Nuclear Astrophysics: An Chemical Evolution/End-User Perspective

Brad Gibson
Chair, Theoretical & Computational Astrophysics
Jeremiah Horrocks Institute
University of Central Lancashire

Figuring out what you might like to hear...

Figuring out what you might like to hear...

- AGB = SNe
  (Stephen
- models +
  data + m
  (Alex)
- isotopes
  (Karin)
- neutrons
- grains + r
  (Monica
- C > Fe > Li
  (Marco,
- uncertain
  (Christia
- Galactic C
  (Brad)

Outline

- warning: very little “classical” nuclear (astro)physics…
- Galactic Chemical Evolution… “application” end of nuclear astrophysics
    - what is it?
    - examples where GCE can (or has) guide nuclear end of things
    - cautionary note
- some recent (highly biased) work which has caught my attention
- the near-future (highly biased) nuclear astrophysics “landscape”

Building Blocks of Galactic Chemical Evolution

To put together a basic model for the chemical evolution of galaxies, one needs a few ingredients:

- **initial conditions**
  Big Bang Nucleosynthesis; Prompt Initial Enrichment
- **birthrate function**
  star formation rate; initial mass function
- **(stellar) nucleosynthesis**
  supernovae; stellar winds; binary stars
- **gas flows**
  infall; outflowing super-winds; radial flows

Galactic Chemical Evolution in One Slide

Semi-analytical Galactic Chemical Evolution codes boil down to a single 1st-order delay differential equation:

Evolution of element ‘i’

$$
\begin{aligned}
\frac{\mathrm{d}G_i(t)}{\mathrm{d}t} &= -\psi(t)X_i(t) \\
&+ \int_{M_L}^{M_{B_m}} \psi(t-\tau_m)Q_{\mathrm{mi}}(t-\tau_m)\phi(m)\mathrm{d}m \\
&+ A \int_{M_{B_m}}^{M_{B_M}} \phi(m)\left[\int_{\mu_{\mathrm{m}}}^{0.5} f(\mu)Q_{\mathrm{mi}}(t-\tau_{\mathrm{m}_2})\psi(t-\tau_{\mathrm{m}_2})\mathrm{d}\mu\right]\mathrm{d}m \\
&+ (1-A) \int_{\mathrm{M}_{\mathrm{B_m}}}^{M_{\mathrm{B_M}}} \psi(t-\tau_m)Q_{\mathrm{mi}}(t-\tau_m)\phi(m)\mathrm{d}m \\
&+ \int_{\mathrm{M}_{\mathrm{B_M}}}^{M_U} \psi(t-\tau_m)Q_{\mathrm{mi}}(t-\tau_m)\phi(m)\mathrm{d}m \\
&+ \left(\frac{\mathrm{d}G_i(t)}{\mathrm{d}t}\right)_{\mathrm{infall}} - W(t)X_i(t) + \left(\frac{\mathrm{d}G_i(t)}{\mathrm{d}t}\right)_{\mathrm{acc}}, \qquad (1)
\end{aligned}
$$

Depletion due to star formation

Low mass single stars

SNe Ia

Intermediate mass single stars

SNe II

Early Infall

Outflow

Secondary Accretion

GCE hinges on one thing: the metal ejection rate (i.e., how many stars of a given mass are dying at time 't')

i.e., you need to know the relative distribution of stellar masses in a stellar generation (the IMF $\varphi(m)$), the star formation rate at the time at which the stars of mass 'm' dying today were born ($\psi(t - \tau_m)$). The key new ingredient here is the mass of metals (or a single element or isotope) ejected from a star of mass m and metallicity Z:

$$\int_{m^1}^{m_{\rm Bm}} \frac{\phi(m)}{m}\psi(t-\tau_m)\, m^{\rm ej}_{Z,m}\, dm$$

The predicted values of $m^{ej}_{Z,m}$ - or the **stellar yield** - depend upon the physics of stellar evolution, and are fundamental to any chemical evolution analysis.

Stellar Nucleosynthesis Sites

Type II Supernovae

α-elements (O,Ne,Mg,Si,S,Ca);

some Fe; s-process (A<90);

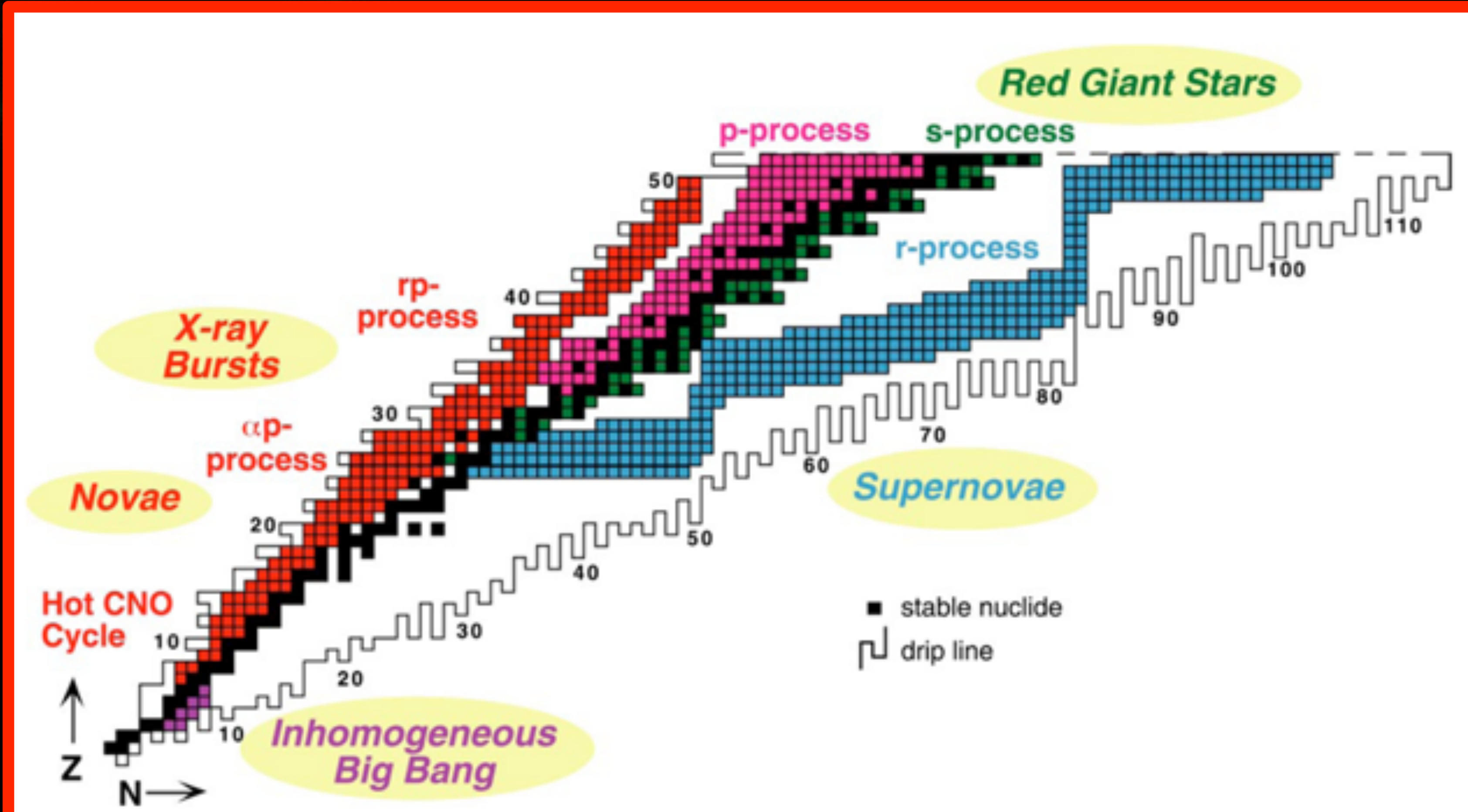
r-process

Type Ia Supernovae

Fe-peak elements

Low- and Intermediate-Mass Stars

^{4}He,C,N,s-process (A>90)



Type II Supernovae Yields

There are a number of excellent stellar yield compilations available, each which approach the physics of stellar evolution in their own unique manner - these compilations include those of Arnett (1996: A96), Langer & Hankel (1995: LH95), Maeder (1992: M92), Tsujimoto et al. (1995: T95), and Woosley & Weaver (1995: W95).

Mass loss? — Reaction Rate — Unprocessed ejecta included? — Explosive nucleosynthesis included?

Yield Source	$\dot{M}$(?)	Convection	$^{12}C(\alpha,\gamma)^{16}O$	Z	m^{unp}(?)	exp nuc(?)	init state
T95	N	Sch	C85	$Z_\odot$	N	Y	He
M92	Y	Sch+over	C85	$Z_\odot/20$	N	N	ZAMS
W95	N	Led+semi	0.74×C85	$Z_\odot/10$	Y	Y	ZAMS
A96	N	ad+chem hom+semi hom	0.74×C85	$Z_\odot$	Y	N	ZAMS
LH95	Y	~Led+semi	0.74×C85	$Z_\odot/10$	Y	N	ZAMS

Type II Supernovae Yields

The different input physics manifests itself in different predictions for the nucleosynthetic yields. Shown below are the IMF-weighted yield predictions for various elements y.

Some elements appear more robust to the subtleties of the input physics (e.g. Si, S), while others can vary by factors of two-to-three between the compilations (e.g. Fe, O, Mg, Ne).

Type II SNe Yields

Yield Source	$< y_{Fe,SNII} >$	$< y_{O,SNII} >$	$< y_{Si,SNII} >$	$< y_{Mg,SNII} >$	$< y_{Ne,SNII} >$	$< y_{S,SNII} >$
A96	0.071	0.593	n/a	0.054	0.101	n/a
T95	0.121	1.777	0.133	0.118	0.232	0.040
T95+M92	0.121	0.923	n/a	n/a	n/a	n/a
W95;A;$10^{-4}Z_\odot$	0.073	0.806	0.104	0.036	0.095	0.059
W95;B;$10^{-4}Z_\odot$	0.085	1.455	0.118	0.066	0.223	0.065
W95;A;$Z_\odot$	0.113	1.217	0.124	0.065	0.181	0.058
W95;B;$Z_\odot$	0.141	1.664	0.143	0.094	0.265	0.064
Yield Source	$< y_{Fe,SNIa} >$	$< y_{O,SNIa} >$	$< y_{Si,SNIa} >$	$< y_{Mg,SNIa} >$	$< y_{Ne,SNIa} >$	$< y_{S,SNIa} >$
TNH93	0.744	0.148	0.158	0.009	0.005	0.086

Type Ia SNe Yields

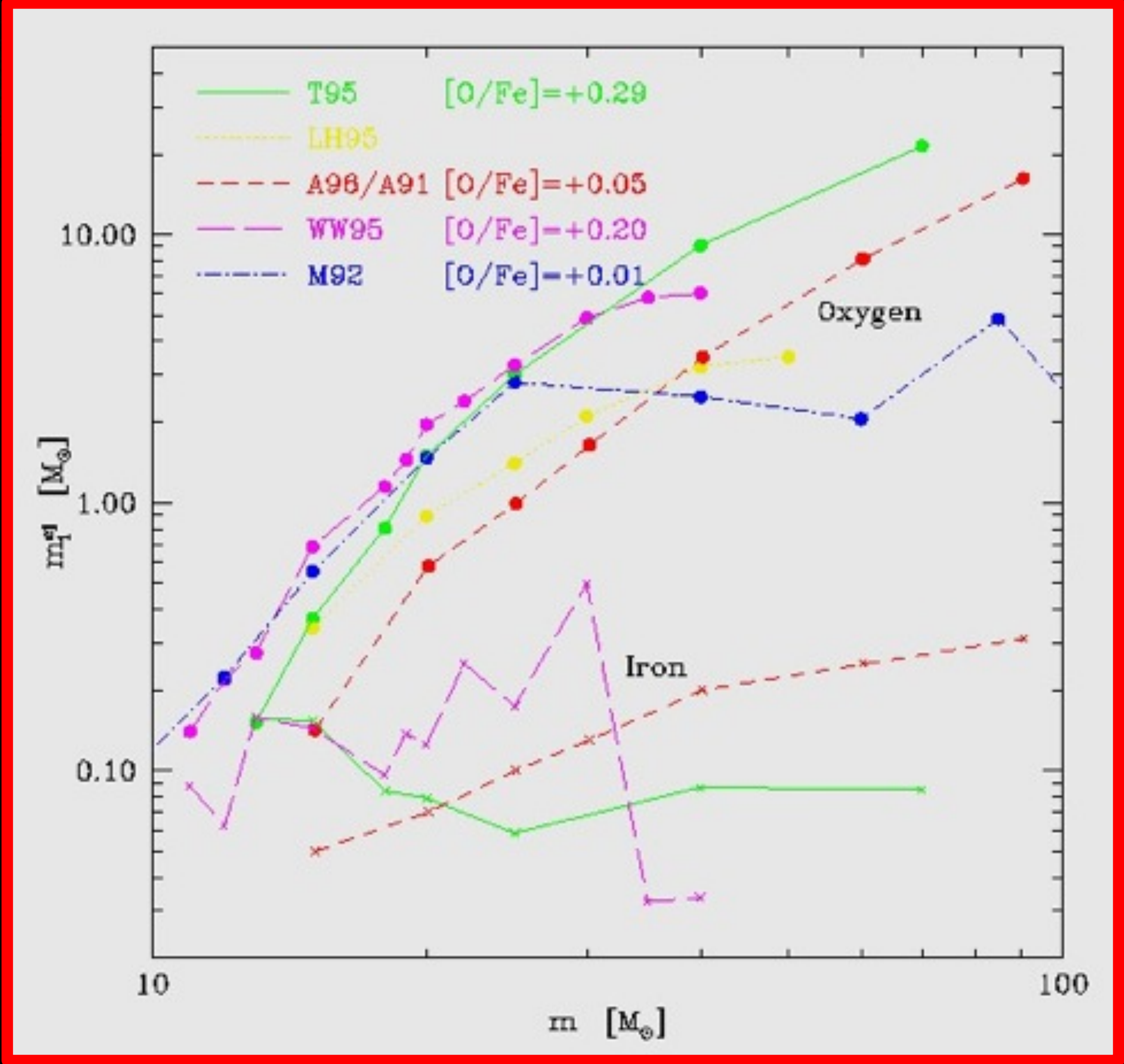
Type II Supernovae Yields

Gibson (2002)

Elements which are produced primarily via hydrostatic burning in the outer layers (e.g. oxygen) show an increasing trend with increasing mass.

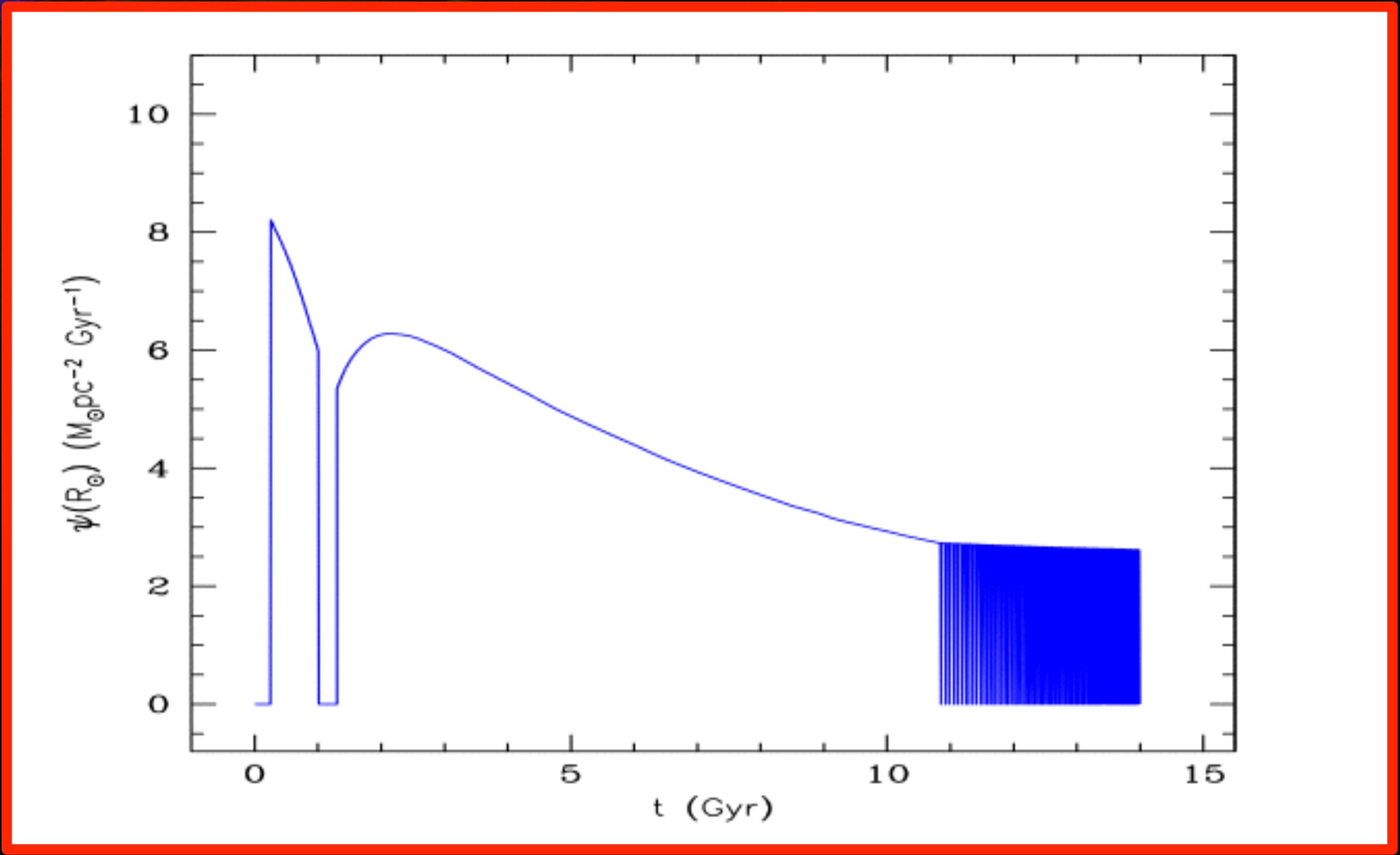
Conversely, elements produced primarily via explosive nucleosynthesis in the core and inner layers (e.g. iron), are less dependent upon the stellar mass m.

These trends hold regardless of yield compilation.



GCE Boundary Conditions

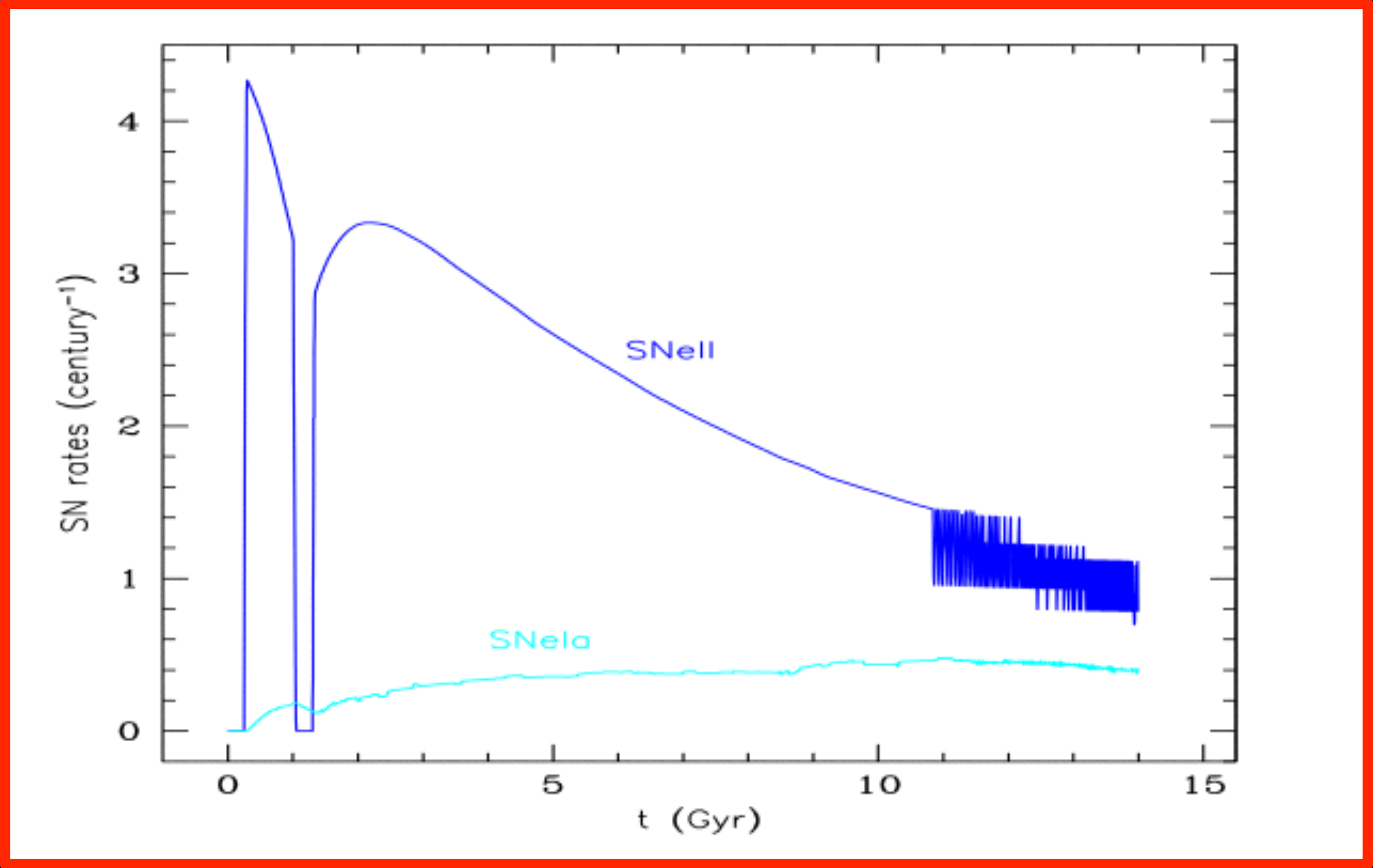
Star formation rate in the solar neighbourhood:



Oscillatory behaviour at late times (and the gap which exists between the halo and disk phases) due to the imposition of a star formation threshold

GCE Boundary Conditions

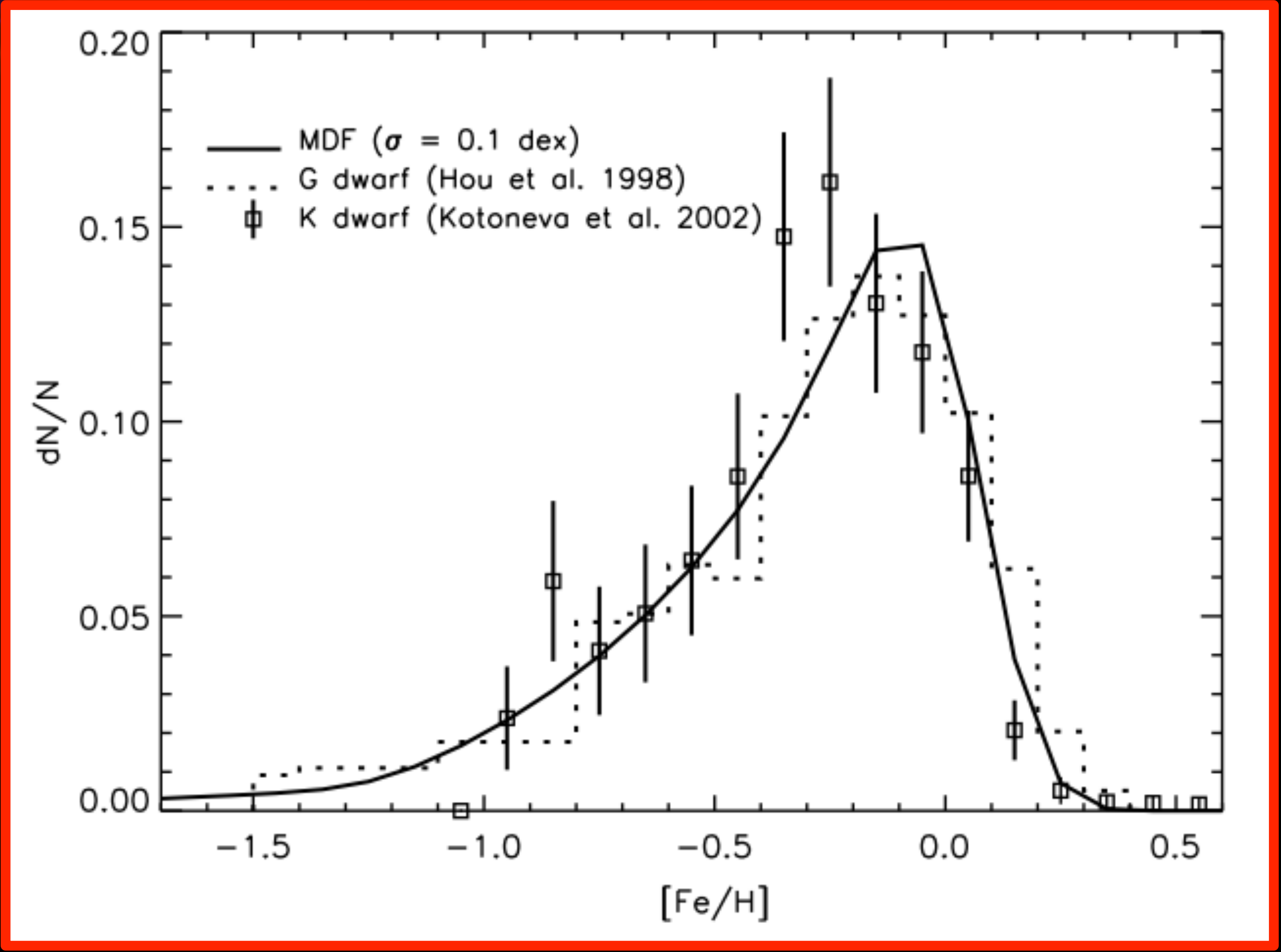
Supernovae rates in the solar neighbourhood:



GCE Boundary Conditions

Fenner et al. (2003)

Metallicity Distribution Function in the solar neighbourhood:

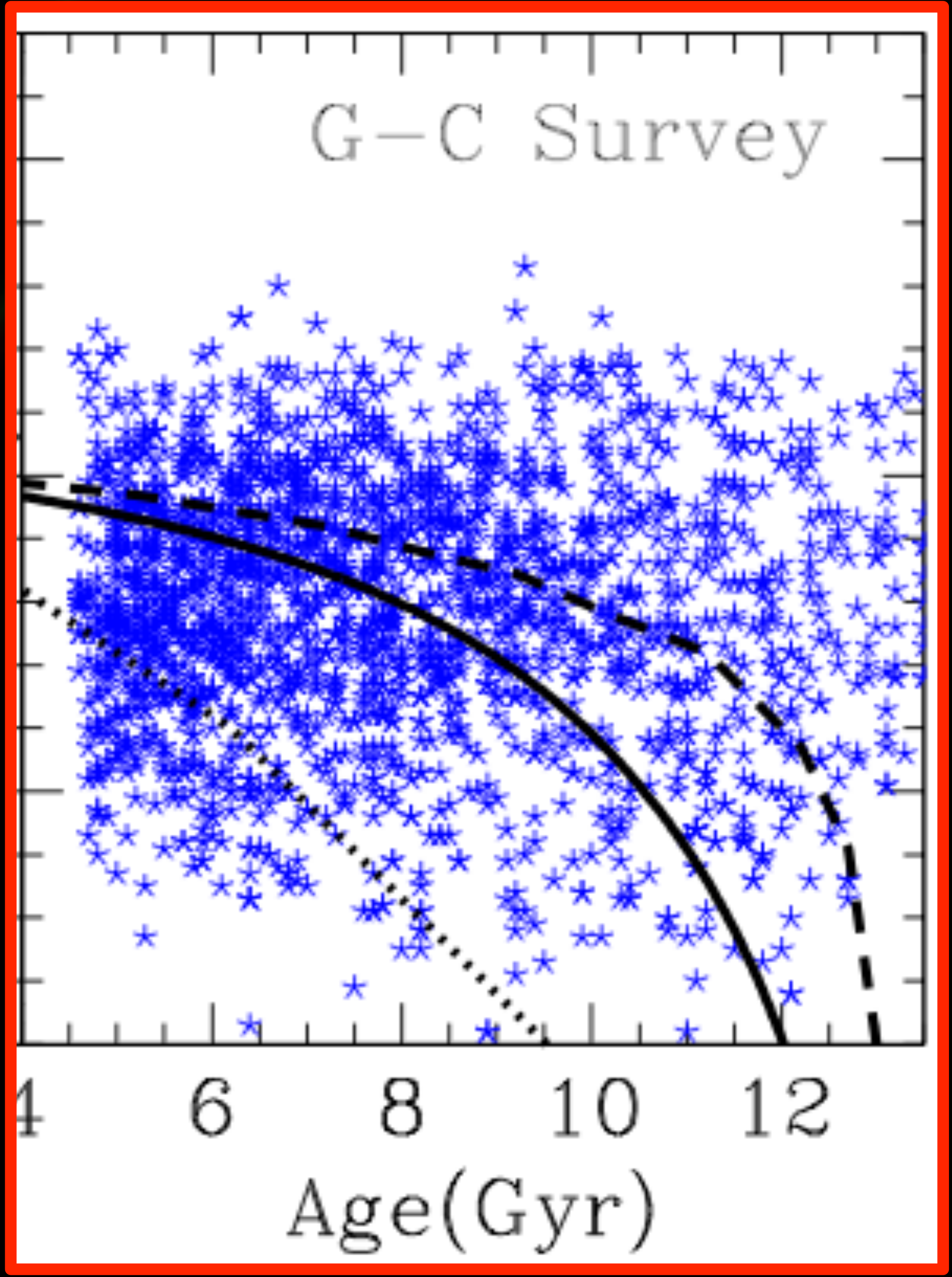


GCE Boundary Conditions

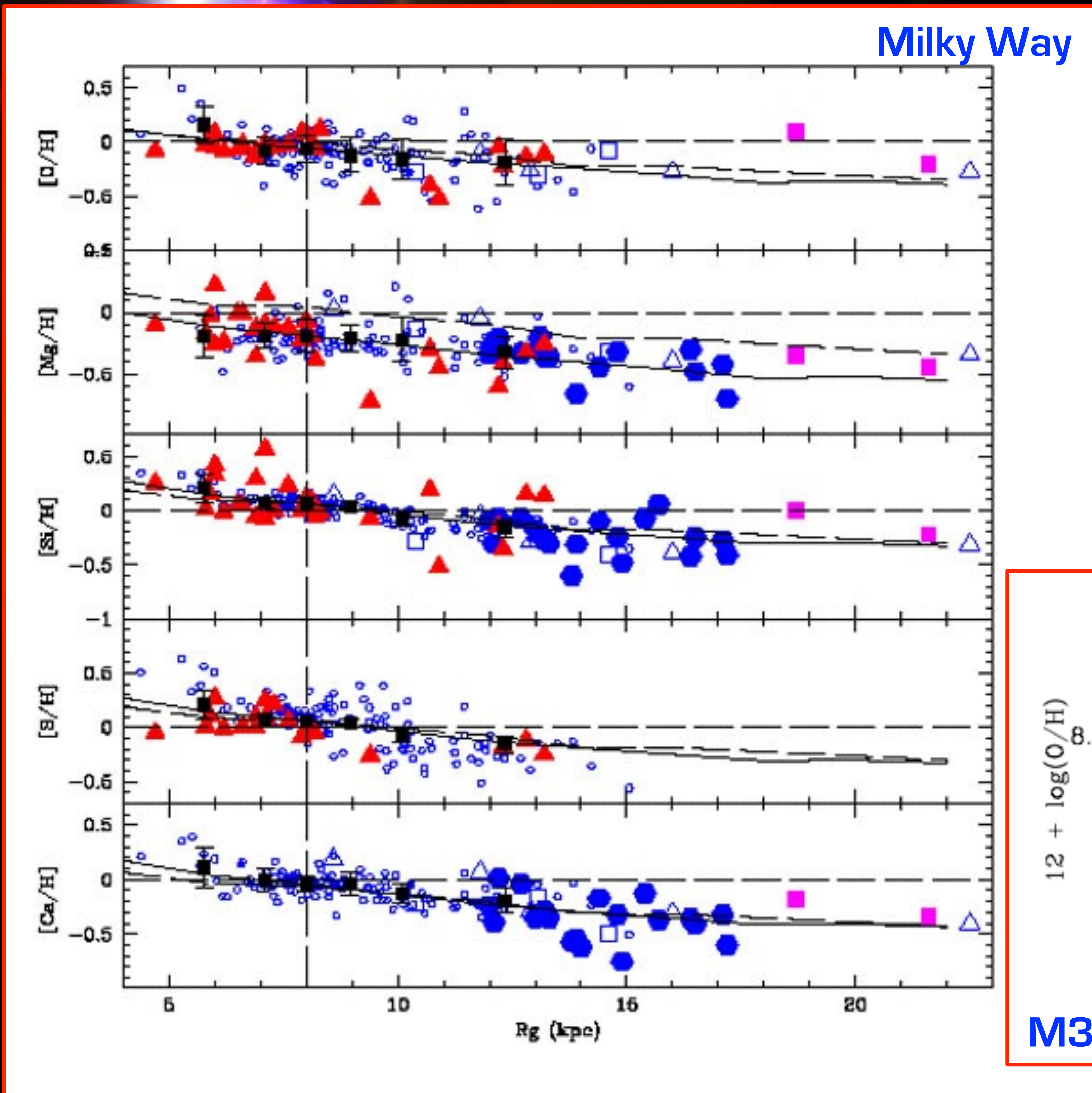
Lugaro et al. (2013)

Age-Metallicity Relation
for the Solar Neighbourhood

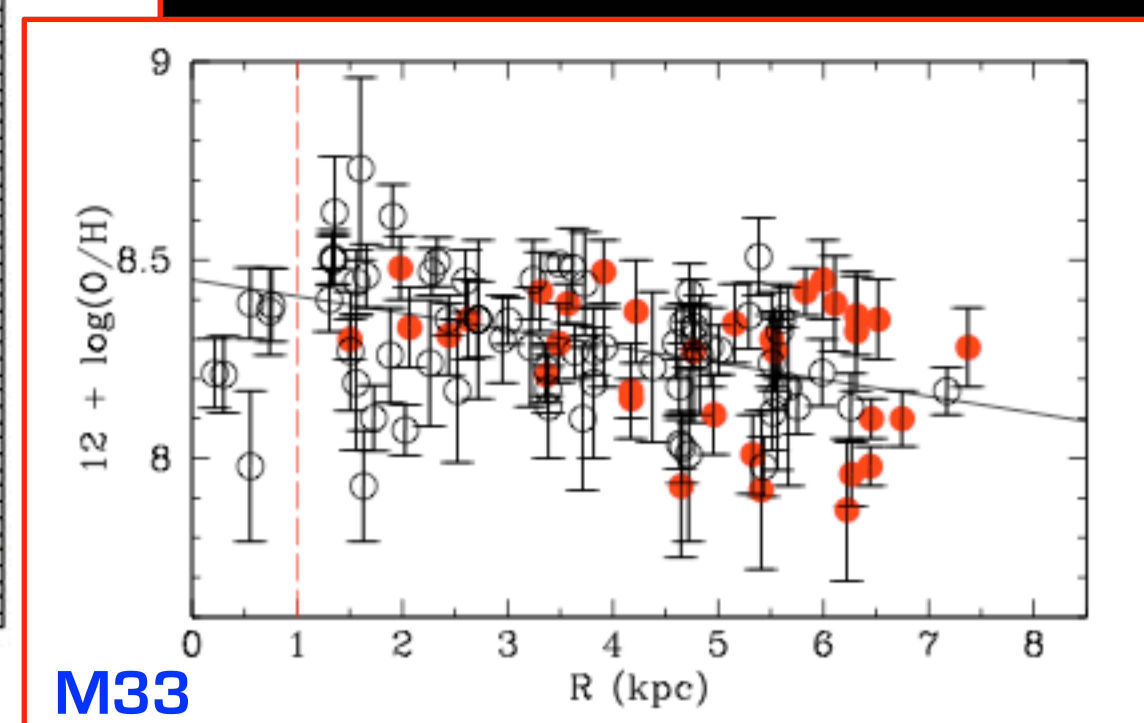
[Fe/H]



GCE Boundary Conditions

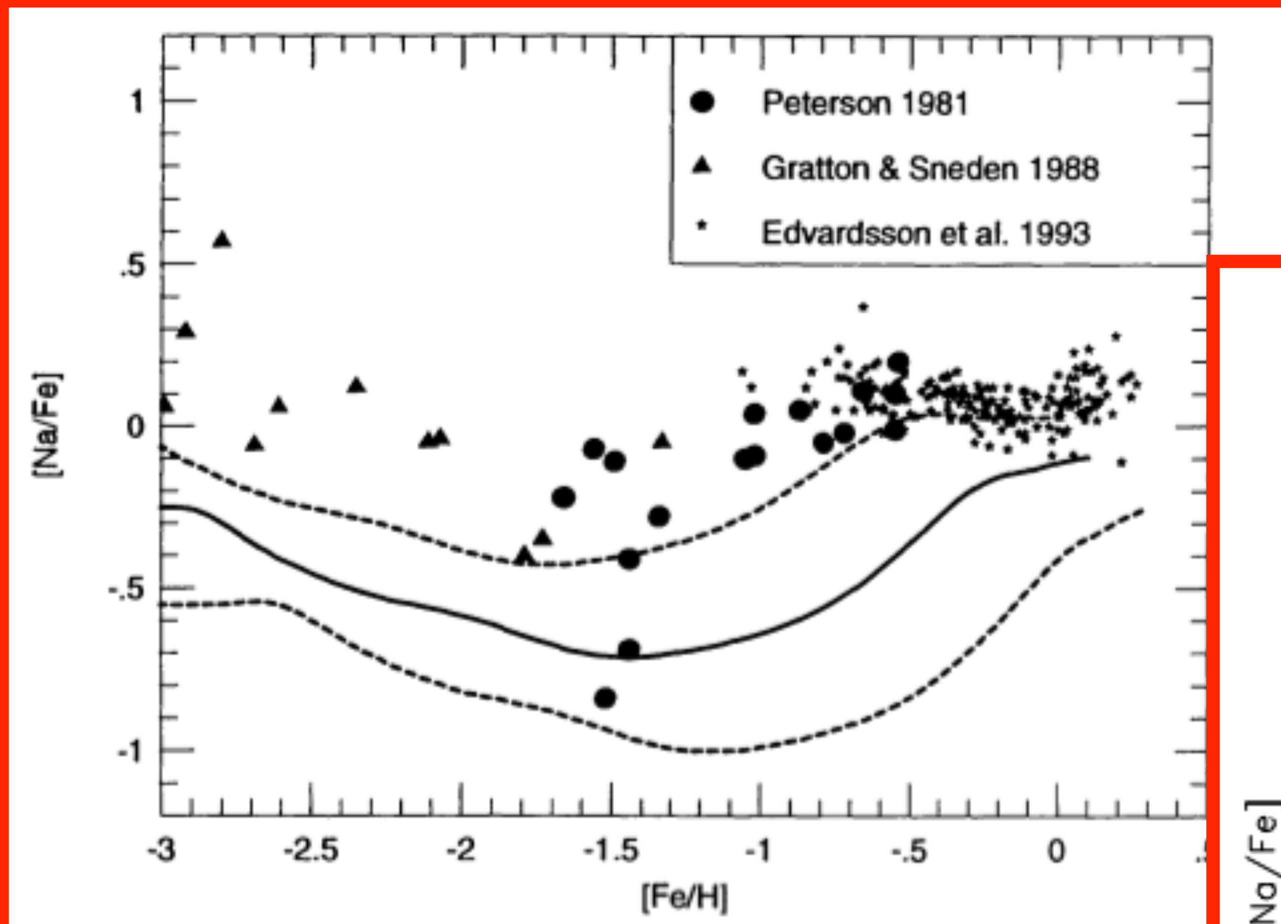


Disk galaxies have abundance gradients of about –0.05 dex/kpc, today.



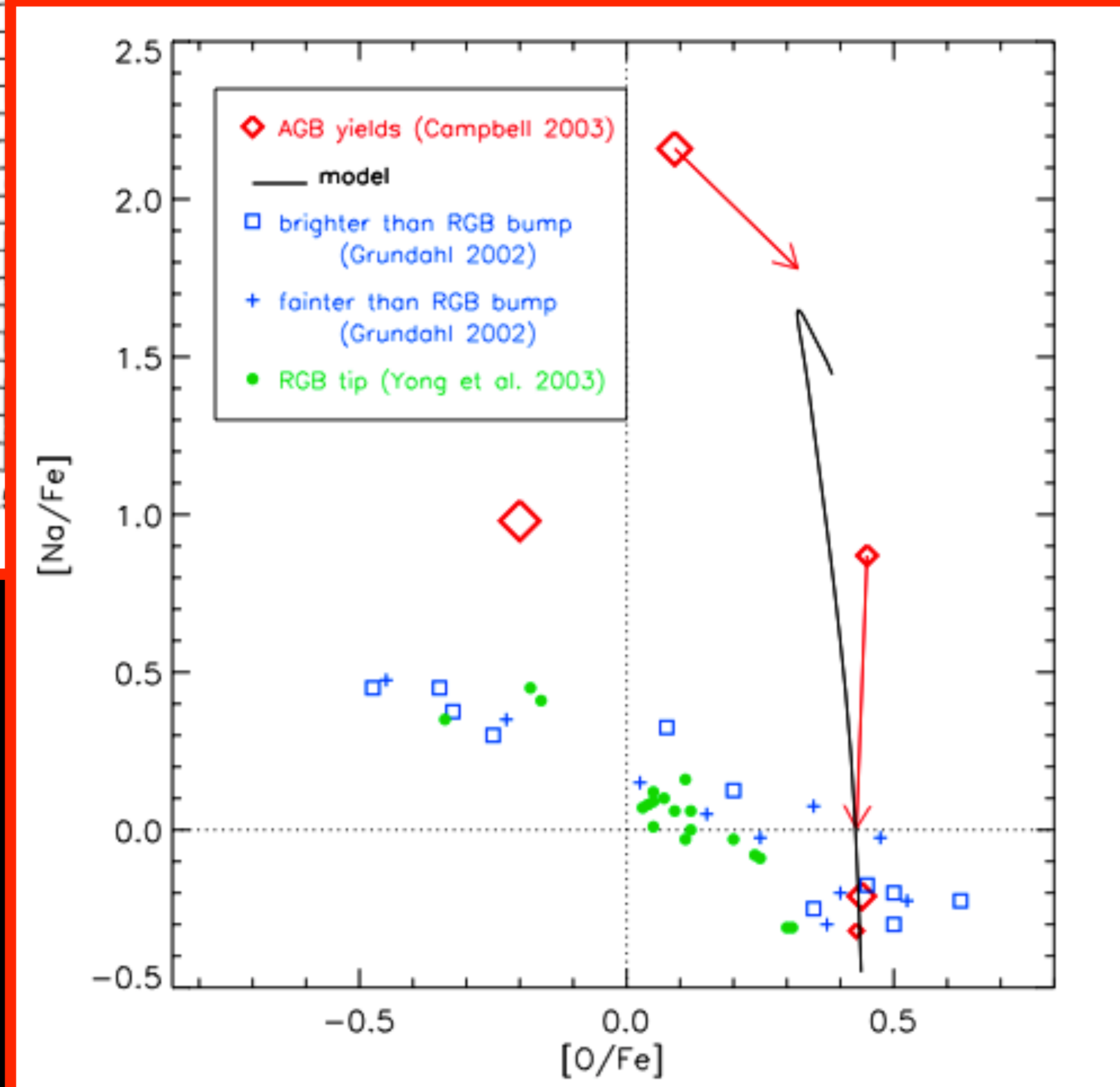
GCE Boundary Conditions

Sodium: GCE Identifies
Reaction Rate Problem



Timmes et al. (1995)
SNeII: WW95 (Na low!)
AGB: n/a

Fenner et al. (2004)
AGB rates too high!

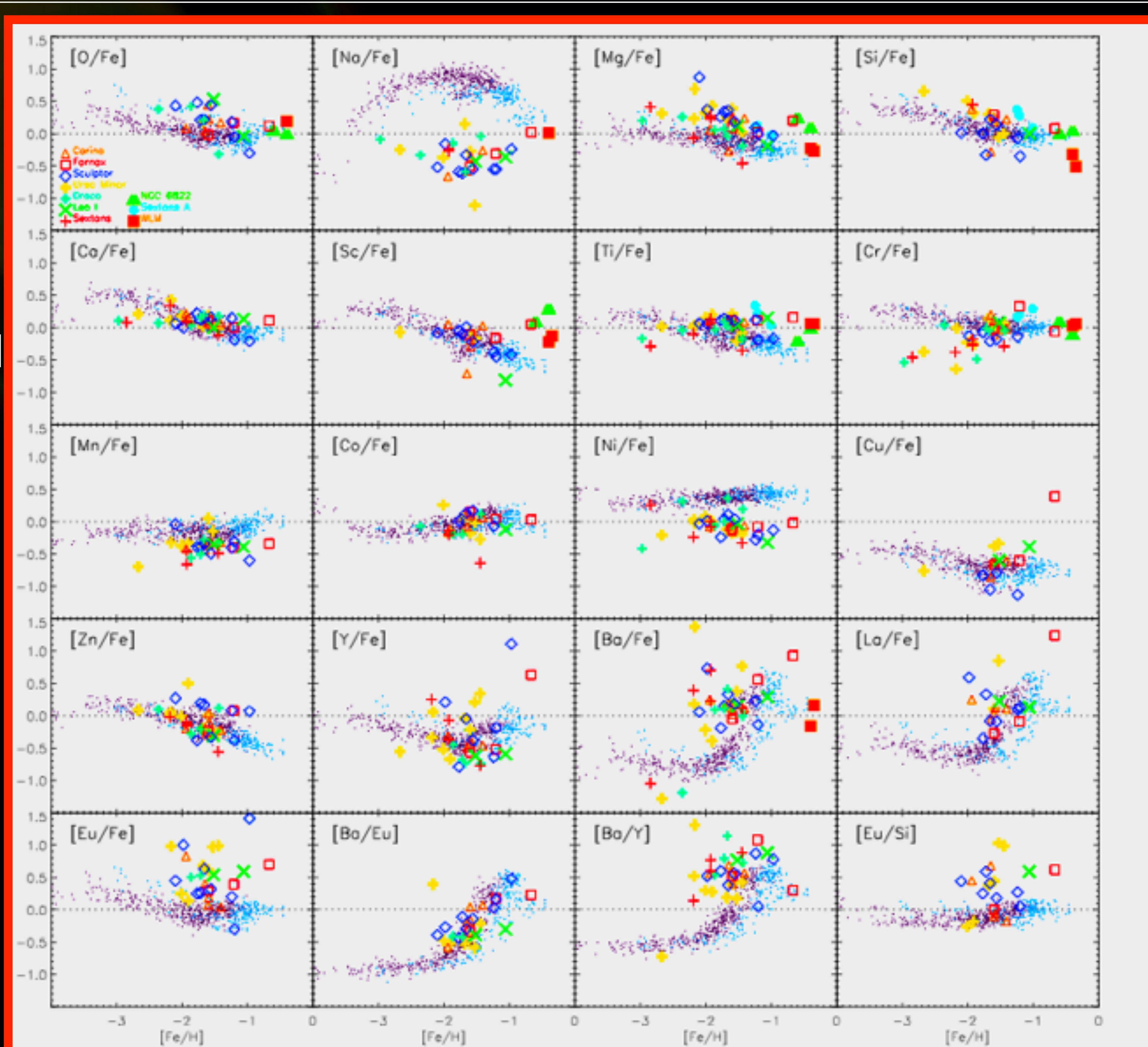


GCE Boundary Conditions

Gibson (2007)

Elemental Abundance for Local Group Dwarf Galaxies

- SNe (WW95) + AGB + (rough!) neutron capture
- Na reaction rate employed in AGB models too high
- Ti ok, but isotopes? (shortly)
- Sc ok
- s- and r-process too low
- Ni high; Cr off @ low-Z

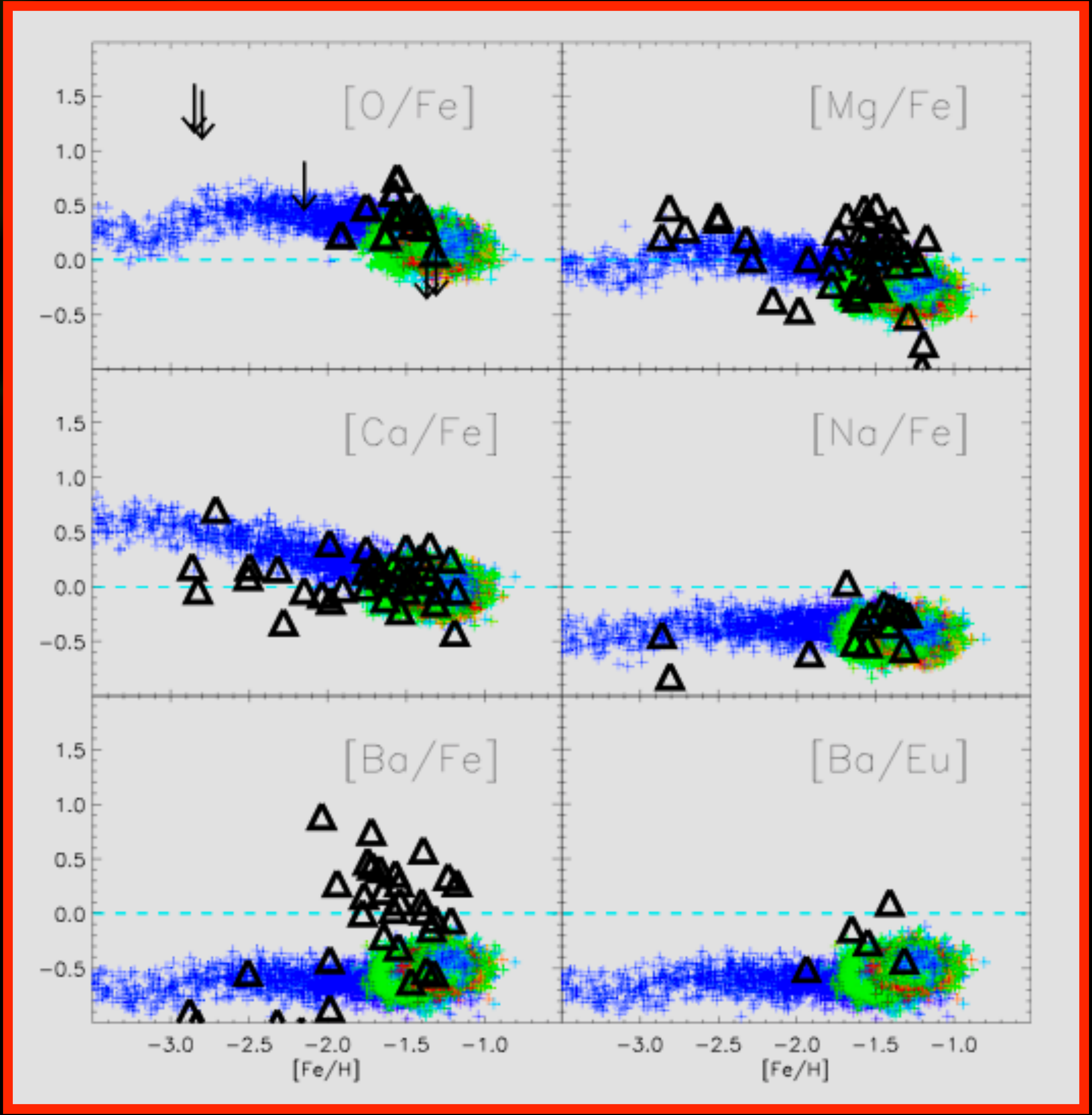


GCE Boundary Conditions

Pilkington & Gibson (2012)

Elemental Abundances for Carina Dwarf Spheroidal

- SNe + AGB, incl. neutron capture
- revised Na reaction rate implemented and all good now
- s- and r-process still too low

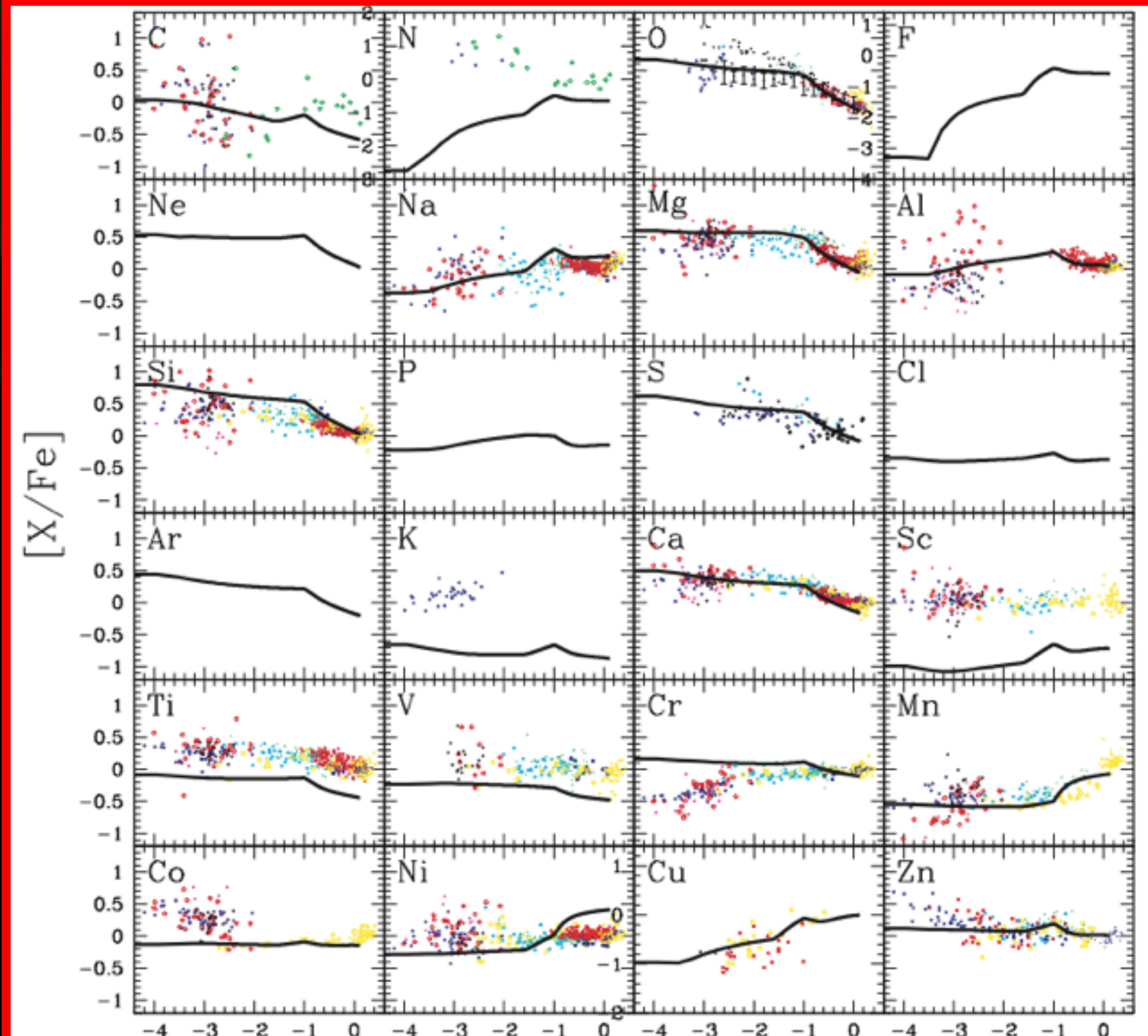


GCE Boundary Conditions

Kobayashi et al. (2006)

Elemental Abundance Ratios in the Solar Neighbourhood

- SNe yields only
- problems for C, N, K, and iron peak
- missing AGB, mixing/ fallback processes, explosion energy, e^- excess?
- Sc "fixed" upwards by 10x with ν-processes (V,Mn??)
- Ti off
- Na high, even w/out AGB
- Ni?

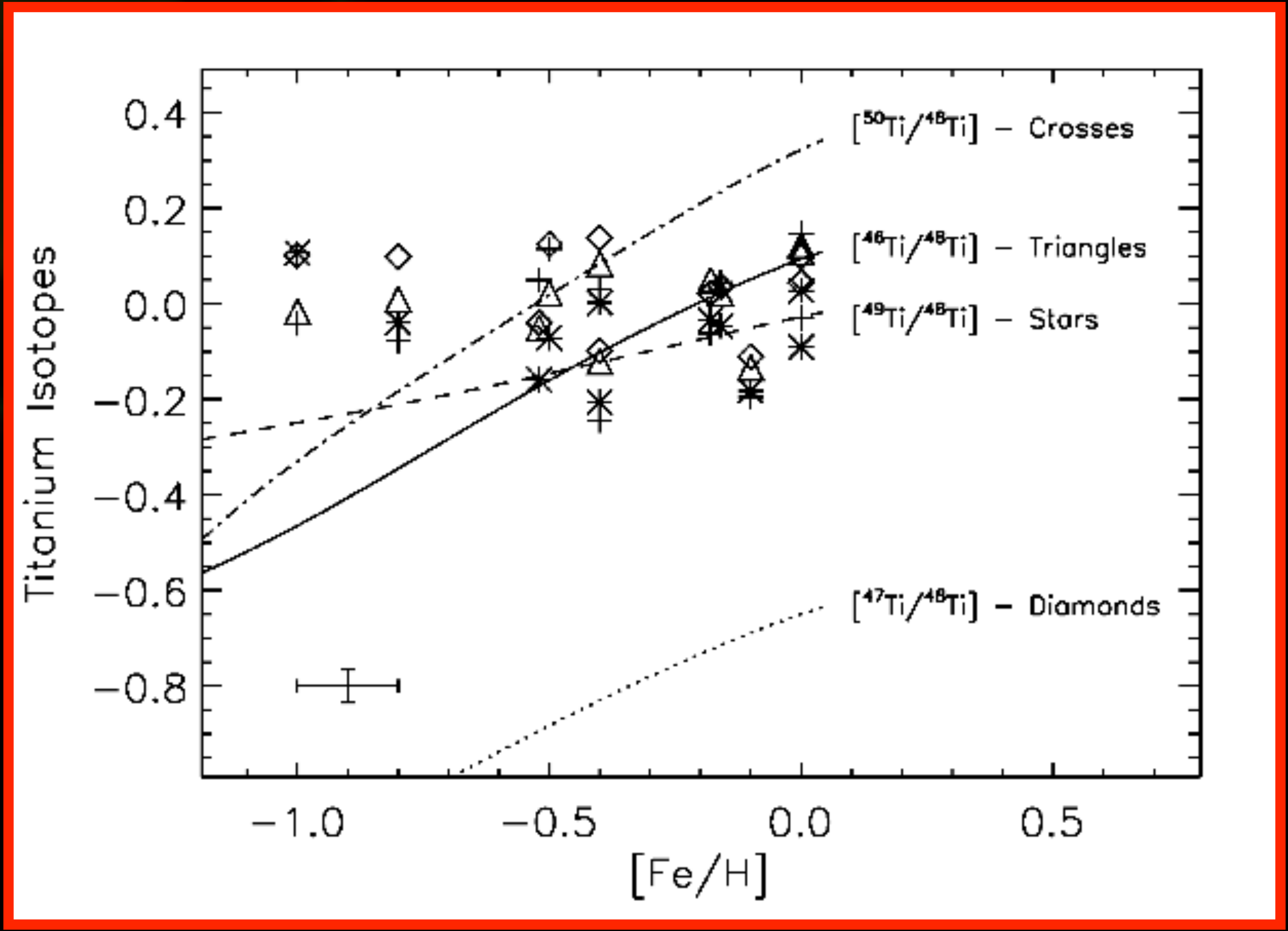


GCE Boundary Conditions

Hughes et al. (2008)

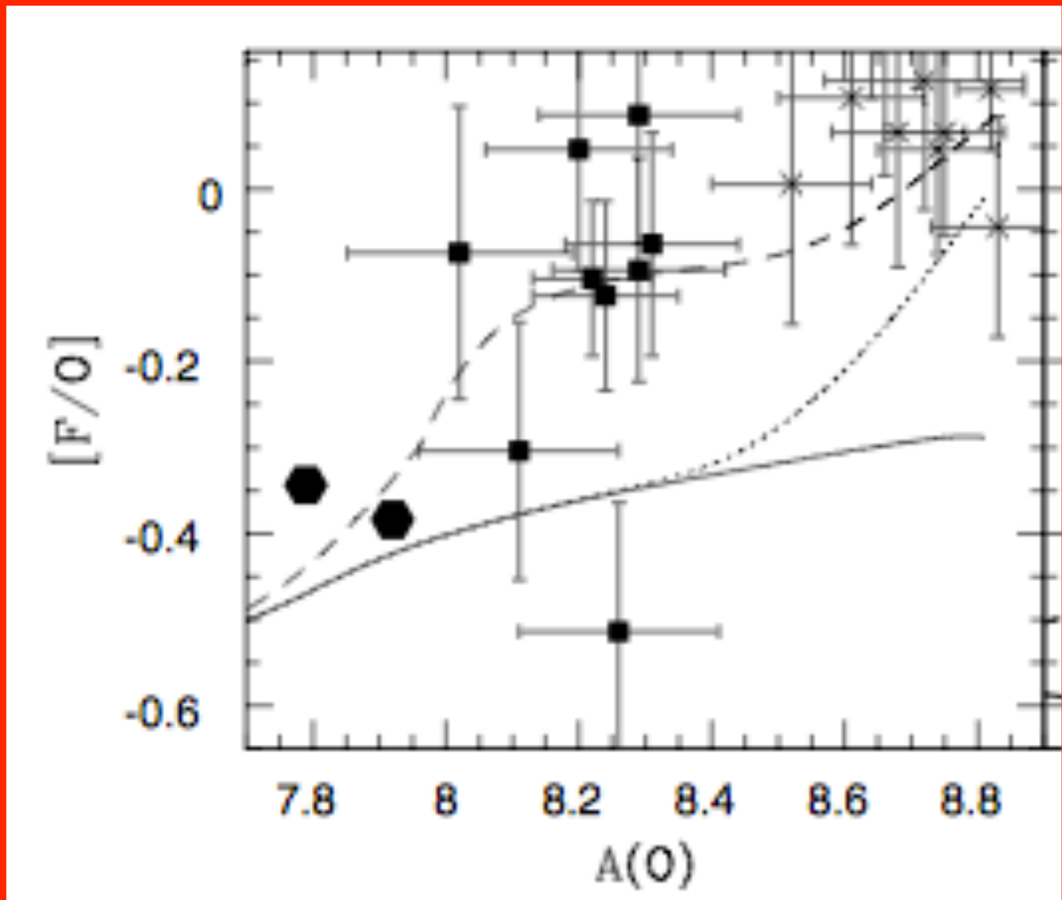
Elemental Abundance Ratios in the Solar Neighbourhood

- missing site for ^{47}Ti (He detonation in sub-Chandrasekhar mass SNeIa?)
- lack of correlation with [Fe/H] not understood

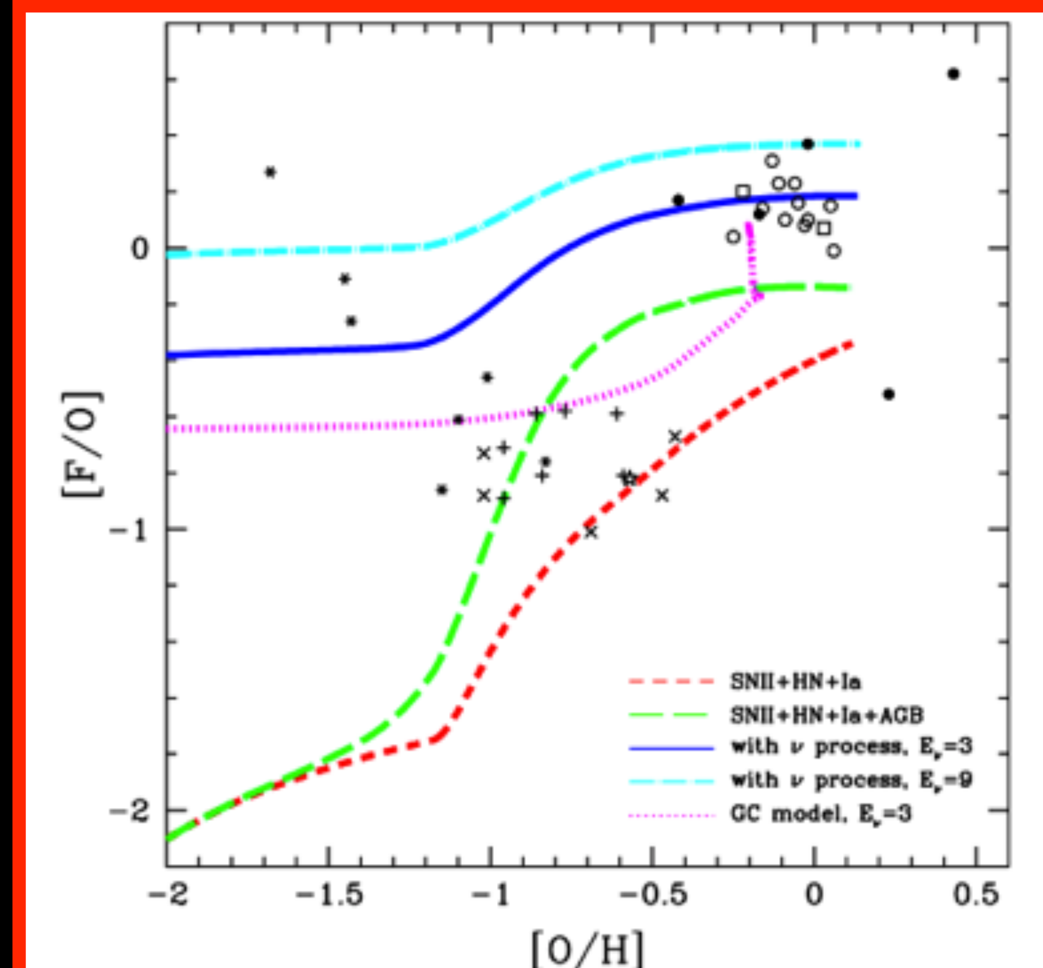


GCE Boundary Conditions

Renda et al. (2004); Kobayashi et al (2011)



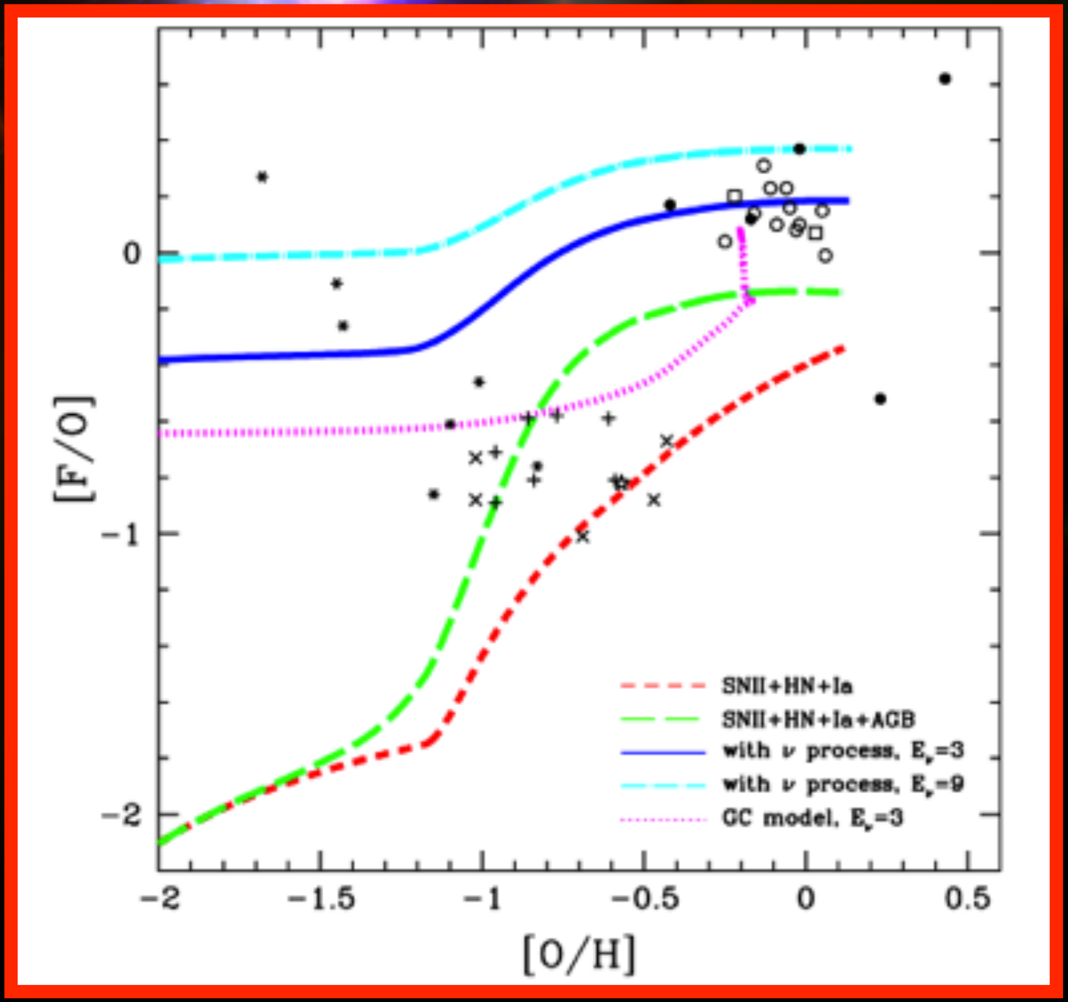
- ν energy of 1e53 erg + SNeII + AGB +WR (Renda et al) ... or
- ν energy of 3-9e53 erg + SNeII + >AGB (Kobayashi et al)



- ^{19}F from SNe via $^{15}N(\alpha,\gamma)^{19}F$ in convective He shell (secondary)
- ν-process via $^{20}Ne(\nu,\nu' p)^{19}F$ in O- and Ne-enriched region
- in AGB, primary via $^{18}O(n,\gamma)^{19}O(\beta^-)^{19}F$ but modulated by $^{19}F(\alpha,p)^{22}Ne$
- strong Wolf-Rayet winds might stop ^{19}F destruction via α-captures

GCE Boundary Conditions

Renda et al. (2004); Kobayashi et al (2011)

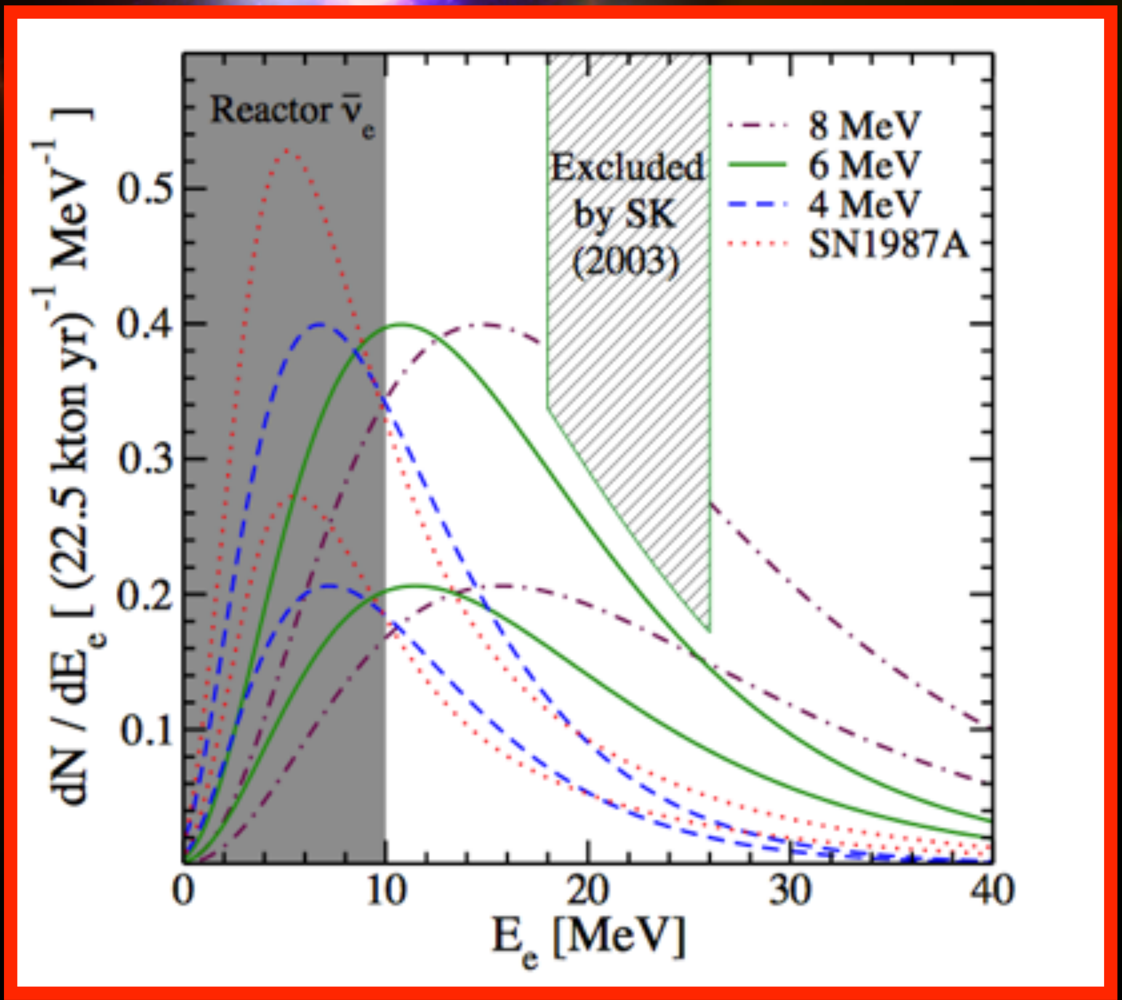


- ν energy of 1e53 erg + SNeII + AGB +WR (Renda et al) ... or
- ν energy of 3-9e53 erg + SNeII + >AGB (Kobayashi et al)

- but, factors of 10 variation in ν luminosity can have significant implications for the Diffuse SN Background (Beacom et al 2012)

GCE Boundary Conditions

Renda et al. (2004); Kobayashi et al (2011)

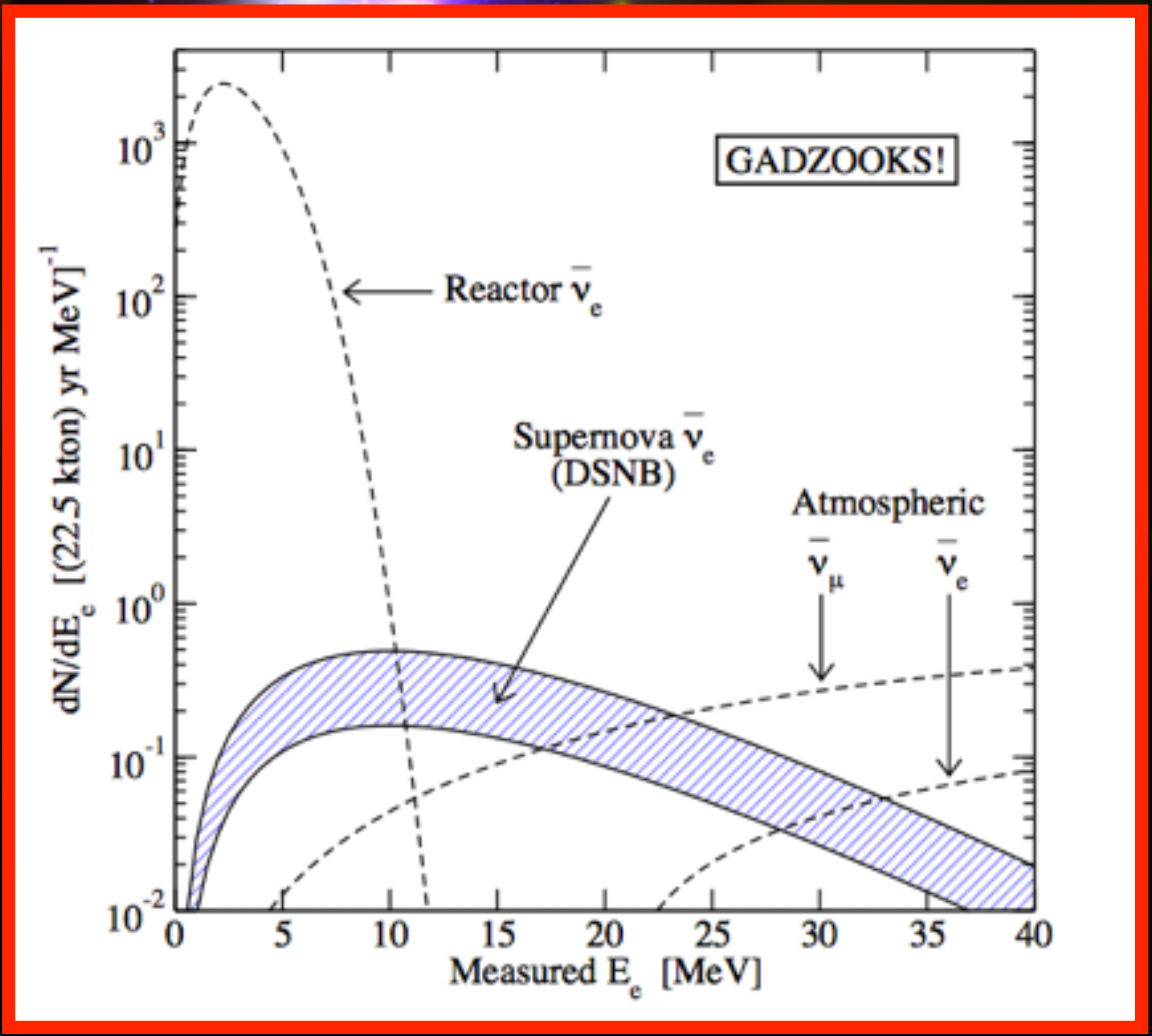


- ν energy of 1e53 erg + SNeII + AGB +WR (Renda et al) ... or
- ν energy of 3-9e53 erg + SNeII + >AGB (Kobayashi et al)

- but, factors of 10 variation in ν luminosity can have significant implications for the Diffuse SN Background (Beacom et al 2012)
- current SuperKamionde exclusion region already starting to eliminate the high-energy limit

GCE Boundary Conditions

Renda et al. (2004); Kobayashi et al (2011)



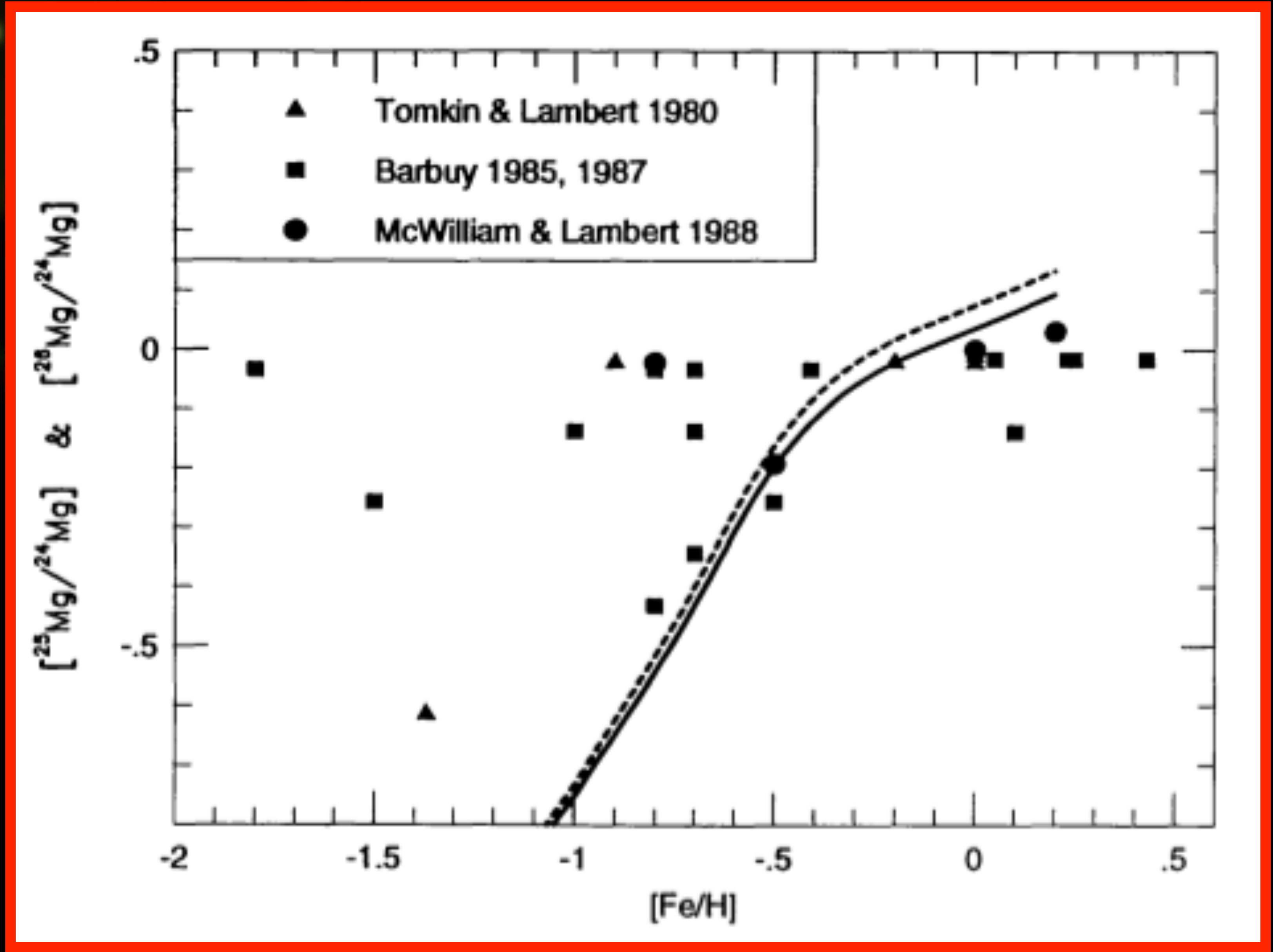
- ν energy of 1e53 erg + SNeII + AGB +WR (Renda et al) ... or
- ν energy of 3-9e53 erg + SNeII + >AGB (Kobayashi et al)

- but, factors of 10 variation in ν luminosity can have significant implications for the Diffuse SN Background (Beacom et al 2012)
- DSNB detection reaction is $\bar{\nu}_e + p \to e^+ + n$, while detector background reactions mostly don't produce these low-energy neutrons
- Gd-infused water @ SuperKamiokande should reduce threshold by 100x
- testing now (SuperKGD) at LSC (Canfranc)

GCE Boundary Conditions

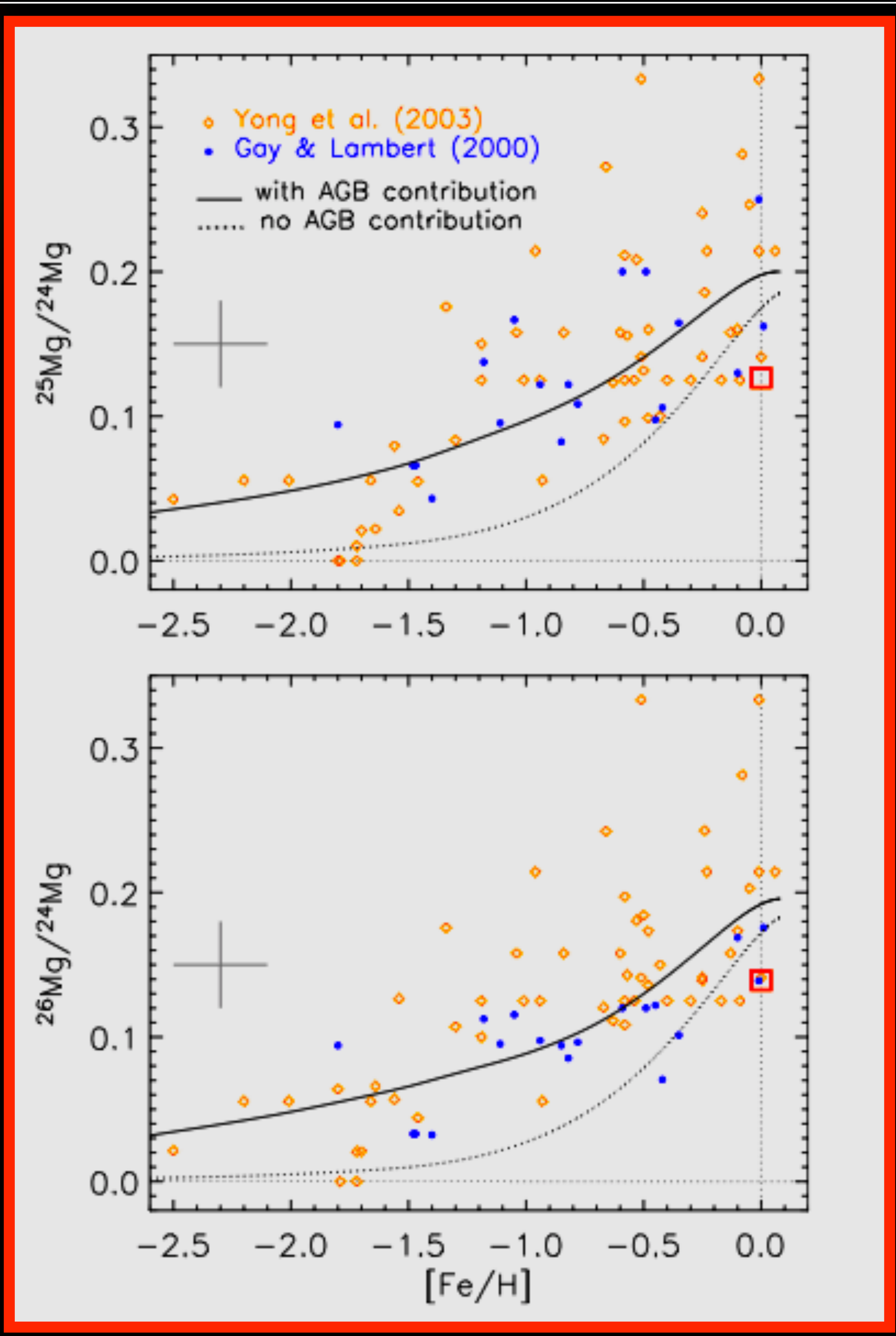
Fenner et al. (2003); Timmes et al (1995)

- classic GCE model of Timmes et al (1995) showed SNeII incapable of recovering abundance pattern of neutron-rich isotopes of Mg



GCE Boundary Conditions

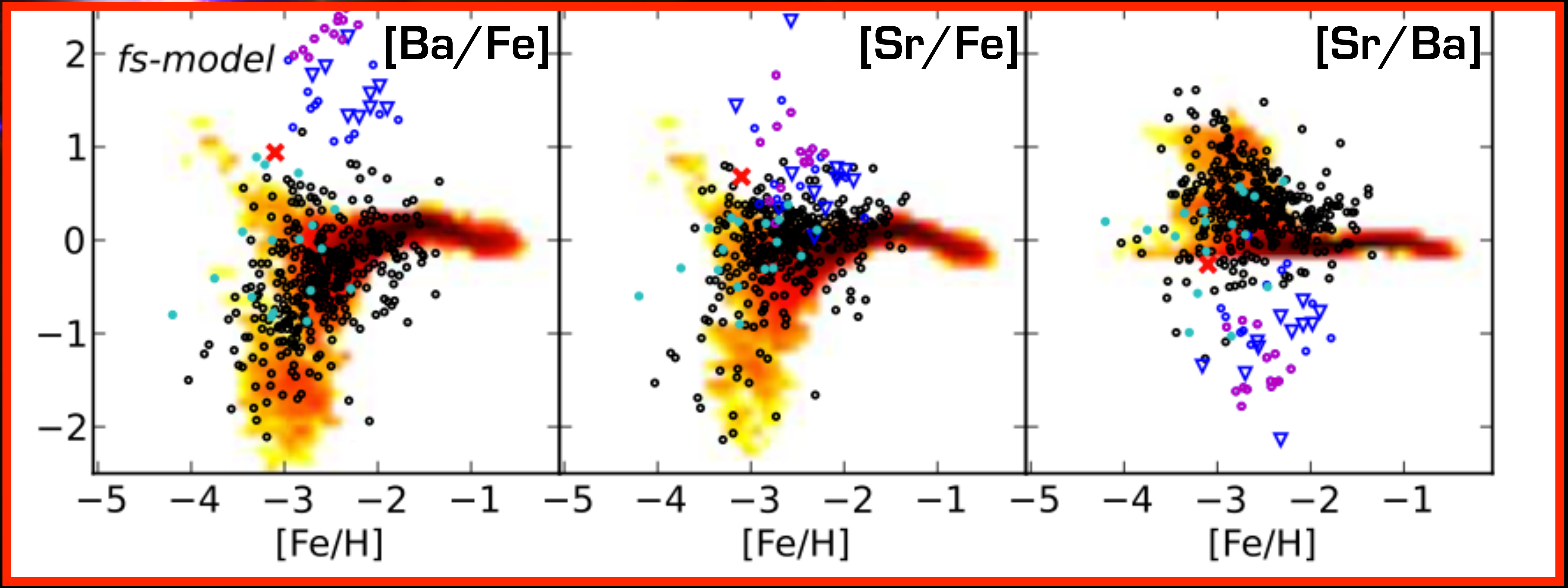
Fenner et al. (2003); Timmes et al (1995)



- α-capture onto ^{22}Ne triggered by He shell thermal pulsing in 4-6 solar mass stars at low(ish) metallicity coupled with GEtool models (Fenner et al (2003) demonstrated the solution to this problem

GCE Boundary Conditions

Cescutti et al (2013)



- classic GCE models predict zero scatter in abundances at a given metallicity
- model w/(rough) inhomogeneous GCE treatment (100 spherical unmixed regions of the halo) with standard r-process + fast spinning stars + $^{17}O(\alpha,\gamma)^{21}Ne$ rate 10x lower than standard (to increase weak-s)

A remarkable star...

Keller et al (2014)

A single low-energy, iron-poor supernova as the source of metals in the star SMSS J031300.36-670839.3

S. C. Keller[\], M. S. Bessell[\], A. Frebel[*], A. R. Casey[\], M. Asplund[\], H. R. Jacobson[*], K. Lind[*], J. E. Norris[\], D. Yong[\], A. Heger[+], Z. Magic[△\], G. S. Da Costa[\], B. P. Schmidt[\], & P. Tisserand[\]

A remarkable star…

Keller et al (2014)

- [Fe/H] < -7.1 !

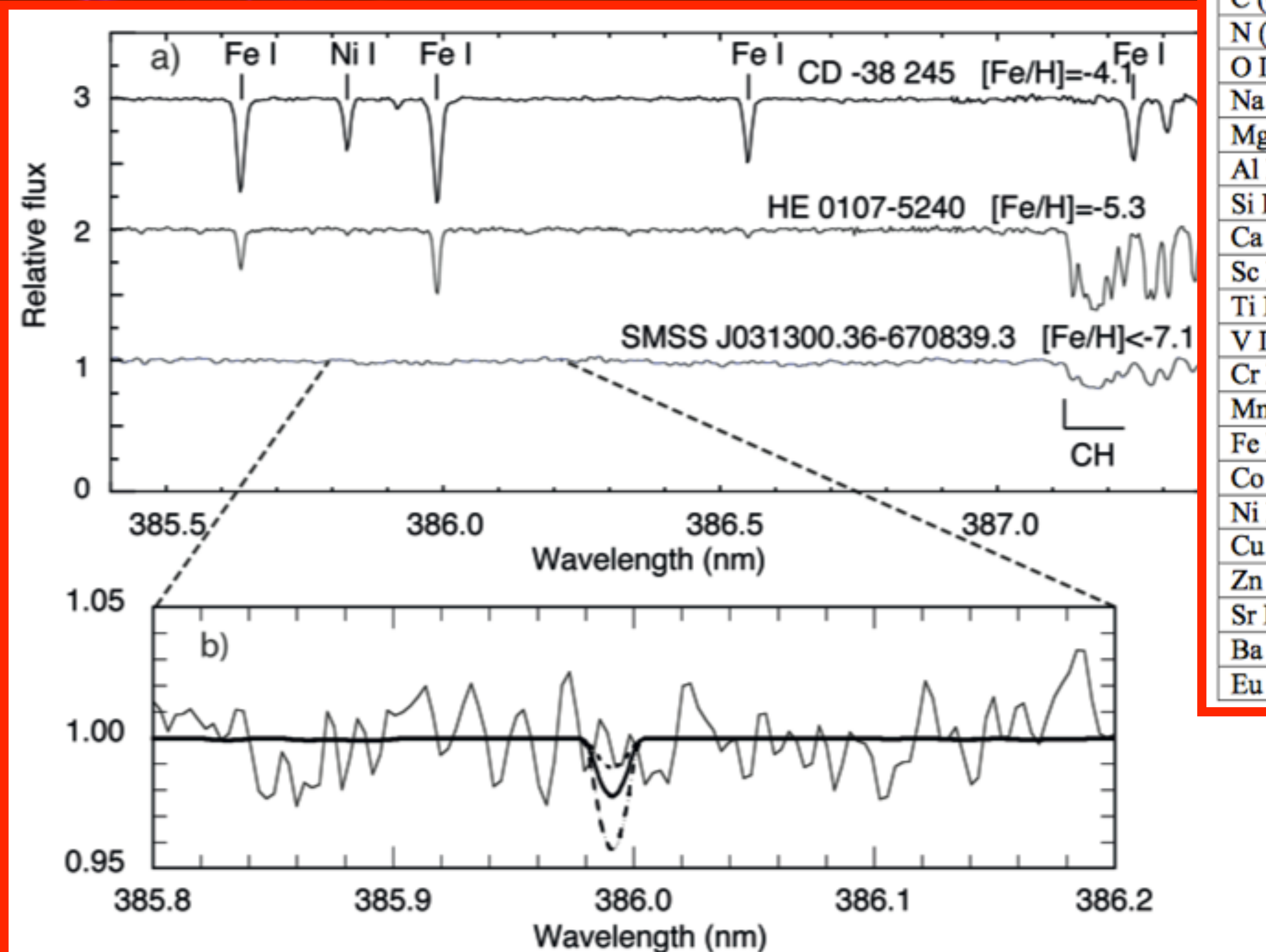


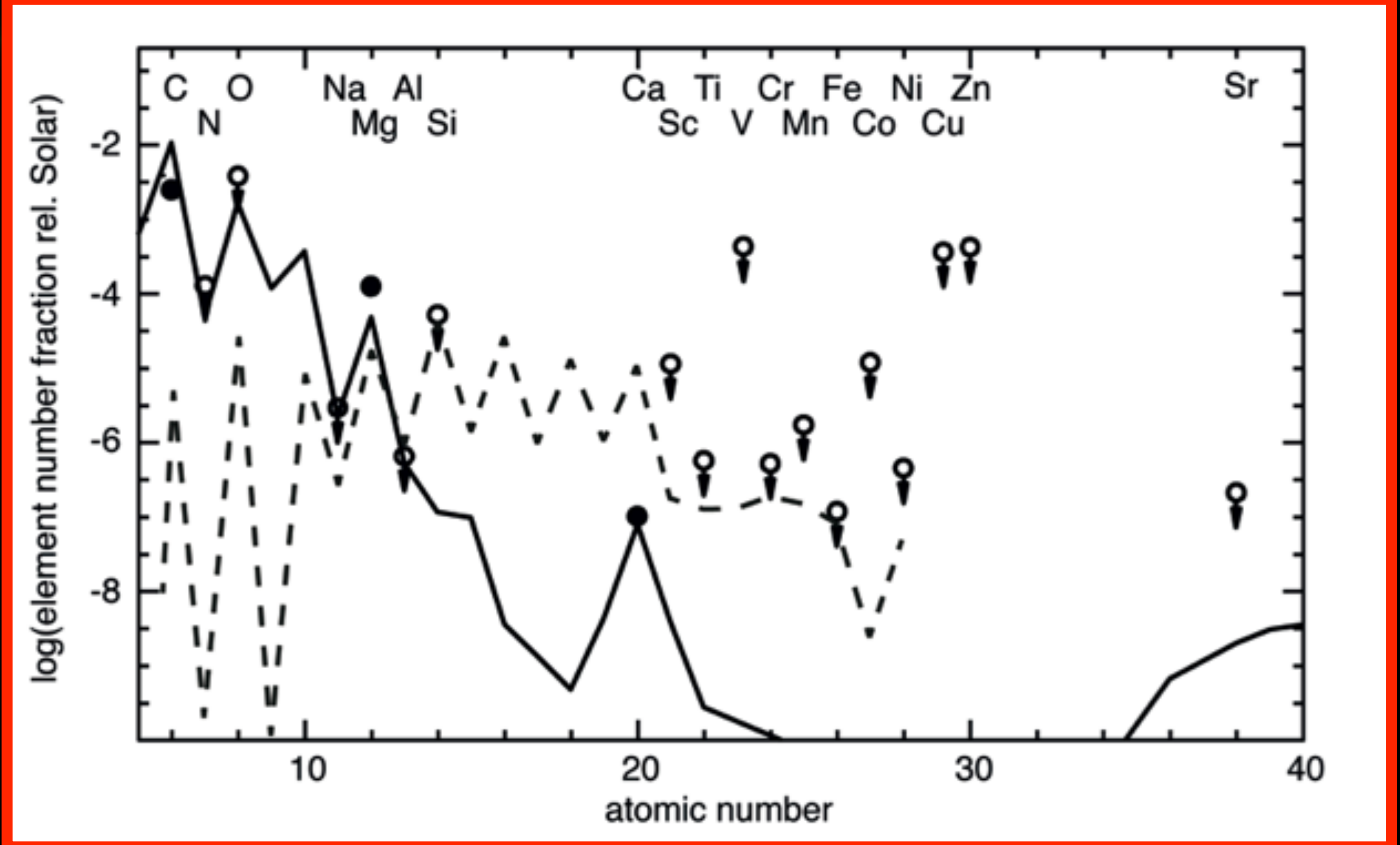
Table 1 Chemical abundances of SMSS 0313-6708

Element	$[X/H]_{1\text{-d, LTE}}$	$[X/H]_{<3\text{-d}>}$
Li I	0.7	0.7
C (CH)	-2.4	-2.6[a]
N (NH)	<-3.5	<-3.9[a]
O I	<-2.3	<-2.4[a]
Na I	<-5.5	<-5.5[b]
Mg I	-4.3	-3.8[b]
Al I	<-6.2	
Si I	<-4.3	
Ca II	-7.2	-7.0[b]
Sc II	<-5.0	
Ti II	<-6.3	
V II	<-3.3	
Cr I	<-6.3	
Mn I	<-5.8	
Fe I	<-7.3	<-7.1[b]
Co I	<-4.9	
Ni I	<-6.4	
Cu I	<-3.5	
Zn I	<-3.4	
Sr II	<-6.7	
Ba II	<-6.1	
Eu II	<-2.9	

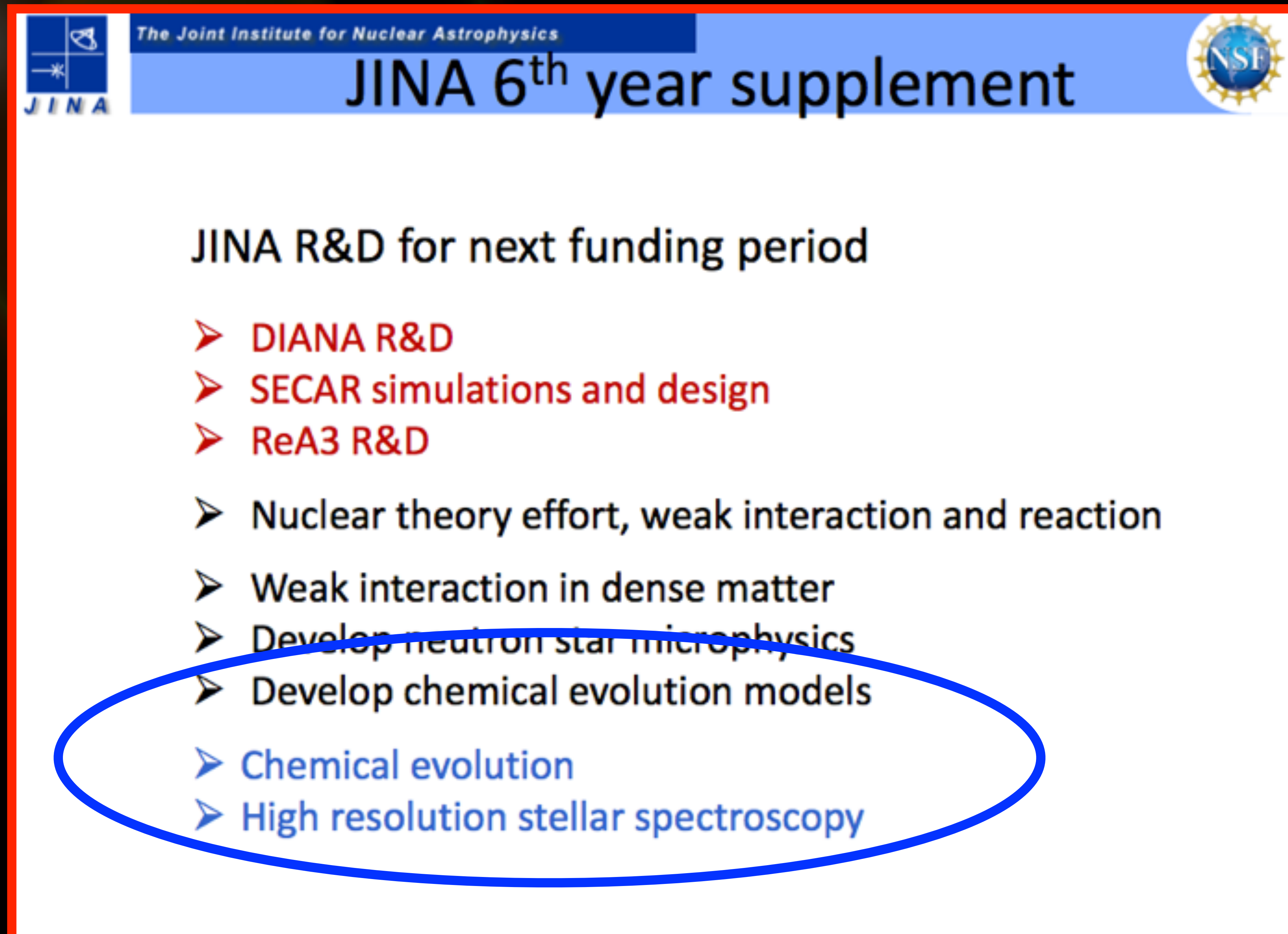
A remarkable star...

Keller et al (2014)

- abundance pattern strongly suggests it was seeded by a single 60 Msun star which exploded as a low (i.e., normal)-energy CC SN (solid) rather than 200 Msun PISN (dashed)
- high [Mg/Fe] suggests it was an axi-symmetric explosion
- relatively low N suggests it was non-rotating progenitor



Just because someone else does it is not necessarily a reason to do it yourself, but ...



- JINA funding this year earmarked for GCE, to link with their nuclear programmes

Just because someone else does it is not necessarily a reason to do it yourself, but ...

- JINA-III have identified GCE as one of their pillars

The Joint Institute for Nuclear Astrophysics

JINA Future Projections

New JINA team members:

John Beacon (OSU)
Anna Frebel (MIT)
George Fuller (UCSD)
Gail McLaughlin (NC-State)
Yong Qian (U. Minnesota)
Sanjay Reddy (INT Washington)

New JINA Director

Michael Wiescher until: 8. 2014
Hendrik Schatz from: 9. 2014
Revised management and internal review structure will be developed and evaluated in coming year

New project directions

Galactic Chemical Evolution	(Frebel, McShea, Beers, Schatz)
Weak interaction in dense matter	(Beacon, Fröhlich, Fuller, McLaughlin, Reddy, Brown, Schatz)
r-process site scenarios	(Surman, McLaughlin, Aprahamian)
DIANA development	(LUNA-MV, Wiescher)
SECAR development	(Schatz, Wiescher)

José & Iliadis (2012) Key Questions

- do predictions of helioseismology disagree with those of the SSM?
- what is the solution to the Li problem in BBN?
- what do light-nuclide and s-process tell us about convection and dredge-up in massive stars and AGB stars?
- what are the production sites of γ-ray emitting radioisotopes ^{26}Al, ^{44}Ti, and ^{60}Fe?
- what is the origin of about 30 rare and neutron deficient nuclides beyond the iron peak (p-nuclides)?
- what causes core-collapse SNe to explode?
- what is the extent of neutrino-induced nucleosynthesis (ν-process)?
- what is the extent of the nucleosynthesis in proton-rich outflows in the early ejecta of CC SNe (νp-process)?
- what are the sites of the r-process?
- what causes the discrepancy between models and observations regarding mass ejected during classical nova outbursts?
- what are the physical mechanisms driving convective mixing in novae?
- what are the progenitors of Type Ia SNe?
- what is the nucleosynthesis endpoint in type I x-ray bursts? is there any matter ejected from those systems?
- what is the impact of stellar mergers on Galactic chemical abundances?
- what are the production and acceleration sites of Galactic cosmic rays?