.. and **Neutron Stars**

# Chemical Evolution and the Mass Function of Stellar Mass Black Holes


Benoit Côté
Postdoctoral Fellow

Collaborators
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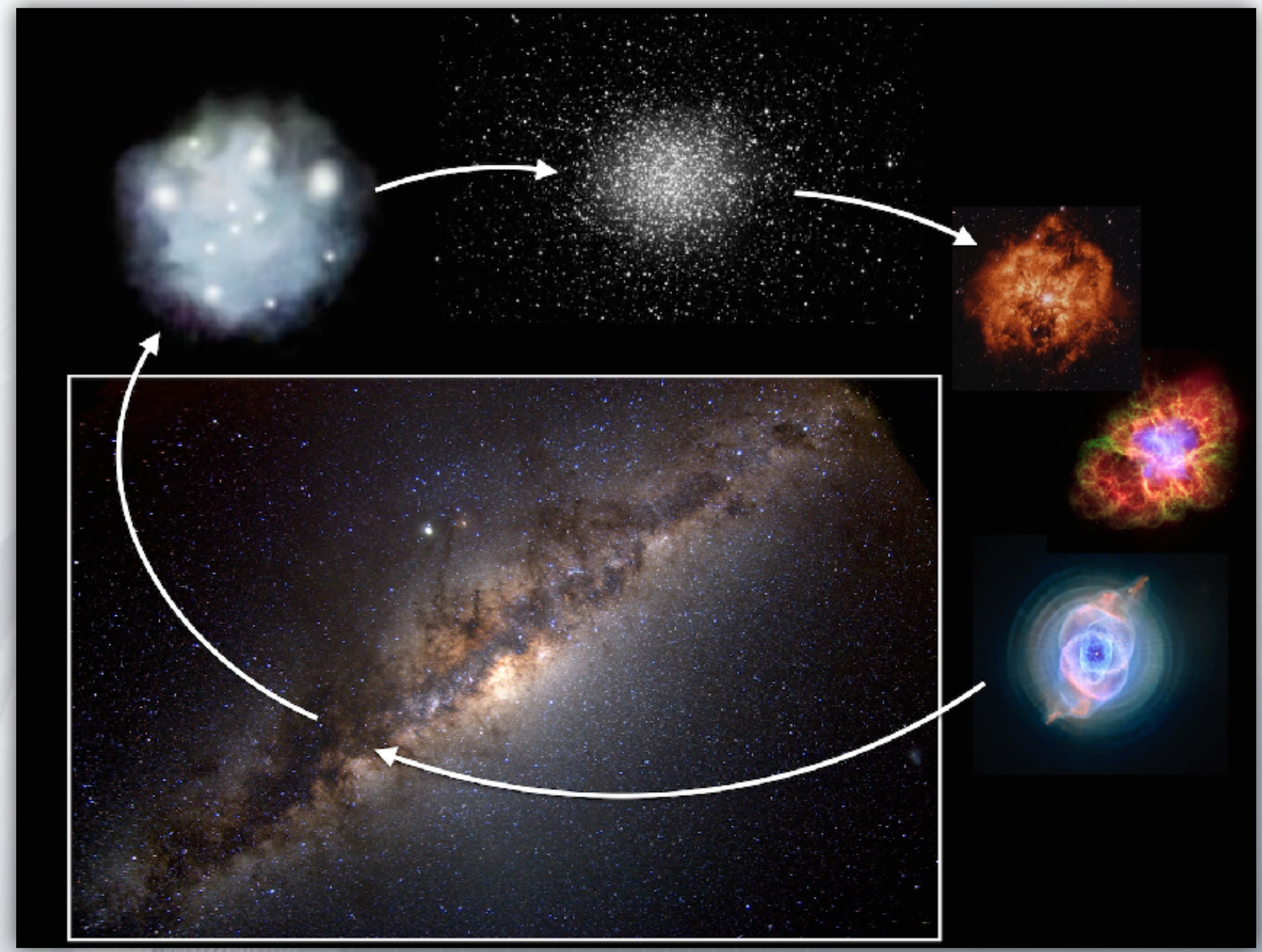
2017 Sagan Exoplanet Summer Workshop
Microlensing in the Era of WFIRST

NASA Exoplanet Science Institute, Caltech
August 8th 2017

# Life Cycle of Stars



# Definition of Metals

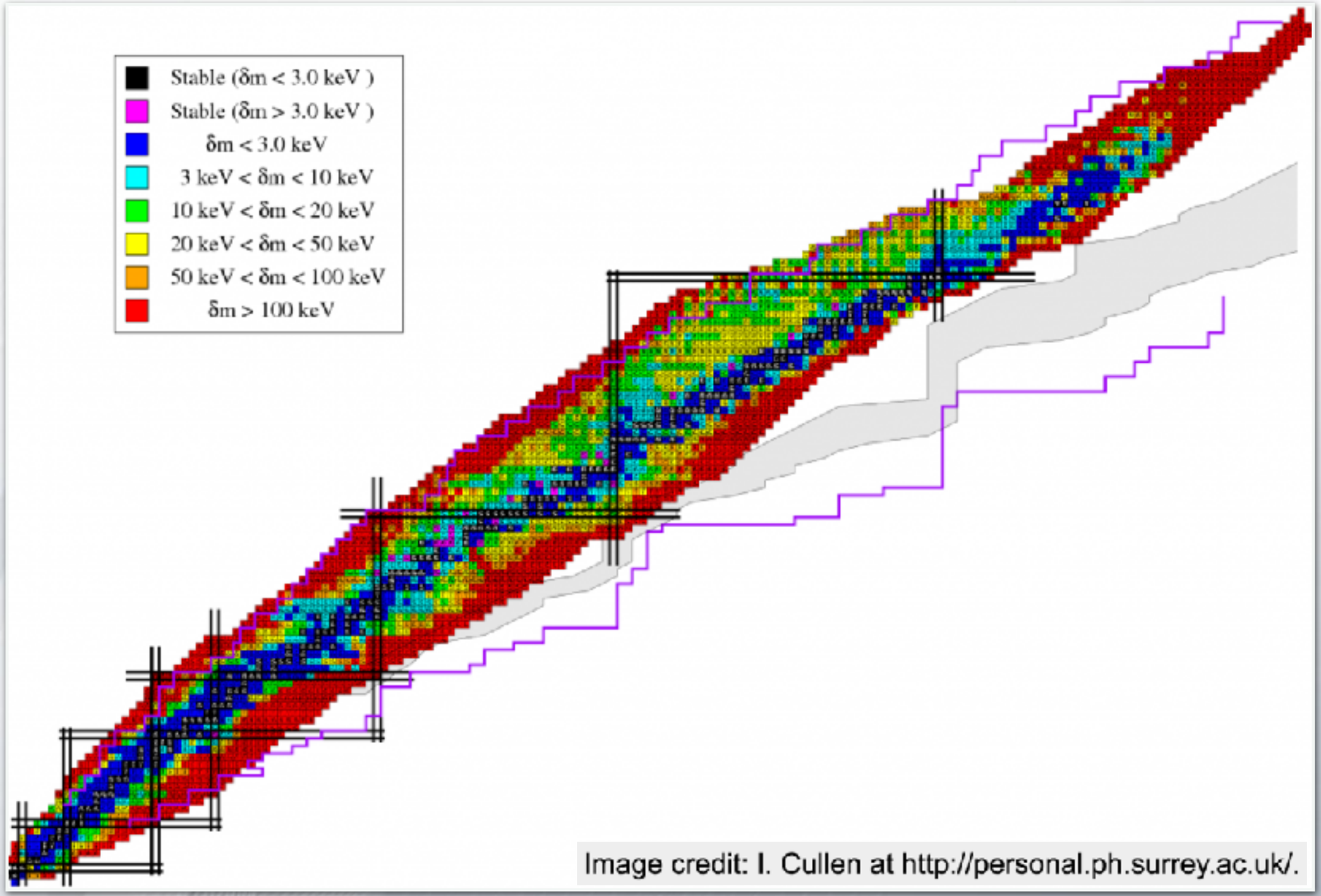



Image credit: I. Cullen at http://personal.ph.surrey.ac.uk/.

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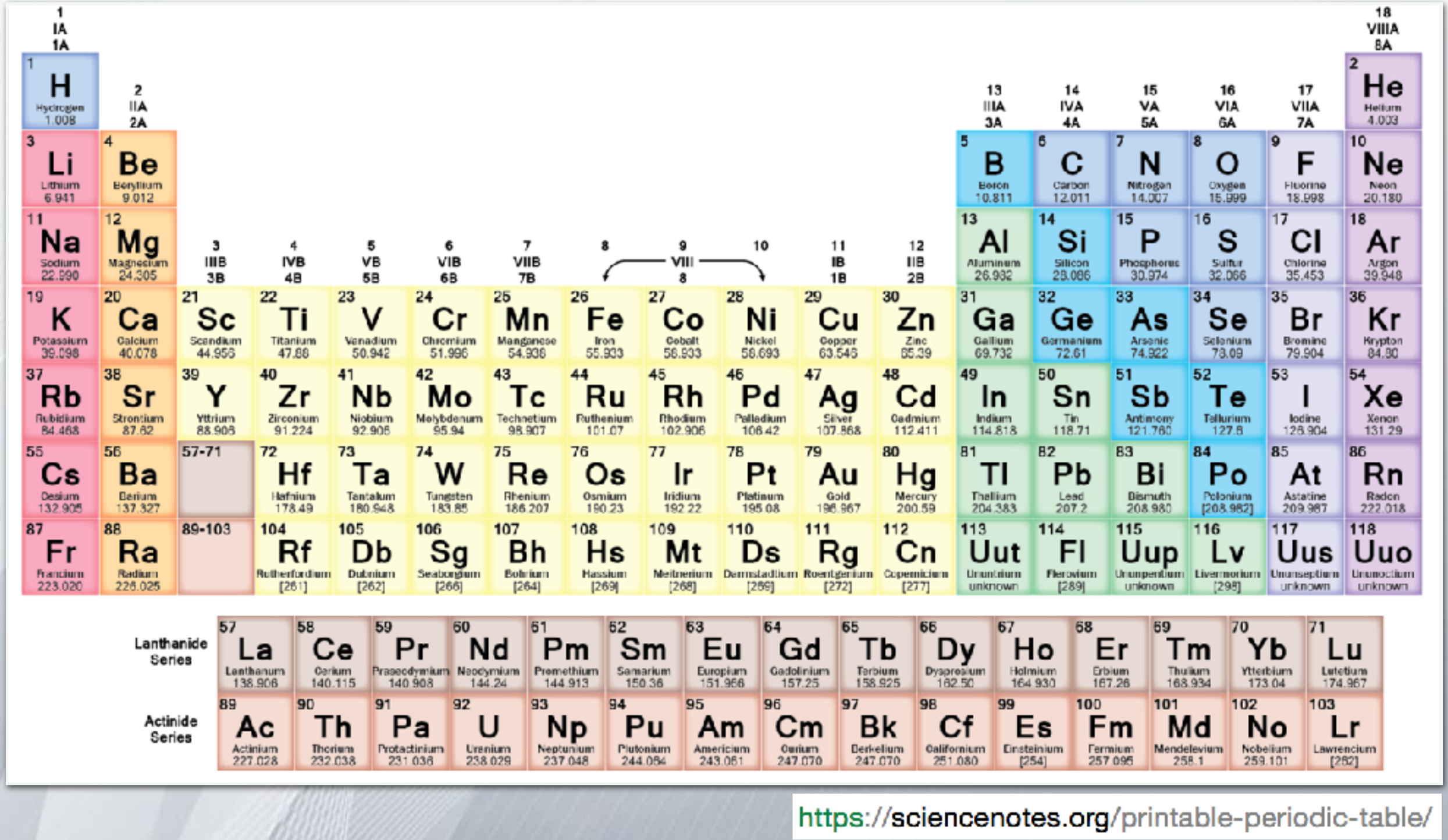


https://sciencenotes.org/printable-periodic-table/

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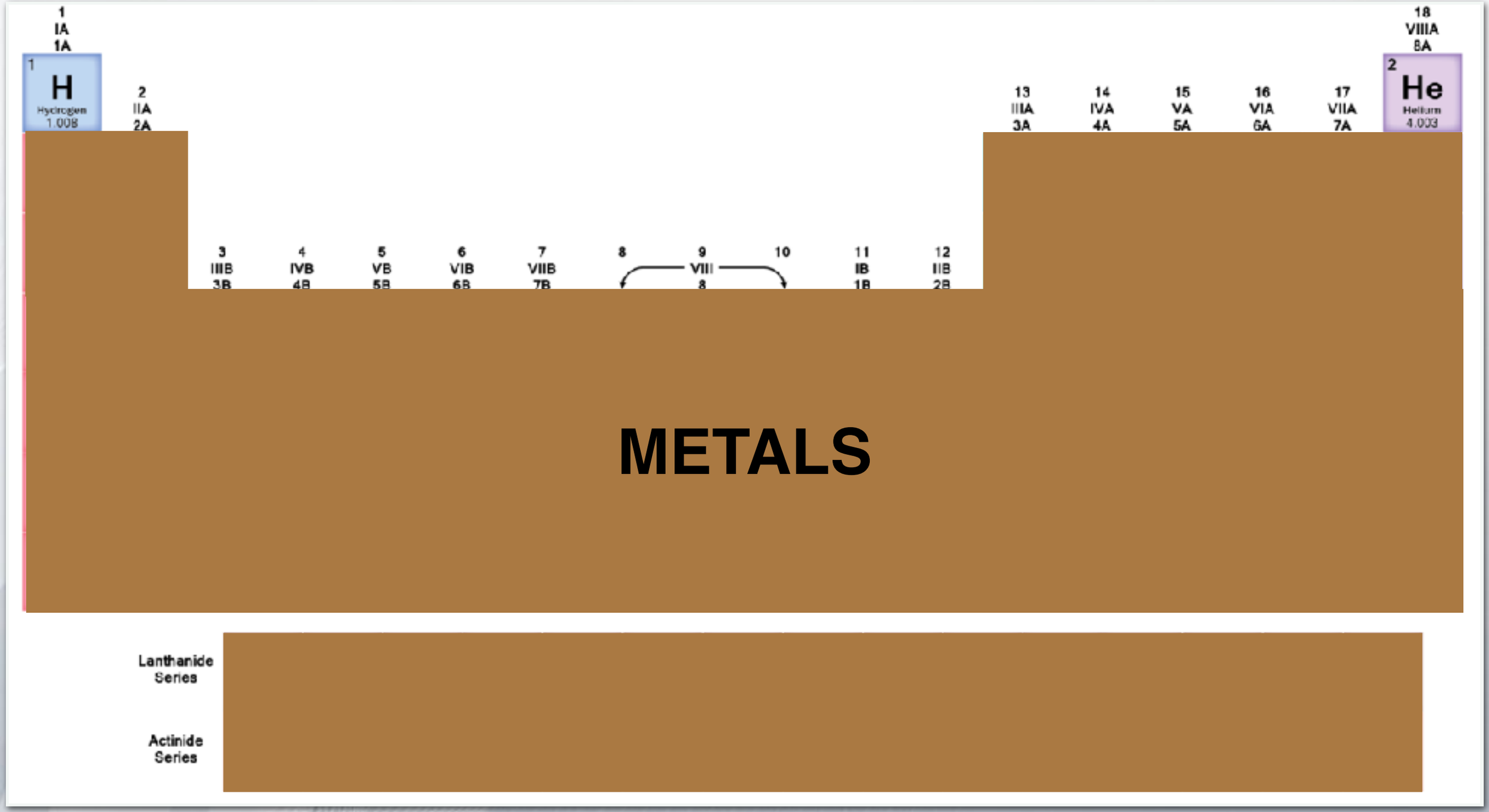

# Sources of Chemical Enrichments

Core-collapse supernovae

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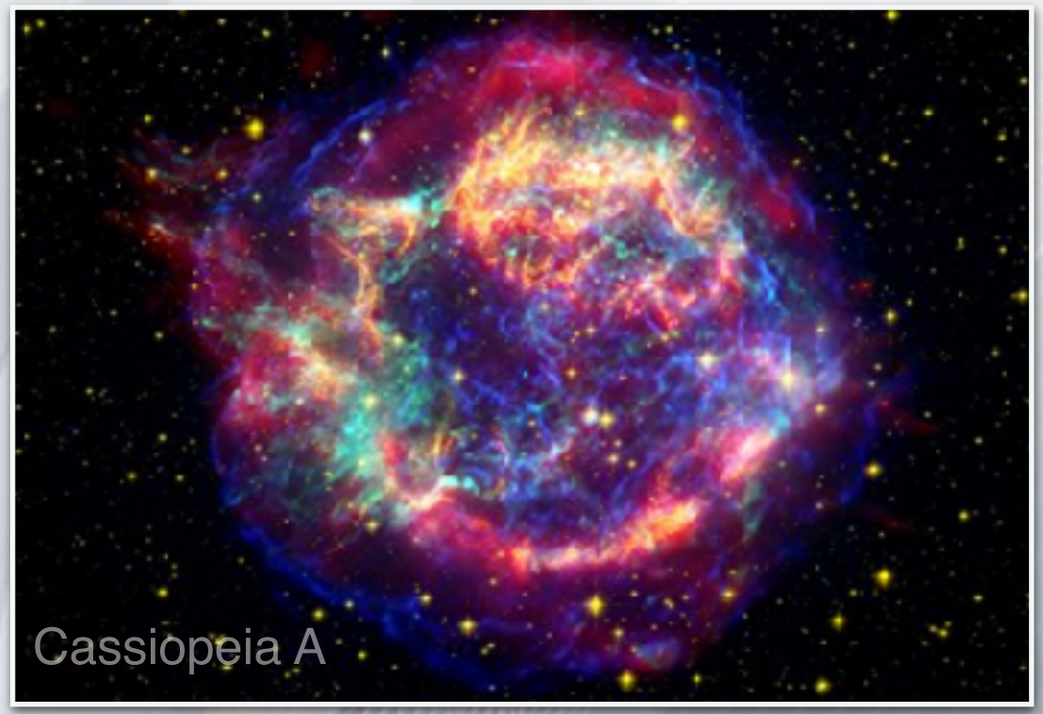
Core-collapse supernovae


Type Ia supernovae



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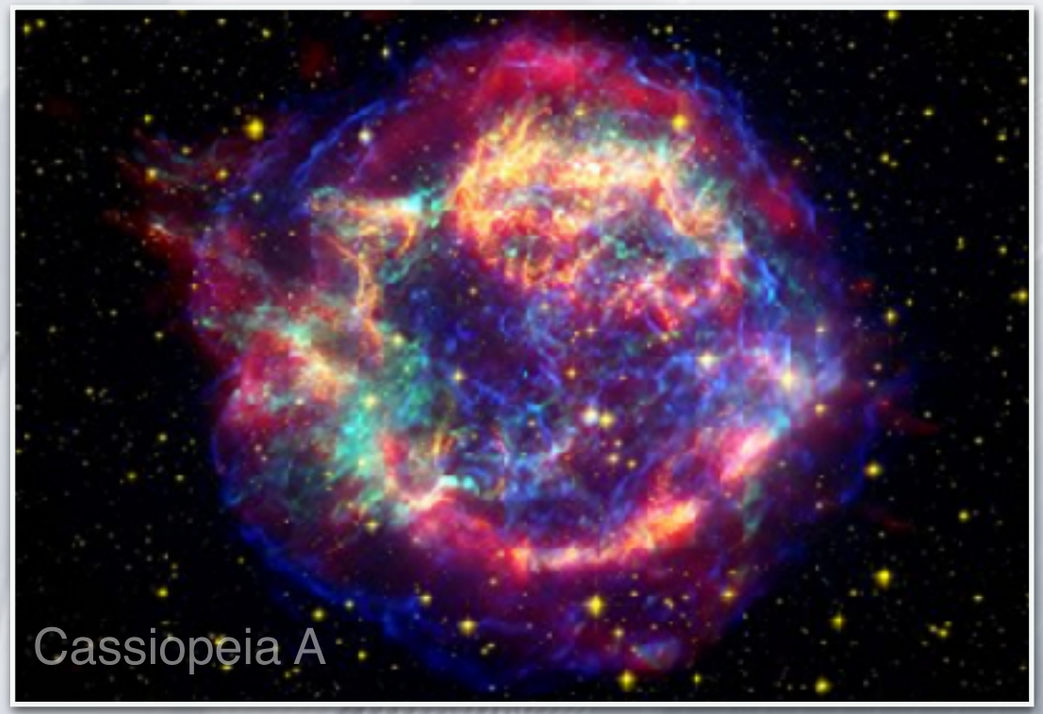


Stellar winds from low-mass stars

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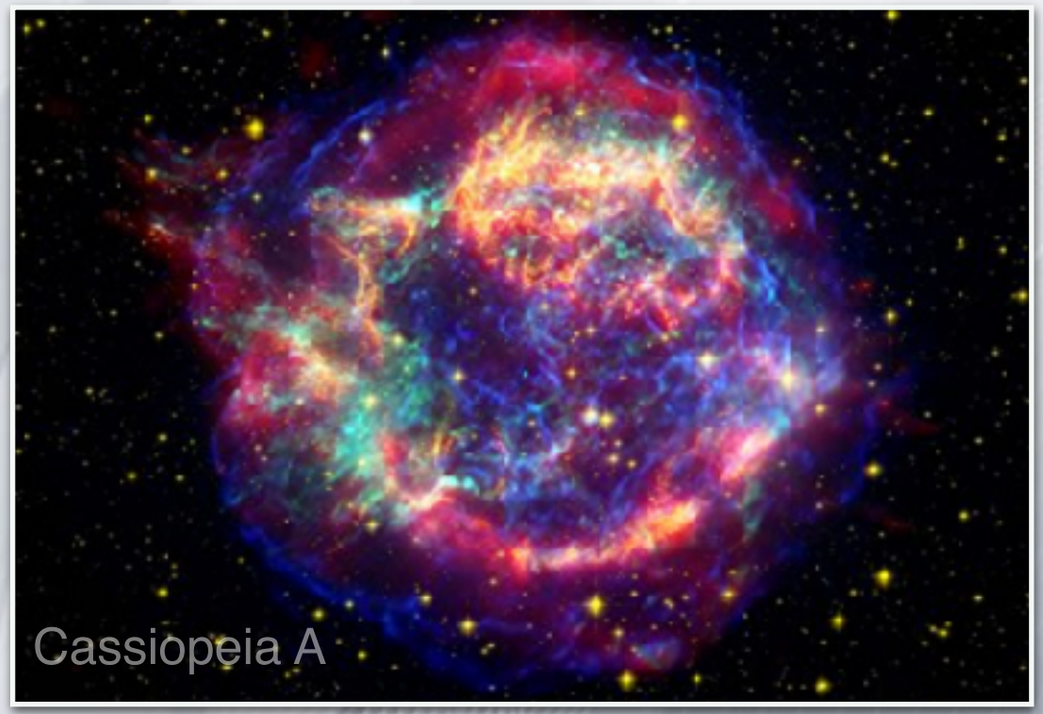


Neutron star merger


Stellar winds from low-mass stars

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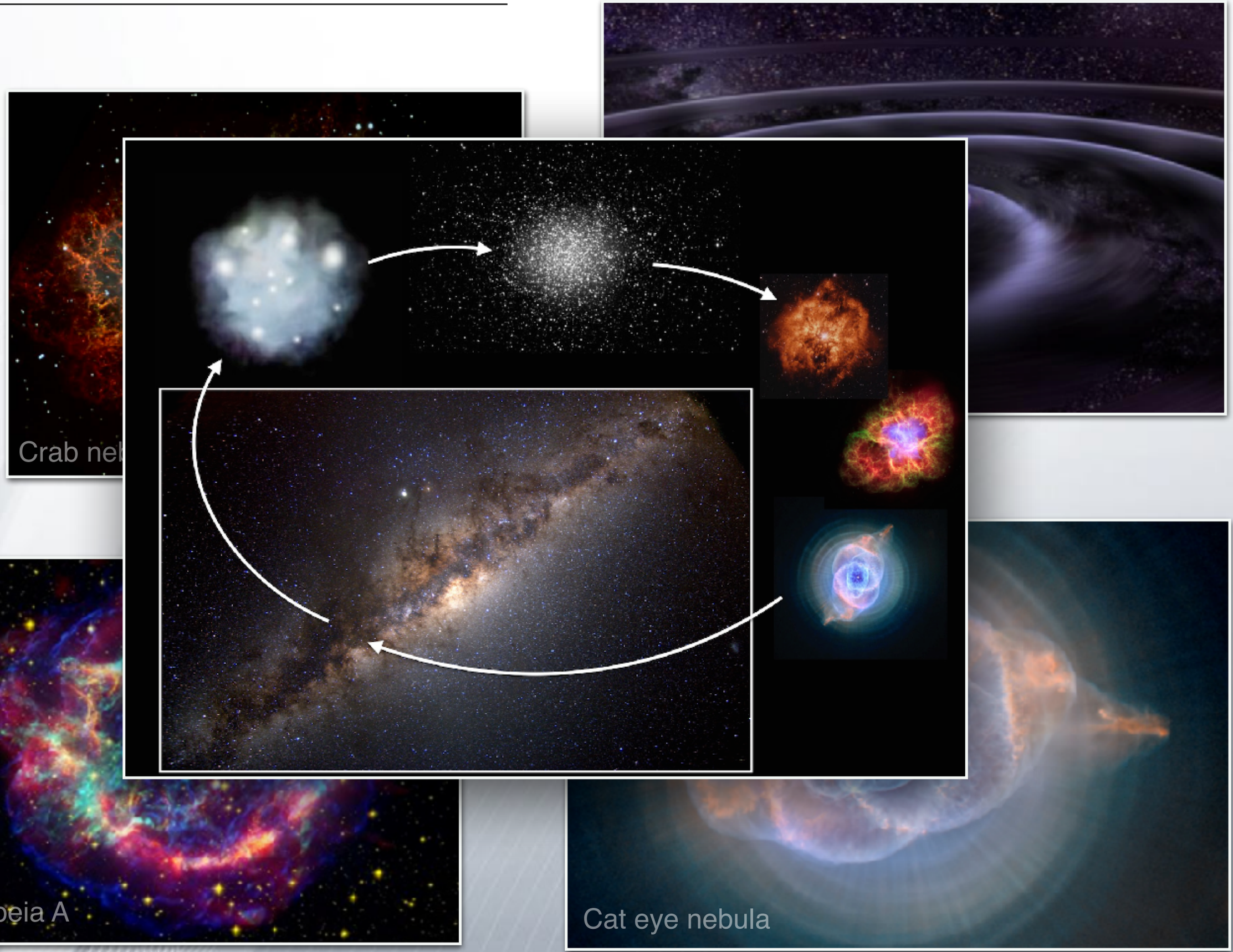
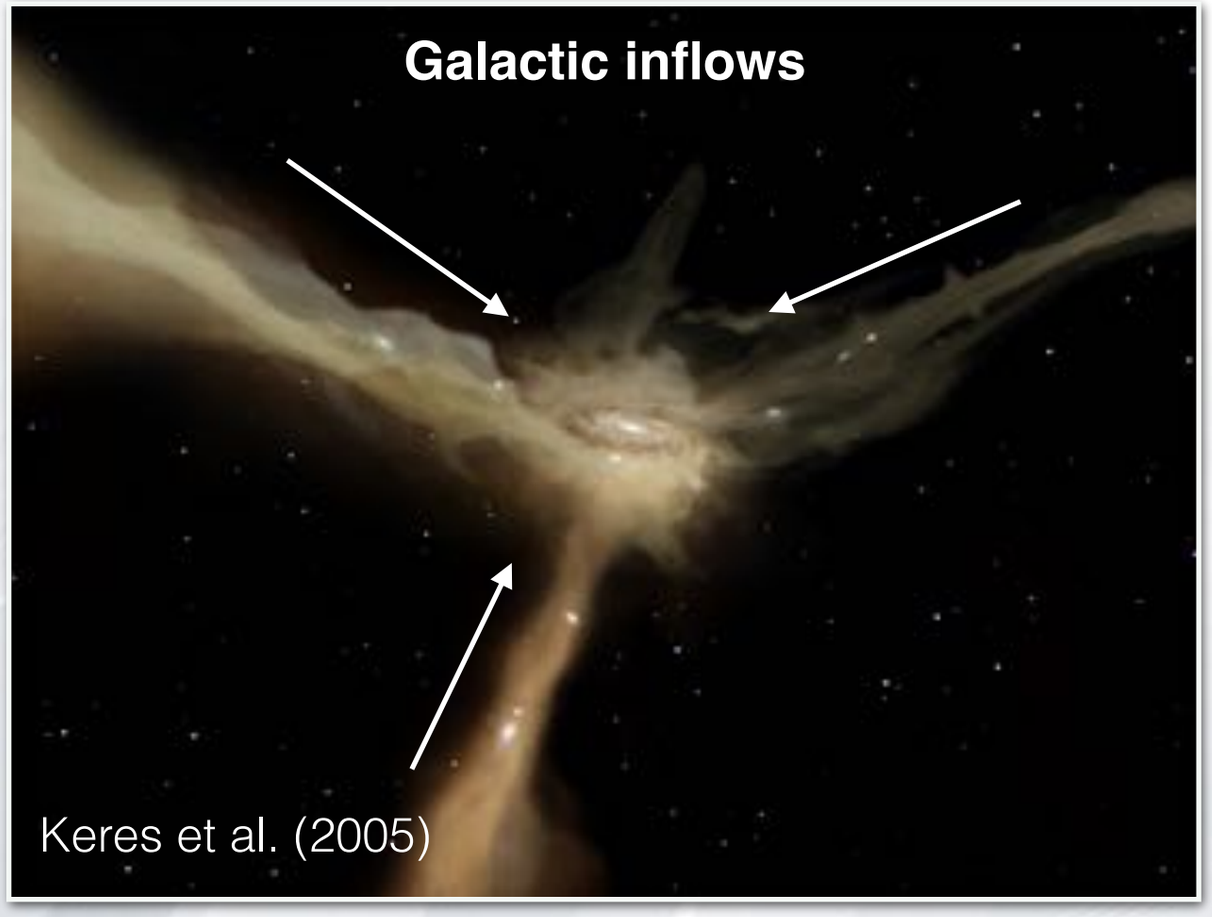


# Galaxy Evolution and Gas Circulation



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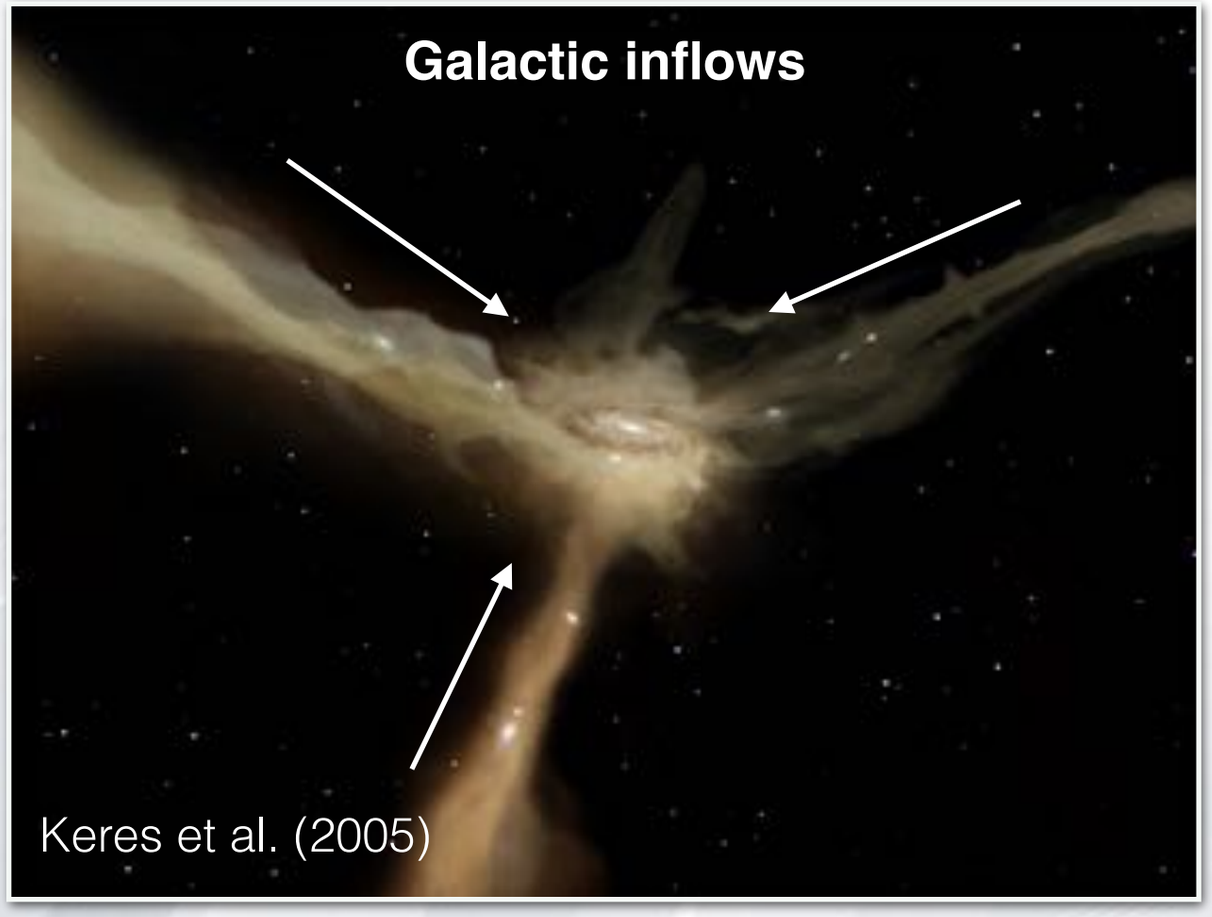


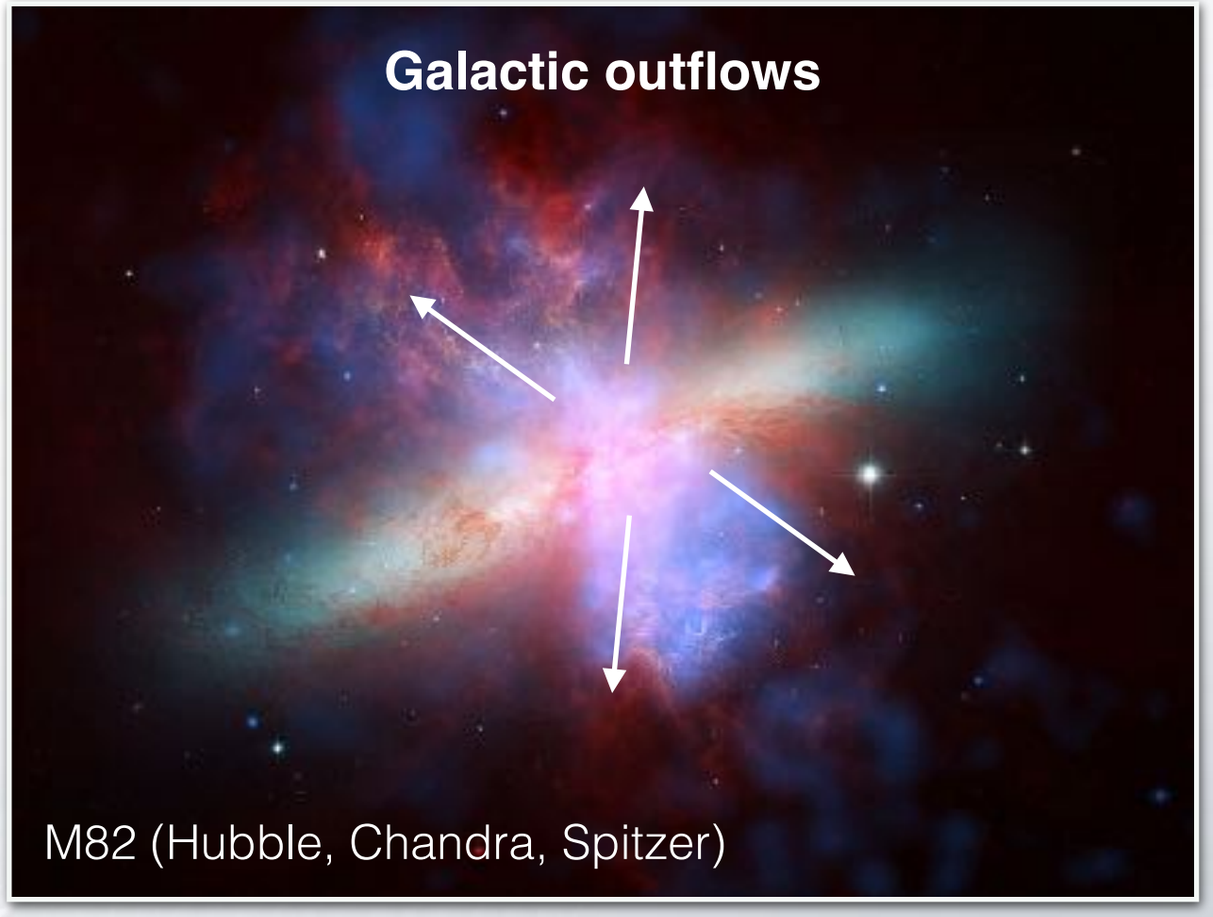

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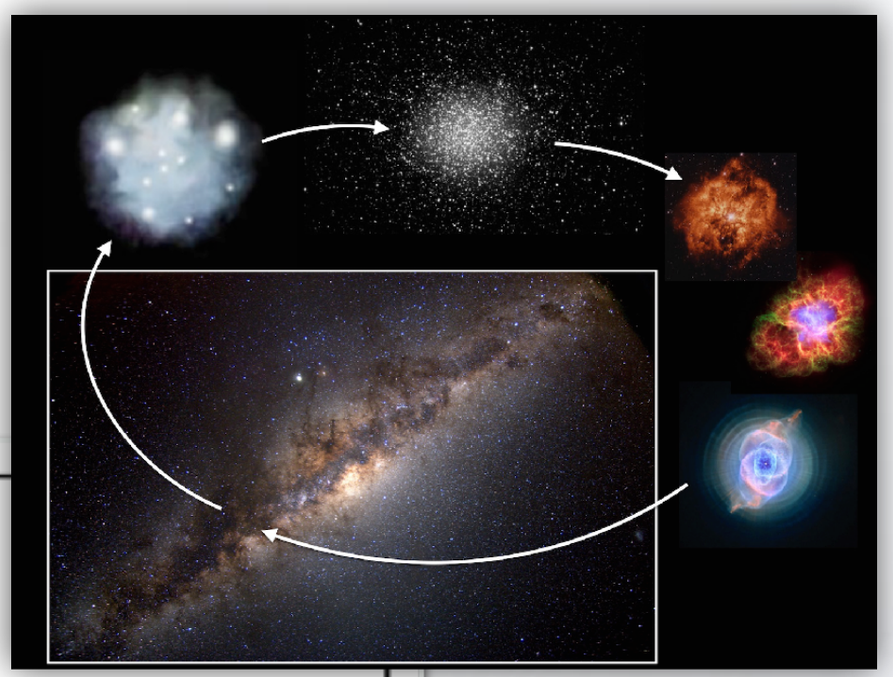

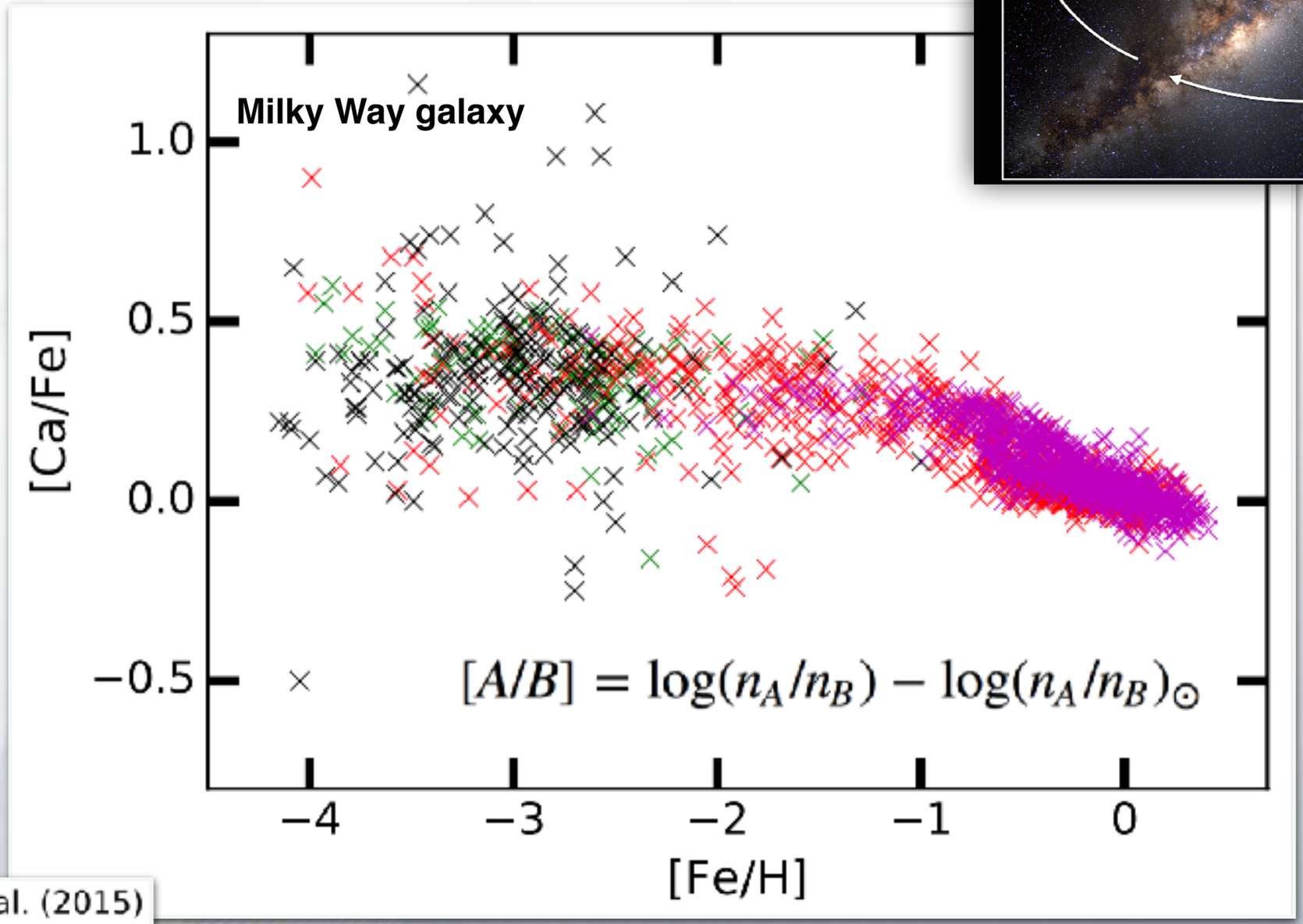


Jacobsen et al. (2015)
Venn et al. (2004) **
Yong et al. (2013)
Bensby et al. (2014)

@Using STELLAB

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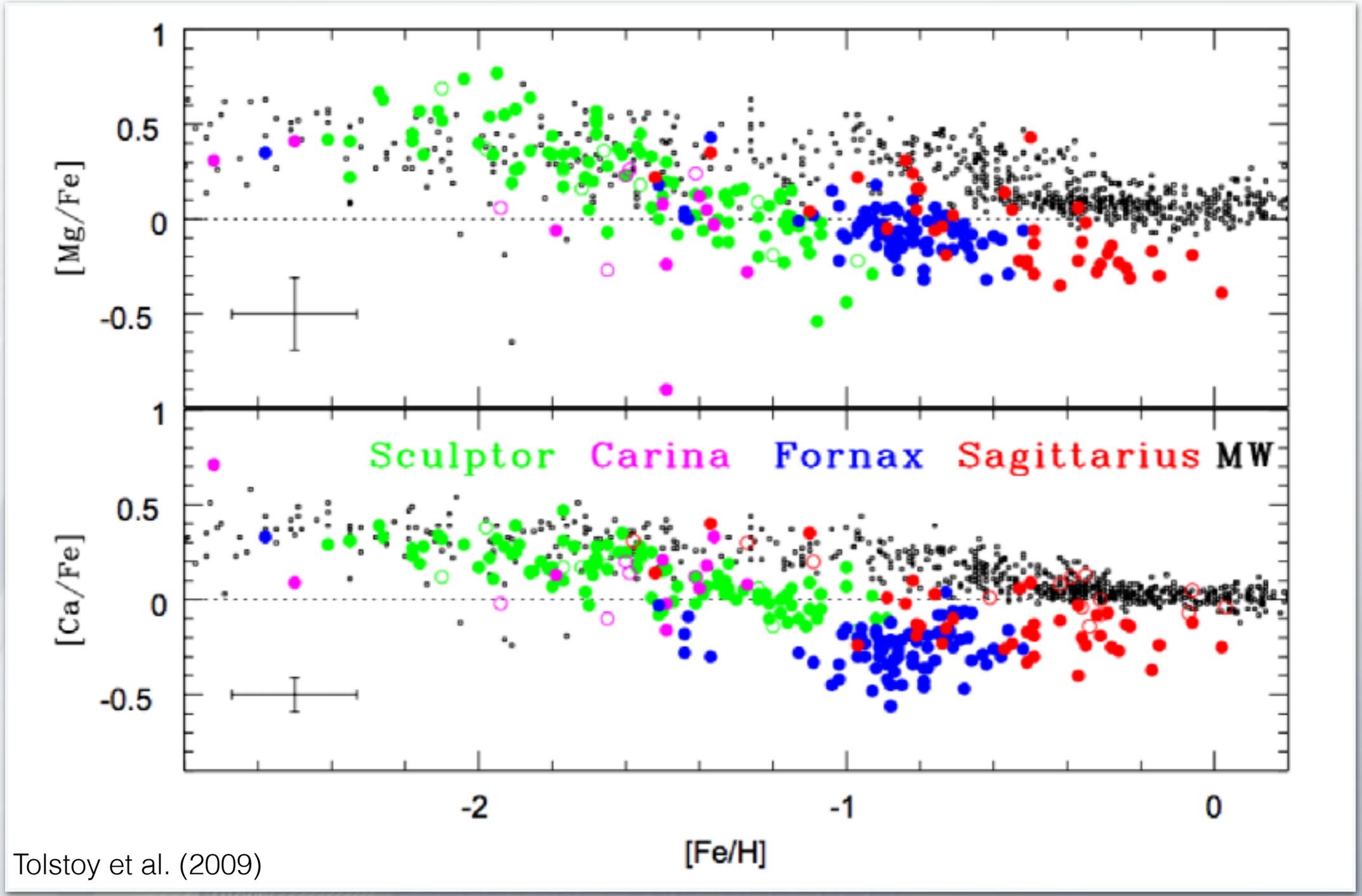
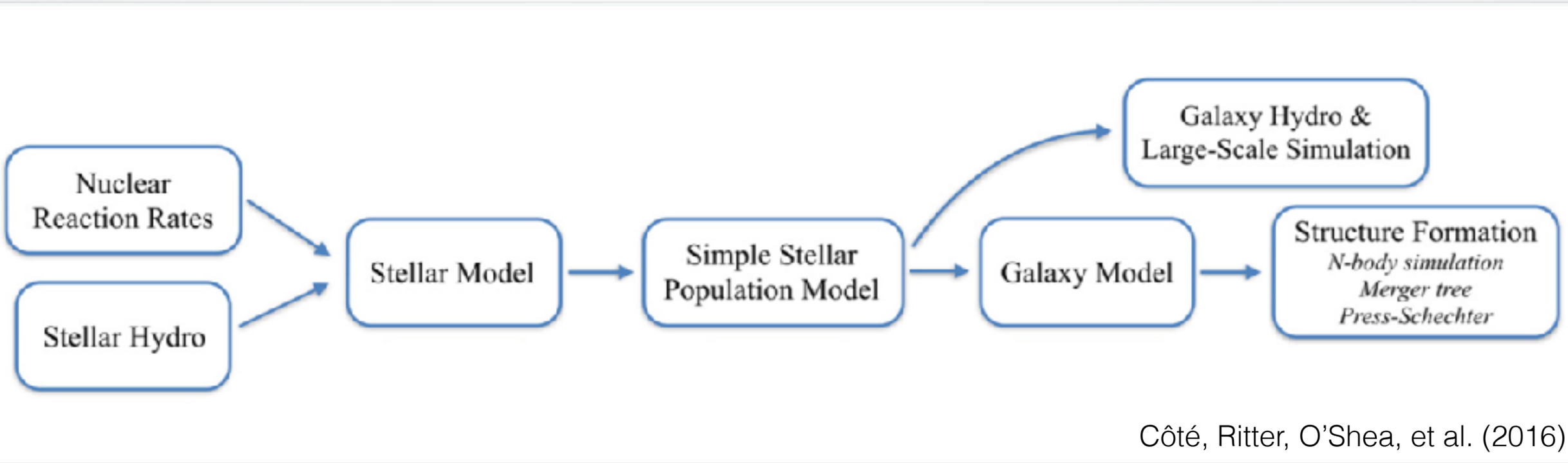



Tolstoy et al. (2009)

# Connecting the Smallest and the Largest Scales




Côté, Ritter, O'Shea, et al. (2016)

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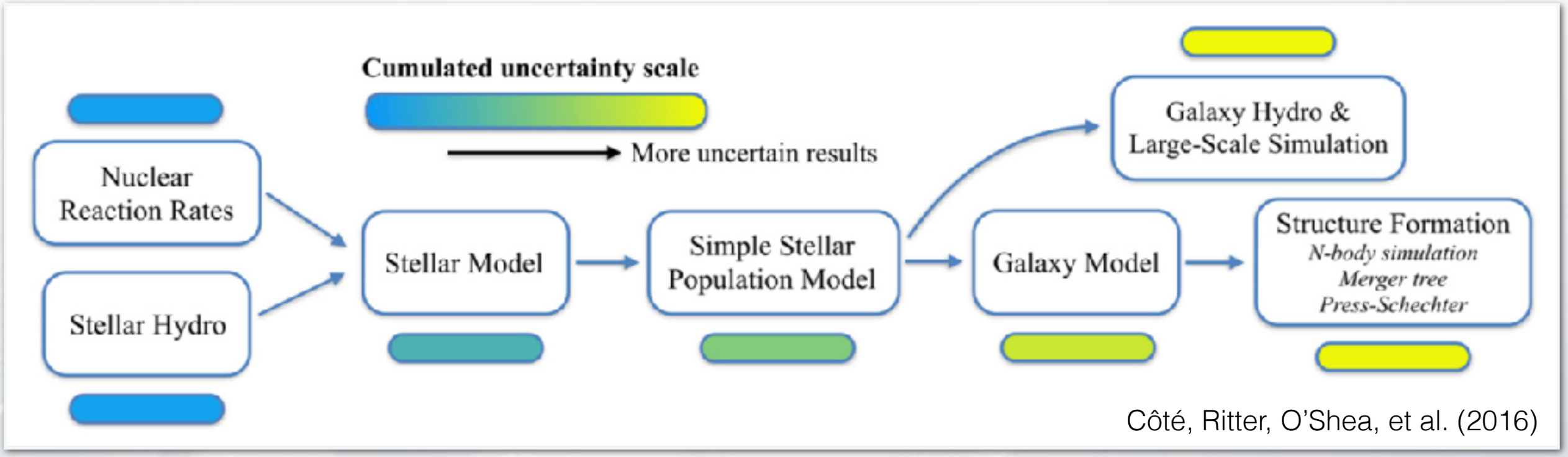


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Comes with the difficult **challenge** of dealing with uncertainties at all scales.

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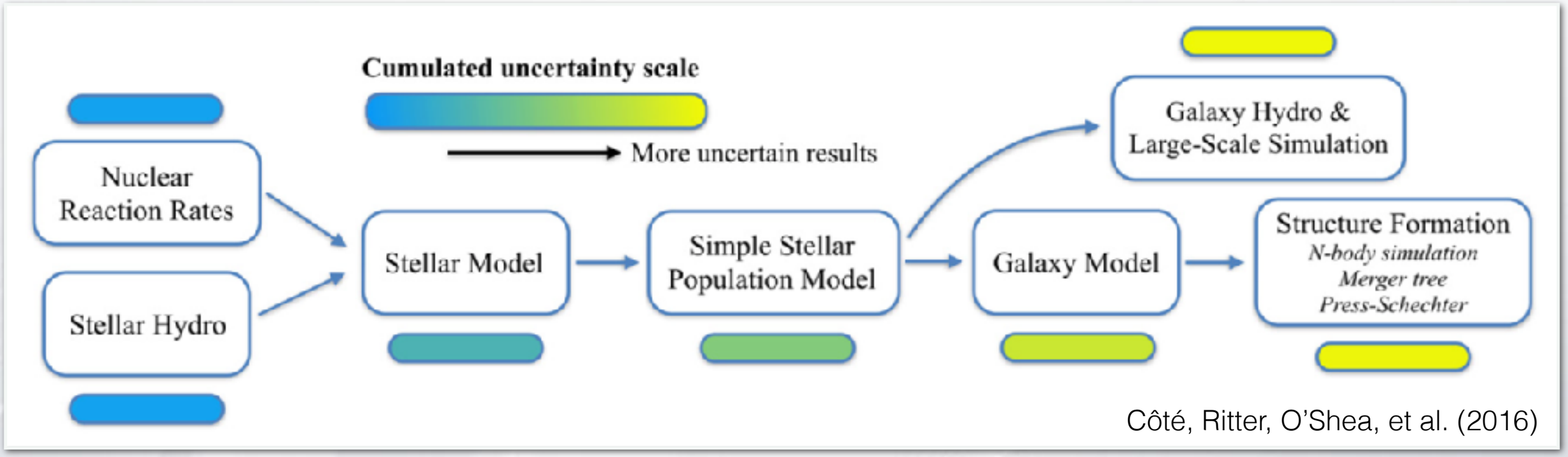


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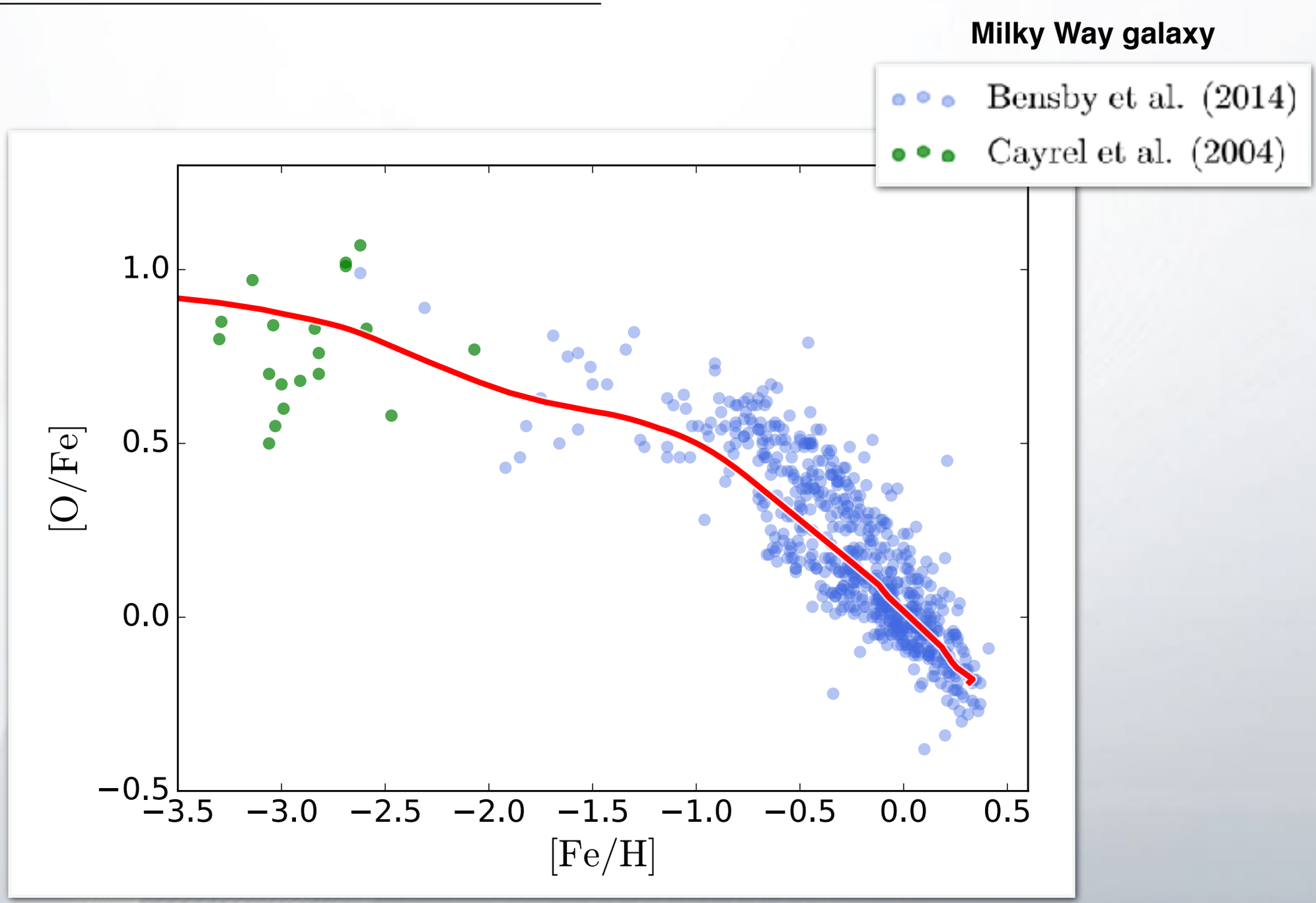
What about neutron stars and black holes?

# Production of Oxygen in Massive Stars




@Using OMEGA and Kobayashi et al. (2006) massive star yields

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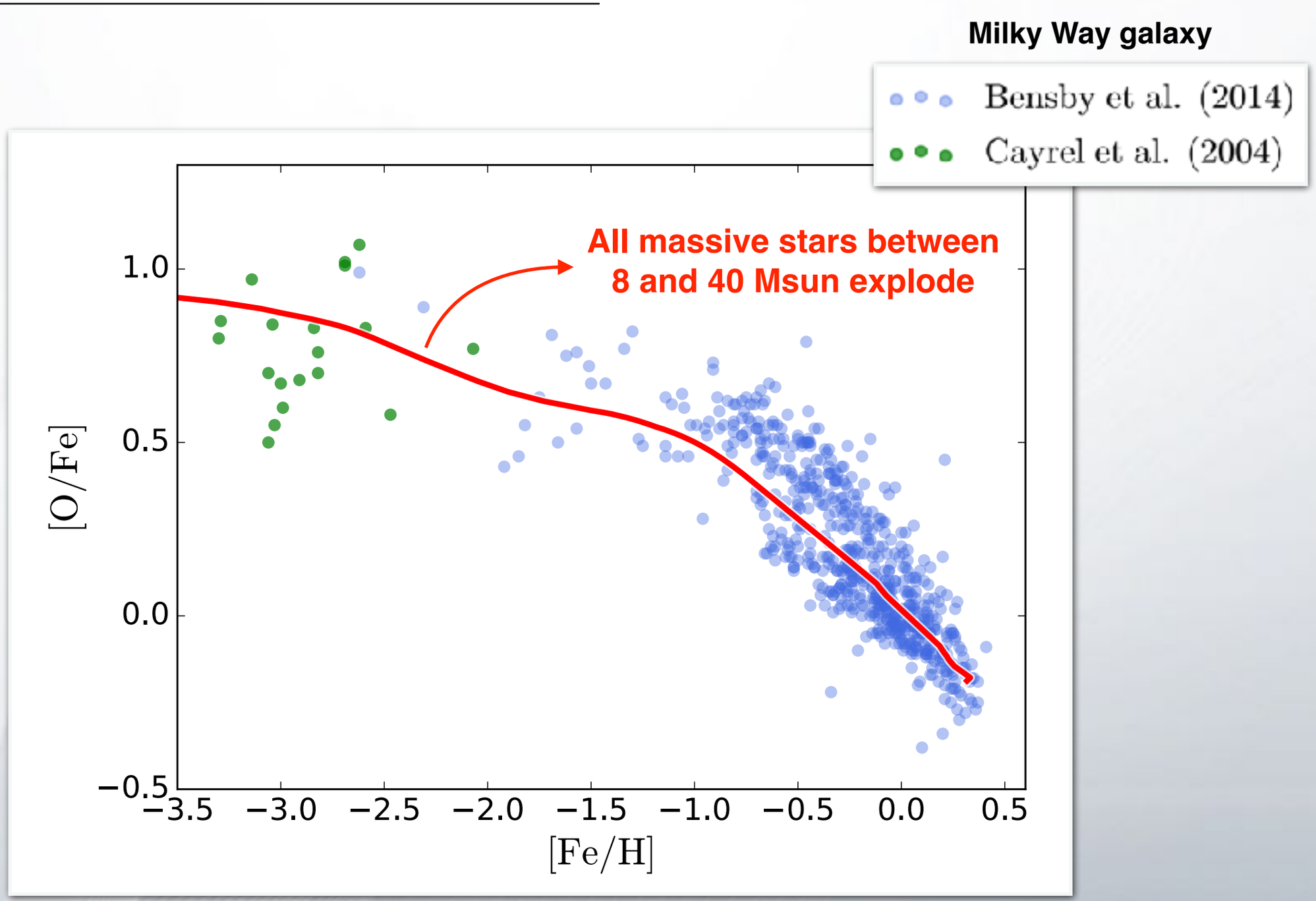


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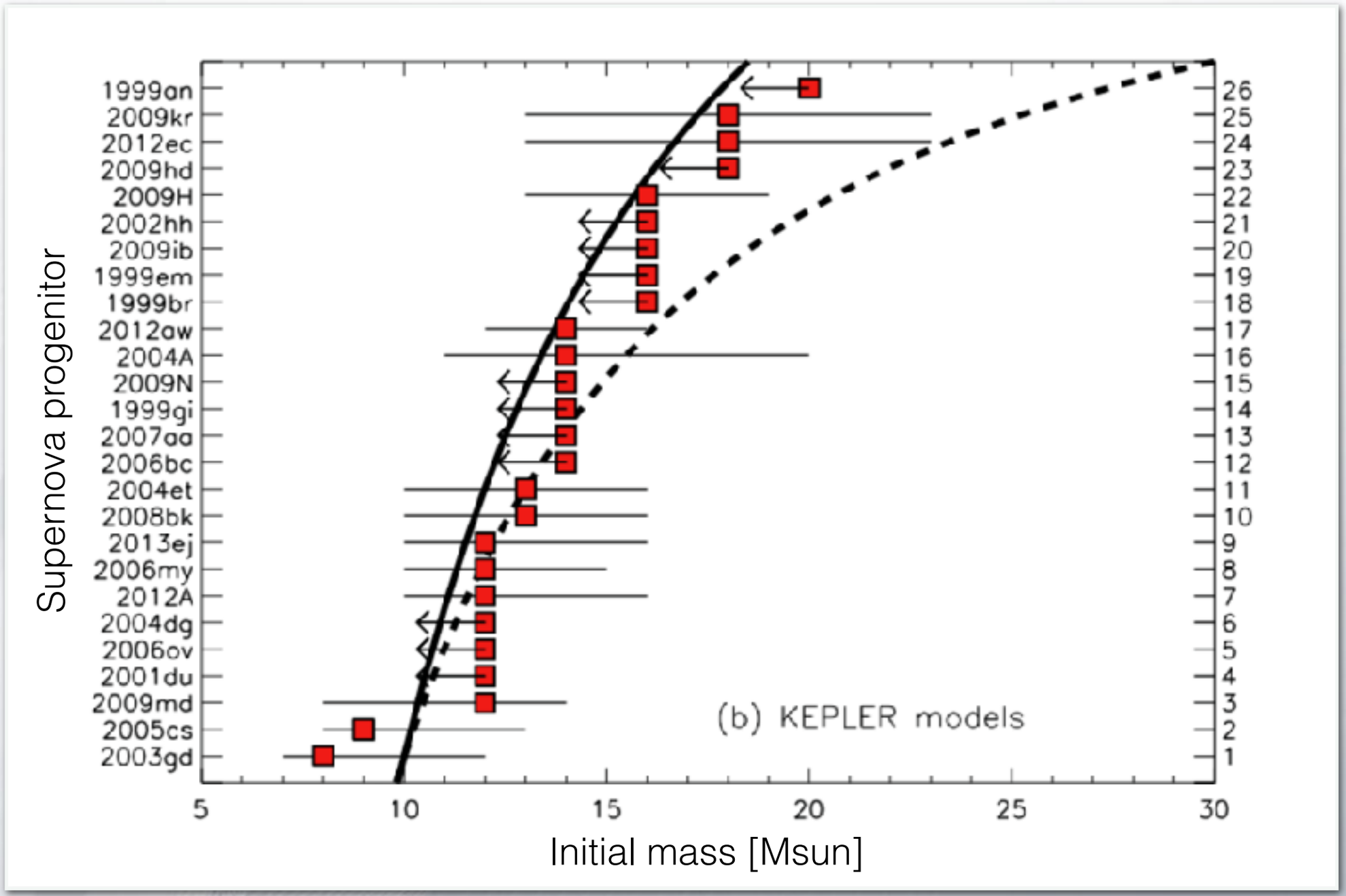
# Oxygen, Massive Stars, and Black Holes

Smartt (2015)



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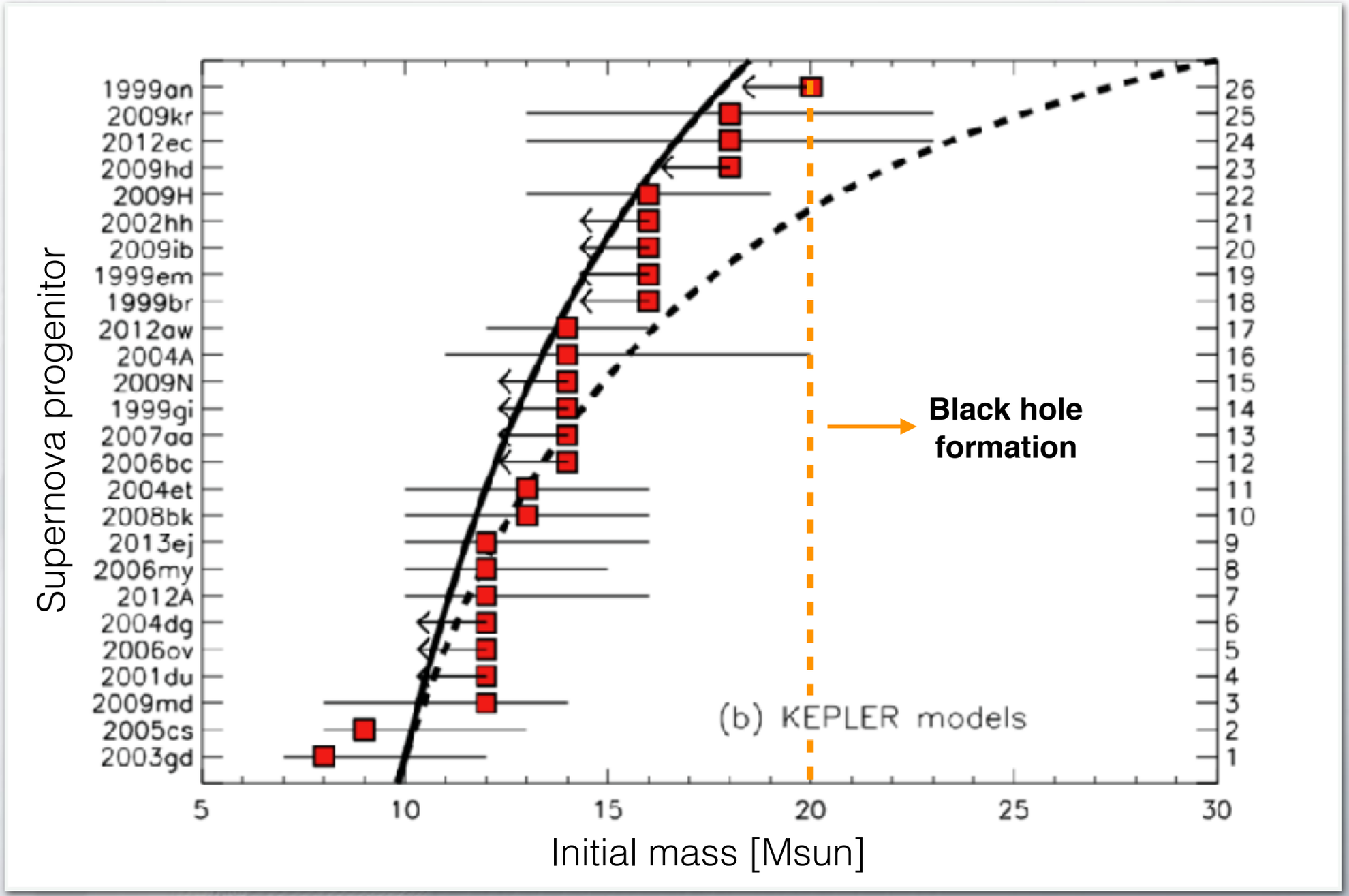

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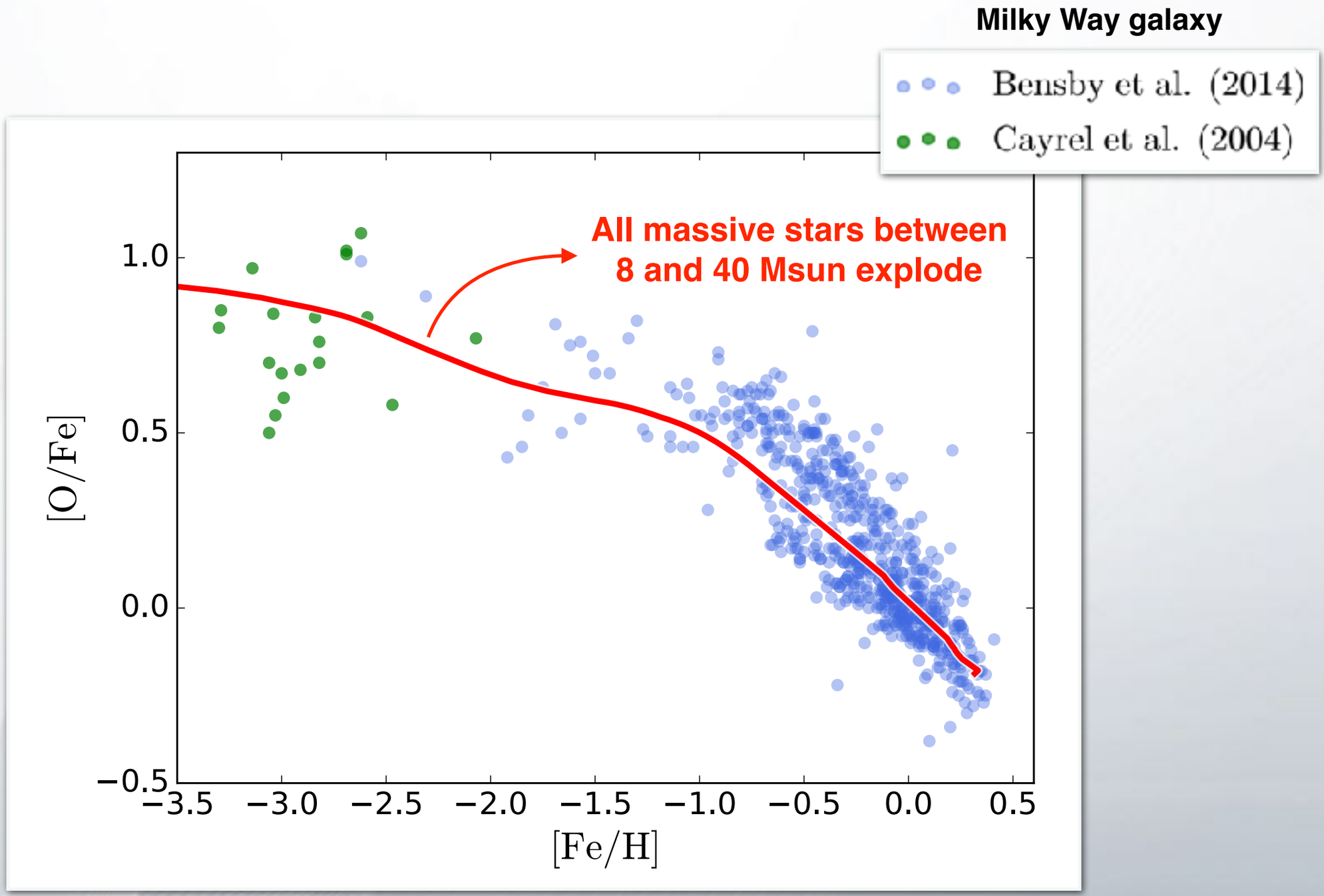


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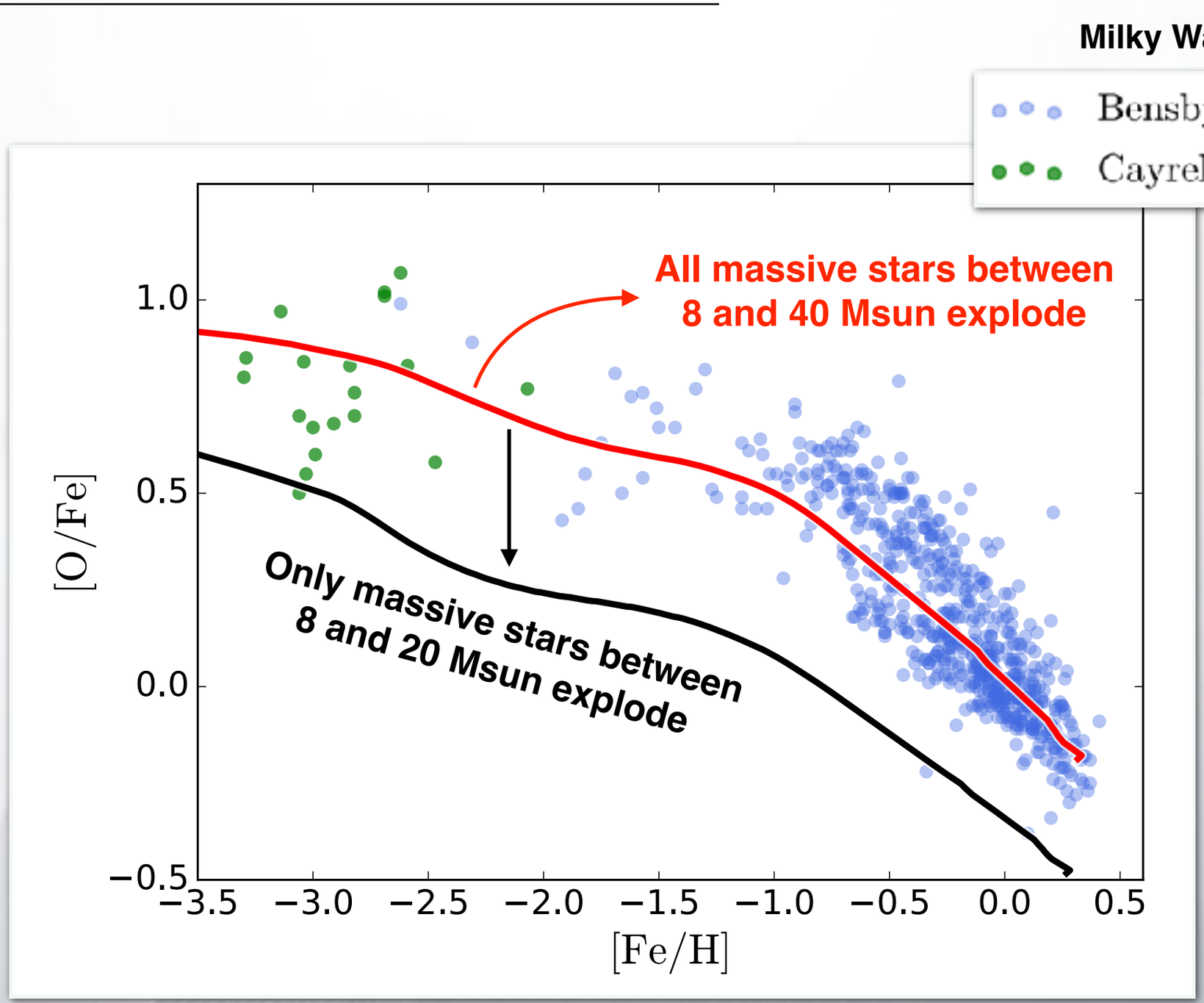


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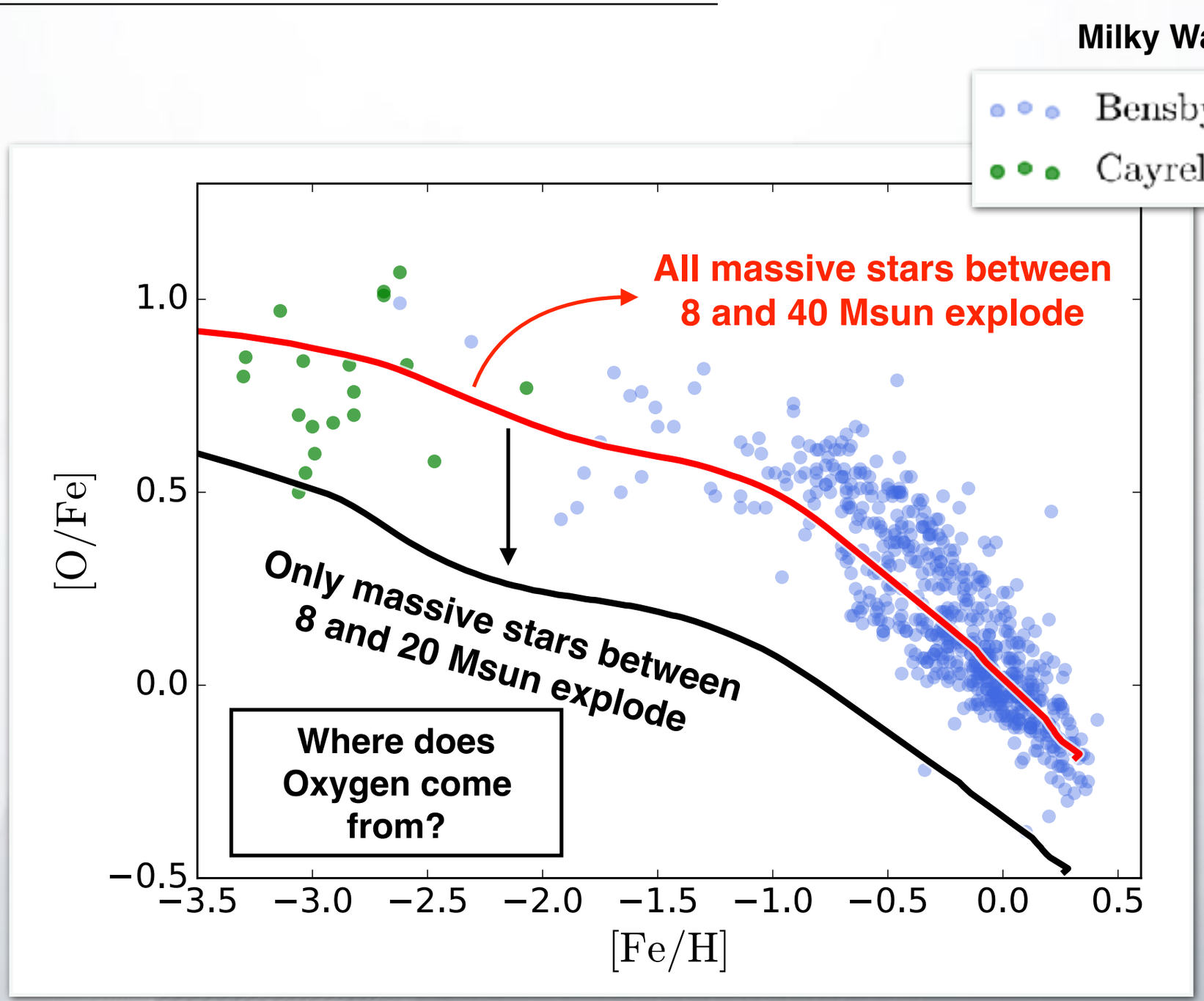


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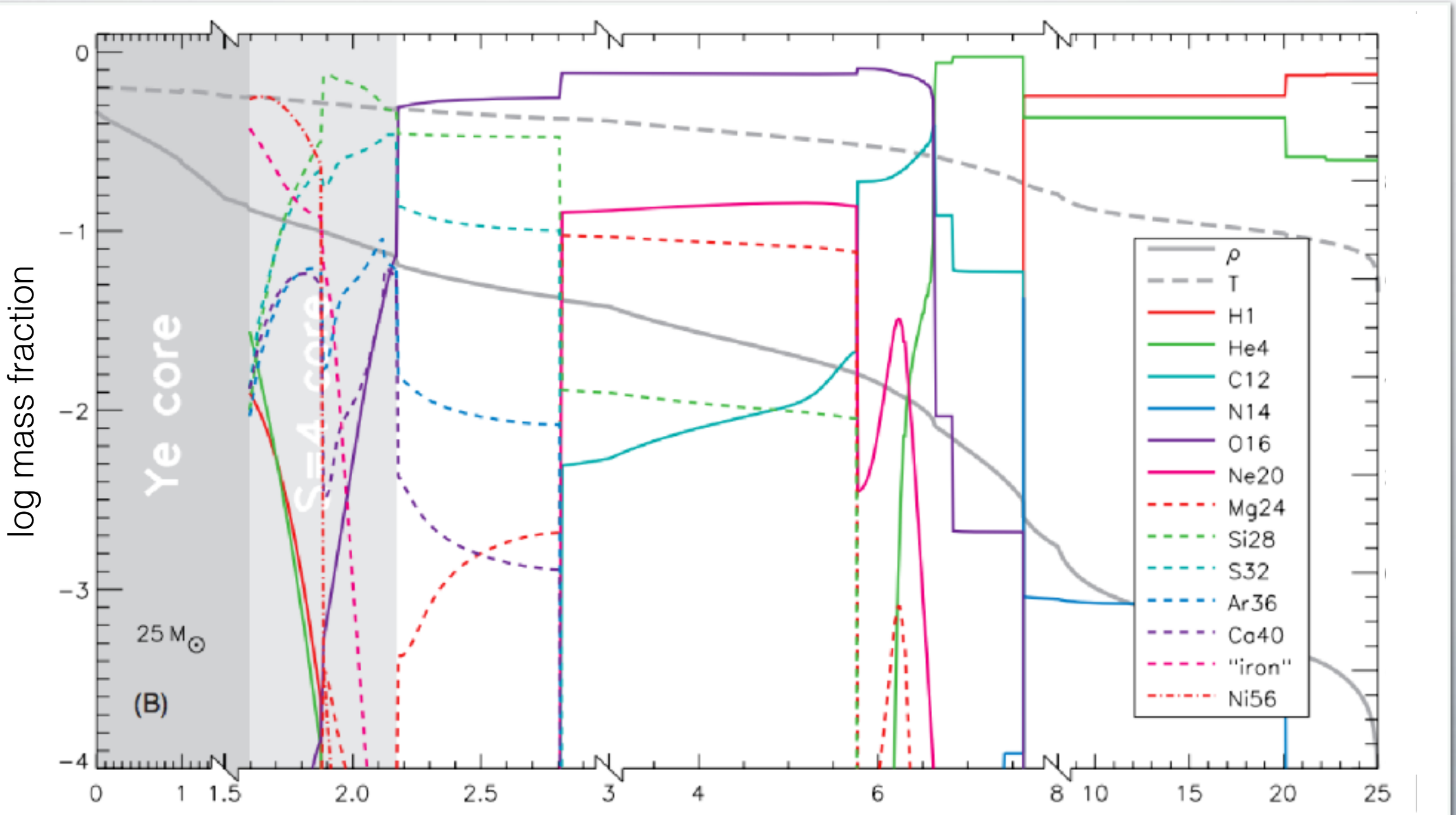
# Massive Star and Supernova Models




Heger & Woosley (2010)

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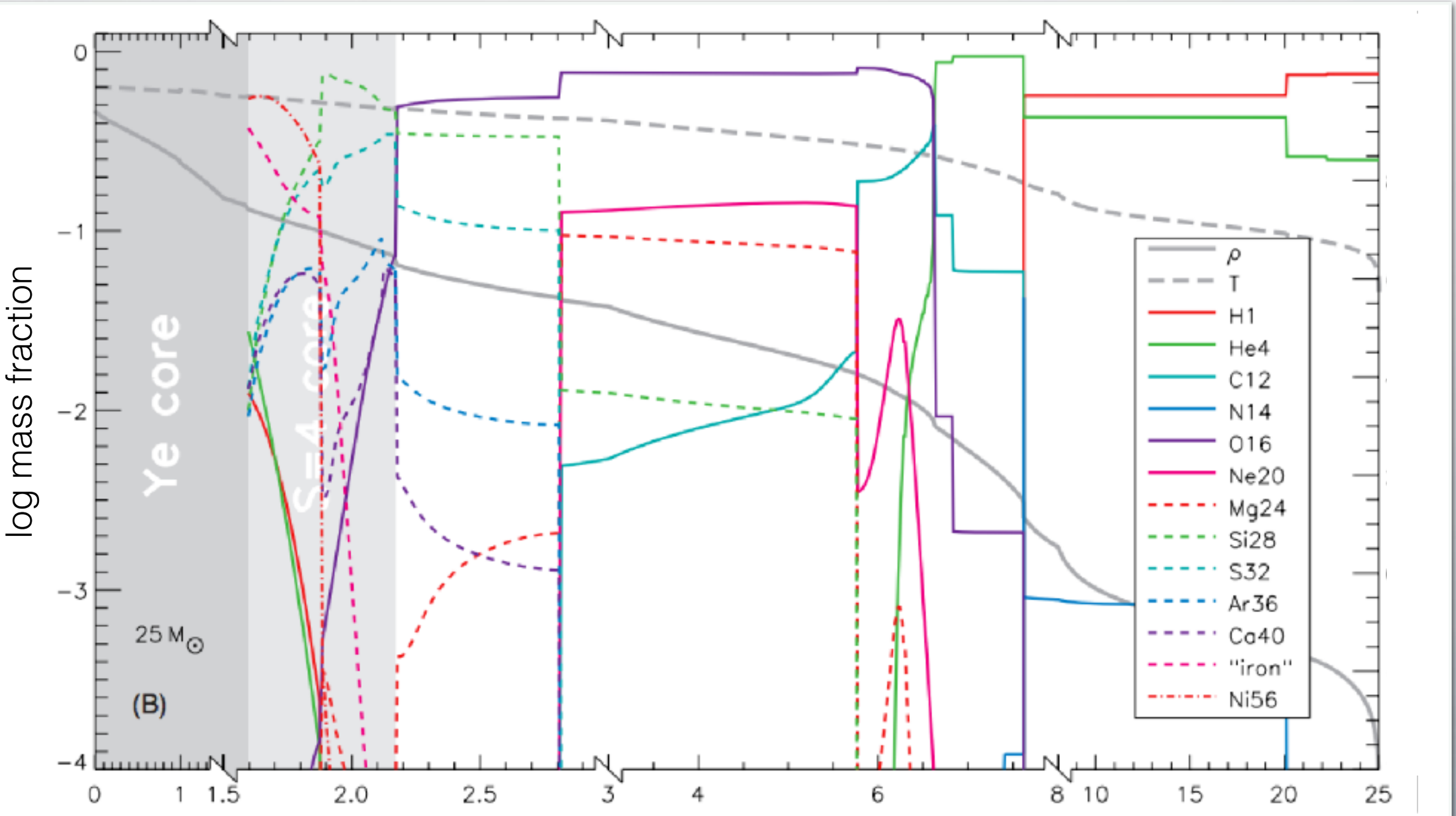
Fe Si O He H

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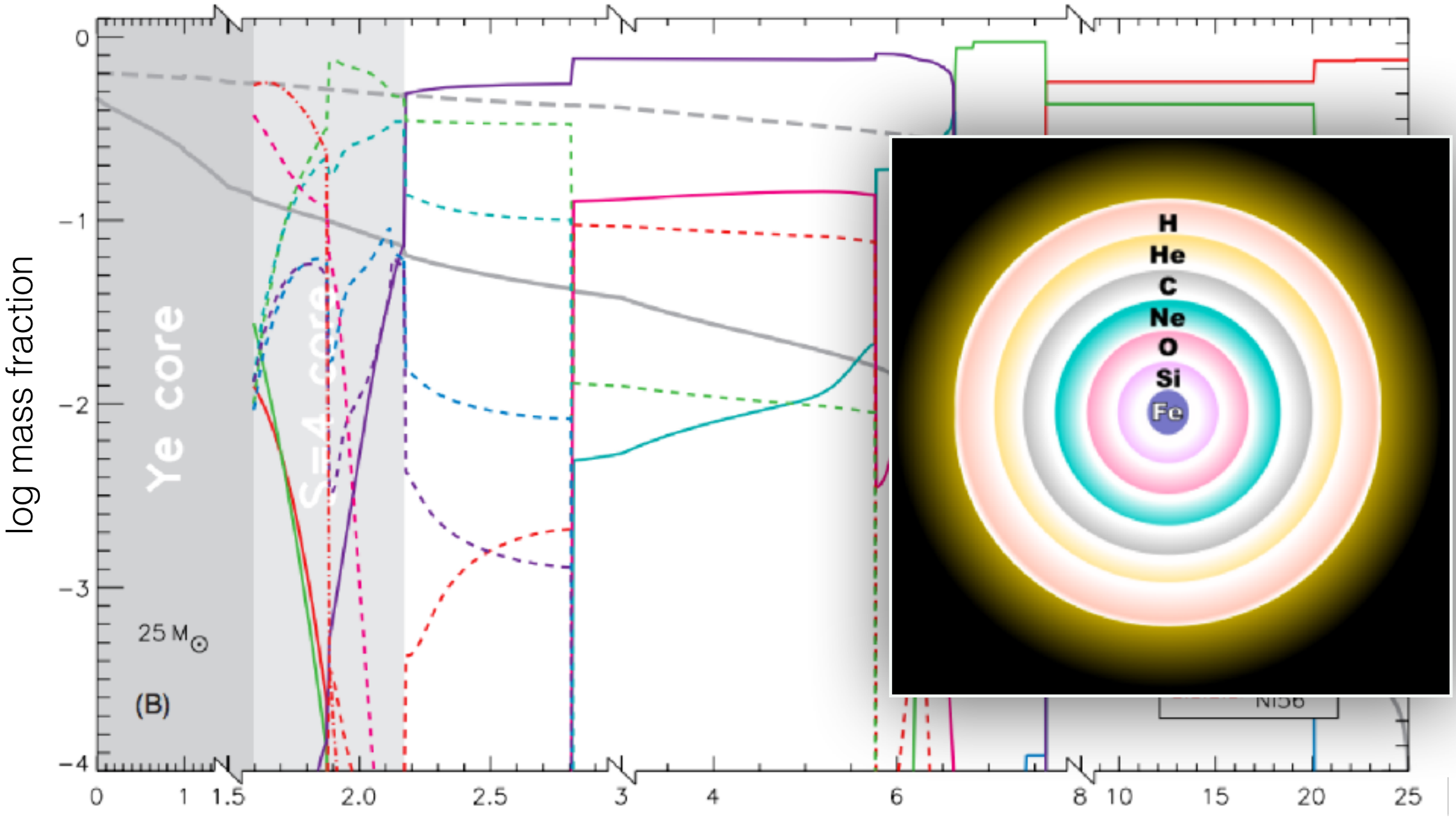


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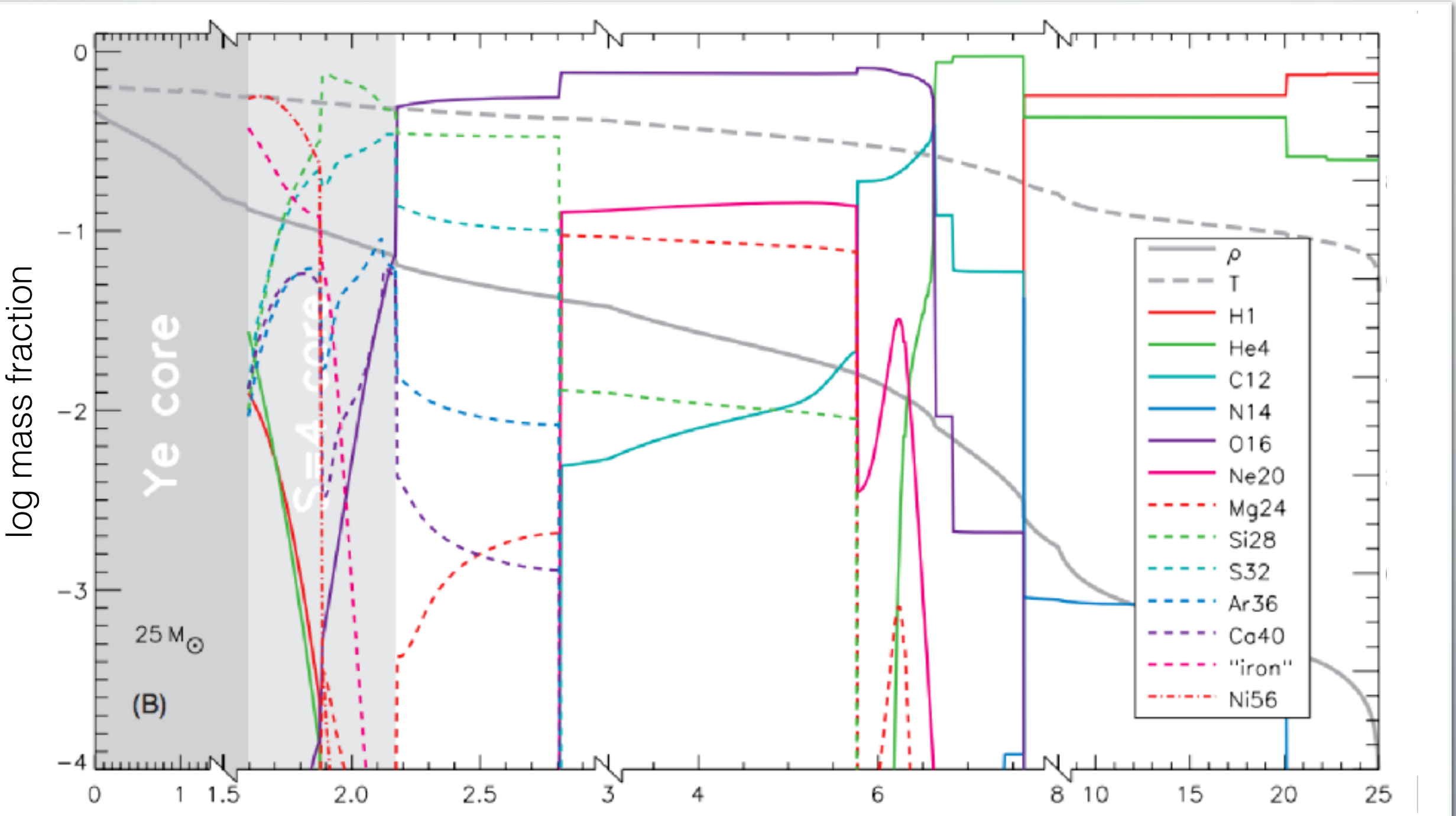


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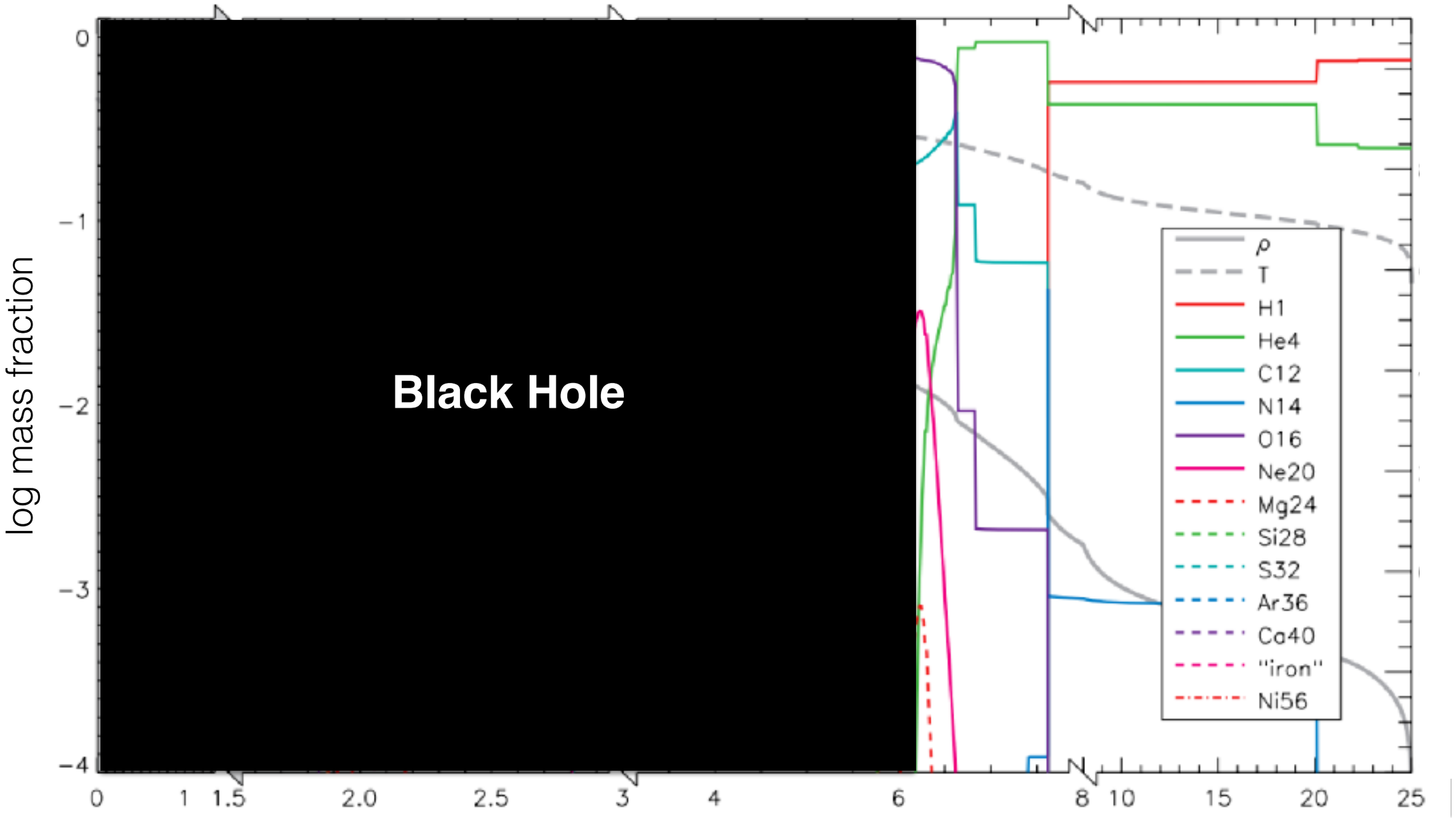


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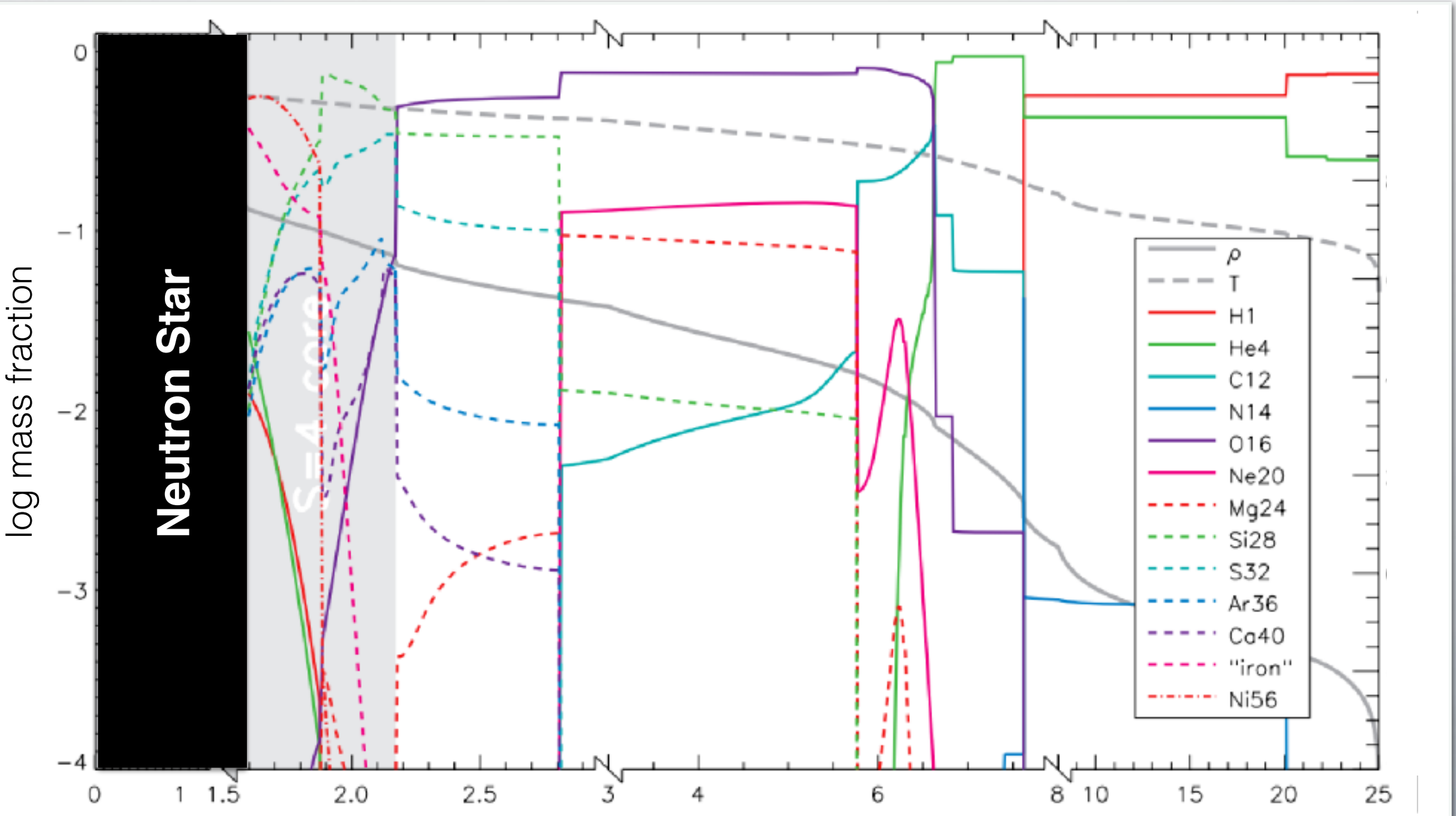


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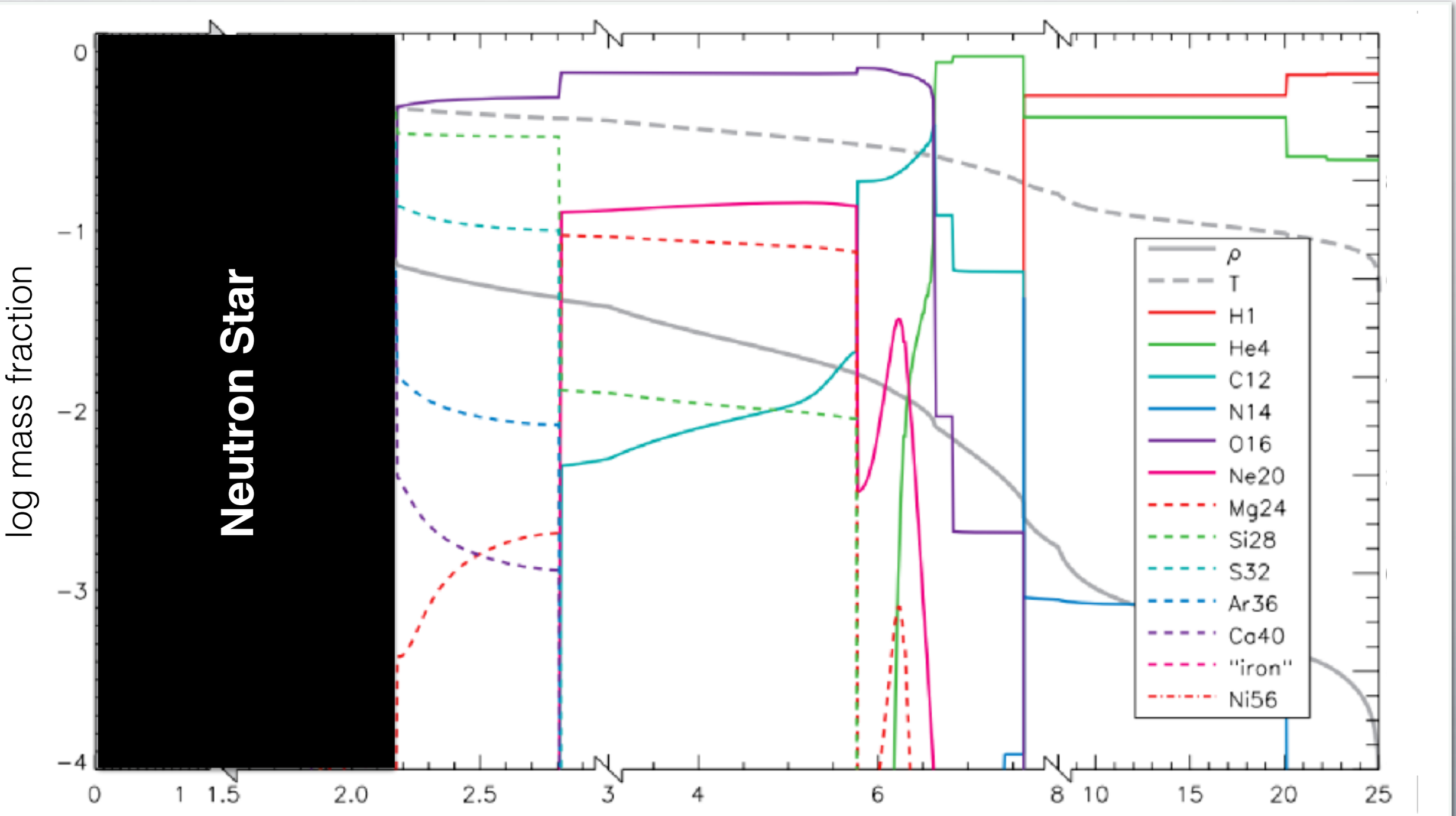


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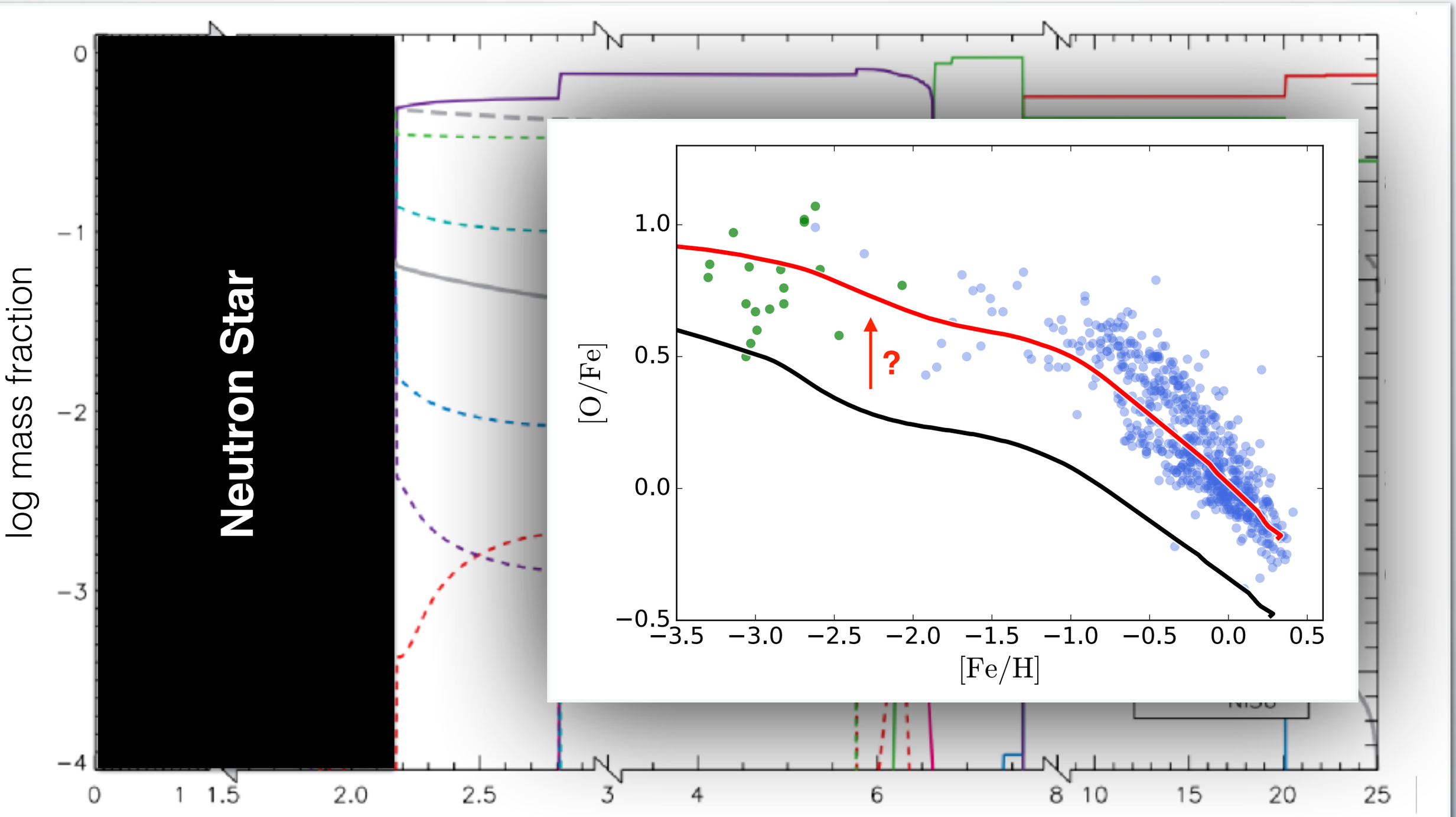


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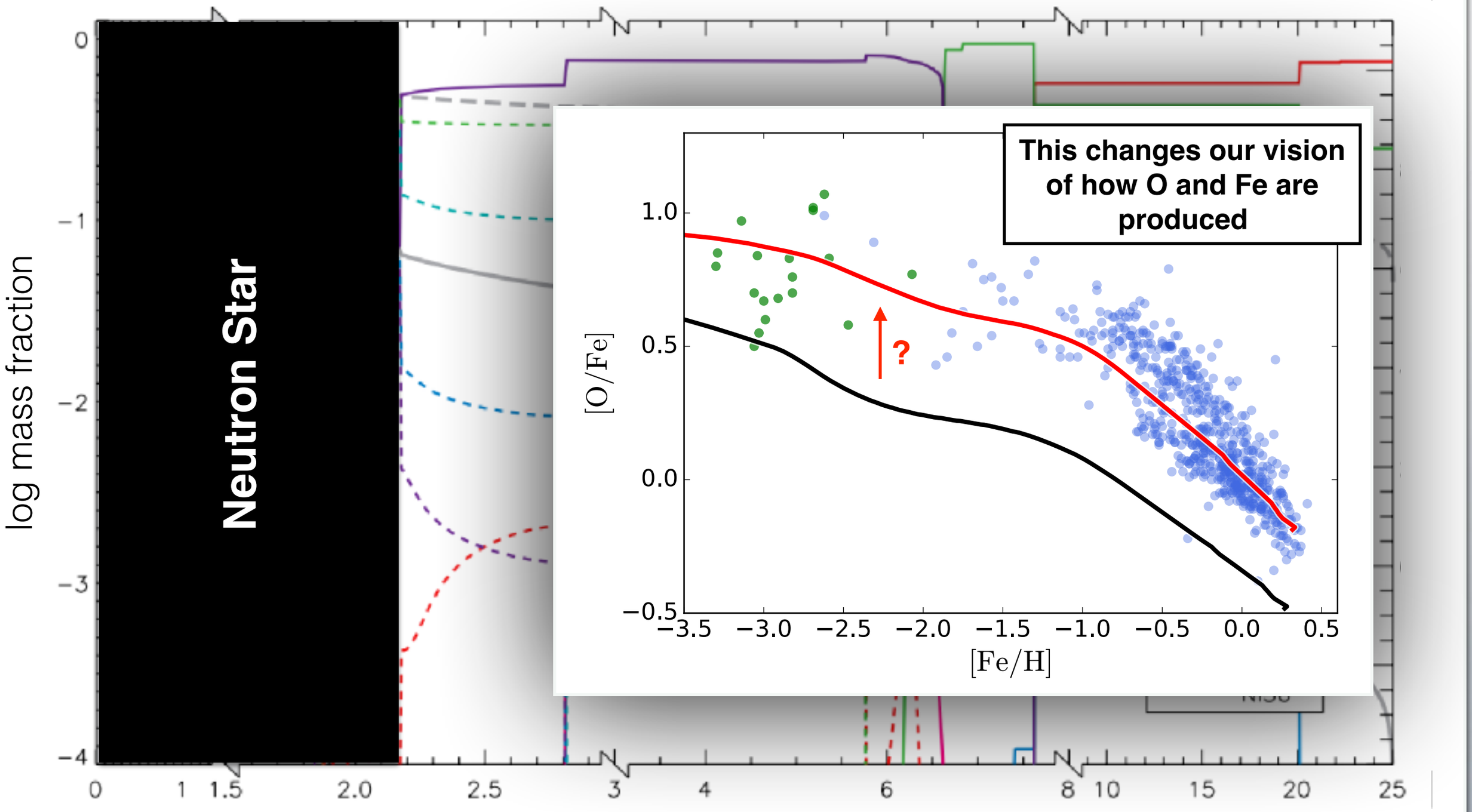


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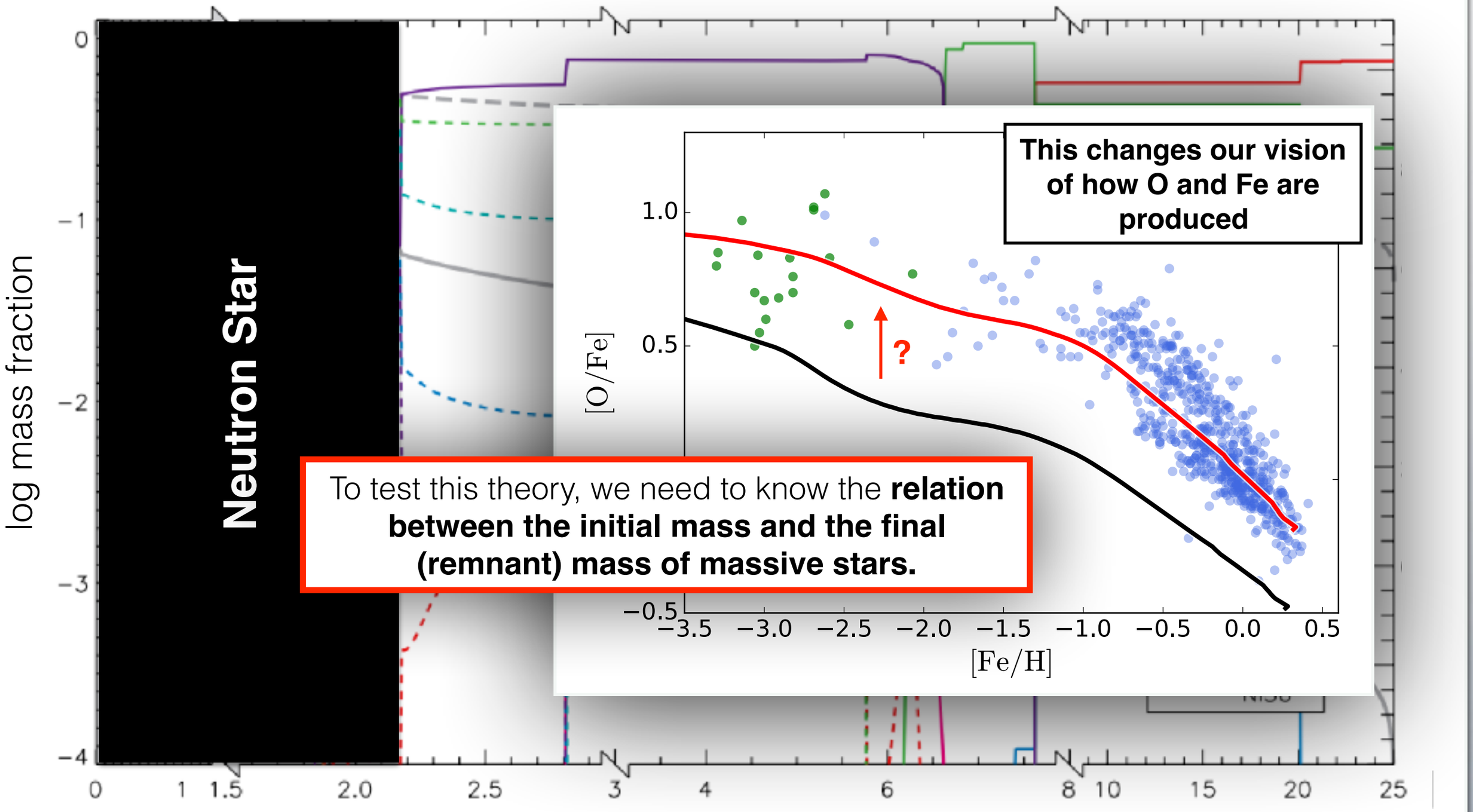


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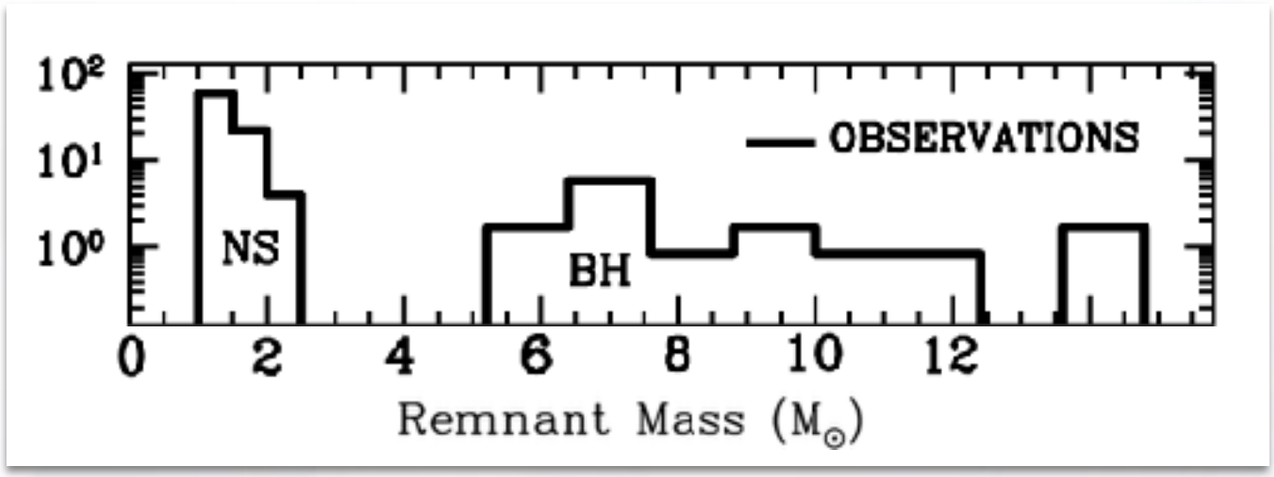
# Neutron Star and Black Hole Mass Function

**Observation of binary systems** →

Belczynski, Wiktorowicz, Fryer, et al. (2012)



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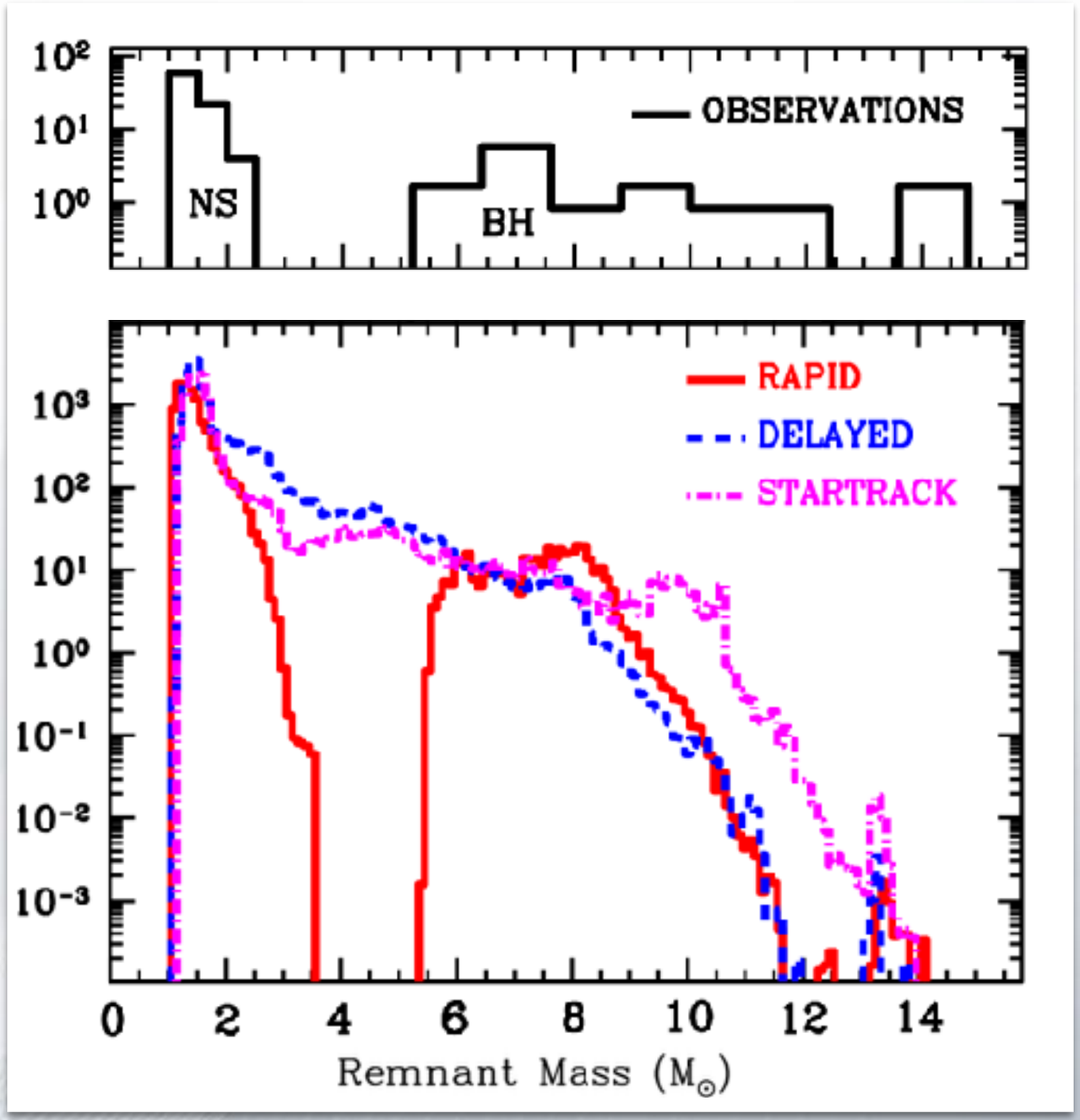

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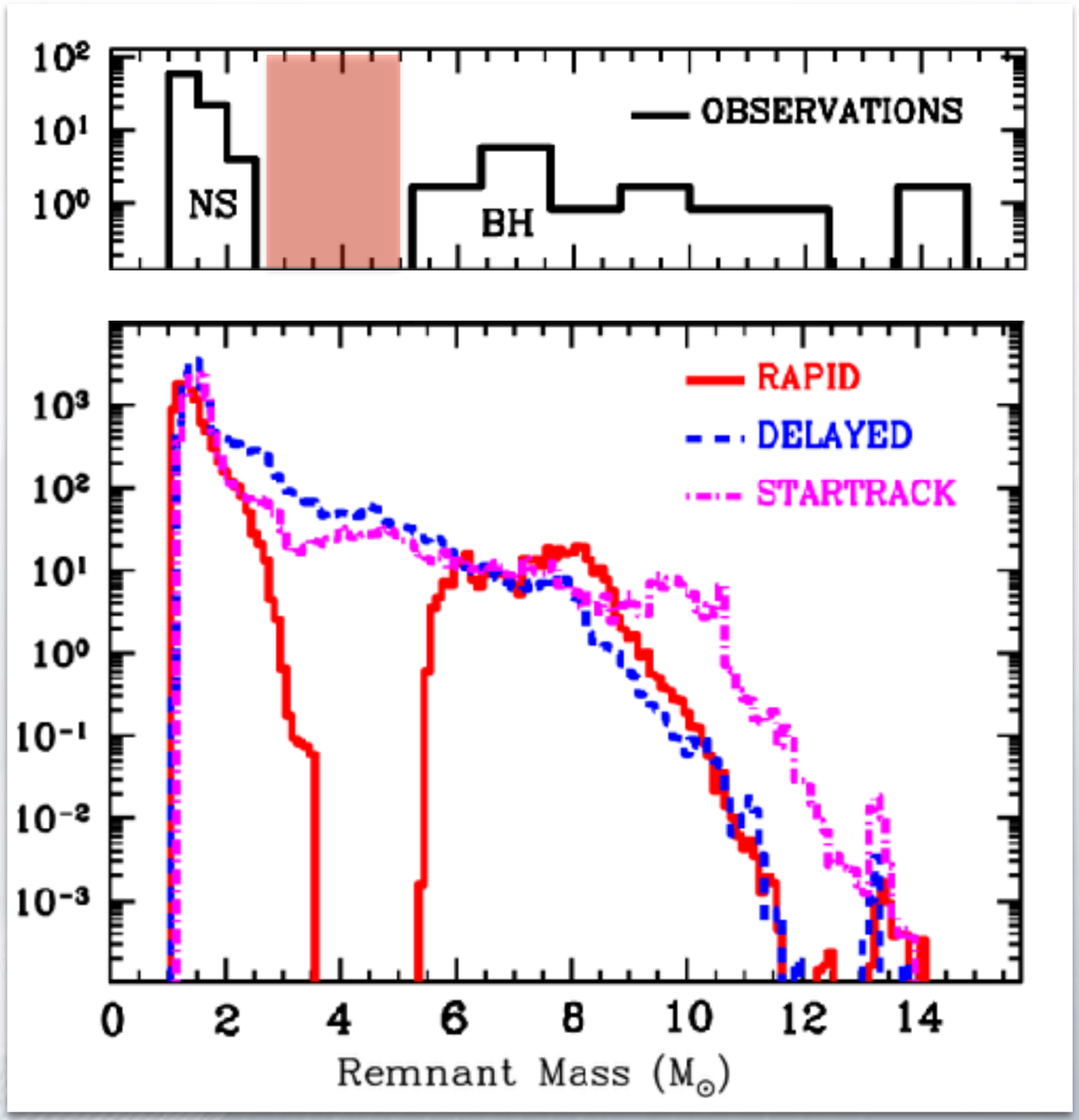

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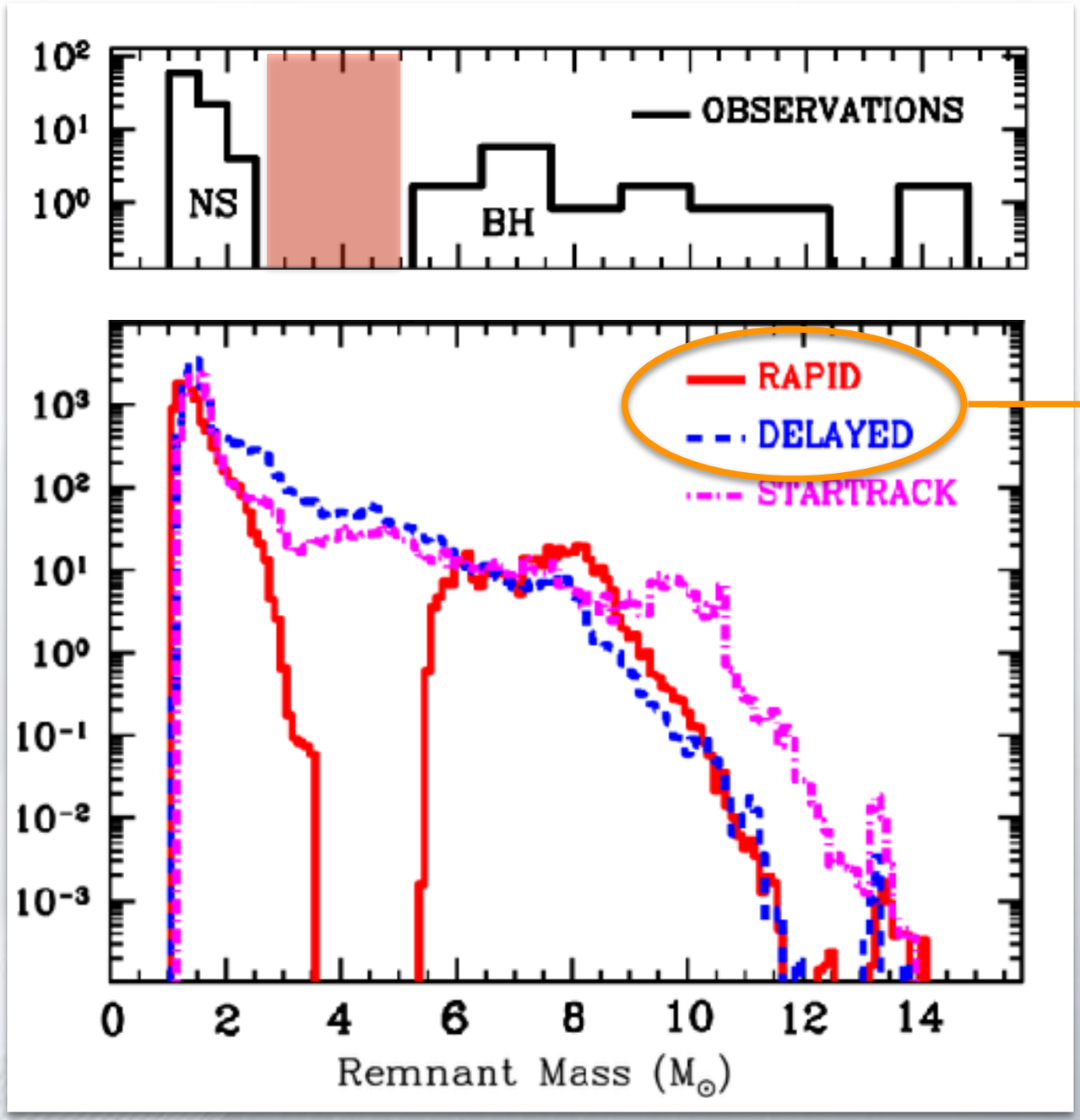


**Prescription used by the NuGrid collaboration**
(Pignatari et al. 2016;
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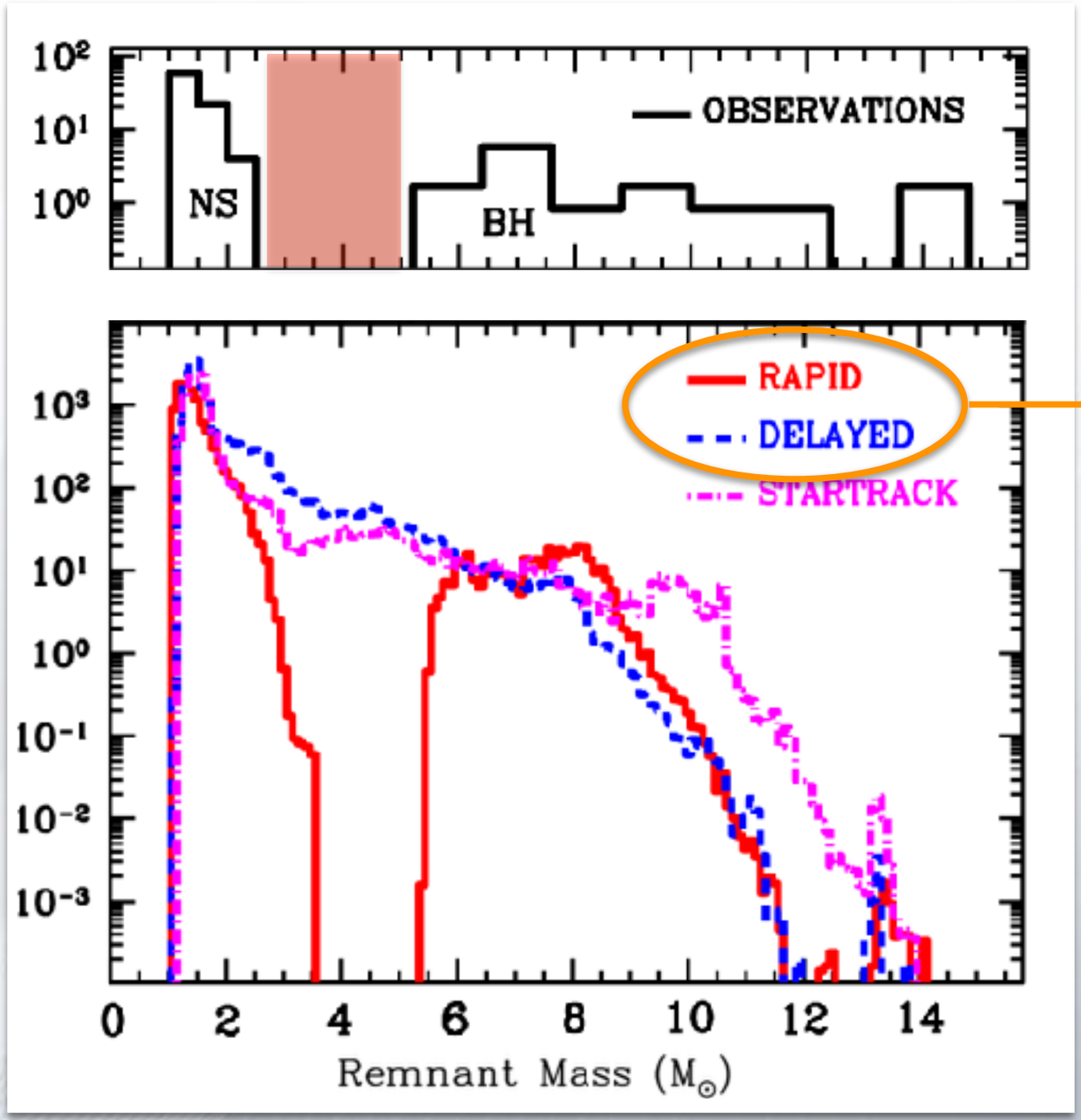


**~ 80 neutron stars**

**~ 20 black holes**

→ **Prescription used by the NuGrid collaboration**
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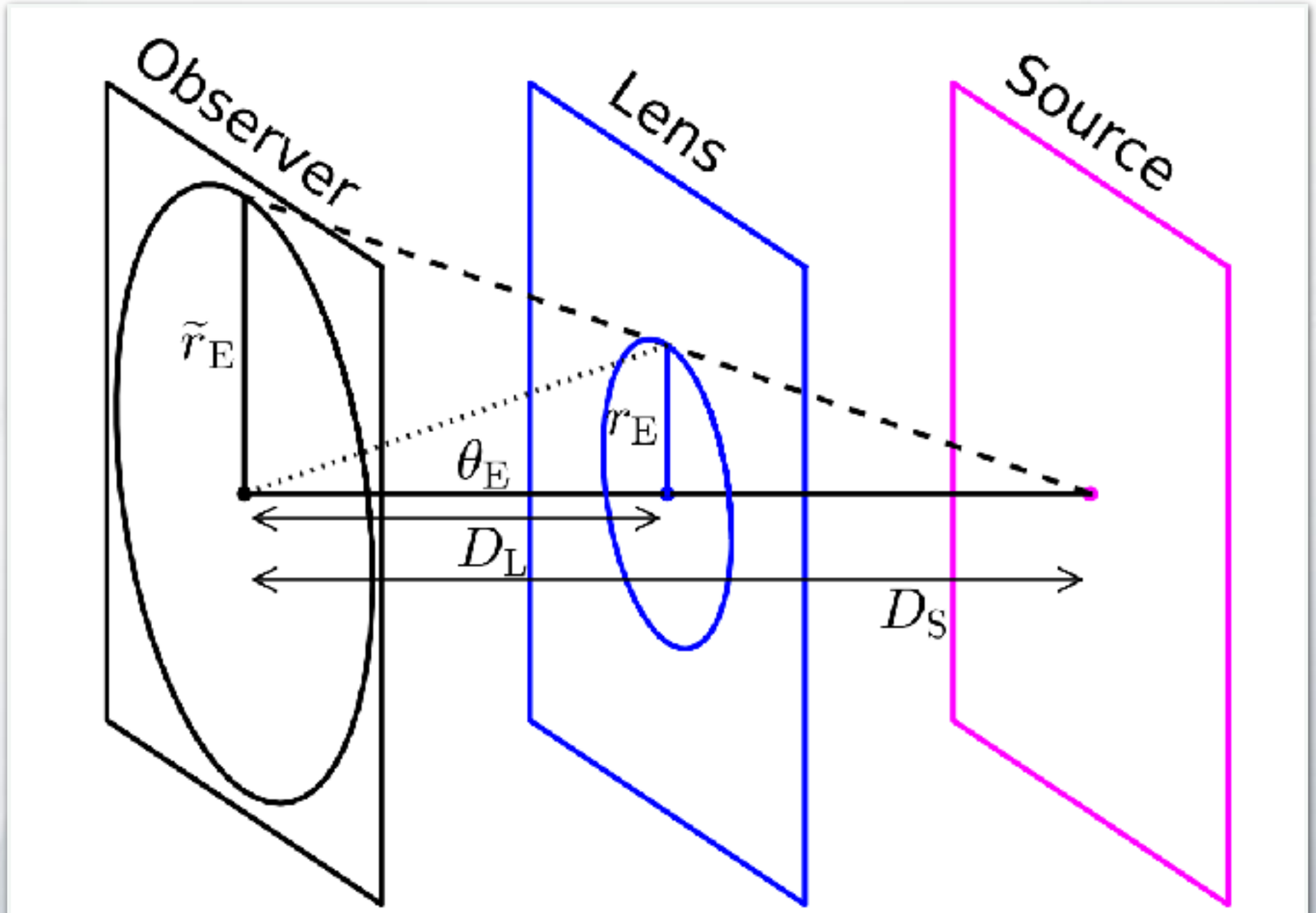
# Neutron Star and Black Hole Mass with Microlensing

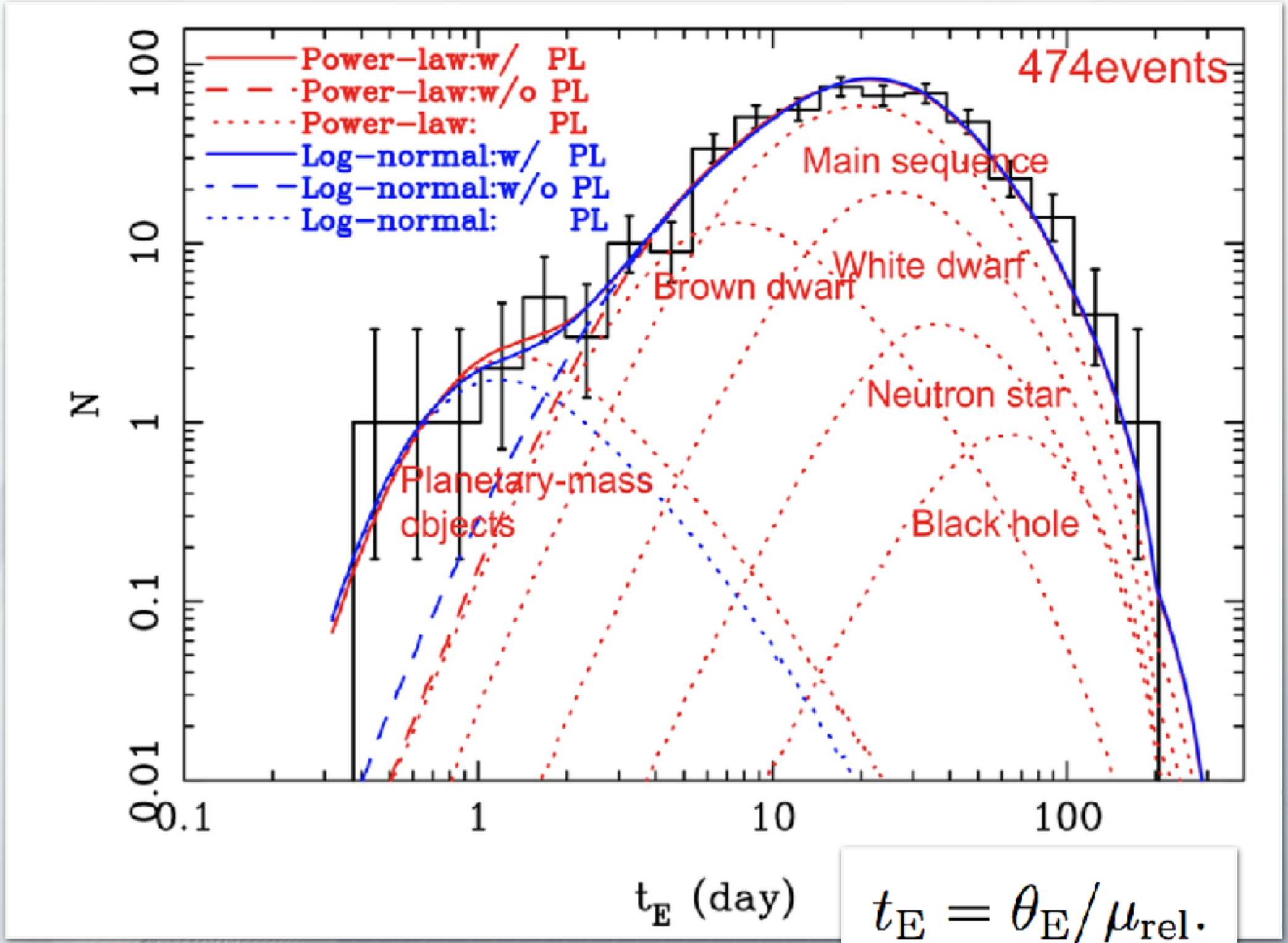
J. C. Yee & C. B. Henderson (Themes document)




$$r_{\rm E} = \sqrt{\kappa M_\ell \frac{D_\ell (D_\ell - D_s)}{D_s}},$$

# Neutron Star and Black Hole Mass with Microlensing

Barry, Kruk, Anderson, et al. (2014)




$$t_{\rm E} = \theta_{\rm E}/\mu_{\rm rel}.$$

# Neutron Star and Black Hole Mass with Microlensing

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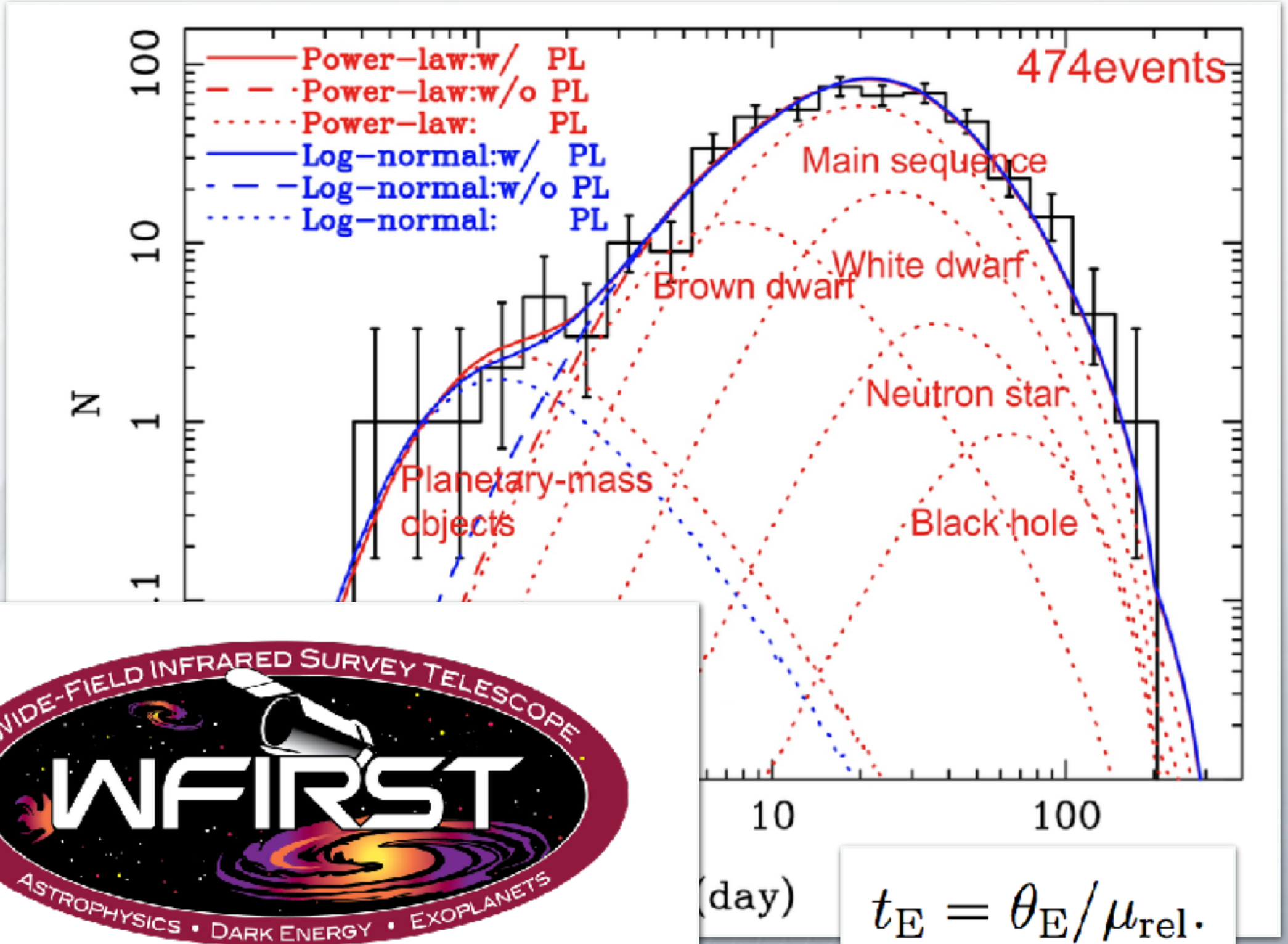





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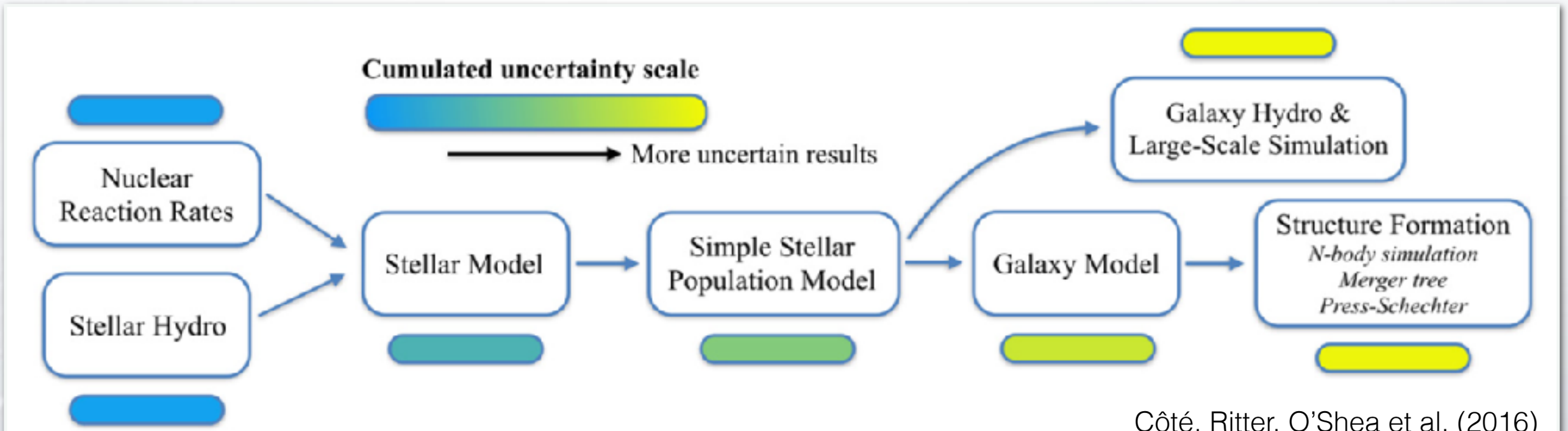
# WFIRST and Galactic Chemical Evolution




Côté, Ritter, O'Shea et al. (2016)

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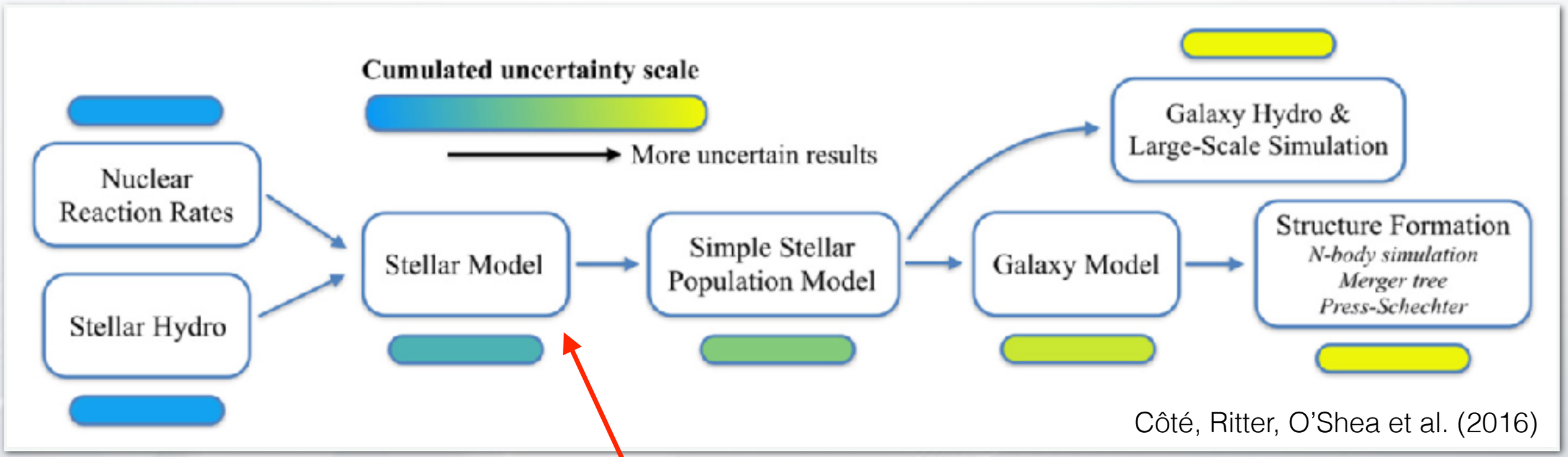


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**Neutron star and black hole mass distributions**

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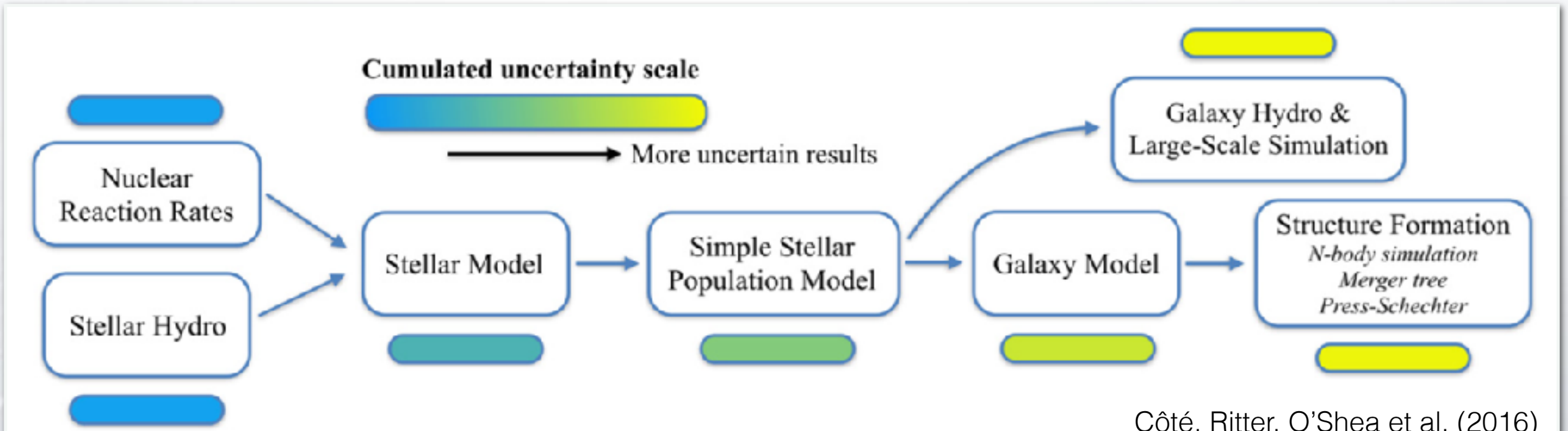


Côté, Ritter, O'Shea et al. (2016)

**Uncertainties in the remnant mass make stellar models very uncertain (Fe yields).**

# Enrichment Timing and Evolution of [Fe/H]

**Origin of r-process elements — neutron star mergers?**
Using Europium (Eu) as a tracer

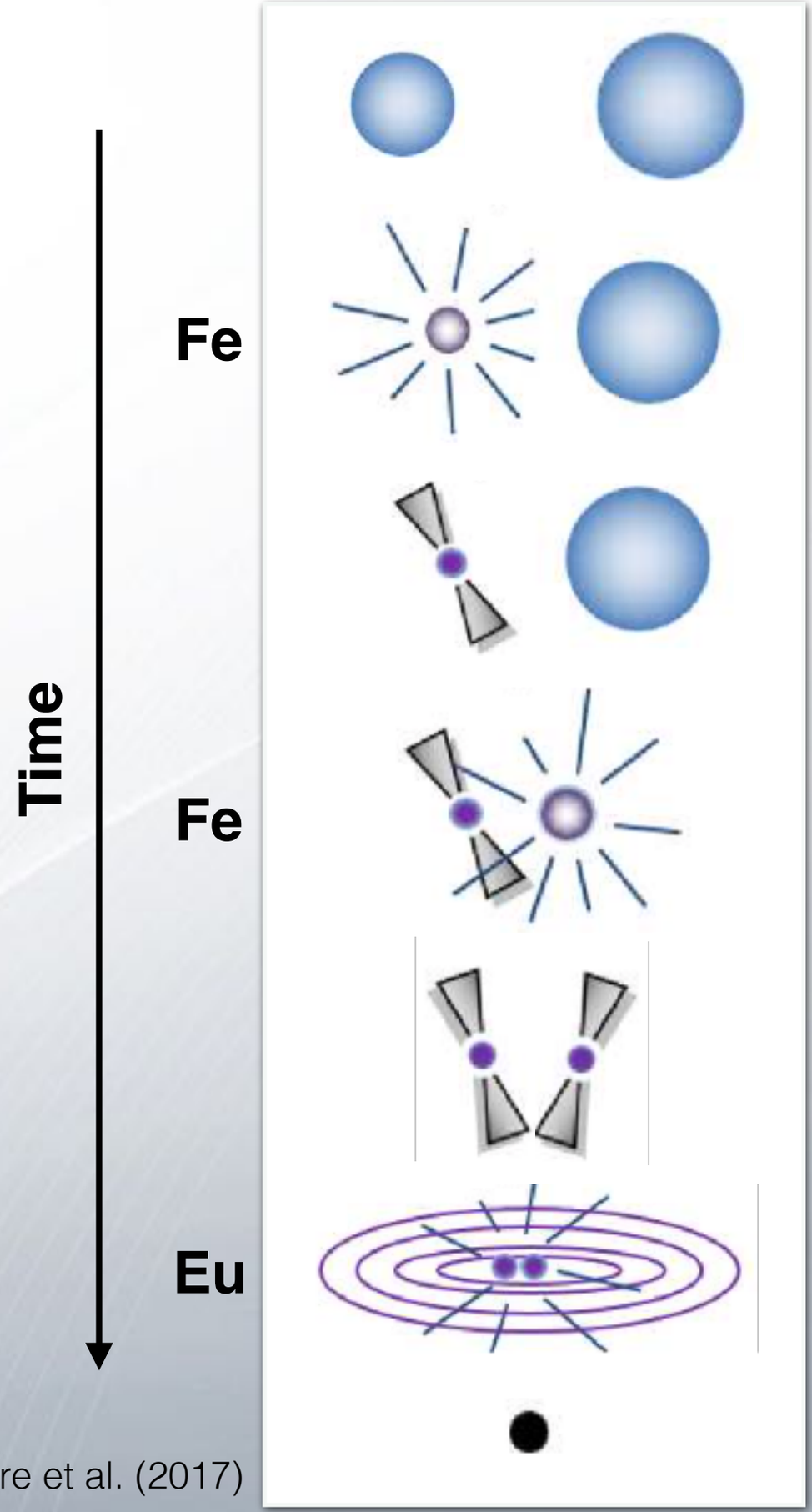


Image built from Tauris, Kramer, Freire et al. (2017)

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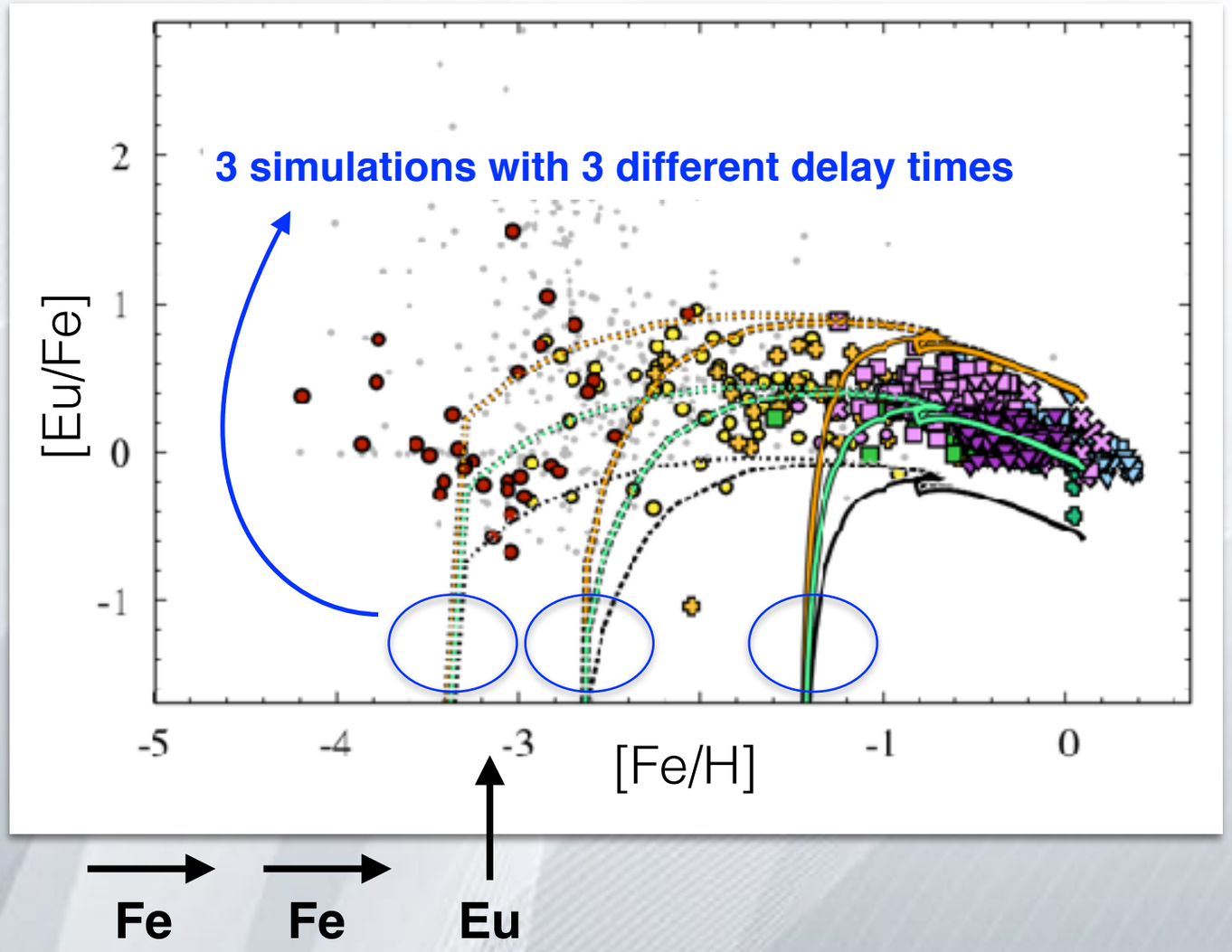
Matteucci, Romano, Arcones, et al. (2014)



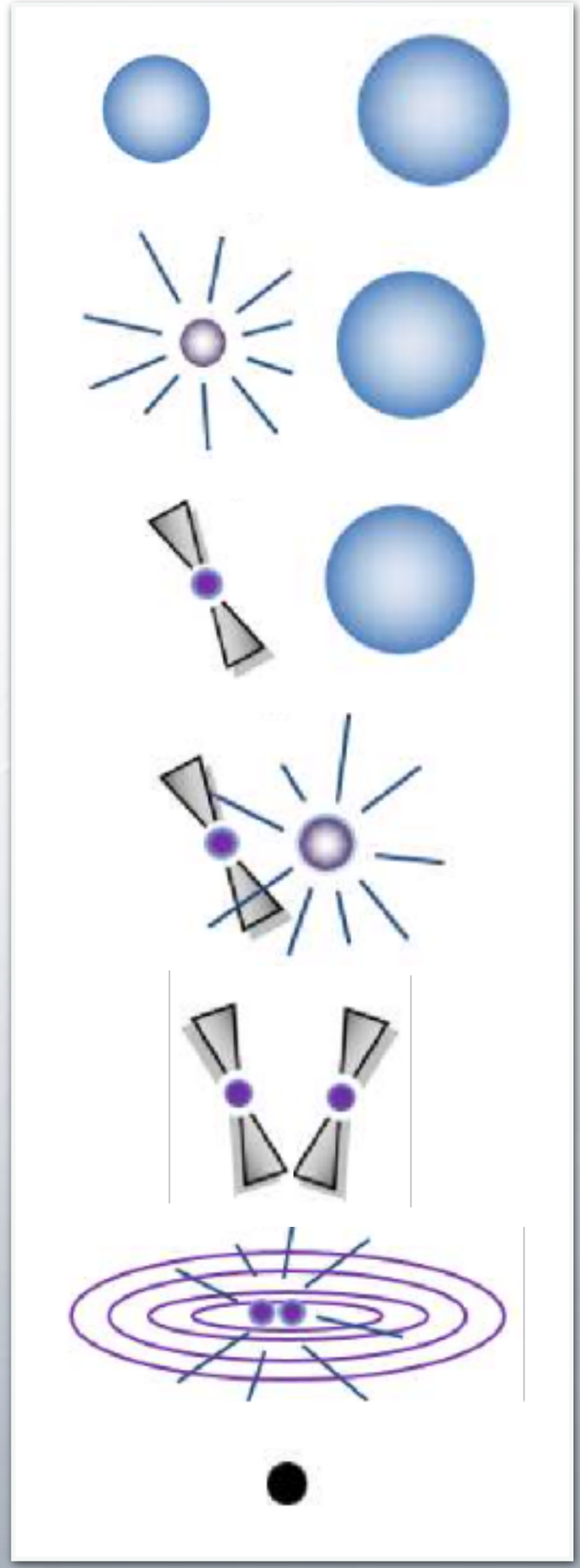
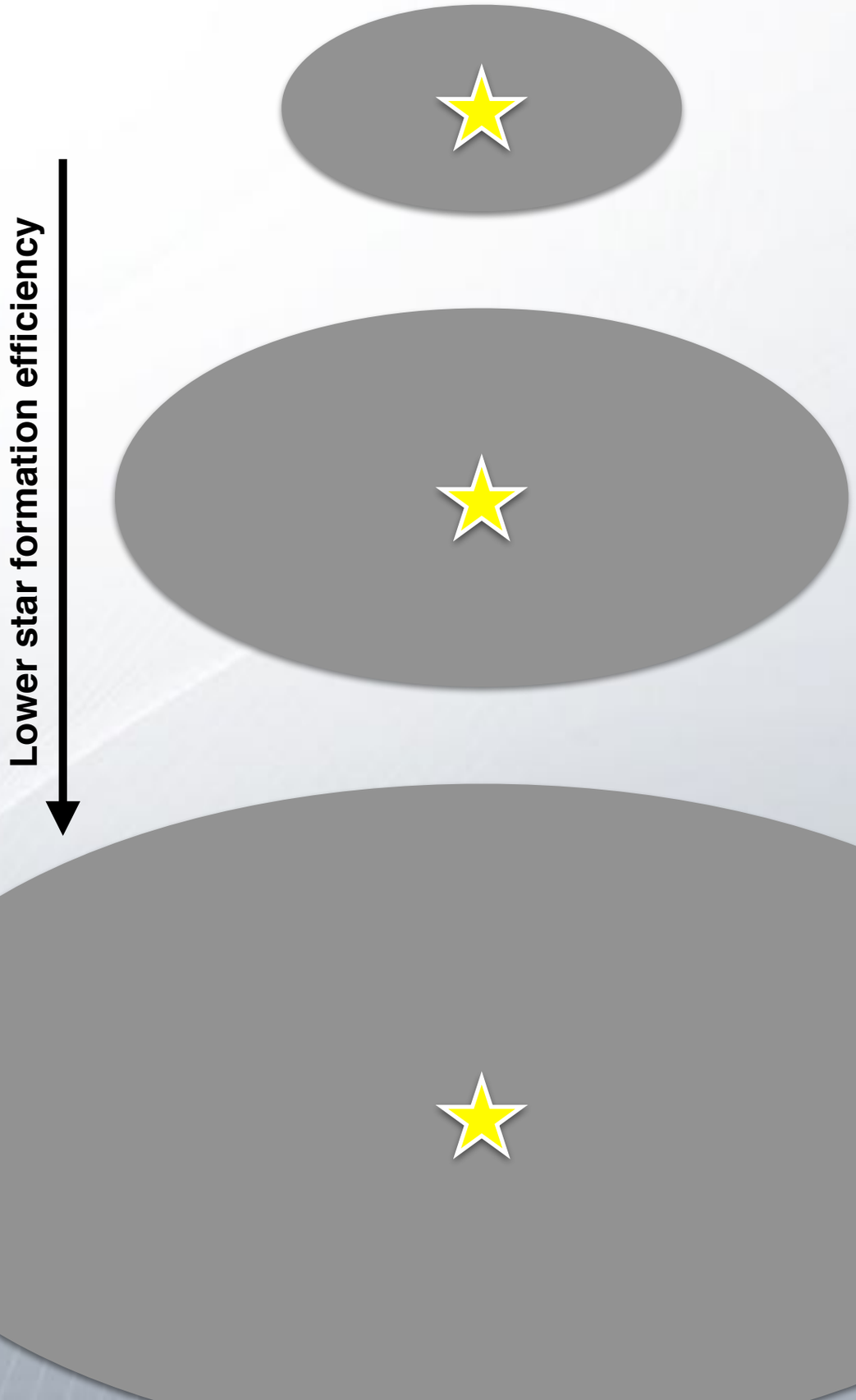




Image built from Tauris, Kramer, Freire et al. (2017)

# Enrichment Timing and Evolution of [Fe/H]

How about slowing down the evolution of [Fe/H]?



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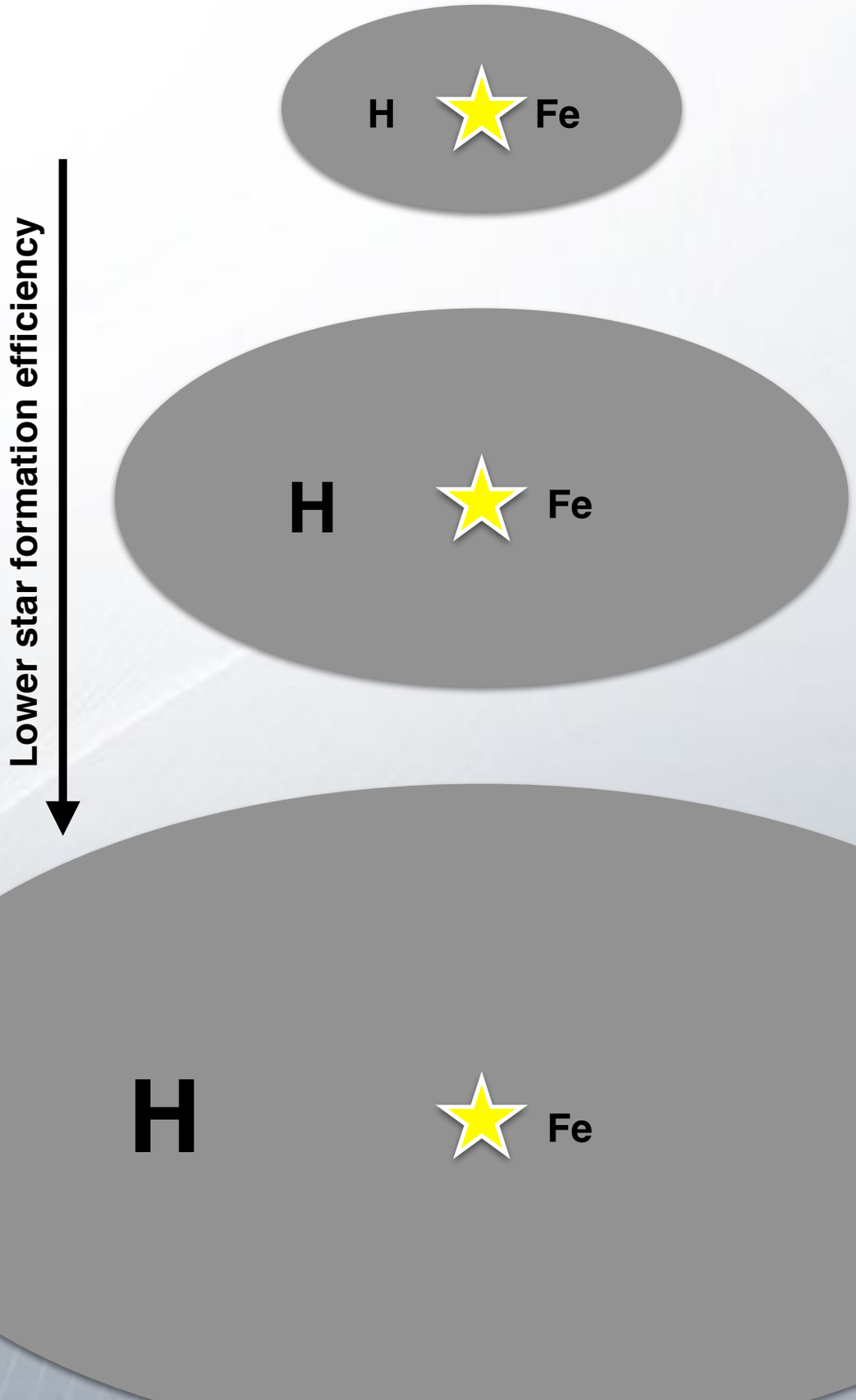

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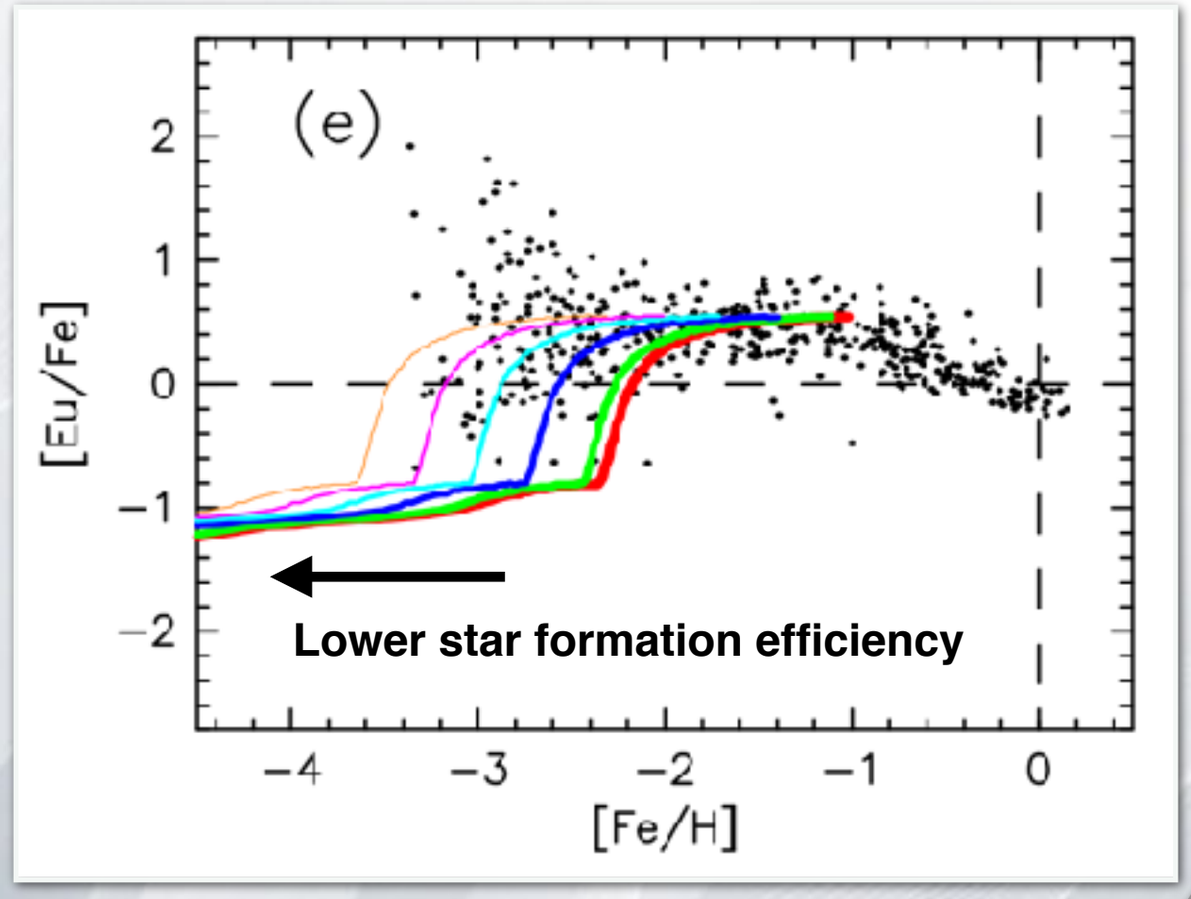
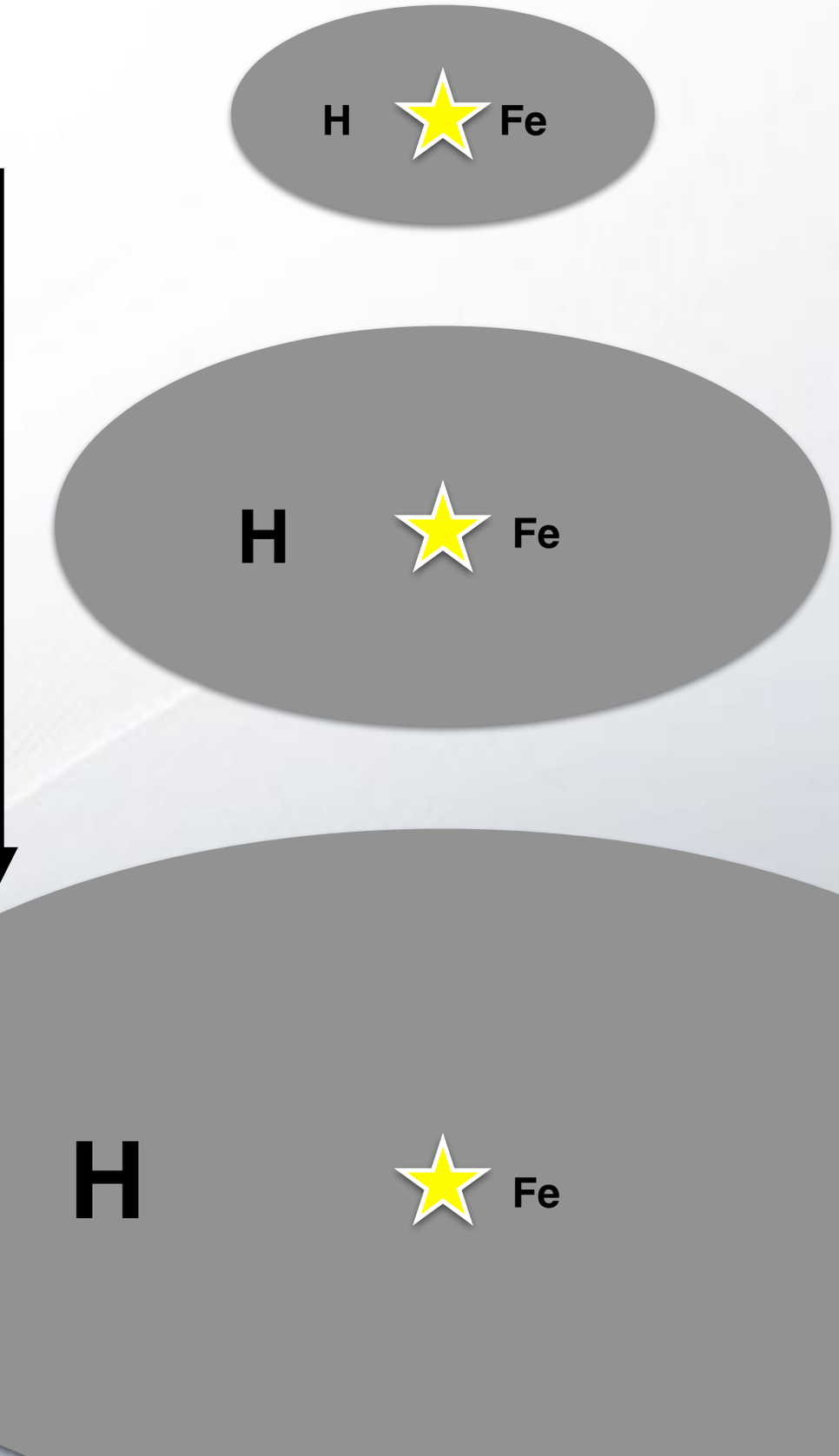



**Bigger gas reservoirs reduce [Fe/H]**



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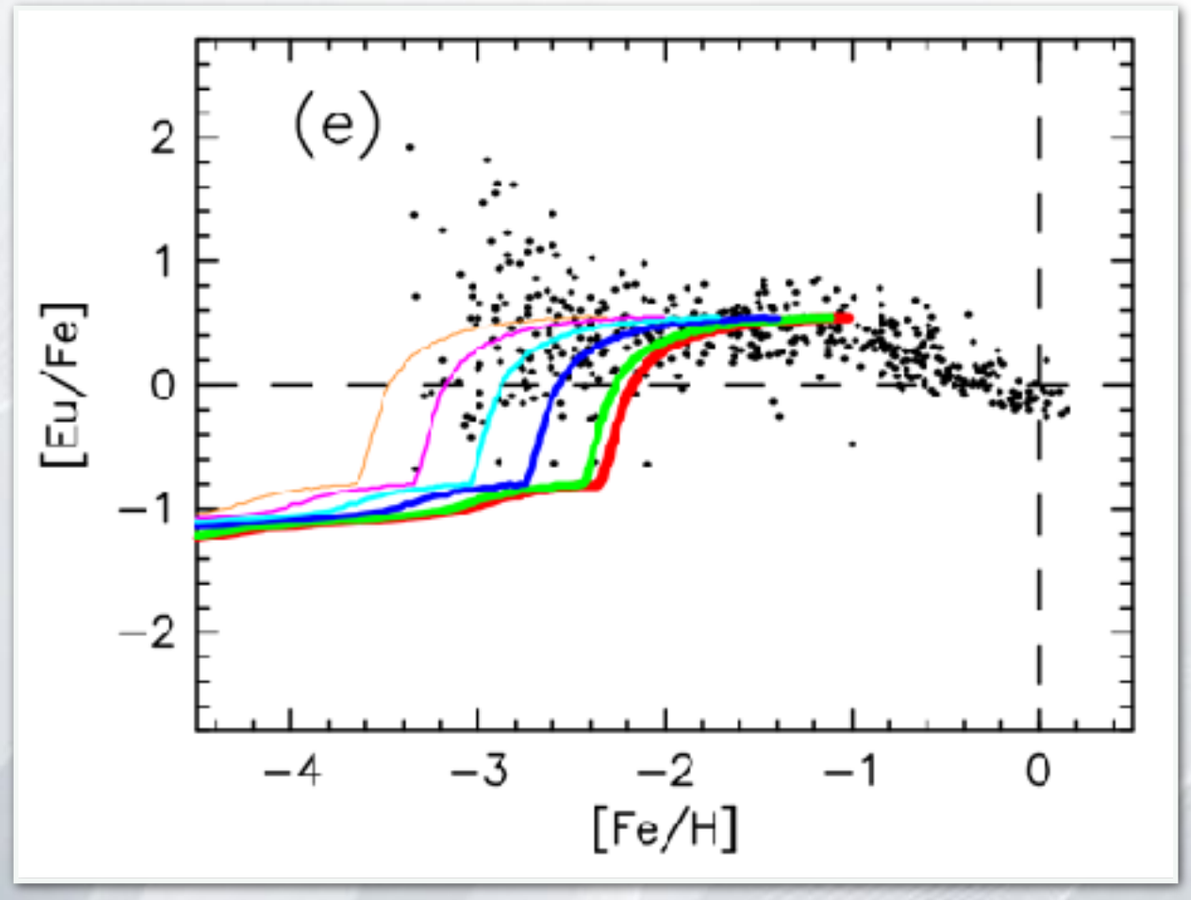


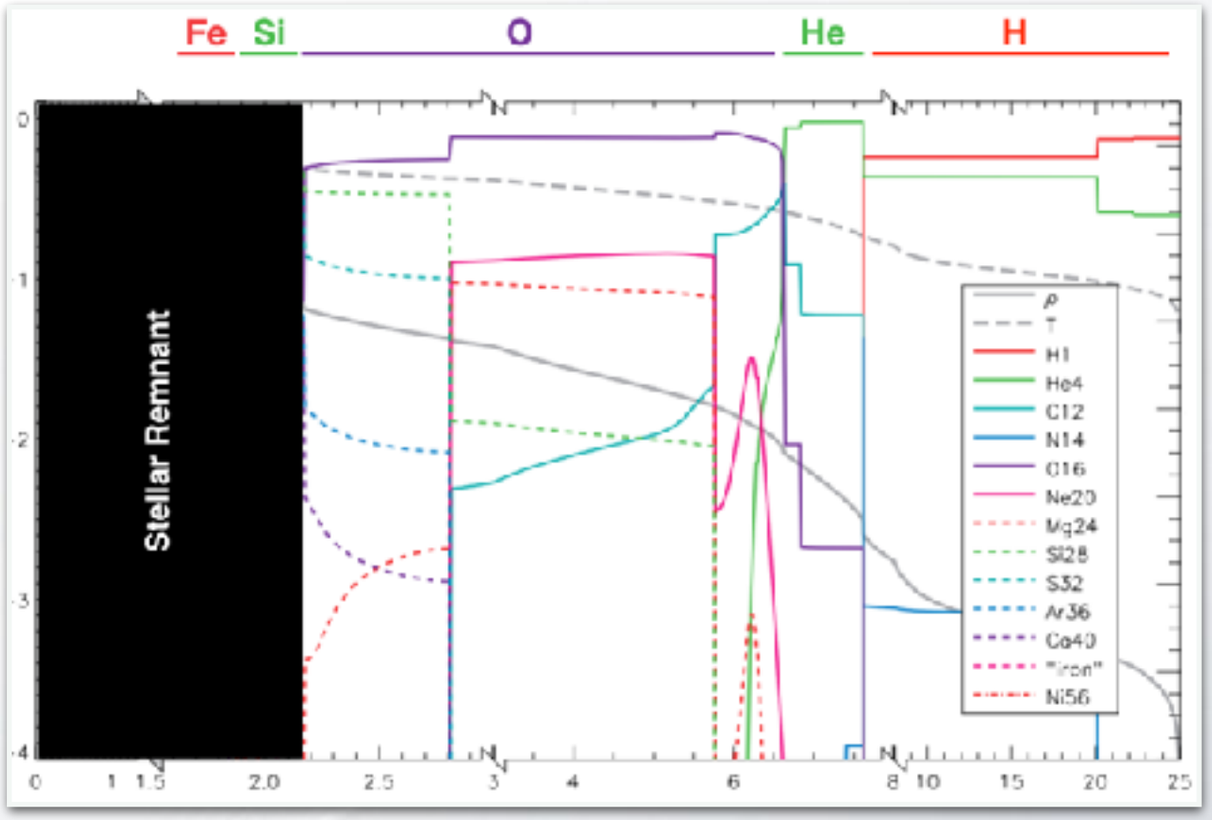


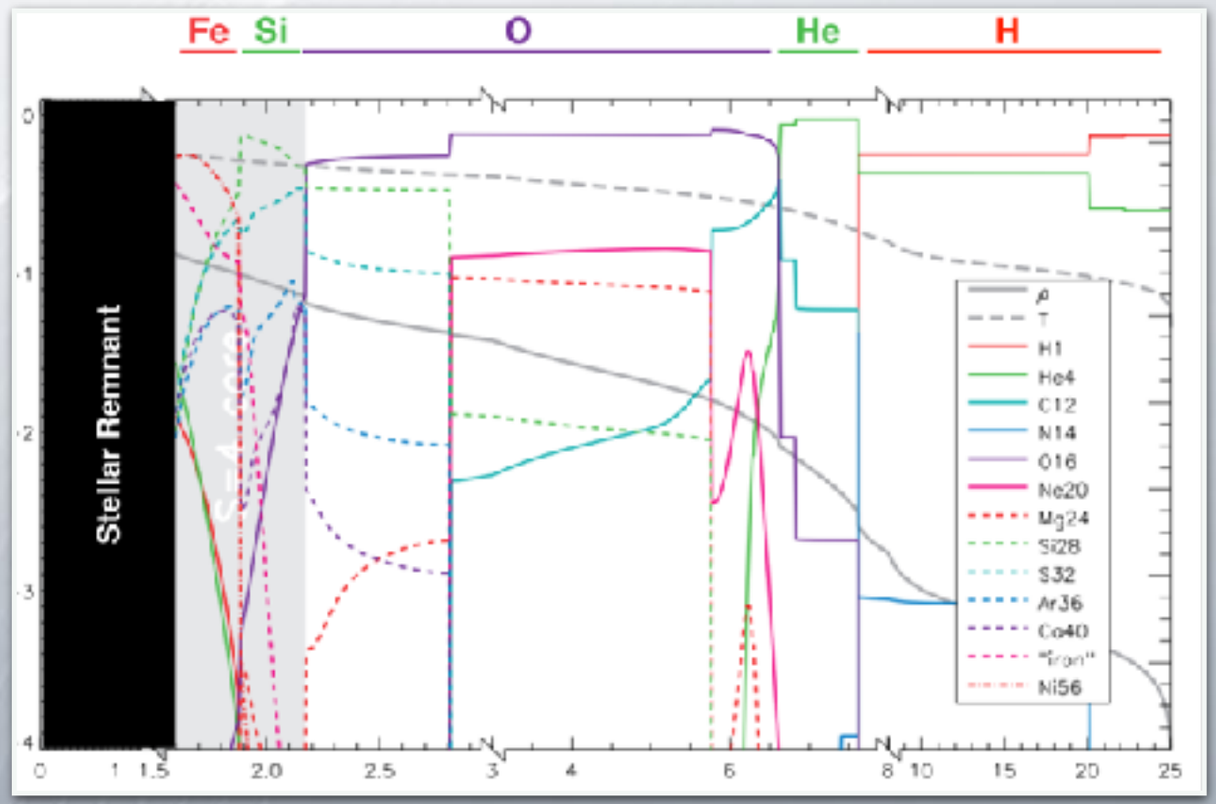

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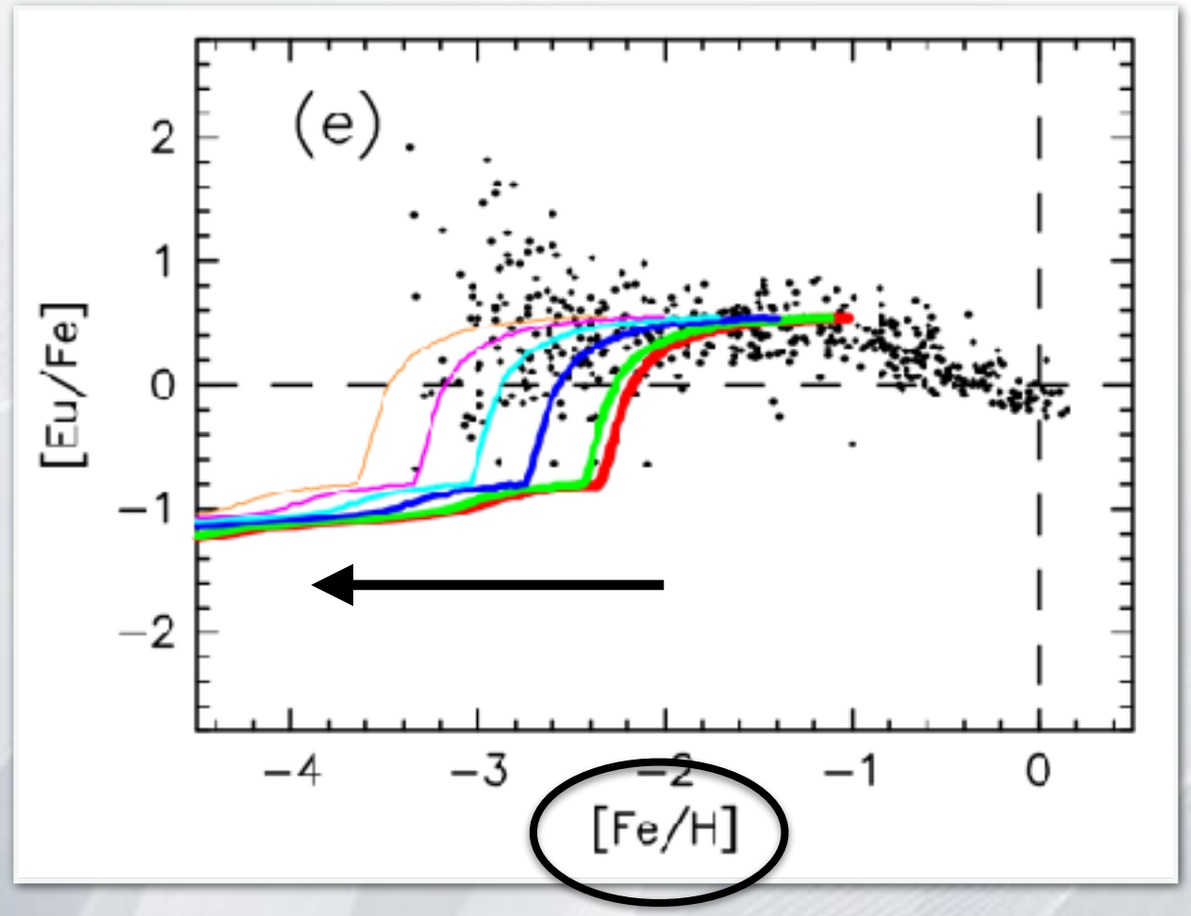


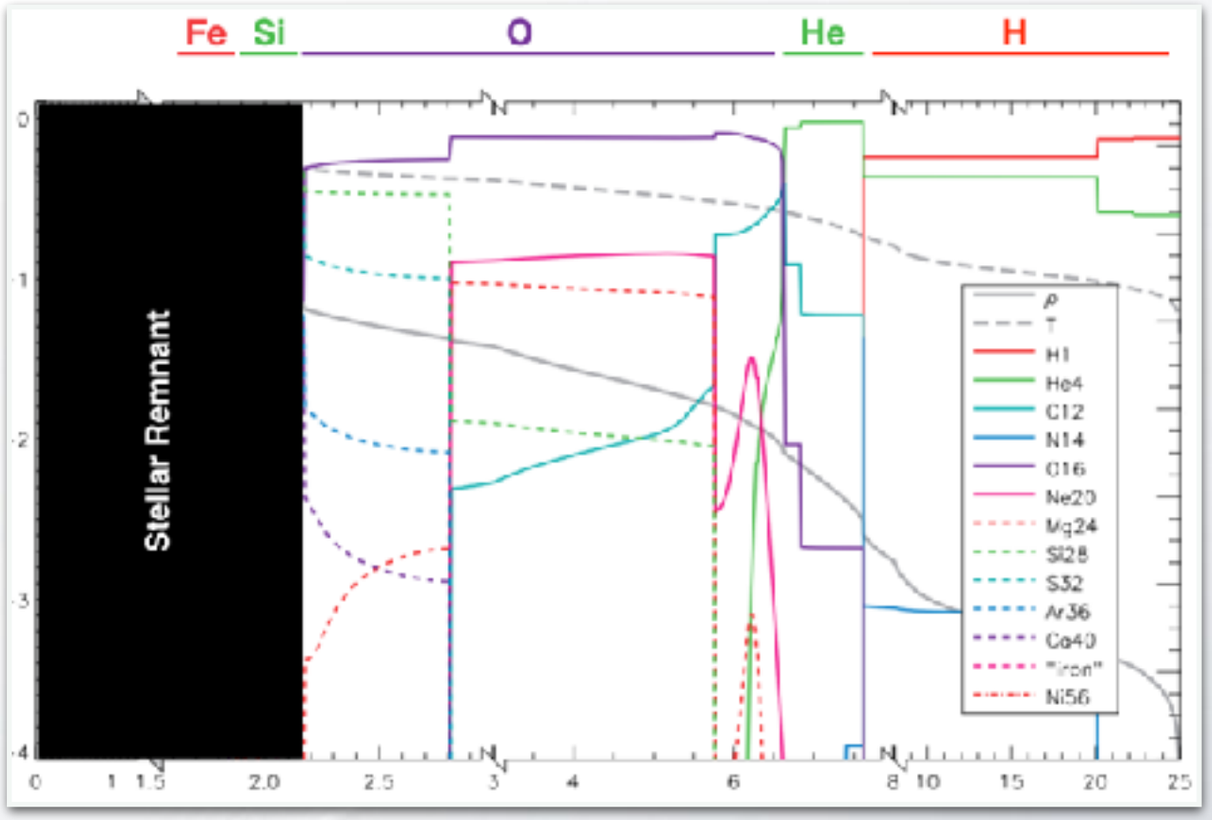


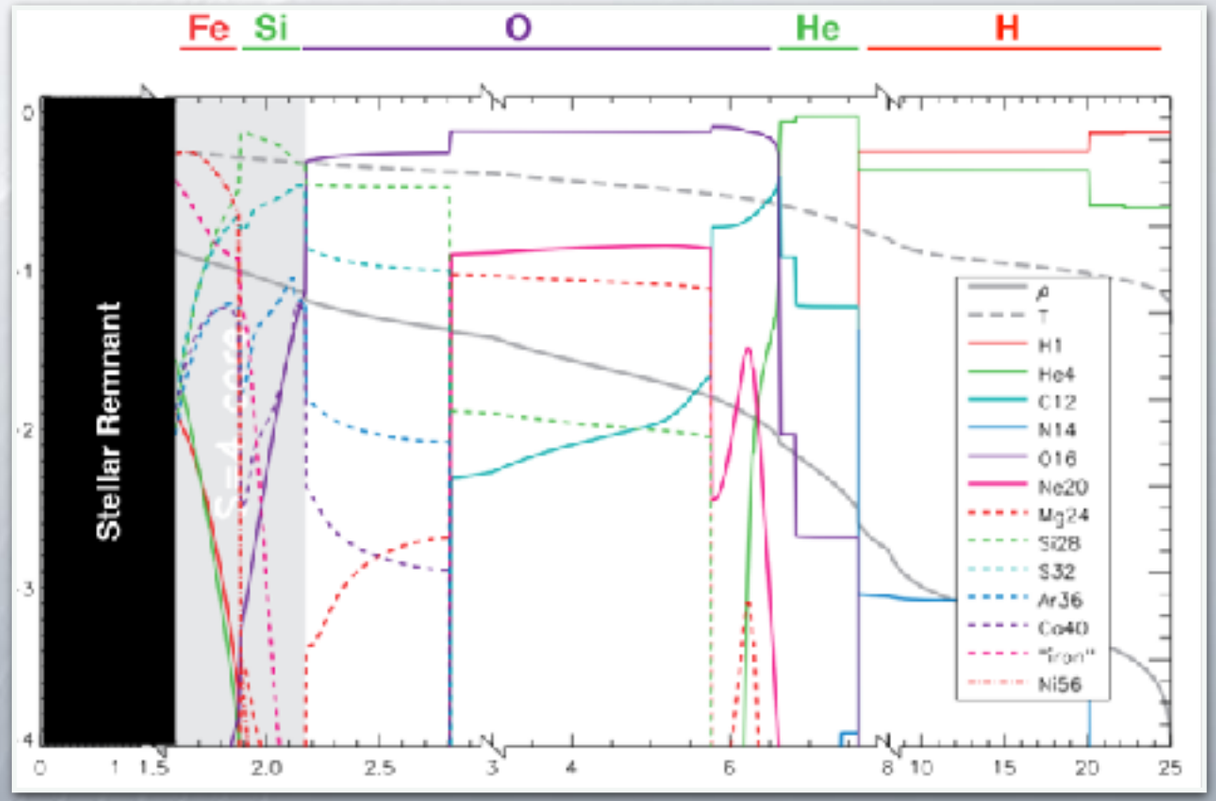

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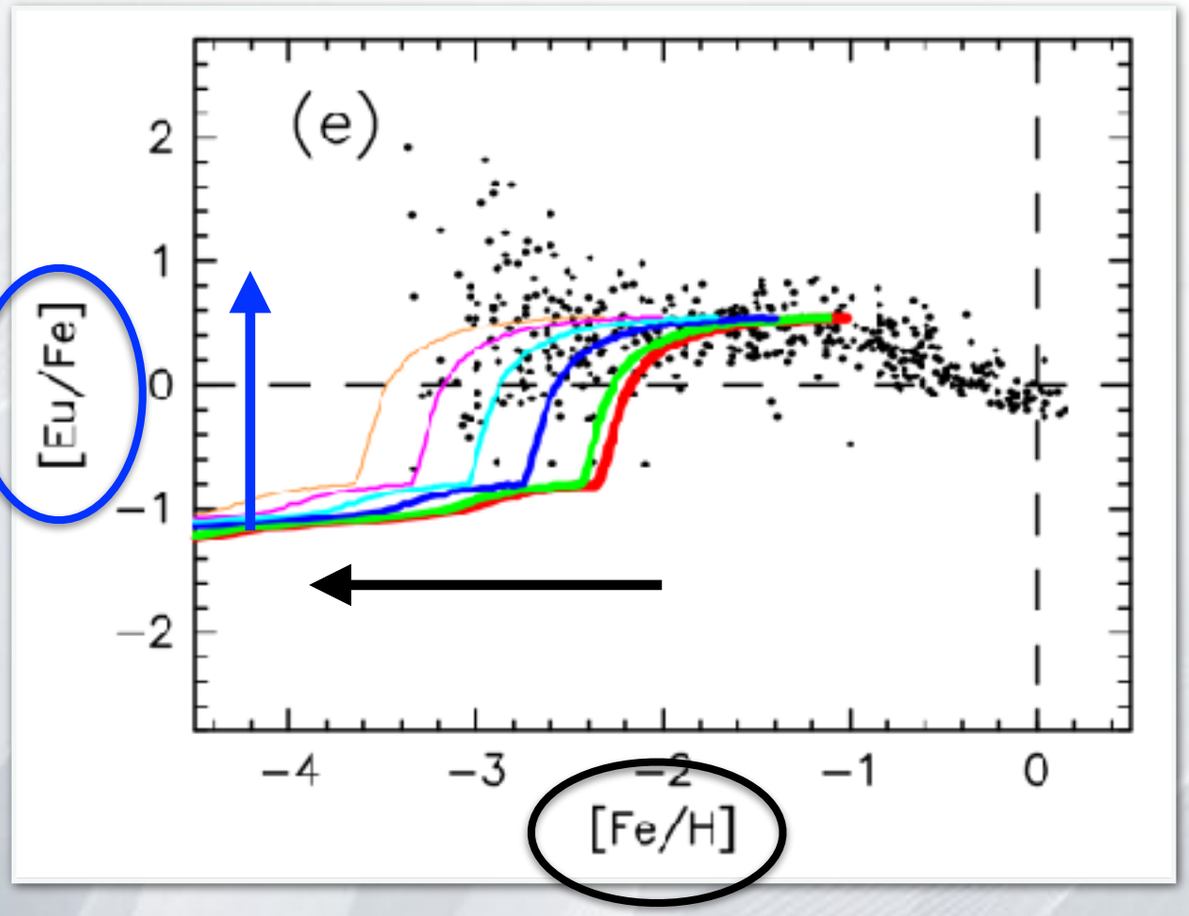


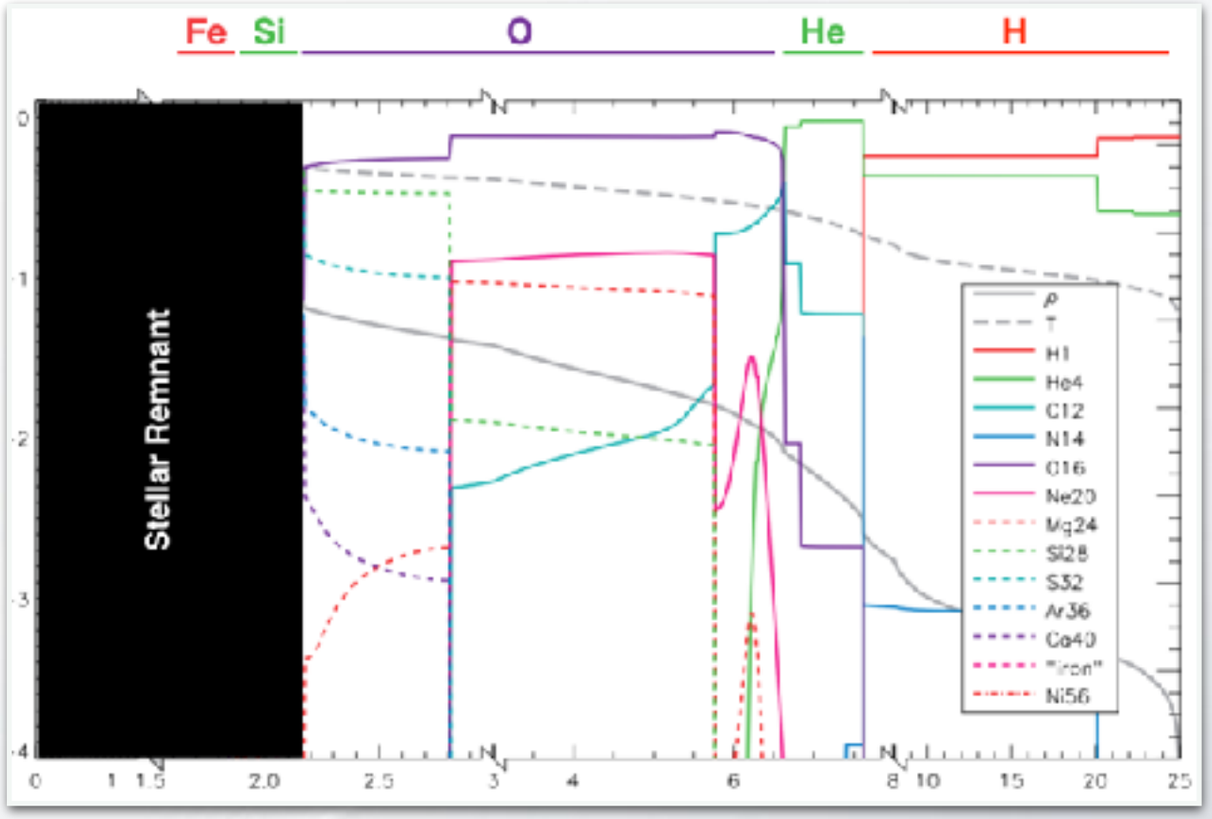


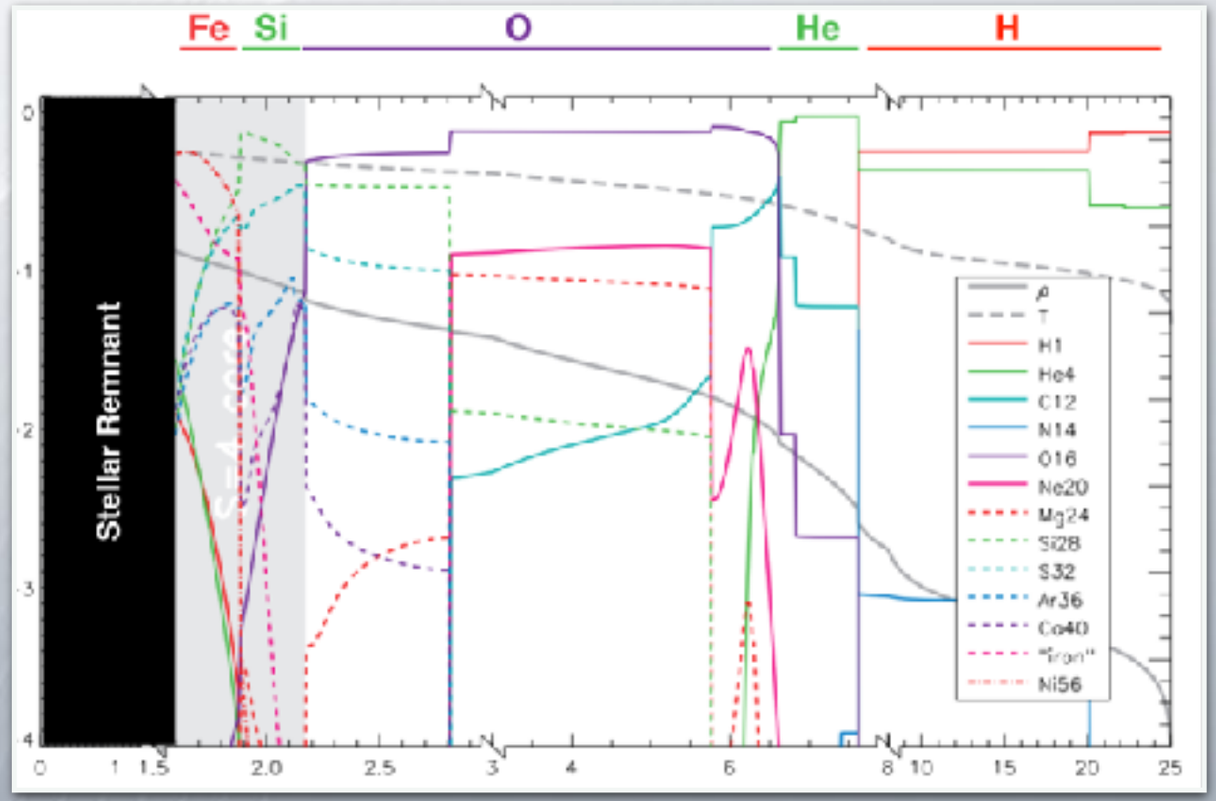

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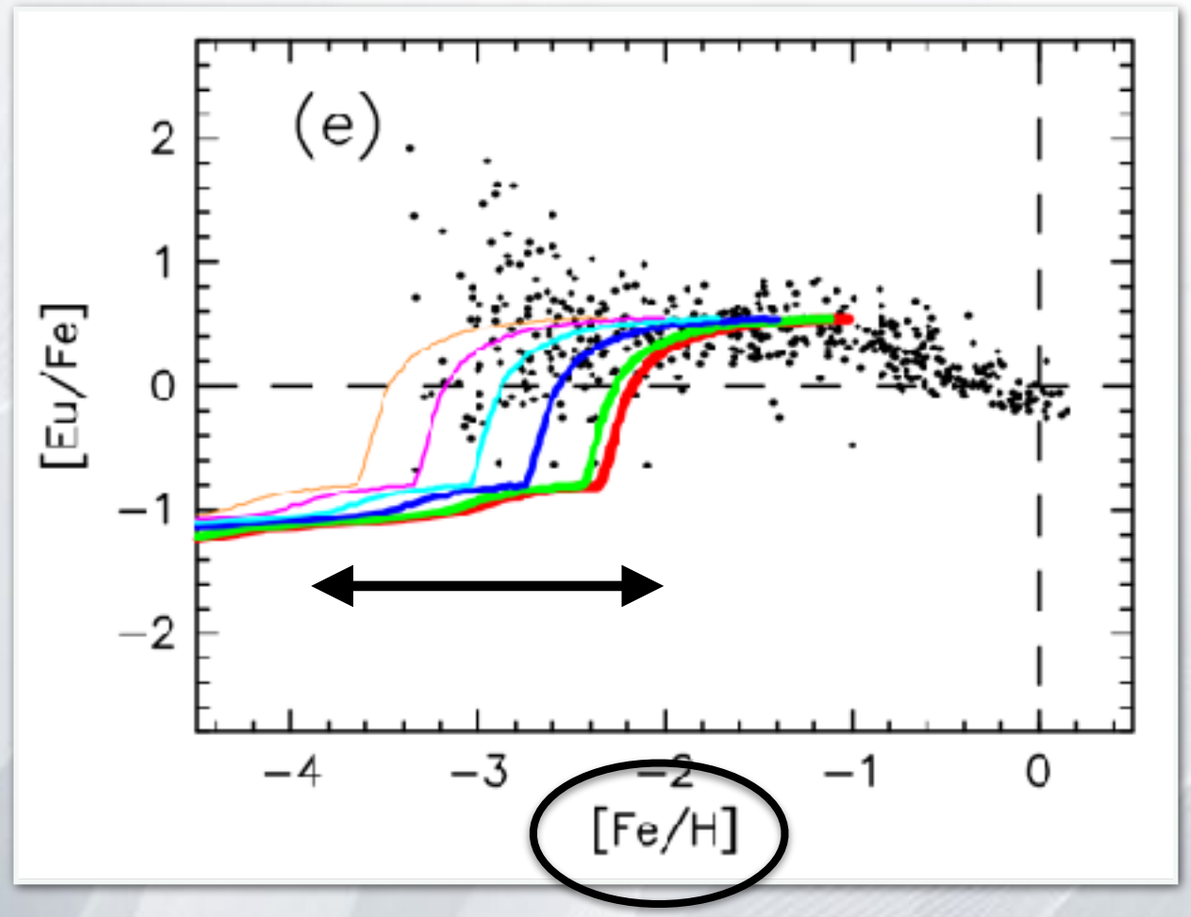


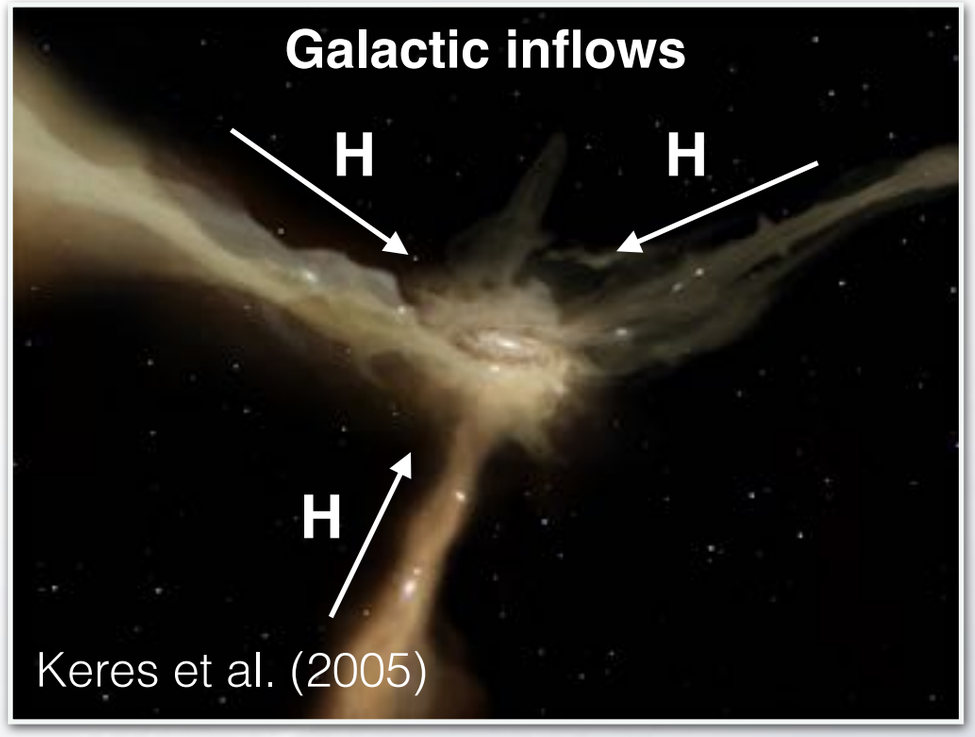


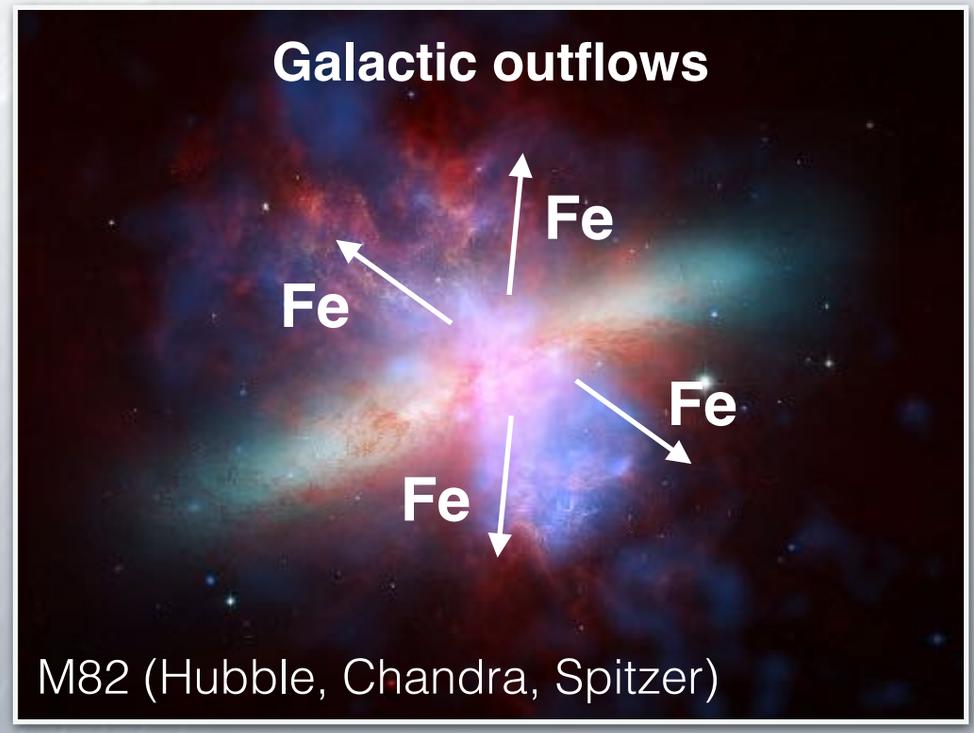

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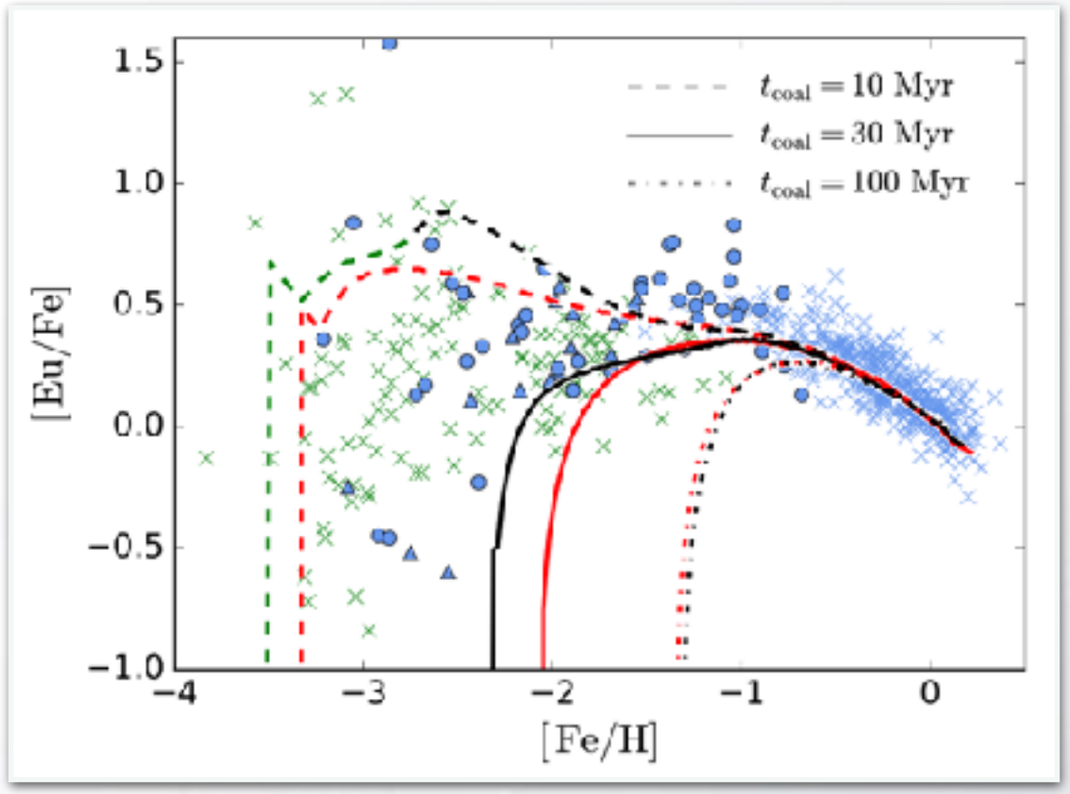
Côté, Belczynski, Fryer, et al. (2017)



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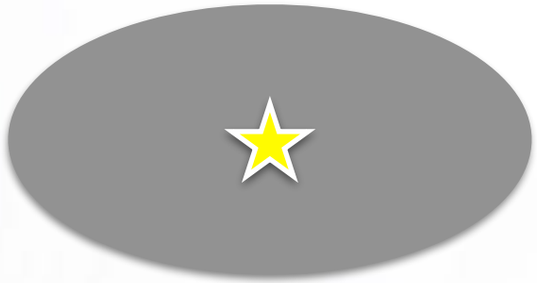

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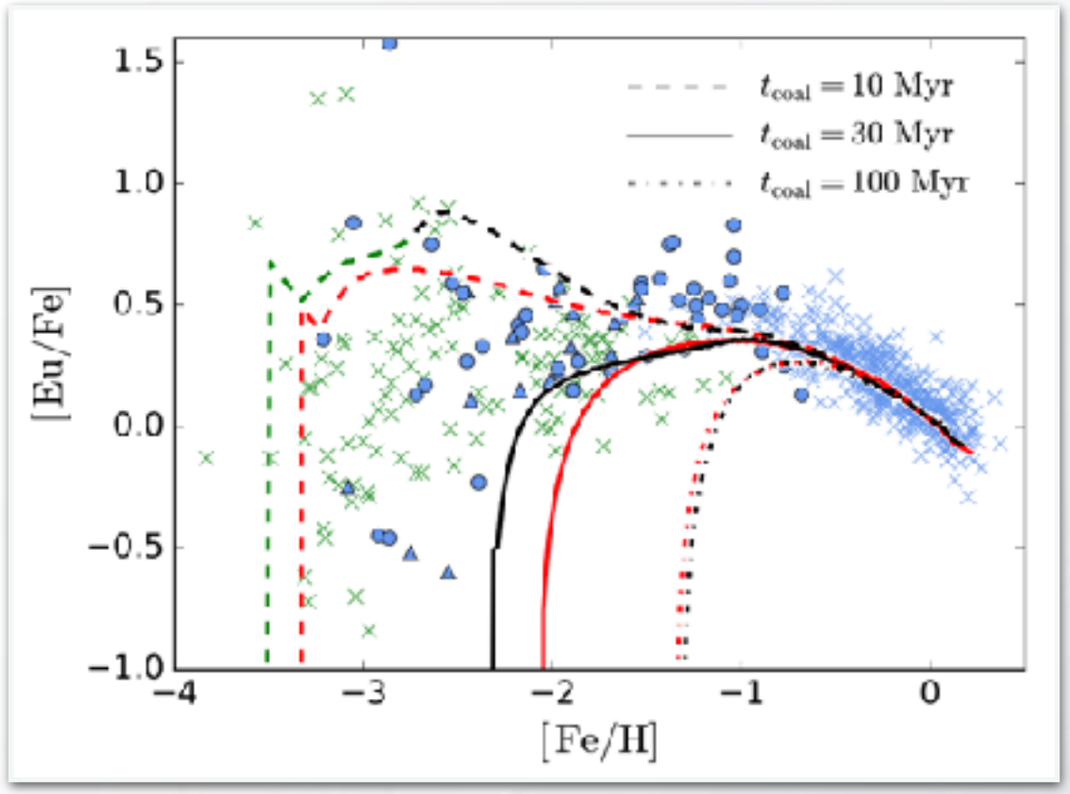

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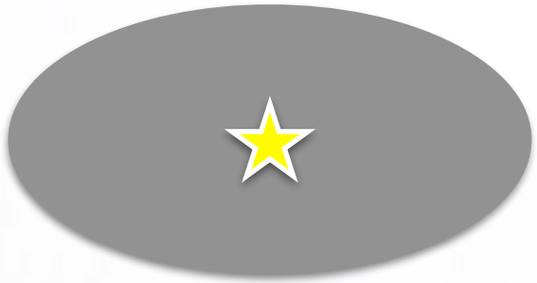
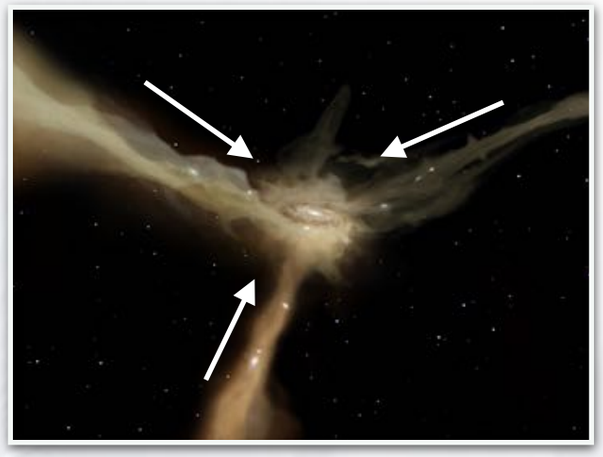
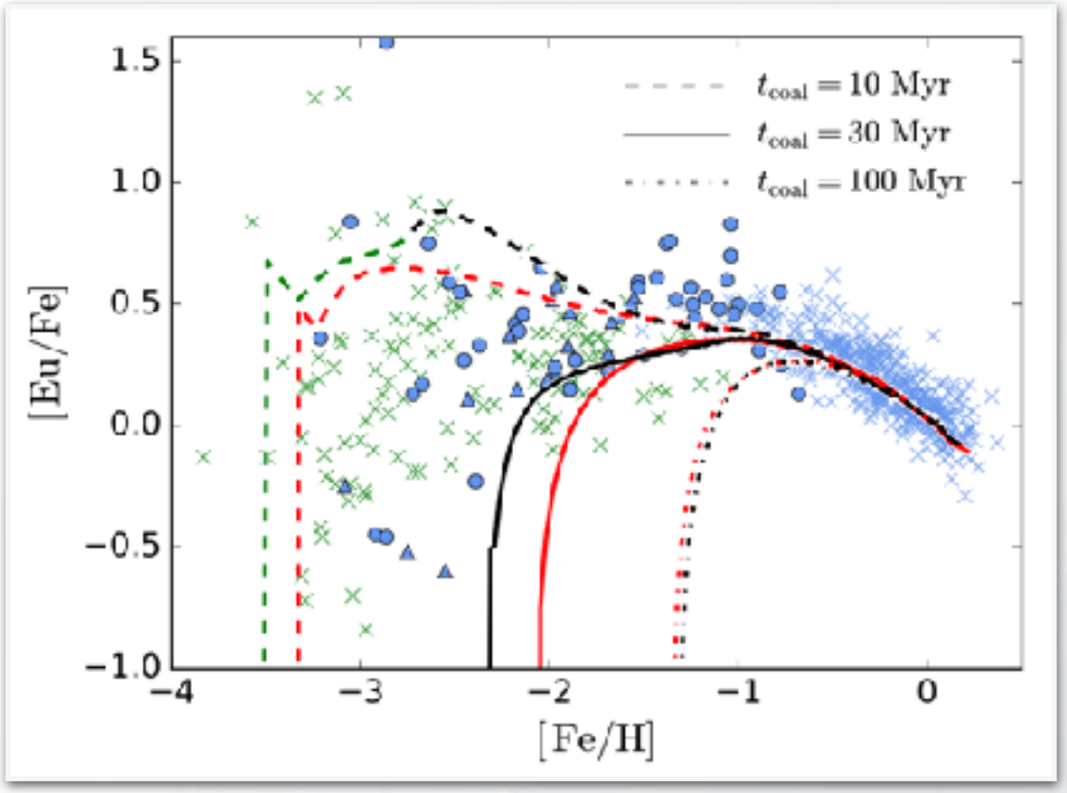




**Gas circulation [Fe/H]**



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

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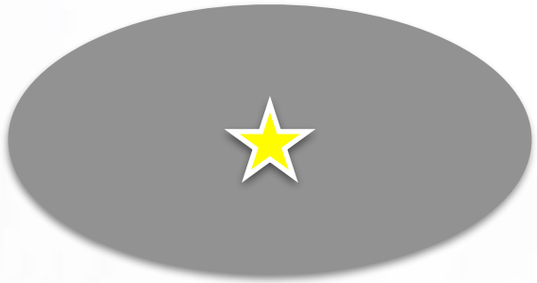

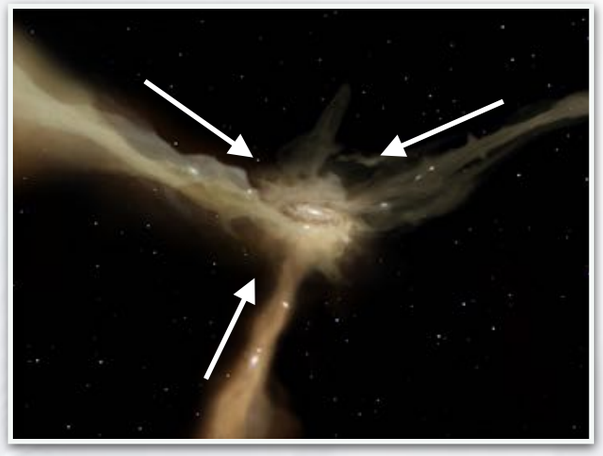

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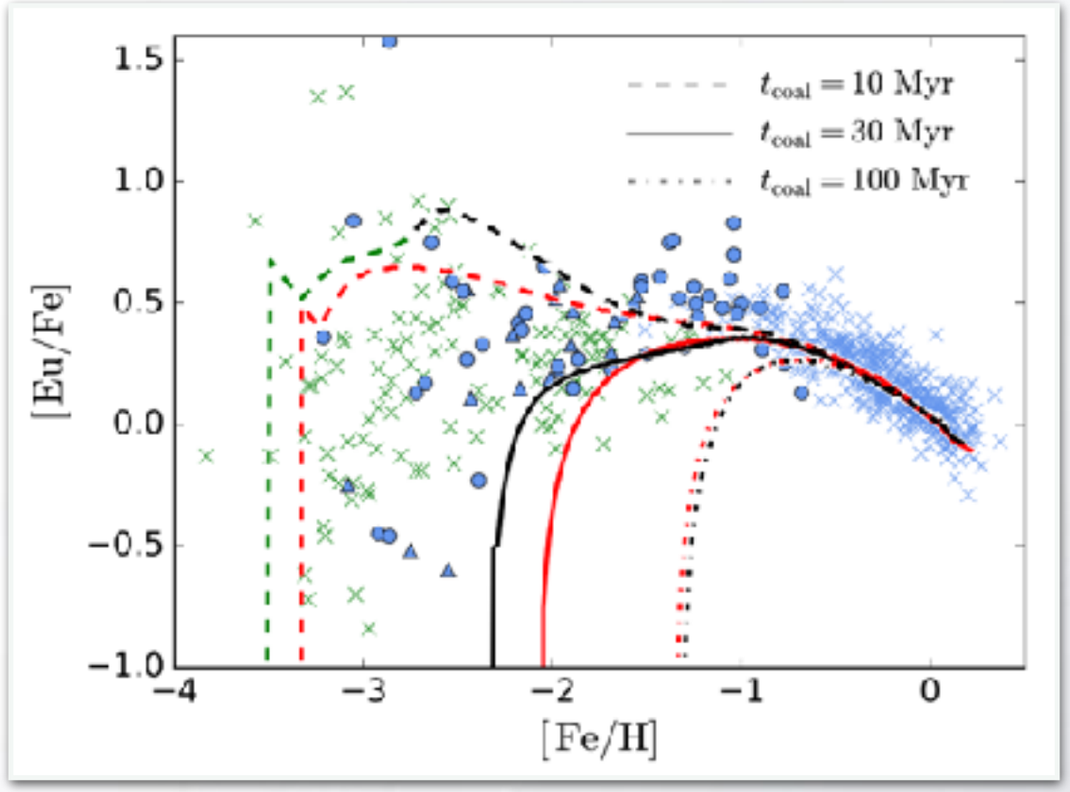
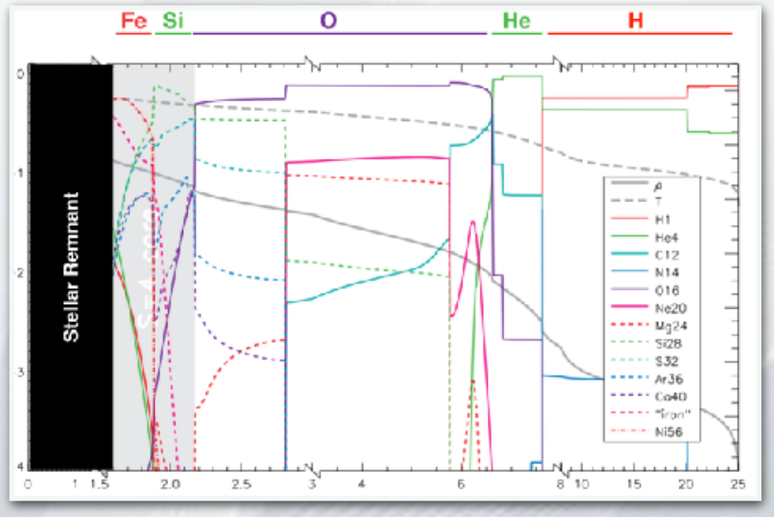



**Stellar models (Fe)**



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

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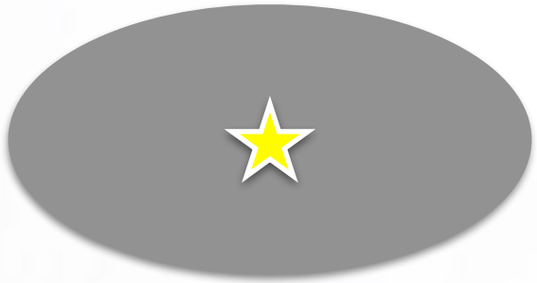

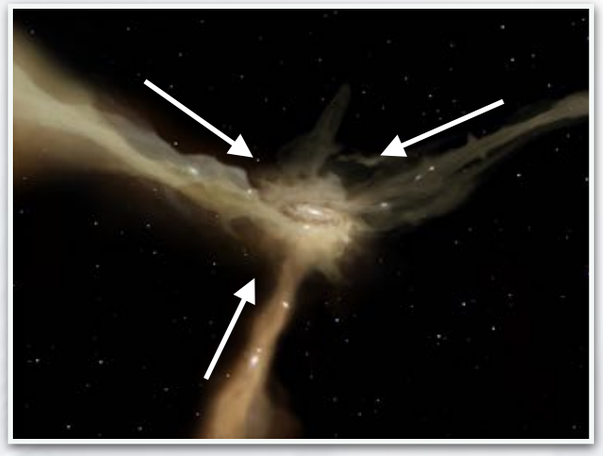

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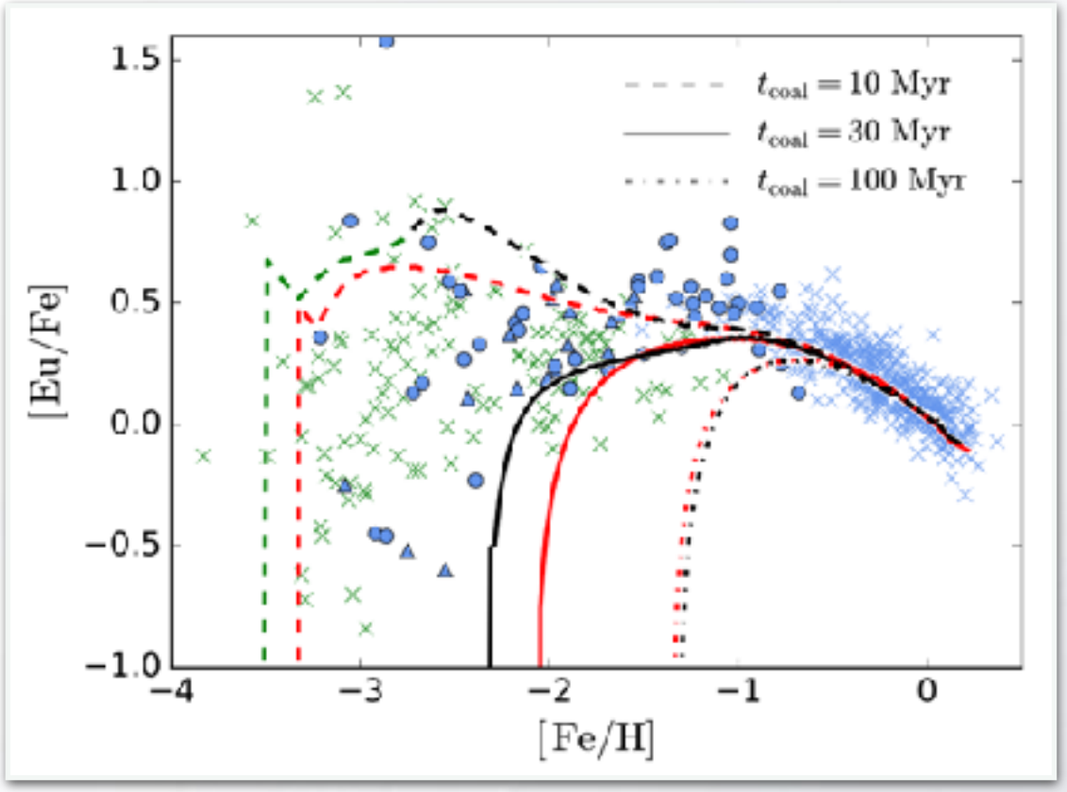


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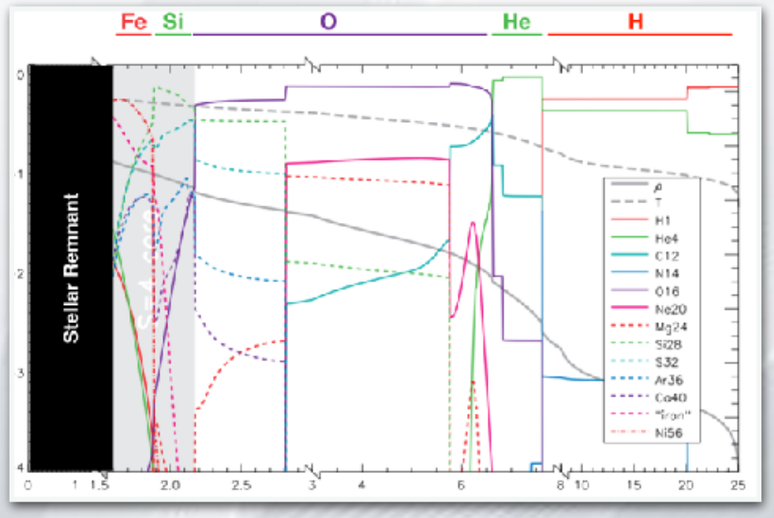
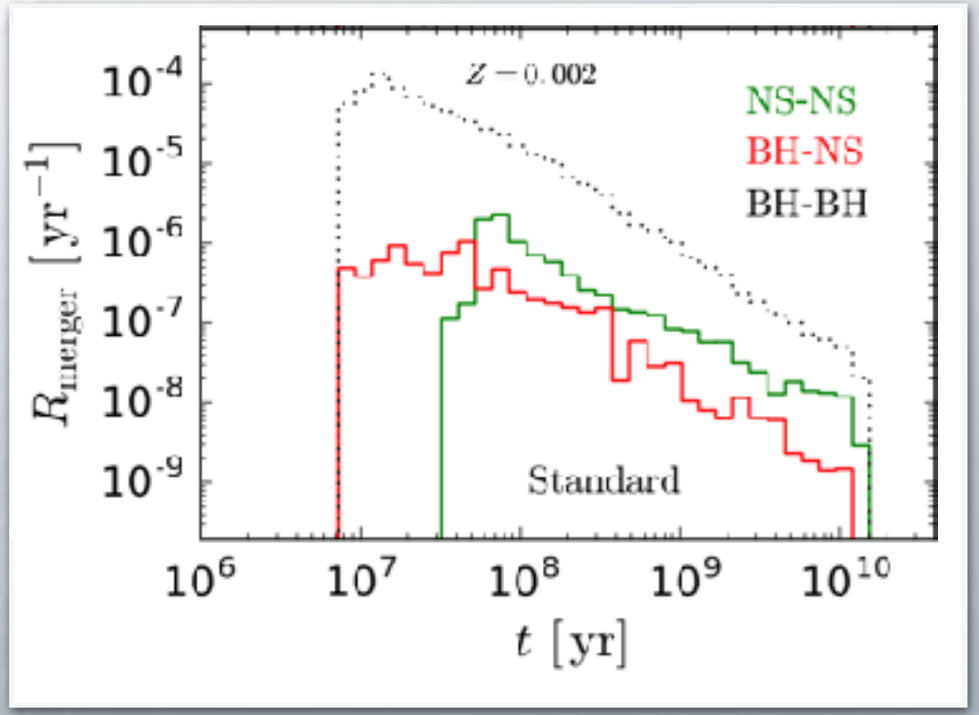



K. Belczynski's models




**Merger rates of compact binary objects (Eu)**

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

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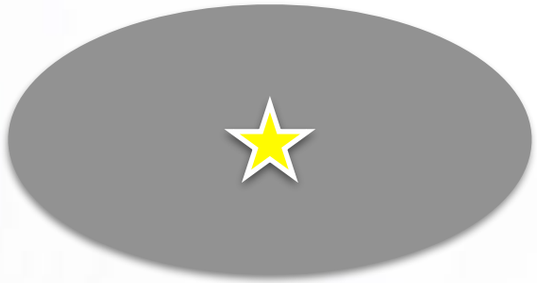

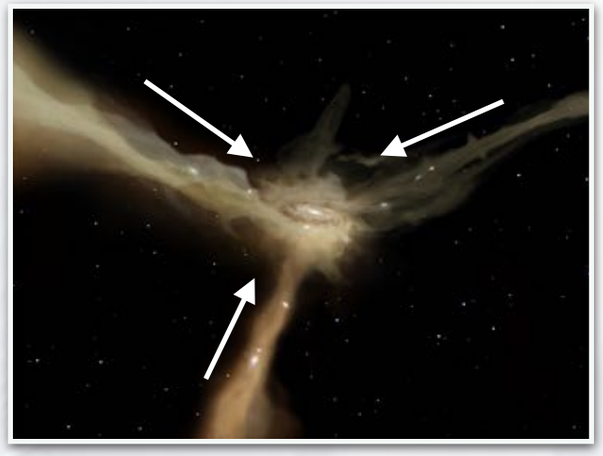

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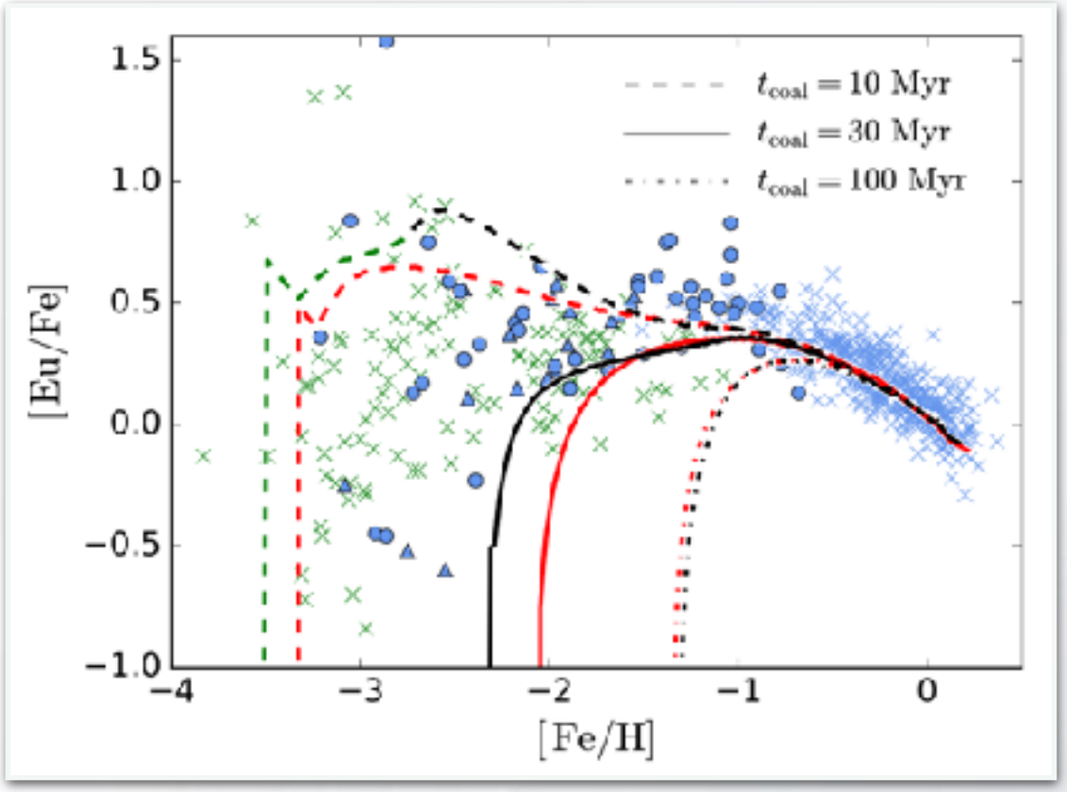


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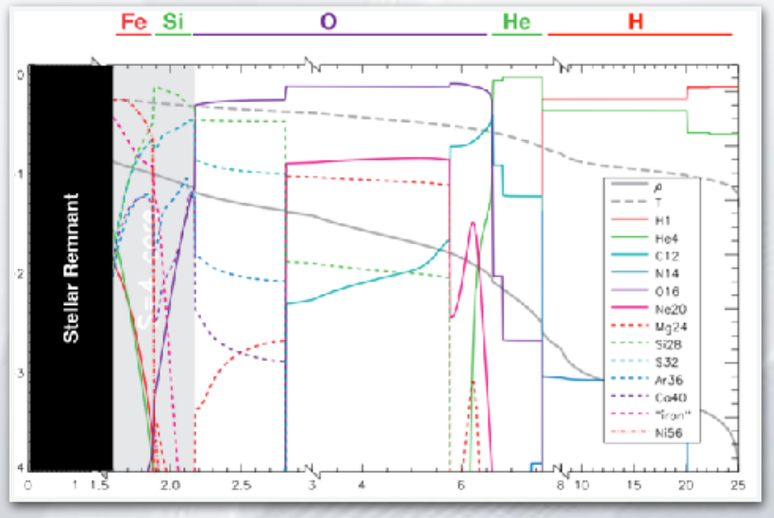
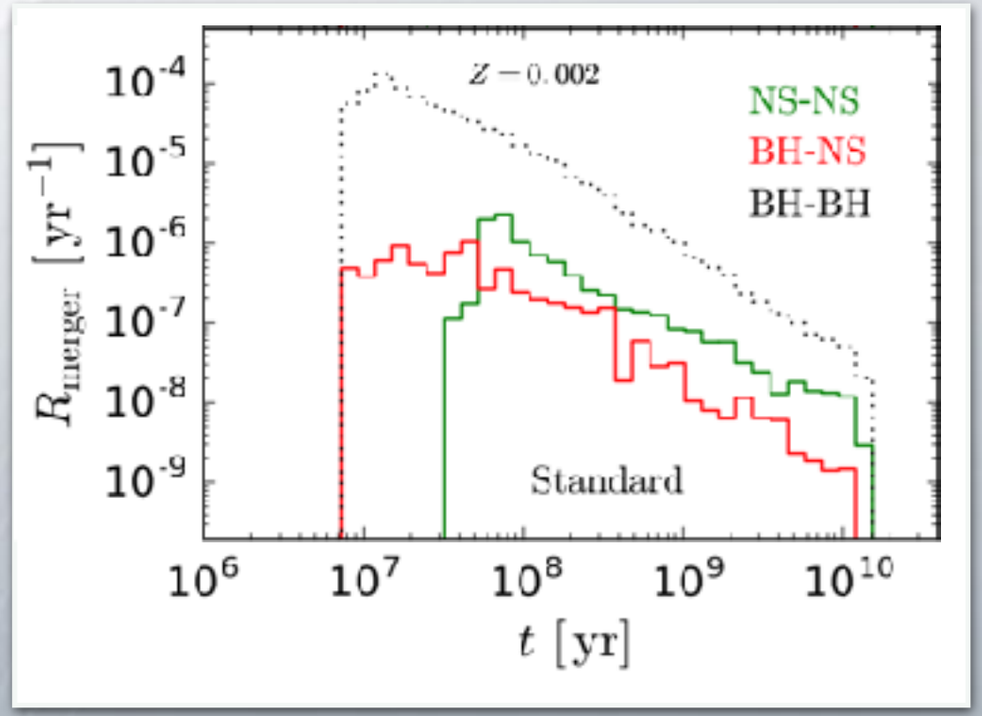



**Relation between initial and remnant mass (neutron stars and black holes)**

K. Belczynski's models

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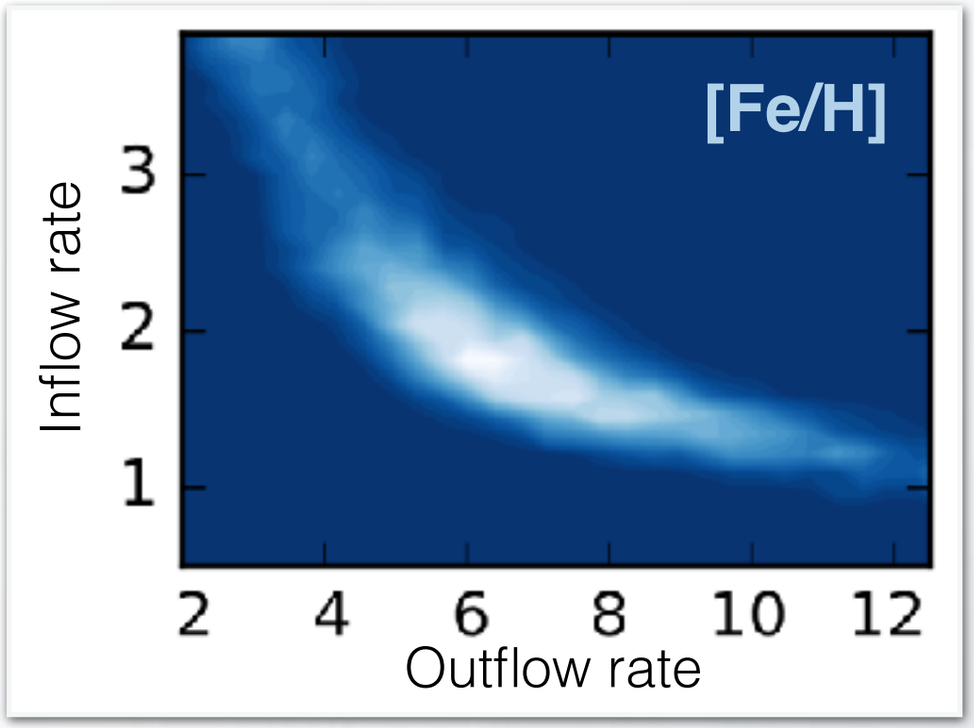
# Breaking the Degeneracy

**We need multiple constraints to break the degeneracy.**

Côté, O'Shea, Ritter, et al. (2017)



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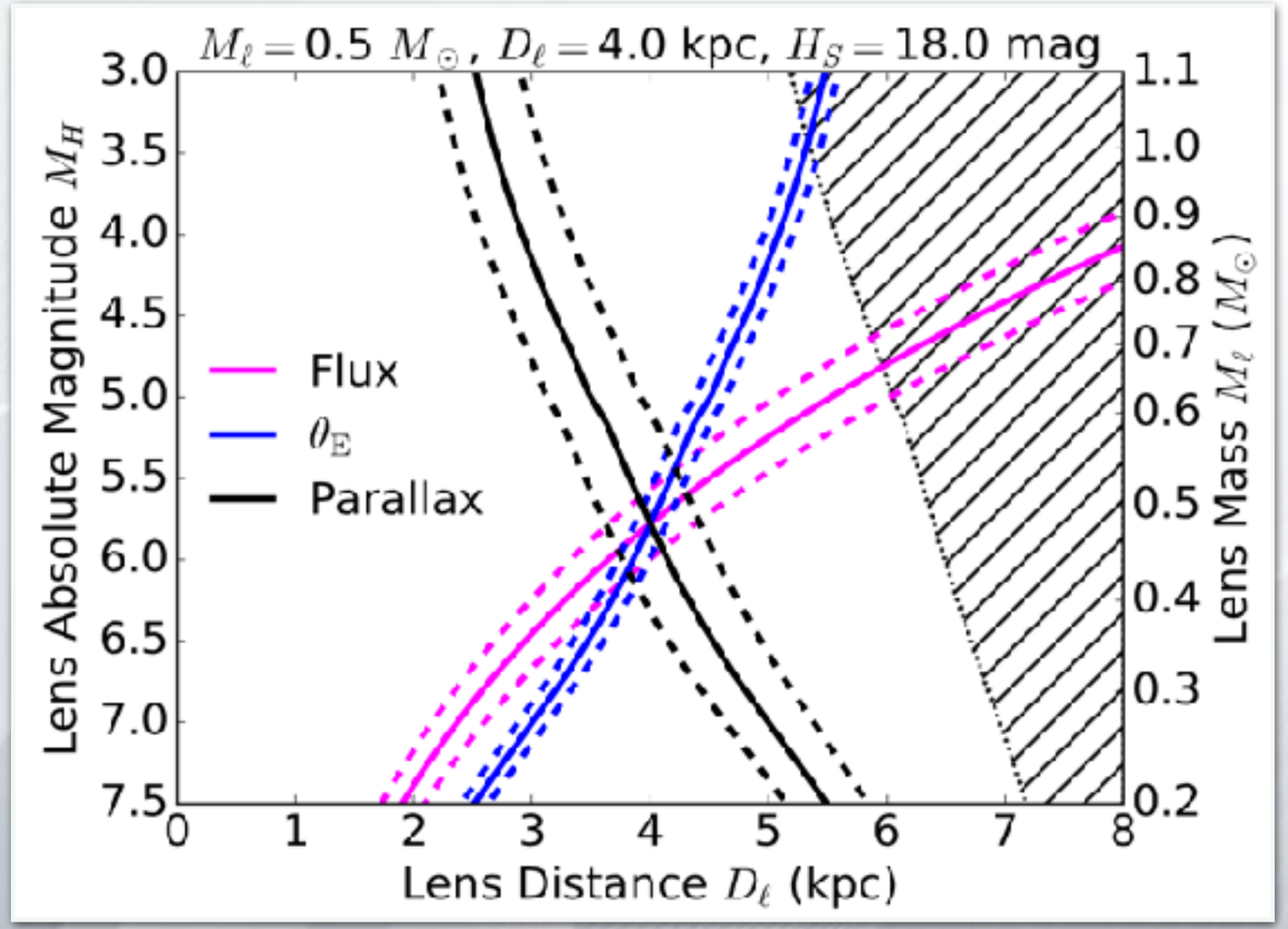
J. C. Yee & C. B. Henderson (Themes document)

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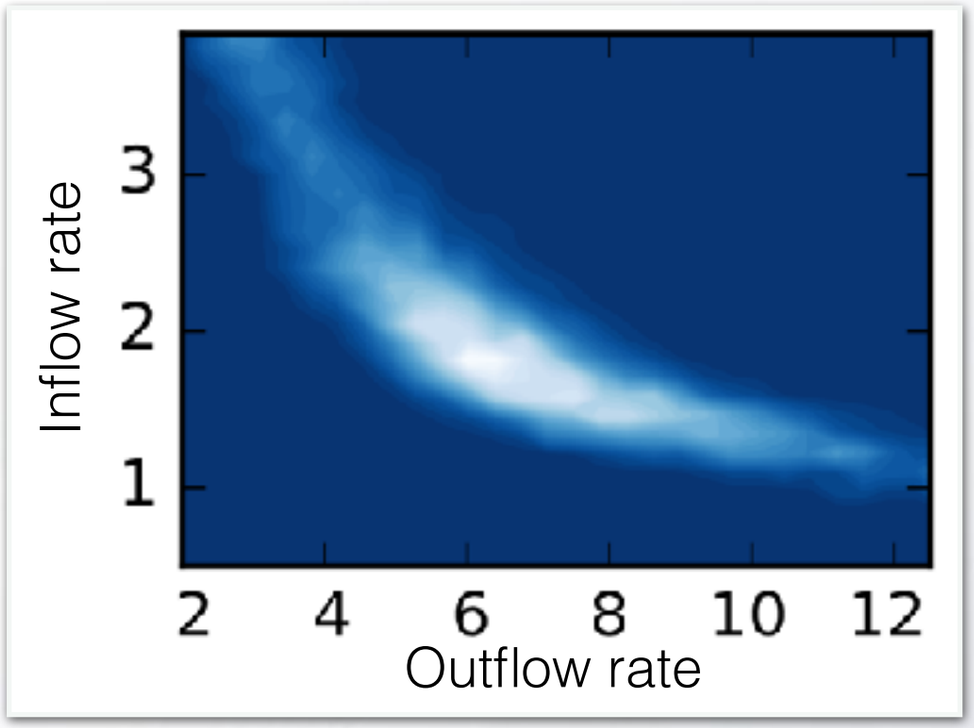

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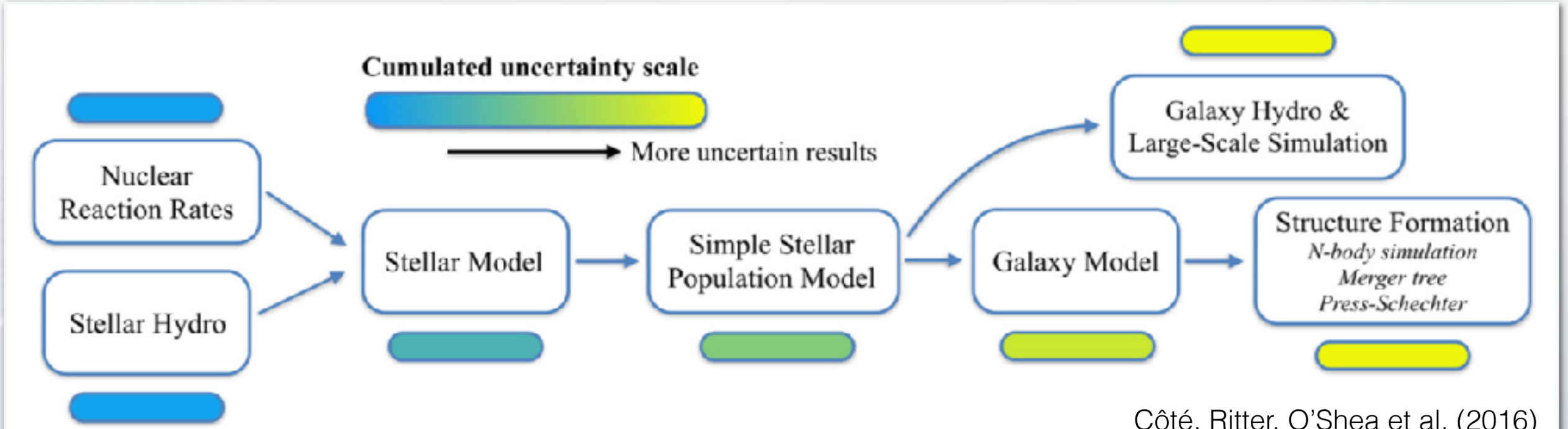


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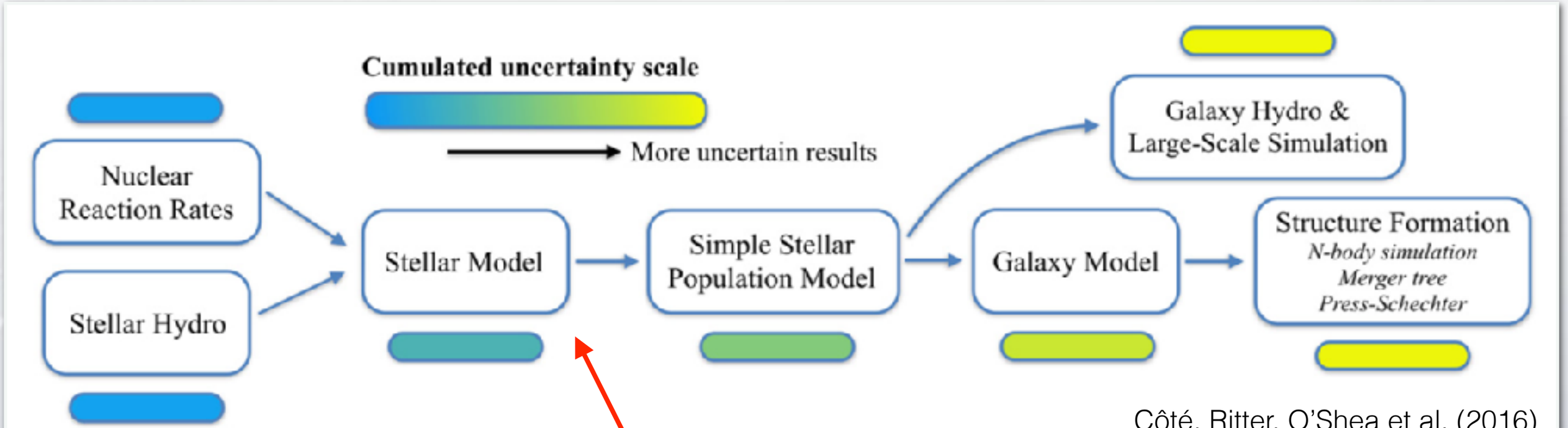


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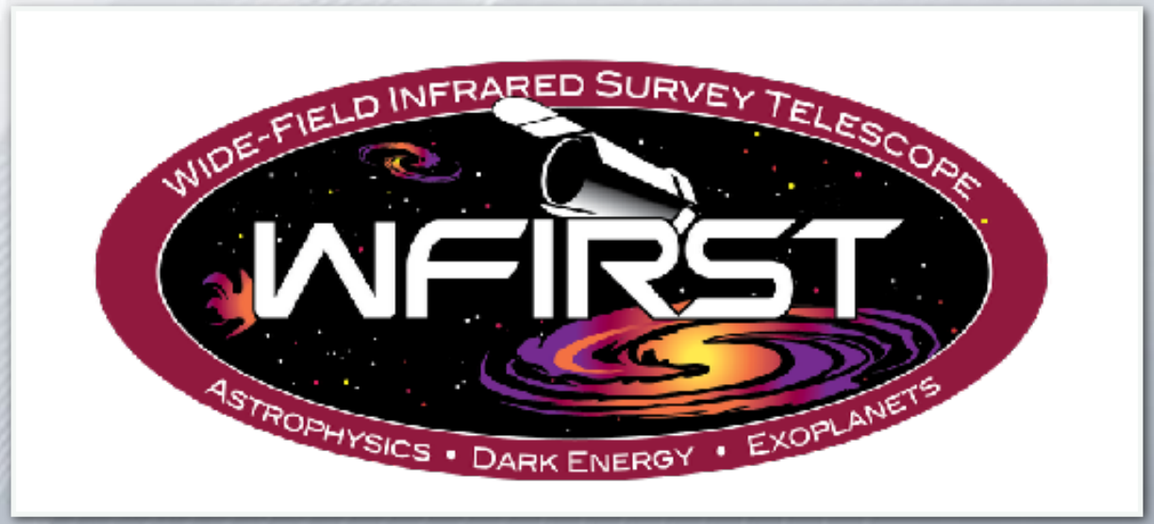
**Neutron star and black hole mass distributions**



# Conclusions

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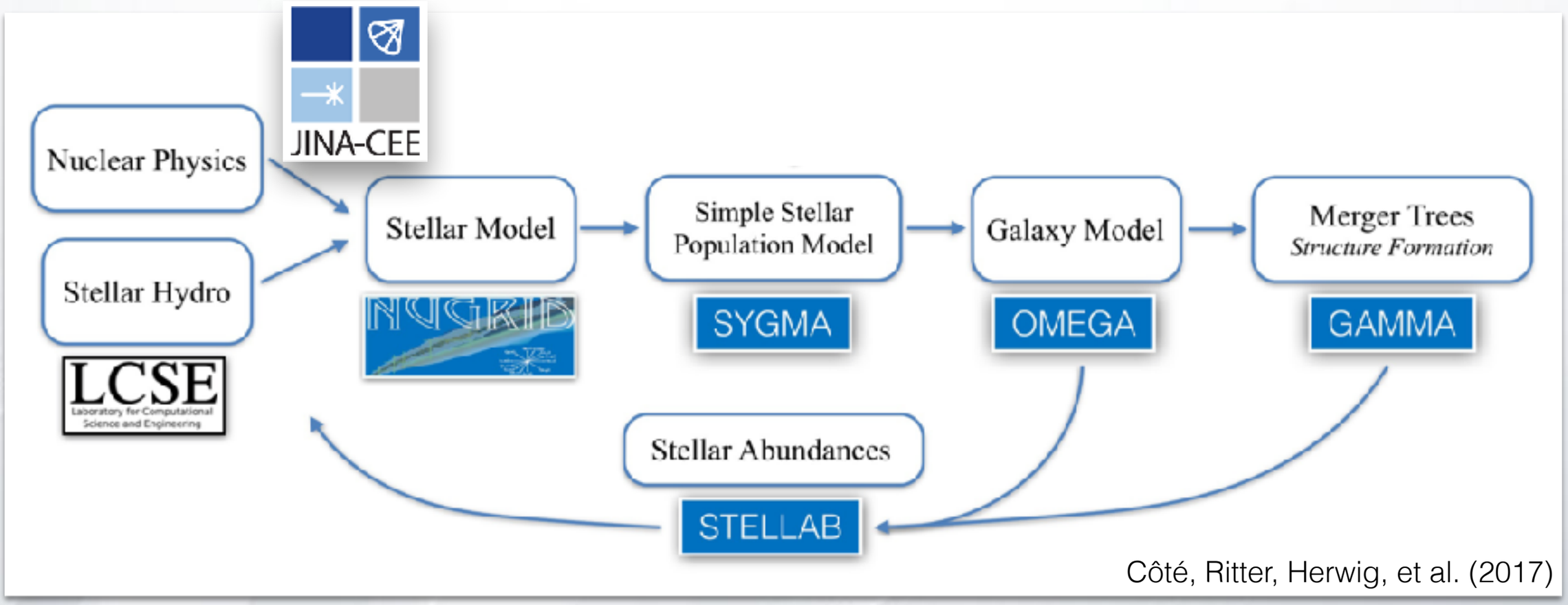
WFIRST and microlensing can constrain the mass function of neutron stars and black holes.

The field of chemical evolution allows to create a more coherent picture of how stars and galaxies evolve and interact.
Any additional constraint help in getting closer to this big picture.

# Open-Source Chemical Evolution Pipeline




Côté, Ritter, Herwig, et al. (2017)

- **SYGMA** - **S**tellar **Y**ields for **G**alactic **M**odeling **A**pplications (*C. Ritter et al. 2017, in prep.*)
- **OMEGA** - **O**ne-zone **M**odel for the **E**volution of **GA**laxies (*Côté, O'Shea, Ritter, et al. 2017)*
- **GAMMA** - **G**alaxy **A**ssembly with **M**erger-trees for **M**odeling **A**bundances *(Côté et al. in prep.)*
- **STELLAB** - STELLar ABundances, observational data plotting tool

Open-source codes **http://nugrid.github.io/NuPyCEE/**