



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



# The Impact of Nuclear Astrophysics on Chemical Evolution Predictions

**Benoit Côté**

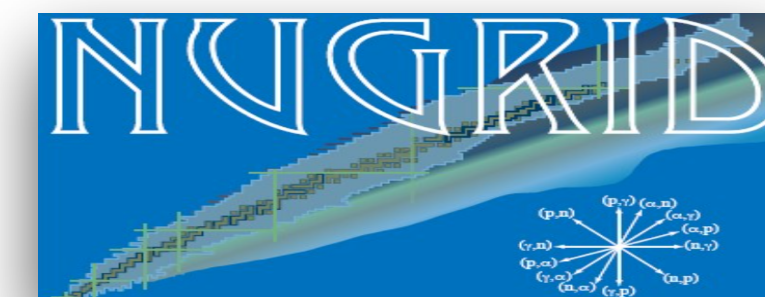
Research Staff at Konkoly Observatory (Hungary)

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

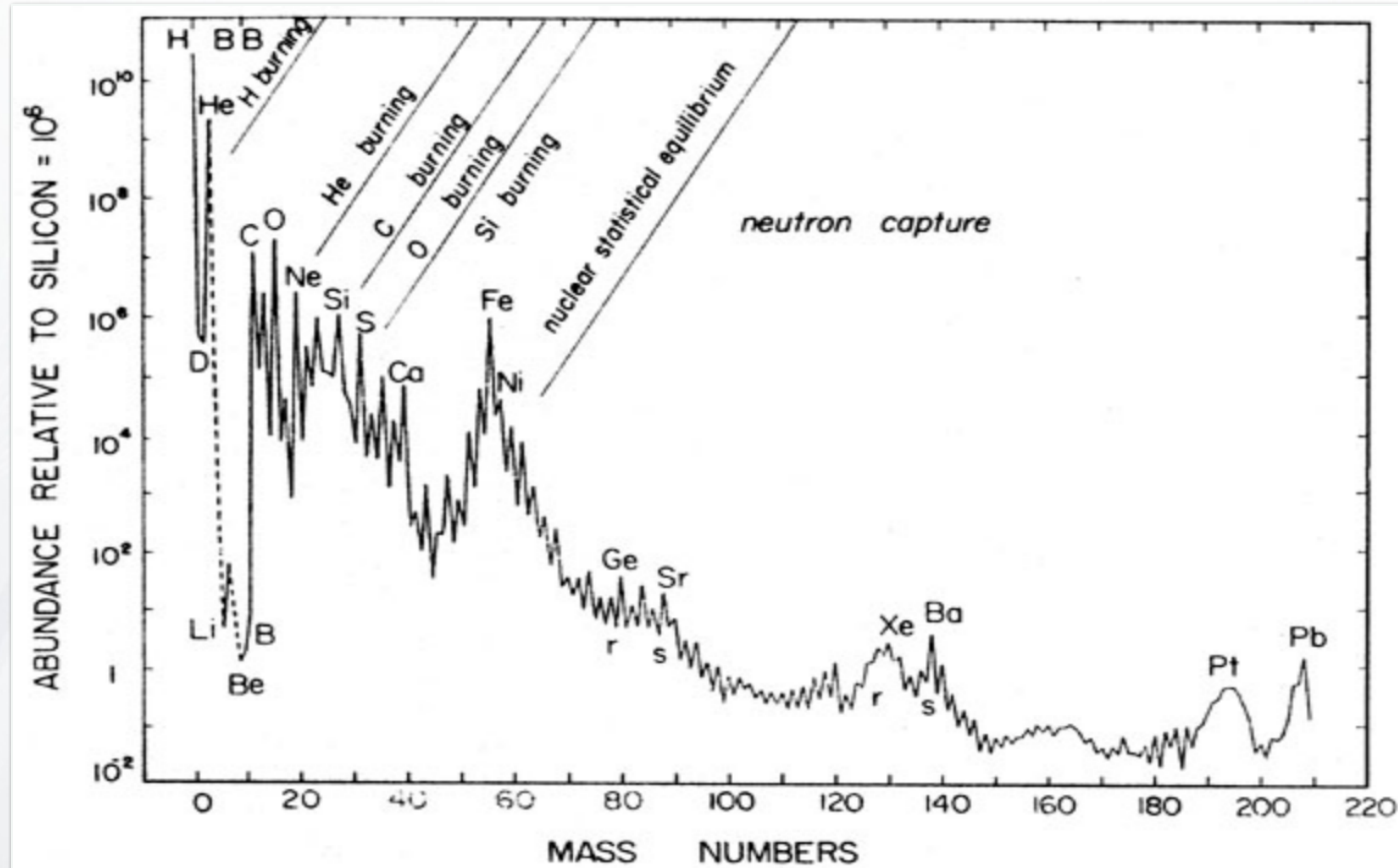
**Periodic Table of the Elements**

Atomic Number  
 Symbol  
 Name  
 Atomic Mass

1 IA 1A	2 IIA 2A											13 IIIA 3A	14 IVA 4A	15 VA 5A	16 VIA 6A	17 VIIA 7A	18 VIIIA 8A						
1 <b>H</b> Hydrogen 1.008																	2 <b>He</b> Helium 4.003						
3 <b>Li</b> Lithium 6.941	4 <b>Be</b> Beryllium 9.012																	5 <b>B</b> Boron 10.811	6 <b>C</b> Carbon 12.011	7 <b>N</b> Nitrogen 14.007	8 <b>O</b> Oxygen 15.999	9 <b>F</b> Fluorine 18.998	10 <b>Ne</b> Neon 20.180
11 <b>Na</b> Sodium 22.990	12 <b>Mg</b> Magnesium 24.305	3 IIIB 3B	4 IVB 4B	5 VB 5B	6 VIB 6B	7 VIIB 7B	8 VIII 8	9 VIII 8	10 VIII 8	11 IB 1B	12 IIB 2B	13 <b>Al</b> Aluminum 26.982	14 <b>Si</b> Silicon 28.086	15 <b>P</b> Phosphorus 30.974	16 <b>S</b> Sulfur 32.066	17 <b>Cl</b> Chlorine 35.453	18 <b>Ar</b> Argon 39.948						
19 <b>K</b> Potassium 39.098	20 <b>Ca</b> Calcium 40.078	21 <b>Sc</b> Scandium 44.956	22 <b>Ti</b> Titanium 47.88	23 <b>V</b> Vanadium 50.942	24 <b>Cr</b> Chromium 51.996	25 <b>Mn</b> Manganese 54.938	26 <b>Fe</b> Iron 55.933	27 <b>Co</b> Cobalt 58.933	28 <b>Ni</b> Nickel 58.693	29 <b>Cu</b> Copper 63.546	30 <b>Zn</b> Zinc 65.39	31 <b>Ga</b> Gallium 69.732	32 <b>Ge</b> Germanium 72.61	33 <b>As</b> Arsenic 74.922	34 <b>Se</b> Selenium 78.09	35 <b>Br</b> Bromine 79.904	36 <b>Kr</b> Krypton 84.80						
37 <b>Rb</b> Rubidium 84.468	38 <b>Sr</b> Strontium 87.62	39 <b>Y</b> Yttrium 88.906	40 <b>Zr</b> Zirconium 91.224	41 <b>Nb</b> Niobium 92.906	42 <b>Mo</b> Molybdenum 95.94	43 <b>Tc</b> Technetium 98.907	44 <b>Ru</b> Ruthenium 101.07	45 <b>Rh</b> Rhodium 102.906	46 <b>Pd</b> Palladium 106.42	47 <b>Ag</b> Silver 107.868	48 <b>Cd</b> Cadmium 112.411	49 <b>In</b> Indium 114.818	50 <b>Sn</b> Tin 118.71	51 <b>Sb</b> Antimony 121.760	52 <b>Te</b> Tellurium 127.6	53 <b>I</b> Iodine 126.904	54 <b>Xe</b> Xenon 131.29						
55 <b>Cs</b> Cesium 132.905	56 <b>Ba</b> Barium 137.327	57-71	72 <b>Hf</b> Hafnium 178.49	73 <b>Ta</b> Tantalum 180.948	74 <b>W</b> Tungsten 183.85	75 <b>Re</b> Rhenium 186.207	76 <b>Os</b> Osmium 190.23	77 <b>Ir</b> Iridium 192.22	78 <b>Pt</b> Platinum 195.08	79 <b>Au</b> Gold 196.967	80 <b>Hg</b> Mercury 200.59	81 <b>Tl</b> Thallium 204.383	82 <b>Pb</b> Lead 207.2	83 <b>Bi</b> Bismuth 208.980	84 <b>Po</b> Polonium [208.982]	85 <b>At</b> Astatine 209.987	86 <b>Rn</b> Radon 222.018						
87 <b>Fr</b> Francium 223.020	88 <b>Ra</b> Radium 226.025	89-103	104 <b>Rf</b> Rutherfordium [261]	105 <b>Db</b> Dubnium [262]	106 <b>Sg</b> Seaborgium [266]	107 <b>Bh</b> Bohrium [264]	108 <b>Hs</b> Hassium [269]	109 <b>Mt</b> Meitnerium [268]	110 <b>Ds</b> Darmstadtium [269]	111 <b>Rg</b> Roentgenium [272]	112 <b>Cn</b> Copernicium [277]	113 <b>Uut</b> Ununtrium unknown	114 <b>Fl</b> Flerovium [289]	115 <b>Uup</b> Ununpentium unknown	116 <b>Lv</b> Livermorium [298]	117 <b>Uus</b> Ununseptium unknown	118 <b>Uuo</b> Ununoctium unknown						
Lanthanide Series		57 <b>La</b> Lanthanum 138.906	58 <b>Ce</b> Cerium 140.115	59 <b>Pr</b> Praseodymium 140.908	60 <b>Nd</b> Neodymium 144.24	61 <b>Pm</b> Promethium 144.913	62 <b>Sm</b> Samarium 150.36	63 <b>Eu</b> Europium 151.966	64 <b>Gd</b> Gadolinium 157.25	65 <b>Tb</b> Terbium 158.925	66 <b>Dy</b> Dysprosium 162.50	67 <b>Ho</b> Holmium 164.930	68 <b>Er</b> Erbium 167.26	69 <b>Tm</b> Thulium 168.934	70 <b>Yb</b> Ytterbium 173.04	71 <b>Lu</b> Lutetium 174.967							
Actinide Series		89 <b>Ac</b> Actinium 227.028	90 <b>Th</b> Thorium 232.038	91 <b>Pa</b> Protactinium 231.036	92 <b>U</b> Uranium 238.029	93 <b>Np</b> Neptunium 237.048	94 <b>Pu</b> Plutonium 244.064	95 <b>Am</b> Americium 243.061	96 <b>Cm</b> Curium 247.070	97 <b>Bk</b> Berkelium 247.070	98 <b>Cf</b> Californium 251.080	99 <b>Es</b> Einsteinium [254]	100 <b>Fm</b> Fermium 257.095	101 <b>Md</b> Mendelevium 258.1	102 <b>No</b> Nobelium 259.101	103 <b>Lr</b> Lawrencium [262]							

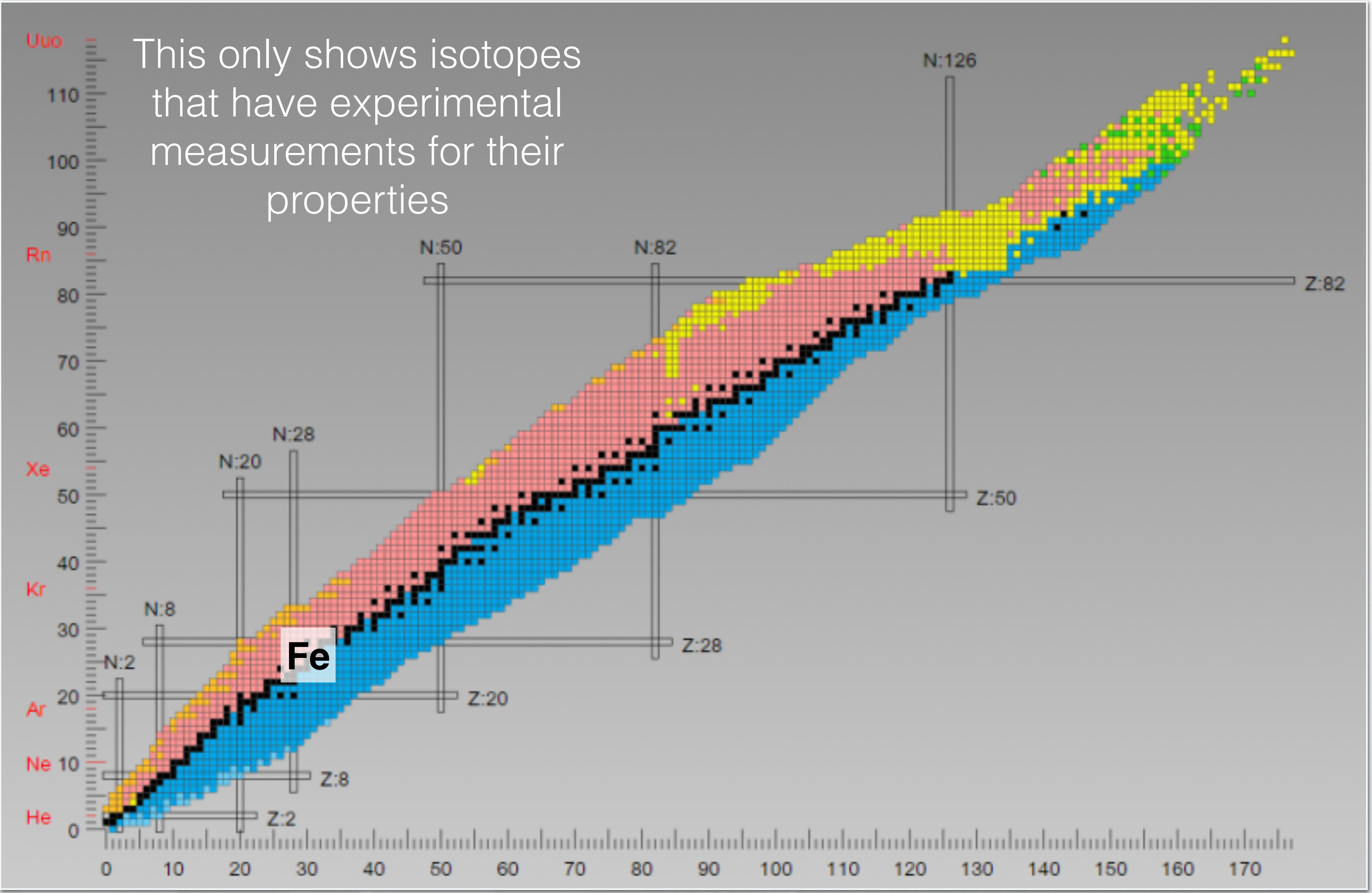
# Chemical Elements and Isotopes

Cameron (1982)



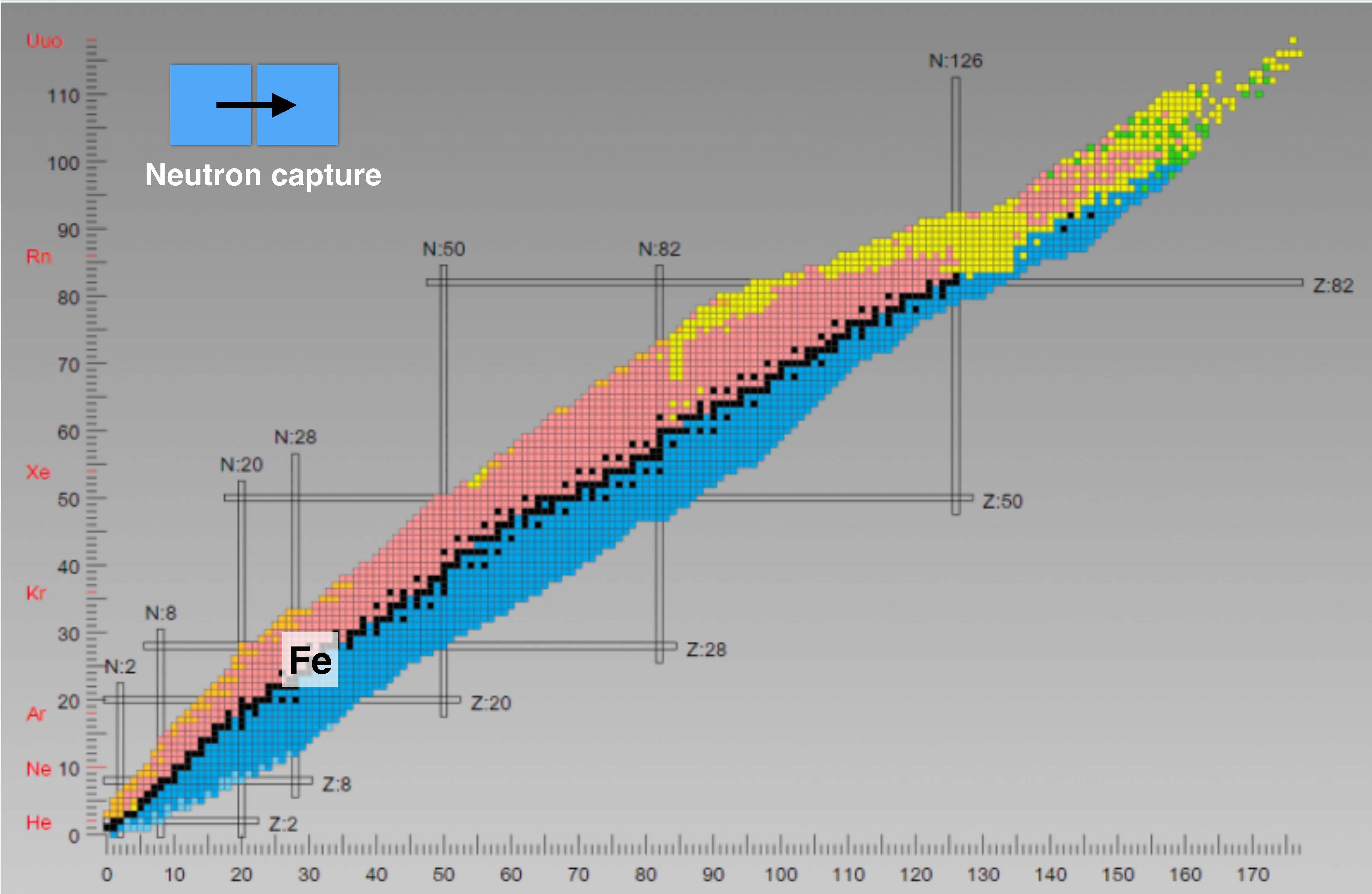
Number of **protons** ↑

This only shows isotopes that have experimental measurements for their properties



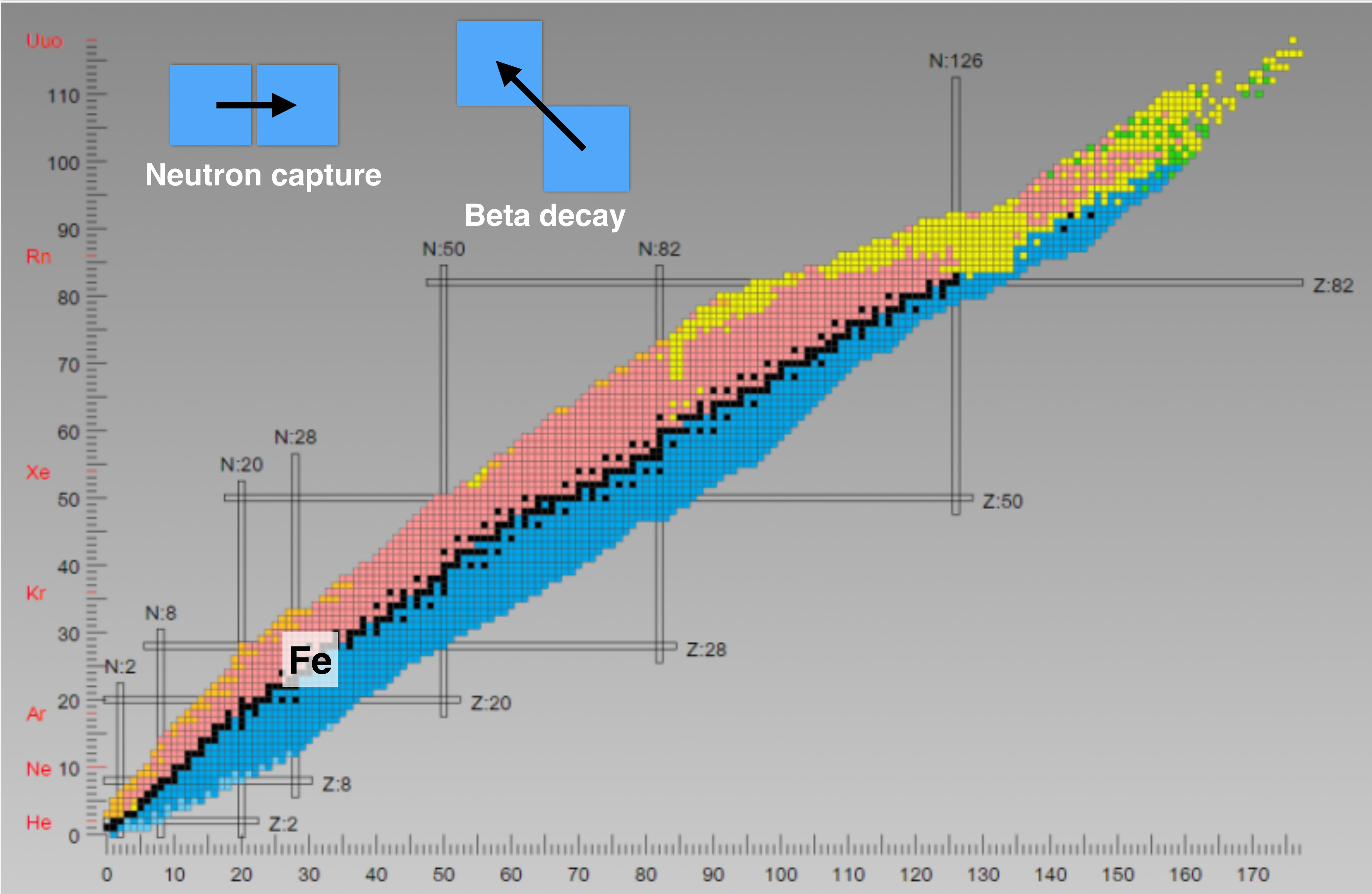
Number of **neutrons** →

Number of **protons** ↑



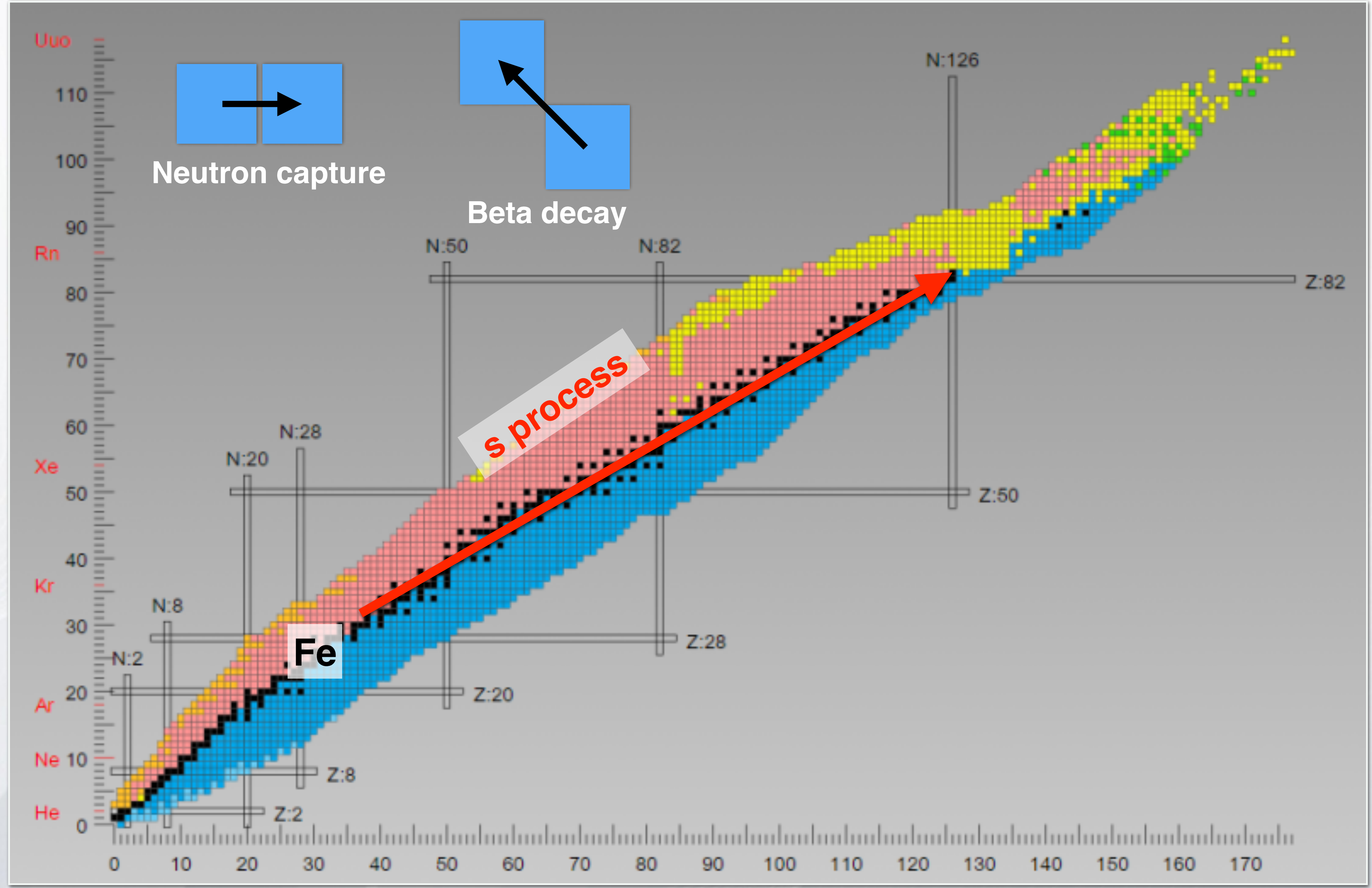
Number of **neutrons** →

Number of **protons** ↑



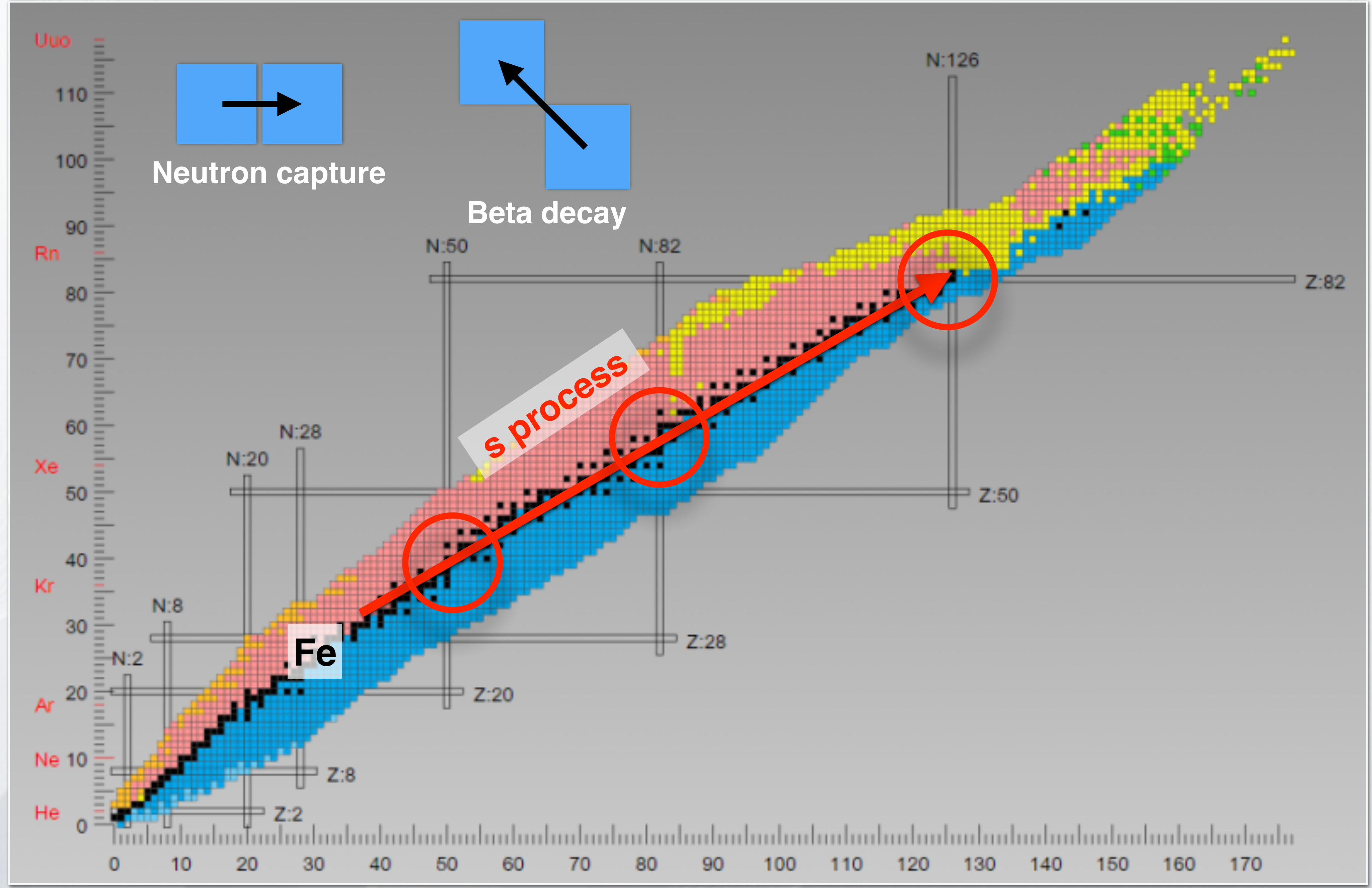
Number of **neutrons** →

Number of **protons** ↑



Number of **neutrons** →

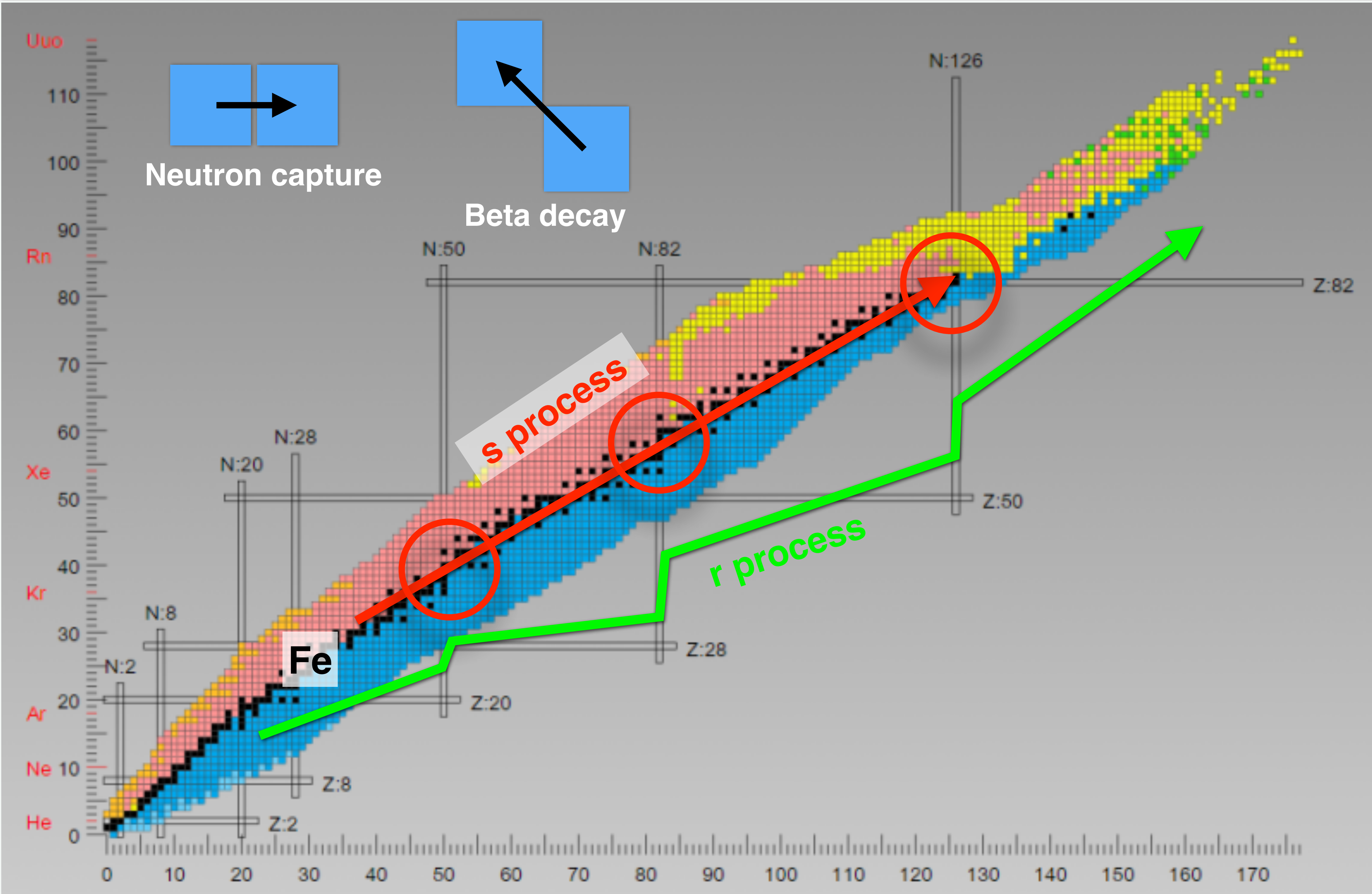
Number of **protons** ↑



Number of **neutrons** →



Number of **protons**



Neutron capture

Beta decay

s process

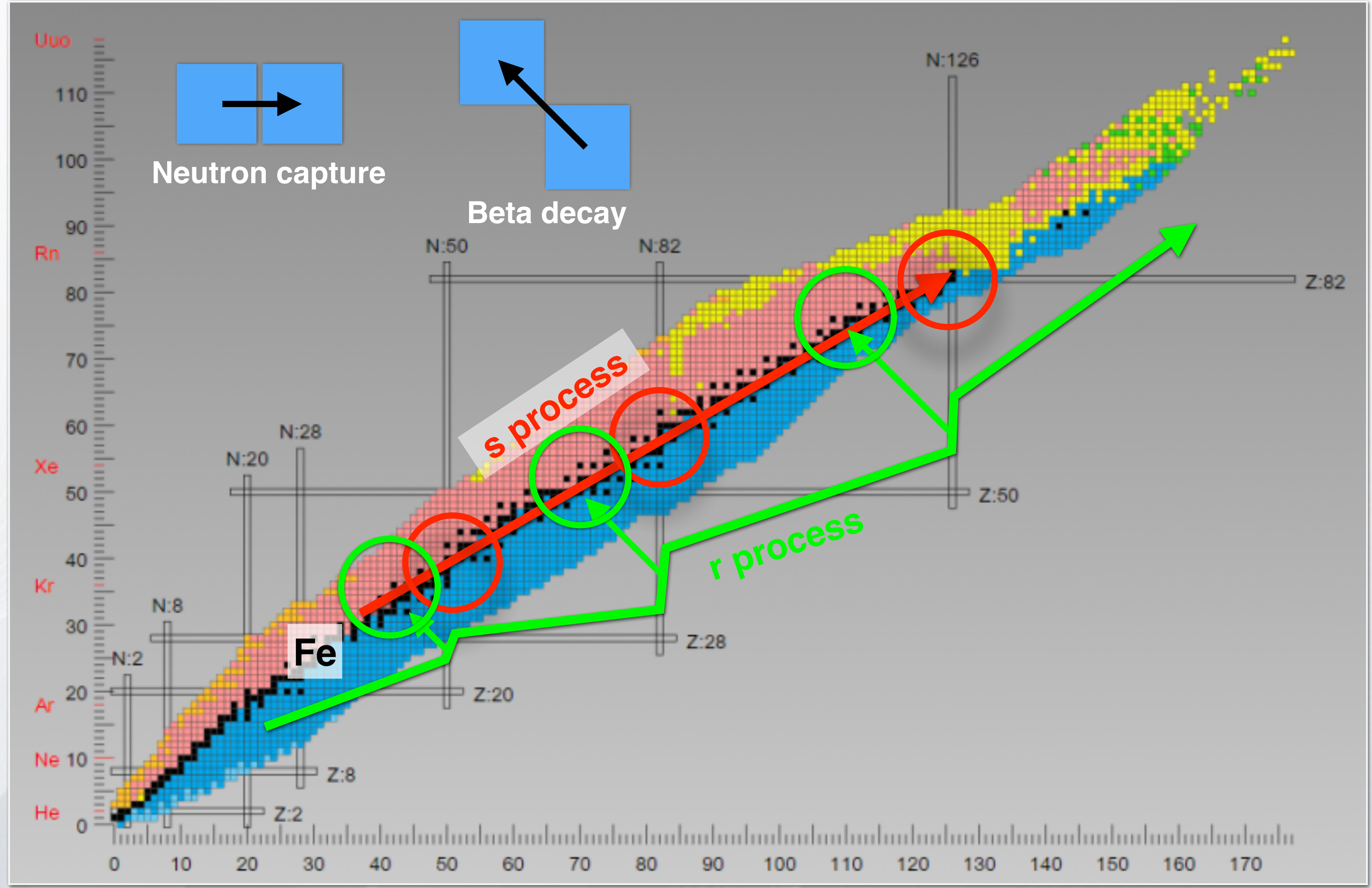
r process

Fe

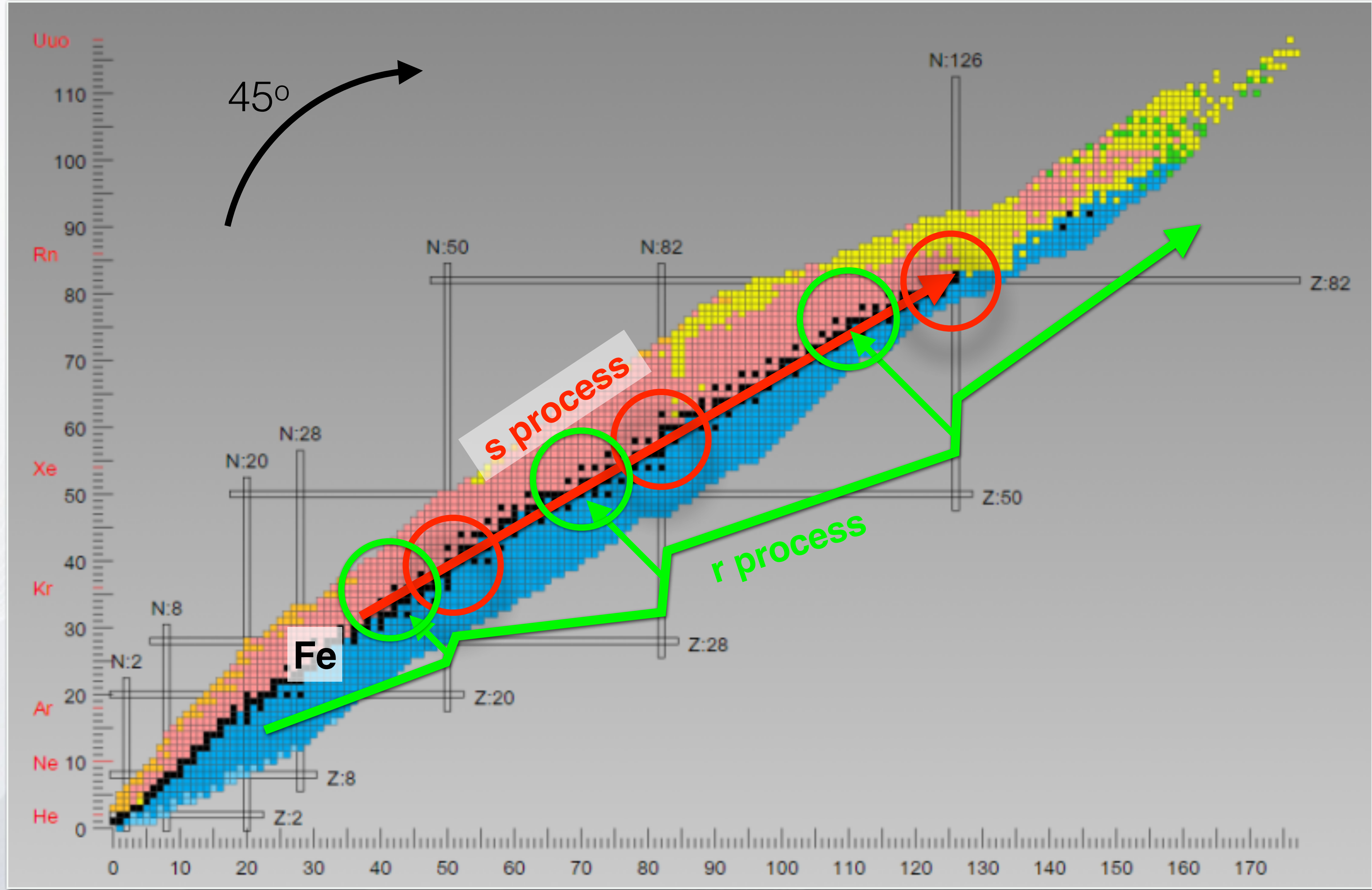
Number of **neutrons**

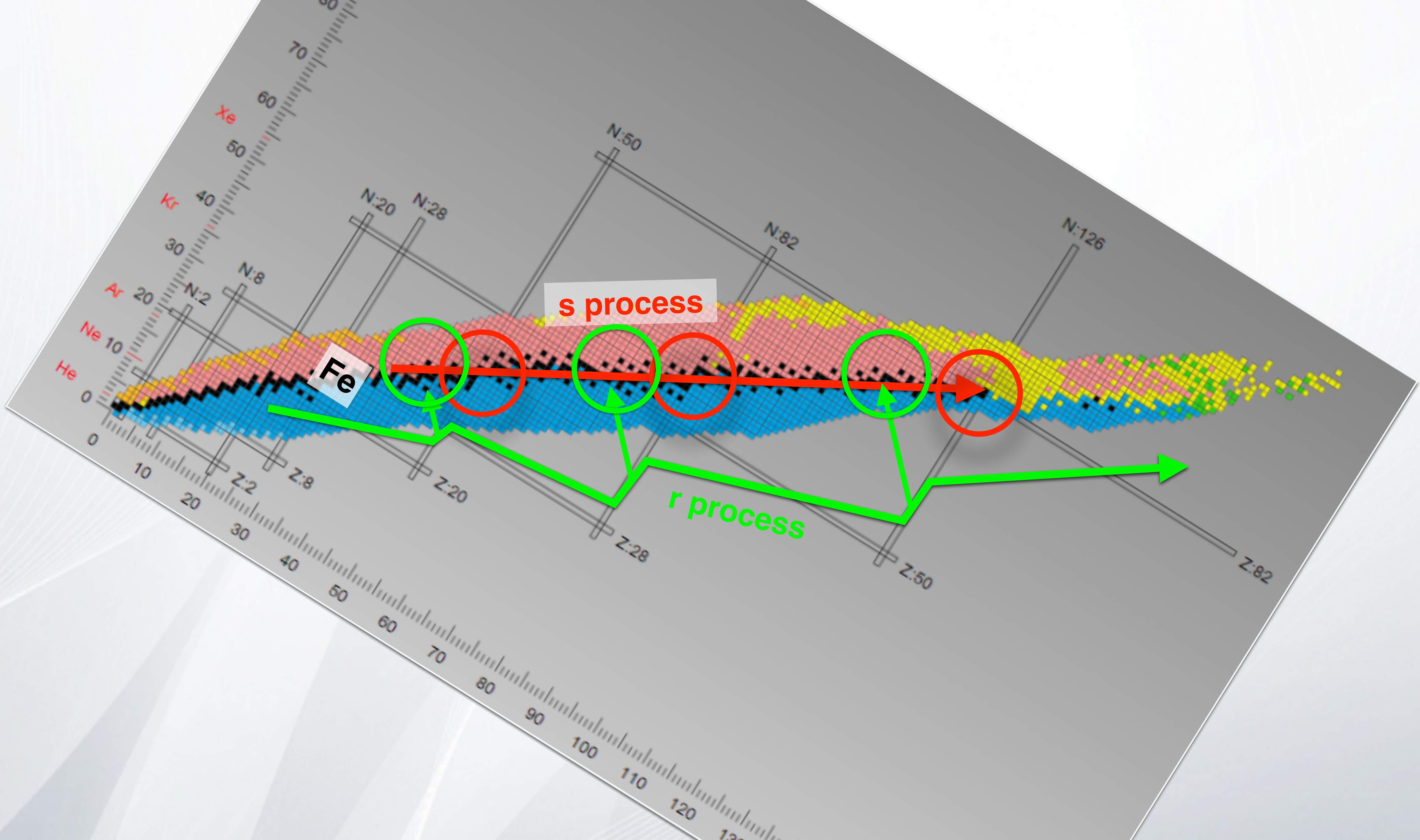
Wikipedia

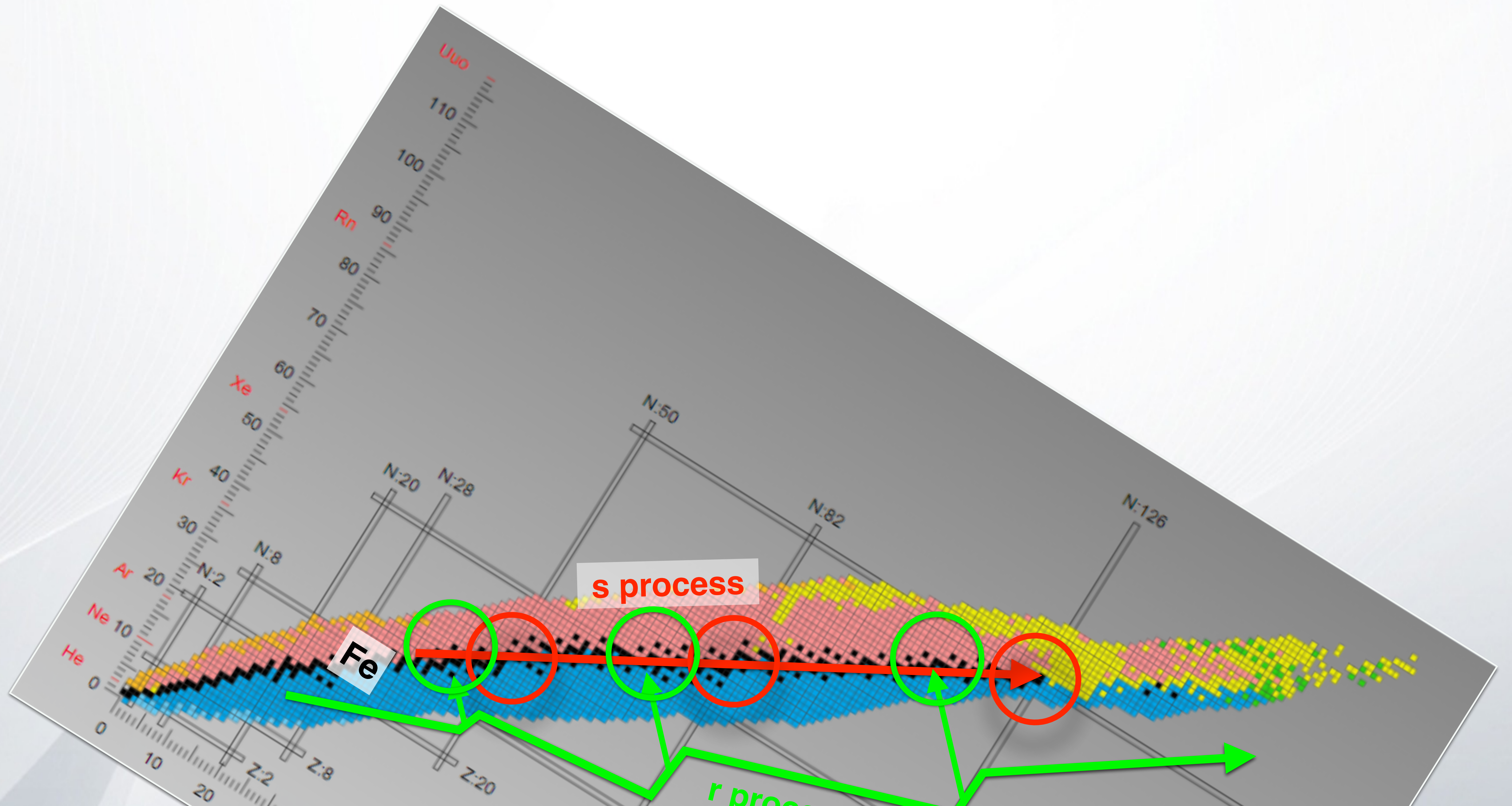
Number of **protons** ↑



Number of **neutrons** →





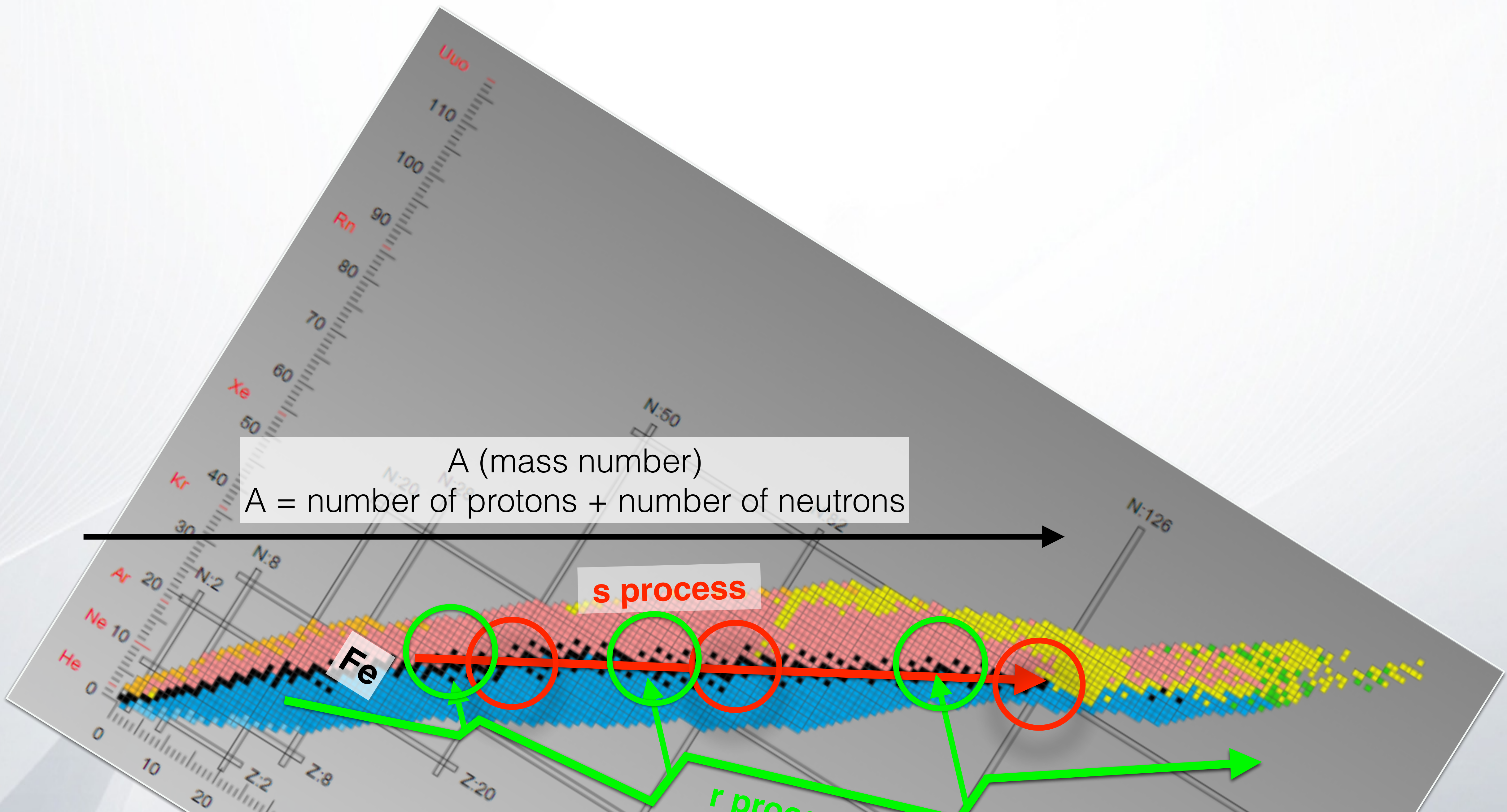


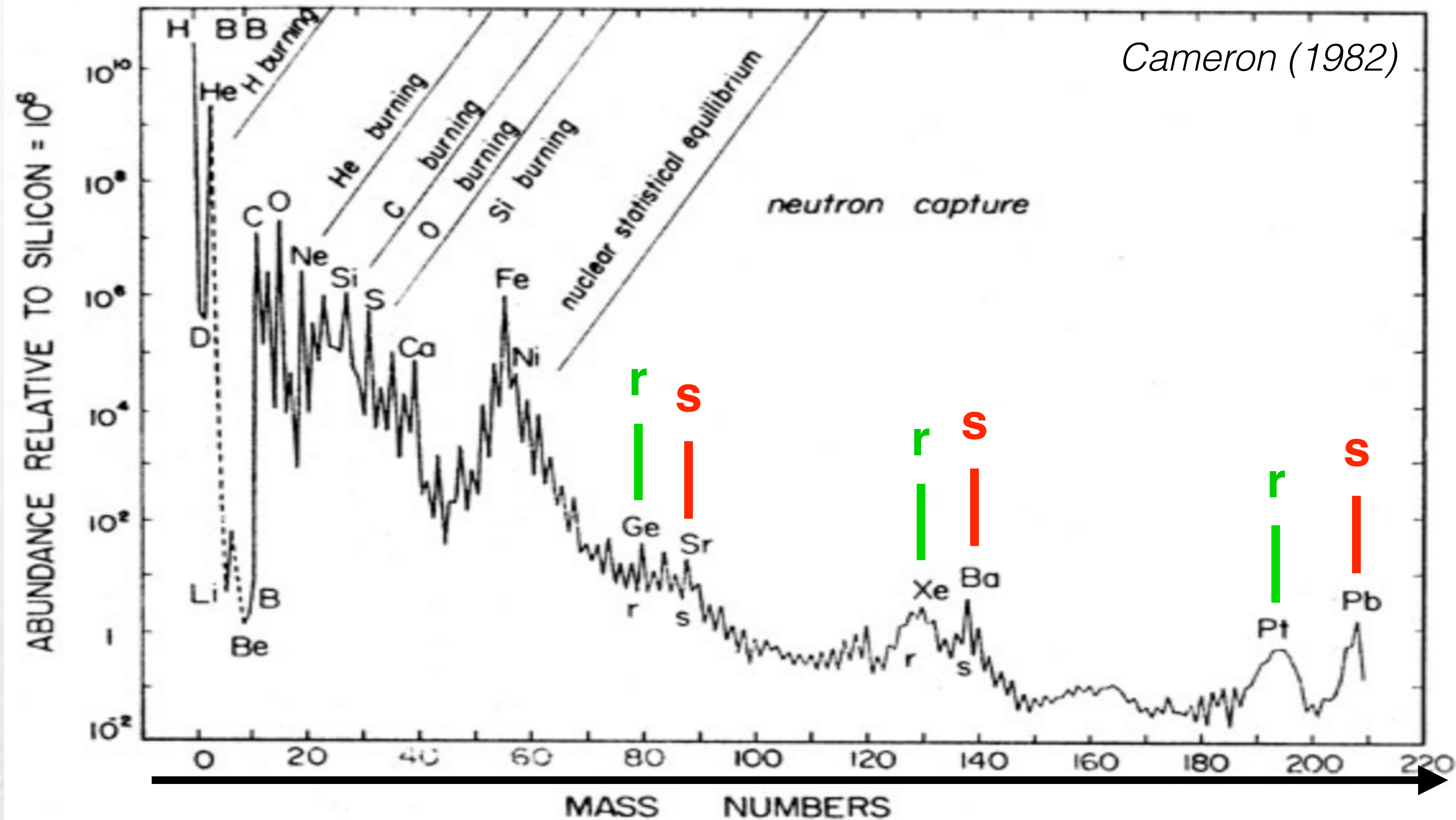
A (mass number)  
A = number of protons + number of neutrons

s process

Fe

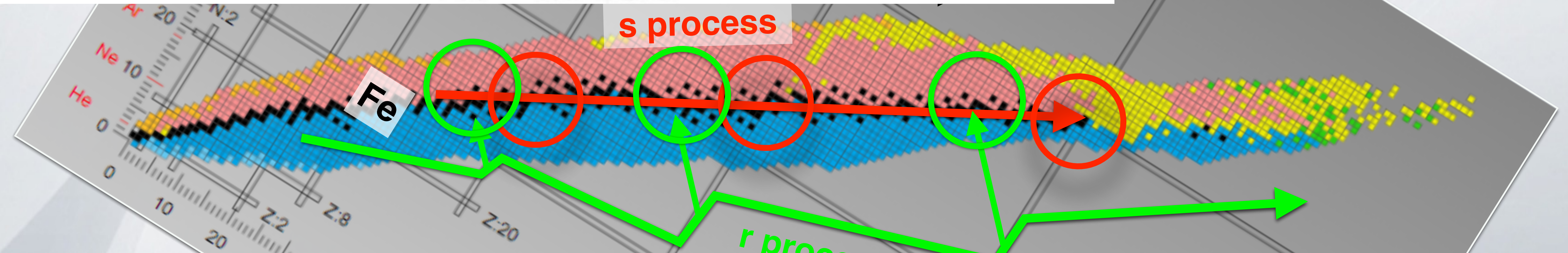
r process

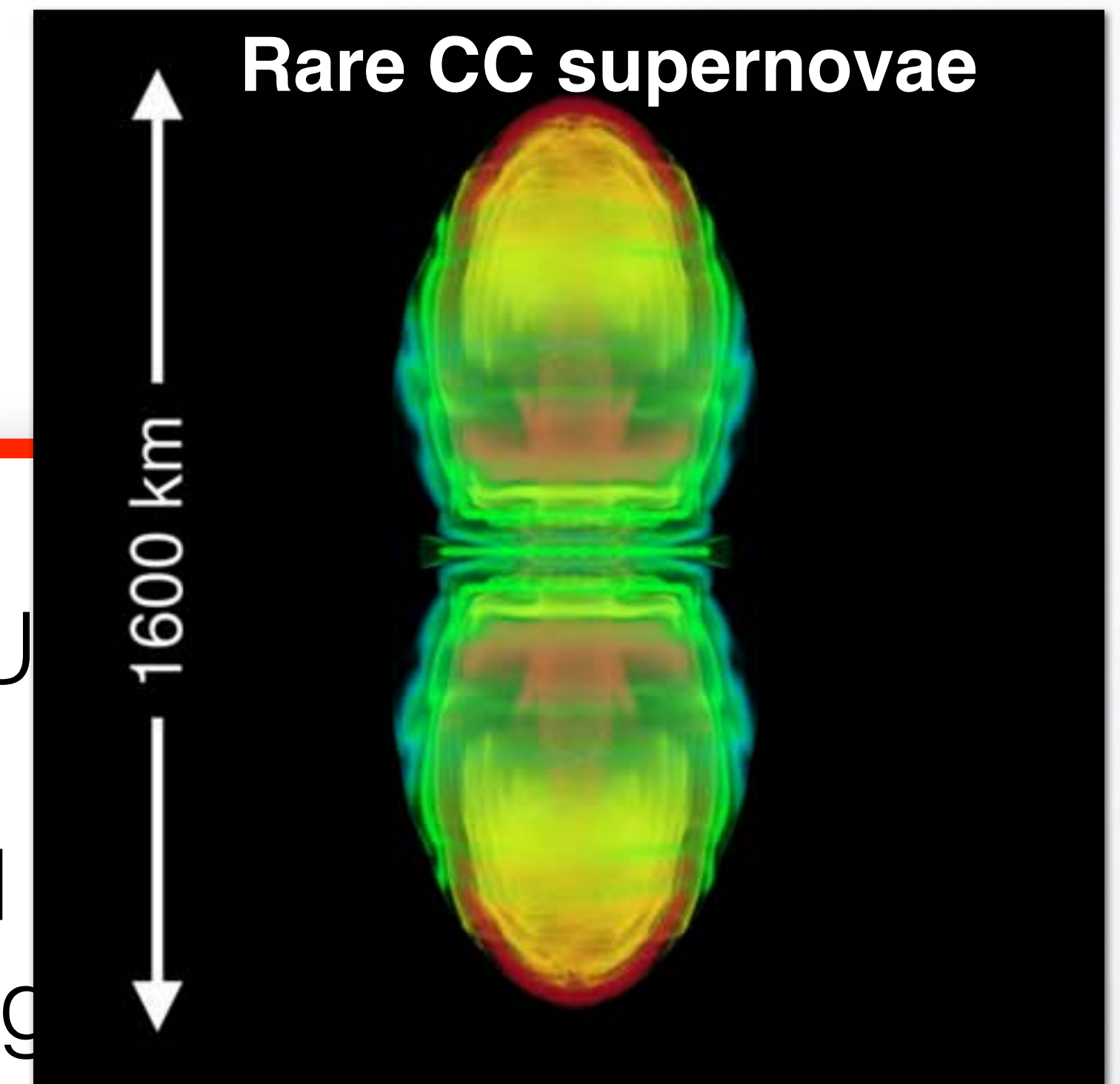
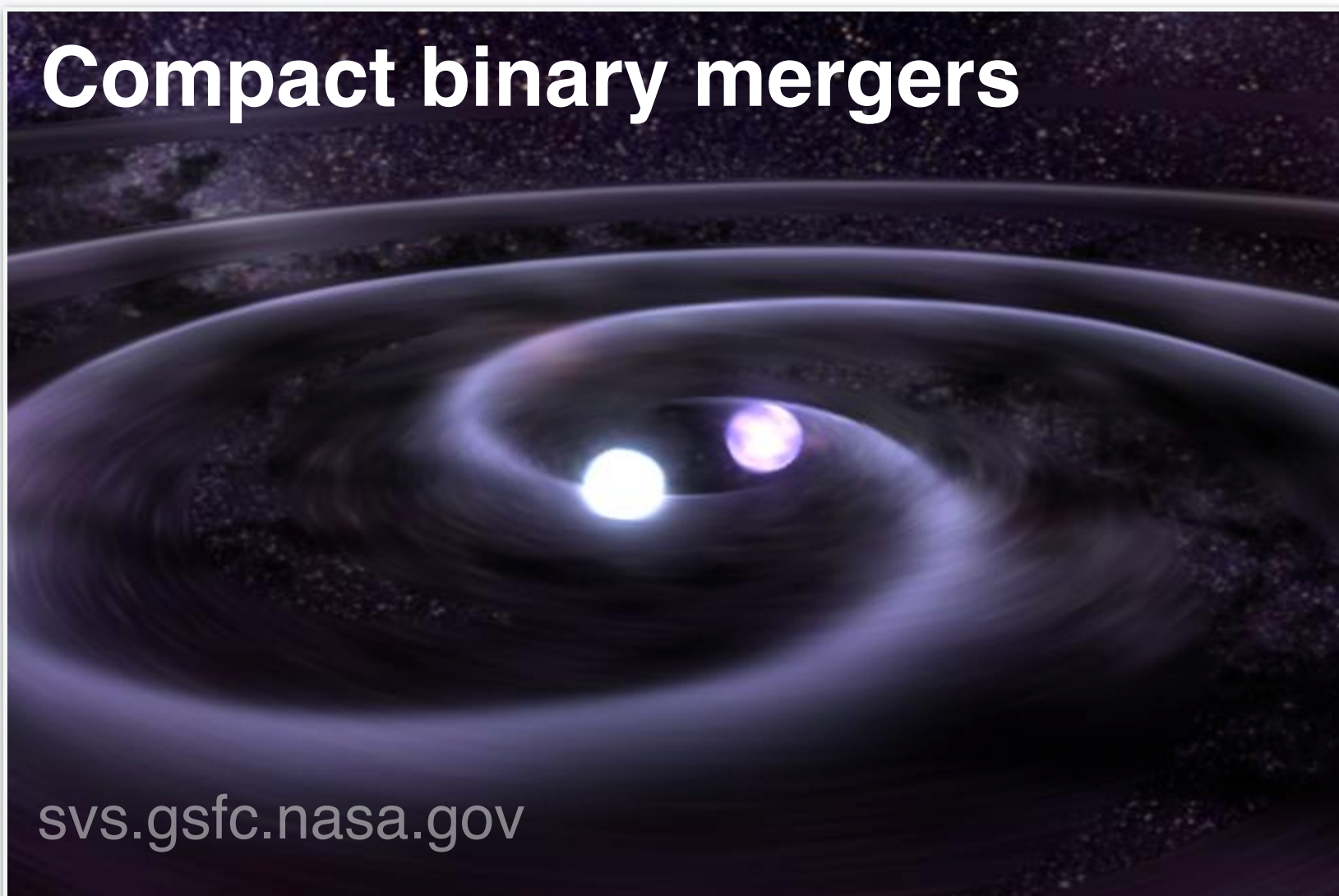




see Burbidge et al. (1957)

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





Where do the r-process occur in the Universe?  
Which astrophysical site has produced the r-process elements we see today in galaxies?

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

*Mosta et al. (2018)*



# The Basics of Chemical Evolution

Select to add a body text box.

## Simulation of the star formation process

### Core-collapse supernovae

Ca, Ti, Fe, ...  
r-process??

Crab nebula

### Type Ia supernovae

Fe, Mn

Tycho SN

©ESA and Justyn Maund (Queens University Belfast)

### Compact binary mergers

r-process

svs.gsfc.nasa.gov

### Low- and intermediate-mass stars

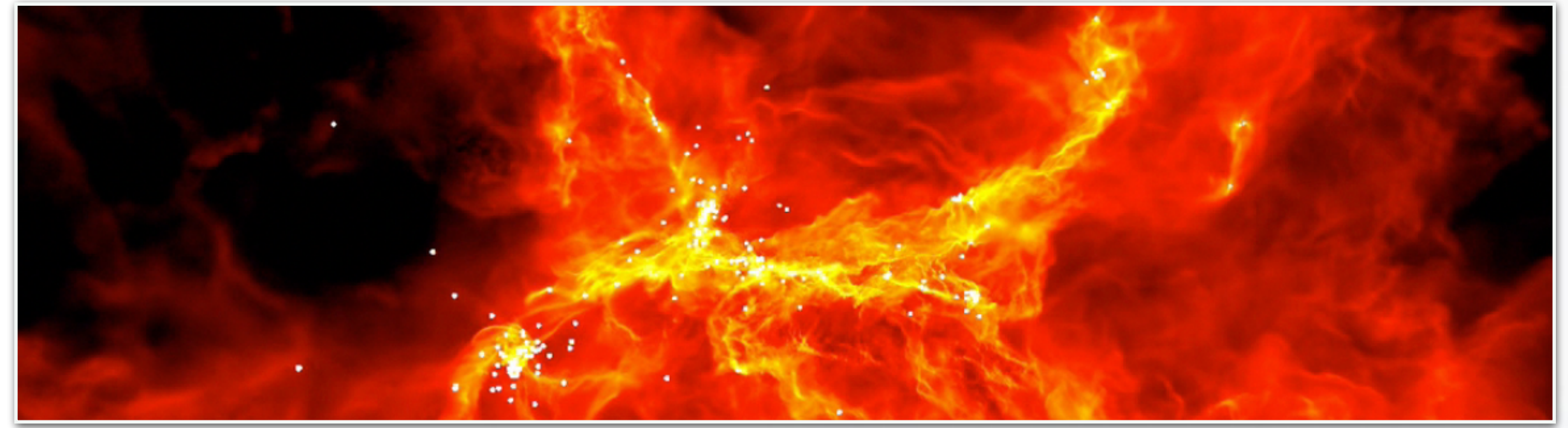
C, s-process, ..

Cat eye nebula

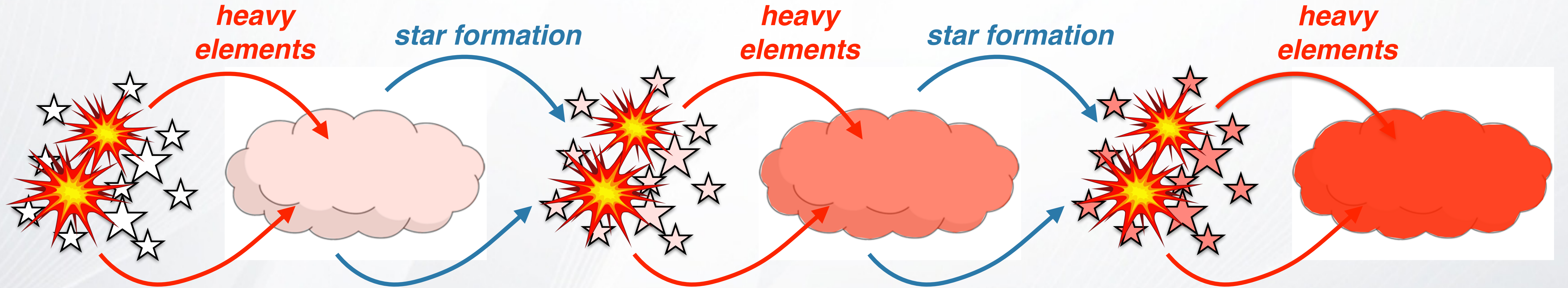
Matthew Bate

UNIVERSITY OF  
EXETER

# 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

*higher **concentration** of  
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# The Basics of Chemical Evolution

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



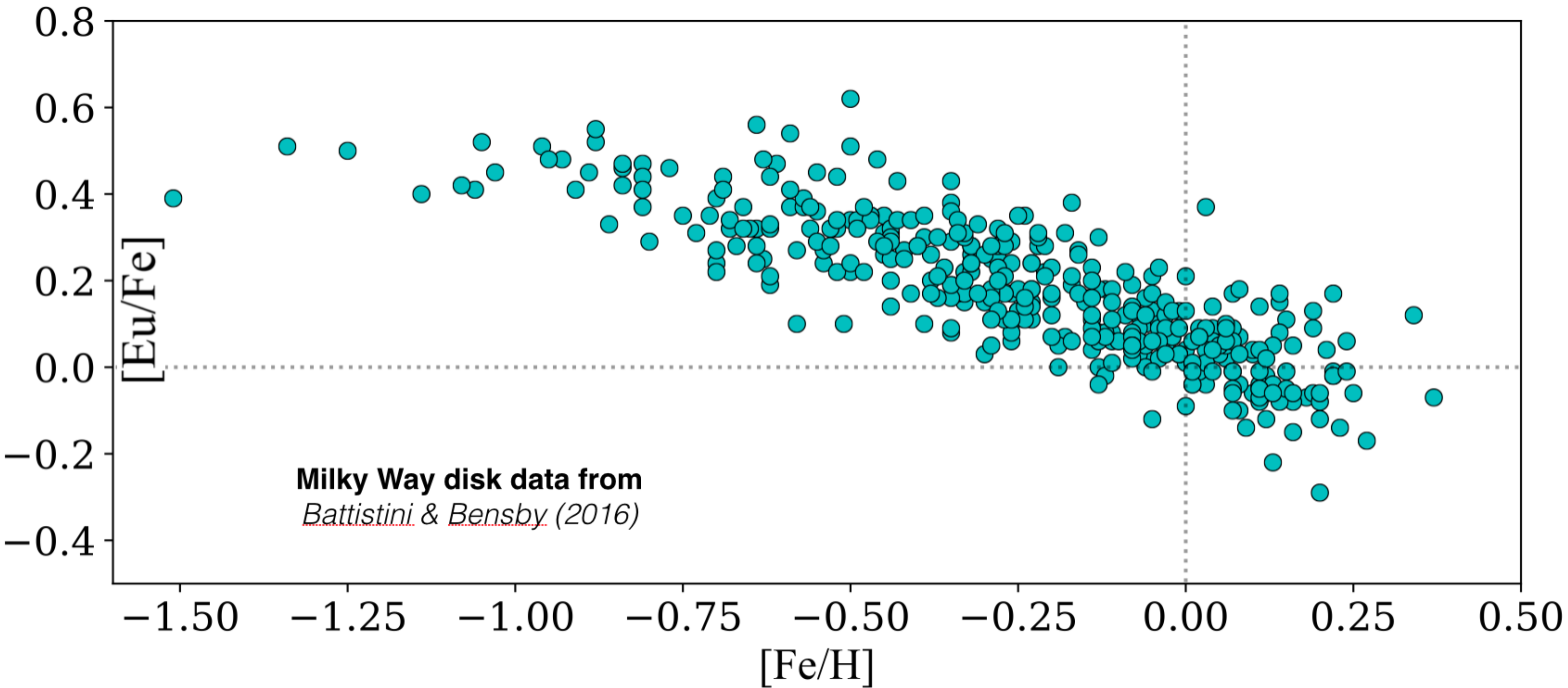
(~13 Gyr ago)

**Time**

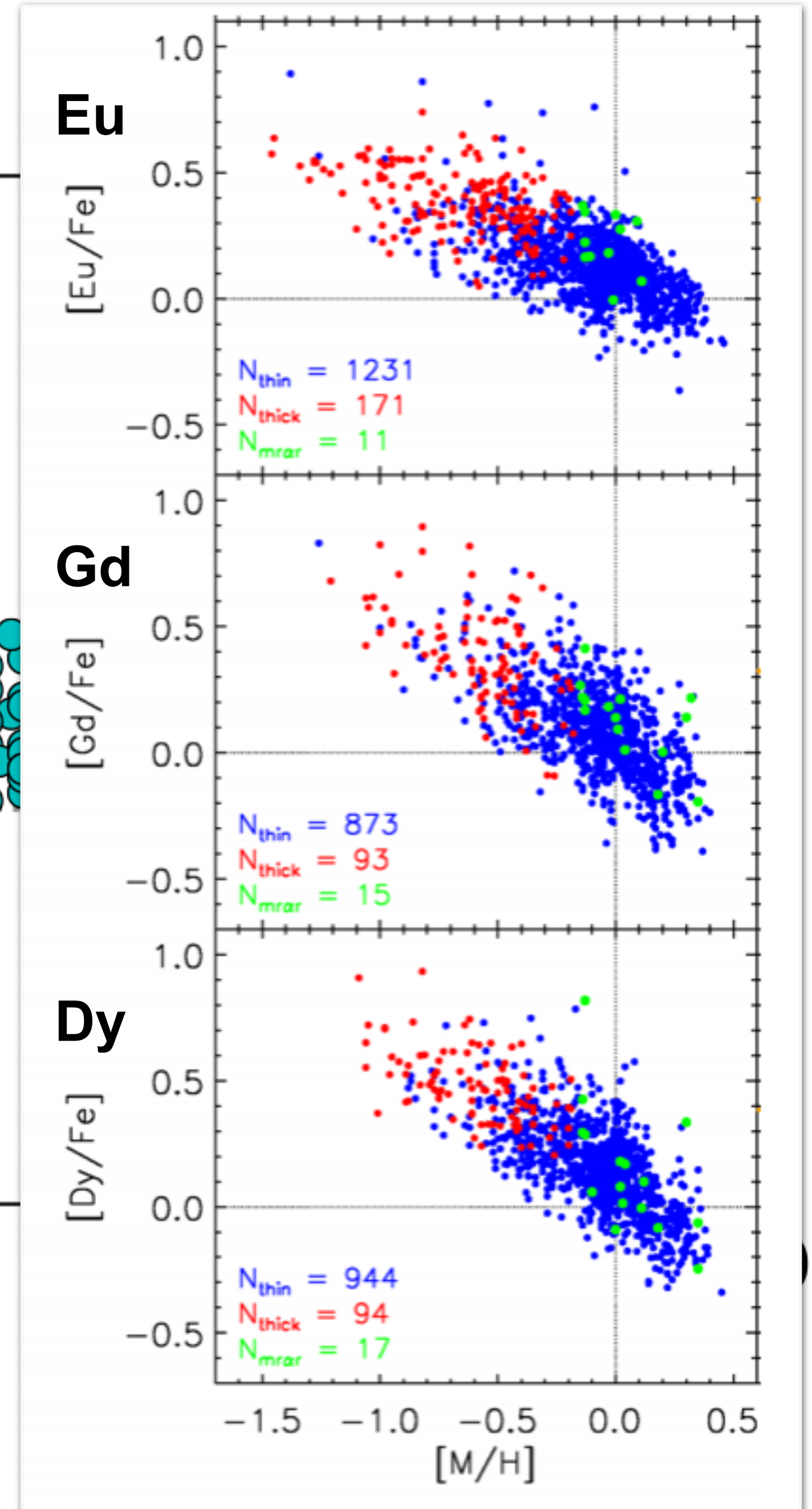
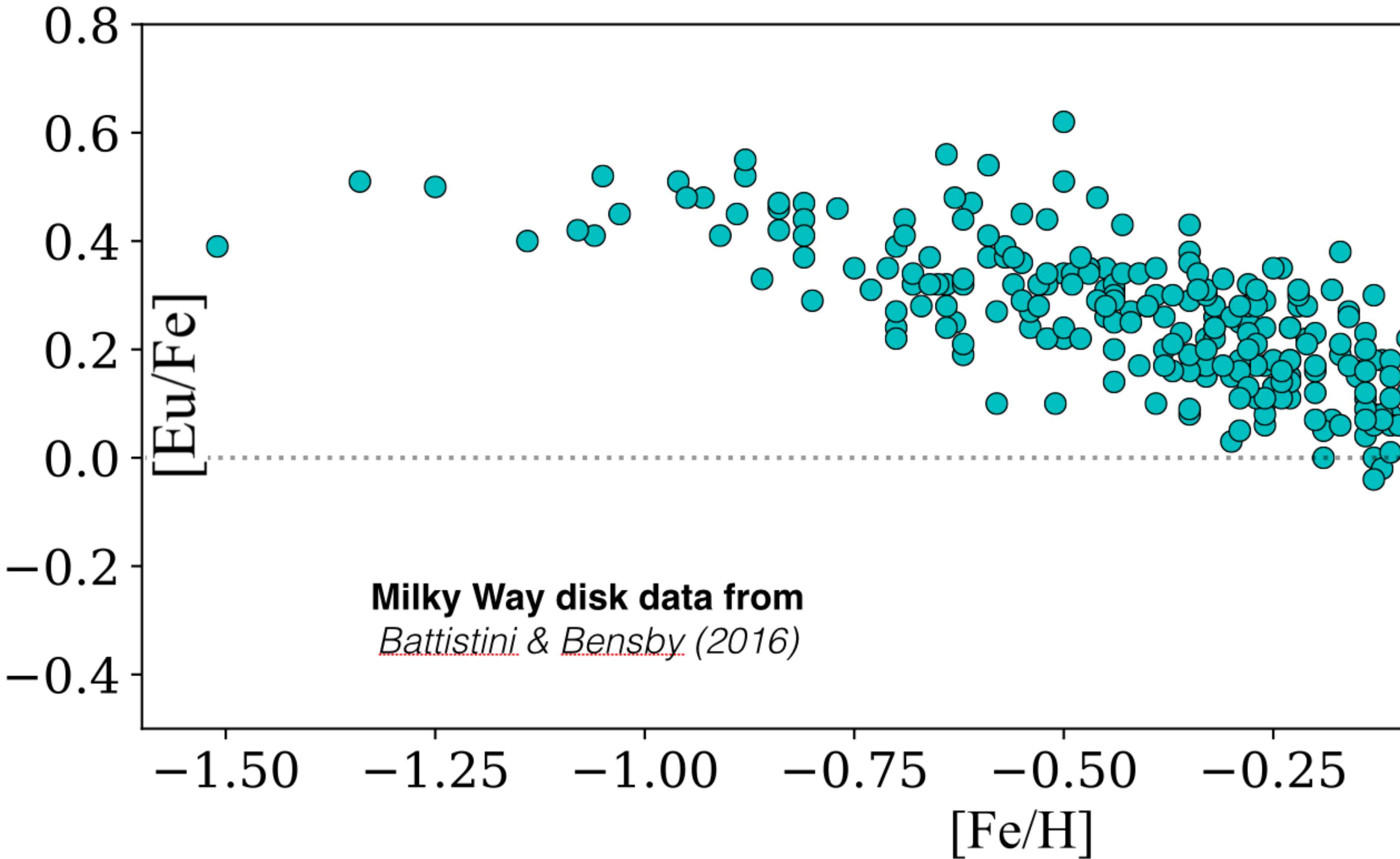
(evolution of our Galaxy)

Today

# How to « Observe » Chemical Evolution?



## Chemical Evolution in the Disk of our Milky Way Galaxy



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

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

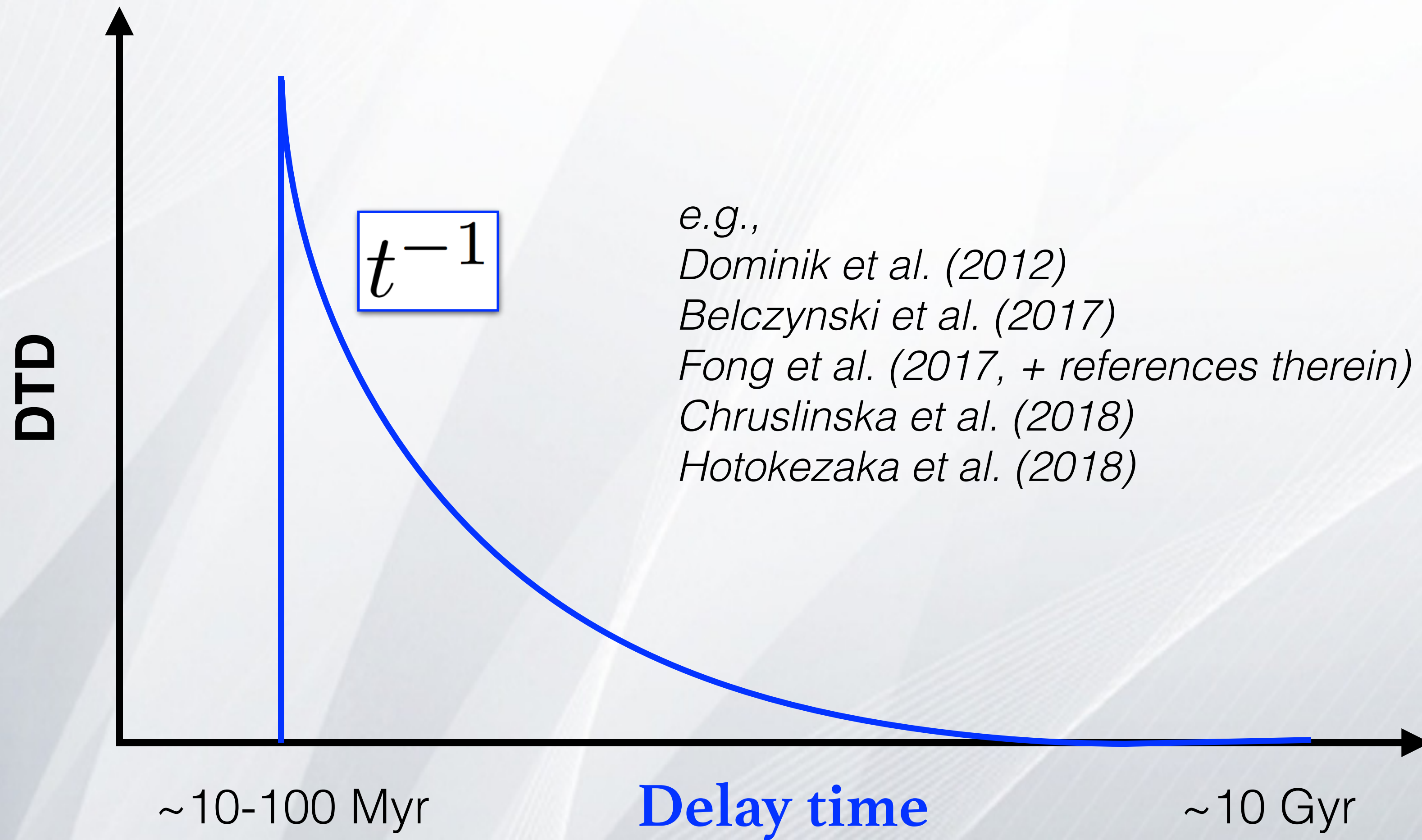
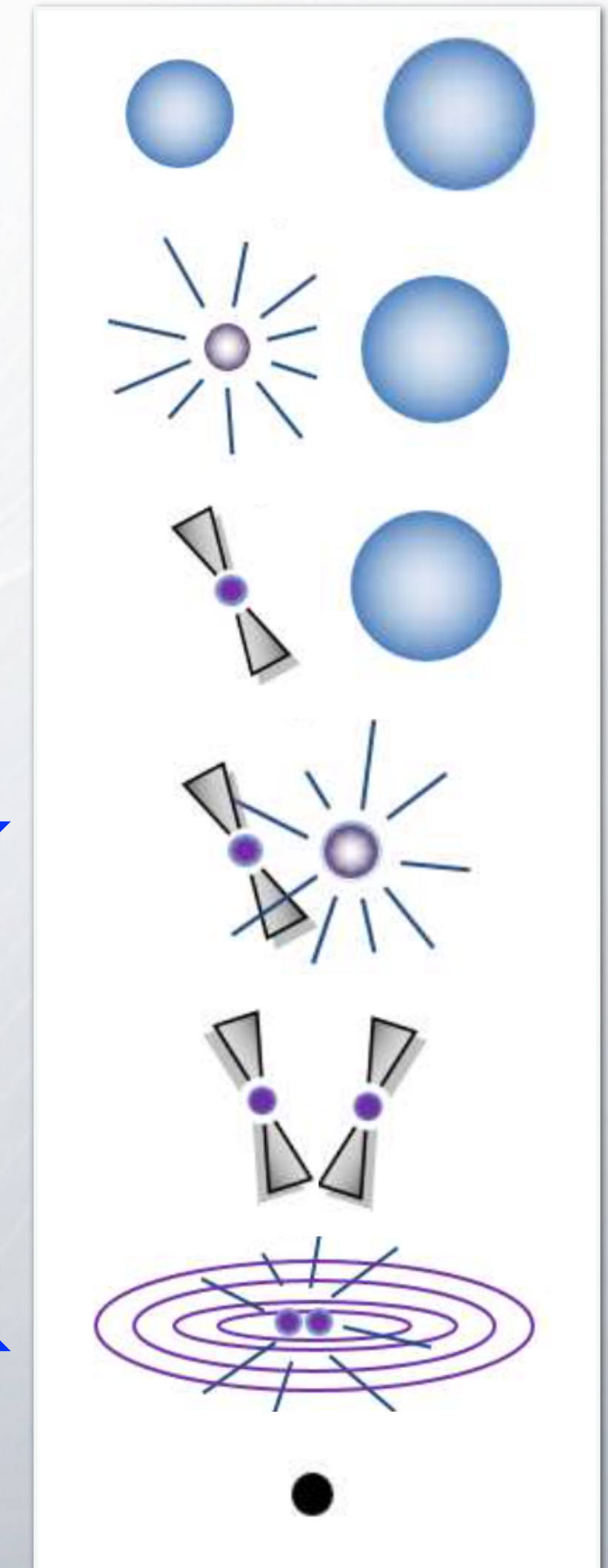
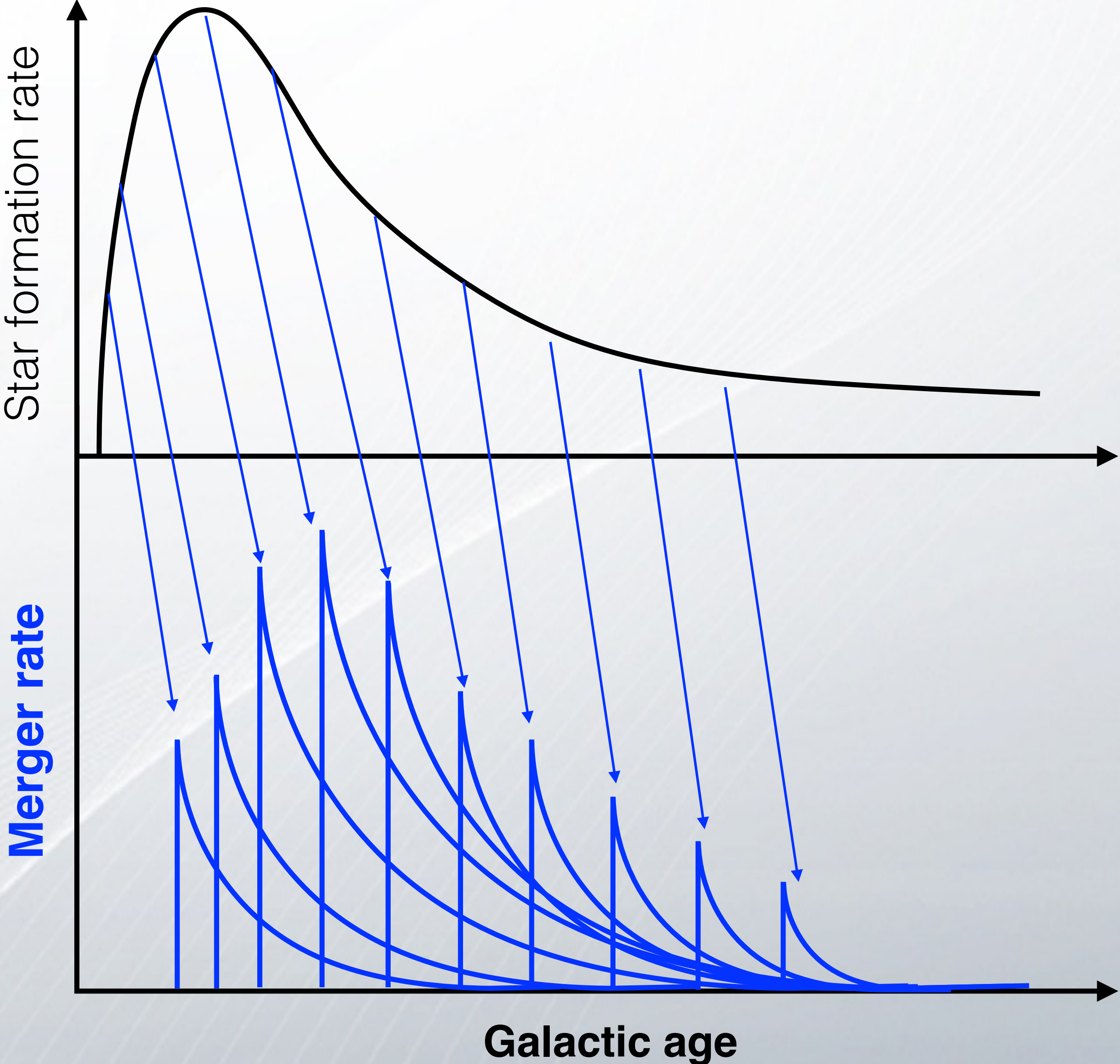


Image built from  
*Tauris et al. (2017)*

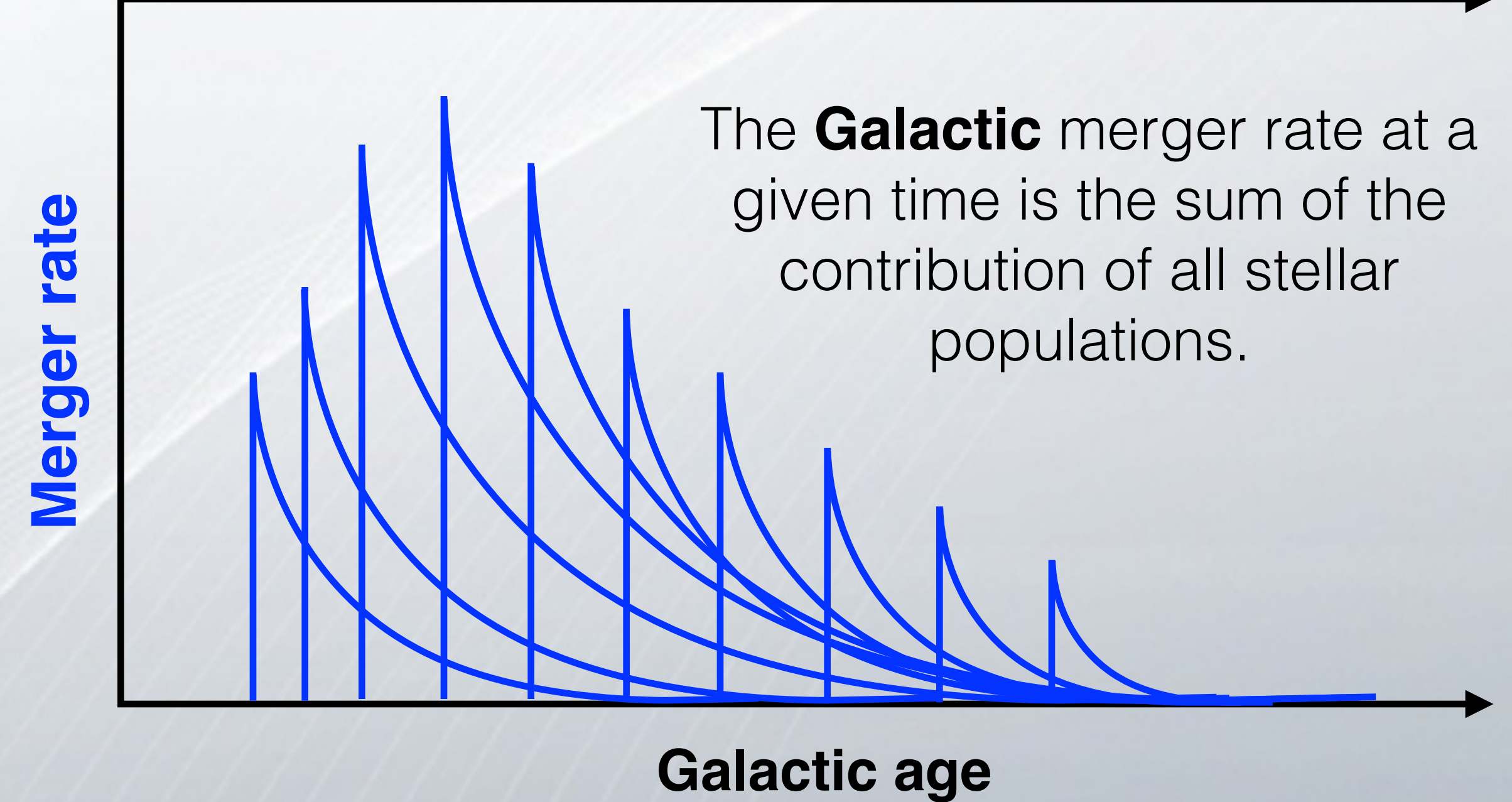
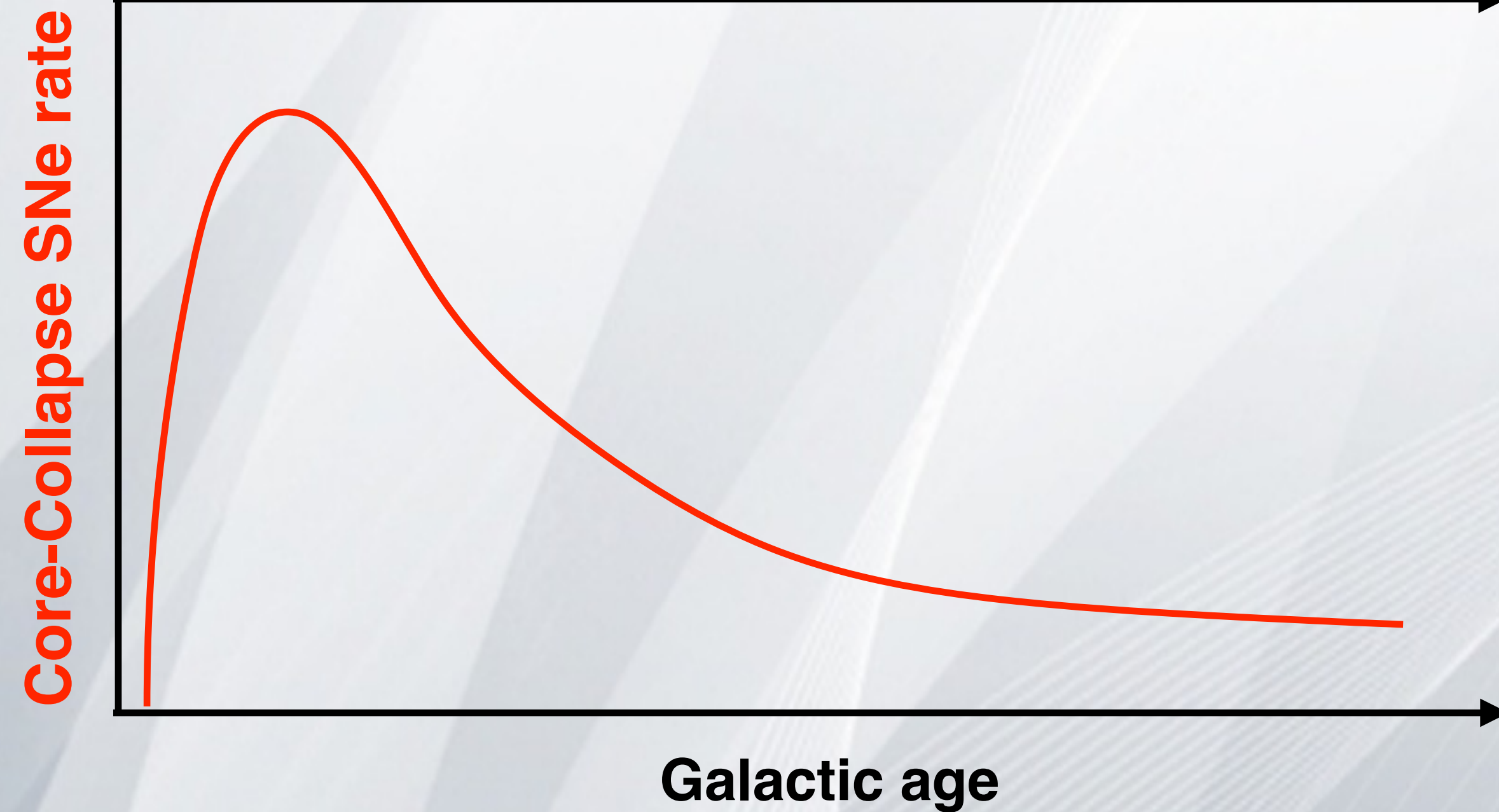
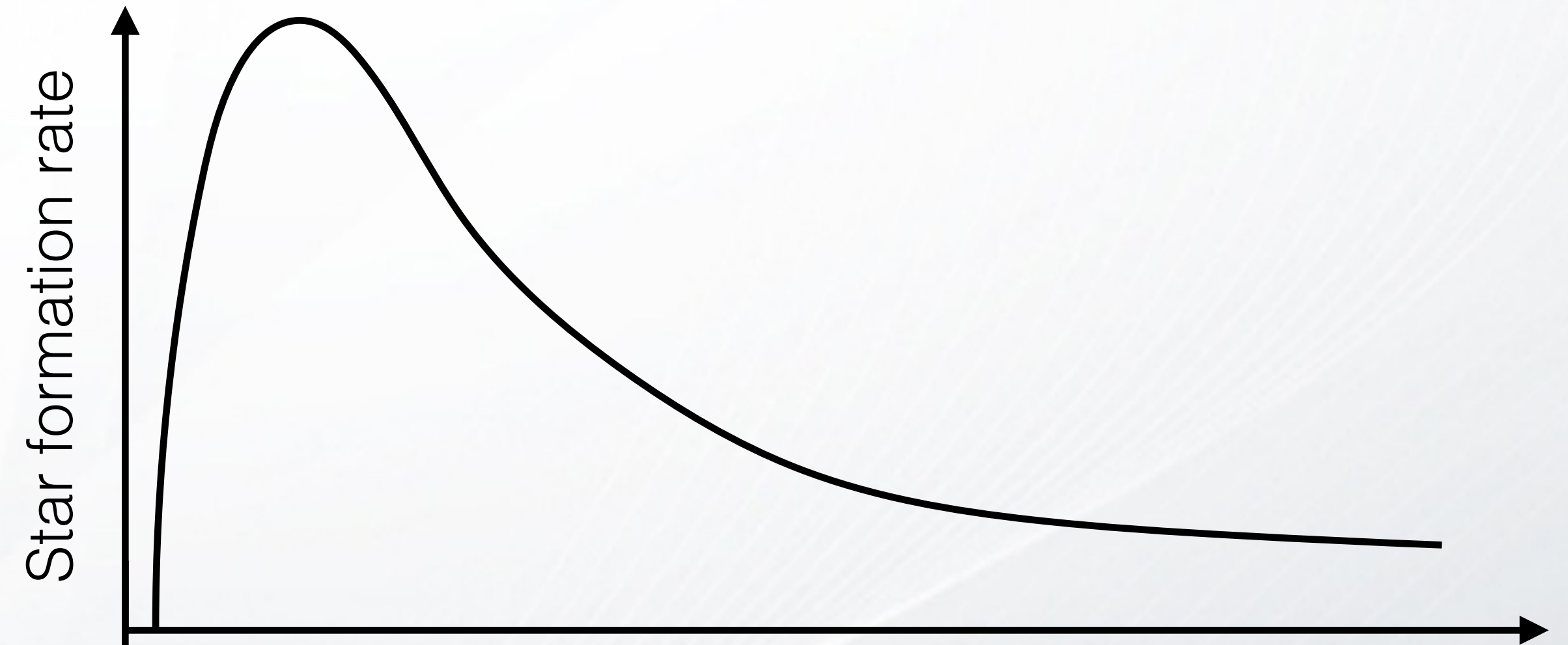
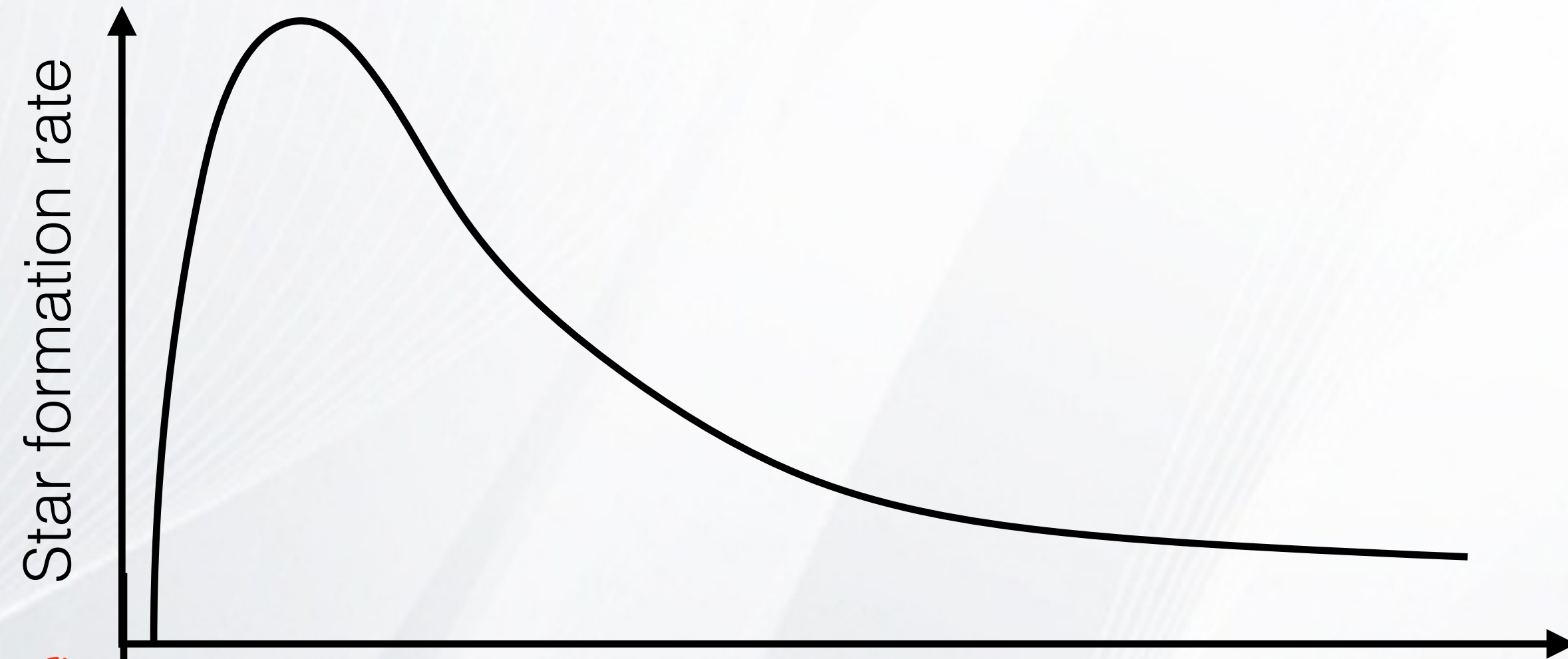


# Delay-Time Distribution Functions in Chemical Evolution Codes



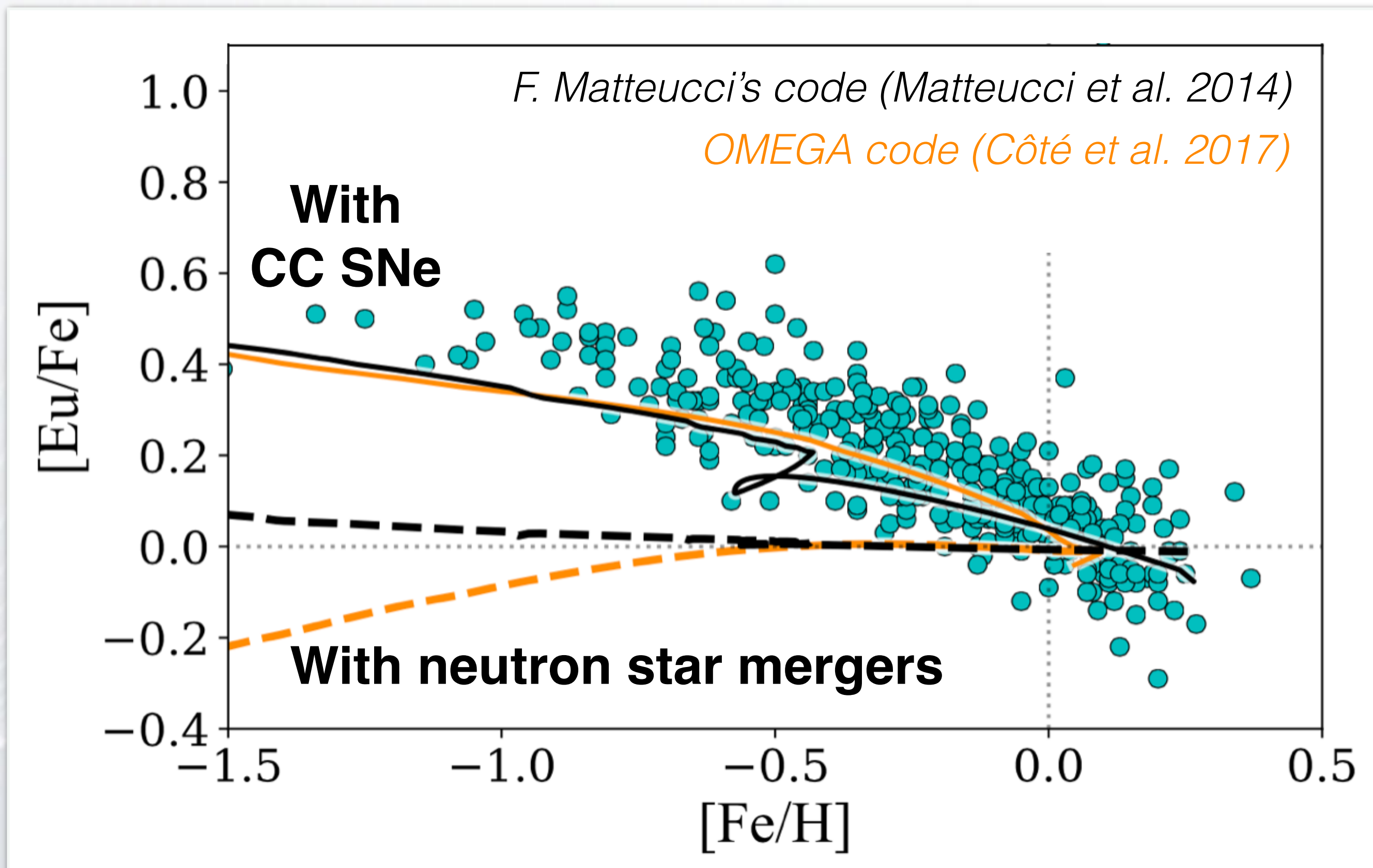


# Delay-Time Distribution Functions in Chemical Evolution Codes



# How Can we Fit the Decreasing Chemical Evolution Trend?

*Côté, Eichler, Arcones, et al. (2019)*



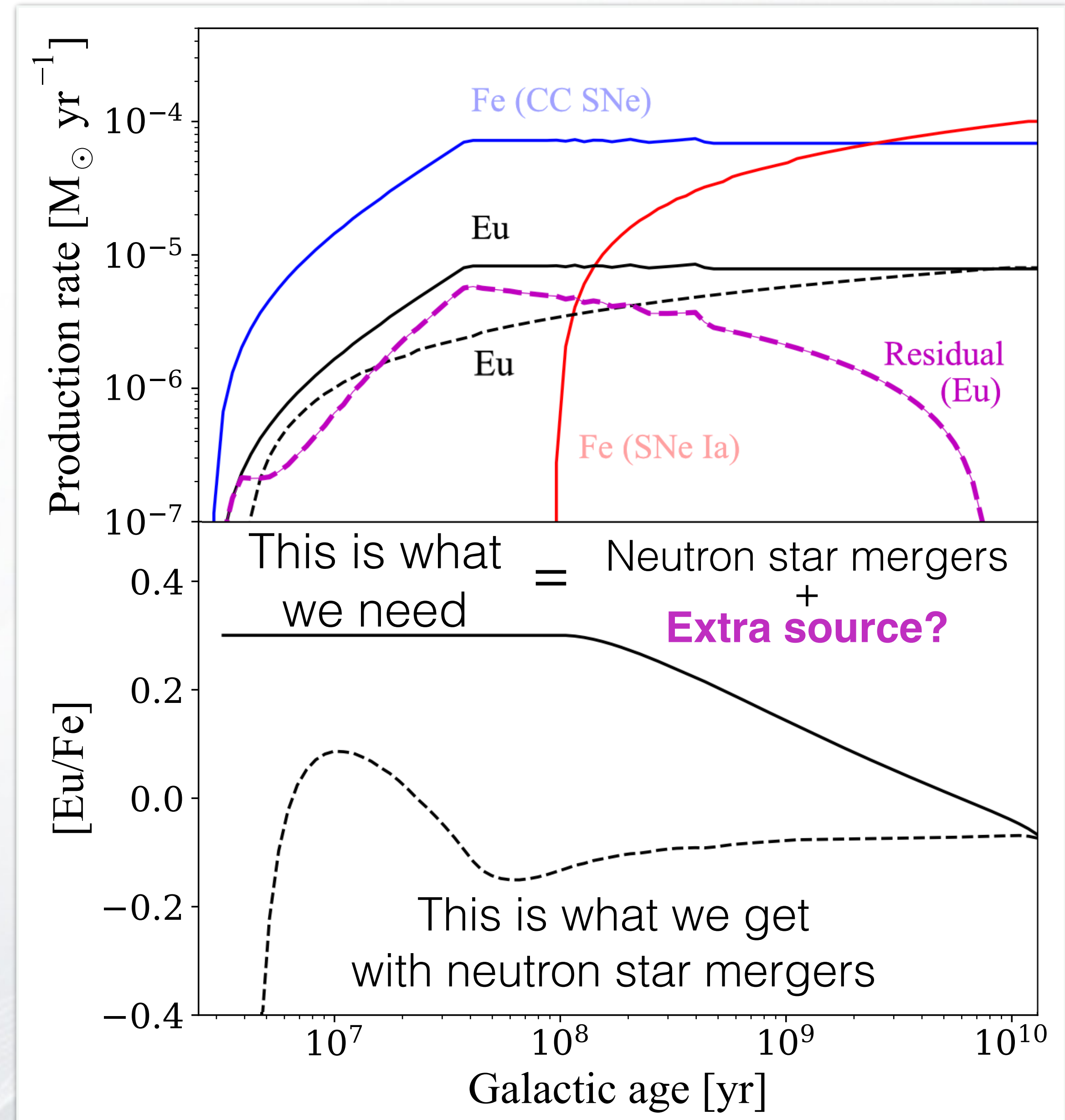
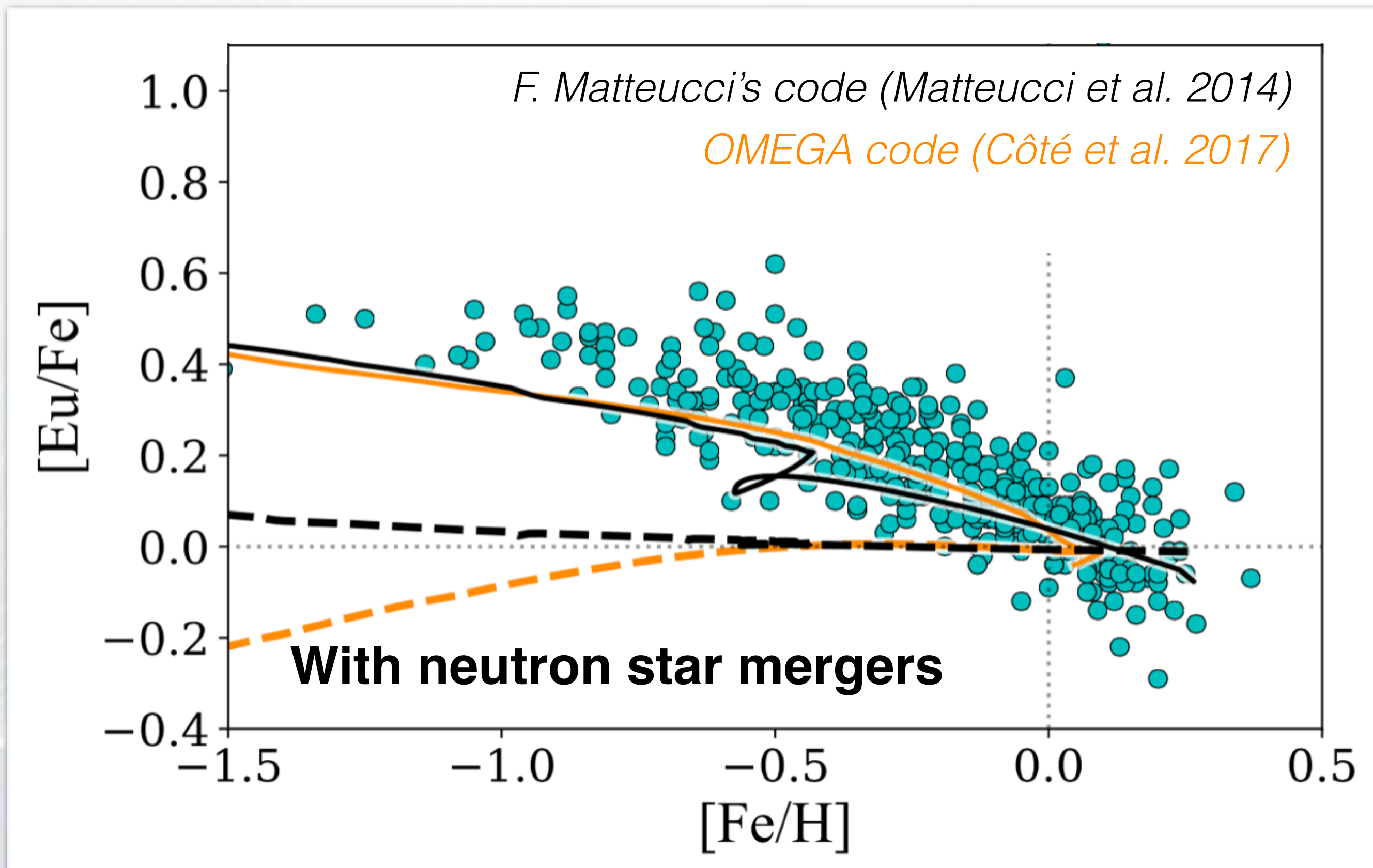
## Chemical evolution simulations for r-process elements

*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)

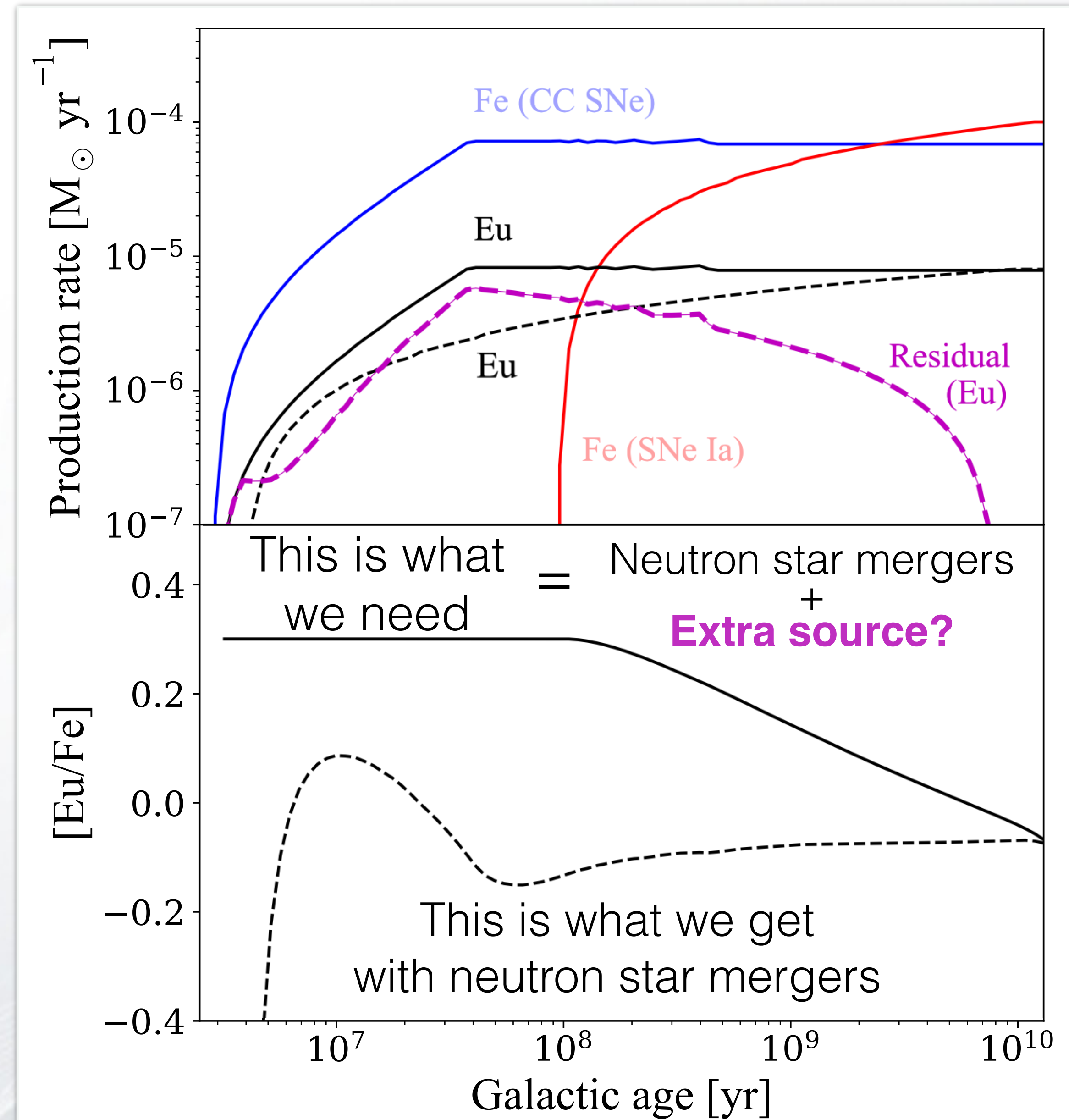


# How Can we Fit the Decreasing Chemical Evolution Trend?





*Côté, Eichler, Arcones, et al. (2019)*

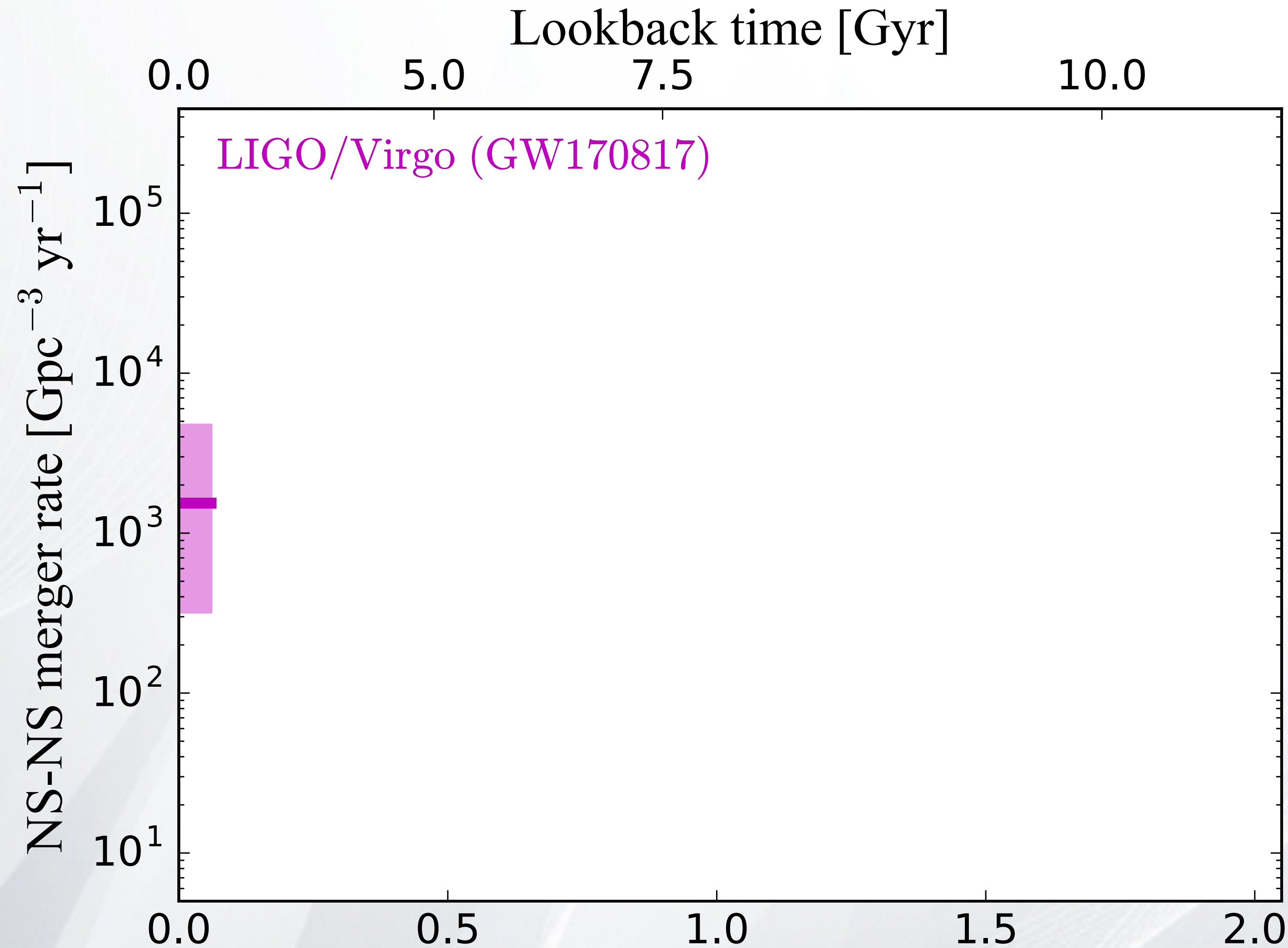
## Two r-process sites in the early Universe?

*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<sup>1,2,8</sup> , Chris L. Fryer<sup>2,3,8</sup> , Krzysztof Belczynski<sup>4</sup>, Oleg Korobkin<sup>2,3</sup> , Martyna Chruślińska<sup>5</sup>, Nicole Vassh<sup>6</sup>, Matthew R. Mumpower<sup>2,3,7</sup>, Jonas Lippuner<sup>2,3</sup> , Trevor M. Sprouse<sup>6</sup>, Rebecca Surman<sup>2,6</sup>, and Ryan Wollaeger<sup>3</sup>



## Chemical evolution simulations for *r*-process elements

*Argast et al. (2004)*

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*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)*

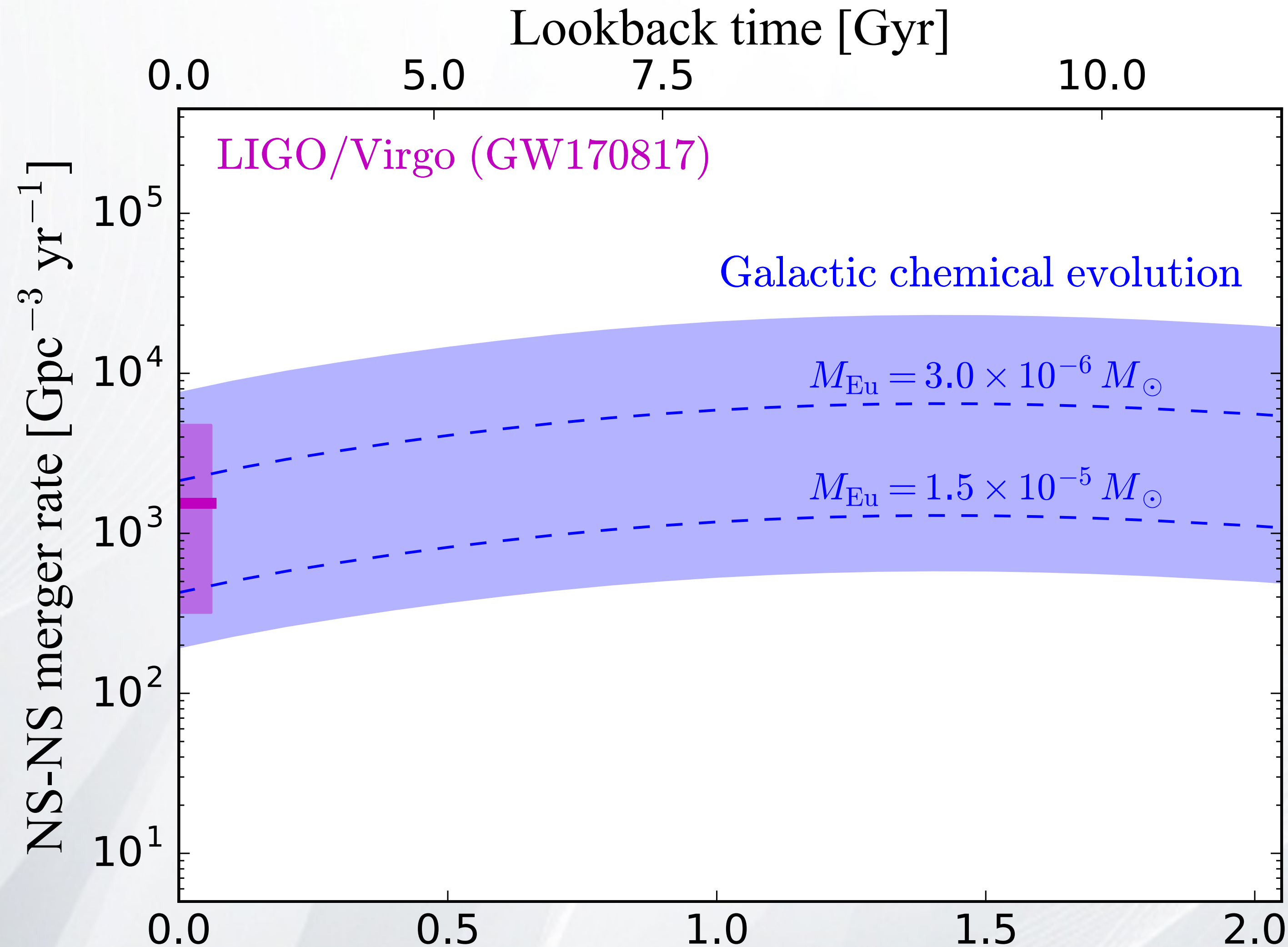
*Simonetti et al. (2019)*

...

*Côté, Fryer, Belczynski, et al. (2018)* z (redshift)





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

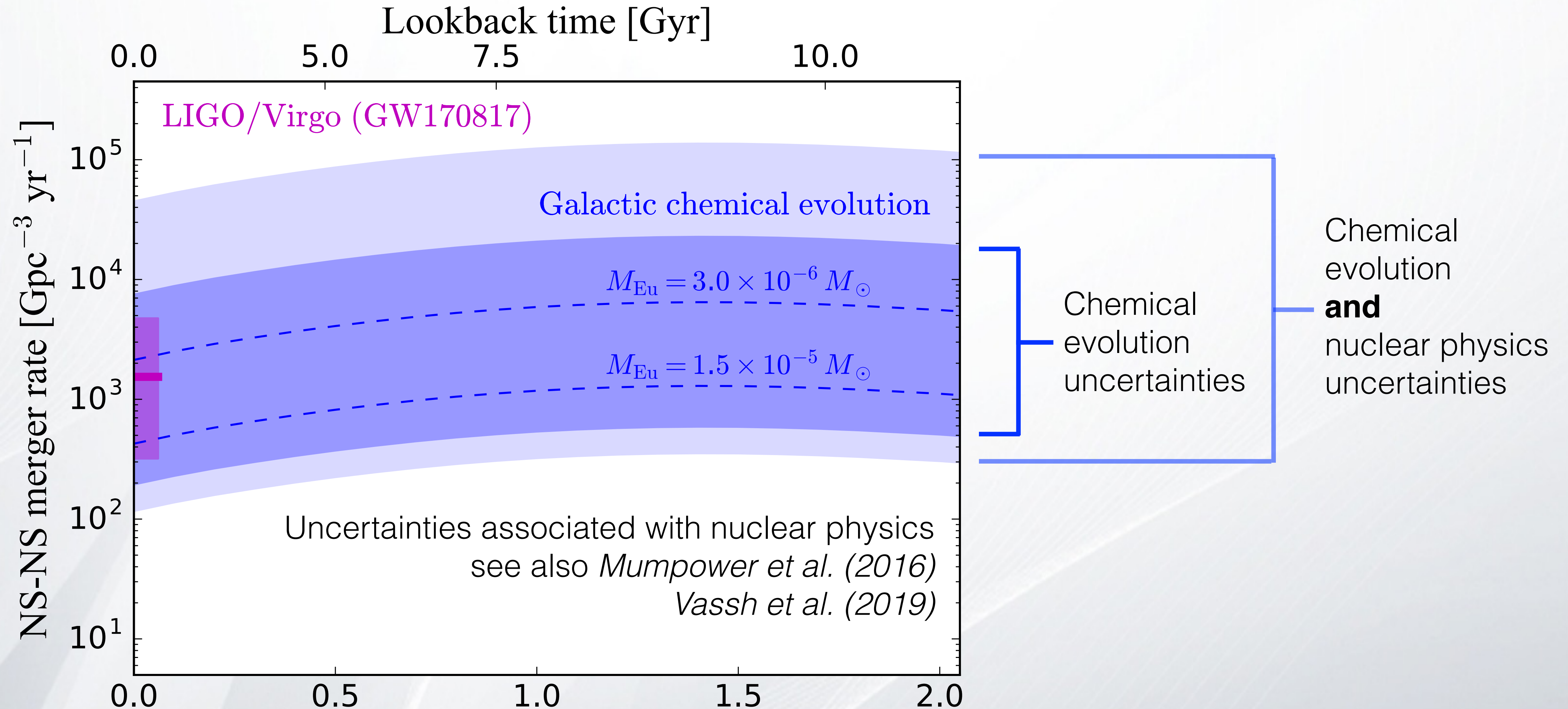
Benoit Côté<sup>1,2,8</sup> , Chris L. Fryer<sup>2,3,8</sup> , Krzysztof Belczynski<sup>4</sup>, Oleg Korobkin<sup>2,3</sup> , Martyna Chruślińska<sup>5</sup>, Nicole Vassh<sup>6</sup>, Matthew R. Mumpower<sup>2,3,7</sup>, Jonas Lippuner<sup>2,3</sup> , Trevor M. Sprouse<sup>6</sup>, Rebecca Surman<sup>2,6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



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



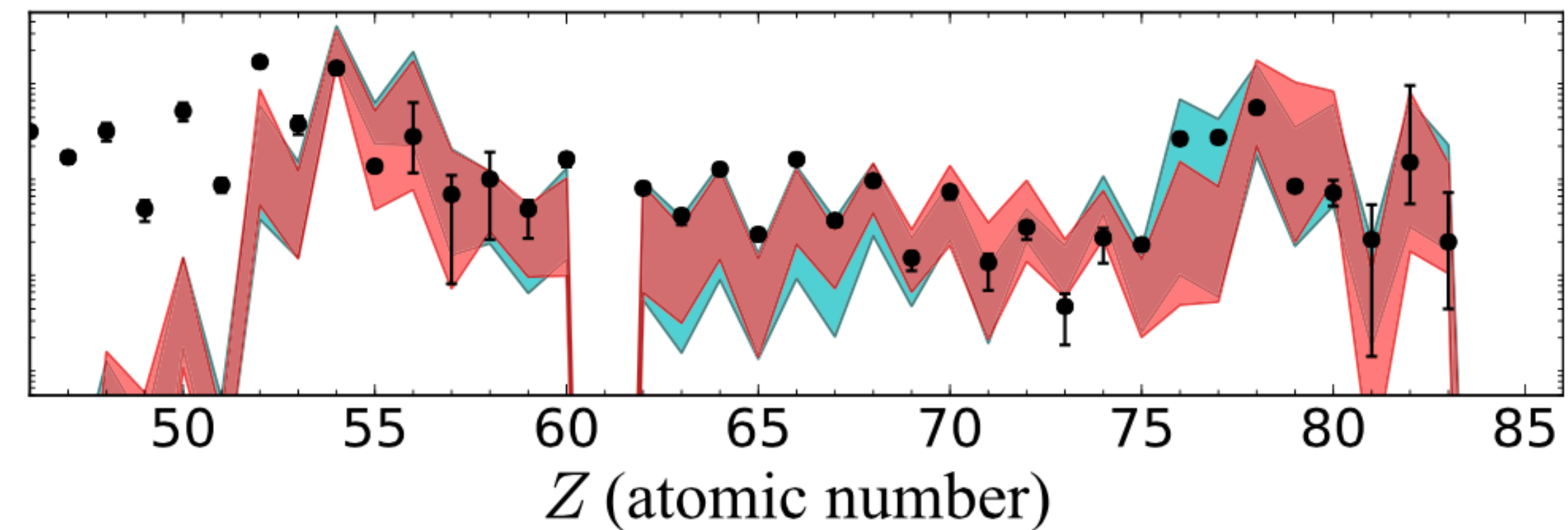
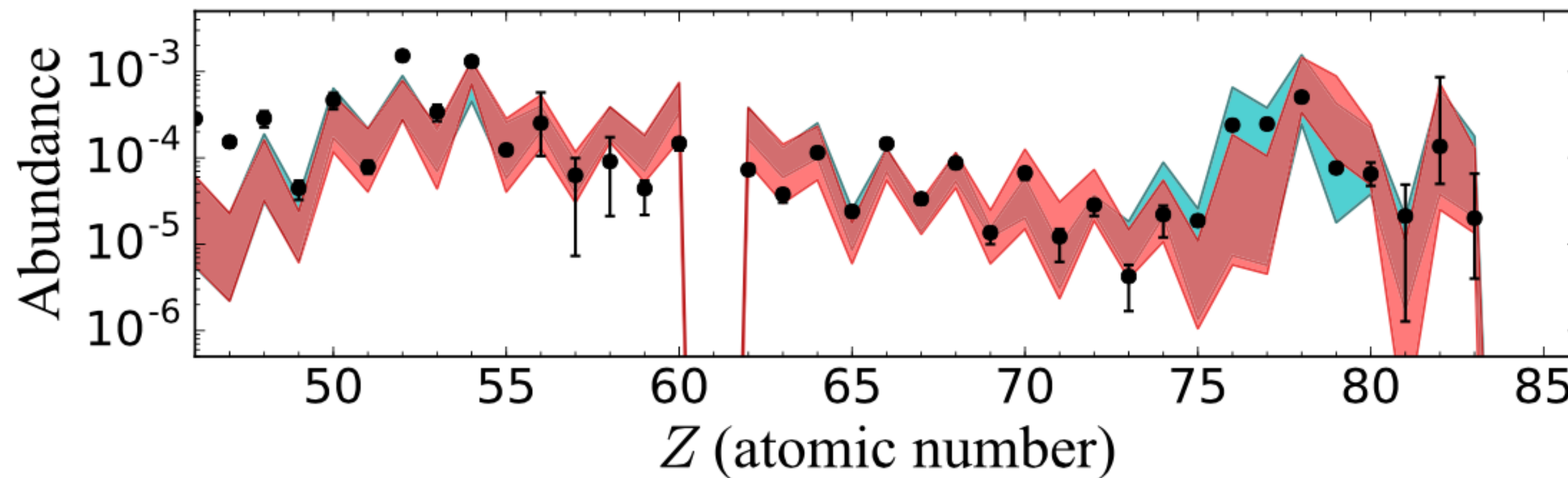
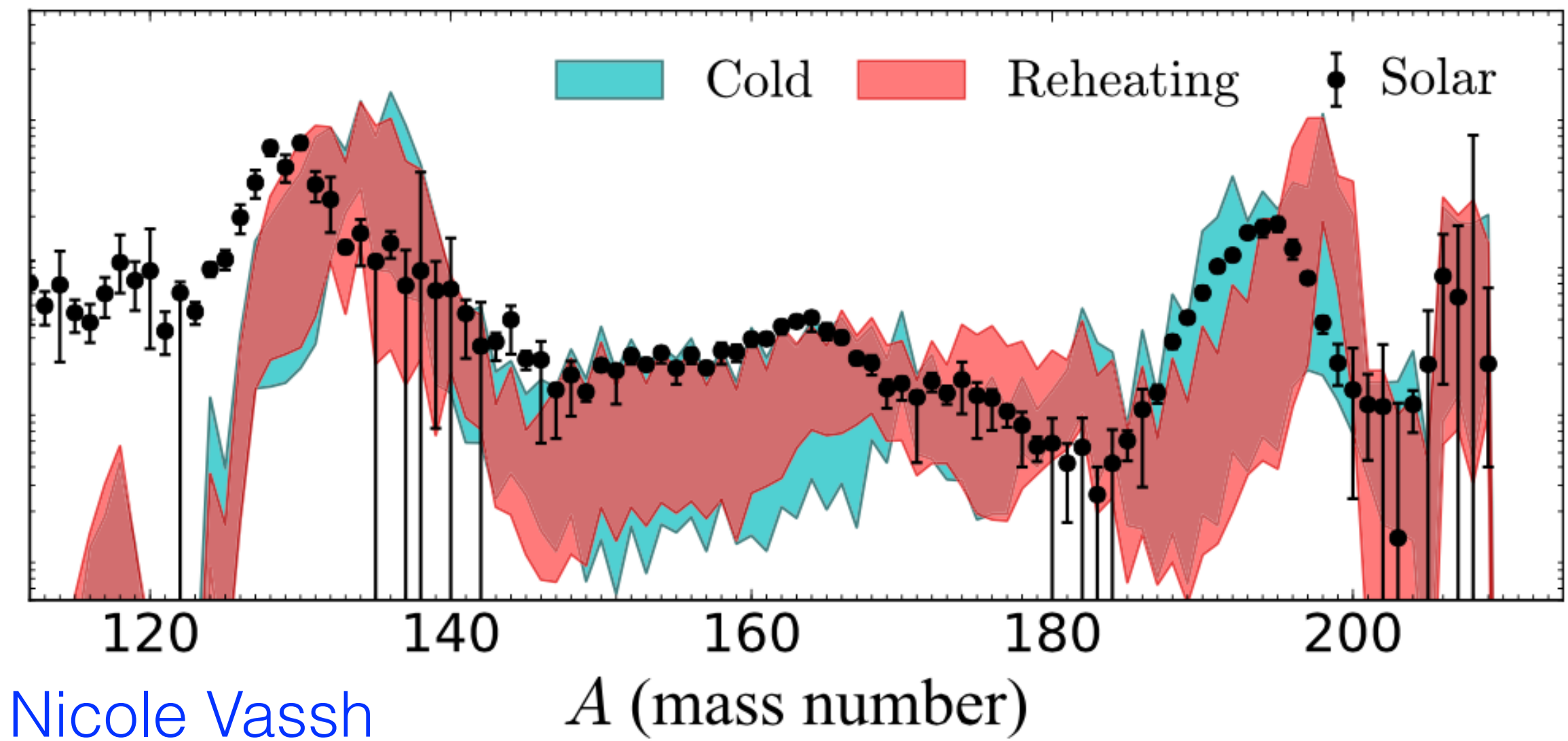
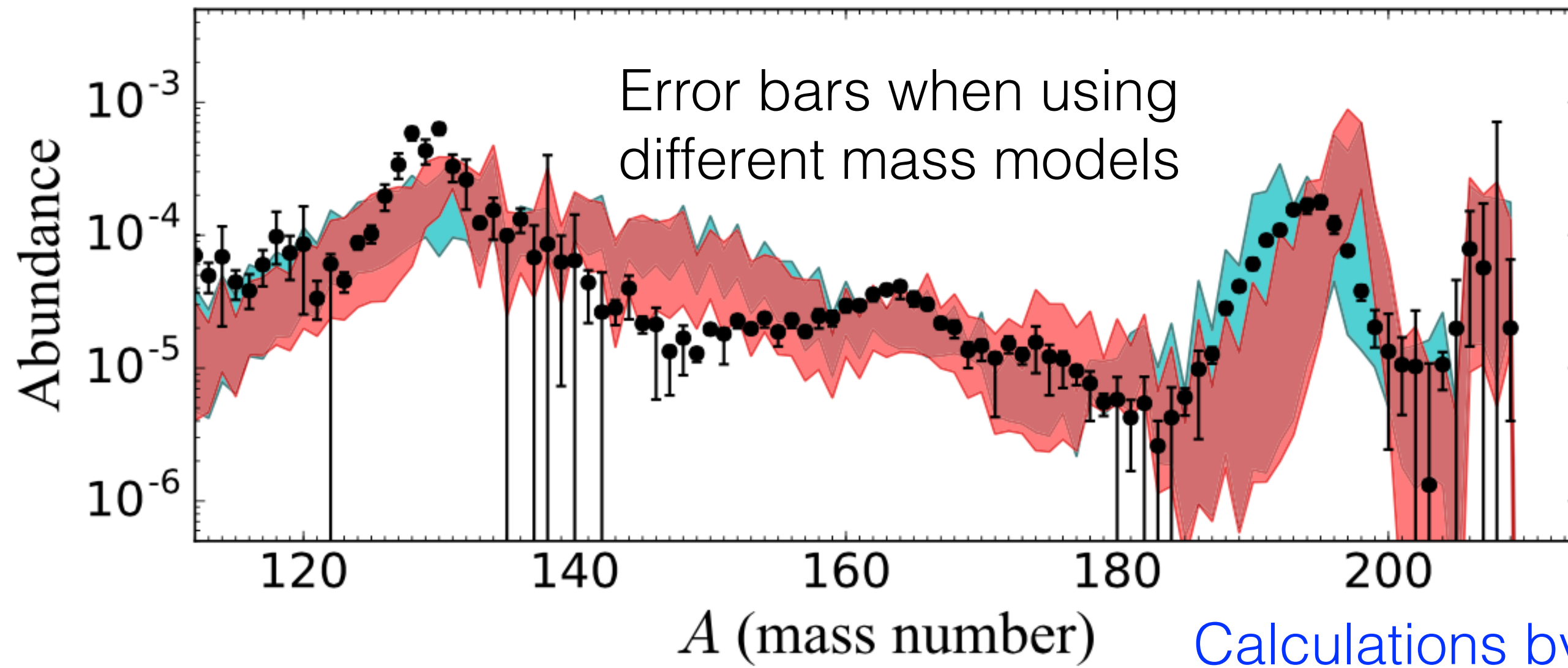
Côté, Fryer, Belczynski, et al. (2018)  $z$  (redshift)

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

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

Kodama & Takahashi (1975; left panels)

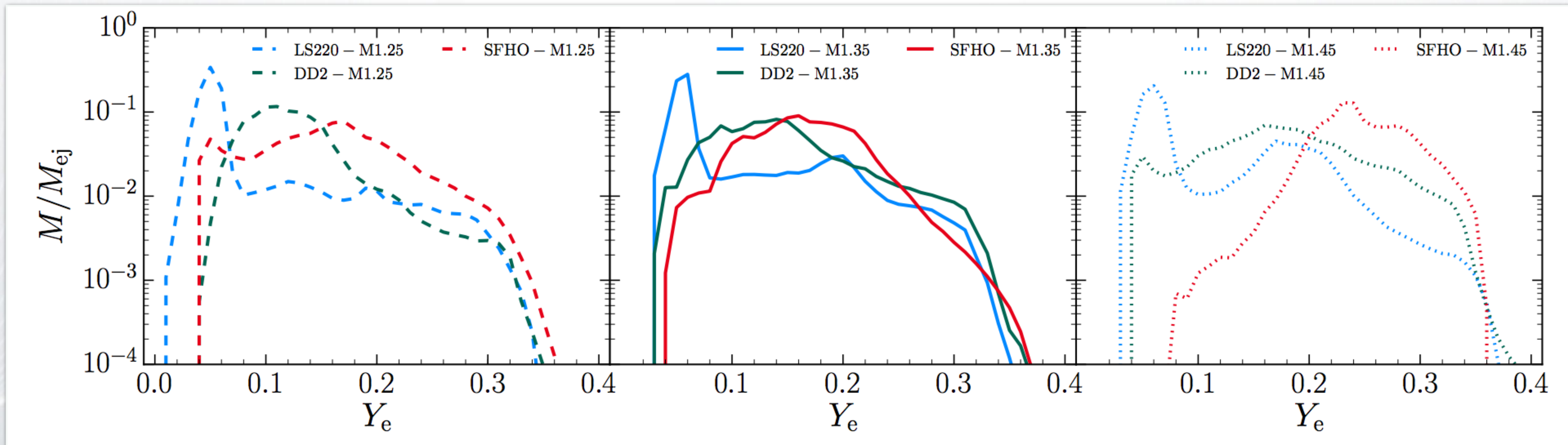
symmetric split (right panels)





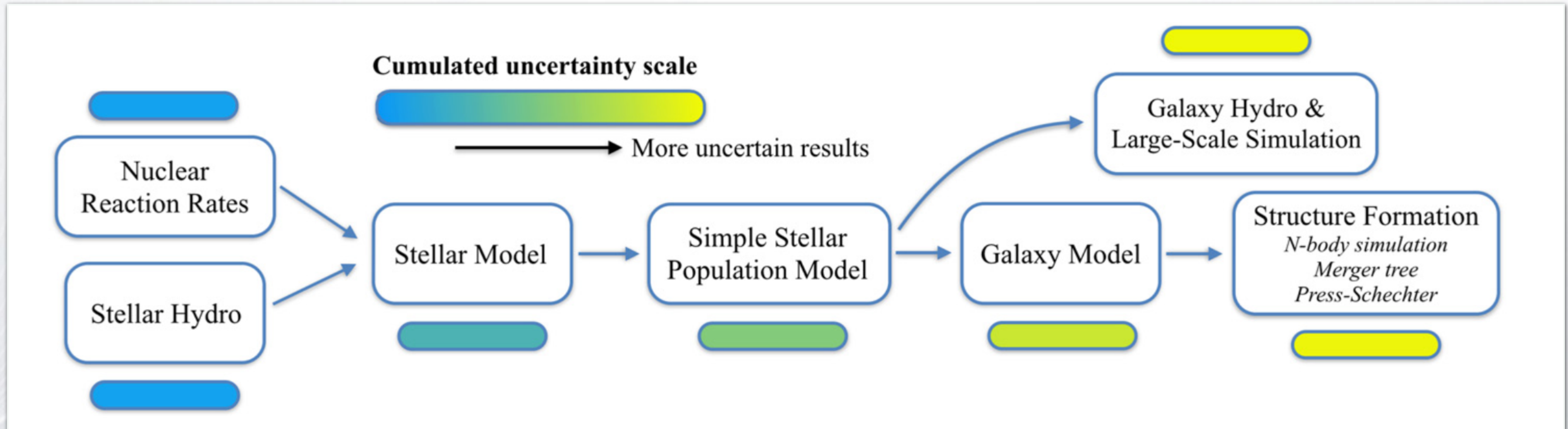
# The Impact of the Equation of State on the Physical Conditions

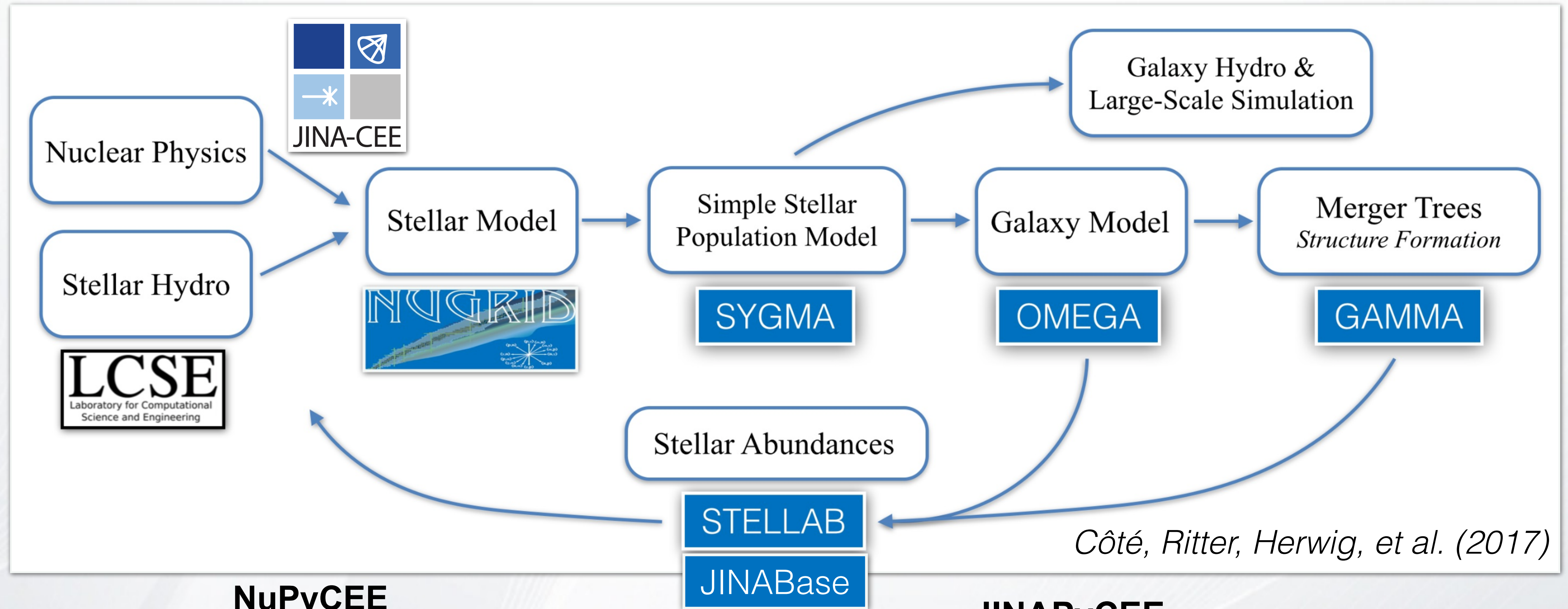
*Bovard et al. (2017)*



# Propagation of Uncertainties from Nuclear to Astronomical Scale

*Côté, Ritter, O'Shea, et al. (2016)*





## 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)

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[www.chetec.eu](http://www.chetec.eu)

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