First stars: how to constrain their properties

Stefania Salvadori

Florence University – Department of Physics and Astronomy

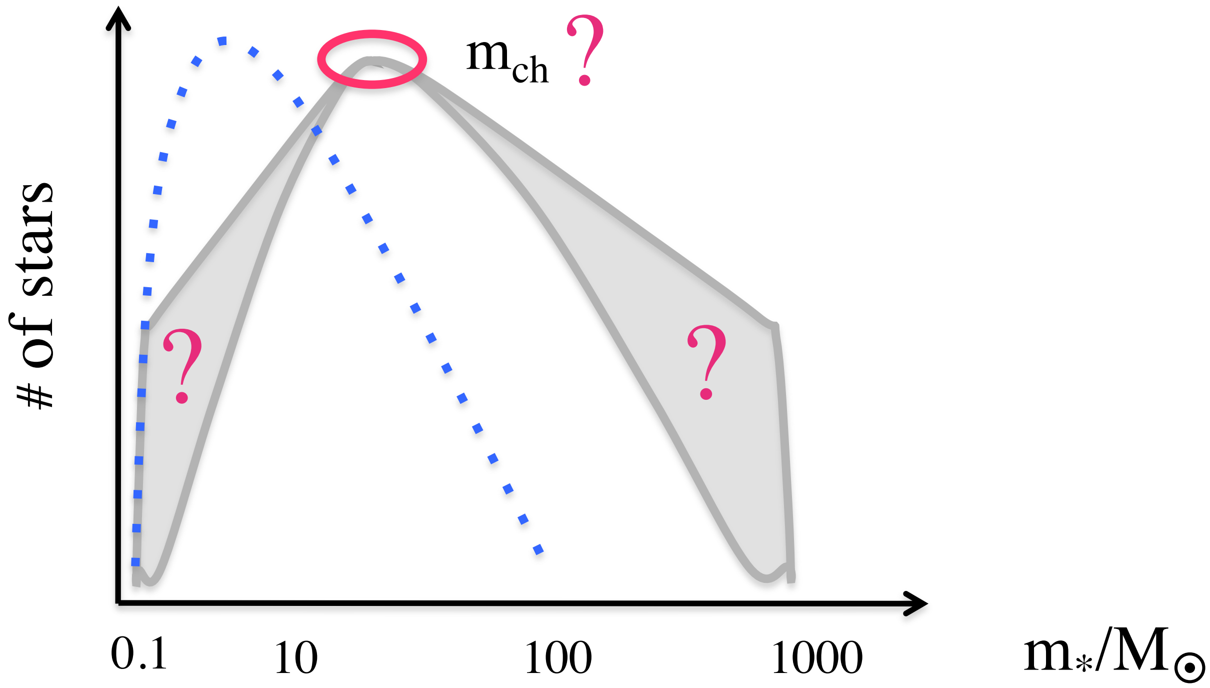
Key collaborators: Aguado, Amarsi, Bonifacio, Caffau, D'Odorico, Ferrara, Gelli, Koutsouridou, Pagnini, Pallottini, Rossi, Saccardi, Skuladottir, Tolstoy, Vanni

UNIVERSITÀ DEGLI STUDI FIRENZE

FirstStars@IFPU

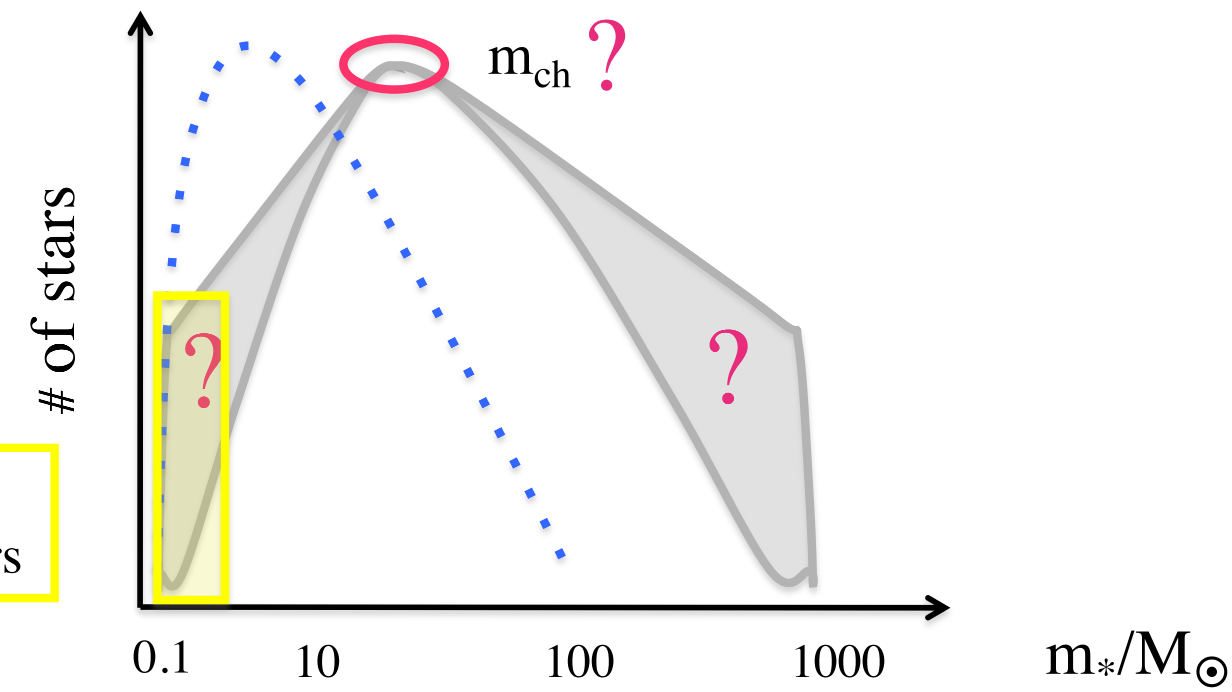
Trst, May the 18th, 2023

THE UNKNOWN FIRST STARS' MASS DISTRIBUTION



- Did low-mass long-lived first stars form?
- Did very massive $m_* > 140\ M_\odot$ first stars form?
- How can we probe the first stars' mass distribution?

THE UNKNOWN FIRST STARS' MASS DISTRIBUTION



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?

$m_* < 0.8\ M_\odot$
$\tau_* > 14 \times 10^9$ years

They can survive until present-day and be observed.

No metal-free stars have been detected so far:
are there implications for the low-mass end ?

THE LOW-MASS END OF THE FIRST STARS' MASS DISTRIBUTION

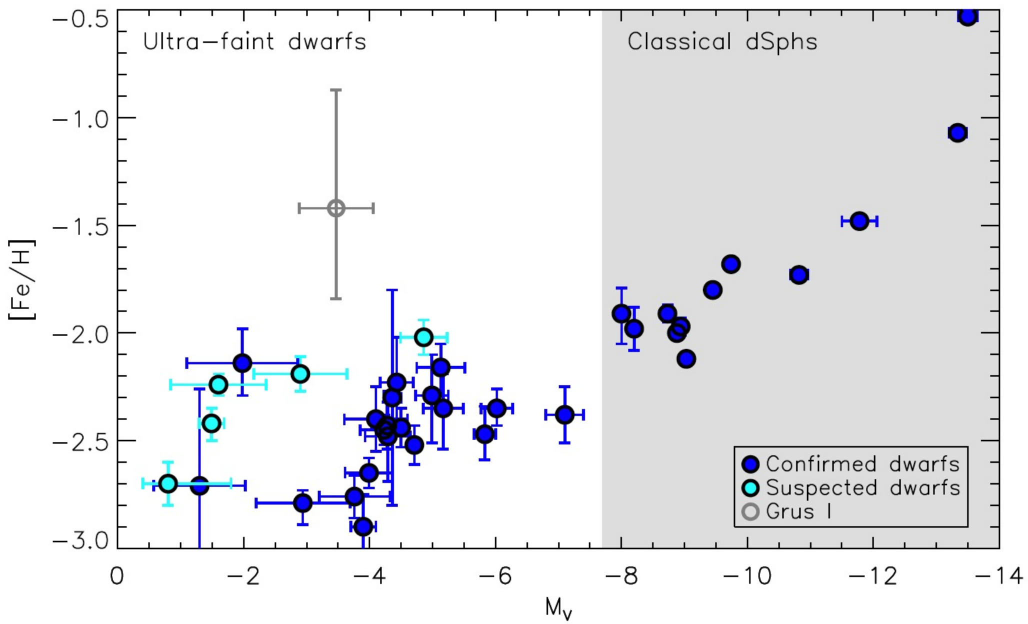
e.g. Oey 2003; Tumlinson 06/07; Salvadori+07/10; Komiya+07/09; de Bennassuti+14/16; Hartwig+15; Ishiyama+16; Rossi+21

Implications of the persisting non-detection of metal-free stars

Salvadori+07: Assuming a normal mass distribution for Pop III stars we find 0.75% of MW stars @ [Fe/H] < -2.5 with Z = 0 → $m_{min} > 0.8\ M_{\odot}$

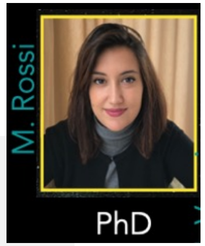
Hartwig+15: Large stellar samples, $N_{star} > 10^{7.5}$ ($10^{6.5}$), required for the MW halo to constrain $m_{min} > 0.8\ M_{\odot}$ at 99% (68%) confidence level

Too many stars! But we can use ultra-faint dwarf galaxies



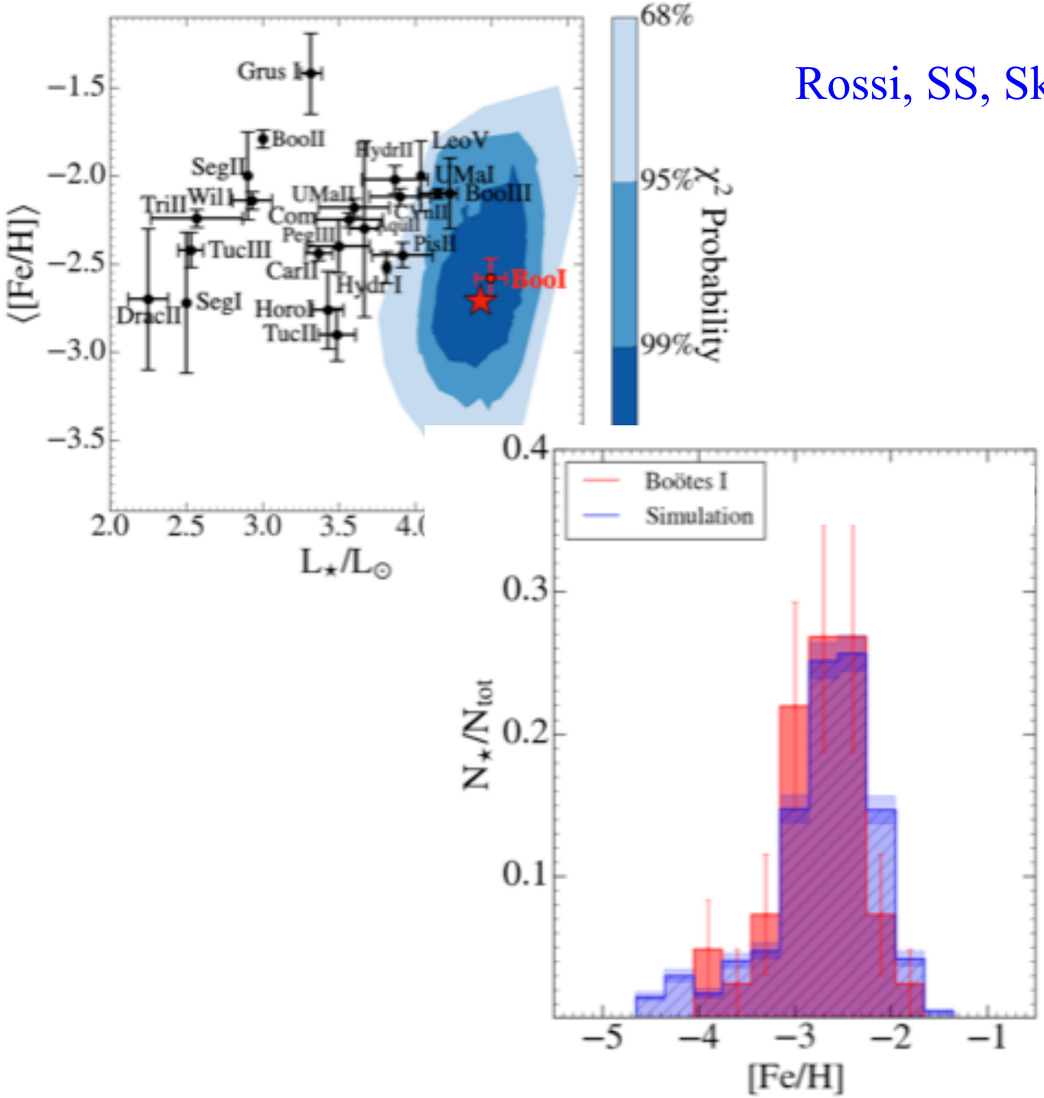
Simon 2019

CHEMICAL EVOLUTION MODEL FOR BOOTES I

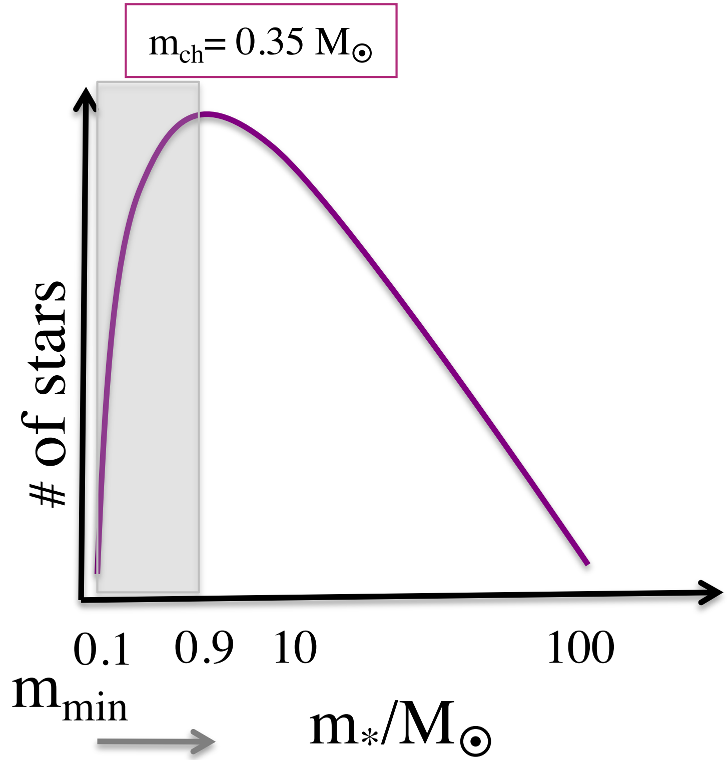


Initial conditions and dark matter evolution from cosmological models (SS+2015) Data-calibrated. Incomplete sampling of the Pop III/II IMF

Rossi, SS, Skuladottir 2021



Changing the IMF of first stars



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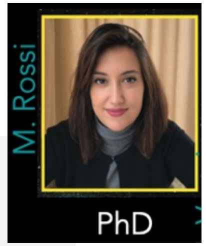

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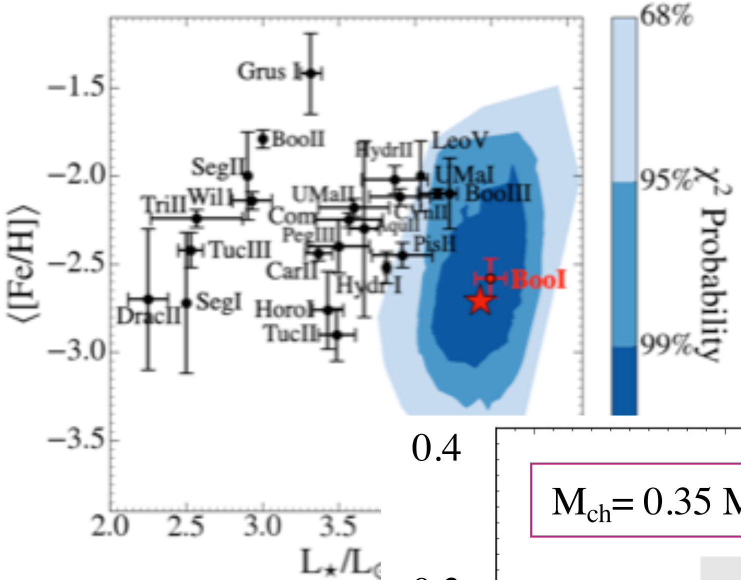
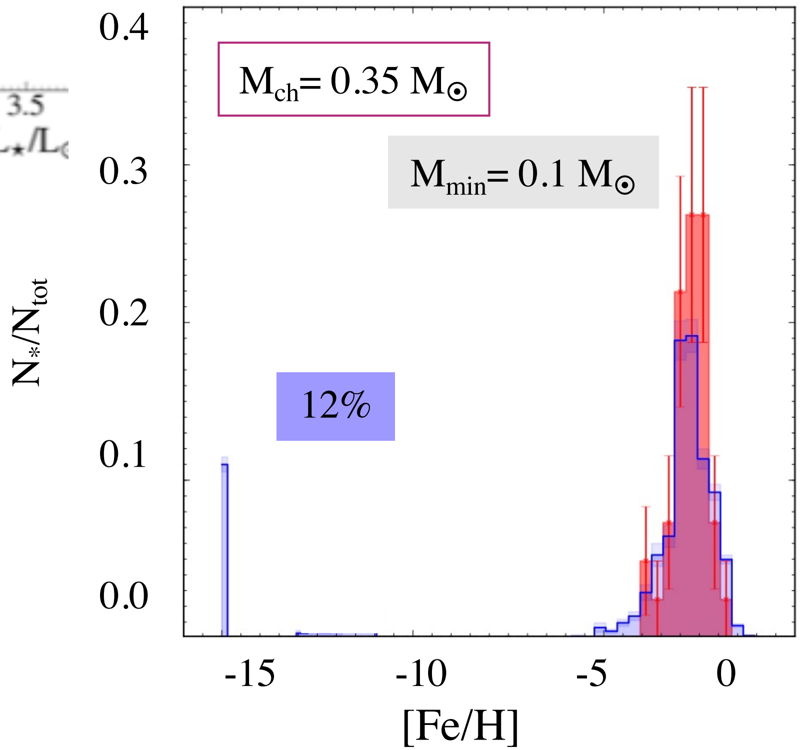
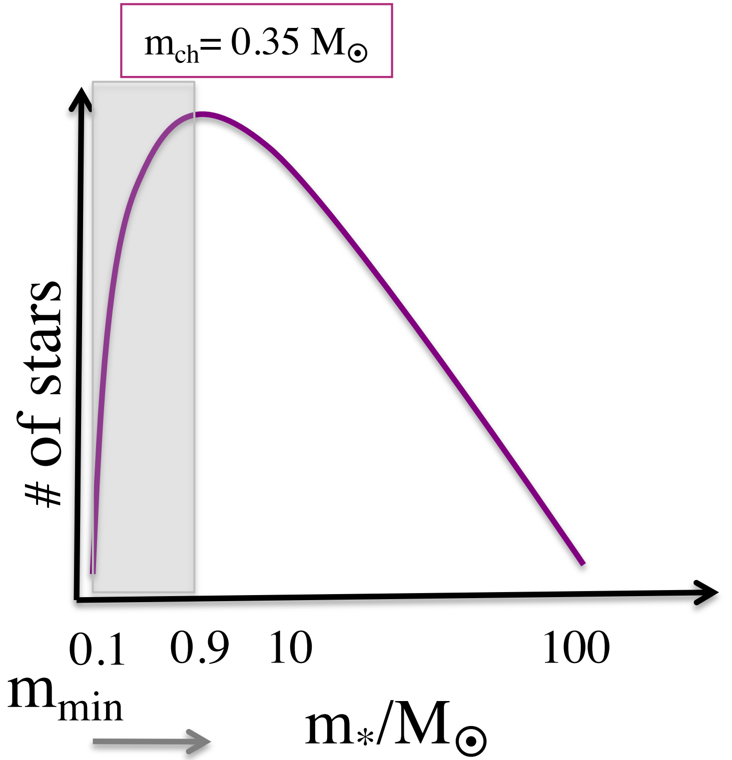


Rossi, SS, Skuladottir 2021



Changing the IMF of first stars



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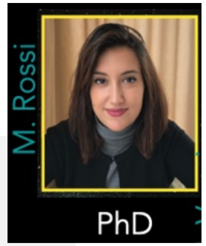

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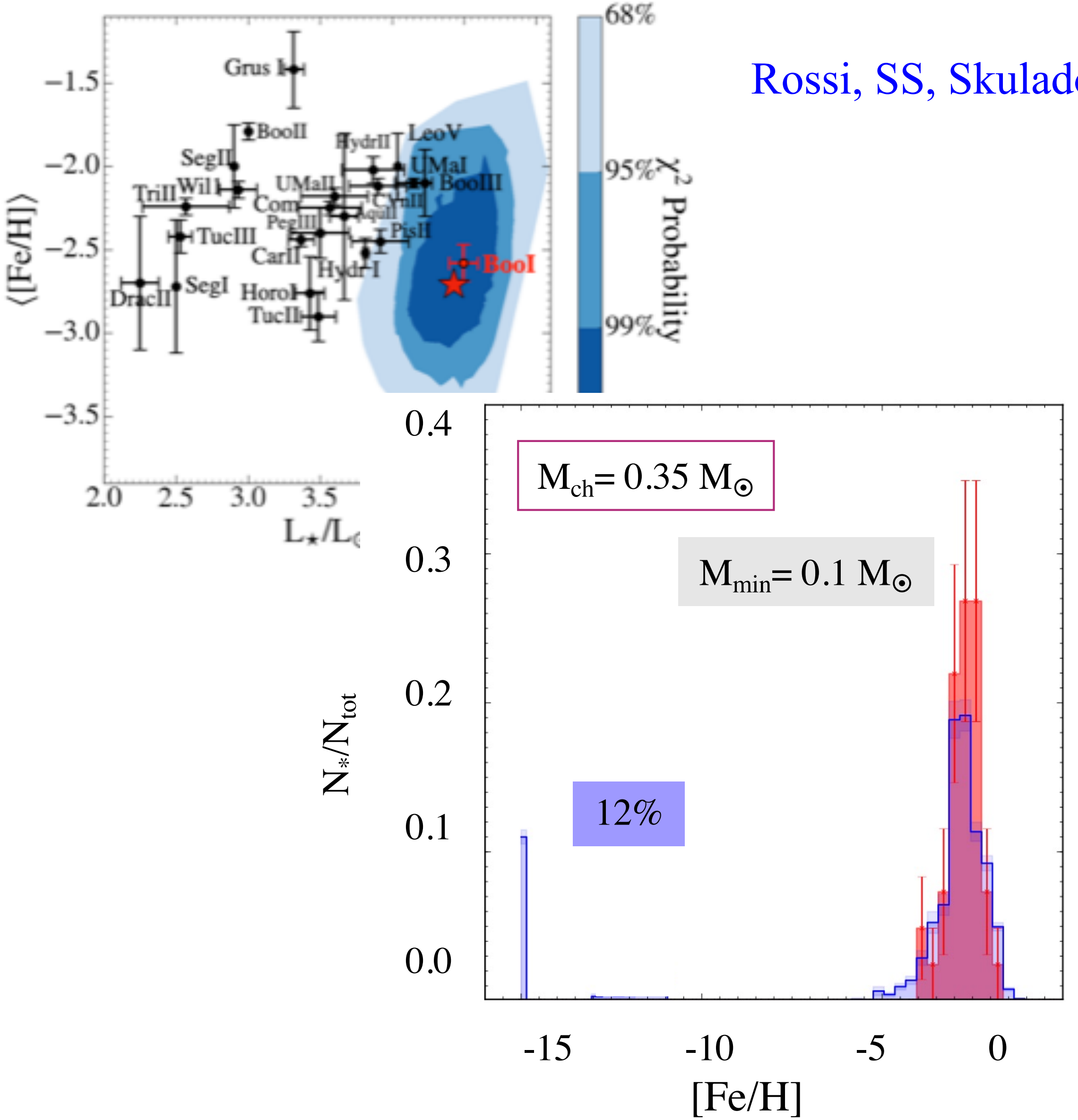

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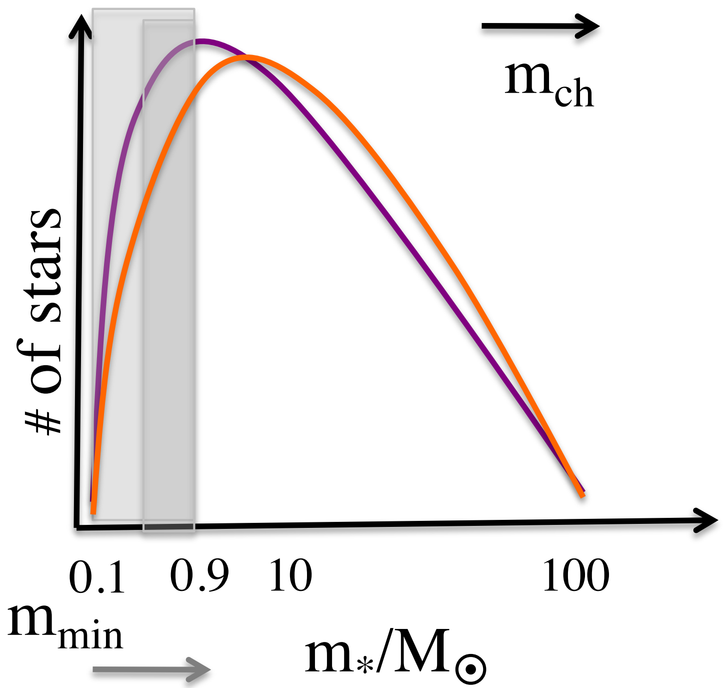

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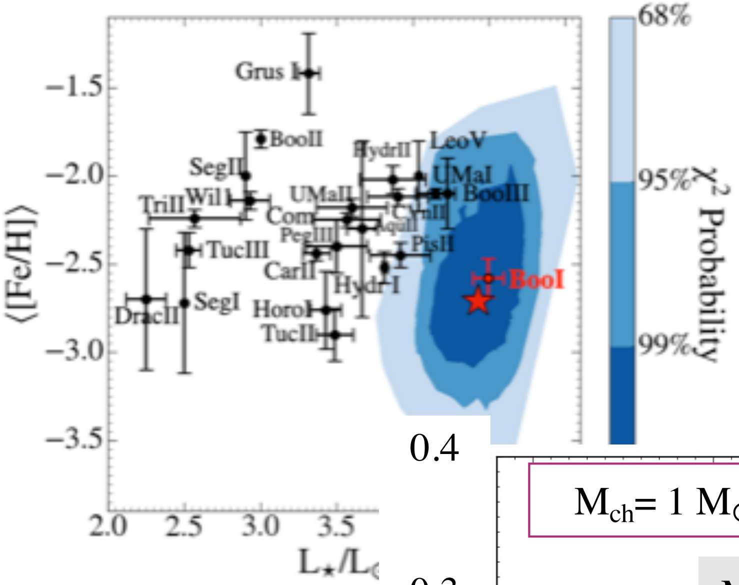
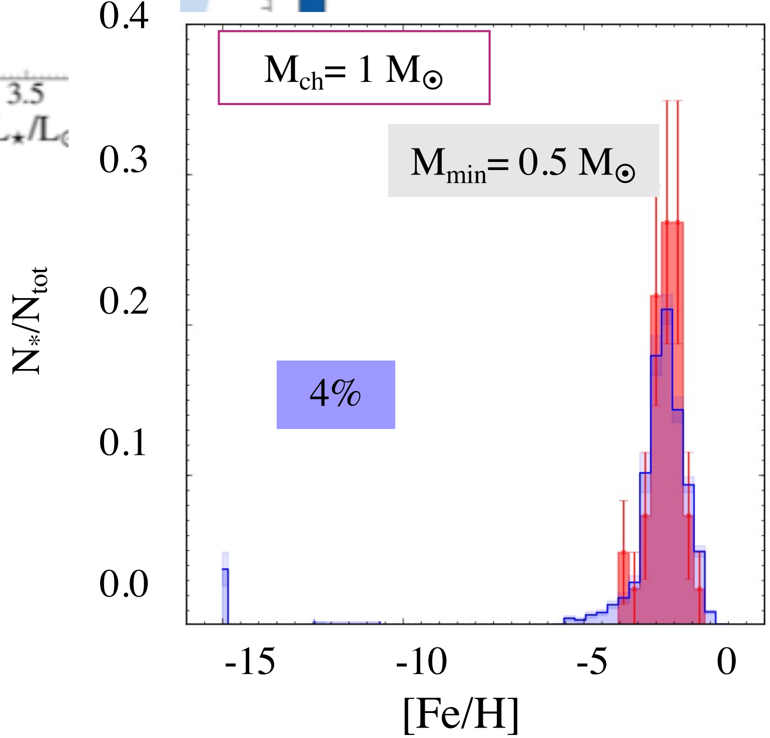


Rossi, SS, Skuladottir 2021



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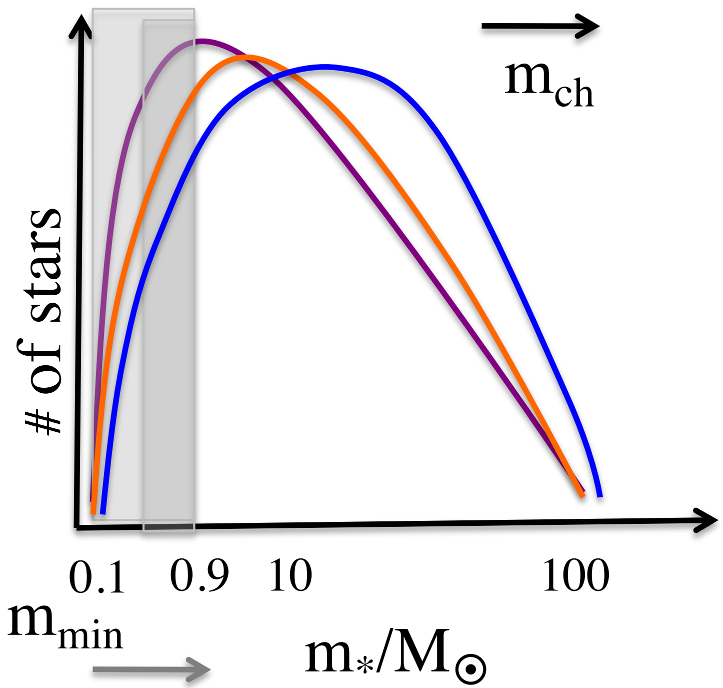
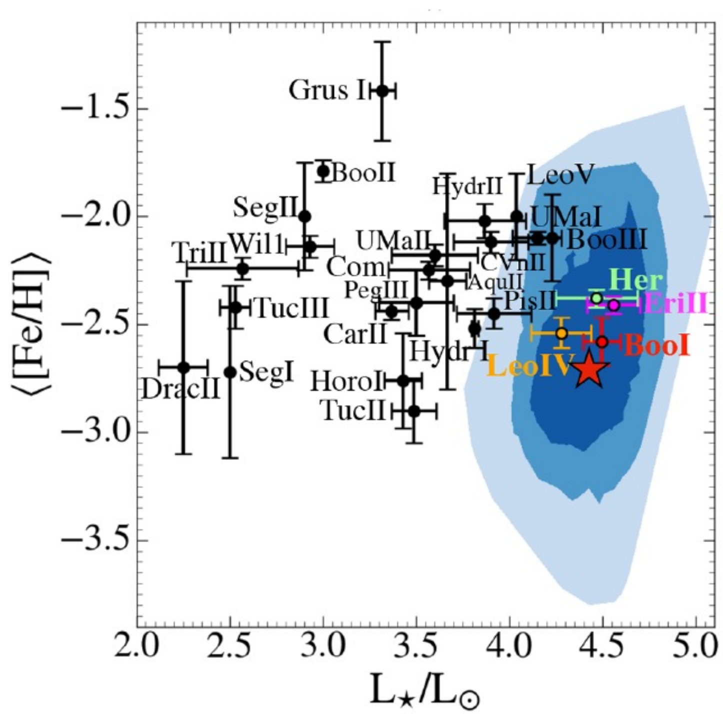
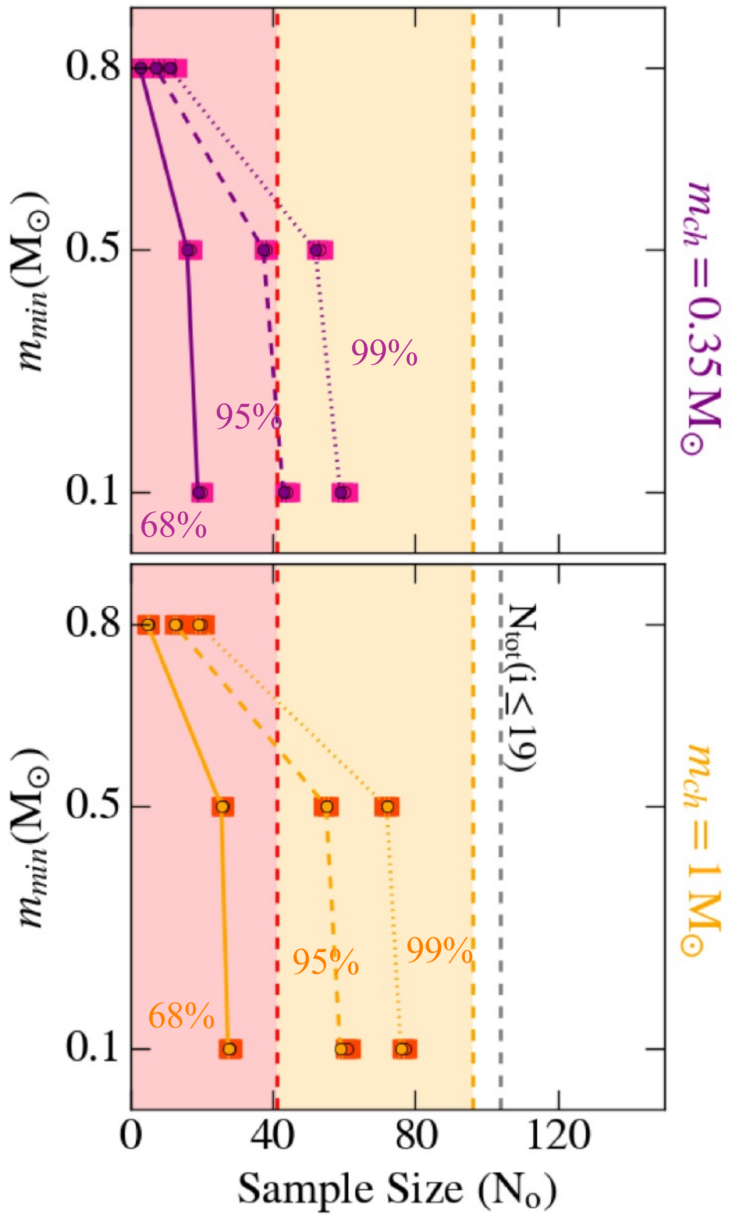


CONSTRAINING THE MINIMUM MASS OF THE FIRST STARS

Rossi, SS, Skuladottir 2021

Sample size of stars that *can be* observed required to constrain m_{min}





~ 40 stars observed in Bootes I

~100 stars in BooI+Herc+LeoIV+EriII

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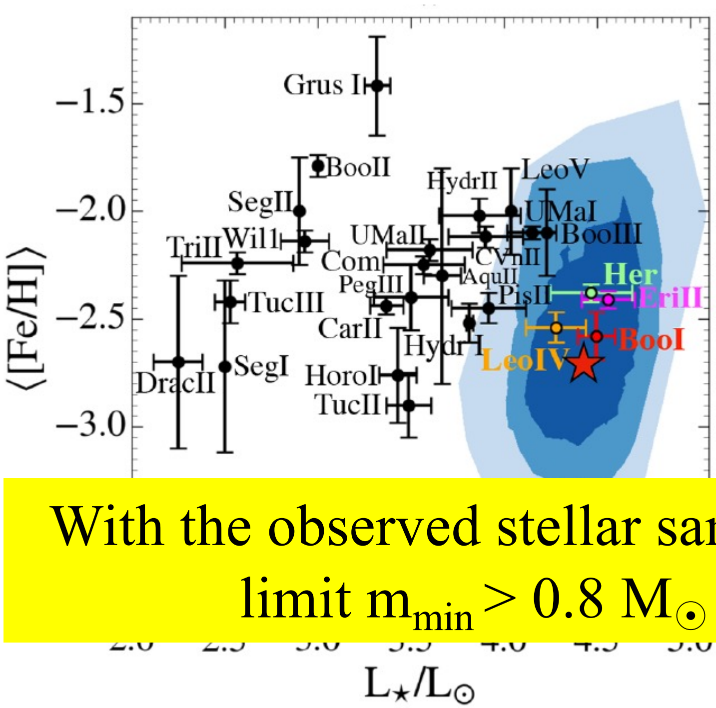
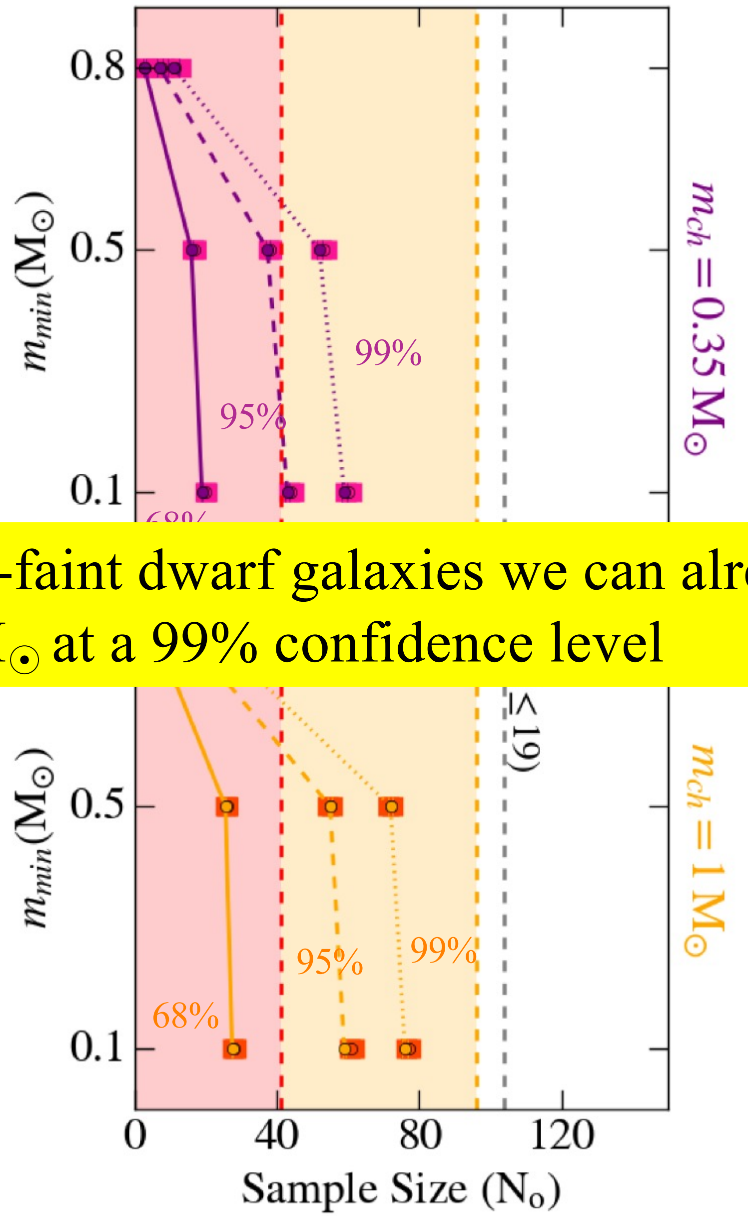




With the observed stellar sample in ultra-faint dwarf galaxies we can already limit $m_{min} > 0.8\ M_\odot$ or $m_{ch} > 1\ M_\odot$ at a 99% confidence level

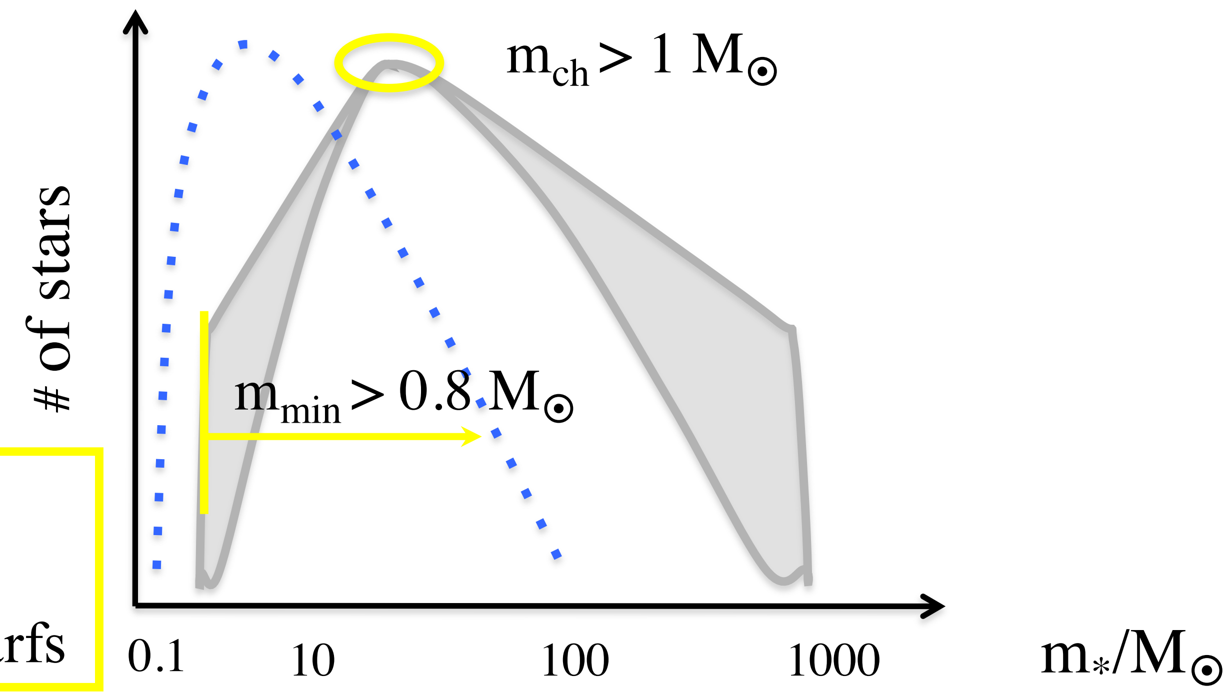
~ 40 stars observed in Bootes I

~100 stars in BooI+Herc+LeoIV+EriII

CONSTRAINING THE FIRST STARS' MASS DISTRIBUTION

small

Non-detection
of Z = 0 stars
in ultra-faint dwarfs



CONSTRAINING THE FIRST STARS' MASS DISTRIBUTION

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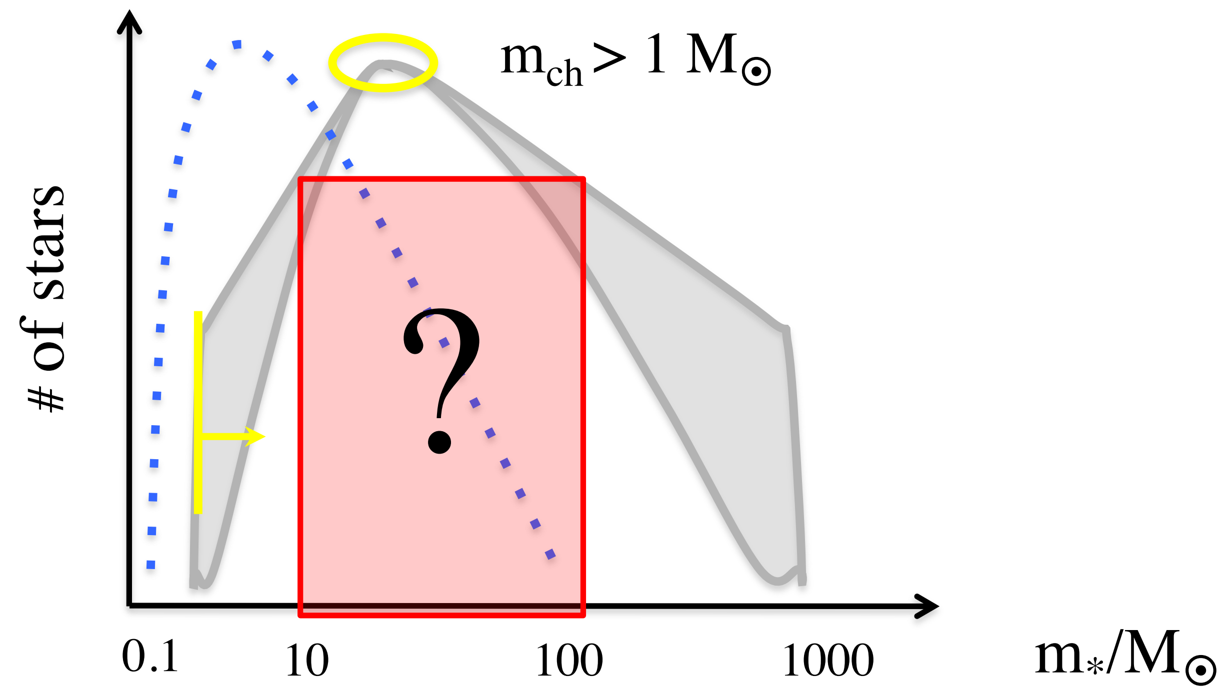

THE FIRST STARS' MASS & ENERGY DISTRIBUTION

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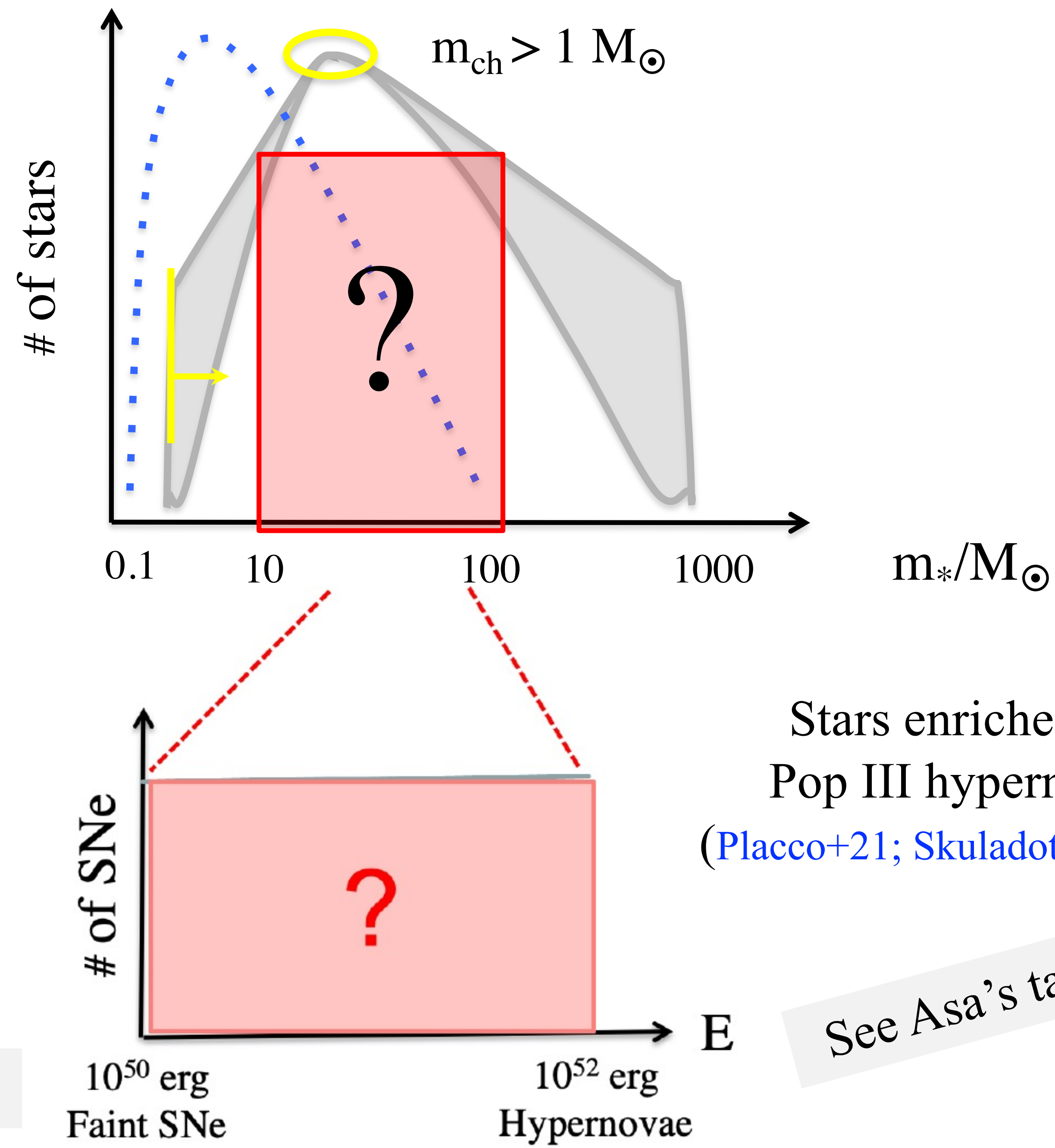


Stars enriched by
Pop III hypernovae
(Placco+21; Skuladottir,SS+21)

See Asa's talk!

See Chiaki's talk!

A SIMPLE AND GENERAL PARAMETRIC STUDY

SS, Bonifacio, Caffau et al. 2019; Vanni, SS, Skuladottir et al. submitted

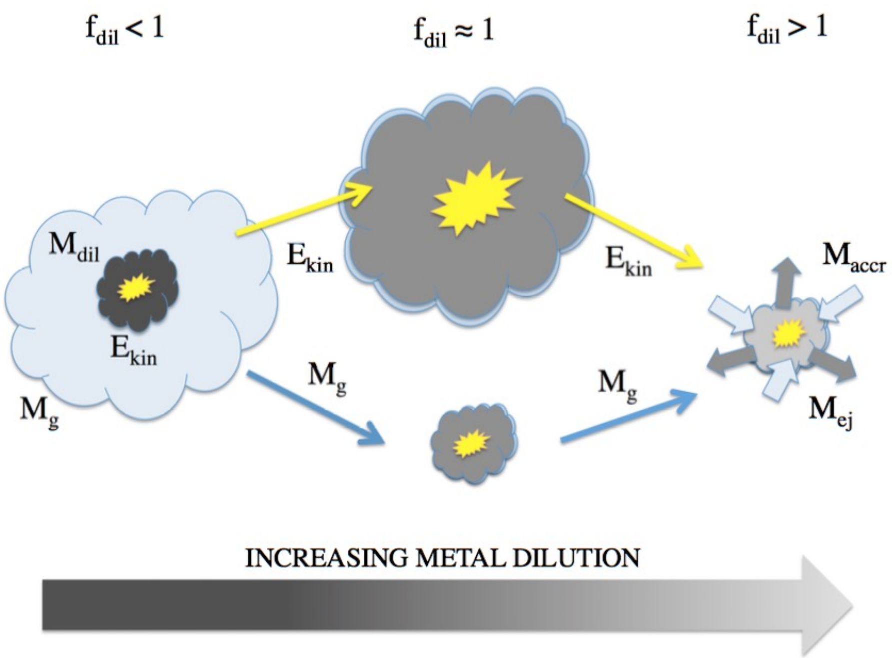
Investigating the chemical properties of an ISM *predominantly* imprinted by Pop III stars (> 50% of metals) and subsequent generation of normal Pop II stars

THREE KEY UNKNOWNS

Star-formation efficiency f_*

Dilution factor f_{dil}

Mass fraction of PopIII metals f_{PopIII}



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THREE KEY UNKNOWNS: SIMPLE EQUATIONS

f_*, f_{dil}, f_{PopIII}

$\beta = (1 - f_{PopIII})/f_{PopIII}$

$$[\mathrm{X/H}]_{\mathrm{ISM}} = \log\left[\frac{f_*}{f_{dil}}\left[Y_X^{PopIII} + \beta\frac{Y_X^{popII}Y_Z^{PopIII}}{Y_Z^{popII}}\right]\right] - \log\left[\frac{M_X}{M_H}\right]_\odot$$

$$[\mathrm{X/Fe}]_{\mathrm{ISM}} = \log\left[\frac{Y_X^{PopIII} + \beta\frac{Y_Z^{PopIII}}{Y_Z^{popII}}Y_X^{popII}}{Y_{Fe}^{PopIII} + \beta\frac{Y_Z^{PopIII}}{Y_Z^{popII}}Y_{Fe}^{popII}}\right] - \log\left[\frac{M_X}{M_{Fe}}\right]_\odot$$

Pop III stars: Heger & Woosley 2010 with different mass and energies

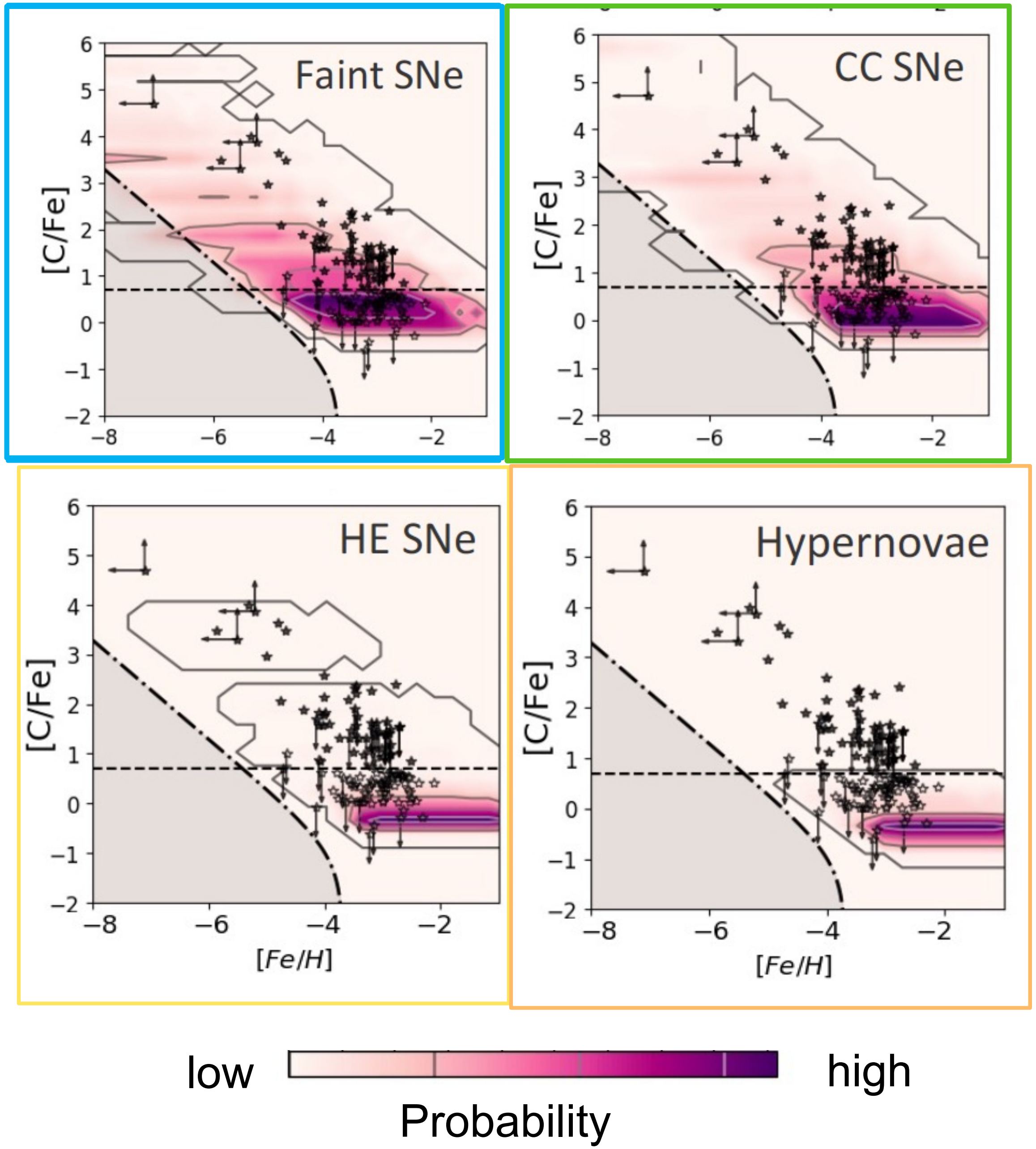
Pop II stars: IMF integrated yields from Limongi & Chieffi 2012 + WW95

POP III STARS' ENRICHED ENVIRONMENTS

Vanni, SS, Skuladottir 2023; Vanni+ to be submitted

LOW-ENERGY
Pop III SNe

HIGH -ENERGY
Pop III SNe



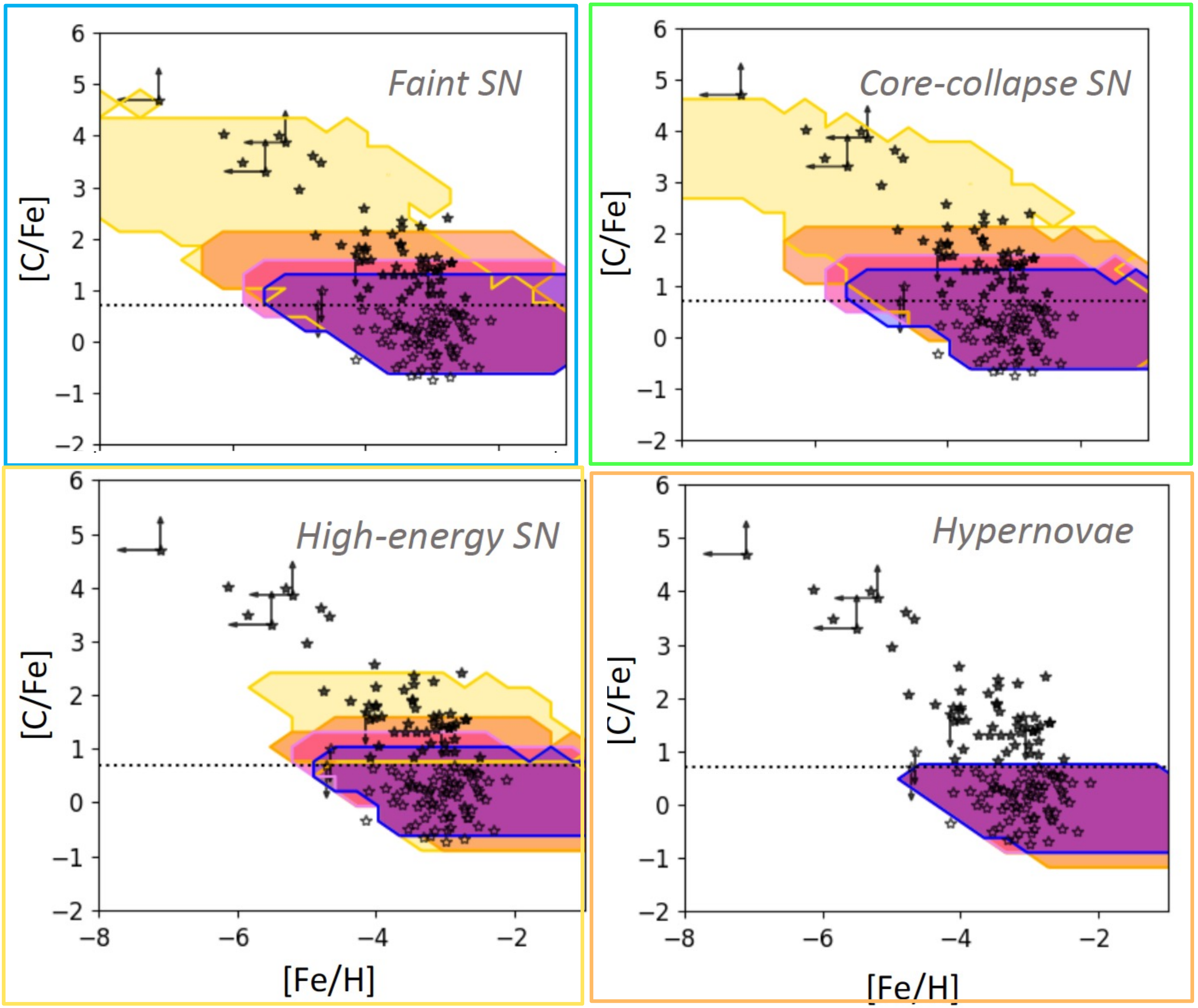
Same for [O/Fe], [Mg/Fe], [Si/Fe]

DECREASING CONTRIBUTION FROM POPIII STARS

Vanni, SS, Skuladottir 2023; Vanni+ to be submitted

LOW-ENERGY POPIII SN

HIGH-ENERGY POPIII SN



100% PopIII

90% PopIII

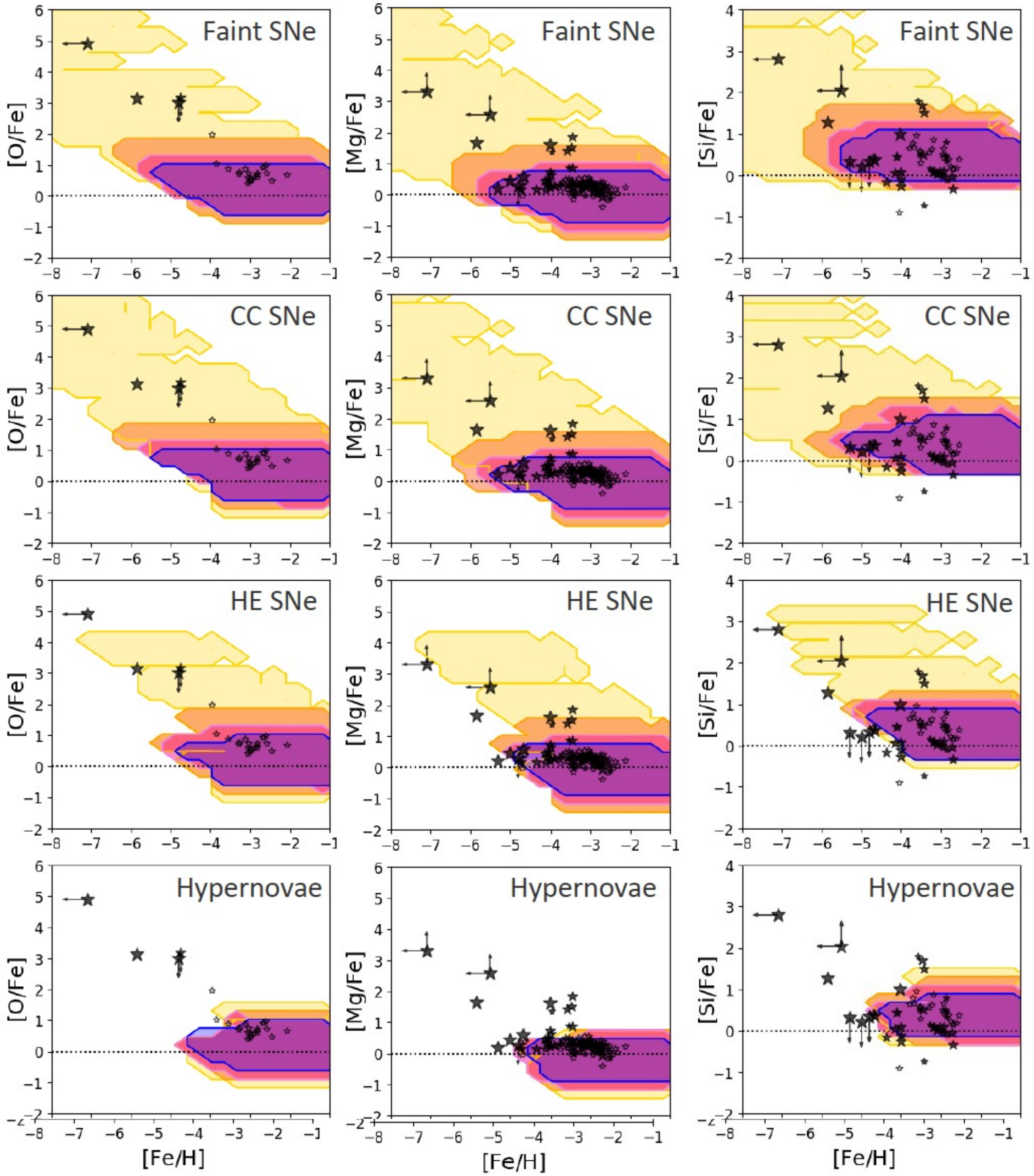
70% PopIII

50% PopIII

The most Fe-poor CEMP-no are truly 2nd generation stars!

DIFFERENT CHEMICAL ELEMENTS

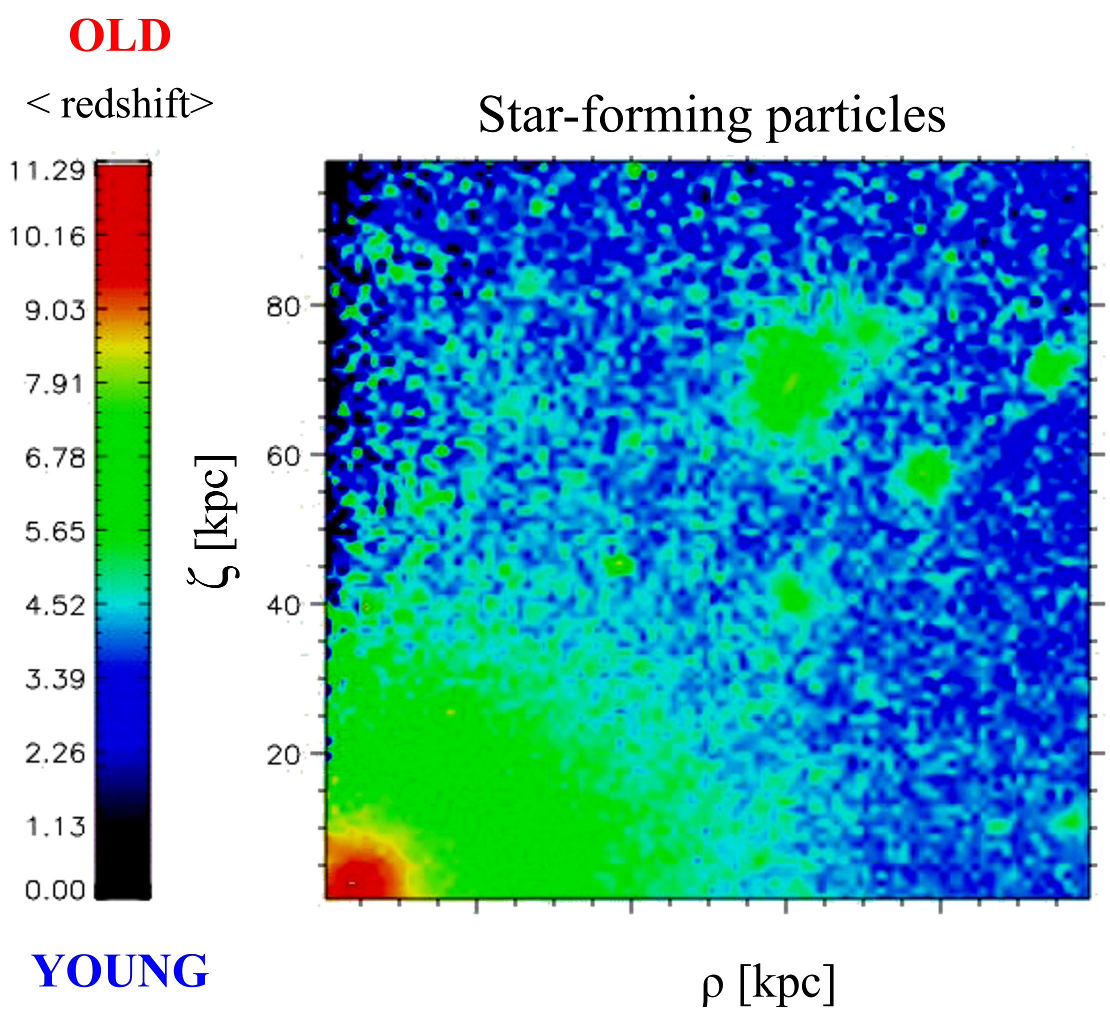
Vanni, SS, Skuladottir et al. to be submitted



N-BODY SIMULATION FOR THE LOCAL GROUP

Koutsouridou, SS, Skuladottir + submitted

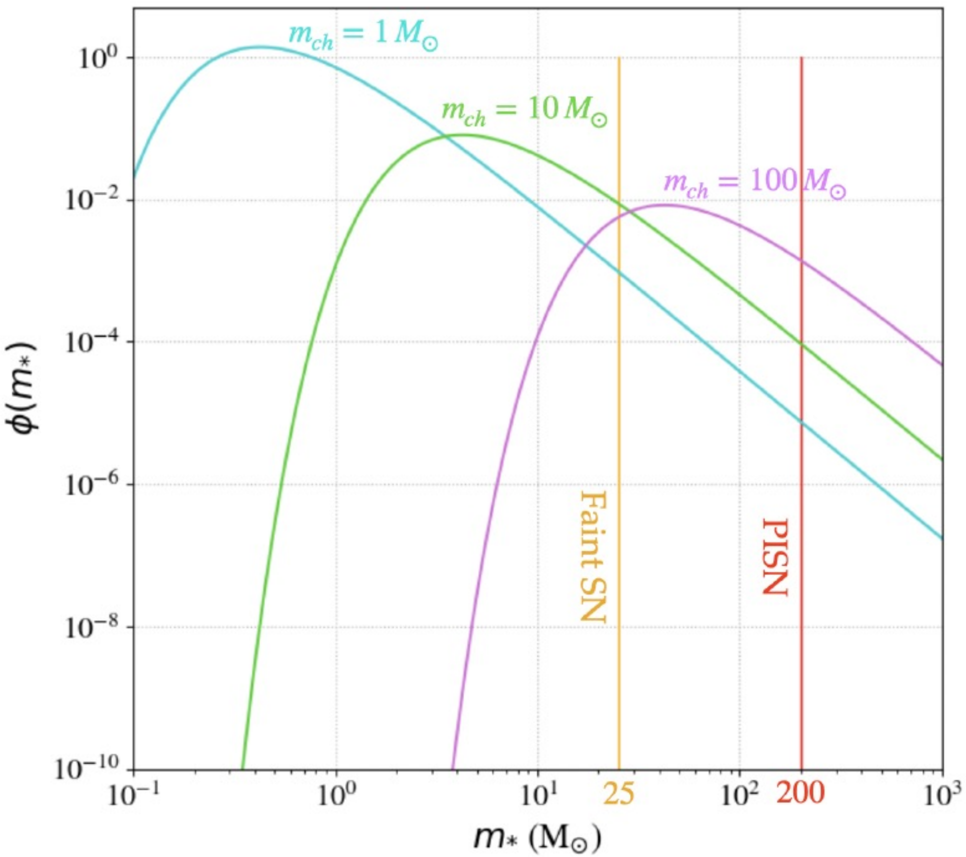
N-body simulation of a Milky Way analogue
+ semi-analytical chemical evolution model



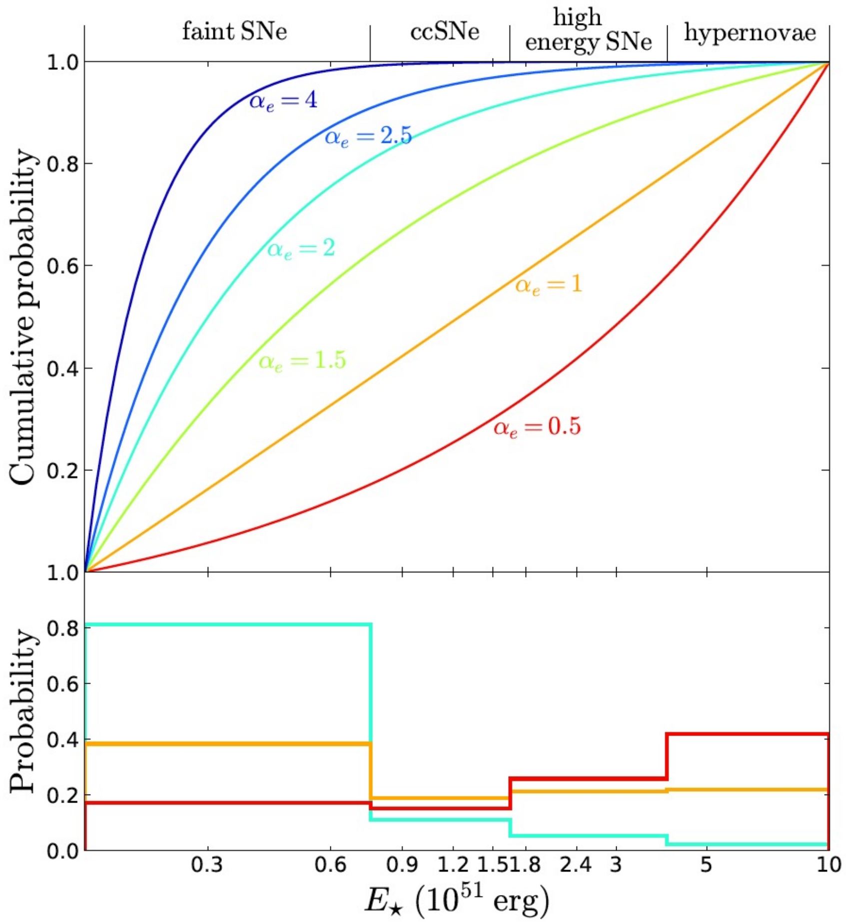
THE POPIII MASS & ENERGY DISTRIBUTIONS

Koutsouridou, SS, Skuladottir + submitted

IMF $\propto m^{-2.35} \exp(m_{ch}/m_*)$

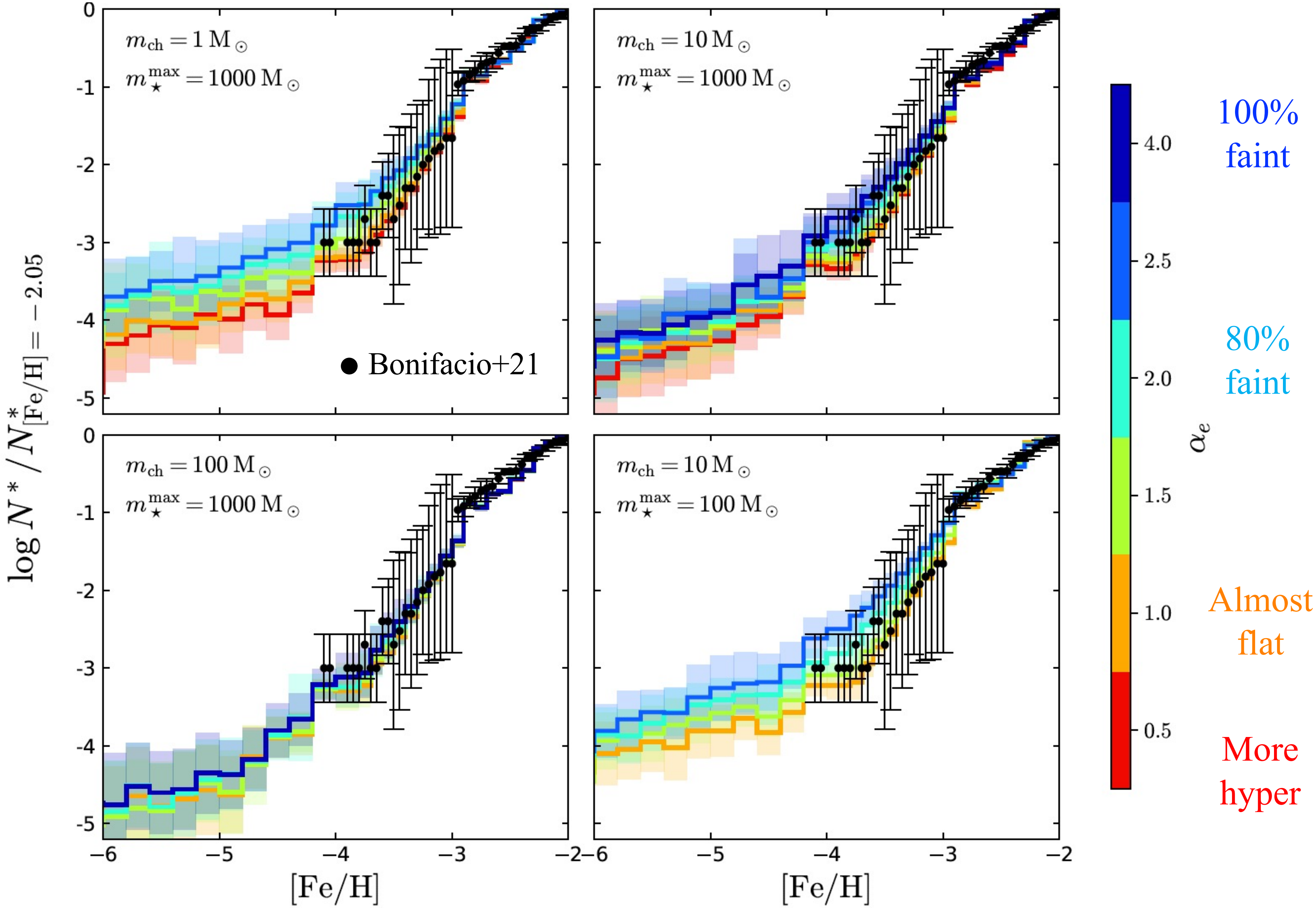


Energy Distribution Function



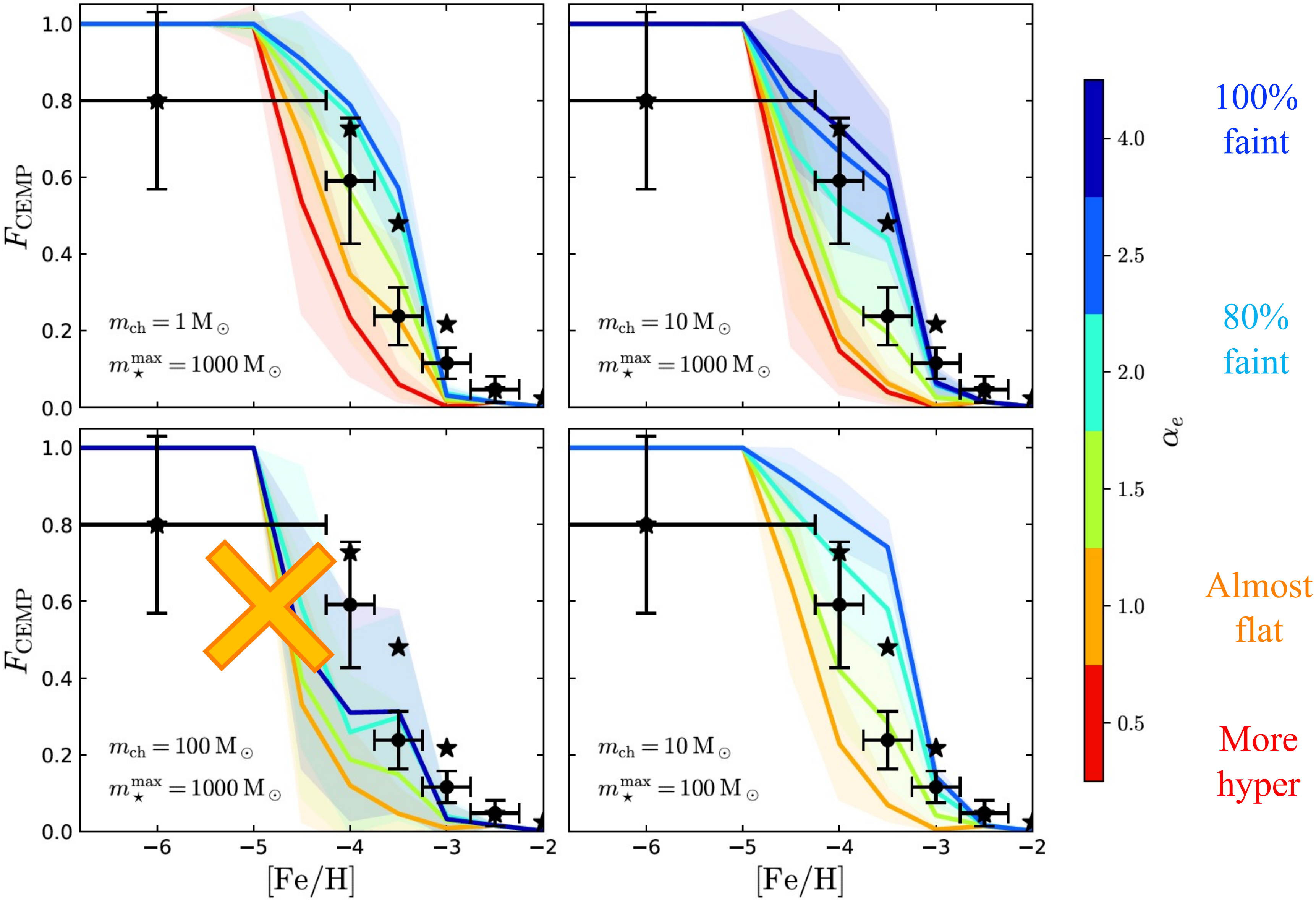
METALLICITY DISTRIBUTION FUNCTION

Koutsouridou, SS, Skuladottir + submitted



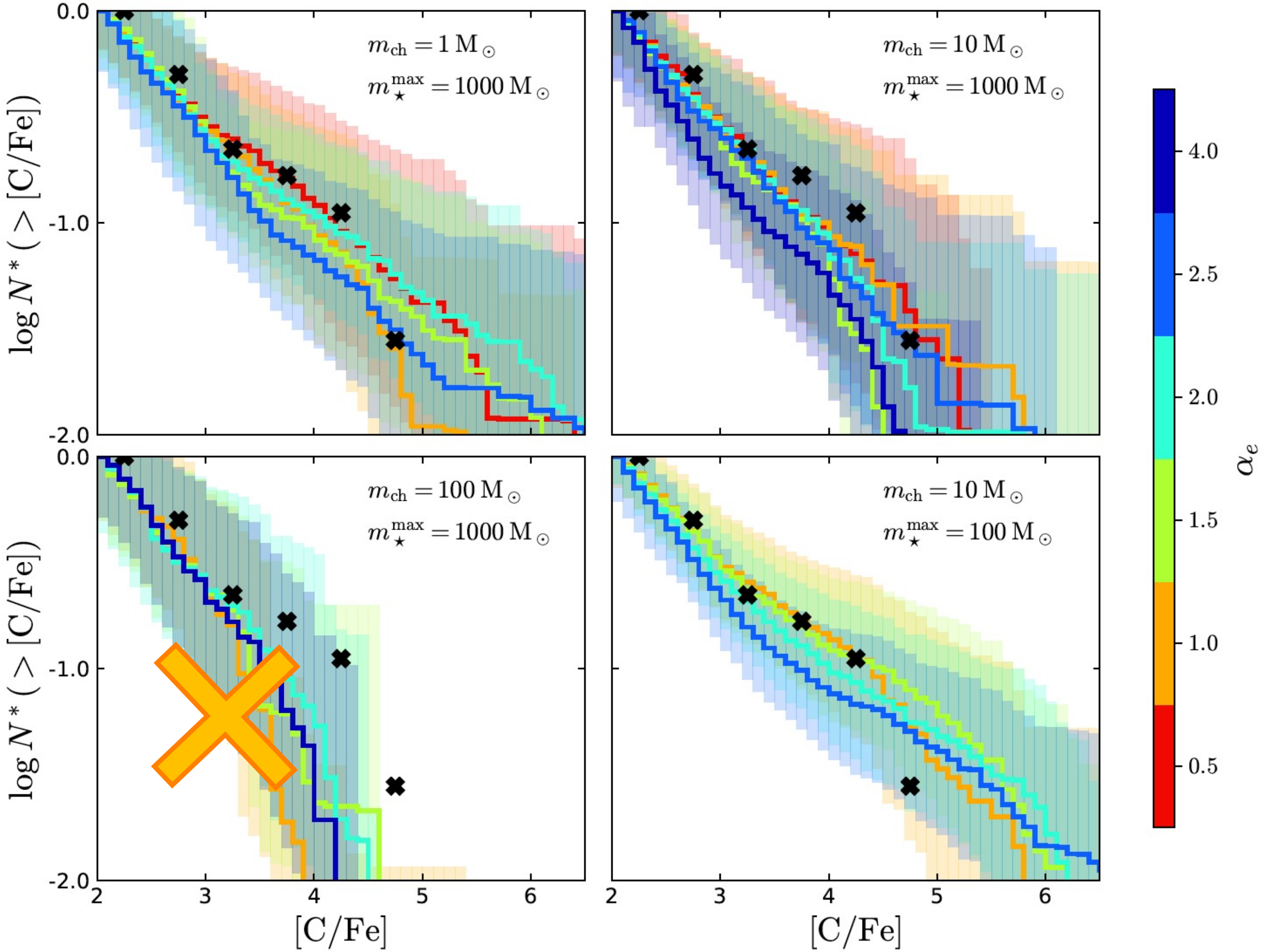
FRACTION OF CEMP-no STARS

Koutsouridou, SS, Skuladottir + submitted



CARBONICITY DISTRIBUTION FUNCTION

Koutsouridou, SS, Skuladottir + submitted



100% faint

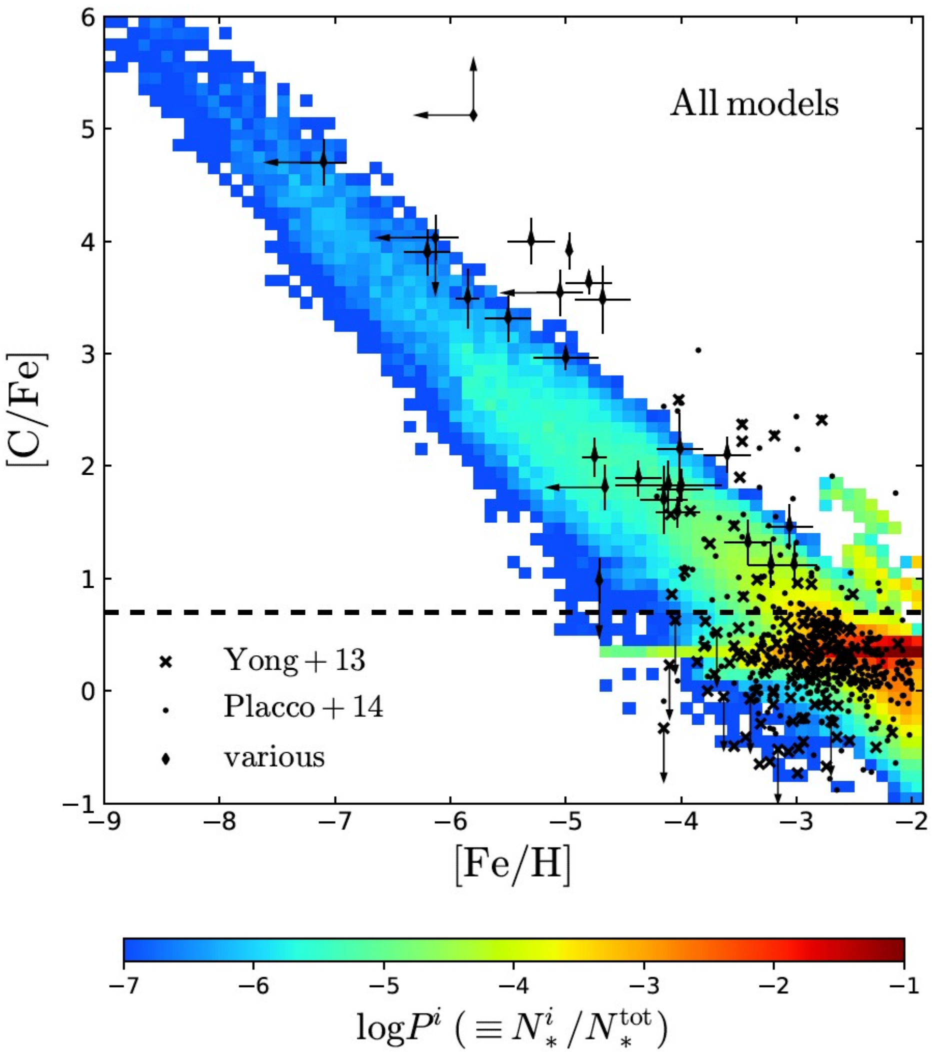
80% faint

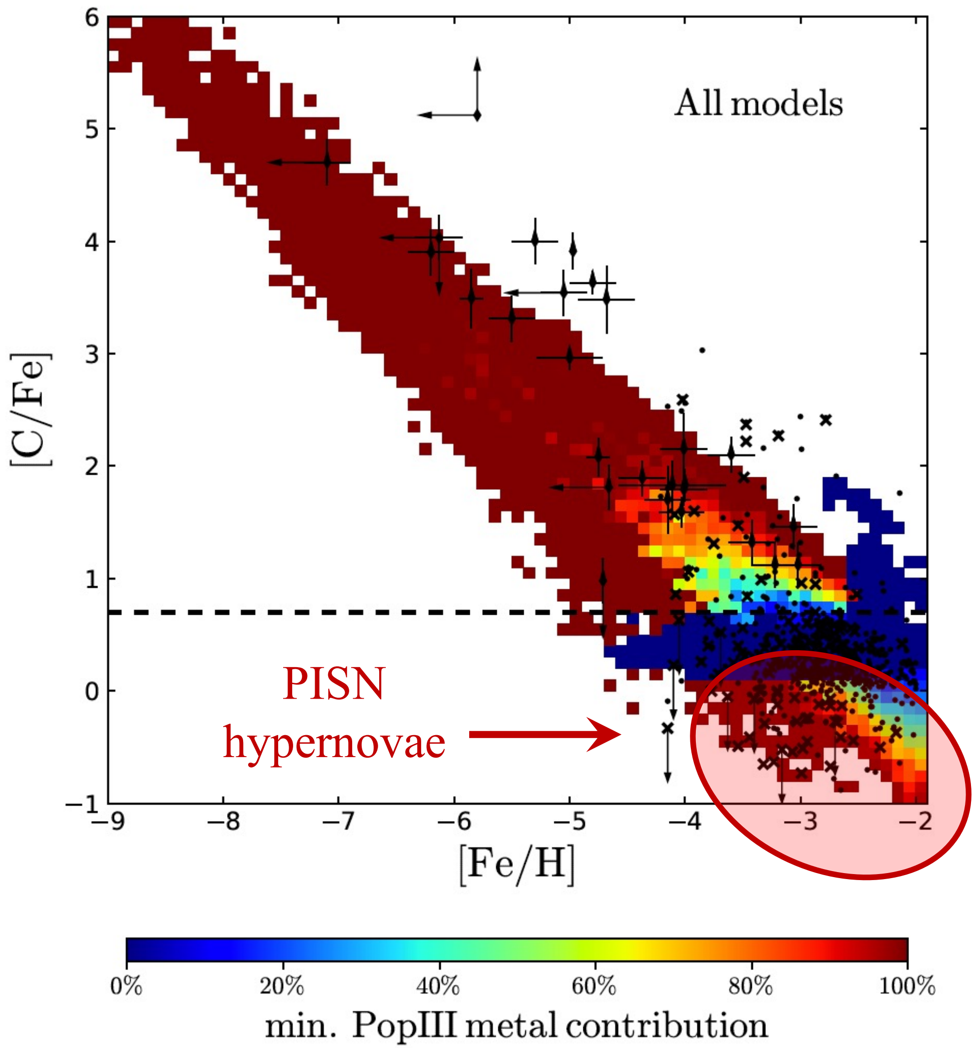
Almost flat

More hyper

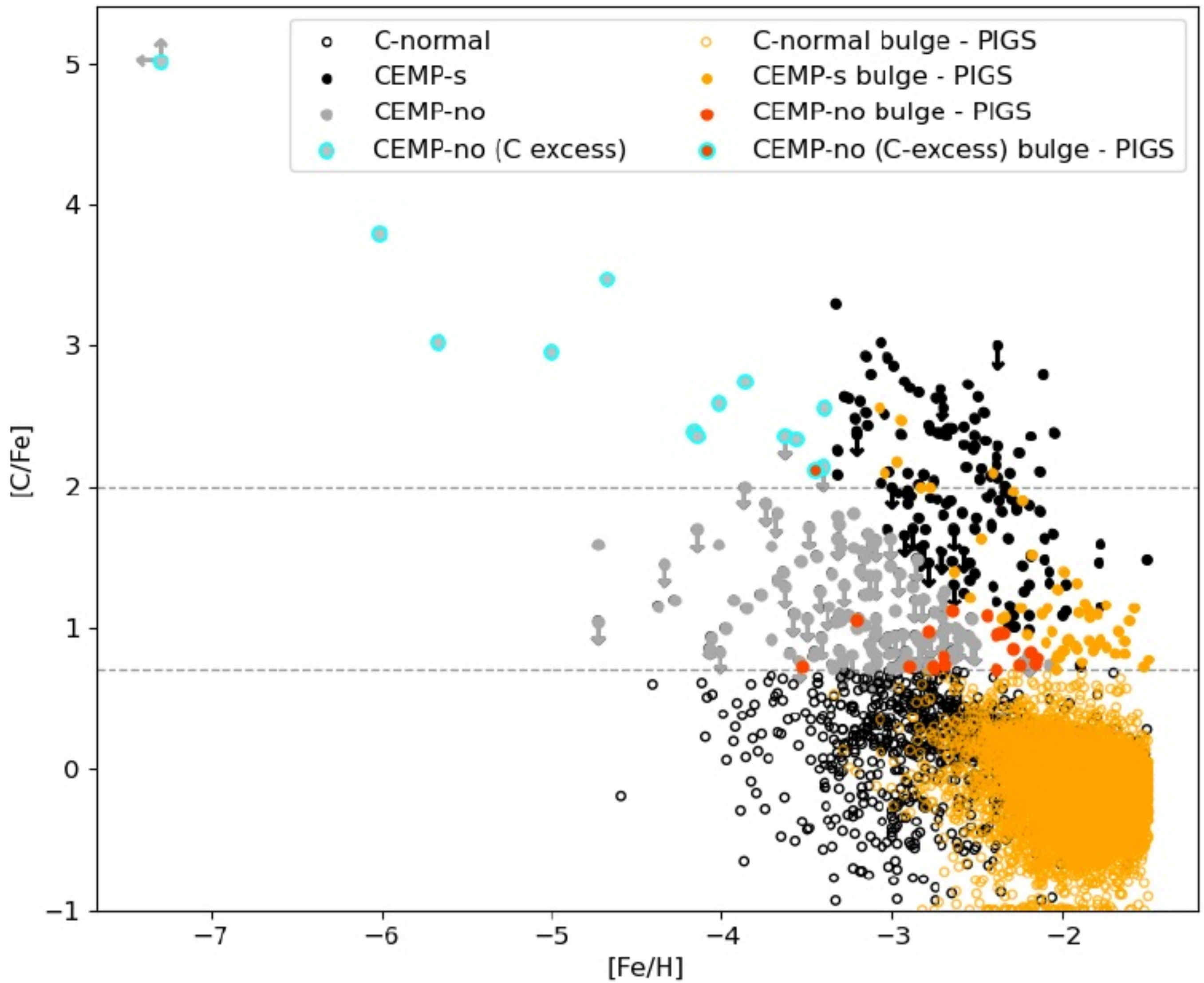
GENERAL PROPERTIES: CEMP vs C-NORMAL STARS

Koutsouridou, SS, Skuladottir + submitted





LACK OF VERY C-RICH STARS IN THE BULGE

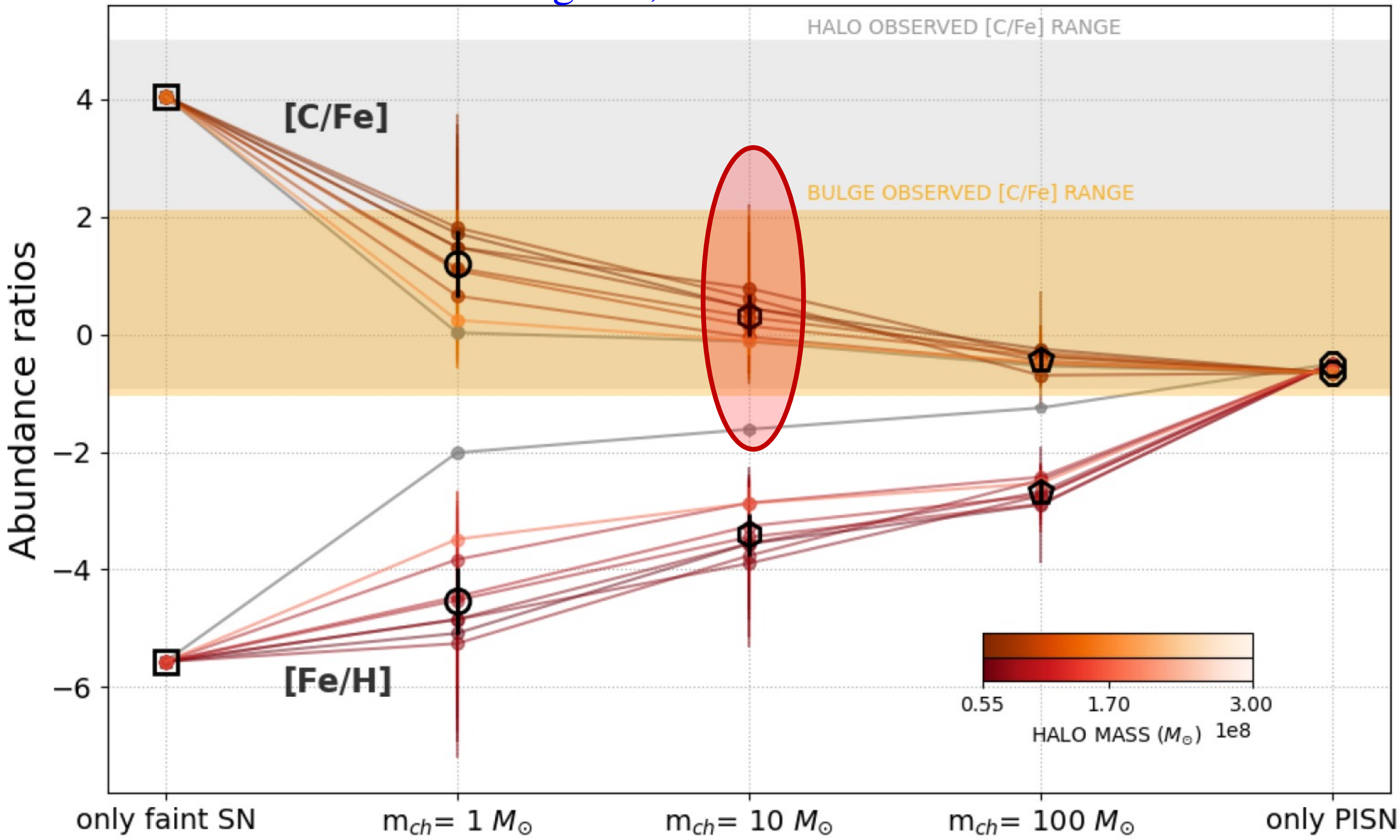


Lack of CEMP-no stars with [C/Fe] > + 2.5 (Howes+2015;2016)
also confirmed by the PIGS (Pristine) survey (see Aarentsen+21)

AN INDIRECT PROBE OF MASSIVE FIRST STARS?

Following the chemical evolution of the first star forming halos currently located into the bulge and assuming different first star mass distributions

Pagnini, SS et al. 2023

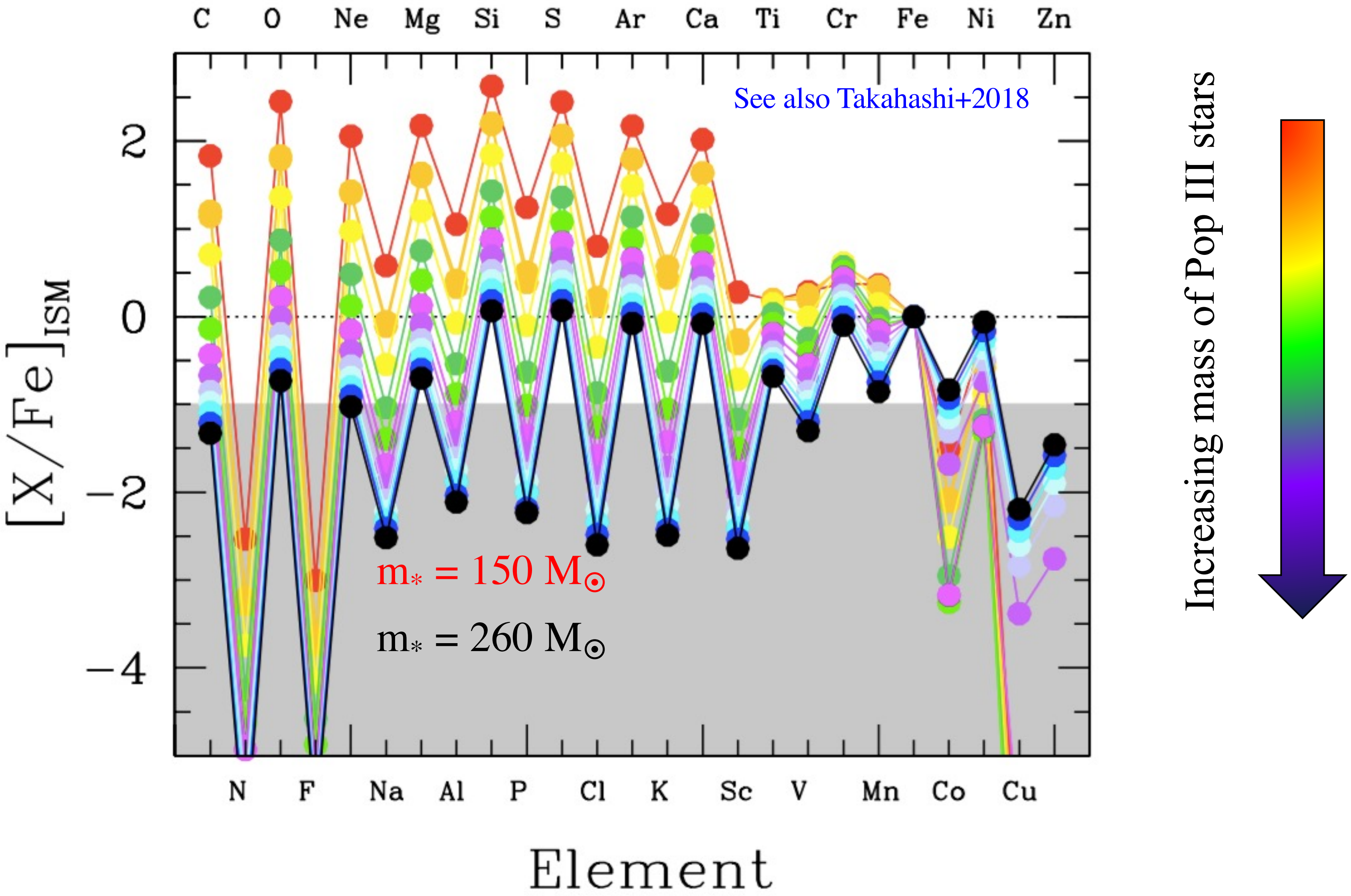


A single PISN decrease the [C/Fe] value → the dearth of CEMP stars probe PISN!

THE CHEMICAL IMPRINT OF PISN

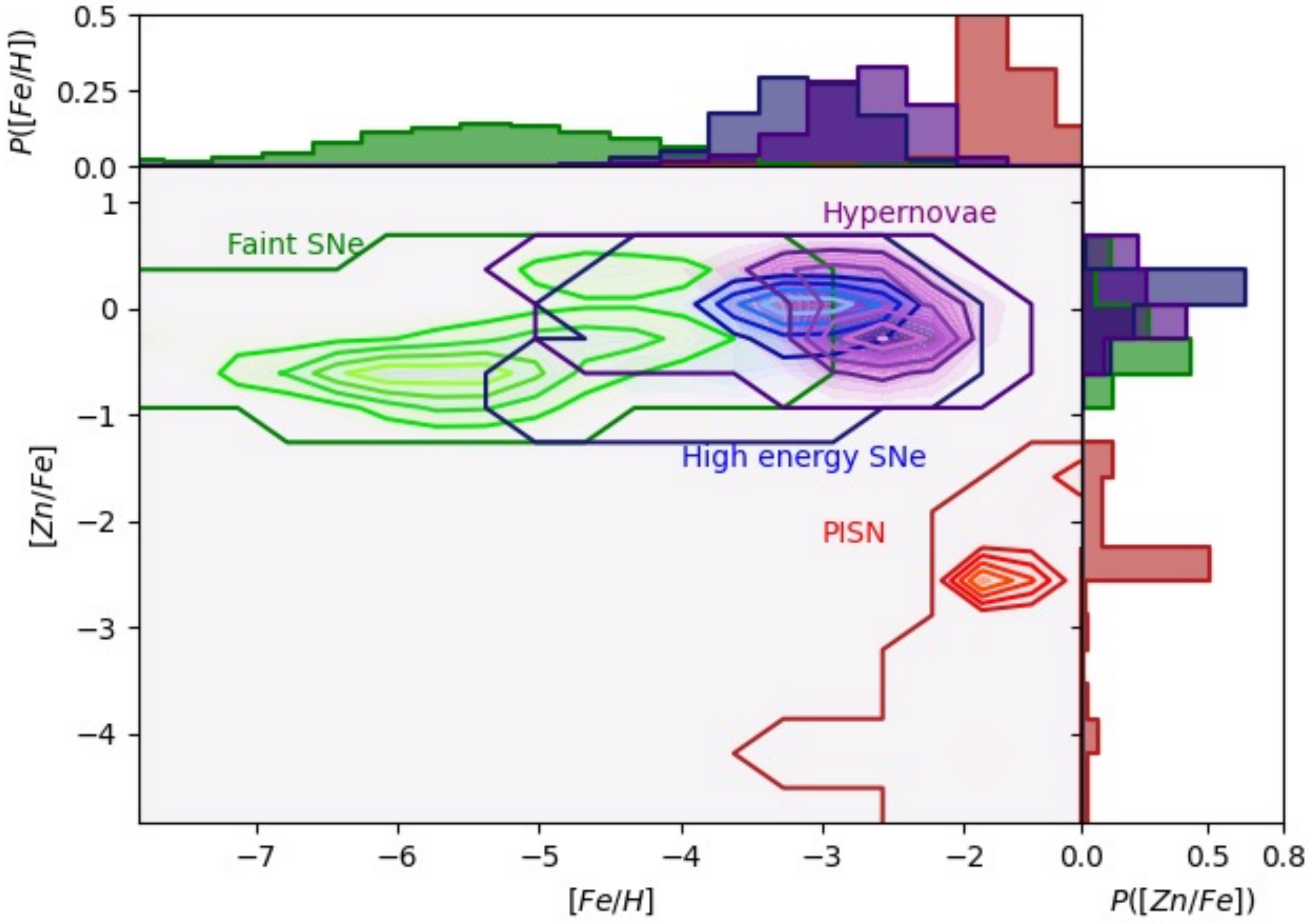
SS, Bonifacio, Caffau +19

Abundance pattern of an ISM enriched by as single massive first star



THE CHEMICAL IMPRINT OF PISN

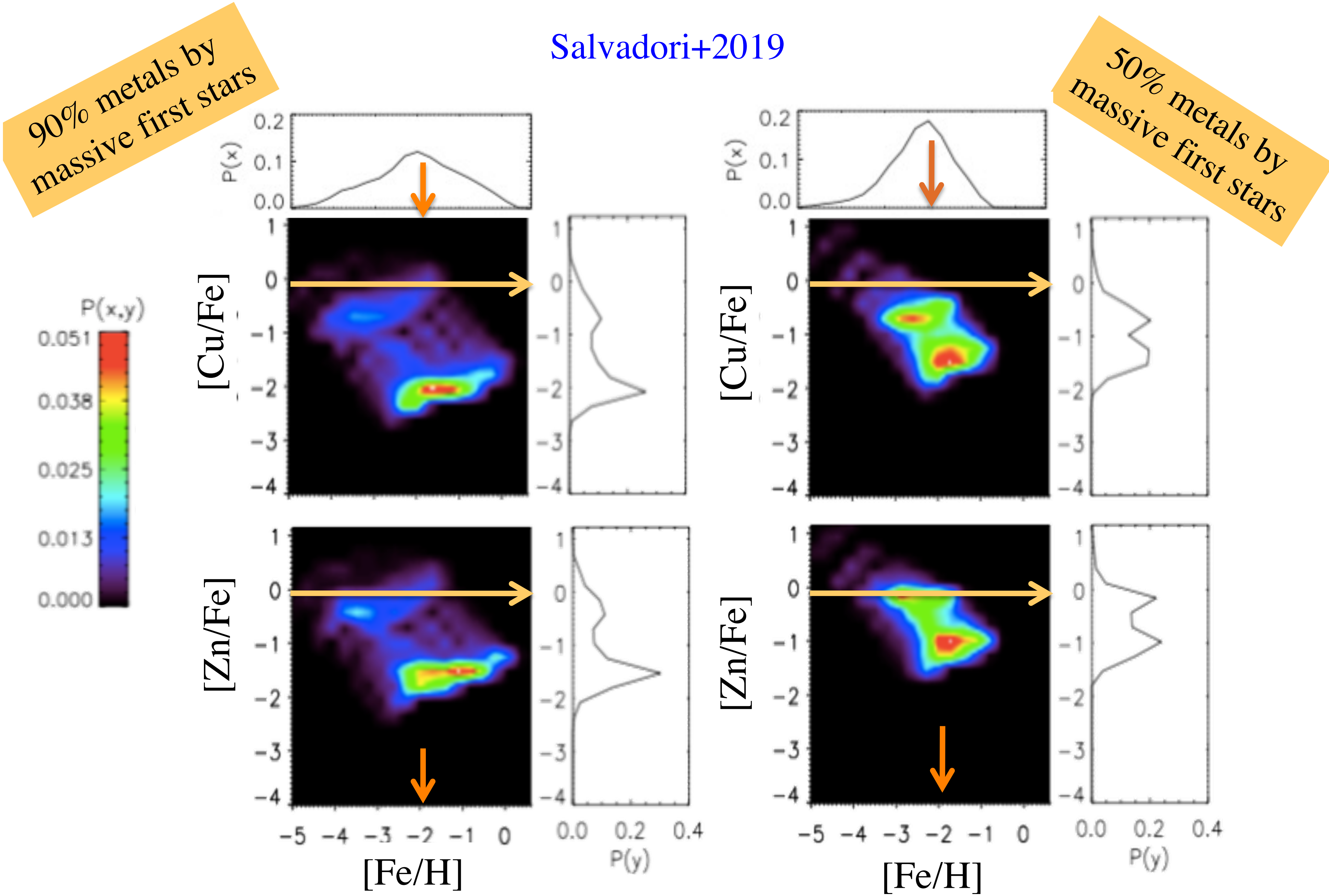
Very massive first stars exploding as PISN produce small zinc-to-iron ratios (and Cu)!



Vanni, SS, Skuladottir + in prep.

“KILLING ELEMENTS” FOR MASSIVE FIRST STARS

Salvadori+2019



PROBLEM: ONLY FEW Zn MEASUREMENTS

THE PISN-EXPLORER

Aguado, SS, Skuladottir, Bonifacio, Caffau, Vanni, Koutsouridou, Gelli 2023

Exploiting all the available elements and the full chemical abundance patterns predicted by models to identify candidates PISN descendants in available surveys

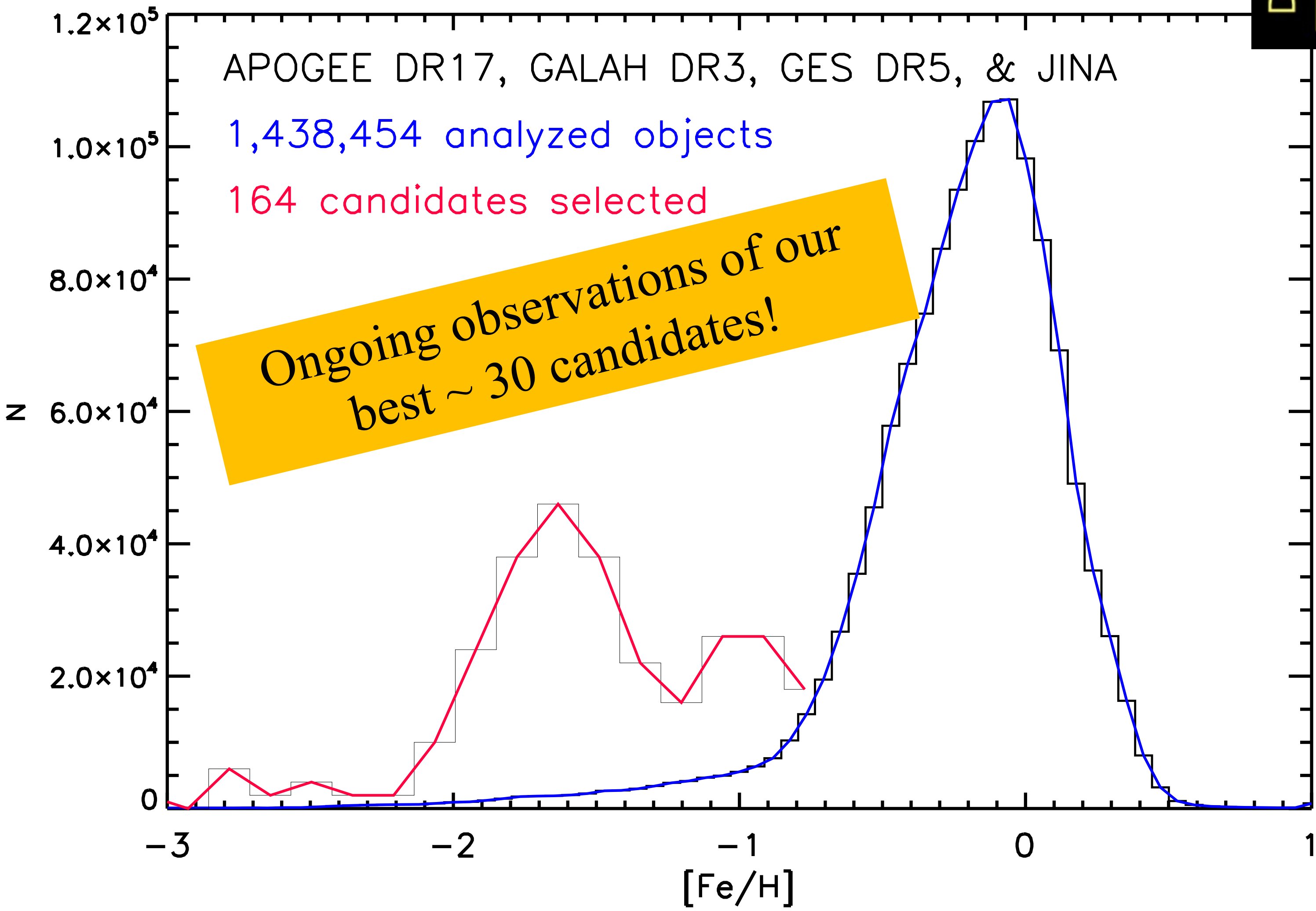
Theoretical predictions (SS+19) for stars born in ISM predominantly polluted by massive first stars exploding as PISN (>50% of metals)

+

FERRE code (Allende Prieto+06/14; Aguado+17) to efficiently analyze data and interpolate among a grid of models to get the best solution

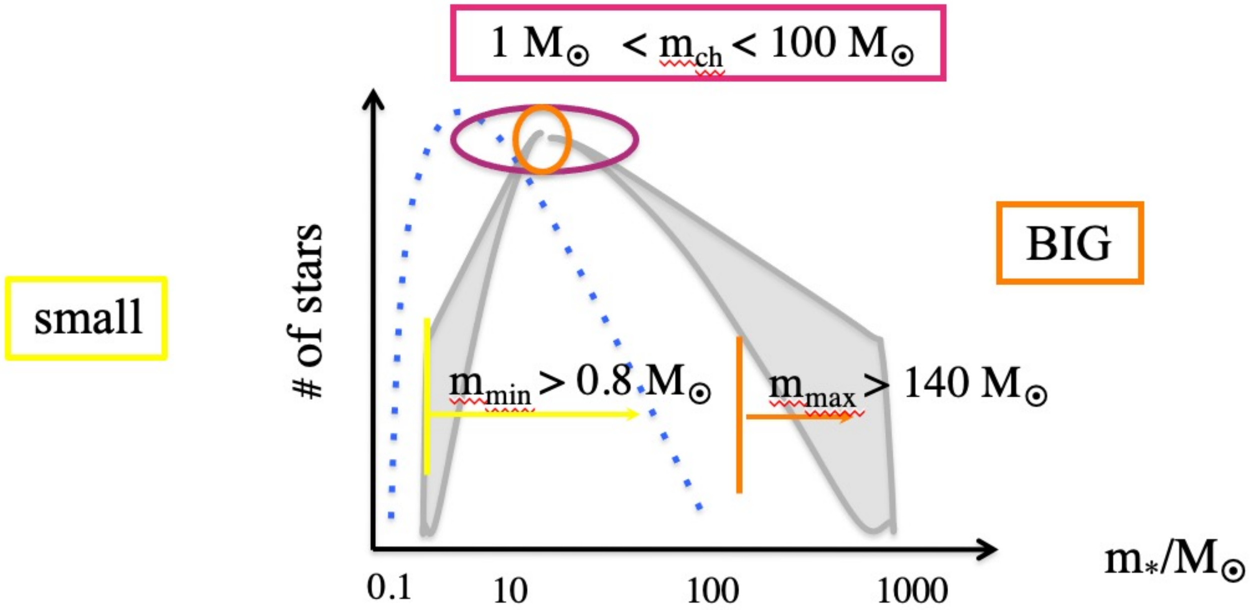
THE PISN-EXPLORER: SELECTING CANDIDATES

Aguado, SS, Skuladottir + 2023



CONCLUSIONS

- Non detection of Z = 0 stars in ultra-faint dwarfs: $m_{min} > 0.8\ M_\odot$ or $m_{ch} > 1\ M_\odot$
- CEMP-no stars are first stars' descendants, imprinted by low/medium-energy Pop III SNe at > 50% level. Those with [C/Fe] > +2 are second-generation stars
- C-normal stars are mainly imprinted by normal Pop II stars → $m_{ch} < 100\ M_\odot$
- The dearth of [C/Fe] > +2 stars in the bulge indirectly probe PISN also setting $m_{ch} \sim 10\ M_\odot$ → PISN-explorer and Zn-surveys to get tighter constraints



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