First Stars and their Local Relics

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DAVID

The Dark Ages VIrtual Department

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Sequence of events

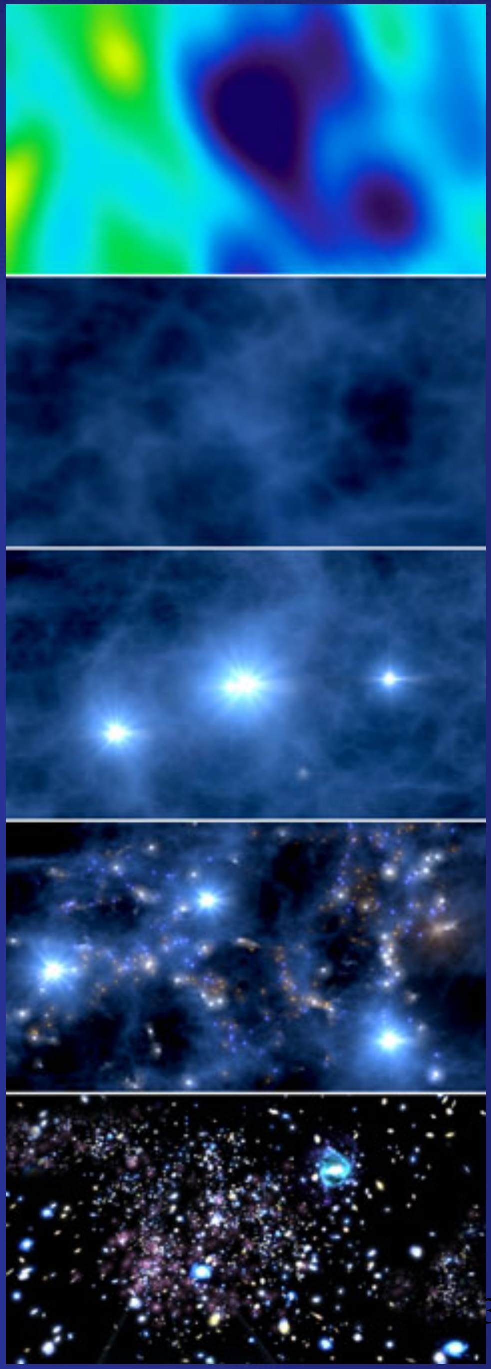
At z=1000 the Universe has cooled down to 3000 K. Hydrogen becomes neutral ("Recombination").

At z < 20 the first "PopIII" star (clusters)/small galaxies form.

At z ~ 6-15 these gradually photo-ionize the hydrogen in the IGM ("Reionization").

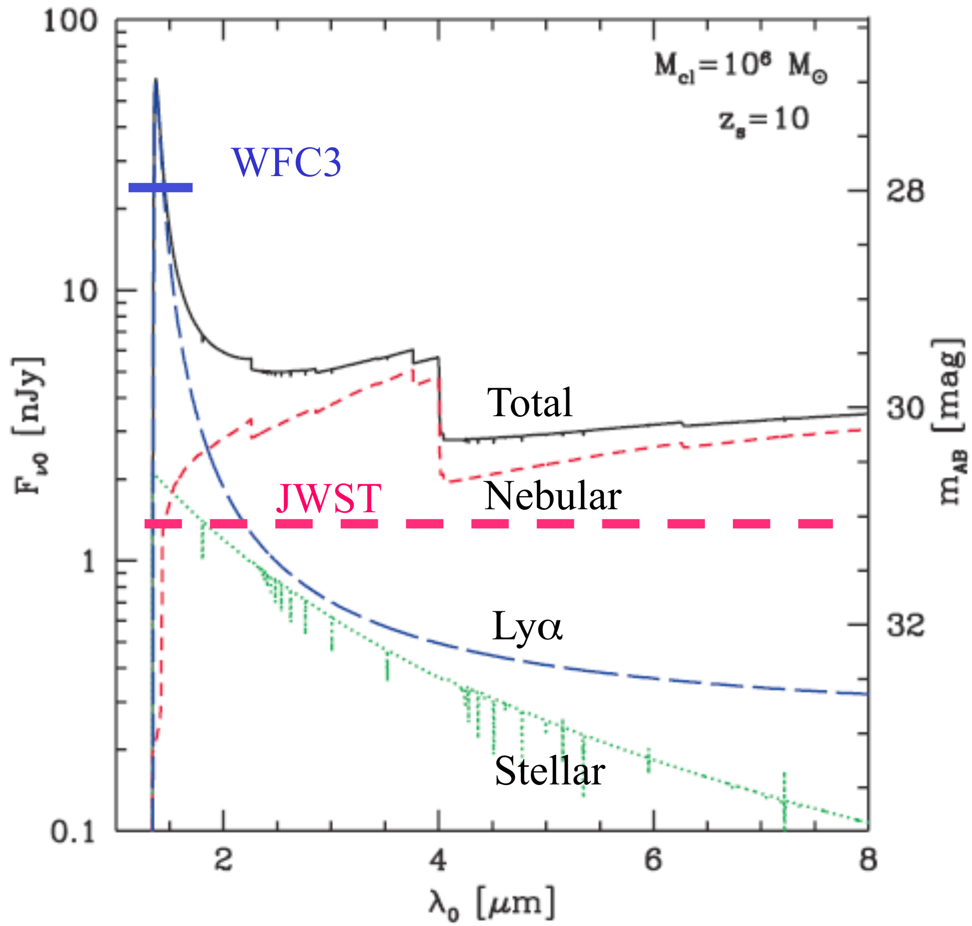
At z<6 galaxies form most of their stars and grow by merging.

At z<1 massive galaxy clusters are assembled.



Time

DIRECT DETECTABILITY

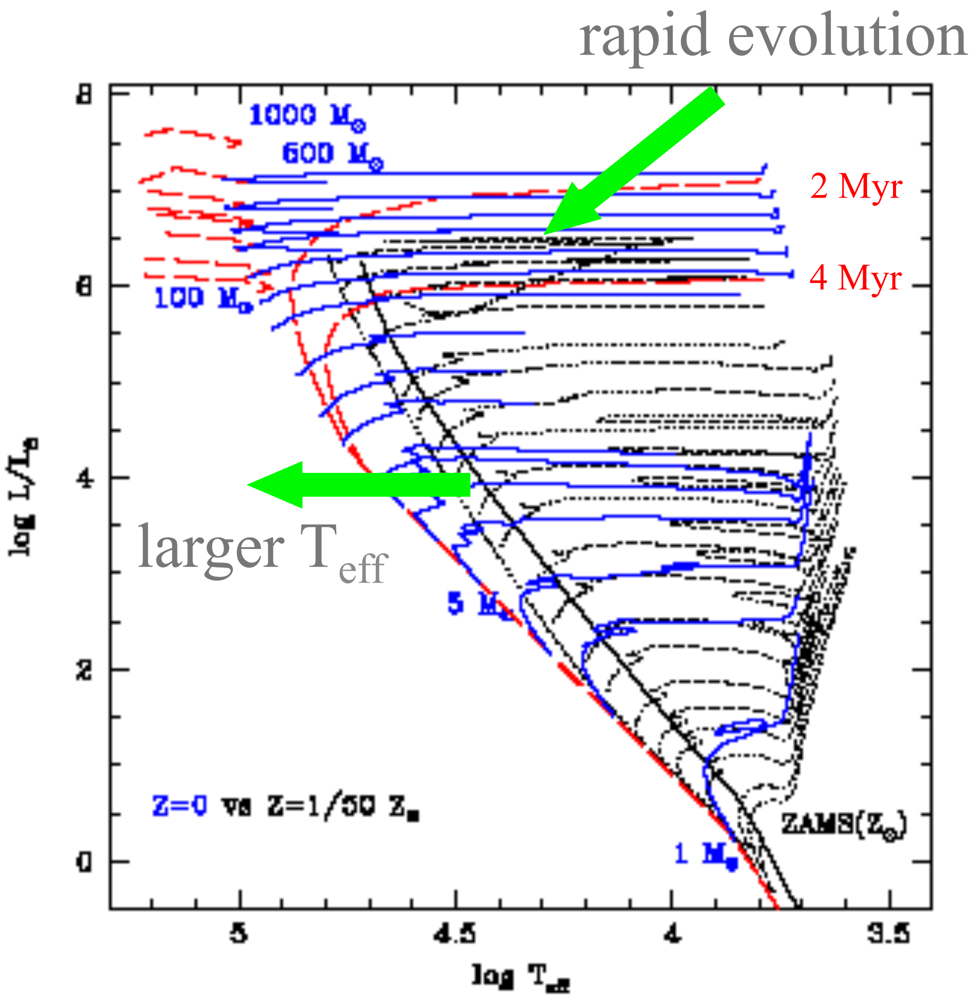


Pop III cluster

$M = 10^6\, M_\odot$
$z = 10$
$M_\star = 300\, M_\odot$

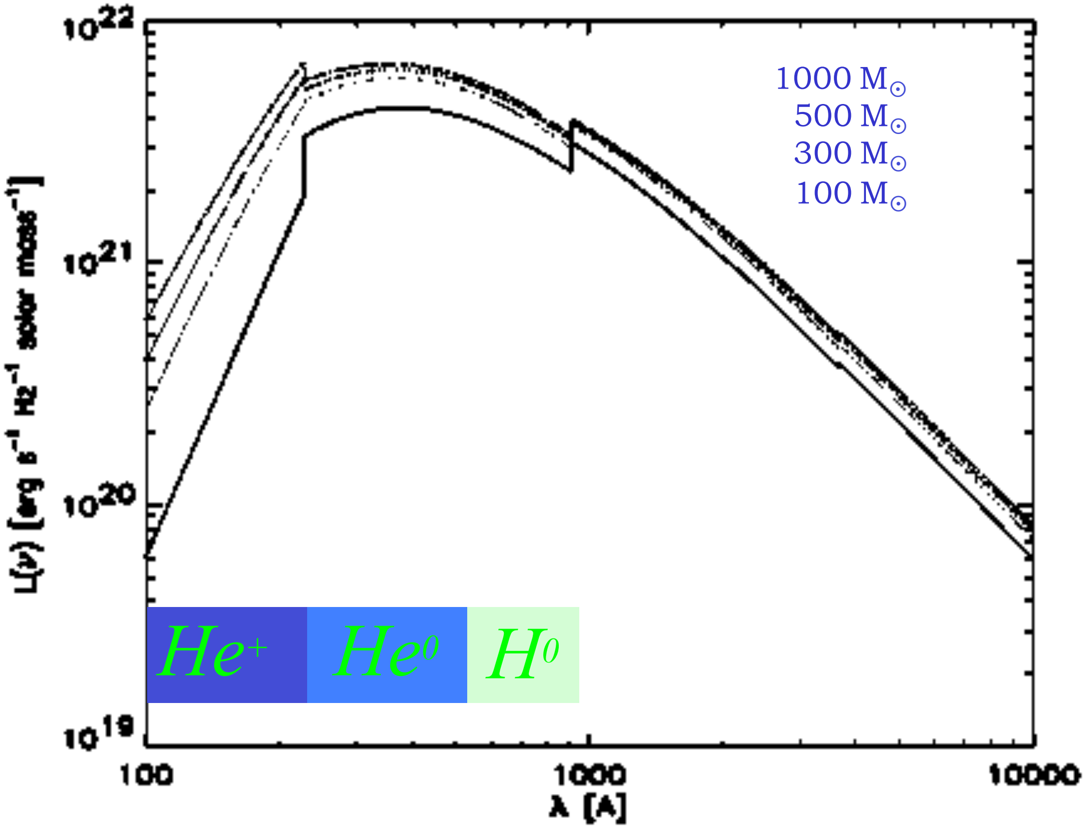
Schaerer 2002

STELLAR TRACKS



Bromm+ 2001

EMISSION SPECTRUM



IONIZING POWER

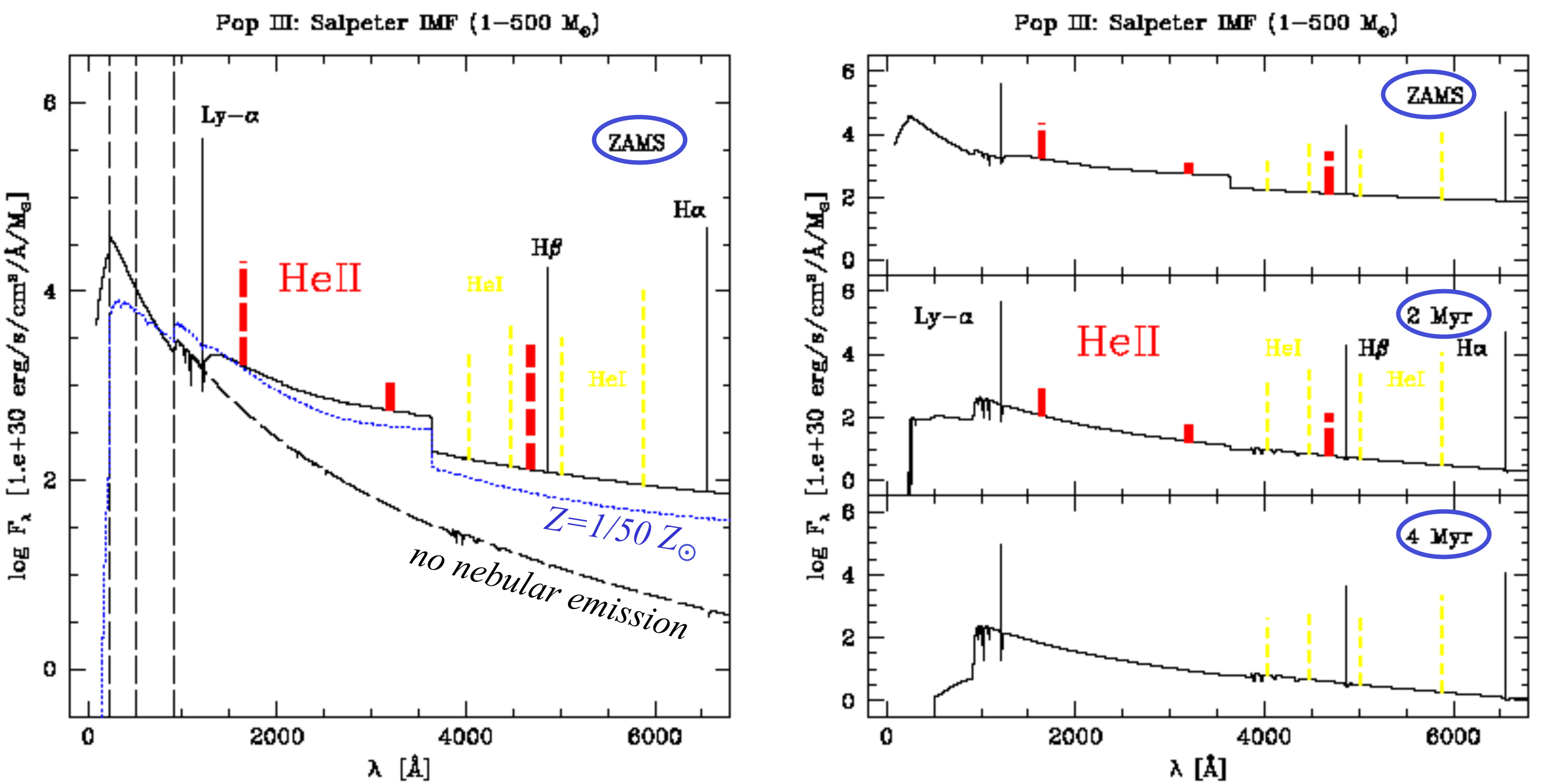
$$Q_i = 4\pi R_\star^2 q_i = 4\pi R_\star^2 \int_{\nu_i}^{\infty} \frac{F_\nu}{h\nu} d\nu, \qquad \bar{Q}_i(M) = \frac{\int_0^{t_\star(M)} Q_i(t, M) dt}{t_\star(M)},$$

Time-averaged quantities

$M_{\rm ini}$	lifetime	$\bar{Q}$(H)	$\bar{Q}(\mathrm{He}^0)$	$\bar{Q}(\mathrm{He}^+)$	$\bar{Q}(\mathrm{H}_2)$	$\bar{Q}(\mathrm{He}^0)/\bar{Q}(\mathrm{H})$	$\bar{Q}(\mathrm{He}^+)/\bar{Q}(\mathrm{H})$
1000.		not available					
500.00	1.899E+06	6.802E+50	3.858E+50	5.793E+49	7.811E+50	0.567E+00	0.852E-01
400.00	1.974E+06	5.247E+50	3.260E+50	5.567E+49	5.865E+50	0.621E+00	0.106E+00
300.00	2.047E+06	3.754E+50	2.372E+50	4.190E+49	4.182E+50	0.632E+00	0.112E+00
200.00	2.204E+06	2.624E+50	1.628E+50	1.487E+49	2.918E+50	0.621E+00	0.567E-01
120.00	2.521E+06	1.391E+50	7.772E+49	5.009E+48	1.608E+50	0.559E+00	0.360E-01
80.00	3.012E+06	7.730E+49	4.317E+49	1.741E+48	8.889E+49	0.558E+00	0.225E-01
60.00	3.464E+06	4.795E+49	2.617E+49	5.136E+47	5.570E+49	0.546E+00	0.107E-01
40.00	3.864E+06	2.469E+49	1.316E+49	8.798E+46	2.903E+49	0.533E+00	0.356E-02
25.00	6.459E+06	7.583E+48	3.779E+48	3.643E+44	9.387E+48	0.498E+00	0.480E-04
15.00	1.040E+07	1.861E+48	8.289E+47	1.527E+43	2.526E+48	0.445E+00	0.820E-05
9.00	2.022E+07	2.807E+47	7.662E+46	3.550E+41	5.576E+47	0.273E+00	0.126E-05
5.00	6.190E+07	1.848E+45	1.461E+42	1.270E+37	6.281E+46	0.791E-03	0.687E-08
$R_{120/15}$	0.25	74	94	3×10^5	64	1.25	4390

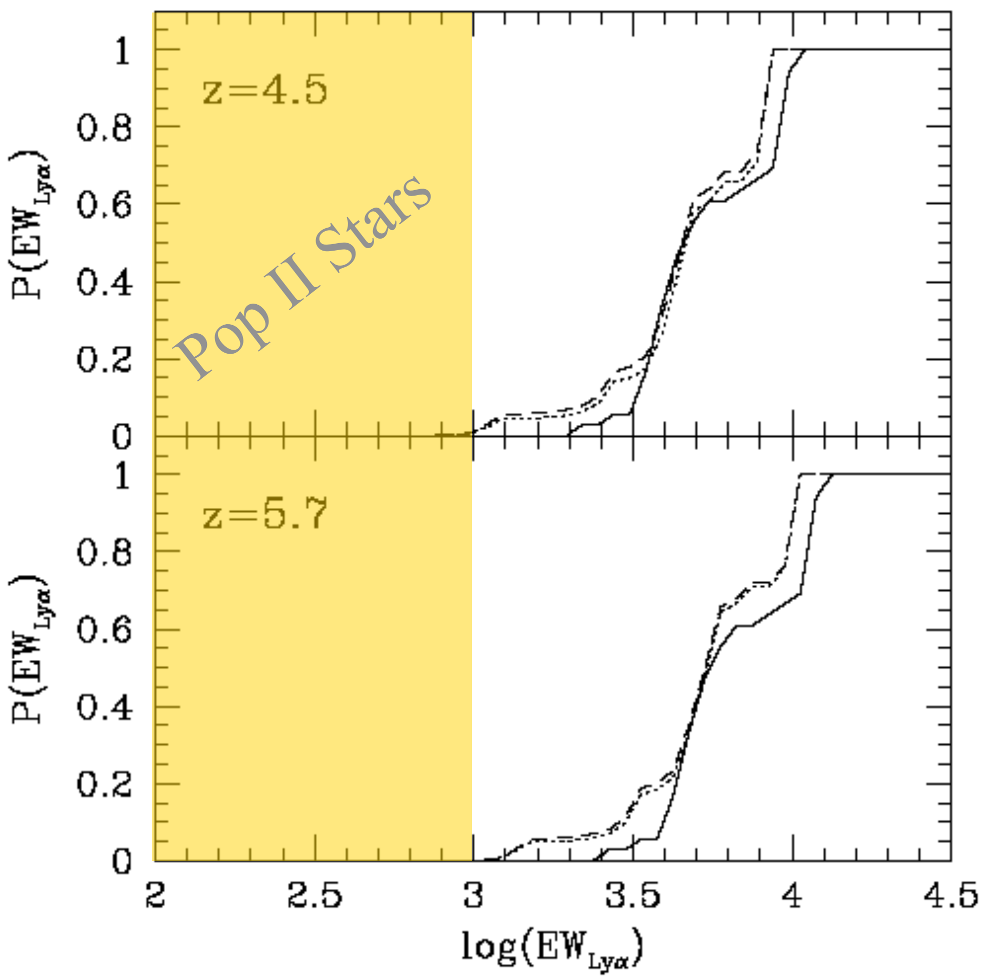
Schaerer 2002

HE NEBULAR LINES



Scannapieco+ 2002

LYA EW OF POP III STARS



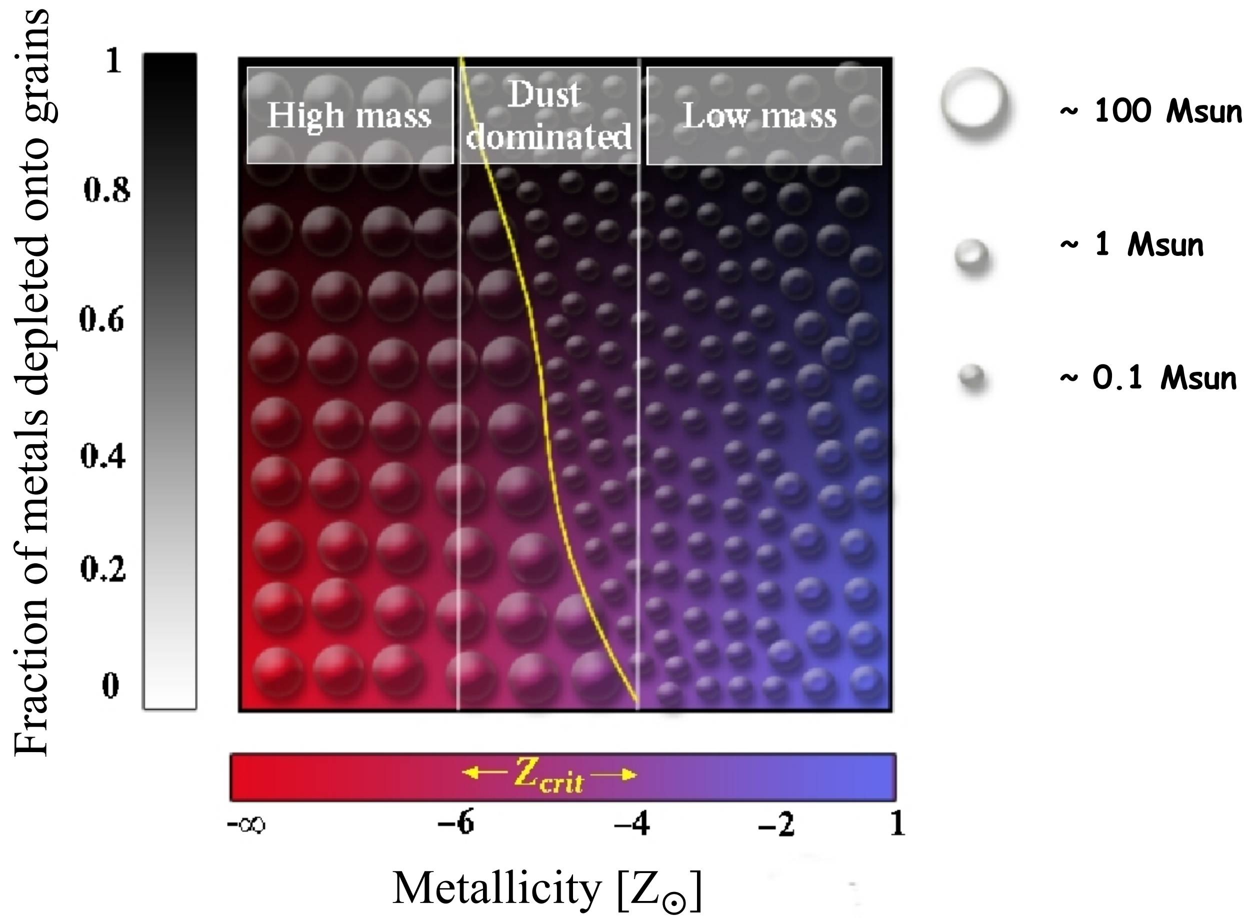
Pop III IMF

Salpeter 50-500 $M_\odot$

Salpeter 1-500 $M_\odot$

Schneider+ 2002, Schneider+ 2006

MASS OF EARLY STARS



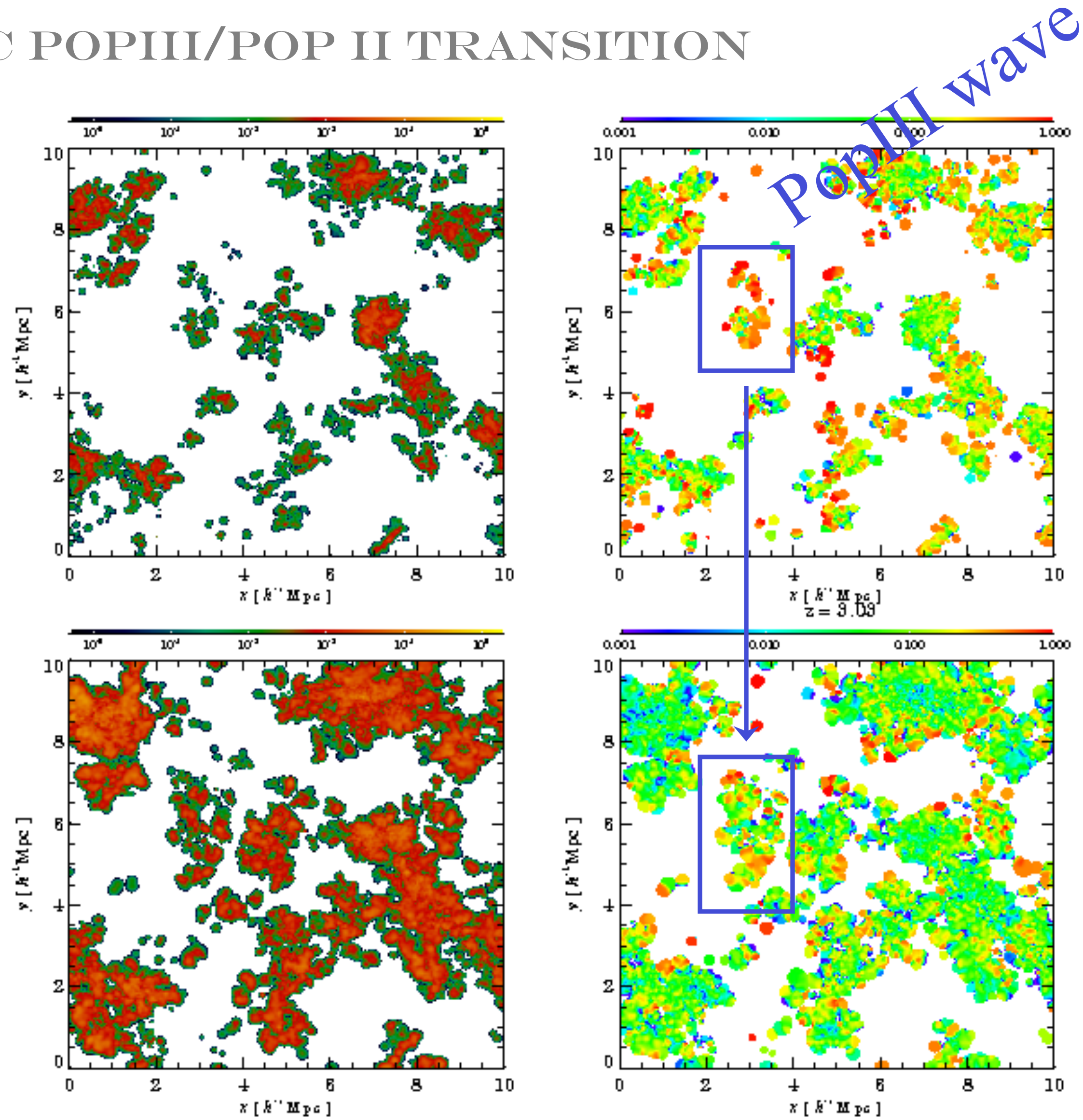
Tornatore, AF & Schneider 2007

COSMIC POPIII/POP II TRANSITION

Total Metallicity

z=5

z=3



z=5

z=3

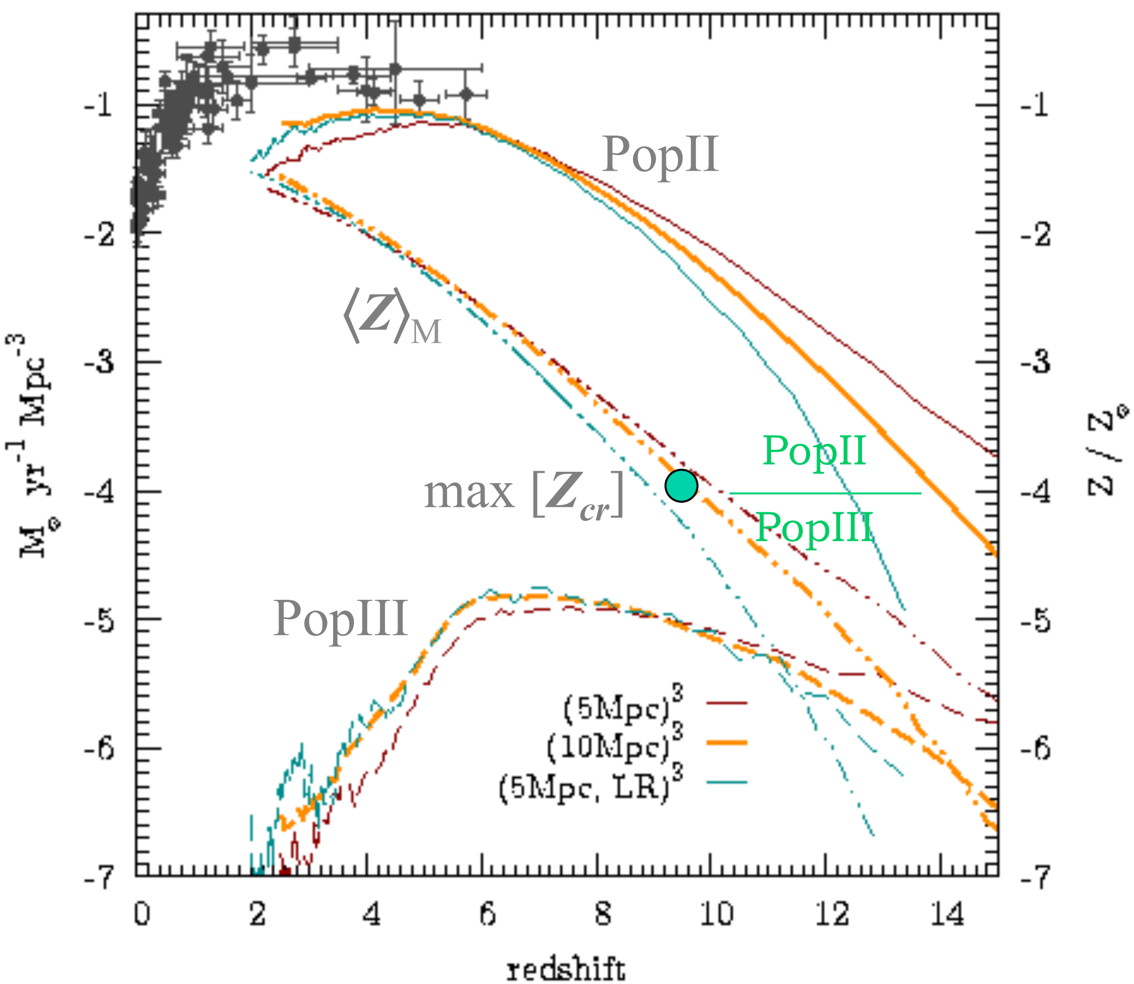
Pop III

Pop II

Fraction of PopIII forming sites

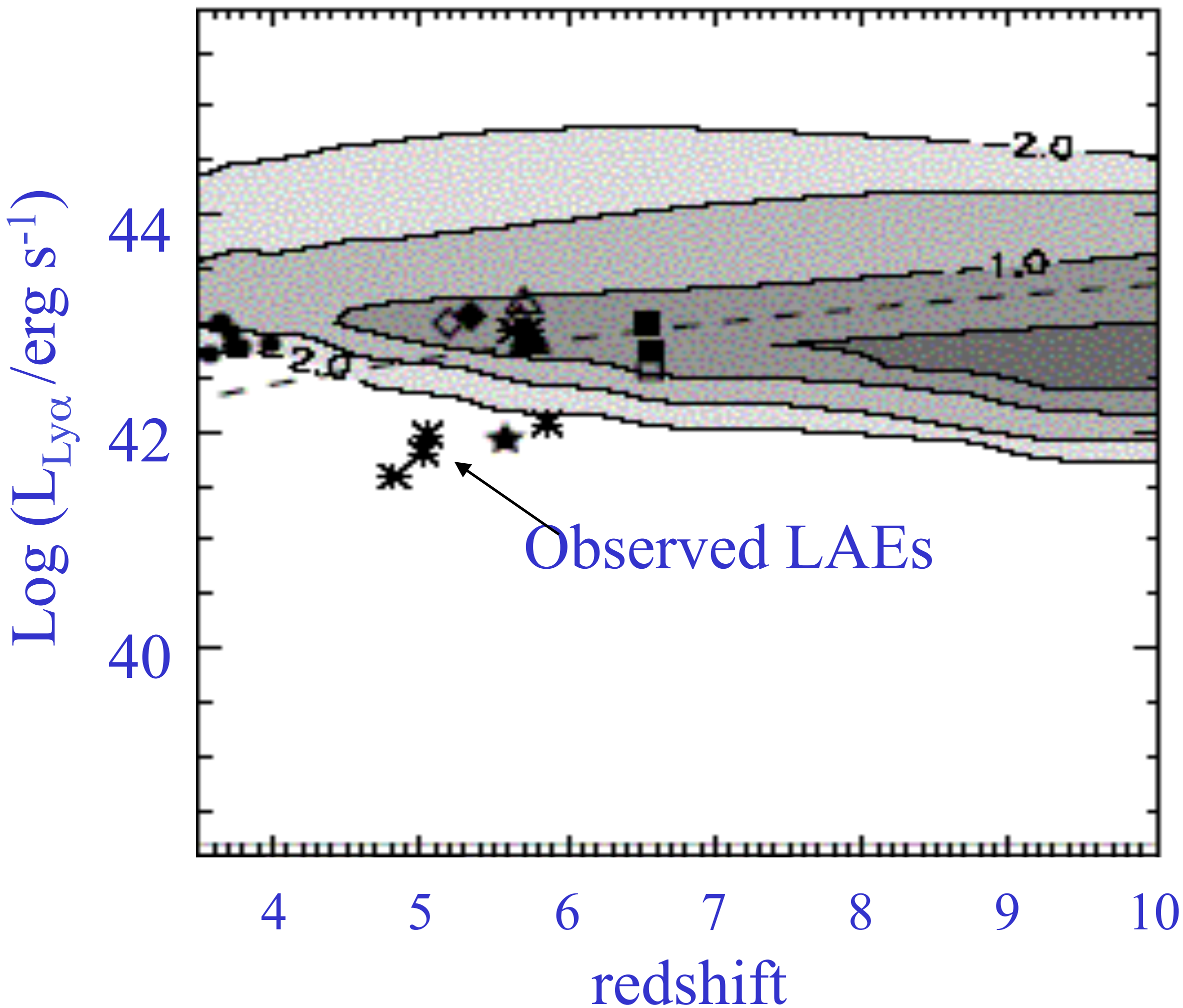
Tornatore, AF & Schneider 2007

STAR FORMATION RATES



Scannapieco+ 2002

POPIII DETECTION PROBABILITY



AVAILABLE SURVEYS

1. HK

Started 1980, 300 plates covering 2800 deg^2 (4100 deg^2) in the Northern (Southern) hemisphere, Plates visual inspection with binocular 10X microscope.Med-red (1 Å) spectroscopic follow-up with 2m-class telescopes

2. Hamburg/ESO Survey (HES)

*Greatly increased numbers. Objective-prism survey, **2 mag deeper than HK**, regions of sky not sampled by HK. 8225 deg^2 above $|b|=30^o$. Selection using automatic spectral classification. Medium-res follow-up using 4m-class telescopes, JHK from 2MASS*

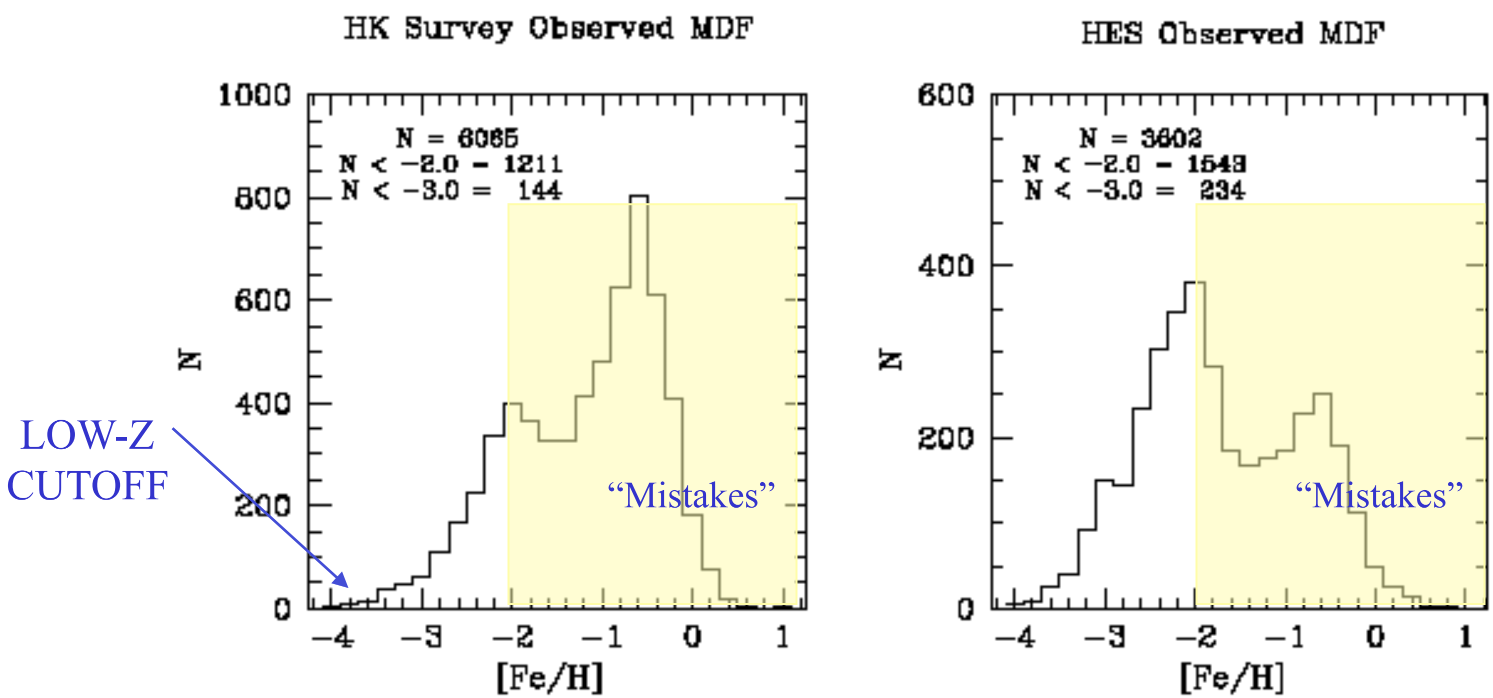
3. Sloan Digital Sky Survey (SDSS)

Med-res spectra + ugriz photometry for about 70000 stars, not targeted specifically to search for metal-poor stars, inhomogeneous assembly. Useful to test the tail of MDF

Table 1. Observational Follow-Up of Surveys

Survey	Spectra	Unique	UBV	JHK
HK	14488	11212	4944	10438
HES	7465	6212	812	5078
SDSS-DR3	71396	$\sim$ 70000	...	...

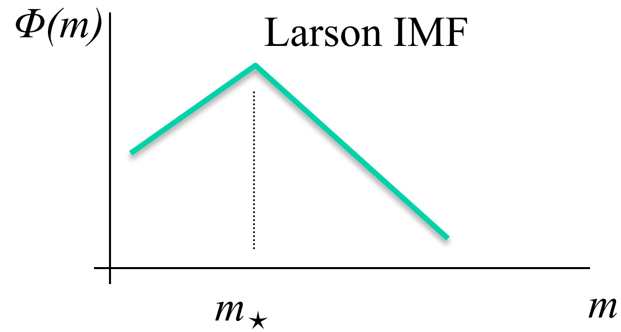
METALLICITY DISTRIBUTION FUNCTION

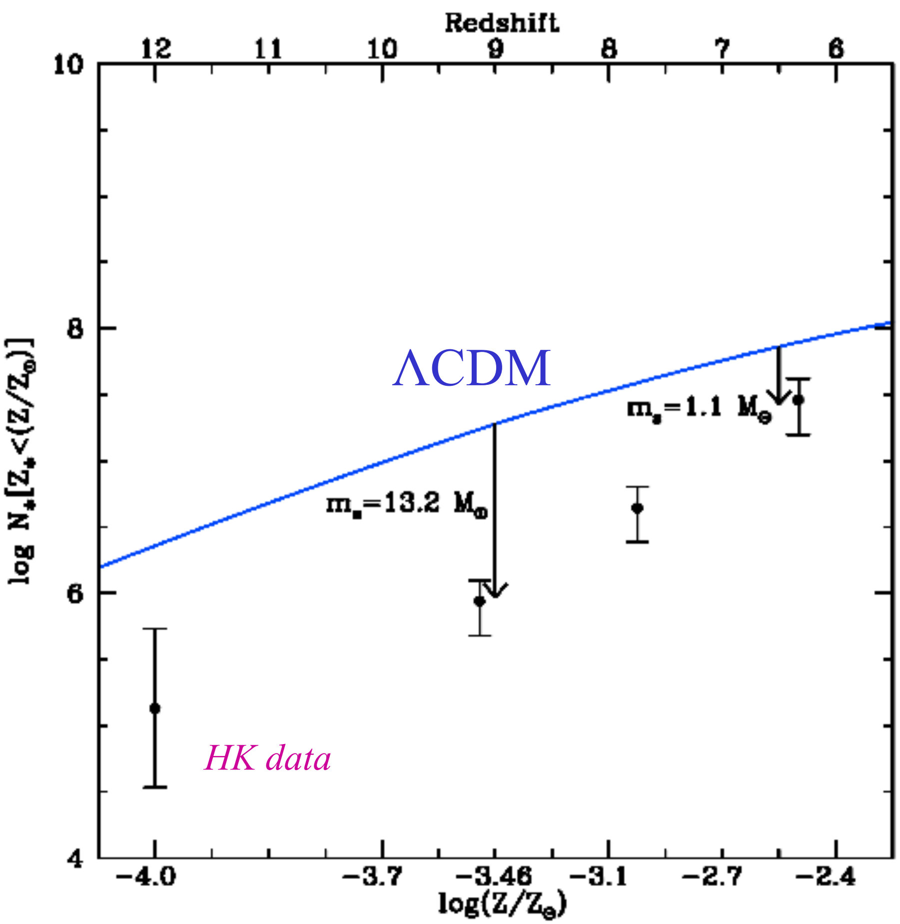


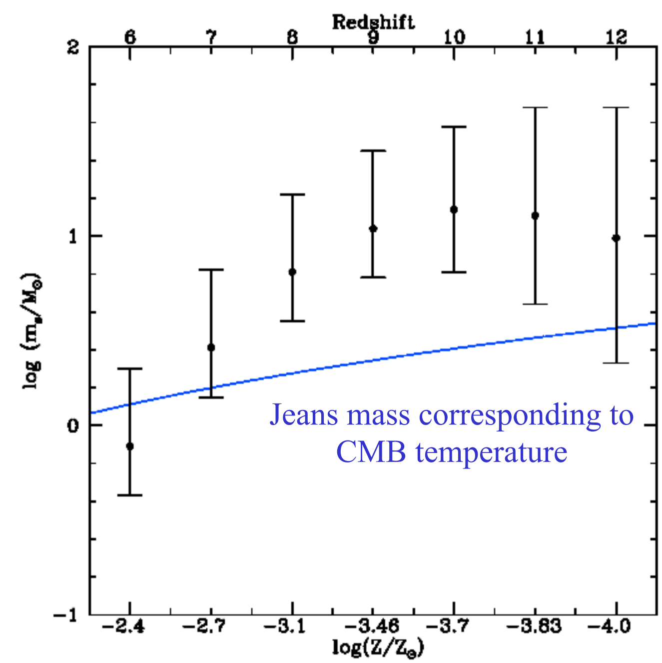
- *Total sample: 2700 stars with [Fe/H]<-2.0 and 400 with [Fe/H]<-3.0*
- *Bias due to selection criterion in the range –2.5 < [Fe/H]<-2.0*
- *Possible underestimate of the metallicity of cooler stars; spectrum-by-spectrum analysis.*

Hernandez & AF 2000

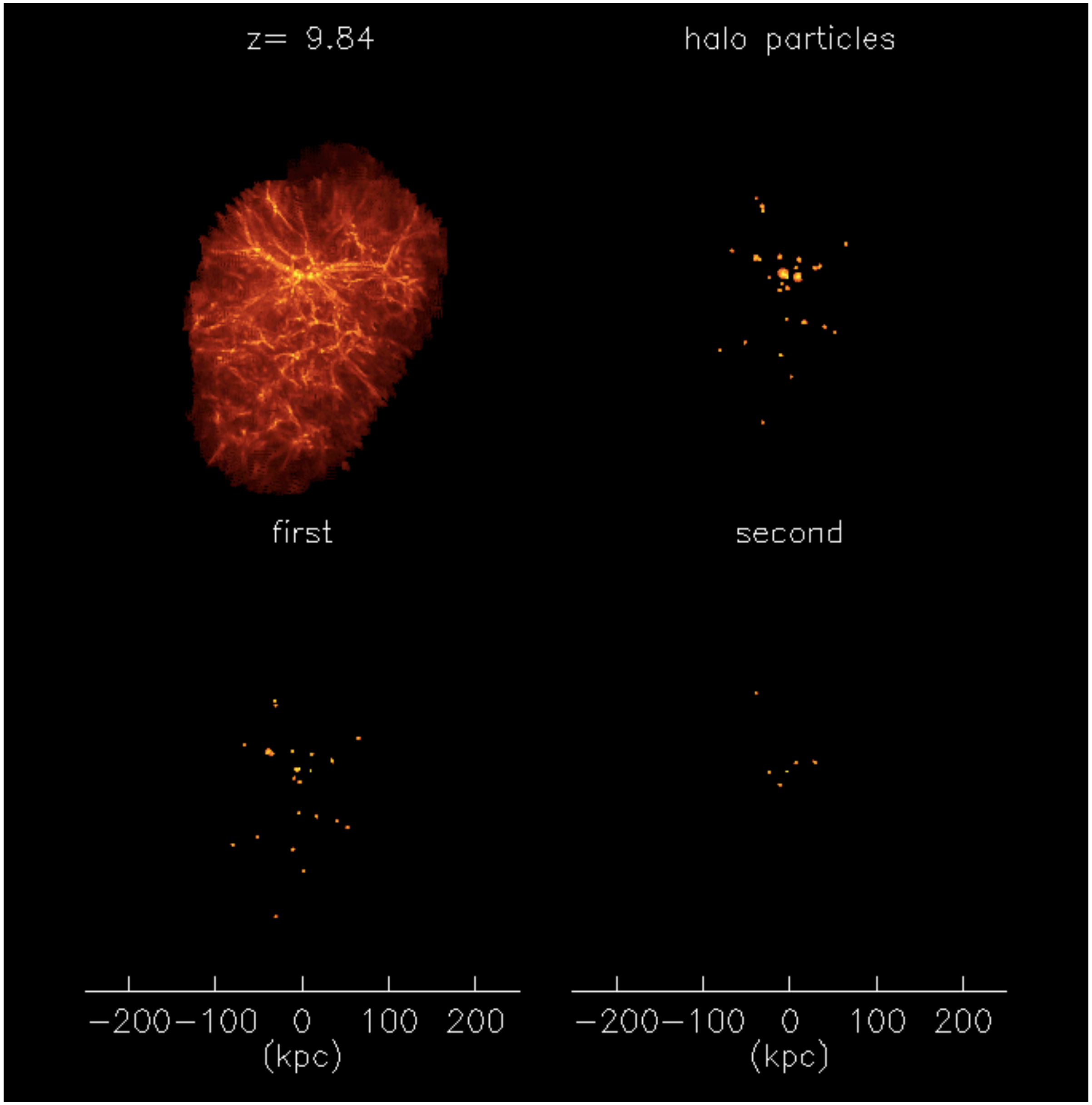
MDF INTERPRETED – I.

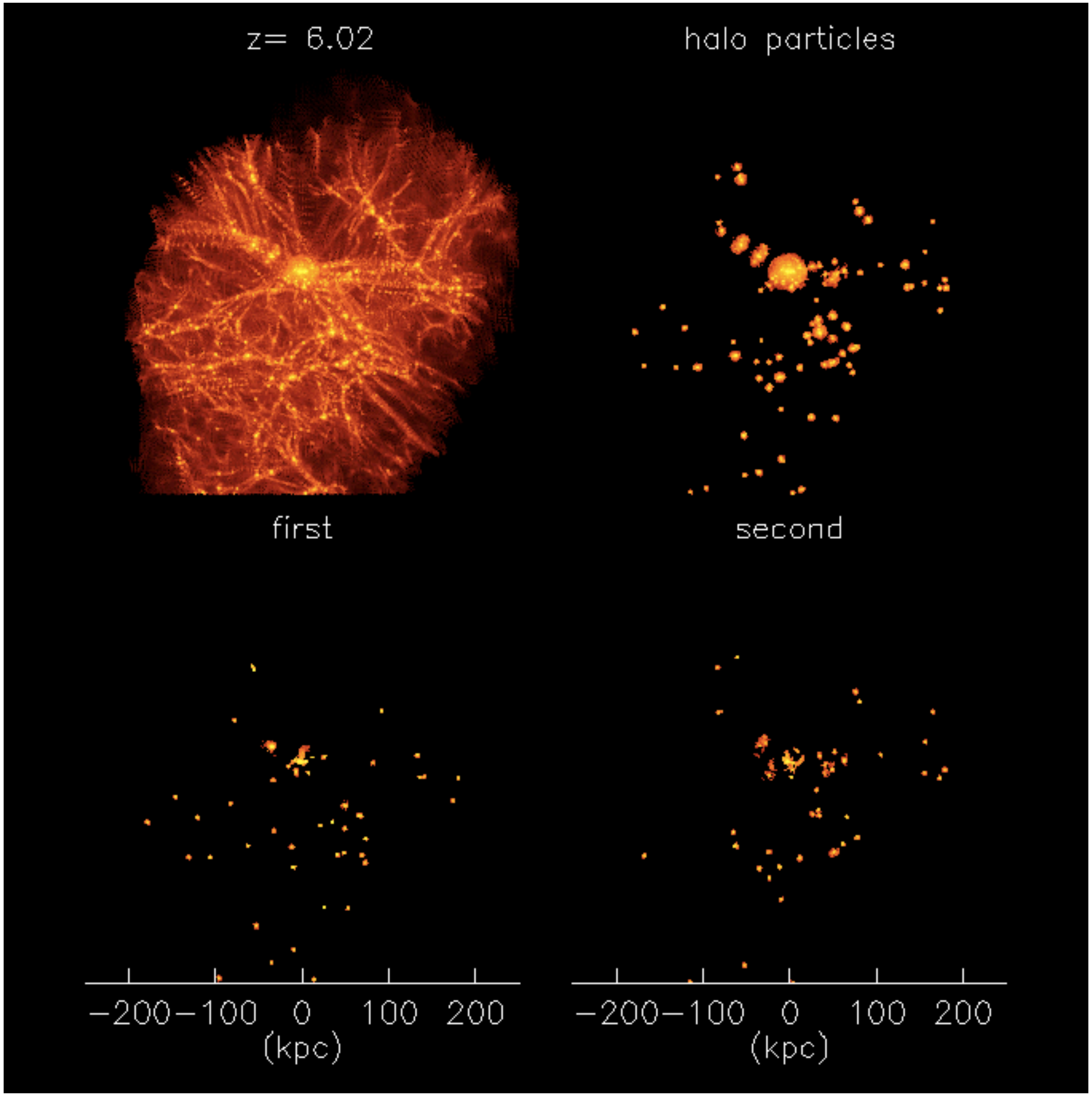


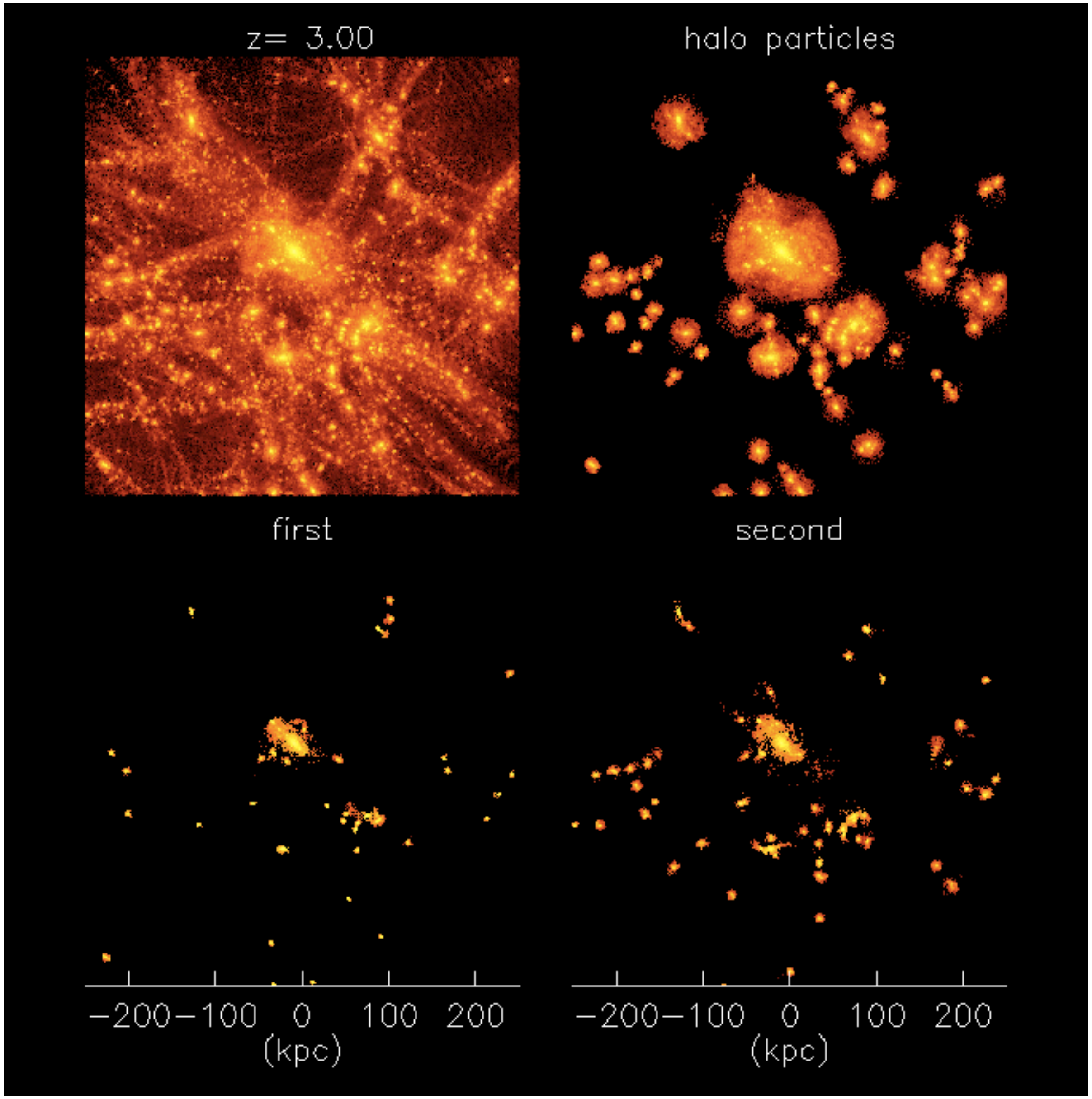


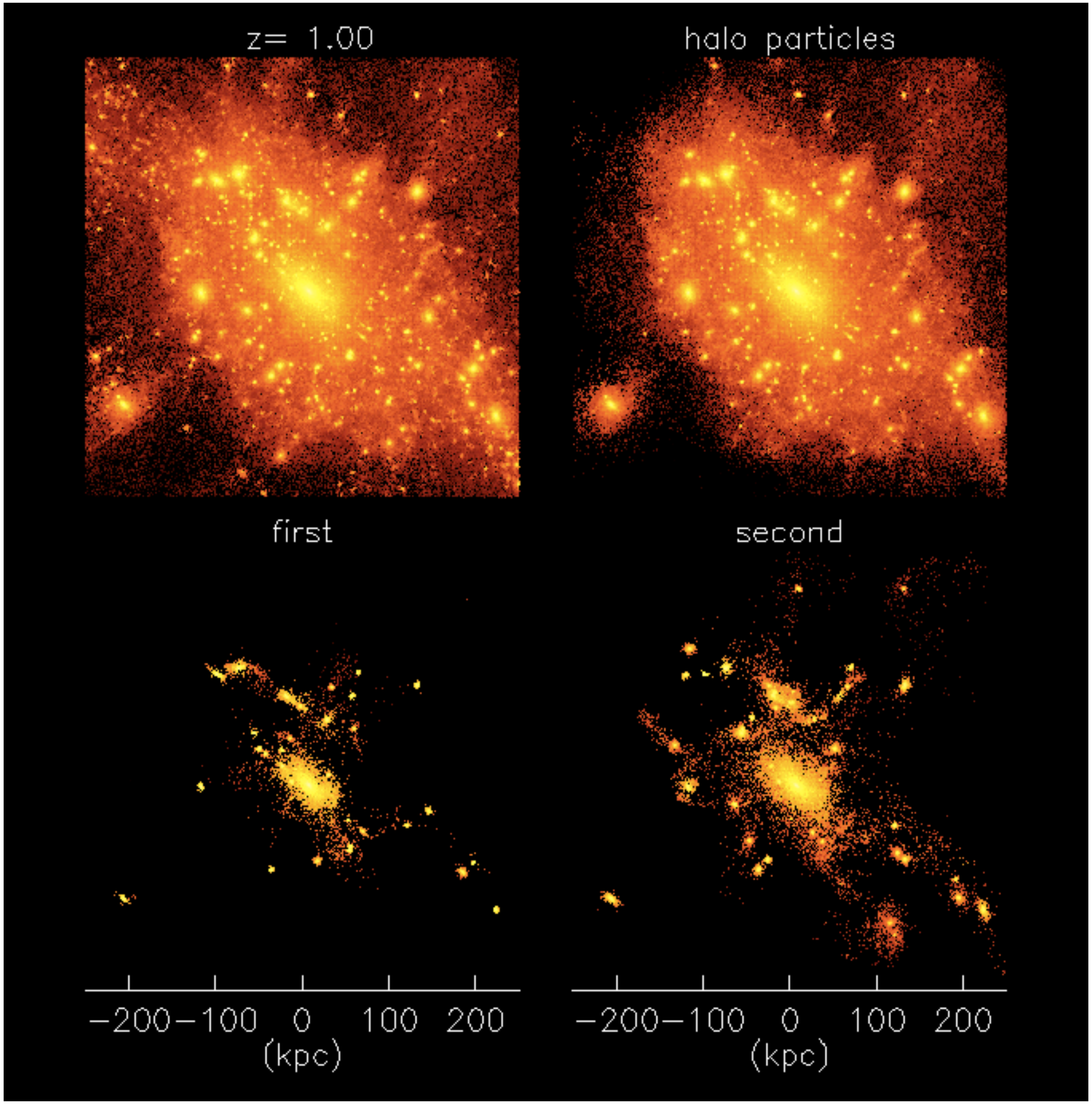


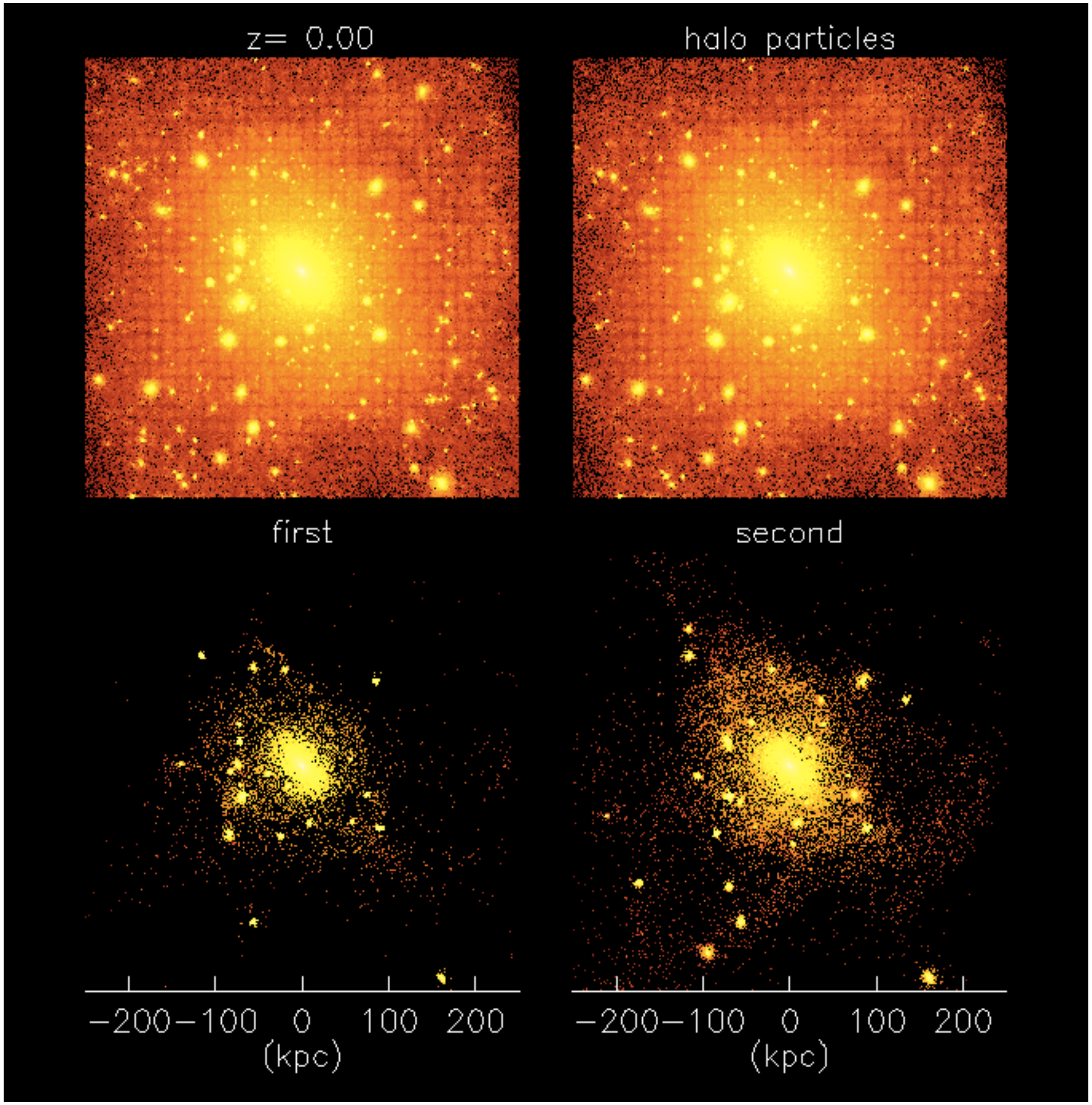
Scannapieco+ 2006




z= 6.02
halo particles
first
second
−200−100 0 100 200
(kpc)
−200−100 0 100 200
(kpc)


z= 3.00
halo particles
first
second
−200−100 0 100 200
(kpc)
−200−100 0 100 200
(kpc)

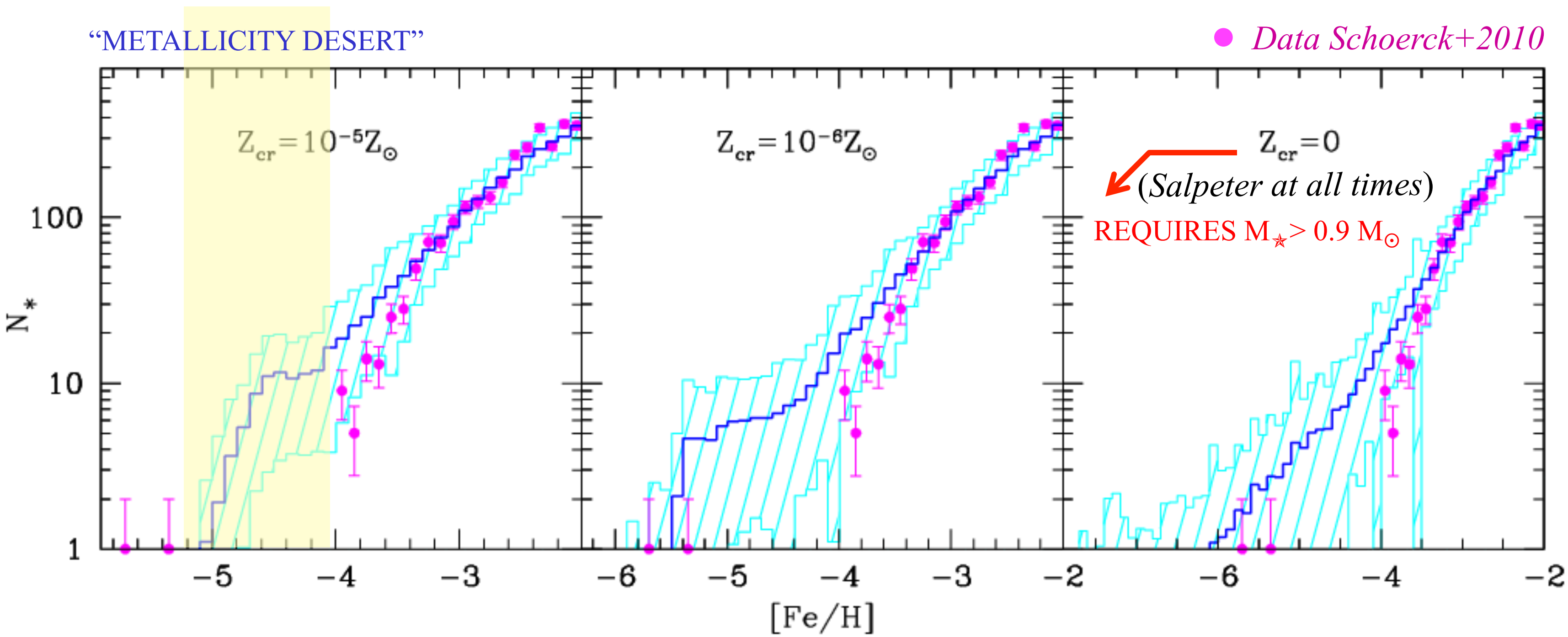

z= 1.00
halo particles
first
second
−200 −100 0 100 200
(kpc)
−200 −100 0 100 200
(kpc)


z= 0.00
halo particles
first
second
−200−100 0 100 200
(kpc)
−200−100 0 100 200
(kpc)

Salvadori, Schneider, AF 2006, Tumlinson 2006

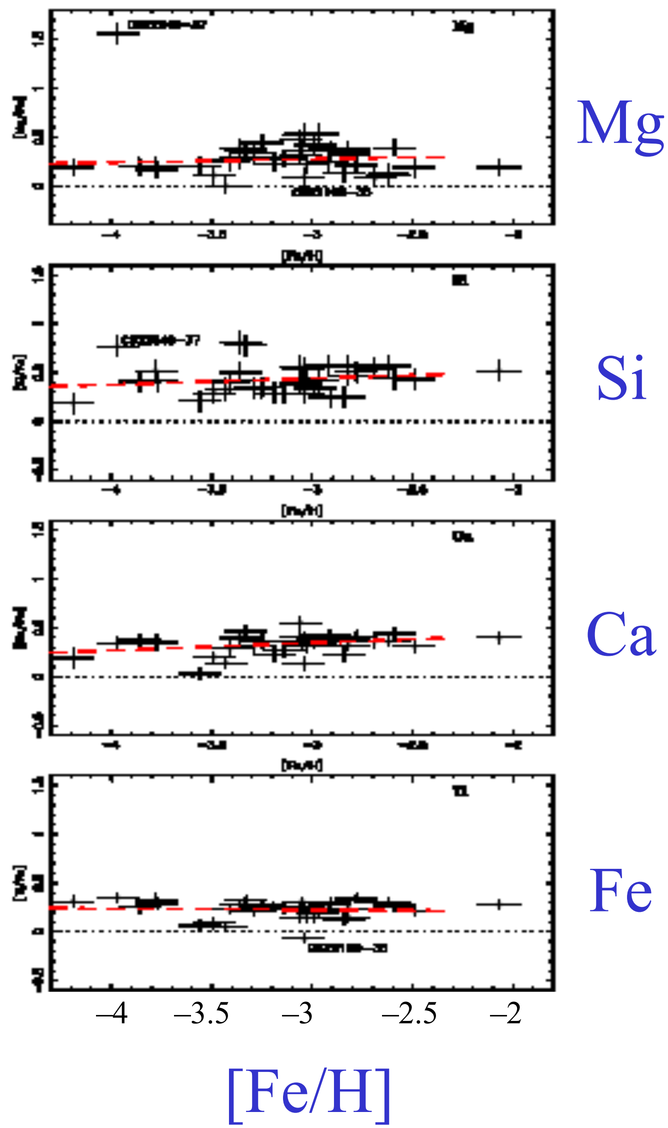
MDF INTERPRETED – II.

- ✓ Stellar / chemical evolution of the Milky Way based on ΛCDM merger-tree
- ✓ Joint HK/HES Metallicity Distribution Function, 2756 stars with [Fe/H] < – 2.



Cayrel+ 2004

ABUNDANCE PATTERNS



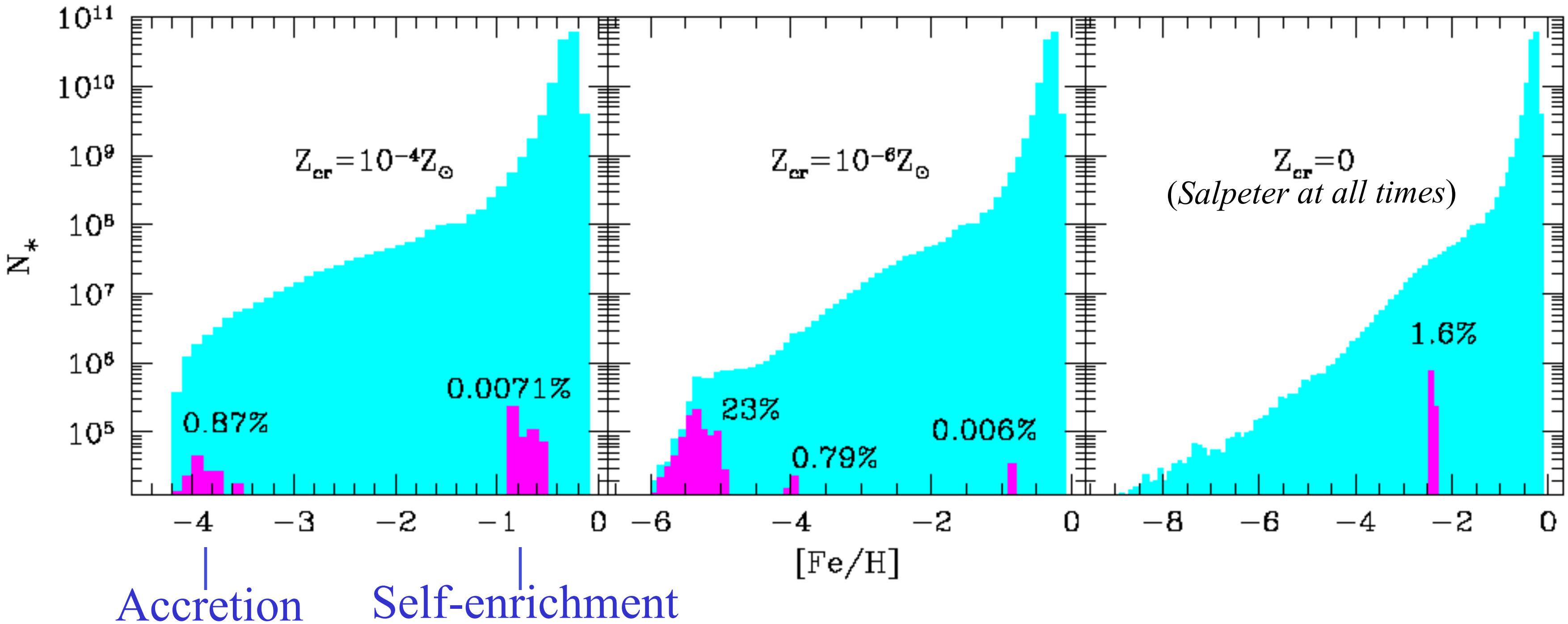
- ✓ 30/35 stars with –4.1 < [Fe/H] < –2.7
- ✓ 17 elements from C to Zn measured

Very small scatter: $\sigma < 0.05$ dex

- ▷ Unlikely resulting from *individual* SN ejecta
- ▷ Ratios *do not* match PISN yields

Salvadori, Schneider, AF 2006

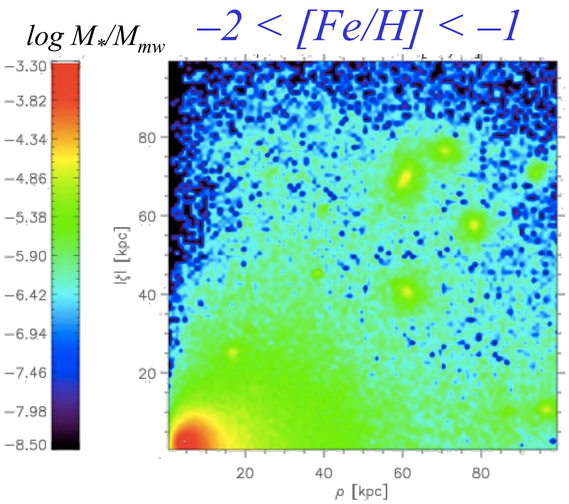
SECOND GENERATION STARS

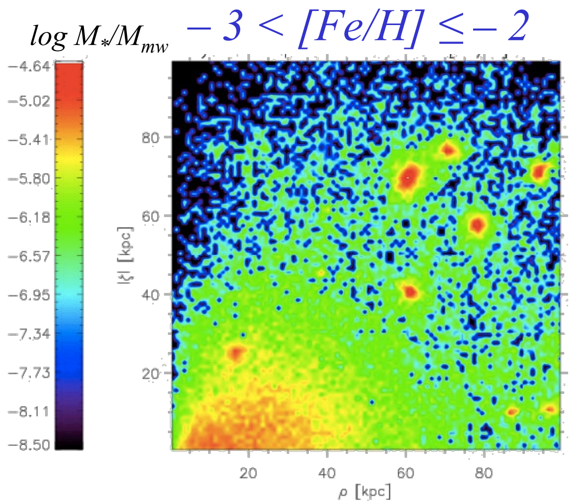


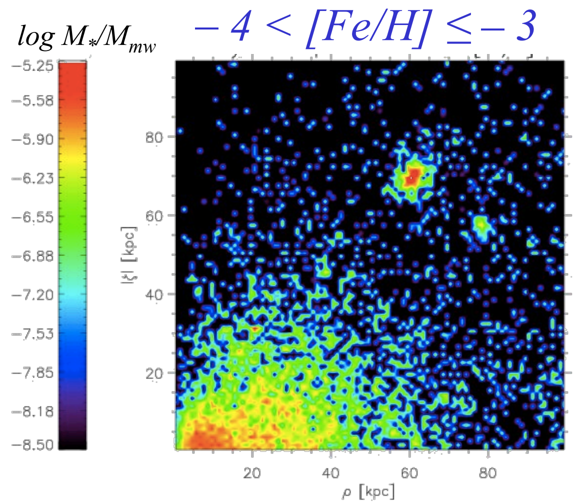
Joint HK/HES sample: 2756 stars with [Fe/H] < – 2.

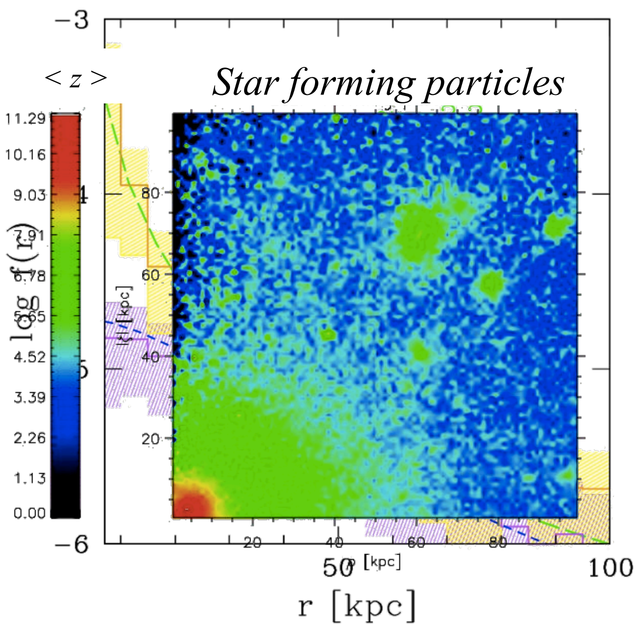
Z_{crit}	Expected number of second-generation stars
10^{-4} $Z_\odot$	1.3
10^{-6} $Z_\odot$	0.3
0	0 06

Salvadori+2010









The relative contribution of [Fe/H] < –2 stars increases from 17% for r < 20 kpc up to > 40% for r > 20 kpc

(Carollo+07/09; DeLucia & Helmi 08; Zolotov+10)

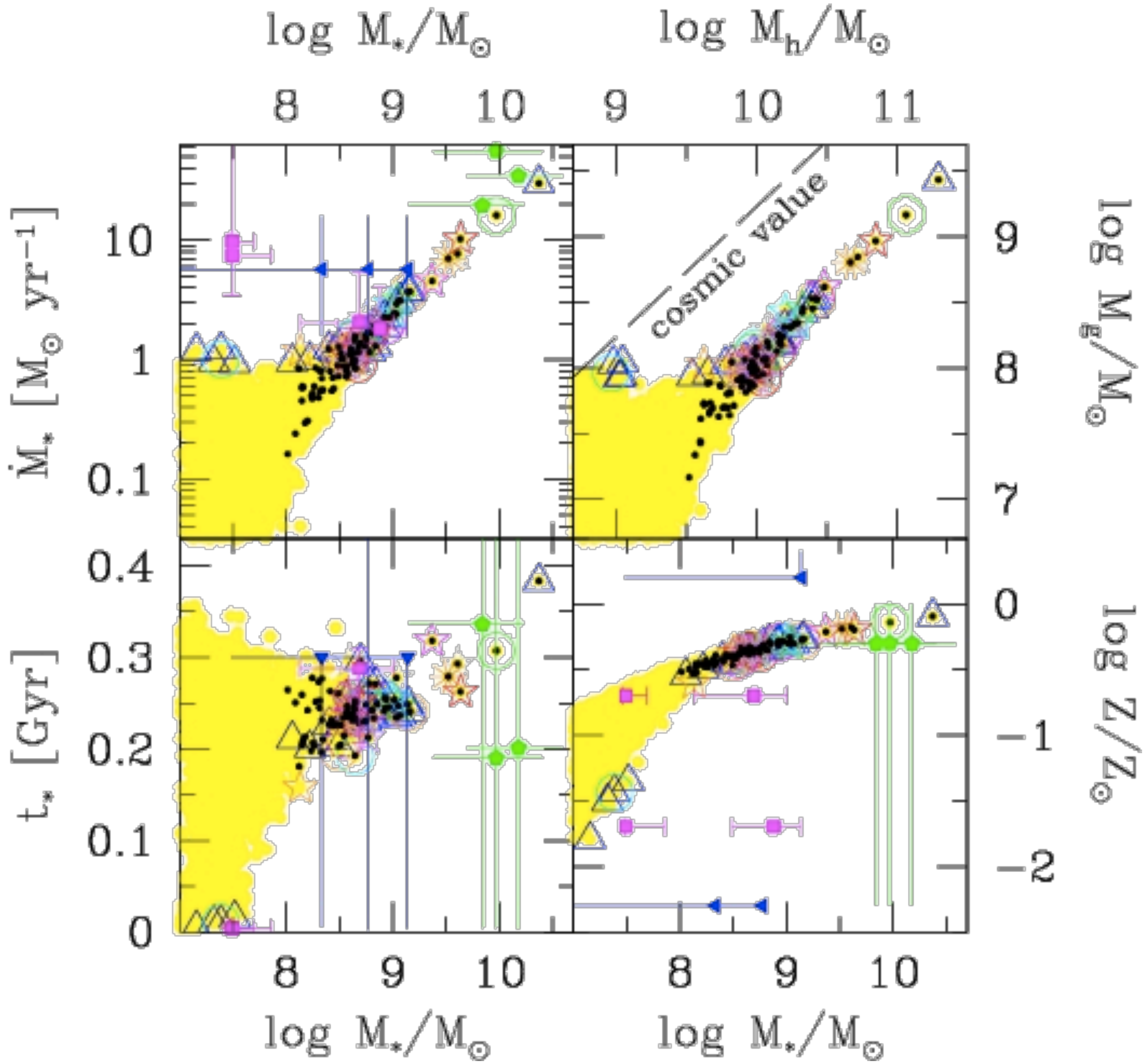
Dayal, Salvadori & AF 2010

80 Monte Carlo realizations
Yellow: all progenitors
Black: major branch
Symbols: LAE progenitors

LAEs selection criteria:
$L_\alpha > 10^{40}$ erg s^{-1}
$EW > 20$ Å

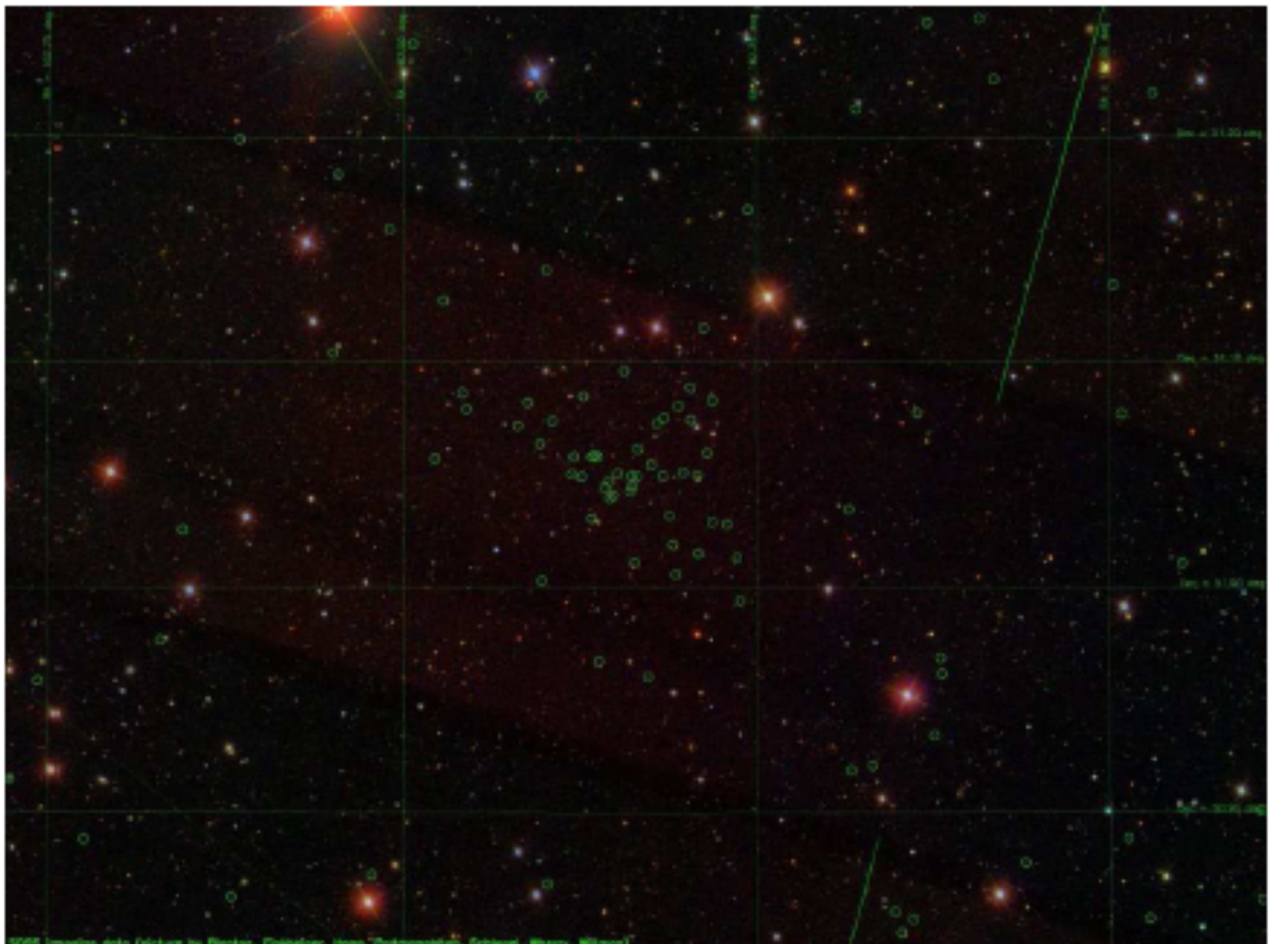
Observations:

- ■ Ono+10
- ▲ Pirzkal+07
- ● Lai+07



WHAT ARE THEY ?

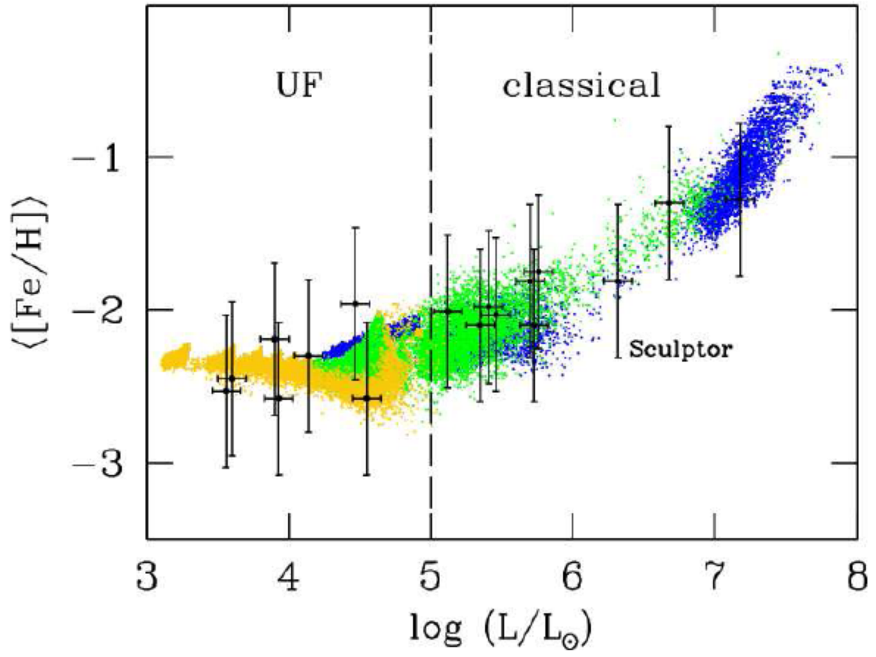
Willman+ 2006, Simon & Geha 2007

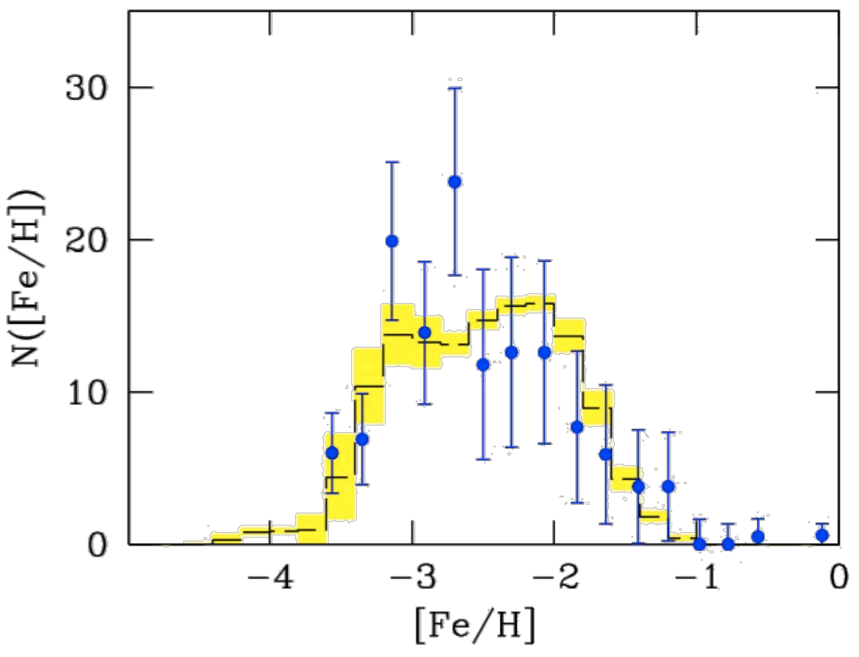


Salvadori & AF 2009, Bovill & Ricotti 2009, Wyse+2010

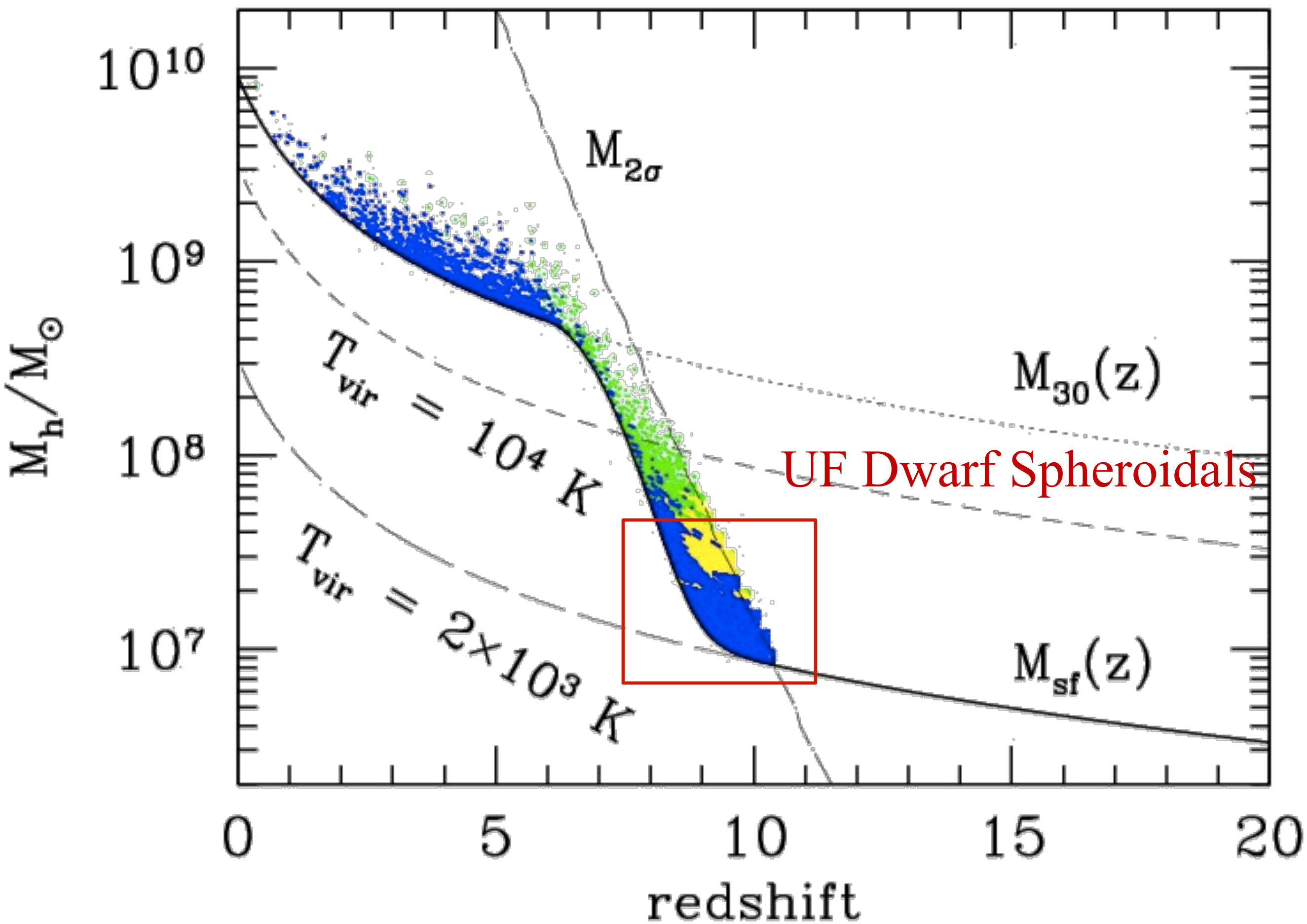
ULTRA FAINT DSPHs: METALLICITY

data: Kirby+2007





UFs: MASS & FORMATION EPOCH



- (Massive) PopIII stars strongly influcence first stages of cosmic reionization
- Transition to normal stars occurs when $Z > Z_{crit} \sim 10^{-5\pm1} Z_{\odot}$; strongly governed by dust
- Pop III SF continues to $z \sim 3$ at periphery of collapsing structures. Observable in LAEs ?
- Metallicity Distribution Function of EMPs in the MW halo: hints on primordial IMF
- The outer halo (20 kpc < r < 40 kpc) is the most promising region for EMP searches
- Faintest LAEs at $z \approx 5.7$ may represent the MW in its infancy
- UFs MDF shifted towards lower [Fe/H] with respect to classical dSphs
- UFs are the best objects to search for extremely metal-poor stars (2G stars?)

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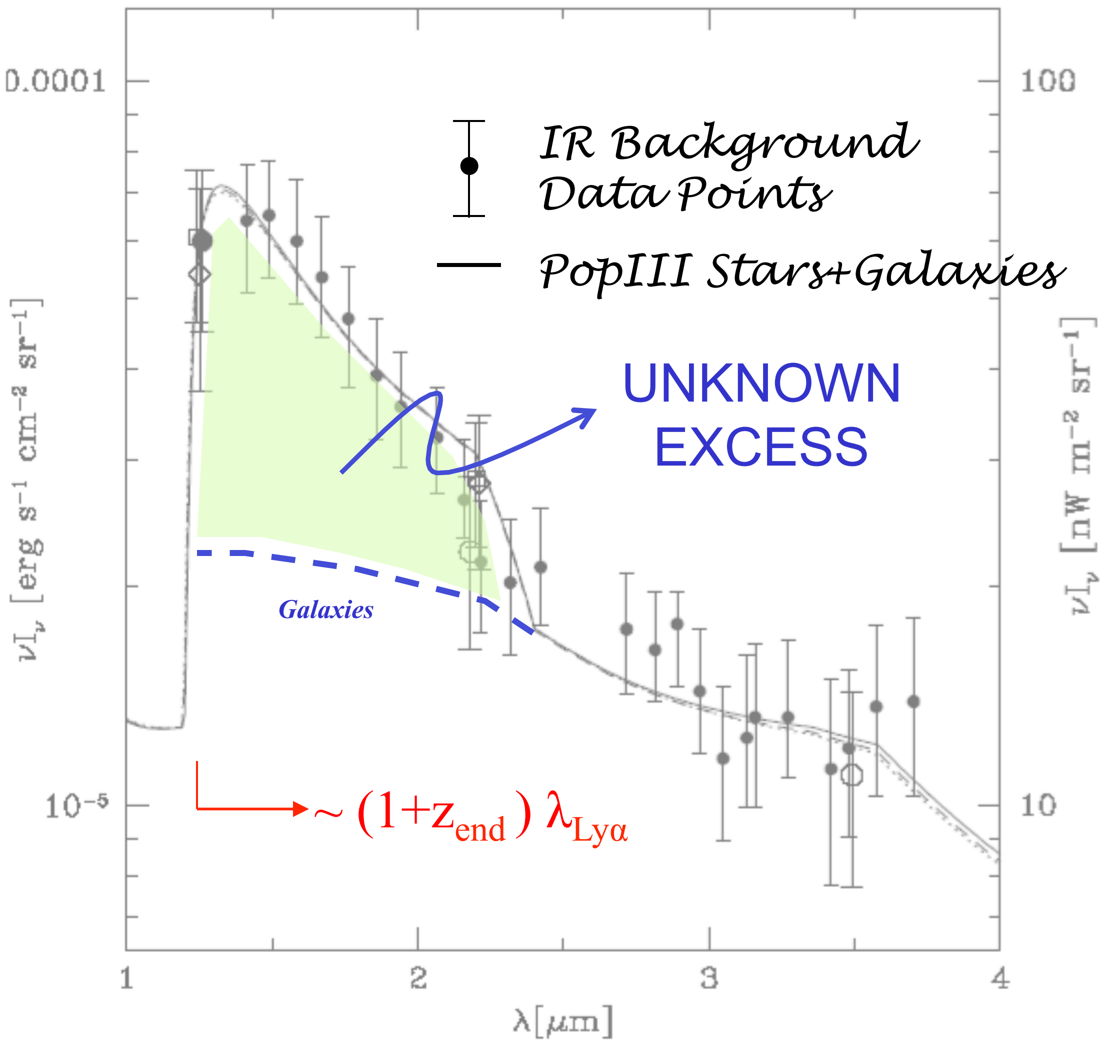
Salvaterra & AF 2002, Santos+2002

A PUZZLING EXCESS



Best fit model to NIR data

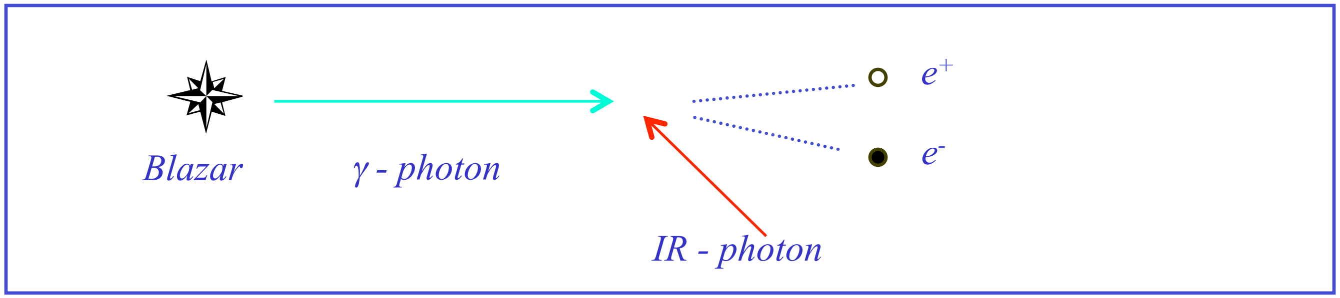
$$z_{end} = 8.8$$

$$f_\star \approx 30\%$$

Massive Pop III stars can explain NIRB excess

GAMMA-RAY CONSTRAINTS

- *TeV-GeV photons absorbed by optical/IR photons via $e^+ - e^-$ pair production.*



$$\tau(E) = \int_0^{z_{em}} dz \frac{dl}{dz} \int_{-1}^{1} dx \, \frac{(1-x)}{2} \int_{\epsilon_{th}}^{\infty} d\epsilon \, n(\epsilon) \, \sigma(\epsilon, E, x)$$

σ peaks at $\lambda_{IR} \sim 2.37\ (E/TeV)\ \mu m$.

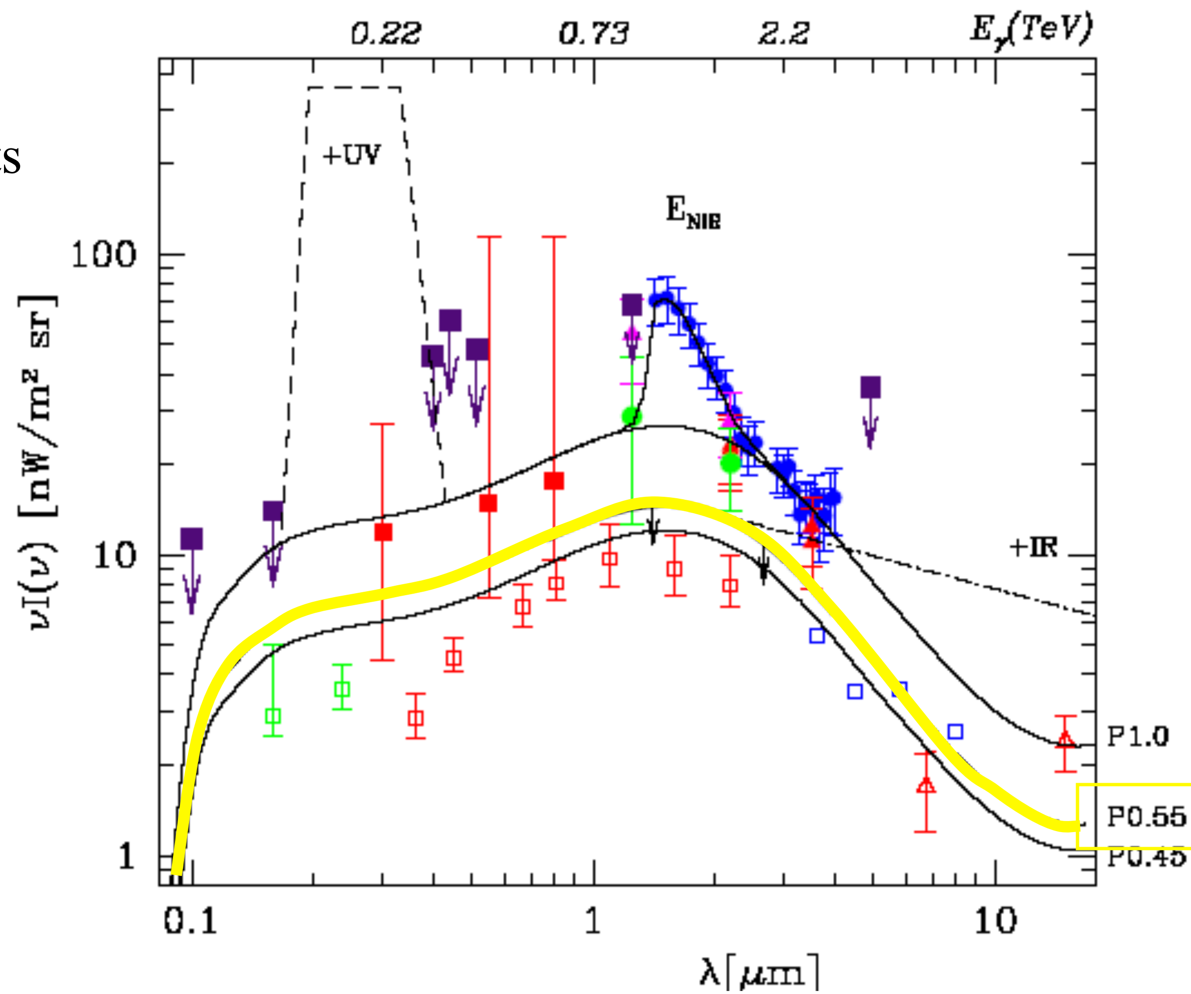
- *The observed spectrum of blazar reproduced by convolving the unabsorbed (power-law) spectrum with the optical depth:*

$$(dN/dE)_{abs} \propto e^{-\tau} E^{-\alpha}$$

Mapelli+ 2005, Aharonian+ 2005

GAMMA-RAY CONSTRAINTS

- ○ Galaxy counts
- ● Direct measurements



Salvaterra+ 06, Cooray+ 06, Sullivan+06, Thompson+ 07a,b

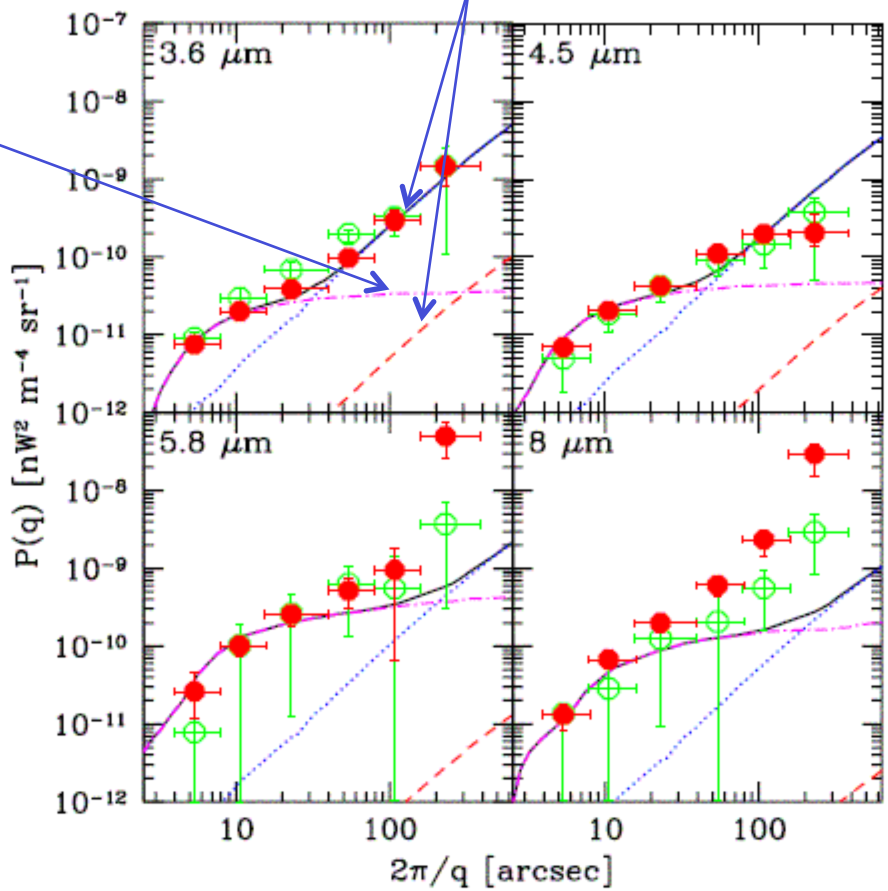
FLUCTUATIONS

Clustering *z* >5 galaxies

Shot noise
z <5 galaxies

POPII

POPIII



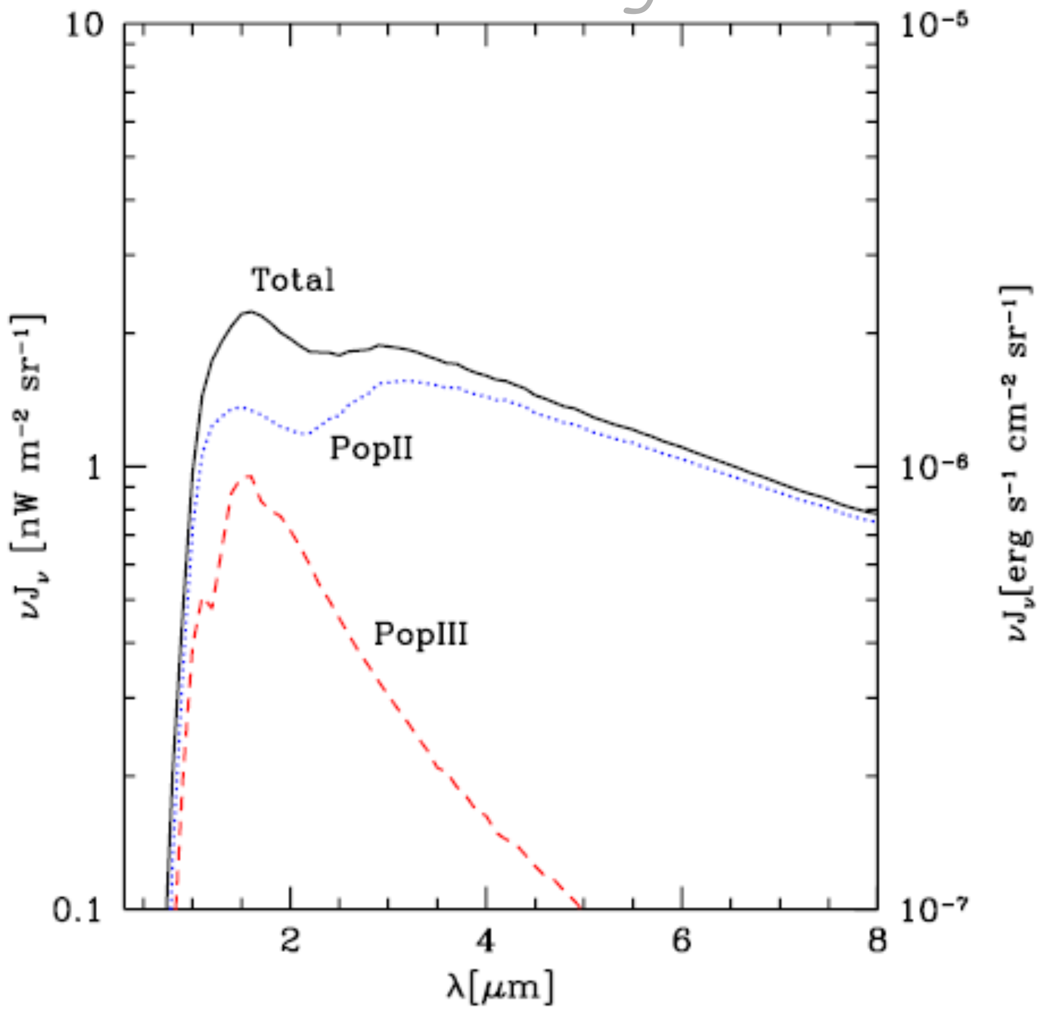
Spitzer/IRAC data

Kashlinsky+ 2005, 2007

Salvaterra+ 2006, Fernandez & Komatsu 2006

INTENSITY

$5 \le z \le 9$ galaxies

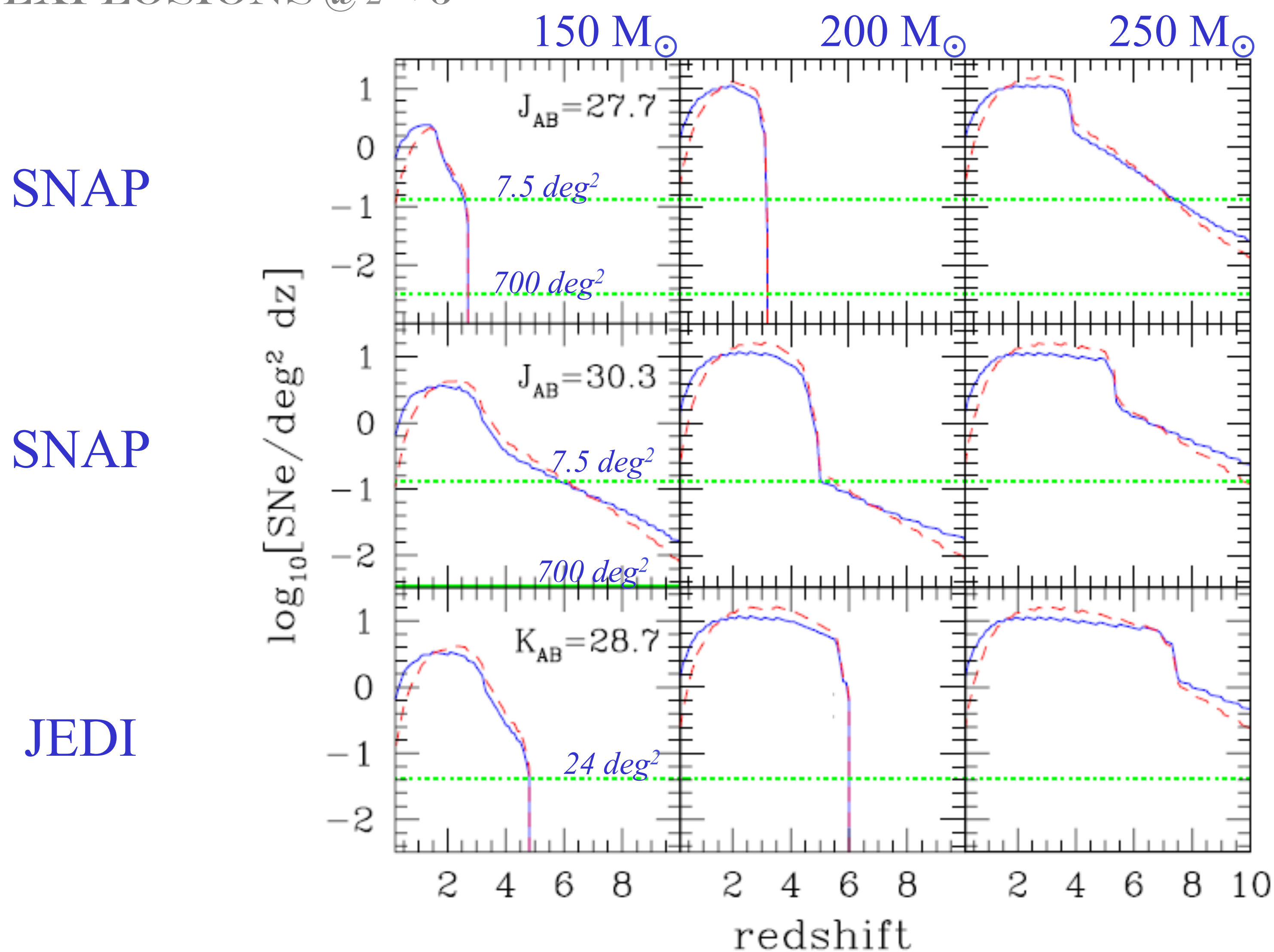


NIRB PHOTON BUDGET

	$nW\ m^{-2}\ sr^{-1}$ @ 1.4 μm
Observed	70
After zodi-subtraction (Wright)	17
Gamma rays	~15
Low-*z* galaxy contribution	> 8
Left unexplained	< 7
z>5 galaxies (from fluctuations)	2.5

Scannapieco+ 2005, Weinmann & Lilly 2005

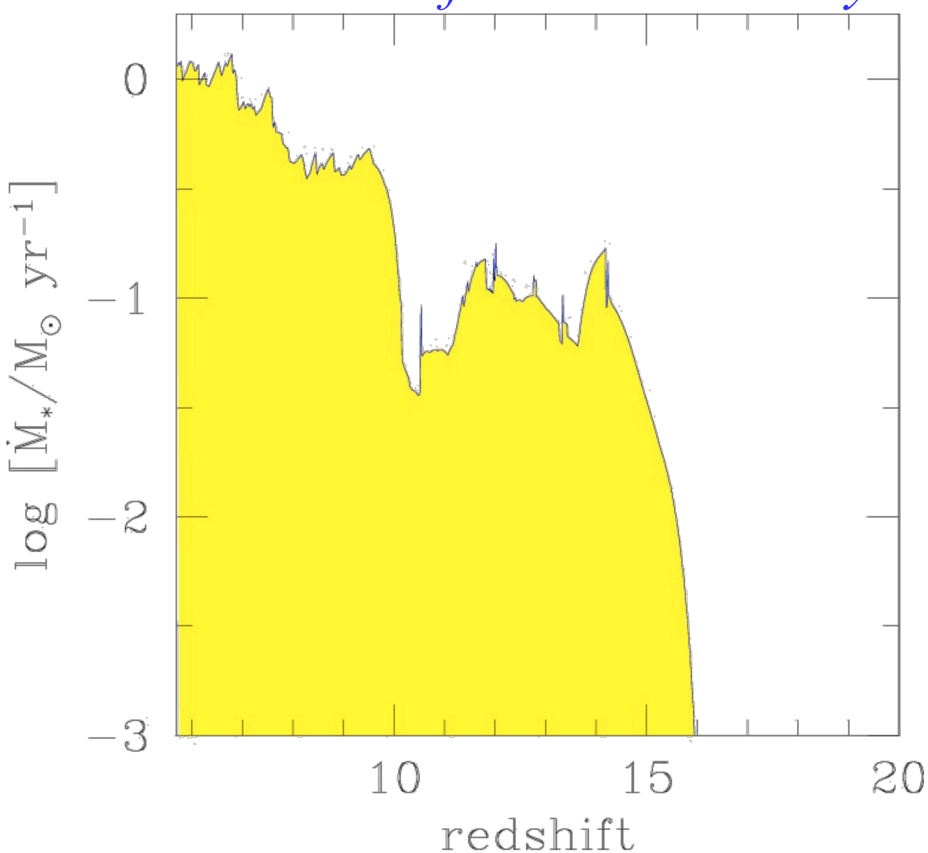
PISN EXPLOSIONS @ $z < 6$



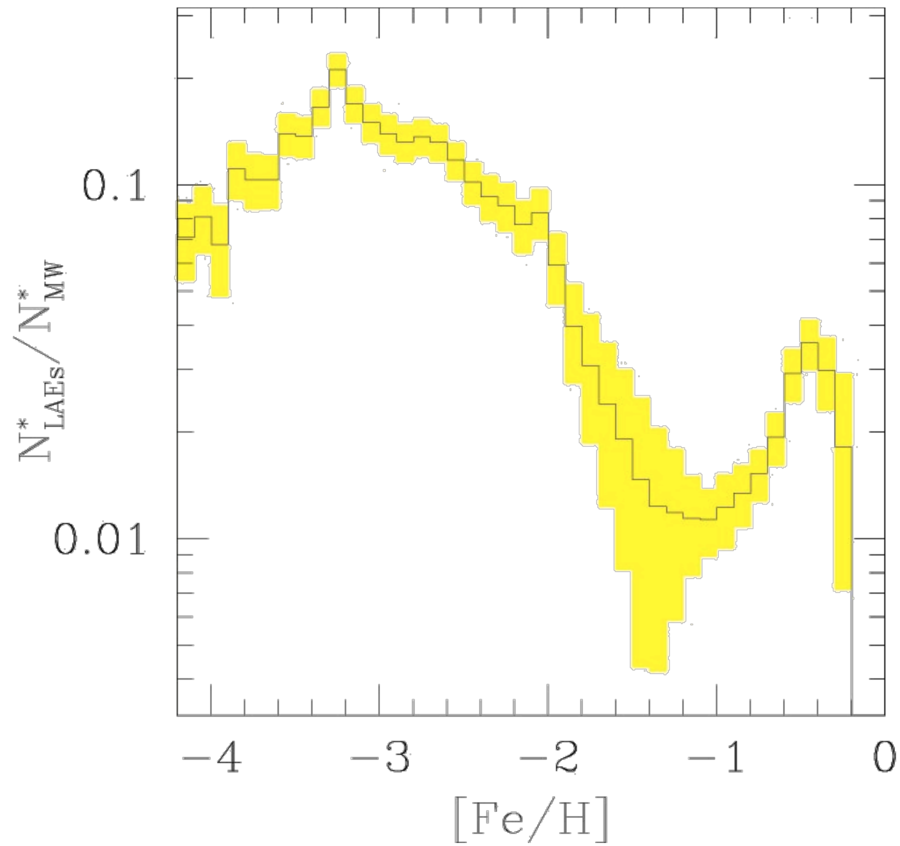
LAEs candidates: the infant MW

Salvadori, Dayal & Ferrara 2010

Star formation history



Relative MDF



The LAE candidates provide more than the 10% of the very metal-poor stars observed today in the Galactic halo