

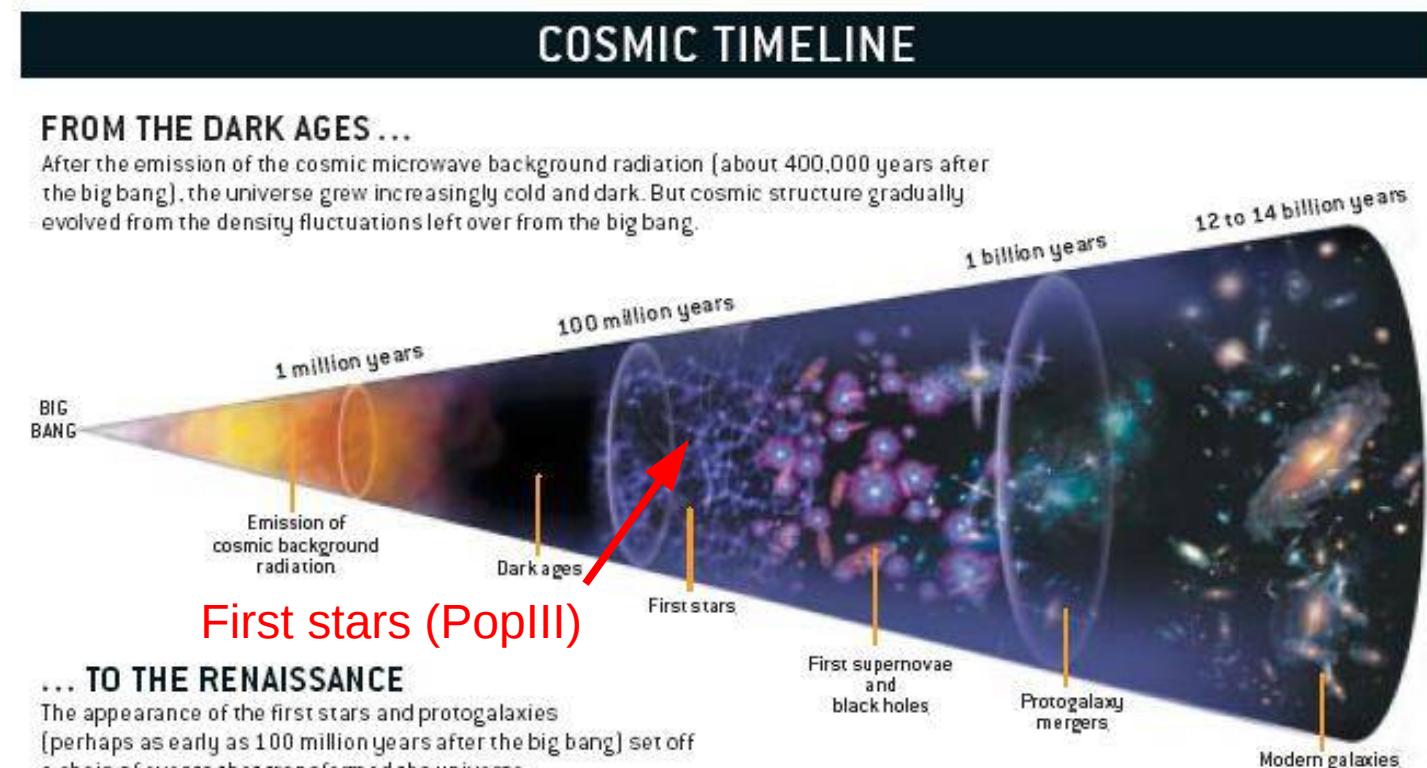
# Étude des premières galaxies



Roser Pelló (astronome à l'IRAP – Toulouse - France)

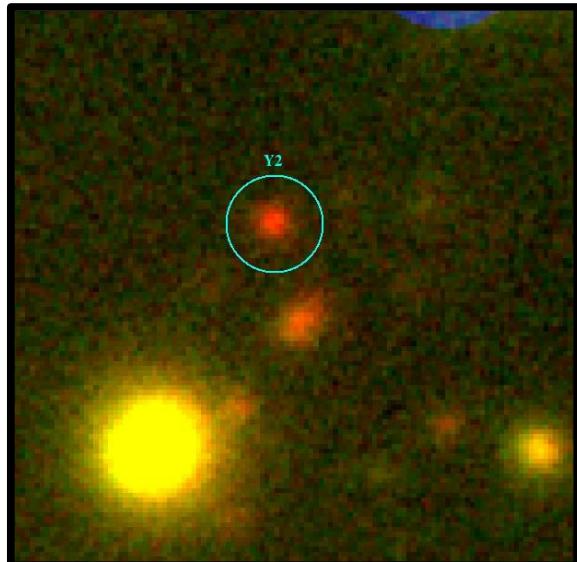
## The formation of the first stars & galaxies :

- CMB :
  - the universe started out simple, homogeneous and isotropic
  - small fluctuations described by linear perturbation analysis
- Present-day universe : clumpy & complicated
- The formation of the first bounded objects marks the transition from simplicity to complexity ...



## Galaxy formation & Reionization

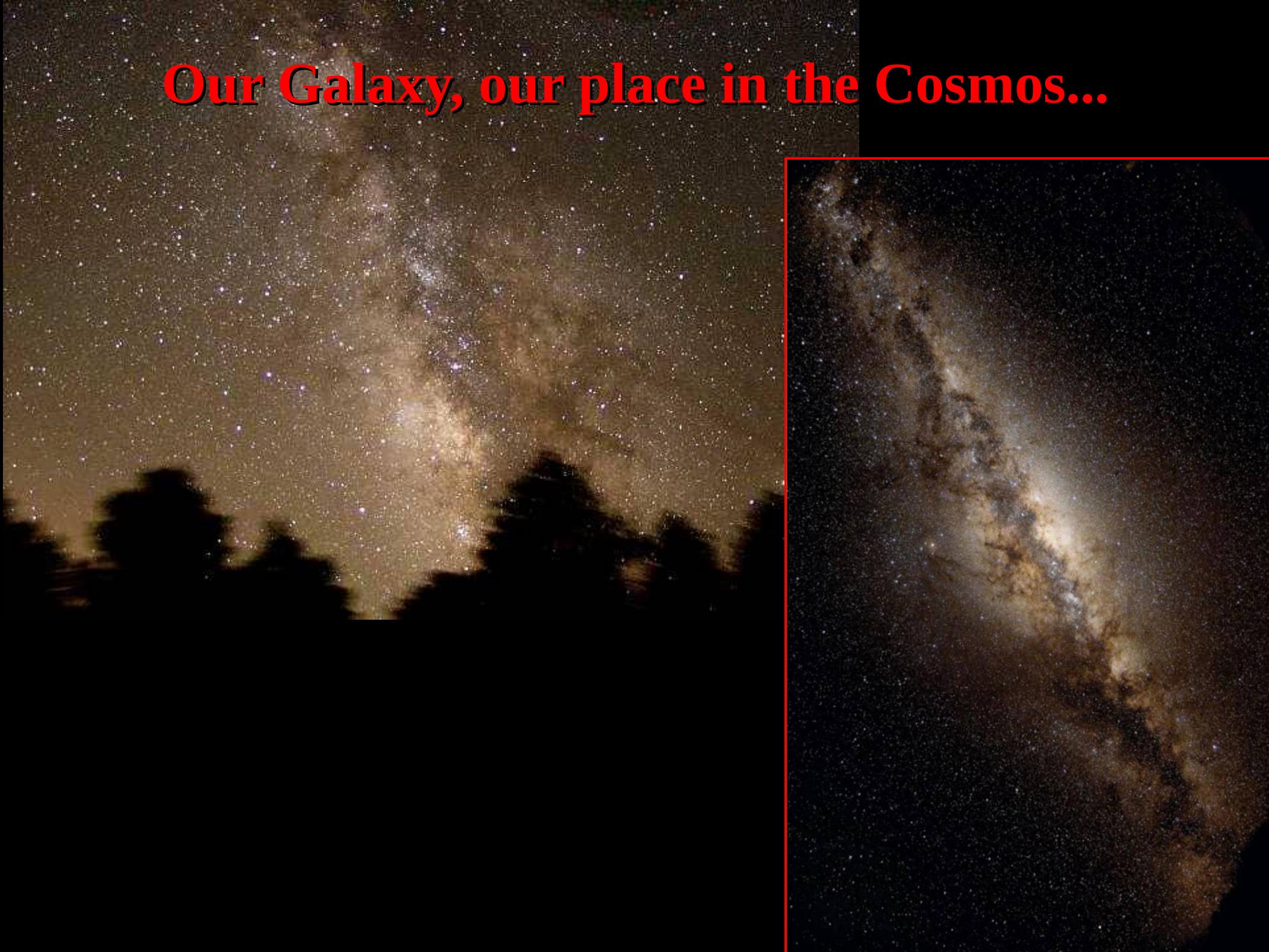
- Introduction : the world of galaxies
- Constraints on the Re-ionization epoch & galaxy formation scenarios
- Theoretical considerations
- Observational approaches : identification and characterization of primeval galaxies
- Present results ... and open issues
- Discussion. Perspectives

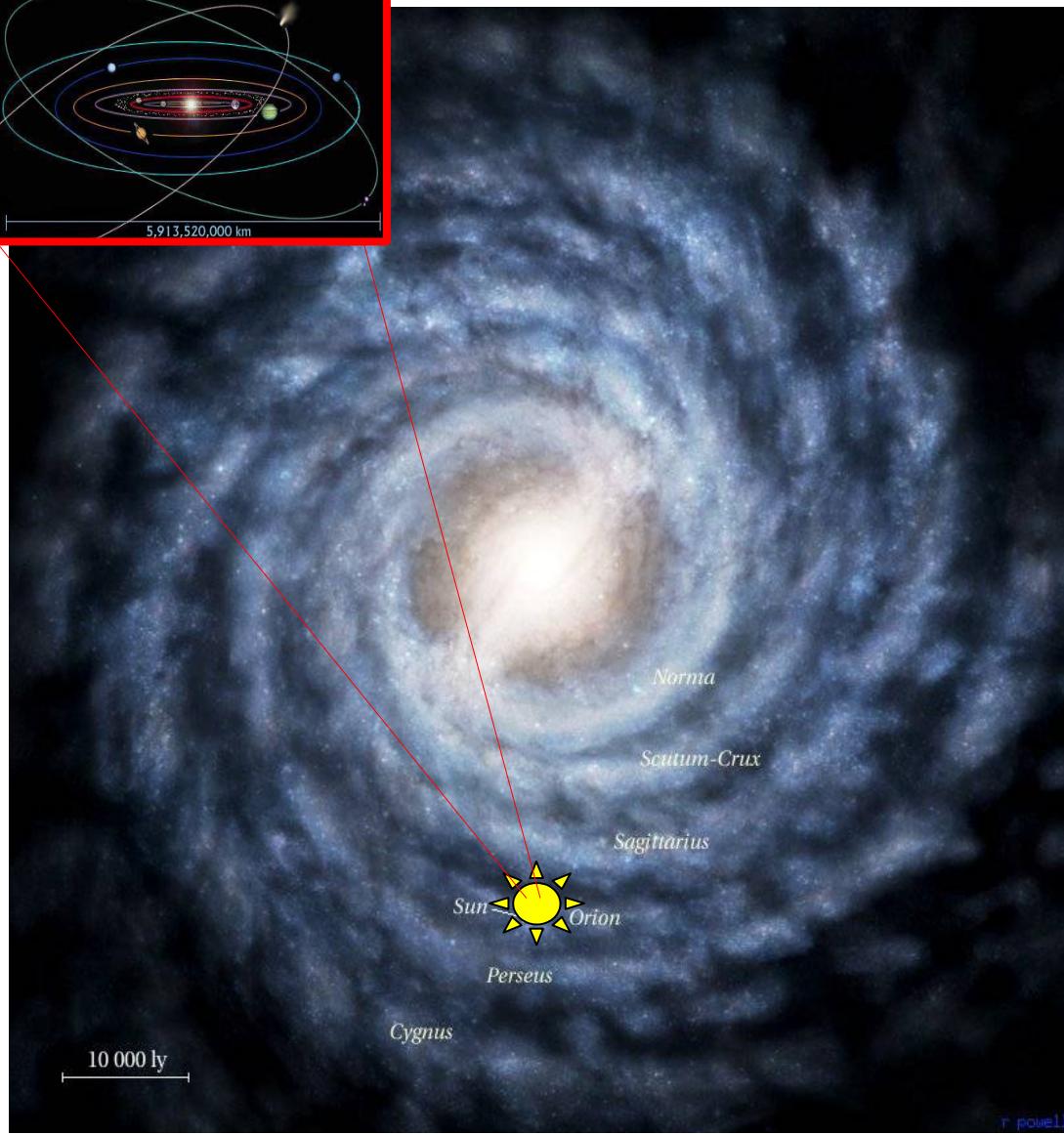
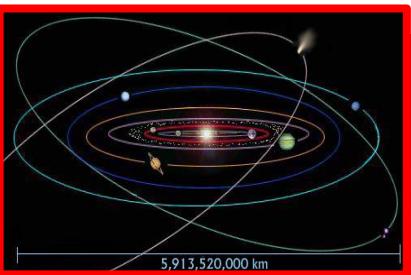




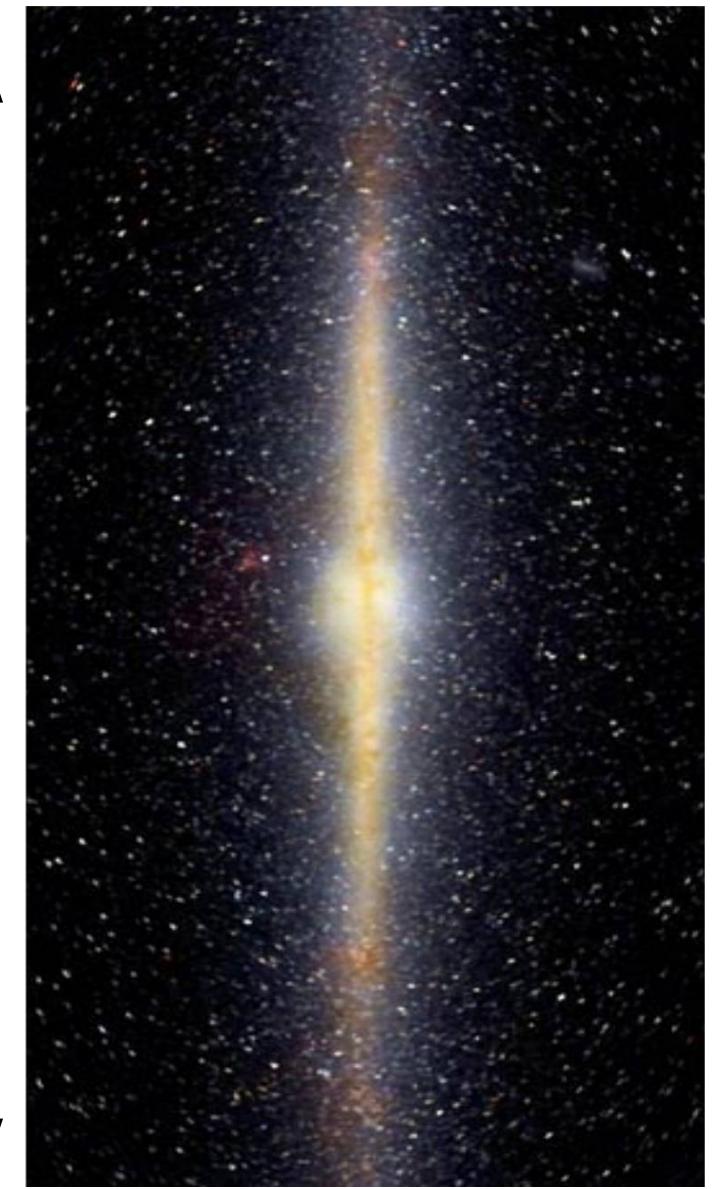
The world of  
galaxies

**Our Galaxy, our place in the Cosmos...**





120.000 années-lumière



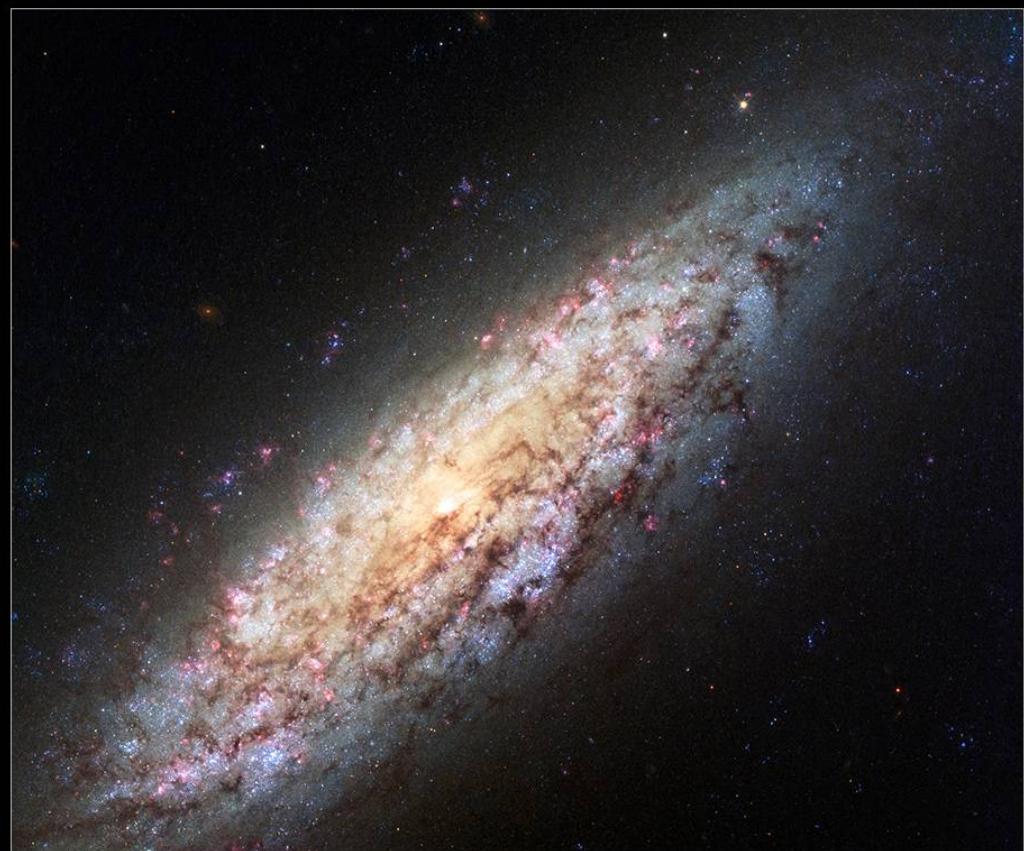
Halo: 30 kpc  
Disque: 25 kpc  
Bulbe: 4 kpc

## Notre Galaxie :

~  $10^{11}$  fois la masse du Soleil



Spiral Galaxy NGC 6503



Hubble  
Heritage

## ***SPIRAL GALAXIES ...***



Spiral Galaxy NGC 1309

NGC 4302 and NGC 4298





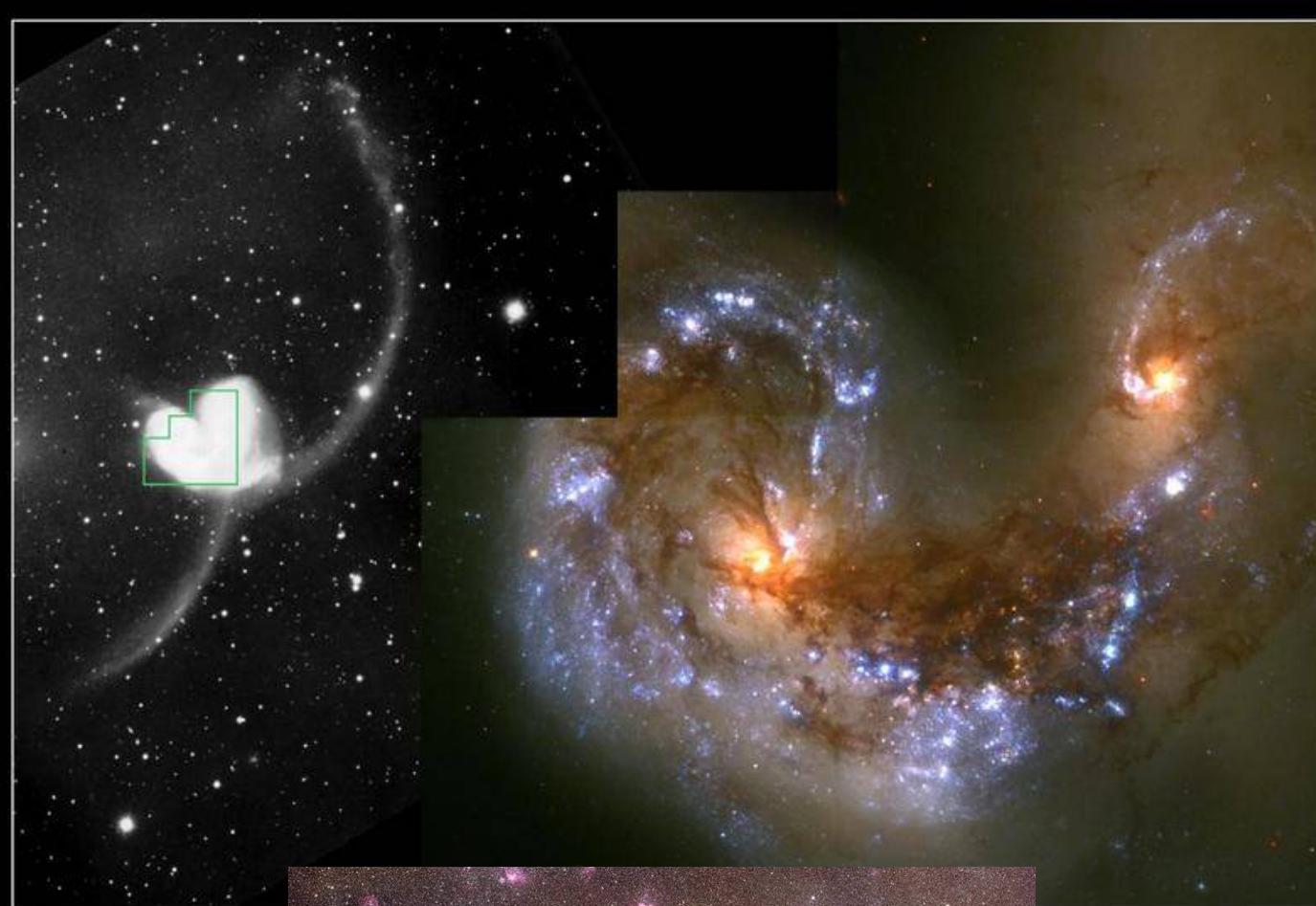
**NGC1132**

*ELLIPTICAL GALAXIES ...*





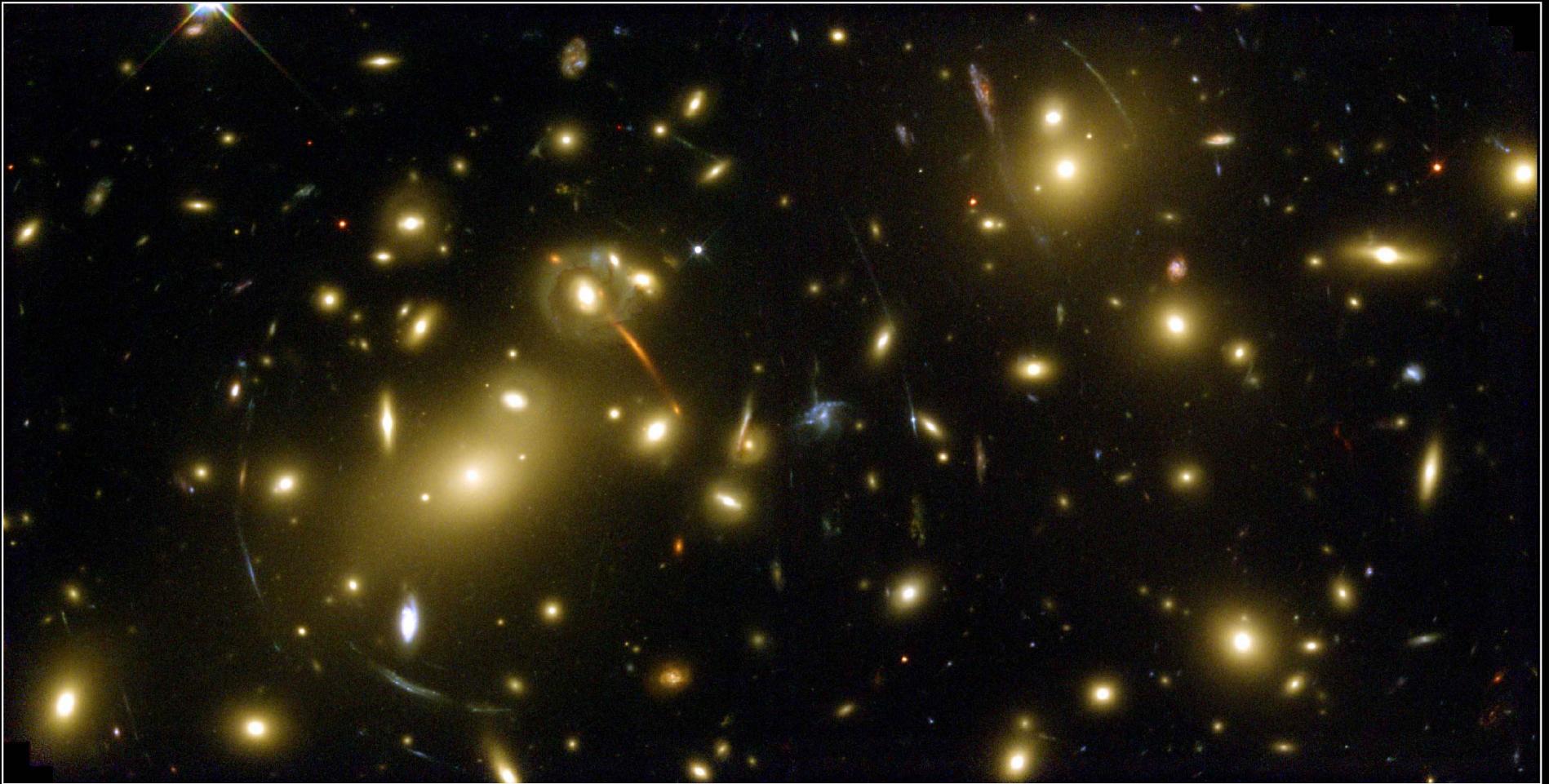
Dwarf Galaxy M60-UCD1



**DWARF GALAXIES  
INTERACTING GALAXIES...**



© Anglo-Australian Observatory, Royal Observatory, Edinburgh



**Galaxy Cluster Abell 2218**  
Hubble Space Telescope • WFPC2

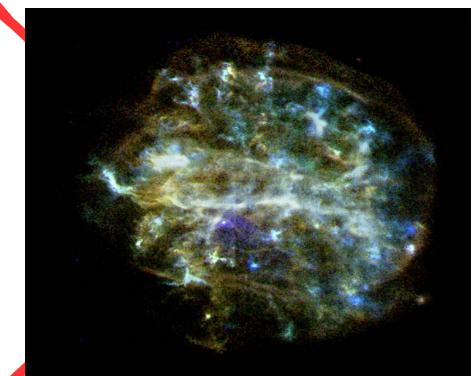
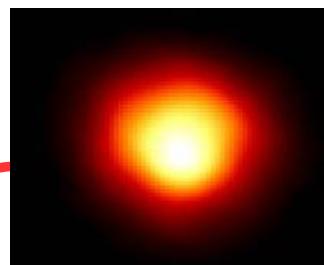
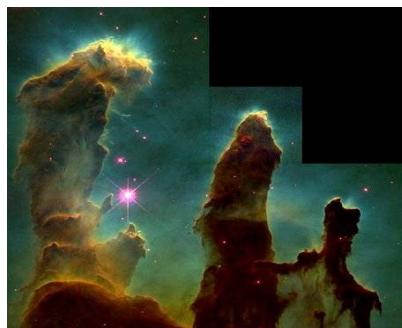
NASA, A. Fruchter and the ERO Team (STScI, ST-ECF) • STScI-PRC00-08

***CLUSTERS OF GALAXIES ...***



Death of the stars :  
supernovae, planetary  
nebulae, ...  
+ stellar winds

Chemical  
enrichment of the ISM



### Cycle of life in a galaxie:

Chemical & Spectro-photometrical  
evolution of galaxies

New stars are  
born from the  
Interstellar Medium  
(ISM)



STARS & ISM

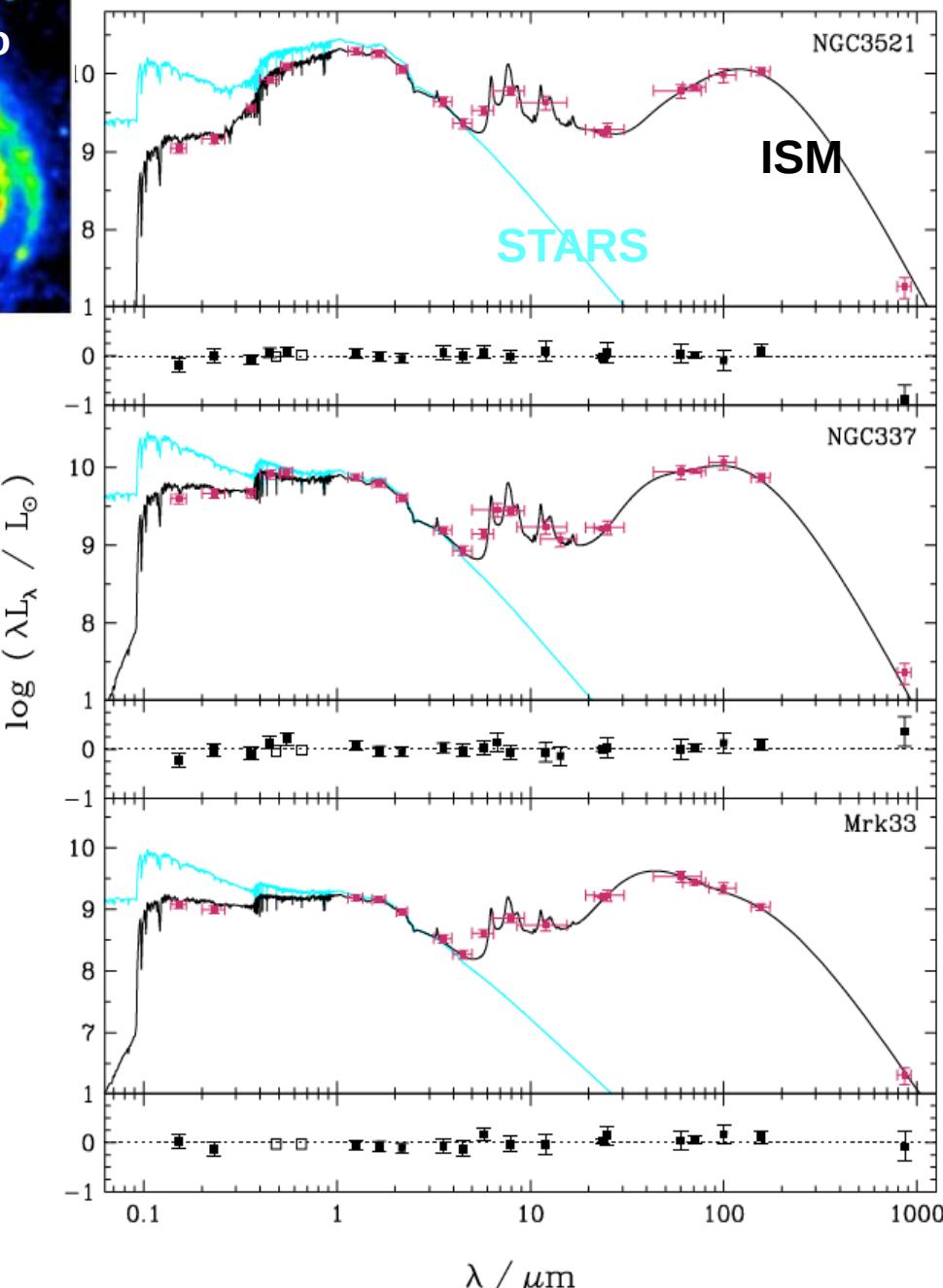
# The Spectral Energy Distribution of galaxies



**SED : distribution en énergie en fonction de la longueur d'onde ou de la fréquence**

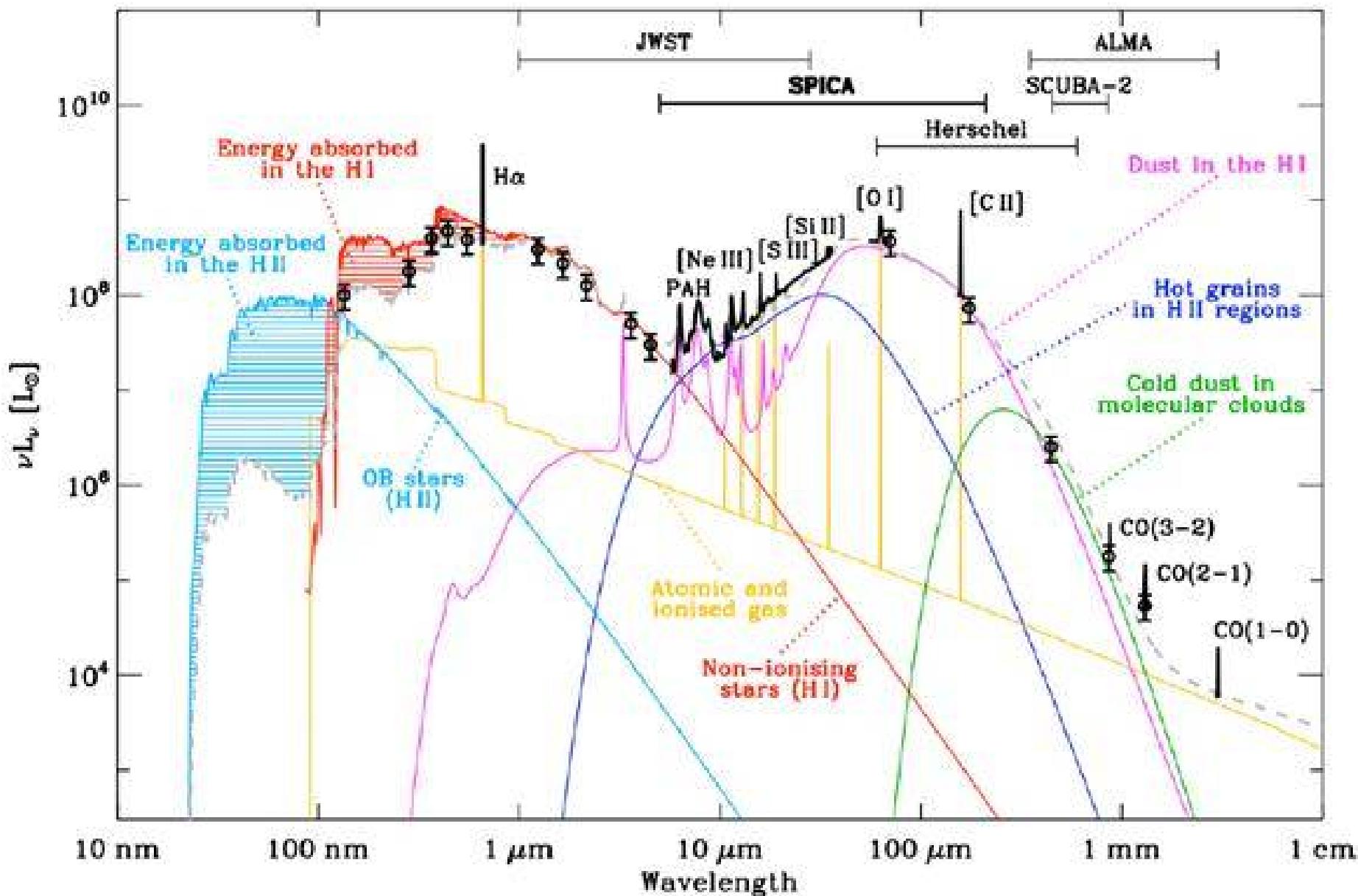
- **Domaine UV → IR** : les étoiles dominent !
- **Domaine IR → mm** : le MIS domine !

La **photométrie multi-longueur d'onde** et la **spectroscopie** sont utilisés en combinaison

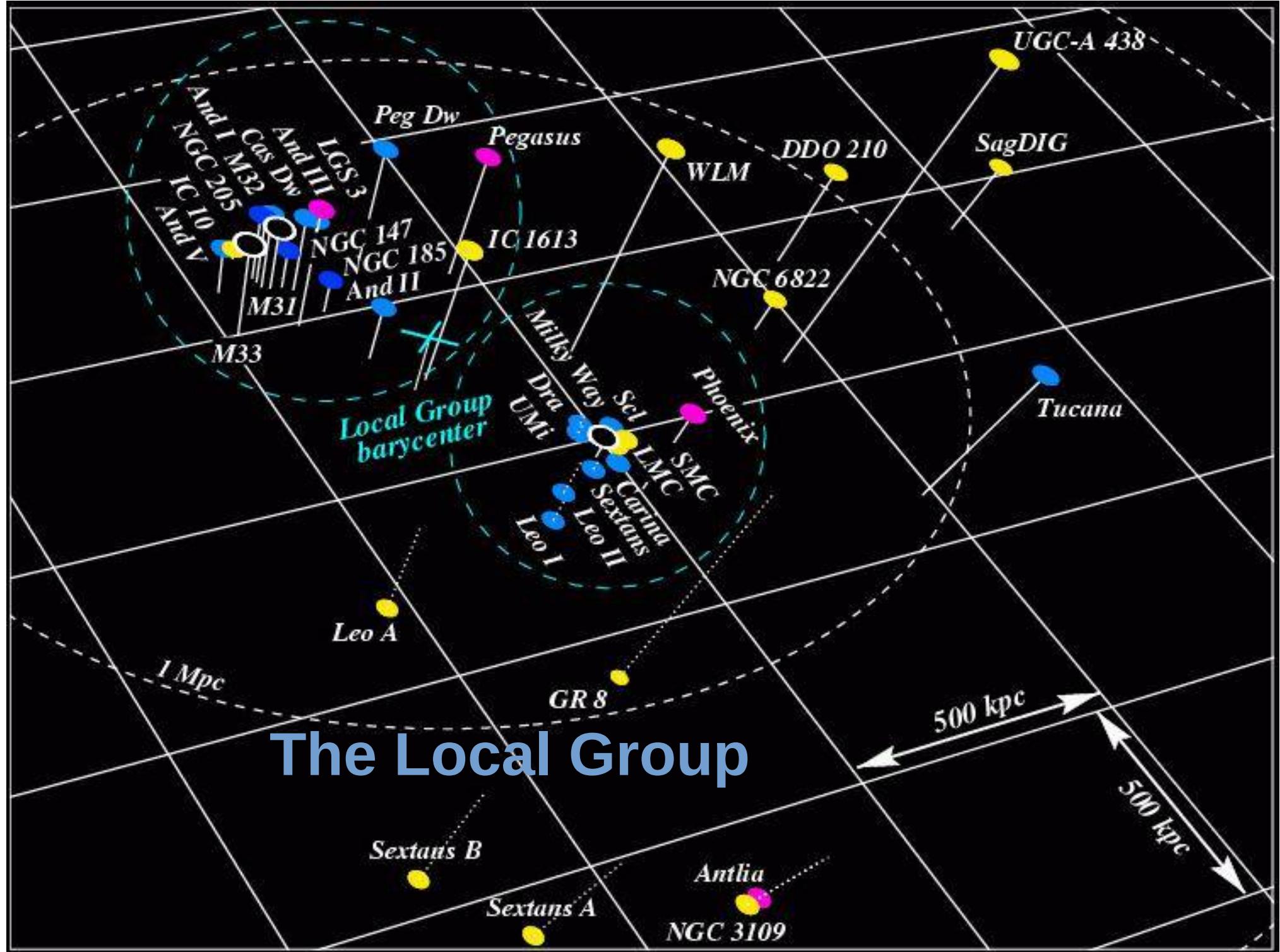


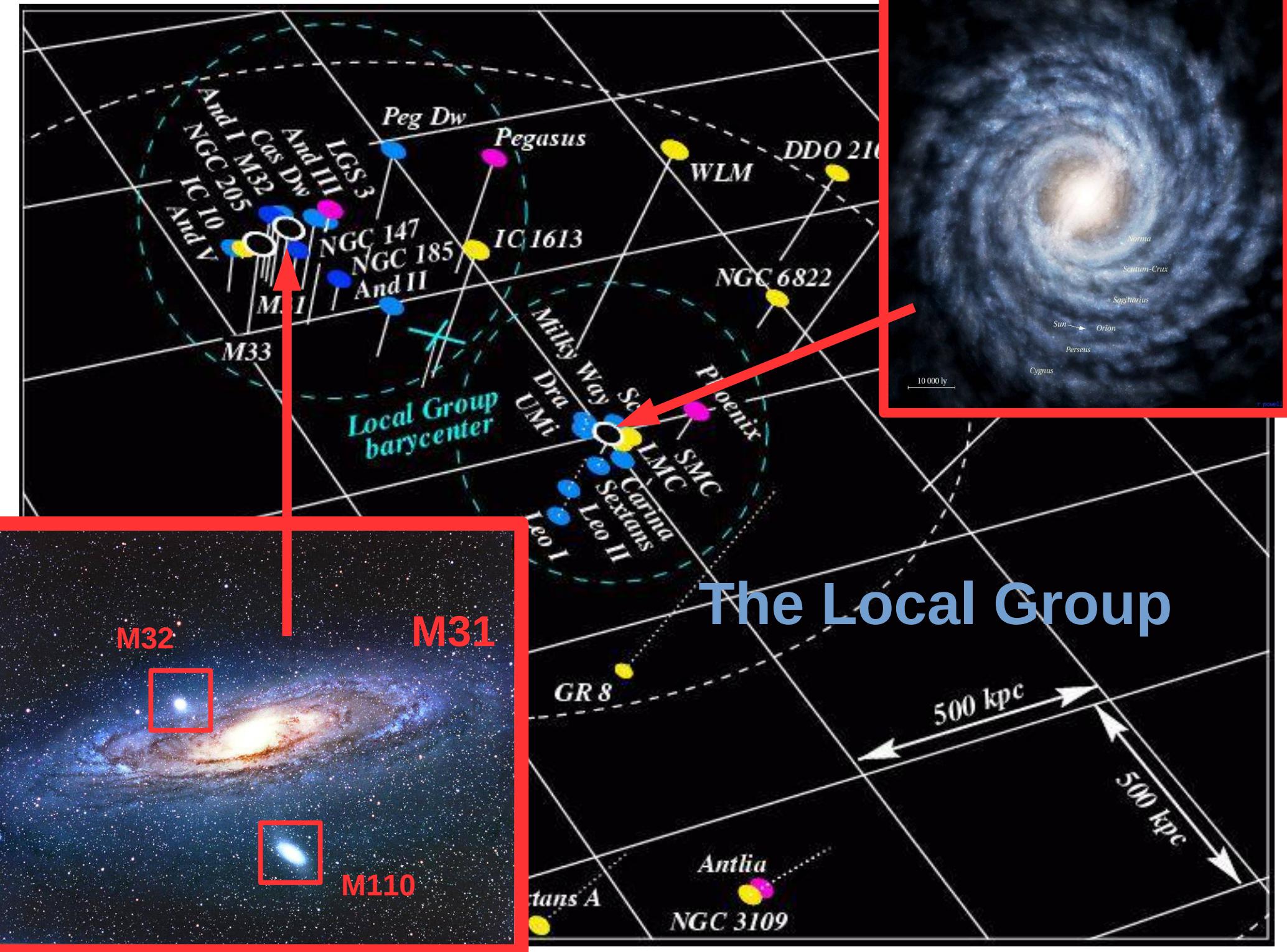
# The Spectral Energy Distribution of galaxies

Galliano et al. 2008

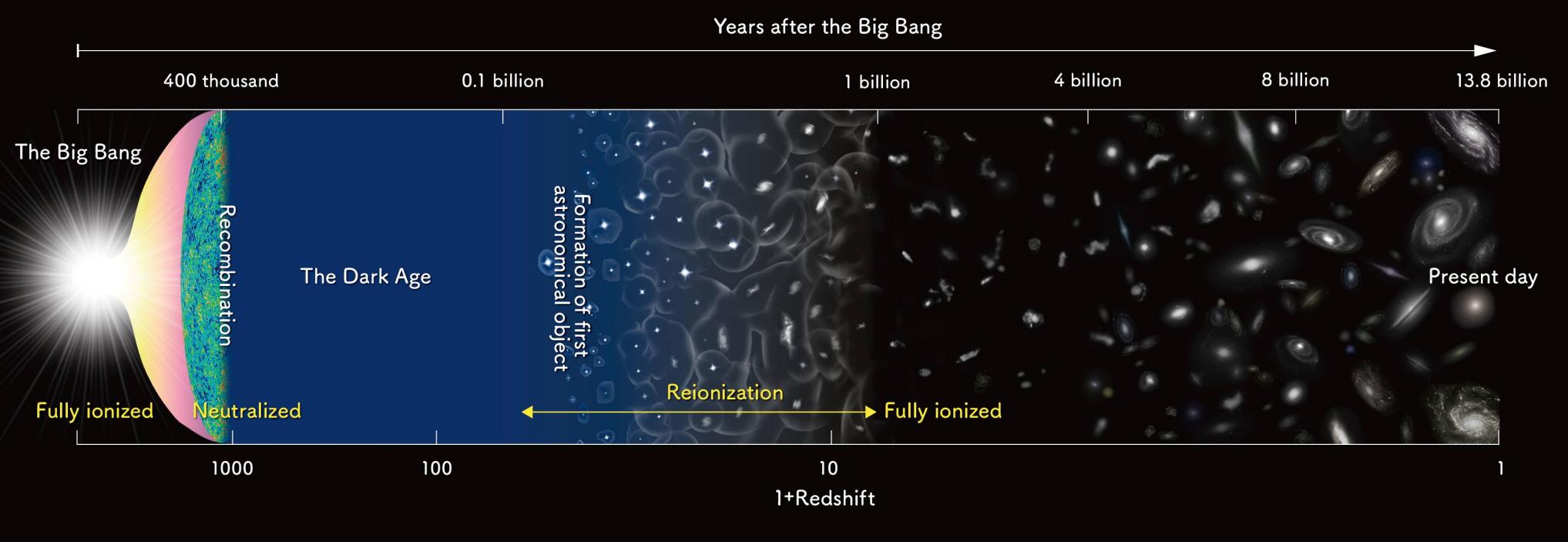


# The Local Group

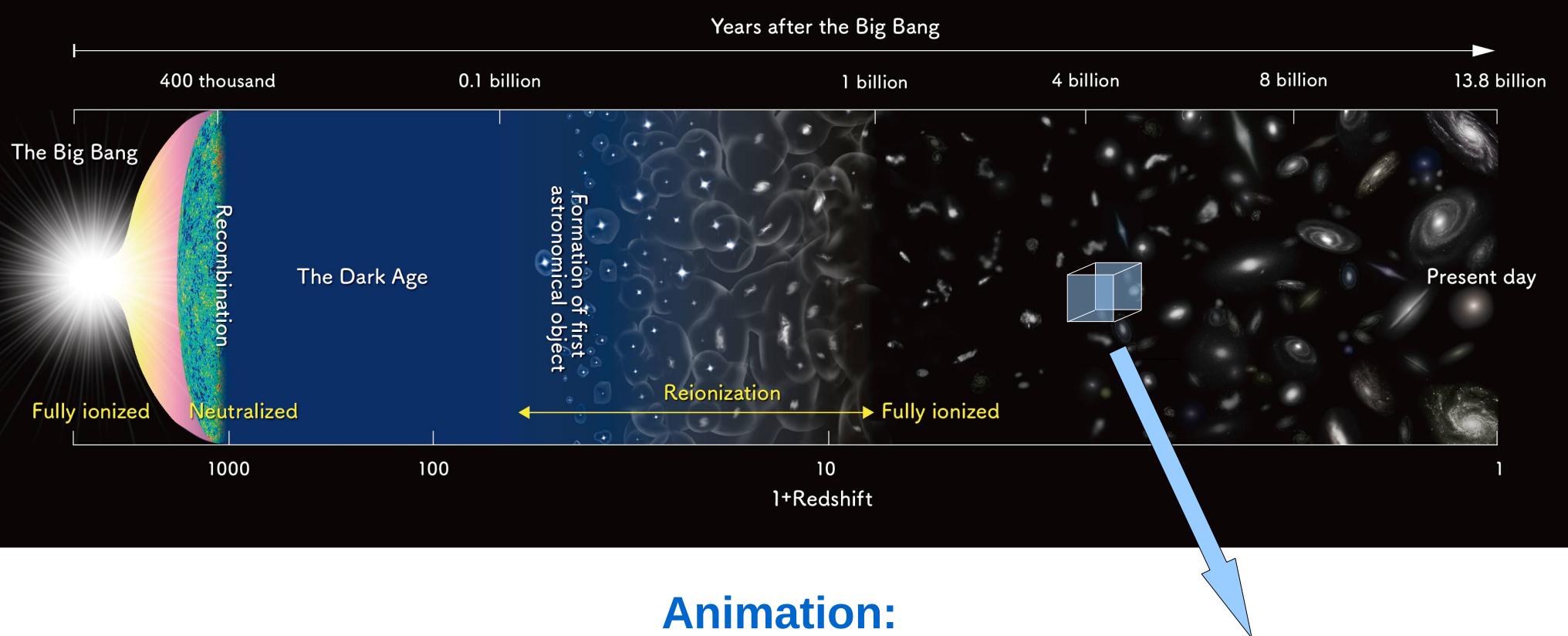




# Formation of Galaxies and Large Scale Structure



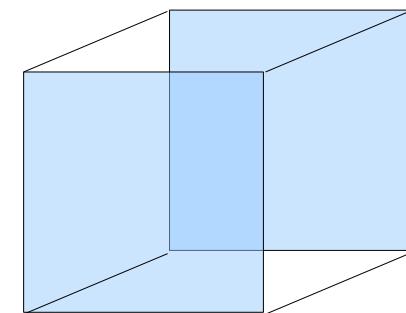
# Formation of Galaxies and Large Scale Structure



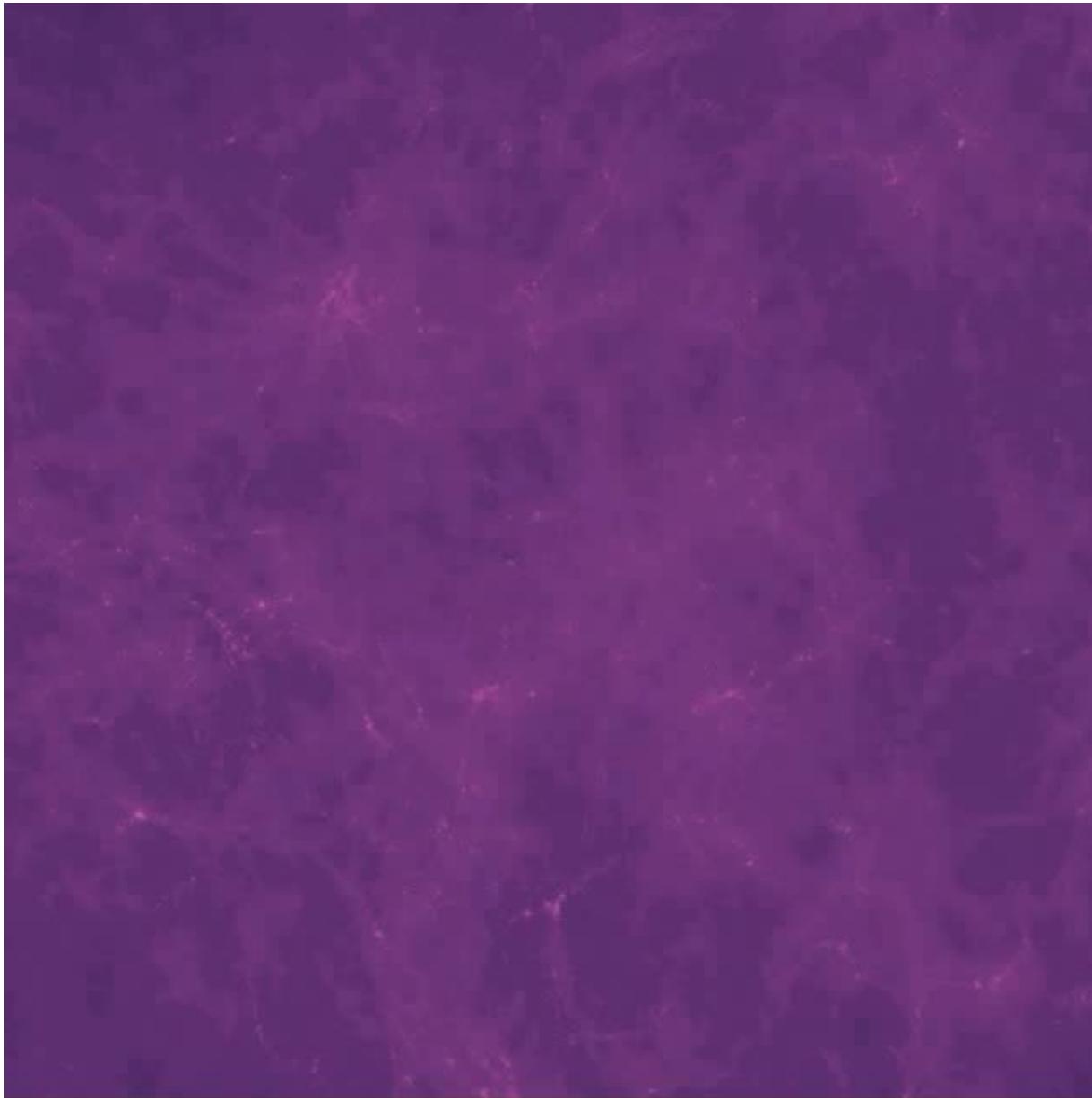
**Animation:**

**Formation des  
galaxies / structures  
entre z=20 et z=0**

**~100 Mpc**



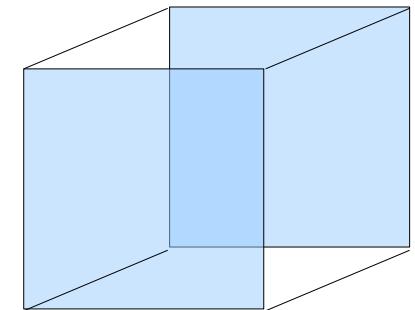
# Croissance des galaxies par assemblage successif des halos de matière sombre



Animation:

Formation des  
galaxies / structures  
entre  $z=20$  et  $z=0$

~100 Mpc



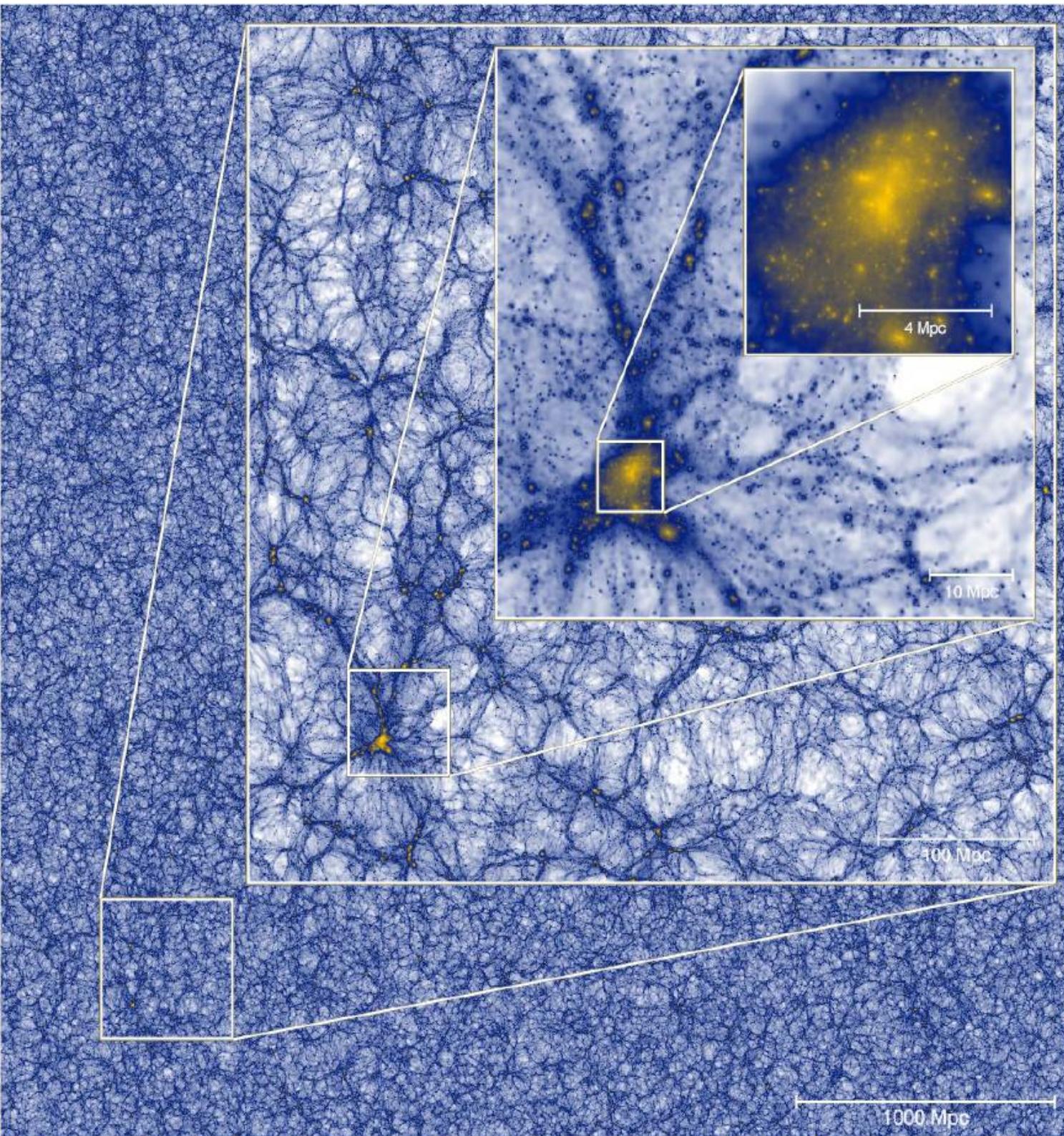
*Virgo Consortium &  
Millenium Simulation*

# Millennium-XXL

303 billion particles

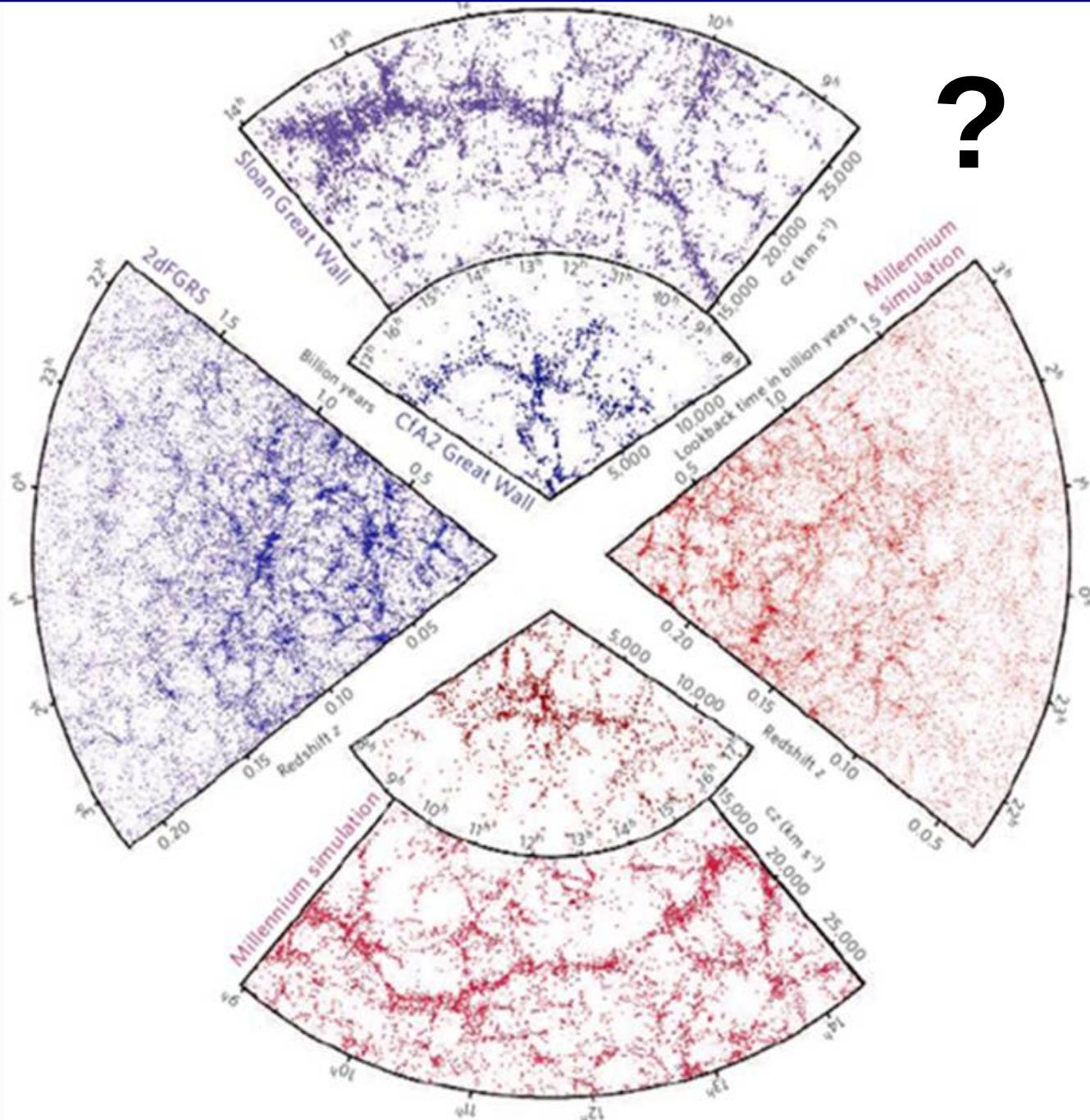
A very large  
high-resolution  
N-body simulation

$10^9$  pc



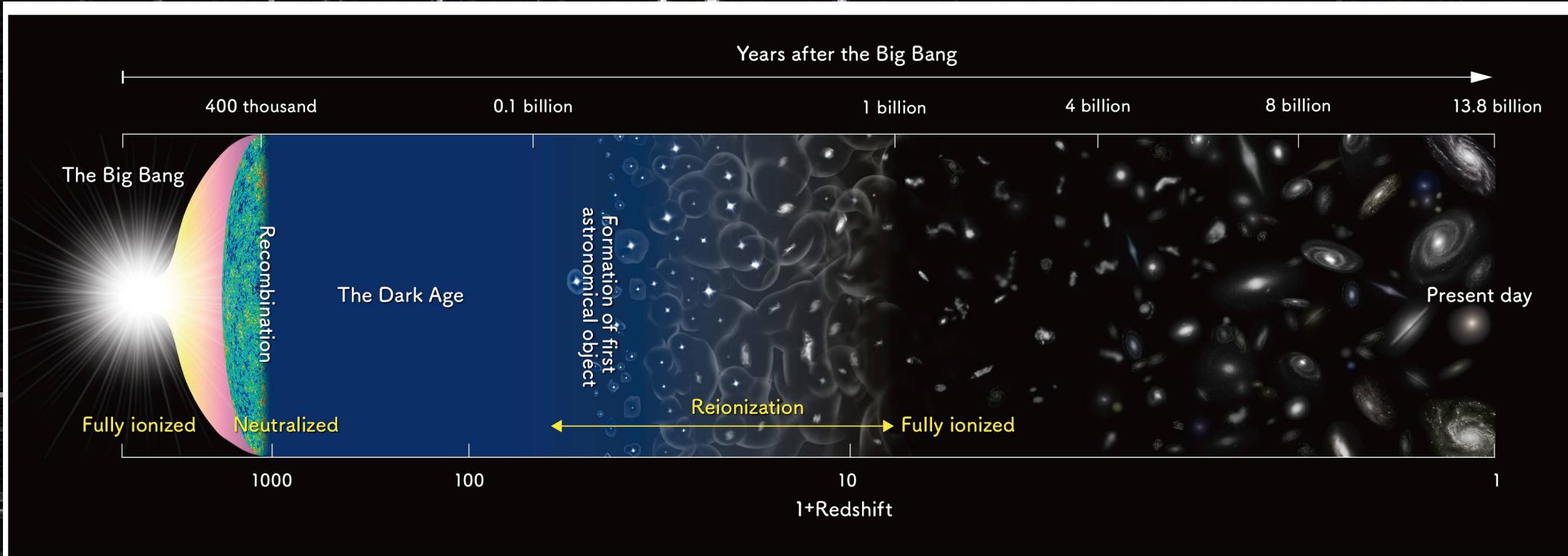
Angulo, Springel,  
White et al. (2011)

# Formation of Galaxies and Large Scale Structure



**L'assemblage des galaxies est complètement corrélé avec la formation des structures à grande échelle**

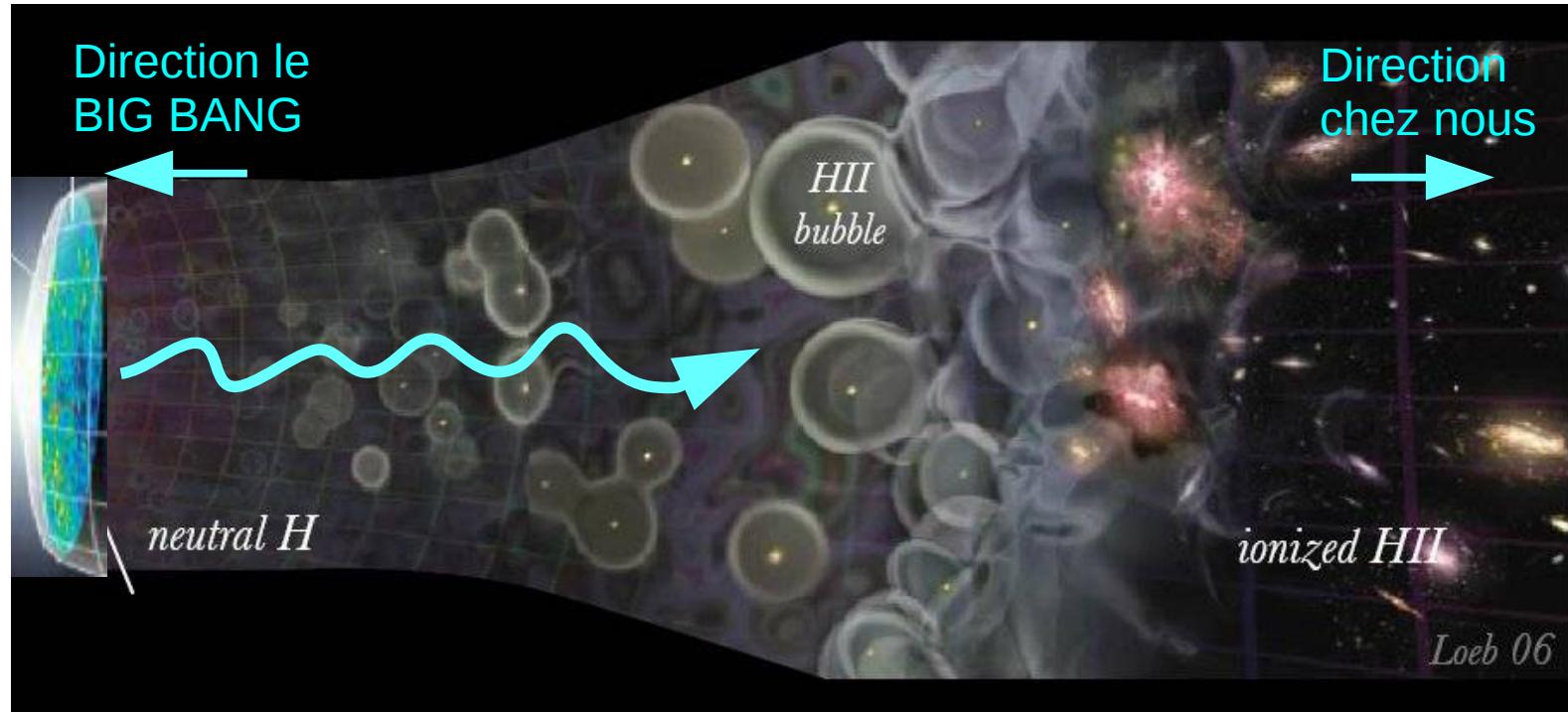
**La GRAVITE est le principale force responsable de cette structuration**



# Les BBS galaxie

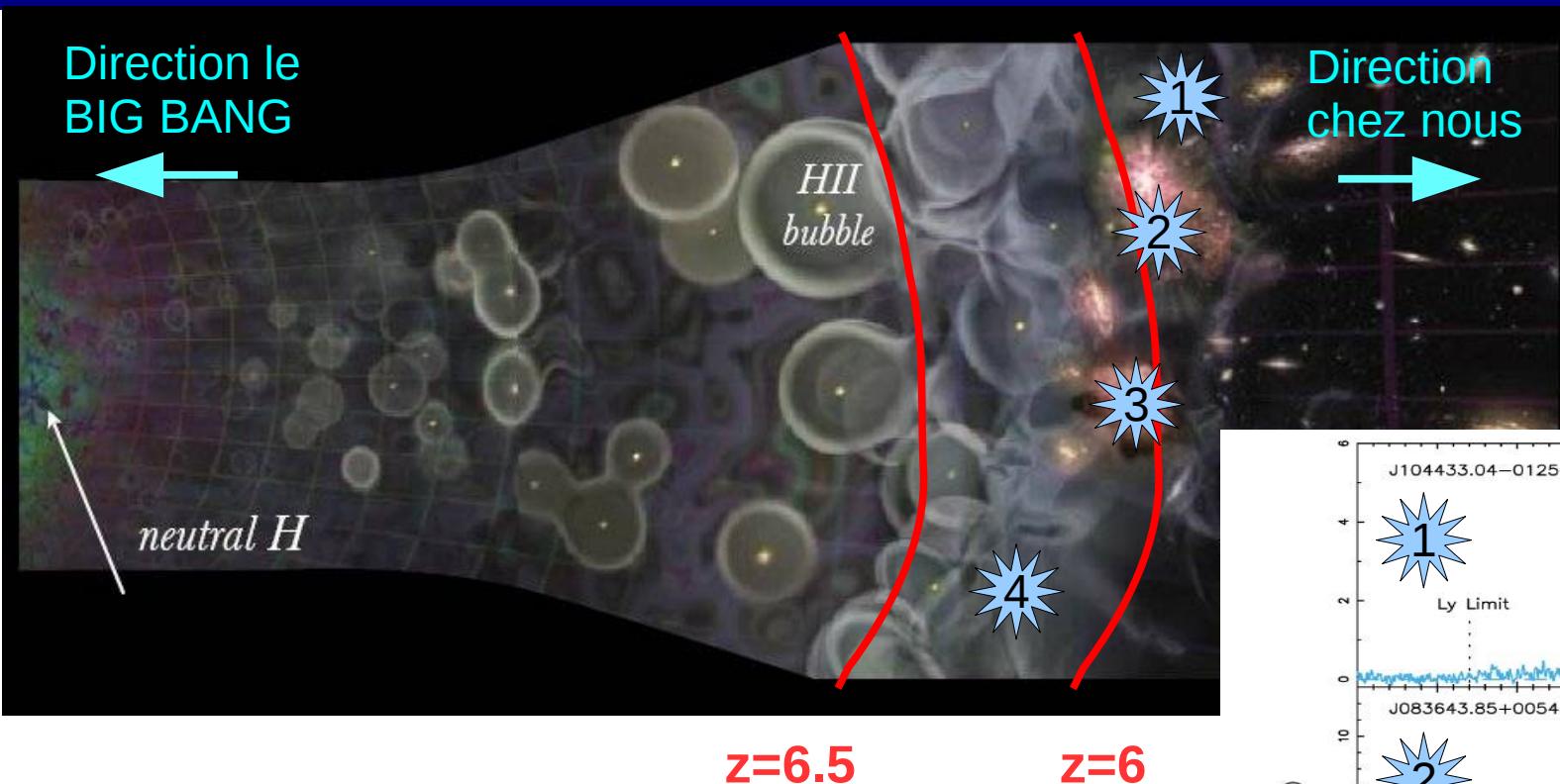


# The beginning of the reionization



- Foreground **electron scattering of CMB photons** with an optical depth corresponding to  $z(\text{reionization})$ .
- $z(\text{reionization}) = 11 \pm 1.2$  (Komatsu et al. 2011) WMAP  
11.4 [+4.0/-2.8] (Planck col. 2014) PLANCK  
7.8 – 8.8 (model dependent) PLANCK 2016  
< 10% ionization at  $z > 10$
- Uncertainties remain... The actual value depends on the reionization process ("instantaneous" versus more complex scenarios).

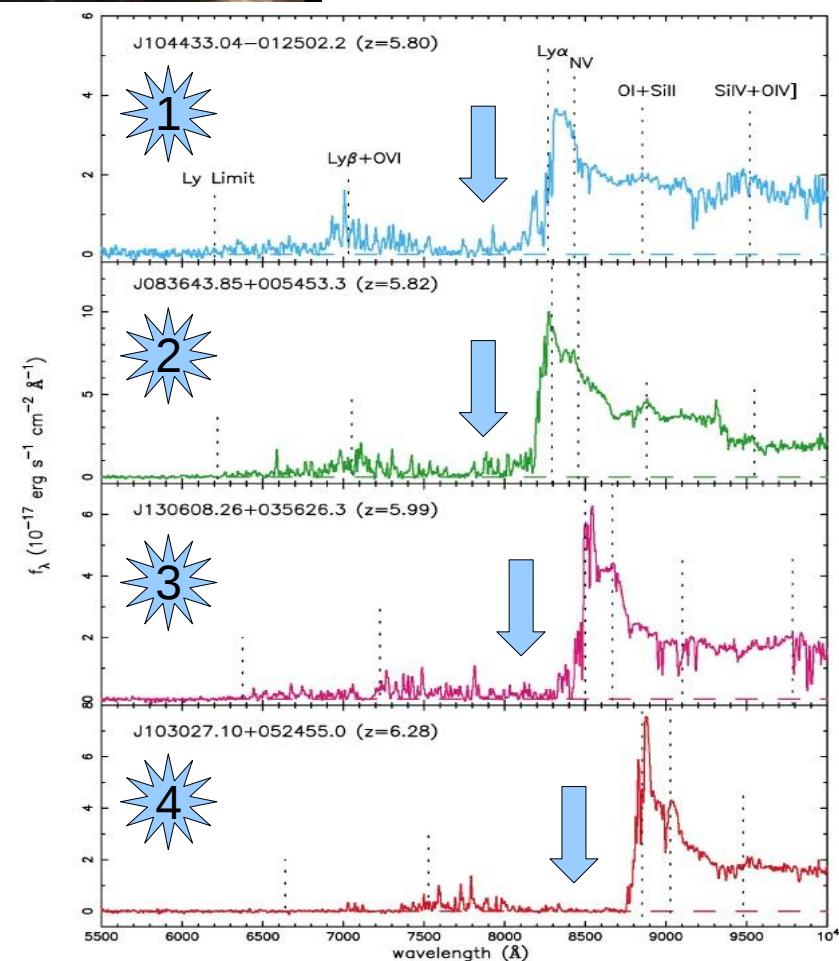
# The end of the reionization



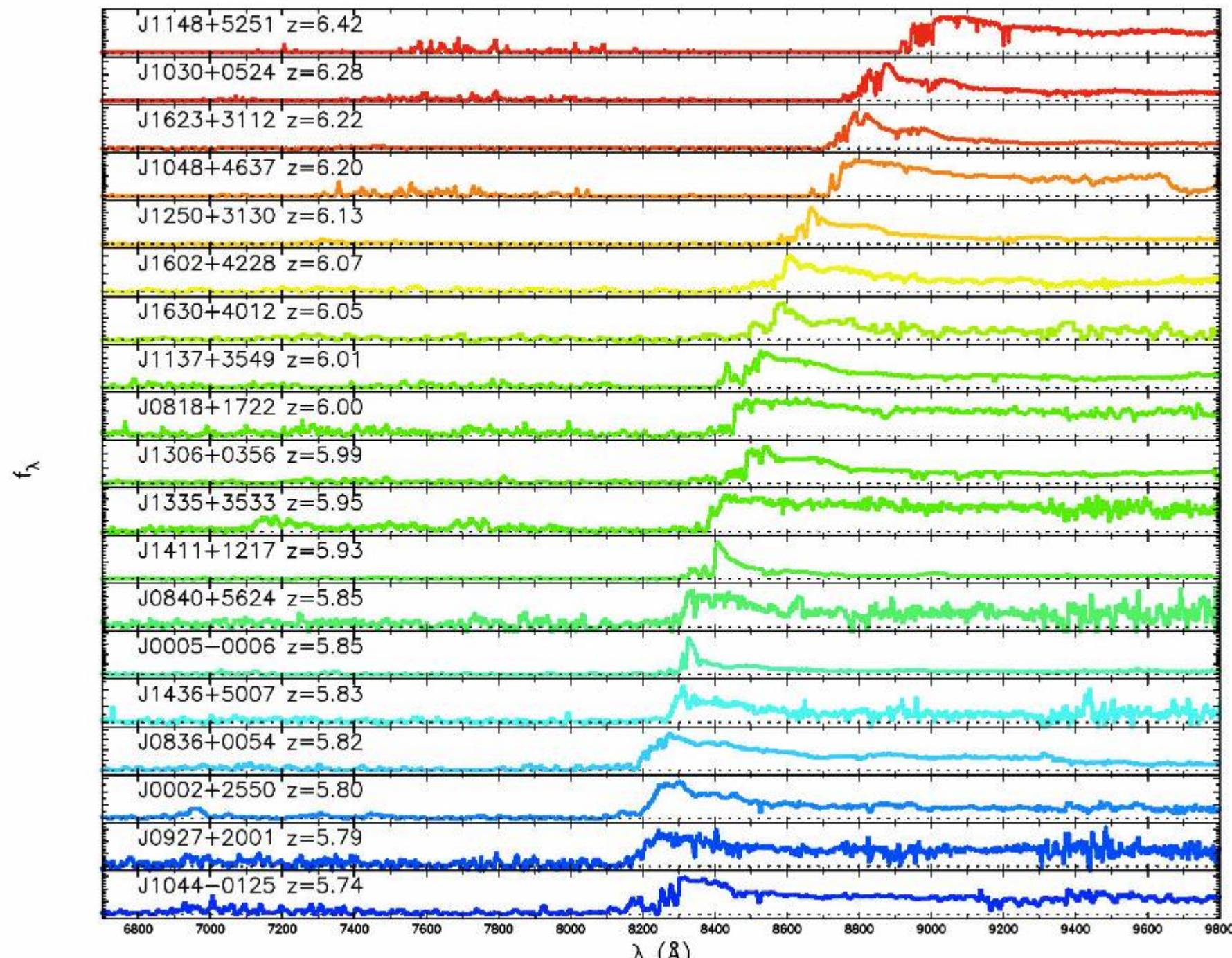
Fraction d'Hydrogène neutre  
augmente dramatiquement à  
 $z \sim 6 - 6.5$

A  $z > 10$ , l'Univers est neutre à  
plus de 90 % !

Fan et al 2006



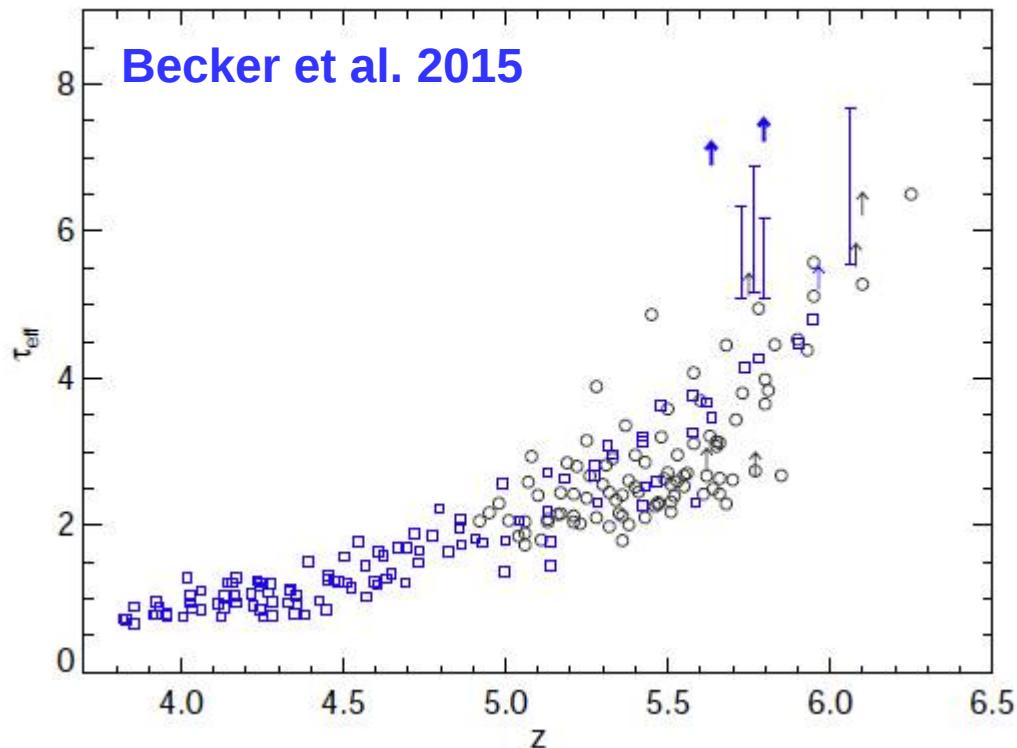
# The end of the reionization



# Sources of the reionization and actual process

What were the sources responsible for the reionization?

- Galaxies : *main contribution* ?
- AGNs / accreting BH : *not enough for a dominant contribution...*
- Others ? GRB, exotic matter,...

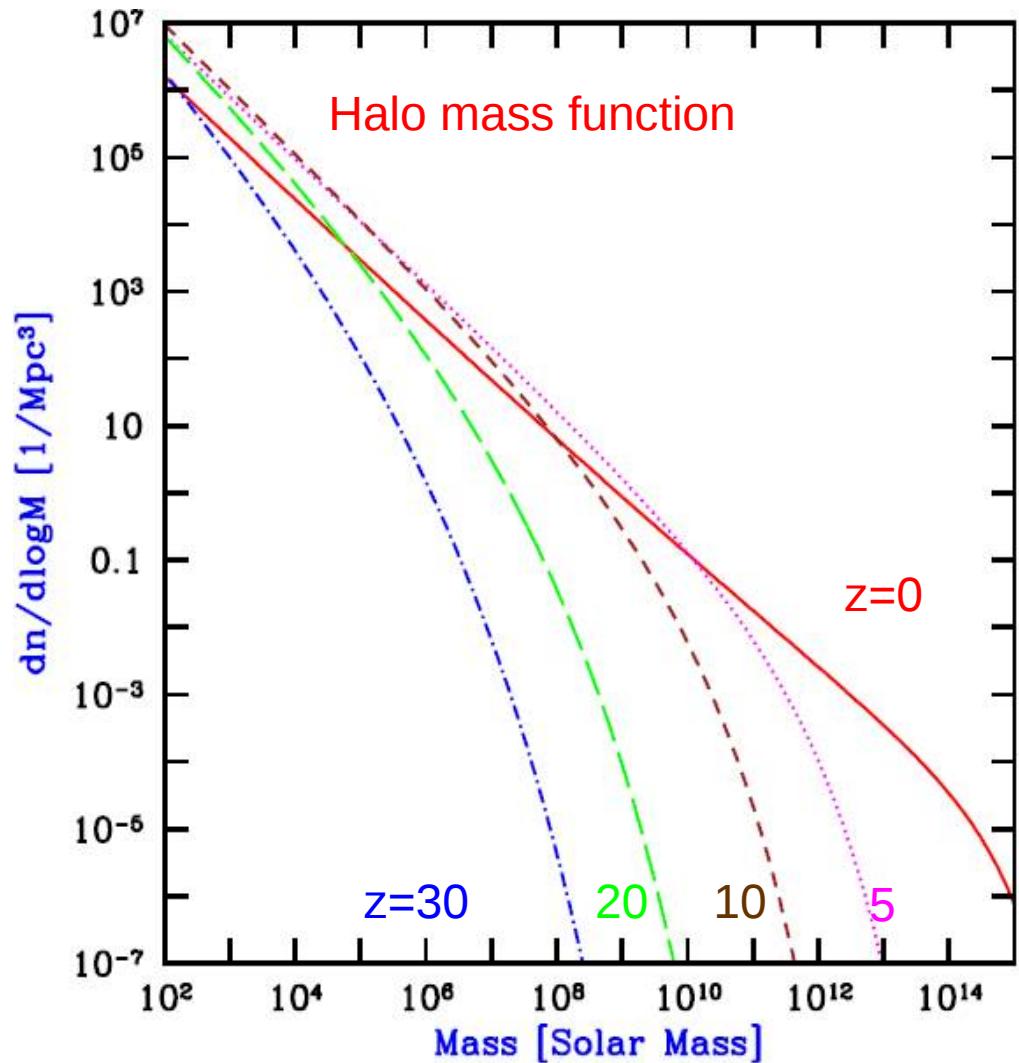


- When and how reionization occurred?
- Evidences for a “patchy” H reionization (inhomogeneous at  $\sim 100$  Mpc scale; see Becker et al. 2015)
- A gradual process? Multiple phases?

# Theoretical considerations

## Galaxy formation models

- Model baryonic processes:
  - Semi-analytic models ==> simple spherical symmetry, analytic recipes
  - Hydrodynamical simulations ==> hydro equations solved numerically
- **Gas infall & cooling in DM halos**
  - DM dominates gravity
  - The baryonic mass that can accrete into a final DM potential well is ~ the Jeans mass
  - Two independent mass thresholds for Star Formation : the Jeans mass (accretion) and the cooling mass (fragmentation into stars)
  - Lower limit is  $M \sim 10^4$  solar masses at  $z \sim 20$

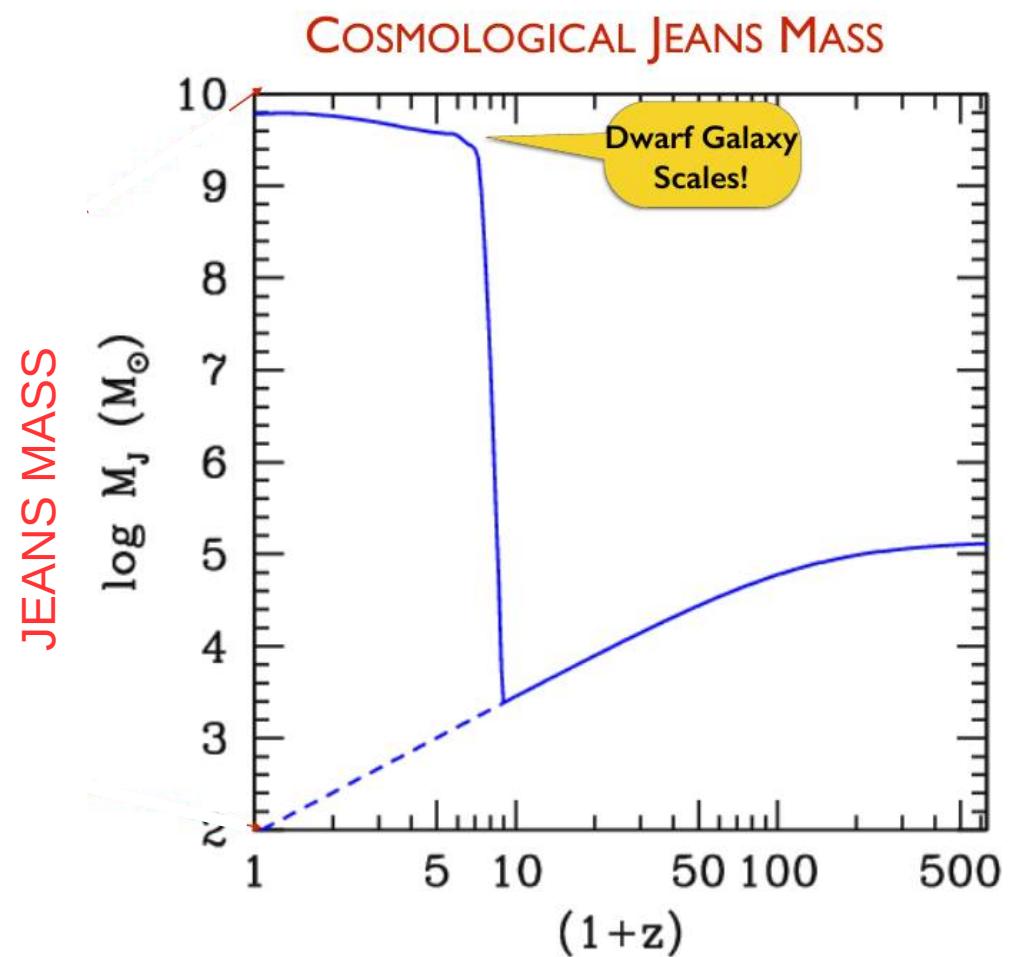


# Theoretical considerations

## Galaxy formation models

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(from Madau, 2015)

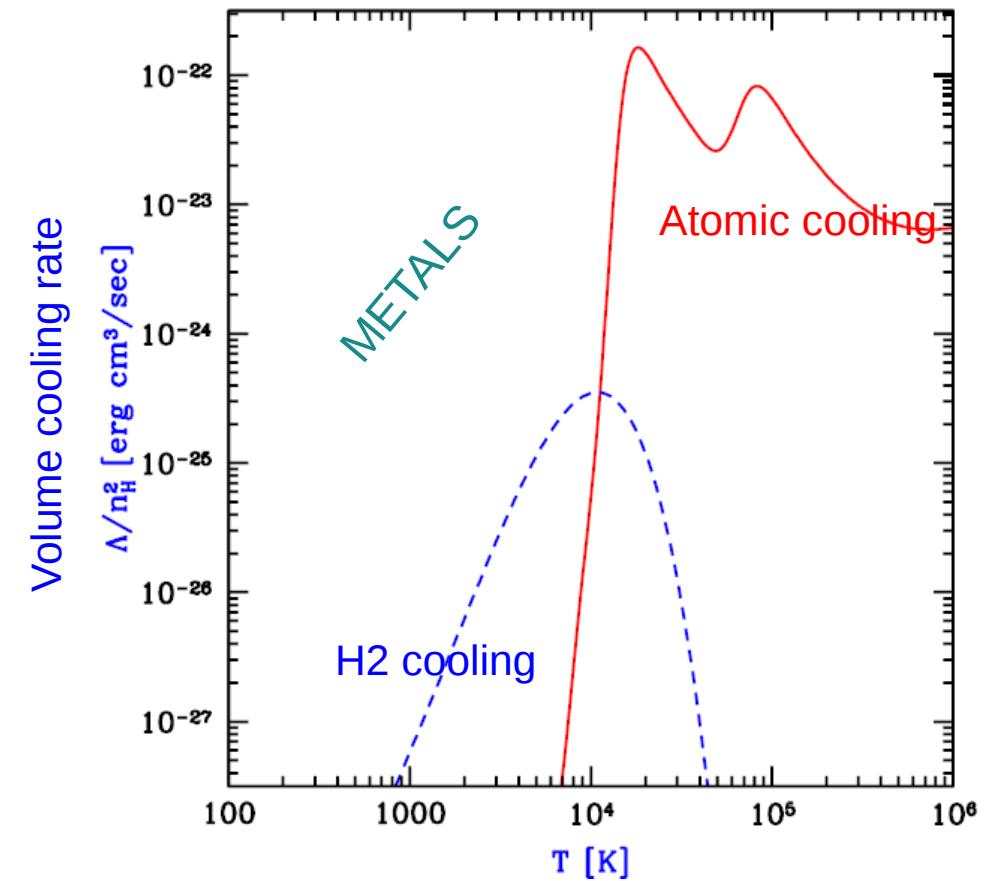


# Theoretical considerations

## Galaxy formation models

- First stars :
  - Formed in mini-halos ( $10^6$  solar masses)
  - $T_{vir} \sim$  a few  $10^3$  K
  - Cooling process: molecular H ( $H_2$  ; see Abel & Haiman 2000 )
  - $H_2$  is photo-dissociated by UV photons
- First galaxies :
  - Formed in larger halos ( $\sim 10^8$  solar masses)
  - $T_{vir} \geq 10^4$  K
  - Cooling : atomic hydrogen

Barkana & Loeb (2001)

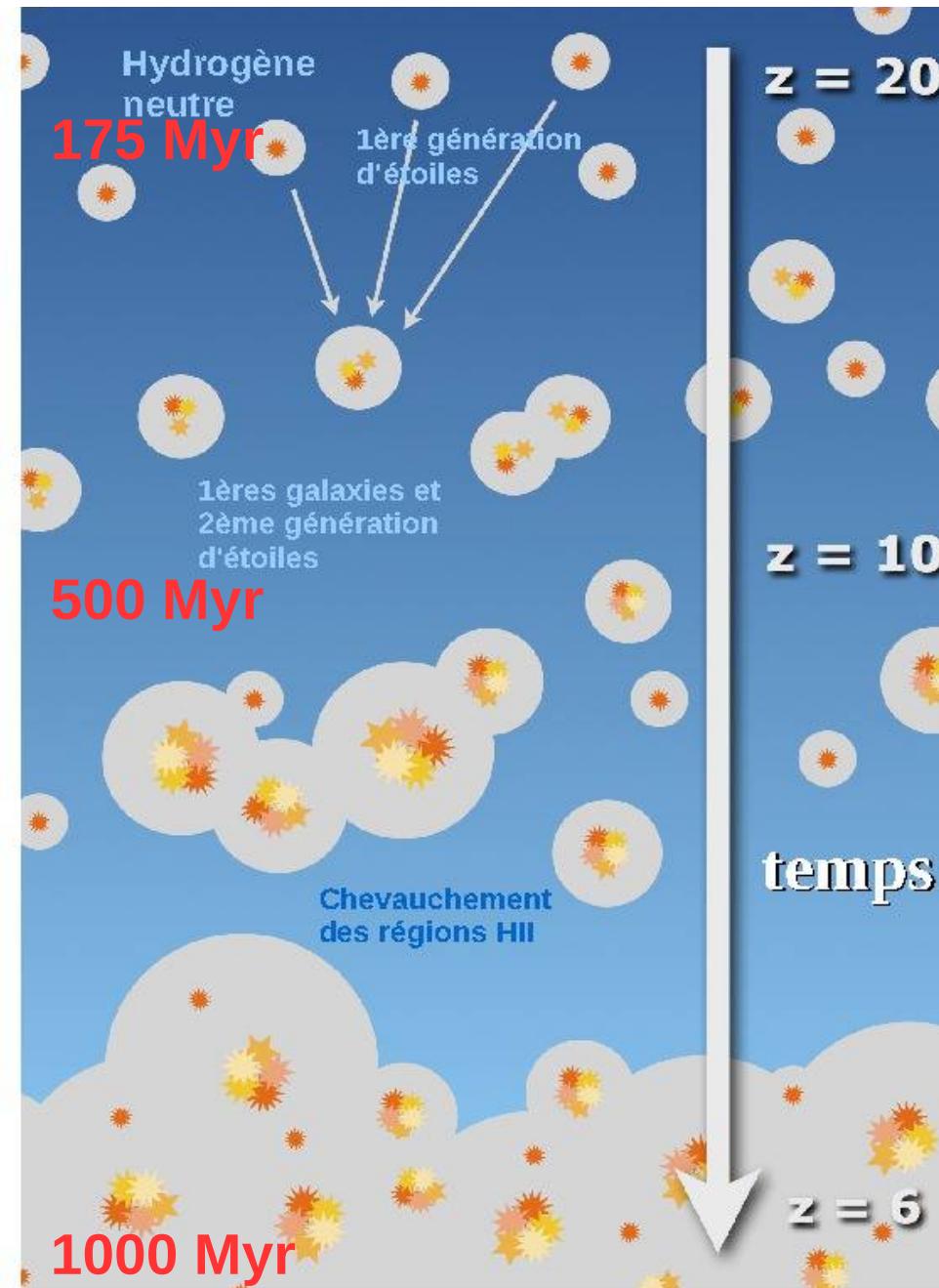


Virial temperature (PopIII)

Dominant  $H_2$  formation process

$$H + e^- \rightarrow H^- + h\nu$$
$$H^- + H \rightarrow H_2 + e^-$$

# Theoretical considerations



## Galaxy formation models

- $\text{H}_2$  is easily photo-dissociated by UV photons.
- The UV flux needed to photo-dissociate  $\text{H}_2$  is  $\sim 2$  orders of magnitude lower than the minimum to ionize the universe ==> as soon as the first stars form, the  $\text{H}_2$  cooling is suppressed
- New stars form in larger halos ( $T_{\text{vir}} \geq 10^4$  K) through atomic-line cooling ==>  $M(\text{total}) > 10^8 \times [(1+z)/10]^{-3/2}$  solar masses

**Comparison** : Our Galaxy has  $\sim 10^{11}$  solar masses !

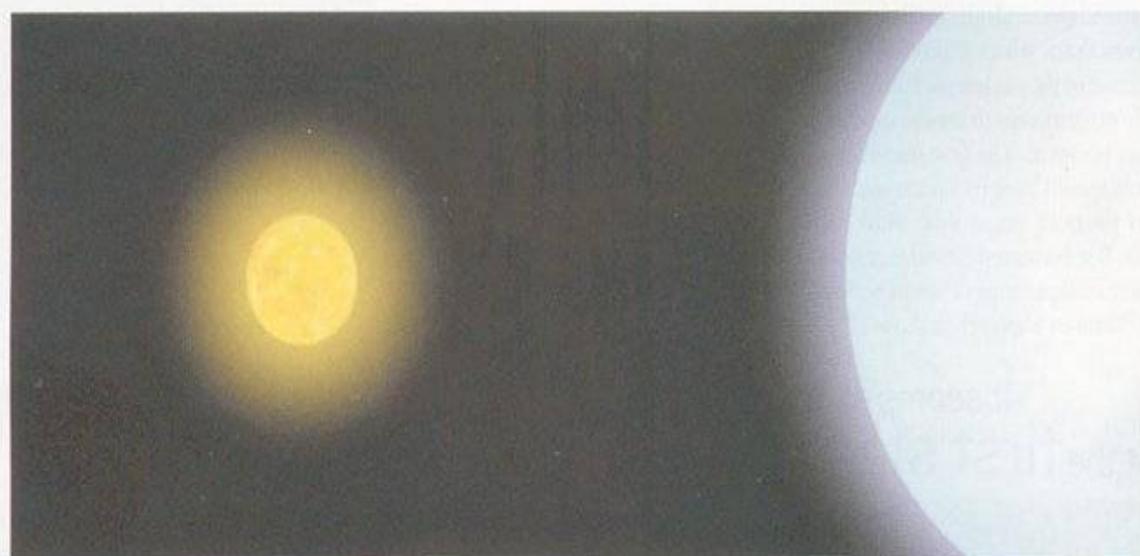


# Les Premières étoiles (Population III)

- Ces premières étoiles sont beaucoup plus massives que les étoiles dans l'univers actuel : jusqu'à 100 à 1000 masses solaires
- Elles naissent « isolées » : pas plus de 1 étoile / halo de  $10^6$  masses solaires (la taille des simulations actuelles)

## COMPARING CHARACTERISTICS

Computer simulations have given scientists some indication of the possible masses, sizes and other characteristics of the earliest stars. The lists below compare the best estimates for the first stars with those for the sun.



### SUN

MASS:  $1.989 \times 10^{30}$  kilograms

RADIUS: 696,000 kilometers

LUMINOSITY:  $3.85 \times 10^{26}$  kilowatts

SURFACE TEMPERATURE: 5,780 kelvins

LIFETIME: 10 billion years

### FIRST STARS

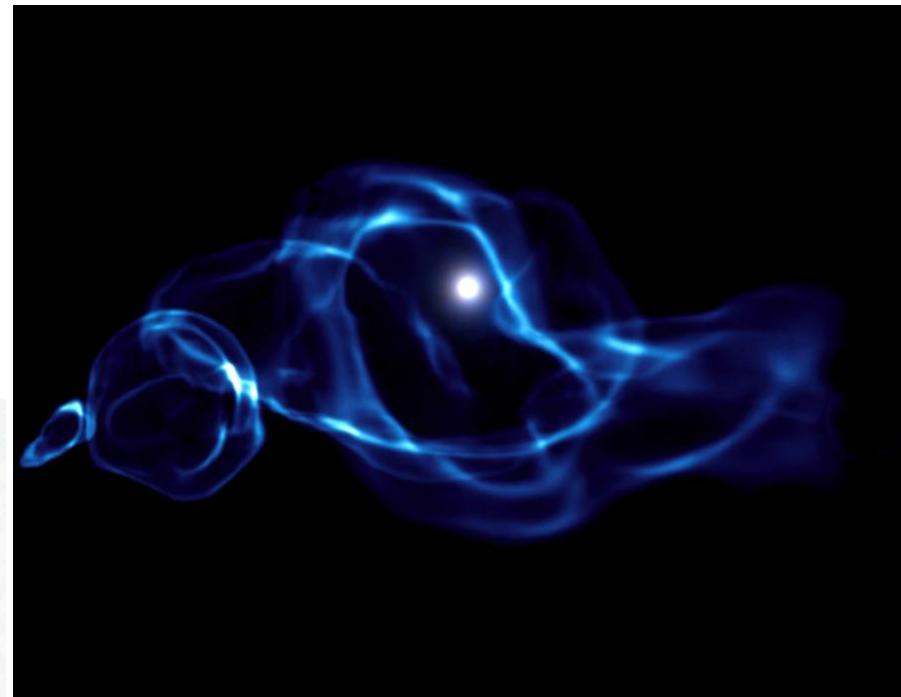
MASS: 100 to 1,000 solar masses

RADIUS: 4 to 14 solar radii

LUMINOSITY: 1 million to 30 million solar units

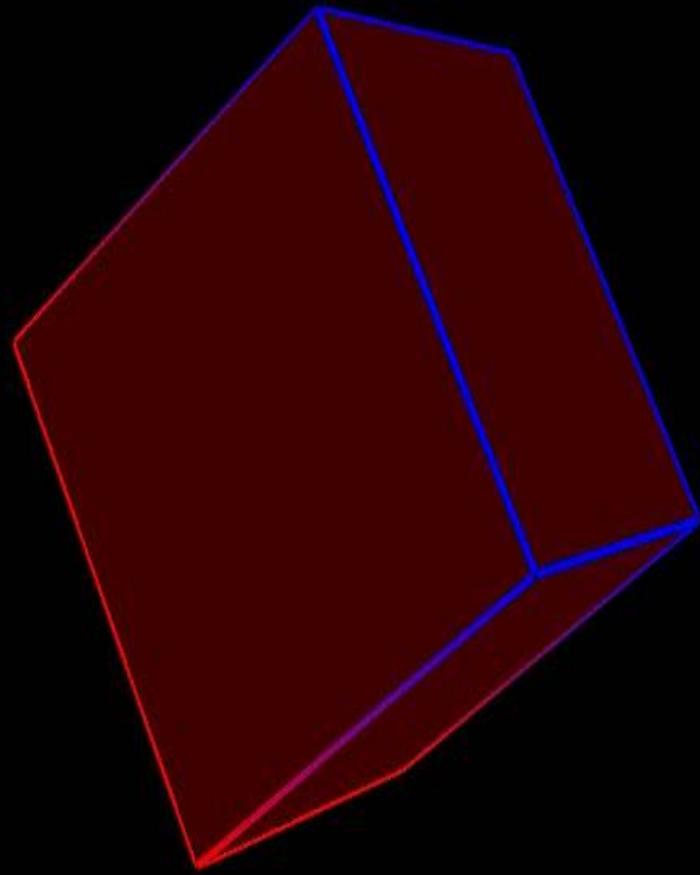
SURFACE TEMPERATURE: 100,000 to 110,000 kelvins

LIFETIME: 3 million years



- Ces premières étoiles vivent peu de temps, moins de  $10^6$  années.
- Elles sont plus chaudes que les étoiles dans notre univers local
- Elles vont avoir un grand impact : formation de métaux → refroidissement facilité → formation de nouvelles étoiles jusqu'à des petites masses cette fois-ci.

# In summary : First stars / galaxies / Reionization



*Simulations by N. Gnedin*

## **Gas infall & cooling in DM halos**

- DM dominates gravity
- The baryonic mass accreted into a final DM potential well is ~ the Jeans mass
- Two independent mass thresholds for SF : the Jeans mass (accretion) and the cooling mass (fragmentation into stars) => lower limit  $M \sim 10^4$  solar masses at  $z \sim 20$

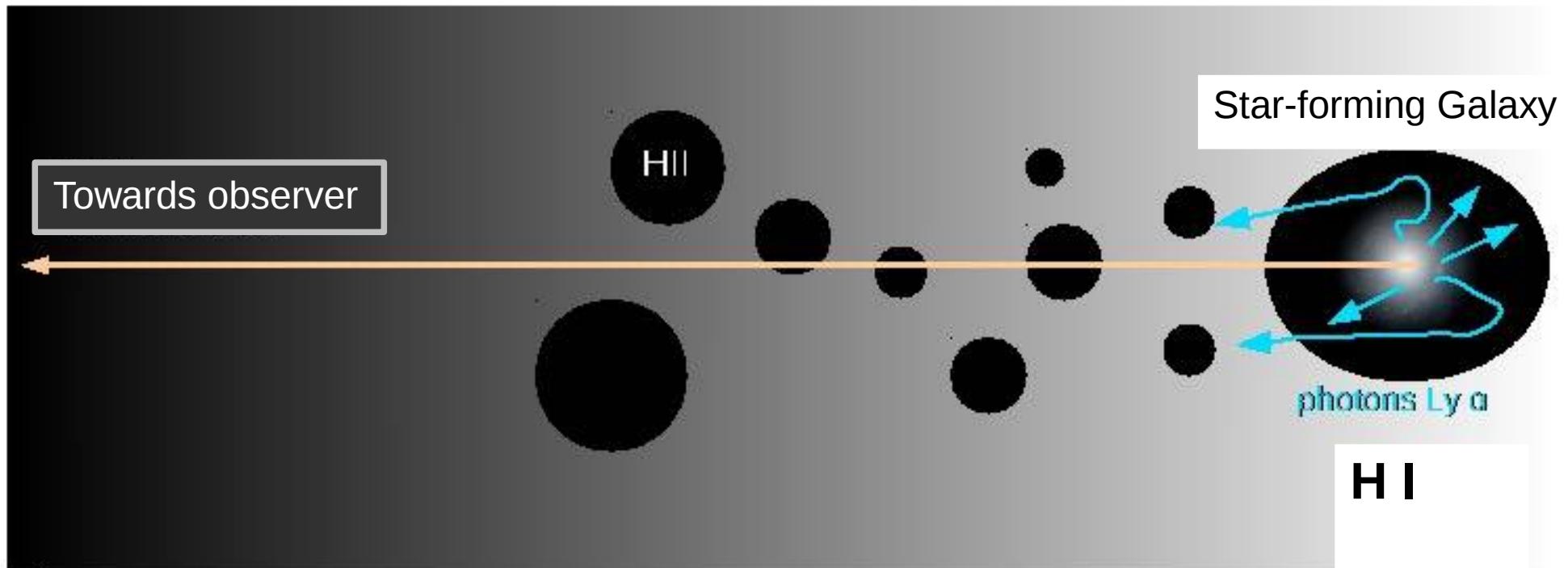
## **First stars : $z \sim 20$**

- Formed in mini-halos ( $10^6$  solar masses DM). Cooling : molecular H ( $H_2$ )

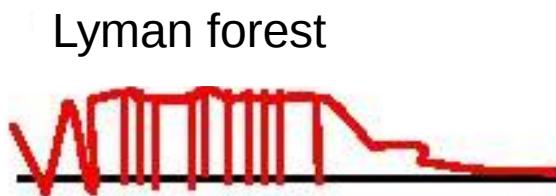
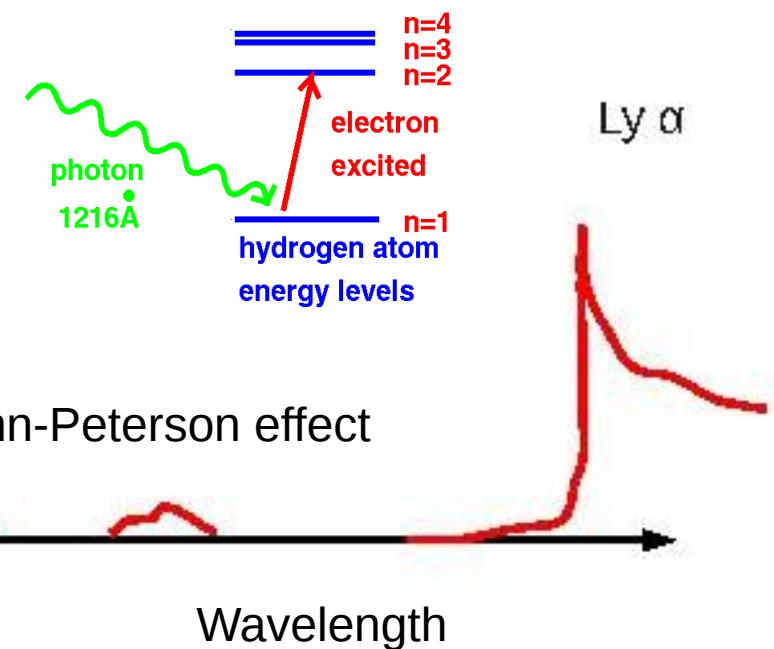
## **First galaxies : $z \sim 10$**

- Formed in larger halos ( $\sim 10^8$  solar masses). Cooling : atomic hydrogen

# Observable properties of the “first” galaxies



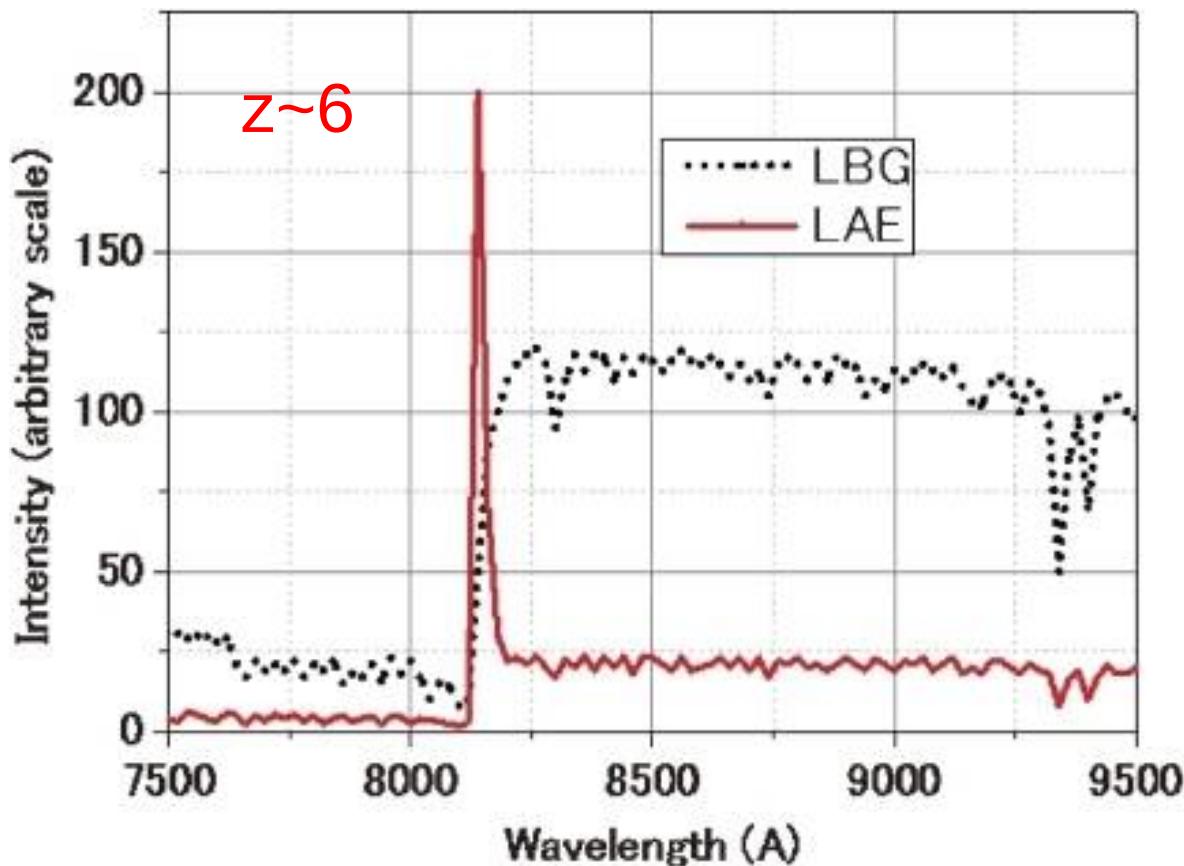
UV continuum  
Ly  $\alpha$



Gunn-Peterson effect

Wavelength

# Main signatures :



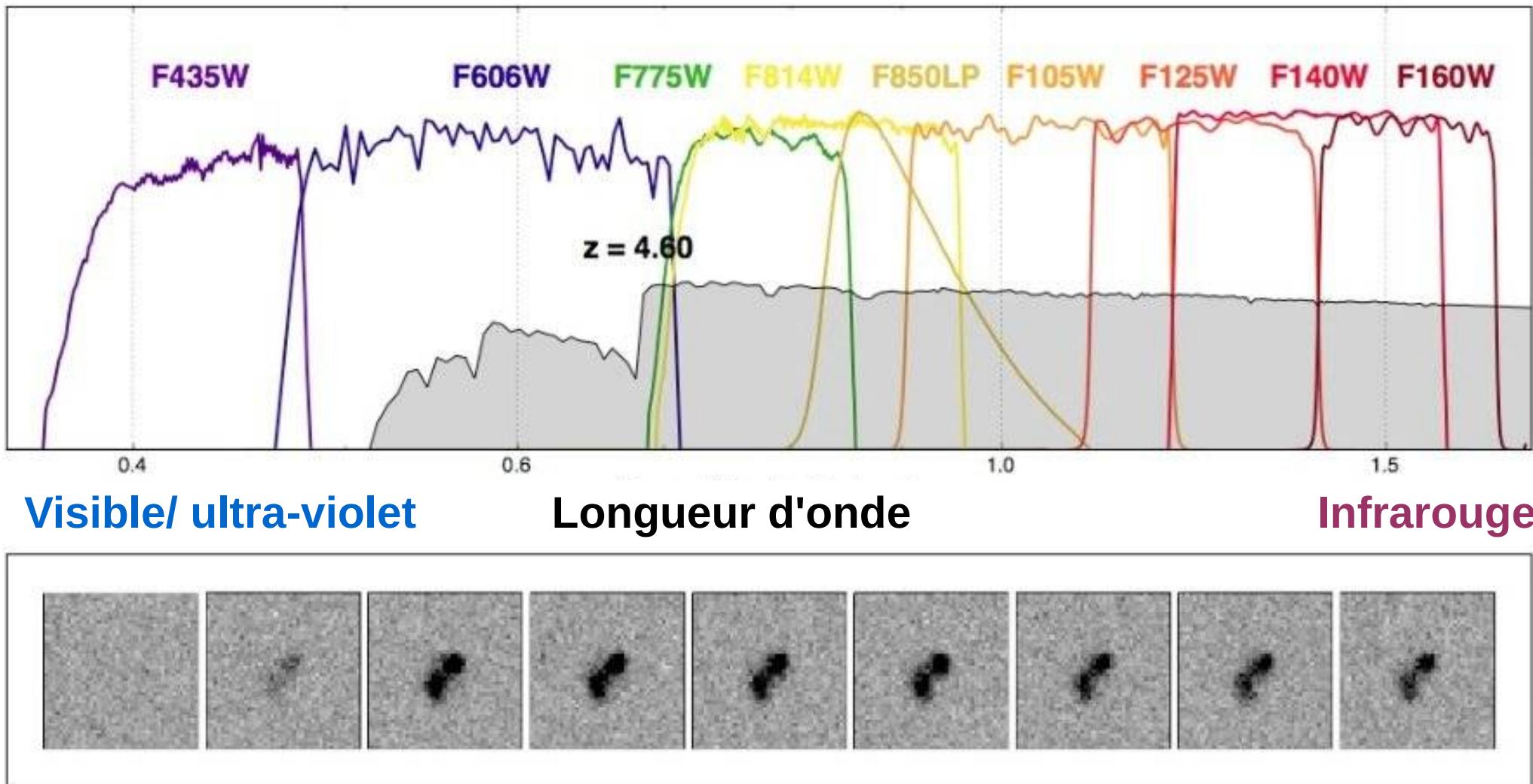
## Observational needs :

- Ultra-deep imaging from the ground and space  $\Rightarrow$  largest telescopes (VLT/ELT) and/or spatial facilities (Hubble Telescope and JWST)
- Spectroscopy to assess the reality of the candidates, determine the redshift accurately and (if possible) derive the physical parameters.

- **Lyman Break**  
signature dropout due to interstellar & intergalactic scattering by neutral H : “Lyman Break Galaxies” (LBG)
- **Lyman alpha**  
emission (LAE galaxies)

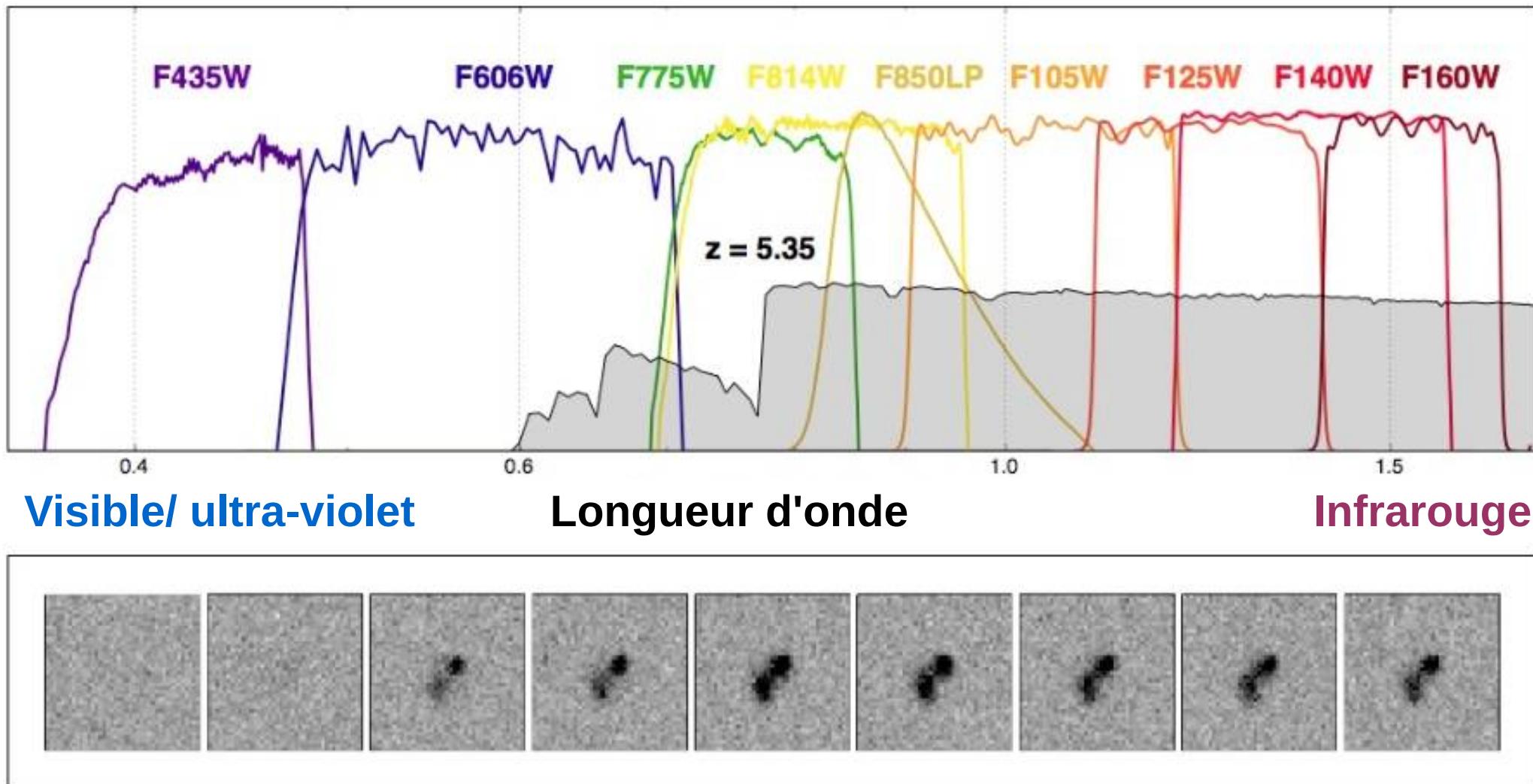
The two signatures may be present !

# Detection of Lyman Break Galaxies (LBG)



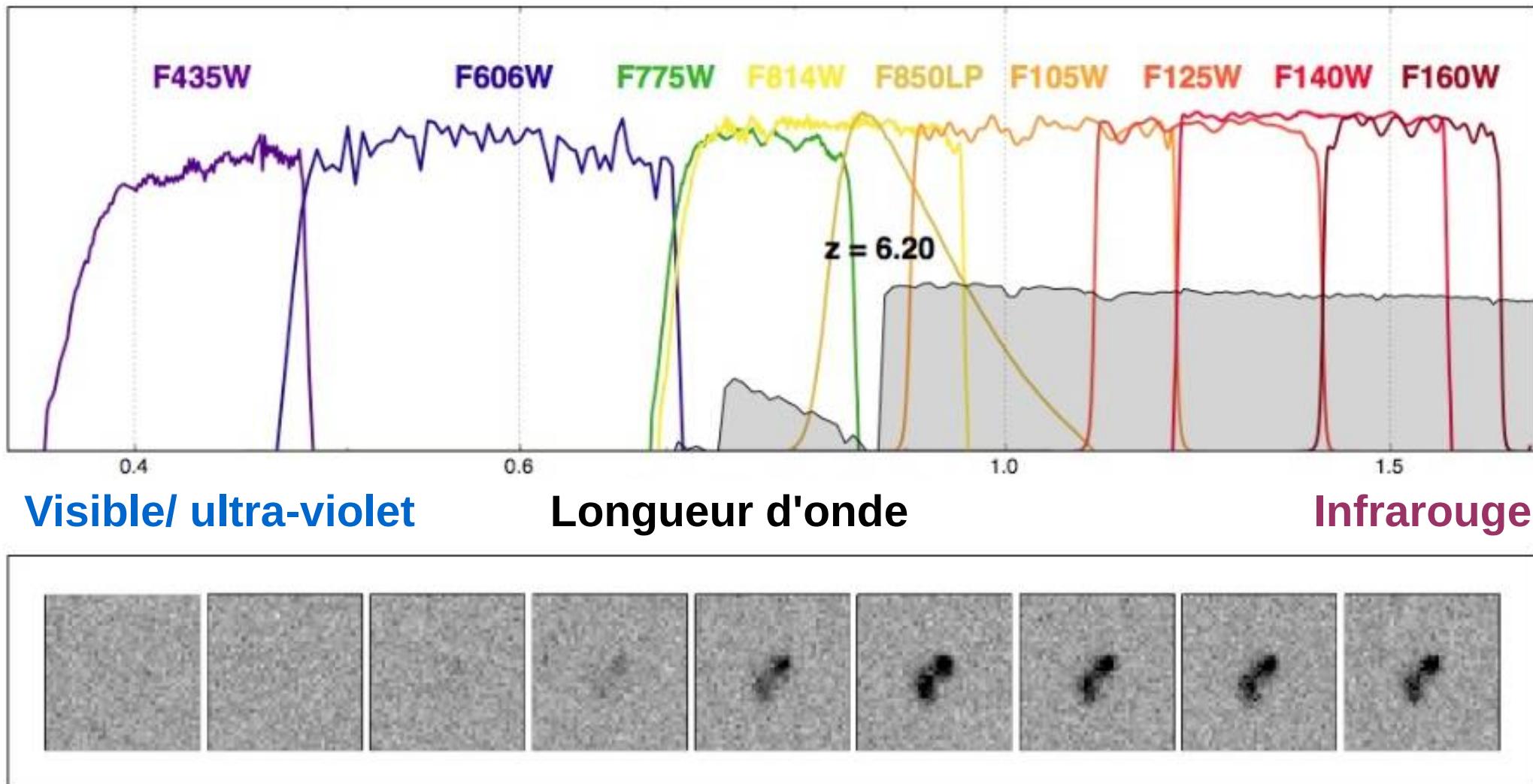
Images dans des filtres successifs  $\Rightarrow$

# Detection of Lyman Break Galaxies (LBG)



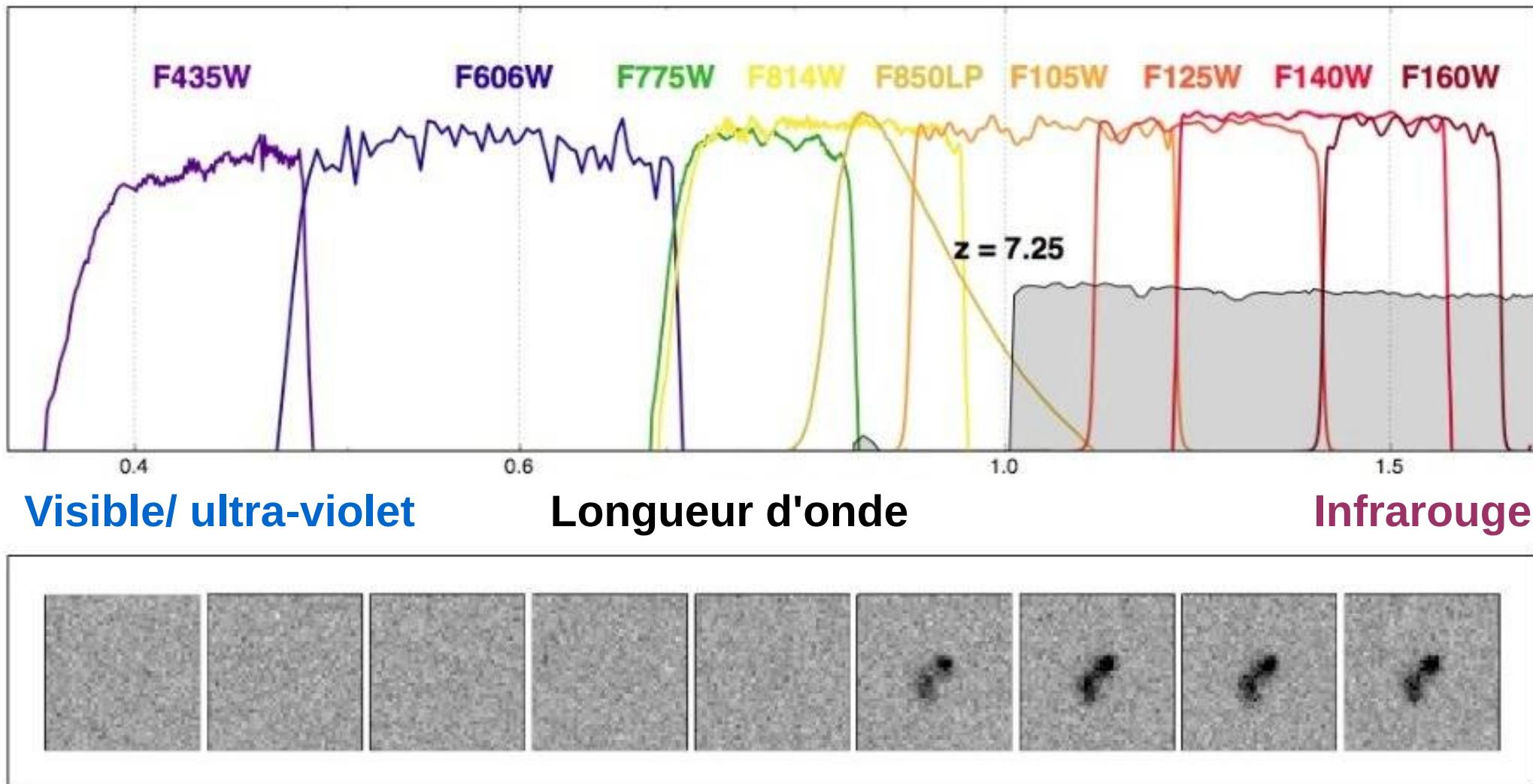
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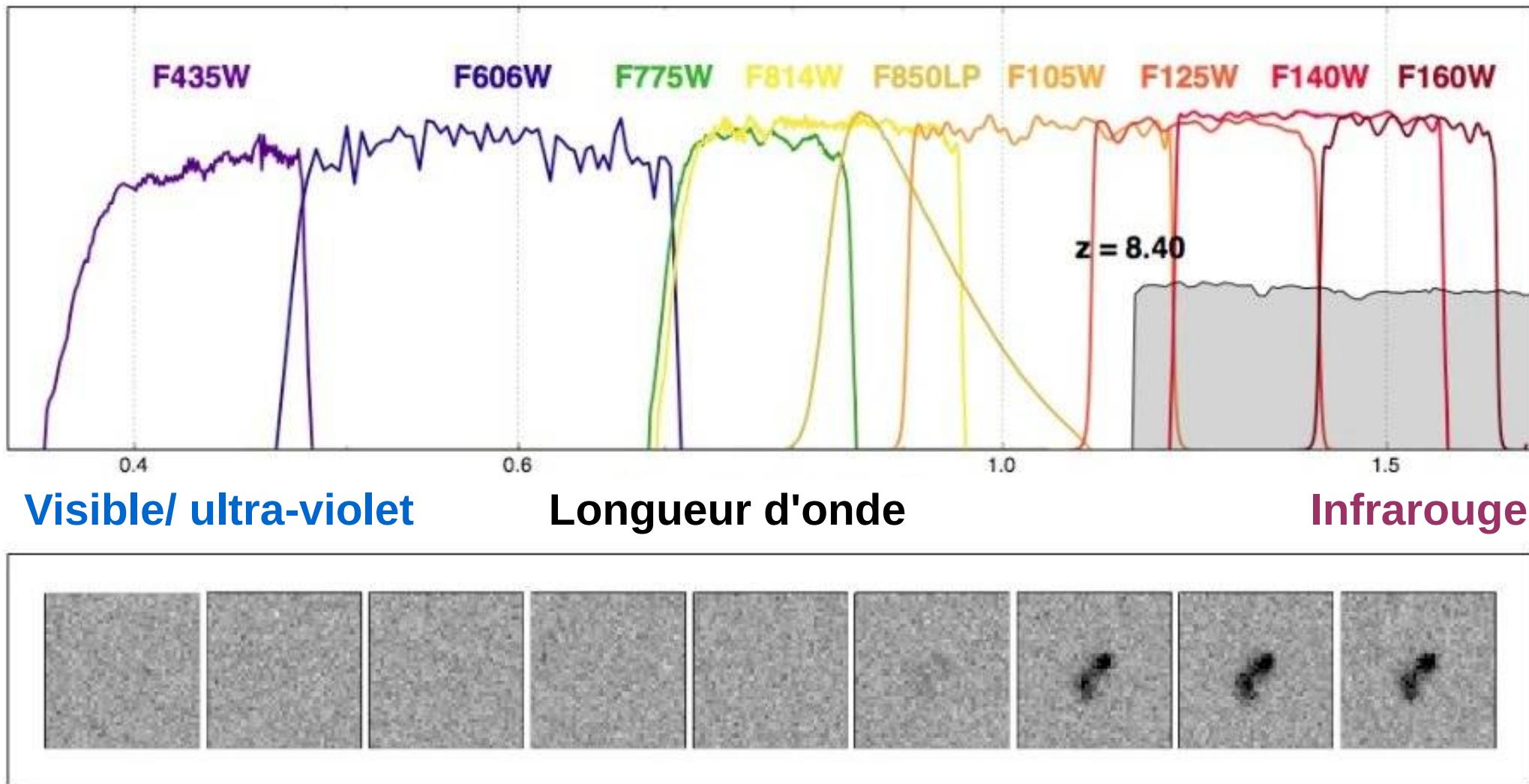
Images dans des filtres successifs ⇒

# Detection of Lyman Break Galaxies (LBG)



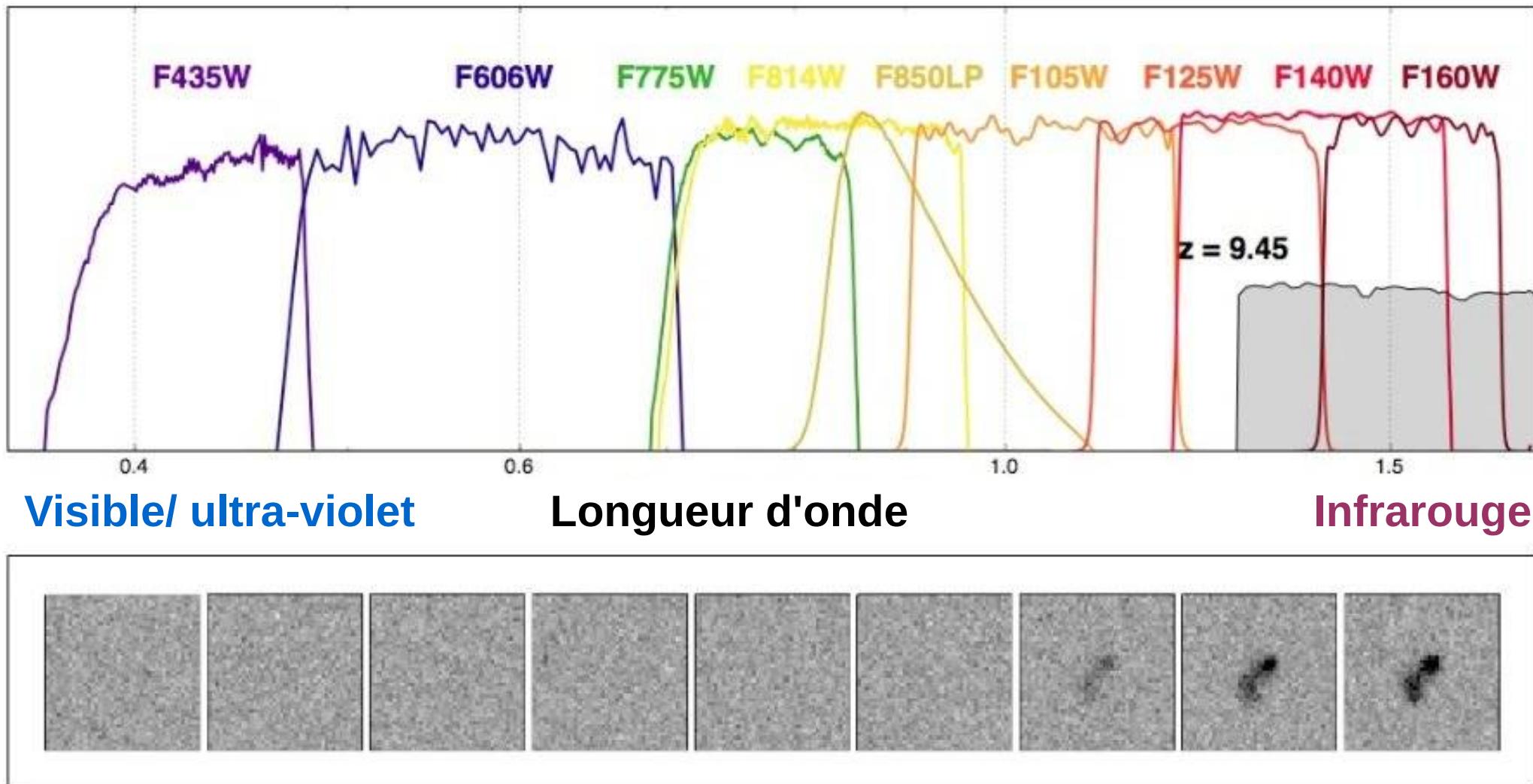
Images dans des filtres successifs  $\Rightarrow$

# Detection of Lyman Break Galaxies (LBG)



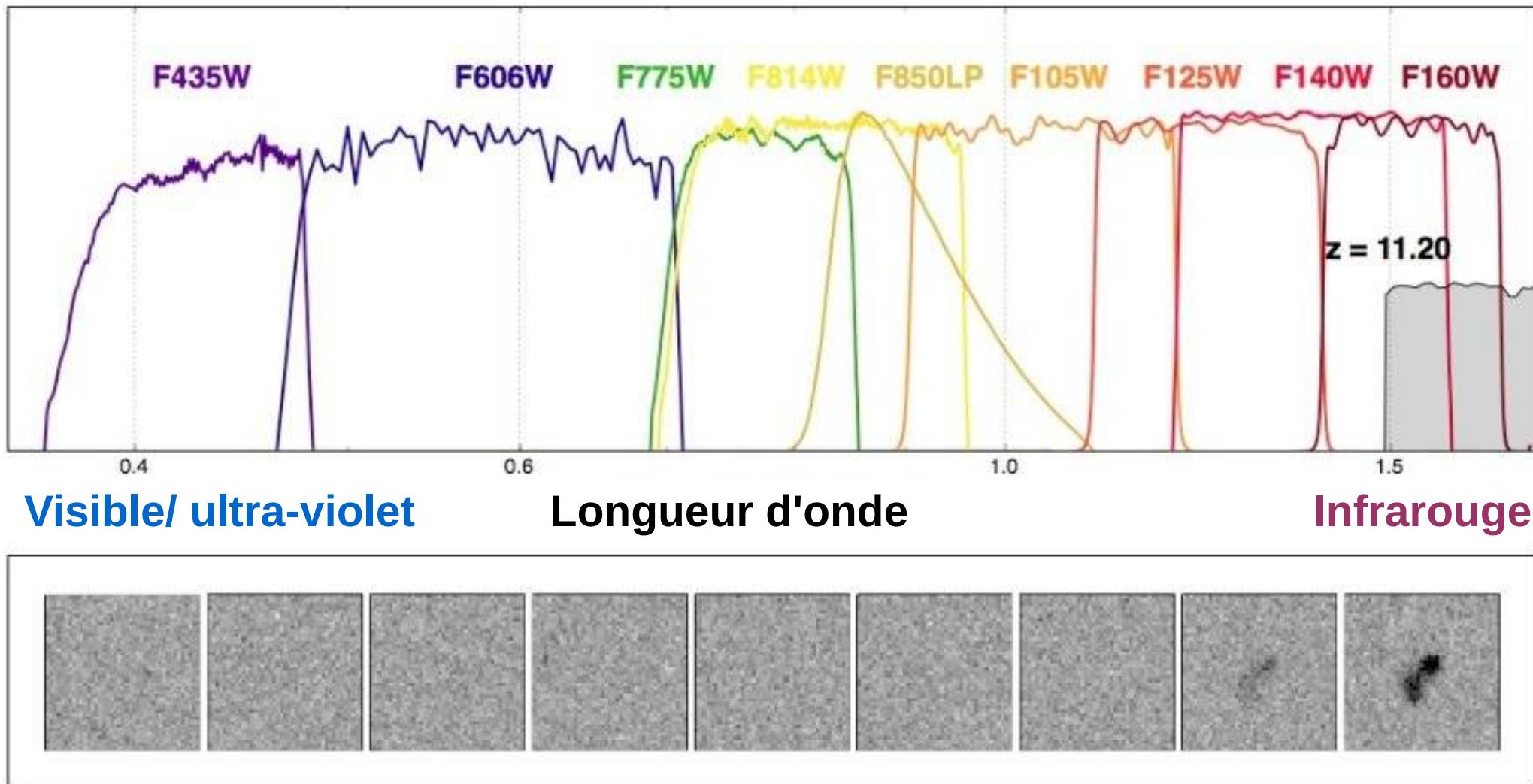
Images dans des filtres successifs  $\Rightarrow$

# Detection of Lyman Break Galaxies (LBG)



Images dans des filtres successifs  $\Rightarrow$

# Detection of Lyman Break Galaxies (LBG)



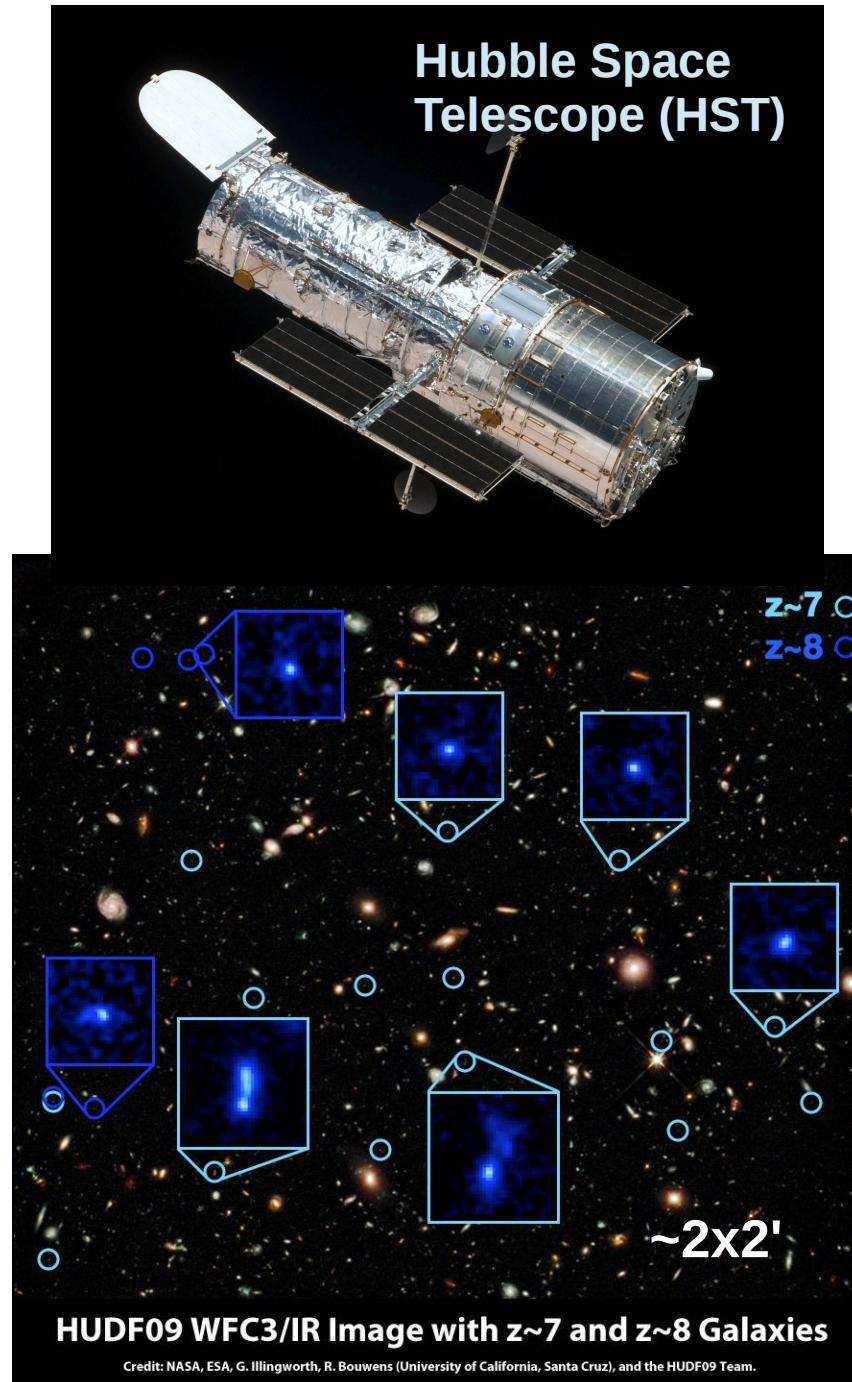
Images dans des filtres successifs  $\Rightarrow$

# Present Surveys

- **Extremely deep Surveys** combining optical+near-IR data : HUDF09, UKIDSS Ultra Deep Survey, GOODS, CANDELS, Extended Groth Strip, Chandra Deep Field, ...
- Multi-wavelength data (HST, Spitzer,...)
- High-z samples are “faint”, typically  $m \sim 28-29$  at  $z \sim 7-8$

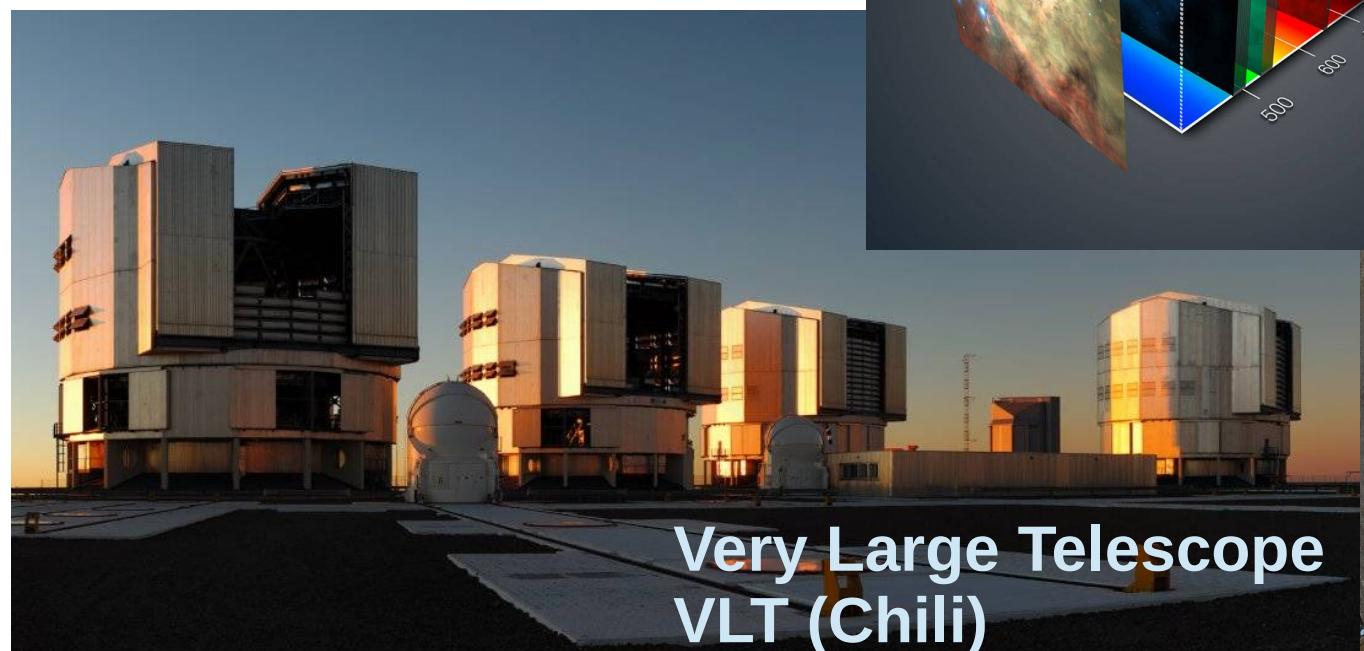
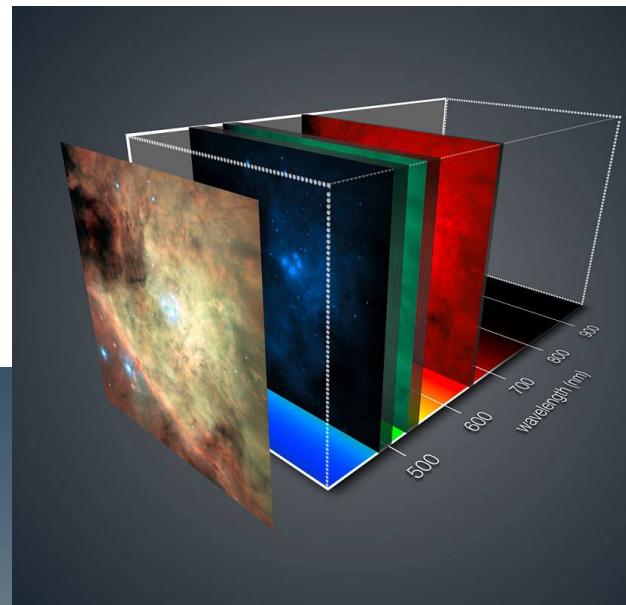
+ cluster lenses (e.g. CLASH SURVEY & Frontier Fields)

- Spectroscopic follow up is difficult with 8-10m class telescopes! Only the brightest candidates are accessible to current facilities...

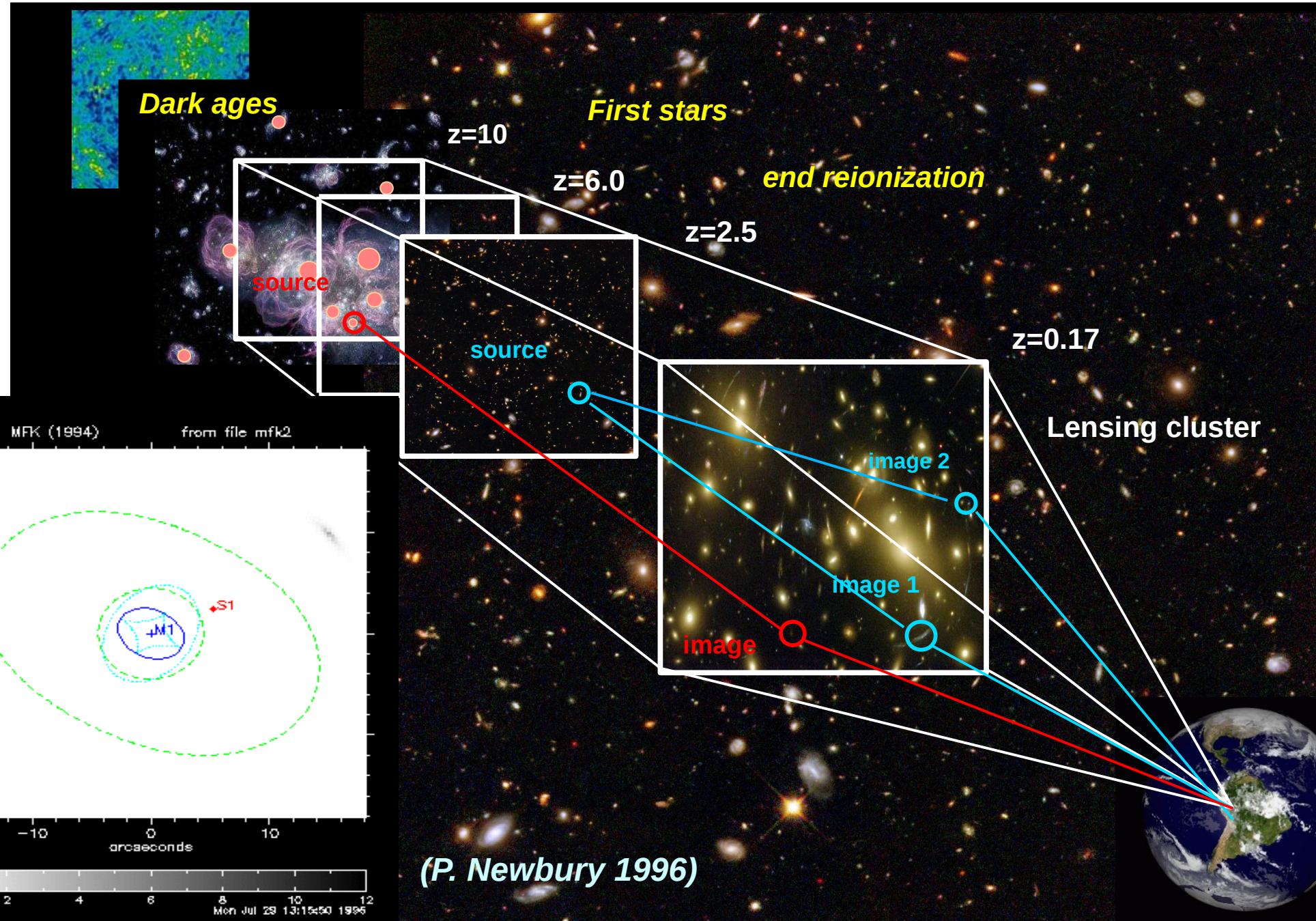


# Les Sondages actuels : Spectroscopie

- **Mesures des redshifts** (basés sur Ly alpha + autres raies en émission).  
Détermination de la nature des galaxies à grand redshift
- Spectroscopie 3D : **Recensement complet des sources ionisantes dans le domaine de redshift sensible**  $z \sim 5 - 12$ , en champs vides et champs d'amas



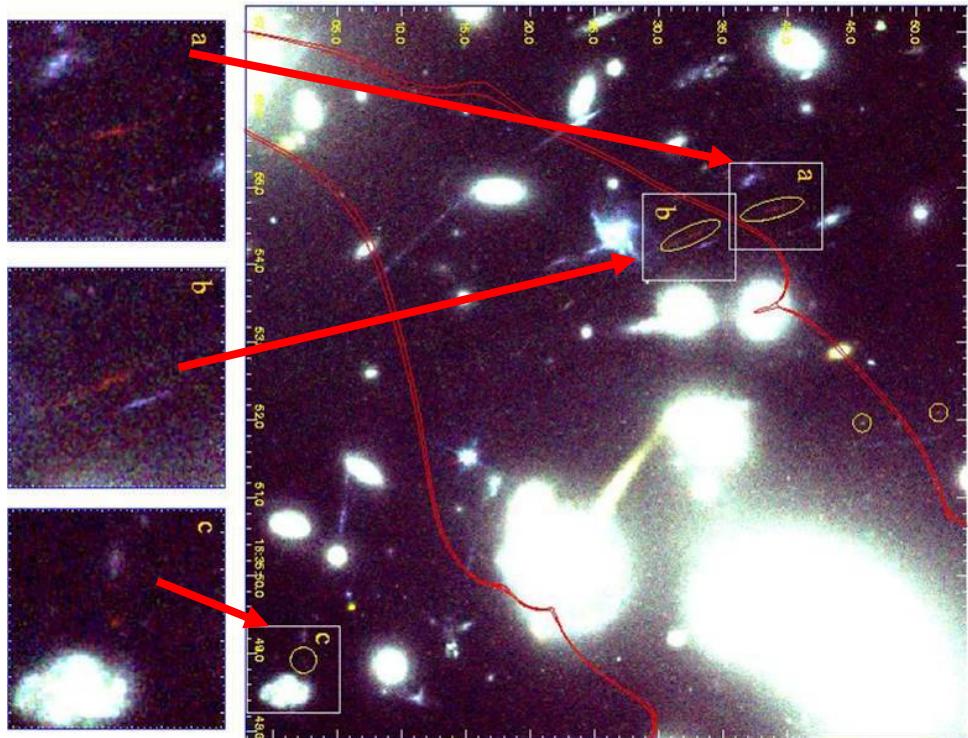
# Lensing clusters used as gravitational telescopes





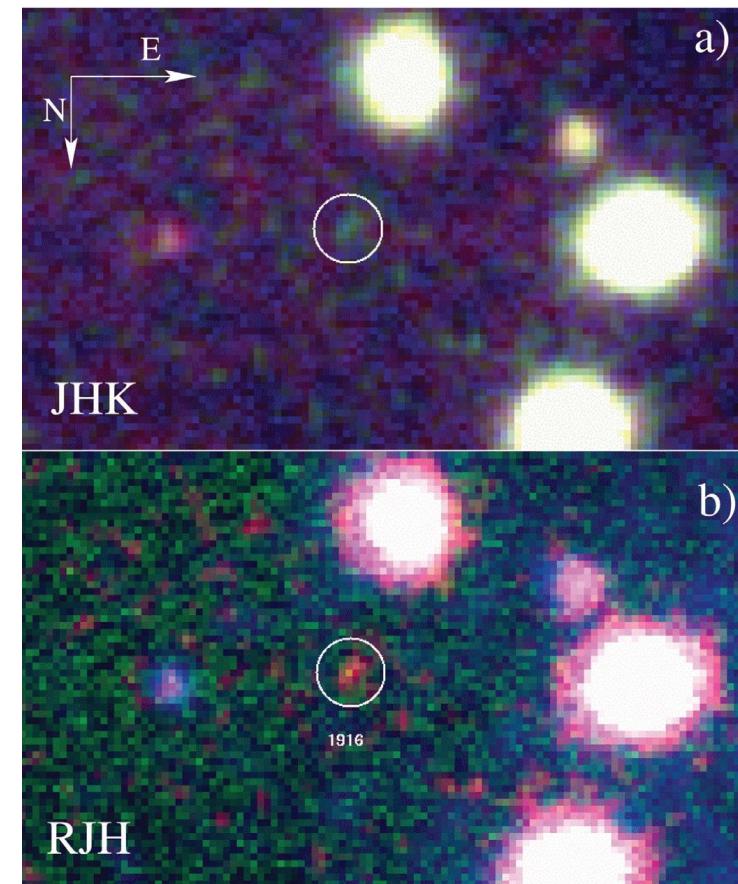
**Some results ....**

# Pioneering work... behind lensing clusters !



*Kneib et al. 2004*

- 3 images of the same source at  $z \sim 7$  behind the cluster A2218.
- Images HST+SPITZER
- Spectroscopy not available...

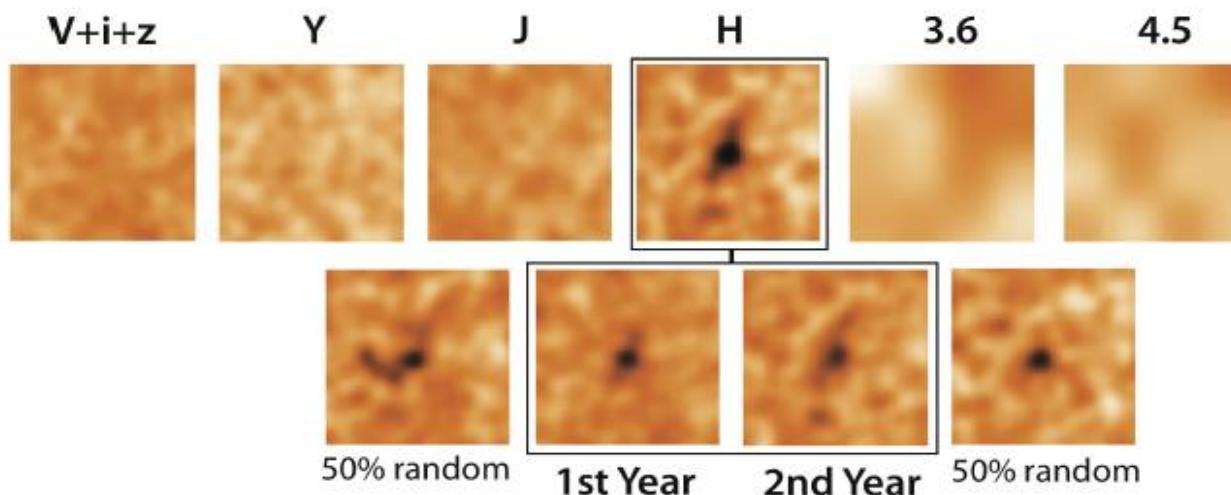


- The first candidate at  $z \sim 10$  behind the cluster A1835.
- Images VLT/ISAAC + HST
- Emission line confirms  $z \sim 10$
- Controversial result ...

*Pello et al. 2004*

# Photometric Candidates in the Hubble Ultra-Deep Field

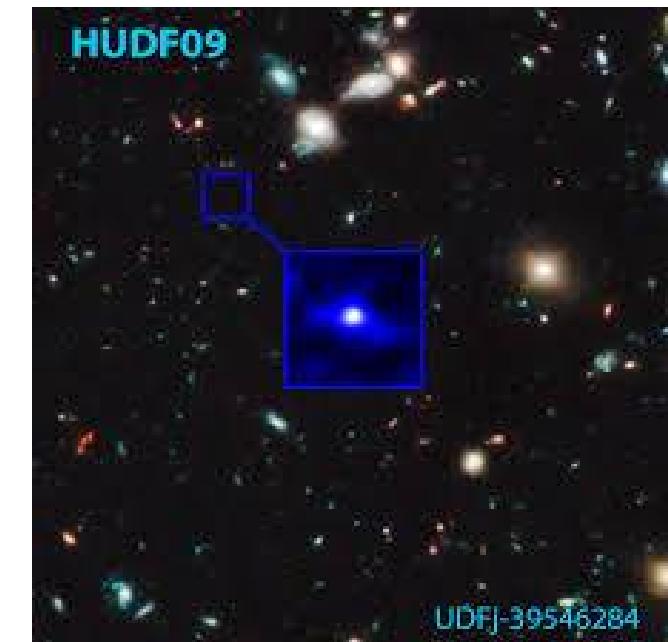
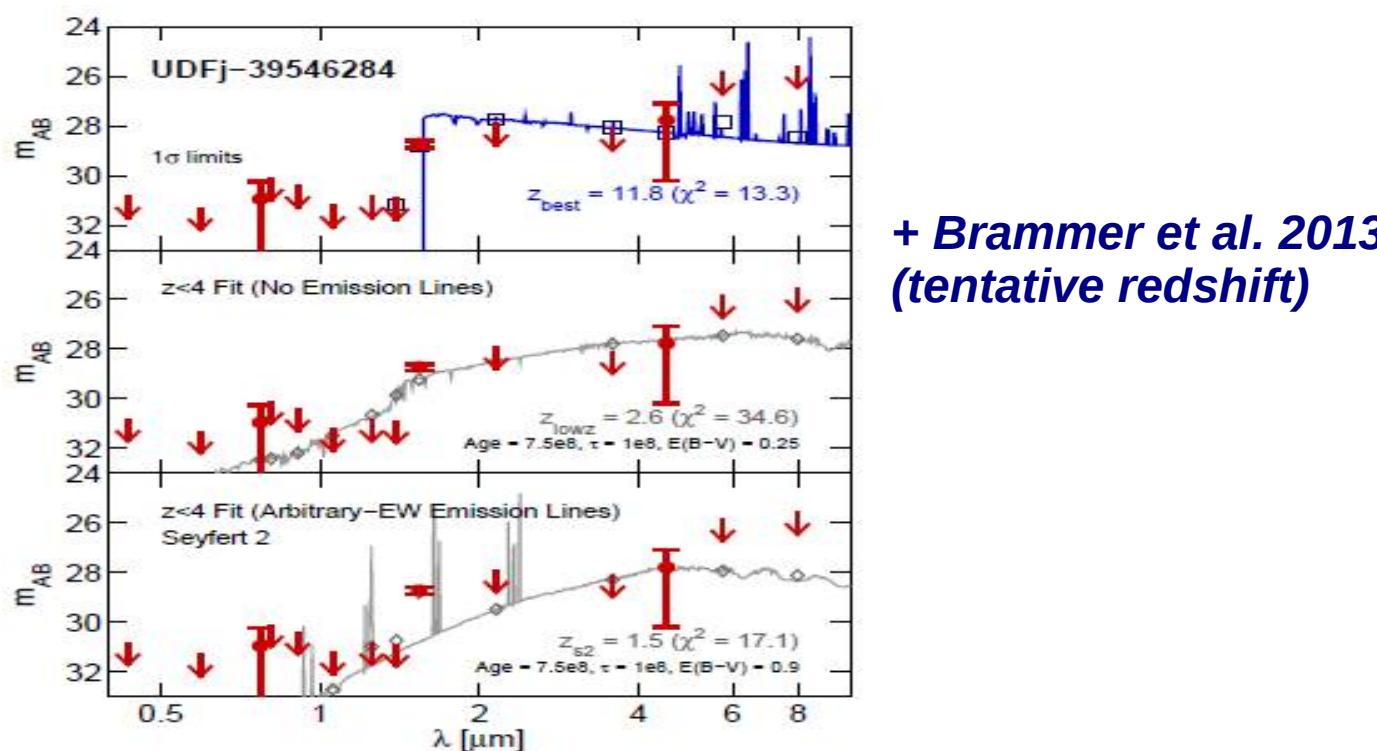
**UDFj-39546284**  $H=28.9$   $J-H>2.0$



*Bouwens et al. 2011*

*Bouwens et al. 2013*

- Candidate at  $z \sim 10$  in the HUDF, detected in a single filter
- Tentative spectroscopic redshift



# Hubble Legacy Surveys – lensing clusters



- **CLASH** : Cluster Lensing And Supernova survey with Hubble.
- 25 clusters (X-rays and/or strong lensing)
- 16 filters
- Z(clusters) ~ 0.2 à 0.9



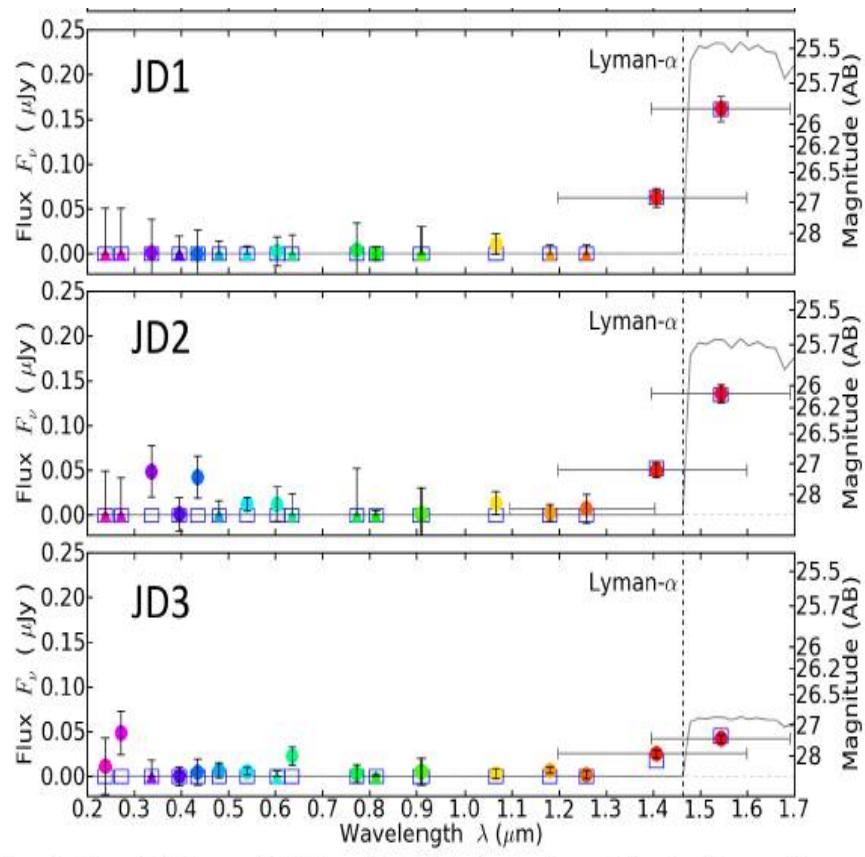
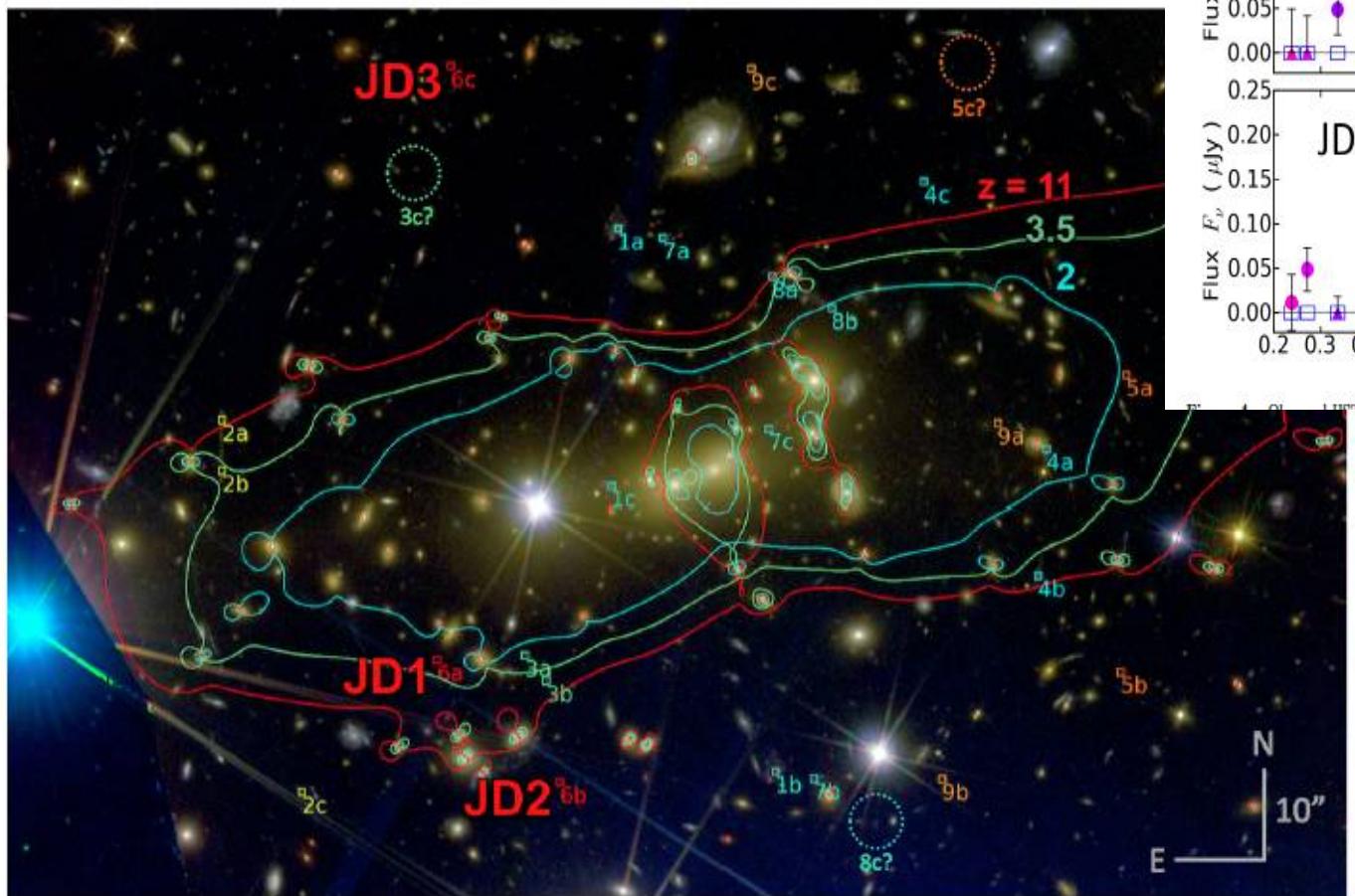
MACSJ1206-08

CLASH Cluster Sample			
Cluster name	Redshift	Cluster name	Redshift
Abell 383	0.187	MACSJ0429-02	0.399
Abell 209	0.206	MACSJ1206-08	0.440
Abell 1423	0.213	MACSJ0329-02	0.450
Abell 2261	0.224	RXJ1347-1145	0.451
RXJ2129+0005	0.234	MACSJ1311-03	0.494
Abell 611	0.288	MACSJ1149+22	0.544
MS 2137-2353	0.313	MACSJ1423+24	0.545
RXJ1532+30	0.345	MACSJ0717+37	0.548
RXJ2248-4431	0.348	MACSJ2129-07	0.570
MACSJ1931-26	0.352	MACSJ0647+70	0.584
MACSJ1115+01	0.352	MACSJ0744+39	0.686
MACSJ1720+35	0.391	CLJ1226+3332	0.890
MACSJ0416-24	0.396		

# Candidate at $z \sim 11$ behind CLASH MACSJ0647.7

Coe et al. 2013

3 images of the same source

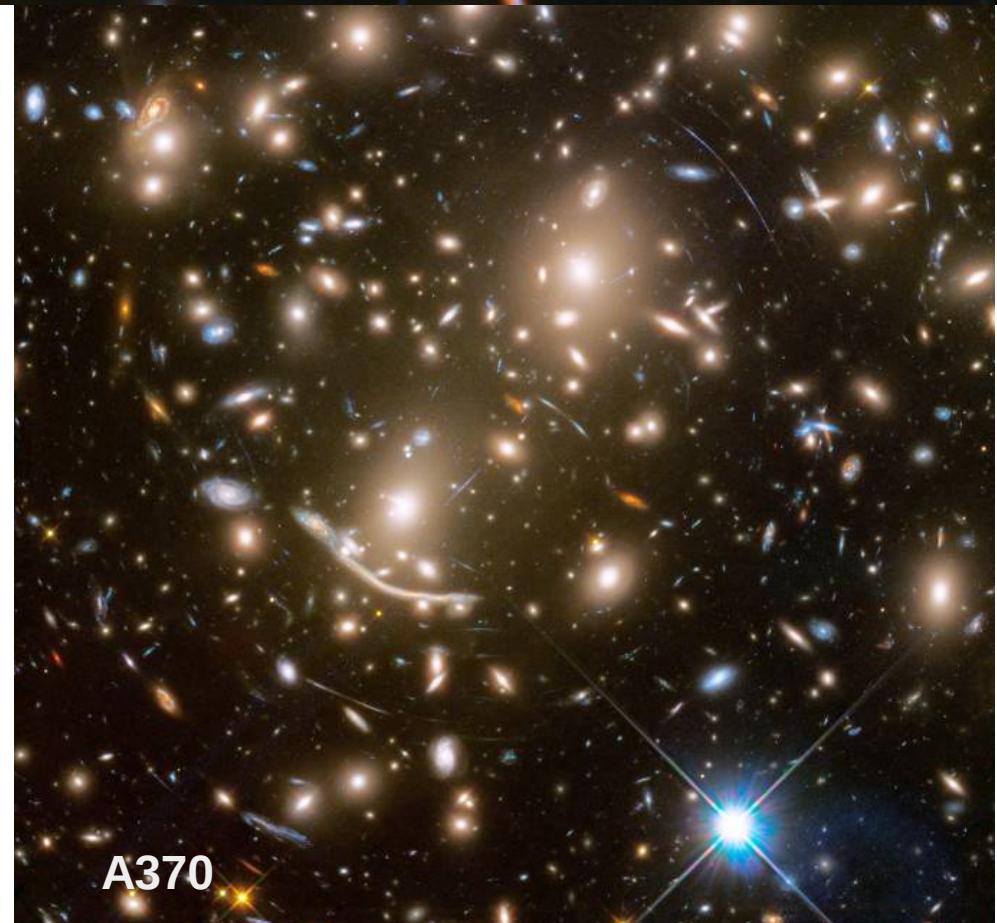


# Hubble Legacy Surveys – lensing clusters

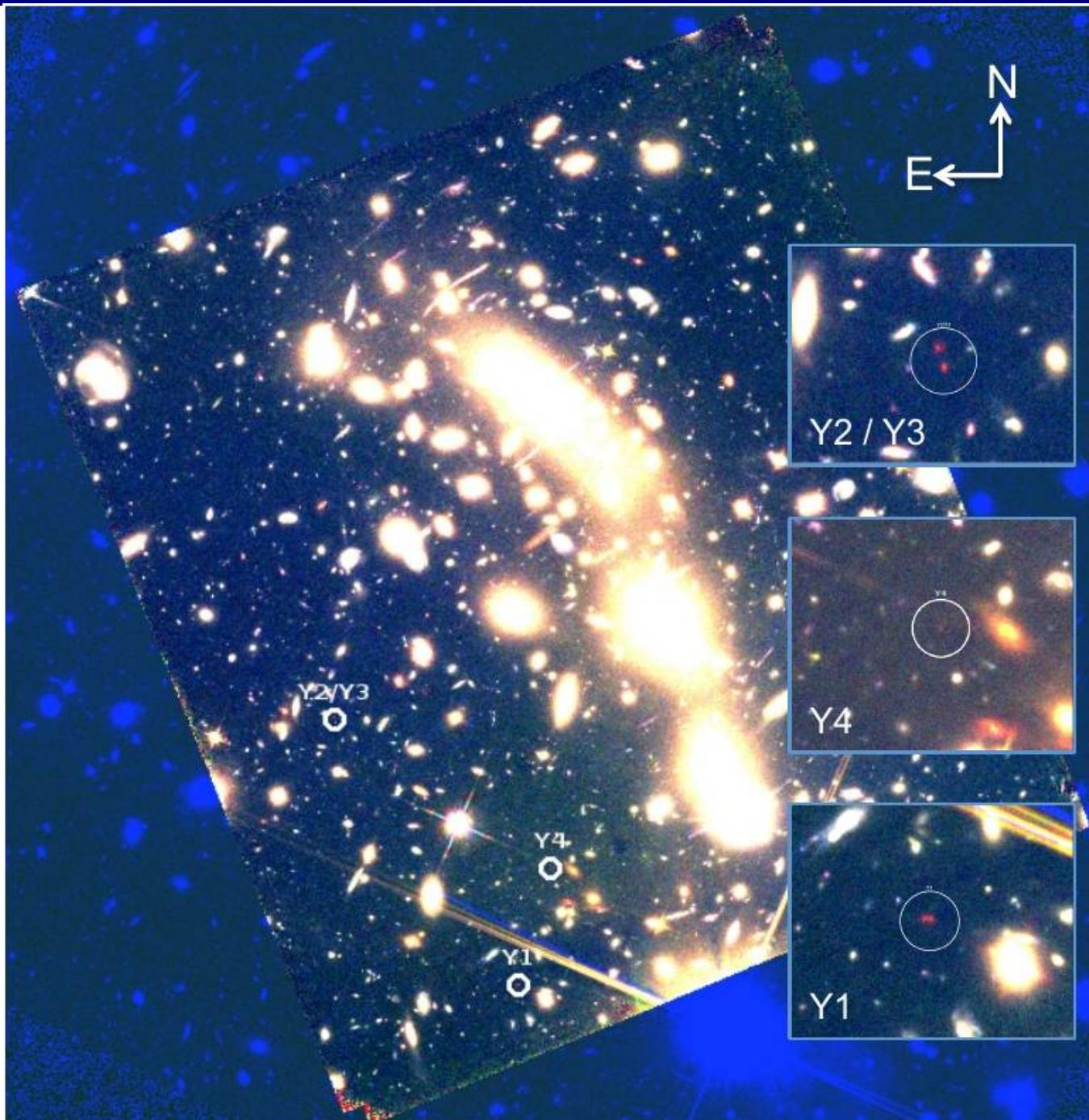


- **Hubble FF:** 2013-2017
- 6 clusters
- 7 filters, deeper than CLASH ! ( $m \sim 28.5$ - $29$ )
- $Z(\text{clusters}) \sim 0.3 \text{ à } 0.55$

Cluster Name	$z$
Year 1:	
Abell 2744	0.308
MACSJ0416.1-2403	0.396
Year 2:	
MACSJ0717.5+3745	0.545
MACSJ1149.5+2223	0.543
Year 3:	
Abell S1063 (RXCJ2248.7-4431)	0.348
Abell 370	0.375

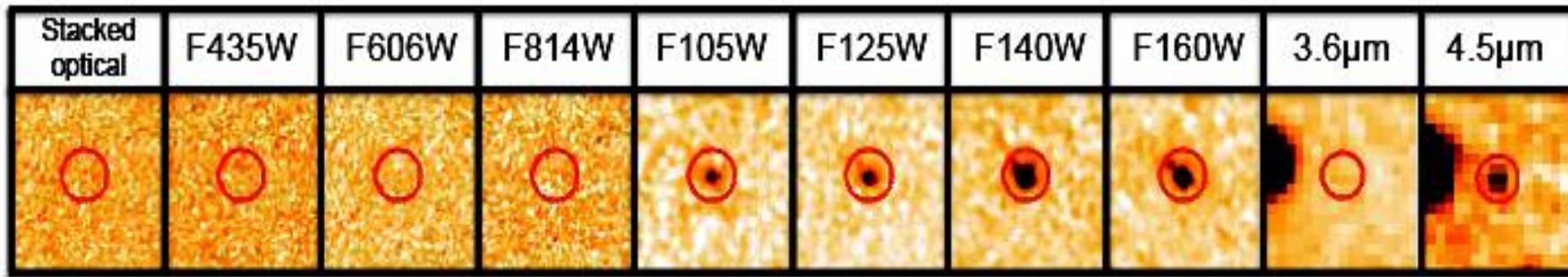


# 3 Candidates at z~8 behind MACS0416-2403

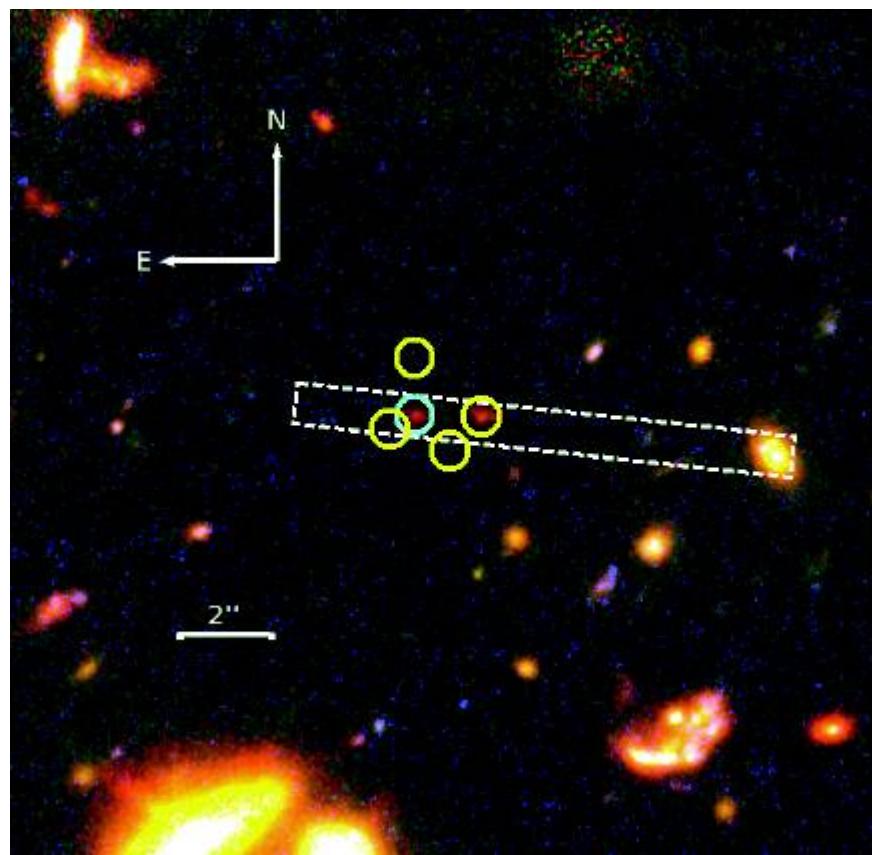


Laporte et al. 2015

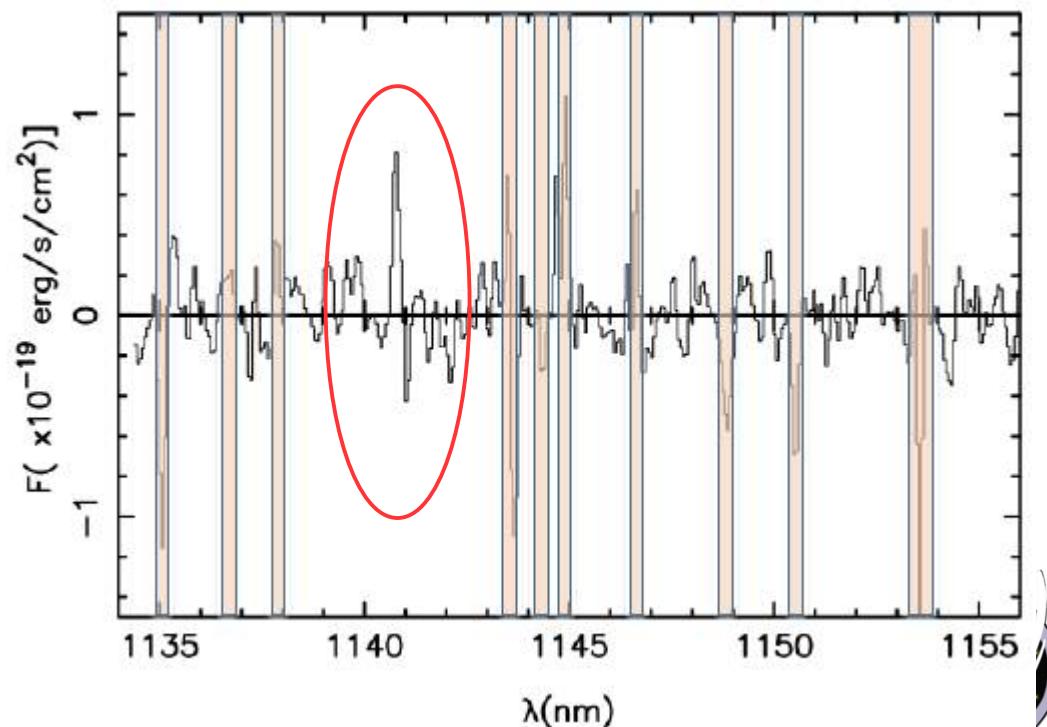
# Candidate at z~8 behaind A2744



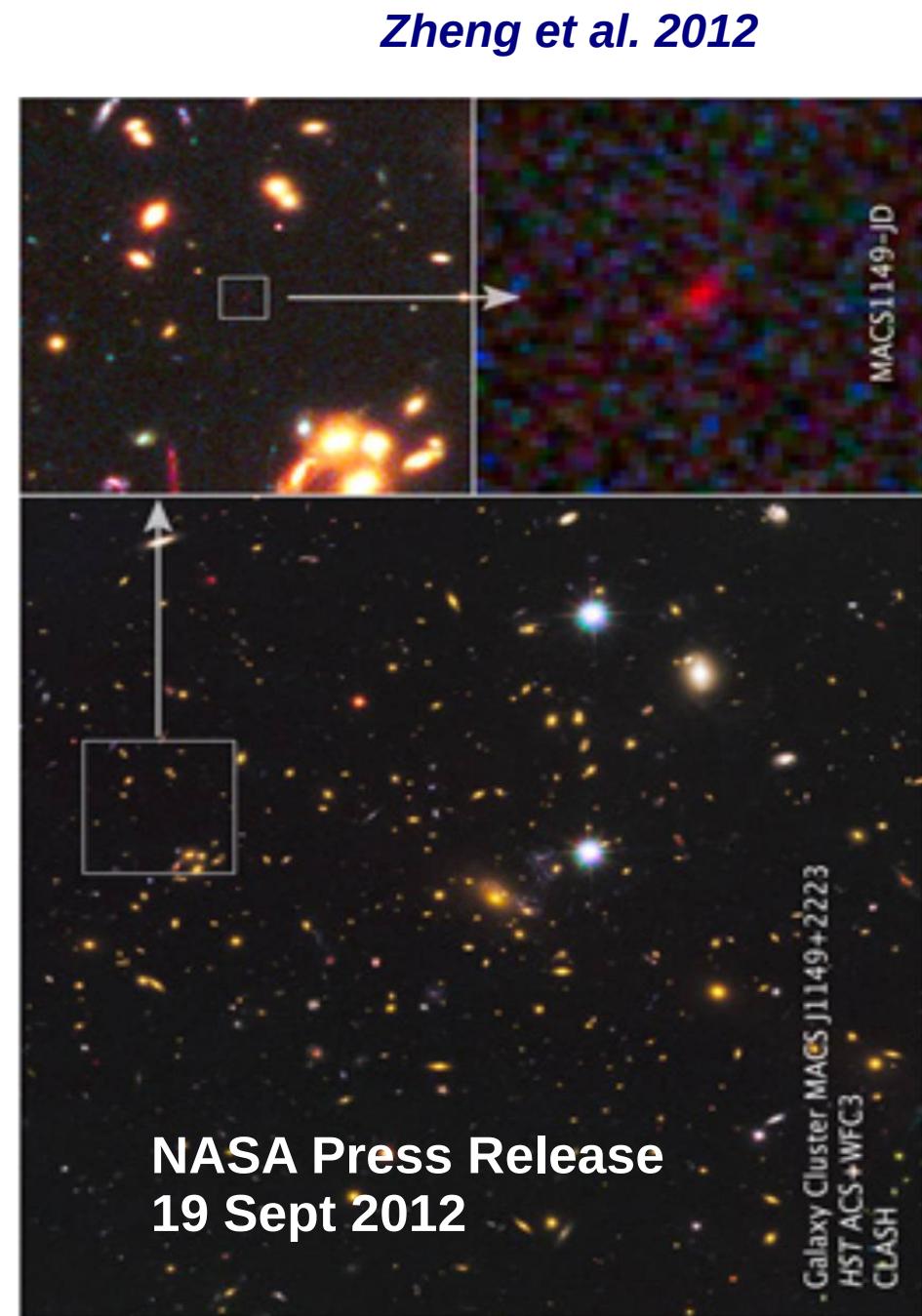
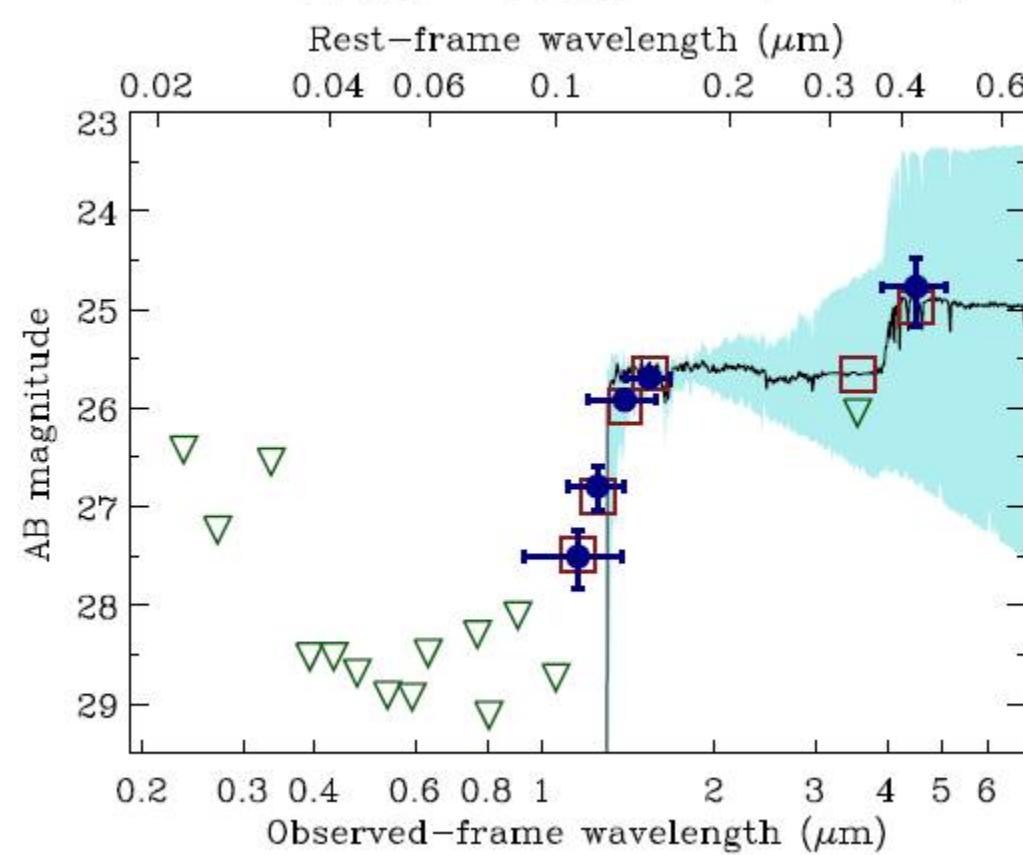
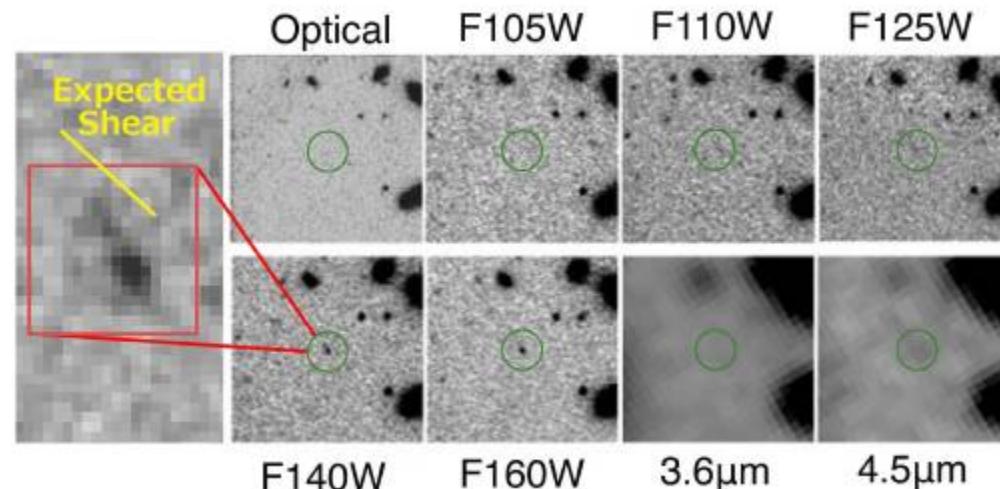
Laporte et al. 2014, 2017



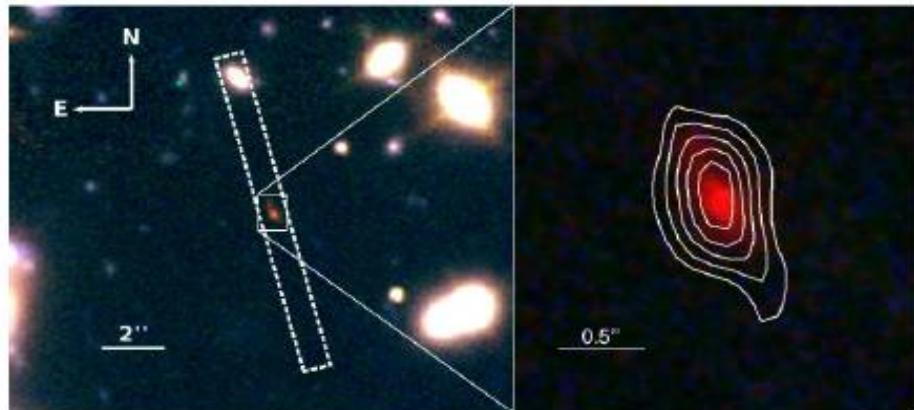
- Confirmation spectroscopique à  $z=8.38$  avec X-Shooter/VLT et ALMA



# Candidate z~9.6 behind MACSJ1149.6+22



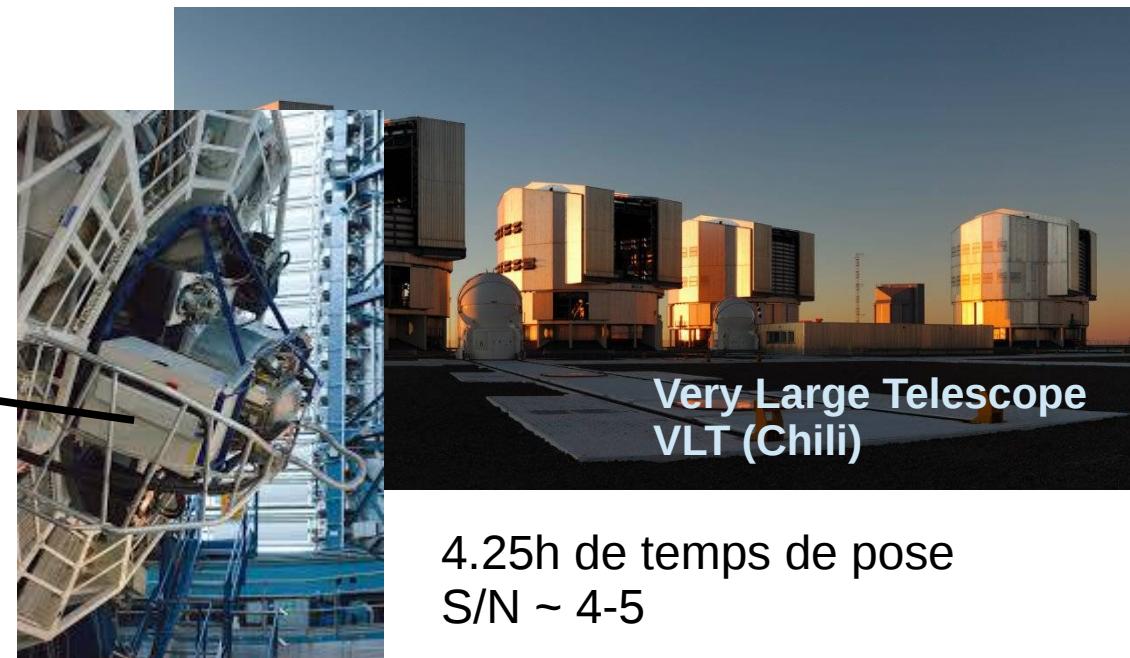
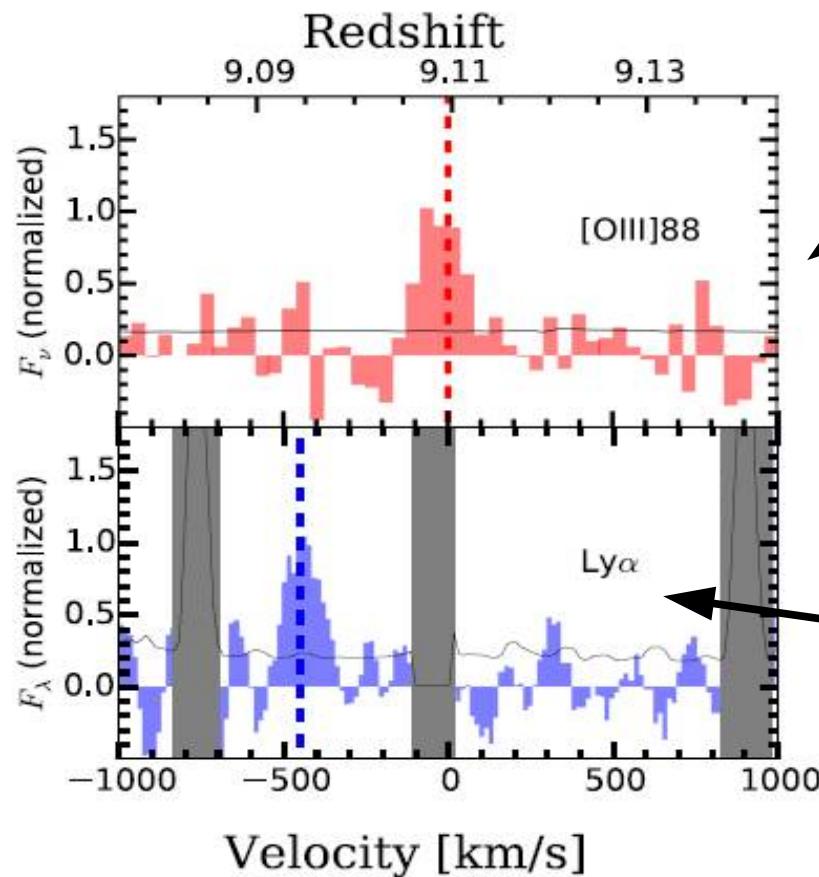
# MACSJ1149.6+22-JD1, confirmed at z=9.1 !



*Hashimoto, Laporte et al., Nature 2018*



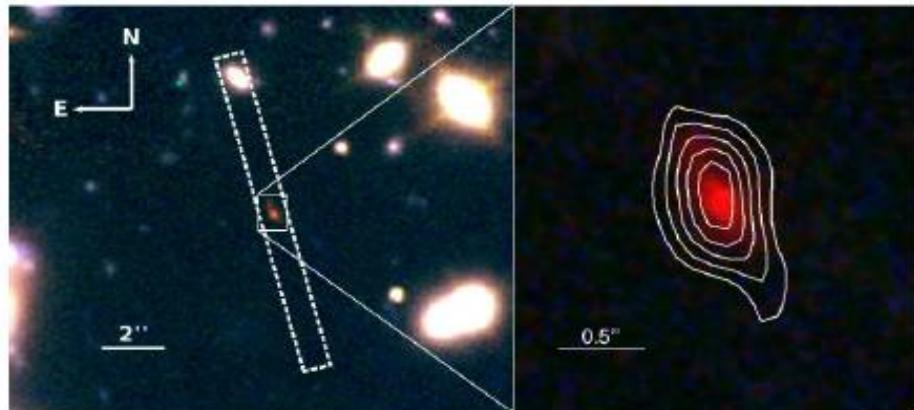
ALMA (Chili)



Very Large Telescope  
VLT (Chili)

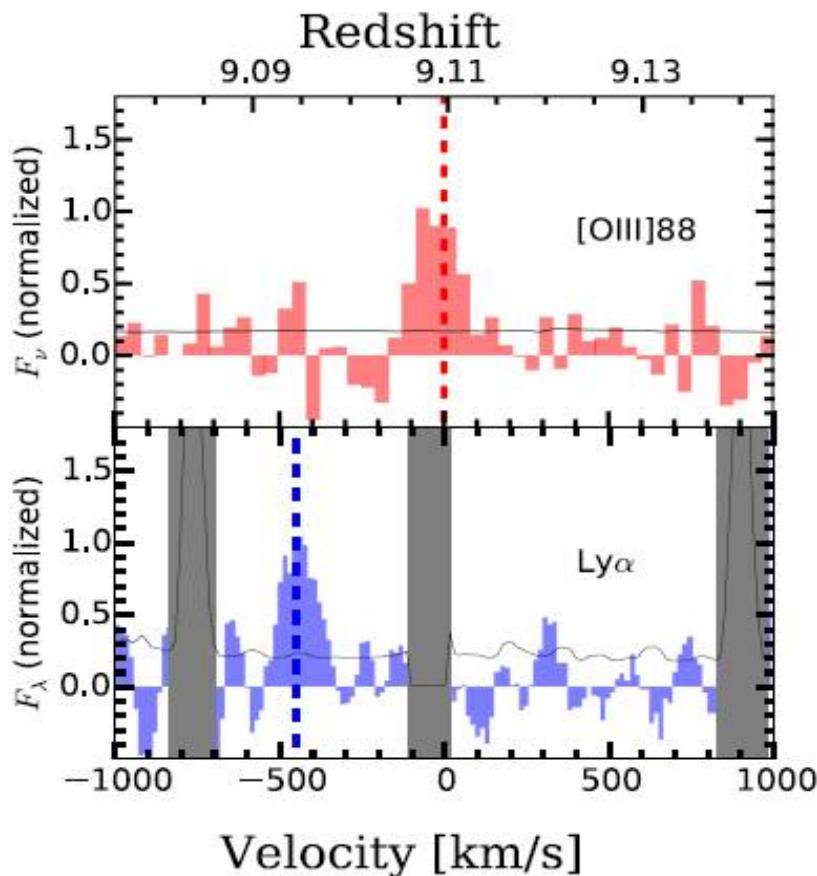
4.25h de temps de pose  
S/N ~ 4-5

# MACSJ1149.6+22-JD1, confirmed at z=9.1 !

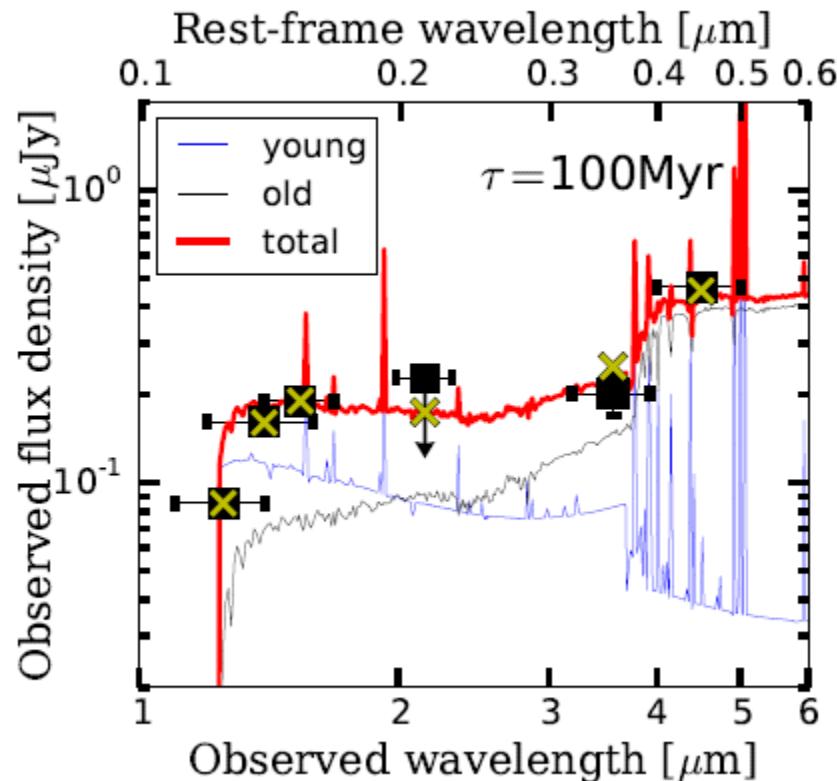


*Hashimoto, Laporte et al., Nature 2018*

Size <sub>[OIII]</sub> ( $\text{''}$ )	$(1.2 \pm 0.1) \times (0.8 \pm 0.1)^a$
Stellar mass [ $10^9 M_\odot$ ]	$1.08^{+0.53}_{-0.18} \times (10/\mu)$
Star formation rate [ $M_\odot \text{ yr}^{-1}$ ]	$4.2^{+0.8}_{-1.1} \times (10/\mu)$
Dust mass ( $10^5 M_\odot$ )	$< 5.2 \times (10/\mu) \text{ (3}\sigma\text{)}^b$



*This object started to form stars at z~15 !*



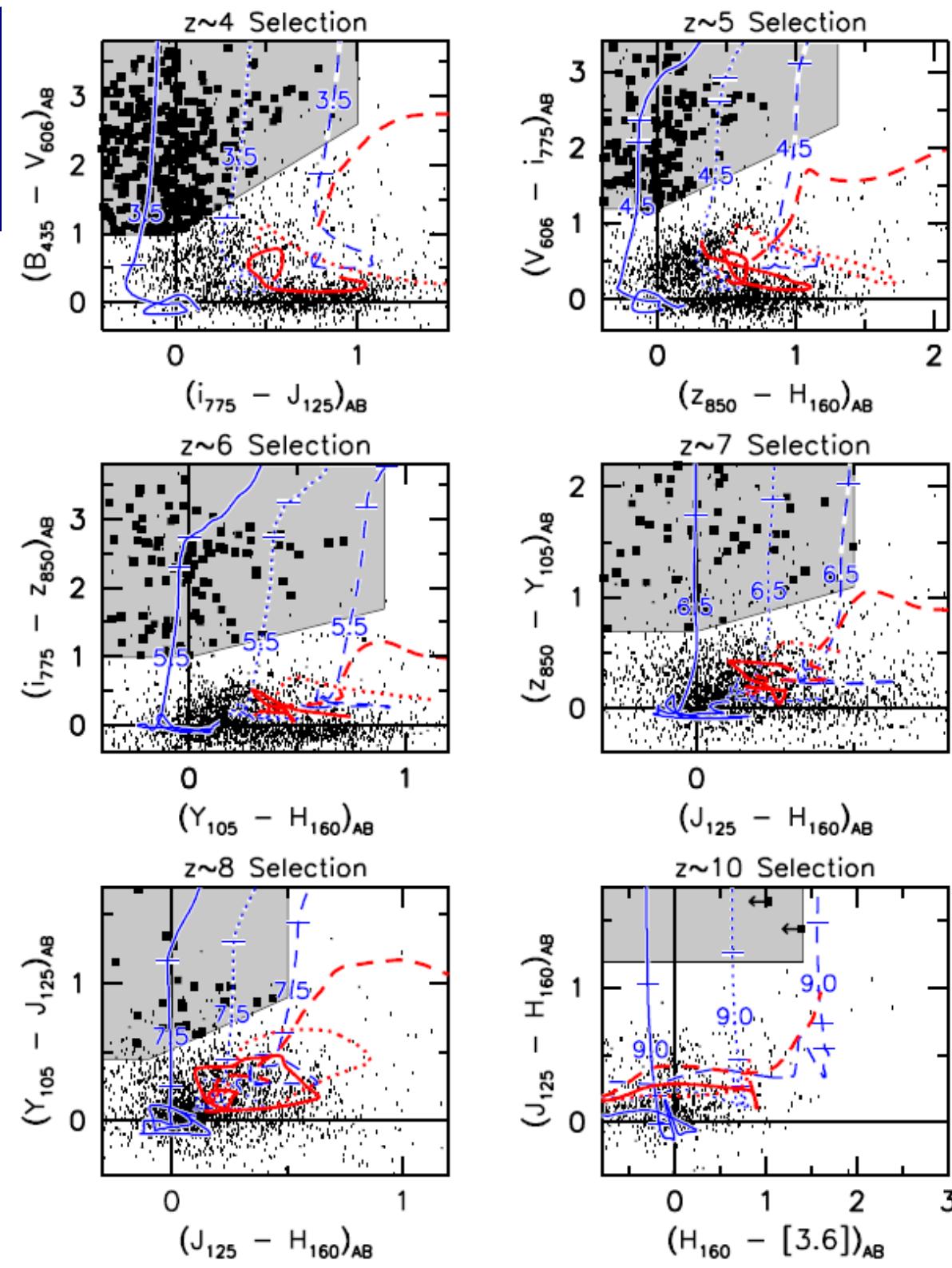
# LBG Surveys : UV Luminosity Function

- HST Legacy surveys :

- ➔ CANDELS,
- ➔ HUDF09,
- ➔ HUDF12,
- ➔ ERS
- ➔ BORG/HIPPIES

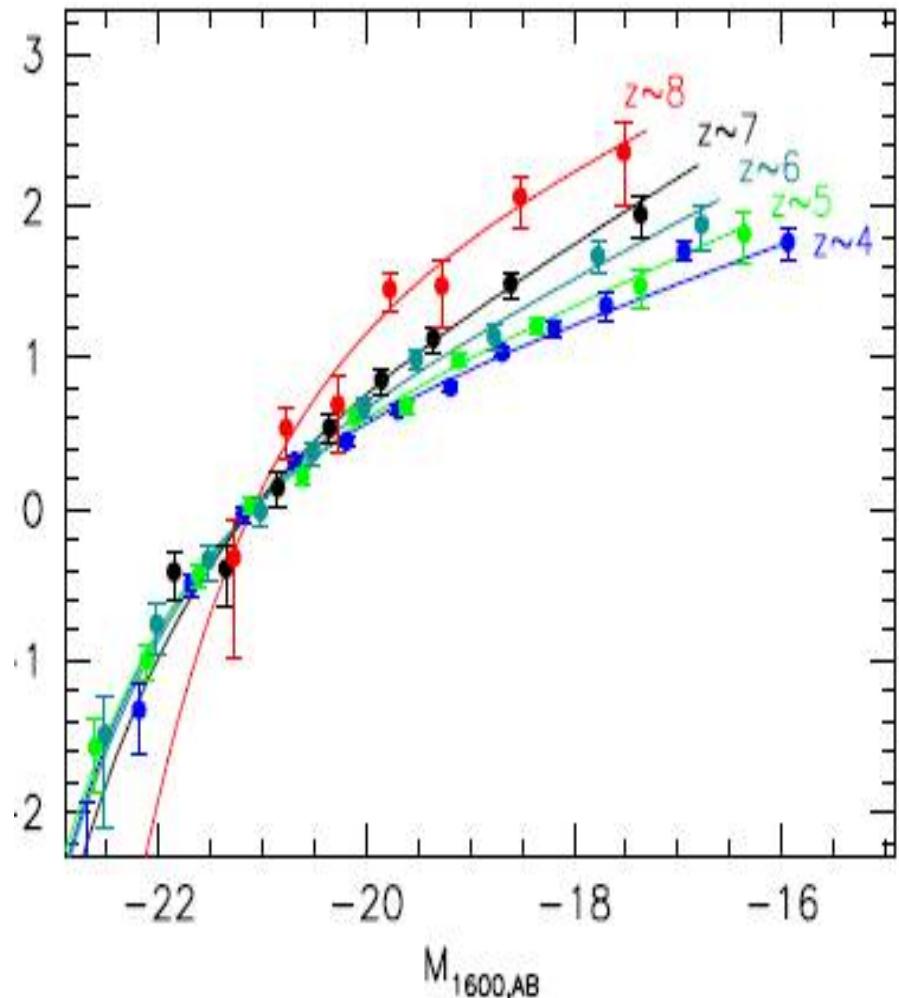
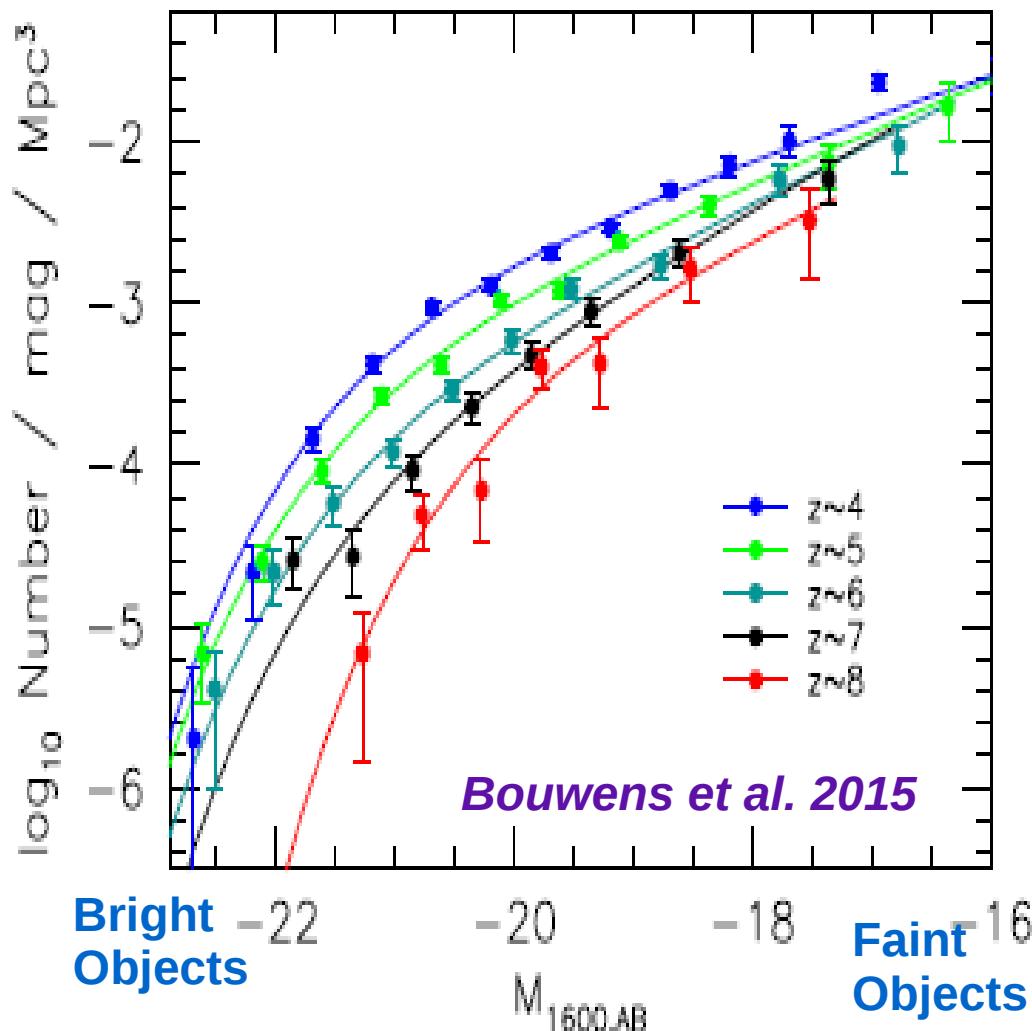
~1000 arcmin<sup>2</sup>

*Bouwens et al. 2015*

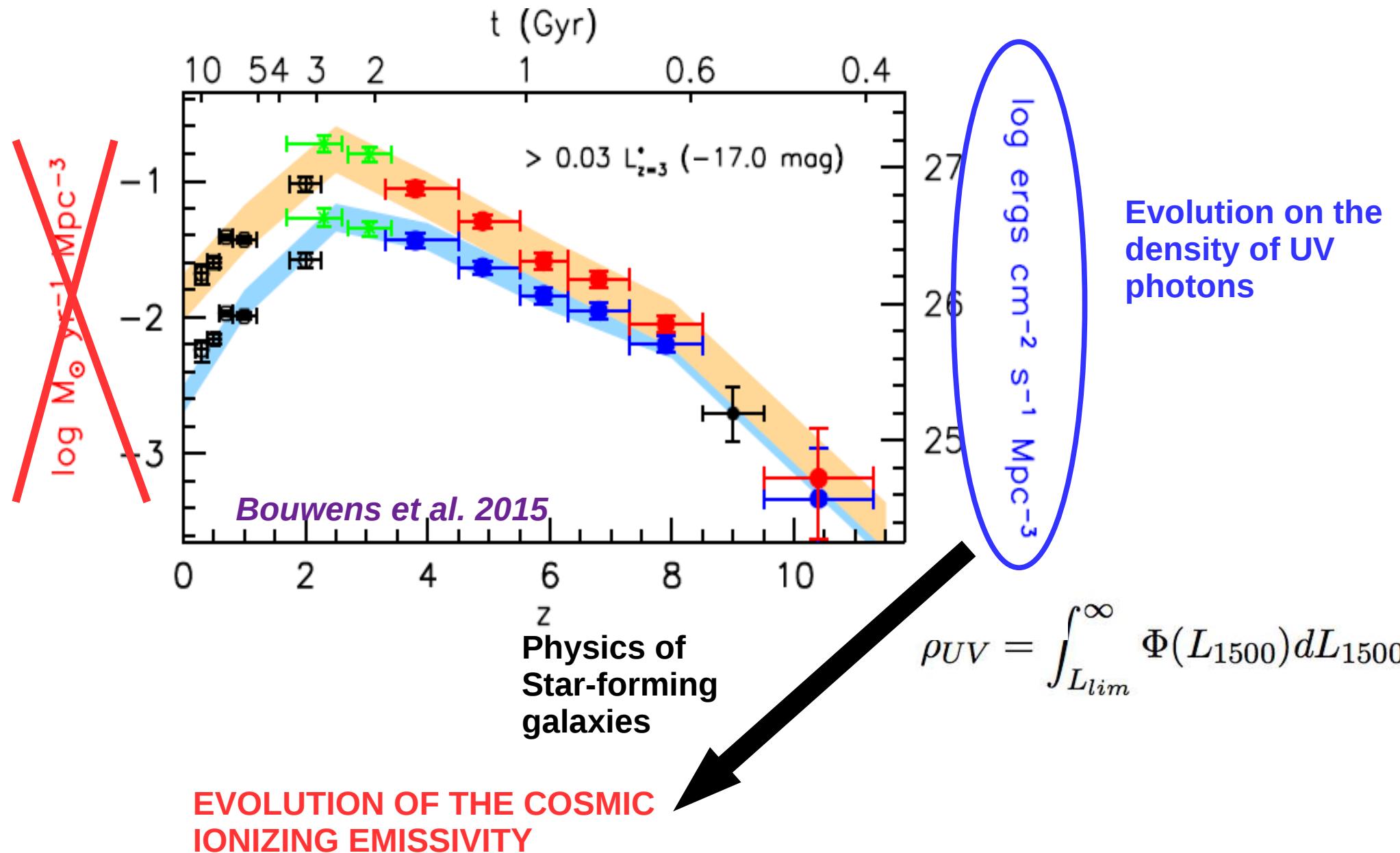


# LBG Surveys: Luminosity Function

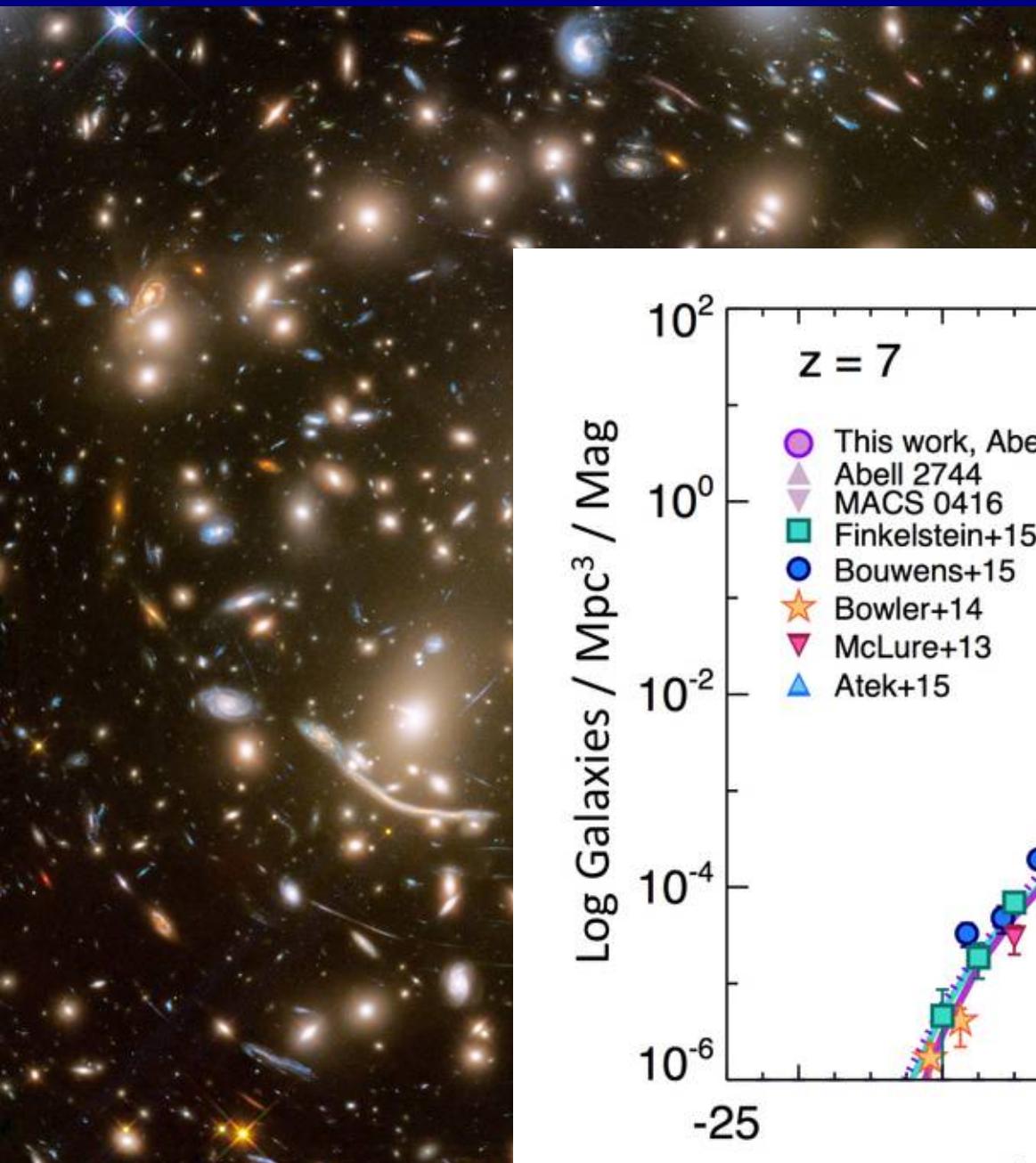
- There is a strong evolution in the luminosity distribution with redshift / age of the Univers
- At high-redshift « faint» galaxies dominate the LF. They could have a strong contribution to cosmic reionisation



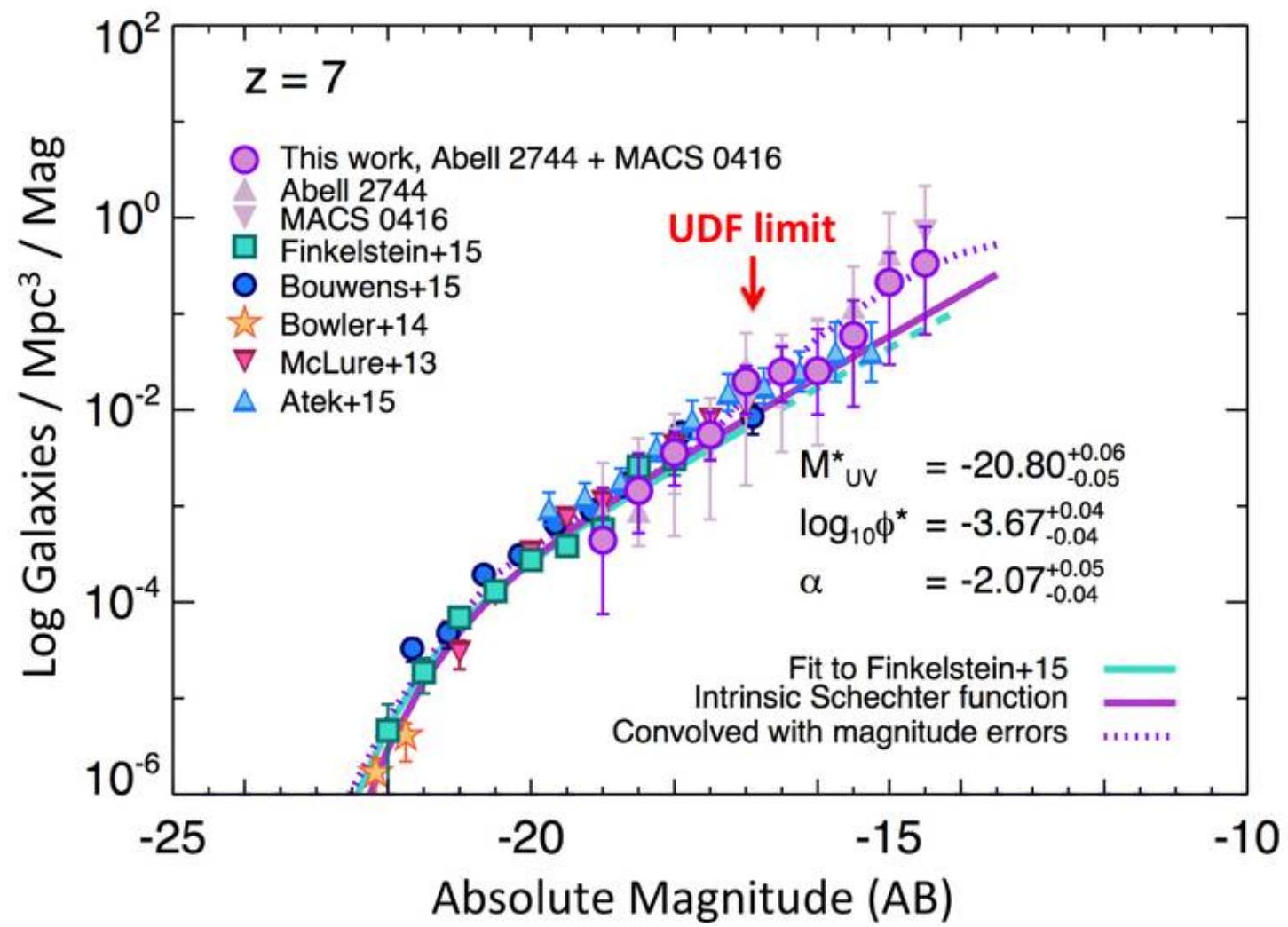
# Cosmic SF History



# LBG Surveys (Lensing Fields)



Coe+ 2016  
Hubble FF

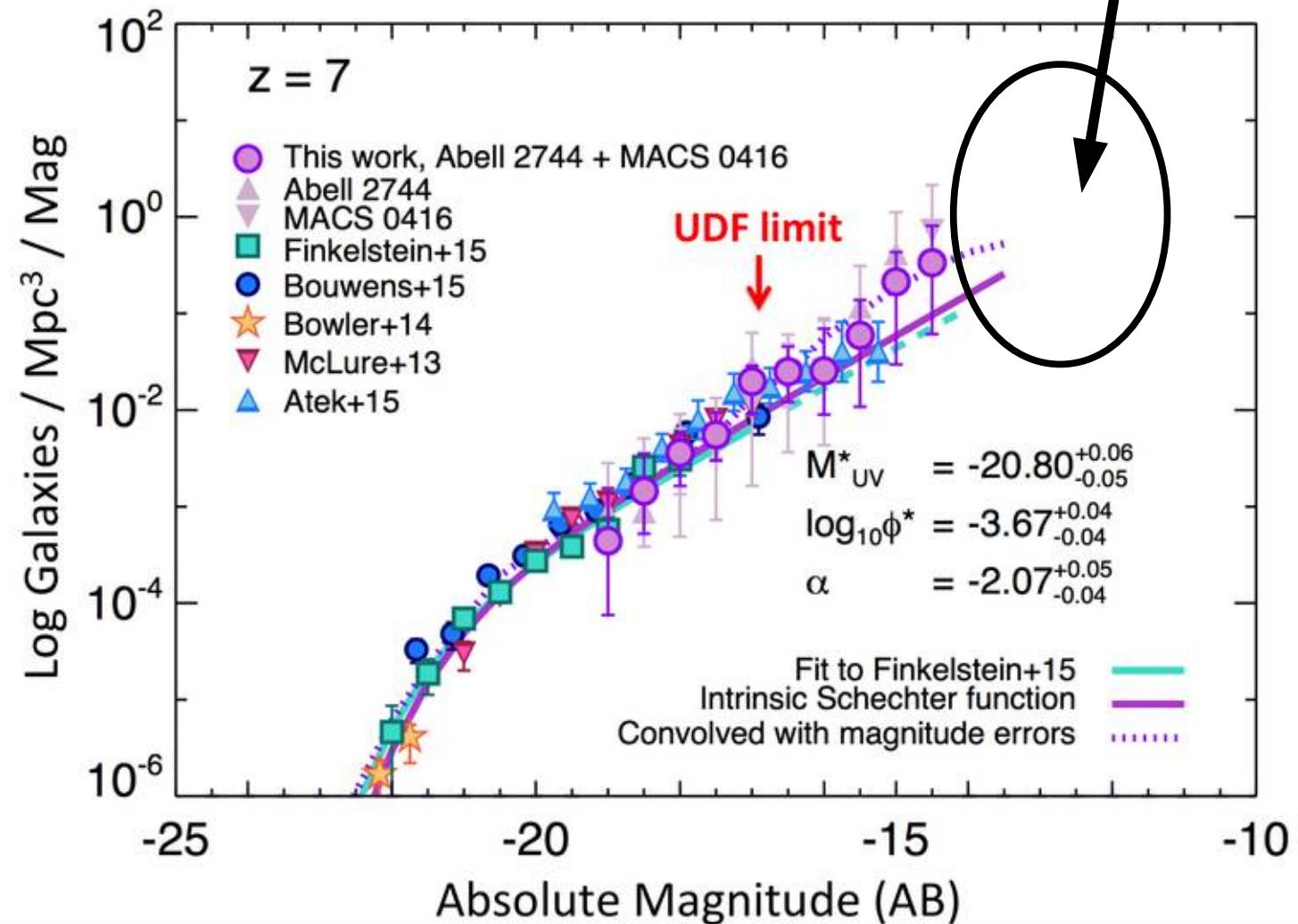


# LBG Surveys (Lensing Fields)



Coe+ 2016  
Hubble FF

Y a-t-il vraiment des  
objets aussi  
faibles ?



# Summary (I)

- Linear growth of small density fluctuations in the primeval universe, formation of halos in non-linear regime, deriving the expected number of halos as a function of DM halo mass & redshift is **relatively well understood** (numerical experiments & physically-motivated analytical models)
- Star & Galaxy formation processes involving (complex) baryon physics and feedback are much more problematic... Rapid evolution is expected in this field.
- It is likely that the first stars formed in the universe were “massive” (top-heavy IMF) ==> strong impact on early star-formation & radiation field. Rapid evolution of metal enrichment.
- Typical values for L\* galaxies at  $z > 8$  :  $M^* \sim \text{few } 10^7 - 10^8$  solar masses, sizes ( $\sim 100$  pc to 1 kpc), SFR (1-10 solar masses/yr), Lyman alpha fluxes ( $\sim \text{a few } 10^{-18} - 10^{-19}$  erg/cm<sup>2</sup>/sec), ... ==> **lensing fields are making a major contribution to this area!**

# Summary (II)

- A rapid evolution in the global properties of galaxies is expected at  $z \sim >8$ , and this trend is indeed observed (LF of LBGs & LAEs).
- Predictions are very sensitive to physical parameters used in simulations, in particular dust extinction, feedback, IMF, and SF regime (burst duration & strength). Degenerate solutions when only photometric “global” samples are used. Spectroscopy is needed to make progress.



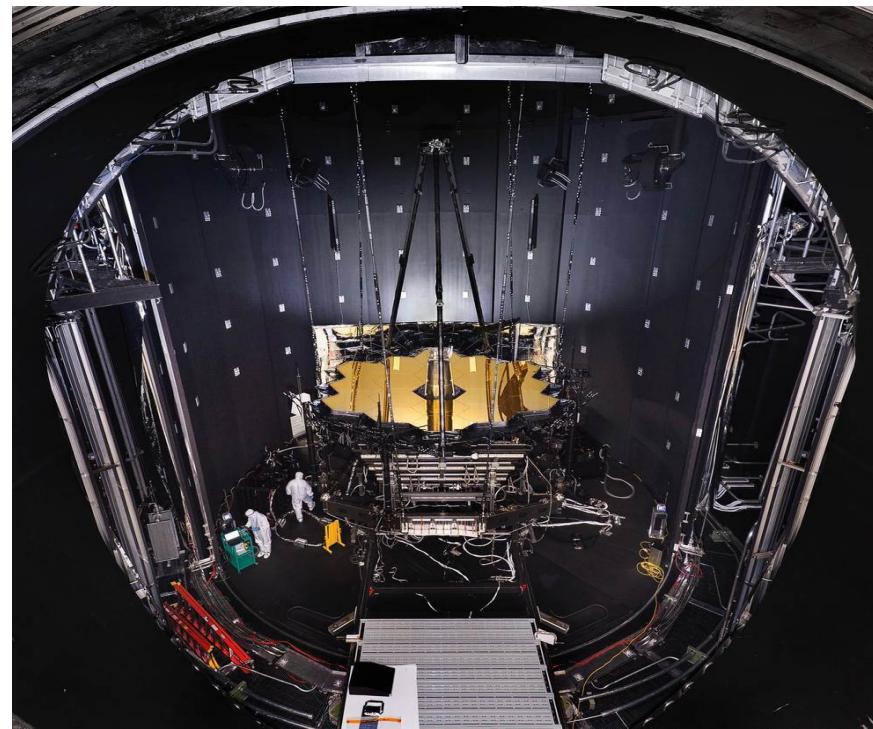
# Discussion : Other issues...

- Reionization scenarios discussed before, requiring appreciable star formation in small halos (e.g.  $M(\text{vir}) \sim 10^8$  solar masses at  $z \sim 8$ ) seem to be in **serious tension with galaxy counts in the Local Group** (Boylan-Kolchin et al. 2014).
- Implication : Star-formation **became inefficient in halos smaller than  $\log(M) \sim 9$  at early epochs** ==> the LF must break at  $M(\text{UV})$  brighter than -14 (as usually assumed), and star formation efficiency must increase to keep the universe reionized.
- Ionizing emissivity depends on the **physical parameters of star-forming galaxies** (e.g. star-formation history, ...), and is is (still) poorly constrained.
- Detailed multi-wavelength (e.g. with ALMA) AND spectroscopic studies at the depth of JWST or HST Frontier Fields (lensing) is needed to conclude... ( $m(\text{AB}) \sim 32$ )

# Perspectives : James Webb Space Telescope

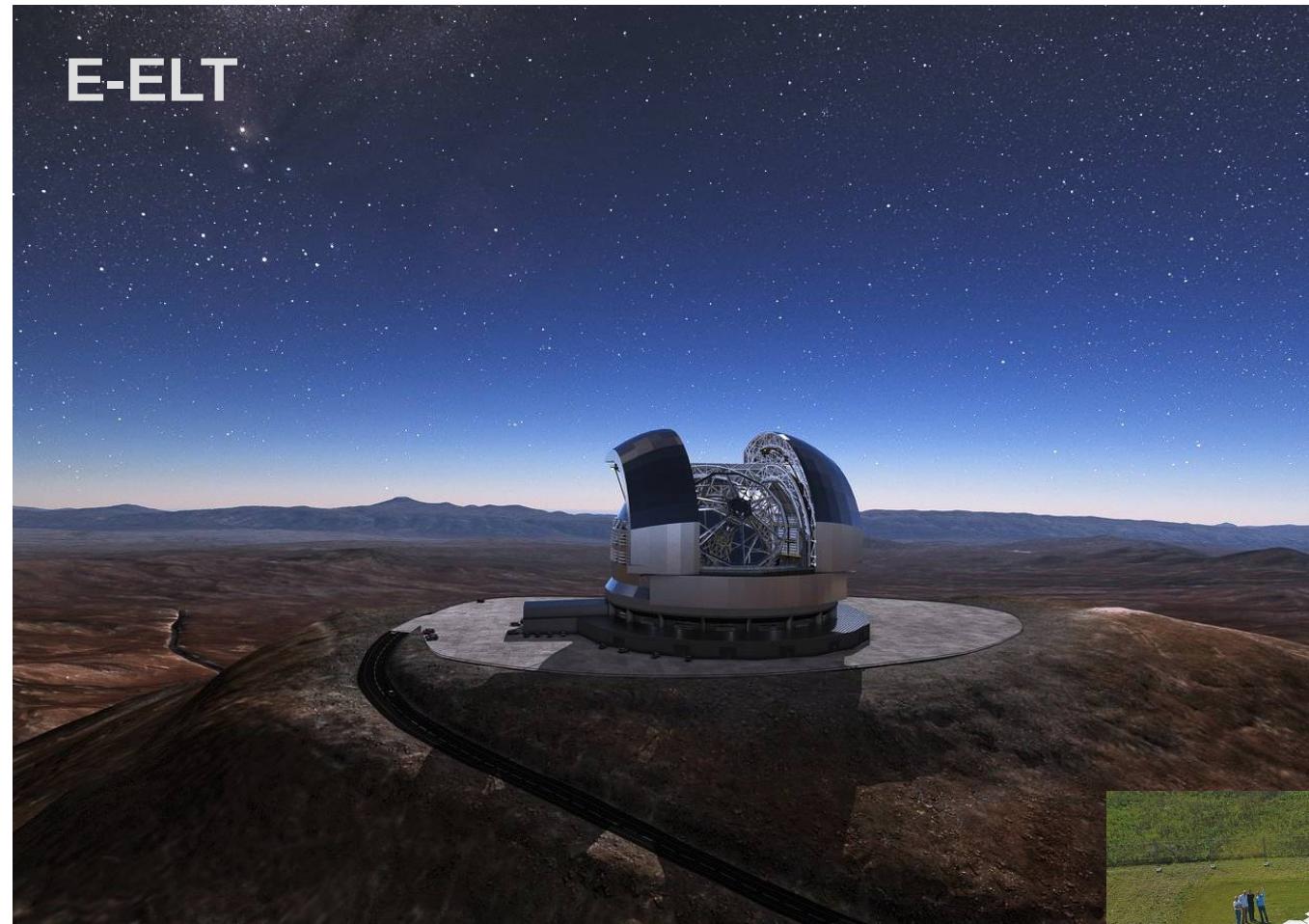


- Télescope spatial de nouvelle génération : **6.5 m** de diamètre
- Remplacera le Hubble Space Telescope en automne 2021 pour une mission de 5 – 6 ans.
- Observe surtout dans l'IR ⇒ idéal pour étudier les premières galaxies



# Perspectives : E-ELT

E-ELT



- Télescope géant Européen : 39 m de diamètre
- Date de mise en service : 2024
- Cerro Armazones (Chili)



# Merci!

