



.. and **Neutron Stars**

Chemical Evolution and the Mass Function of Stellar Mass Black Holes

Benoit Côté
Postdoctoral Fellow

Collaborators

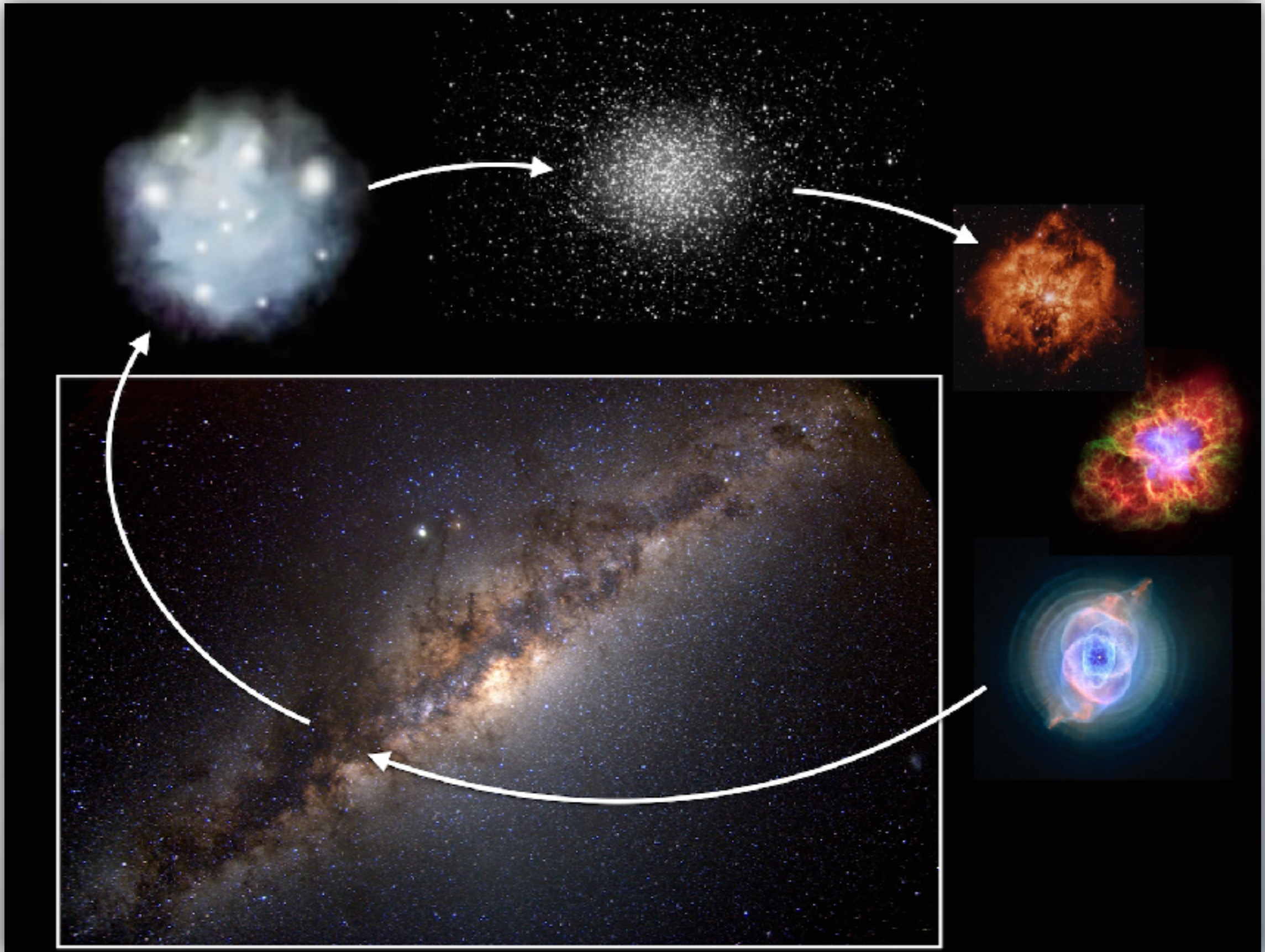
C. Fryer, K. Belczynski, B. O'Shea, C. Ritter, F. Herwig, M. Pignatari, B. Wehmeyer

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

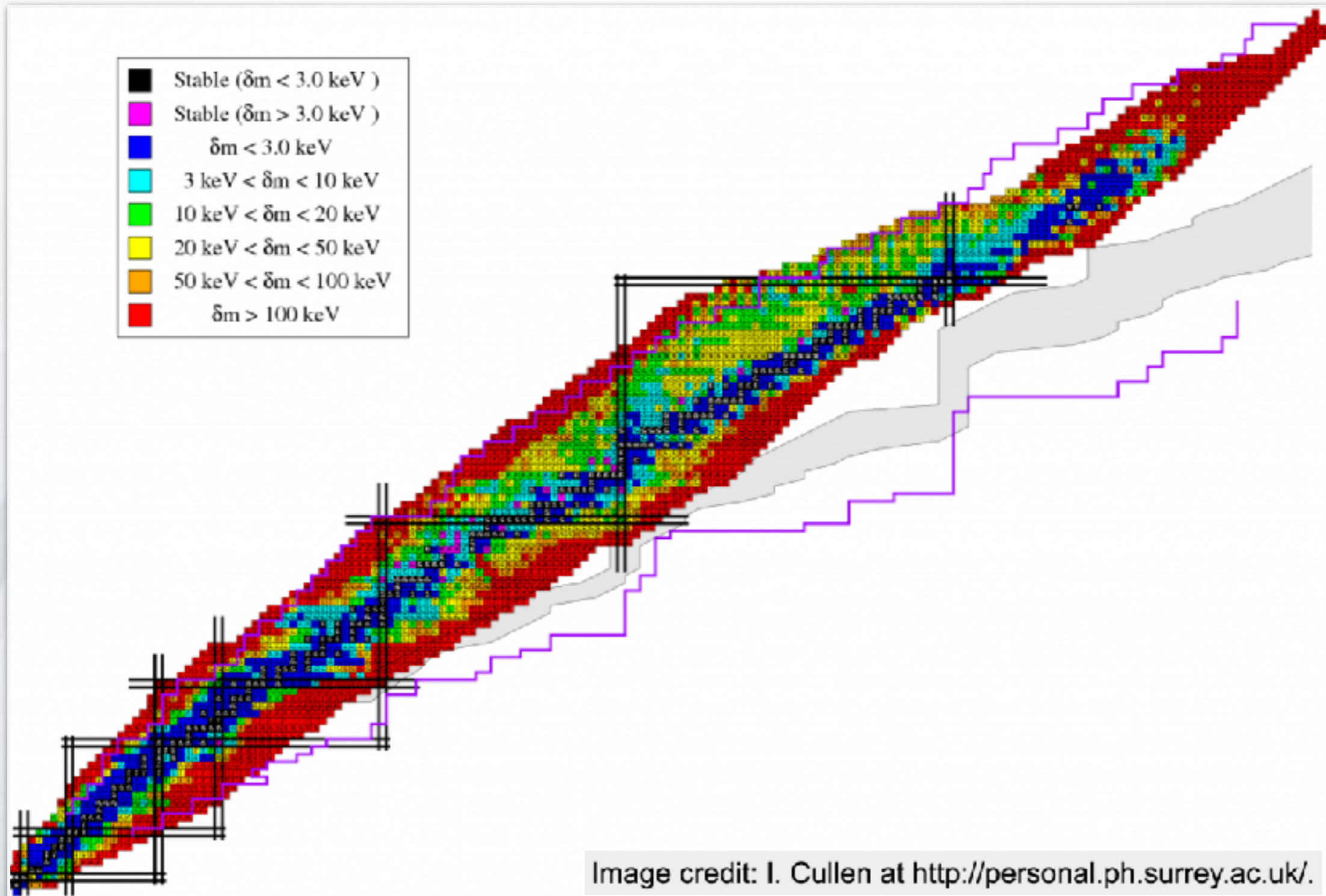


Image credit: I. Cullen at <http://personal.ph.surrey.ac.uk/>.

Definition of Metals

1 IA 1A																	18 VIIIA 8A
1 H Hydrogen 1.008																	2 He Helium 4.003
3 Li Lithium 6.941	4 Be Beryllium 9.012											5 B Boron 10.811	6 C Carbon 12.011	7 N Nitrogen 14.007	8 O Oxygen 15.999	9 F Fluorine 18.998	10 Ne Neon 20.180
11 Na Sodium 22.990	12 Mg 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 Al Aluminum 26.982	14 Si Silicon 28.086	15 P Phosphorus 30.974	16 S Sulfur 32.066	17 Cl Chlorine 35.453	18 Ar Argon 39.948
19 K Potassium 39.098	20 Ca Calcium 40.078	21 Sc Scandium 44.956	22 Ti Titanium 47.88	23 V Vanadium 50.942	24 Cr Chromium 51.996	25 Mn Manganese 54.938	26 Fe Iron 55.833	27 Co Cobalt 58.933	28 Ni Nickel 58.693	29 Cu Copper 63.546	30 Zn Zinc 65.39	31 Ga Gallium 69.732	32 Ge Germanium 72.61	33 As Arsenic 74.922	34 Se Selenium 78.96	35 Br Bromine 79.904	36 Kr Krypton 84.90
37 Rb Rubidium 84.468	38 Sr Strontium 87.62	39 Y Yttrium 88.906	40 Zr Zirconium 91.224	41 Nb Niobium 92.906	42 Mo Molybdenum 95.94	43 Tc Technetium 98.907	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.906	46 Pd Palladium 106.42	47 Ag Silver 107.868	48 Cd Cadmium 112.411	49 In Indium 114.818	50 Sn Tin 118.71	51 Sb Antimony 121.760	52 Te Tellurium 127.6	53 I Iodine 126.904	54 Xe Xenon 131.29
55 Cs Cesium 132.905	56 Ba Barium 137.327	57-71	72 Hf Hafnium 178.49	73 Ta Tantalum 180.948	74 W Tungsten 183.85	75 Re Rhenium 186.207	76 Os Osmium 190.23	77 Ir Iridium 192.22	78 Pt Platinum 195.08	79 Au Gold 196.967	80 Hg Mercury 200.59	81 Tl Thallium 204.383	82 Pb Lead 207.2	83 Bi Bismuth 208.980	84 Po Polonium [208.982]	85 At Astatine 209.987	86 Rn Radon 222.018
87 Fr Francium 223.020	88 Ra Radium 226.025	89-103	104 Rf Rutherfordium [261]	105 Db Dubnium [262]	106 Sg Seaborgium [266]	107 Bh Bohrium [264]	108 Hs Hassium [269]	109 Mt Meitnerium [268]	110 Ds Darmstadtium [265]	111 Rg Roentgenium [272]	112 Cn Copernicium [277]	113 Uut Ununtrium unknown	114 Fl Flerovium [289]	115 Uup Ununpentium unknown	116 Lv Livermorium [293]	117 Uus Ununseptium unknown	118 Uuo Ununoctium unknown

Lanthanide Series	57 La Lanthanum 138.906	58 Ce Cerium 140.115	59 Pr Praseodymium 140.908	60 Nd Neodymium 144.24	61 Pm Promethium 144.913	62 Sm Samarium 150.36	63 Eu Europium 151.966	64 Gd Gadolinium 157.25	65 Tb Terbium 158.925	66 Dy Dysprosium 162.50	67 Ho Holmium 164.930	68 Er Erbium 167.26	69 Tm Thulium 168.934	70 Yb Ytterbium 173.04	71 Lu Lutetium 174.967
Actinide Series	89 Ac Actinium 227.028	90 Th Thorium 232.038	91 Pa Protactinium 231.038	92 U Uranium 238.029	93 Np Neptunium 237.048	94 Pu Plutonium 244.084	95 Am Americium 243.061	96 Cm Curium 247.070	97 Bk Berkelium 247.070	98 Cf Californium 251.080	99 Es Einsteinium [254]	100 Fm Fermium 257.095	101 Md Mendelevium 258.1	102 No Nobelium 259.101	103 Lr Lawrencium [262]

Definition of Metals

The image shows a periodic table where the majority of elements are shaded in brown and labeled as "METALS". The shaded area covers groups 1 through 10, 12, and 13, as well as the Lanthanide and Actinide series. The unshaded elements are Hydrogen (H) and Helium (He).

1 IA 1A	2 IIA 2A	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 IIIA 3A	14 IVA 4A	15 VA 5A	16 VIA 6A	17 VIIA 7A	18 VIIIA 8A
1 H Hydrogen 1.008																	2 He Helium 4.003

Lanthanide Series

Actinide Series

Sources of Chemical Enrichments

Core-collapse supernovae



Sources of Chemical Enrichments

Core-collapse supernovae



Type Ia supernovae



Sources of Chemical Enrichments

Core-collapse supernovae



Type Ia supernovae



Stellar winds from low-mass stars



Sources of Chemical Enrichments

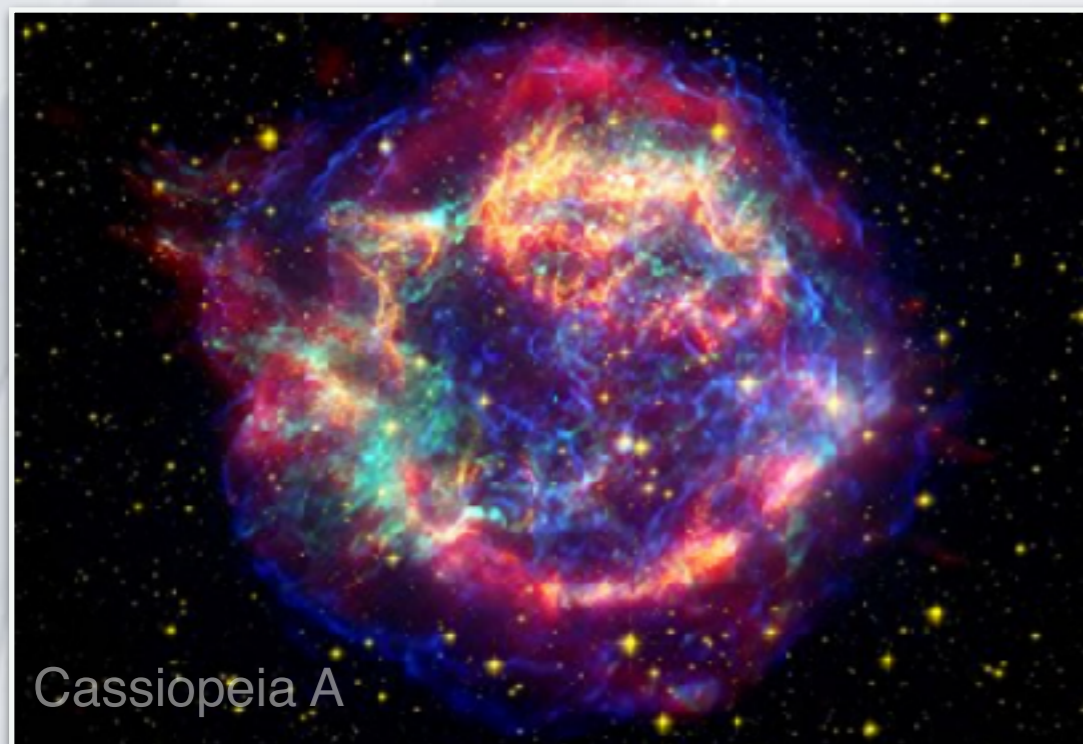
Core-collapse supernovae



Neutron star merger



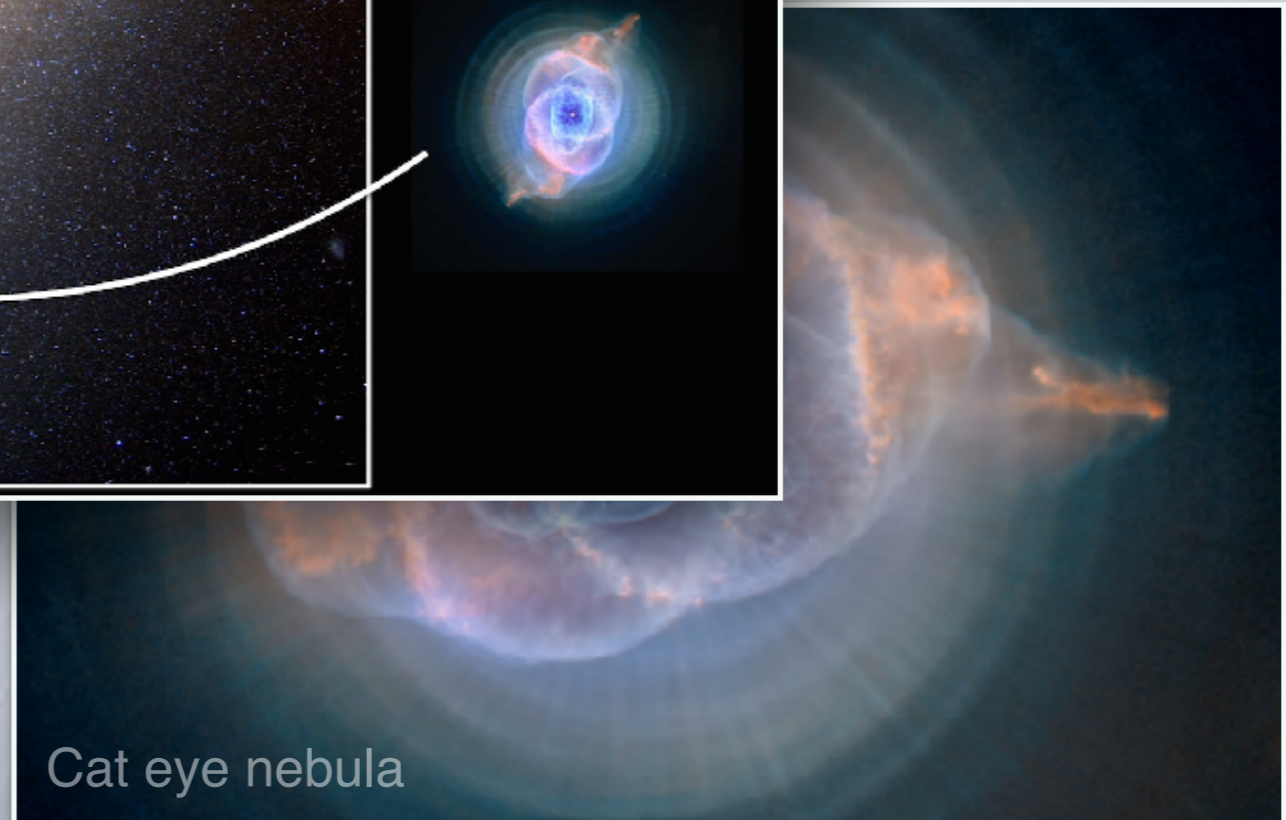
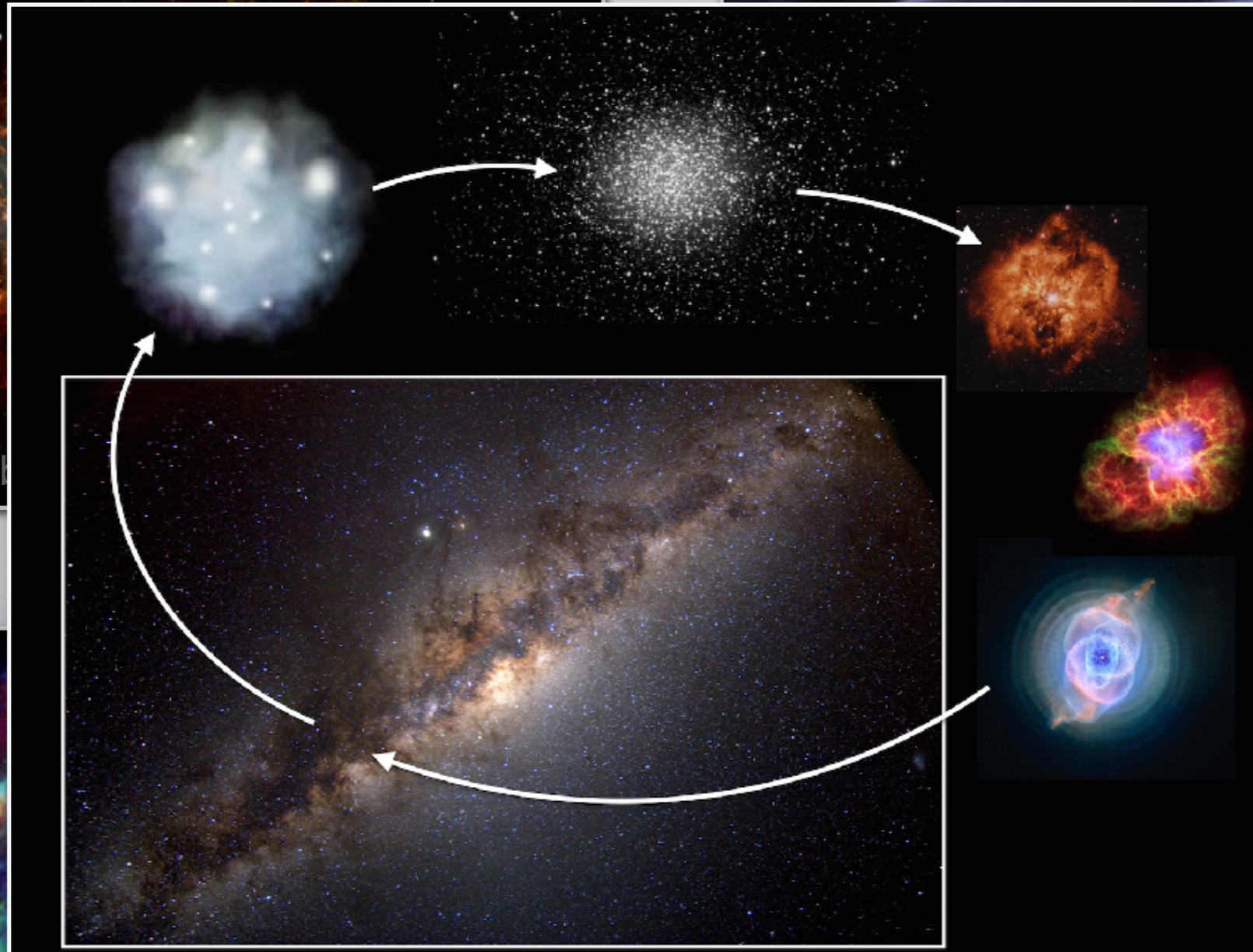
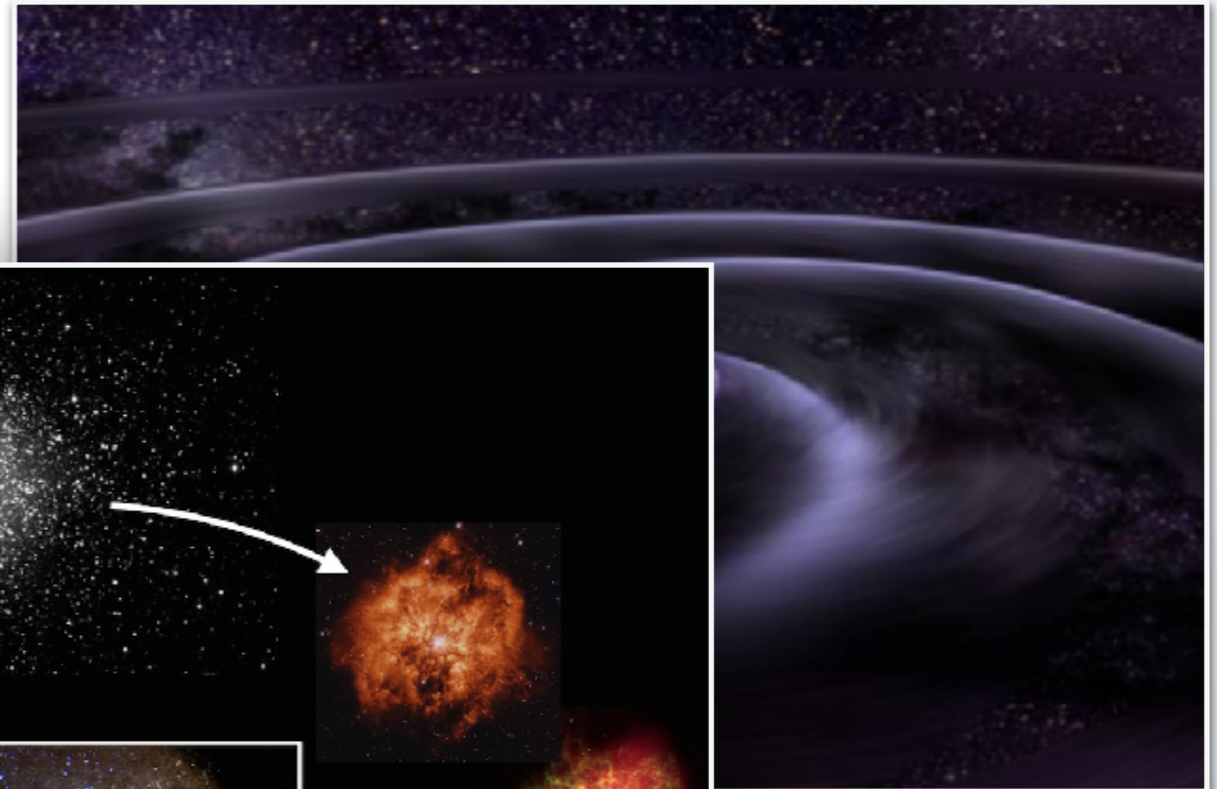
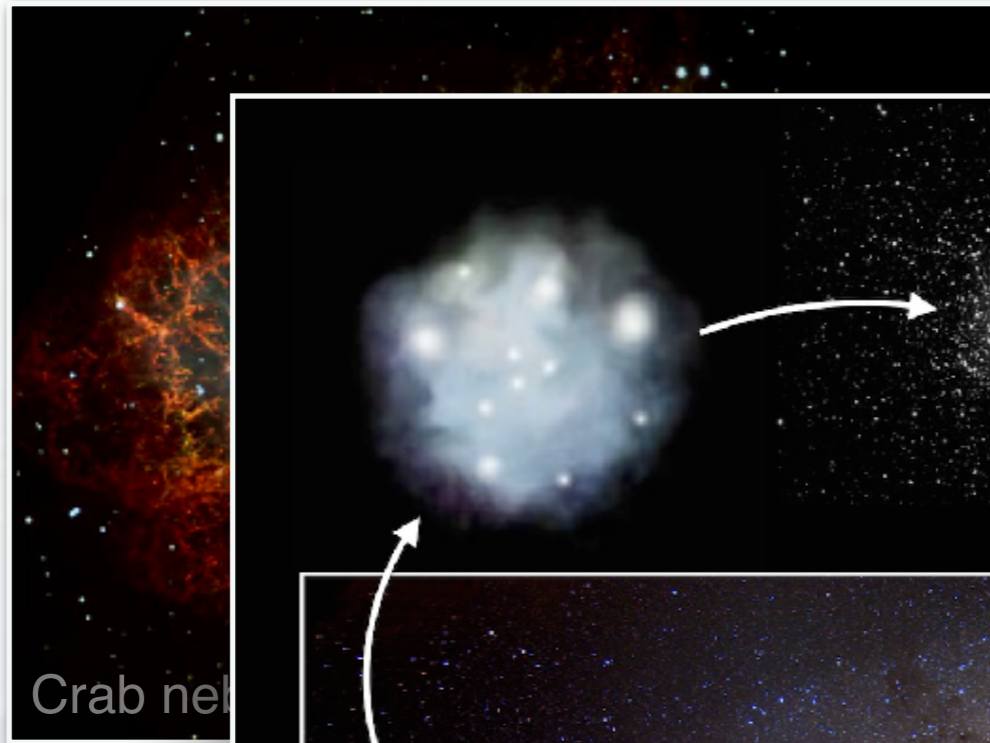
Type Ia supernovae



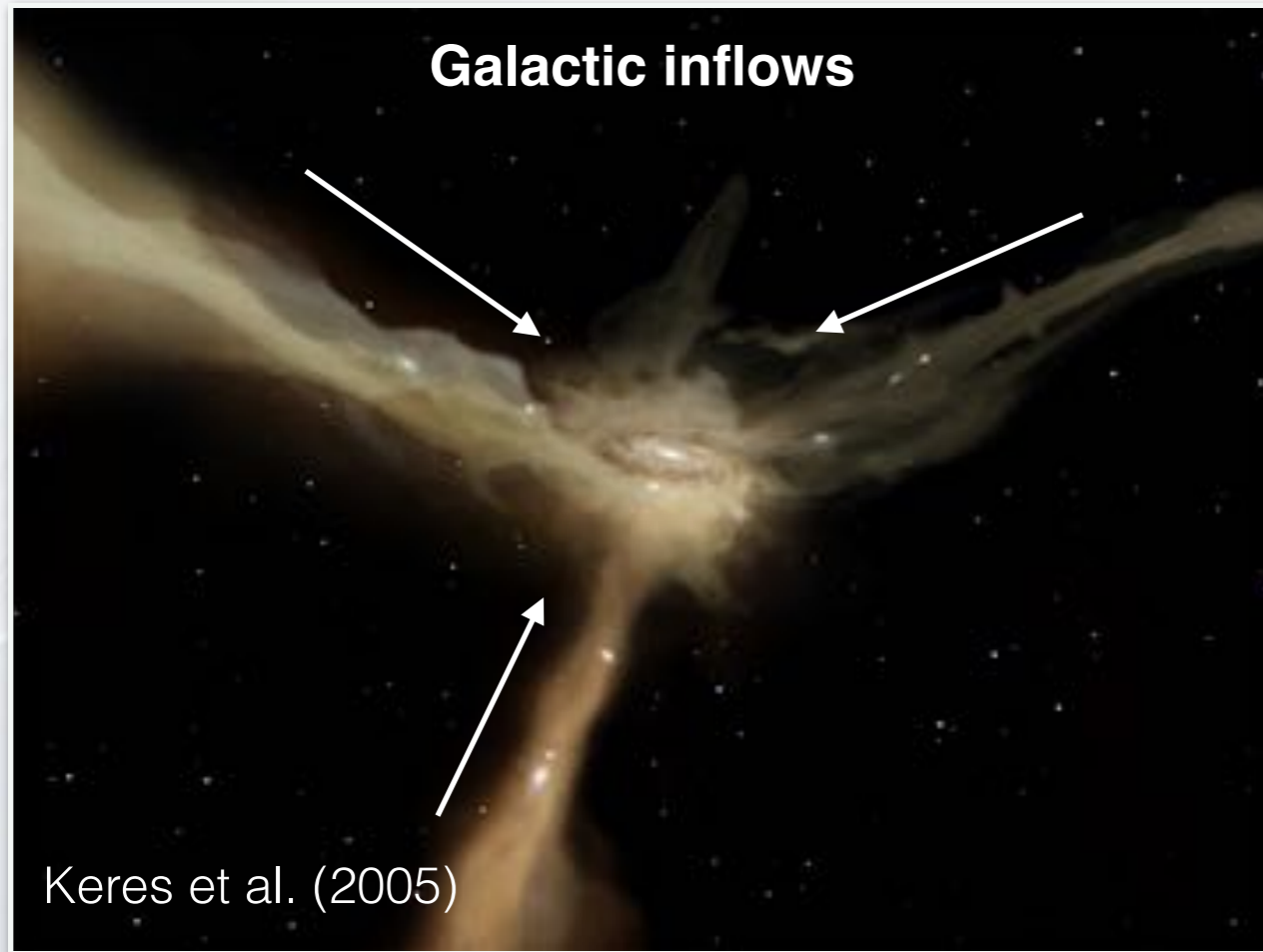
Stellar winds from low-mass stars



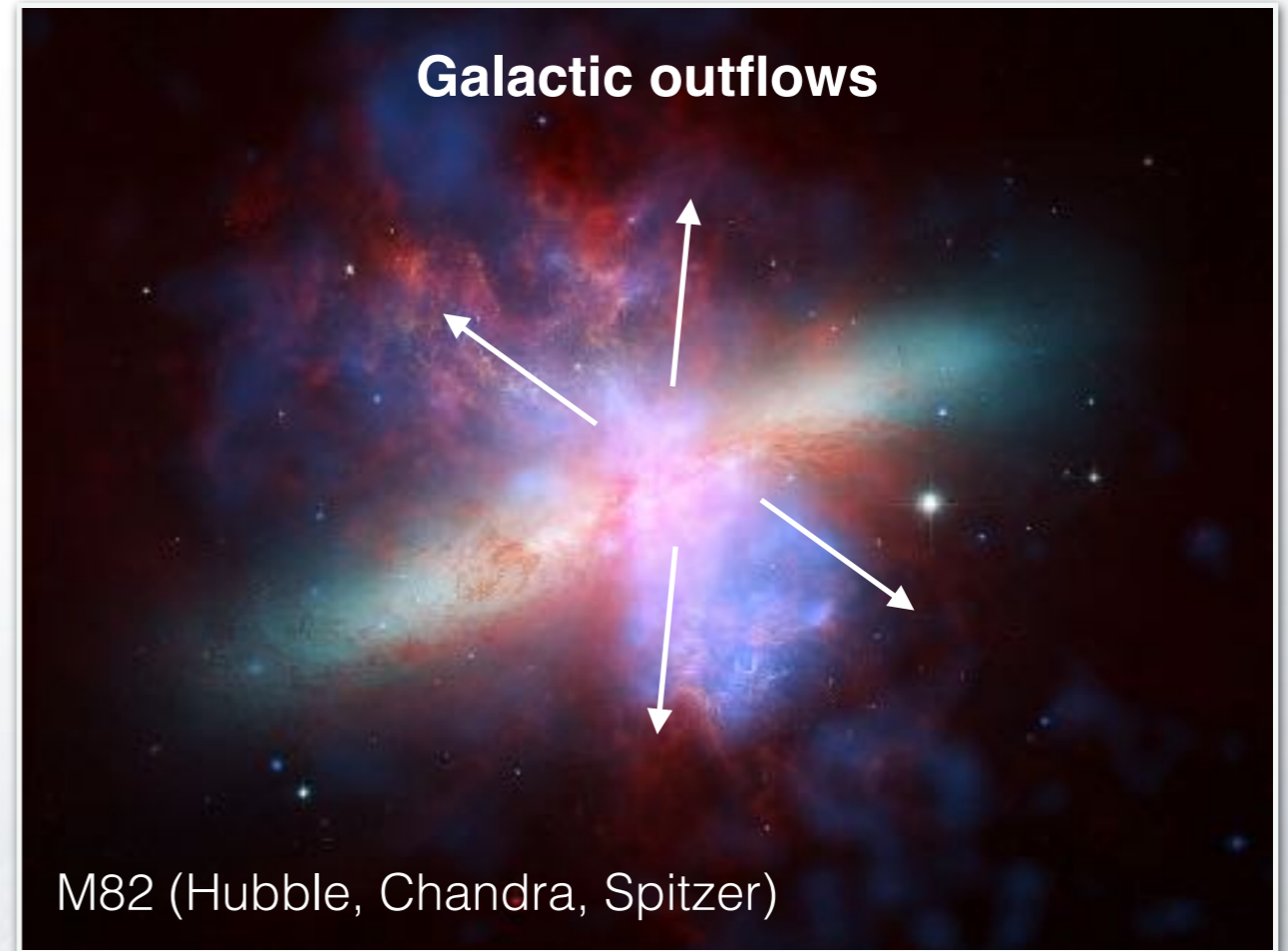
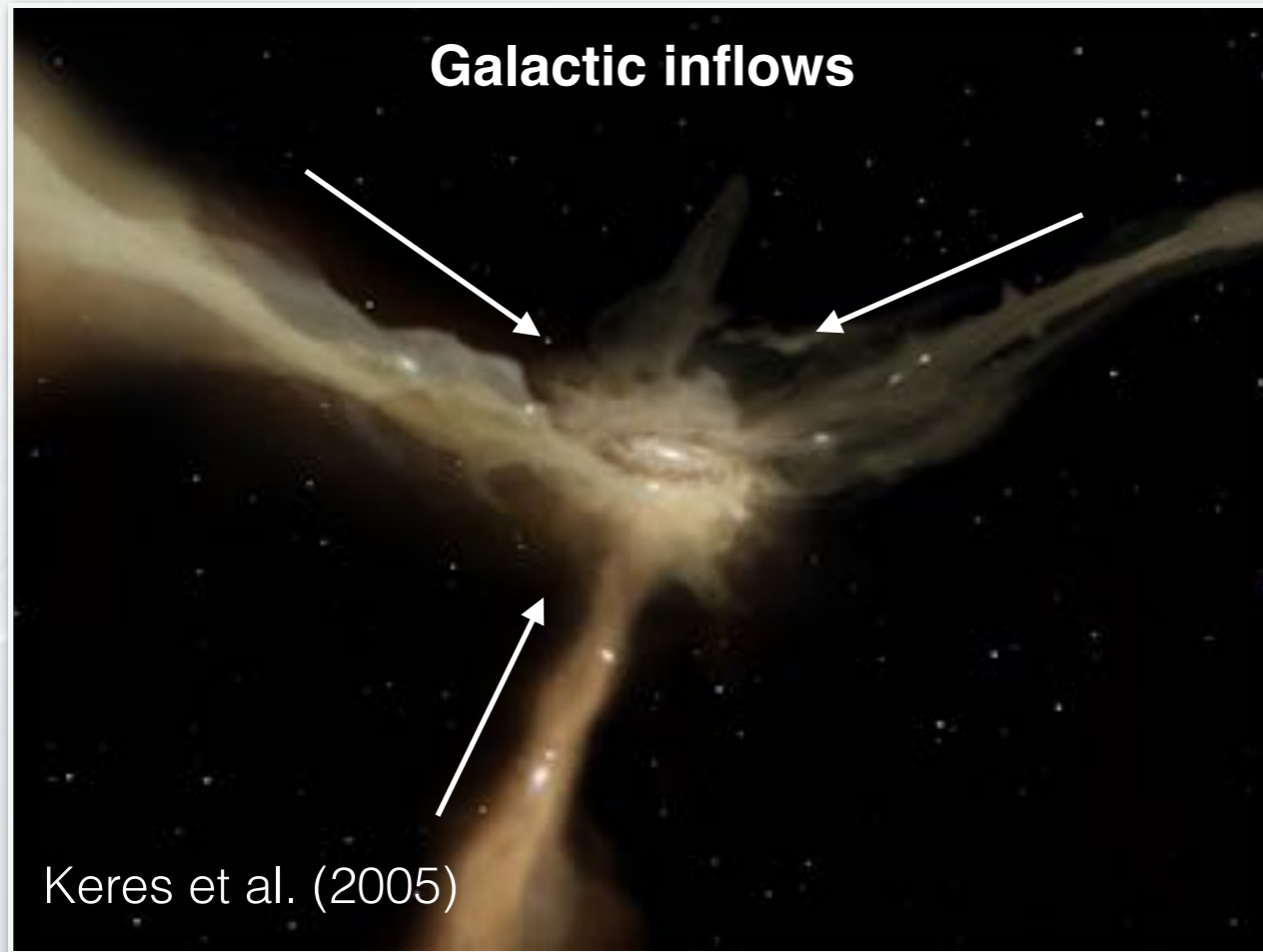
Sources of Chemical Enrichments



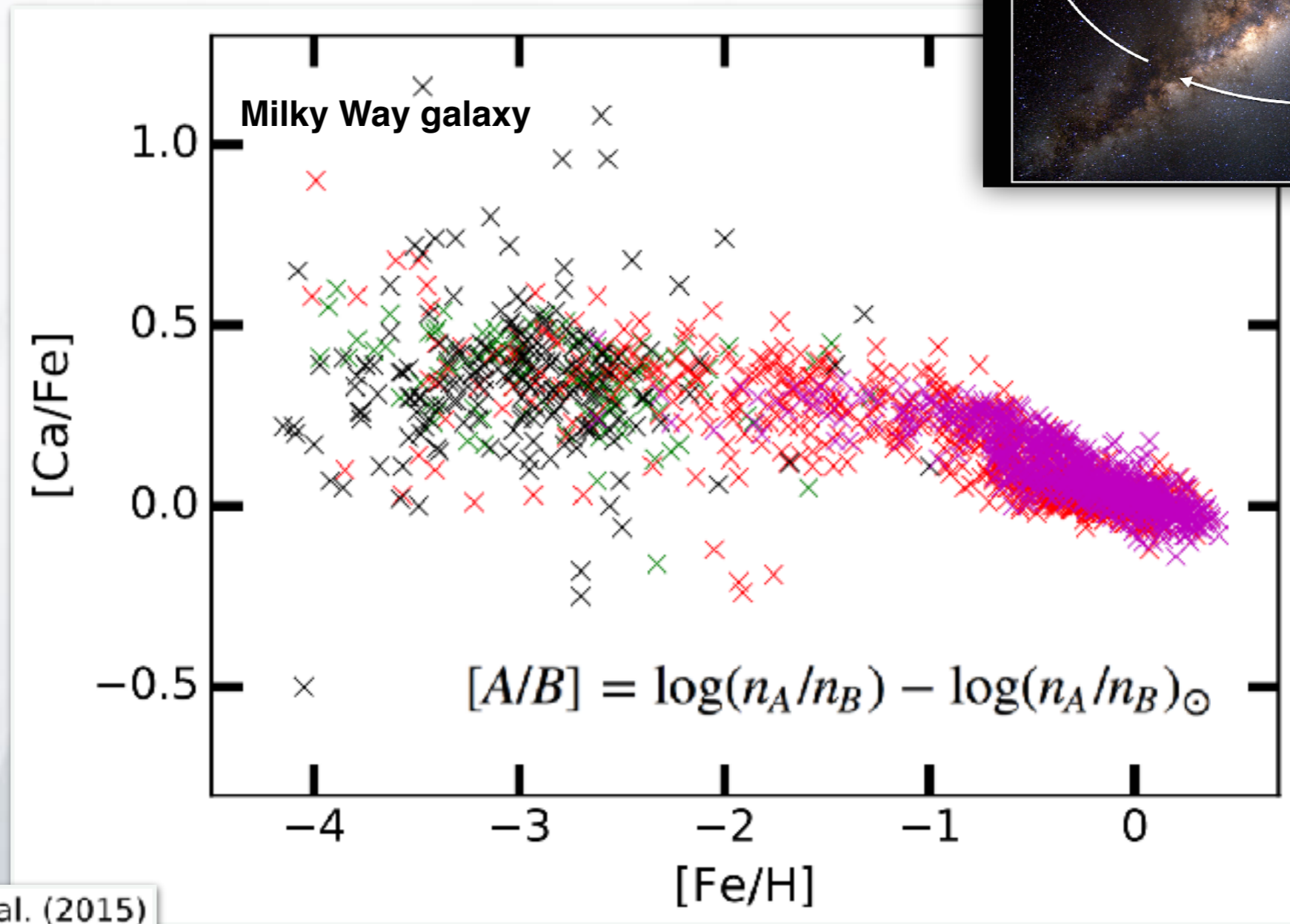
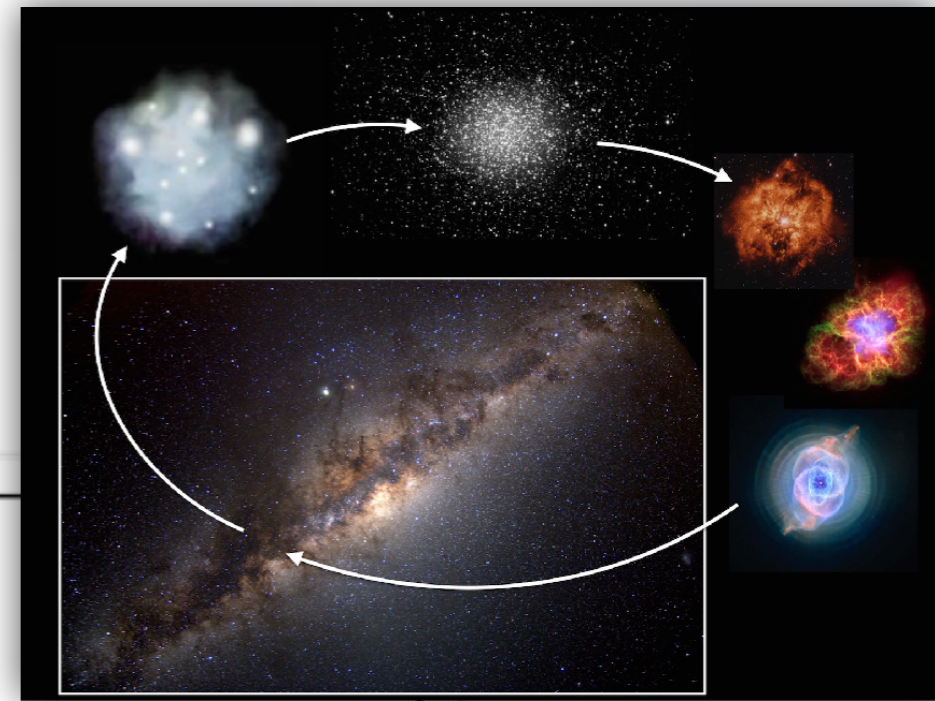
Galaxy Evolution and Gas Circulation



Galaxy Evolution and Gas Circulation



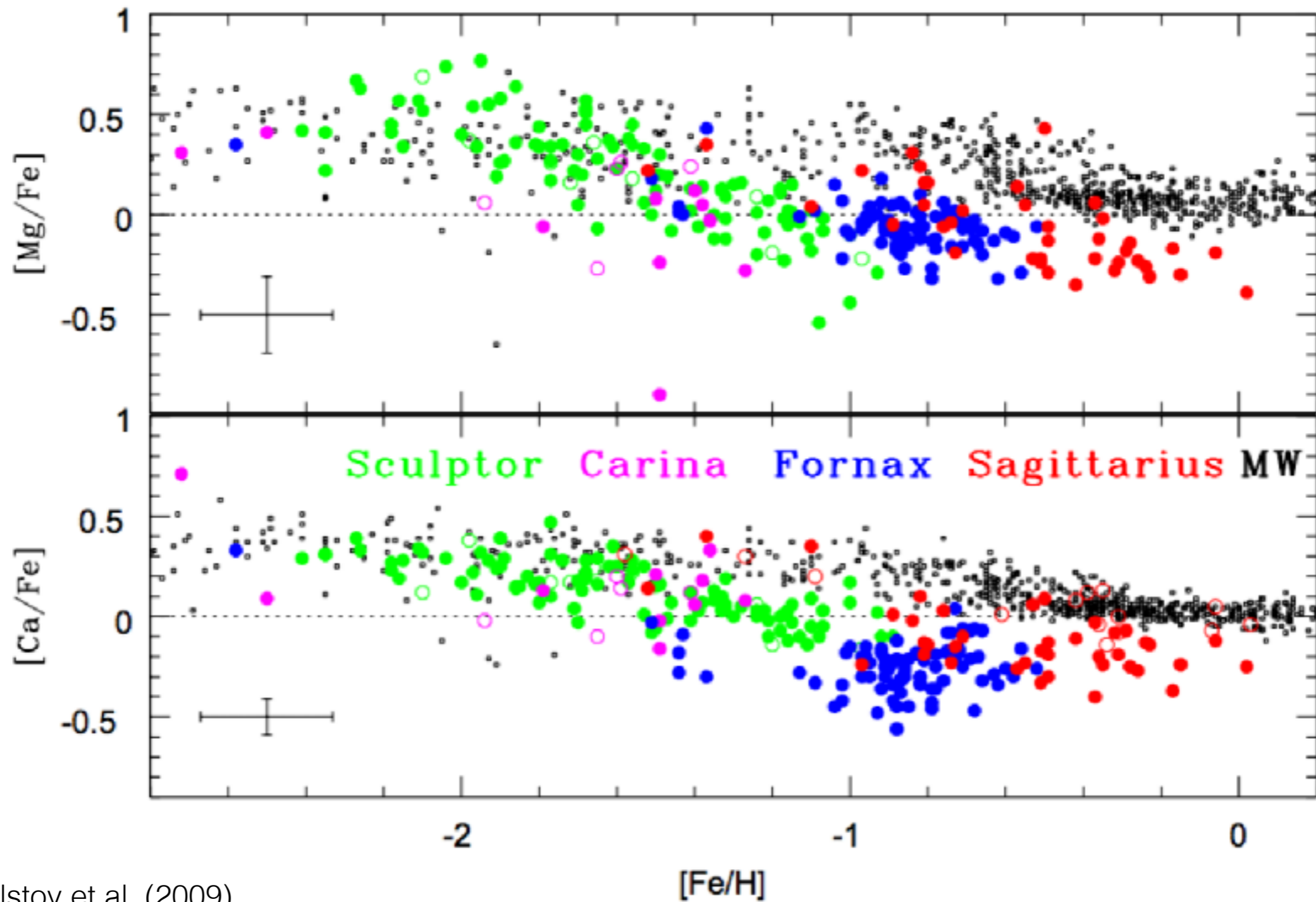
Galactic Chemical Evolution



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

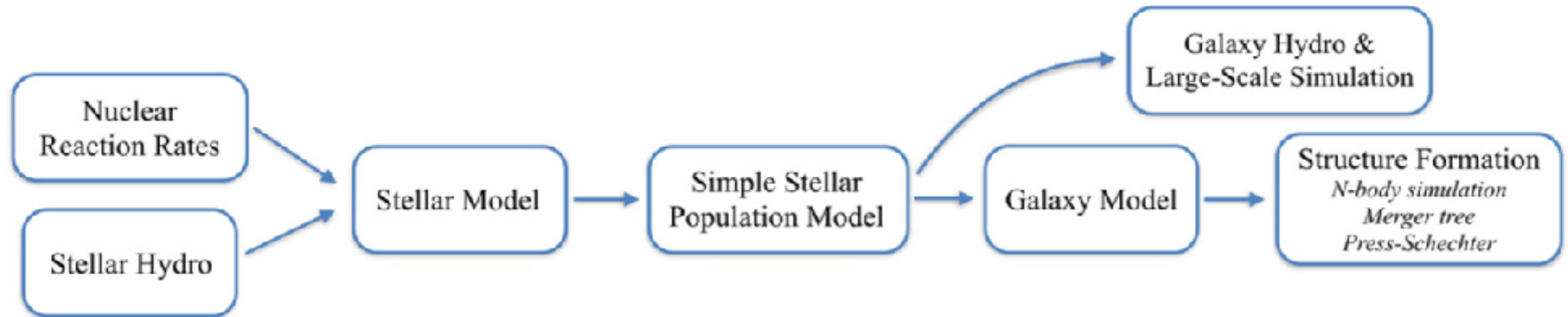
@Using STELLAB

Galactic Chemical Evolution



Tolstoy et al. (2009)

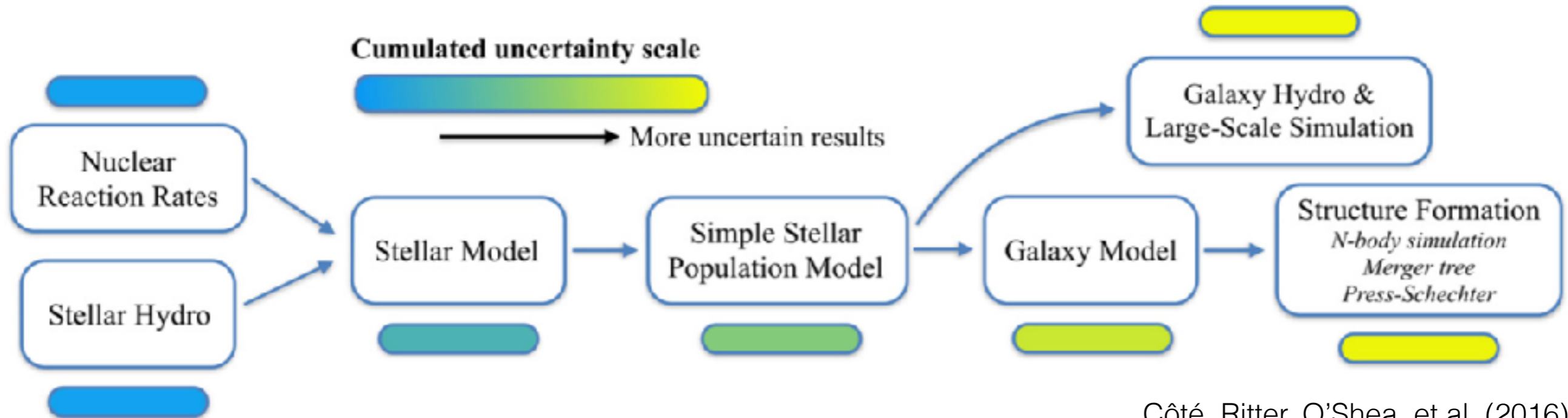
Connecting the Smallest and the Largest Scales



Côté, Ritter, O'Shea, et al. (2016)

see also Côté, Ritter, Herwig, et al. (2017)

Connecting the Smallest and the Largest Scales

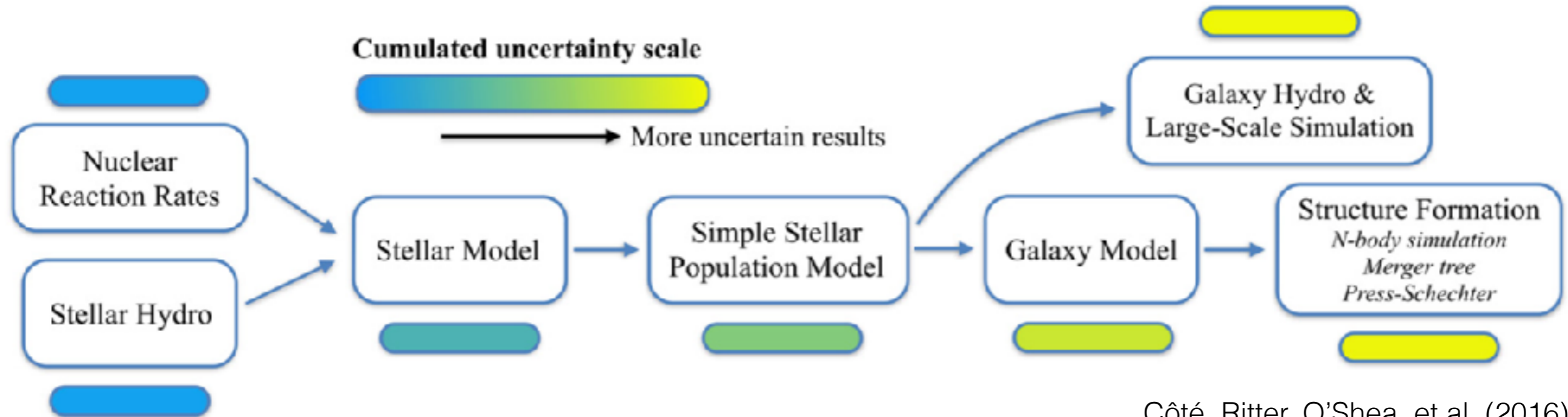


Côté, Ritter, O'Shea, et al. (2016)

see also Côté, Ritter, Herwig, et al. (2017)

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

Connecting the Smallest and the Largest Scales

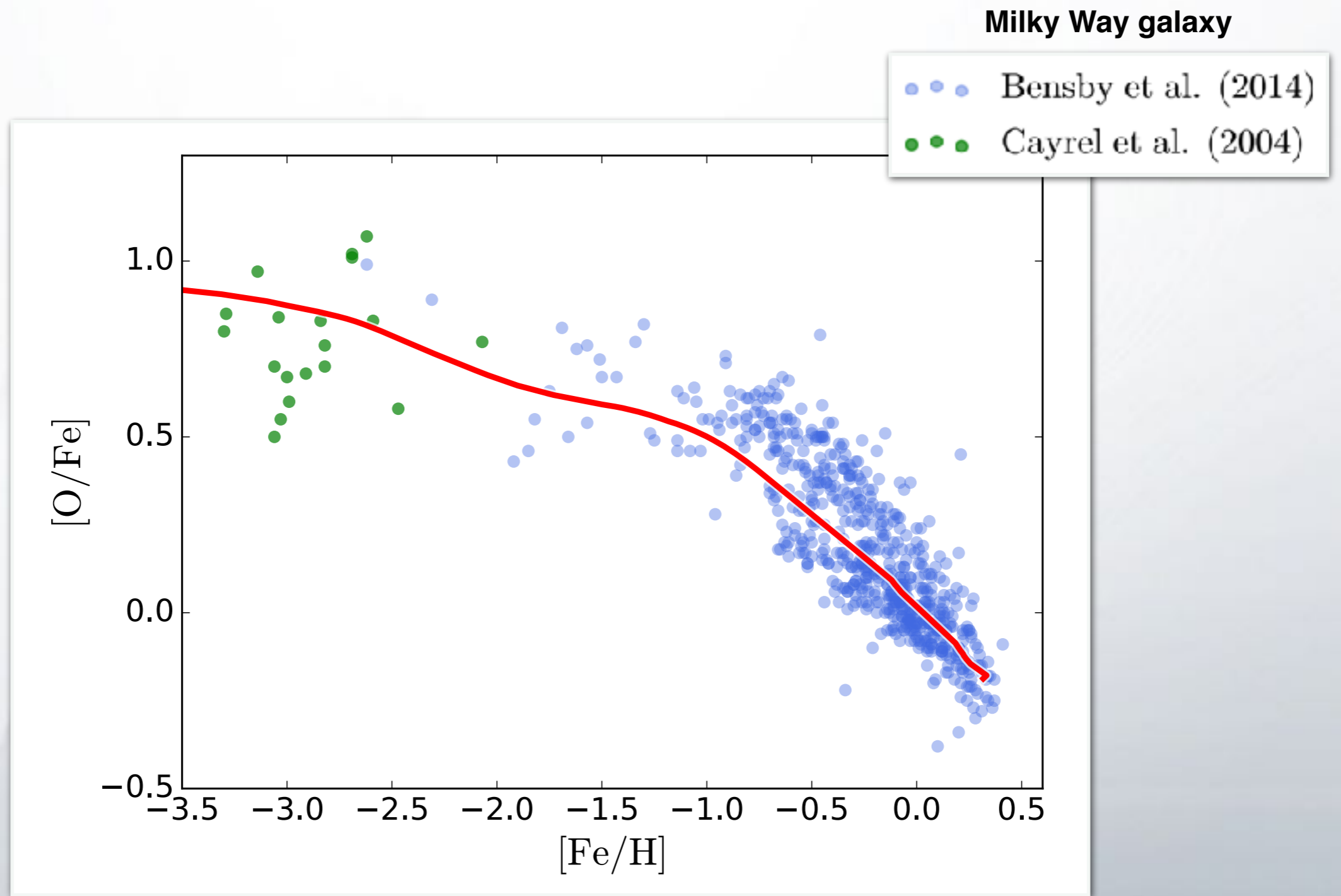


Côté, Ritter, O'Shea, et al. (2016)

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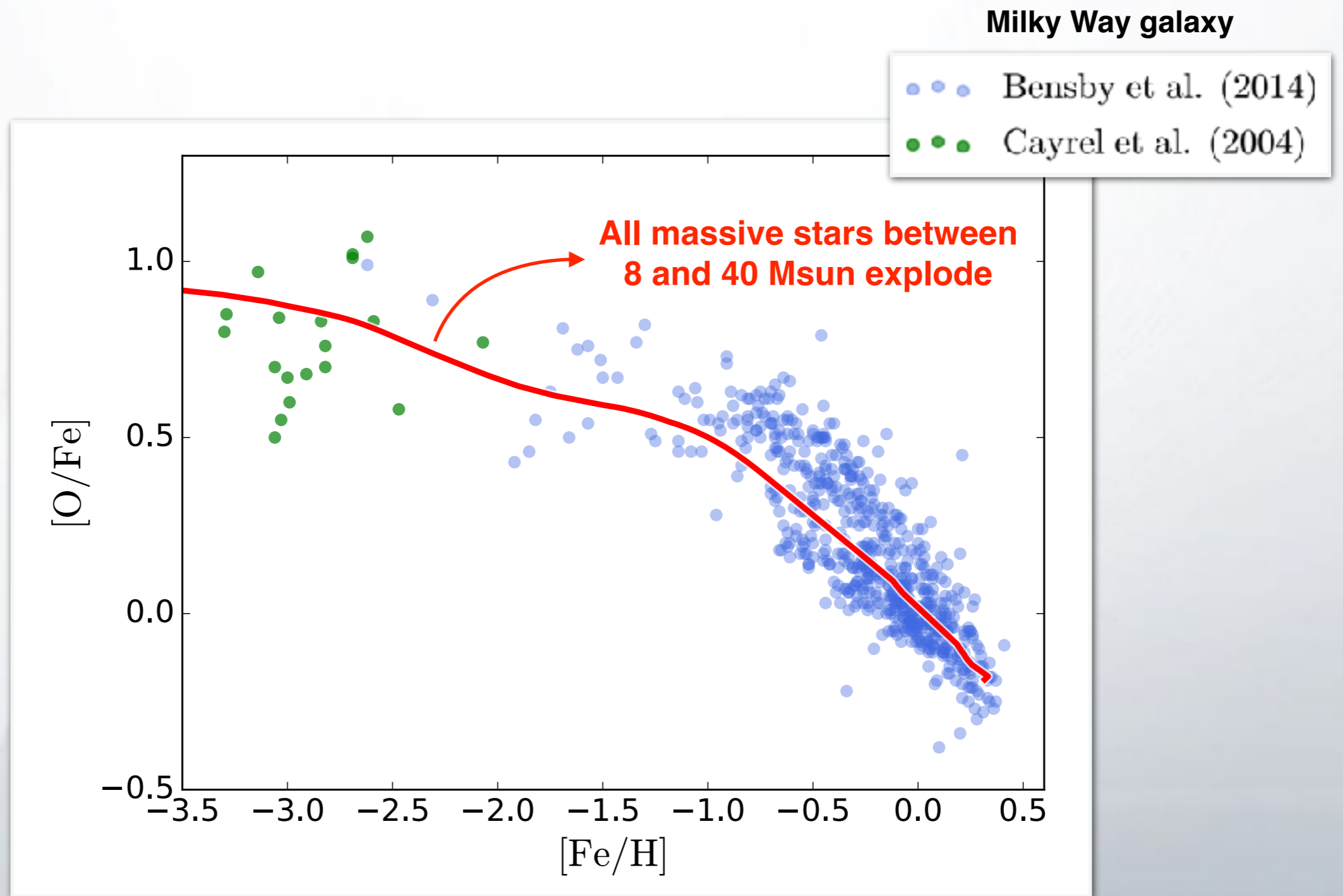
What about neutron stars and black holes?

Production of Oxygen in Massive Stars



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

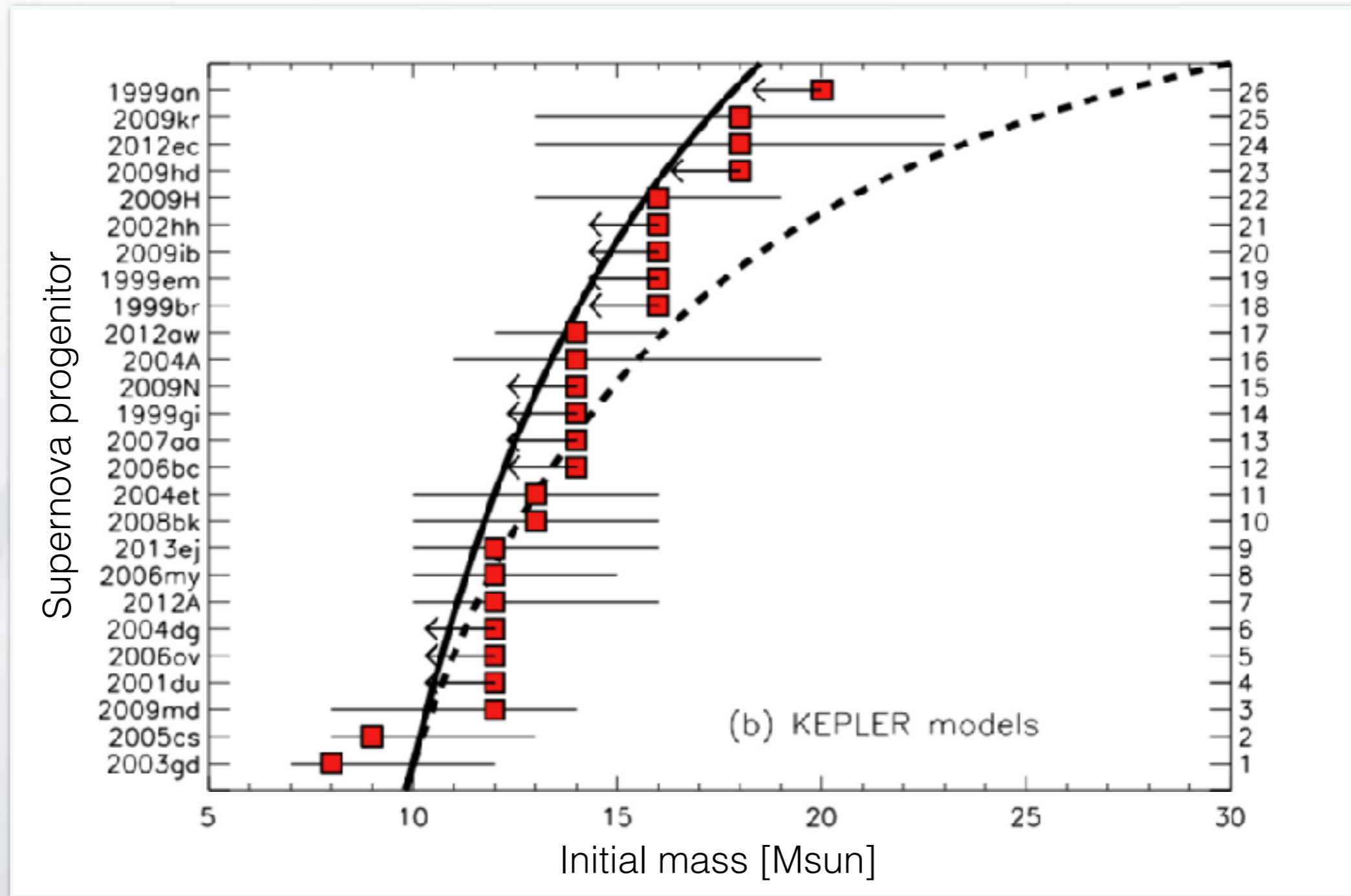
Production of Oxygen in Massive Stars



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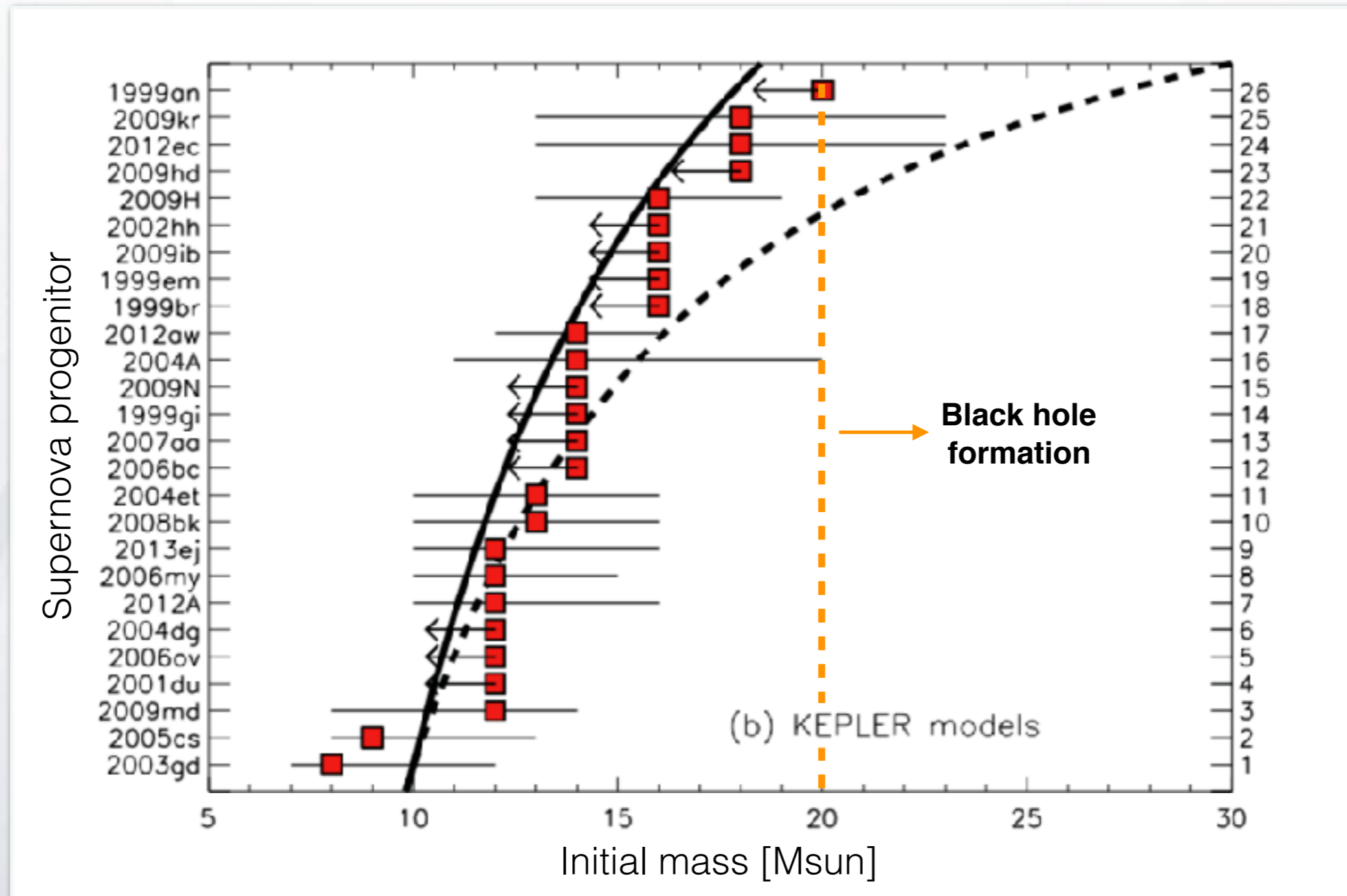
Oxygen, Massive Stars, and Black Holes

Smartt (2015)

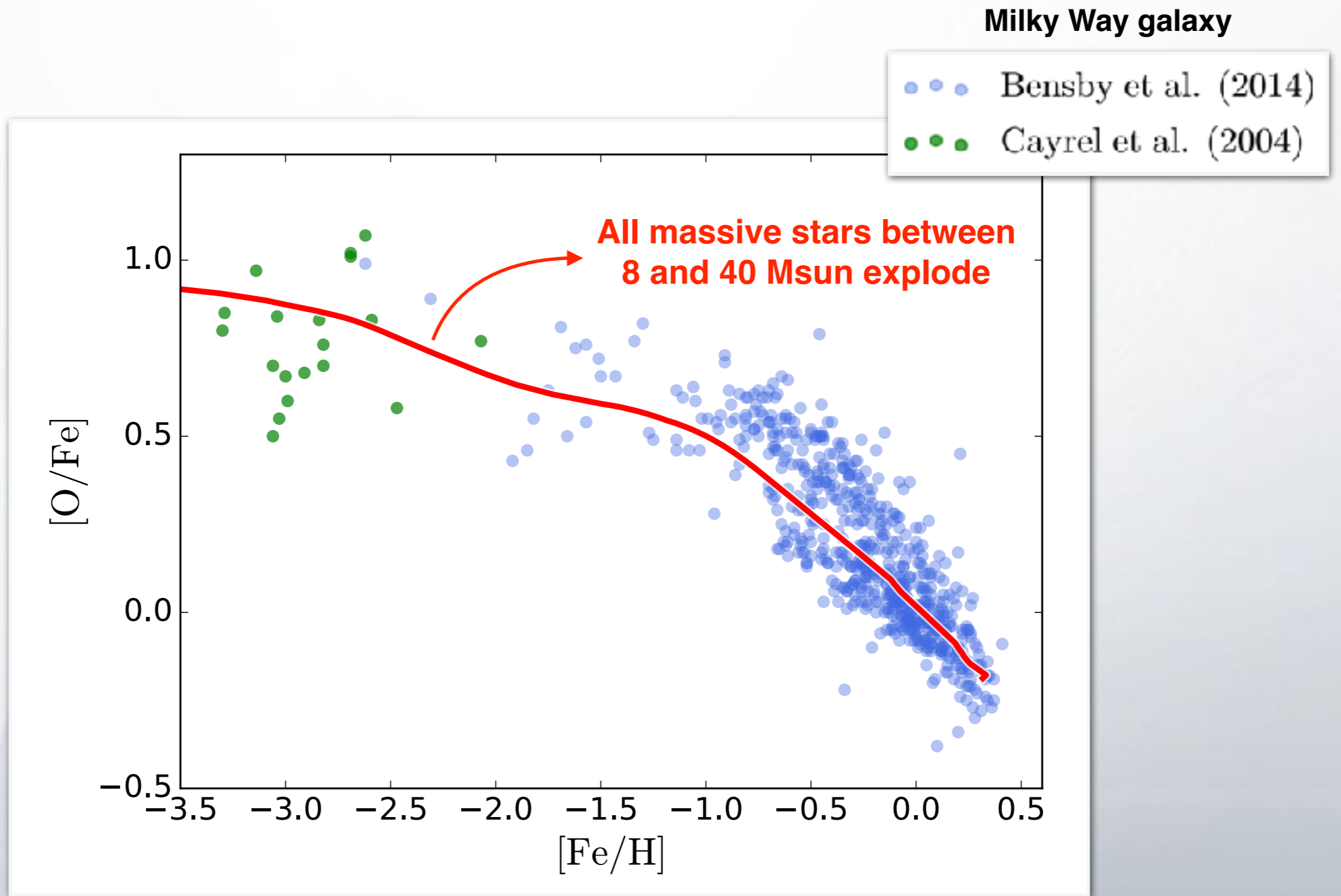


Oxygen, Massive Stars, and Black Holes

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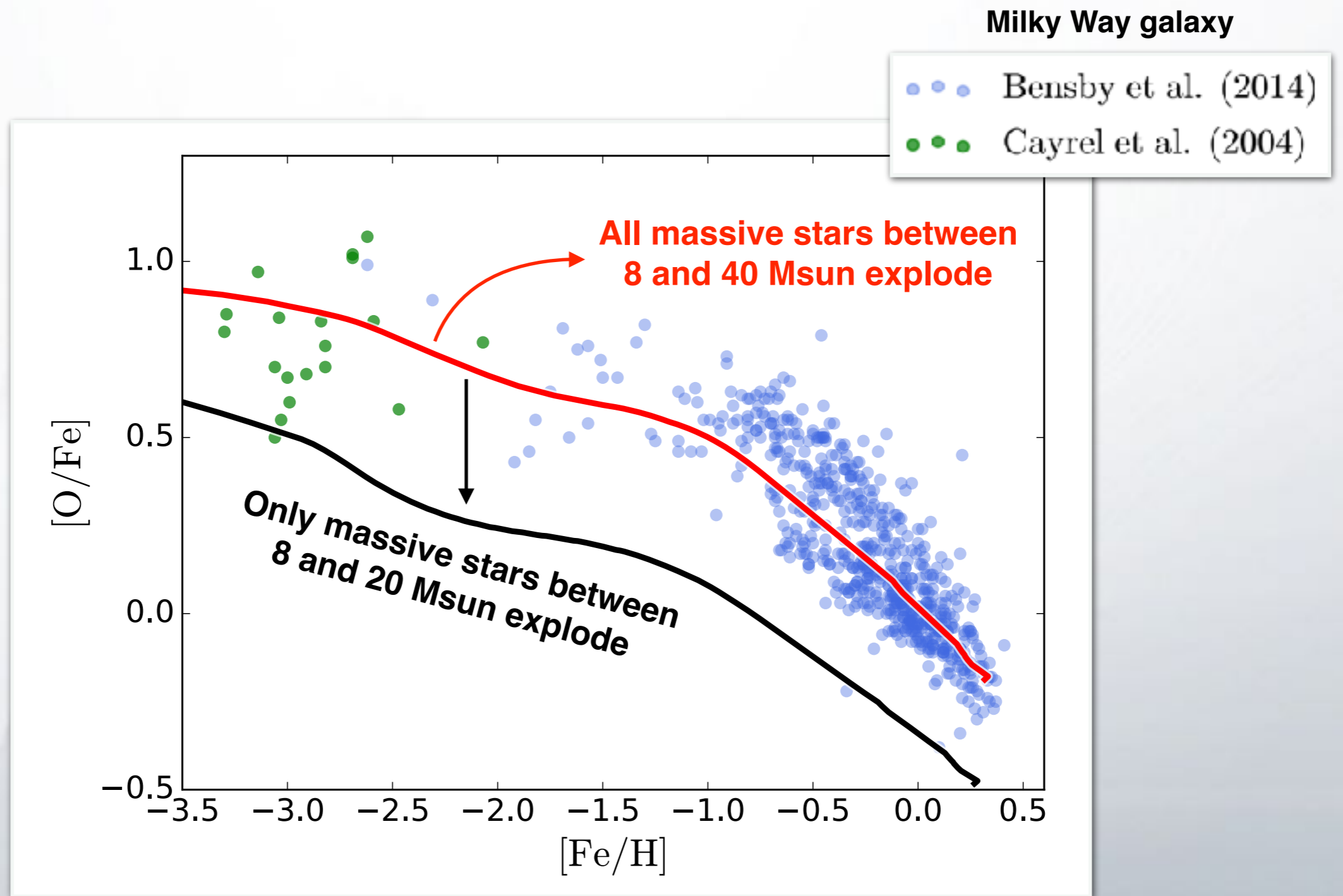


Oxygen, Massive Stars, and Black Holes



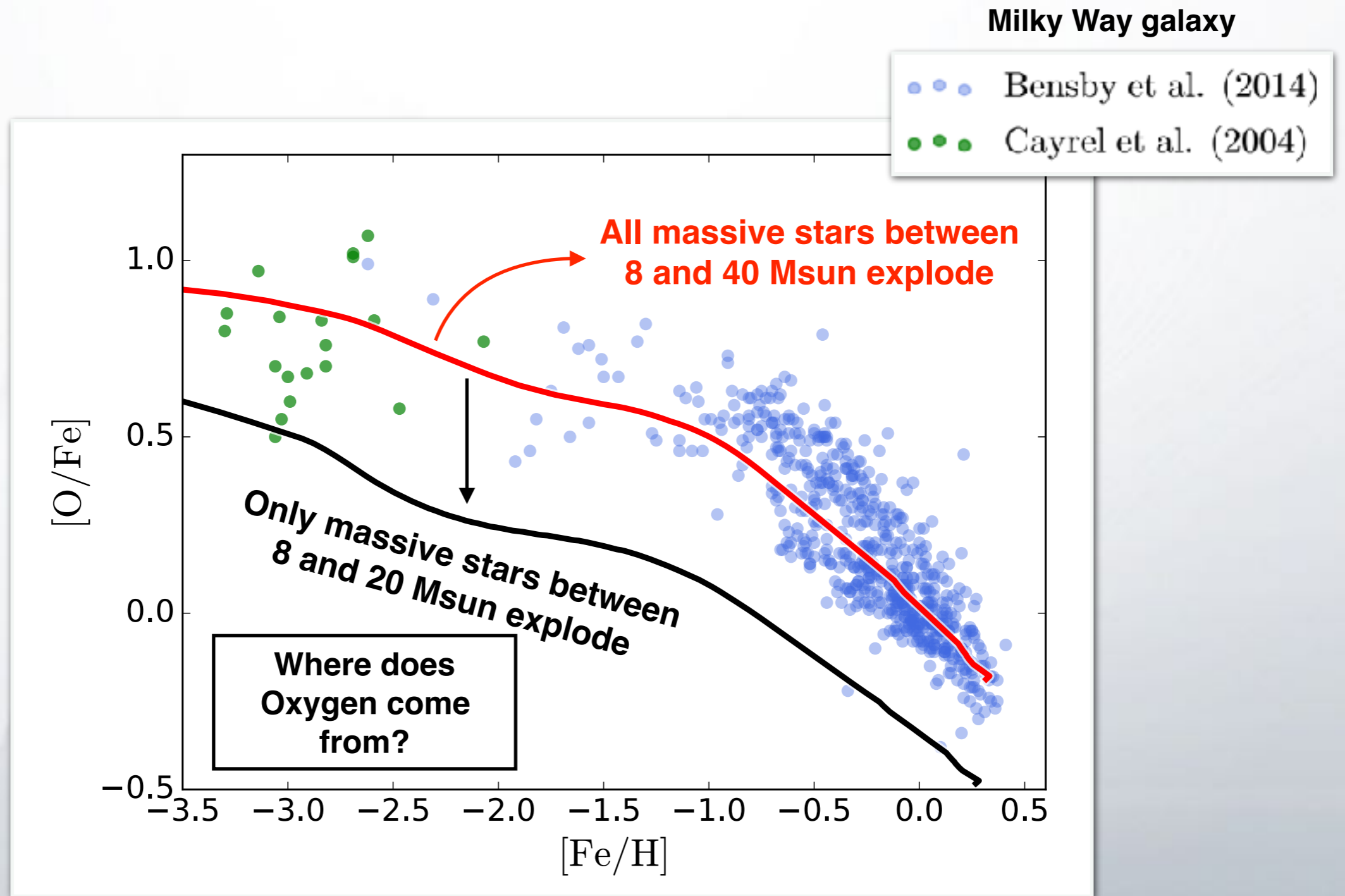
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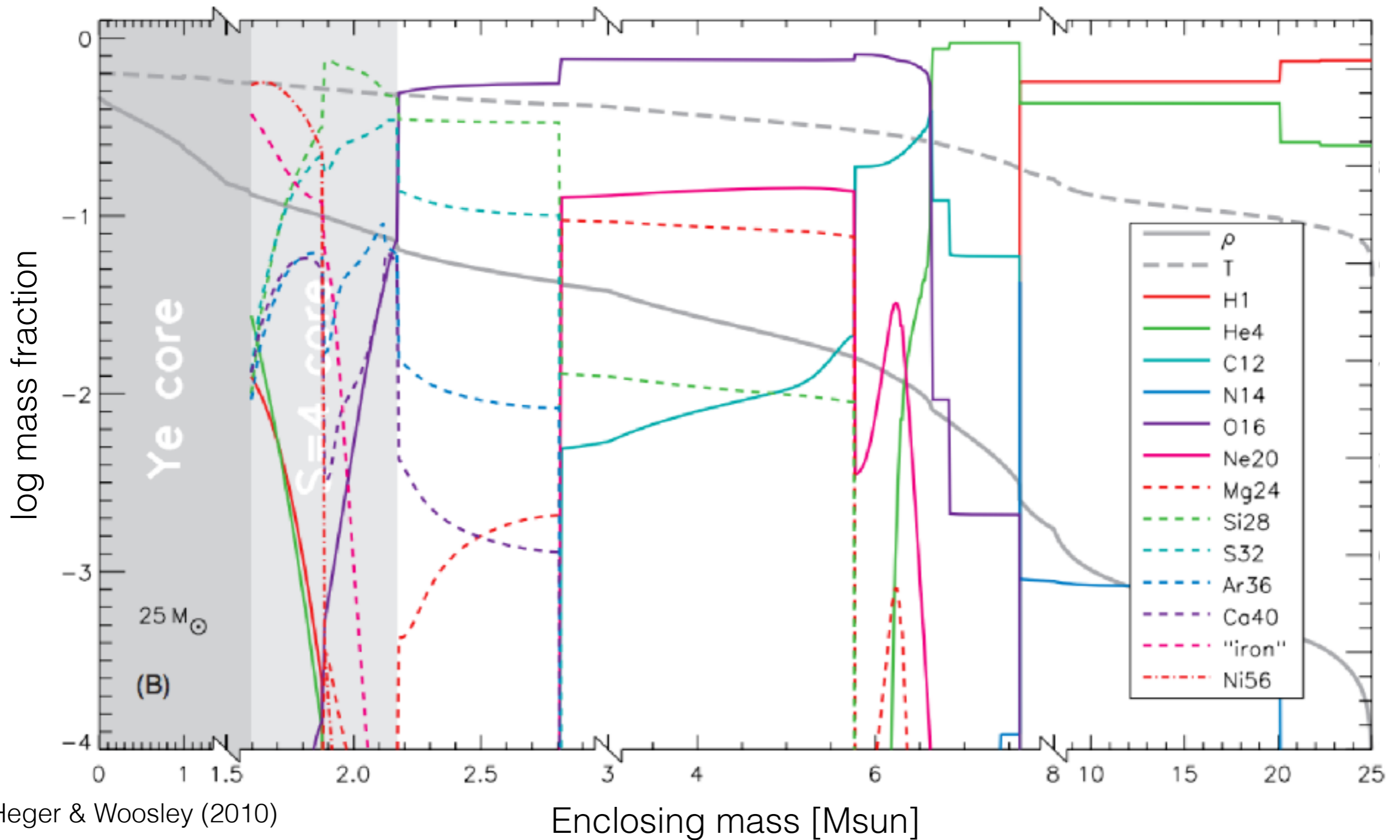
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Oxygen, Massive Stars, and Black Holes



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Massive Star and Supernova Models

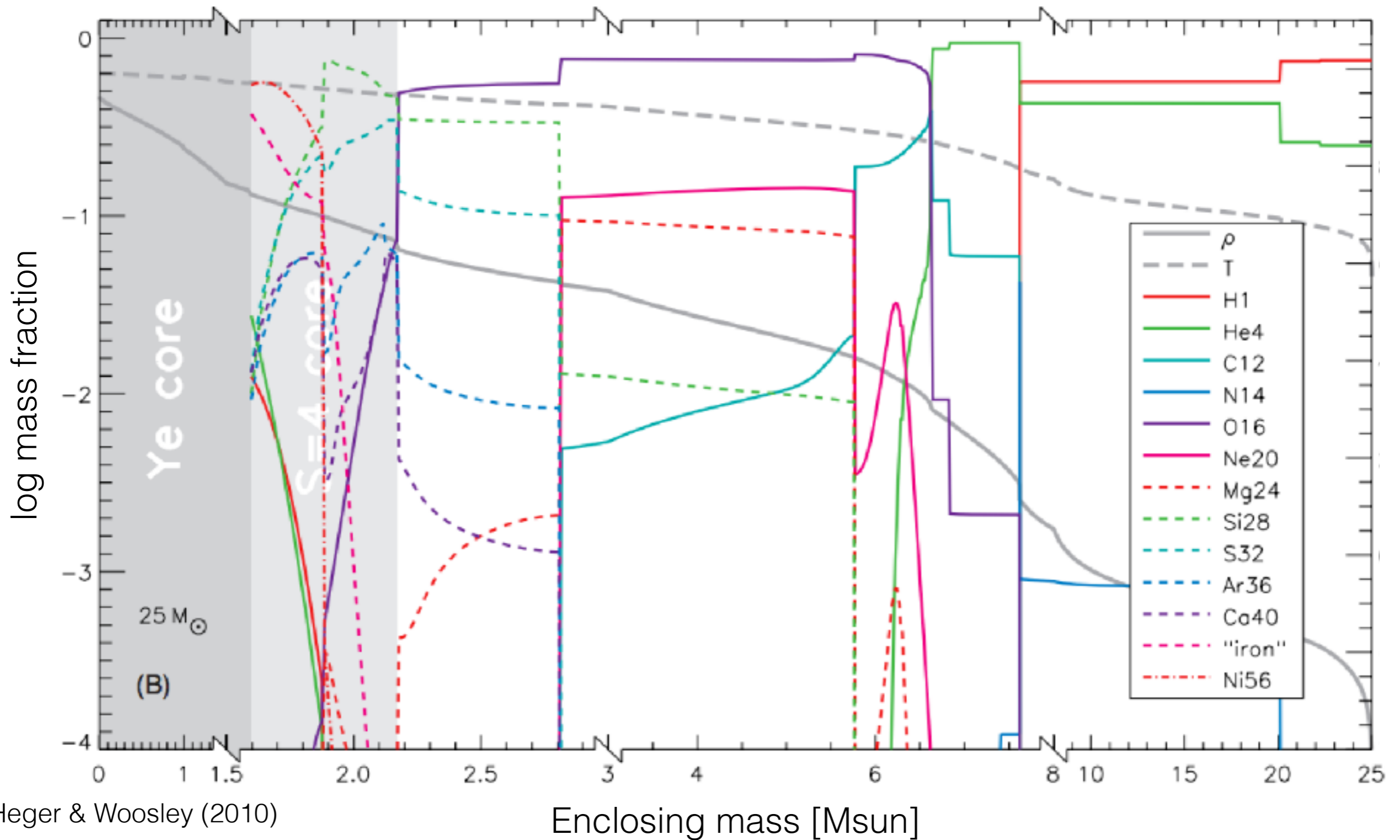


Heger & Woosley (2010)

see also Heger, Fryer, Woosley, et al. (2003)

Massive Star and Supernova Models

Fe **Si** **O** **He** **H**

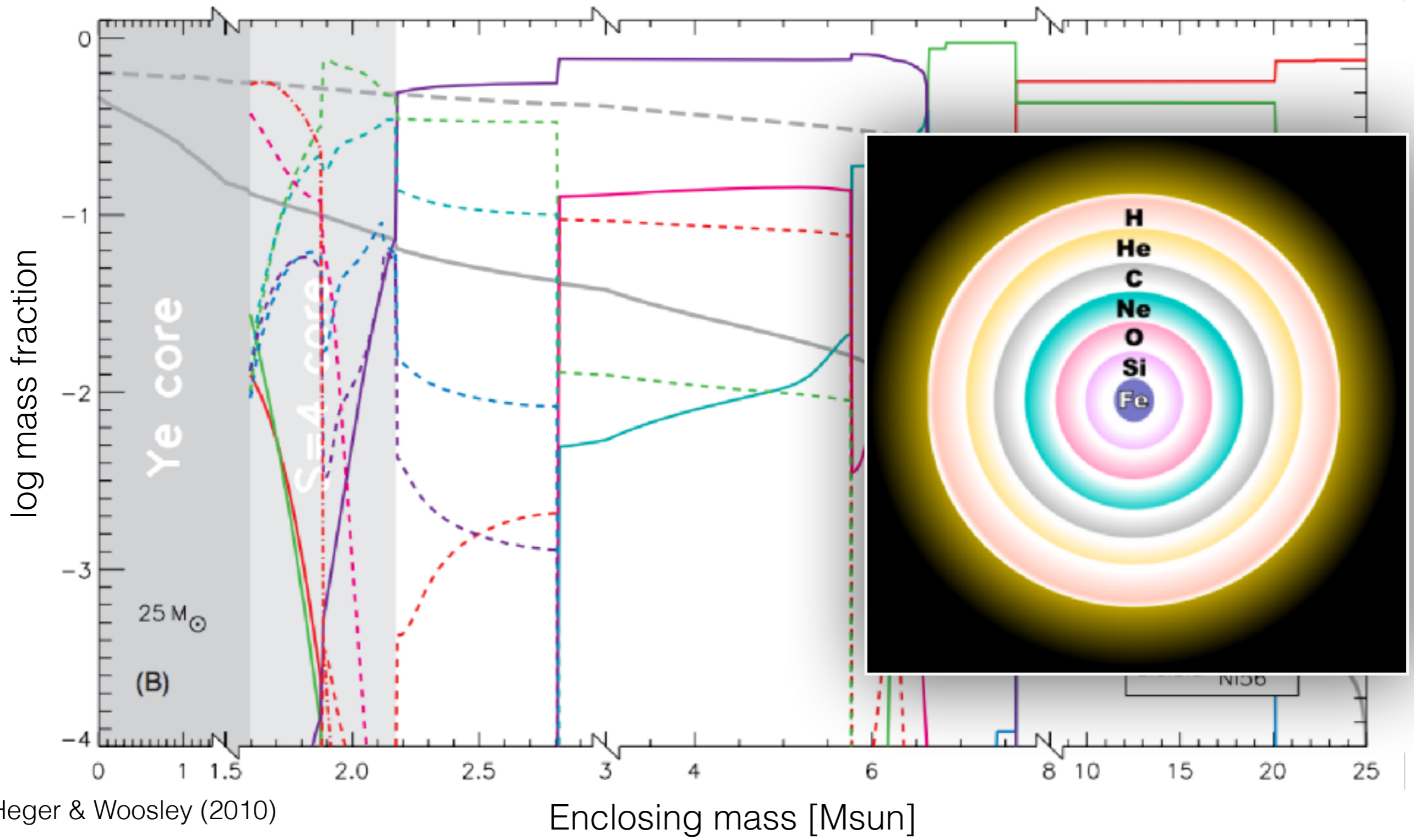


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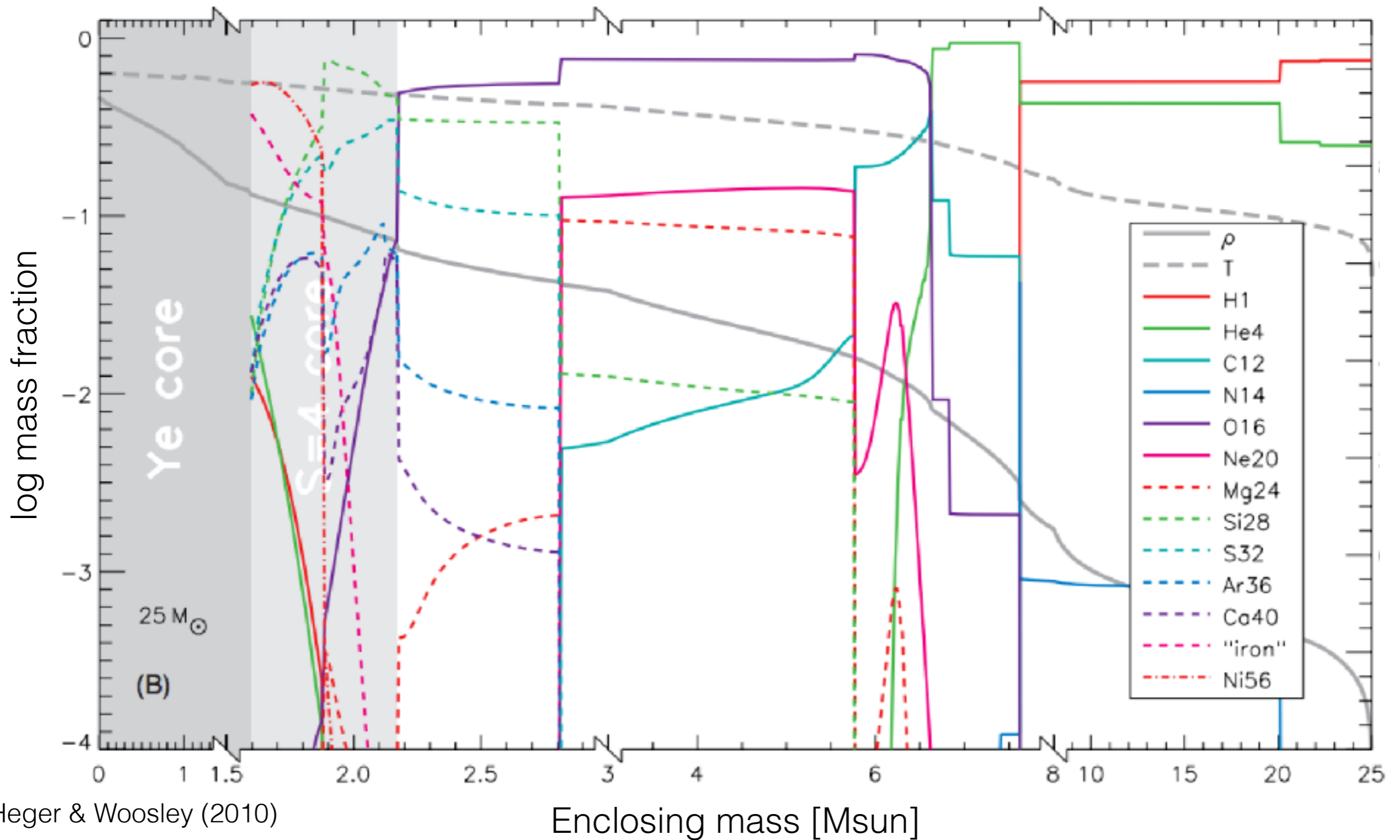


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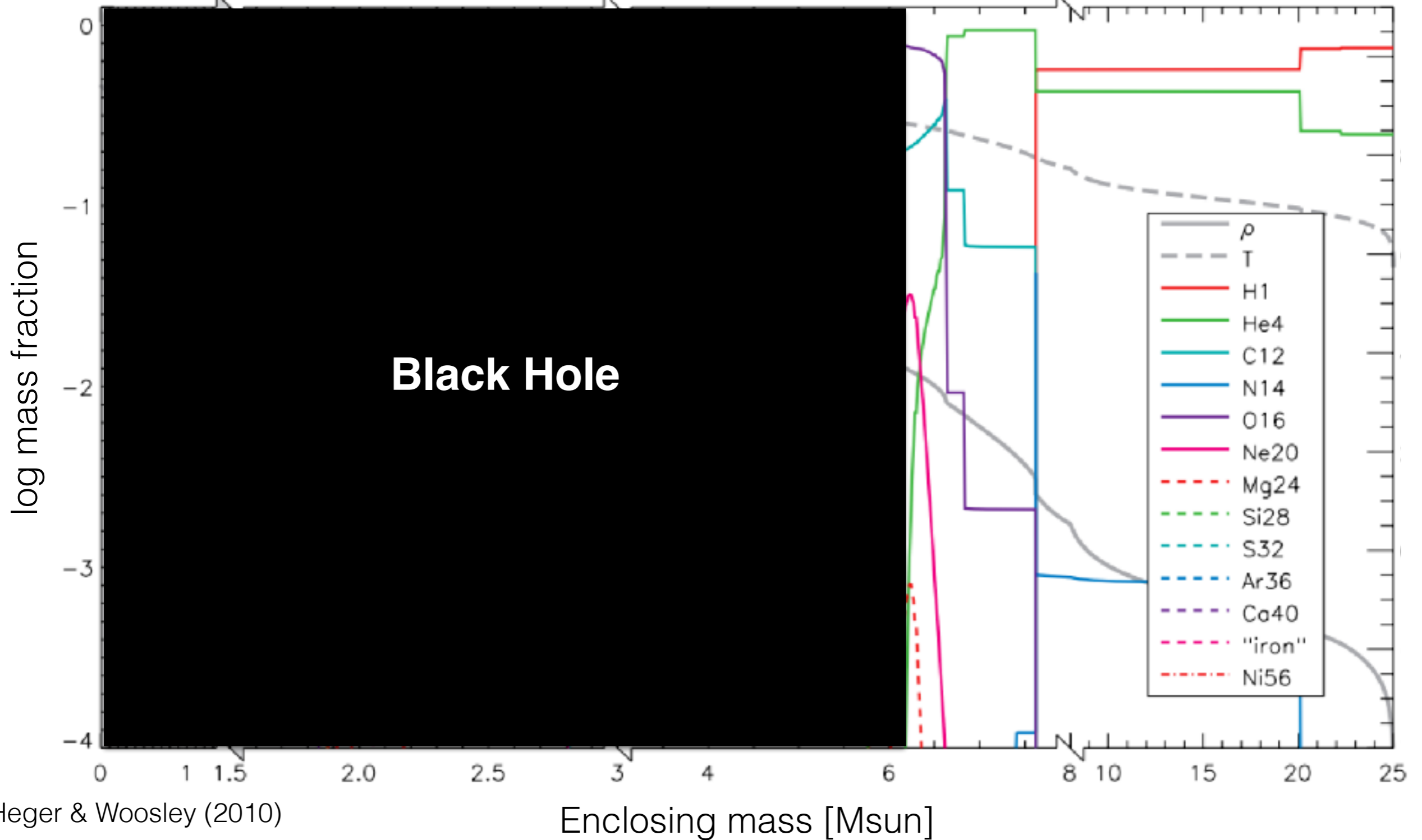
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Massive Star and Supernova Models

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Black Hole

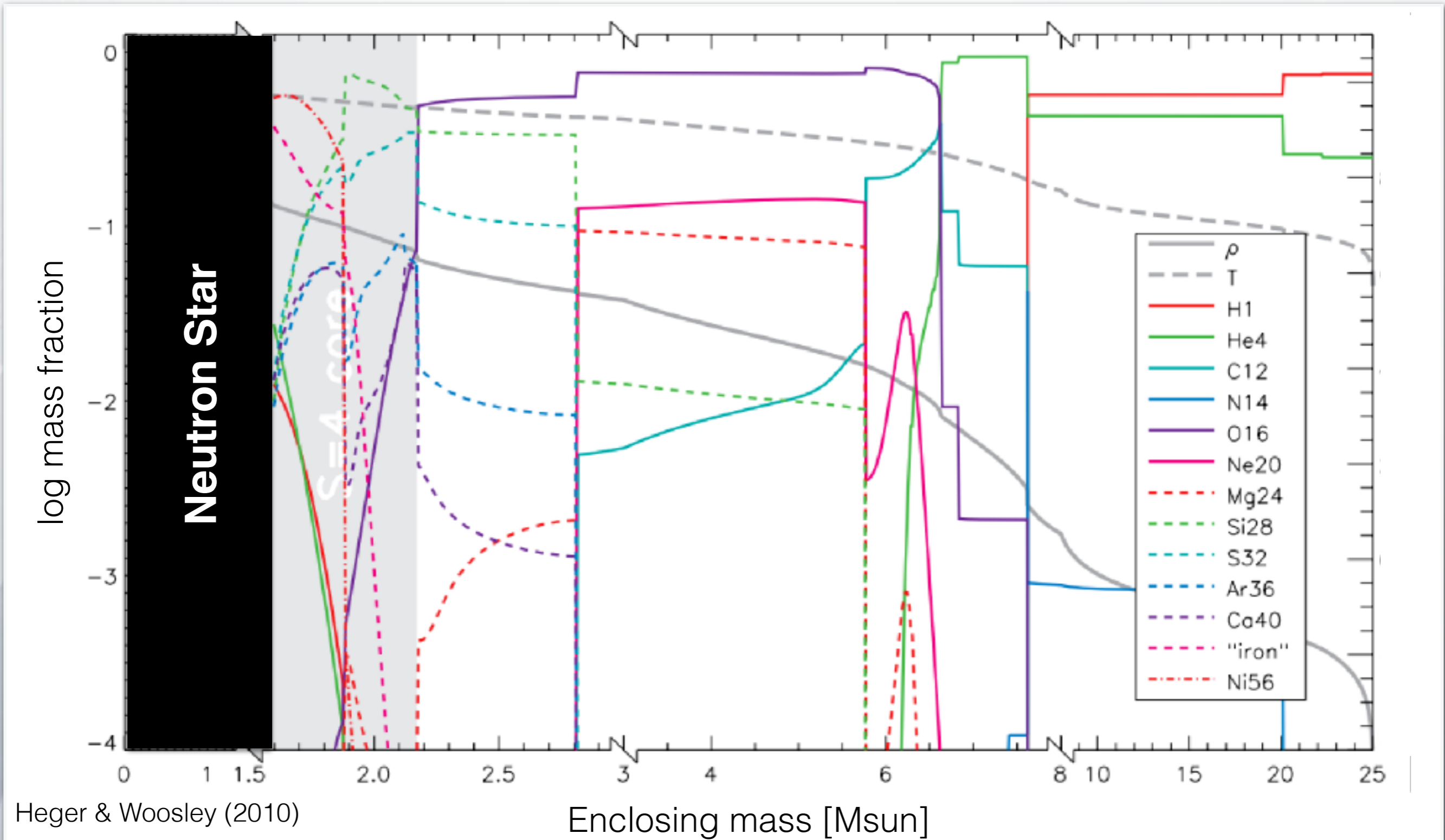


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Massive Star and Supernova Models

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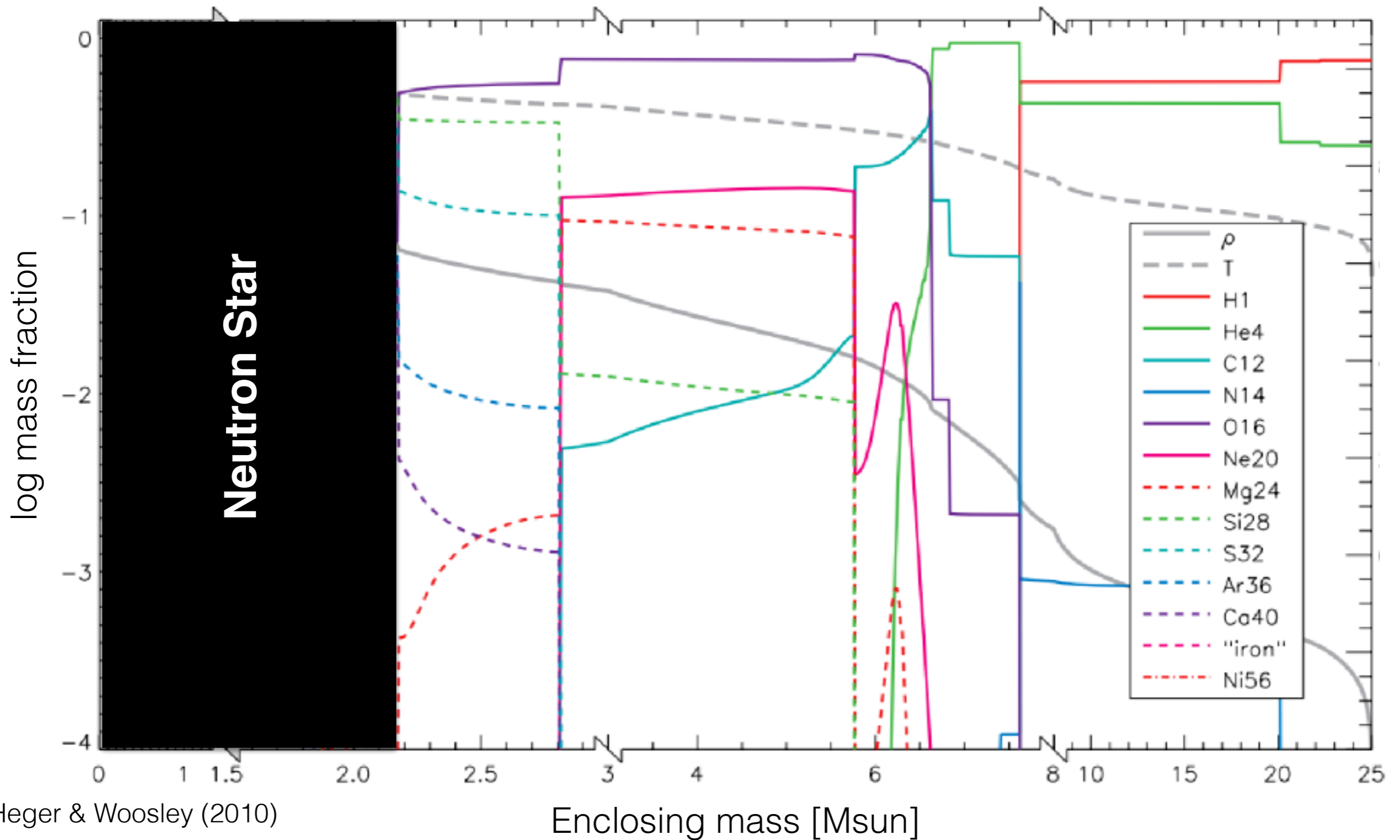


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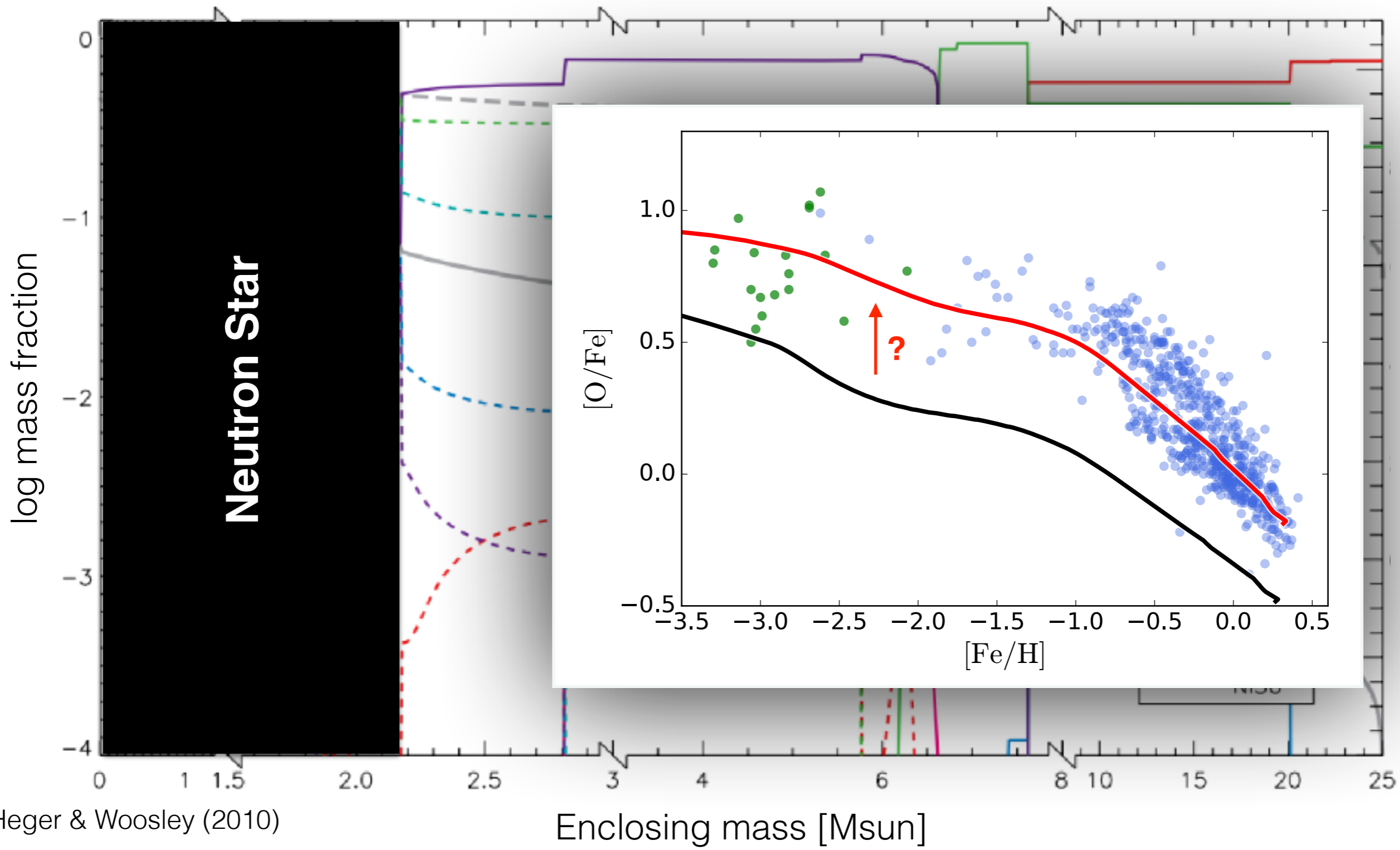


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Massive Star and Supernova Models

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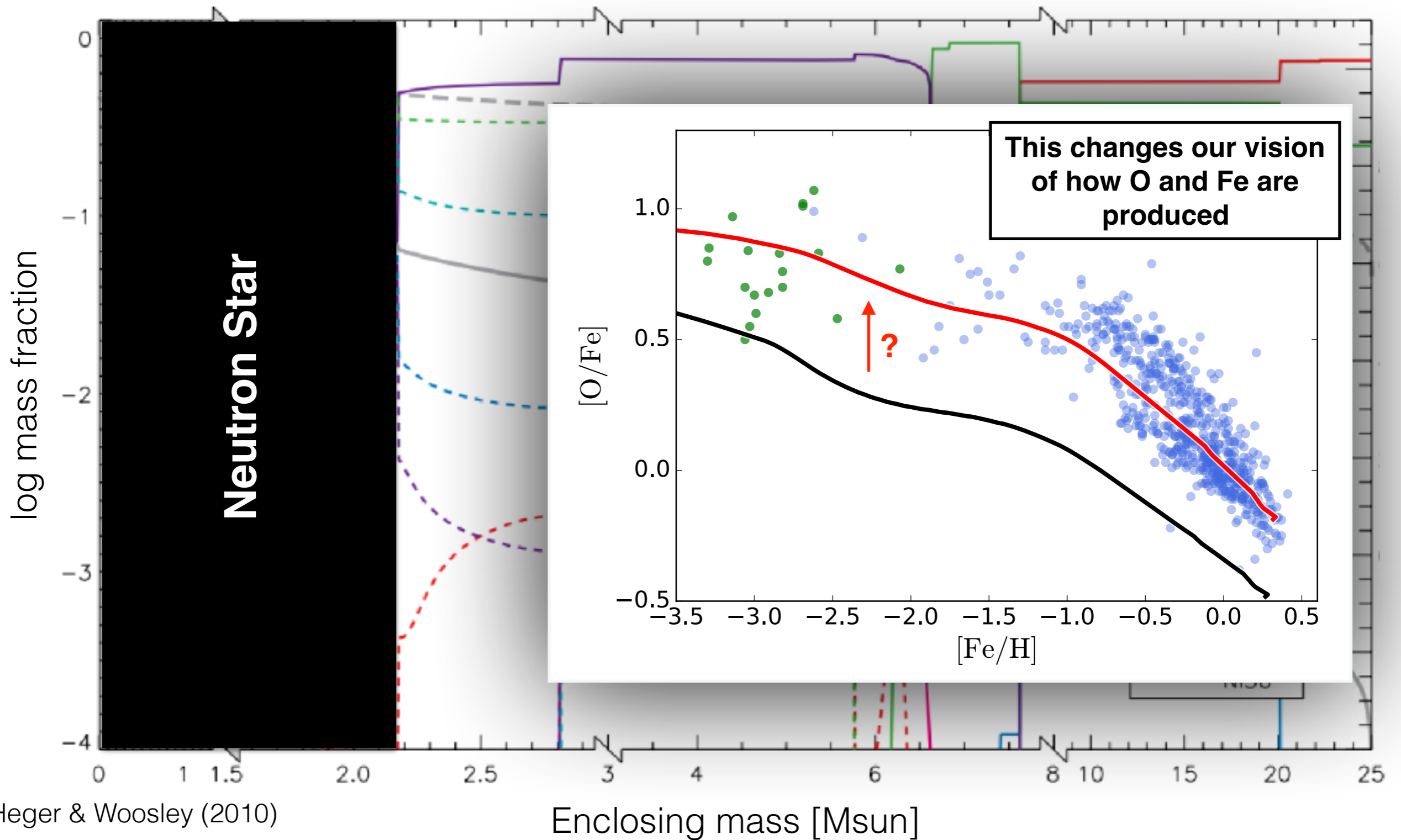
Heger & Woosley (2010)

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Enclosing mass [Msun]

Massive Star and Supernova Models

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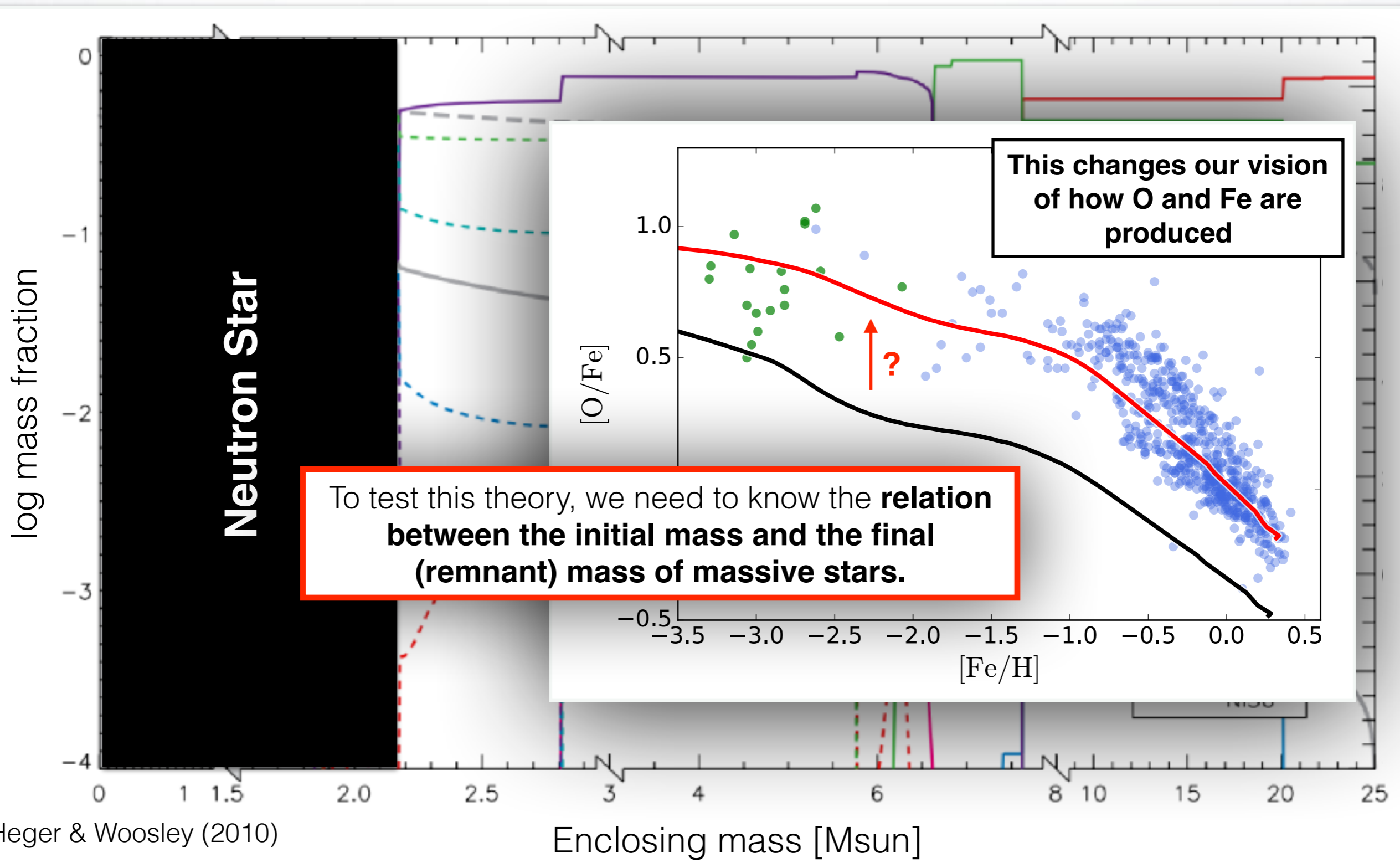


Heger & Woosley (2010)

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Massive Star and Supernova Models

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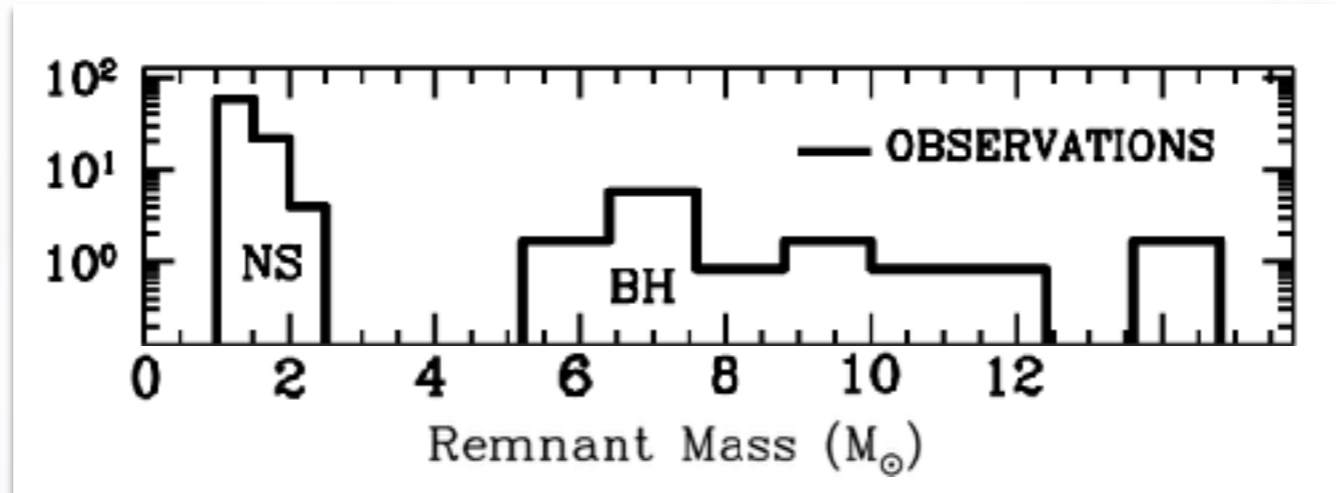
Heger & Woosley (2010)

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Neutron Star and Black Hole Mass Function

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

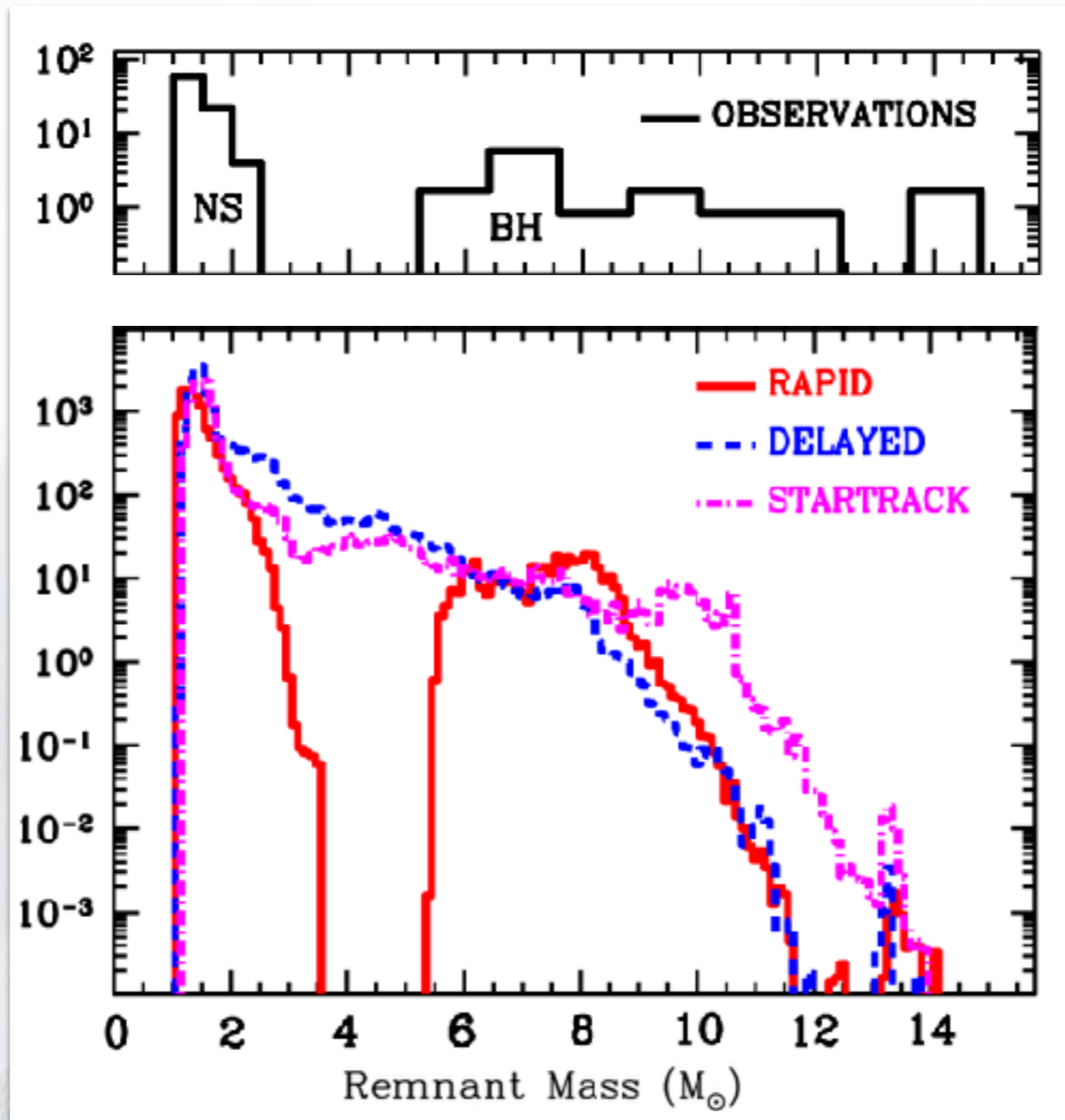
Observation of
binary systems →



Neutron Star and Black Hole Mass Function

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

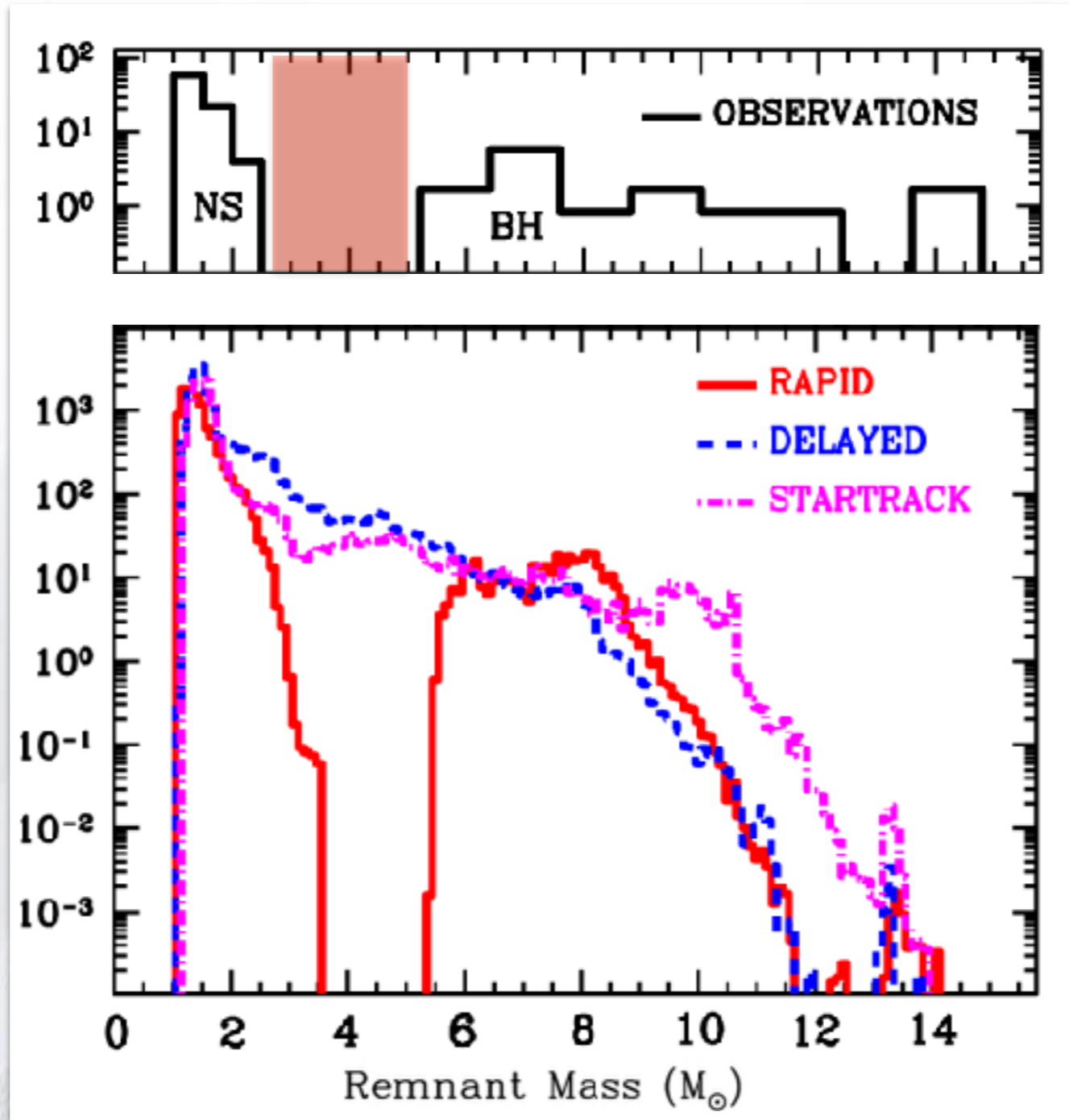
Observation of
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Neutron Star and Black Hole Mass Function

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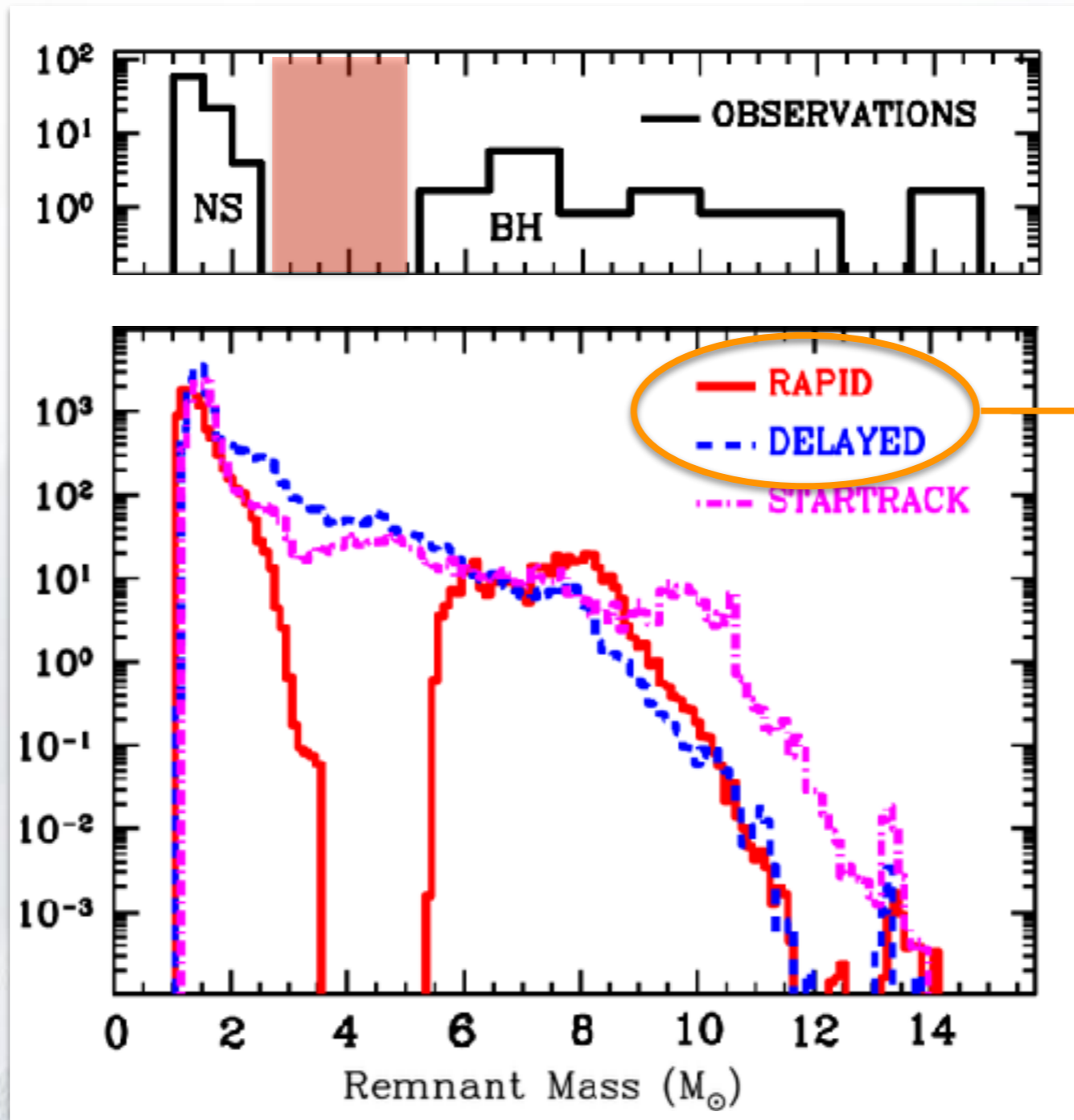
Observation of
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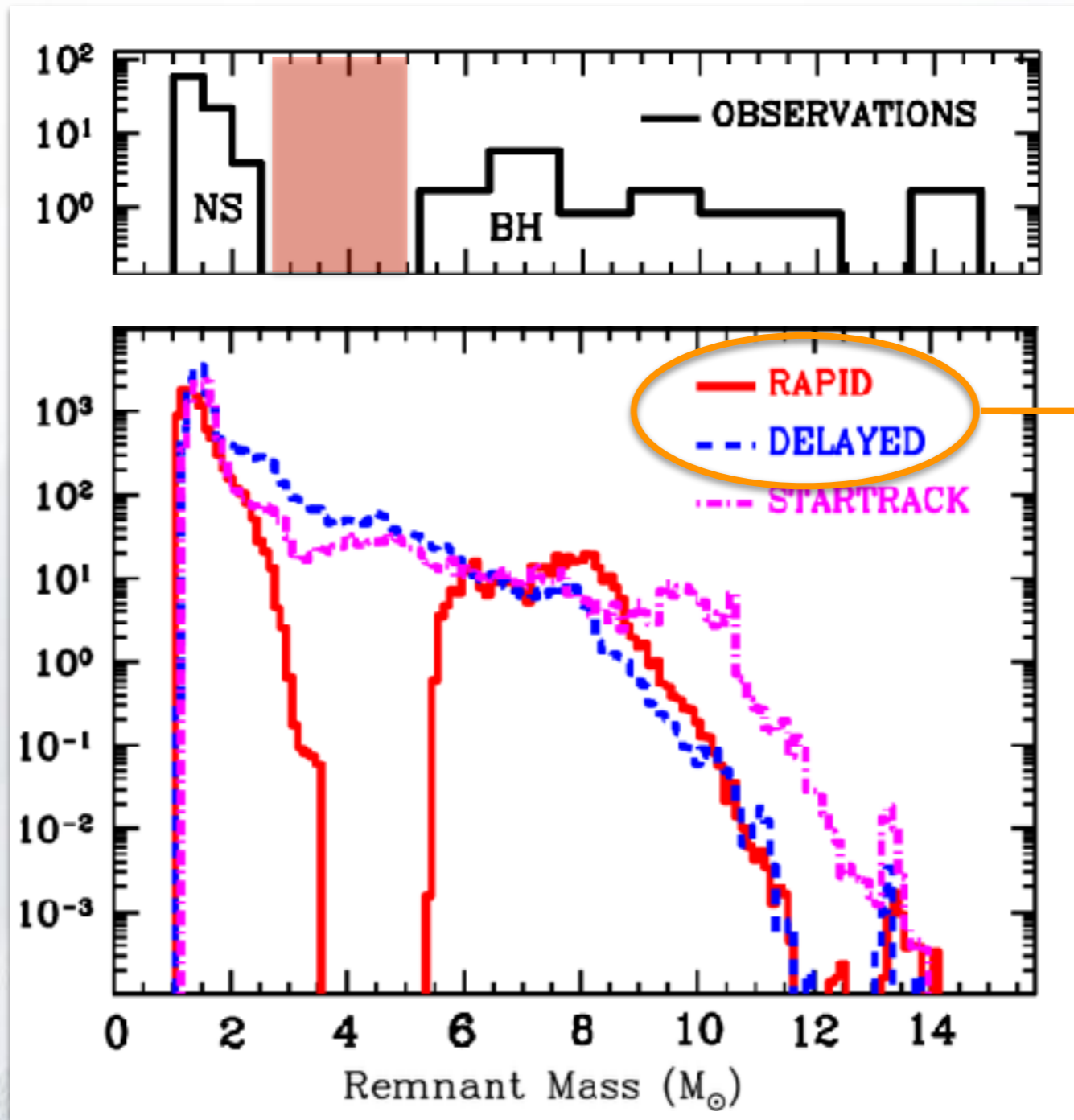


→ Prescription used by
the NuGrid
collaboration
(Pignatari et al. 2016;
C. Ritter et al. in prep.)

Neutron Star and Black Hole Mass Function

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

Observation of
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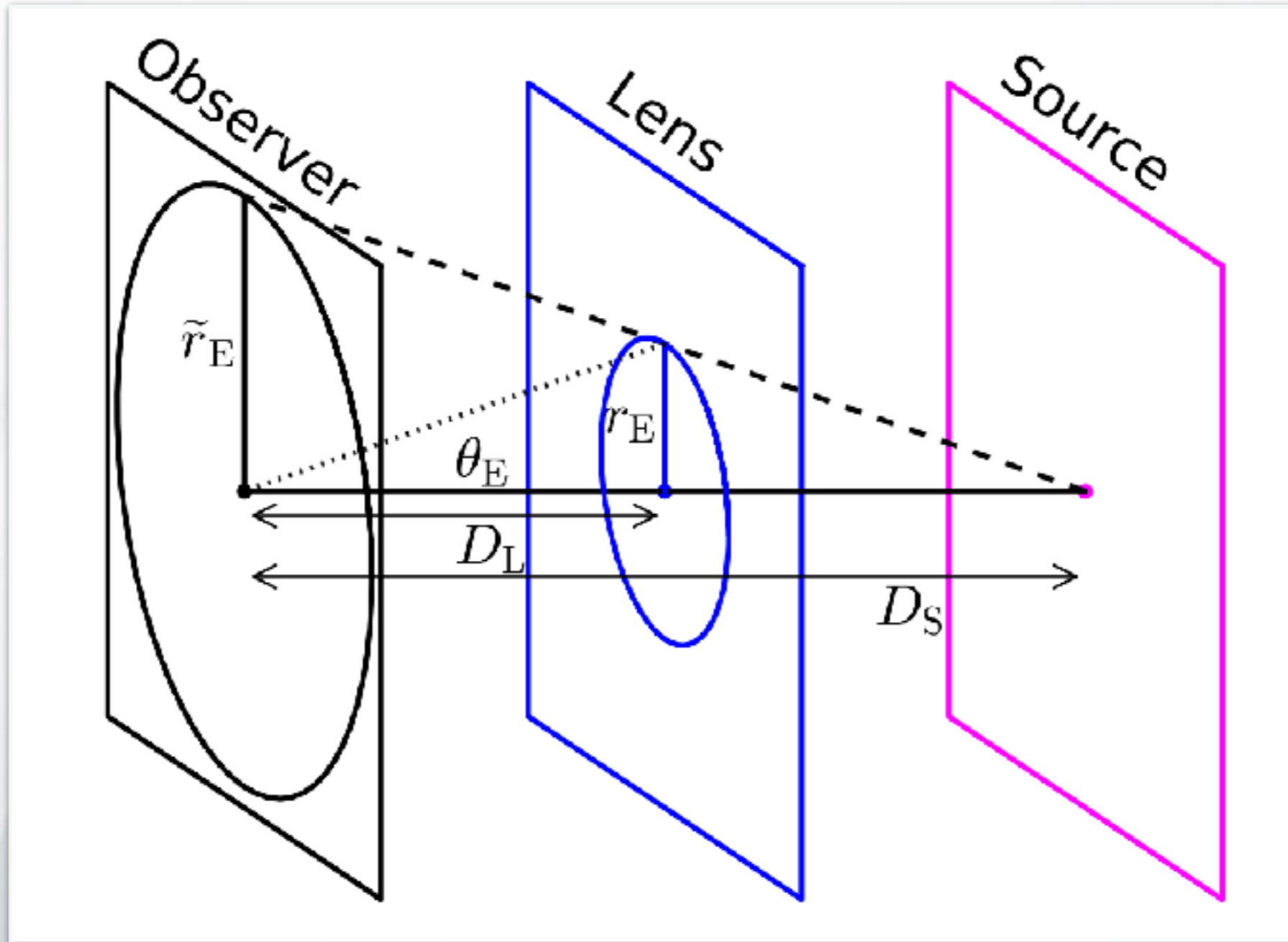
~ 80 neutron stars

~ 20 black holes

Prescription used by
the NuGrid
collaboration
(Pignatari et al. 2016;
C. Ritter et al. in prep.)

Neutron Star and Black Hole Mass with Microlensing

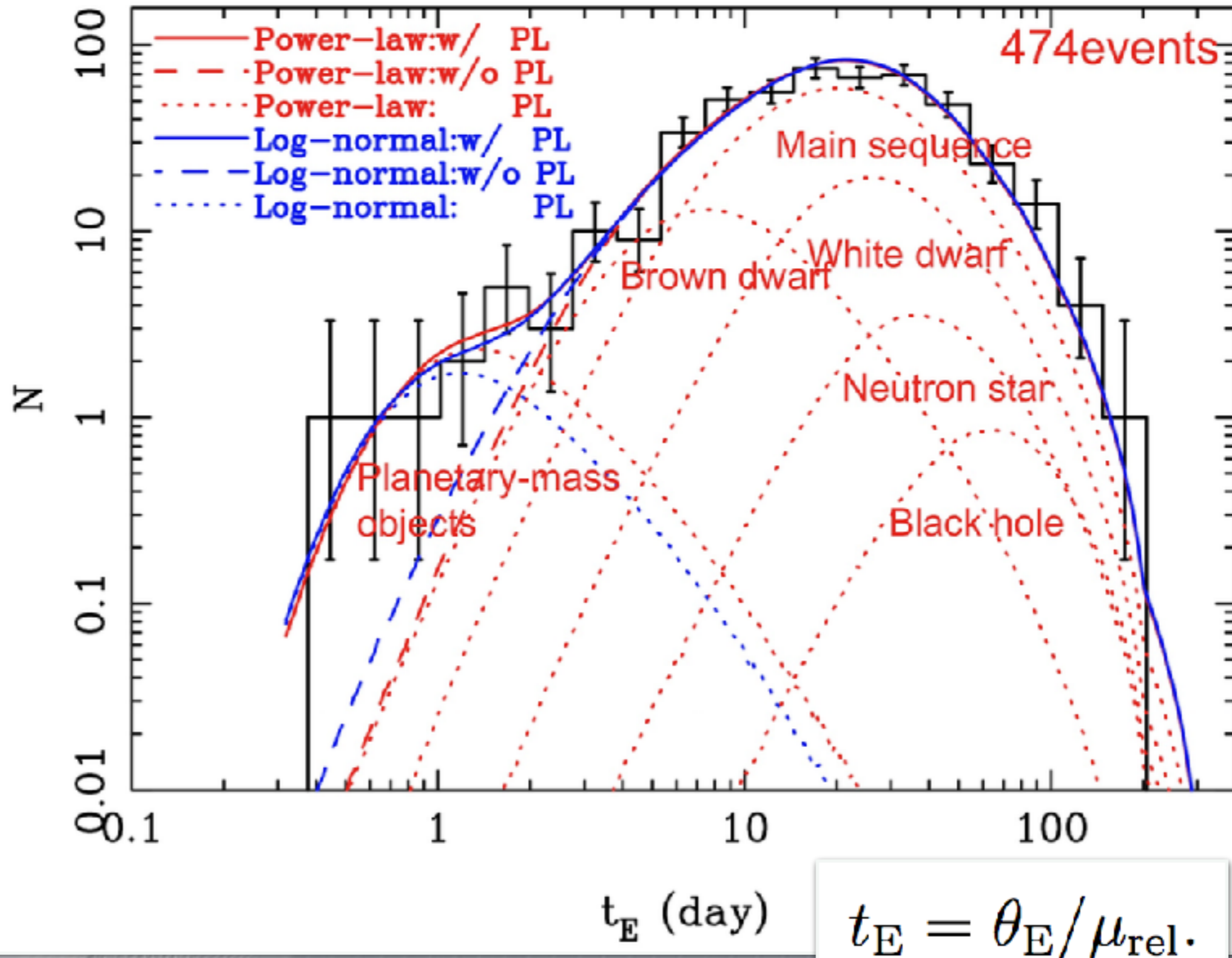
J. C. Yee & C. B. Henderson (Themes document)



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

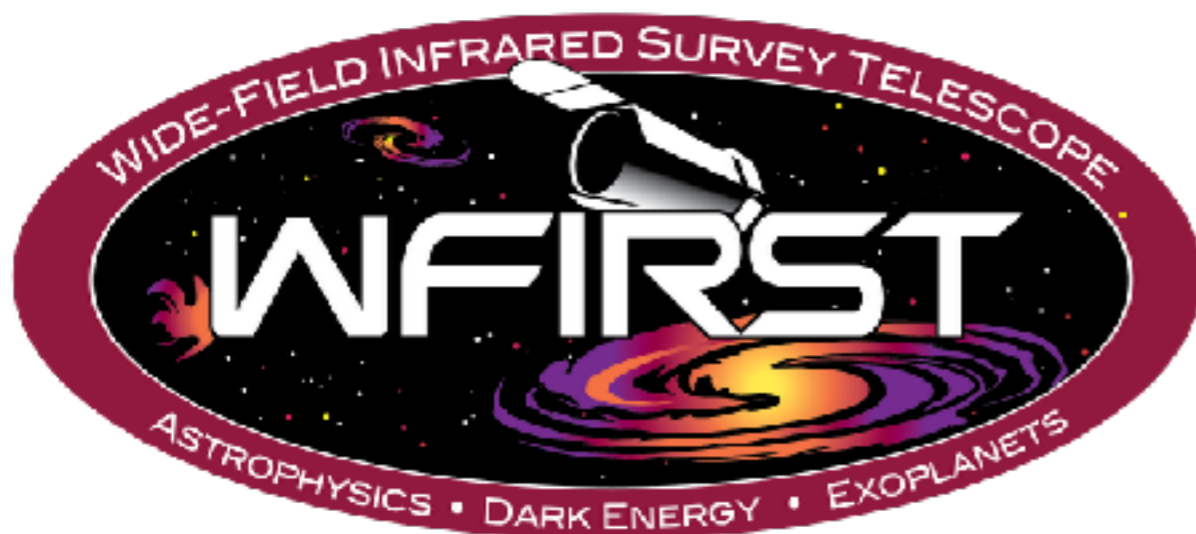
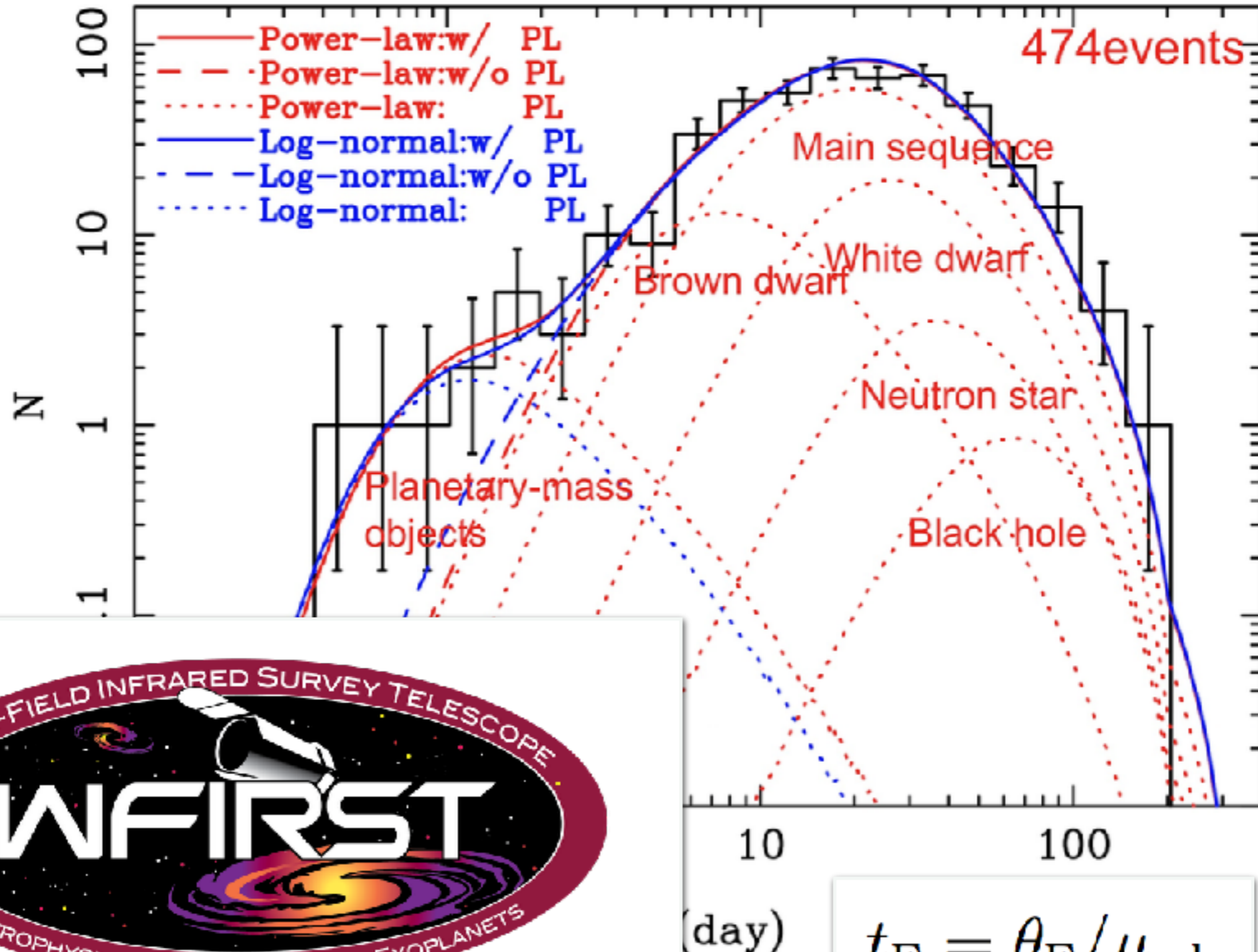
Neutron Star and Black Hole Mass with Microlensing

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



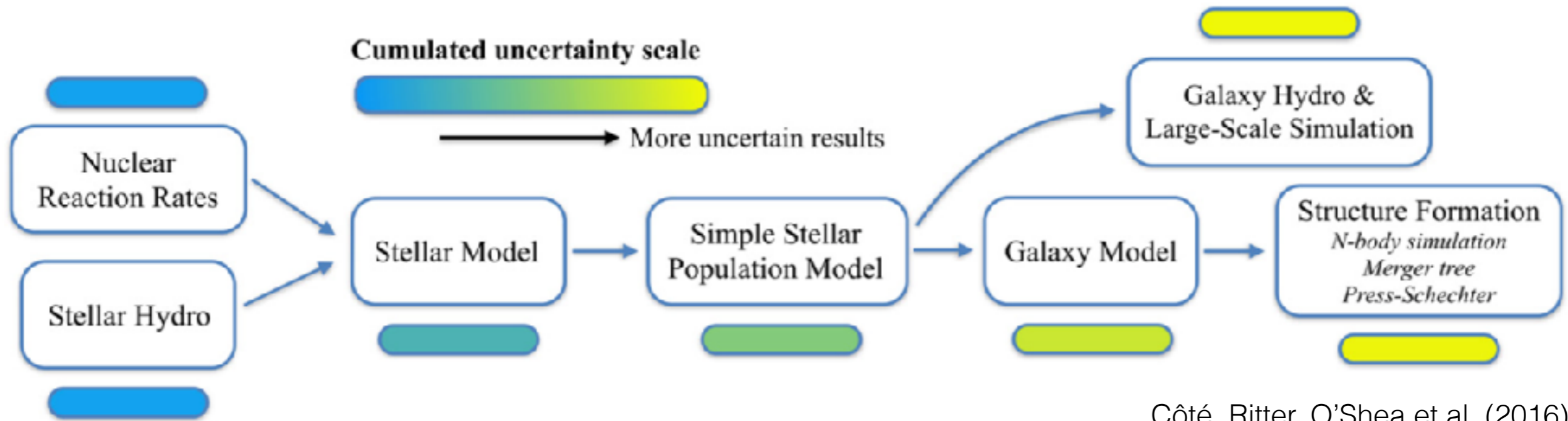
Neutron Star and Black Hole Mass with Microlensing

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



$$t_E = \theta_E / \mu_{\text{rel}}$$

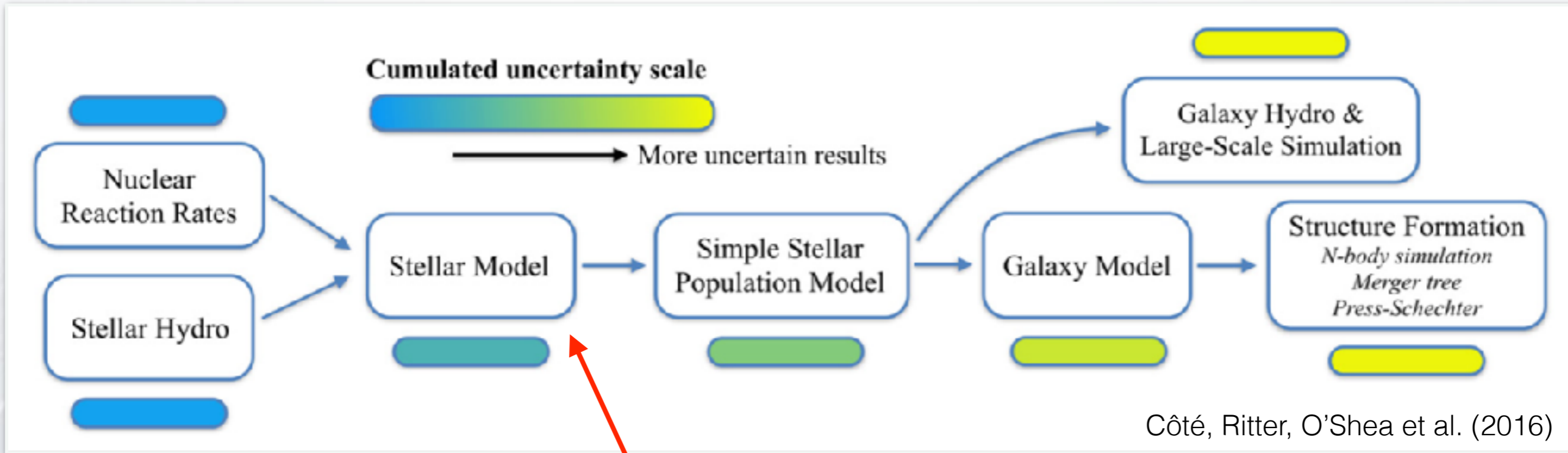
WFIRST and Galactic Chemical Evolution



Côté, Ritter, O'Shea et al. (2016)

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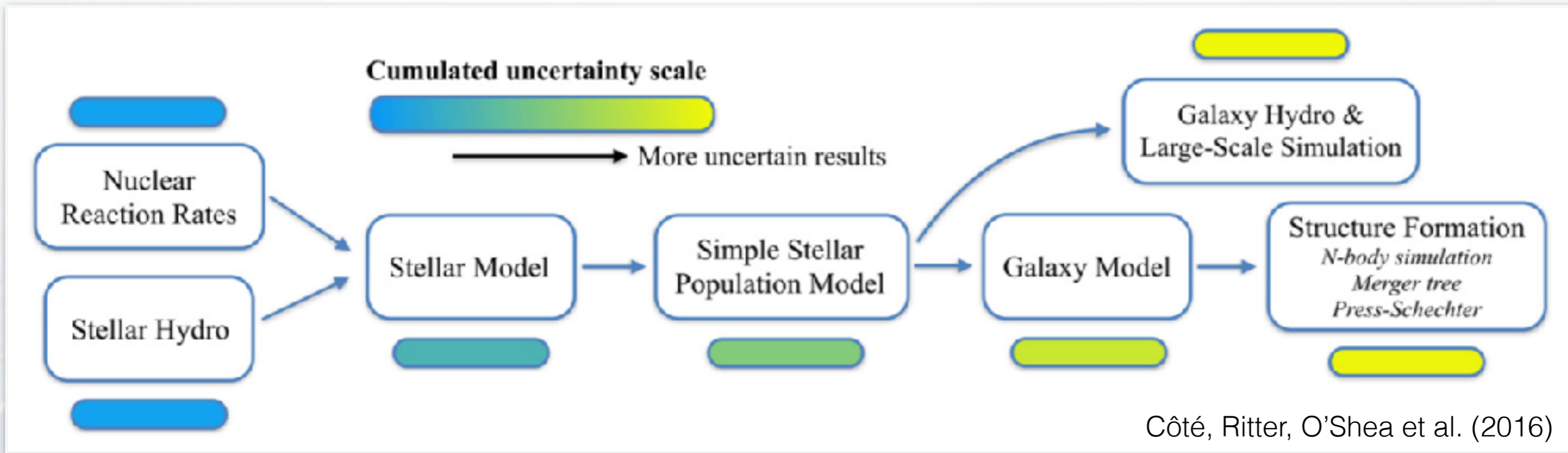
WFIRST and Galactic Chemical Evolution



Neutron star and black hole mass distributions



WFIRST and Galactic Chemical Evolution



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?

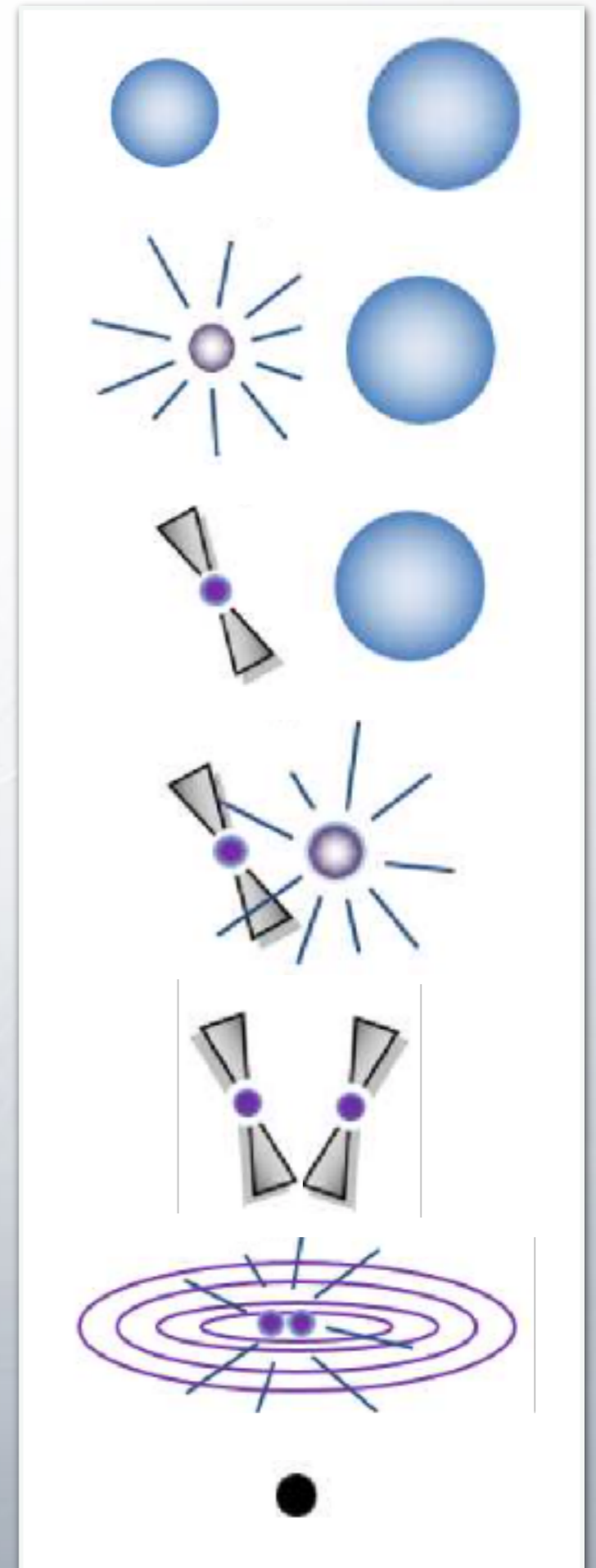
Using Europium (Eu) as a tracer

Time

Fe

Fe

Eu

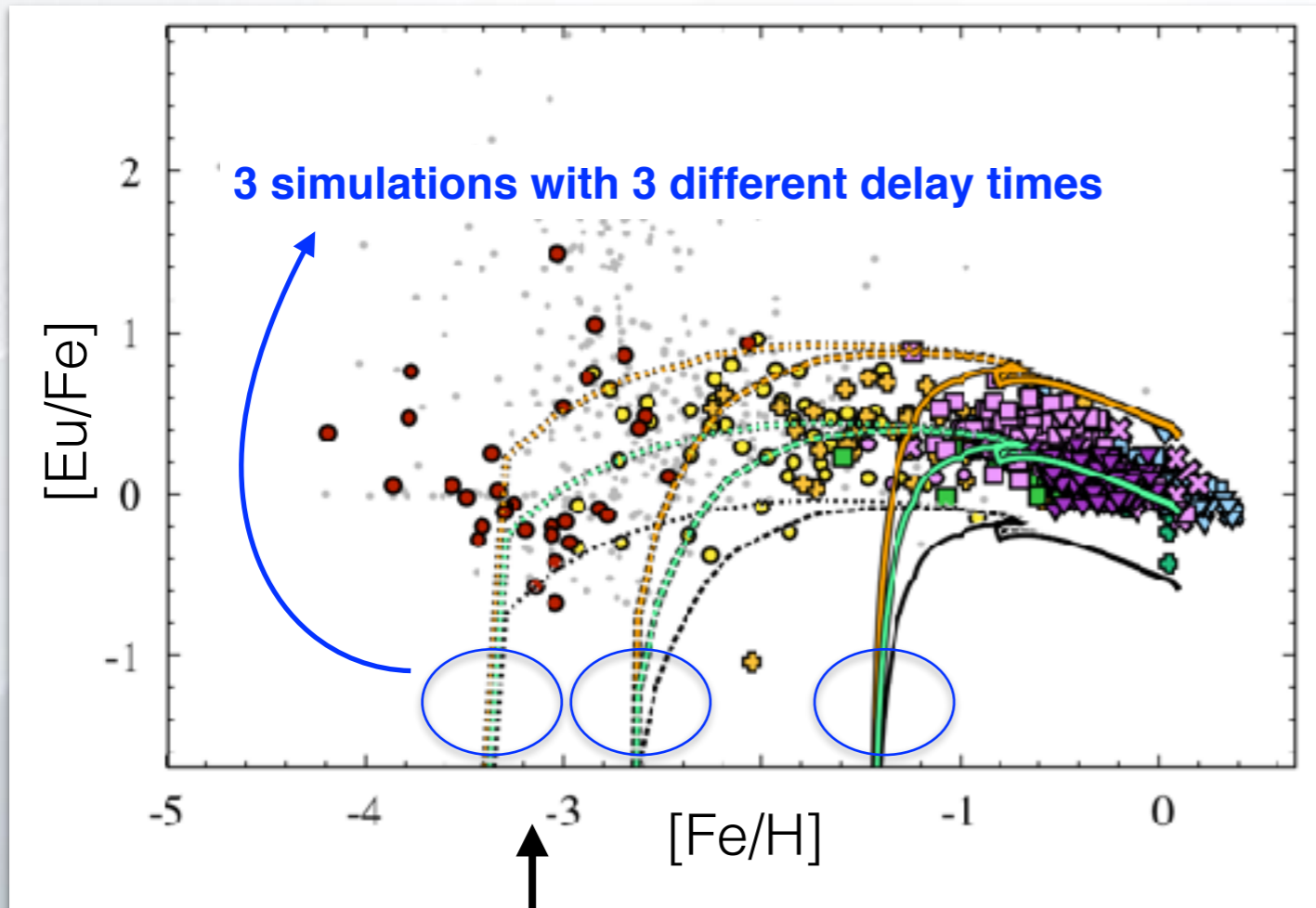


Enrichment Timing and Evolution of [Fe/H]

Origin of r-process elements — neutron star mergers?

Using Europium (Eu) as a tracer

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



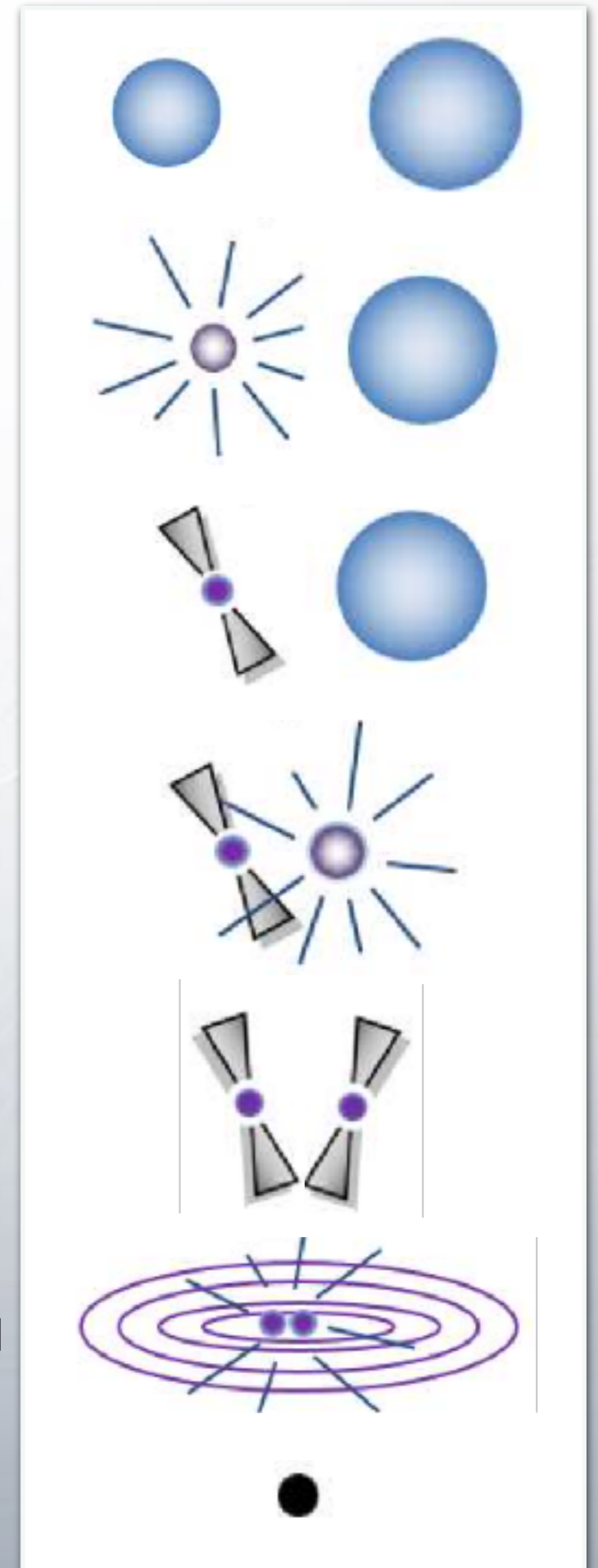
Fe → Fe → Eu

Time

Fe

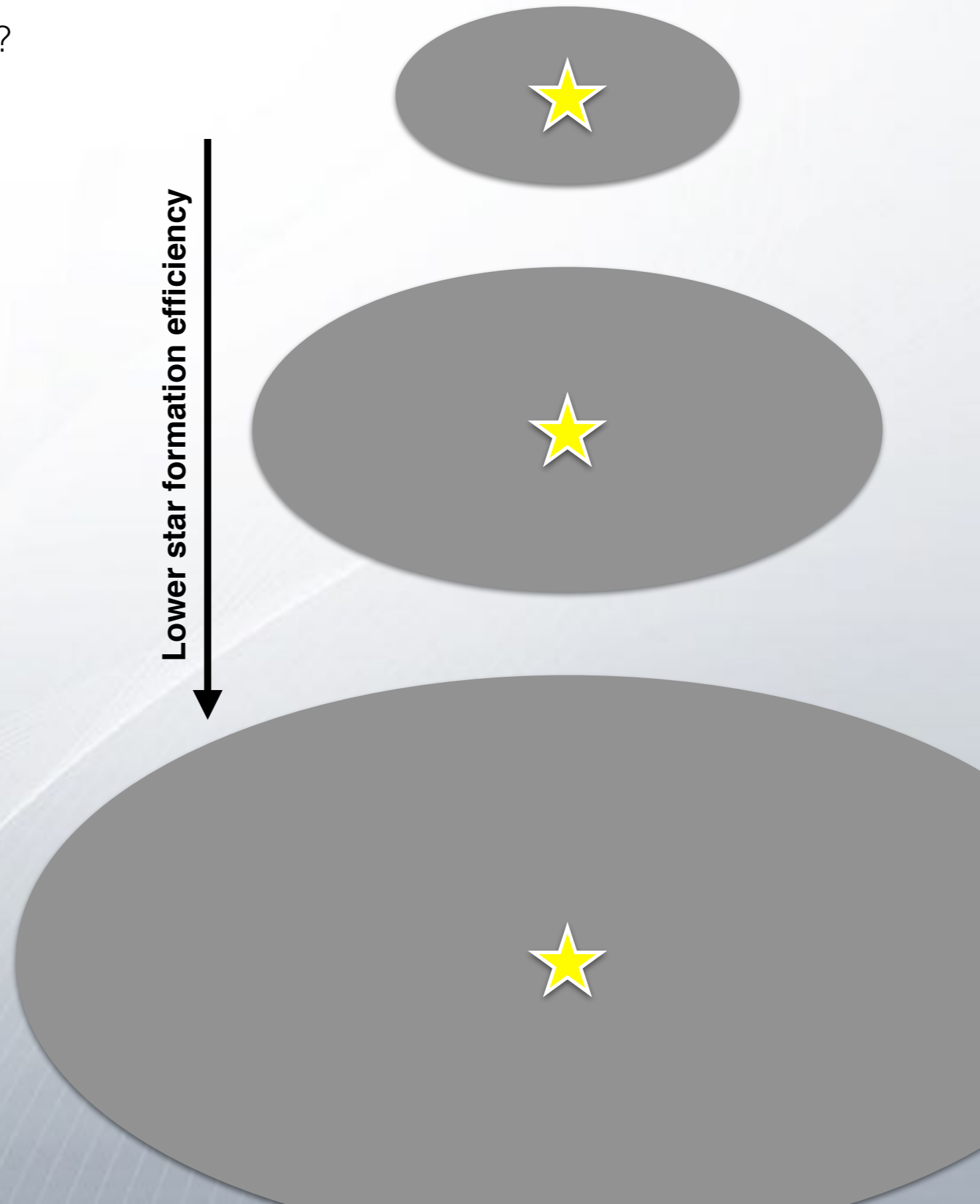
Fe

Eu



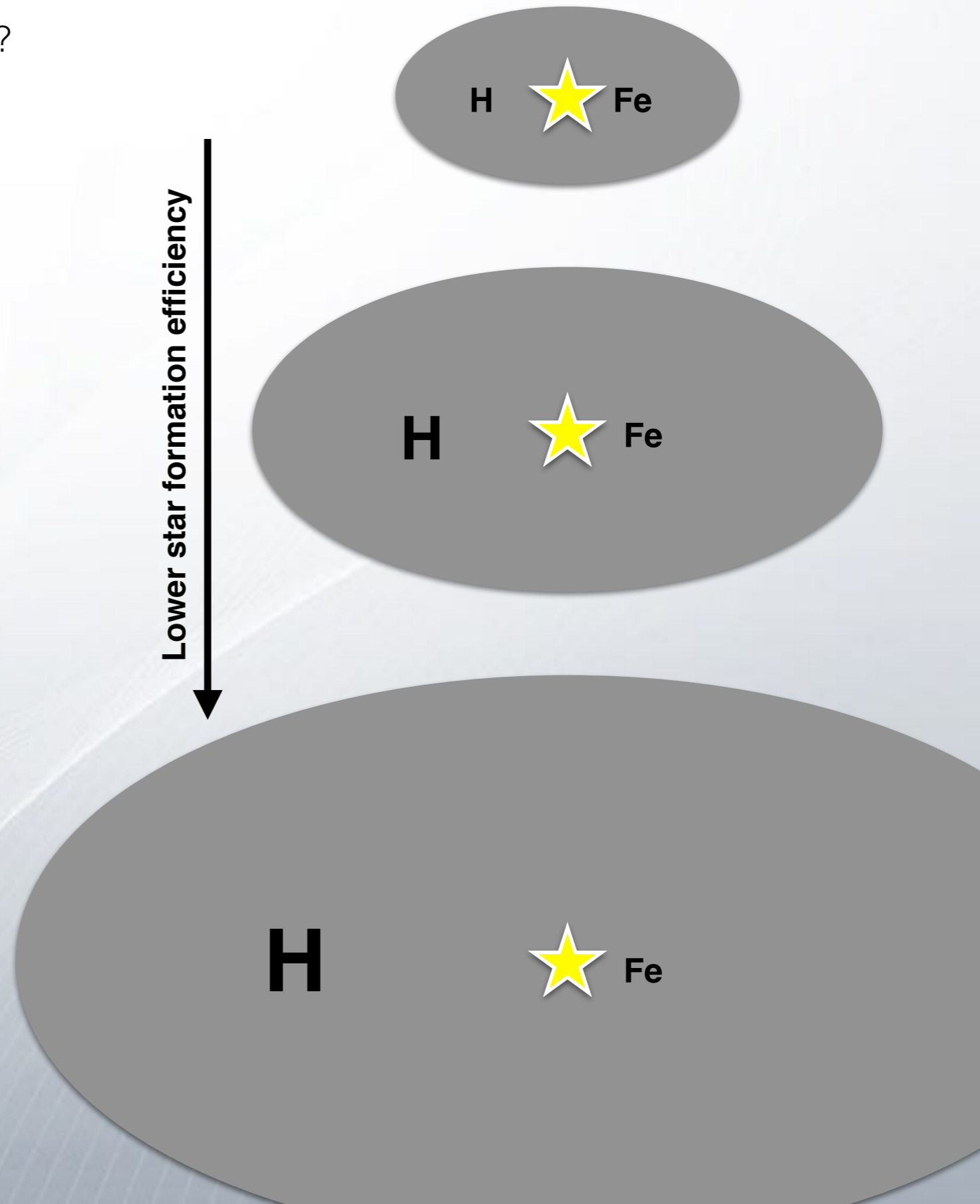
Enrichment Timing and Evolution of $[Fe/H]$

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



Enrichment Timing and Evolution of $[Fe/H]$

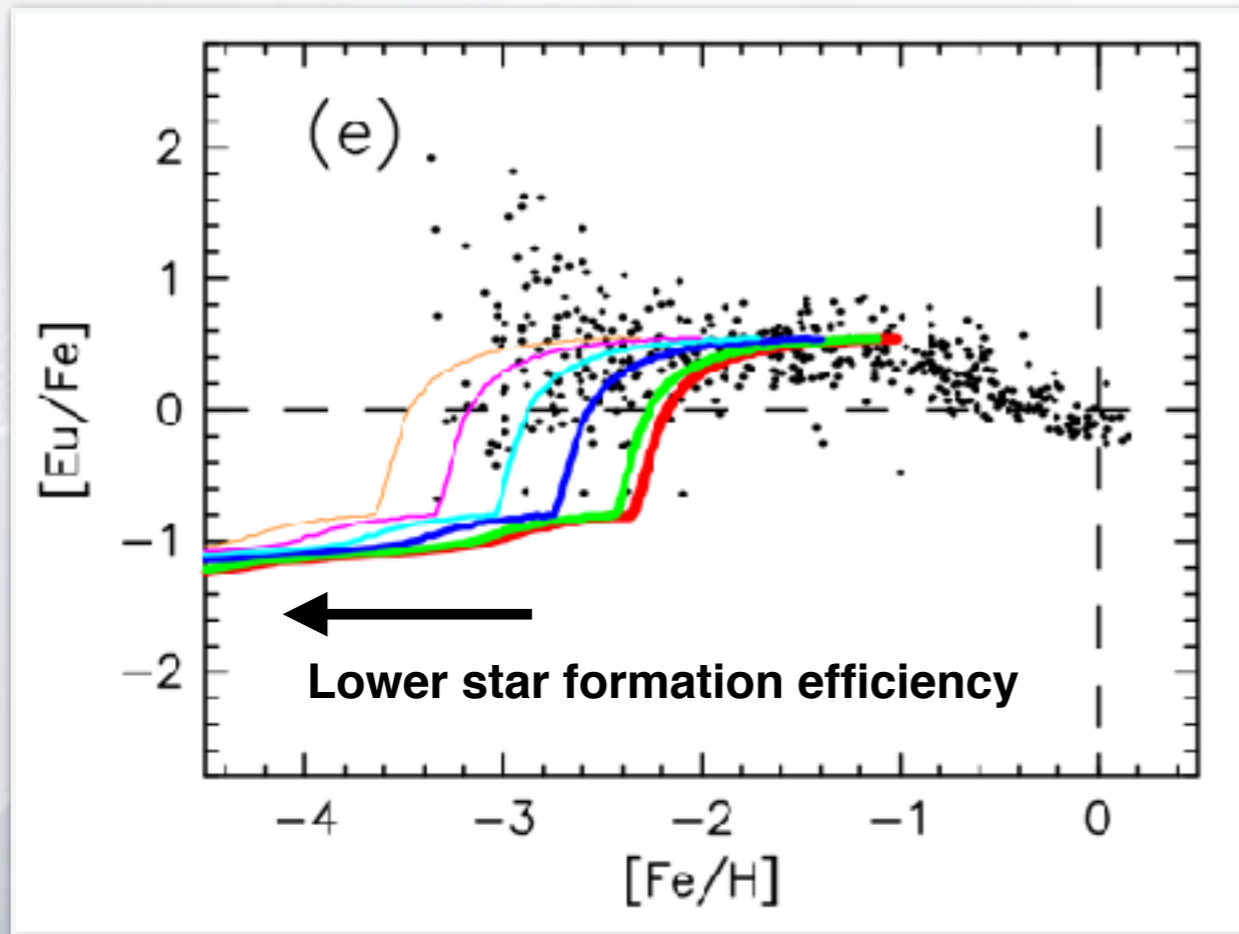
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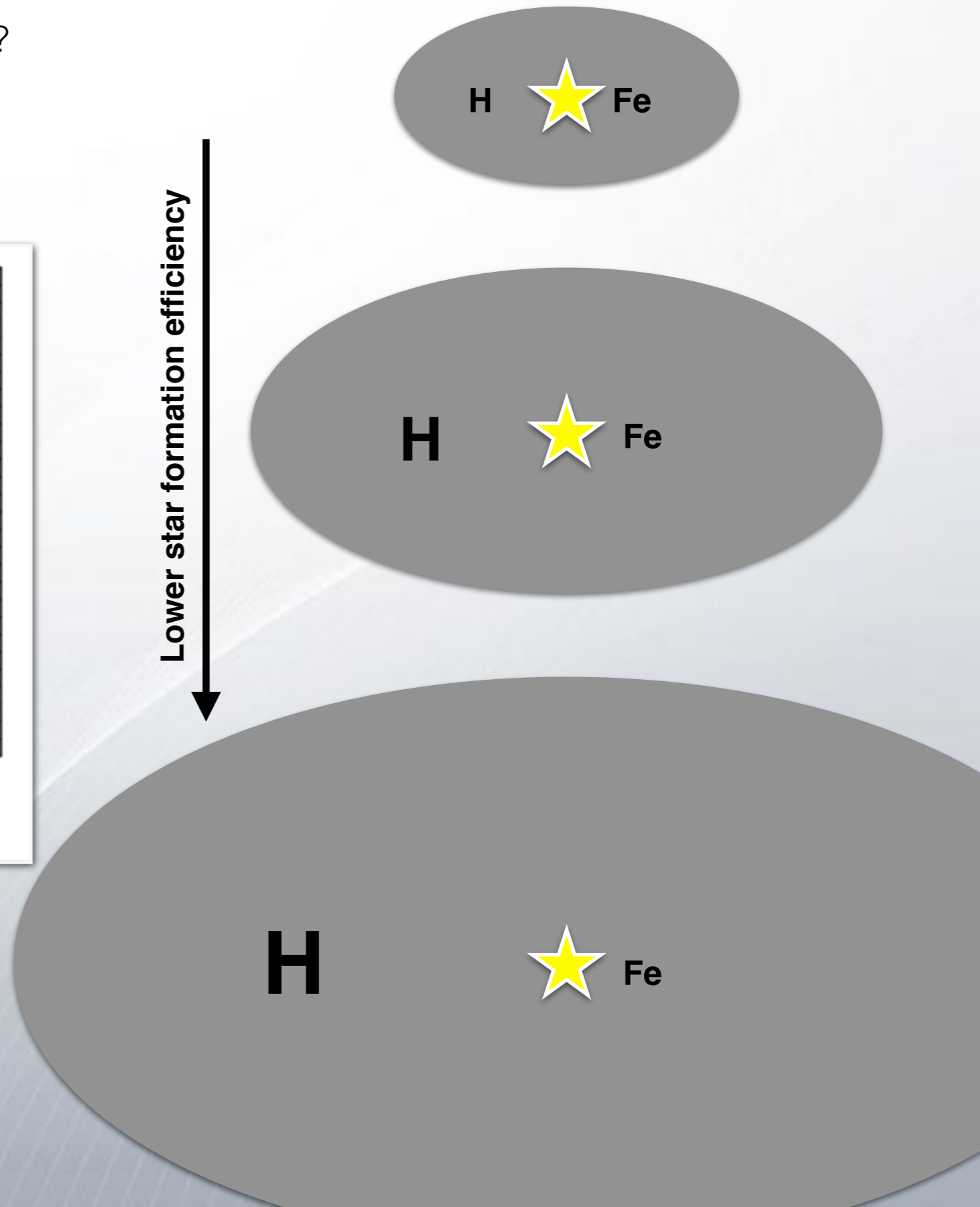
Enrichment Timing and Evolution of $[Fe/H]$

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

Ishimaru, Wanajo & Prantzos (2015)

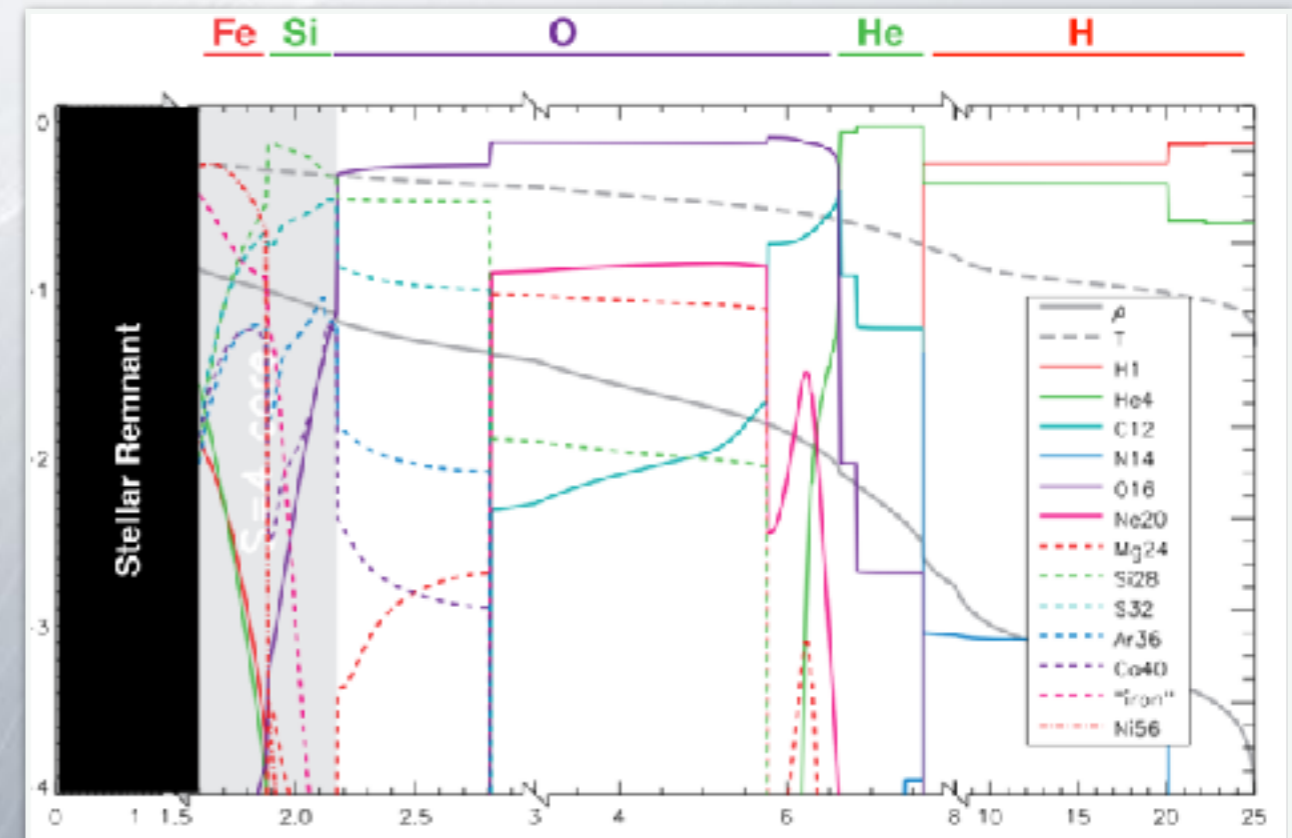
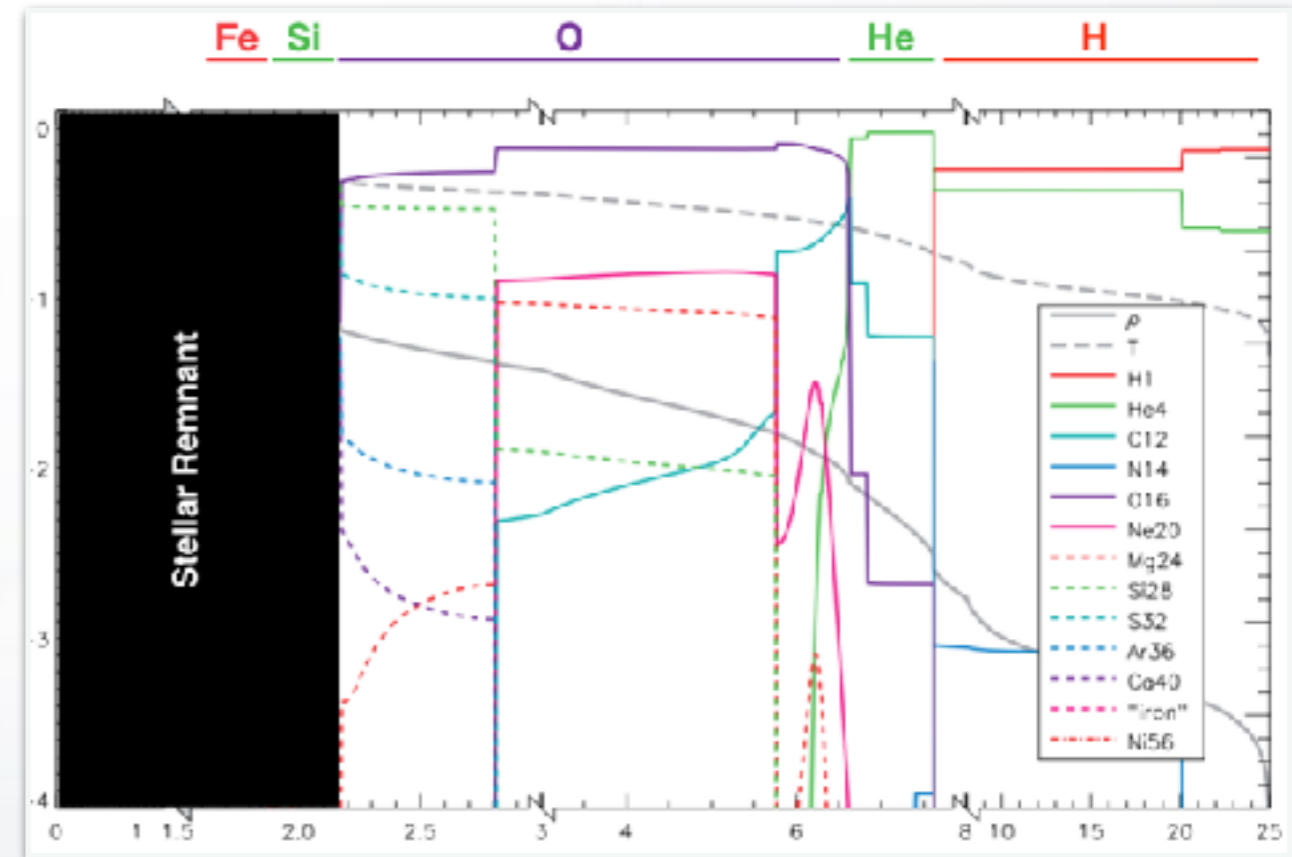
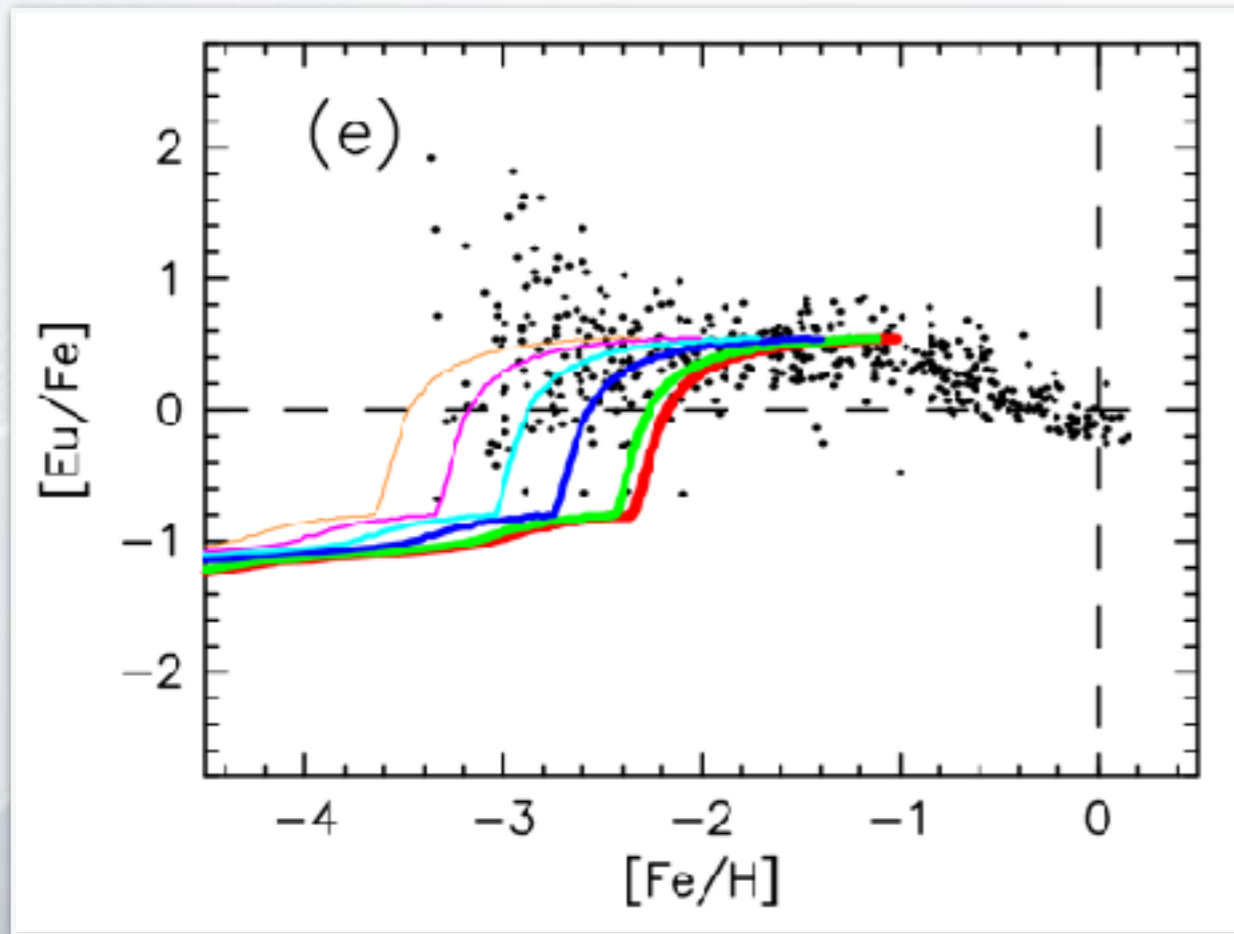


Bigger gas reservoirs reduce $[Fe/H]$



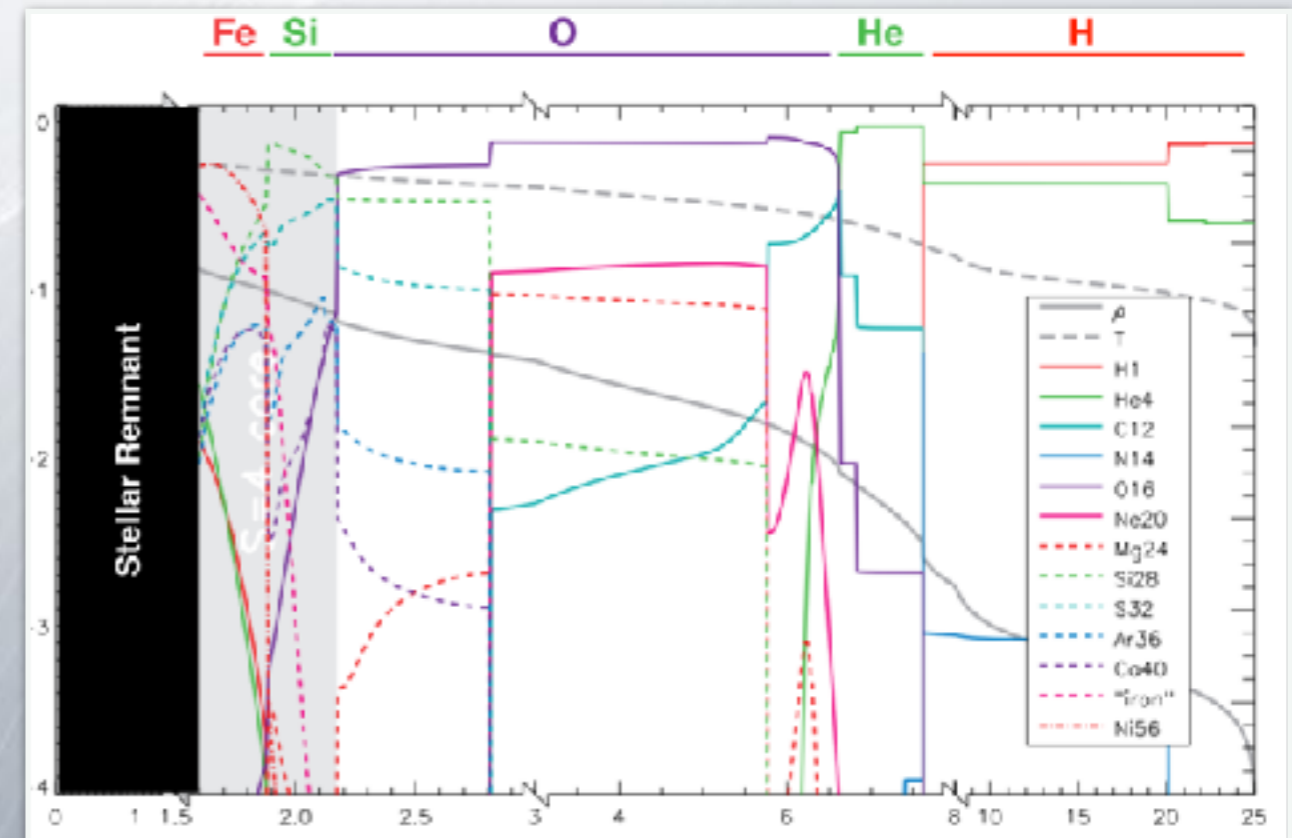
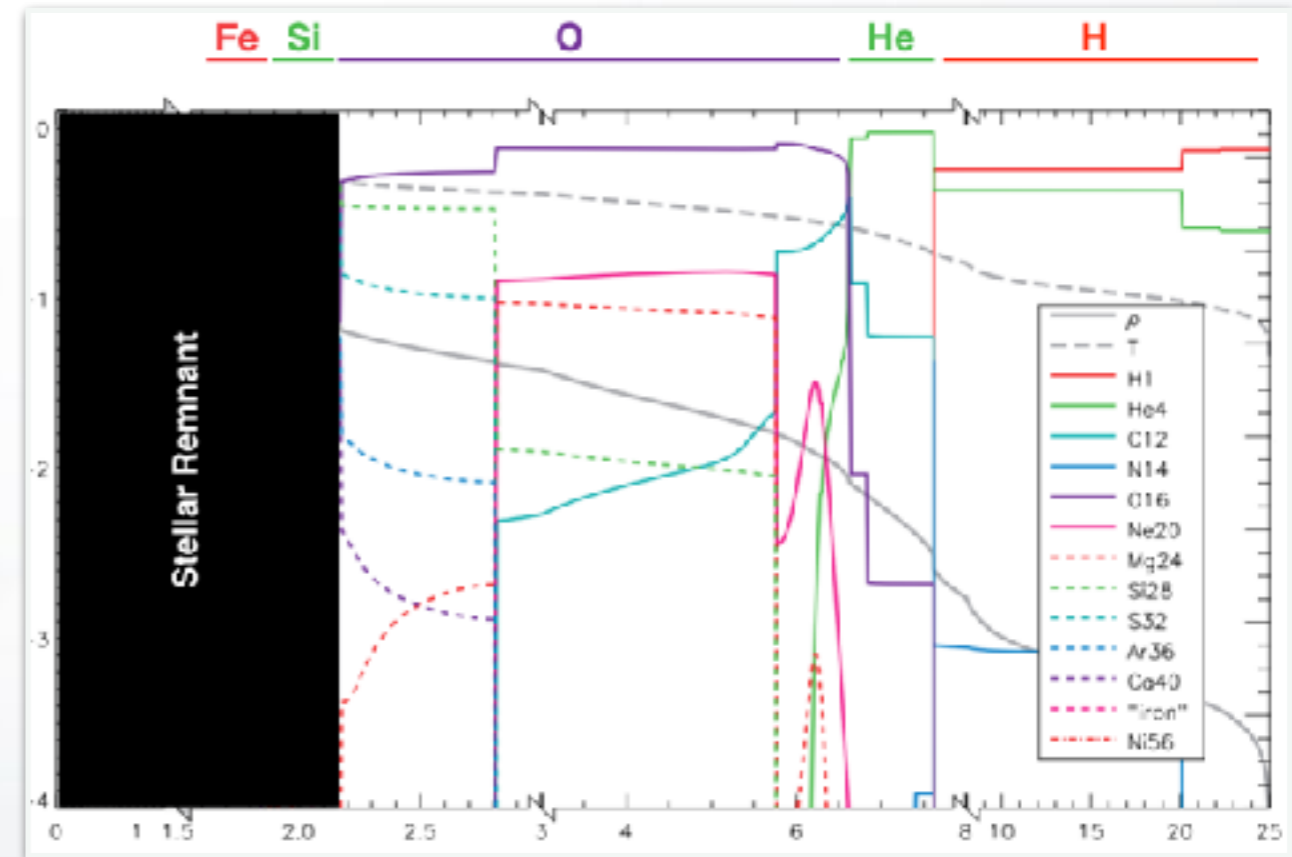
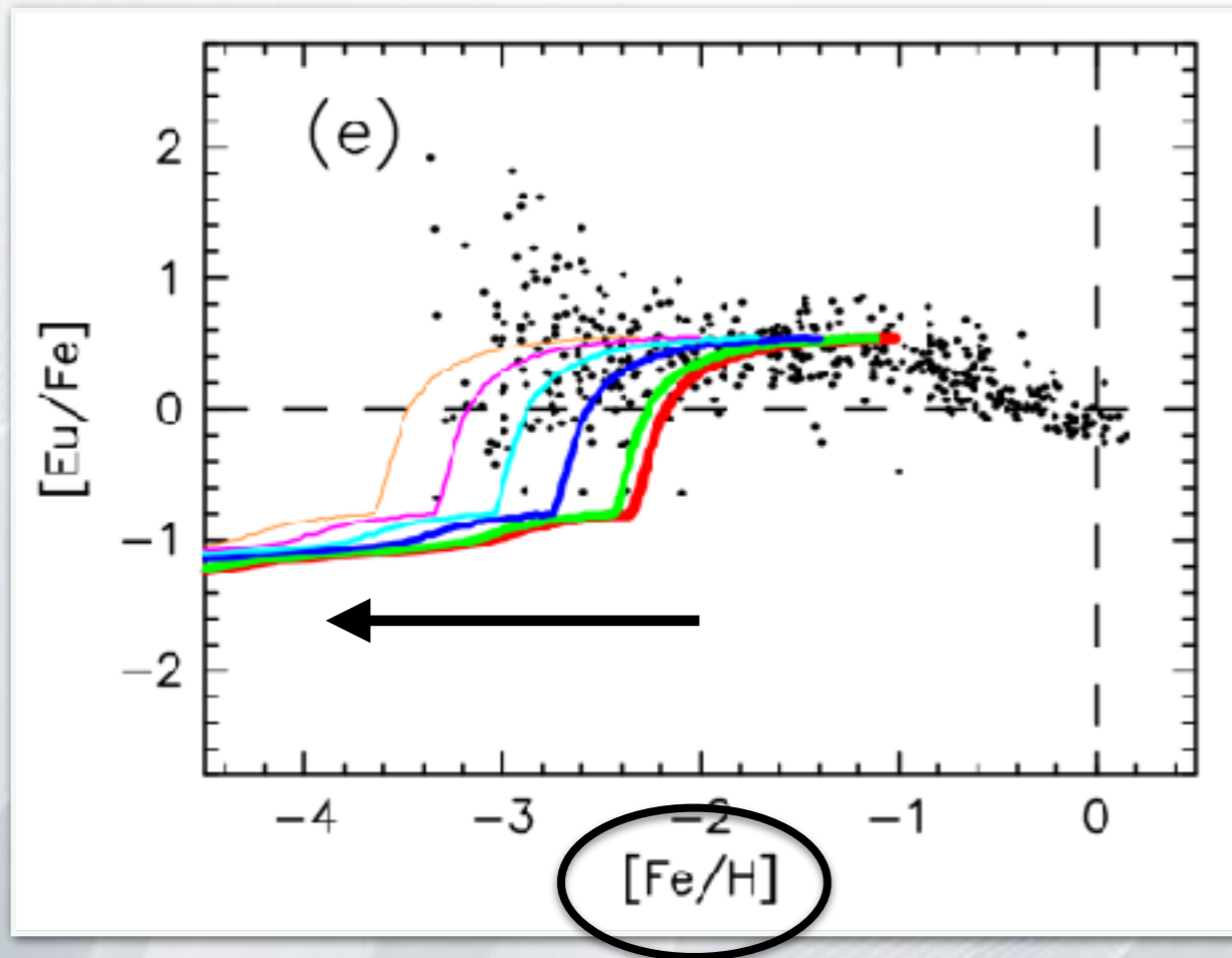
Enrichment Timing and Evolution of [Fe/H]

Ishimaru, Wanajo & Prantzos (2015)



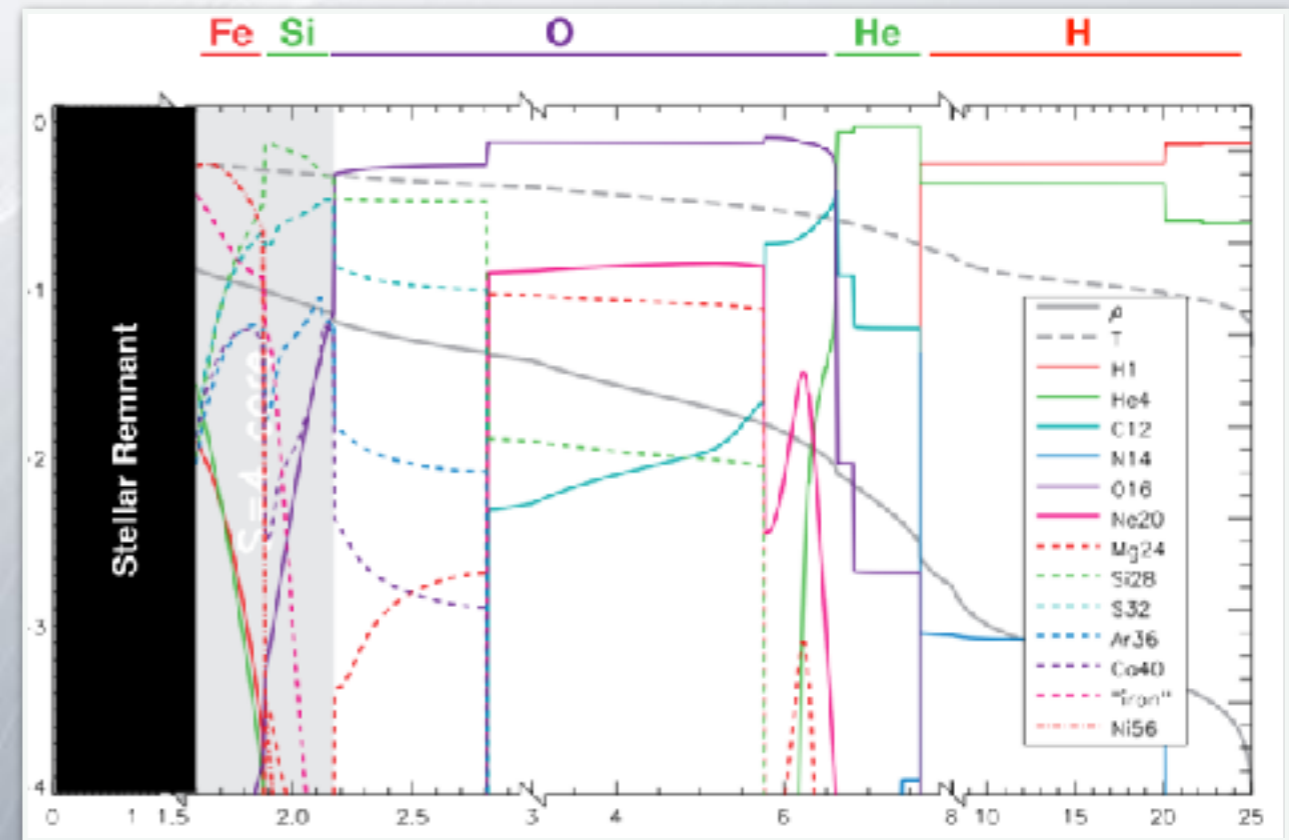
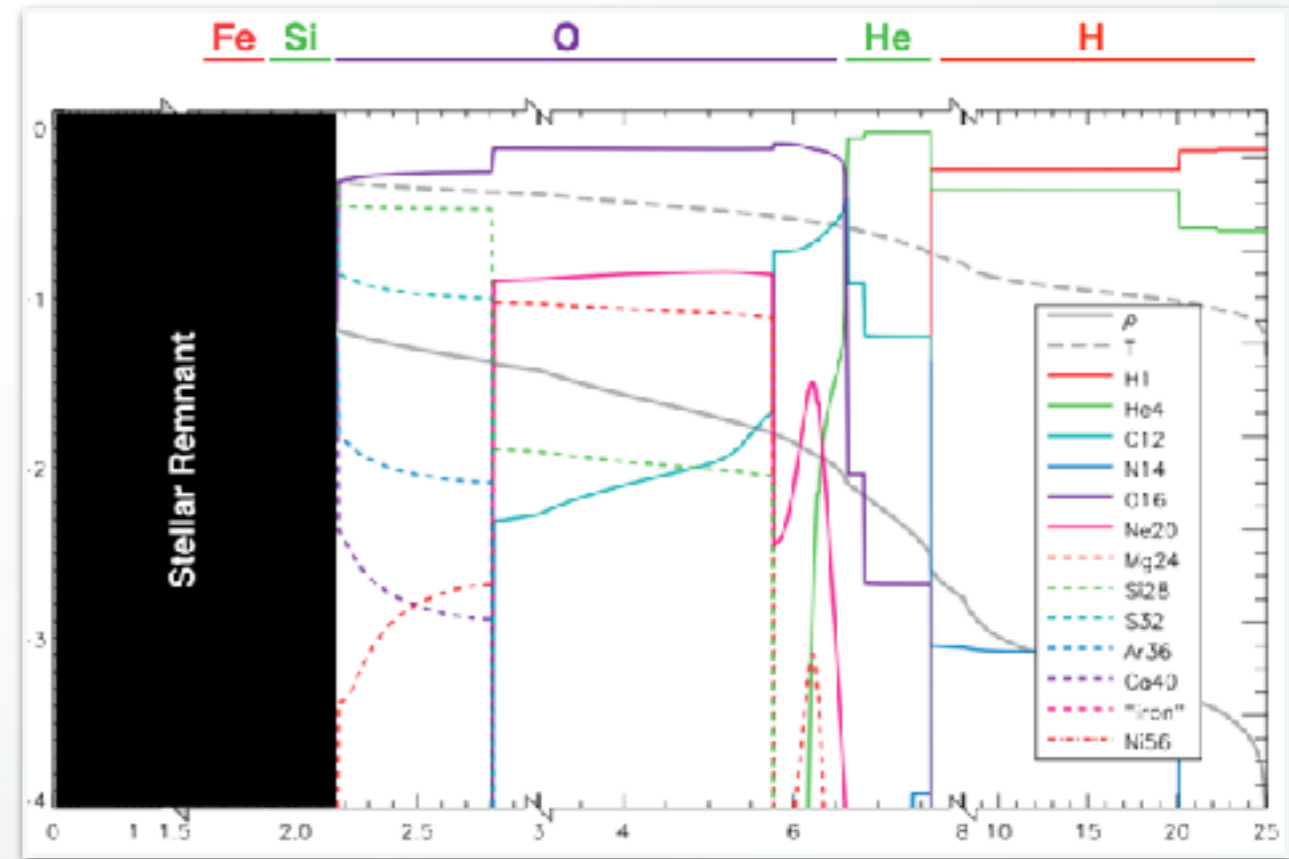
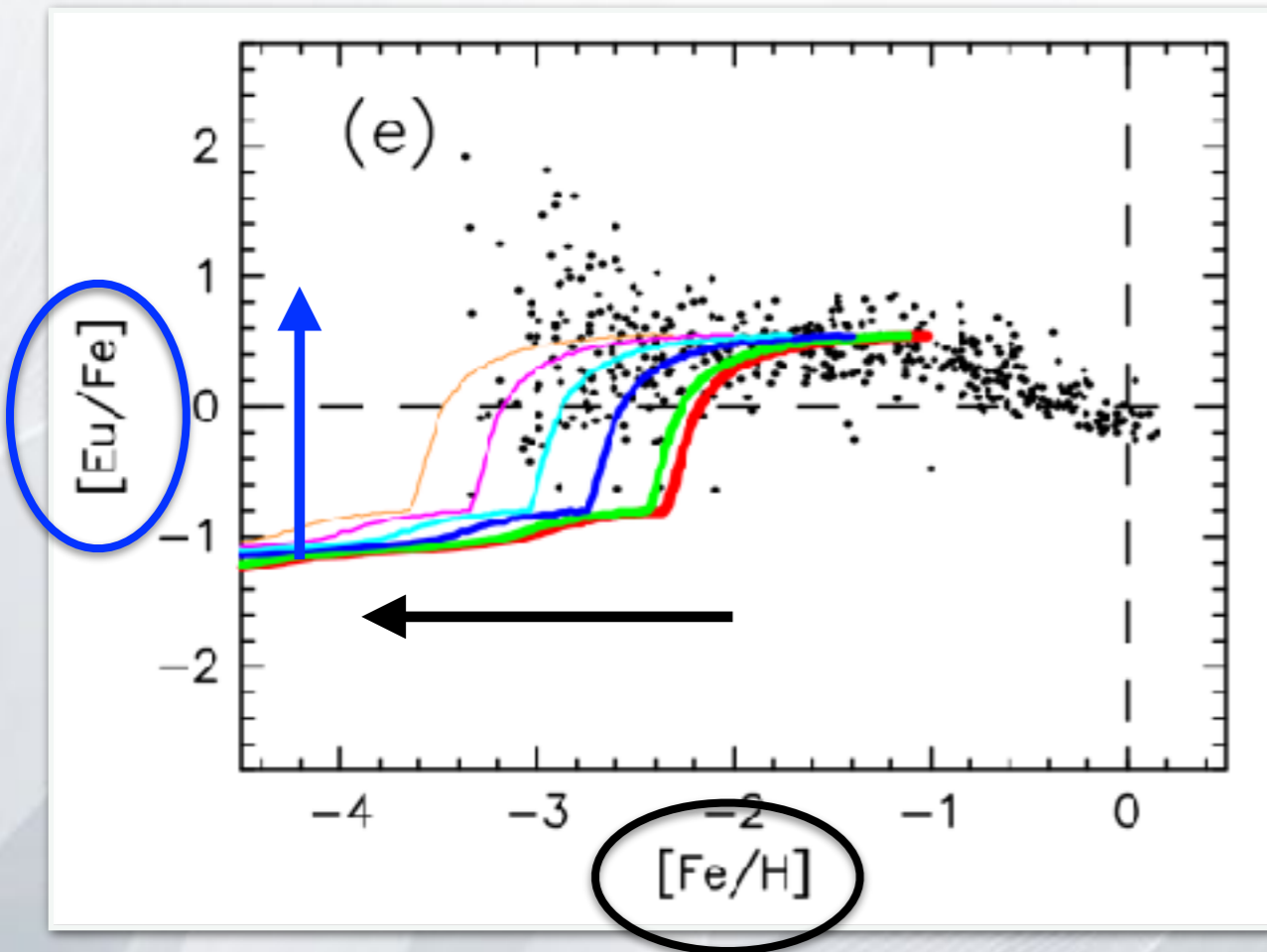
Enrichment Timing and Evolution of [Fe/H]

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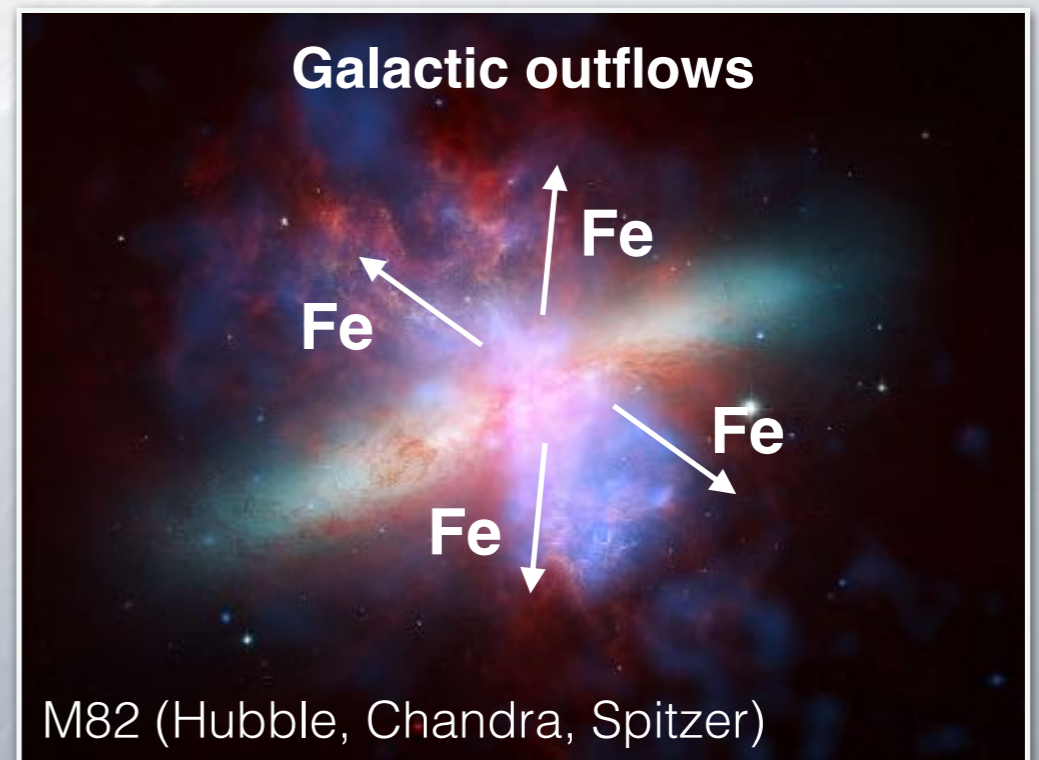
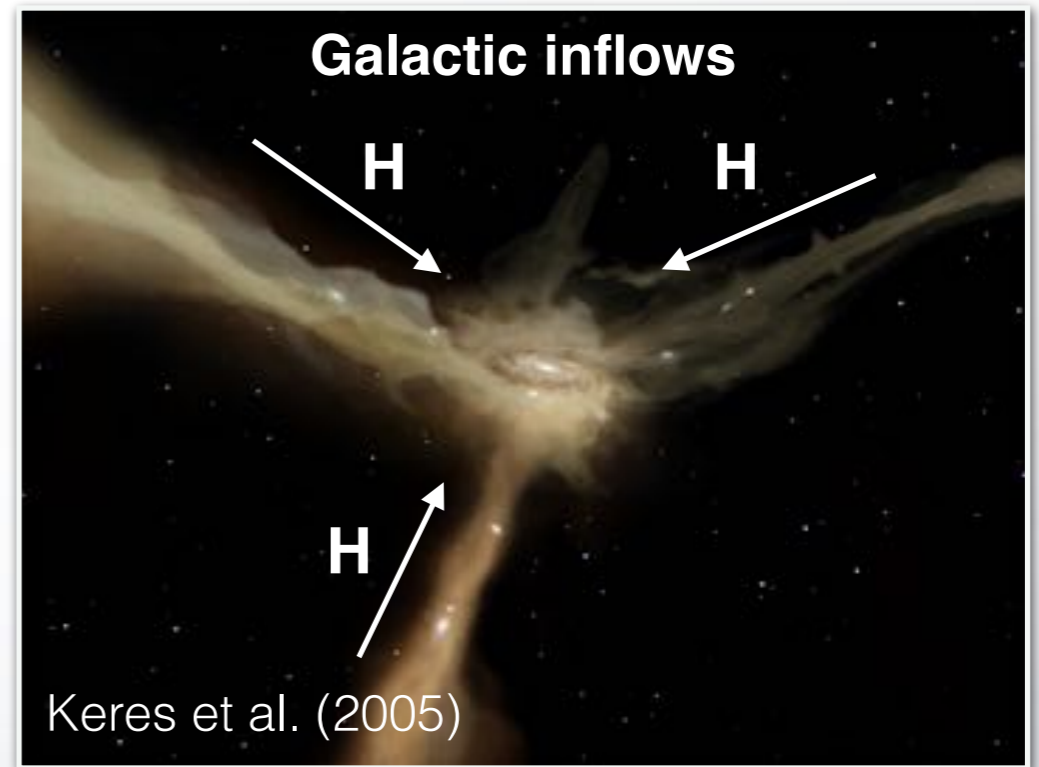
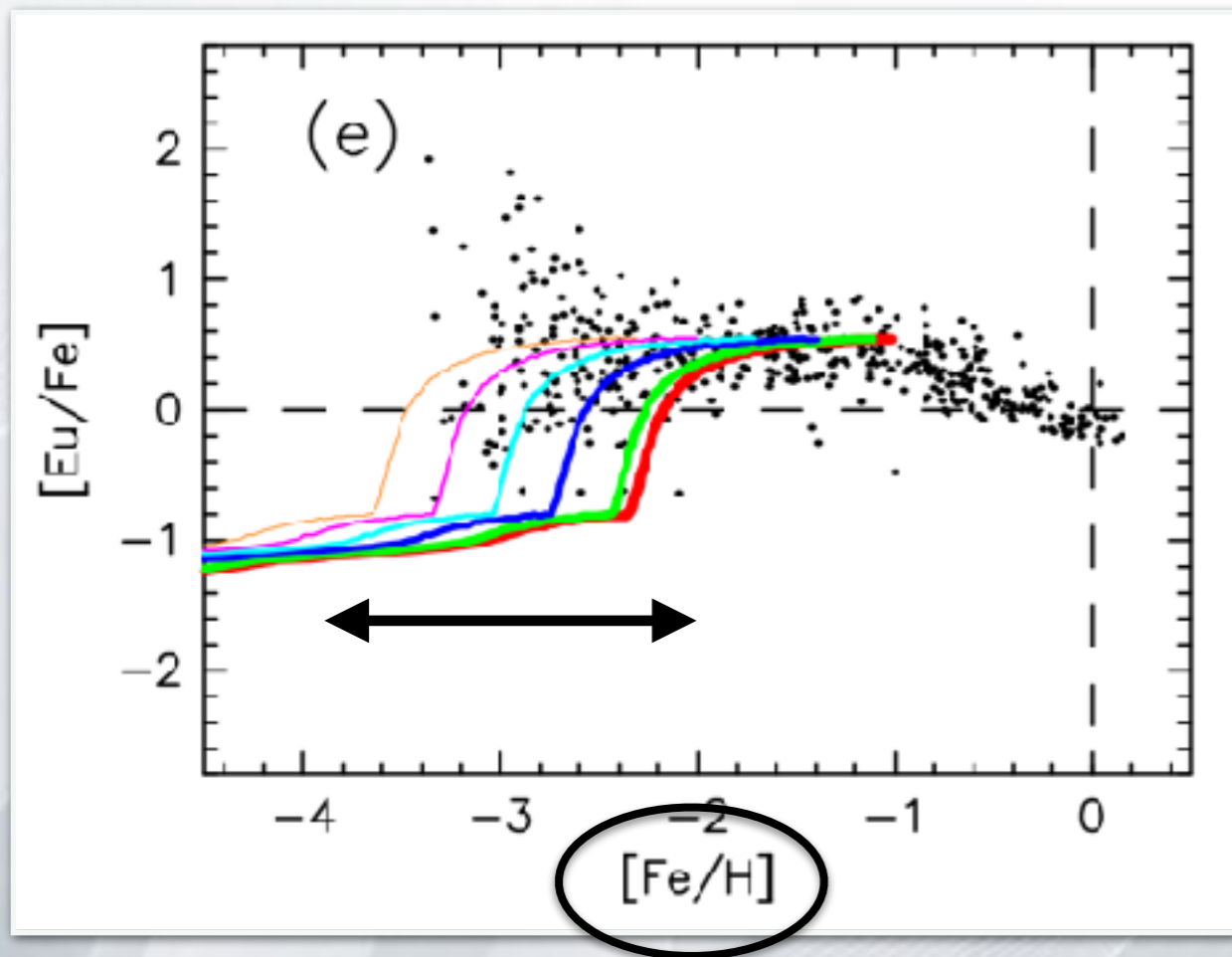
Enrichment Timing and Evolution of $[Fe/H]$

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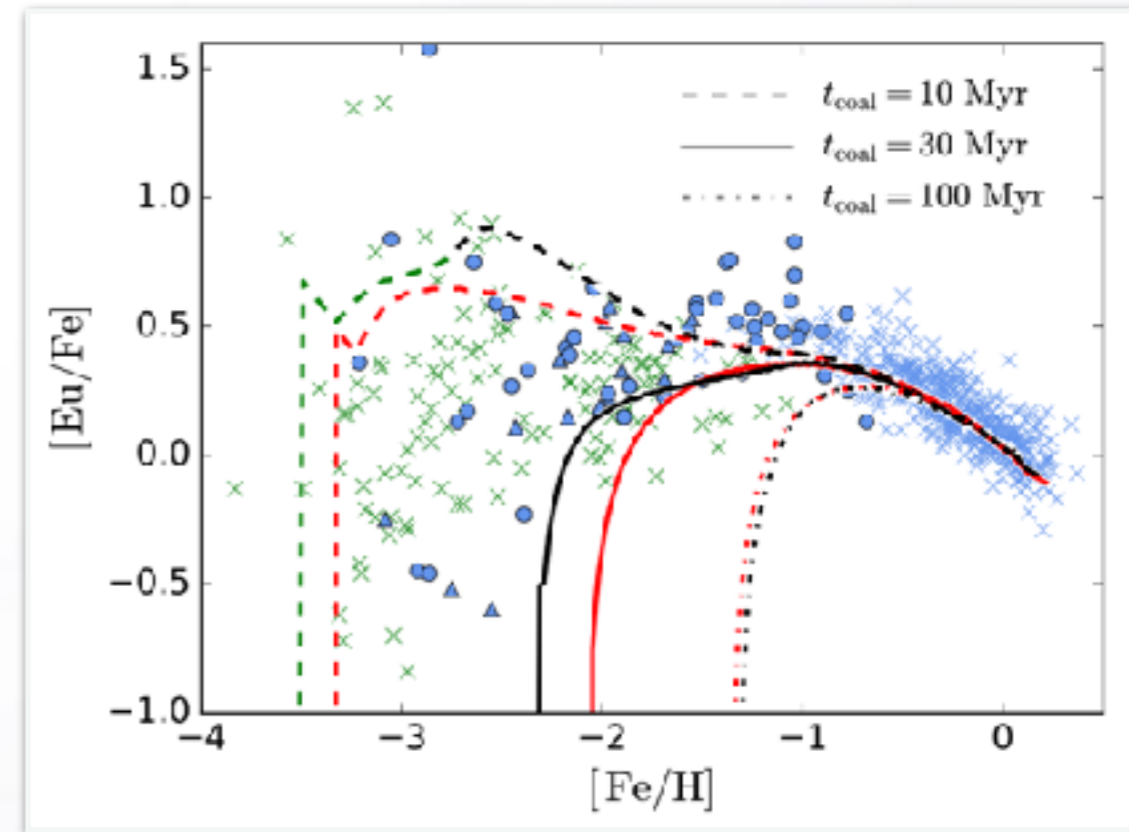


Enrichment Timing and Evolution of $[\text{Fe}/\text{H}]$

Ishimaru, Wanajo & Prantzos (2015)

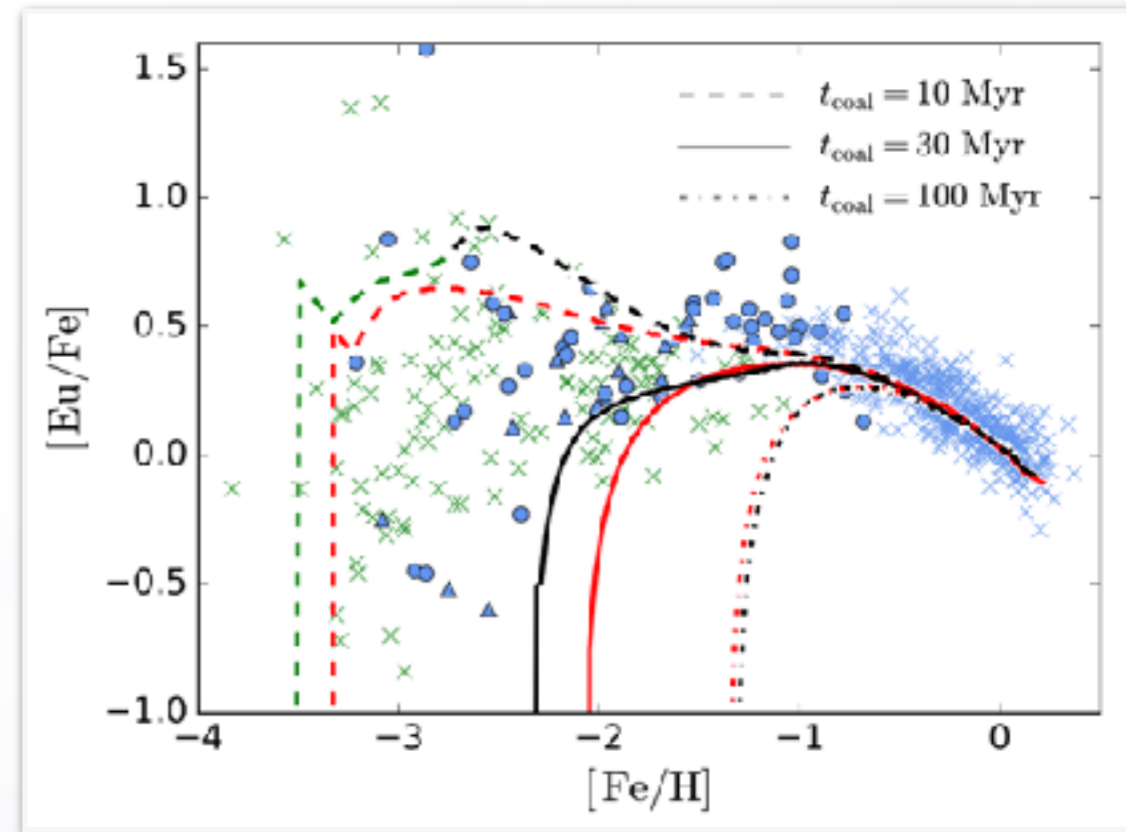
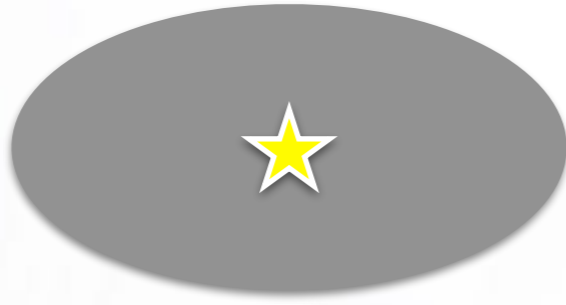


Physics Behind the [Eu/Fe]-[Fe/H] Plot

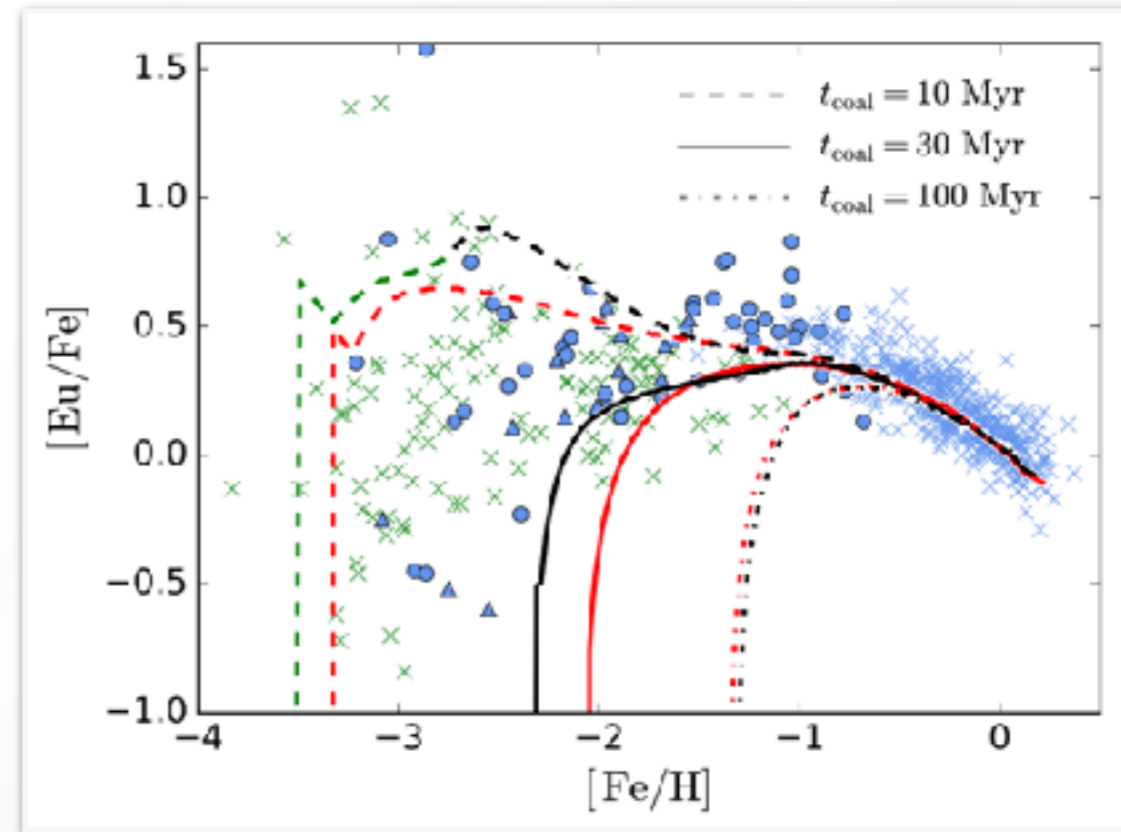
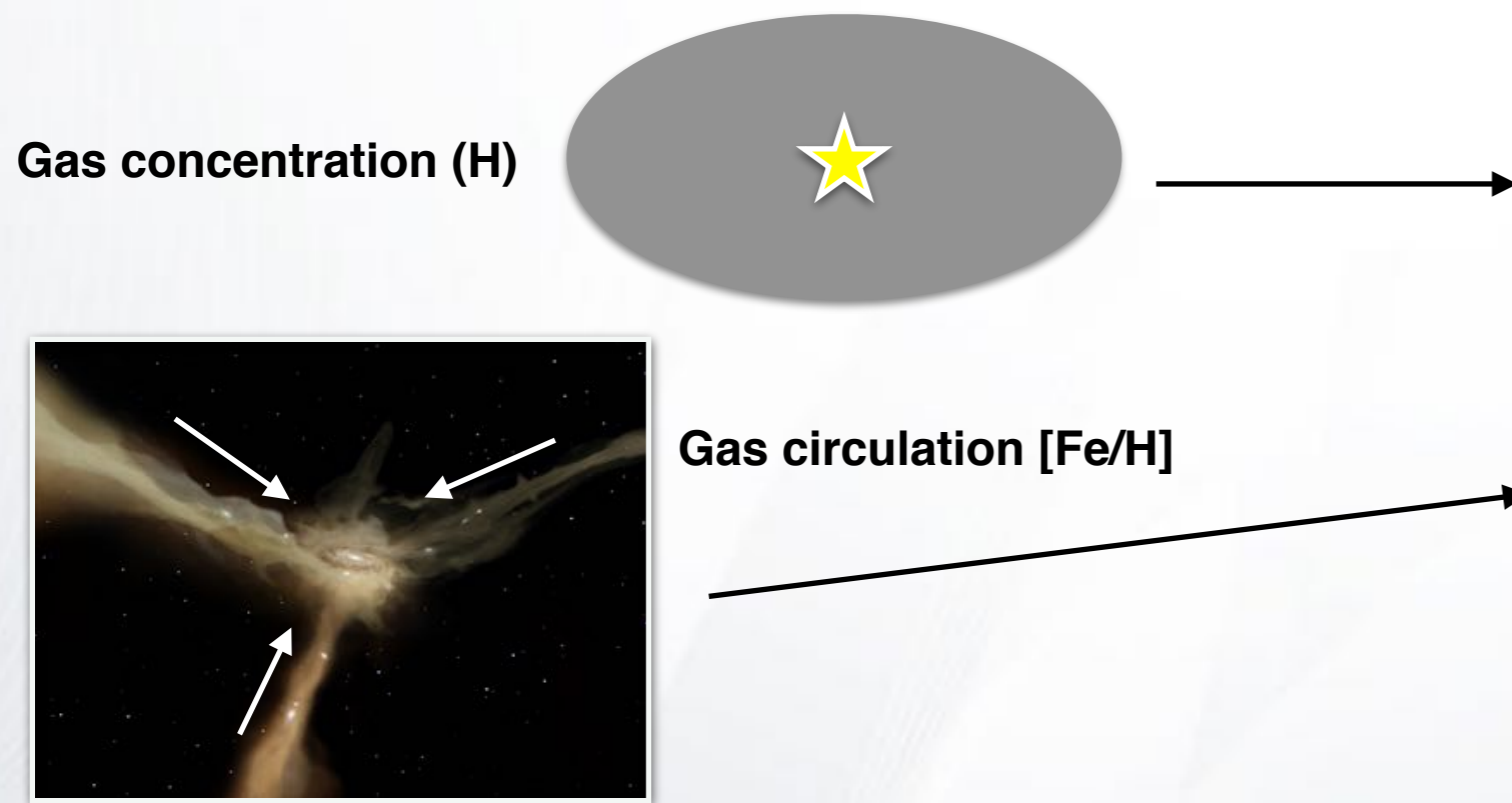


Physics Behind the [Eu/Fe]-[Fe/H] Plot

Gas concentration (H)

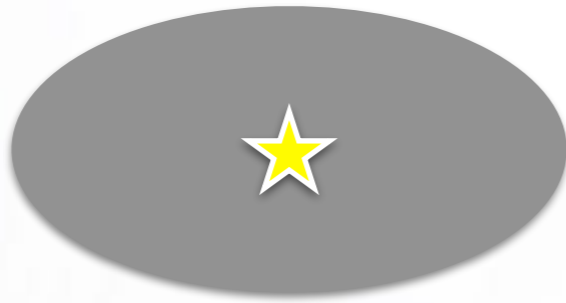


Physics Behind the [Eu/Fe]-[Fe/H] Plot

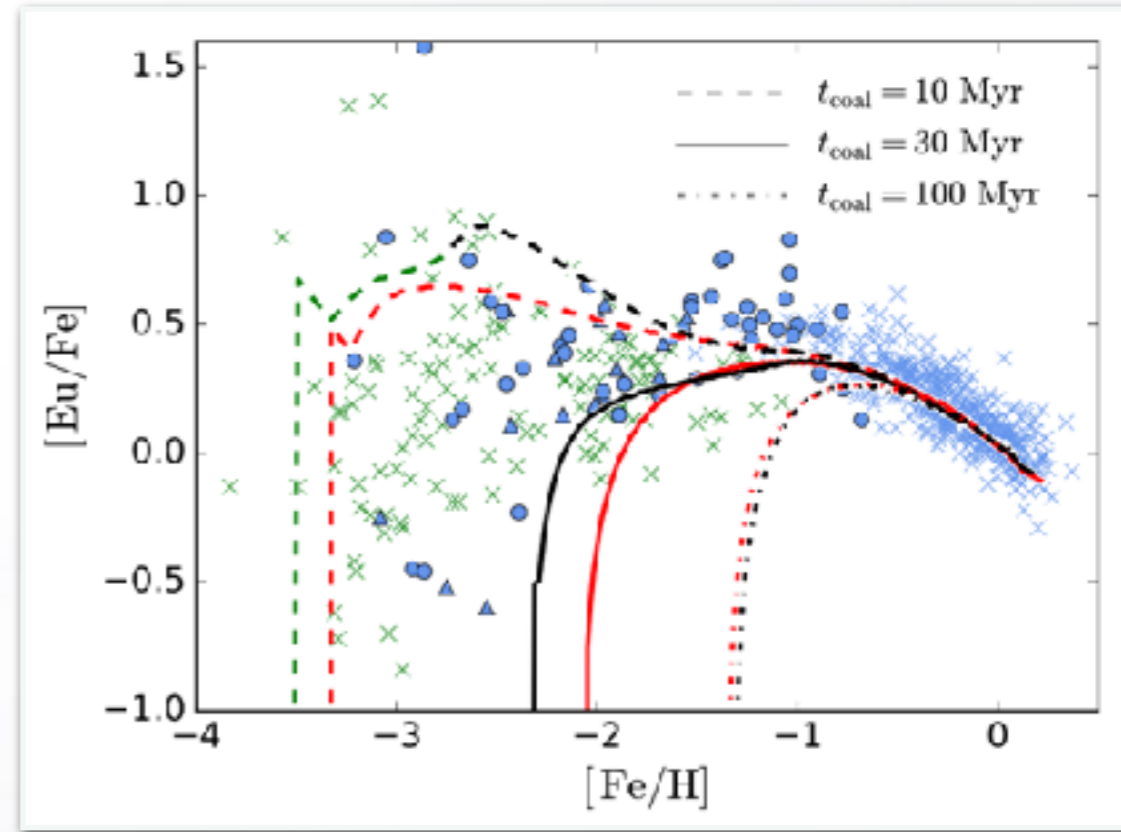
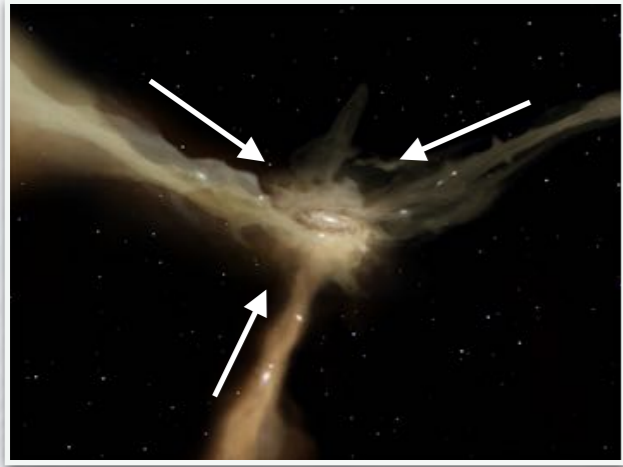


Physics Behind the [Eu/Fe]-[Fe/H] Plot

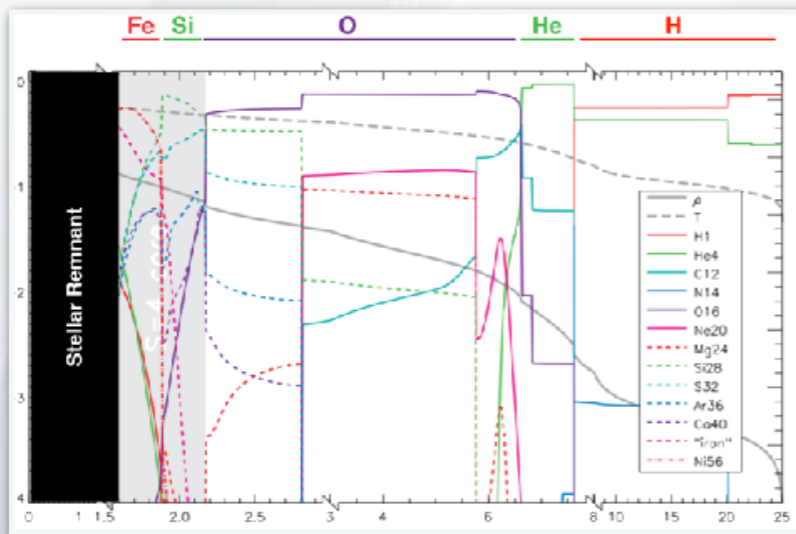
Gas concentration (H)



Gas circulation [Fe/H]

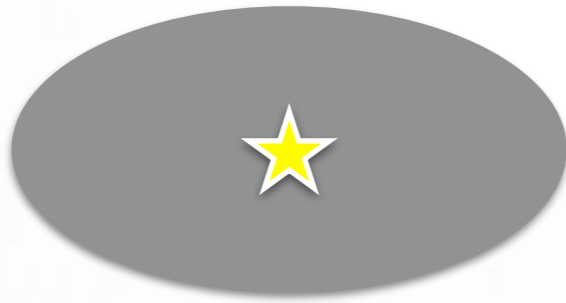


Stellar models (Fe)

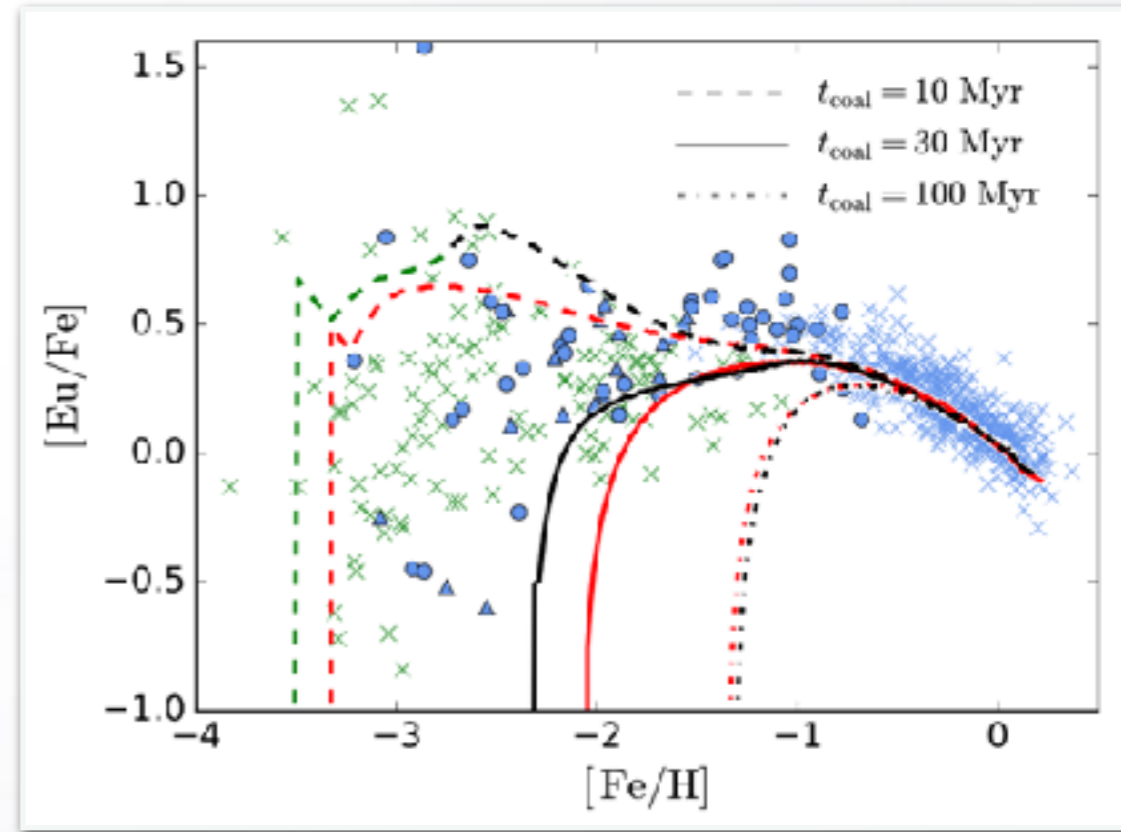
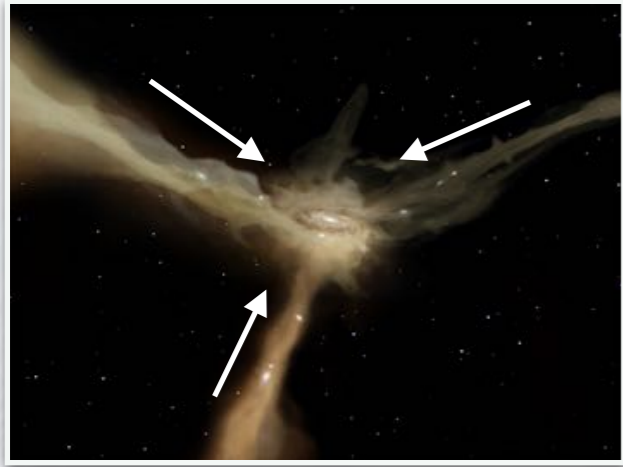


Physics Behind the [Eu/Fe]-[Fe/H] Plot

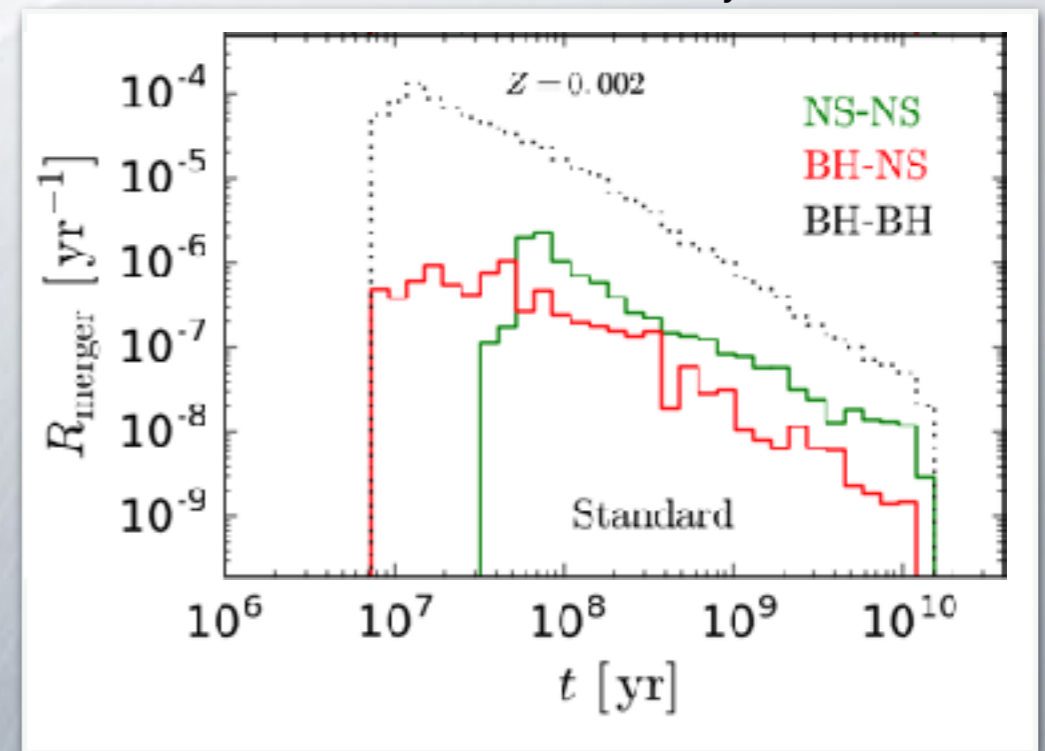
Gas concentration (H)



Gas circulation [Fe/H]

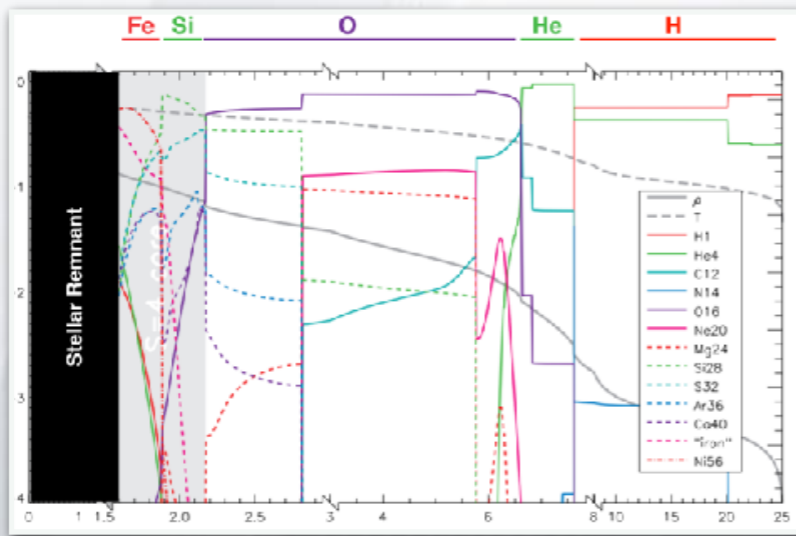


K. Belczynski's models

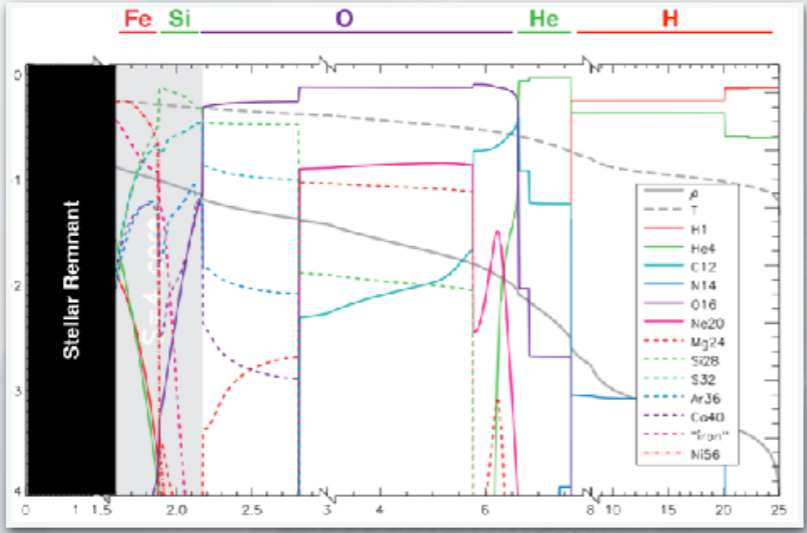
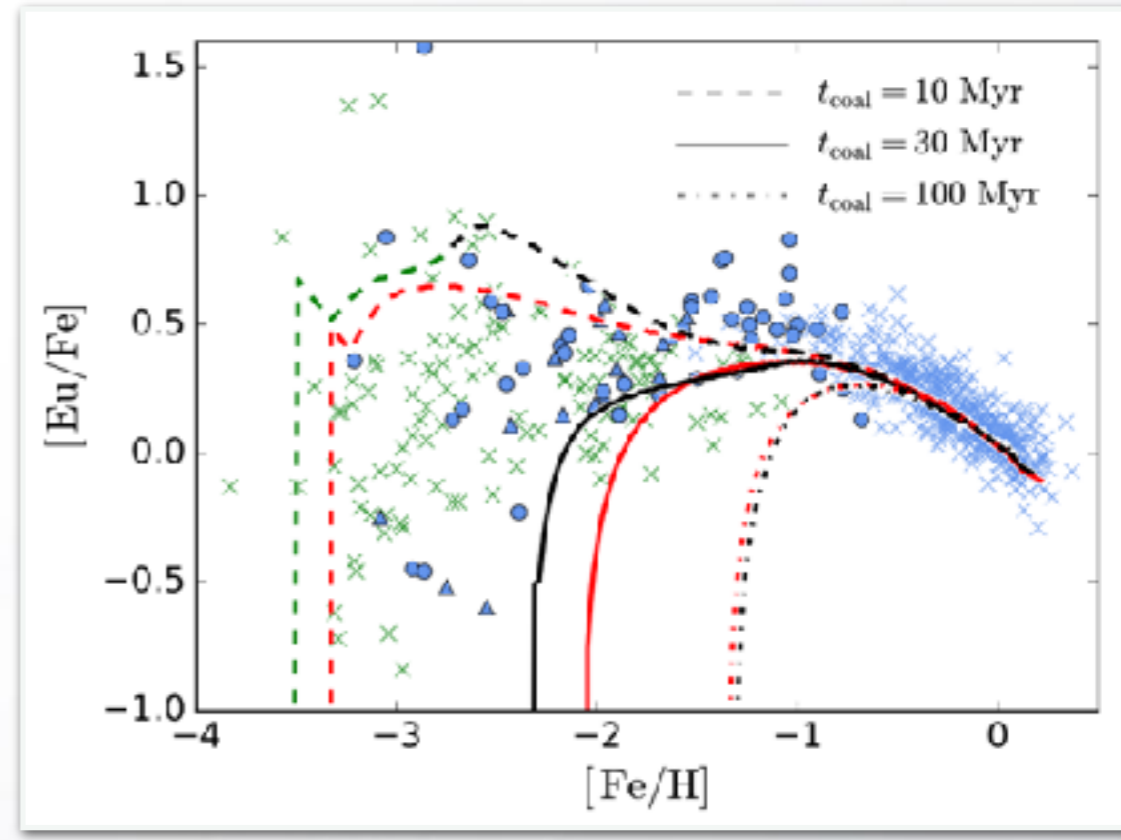
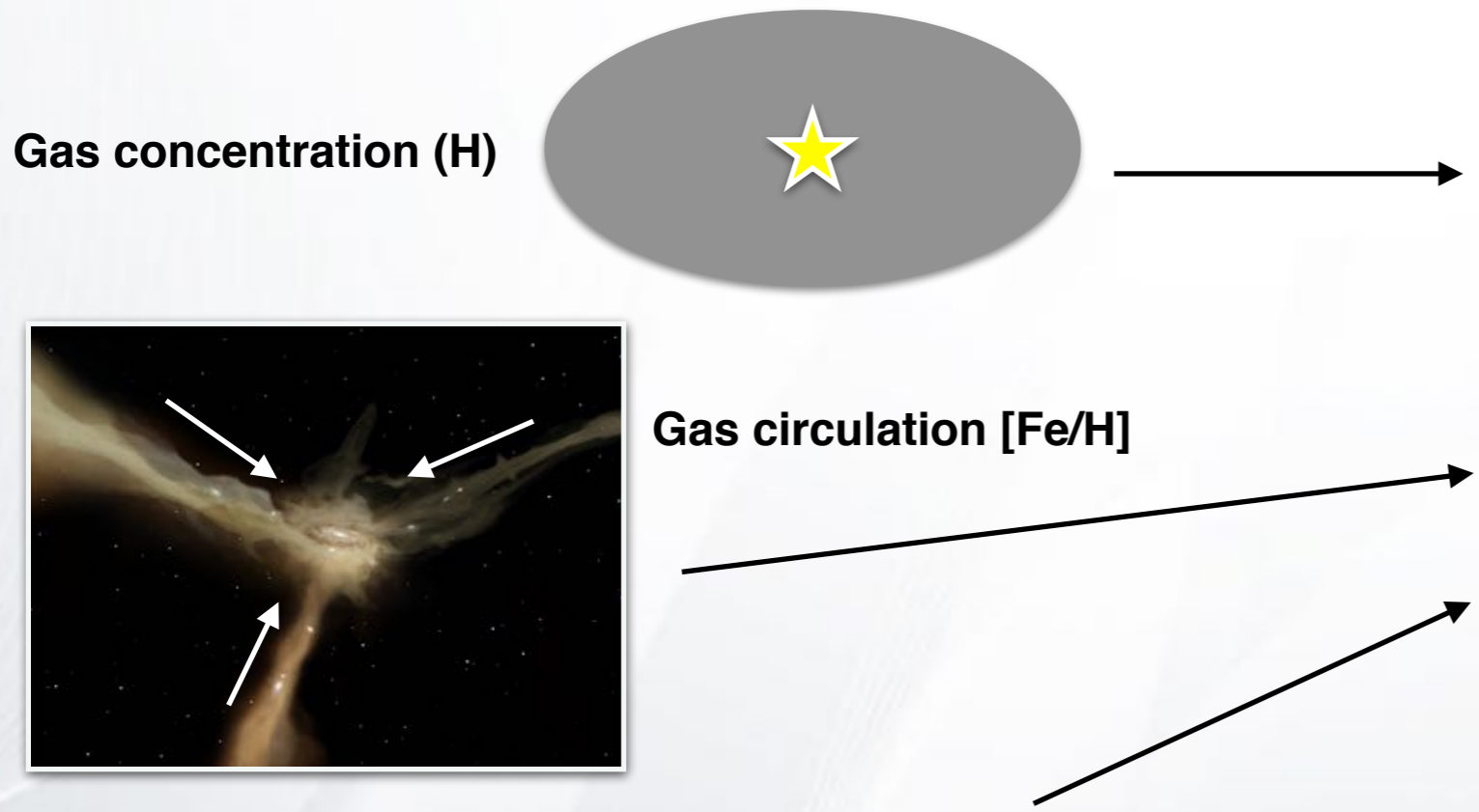


Merger rates of compact binary objects (Eu)

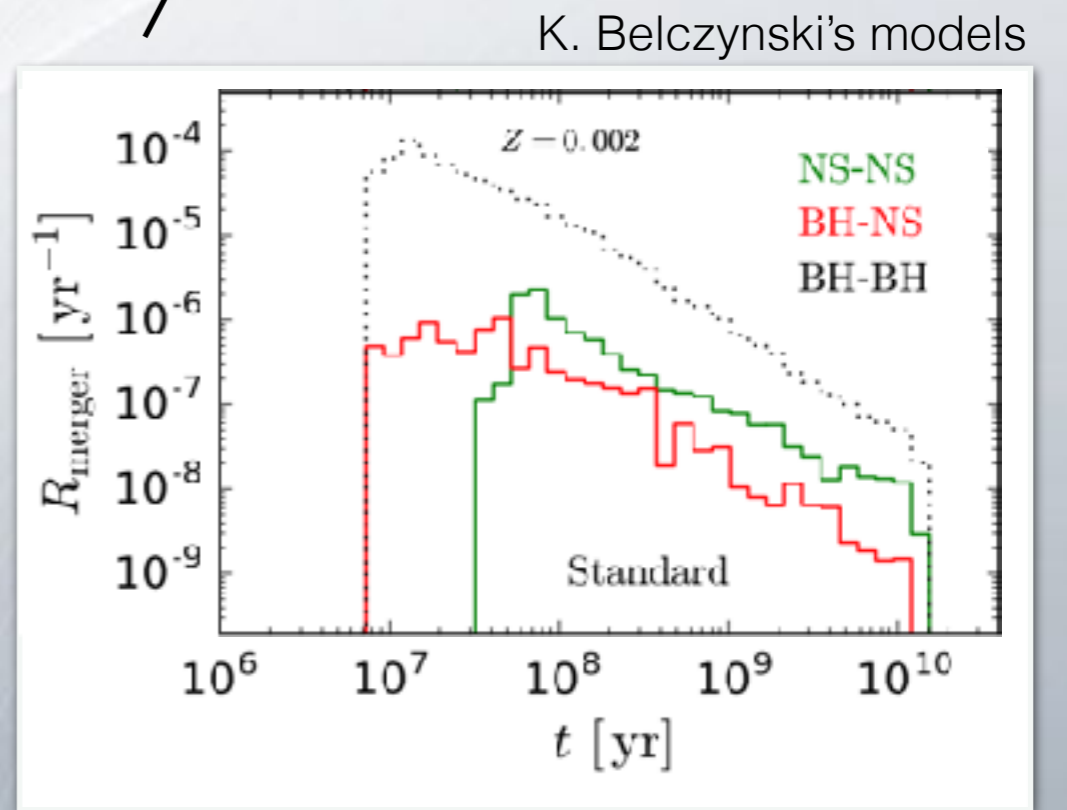
Stellar models (Fe)



Physics Behind the [Eu/Fe]-[Fe/H] Plot



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

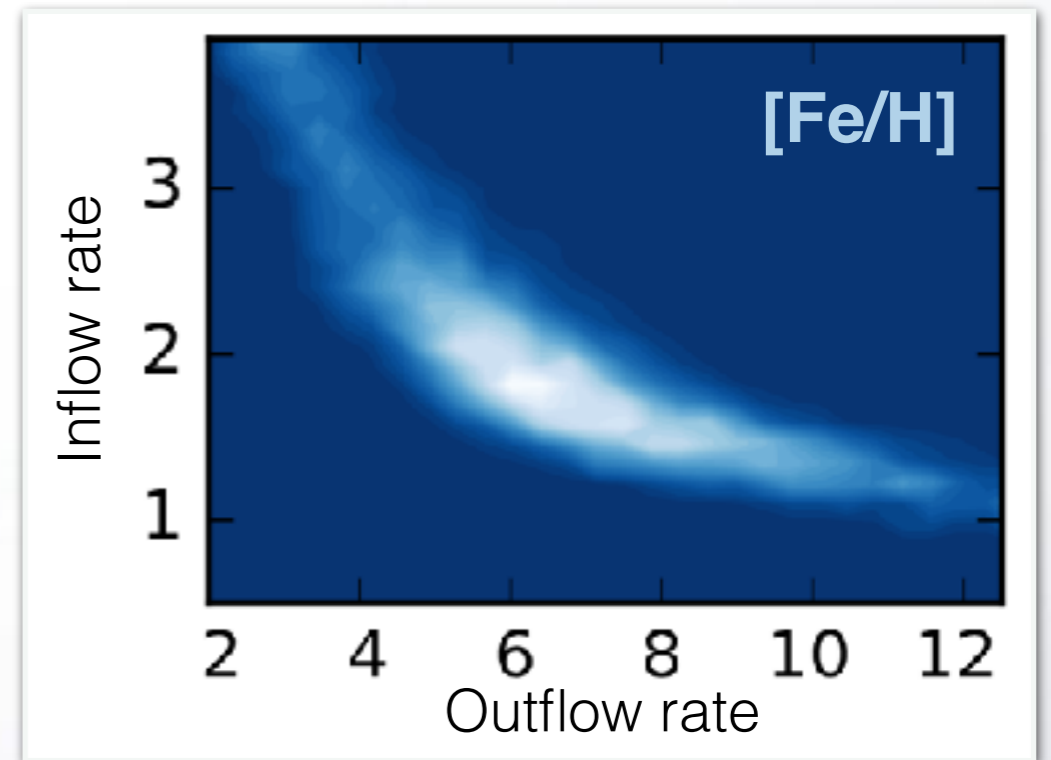


Merger rates of compact binary objects (Eu)

Breaking the Degeneracy

We need multiple constraints to break the degeneracy.

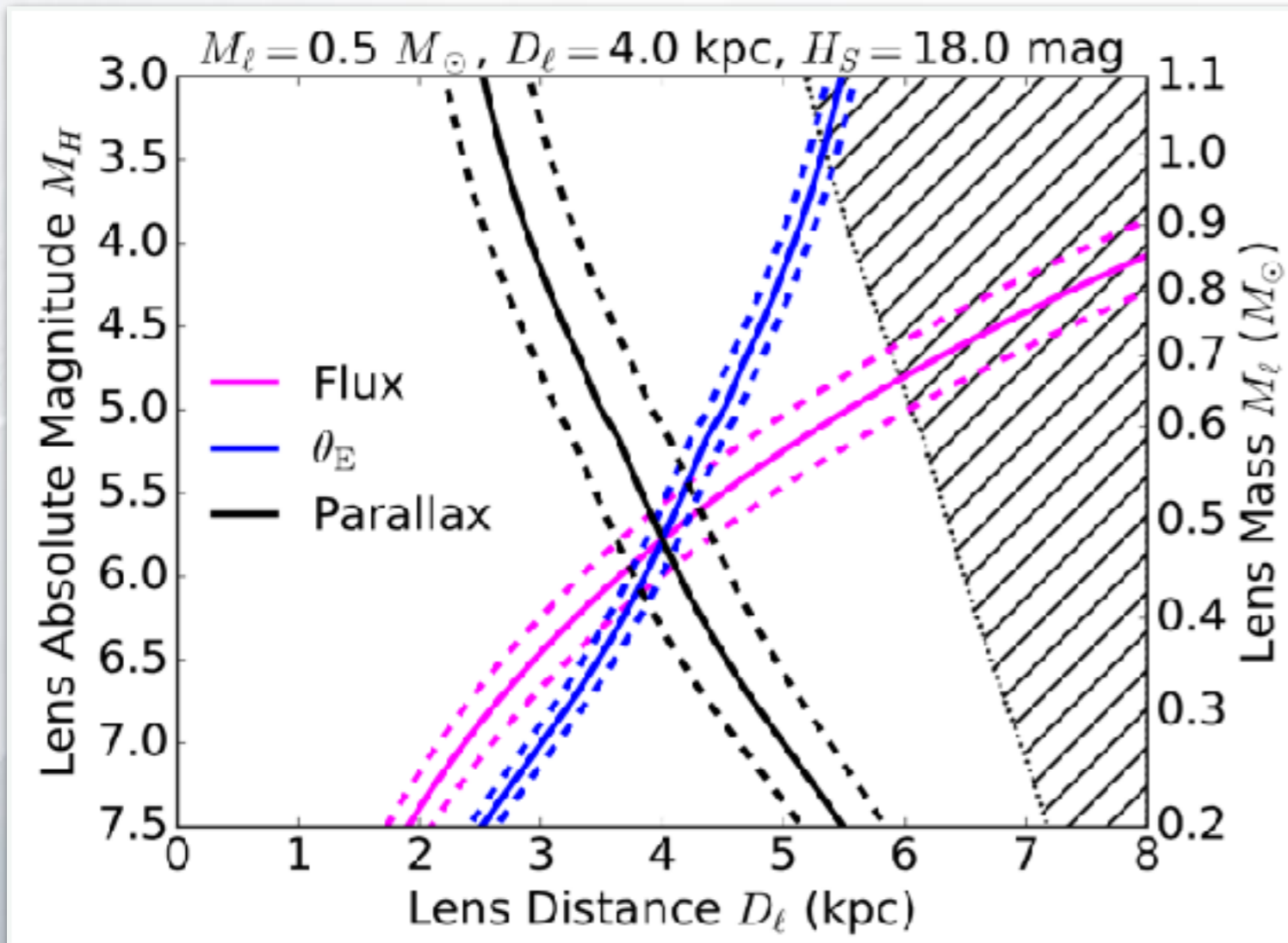
Côté, O'Shea, Ritter, et al. (2017)



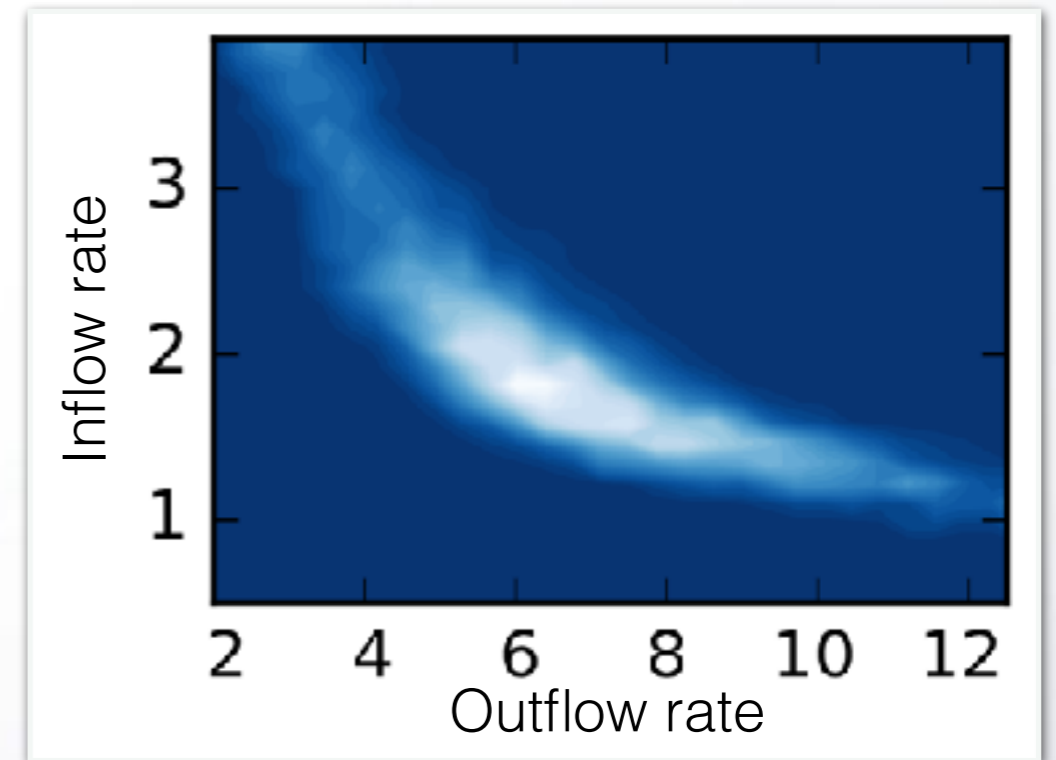
Breaking the Degeneracy

We need multiple constraints to break the degeneracy.

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



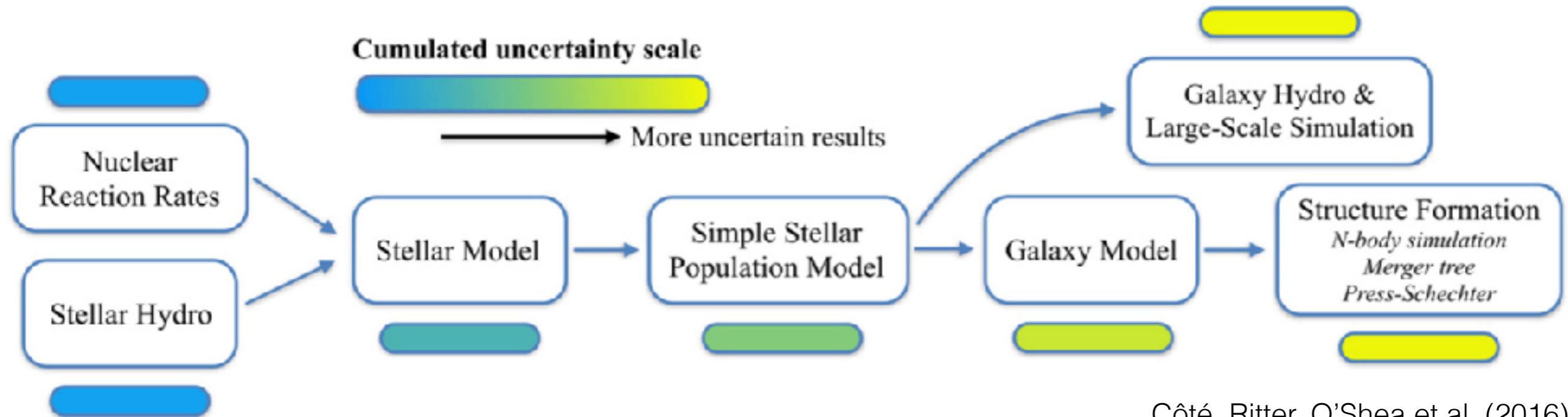
Côté, O'Shea, Ritter, et al. (2017)



Breaking the Degeneracy

We need multiple constraints to break the degeneracy.

We need to break the degeneracy at all scales.



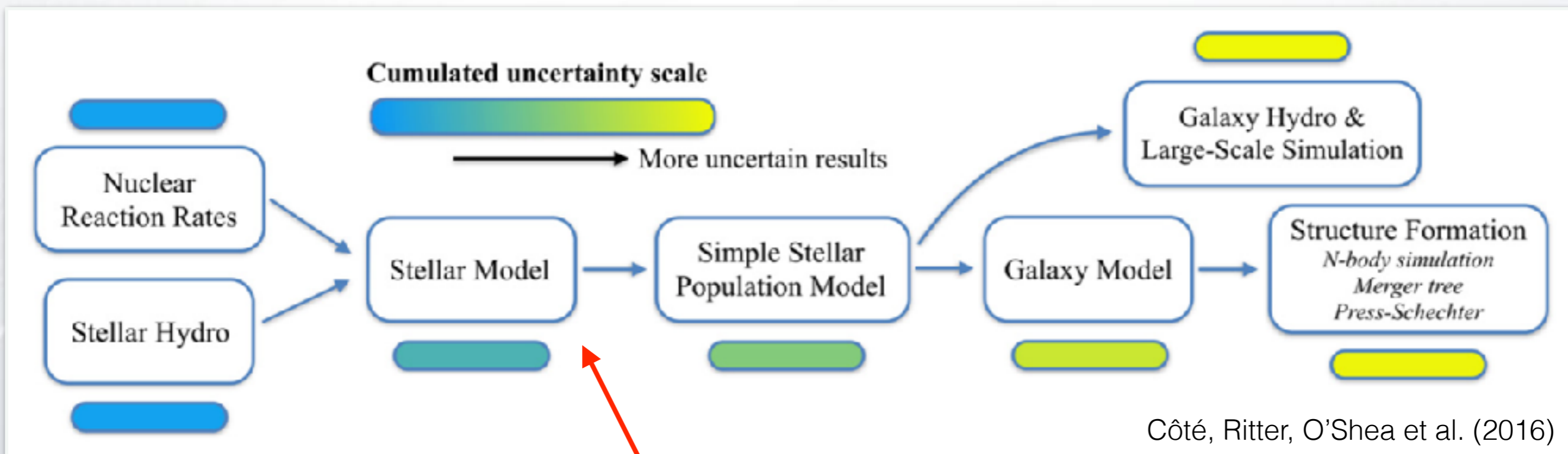
Côté, Ritter, O'Shea et al. (2016)

see also Côté, Ritter, Herwig, et al. (2017)

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Côté, Ritter, O'Shea et al. (2016)

see also Côté, Ritter, Herwig, et al. (2017)

Neutron star and black hole mass distributions



Conclusions

Understanding the evolution of stars and galaxies using chemical elements is a degenerate process, and the **stellar models are the foundation.**

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

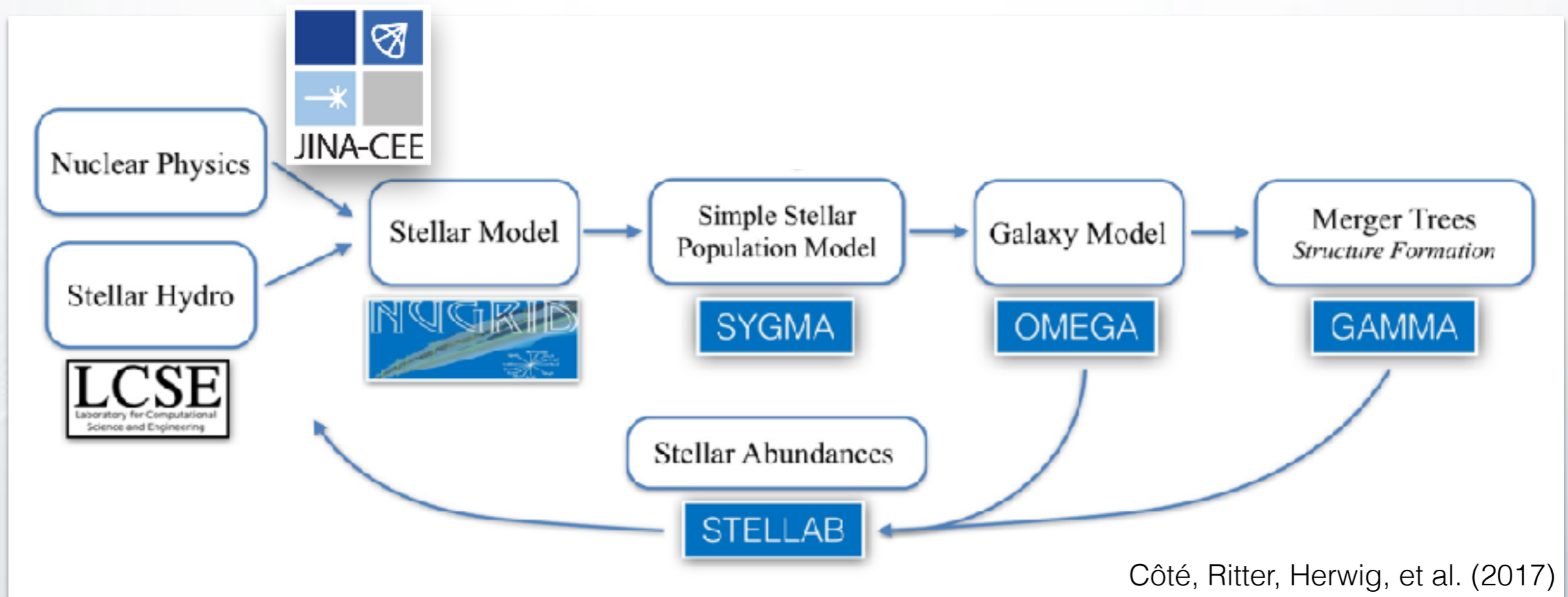
Conclusions

Understanding the evolution of stars and galaxies using chemical elements is a degenerate process, and the **stellar models are the foundation**.

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



- **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 **G**alaxies (*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/>