2008 ASPEN WINTER WORKSHOP
The first 2 billion years of
Galaxy Formation

The MareNostrum Universe: Multi-billion particle simulations of High Redshift Galaxy Formation

Gustavo Yepes
Universidad Autónoma de Madrid

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The MareNostrum Numerical Cosmology Project

האוניברסיטה העברית בירושלים
The Hebrew University of Jerusalem

THE UNIVERSITY OF CHICAGO

NM STATE NEW MEXICO STATE UNIVERSITY

International collaboration to perform GRAND CHALLENGE SIMULATIONS on the *MareNostrum* supercomputer

Different scales, physics, codes: **(GADGET, ART)**

- **MareNostrum Universe SPH 2x1024^3 particles**
  - *Galaxy Cluster simulations. (AMR and SPH)*
- **MN Galaxy formation: > 2 G (dark+gas+stars)**
  - *71.4 Mpc. High redshift objects*
- **Local Universe (SIMU-LU)**
  - *160- 64 Mpc . Local neighbourhood:*
    - *The Local Group + Local Supercluster*
    - *Upt to 1 Gparticle simulation.*

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MNCP: 2-G Gal Simulation

One of the world's largest GALAXY FORMATION SIMULATION S

71.4 ($50h^{-1}$) Mpc box
Gasdynamical and N-body simulation
with 1024^3 particles

+

(G)Astrophysics

Two different runs :

SPH + N-body (2 x 1024^3 particles) (GADGET2)
AMR + N-body (1024^3 + 4 billion AMR cells) (RAMSES)

(G)ASTROPHYSICAL PROCESSES

To study in detail the galaxy formation process we take into account:

- ***Radiative and Compton cooling***
- ***UV-photoionization***
- ***Multiphase ISM.***
- ***Star Formation.***
- ***Star-Gas back-reactions***
  - **SN's thermal Feedbacks: Cloud Evaporation and gas reheating**
  - **Stellar Winds**

Springel-Hernquist (2003) implementation of multiphase SPH modeling in GADGET-2.

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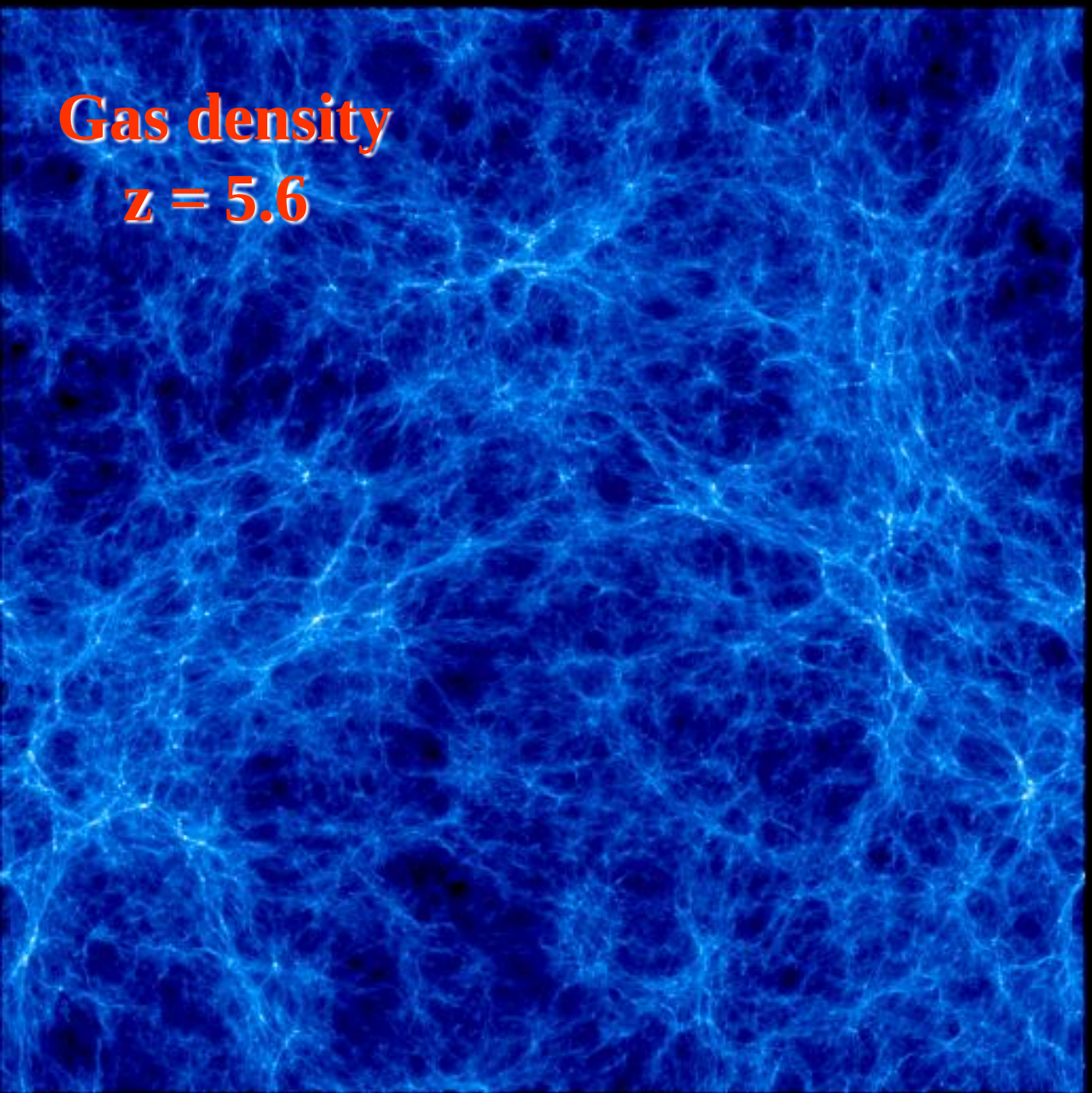
MNCP-2G SPH simulation



Box 71.4 Mpc
2x 10^9 gas+dark
ΛCDM model WMAP1
M_{gas}=1.4 x10^6 Msun
M_{dark}=8x10^6 Msun.
M_{halos} > 10^9 Msun
Smoothing: 700 pc.
Starting z=50
currently at z=4.9

Computational resources

GADGET2 TreePM+SPH
800 processors of MN
1024^3 mesh for FFT
11,100 timestep so far
Total computing time:
2.7x10^6 hours
313 years

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MN UNIVERSE AMR SIMULATION

Same initial conditions than GADGET MN-2G simulation RAMSES (Teyssier 2002) AMR MPI code.

- **1024^3 dark matter particles (M_{dark}= 8x10^6 Msun)**
- **4 billion AMR cells.**
- **1024^3 base grid +5 levels of refinement**
  - **(smallest cell is 2 kpc *physical)***
- **cooling, star formation, supernovae blast waves, metals**
- **2048 processors of MareNostrum**
- **120 years of CPU time.**
- **Simulation at z =1.2 now**
- **More than 100,000 galaxies**
- **More than 120 million stars formed**
- **Luminosity of stars computed from STARDUST model (Devriendt et al 99)**

- ***http://www.projet-horizon.fr***

People behind

Gustavo Yepes
Raúl Sevilla
Luis Martínez
N. Espino

Stefan Gottlöber
Arman Khalatyan
Christian Wagner
Y. Ascasibar

R. Teyssier
J. Devriendt
C. Pichon
D. Aubert
E. Audit
…

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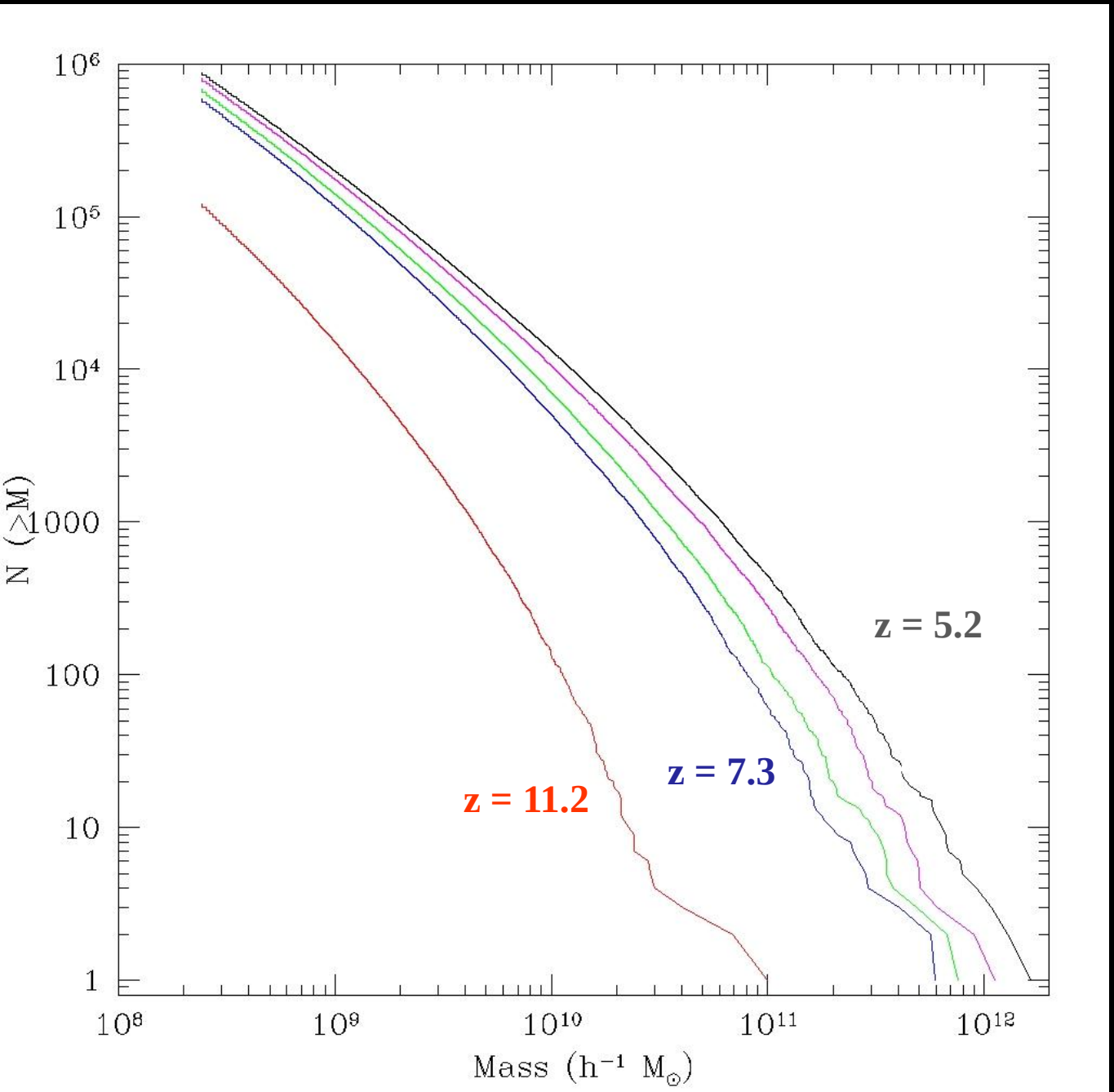
MNCP-2G SPH simulation



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2x 10^9 gas+dark

ΛCDM model

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Halos Mass Functions
FoF halo finder
20 dark matter
particles minimum

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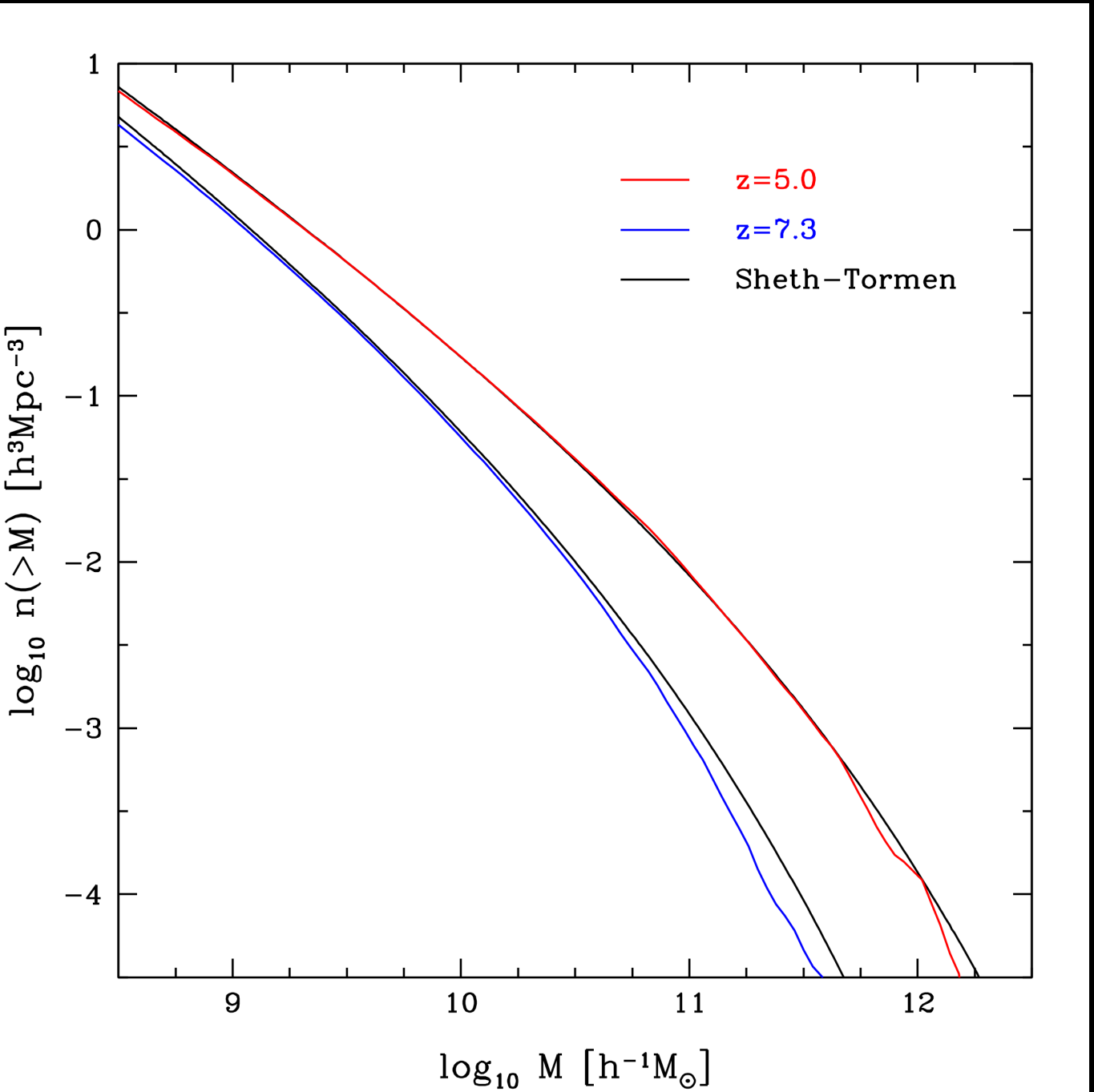
MNCP-2G SPH simulation



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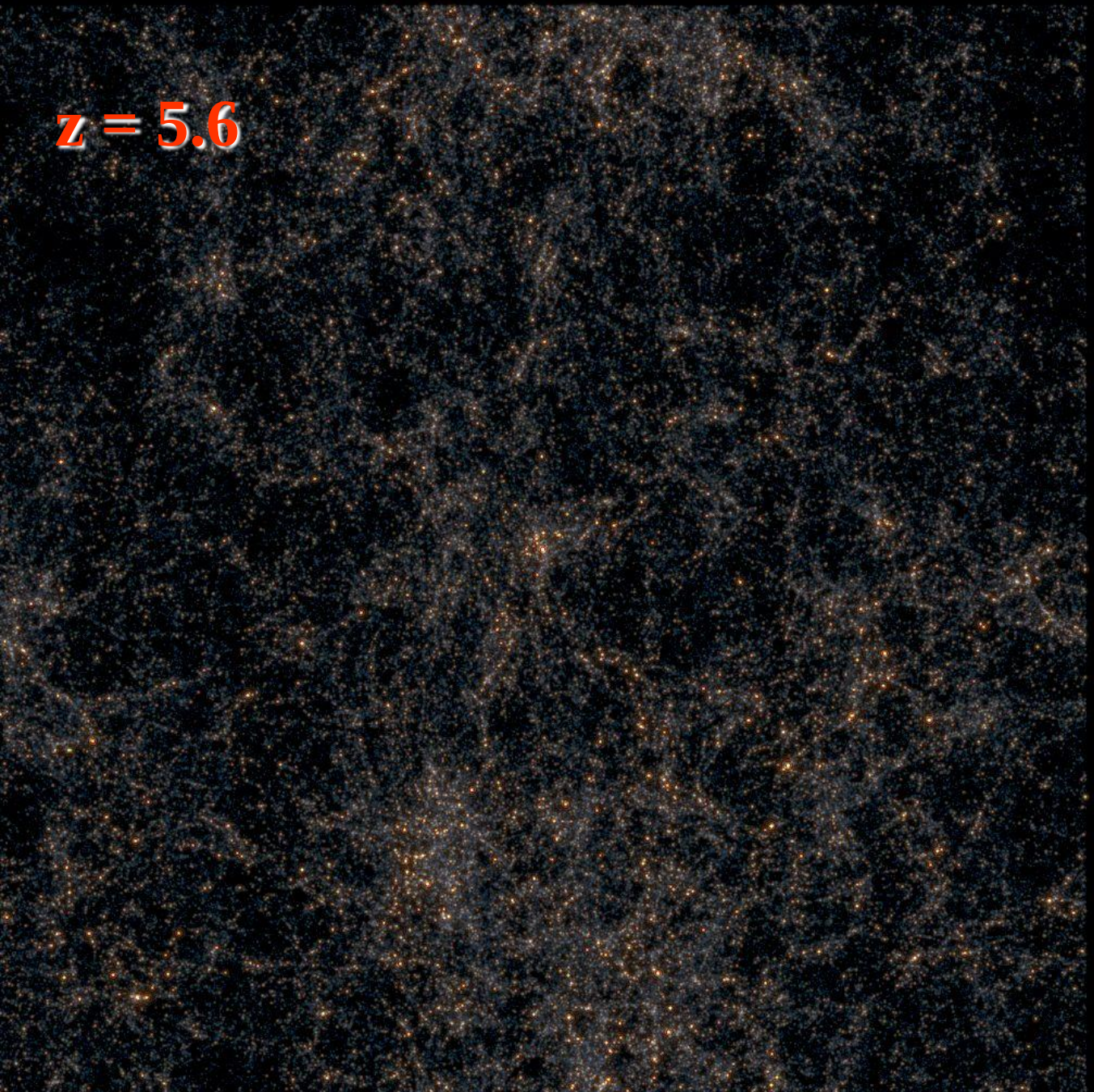

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Stellar objects

FoF Group finder

50 stellar particles minimum

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MNCP-2G SPH simulation

z = 5.6

Box 71.4 Mpc

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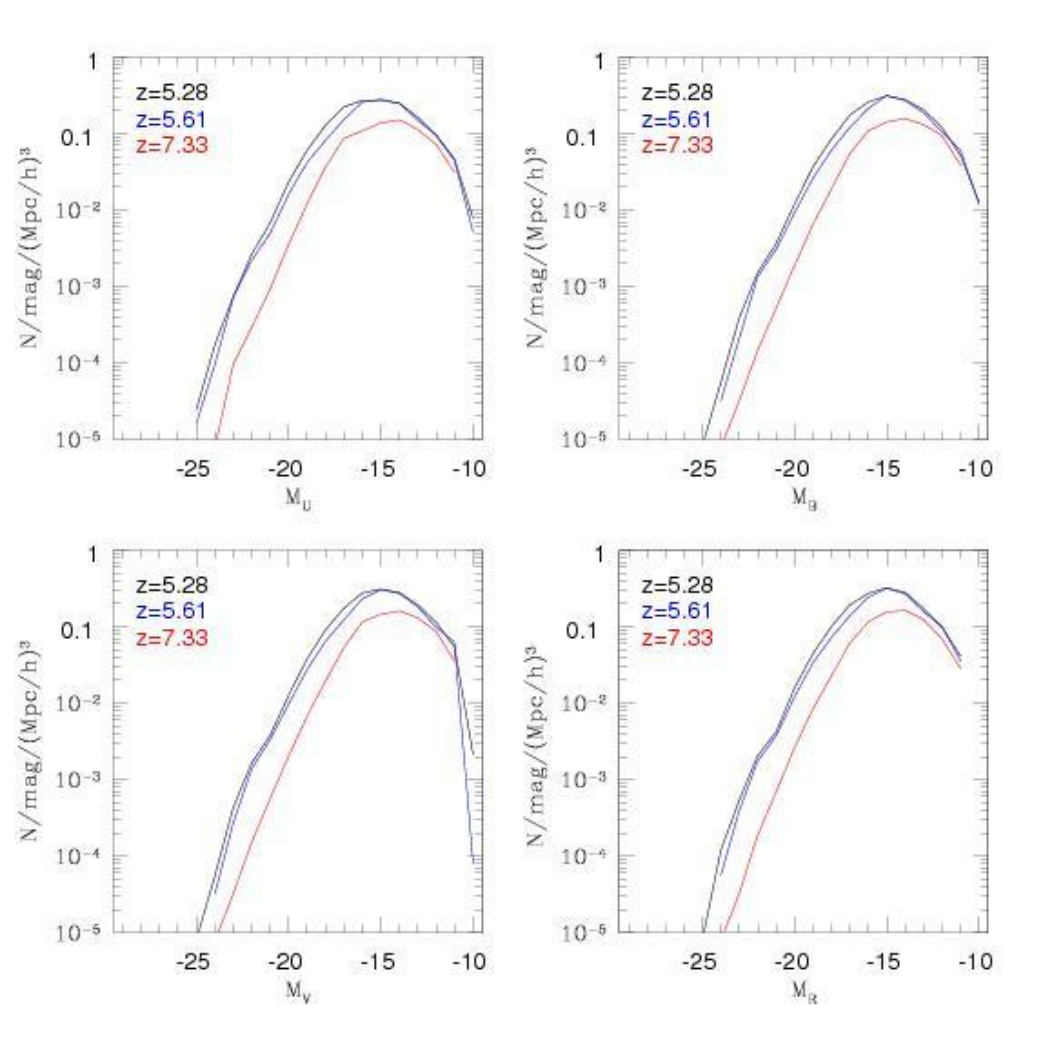

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Luminosity of stars

STARDUST SSP
(Devriendt et al 99)

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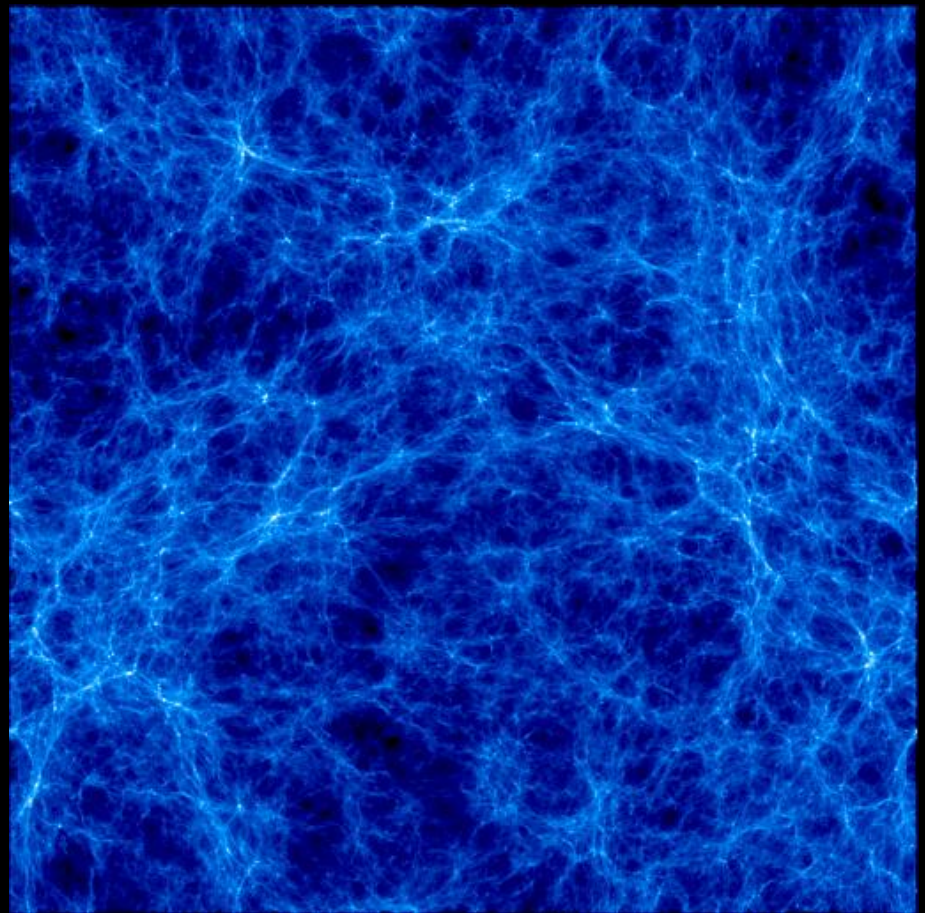
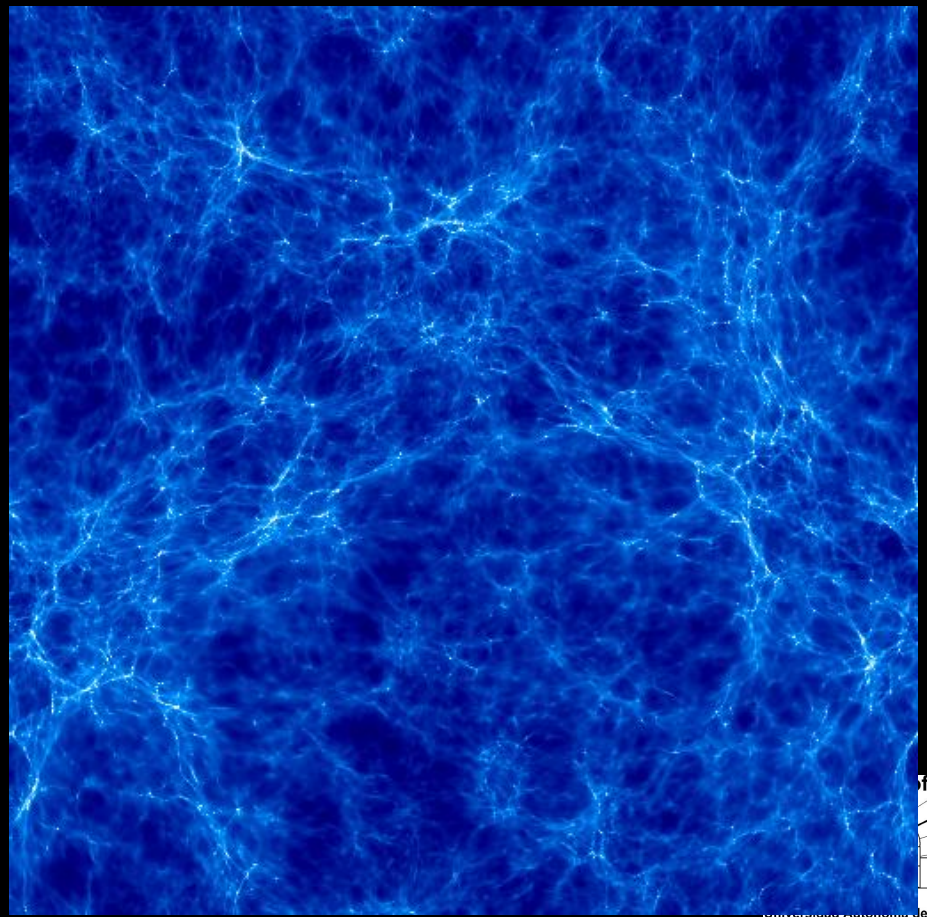
COMPARISON OF SIMULATIONS

MNCP GADGET (SPH)
800 processors of MN
Resolution: 700 pc.
313 YEARS of CPU
http://astro.ft.uam.es/marenostrum



HORIZON -RAMSES (AMR)
More than 2000 processors MN
Resolution: 2 kpc
110 YEARS CPU
http://www.projet-horizon.fr



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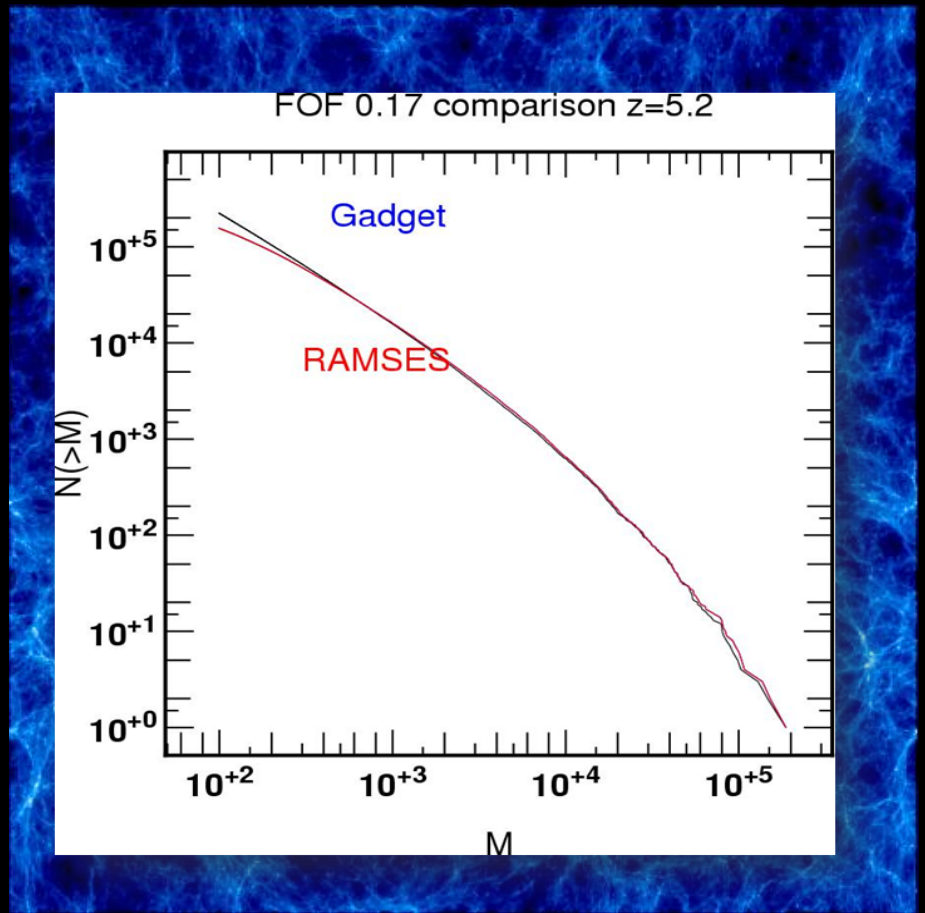

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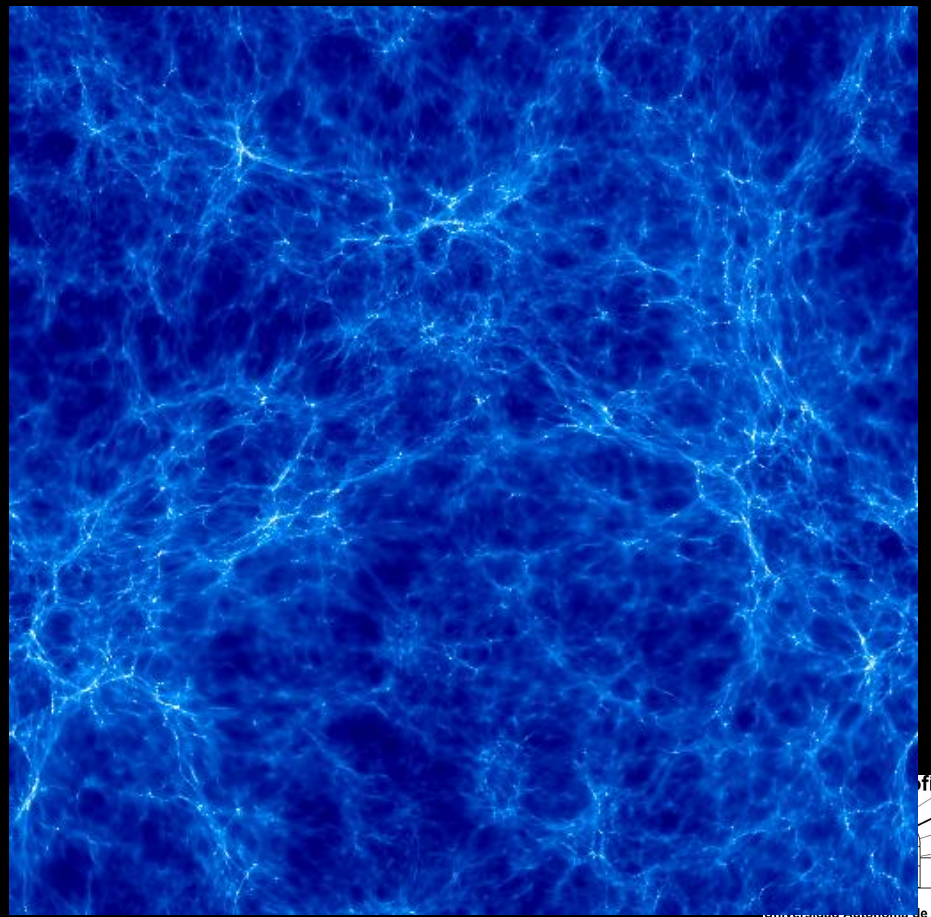

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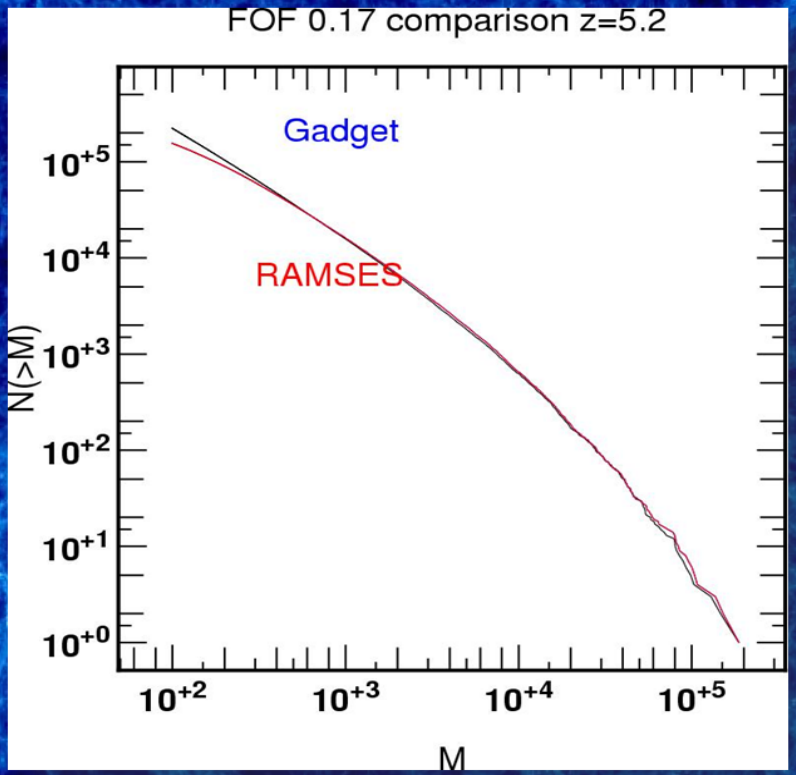

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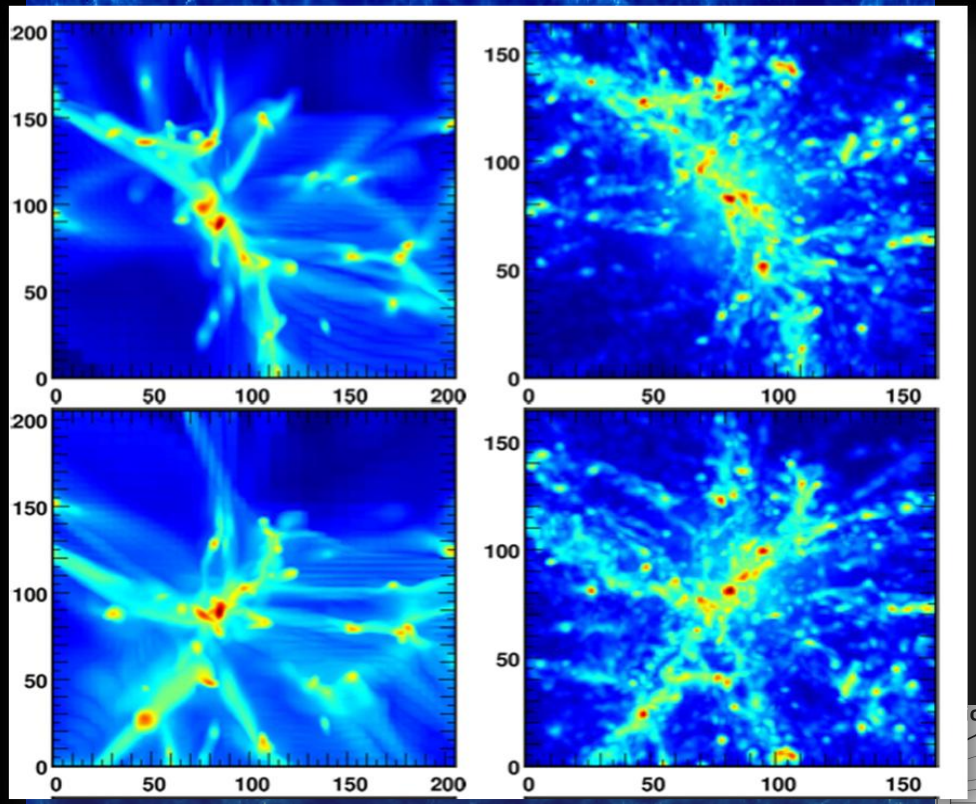

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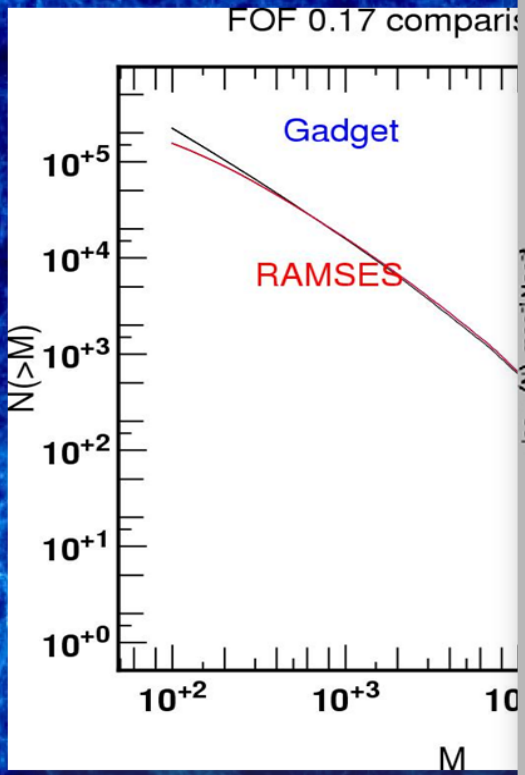
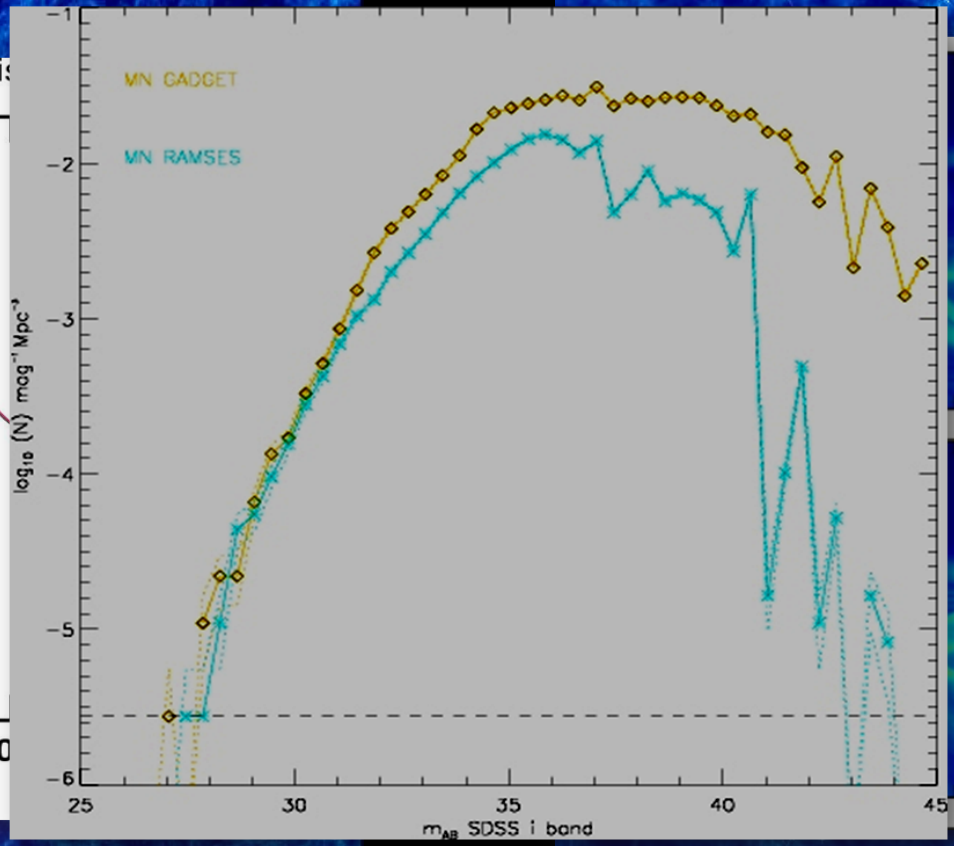
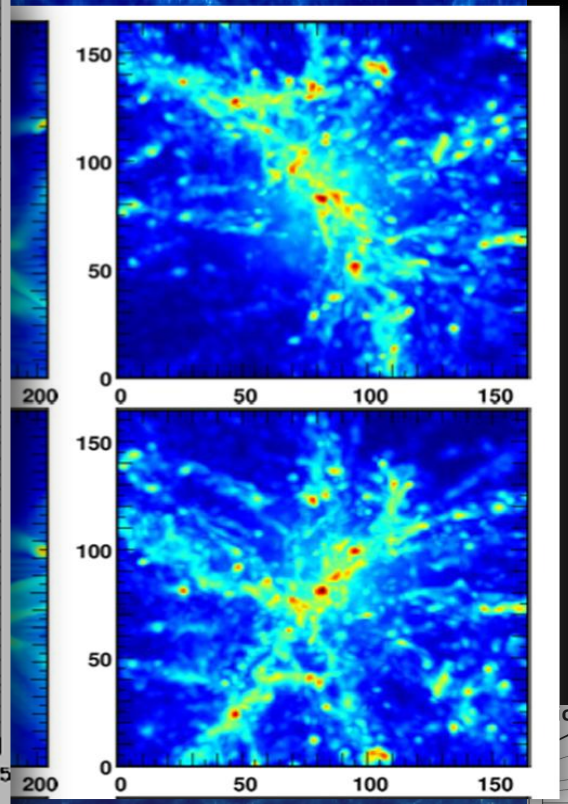
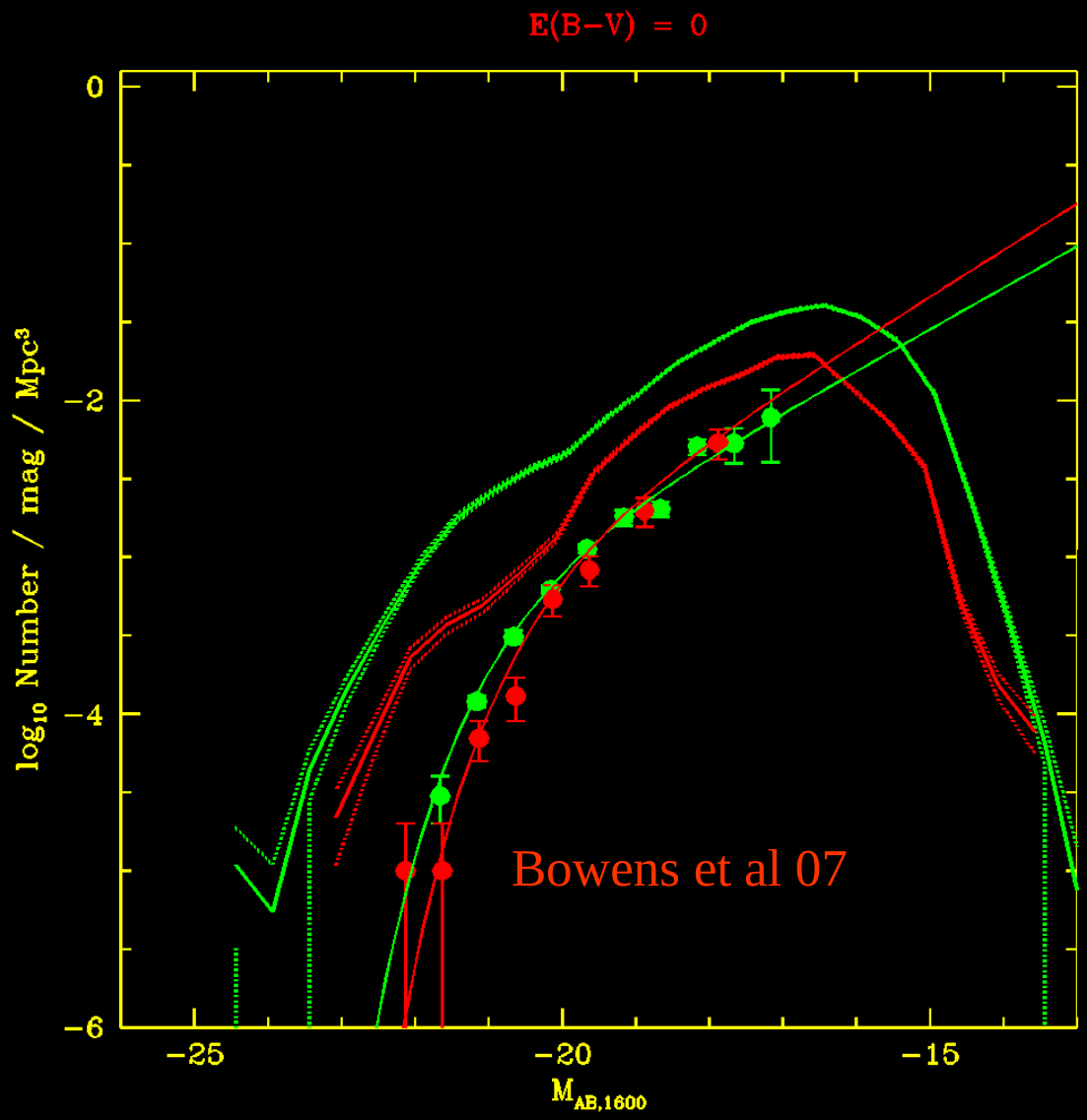






UV Luminosity Function @ z=5-6



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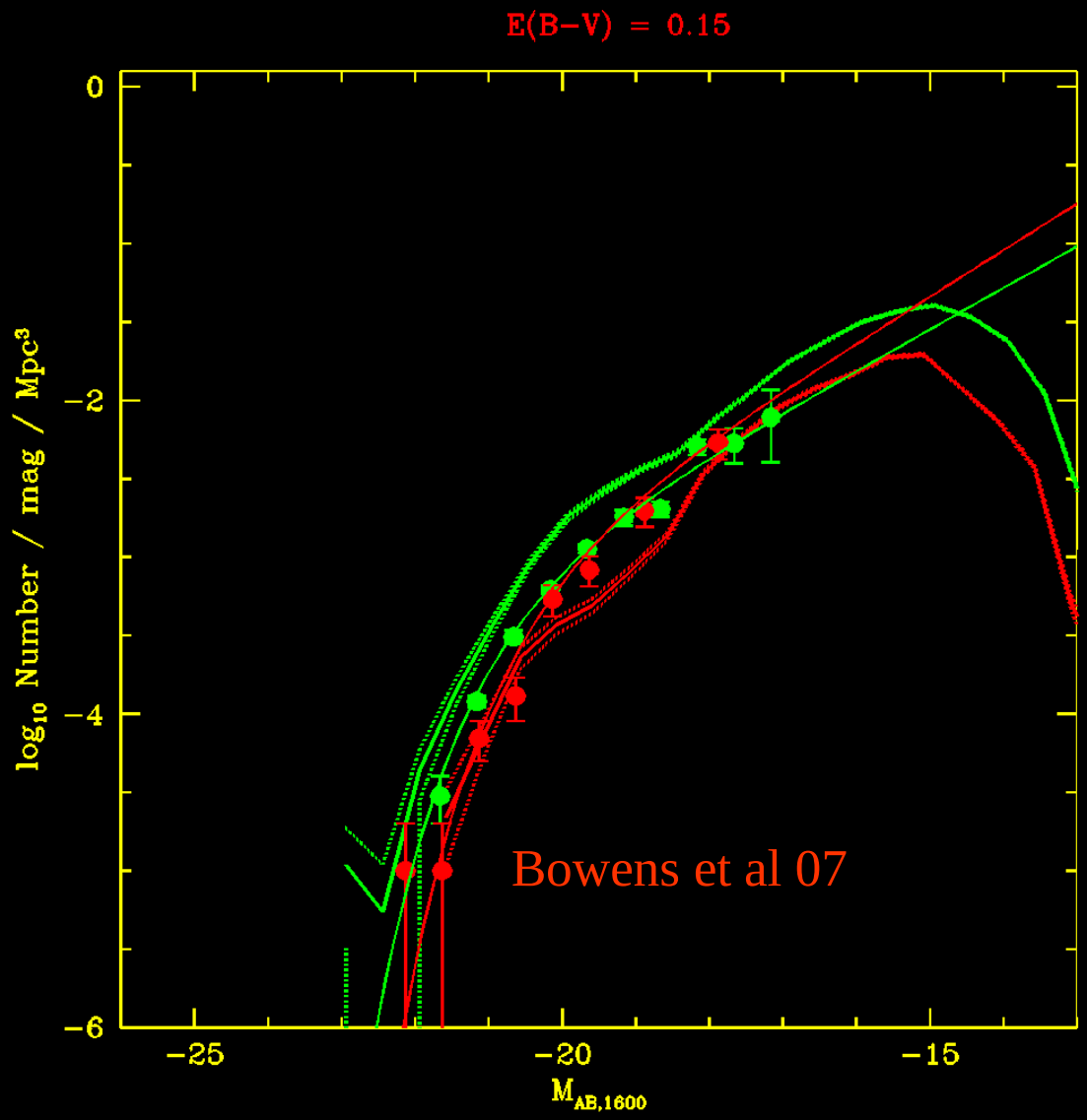
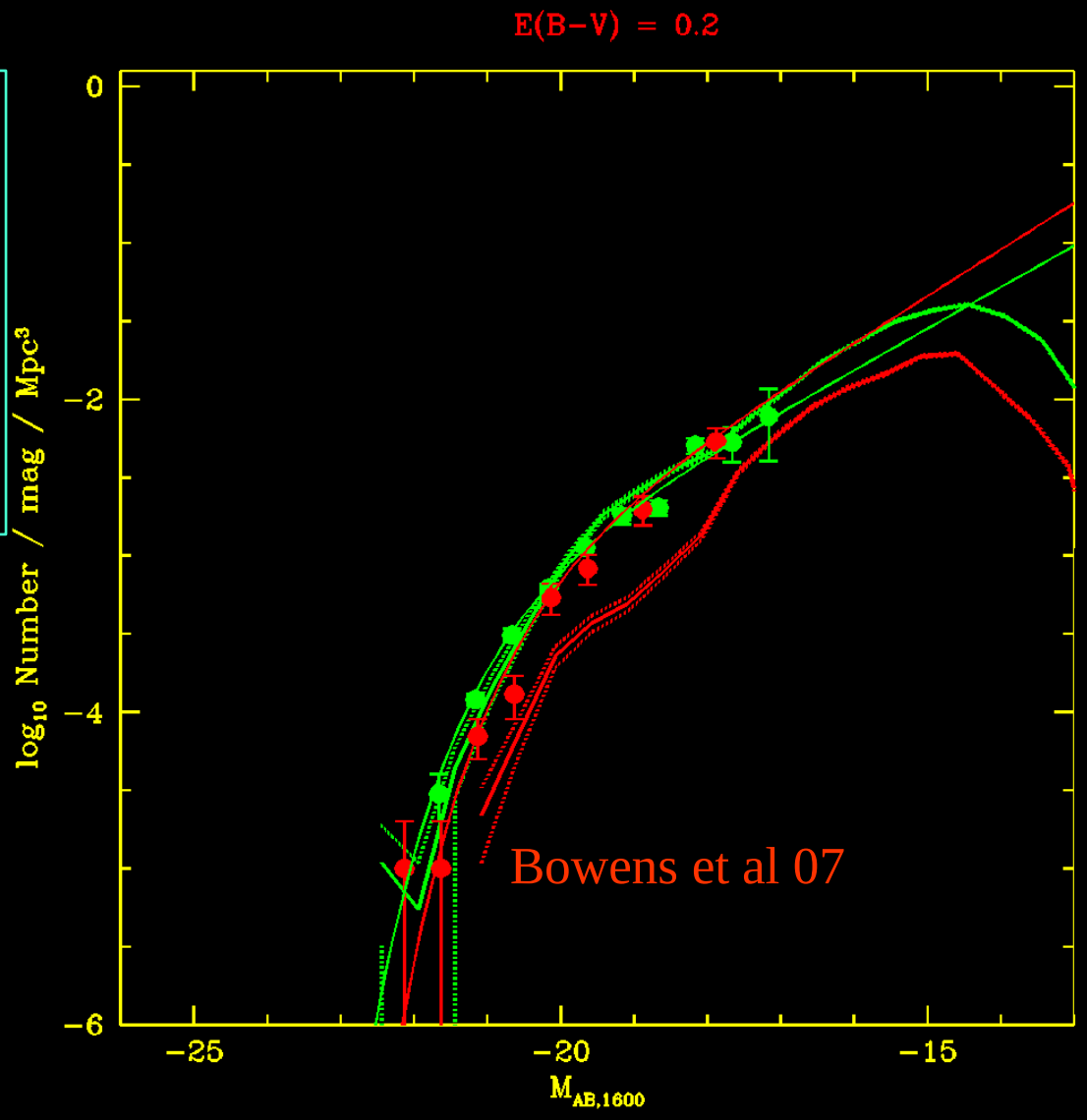


UV Luminosity Function @ z=5-6

Good fit
if dust extinction
evolves from
E(B-V)=0.15
@z=6 to
E(B-V)=0.2
@z=5



Faint end slopes
consistent with
observed ones

$\alpha \sim -1.6 , -1.7$

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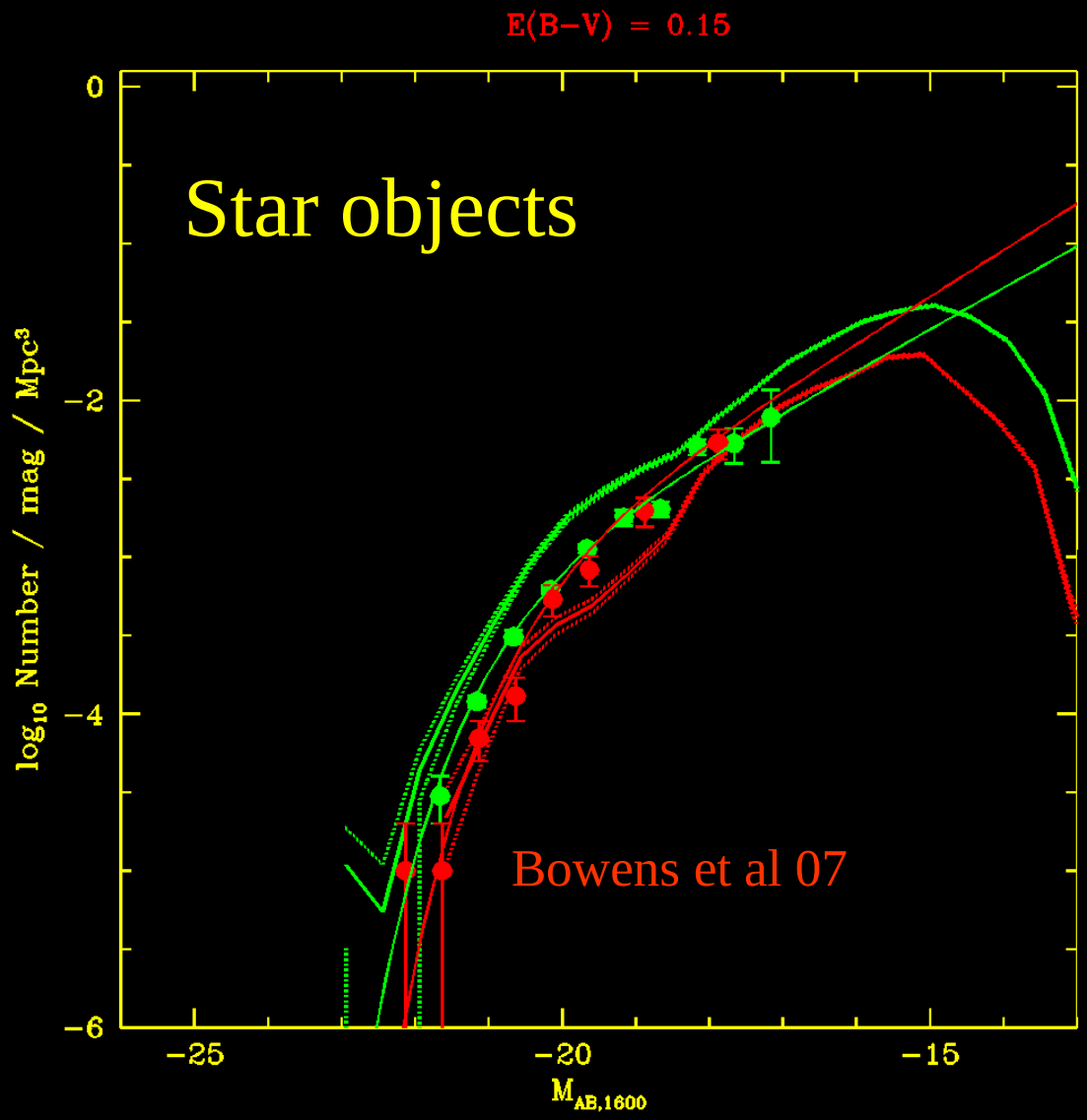

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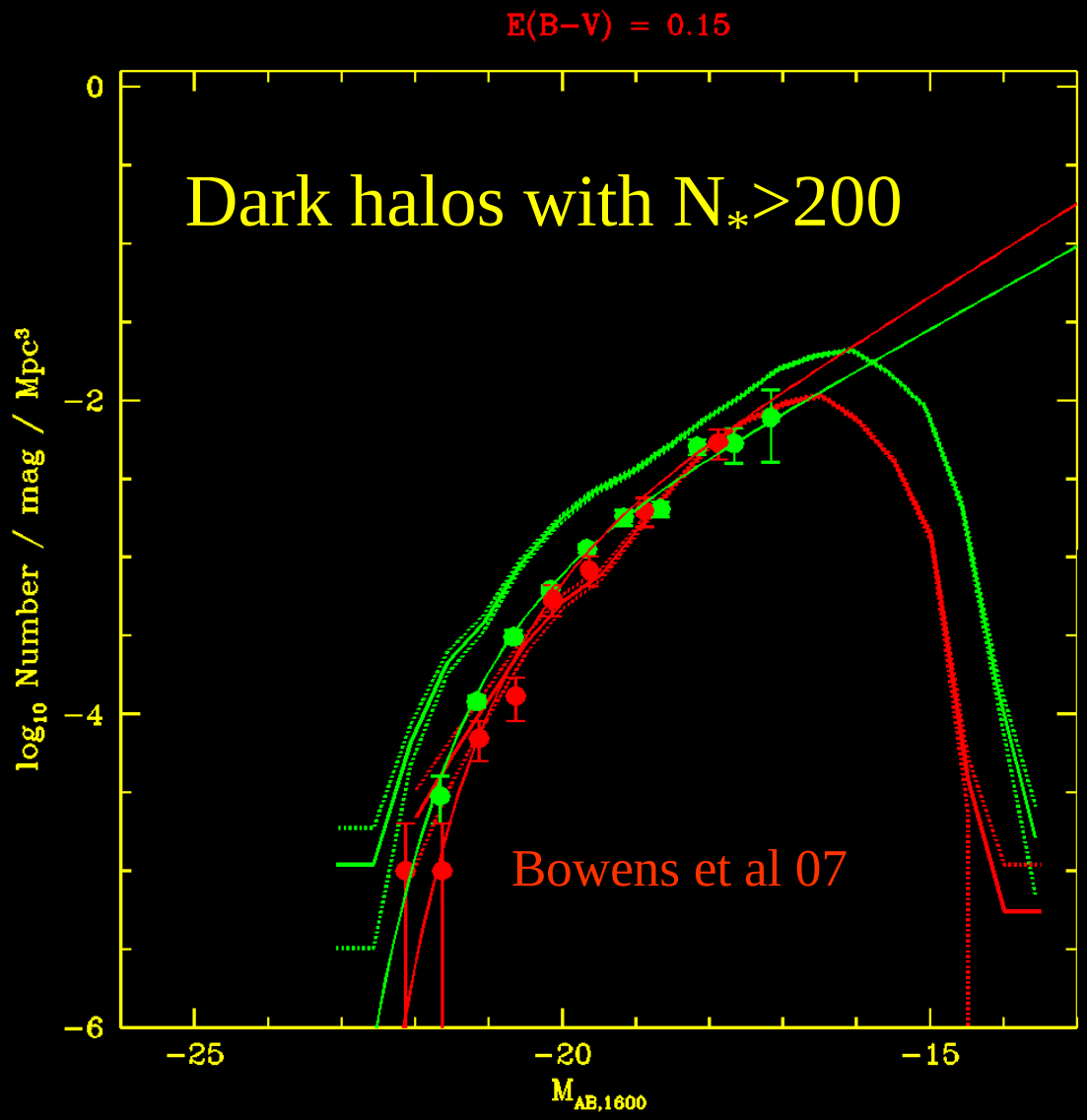

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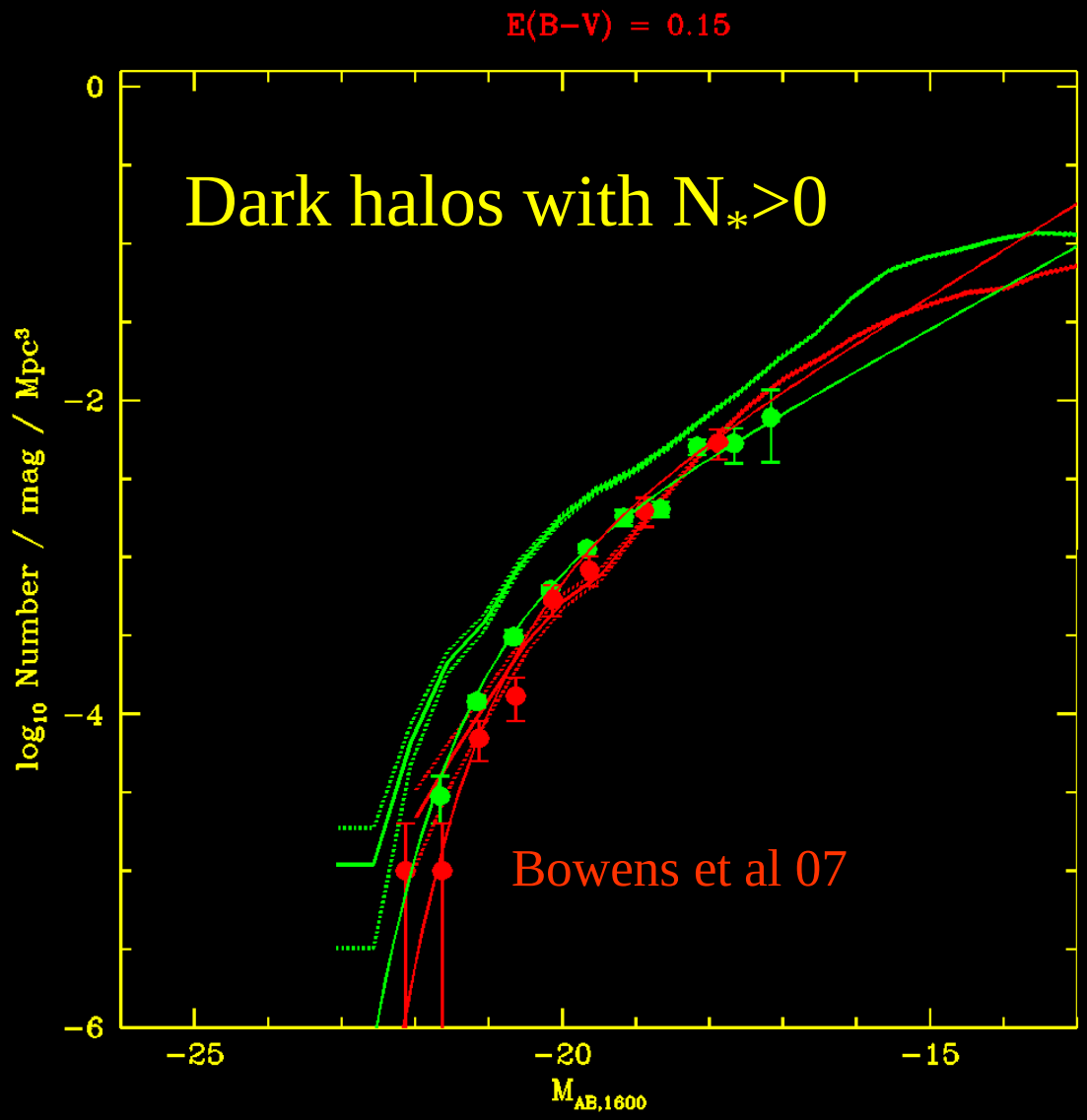

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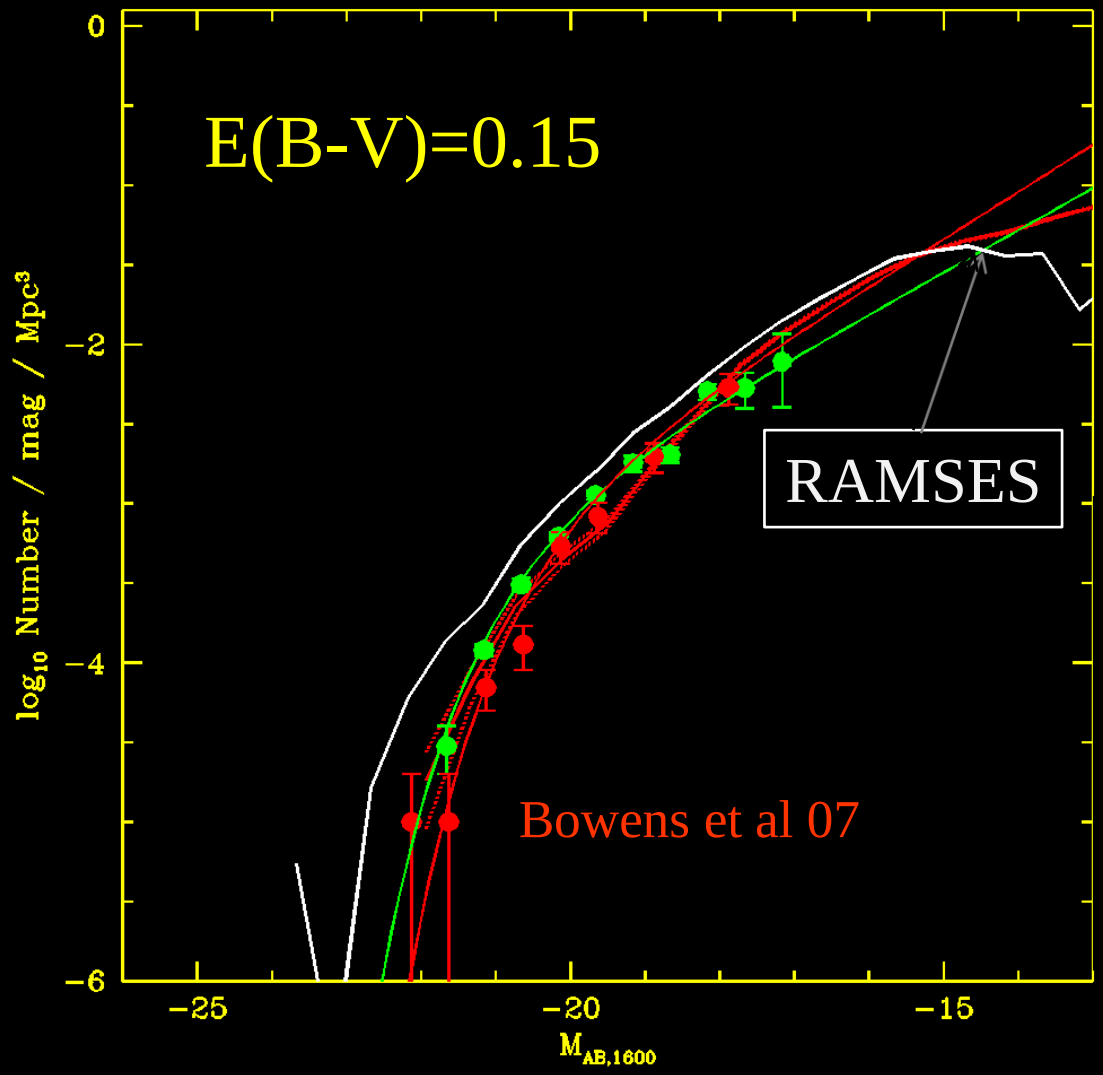
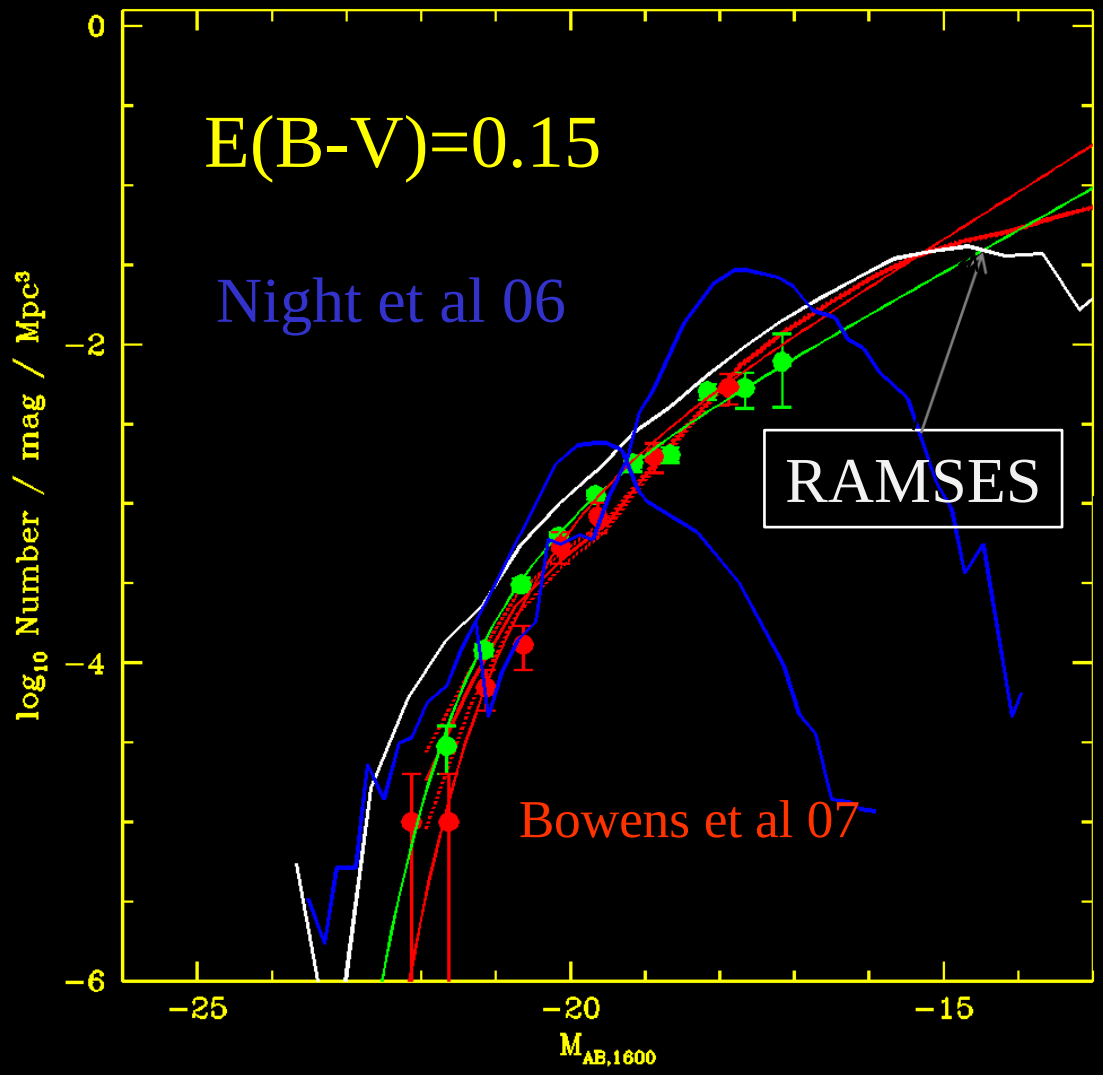
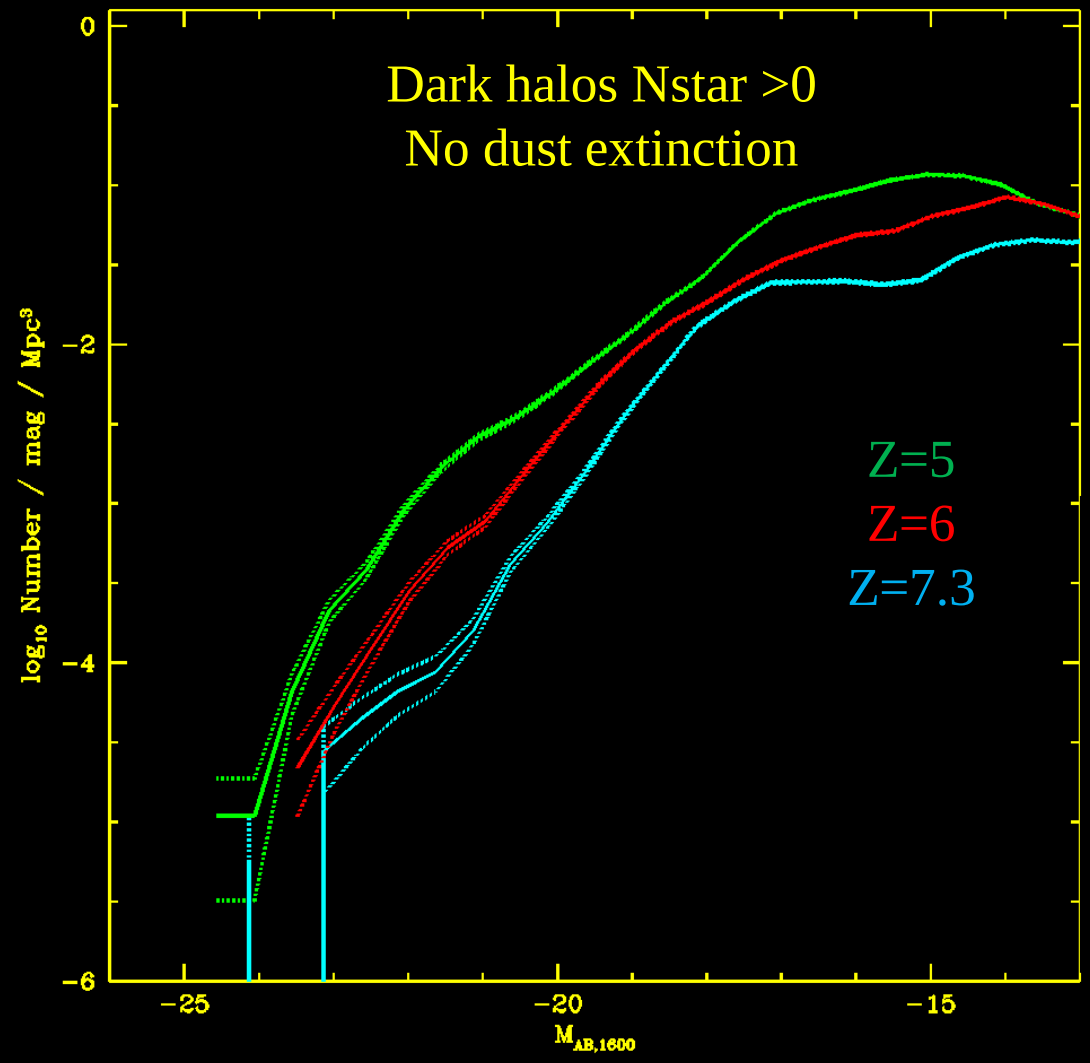


UV Luminosity Function @ z=6



UV Luminosity Function @ z>6



Change of faint end slope for z <6, when UV reionization is switched on.

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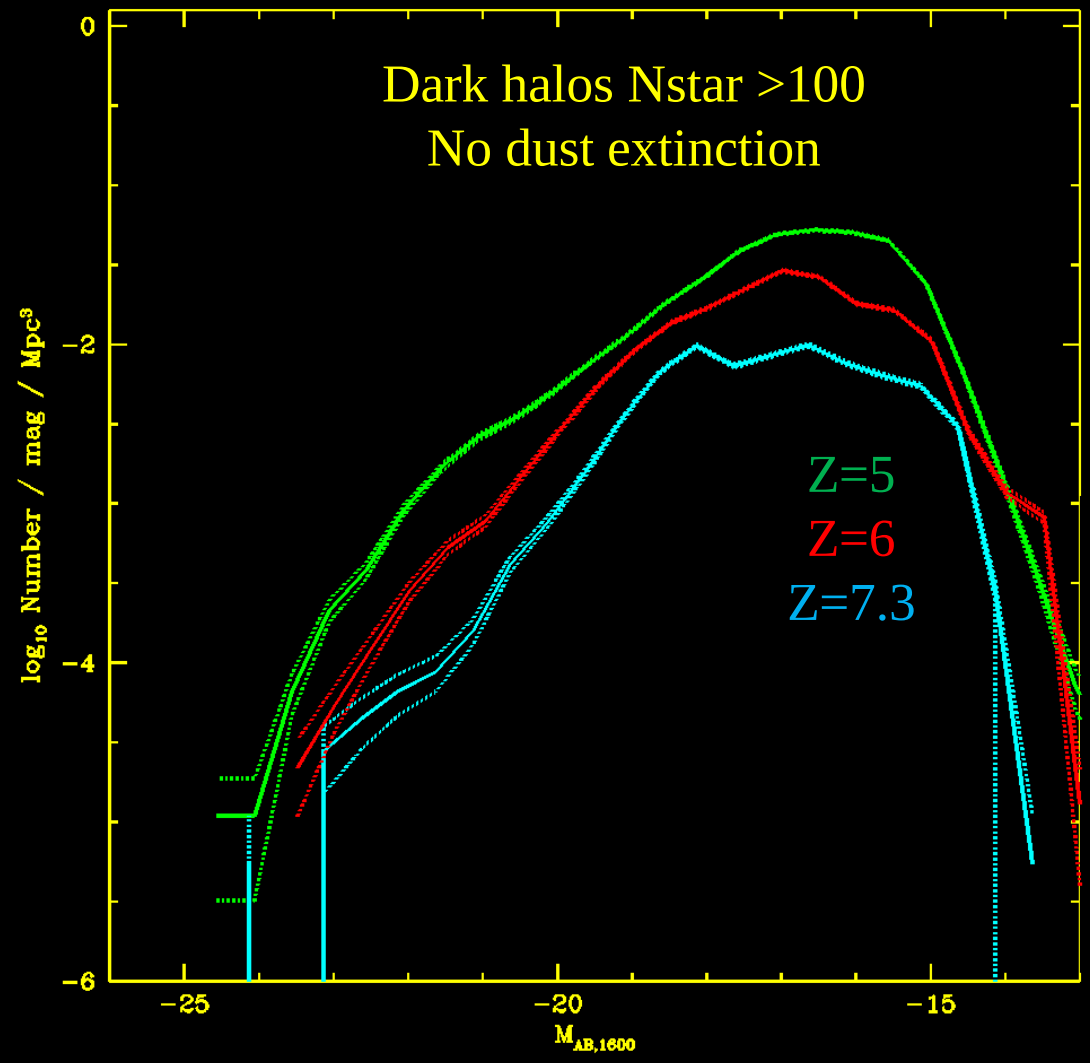
UV Luminosity Function @ z>6



Change of faint end slope for z <6, when UV reionization is switched on.

Slope
-2.3 @z=7.3 to
-1.8 @z=6
-1.68 @z=5

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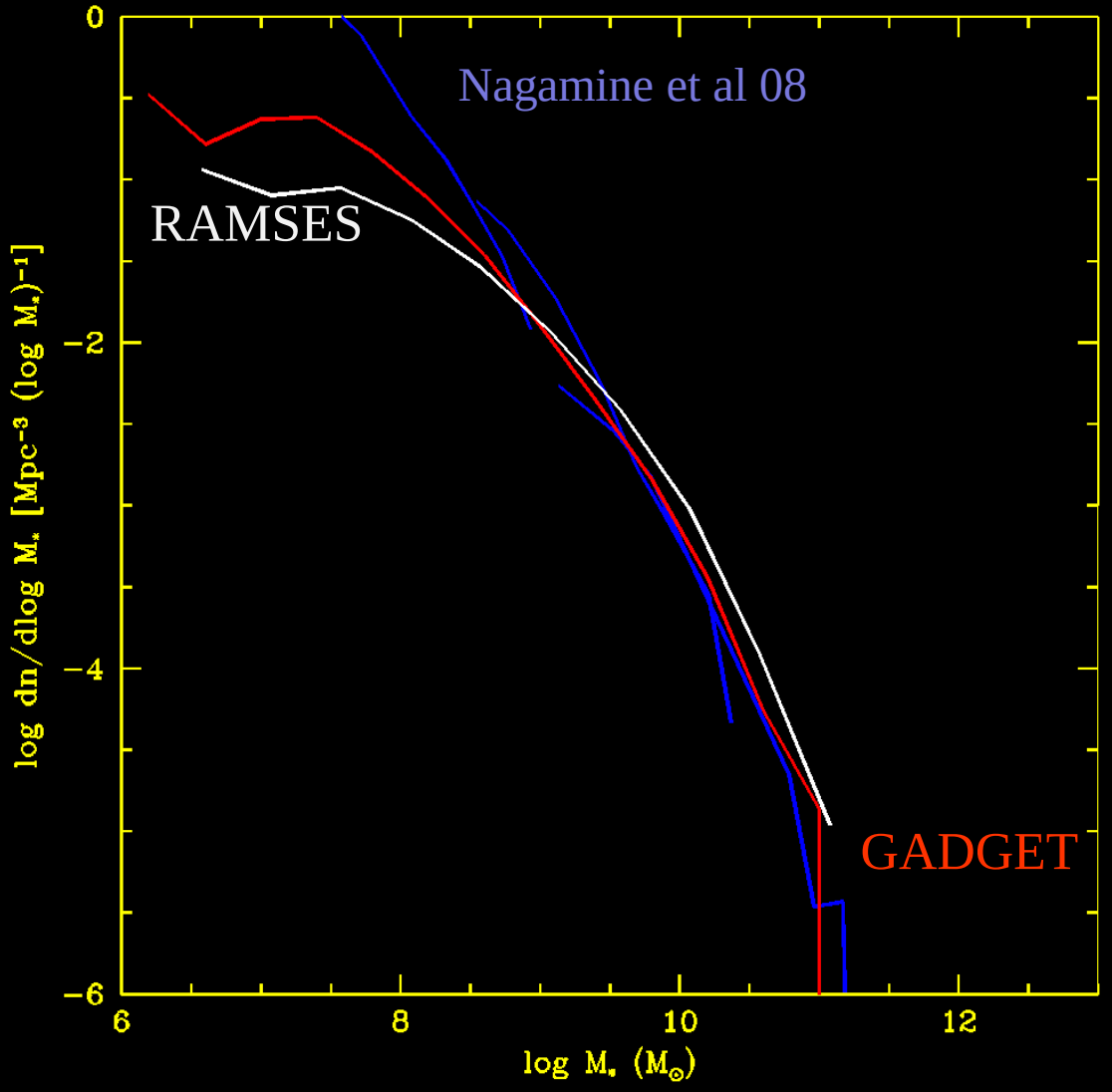
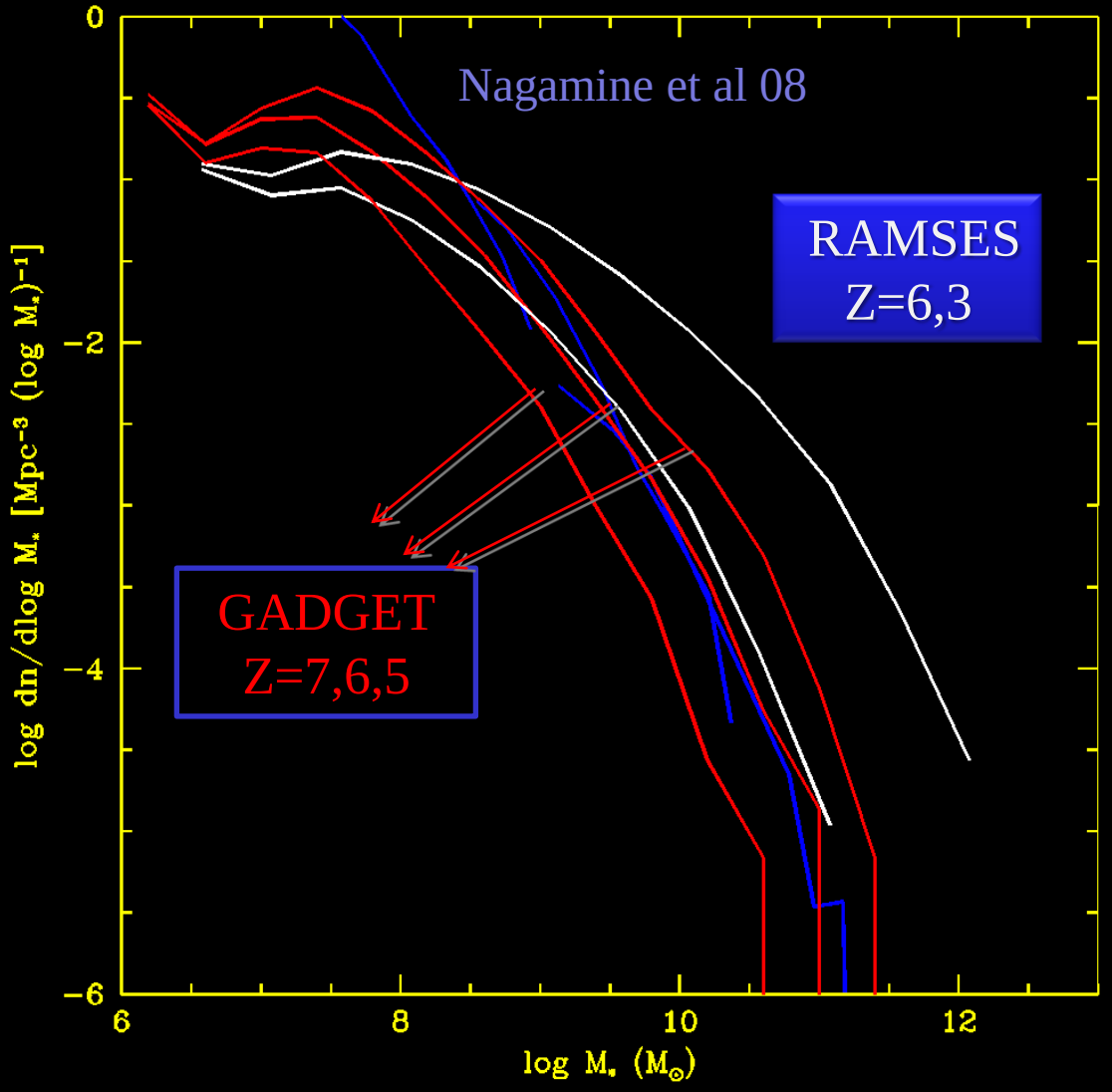
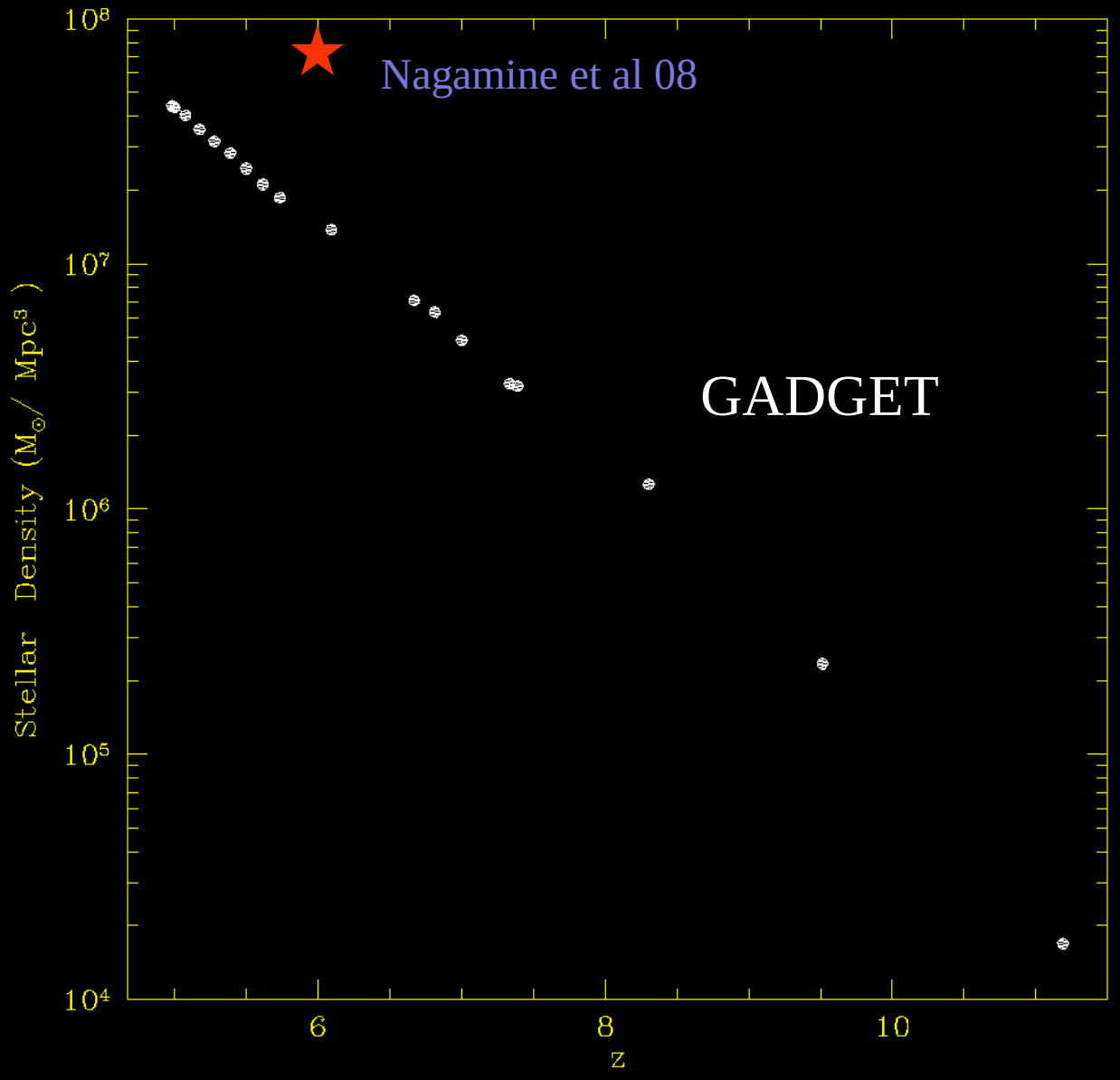
Stellar Mass function @ z=6



Stellar Mass function @ z=7-3



Stellar density evolution @ z=11-5



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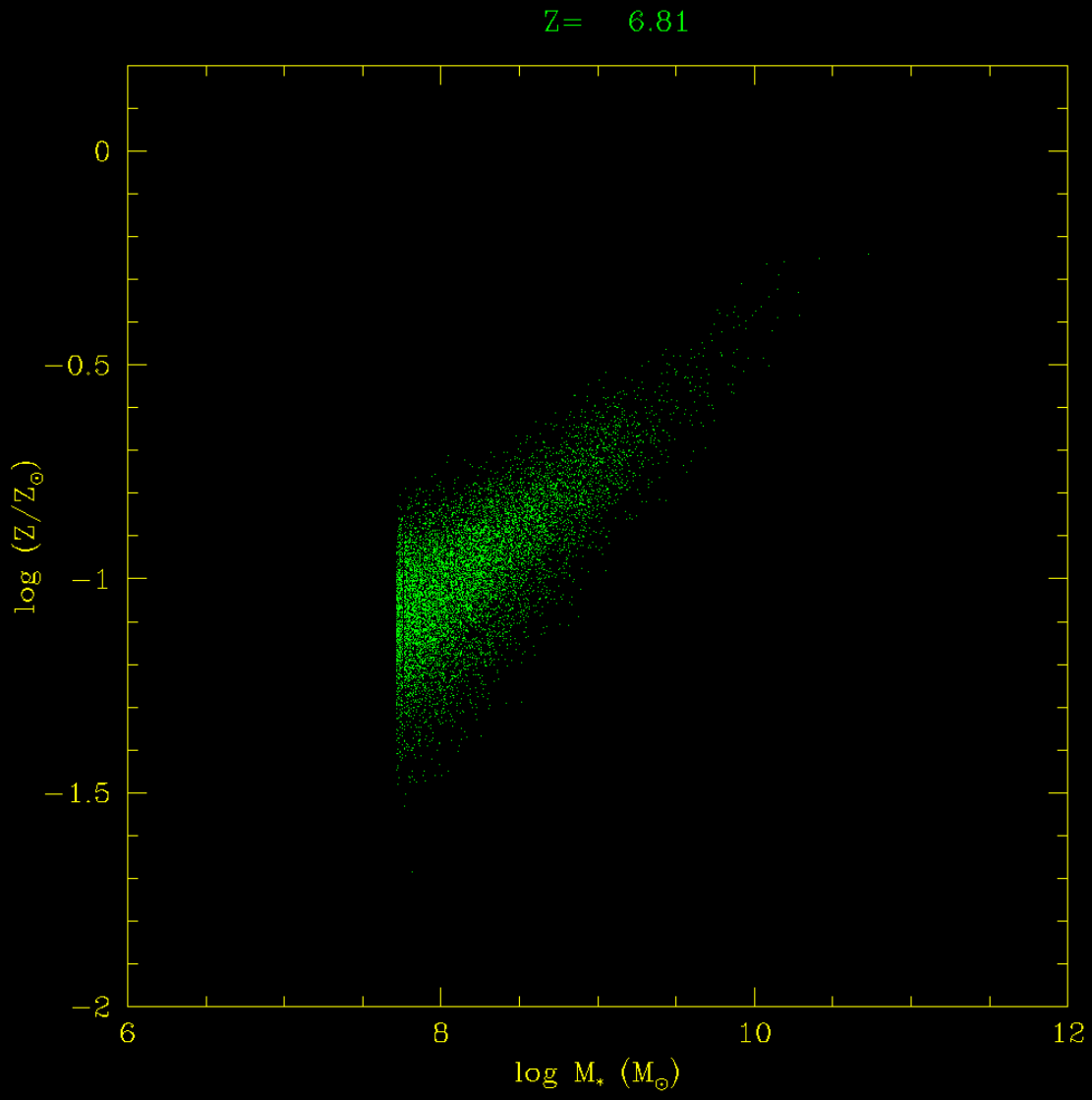
Galaxy stellar Metallicity evolution



Positive correlation between Z and M_*

Most of the objects with $M_* < 10^{10}$ Msun have $Z/Z_\odot < 1/3$

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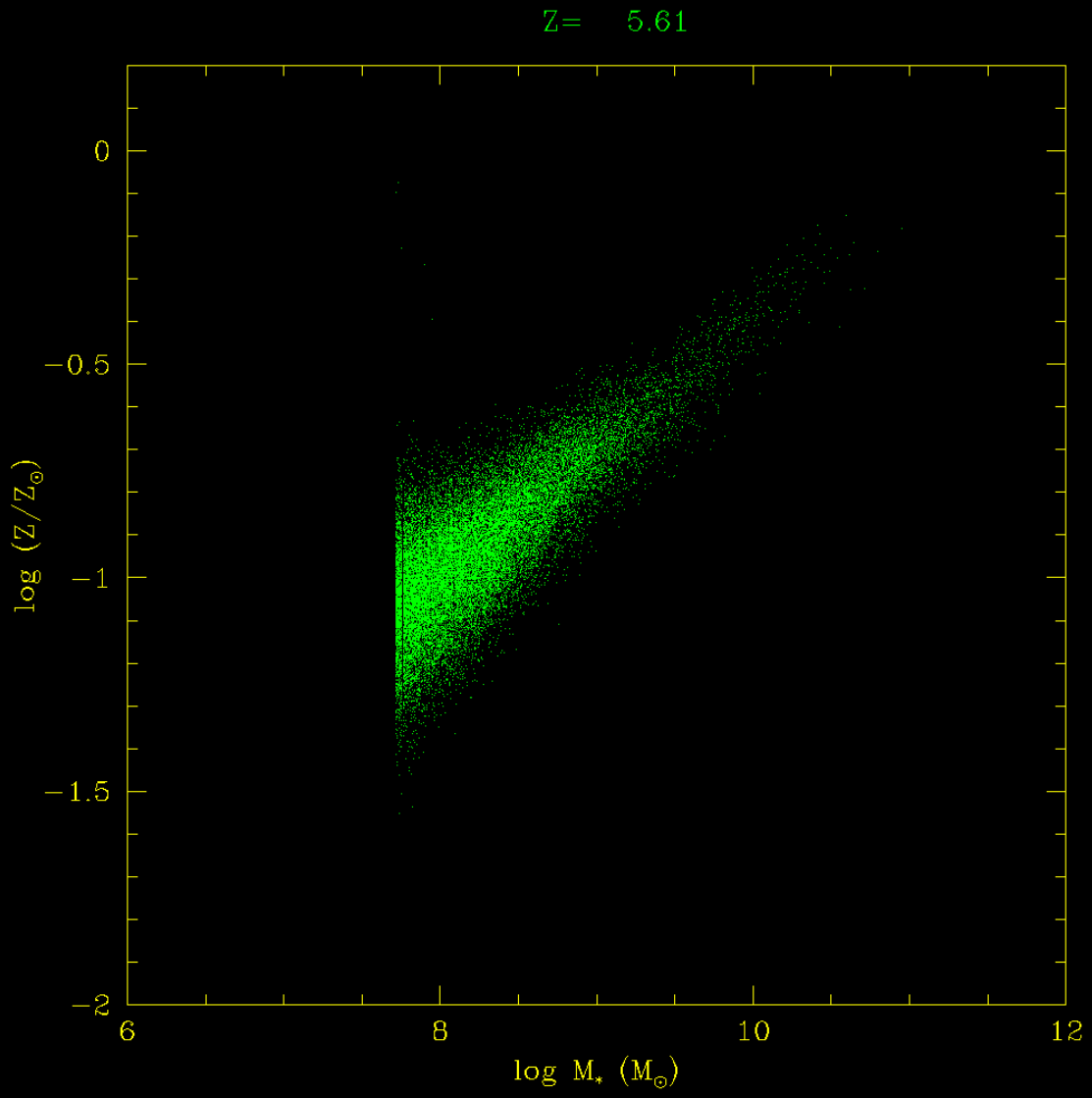
Galaxy stellar Metallicity evolution



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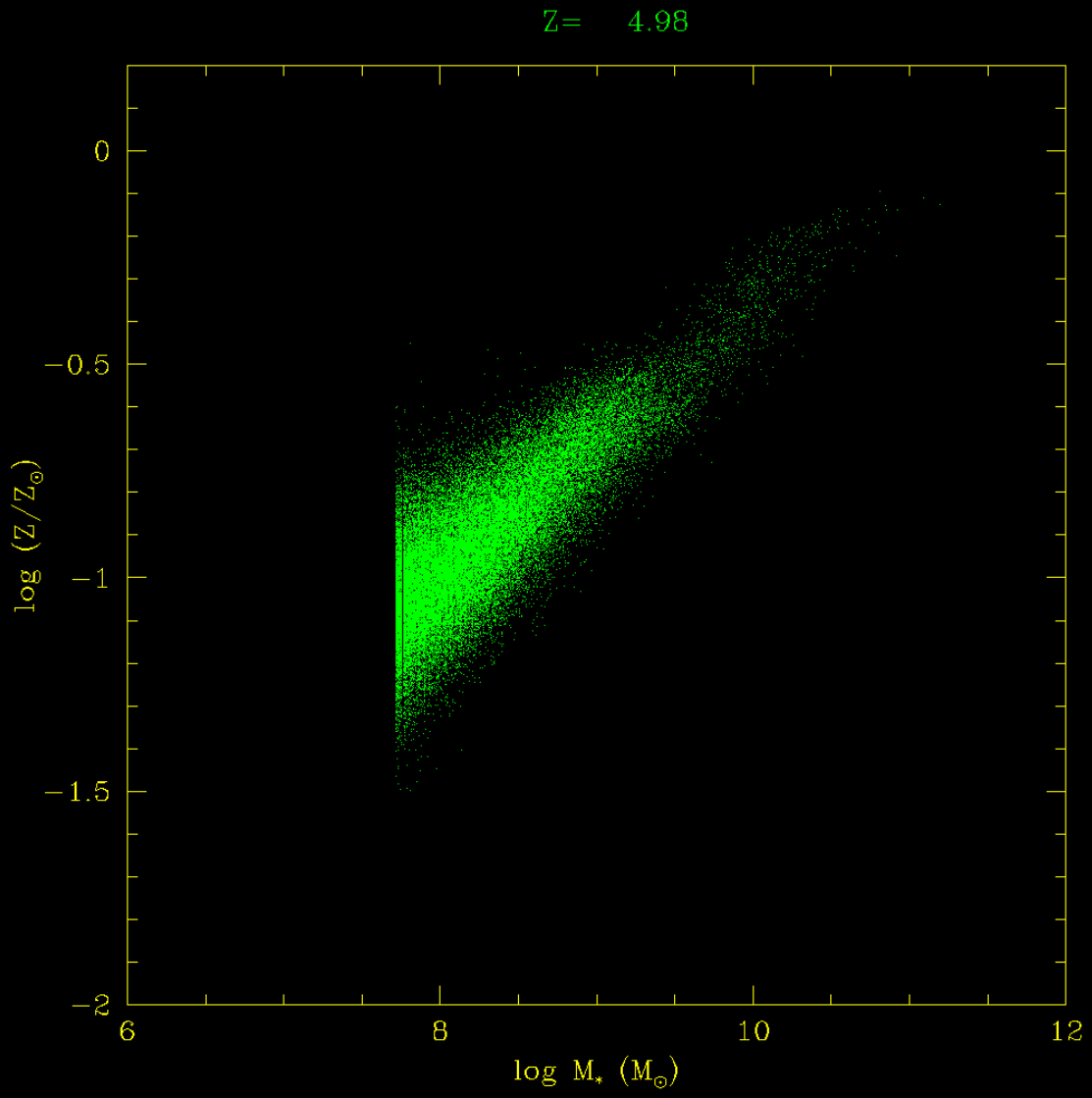

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CONCLUSIONS

- Multi-billion particles simulations run with two different codes:RAMSES and GADGET. Large statistical samples.
- Good agreement on the mass function and Luminosity functions at faint end between the two simulations
- The faint end LF flattens after z < 6 probably due to UV heating.
- Good agreement with observed LF @z=5-6 if
  - $E(B\text{-}V)_{z=6} = 0.15$ and $E(B\text{-}V)_{z=5} = 0.2$.
- Both simulations show that
  - The faint end slope for z=5 -6 is -1.6 -- -1.7, in very good agreement with HUDF.
- We do not see the steepening found in other GADGET simulations (Nagamine et al 08)
  - Stellar mass function flattens at $M_* < 10^9$ Msun
  - Differences due to galaxy finders, modeling, initial conditions?

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THANK YOU

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http://astro.ft.uam.es/marenostrum

- **MareNostrum Universe Simulation:**
  $2x1024^3$ 500/h Mpc SPH
- **MN High z Galaxy Formation Simulation:**
  $2x1024^3$ 50/h Mpc SPH +gastrophysics
- **MN Local Universe Constrained Simulations**
- $2x1024^3$ 64 to 320/h Mpc boxes N-body , SPH+gastrophysics

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