

DIS Galactic Archaeology module

Lecture 6: Chemical evolution & hands-on session

Dr Anke Ardern-Arentsen

Recap from the previous lecture

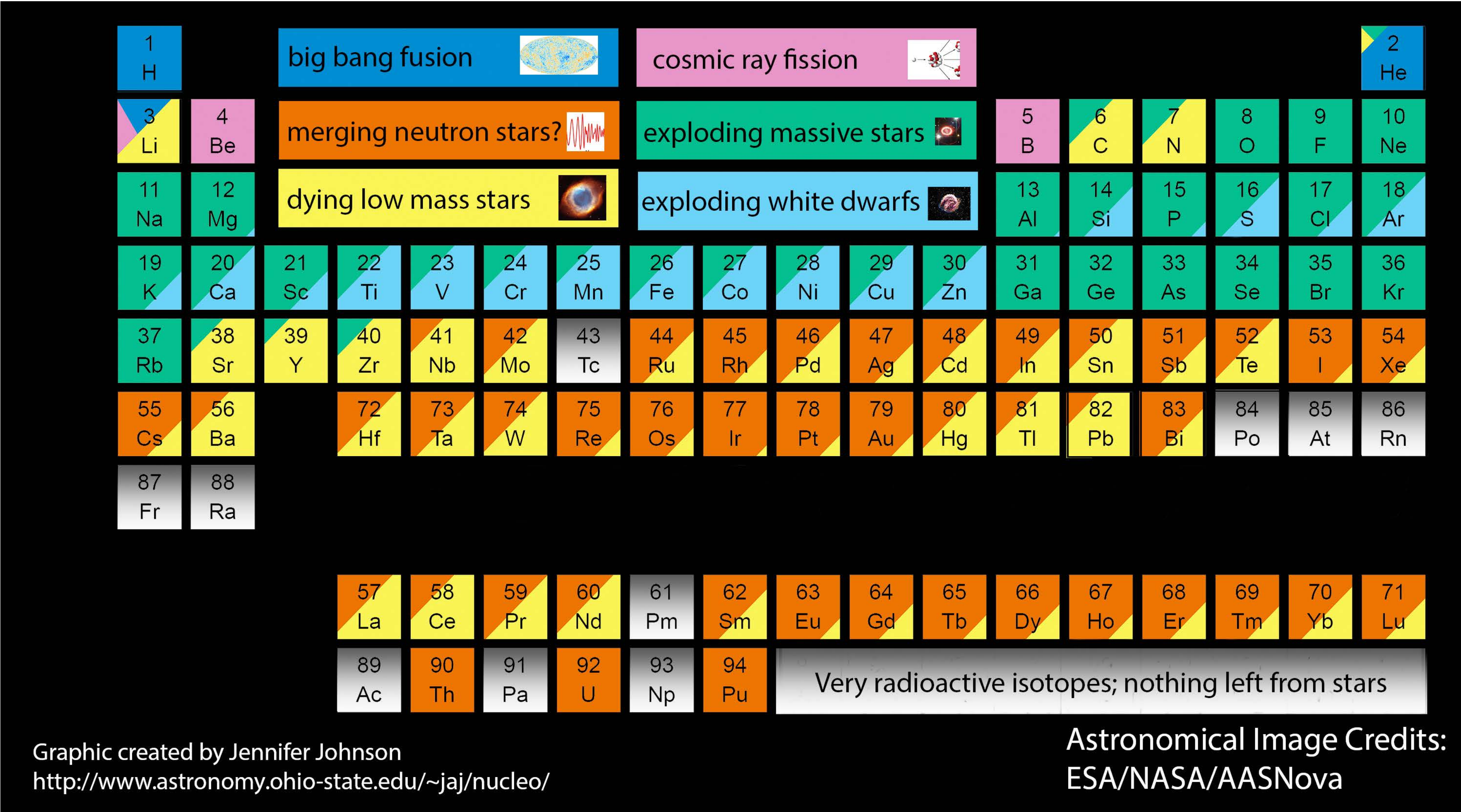
- How to build an astronomical dataset? It’s a lot of effort!
- Public survey data products are extremely useful, but they are not perfect

The *Gaia* mission[★]

Gaia Collaboration, T. Prusti^{1,★★}, J. H. J. de Bruijne¹, A. G. A. Brown², A. Vallenari³, C. Babusiaux⁴, C. A. L. Bailer-Jones⁵, U. Bastian⁶, M. Biermann⁶, D. W. Evans⁷, L. Eyer⁸, F. Jansen⁹, C. Jordi¹⁰, S. A. Klioner¹¹, U. Lammers¹², L. Lindegren¹³, X. Luri¹⁰, F. Mignard¹⁴, D. J. Milligan¹⁵, C. Panem¹⁶, V. Poinsignon¹⁷, D. Pourbaix^{18,19}, S. Randich²⁰, G. Sarri²¹, P. Sartoretti⁴, H. I. Siddiqui²², C. Soubiran²³, V. Valette¹⁶, F. van Leeuwen⁷, N. A. Walton⁷, C. Aerts^{24,25}, F. Arenou⁴, M. Cropper²⁶, R. Drimmel²⁷, E. Høg²⁸, D. Katz⁴, M. G. Lattanzi²⁷, W. O’Mullane¹², E. K. Grebel⁶, A. D. Holland²⁹, C. Huc¹⁶, X. Passot¹⁶, L. Bramante³⁰, C. Cacciari³¹, J. Castañeda¹⁰, L. Chaoul¹⁶, N. Cheek³², F. De Angeli⁷, C. Fabricius¹⁰, R. Guerra¹², J. Hernández¹², A. Jean-Antoine-Piccolo¹⁶, E. Masana¹⁰, R. Messineo³⁰, N. Mowlavi⁸, K. Nienartowicz³³, D. Ordóñez-Blanco³³, P. Panuzzo⁴, J. Portell¹⁰, P. J. Richards³⁴, M. Riello⁷, G. M. Seabroke²⁶, P. Tanga¹⁴, F. Thévenin¹⁴, J. Torra¹⁰, S. G. Els^{35,6}, G. Gracia-Abril^{35,10}, G. Comoretto²², M. García-Reinaldos¹², T. Lock¹², E. Mercier^{35,6}, M. Altmann^{6,36}, R. Andrae³, T. L. Astraatmadja⁵, I. Bellas-Velidis³⁷, K. Benson²⁶, J. Berthier³⁸, R. Blomme³⁹, G. Busso⁷, B. Carry^{14,38}, A. Cellino²⁷, G. Clementini³¹, S. Cowell⁷, O. Creevey^{14,40}, J. Cuypers³⁹, M. Davidson⁴¹, J. De Ridder²⁴, A. de Torres⁴², L. Delchambre⁴³, A. Dell’Oro²⁰, C. Ducourant²³, Y. Frémat³⁹, M. García-Torres⁴⁴, E. Gosset^{43,19}, J.-L. Halbwachs⁴⁵, N. C. Hambly⁴¹, D. L. Harrison^{7,46}, M. Hauser⁶, D. Hestroffer³⁸, S. T. Hodgkin⁷, H. E. Huckle²⁶, A. Hutton⁴⁷, G. Jasiewicz⁴⁸, S. Jordan⁶, M. Kontizas⁴⁹, A. J. Korn⁵⁰, A. C. Lanzafame^{51,52}, M. Manteiga⁵³, A. Moitinho⁵⁴, K. Muinonen^{55,56}, J. Osinde³⁷, E. Pancino^{20,58}, T. Pauwels³⁹, J.-M. Petit⁵⁹, A. Recio-Blanco¹⁴, A. C. Robin⁵⁹, L. M. Sarro⁶⁰, C. Siopis¹⁸, M. Smith²⁶, K. W. Smith⁵, A. Sozzetti²⁷, W. Thuillot³⁸, W. van Reeve⁴⁷, Y. Viala⁴, U. Abbas²⁷, A. Abreu Aramburu⁶¹, S. Accari⁶², J. J. Aguado⁶⁰, P. M. Allan³⁴, W. Allasia⁶³, G. Altavilla³¹, M. A. Álvarez⁵³, J. Alves⁶⁴, R. I. Anderson^{65,8}, A. H. Andrei^{66,67,36}, E. Anglada Varela^{57,32}, E. Antiche¹⁰, T. Antoja¹, S. Antón^{68,69}, B. Arcay⁵³, A. Atzei²¹, L. Ayache⁷⁰, N. Bach⁴⁷, S. G. Baker²⁶, L. Balaguer-Núñez¹⁰, C. Barache³⁶, C. Barata⁵⁴, A. Barbier⁶², F. Barblan⁸, M. Baroni²¹, D. Barrado y Navascués⁷¹, M. Barros⁵⁴, M. A. Barstow⁷², U. Becciani⁵², M. Bellazzini³¹, G. Bellei⁷³, A. Bello García⁷⁴, V. Belokurov⁷, P. Bendjoya¹⁴, A. Berihuete⁷⁵, L. Bianchi⁶³, O. Bienaymé⁴⁵, F. Billebaud²³, N. Blagorodnova⁷, S. Blanco-Cuadros^{8,23}, T. Boch⁴⁵, A. Bombrun⁴², R. Borrachero¹⁰, S. Bouquillon³⁶, G. Bourda²³, H. Bouy⁷¹, A. Bragaglia³¹, M. A. Breddels⁷⁶, N. Brouillet²³, T. Brüsemeister⁶, B. Bucciarelli²⁷, F. Budnik¹⁵, P. Burgess⁷, R. Burgon²⁹, A. Burlacu¹⁶, D. Busonero²⁷, R. Buzzzi²⁷, E. Caffau⁴⁷, J. Cambras⁷⁷, H. Campbell⁷⁷, R. Cancelliere⁷⁸, T. Cantat-Gaudin³, T. Carlucci³⁶, J. M. Carrasco¹⁰, M. Castellani⁷⁹, P. Charlot²³, J. Chamas³³, P. Charvet¹⁷, F. Chassat¹⁷, A. Chiavassa¹⁴, M. Clotet¹⁰, G. Cocozza³¹, R. S. Collins⁴¹, P. Collins¹⁵, G. Costigan², F. Crifo⁴, N. J. G. Cross⁴¹, M. Crosta²⁷, C. Crowley⁴², C. Dafonte³³, Y. Damerdjij^{43,80}, A. Dapergolas³⁷, P. David³⁸, M. David⁸¹, P. De Cat³⁹, F. de Felice⁸², P. de Laverny¹⁴, F. De Luise⁸³, R. De March³⁰, D. de Martino⁸⁴, R. de Souza⁸⁵, J. Debosscher²⁴, E. del Pozo⁴⁷, M. Delbo¹⁴, A. Delgado⁷, H. E. Delgado⁶⁰, F. di Marco⁸⁶, P. Di Matteo⁴, S. Diakite⁵⁹, E. Distefano⁵², C. Dolding²⁶, S. Dos Anjos⁸⁵, P. Drazinos⁴⁹, J. Durán⁵⁷, Y. Dzigan^{87,88}, E. Ecale¹⁷, B. Edvardsson⁵⁰, H. Enke⁸⁹, M. Erdmann²¹, D. Escolar²¹, M. Espina¹⁵, N. W. Evans⁷, G. Eynard Bontemps⁹², C. Fabre⁹⁰, M. Fabrizio^{58,83}, S. Faigler⁹¹, A. J. Falcão⁹², M. Farrás Casas¹⁰, F. Faye¹⁷, L. Federici³¹, G. Fedorets⁵⁵, J. Fernández-Hernández³², P. Fernique⁴⁵, A. Fienga⁹³, F. Figuera¹⁰, F. Filippi³⁰, K. Findeisen⁴, A. Fonti³⁰, M. Fouesneau³, E. Fraile⁹⁴, M. Fraser⁷, J. Fuchs³, R. Furnell⁵¹, M. Gai²⁷, S. Galletti⁵¹, L. Galuccio¹⁴, D. Garabato⁵³, F. García-Sedano⁹⁰, P. Garé²¹, A. Garofalo³¹, N. Garralda¹⁰, P. Gavras¹⁴, J. Gerssen⁸⁹, R. Geyer¹¹, G. Gilmore⁷, S. Girona⁹⁶, G. Giuffrida³⁸, M. Gomes³⁴, A. González-Marcos⁹⁷, J. González-Núñez^{32,98}, J. J. González-Vidal¹⁰, M. Granvik⁵⁵, A. Guerrier⁴⁹², P. Guillout⁴⁵, J. Guiraud¹⁶, A. Gúrpide¹⁰, R. Gutiérrez-Sánchez²², L. P. Guy³³, R. Haigron⁴, D. Hatzidimitriou⁴⁹, M. Haywood⁴, U. Heiter⁵⁰, A. Helmi⁷⁶, D. Hobbs¹³, W. Hofmann⁶, B. Holl⁸, G. Holland⁷, J. A. S. Hunt²⁶, A. Hypki², V. Icardi³⁰, M. Irwin⁷, G. Jevardat de Fombelle³³, P. Jofre^{7,23}, P. G. Jonker^{99,25}, A. Jorissen¹⁸, F. Julbe¹⁰, A. Karampelas^{49,37}, A. Kochoska¹⁰⁰, R. Kohley¹², K. Kolenberg^{101,24,102}, E. Kontizas³⁷, S. E. Kopusov⁷, G. Kordopatis^{89,14}, P. Koubsky⁹⁵, A. Kowalczyk¹⁵, A. Krone-Martins⁵⁴, M. Kudryashova³⁸, I. Kull⁹¹, R. K. Bachchan¹³, F. Lacoste-Seris⁶², A. F. Lanza²², J.-B. Lavigne⁶², C. Le Poncin-Lafitte³⁶, Y. Lebreton^{4,103}, T. Lebzelter⁹⁴, S. Leccia⁸⁴, N. Leclerc⁴, I. Lecoeur-Taib³³, V. Lemaître⁶², H. Lenhardt⁶, F. Leroux⁶², S. Liao^{27,104}, E. Licata⁶³, H. E. P. Lindstrøm^{28,105}, T. A. Lister¹⁰⁶, E. Livanou⁴⁹, A. Lobel³⁹, W. Löffler⁶, M. López⁷¹, A. Lopez-Lozano¹⁰⁷, D. Lorenz⁶⁴, T. Loureiro¹⁵, I. MacDonald⁴¹, T. Magalhães Fernandes⁹², S. Managau⁶², R. G. Mann⁴¹, G. Mantelet⁶, O. Marchal⁴, J. M. Marchant¹⁰⁸, M. Marconi⁸⁴, J. Marie¹⁰⁹, S. Marinoni^{79,58}, P. M. Marrese^{79,58}, G. Marschall^{6110,111}, D. J. Marshall¹¹², J. M. Martín-Fleitas⁴⁷, M. Martino³⁰, N. Mary⁶², G. Matijević⁸⁹, T. Mazeh⁹¹, P. J. McMillan¹³, S. Messina⁵², A. Mestre¹¹³, D. Michalik¹³, N. R. Millar⁷, B. M. H. Miranda⁵⁴, D. Molina¹⁰, R. Molinaro⁸⁴, M. Molinaro¹¹⁴, L. Molnár¹¹⁰, M. Moniez¹¹⁵, P. Montegriffo³¹, D. Monteiro²¹, R. Mor¹⁰, A. Mora³⁷, R. Morbidelli²⁷, T. Morel⁴³, S. Morgenthaler¹¹⁶, T. Morley⁸⁶, D. Morris⁴¹, A. F. Mulone³⁰, T. Muraveva³¹, I. Musella⁸⁴, J. Narbonne⁶², G. Nelemans^{25,24}, L. Nicastro¹¹⁷, L. Noval⁶², C. 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Steele¹⁰⁸, H. Steidelmüller¹¹, C. A. Stephenson²², H. Stoev¹²⁷, F. F. Suess⁷, M. Süveges³³, J. Surdej⁴³, L. Szabados¹¹⁰, E. Szegedi-Elek¹¹⁰, D. Tapiador^{128,129}, F. Taris³⁶, G. Tauran⁶², M. B. Taylor¹³⁰, R. Teixeira⁸⁵, D. Terrett³⁴, B. Tingley¹³¹, S. C. Trager⁷⁶, C. Turon⁴, A. Ulla¹³², E. Utrilla⁴⁷, G. Valentini⁸³, A. van Elteren², E. Van Hemelryck³⁹, M. van Leeuwen⁷, M. Varadi^{8,110}, A. Vecchiato²⁷, J. Veljanoski⁷⁶, T. Via⁷⁷, D. Vicente⁹⁶, S. Vogt¹³³, H. Voss¹⁰, V. Votrubá⁹⁵, S. Voutsinas⁴¹, G. Walmsley¹⁶, M. Weiler¹⁰, K. Weingrill⁸⁹, D. Werner¹⁵, T. Wevers²⁵, G. Whitehead¹⁵, Ł. Wyrzykowski^{7,134}, A. Yoldas⁷, M. Žerjal¹⁰⁰, S. Zucker⁸⁷, C. Zurbach⁴⁸, T. Zwitter¹⁰⁰, A. Alecu¹, M. Allen¹, C. Allende Prieto^{26,135,136}, A. Amorim⁵⁴, G. Anglada-Escudé¹⁰, V. Arsenijevic⁵⁴, S. Azaz¹, P. Balm²², M. Beck³⁵, H.-H. Bernstein^{1,6}, L. Bigot¹⁴, A. Bijaoui¹⁴, C. Blasco¹³⁷, M. Bonfigli⁸⁵, G. Bono⁷⁹, S. Boudreault^{26,138}, A. Bressan¹³⁹, S. Brown⁷, P.-M. Brunet¹⁶, P. Bunclark^{1,7}, R. Buonanno⁷⁹, A. G. Butkevich¹¹, C. Carret¹¹⁹, C. Carrión⁶⁰, L. Chemin^{23,140}, F. Chéreau⁴, L. Corcione²⁷, E. Darmigny¹⁶, K. S. de Boer¹⁴¹, P. de Teodoro³², P. T. de Zeeuw^{2,142}, C. Delle Luche^{4,62}, C. D. Domingues¹⁴³, P. Dubath³³, F. Fodor¹⁶, B. Frézouls¹⁶, A. Fries¹⁰, D. Fustes³³, D. Fyfe⁷², E. Gallardo¹⁰, J. Gallegos³², D. Gardiol²⁷, M. Gebran^{10,144}, A. Gomboc^{100,145}, A. Gómez⁴, E. Grux³⁹, A. Gueguen^{4,146}, A. Heyrovsky⁴¹, J. Hoar¹², G. Iannicola⁷⁹, Y. Isasi Parache¹⁰, A.-M. Janotto¹⁶, E. Joliet^{42,147}, A. Jonckheere³⁹, R. Keil^{148,149}, D.-W. Kim³, P. Klagiyivik¹¹⁰, J. Klar⁸⁹, J. Knude²⁸, O. Kochukhov⁵⁰, I. Kolka¹⁵⁰, J. Kos^{100,151}, A. Kutka^{95,152}, V. Lainey³⁸, D. LeBouquin⁶², C. Liu^{5,153}, D. Loreggia²⁷, V. V. Makarov¹⁵⁴, M. G. Marseille⁶², C. Martayan^{39,155}, O. Martinez-Rubi¹⁰, B. Massart^{14,62,17}, F. Meynadier^{4,36}, S. Mignot⁴, U. Munari³, A.-T. Nguyen¹⁶, T. Nordlander⁵⁰, P. Ocirk^{89,45}, K. S. O’Flaherty¹⁵⁶, A. Olías Sanz¹⁵⁷, P. Ortiz⁷², J. Osorio⁶⁸, D. Oszkiewicz^{55,158}, A. Ouzounis⁴¹, M. Palmer¹⁰, P. Park⁴, E. Pasquato¹⁸, C. Peltzer⁴, J. Peralta¹⁰, F. Péturaud⁴, T. Pieniluoma⁵⁵, E. Pigozzi³⁰, J. Poels^{1,43}, G. Prat⁵⁹, T. Prod’homme^{2,21}, F. Raison^{160,146}, J. M. Rebordao¹⁴³, D. Riskez², B. Rocca-Volmerange¹⁶¹, S. Rosen^{26,72}, M. I. Ruiz-Fuertes³³, F. Russo²⁷, S. Sembay⁷², I. Serraller Vizcaino¹⁶², A. Short¹, A. Siebert^{45,89}, H. Silva⁹², D. Sinachopoulos³⁷, E. Slezak¹⁴, M. Soffel¹¹, D. Sosnowska⁸, V. Straizys¹⁶³, M. ter Linden^{42,164}, D. Terrell¹⁶⁵, S. Theil¹⁶⁶, C. Tiede^{5,167}, L. Troisi^{58,168}, P. Tsalmantzas⁵, D. Tur⁷⁷, M. Vaccari^{169,170}, F. Vachier³⁸, P. Valles¹⁰, W. Van Hamme¹⁷¹, L. Veltz^{89,40}, J. Virtanen^{55,56}, J.-M. Wallut¹⁶, R. Wichmann¹⁷², M. I. Wilkinson^{7,72}, H. Ziaepour⁵⁹, and S. Zschocke¹¹

Chemical evolution

The origin of the elements



The origin of the elements & associated timescales

Element Group	Tracer	Mode of entry into the Interstellar Medium	Timescale	Example Elements
Alpha	High mass stars $M > 8 M_{\odot}$	Core collapse (CC) supernovae	0 - 100 Myr	O, Na, Mg, Al, Si, Ca, Ti
Iron peak	Low mass stars $M < 8 M_{\odot}$	mostly Type Ia supernovae (exploding white dwarfs)	100 Myr - 1 Gyr	Ti, V, Cr, Mn, Fe, Co, Ni, Cu, Zn
Iron	Low AND high mass stars	CC SNe, Type Ia SNe	0 - 100 Myr 100 Myr - 1 Gyr	Fe
Slow neutron-capture (s-)process	Low mass stars $1 M_{\odot} < M < 3 M_{\odot}$	Winds during asymptotic giant branch phase	300 Myr - 5 Gyr	Sr, Y, Zr, Ba, La, Ce, Nd
Rapid neutron-capture (r-)process	High mass stars $8 M_{\odot} < M < 22 M_{\odot}$	CC SNe Neutron star mergers	0 - 100 Myr 50 Myr - 14 Gyr	Nd, Eu, Th, U

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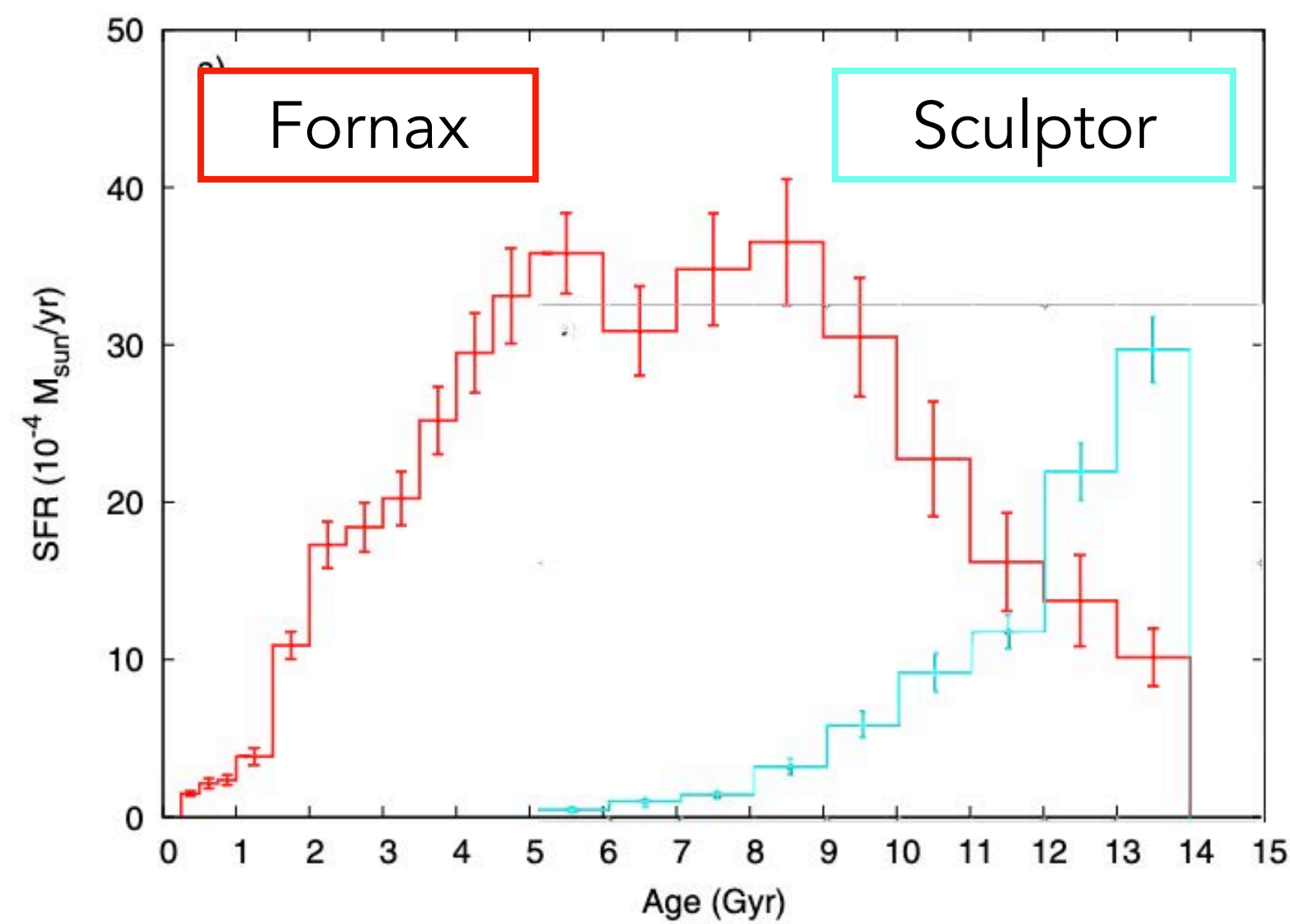
Chemical evolution models

Key ingredients:

Chemical evolution models

Key ingredients:

- Star formation history and efficiency: how many stars were formed at each time?

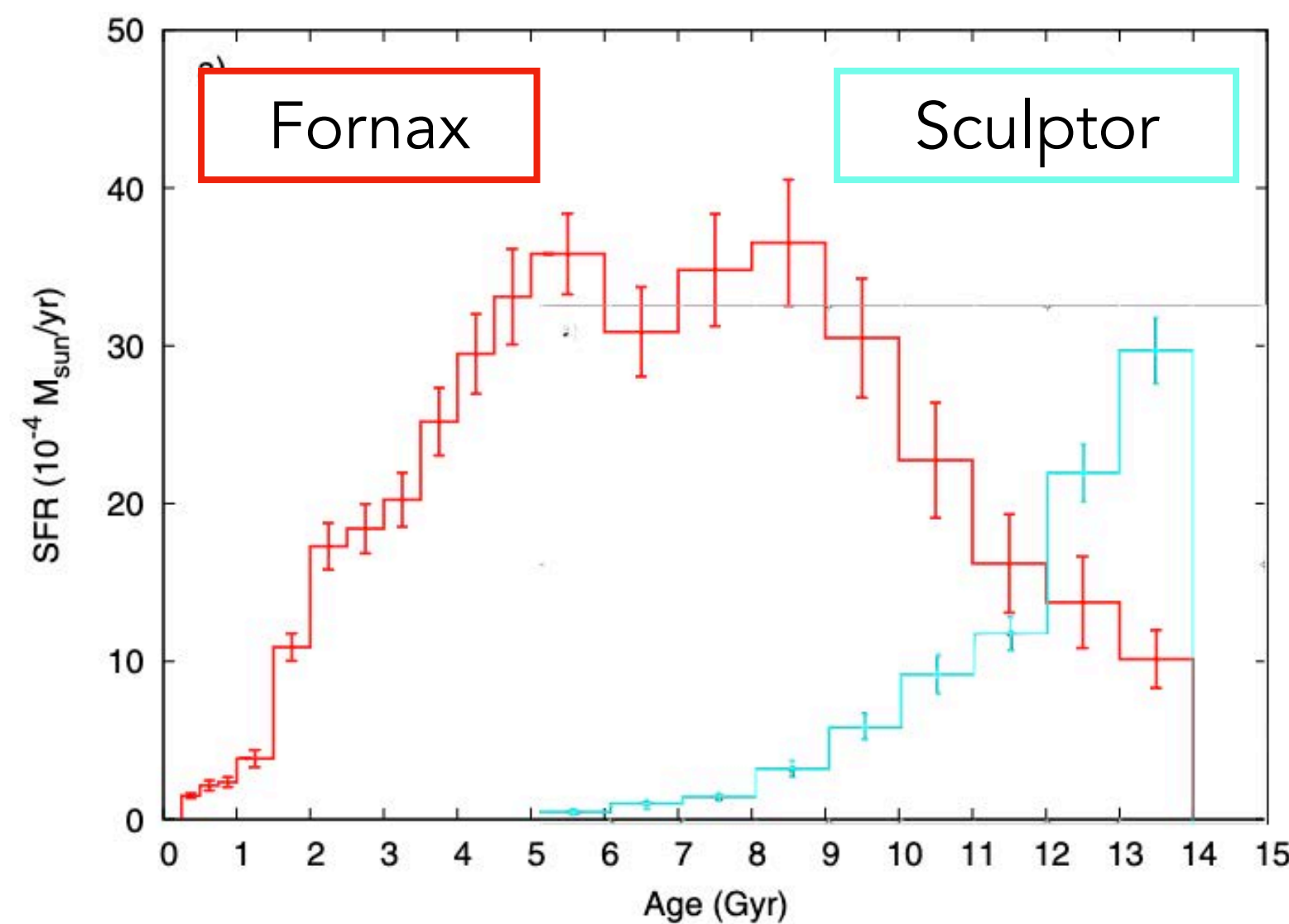


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Chemical evolution models

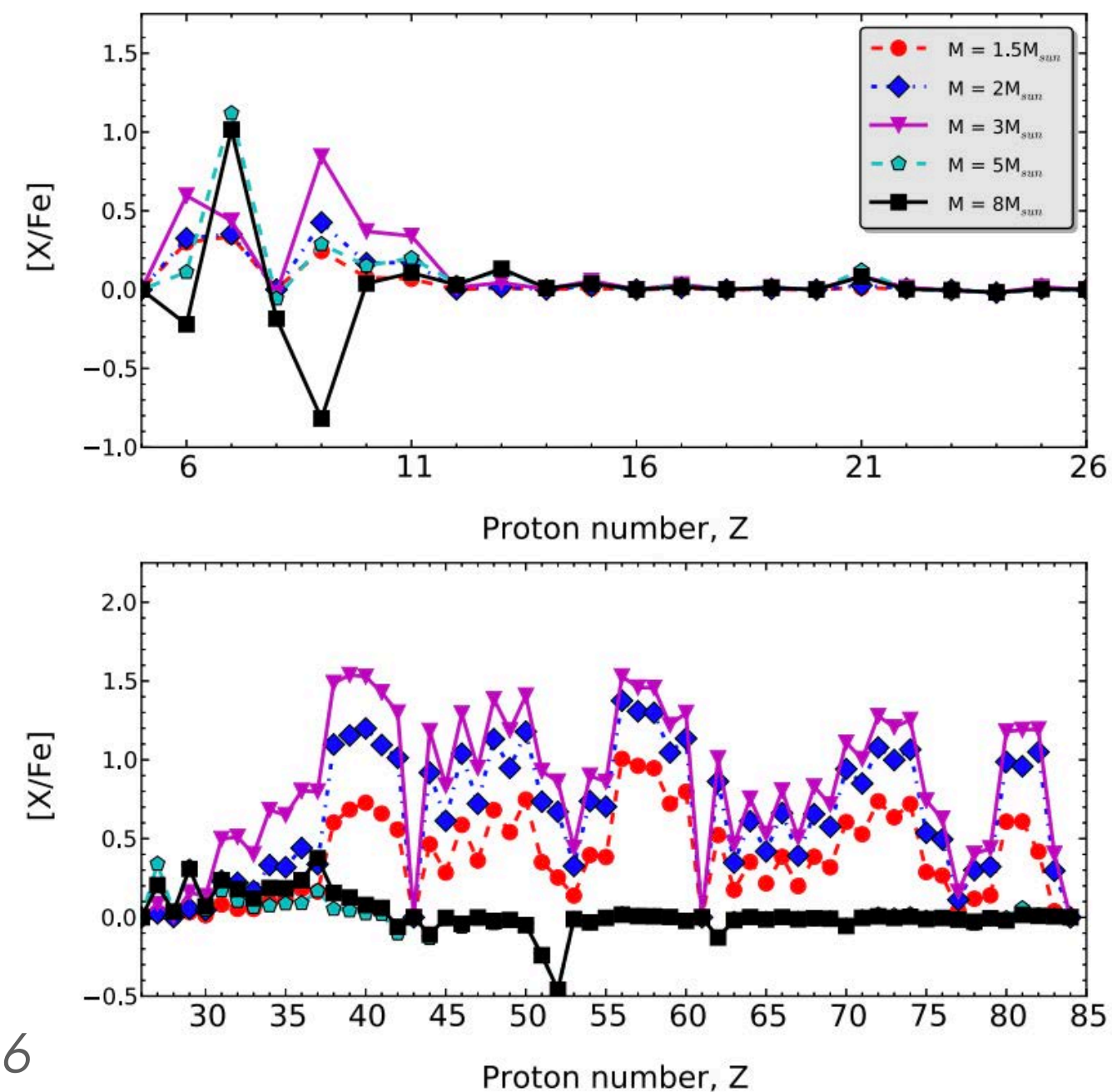
Key ingredients:

- Star formation history and efficiency: how many stars were formed at each time?
- Chemical yields: how much of each element is made in each progenitor? (model-dependent)



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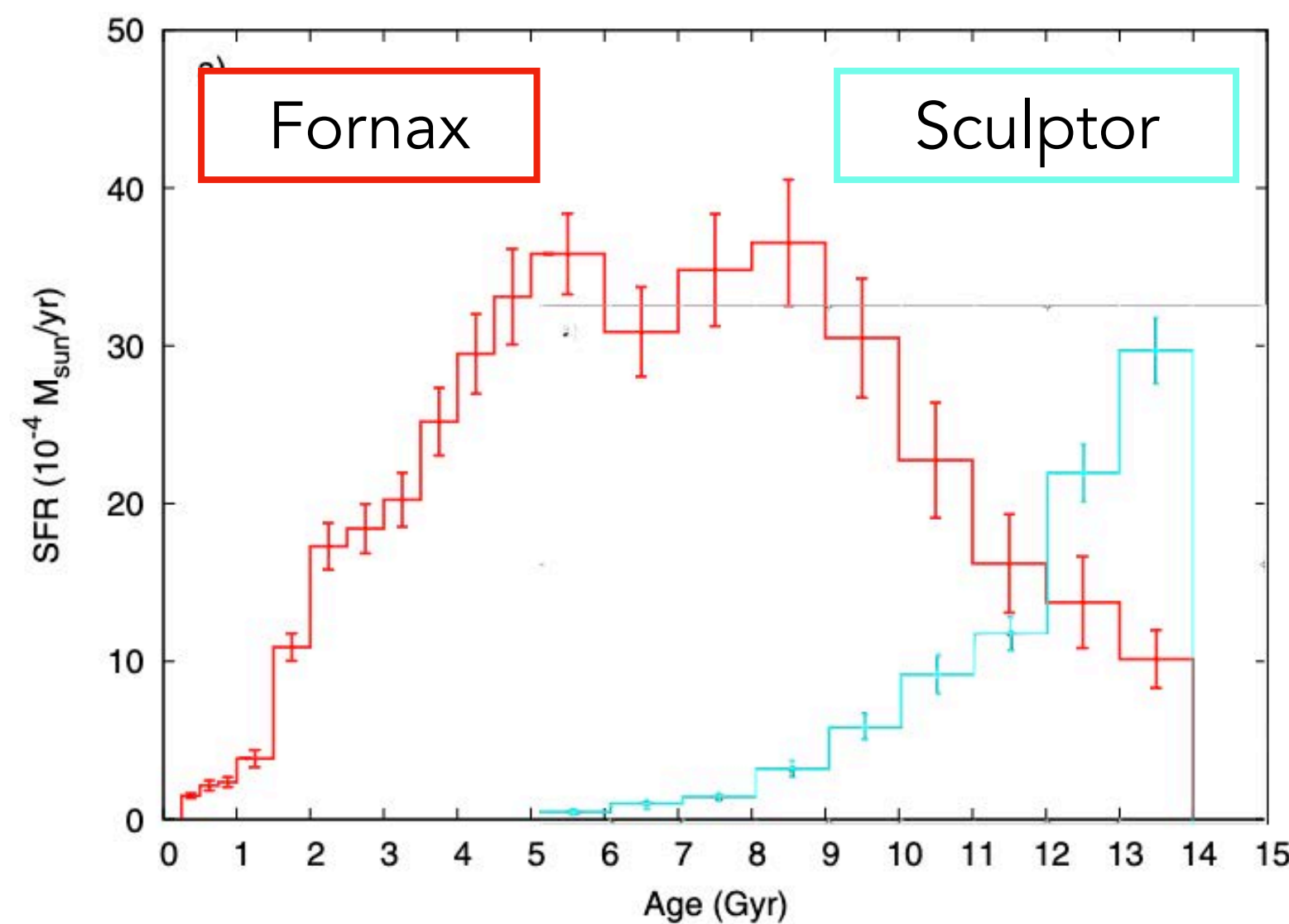
Karakas & Lugaro 2016



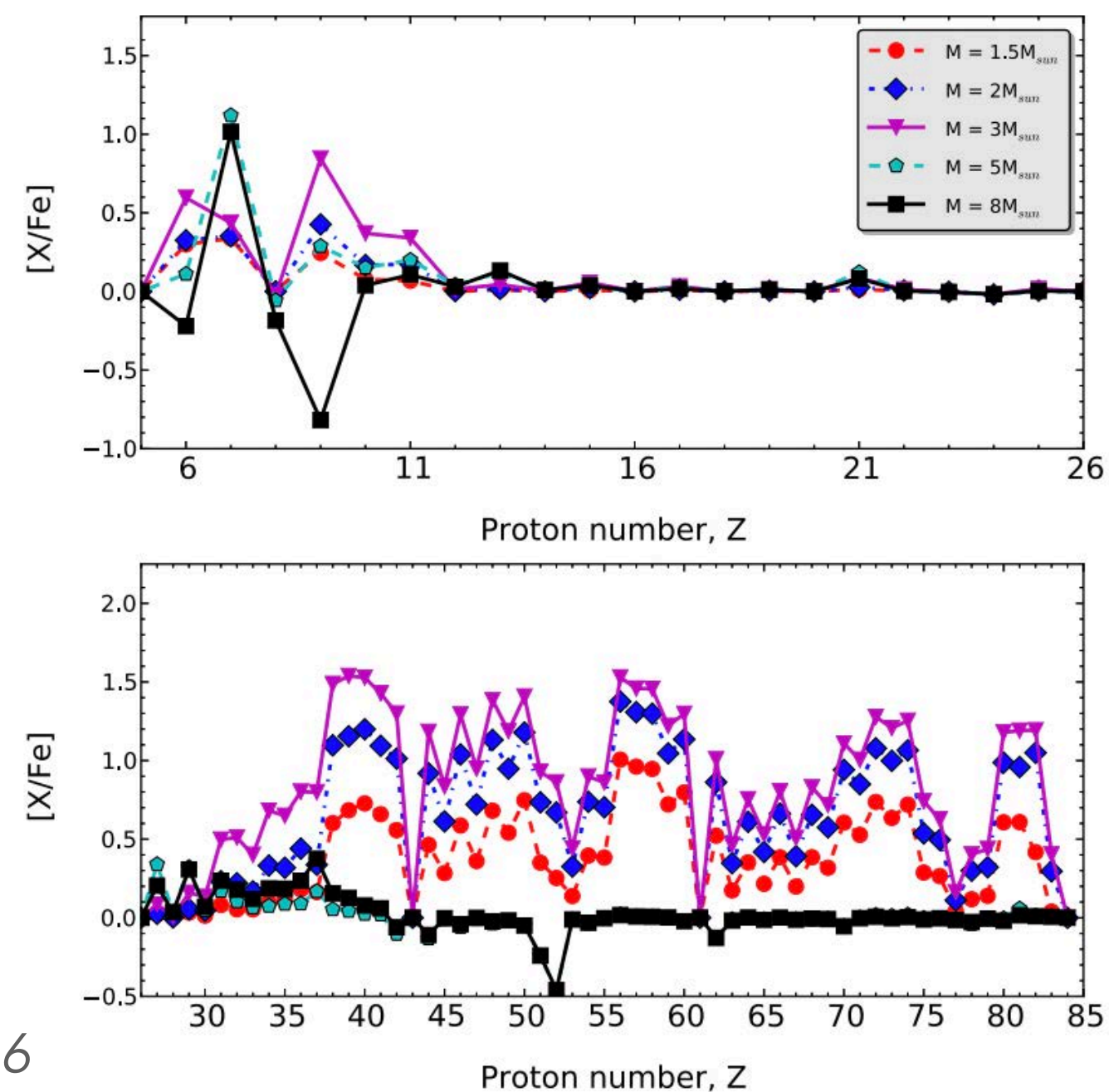
Chemical evolution models

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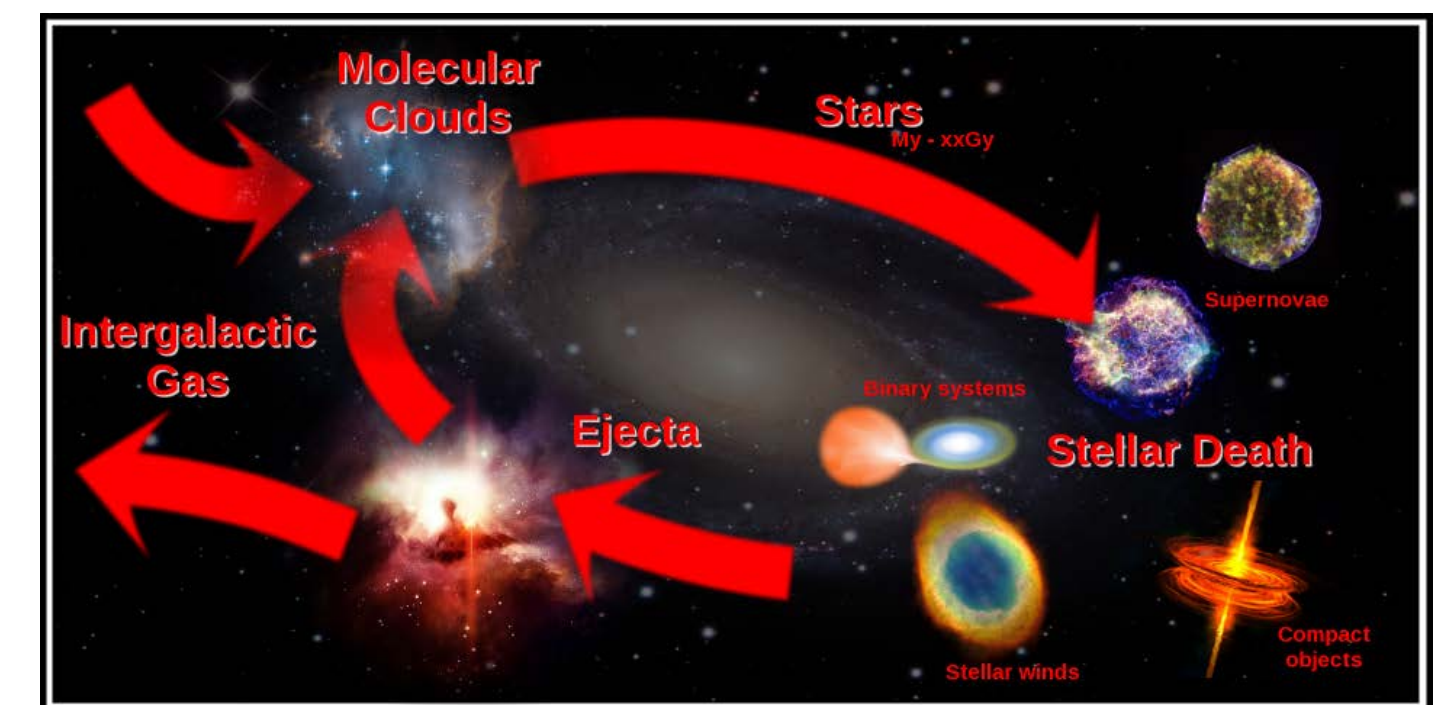
- Star formation history and efficiency: how many stars were formed at each time?
- Chemical yields: how much of each element is made in each progenitor? (model-dependent)
- Other model assumptions: how does the enriched gas mix? Is the system closed?



De Boer et al. 2012

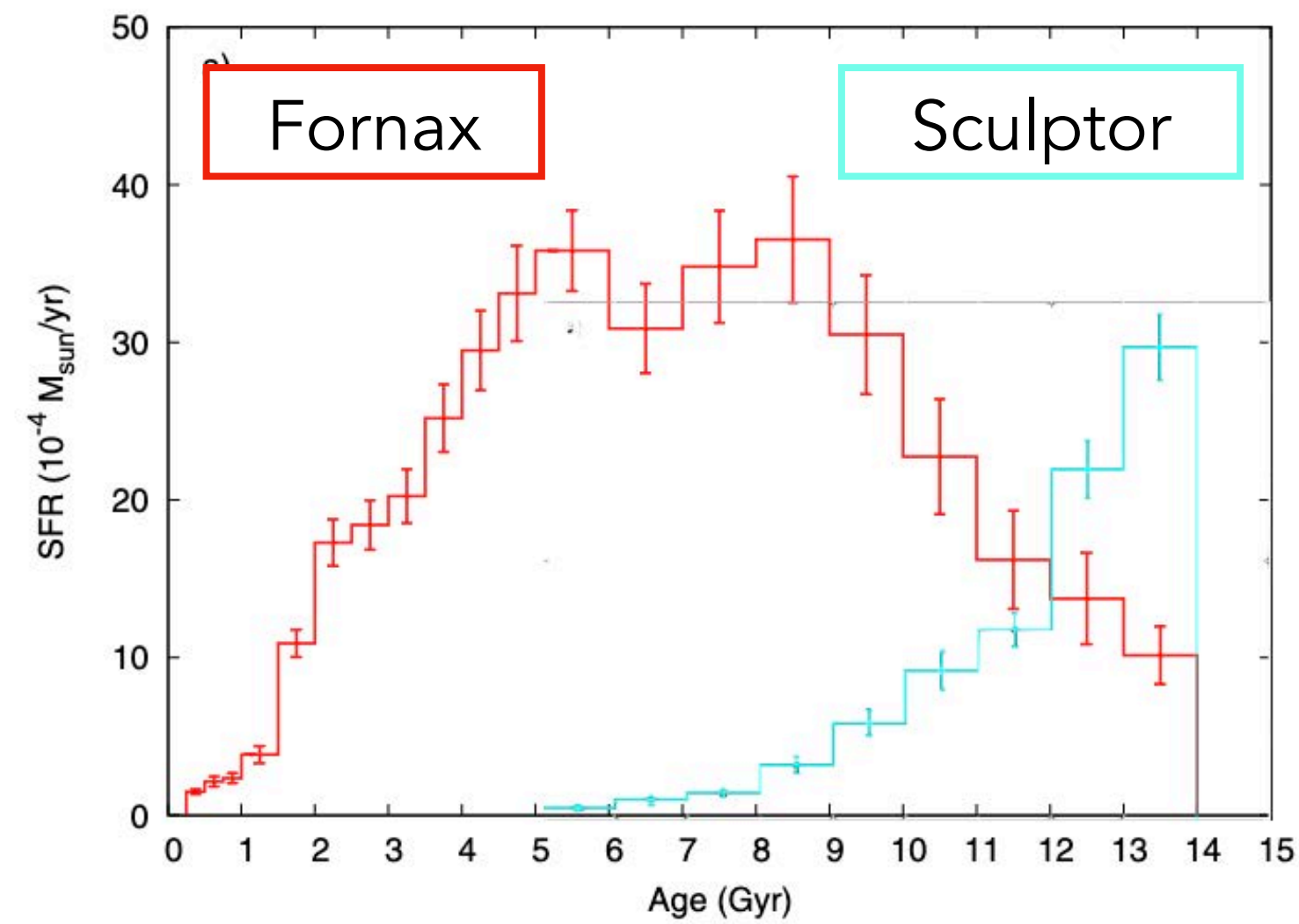


Karakas & Lugaro 2016



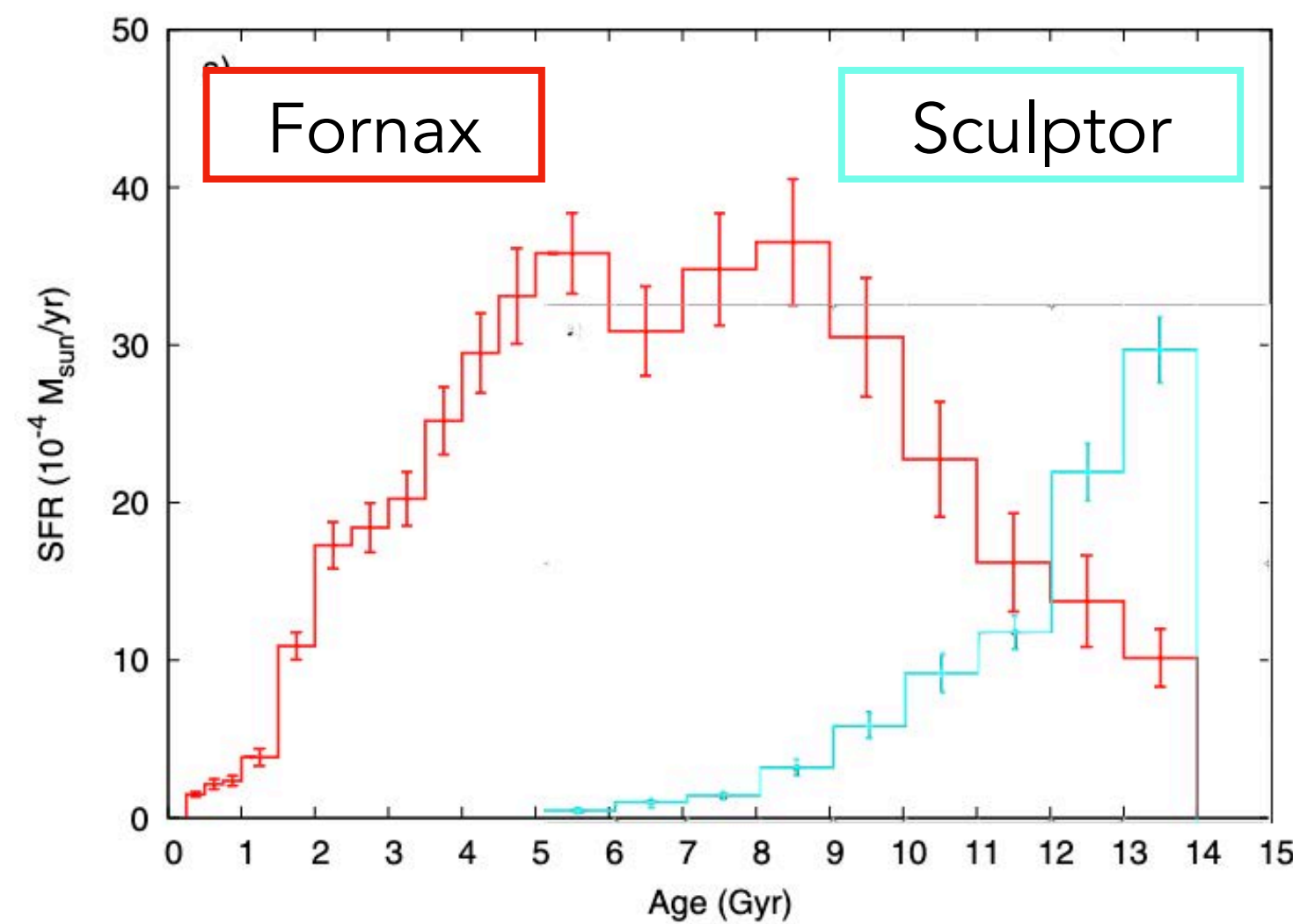
Chemical evolution — dwarf galaxies

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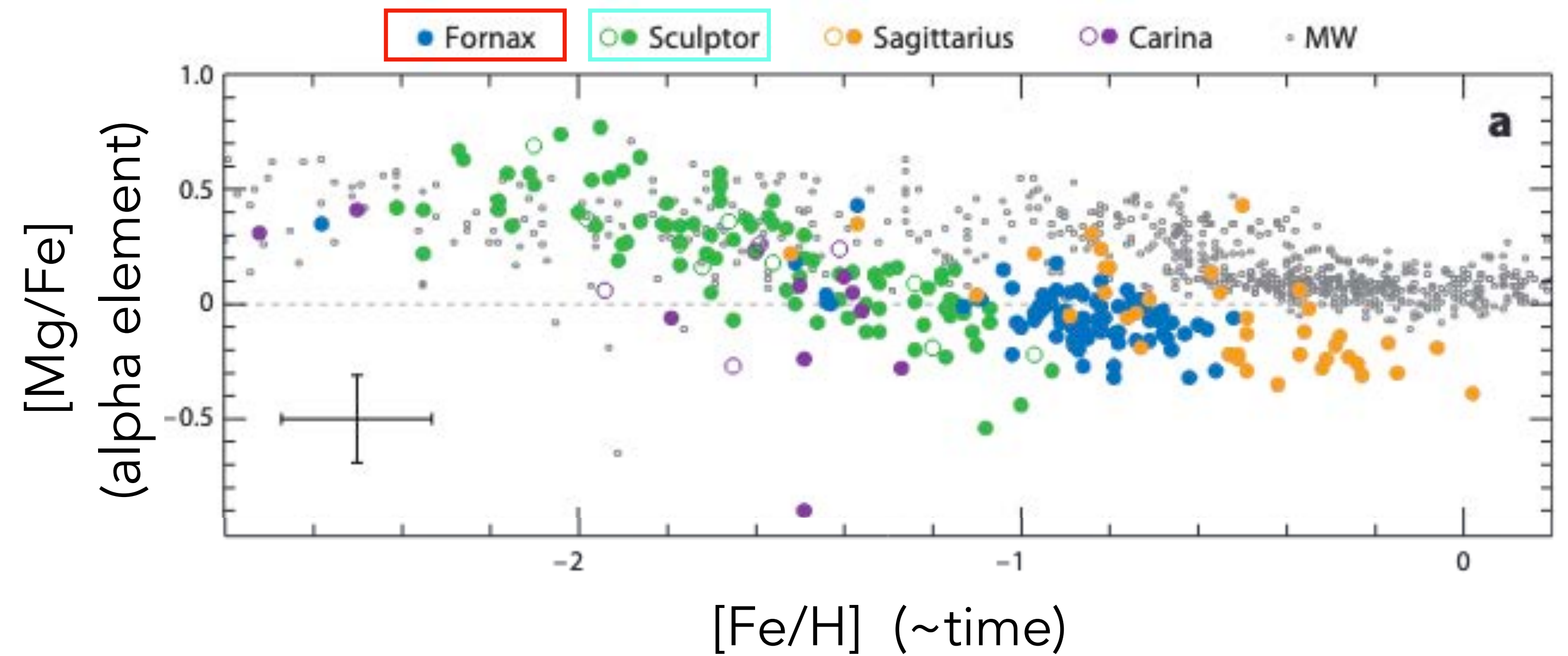


Chemical evolution — dwarf galaxies

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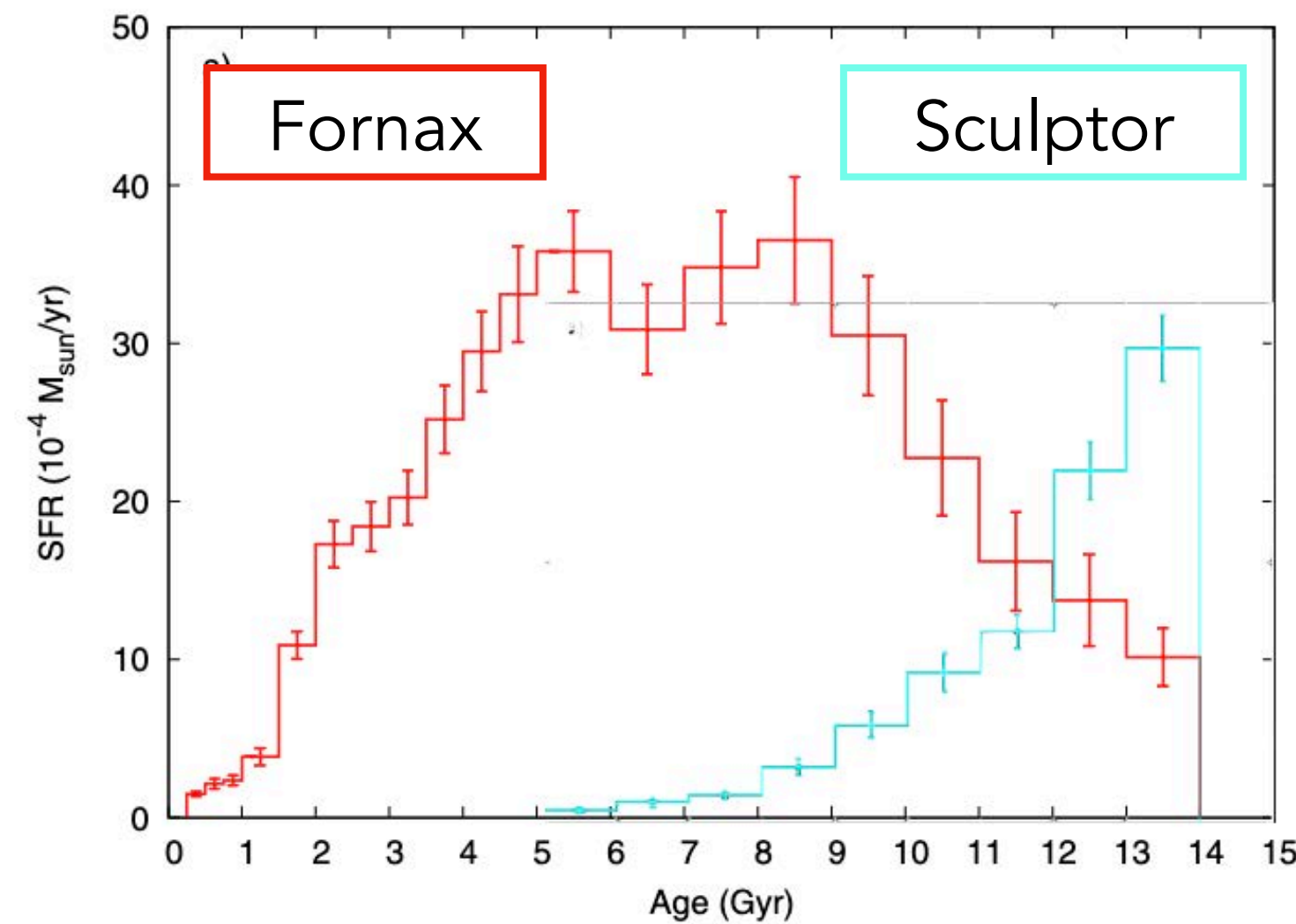


Tolstoy et al. 2009

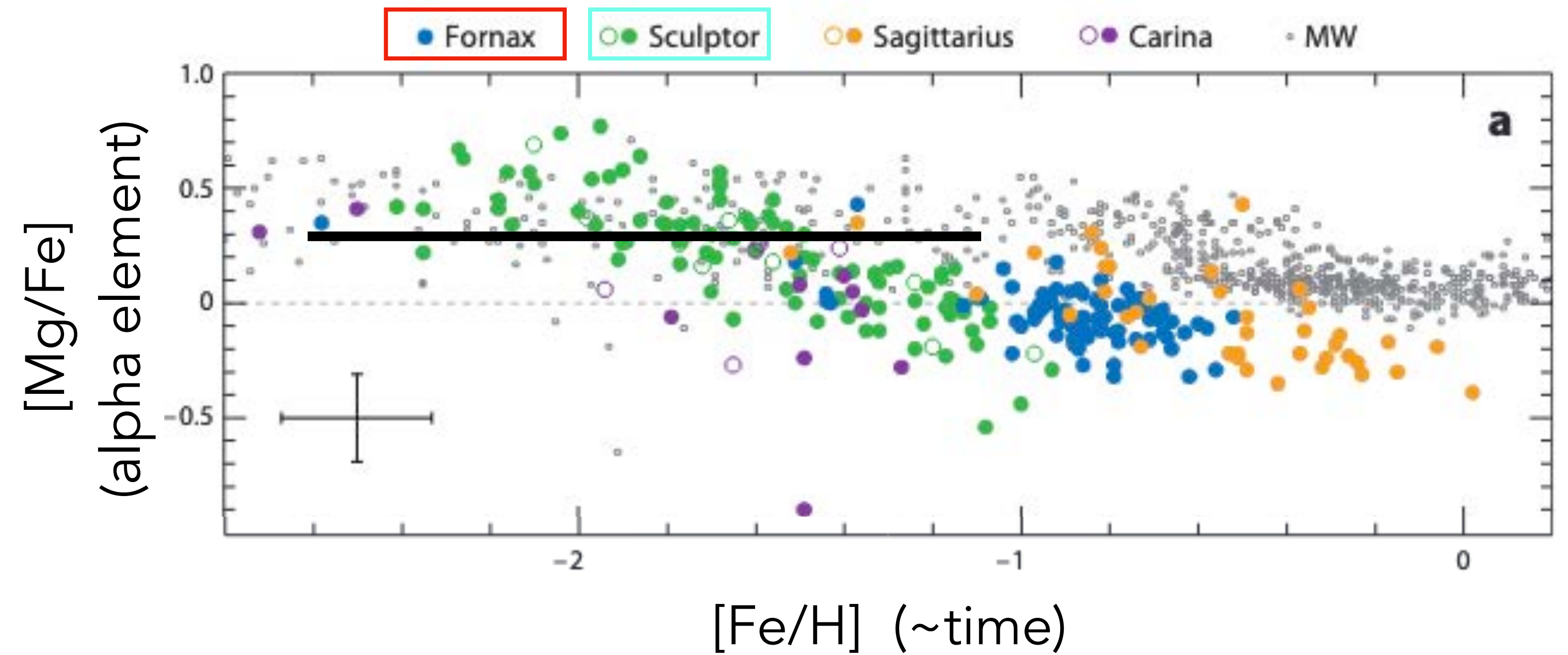


Chemical evolution — dwarf galaxies

De Boer et al. 2012

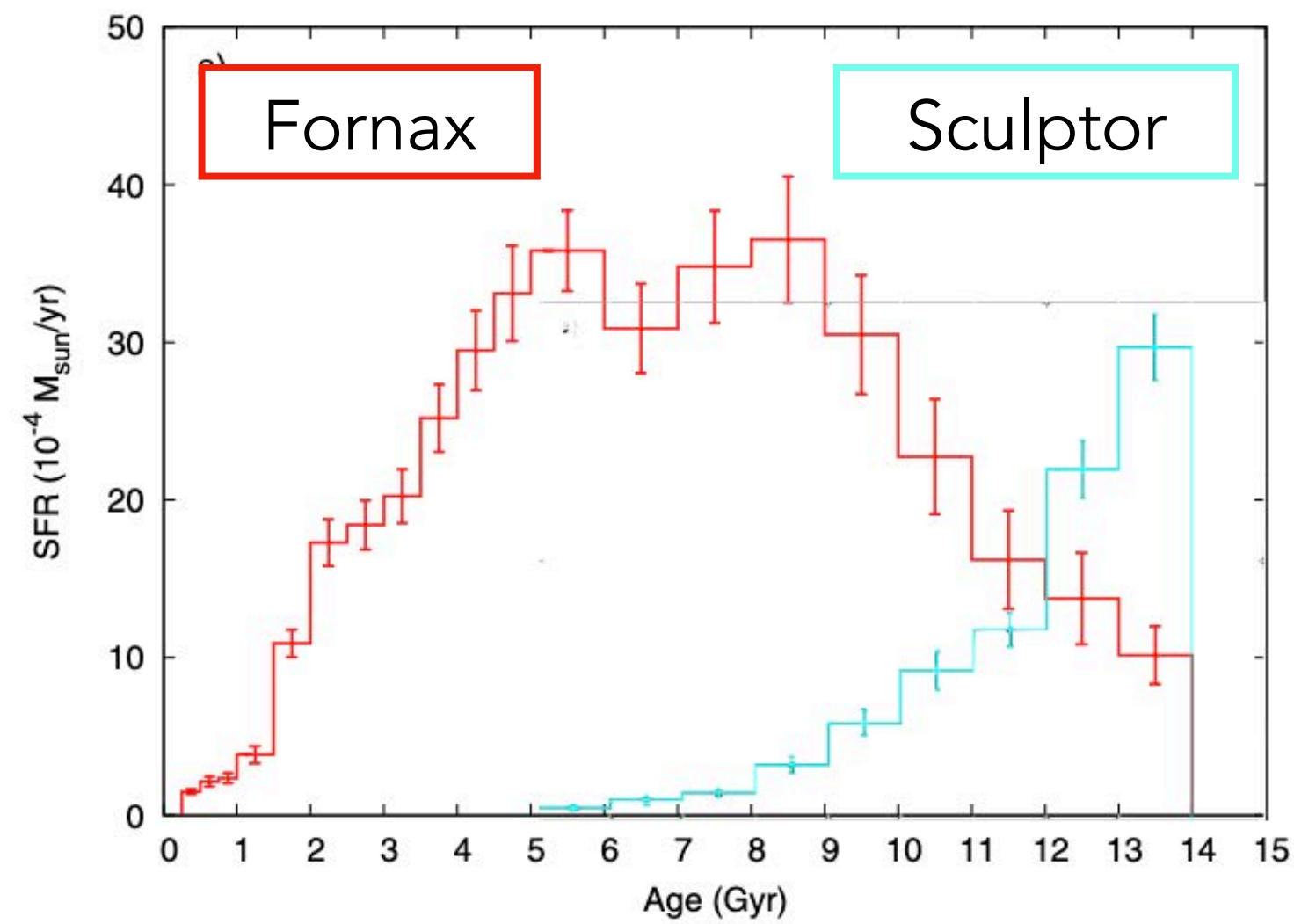


Tolstoy et al. 2009

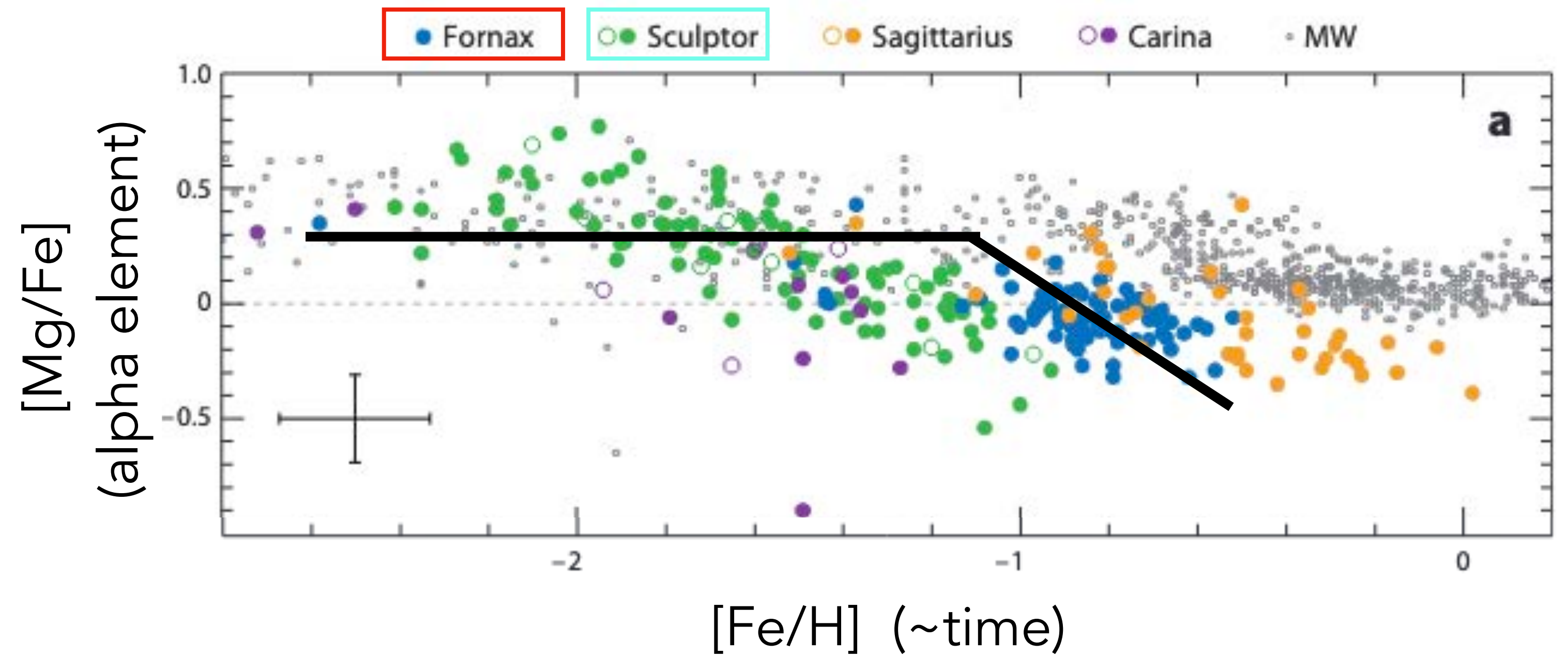


Chemical evolution — dwarf galaxies

De Boer et al. 2012

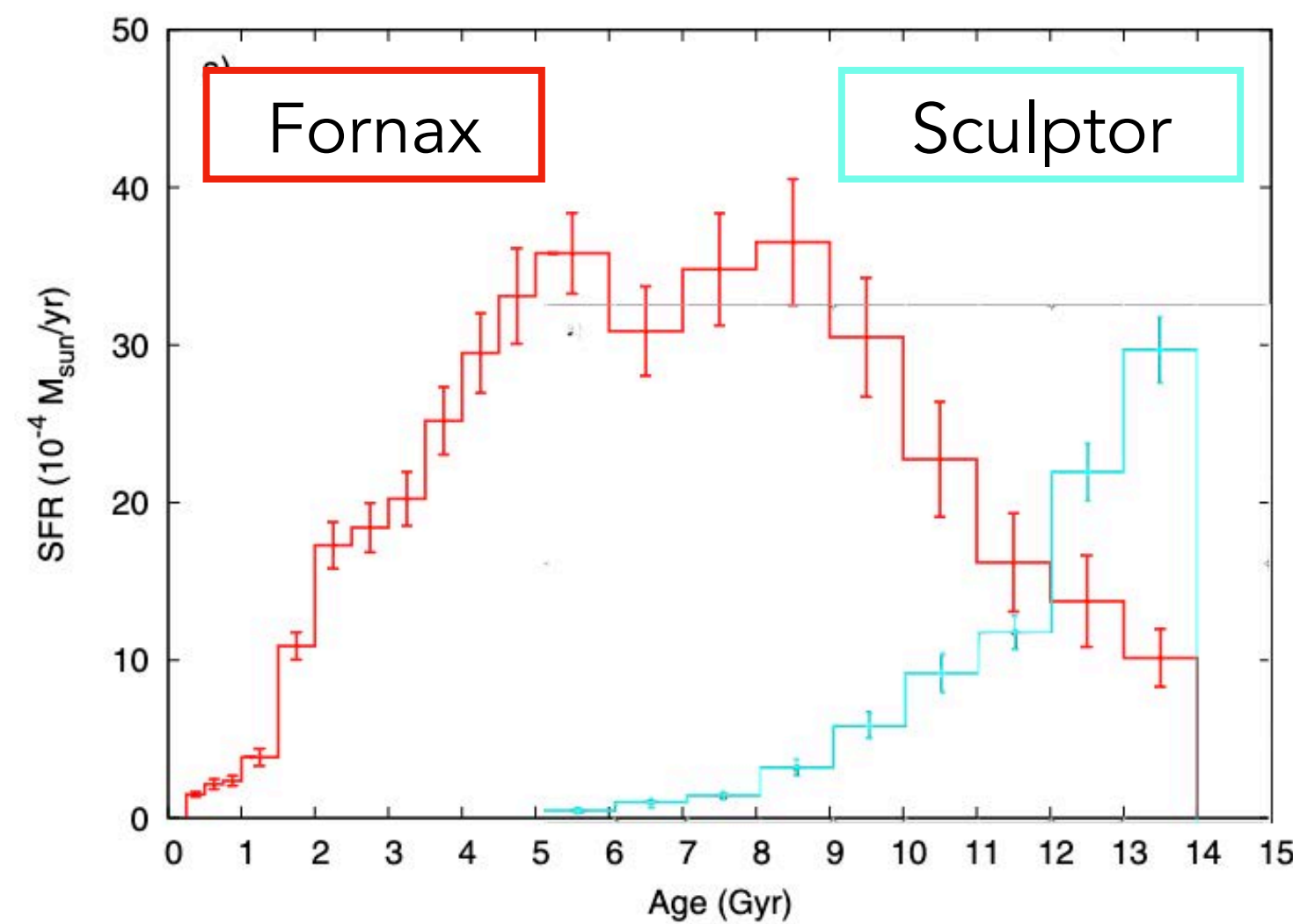


Tolstoy et al. 2009

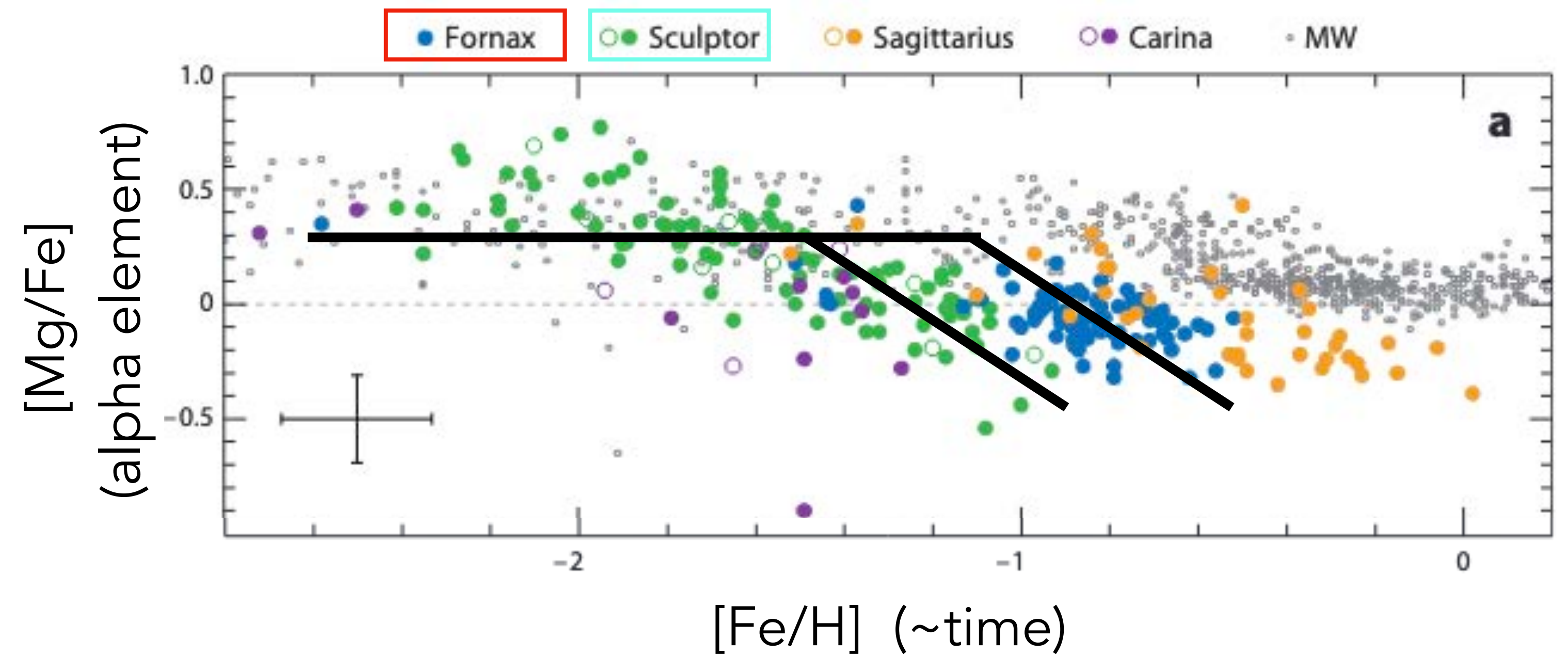


Chemical evolution — dwarf galaxies

De Boer et al. 2012

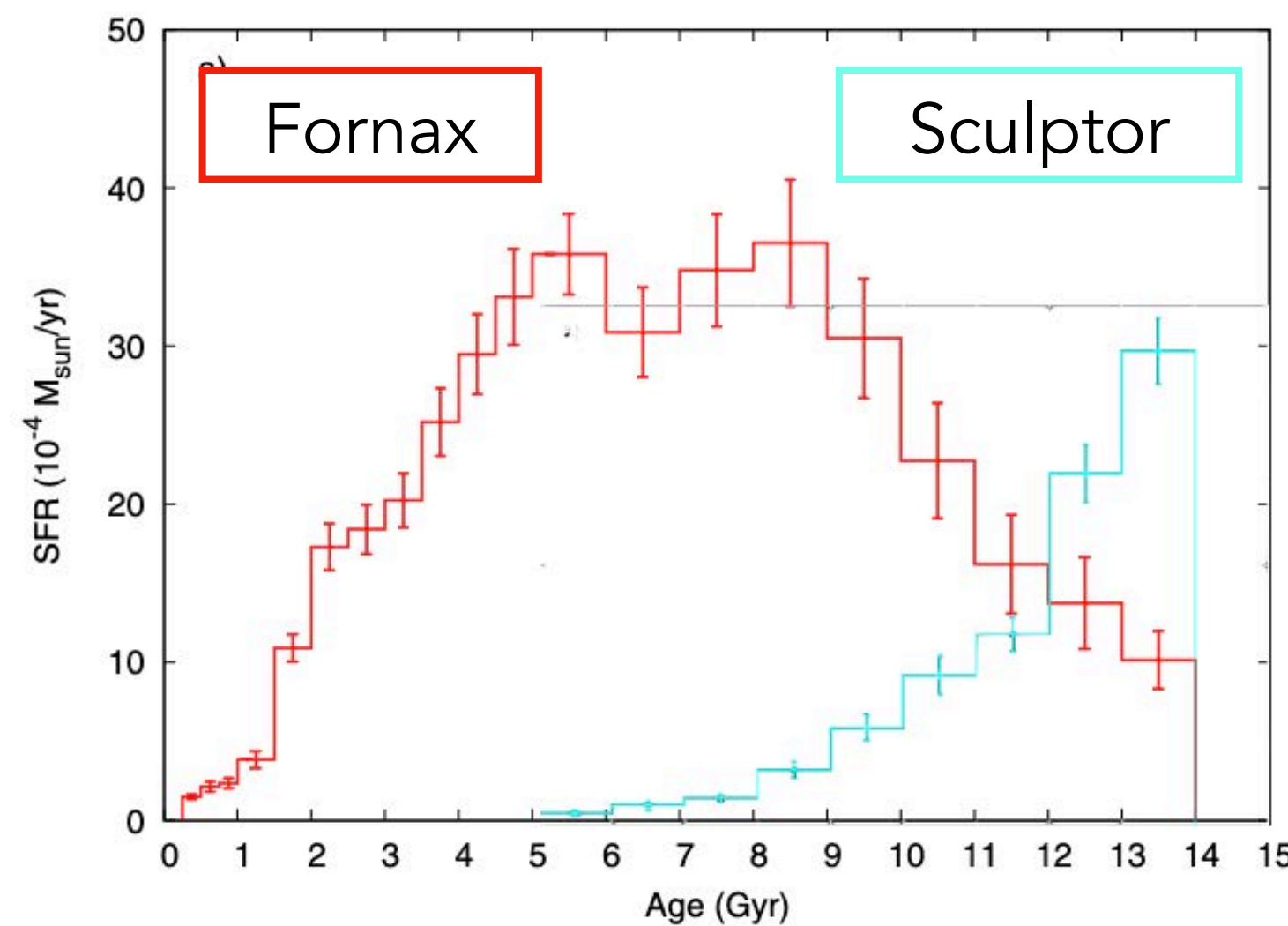


Tolstoy et al. 2009

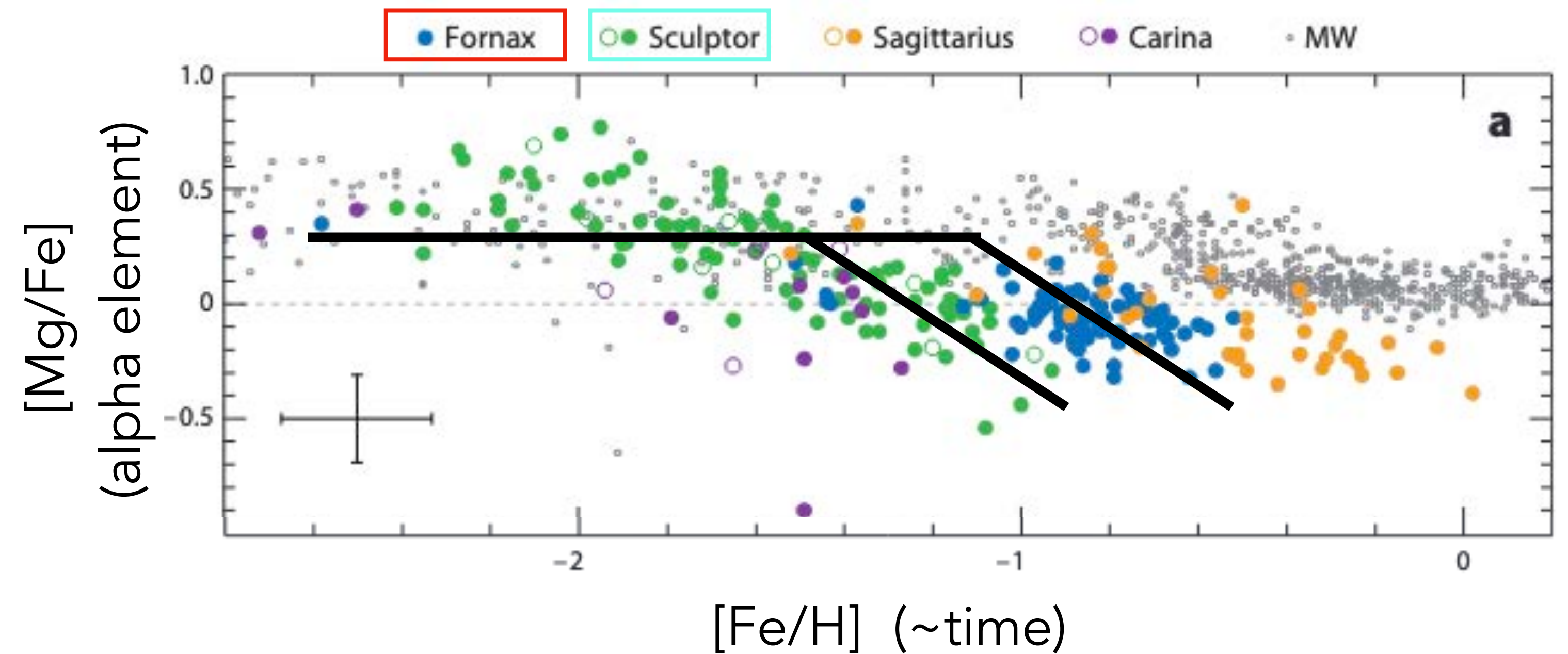


Chemical evolution — dwarf galaxies

De Boer et al. 2012



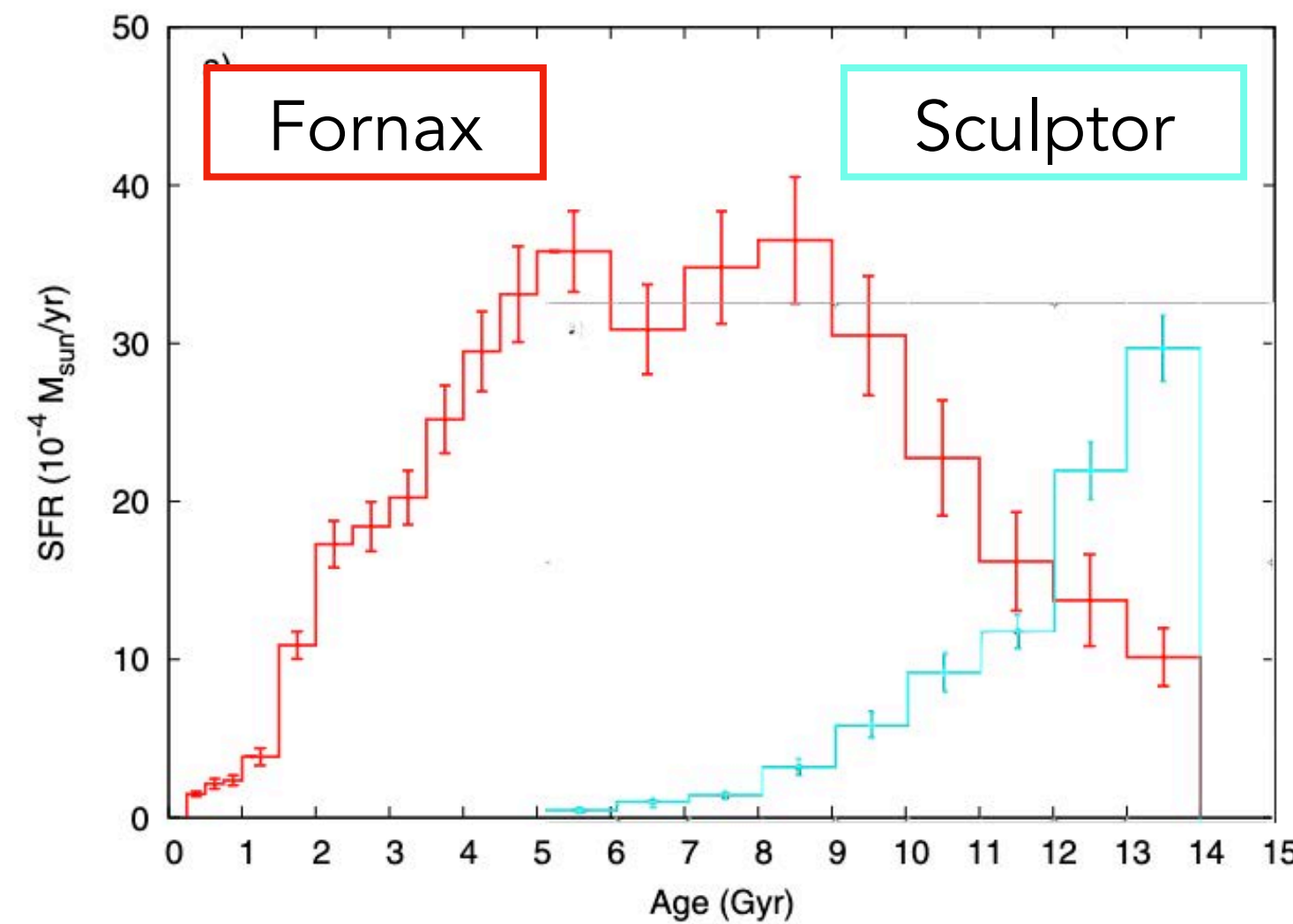
Tolstoy et al. 2009



What could cause the difference between Fornax and Sculptor?

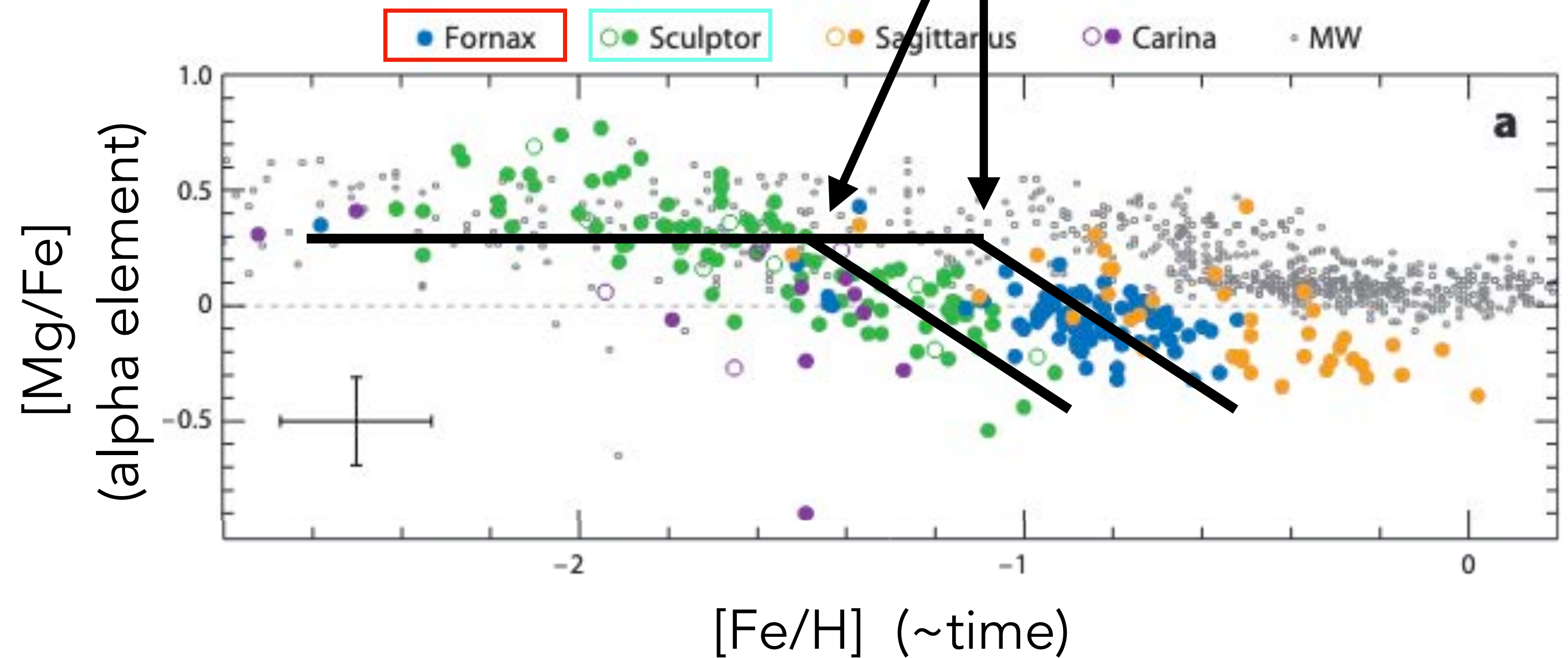
Chemical evolution — dwarf galaxies

De Boer et al. 2012



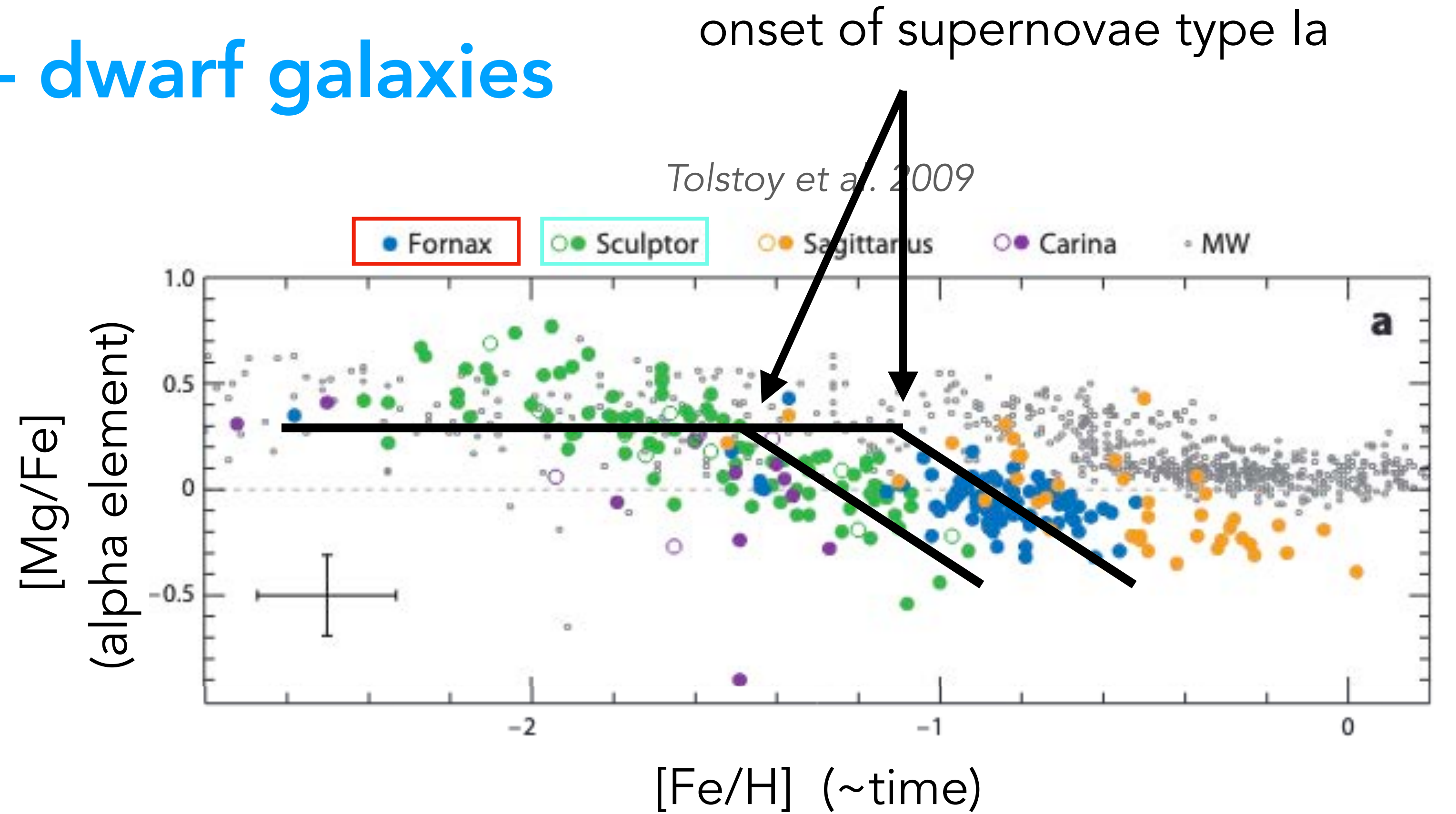
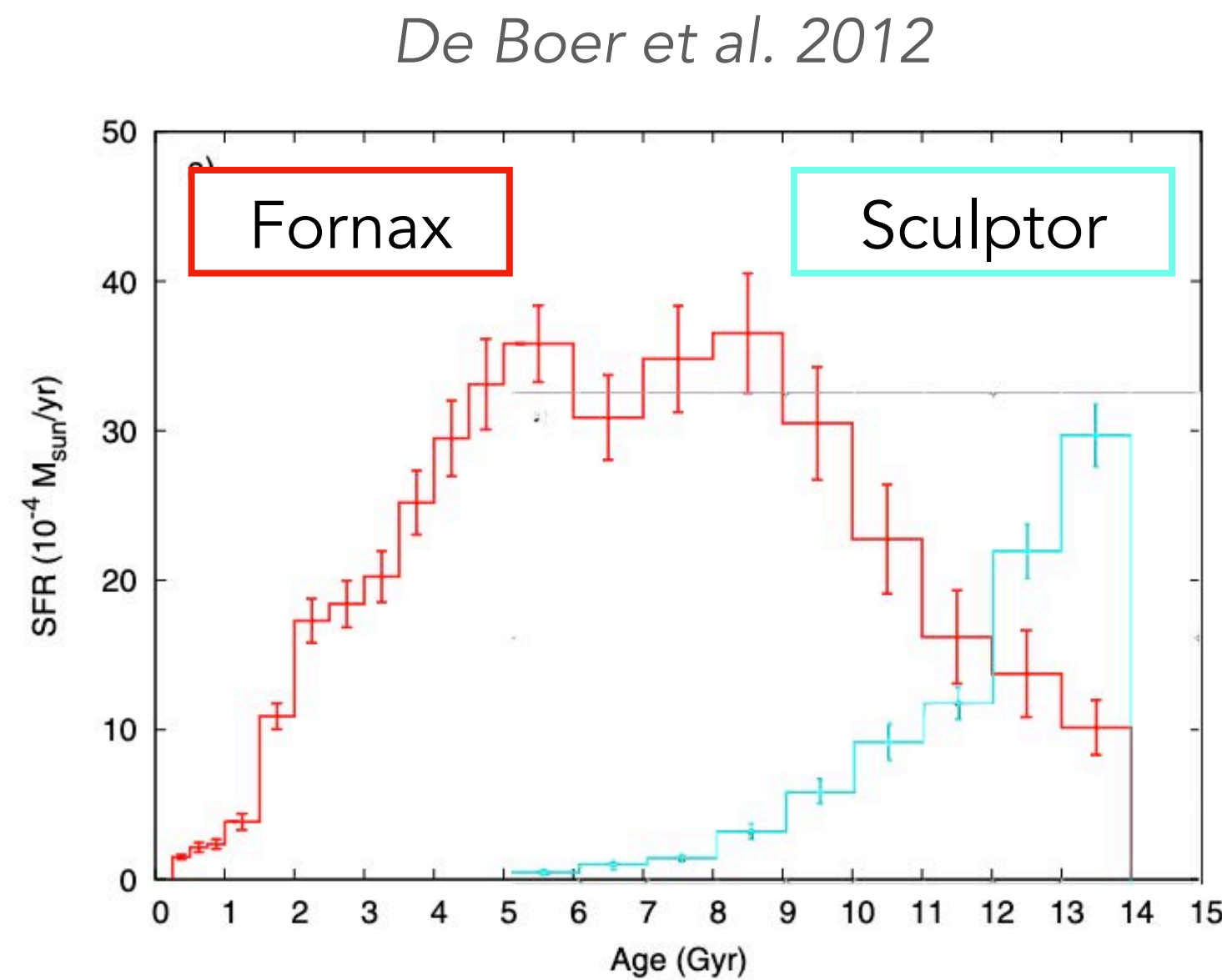
onset of supernovae type Ia

Tolstoy et al. 2009



What could cause the difference between Fornax and Sculptor?

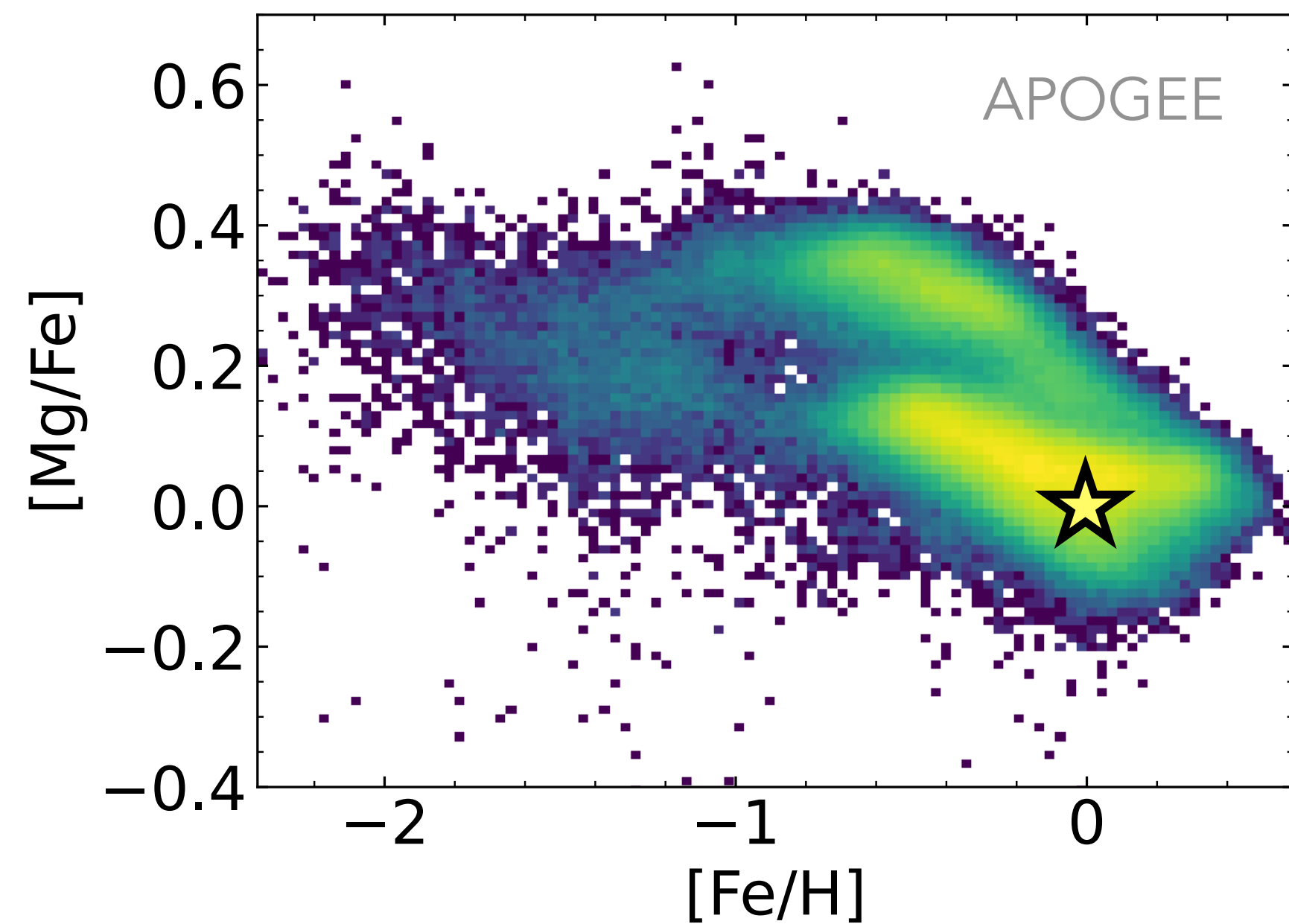
Chemical evolution — dwarf galaxies



- Fornax formed stars for **longer** (higher metallicity)
- Fornax formed stars **more efficiently** ("alpha knee" location)

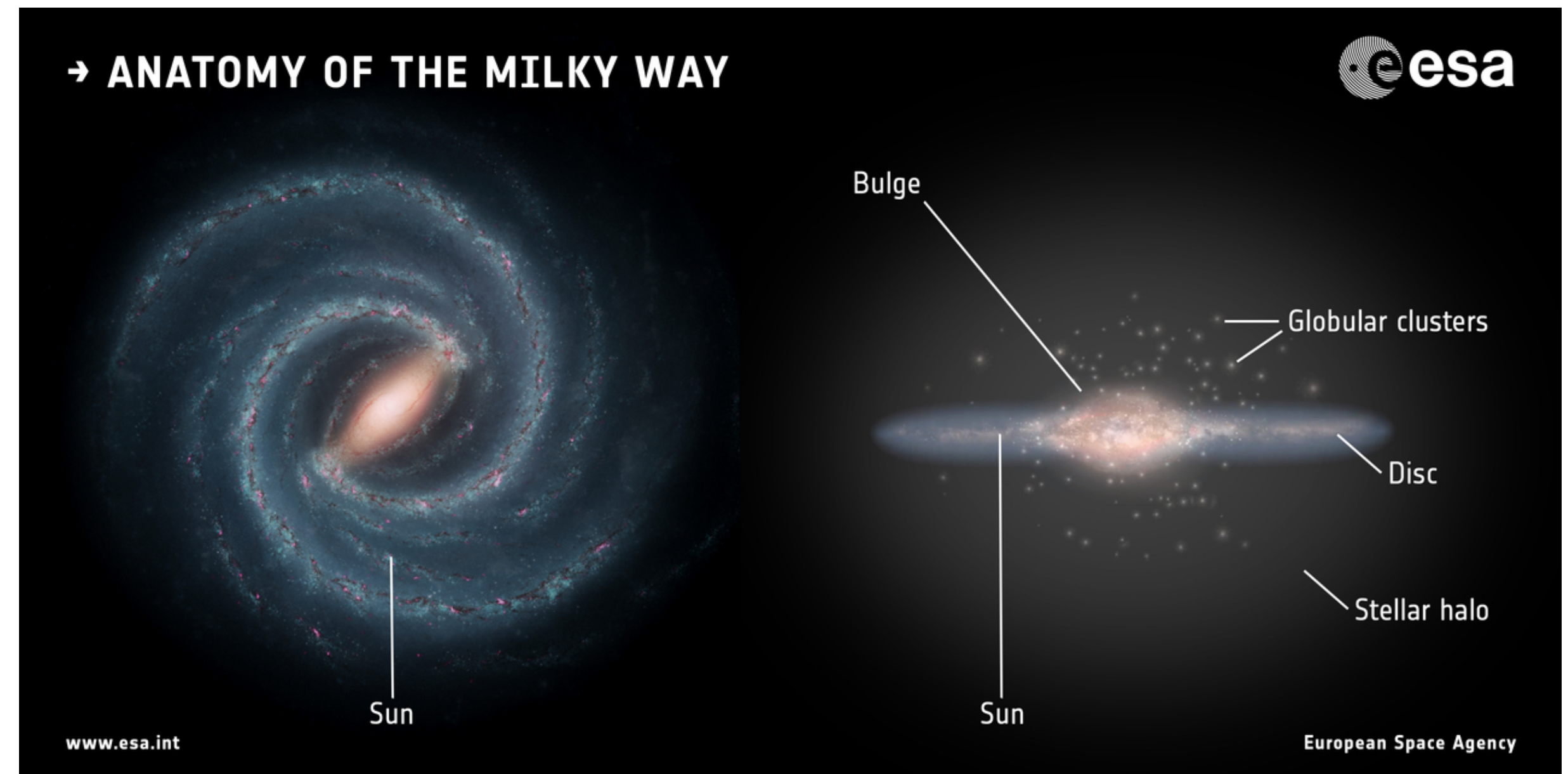
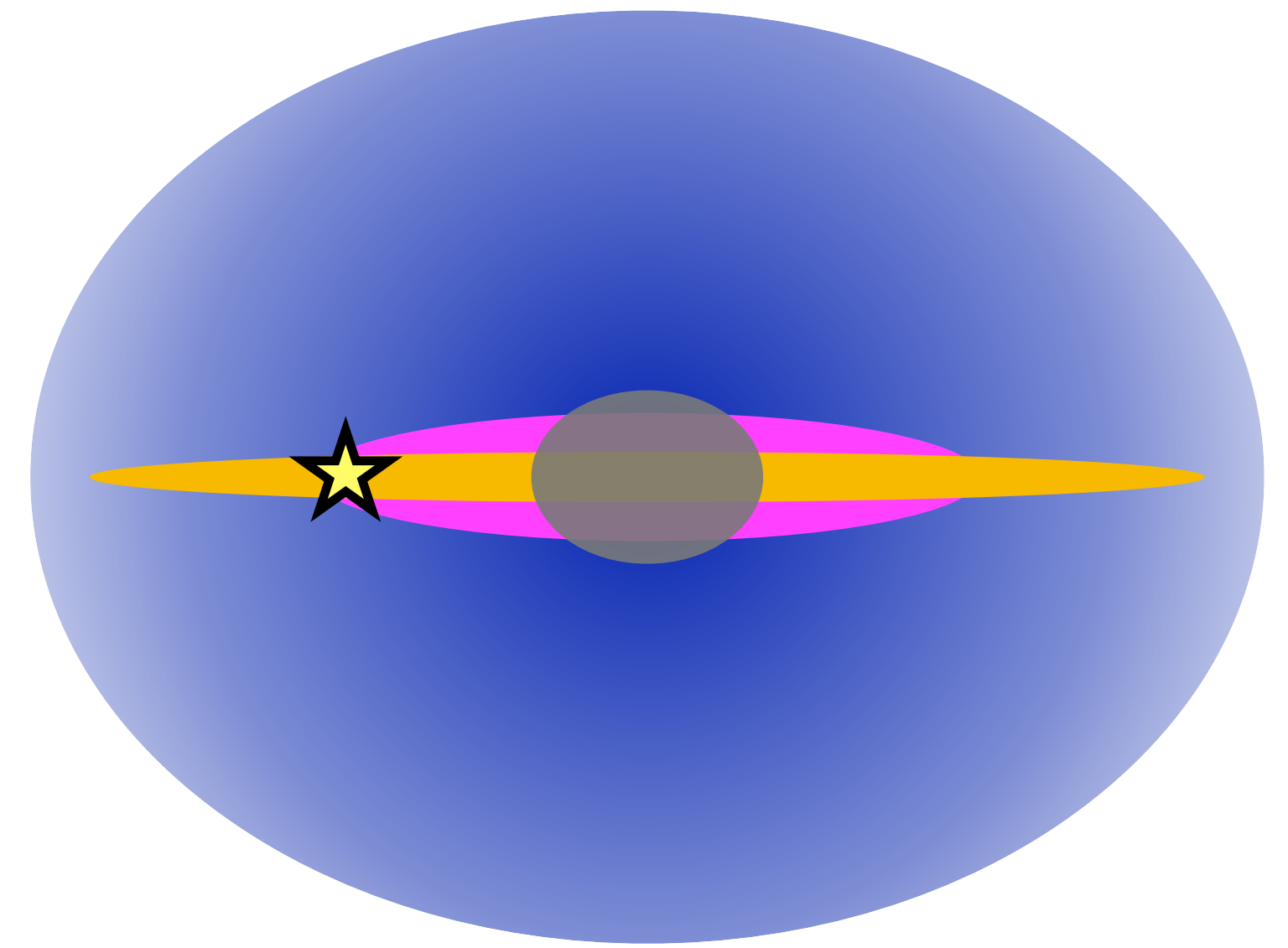
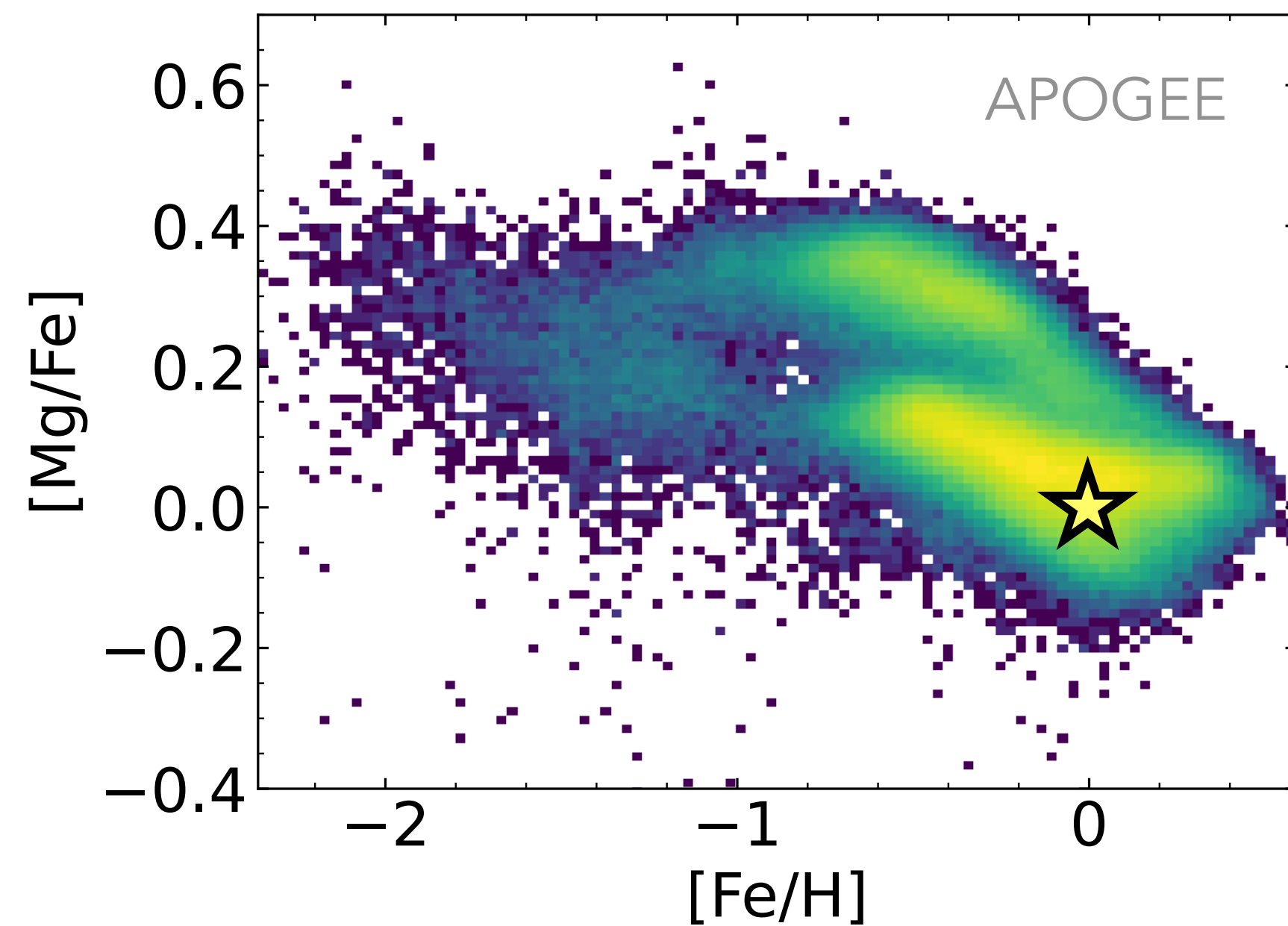
Chemical evolution — the Milky Way

Not a closed box... and not the same everywhere!



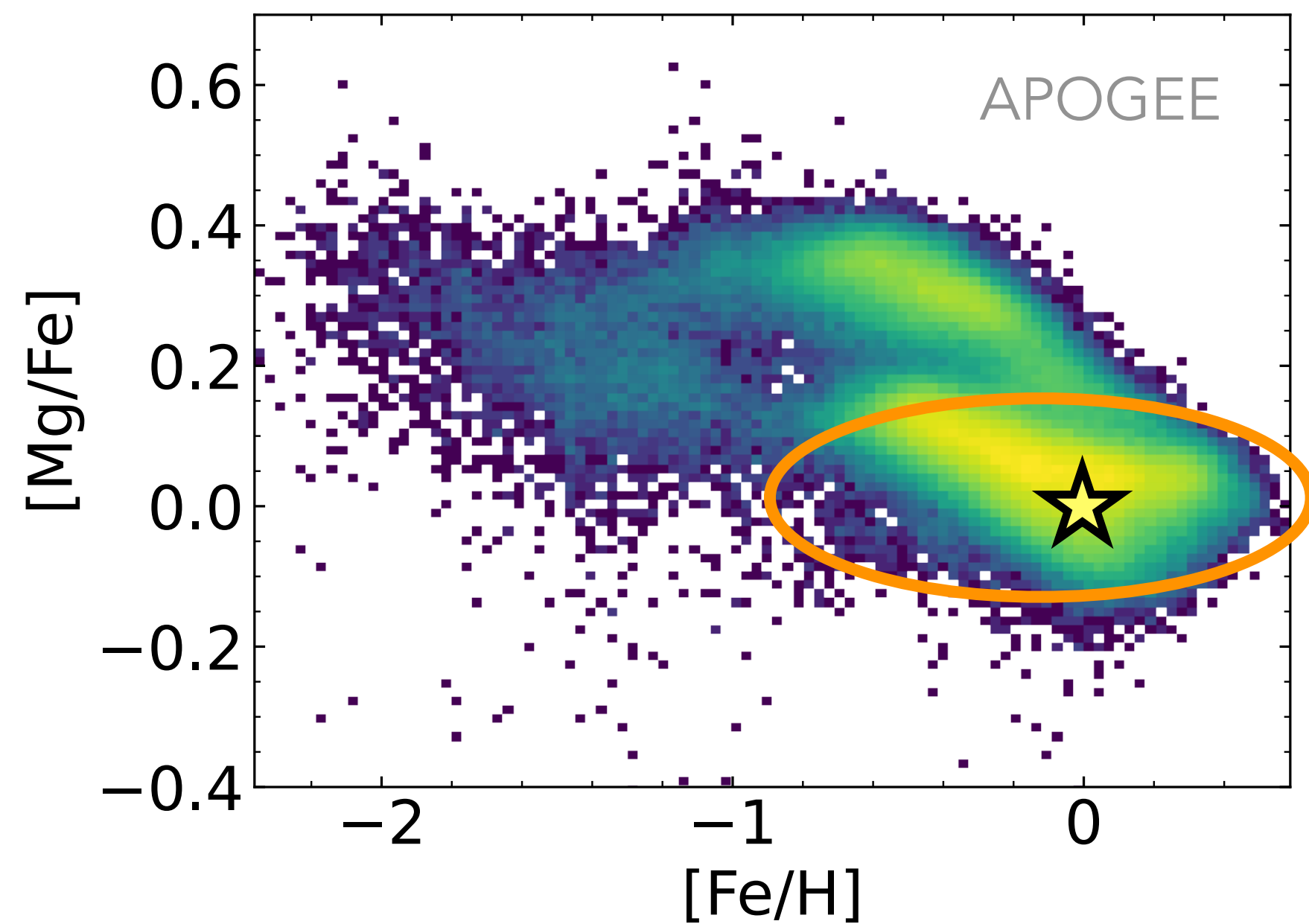
Chemical evolution — the Milky Way

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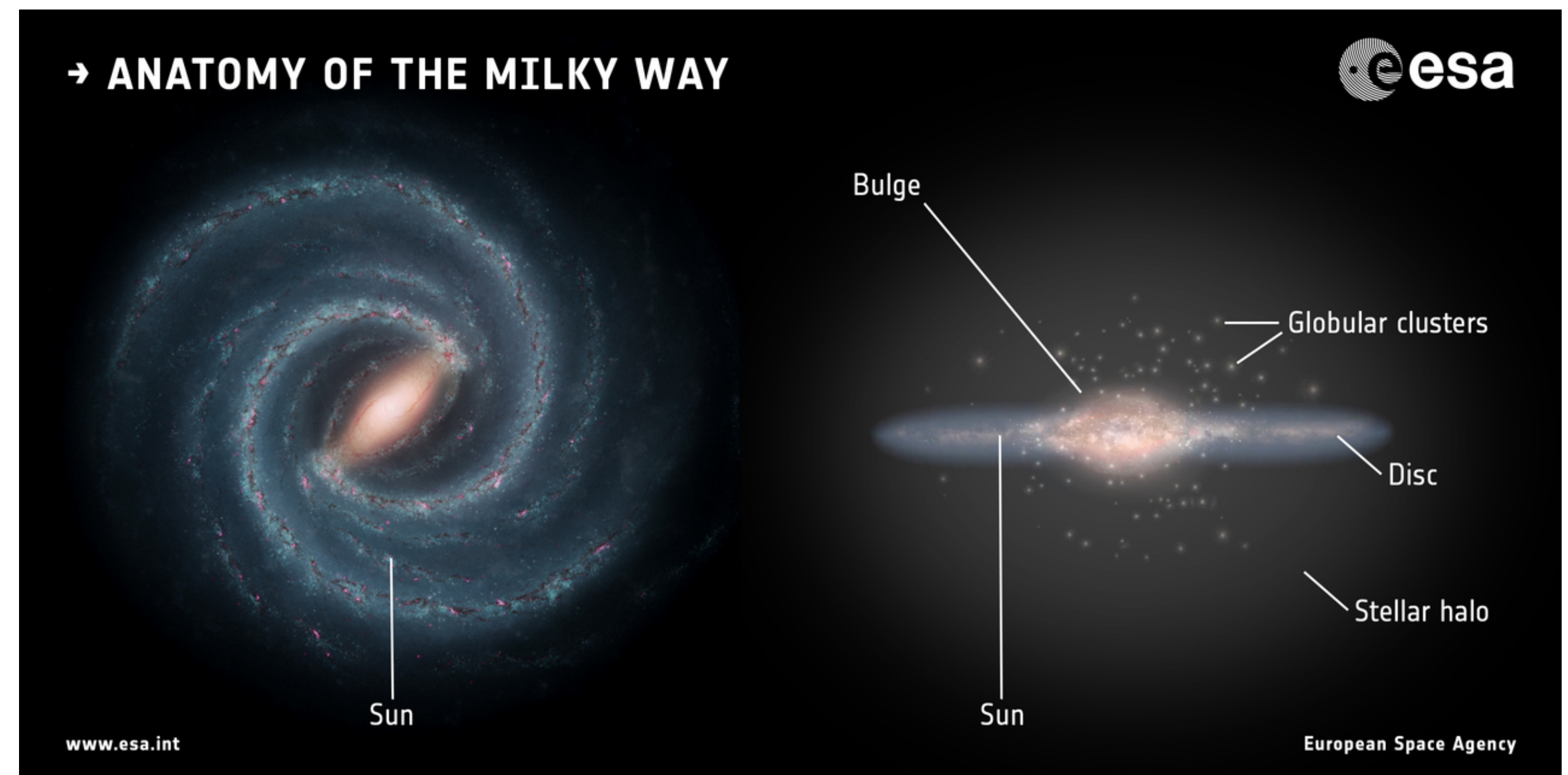
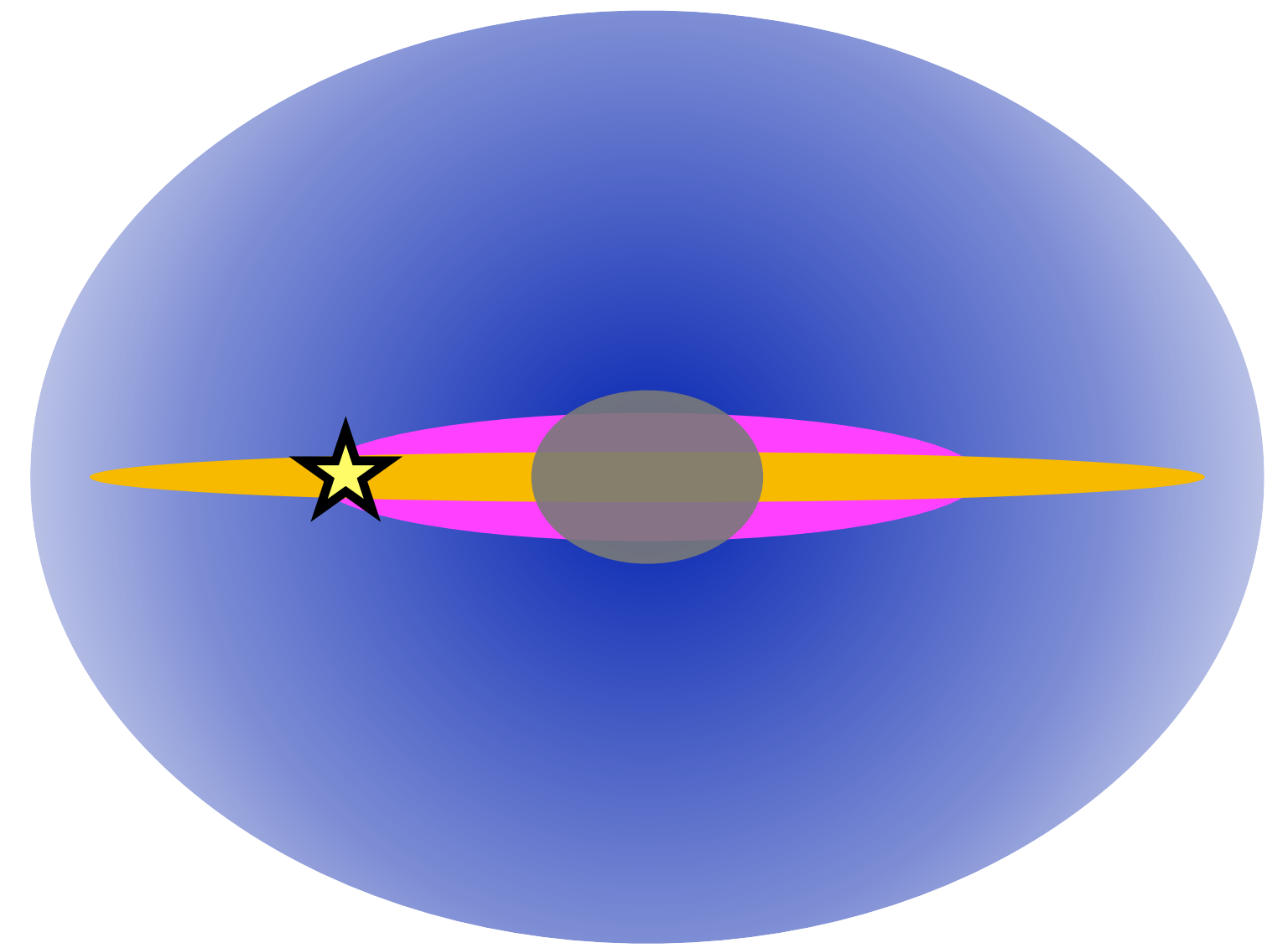


Chemical evolution — the Milky Way

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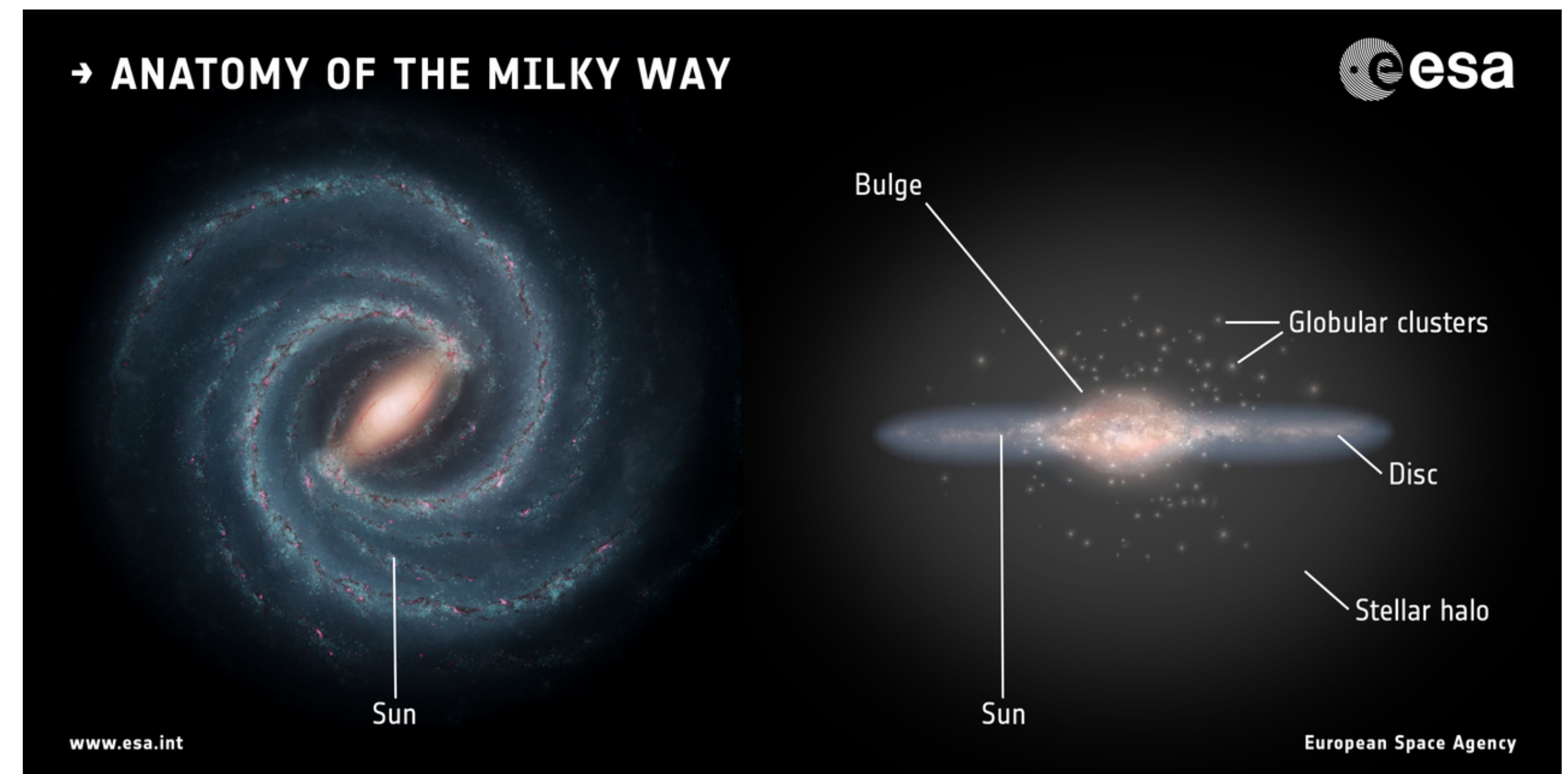
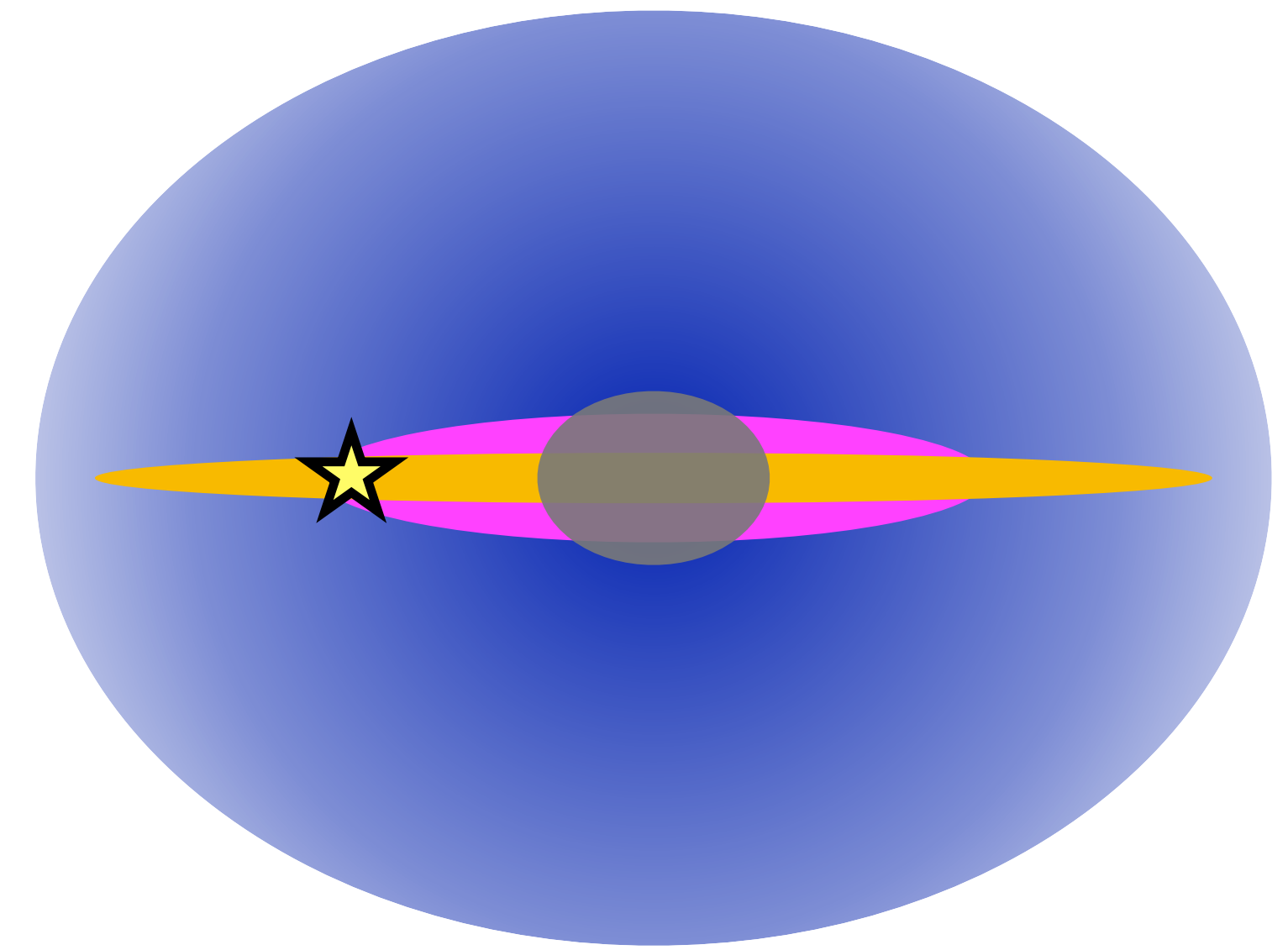
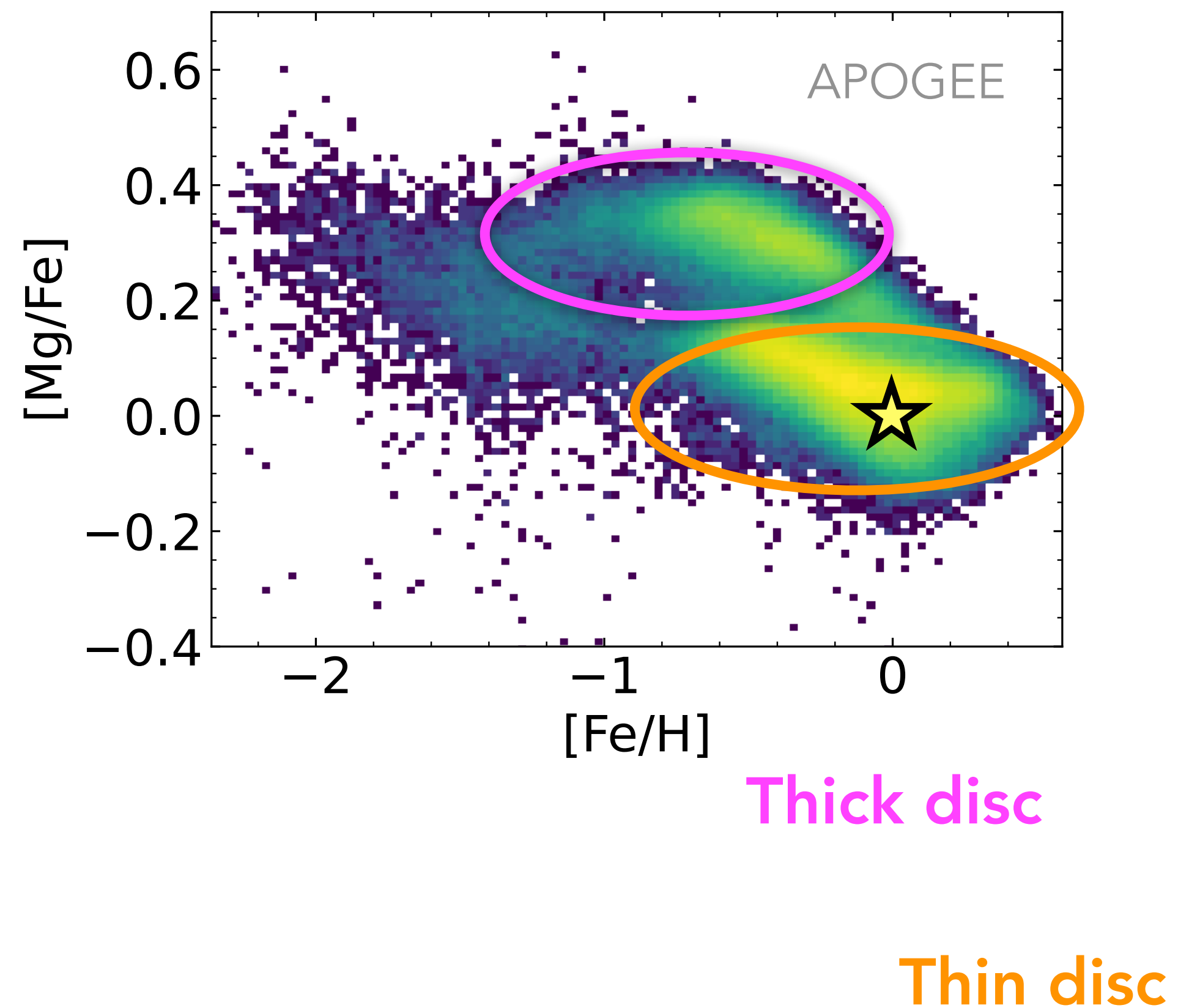


Thin disc



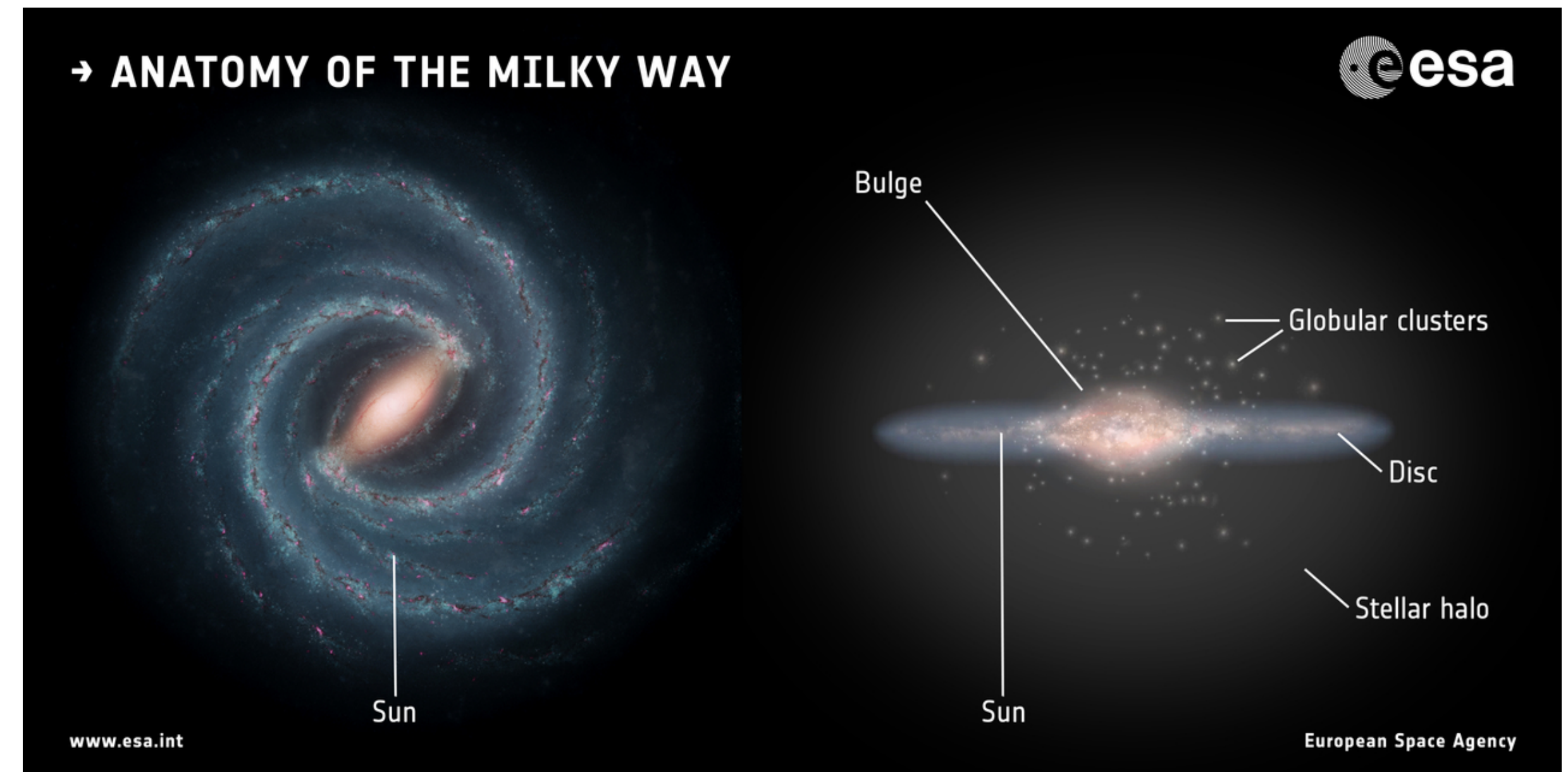
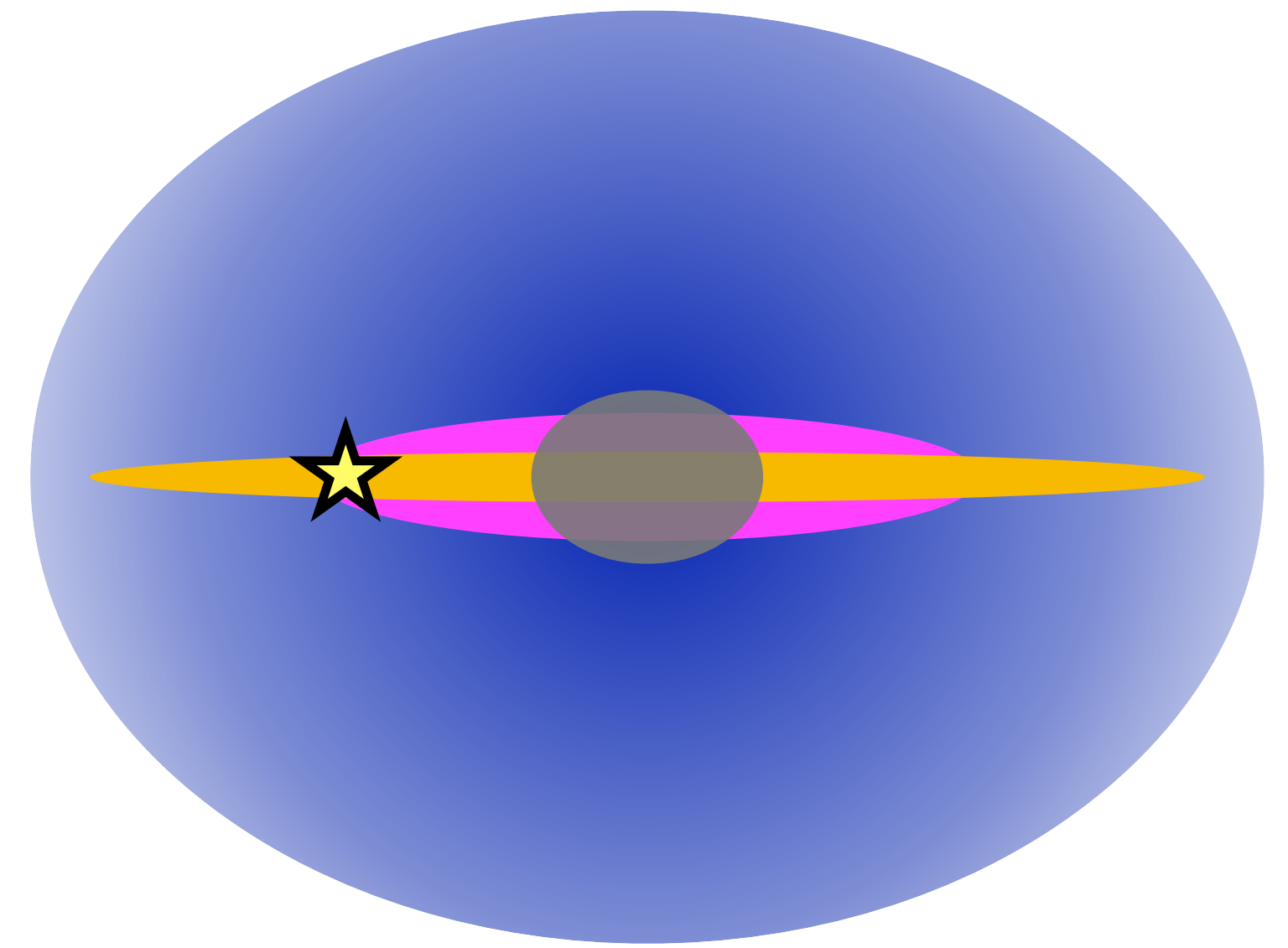
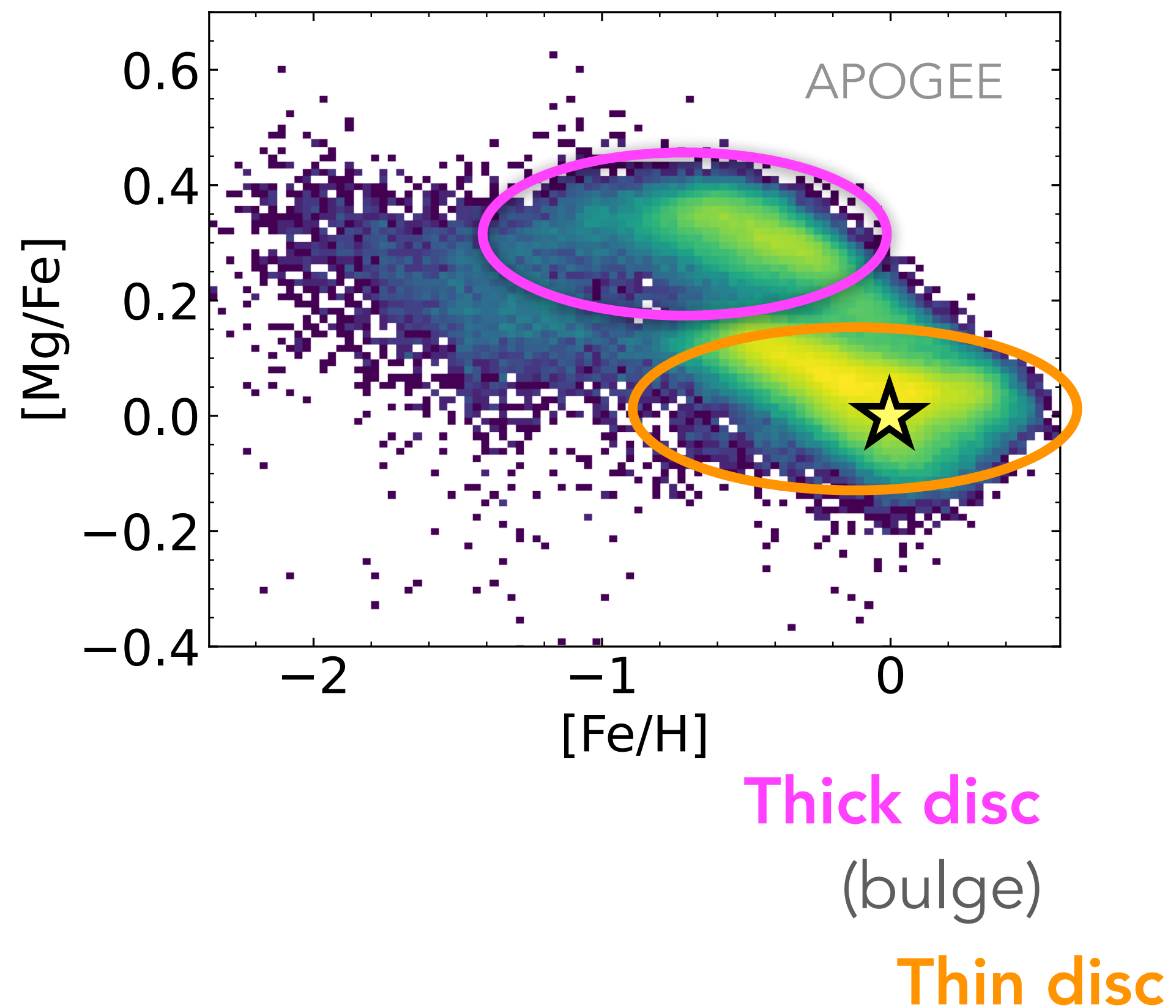
Chemical evolution — the Milky Way

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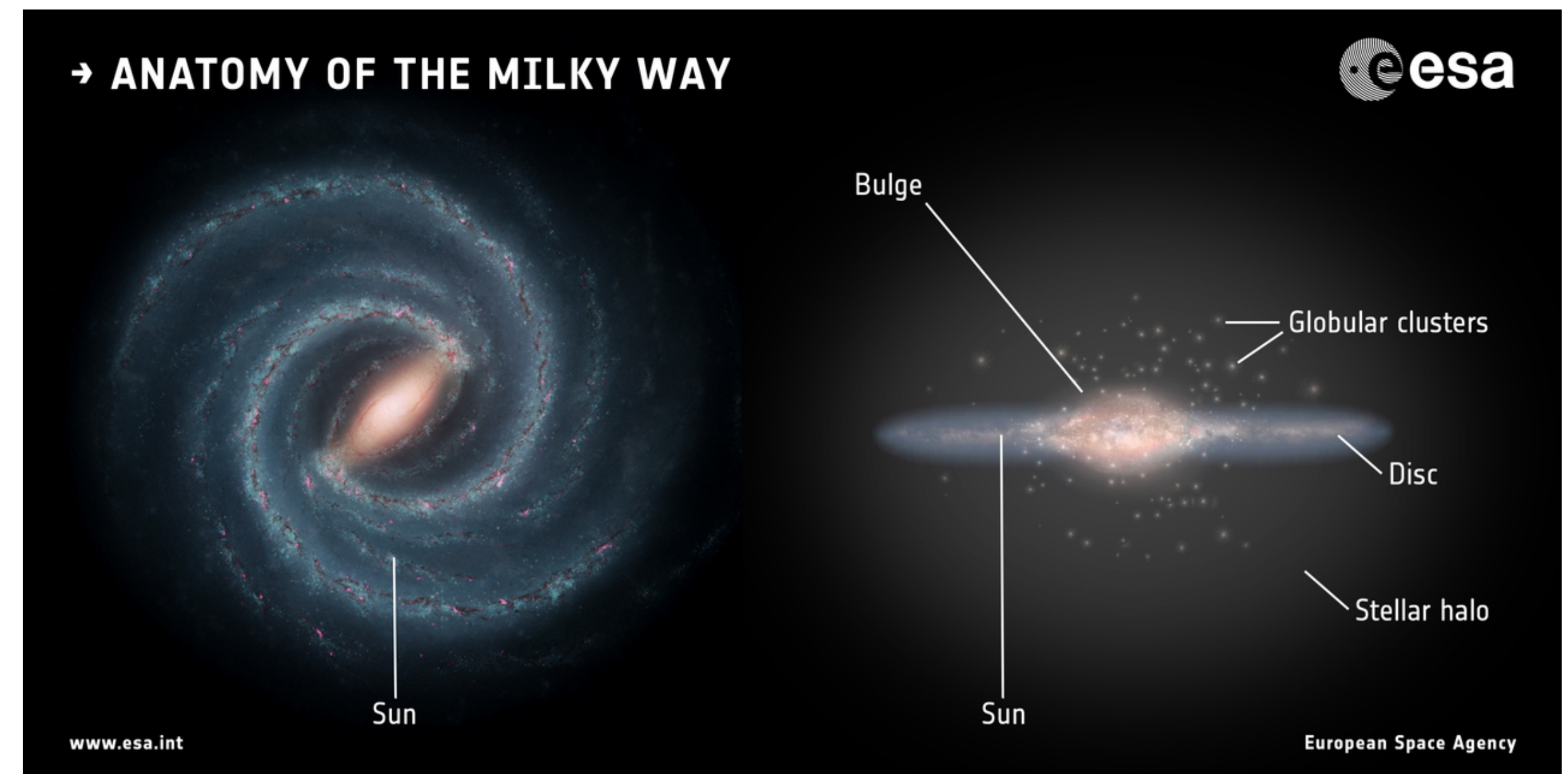
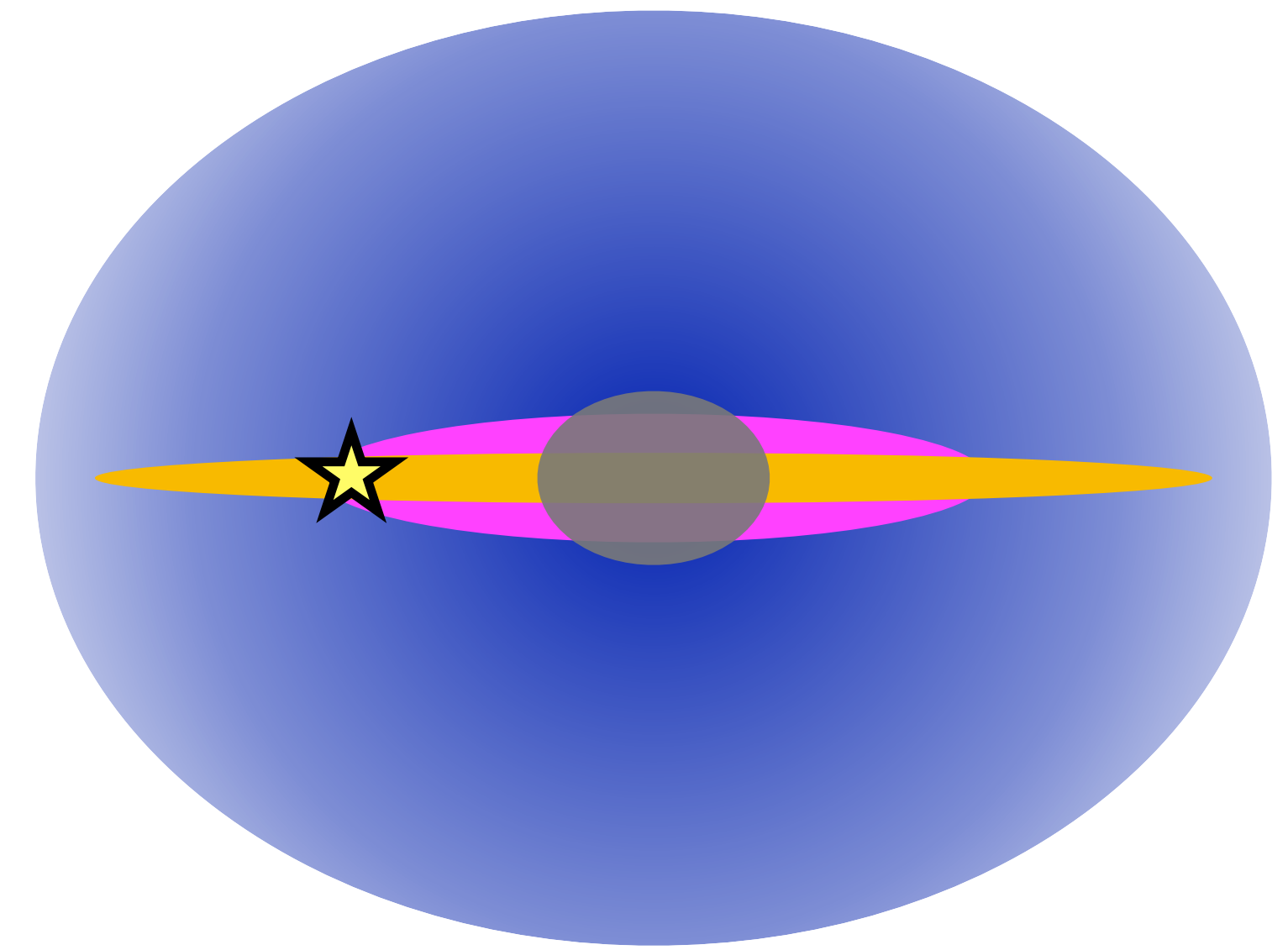
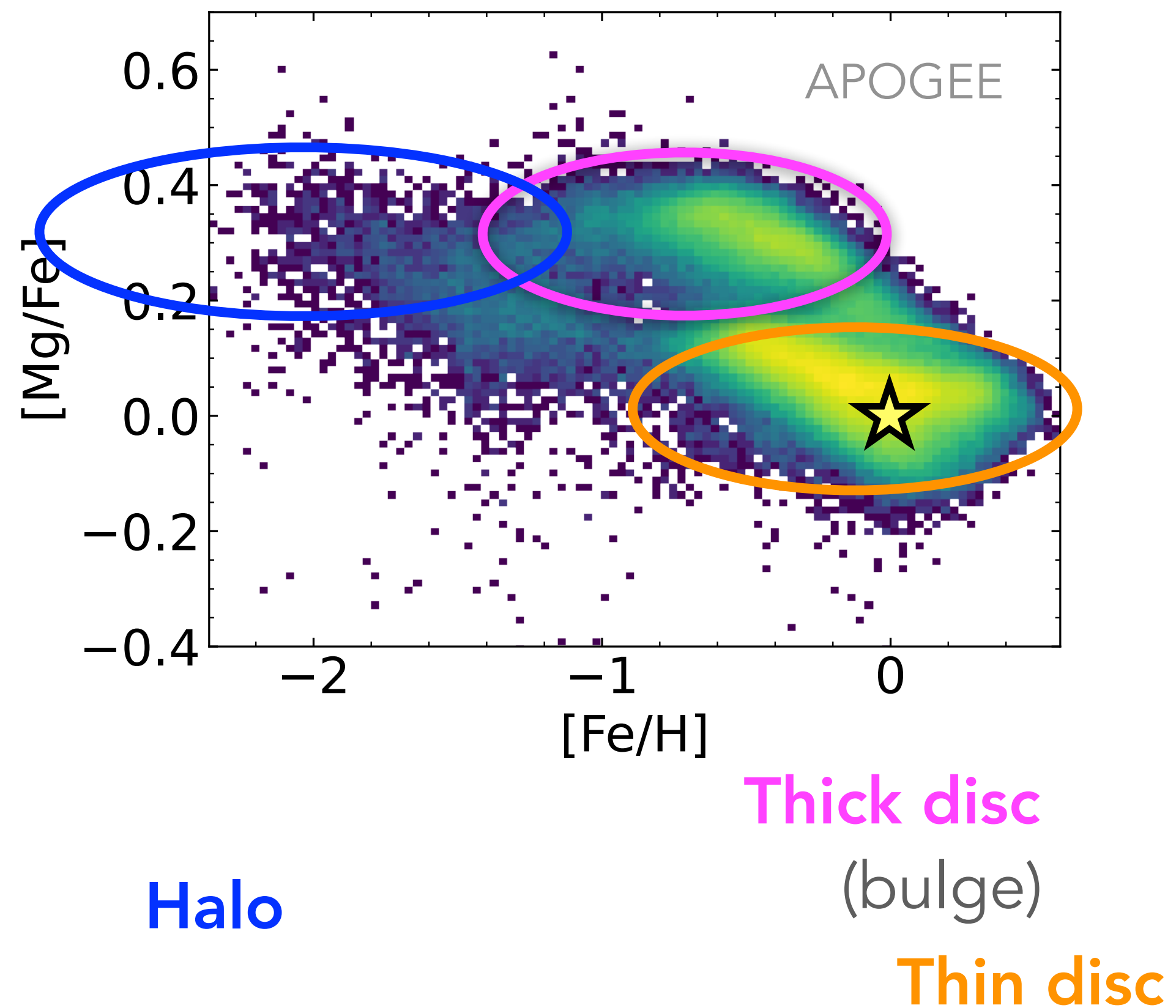
Chemical evolution — the Milky Way

Not a closed box... and not the same everywhere!



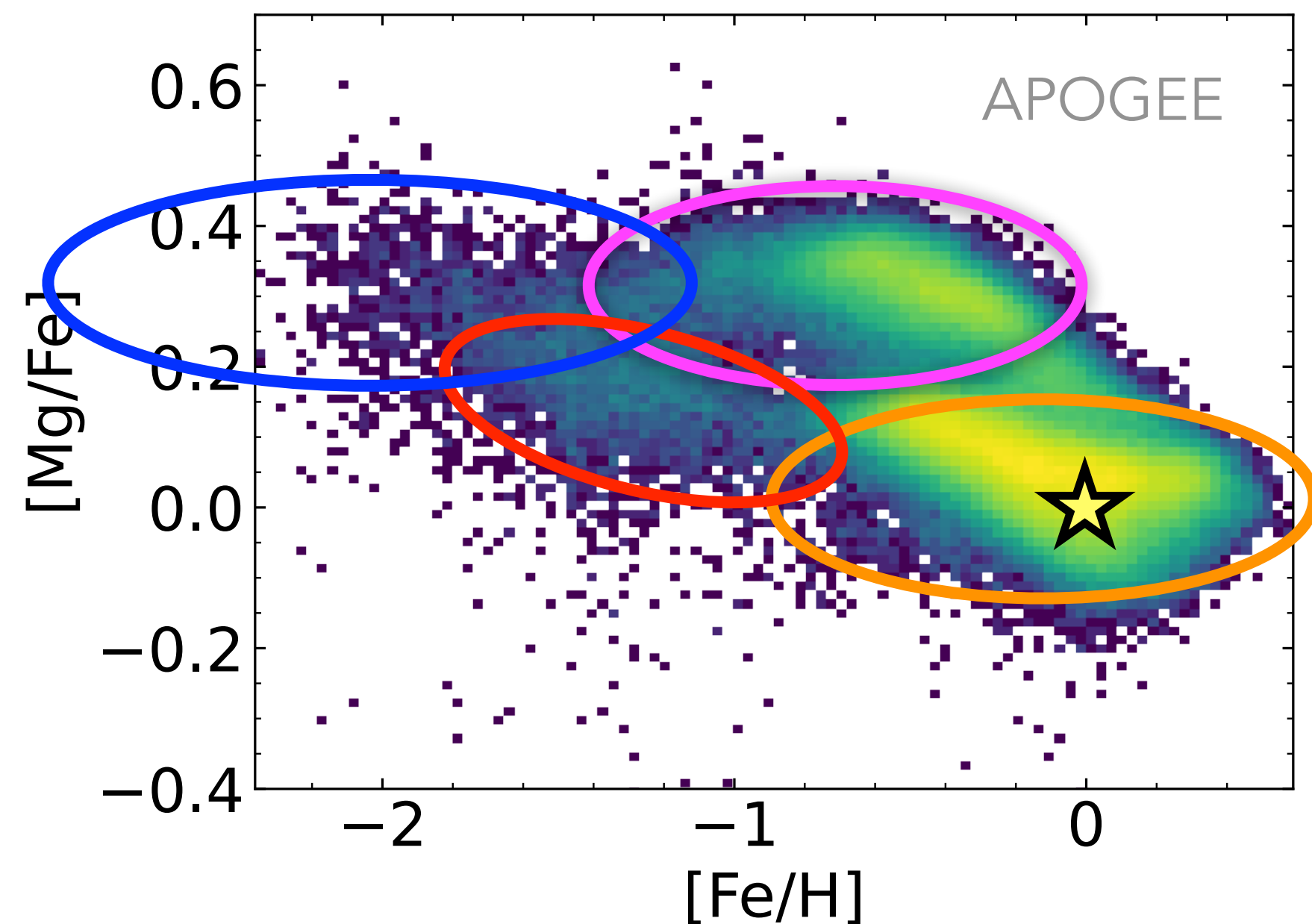
Chemical evolution — the Milky Way

Not a closed box... and not the same everywhere!



Chemical evolution — the Milky Way

Not a closed box... and not the same everywhere!

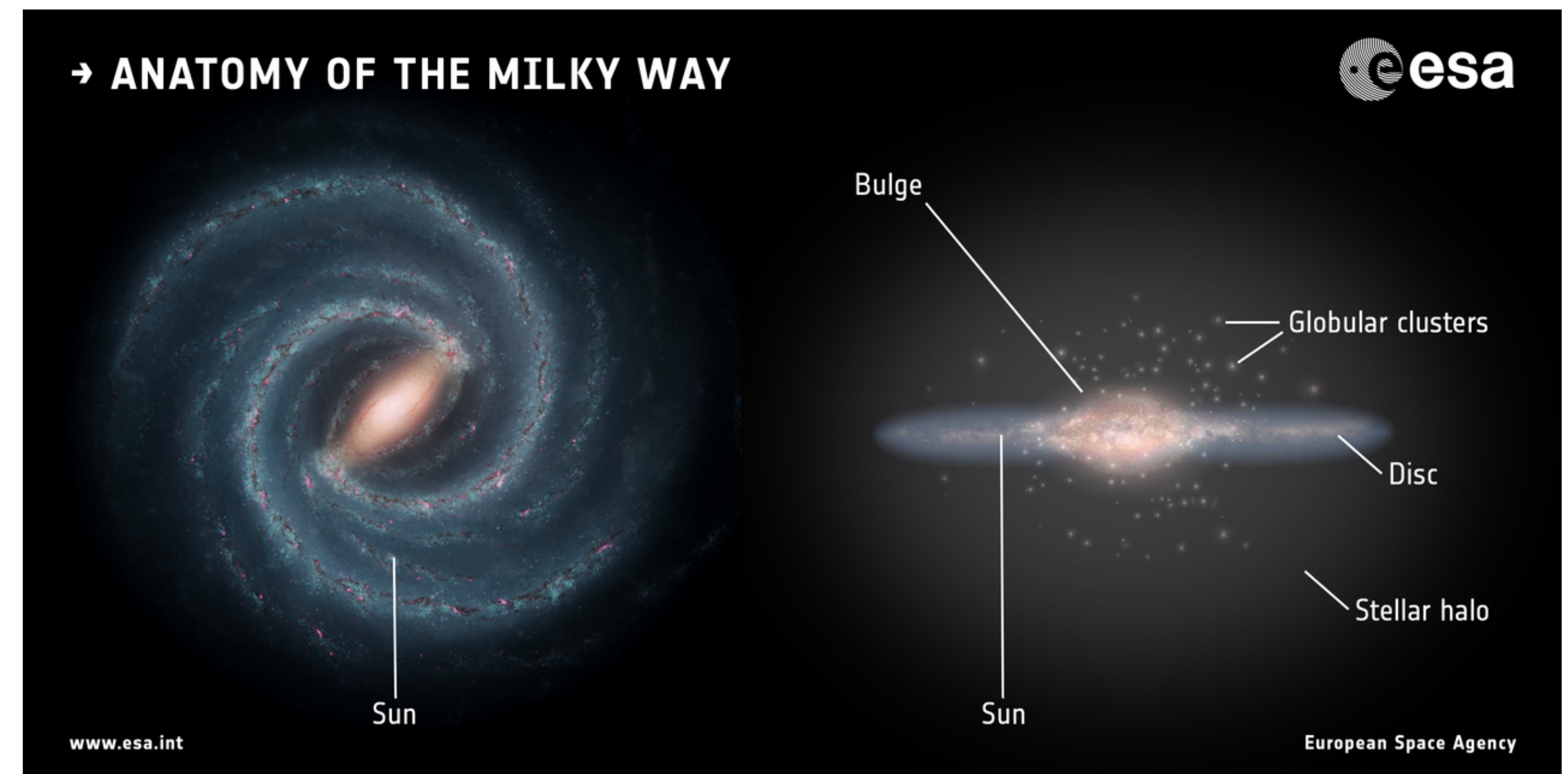
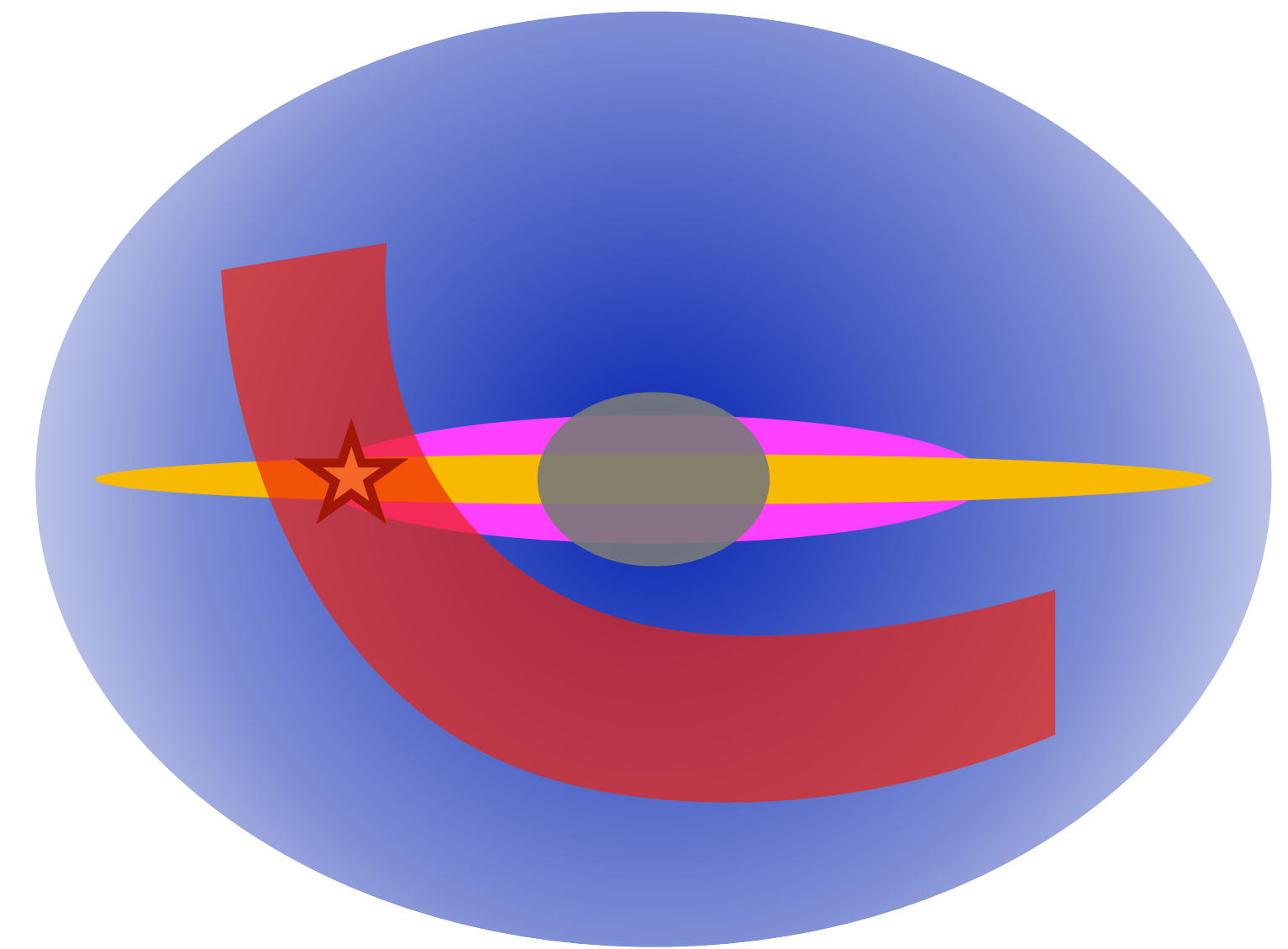


Halo

Accreted
dwarf

Thick disc
(bulge)

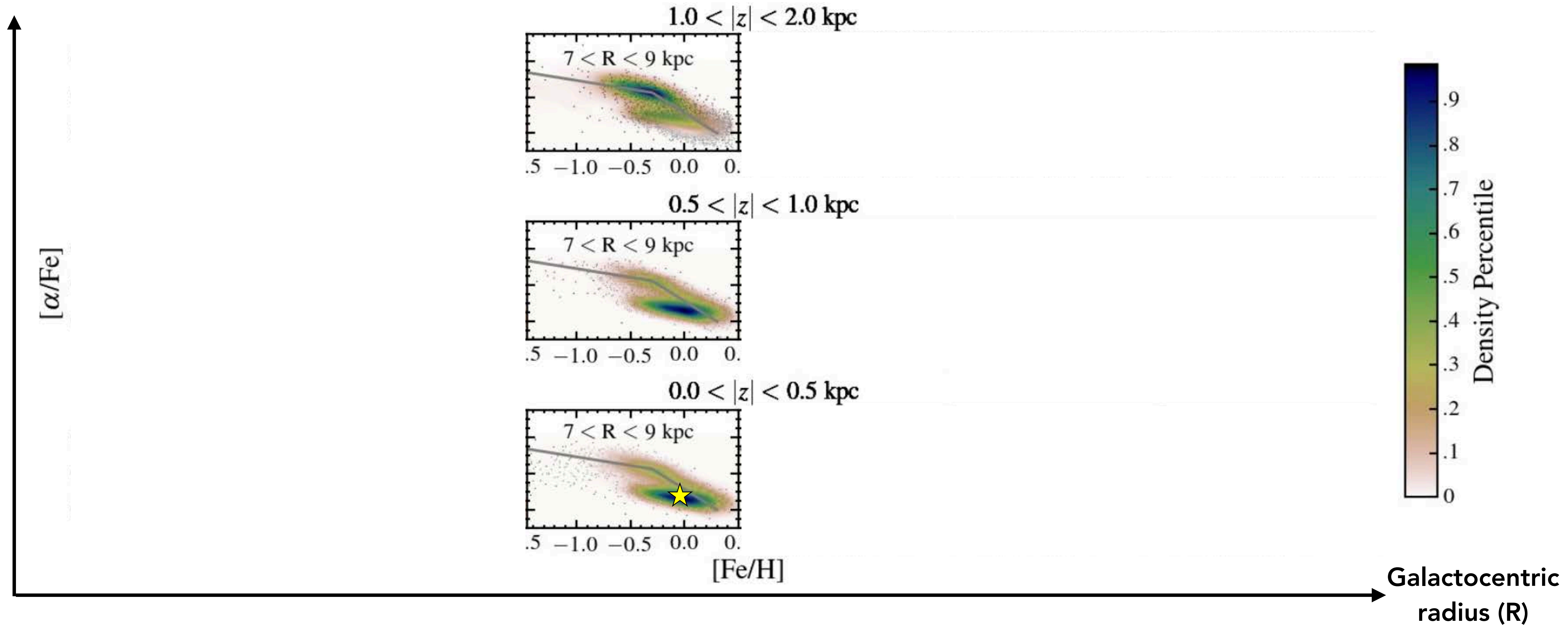
Thin disc



Chemical evolution — the Milky Way

Height above the
Galactic plane (z)

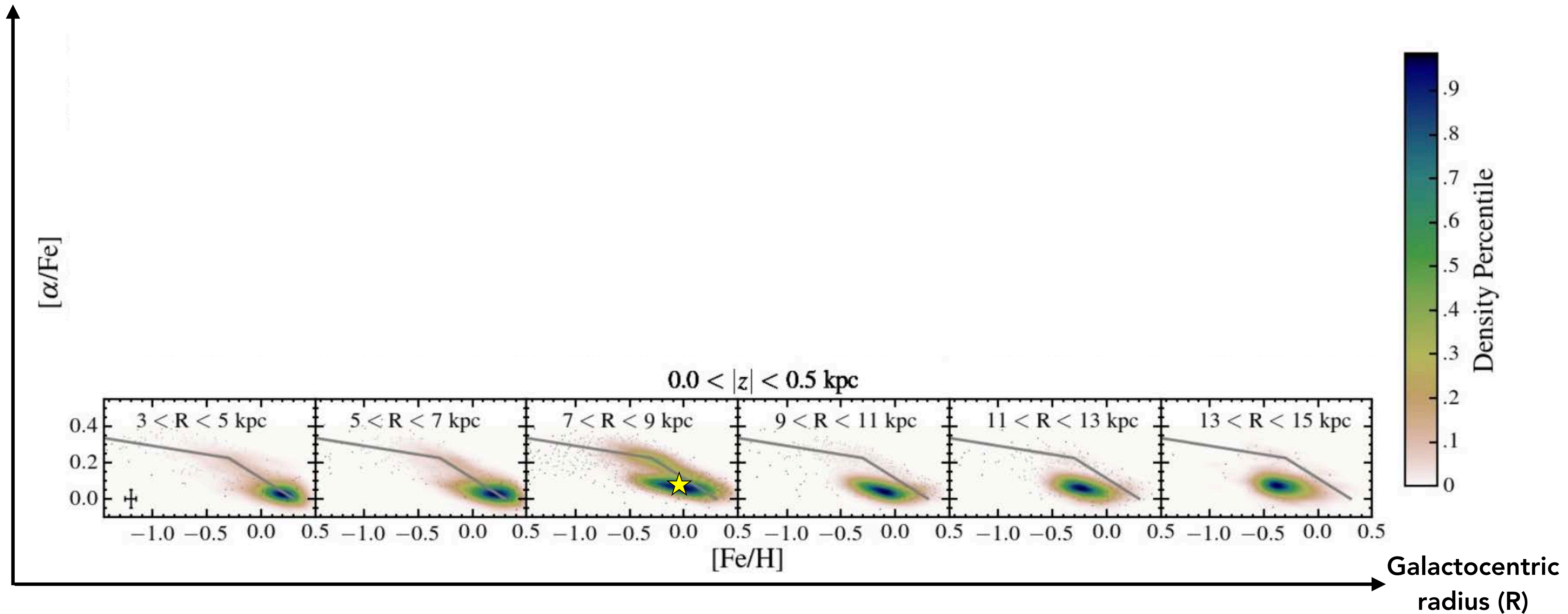
Hayden et al. 2015



Chemical evolution — the Milky Way

Height above the
Galactic plane (z)

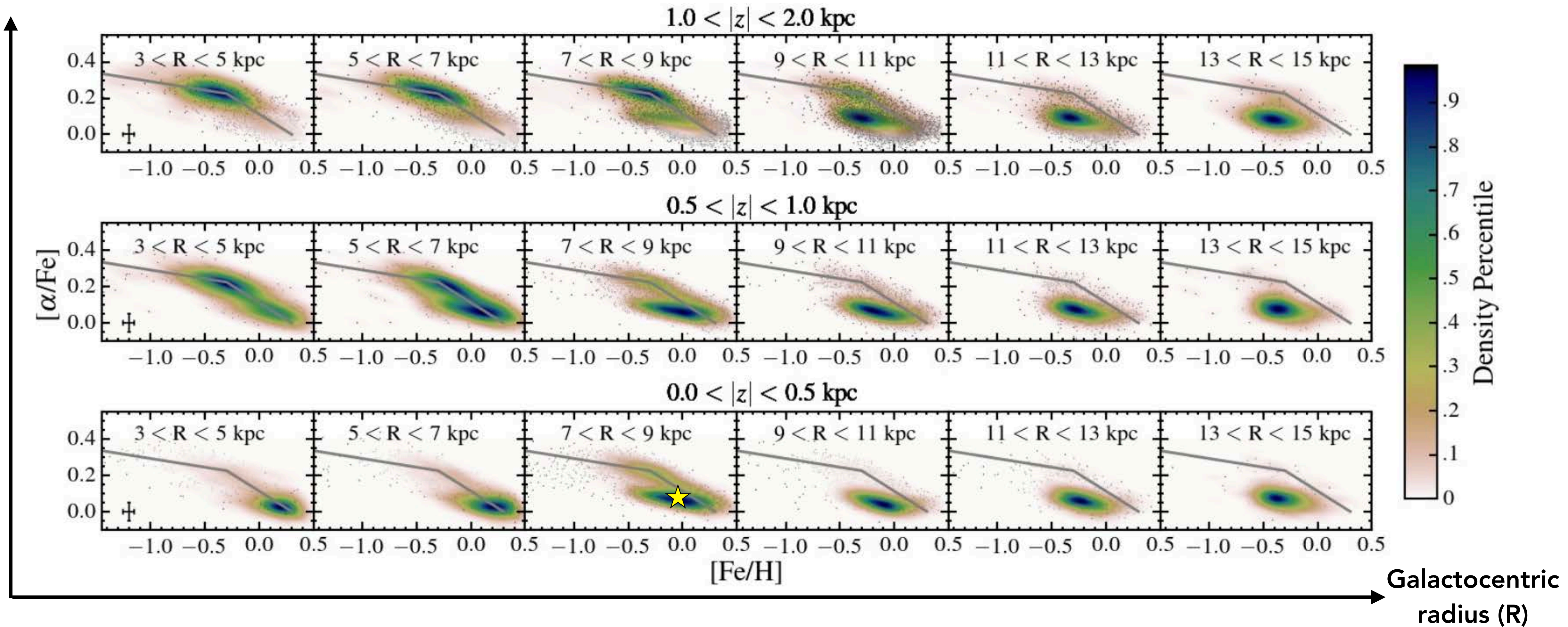
Hayden et al. 2015



Chemical evolution — the Milky Way

Height above the
Galactic plane (z)

Hayden et al. 2015

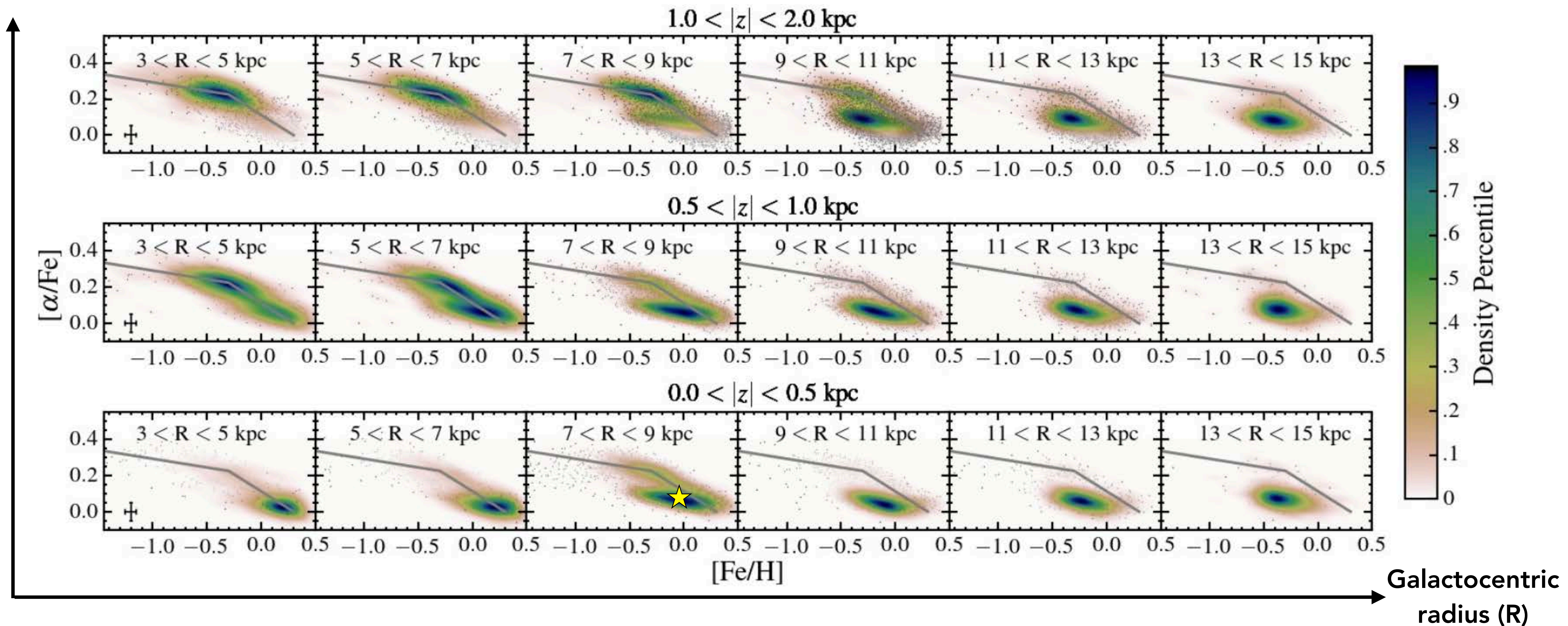


Chemical evolution — the Milky Way

more on Milky Way chemo-dynamics
in the lectures by GyuChul

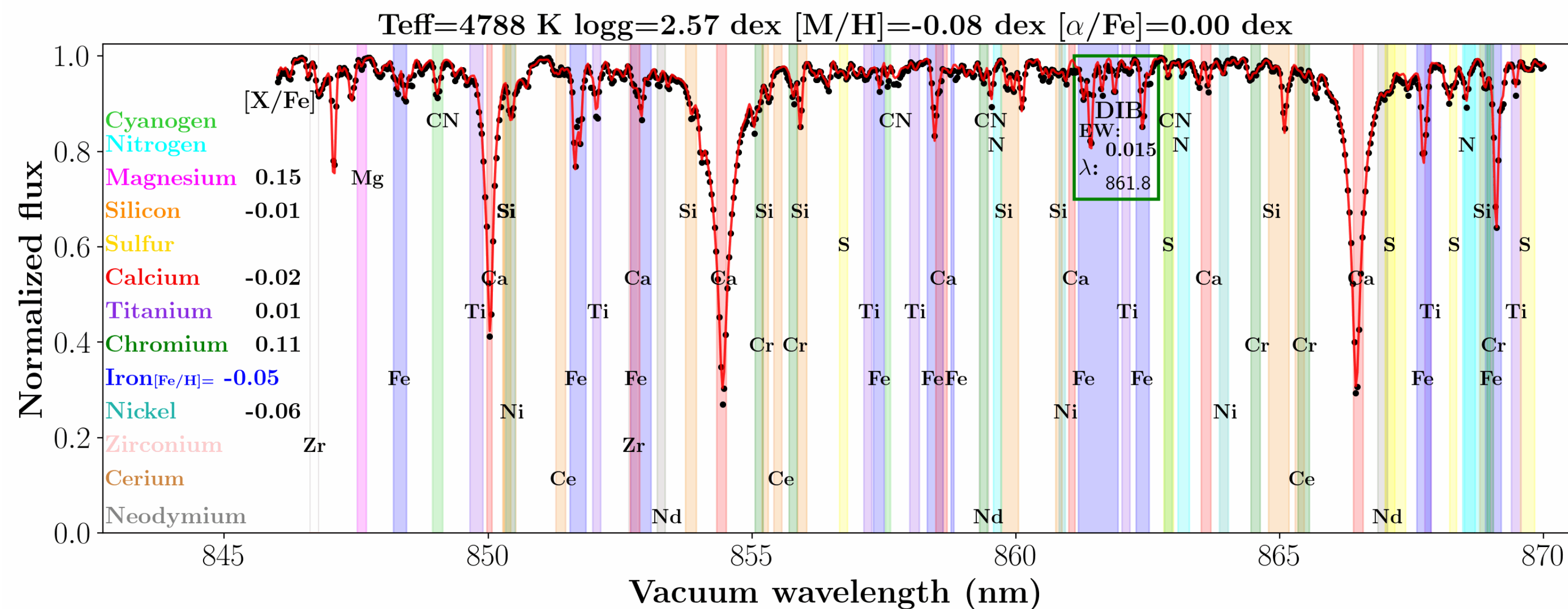
Height above the
Galactic plane (z)

Hayden et al. 2015



Hands-on session

- Via the Notebooks sub-folder on Moodle, with a link to the data inside the notebook (Lecture6_hands-on_Gaia-RVS.ipynb)
- Exploring the Gaia Radial Velocity Spectrometer (RVS) spectra



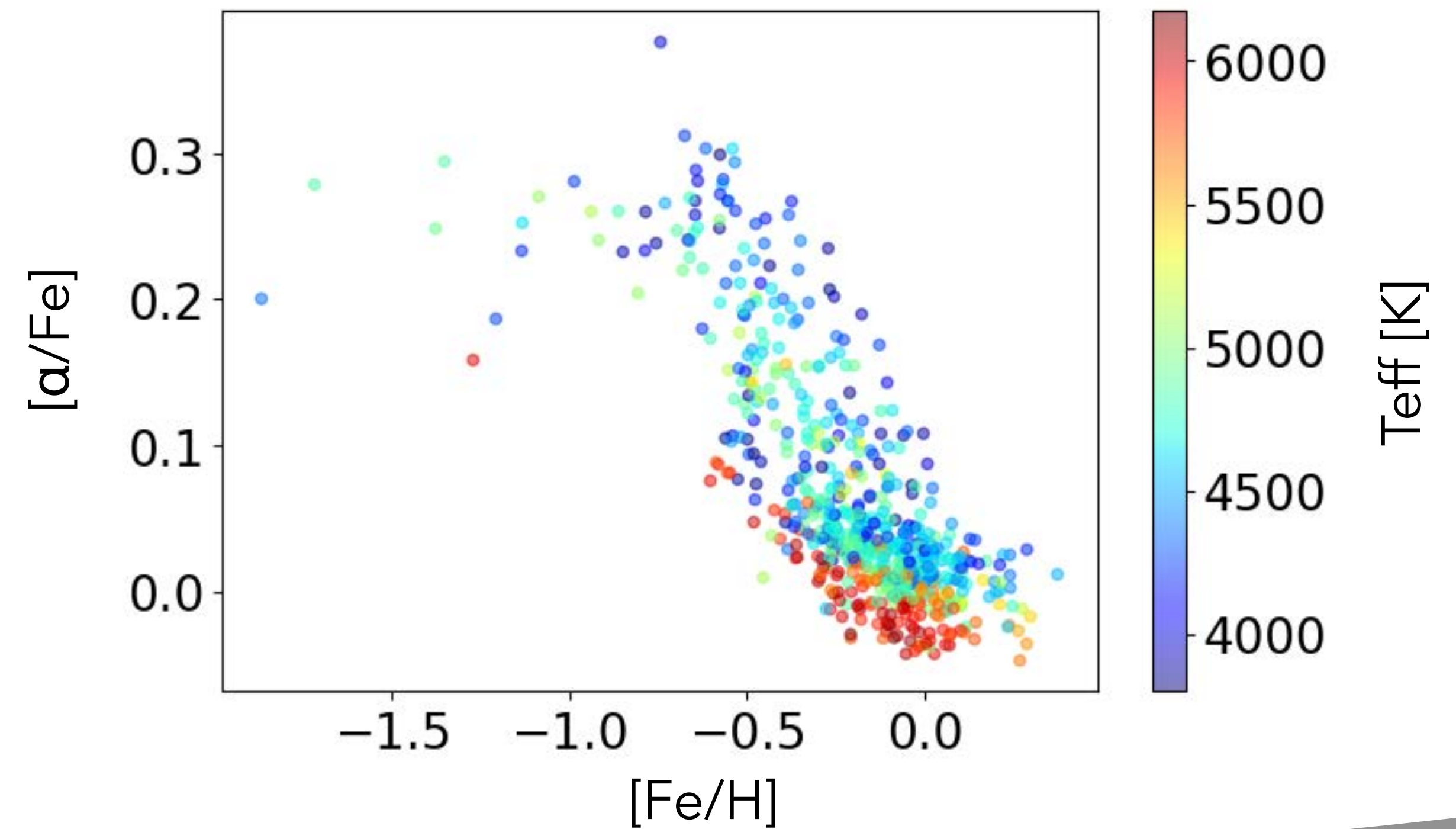
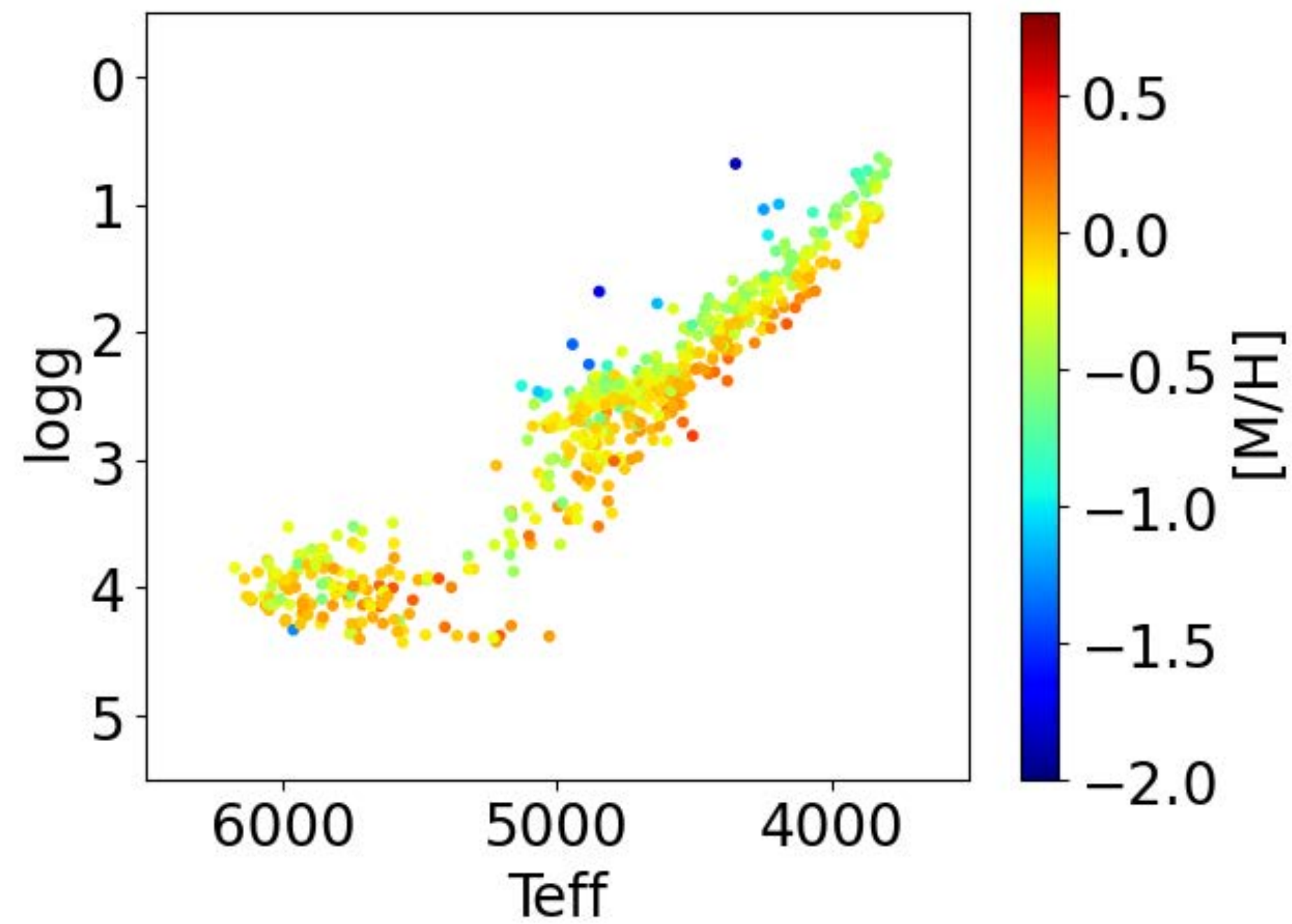
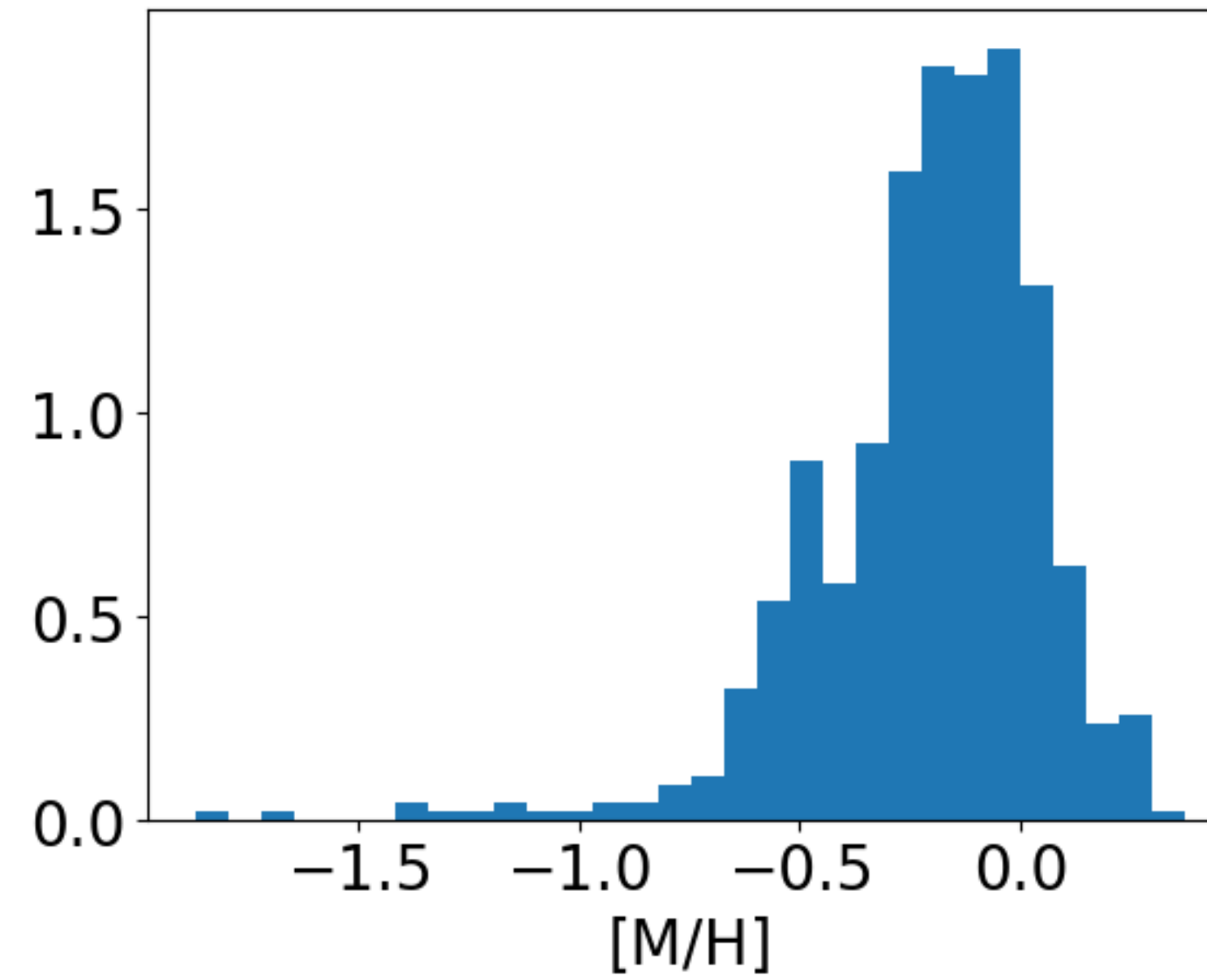
To do

- Plot the Kiel diagram, metallicity distribution and $[\alpha/\text{Fe}]$ vs. $[\text{Fe}/\text{H}]$ diagram
- Explore what the differences are in the spectra for different stellar parameters
- Run dimensionality reduction algorithms, explore trends with stellar parameters

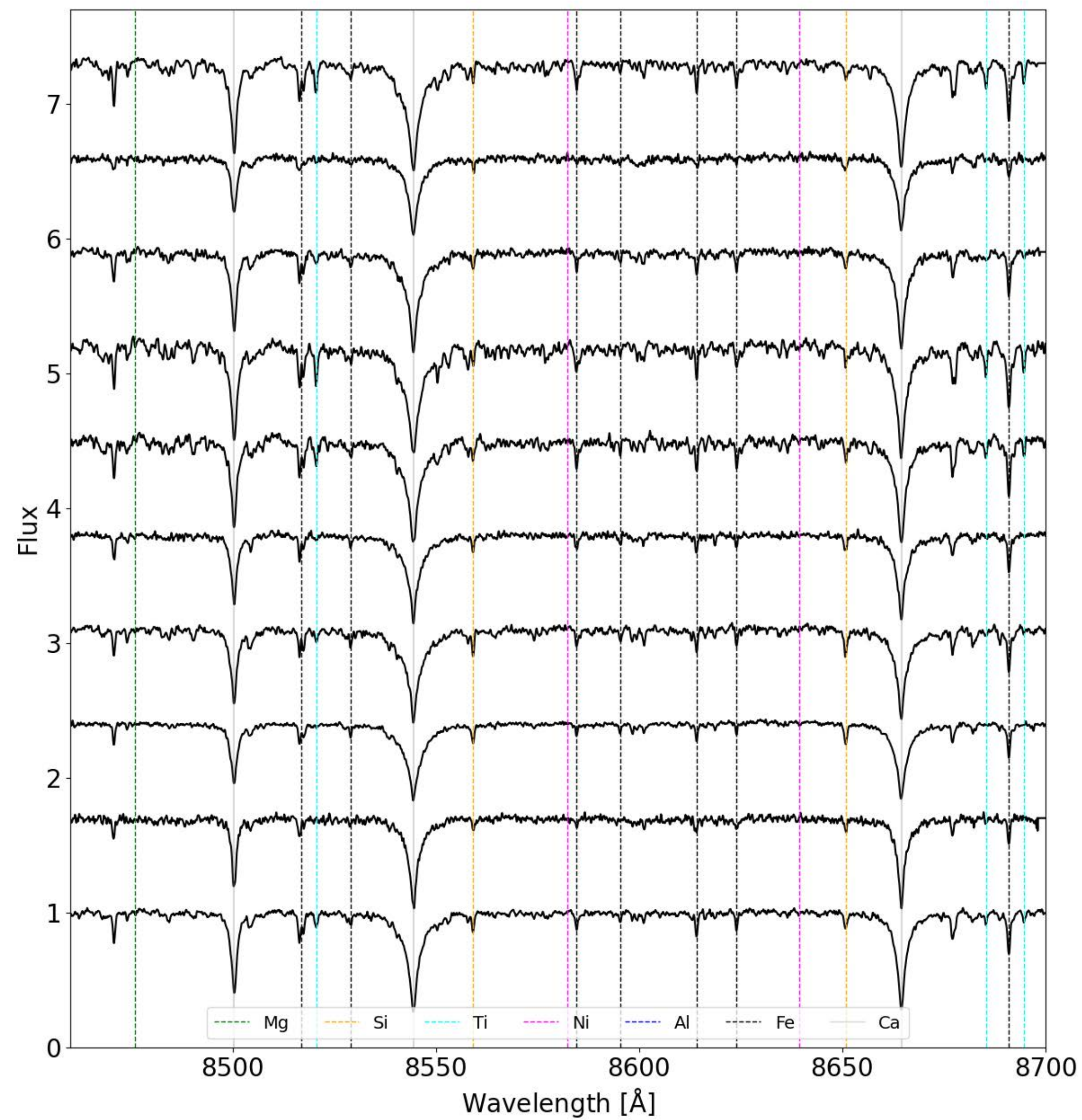
Some things to try next (order up to you):

- Relax or remove quality cuts on the stellar parameters & repeat the above
- Compare the Gaia collaboration & the Guiglion/CNN stellar parameters
- Vary the dimensionality reduction algorithms' parameters
- Anything else you'd like to explore

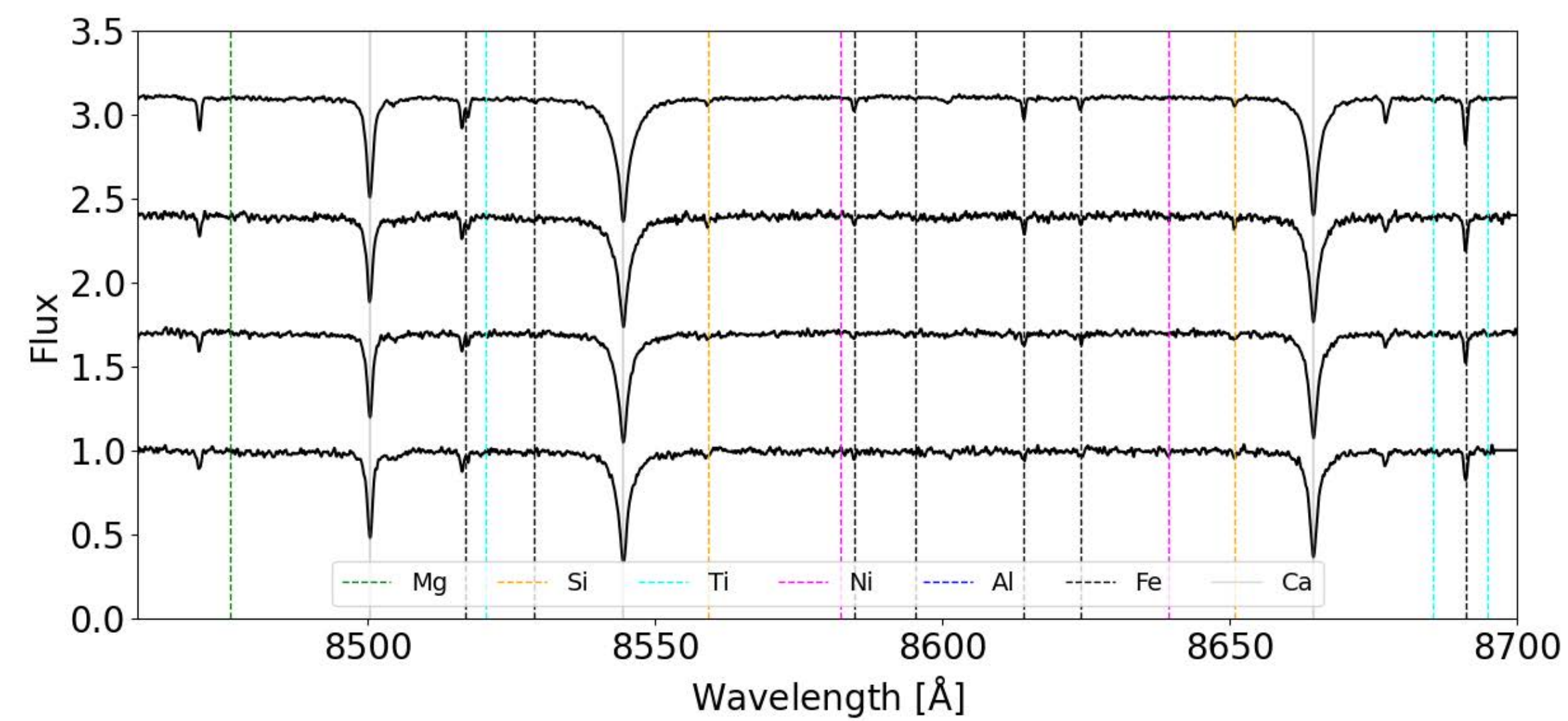
Example results



10 random spectra



$[\text{Fe}/\text{H}] < -1.3$



Dimensionality reduction

