Gaia-Sausage-Enceladus star formation history as revealed by detailed elemental abundances

Ernandes et al. 2024

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Hierarchical galaxy formation

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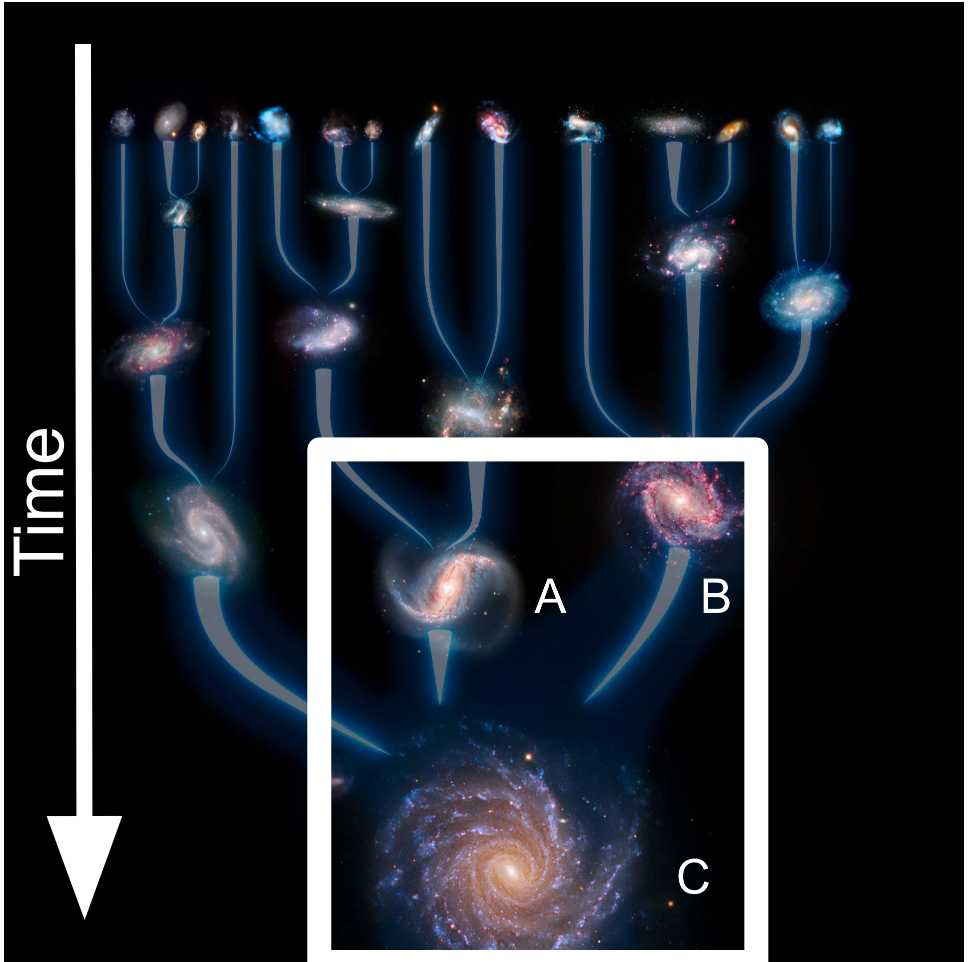
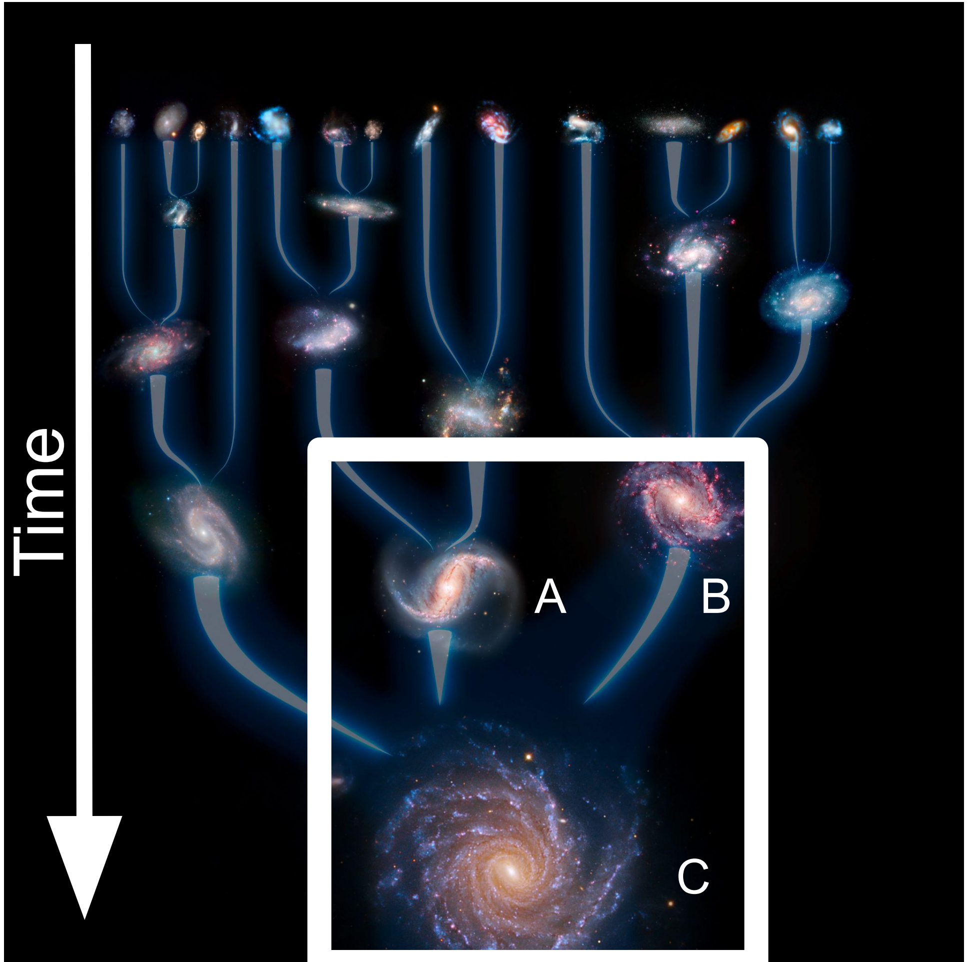


This image will be on display in the ESO Supernova Planetarium & Visitor Centre in Garching, Munich.

Hierarchical formation of galaxy formation

- Smaller galaxies born, enrich themself, and merge
-
- What if we take just this snapshot:
  - galaxy A with their own singular star formation history merging a bigger galaxy B resulting in a much larger galaxy C.
- The ‘new’ born galaxy C will contain both stellar populations and possibly a new population that will born from the merger, since the galaxy C will continue forming stars.

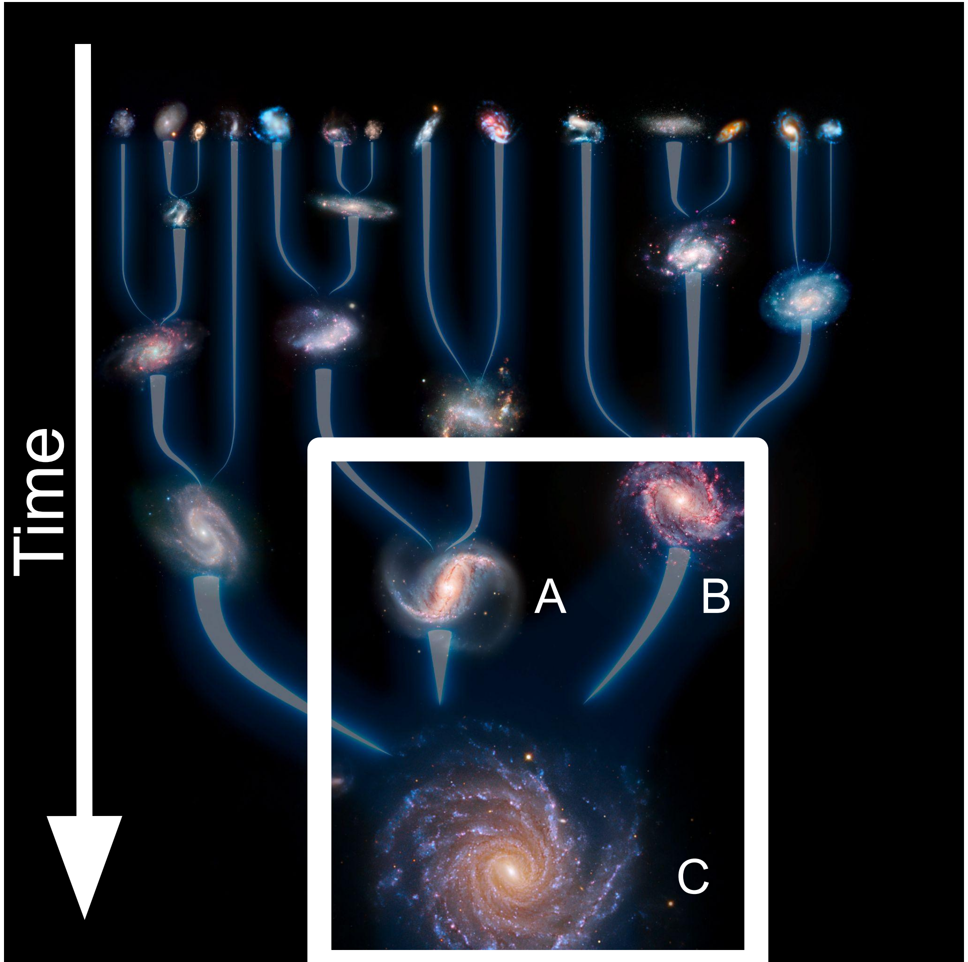
How do we study the A knowing C



ESO Supernova Planetarium & Visitor Centre in Garching, Munich.

The importance of studying fossils in astronomy.

How do we study the A knowing C

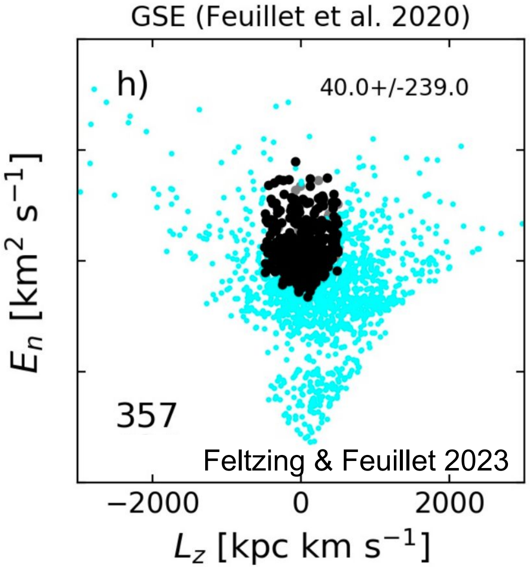


ESO Supernova Planetarium & Visitor Centre in Garching, Munich.

The importance of studying fossils in astronomy.

This Pterosaur that was found in Bavaria (Germany).
(https://education.nationalgeographic.org/resource/fossil/)

The Fossil



This found by Belokurov et al. 2018 and

Helmi et al. 2018 on the Milky Way Halo using Gaia data.

- GSE was the Milky Way last major merger that happened ~8-10 Gyr ago and it had
- M ~10^9 Msun (Feuillet et al. 2020 [Mass Metallicity])(~ M of LMC)

We have many other possible selection. They can use Energy and Angular momentum of

One of the possible selections is Feuillet et al. 2020.

Feuillet et al. (2020)	$30 < \sqrt{(J_r)} < 50$	$(\mathrm{kpc\,km\,s^{-1}})^{1/2}$
	$-500 < L_z < 500$	$\mathrm{kpc\,km\,s^{-1}}$

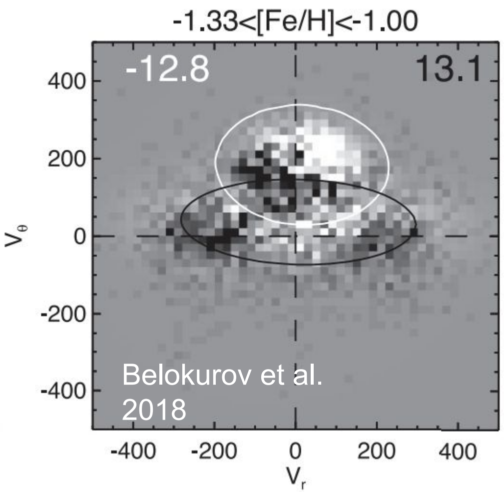
Now that we found this fossil how can we study it?

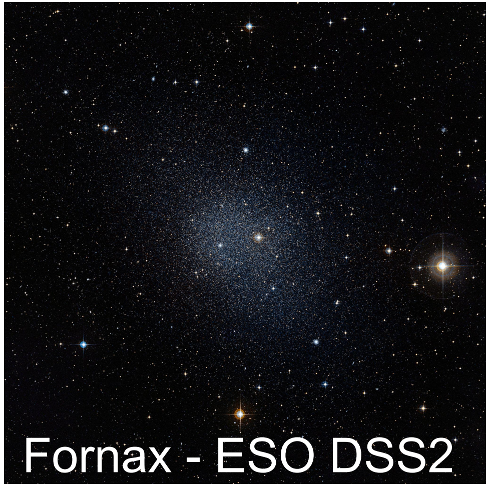
How do we study the A knowing C

The same way we can study the Pterosaur fossil by comparing with the “Dinosaurs” the survived we can study GSE by comparing it with the Dwarf Galaxies that survived the interaction with the Milky Way.

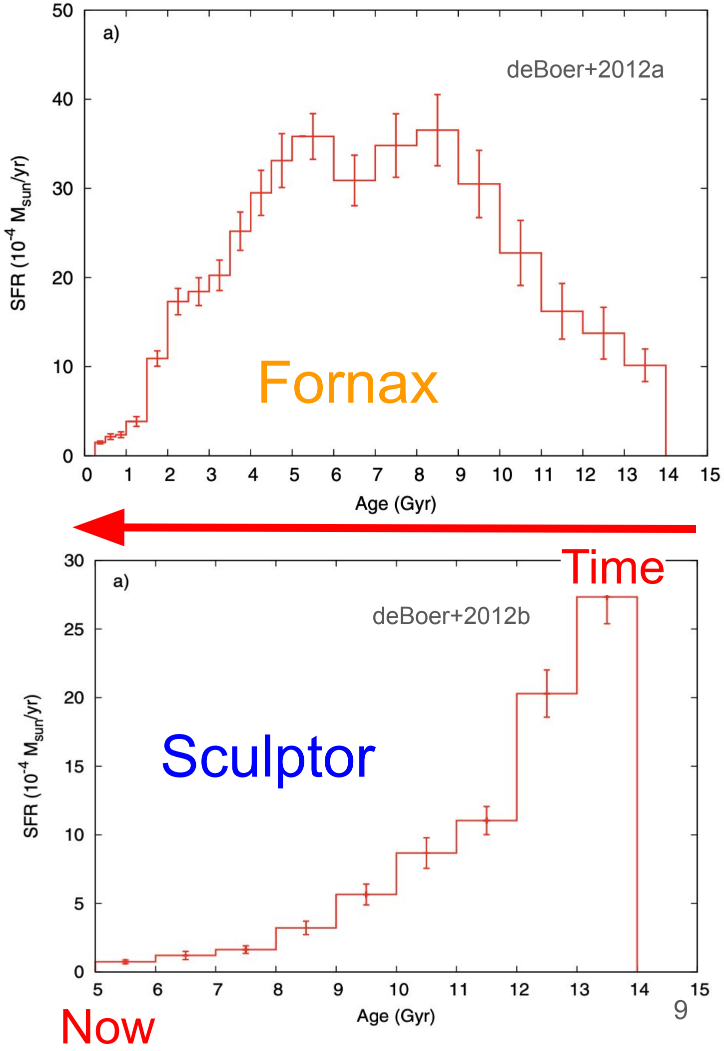
To do that we need some tools:

- **Dwarf Galaxy star formation history**
- **Nucleosynthesis**
- **Chemical evolution**
- **A good data set that covers the entire metallicity range**
- **Kinematic data and selection**

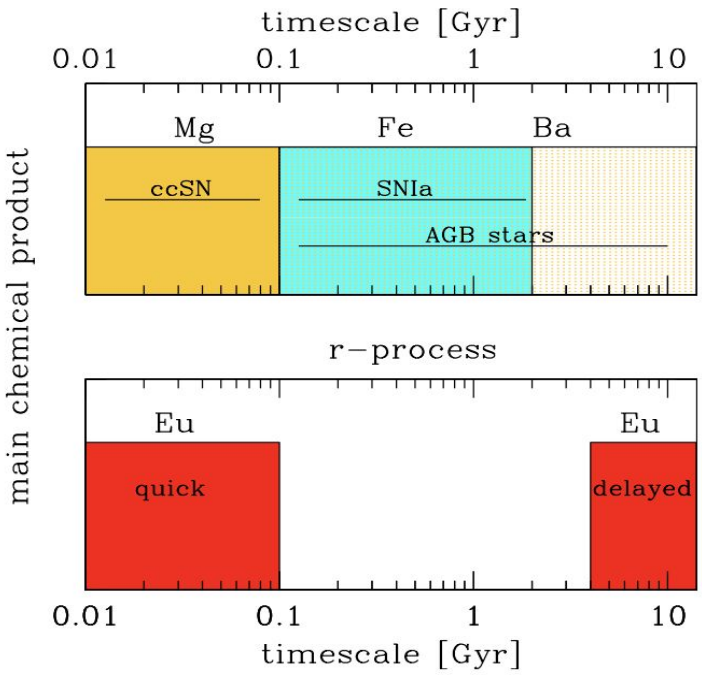




Dwarf Galaxies

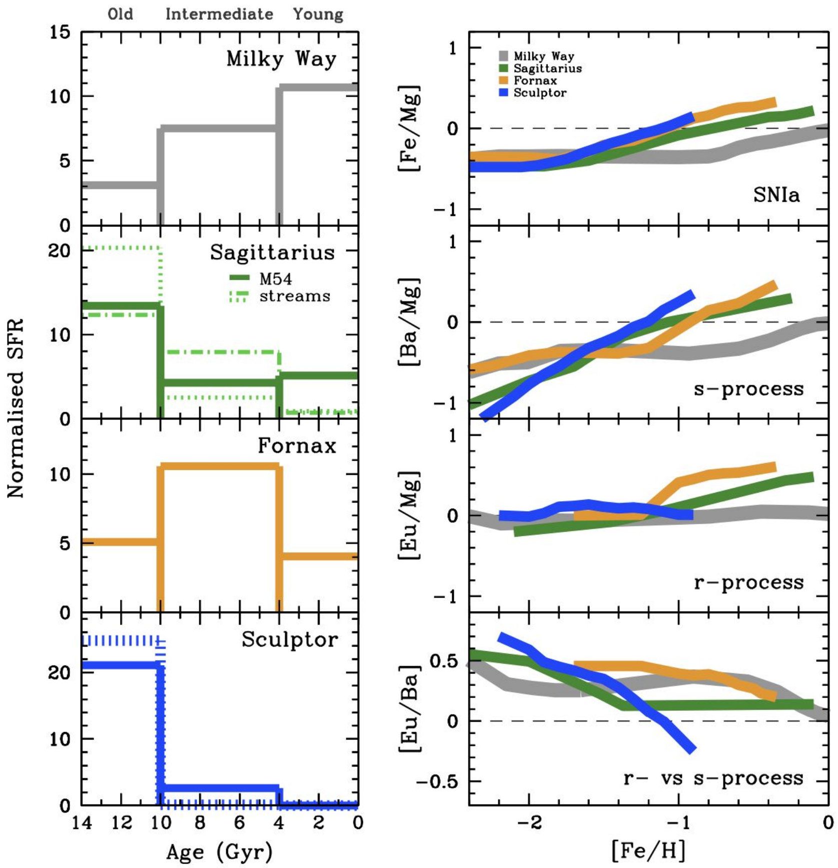


Abundances can tell a story



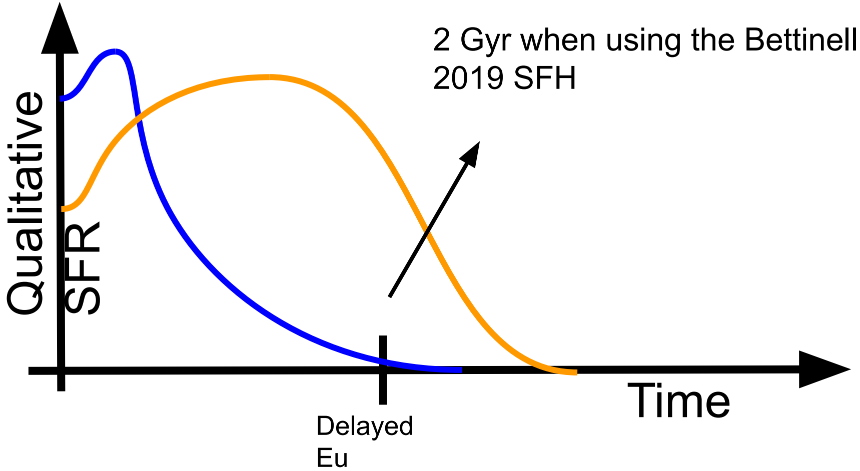
4 Gyr in Skúladóttir & Salvadori 2020
2 Gyr when using the Bettinelli et al. 2019 SFH

Skúladóttir & Salvadori 2020

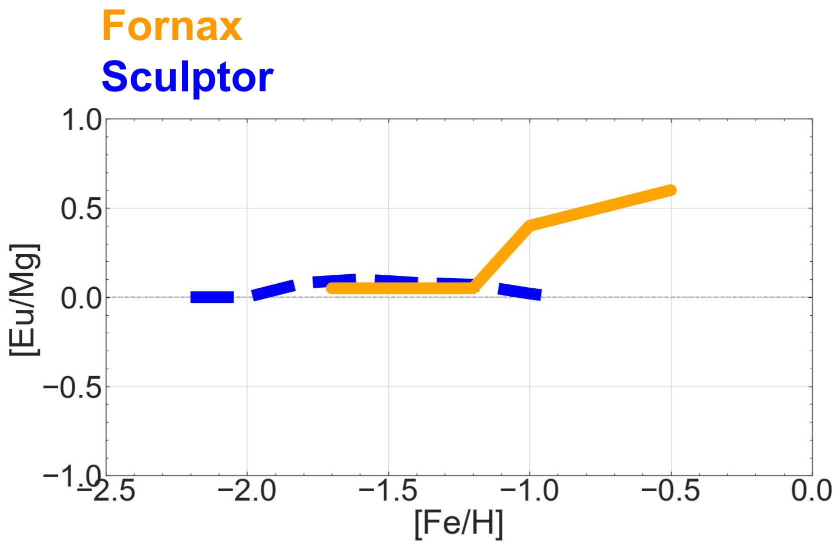


Abundances can tell a story → Qualitative SFH

Some aspects of the SFH:
Fornax: Slow initial star formation, extended,
Natural suppression of the star formation.
Sculptor: Strong initial star formation, early burst.
Star formation ceased star formation before the delayed Eu source.



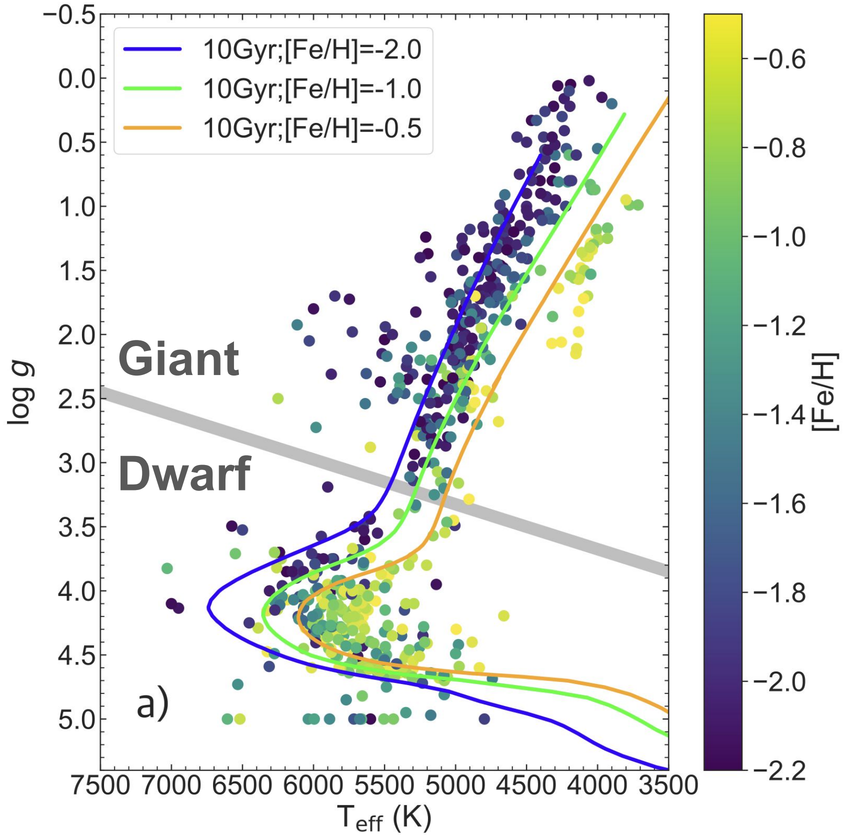
Skúladóttir & Salvadori 2020



Fornax data from Reichert et al. 2020
Sculptor data from Skúladóttir et al. 2019

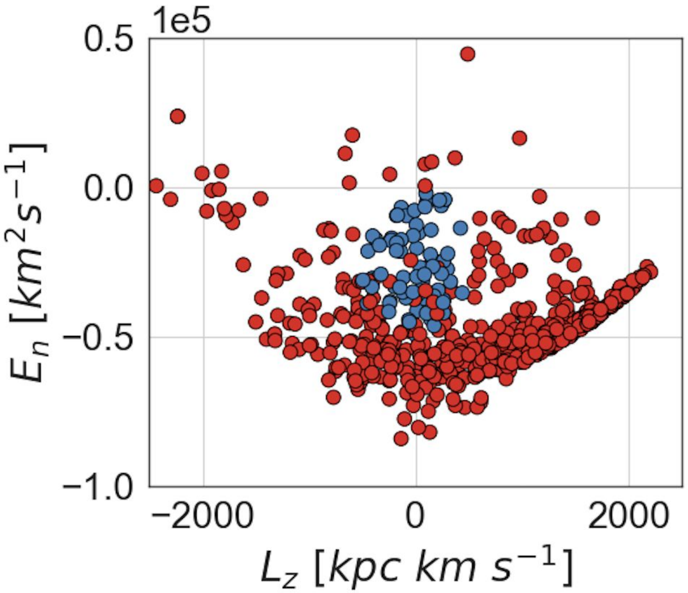
What if we reverse the Skúladóttir & Salvadori 2020 for the Gaia-Sausage-Enceladus stars?

SAGA data

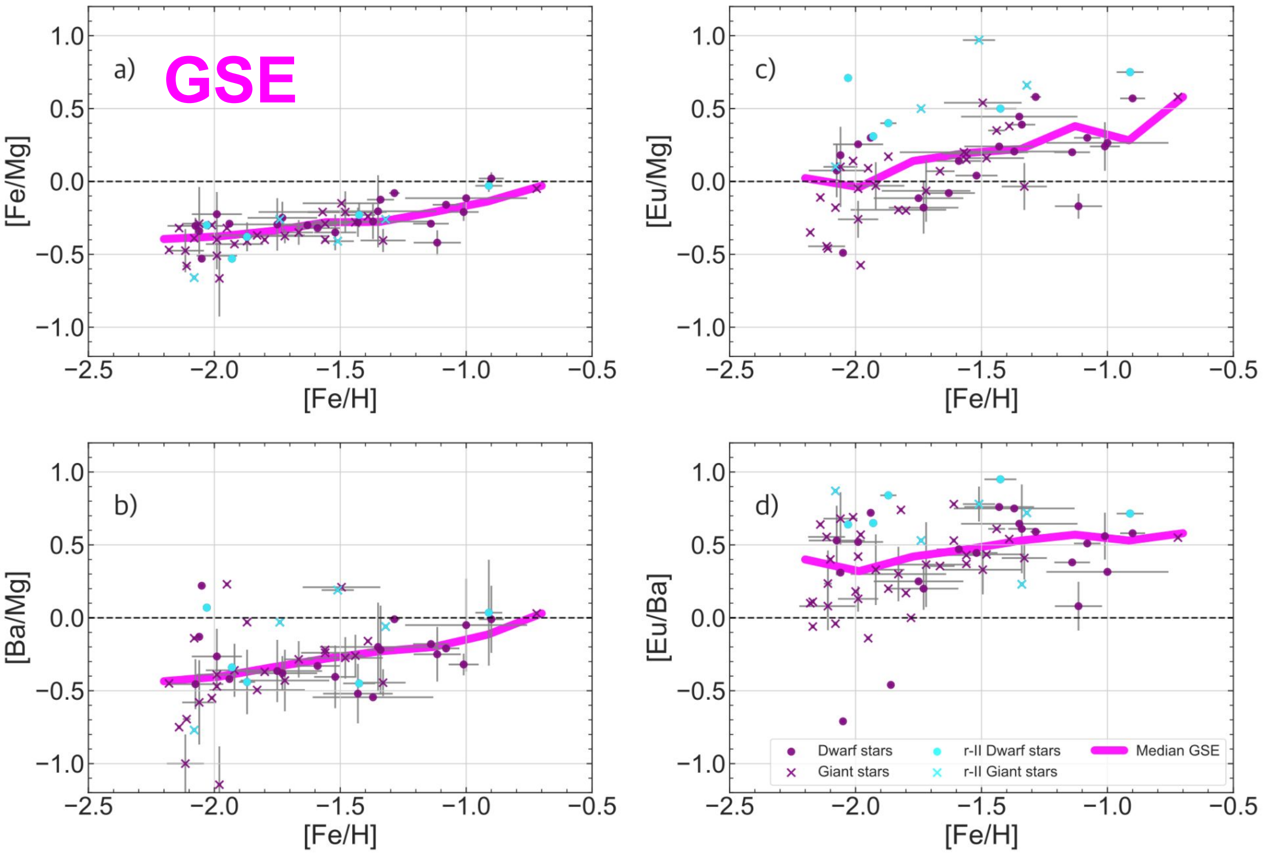


~600 stars with Eu and Fe measurements between -2.2 < [Fe/H] < -0.5 and Gaia data.

Feuillet et al. 2020 selection



Abundances space for our sample



For the elemental abundance we took median values.

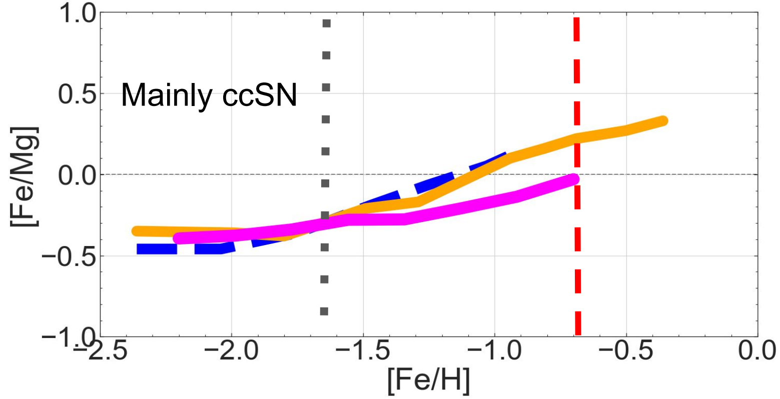
Uncertainty as median absolute deviation (MAD)

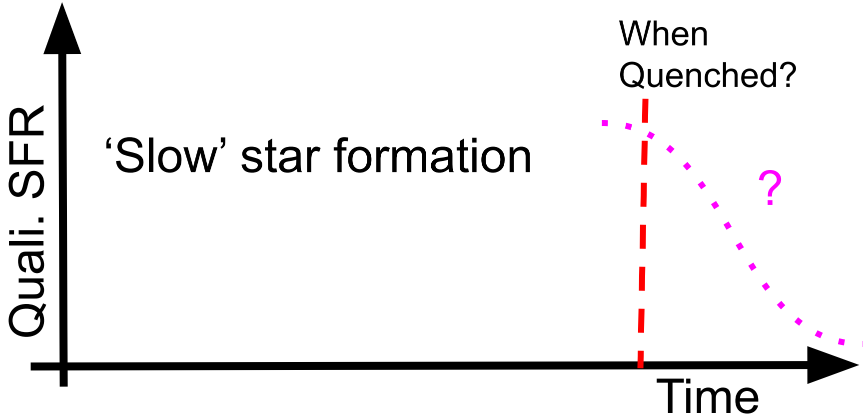
The GSE Giant and dwarfs have the distribution in all panels

Elemental abundance trends made with running median

[Fe/Mg]

Sculptor **Fornax** **GSE**





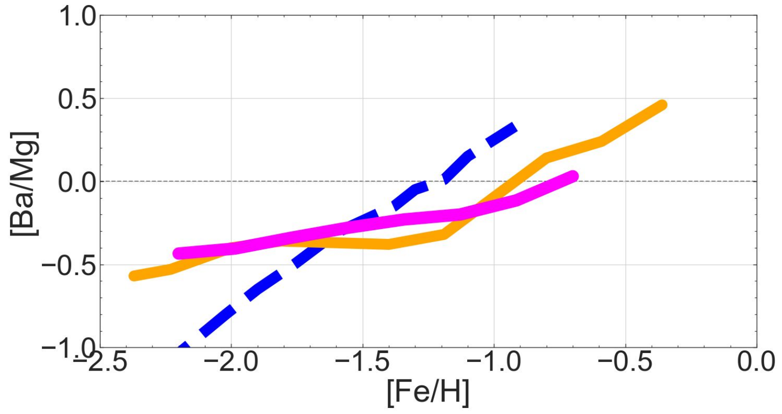
[Fe/Mg] ratio shows the balance between the quick ccSN enrichment (Mg) and the delayed SN Ia (Fe).

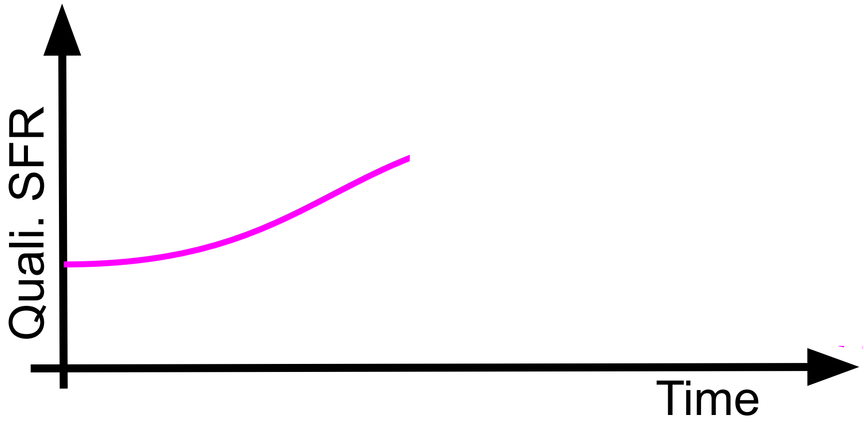
1. In the metal-poor end ccSN is the main source of Fe and the source of Mg
2. Steeper slopes means stronger the contribution of ccSN in their SFH. Which means fast star formation.
3. GSE stopping at [Fe/H] ~ -0.7 and [Fe/Mg] below solar can be a sign of quenching

Note: We can see the contribution of SN Ia in GSE, it has rising slope.

[Ba/Mg]

Sculptor **Fornax** **GSE**



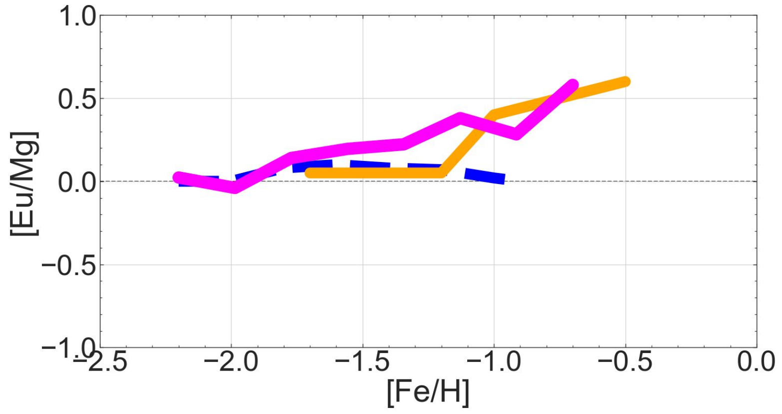


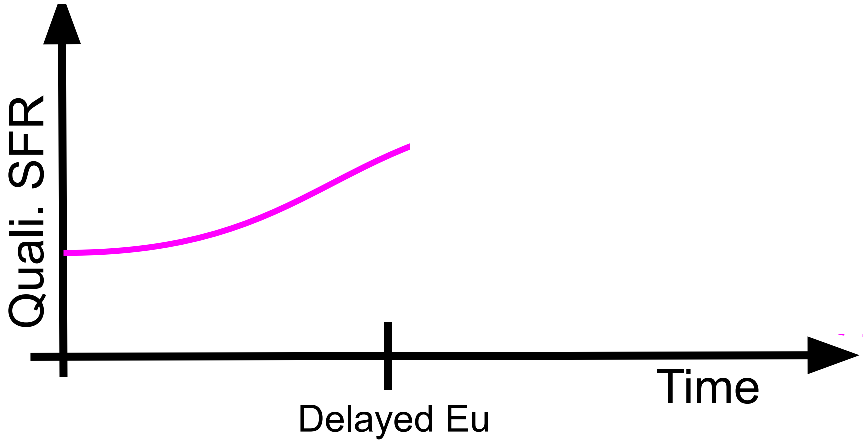
[Ba/Mg] ratio indicates the balance between the fast/immediate ccSN (Mg) and the delayed and ‘extended’ AGB (Ba).

1. The lower is the ratio the strong is the initial star formation.
2. The steeper slopes for Sculptor means that it had a fast star formation that ceased quickly (no/little Mg over lager Ba contribution).
3. GSE having a gentle increase and starting at [Ba/Mg] ~ -0.5 indicates a weak initial star formation succeeded by a moderate and extended star formation.

[Eu/Mg]

Sculptor **Fornax** **GSE**

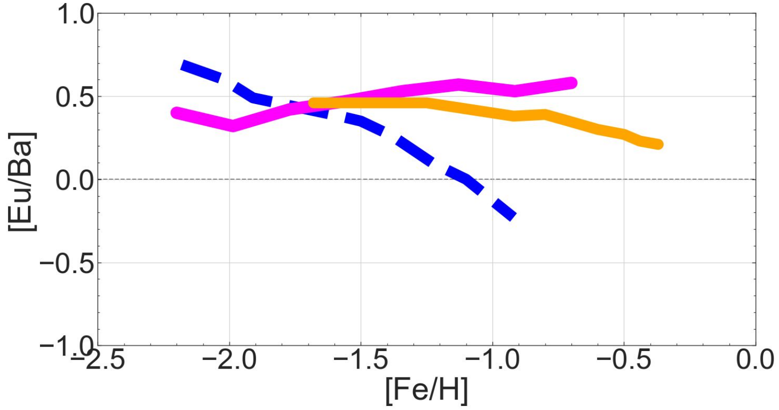


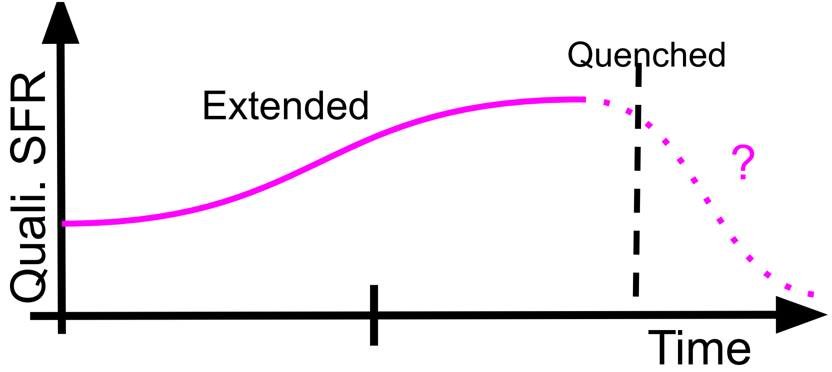


[Eu/Mg] ratio express the balance between immediate source of Mg vs. the sources of Eu. As seen in Skúladóttir & Salvadori 2020.

1. A flat trend means that while the galaxy enrich in Fe some source adds Eu at same amount as Mg [Not necessarily the same source]
2. If it is not flat we may have a second source of Eu (?), a delayed one that does not match the immediate enrichment of Mg.
3. Therefore GSE shows signs of and extended star formation beyond the delay time of the delayed source of Eu.

[Eu/Ba] **Sculptor** **Fornax** **GSE**





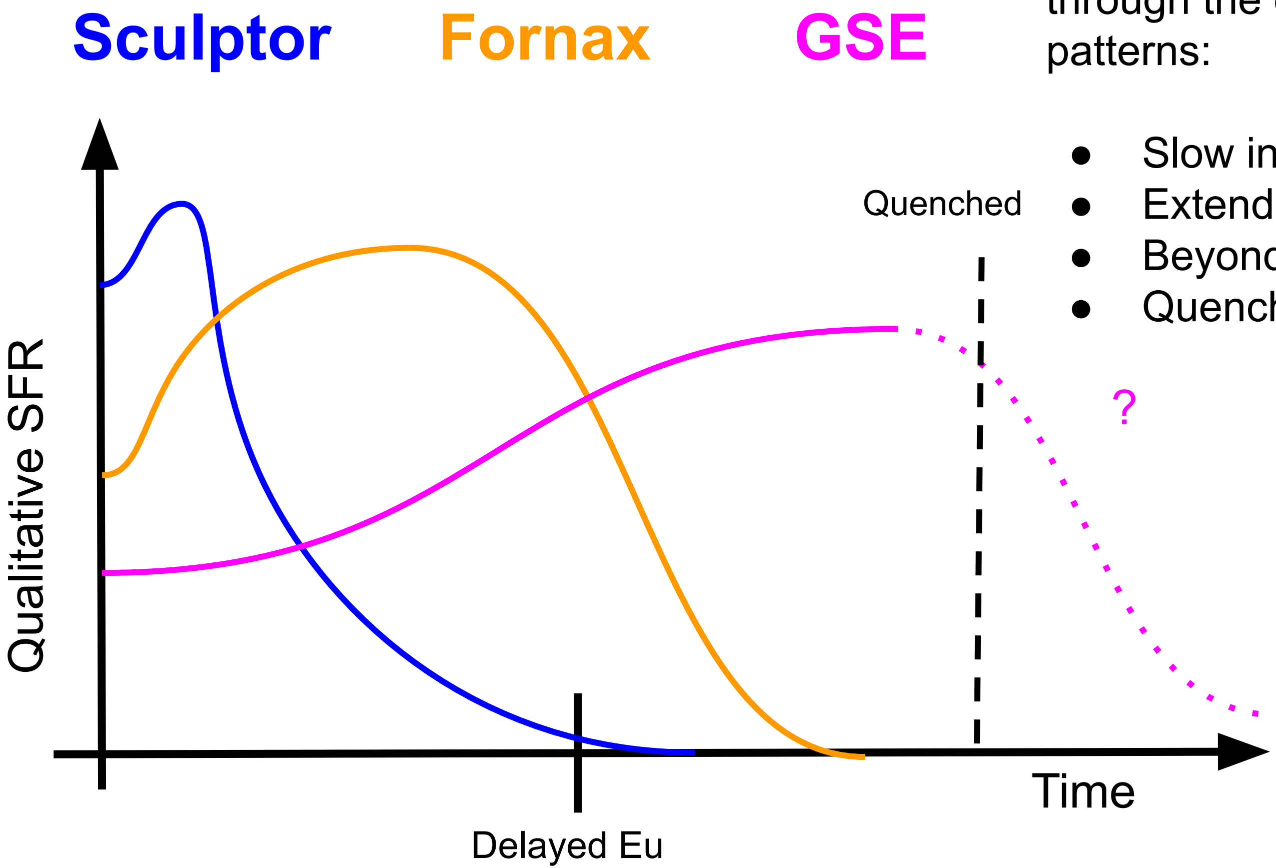
Delayed Eu

[Eu/Ba] ratio express the balance between delayed and extended source of Ba vs. the two sources of Eu, the delayed and the immediate.

1. When we see a steeply decrease in Sculptor (the inverse of [Ba/Mg]) it means that we do not have a secondary source of Eu contributing to the abundance pattern.
2. When this pattern stays high it means that something is adding Eu while AGB contribute with Ba, maybe delayed source of Eu.
3. Decreasing in high metallicities can mean a that we see the contribution of AGB, a result of a ‘Natural death’

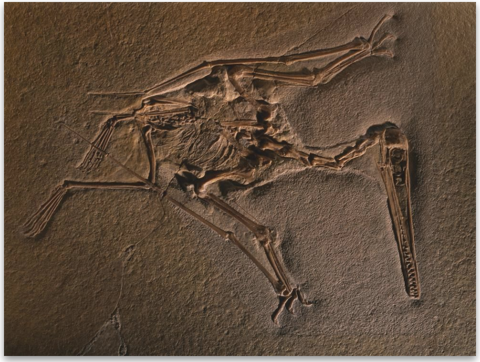
Note: In GSE we see the SNIa effects in [Fe/Mg], the AGB in [Ba/Mg] but not the AGB effects in [Eu/Ba].

Summary

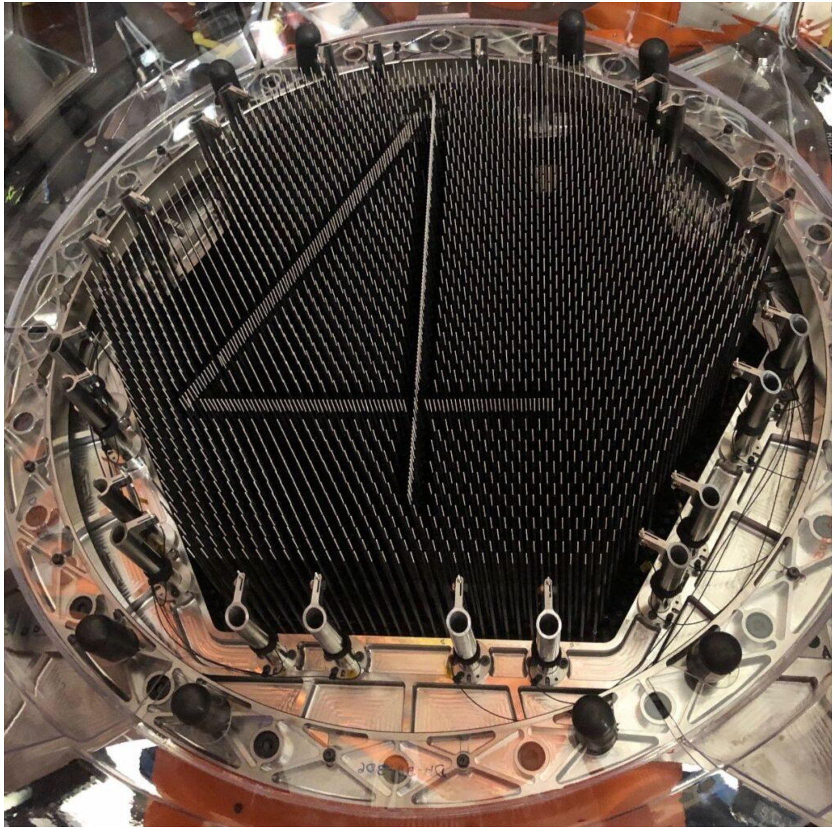


Key aspects of the GSE-SFH as seen through the elemental abundances patterns:

- Slow initial star formation – [Ba/Mg]
- Extended – [Eu/Ba]
- Beyond 2 Gyr – [Eu/Mg]
- Quenched – [Fe/Mg] and [Eu/Ba]



Future perspectives



The AESOP fibre positioner for 4MOST that controls 2448 fibre spines. Credit: F. Watson.

We need more that to probe the metal-rich part of GSE.

- Observations

Large surveys. With 4MOST on VISTA we are able to measure elemental abundances not only for more stars but also find stars that covers the whole GSE metallicity range.

In particular S2 - Halo High-resolution

Next steps:

- Galactic Chemical Evolution models

Using Galactic chemical evolution models to study the star formation history of GSE.

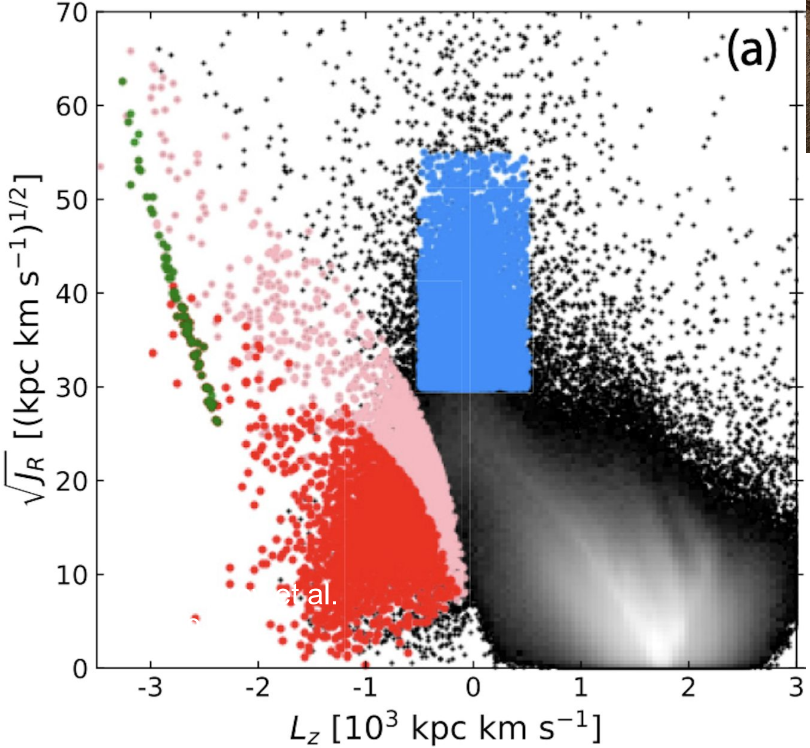
Collaboration with Cescutti - Trieste.

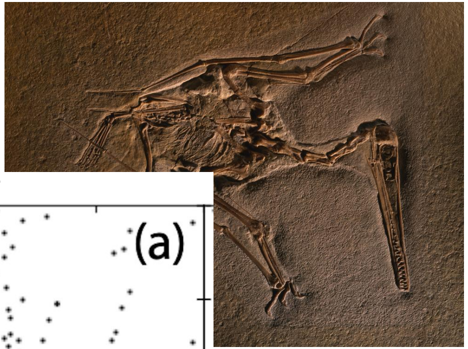

Questions?

Going back to our Fossil- Selection

Feuillet et al. 2021

Gaia DR2 RVS





There are several ways to ‘find’ the GSE.

We have tested some selection criteria

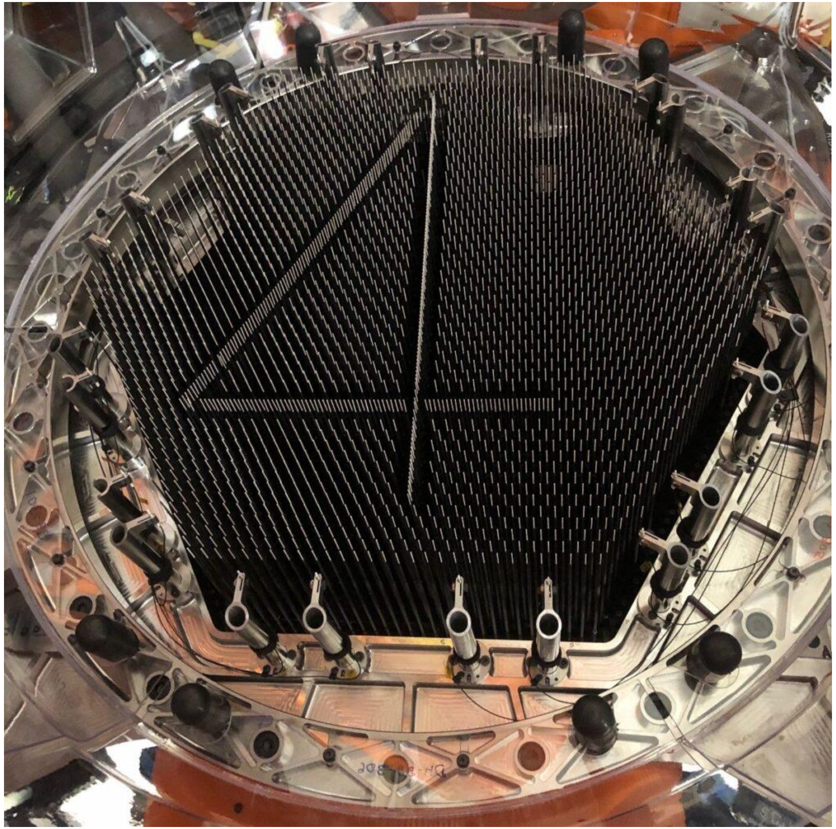
- Helmi et al. (2018) $-1500 < L_z < 150$, $E_n > -1.8 \times 10^5$
- Naidu et al. (2020) $e > 0.7$
- Feuillet et al. (2021) $-500 \leq L_z \leq 500$, $30 \leq \sqrt{J_r} \leq 55$

Based on the findings in Carrillo et al. (2023), the most complete selection criteria is the one that considers cuts in eccentricity (usual e> 0.7 Naidu et al. 2020) and the most pure is the one using Lz and √Jr (Feuillet et al. 2021).

For this work the purity is more important so we decided to take Feuillet et al. (2021) scheme

Future perspectives

4MOST and S2



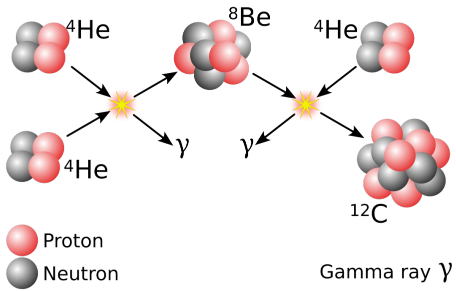
The AESOP fibre positioner for 4MOST that controls 2448 fibre spines. Credit: F. Watson.

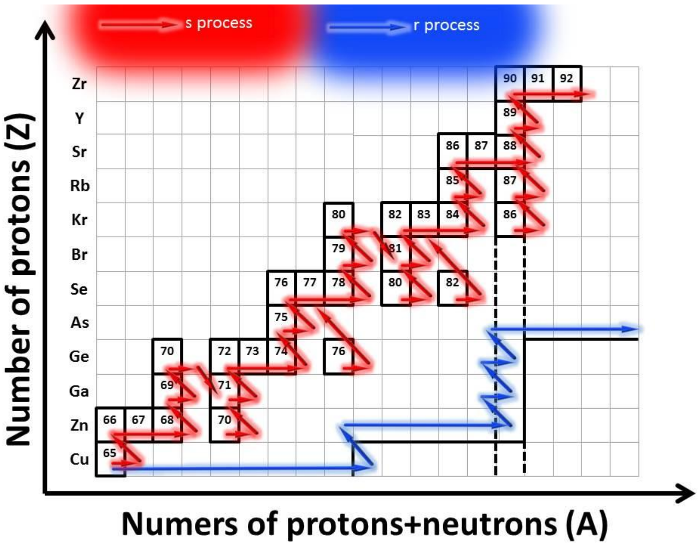
Baseline Specification

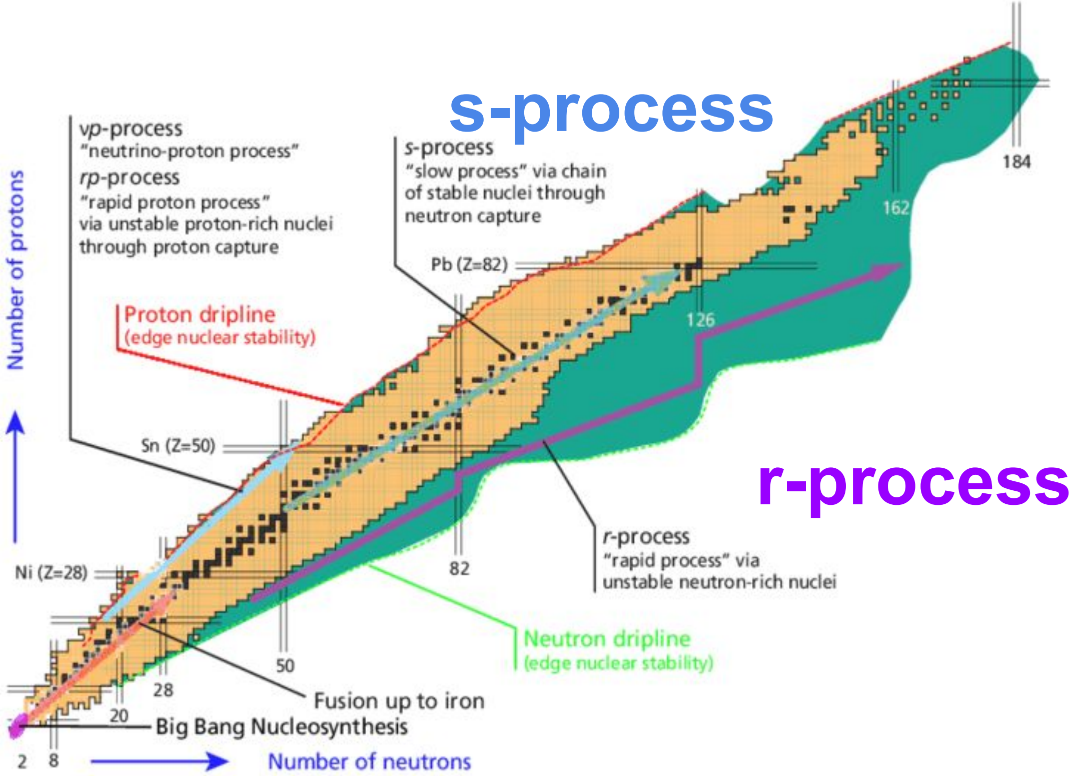
Requirement	**Baseline Specification**
Field-of-View in hexagon	4.1 degree^2
Fibre multiplex per pointing	2436
Smallest target separation	<17″
Low-Resolution Spectrographs (LRS)	
Fibre multiplex	1624
Spectral resolution	R>4000–7800
Wavelength coverage	370–950 nm
High-Resolution Spectrographs (HRS)	
Fibre multiplex	812
Spectral resolution	R>18,500
Wavelength coverage	392.6–435.5, 516–573 & 610–679 nm

Criterion #	Bright survey	Faint survey	Deep survey
1	$+20° \geq \text{dec} \geq -80°$		Selected areas
2	$\lvert b \rvert > 20°$		
3	$[\text{Fe/H}] < -0.5$		
4	$12.0 \leq G \leq 14.5$	$14.5 < G \leq 15.5$	$15.5 < G \leq 17.0$
5	$0.15 \leq (G_{BP}-G_{RP})_0 \leq 1.10$		
6	$(1.10 < (G_{BP}-G_{RP})_0 \leq 1.60)$ & $(M_G < 3.5)$		
Total number of targets	1 150 000	800 000	26 000
Targets at [Fe/H] < −2.0	13 000	18 000	100

How do we make elements - burning and explosive

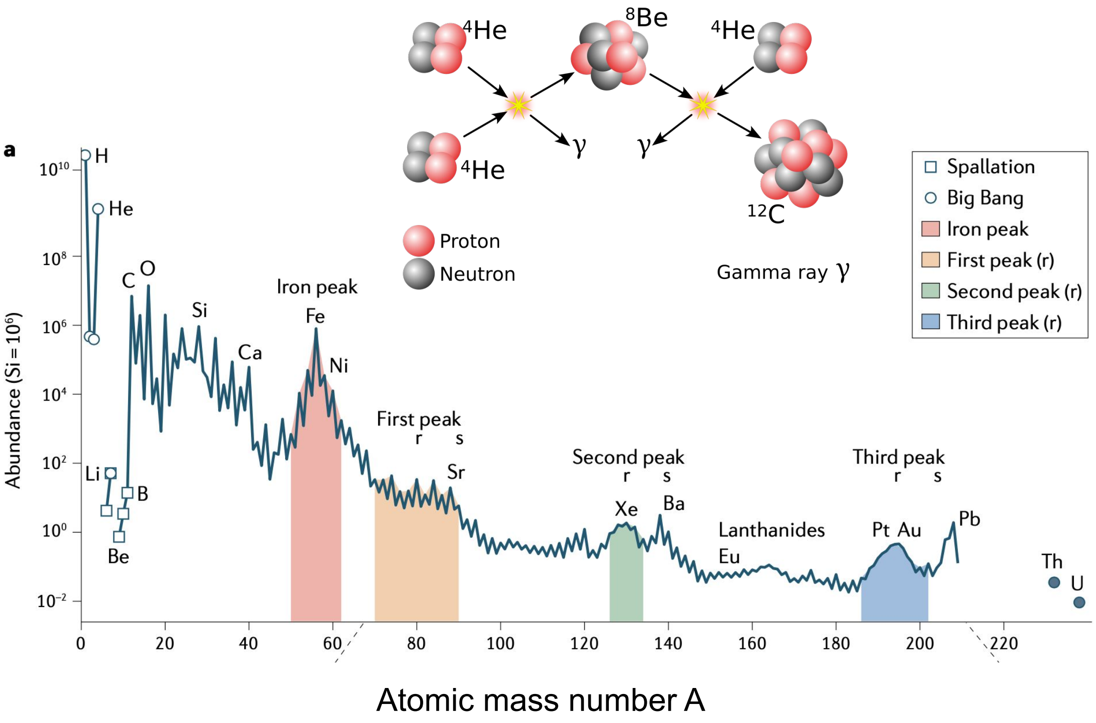


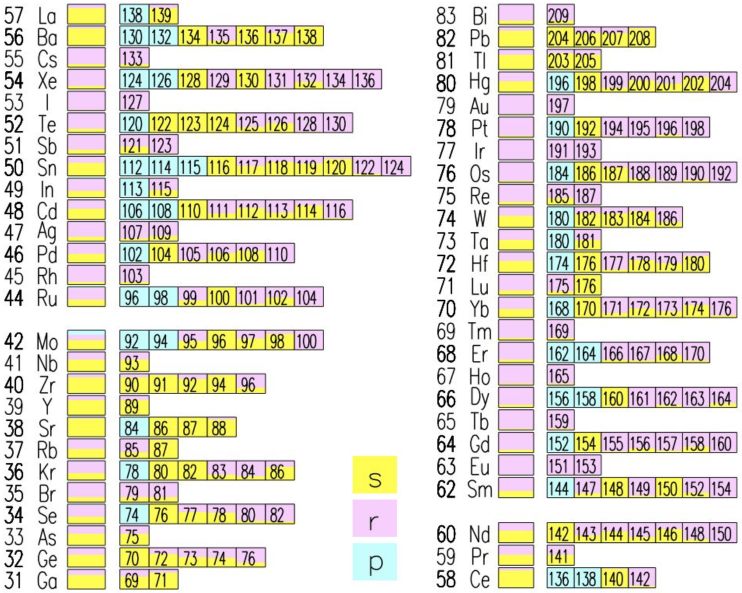




Credit: Sergio Cristallo

Nucleosynthesis



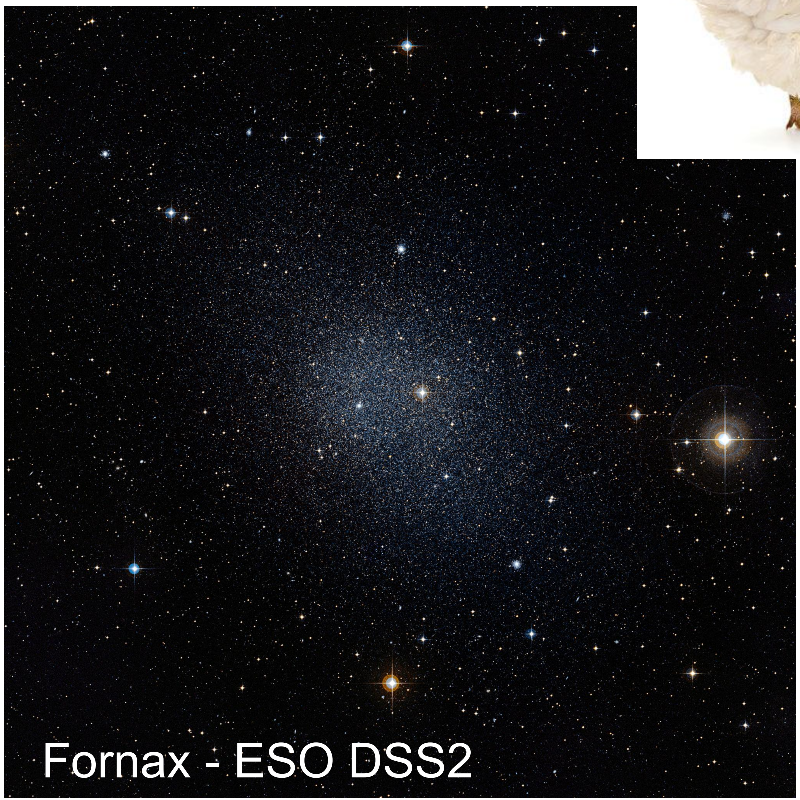


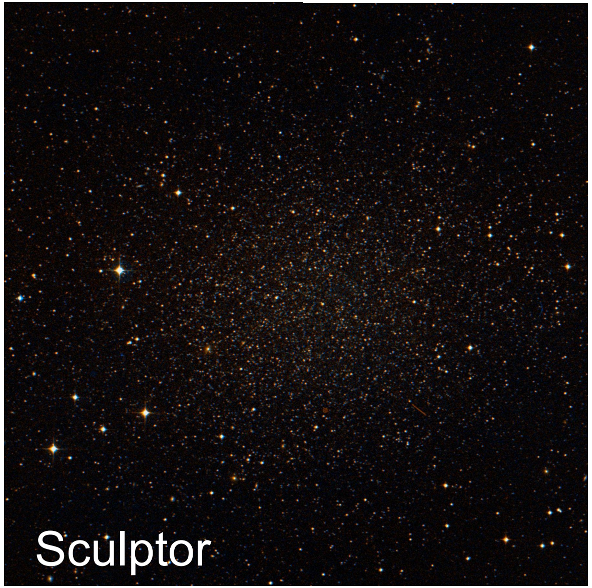
Siegel et al. 2022

Prantzos et al. 2020

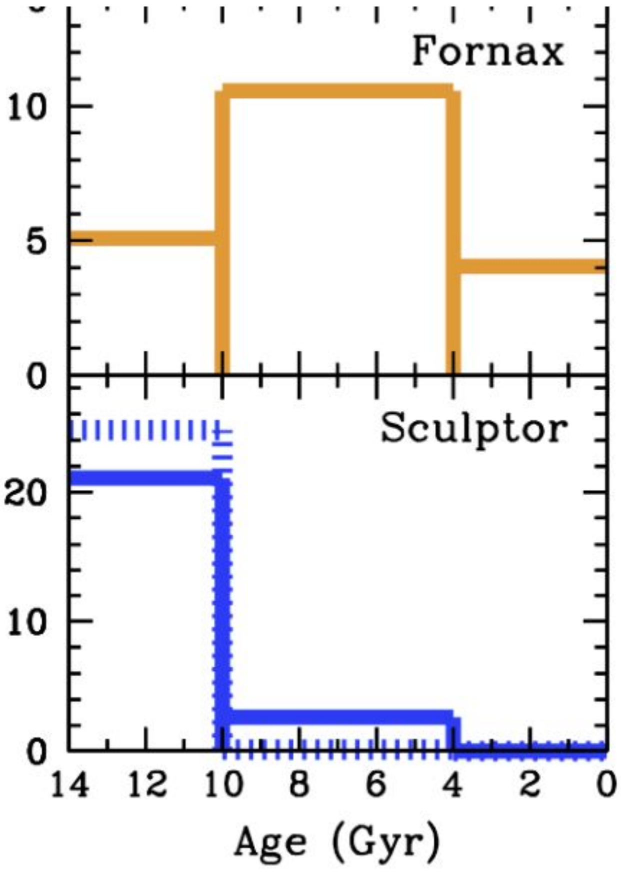
Dwarf Galaxies

M_{Stellar} [$M_\odot$]	M_{Total} [$M_\odot$]	Reference
	Gaia-Sausage-Enceladus	
$10^{8.85-9.85}$	—	Feuillet et al. (2020)
	LMC	
1.5×10^9	$1.38^{+0.27}_{-0.24} \times 10^9$	McConnachie (2012) Erkal et al. (2019)
	Fornax	
2×10^7	5.6×10^7	McConnachie (2012)
	Sculptor	
2.3×10^6	14×10^6	McConnachie (2012)



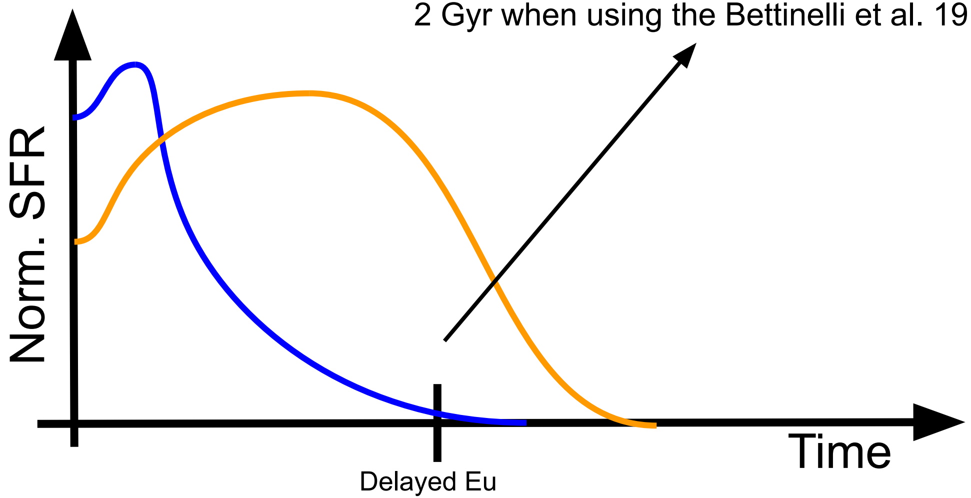


SFH for SC and FORNAX (only) BEST PLACE?

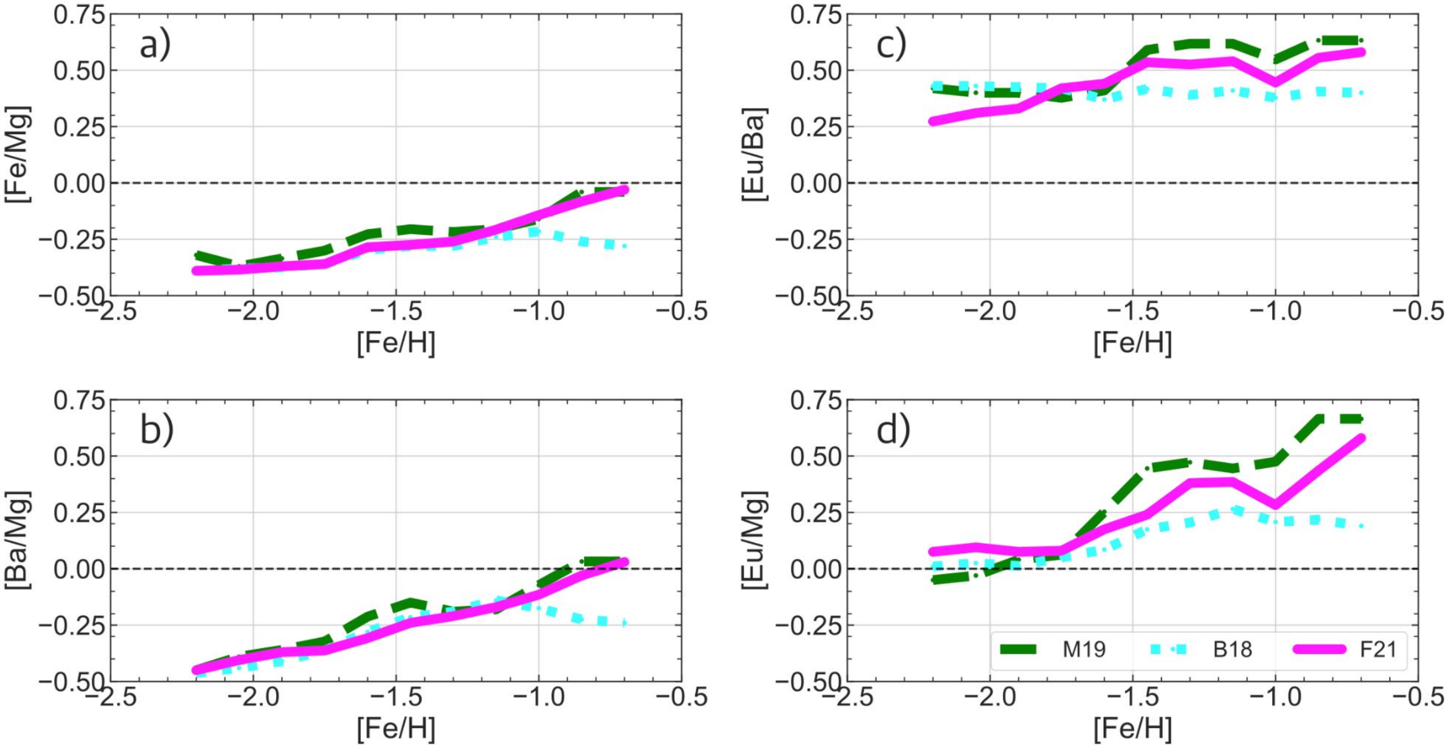


Some aspects of the SFH:
Fornax: Slow initial star formation, extended, Natural suppression of the star formation.
Sculptor: Strong initial star formation, early burst, and ceased star formation before the delayed Eu source.

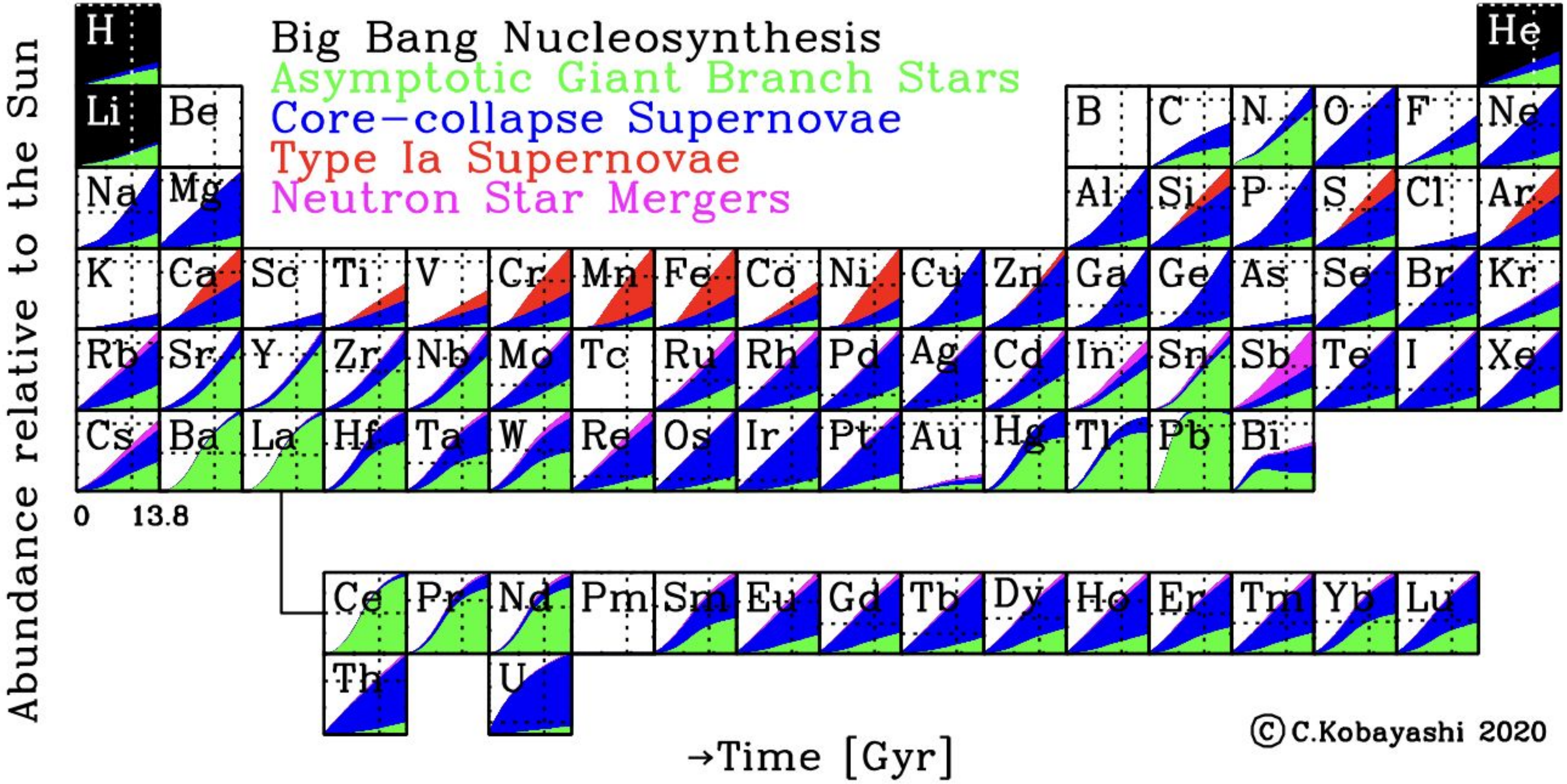
4 Gyr in Skúladóttir & Salvadori 2020
2 Gyr when using the Bettinelli et al. 19 SFH



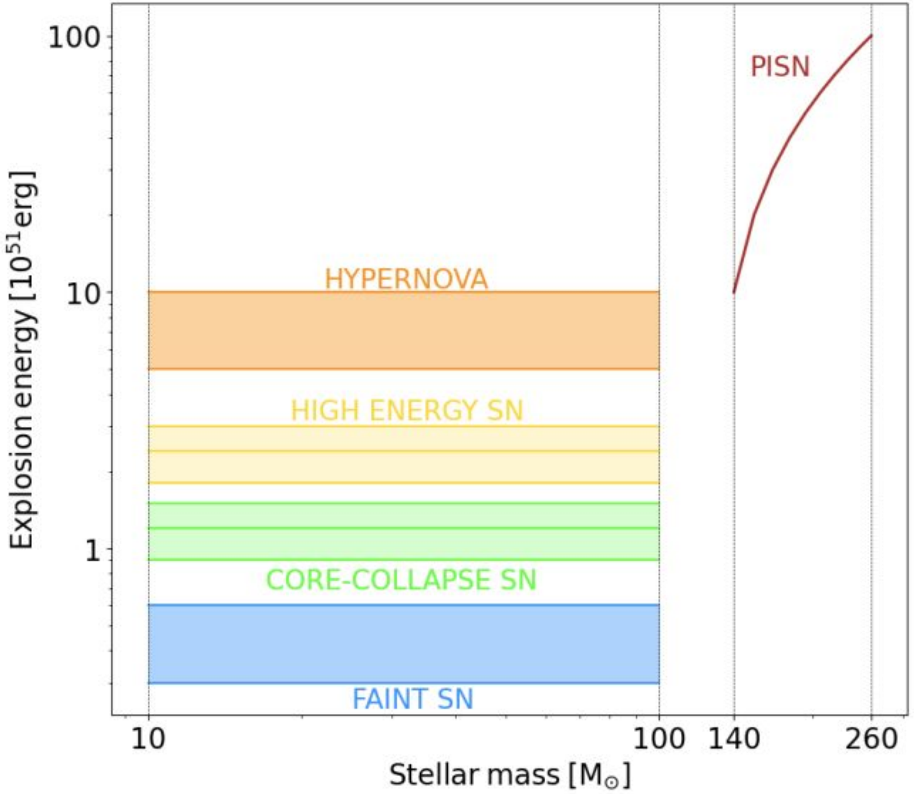
GSE selections



Nucleosynthesis - Where it happens



Understanding r-rich progenitors



Vanni et al. 2023

The astrophysical site that can synthesize the r-process elements:

- CCSN and which energy?
- Magnetorotational driven SN?
- Jet-driven SN?
- NSM?
- BHNSM?

Understanding r-rich progenitors

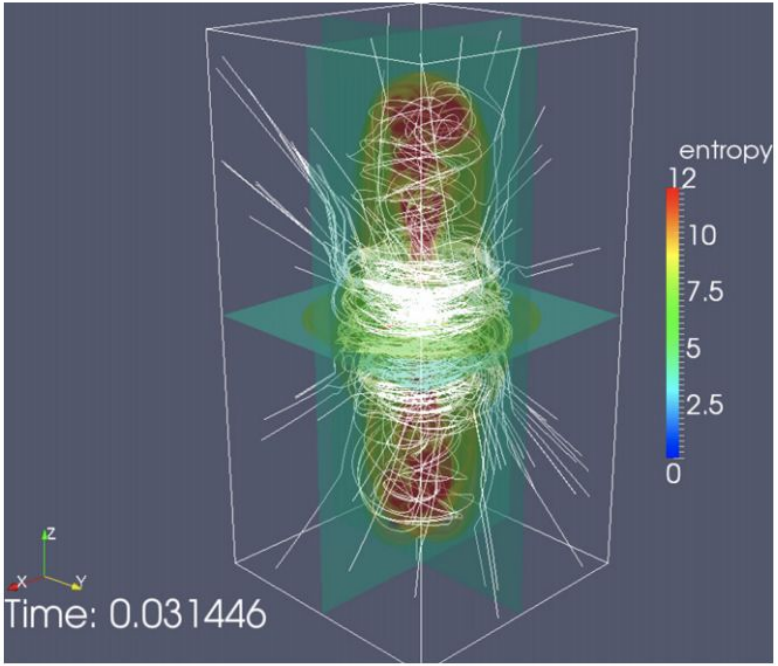


Figure 1. 3D entropy contours spanning the coordinates planes with magnetic field lines (white lines) of the MHD-CCSN simulation ~31 ms after bounce. The 3D domain size is 700 × 700 × 1400 km.

The astrophysical site that can synthesize the r-process elements:

- CCSN and which energy?
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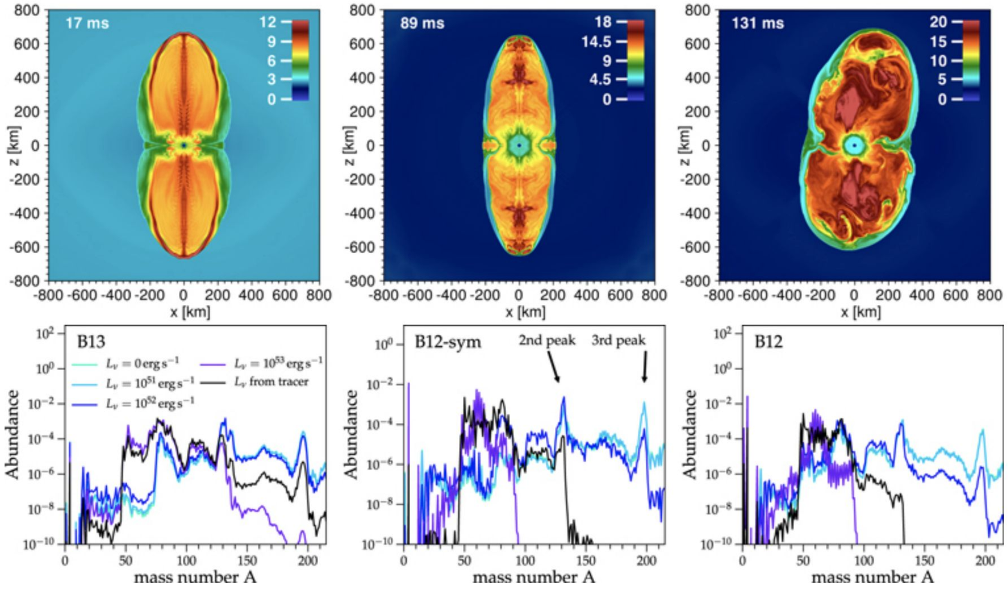
Winteler et al. 2012

Understanding r-rich progenitors



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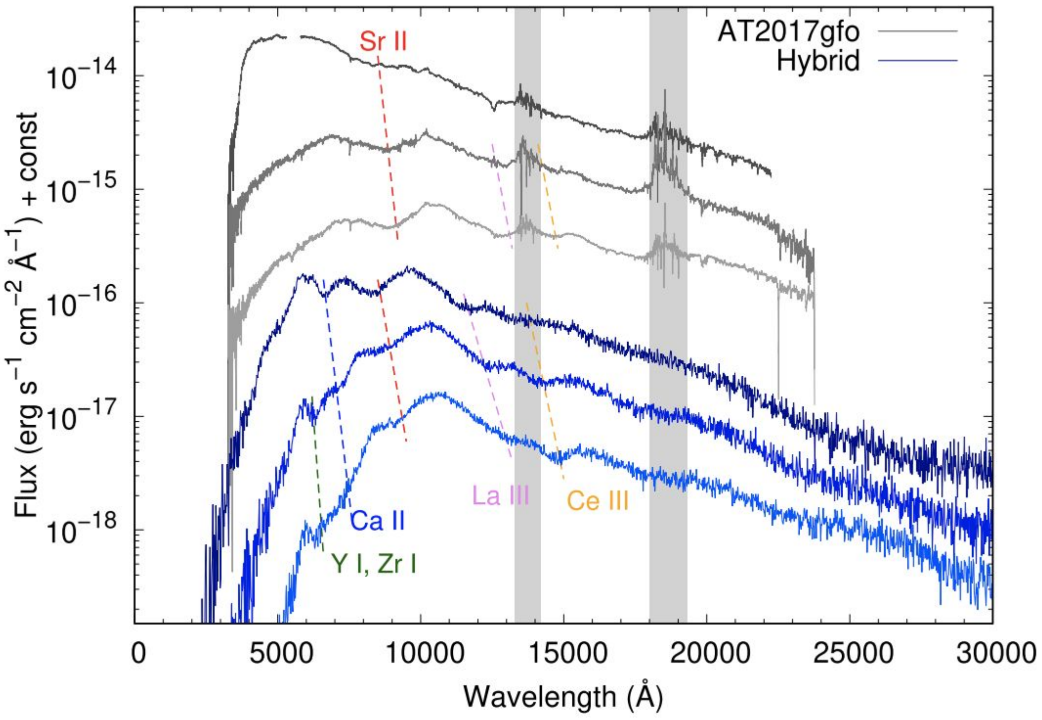
Obergaulinger & Reichert et al. 2023

Understanding r-rich progenitors



The astrophysical site that can synthesize the r-process elements:

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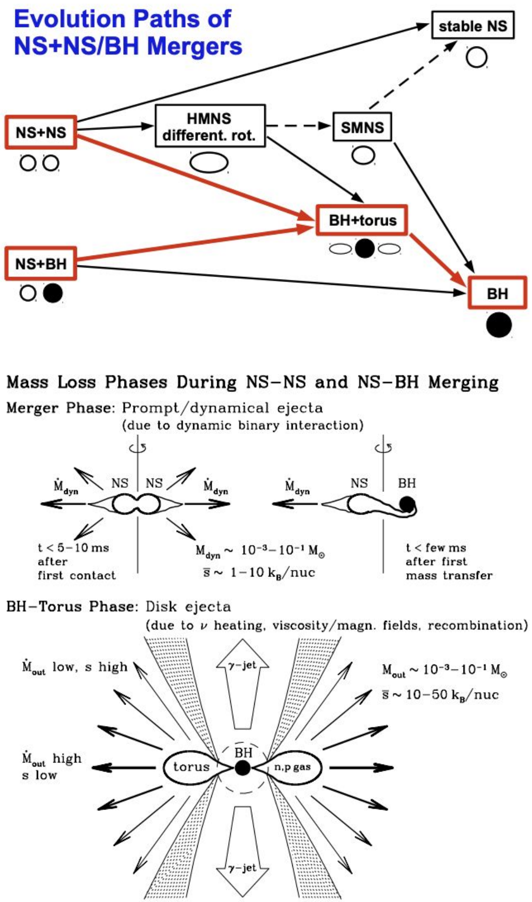
Domoto et al. 2022

Understanding r-rich progenitors



Just et al. 2015

The astrophysical site that can synthesize the r-process elements:

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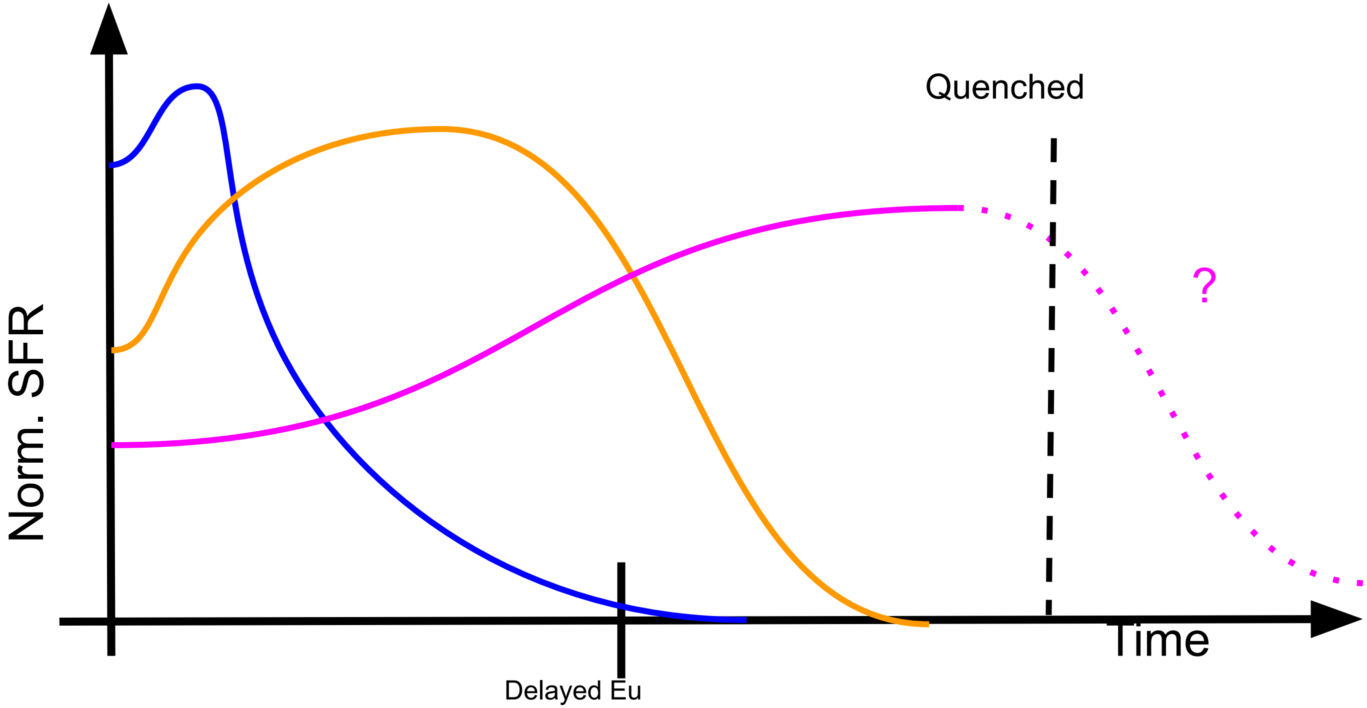
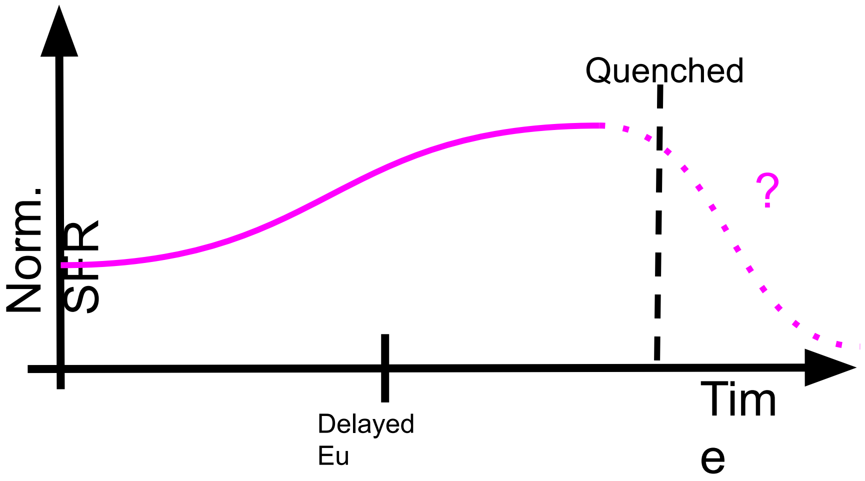
- BHNSM?


Norm. SFR
Quenched
?
Time
Delayed Eu



Norm. SFR
Quenched
?
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e