The Physics of Early Galaxy Formation

Andrea Ferrara

SISSA/International School for Advanced Studies

"Historical" material

- Barkana, R. & Loeb, A. 2001, *Phys. Rep.*, **349**, 125
- Bromm, V. & Larson, R. 2004, *ARA&A*, **42**, 79
- Ciardi, B. & Ferrara, A. 2006, *SSRv*, **116**, 625

Additional material

Ferrara, A. 2006, Saas-Fee School, available at web site
obswww.unige.ch/saas-fee/

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.

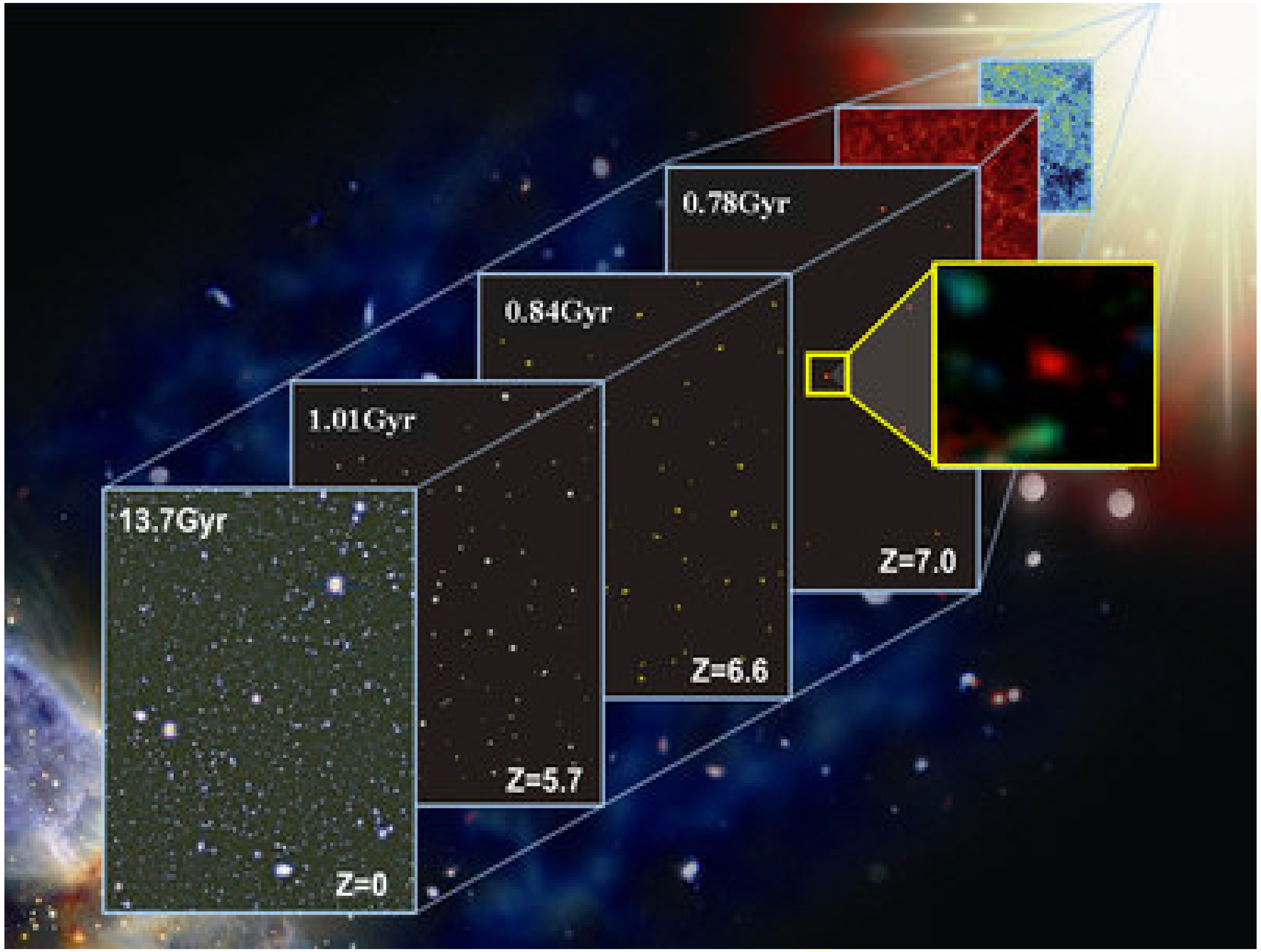
At z ~ 6-15 these gradually photo-ionize the hydrogen in the IGM (“Reionization”).

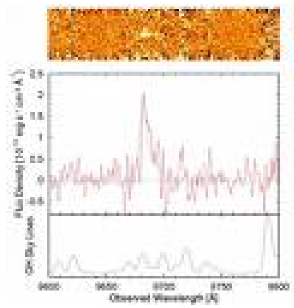
At z<6 galaxies form most of their stars and grow by merging.

At z<1 massive galaxy clusters are assembled.

Iye+ 2006, Kashikawa+ 2006, Nagao+ 2007

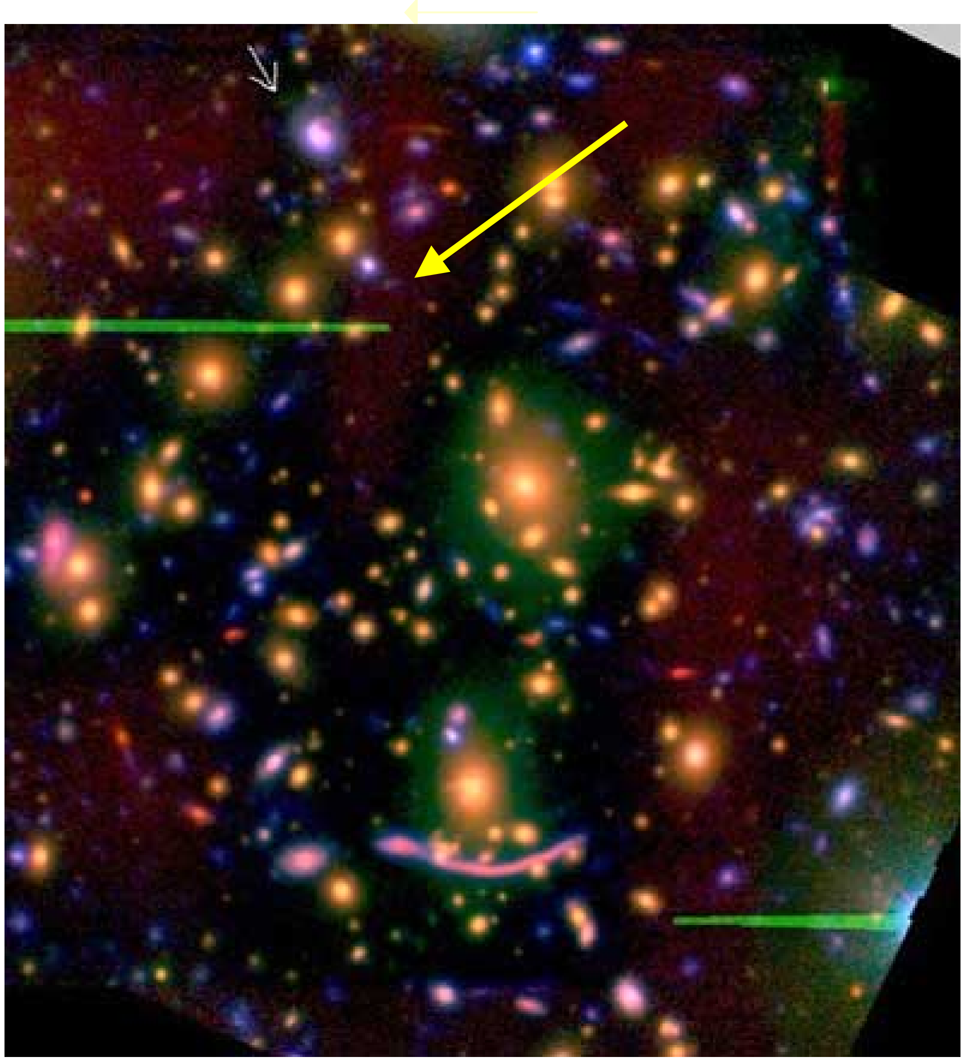
LYMAN ALPHA EMITTERS





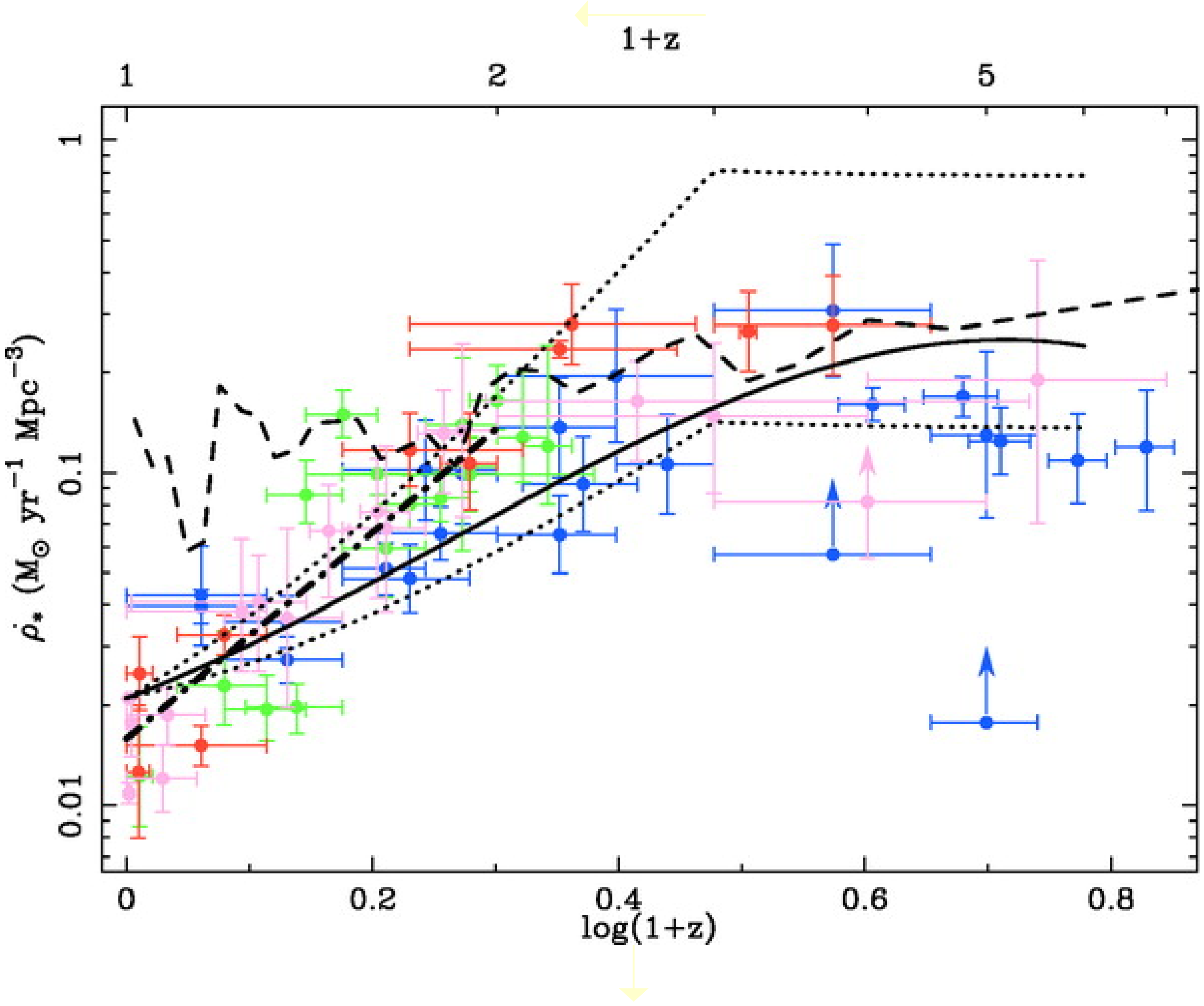
Hu+ 2002, Santos+ 2006, Bouwens+ 2006, Pello+ 2006

LENSED DROPOUT AT Z=6.56



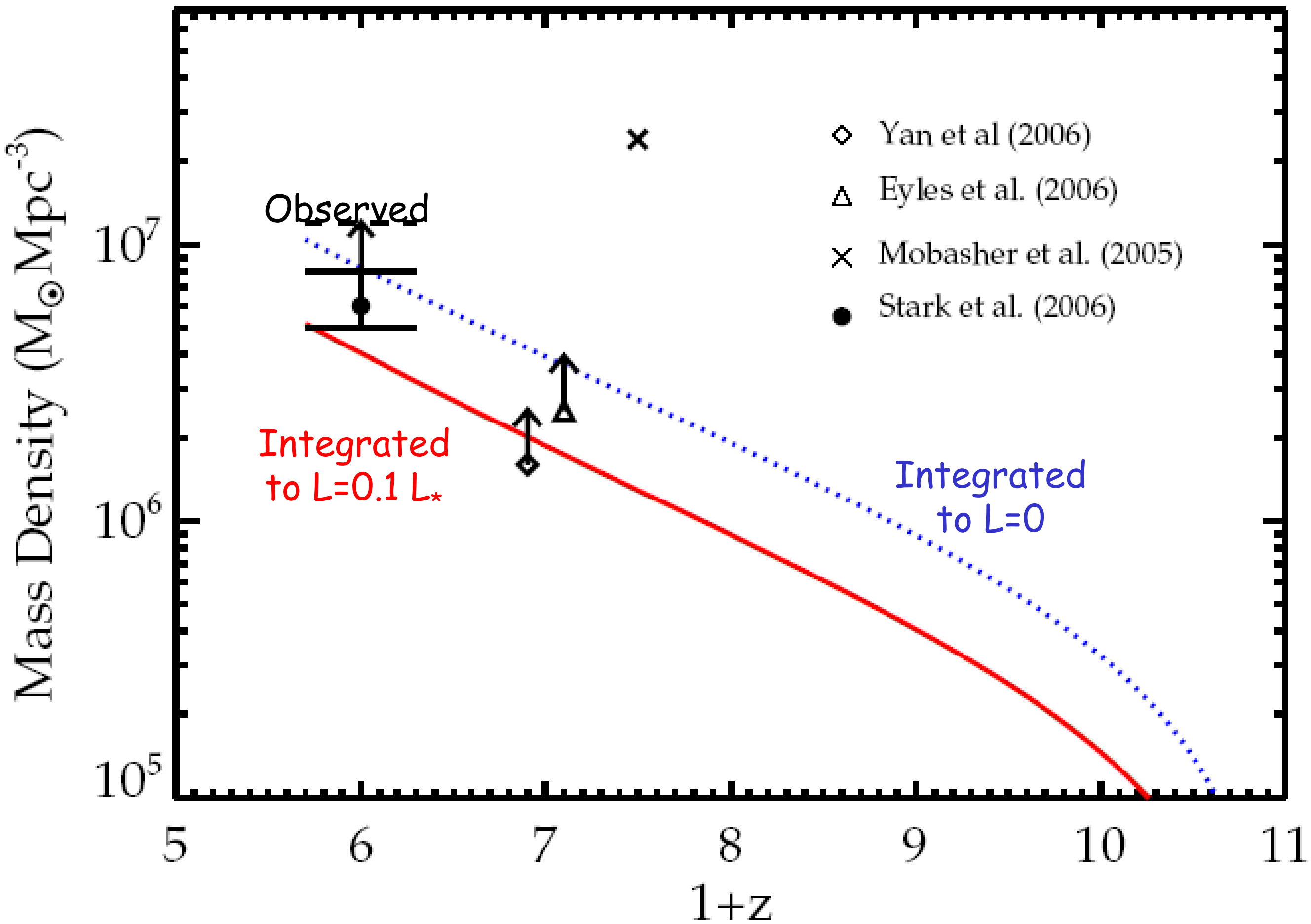
Hopkins 2004

COSMIC STAR FORMATION



Stark+ 2006

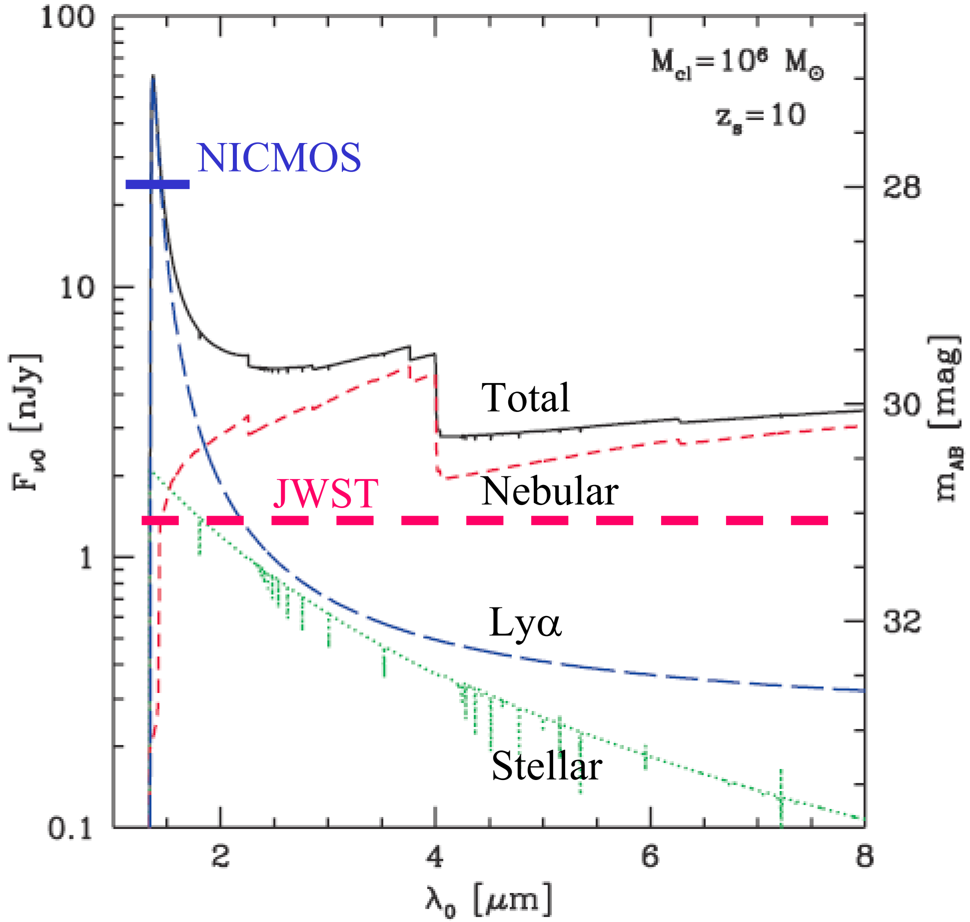
HIGH-Z STAR FORMATION



Lots of **hidden/missing** high-z star formation

The First Stars

DIRECT DETECTABILITY

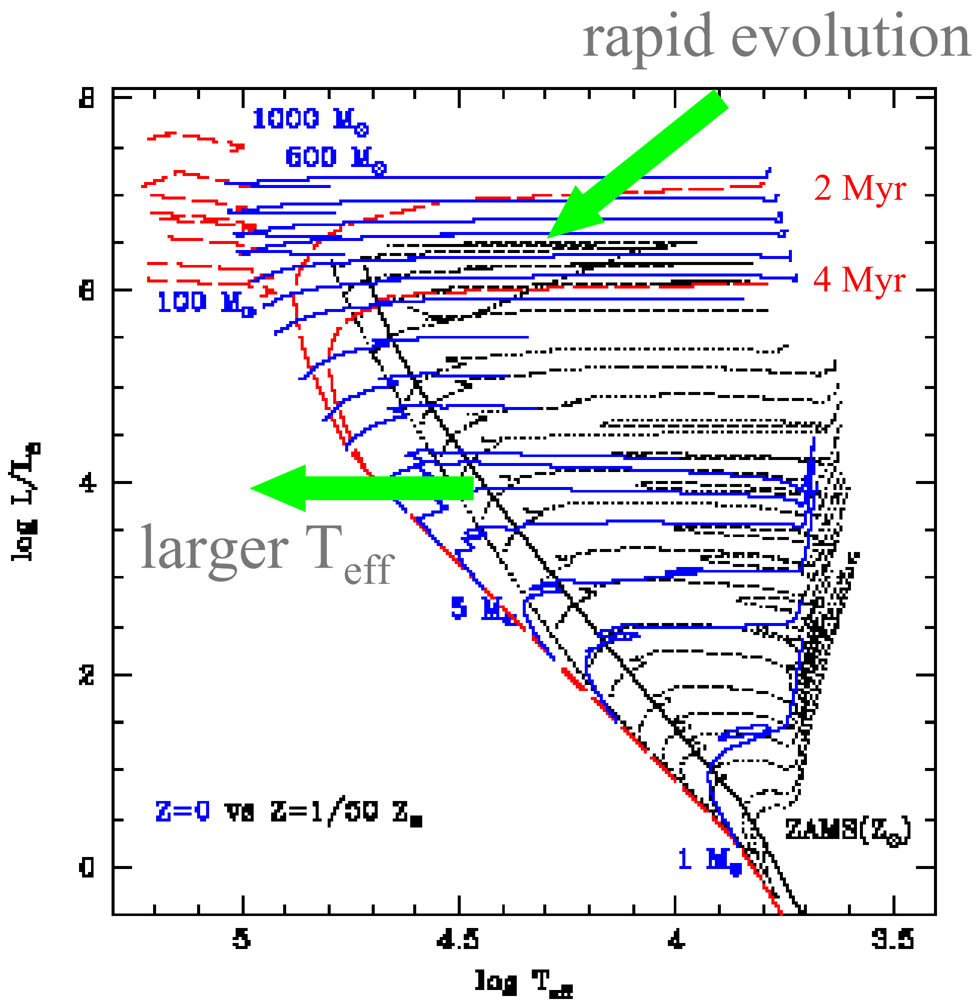


Pop III cluster

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

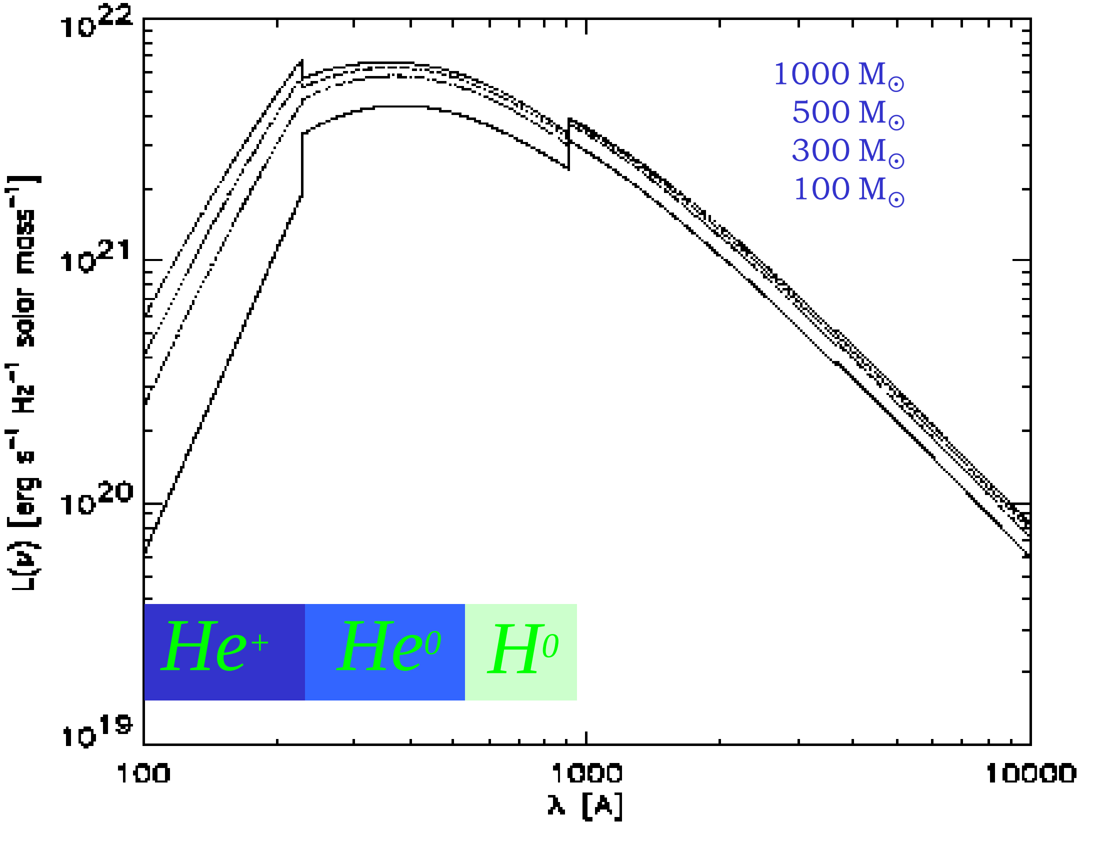
Schaerer 2002

STELLAR TRACKS



Bromm+ 2001

EMISSION SPECTRUM



IONIZING POWER

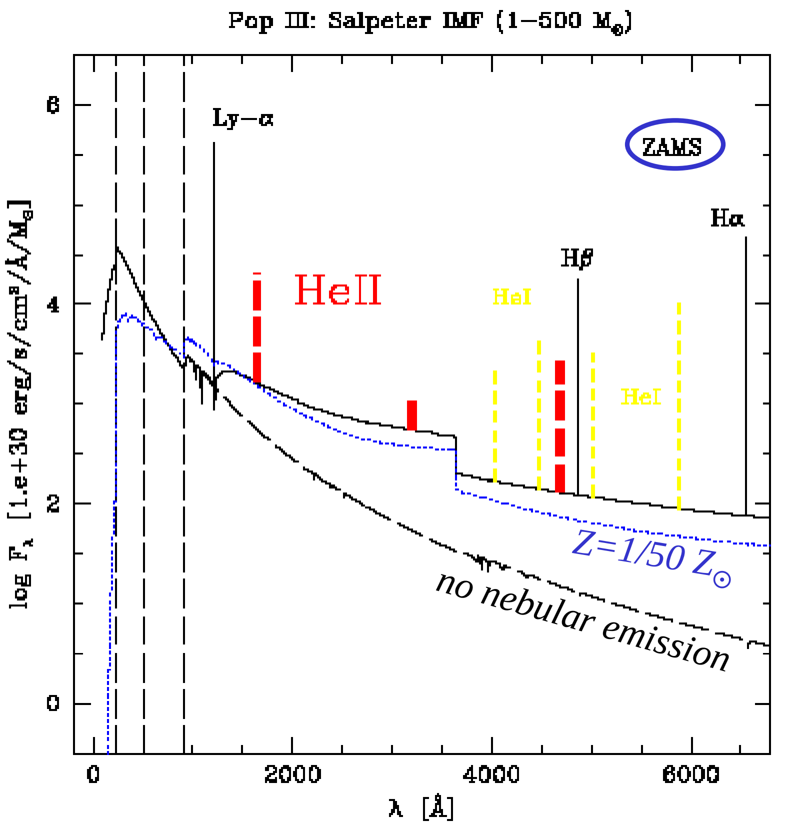
$$Q_i = 4\pi R_\star^2 q_i = 4\pi R_\star^2 \int_{\nu_i}^{\infty} \frac{F_\nu}{h\nu} d\nu, \qquad \bar{Q}_i(M) = \frac{\int_0^{t_\star(M)} Q_i(t, M) dt}{t_\star(M)},$$

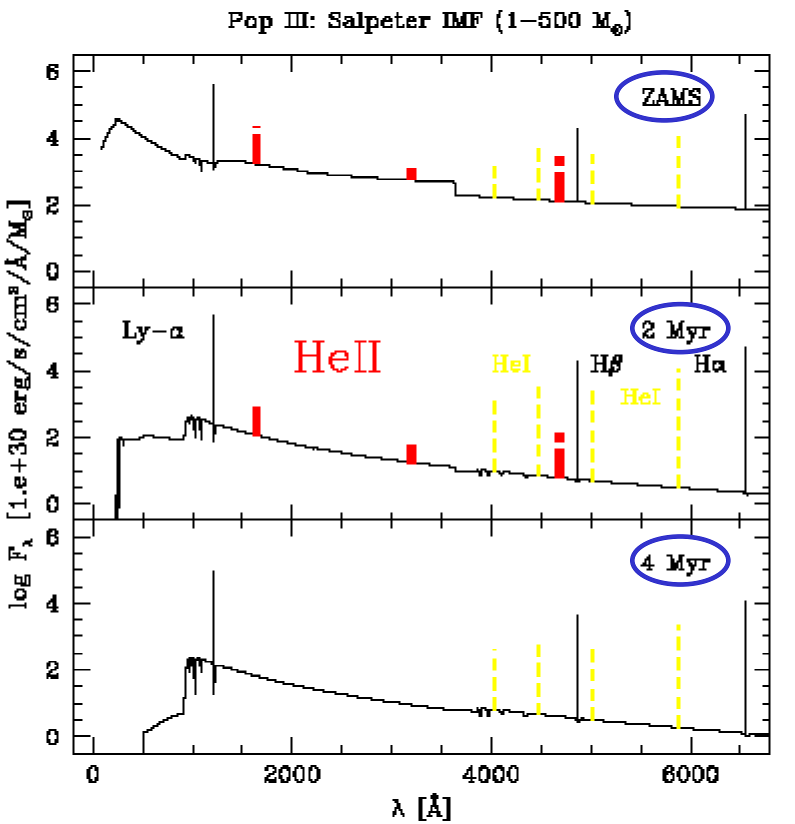
Time-averaged quantities

$M_{\rm ini}$	lifetime	$\bar{Q}$(H)	$\bar{Q}$(He^0)	$\bar{Q}$(He$^+$)	$\bar{Q}$(H$_2$)	$\bar{Q}$(He^0)/$\bar{Q}$(H)	$\bar{Q}$(He$^+$)/$\bar{Q}$(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

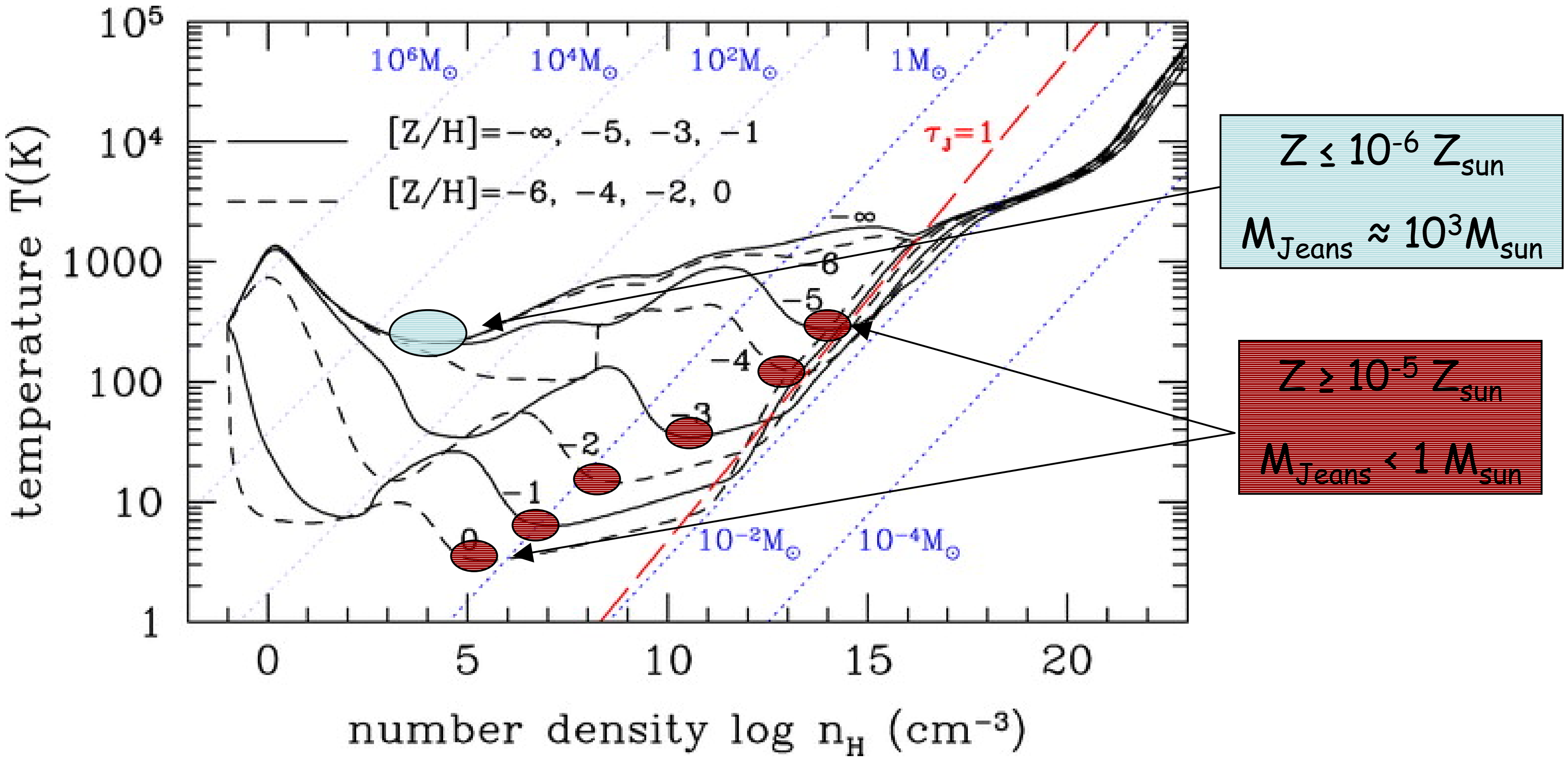
HE NEBULAR LINES





Schneider+ 2002, Omukai+ 2006

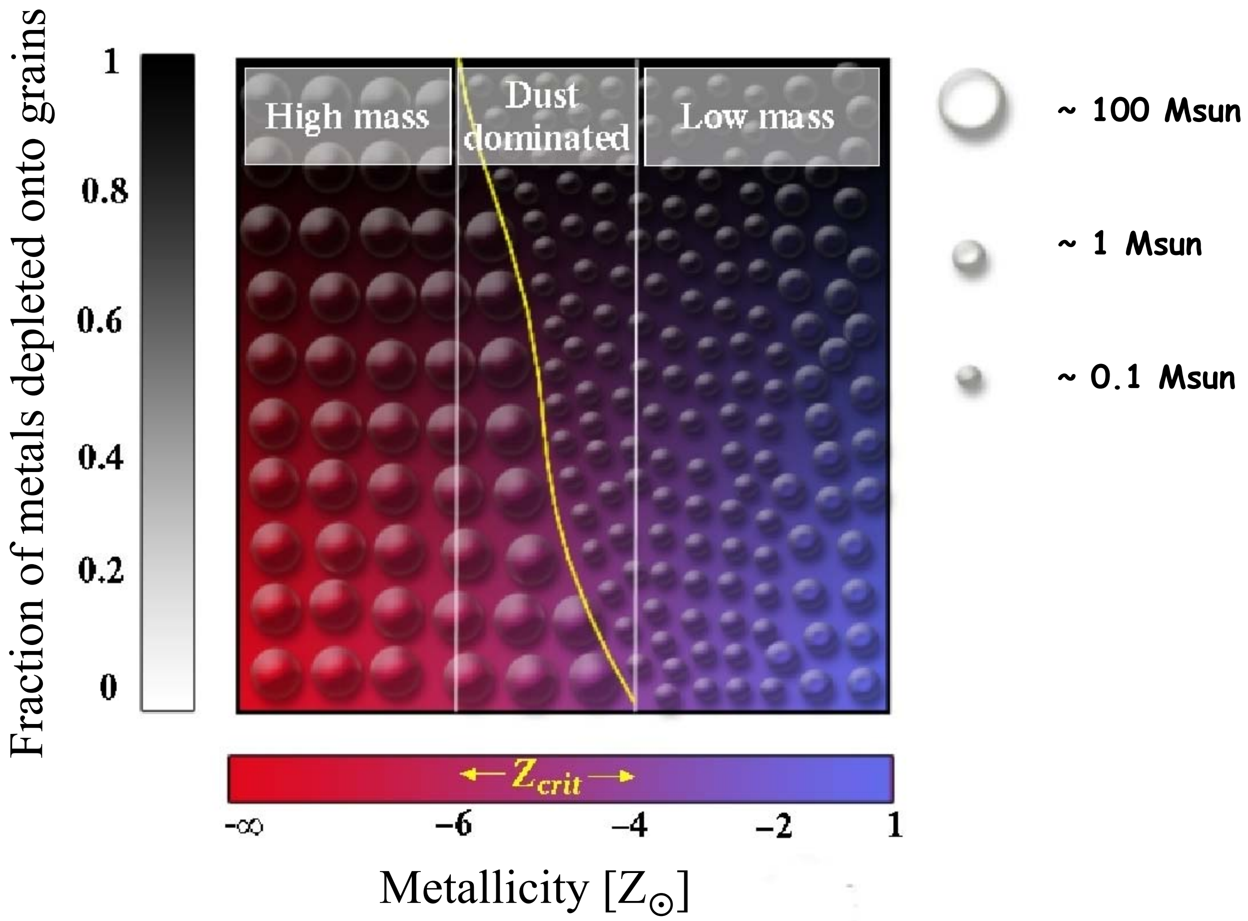
Z-DEPENDENT FRAGMENTATION



- ✓ One-zone model with simplified dynamics but detailed chemical and thermal evolution (478 reactions for 50 species)
- ✓ D chemistry and HD cooling

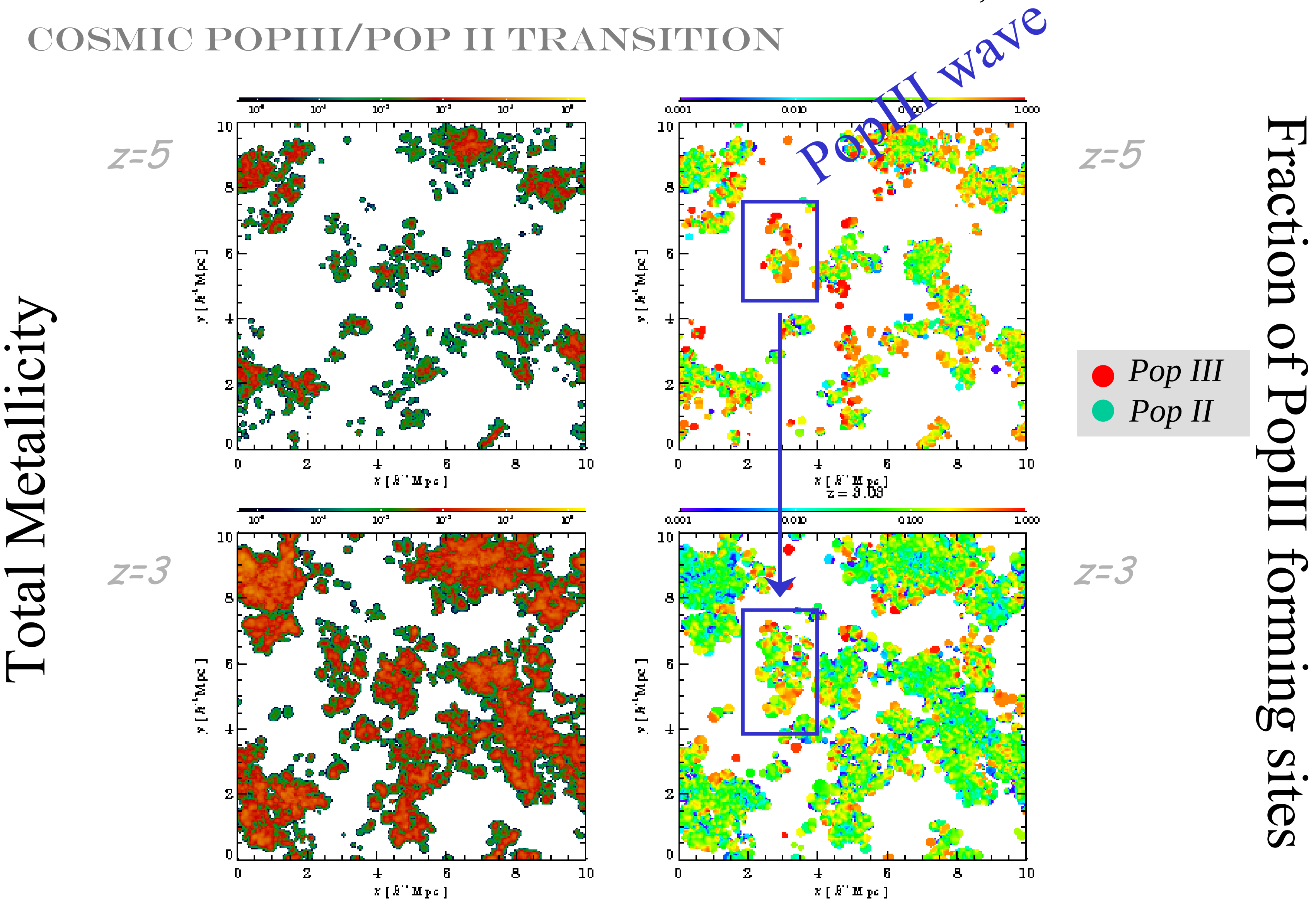
Schneider+ 2002, Schneider+ 2006

MASS OF EARLY STARS



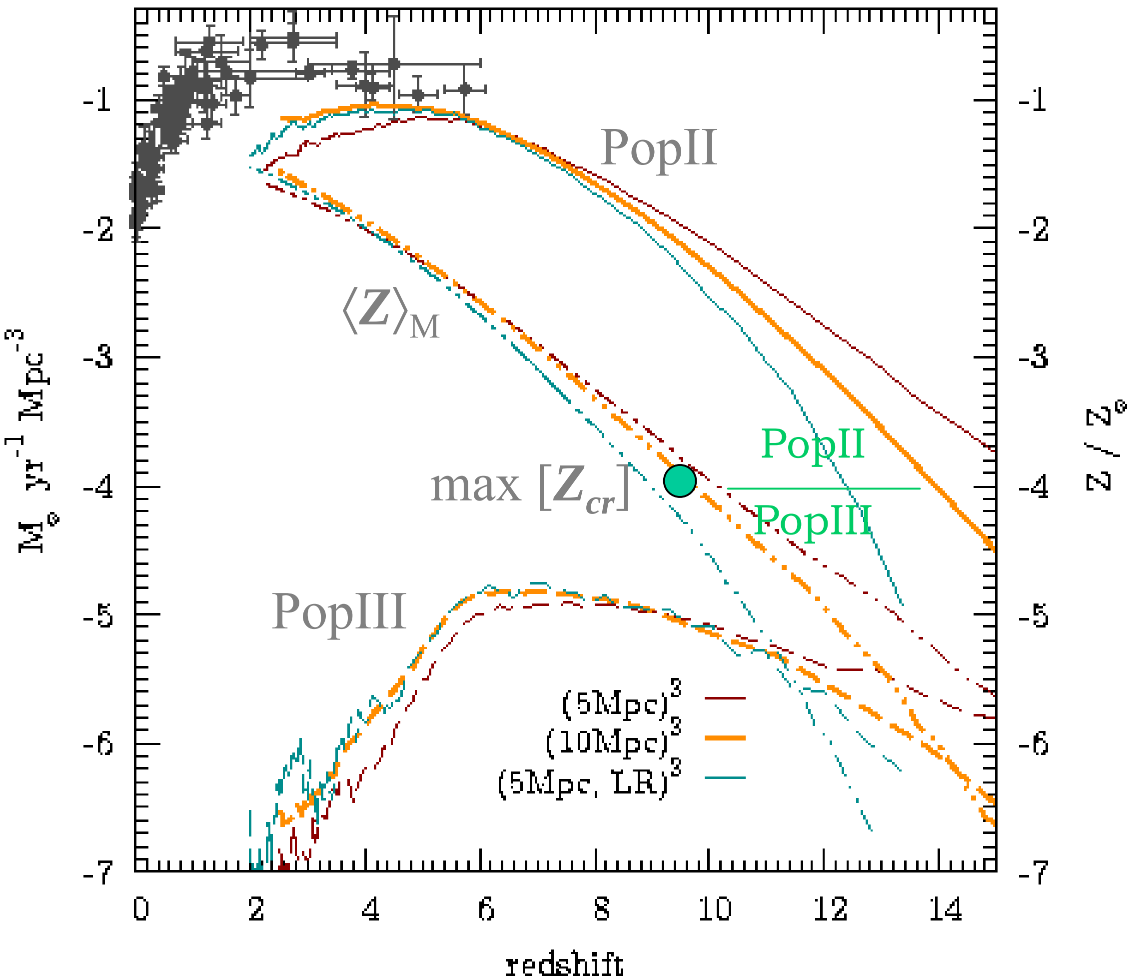
Tornatore, AF & Schneider 2007

COSMIC POPIII/POP II TRANSITION



Tornatore, AF & Schneider 2007

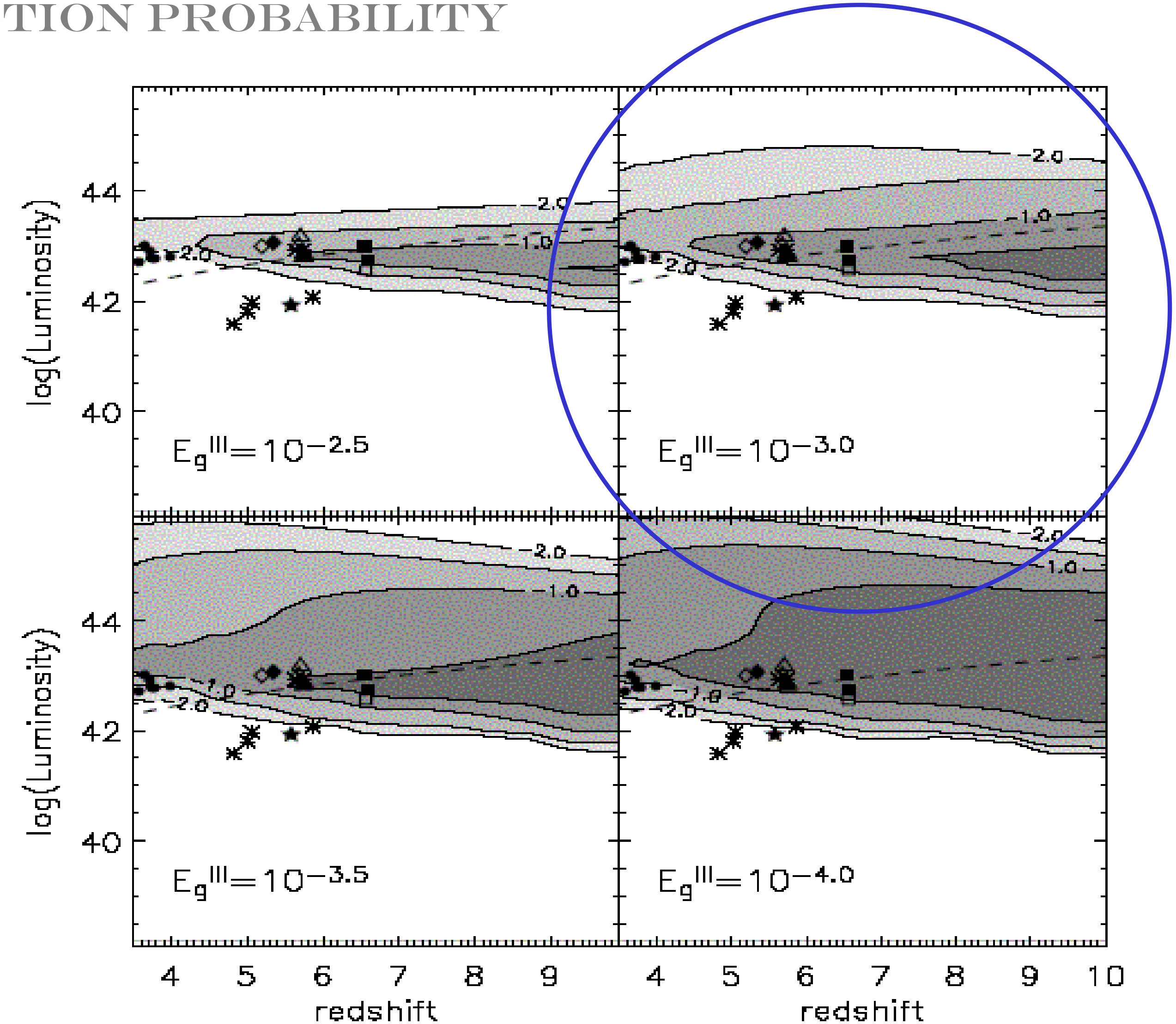
STAR FORMATION RATES



Scannapieco+ 2002

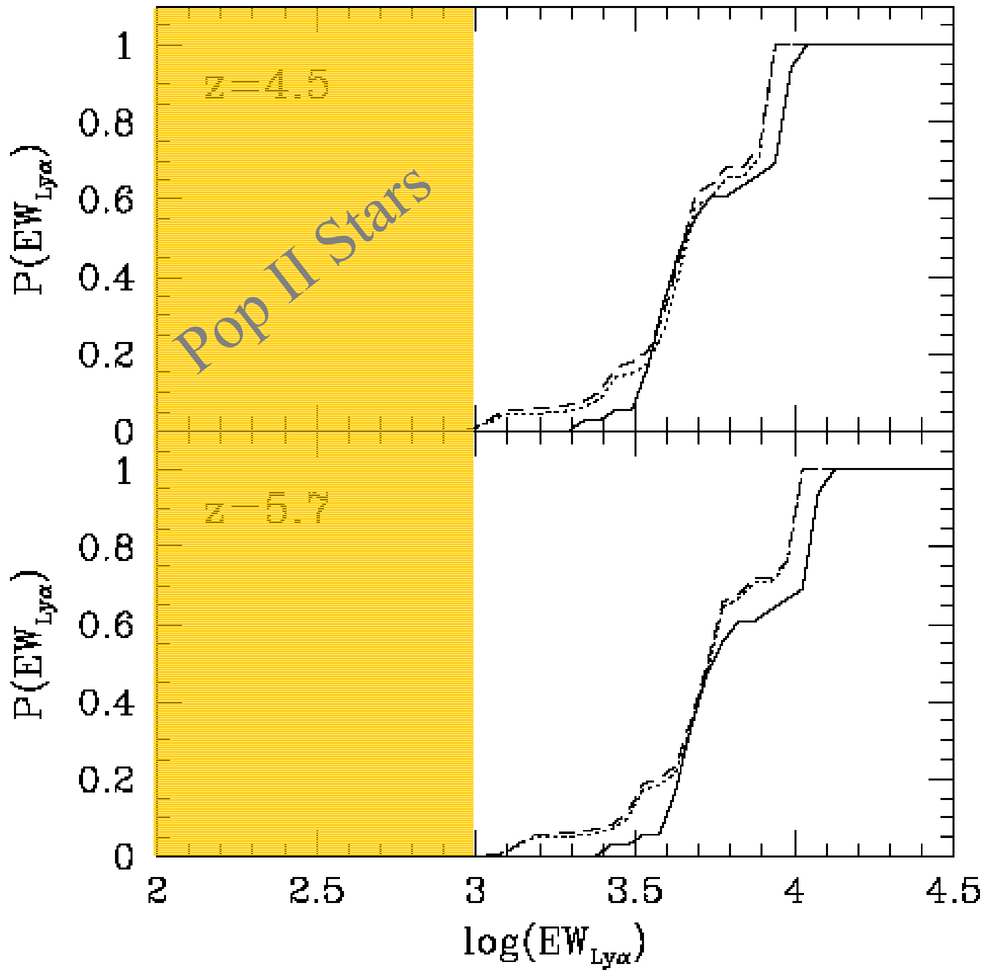
DETECTION PROBABILITY

Lyman Alpha Emitters



Scannapieco+ 2002

LYA EW OF POP III STARS

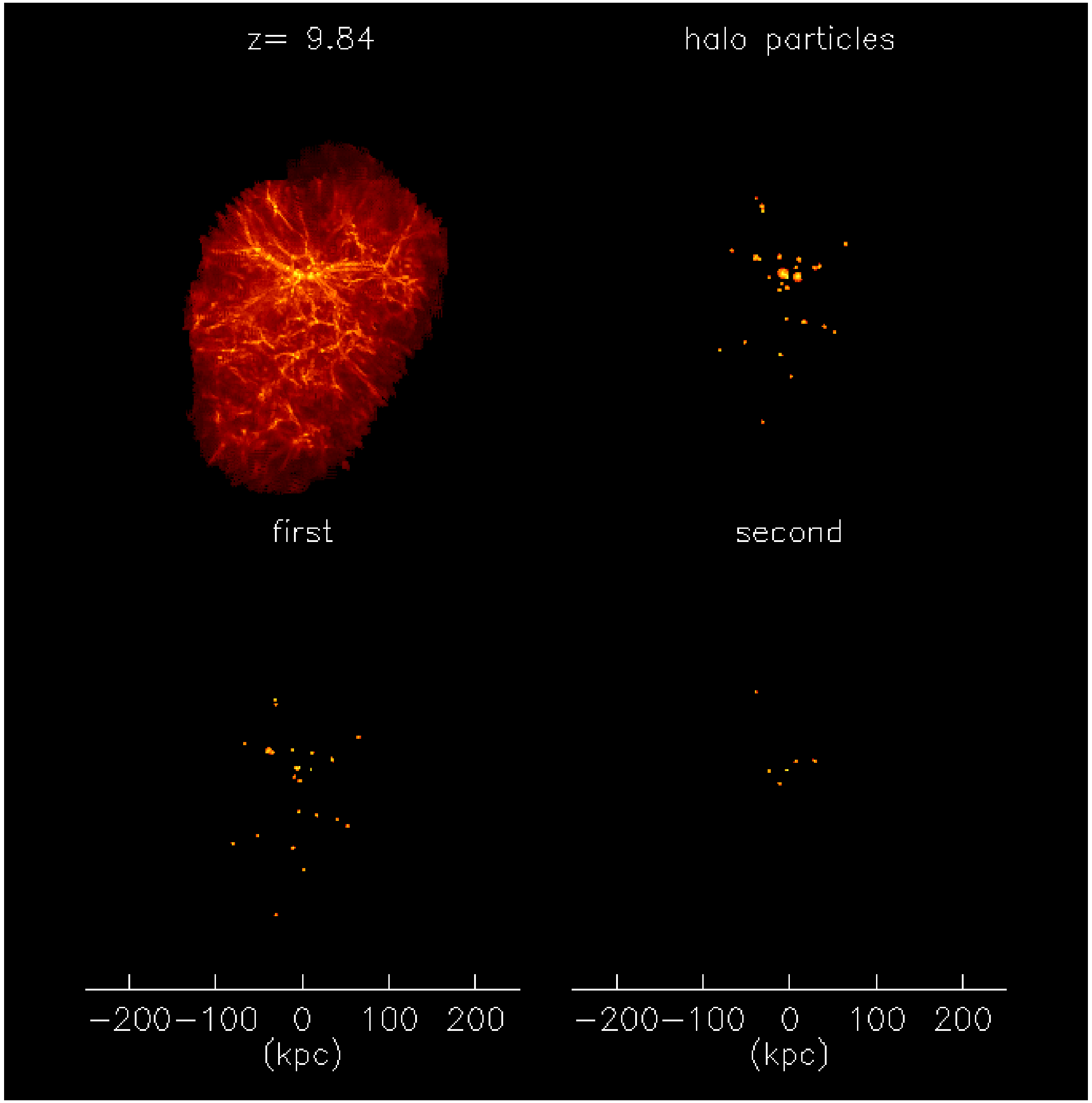


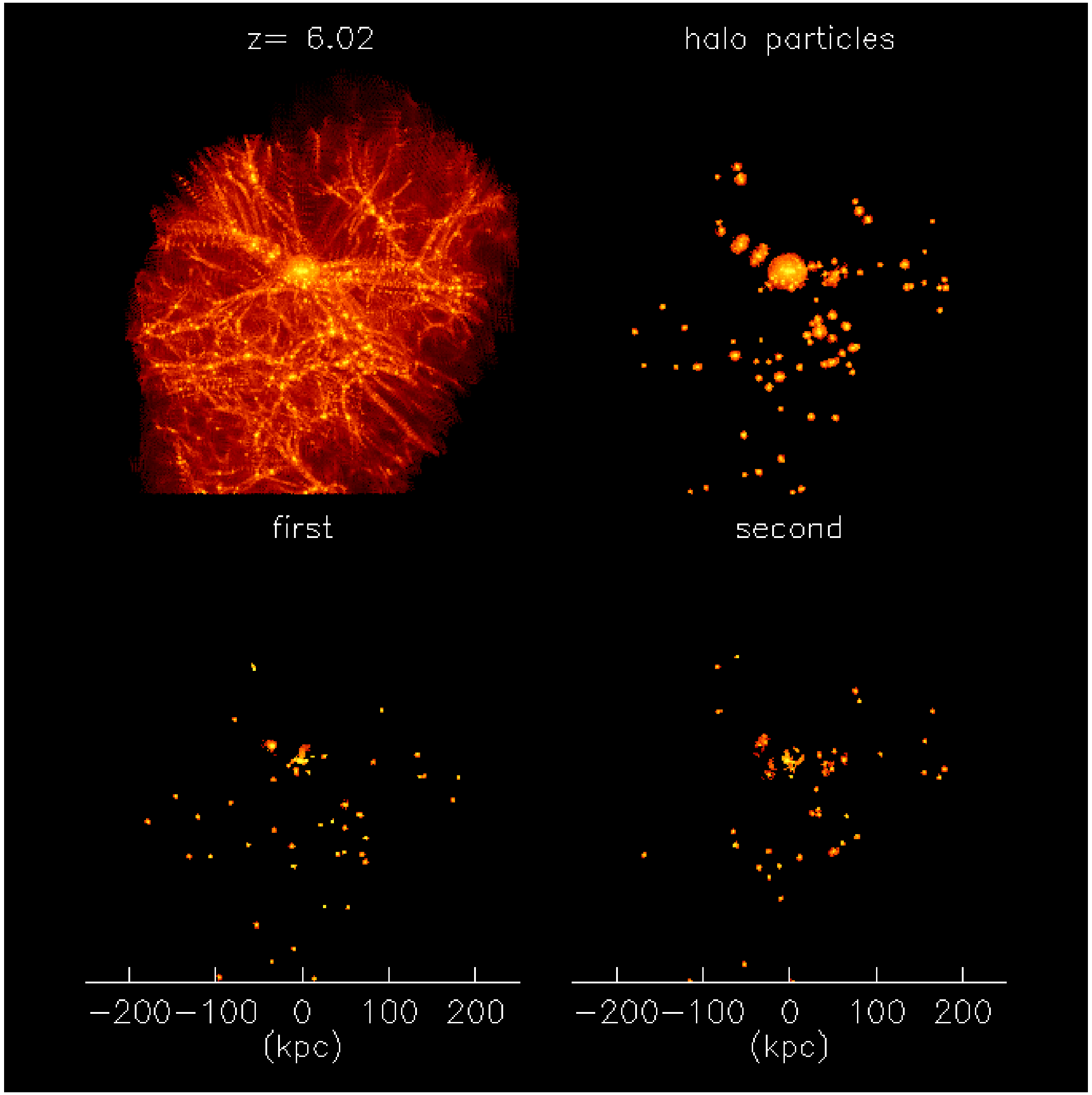
Pop III IMF

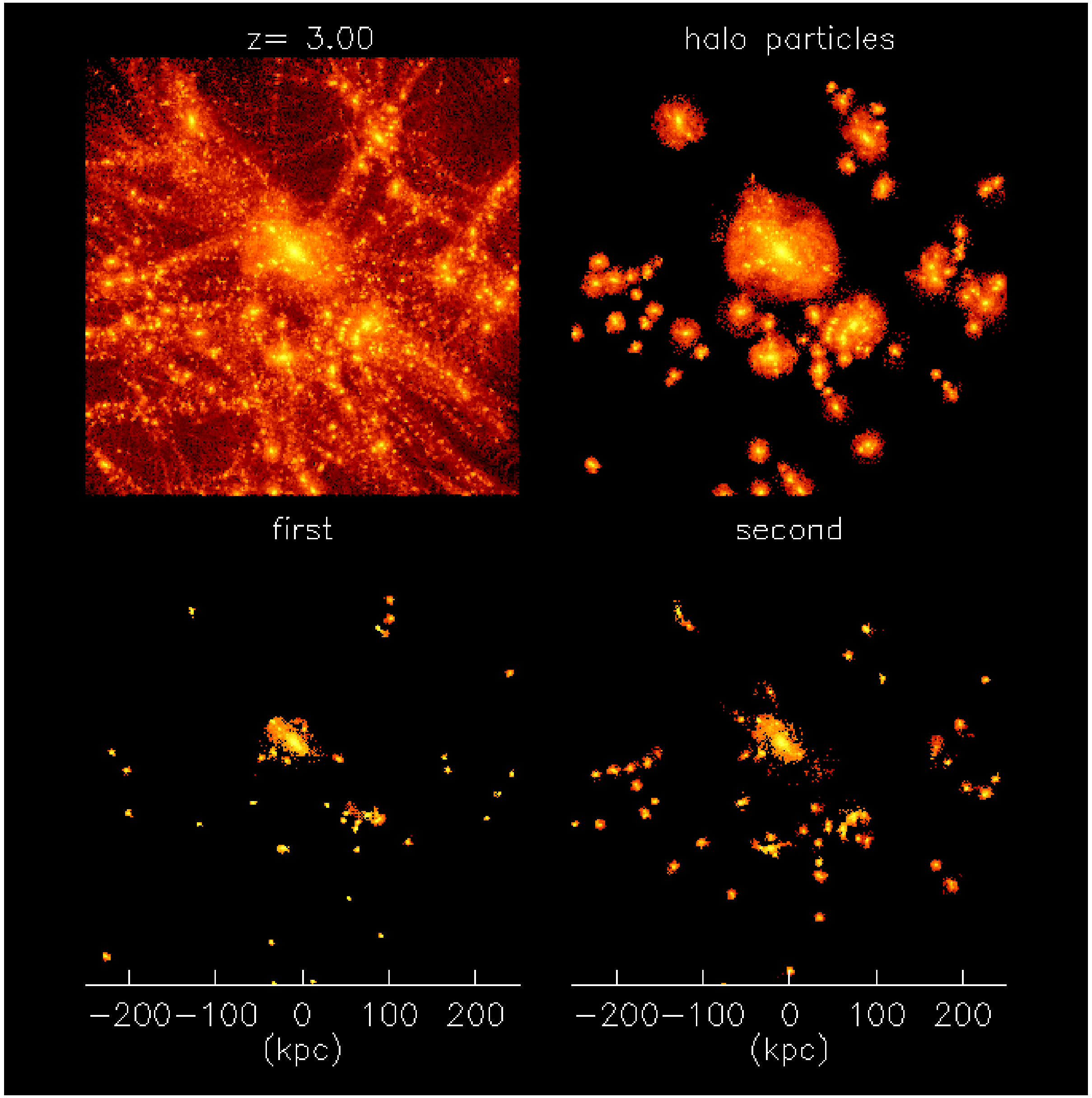
Salpeter 50-500 $M_\odot$

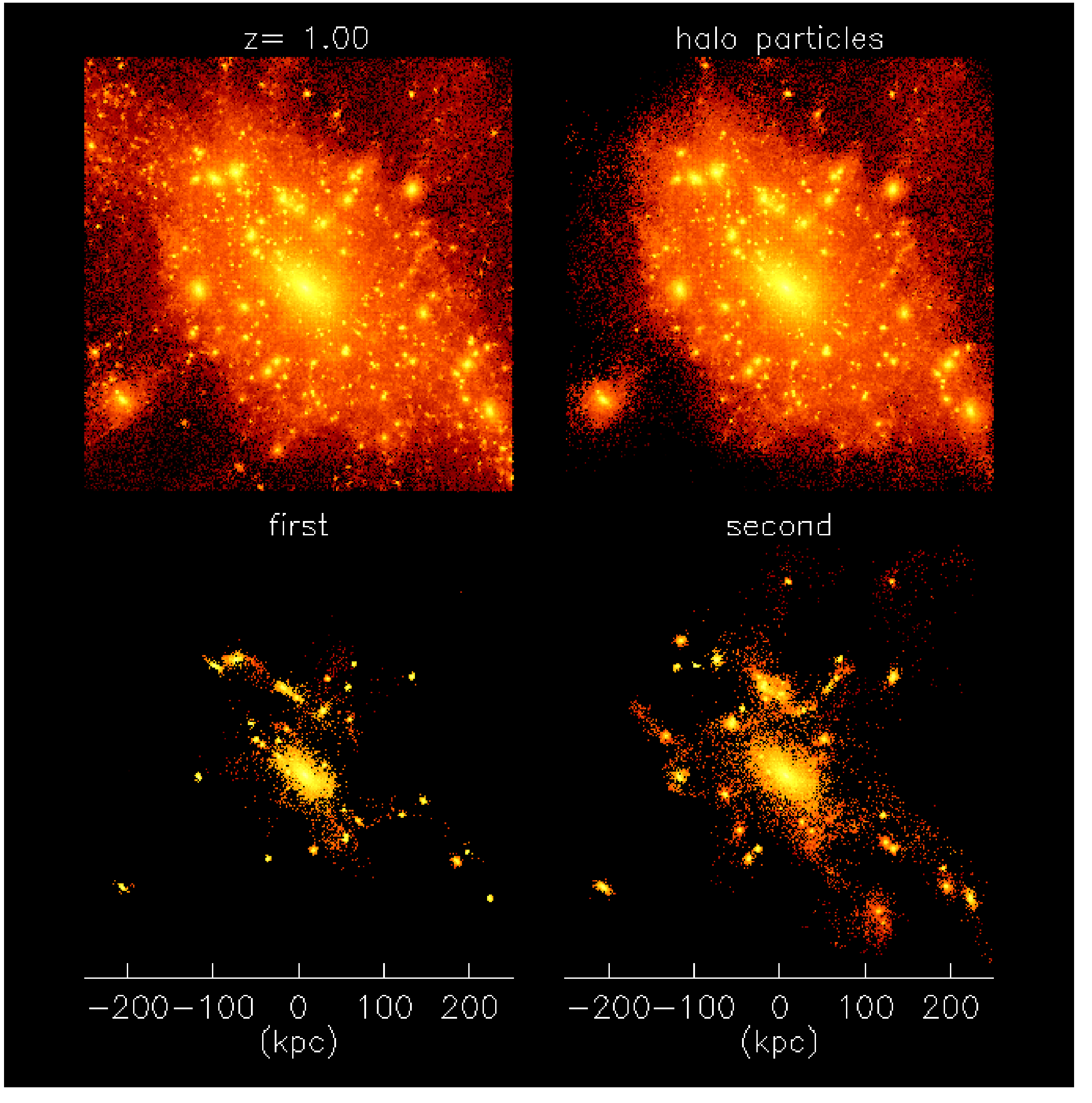
Salpeter 1-500 $M_\odot$

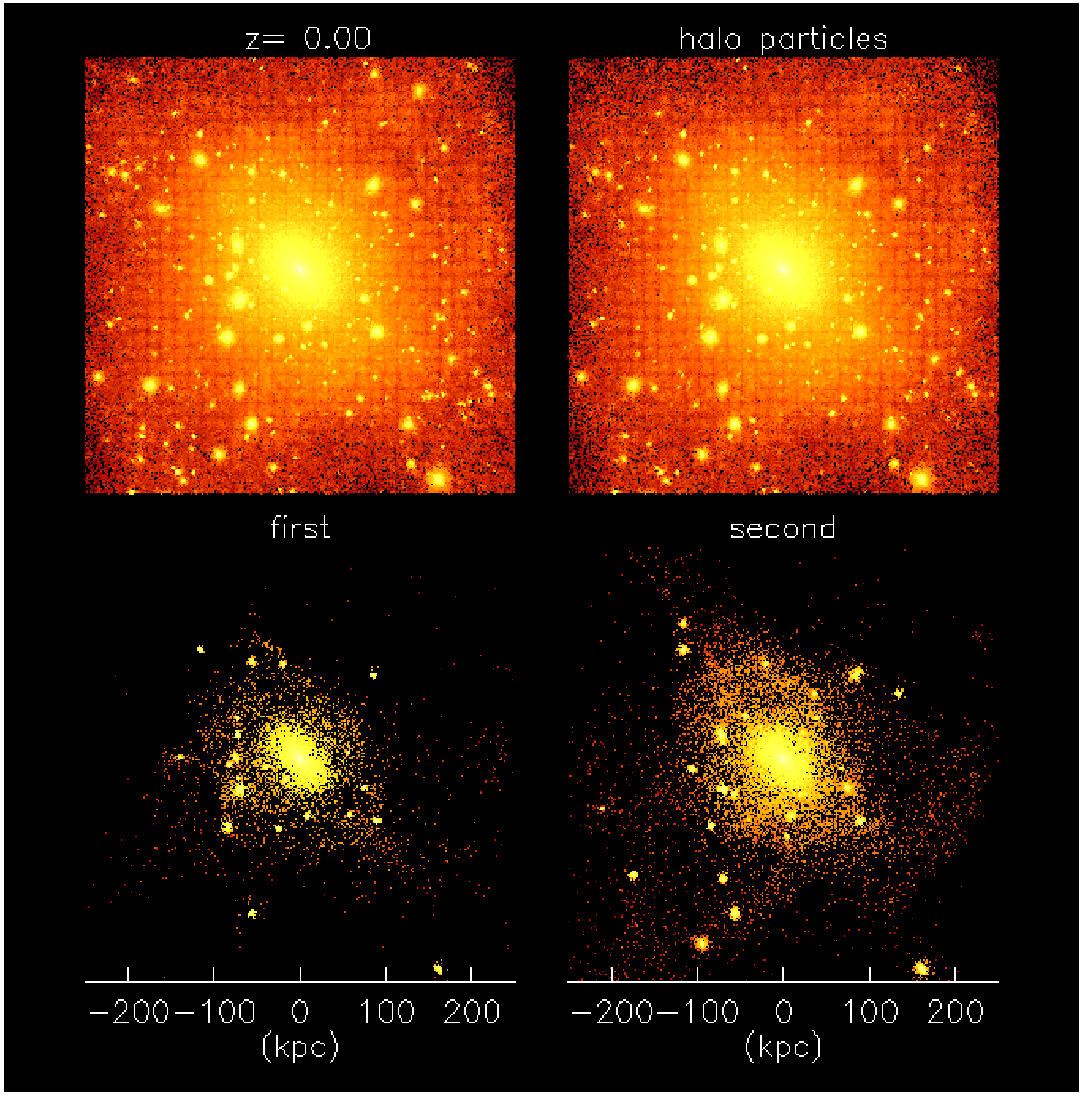
Scannapieco+ 2006




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)

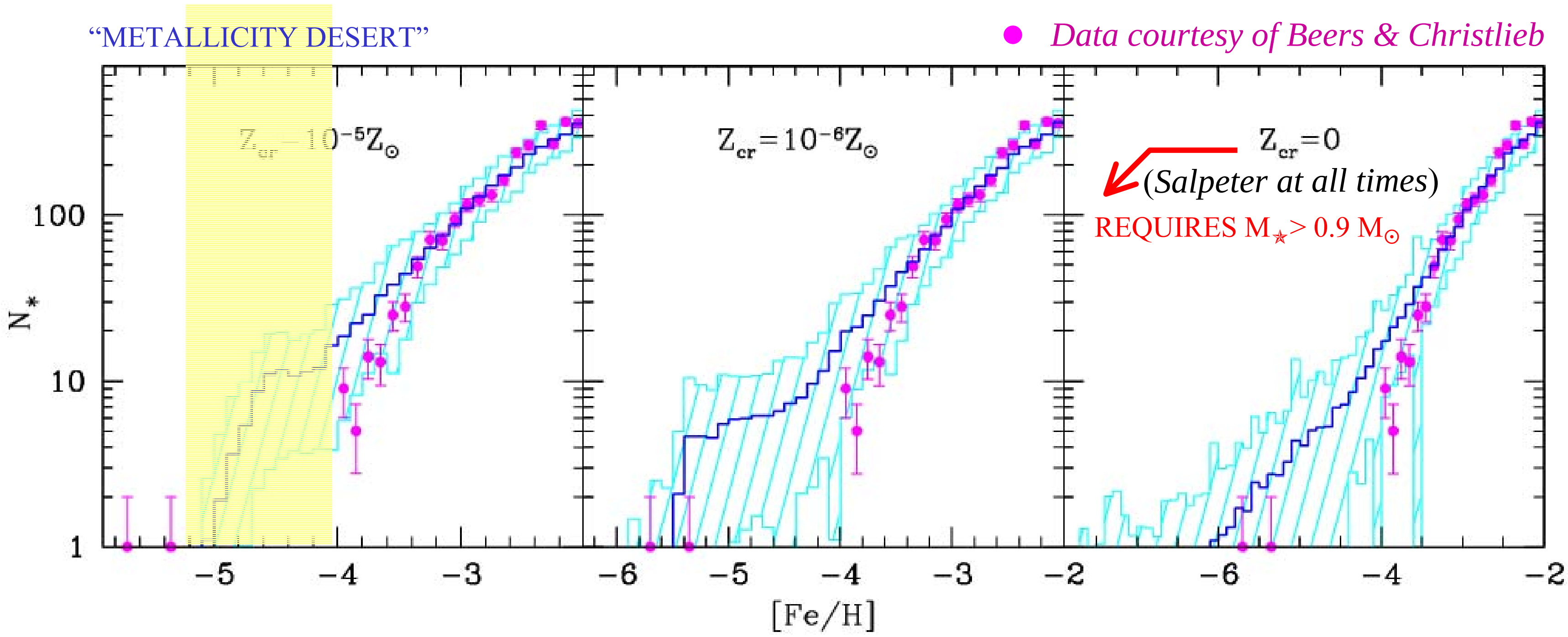

z= 1.00
halo particles
first
second
−200−100 0 100 200
(kpc)
−200−100 0 100 200
(kpc)


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

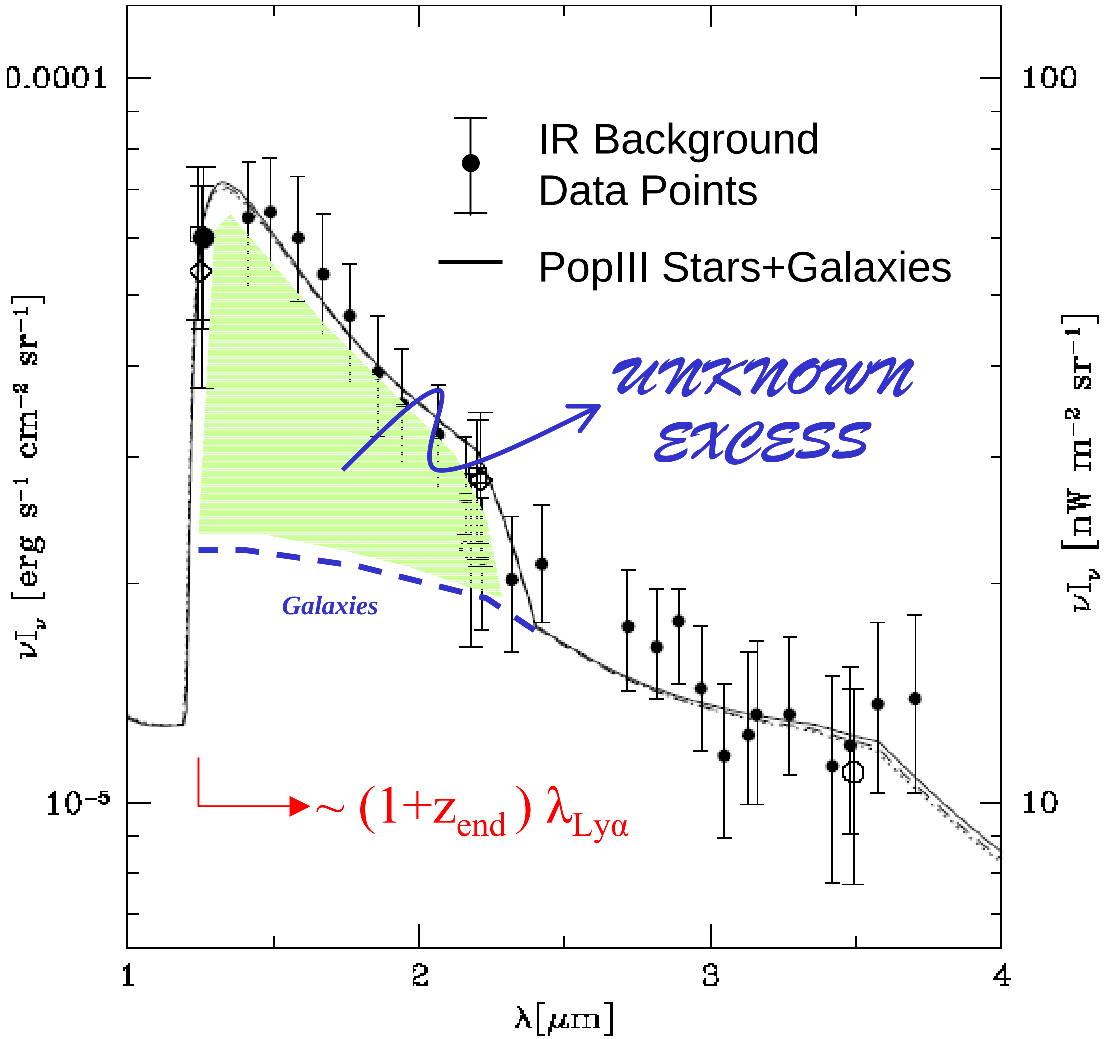
MDF INTERPRETED – II.

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



Salvaterra & AF 2002, Santos+2002

A PUZZLING EXCESS



Best fit model to NIR data

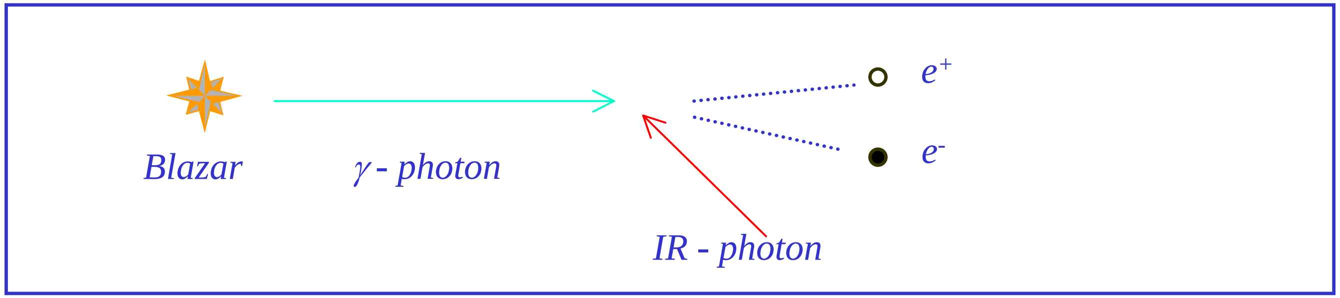
$z_{end} = 8.8$

$f_{\star} \approx 30\%$

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

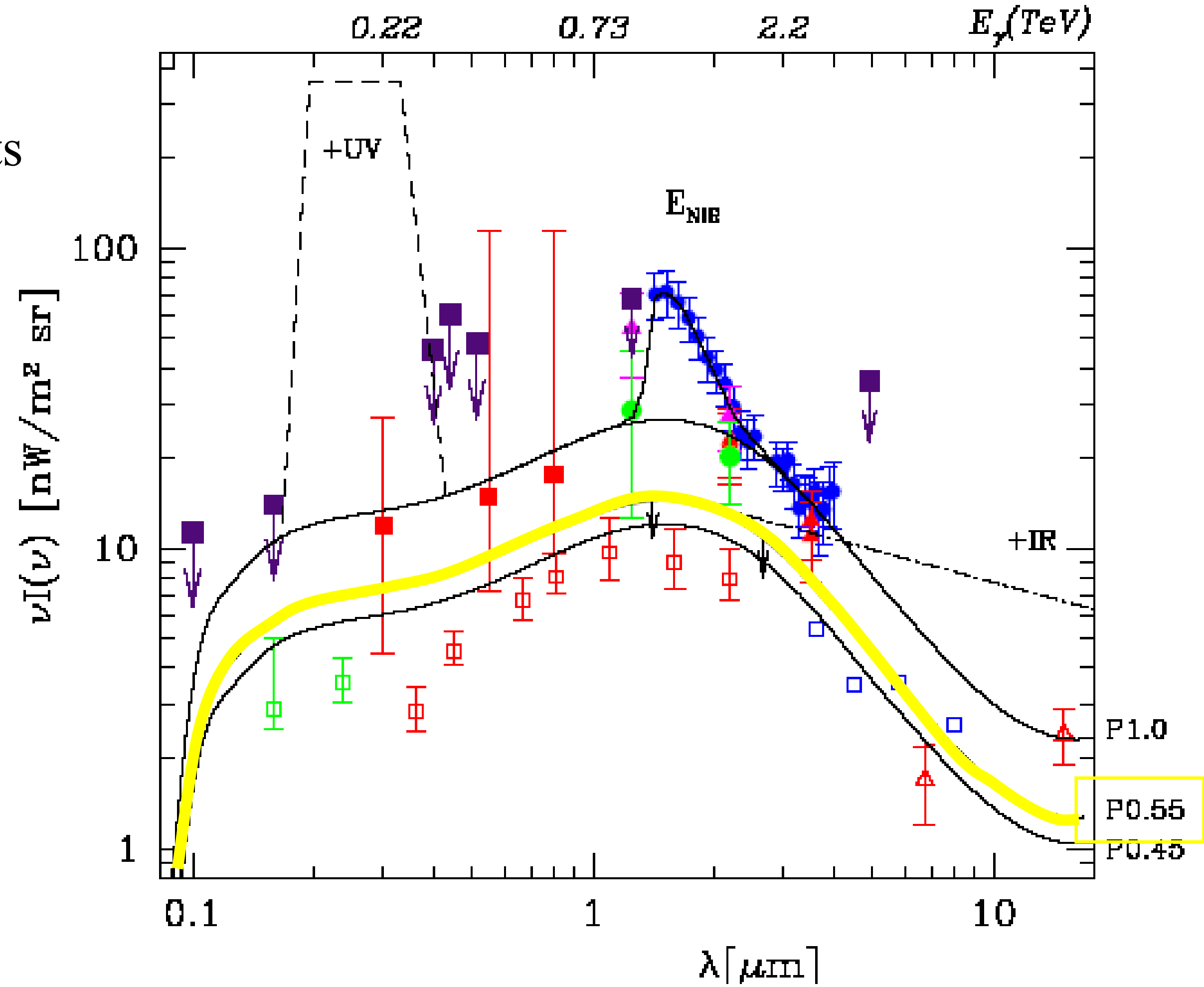
- *The observed spectrum of blazar reproduced by convolving the unabsorbed (power-law) spectrum with the optical depth:*

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

Mapelli+ 2005, Aharonian+ 2005

GAMMA-RAY CONSTRAINTS

- ○ Galaxy counts
- ● Direct measurements



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

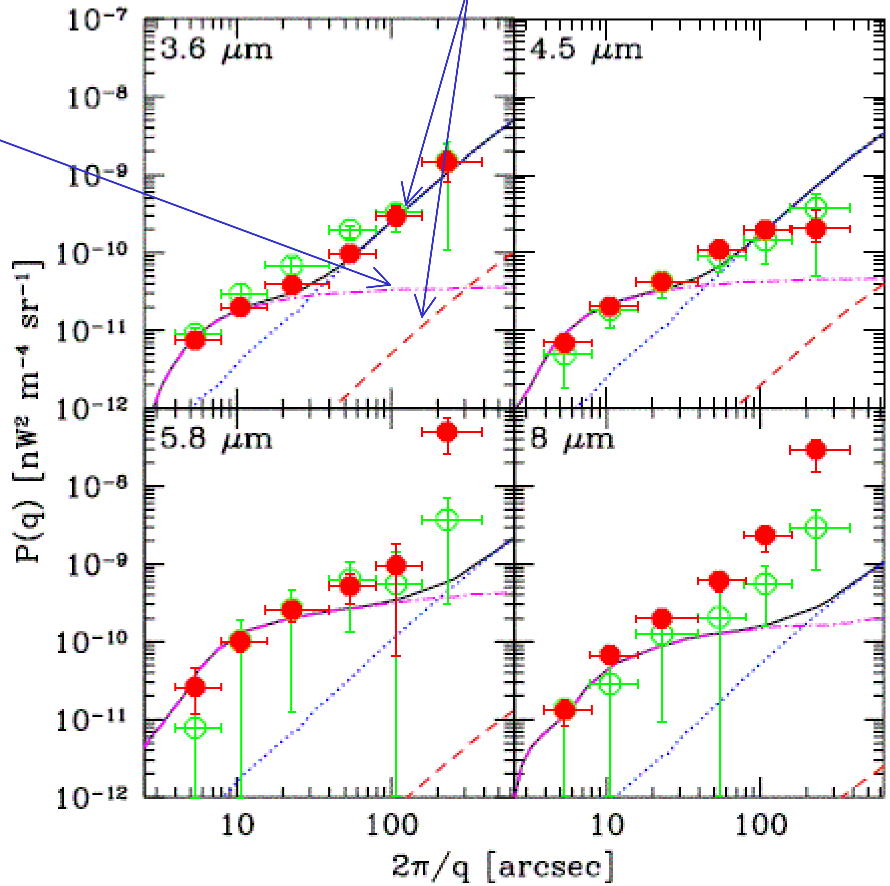
FLUCTUATIONS

Clustering z >5 galaxies

Shot noise
z <5 galaxies

POPII

POPIII

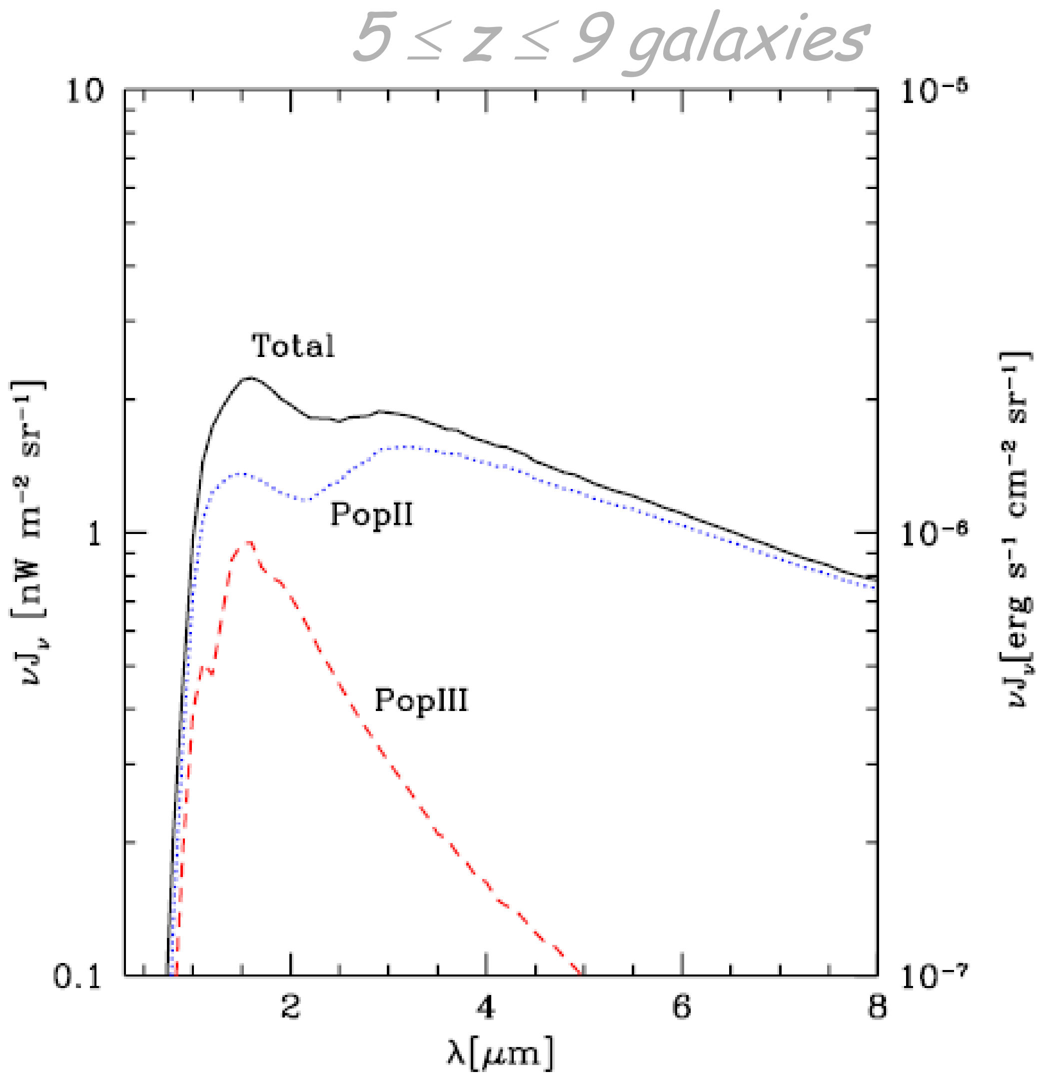


Spitzer/IRAC data

Kashlinsky+ 2005, 2007

Salvaterra+ 2006, Fernandez & Komatsu 2006

INTENSITY



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

- (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
- Imprint of very early (z>6) star formation activity left in the NIRB
- Experimental constraints on NIRB: intensity, fluctuations & pair-production opacity
- PISN explosions at moderate ($z < 6$) redshifts with JDEM

The End