Nuclear Equation of State and Neutron Stars
January 12-18, 2020 — Hirschegg, Austria

The Impact of Nuclear Astrophysics on Chemical Evolution Predictions

Benoit Côté

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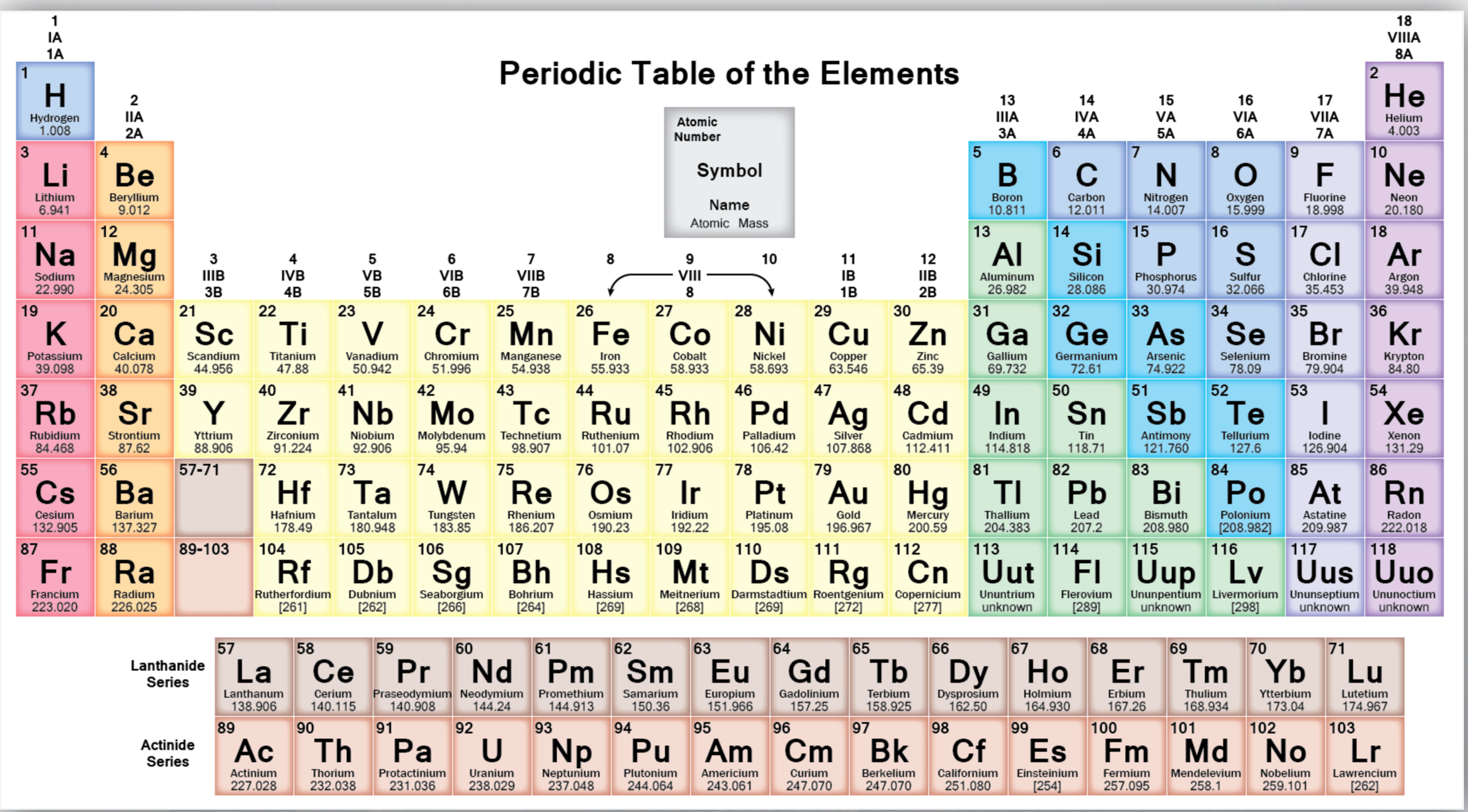
Joint Institute for Nuclear Astrophysics - Center for the Evolution of the Elements (JINA-CEE)

Collaborators (**in alphabetic order**)
A. Arcones, K. Belczynski, M. Chruslinska, M. Eichler, A. Frebel, C. Fryer, B. Gibson, C. J. Hansen, F. Herwig, S. Jones, 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

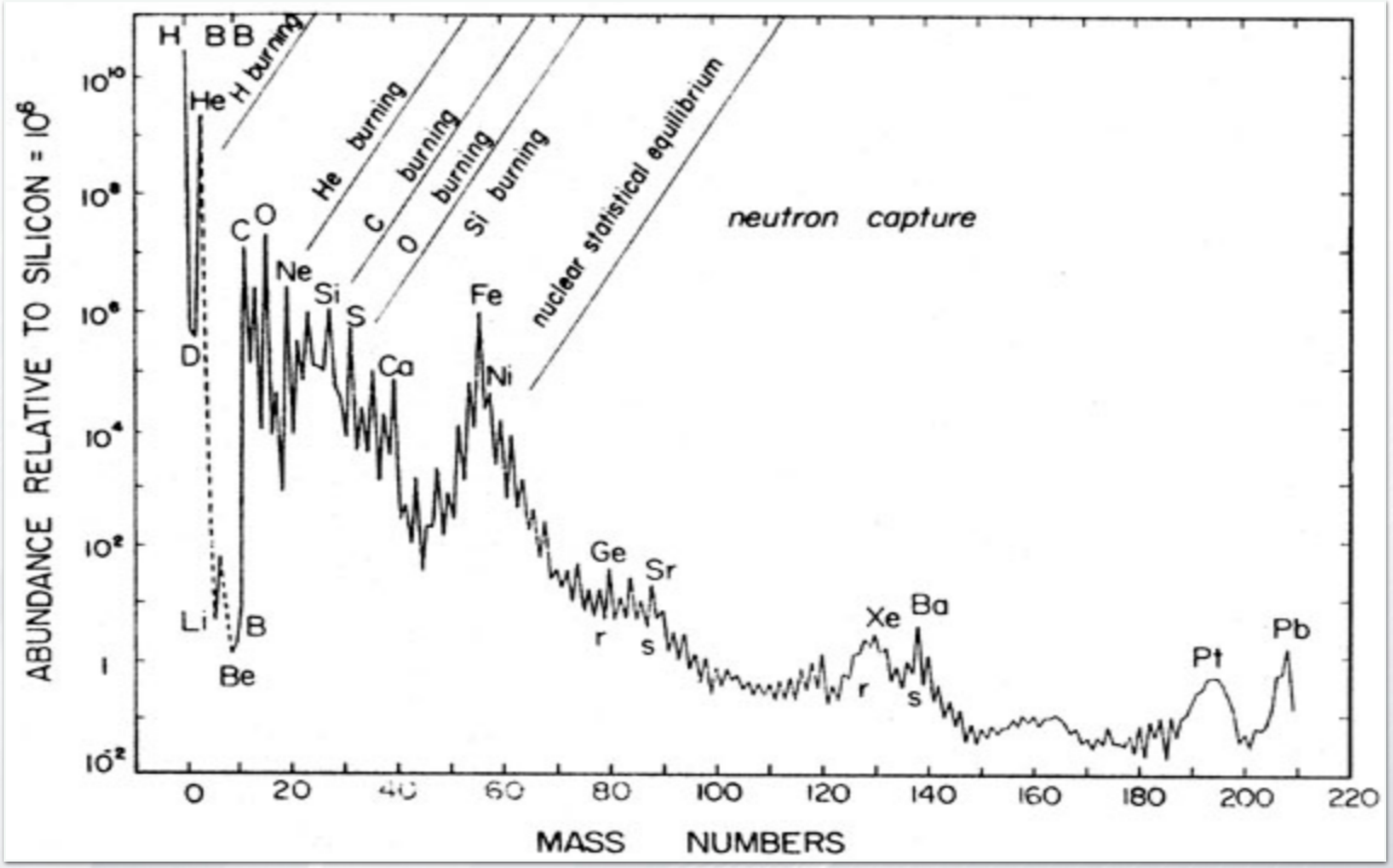
Image credit: The Renaissance Simulation (O'Shea et al. 2015, Xu et al. 2016)

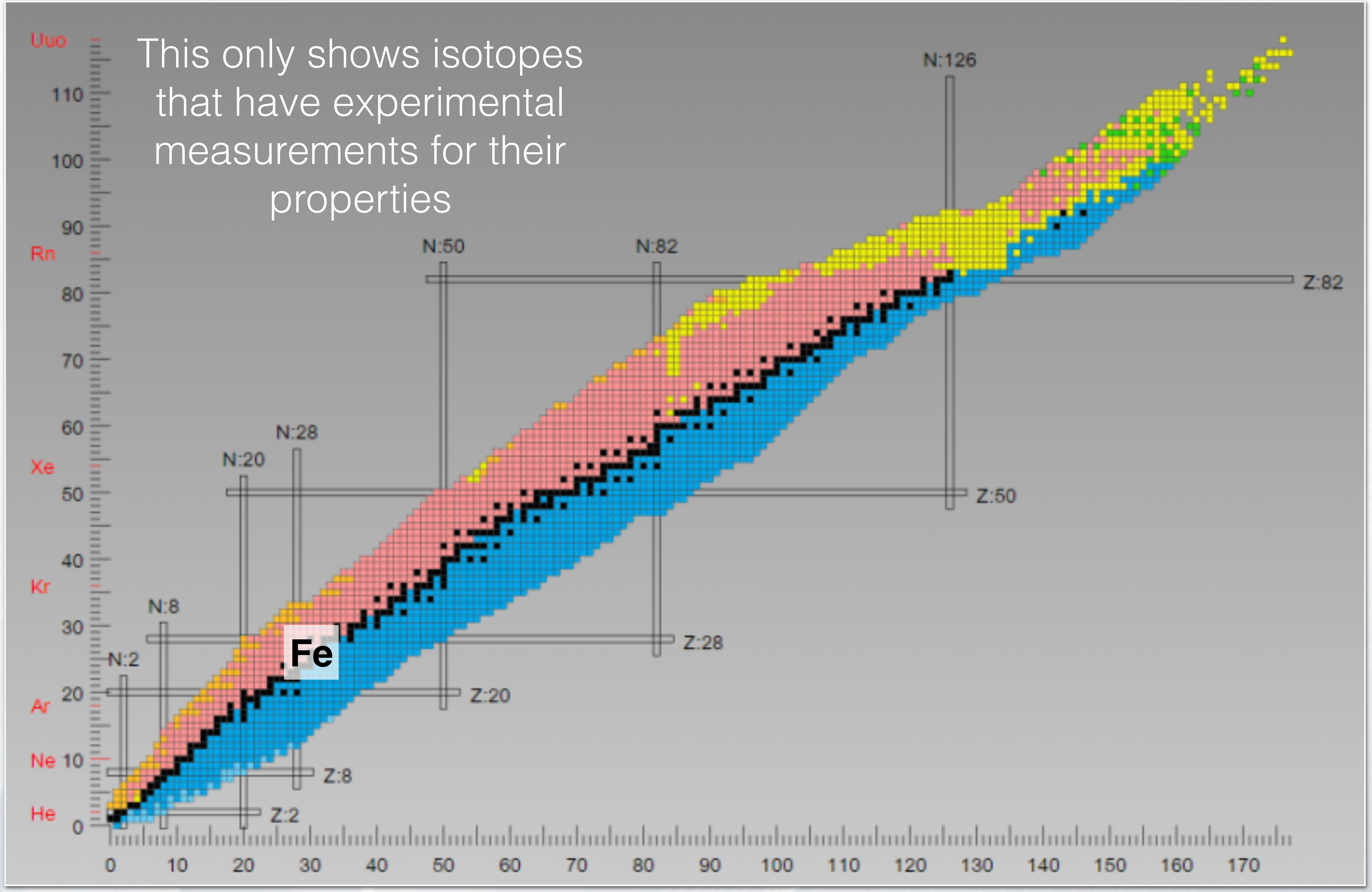
Chemical Elements and Isotopes



Chemical Elements and Isotopes

Cameron (1982)

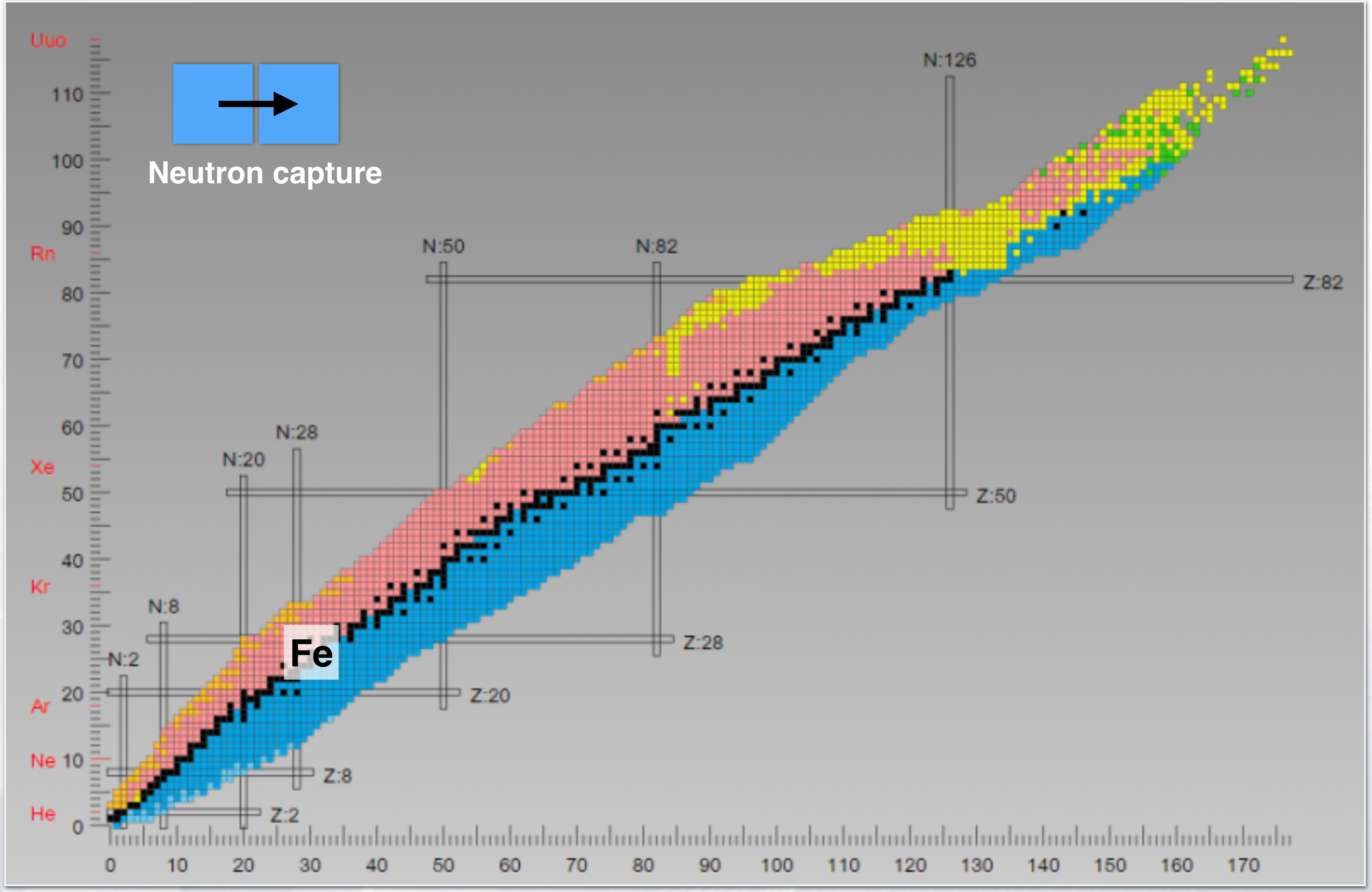




Number of **protons**

Number of **neutrons**

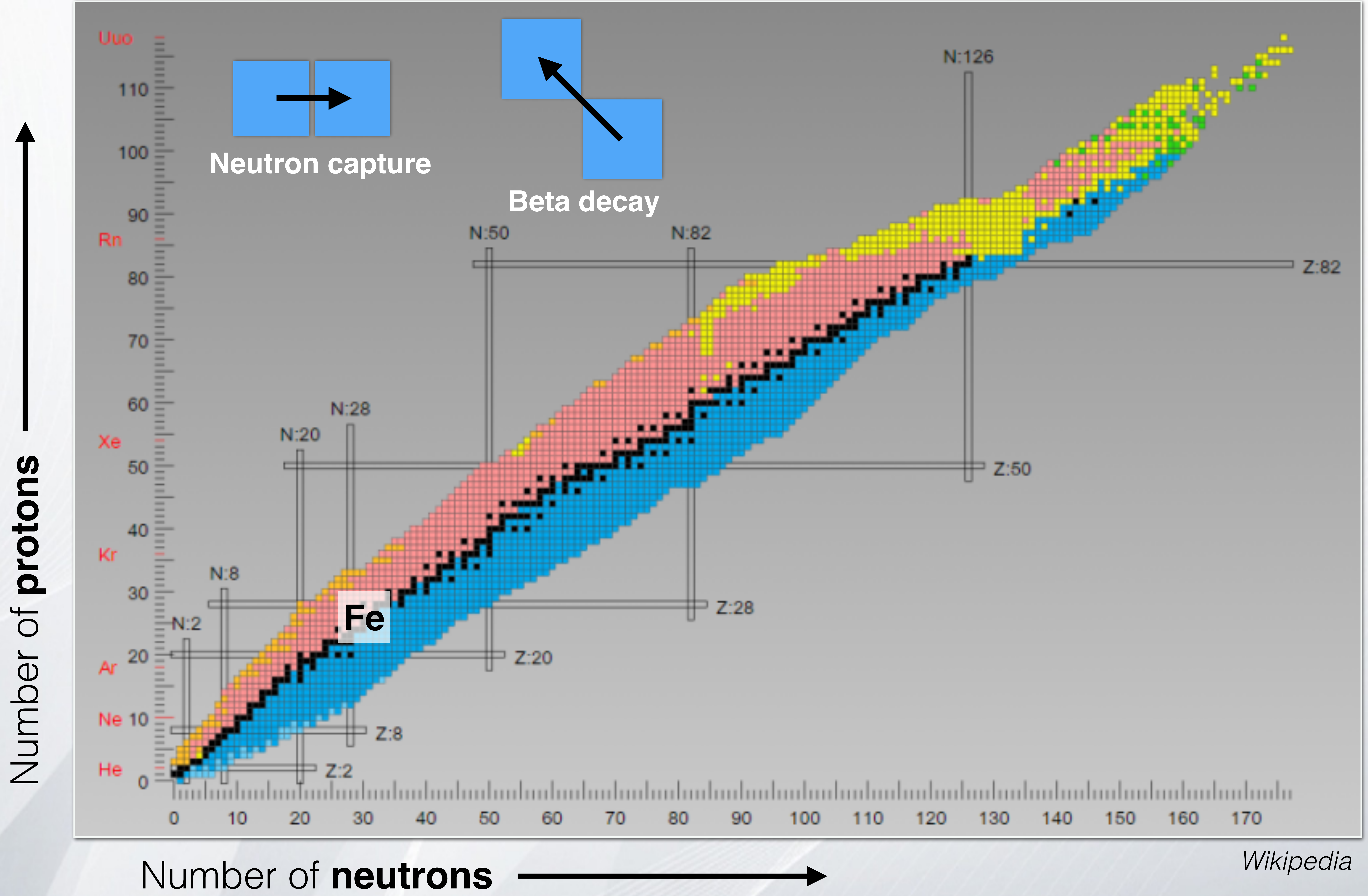
Wikipedia



Number of **protons**

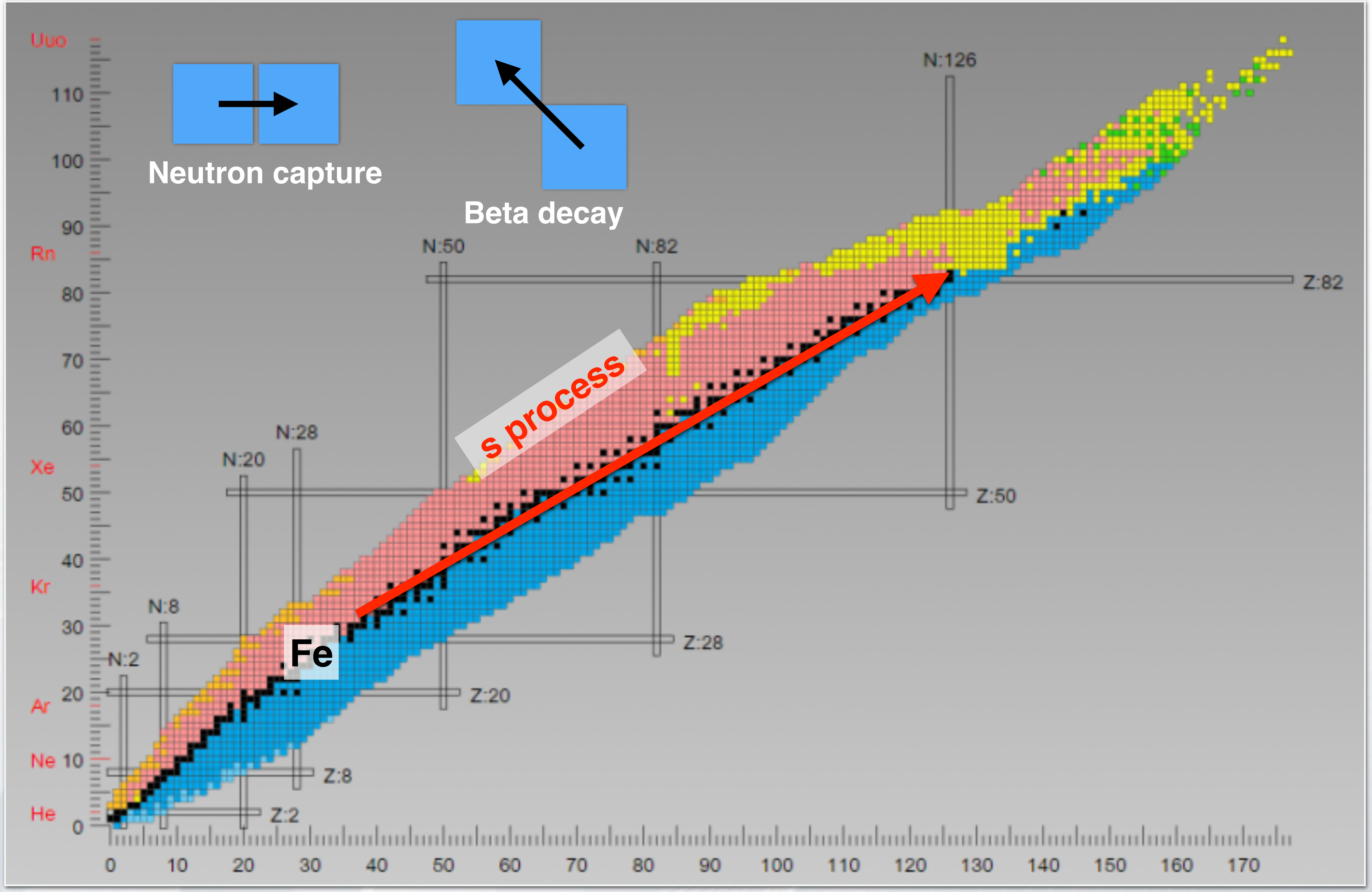
Number of **neutrons**

Wikipedia



Number of protons
Number of neutrons
Neutron capture
Beta decay
Fe
Uuo
Rn
Xe
Kr
Ar
Ne
He
N:2
N:8
N:20
N:28
N:50
N:82
N:126
Z:2
Z:8
Z:20
Z:28
Z:50
Z:82
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170

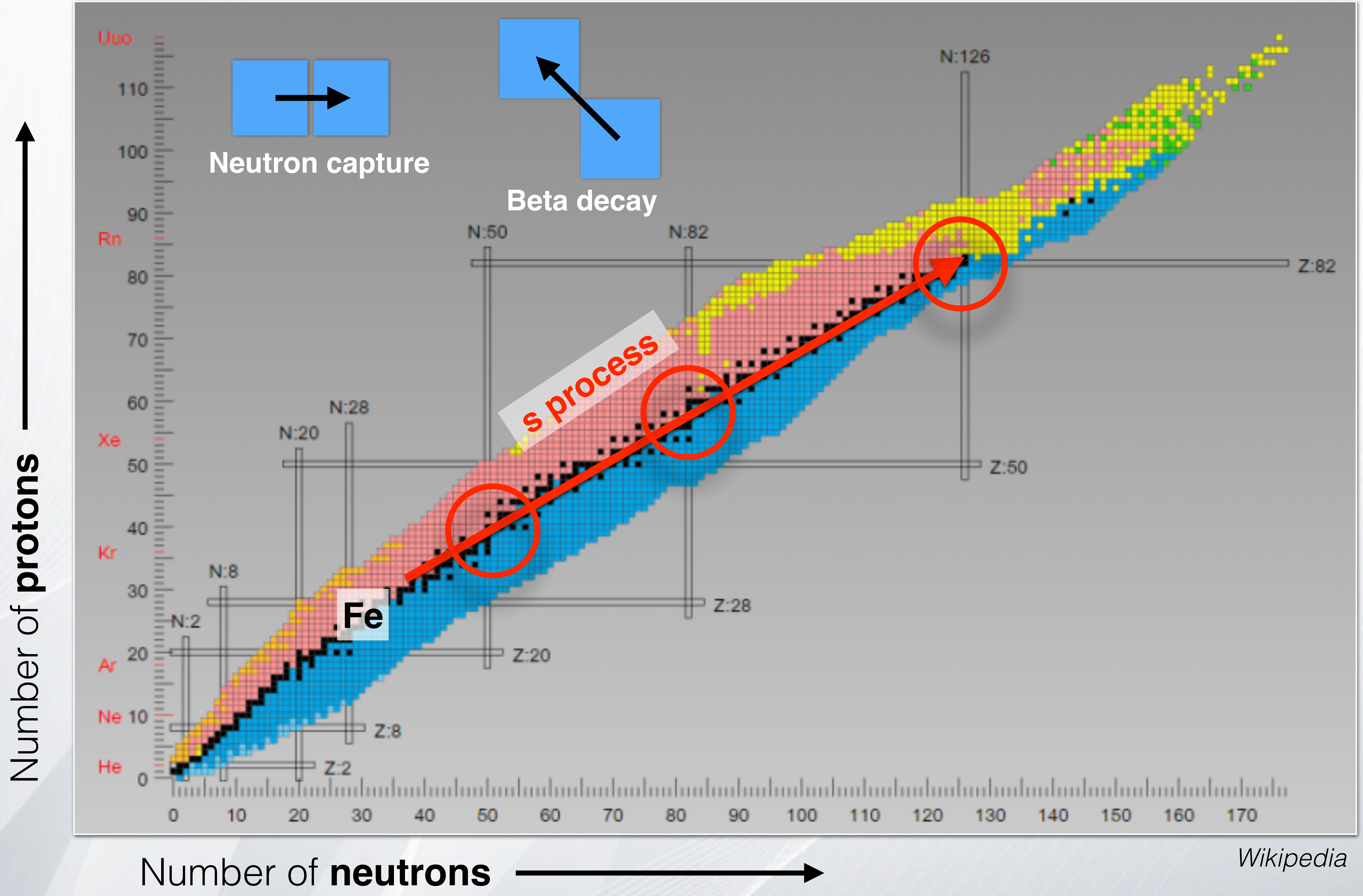
Wikipedia



Number of **protons**

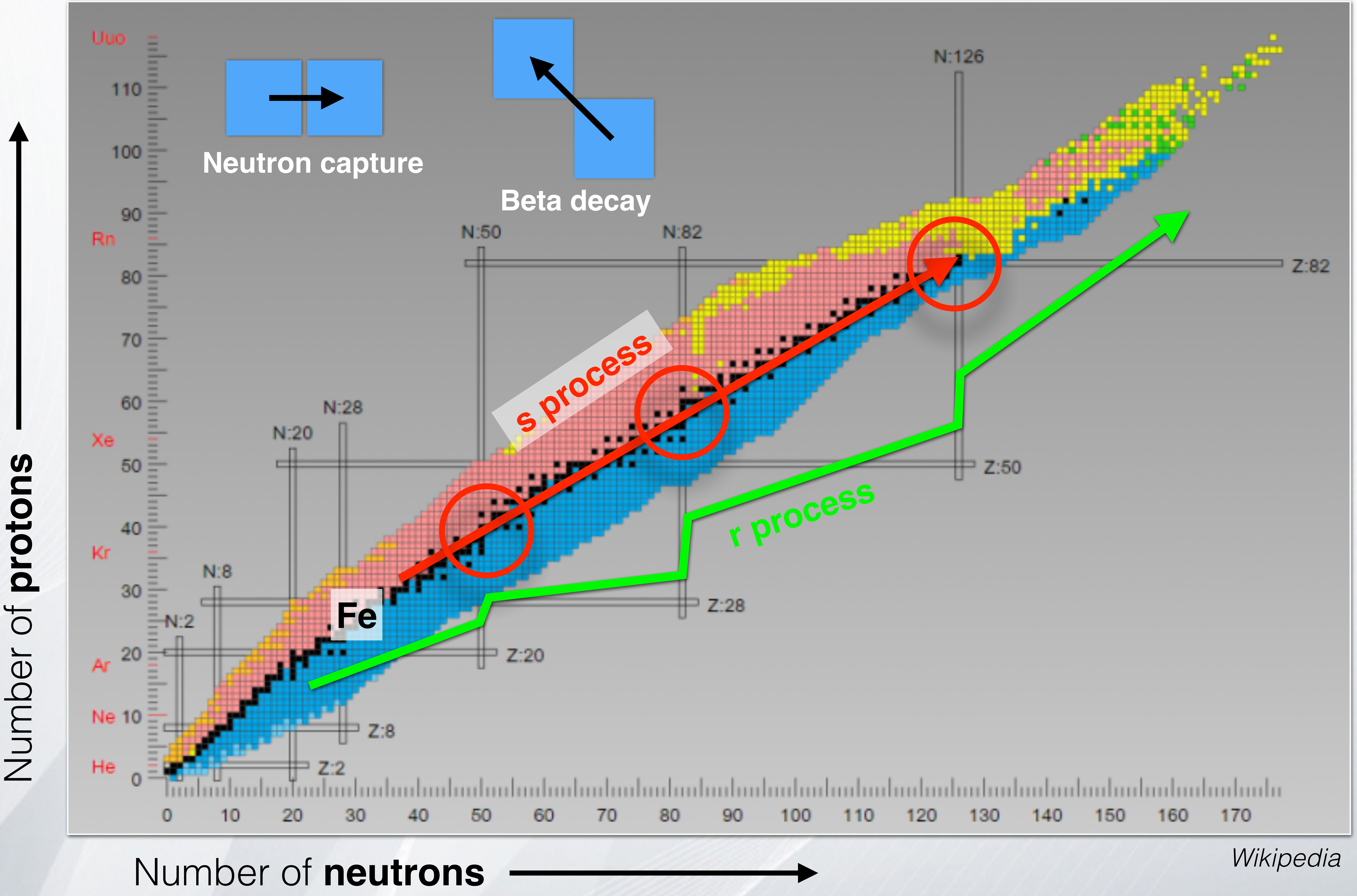
Number of **neutrons**

Wikipedia



Neutron capture
Beta decay
s process
Fe
Uuo
Rn
Xe
Kr
Ar
Ne
He
N:2
N:8
N:20
N:28
N:50
N:82
N:126
Z:2
Z:8
Z:20
Z:28
Z:50
Z:82
Number of protons
Number of neutrons

Wikipedia


Neutron capture
Beta decay
s process
r process
Fe
N:2
N:8
N:20
N:28
N:50
N:82
N:126
Z:2
Z:8
Z:20
Z:28
Z:50
Z:82
Uuo
Rn
Xe
Kr
Ar
Ne
He
0
10
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70
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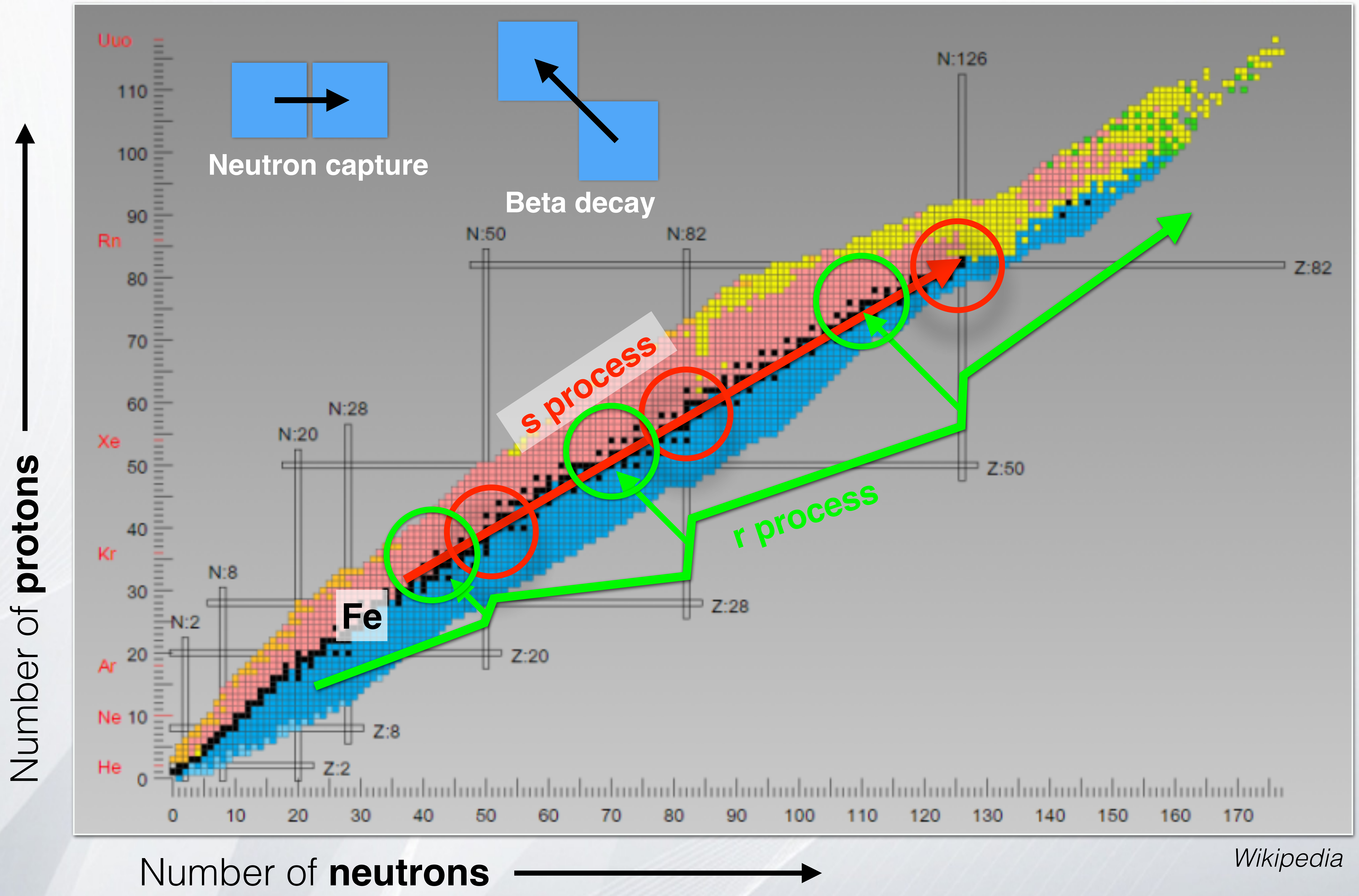
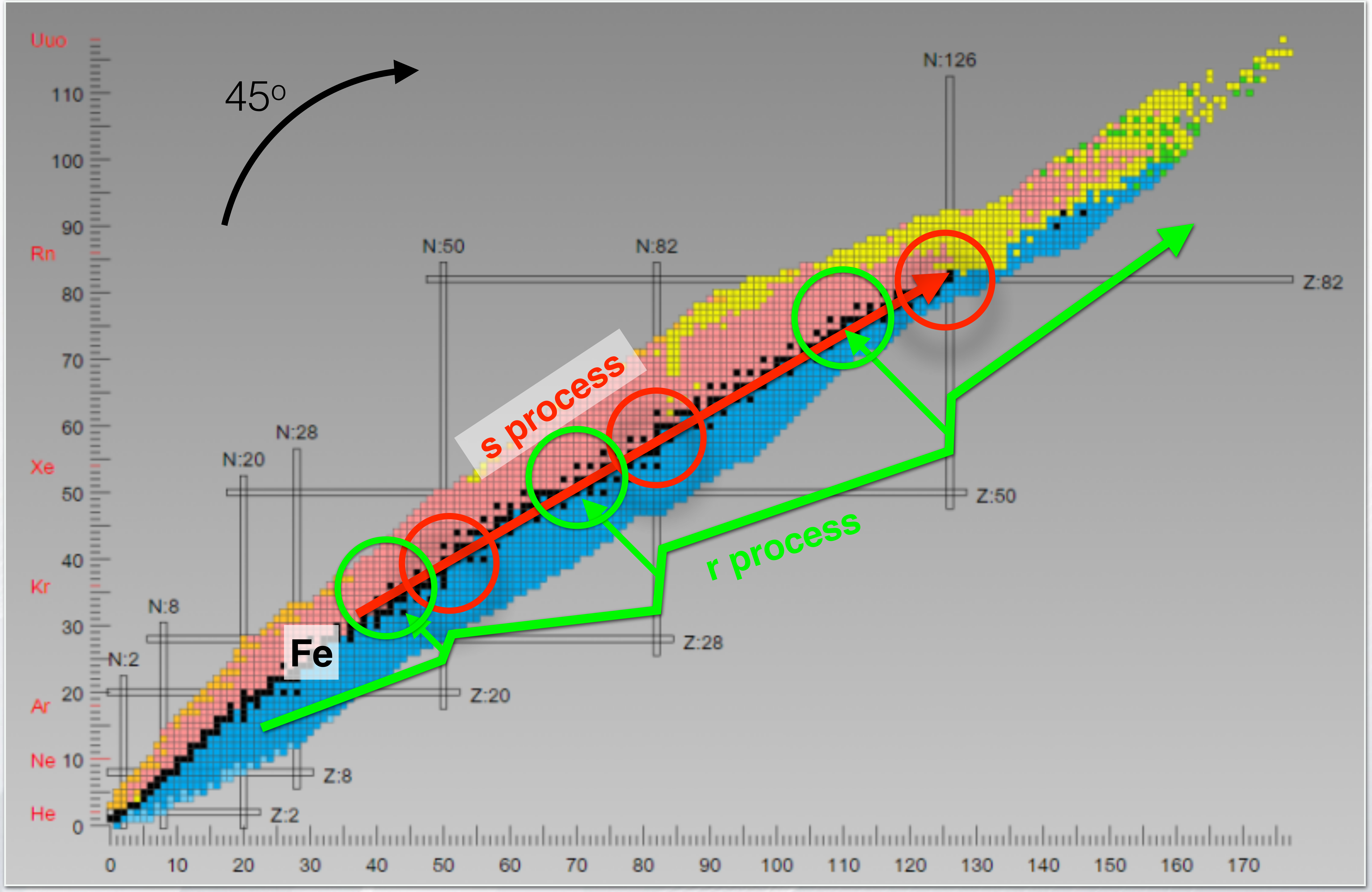
90
100
110
120
130
140
150
160
170
Number of protons
Number of neutrons

Wikipedia


Neutron capture
Beta decay
s process
r process
Fe
N:2
N:8
N:20
N:28
N:50
N:82
N:126
Z:2
Z:8
Z:20
Z:28
Z:50
Z:82
Uuo
Rn
Xe
Kr
Ar
Ne
He
Number of protons
Number of neutrons
Wikipedia



45°
s process
r process
Fe
N:2
N:8
N:20
N:28
N:50
N:82
N:126
Z:2
Z:8
Z:20
Z:28
Z:50
Z:82
Uuo
Rn
Xe
Kr
Ar
Ne
He
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110
120
130
140
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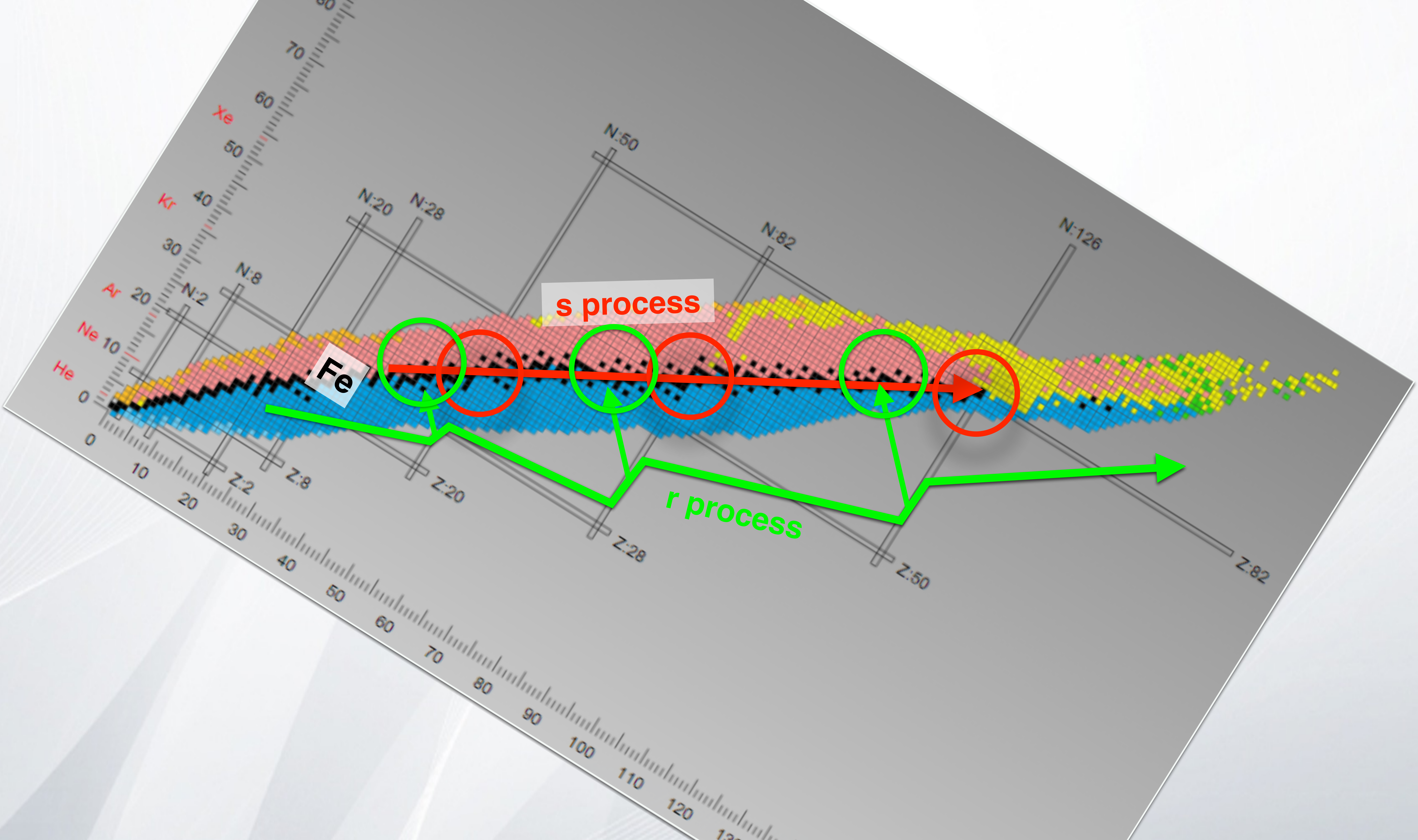
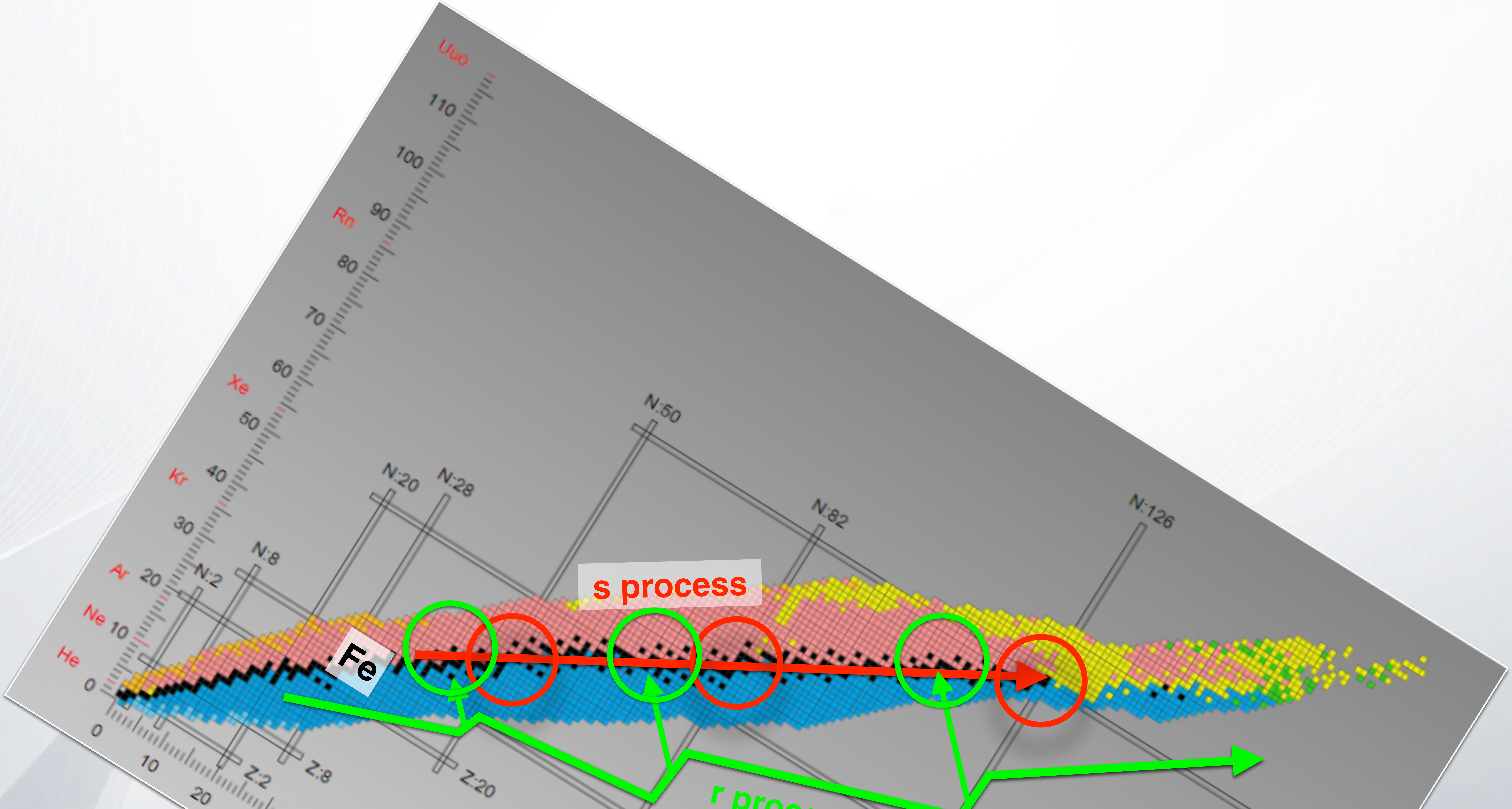
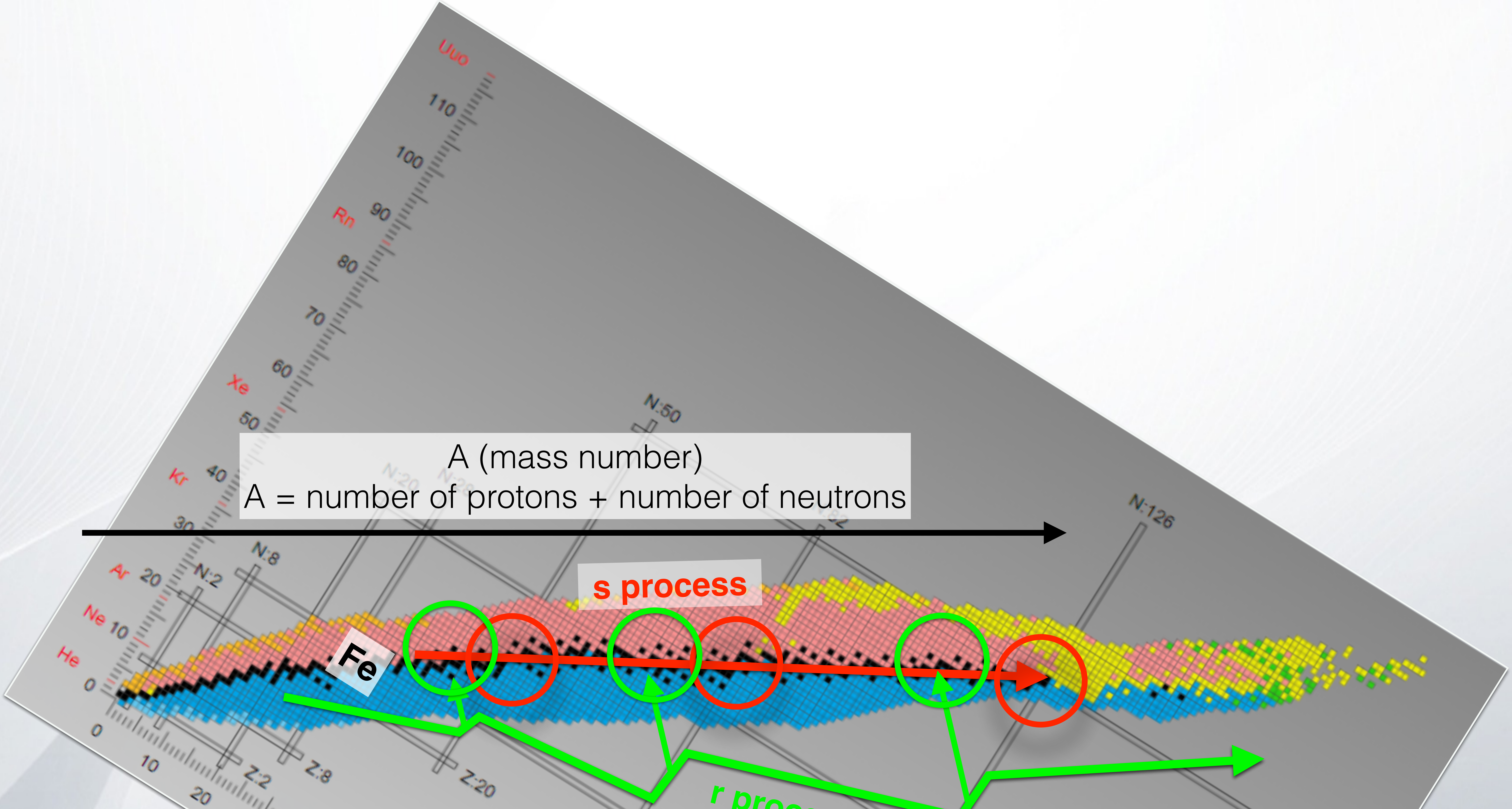
170


s process
r process
Fe
N:2
N:8
N:20
N:28
N:50
N:82
N:126
Z:2
Z:8
Z:20
Z:28
Z:50
Z:82
He
Ne
Ar
Kr
Xe



s process
Fe
N:2
N:8
N:20
N:28
N:50
N:82
N:126
Z:2
Z:8
Z:20
He
Ne
Ar
Kr
Xe
Rn
Uuo

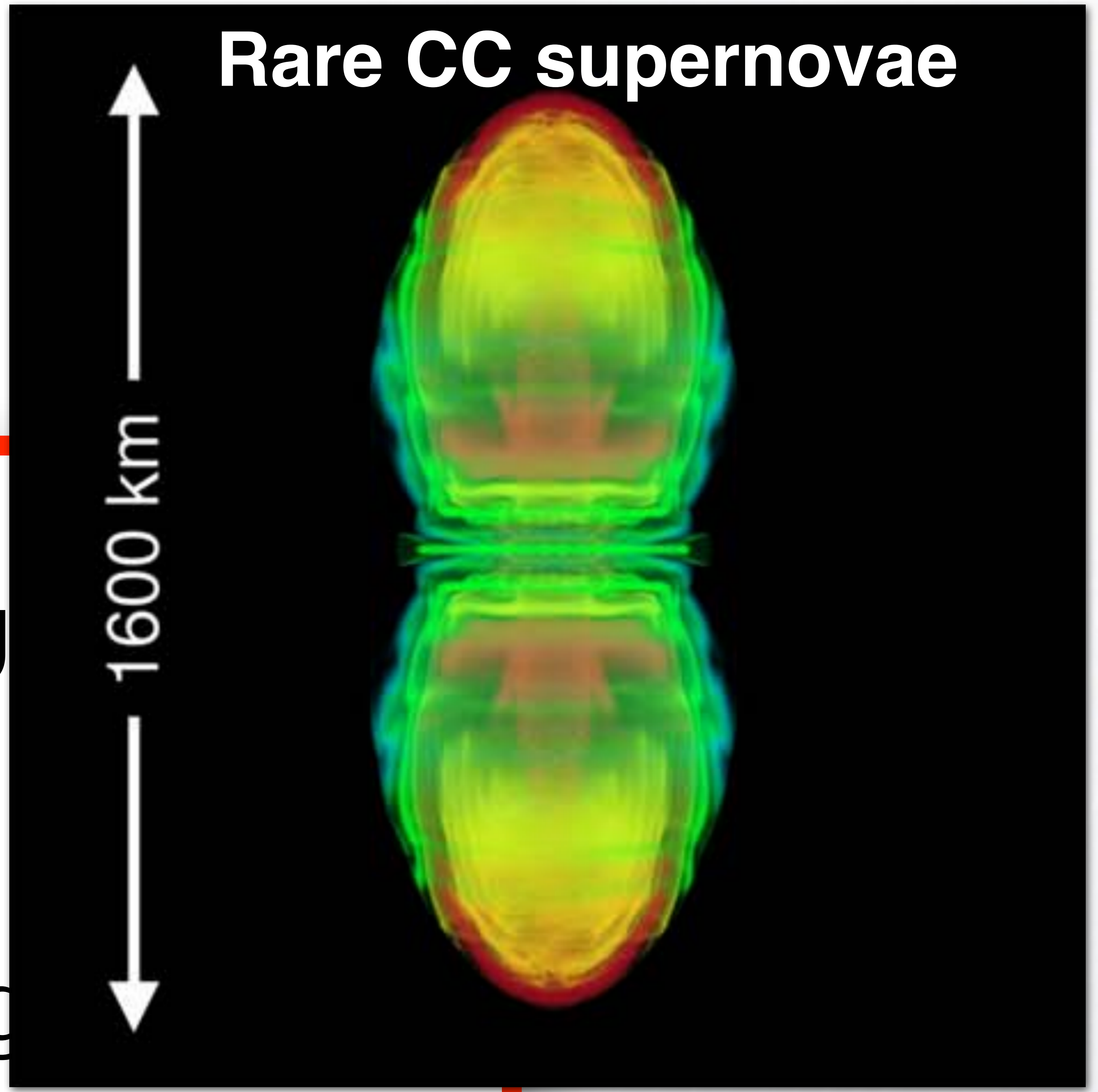

A (mass number)
A = number of protons + number of neutrons
s process
Fe
r process
Uuo
Rn
Xe
Kr
Ar
Ne
He
N:2
N:8
N:50
N:126
Z:2
Z:8
Z:20

see Burbidge et al. (1957)

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

…e r-process occur in the U…

Which astrophysical site has produced
the r-process elements we see today in g…

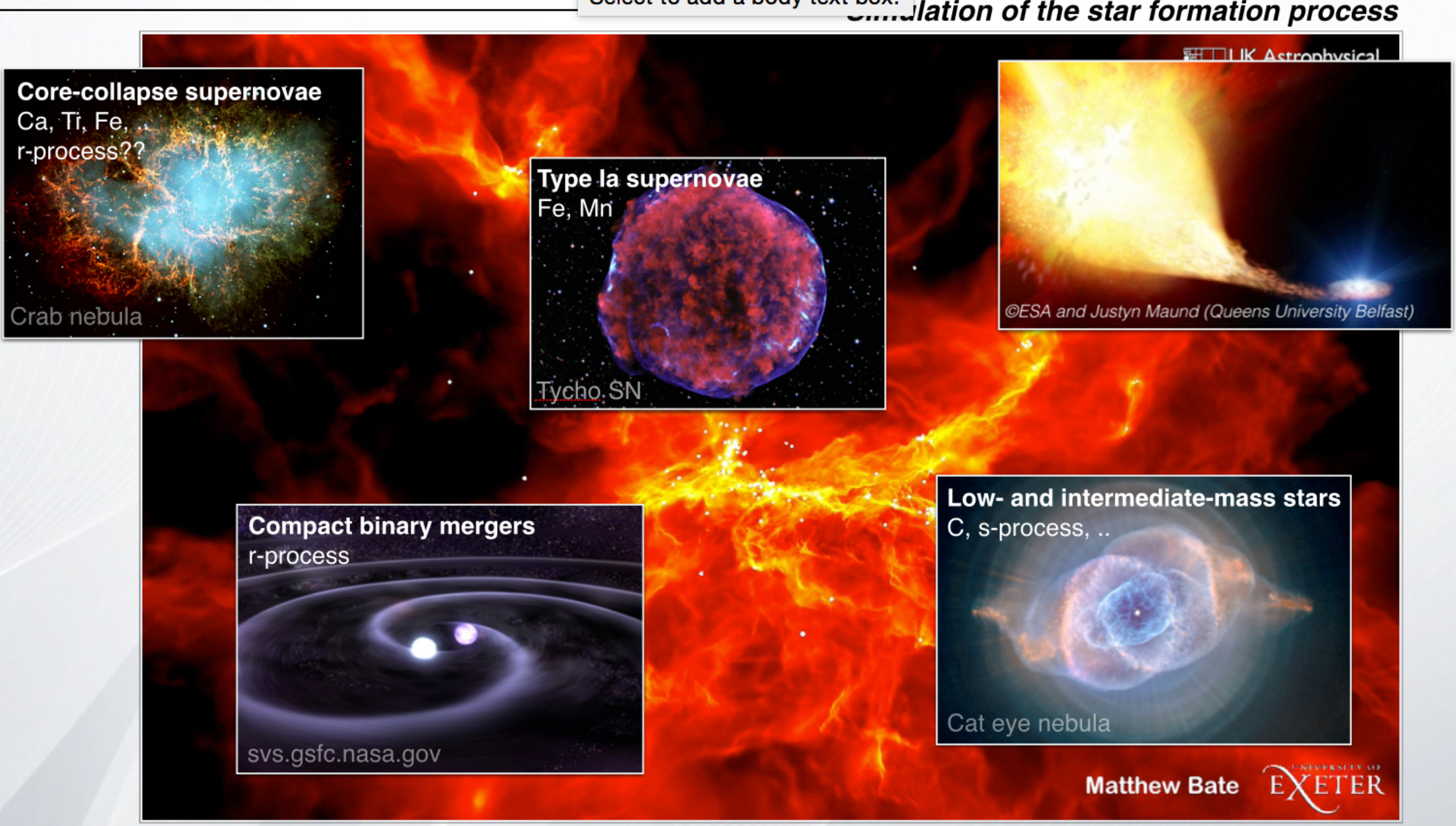


Mosta et al. (2018)

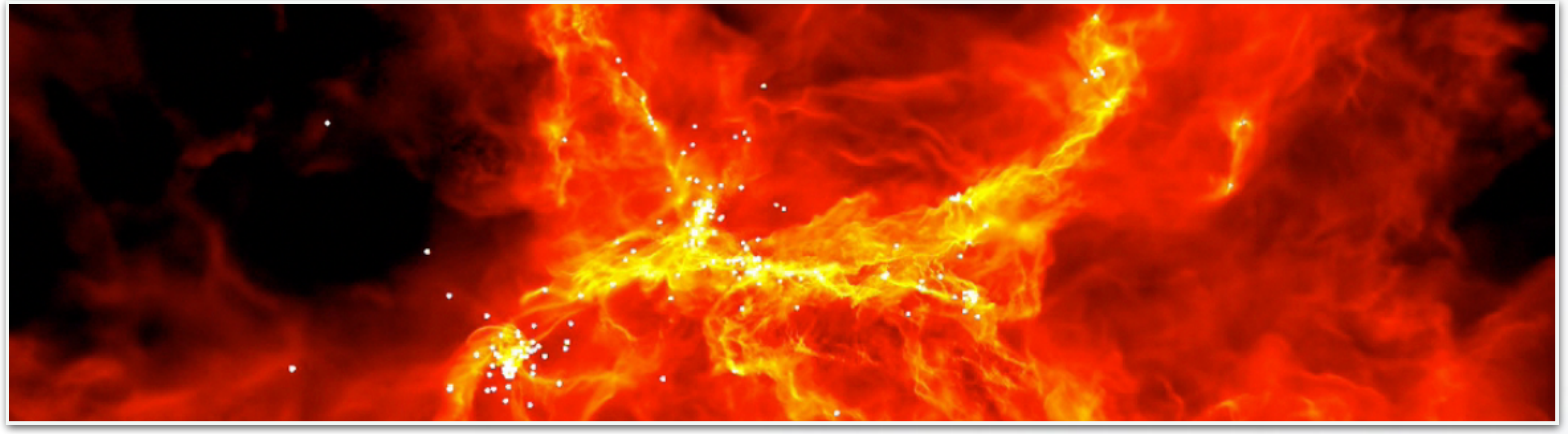
Neutron star mergers?
Black hole neutron star mergers?
Rare class of core-collapse supernovae?

The Basics of Chemical Evolution

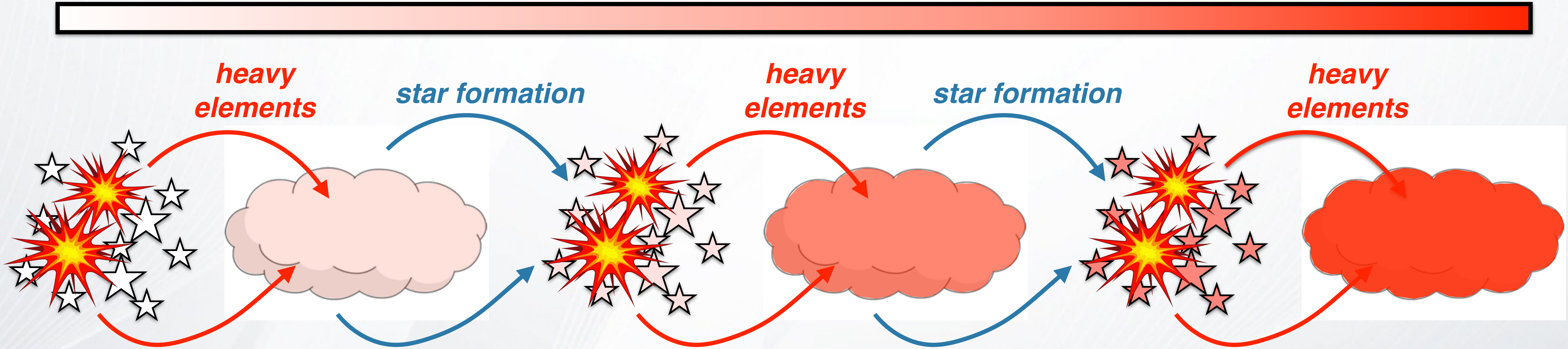
Select to add a body text box.



The Basics of Chemical Evolution



*higher **concentration** of heavy element (metallicity)*



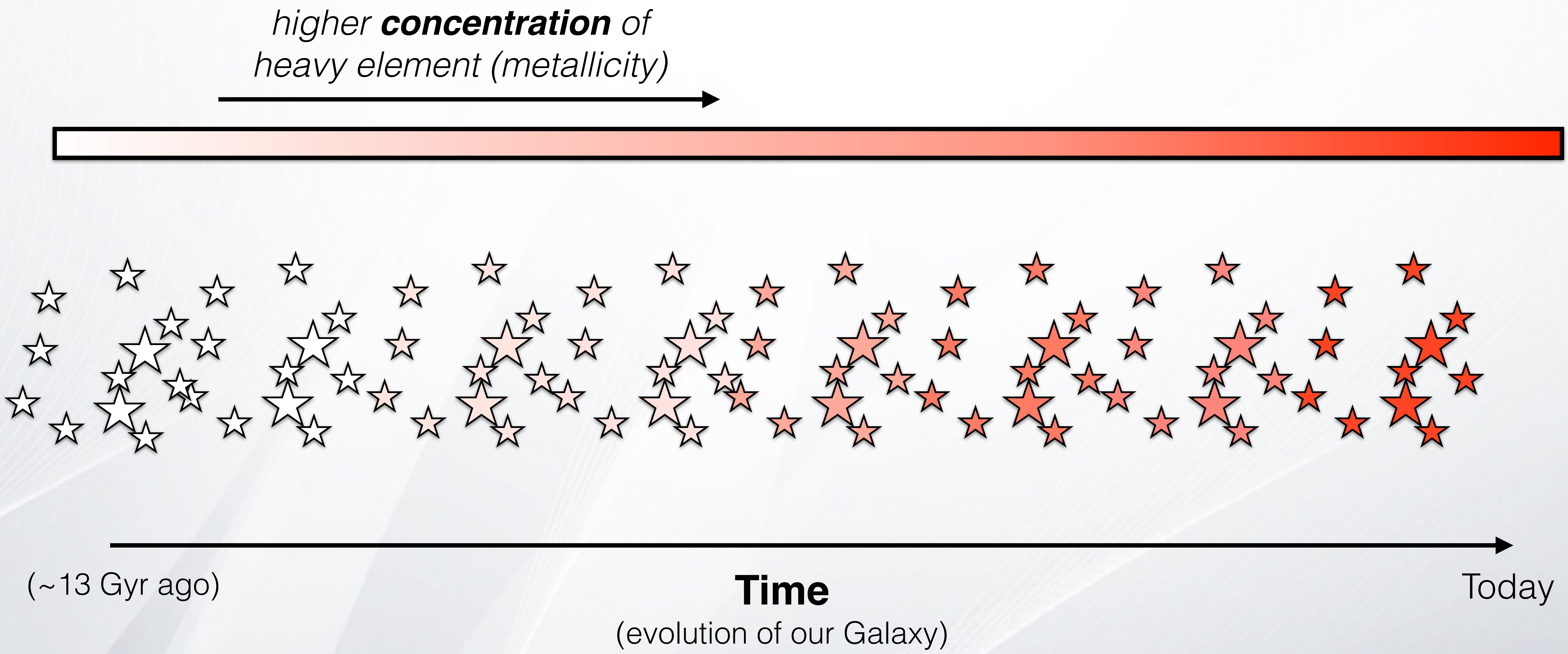
(~13 Gyr ago)

Time

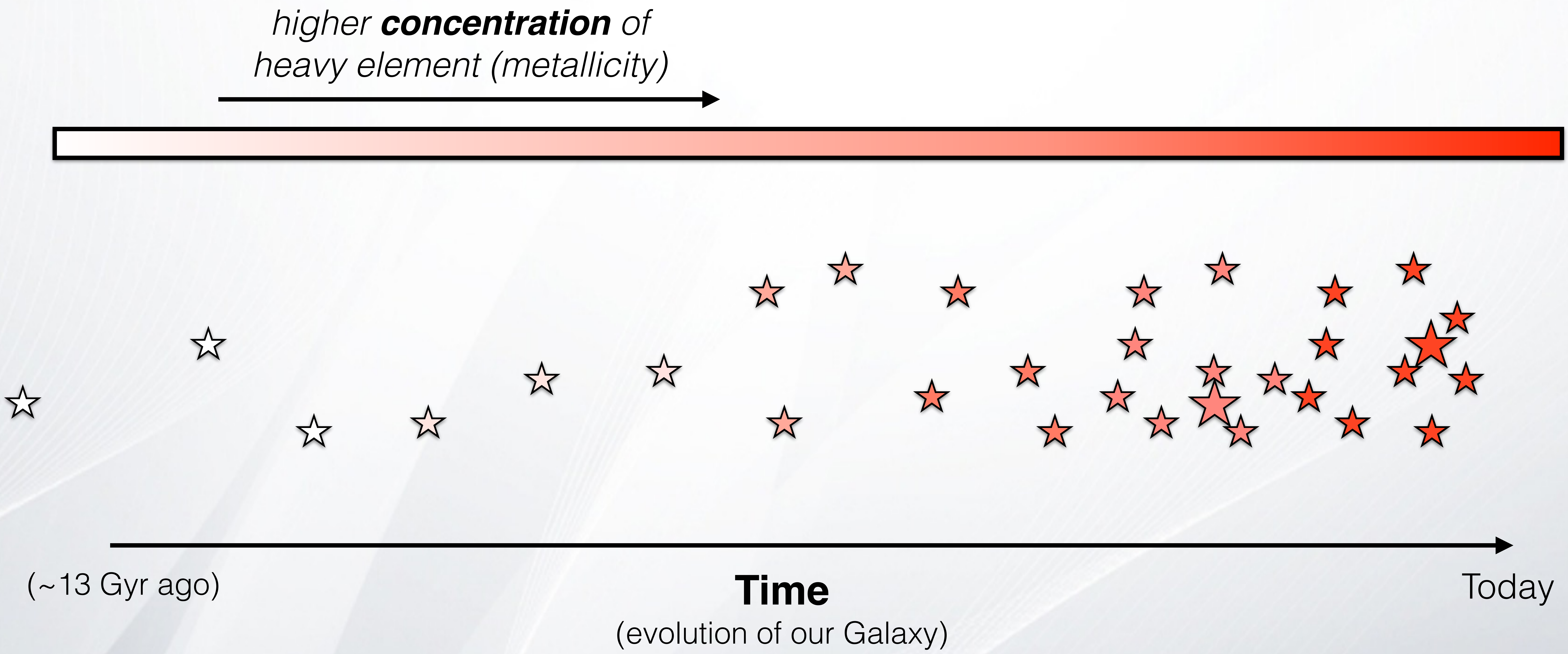
(evolution of our Galaxy)

Today

The Basics of Chemical Evolution

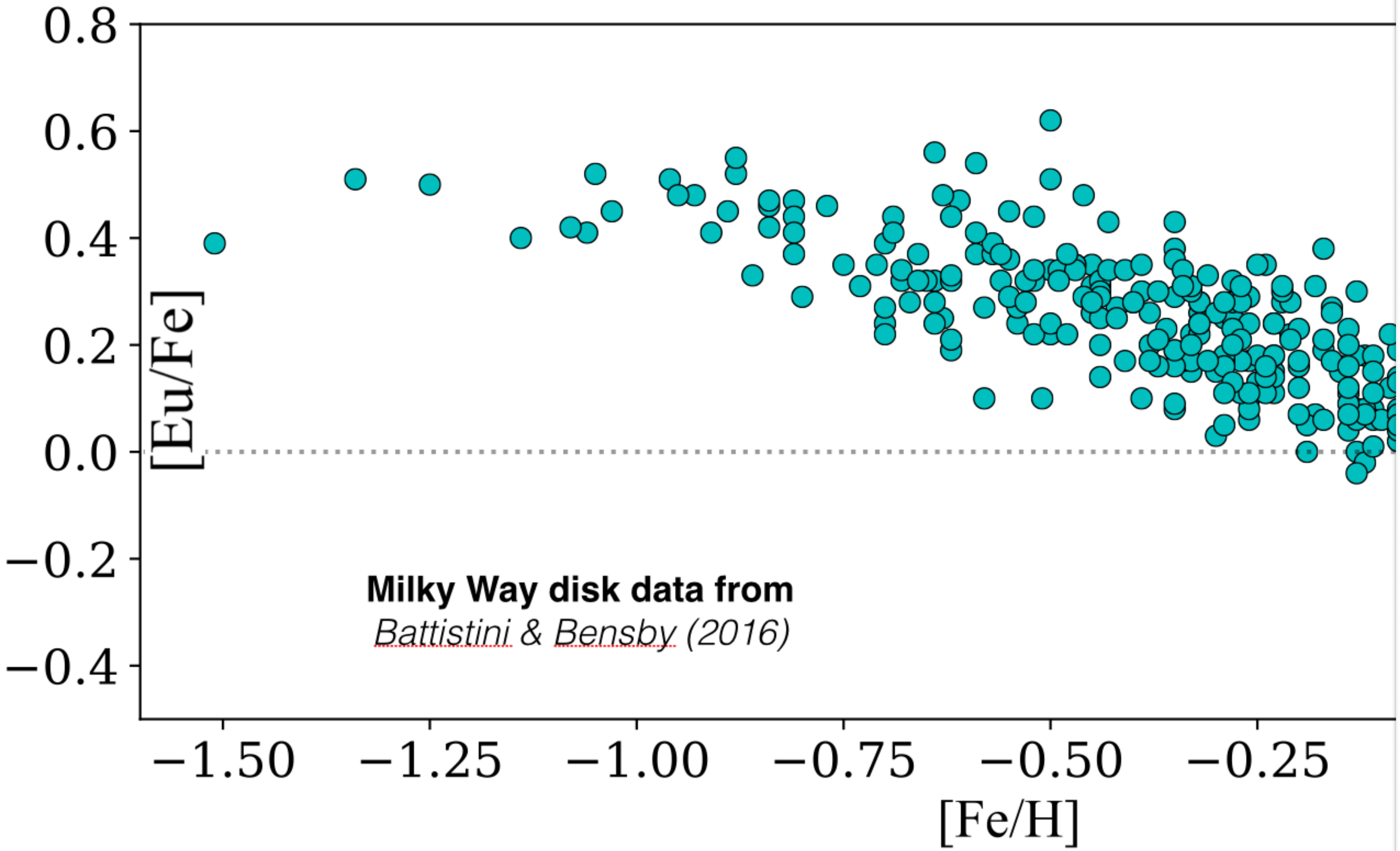


The Basics of Chemical Evolution

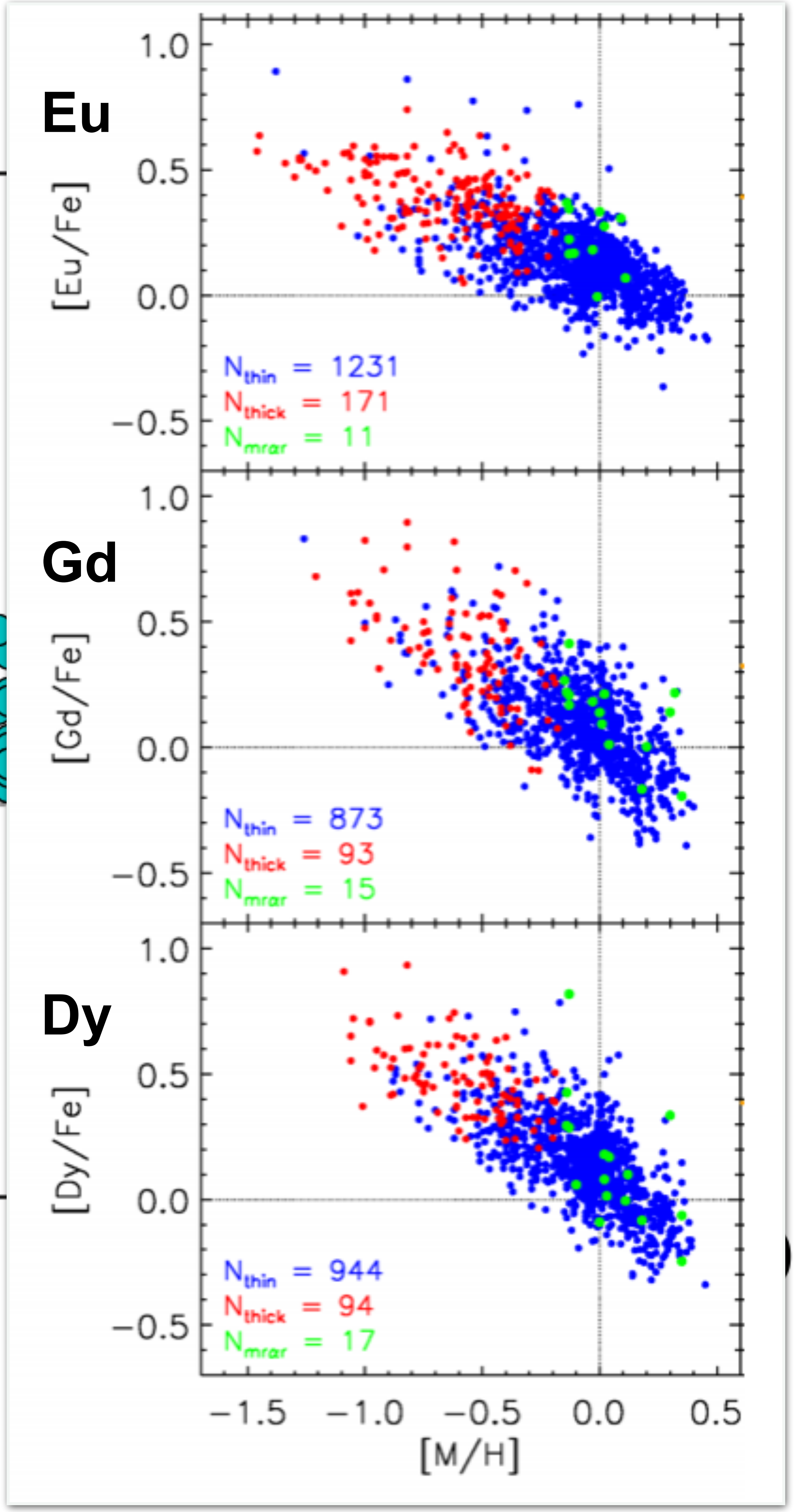


How to « Observe » Chemical Evolution?

Chemical Evolution in the Disk of our Milky Way Galaxy

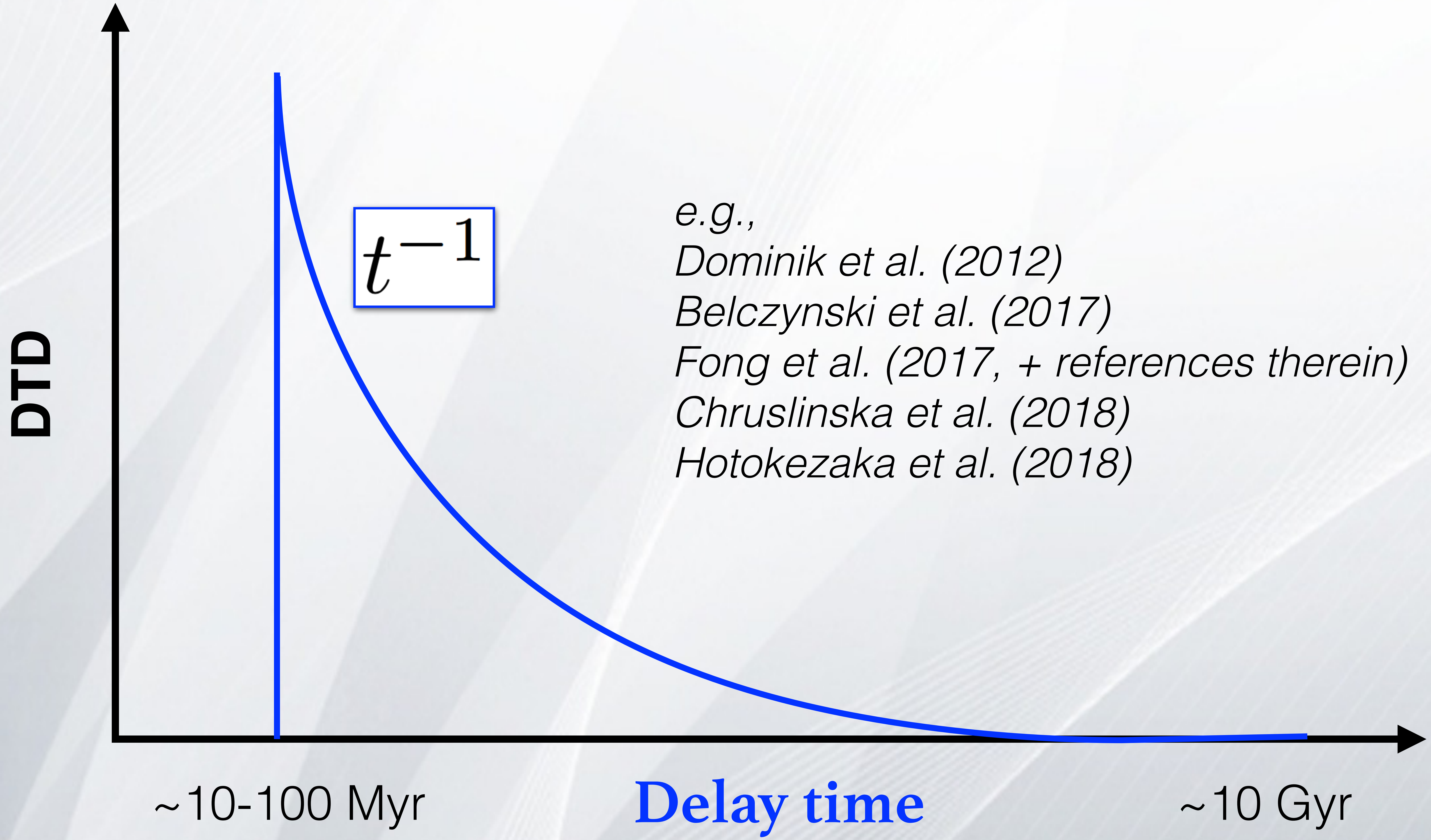


Guiglion et al. (2018)



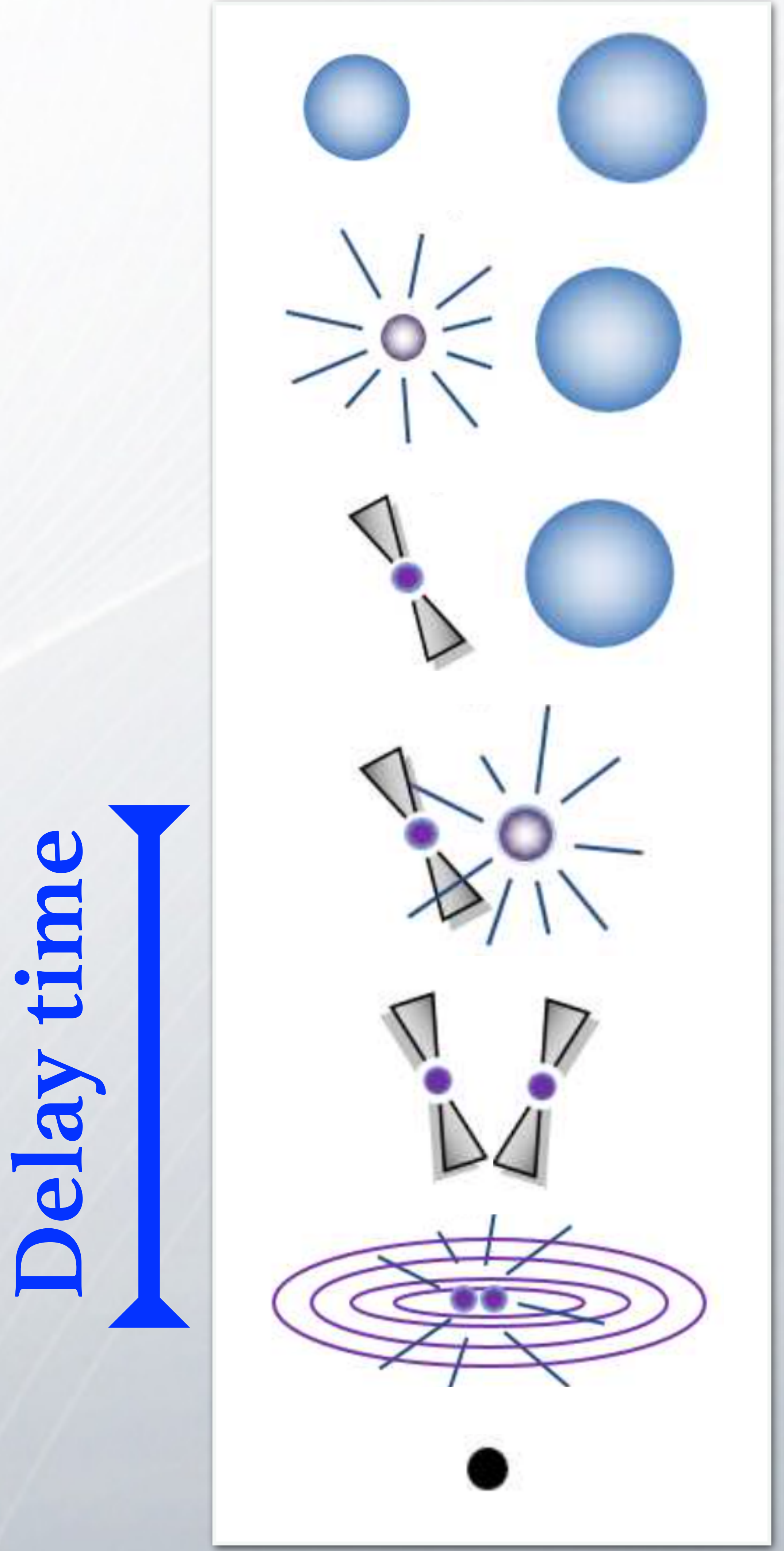
Delay-Time Distribution (**DTD**) Function of Neutron Star Mergers

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

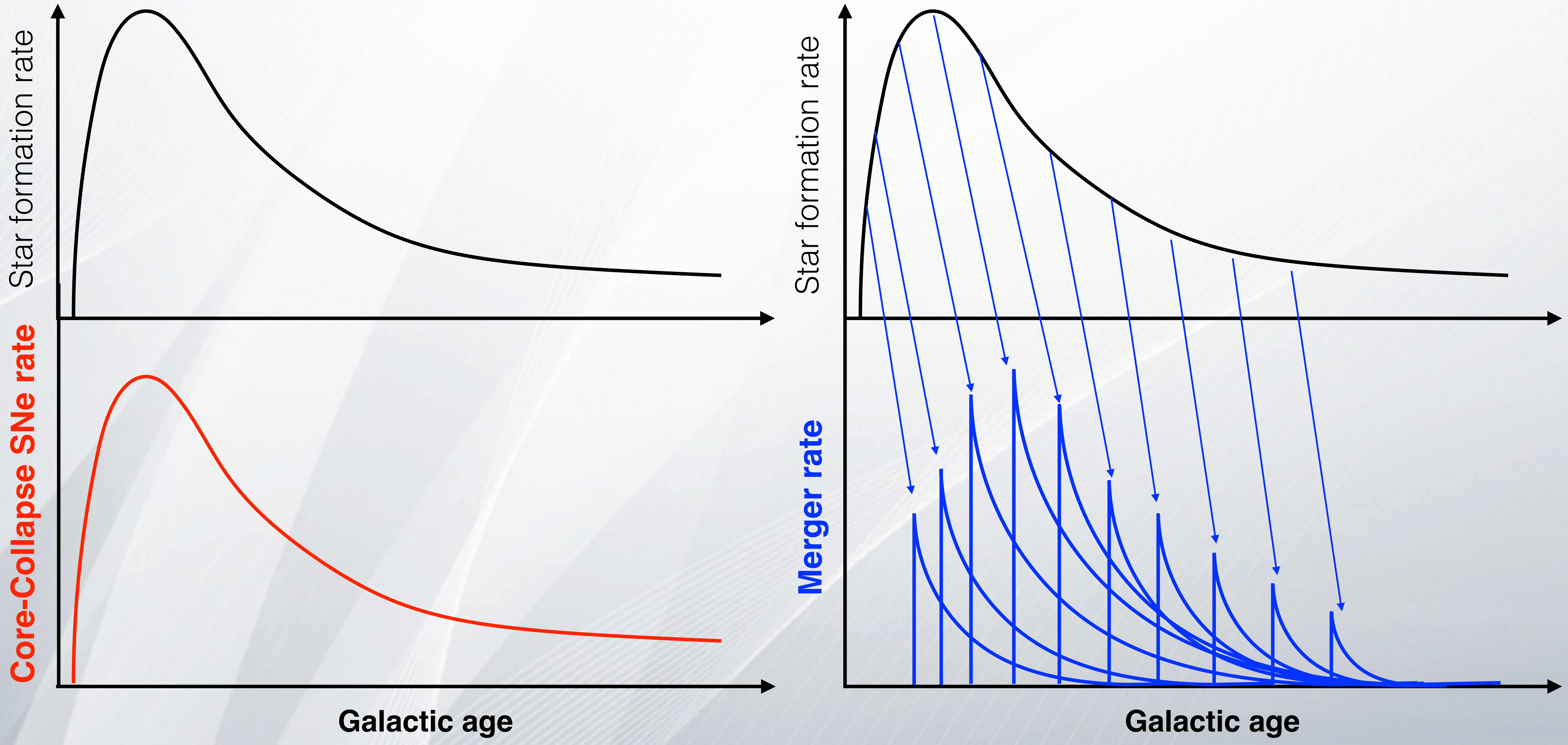


e.g.,
Dominik et al. (2012)
Belczynski et al. (2017)
Fong et al. (2017, + references therein)
Chruslinska et al. (2018)
Hotokezaka et al. (2018)

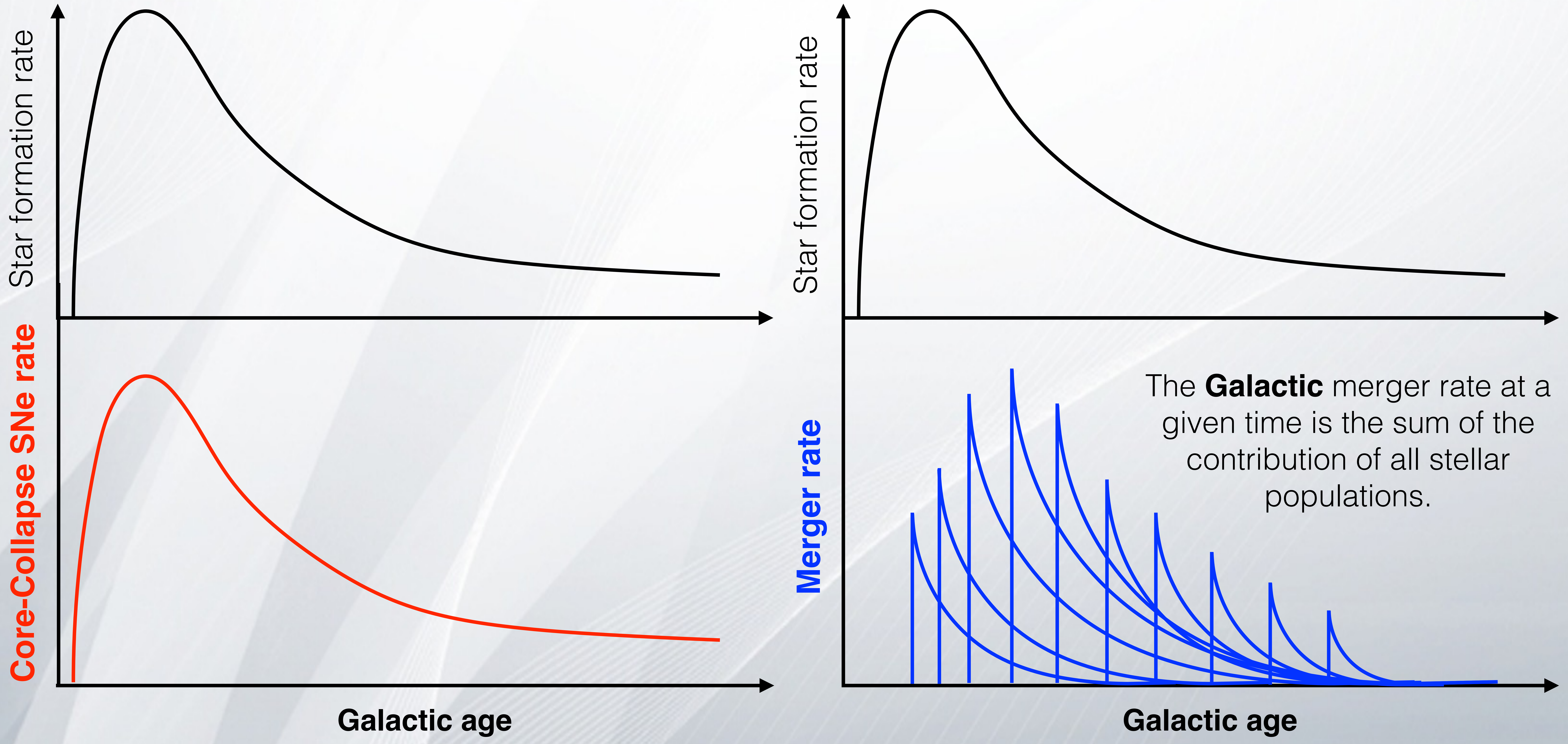
Image built from
Tauris et al. (2017)



Delay-Time Distribution Functions in Chemical Evolution Codes



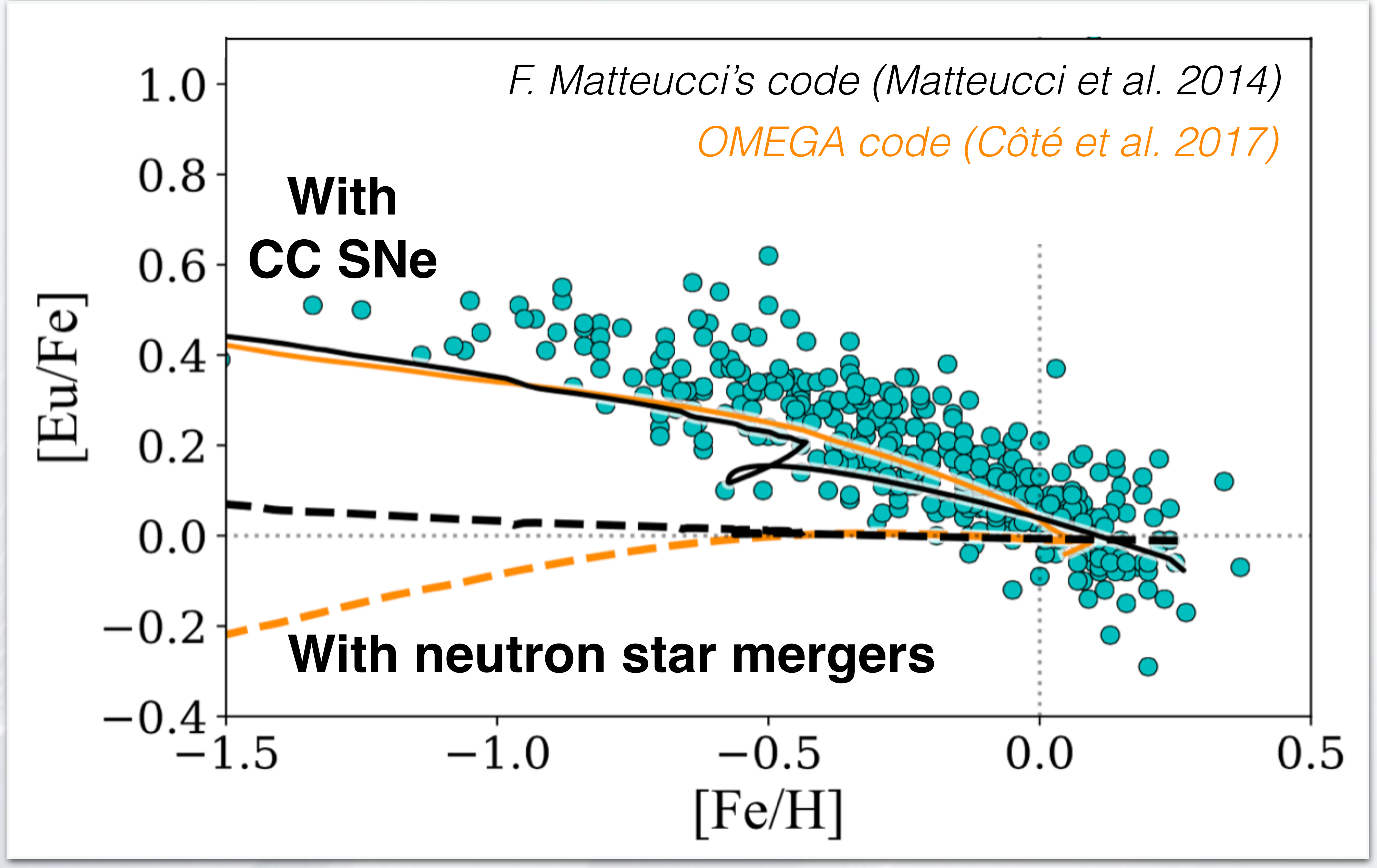
Delay-Time Distribution Functions in Chemical Evolution Codes



The **Galactic** merger rate at a given time is the sum of the contribution of all stellar populations.

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)

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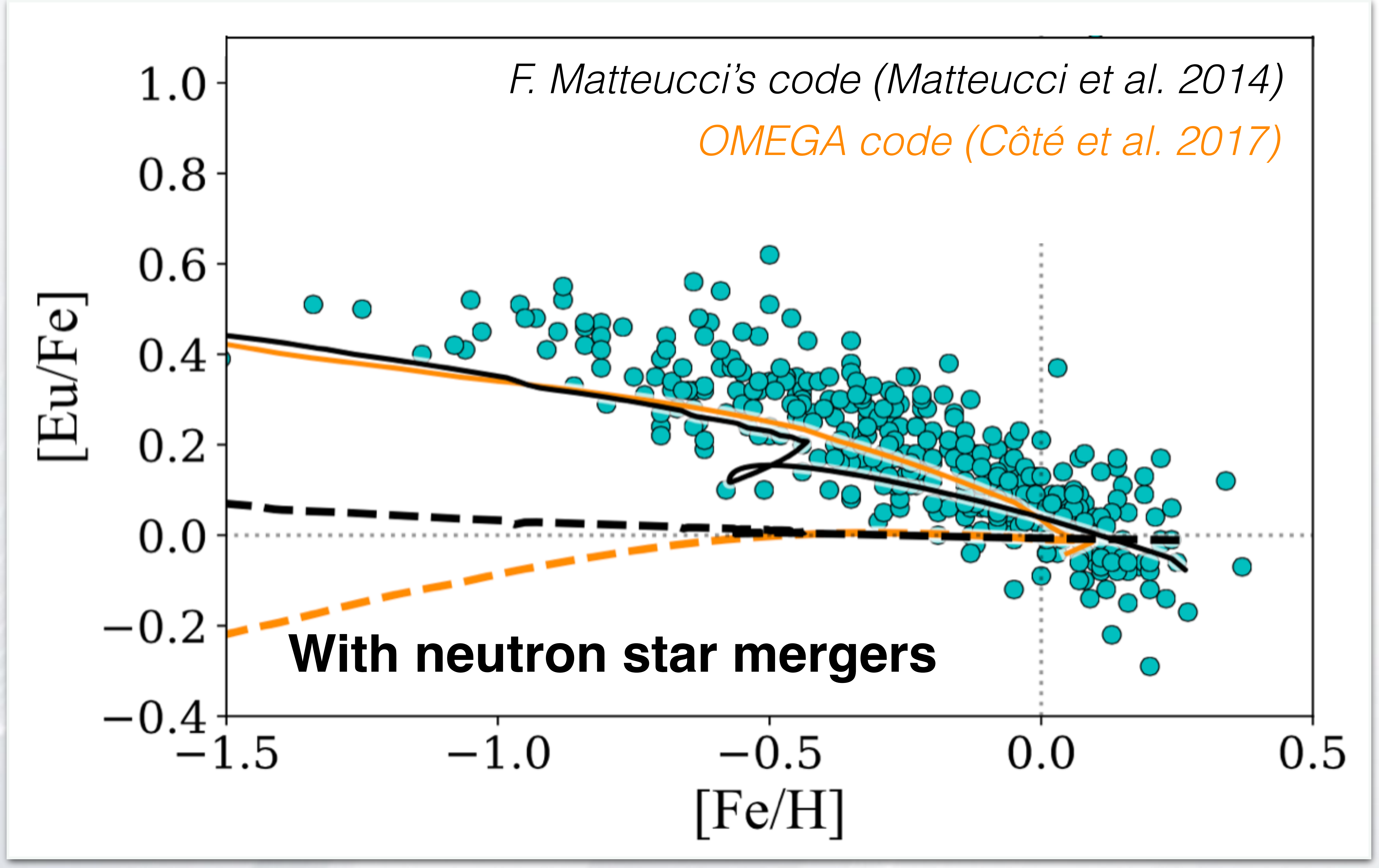
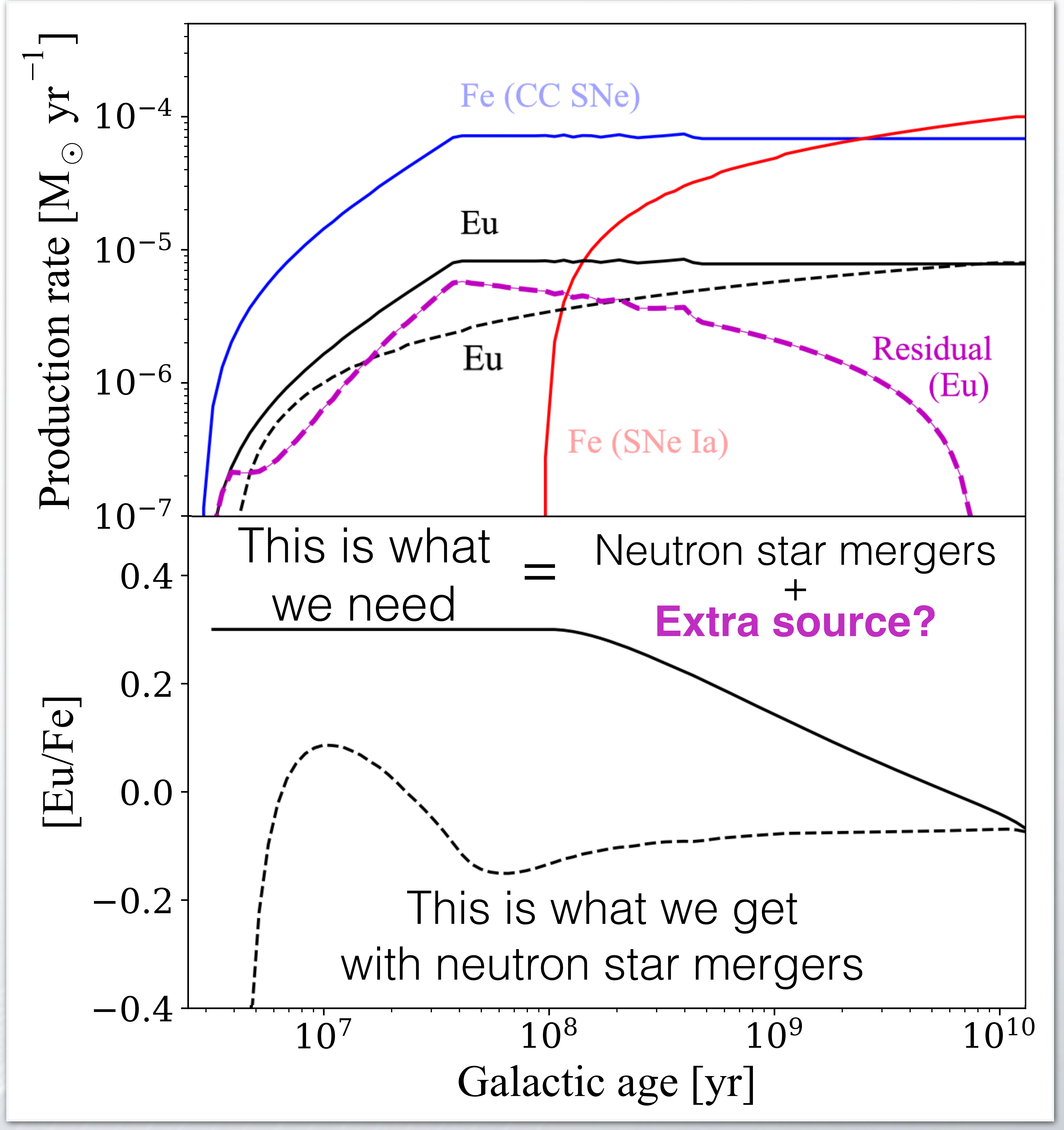


Côté, Eichler, Arcones, et al. (2019)

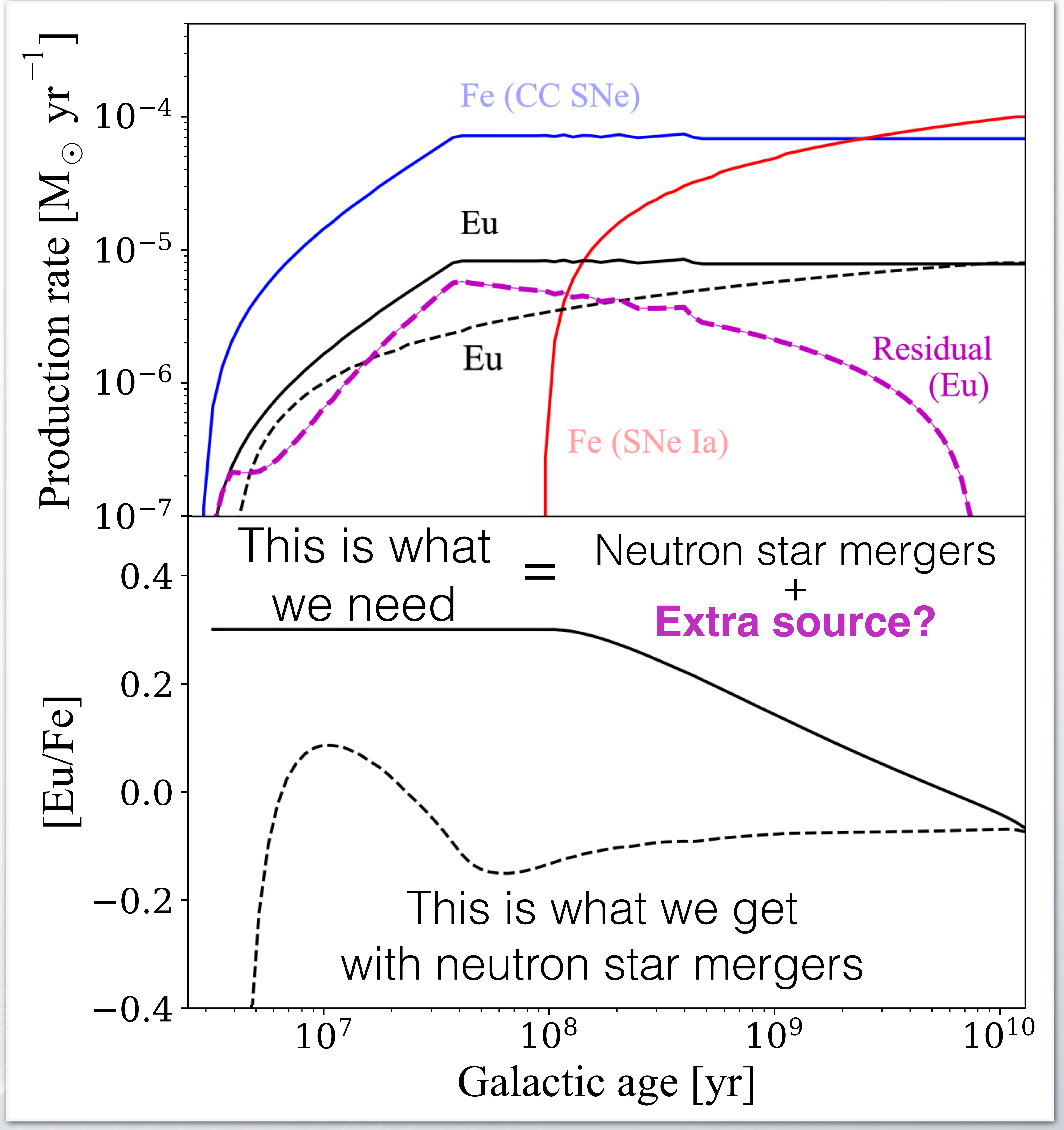


How Can we Fit the Decreasing Chemical Evolution Trend?

Côté, Eichler, Arcones, et al. (2019)

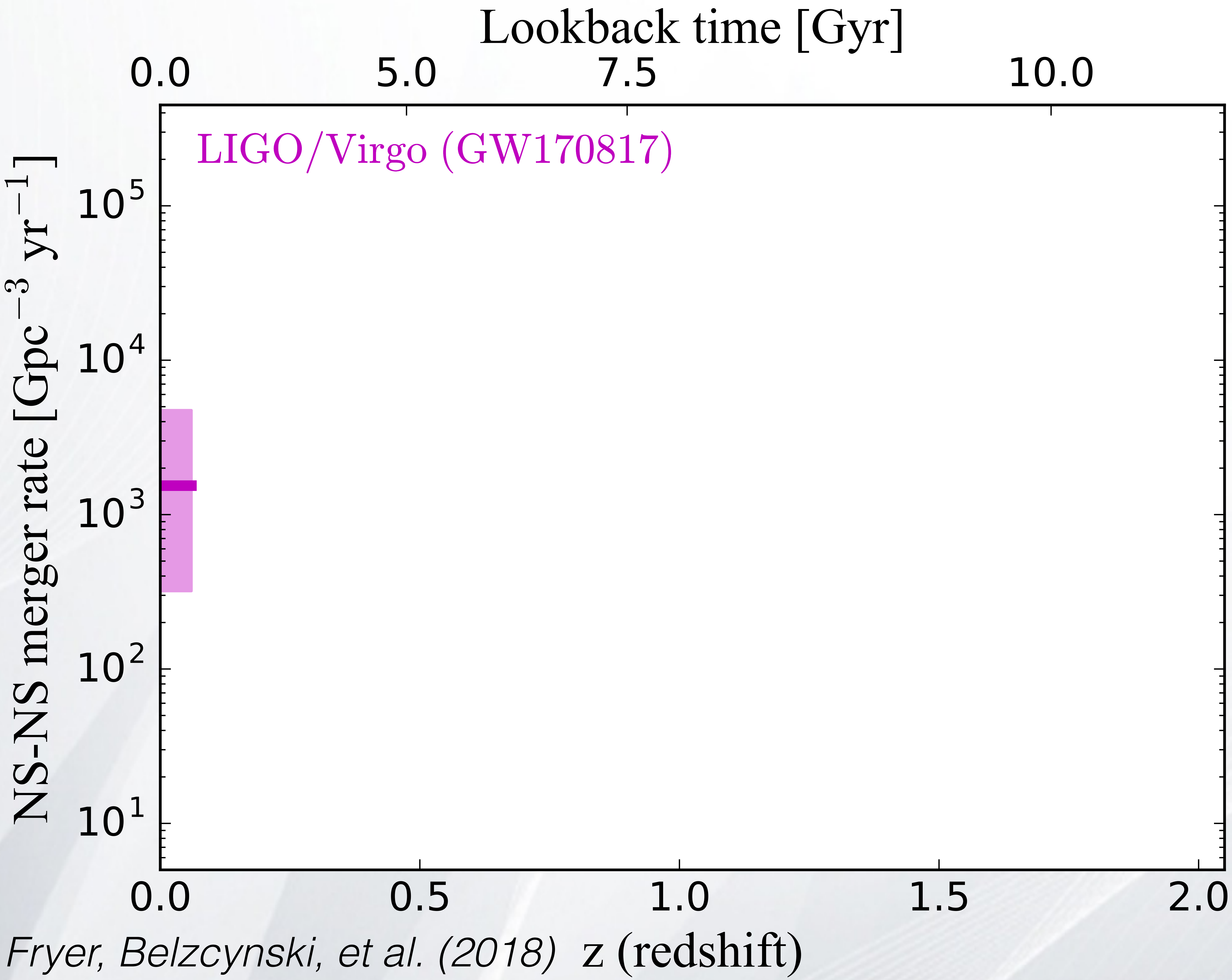
Two r-process sites in the early Universe?

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. (2019)



The Origin of *r*-process Elements in the Milky Way *(2018)*

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)

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)
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Haynes & Kobayashi (2019)
Simonetti et al. (2019)
...

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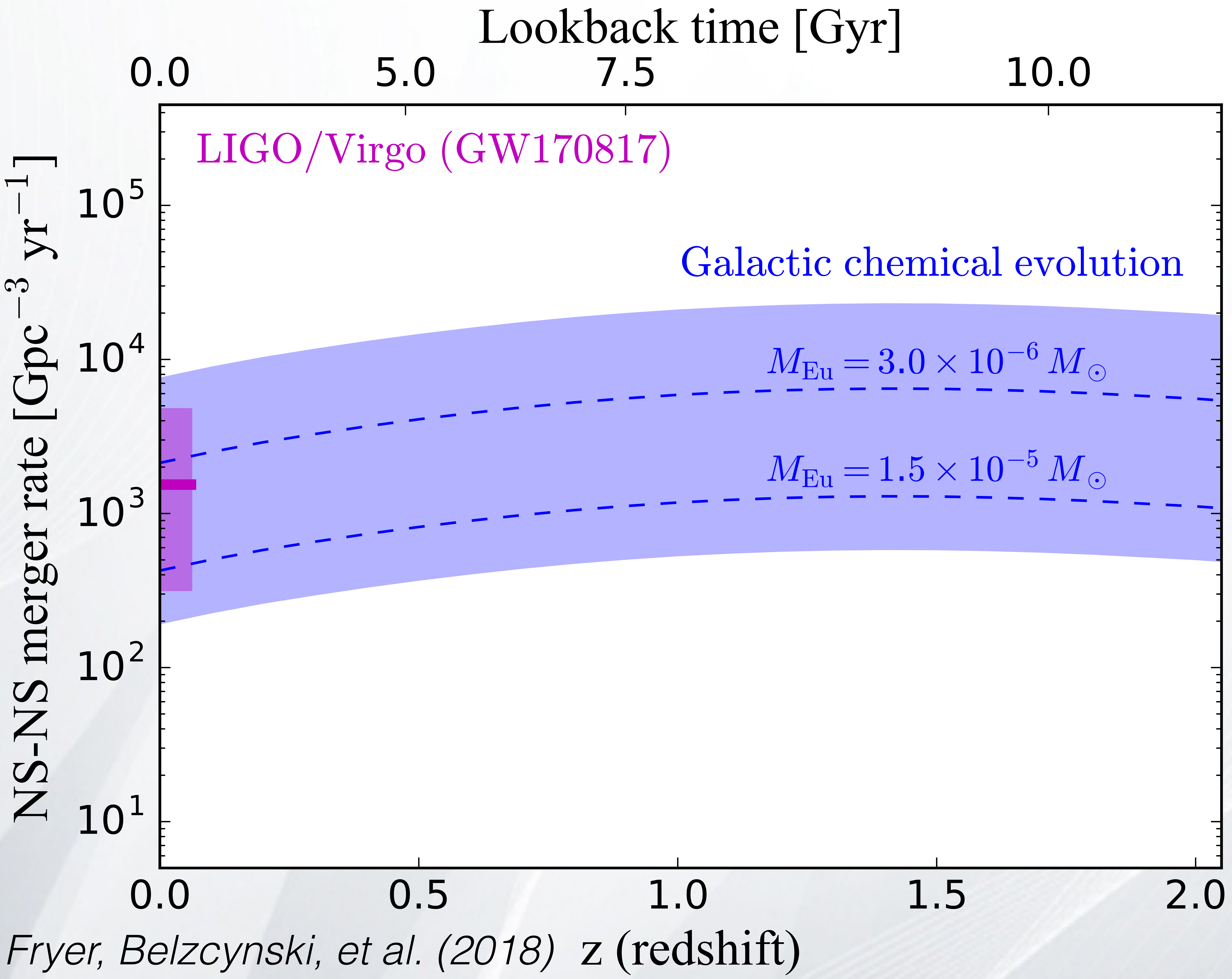
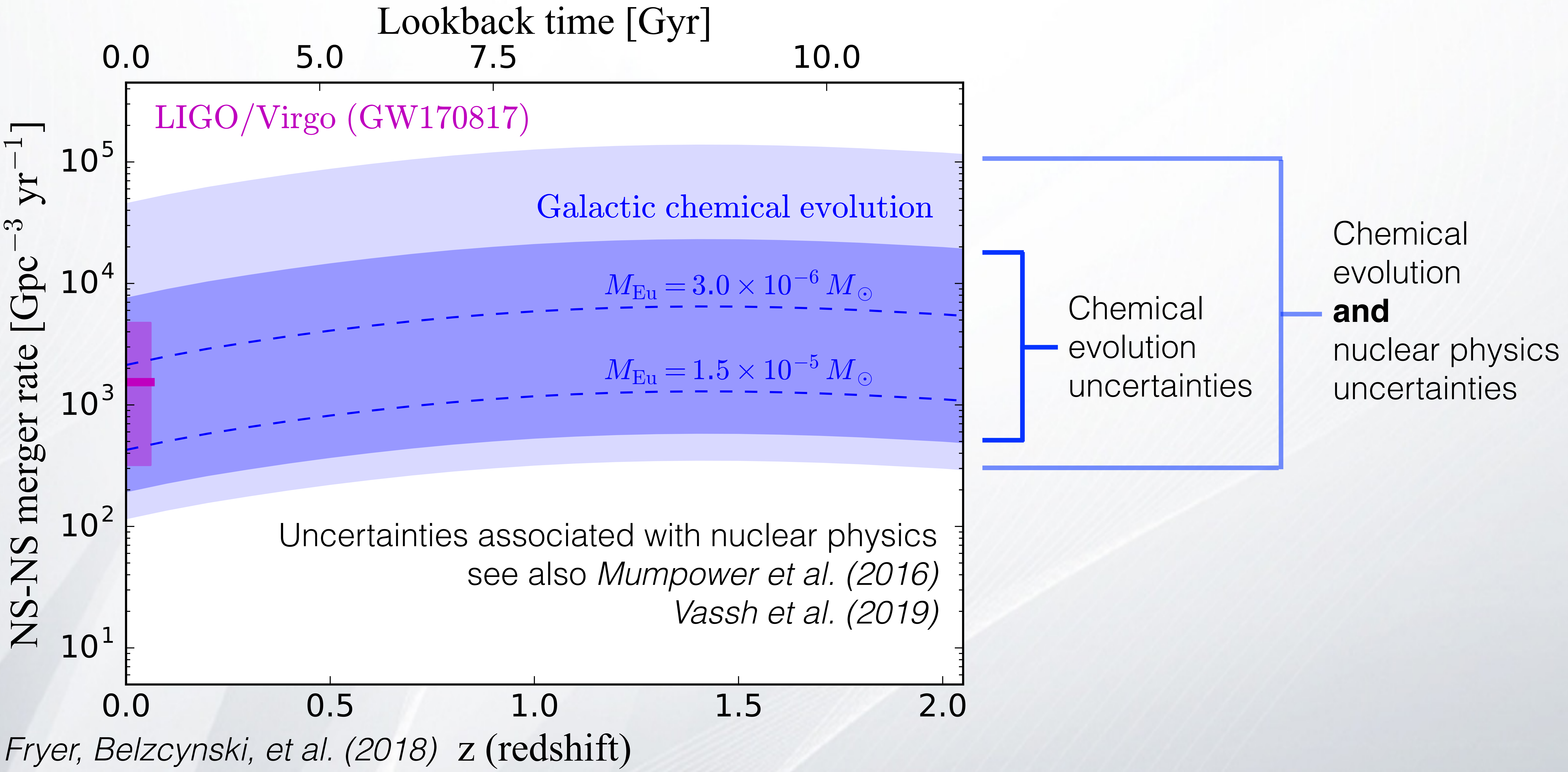


Côté, Fryer, Belczynski, et al. (2018)

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)

The Origin of *r*-process Elements in the Milky Way *(2018)*

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)

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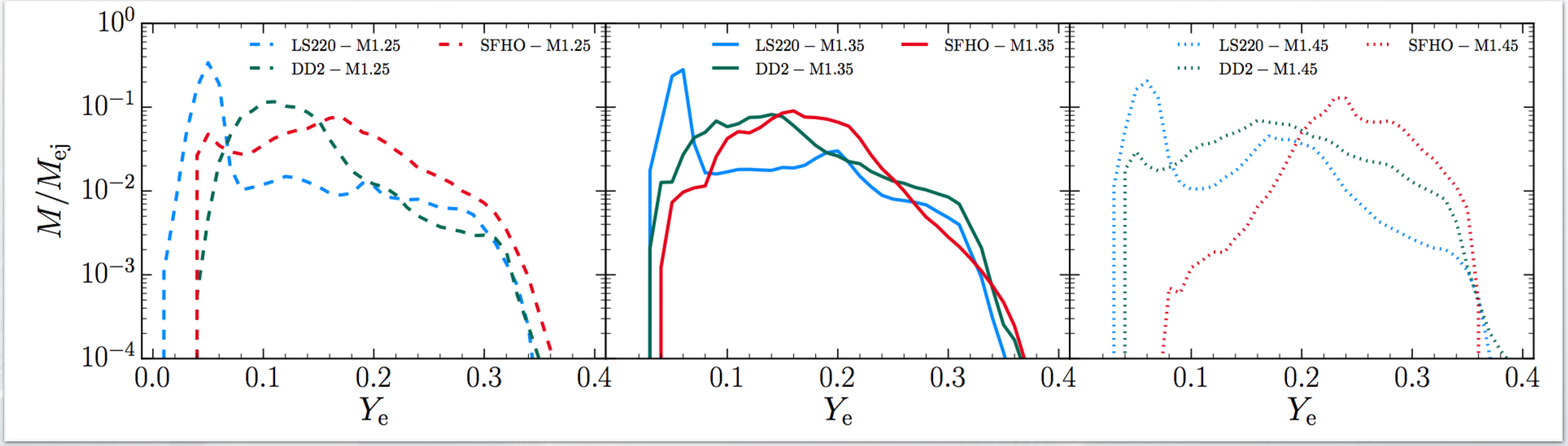
Kodama & Takahashi (1975; left panels) symmetric split (right panels)

Calculations by Nicole Vassh

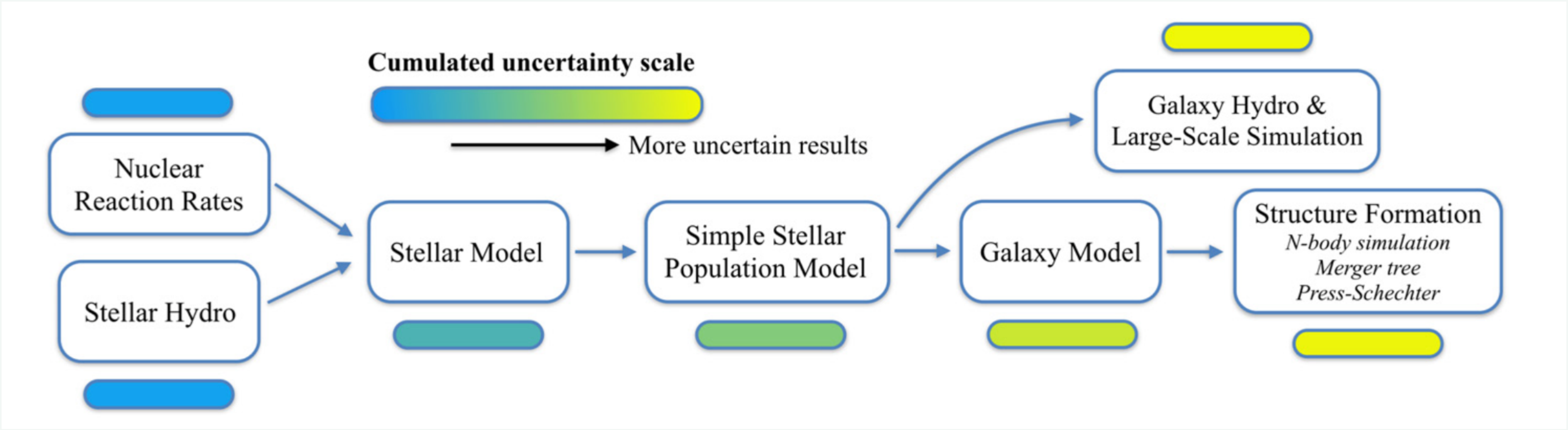
The Impact of the Equation of State on the Physical Conditions

Bovard et al. (2017)



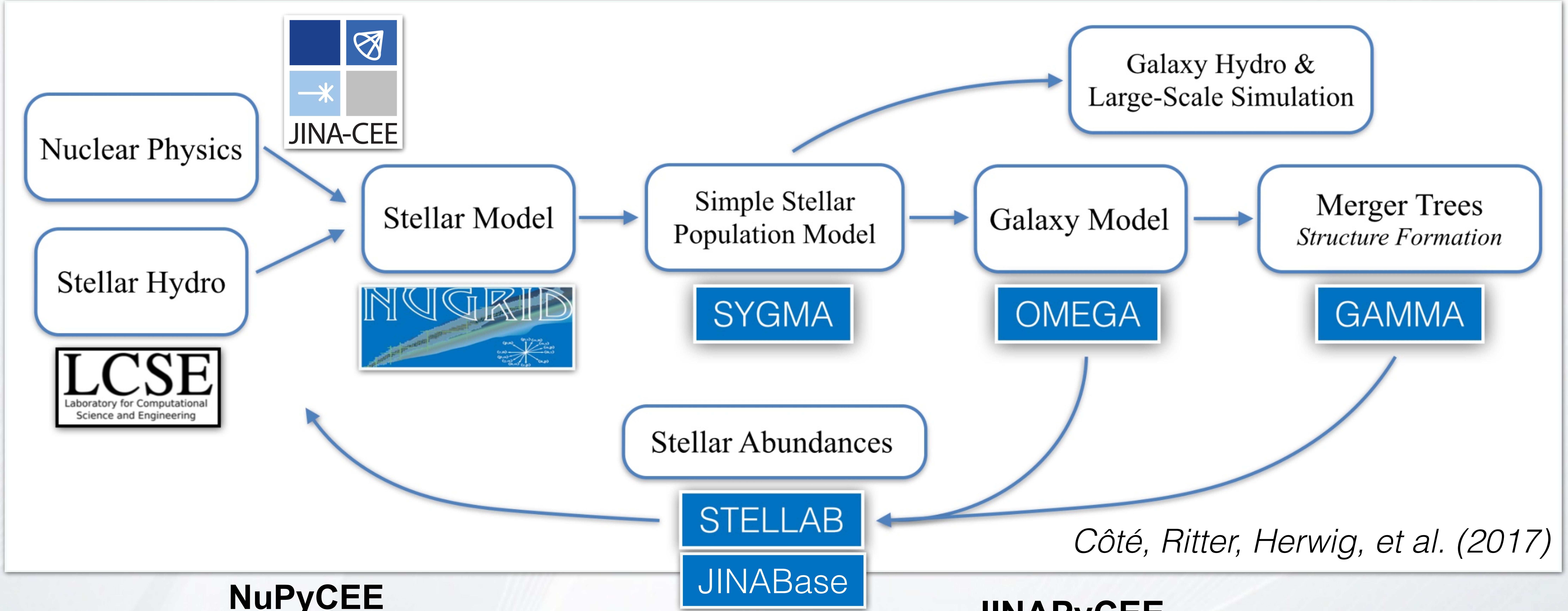
Propagation of Uncertainties from Nuclear to Astronomical Scale

Côté, Ritter, O'Shea, et al. (2016)



Connecting Nuclear Astrophysics to Cosmological Scales

Open-source codes



NuPyCEE
https://github.com/NuGrid/NuPyCEE

SYGMA (Ritter, Côté, Herwig, et al. 2017, submitted)
Stellar Yields for Galactic Modeling Applications

OMEGA (Côté, O'Shea, Ritter, et al. 2017)
One-zone Model for the Evolution of Galaxies

STELLAB for high-Z (Côté & Ritter 2016)
JINABase for low-Z (Abohalima & Frebel, 2018)

JINAPyCEE
https://github.com/becot85/JINAPyCEE

OMEGA+ (Côté, Silvia, O'Shea, et al. 2018)
Two-zone model based on OMEGA

GAMMA (Côté, Silvia, O'Shea, et al. 2018)
Galaxy Assembly with Merger-trees for Modeling Abundances, based on OMEGA+

See also
ChemPy: Rykizki(2017)
flexCE: Andrews (2017)
CELib: Saitoh (2017)

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