Views on the evolution of the Milky Way

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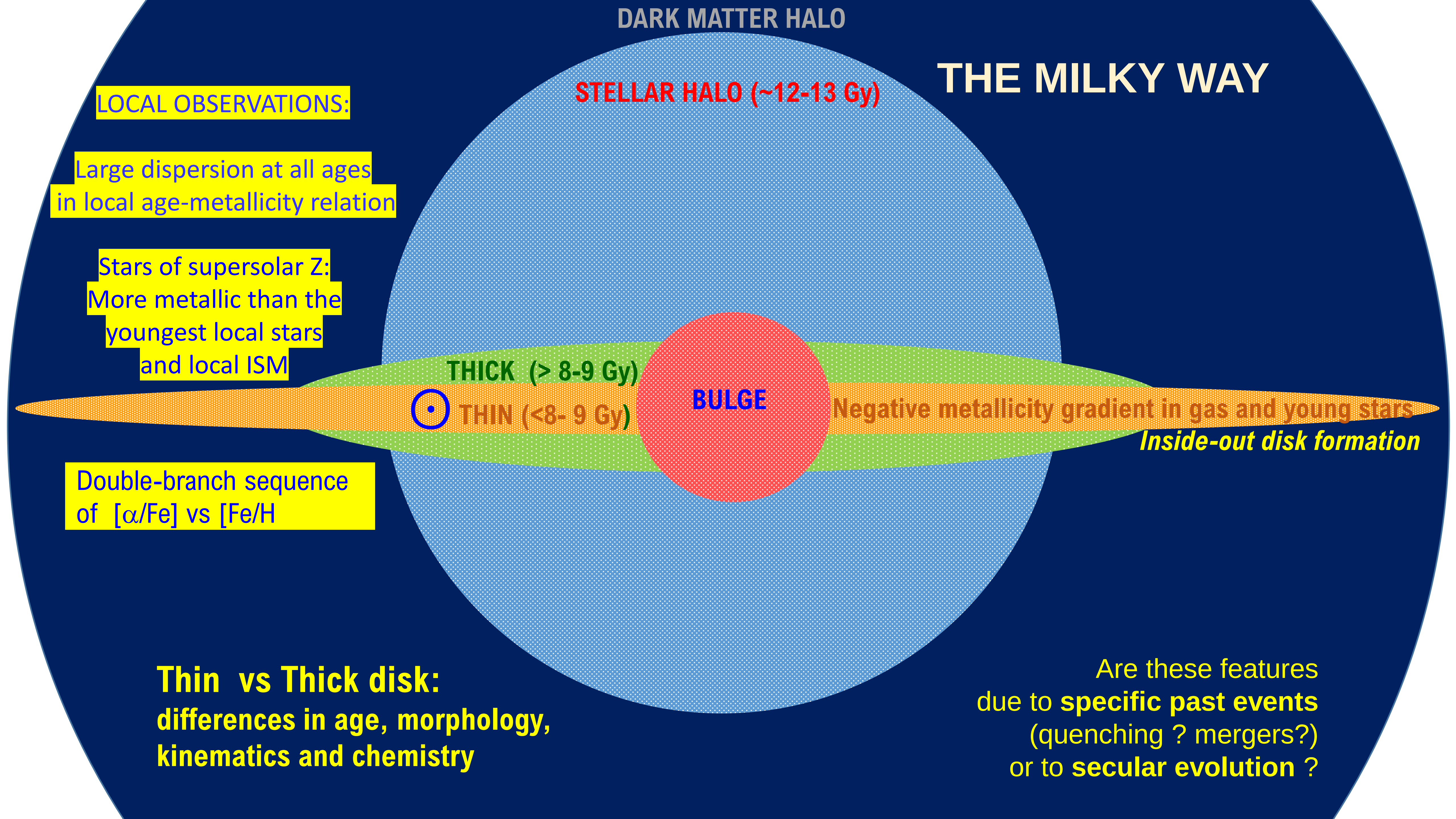
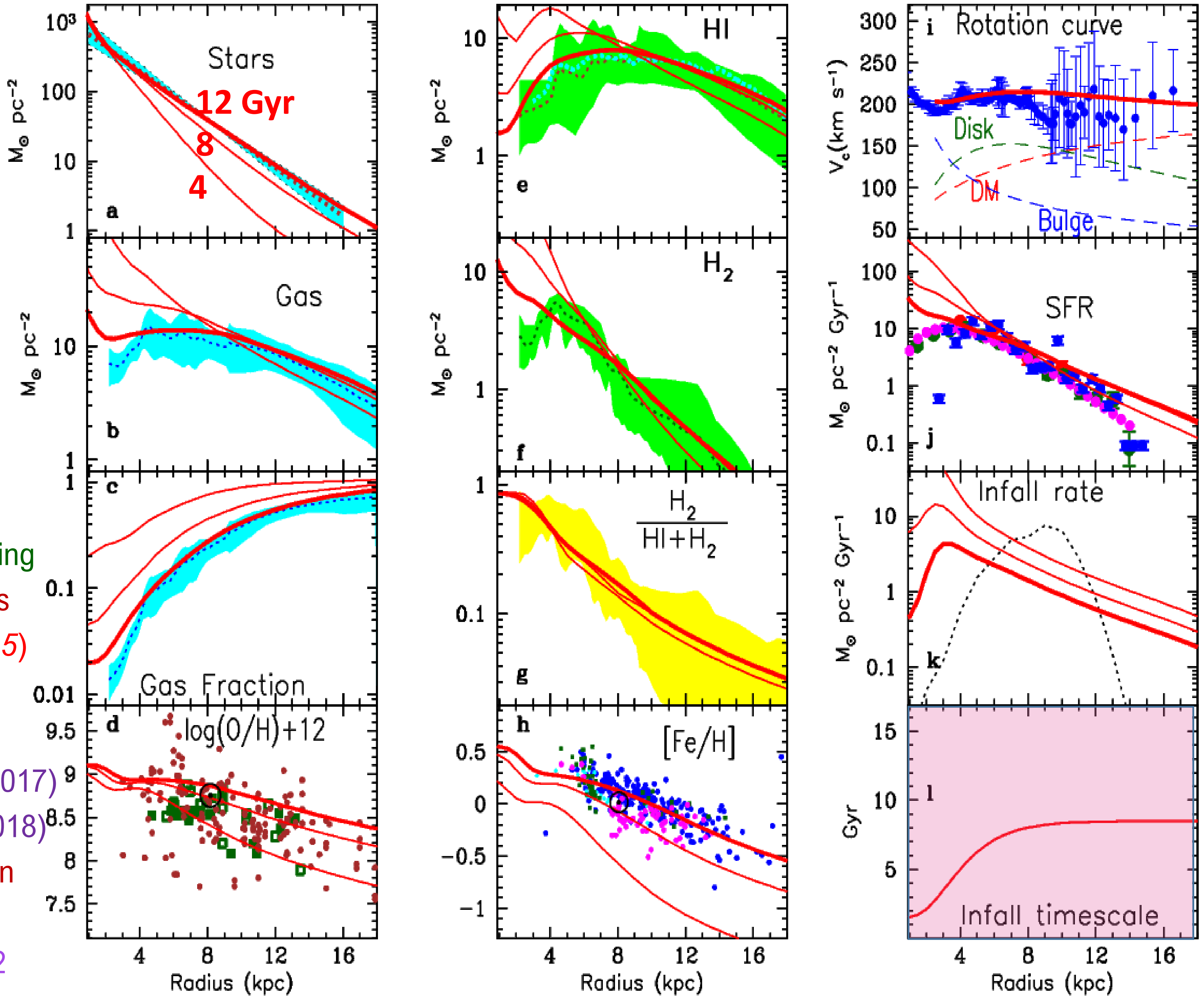

DARK MATTER HALO
THE MILKY WAY
STELLAR HALO (~12-13 Gy)
LOCAL OBSERVATIONS:
Large dispersion at all ages in local age-metallicity relation
Stars of supersolar Z: More metallic than the youngest local stars and local ISM
THICK (> 8-9 Gy)
THIN (<8- 9 Gy)
BULGE
Negative metallicity gradient in gas and young stars
Inside-out disk formation
Double-branch sequence of [α/Fe] vs [Fe/H
Thin vs Thick disk:
differences in age, morphology, kinematics and chemistry
Are these features due to specific past events (quenching ? mergers?) or to secular evolution ?

_**Model: NP+2023,** update of *Kubryk, NP, Athanassoula (2015a,b)*: multi-zone,_1D, radial symmetry

- Parametrized infall in an evolving DM halo of 1.2 10^{12} M☉
- Inside-out disk formation
- SFR proportional to H2
- Stellar IMF from *Kroupa (2002)*
- Radial motions of gas (radial inflow)
- **Radial migration of stars** *(parametrized from N-body simulations)*, blurring+churning
- Detailed chemical evolution of all isotopes
- Yields of H to Pb from LIM (*Cristallo+2015*) and Rotating Massive Stars (*LC2018*) including weak s_process
- SNIa : observed DTD from Maoz&Gror (2017) Z-dependent yields of Leung&Nomoto(2018)
- r- process from Collapsars and/or Neutron star mergers (semi-empirical DTD)
- Nova: theoretical DTDs from Kemp+2022



PLAN

1. Overview of main results, including local double-branch sequence of [α/Fe] vs [Fe/H]

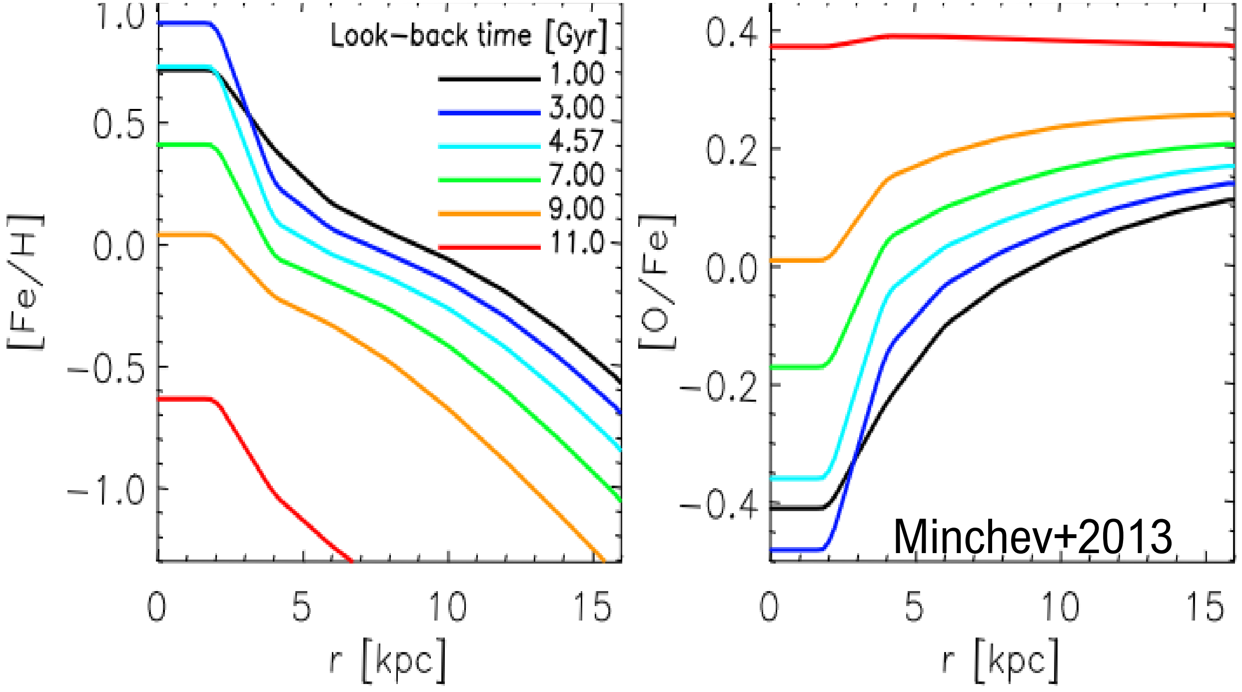
2. Other X/Y abundance ratios and their diagnostic potential

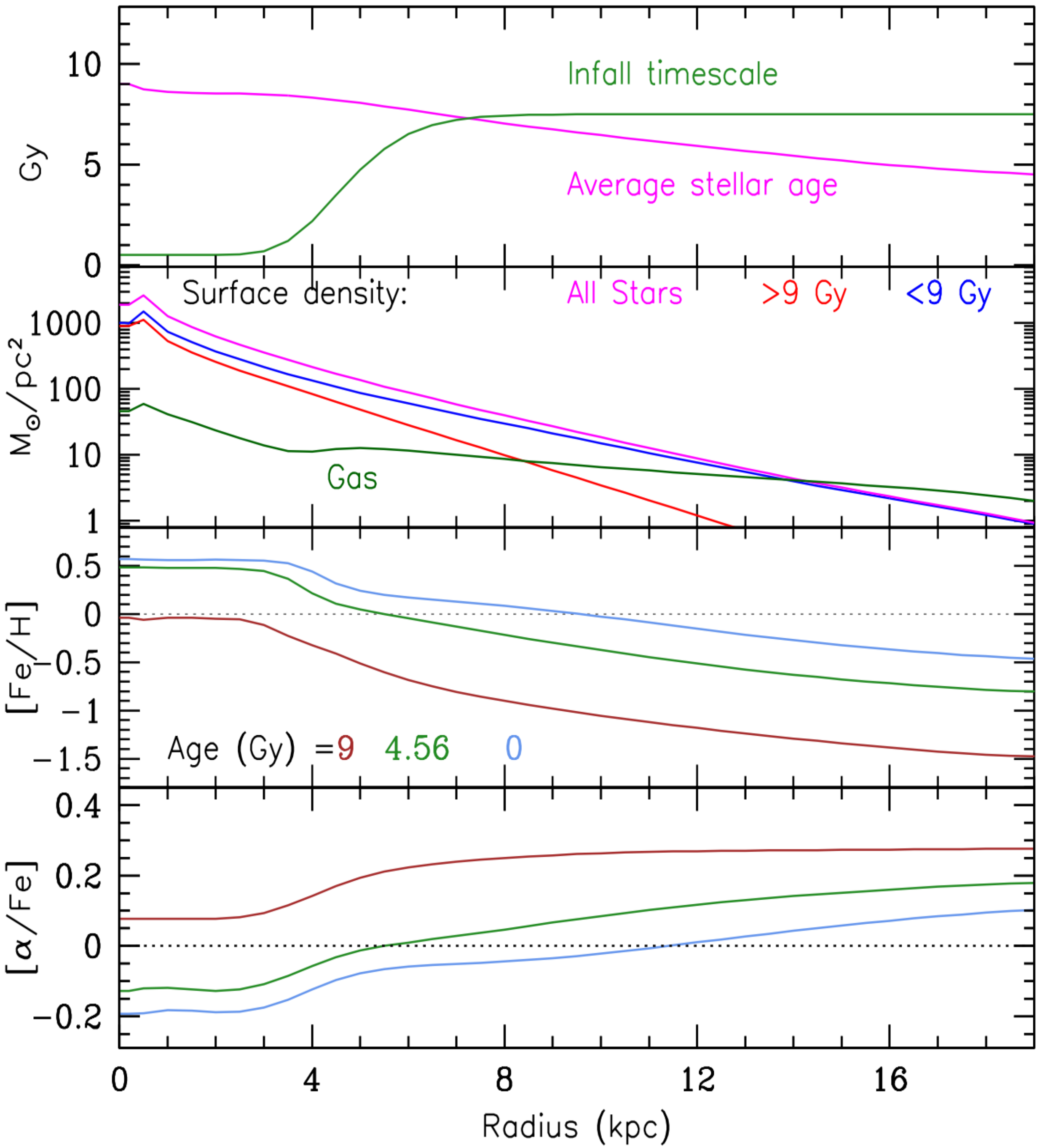
3. Reconstructing the evolution of abundance gradient ?

4. Impact of star formation episodes on chemical properties

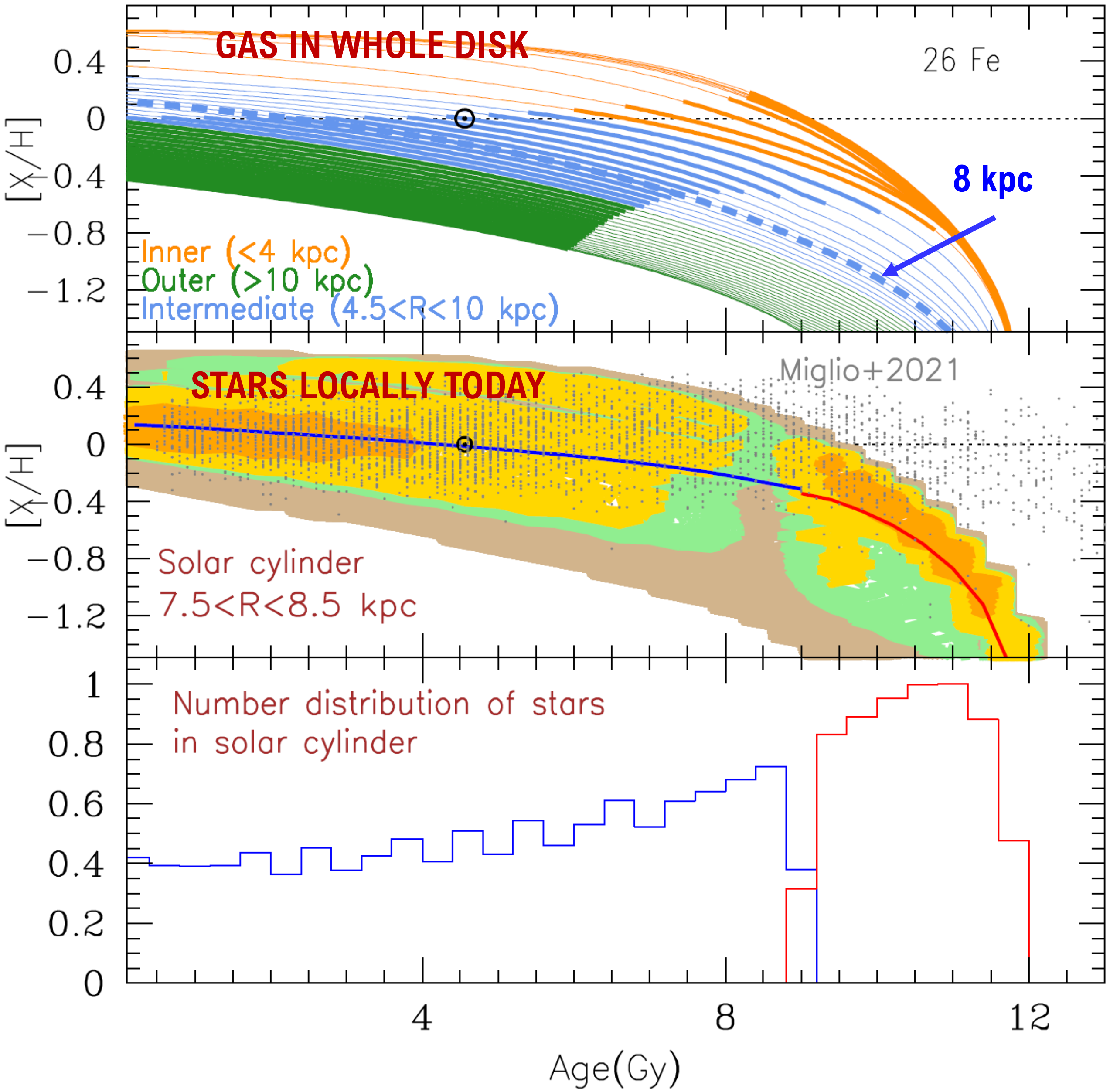
Probabilistic treatment of radial migration:
Time and radius-dependent « transfert coefficients »
Difference w.r.t. Kubryk+2015 :
Thick disk formed in a highly turbulent early gas

Transfer concerns not only low-mass long-lived stars
(« passive » tracers of radial migration)
But also long-lived sources of metals
(« active » tracers of migration)
(SNIa for Fe, AGBs for s-, NSM for r-)





Age – metallicity relations (NP+2023)



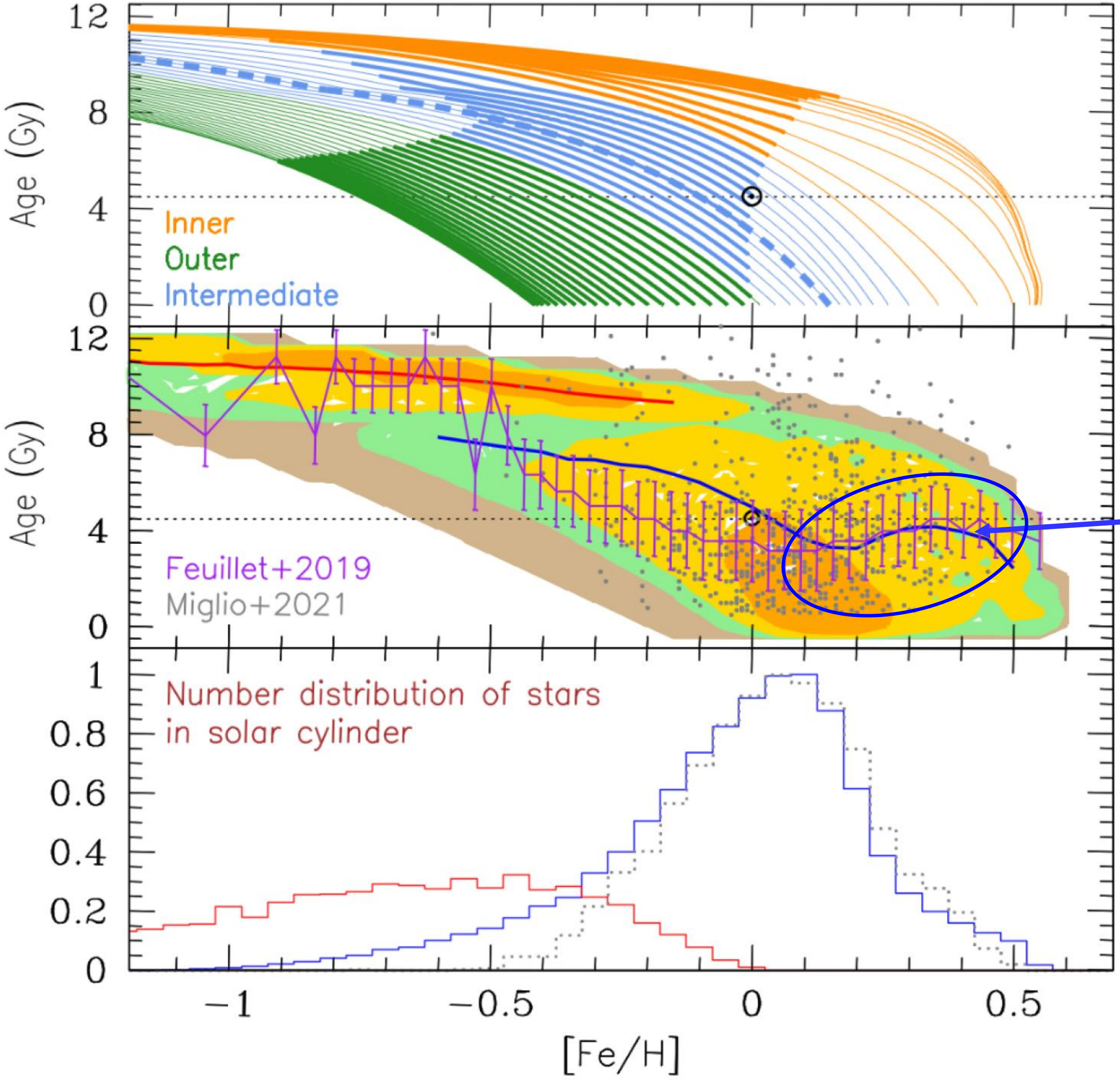
What we see locally (R=8 kpc) today
is the result of things that happened
both locally and elsewhere
with more « weight »
of the inner regions for older objects

The obtained local relation
is flatter than the one
of stars made *in situ* (at R=8 kpc)

The Sun was formed inwards of its
present day position (*Roskar 2008*)

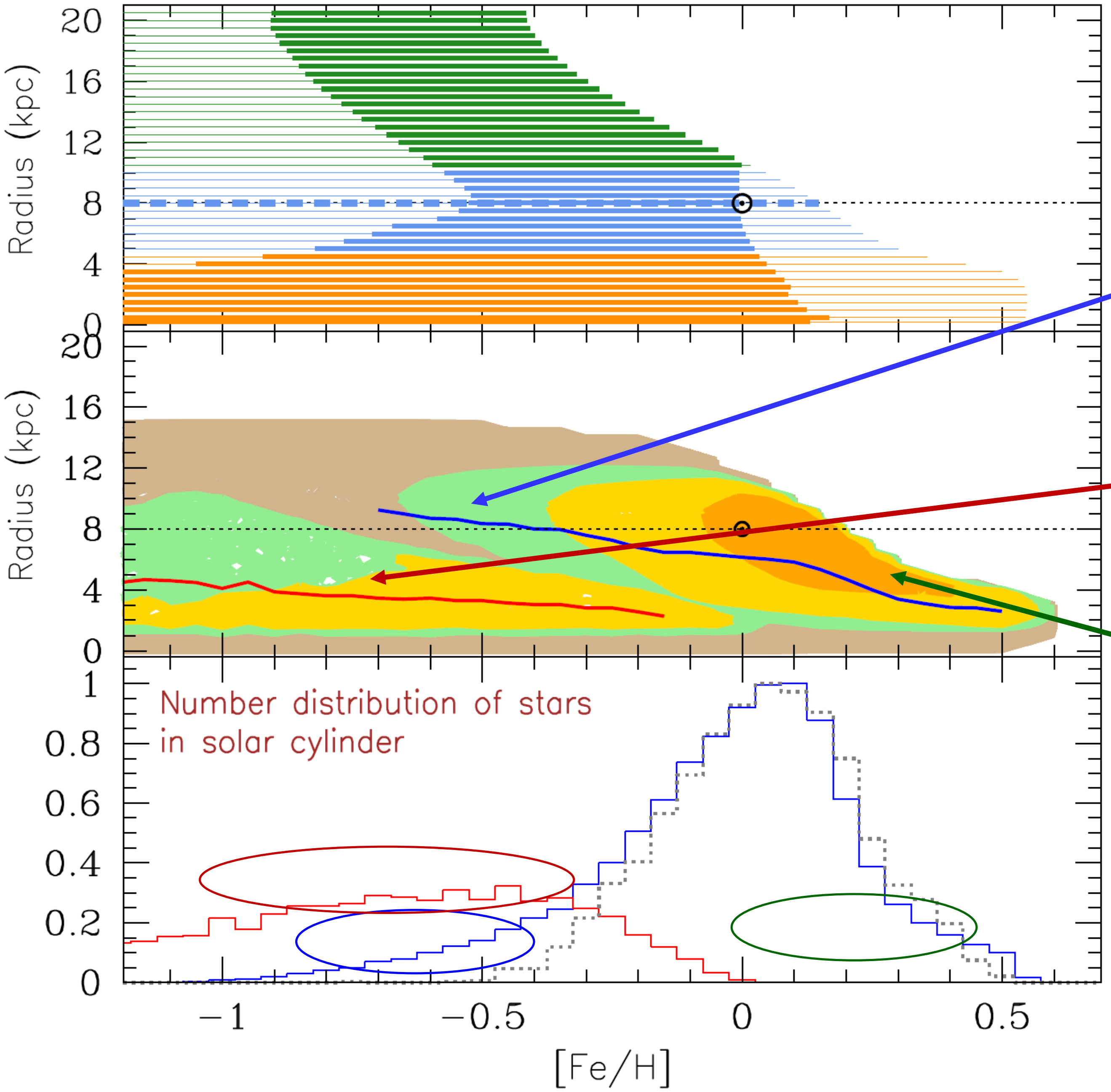
Overdensities naturally created
in the local phase-space of
various chemical properties

Age – metallicity relations (NP+2023)



The local
super-solar metallicity stars
come from the inner disk
and are on average older than
the solar-metallicity ones
(Kubryk+2015a)

Birth place of stars vs metallicity (NP+2023)

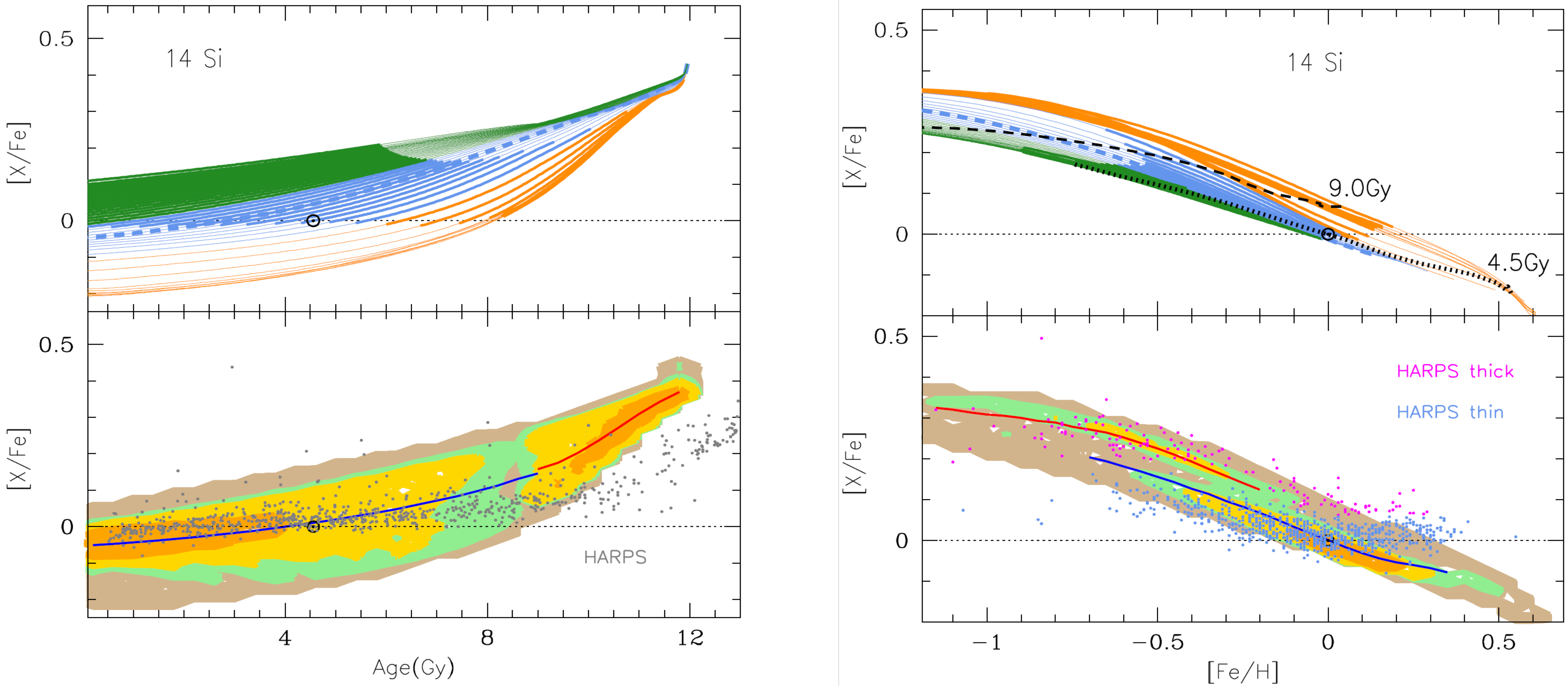


Local low-Z young stars (<9 Gy)
mostly from outer regions (low a/Fe)
(and mergers)

Local low-Z old stars (>9 Gy),
mostly from inner regions (high a/Fe)

Local supersolar Z stars
exclusively from inner disk

The local [α/Fe] relation



Local 2-branch behaviour of Si/Fe vs Fe/H obtained « naturally » as a result of inside-out disk formation accompanied by radial star motions

Stars formed in a short time scale (= high [α/Fe]) in the inner disk migrate to a region of slower star formation (low [α/Fe]) in the solar neighborhood)

1. Overview of the model and main results, including local double-branch sequence of [α/Fe] vs [Fe/H]

2. Other X/Y abundance ratios and their diagnostic potential

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4. Impact of star formation episodes on chemical properties

Local [α/Fe] pattern results because α-elements have a short lived source (CCSN) while Fe has a long-lived source (SNIa)

What about other elements?

An element is defined by

1. Timescale of its source
- ***Short-lived*** (a few My, *CCSN*)
- ***Long-lived*** (~Gy, *AGB, SNIa, NSM, novae*)

2. Its production as
- ***Primary*** (Yield Z-independent, e.g. O, **α**, Fe)
- ***Secondary or Odd*** (Yield Z-dependent, e.g. Na, Al, s-elements)

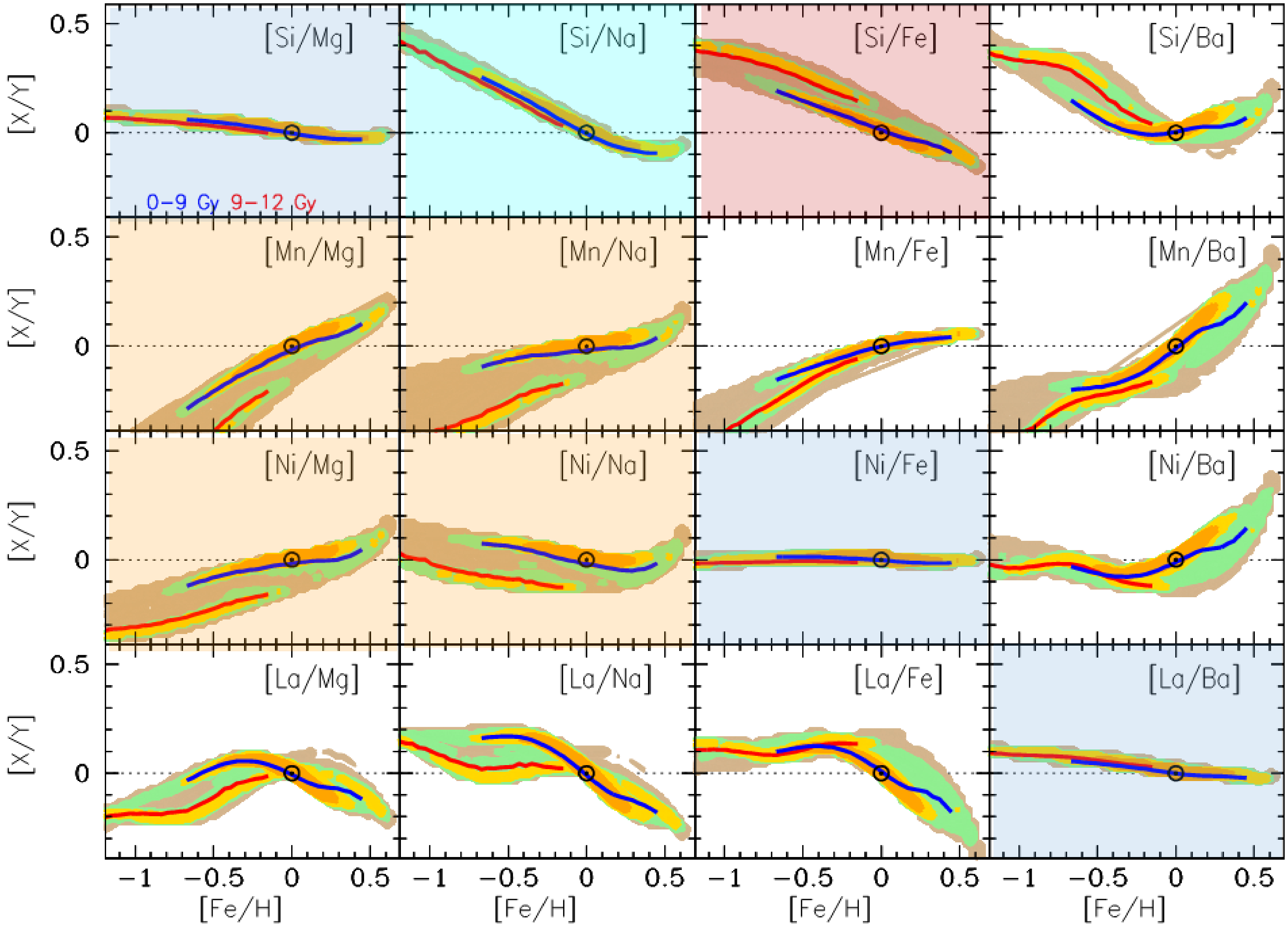
4 combinations possible for an element X

16 combinations for the ratio of 2 elements X/Y

Table 1. Expected 1-branch (1-B) or 2-branch (2-B) behaviour of abundance ratios of elements belonging to classes A, B, C and D (as defined below) in the local thick and thin disks.

	A : SL-MI *Mg*	B : SL-MD *Na*	C : LL-MI *Fe*	D: LL-MD *Ba*
A : SL-MI *Si*	1-B, s=0 *[Si/Mg]*	1-B, s<0 *[Si/Na]*	2-B, s<0 *[Si/Fe]*	2-B ? *[Si/Ba]*
B : SL-MD *Al*	1-B, s>0 *[Al/Mg]*	1-B, s~0 *[Al/Na]*	2-B, s~0 *[Al/Fe]*	2-B ? *[Al/Ba]*
C : LL-MI *Ni*	2-B, s>0 *[Ni/Mg]*	2-B, s~0 *[Ni/Na]*	2-B, s=0 *[Ni/Fe]*	1-B *[Ni/Ba]*
D : LL-MD *La*	2-B B *[La/Mg]*	? *[La/Na]*	1-B *[La/Fe]*	1-B, s~0 *[La/Ba]*

Lifetimes of nucleosynthesis sources : Short Lived (~10 Ma, CCSN): SL ; Long Lived (~1 Ga, SNIa, AGB): LL.
Source nucleosynthesis yields : Metallicity Independent (primaries, even): MI; Metallicity Dependent (secondaries, odd): MD
s is the slope of the relation [X/Y] vs [Fe/H], with X on the left column and Y in the top raw.



X/Y vs Fe/H

1-branch

If X and Y produced on same timescales

- Const. if both Odd or even

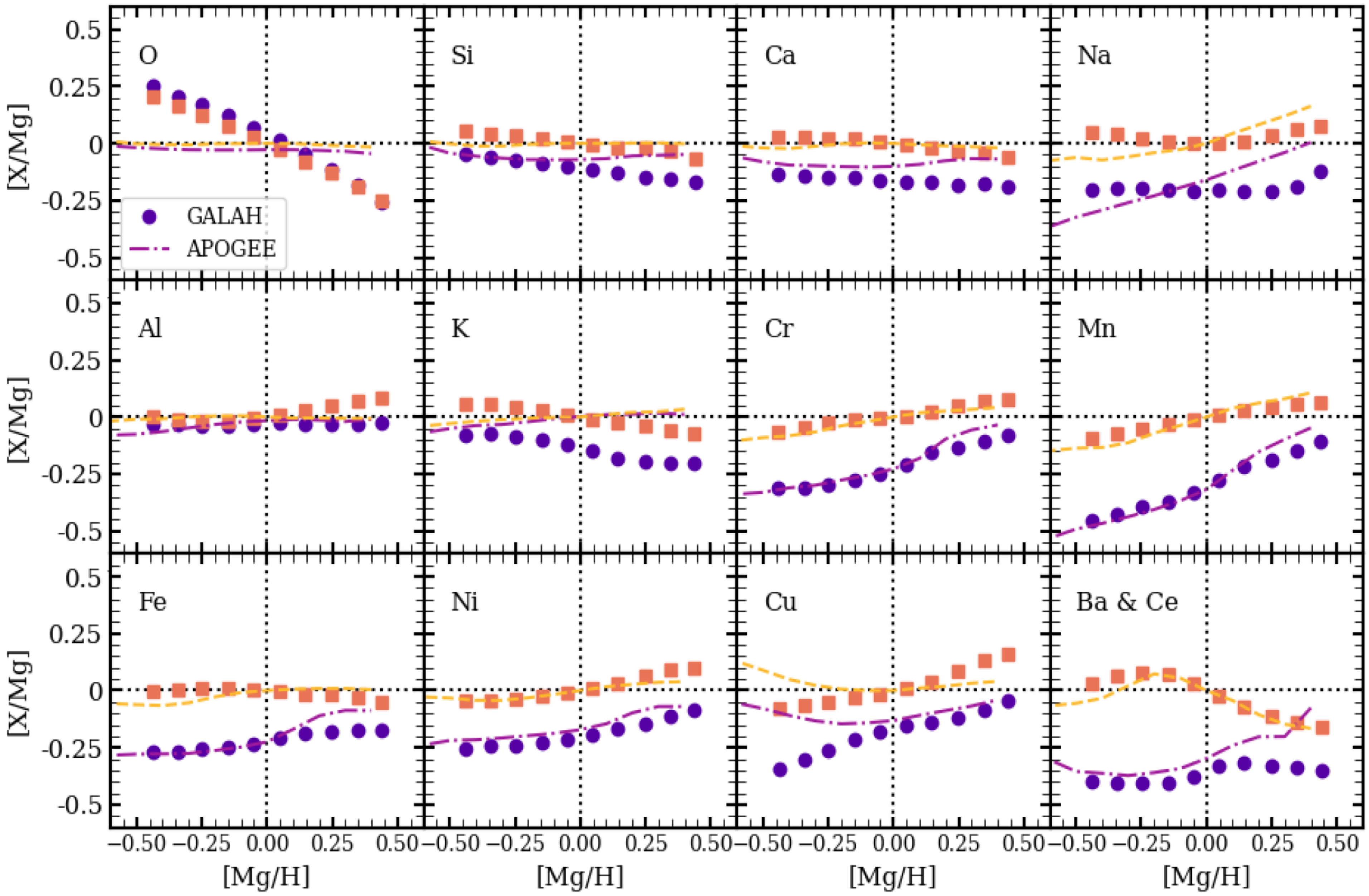
Varying if one of them Odd and the other Even

2-branch

If X and Y produced on different timescales

Heavier than Fe elements: more tricky behaviour (r -: CCSN or NSM ?)

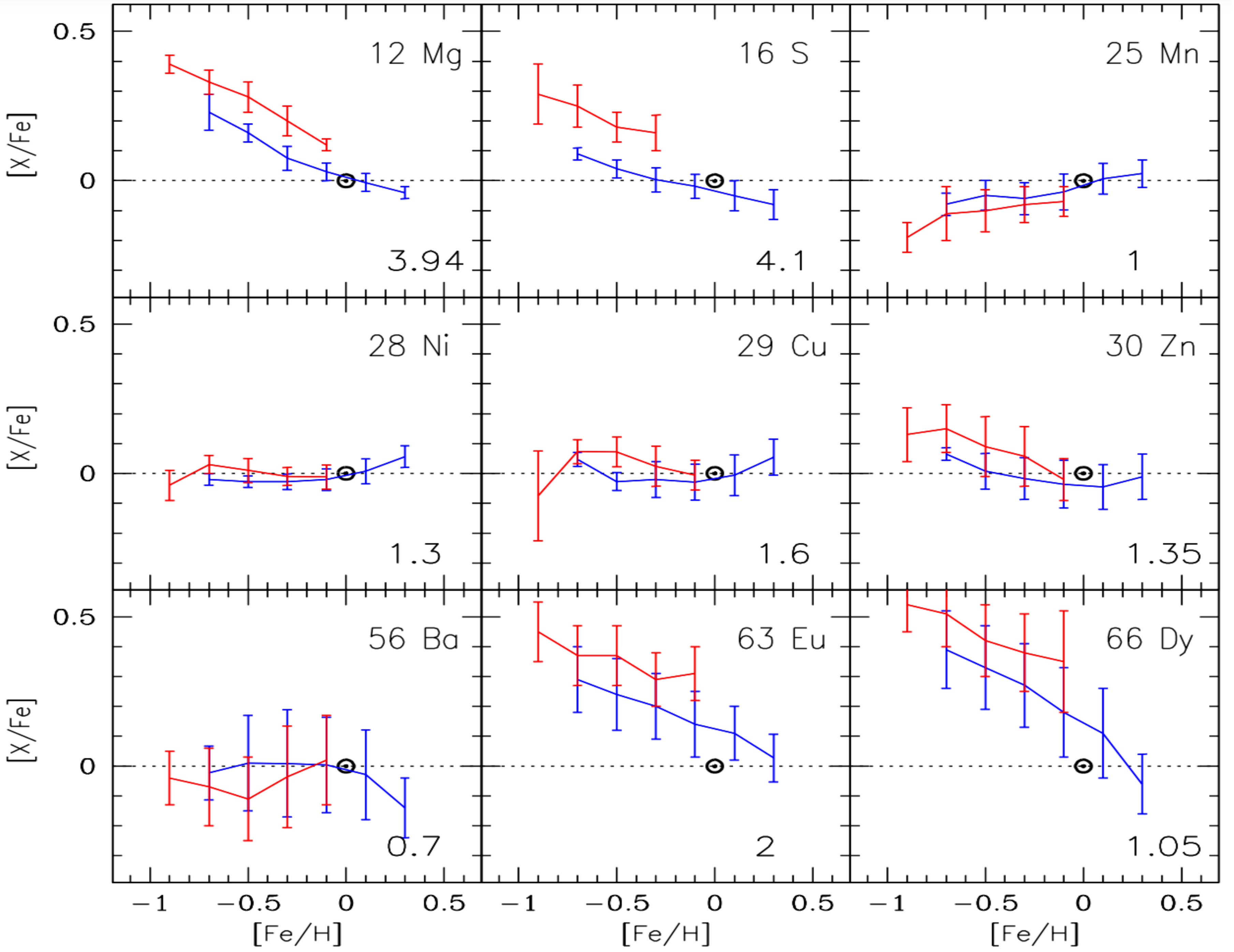
Test for massive star Nucleosynthesis and source lifetimes



Griffith+2022

High-Ia (low-α)

Low-Ia (high-α)



1 or 2 X/Y sequences ?

True dispersion
Vs measurement errors

AMBRE project :~7000 stars
ESO spectra with
high S/N and Δλ/λ
(*Mikolaitis+2016, Guiglion+2018*
Perdigon+2020)

Distance D between
2 data sets

$$D = \frac{1}{N}\Sigma(Y_1 - Y_2)/u$$

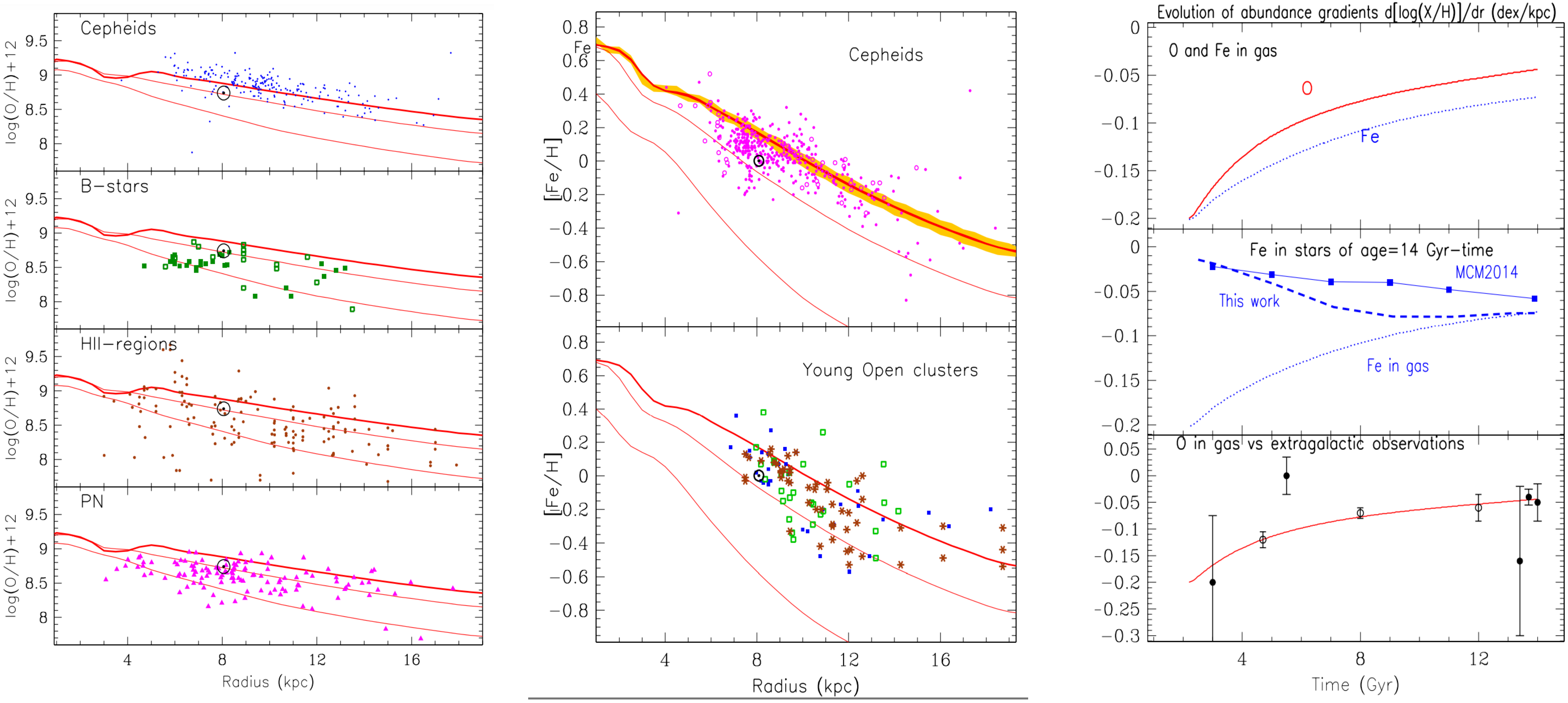
$$u = \sqrt{\sigma_1^2 + \sigma_2^2}$$

1. Overview of the model and main results, including local double-branch sequence of [α/Fe] vs [Fe/H]

2. Other X/Y abundance ratios and their diagnostic potential

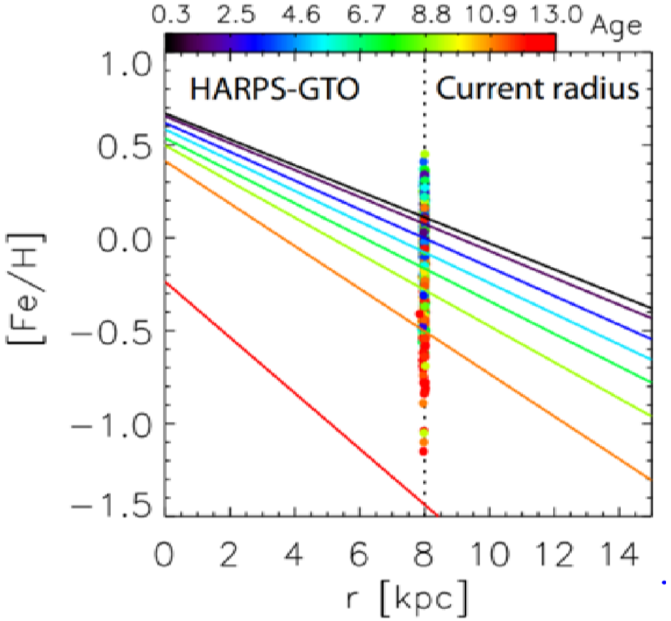
3. Reconstructing from local observations the evolution of abundance gradient (at birth place)?

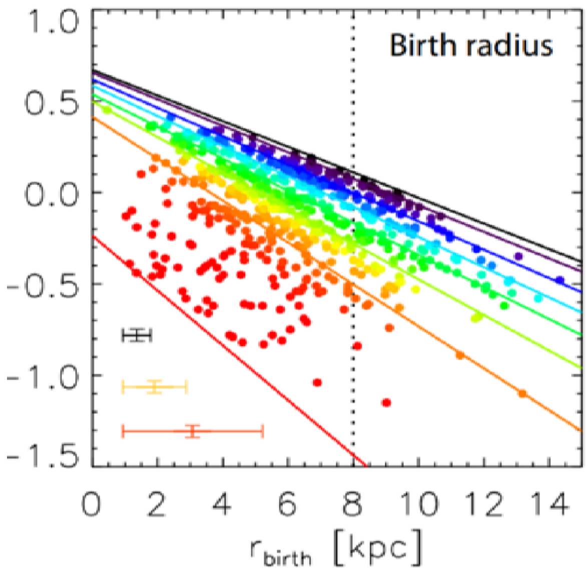
4. Impact of star formation episodes on chemical properties



Kubryk, NP, Athanassoula+2015b

Minchev+2018 : Evaluating past abundance gradients **from local observations** of Fe/H + age

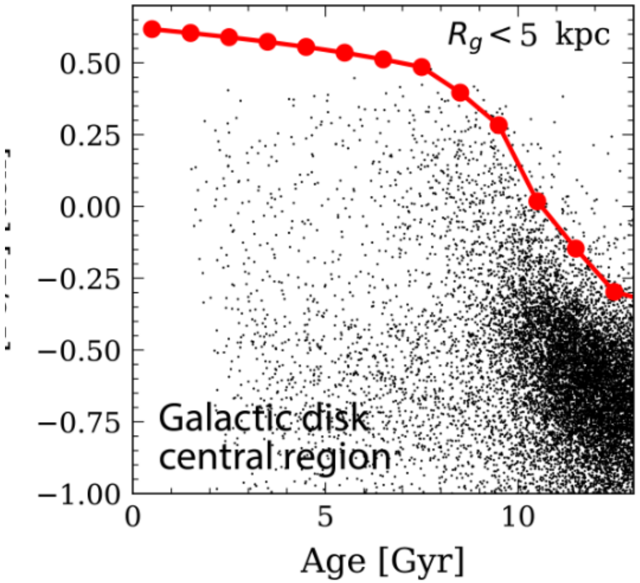




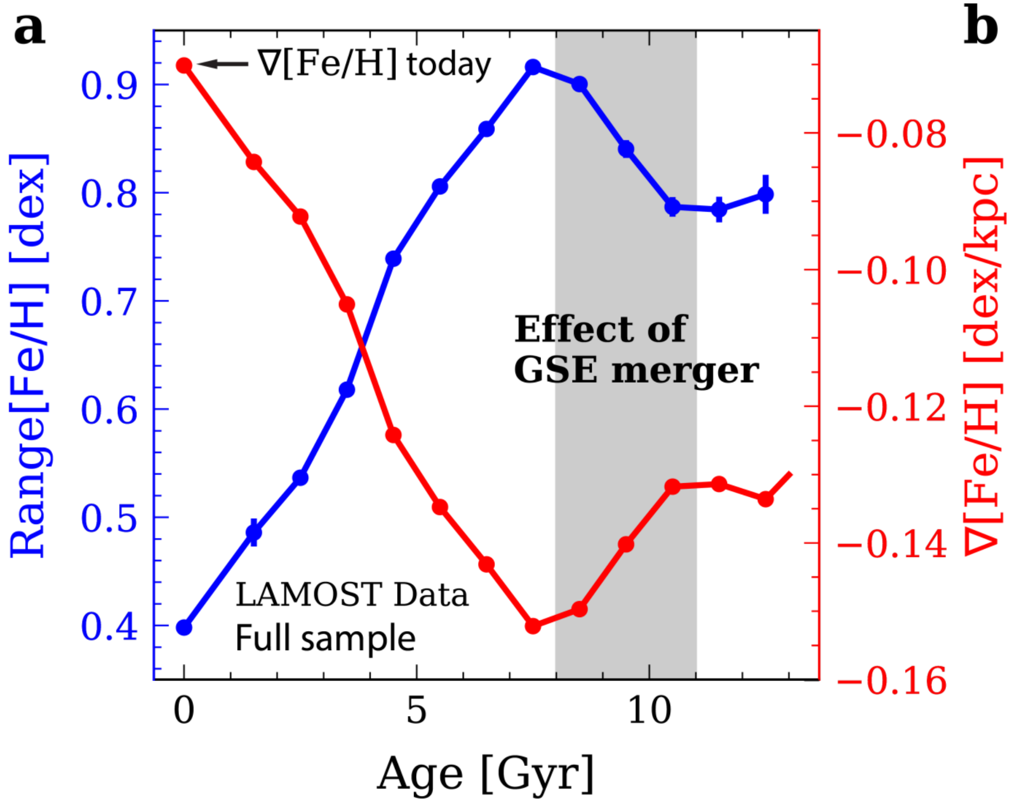
Key assumptions:

1. gradient characterized by unique slope over the whole disk always

2. The evolution of [Fe/H] In one point (GalCenter) also required

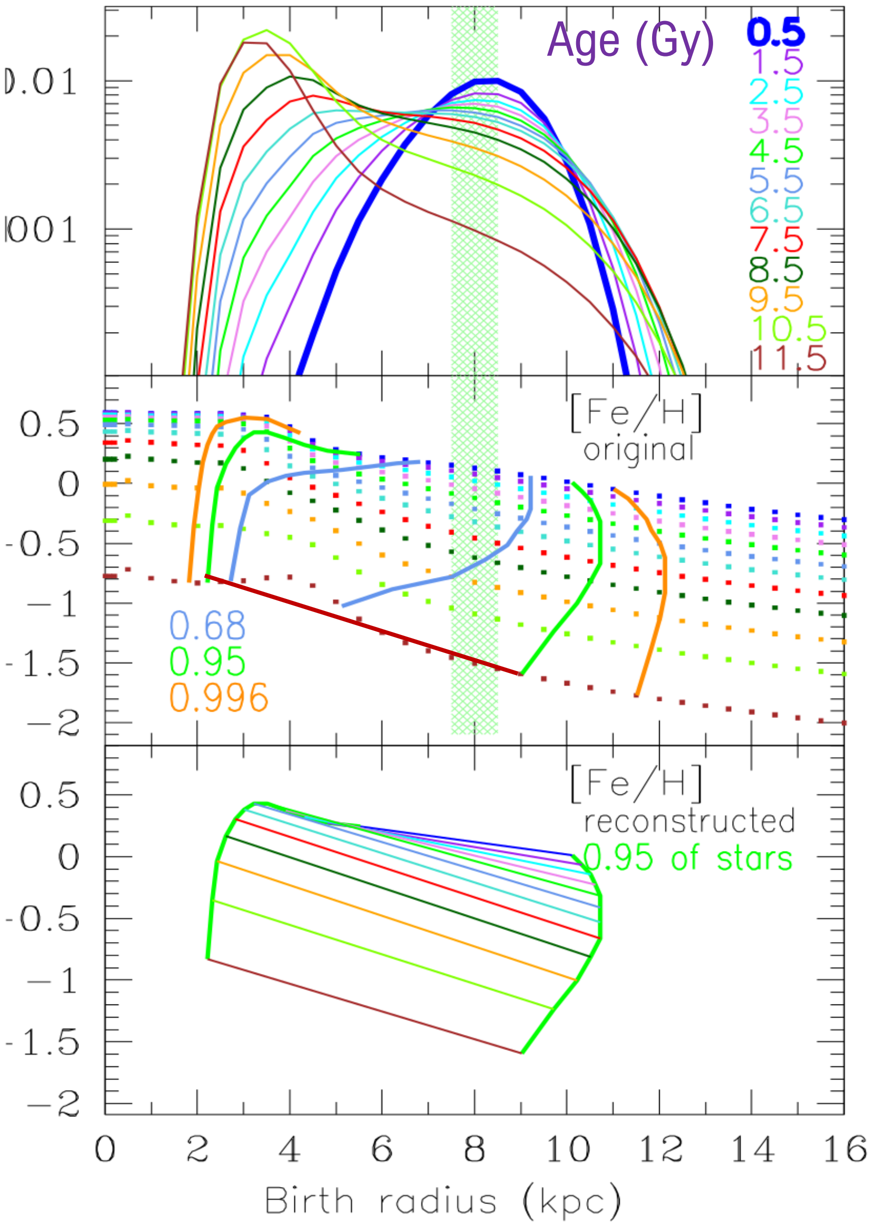


Lu+2022 : determining past gradient <u>in birth radii of stars</u>

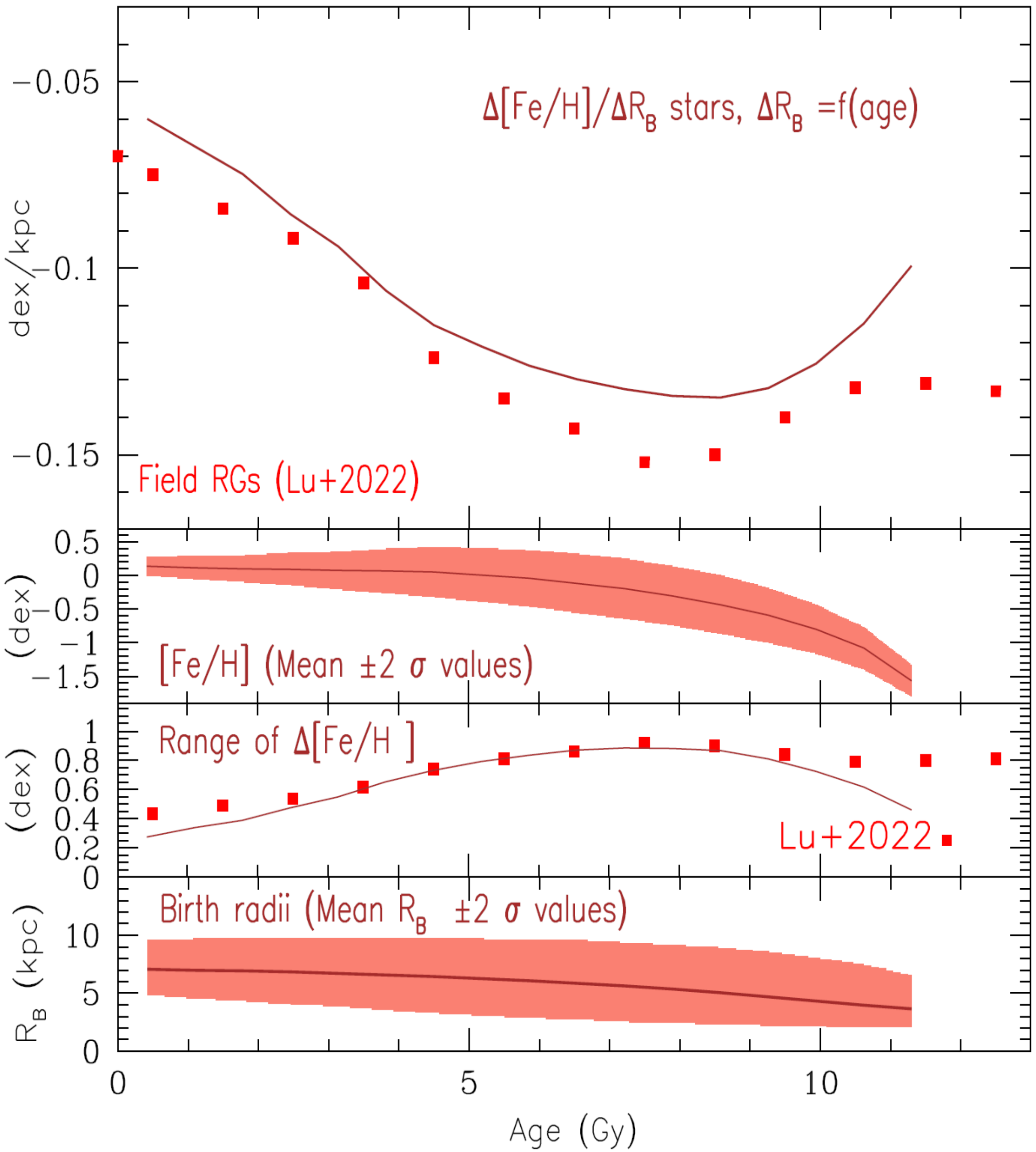


Gradient steeper in the past**, but** flattening for ages>8-9 Gy **=> Merger**

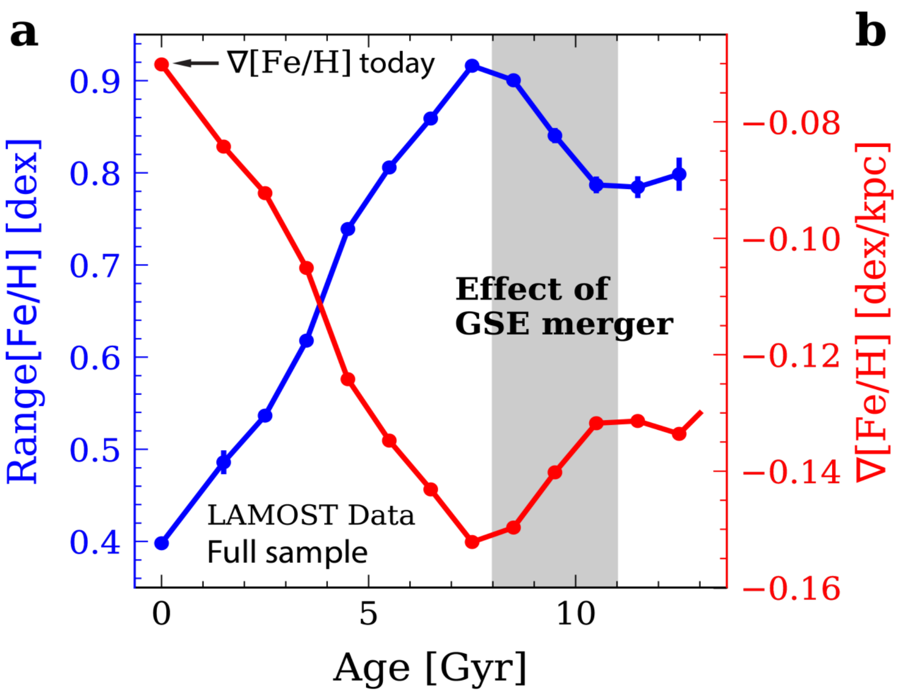
NP+2023: Evaluating past abundance gradients
In the birth place of our **model local stars**



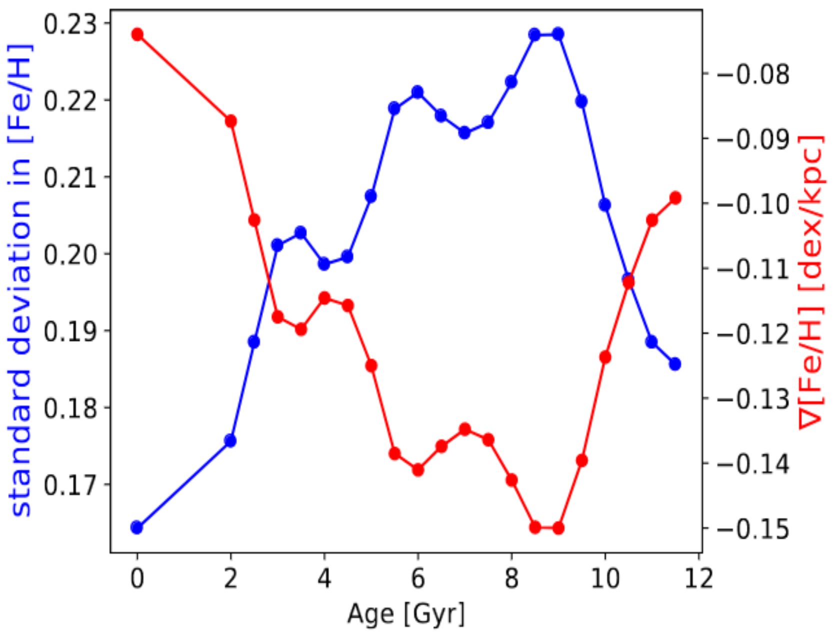
NP+2023 :smoothly non-monotonic behaviour through **secular evolution**



Lu+2022 ; early merger



Ratcliffe+2023



NP+2023 ; not necessarily

Secular evolution can do it

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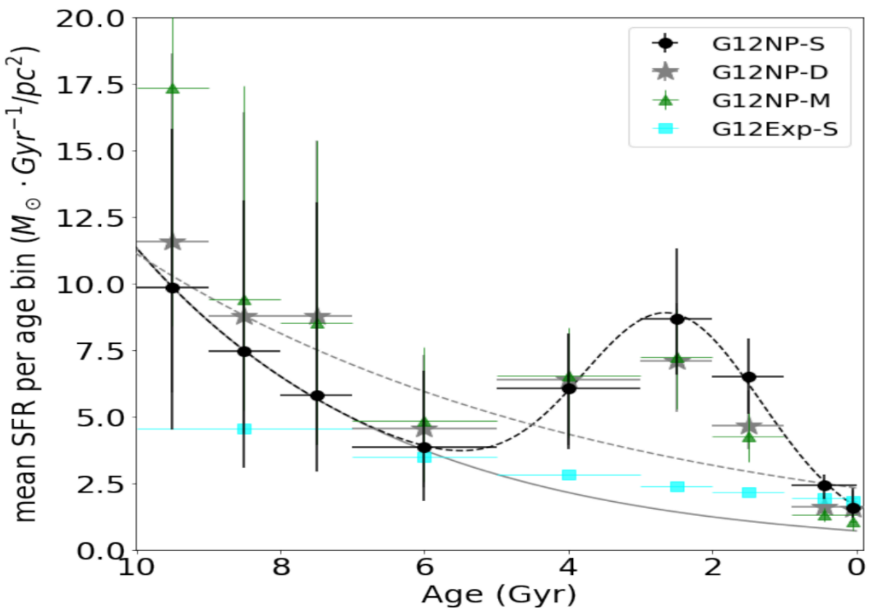
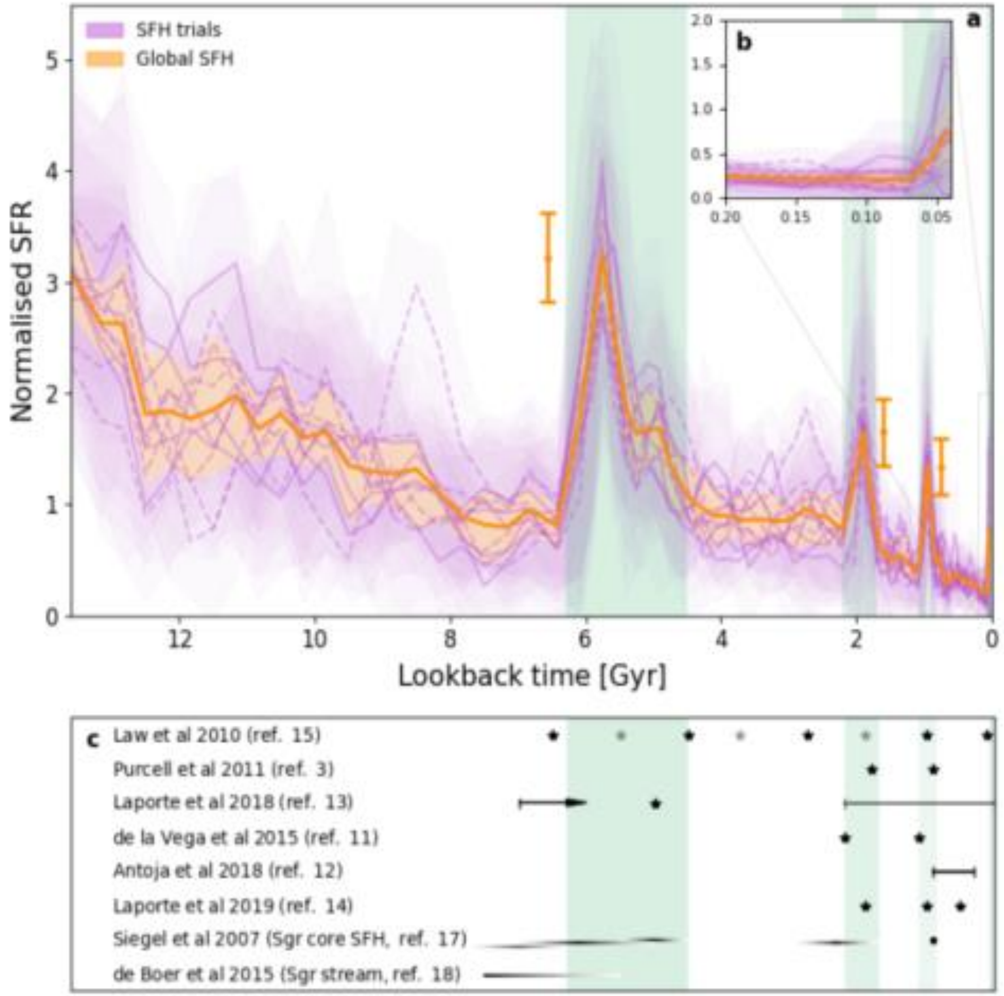
Recent star formation episodes in the MW disk ?

Mor+2019
2 800 000 stars
from GAIA DR2
Magnitude G<12

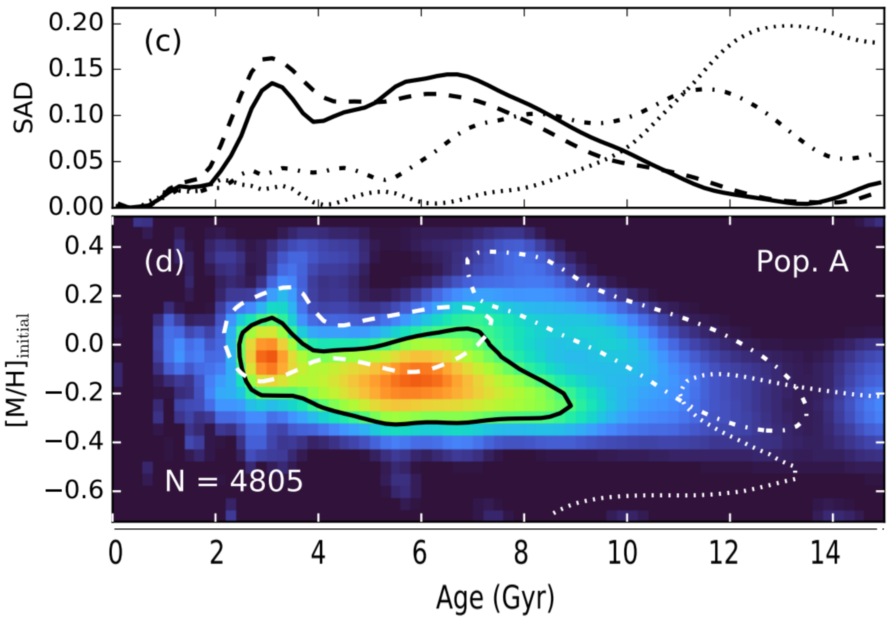
1 broad SF « burst »
4-2 Gy ago





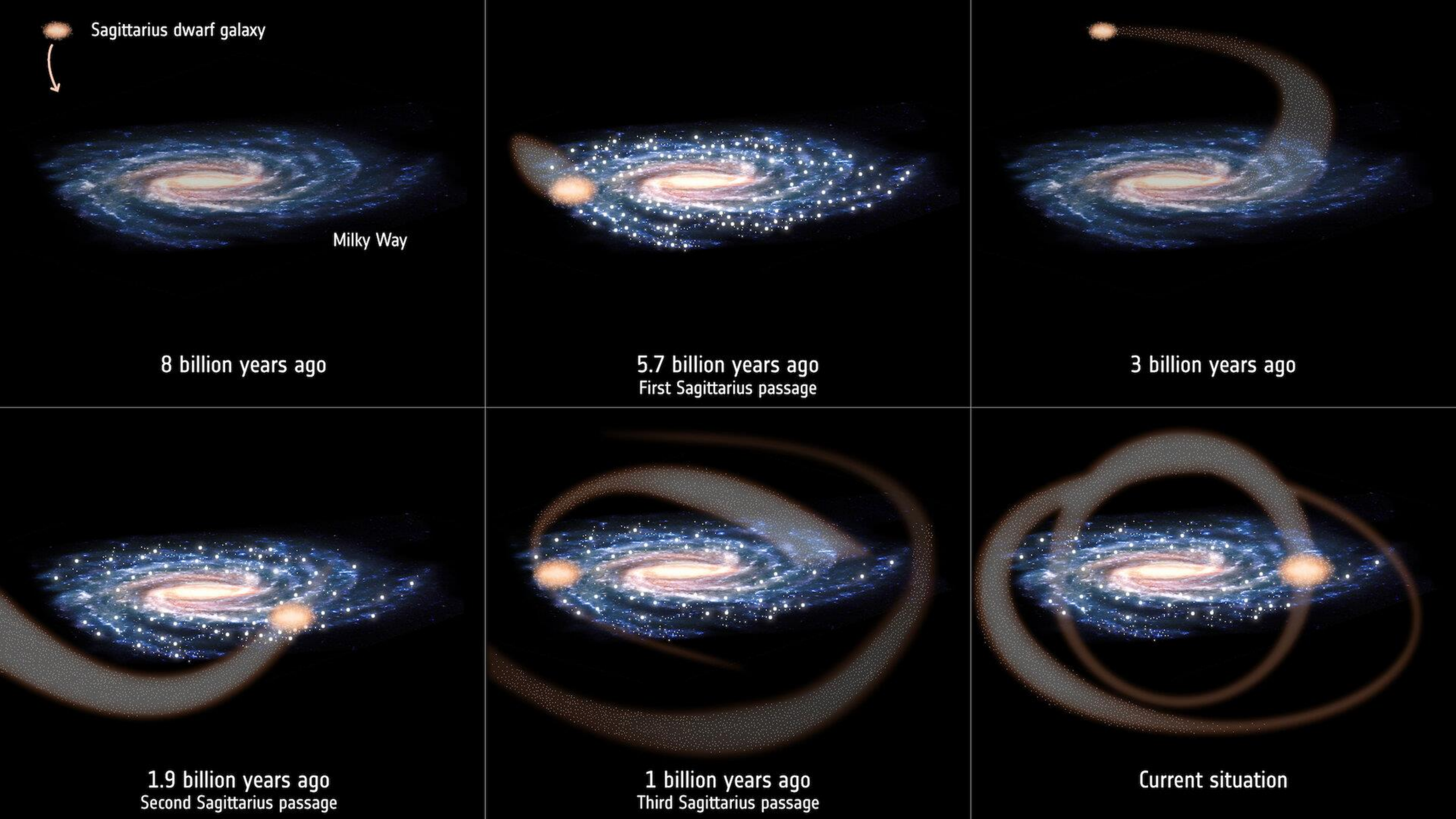
Sahlholdt+2020
~180 000 stars
from GALAH

2 SF « bursts »
in thin disk
3 and 5-7 Gy ago



Ruiz-Lara+2022
3 narrow SF « bursts » 1, 2 and 6 Gy ago

Coinciding with perigalacticon passages of Sagittarius dwarf galaxy ?



Sagittarius dwarf galaxy
Milky Way
8 billion years ago
5.7 billion years ago
First Sagittarius passage
3 billion years ago
1.9 billion years ago
Second Sagittarius passage
1 billion years ago
Third Sagittarius passage
Current situation

T. Chen and NP (submitted)

Modelling SF episodes
with Gaussians
in space and time

SFR: Schmidt–Kennicut law

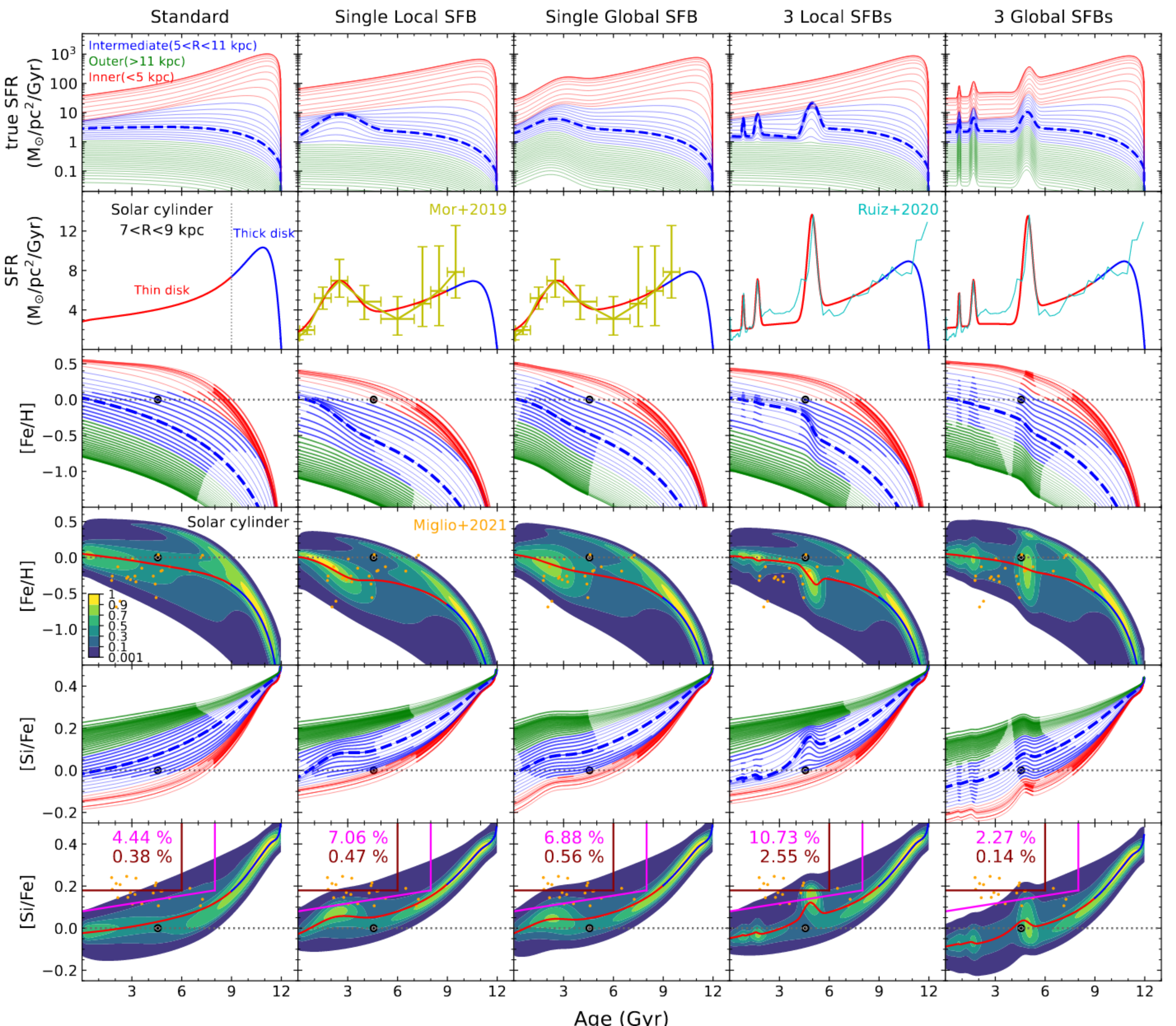
$$\Psi(r,t) = \alpha \sum_{H_2}(R,t)^N \left(1 + \sum_{i=1}^{n_{burst}} \beta_i G_i(R,t)\right)$$

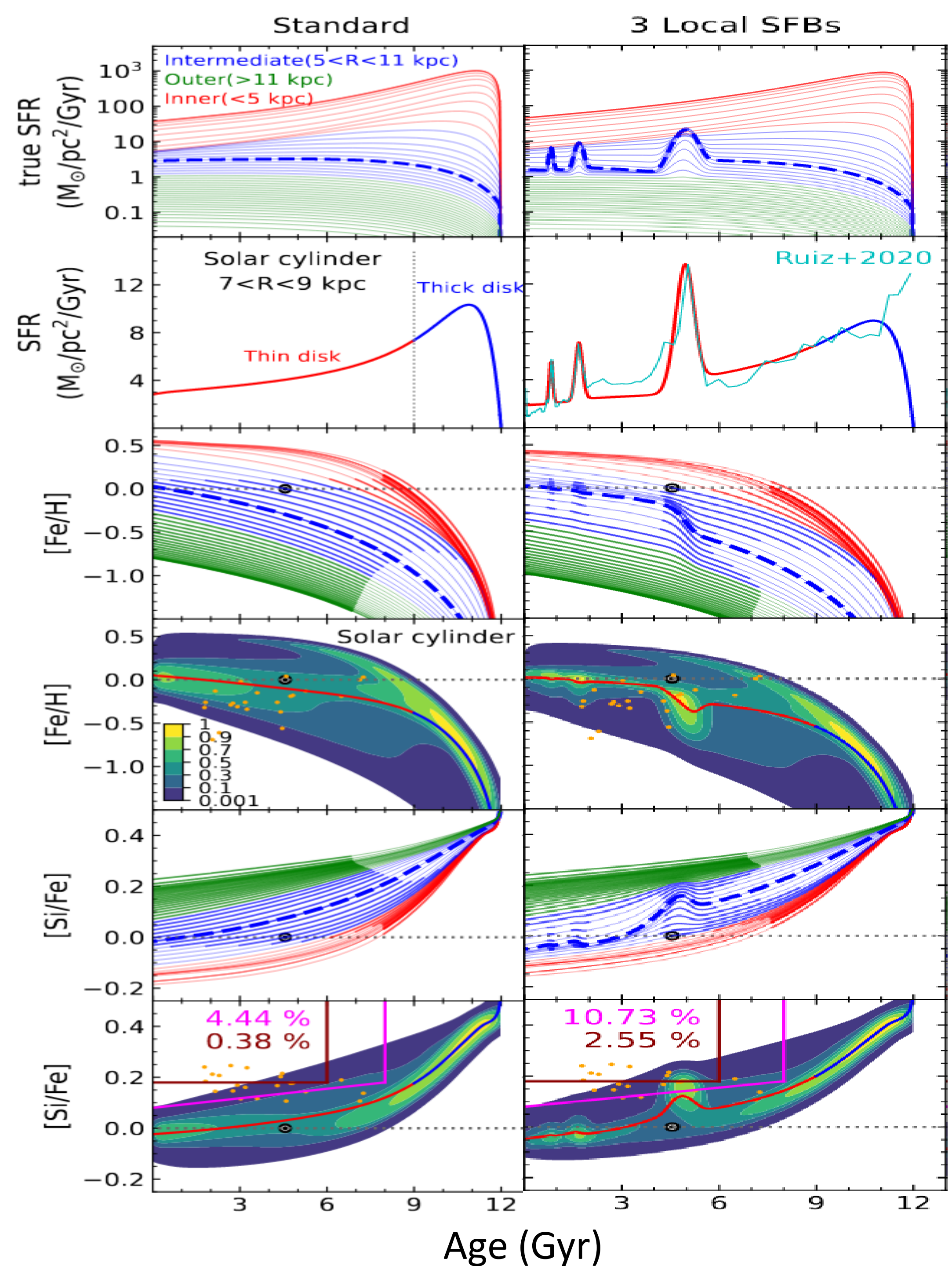
SFBs induced by Star Formation Efficiency

$$G(R,t) = \frac{1}{2\pi\sigma_R\sigma_t} e^{-\frac{(R-\mu_R)^2+(t-\mu_t)^2}{2\sigma_R\sigma_t}}$$

Temporary enhancement of
Fe/H and alpha/Fe in the gas

Overdensities in local stars
of Metallicity vs Age and
Alpha/Fe vs Age relations



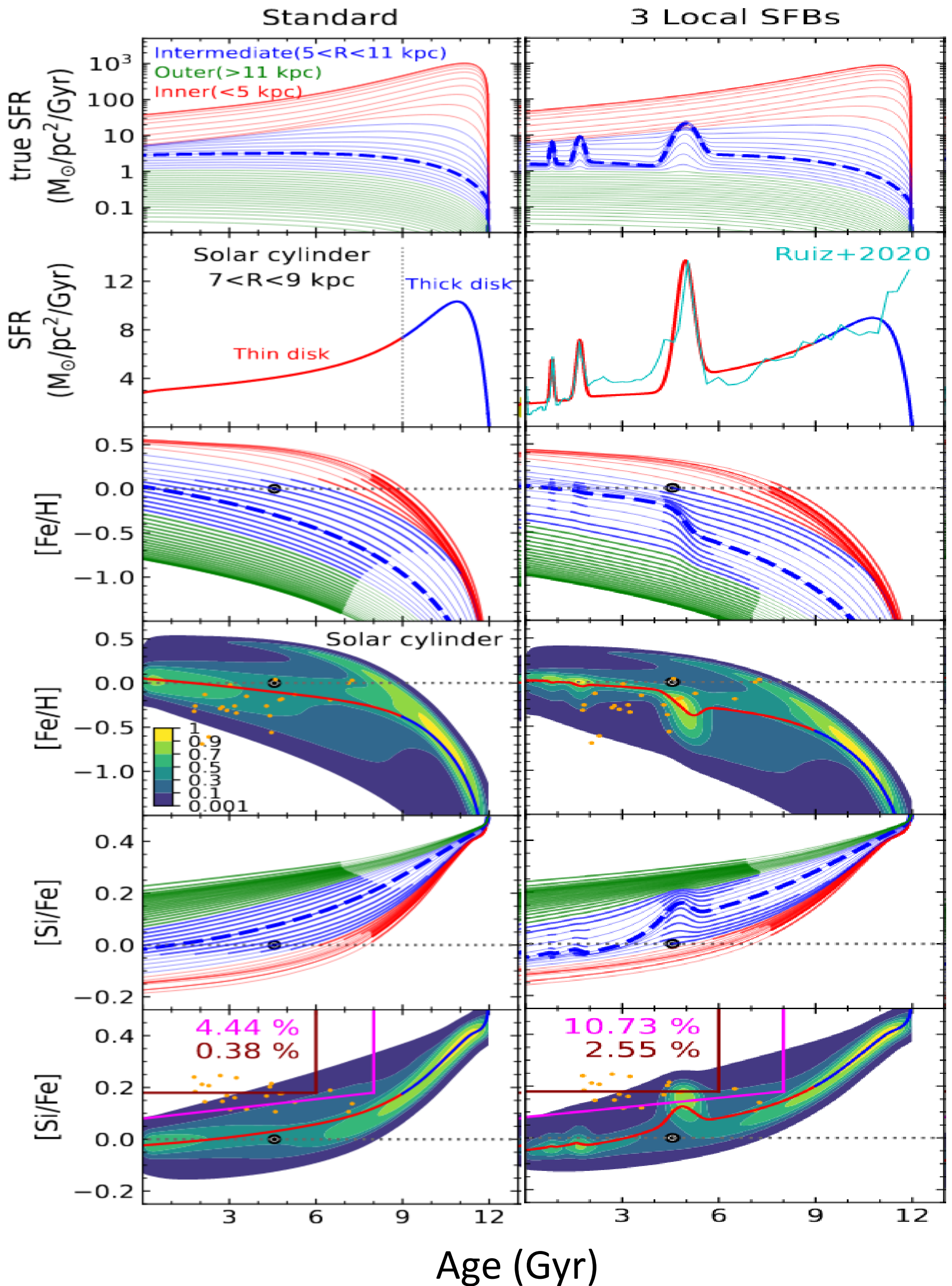


Impact of a local SFB on the existence of young α/Fe-rich stars

Observations find a fraction of local stars (a few %) with [α/Fe] > 0.15, [Fe/H]<-0.1 and a few Gyr old (young high- αFe) with masses ~1.1 – 1.6 Msun
(Chiappini+2014, Martig+2015, Zhang+2021)

Current idea: not young, but mergers of old thick disk stars

Our study: Recent starbursts may increase the fraction of such stars and presumably modify the kinematics of their gas at birth, but cannot explain the youngest ages, unless many such recent bursts are invoked



Impact of a local SFB on the evaluation of the birthplace of the Sun

Observations show that local young stars (B stars) and local ISM have a metallicity ~Zsun (Cartledge+2006, Nieva+Przybilla2012, Ritchie+2023)

Most models find a sizeable increase of local ISM metallicity between – 4.5 Gyr and today (~0.2-0.3 dex)

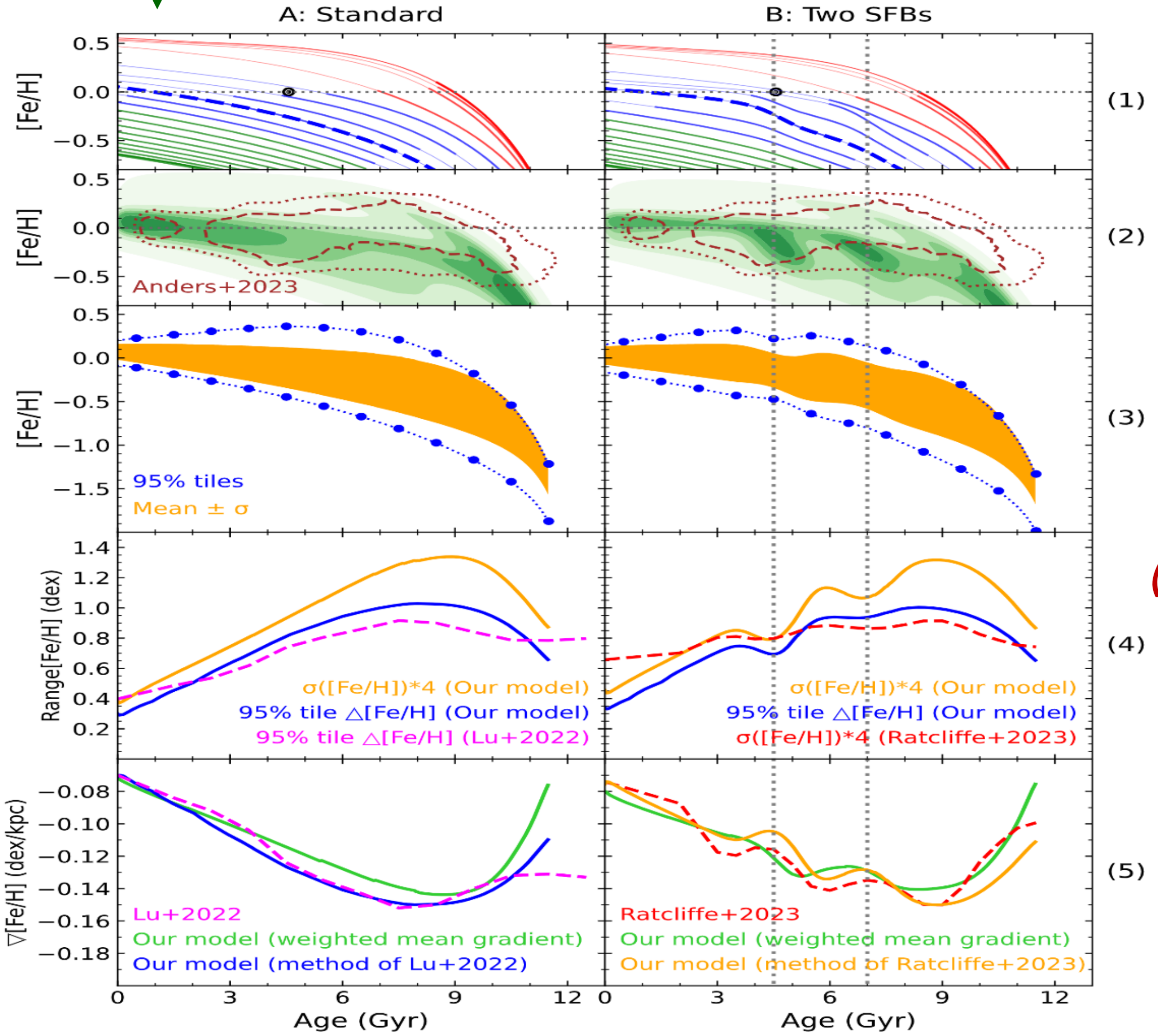
Potential solution: Sun formed in and migrated from the inner disk: R_{BIRTH} ~5 – 7 kpc

Our baseline model : R_{SUN} ~6 kpc
With strong local SFB prior to Sun's formation ~5 kpc

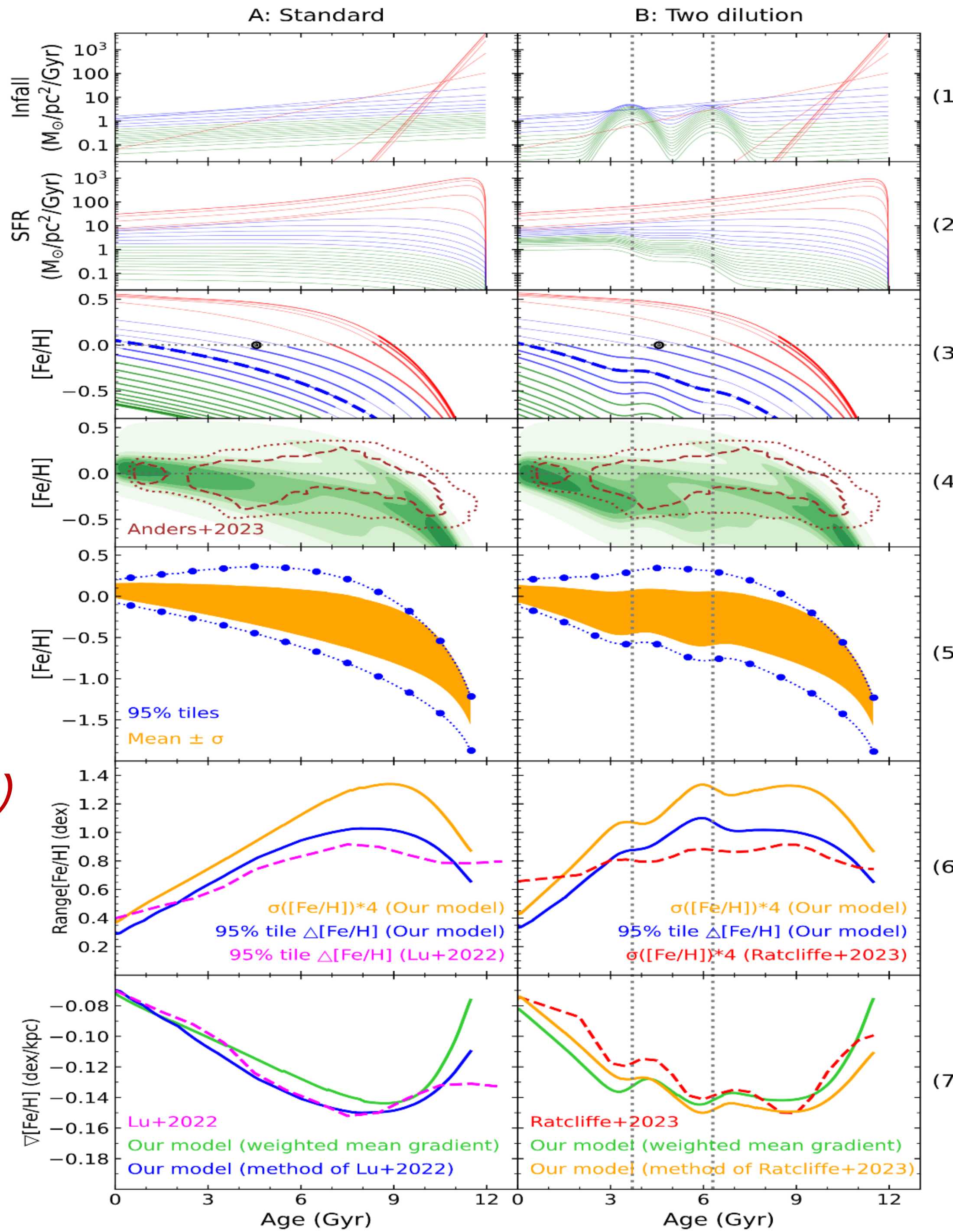
A local SFB increases local Fe production
To avoid local Fe overabundance today, we reduce overall SF efficiency
This reduces Fe production in all unperturbed zones
The zone with X(Fe) = Fe_{SUN} at t = -4.5 Gyr is now at R=5 kpc

Which has also solar [α/Fe]~0 at t = -4.5 Gyr

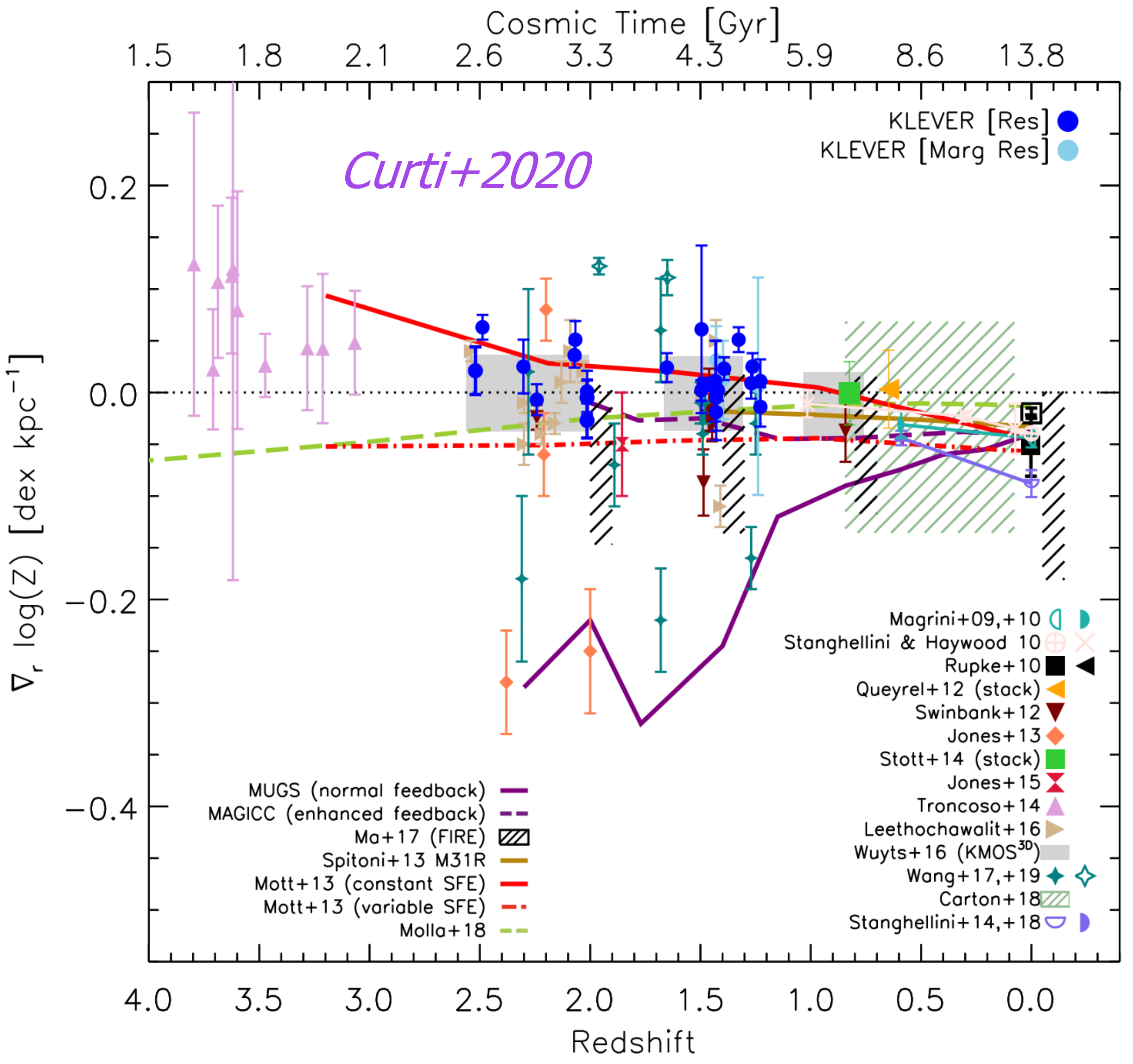
Episodes of both,
enhanced star formation
and enhanced gas accretion
can produce a "wiggly" evolution
of the past abundance gradient

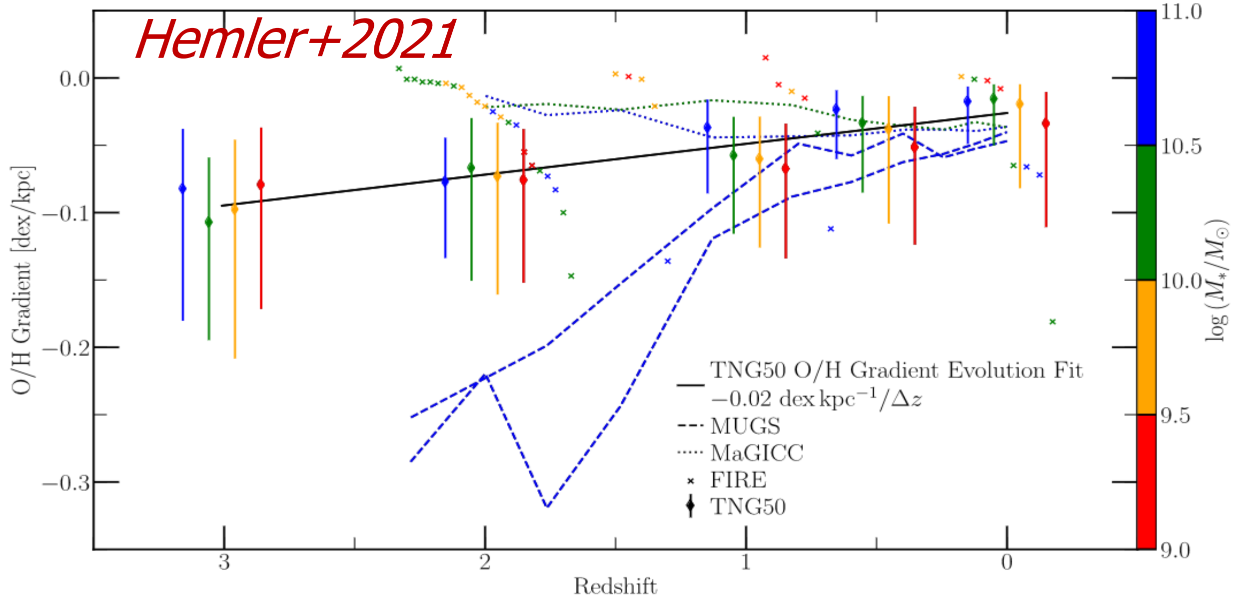


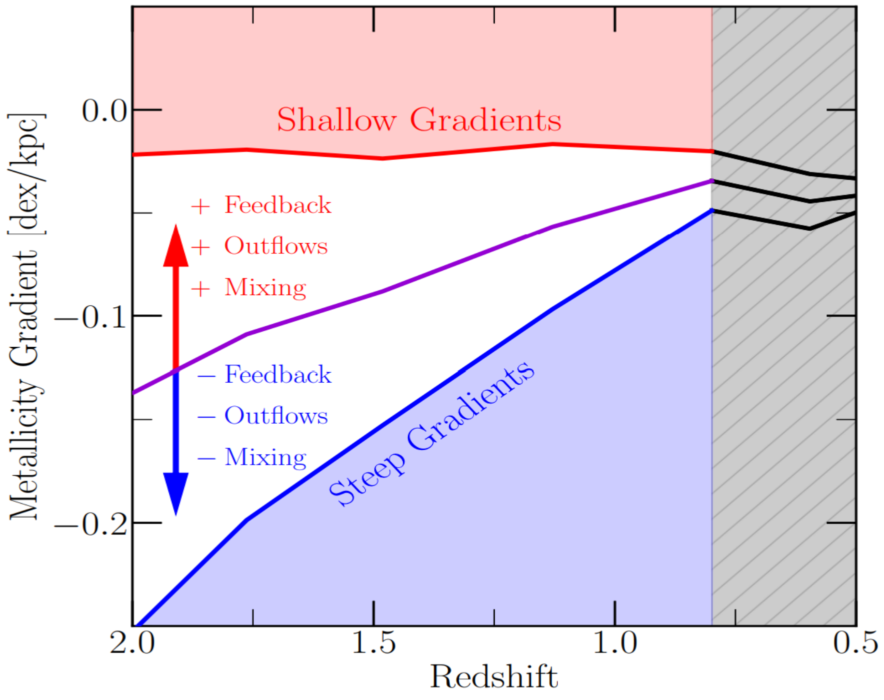
T. Chen
+ NP
(submitted)



What is the cosmic evolution of disk abundance gradients?







How typical is our Galaxy among spirals ?

SUMMARY

Secular disk evolution can explain several chemical features of the local disk
e.g. Local super-solar metallicity stars, 2-branch behaviour of [α/Fe], evolution of abundance gradient at birth place

Local 2-branch behaviour (thin/thick disks)is found in abundance patterns X/Y for elements X and Y produced on different time-scales in different places with different SF histories

Up to now observed clearly for a/Fe vs Fe/H
Observations of other ratios X/Y will allow to probe their sources (short-lived vs long-lived) and nature (Z-dependent vs Z-independent yields)

Recent local SF episodes affect chemical signatures and may perturb the evolution of gas abundance gradient (= star at birth place)

Observations of gas gradient (=birth place) at high redshifts seems to favor little or no evolution of the abundance gradient. Is the Milky Way a rare case of disk galaxy ?