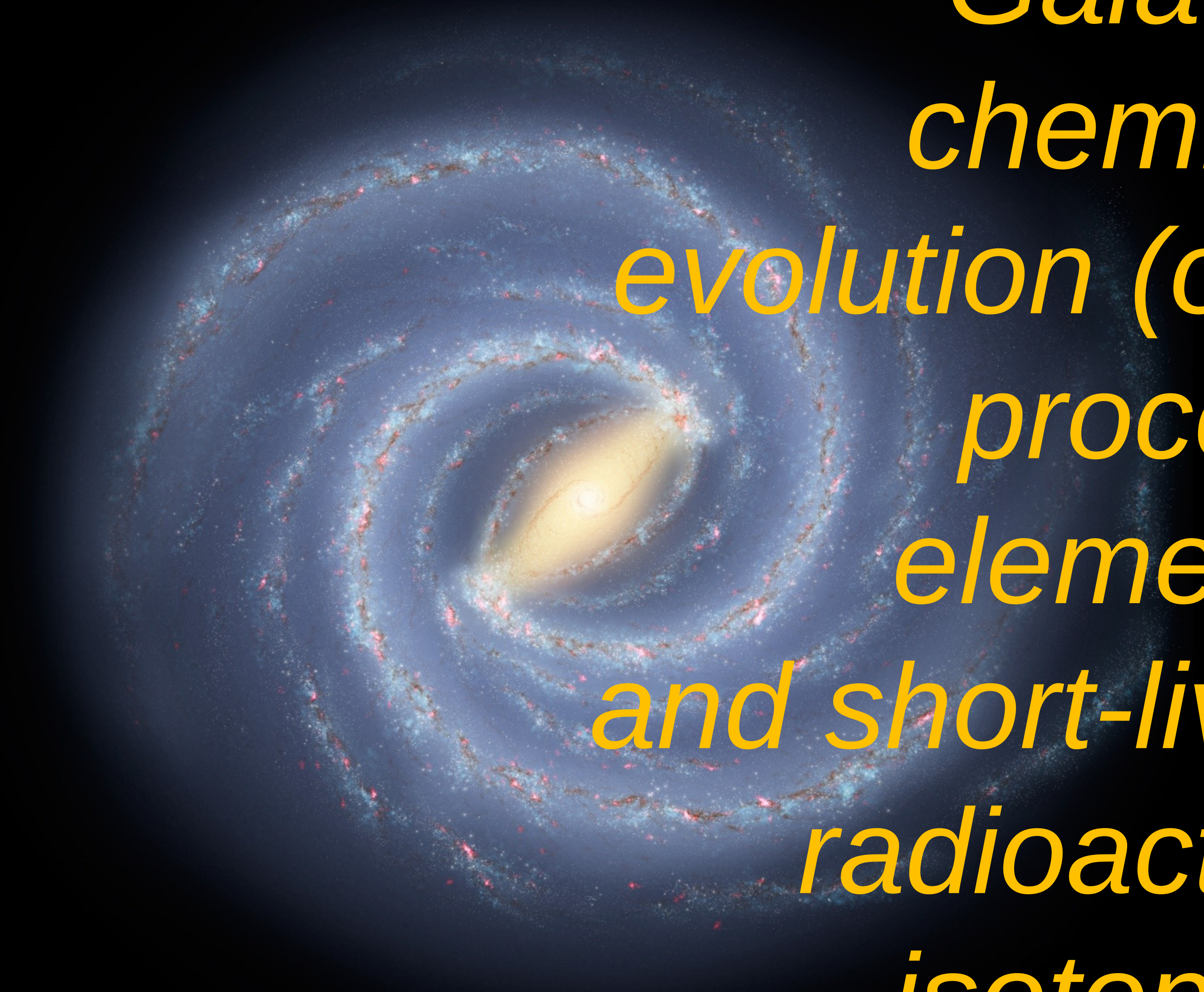
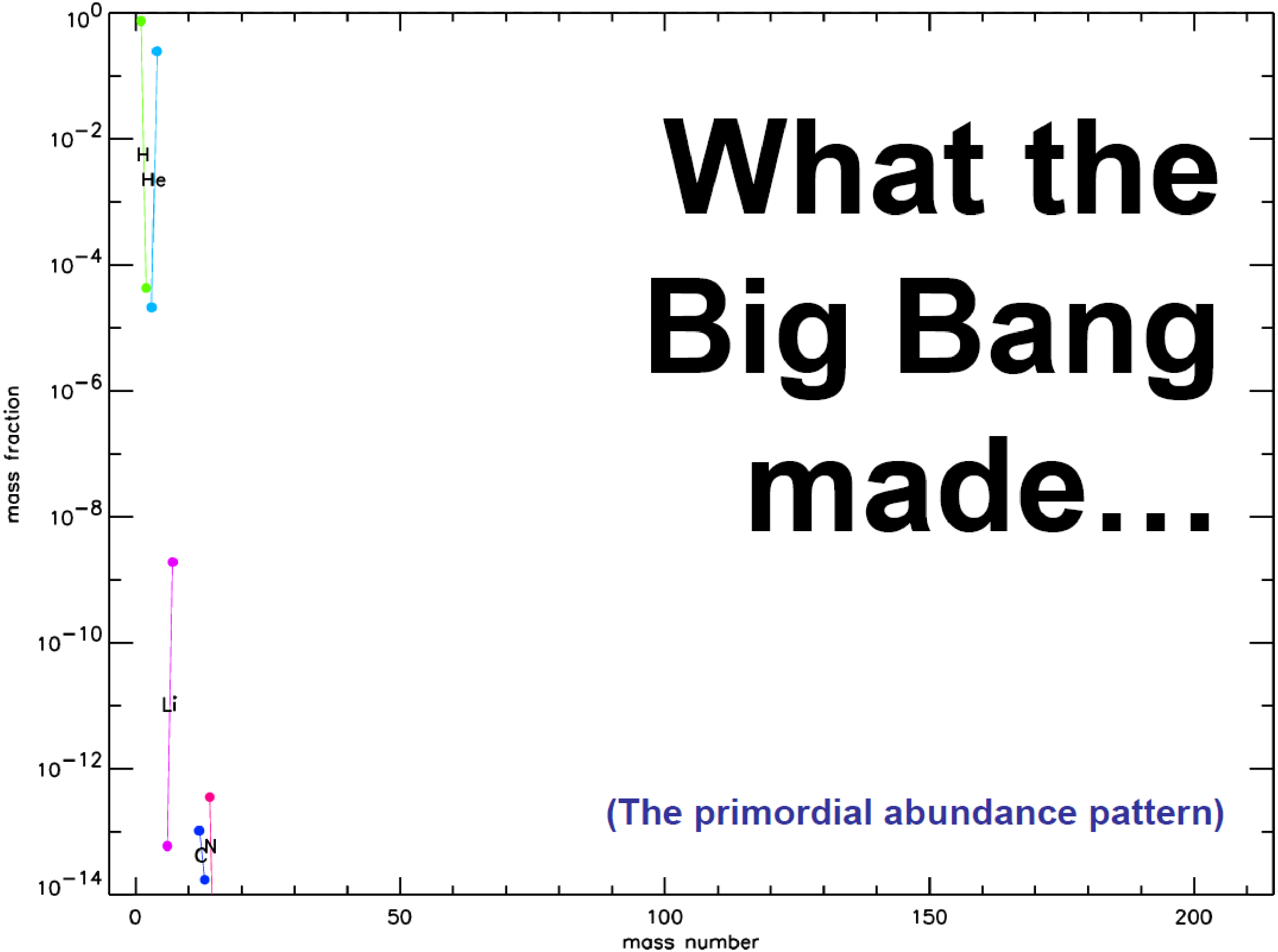


Galactic chemical evolution (of r-process elements and short-lived radioactive isotopes)

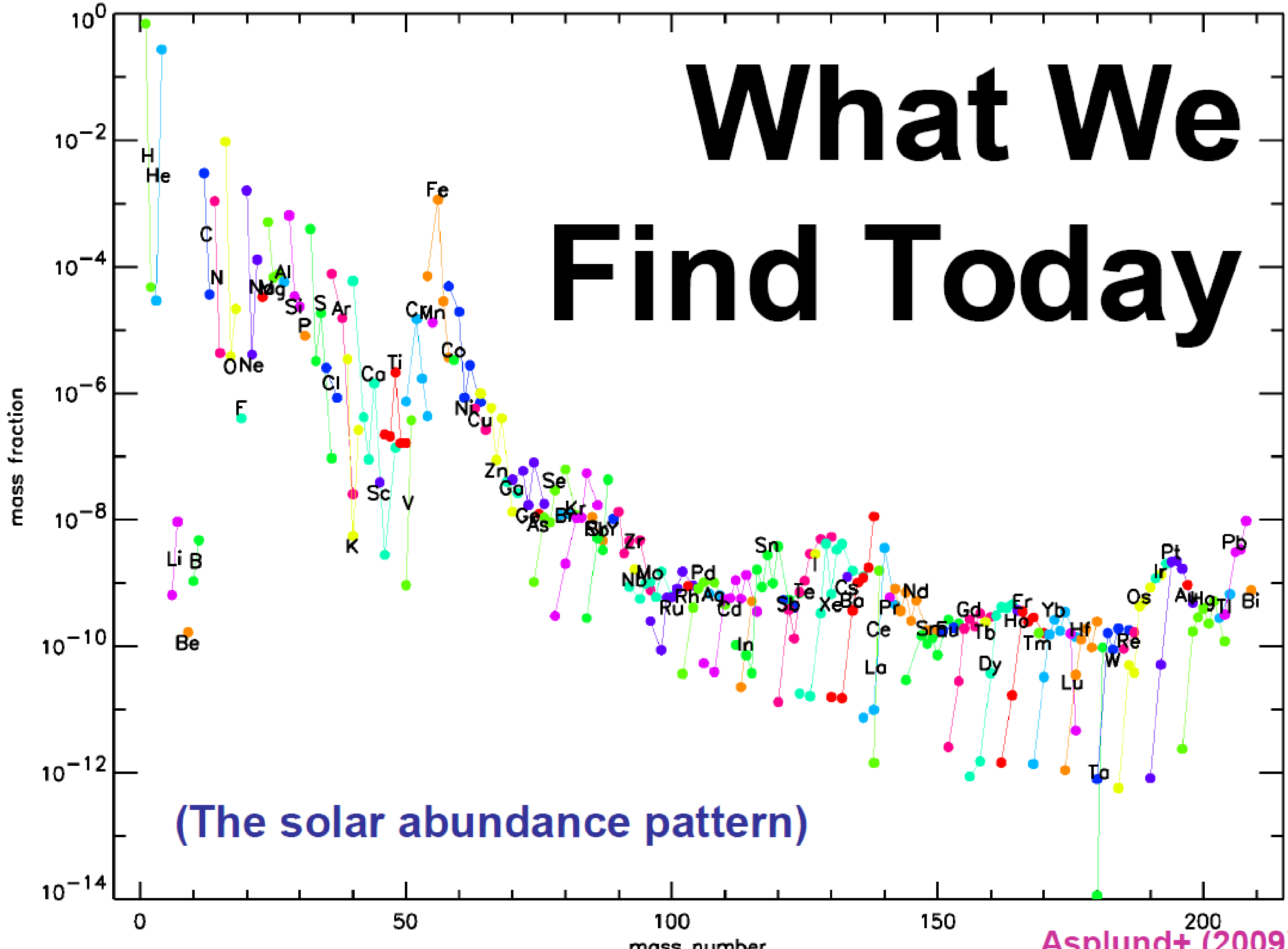
Benjamin Wehmeyer

http://www.nasa.gov/images/content/138785main_image_feature_460_ys_full.jpg



Extracted from Fields et al. (2002),
slide from A. Heger

What We Find Today

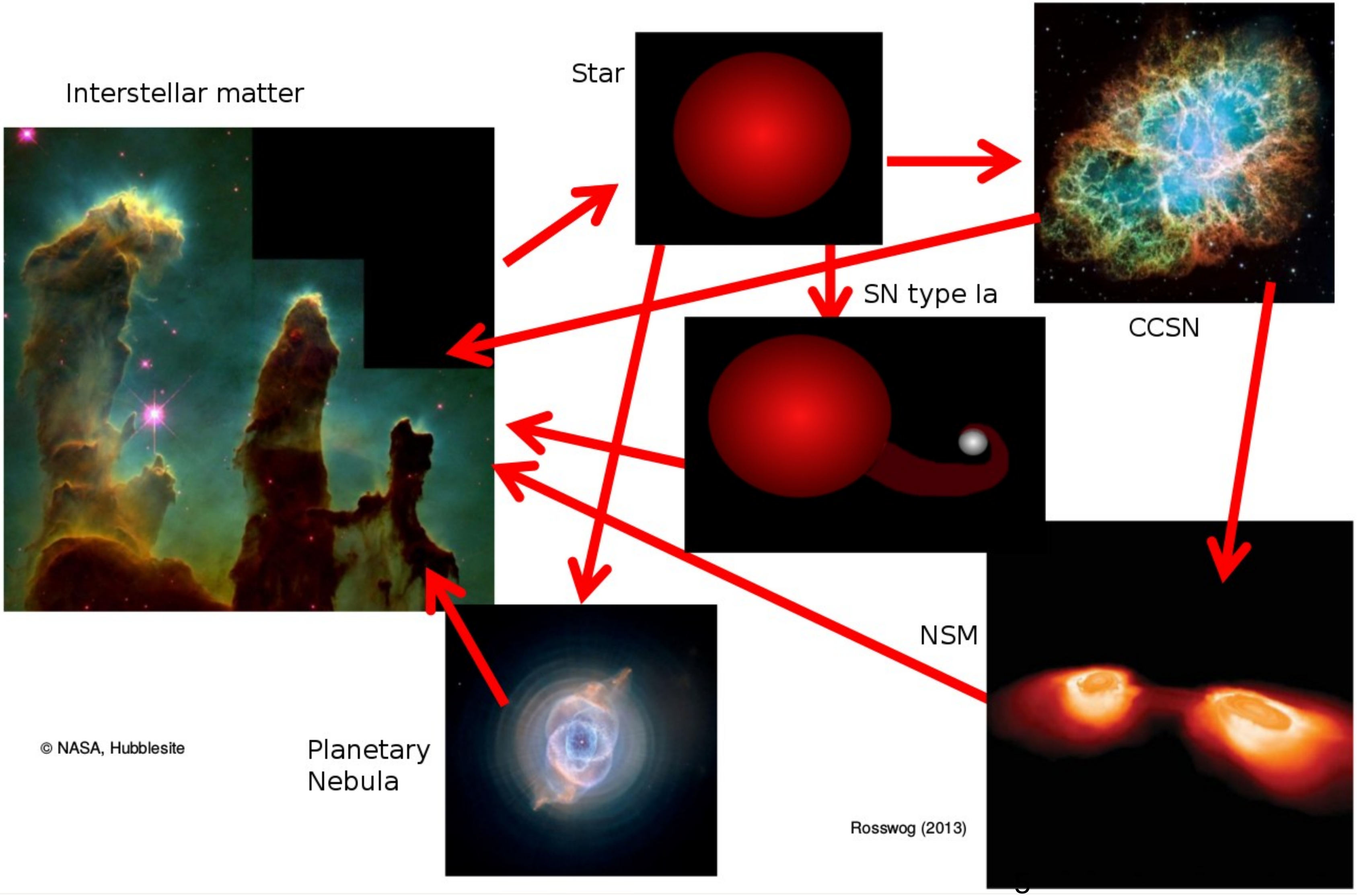


Asplund+ (2009)

Extracted from Fields et al. (2002),
slide from A. Heger

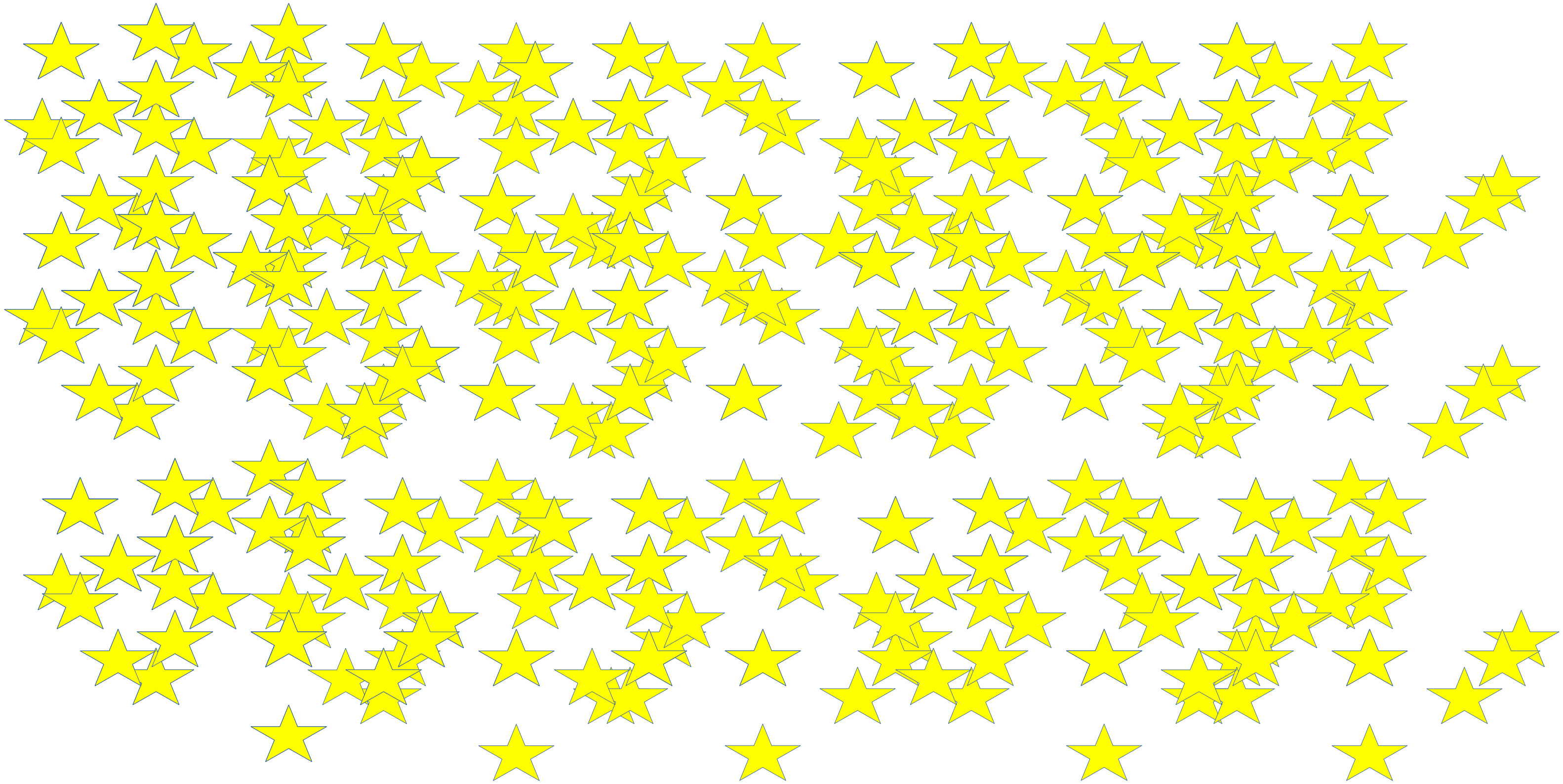
What happens in between???

What does a GCE model do?



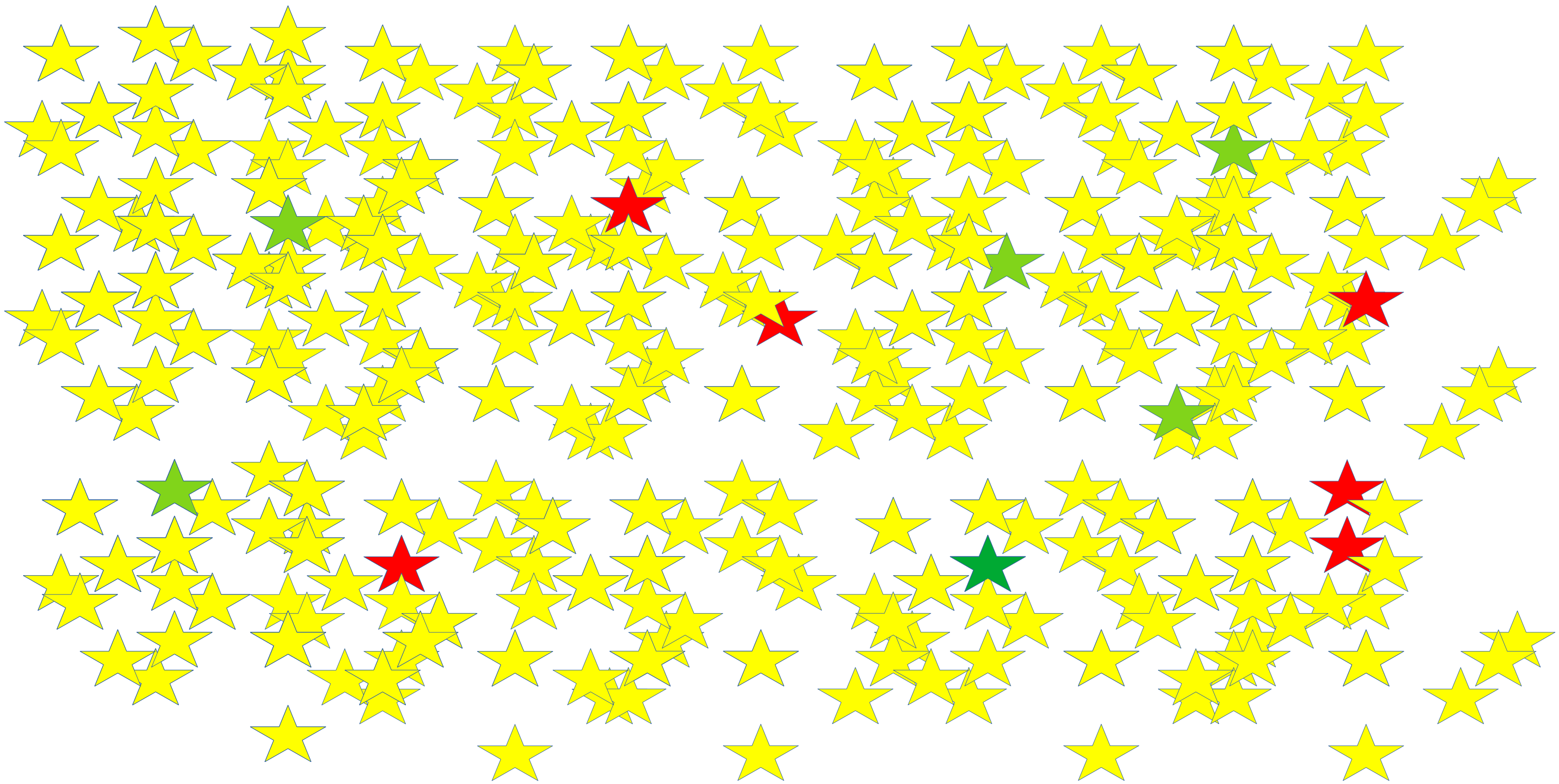
Brief introduction: Galactic Chemical Evolution

<u>Look at the night sky:</u> Unsorted stars.



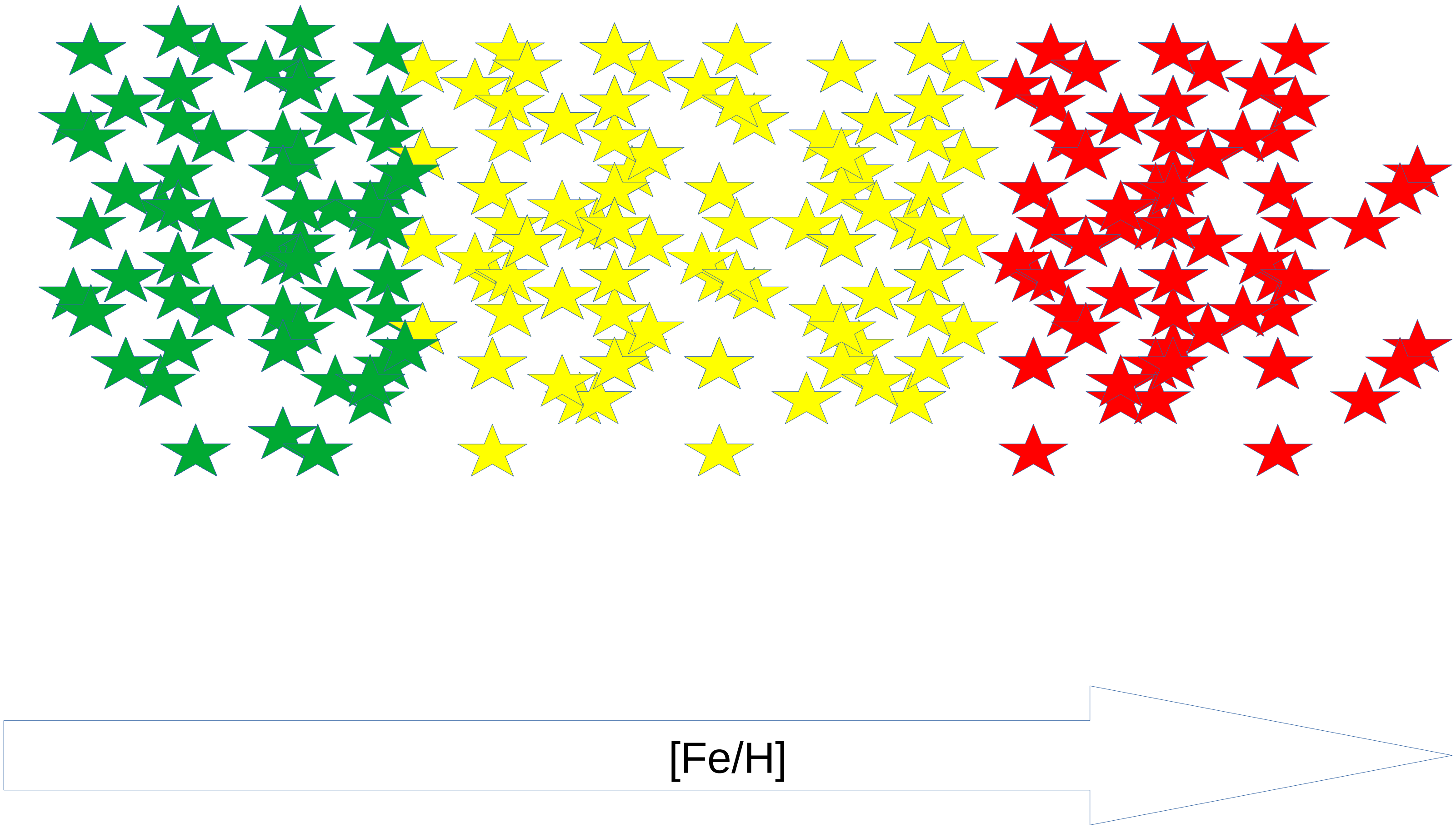
Brief introduction: Galactic Chemical Evolution

<u>Now: Identify Fe contents</u>: Solar metallicity, metal poor, extremely metal poor



Brief introduction: Galactic Chemical Evolution

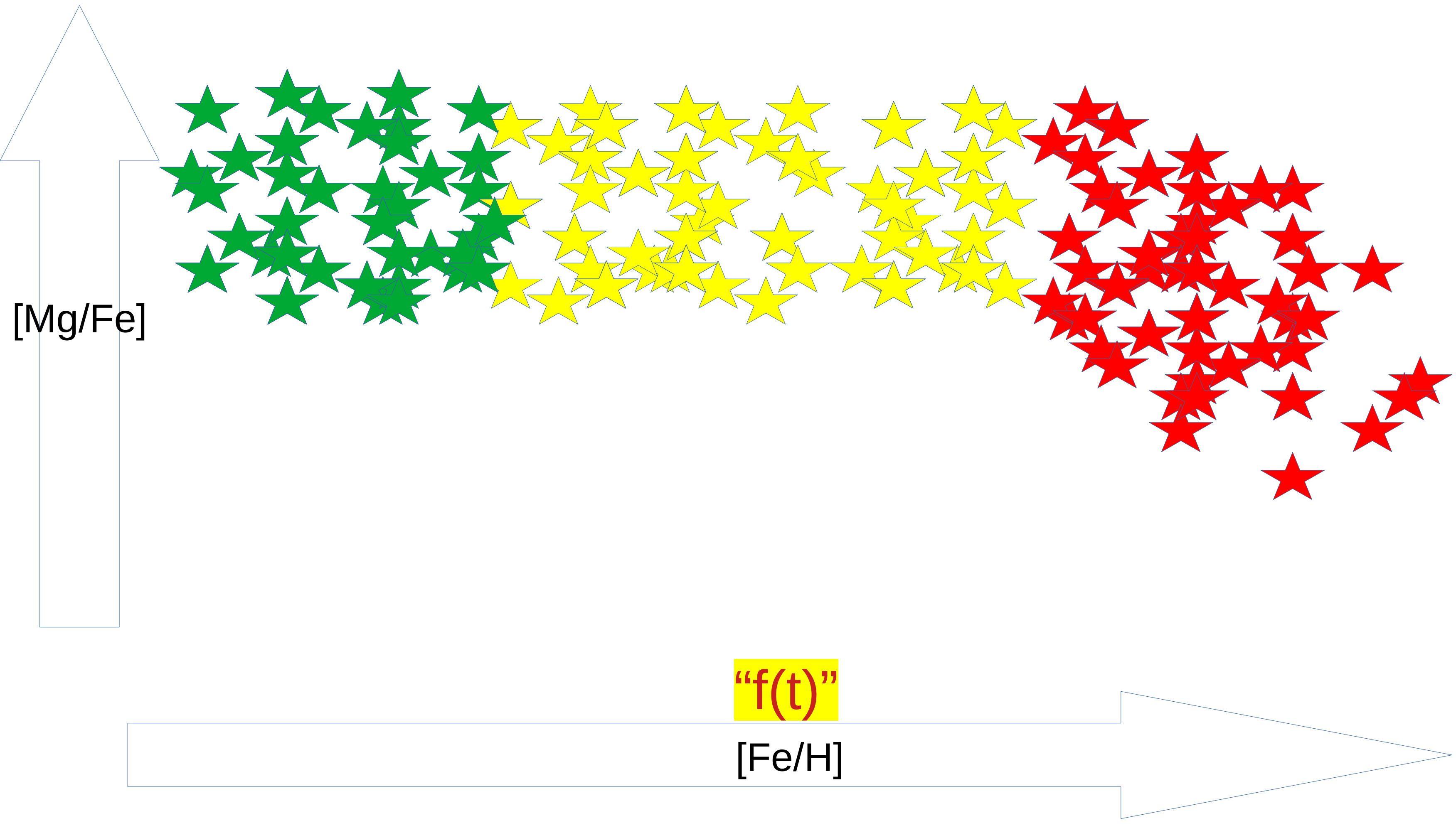
Sort the stars according to their Fe contents:



$$[X/Y] = \log (X/Y)_{star} - \log (X/Y)_{Sun}$$

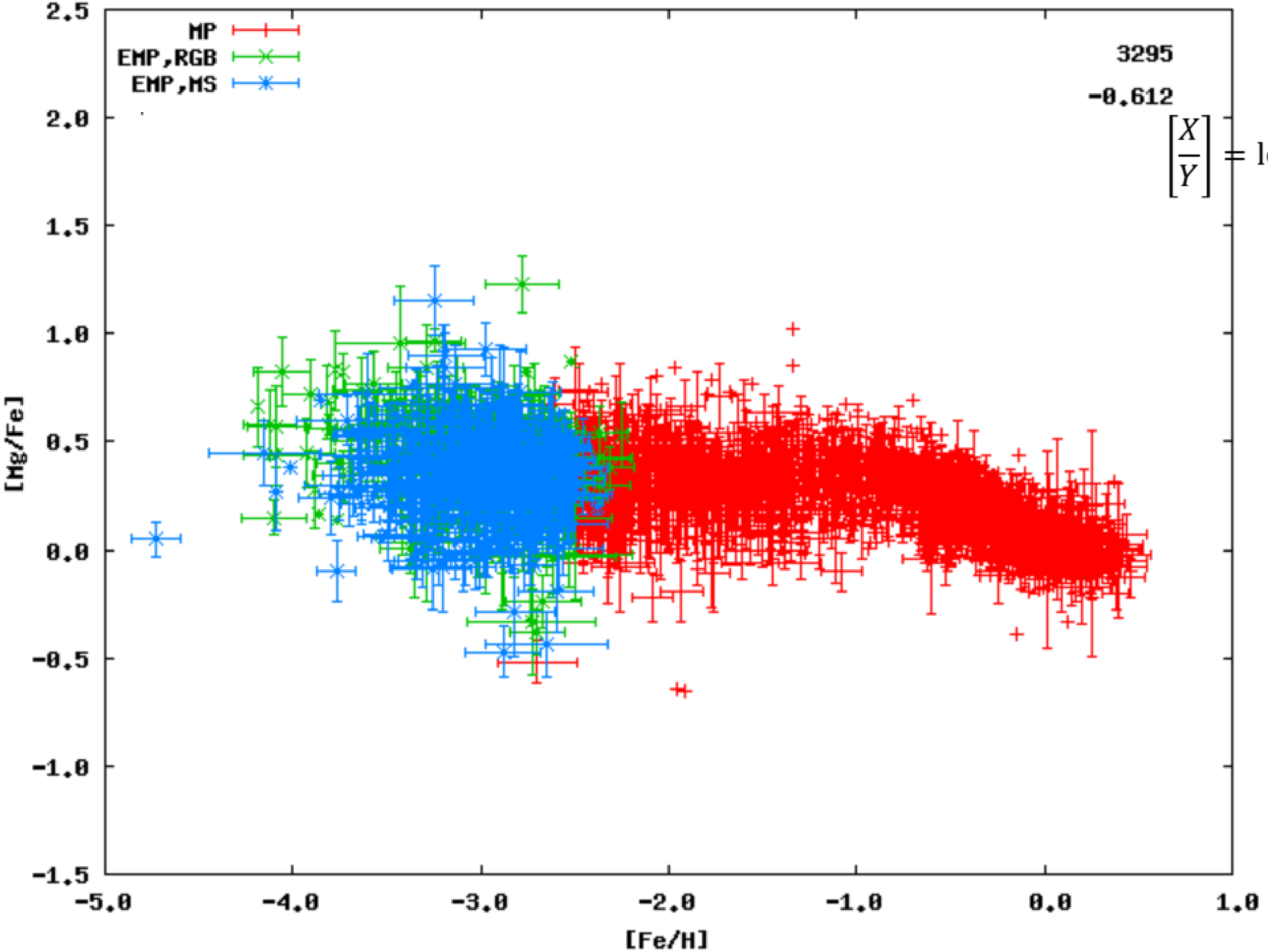
Brief introduction: Galactic Chemical Evolution

Now: introduce alpha element y-axis.



$$[X/Y] = \log (X/Y)_{star} - \log (X/Y)_{Sun}$$

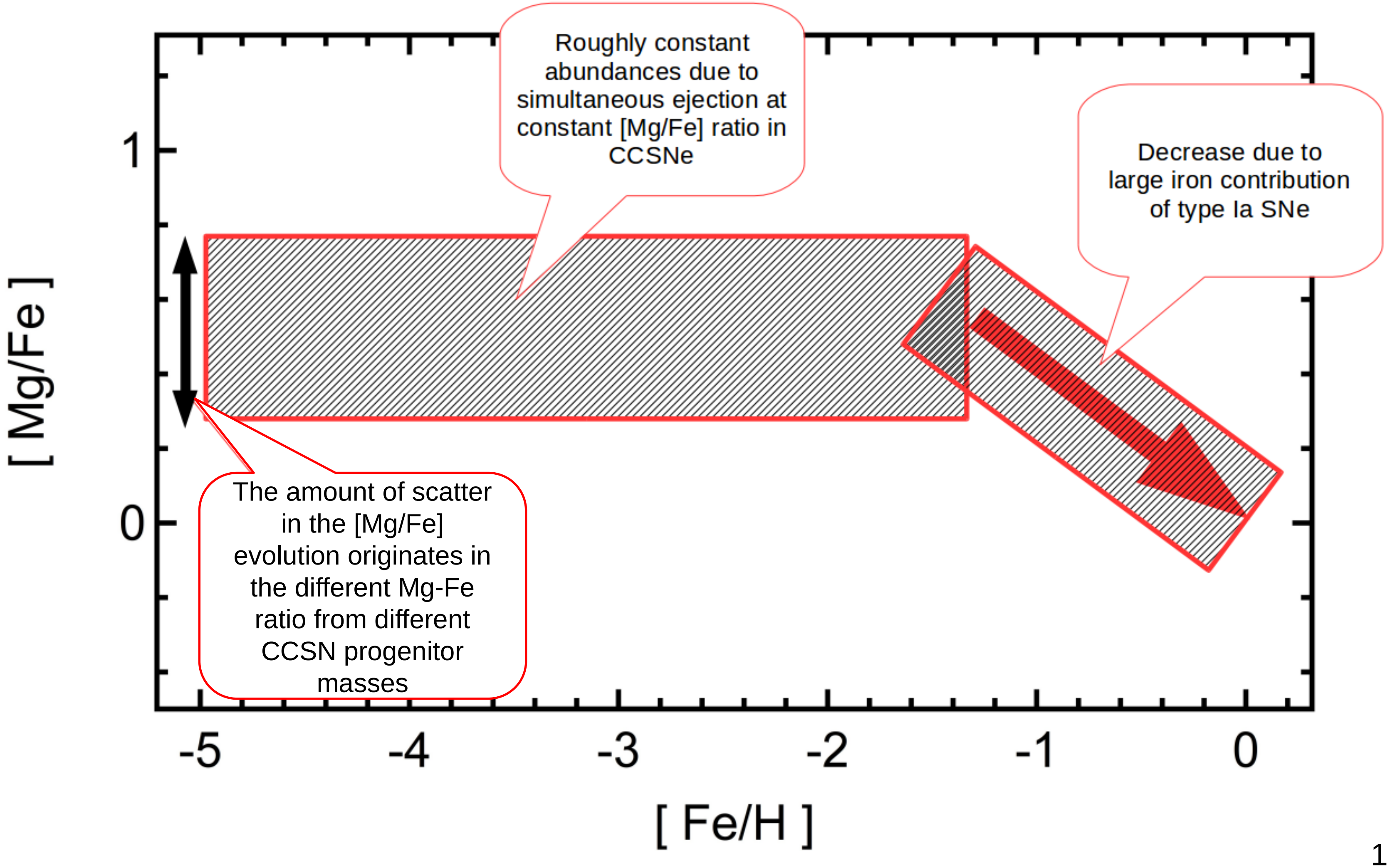
Now: Real data.



$$\left[\frac{X}{Y}\right] = \log \frac{X_{Star}/Y_{Star}}{X_{Sol}/Y_{Sol}}$$

From SAGA database, e.g., *T. Suda et al.*, PASJ, 60, 1159-1171, 2008.

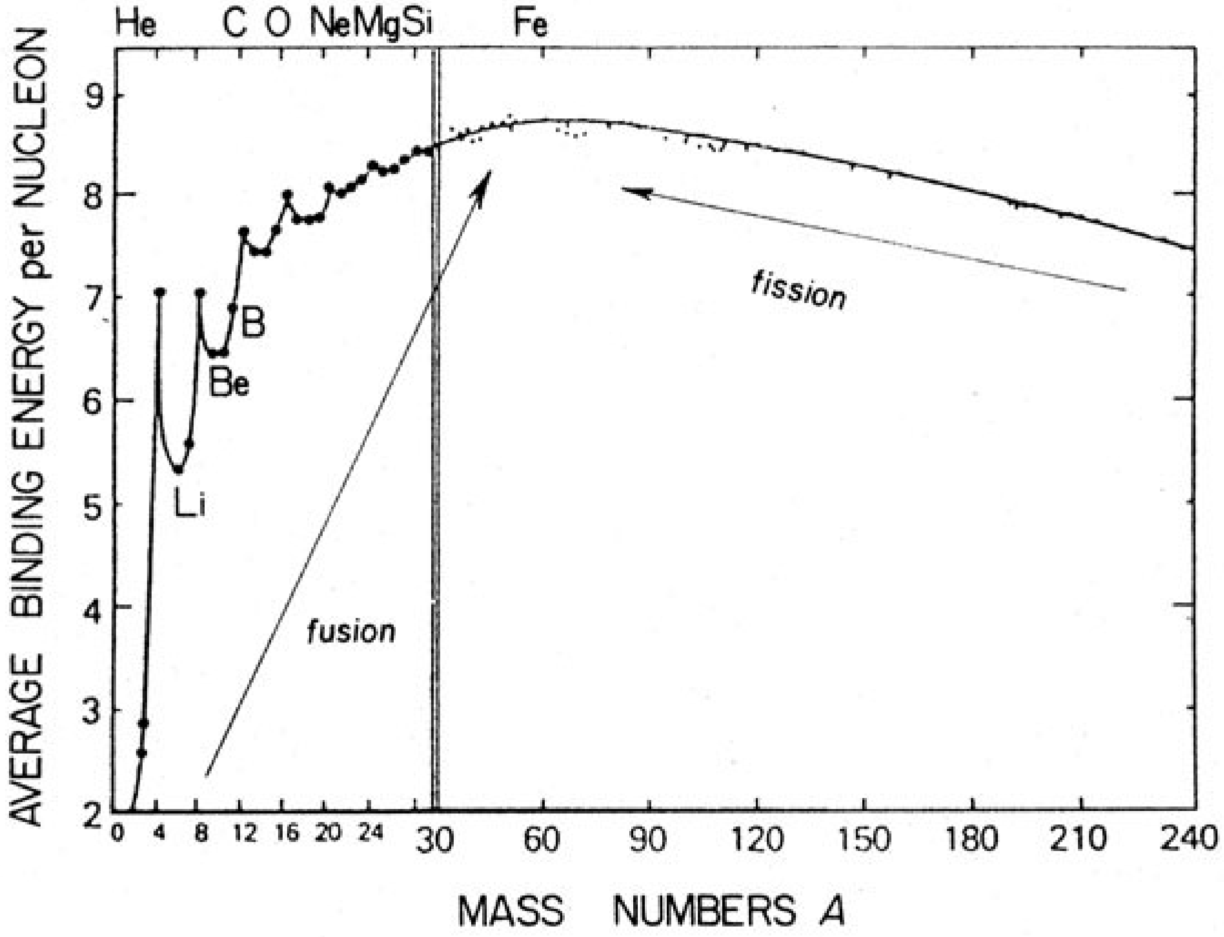
How can this evolution be explained?



Done?

Unfortunately not….

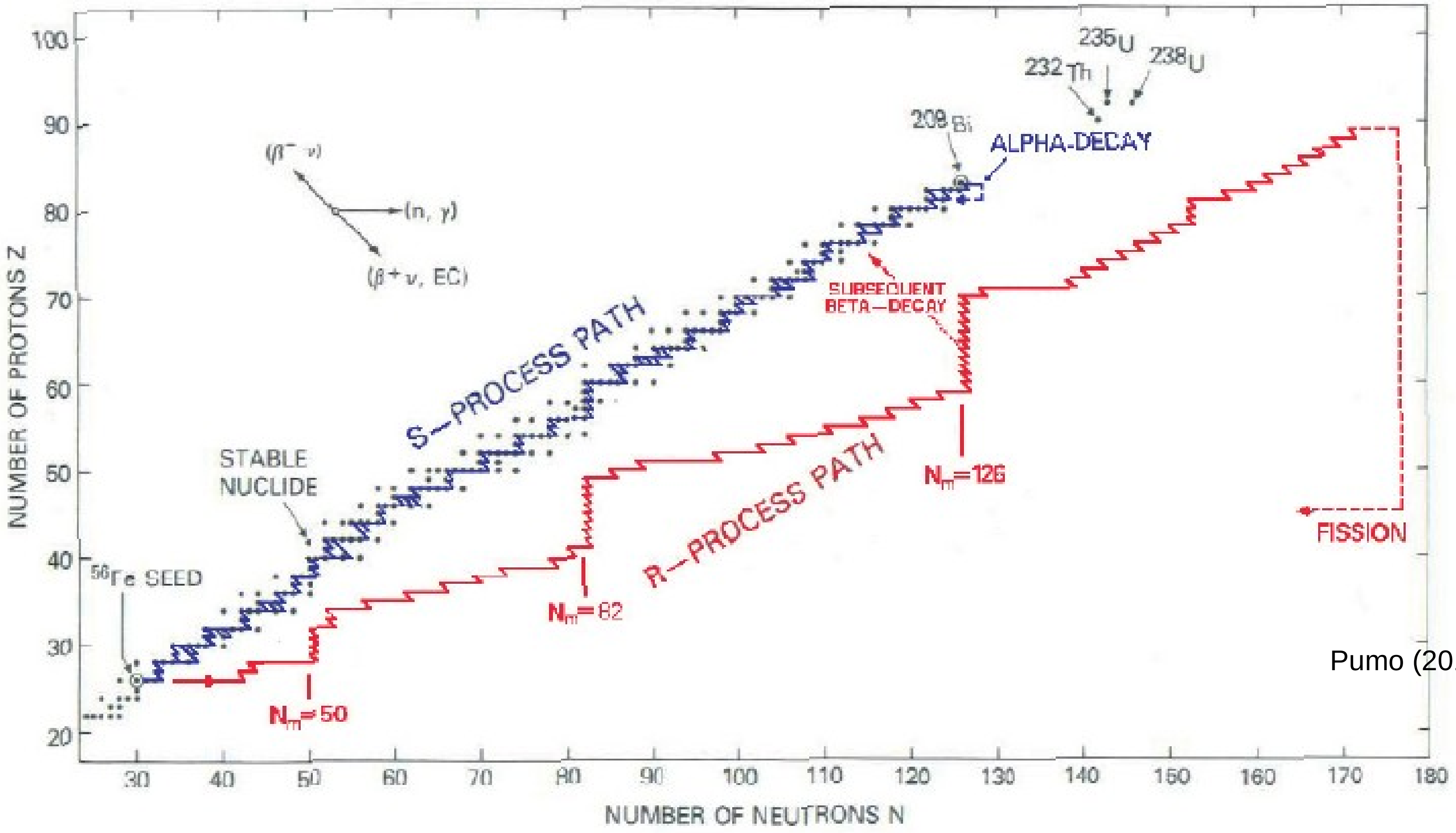
Hydrostatic stellar burning only until Fe



From "physics forums"

=> How do we produce the heavier elements?

Then, we need: “neutron capture processes”



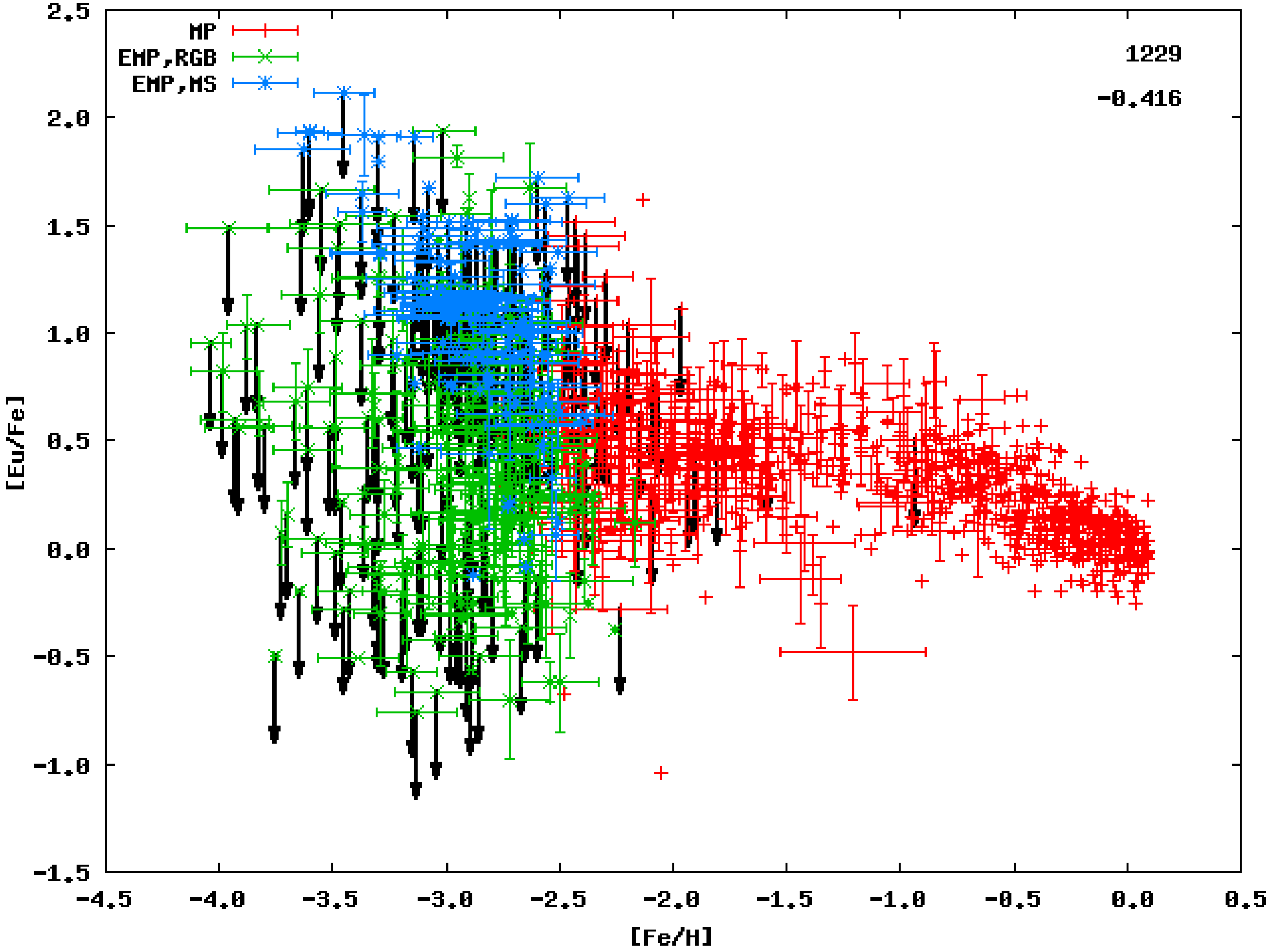
Pumo (2012)

=> “Walk around” the binding energy peak, then decay towards valley of stability

Responsible for ~50% of the heavi(est) elements

<u>You need a lot of neutrons!!</u>

r-process elements vs. metallicity

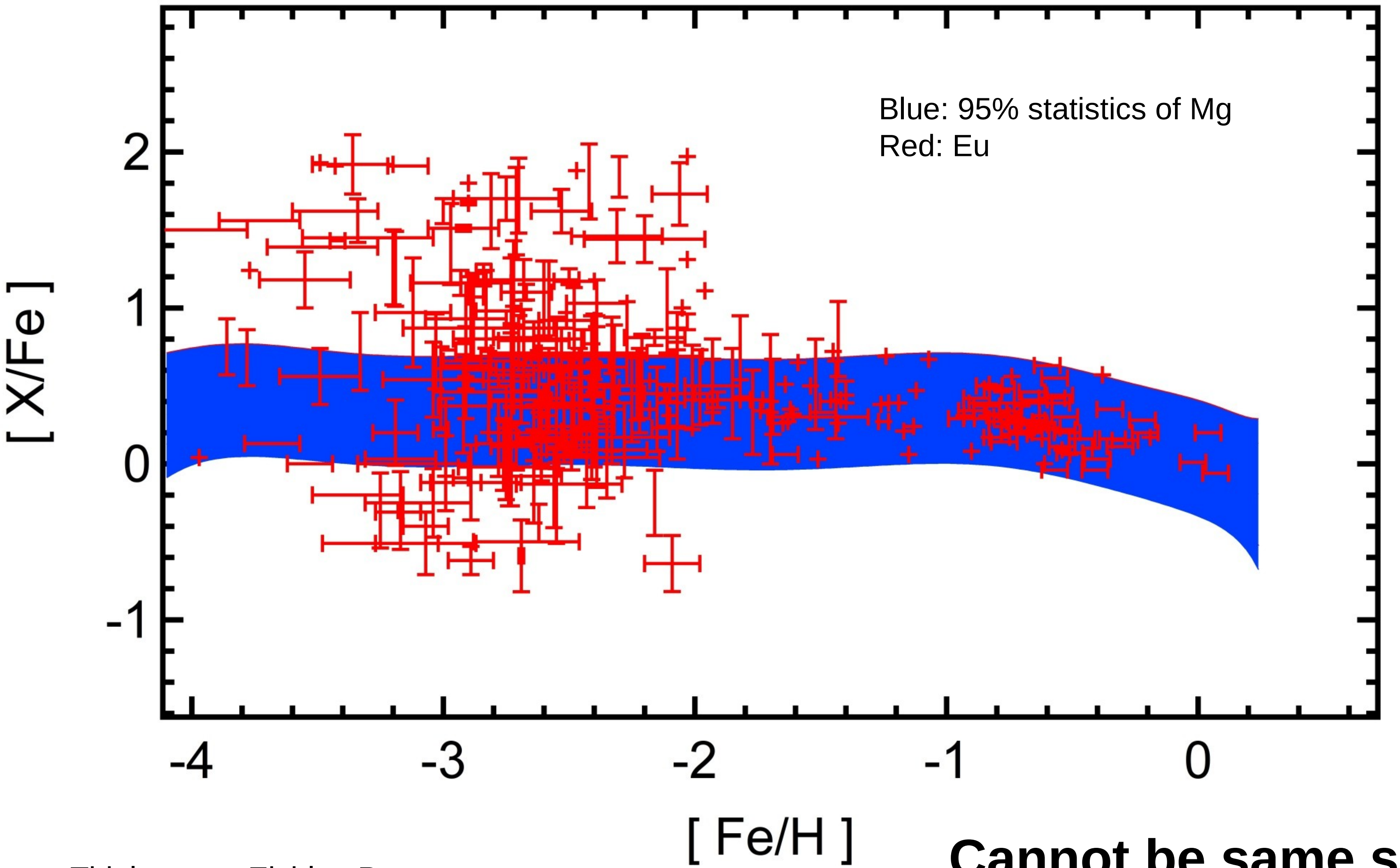


Europium is taken as diagnostic for r-process elements

- ~96% produced by the r-process
- Has two good lines at 4192.70 and 4205.05 Å

From SAGA database, e.g., *T. Suda et al.*, PASJ, 60, 1159-1171, 2008.

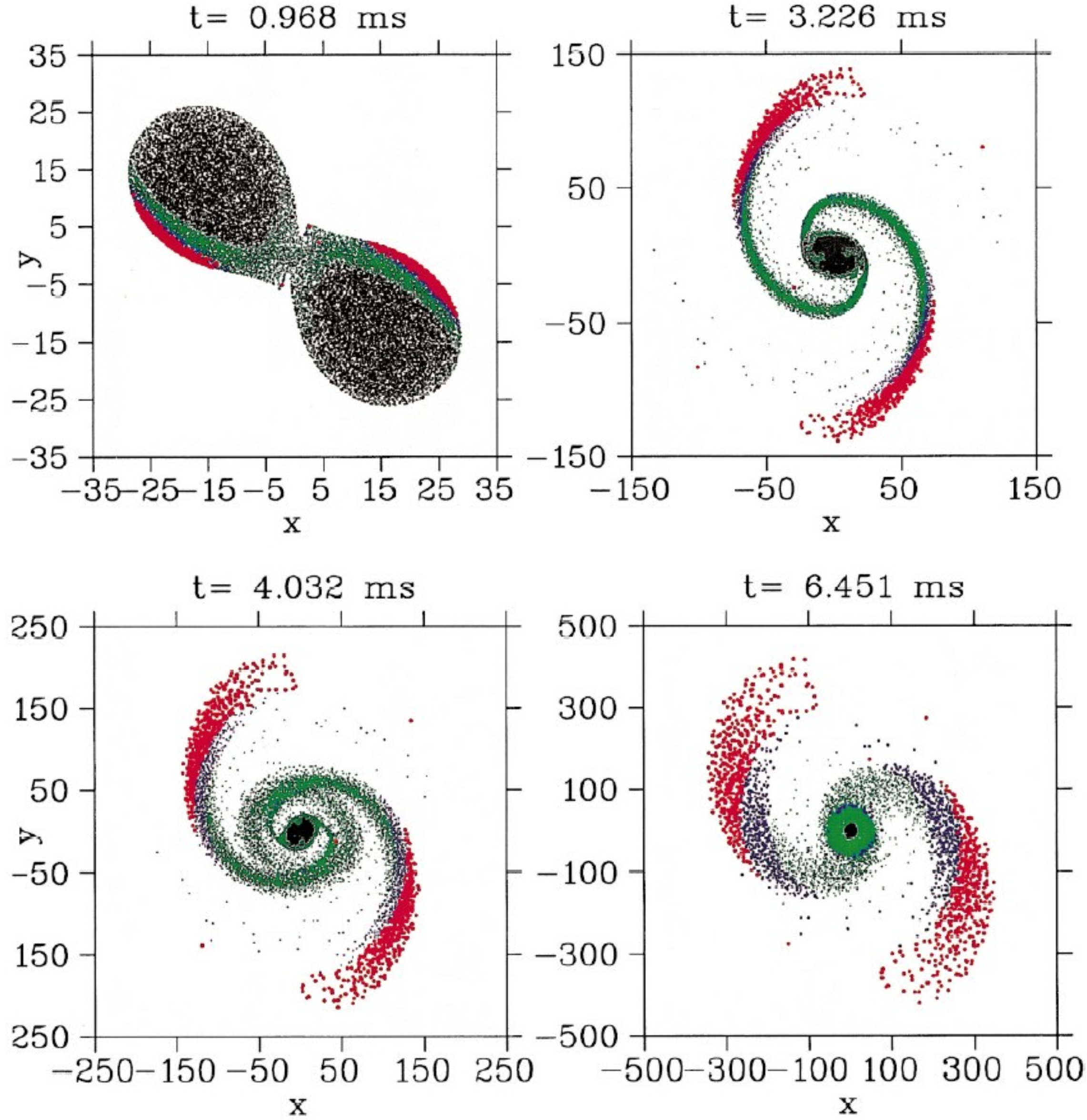
- alpha- and r-process elements



Cannot be same site!

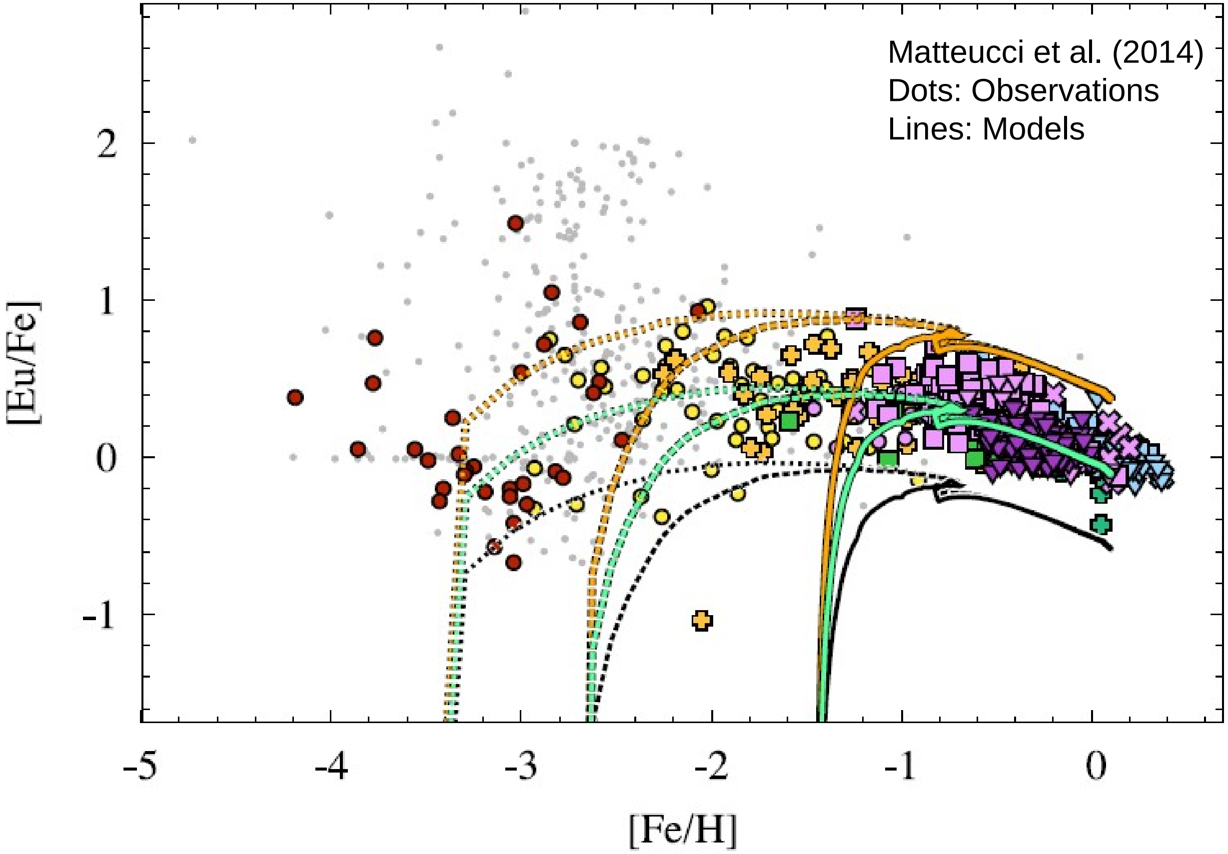
Thielemann, Eichler, Panov, Pignatari, BW, 2016

„Classical“ r-process site: NSM



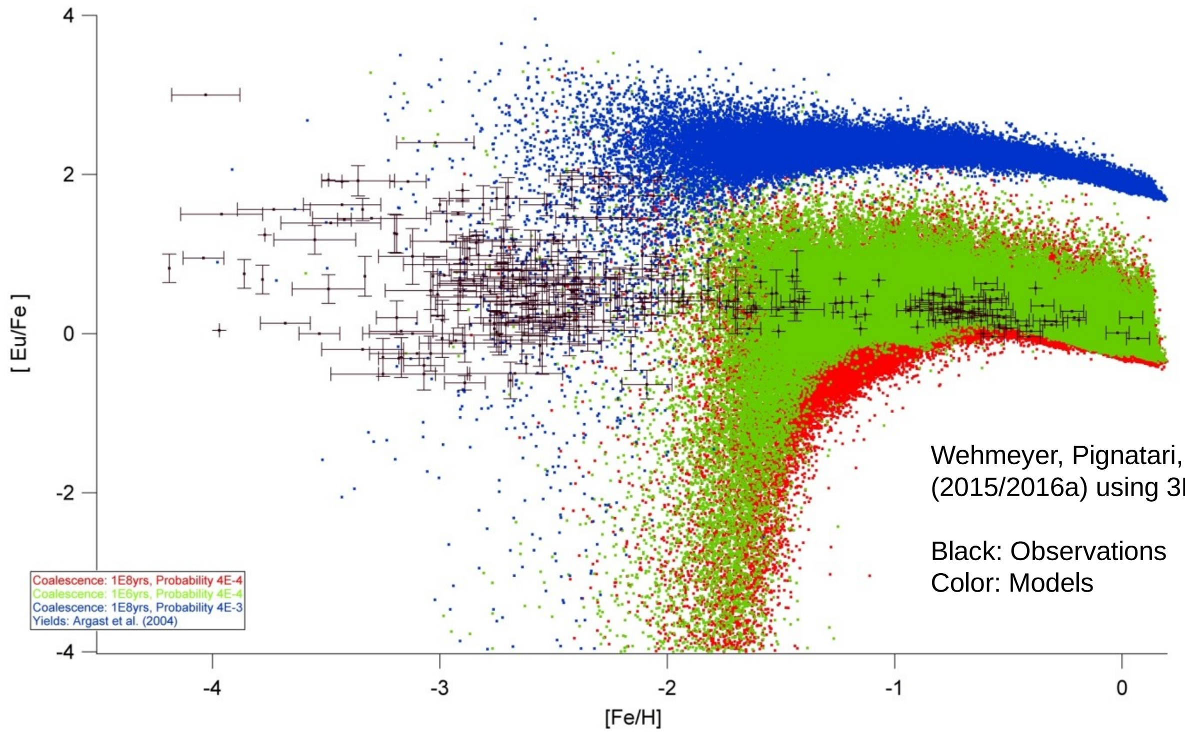
Rosswog et al.
A&A 341 (1999)
499

Classical site (NSMs) works in 1D models



Ejecta of a site propagate ***everywhere immediately***
1D models always predict a **line**
Overlap of lines matches observations

But the classical site (NSM) has a hard time in 3D



Wehmeyer, Pignatari, Thielemann (2015/2016a) using 3D model “ICE”

Black: Observations
Color: Models

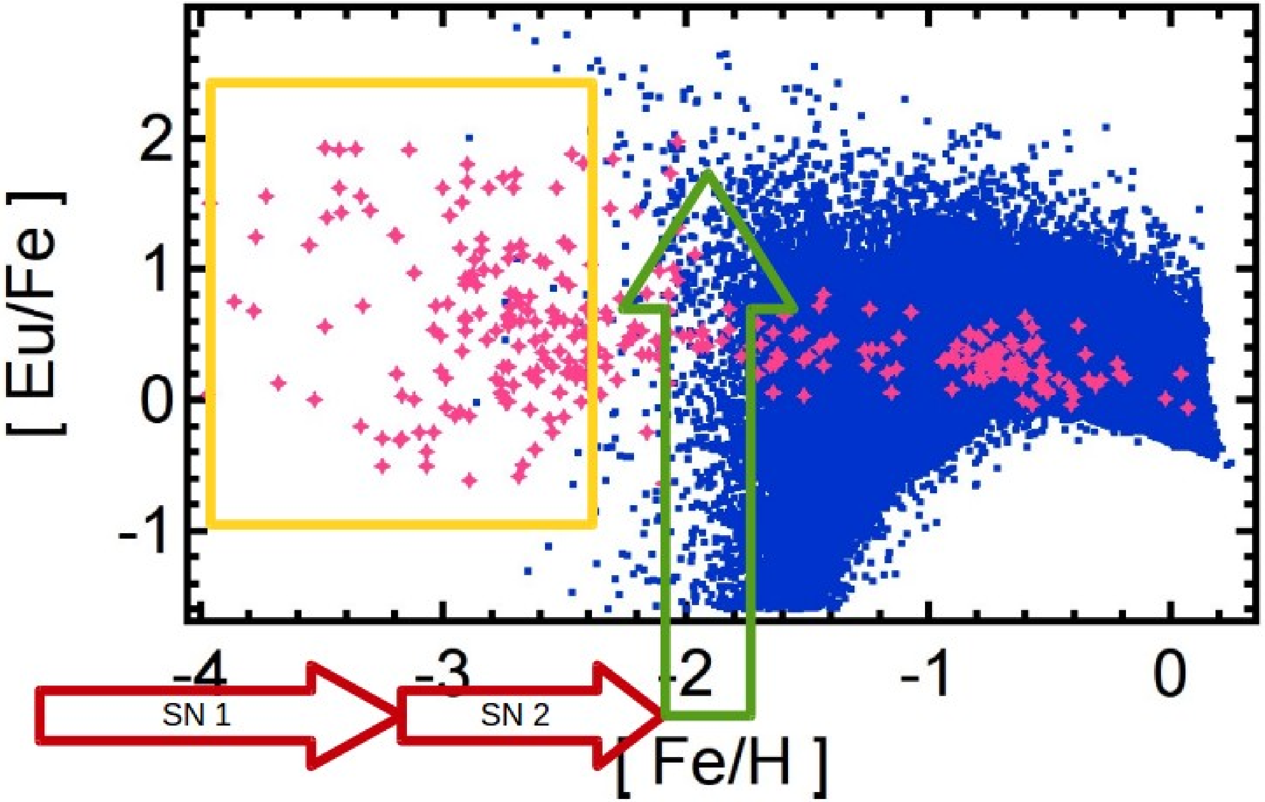
3D models **<u>can account for the scatter of elements</u>**

No matter which parameter is altered, it is **<u>difficult to match the observed abundances:</u>**

- Red dots are model stars with the canonical parameters
- Green dots are model stars in a model with extremely low coalescence time scales for NSM, but shift is marginal
- Blue dots are model stars with increased NSM probability

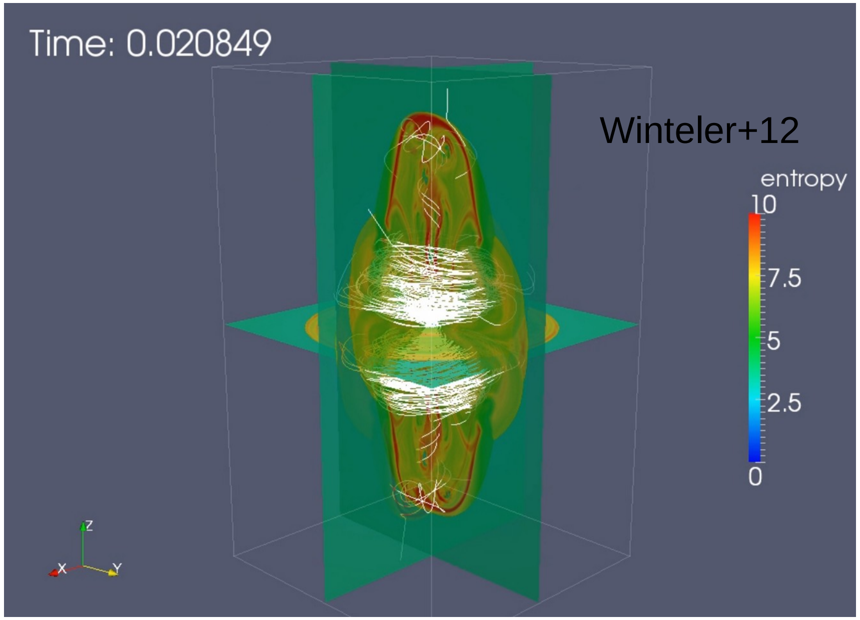
Explanation: **local inhomogeneities**

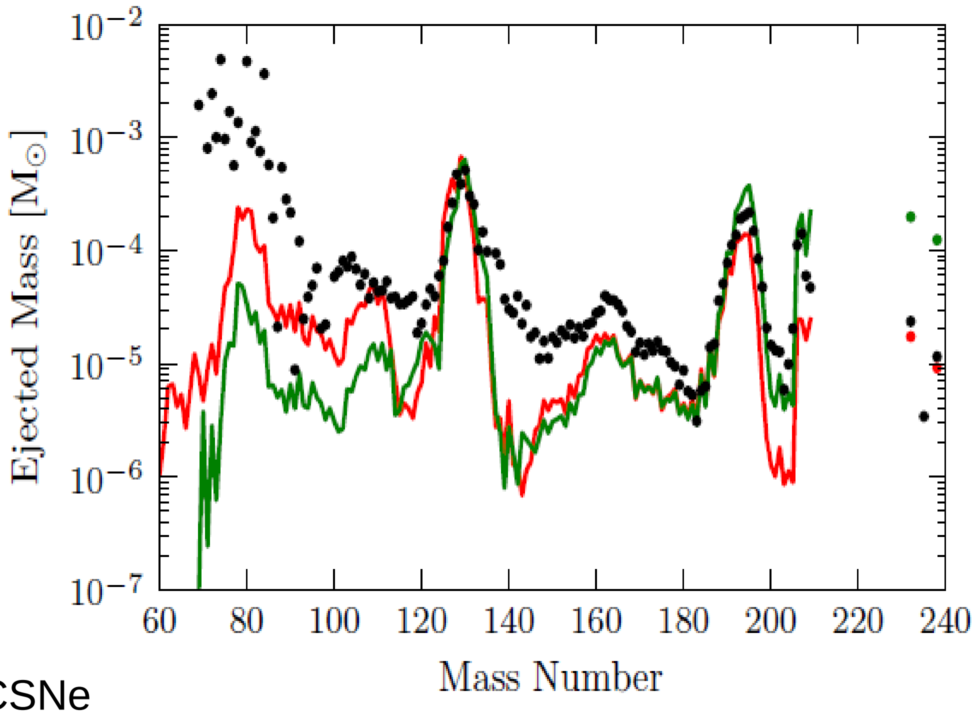
Wehmeyer+15+16a
Magenta:Observations
Blue: Model stars



A neutron star merger requires **2** neutron stars
Thus **2** supernovae necessary!

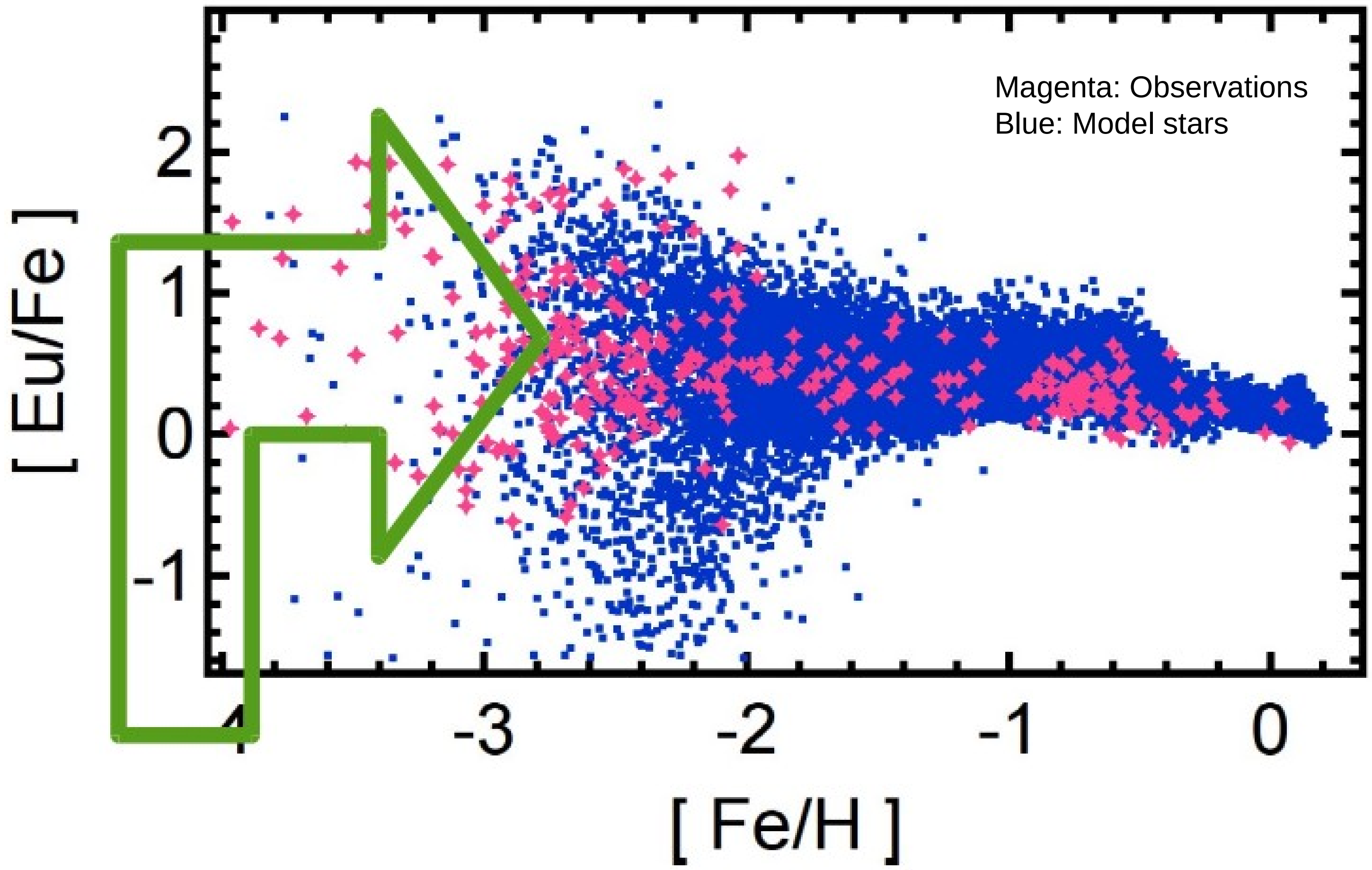
A solution: A **<u>second</u>** r-process site
Acting at low metallicities, e.g., MHD-SNe





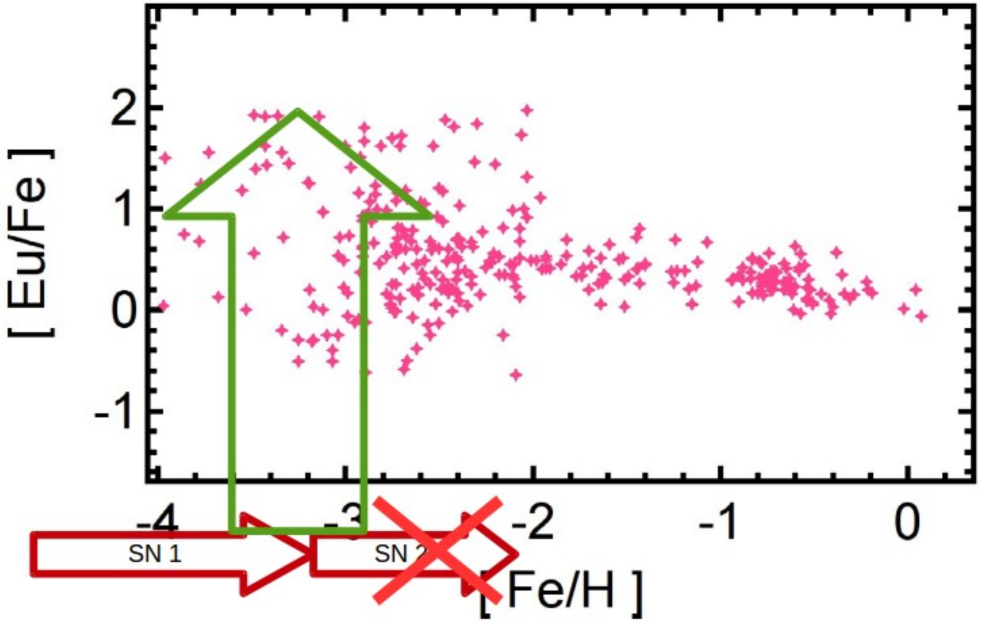
MHD-SNe are a very rare sub-class of CCSNe
Their progenitors are extremely fast rotating and highly magnetized
During explosion, the magnetic field lines force the emergence of polar jets
In the jets, requirements for an r-process are met (Winteler+12, Nishimura+15)
Advantage: r-process contribution already at low metallicities!!

Low-met region accessible!

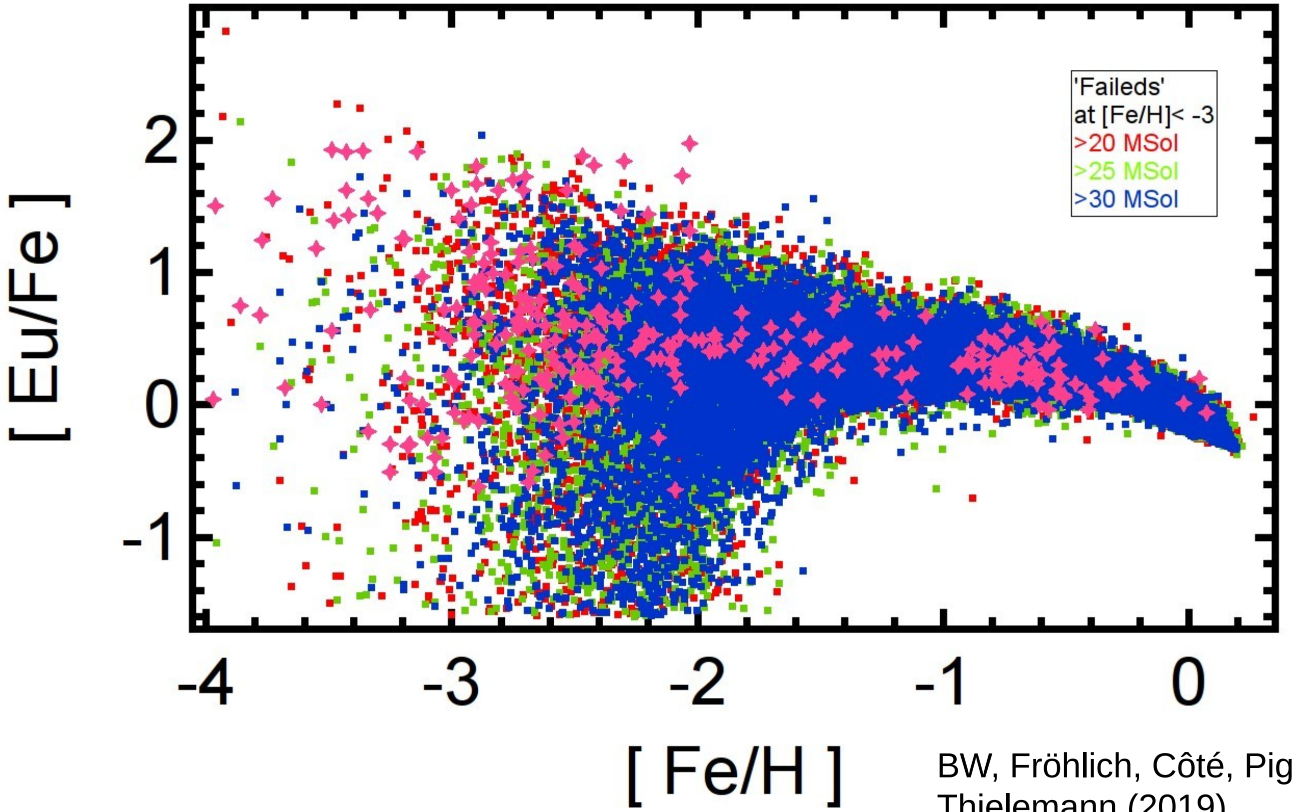


MHD-SNe eject Fe and Eu simultaneously!
MHD-SNe and NSMs together are a good combination

Another possibility? BHNSMs

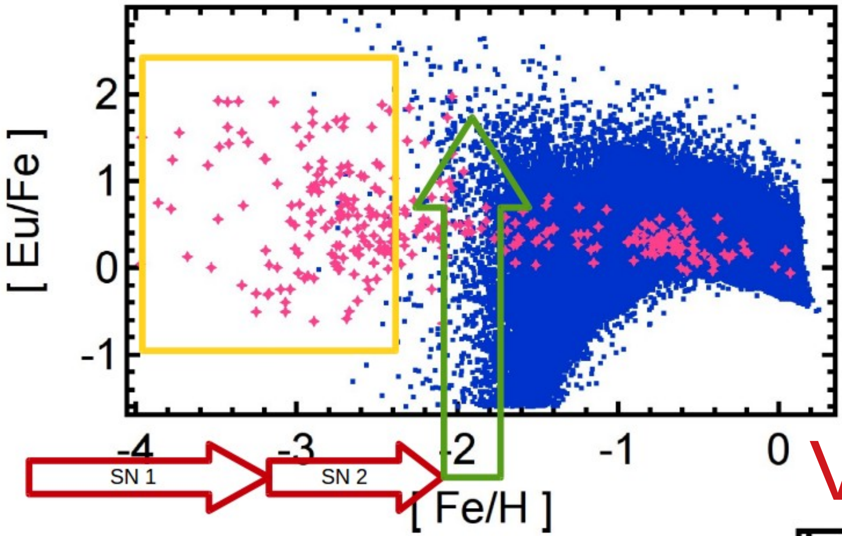


Model results show good agreement with observations!

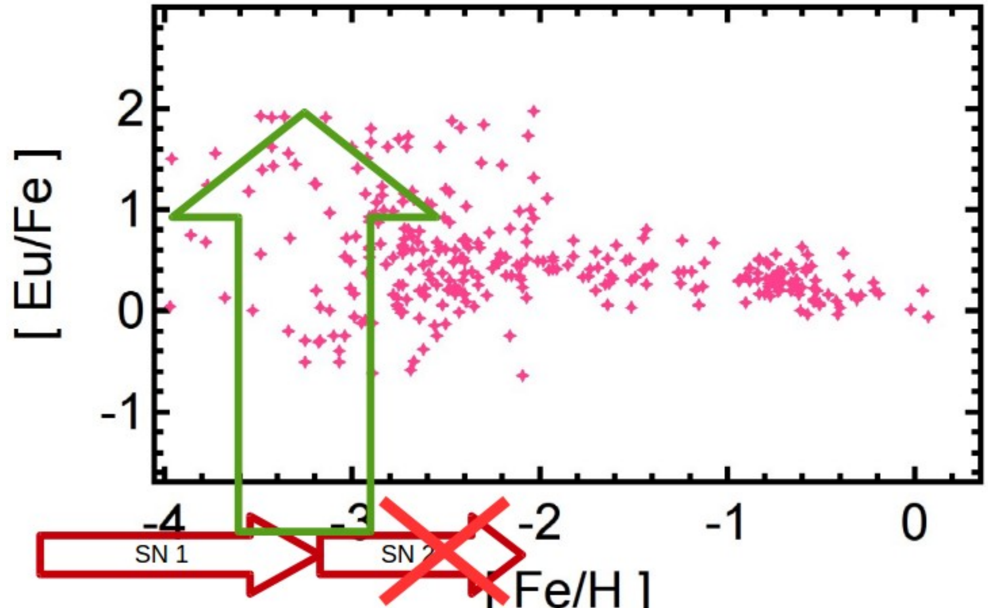


BW, Fröhlich, Côté, Pignatari, Thielemann (2019)

- Skip one CCSN per r-process event
- Age-metallicity relation is slowed down
- Effect is very localised



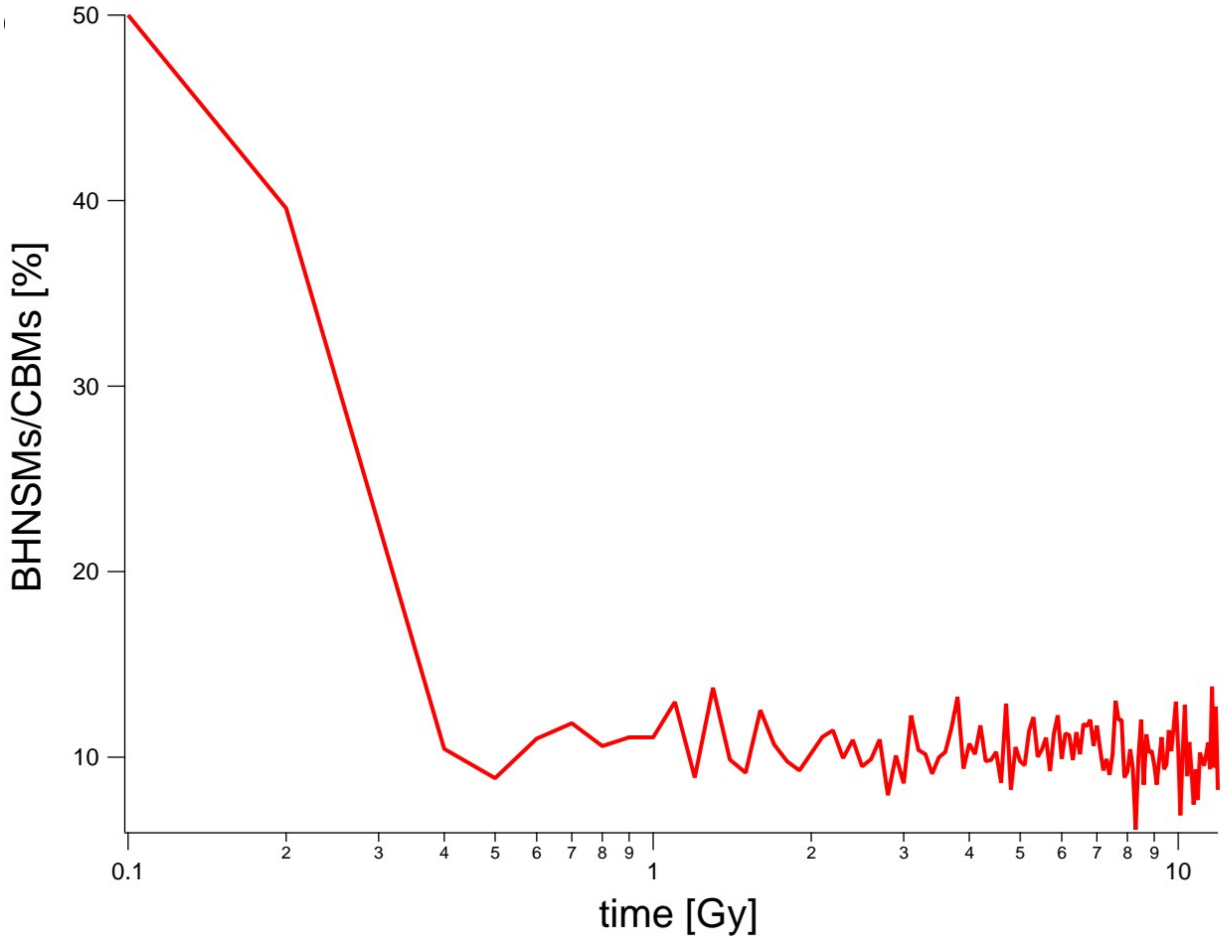
Vs.



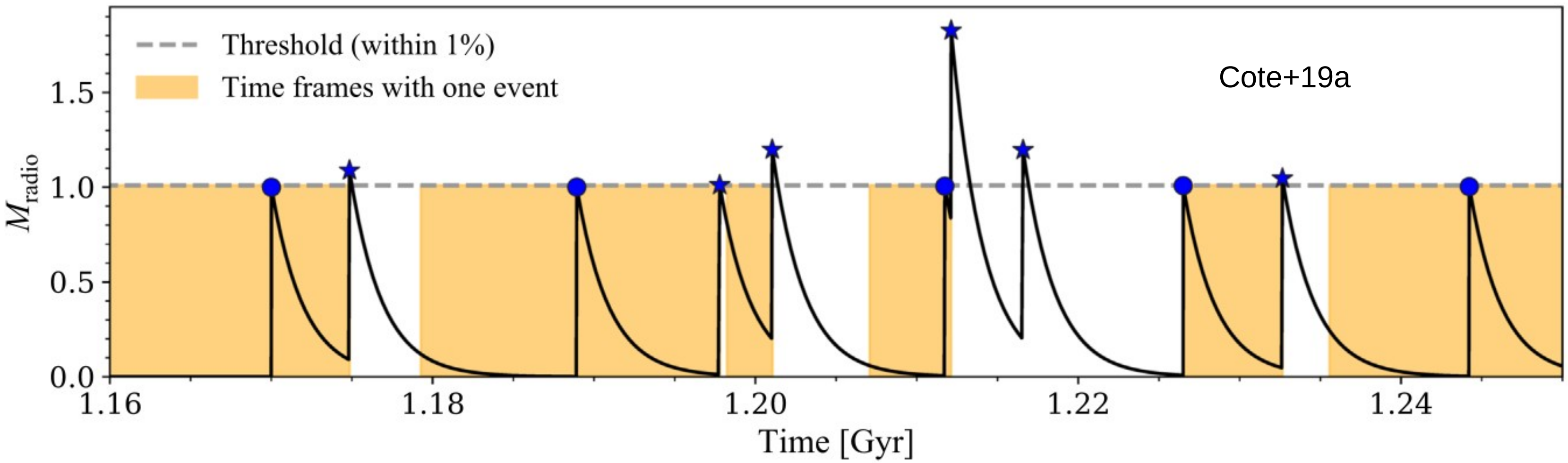
Wehmeyer+17+18

Dominant process

We know location and time of all nucleosynthesis sites
> Allows us to determine which process is dominant at which
Galacti

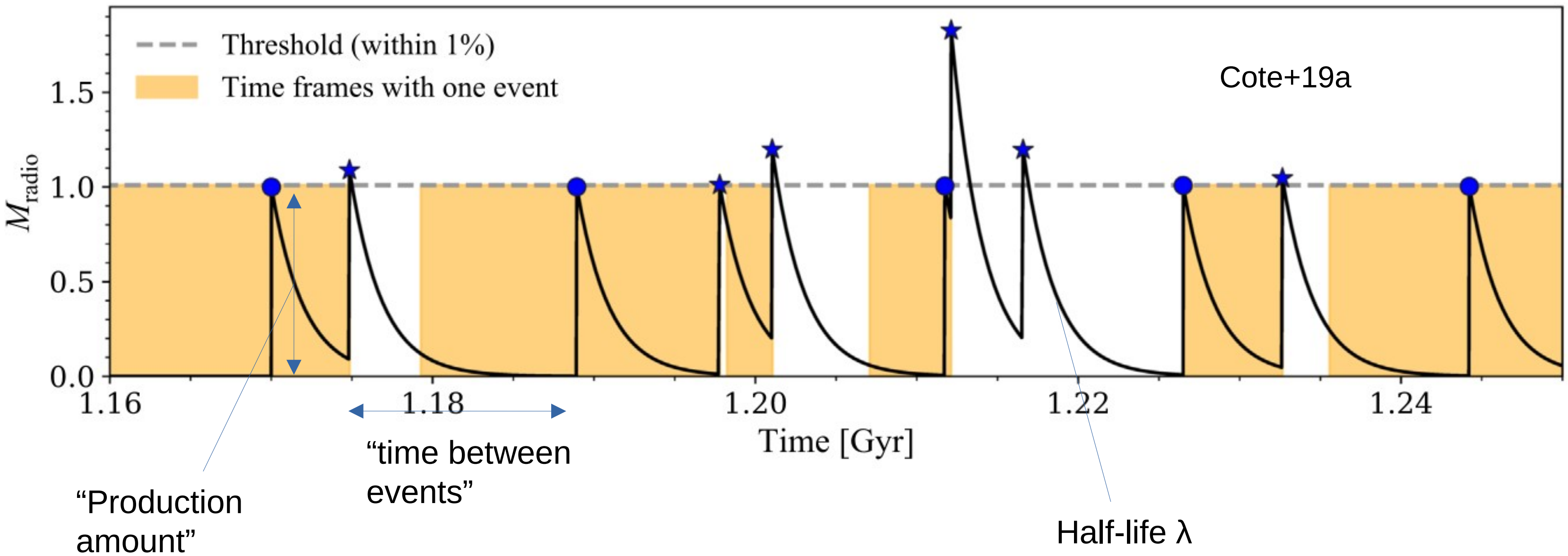


Short lived (~My) radioisotopes have an additional advantage:
They provide **timing** information!



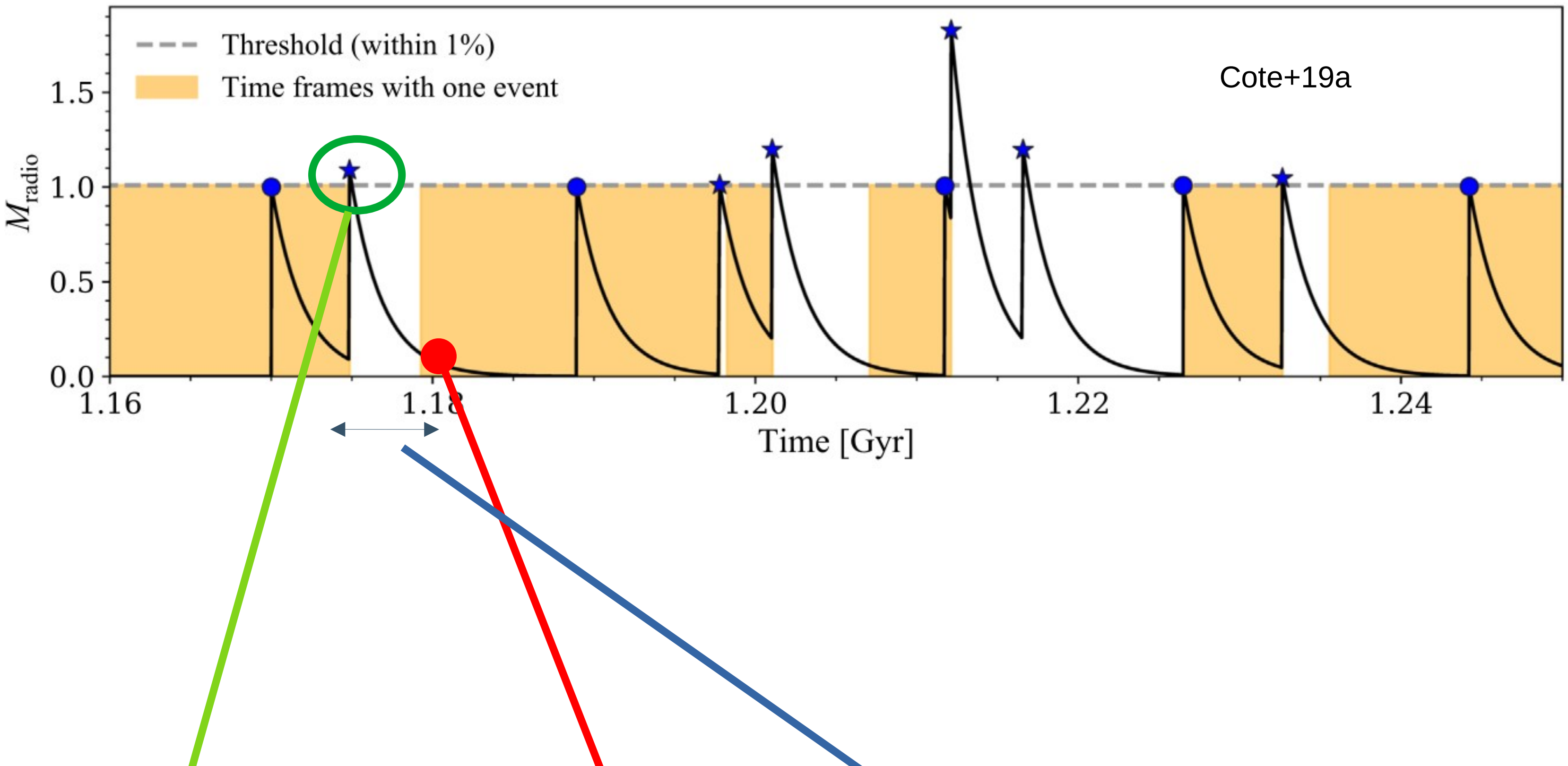
Production value, observed value, elapsed time:
If you know two, you may derive the third!

Imagine an arbitrary astrophysical source of radioactive isotopes:



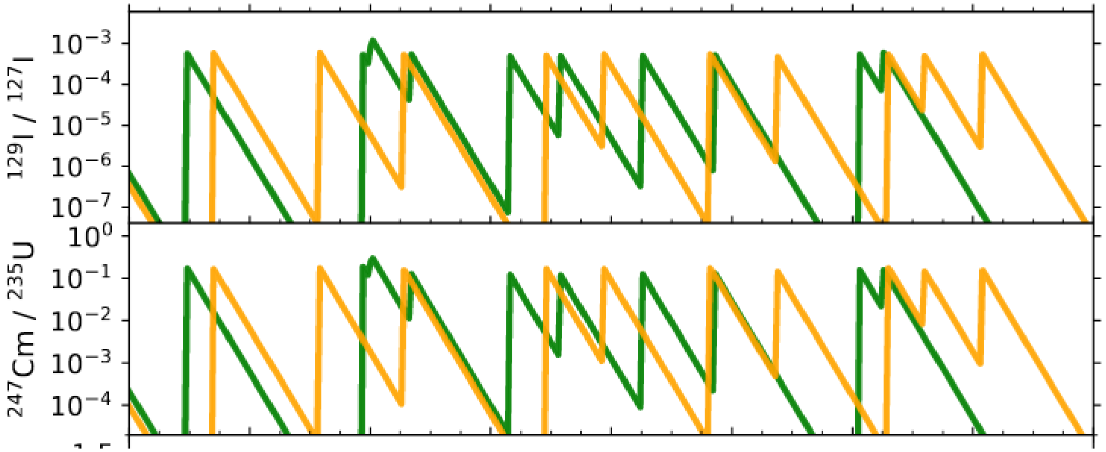
Production value, observed value, elapsed time:
If you know two, you may draw conclusions about the third!

Imagine an arbitrary astrophysical source of radioactive isotopes:



Production value, observed value, elapsed time:
If you know two, you may draw conclusions about the third!

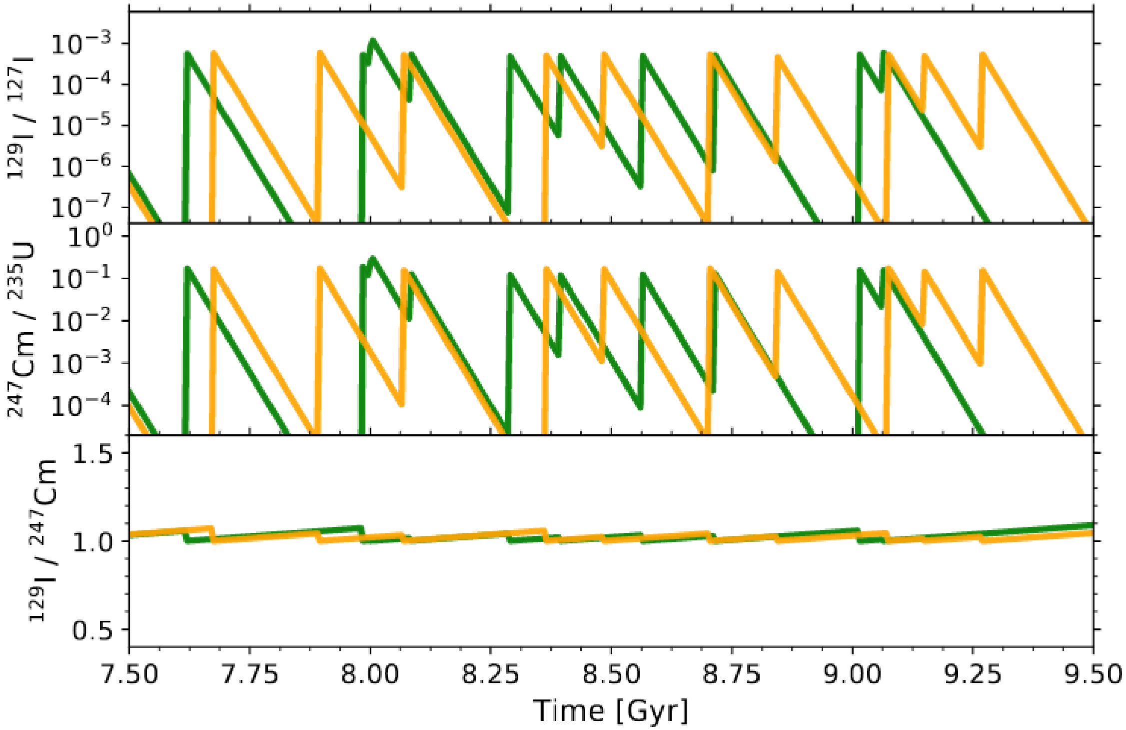
If you build the ratio of a combination of two **great, special** isotopes...



Côté+, 2021Science 371, 945C

Produced exclusively by the r-process...
...and have very similar half-lives...

If you build the ratio of a combination of two **great, special** isotopes...

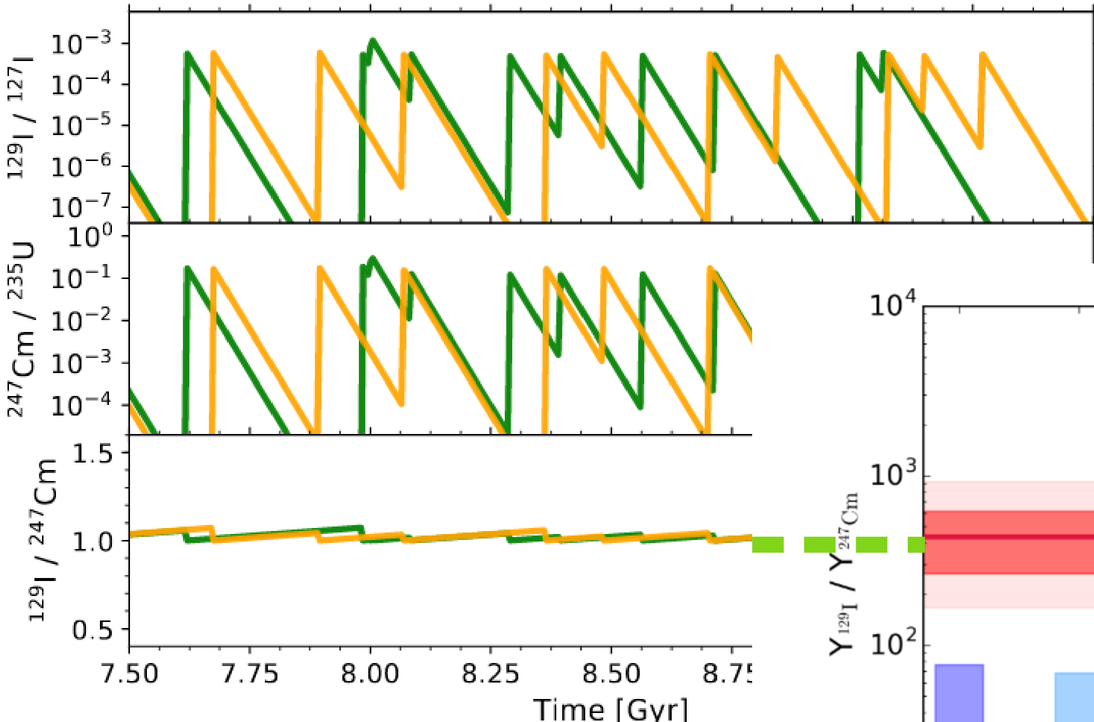


Côté+, 2021Science 371, 945C

Produced exclusively by the r-process...
...and have very similar half-lives...
You'll end up with a **LINE!**

If you build the ratio of a combination of two **great, special** isotopes...

Côté+, 2021Science 371, 945C



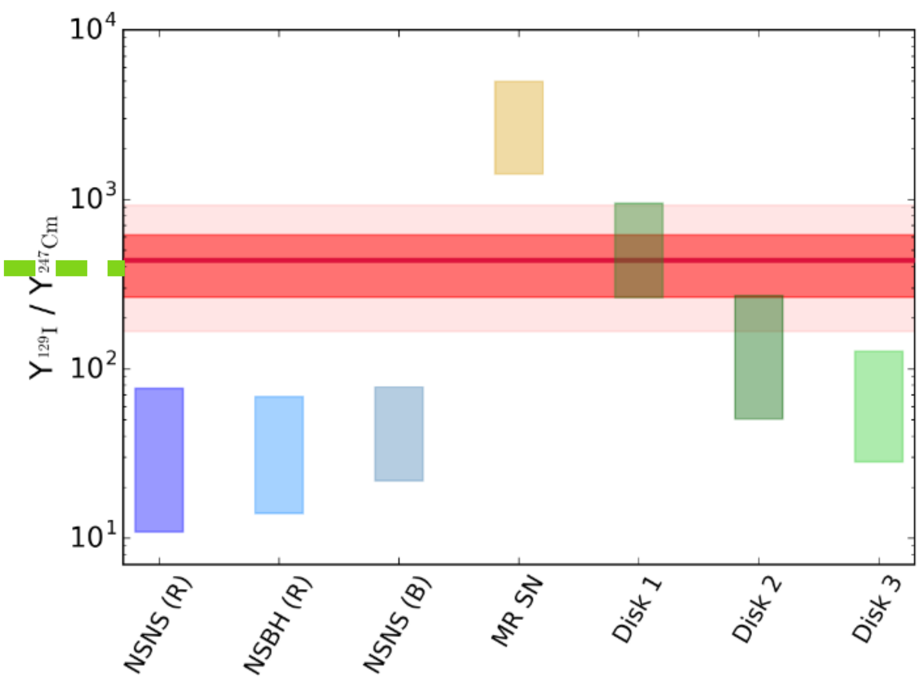
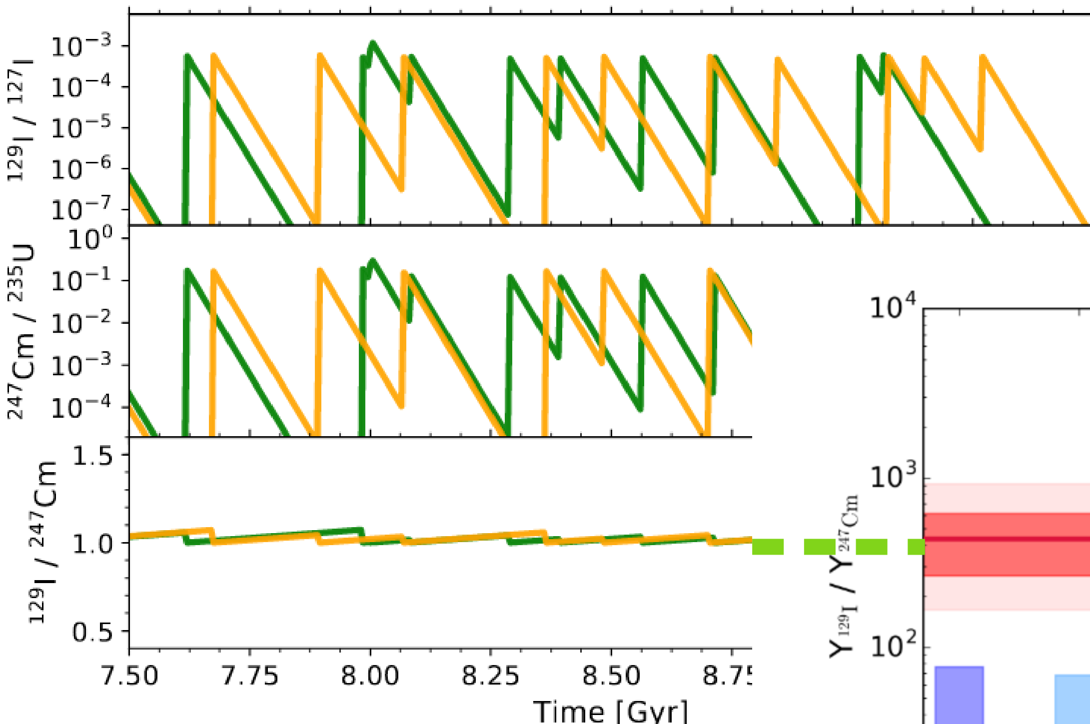


Fig. 2. ^{129}I / ^{247}Cm abundance ratios predicted by our theoretical r-process models (see Methods section). The red horizontal line and horizontal bands show the meteoritic ratio along with its 1σ and 2σ uncertainty (see Methods section).

If you build the ratio of a combination of two **great, special** isotopes...



Côté+, 2021Science 371, 945C

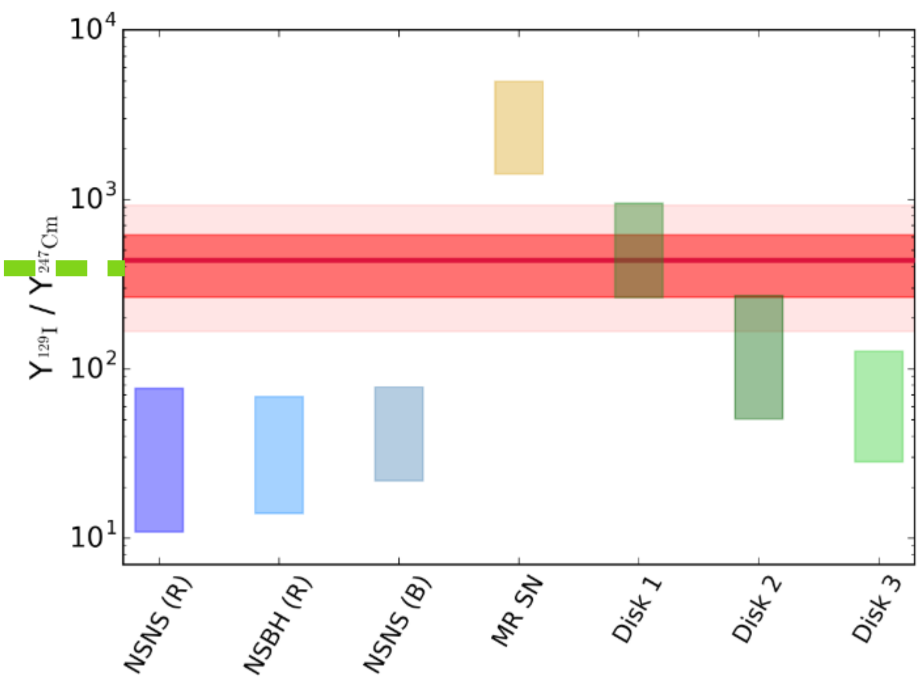


Fig. 2. ^{129}I / ^{247}Cm abundance ratios predicted by our theoretical *r*-process models (see Methods section). The red horizontal line and horizontal bands show the meteoritic ratio along with its

...allowing you to directly probe the yield ratios of the last r-process event!!!!!

Why does this work?

Côté+, 2021Science 371, 945C

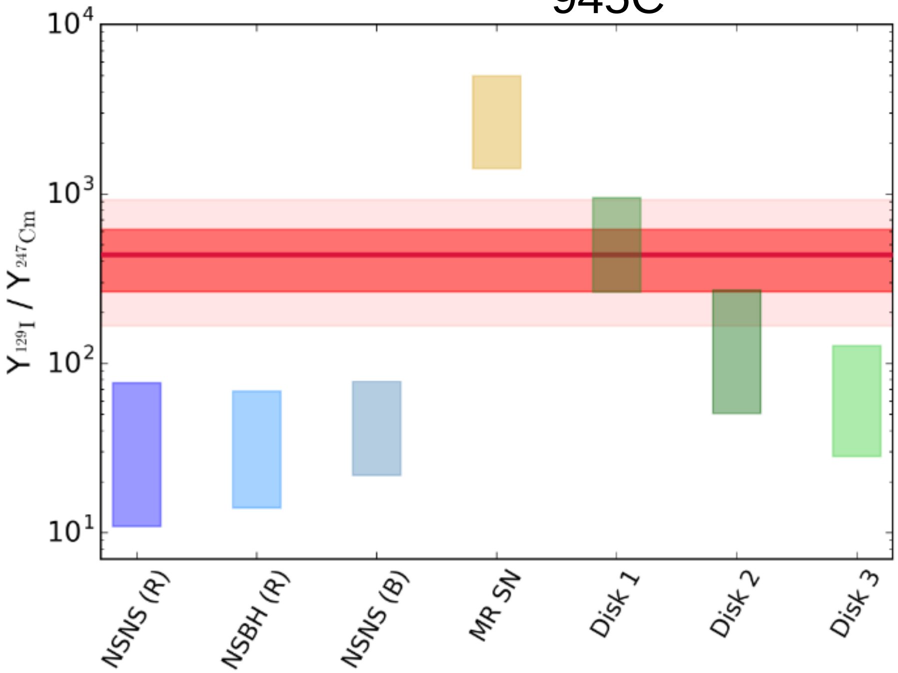


Fig. 2. ^{129}I / ^{247}Cm abundance ratios predicted by our theoretical r-process models (see Methods section). The red horizontal line and horizontal bands show the meteoritic ratio along with its 1σ and 2σ uncertainty (see Methods section).

Why does this work?

Côté+, 2021Science 371, 945C

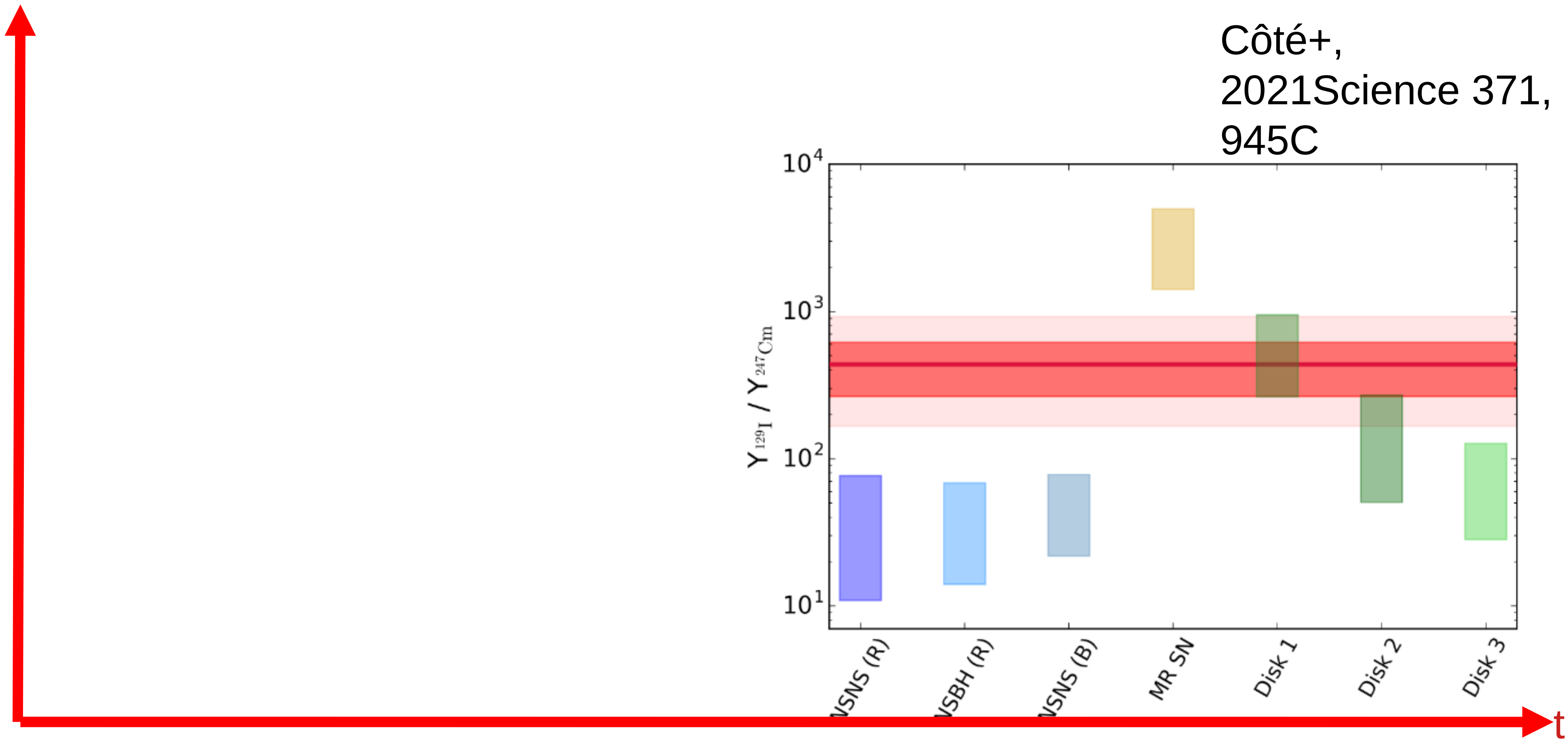


Fig. 2. $^{129}I / ^{247}Cm$ abundance ratios predicted by our theoretical r-process models (see Methods section). The red horizontal line and horizontal bands show the meteoritic ratio along with its 1σ and 2σ uncertainty (see Methods section).

Let's look at the evolution before the formation of the Solar system.

Why does this work?

...because **even if any other r-process sources have contributed** to the ratio before,

Côté+, 2021Science 371, 945C

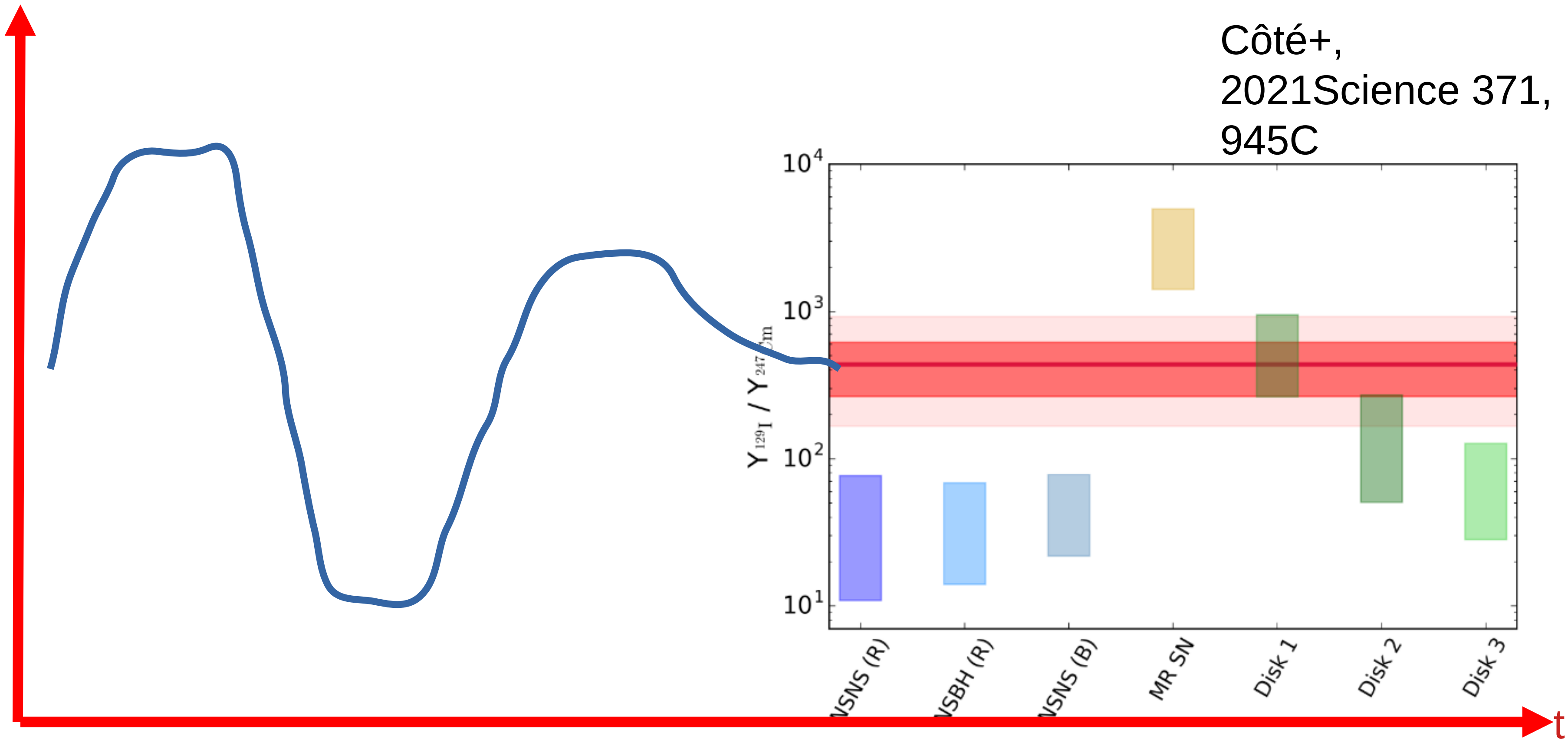


Fig. 2. ^{129}I / ^{247}Cm abundance ratios predicted by our theoretical r-process models (see Methods section). The red horizontal line and horizontal bands show the meteoritic ratio along with its 1σ and 2σ uncertainty (see Methods section).

Why does this work?

...because **even if any other r-process sources have contributed** to the ratio before, their contribution is **gone**!

Côté+, 2021Science 371, 945C

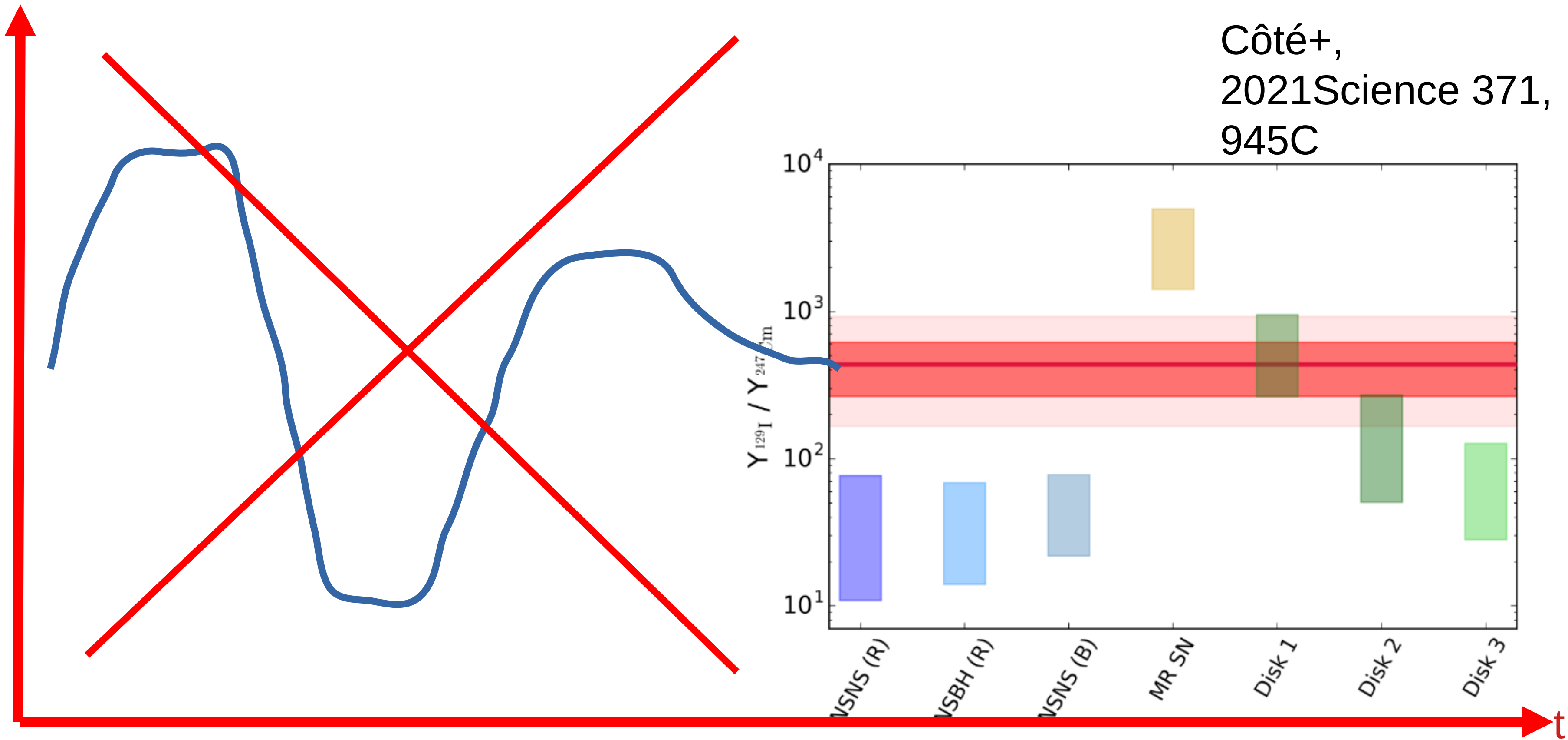


Fig. 2. ^{129}I / ^{247}Cm abundance ratios predicted by our theoretical r-process models (see Methods section). The red horizontal line and horizontal bands show the meteoritic ratio along with its 1σ and 2σ uncertainty (see Methods section).

...this enables us to precisely study the LAST r-process event that contributed to the Solar system!

If you look at the whole Galaxy, however,
And have variable delay times (NSMs)...

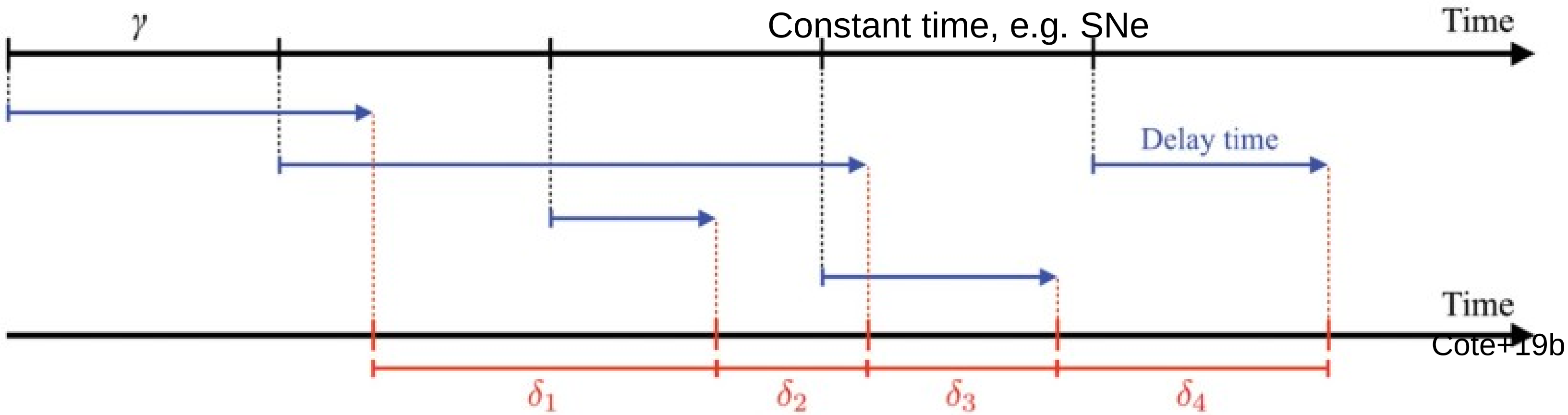


Figure 2. Visualization of the key parameters involved in our Monte Carlo calculations. Here γ is the constant time interval between the formation of two progenitors. The delay times (blue arrows) represent the time intervals between the formation of the progenitors and their associated enrichment event. Those delay times are randomly sampled from an input DTD function. The different δ values are the time intervals between two consecutive enrichment events, regardless of the formation time of the progenitors. This means that δ cannot have negative values.

If you look at the whole Galaxy, however,
And have variable delay times (NSMs)...

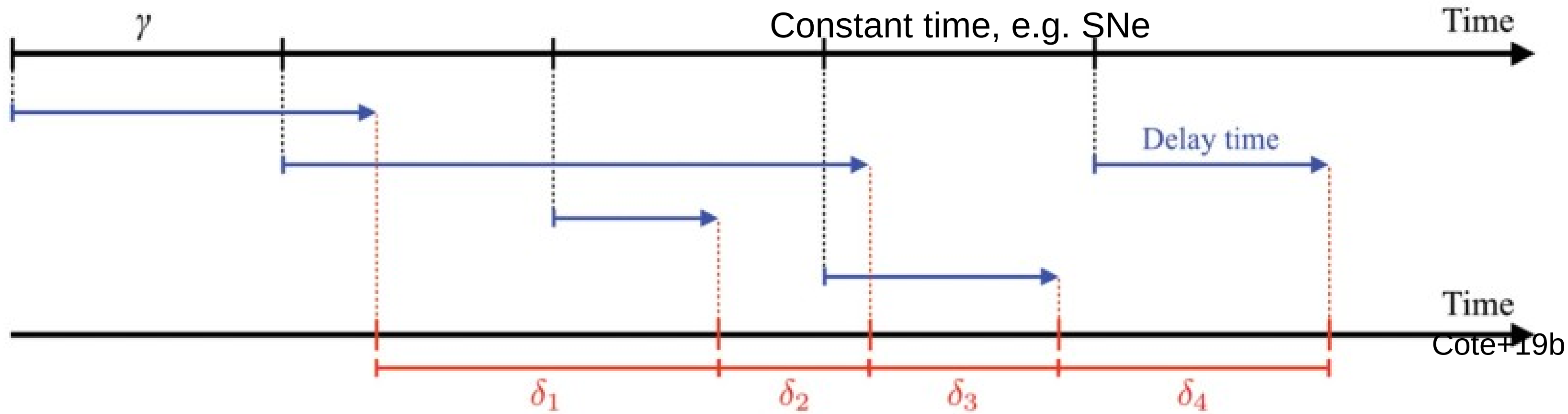
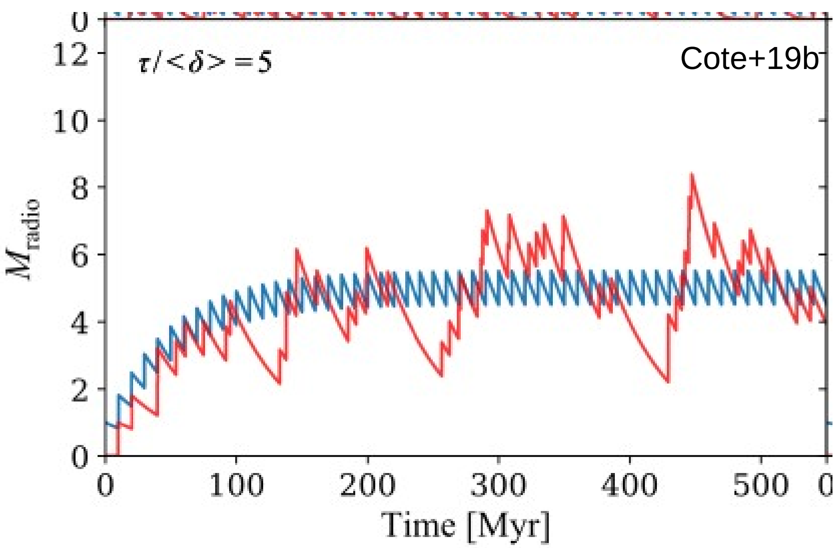
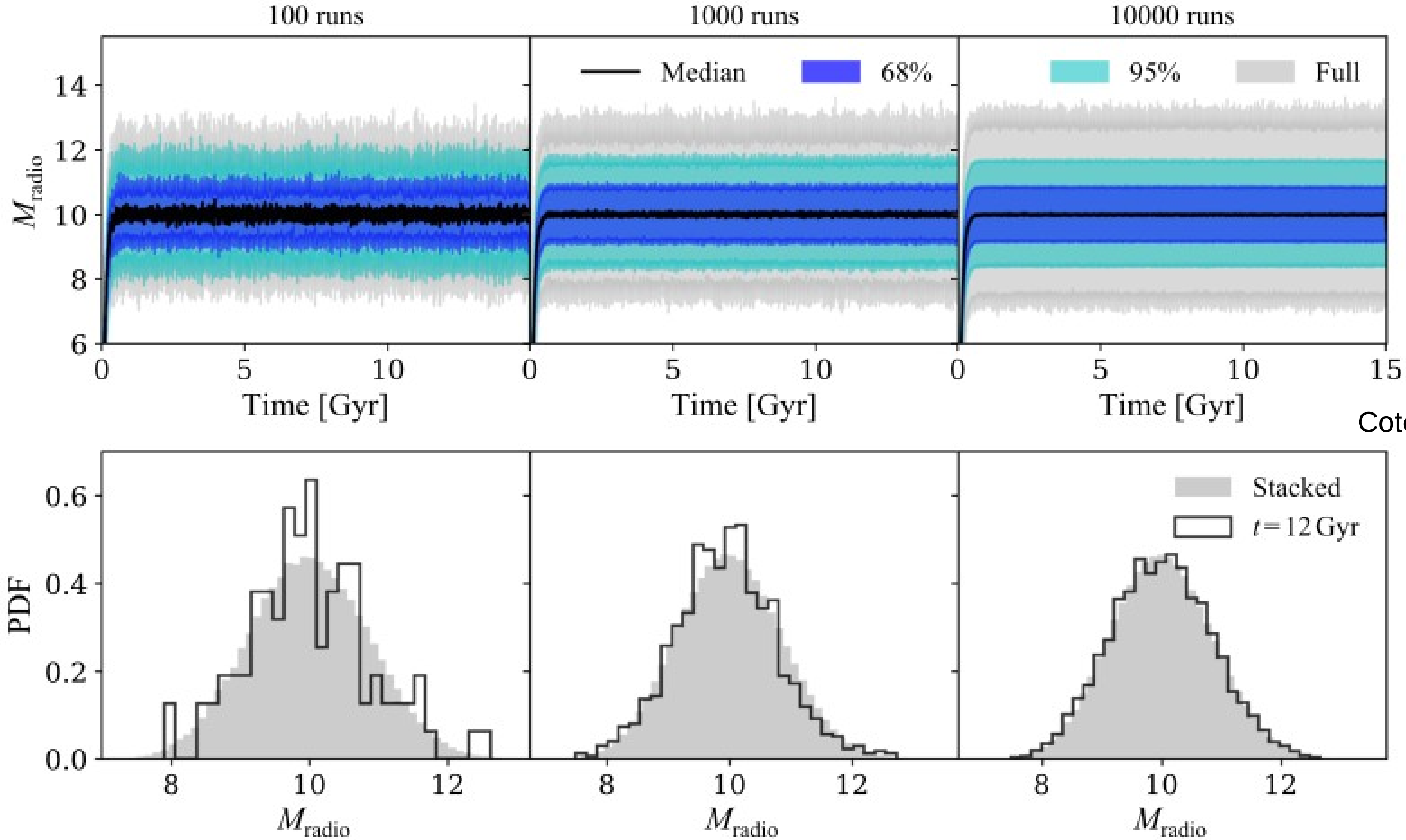


Figure 2. Visualization of the key parameters involved in our Monte Carlo calculations. Here γ is the constant time interval between the formation of two progenitors. The delay times (blue arrows) represent the time intervals between the formation of the progenitors and their associated enrichment event. Those delay times are randomly sampled from an input DTD function. The different δ values are the time intervals between two consecutive enrichment events, regardless of the formation time of the progenitors. This means that δ cannot have negative values.

...this this tends to extend the steady-state value…



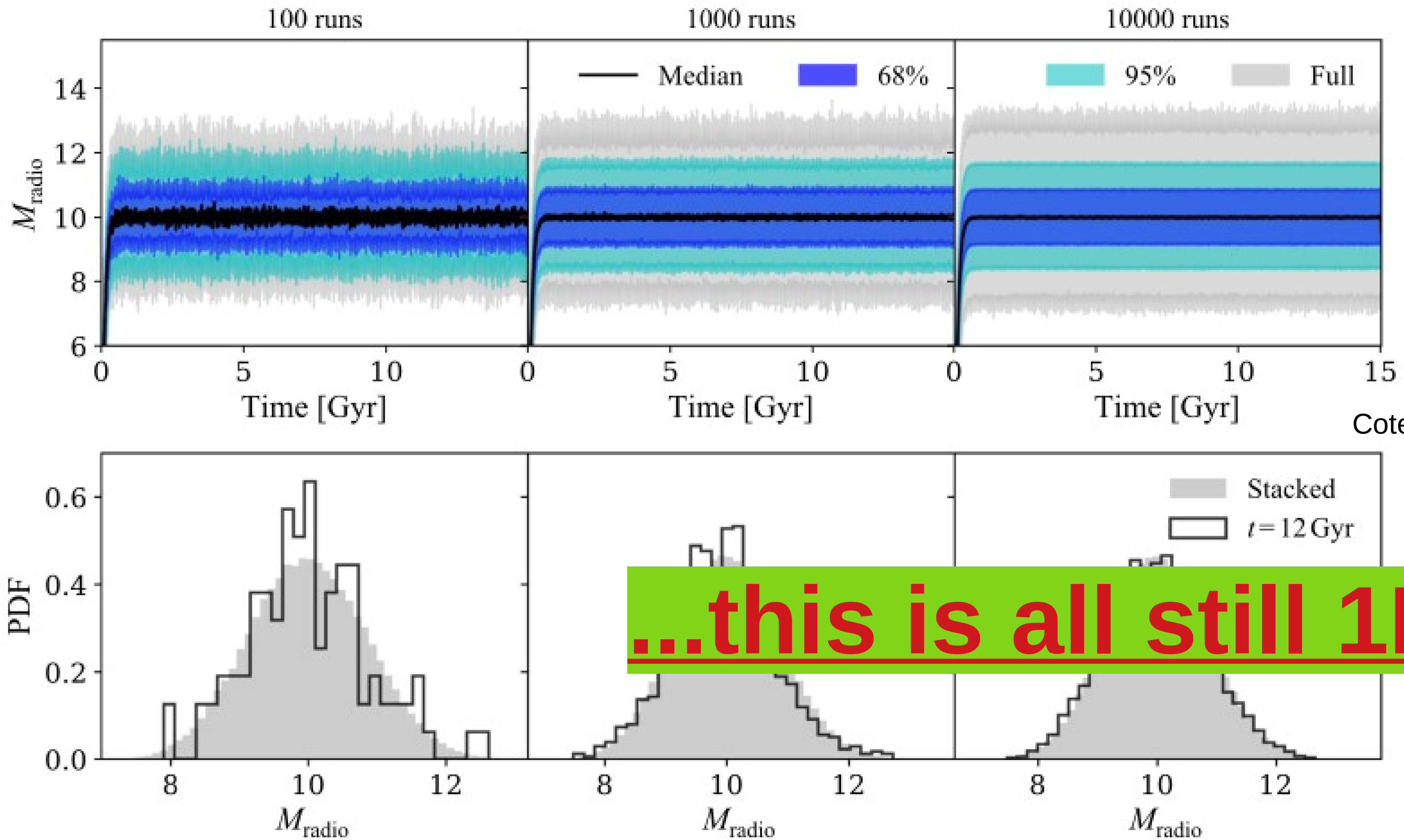
...leading rather to a ***<u>spectrum</u>*** of abundances:



Cote+19b

Figure 3. Top panels: evolution of the median and 68% and 95% confidence levels of the mass of radionuclei (M_{radio}) as a function of time using Monte Carlo calculations with 100, 1000, and 10,000 runs (from left to right), with $\gamma = 10$ Myr and the 3–50 Myr box DTD function. The gray shaded area represents the maximum and minimum values reached during the calculations. Bottom panels: distribution of predicted M_{radio} at 12 Gyr (black histograms) for the calculations with 100, 1000, and 10,000 runs (from left to right). The gray histograms show the distribution of M_{radio} when all time steps between 12 and 14 Gyr are stacked together to improve the statistics.

...leading rather to a ***spectrum*** of abundances:

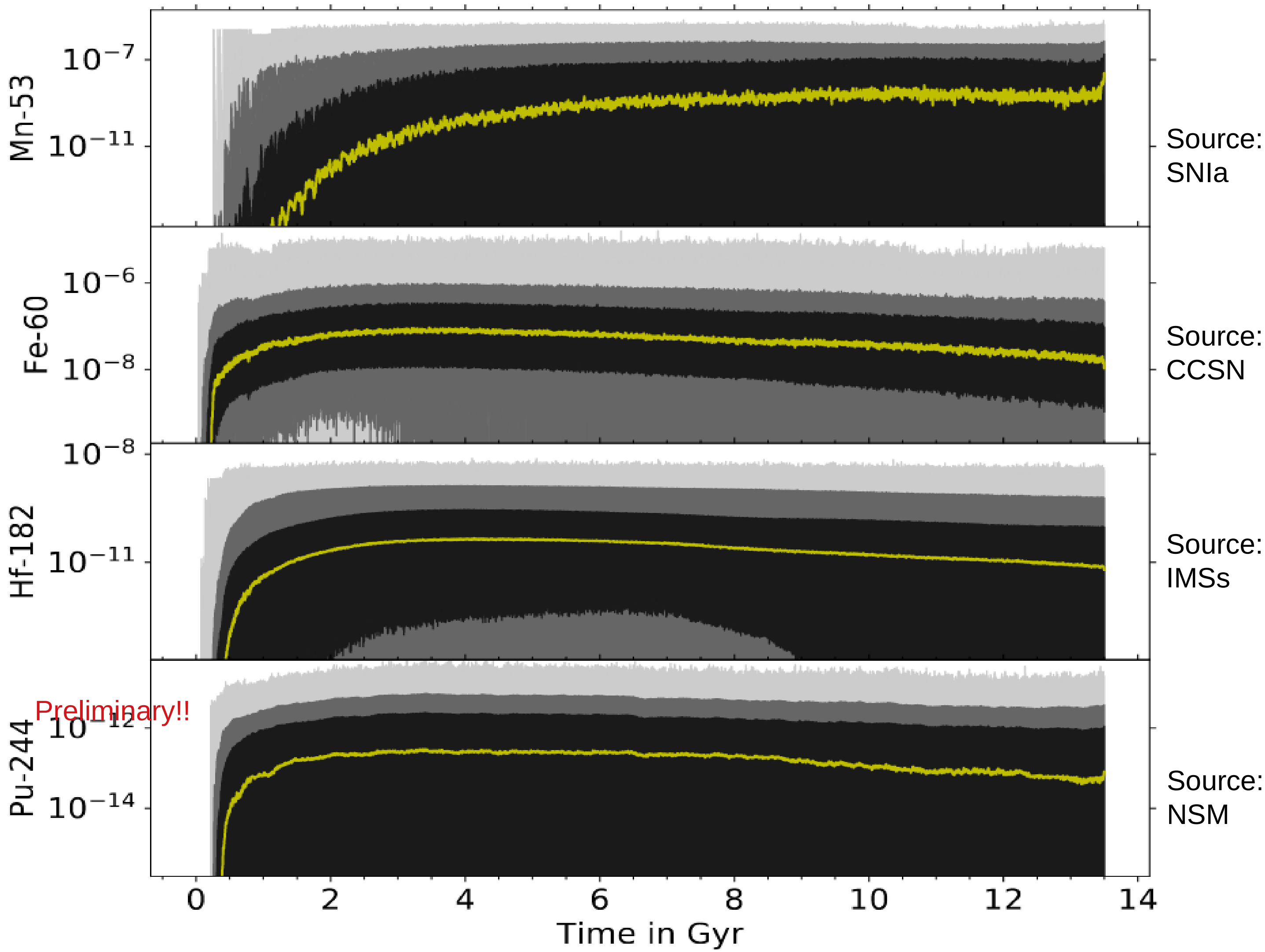


Cote+19b

...this is all still 1D!!!

Figure 3. Top panels: evolution of the median and 68% and 95% confidence levels of the mass of radionuclei (M_{radio}) as a function of time using Monte Carlo calculations with 100, 1000, and 10,000 runs (from left to right), with $\gamma = 10$ Myr and the 3–50 Myr box DTD function. The gray shaded area represents the maximum and minimum values reached during the calculations. Bottom panels: distribution of predicted M_{radio} at 12 Gyr (black histograms) for the calculations with 100, 1000, and 10,000 runs (from left to right). The gray histograms show the distribution of M_{radio} when all time steps between 12 and 14 Gyr are stacked together to improve the statistics.

Moving to 3D this gets even more complicated!



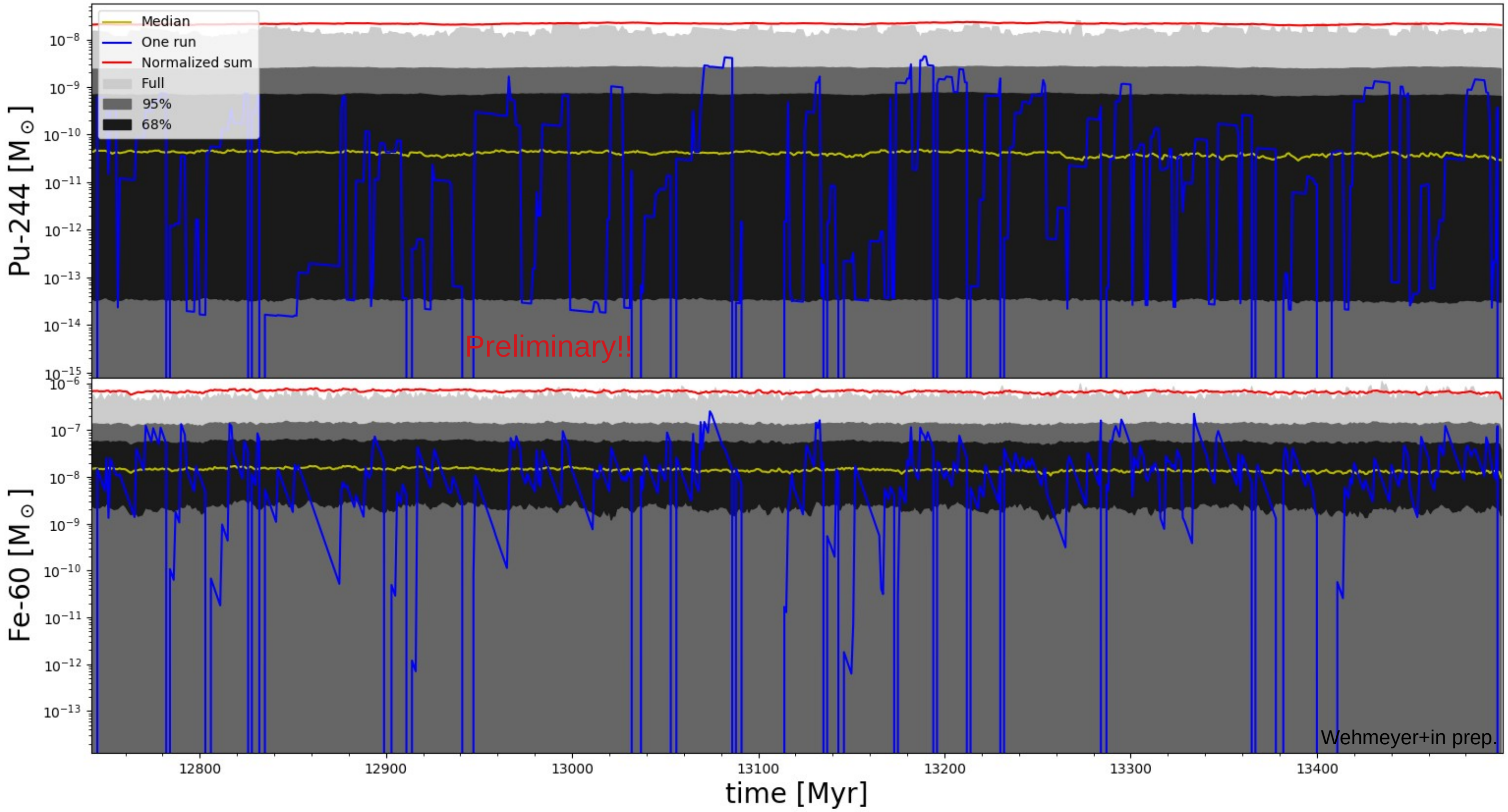
Wehmeyer+subm.

- All follow the Galactic SFH

Yellow: median, grey scales: statistics

Moving to 3D this gets even more complicated!

Zoom in

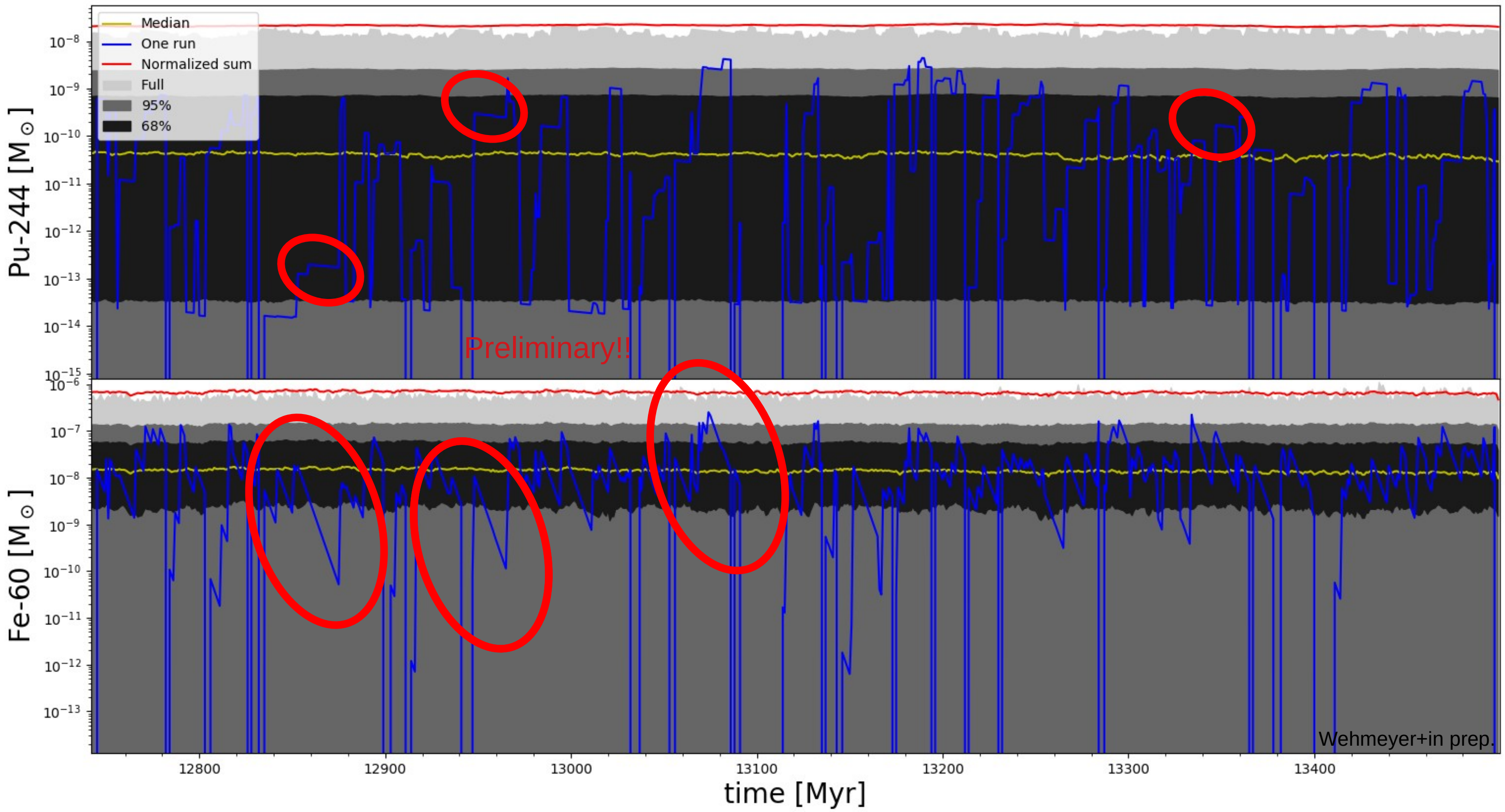


Source: NSM

Source: CCSN

Yellow: median, grey scales: statistics
Blue: Single sub-cell of the 3D simulation

Moving to 3D this gets even more complicated!



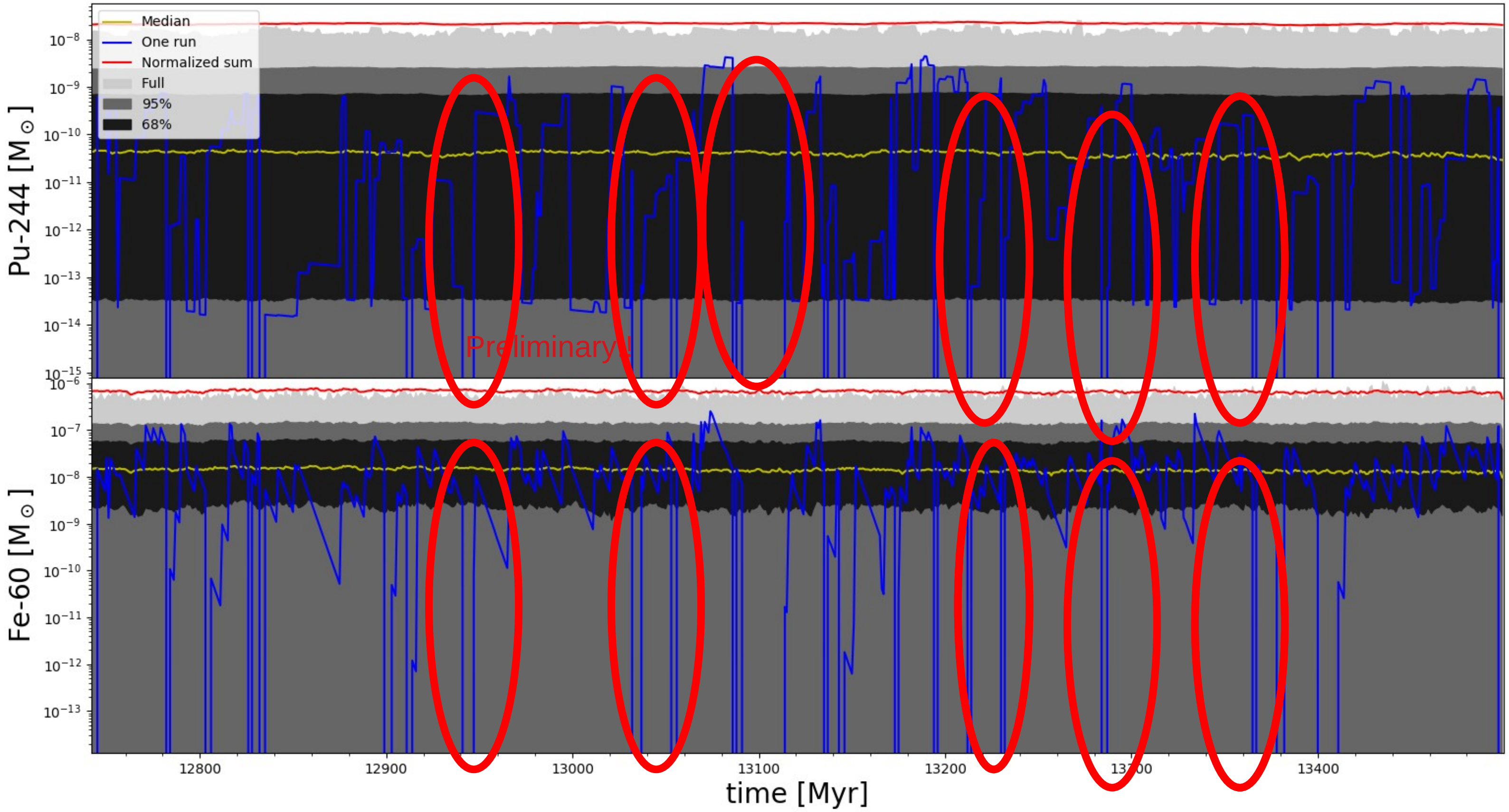
Source: NSM

Source: CCSN

Remarks:

- Radioactive decay is visible in single cells (between nucl events)

Moving to 3D this gets even more complicated!



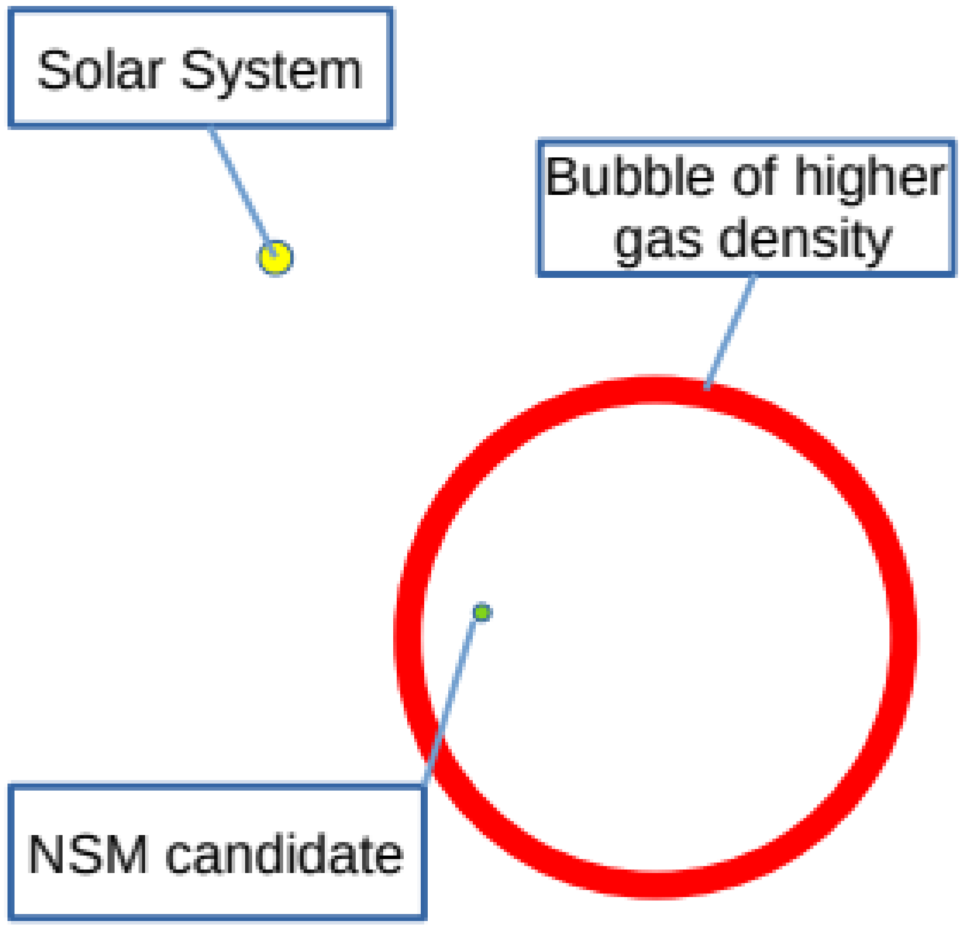
Source: NSM

Source: CCSN

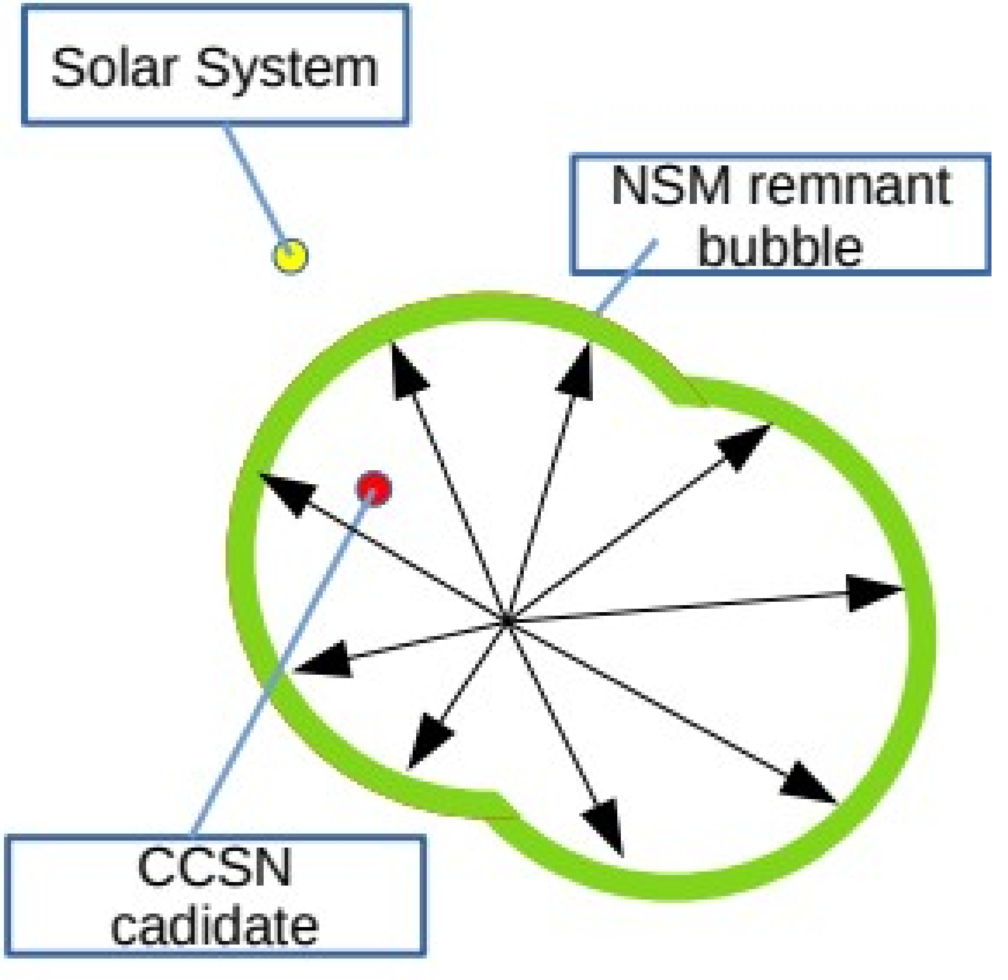
<u>Remarks:</u>

- Radioactive decay is visible in single cells (between nucl events)
- This is often hidden behind the SN blast wave effect
- Pu-244 & Fe-60 always seem to appear **<u>simultaneously</u>**

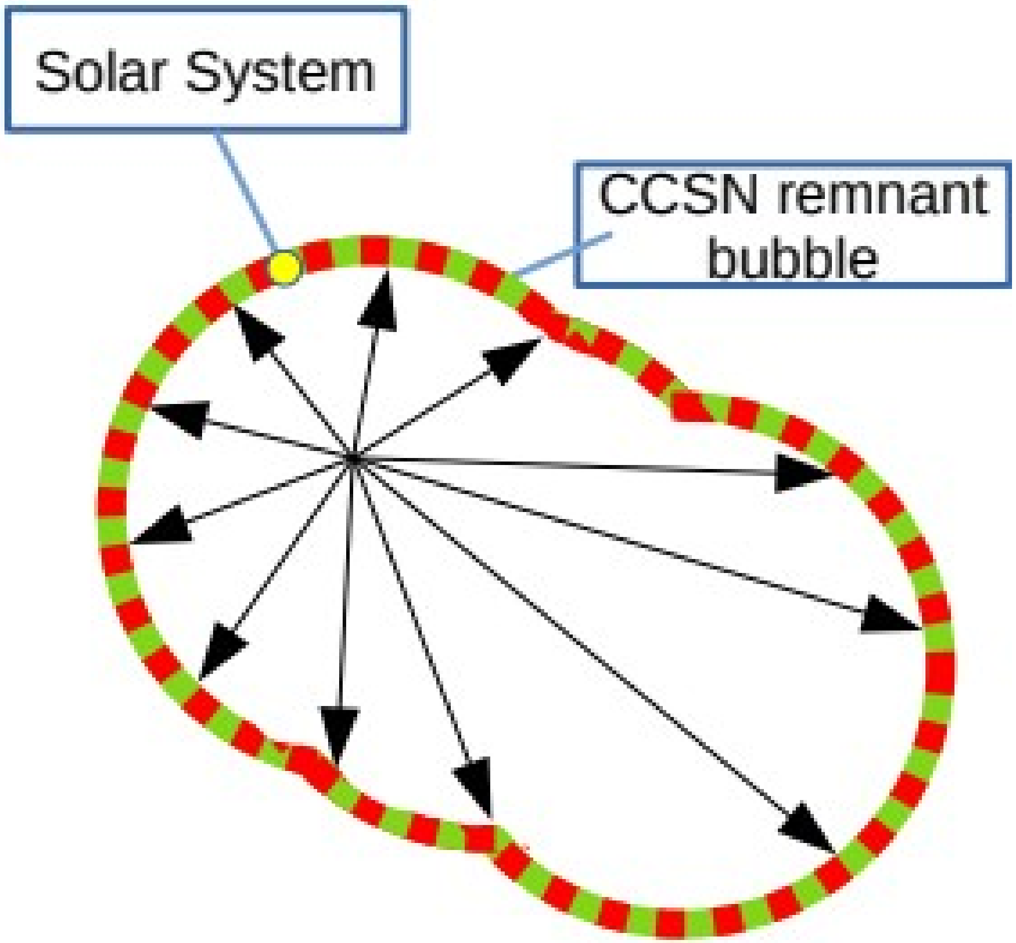
What happens if NSM ejecta get “bulldozed” by CCSN bubbles?



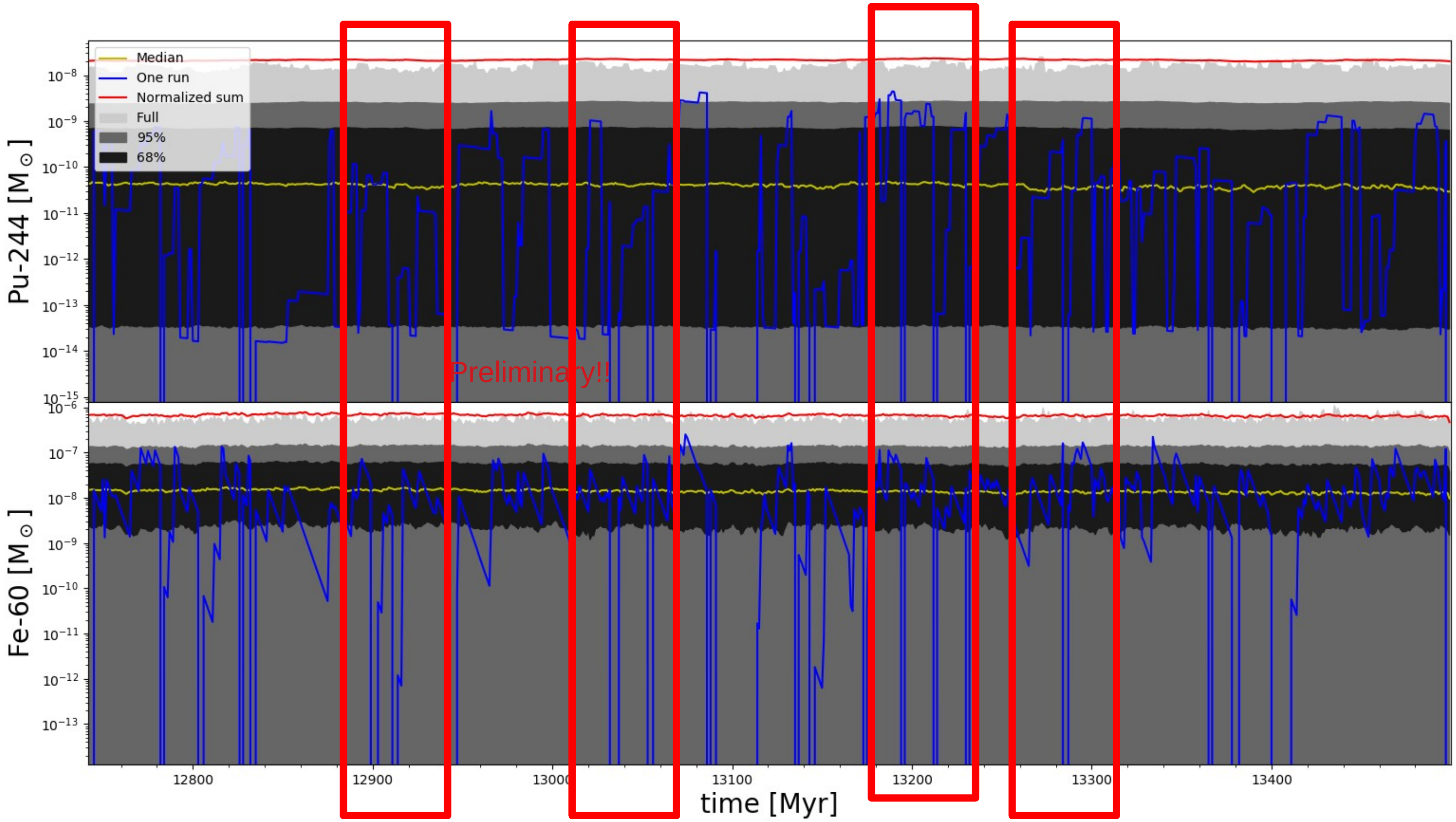
What happens if NSM ejecta get “bulldozed” by CCSN bubbles?



What happens if NSM ejecta get “bulldozed” by CCSN bubbles?



Moving to 3D this gets even more complicated!

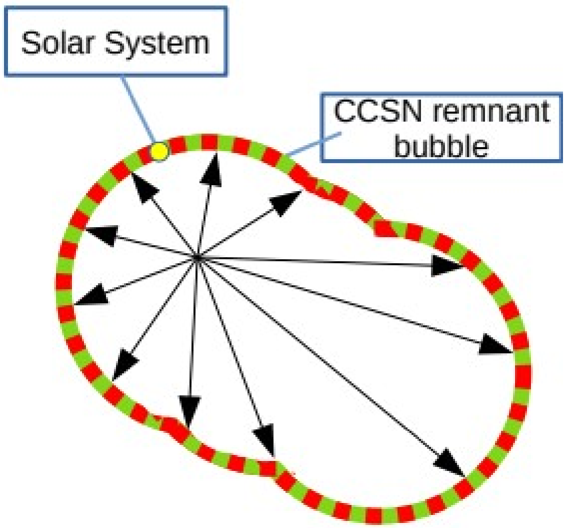


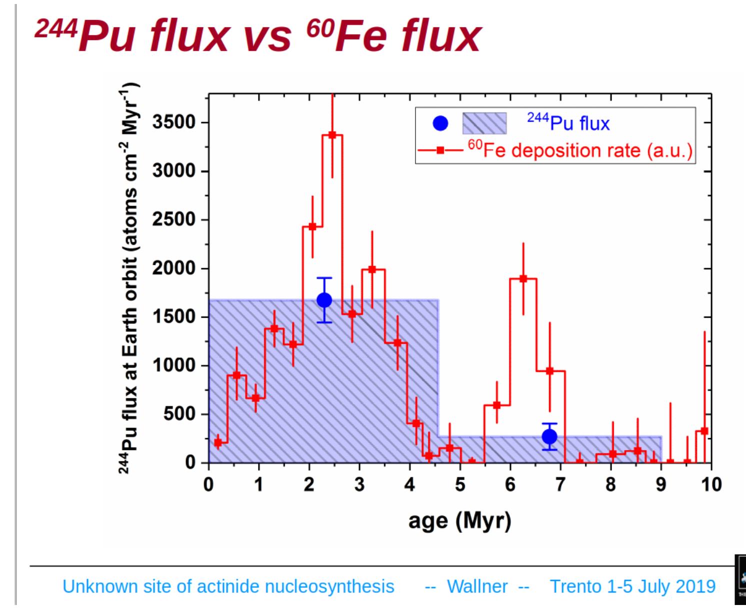
Source: NSM

Source: CCSN

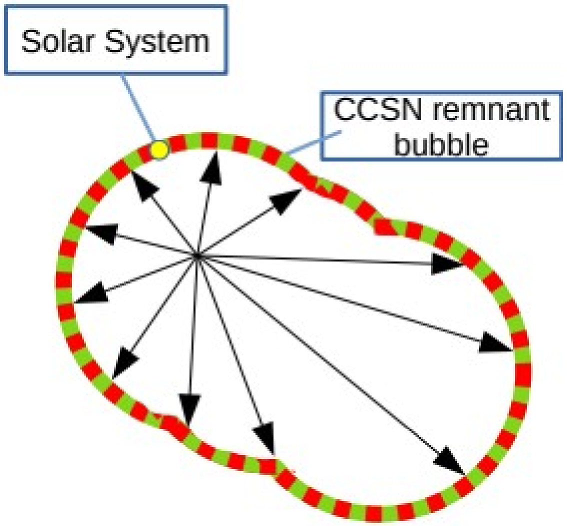
Remarks:

- Radioactive decay is visible in single cells (between nucl events)
- This is hidden behind the SN blast wave effect
- Pu-244 & Fe-60 always seem to appear **simultaneously**

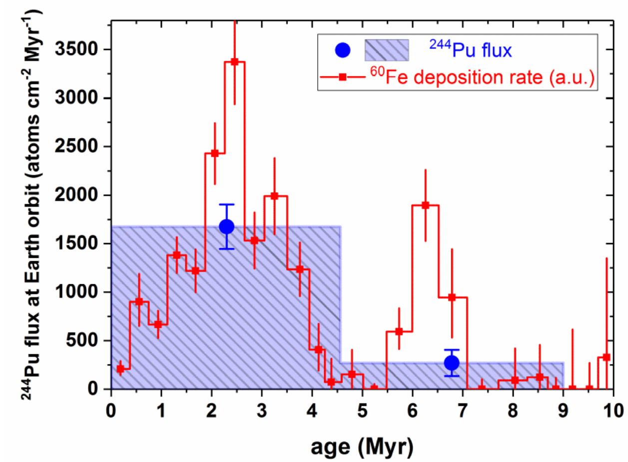




...confirms what is seen
in deep-sea sediments:
Fe-60 and Pu-244 seem to
arrive simultaneously on Earth!



^{244}Pu flux vs ^{60}Fe flux



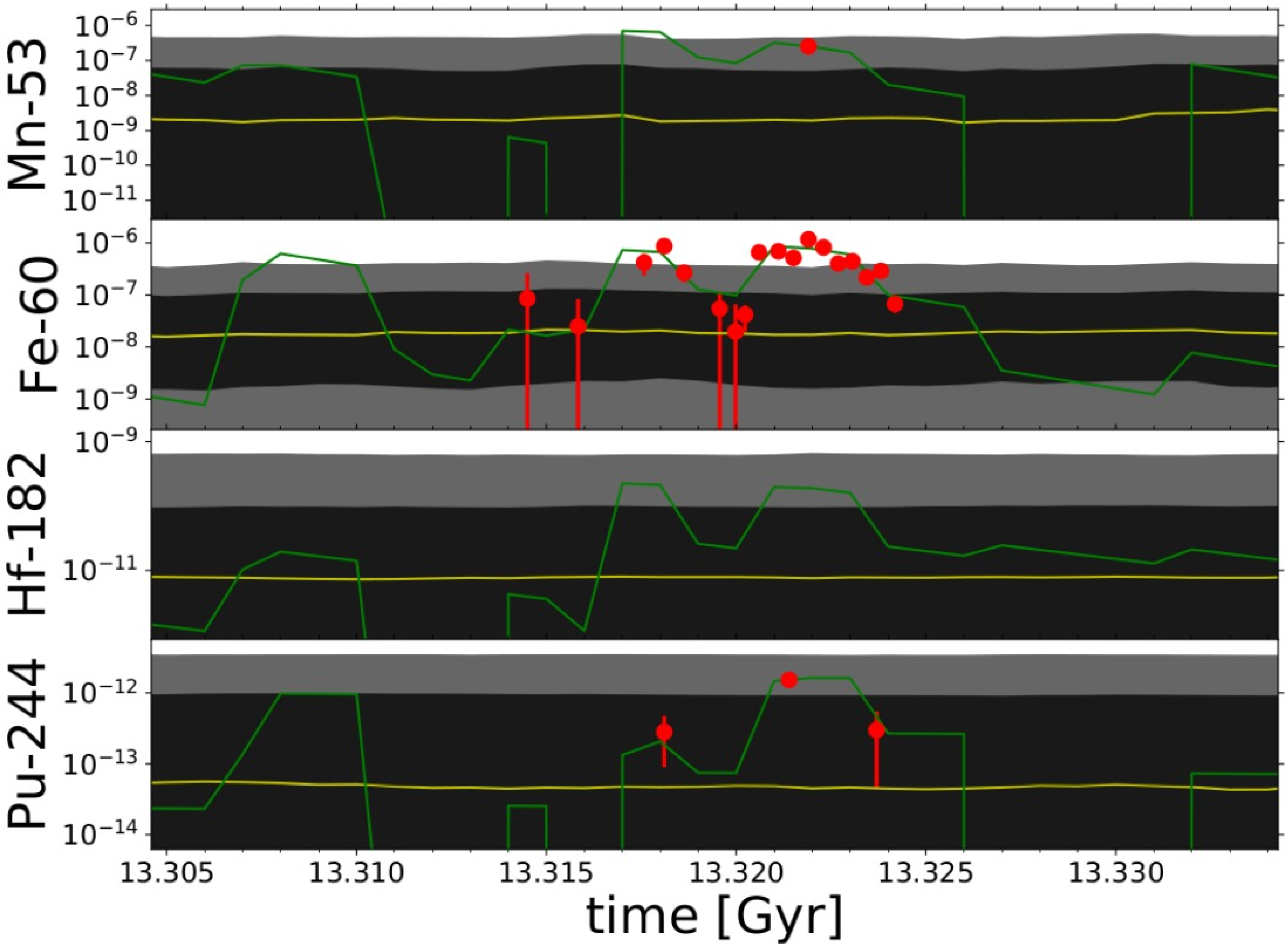
RESEARCH

NUCLEAR ASTROPHYSICS

^{60}Fe and ^{244}Pu deposited on Earth constrain the r-process yields of recent nearby supernovae

A. Wallner[1,2]*, M. B. Froehlich[1], M. A. C. Hotchkis[3], N. Kinoshita[4], M. Paul[5], M. Martschini[1]†, S. Pavetich[1], S. G. Tims[1], N. Kivel[6], D. Schumann[6], M. Honda[7]‡, H. Matsuzaki[8], T. Yamagata[8]

Compare 3D model to deep-sea detection values



Fe-60, Pu-244 from Wallner+, Mn-53 from Korschinek+, time shifted

THE ASTROPHYSICAL JOURNAL, 894:9 (13pp), 2020 May 1 https://doi.org/10.3847/1538-4357/ab86b0

Core-collapse Supernova Explosions Driven by the Hadron-quark Phase Transition as a Rare *r*-process Site

Tobias Fischer[1], Meng-Ru Wu[2,3,4], Benjamin Wehmeyer[5,6], Niels-Uwe F. Bastian[1], Gabriel Martínez-Pinedo[7,8], and Friedrich-Karl Thielemann[7,9]
[1] Institute of Theoretical Physics, University of Wrocław, 50-204 Wrocław, Poland; tobias.fischer@uwr.edu.pl
[2] Institute of Physics, Academia Sinica, Taipei, 11529, Taiwan; mwu@gate.sinica.edu.tw
[3] Institute of Astronomy and Astrophysics, Academia Sinica, Taipei, 10617, Taiwan

THE ASTROPHYSICAL JOURNAL, 894:9 (13pp), 2020 May 1 Fischer et al.

Table 3
Ejecta Properties of the Supernova Explosion Models

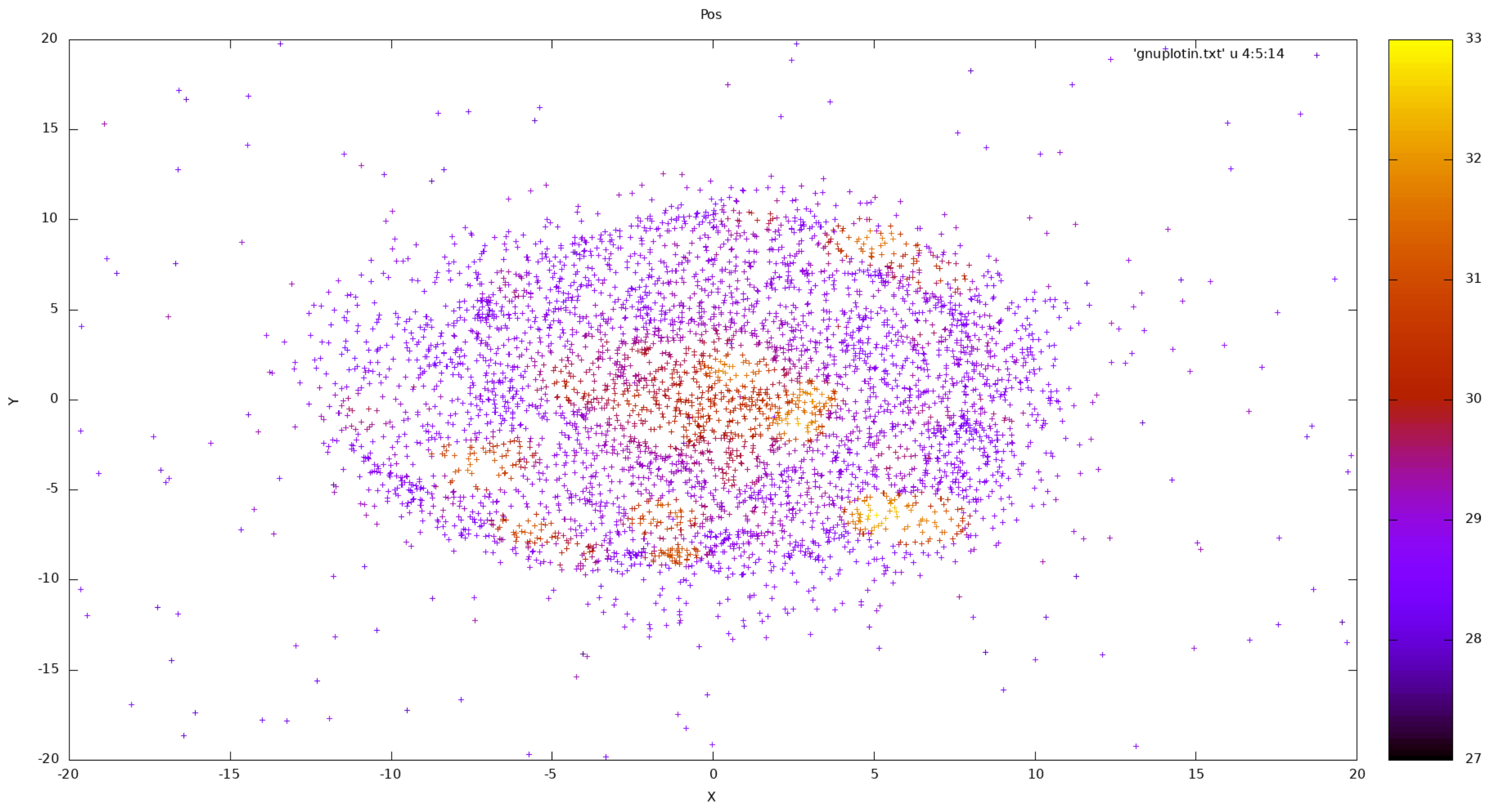
M_{prog}[a] ($M_\odot$)	$M_{inner\ ejecta}$[b] ($10^{-2}\ M_\odot$)	M_{direct}[c] ($10^{-2}\ M_\odot$)	$M_{intermediate}$[d] ($10^{-3}\ M_\odot$)	M_{NDW}[e] ($10^{-3}\ M_\odot$)	M_{Fe}[f] ($10^{-2}\ M_\odot$)	M_{Sr}[f] ($10^{-4}\ M_\odot$)	M_{Eu}[f] ($10^{-6}\ M_\odot$)	$M_{^{244}Pu}$[f,g] ($10^{-10}\ M_\odot$)	$M_{^{60}Fe}$[h] ($10^{-5}\ M_\odot$)
35†	1.44	1.03	3.72	0.33	7.15	6.50	7.86	2.09	12.2
40†	1.33	0.97	3.19	0.43	7.62	6.15	2.26	2.64	3.2
50‡	1.80	1.45	3.06	0.46	3.73	8.22	11.03	22.59	0.5

Notes. All yields are evaluated after about 1 Gyr.
[a] ZAMS masses of the stellar models (same as in Table 2), †: Rauscher et al. (2002) and ‡: Umeda & Nomoto (2008).
[b] Total *inner ejecta* mass, launched from the PNS surface.

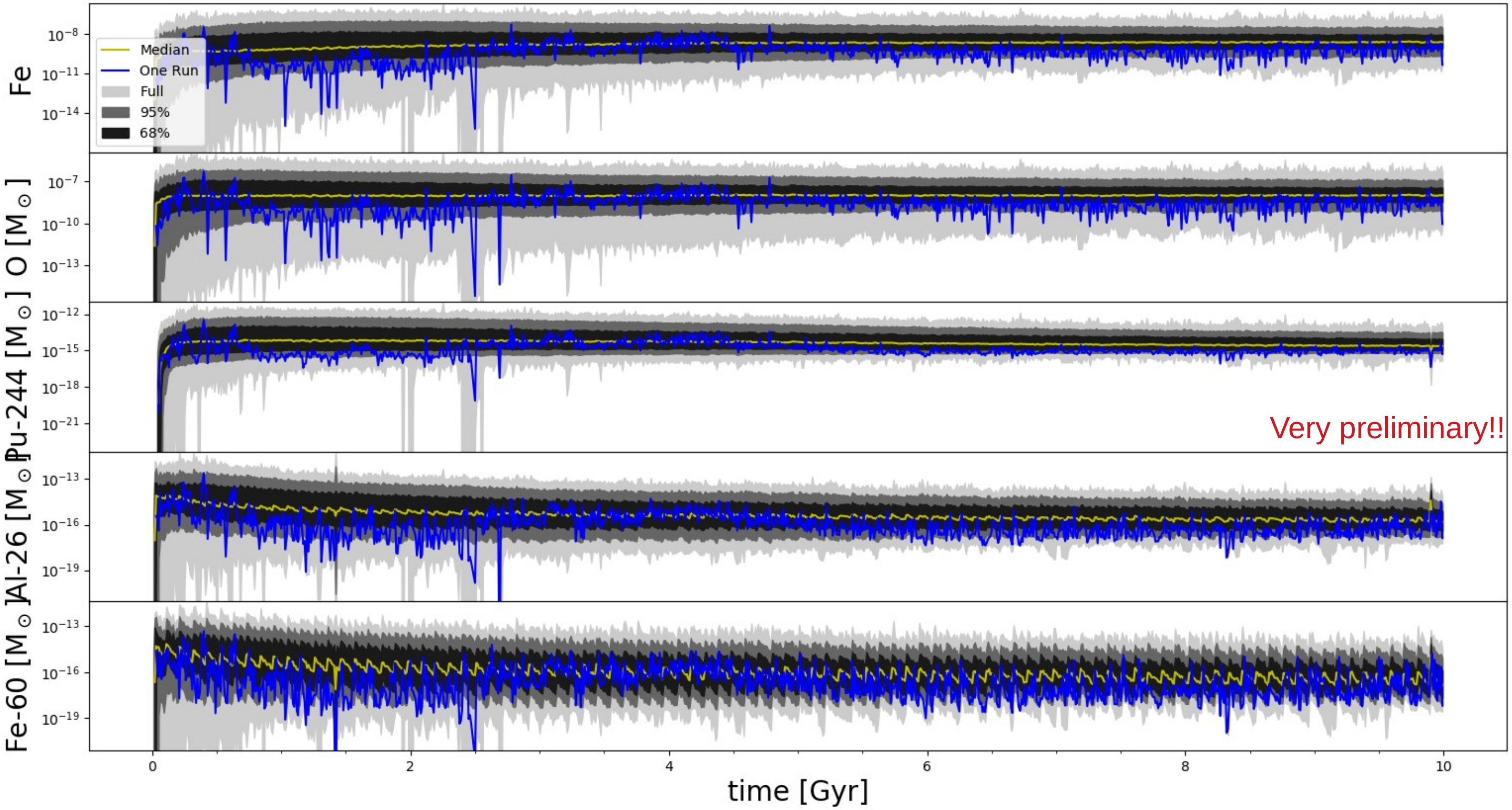
See also yesterday's talk:

Constraining the onset density for the QCD phase transition with the supernova neutrino signal *Noshad Khosravi Largani*
Aula Grande, FBK Headquarters 15:10 - 15:30

One step further: implementing SLRs in Kobayashi **chemodynamical cosmological zoom-in SPH model**

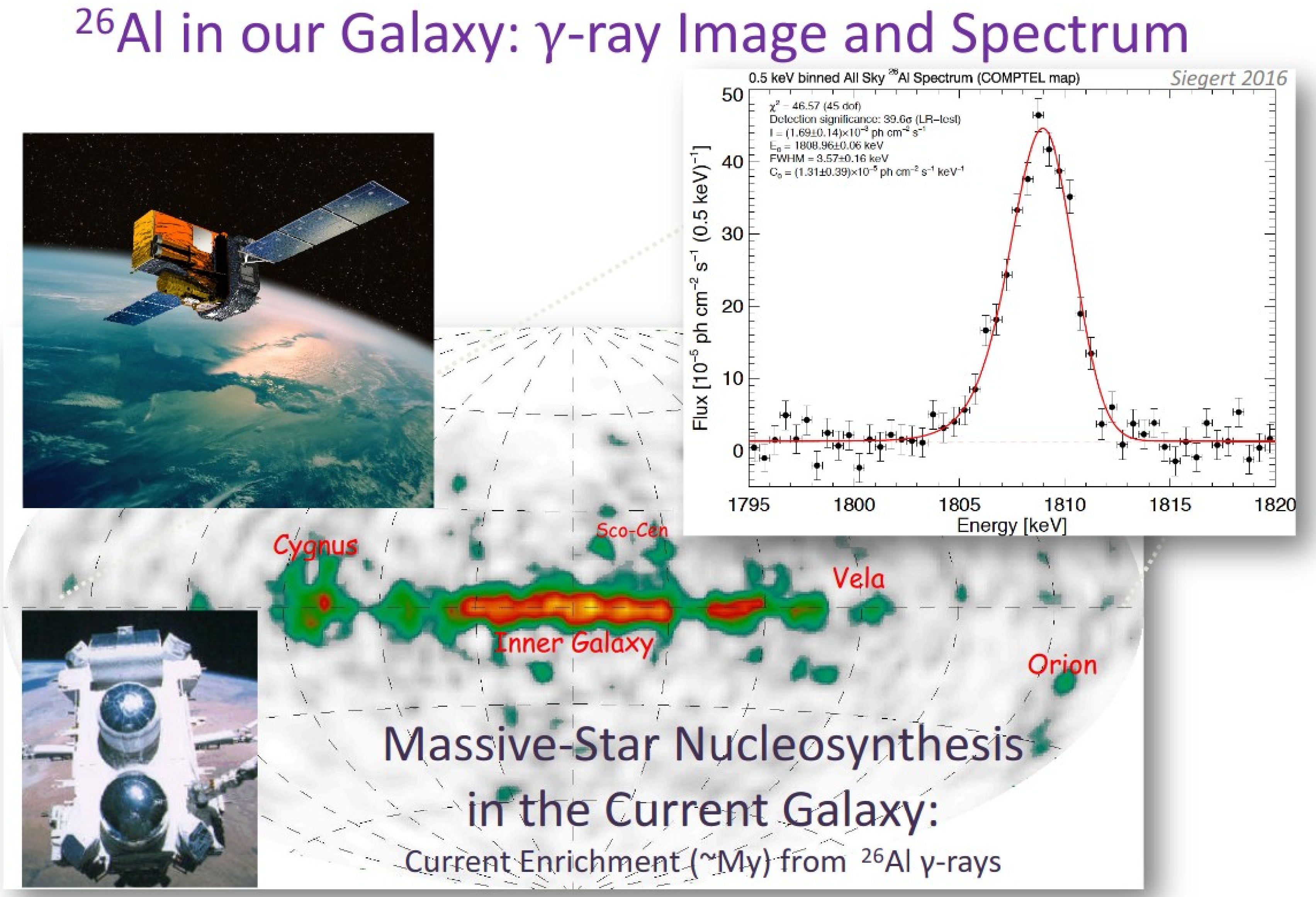


One step further: implementing SLRs in
Kobayashi **chemodynamical cosmological zoom-in SPH model**



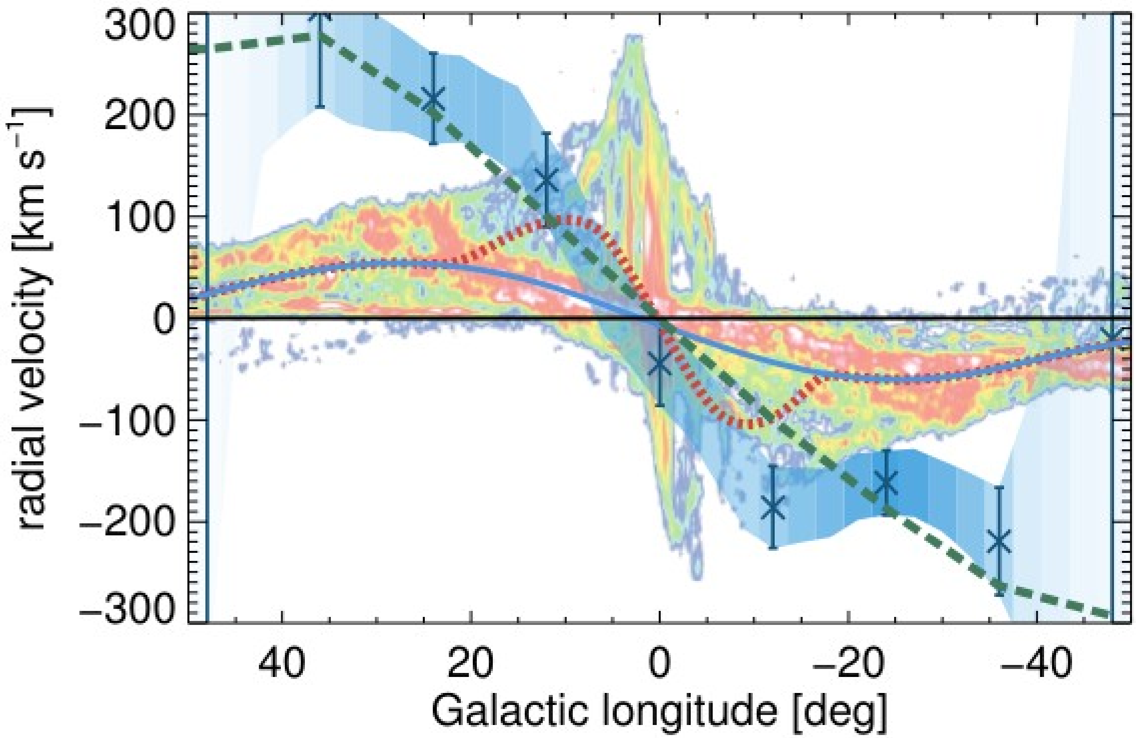
- Many features (DM, hydrodynamics, feedback) are included
- Know exactly where (spiral arms?) in the Galaxy and when which SLRs can be found

We can use current Al-26 emission to pinpoint stellar activity!



...Slide stolen from R. Diehl, see many talks this workshop

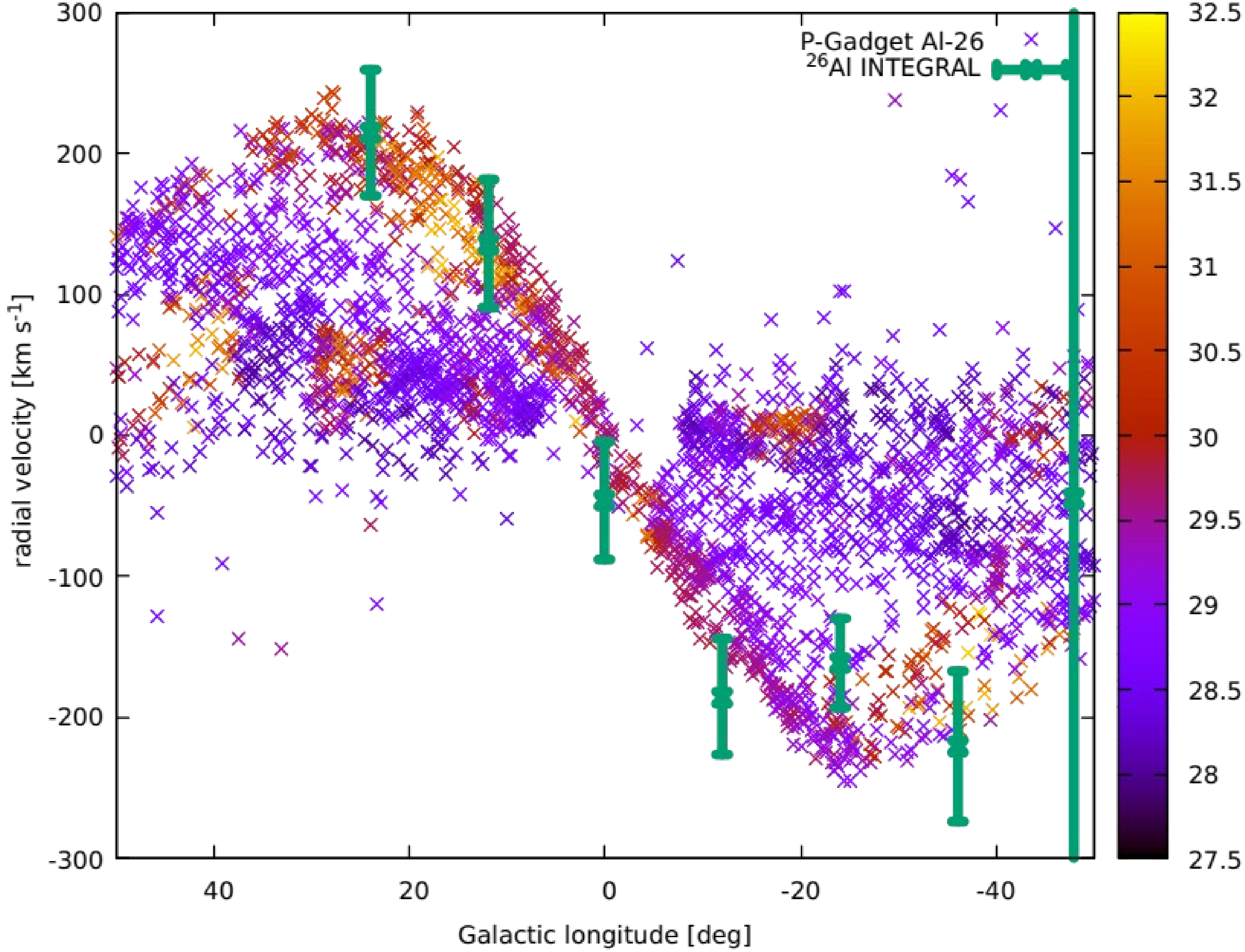
It will provide us with an “emission map” of the Galaxy:
We can interpret it using Galaxy models!



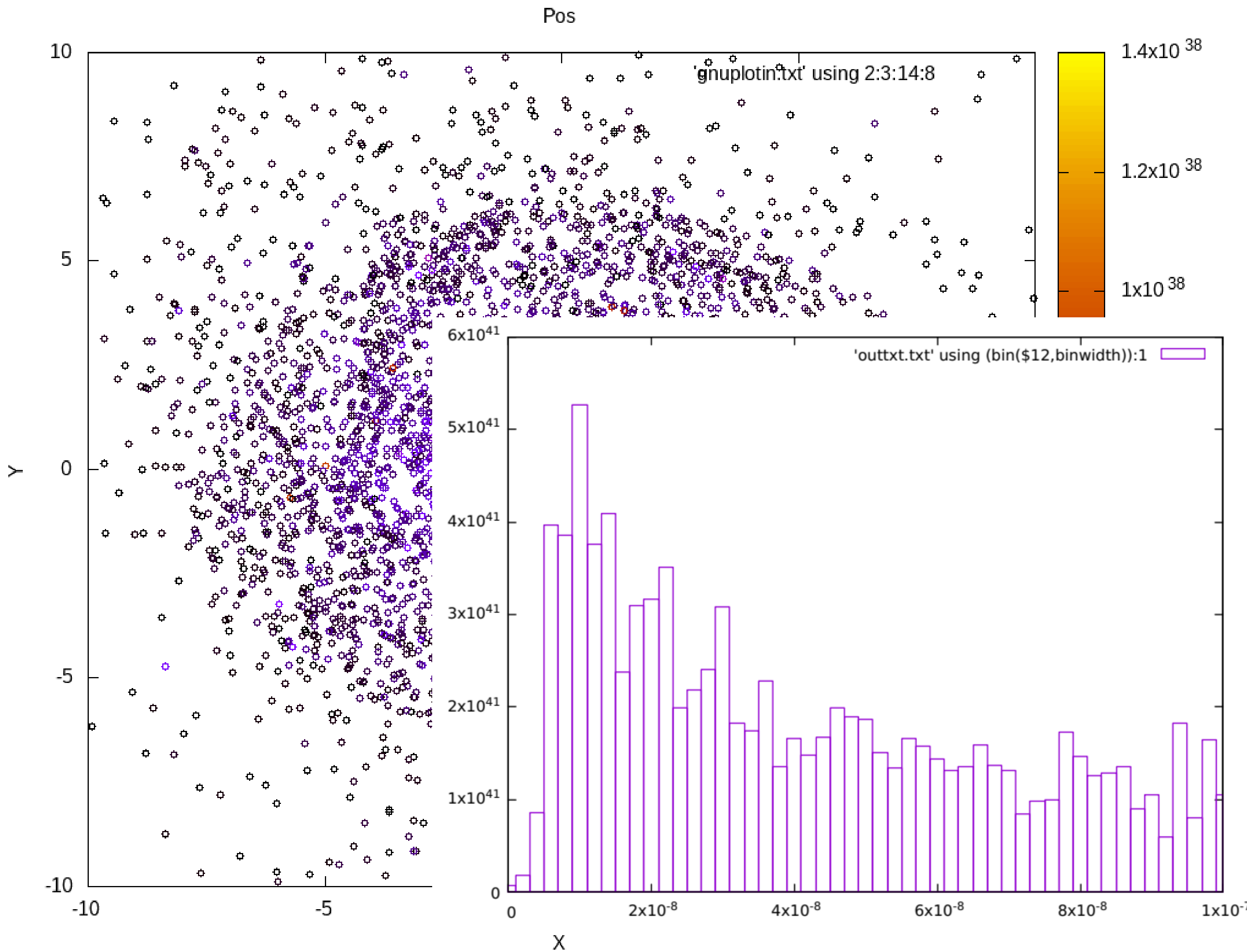
Kretschmer+13

Fig. 8. Longitude-velocity diagram comparing γ-ray-measured velocities (crosses, including error bars) with other objects in our Galaxy. ^{26}Al line-centroid energies were fitted to determine velocities in longitude bins of 12° and latitude ranges ±5°. For comparison, different models are shown (blue solid, red dotted, and green dashed lines), as well as the velocity information from molecular gas seen in CO (see Sect. 4 for details).

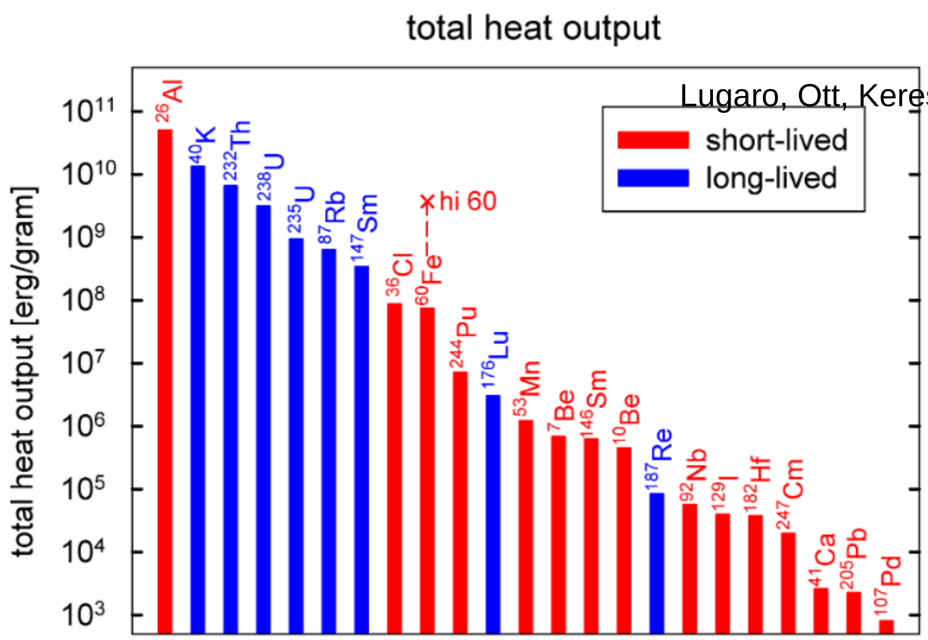
It will provide us with an “emission map” of the Galaxy:
We can interpret it using Galaxy models!



This might also help to find Galactic areas with habitable planets!



With radioactive isotopes also heating planetesimals



Lugaro, Ott, Kereszturi (2018)

Figure 15: Total energy available for heating from radioactive decay per gram of material in the Solar System (CI meteorite composition) after the initially present isotope has completely decayed. For ^{10}Be/^{9}Be a value of 1×10^{-3} was used. For ^{60}Fe also the situation for a high abundance (^{60}Fe/^{56}Fe $= 5 \times 10^{-7}$ as compared to 1.01×10^{-8} given in Table 2) is indicated.

Conclusions

NSMs alone have difficulties explaining high r-process abundances at low metallicities

- >> Additional site can cure this (BHNS-M, MHD-SNe, Exotic SNe)
- We can constrain the SLR abundances and uncertainties by using the timing information of the sources (δ, γ), and vice versa
- SLRs may give us information about the nucleosynthesis conditions of the last event before formation of the Solar system
- SLRs seem to arrive on Earth simultaneously
  - This can be explained with the appropriate statistical tools
  - Can be further constrained by more deep-sea sediment detections
- Al-26 maps can help us locate stellar activity
  - This can be modeled with Galaxy evolution models
- We can identify regions in the Galaxy with enhanced isotope abundances
  - Might help to find areas with potentially habitable planets

We acknowledge support from the European Research Council under ERC Consolidator Grant Agreement No. 724560 “RADIOSTAR” (PI: Maria Lugaro), and the Swiss National Science Foundation (SNF). This work benefited from COST action ChETEC (16117) and support from the National Science Foundation Grant no. PHY-1430152 (JINA Center for the Evolution of the Elements), and Grant no. OISE-1927130 (IreNA), and NCN SONATA grant No. 2022/47/D/ST9/03092.

erc

Narodowe Centrum Nauki