Nuclei in the Cosmos XV
June 24-29, Assergi, L'Aquila, Italy

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

Connecting Nuclear Astrophysics to Cosmological Structure Formation

Benoit Côté
Postdoctoral Researcher

Collaborators

K. Belczynski, H. Brinkman, M. Chruslinska, M. Eichler, C. Fryer, B. Gibson, F. Herwig, S. Jones, O. Korobkin, J. Lippuner, M. Lugaro, F. Matteucci, M. Mumpower, B. O'Shea, M. Pignatari, C. Ritter, A. Ruiter, D. Silvia, B. Smith, T. Sprouse, R. Surman, N. Vassh, J. Wise, R. Wollaeger

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Connecting Nuclear Astrophysics to

Metallicity = (Mass of **metals**) / (Total mass of gas)

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Connecting Nuclear Astrophysics to

Metallicity = (Mass of **metals**) / (Total mass of gas)

Metals = All the elements.. except H and He

Collaborators

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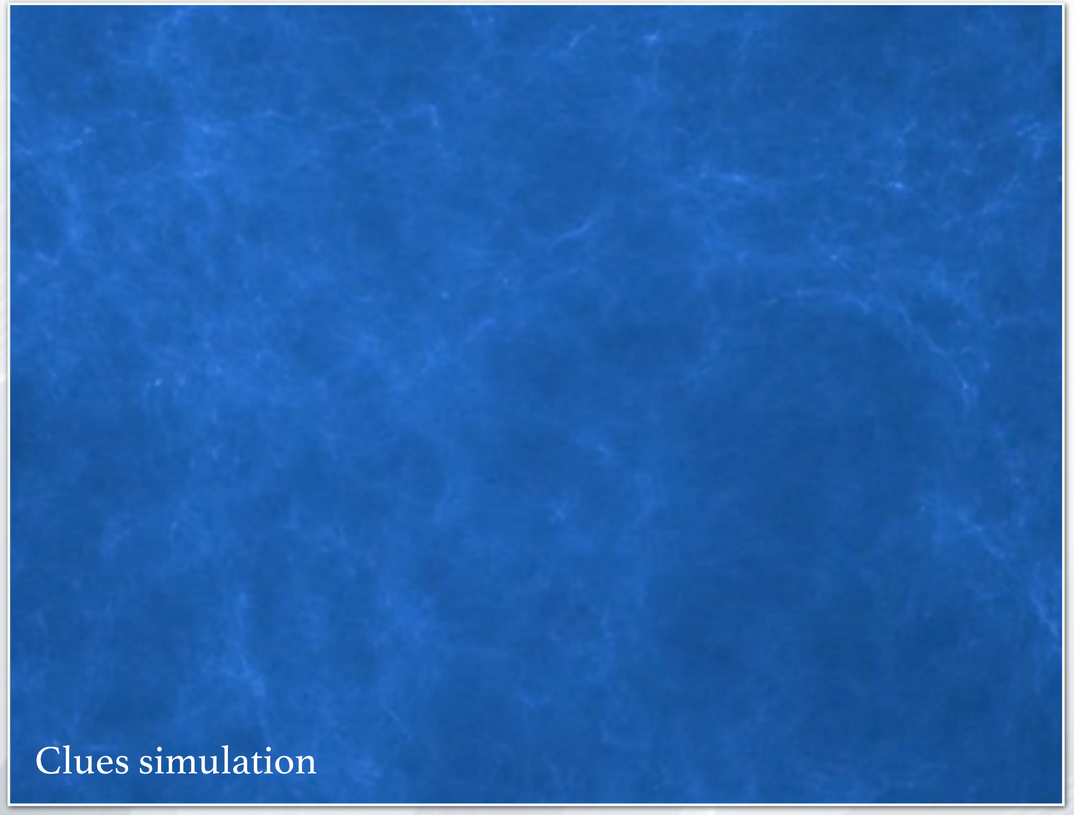
CHEMICAL EVOLUTION

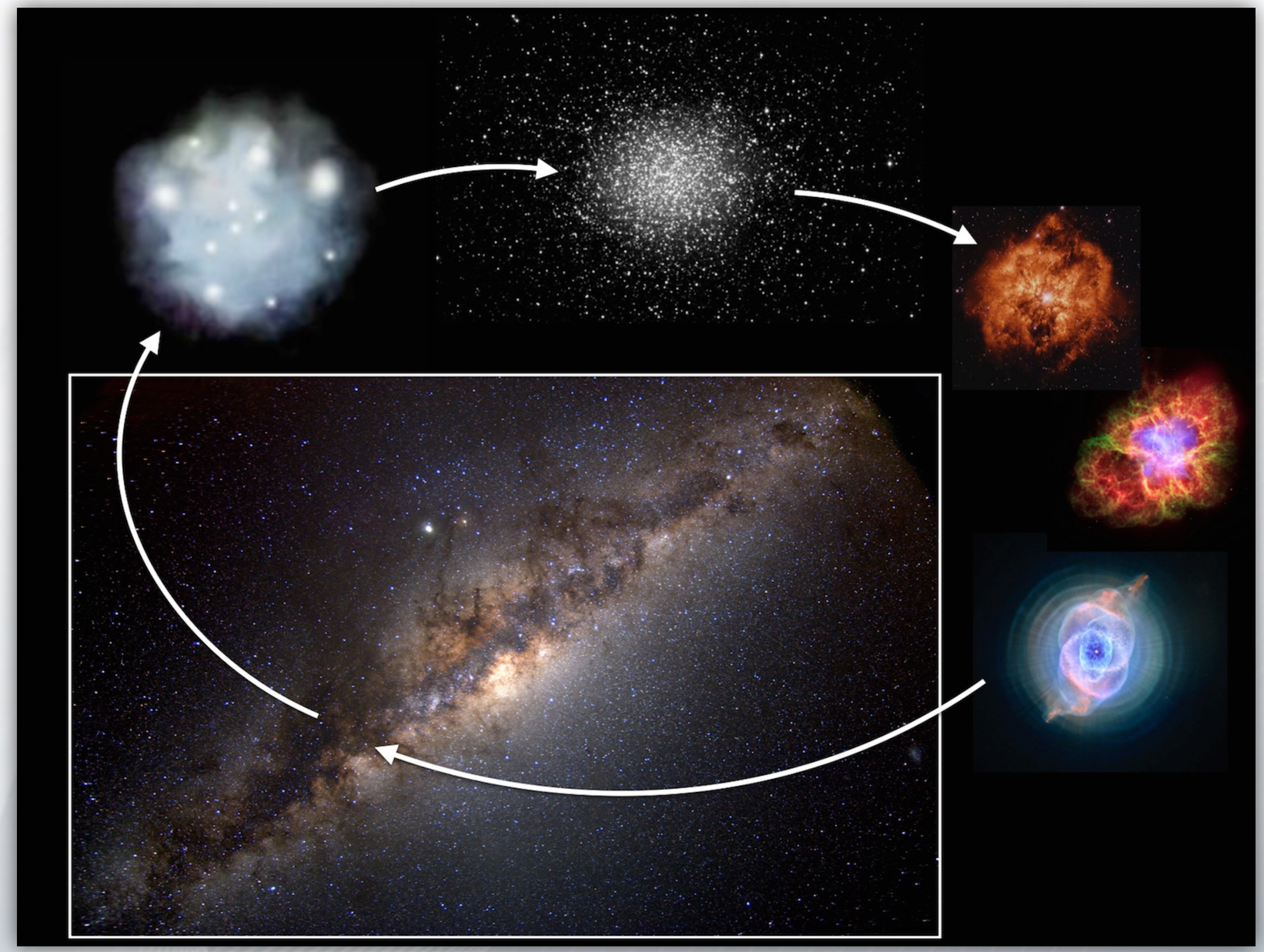
Early universe (Big Bang nucleosynthesis)
H, He, Li



Current universe (~13 Gyr later)
H, He, Li, C, N, O, Fe, Ni, Sr, Y, Ba, Eu, Ir, Hf, ...

LIFE CYCLE OF STARS

Made with images from: S. Brunier, J. Schmidt, J. Hester, A. Loll, R. Gehrz, Pearson Education, 2MASS project, NASA, STScI, ESA, CXC, ASU, HEIC, Hubble/Chandra/Spitzer Space Telescopes, JPL-Caltech, U. of Minnesota.



OBSERVING CHEMICAL EVOLUTION

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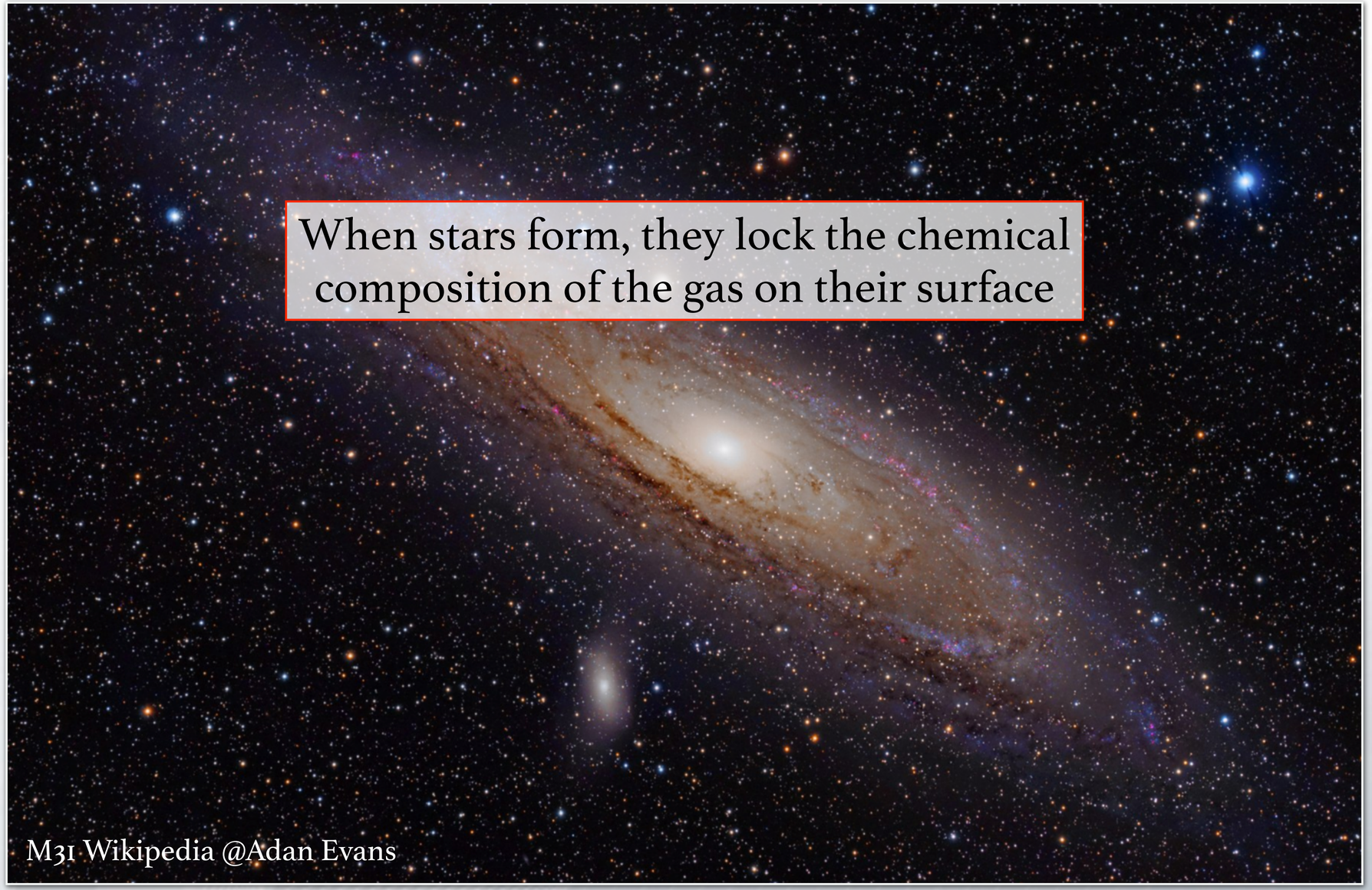
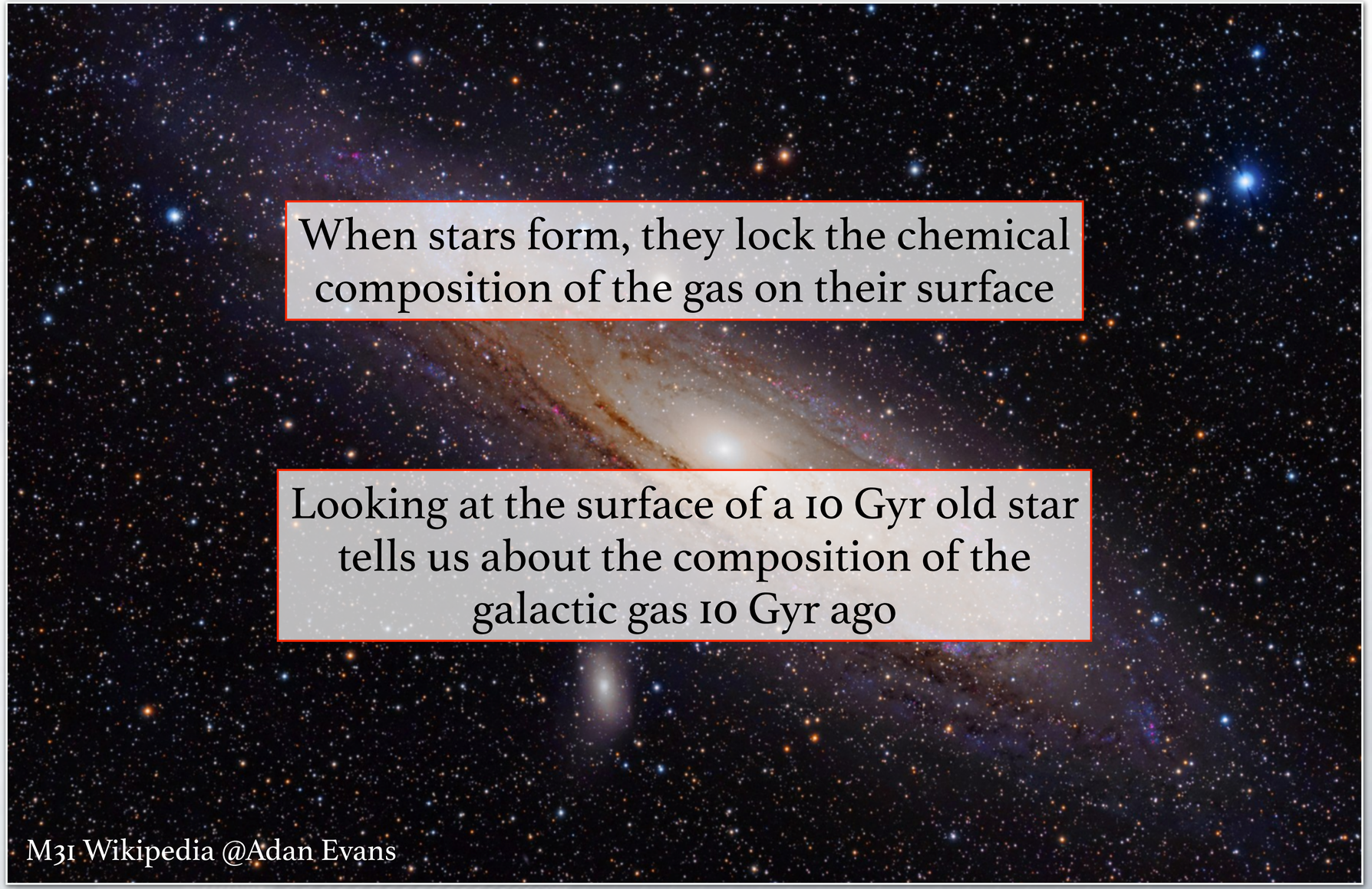
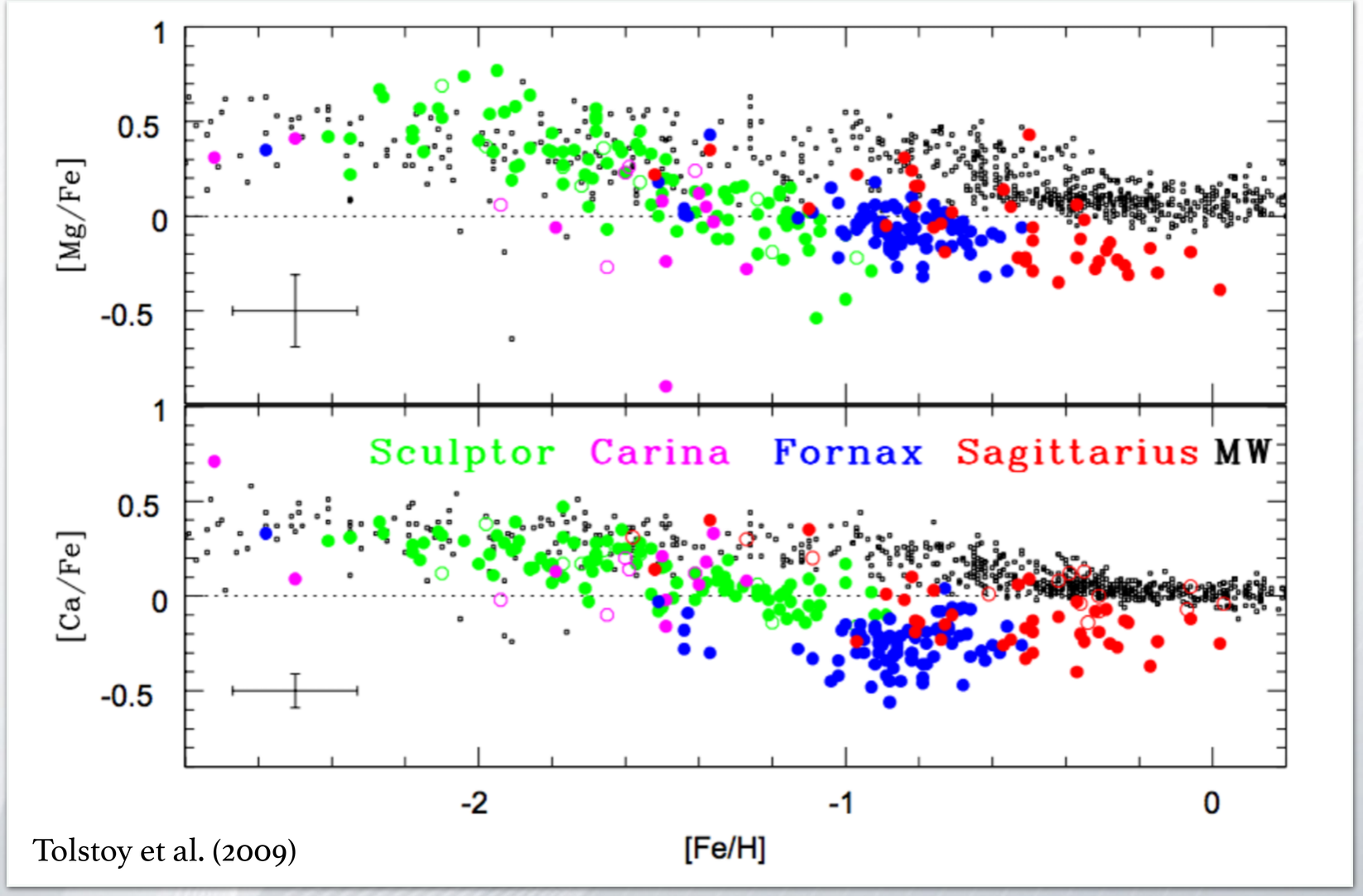


OBSERVING CHEMICAL EVOLUTION



STELLAR ABUNDANCES IN DIFFERENT GALAXIES

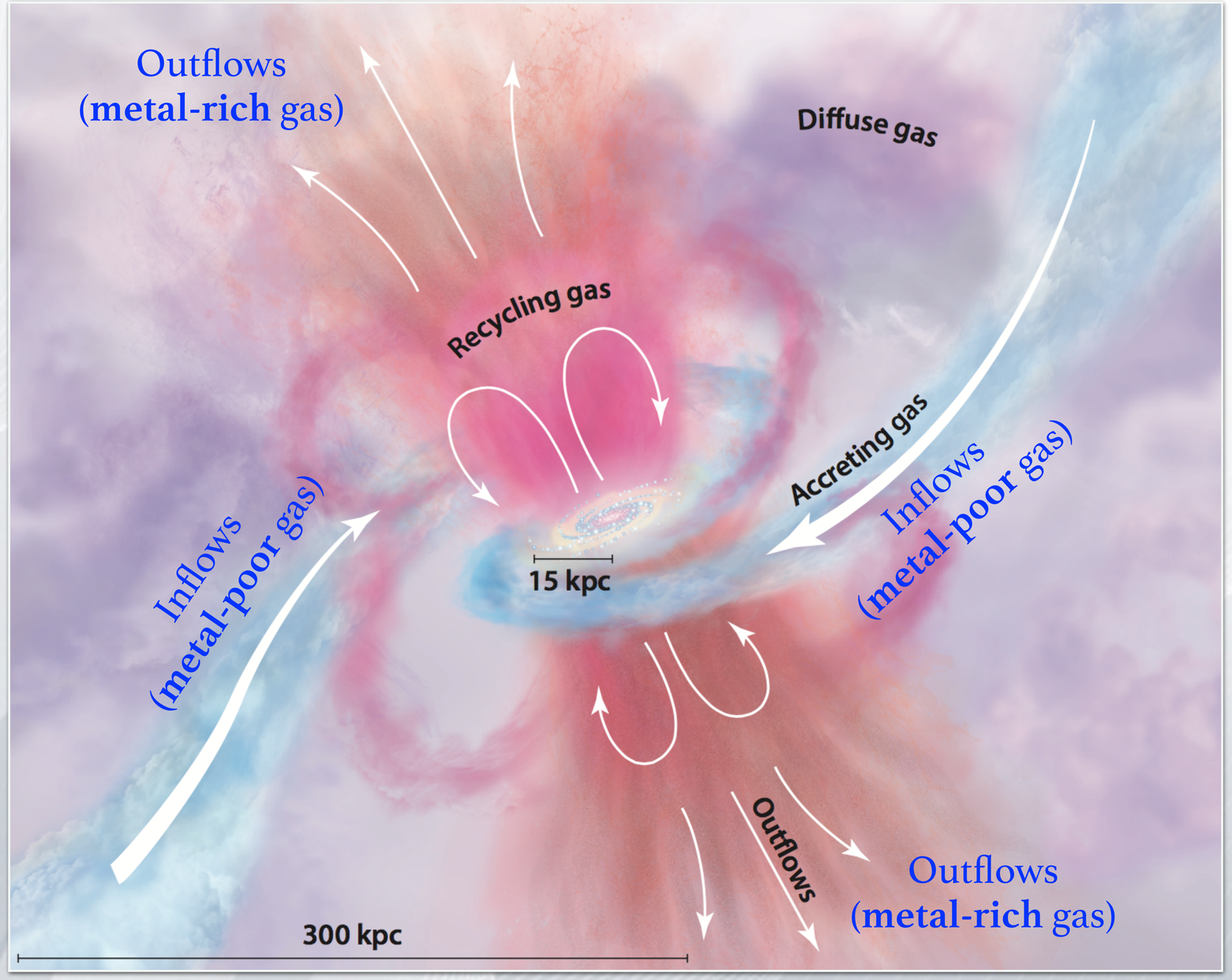
Milky Way and dwarf spheroidal galaxies



Tolstoy et al. (2009)

GAS CIRCULATION AT LARGE SCALE

Tumlinson, Peeples & Werk (2017)



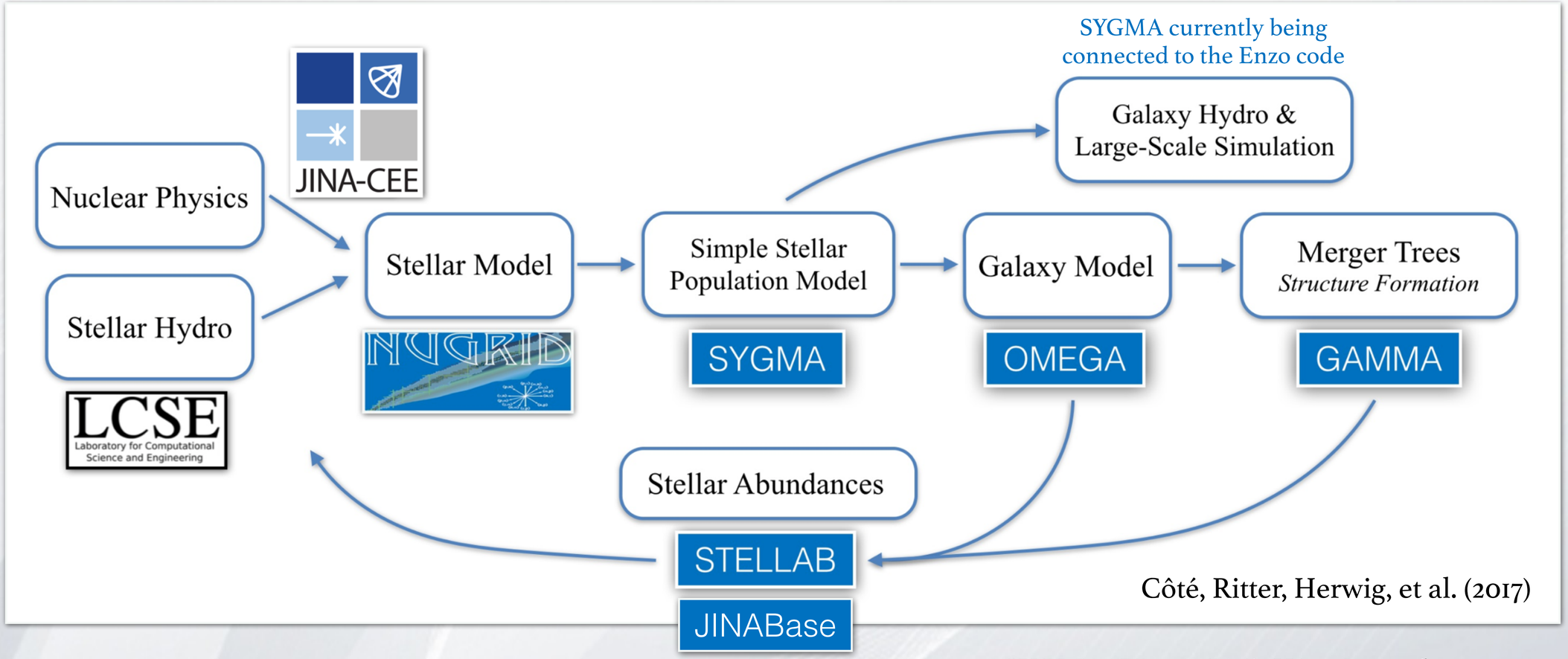
Galaxies are not isolated object
They interact with their surrounding

Inflows will dilute the metal concentration of the galactic gas

Outflows remove metals from galaxies

OPEN-SOURCE CHEMICAL EVOLUTION PIPELINE

See also ChemPy: Rykizki, Just & Rix (2017)
flexCE: Andrews, Weinberg, Schönrich, et al. (2017)



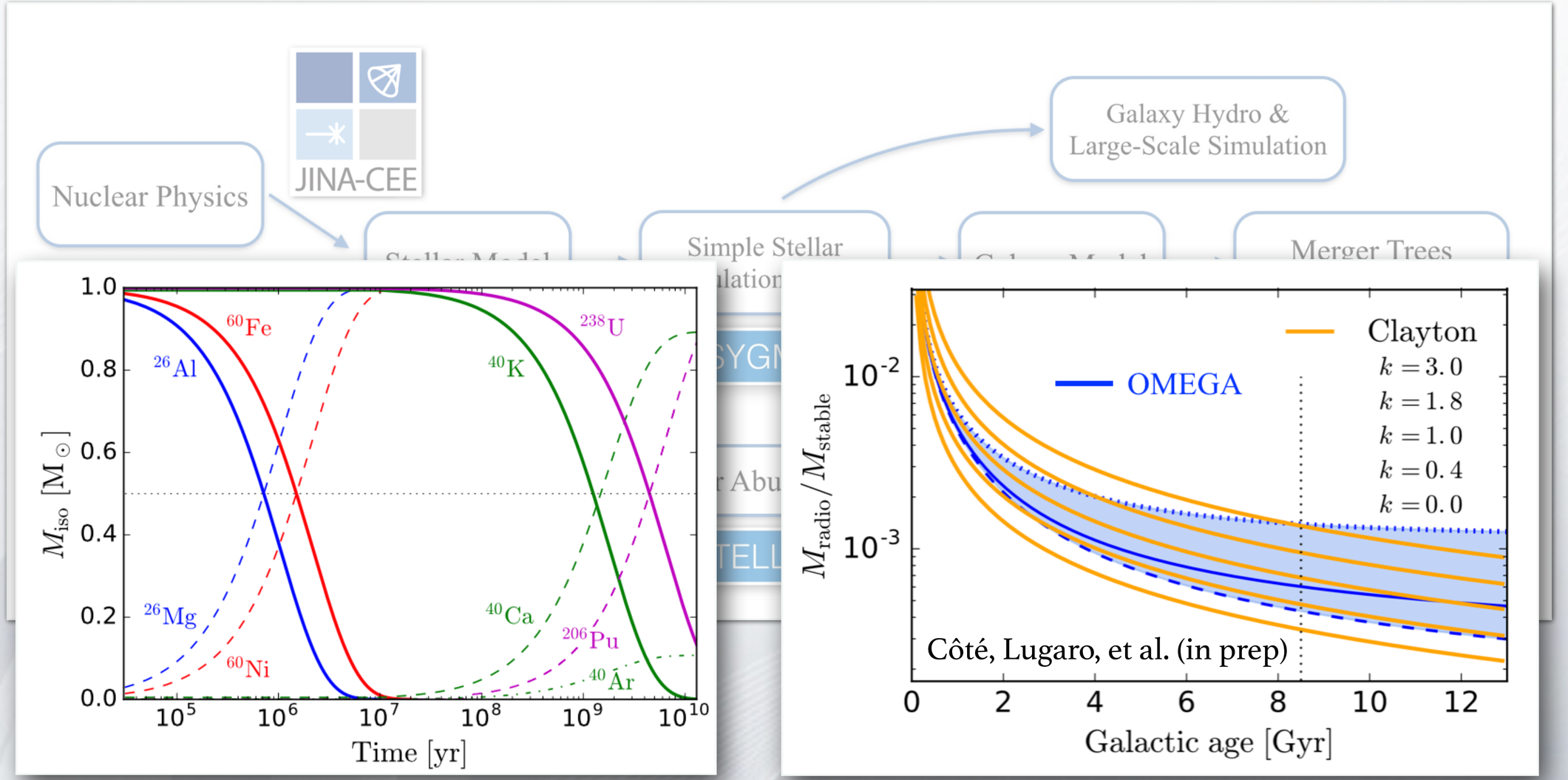
Côté, Ritter, Herwig, et al. (2017)

NuPyCEE
NuGrid Python Chemical Evolution Environment
https://github.com/NuGrid/NuPyCEE

JINAPyCEE
JINA Python Chemical Evolution Environment
https://github.com/becot85/JINAPyCEE

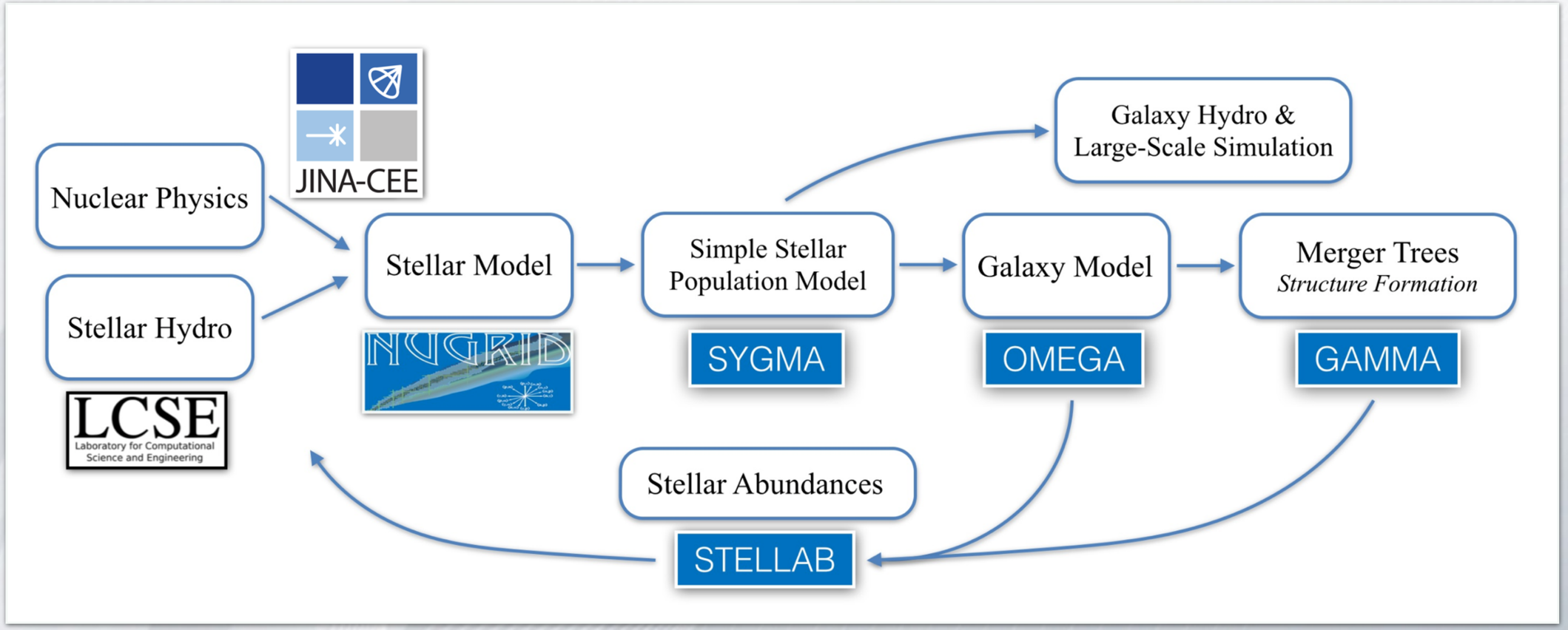
SYGMA (Ritter, Côté, Herwig, et al. 2017)
OMEGA (Côté, O'Shea, Ritter, et al. 2017)
STELLAB (Côté & Ritter 2016)
OMEGA+ (Côté, Silvia, O'Shea, et al. 2018)
GAMMA (Côté, Silvia, O'Shea, et al. 2018)
JINABase for low-Z (Abohalima & Frebel, 2017)
http://jinabase.pythonanywhere.com/plot

OPEN-SOURCE CHEMICAL EVOLUTION PIPELINE



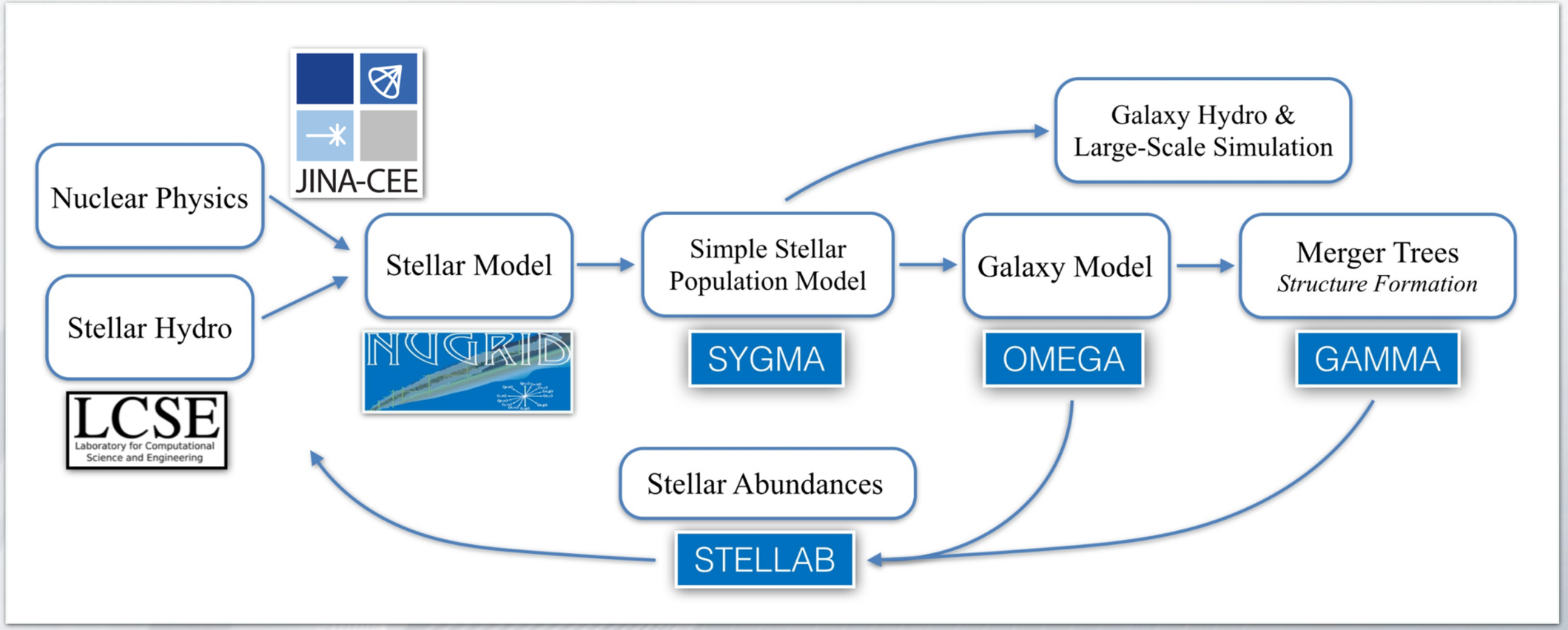
Chemical evolution of radioactive isotopes

CHEMICAL EVOLUTION AT DIFFERENT SCALES



CHEMICAL EVOLUTION AT DIFFERENT SCALES

Probe the origin of the elements
Confront nuclear astrophysics with observations

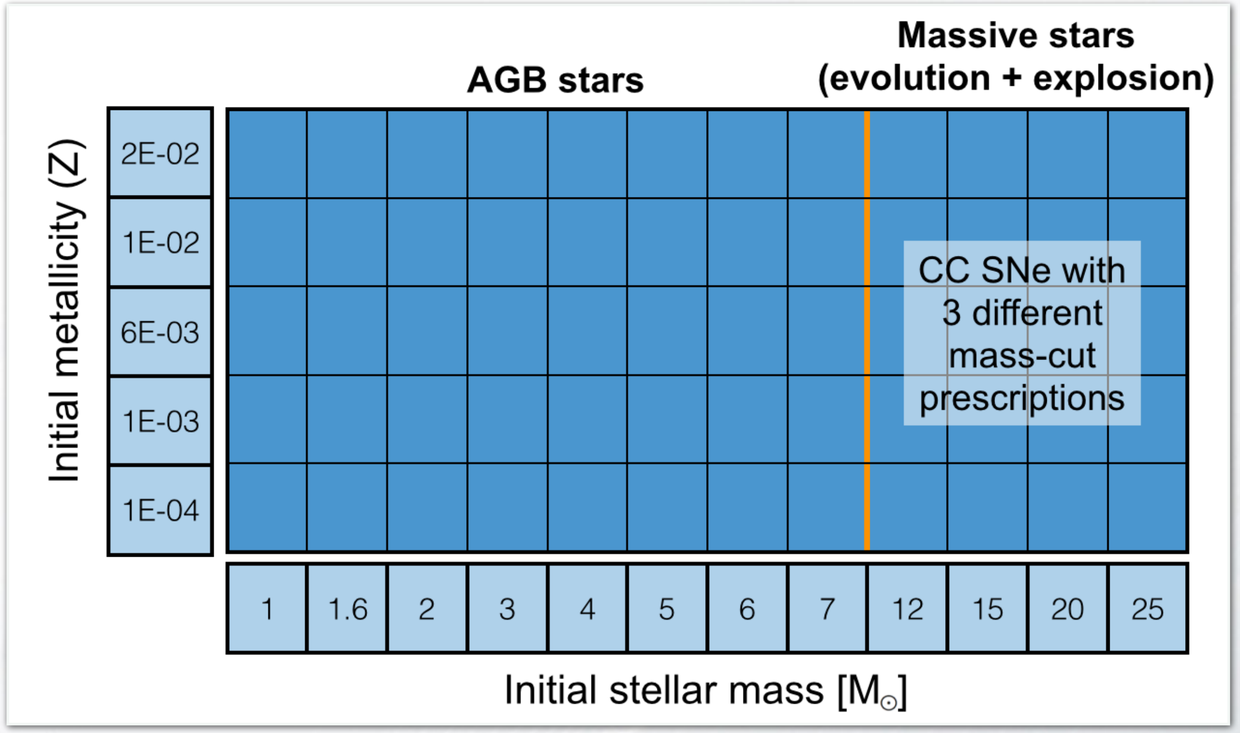


PRODUCTION OF ODD-Z ELEMENTS

NuGrid yields — Set II

Ritter, Herwig, Jones, et al. (2017, accepted)

- Same code, same physics assumptions
- Stellar yields from H to Bi (280 stable isotopes)
- All models are publicly available online
  - See Cyberhubs (Herwig, Andrassy, Annau, et al. 2018)



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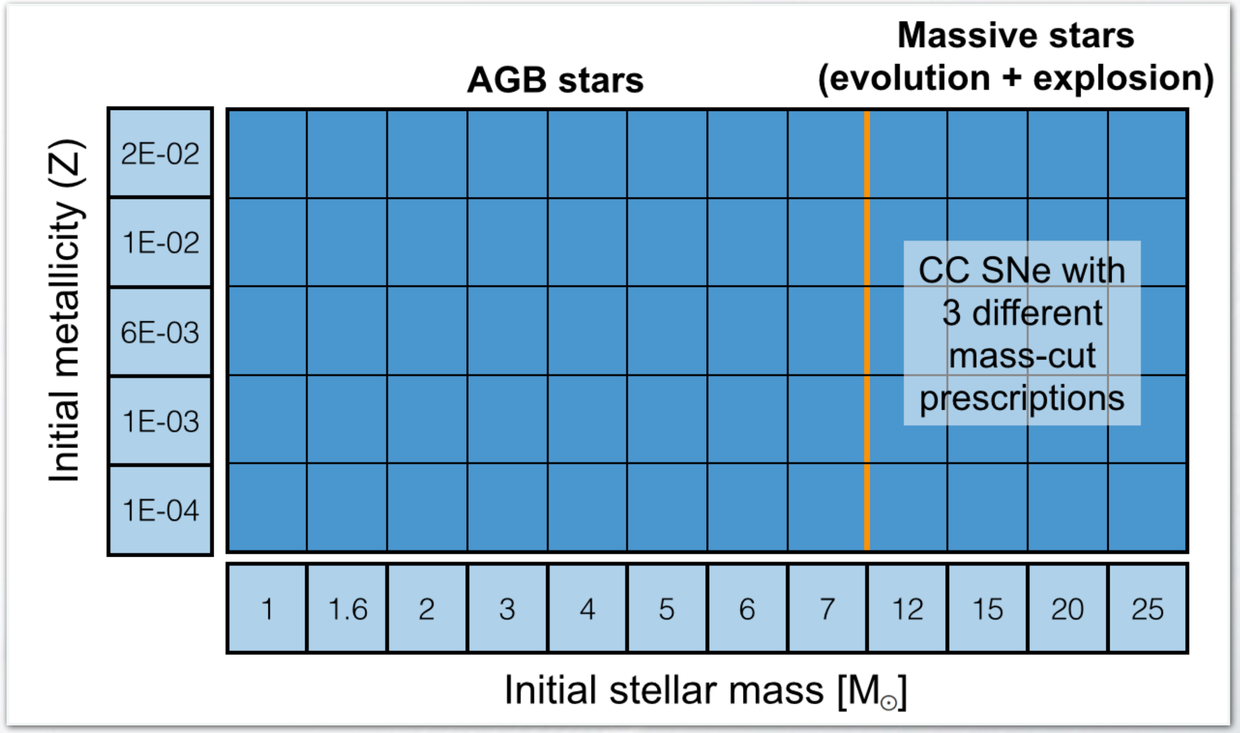
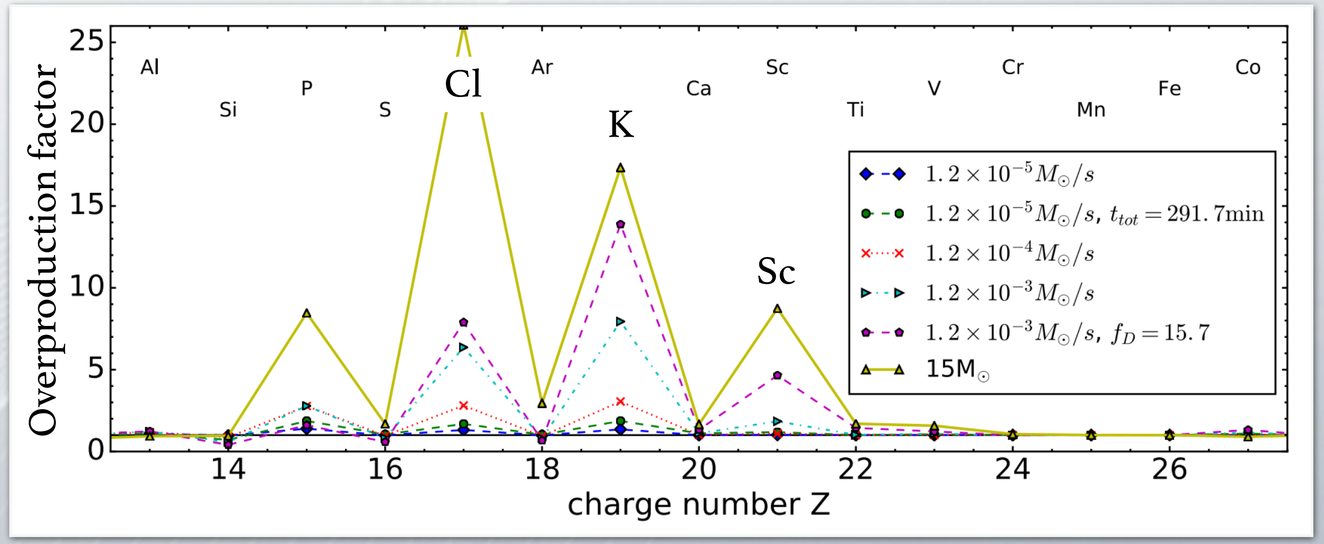


Ritter, Andrassy, Côté, et al. (2018)

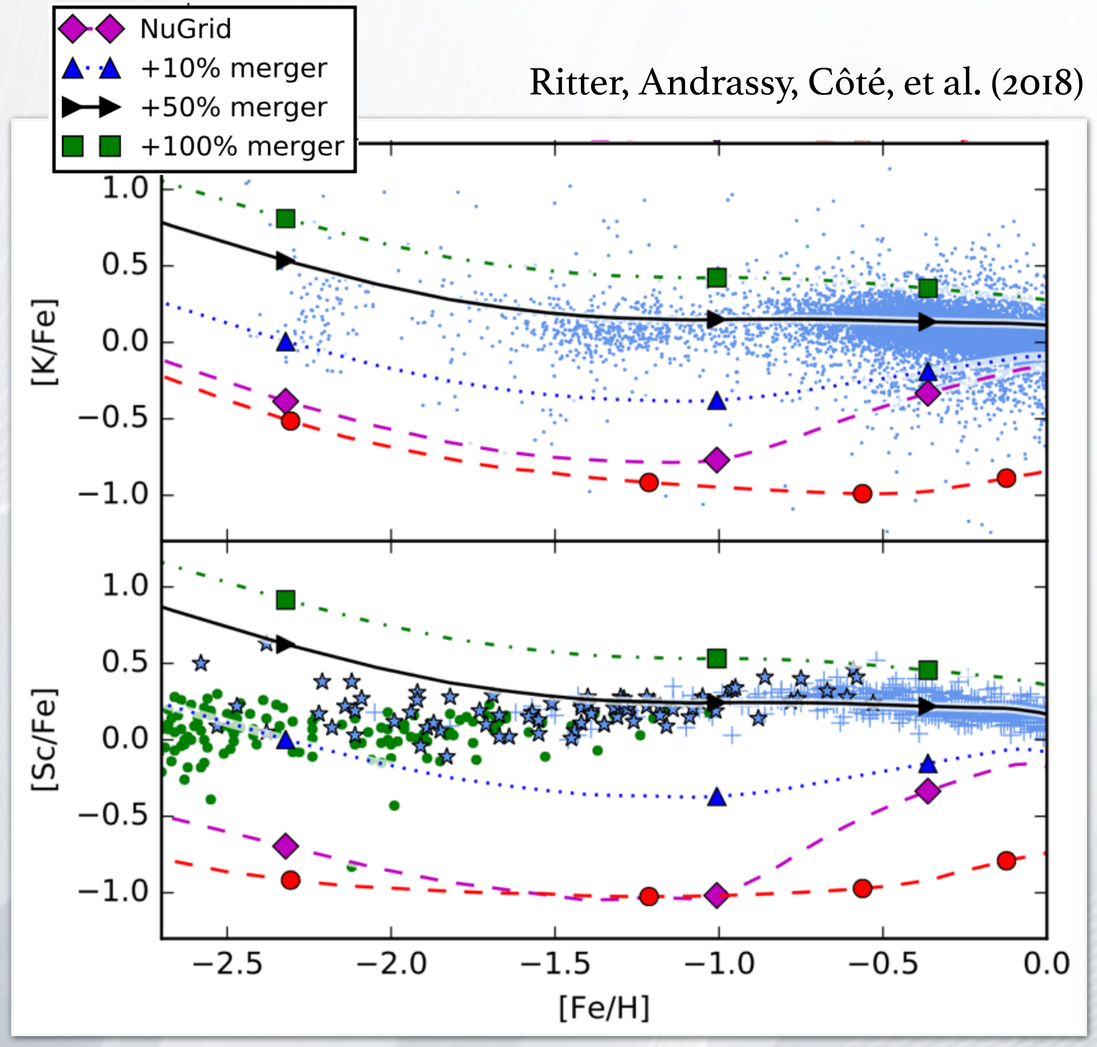
Convective-reactive nucleosynthesis

Production of odd-Z elements in C-O shell mergers

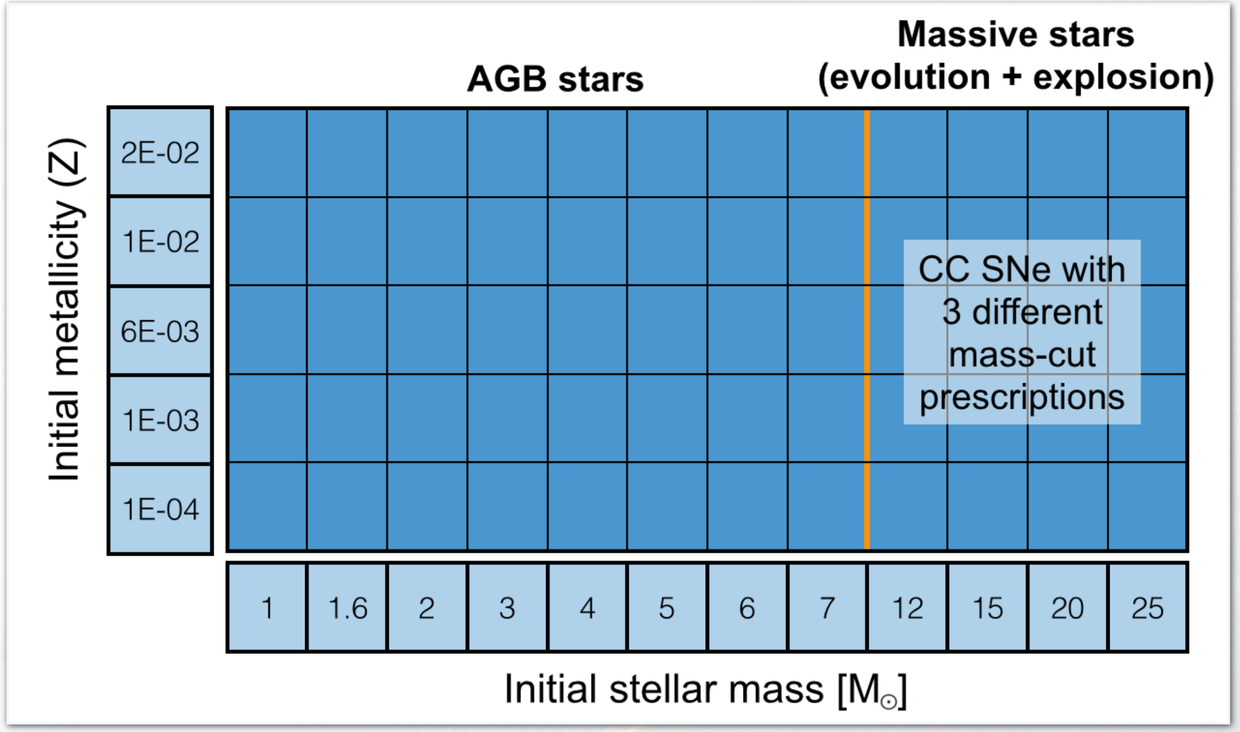


PRODUCTION OF ODD-Z ELEMENTS

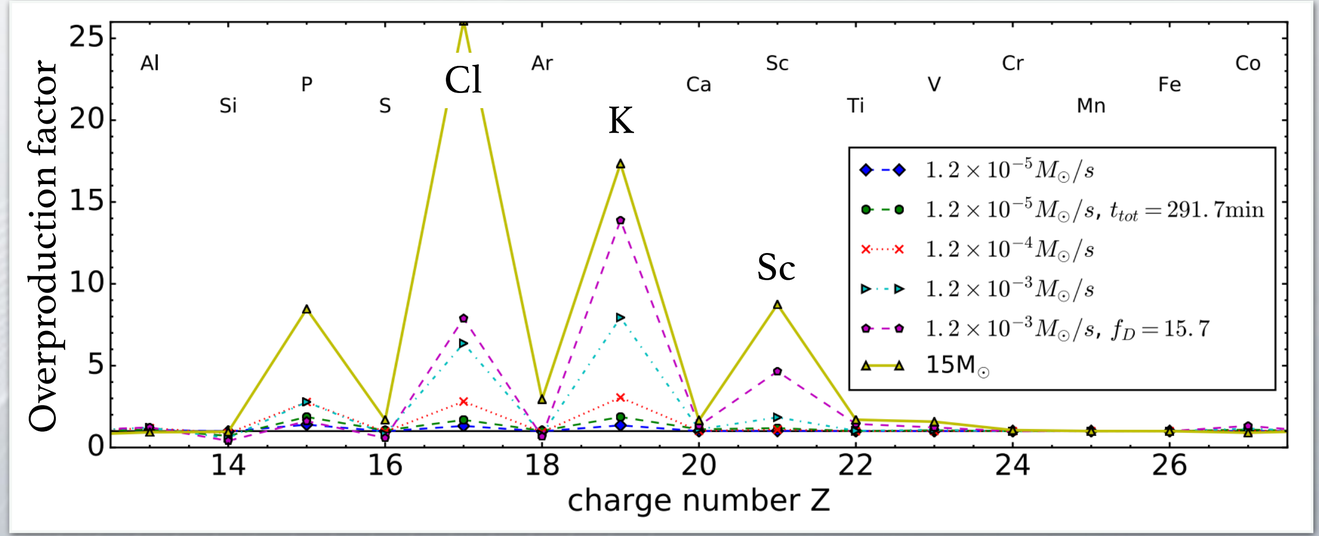
Ritter, Andrassy, Côté, et al. (2018)



Simple test with the Milky Way

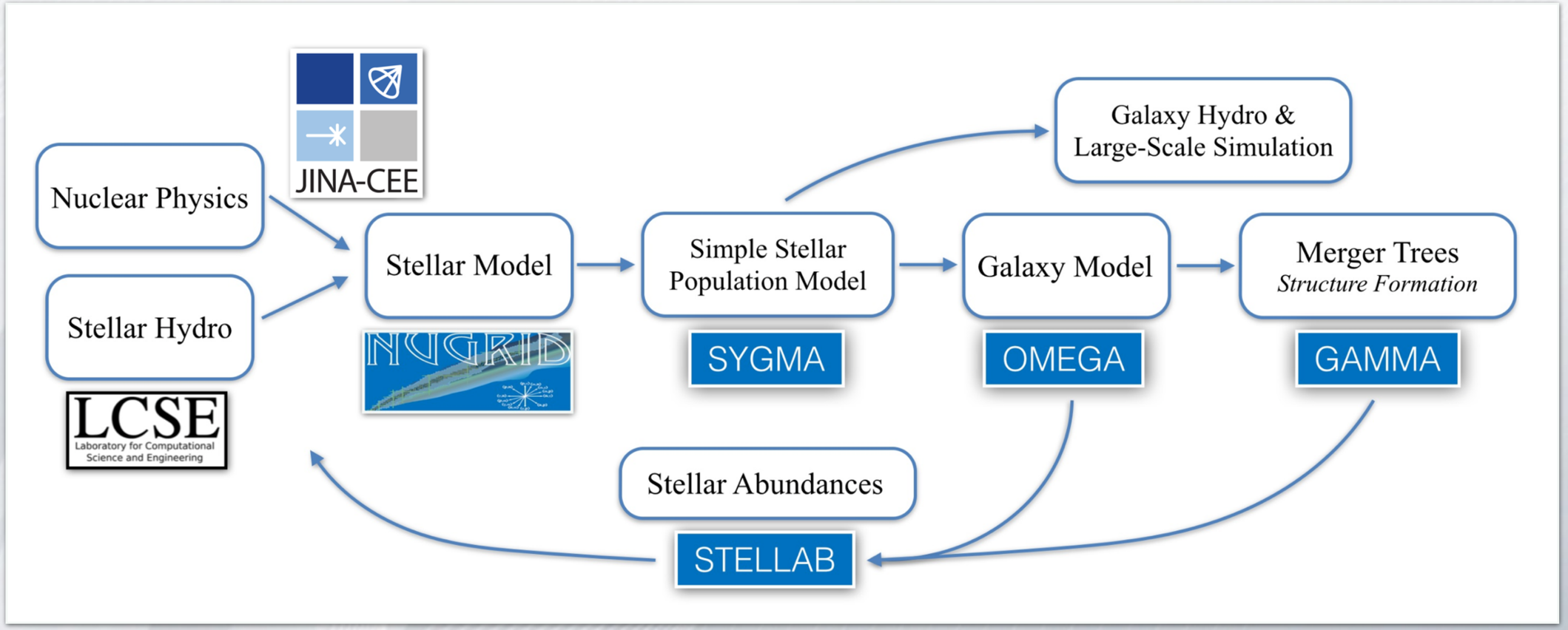


Ritter, Andrassy, Côté, et al. (2018)



CHEMICAL EVOLUTION AT DIFFERENT SCALES

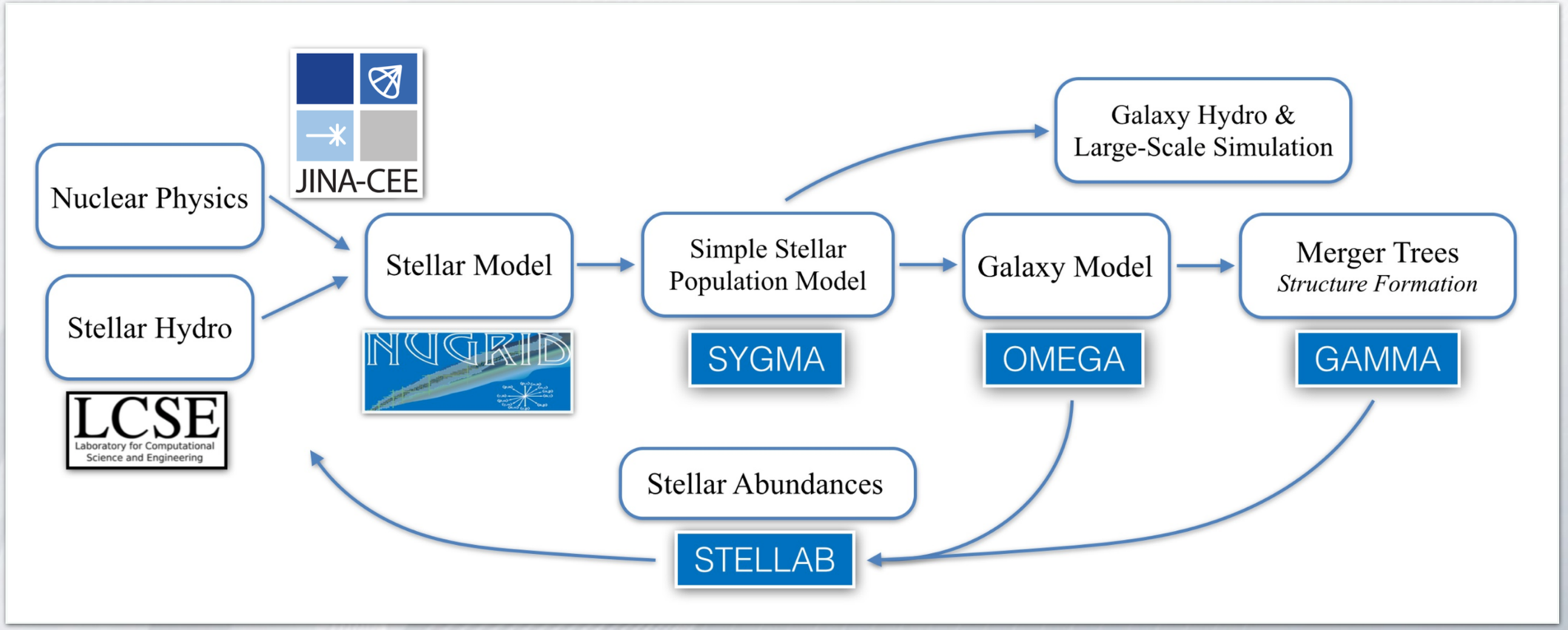
Probe the origin of the elements
Confront nuclear astrophysics with observations



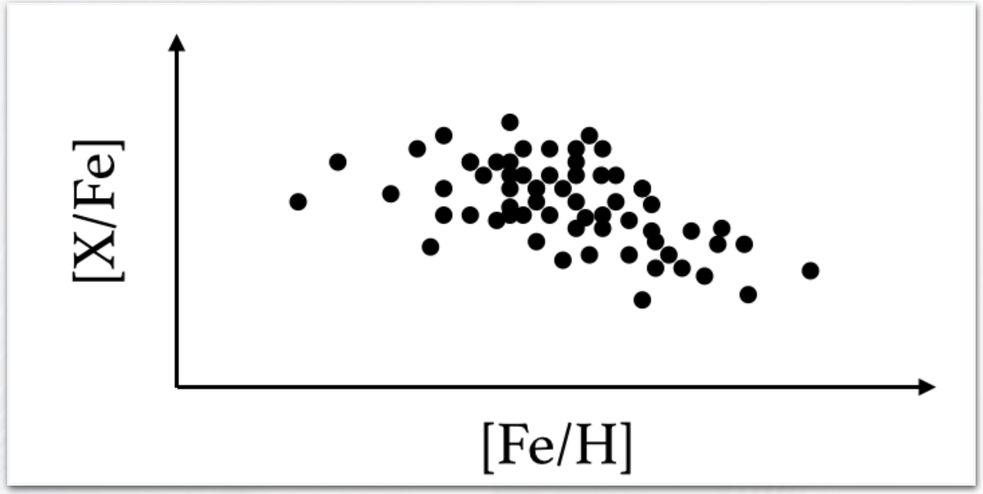
CHEMICAL EVOLUTION AT DIFFERENT SCALES

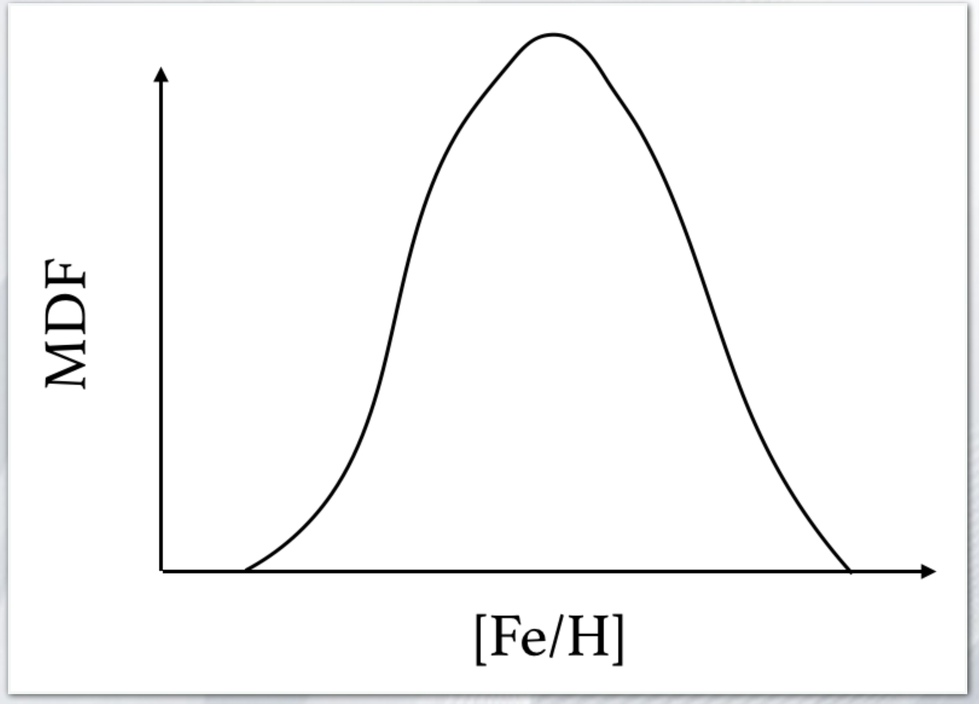
Probe the origin of the elements
Confront nuclear astrophysics with observations

Probe the role of galaxy formation
Using chemical abundances to trace the evolution of galaxies



METALLICITY DISTRIBUTION FUNCTION (**MDF**)





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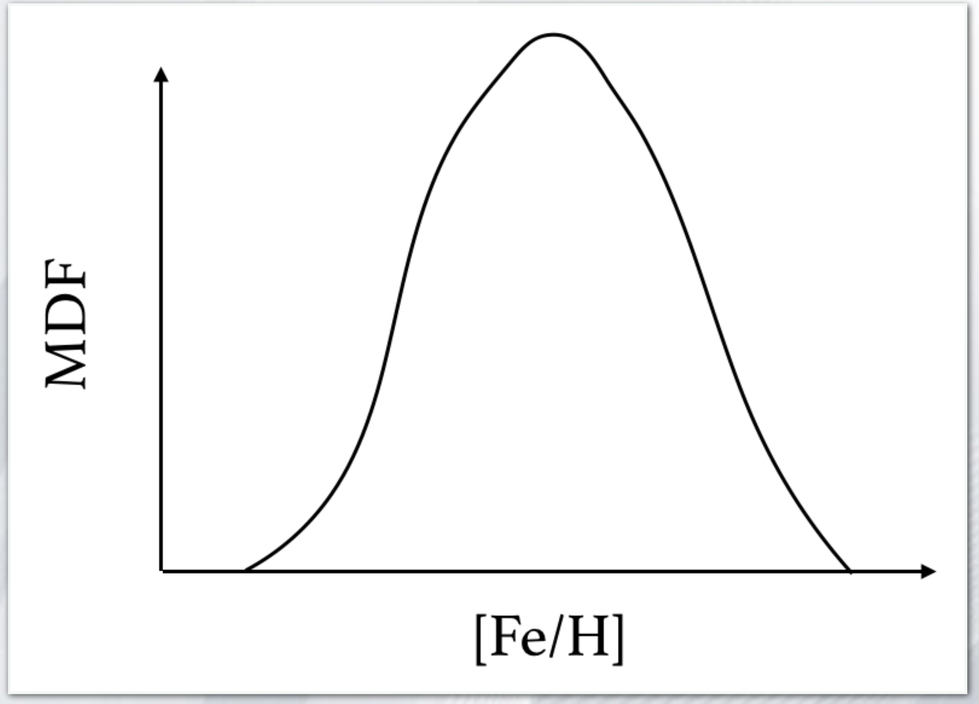

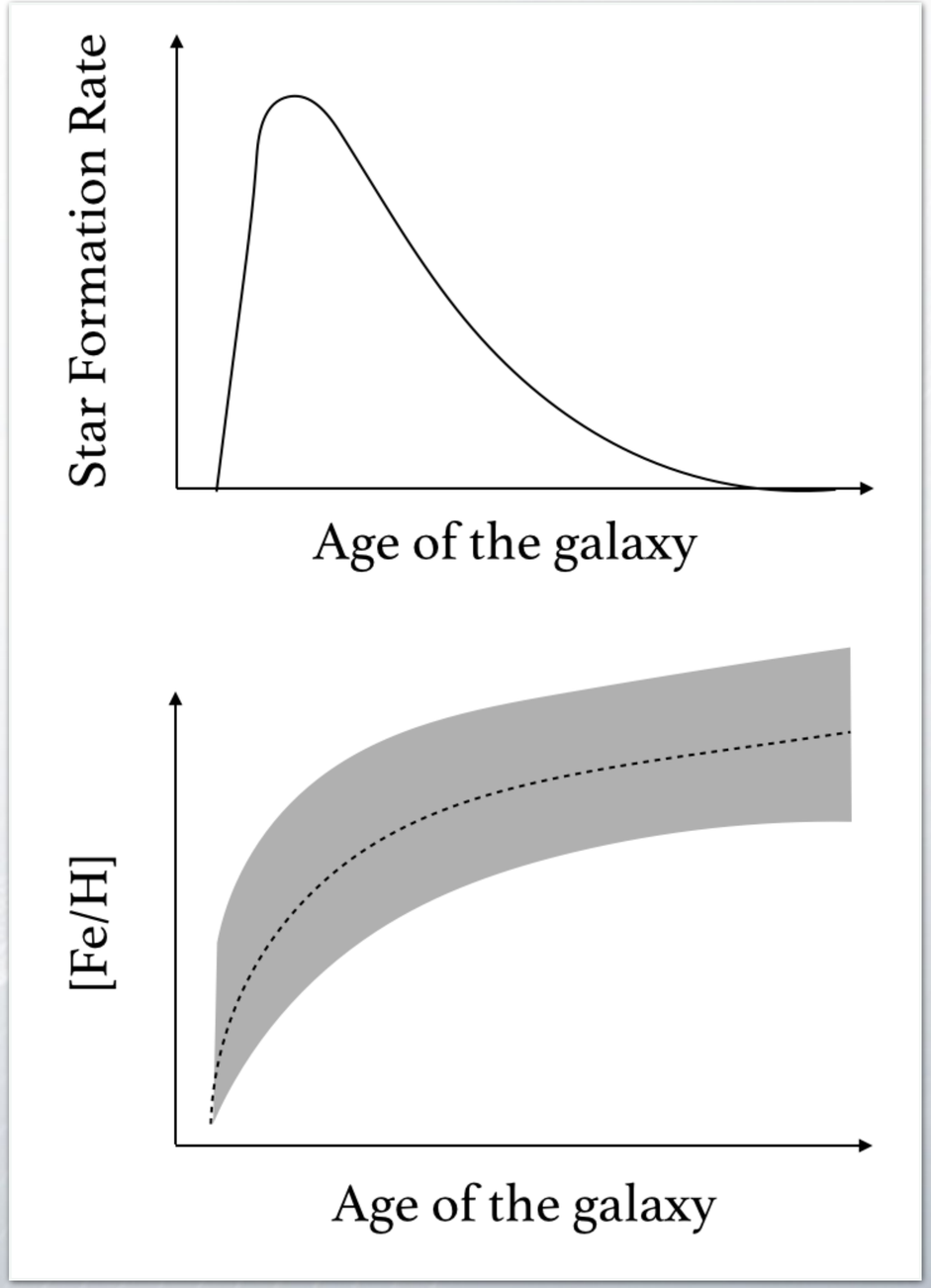

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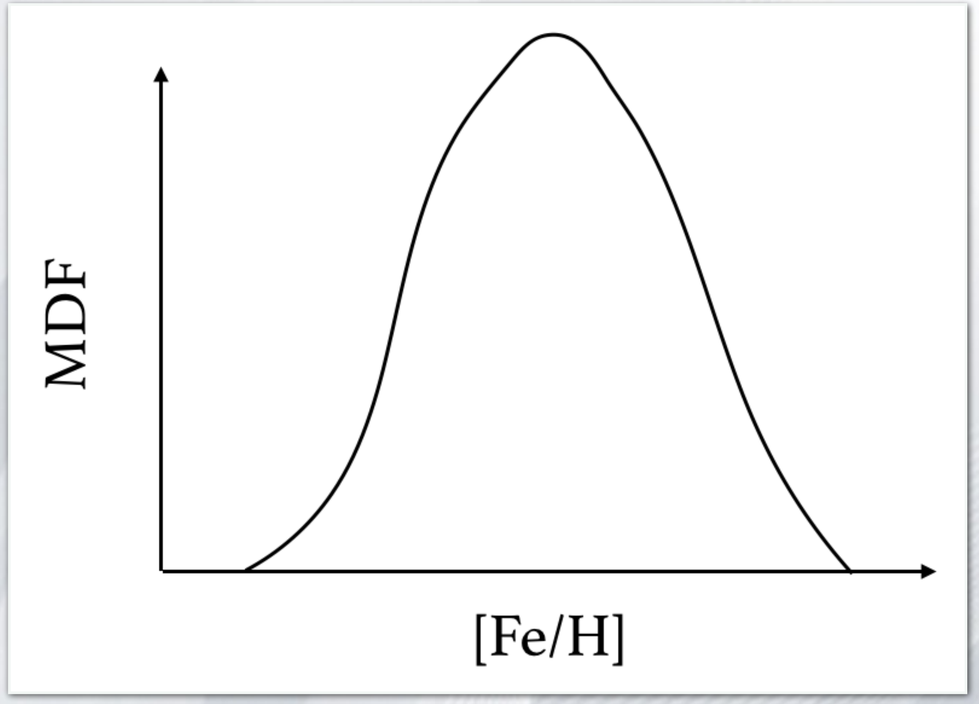
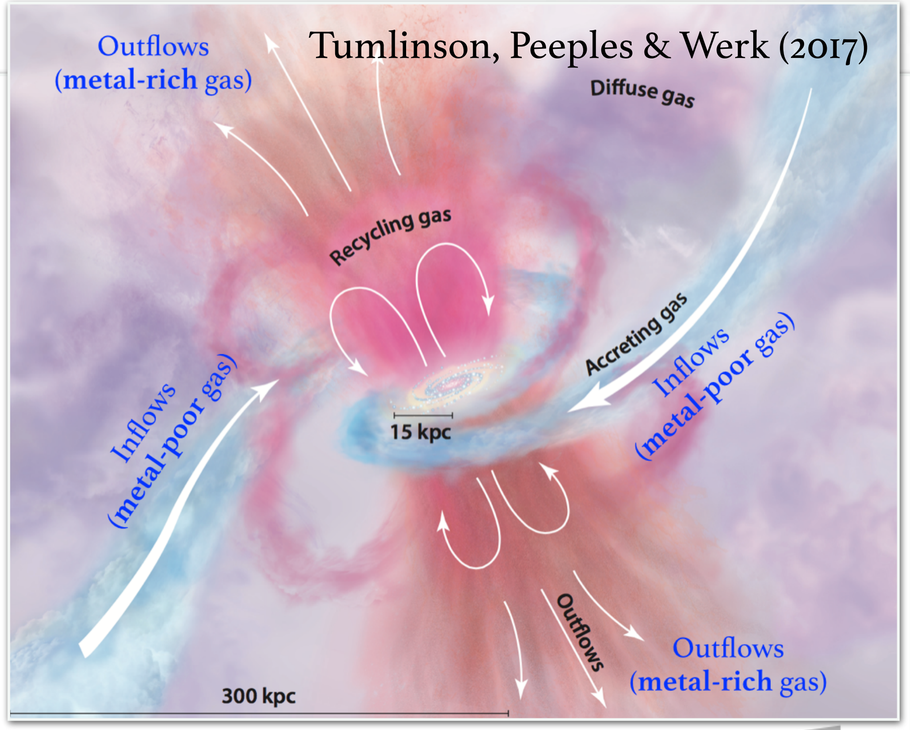
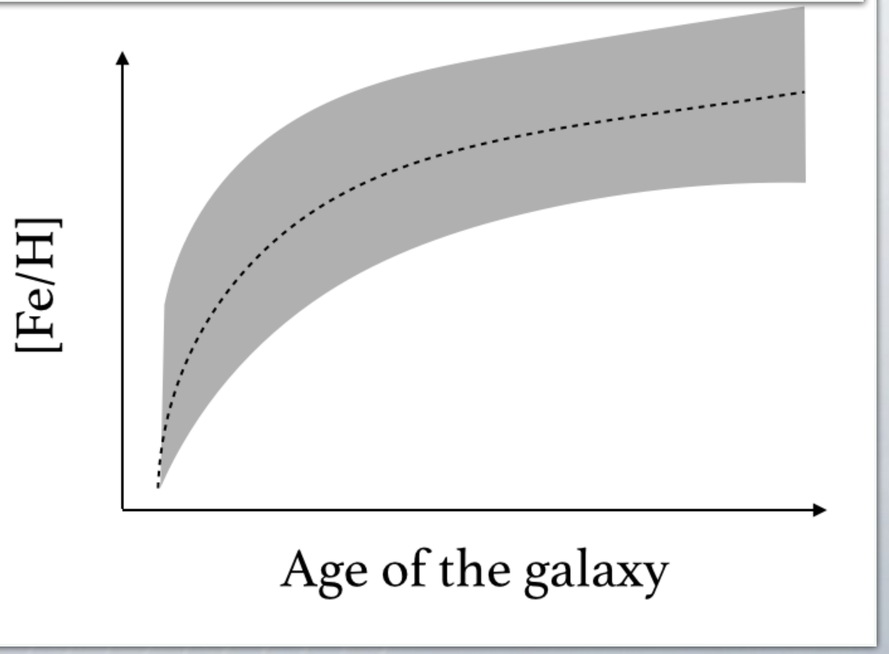
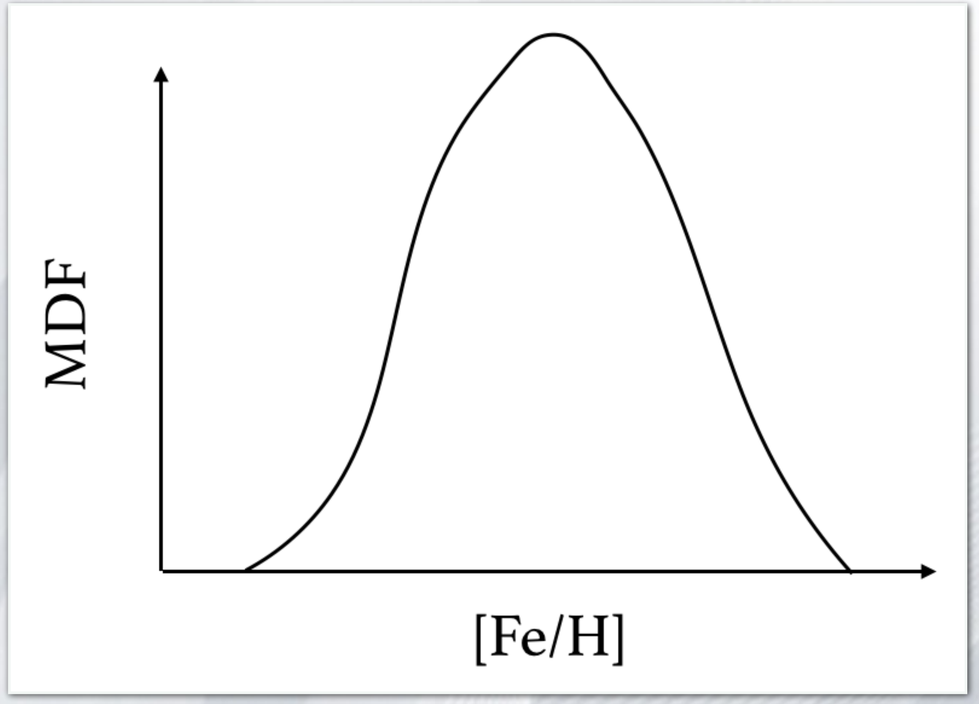


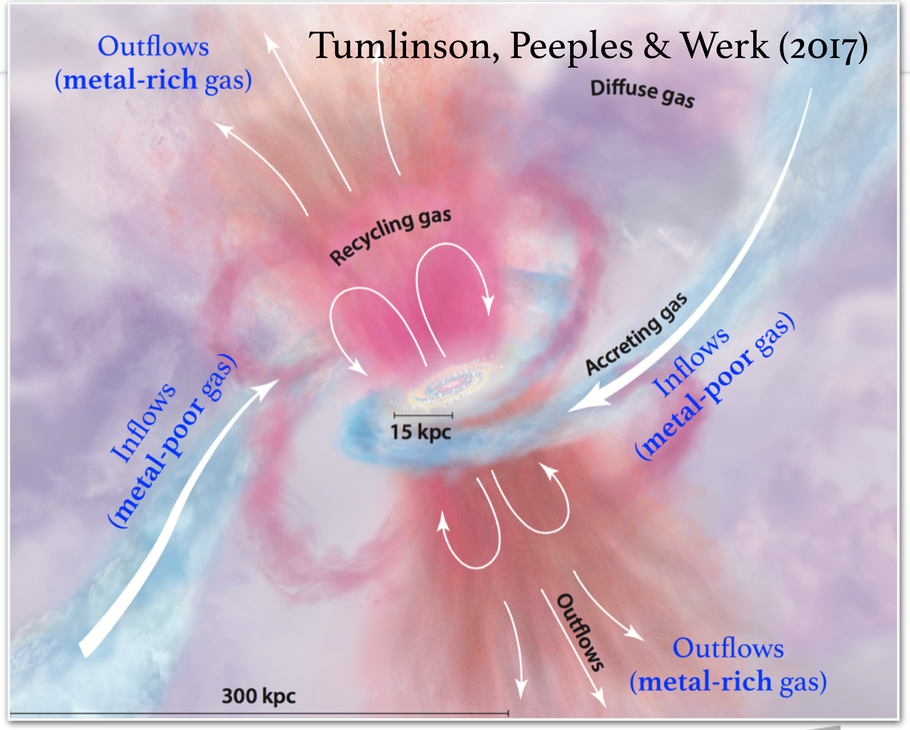


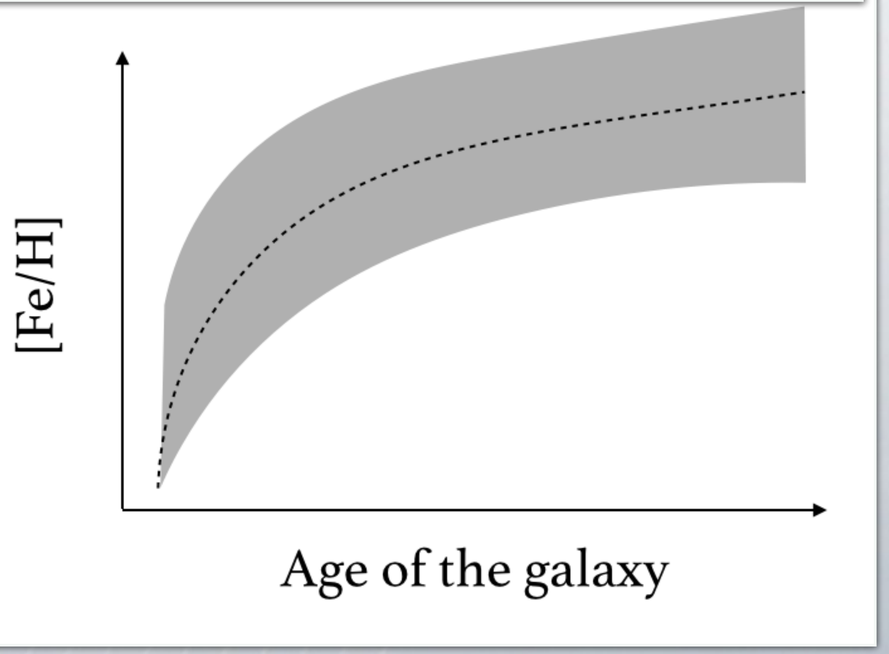


METALLICITY DISTRIBUTION FUNCTION (**MDF**)

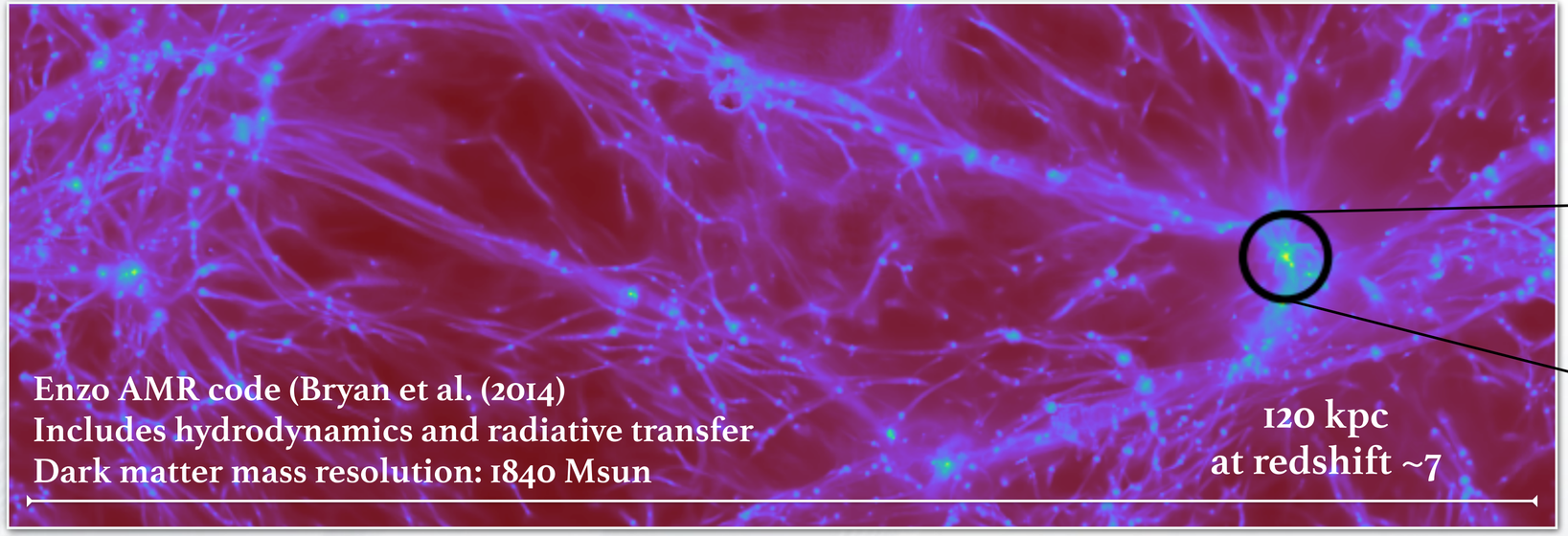
Can we constrain the gas circulation of a galaxy by fitting its MDF with models?

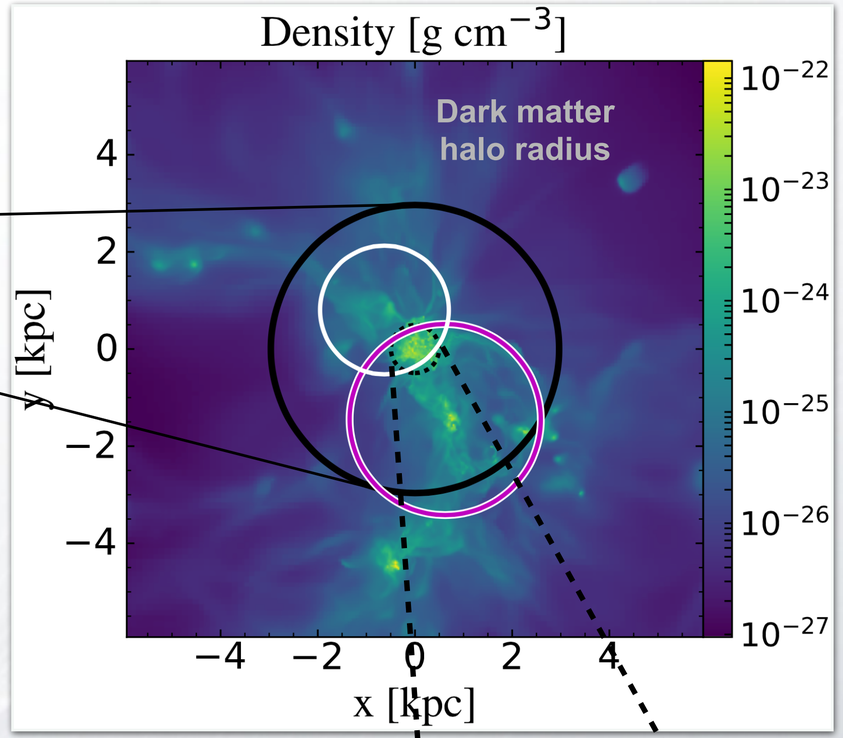






GALAXY FORMATION IN A COSMOLOGICAL CONTEXT





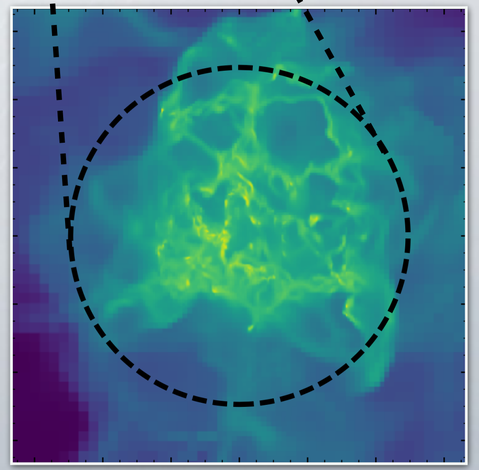
Côté, Silvia, O'Shea, et al. (2018)

Re-analyzing the simulation of Wise et al. (2012)

$M_{\rm DM} = 5.5 \times 10^8\ M_\odot$

$M_\star = 3.5 \times 10^6\ M_\odot$

Final redshift = 7.3



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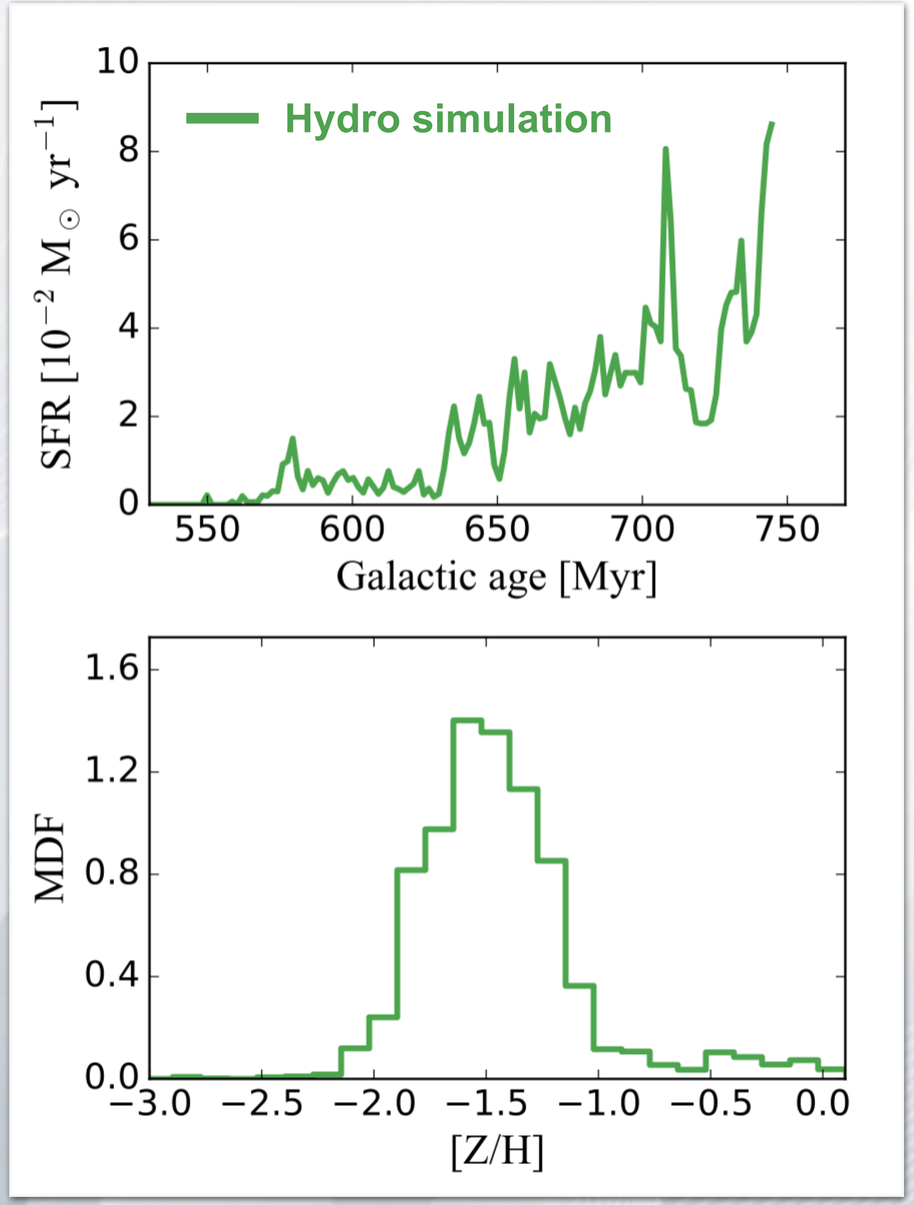

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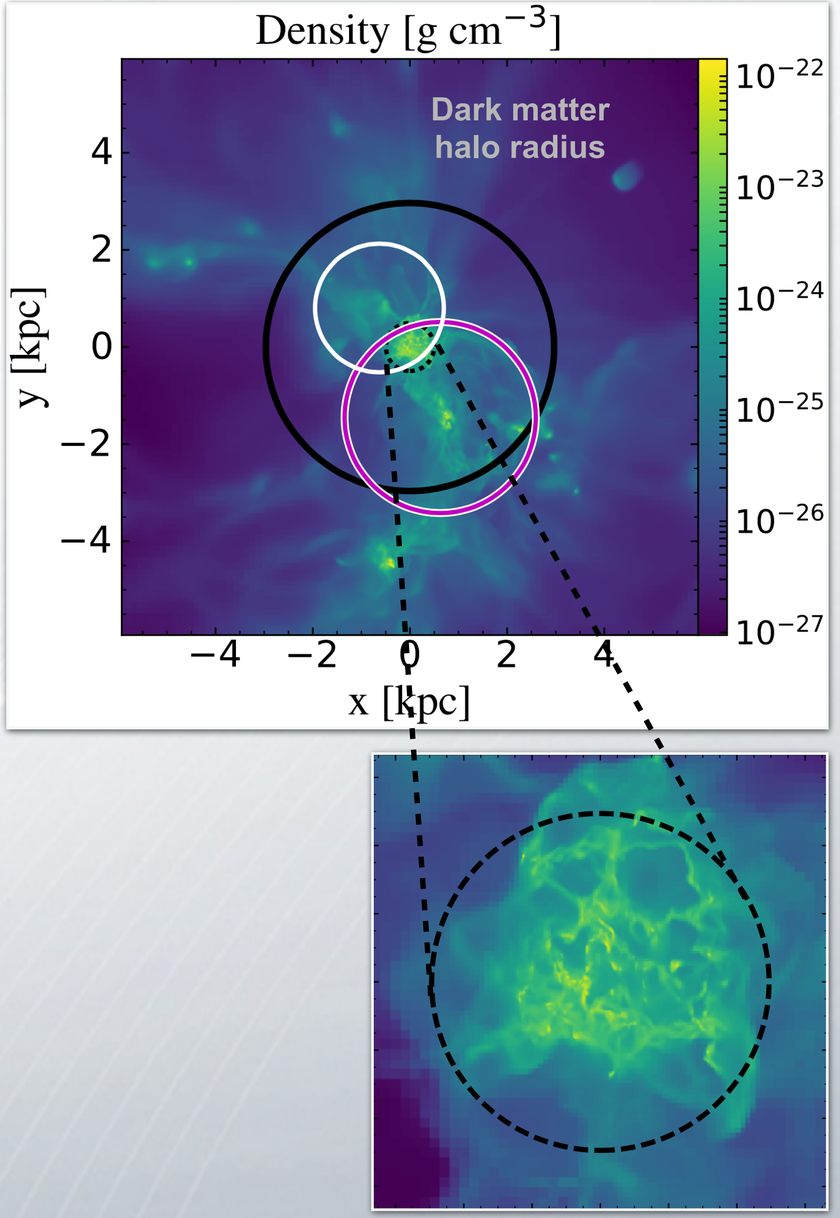

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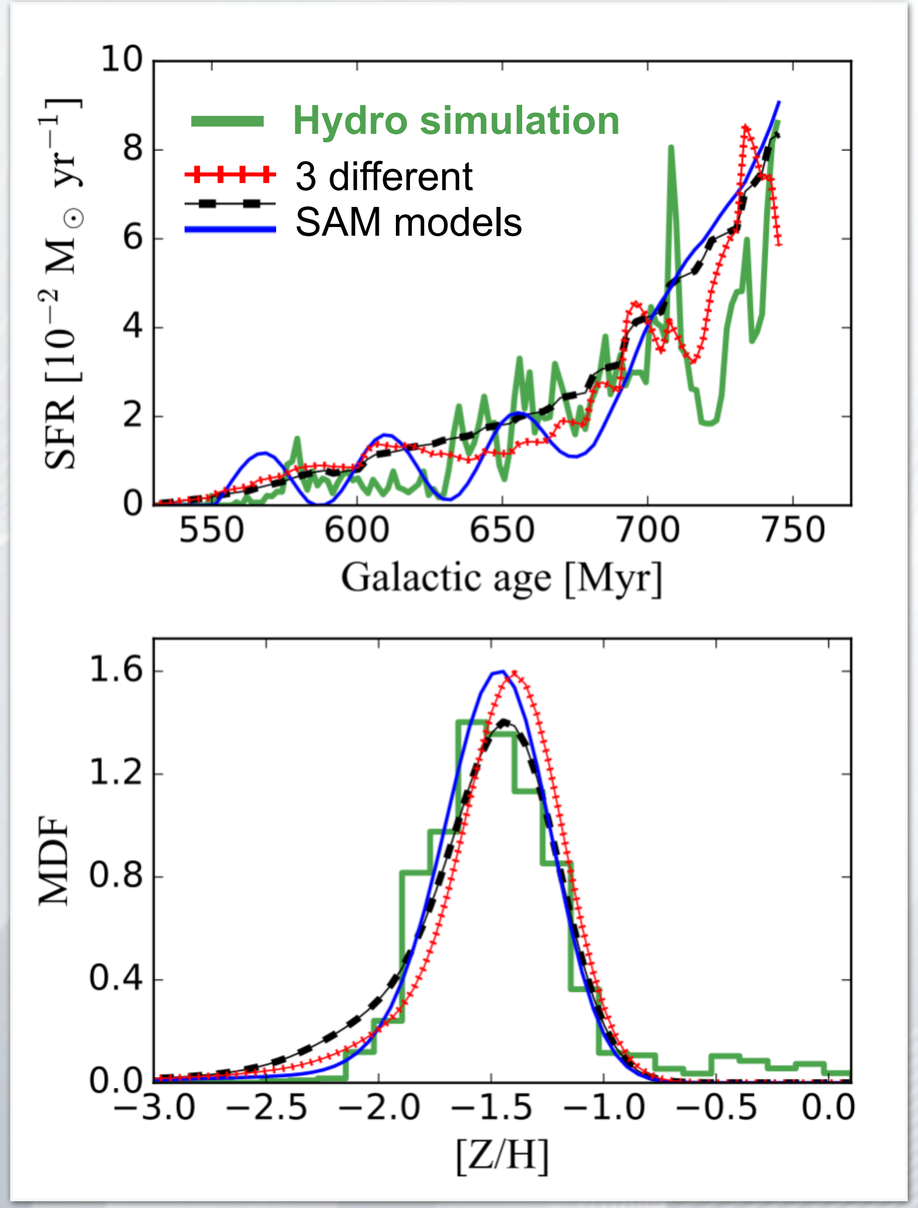

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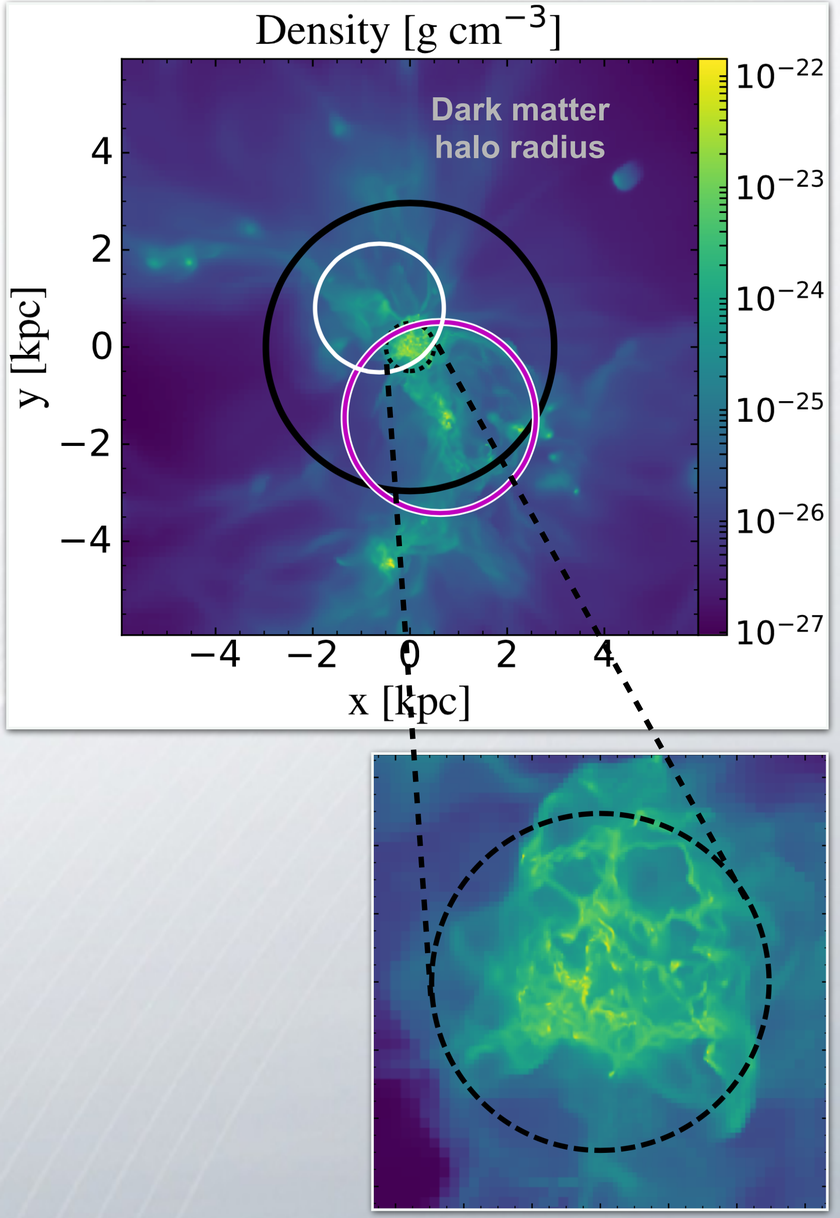

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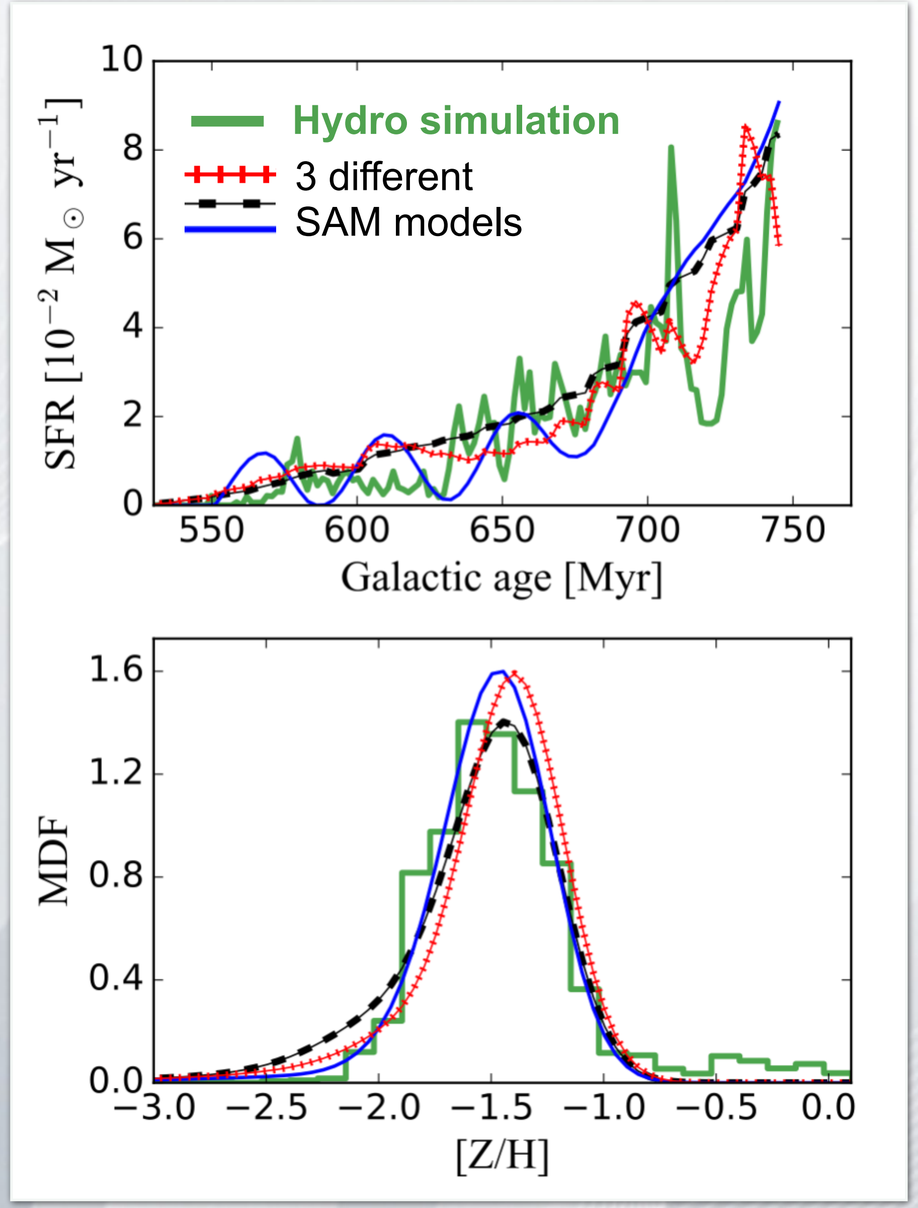
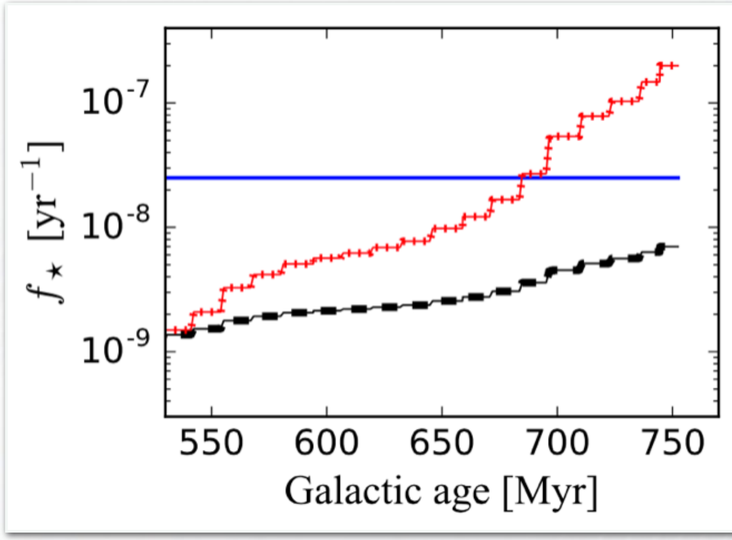
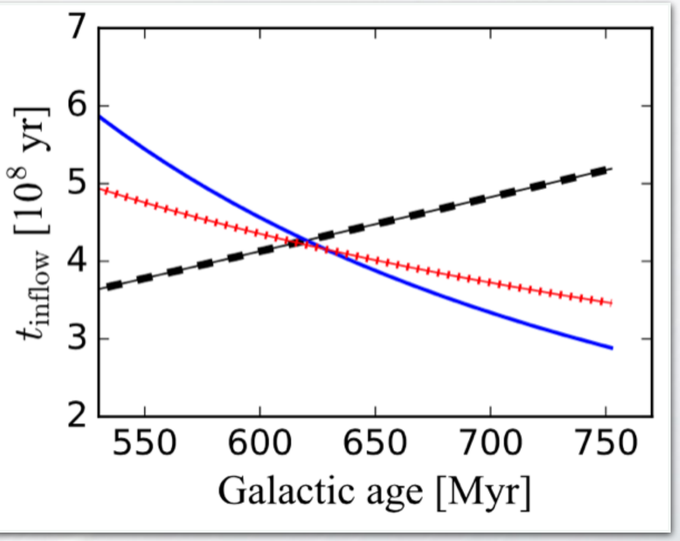


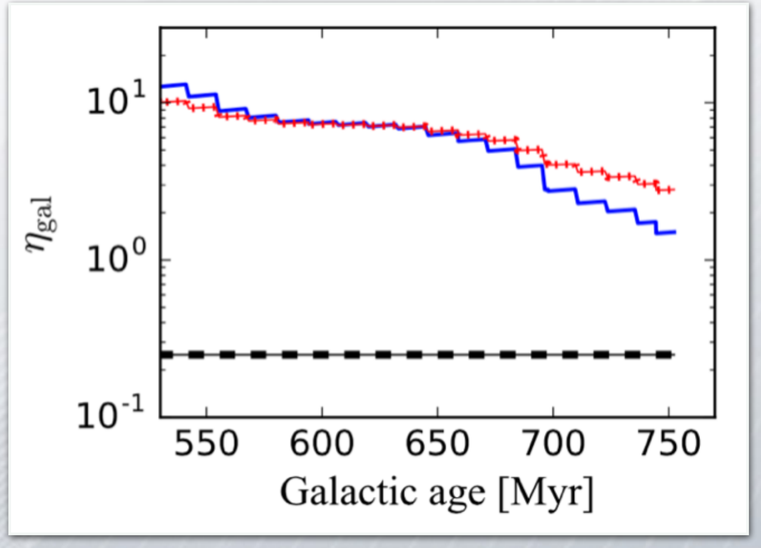
Star formation efficiency



Gas inflow timescale



Gas outflow rate



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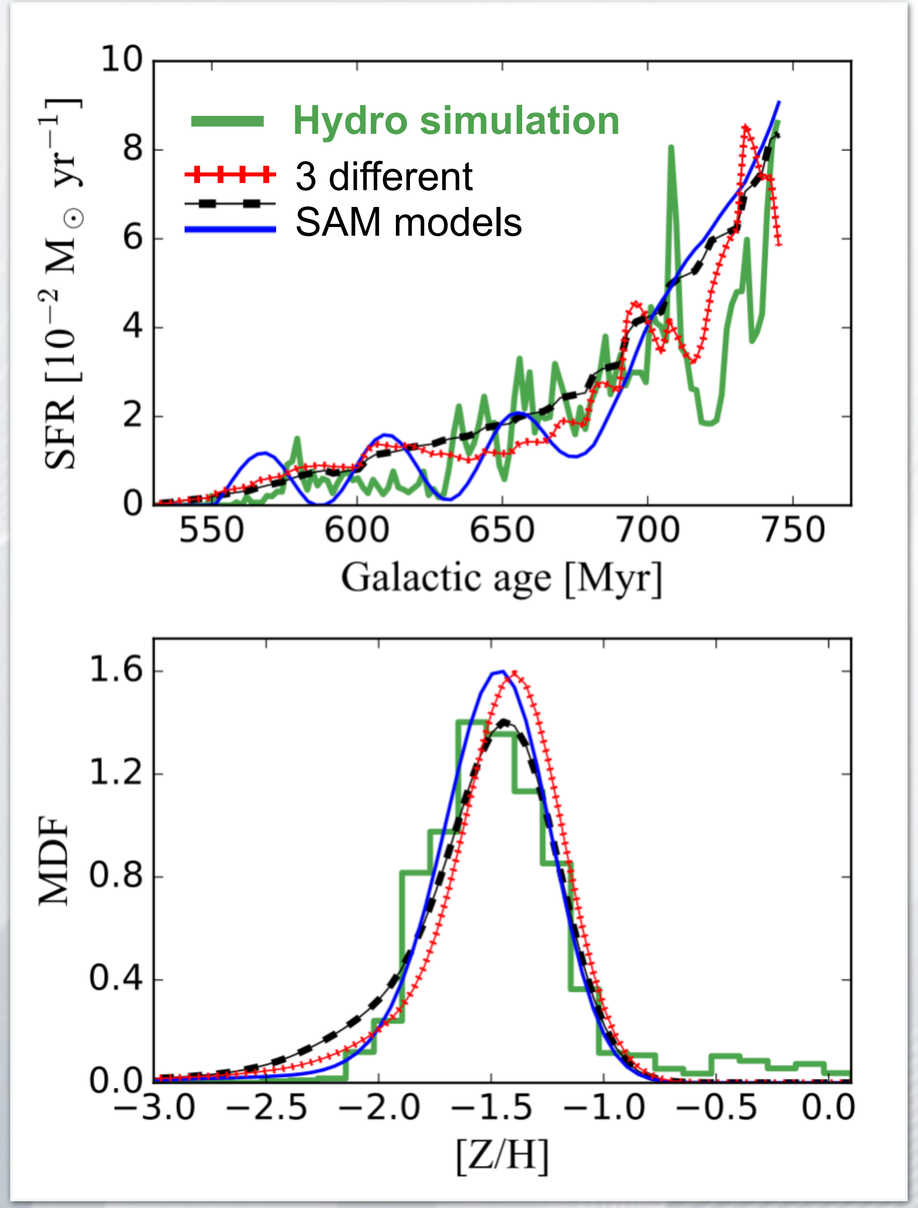

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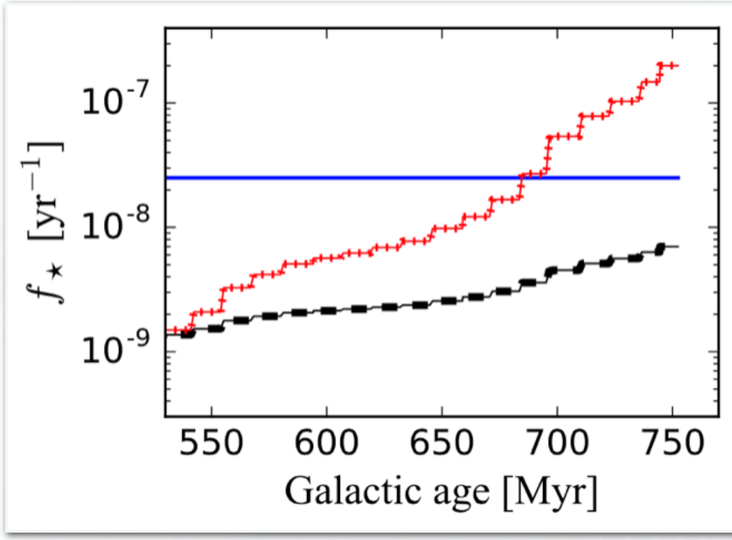

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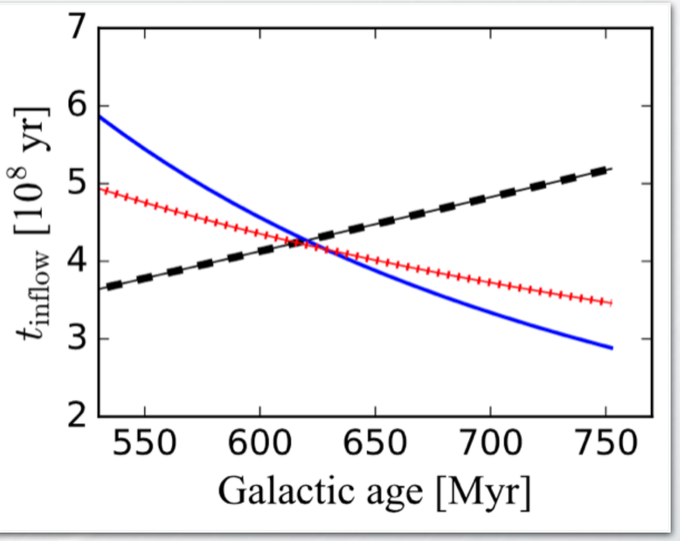

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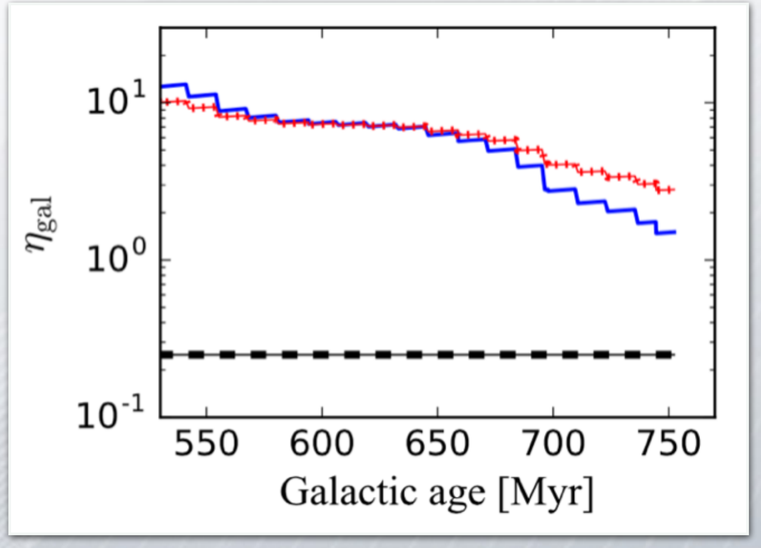
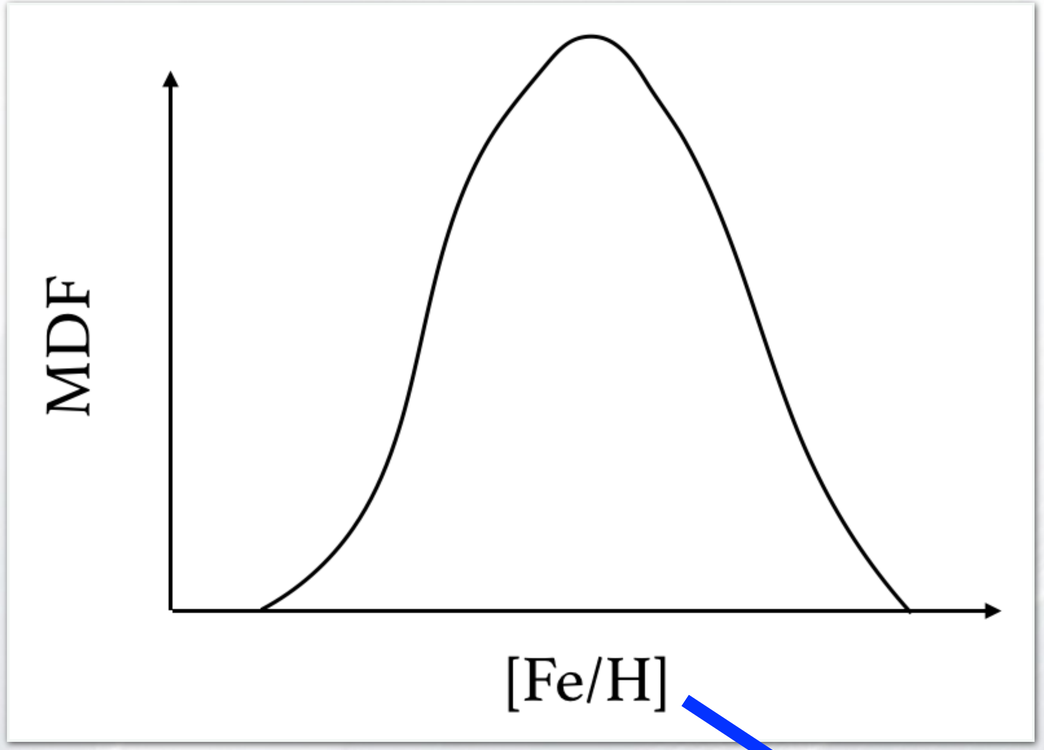


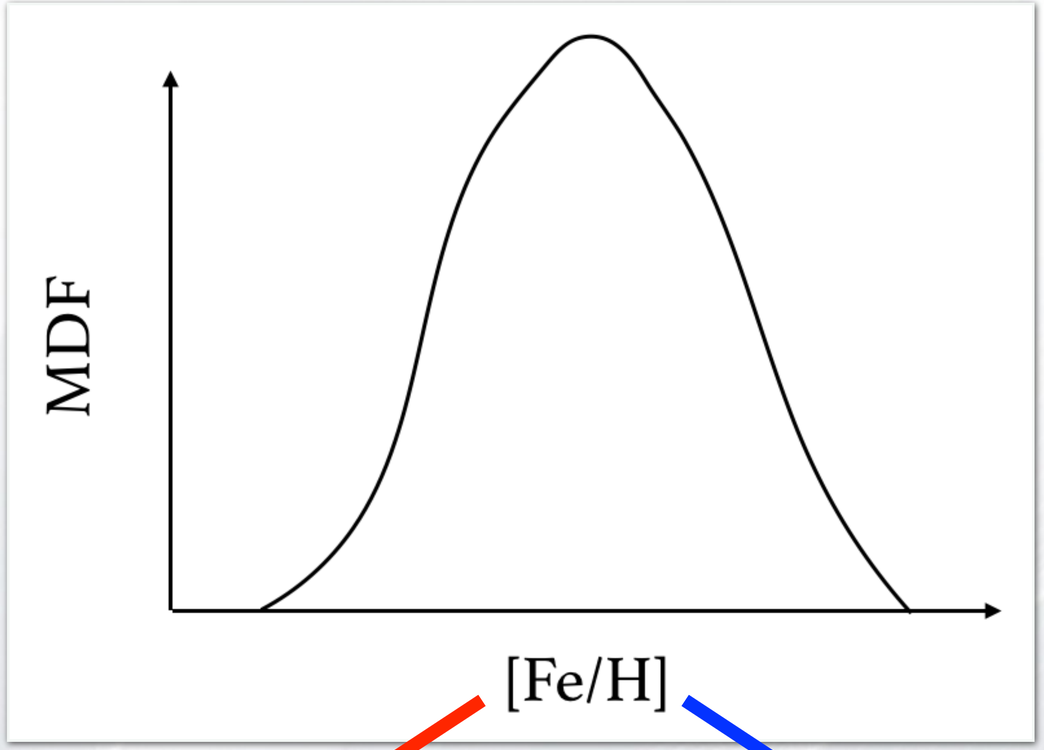
You can fit the data for the wrong reason

ANOTHER LAYER OF DEGENERACY



Star formation efficiency
Galactic inflows
Galactic outflows
Mass assembly history

ANOTHER LAYER OF DEGENERACY



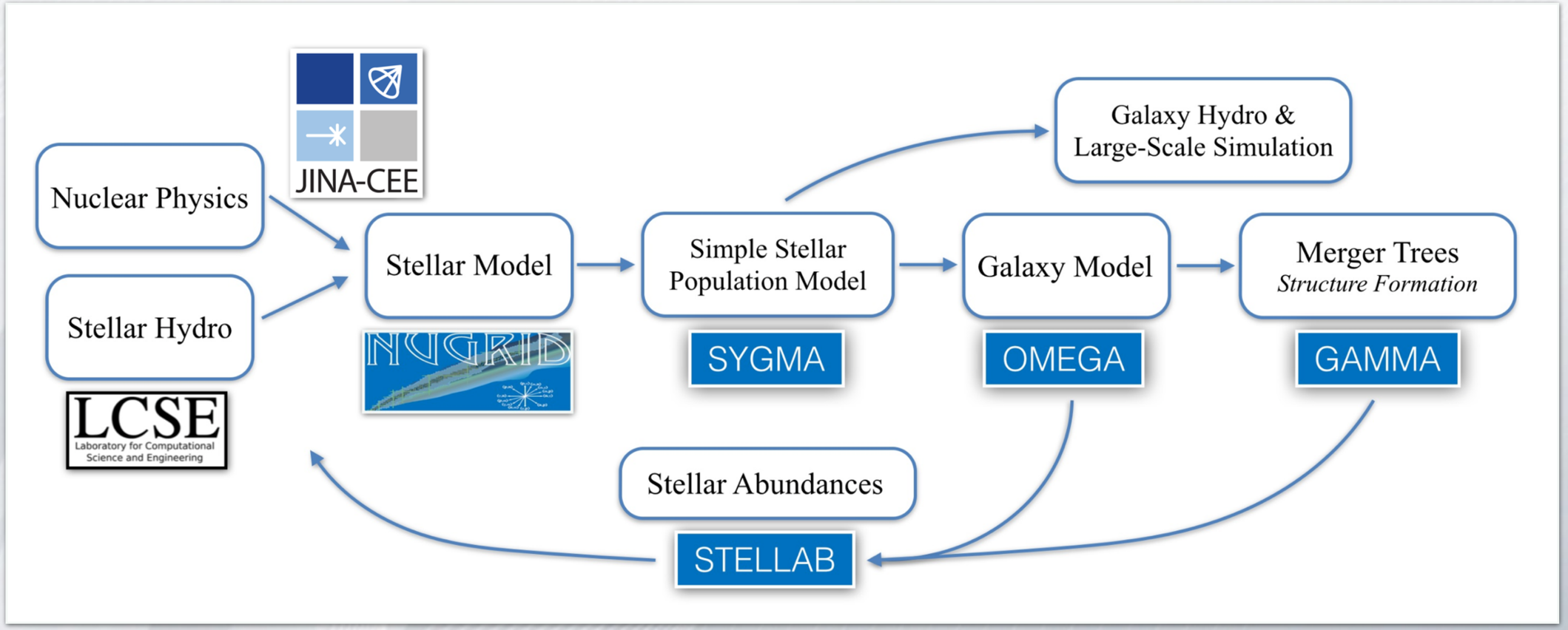
Fe yields

Star formation efficiency
Galactic inflows
Galactic outflows
Mass assembly history

CHEMICAL EVOLUTION AT DIFFERENT SCALES

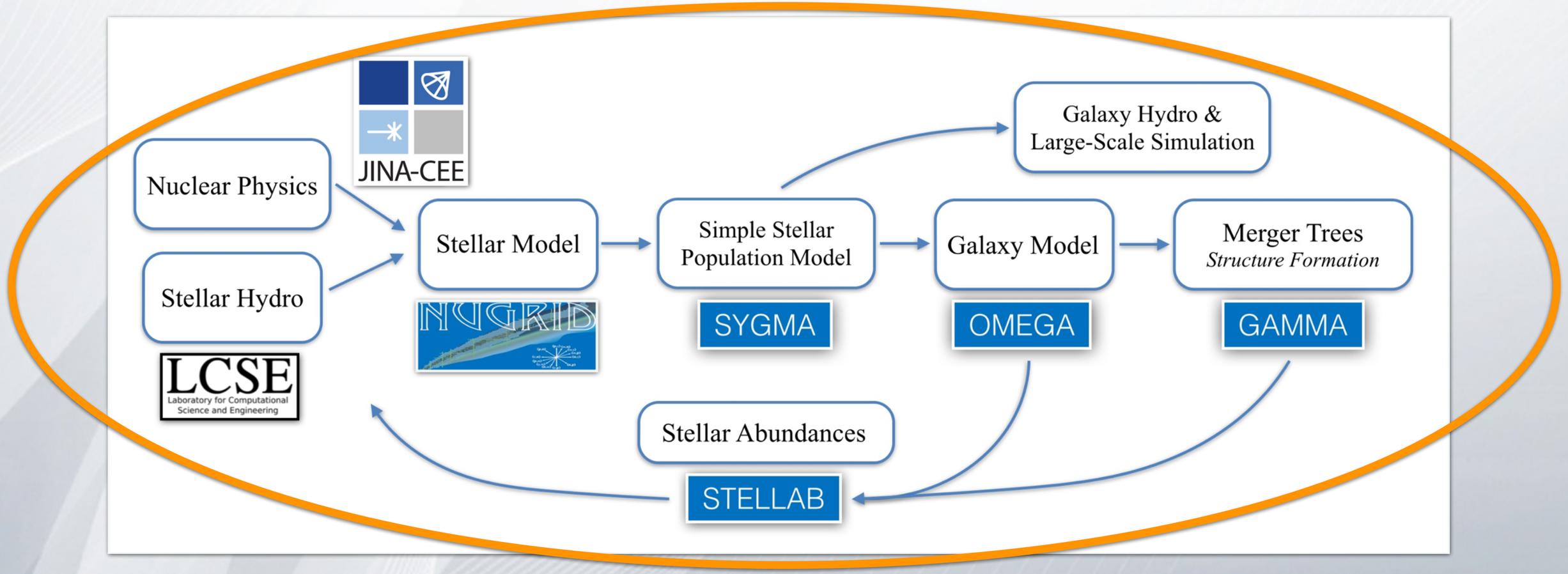
Probe the origin of the elements
Confront nuclear astrophysics with observations

Probe the role of galaxy formation
Using chemical abundances to trace the evolution of galaxies



CHEMICAL EVOLUTION AT DIFFERENT SCALES

For some problems, nuclear astrophysics and galaxy evolution must be addressed simultaneously within the same study, as they can sometime affect numerical predictions in a similar way.

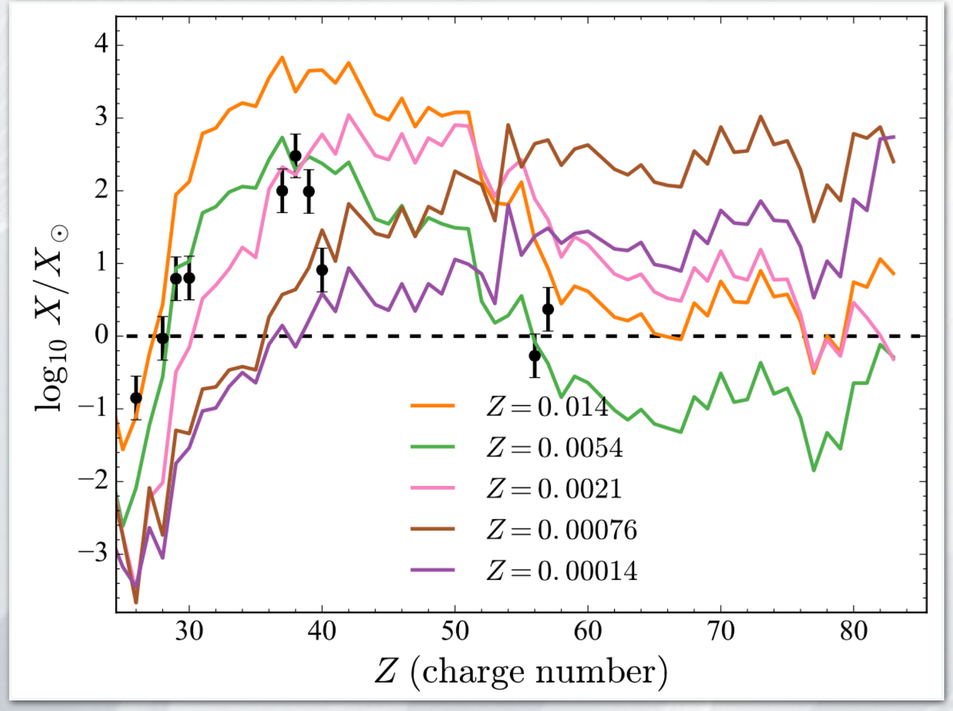


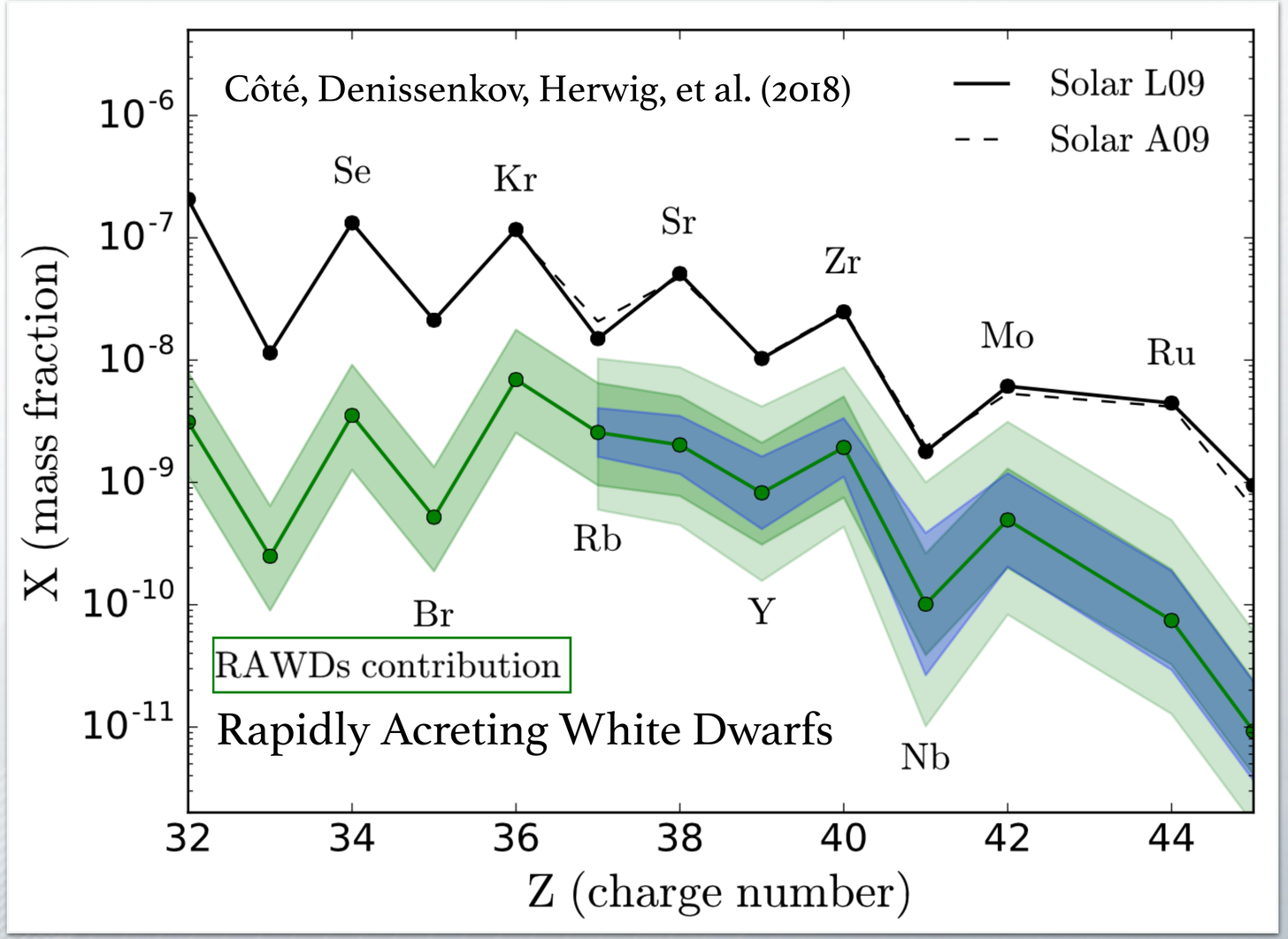
PROPAGATION OF UNCERTAINTIES

Galaxy evolution uncertainties

Nuclear reaction rate uncertainties
(*n*, *gamma*) cross sections
see Denissenkov, Perdikakis, Herwig, et al. (2018)

Metallicity-dependent i-process yields
see Denissenkov, Herwig, Battino, et al. (2017)





NEUTRON STAR MERGERS AND THE R-PROCESS

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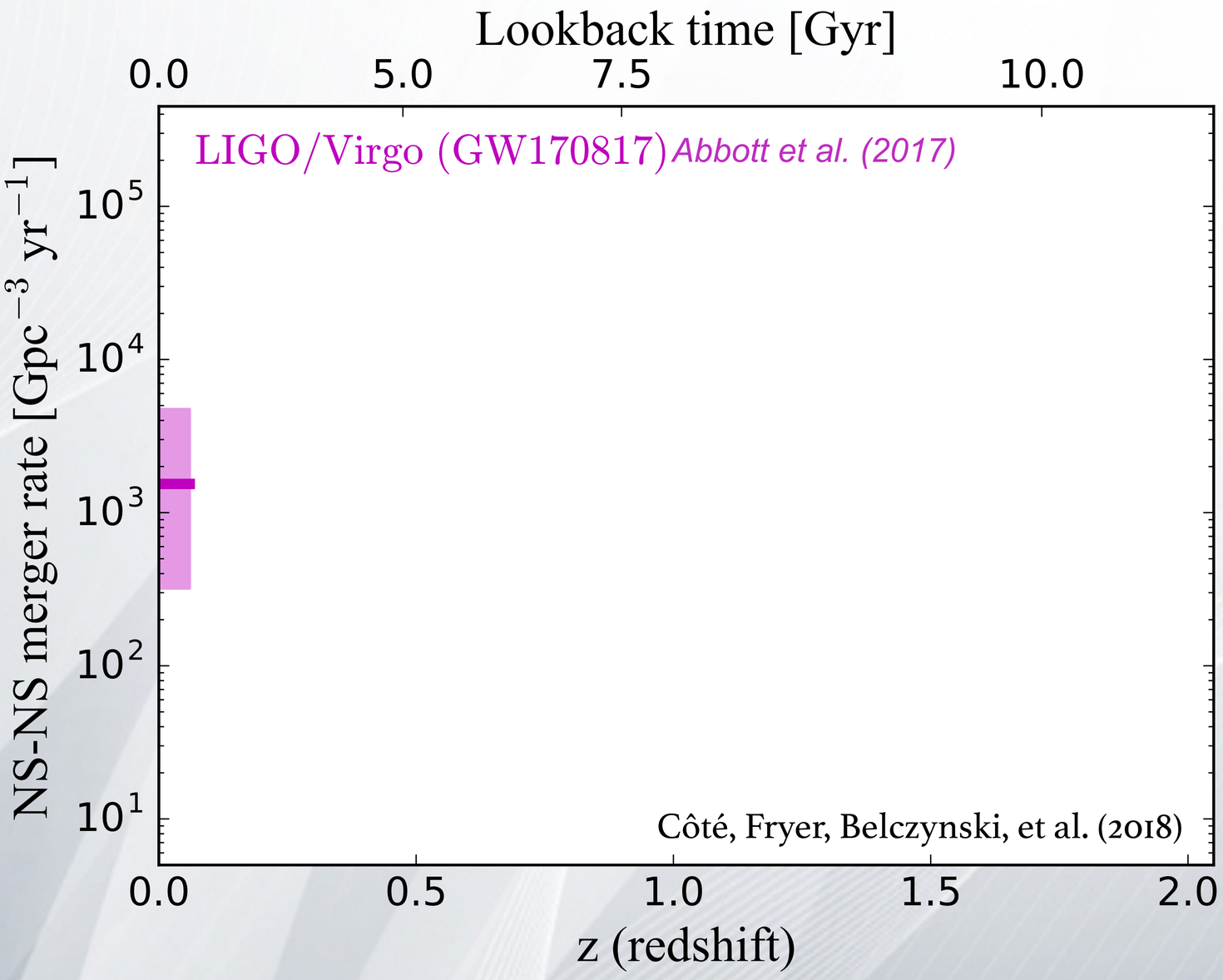

Chemical evolution simulations of the Milky Way

Argast et al. (2004)
Matteucci et al. (2014)
Cescutti et al. (2015)
Hirai et al. (2015)
Ishimaru et al. (2015)
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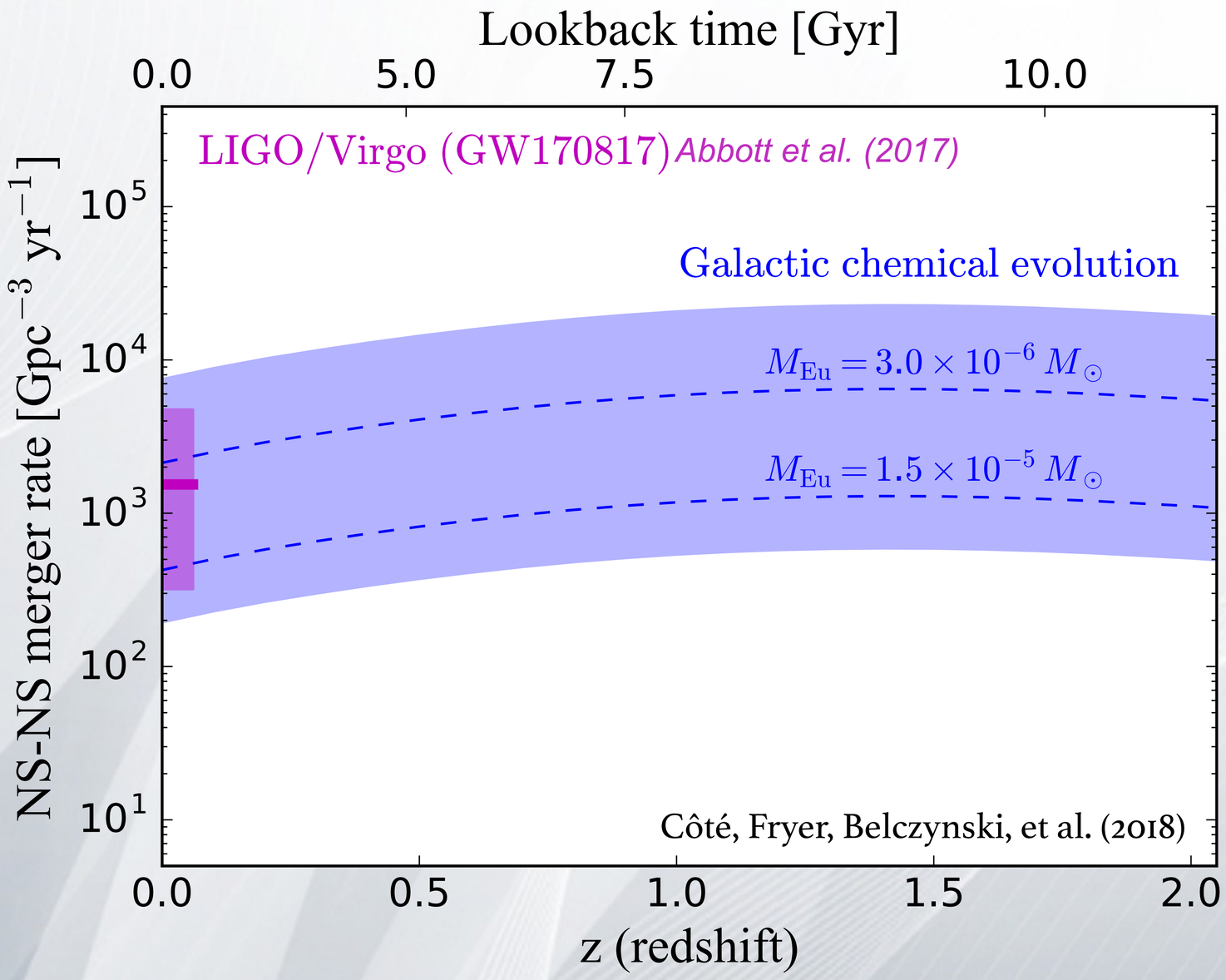

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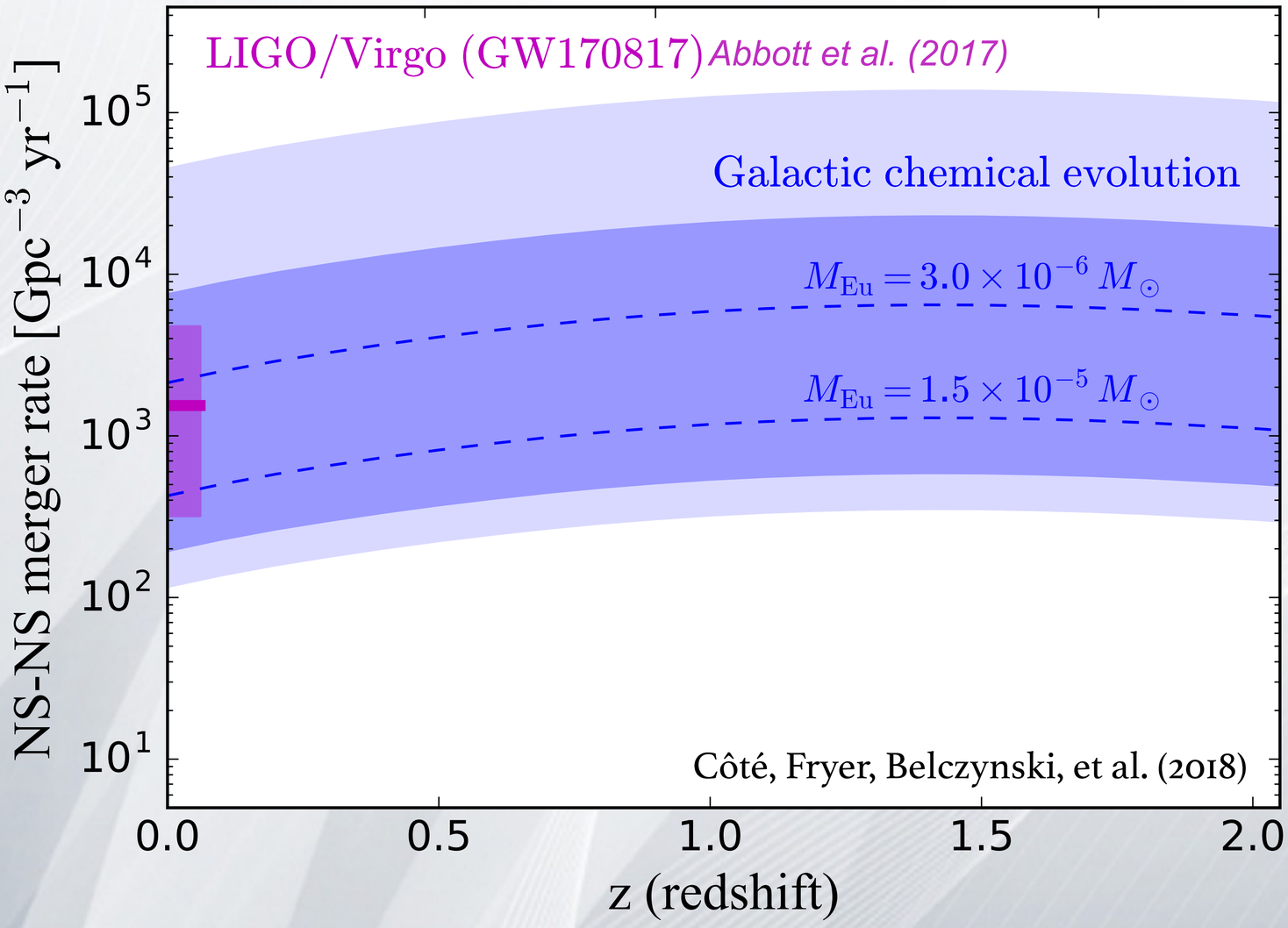
See also analytical estimates

Abbott et al. (2017), Cowperthwaite et al. (2017), Chornock et al. (2017), Gompertz et al. (2017), Kasen et al. (2017), Rosswog et al. (2017), Tanaka et al. (2017), Wang et al. (2017), Hotokesaka et al. (2018)

NEUTRON STAR MERGERS AND THE R-PROCESS

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]



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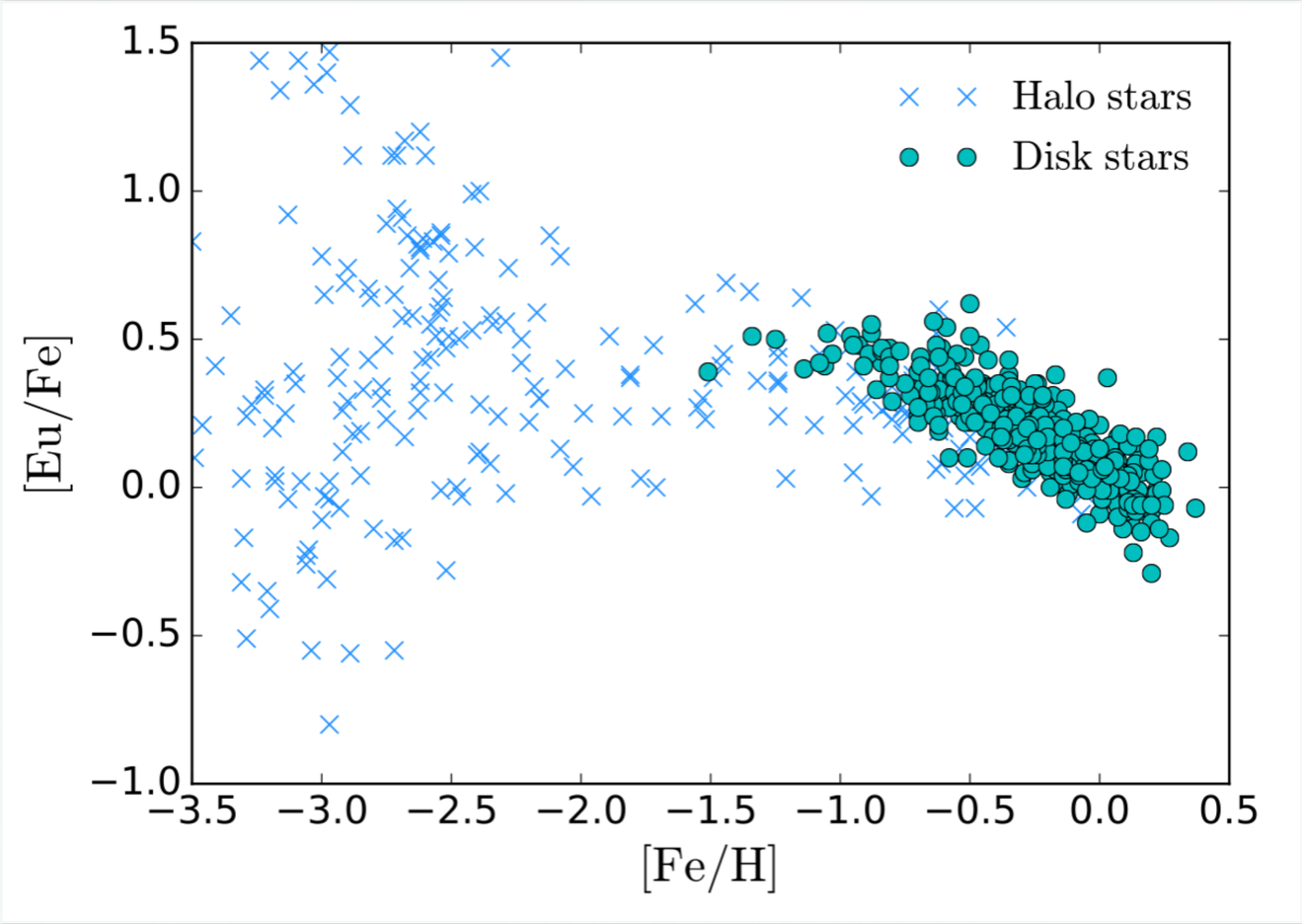
THE DECREASING TREND OF [Eu/Fe] IN THE GALACTIC DISK



- *Battistini & Bensby (2016)*
- **JINABase** (Abohalima & Frebel 2017, submitted) including: Cohen et al. (2013), and Placco et al. (2014), Fulbright (2000), Roederer et al. (2009, 2012, 2014a,b)

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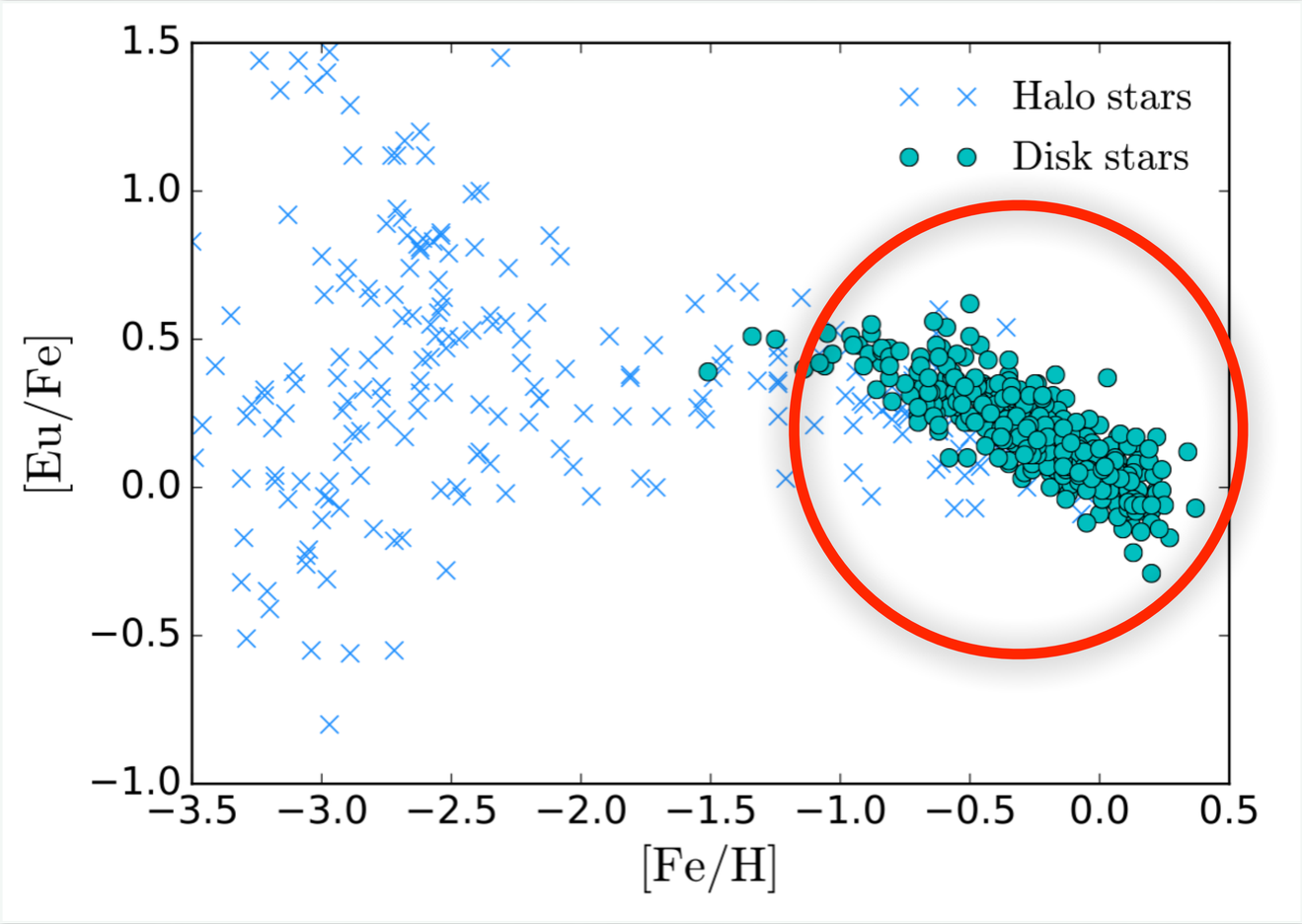

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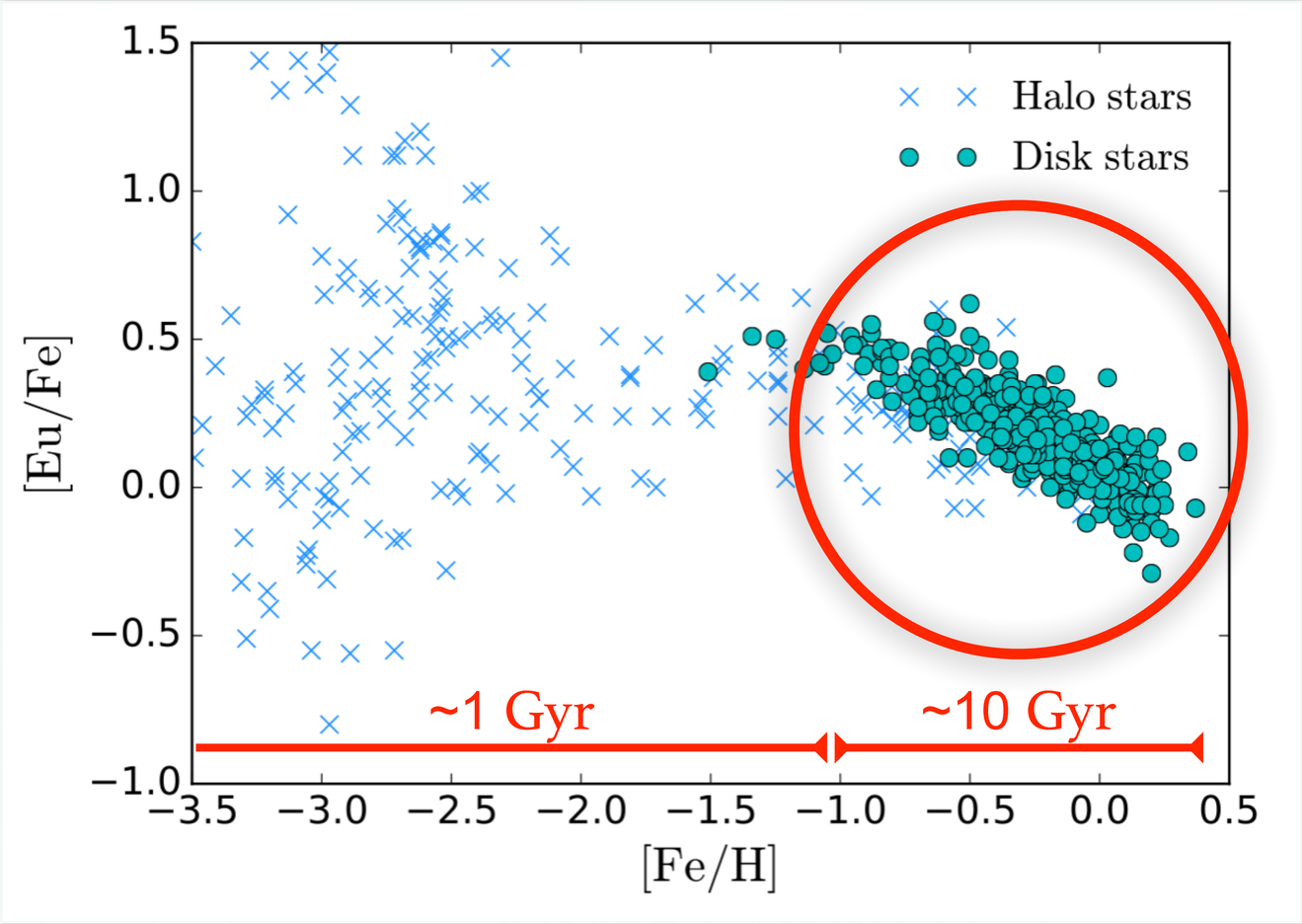

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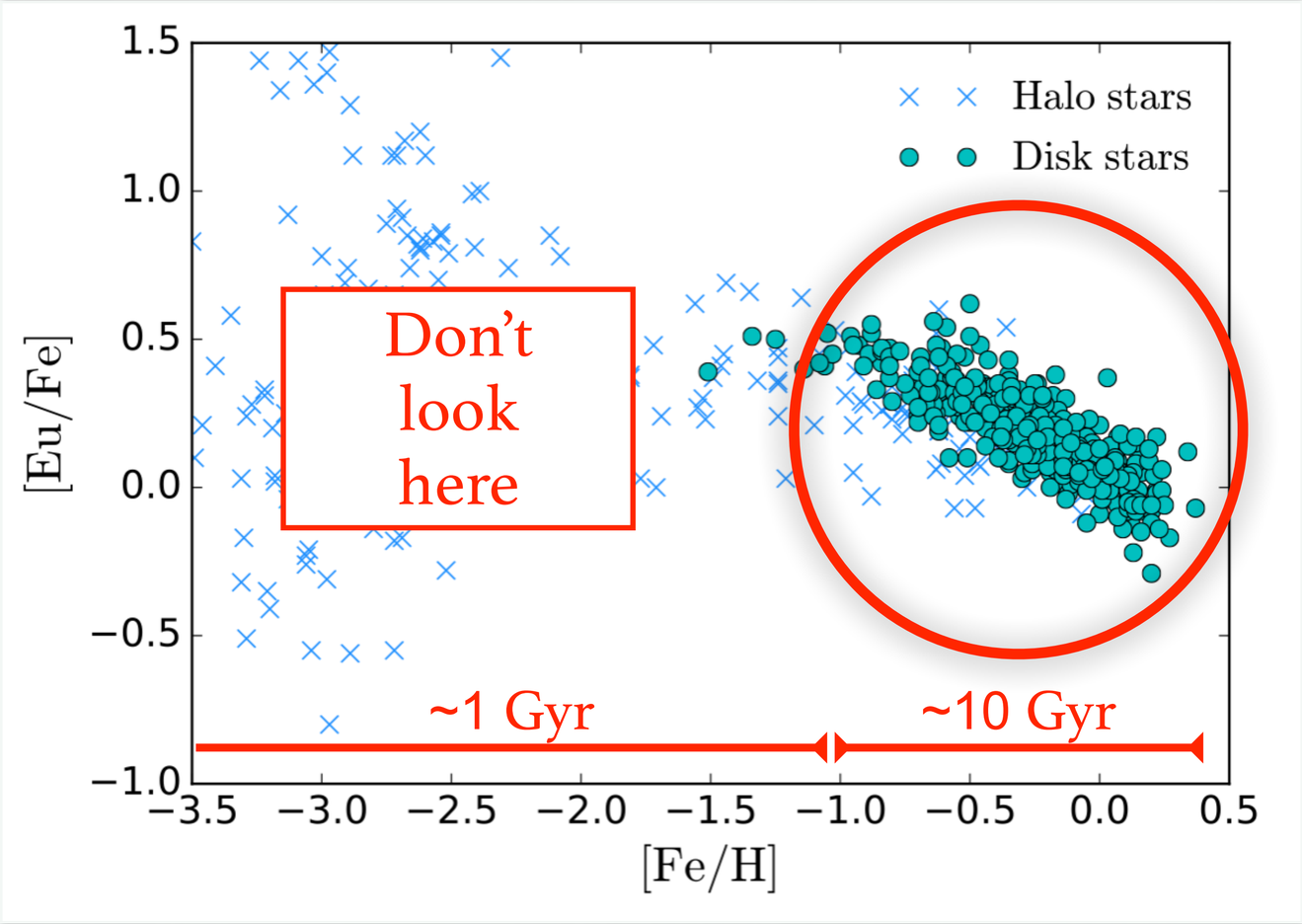

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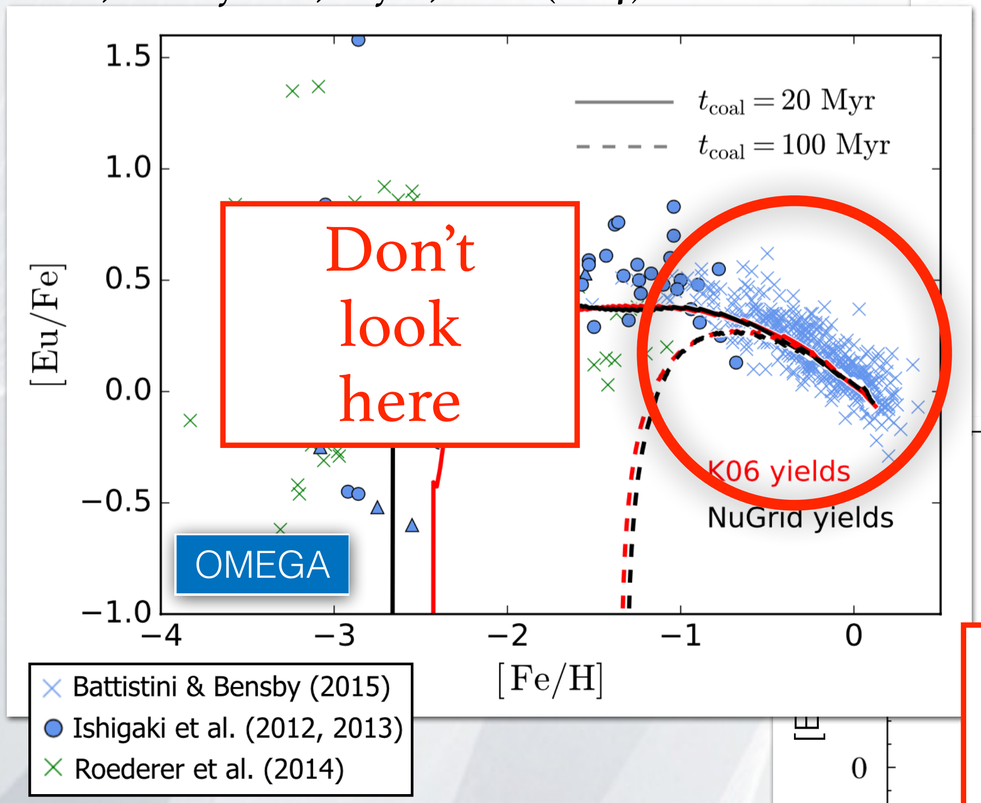
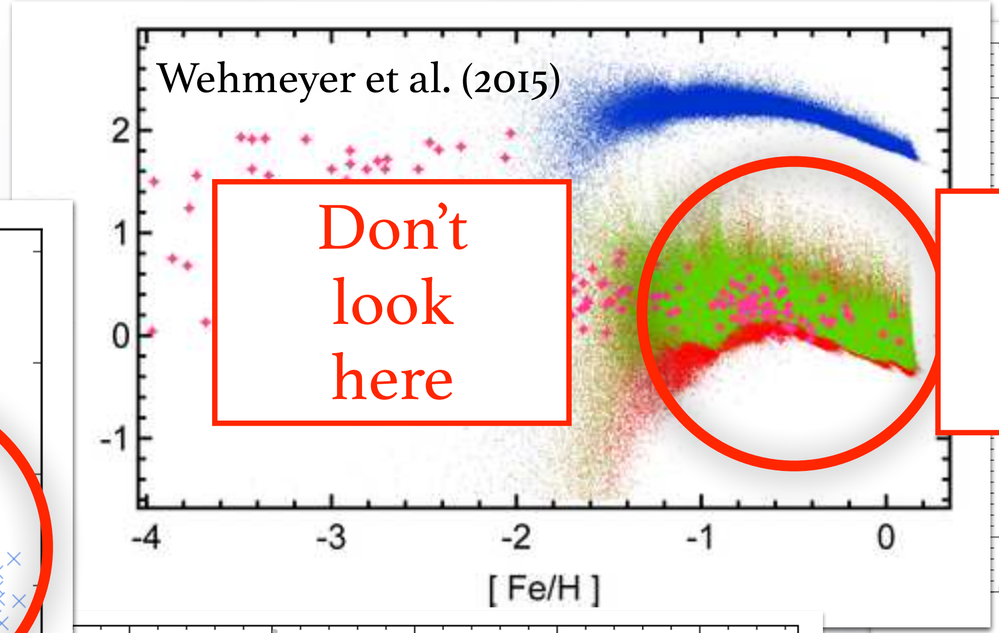
USING NEUTRON STAR MERGERS IN CHEMICAL EVOLUTION SIMULATIONS

With **constant delay times**

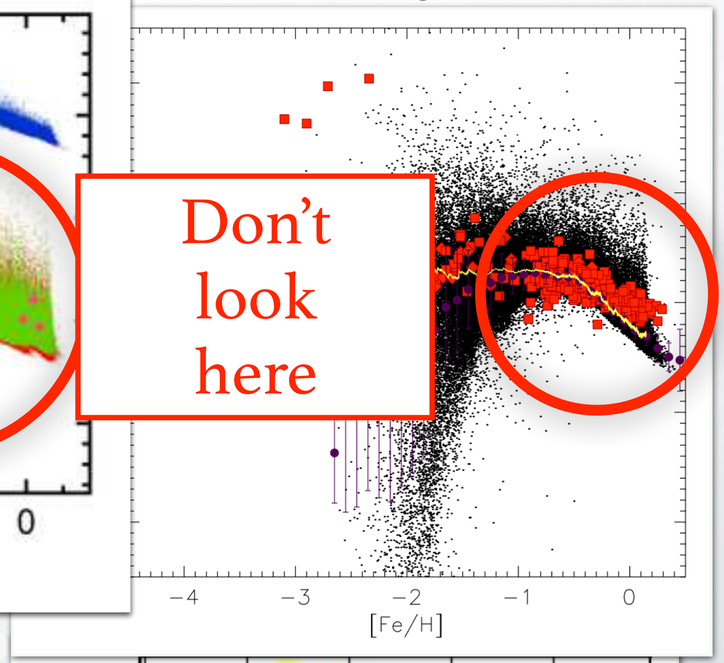
Côté, Belczynski, Fryer, et al. (2017)



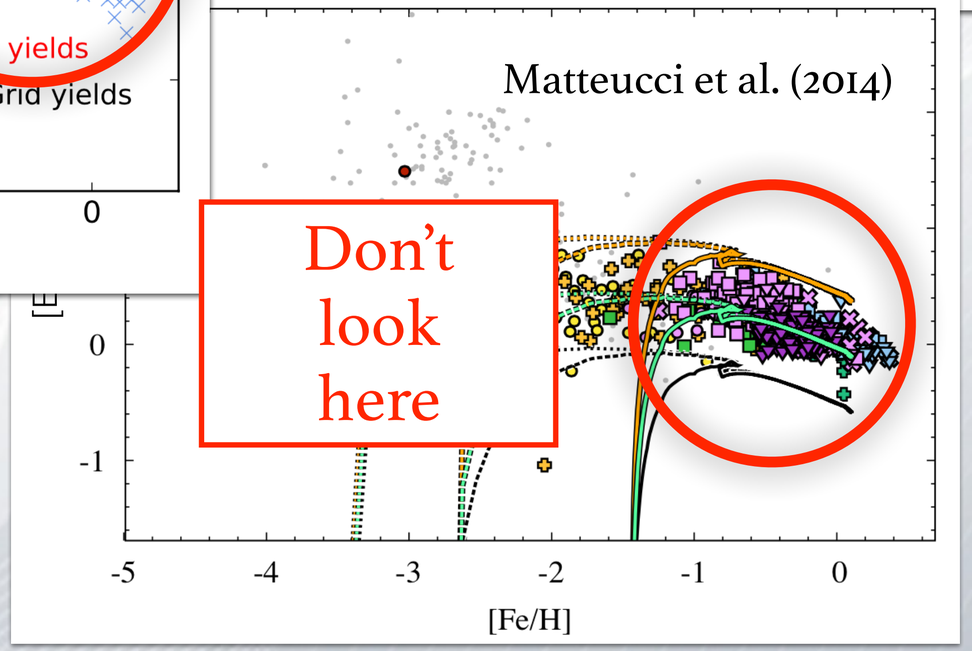
Wehmeyer et al. (2015)

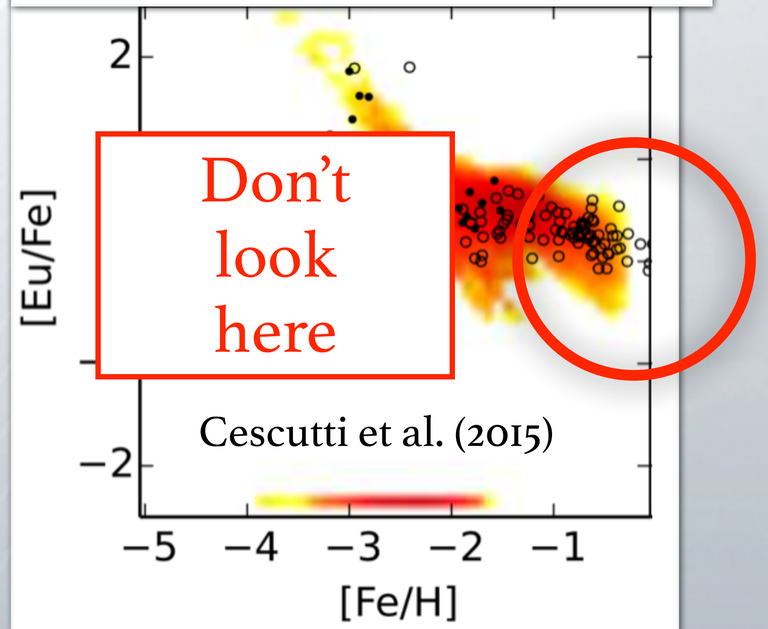


Argast et al. (2004)



Matteucci et al. (2014)





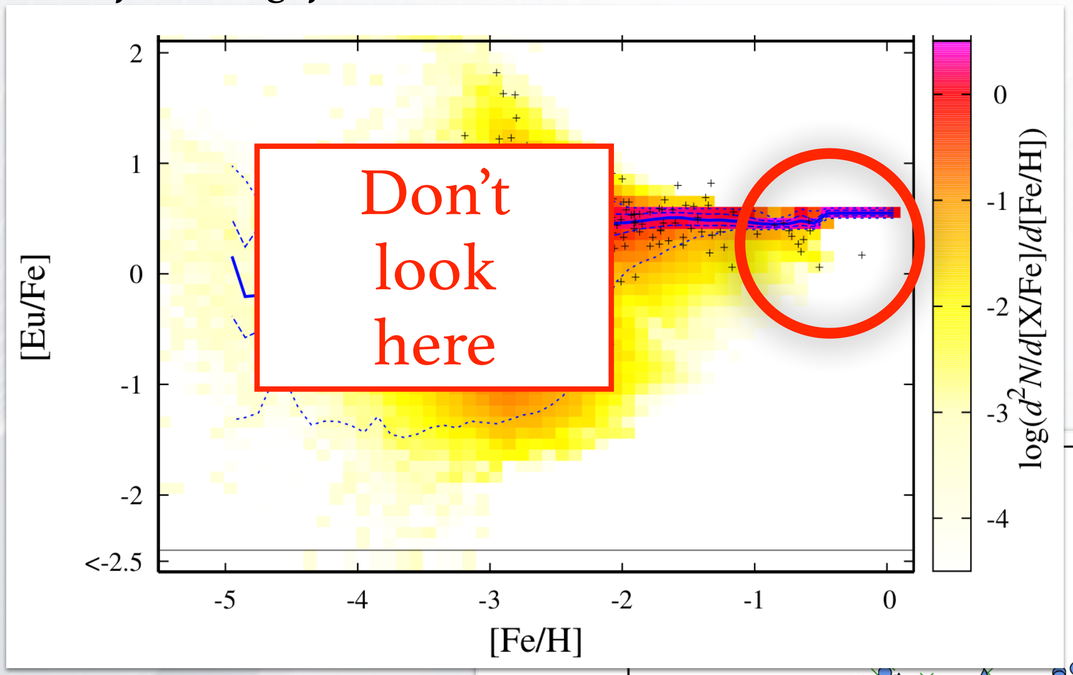
Cescutti et al. (2015)

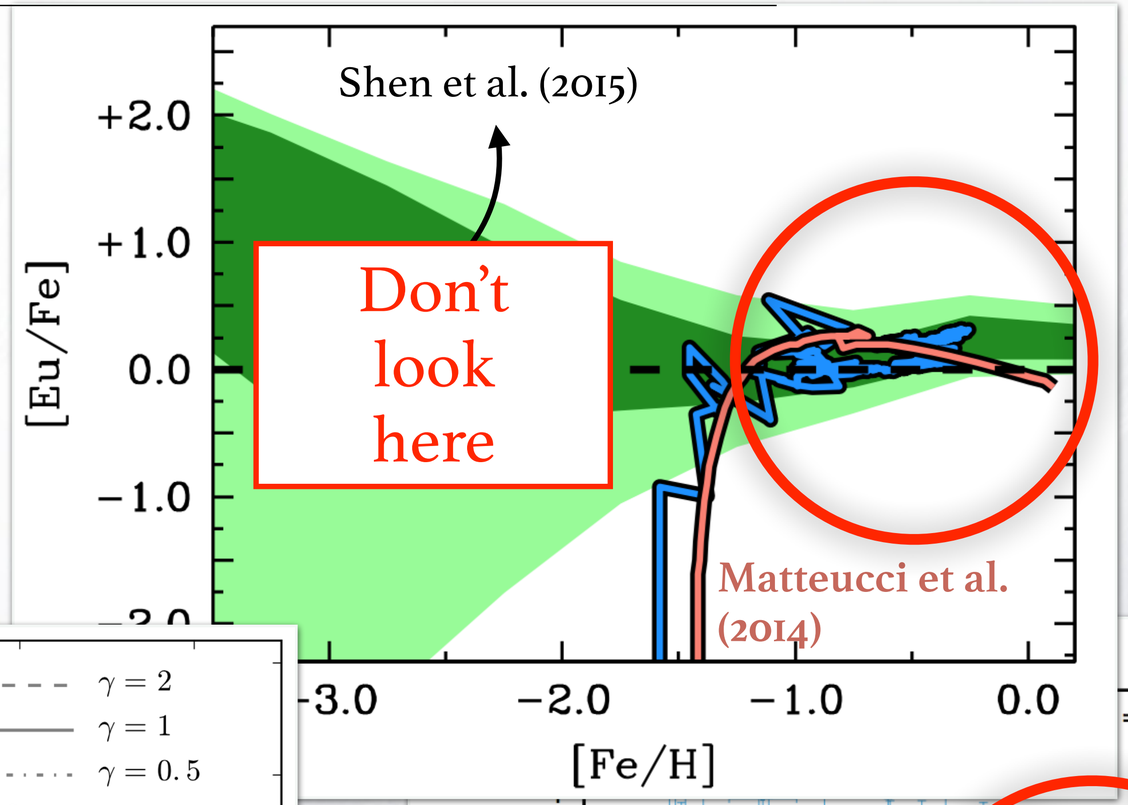
Most of these studies also includes CC SNe (not shown here)

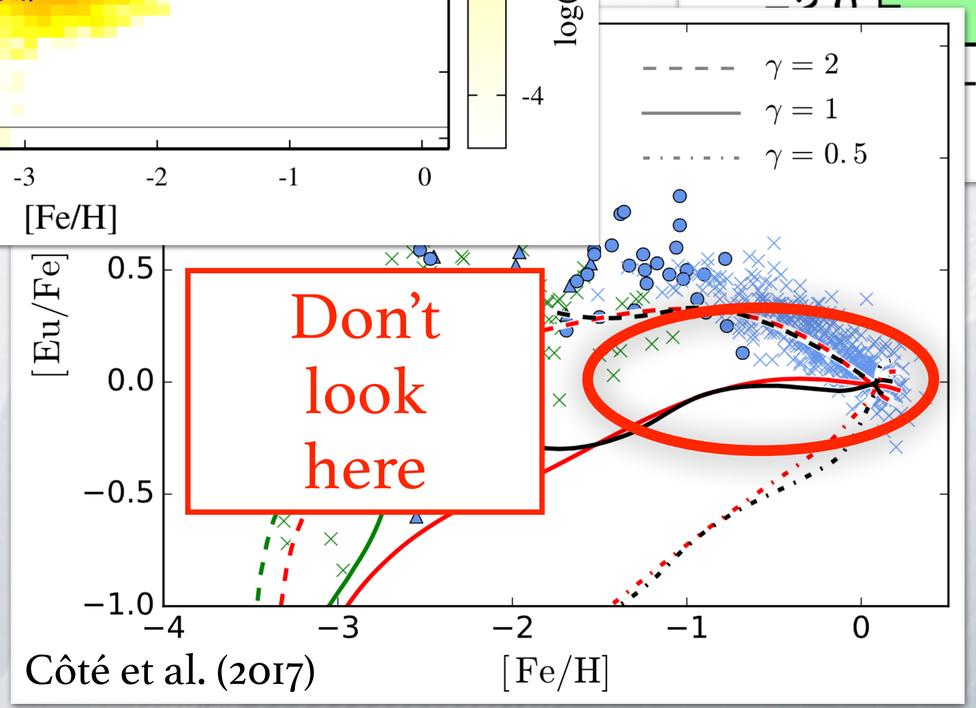
USING NEUTRON STAR MERGERS IN CHEMICAL EVOLUTION SIMULATIONS

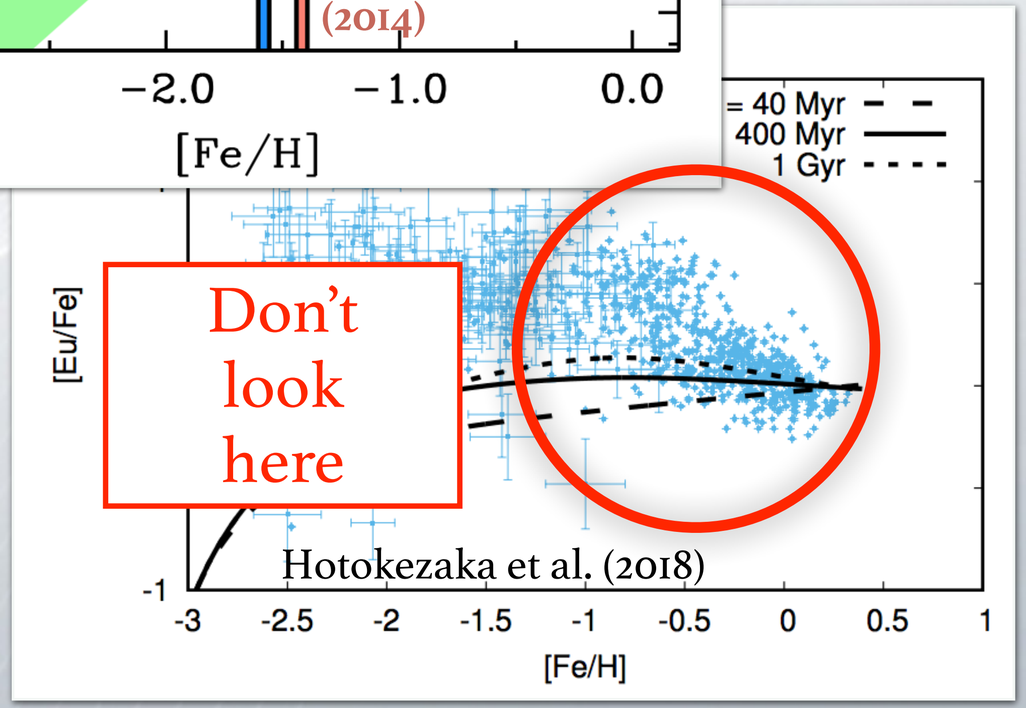
With a **delay-time distribution**

Komiya & Shigeyama(2016)







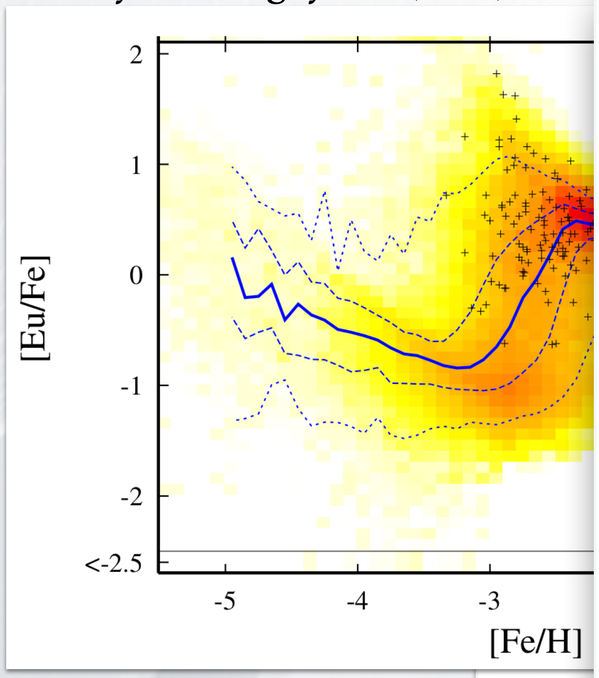


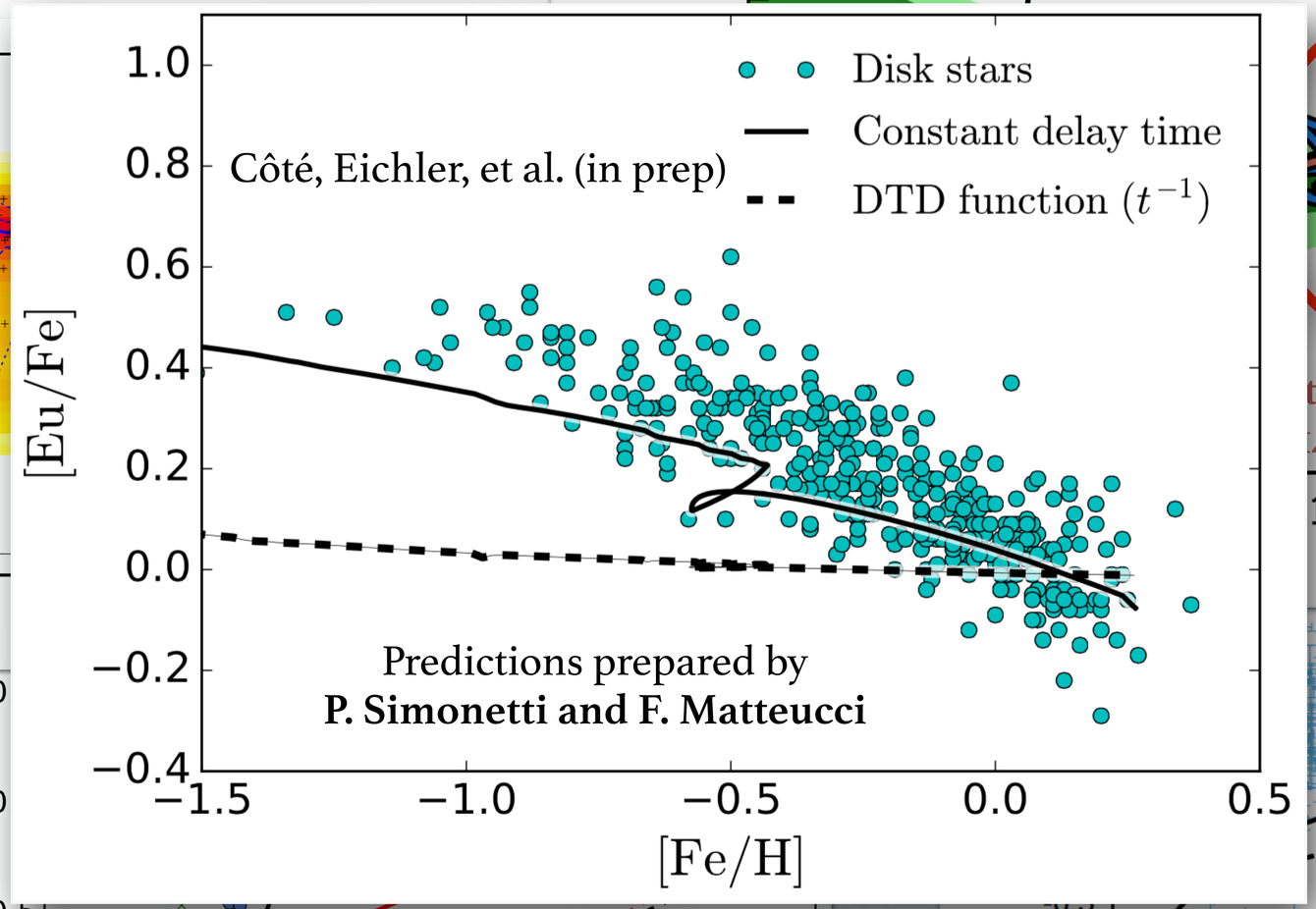
See also
van de Voort et al. (2015)
Naiman et al. (2018)

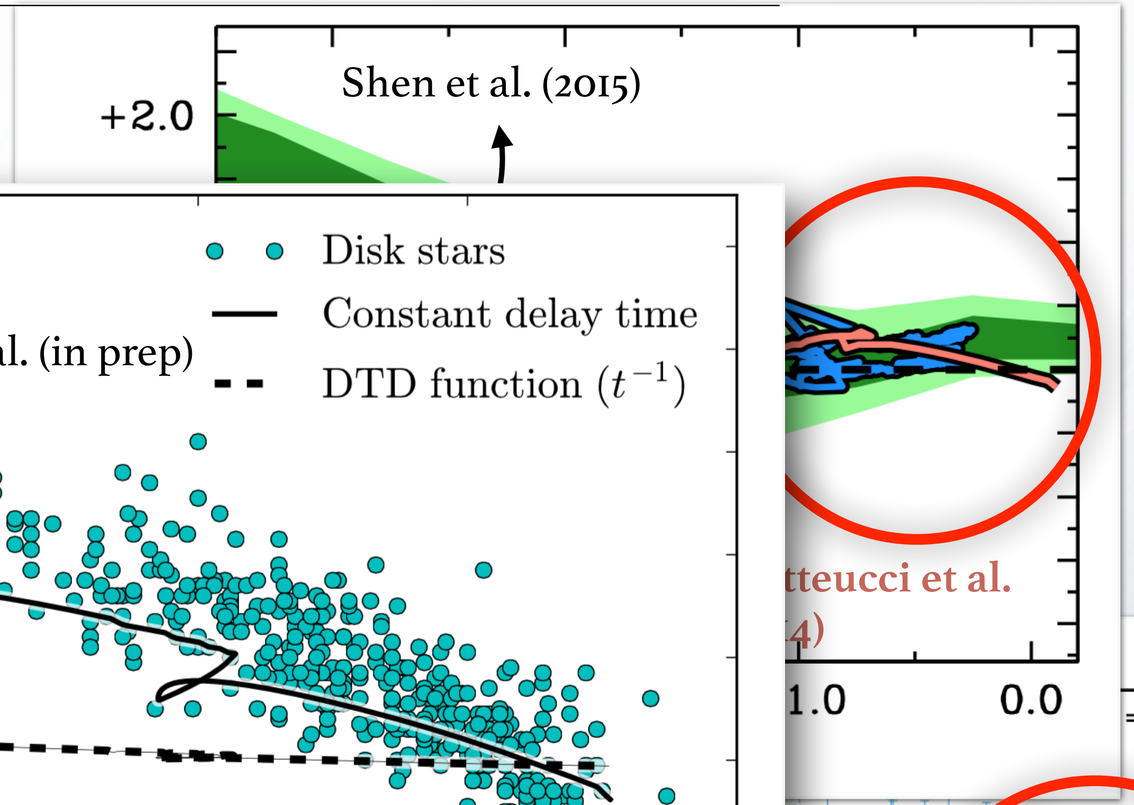
USING NEUTRON STAR MERGERS IN CHEMICAL EVOLUTION SIMULATIONS

With a **delay-time distribution**

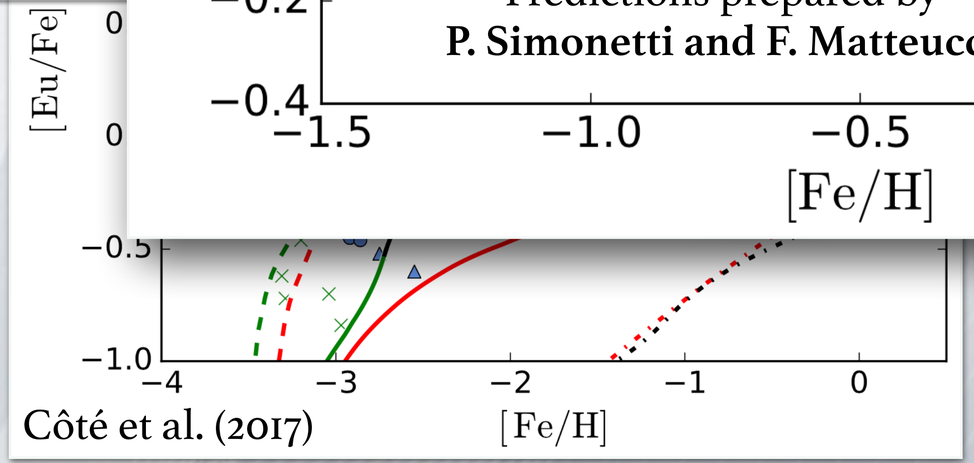
Komiya & Shigeyama(2016)



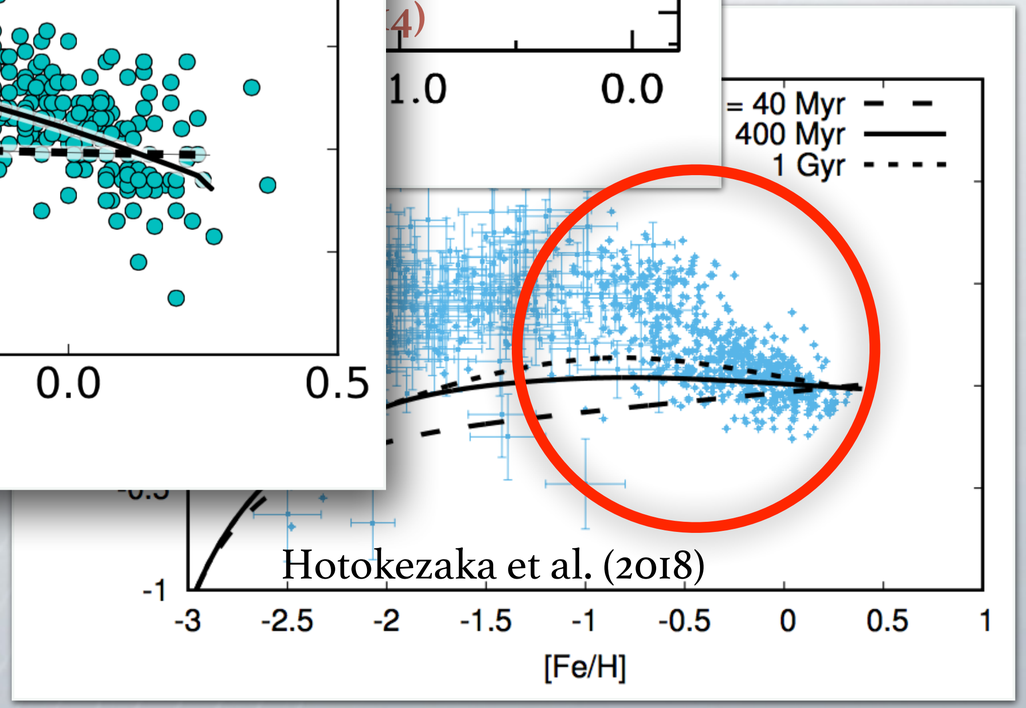




tteucci et al.
4)



Côté et al. (2017)



Hotokezaka et al. (2018)

See also
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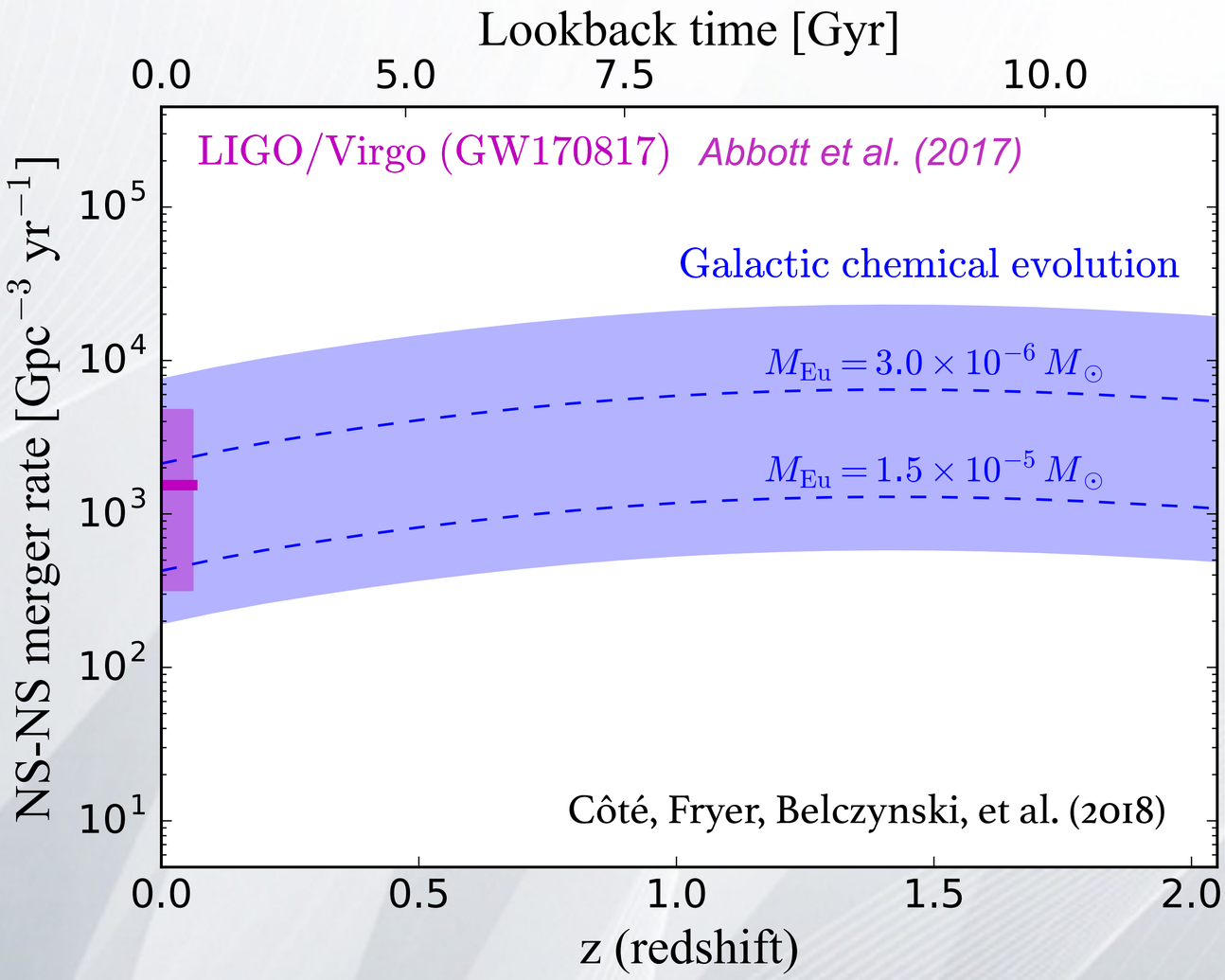
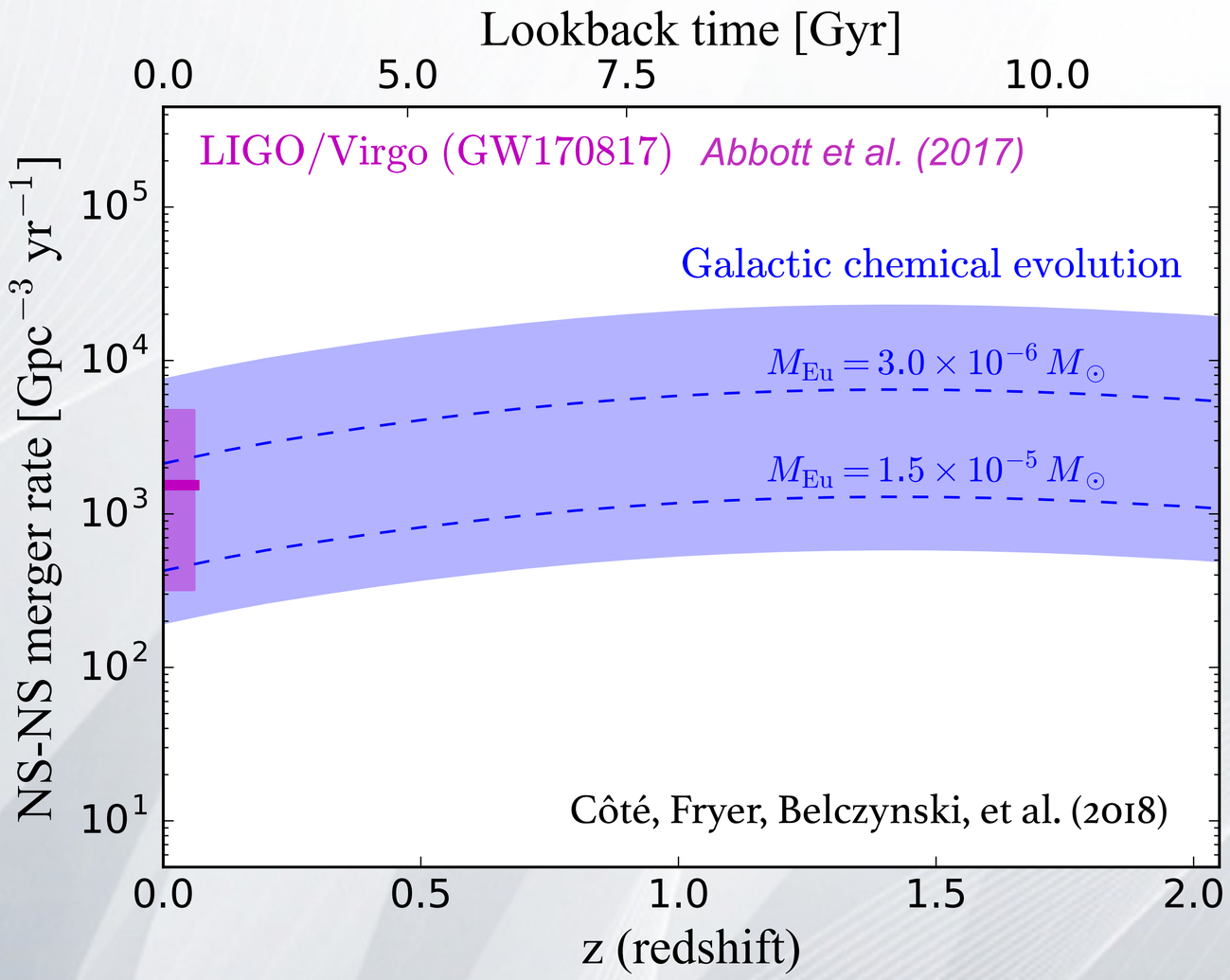
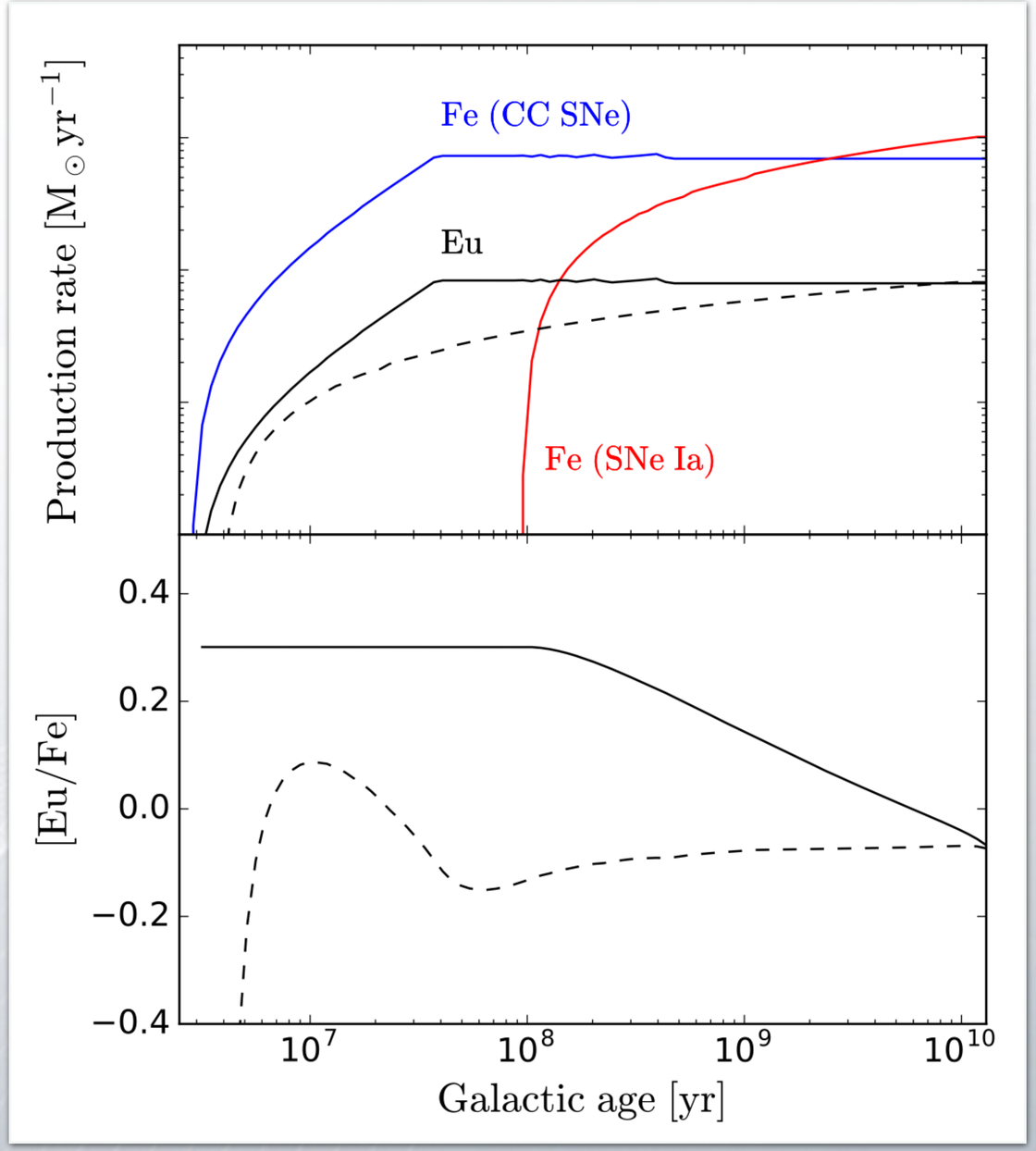
THE DECREASING TREND OF [Eu/Fe] IN THE GALACTIC DISK



THE DECREASING TREND OF [Eu/Fe] IN THE GALACTIC DISK

Côté, Eichler, et al. (in prep)





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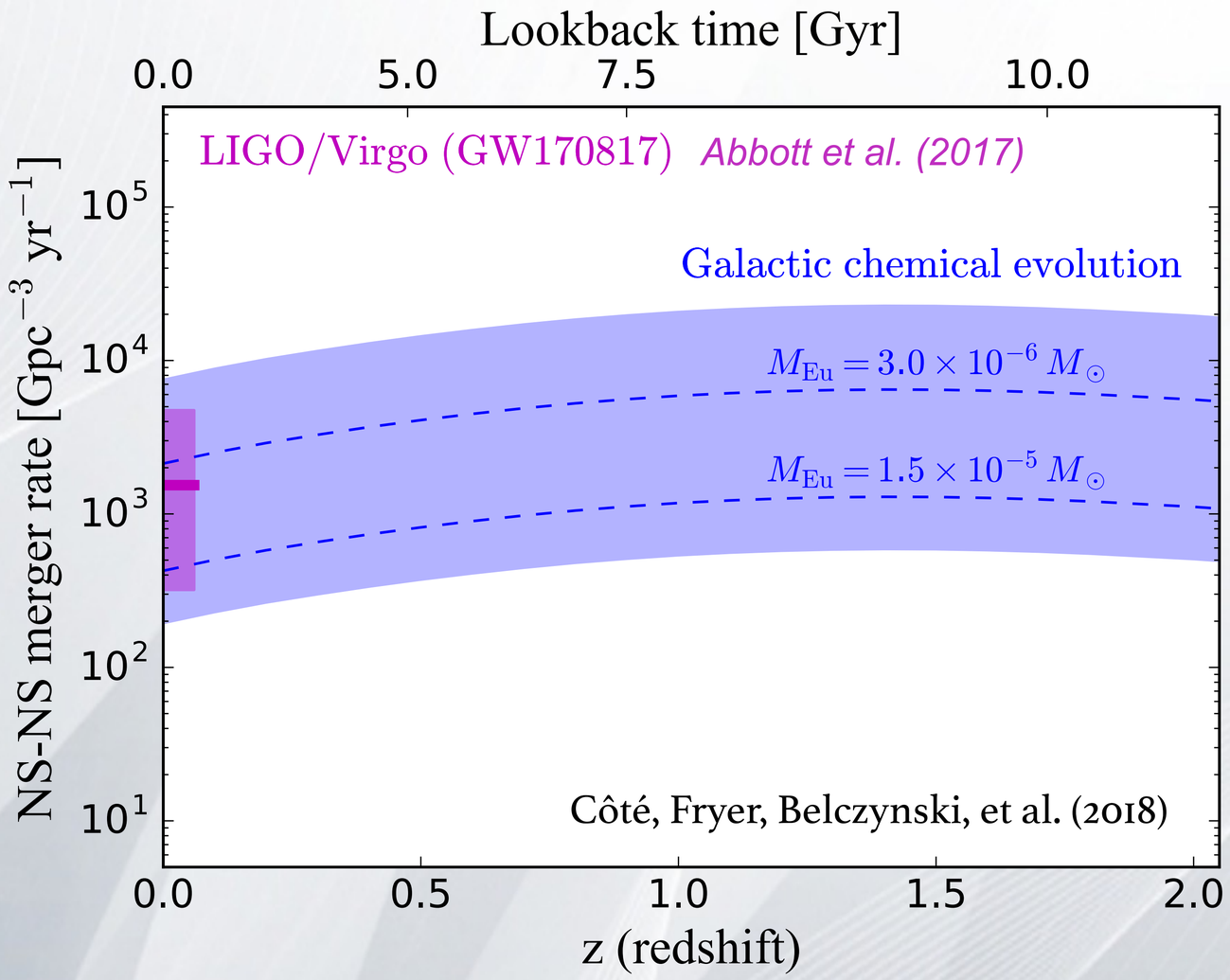
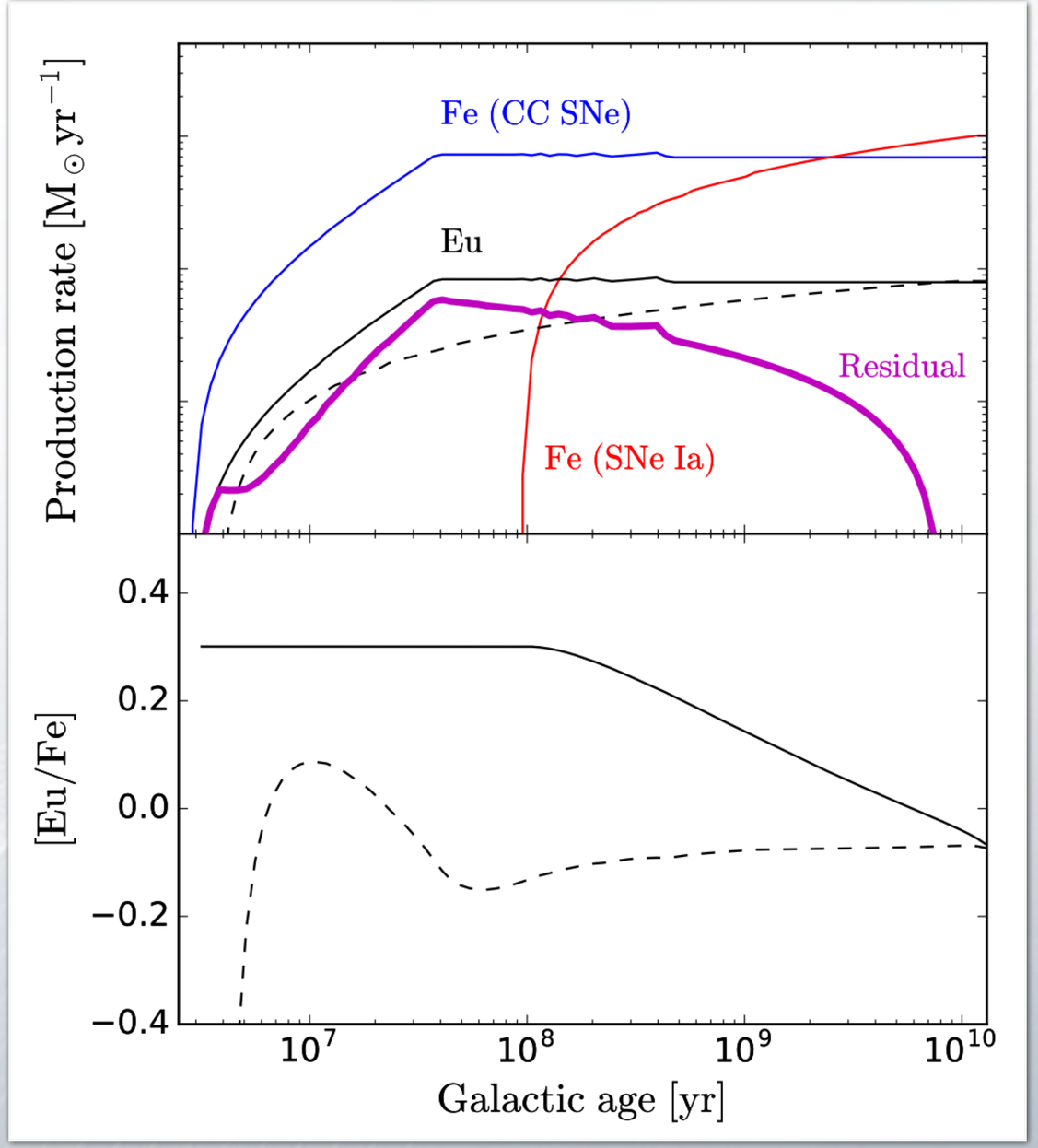




TAKE-AWAY MESSAGES

Chemical evolution is a multi-disciplinary field of research with a lot of learning opportunities, but also with a lot of challenges and uncertainties.

We should not ignore nuclear astrophysics uncertainties when probing the evolution of galaxies, and we should not ignore galaxy evolution uncertainties when probing the origin of elements.

Assuming that neutron star mergers play an important role in the evolution of r-process elements in the Milky Way, the decreasing trend of [Eu/Fe] in the Galactic disk cannot be recovered when using the canonical delay-time distribution.

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.

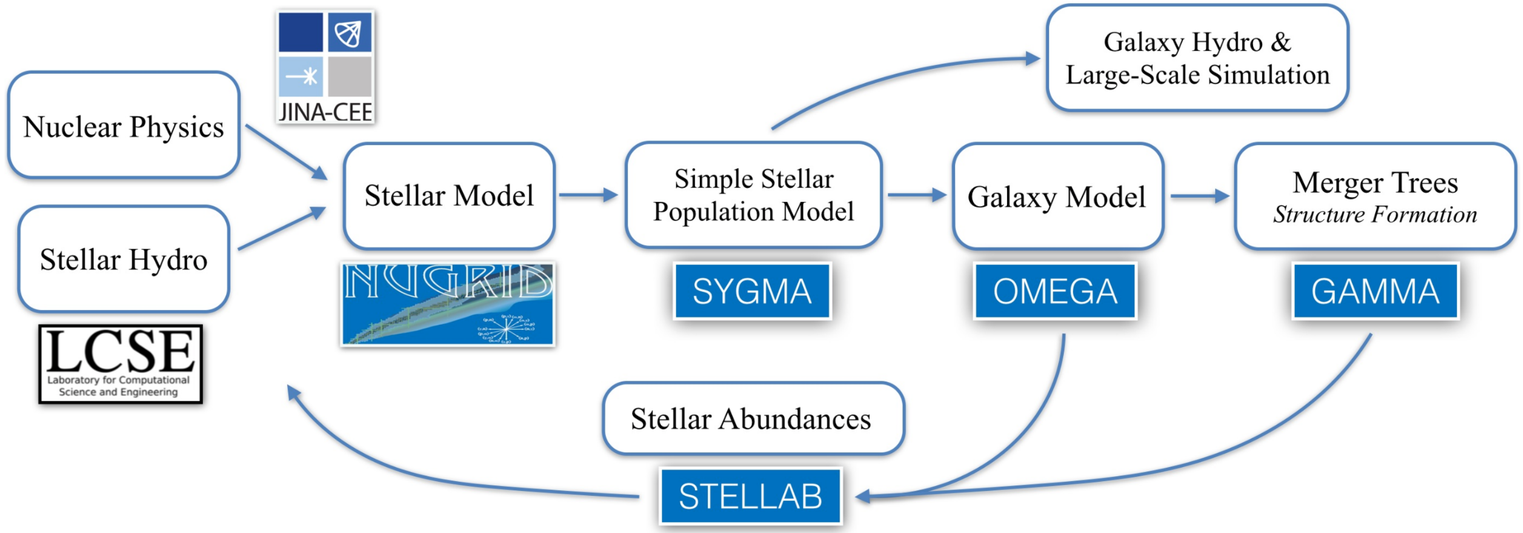
cost EUROPEAN COOPERATION IN SCIENCE & TECHNOLOGY

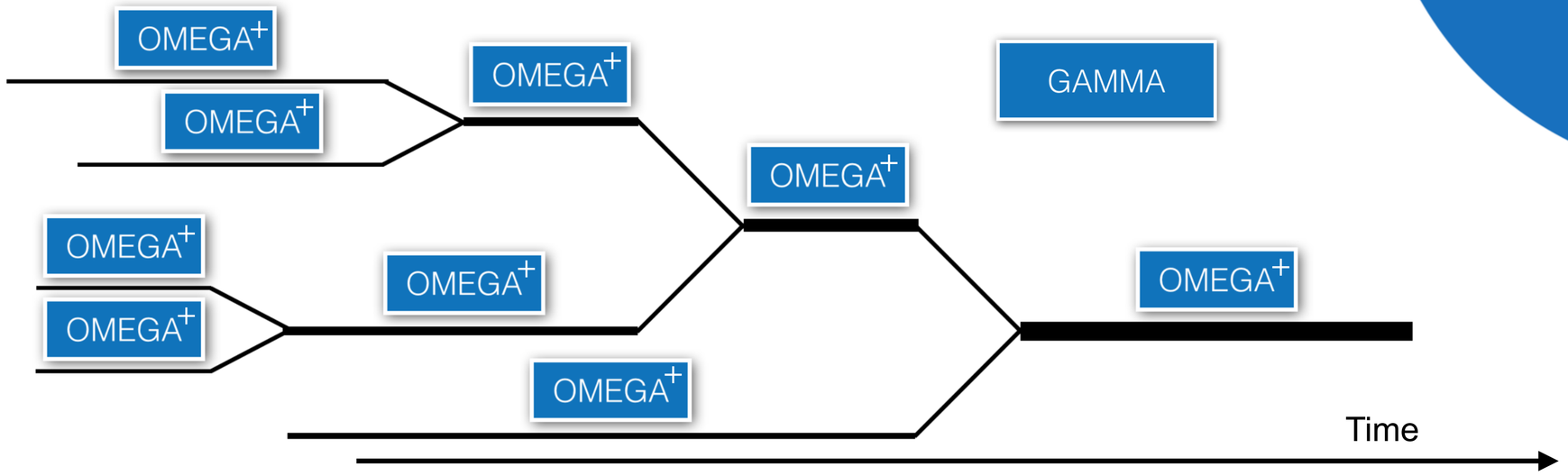
Funded by the Horizon 2020 Framework Programme of the European Union

JINA-CEE

RADIOSTAR erc

EXTRA SLIDES


Nuclear Physics
Stellar Hydro
JINA-CEE
LCSE
Laboratory for Computational Science and Engineering
Stellar Model
NUGRID
Simple Stellar Population Model
SYGMA
Galaxy Hydro & Large-Scale Simulation
Galaxy Model
OMEGA
Merger Trees
Structure Formation
GAMMA
Stellar Abundances
STELLAB


OMEGA+
OMEGA+
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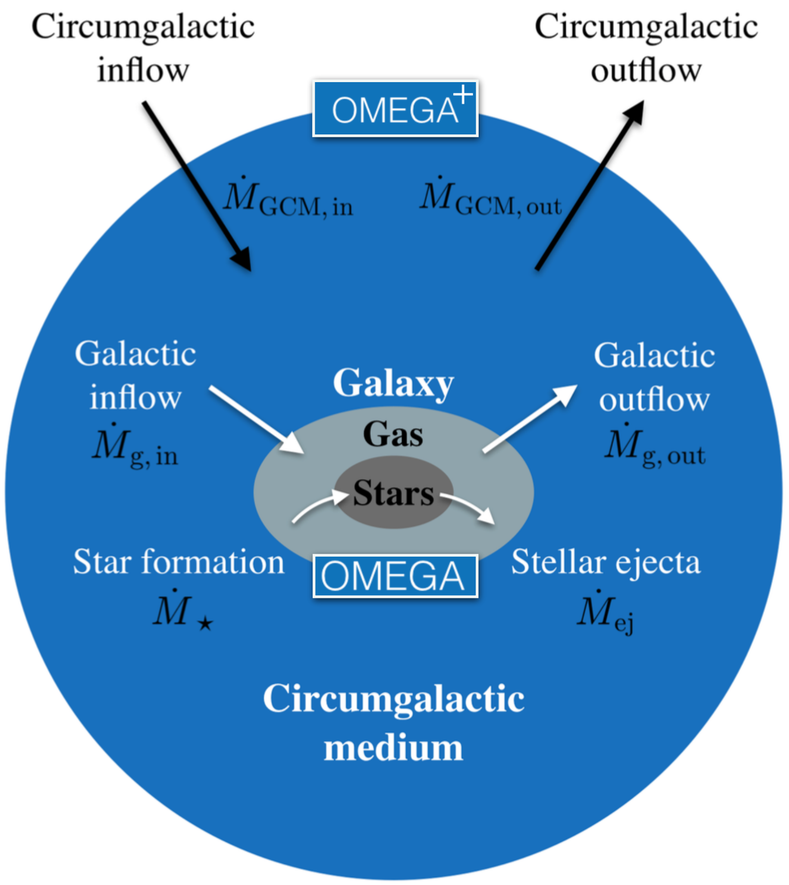
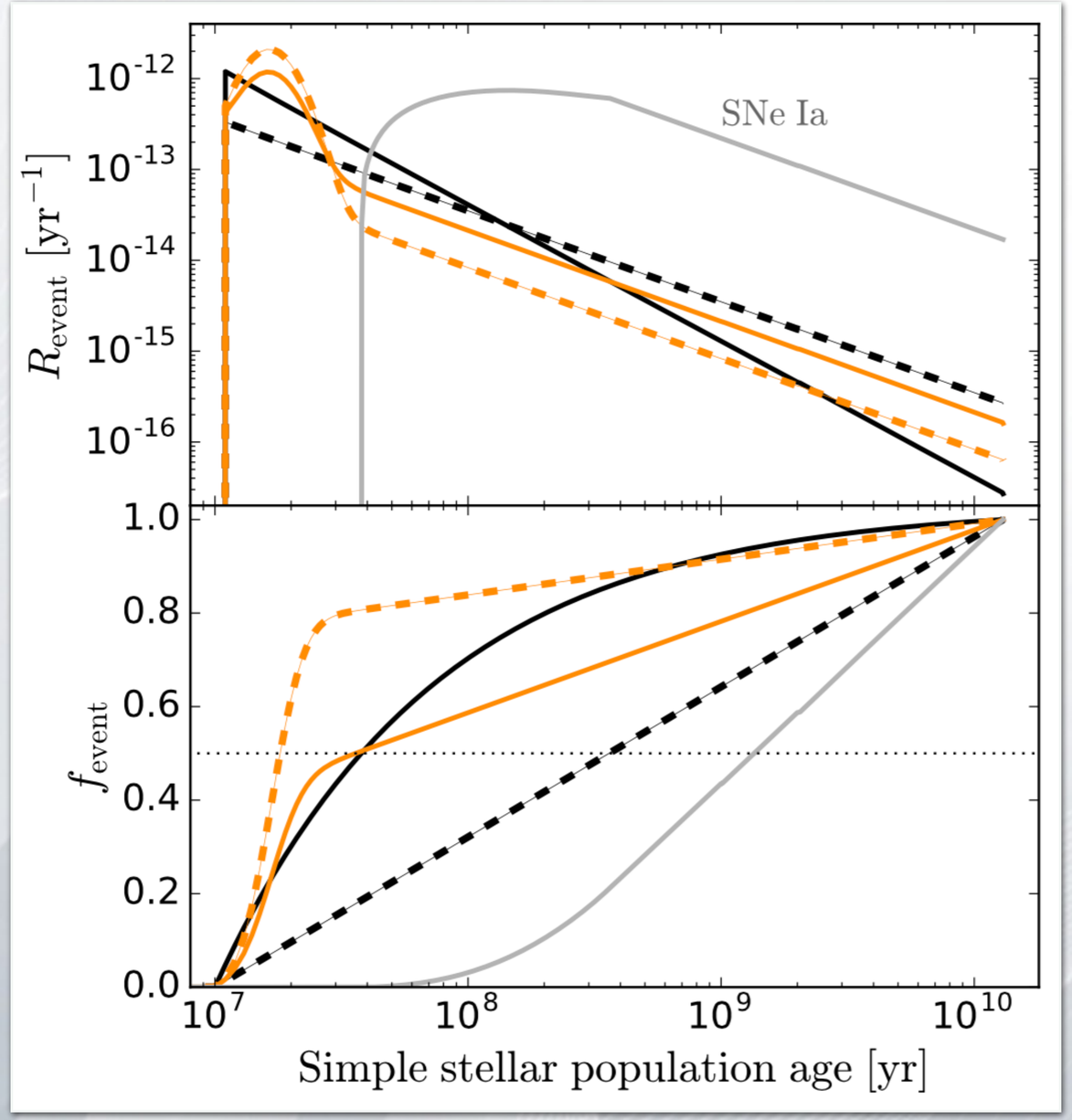
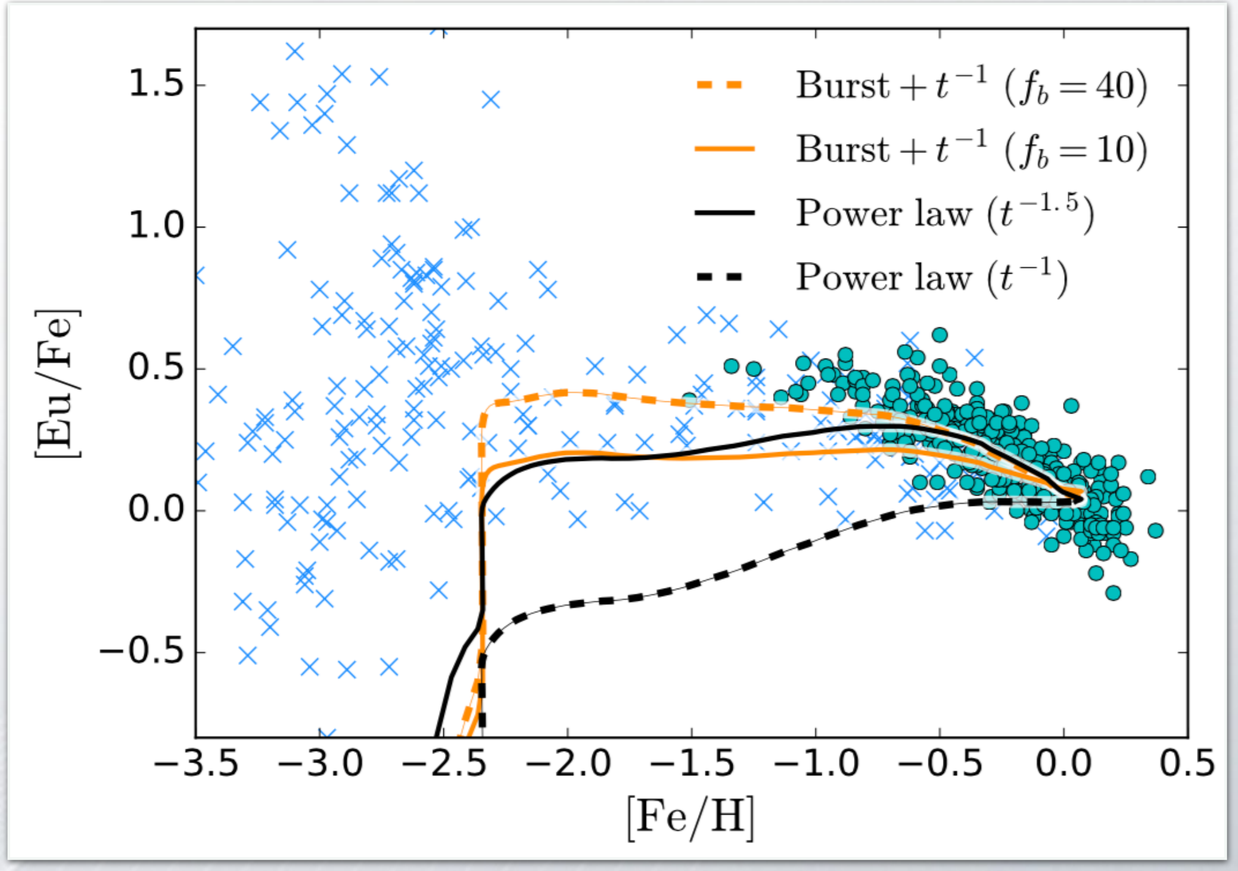
OMEGA+
OMEGA+
GAMMA
OMEGA+
Time

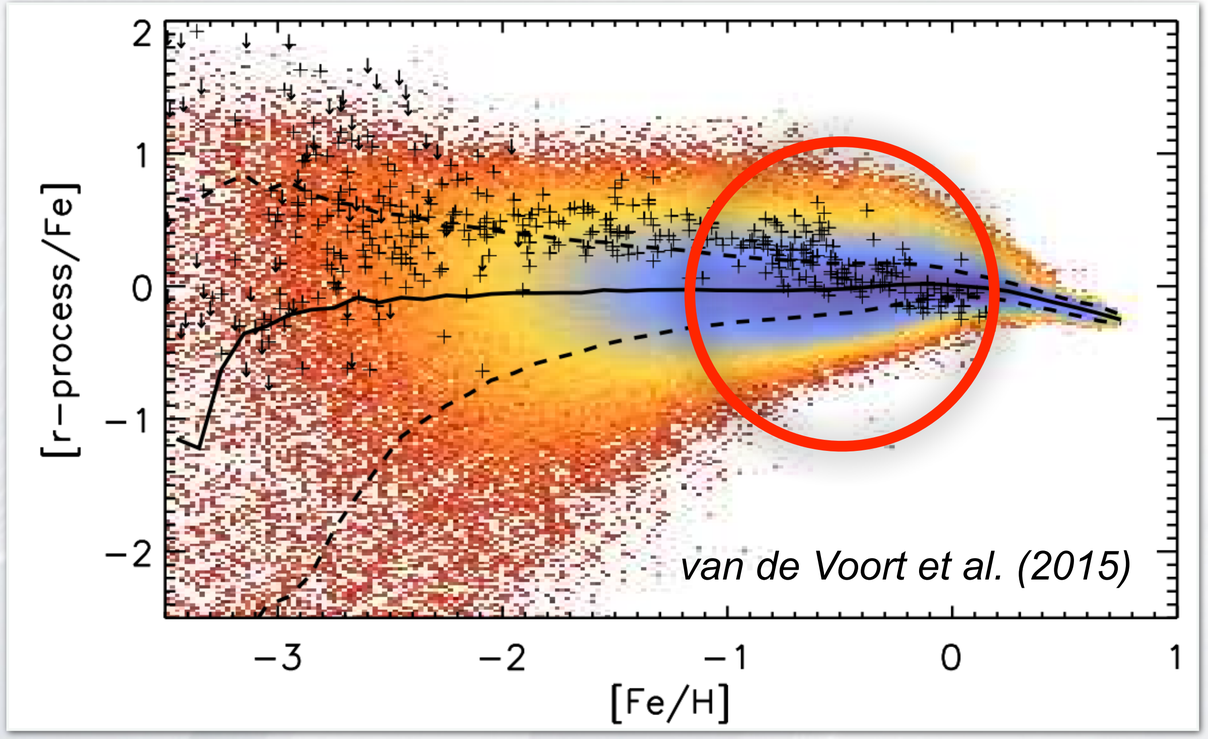

Circumgalactic inflow
Circumgalactic outflow
OMEGA+
$\dot{M}_{\rm GCM,\,in}$
$\dot{M}_{\rm GCM,\,out}$
Galactic inflow
$\dot{M}_{\rm g,\,in}$
Galaxy
Gas
Stars
Galactic outflow
$\dot{M}_{\rm g,\,out}$
Star formation
$\dot{M}_{\star}$
OMEGA
Stellar ejecta
$\dot{M}_{\rm ej}$
Circumgalactic medium

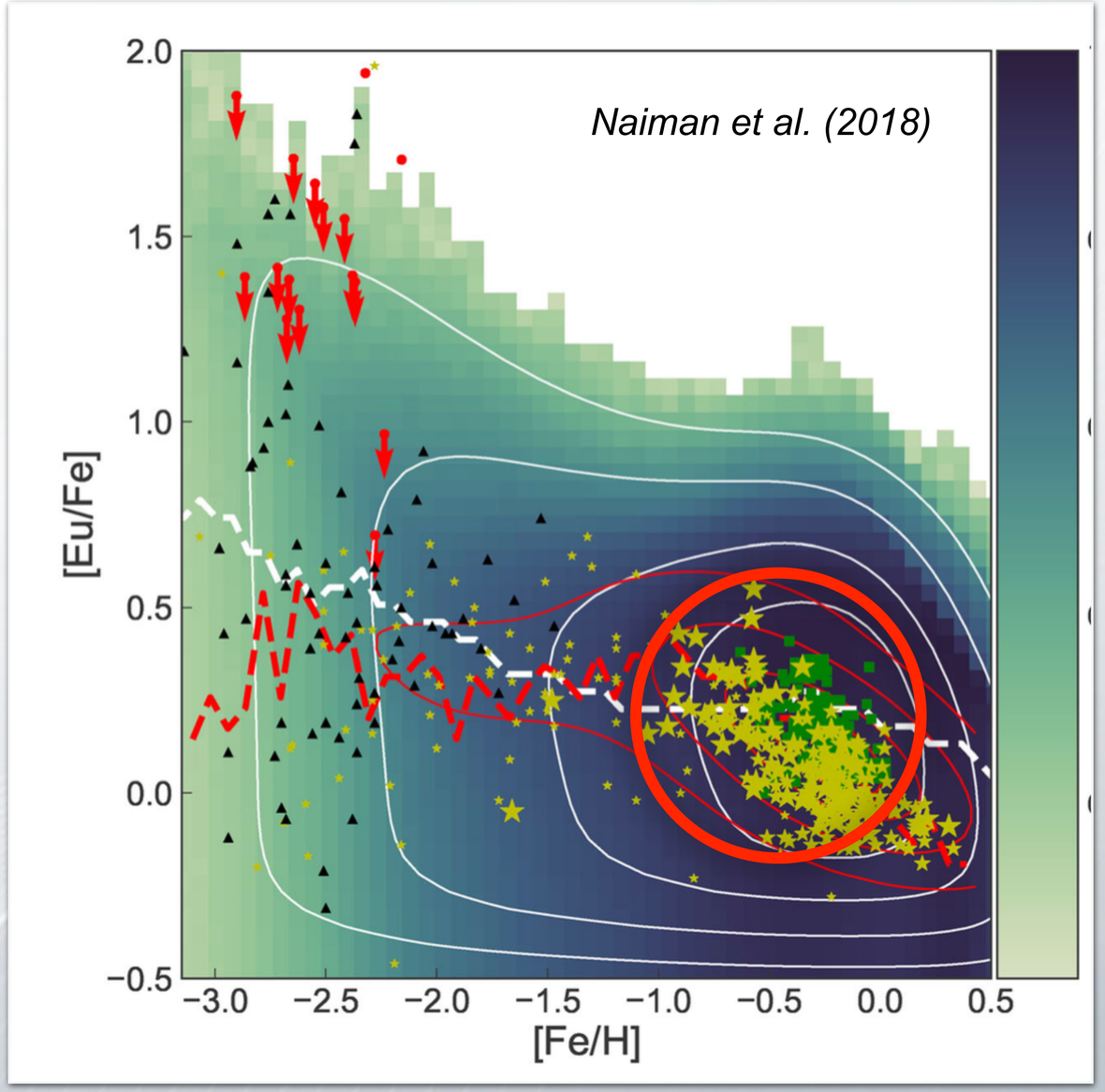
THE DECREASING TREND OF [Eu/Fe] IN THE GALACTIC DISK



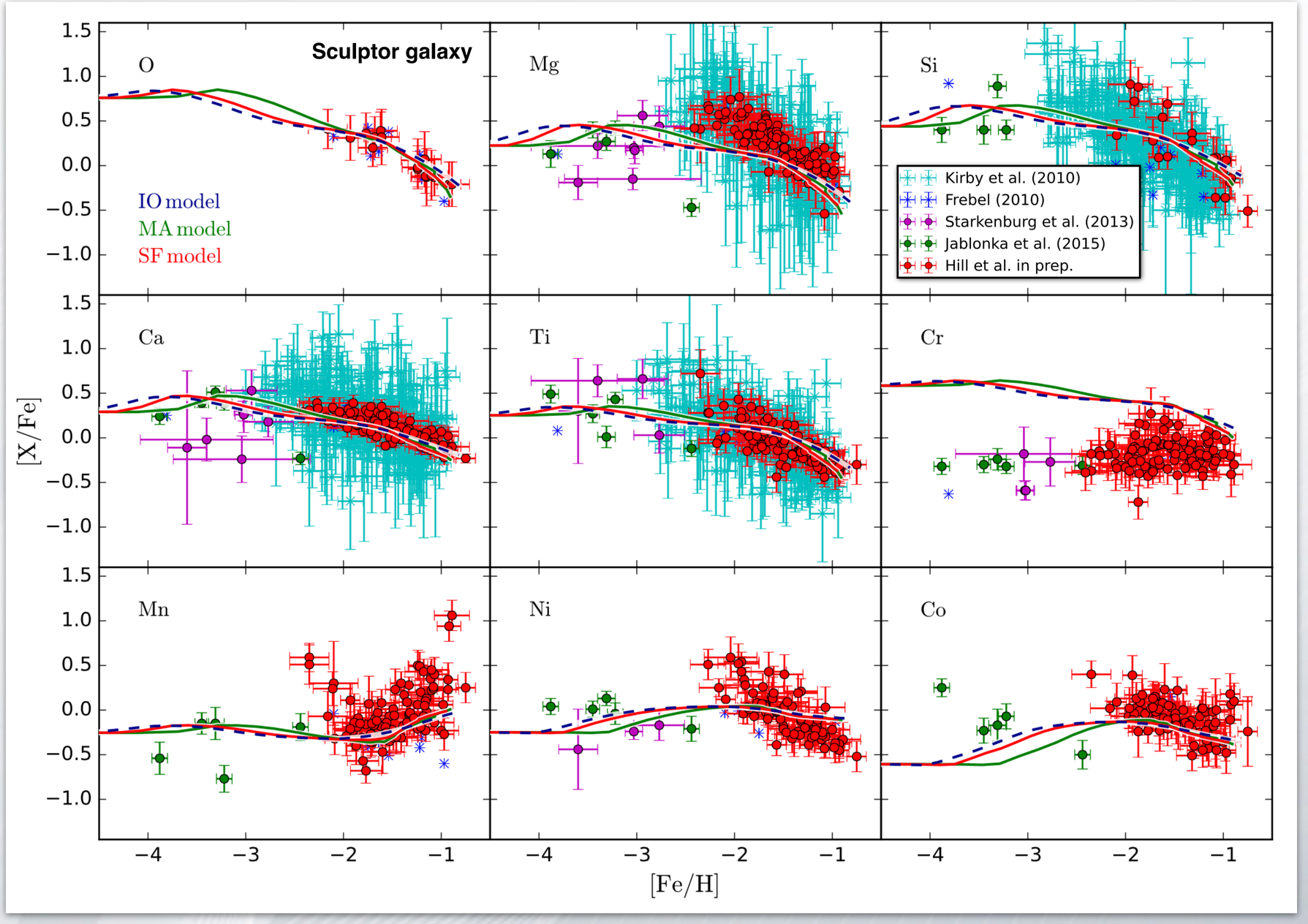
Côté, Eichler, et al. (in preparation)



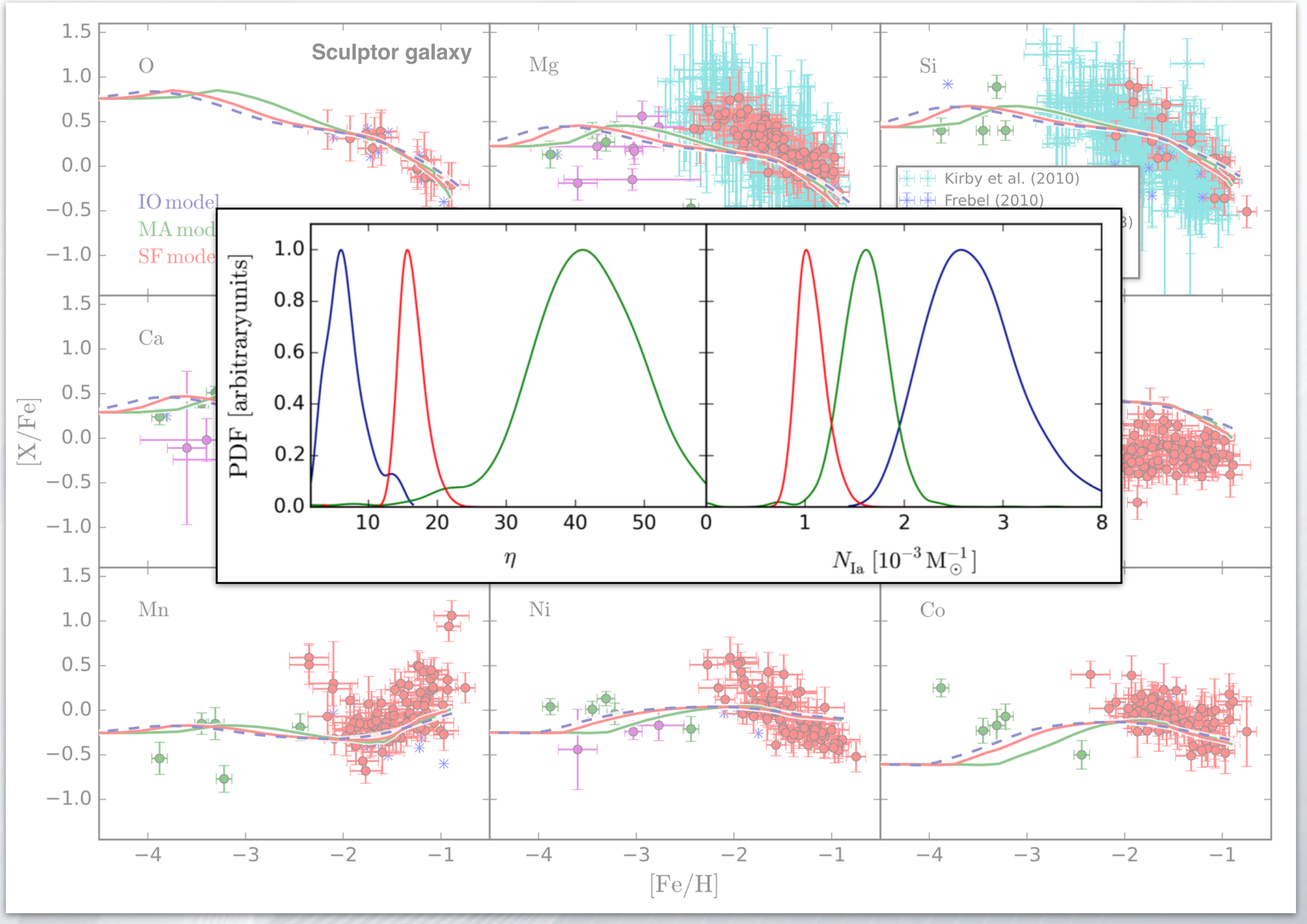

[r−process/Fe]
[Fe/H]
van de Voort et al. (2015)


Naiman et al. (2018)
[Eu/Fe]
[Fe/H]

Côté, O'Shea, Ritter, et al. (2017)



Côté, O'Shea, Ritter, et al. (2017)



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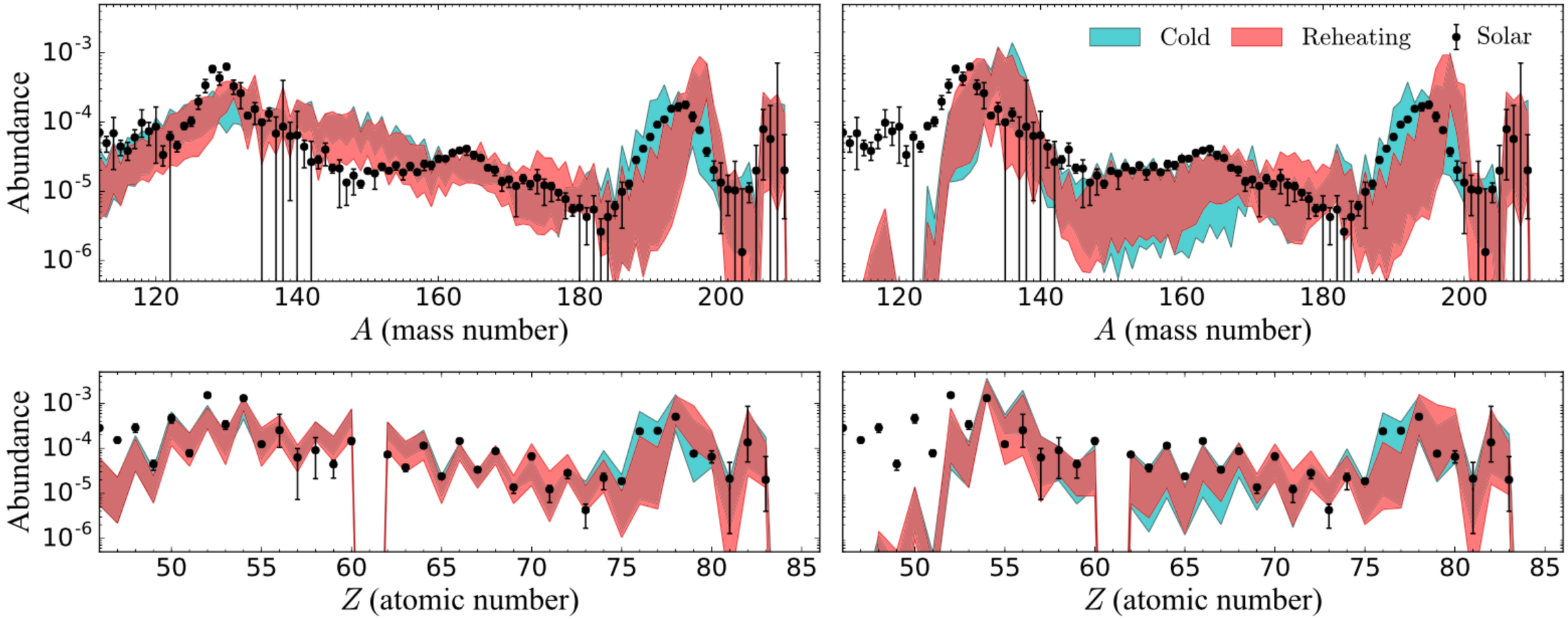
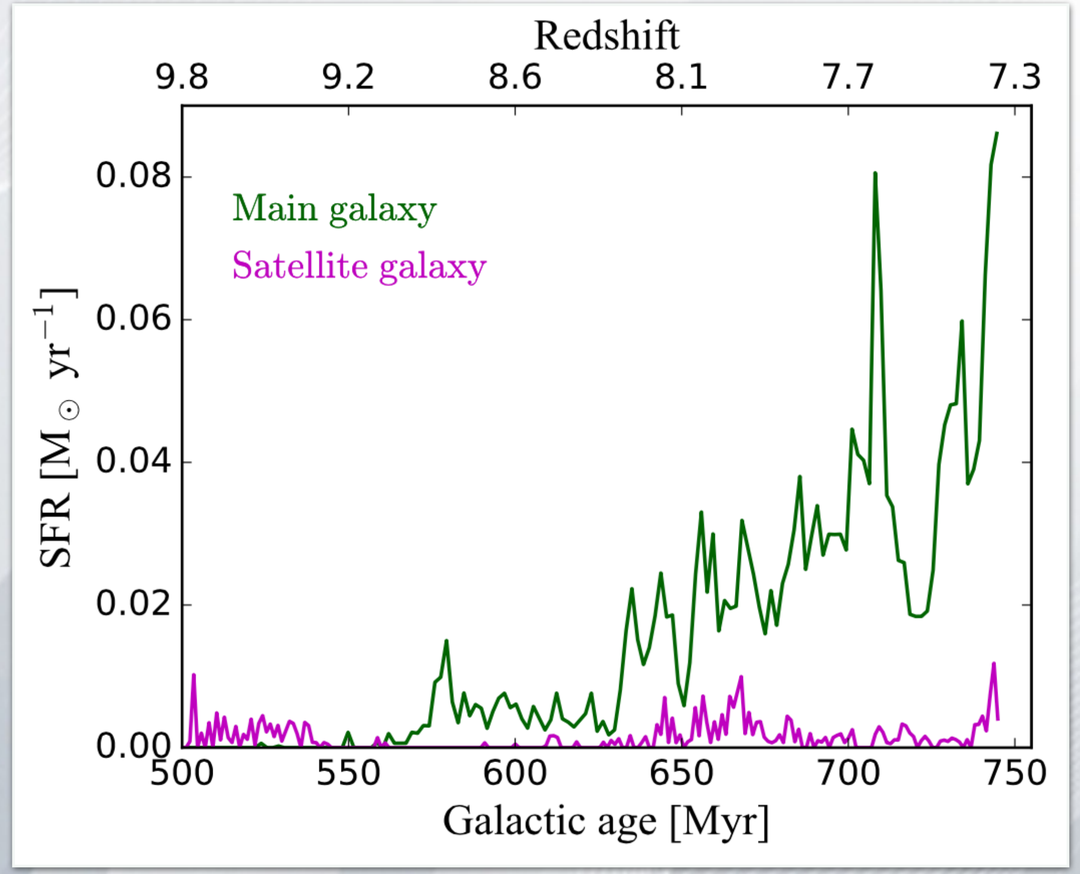
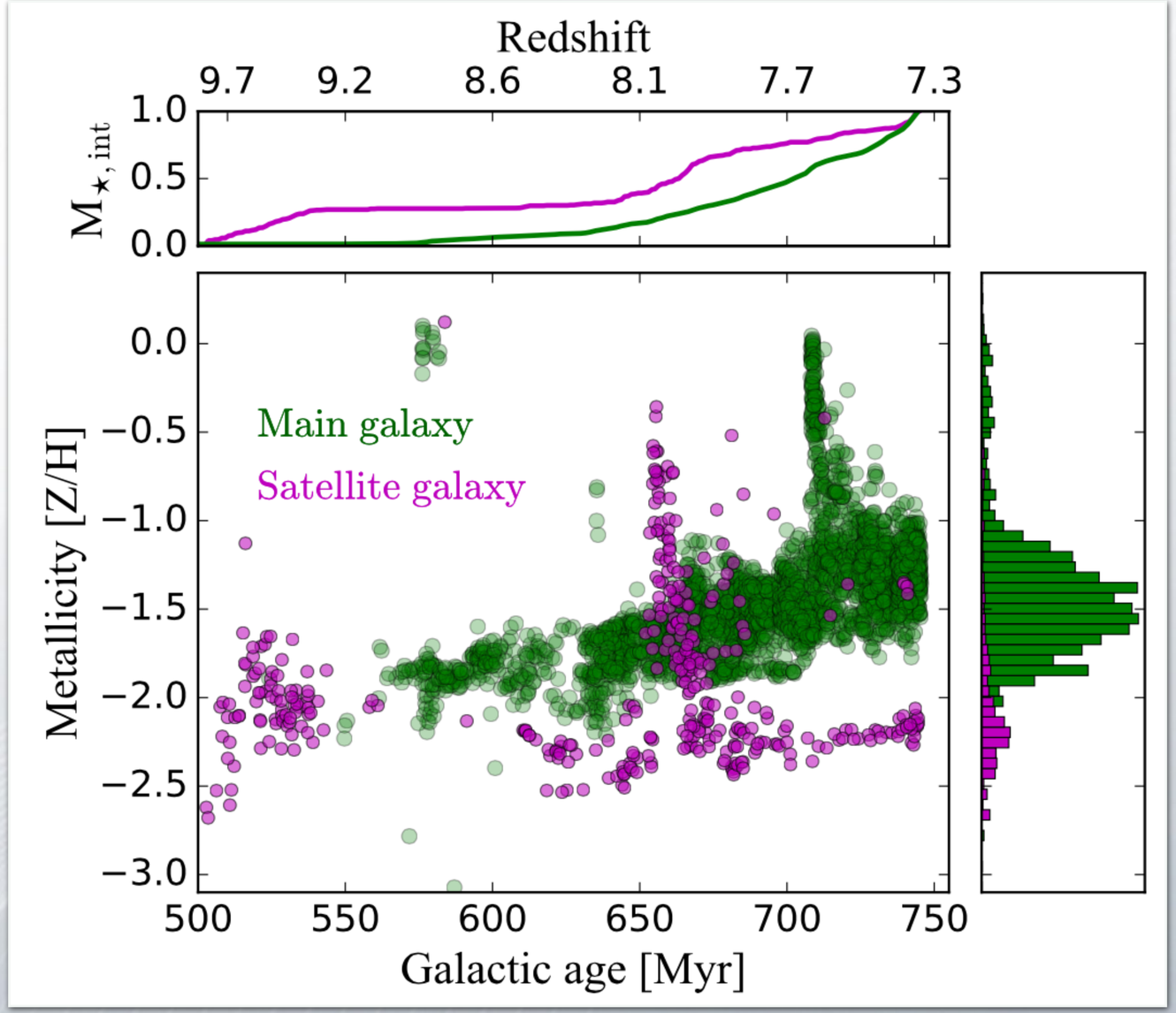


Figure 2. The range in the calculated low-Y_e *r*-process abundances as a function of mass number *A* (upper row) and atomic number *Z* (lower row) generated from the same 10 mass models as in Figure 1, assuming Kodama & Takahashi (1975; left panels) and a symmetric split (right panels) for the fission fragment distribution. Turquoise bands represent very neutron-rich, cold merger outflow conditions (Just et al. 2015) without reheating while red bands represent conditions for "slow" ejecta (Mendoza-Temis et al. 2015) with reheating included. The dots are the observed solar *r*-process residuals (taken from Arnould et al. 2007).

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