Connecting Nuclear Astrophysics to Cosmological Structure Formation

with Galactic Chemical Evolution

Benoit Côté

Postdoctoral Fellow

Collaborators

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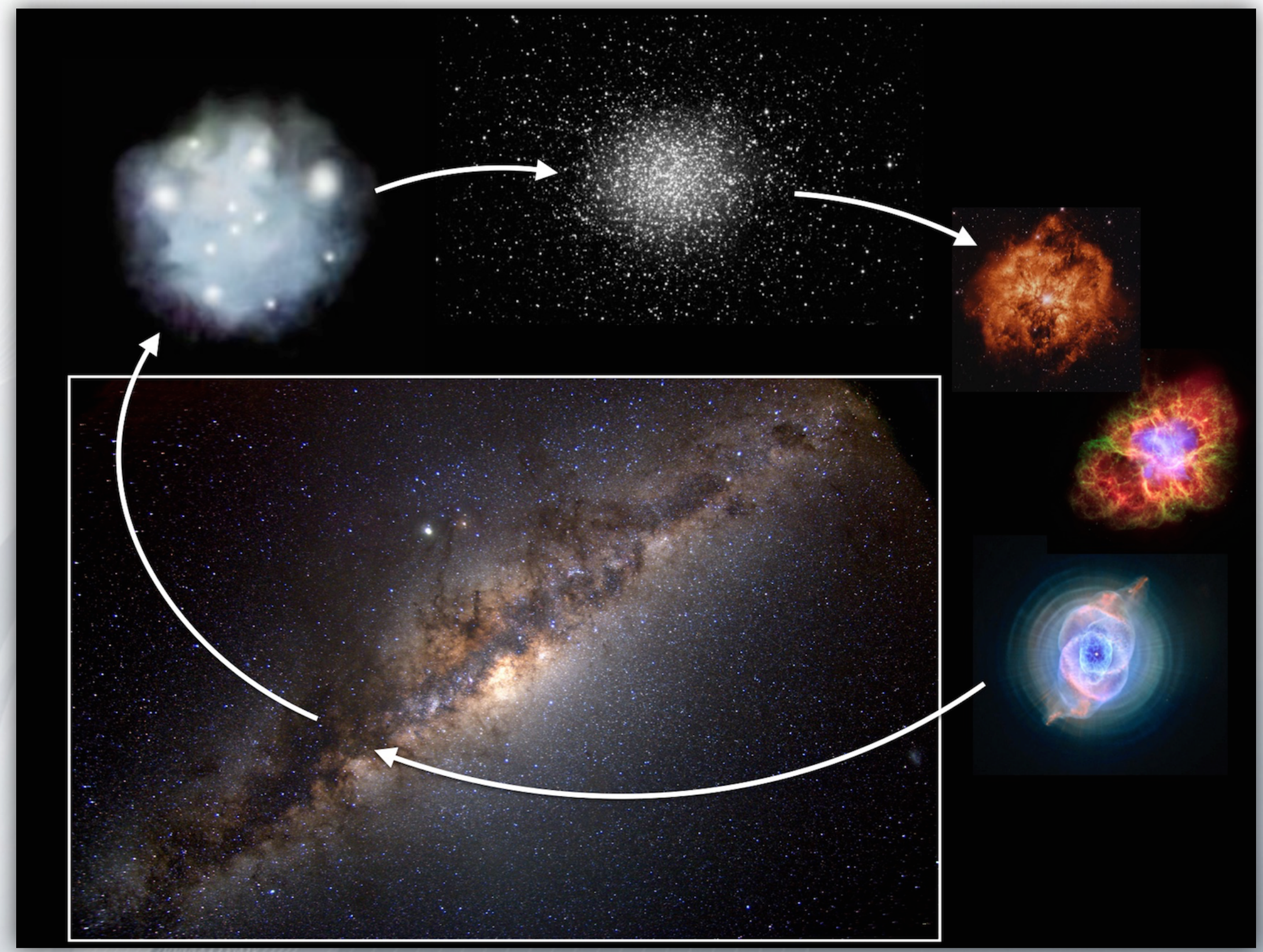
The Banff Centre

WNPPC 2017

February 16-19

LIFE CYCLE OF STARS



DEFINITION OF METALS IN ASTRONOMY

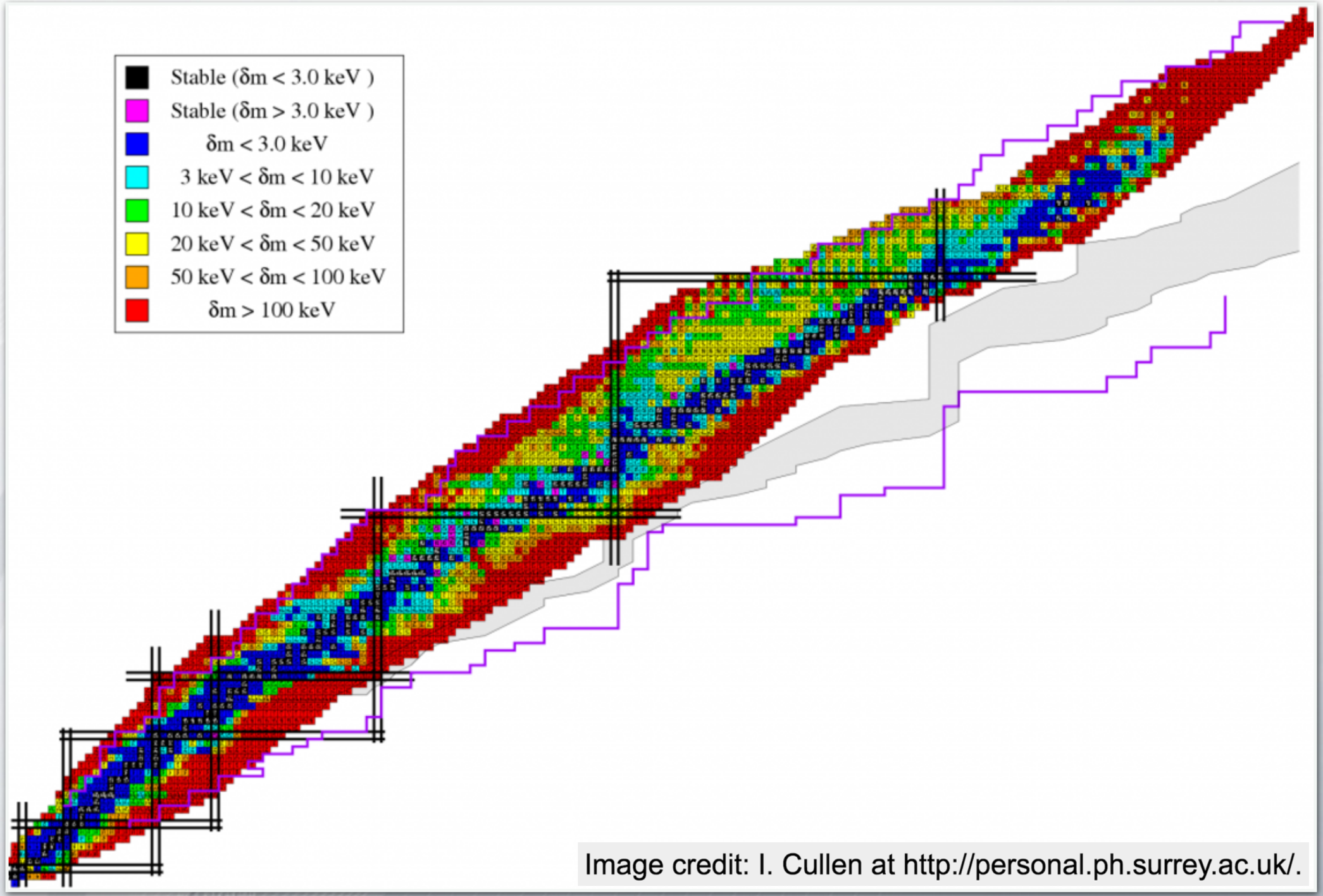


Image credit: I. Cullen at http://personal.ph.surrey.ac.uk/.

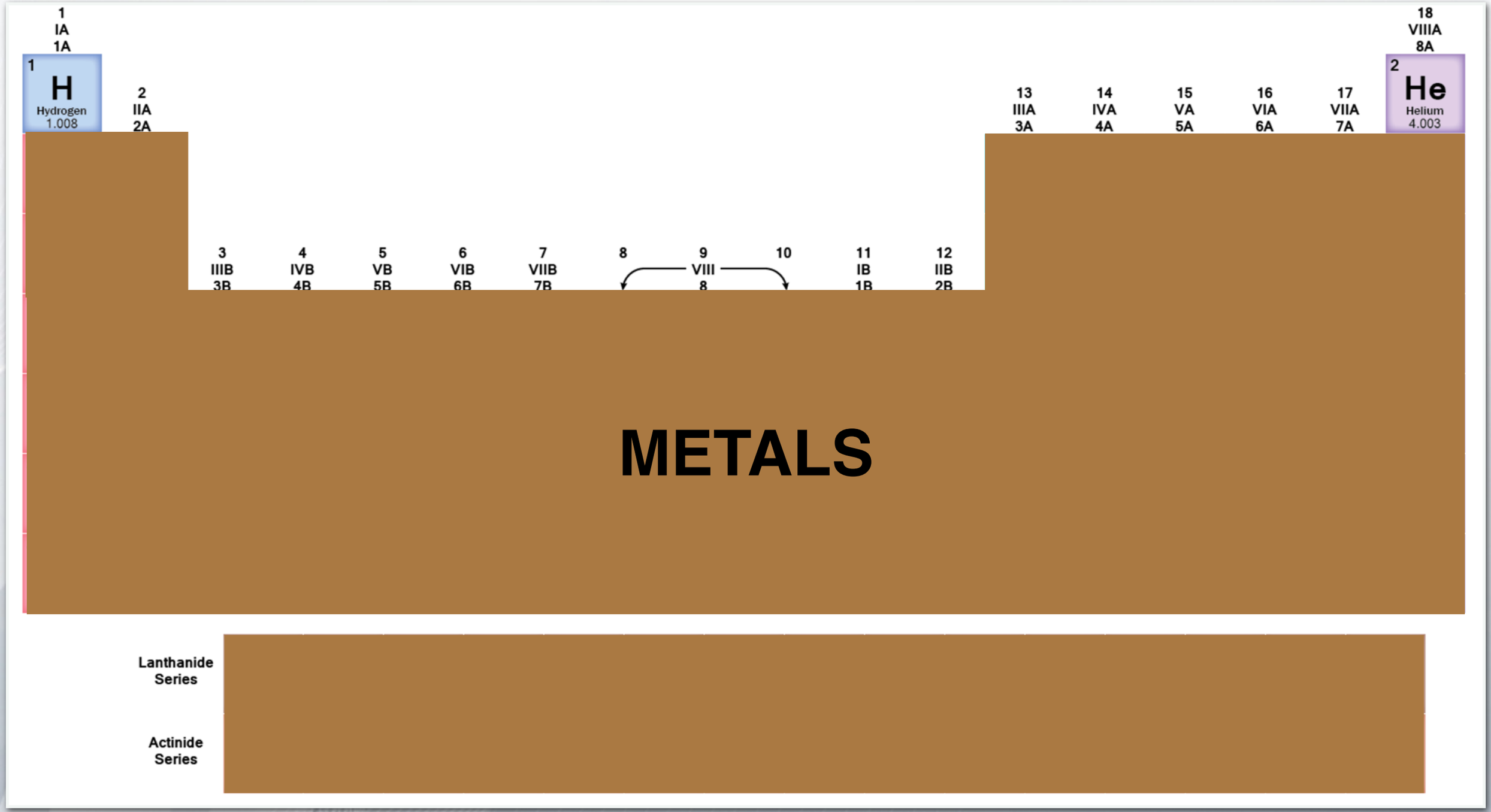
DEFINITION OF METALS IN ASTRONOMY

1 IA 1A	2 IIA 2A	3 IIIB 3B	4 IVB 4B	5 VB 5B	6 VIB 6B	7 VIIB 7B	8	9 VIII 8	10	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
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											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 55.933	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 78.09	35 Br Bromine 79.904	36 Kr Krypton 84.80
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 [269]	111 Rg Roentgenium [272]	112 Cn Copernicium [277]	113 Uut Ununtrium unknown	114 Fl Flerovium [289]	115 Uup Ununpentium unknown	116 Lv Livermorium [298]	117 Uus Ununseptium unknown	118 Uuo Ununoctium unknown

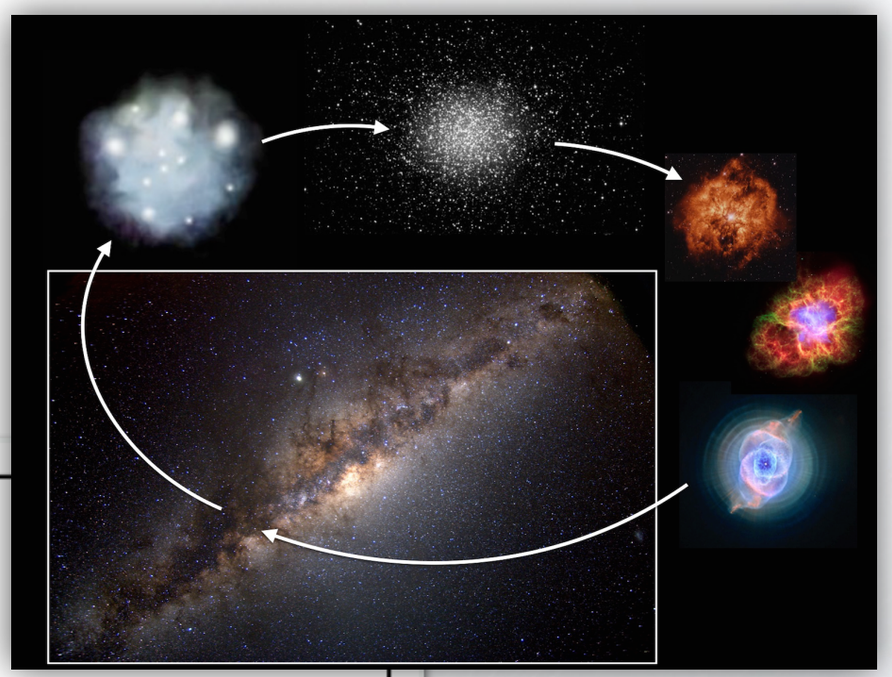
Lanthanide Series	57 La Lanthanum 138.906	58 Ce Cerium 140.115	59 Pr Praseodymium 140.908	60 Nd Neodymium 144.24	61 Pm Promethium 144.913	62 Sm Samarium 150.36	63 Eu Europium 151.966	64 Gd Gadolinium 157.25	65 Tb Terbium 158.925	66 Dy Dysprosium 162.50	67 Ho Holmium 164.930	68 Er Erbium 167.26	69 Tm 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 231.036	92 U Uranium 238.029	93 Np Neptunium 237.048	94 Pu Plutonium 244.064	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]

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

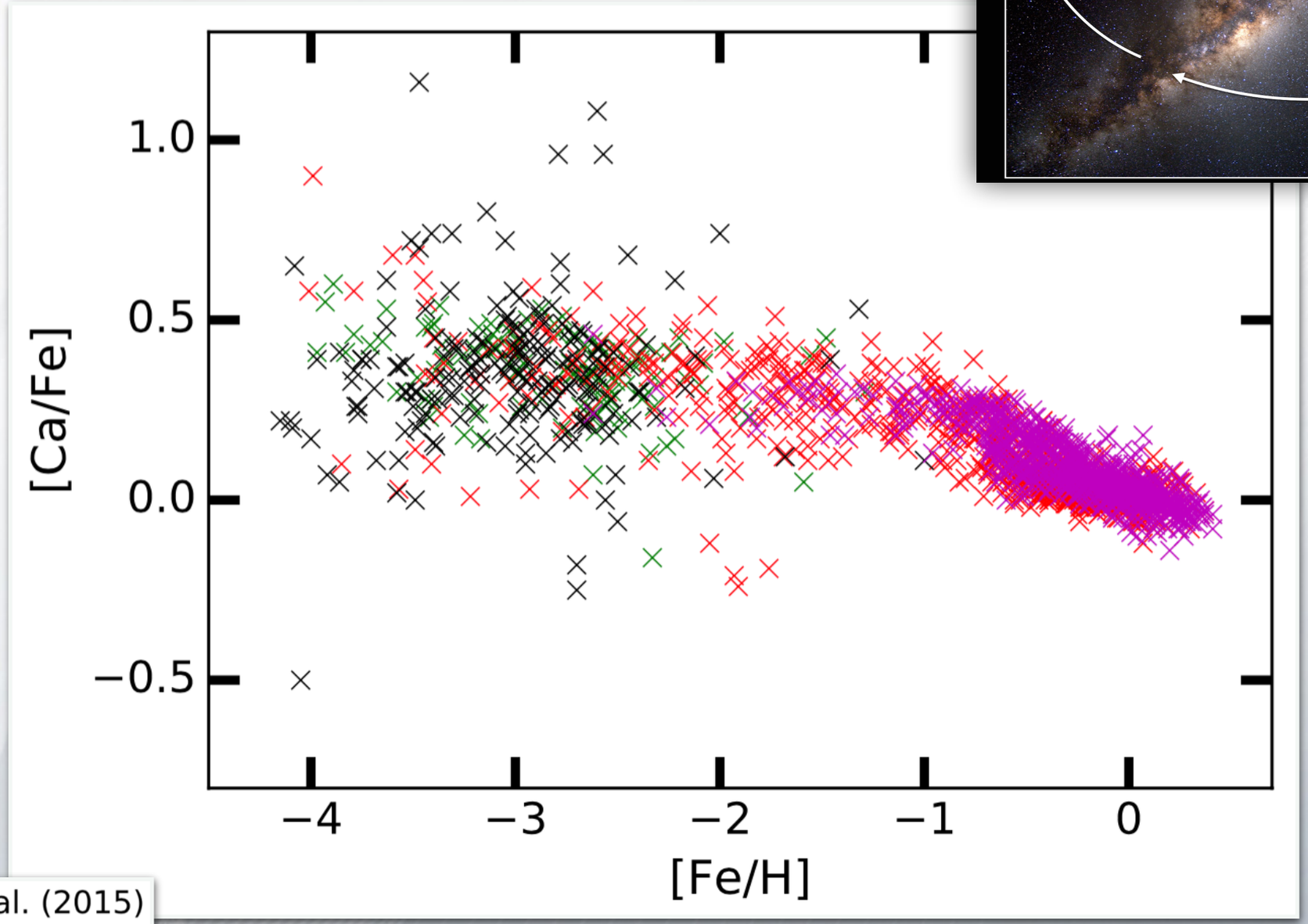
DEFINITION OF METALS IN ASTRONOMY



GALACTIC CHEMICAL EVOLUTION



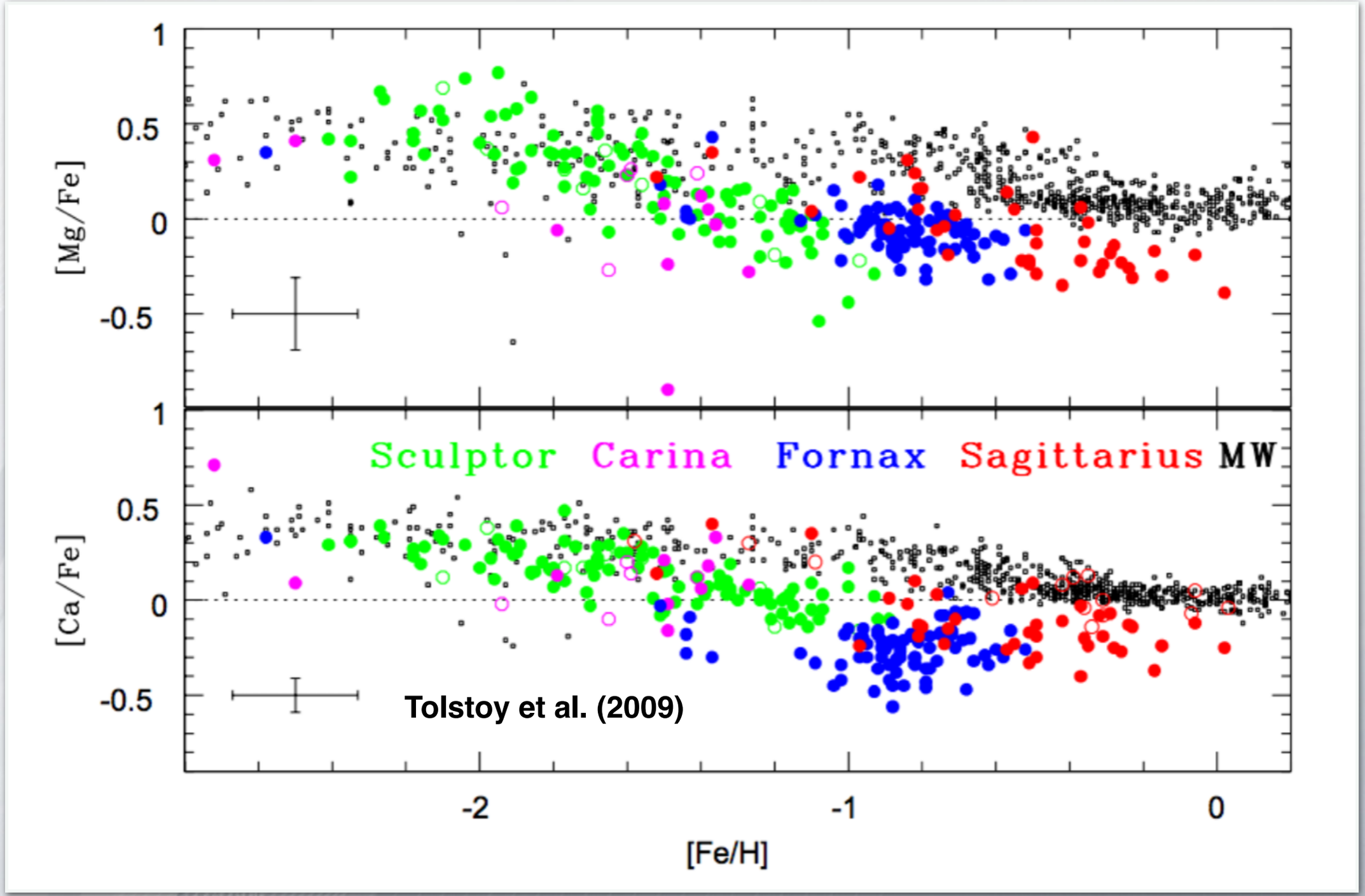
Milky Way galaxy



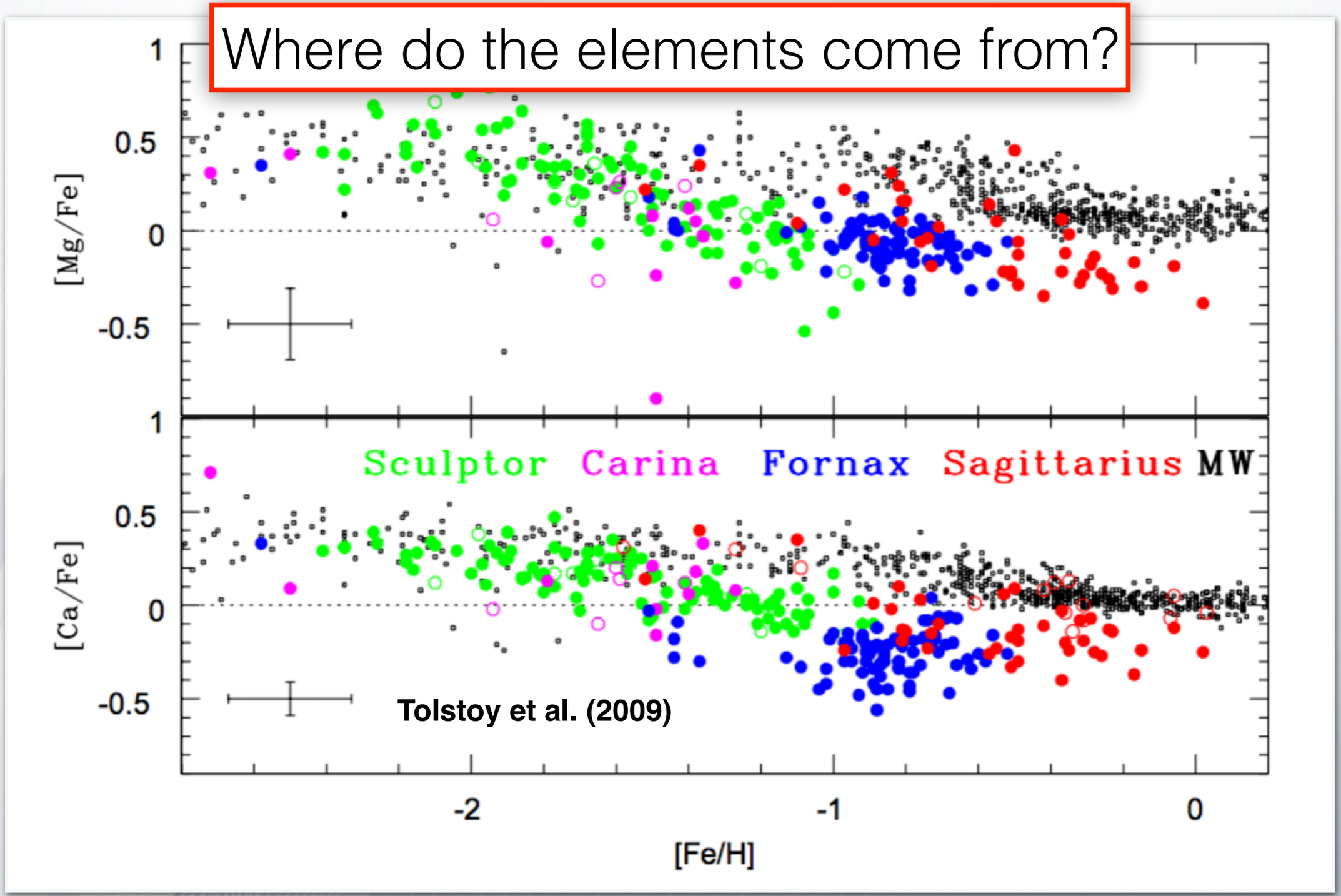
× × Jacobsen et al. (2015)
× × Venn et al. (2004) **
× × Yong et al. (2013)
× × Bensby et al. (2014)

$$[A/B] = \log(n_A/n_B) - \log(n_A/n_B)_\odot$$

GALACTIC CHEMICAL EVOLUTION



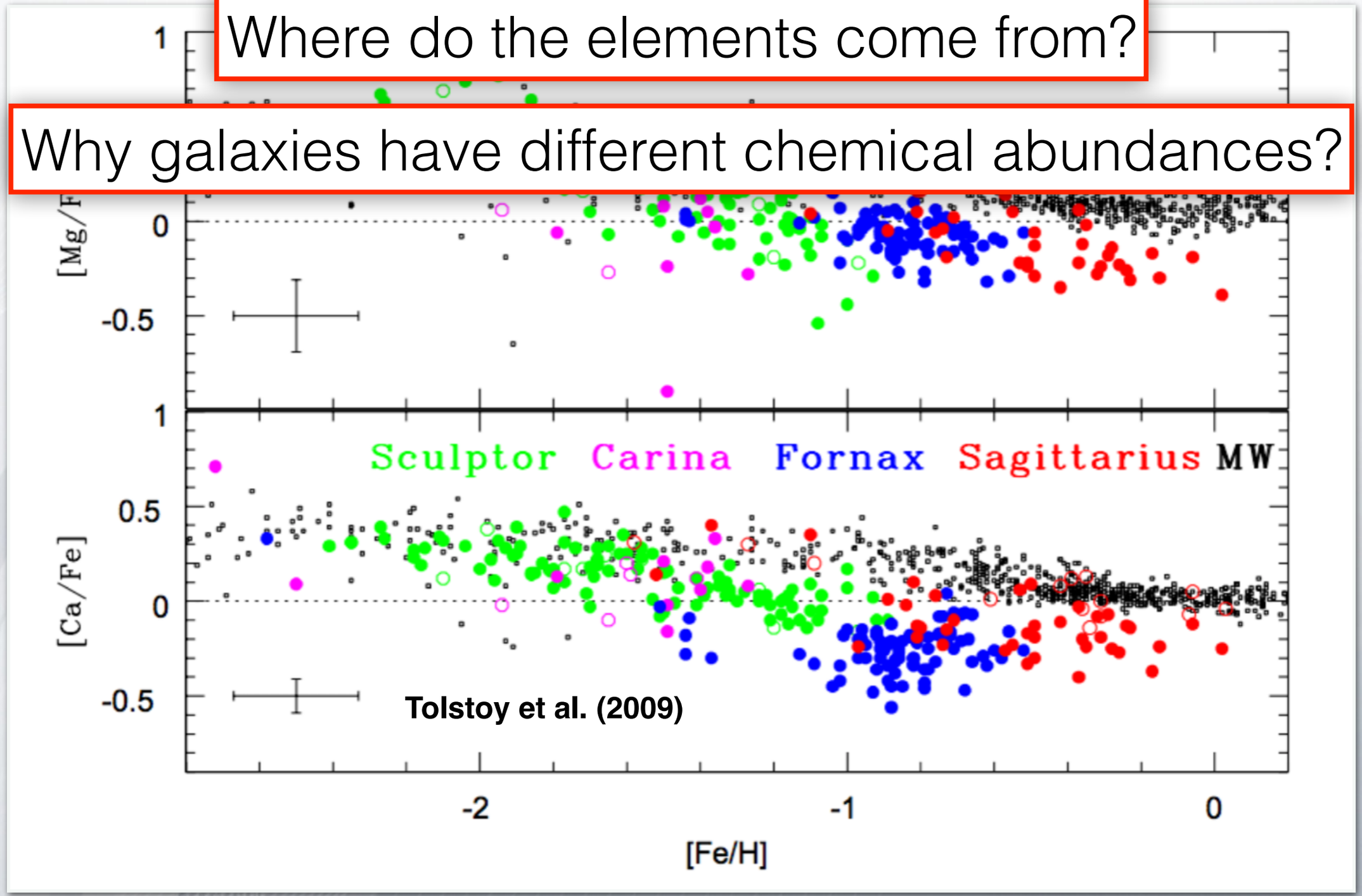
GALACTIC CHEMICAL EVOLUTION



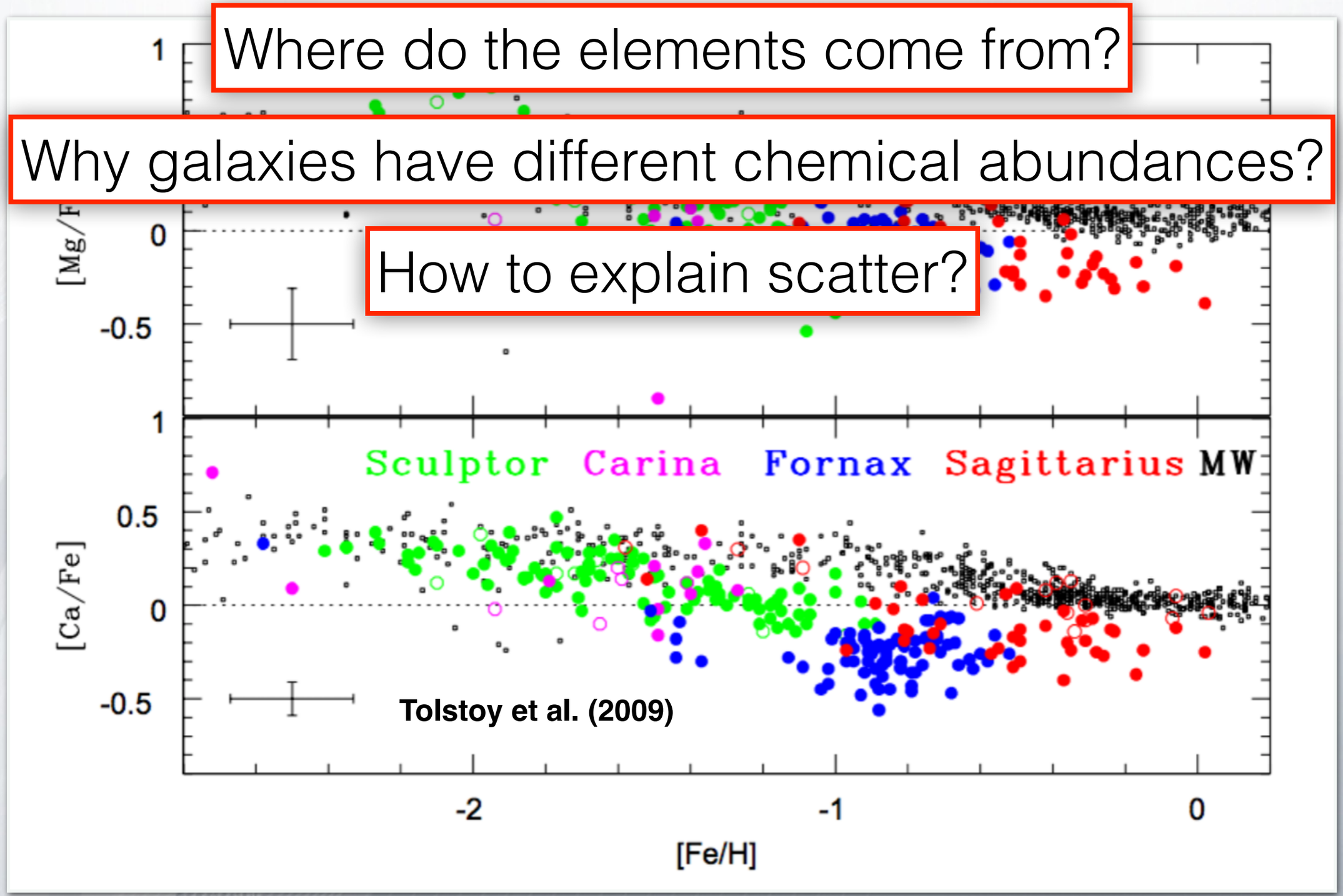
GALACTIC CHEMICAL EVOLUTION

Where do the elements come from?

Why galaxies have different chemical abundances?



GALACTIC CHEMICAL EVOLUTION



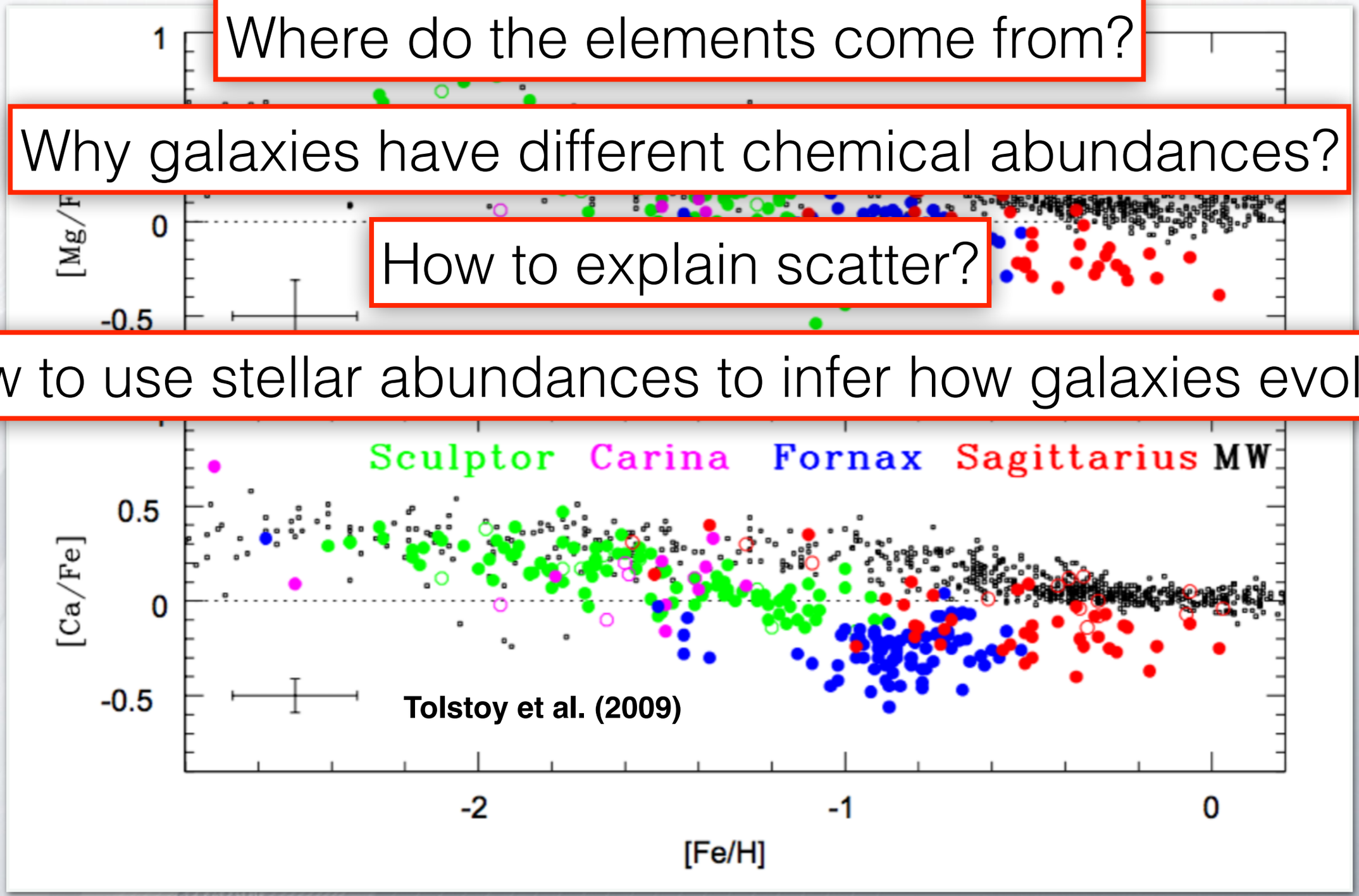
GALACTIC CHEMICAL EVOLUTION

Where do the elements come from?

Why galaxies have different chemical abundances?

How to explain scatter?

How to use stellar abundances to infer how galaxies evolve?



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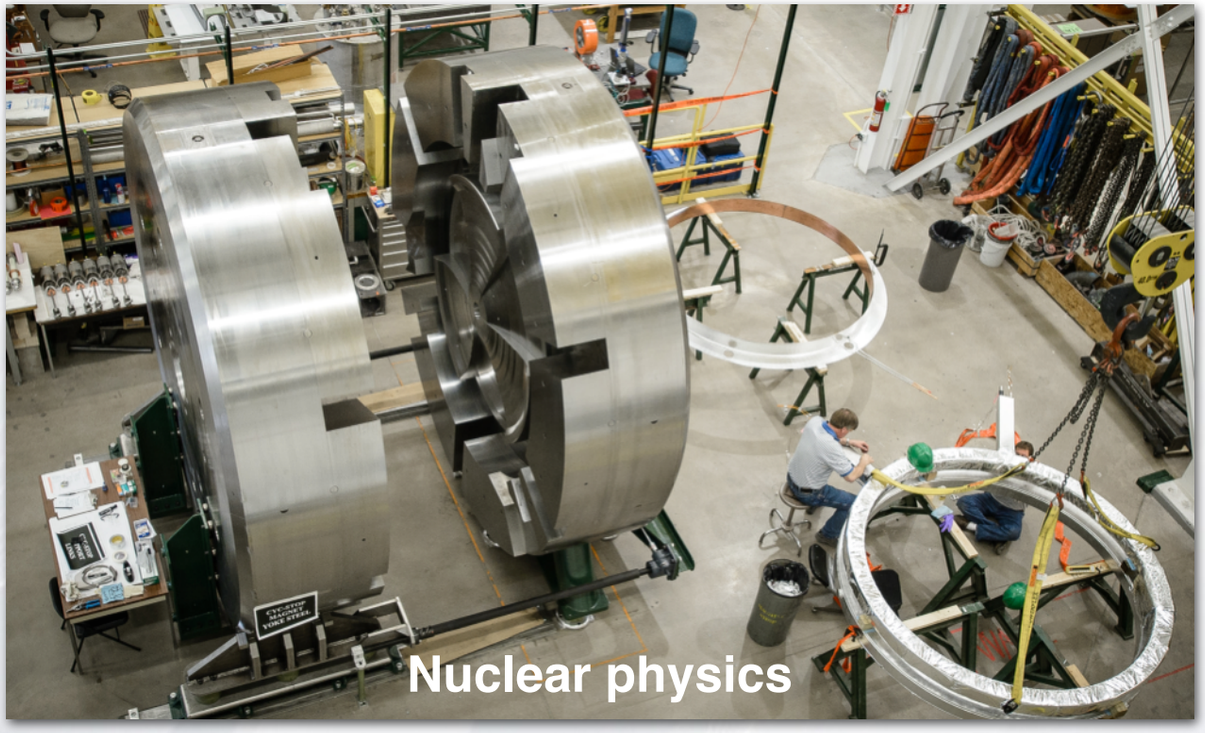
WHY CONNECTING?

April 25, 2013, http://msutoday.msu.edu/
Facility for Rare Isotope Beam (FRIB), cyclotron stopper

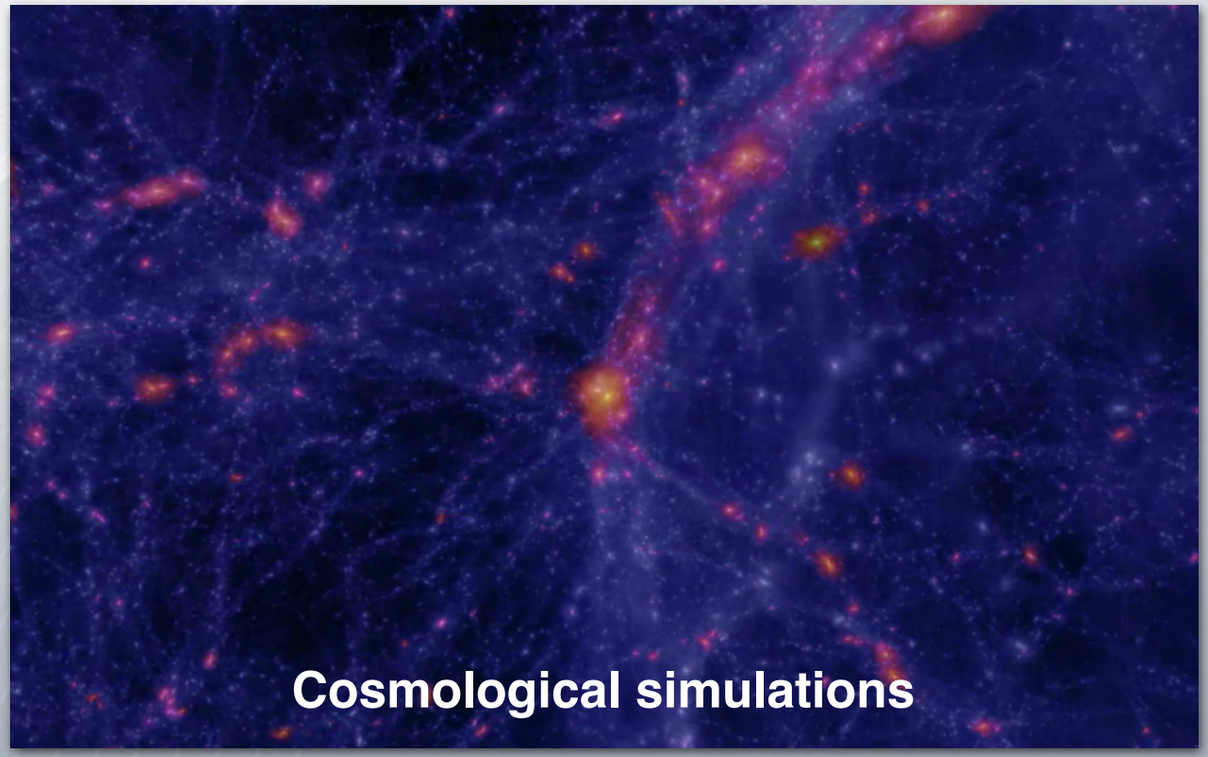


Nuclear physics

- Nuclear physics experiments and theories provide an explanation of how elements can be synthesized.

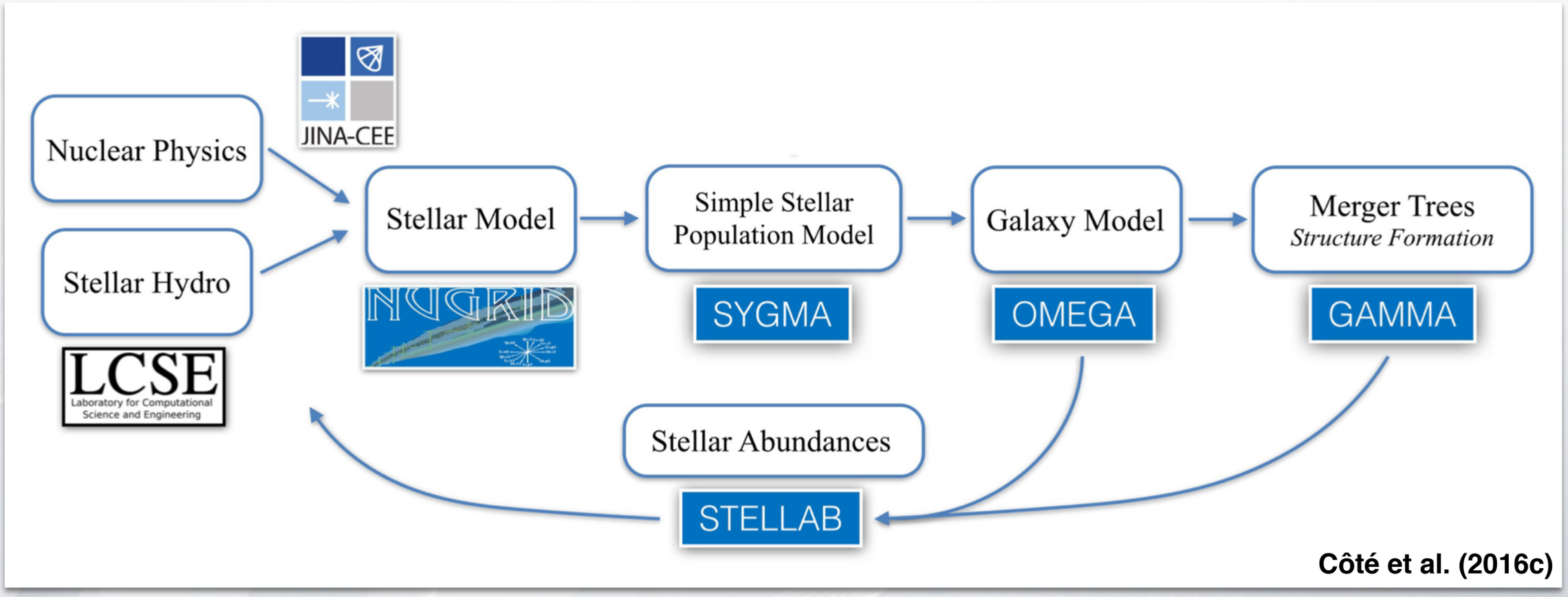
- Galaxy evolution in a cosmological context inform us on how galaxies form, how gas flows inside and around galaxies, and how elements are mixed and recycled into stars.

The EAGLE Project
http://icc.dur.ac.uk/Eagle/index.php



Cosmological simulations

CHEMICAL EVOLUTION PIPELINE

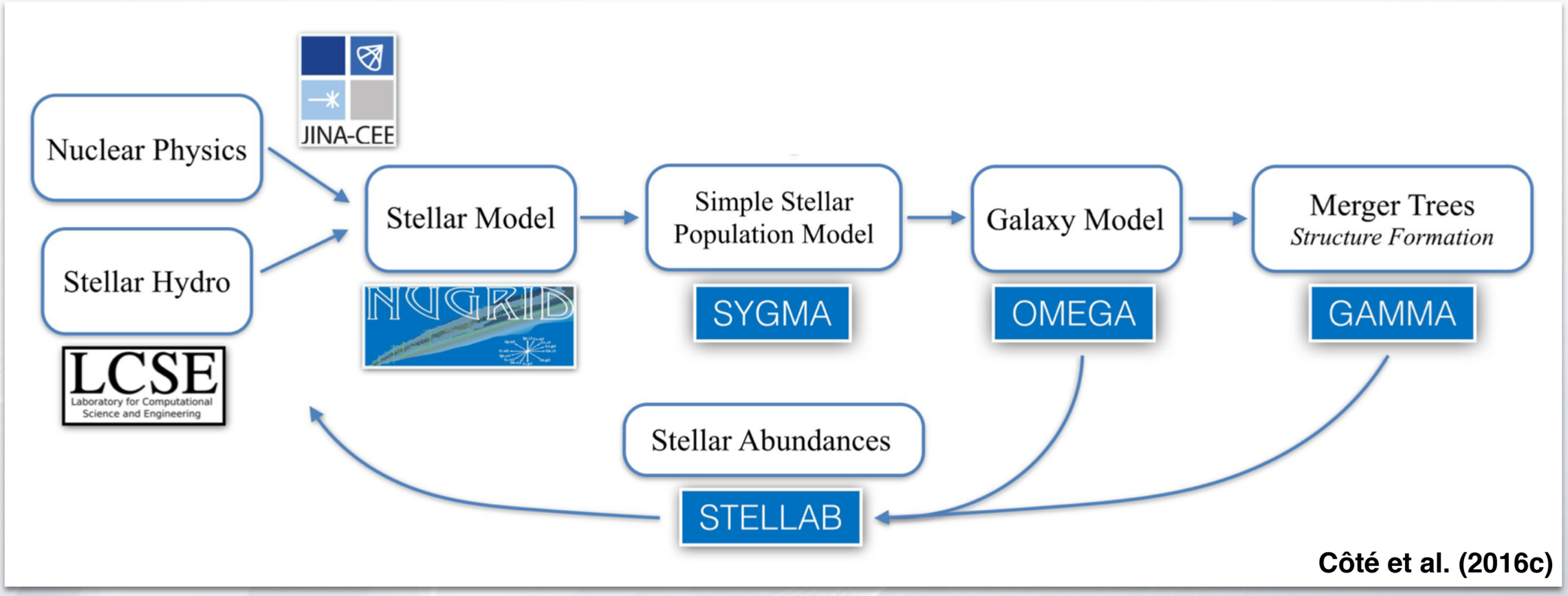


- **SYGMA** - **S**tellar **Y**ields for **G**alactic **M**odeling **A**pplications (*C. Ritter et al. in prep.*)
- **OMEGA** - **O**ne-zone **M**odel for the **E**volution of **GA**laxies (*Côté et al. 2016c)*
- **GAMMA** - **G**alaxy **A**ssembly with **M**erger-trees for **M**odeling **A**bundances *(Côté et al. in prep.)*
- **STELLAB** - STELLar ABundances, observational data plotting tool

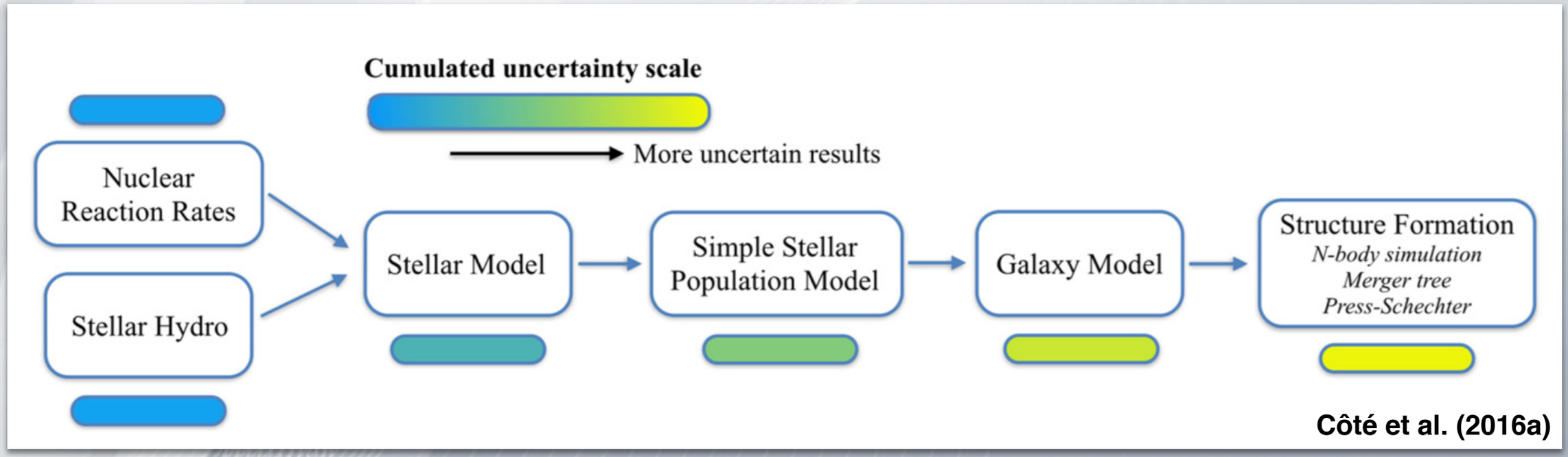
Open-source codes **http://nugrid.github.io/NuPyCEE/**

CHEMICAL EVOLUTION PIPELINE

Uncertainties in chemical evolution models, see also
Romano et al. (2005, 2010)
Matteucci et al. (2009)
Molla et al. (2015)

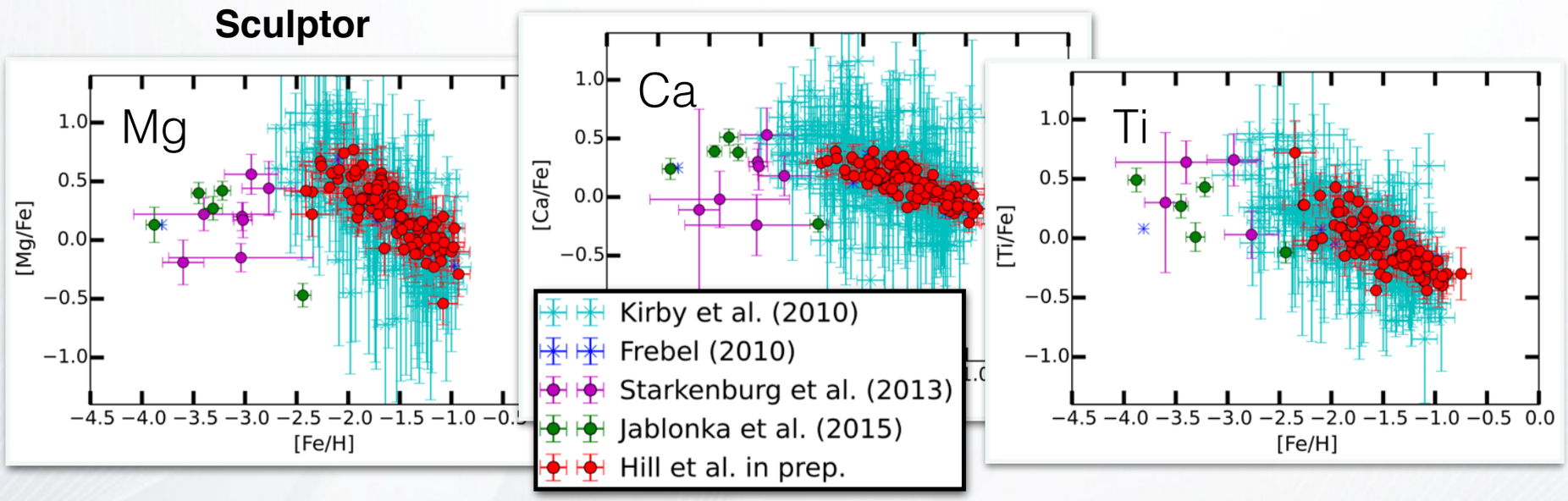


Côté et al. (2016c)



Côté et al. (2016a)

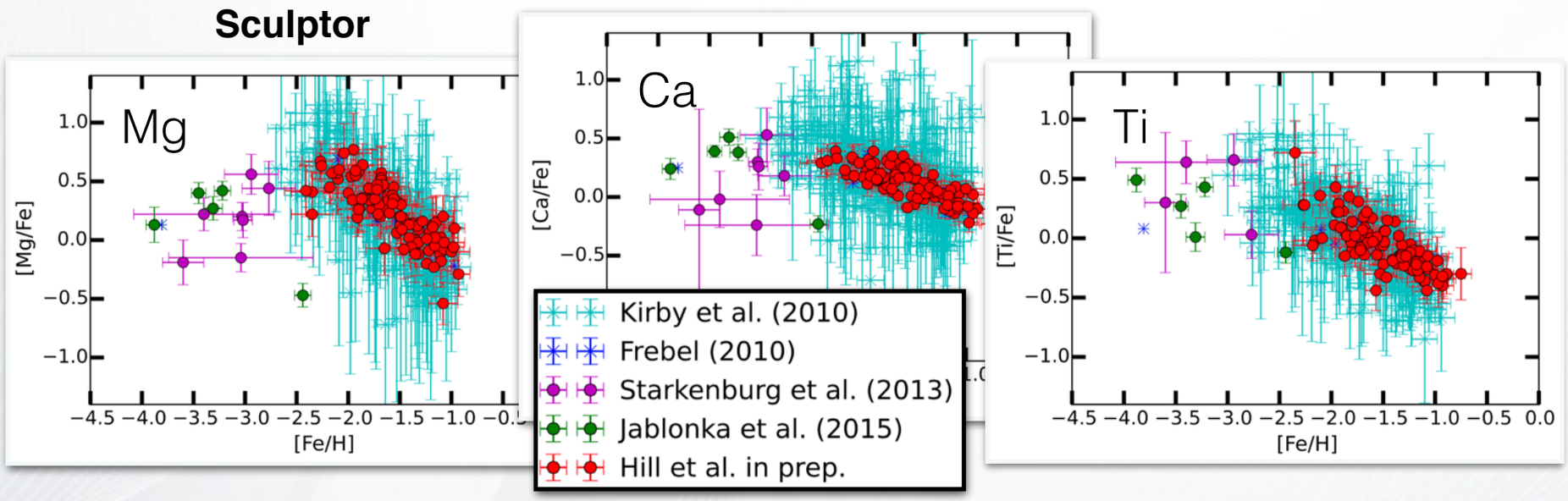
UNCERTAINTIES FROM MODELING ASSUMPTIONS



+ OMEGA

Chemical evolution code

UNCERTAINTIES FROM MODELING ASSUMPTIONS



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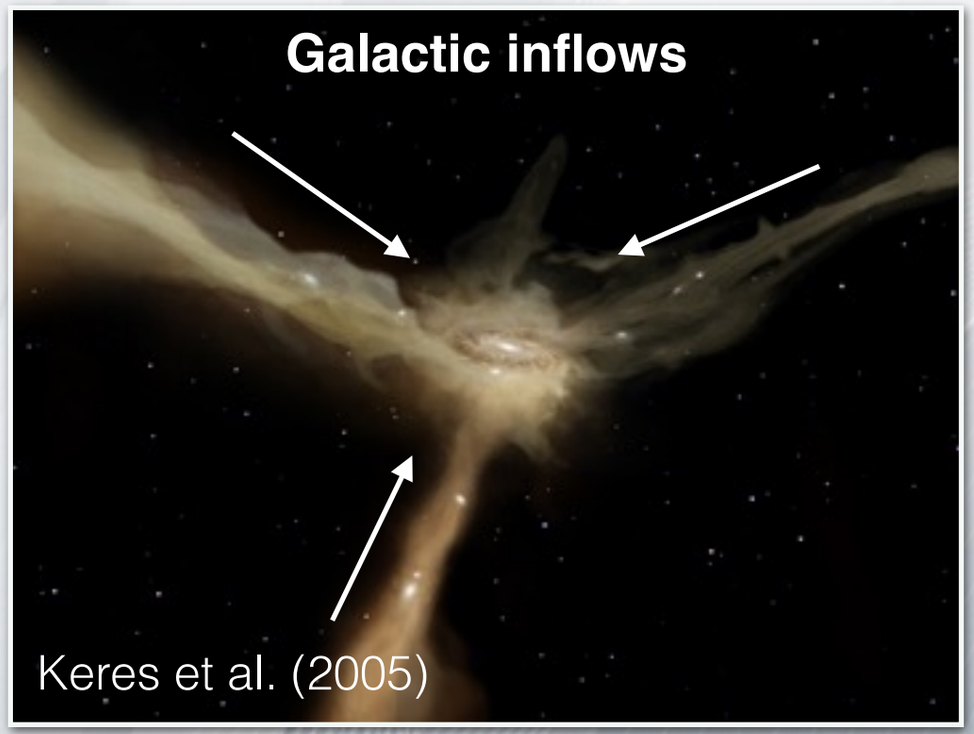

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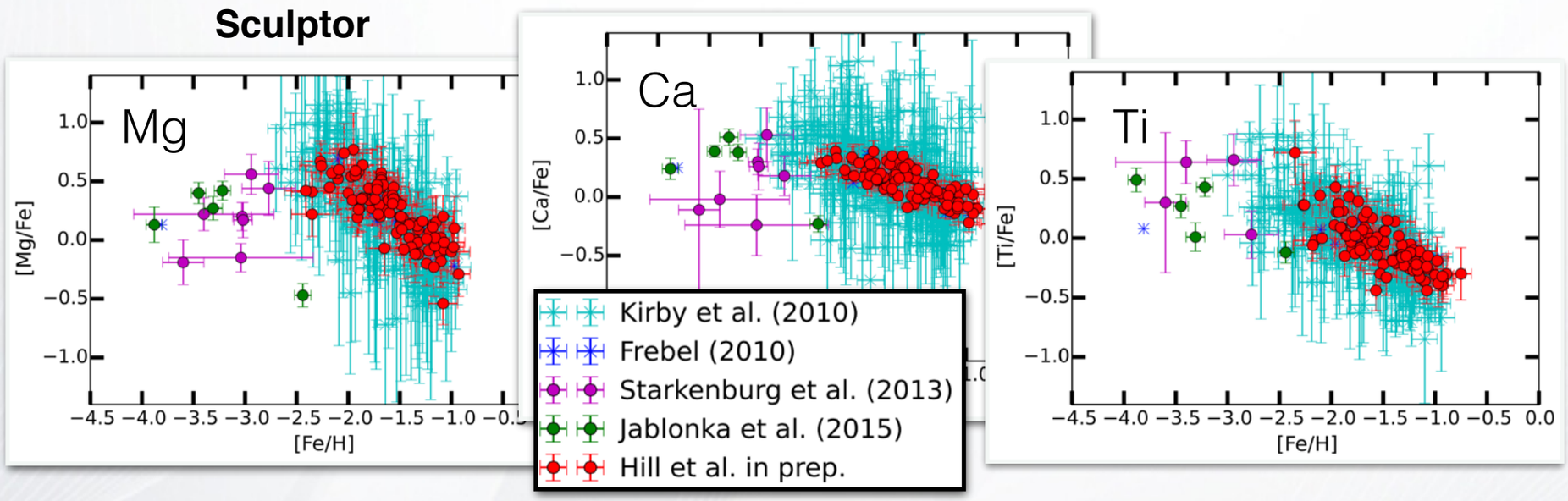

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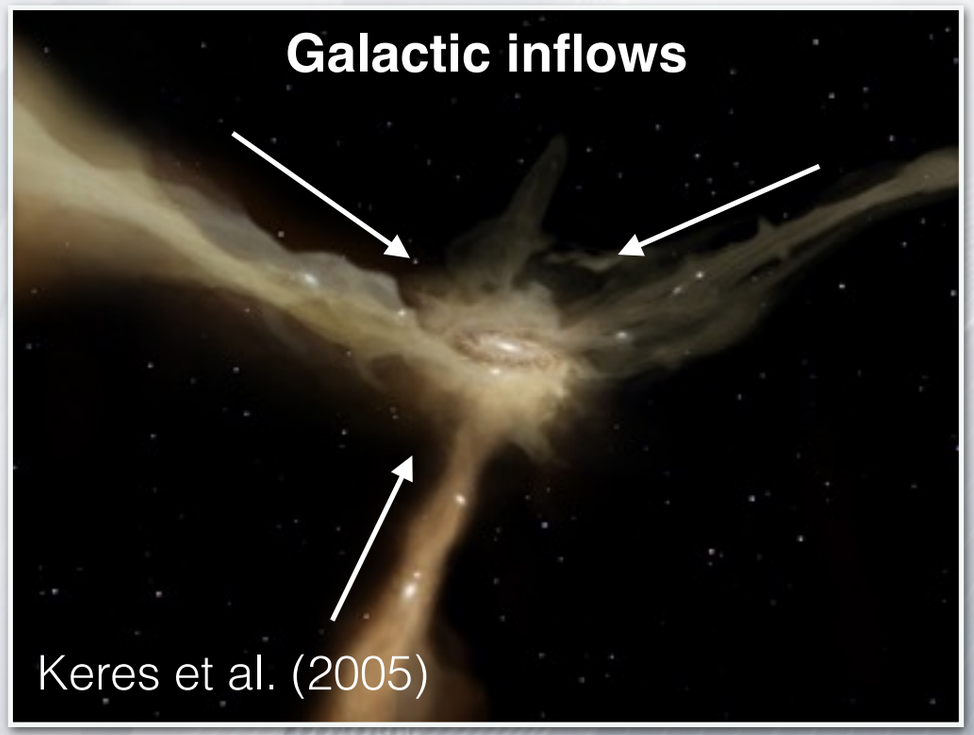
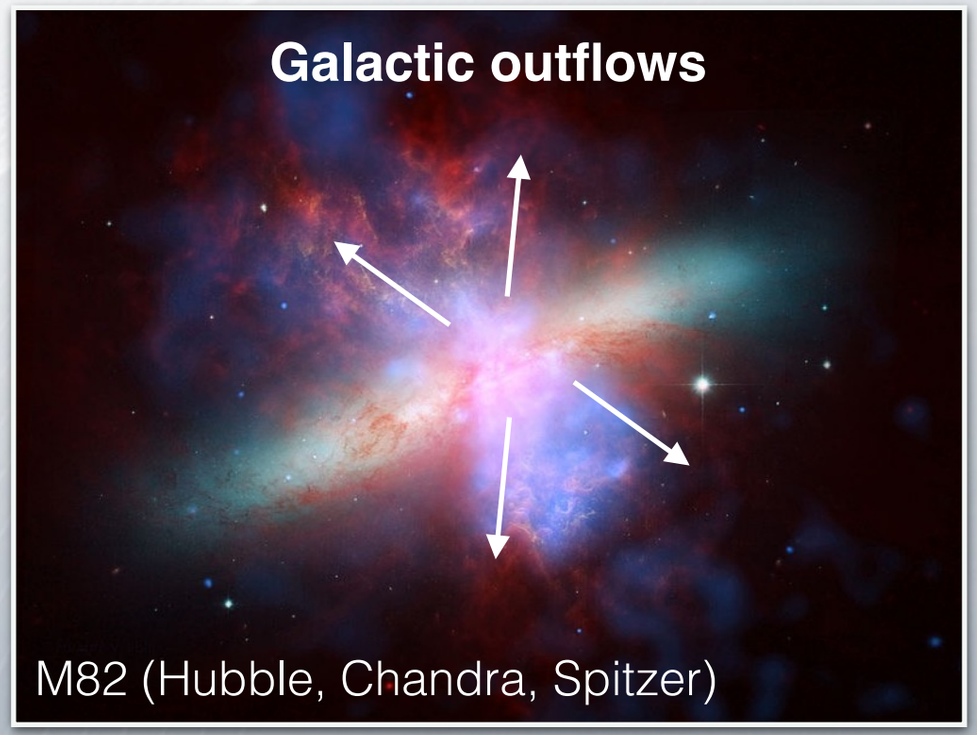
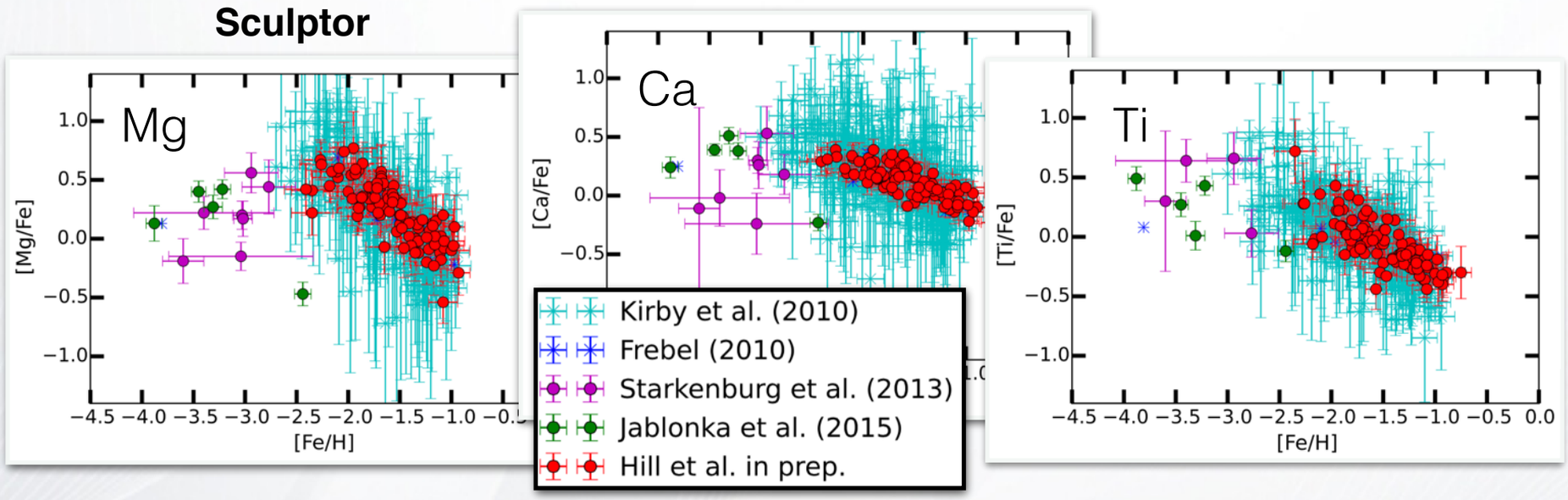




UNCERTAINTIES FROM MODELING ASSUMPTIONS

Sculptor

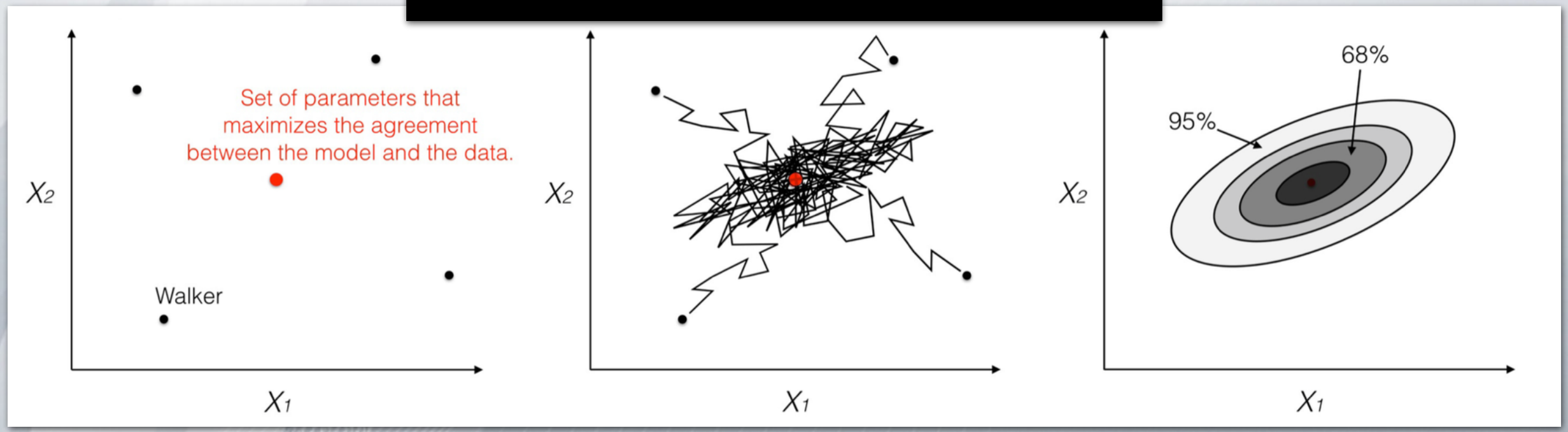


\+ OMEGA

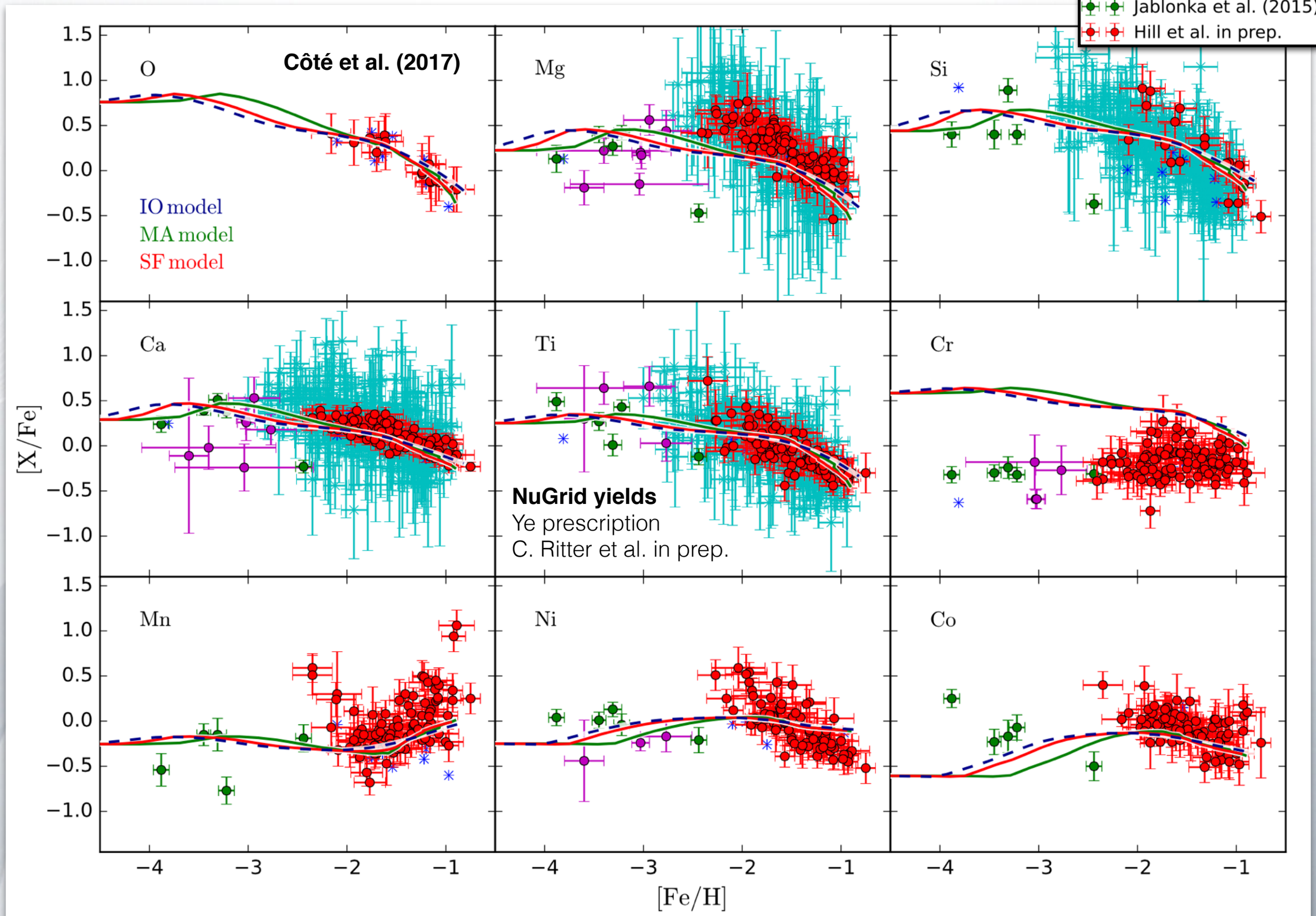
Chemical evolution code

emcee code (Foreman-Mackey et al. 2013)

Markov Chain Monte Carlo (MCMC)



CONSTRAINTS FROM STELLAR ABUNDANCES



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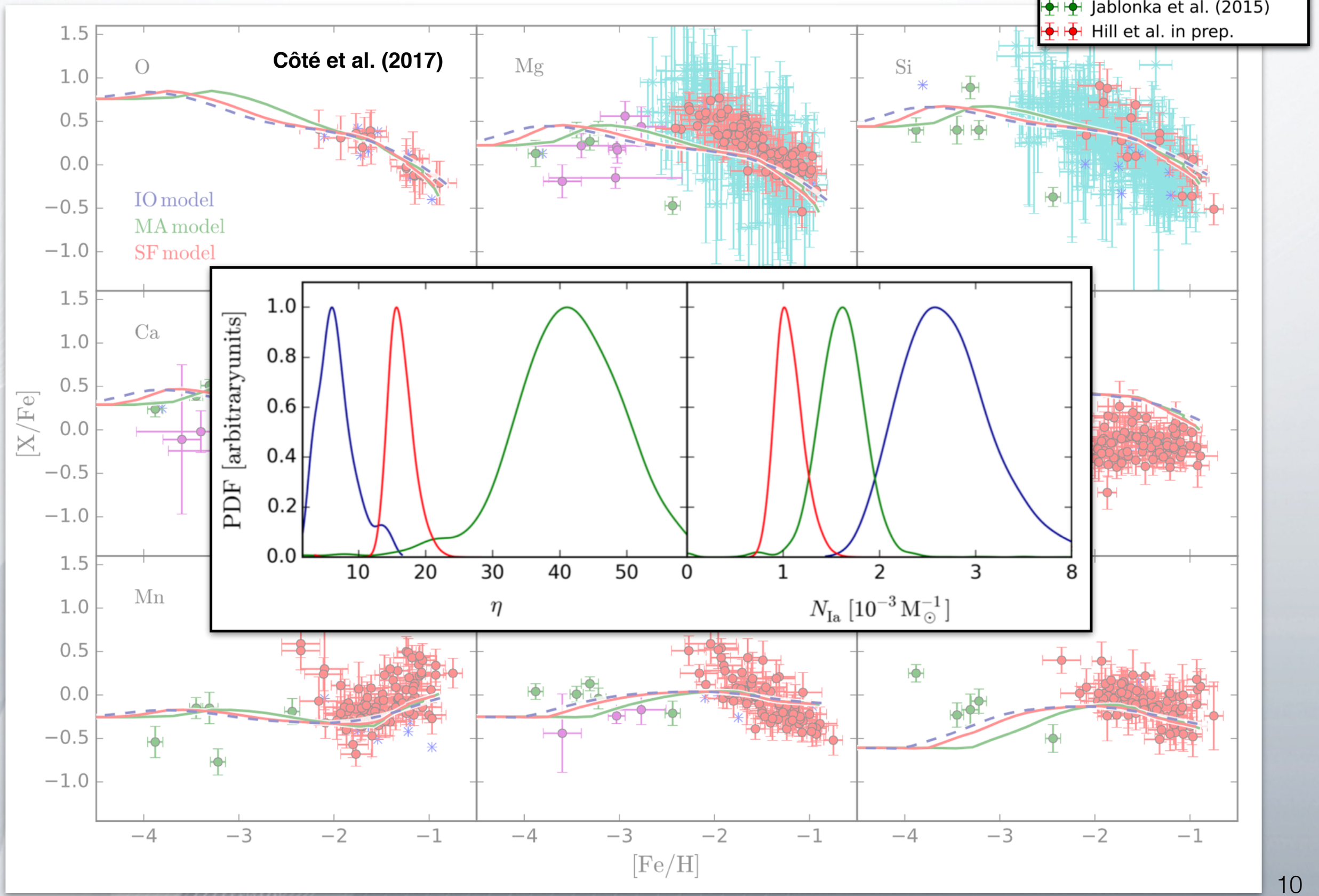

MULTIPLE CONSTRAINTS

What is the main astrophysical site r-process elements?
Core-collapse or compact binary mergers?

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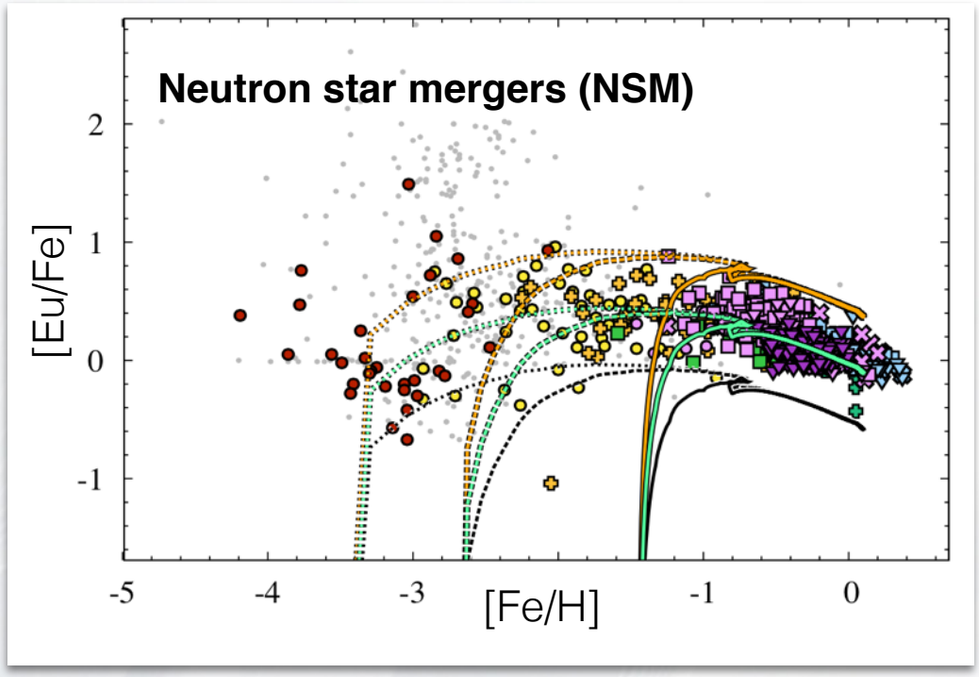
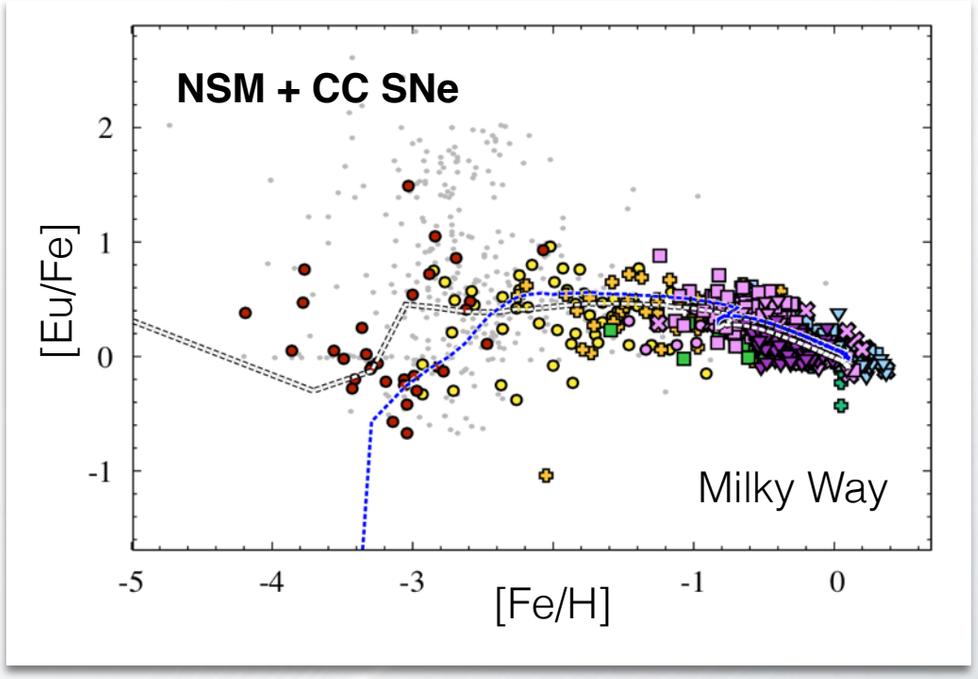
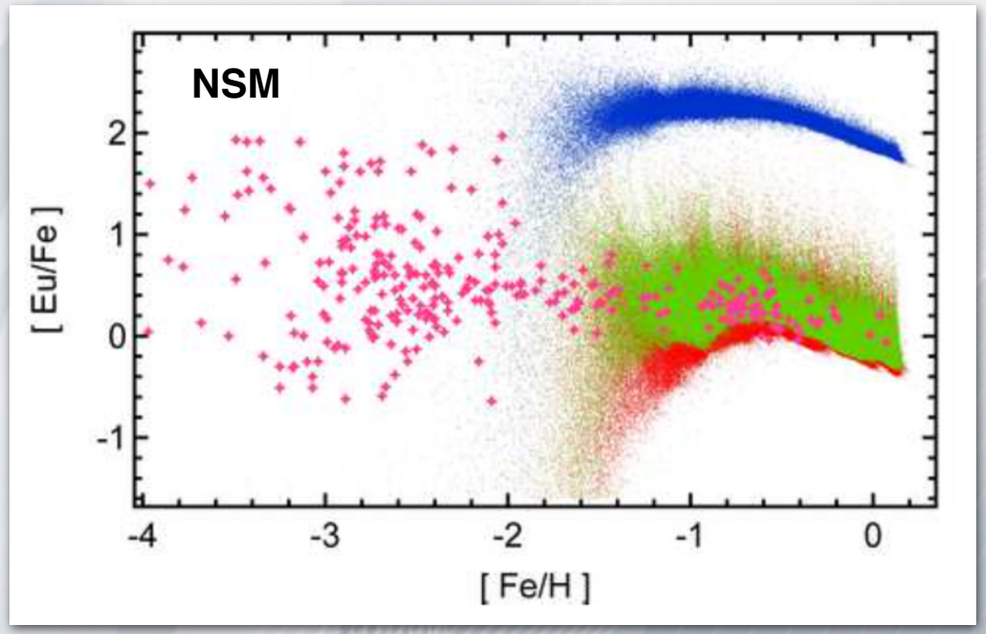
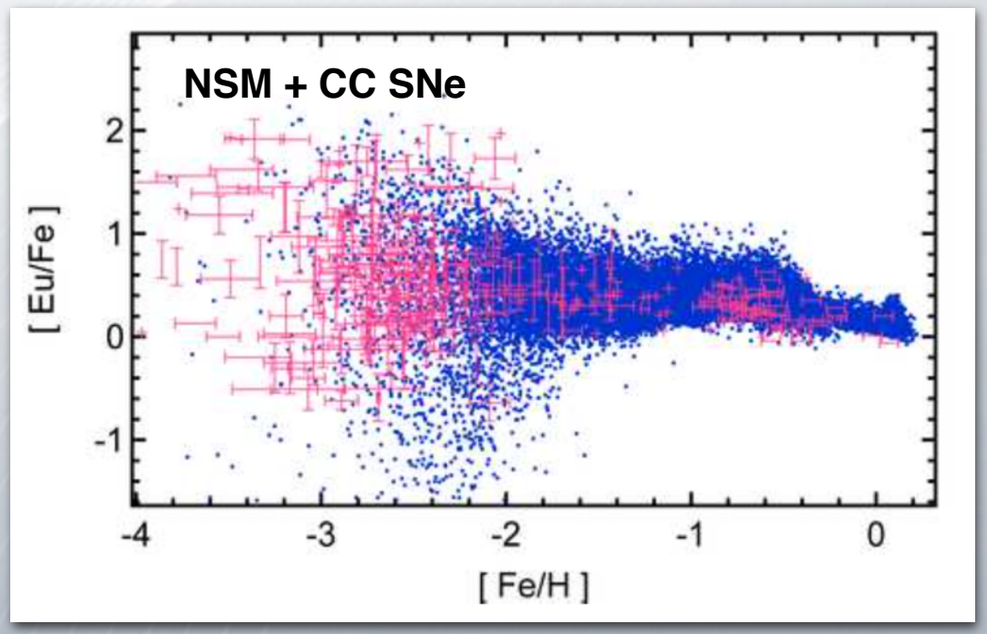
Matteucci et al. (2014)





Wehmeyer et al. (2015)





See also **Argast et al. (2004)**

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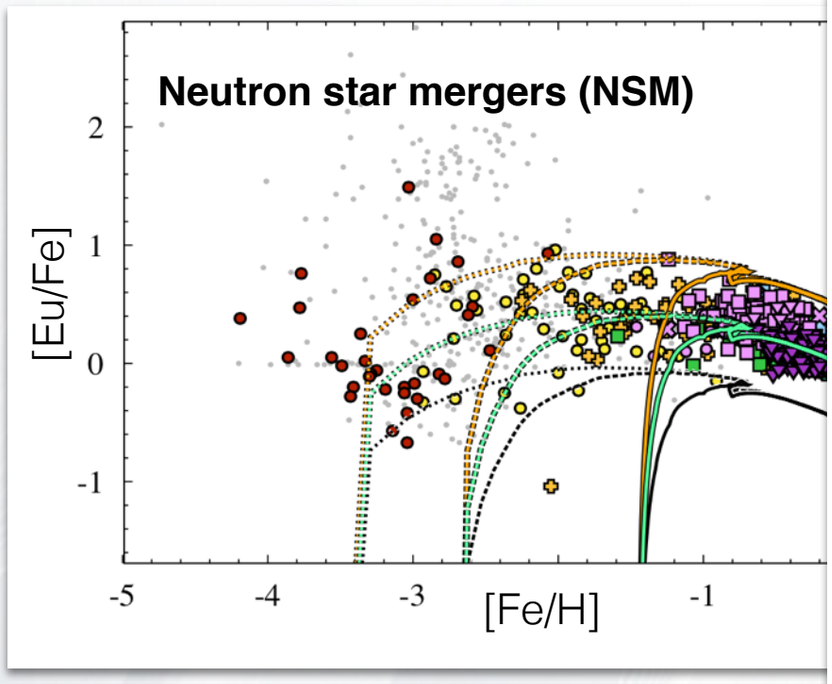

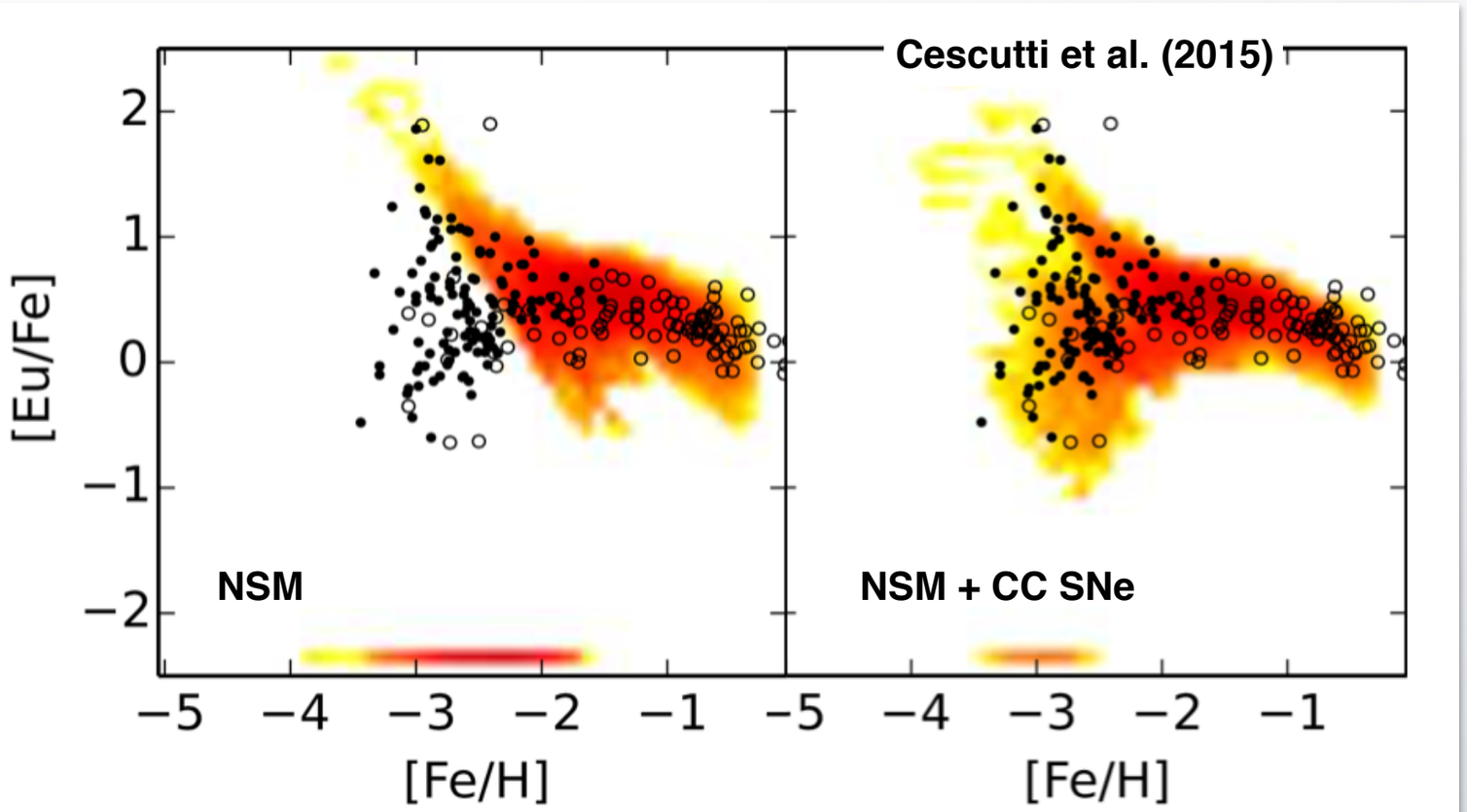

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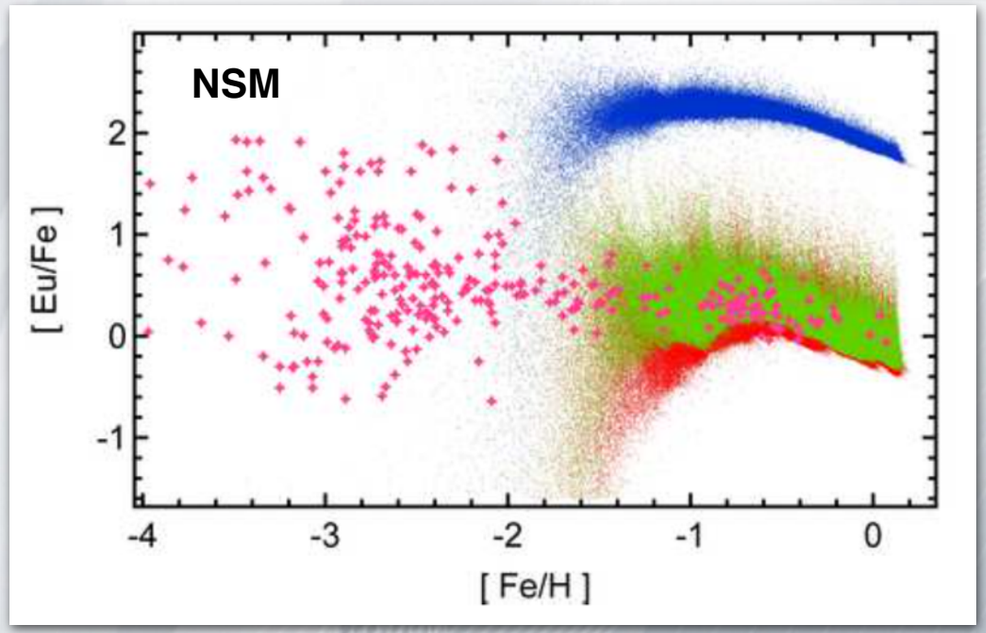

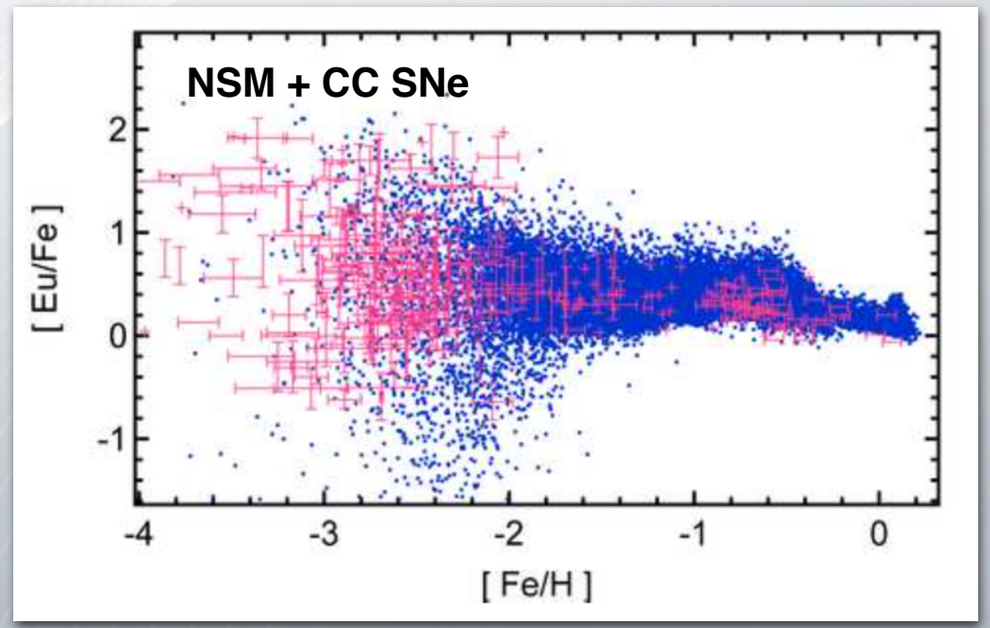

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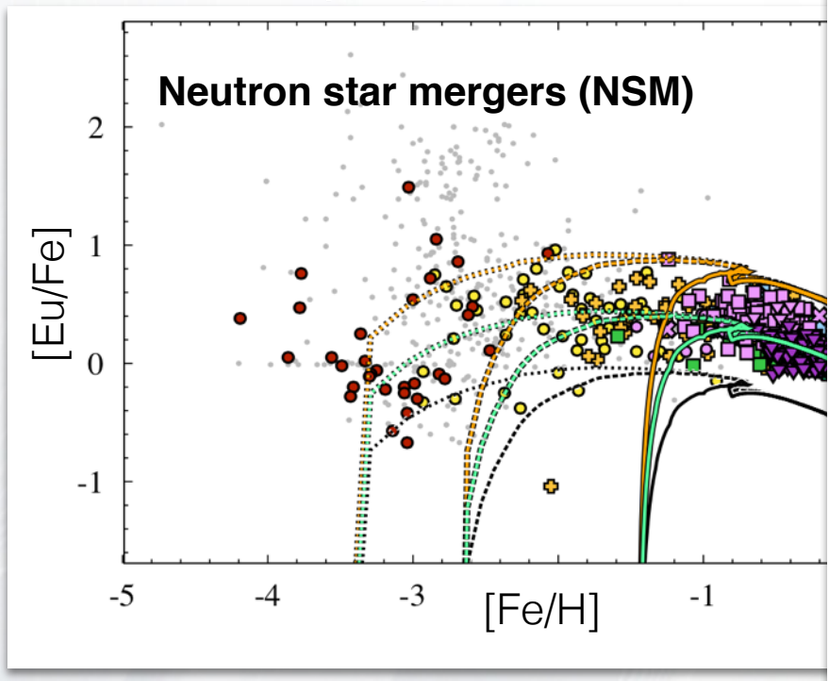
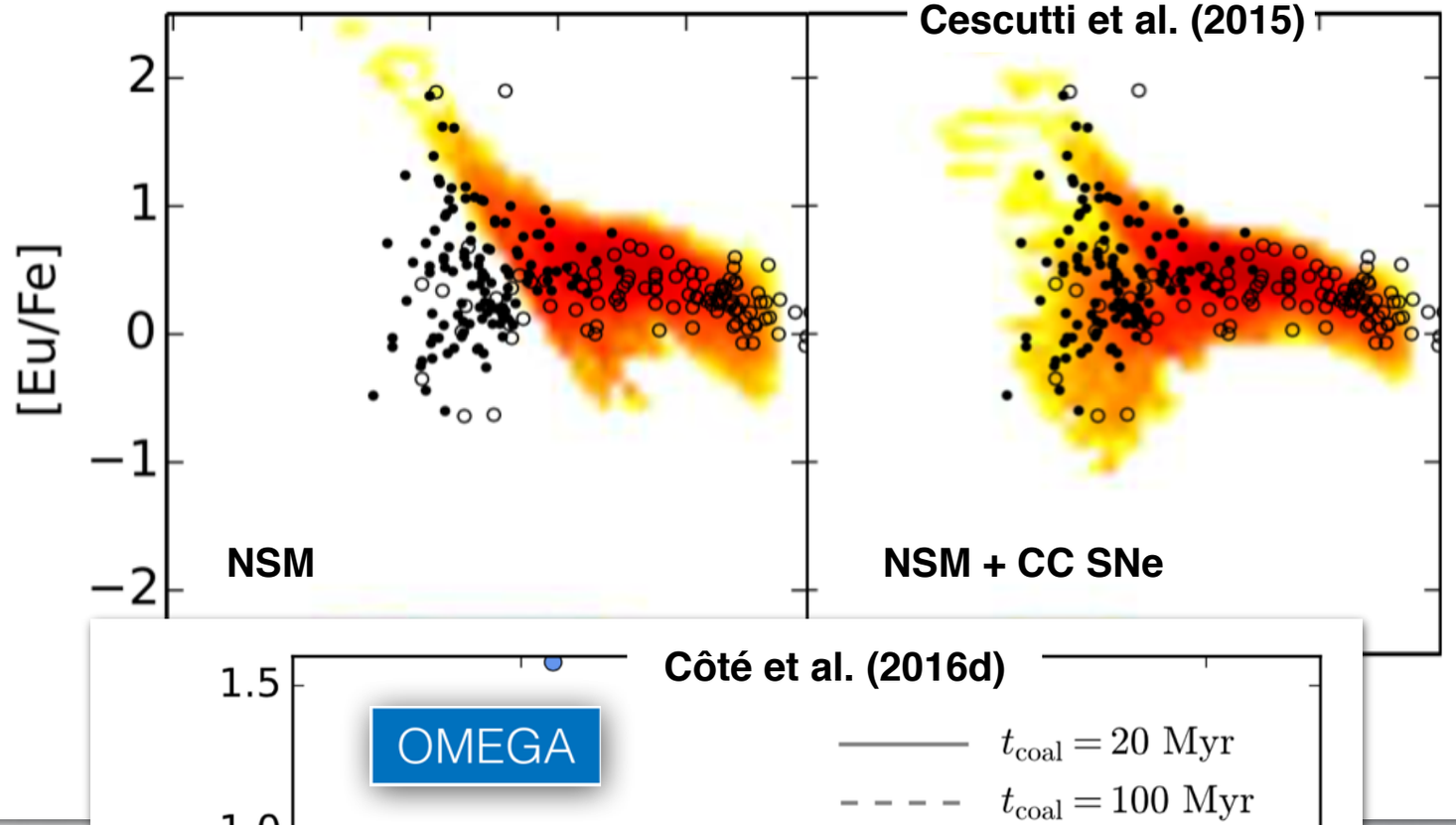
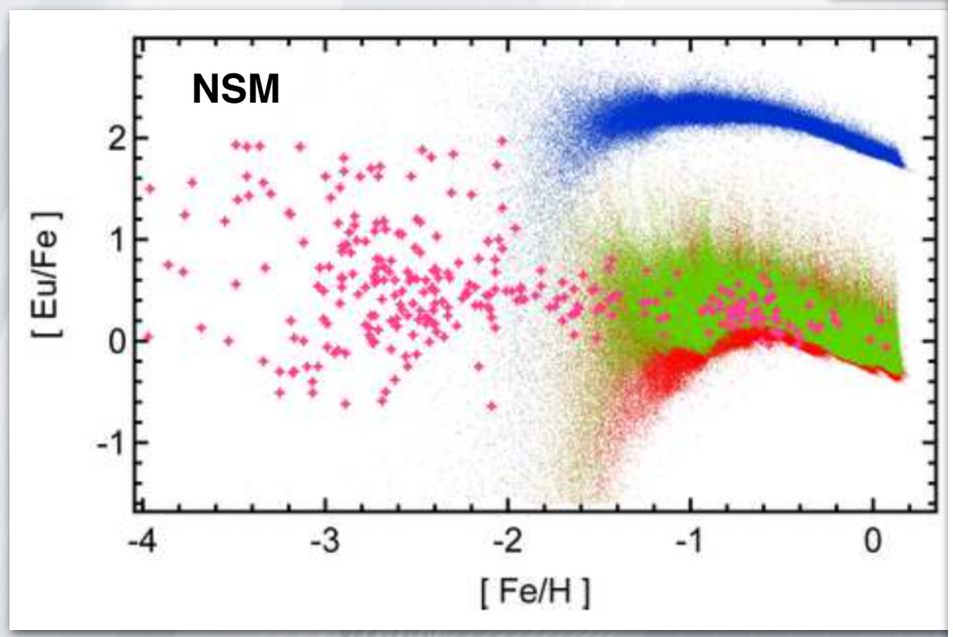


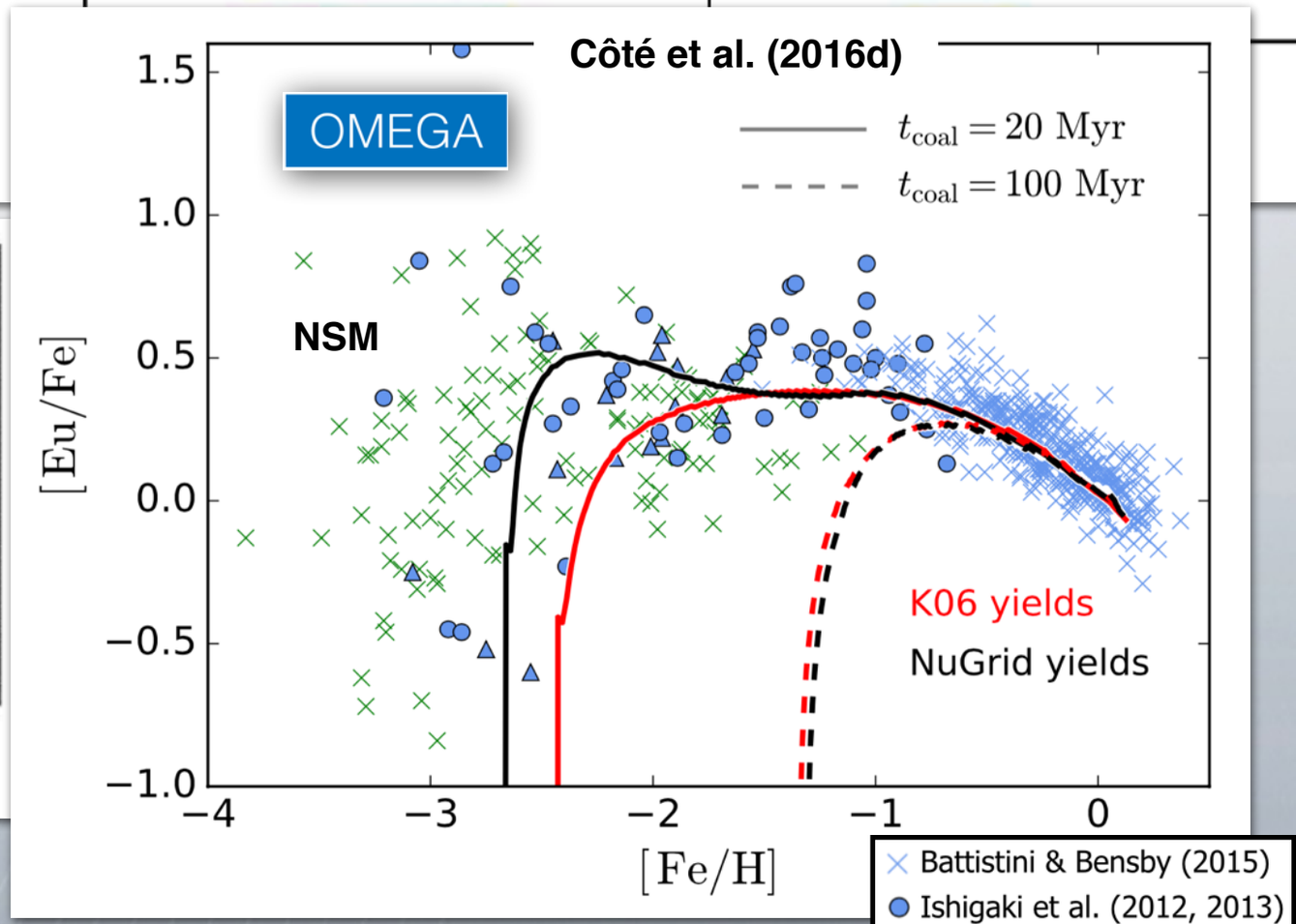
Cescutti et al. (2015)



Wehmeyer et al. (2015)



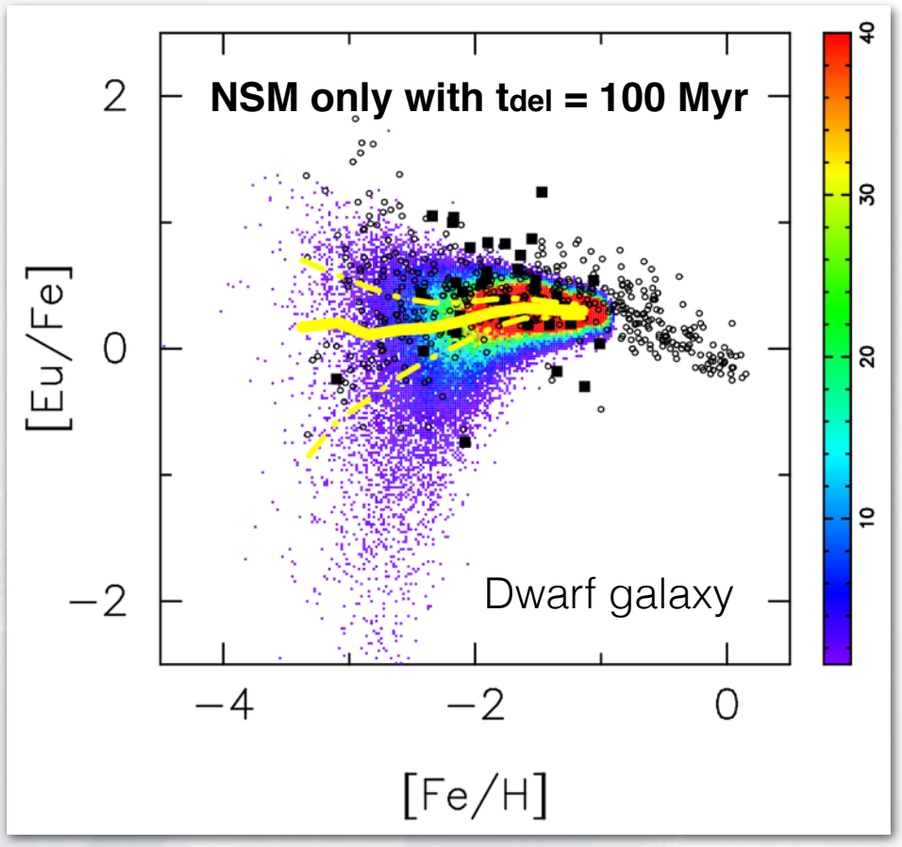
Côté et al. (2016d)



MULTIPLE CONSTRAINTS

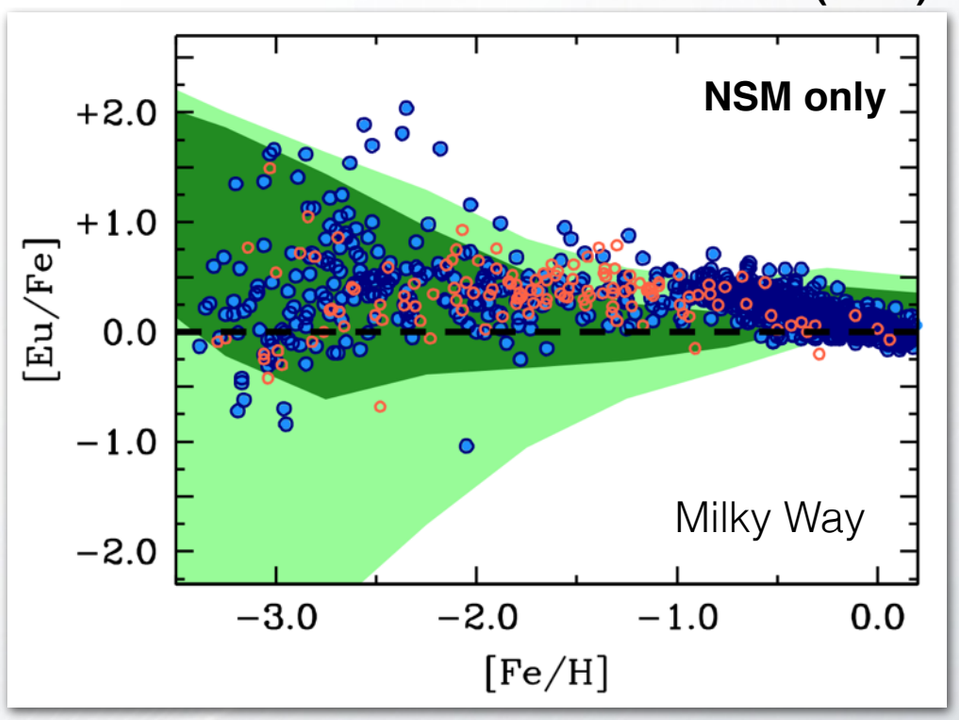
What is the main astrophysical site r-process elements?
Core-collapse or compact binary mergers?

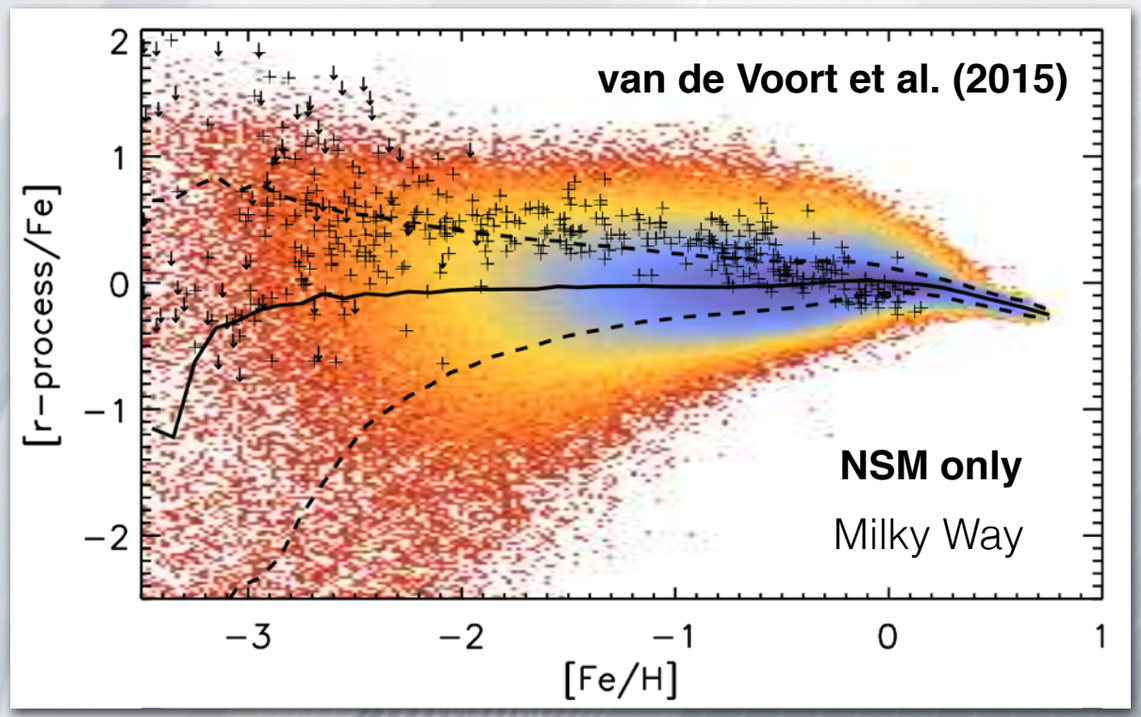
Hirai et al. (2015)



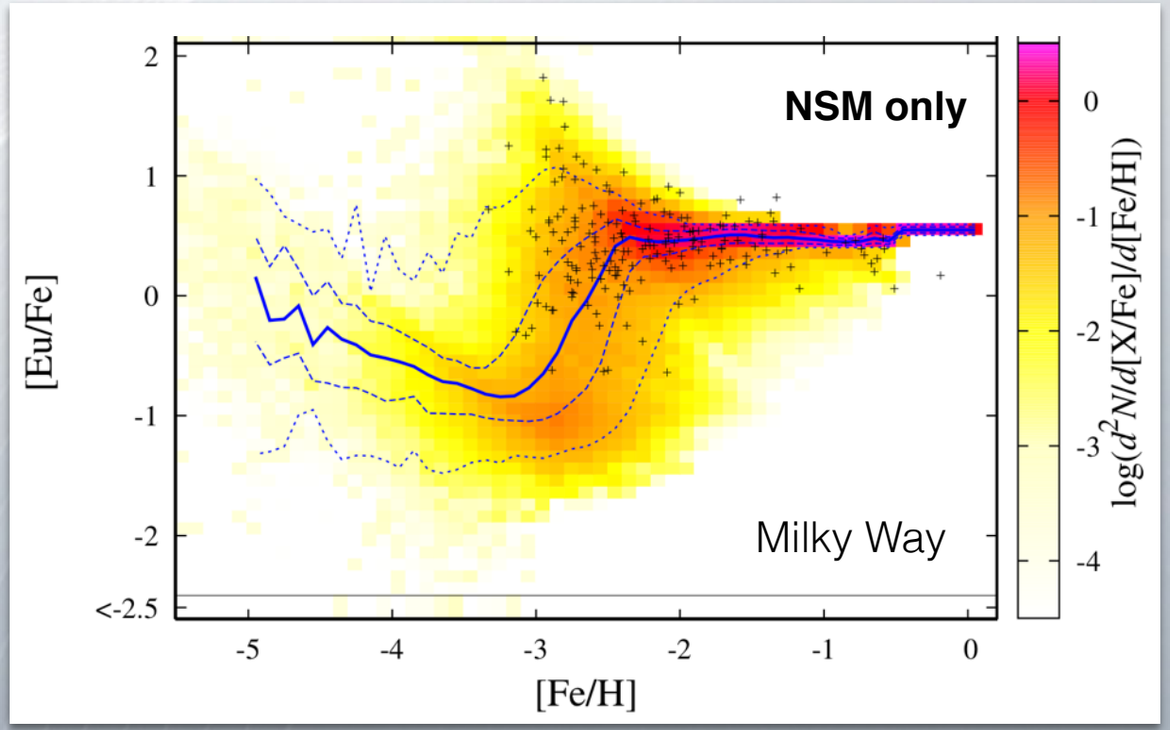
See also
Ishimaru et al. (2015)

Shen et al. (2015)



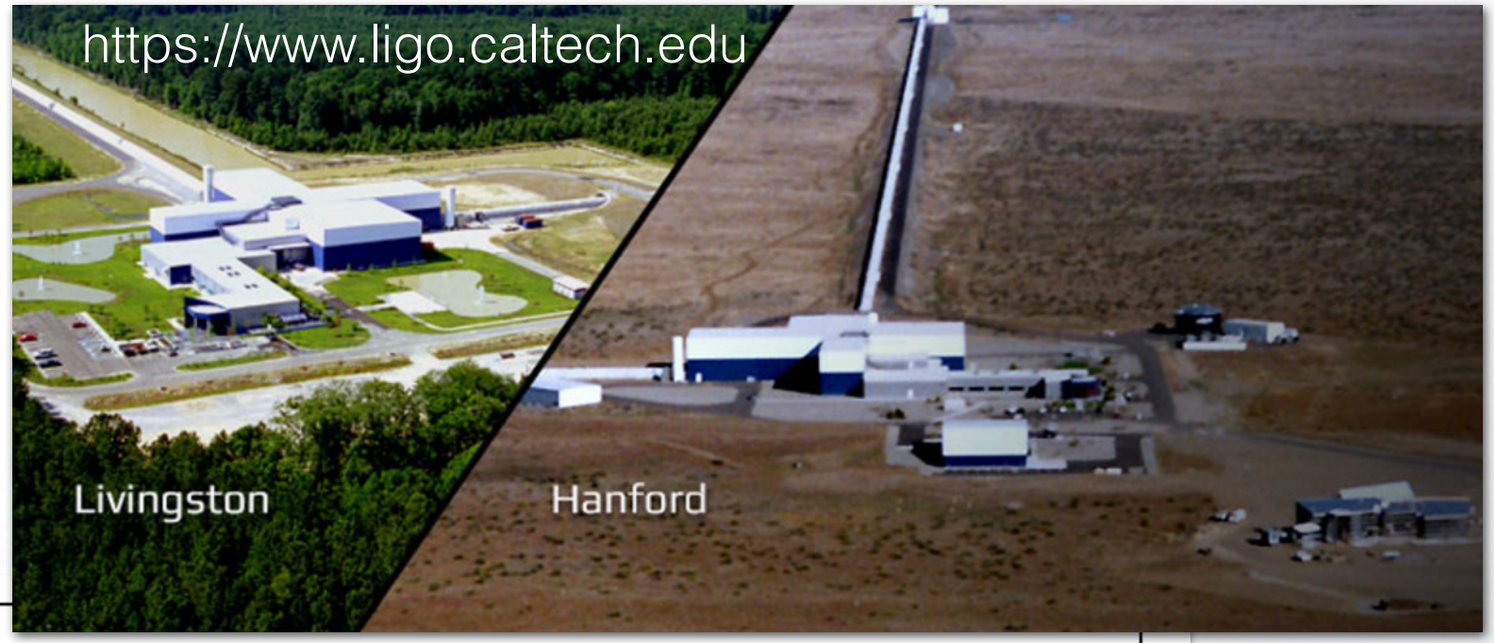


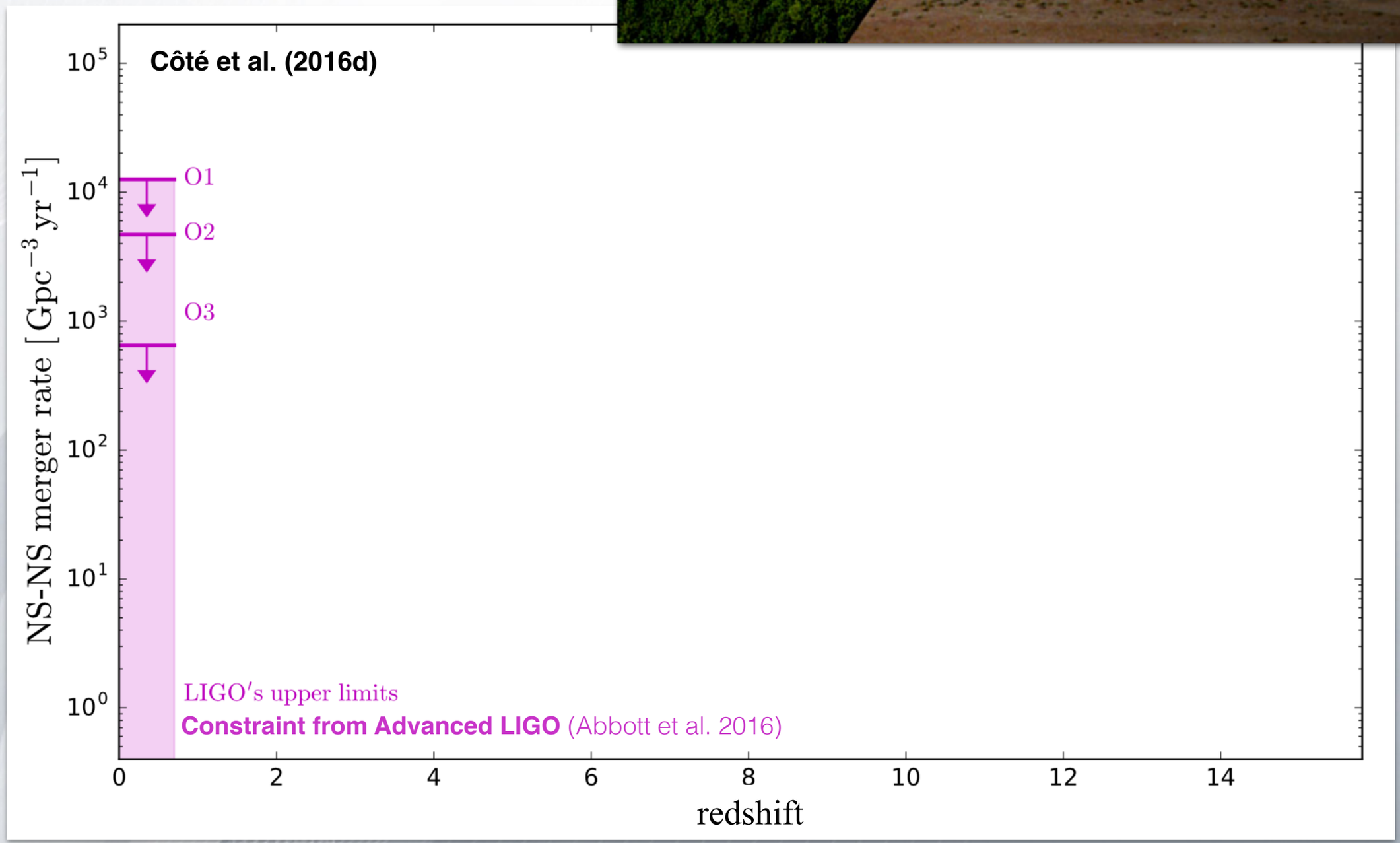
Komiya & Shigeyama (2016)



MULTIPLE CONSTRAINTS

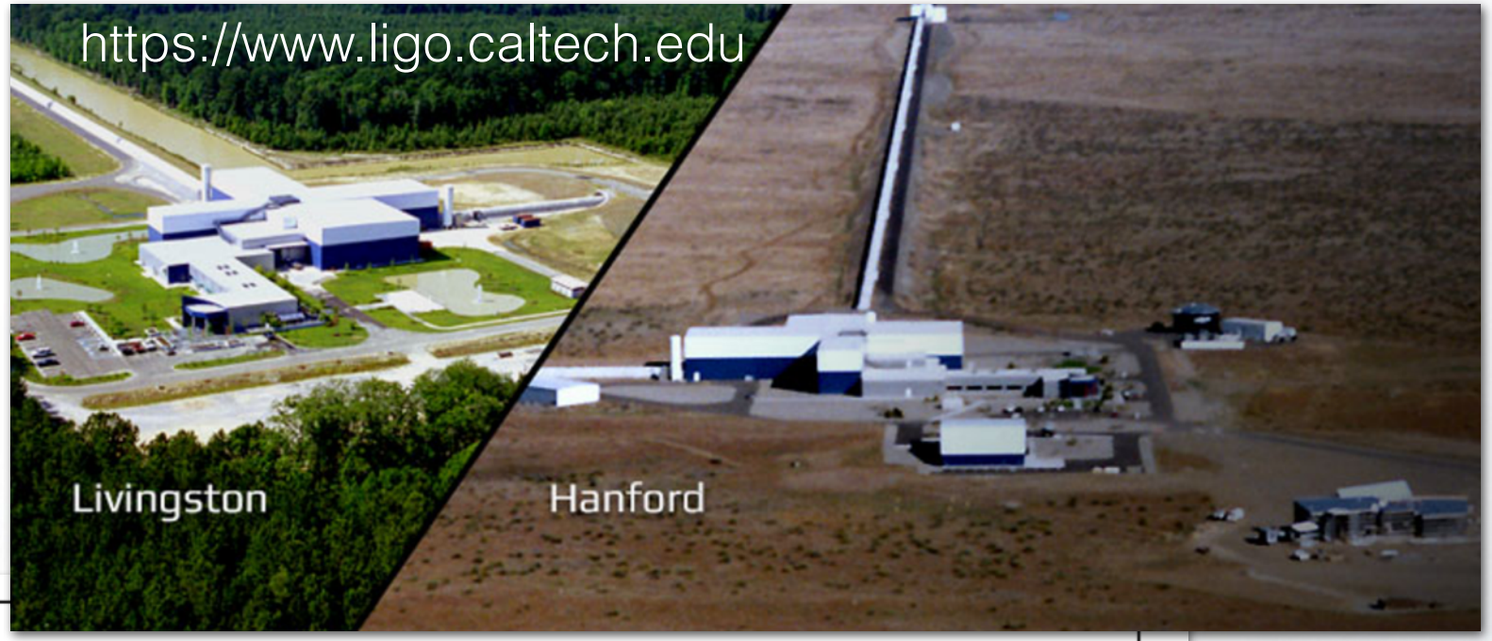
- **LIGO**, Laser Interferometer Gravitational-Wave Observatory

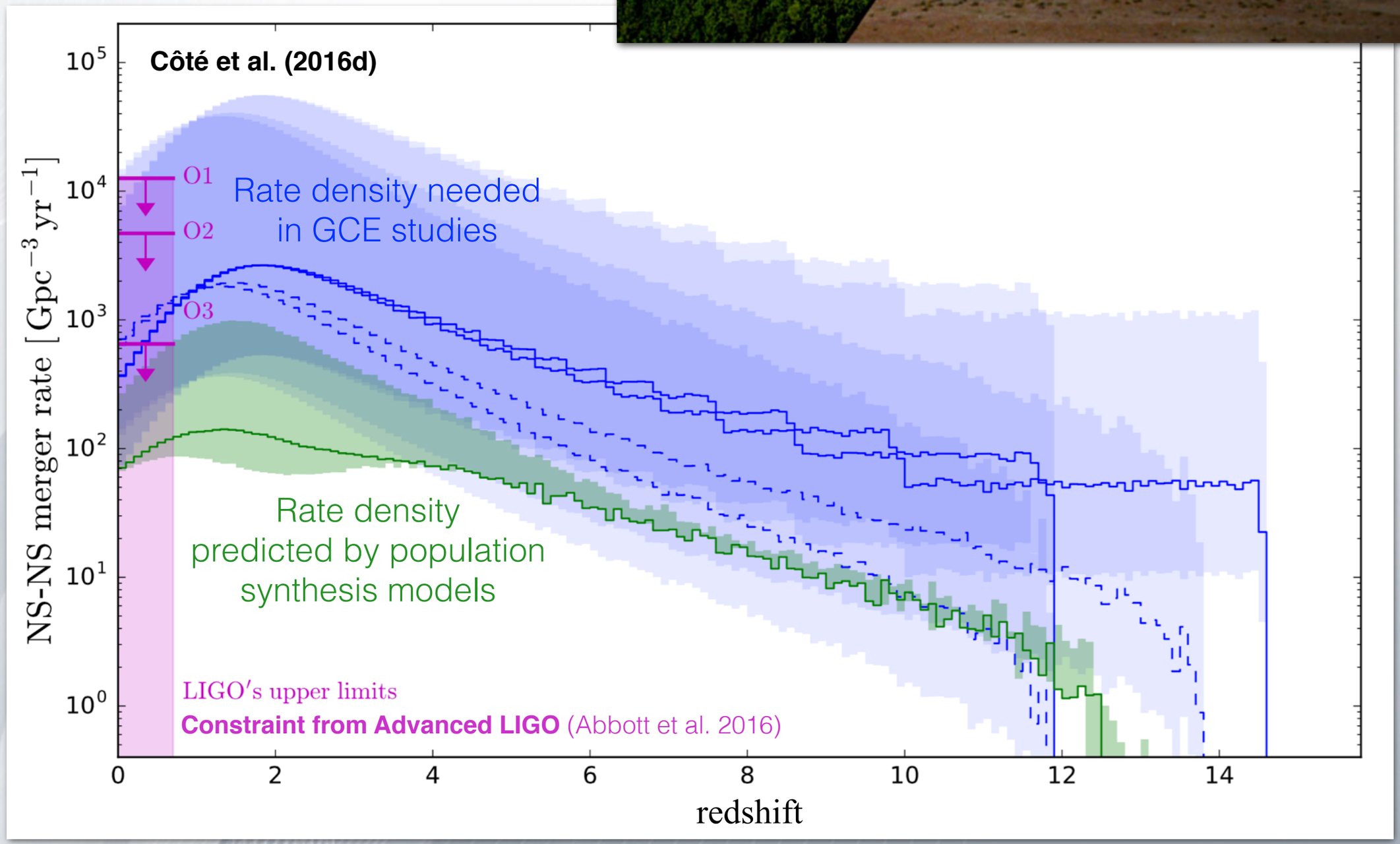




MULTIPLE CONSTRAINTS

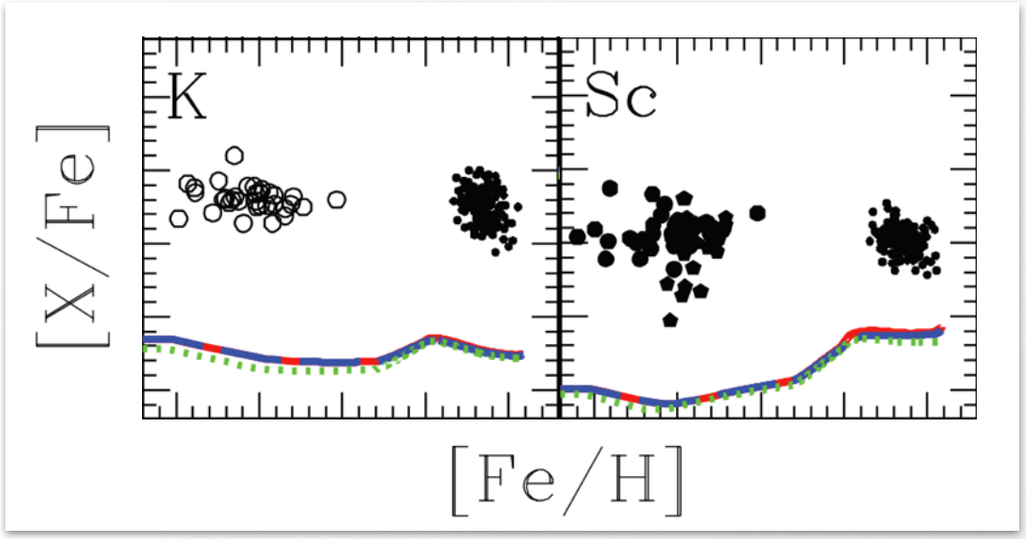
- **LIGO**, Laser Interferometer Gravitational-Wave Observatory





PROBING NUCLEAR ASTROPHYSICS

Kobayashi et al. (2011a)



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Christian Ritter and the UVic stellar astrophysics team analyzed NuGrid massive star models and found that some models experience O-C shell mergers. After calculating the nucleosynthesis signature, they found:

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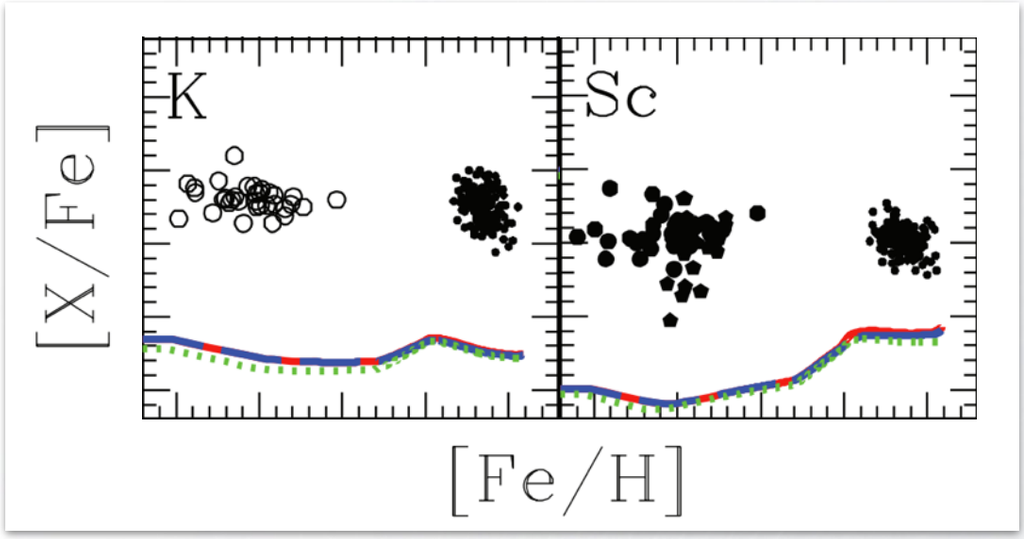

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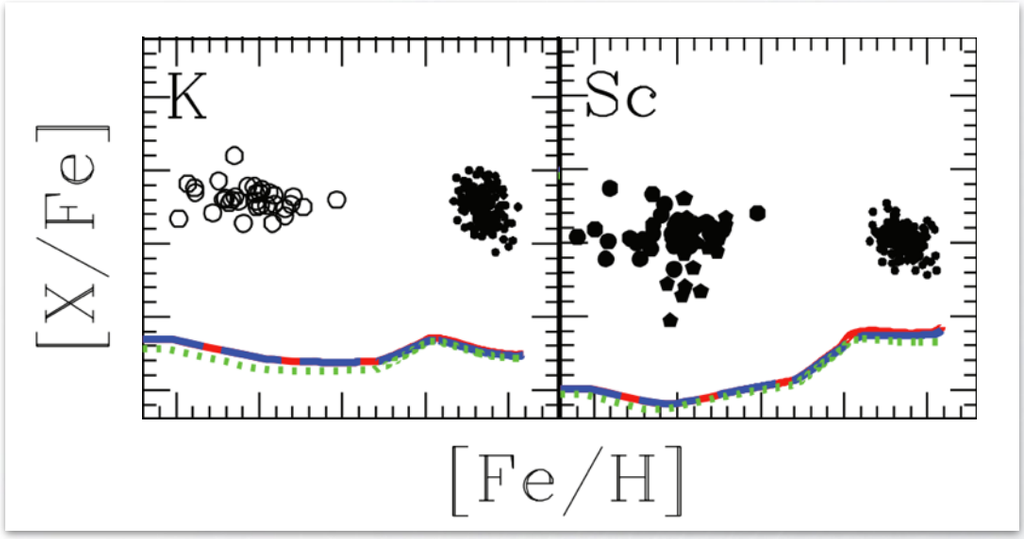
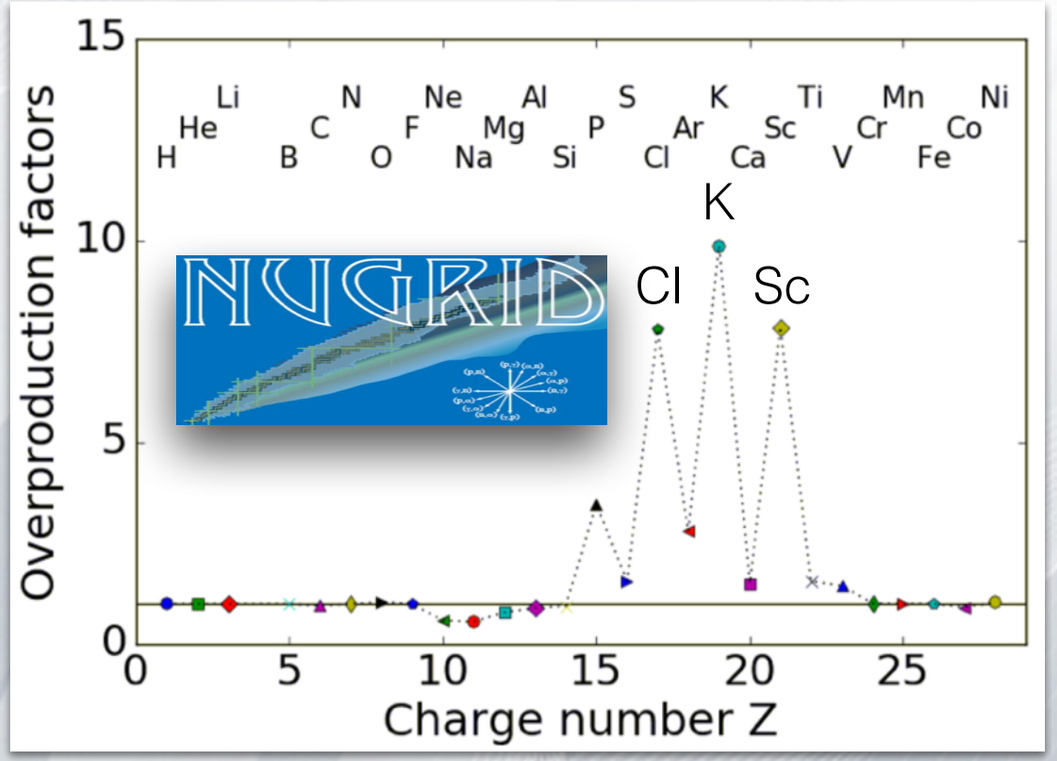


C. Ritter et al. (in prep.)



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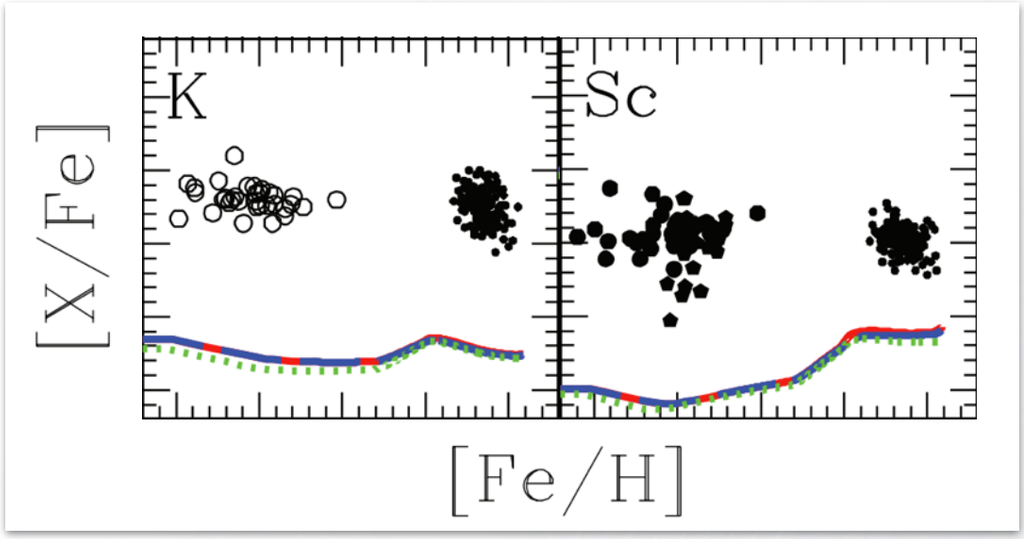

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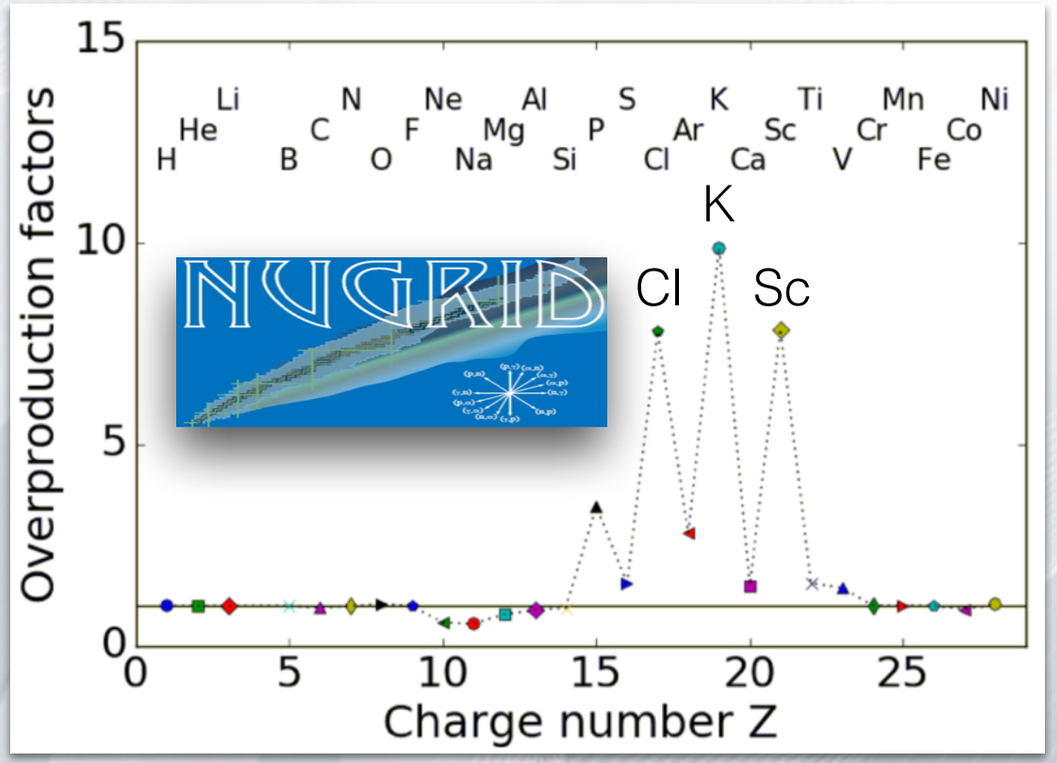

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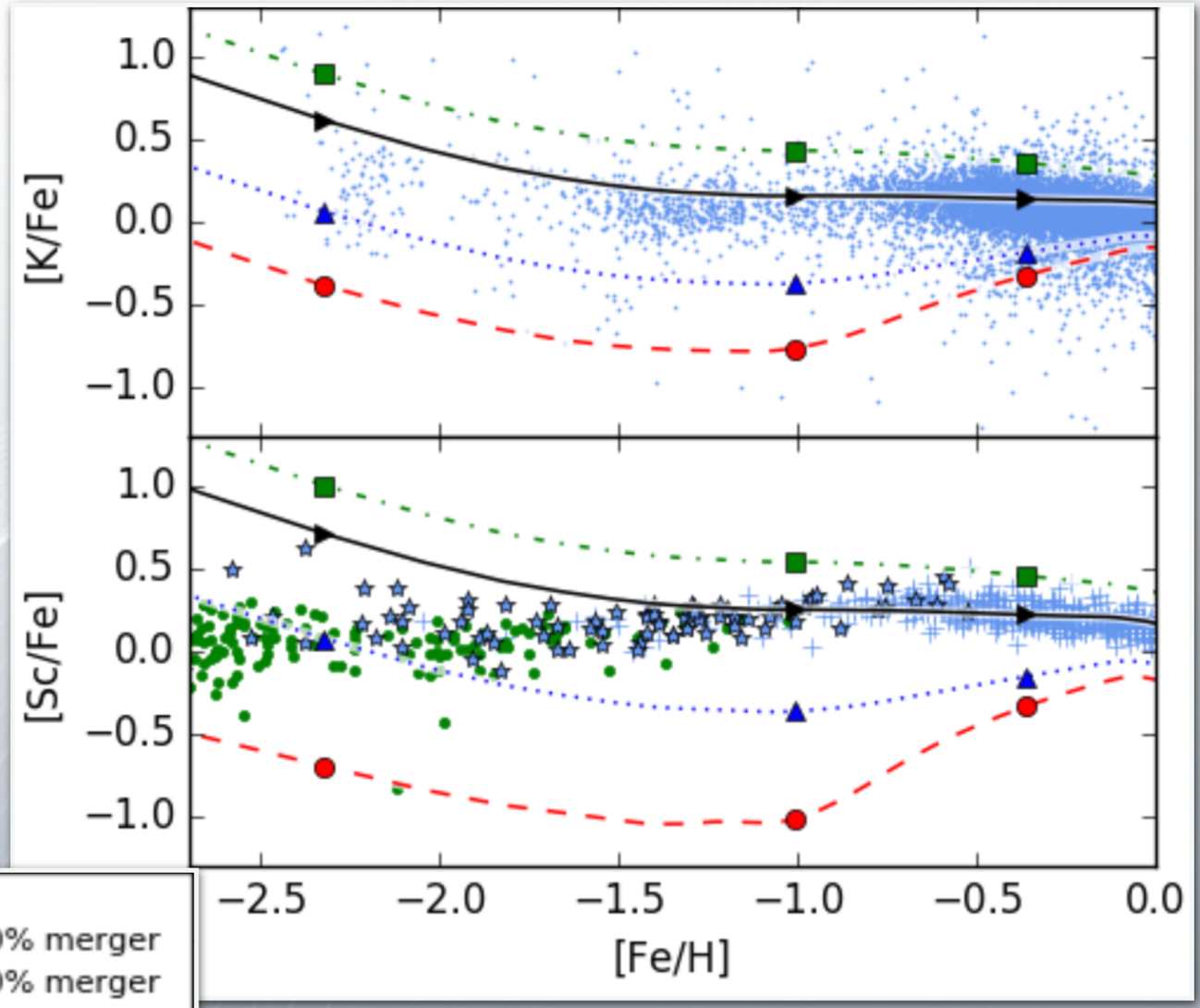
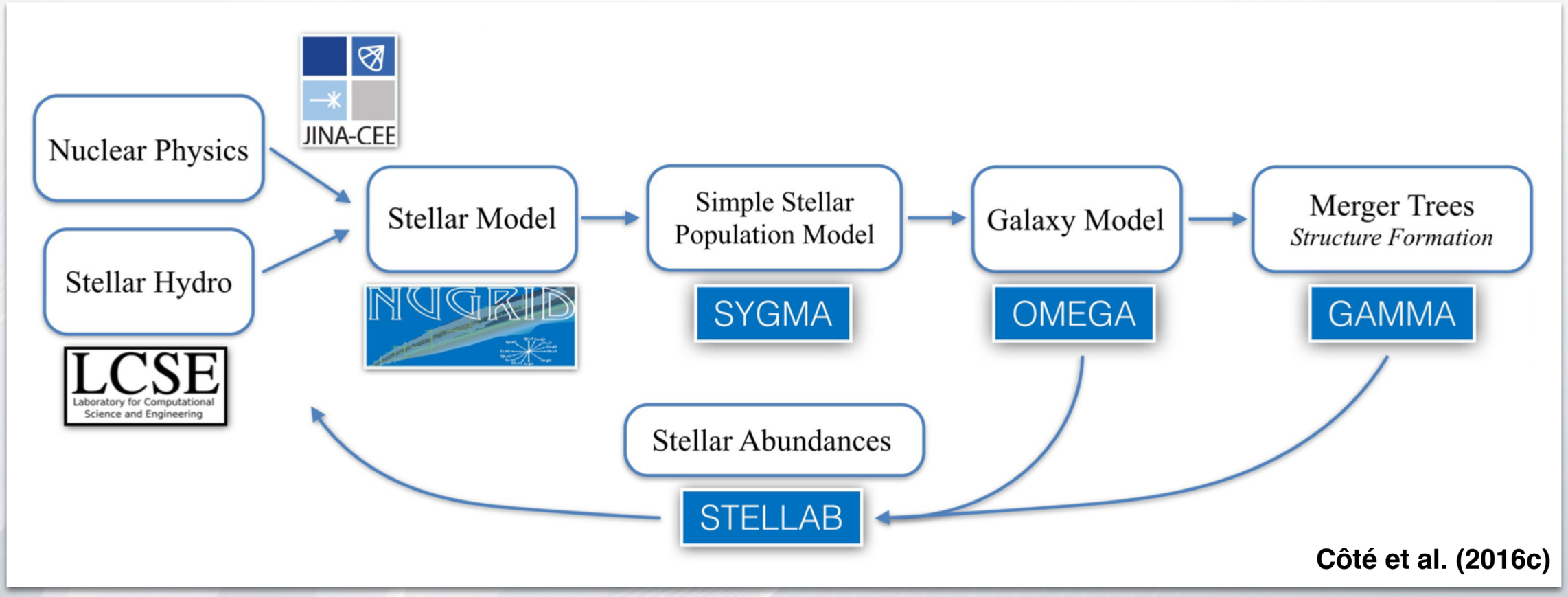
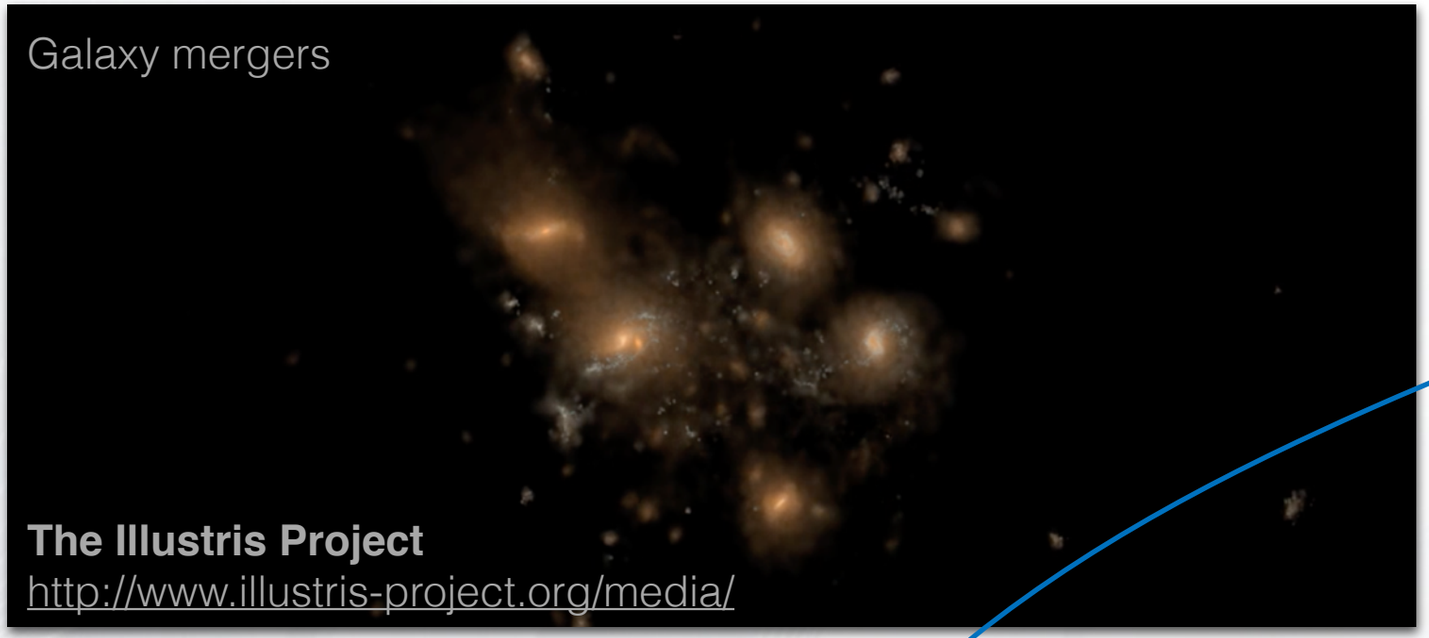


CHEMICAL EVOLUTION PIPELINE



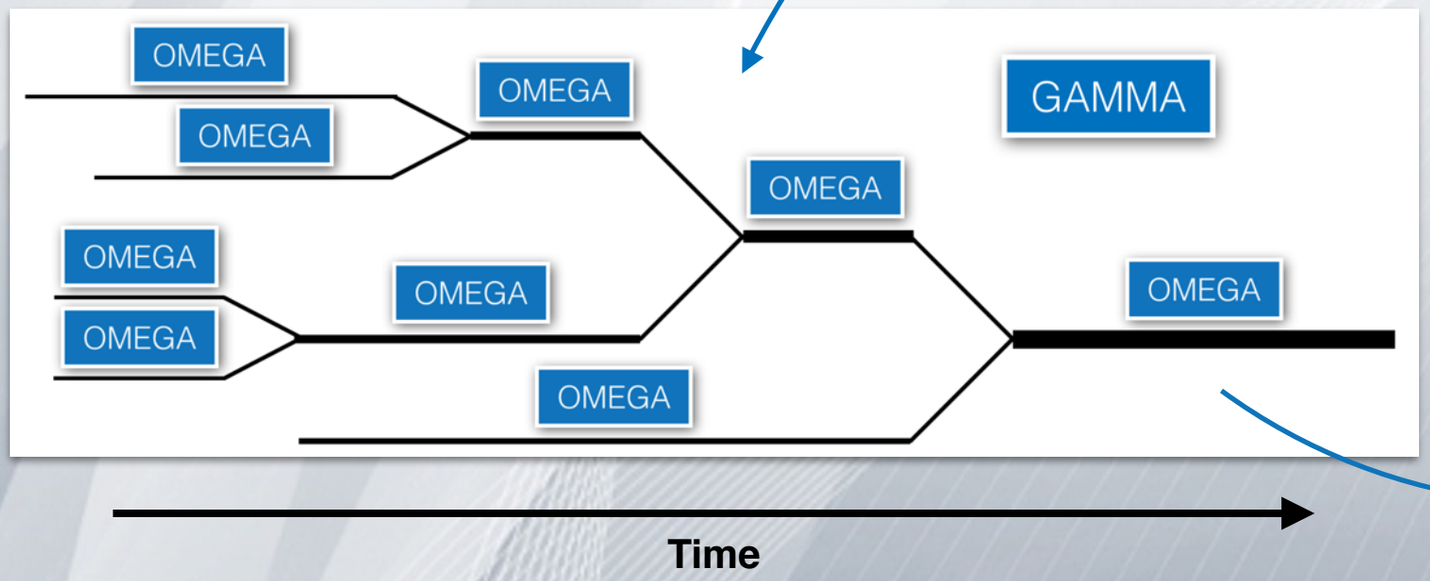
Côté et al. (2016c)

GALAXY ASSEMBLY

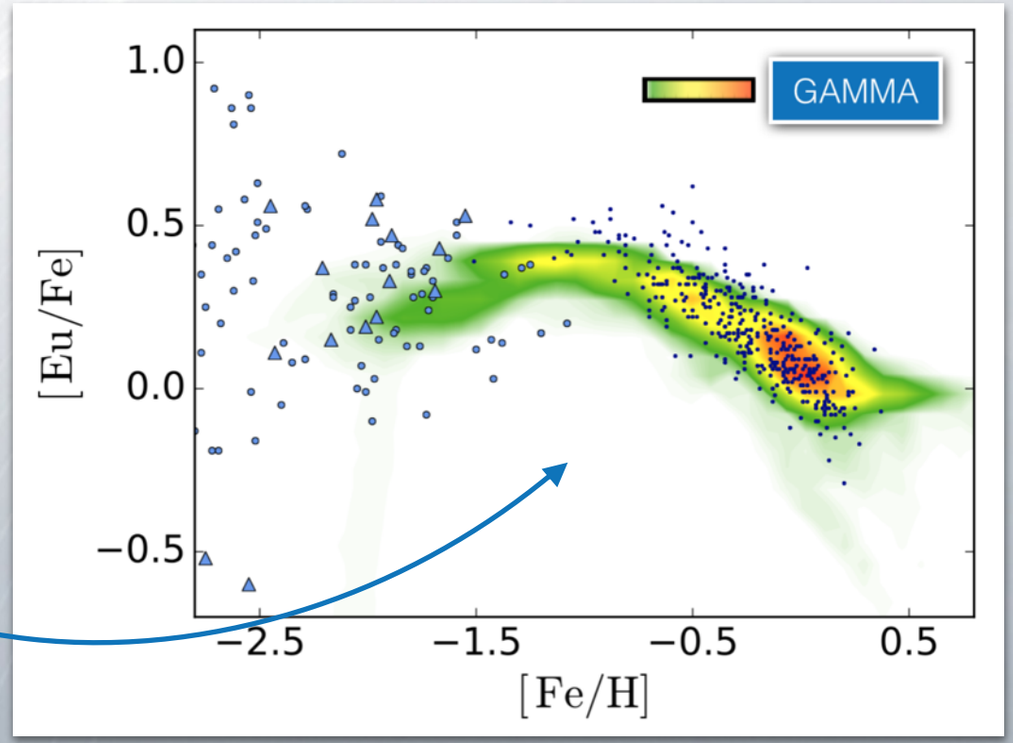


Griffen et al. (2016) - The Caterpillar Project

GAMMA calculates the chemical evolution of 280 isotopes.



Côté et al. in prep.

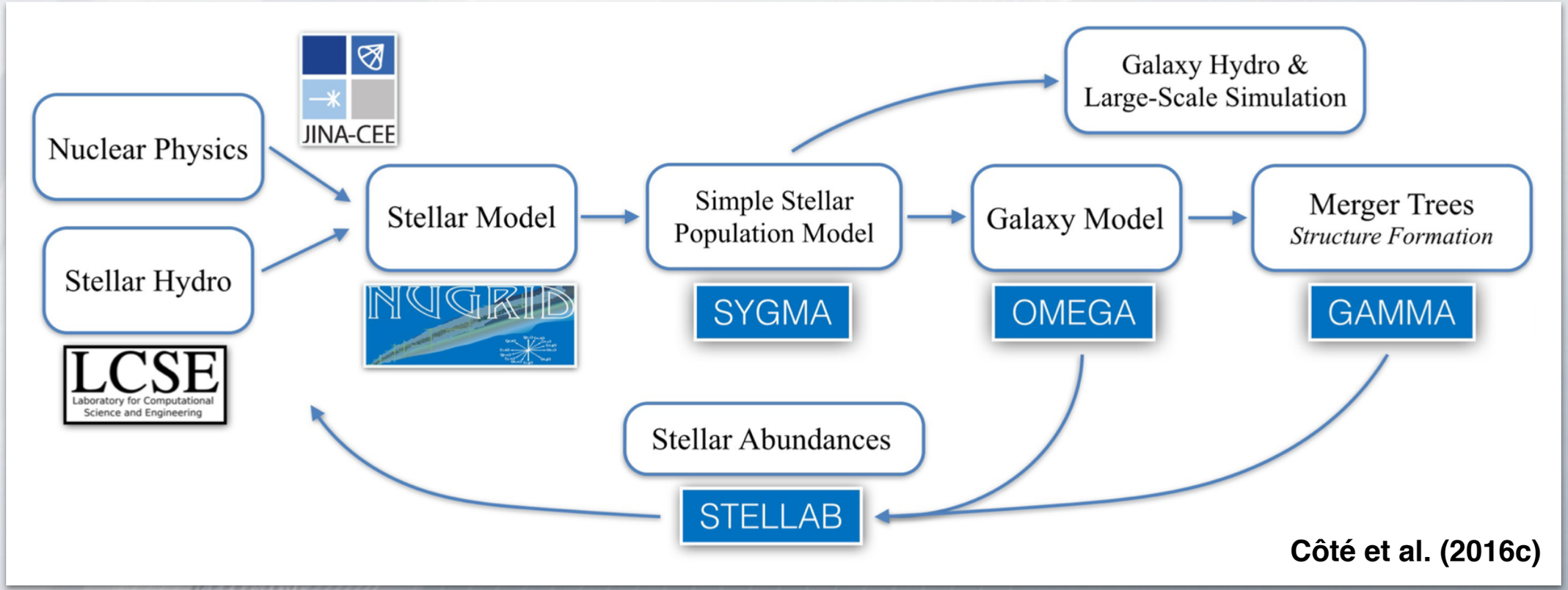


CONCLUSIONS

Multiple constraints are needed to ensure reliable interpretations of numerical predictions.

Our flexible chemical evolution pipeline provides allows to probe
the **impact of nuclear astrophysics in a galactic chemical evolution context**.

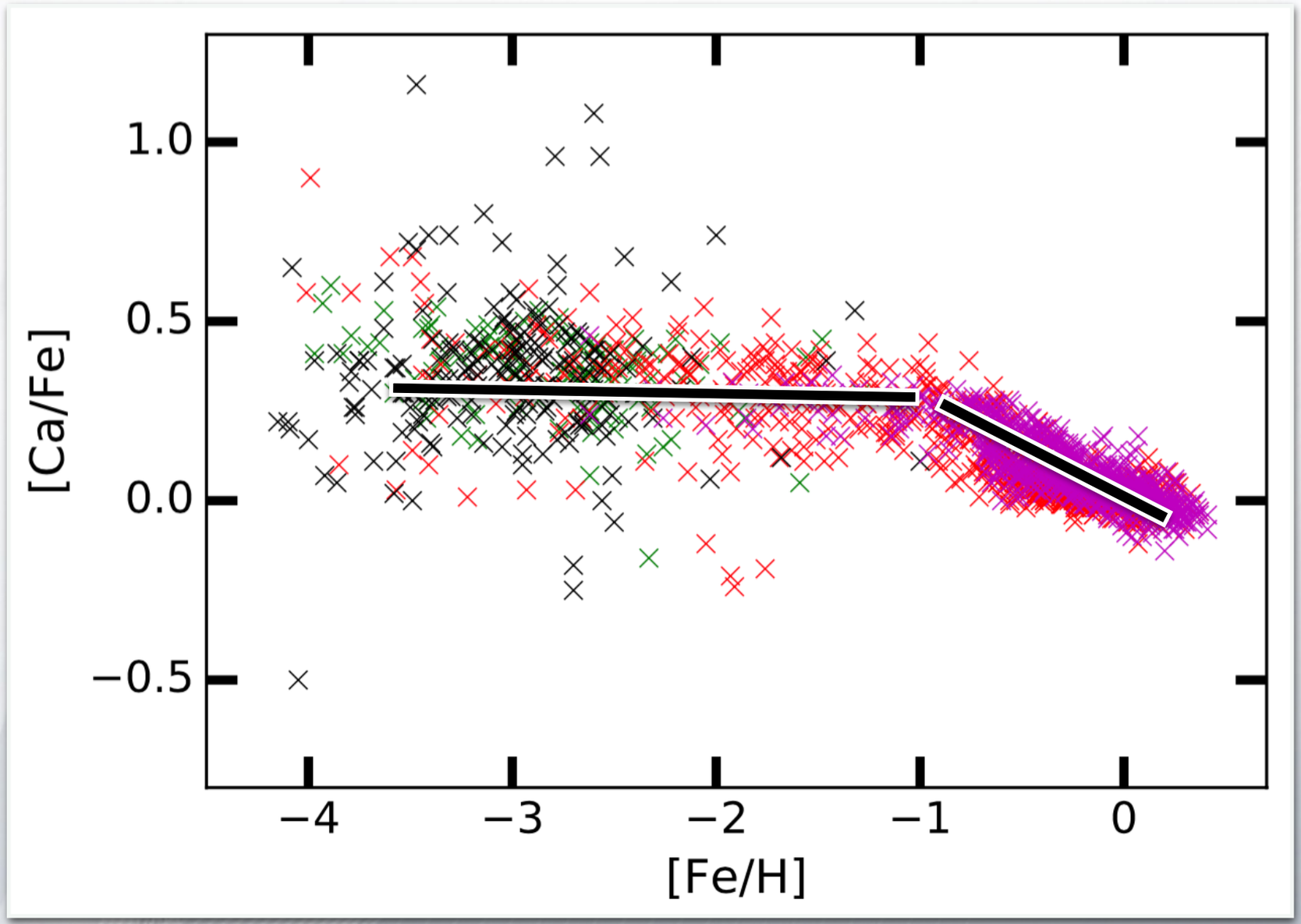
A better **quantification of uncertainties propagation** will improve our ability to constrain and understand the formation history of the Milky Way in a cosmological context.



Côté et al. (2016c)

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

GALACTIC CHEMICAL EVOLUTION



$$[A/B] = \log(n_A/n_B) - \log(n_A/n_B)_\odot$$

CONTRIBUTION OF DIFFERENT STARS

Core-collapse supernova

O, Mg, Ca, Si, Ti, Fe, ..

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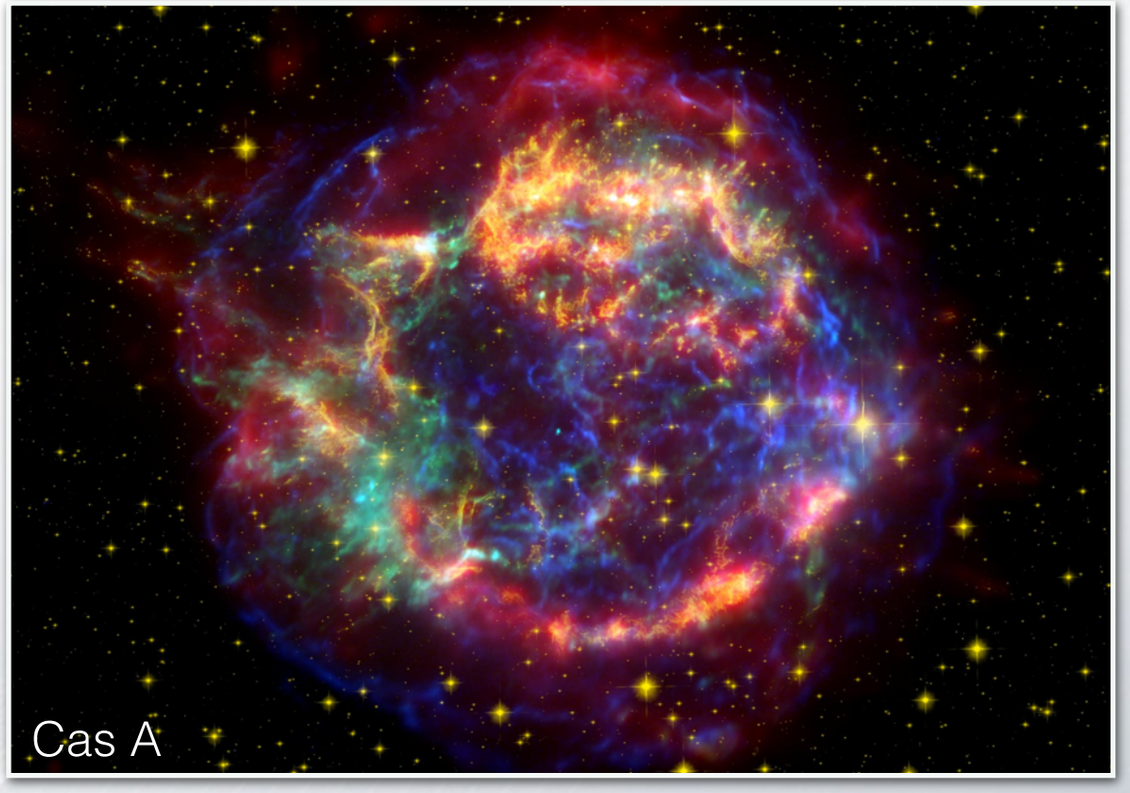

Fe, ..

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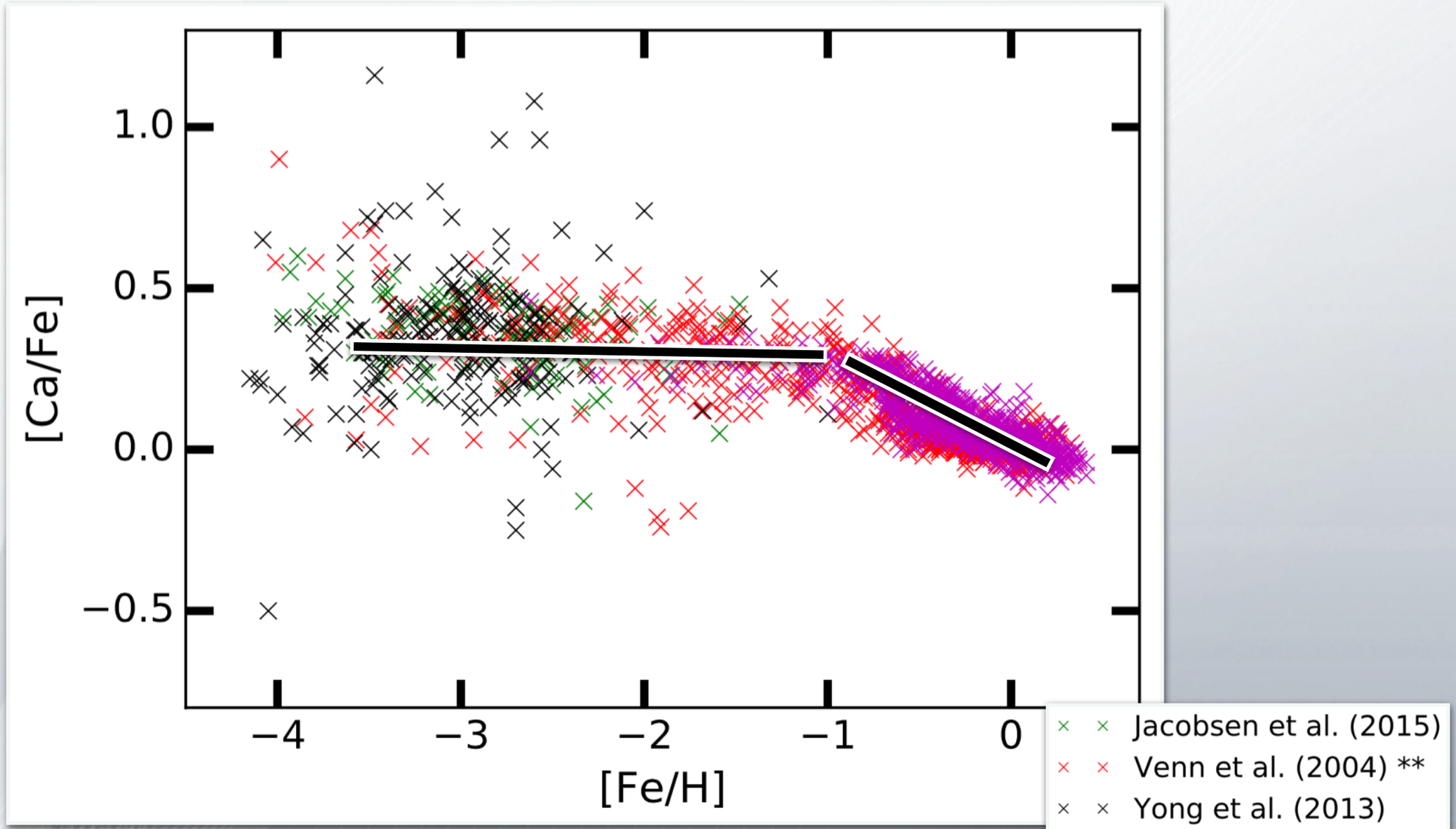
Core-collapse SNe (**Ca**, **Fe**)

Milky Way galaxy



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