupa 2008)

Their model predictions have been shown to be consistent with the observed trend for the Hα-to-FUV flux ratio (Lee+ 2009).

the stellar mass budget by galaxy type



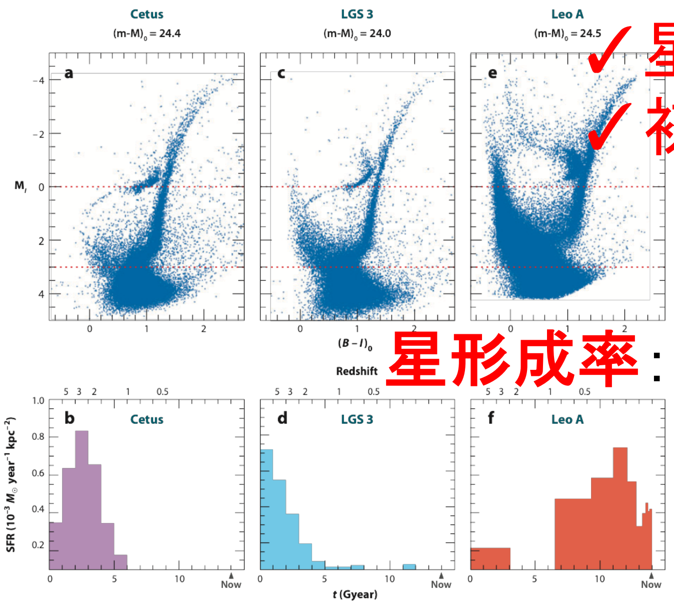
(Moffett+ 2015)

全体のa few percentはSNe with NSのみ持つ銀河の可能性が

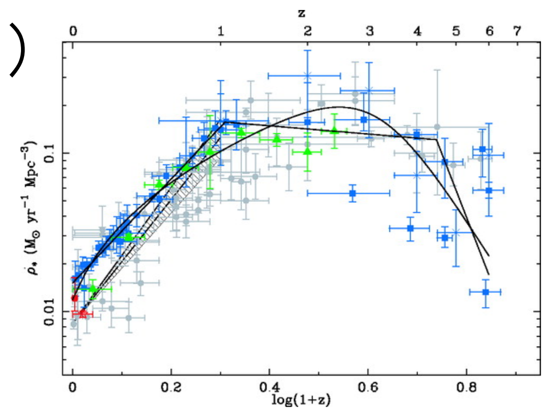
(≤ ~5%)

ニュートリノ の観点から検証可能か？

宇宙化学進化を駆動するのは、



✓星形成率
✓初期質量関数（大質量星の）



星形成率：ある程度わかっている

初期質量関数：？？

初期質量関数 ≈ *N*_(SNe with NS)／*N*_(SNe with BH)

元素情報: r過程元素 (1/0)、他の元素 (0.3/0.7)
ニュートリノ 情報: 両者での放射の違いを理論的に予言