Are ancient dwarf satellites the building blocks of the Galactic halo?

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Outline

- The chemical evolution model for
  - A) The Galactic halo
  - B) dSphs and UfDs
- The enriched infall of gas
- The results
  - I) dSphs and UfDs vs. the Galactic halo
  - II) Including the enriched infall
- Conclusions

The chemical evolution models:

The chemical evolution models:

The Milky Way (Brusadin et al. 2013)

The Milky Way: the solar neighborhood model parameters

Models	Infall type	τ_H [Gyr]	τ_D [Gyr]	Threshold [$M_\odot pc^{-2}$]	k	ν [Gyr^{-1}]	IMF	ω [Gyr^{-1}]
2IM	2 infall	0.8	7	4 (halo-thick disc) 7 (thin disc)	1.5	2 (halo-thick disc) 1 (thin disc)	Scalo (1986)	/
2IMW	2 infall	0.2	7	4 (halo-thick disc) 7 (thin disc)	1.5	2 (halo-thick disc) 1 (thin disc)	Scalo (1986)	14

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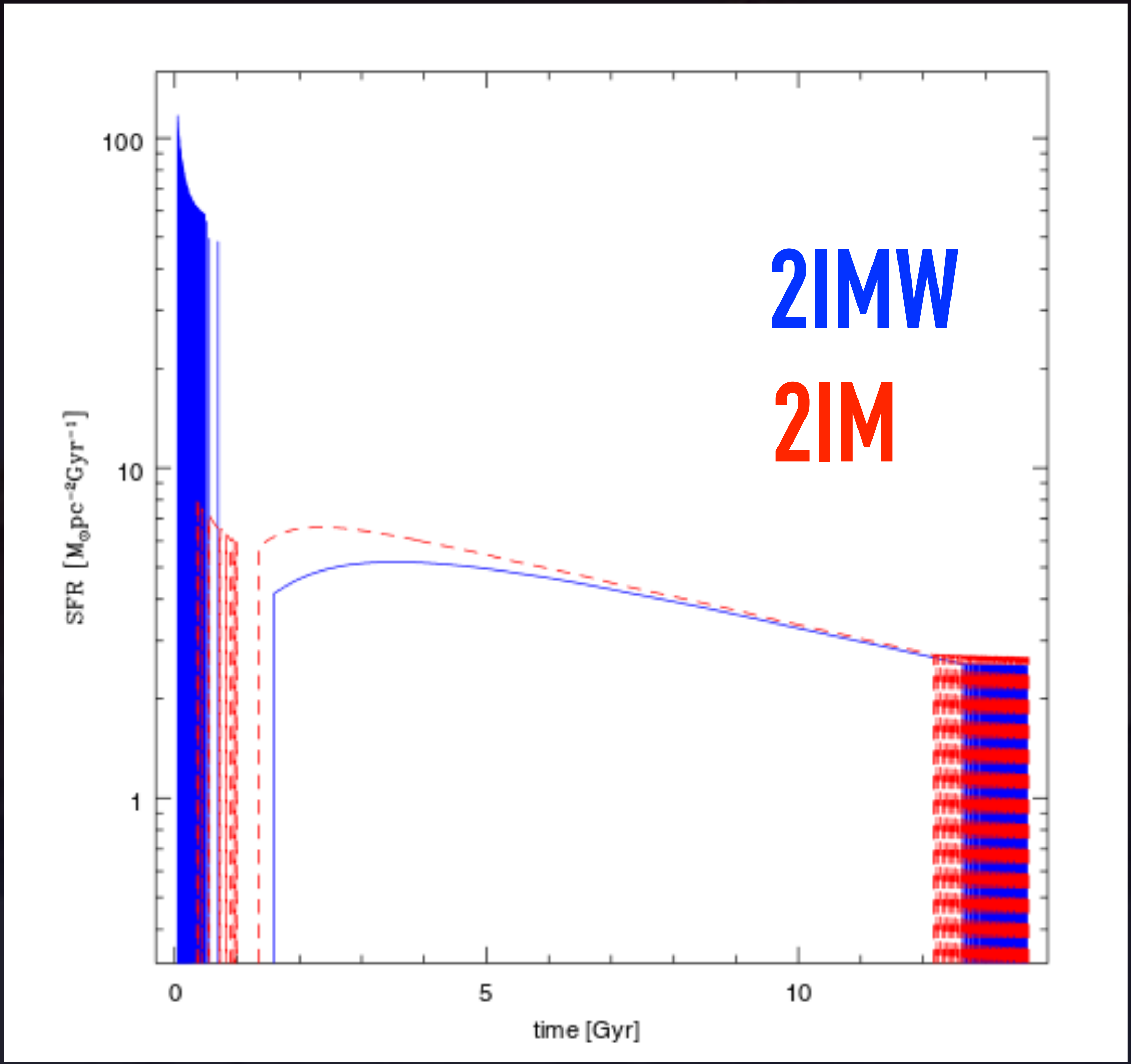
2IMW	2 infall	0.2	7	4 (halo-thick disc) 7 (thin disc)	1.5	2 (halo-thick disc) 1 (thin disc)	Scalo (1986)	14

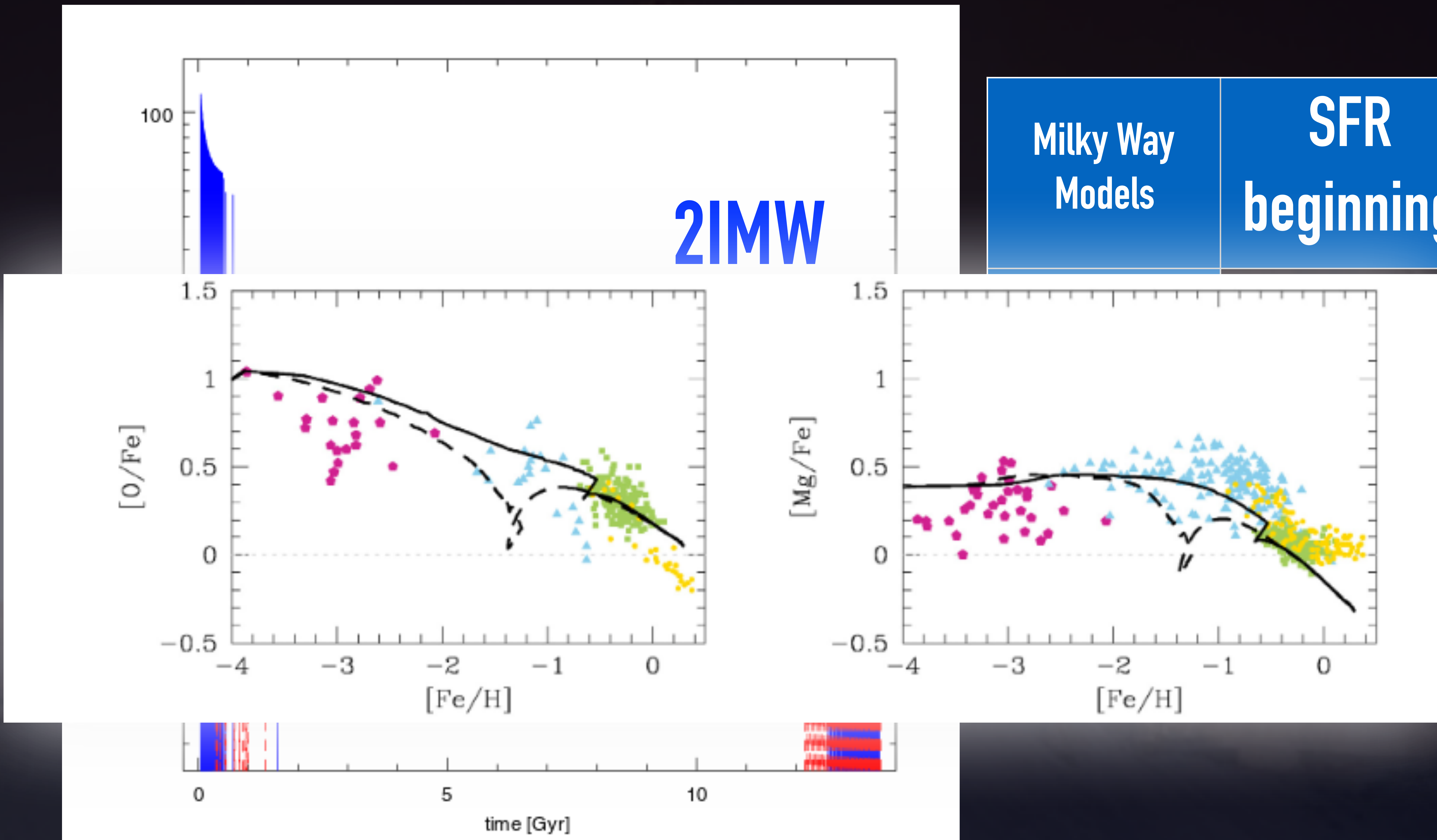
In the model 2IMW a gas outflow occuring during the halo phase with a rate proportional to the star formation rate: $$\frac{d\sigma_w}{dt} = -\omega\Psi(t)$$ **(Hartwick 1976)**

The Milky Way (Brusadin et al. 2013)



Milky Way Models	SFR beginning
2IM	t=0.356 Gyr
2IMW	t=0.05 Gyr

The Milky Way (Brusadin et al. 2013)



Milky Way Models	SFR beginning

The chemical evolution models:

The “classical” dSphs

We refer to Vincenzo et al. (2014)

dSphs: parameters of the model

ν [Gyr^{-1}]	k	ω	τ_{inf} [Gyr]	SFH [Gyr]	M_{inf} ($M_\odot$)	M_{DM} ($M_\odot$)	r_L [pc]	$S = \frac{r_L}{r_{DM}}$	IMF	t_{gw} [Gyr]
0.1	1	10	0.5	0-14	10^7	$3.4 \cdot 10^8$	260	0.52	Salpeter (1955)	0.013

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dSphs: parameters of the model

ν [Gyr^{-1}]	k	ω	τ_{inf} [Gyr]	SFH [Gyr]	M_{inf} ($M_\odot$)	M_{DM} ($M_\odot$)	r_L [pc]	$S = \frac{r_L}{r_{DM}}$	IMF	t_{gw} [Gyr]
0.1	1	10	0.5	0-14	10^7	$3.4 \cdot 10^8$	260	0.52	Salpeter (1955)	0.013

$[Fe/H]_{peak}$= −2.1 dex

The chemical evolution models:

The "classical" UfDs

UfDs: parameters of the model

ν [Gyr^{-1}]	k	ω	τ_{inf} [Gyr]	SFH [Gyr]	M_{inf} ($M_\odot$)	M_{DM} ($M_\odot$)	r_L [pc]	$S = \frac{r_L}{r_{DM}}$	IMF	t_{gw} [Gyr]
0.01	1	10	0.001	0-14	10^5	10^6	35	0.1	Salpeter (1955)	0.088

The chemical evolution models:

The "classical" UfDs

UfDs: parameters of the model

ν [Gyr^{-1}]	k	ω	τ_{inf} [Gyr]	SFH [Gyr]	M_{inf} ($M_\odot$)	M_{DM} ($M_\odot$)	r_L [pc]	$S=\frac{r_L}{r_{DM}}$	IMF	t_{gw} [Gyr]
0.01	1	10	0.001	0-14	10^5	10^6	35	0.1	Salpeter (1955)	0.088

$[Fe/H]_{peak} = -3.3$ dex

The enriched infall of gas

The enriched infall of gas

The enriched infall of gas

Primordial infall of gas (Brusadin et al. 2013)

Enriched infall with chemical abundances of the outflows from dSphs and UfDs (Spitoni et al. 2016, submitted on MNRAS)

$$A(r,t,i) = X_{A_i}(t)\,a(r)\,e^{-t/\tau_H(r)}$$

Galactic halo

The enriched infall of gas

The infall of gas which forms the Galactic halo is primordial up to the time at which the galactic wind in dSphs (or UfDs) starts

The enriched infall of gas

The infall of gas which forms the Galactic halo is primordial up to the time at which the galactic wind in dSphs (or UfDs) starts

Model i): After t_{gw} the infalling gas presents the chemical abundances of the wind

The enriched infall of gas

The infall of gas which forms the Galactic halo is primordial up to the time at which the galactic wind in dSphs (or UfDs) starts

Model i): After t_{gw} the infalling gas presents the chemical abundances of the wind

Model ii): After t_{gw} Diluted infall , the chemical composition by 50% contributed by UfDs (dSphs), 50% by primordial gas infall

The chemical evolution models with enriched gas infall

2IM(W)+dSph	enriched infall from dSphs
2IM(W)+UfD	enriched infall from UfDs

Model i)

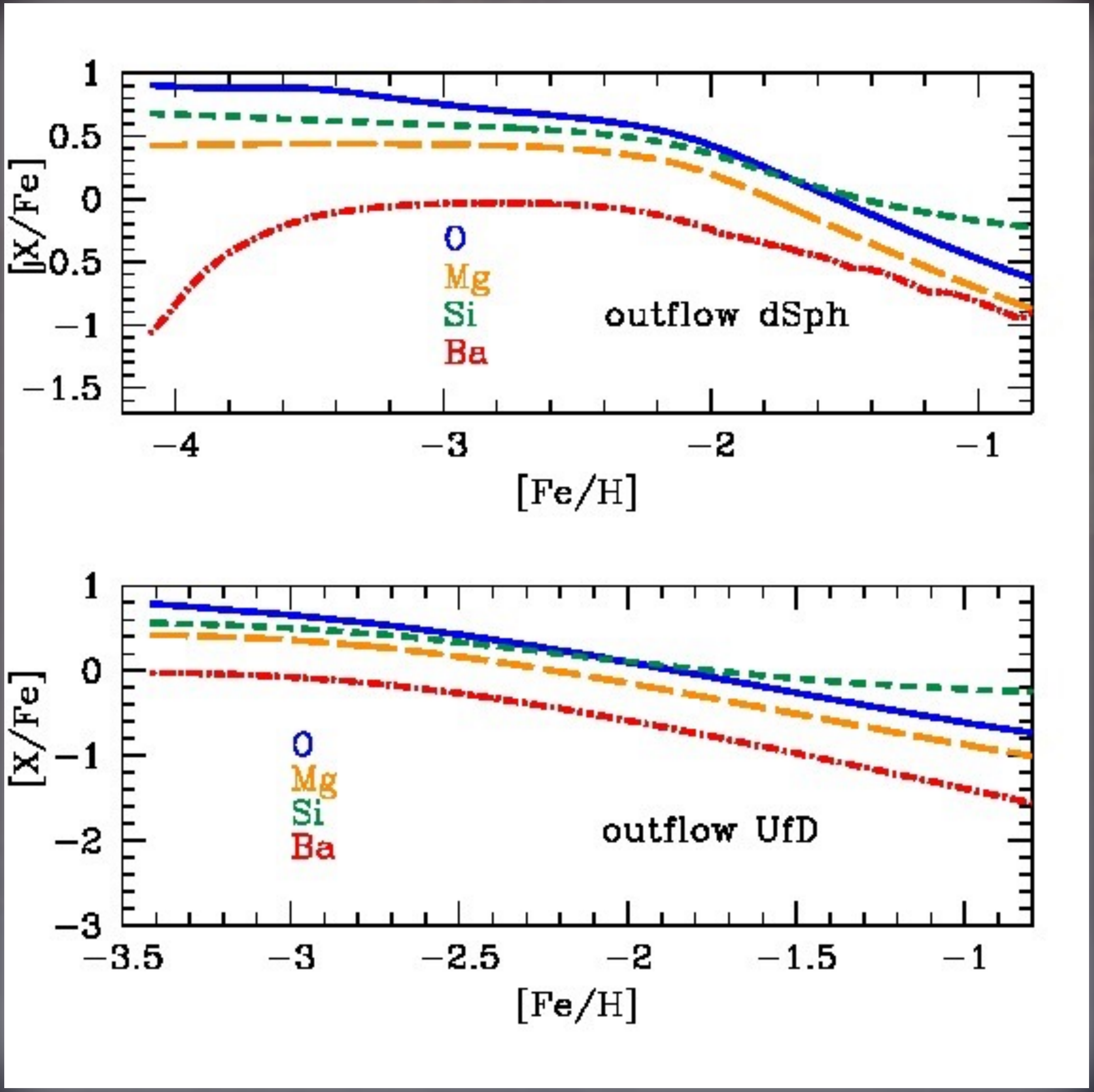
The chemical evolution models with enriched gas infall

Model ii)	
2IM(W)+dSph MIX	The enriched gas infall from dSph is diluted by pristine gas
2IM(W)+UfD MIX	The enriched gas infall from UfDs is diluted by pristine gas

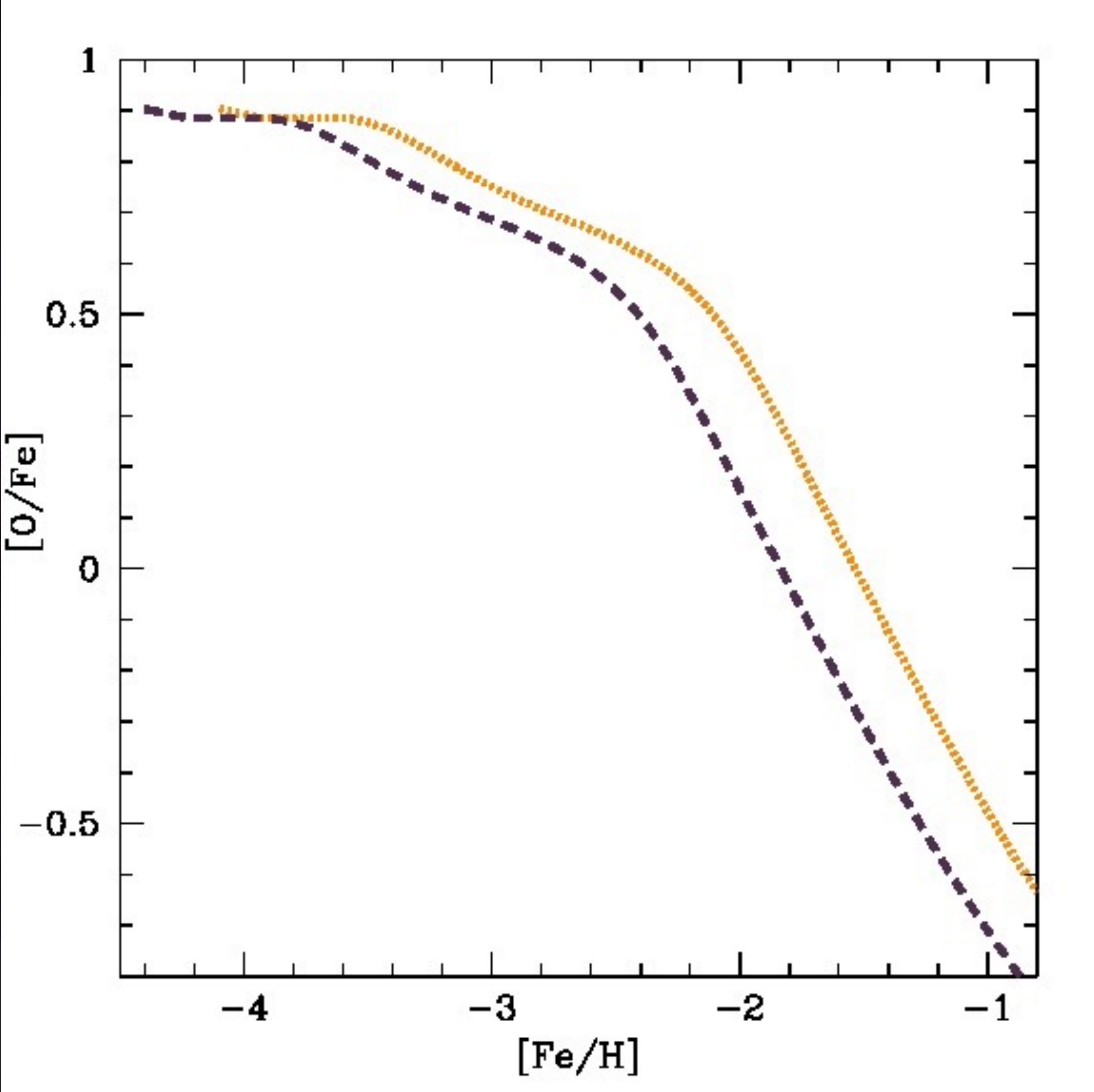
The chemical evolution models with enriched gas infall

2IM(W)+dSph	enriched infall from dSphs
2IM(W)+UfD	enriched infall from UfDs
2IM(W)+dSph MIX	The enriched gas infall from dSph is diluted by pristine gas
2IM(W)+UfD MIX	The enriched gas infall from UfDs is diluted by pristine gas

The chemical abundances of the outflowing gas from dSph and UfD galaxies

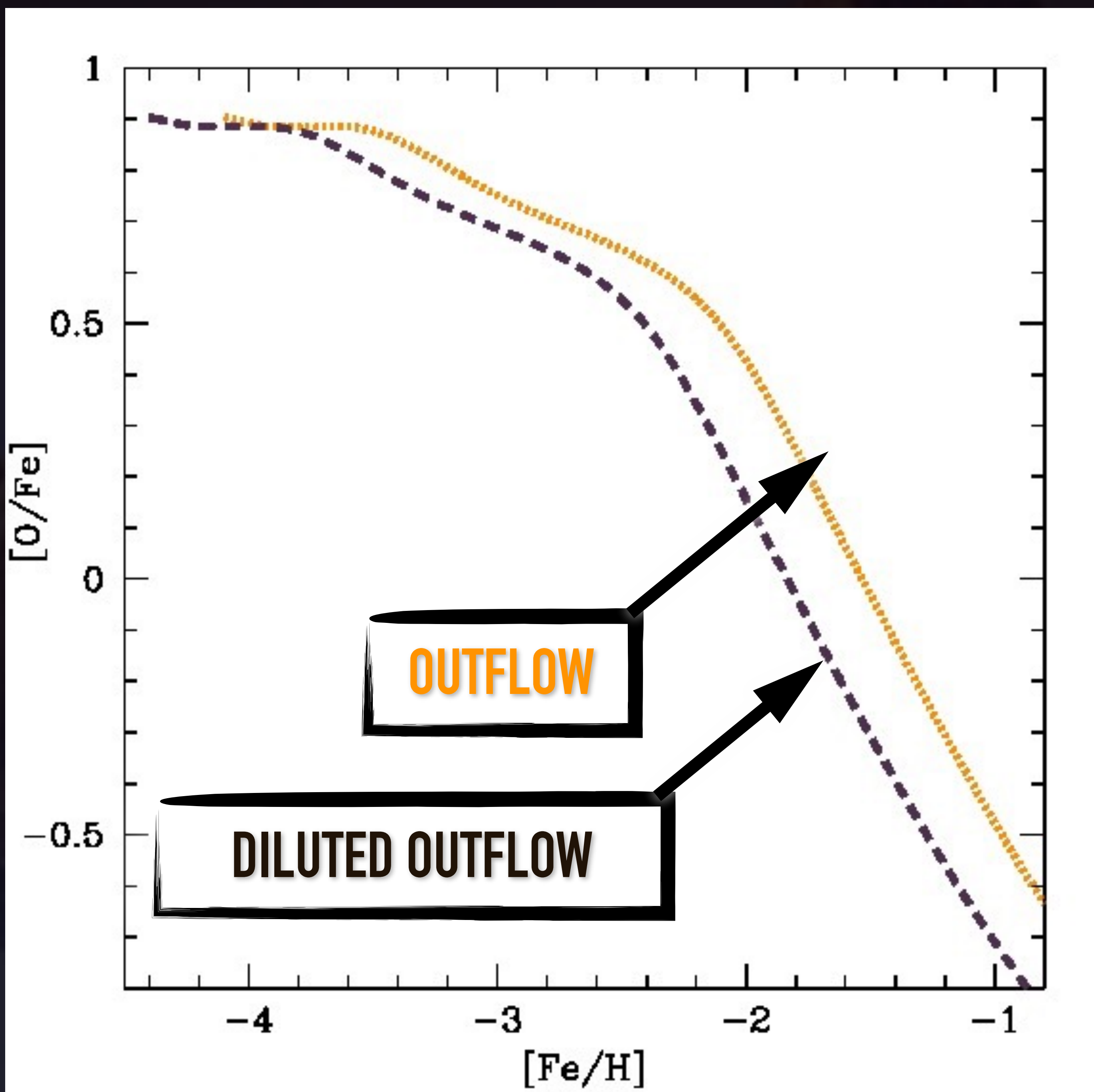


The effect of the dilution on the dSph outflow abundance



The effect of the dilution following the model ii) prescription on the chemical abundances of the dSph gas outflows

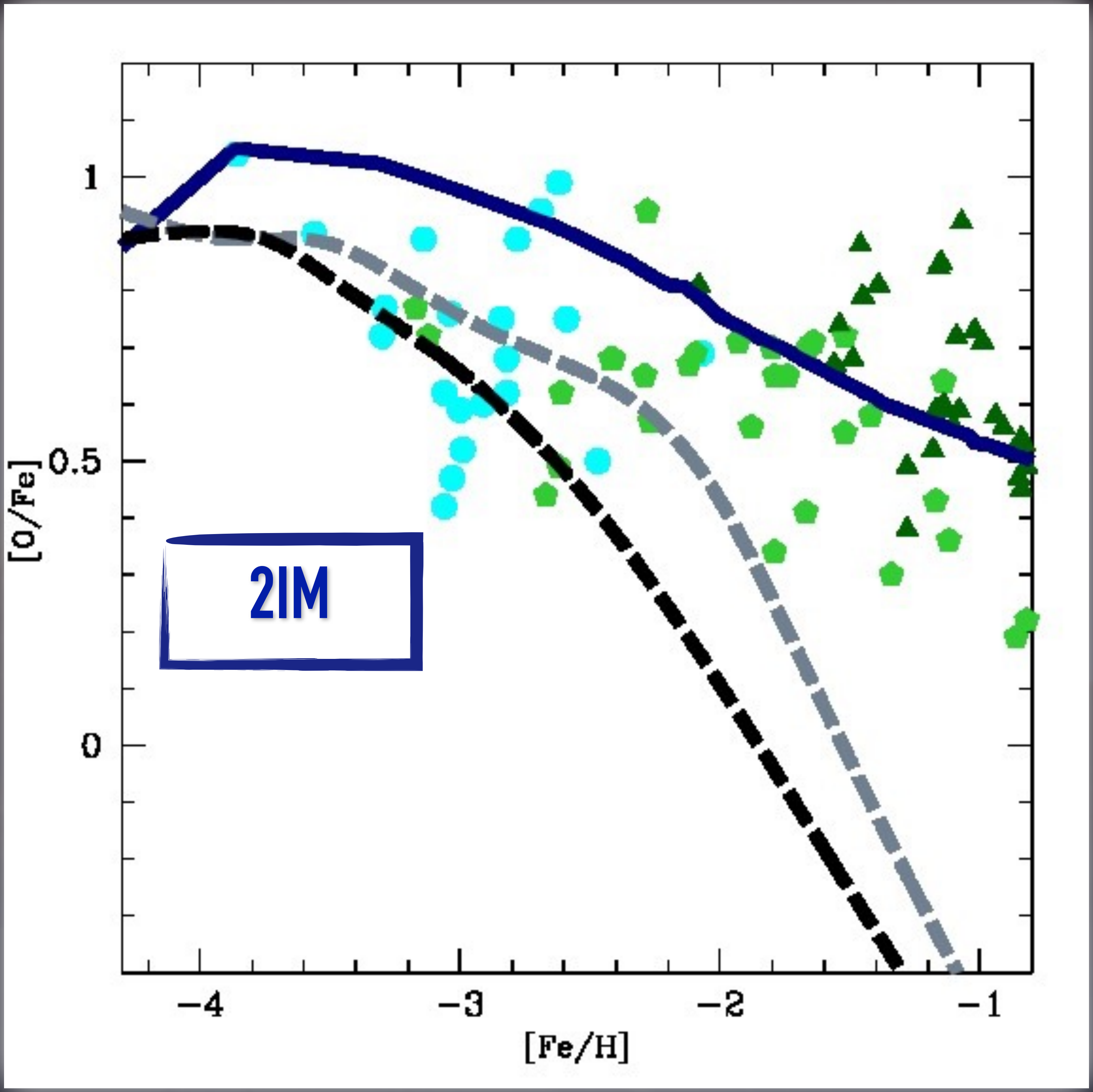
The effect of the dilution on the dSph outflow abundance

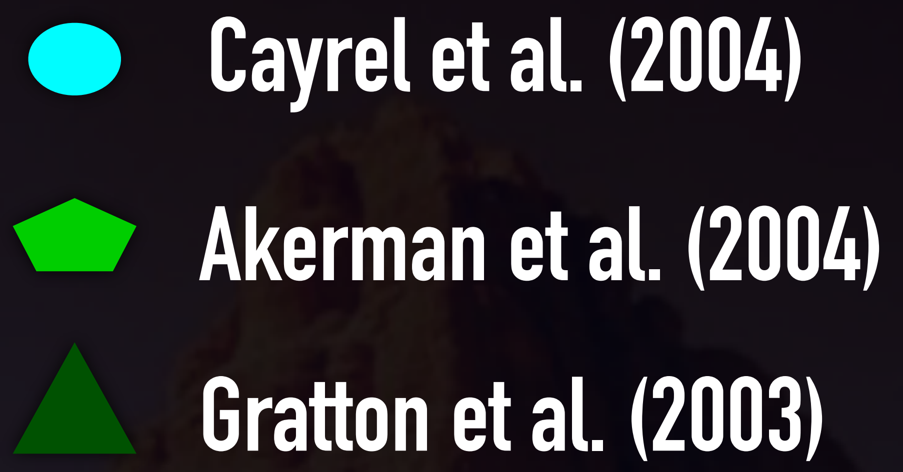


The effect of the dilution following the model ii) prescription on the chemical abundances of the dSph gas outflows

The results I)
The Galactic halo in the model 2IM

The chemical evolution of O for the 2IM, dSph and UfD models





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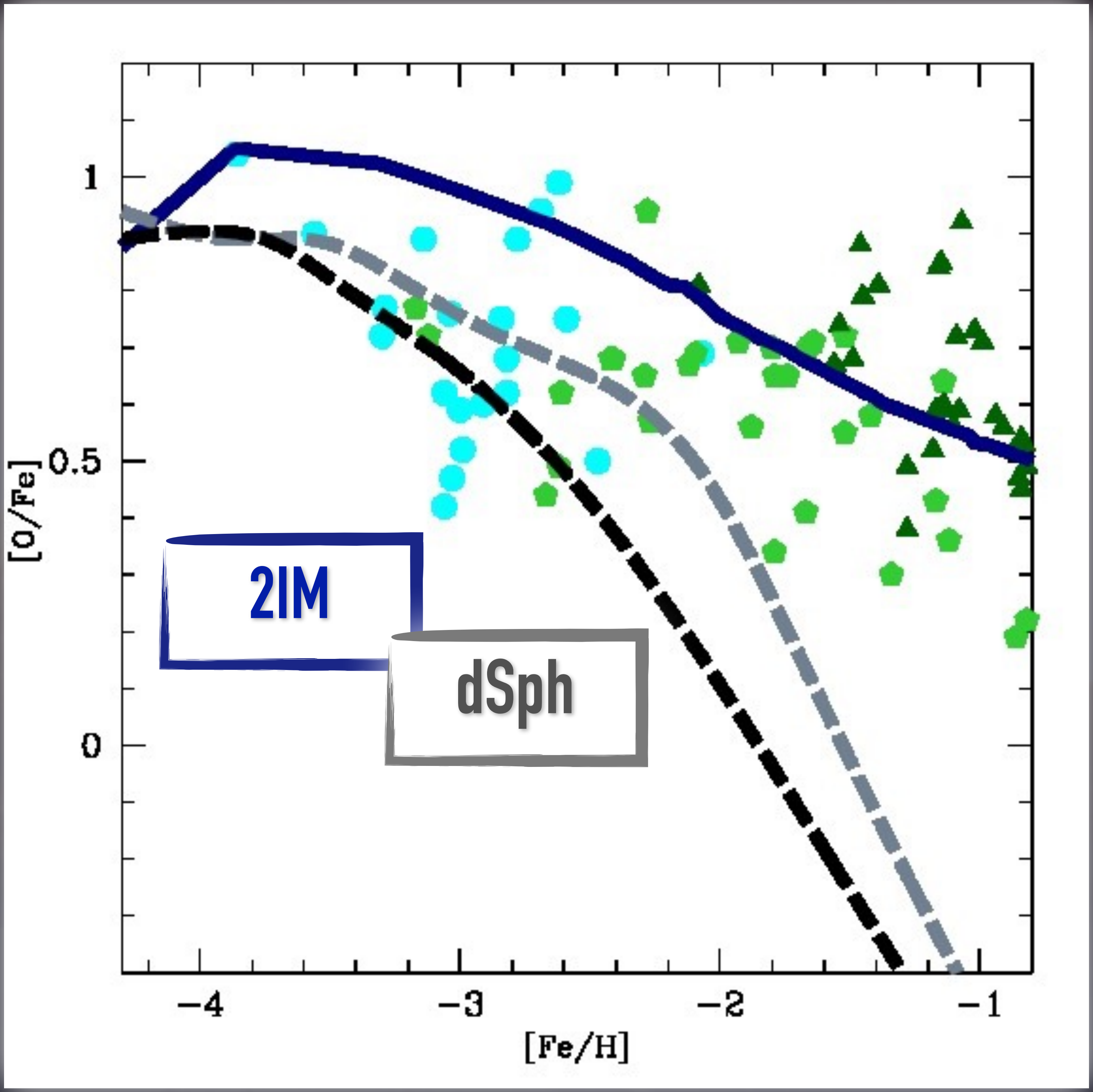
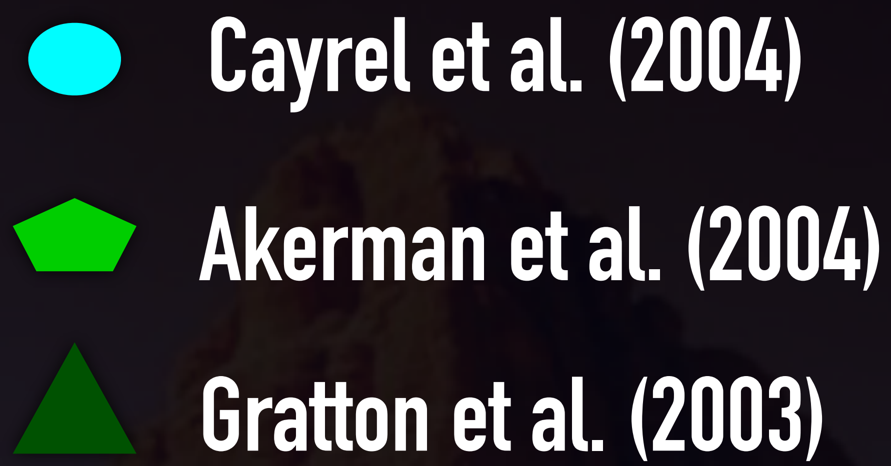
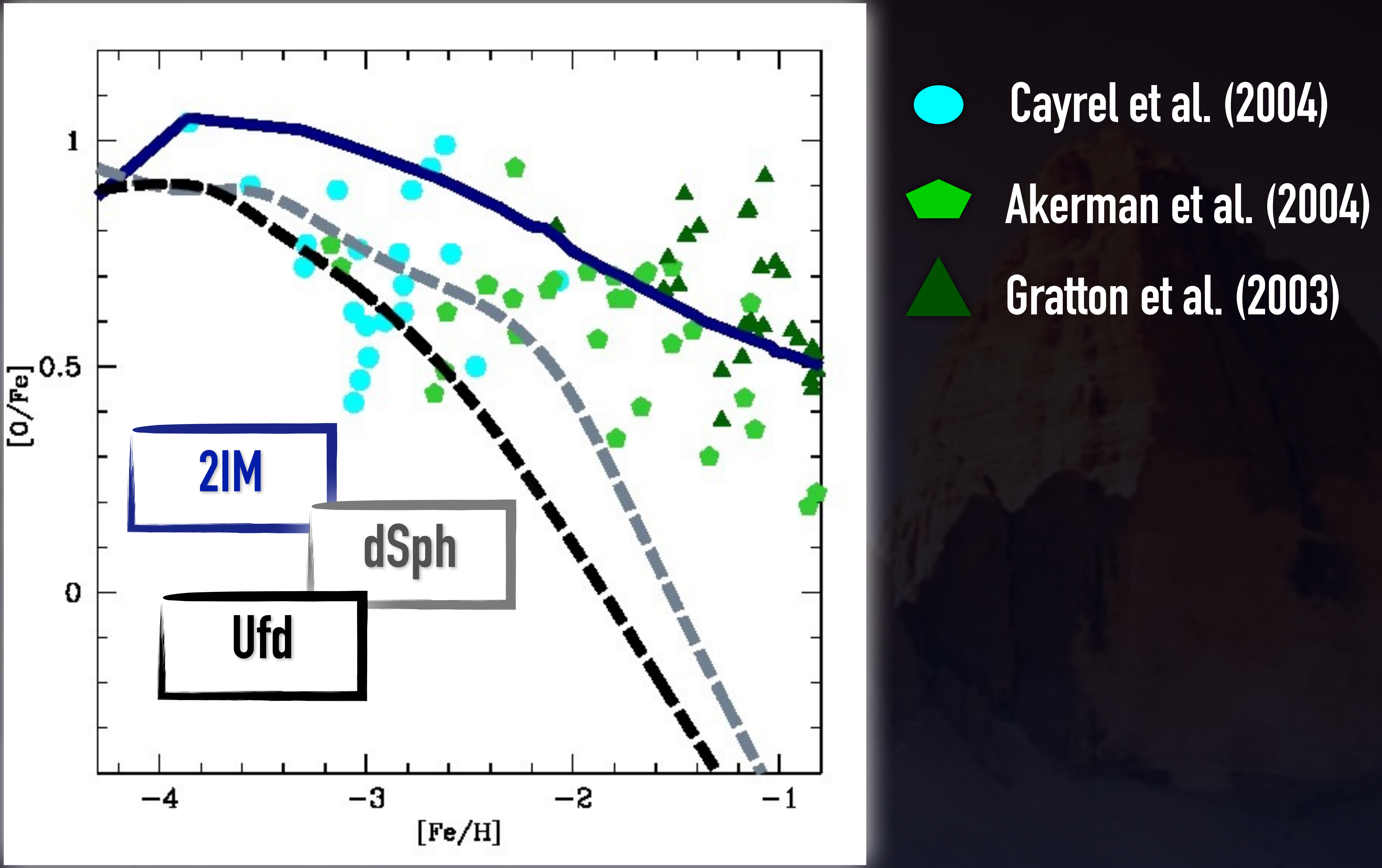




The chemical evolution of O for the 2IM, dSph and UfD models



- The dSph and UfD models cannot explain the [α/Fe] plateau which Galactic halo stars exhibit for [Fe/H] > -2.0 dex; in fact, halo stars have always larger [O/Fe] ratios than dSph and UfD stars.

The enriched infall from dSphs (model 2IM)

2IM+dSph

2IM+dSph MIX

The enriched infall from dSphs (model 2IM)

2IM+dSph

2IM+dSph MIX

It is possible to distinguish 3 different phases in the halo

chemical evolution

3 different phases

infall from dSph

Phase a)
The infall is primordial, the wind in dSphs has not started yet

t_{gw} (dSph)= 0.013 Gyr

$t_{SFR}(MW_{2IM})$=0.356 Gyr

3 different phases

infall from dSph

Phase b)
The infall is enriched by dSphs, SFR=0

t_{gw} (dSph)= 0.013 Gyr

$t_{SFR}(MW_{2IM})$=0.356 Gyr

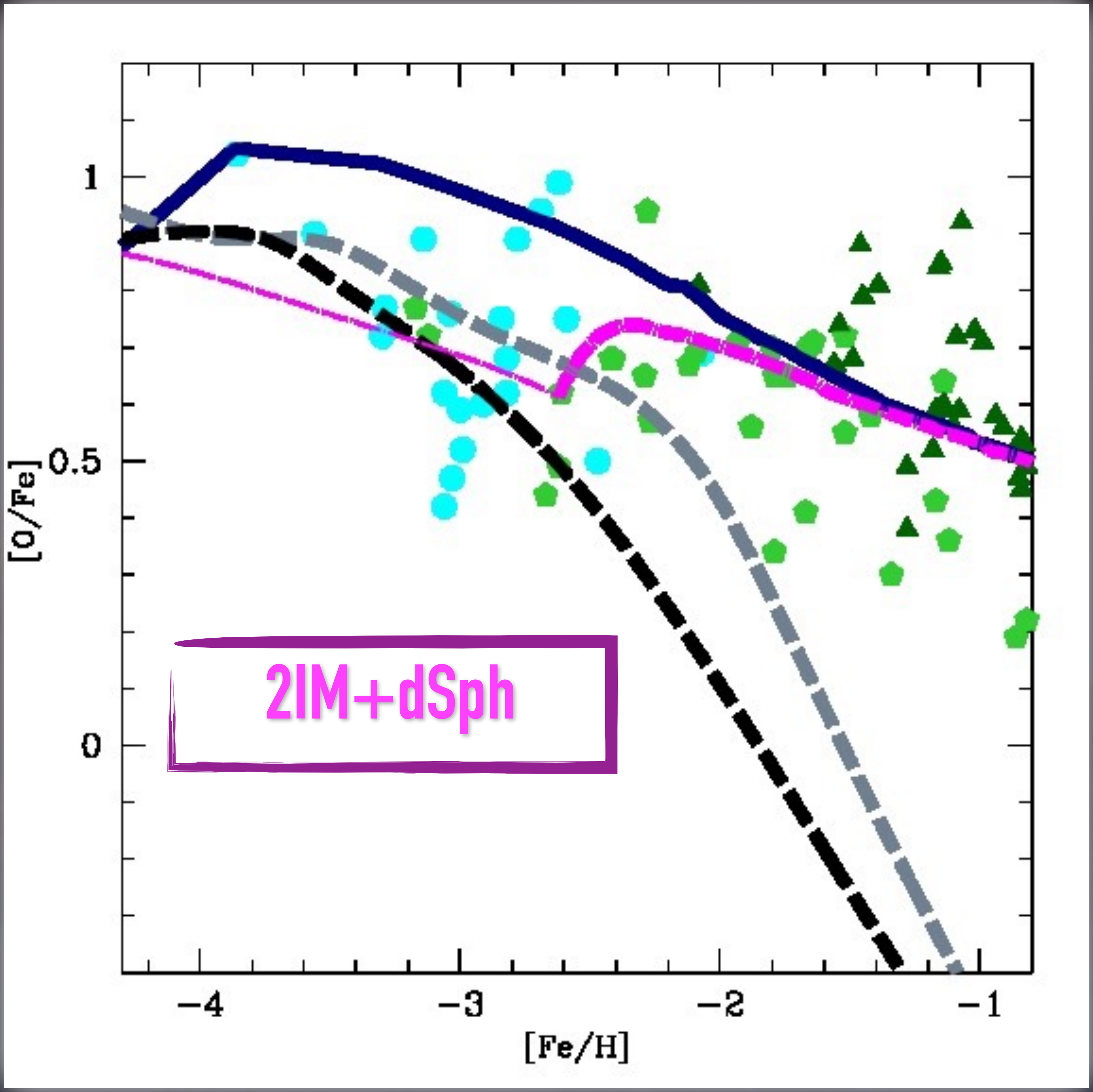
3 different phases

infall from dSph

Phase c)
The infall is enriched by dSphs, $t>t_{SFR}(MW_{2IM})$

t_{gw} (dSph)$=$ 0.013 Gyr

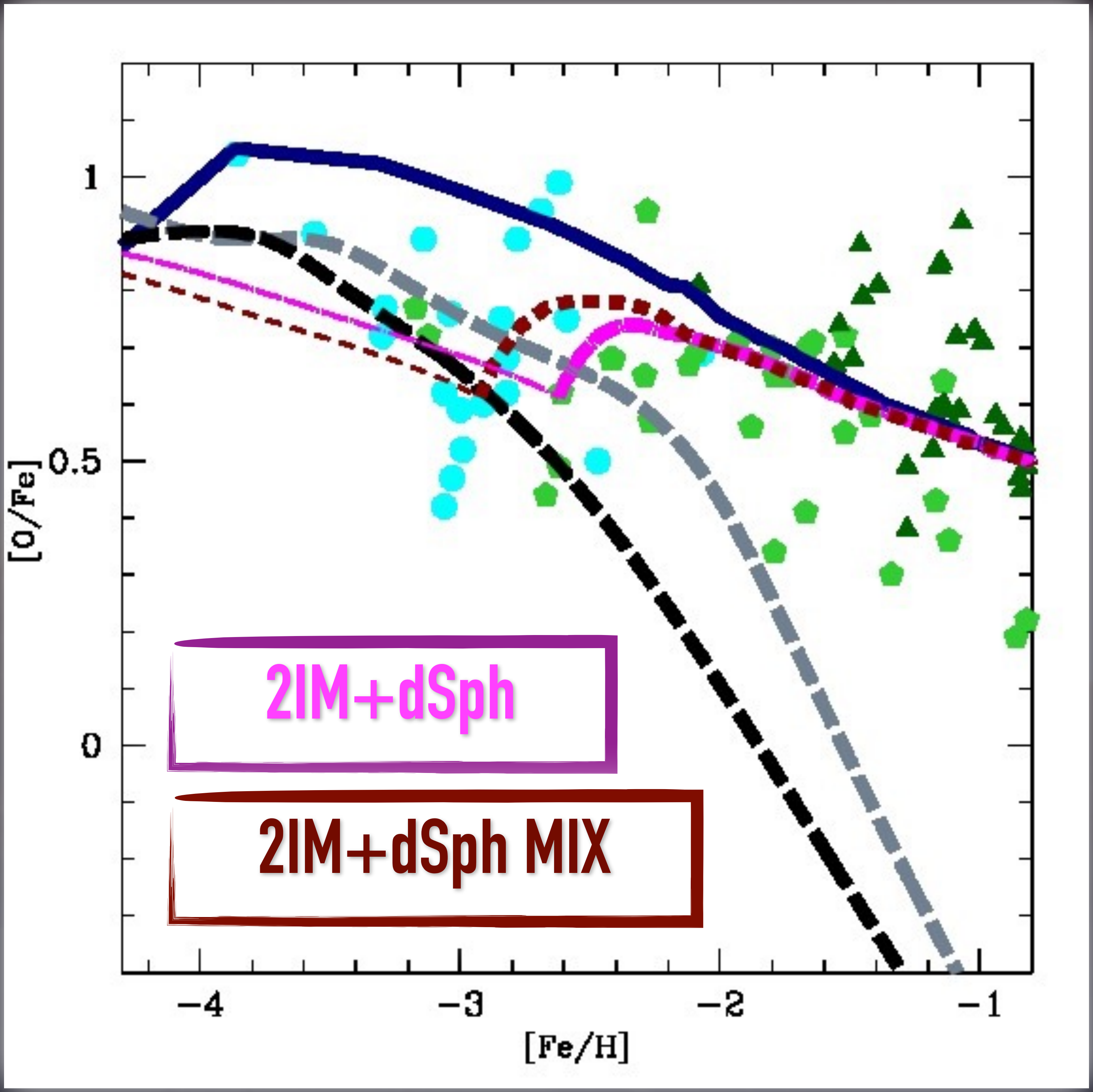
$t_{SFR}(MW_{2IM})$$=$0.356 Gyr



NO STAR

STAR

- The entire spread of the data cannot be explained assuming time dependent enriched infall
- To explain data for stars with [Fe/H] <-2.4 dex we need stars formed in dSph systems



2IM+dSph
2IM+dSph MIX
[O/Fe]
[Fe/H]
1
0.5
0
−4
−3
−2
−1

The enriched infall from UfDs (model 2IM)

2IM+UfD

2IM+UfD MIX

t_{gw} (UfD)= 0.088 Gyr

t_{SFR}(MW$_{2IM}$)=0.356 Gyr

The enriched infall from UfDs (model 2IM)

t_{gw} (dSph) < t_{gw} (UfD) = 0.088 Gyr

$t_{SFR}(MW_{2IM})$ = 0.356 Gyr

2IM+UfD

2IM+UfD MIX

The enriched infall from UfDs (model 2IM)

2IM+UfD

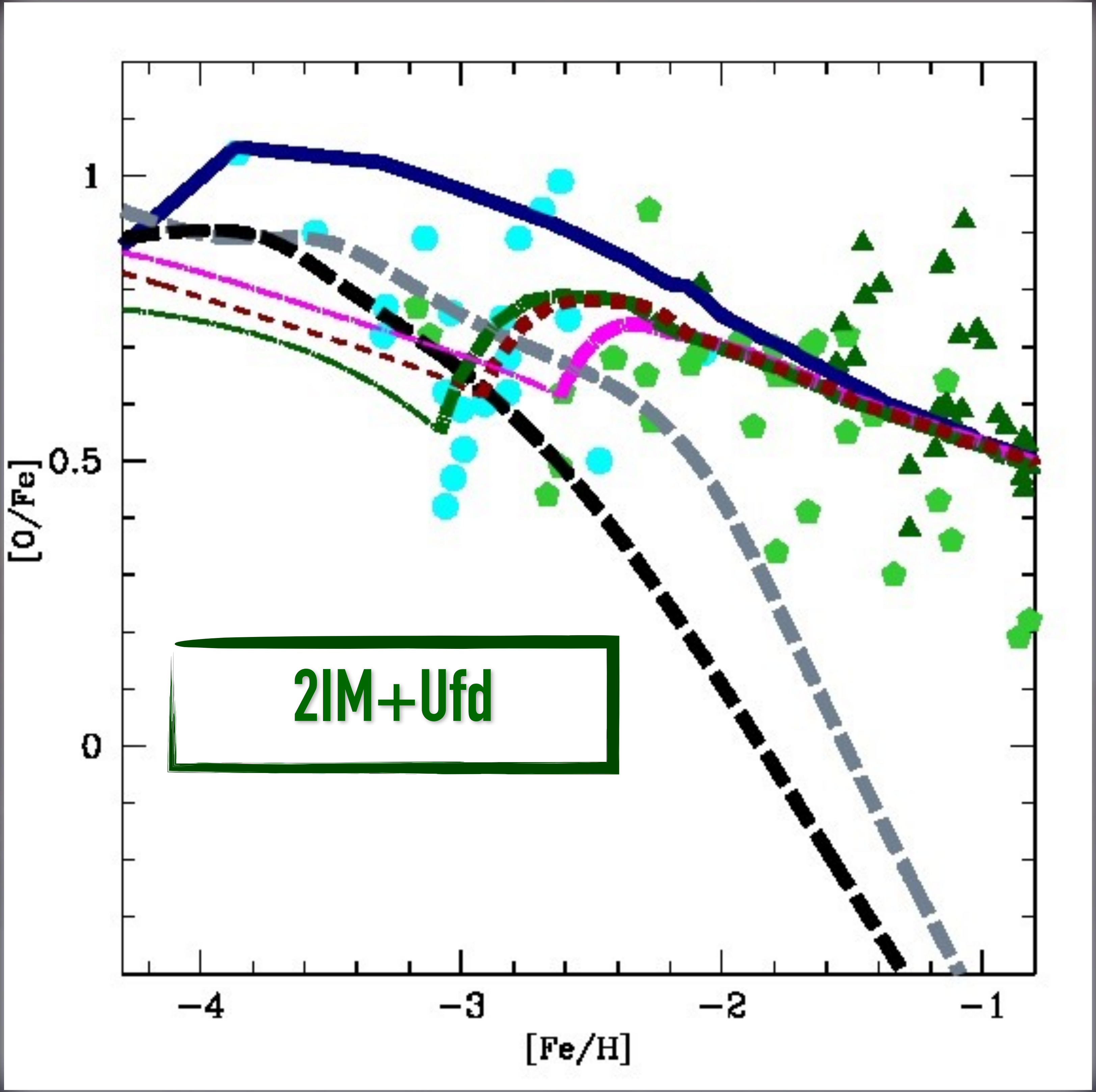
2IM+UfD MIX

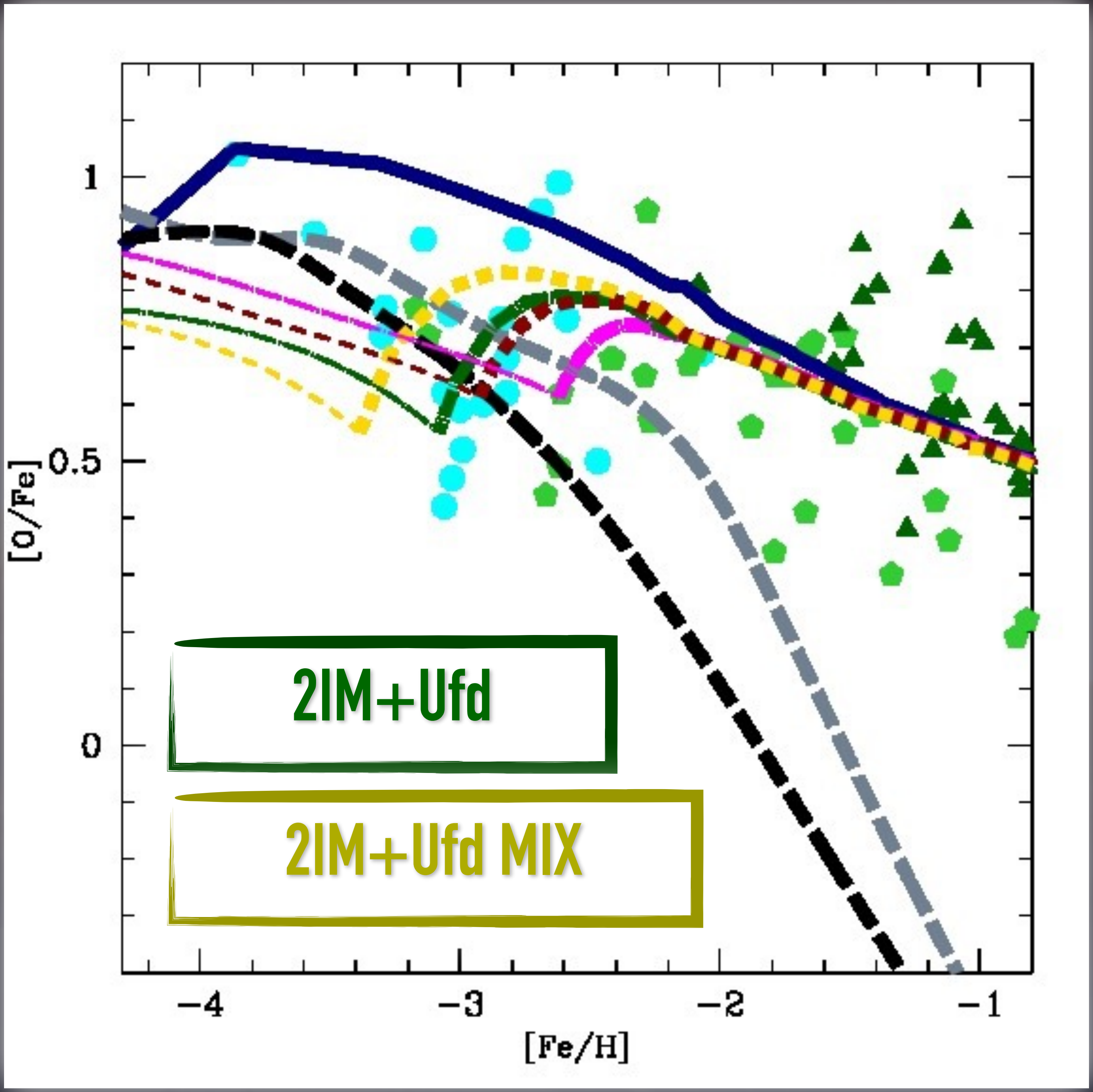
t_{gw} (dSph) < t_{gw} (UfD) = 0.088 Gyr

$t_{SFR}(MW_{2IM})$ = 0.356 Gyr

It is possible to distinguish 3 different phases in the halo chemical evolution

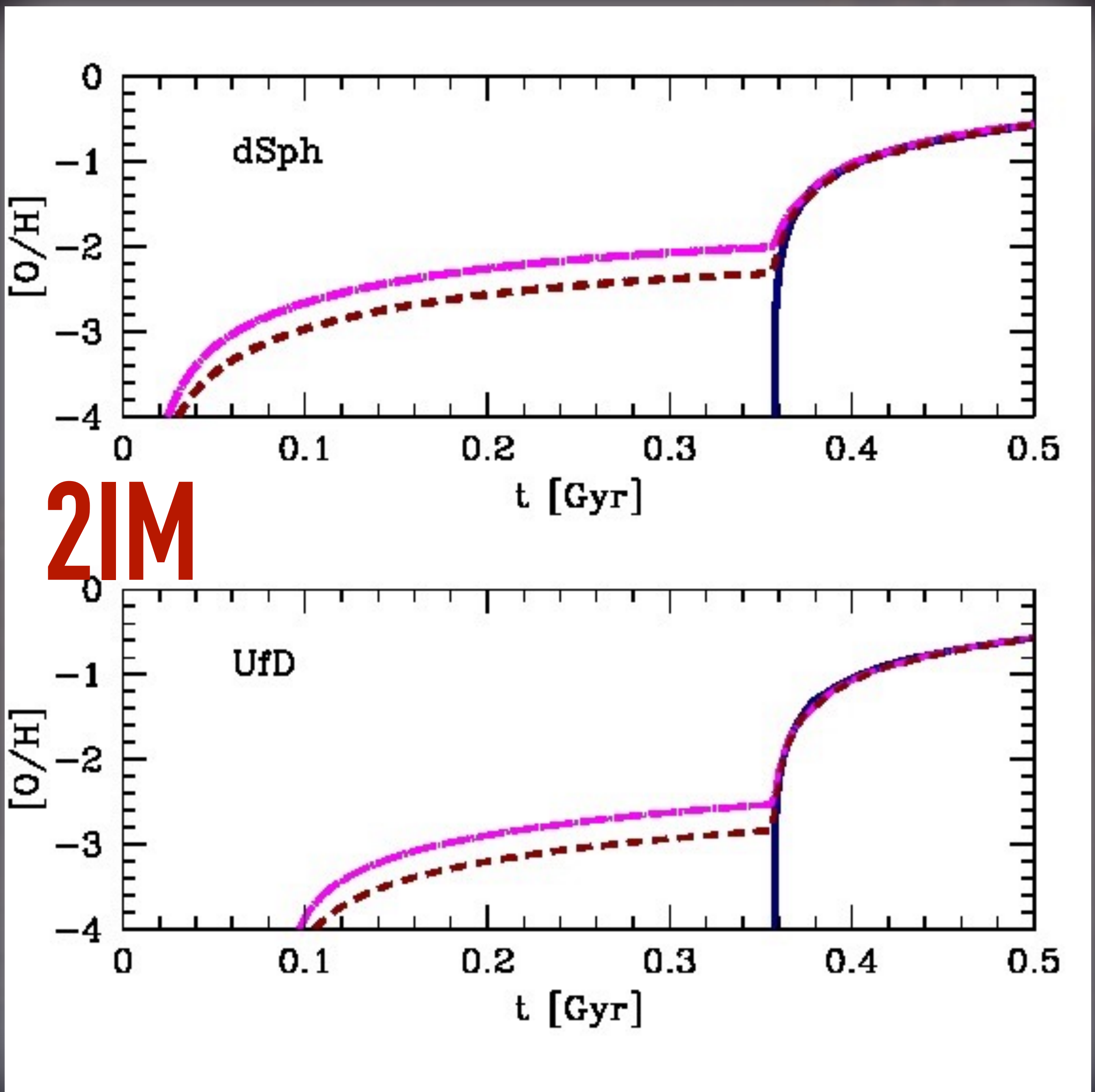
The enriched infall from UfD objects





1
0.5
0
[O/Fe]
−4
−3
−2
−1
[Fe/H]
2IM+Ufd
2IM+Ufd MIX

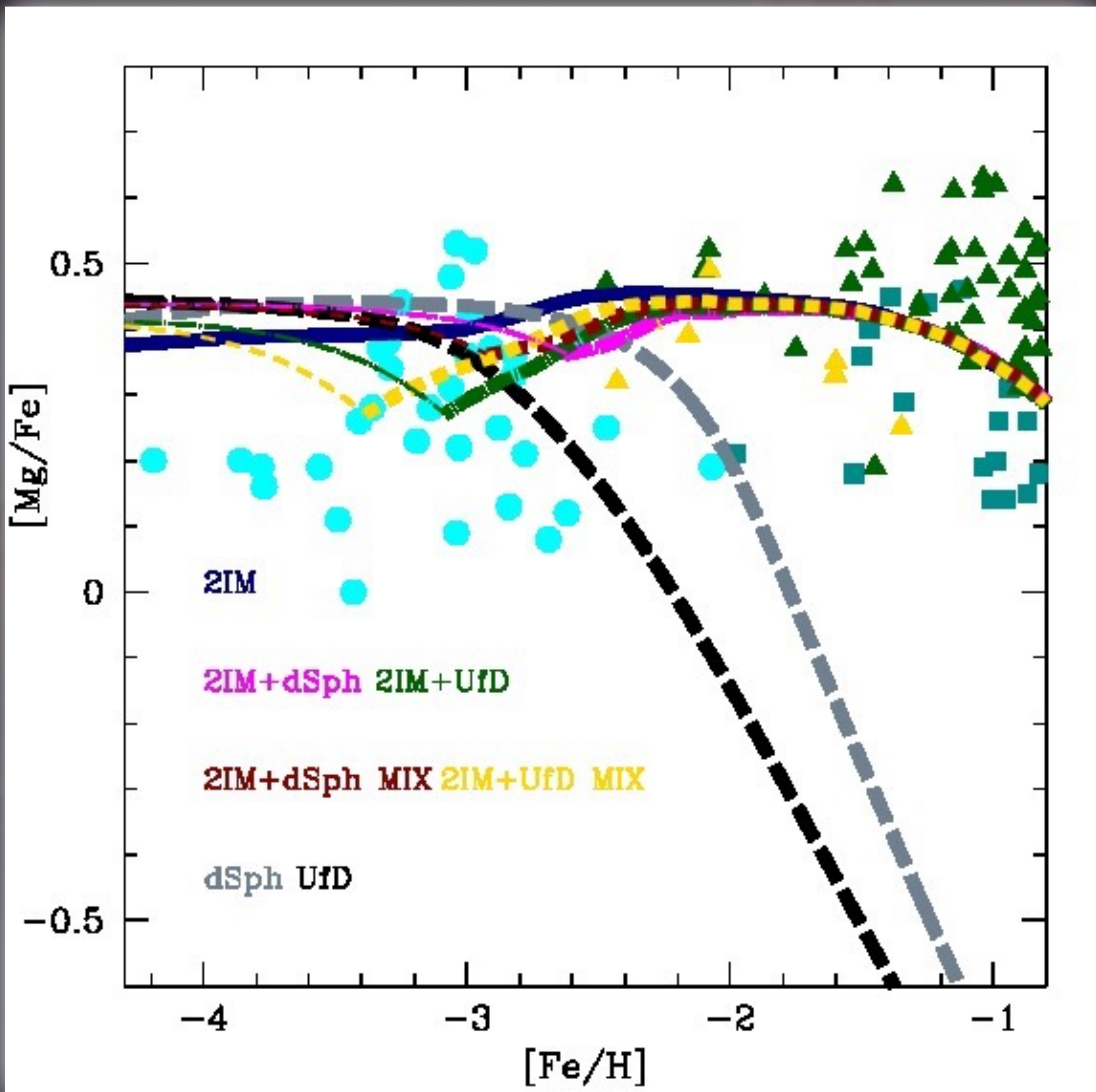
The time evolution of [O/H]



The models with enriched infalls which show the fastest chemical enrichment are the ones with infall abundances taken from the outflows of dSphs.

t_{gw} (dSph) $<$ t_{gw} (UfD)

The chemical evolution of Mg for the 2IM, dSph and UfD models and models with enriched infall



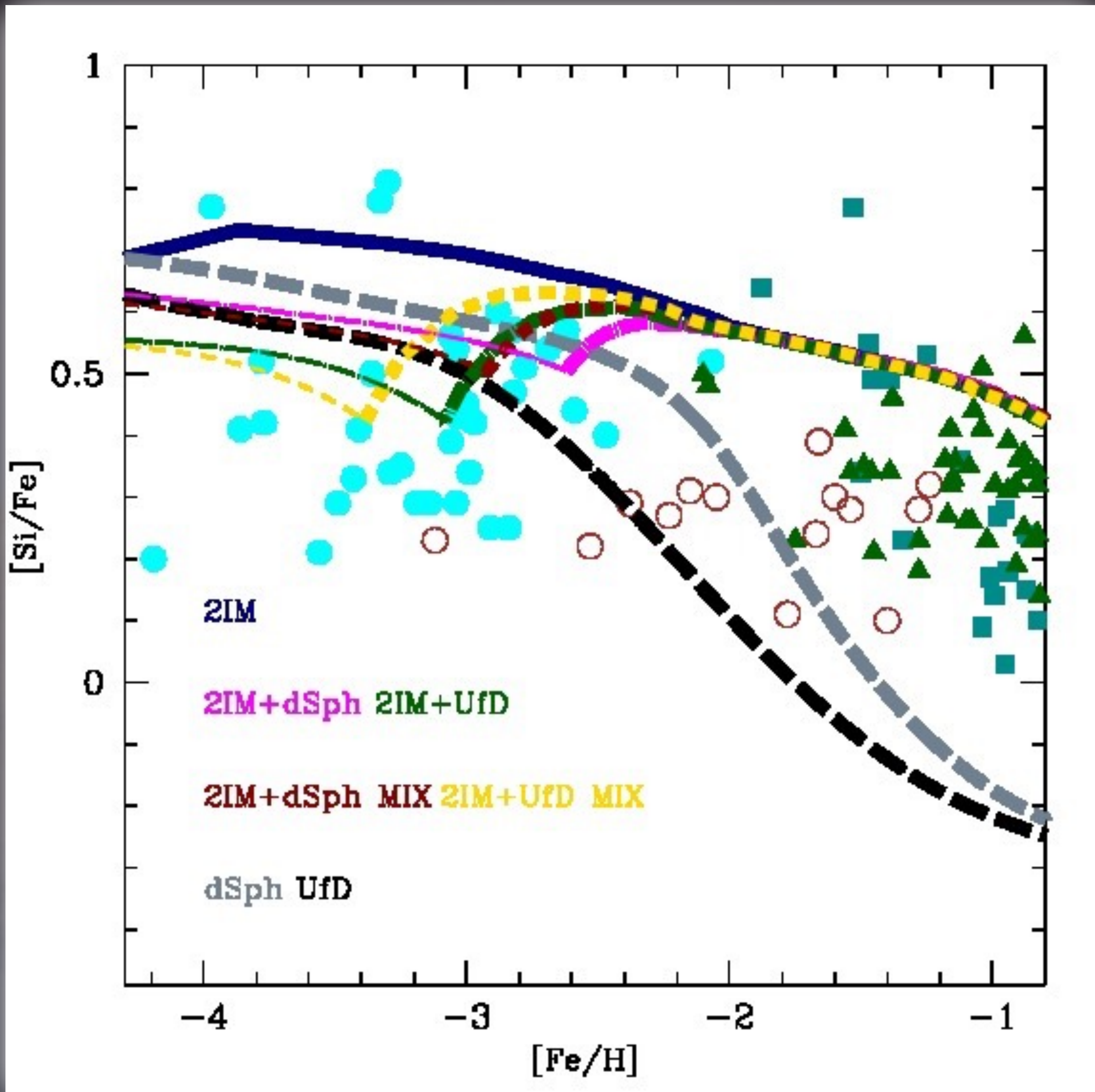
Cayrel et al. (2004)

Moshonkina et al. (2007)

Gratton et al. (2003)

Reddy et al. (2006)

The chemical evolution of Si for the 2IM, dSph and UfD models and models with enriched infall



Cayrel et al. (2004)

Moshonkina et al. (2007)

Gratton et al. (2003)

Reddy et al. (2006)

Cayrel et al. (2004)

- As concluded for O, our reference chemical evolution models for dSph and UfD galaxies cannot explain the observed Galactic halo data over the entire range of [Fe/H] abundances.

The hypothesis that all Galactic halo stars were stripped or accreted in the past from dSphs or UfDs is ruled out

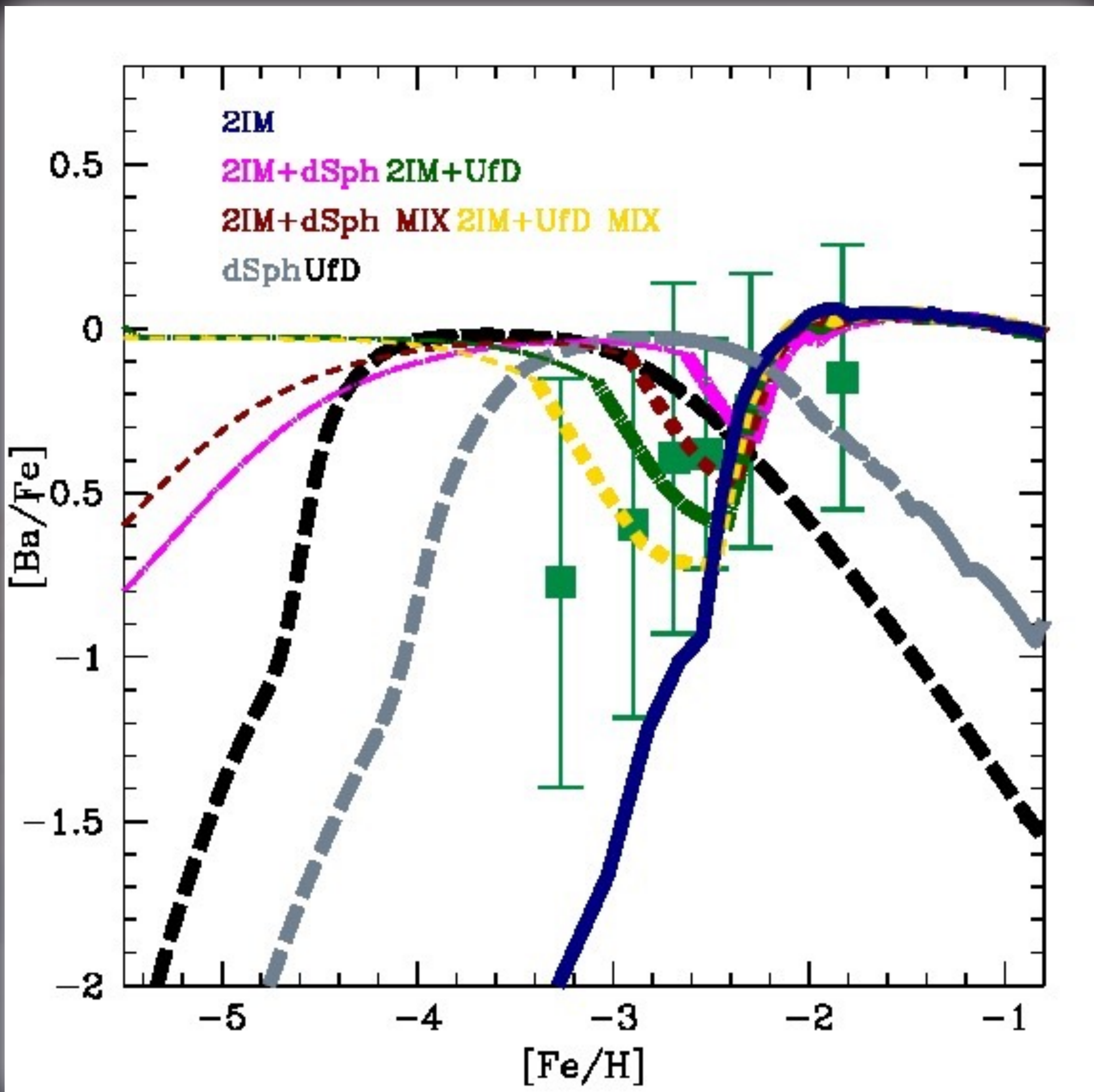
• A … e … cannot e … the e …

• A
e cannot
e
e

The hypothesis that all Galactic halo stars were stripped or
a
o

If we assume that the Galactic halo formed by accreting enriched gas from dSphs or UfDs, we also need a stellar contribution from dSphs and UfDs to explain the stars at very low [Fe/H]

The chemical evolution of Ba for the 2IM models



Frebel et al. (2010)

For Ba we assume the stellar yields of Cescutti et al. (2006)

Ba in MW 2IM model and dSphs UfDs

- The 2IM model does not provide a good agreement with the observed data-set for [Fe/H] < -2.5 dex.
- Our chemical evolution models for dSph and Ufd fail in reproducing the observed data. That is due to the very low SFEs assumed for dSphs and UfDs, which cause the first Ba-polluters to enrich the ISM at extremely low [Fe/H] abundances.

Ba in MW 2IM model with enriched infall

- All our models deviate substantially from the observed trend of the [Ba/Fe] versus [Fe/H] abundance pattern in Galactic halo stars. Such a discrepancy enlarges for [Fe/H] < -2.4 dex, where those models predict always larger [Ba/Fe] ratios than the 2IM model.

The results II)

The Galactic halo in the model 2IMW (model with a wind in the halo phase)

The enriched infall from dSphs for the reference model 2IMW:

2IMW+dSph

2IMW+dSph MIX

t_{gw} (dSph)= 0.013 Gyr

$t_{SFR}(MW_{2IMW})$=0.05 Gyr

The enriched infall from dSphs for the reference model 2IMW:

2IMW+dSph

2IMW+dSph MIX

As for 2IM It is possible to distinguish 3 different phases in the halo chemical evolution

t_{gw} (dSph)= 0.013 Gyr

$t_{SFR}(MW_{2IMW})$=0.05 Gyr

The enriched infall from UfDs for the reference model 2IMW:

2IMW+UfD

2IMW+UfD MIX

t_{gw} (UfD)= 0.088 Gyr

$t_{SFR}(MW_{2IMW})$=0.05 Gyr

The enriched infall from UfDs for the reference model 2IMW:

2IMW+UfD

2IMW+UfD MIX

In this case there is not the phase with enriched infall and SFR=0

t_{gw} (UfD)= 0.088 Gyr

$t_{SFR}(MW_{2IMW})$=0.05 Gyr

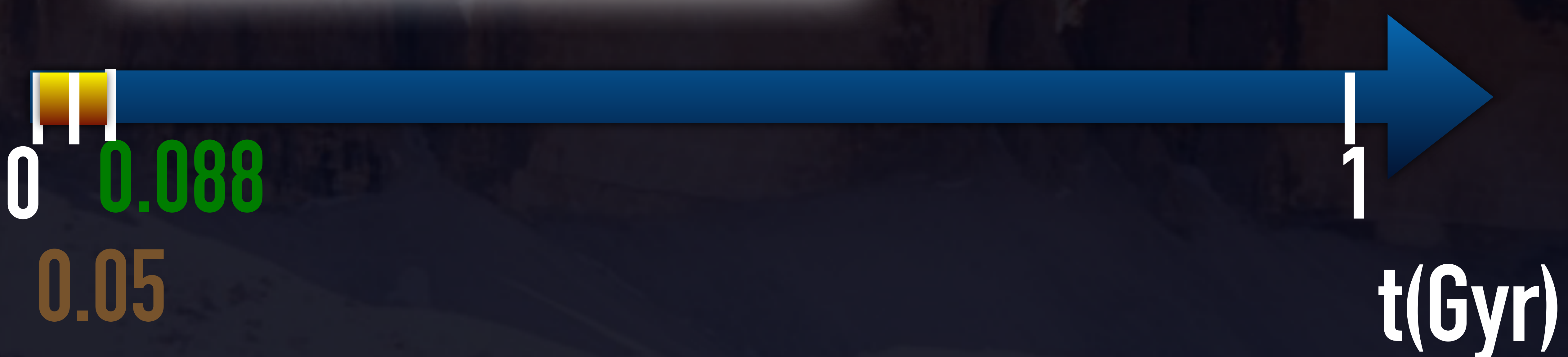
2 different phases

infall from UfD

Phase a)
The infall is primordial, the wind in UfDs has not started yet

t_{gw} (UfD)= 0.088 Gyr

t_{SFR}(MW_{2IMW})=0.05 Gyr



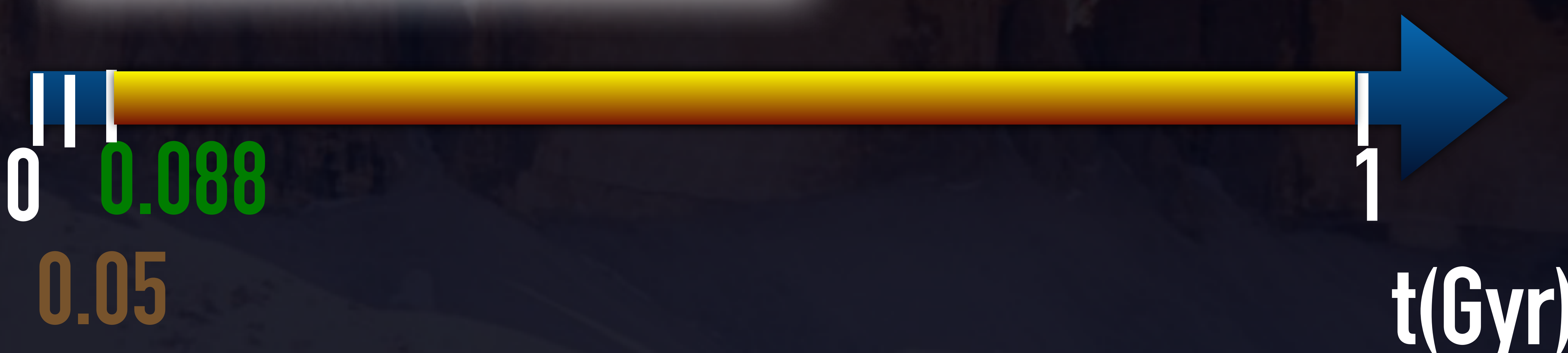
2 different phases

infall from UfD

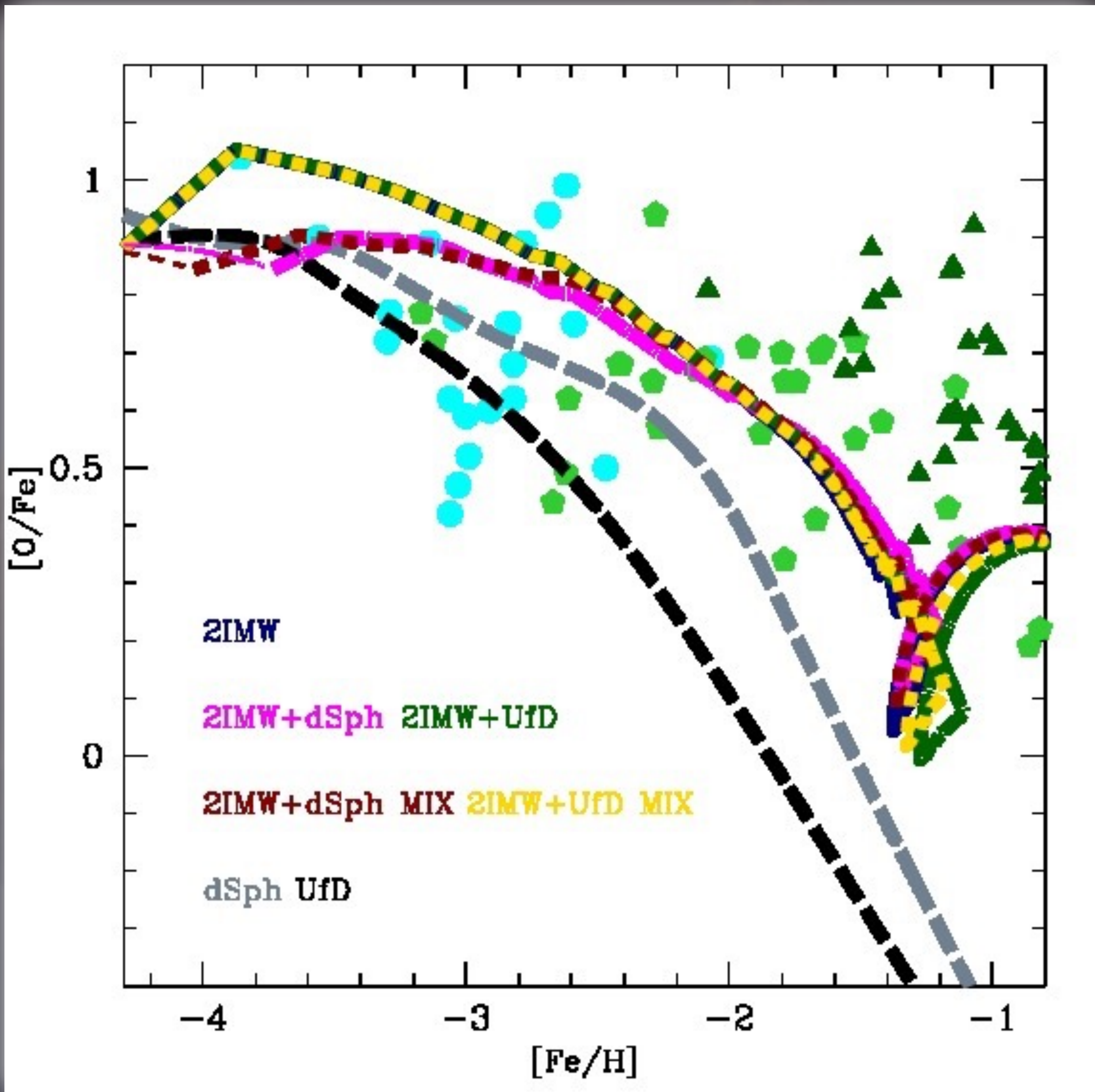
Phase c)
The infall is enriched by UfDs, $t>t_{SFR}(MW_{2IMW})$

t_{gw} (UfD) $=$ 0.088 Gyr

$t_{SFR}(MW_{2IMW})=$ 0.05 Gyr



The chemical evolution of O for the 2IMW, dSph and UfD models and models with enriched infall

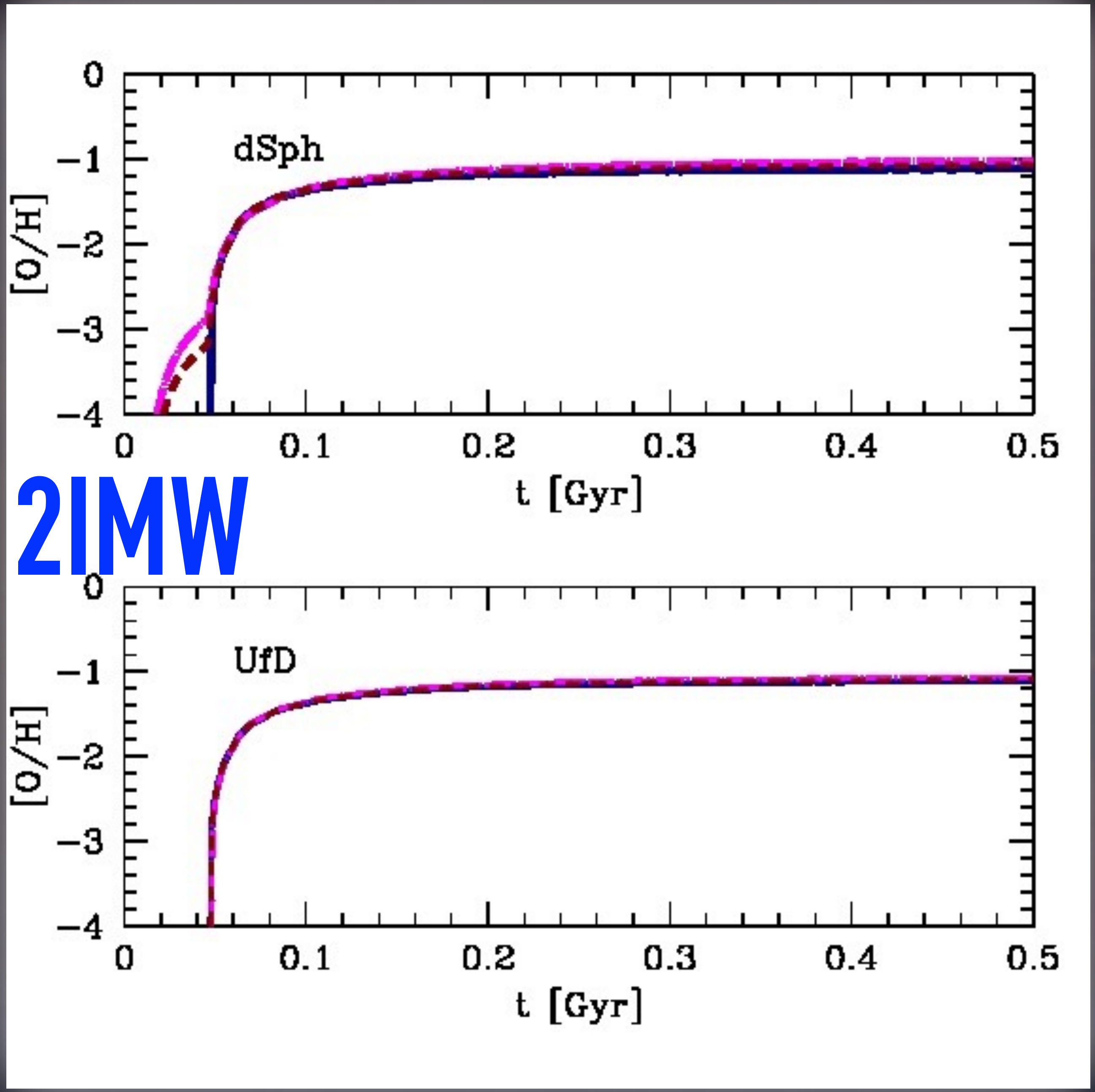


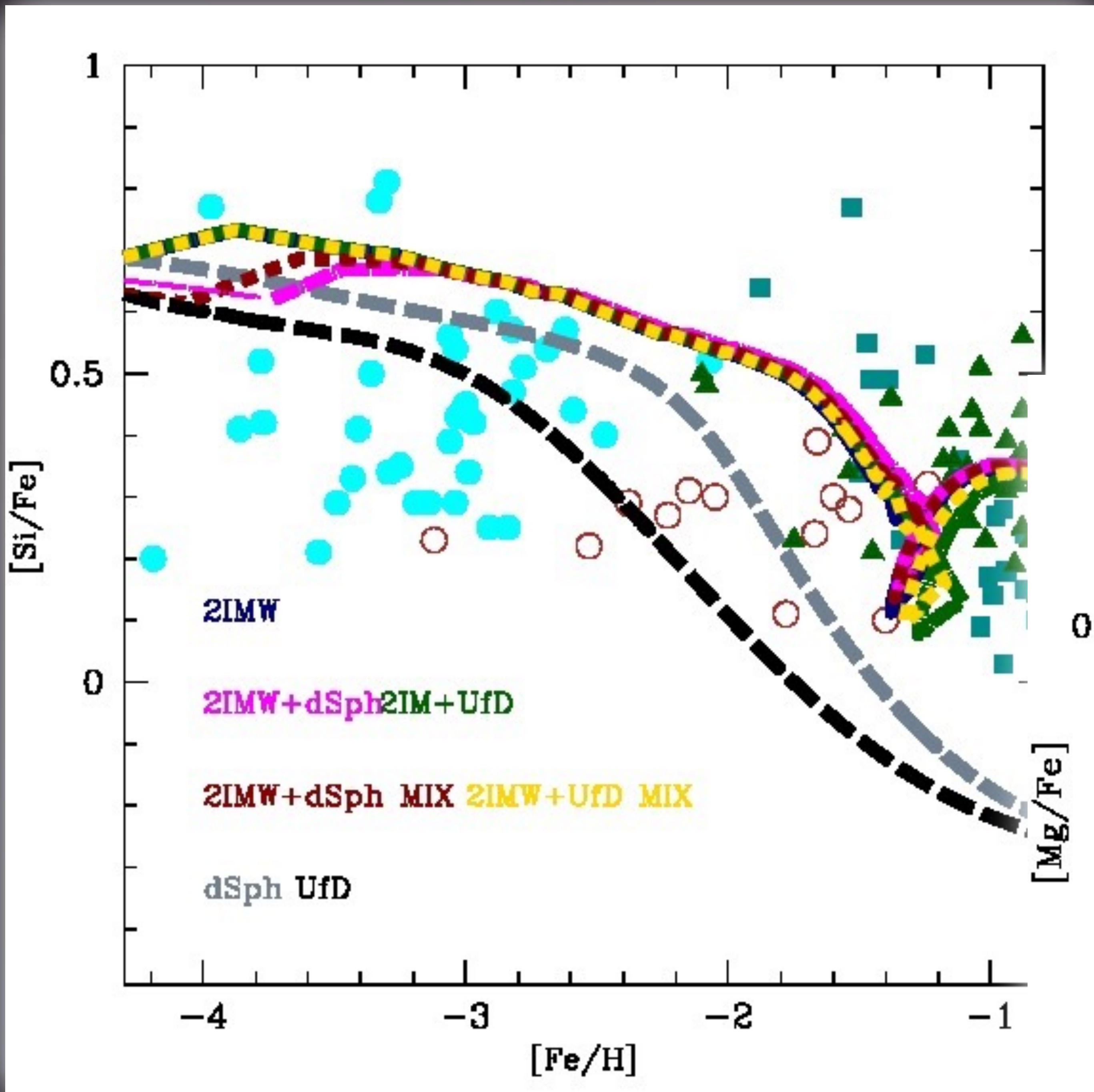
The enriched infall from UfDs (model 2IM)

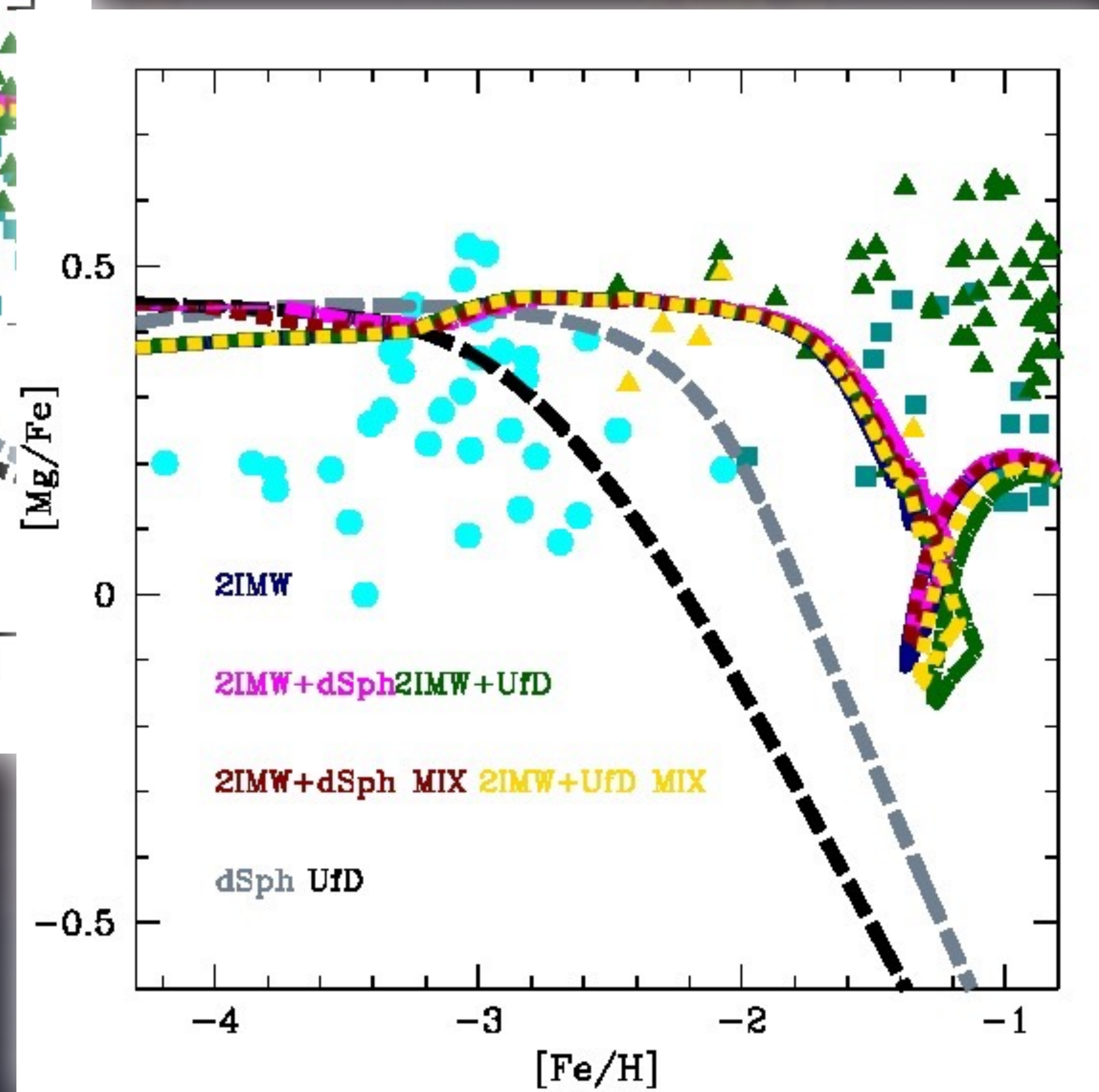
- Models overlap the reference model 2IMW at almost all [Fe/H] abundancies.
- NO PHASE b): The effect of the enriched infall is almost negligible compared to the pollution of chemical elements produced by dying halo stars

The time evolution of [O/H]

The reference model 2IMW shows chemical evolution after t=0.05 Gyr, and we see that for the UfD case the models with enriched infall is almost identical to the reference model 2IMW

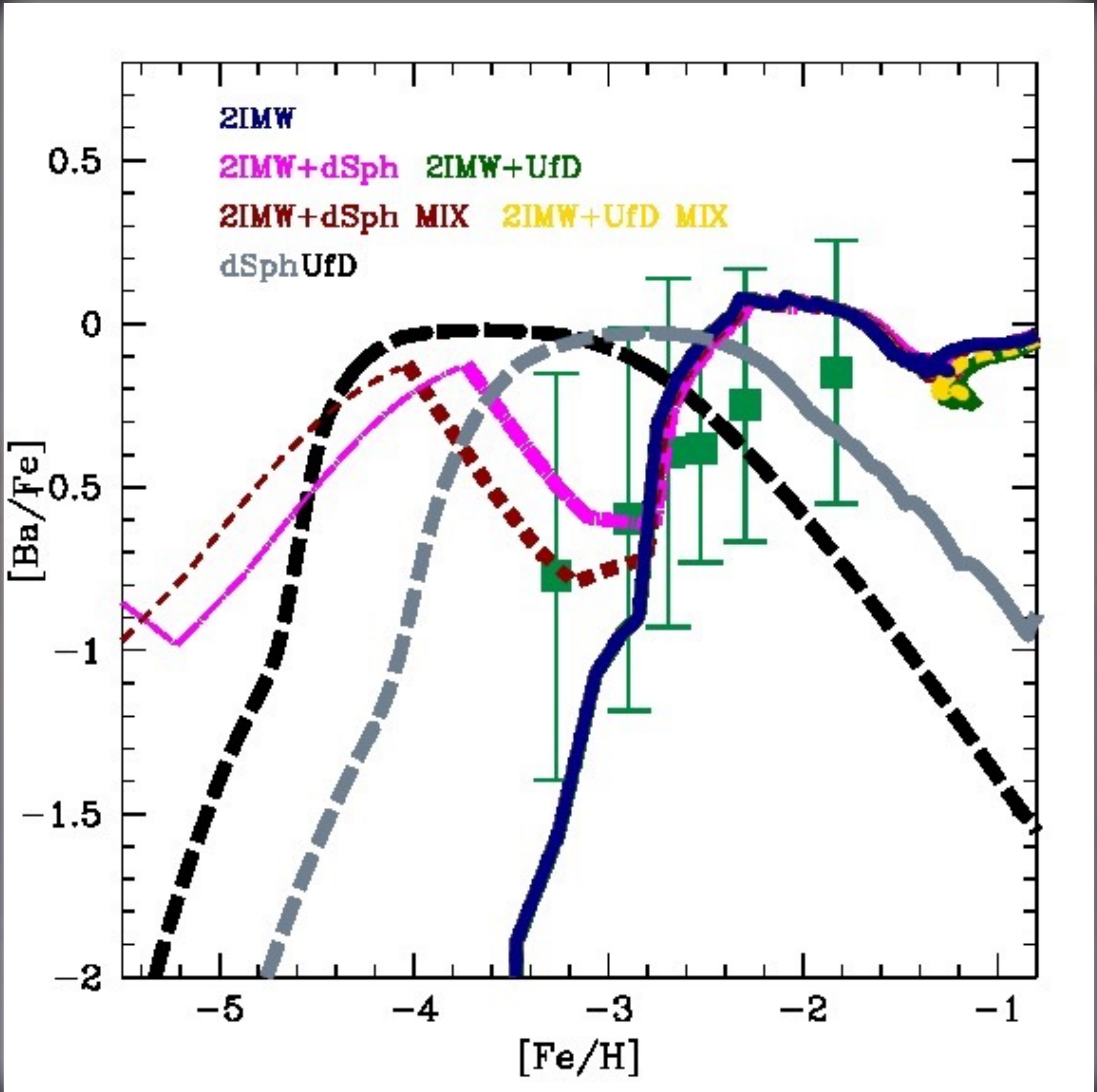



[Si/Fe]
1
0.5
0
−4
−3
−2
−1
[Fe/H]
2IMW
2IMW+dSph
2IM+UfD
2IMW+dSph MIX
2IMW+UfD MIX
dSph
UfD


[Mg/Fe]
0.5
0
−0.5
−4
−3
−2
−1
[Fe/H]
2IMW
2IMW+dSph
2IMW+UfD
2IMW+dSph MIX
2IMW+UfD MIX
dSph
UfD

The hypothesis that all Galactic halo stars were stripped or accreted in the past from dSphs or UfDs is ruled out

The chemical evolution of Ba for the 2IMW models



Ba in MW 2IMW model and dSphs UfDs

- The 2IMW model provides now a better agreement with the observed data than the 2IM model although the predicted [Ba/Fe] ratios at $[Fe/H] < -3$ dex still lie below the observed data
- By assuming an enriched infall from dSph or UfD galaxies, the predicted [Ba/Fe] ratios agree with the observed data also at $[Fe/H] < -3$ dex.

Ba in MW 2IMW model and dSphs UfDs

- The 2IMW model provides now a better agreement wi… ough the… still lie…
- By… fD ga… h the observed data also at [Fe/H] < −3 dex.

In order to reproduce the observed [Ba/Fe] ratios over the entire range of [Fe/H] abundances, a time-dependent enriched infall in the Galactic halo phase is required.

Conclusions

- **dSphs and UfD**: the predicted [α/Fe] versus [Fe/H] abundances deviate substantially from the observed data of the Galactic halo stars only for [Fe/H] $>$-2 dex. For the Ba the chemical evolution models of dSphs and UfDs fail to reproduce them over the whole range

- **MW models with enriched gas infall: A)** [α/Fe] versus [Fe/H] plots depend on the infall time scale for the formation of the halo and the presence of a gas threshold in the star formation. **B)** Stars produced in situ in dSph or UfD objects and accreted later to the Galactic halo are needed to explain the data at lowest [Fe/H].

- The optimal element to test different theories of halo formation is barium since it is different at low metallicity in different galaxies

Conclusions

- C … e
su …] >-2 dex.
Fo … ce them over
the whole range

We rule out the hypothesis that all Galactic halo stars were stripped or accreted in the past from dSphs or UfDs

- **MW models with enriched gas infall: A)** [α/Fe] versus [Fe/H] plots depend on the infall time scale for the formation of the halo and the presence of a gas threshold in the star formation. **B)** Stars produced in situ in dSph or UfD objects and accreted later to the Galactic halo are needed to explain the data at lowest [Fe/H].

- The optimal element to test different theories of halo formation is barium since it is different at low metallicity in different galaxies