ECT* - Nuclear and Astrophysics Aspects for the r Process - Era of Multimessenger
July 1-5, 2019, Trento, Italy

Galactic Chemical Evolution of r-Process Elements

Benoit Côté
Postdoctoral Researcher

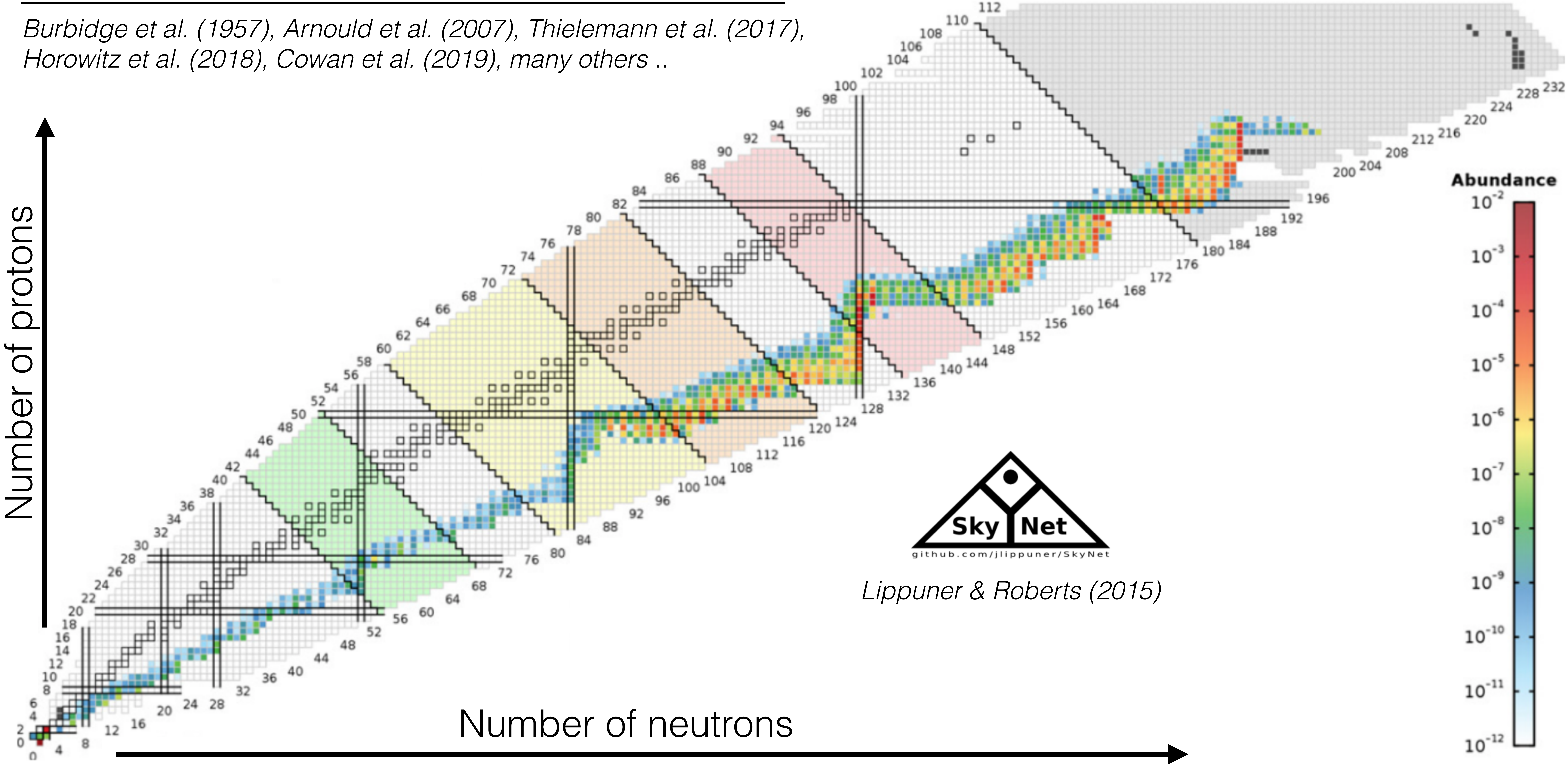
Joint Institute for Nuclear Astrophysics - Center for the Evolution of the Elements
Michigan State University (USA)
Konkoly Observatory (Hungary)

Collaborators (**in alphabetic order**)
A. Arcones, K. Belczynski, M. Chruslinska, M. Eichler, A. Frebel, C. Fryer, B. Gibson, C. J. Hansen, O. Korobkin, J. Lippuner, M. Lugaro, F. Matteucci, M. Mumpower, B. O'Shea, M. Pignatari, M. Reichert, R. Reifarth, D. Silvia, B. Smith, T. Sprouse, P. Simonetti, R. Surman, N. Vassh, J. Wise, B. Villagos, R. Wollaeger, A. Yagüe

Image credit: The Renaissance Simulation (O'Shea et al. 2015, Xu et al. 2016)

Rapid Neutron-Capture Process (r-process)

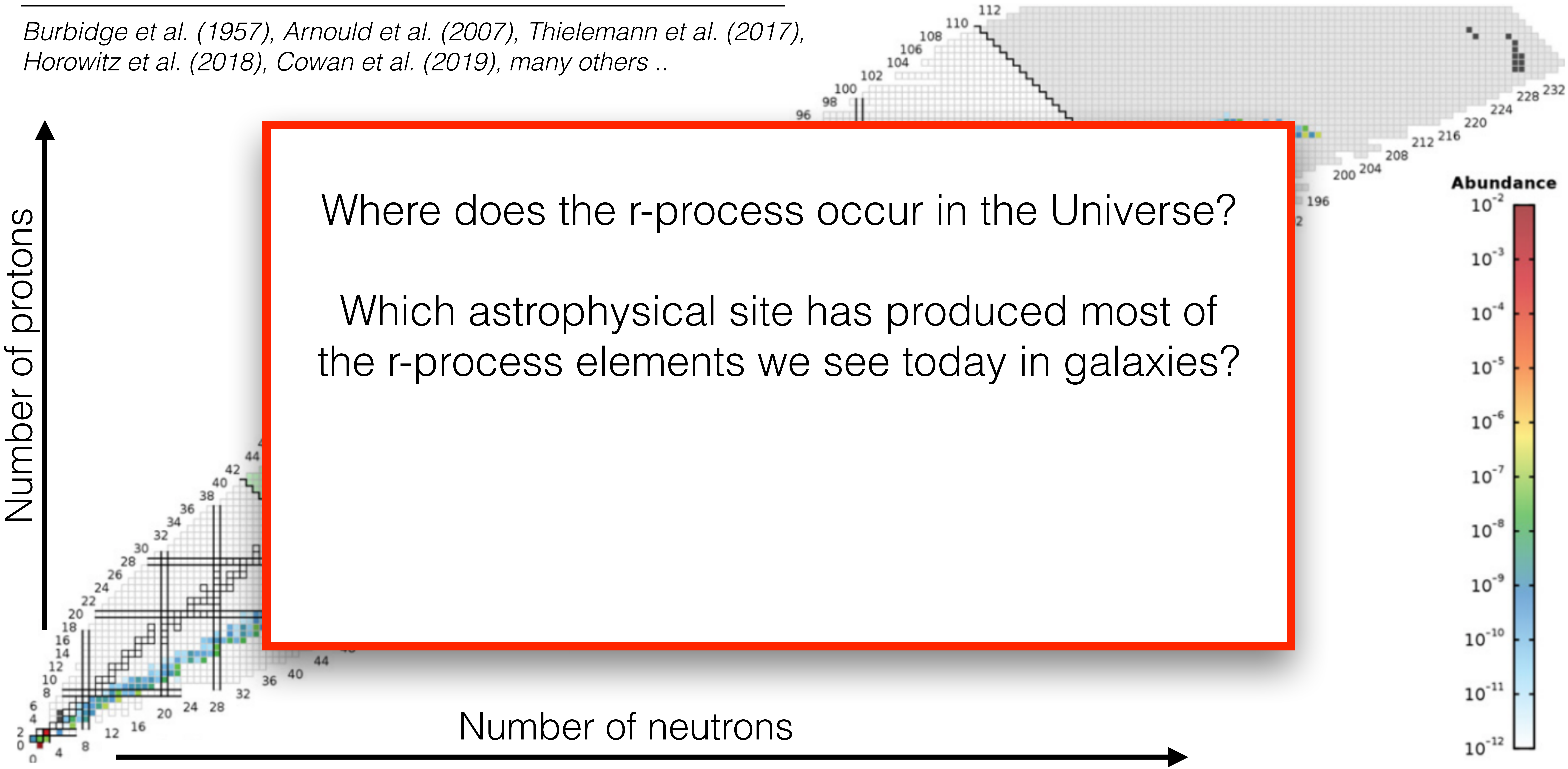
Burbidge et al. (1957), Arnould et al. (2007), Thielemann et al. (2017), Horowitz et al. (2018), Cowan et al. (2019), many others ..



Lippuner & Roberts (2015)

Rapid Neutron-Capture Process (r-process)

Burbidge et al. (1957), Arnould et al. (2007), Thielemann et al. (2017), Horowitz et al. (2018), Cowan et al. (2019), many others ..

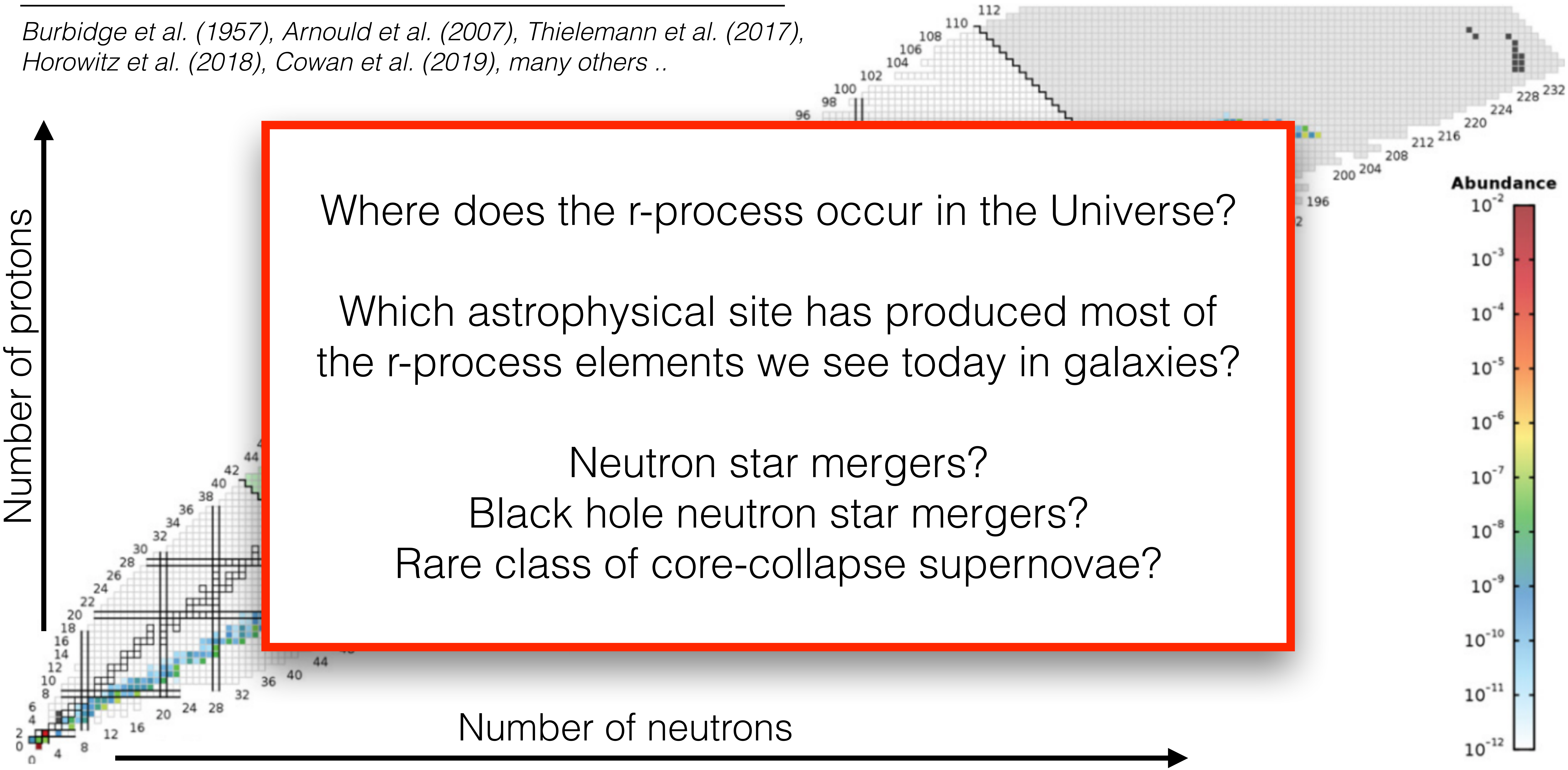


Where does the r-process occur in the Universe?

Which astrophysical site has produced most of the r-process elements we see today in galaxies?

Rapid Neutron-Capture Process (r-process)

Burbidge et al. (1957), Arnould et al. (2007), Thielemann et al. (2017), Horowitz et al. (2018), Cowan et al. (2019), many others ..



Number of protons

Where does the r-process occur in the Universe?

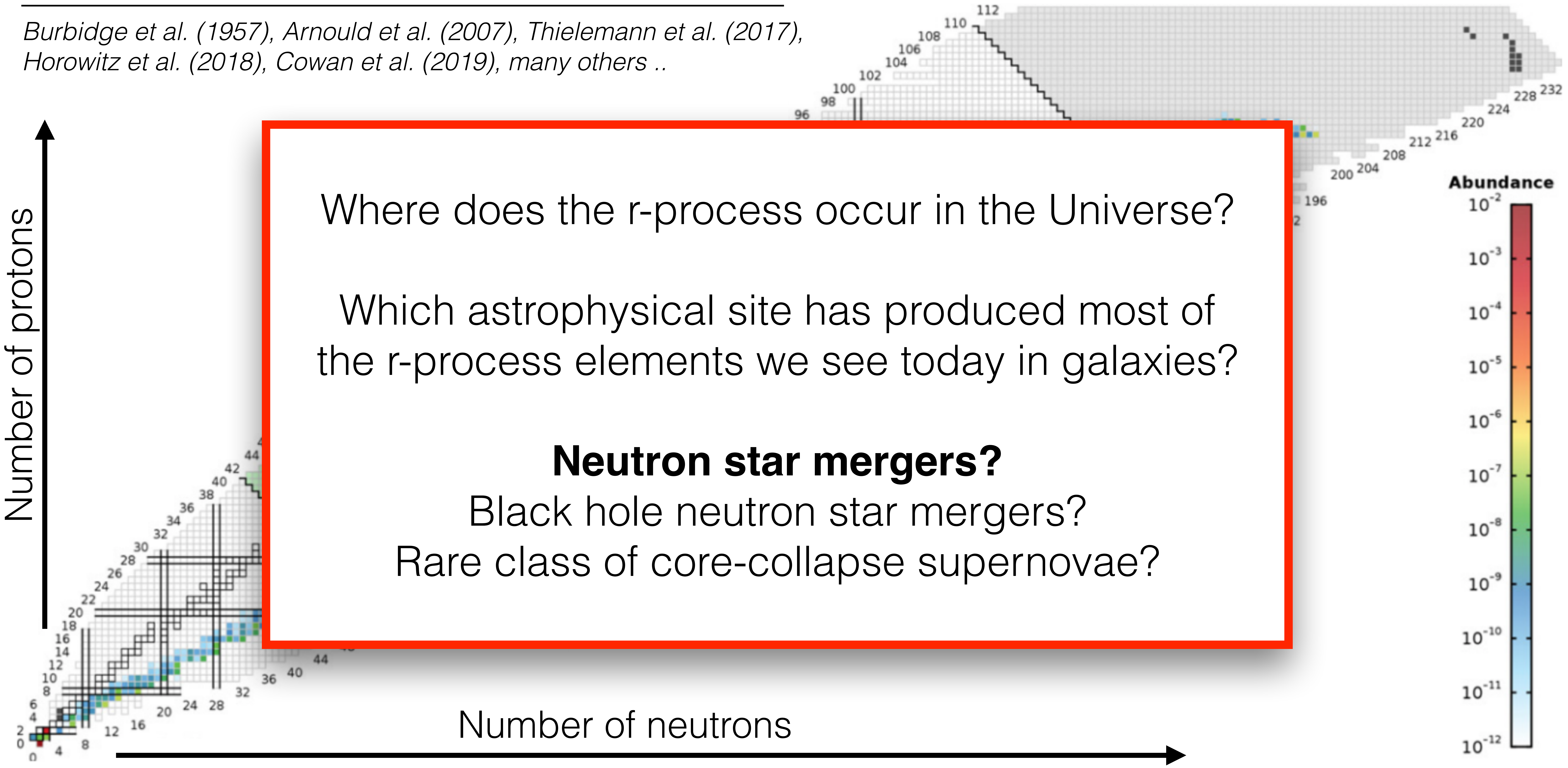
Which astrophysical site has produced most of the r-process elements we see today in galaxies?

Neutron star mergers?
Black hole neutron star mergers?
Rare class of core-collapse supernovae?

Number of neutrons

Rapid Neutron-Capture Process (r-process)

Burbidge et al. (1957), Arnould et al. (2007), Thielemann et al. (2017), Horowitz et al. (2018), Cowan et al. (2019), many others ..

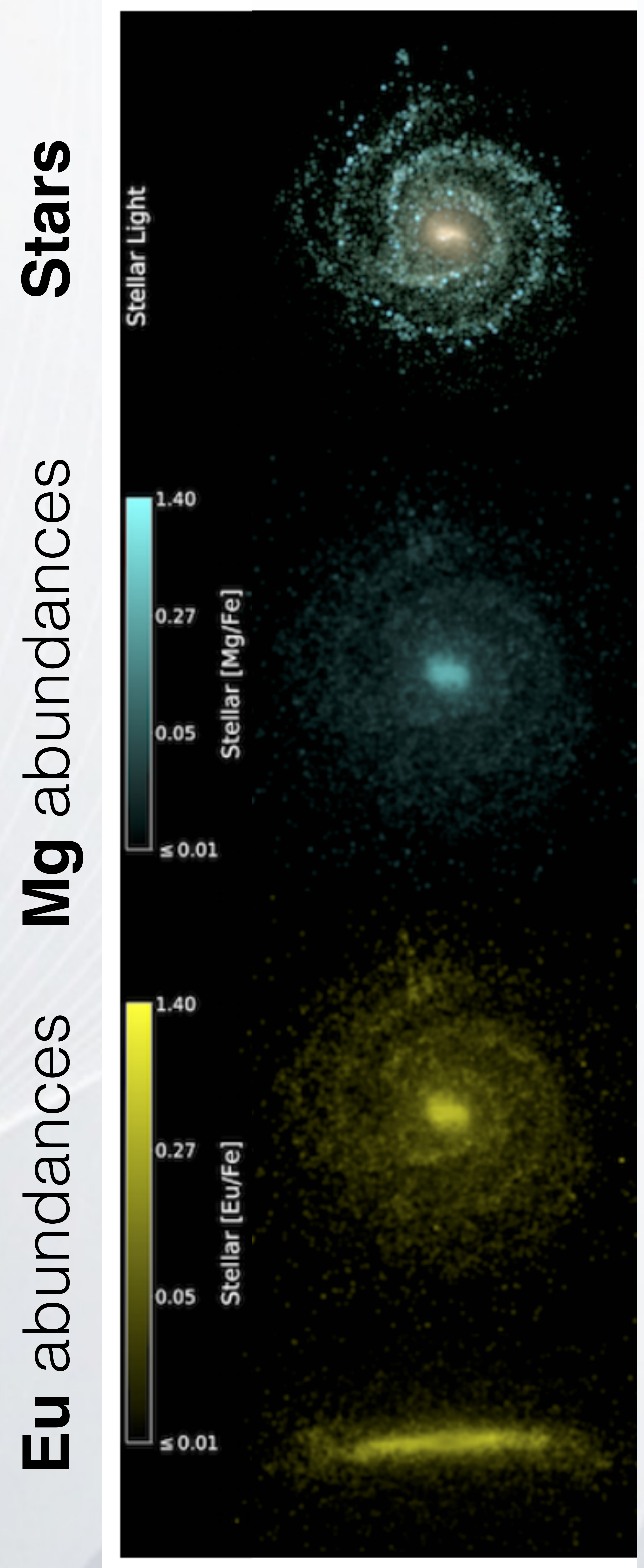


Where does the r-process occur in the Universe?

Which astrophysical site has produced most of the r-process elements we see today in galaxies?

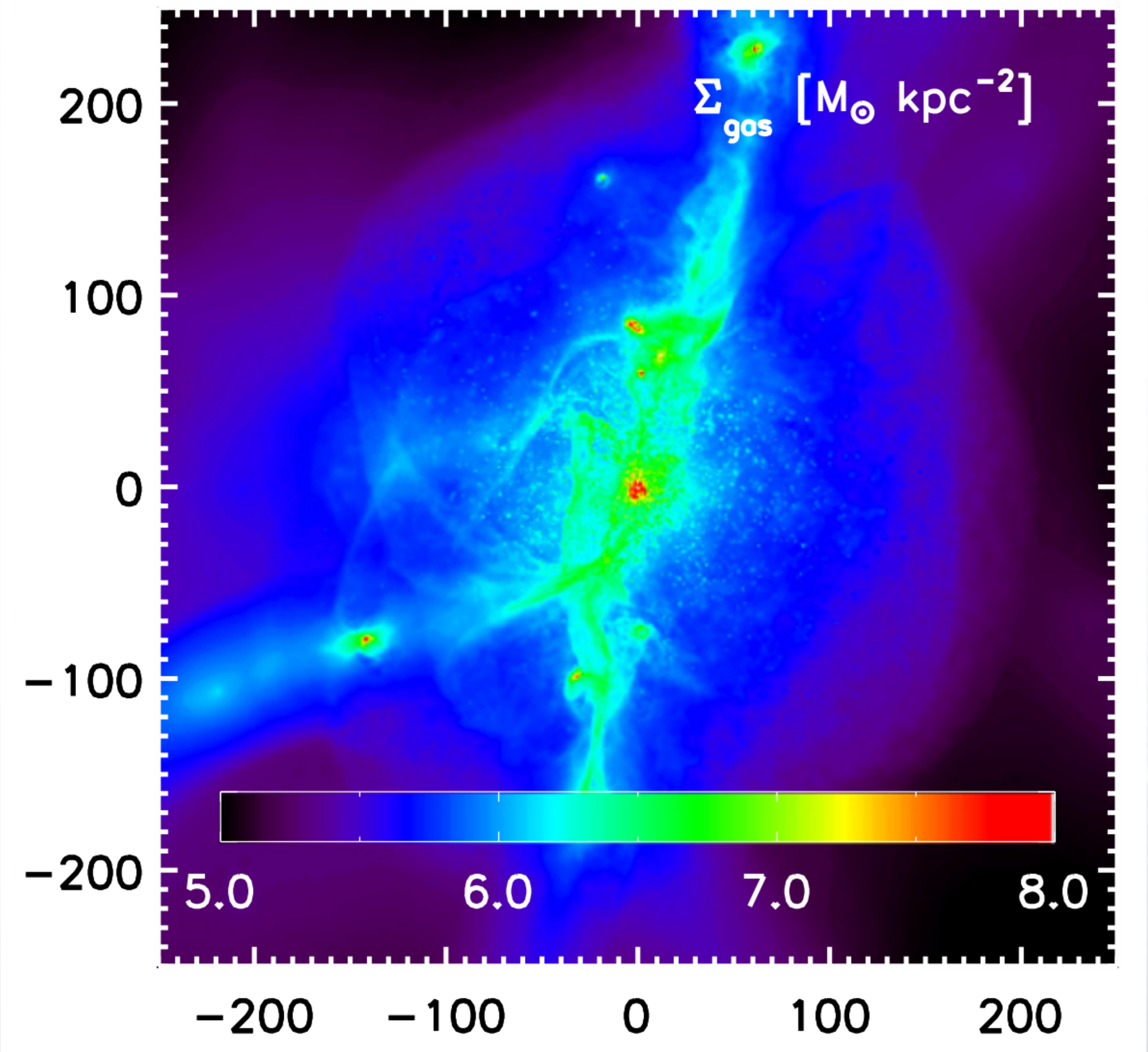
Neutron star mergers?
Black hole neutron star mergers?
Rare class of core-collapse supernovae?

Galaxy Simulations to Recreate the Evolution of r-process Elements



Naiman et al. (2018)

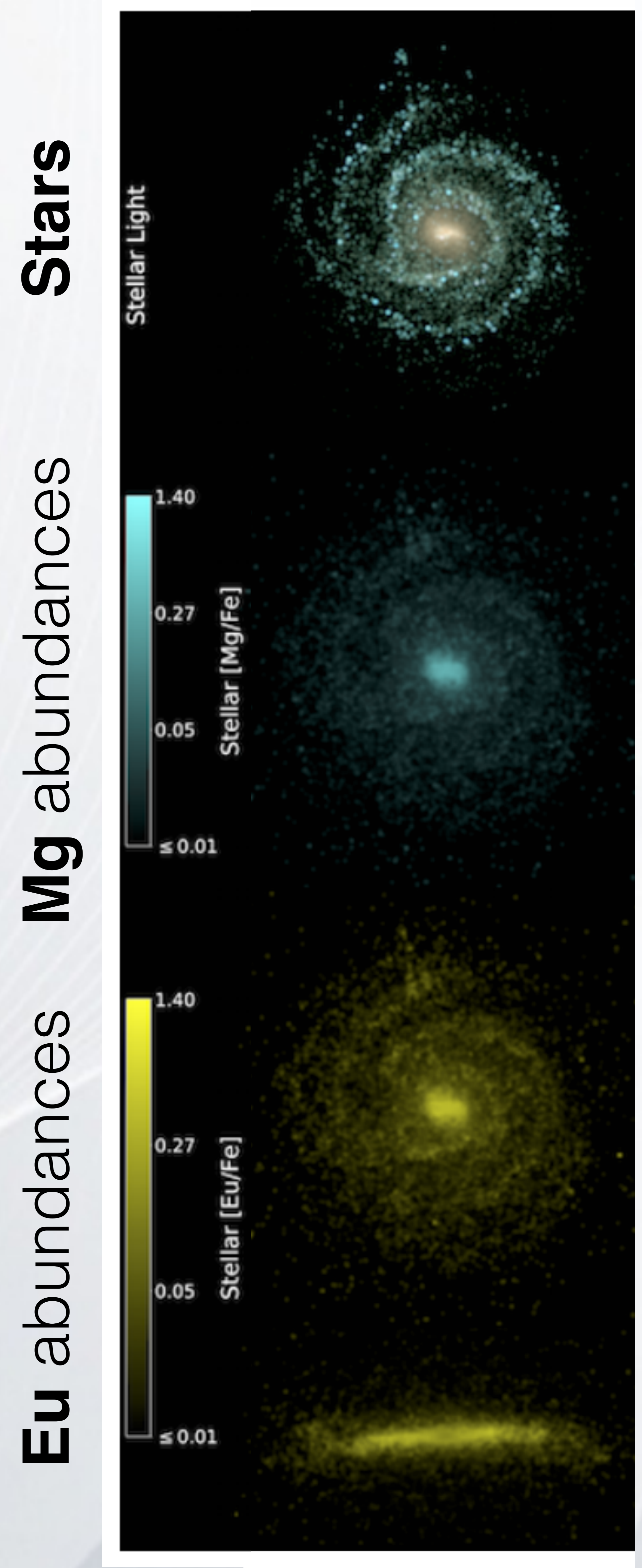
Shen et al. (2015)



Chemical evolution simulations for r-process elements

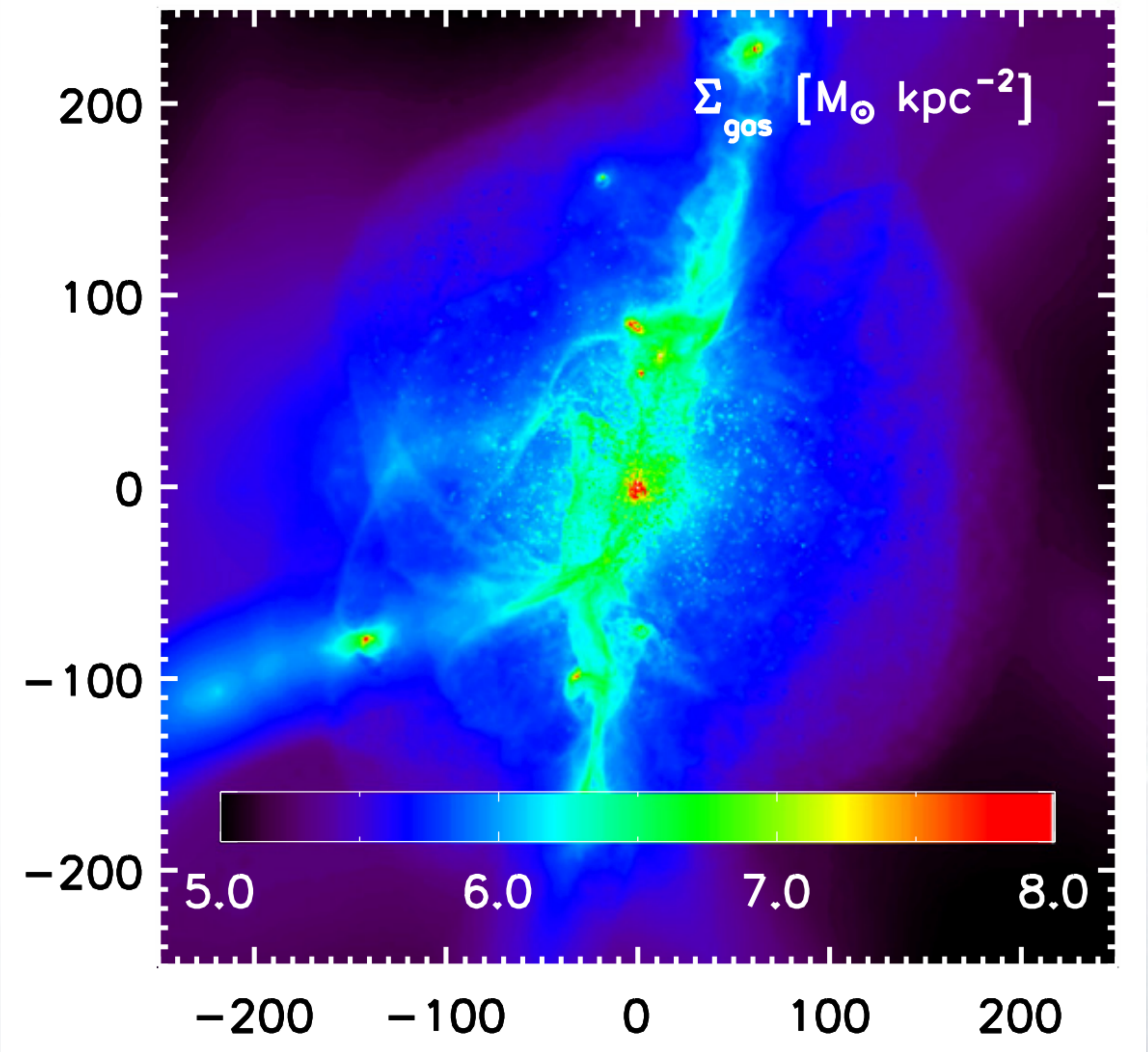
Argast et al. (2004)
Matteucci et al. (2014)
Cescutti et al. (2015)
Hirai et al. (2015)
Ishimaru et al. (2015)
Shen et al. (2015)
van de Voort et al. (2015)
Wehmeyer et al. (2015, 2019)
Komiya & Shigeyama (2016)
Côté et al. (2017, 2019)
Hotokezaka et al. (2018)
Naiman et al. (2018)
Safarzadeh et al. (2018)
Haynes & Kobayashi (2019)
Simonetti et al. (2019)
...

Galaxy Simulations to Recreate the Evolution of r-process Elements



Naiman et al. (2018)

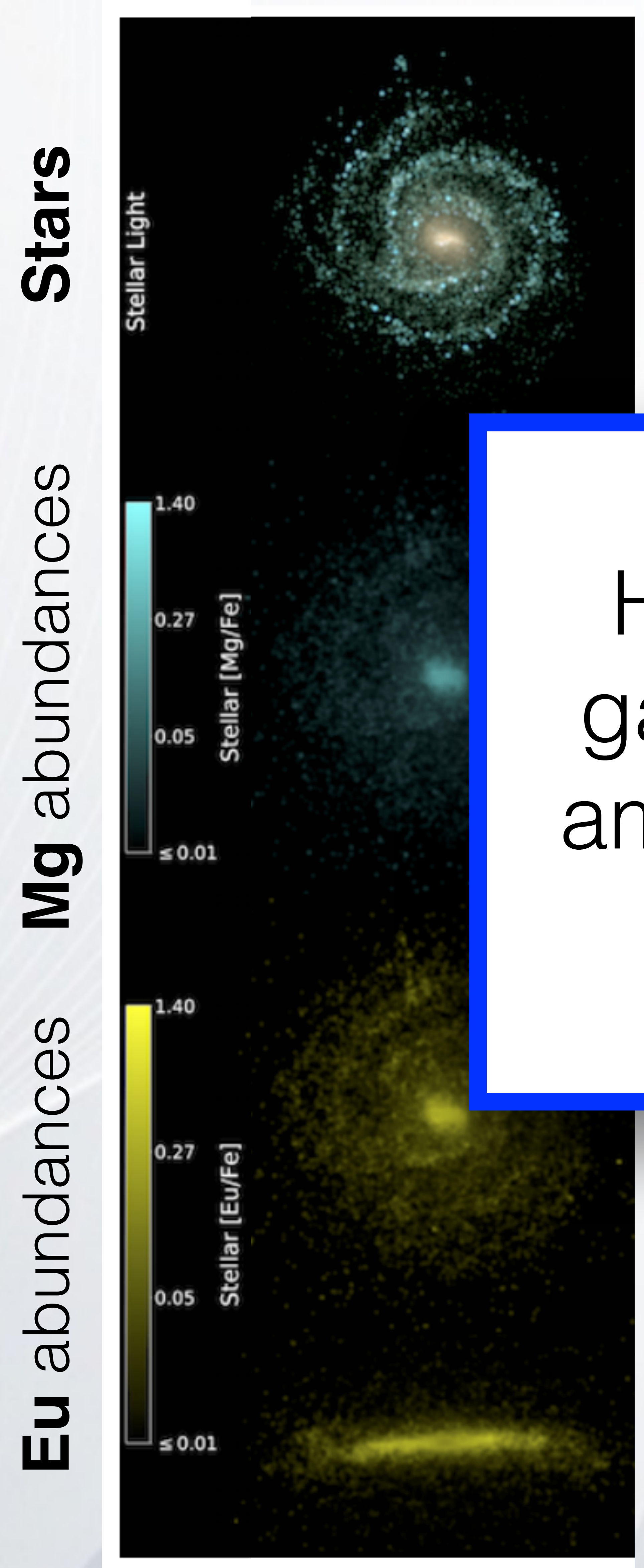
Shen et al. (2015)



Chemical evolution simulations for r-process elements

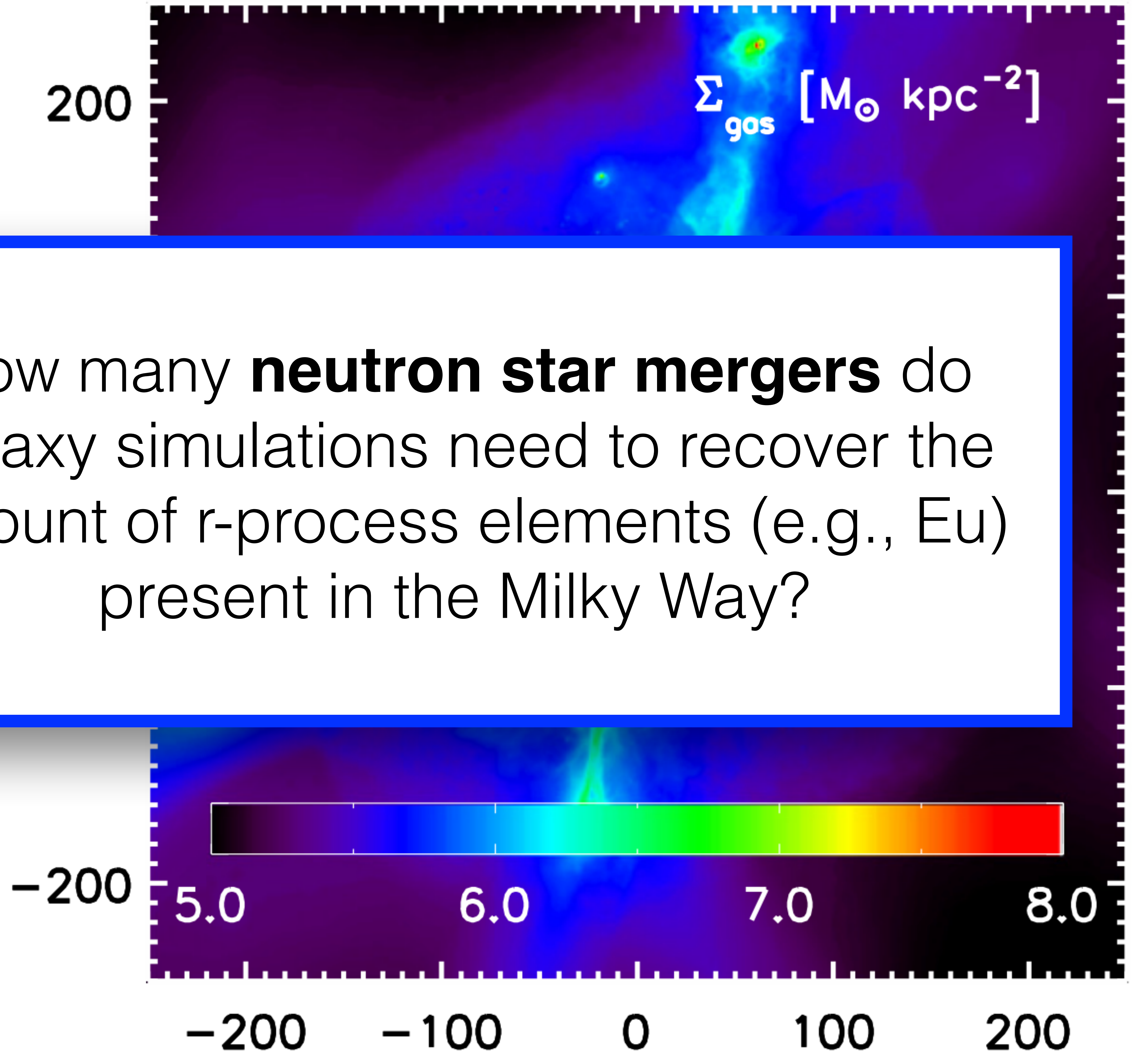
Argast et al. (2004)
Matteucci et al. (2014)
Cescutti et al. (2015)
Hirai et al. (2015)
Ishimaru et al. (2015)
Shen et al. (2015)
van de Voort et al. (2015)
Wehmeyer et al. (2015, 2019)
Komiya & Shigeyama (2016)
Côté et al. (2017, 2019)
Hotokezaka et al. (2018)
Naiman et al. (2018)
Safarzadeh et al. (2018)
Haynes & Kobayashi (2019)
Simonetti et al. (2019)
...

Galaxy Simulations to Recreate the Evolution of r-process Elements



Naiman et al. (2018)

Shen et al. (2015)



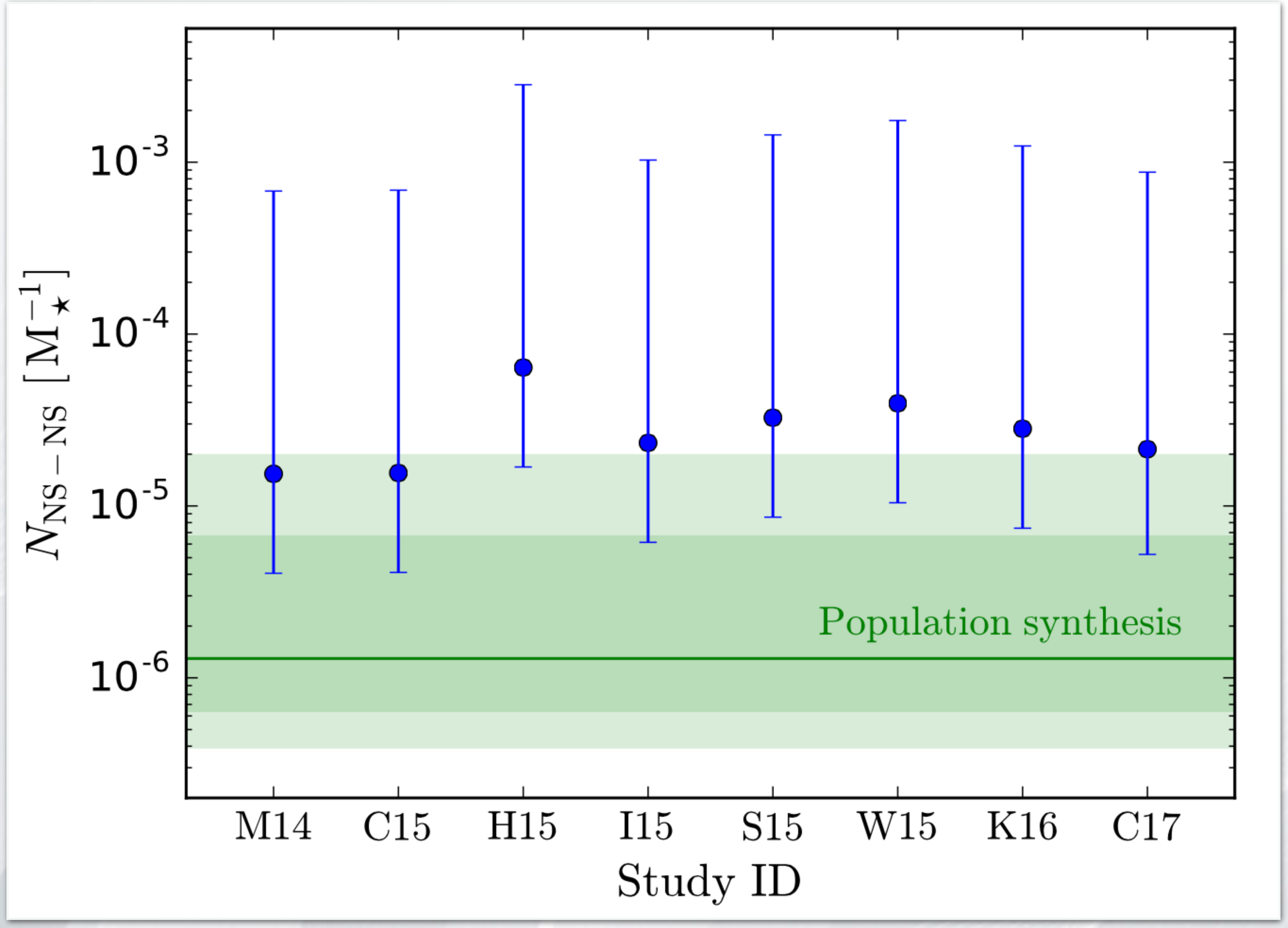
How many **neutron star mergers** do galaxy simulations need to recover the amount of r-process elements (e.g., Eu) present in the Milky Way?

Chemical evolution simulations for r-process elements

Argast et al. (2004)
Matteucci et al. (2014)
Cescutti et al. (2015)
Hirai et al. (2015)
Ishimaru et al. (2015)
Shen et al. (2015)
van de Voort et al. (2015)
Wehmeyer et al. (2015, 2019)
Komiya & Shigeyama (2016)
Côté et al. (2017, 2019)
Hotokezaka et al. (2018)
Naiman et al. (2018)
Safarzadeh et al. (2018)
Haynes & Kobayashi (2019)
Simonetti et al. (2019)
…

Number of Neutron Star Merger per Units of Stellar Mass Formed

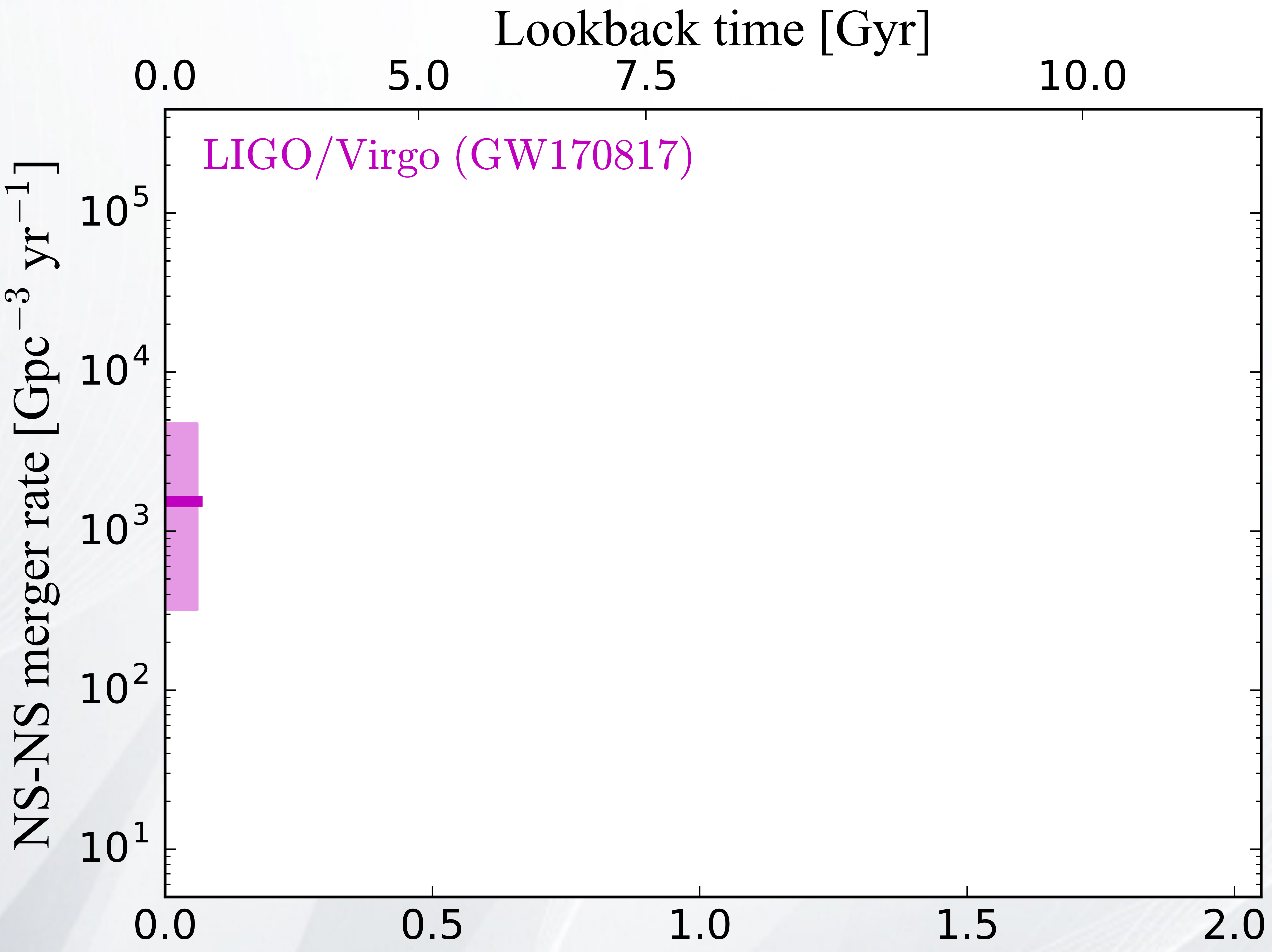
Côté, Belzcynski, Fryer, et al. (2017)



Chemical evolution simulations for r-process elements

Argast et al. (2004)
Matteucci et al. (2014)
Cescutti et al. (2015)
Hirai et al. (2015)
Ishimaru et al. (2015)
Shen et al. (2015)
van de Voort et al. (2015)
Wehmeyer et al. (2015, 2019)
Komiya & Shigeyama (2016)
Côté et al. (2017, 2019)
Hotokezaka et al. (2018)
Naiman et al. (2018)
Safarzadeh et al. (2018)
Haynes & Kobayashi (2019)
Simonetti et al. (2019)
...

Galaxy Simulations and Gravitational Waves

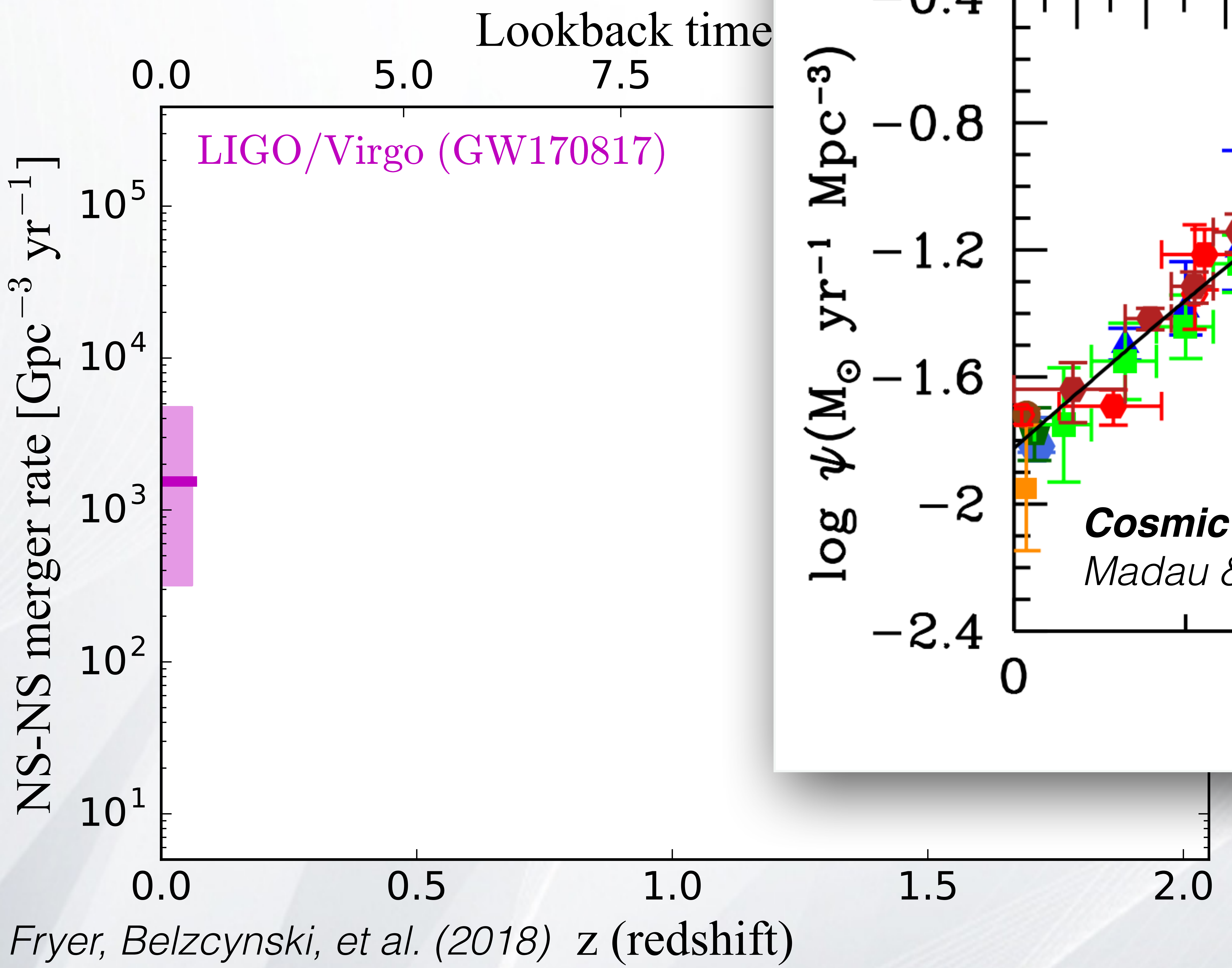


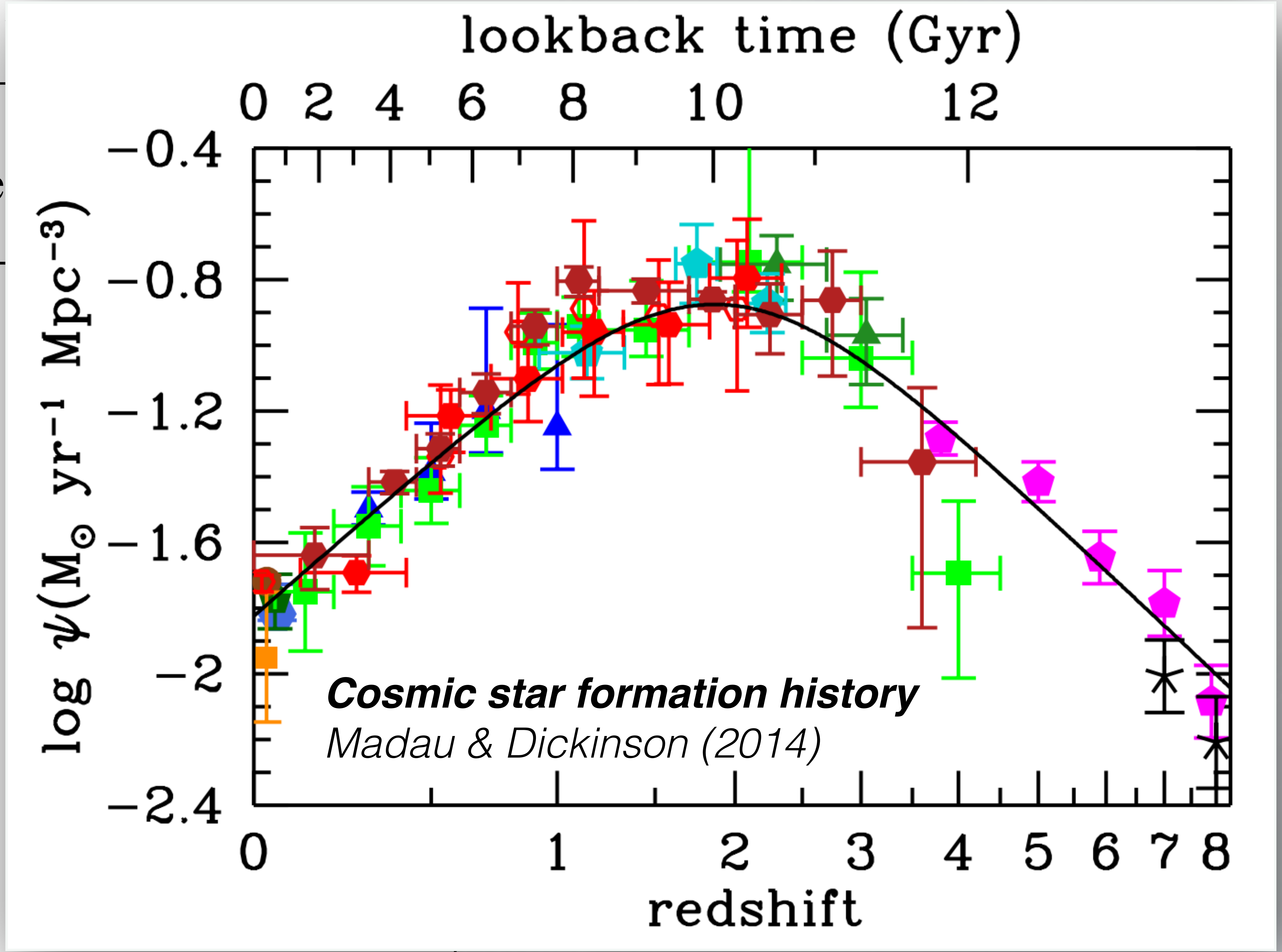
Côté, Fryer, Belzcynski, et al. (2018)

Chemical evolution simulations for r-process elements

Argast et al. (2004)
Matteucci et al. (2014)
Cescutti et al. (2015)
Hirai et al. (2015)
Ishimaru et al. (2015)
Shen et al. (2015)
van de Voort et al. (2015)
Wehmeyer et al. (2015, 2019)
Komiya & Shigeyama (2016)
Côté et al. (2017, 2019)
Hotokezaka et al. (2018)
Naiman et al. (2018)
Safarzadeh et al. (2018)
Haynes & Kobayashi (2019)
Simonetti et al. (2019)
...

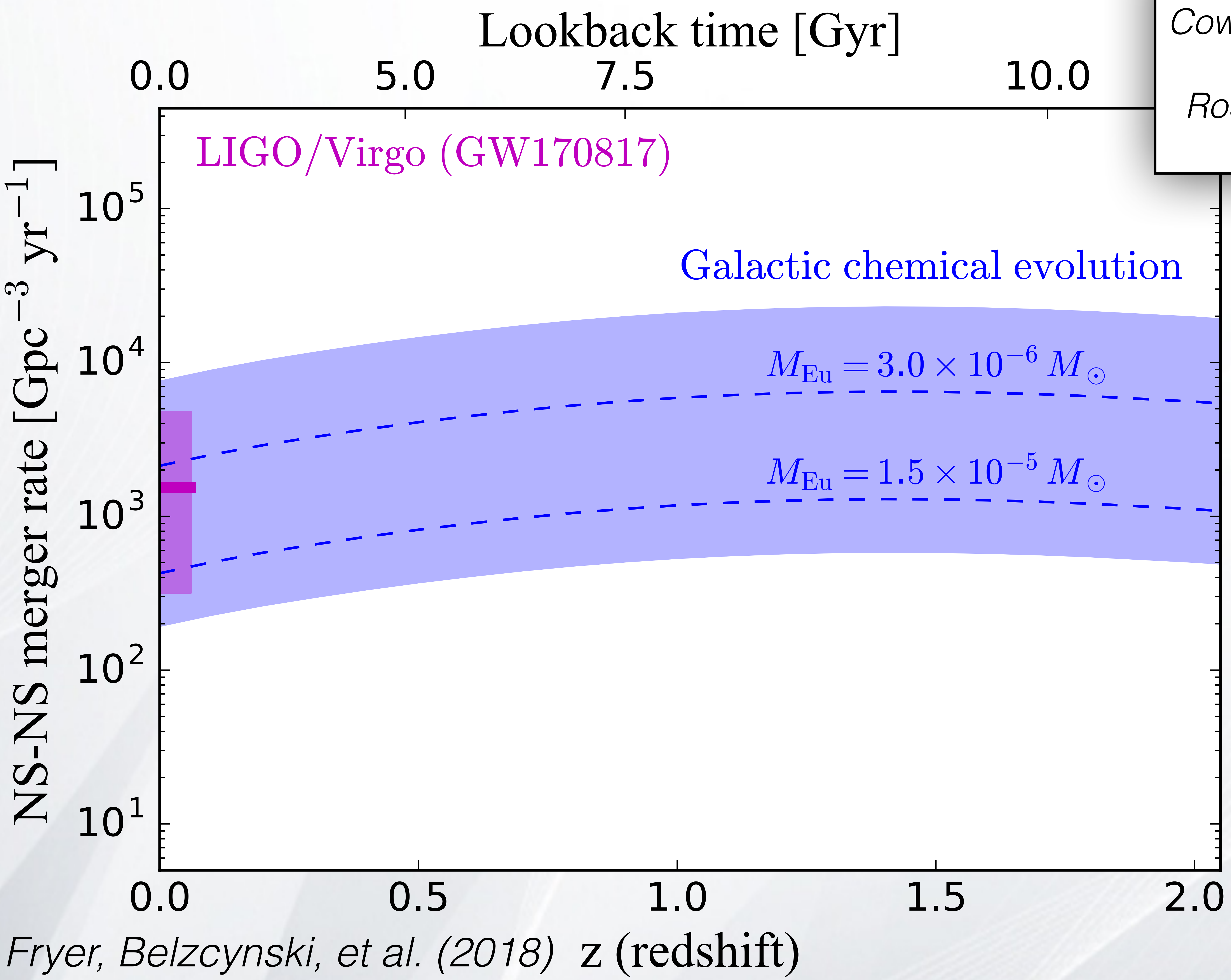
Galaxy Simulations and Gravitational





Côté, Fryer, Belzcynski, et al. (2018)

Galaxy Simulations and Gravitational Waves



Côté, Fryer, Belzcynski, et al. (2018)

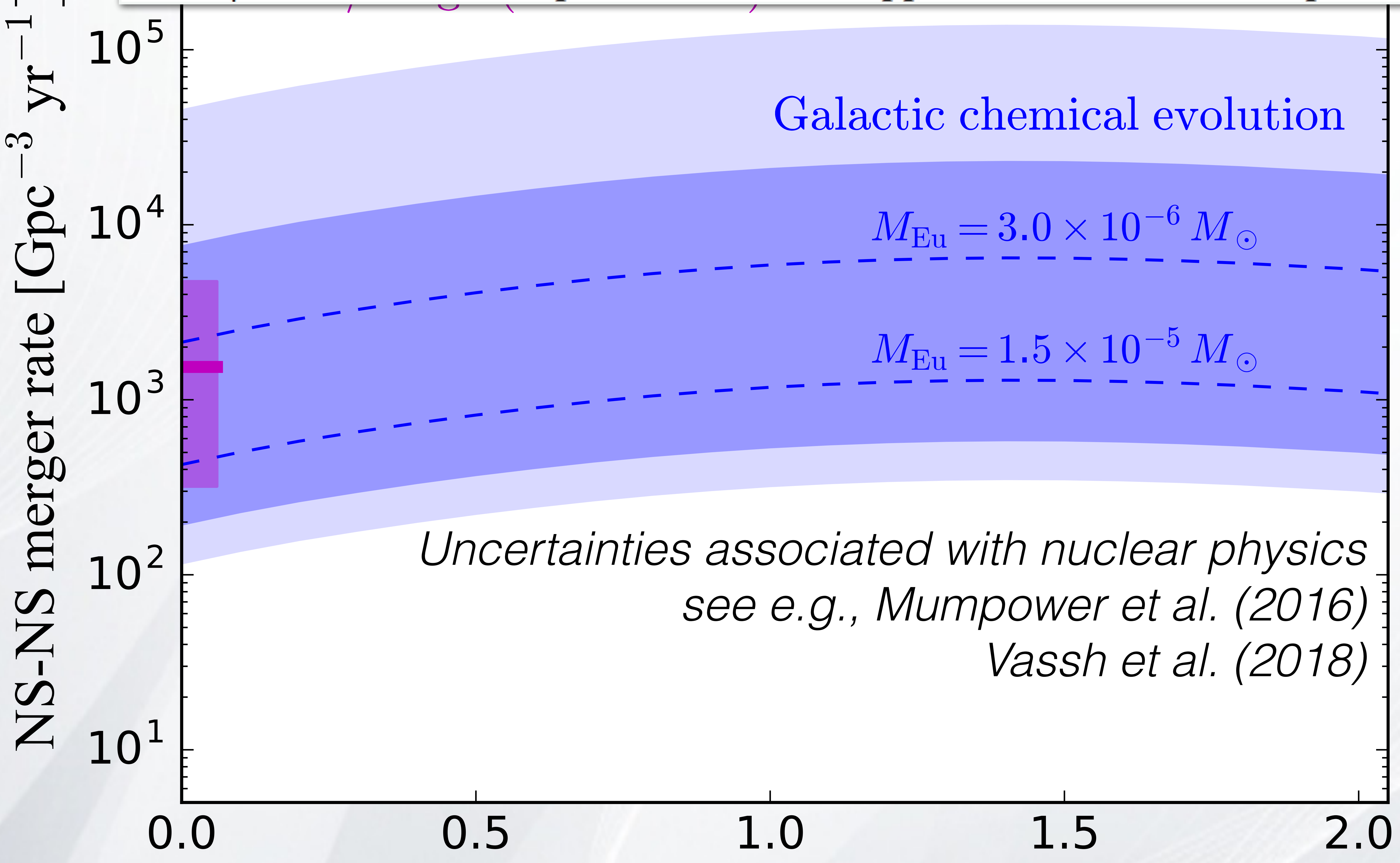
See also analytical estimates of *Abbott et al. (2017), Cowperthwaite et al. (2017), Chornock et al. (2017), Gompertz et al. (2017), Kasen et al. (2017), Rosswog et al. (1999, 2017), Tanaka et al. (2017), Wang et al. (2017), Hotokesaka et al. (2018)*

Argast et al. (2004)
Matteucci et al. (2014)
Cescutti et al. (2015)
Hirai et al. (2015)
Ishimaru et al. (2015)
Shen et al. (2015)
van de Voort et al. (2015)
Wehmeyer et al. (2015, 2019)
Komiya & Shigeyama (2016)
Côté et al. (2017, 2019)
Hotokezaka et al. (2018)
Naiman et al. (2018)
Safarzadeh et al. (2018)
Haynes & Kobayashi (2019)
Simonetti et al. (2019)
...

Galaxy Simulations and Gravitational Waves

The Origin of *r*-process Elements in the Milky Way

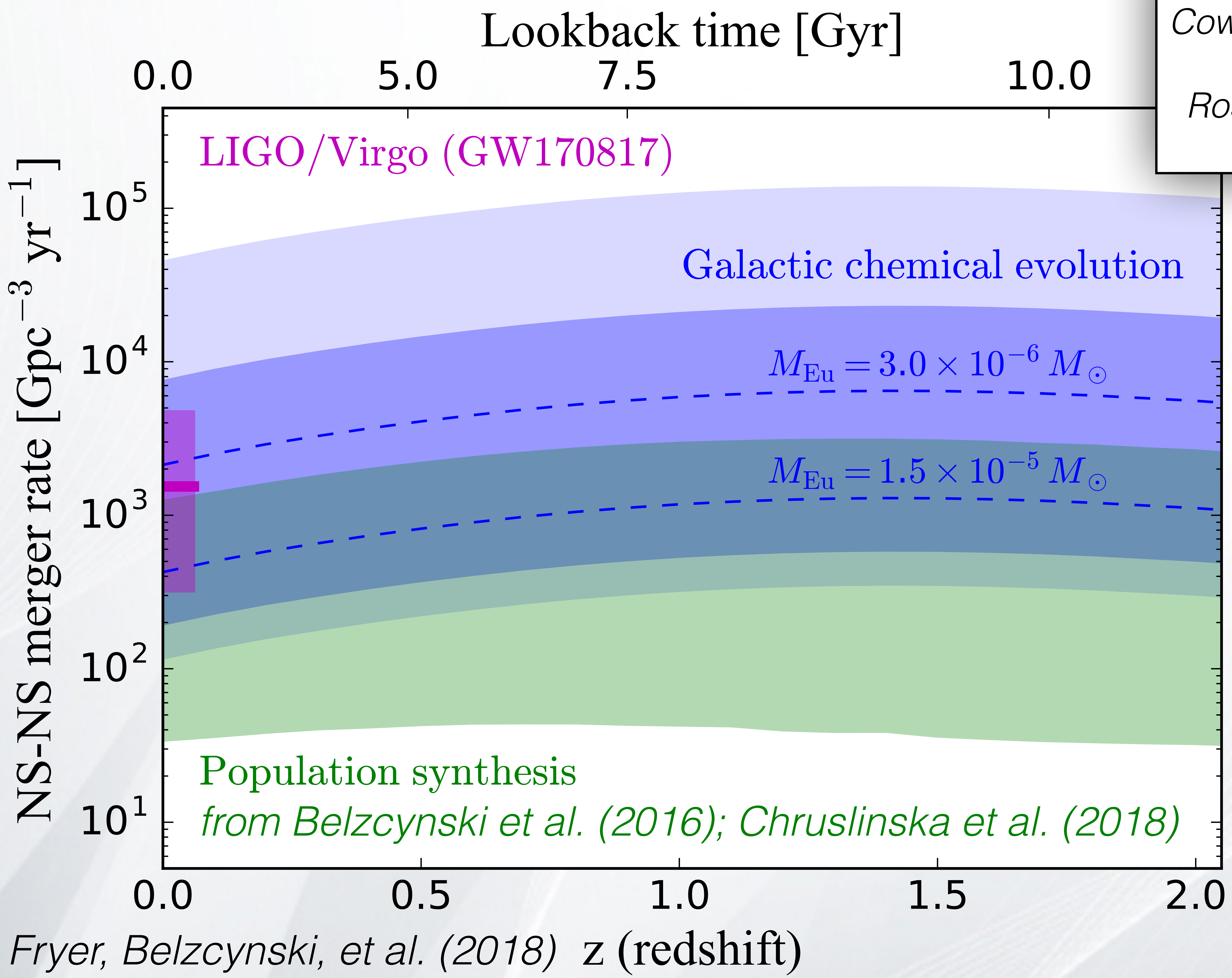
Benoit Côté[1,2,8], Chris L. Fryer[2,3,8], Krzysztof Belczynski[4], Oleg Korobkin[2,3], Martyna Chruślińska[5], Nicole Vassh[6], Matthew R. Mumpower[2,3,7], Jonas Lippuner[2,3], Trevor M. Sprouse[6], Rebecca Surman[2,6], and Ryan Wollaeger[3]



Côté, Fryer, Belczynski, et al. (2018)

Argast et al. (2004)
Matteucci et al. (2014)
Cescutti et al. (2015)
Hirai et al. (2015)
Ishimaru et al. (2015)
Shen et al. (2015)
van de Voort et al. (2015)
Wehmeyer et al. (2015, 2019)
Komiya & Shigeyama (2016)
Côté et al. (2017, 2019)
Hotokezaka et al. (2018)
Naiman et al. (2018)
Safarzadeh et al. (2018)
Haynes & Kobayashi (2019)
Simonetti et al. (2019)
...

Galaxy Simulations and Gravitational Waves

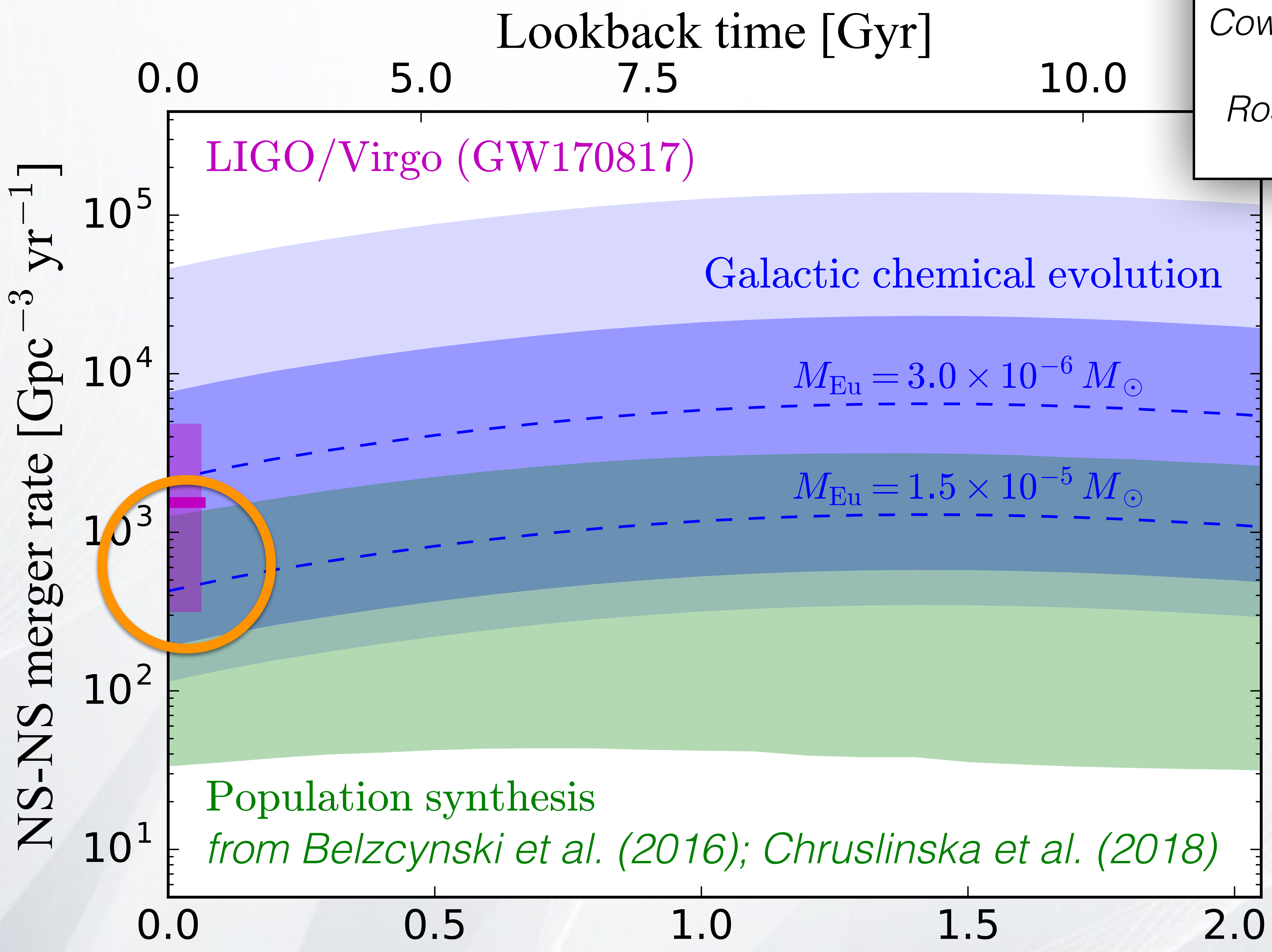


Côté, Fryer, Belzcynski, et al. (2018)

See also analytical estimates of *Abbott et al. (2017), Cowperthwaite et al. (2017), Chornock et al. (2017), Gompertz et al. (2017), Kasen et al. (2017), Rosswog et al. (1999, 2017), Tanaka et al. (2017), Wang et al. (2017), Hotokesaka et al. (2018)*

Argast et al. (2004)
Matteucci et al. (2014)
Cescutti et al. (2015)
Hirai et al. (2015)
Ishimaru et al. (2015)
Shen et al. (2015)
van de Voort et al. (2015)
Wehmeyer et al. (2015, 2019)
Komiya & Shigeyama (2016)
Côté et al. (2017, 2019)
Hotokezaka et al. (2018)
Naiman et al. (2018)
Safarzadeh et al. (2018)
Haynes & Kobayashi (2019)
Simonetti et al. (2019)
...

Galaxy Simulations and Gravitational Waves



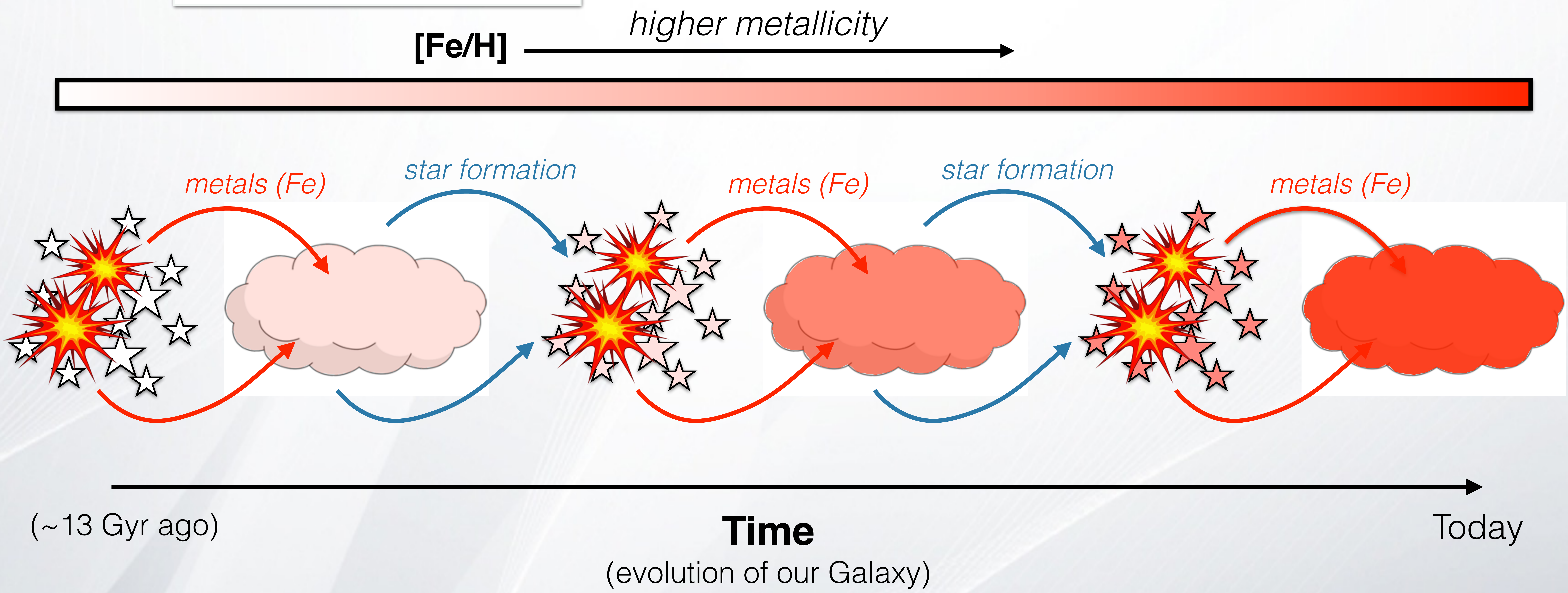
Côté, Fryer, Belzcynski, et al. (2018)

See also analytical estimates of *Abbott et al. (2017), Cowperthwaite et al. (2017), Chornock et al. (2017), Gompertz et al. (2017), Kasen et al. (2017), Rosswog et al. (1999, 2017), Tanaka et al. (2017), Wang et al. (2017), Hotokesaka et al. (2018)*

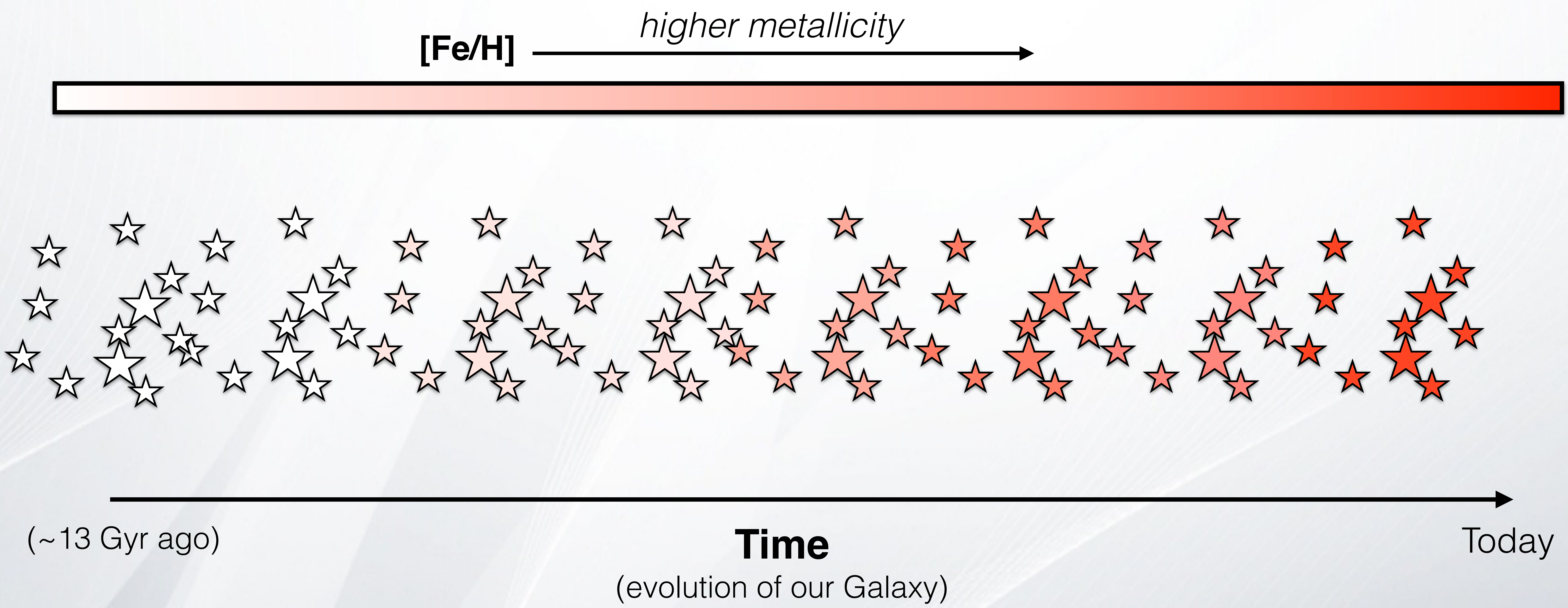
Argast et al. (2004)
Matteucci et al. (2014)
Cescutti et al. (2015)
Hirai et al. (2015)
Ishimaru et al. (2015)
Shen et al. (2015)
van de Voort et al. (2015)
Wehmeyer et al. (2015, 2019)
Komiya & Shigeyama (2016)
Côté et al. (2017, 2019)
Hotokezaka et al. (2018)
Naiman et al. (2018)
Safarzadeh et al. (2018)
Haynes & Kobayashi (2019)
Simonetti et al. (2019)
...

Chemical Evolution in the Disk of our Milky Way Galaxy

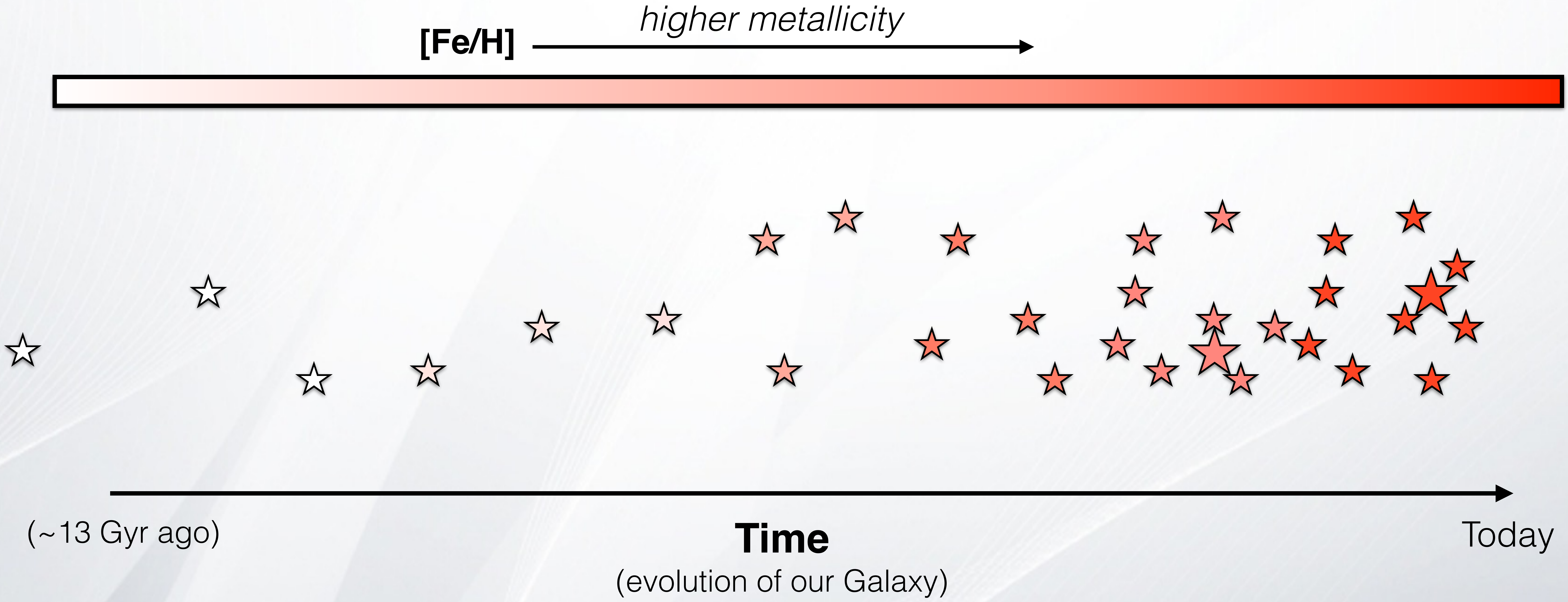
$$[A/B] = \log(n_A/n_B) - \log(n_A/n_B)_\odot$$



Chemical Evolution in the Disk of our Milky Way Galaxy

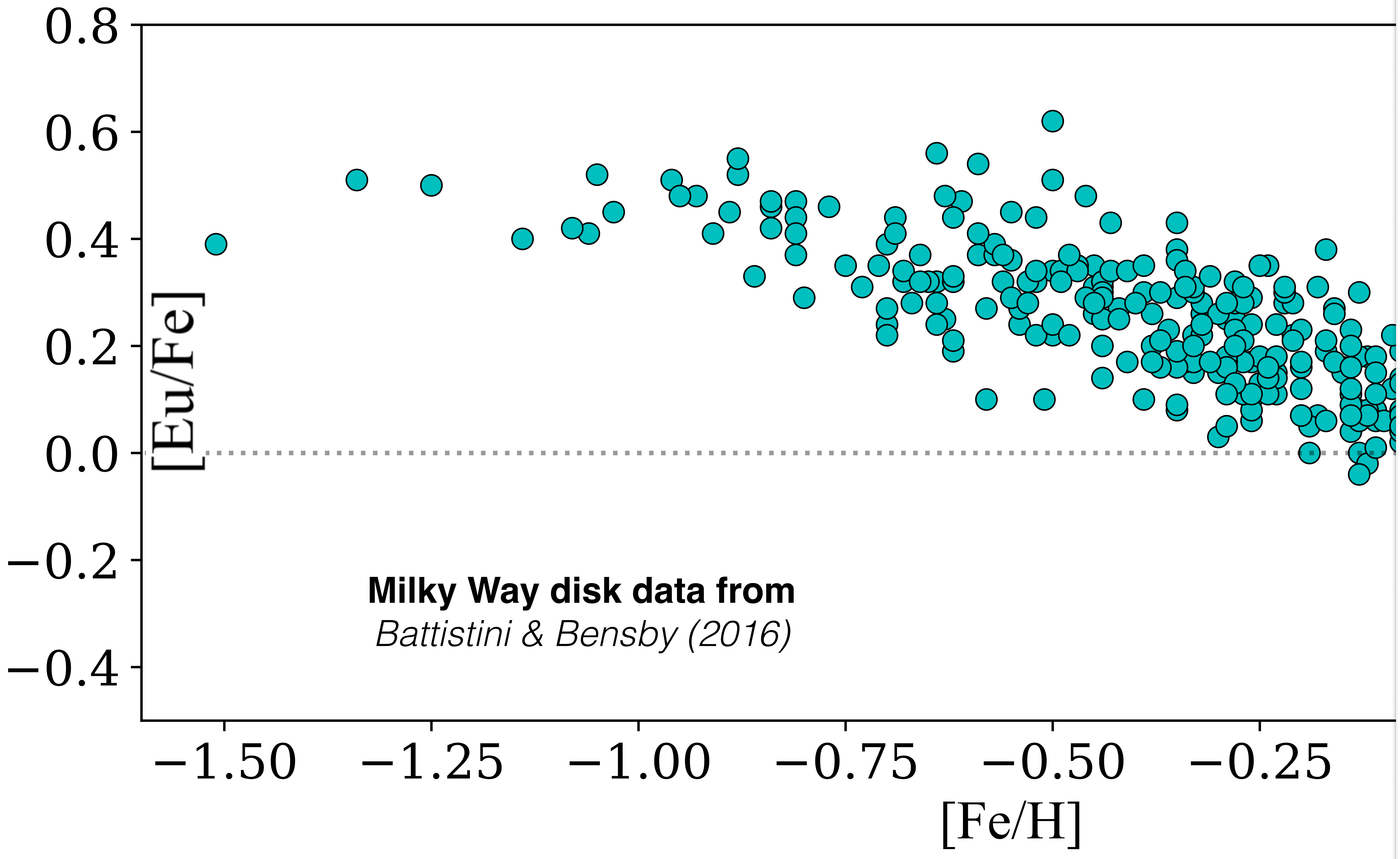


Chemical Evolution in the Disk of our Milky Way Galaxy

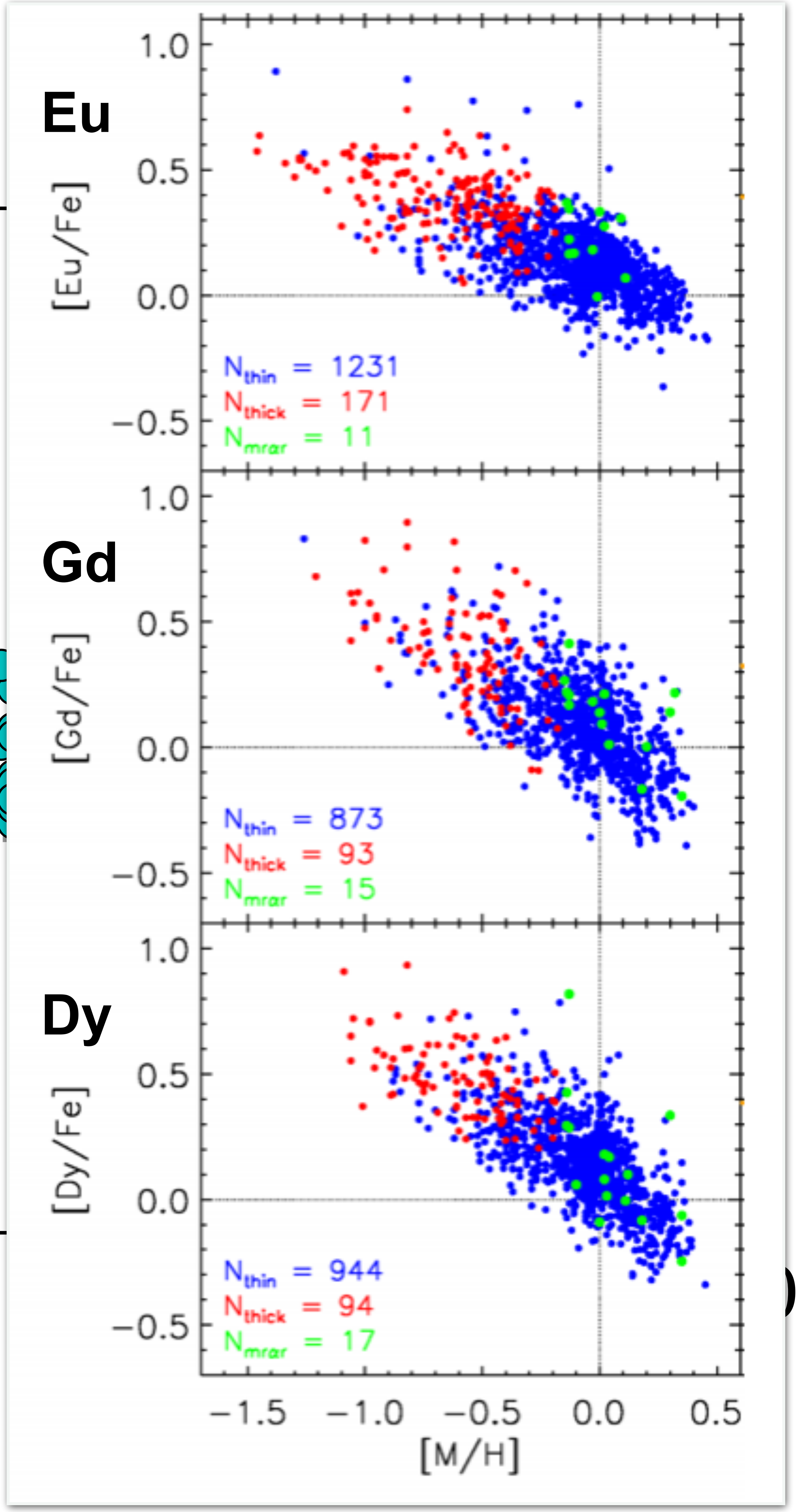


Chemical Evolution in the Disk of our Milky Way Galaxy

Chemical Evolution in the Disk of our Milky Way Galaxy

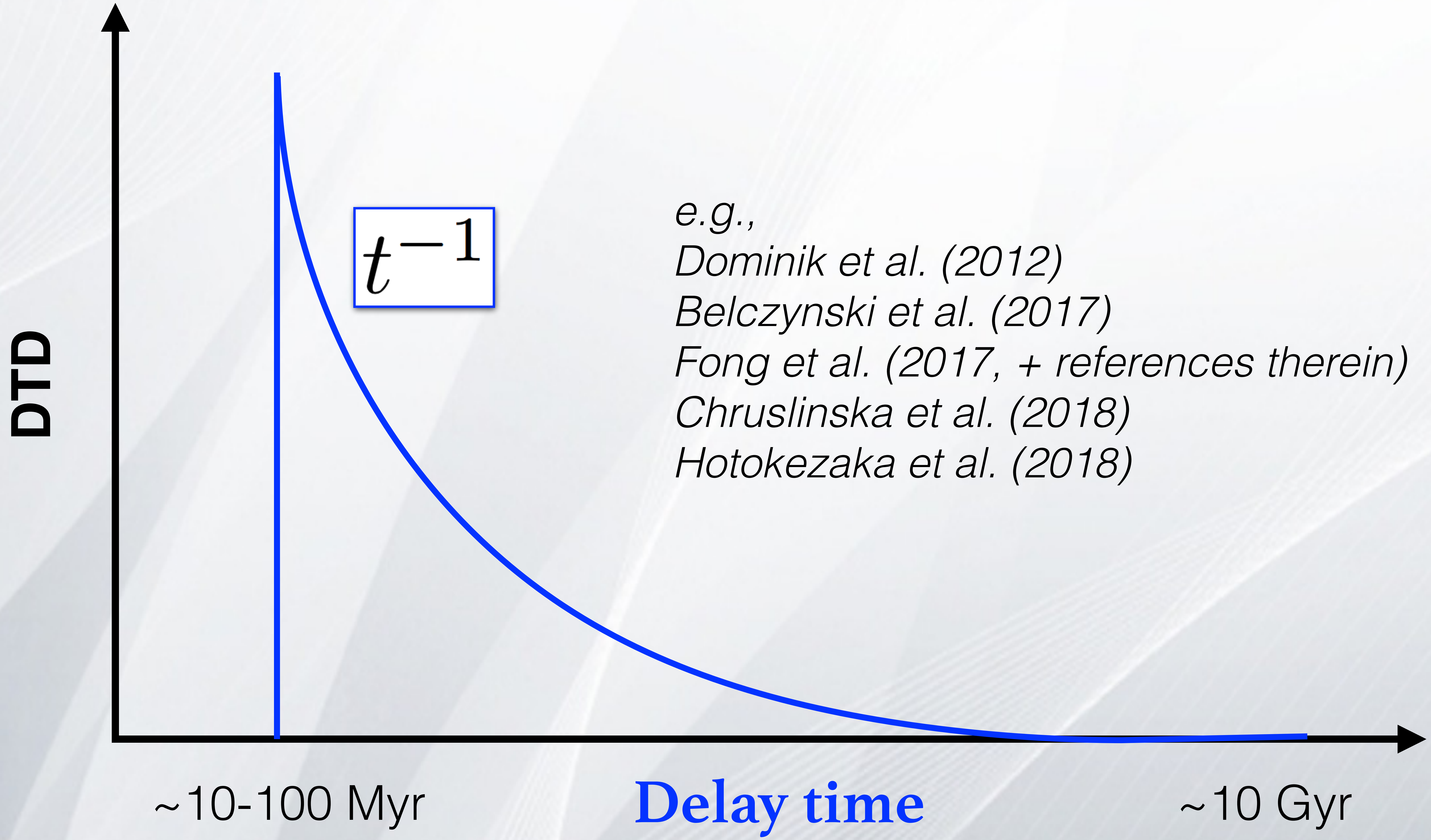


Guiglion et al. (2018)



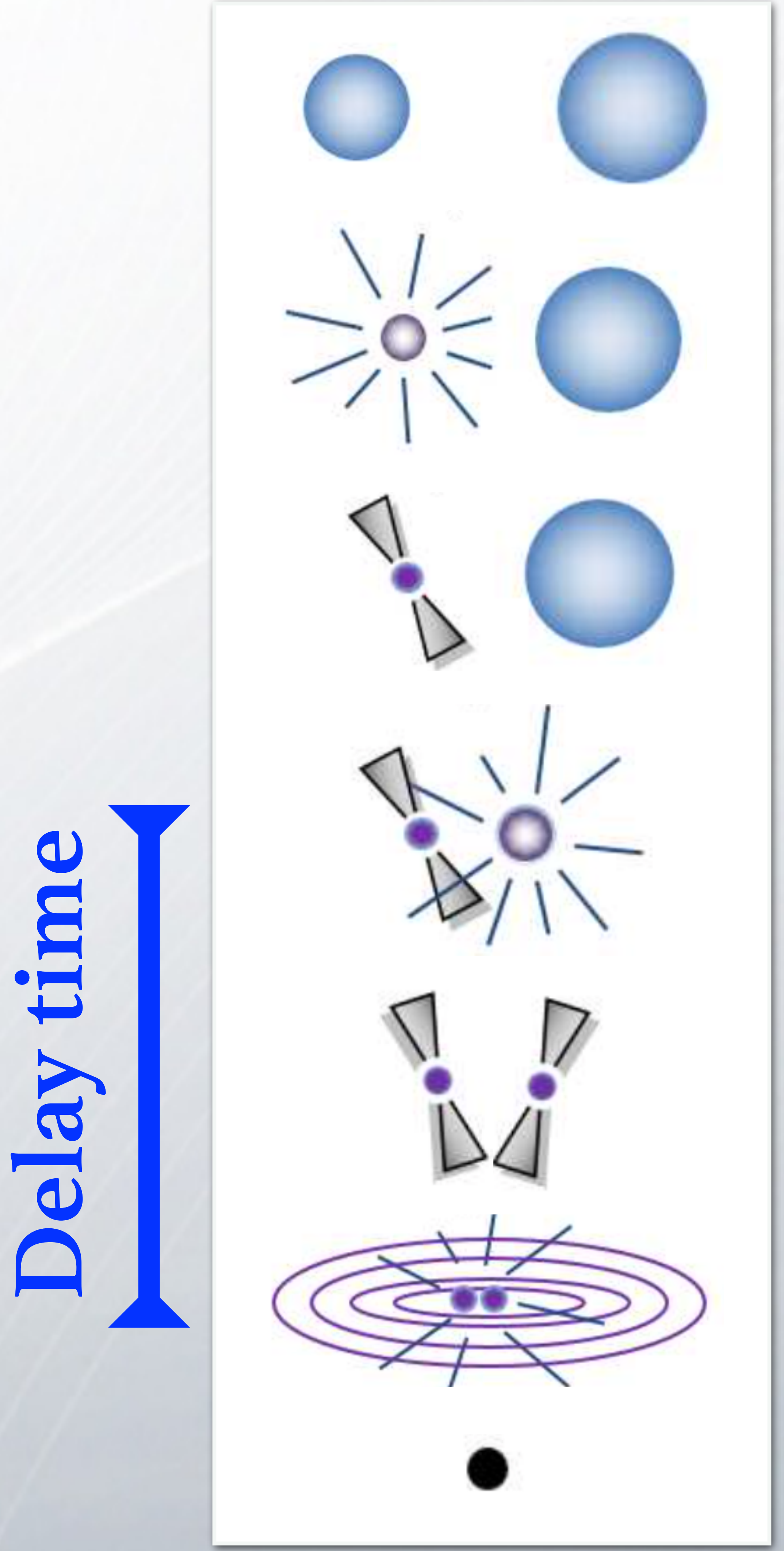
Delay-Time Distribution (**DTD**) Function of Neutron Star Mergers

This is the « problem » for the [Eu/Fe] trend



e.g.,
Dominik et al. (2012)
Belczynski et al. (2017)
Fong et al. (2017, + references therein)
Chruslinska et al. (2018)
Hotokezaka et al. (2018)

Image built from
Tauris et al. (2017)



Delay-Time Distribution (**DTD**) Function of Neutron Star Mergers

This is the « problem » for the [Eu/Fe] trend

Côté, Eichler, Arcones, et al. (2019)

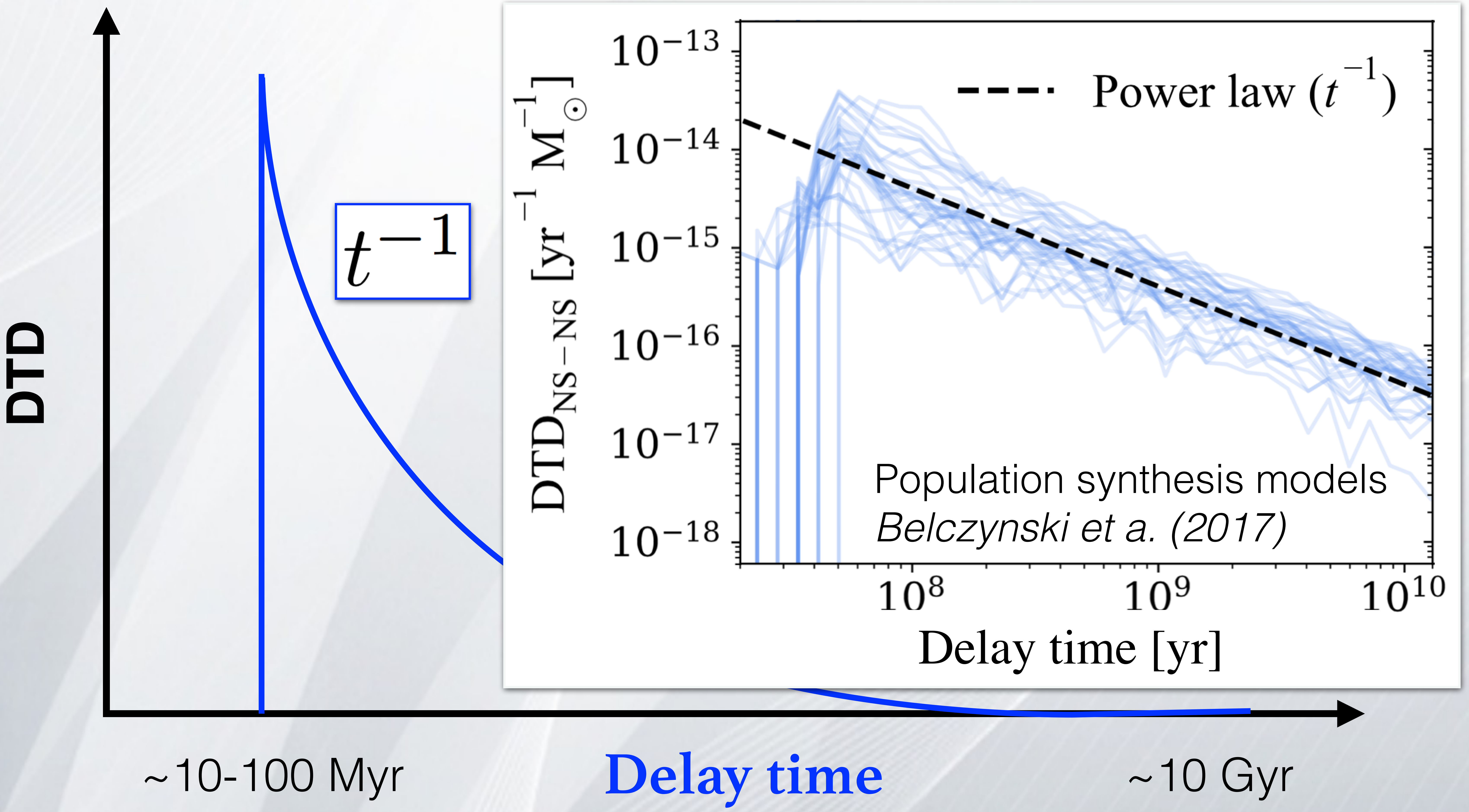
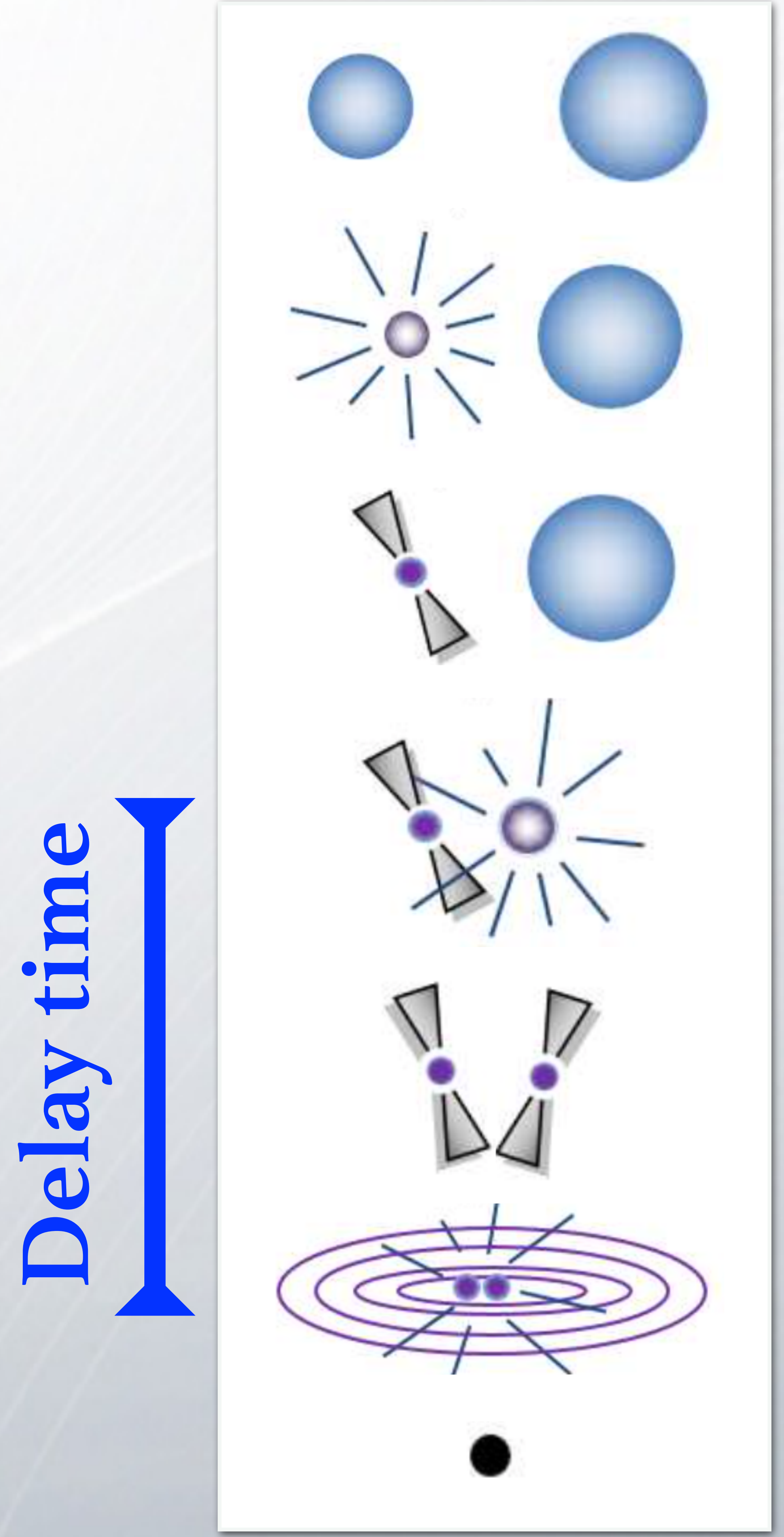
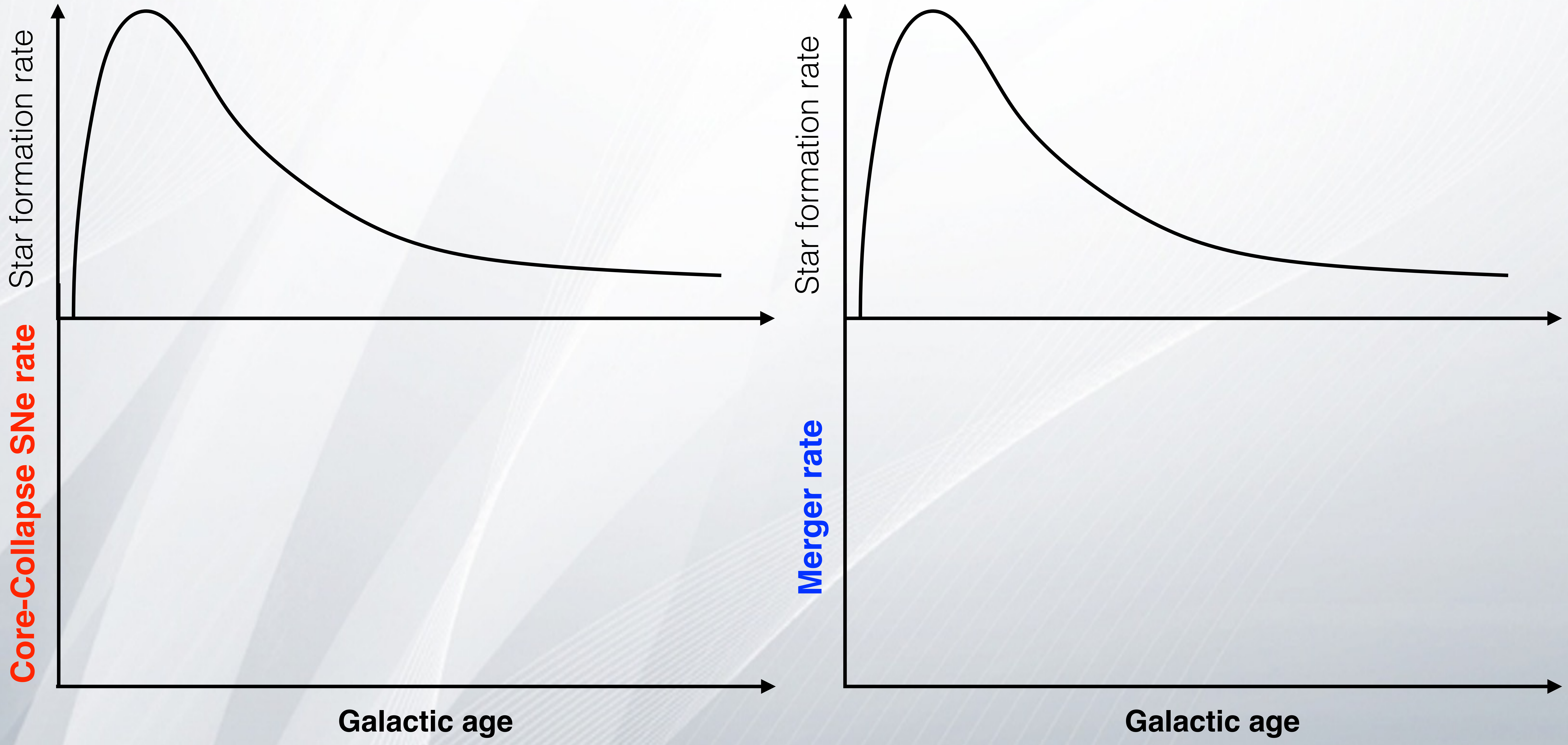


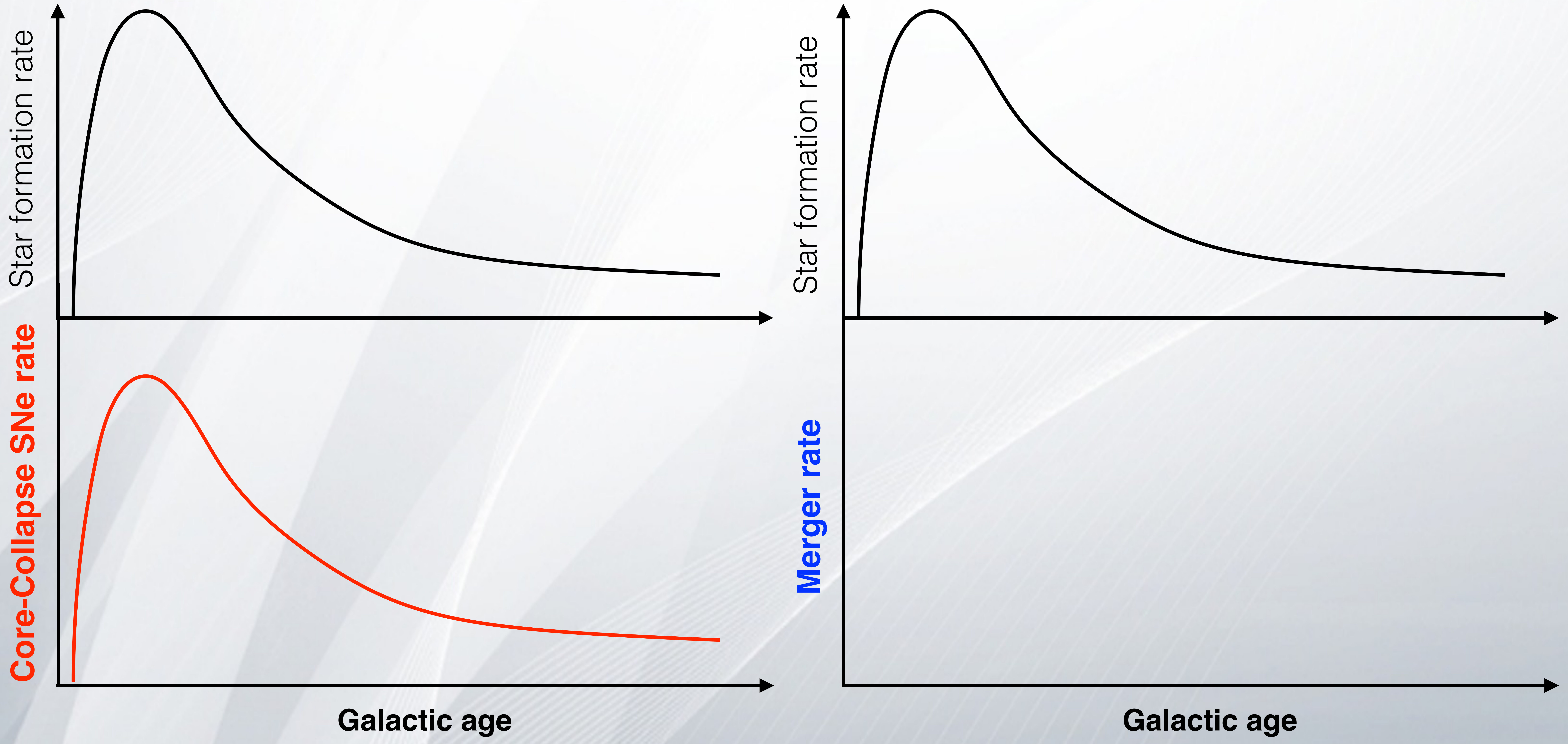
Image built from
Tauris et al. (2017)



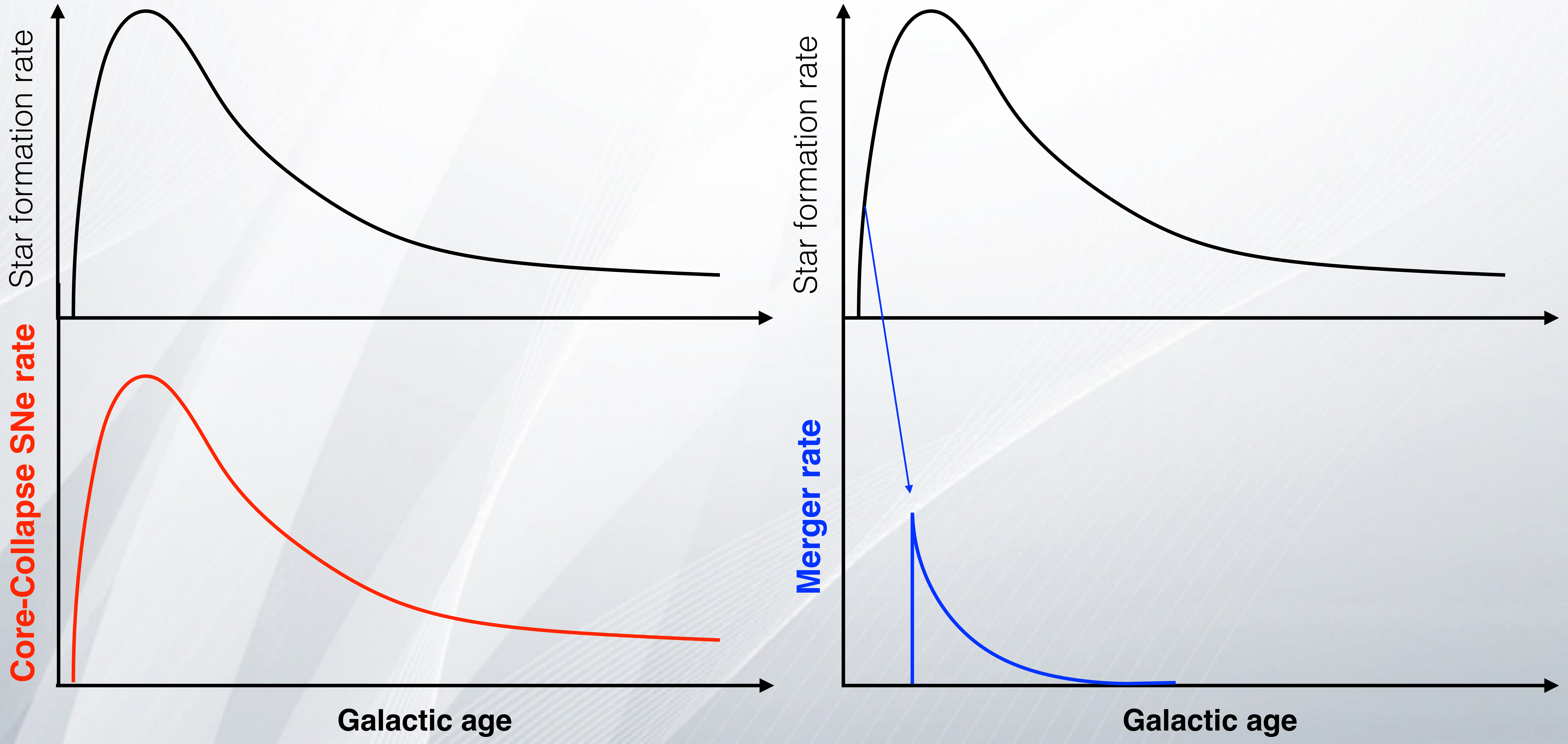
Delay-Time Distribution Functions in Chemical Evolution Codes



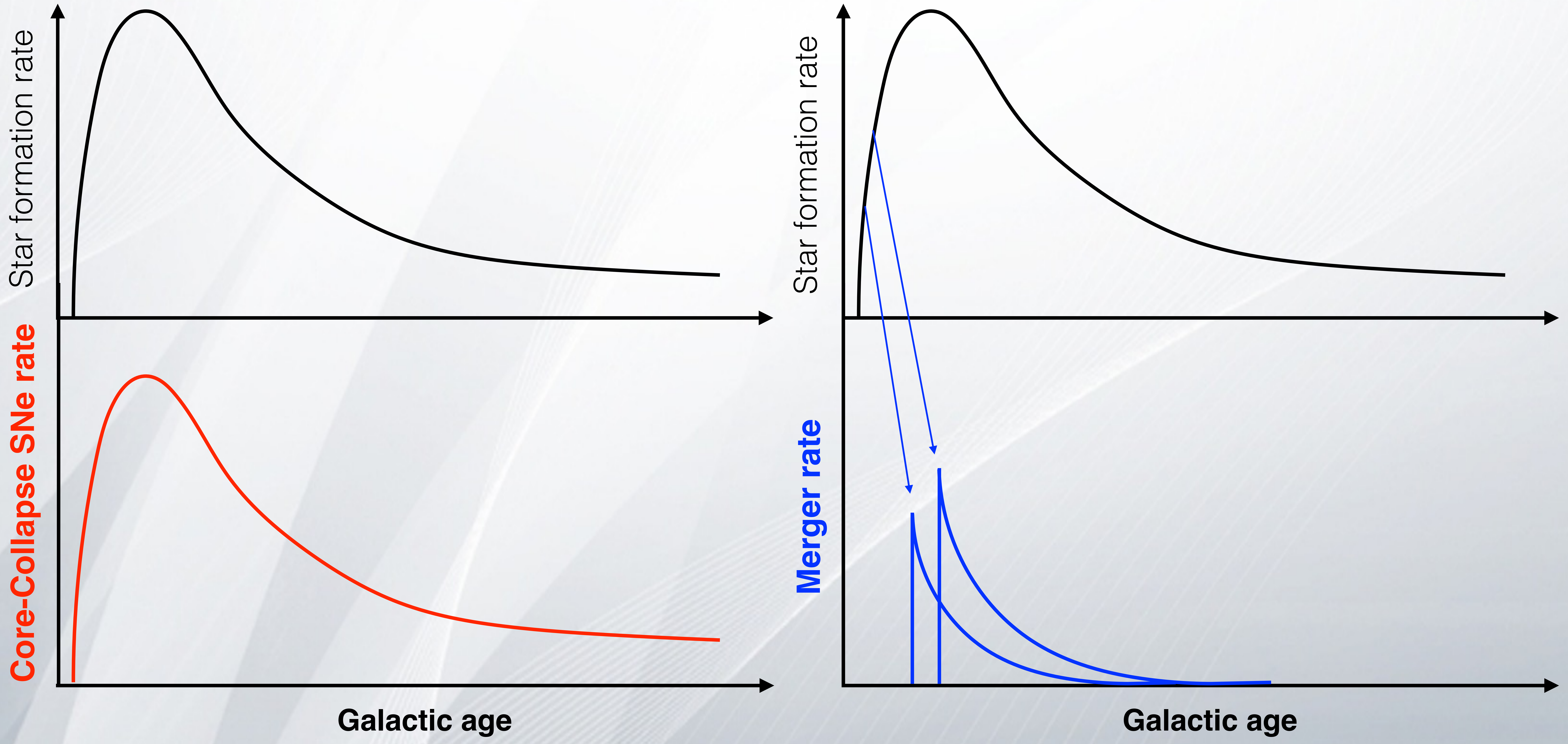
Delay-Time Distribution Functions in Chemical Evolution Codes



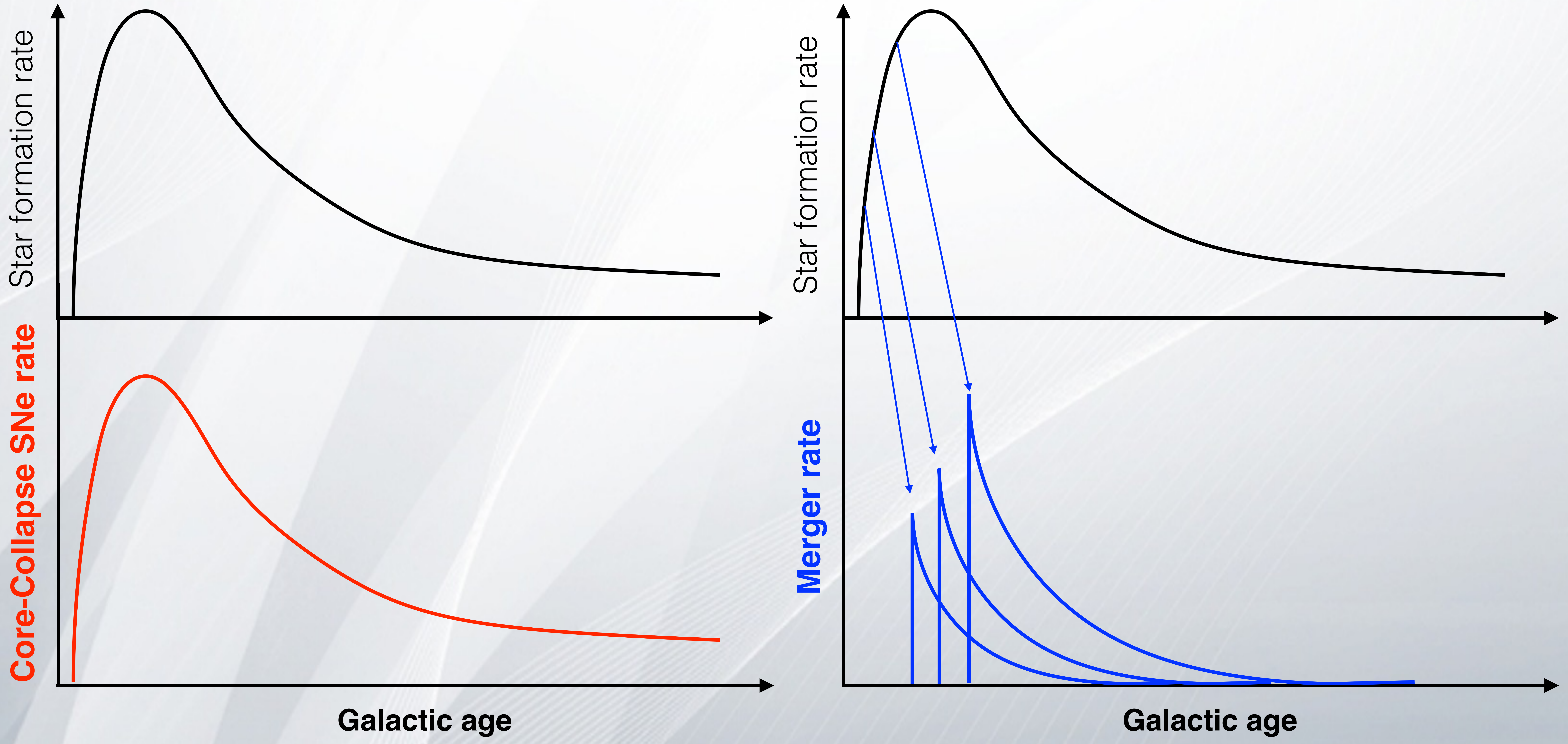
Delay-Time Distribution Functions in Chemical Evolution Codes



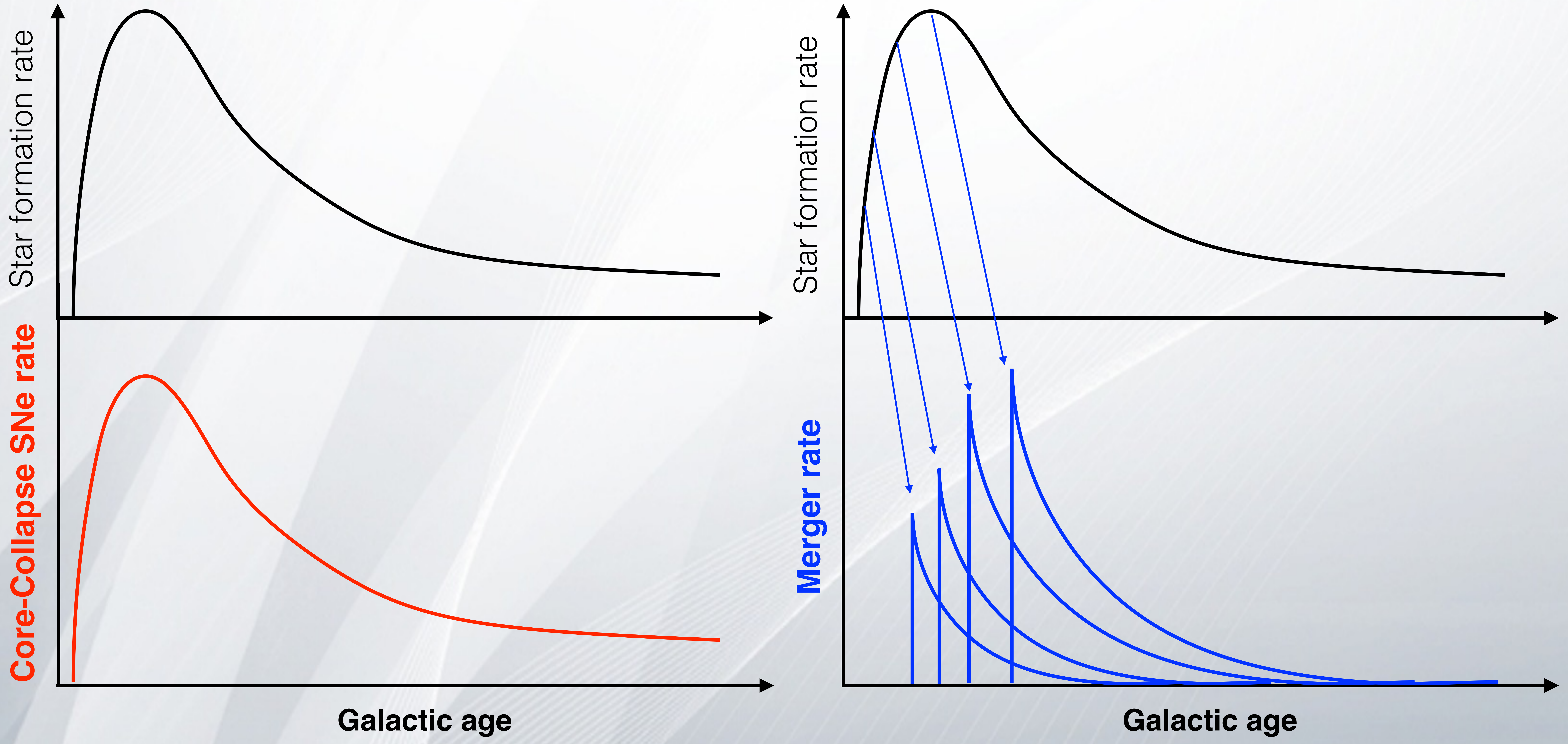
Delay-Time Distribution Functions in Chemical Evolution Codes



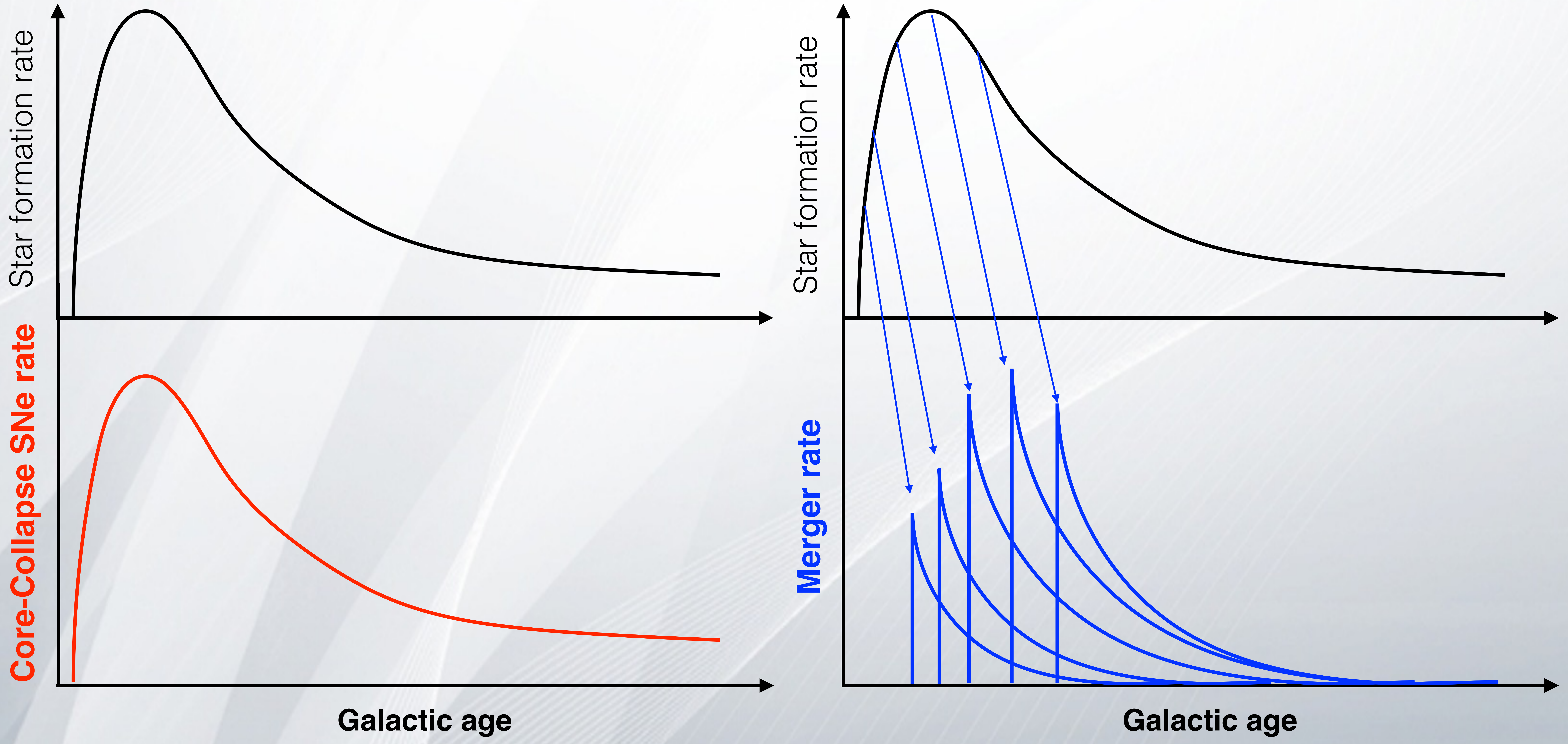
Delay-Time Distribution Functions in Chemical Evolution Codes



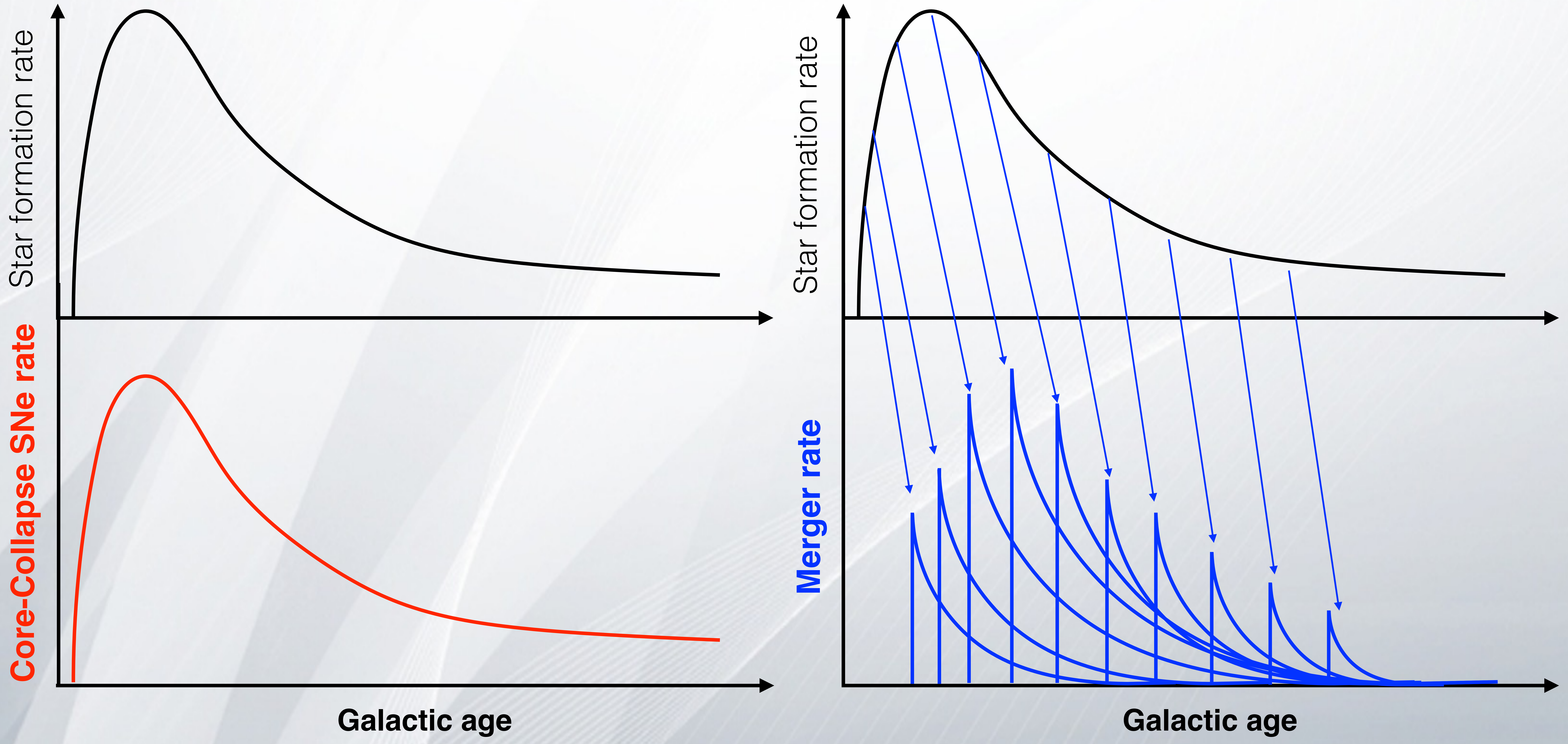
Delay-Time Distribution Functions in Chemical Evolution Codes



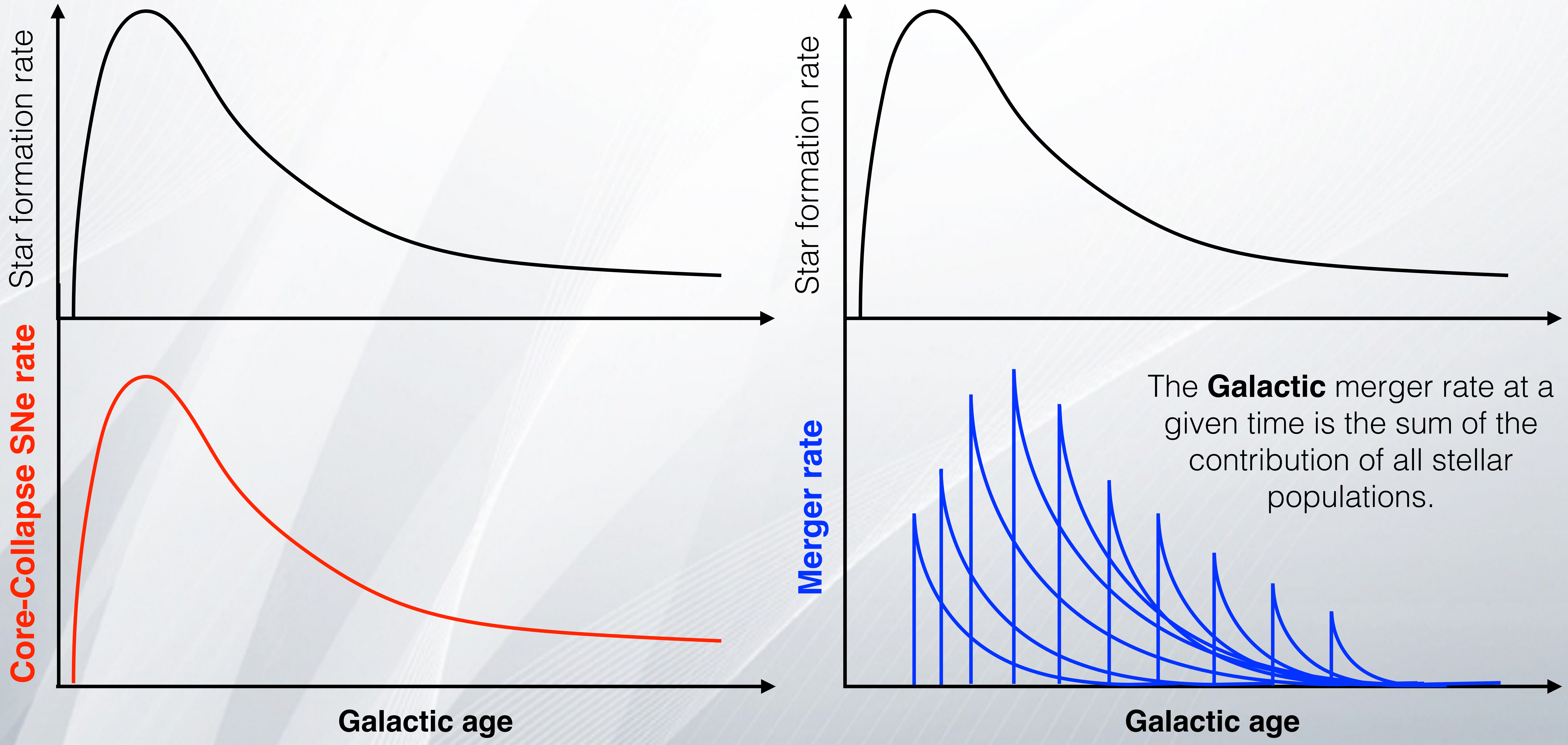
Delay-Time Distribution Functions in Chemical Evolution Codes



Delay-Time Distribution Functions in Chemical Evolution Codes

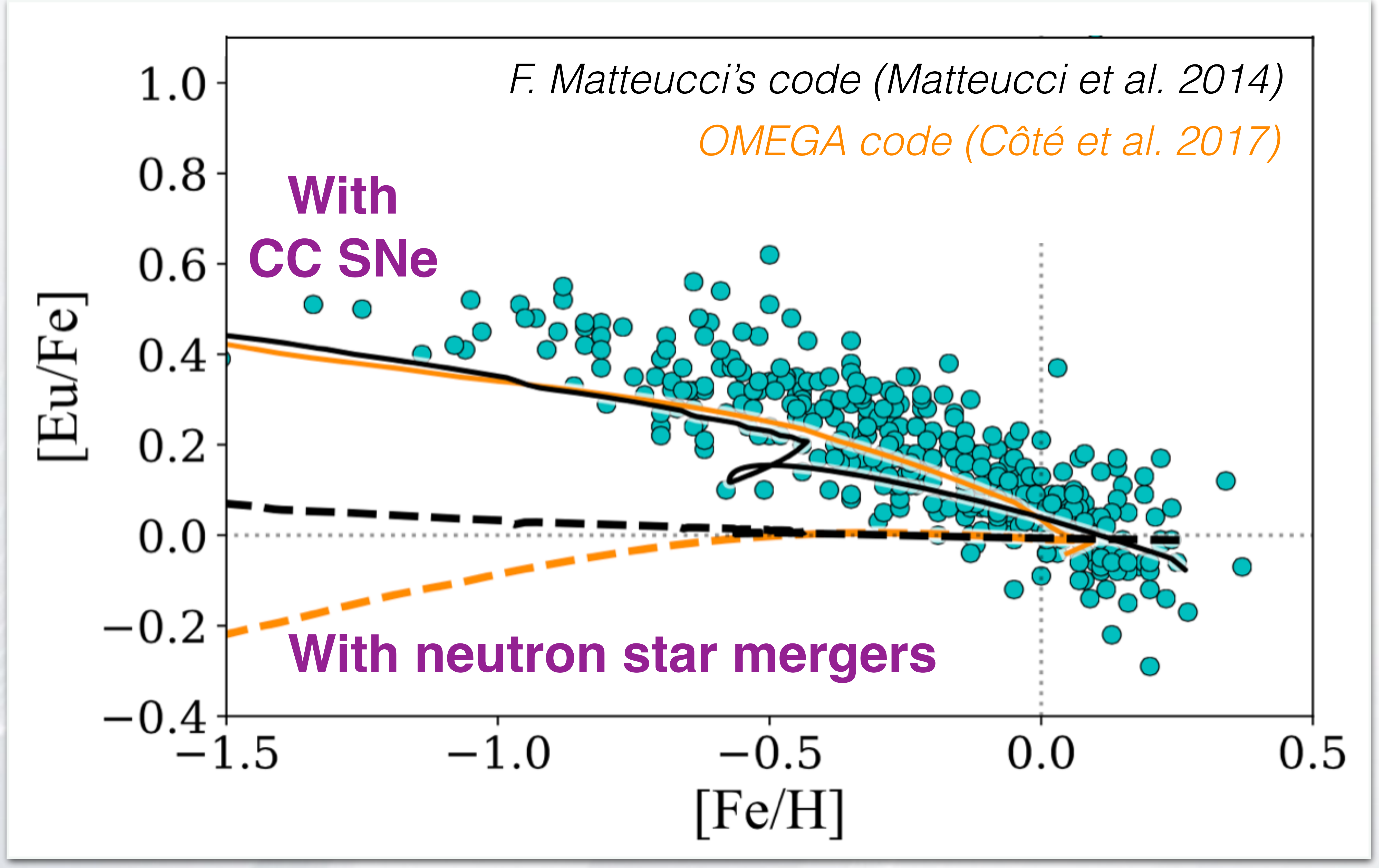


Delay-Time Distribution Functions in Chemical Evolution Codes



How Can we Fit the Decreasing Chemical Evolution Trend?

Côté, Eichler, Arcones, et al. (2019)

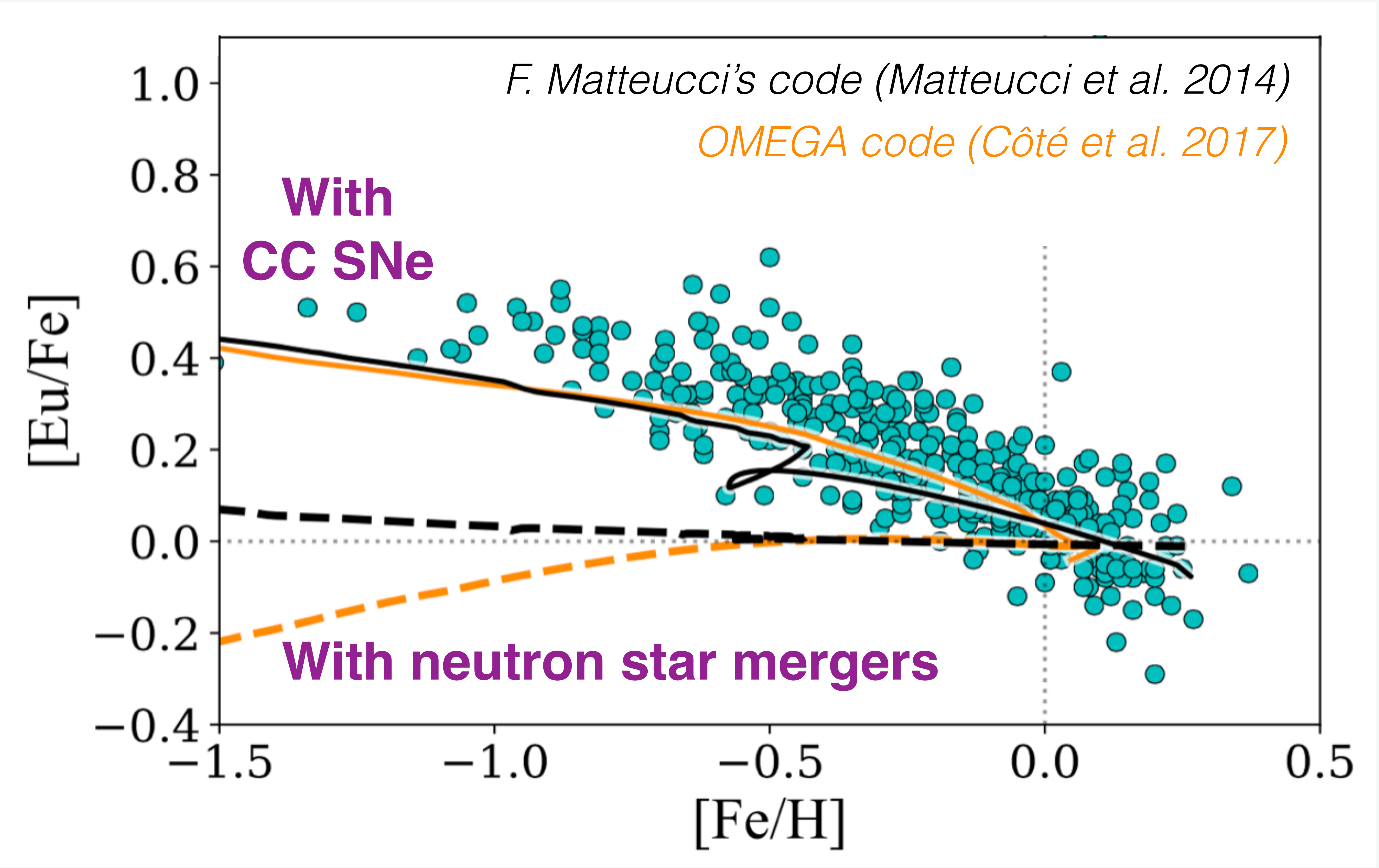


Chemical evolution simulations for r-process elements

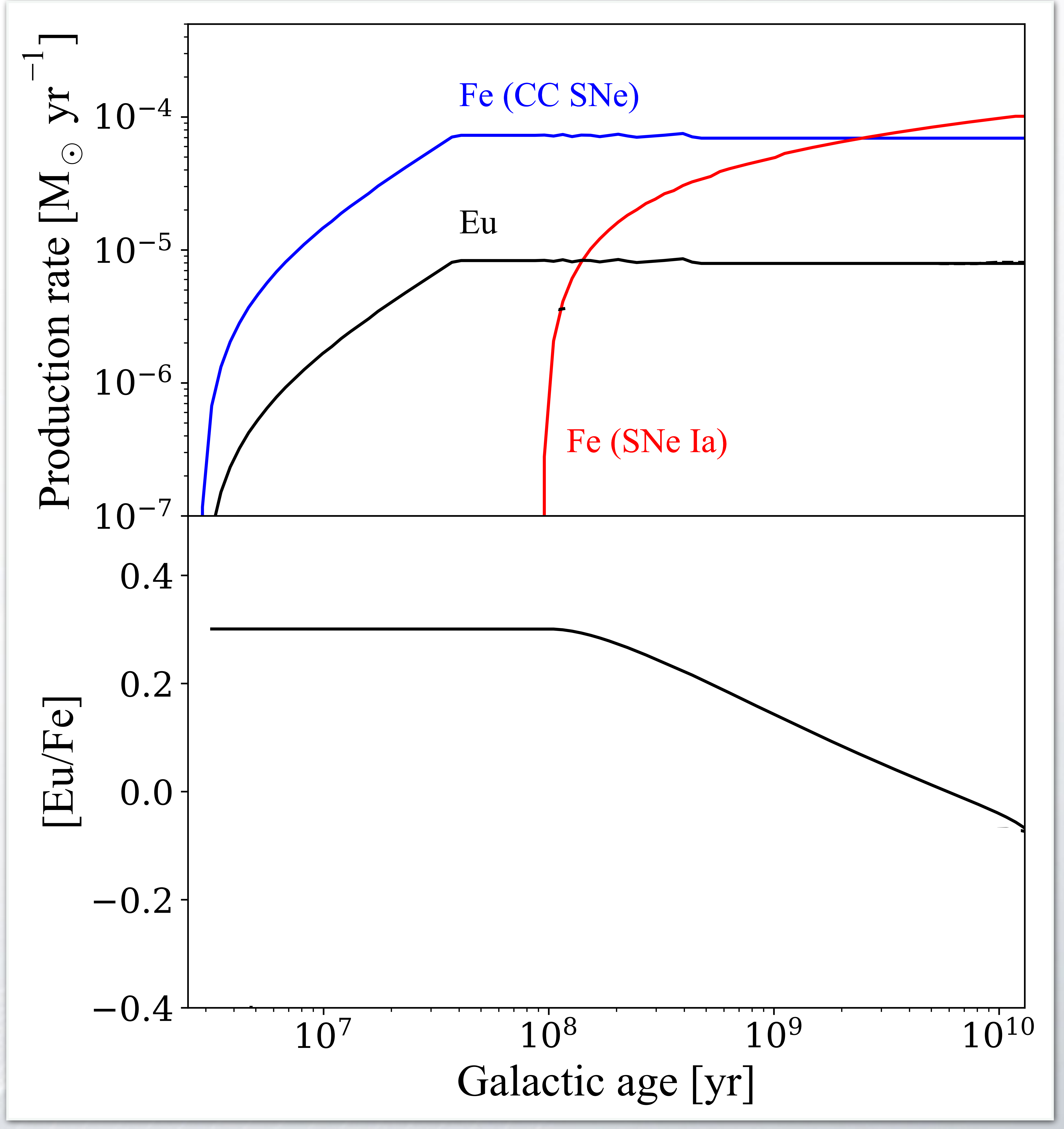
Argast et al. (2004)
Matteucci et al. (2014)
Cescutti et al. (2015)
Ishimaru et al. (2015)
Shen et al. (2015)
van de Voort et al. (2015)
Wehmeyer et al. (2015, 2019)
Komiya & Shigeyama (2016)
Côté et al. (2017, 2019)
Hotokezaka et al. (2018)
Naiman et al. (2018)
Haynes & Kobayashi (2019)
Simonetti et al. (2019)

How Can we Fit the Decreasing Chemical Evolution Trend?

Côté, Eichler, Arcones, et al. (2019)

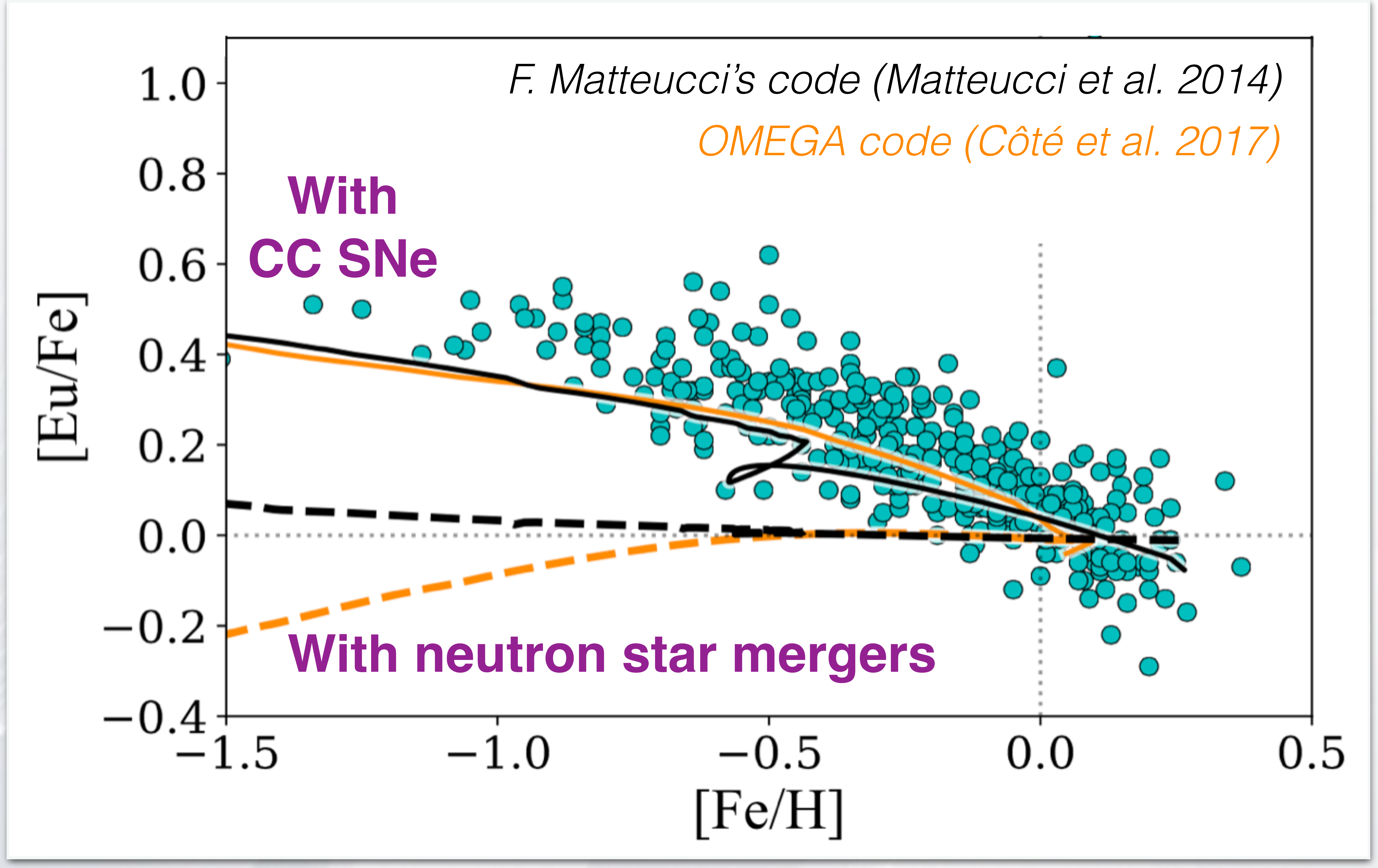


Côté, Eichler, Arcones, et al. (2019)

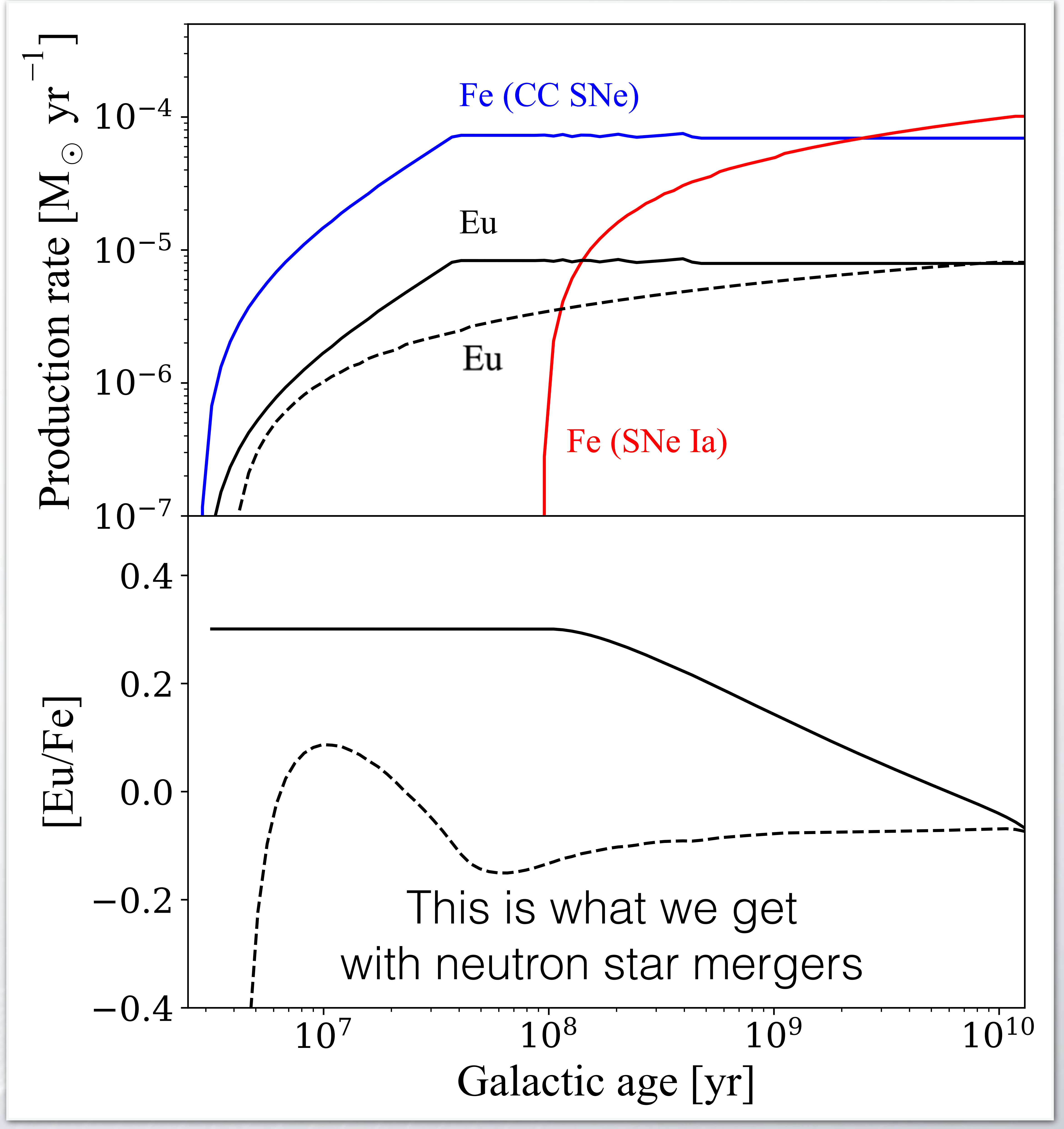


How Can we Fit the Decreasing Chemical Evolution Trend?

Côté, Eichler, Arcones, et al. (2019)

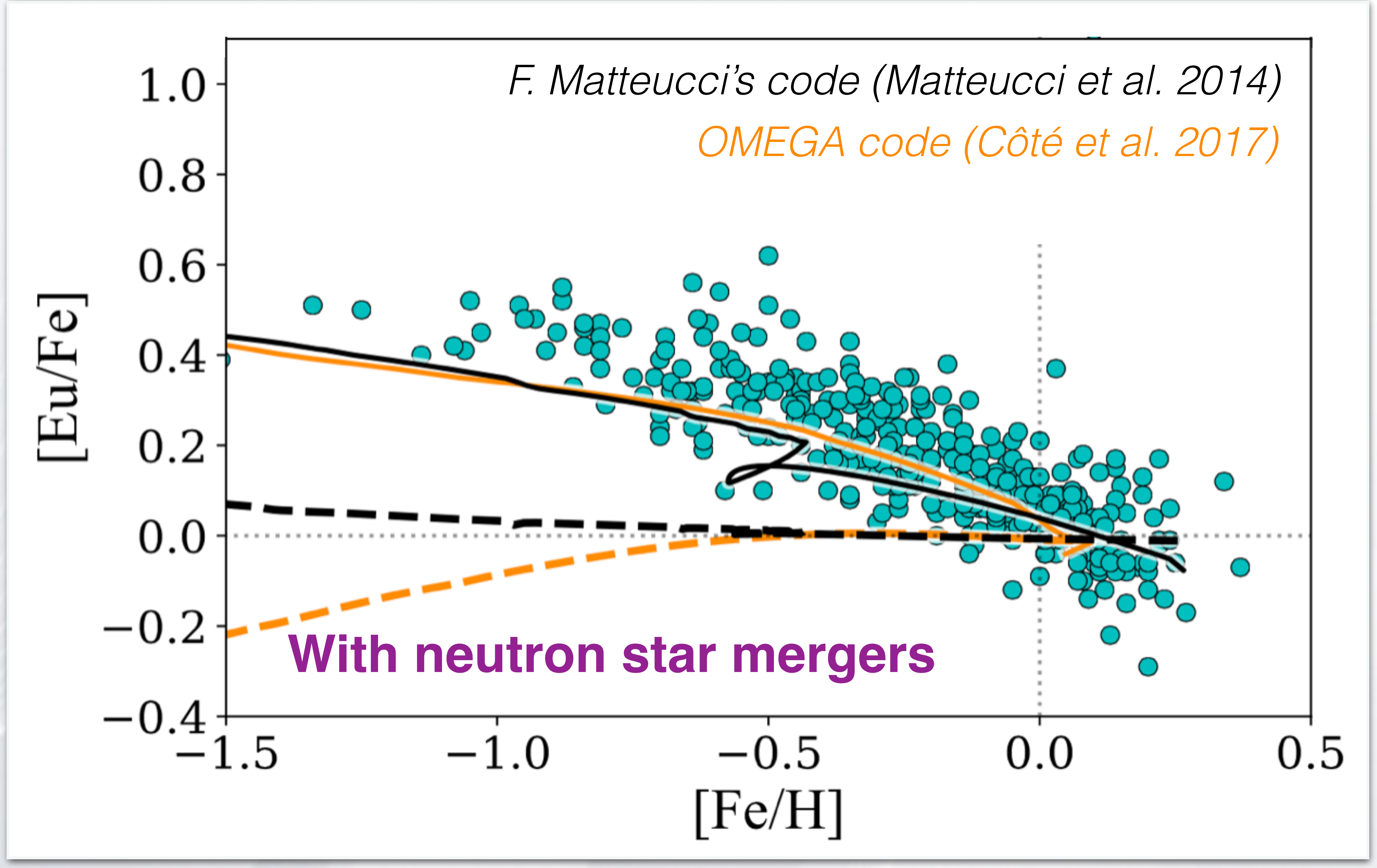


Côté, Eichler, Arcones, et al. (2019)

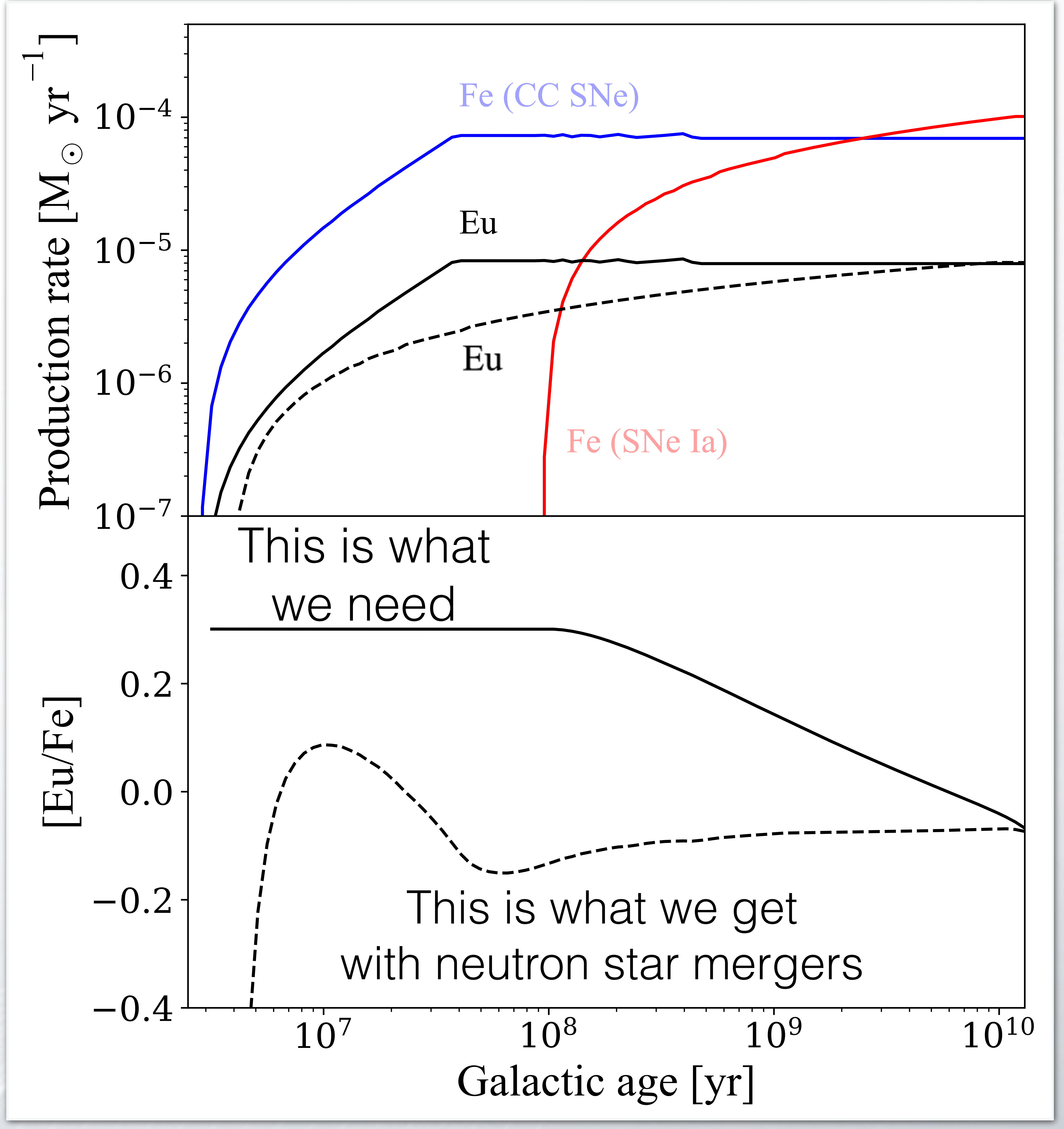


How Can we Fit the Decreasing Chemical Evolution Trend?

Côté, Eichler, Arcones, et al. (2019)

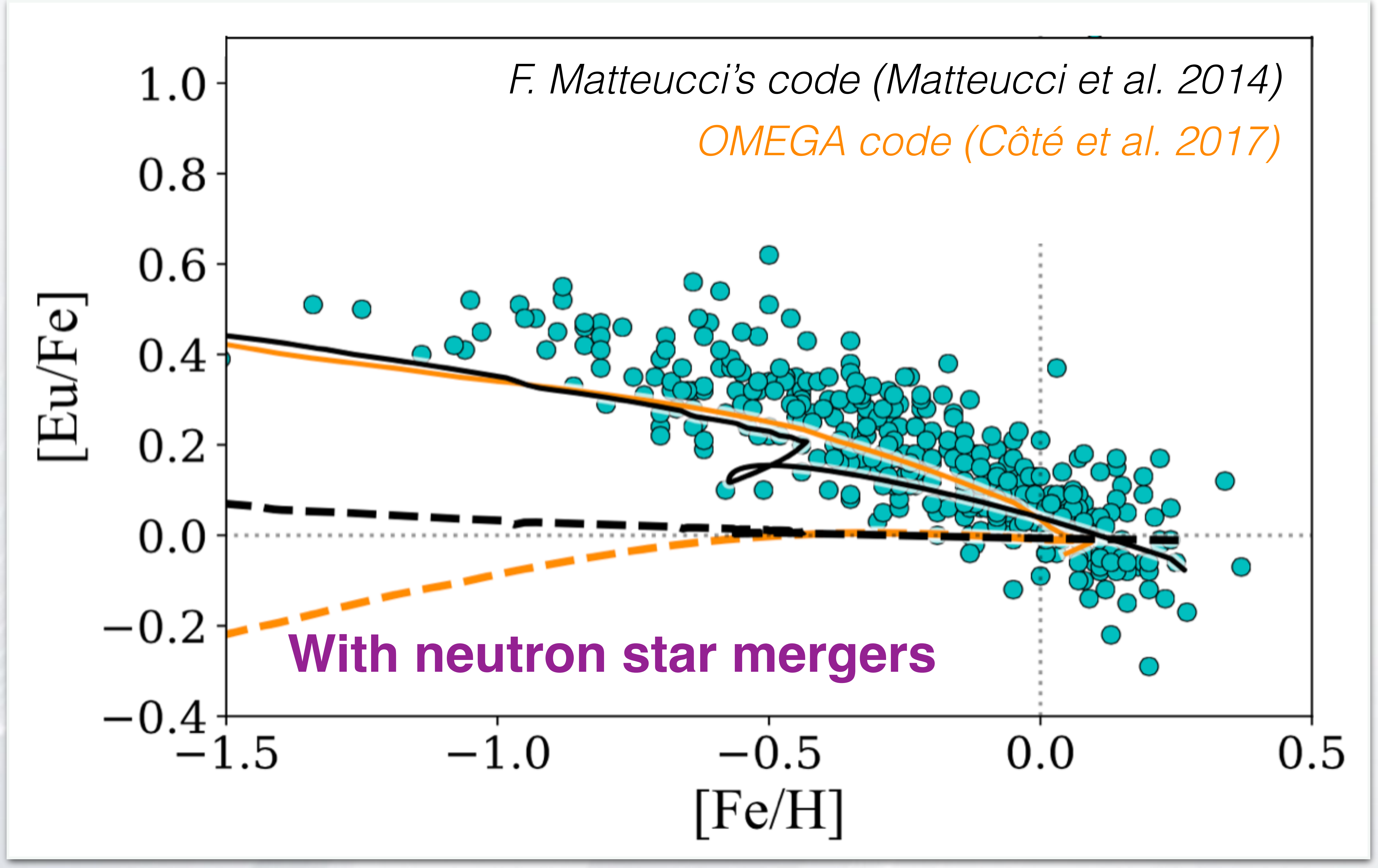


Côté, Eichler, Arcones, et al. (2019)

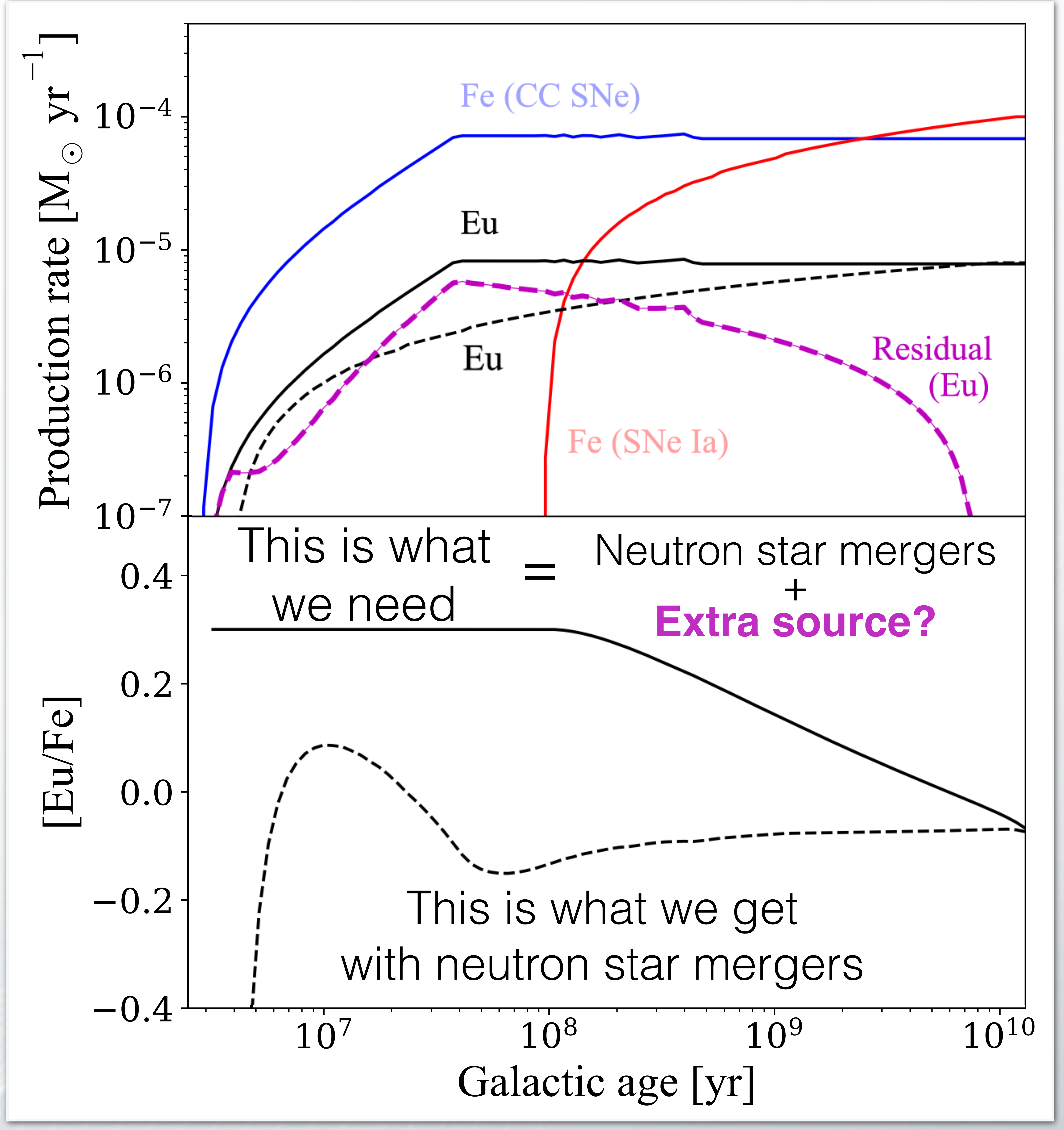


How Can we Fit the Decreasing Chemical Evolution Trend?

Côté, Eichler, Arcones, et al. (2019)



Côté, Eichler, Arcones, et al. (2019)

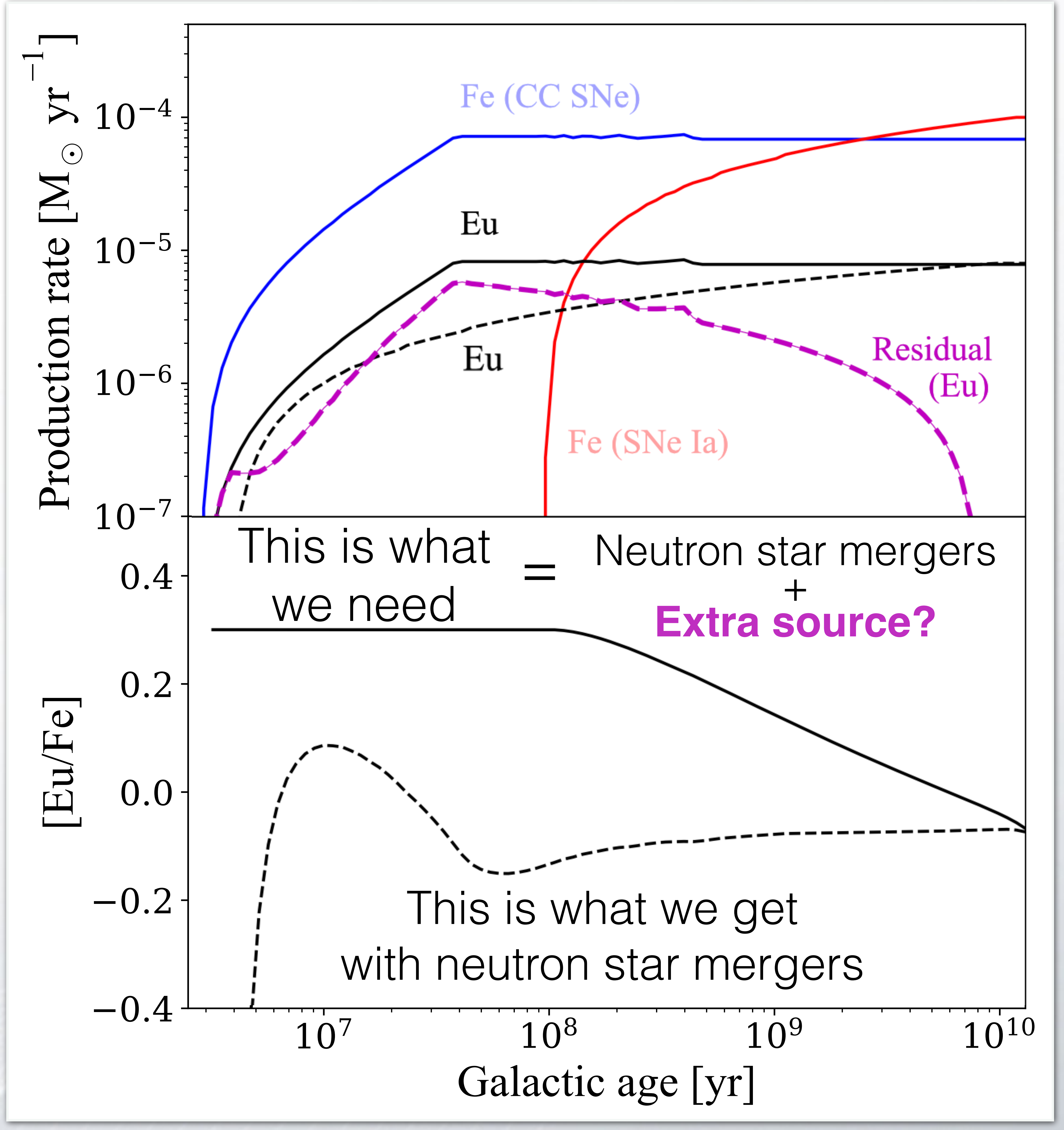


How Can we Fit the Decreasing Chemical Evolution Trend?

Côté, Eichler, Arcones, et al. (2019)

Two r-process sites in the early Universe?

Argast et al. (2004)
Cescutti et al. (2015)
Wehmeyer et al. (2015, 2019)
Haynes & Kobayashi (2018)
Safarzadeh et al. (2018)
Siegel et al. (2018)
Skuladottir et al. (in prep)

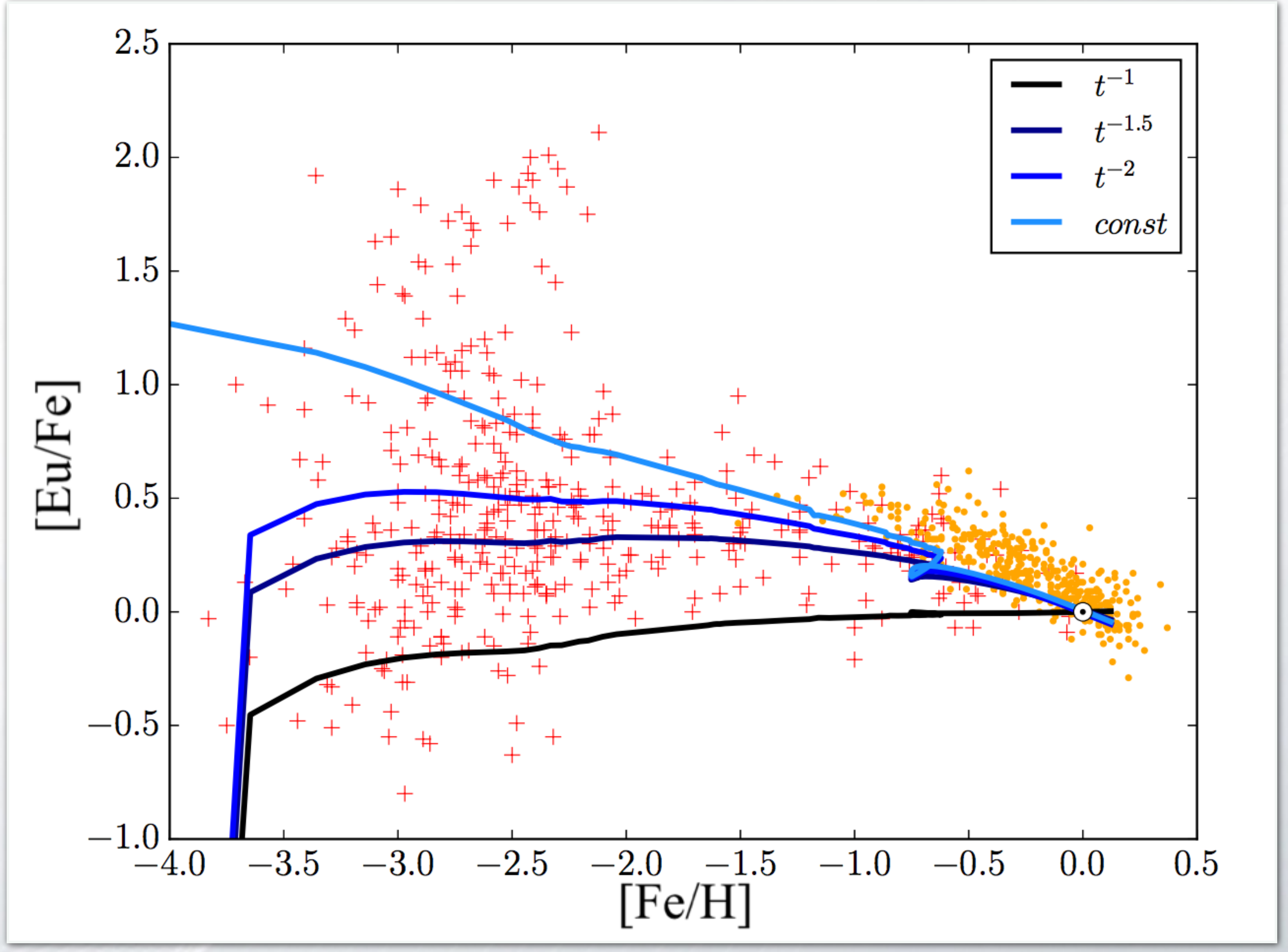


Other Solutions for Fitting [Eu/Fe]

.. with neutron star mergers only

Steeper delay-time distribution function for neutron star mergers?

Simonetti, Matteucci, Greggio & Cescutti (2019)

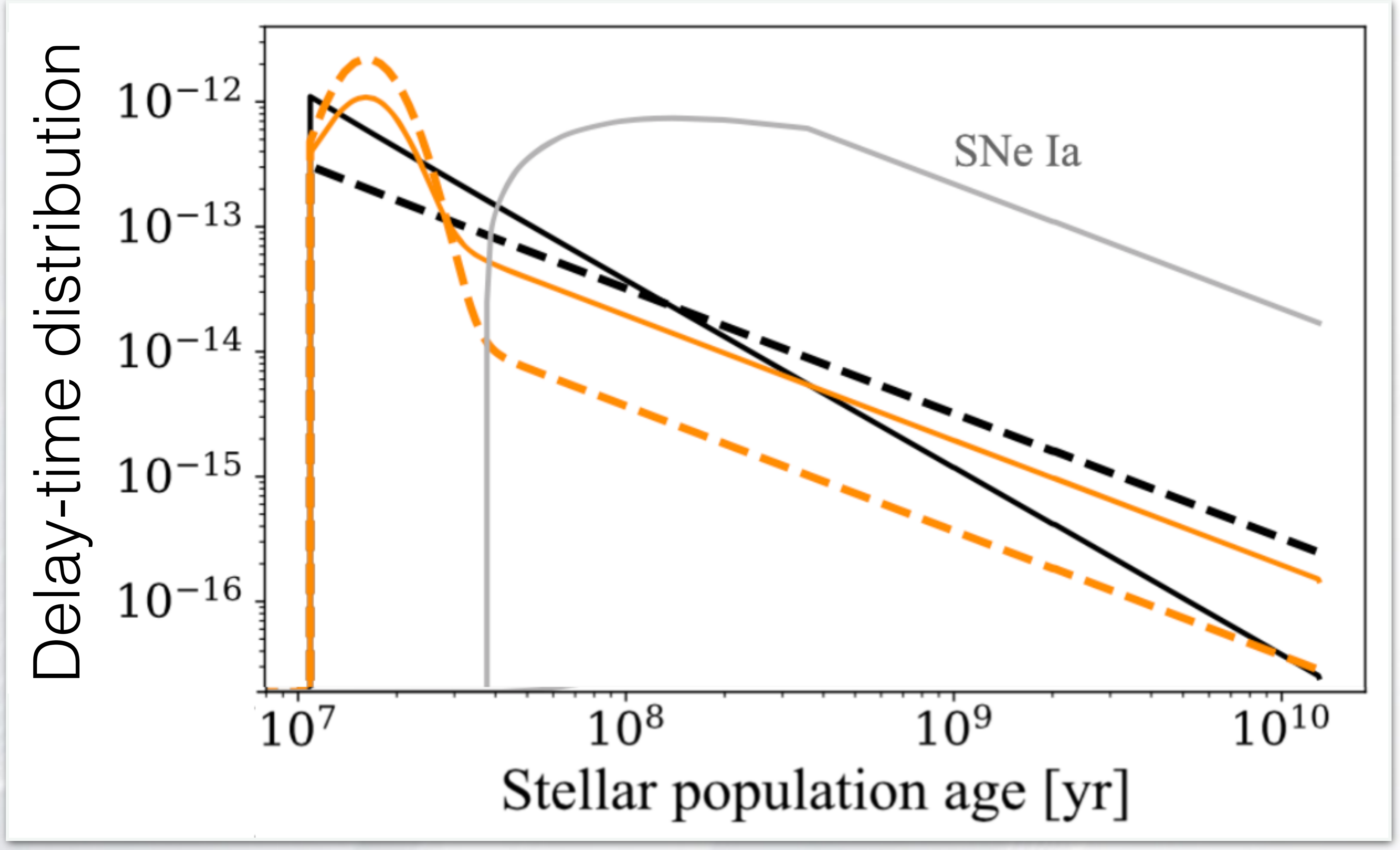


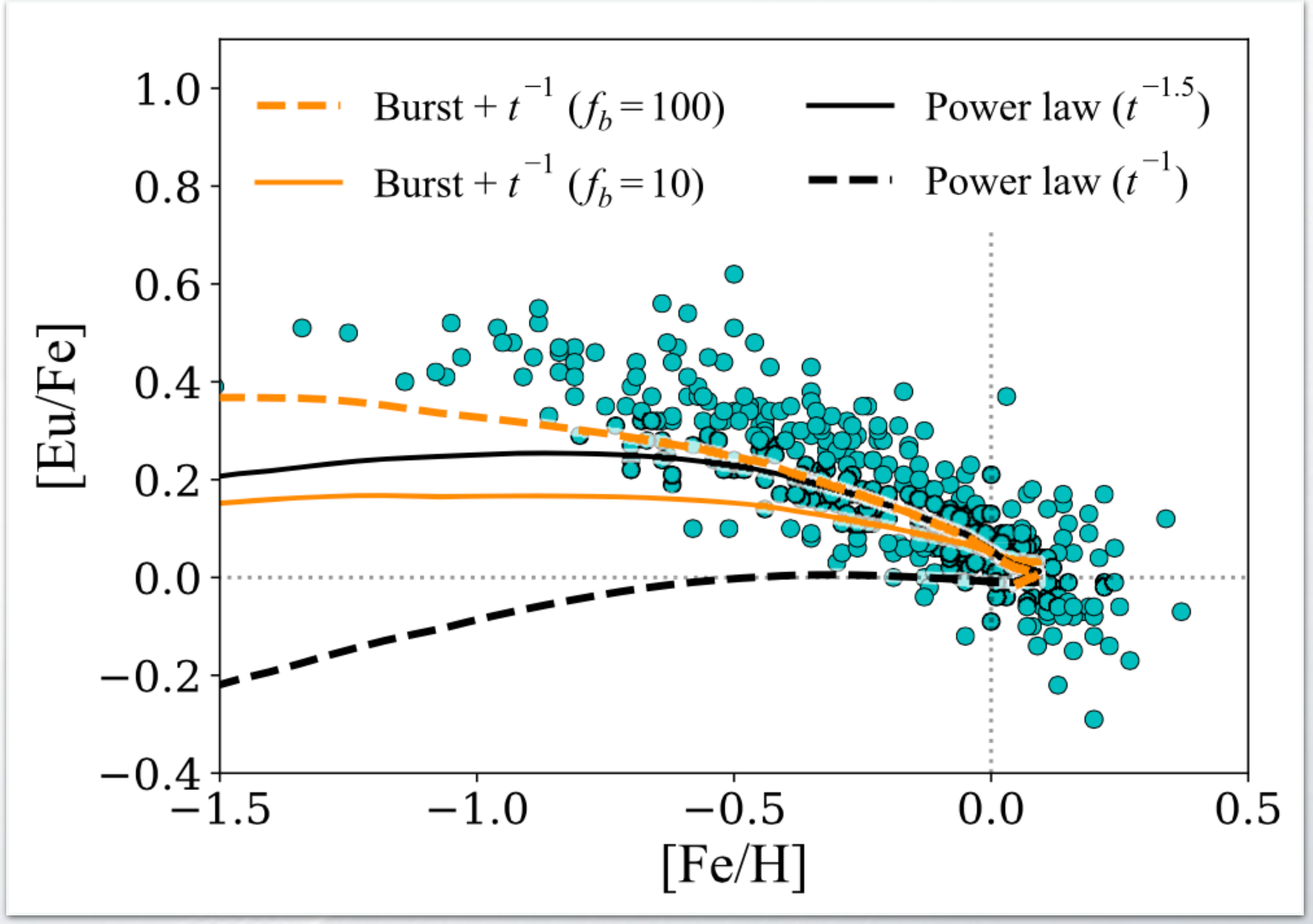
Other Solutions for Fitting [Eu/Fe]

.. with neutron star mergers only

Steeper delay-time distribution function for neutron star mergers?

Côté, Eichler, Arcones, et al. (2019)





See also

Côté et al. (2017)

Hotokezaka et al. (2018)

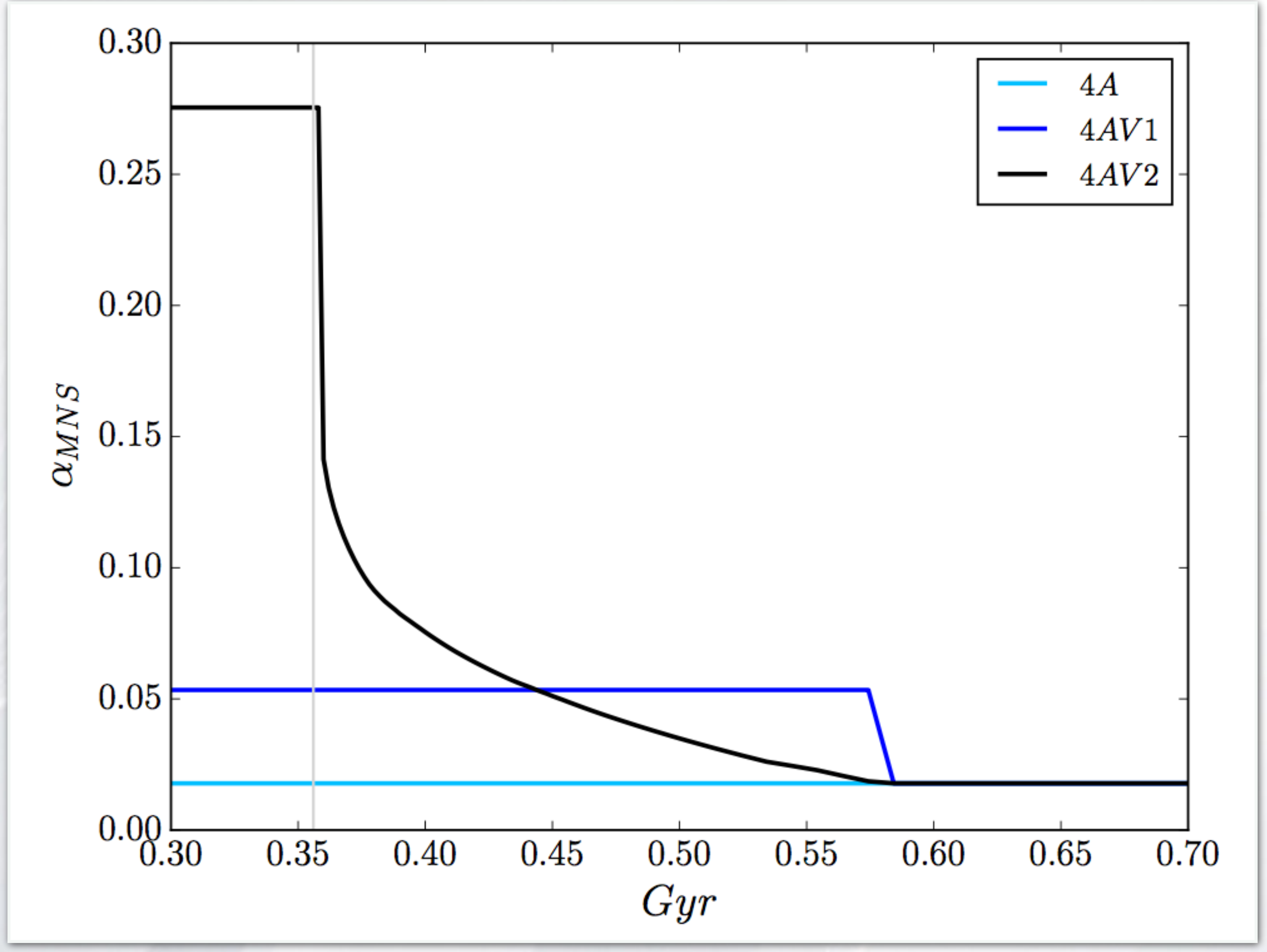
Simonetti et al. (2019)

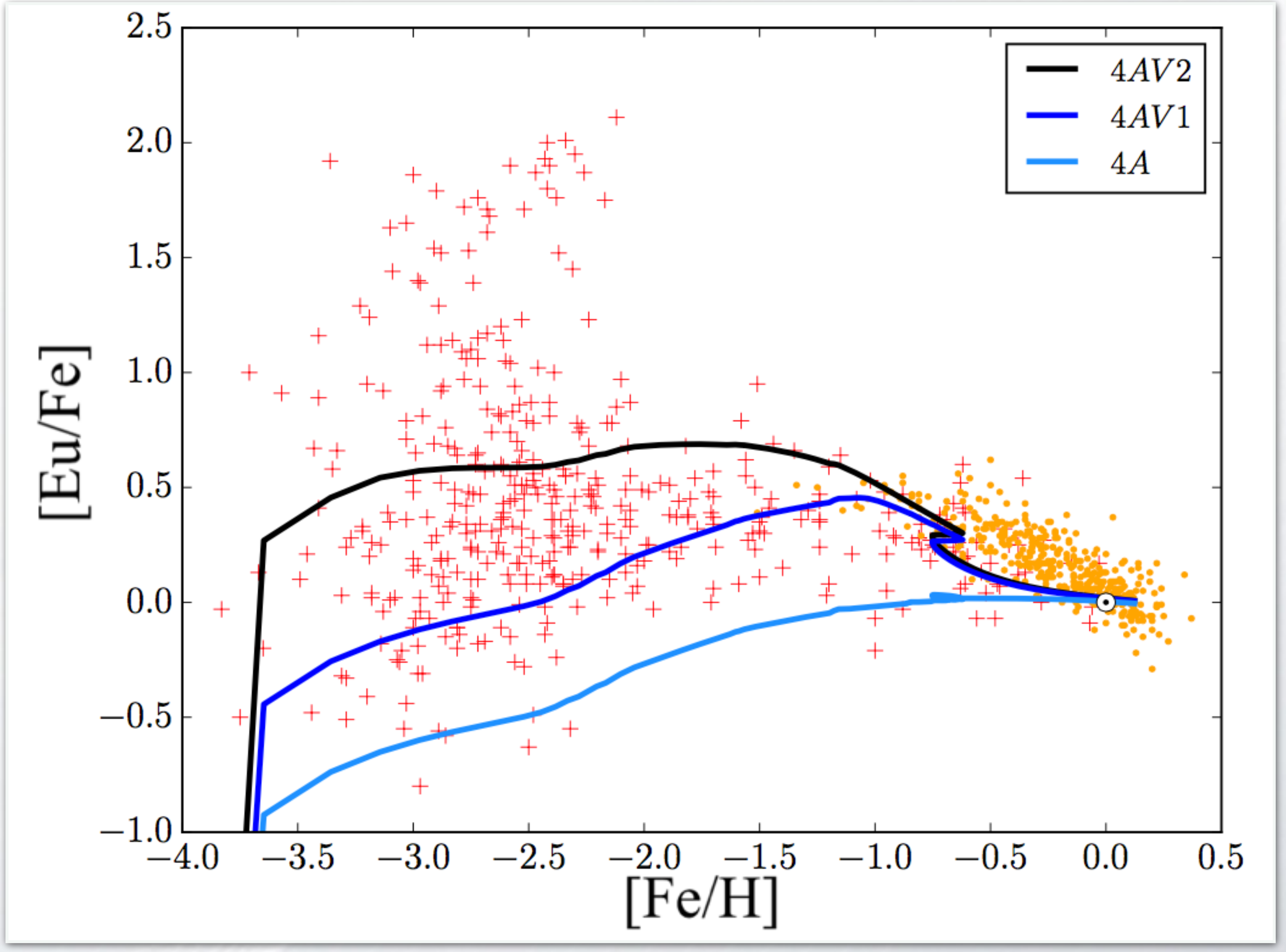
Other Solutions for Fitting [Eu/Fe]

.. with neutron star mergers only

Metallicity-dependent neutron star mergers rate?

Simonetti, Matteucci, Greggio & Cescutti (2019)

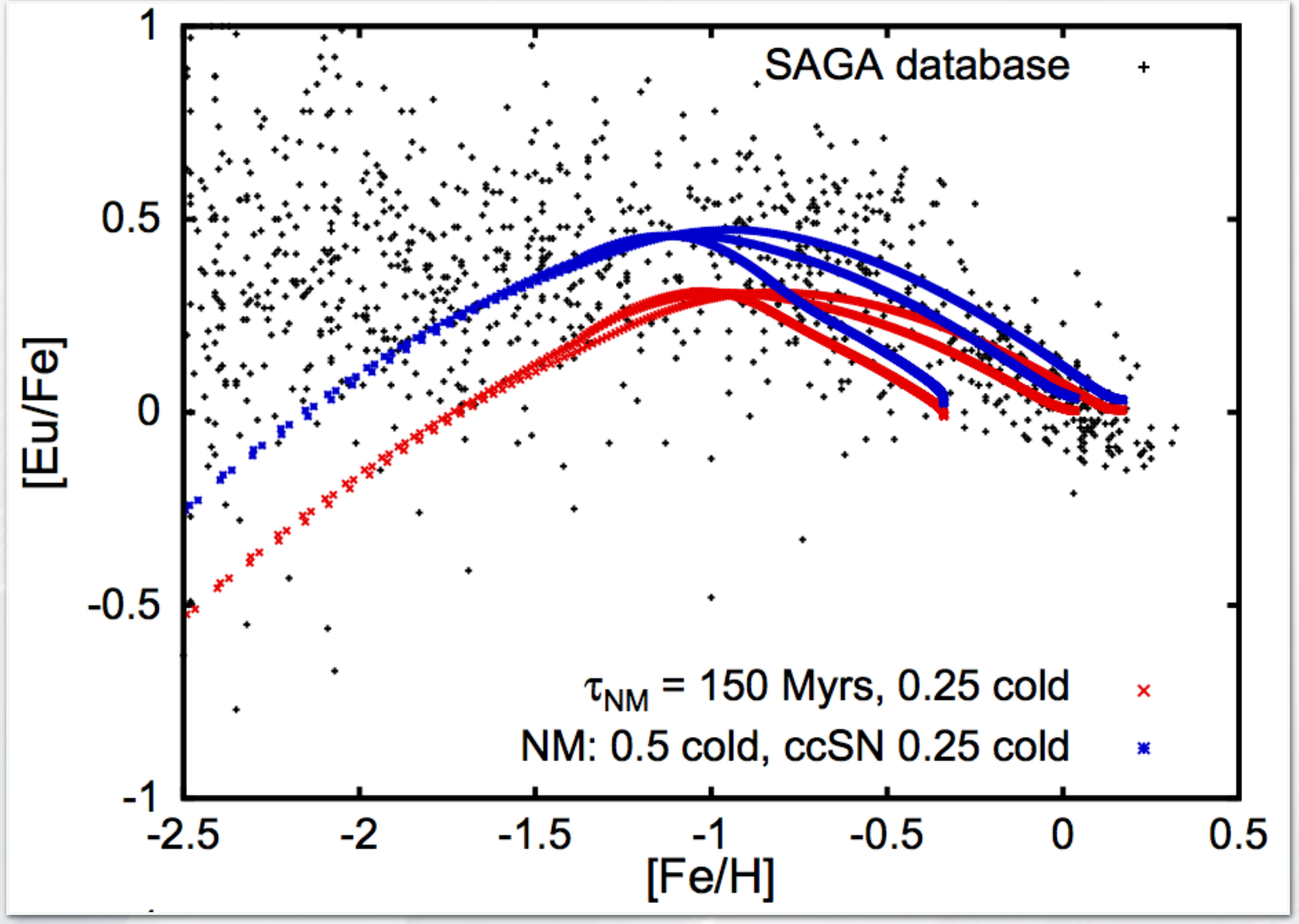




Even More **Potential** Solutions

.. with neutron star mergers only

Mixing in the interstellar medium
Schönrich & Weinberg (2019)



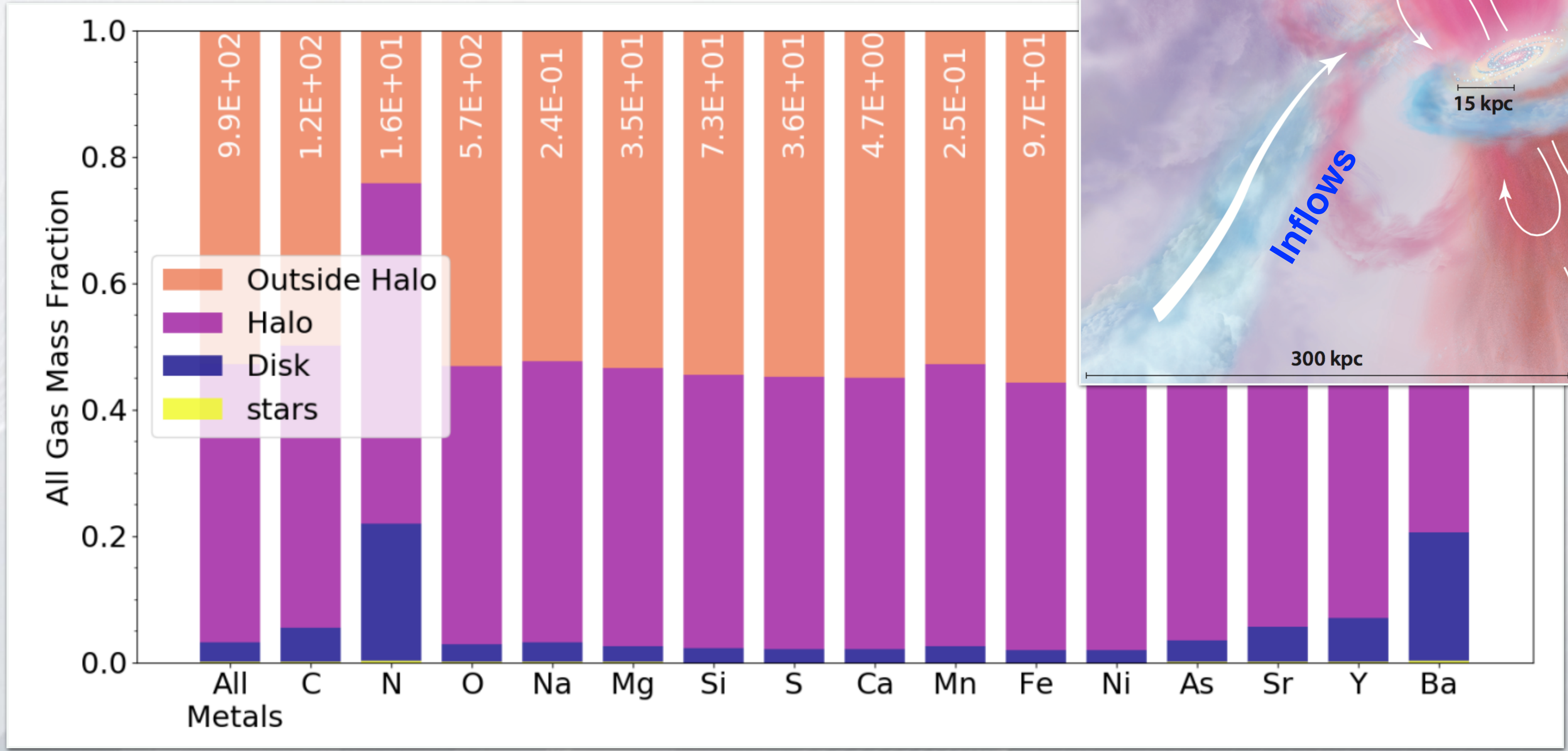
What if the neutron star merger ejecta does not pollute the same gas phase than supernova explosions?

Even More **Potential** Solutions

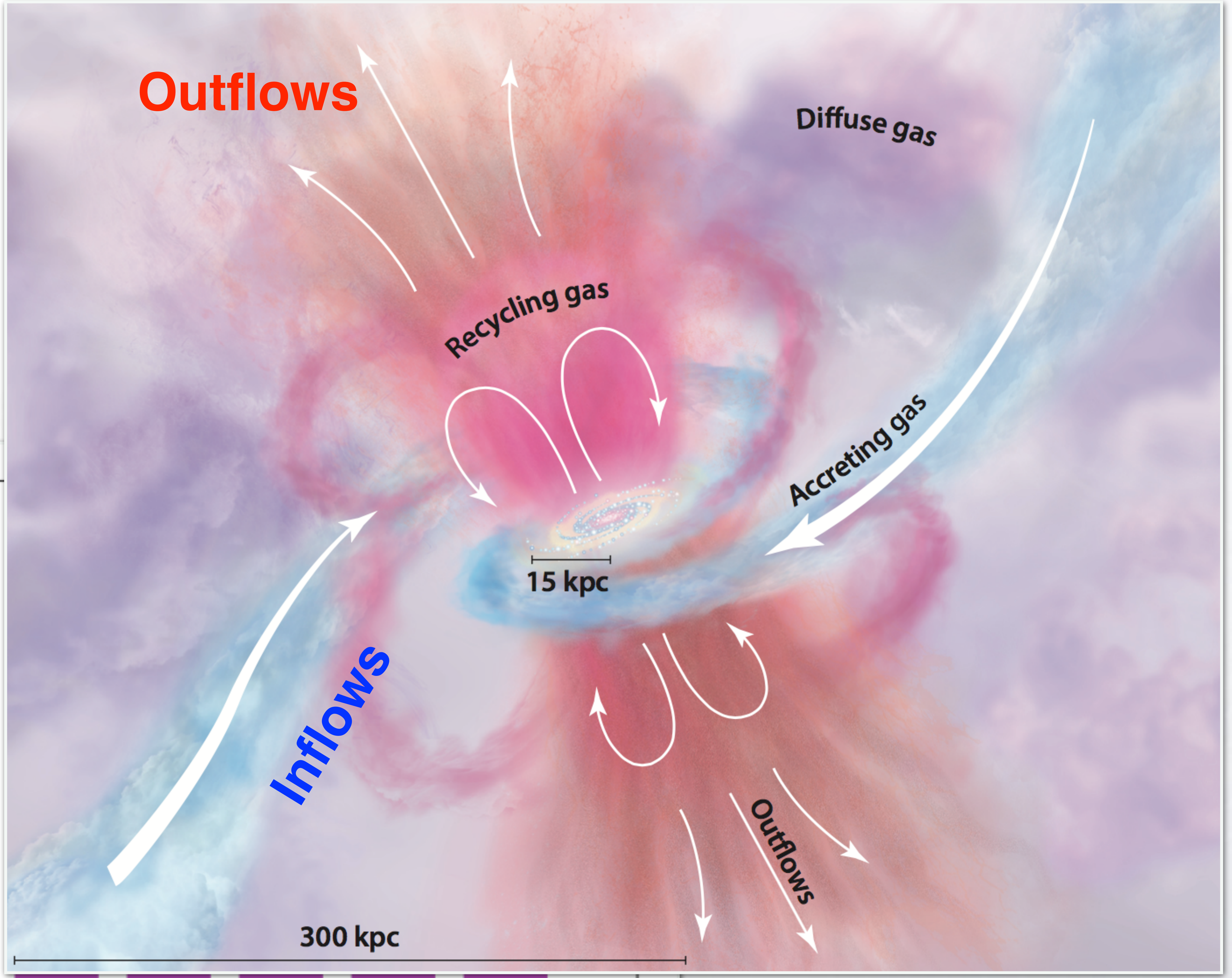
.. with neutron star mergers only

What if r-process ejecta (i.e., Eu) are more retained inside galaxies than Fe?

Emerick, Bryan, Mac Low, Côté, et al. (2018)



Tumlinson, Peeples & Werk (2017)



Take Away Message

Understand what is(are) the dominant r-process site(s) in the Universe
is a **multidisciplinary** challenge.

Gravitational waves
Chemical evolution in galaxies
Nuclear physics and nucleosynthesis
Astrophysical hydrodynamic simulations (SNe, mergers)
Stellar spectroscopy
Binary population synthesis models
Short gamma-ray bursts
Interstellar medium mixing and galactic outflows
Meteorites and cosmochemistry
etc..

It is not only about fitting chemical evolution, it is about **combining all pieces of evidences** to build a coherent and consistent picture.

ACKNOWLEDEMENTS

COST Acknowledgements

www.chetec.eu

See www.chetec.eu for more details

The ChETEC Action (CA16117) is supported by COST (www.cost.eu). COST (European Cooperation in Science and Technology) is a funding agency for research and innovation networks. Our Actions help connect research initiatives across Europe and enable scientists to grow their ideas by sharing them with their peers. This boosts their research, career and innovation.

cost EUROPEAN COOPERATION IN SCIENCE & TECHNOLOGY

Funded by the Horizon 2020 Framework Programme of the European Union

JINA-CEE

RADIOSTAR erc