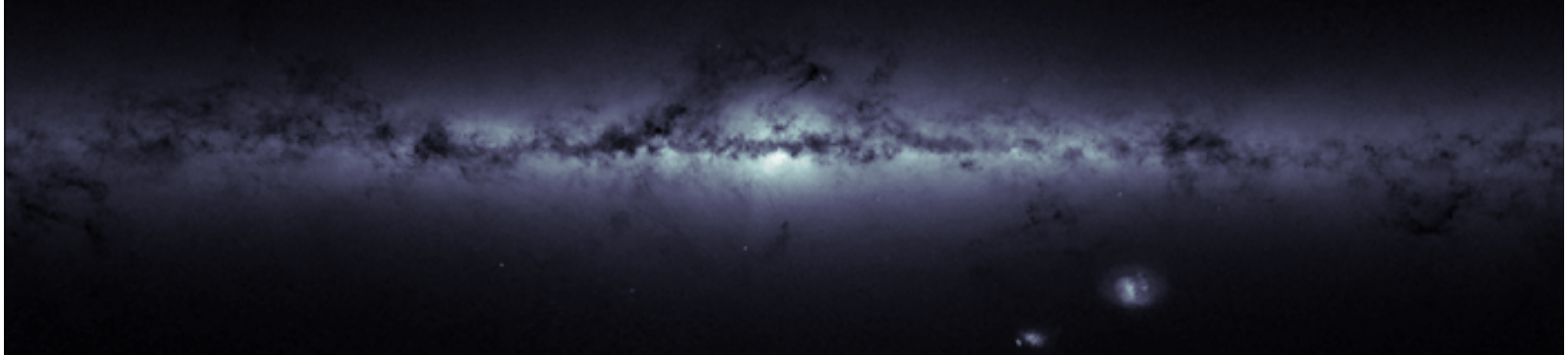
NuPECC: WG4 – Chemical Evolution Part



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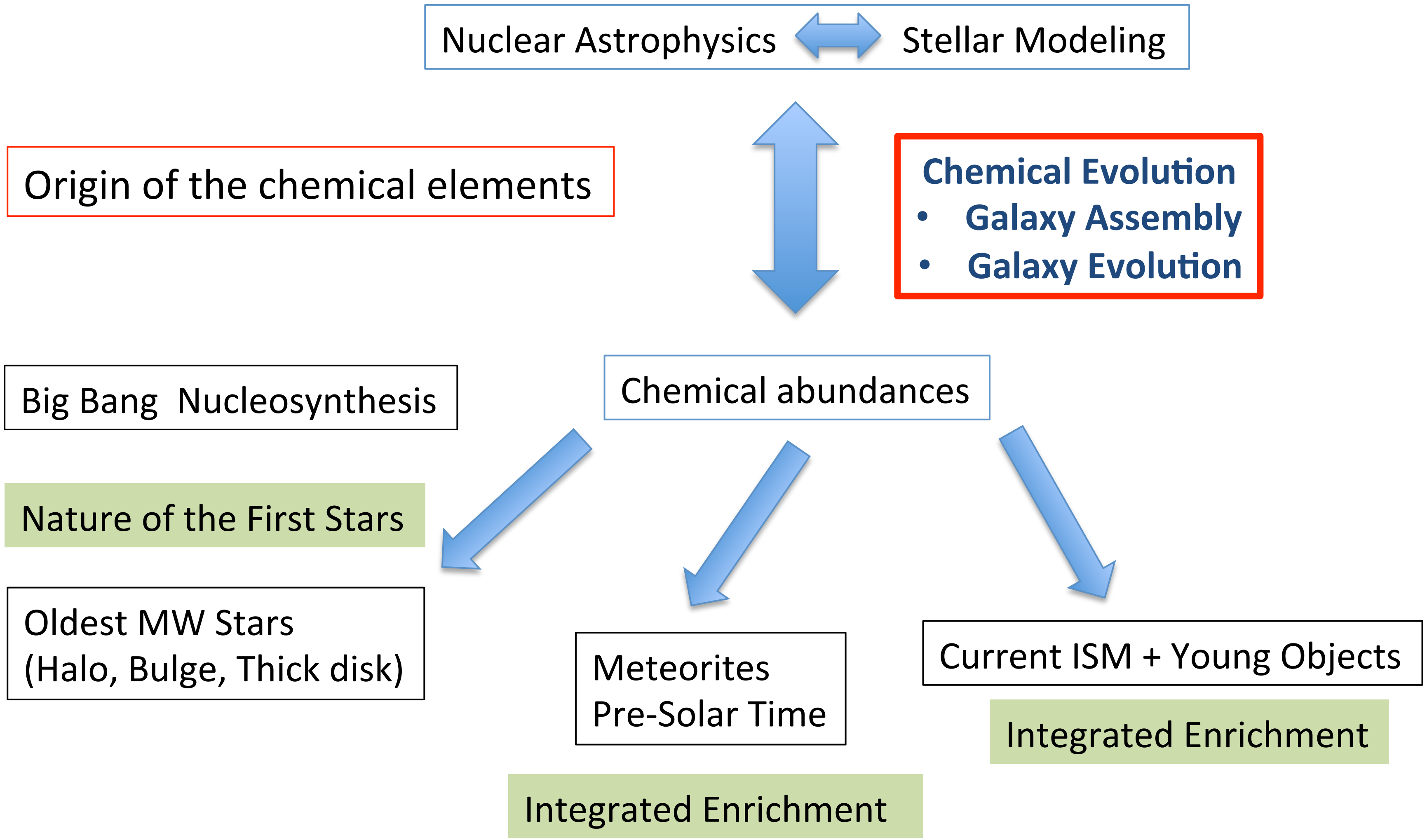
AIP

Contributors from other institutions: Thielemann, Gibson, Kobayashi, Travaglio for their groups

NuPECC and Chemical Evolution



Degeneracies/Multi-facet problems

1. Very Metal Poor Universe -> Main contributors are Massive Stars BUT it is also a phase where Galaxy assembly + mixing complicates analysis

2. Disk metallicity range – several nucleosynthetic sources (on the top of massive stars it comes the contributions of SNIa, Novae, Low and Intermediate mass stars) + internal and external drivers of radial migration of stars. Challenge: how much is the Galactic Archaeology information preserved? Do we see a well mixed interstellar medium (ISM) plus radial migration or unmixed ISM?

Main developments in the last 5 yrs

- Detailed stellar evolution models: stellar yields predictions from several groups/ available also for difficult elements such as r-process and s-process elements (massive stars, AGBs, NSs, rotation + magnetic fields, binarity, new SNIa computations, faint CC SNe, etc..)
- Enormous amount of data – wide coverage of MW and its satellites (RAVE, SEGUE, APOGEE, GES, GALAH)
- New window on inner parts of Galaxy/Bulge – BRAVA, ARGOS, APOGEE, VVV + soon APOGEE South + MOONS and in future 4MOST & WEAVE

- The advent of Asteroseismology and AGES – better stellar model constraints - CoRoT/Kepler/K2 -- approval of PLATO-2 (Rauer et al. 2015), Seismo for Galactic Archaelogy (e.g. Miglio et al 2013, Casagrande et al 2015, Chiappini et al. 2015, Martig et al. 2015. Stello et al. 2015)

- Better age-accuracy when combining Seismo + spectroscopy. Driver of spectroscopic follow=up of seismic targets

- Better Resolution of N-body Hydrodynamic simulations , but still sub-grid physics difficulties

Feedback common point from German Community at RDS Meeting Dec/2015 on MW & Local Volume WG:

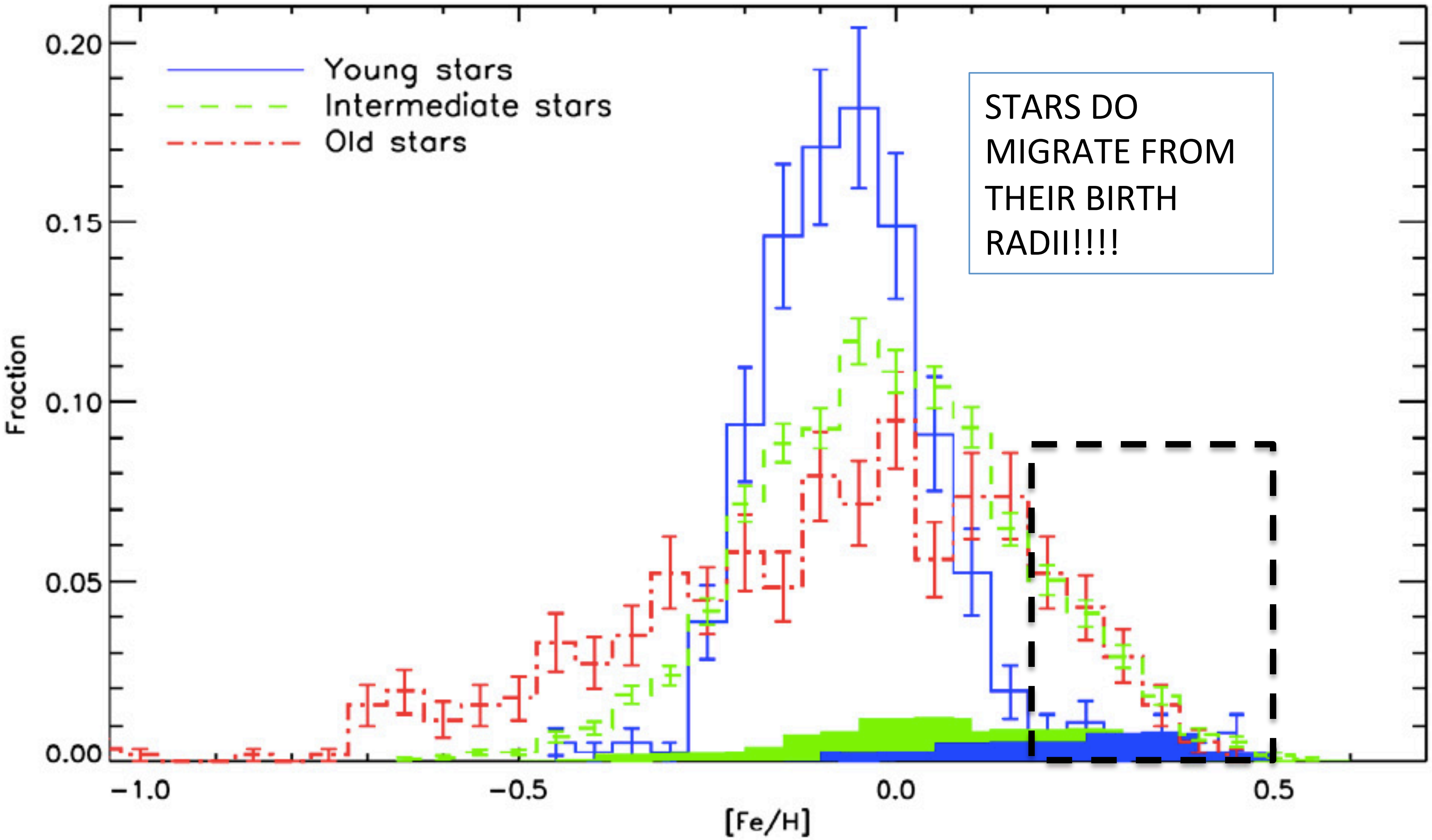
Unprecedented observational details can now be obtained from objects throughout our Galaxy and some of its satellites. Are we ready to exploit Gaia database and follow-up spectroscopy?

Meaningful statistical samples of rare stars (e.g. very metal-poor stars; better understanding of stellar evolutionary channels or rare/especial populations in MW context)

1. Disk metallicity range

- Radial Migration
- [alpha/Fe] proxy for age = but not always

Casagrande et al. 2011 – Geneva Copenhagen Survey - ages

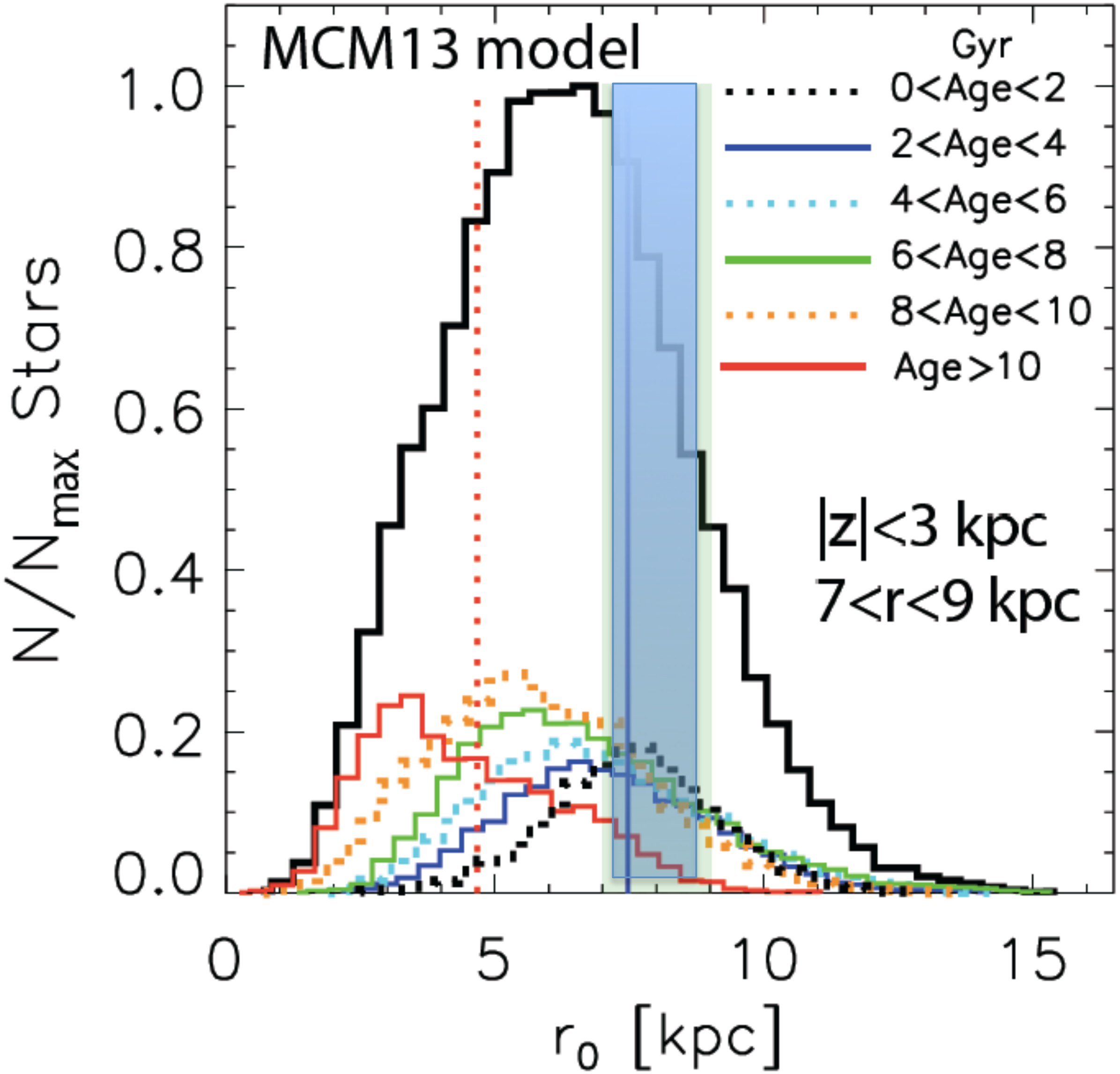


Metal-rich tail of the local MDF is composed mainly by **old + interm. age stars**
Large scatter in the local Age-Metallicity relation (Nordstrom et al. 2004, Holberg et al. 2007)

Stars today at Solar Vicinity are a

Mosaic of stars born at different $R_{initial}$ at different times

New Approach: Chemodynamical model of the MW (Minchev, Chiappini, Martig 2013, 2014)

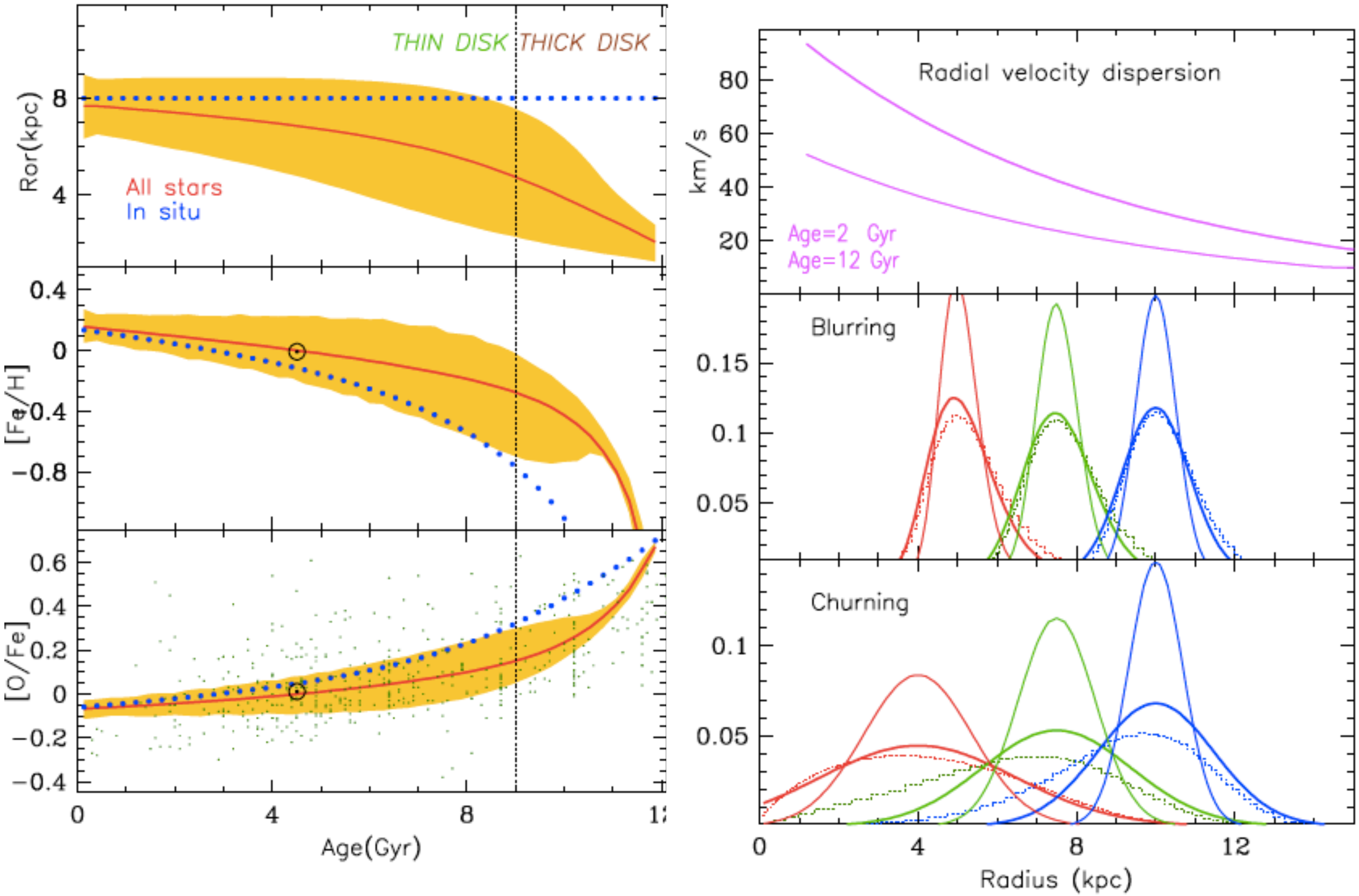


r_0 = Birth Radii in kpc

Input chemistry:
Thin disk only

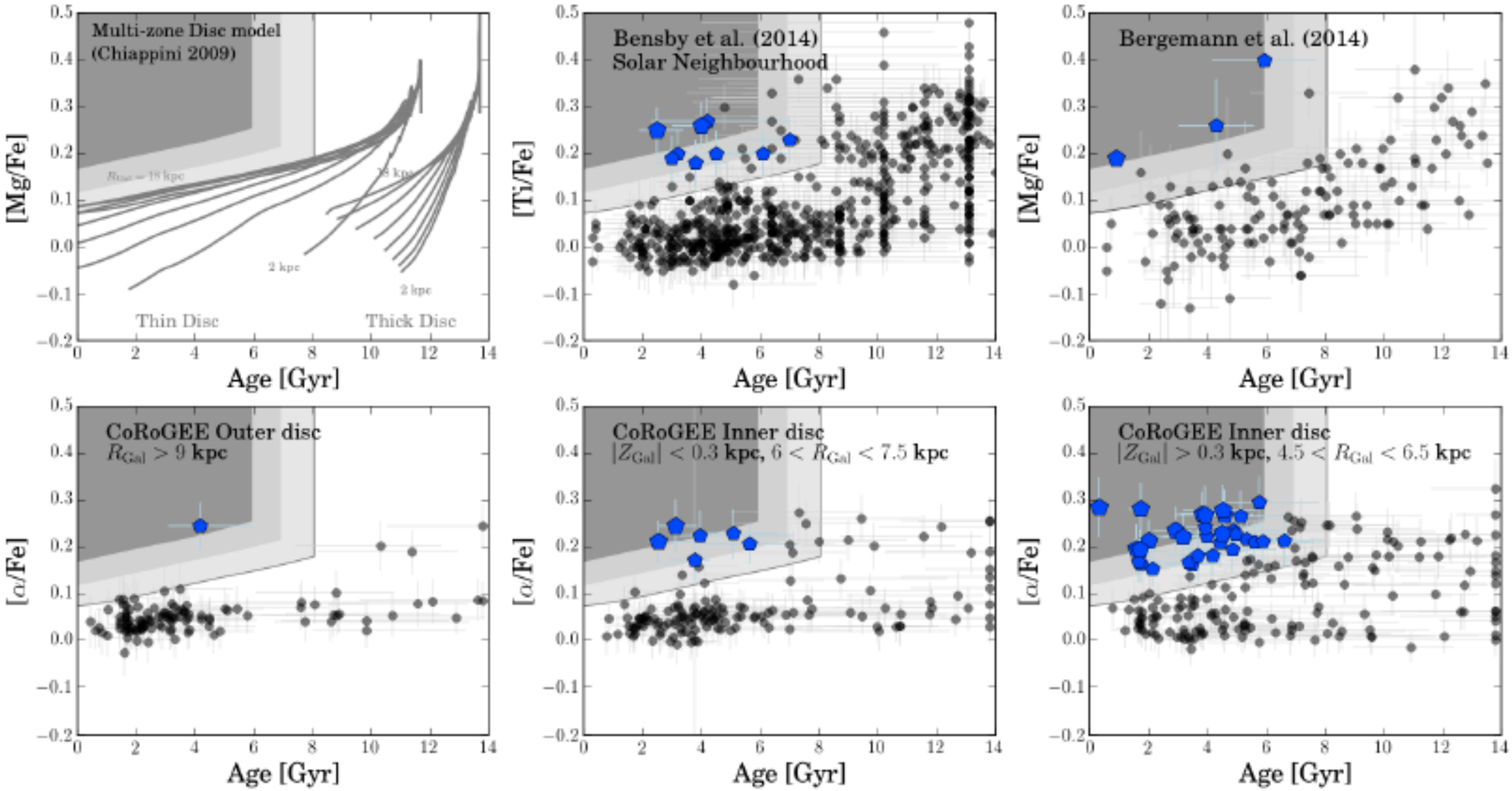
Self-consistent dynamics:

N-body simulation in cosmological framework:
early mergers,
gas infall,
bar,
spirals,
radial migration



Kubryk, Prantzos, Athanassola 2014 Parameterized radial migration – 1D

Young α-enhanced stars in the CoRoGEE sample



Chiappini, Anders et al. 2015

Also found in APOGEE+Kepler (Martig et al. 2015) and GES+CoRoT (Valentini et al.in prep)

Way Forward? Still open issues related to fully self consistent chemodynamic simulations in the cosmological framework

- Difficulties in obtaining MW + sub-grid physics problem
- Need for constrained simulations?
- Need for very large resolution N-body simulations in the cosmological framework

Alternative approaches are welcomed by the community – extracting already many quantitative results from current data. These results show the need for "accurate" yields for the whole stellar mass range

2. Very metal poor Universe

- Impact of rotation in massive stars: s-process
- The r-process nucleosynthetic site
- Type Ia SNe

Chemical Information & CE Tools to translate:

- Abundance patterns -> Timescales
- Abundance scatter -> rare events? Mixing?
- Patterns+Scatter -> nucleosynthetic sites
- Density of points in abundance ratio diagrams (start being possible with large samples) -> much stronger constraints

4 Approaches "early phases":

- Stellar yields vs. one particular star (no CE)
- Chemical evolution models homogeneous (trends only)
- Inhomogeneous Chemical evolution models -> observed scatter
- Hydro-dynamical simulations + cosmological context -> building blocks

Signatures of Fast Rotators in the Early Universe found in the Galactic Halo

① Large amounts of N in the early Universe (Chiappini et al. 2006 A&A Letters)

② Increase in the C/O ratio in the early Universe (Chiappini et al. 2006, Ekstroem et al. 2008)

③ Large amounts of ^{13}C in the early Universe (Chiappini et al. 2008 A&A Letters)

④ Early production of Be and B by cosmic ray spallation (Prantzos 2012)

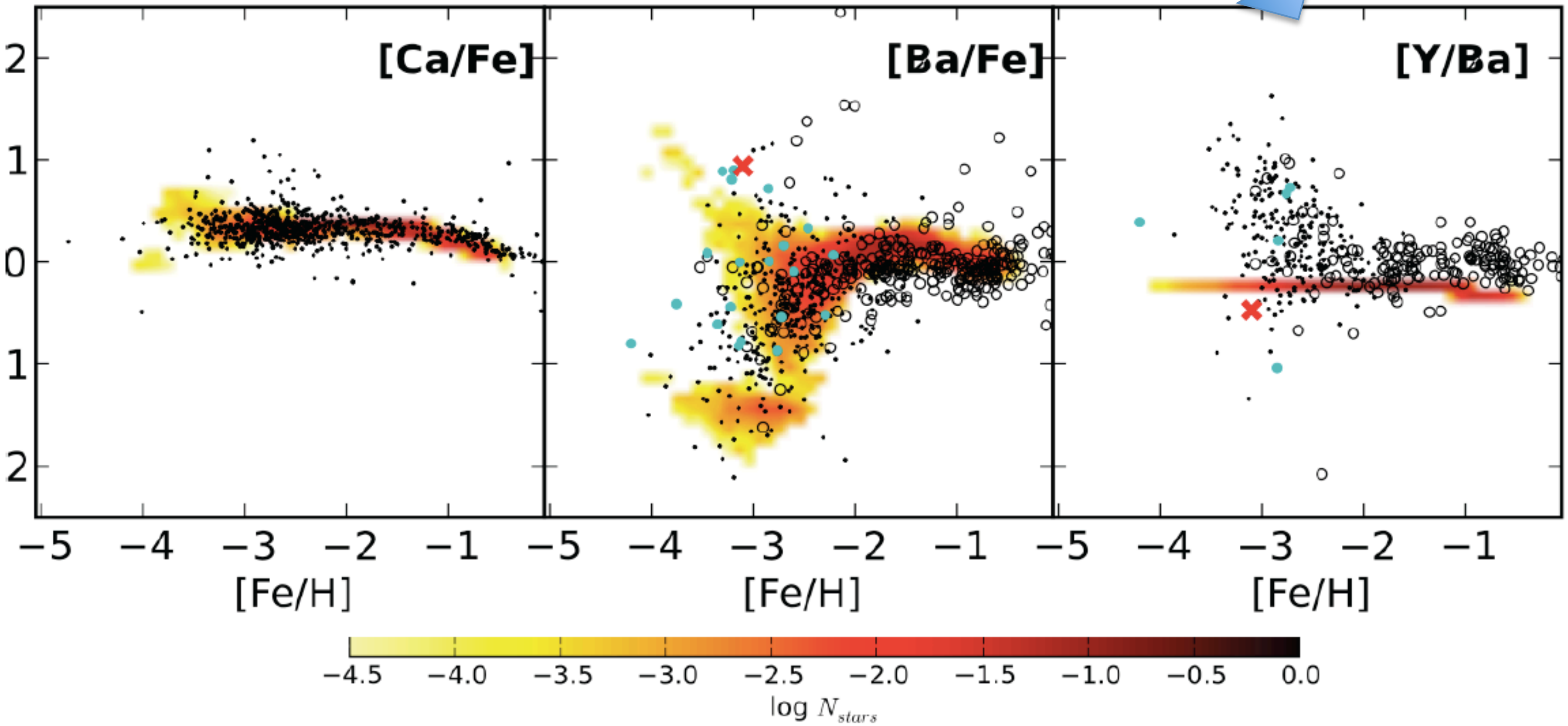
⑤ Early production of s-process elements (La, Ba, Y, Sr …) (Chiappini et al. 2011, Cescutti et al. 2013, Chiappini 2013; Cescutti & Chiappini 2014)

Naturally accounted for if the first stellar generations in the Universe were fast rotators

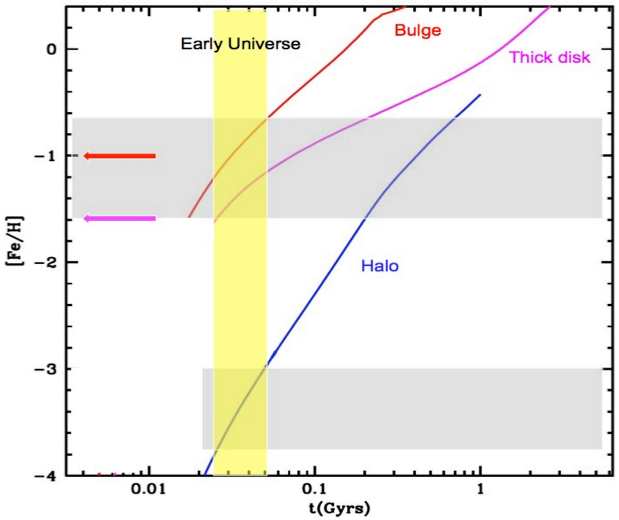
HALO

?

2 r-process sites needed…



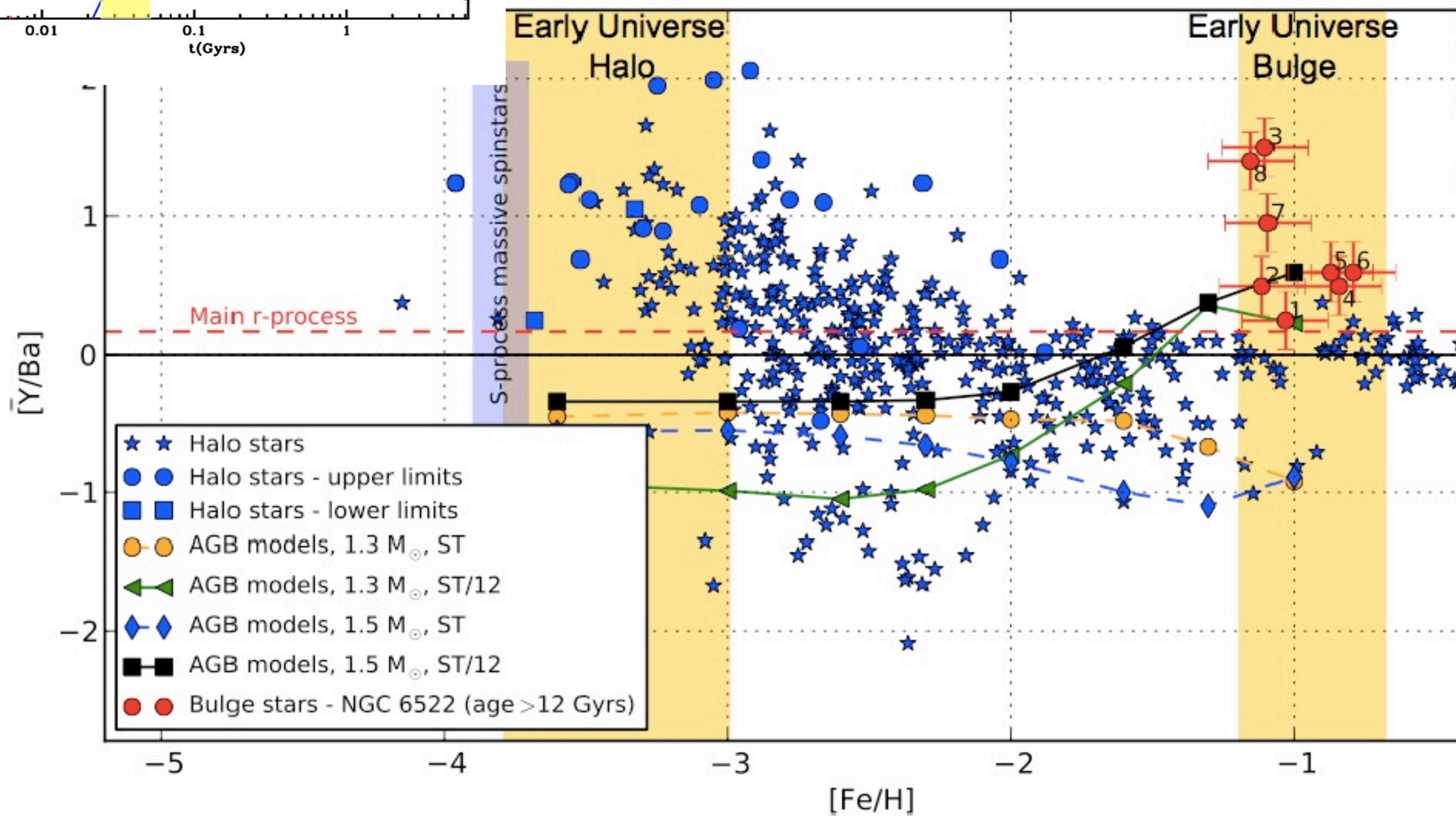
Cescutti 2008 Models (see Chiappini 2013 for a review)



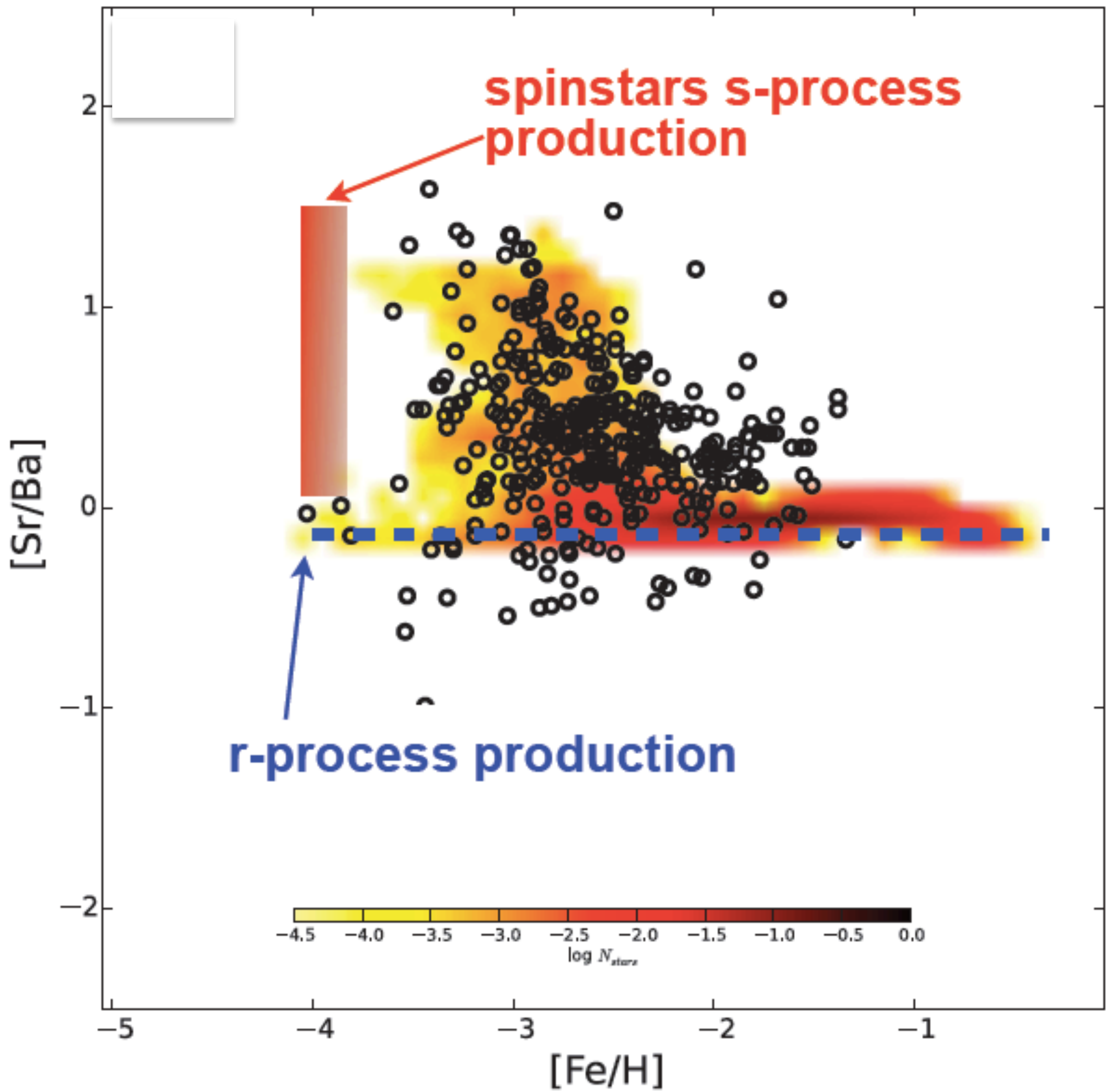
LETTER nature
doi:10.103

Imprints of fast-rotating massive stars in the Galactic Bulge

Cristina Chiappini[1,2,3], Urs Frischknecht[4,5], Georges Meynet[2], Raphael Hirschi[5,6], Beatriz Barbuy[7], Marco Pignatari[′], Thibaut Decressin[2] & André Maeder[2]



Solution: [Y/Ba] scatter in halo VMP stars could be explained by fast rotating massive stars!



Cescutti, Chiappini et al. 2013

HALO

Stochastic CEM:

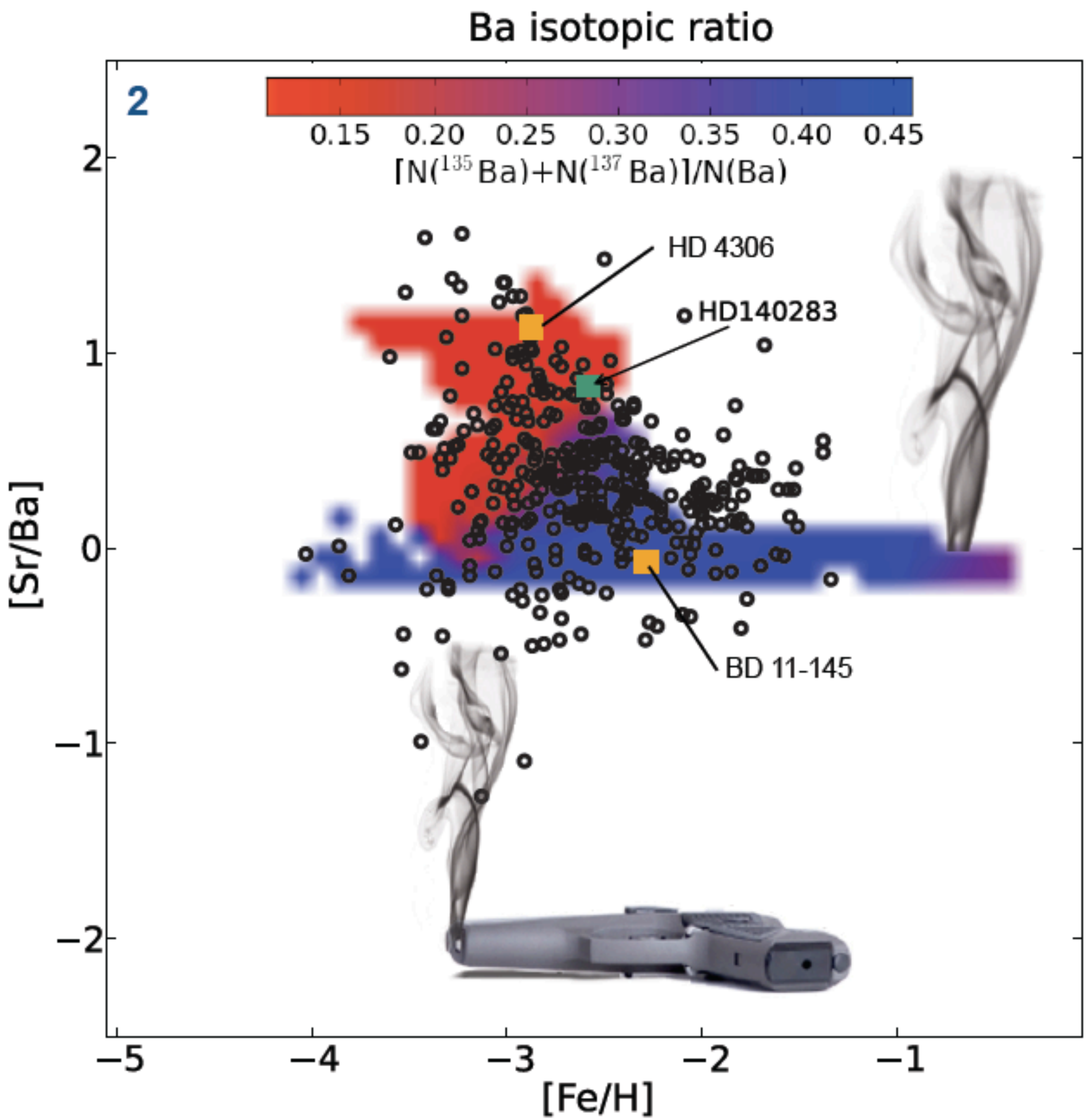
Spinstars = the missing component responsible for the spread in the ratio between a light (Sr) to heavy (Ba) n-capture elements.

Prediction: Isotopic ratio of for the isotopic ratio of Ba in halo stars

Hypothesis: one site for r-process + spinstars -> results are indepent on the choice of r-process scenario!

For different r-process sites see: Cescutti & Chiappini 2014 (EC SN 8-10 Msun vs. magneto rotational driven SNe) and Cescutti, Romano, Matteucci, Chiappini, Hirschi 2015 (for neutron star mergers)

HALO



The density plot is the distribution of the isotopic ratio of Ba according to the models, see the bar above the main figure

The smoking gun of the contribution of spinstars?

(to be confirmed by future data)

Credit: Cescutti

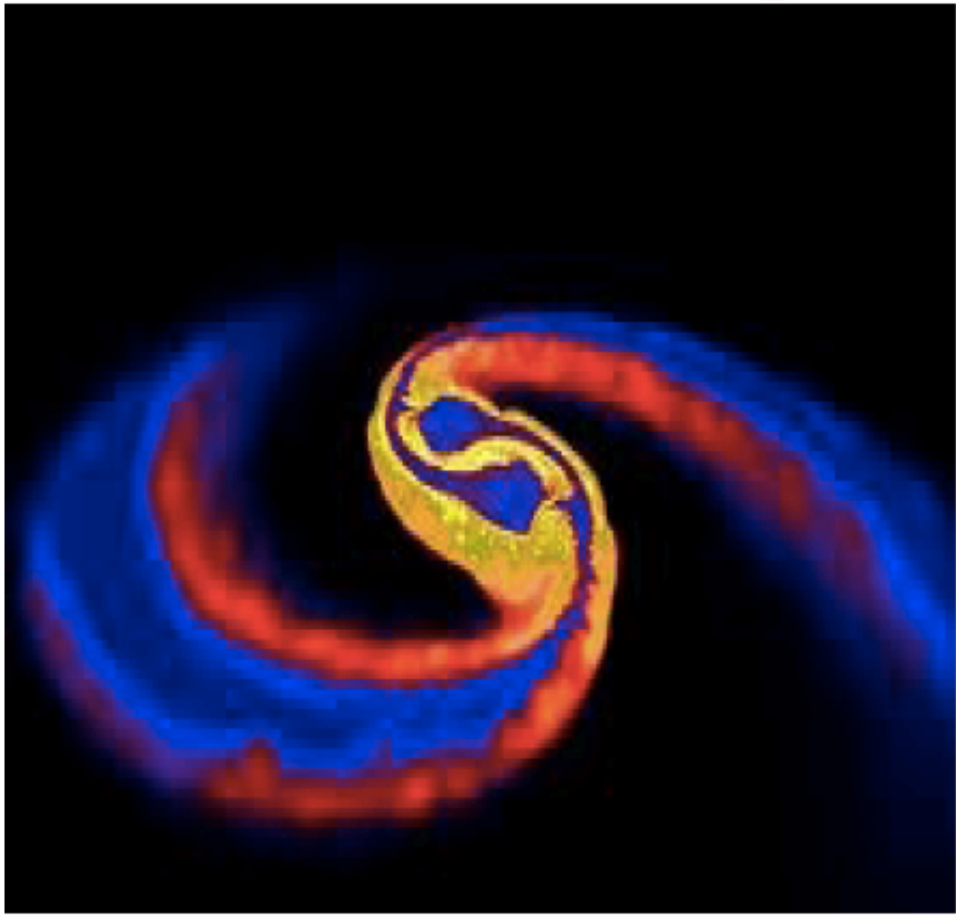
ROYAL ASTRONOMICAL SOCIETY
MNRAS 456, 1803–1825 (2016) doi:10.1093/m

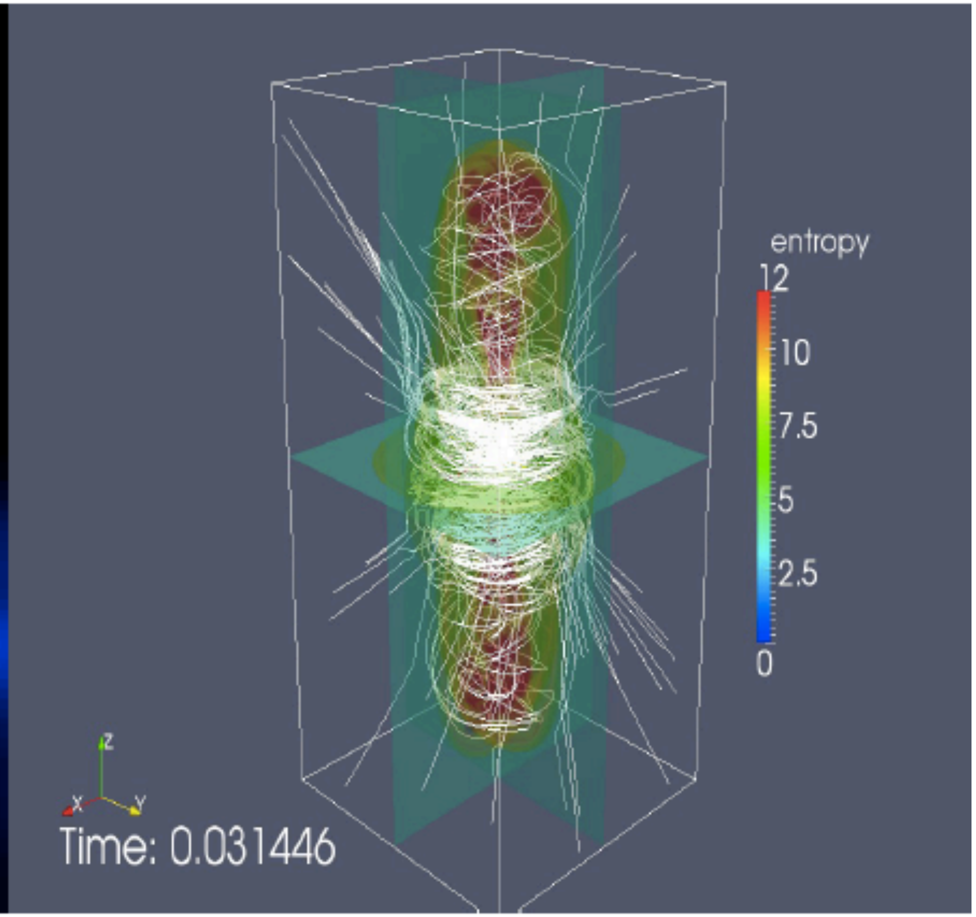
s-process production in rotating massive stars at solar and low metallicities

Urs Frischknecht,[1,2] Raphael Hirschi,[1,3,4★] Marco Pignatari,[5] André Maeder,[6] George Meynet,[6] Cristina Chiappini,[7] Friedrich-Karl Thielemann,[2] Thomas Rauscher,[2,4,8] Cyril Georgy[1] and Sylvia Ekström[6]

“Despite nuclear uncertainties affecting the *s*-process production and stellar uncertainties affecting the rotation-induced mixing, our results show a robust production of *s*-process at low metallicity when rotation is taken into account. Considering models with a distribution of initial rotation rates enables us to reproduce the observed large range of the [Sr/Ba] ratios in (carbon-enhanced and normal) EMP stars.”

Which events contribute to the strong r-Process??





Neutron star mergers in binary stellar systems vs. supernovae of massive stars with fast rotation and high magnetic fields

Friedel Thielemann

Heavy Elements

Friedel

- Problems with regular supernovae, to provide the conditions for a strong r-process
- 60Fe, produced and ejected from massive stars (which would also become a supernova), has been seen in deep-sea sediment with a last addition about 2 Myr ago. This is not the case for 244Pu, which is seen a factor of 10 smaller than expected, if it would have been produced by every supernova in amounts which are consistent with solar abundances. Therefore, we see a bit 244Pu, but this is from much earlier events and it has decayed a lot since then.. Low stats?
- Large scatter of [Eu/Fe] at low metallicties, while this becomes smaller at about [Fe/H] larger than -2 or -1, would be almost consistant with the behavior of alpha elements, but with a much smaller event rate which needs a longer time to converge to the average.

R-process = rare events?

- 1. Neutron star mergers are unquestionably a very strong candidate, all calculations by a variety of groups point strongly to it. The point is that we have very neutron-rich material from the beginning, and most of it is ejected fast without much interactions with neutrinos (which would push Ye up).
  This latter part by some wind can, however, also produce stuff below the 130 peak.

- 2. We have 10^{15} Gauss neutron stars (magnetars) which would be explainable by supernovae with iron cores and an initial magnetic field of beyond 10^{12} Gauss. If these guys rotate fast (unfortunately there are no self-consistent models yet - would about 1 percent of massive stars behave this way) the produce in the core collapse strongly neutron-rich matter which is ejected fast in polar jets, also not being affected too much by neutrinos.
  As said, these things are not yet self-consistent, but seem reasonable

- From population modeling it also seems that 1. is of the order 1 percent of supernova events. Thus 1 as well as 2 are rare events with respect to regular supernovae and the question is whether only one of them (e.g. mergers) can explain what we see in GCE or do we also need 2?

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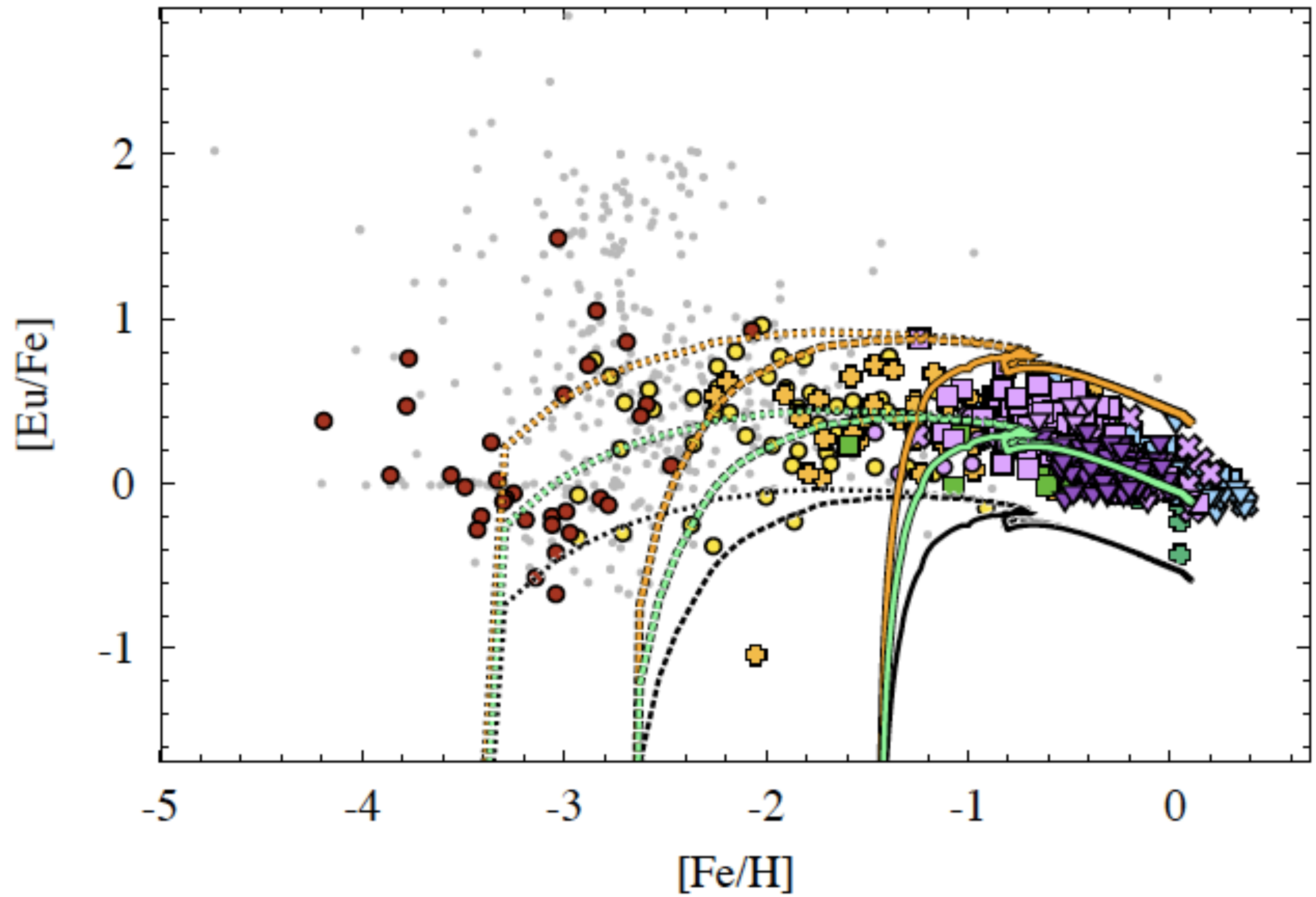
Chemical evolution – General abundance patterns



Matteucci, Romano, Arcones, Korobkin, Rosswog 2014

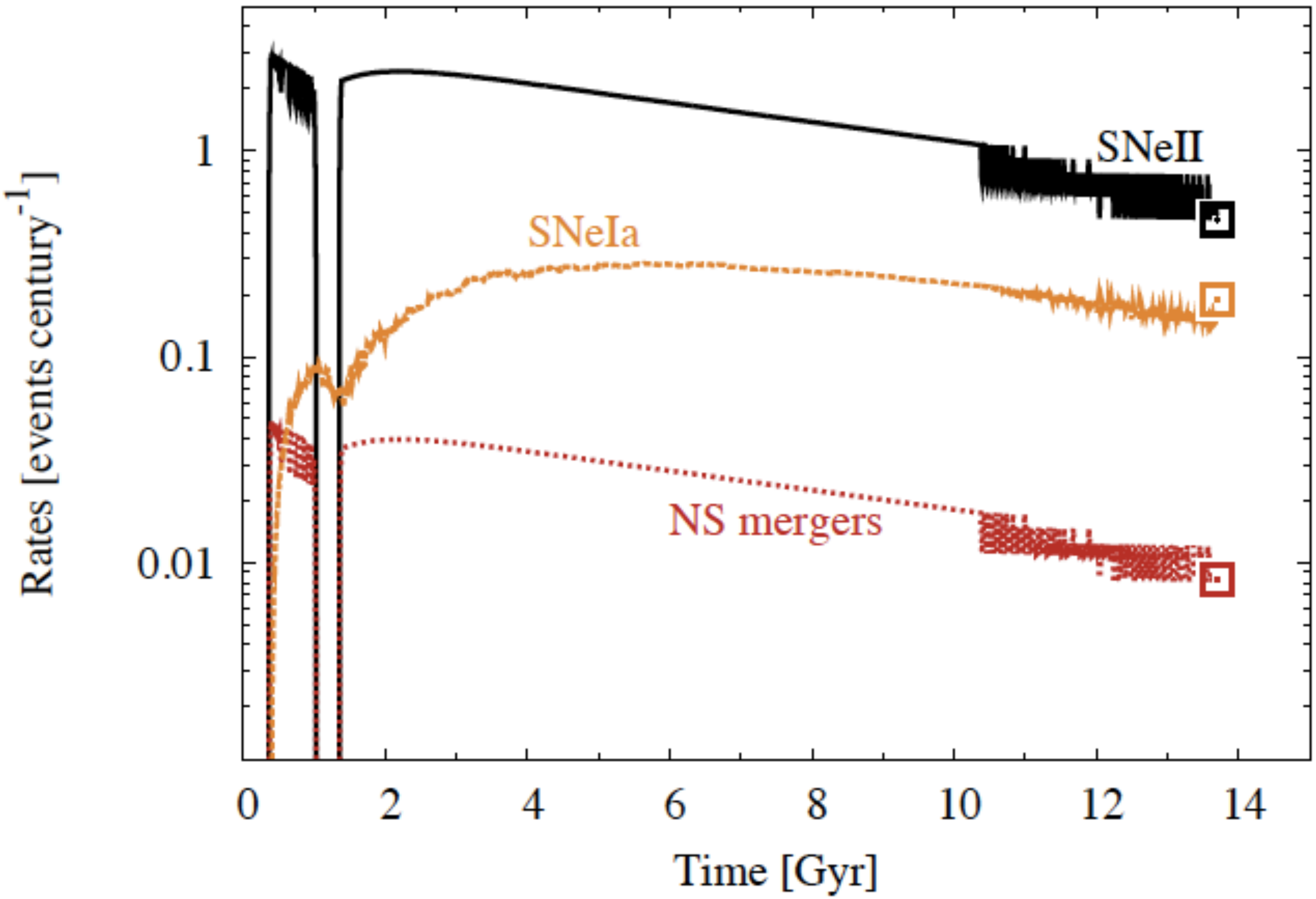
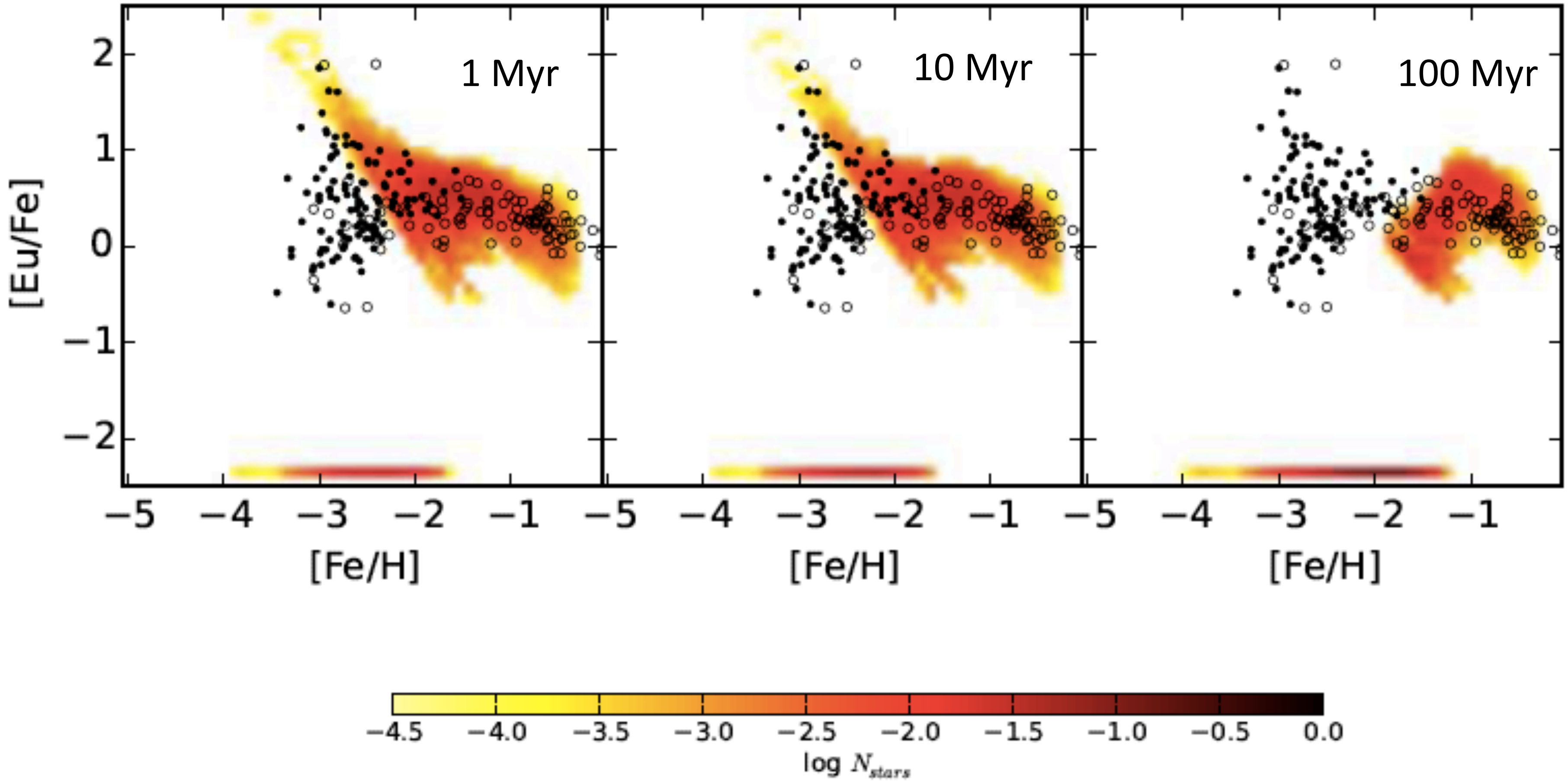


Figure 1. Predicted SNII, SNIa and CBM rates (black solid, orange dashed and red dotted curves, respectively) as functions of cosmic time for the Milky Way. Also shown are the observational present-time values (squares; SN rates: Li et al. 2011; CBM rate: Kalogera et al. 2004).

Inhonogeneous chemical evolution

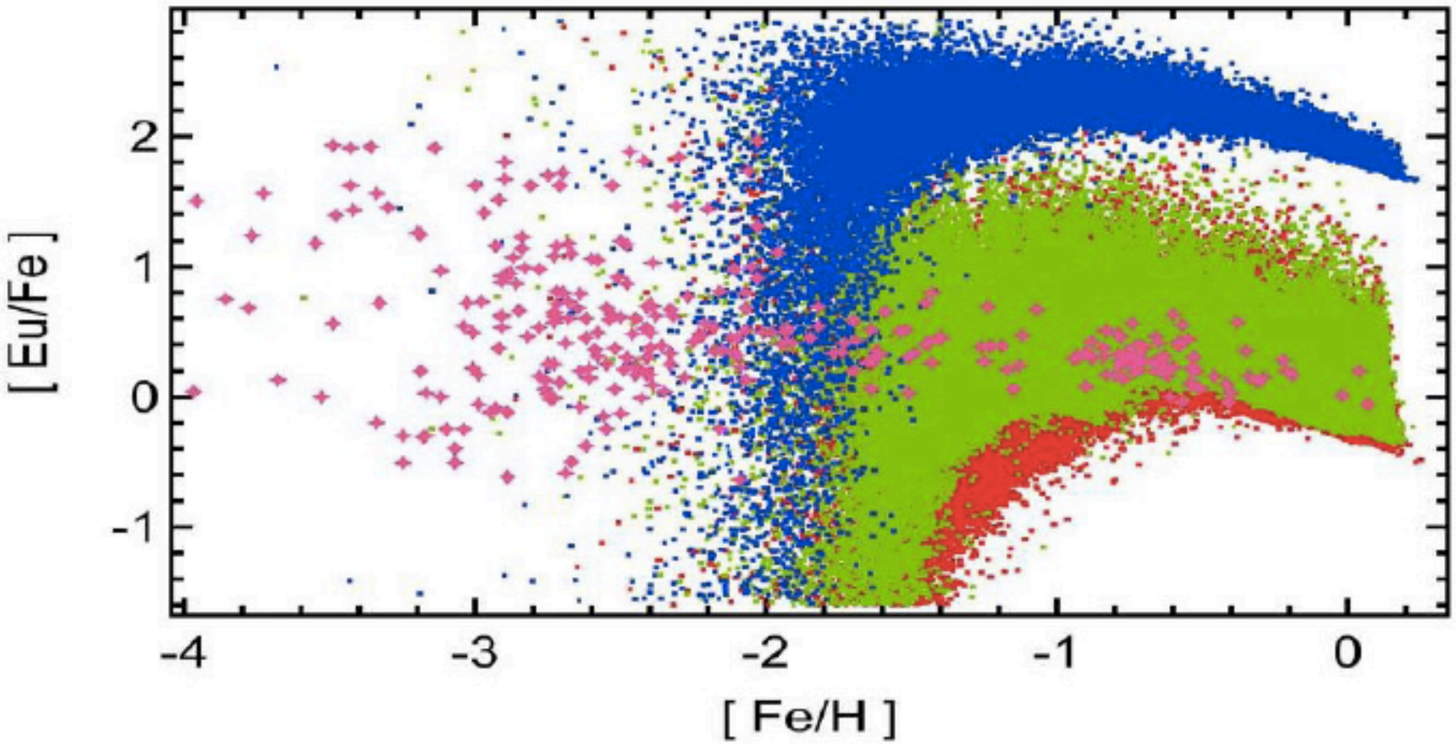
Eu from NS mergers, no contribution from CCSNe

Different time delays for neutron star mergers – with 5 x 10^{-6} solar masses of Eu/merger event



Cescutti, Romano, Matteucci, Chiappini & Hirschi 2015

When only utilizing neutron star mergers, *inhomogenous* chemical evolution models seem to set in at too high metallicities. This *might* be solved by different star formation rates in early galactic subsystems or early large scale mixing (utilizing 10^6 Msol SPH particles for galaxy modeling assumes automatically a mixing on such scales (van de Voort et al. 2015, Shen et al. 2015), while a 10^{51} Sedov blast wave would only mix with $5\ 10^4$ Msol ISM)



Update by Wehmeyer et al. (2015) (of Argast et al. 2004), green/red different merging time scales, blue higher merger rate (not a solution)

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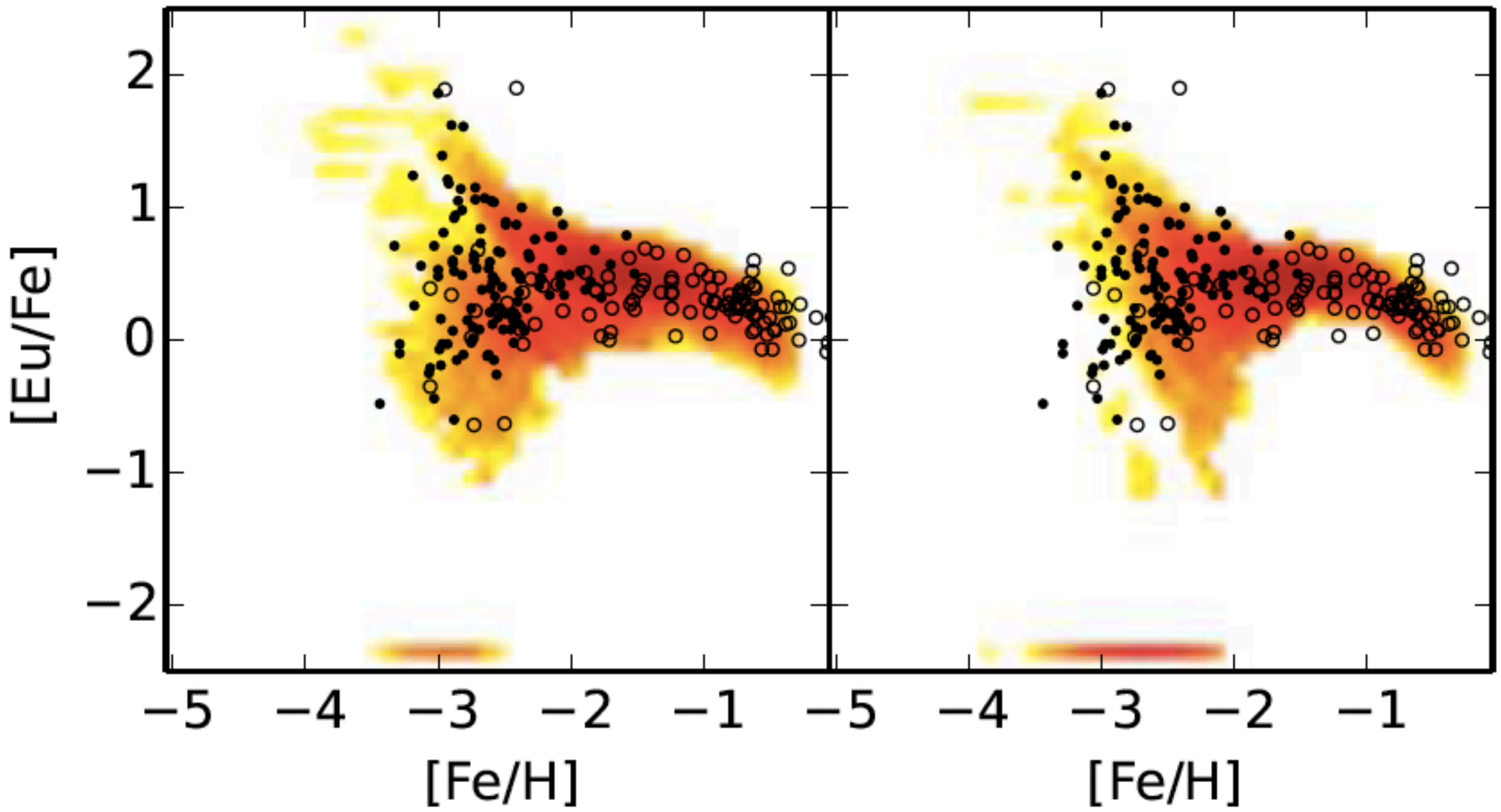
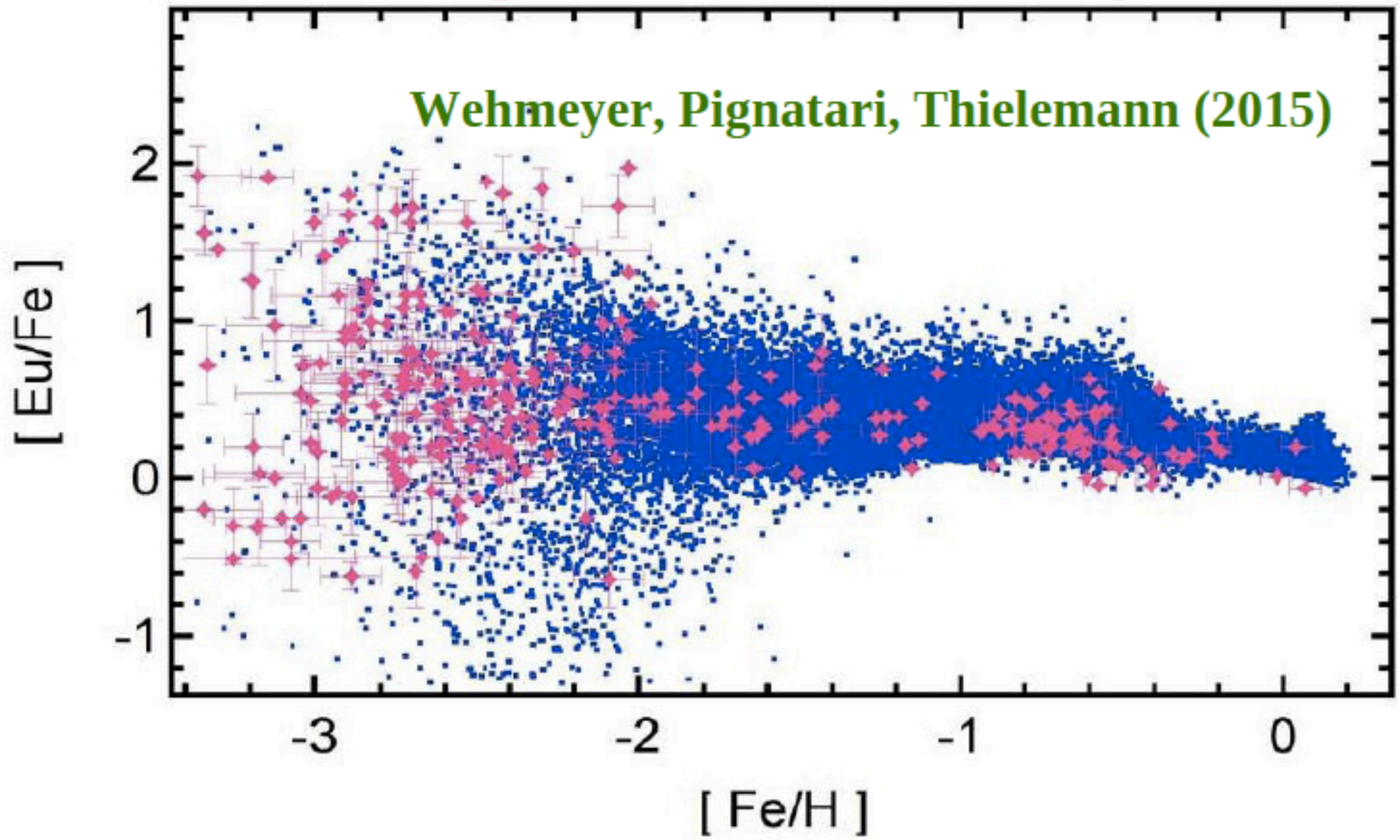
Eu from NS mergers + SNe



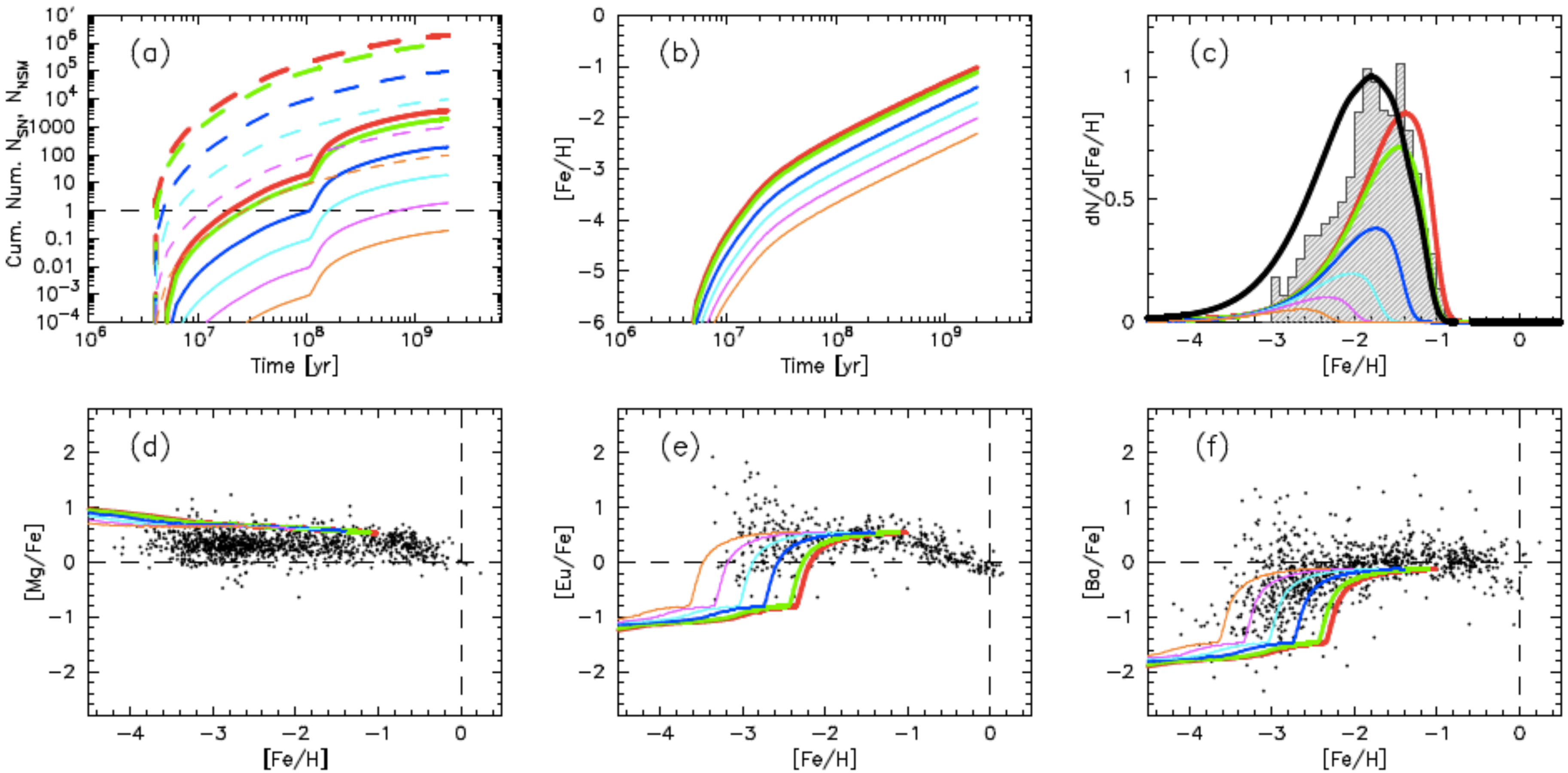
Cescutti, Romano, Matteucci, Chiappini & Hirschi 2015

Combination of NS mergers and magneto-rotational jets



=> in either case, the strong r-process which also produces the actinides is a rare event!!!!!!!!!!!!!

Alternative: Chemical evolution + scatter of different building blocks SFH



Ishimaru, Wanajo, Prantzos 2015

- Inhomogeneous GCE still needs to be improved. But not clear how?

- Large SPH machine take 10^6 Msol SPH star particles (which include then a whole IMF). Whenever an r-process event takes place in whatever environment inside this star particle, this treatment will automatically mix it with 10^6 Msol, while a Sedov blast wave would only mix with about 5 10^4 Msol. Such "artificial" mixing automatically moves convergence to lower metallicities, but it is not at all clear whether it is realistic (ex van de Voort et al, Shen et al.)

- For me the frontier is to have realistic simulations with really high resolution which also cover mixing processes correctly. Only when this is done correctly, we can understand the behavior at low metallicties correctly. This includes to cover star formation regions correctly as well as small scale mixing of individual event and large scale mixing of spiral arms or galactic fountains.

Friedel Thielemann

New Constraints -> Isotopic Ratios Mg, Ba, C…

Density of stars in heave elements plots (in the future)

One big question: biases of these samples…

Development expected around 2020…4MOST & WEAVE

Plans from other groups and general questions

CHEMICAL EVOLUTION OF HEAVY ELEMENTS

Travaglio C. + Bisterzo S. **(INAF-Astrophysical Observatory Turin)**

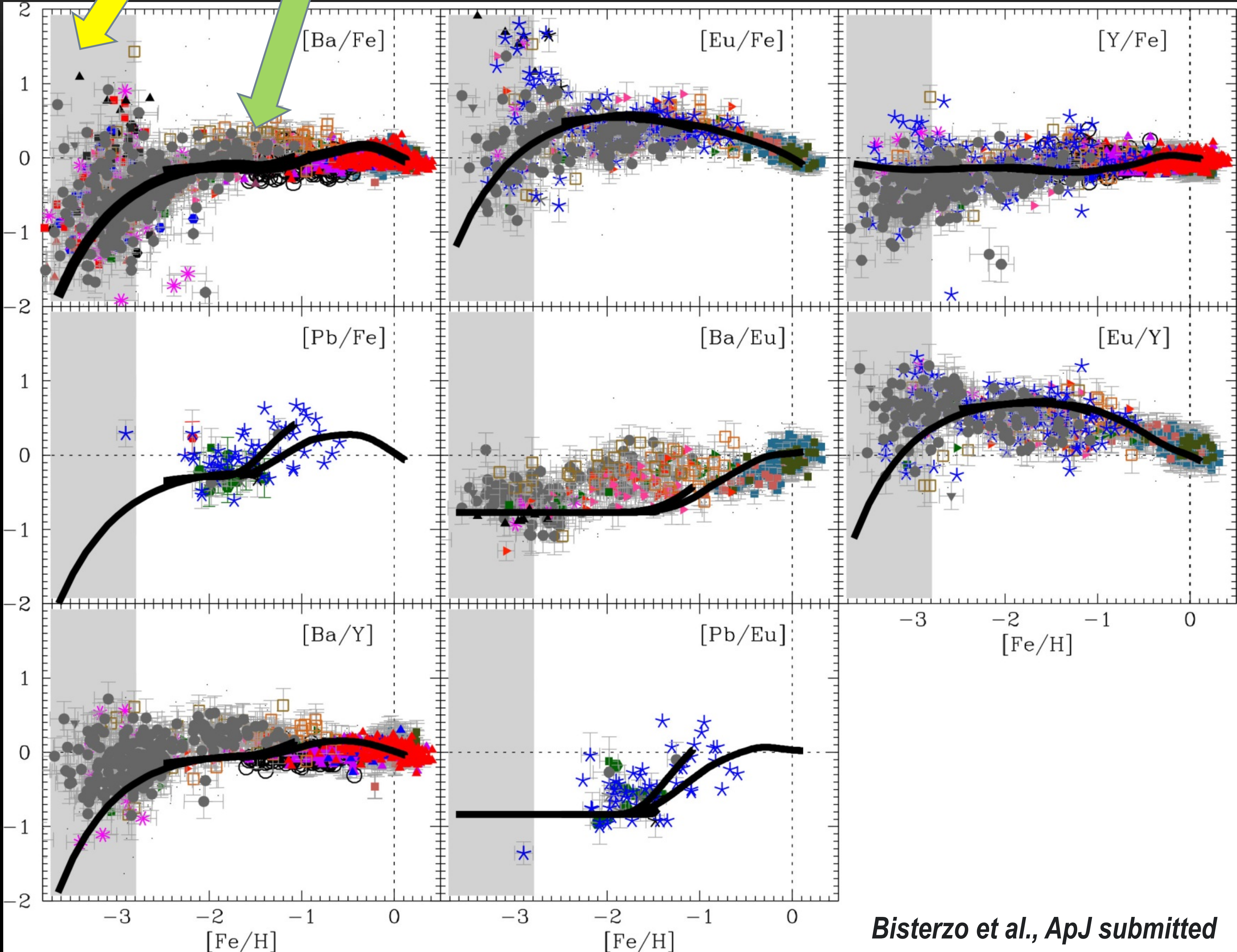
Collaborators: Côté, B. (+ Nugrid collaboration)

WORK in progress

- 1D chemical evolution model: update in progress (better treatment of thick and thin disk, better treatment of the role of binary systems)
- Improvement and investigation of the yields from massive stars/binary systems/mergers in the chemical enrichment of the Galaxy and dSph and consequences for the still mysterious **LEPP** (Light Element Primary Process)
- Chemo-dynamical analysis and interpretation of heavy elements in the early Galaxy (*starting project*)

Chemo-dynamical analysis (starting project)

Thick-think disk transition phase (analysis in progress)



Bisterzo et al., ApJ submitted

Thick-thin disk transition: with the new spectroscopic and kinematics data from the latest surveys (e.g. APOGEE, GAIA) and recent updates of stellar ages determination (e.g. KEPLER, CoRoT), we explore and constrain the Star Formation history in thick and thin disk of our Galaxy. We investigate the consequences for the chemical abundances of heavy elements at critical metallicities corresponding to this transition phase.

Testing yields from massive stars and binary systems: we are testing the effect of new heavy elements nucleosynthesis predictions from type II supernovae with rotation, a better refined grid of masses and metallicities (Côté et al., MNRAS submitted), multi-D effects on the yields. The role of super-AGB stars and electron capture SNe on light heavy-elements enrichment are also taken into account in the light of the newest models available.
The key answer is: which are the consequences for LEPP?
We are also investigating the interplay between mergers, sub-Chandrasekhar and standard Chandrasekhar Type Ia in chemical enrichment of specific heavy elements. *p*-process nucleosynthesis will provide fundamental constraints on the role of these sources in chemical enrichment of the Galaxy.

Recent and planned spectroscopic observations in dSph will provide very important constraints to these studies.

E.A. Milne Centre for Astrophysics University of Hull

http://www2.hull.ac.uk/science/milne-centre.aspx

Research areas:

Solar and stellar physics
Galaxy and Galaxy-Cluster physics
Cosmological and High-Energy Physics

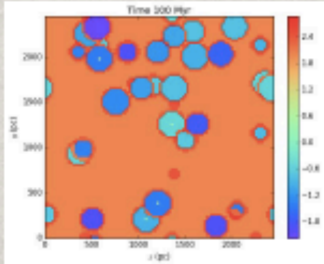
GCE & stellar nucleosynthesis:

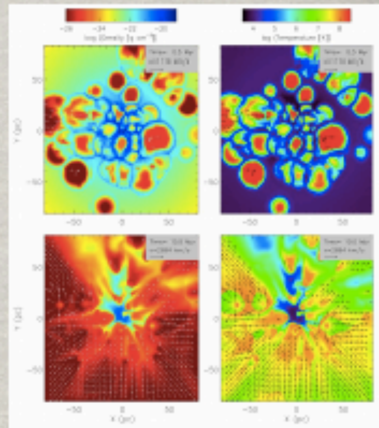
Brad Gibson
Marco Pignatari
Gareth Few
Chris Jordan

- Affiliated with:
  - BRIDGCE: a UK network for Bridging the disciplines related to Galactic Chemical Evolution
  - NuGrid: Nucleosynthesis Grid project

UNIVERSITY OF Hull

E.A. Milne Centre: Interests and Plans

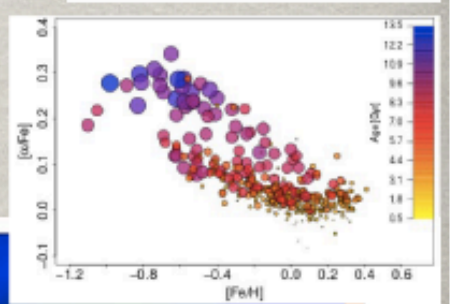




We study Galactic Chemical Evolution in a dynamical context, i.e. with gas mixing, hydrodynamics, galaxy formation and cosmological assembly.

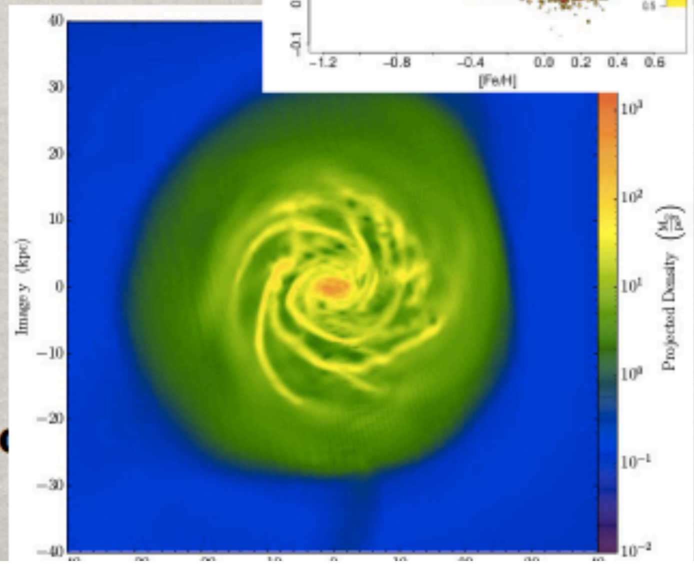
This is achieved via inhomogeneous models (semi-dynamical) on small scales, and with hydrodynamic/N-body simulations coupled with 'sub-grid' chemical evolution which combines:

- **Stellar population models**
- **Stellar evolution models**
- **Nucleosynthesis models**



Future Work

- **Stellar cluster abundance variations**
- **Globular cluster abundance anomalies (C,N,O,Na,Mg,Al)**
- **Spiral galaxy chemical evolution**
- **Thick disc/thin disc chemical decompositi**
- **Evolution of element gradients**
- **Galactic habitability**



E.A. Milne Centre: Interests and Plans

- We are equipped to track any isotope/species provided we have the *abundance in the ejecta of relevant stellar sources as a function of mass and initial composition*, e.g. SNII, SNIa, HN, AGB etc…

- We get these from nucleosynthesis models which themselves rely on updated reaction rates and modelling of stellar structure and explosive processes

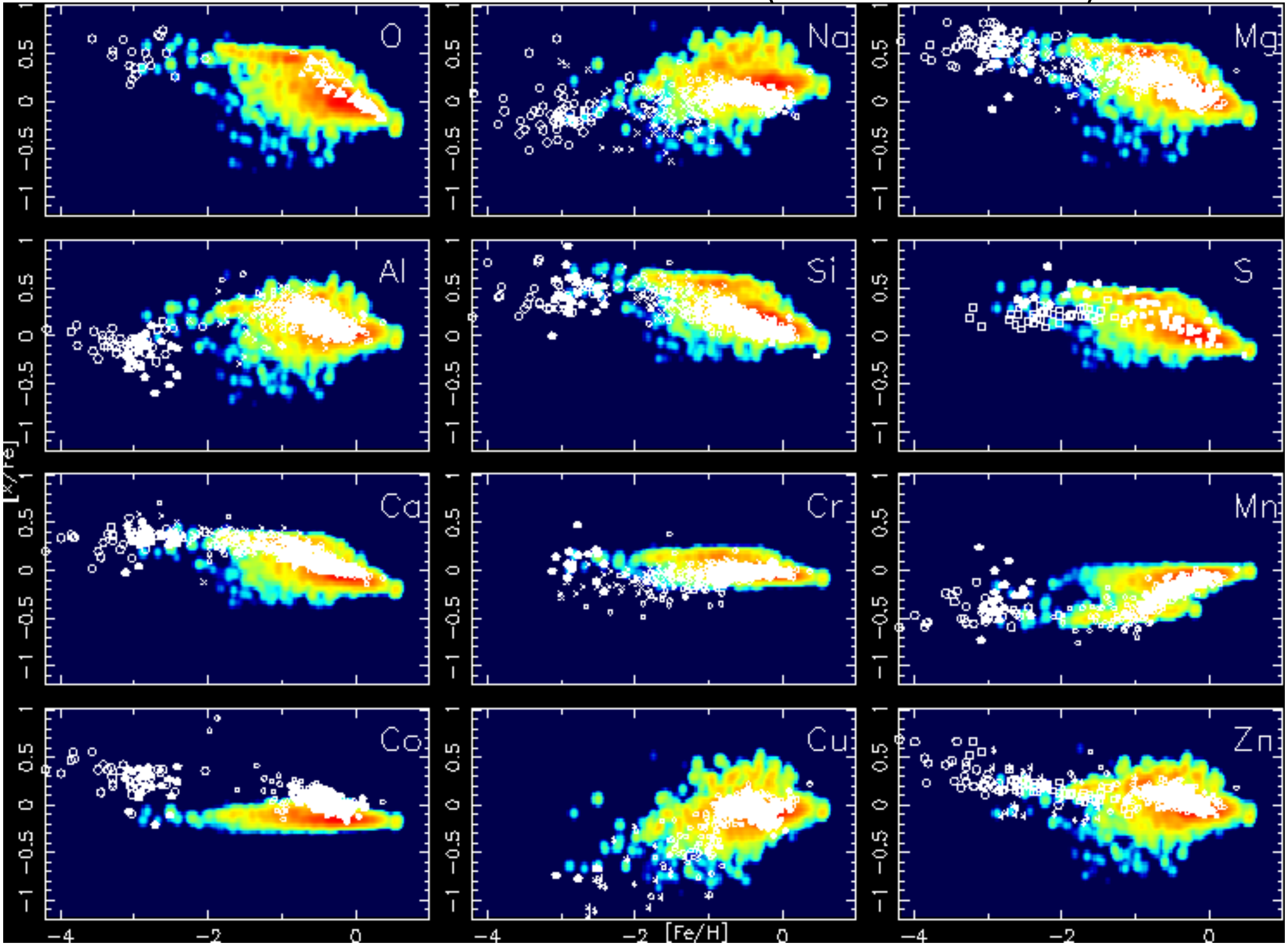
- Benefits from constraints on the errors propagated from nuclear reaction rates to stellar yields and then through to theoretical CE simulations

- Comprehensive use of observations from presolar grains and from stars to constrain stellar models and nuclear physics rates, thanks to the full control on GCE tools

E.A. Milne Centre: Future Work

- Re-design analytical GCE model to incorporate radioactivity for study of long-lived isotopes of U and Th in the galactic halo
- Create a flexible inhomogeneous GCE tool in collaboration with Basel (Wehemeyer, Thielemann)
- Study links between galactic and planetary chemical evolution and identify the mineralogical building blocks of earth-like planets - including high-res N-body simulations to characterise cometary impacts during close encounters and disk/spiral arm crossings
- Characterise the baryon cycle of metals in clusters vs field vs voids, including ram pressure stripping
- Efforts to analyse simulations more like observers by proxying stellar populations in post-processing

Elemental Abundances (CK & Nakasato 2011)

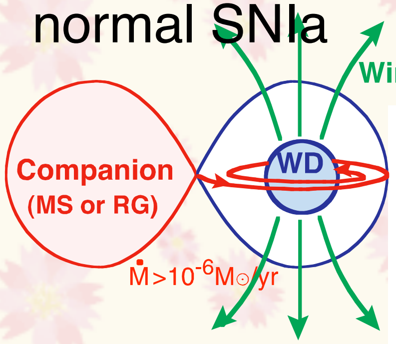


Current status

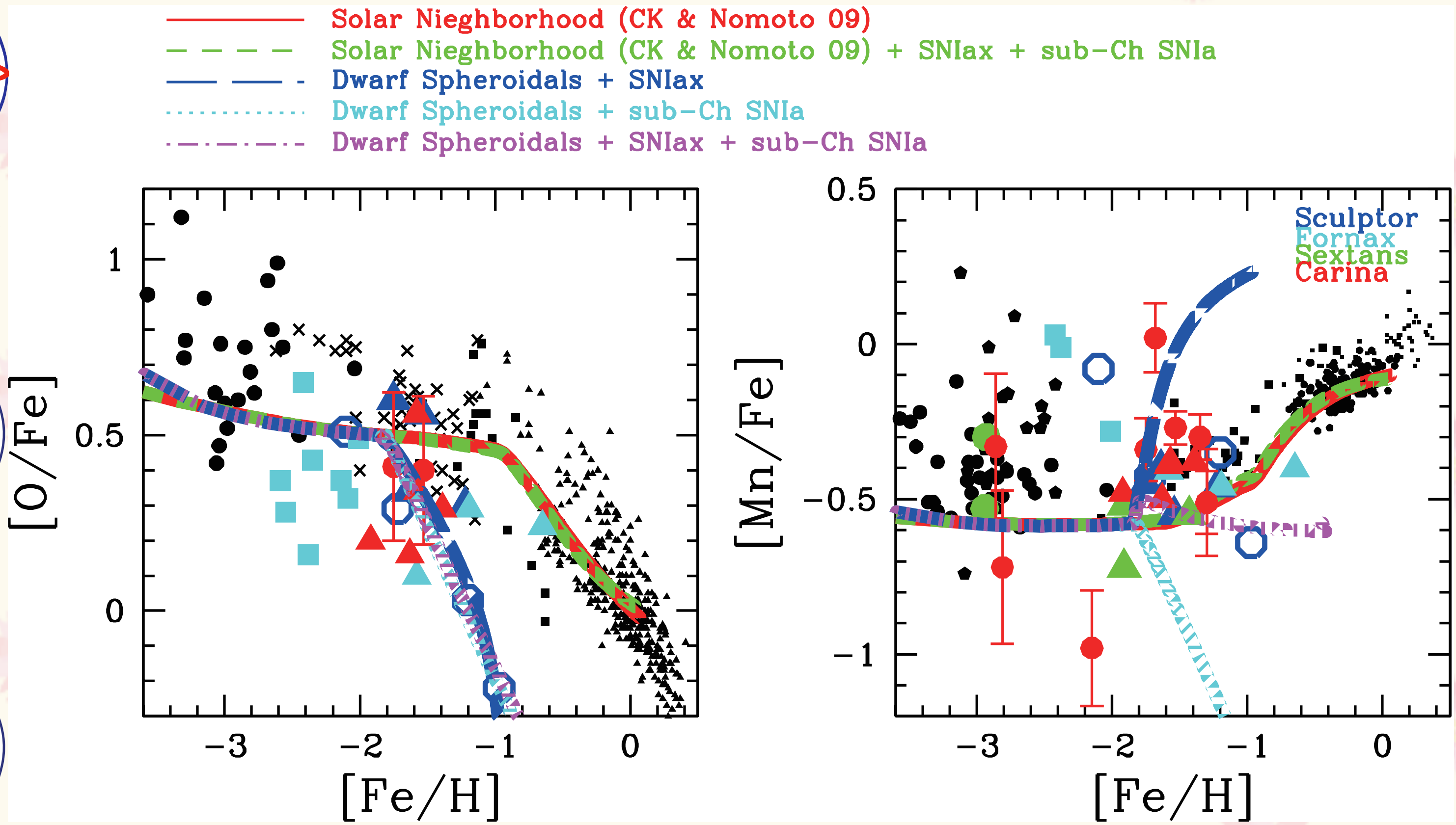
- We have basic understanding of the origin of elements from C to Zn.
  - Elemental abundance ratios and their scatter are well reproduced with chemodynamical simulations (CK & Nakasato 2011).
  - Comparing with GAIA-ESO survey etc., the physics of ISM (mixing) will be explored but it's not the matter of nuclear physics.
- The origin of elements > Zn is still a matter of nuclear physics.
  - Stochastic models (e.g., by Cescutti@Herts; Wehmeyer+) are useful to quickly check the inputs (i.e., yields and sites).
  - Chemodynamical simulations with n-capture elements will come (Haynes & CK@Herts).

Subclasses of SNIa in dSphs?

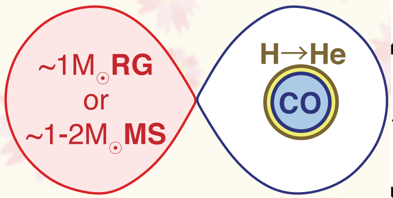
normal SNIa



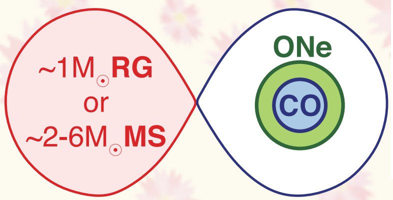
CK, Nomoto, Hachisu 2015, ApJL, 804, 24



sub-Ch SNIa



SN Iax



- In deflagrations, Mn is mostly synthesized in NSE, while in sub-Ch SNeIa, mostly in incomplete-Si burning, which depends on Z.
- A mix of sub-Ch SNIa & SNIax can reproduce [Mn/Fe]~ -0.5.

Goals/big questions/challenges

- What are the effects of multi-D SNcc explosions and stellar evolution? Do they solve the remaining problems such as Ti?
- What are the progenitors of SNe Ia? Do sub-Ch, SN Iax, super-Ch contribute to GCE? (CK, Nomoto, Hachisu 15)
- Are binaries important other than SNIa and NS mergers? Can we distinguish this effect from rotation?
- How can we use the chemical signatures to understand the formation of Milky Way, dSphs, and external galaxies?