Simulating the Chemical Responses to Starbursts

James W. Johnson

University of California at Santa Cruz IMPS Seminar

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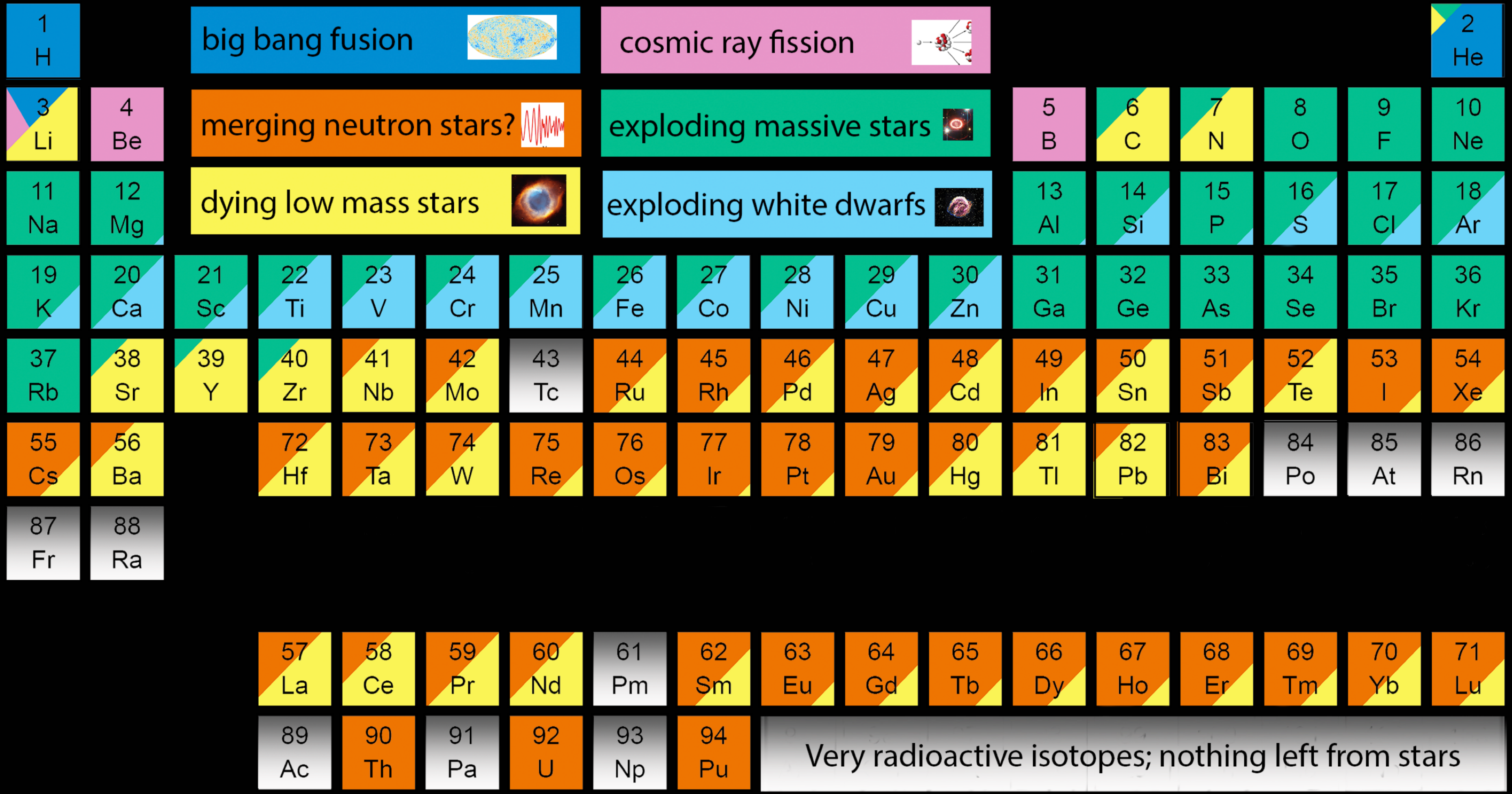
THE OHIO STATE UNIVERSITY

The Origin of the Solar System Elements



Graphic created by Jennifer Johnson
http://www.astronomy.ohio-state.edu/~jaj/nucleo/

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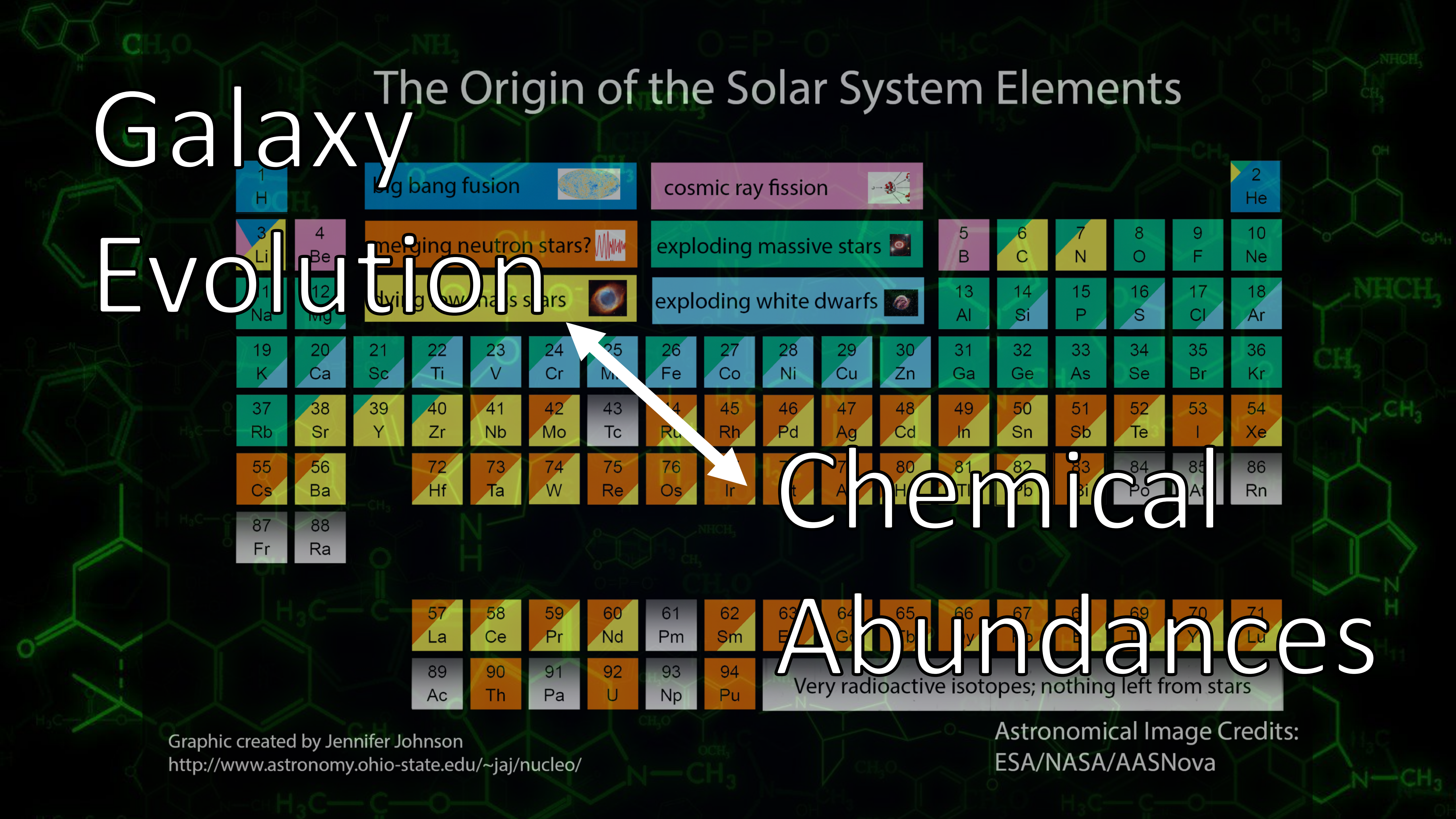
Galaxy Evolution
Chemical Abundances
The Origin of the Solar System Elements
big bang fusion
cosmic ray fission
merging neutron stars?
exploding massive stars
dying low mass stars
exploding white dwarfs
Very radioactive isotopes; nothing left from stars
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The Single-Zone Approximation

Fundamental Assumption: Spatial Homogeneity

- Eliminates need for N-body by construction
- Star formation, gas distribution, etc. all uniform
- Instantaneous mixing of metals in ISM gas
- Accuracy/sophistication vs. computational expense

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Adopt models for nucleosynthetic yields, SNe Ia delay-time distribution, star formation efficiency, etc.

- Initial value problem solved numerically with timestep algorithm

The Single-Zone Approximation

For a Given Element x

$$\dot{M}_x = \dot{M}_{CC} + \dot{M}_{Ia} + \dot{M}_{AGB} - Z_x\dot{M}_* - \xi_{enh} Z_x \dot{M}_{out} + \dot{M}_r + Z_{x,in}\dot{M}_{in}$$

Gas Supply & Star Formation

$$\dot{M}_{gas} = \dot{M}_{in} - \dot{M}_* - \dot{M}_{out} + \dot{M}_r$$

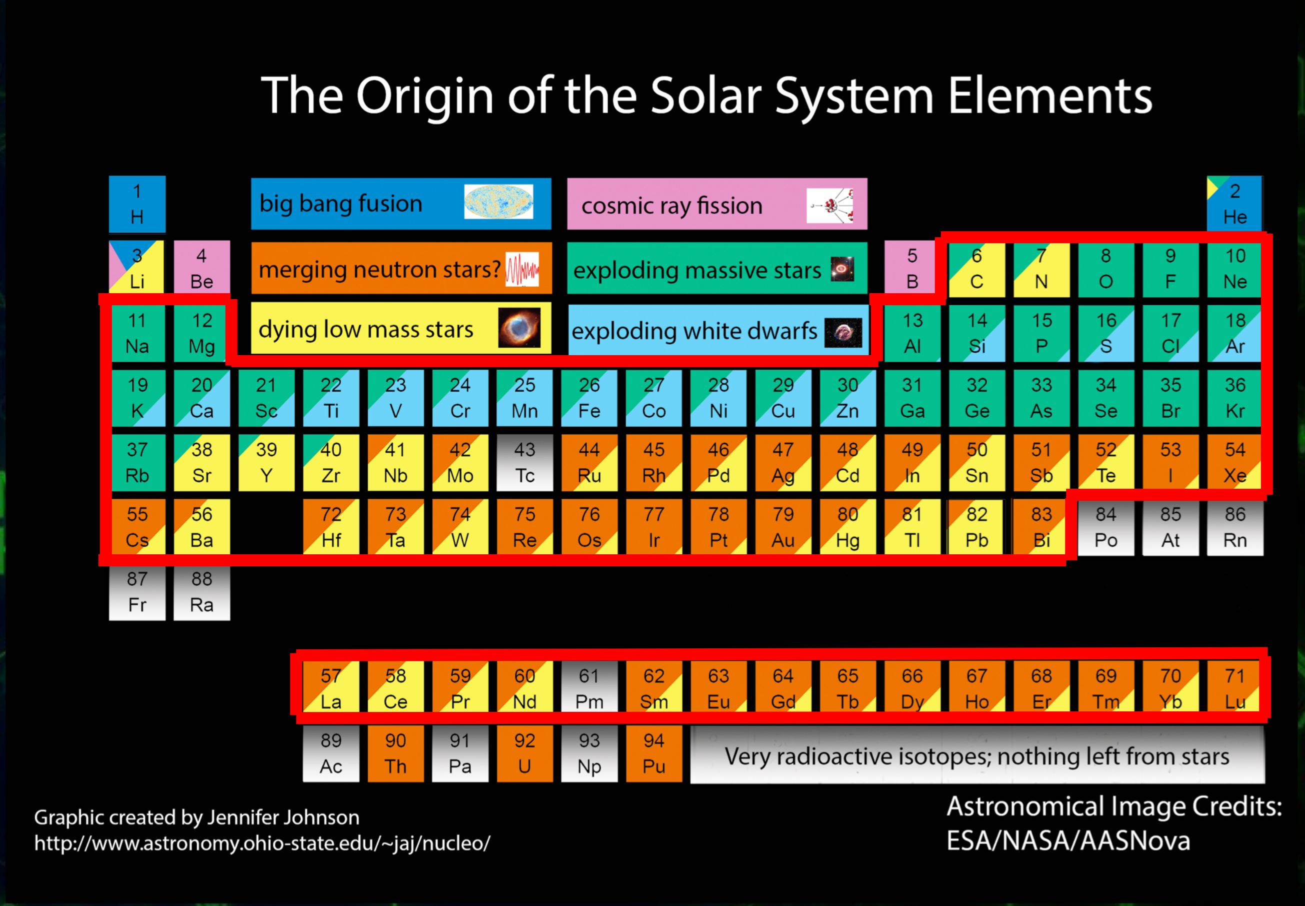
$$\dot{M}_* = M_{gas}\tau_*^{-1}$$

VICE: Versatile Integrator for Chemical Evolution

Python package built for running these simulations

Allows functions of time for many parameters

User-specified yields from CCSNe and SNe Ia



https://github.com/giganano/VICE.git

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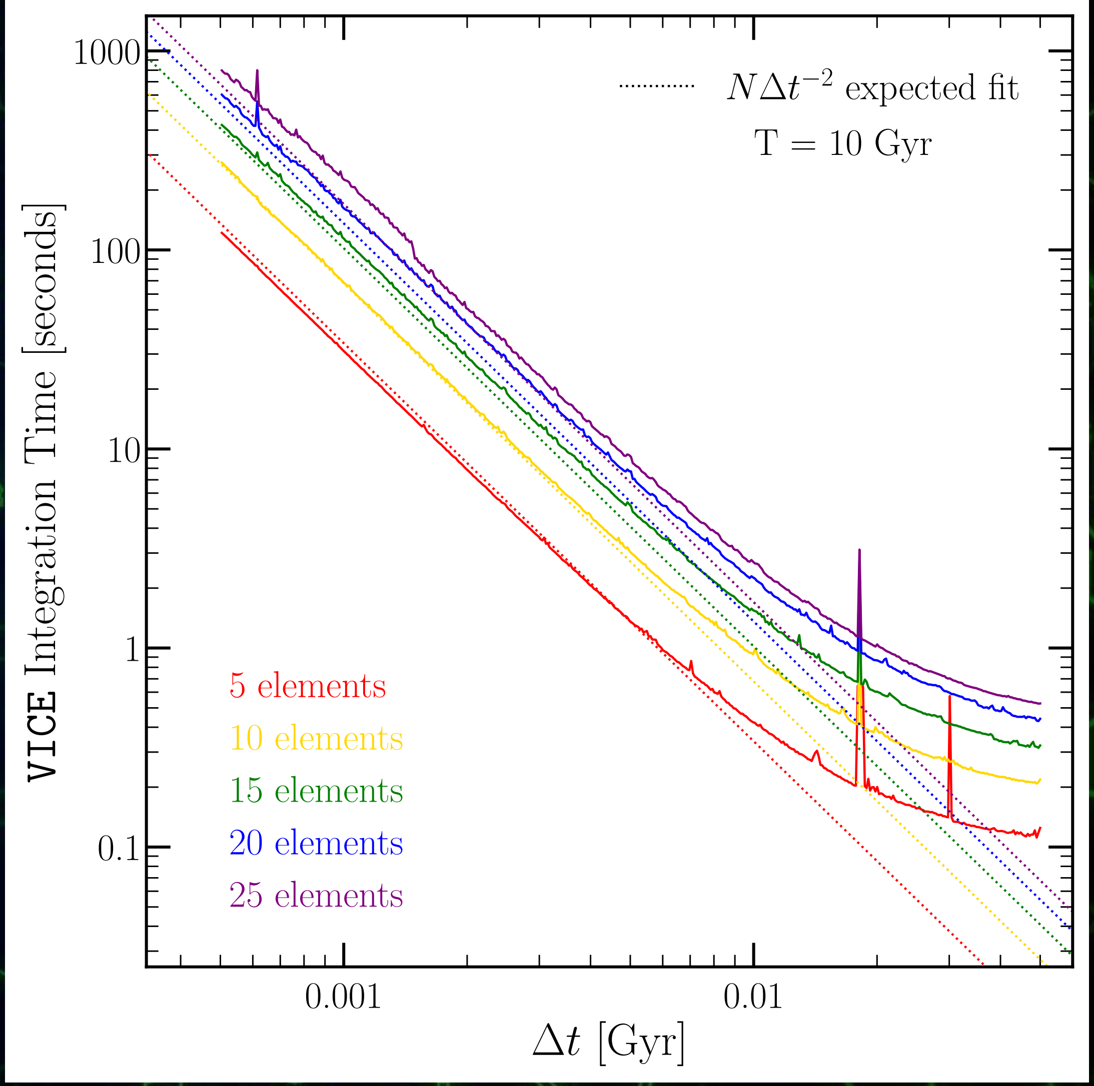
Bonus: implemented in C



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Simulating Starburst Scenarios

VICE allows arbitrary functions of time to describe evolutionary parameters

- Perfect for simulating highly non-linear parameter spaces

David Weinberg (OSU)
The Impact of Starbursts on Element Abundance Ratios
(Johnson & Weinberg 2019, in prep)

Simulating Starburst Scenarios

VICE allows arbitrary functions of time to describe evolutionary parameters

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Some Initial Questions

- How does a given abundance respond to different modes of starbursts?
- How do similar starbursts affect different elements? (Here: O, Fe, Sr)

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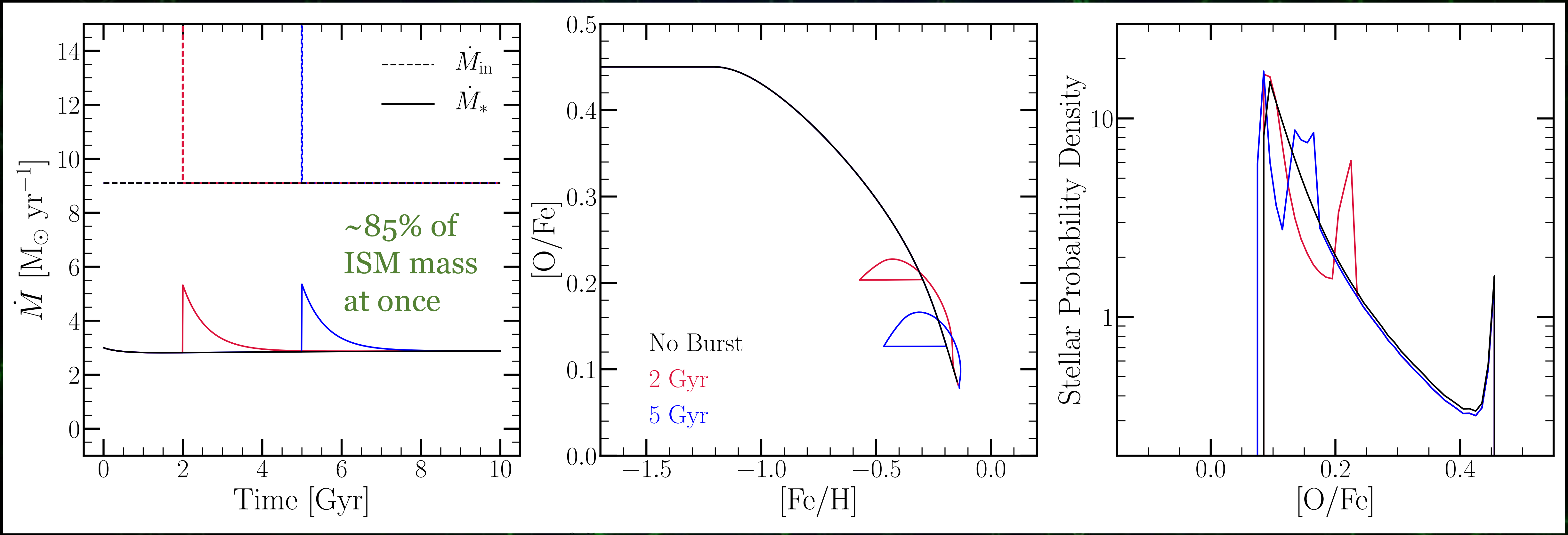
Fiducial Starburst Models

Gas-Driven: short-timescale changes to the gas supply
Tracks driven by lag between CCSNe and SNe Ia



Fiducial Starburst Models

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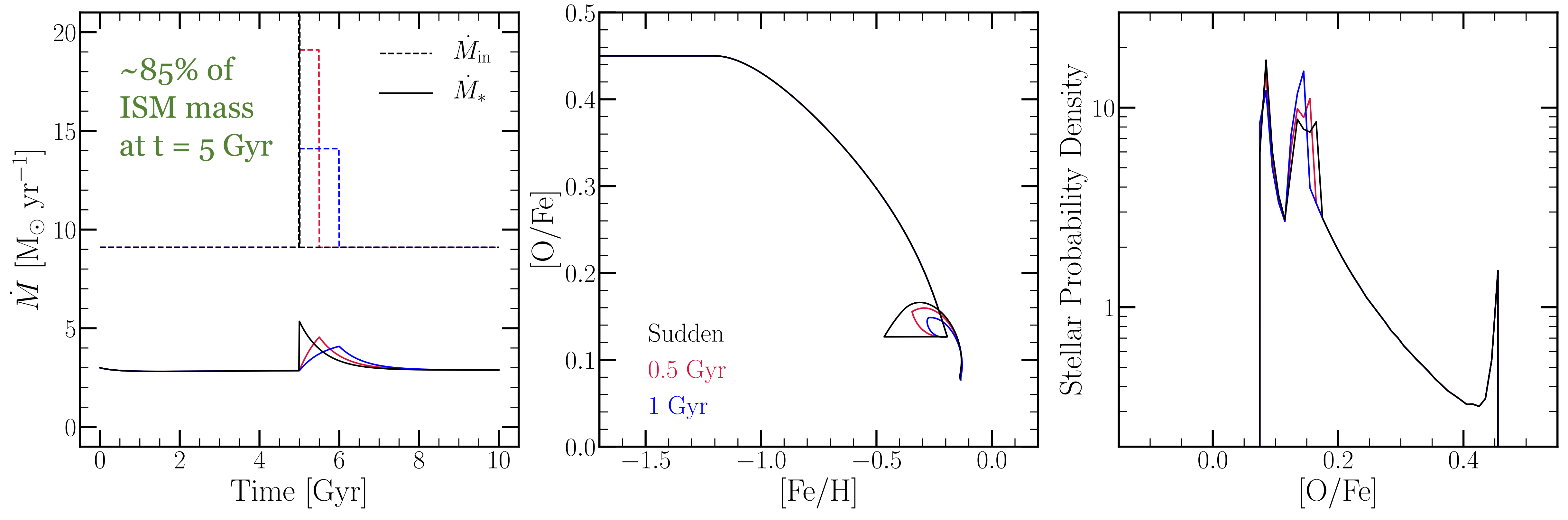
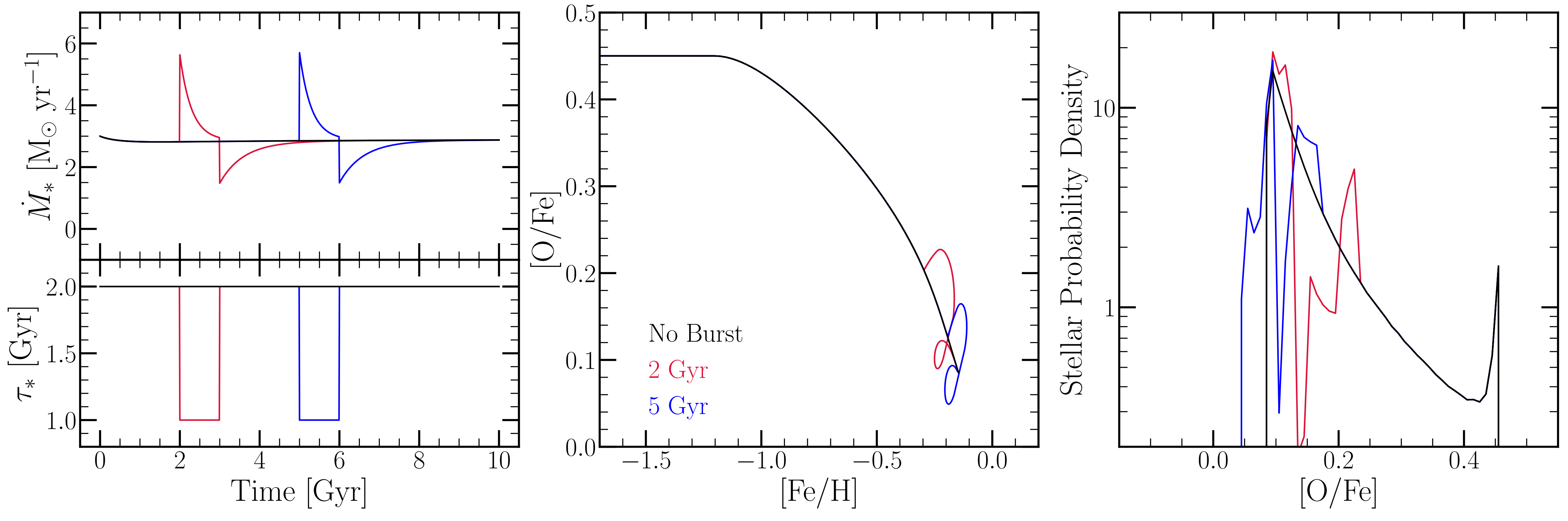


Fiducial Starburst Models

Efficiency-Driven: short-timescale changes to star formation efficiency

Tracks again driven by lag between CCSNe and SNe Ia



Delayed Outflows

Motivation

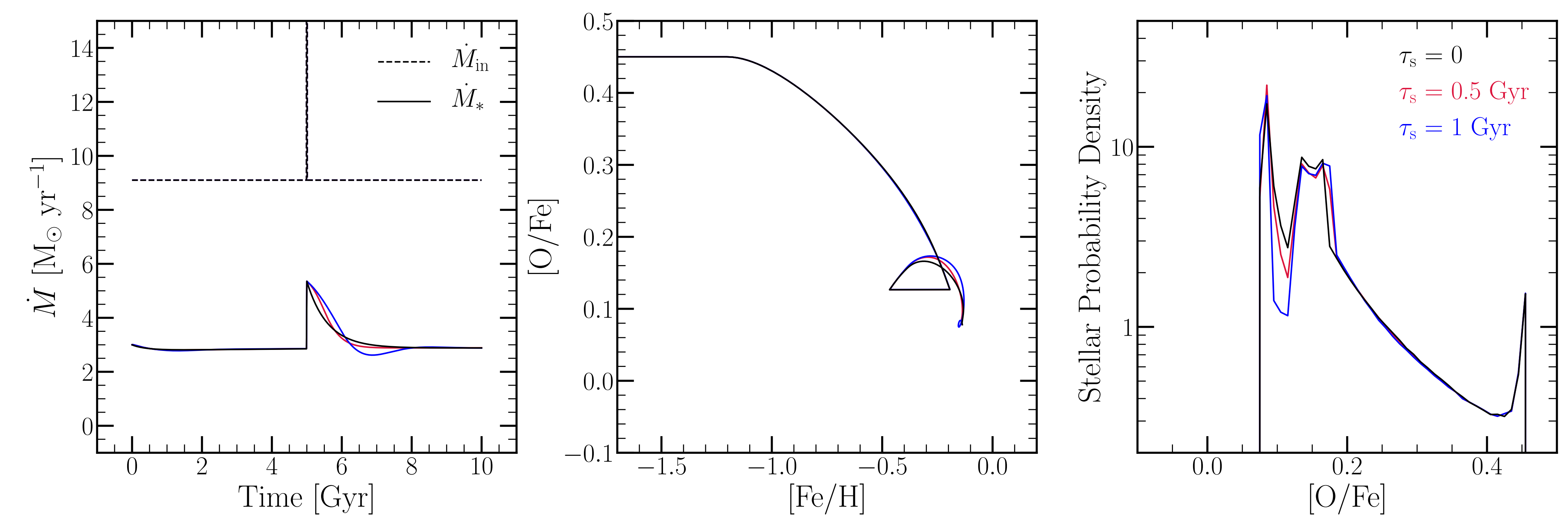
- What if outflows are sensitive to previous generations of stars?
  - SNe Ia contribute? Then $\tau_s \sim 1$ Gyr?
- Introduce new parameter: smoothing time

$$\dot{M}_{out} = \eta(t)\langle \dot{M}_* \rangle_{\tau_s} = \frac{\eta(t)}{\tau_s}\int_{t-\tau_s}^{t} \dot{M}_*(t')dt' \rightarrow \eta(t)\,\dot{M}_*\ (\tau_s = 0)$$

Delayed Outflows

Gas-Driven Scenario

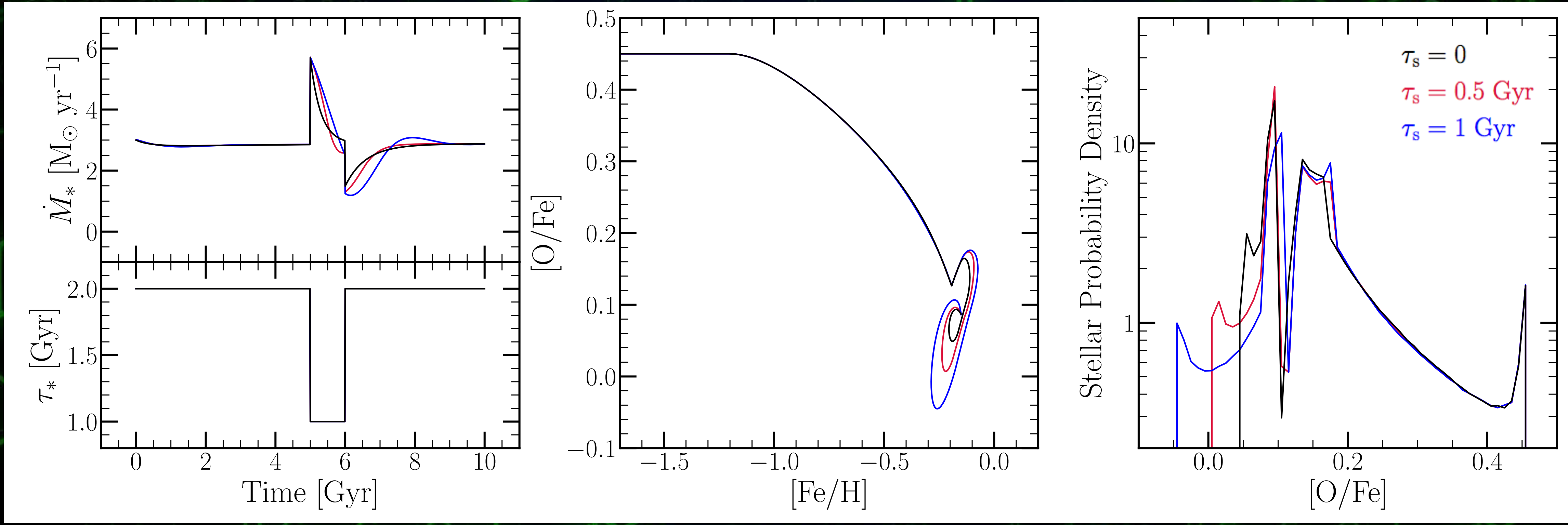
- Delayed outflow => more stars at onset => higher [O/Fe]
- Subtle - likely within observational errors



Delayed Outflows

Efficiency-Driven Scenario: α poor stars

- Period of slow star formation w/ongoing SNe Ia, strong outflows

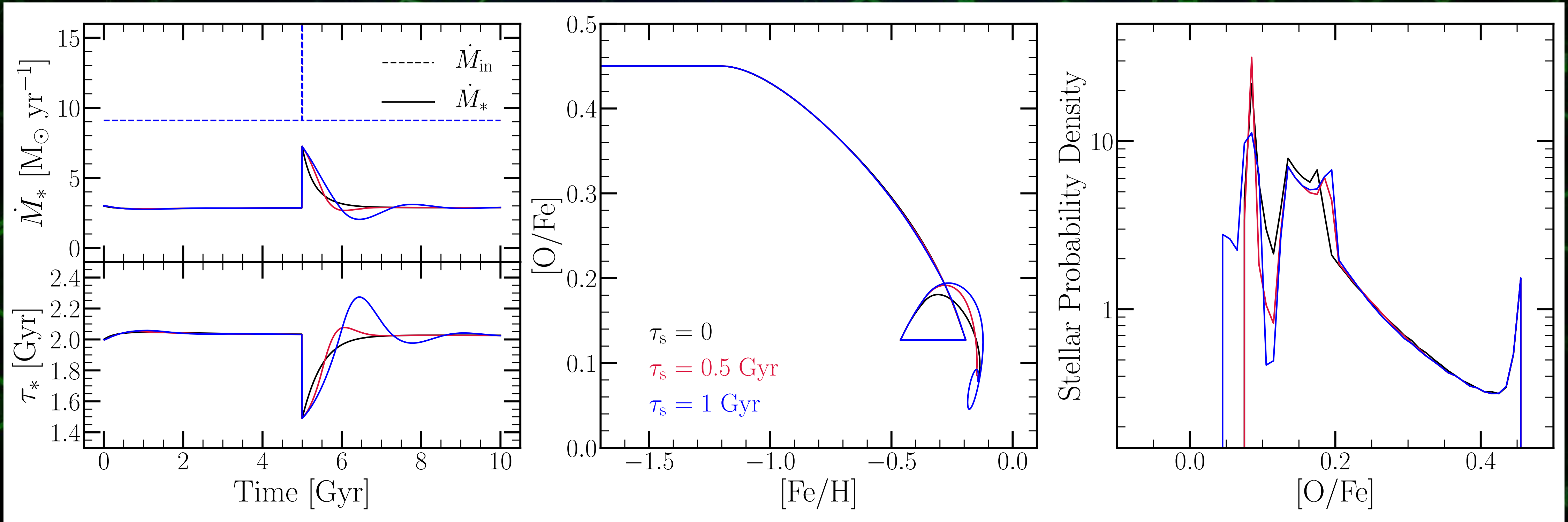


Hybrid: Kennicutt-Schmidt

$$\dot{M}_* \propto \Sigma_g^N \Rightarrow M_g \tau_*^{-1} \propto \Sigma_g^N \Rightarrow \tau_*^{-1} \propto \Sigma_g^{N-1}$$

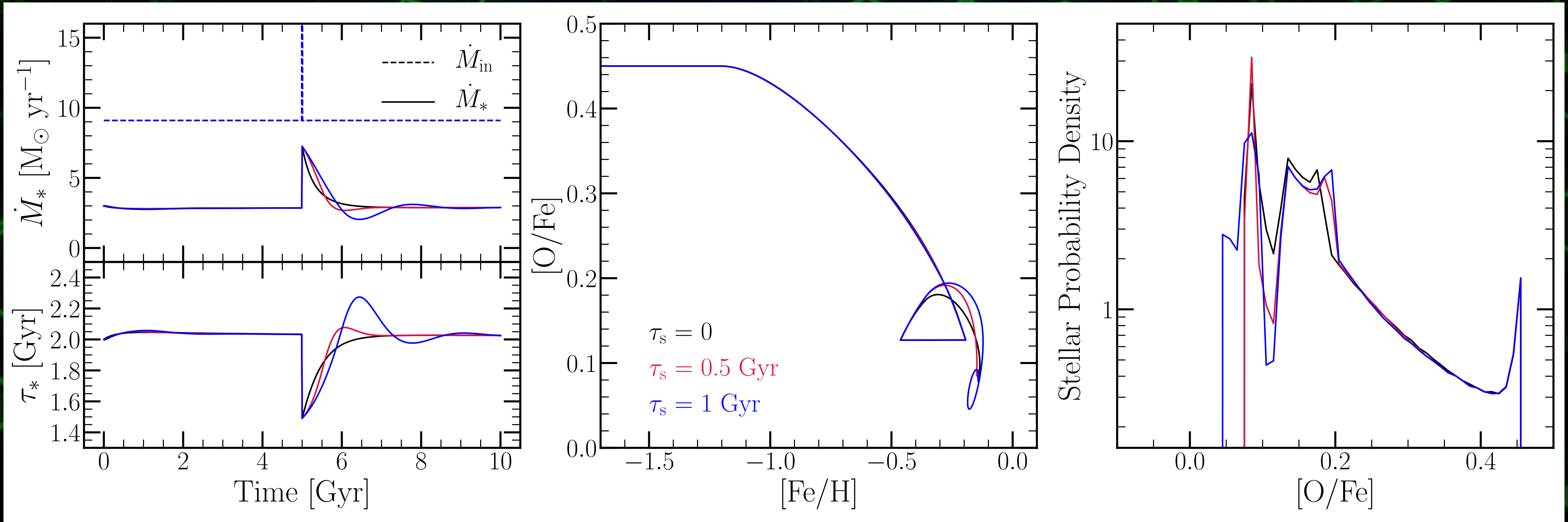
$N = 1.4 \pm 0.15$ (Schmidt 1959, 1963; Kennicutt 1989, 1998)

$$\text{Here: } \tau_*^{-1} = (2\ Gyr)^{-1} \left(\frac{M_g}{6.0\times10^9\ M_\odot} \right)^{0.5}$$



Hybrid: Kennicutt-Schmidt

Gas-driven simple starburst also produces α-poor stars when $\tau_s \gtrsim 1$ Gyr



Hybrid: Kennicutt-Schmidt

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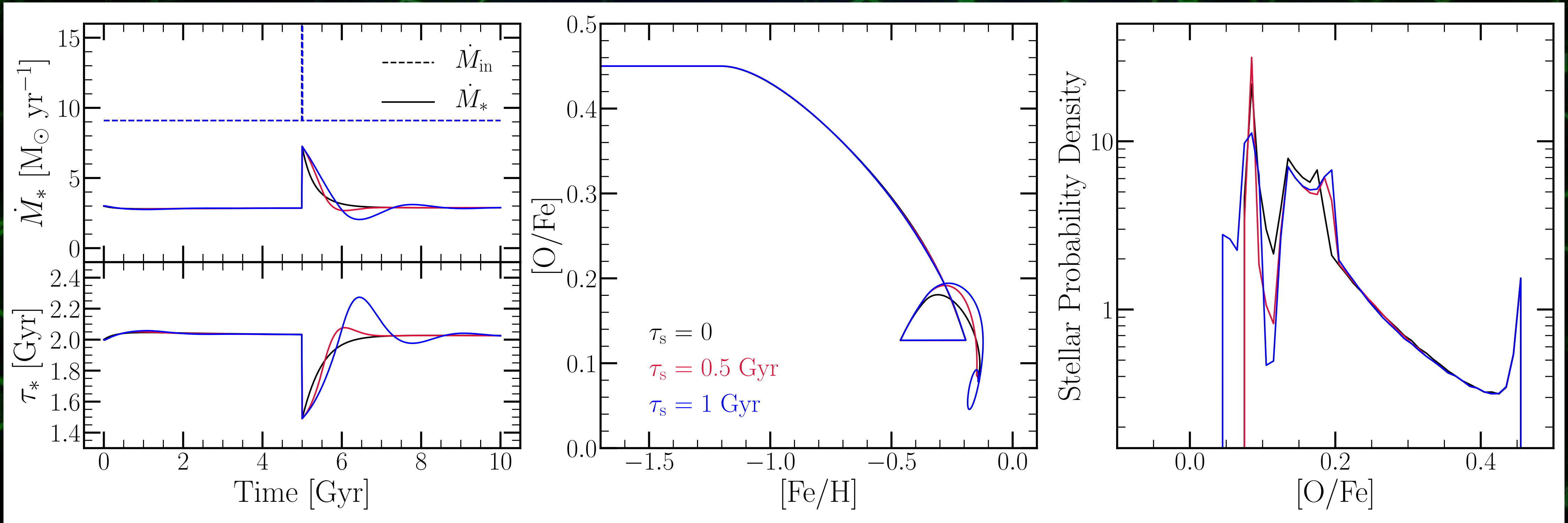
If SNe Ia contribute to winds => τ_s could be important



Strontium: An s-process Element

[Sr/Fe] ≈ 0 for…

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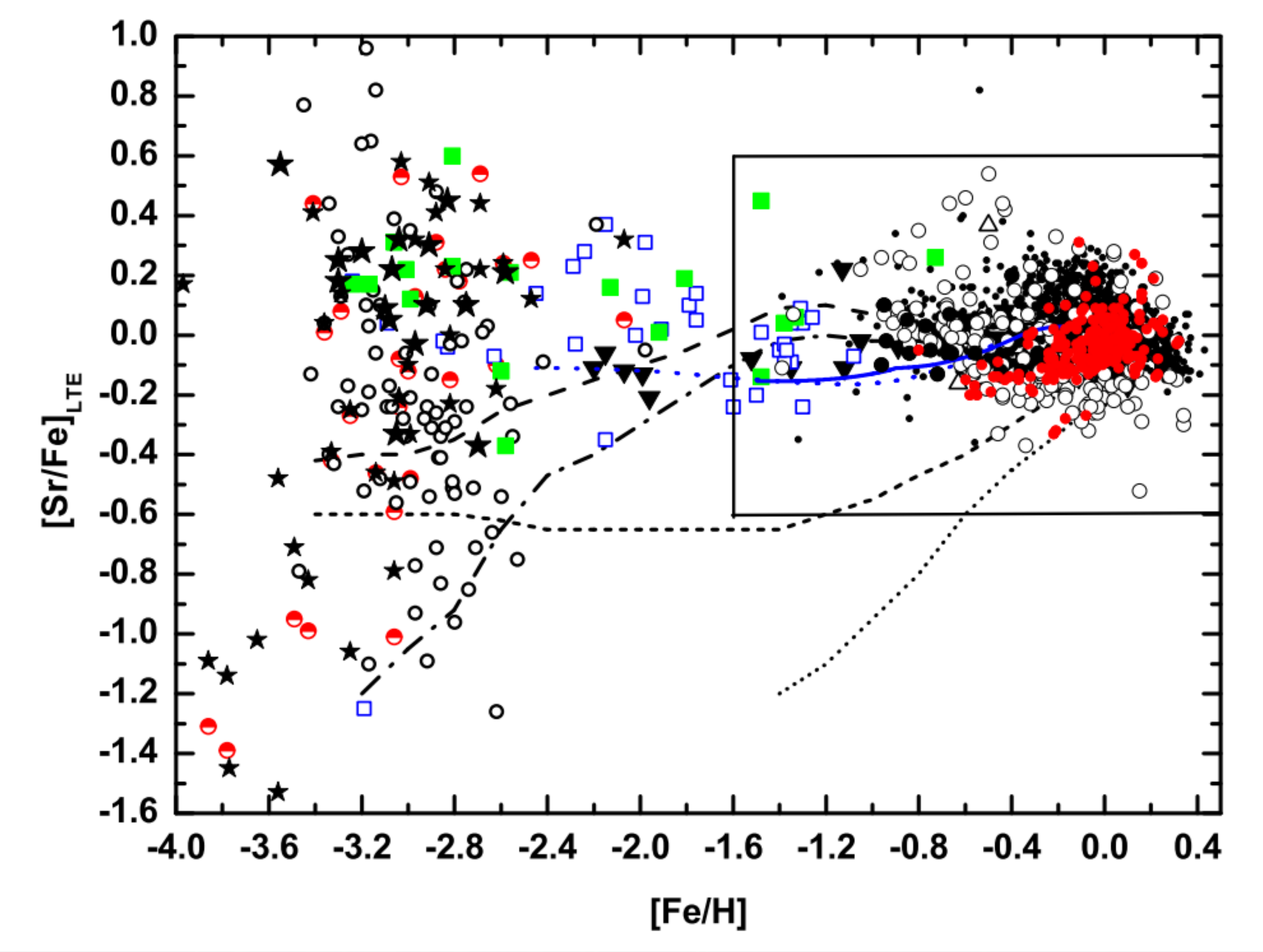
- 276 galactic disk stars

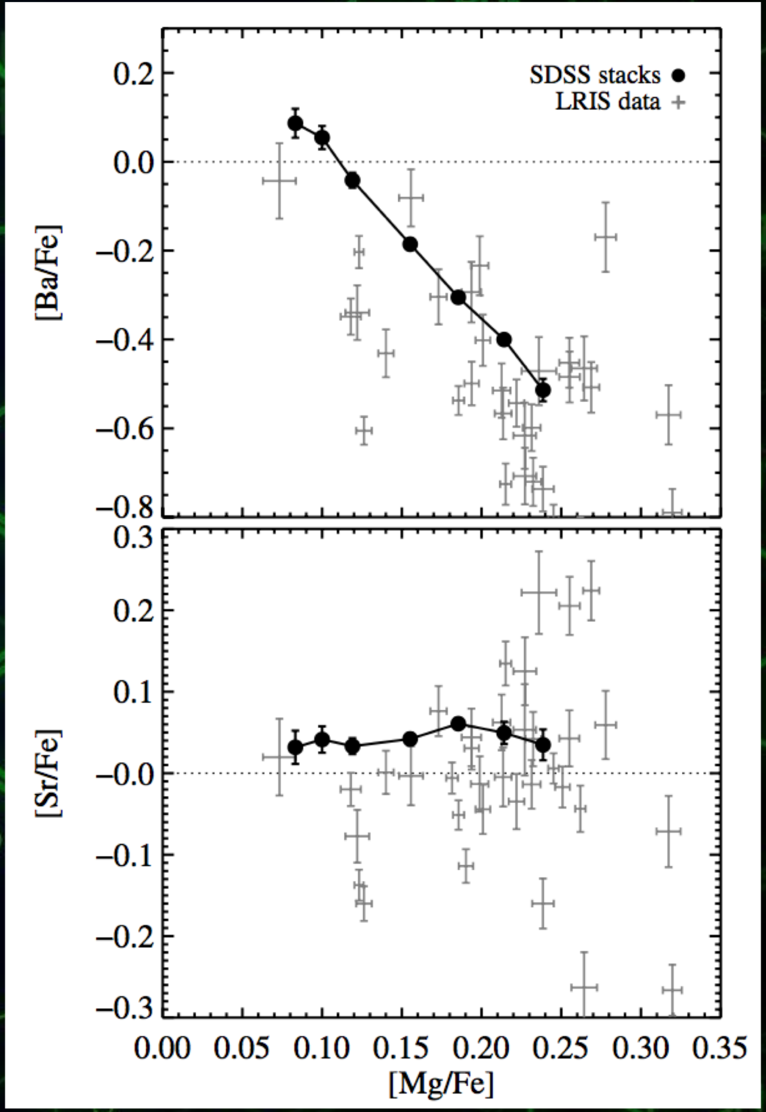


(Figure 8) Mishenina et al. (2019), MNRAS, 484, 3846

Strontium: An s-process Element

[Sr/Fe] ≈ 0 for…

- 276 galactic disk stars
- 34 ETGs
- SDSS stacks (0.02 < *z* < 0.06)



(Figure 4) Conroy, van Dokkum & Graves (2013), ApJL, 763, 25

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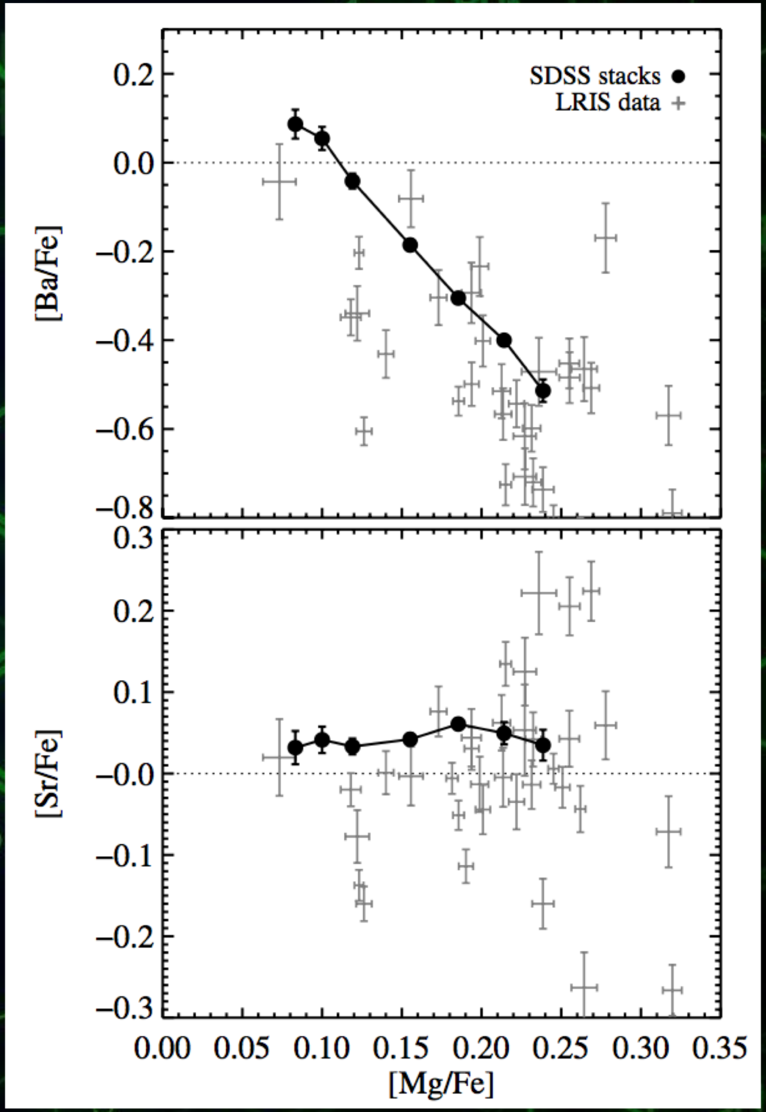
Is this universal?

Different nucleosynthetic origins from Ba. What about Y and Zr?



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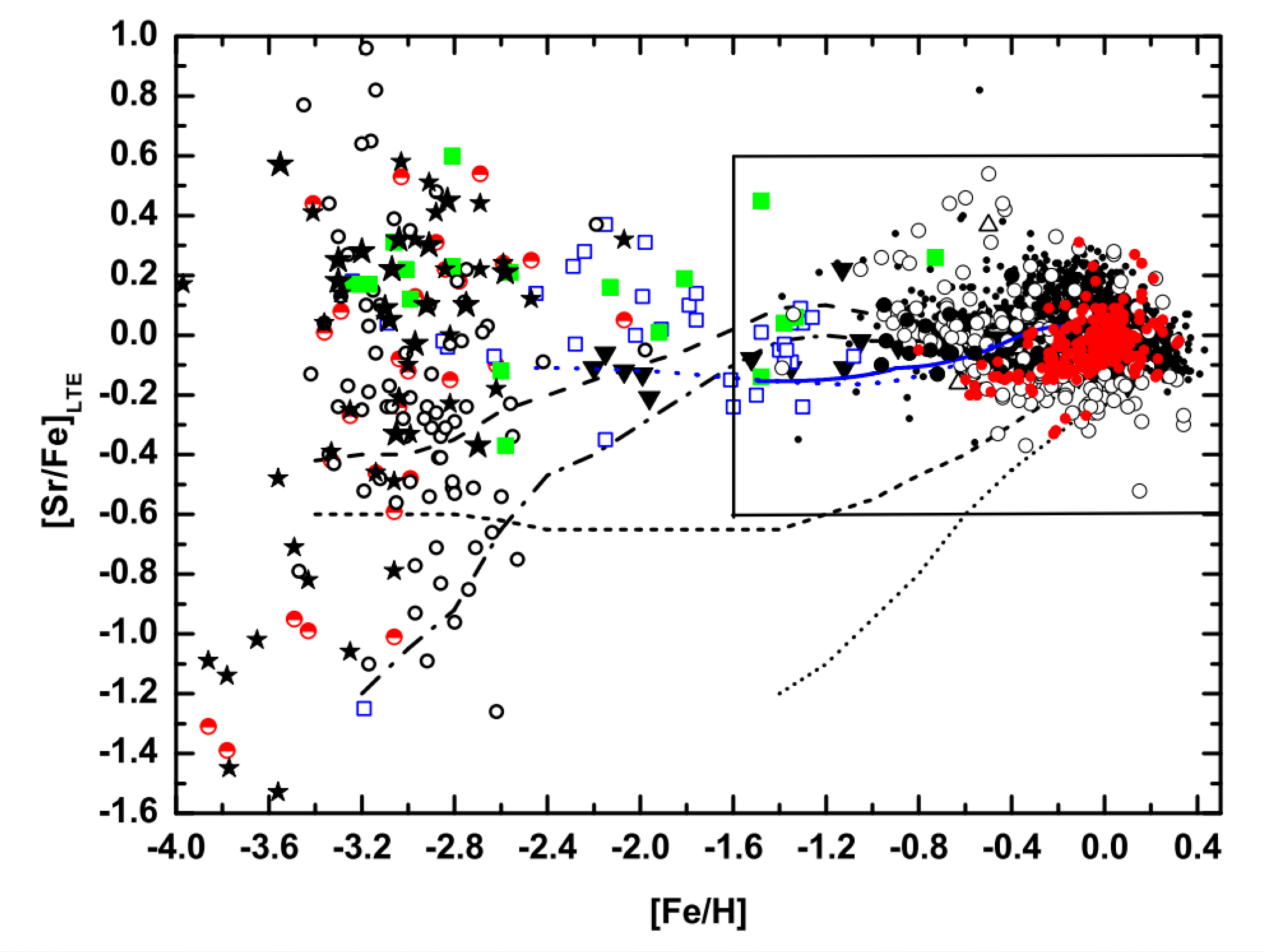
Small r-process contribution to blame for scatter at $[Fe/H] \lesssim -2$?



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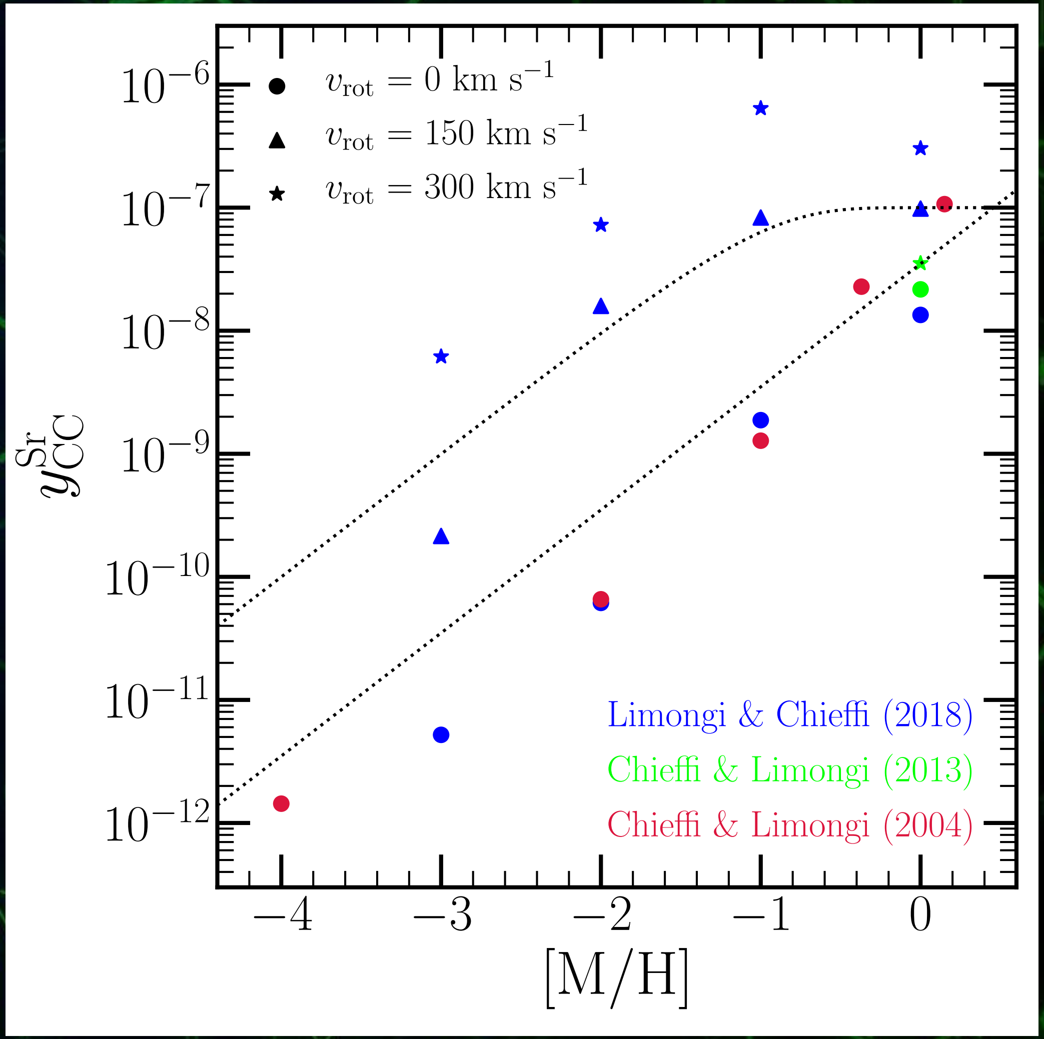
Strontium: An s-process Element

Sources: CCSNe, AGB stars

- Small r-process contribution at [Fe/H] $\lesssim -2$? (Mishenina+ 2019)

Yields from CCSNe depend strongly on Z

- Not the case for oxygen



Strontium: An s-process Element

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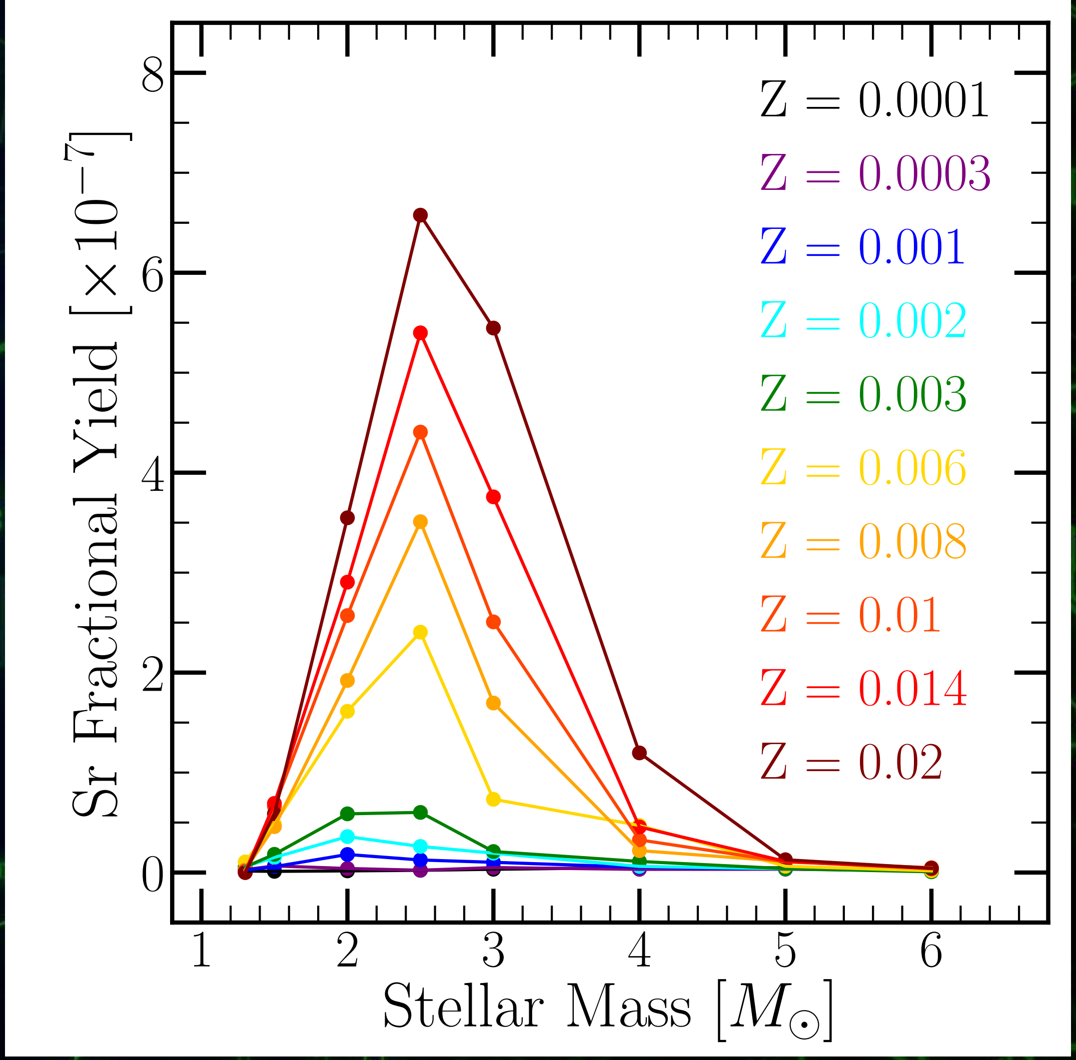
- Small r-process contribution at [Fe/H] $\lesssim -2$? (Mishenina+ 2019)

Yields from AGB stars also depend strongly on Z

- Cristallo et al. (2011) (FRANEC)
- Noticeable jump at $Z \approx 0.004$



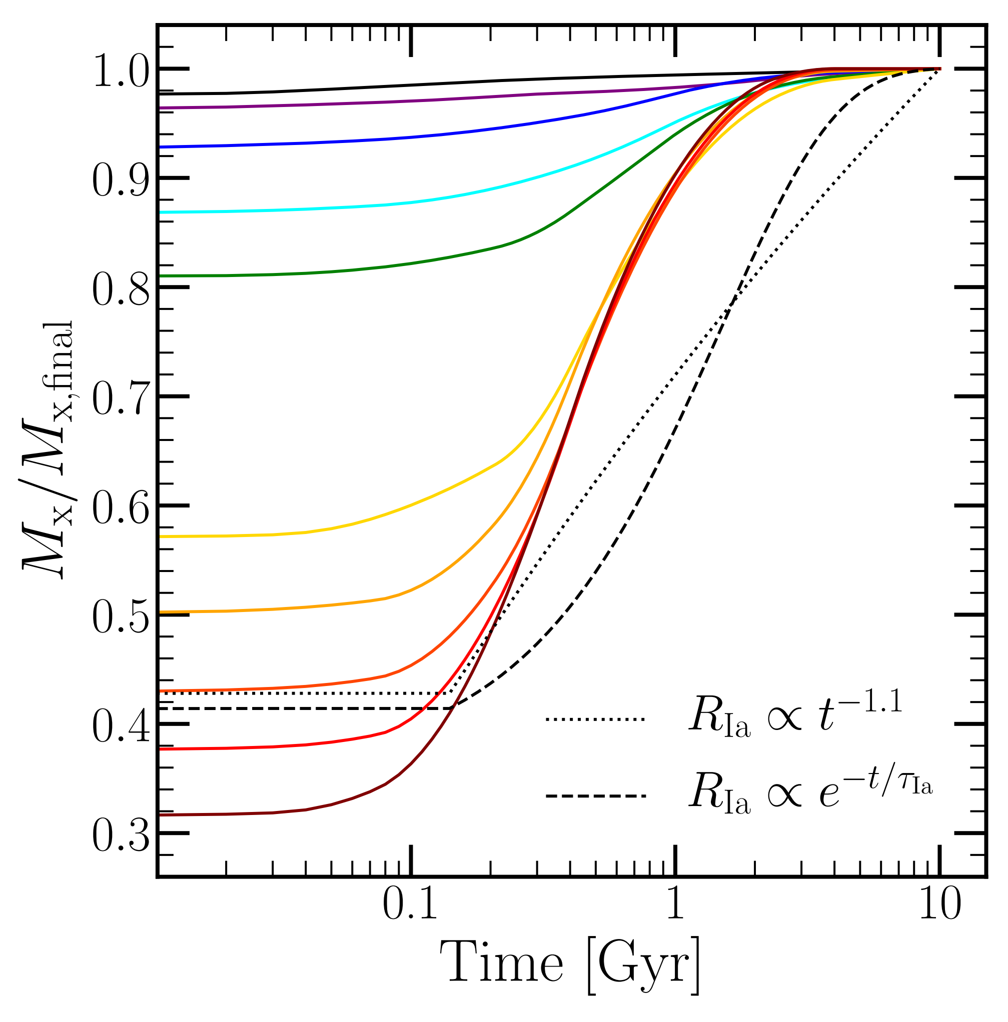
Strontium: An s-process Element

From a Single Stellar Population

- Constant y_{CC}^{Sr} for now

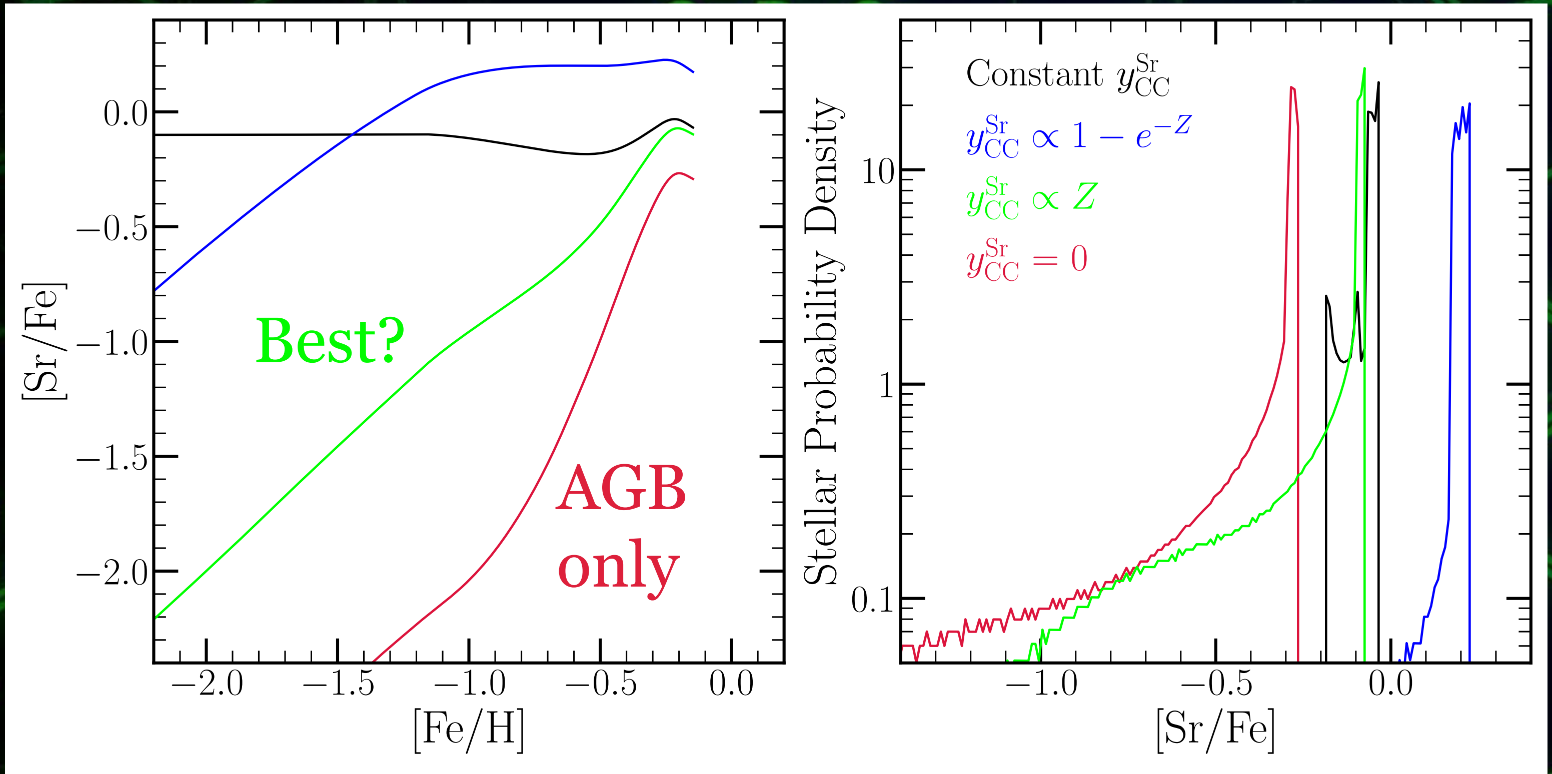
Sr produced before Fe at all Z

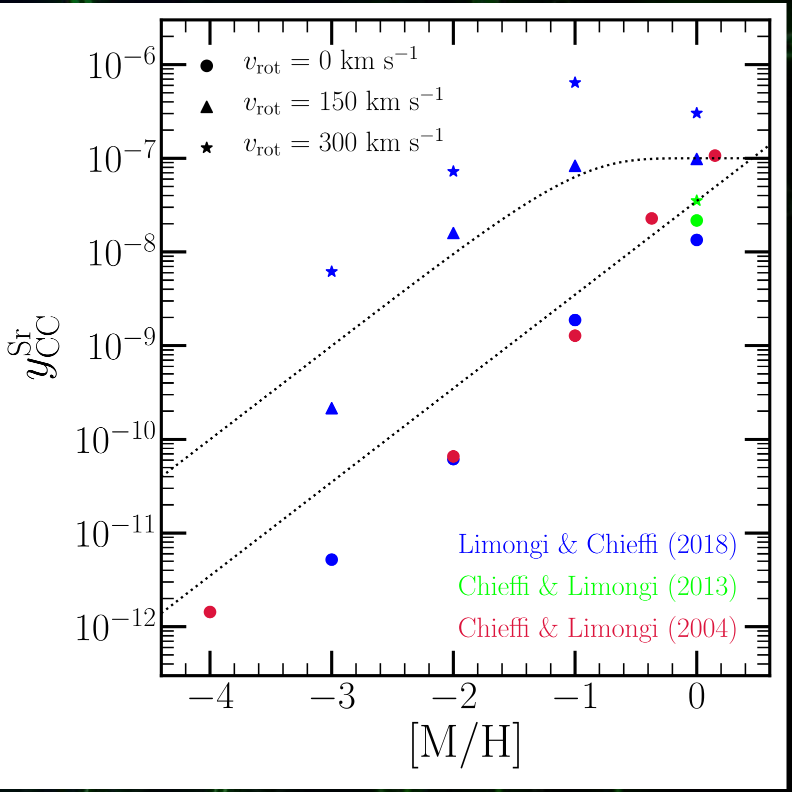
Qualitatively resembles Fe with exponential R_{Ia}



Strontium: An s-process Element

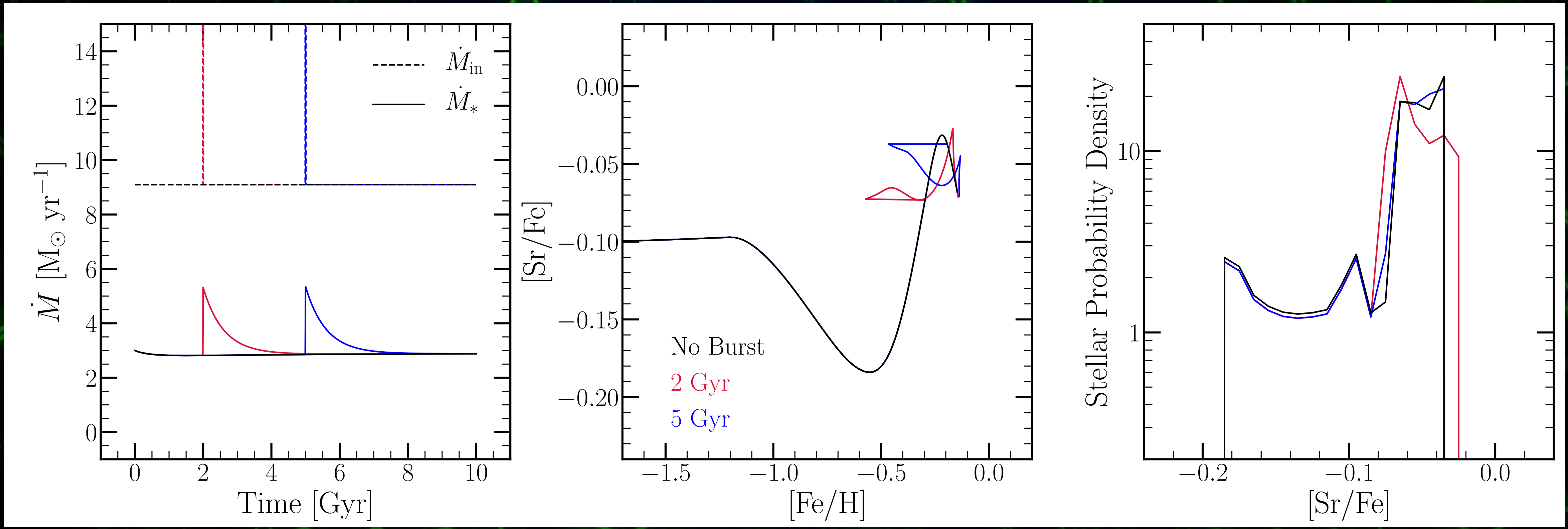
Two regimes: CCSNe @ [Fe/H] $\lesssim -0.5$; AGB otherwise





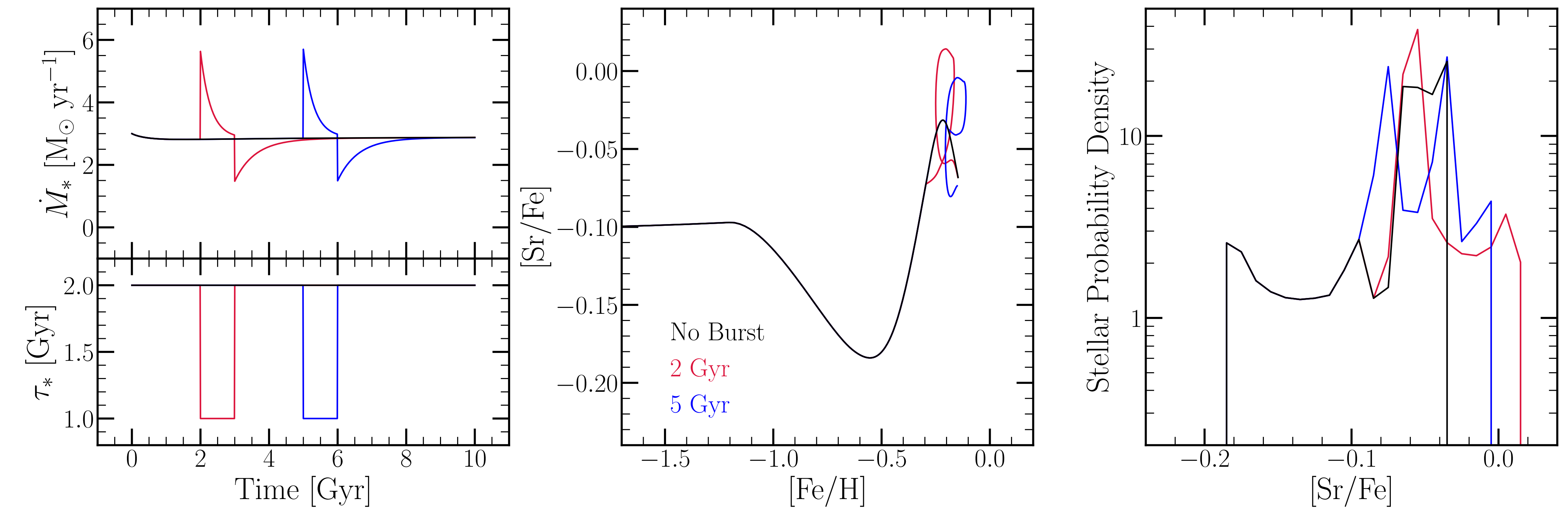
Fiducial Starbursts: Now with Strontium

Gas-Driven: Galaxy must re-enrich before Sr yields from AGB stars return to their pre-burst values



Fiducial Starbursts: Now with Strontium

Efficiency-Driven: No re-enrichment necessary => Sr yields from AGB stars increase immediately following onset



Conclusions from Starburst Simulations

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  - Produce bimodal [α/Fe] due to delayed onset of SNe Ia associated with the starburst
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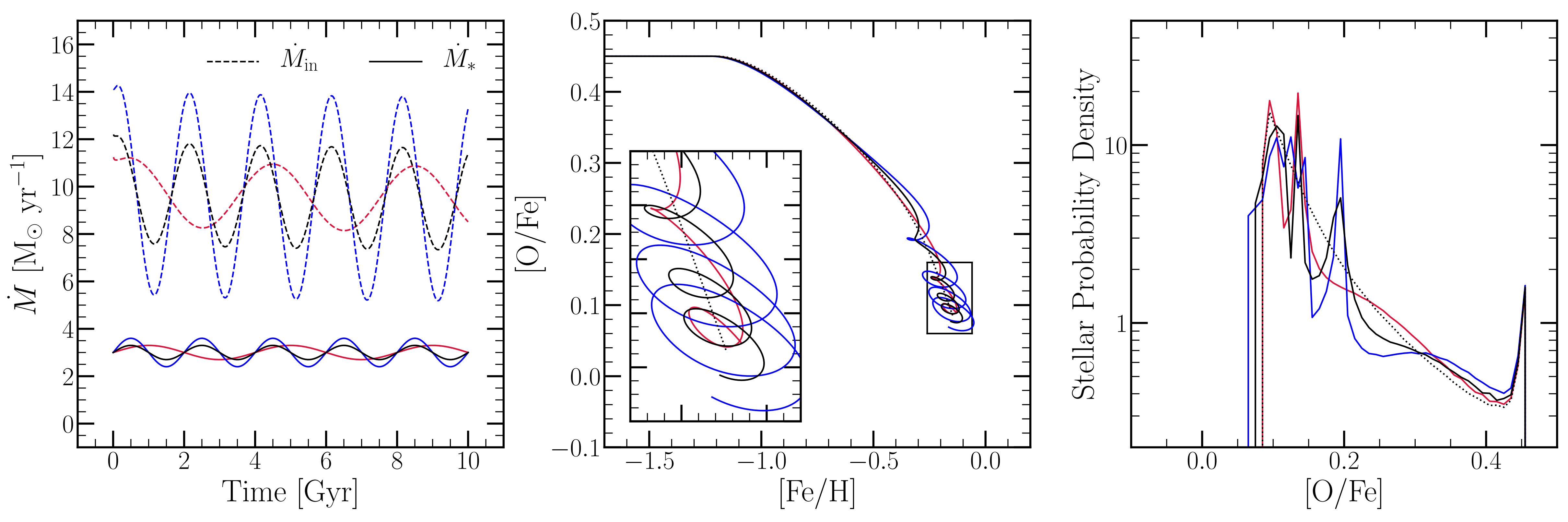
  - [Sr/Fe] $\approx$ 0 => Observations contain little if any information
  - Nonetheless simulations tell us a lot about s-process/Z-dependent yields

Oscillatory Evolution

A potentially real effect introducing physical scatter

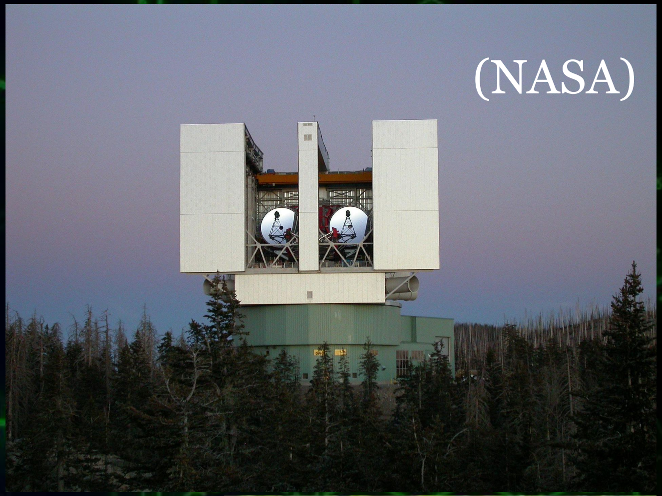
Does not explain bimodality in Milky Way [α/Fe]



Moving Forward: Modeling with VICE

CHemical Abundances Of Spirals (CHAOS)

- ~Dozen low-redshift star-forming spirals
- C, N, O, Si, S abundances derived from HII region recombination lines
- MODS spectrograph at Large Binocular Telescope




Richard Pogge (OSU)

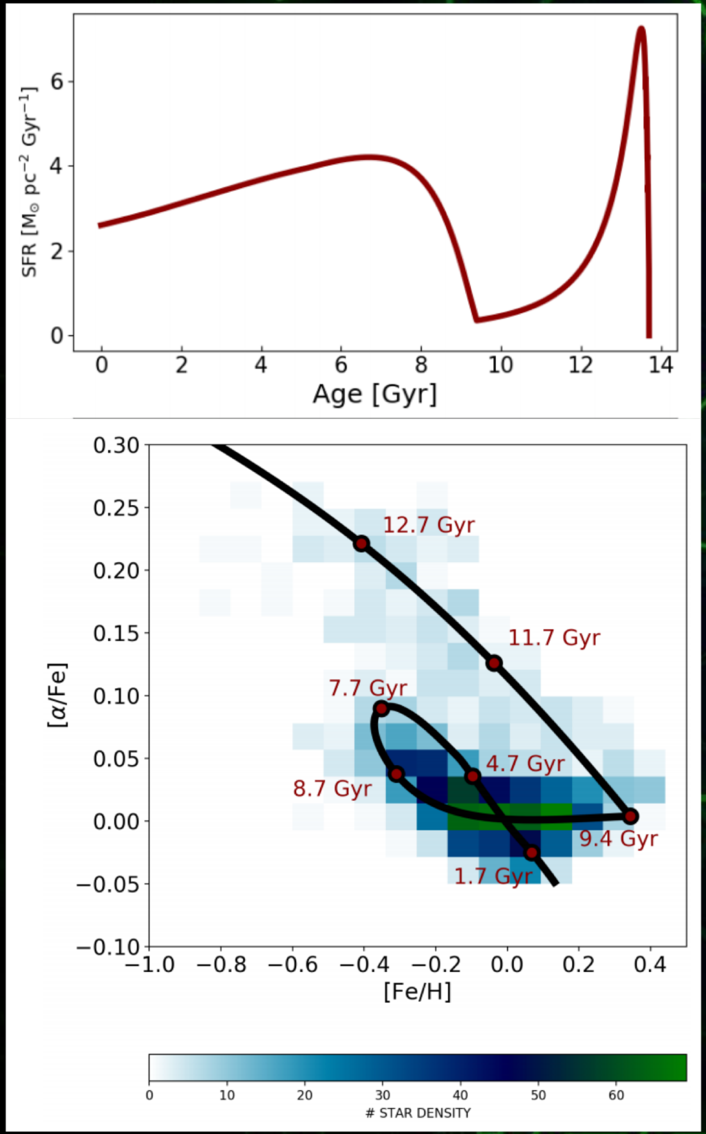

Danielle Berg (OSU)


John Moustakas (Siena)


Evan Skillman (MN)


Ness Mayker (OSU)

Moving Forward: Modeling with VICE



[α/Fe] bimodality in Milky Way

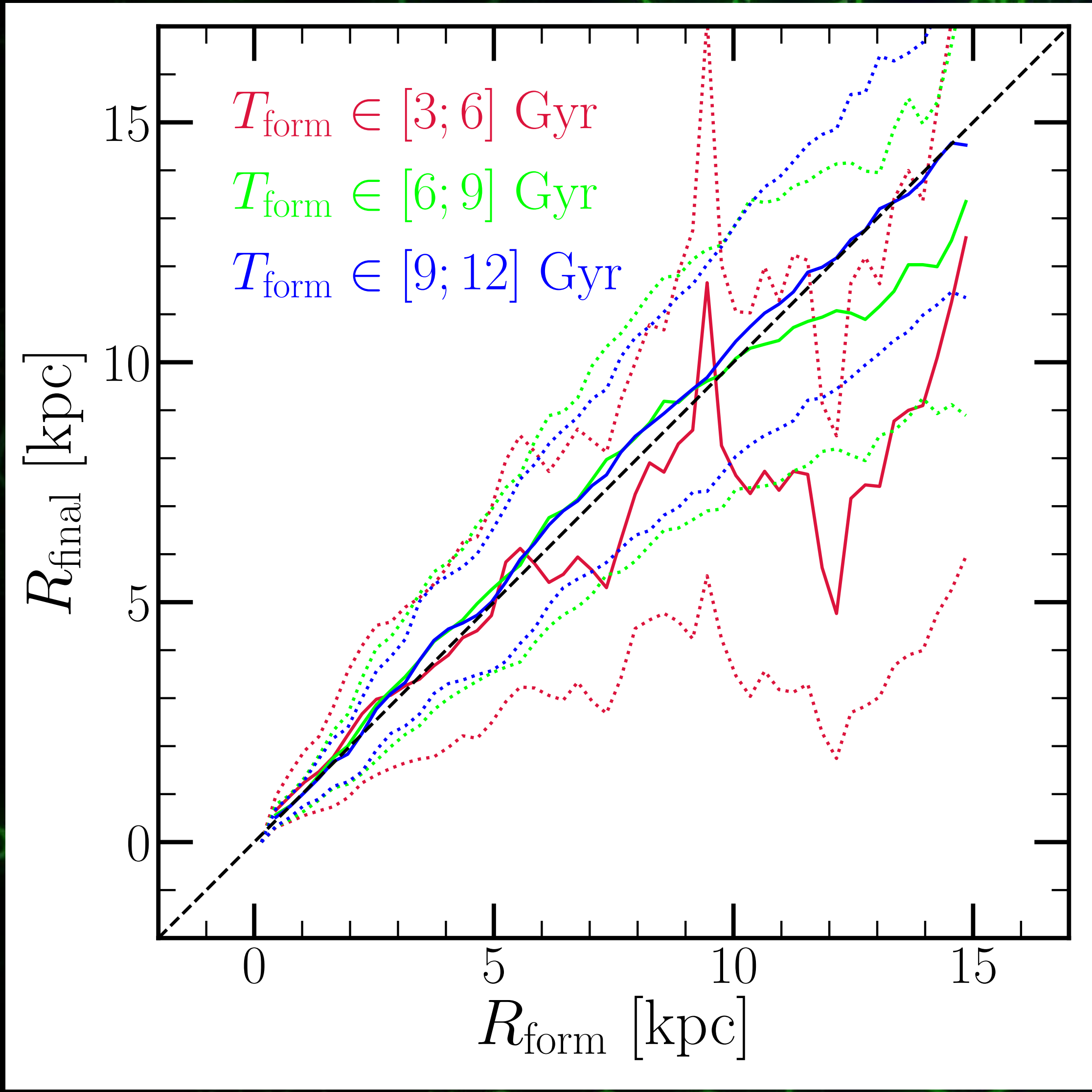
Spitoni+ 2019: Calibrated two-infall model for O, Fe

Does the model change/fail with more elements and relaxed assumptions?

Ness Mayker (OSU)

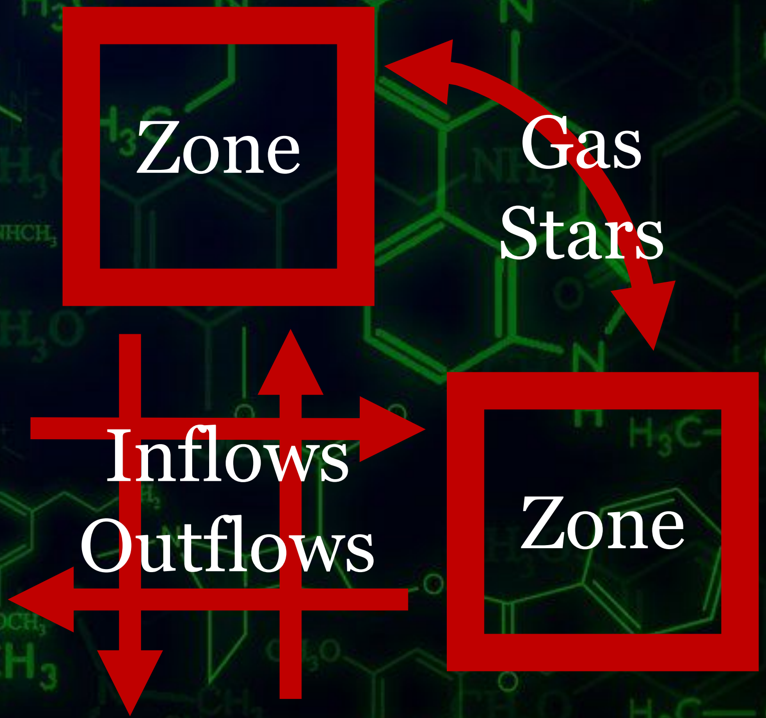
David Weinberg (OSU)

Moving Forward: Multizone Simulations



Attempt to capture mixing with similar zone modeling approach

- Data: UW hydro simulation



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$$\dot{\mathrm{M}}_{\mathrm{gas}} = \dot{\mathrm{M}}_{\mathrm{in}} - \dot{\mathrm{M}}_{*} - \dot{\mathrm{M}}_{\mathrm{out}} + \dot{\mathrm{M}}_{\mathrm{r}} \qquad \dot{\mathrm{M}}_{*} = \mathrm{M}_{\mathrm{gas}}\tau_{*}^{-1}$$

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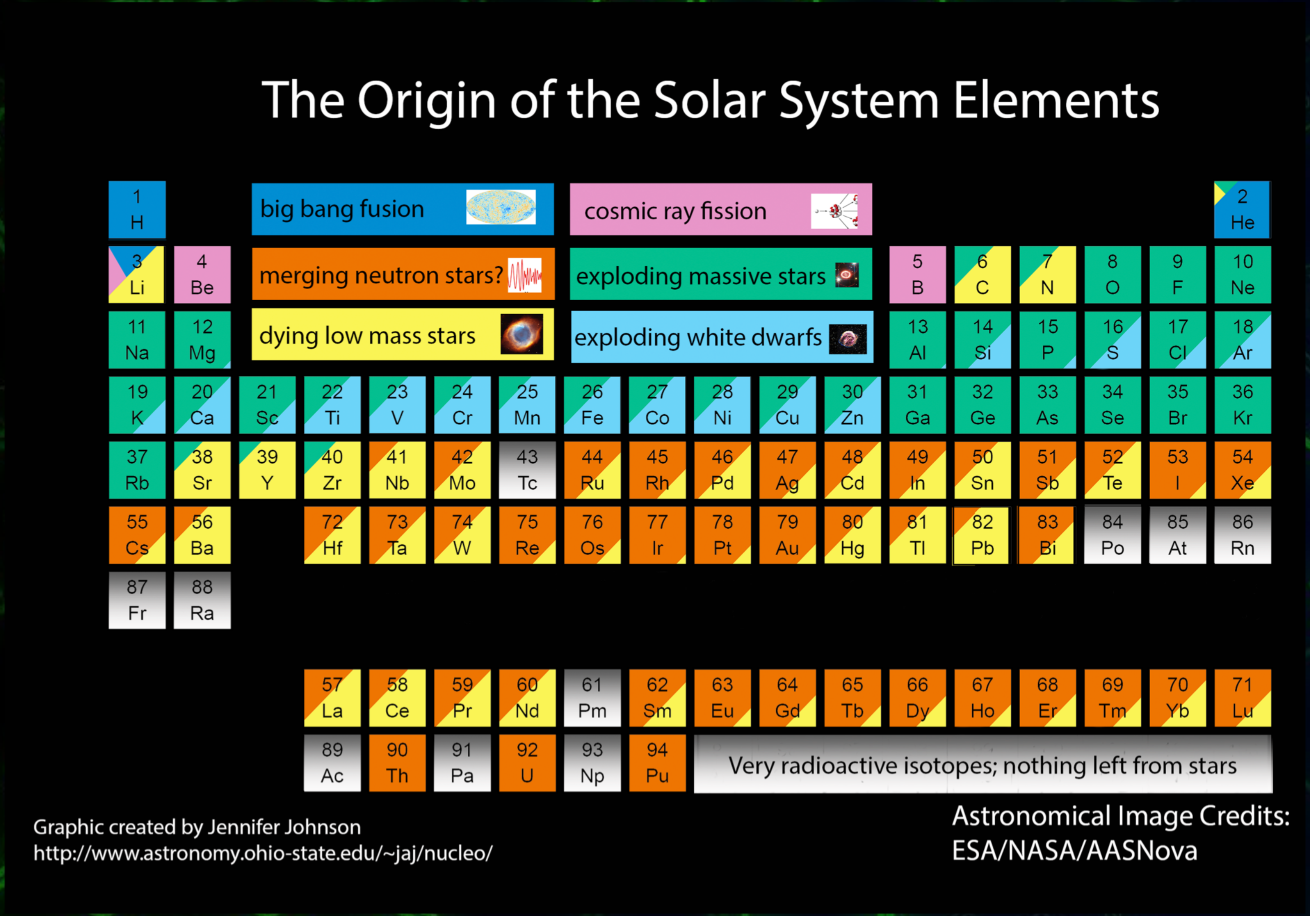
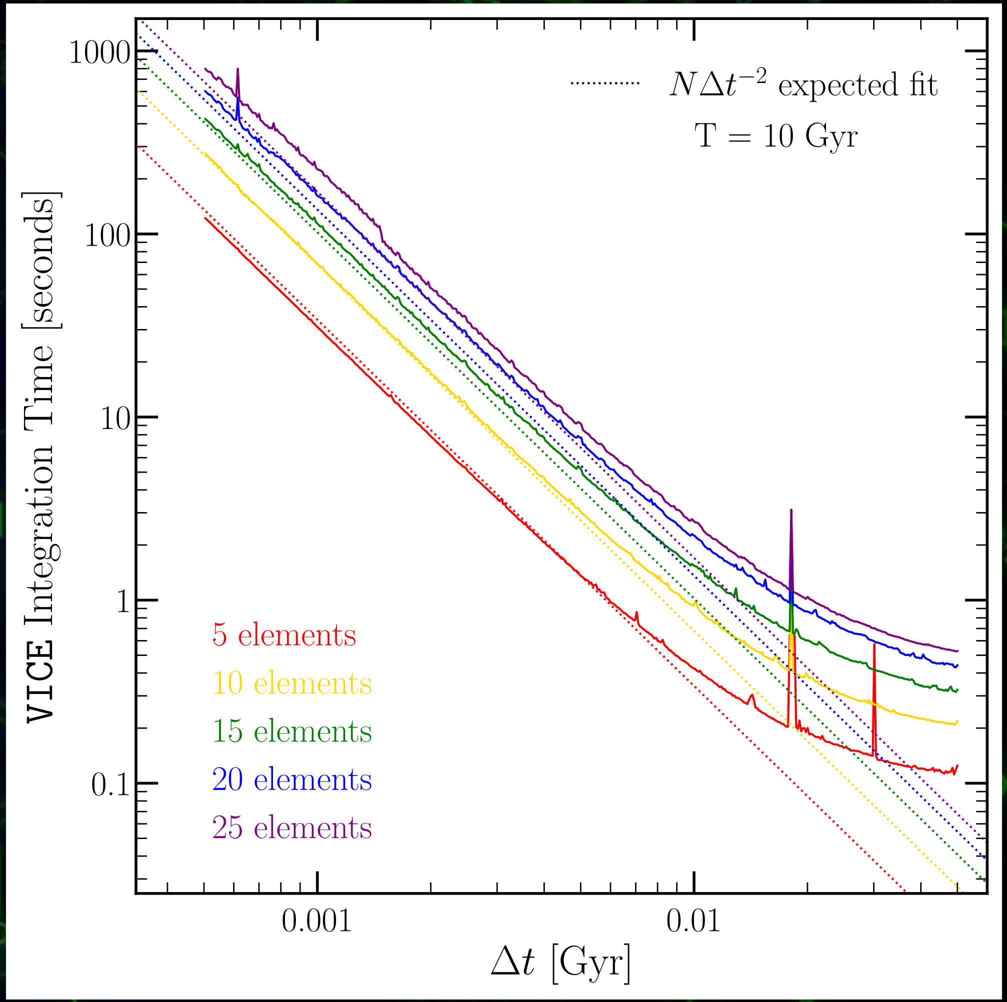
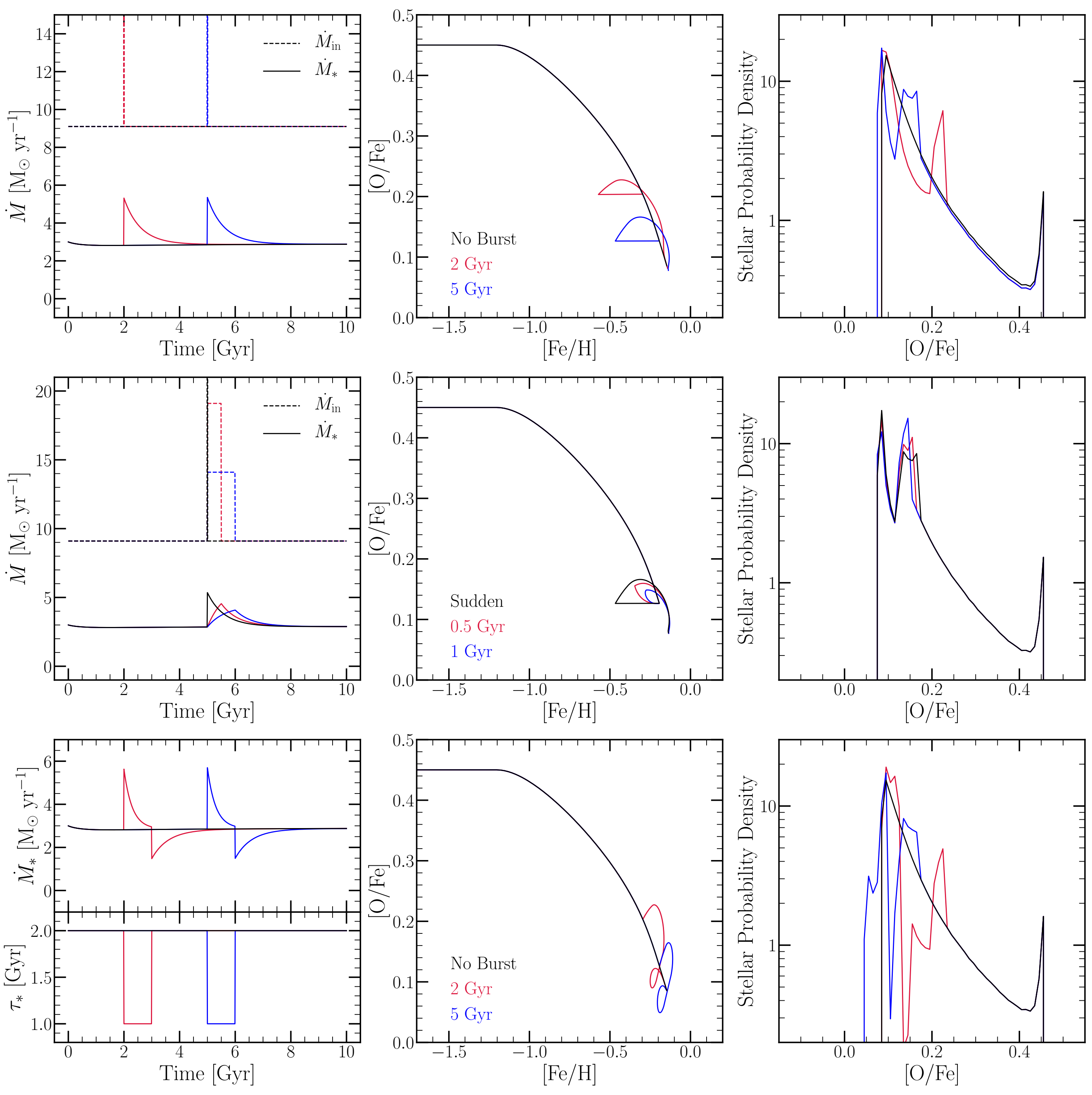
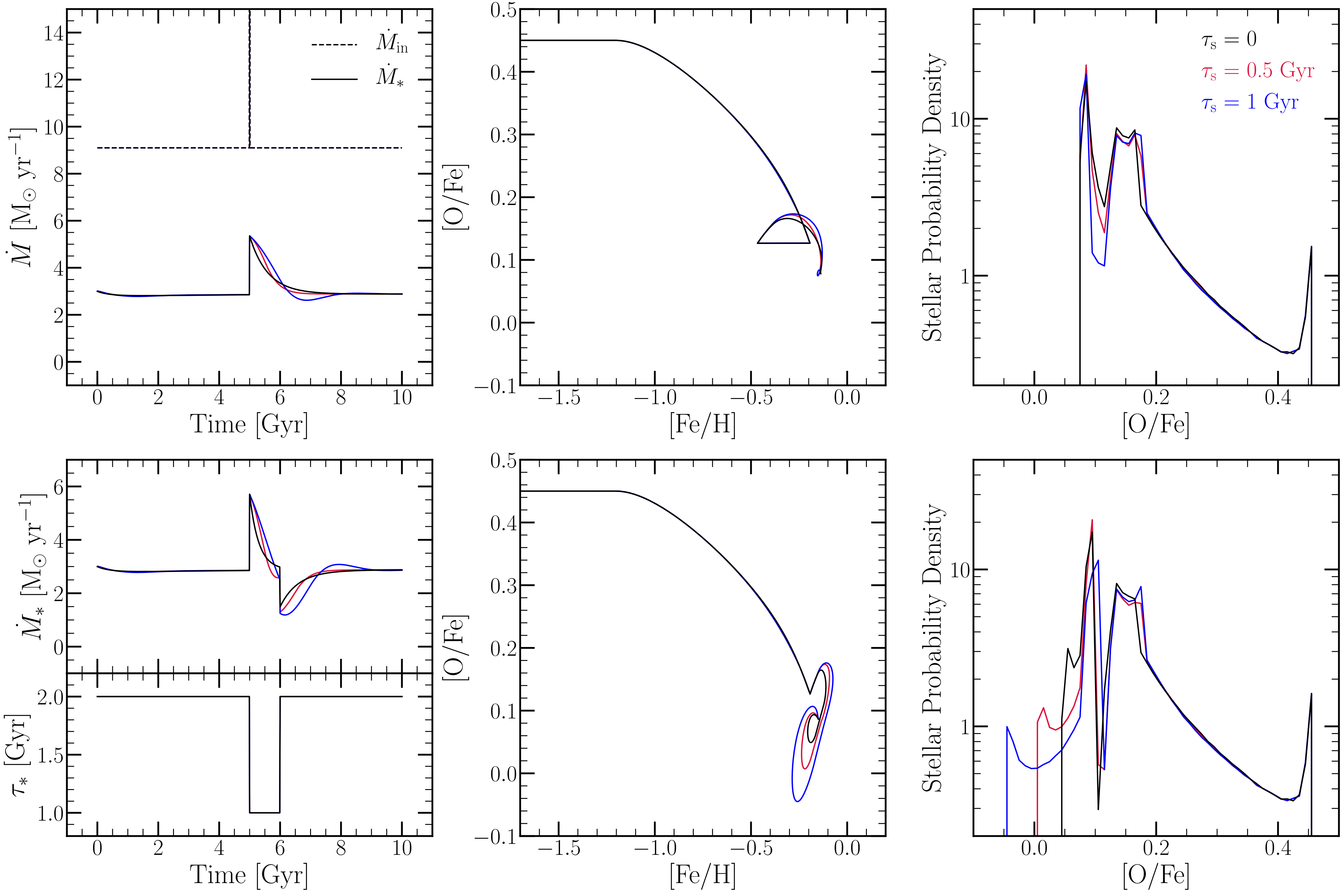
- $\dot{M}_{*} \propto \Sigma_g^N \Rightarrow M_g\tau_{*}^{-1} \propto \Sigma_g^N \Rightarrow \tau_{*}^{-1} \propto \Sigma_g^{N-1}$
- $N = 1.4 \pm 0.15$ (Schmidt 1959, 1963; Kennicutt 1989, 1998)
- Here: $\tau_{*}^{-1} = (2\ Gyr)^{-1}\left(\frac{M_g}{6.0\times10^{9}\ M_{\odot}}\right)^{0.5}$


The Origin of the Solar System Elements
big bang fusion
cosmic ray fission
merging neutron stars?
exploding massive stars
dying low mass stars
exploding white dwarfs
1 H
2 He
3 Li
4 Be
5 B
6 C
7 N
8 O
9 F
10 Ne
11 Na
12 Mg
13 Al
14 Si
15 P
16 S
17 Cl
18 Ar
19 K
20 Ca
21 Sc
22 Ti
23 V
24 Cr
25 Mn
26 Fe
27 Co
28 Ni
29 Cu
30 Zn
31 Ga
32 Ge
33 As
34 Se
35 Br
36 Kr
37 Rb
38 Sr
39 Y
40 Zr
41 Nb
42 Mo
43 Tc
44 Ru
45 Rh
46 Pd
47 Ag
48 Cd
49 In
50 Sn
51 Sb
52 Te
53 I
54 Xe
55 Cs
56 Ba
72 Hf
73 Ta
74 W
75 Re
76 Os
77 Ir
78 Pt
79 Au
80 Hg
81 Tl
82 Pb
83 Bi
84 Po
85 At
86 Rn
87 Fr
88 Ra
57 La
58 Ce
59 Pr
60 Nd
61 Pm
62 Sm
63 Eu
64 Gd
65 Tb
66 Dy
67 Ho
68 Er
69 Tm
70 Yb
71 Lu
89 Ac
90 Th
91 Pa
92 U
93 Np
94 Pu
Very radioactive isotopes; nothing left from stars
Graphic created by Jennifer Johnson
http://www.astronomy.ohio-state.edu/~jaj/nucleo/
Astronomical Image Credits:
ESA/NASA/AASNova

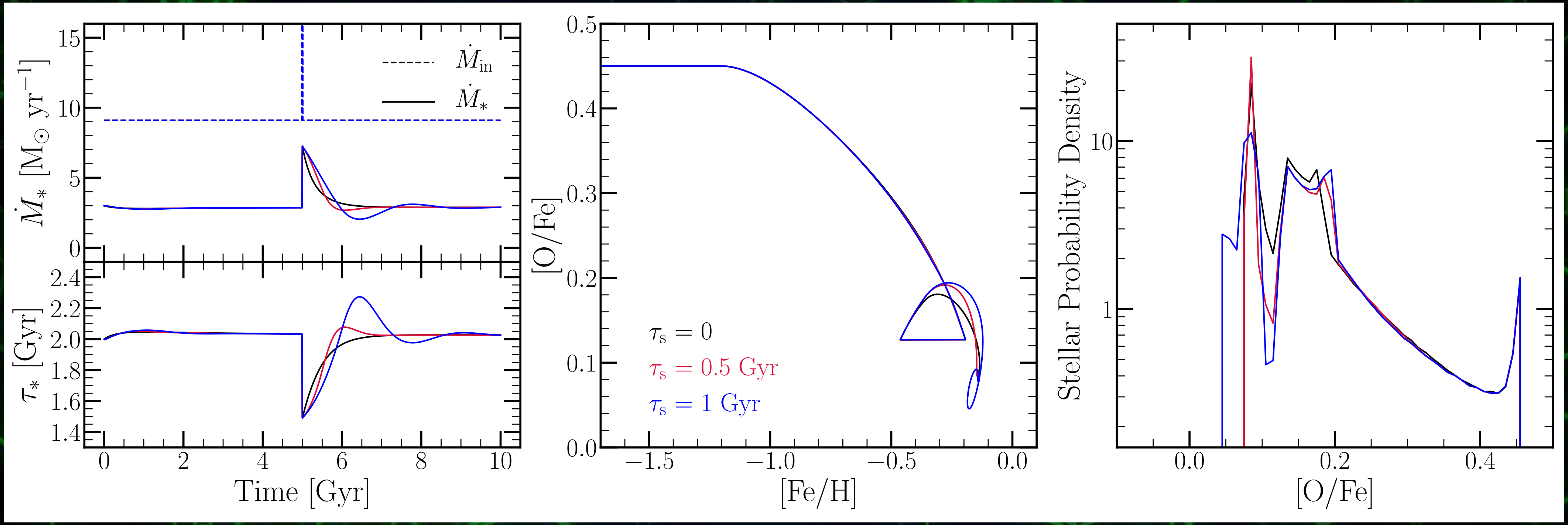

$N\Delta t^{-2}$ expected fit
T = 10 Gyr
VICE Integration Time [seconds]
1000
100
10
1
0.1
5 elements
10 elements
15 elements
20 elements
25 elements
0.001
0.01
Δt [Gyr]



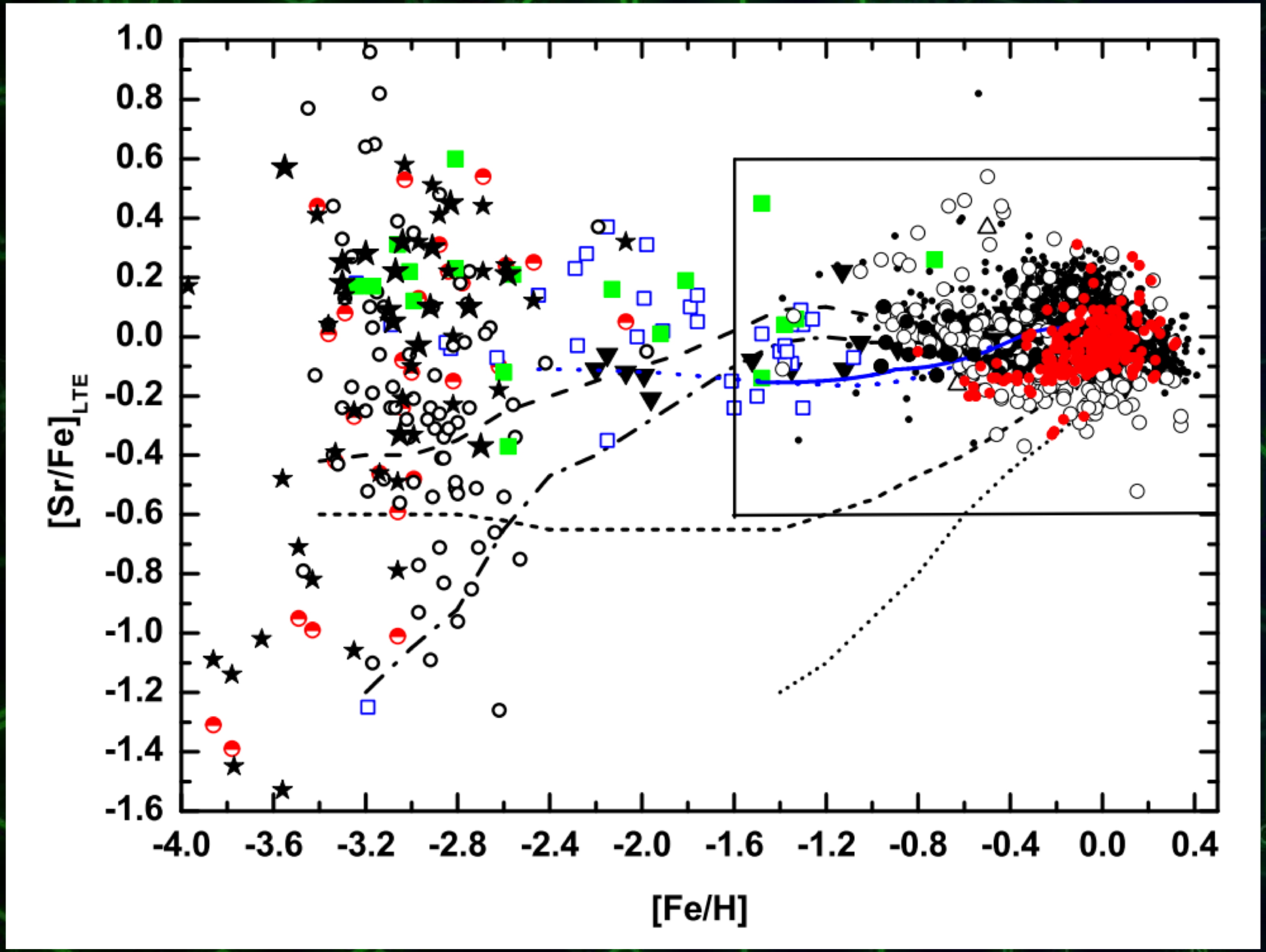
$\dot{M}_{in}$
$\dot{M}_*$
$\dot{M}$ [$M_\odot$ yr^{-1}]
Time [Gyr]
[O/Fe]
[Fe/H]
No Burst
2 Gyr
5 Gyr
Stellar Probability Density
Sudden
0.5 Gyr
1 Gyr
$\dot{M}_*$ [$M_\odot$ yr^{-1}]
τ_* [Gyr]

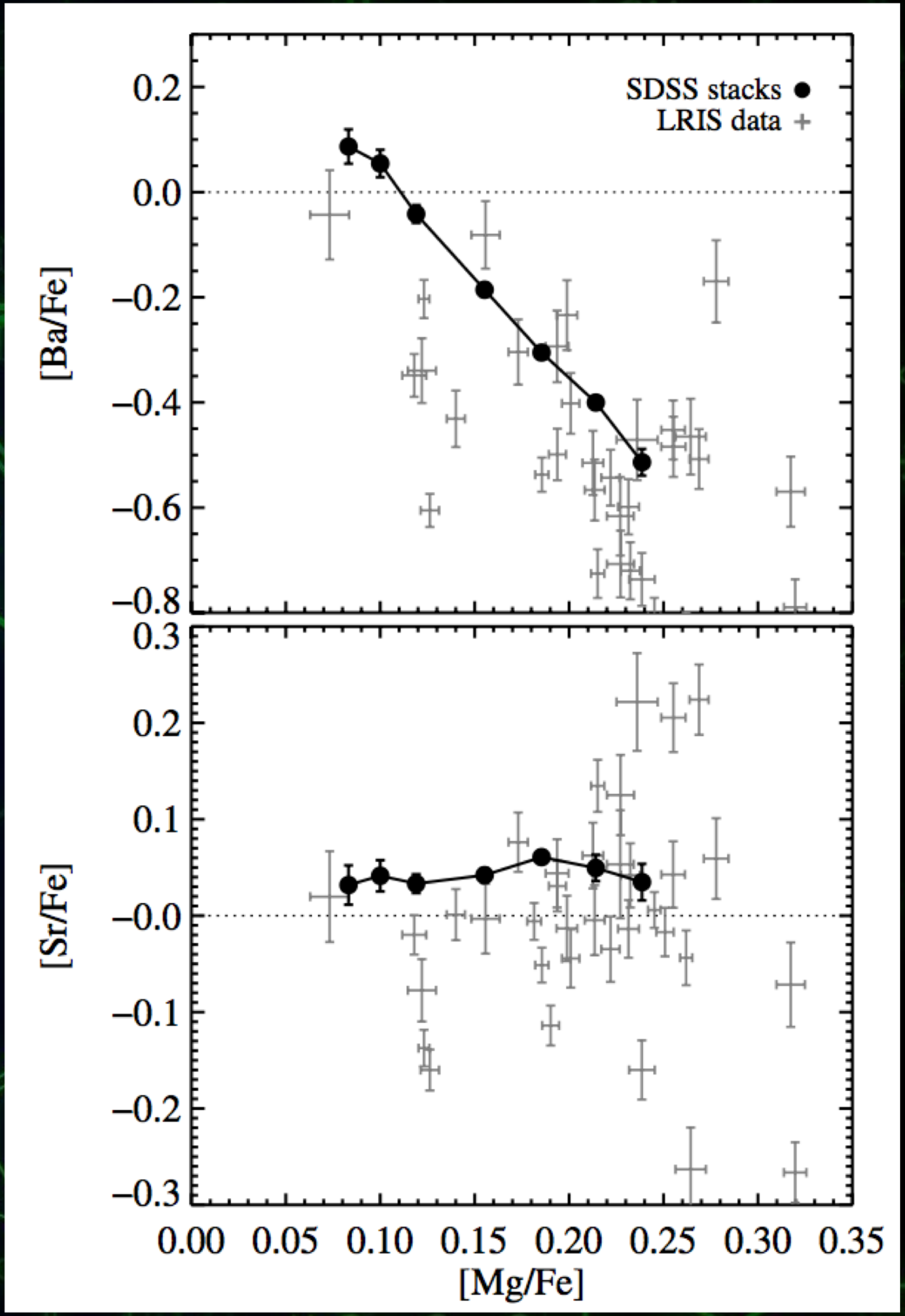


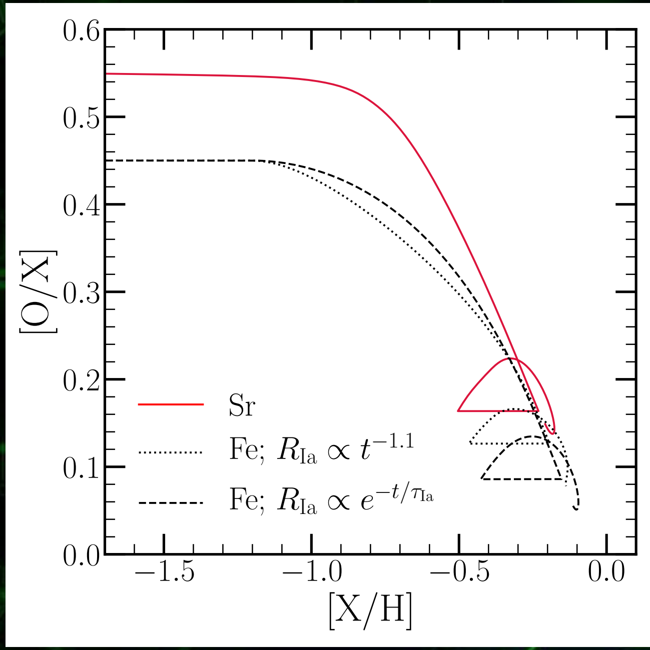
$\dot{M}_{\rm in}$
$\dot{M}_*$
$\dot{M}$ [M$_\odot$ yr^{-1}]
Time [Gyr]
[O/Fe]
[Fe/H]
$\tau_{\rm s} = 0$
$\tau_{\rm s} = 0.5$ Gyr
$\tau_{\rm s} = 1$ Gyr
Stellar Probability Density
$\dot{M}_*$ [M$_\odot$ yr^{-1}]
τ_* [Gyr]



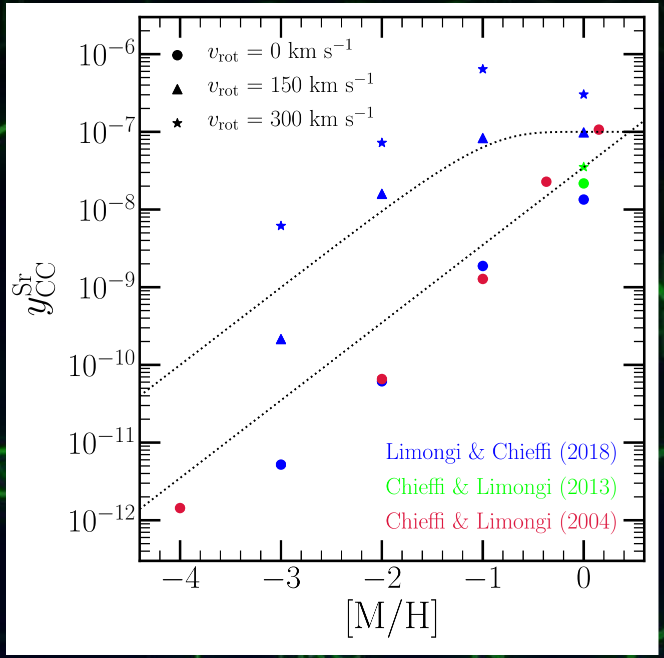
$\dot{M}_{in}$
$\dot{M}_*$
$\dot{M}_*$ [M$_\odot$ yr^{-1}]
τ_* [Gyr]
Time [Gyr]
[O/Fe]
$\tau_s = 0$
$\tau_s = 0.5$ Gyr
$\tau_s = 1$ Gyr
[Fe/H]
Stellar Probability Density
[O/Fe]


[Sr/Fe]LTE
[Fe/H]
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
-1.0
-1.2
-1.4
-1.6
-4.0
-3.6
-3.2
-2.8
-2.4
-2.0
-1.6
-1.2
-0.8
-0.4
0.0
0.4

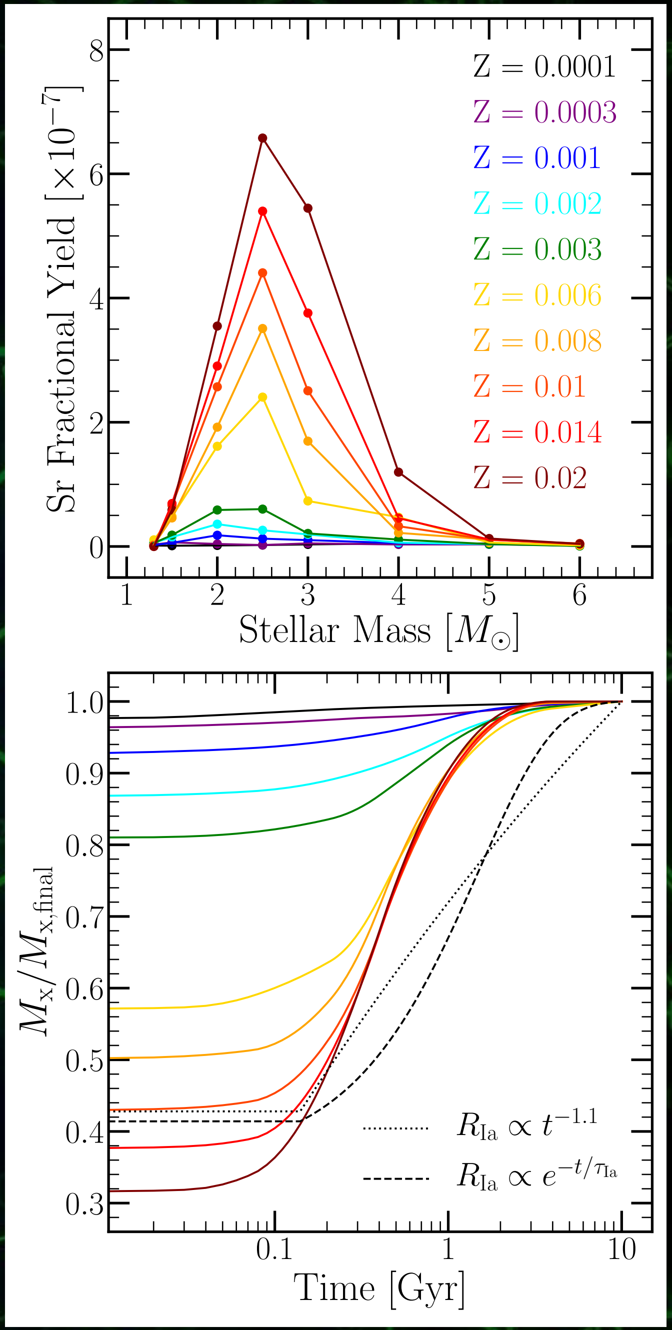

SDSS stacks
LRIS data
[Ba/Fe]
[Sr/Fe]
[Mg/Fe]
0.2
0.0
−0.2
−0.4
−0.6
−0.8
0.3
0.2
0.1
−0.0
−0.1
−0.2
−0.3
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35



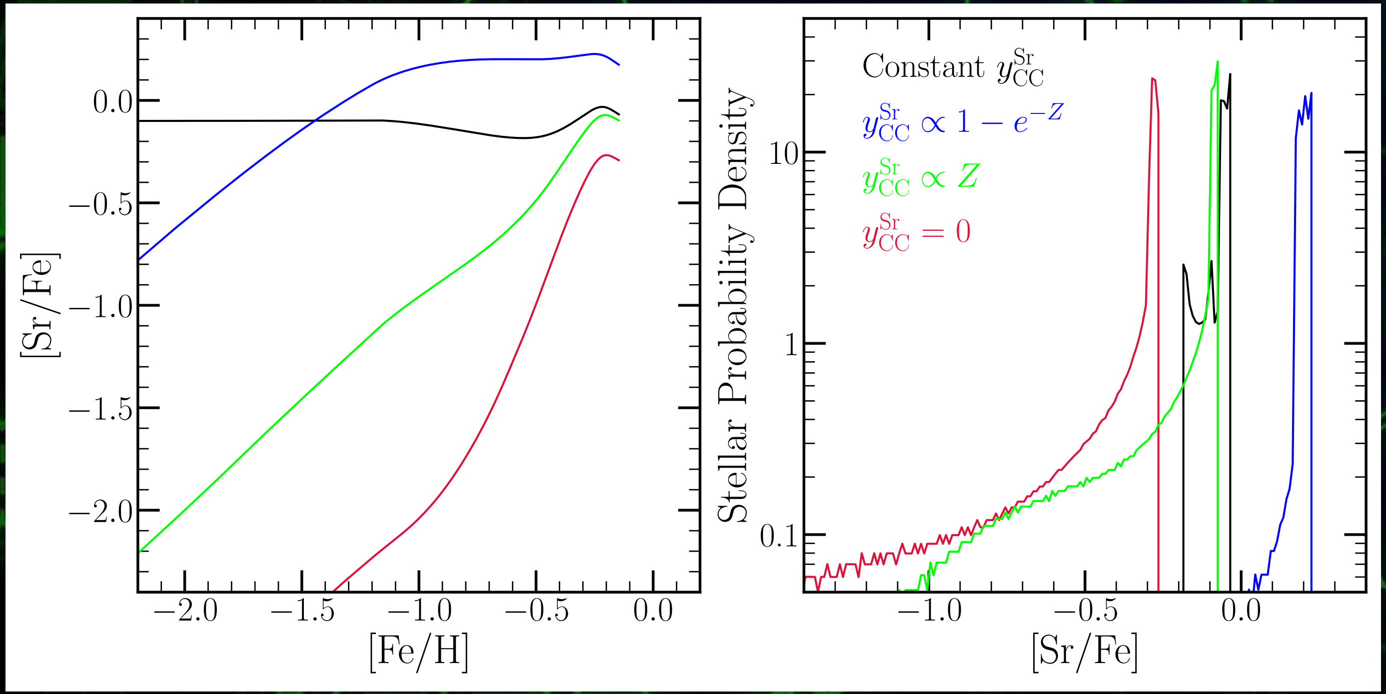
[O/X]
[X/H]
Sr
Fe; $R_{\rm Ia} \propto t^{-1.1}$
Fe; $R_{\rm Ia} \propto e^{-t/\tau_{\rm Ia}}$



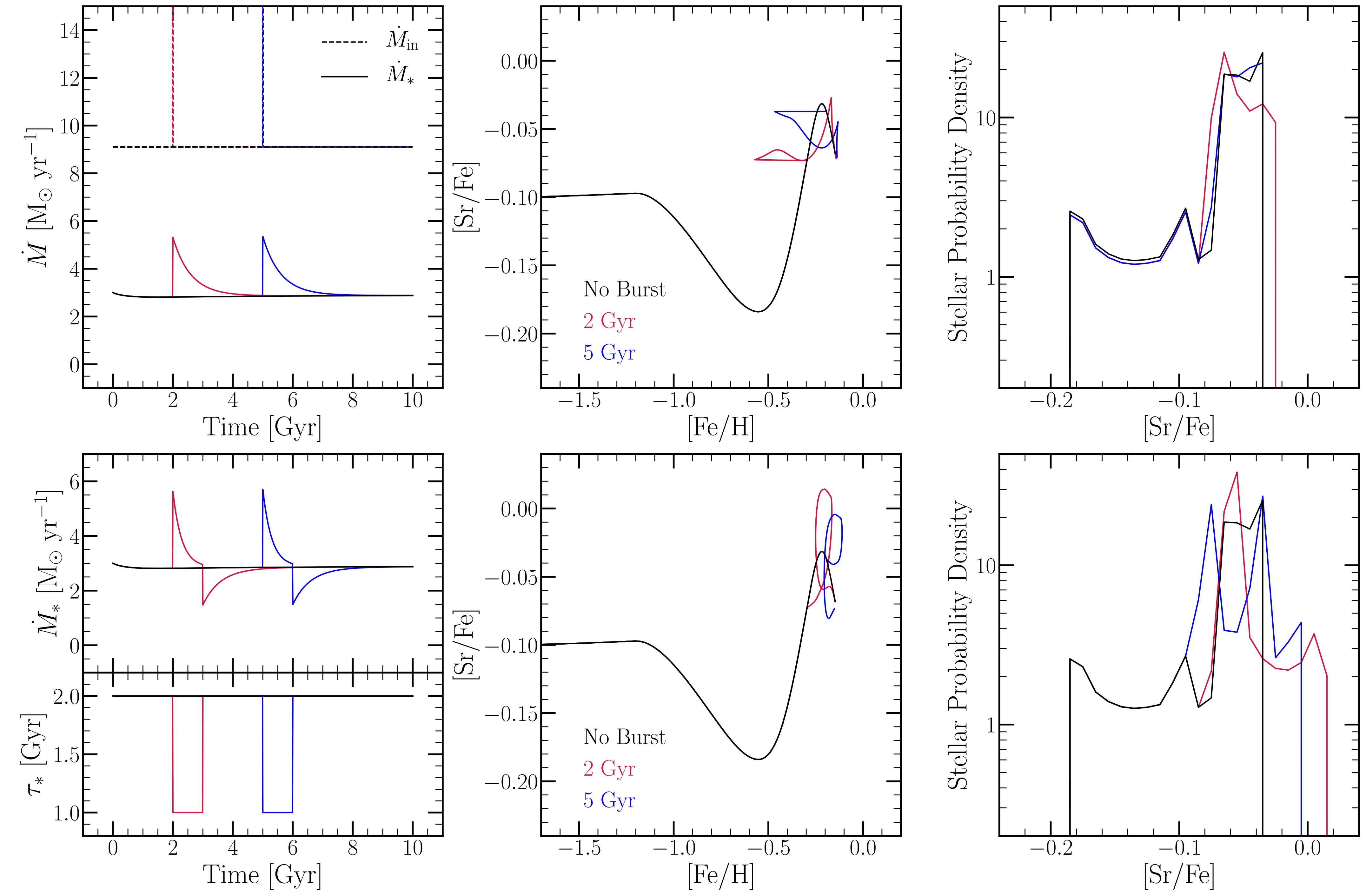
$y^{\rm Sr}_{\rm CC}$
[M/H]
$v_{\rm rot}$ = 0 km s^{-1}
$v_{\rm rot}$ = 150 km s^{-1}
$v_{\rm rot}$ = 300 km s^{-1}
Limongi & Chieffi (2018)
Chieffi & Limongi (2013)
Chieffi & Limongi (2004)



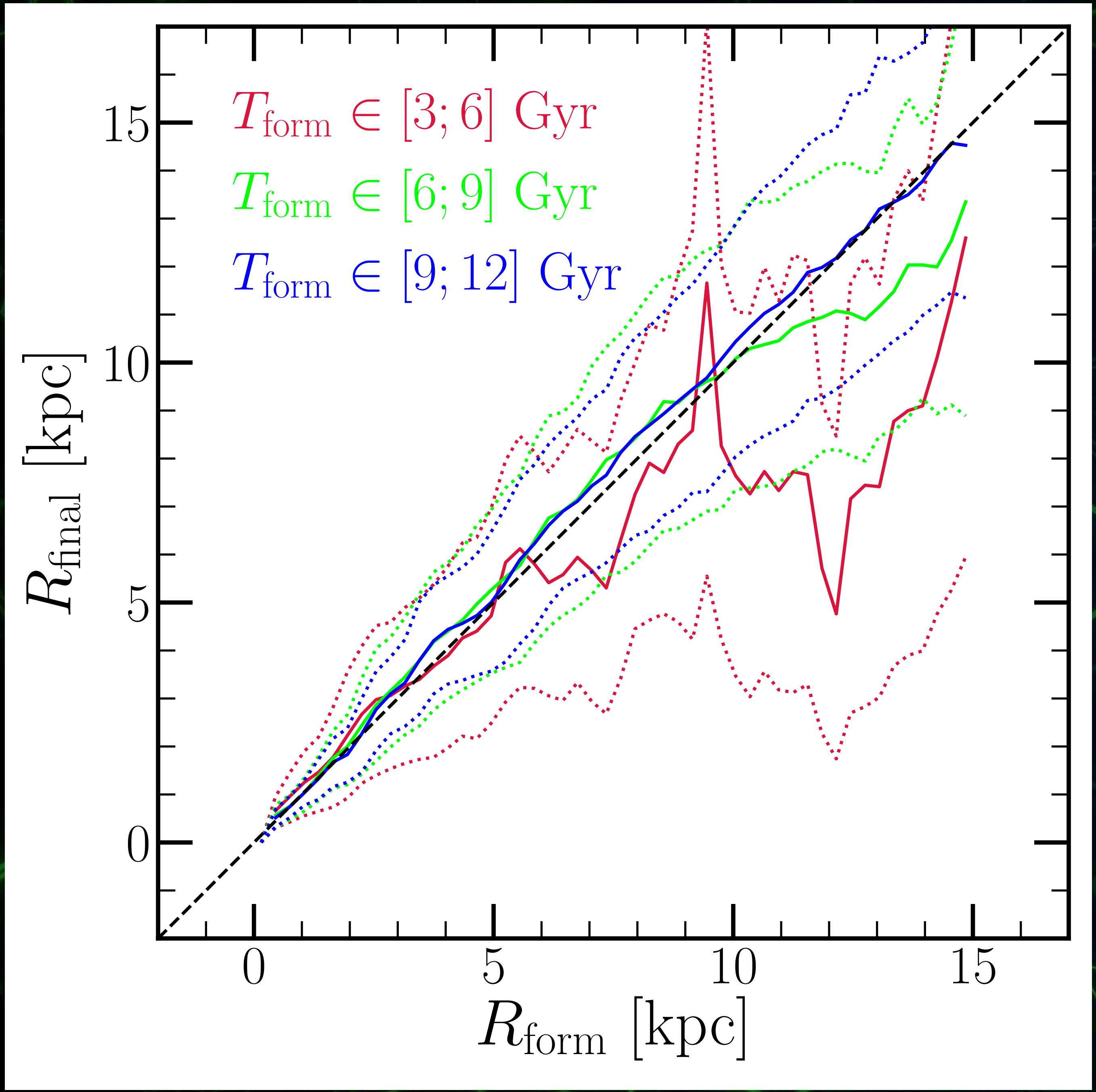
Sr Fractional Yield [$\times 10^{-7}$]
Stellar Mass [$M_\odot$]
Z = 0.0001
Z = 0.0003
Z = 0.001
Z = 0.002
Z = 0.003
Z = 0.006
Z = 0.008
Z = 0.01
Z = 0.014
Z = 0.02
$M_{\rm x}/M_{\rm x,final}$
Time [Gyr]
$R_{\rm Ia} \propto t^{-1.1}$
$R_{\rm Ia} \propto e^{-t/\tau_{\rm Ia}}$

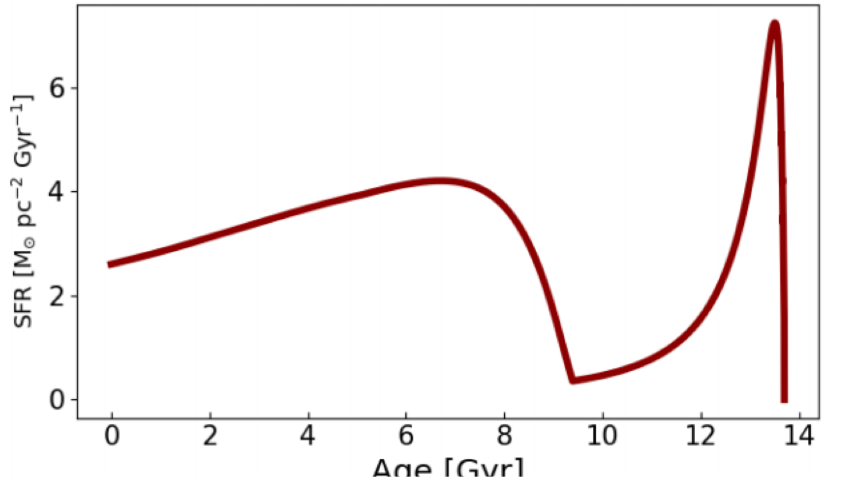


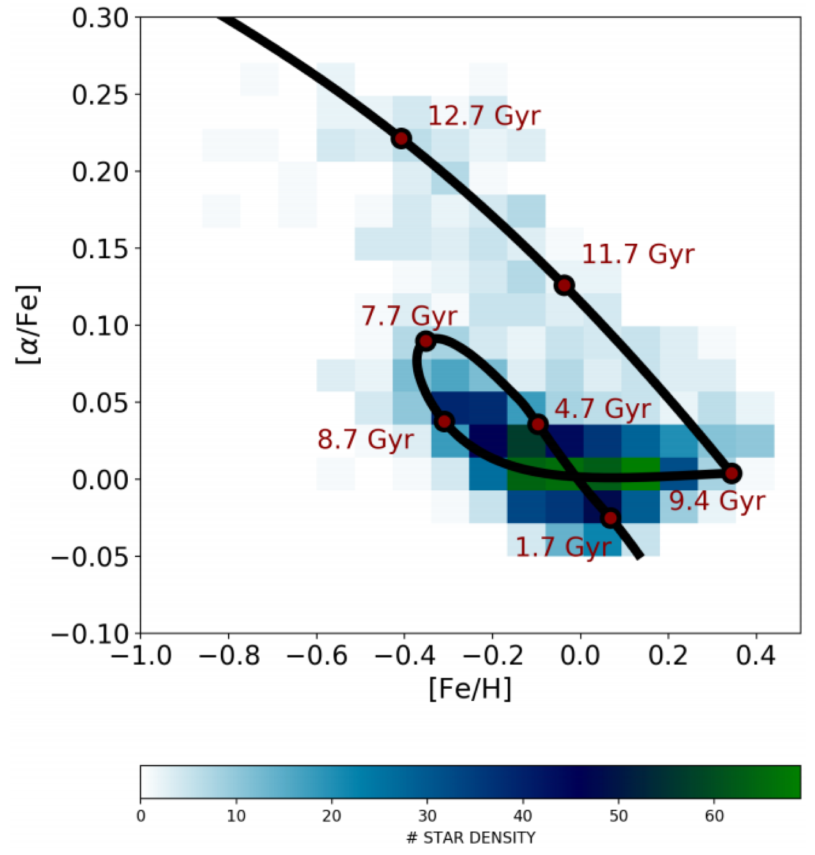
[Sr/Fe]
[Fe/H]
Stellar Probability Density
[Sr/Fe]
Constant $y^{\rm Sr}_{\rm CC}$
$y^{\rm Sr}_{\rm CC} \propto 1 - e^{-Z}$
$y^{\rm Sr}_{\rm CC} \propto Z$
$y^{\rm Sr}_{\rm CC} = 0$



$\dot{M}_{in}$
$\dot{M}_*$
$\dot{M}$ [$M_\odot$ yr^{-1}]
Time [Gyr]
[Sr/Fe]
[Fe/H]
No Burst
2 Gyr
5 Gyr
Stellar Probability Density
[Sr/Fe]
$\dot{M}_*$ [$M_\odot$ yr^{-1}]
τ_* [Gyr]
Time [Gyr]
[Sr/Fe]
[Fe/H]
No Burst
2 Gyr
5 Gyr
Stellar Probability Density
[Sr/Fe]


$T_{\rm form} \in [3; 6]$ Gyr
$T_{\rm form} \in [6; 9]$ Gyr
$T_{\rm form} \in [9; 12]$ Gyr
$R_{\rm final}$ [kpc]
$R_{\rm form}$ [kpc]


SFR [$M_\odot$ pc^{-2} Gyr^{-1}]
Age [Gyr]


12.7 Gyr
11.7 Gyr
7.7 Gyr
4.7 Gyr
8.7 Gyr
9.4 Gyr
1.7 Gyr
[α/Fe]
[Fe/H]
STAR DENSITY