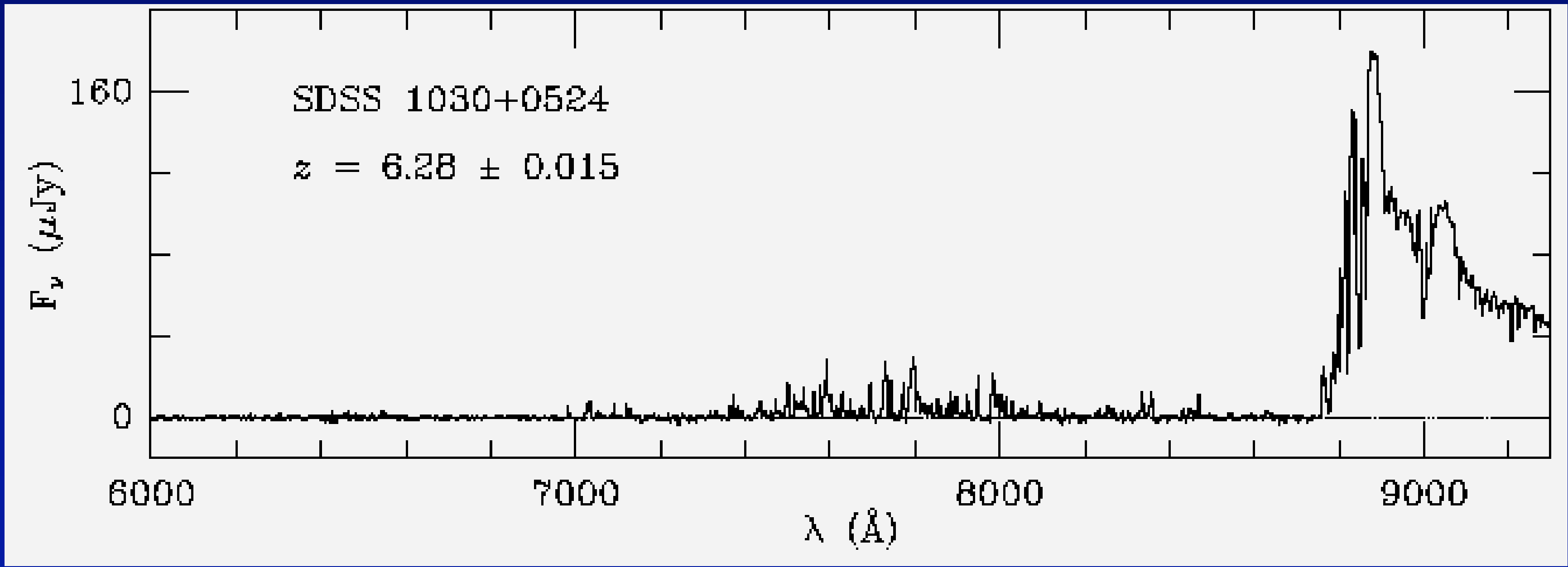

Sources of Ionization
of the Intergalactic Medium
in the Early Universe
[aka The IGM "reionization"]
Nino Panagia
(STScI/INAF/Supernova Ltd)

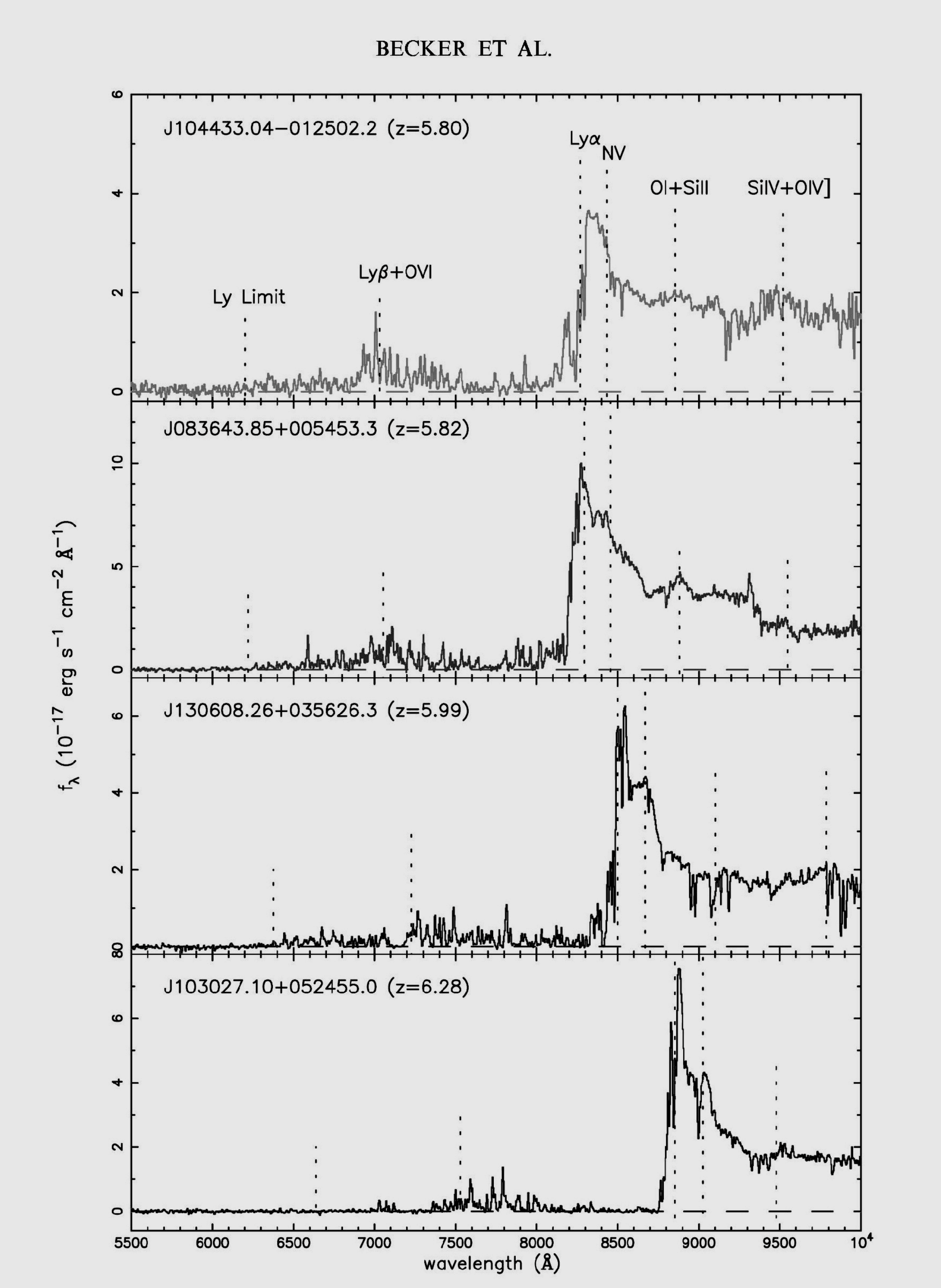

Mostly based on work done
in collaboration with:
Tommy Wiklind
Massimo Stiavelli
Bahram Mobasher
Mike Fall
& the GOODS Team

We know that the Universe is not quite ionized at redshift z=6.28

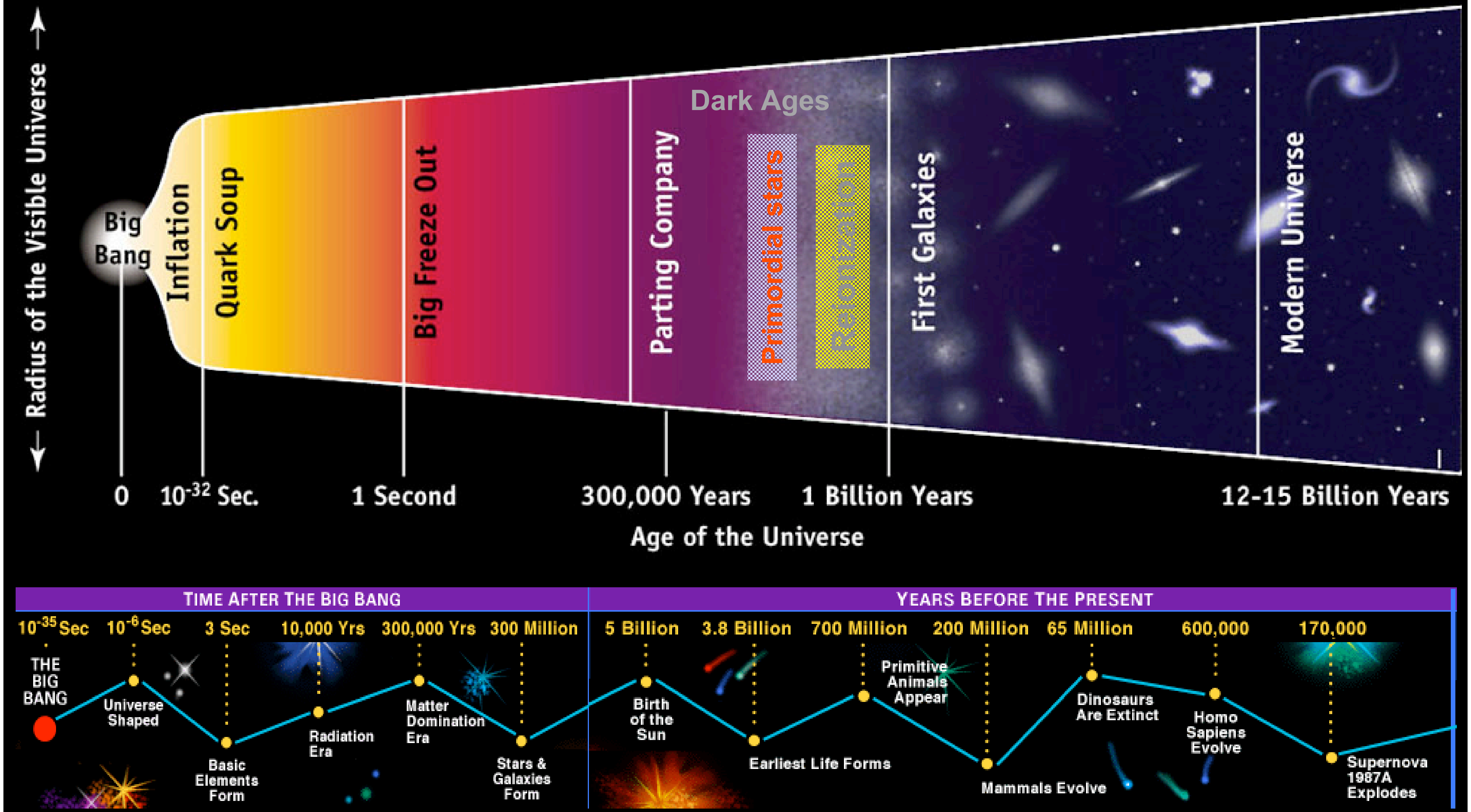


Becker et al. (2001)

Becker et al (2001): The full story

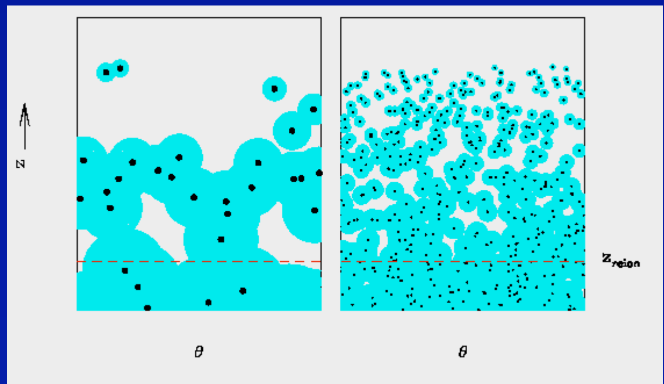


A concise history of the Universe

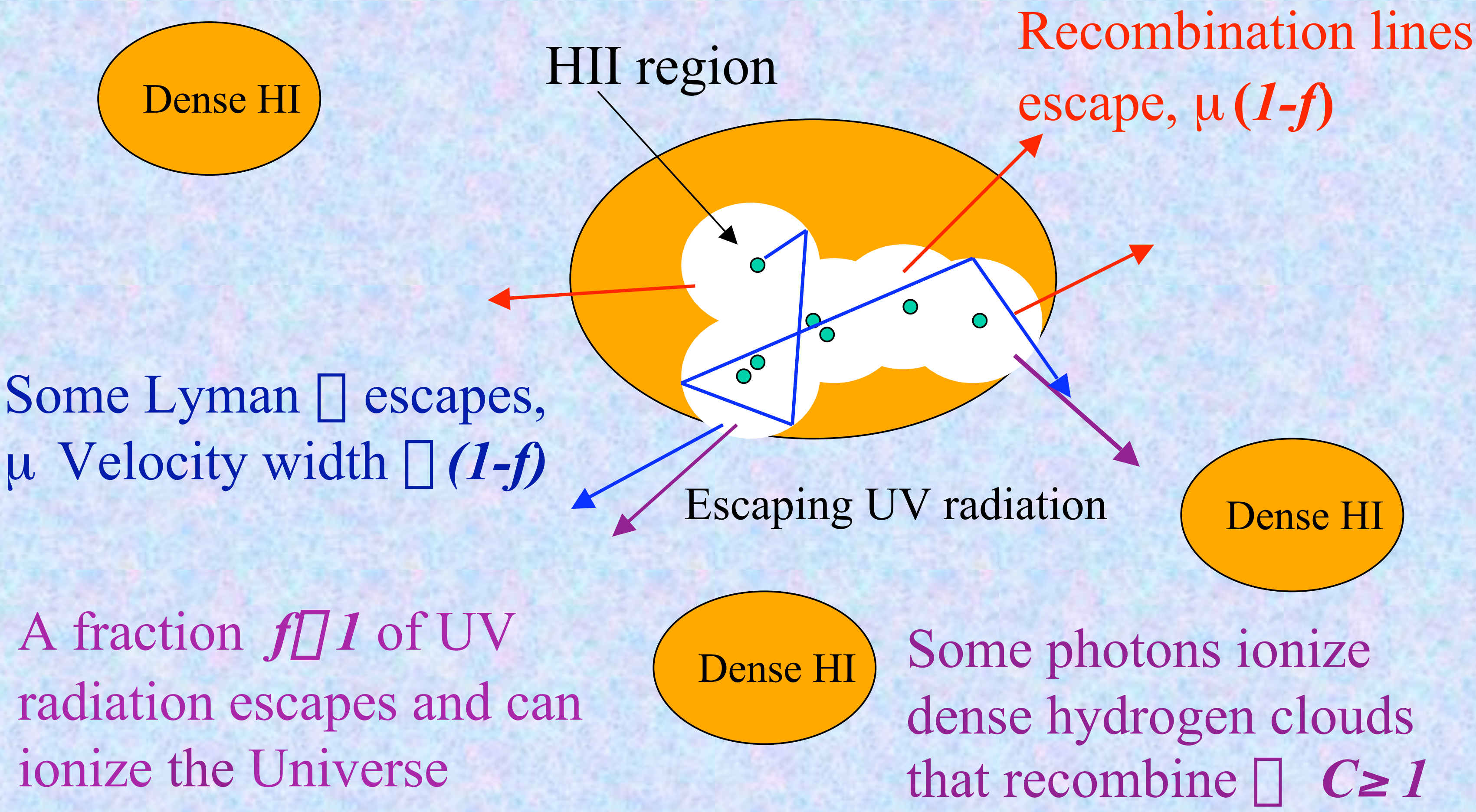


<u>Basic processes</u>

- Review by Barkana & Loeb, Phys. Reports (2001)
- Ionizing UV radiation origin: either *<u>fusion</u>* (pop III and II) or *<u>gravitational energy</u>* (QSO, AGN, BH)
- If fusion, each hydrogen atom releases 7 MeV but requires 13.6 eV to be ionized→ a mass fraction 0.2×10^{-5} undergoing fusion is sufficient to re-ionize all hydrogen (in practice the required mass in stars is 10-100 times larger)
- Different lines of sight may look very different (e.g. QSOs at 6.28 and 6.43).



Let's estimate the luminosity of reionization sources from first principles



The Principles of Reionization (RI)

- ***Reionization requires sources of Lyman continuum photons***

- ***Reionization depends primarily on the UV output of the RI sources integrated over time***

- ***Reionization is a function of the UV photon escape fraction, f, from the RI sources and the clumpiness of the IGM***

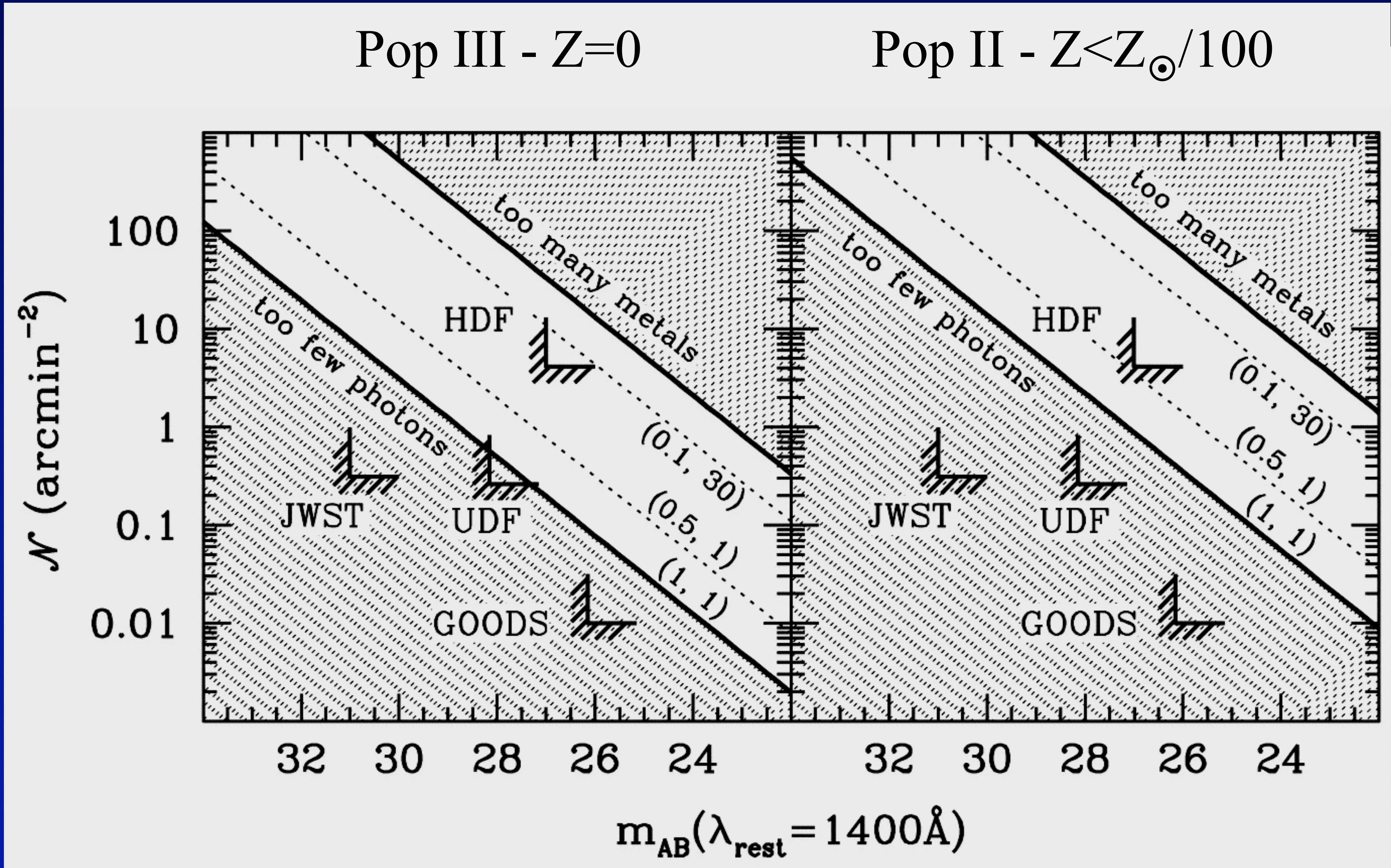
$$\langle Q \rangle \;=\; \langle M_{HI} \rangle \;\_\; f^{-1} \;\_\; B(z_1,z_2,C)$$

Ly-c photons	HI mass = □$_{HI}$ _Volume	escape fraction	photons needed per ionization

Recognizing the Reionization Agents

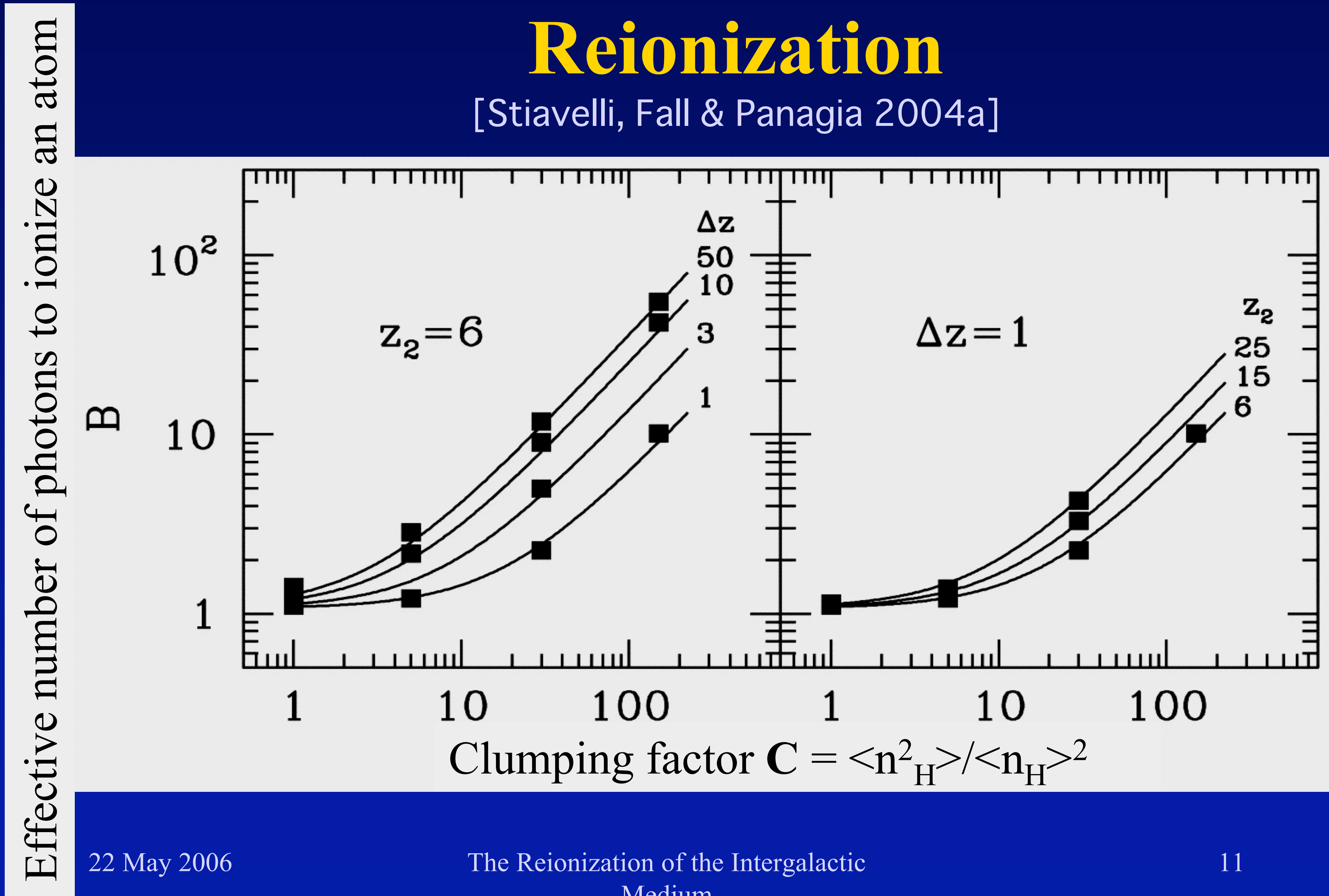
- **(Young Bright) Galaxies at z>6.5**
  are doing it
- **(Evolved Massive) Galaxies at z<6.5**
  have done it
- **Together they define**
  the process of Reionization

Reionization constraints for identical sources



The effect of the IGM clumping on Reionization

[Stiavelli, Fall & Panagia 2004a]



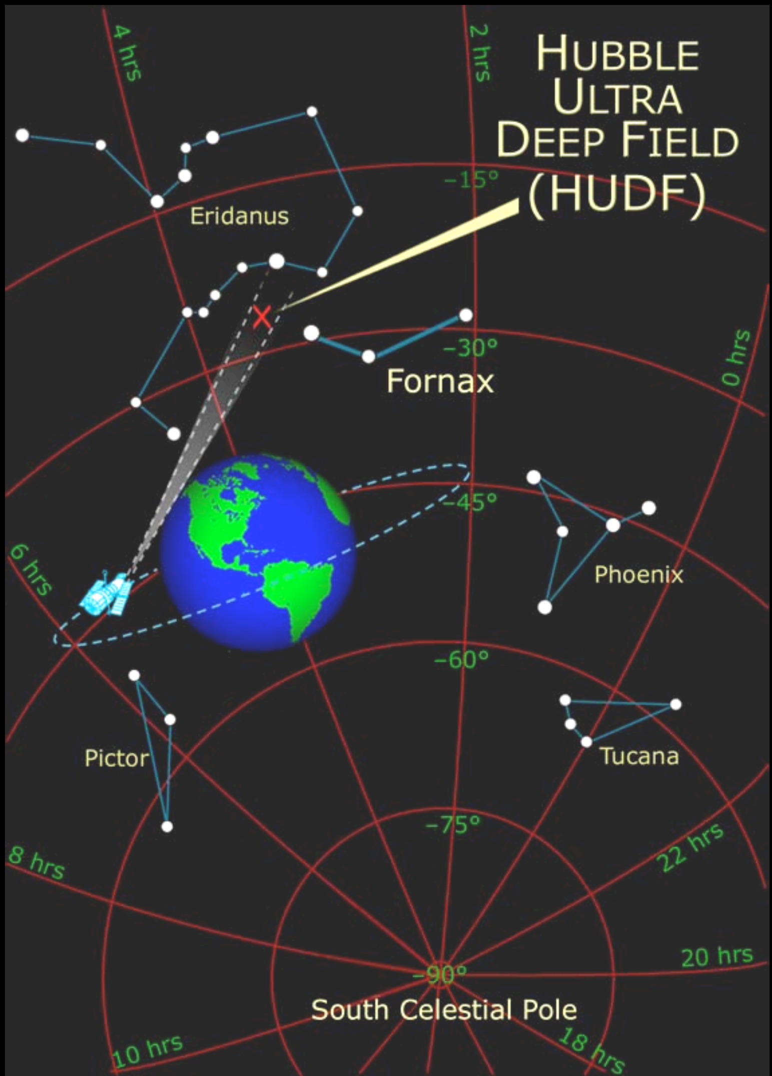
Can we detect the Sources of Reionization NOW?

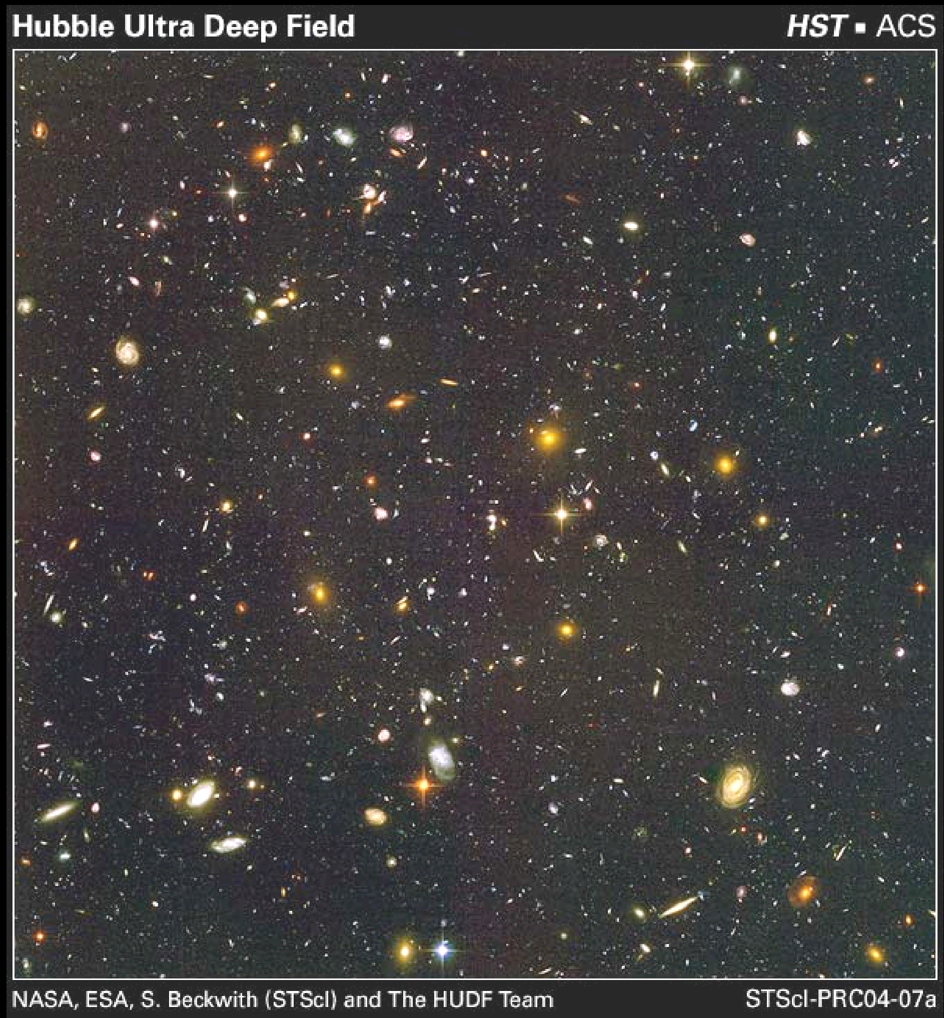
It is not easy…

but it can be done!

Let's interrogate the sky:

The **H**ubble **U**ltra-**D**eep **F**ield





The HUDF Team

Home Team

- **Steven Beckwith – Principal Investigator**
- **Massimo Stiavelli – Home Team Lead**
- Anton Koekemoer – ACS Analysis Lead
- John Caldwell – ACS Analysis
- Massimo Robberto – NICMOS Analysis Lead
- Megan Sosey – NICMOS Analysis
- Richard Hook – Main software "guru"
- Harry Ferguson – Advisor at large
- Michael Corbin – Archive liaison
- Ray Lucas – Parallel fields
- Tricia Royle – Program Scheduling
- Shardha Jogee – ACS Team liaison
- **Nino Panagia – HUDF "Jiminy Cricket"**

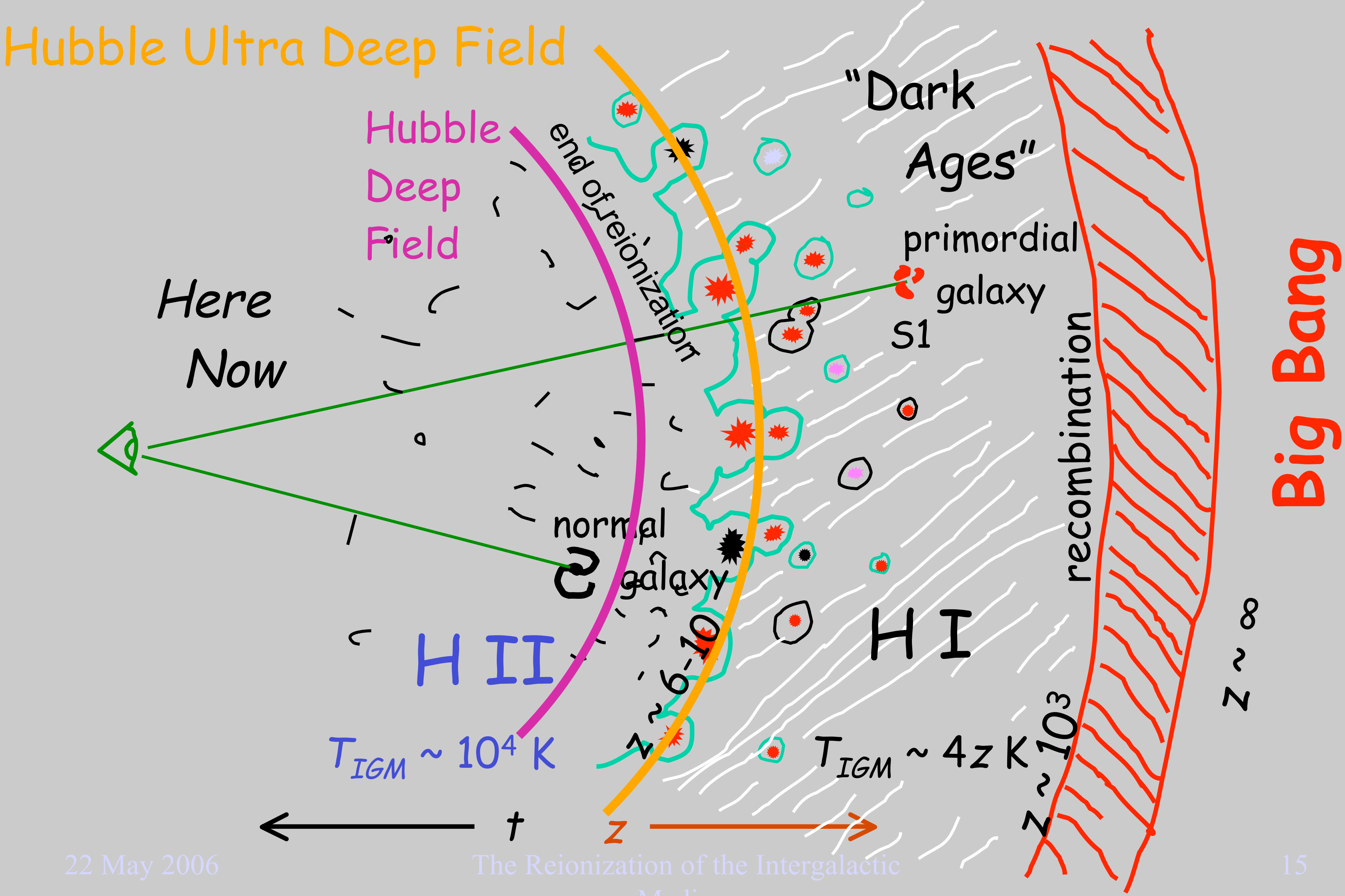
and:

Chris Blades, Stefano Casertano, Mark Clampin, Mark Dickinson, Andy Fruchter, Sangeeta Malhotra, Bruce Margon, Mauro Giavalisco, Alan Patterson, James Rhoads, Rachel Somerville

Scientific Advisory Committee

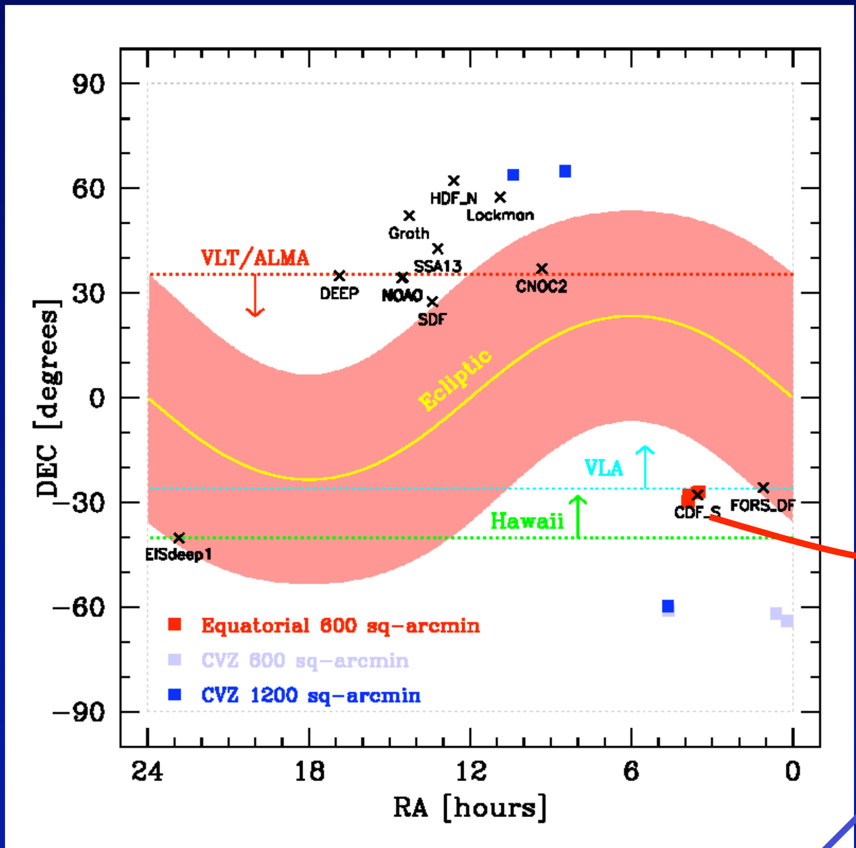
- Ron Ekers, CSIRO
- Catherine Cesarsky, ESO
- Guenther Hasinger, MPE
- Garth Illingworth, UCSC
- Jeremy Mould, NOAO
- Matt Mountain, Gemini
- Anneila Sargent, Caltech
- Tom Soifer, Caltech
- Harvey Tannenbaum, CFA
- Bob Williams, STScI
- Rogier Windhorst, ASU

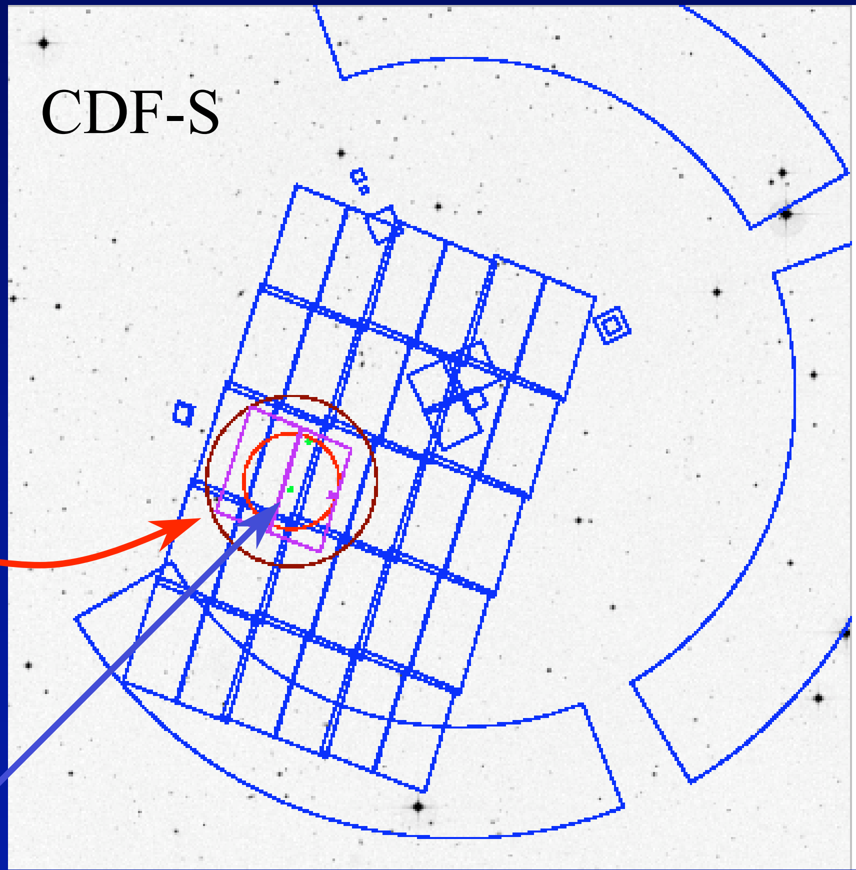
The Renaissance after the Dark Ages



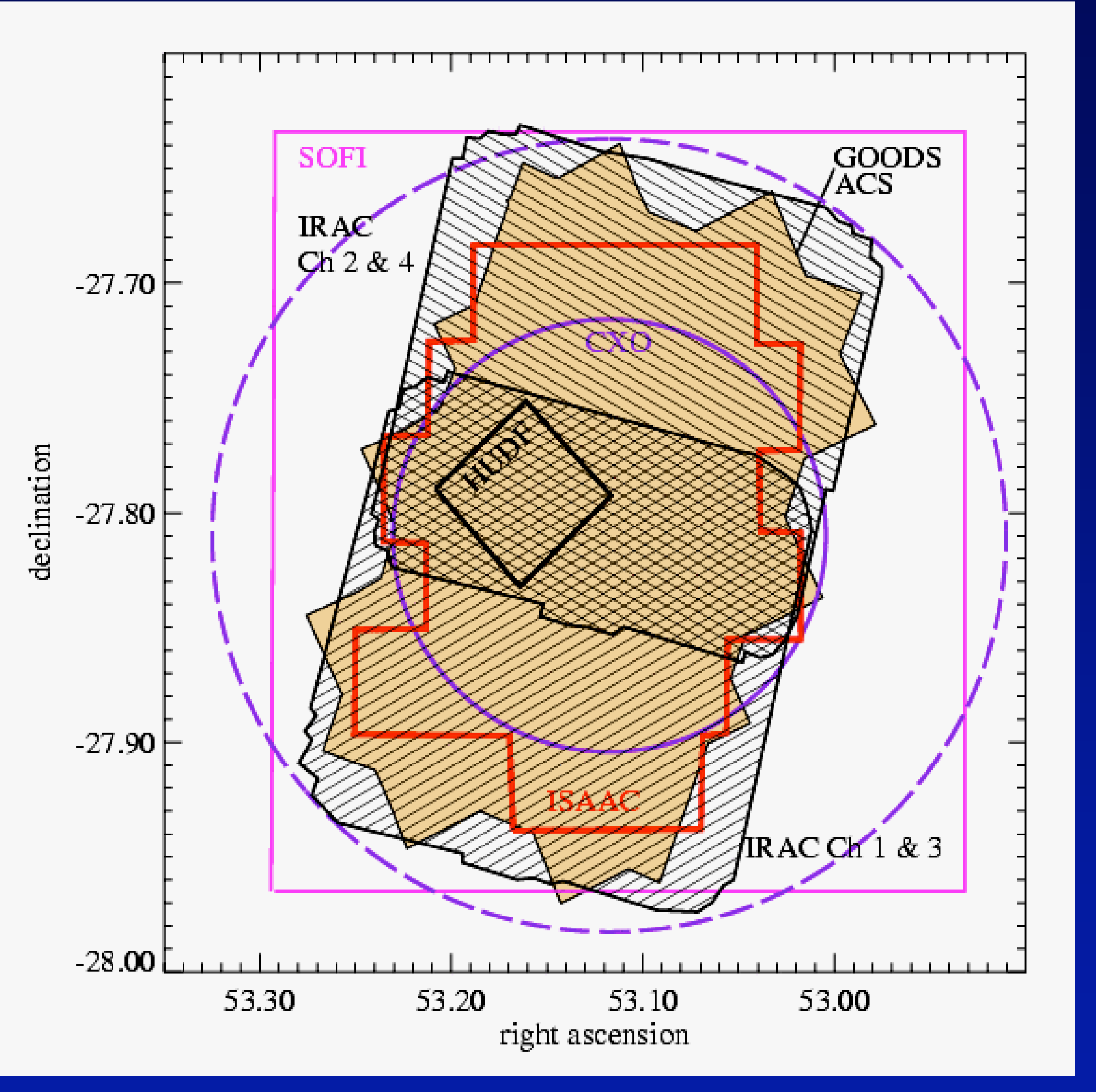
HUDF - Field Selection

RA(2000)=$3^h32^m39^s.0$ Dec(2000)=-27º 47′ 29″.1



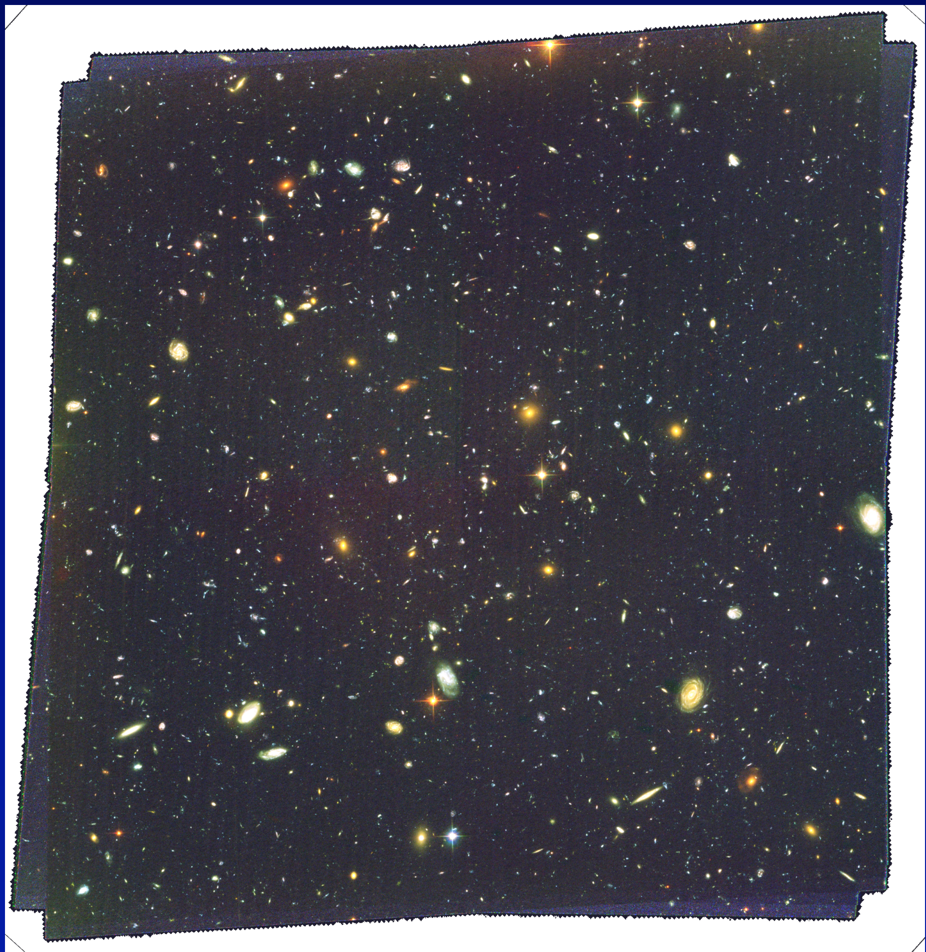


Galaxy at z=5.8 (1 Gyr after BB)



SOFI
GOODS
ACS
IRAC
Ch 2 & 4
CXO
HUDF
ISAAC
IRAC Ch 1 & 3
-27.70
-27.80
-27.90
-28.00
declination
53.30
53.20
53.10
53.00
right ascension

HUDF – Summary



400 orbits, over 4 months:
Sept-Oct (40 d), Dec-Jan (40 d)

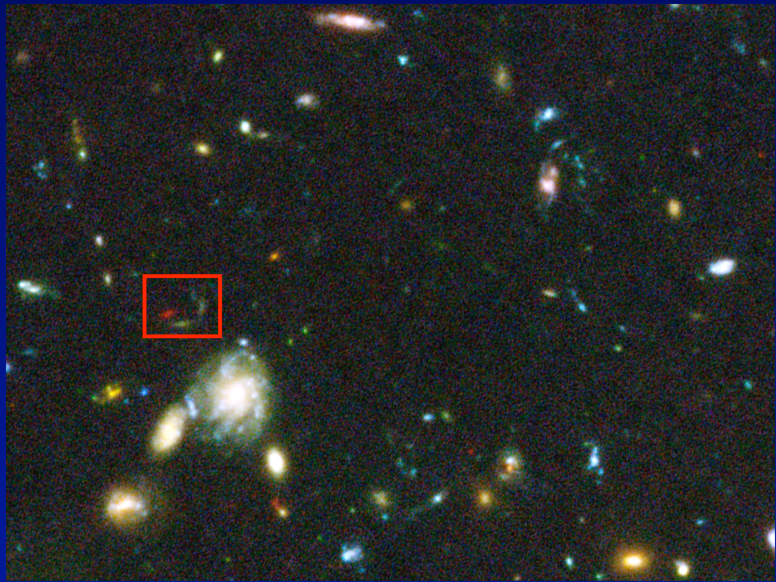
Total exposures (10^6 seconds)

	B	V	I	z	
	F435W	F606W	F775W	F850LP	
	56	56	144	144	orbits
10σ sensitivity (point source):					
	30.4	30.7	30.5	29.7	
10σ sensitivity (extended source 0.5″):					
	28.6	28.9	28.7	28.2	
	28.7	29.0	29.0	28.4	

Faintest object: 31.1^m (5σ)

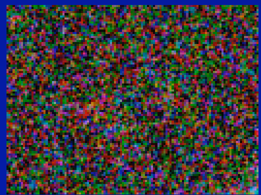
NICMOS parallel fields: deepest near-infrared images ever taken

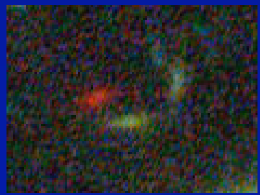
HUDF vs GOODS



GOODS CDFS – 13 orbits

HUDF – 400 orbits





HUDF- z>5.5 objects

- The great SB sensitivity of HUDF allows us to begin seeing substructure in z>5 objects.

QSO at z=5.5 spectroscopically confirmed by GRAPES using ACS/GRISM

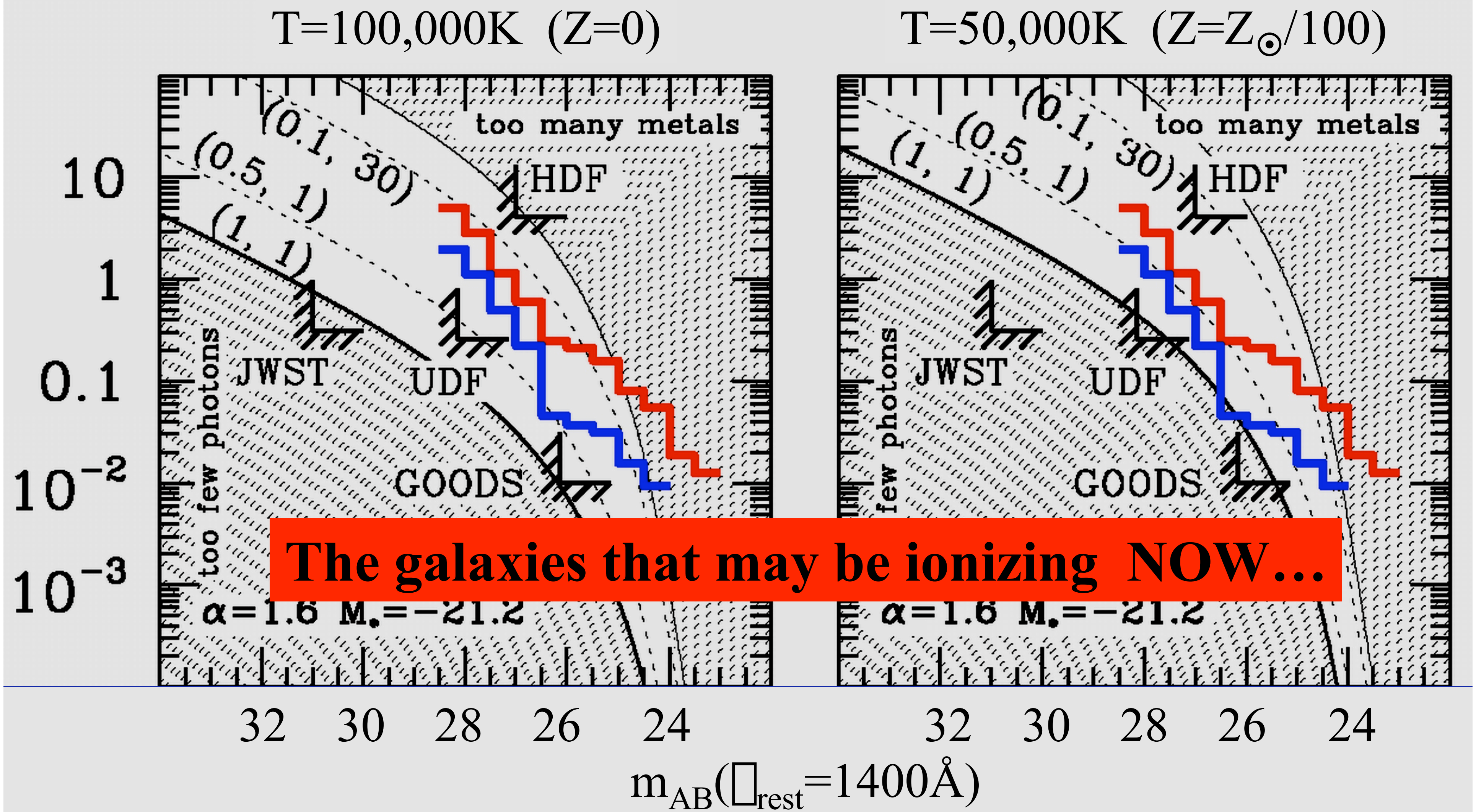
GOODS selected z=5.8 galaxy. In HUDF it has S/N=100.

The large number of z>6 objects opens up the possibility of learning something about the reionization of the Universe.

What did we learn?

Reionization constraints from HUDF observations

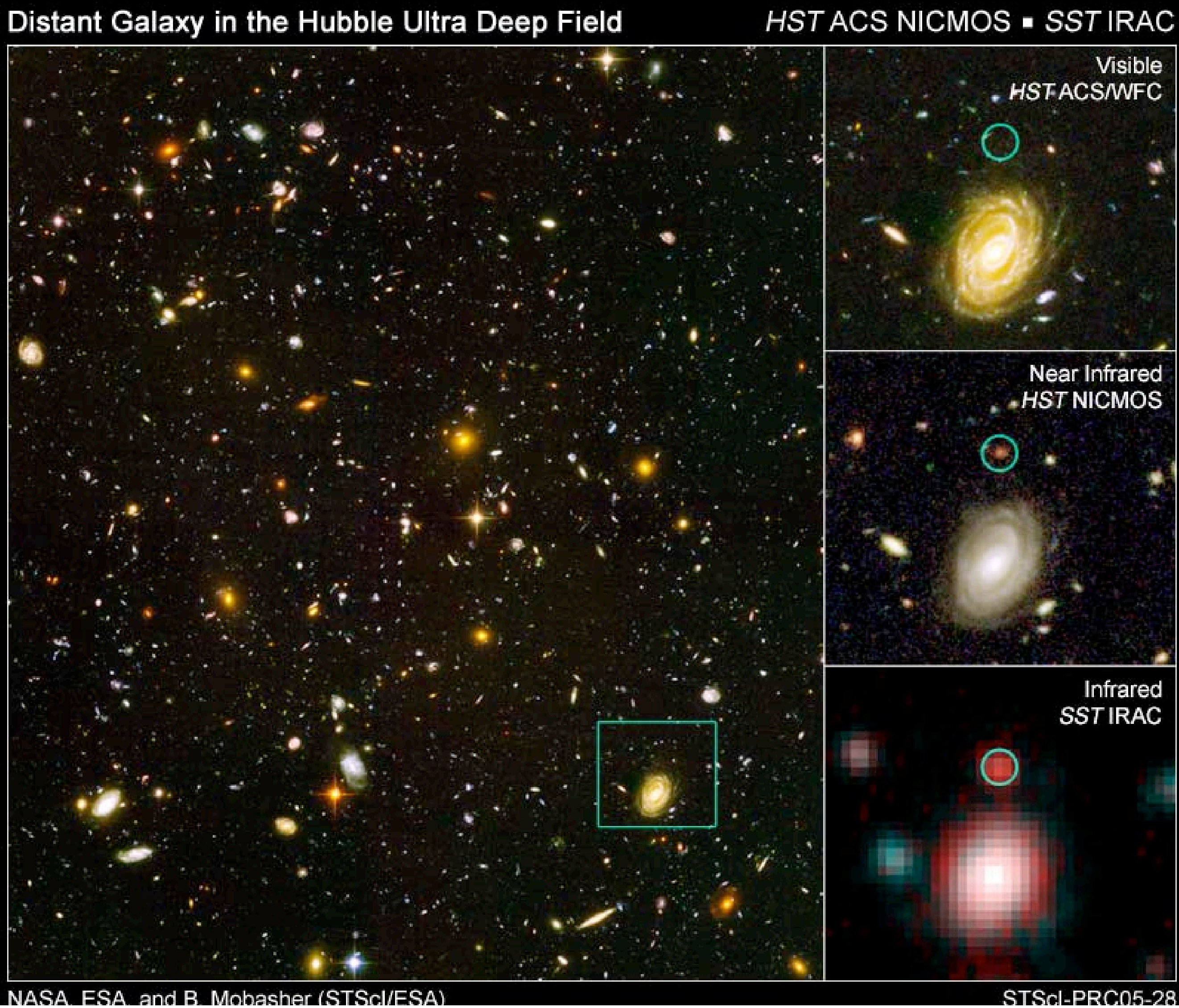
Stiavelli, Fall & Panagia (2004b)

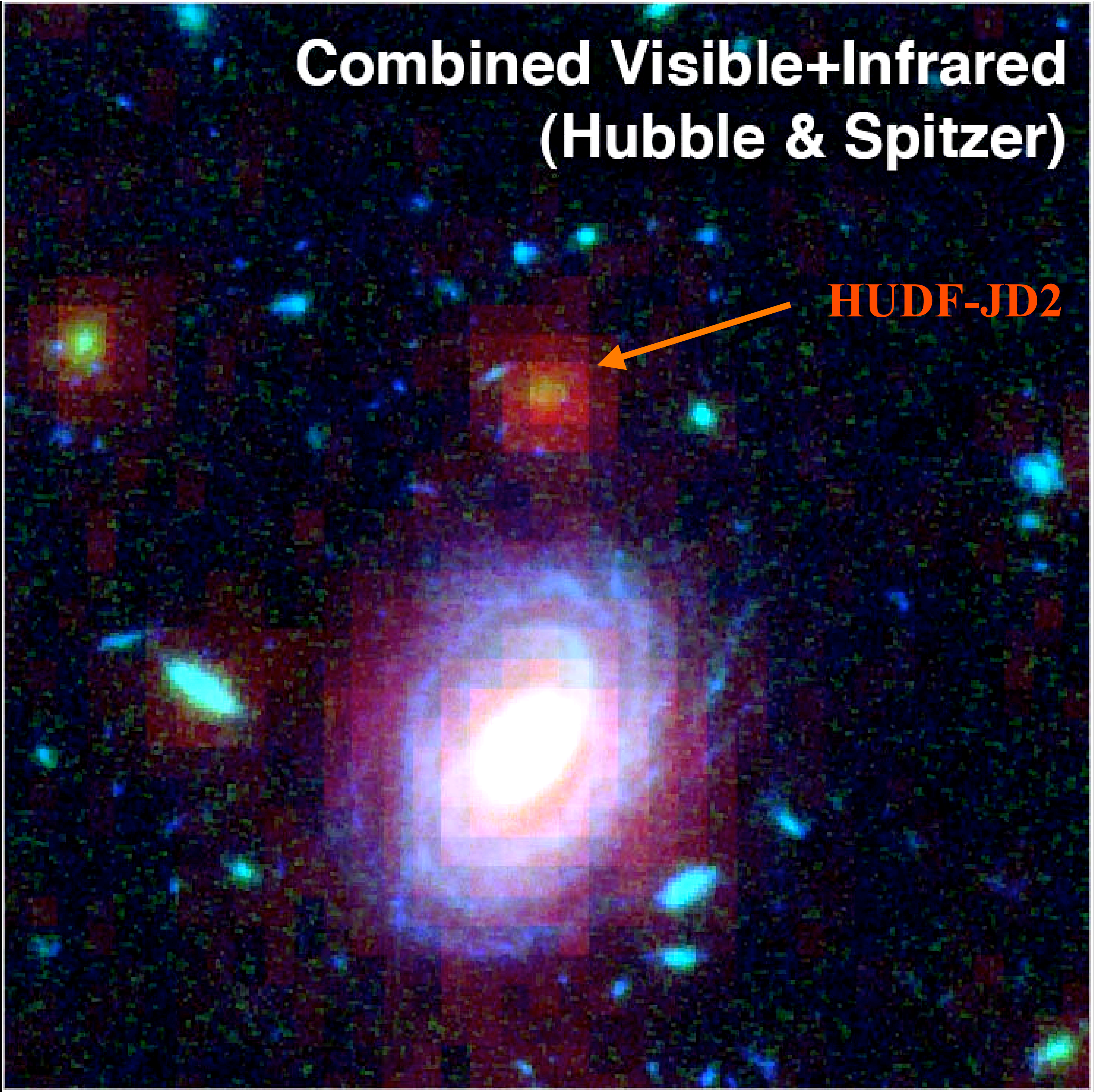


The blue line refers to UDF objects selected by i-z>2, the red one to i-z>1.3.

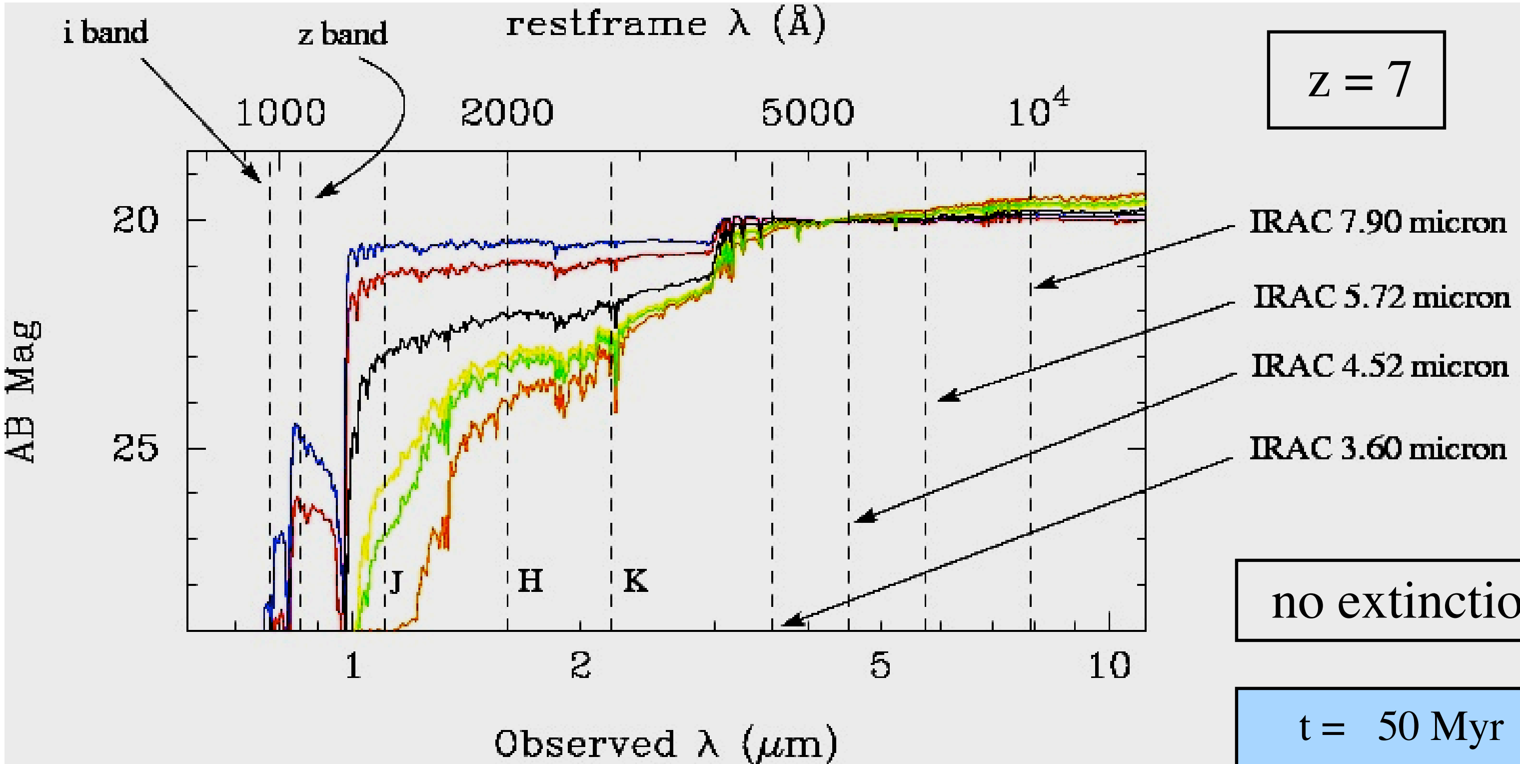

Old Massive Galaxies
in the Early Universe
tell better Stories
about Reionization…
“El diablo sabe mas por viejo que por diablo”
(Spanish proverb)

HUDF-JD2: A Distant Galaxy in the HUDF




Combined Visible+Infrared
(Hubble & Spitzer)
HUDF-JD2

The Balmer break is a prominent feature for stellar populations age t > 100 Myrs



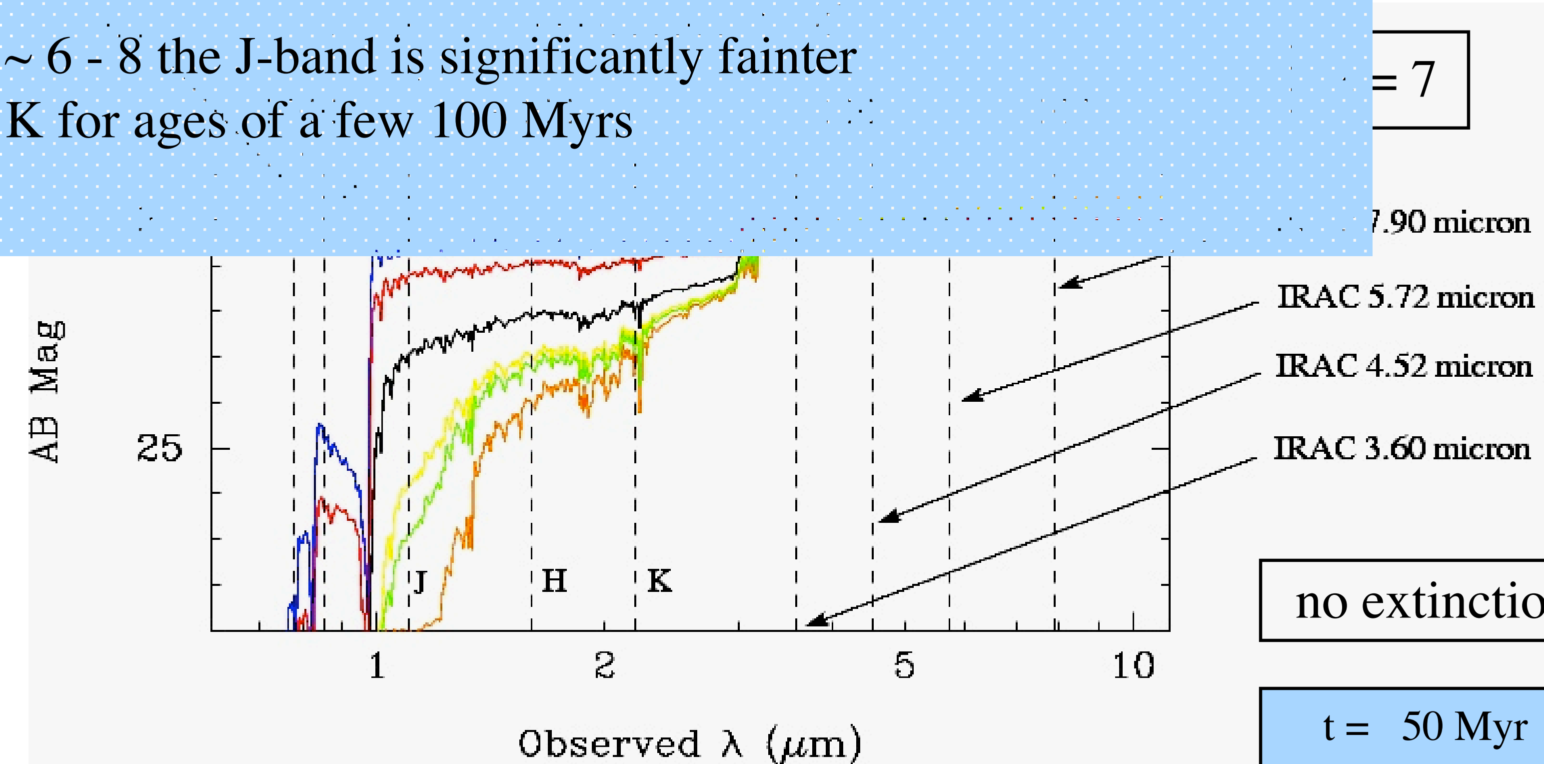
z = 7

no extinction

t = 50 Myr
t = 100 Myr
t = 300 Myr
t = 500 Myr
t = 600 Myr
t = 800 Myr

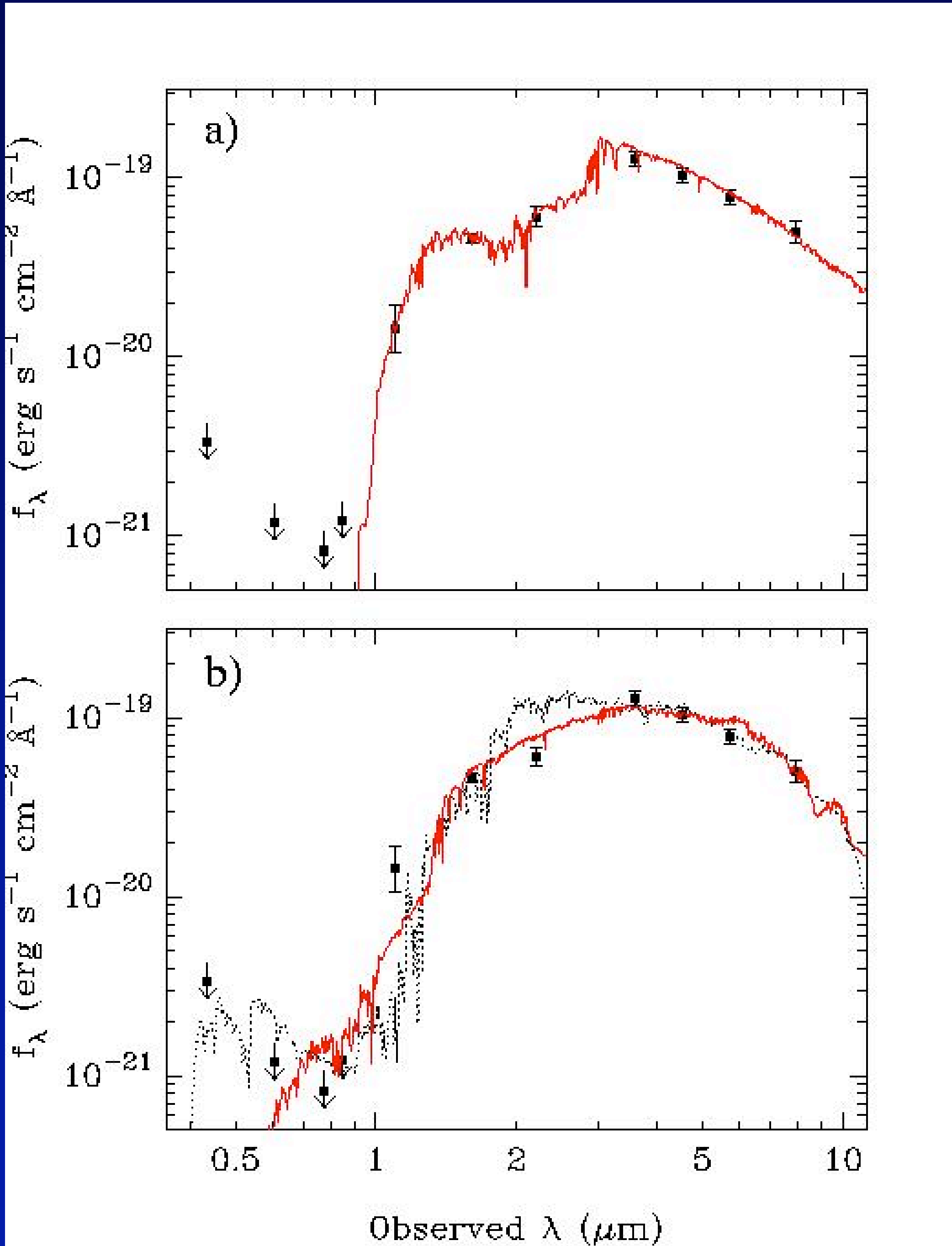
At z ~ 6 - 8 the Balmer break falls between the K-band and the IRAC 3.6 micron band

At z ~ 6 - 8 the J-band is significantly fainter than K for ages of a few 100 Myrs



no extinction

t = 50 Myr
t = 100 Myr
t = 300 Myr
t = 500 Myr
t = 600 Myr
t = 800 Myr



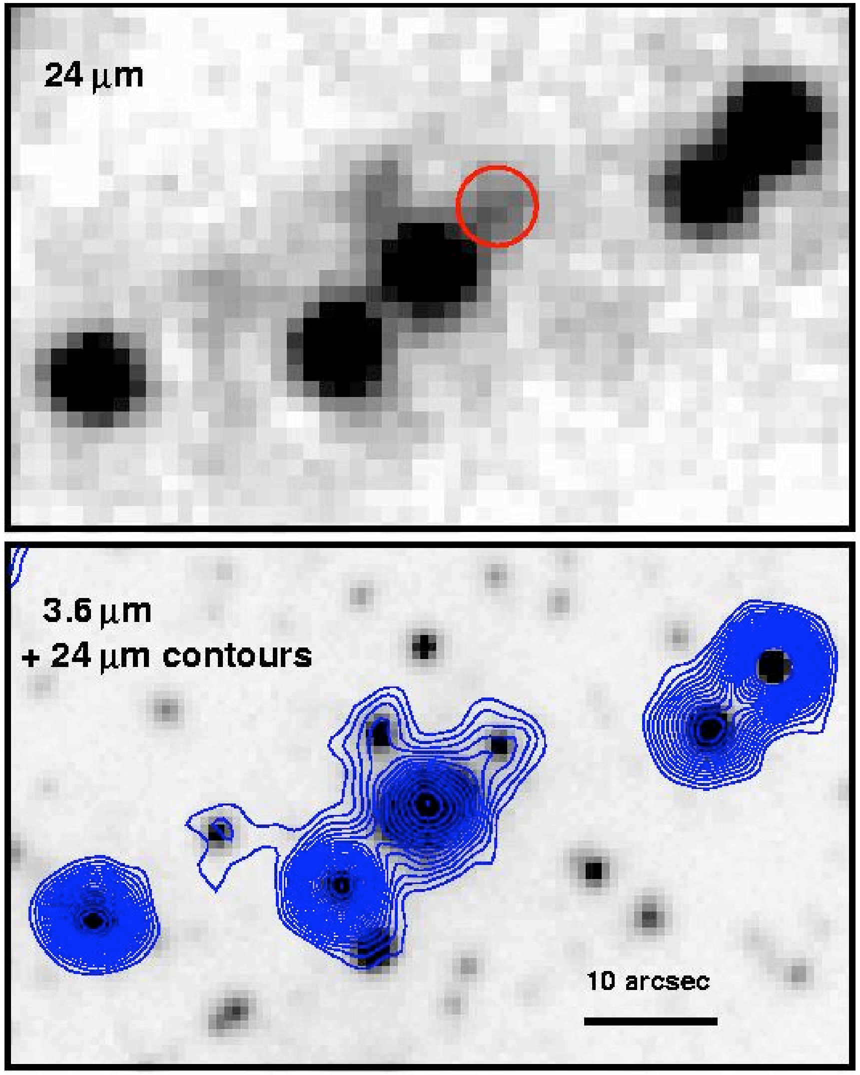
HUDF-JD2

z=6.5 evolved
Massive □$^2_□$ = 1.8
Single burst

z=2.5 dusty
Starburst □$^2_□$=6.7
Continous SFR

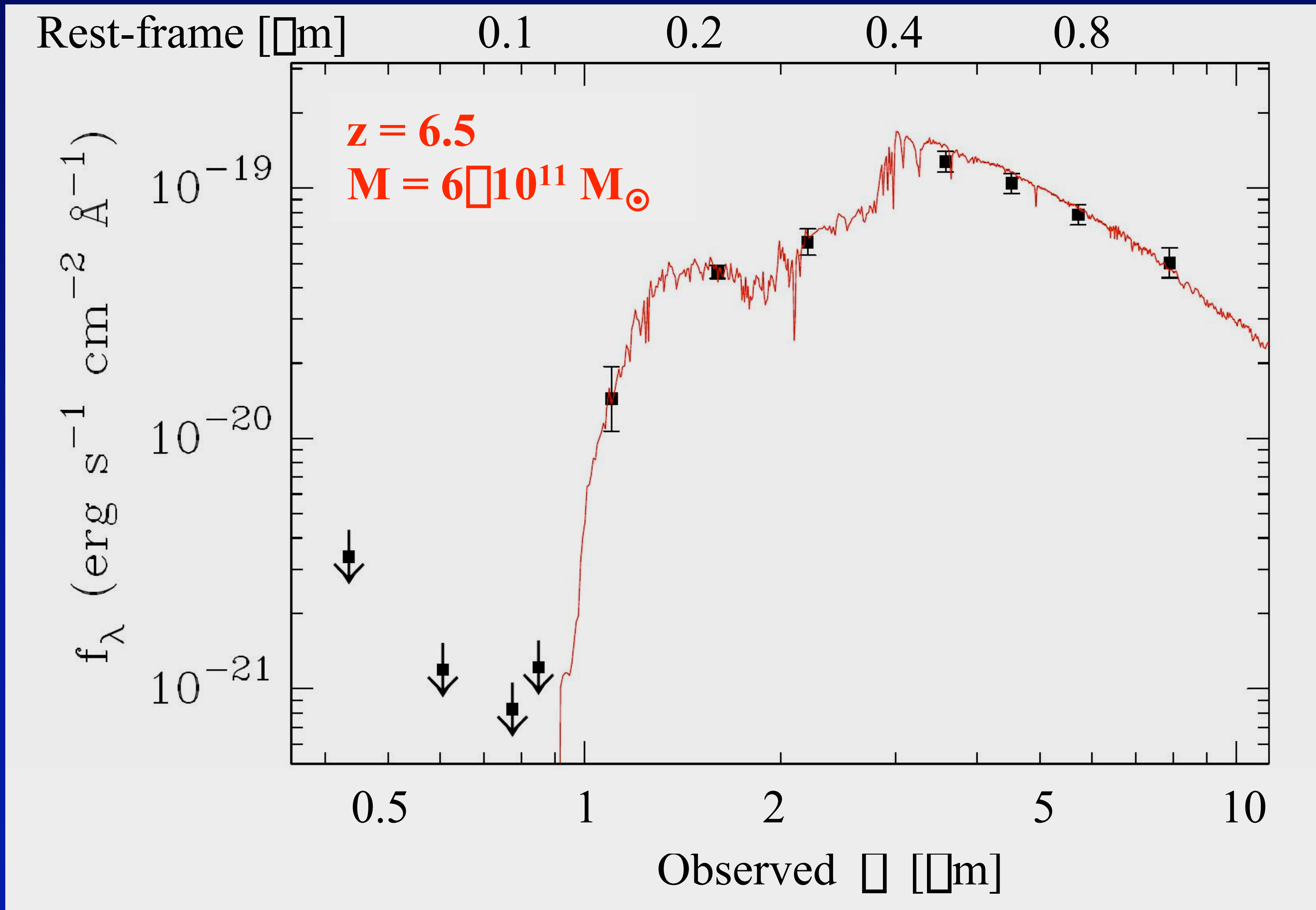
z=3.4 old
evolved □$^2_□$=29.9

HUDF-JD2 NIR and MIR Spitzer Images



HUDF-JD2, a Balmer Break Galaxy prototype A galaxy that did it in the past?

[Mobasher et al. 2005]

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GROWN-UPS IN THE GALACTIC CRADLE

Properties of HUDF-JD2

[Mobasher et al 2005, Panagia et al 2005]

Massive	$M/M_{\odot}$	=	6 _ 10^{11}
Bright	$L/L_{\odot}$	=	10^{12}
Evolved	Age	>	350-650 Myr
	z_{form}	>	9
Ionizing	Q	~	4 _ 10^{72} Ly-c photons

San Francisco Chronicle

Monday, October 10, 2005

Galaxy Like a 3-Year-Old with Bodybuilder Physique

Astronomers Believe HUDF-JD2 Dates from Just 800 Million Years after Big Bang

By Keay Davidson

Suppose that you plant an apple seed in your garden. The next morning, you look out the window and see that it has grown into an apple tree. You'd be startled, right?

Likewise, astronomers are startled by what they're seeing through their telescopes.

As they gaze into the darkest, deepest depths of the universe, they're like travelers in a time machine who gaze far back in time — almost as far back as the Big Bang that spawned our cosmos 13.7 billion years ago.

Recently, while surveying that long-ago realm, they were amazed to see the cosmic equivalent of a fully grown apple tree — a mammoth, mature-looking galaxy where they had expected to see only galactic seedlings or "baby" galaxies.

The discovery might challenge widely held assumptions about the early evolution of galaxies, those disk-, elliptical-, pinwheel- and flying-saucer-shaped clusters of stars that glower like jack-o'-lanterns across the void. The best-known galaxy is our own, the Milky Way, which contains hundreds of billions of stars, including our sun.

According to mainstream cosmological theories, the early cosmos — say, within a billion years after the Big Bang — should have been a dimly lit swirl of cosmic debris. Astronomers would expect to see diffuse matter — like the smoke after an explosion — plus, perhaps, baby galaxies that hadn't had time to become adult galaxies.

Yet astronomers say that when they recently gazed upon the early universe, some of what they saw was amazingly similar to the universe we see today. Among other things, they saw an immense "string" of galaxies 300 million light-years long, said astronomers who first reported their findings last year at the American Astronomical Society meeting in Atlanta. (A light-year is about 5.88 trillion miles, the distance that a beam of light travels in a year.)

Could gravity have condensed so much matter into such massive, huge, mature-looking objects that fast? Experts have their doubts.

On Sept. 27, NASA and other institutions reported the latest remarkable development: Astronomers have spotted a huge, mature-looking galaxy dating from a time just 800 million years after the Big Bang. That's when the universe was only 5 percent of its present-day age, or the cosmic equivalent of a prekindergarten child.

"The puzzling thing about discovery of such a massive galaxy this early in the history of the universe is how such a large mass could assemble and lead to a galaxy during the 800 million years from the beginning of the universe."

***Bahram Mobasher**, team leader*
Space Telescope Science Institute
Baltimore, MD

Named HUDF-JD2, or Hubble Ultra Deep Field, the reddish-orange galaxy "appears to be unusually massive and mature for its place in the young universe.... This came as a surprise to astronomers," space agency officials said in a statement that day. Two of NASA's orbiting robotic observatories, the Hubble and Spitzer space telescopes, detected the galaxy — one of the most distant on record.

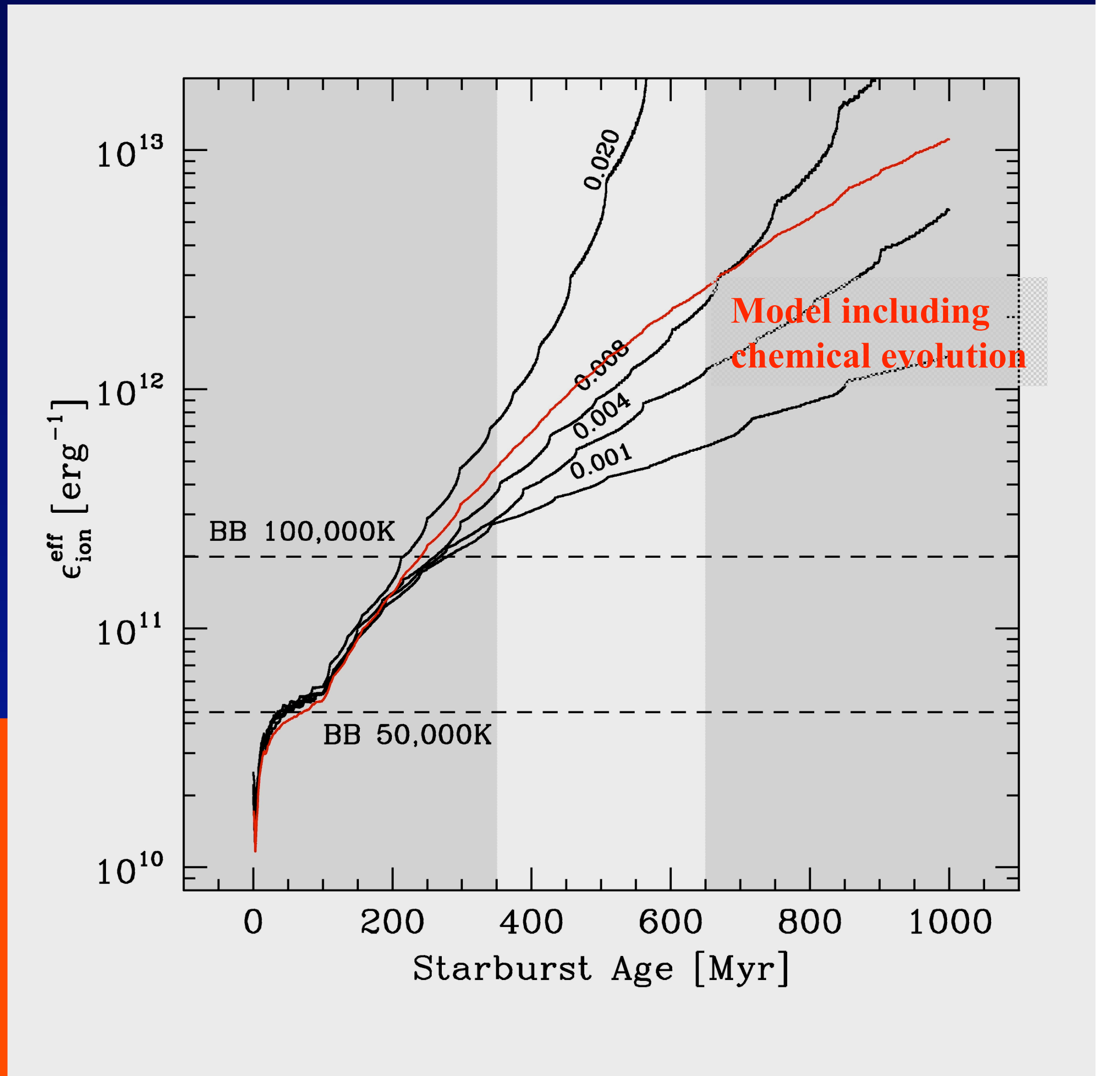
HUDF-JD2 is the Arnold Schwarzenegger of galaxies, with "about eight times more mass in stars than are found in our own Milky Way," said team leader Bahram Mobasher of the Space Telescope Science Institute in Baltimore in the Sept. 27 statement. HUDF-JD2 is about 10 times more massive than the expected baby galaxies, the NASA statement added.

"The puzzling thing about discovery of such a massive galaxy this early in the history of the universe is how such a large mass could assemble and lead to a galaxy during the 800 million years from the beginning of the universe," Mobasher told The Chronicle. "The present scenarios for galaxy formation would be in trouble if we find more such objects or galaxies slightly more massive than this."

HUDF-JD2: An Old Galaxy that did a LOT

[Panagia et al 2005]

□^{eff}: Ratio of the time averaged Lyman continuum photon flux to the present UV flux



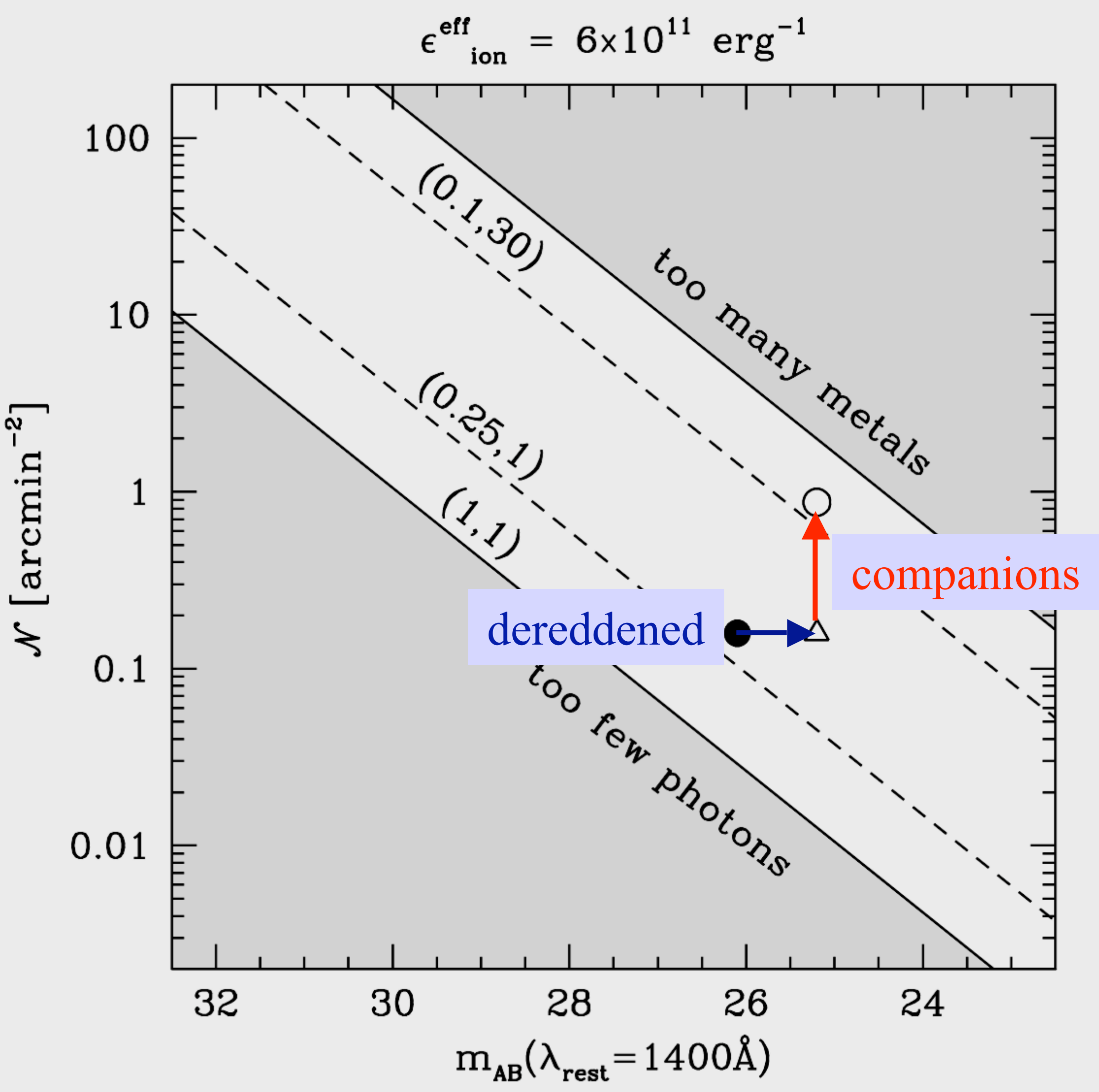
Age

HUDF-JD2

Enough to re-ionize its region of Universe?

By itself ***only if high*** escape fraction and ***low*** clumping

Easily if invisible companions with a reasonable LF are present



Panagia et al. 2005

HUDF-JD2: A summary

- Massive, luminous, protypical Balmer-break galaxy
- It has had an important impact (>20%) on the reionization of the IGM starting a z~15
- With the “help” of fainter companions distributed according to an =1.6 Schechter LF it may account for the whole effect

Is HUDF-JD2 unique?

- Inspecting the GOODS Deep-Field South Wiklind et al (2006) answer this question: ***"not quite"***
- Actually, combining deep HST and Spitzer multi-band photometry they find about one bright BBG every 10 square-arcmin field

From Observations to Physical Parameters

- Fitting the SED:
  - Photometric redshift
  - Age & formation redshift
  - Total Luminosity
  - Average Metallicity
- M/L ratio (from models)
  - Present mass in stars

BBGs in the GOODS Deep Field South

[Wiklind et al 2006, Panagia et al 2006]

ID	z	ID	z	ID	z	ID	z	ID	z	ID	z
432	5.1	432	5.1	432	5.1	432	5.1	432	5.1	432	5.1
547	5.7	547	5.7	547	5.7	547	5.7	547	5.7	547	5.7
861	5.0	861	5.0	861	5.0	861	5.0	861	5.0	861	5.0
1792	6.8	1792	6.8	1792	6.8	1792	6.8	1792	6.8	1792	6.8
2068	5.4	2068	5.4	2068	5.4	2068	5.4	2068	5.4	2068	5.4
2436	6.4	2436	6.4	2436	6.4	2436	6.4	2436	6.4	2436	6.4
2864	5.5	2864	5.5	2864	5.5	2864	5.5	2864	5.5	2864	5.5
3348	5.1	3348	5.1	3348	5.1	3348	5.1	3348	5.1	3348	5.1
3361	5.0	3361	5.0	3361	5.0	3361	5.0	3361	5.0	3361	5.0
3748	6.5	3748	6.5	3748	6.5	3748	6.5	3748	6.5	3748	6.5
4034	6.1	4034	6.1	4034	6.1	4034	6.1	4034	6.1	4034	6.1
4053	5.1	4053	5.1	4053	5.1	4053	5.1	4053	5.1	4053	5.1
4071	5.1	4071	5.1	4071	5.1	4071	5.1	4071	5.1	4071	5.1
4135	5.0	4135	5.0	4135	5.0	4135	5.0	4135	5.0	4135	5.0
4550	5.0	4550	5.0	4550	5.0	4550	5.0	4550	5.0	4550	5.0
5197	5.2	5197	5.2	5197	5.2	5197	5.2	5197	5.2	5197	5.2
5273	6.9	5273	6.9	5273	6.9	5273	6.9	5273	6.9	5273	6.9
5601	6.3	5601	6.3	5601	6.3	5601	6.3	5601	6.3	5601	6.3

18 BBGs
in 160 $arcmin^2$

$\langle \log L/L_\odot \rangle = 11.9$

$\langle \log M/M_\odot \rangle = 11.6$

$\langle \log Q \rangle = 72.5$

Re-Ionization Balance - I

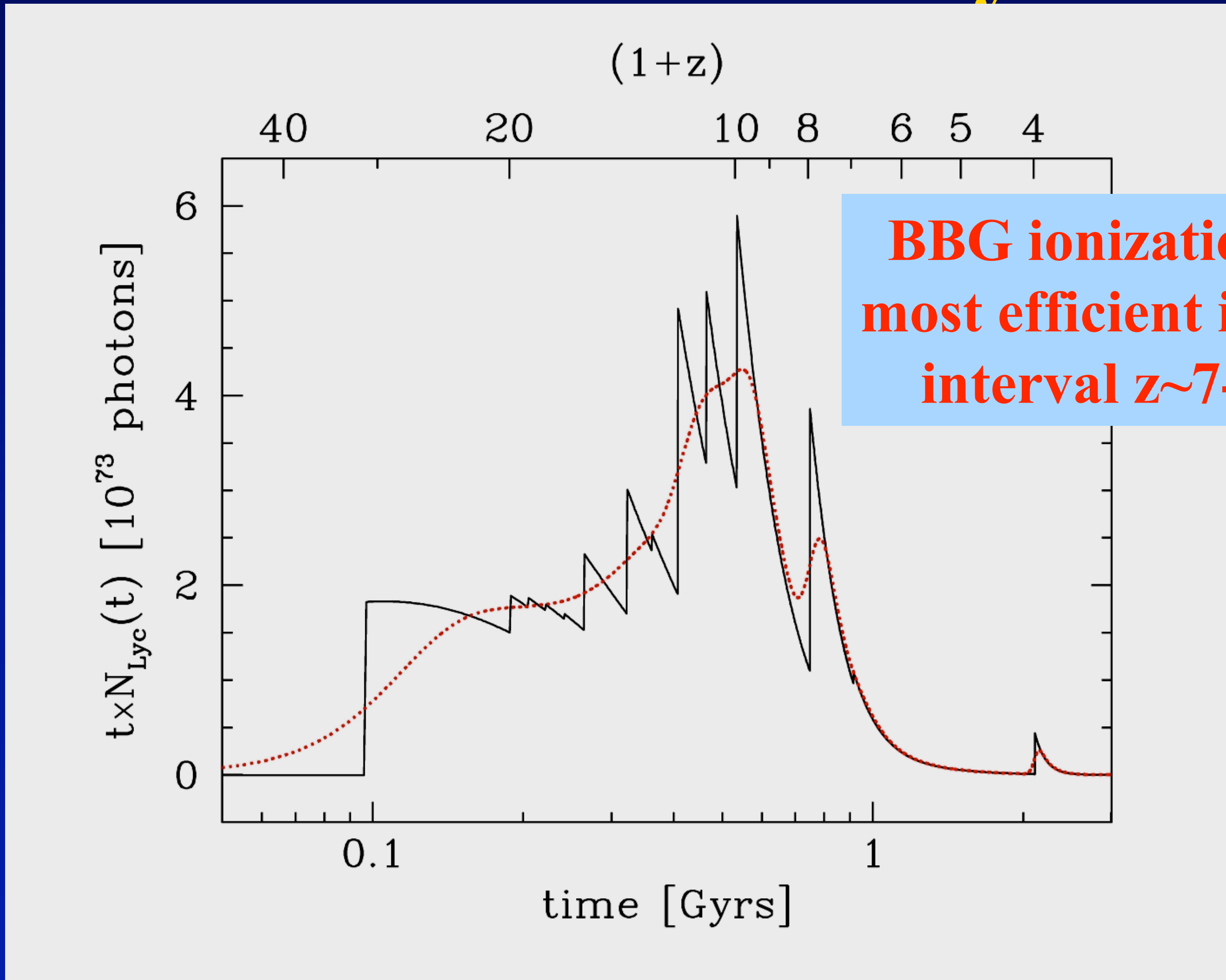
- UV output from BBGs in the Chandra Deep Field South

$$Q_{obs} = 5.1 \_ 10^{73} f \text{ Lyman-continuum photons}$$

- Correcting for incompleteness (50%)

$$Q_{tot} = 10.3 \_ 10^{73} f \text{ Lyman-continuum photons}$$

Lyman Continuum Photon Production History



BBG ionization is most efficient in the interval z~7-15

Re-Ionization Balance - I

- UV output from BBGs in the Chandra Deep Field South

$Q_{obs} = 5.1$ _ $10^{73} f$ Lyman-continuum photons

- Correcting for incompleteness (50%)

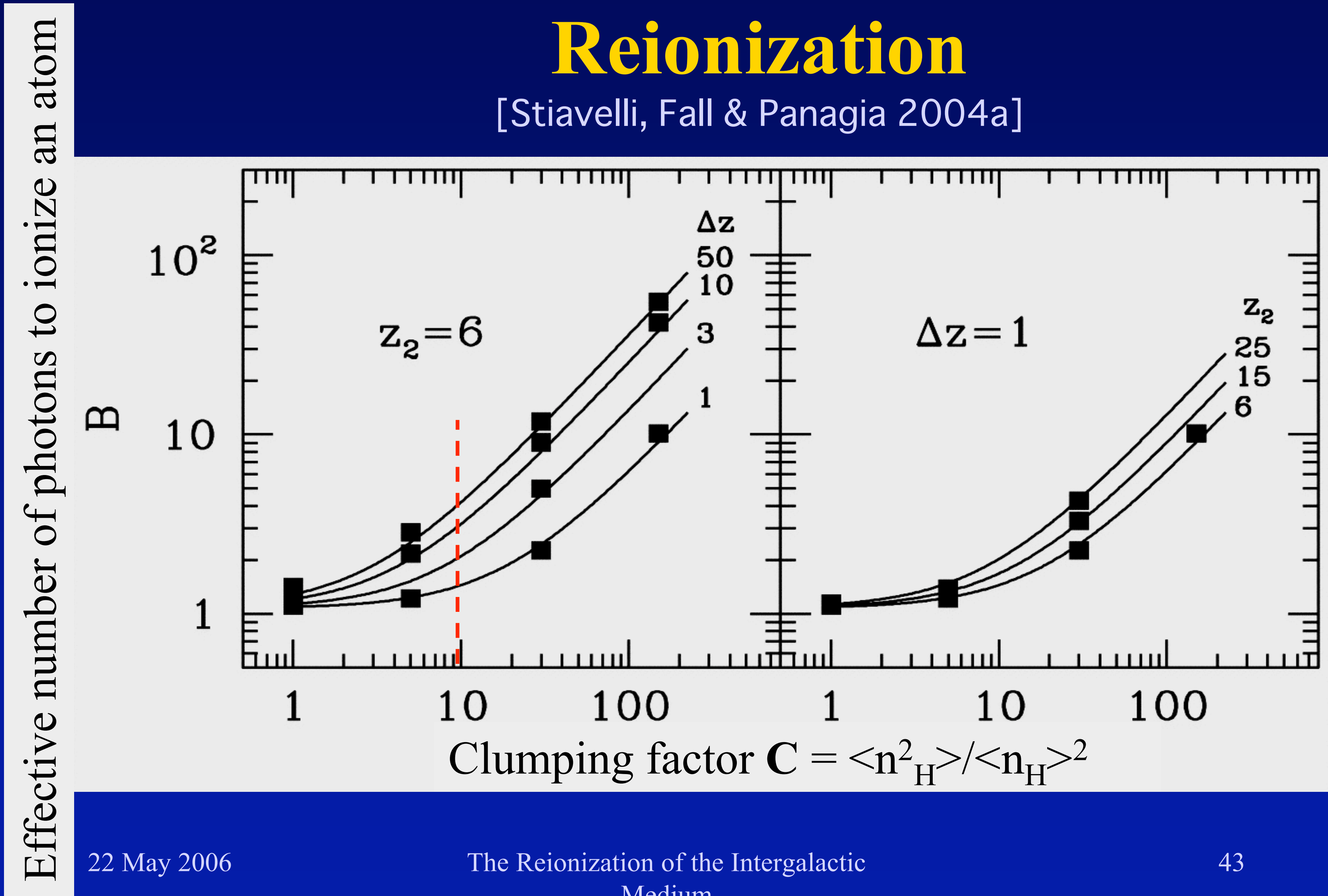
$Q_{tot} = 10.3$ _ $10^{73} f$ Lyman-continuum photons

- H-atoms in a volume in the redshift interval 7-15

$N_H = 0.9$ _ 10^{73} atoms

The effect of the IGM clumping on Reionization

[Stiavelli, Fall & Panagia 2004a]



Re-Ionization Balance - I

- UV output from BBGs in the GOODS Deep-Field South

$$Q_{obs} = 5.1 \_ 10^{73} f \quad \text{Lyman-continuum photons}$$

- Correcting for incompleteness (50%)

$$Q_{tot} = 10.3 \_ 10^{73} f \quad \text{Lyman-continuum photons}$$

- H-atoms in a volume in the redshift interval 7-15

$$N_H = 0.9 \_ 10^{73} \quad \text{atoms}$$

- If the detected BBGs are *the only UV sources* in the field

$$\langle Q \rangle = \langle M_{HI} \rangle \_ f^{-1} \_ B \quad \square \quad B/f = 11.5$$

Re-Ionization Balance - II

- **With a clumping** ***C ~ 10*** **□** ***B < 3*** **□** ***f > 0.25*** ***<u>unlikely!?</u>***

Re-Ionization Balance - II

- With a clumping $C \sim 10$ □ $B < 3$ □ $f > 0.25$ *unlikely!?*
- **The IMF may be top-heavy** ***too easy!!!***

Re-Ionization Balance - II

- With a clumping ***C* ~ 10** □ ***B* < 3** □ ***f* > 0.25** <u>*unlikely!?*</u>
- The IMF may be top-heavy <u>*too easy!!!*</u>
- **Additional, fainter, undetected galaxies contribute to the reionization** <u>***possible***</u>

Re-Ionization Balance - II

- With a clumping ***C ~ 10*** □ ***B < 3*** □ ***f > 0.25*** <u>*unlikely!?*</u>

- The IMF may be top-heavy <u>*too easy!!!*</u>

- Additional, fainter, undetected galaxies contribute to the reionization <u>*possible*</u>

- **In this case, with *C~10* and *f~0.1*, the fainter companions should provide an equal amount of ionizing radiation.**

Re-Ionization Balance - II

- With a clumping ***C ~ 10*** $\Rightarrow$ ***B < 3*** $\Rightarrow$ ***f > 0.25*** <u>*unlikely!?*</u>

- The IMF may be top-heavy <u>*too easy!!!*</u>

- Additional, fainter, undetected galaxies contribute to the reionization <u>*possible*</u>

- In this case, with ***C~10*** and ***f~0.1,*** the fainter companions should provide an equal amount of ionizing radiation.

- **This corresponds to a Schechter luminosity function steeper than α=1.3** <u>***quite reasonable***</u>

Re-Ionization Balance - II

- With a clumping ***C ~ 10*** □ ***B <3*** □ ***f > 0.25*** *unlikely!?*

- The IMF may be top-heavy *too easy!!!*

- Additional, fainter, undetected galaxies contribute to the reionization *possible*

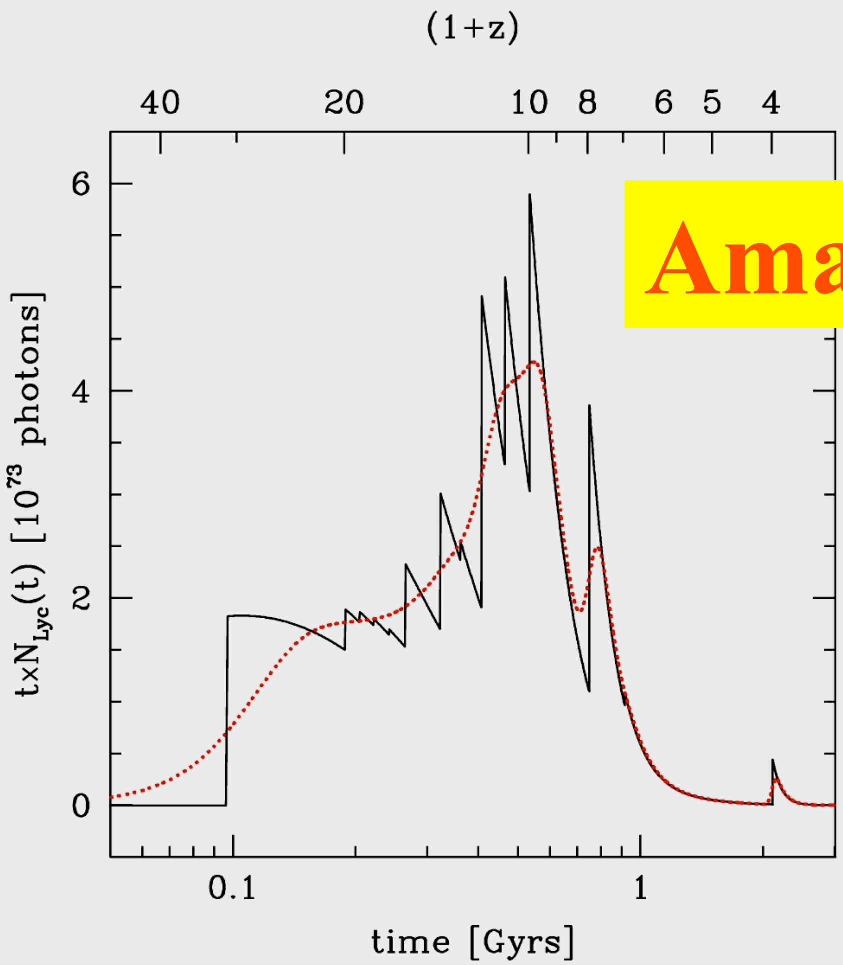
- In this case, with ***C~10*** and ***f~0.1,*** the fainter companions should provide an equal amount of ionizing radiation.

- This corresponds to a Schechter luminosity function steeper than □=1.3 *quite reasonable*

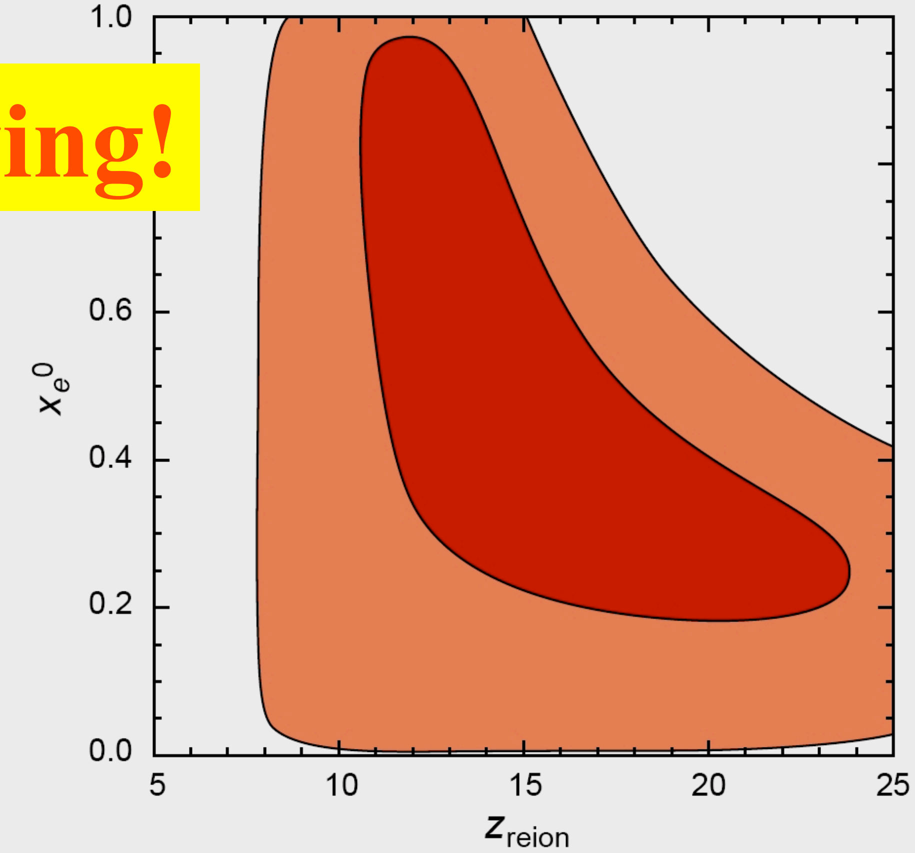
- **Detecting and studying the fainter companions is not easy with current telescopes but it will feasible with JWST.**

Reionization History

BBGs and WMAP



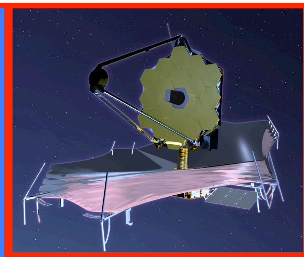
Amazing!



Will we be able to catch reionization sources in the act?

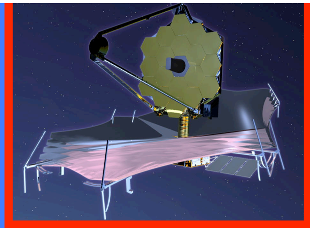
YES, with JWST!

The JWST Telescope



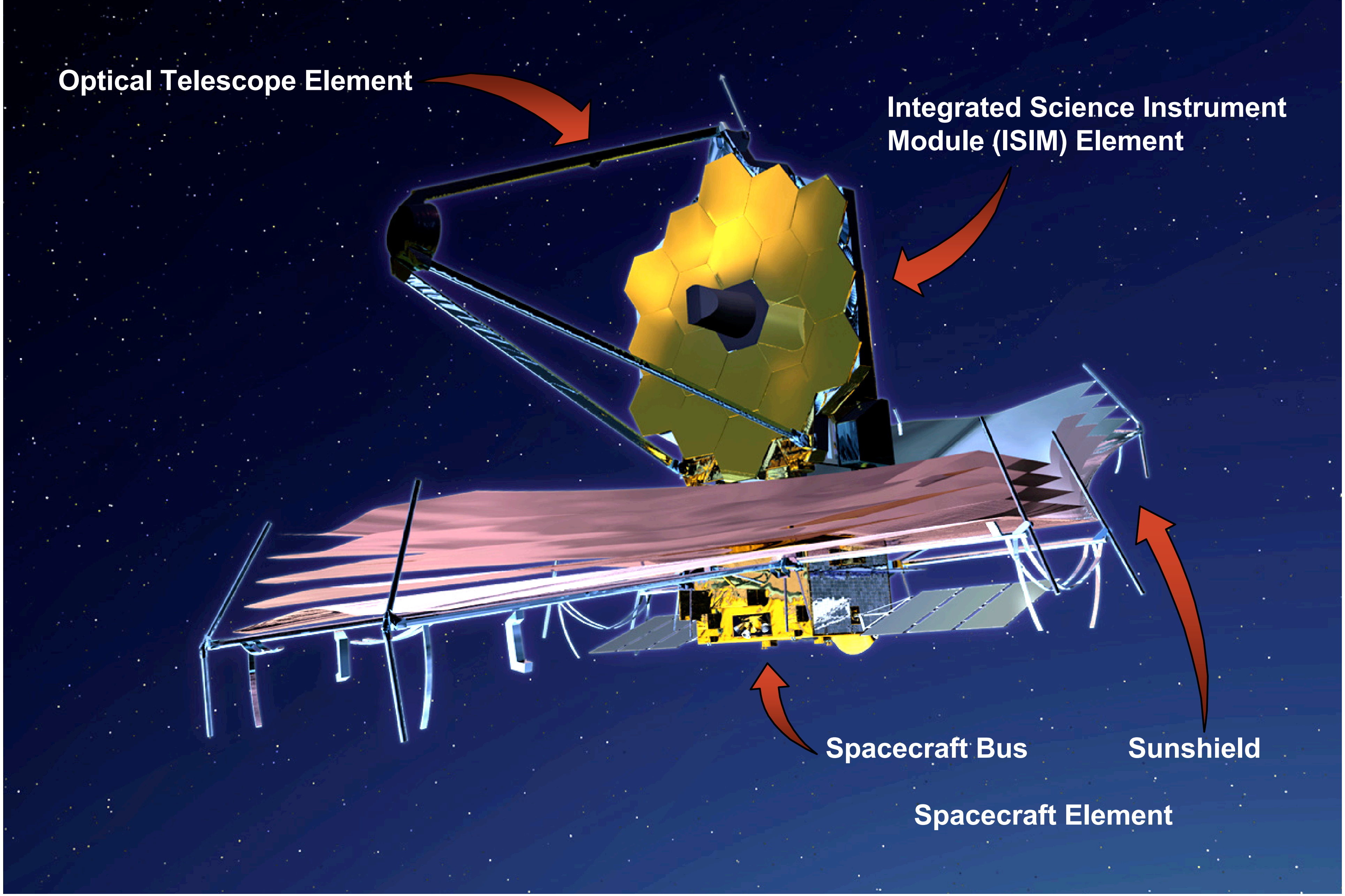
- 6-m class mirror (25 *m*_ area)
- 18 segments made of Beryllium
- 0.6 - 28 □*m* wavelength range
- Operating at Earth-Sun L2
  - 1.5 million *km* from Earth past the Moon
- Large sunshade
- 5 year operations requirement
  - 10 year goal
- Due to be launched mid-2013

The Science Goals of JWST

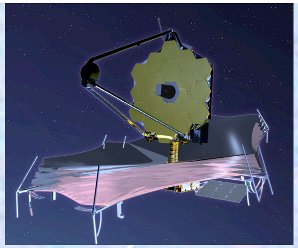


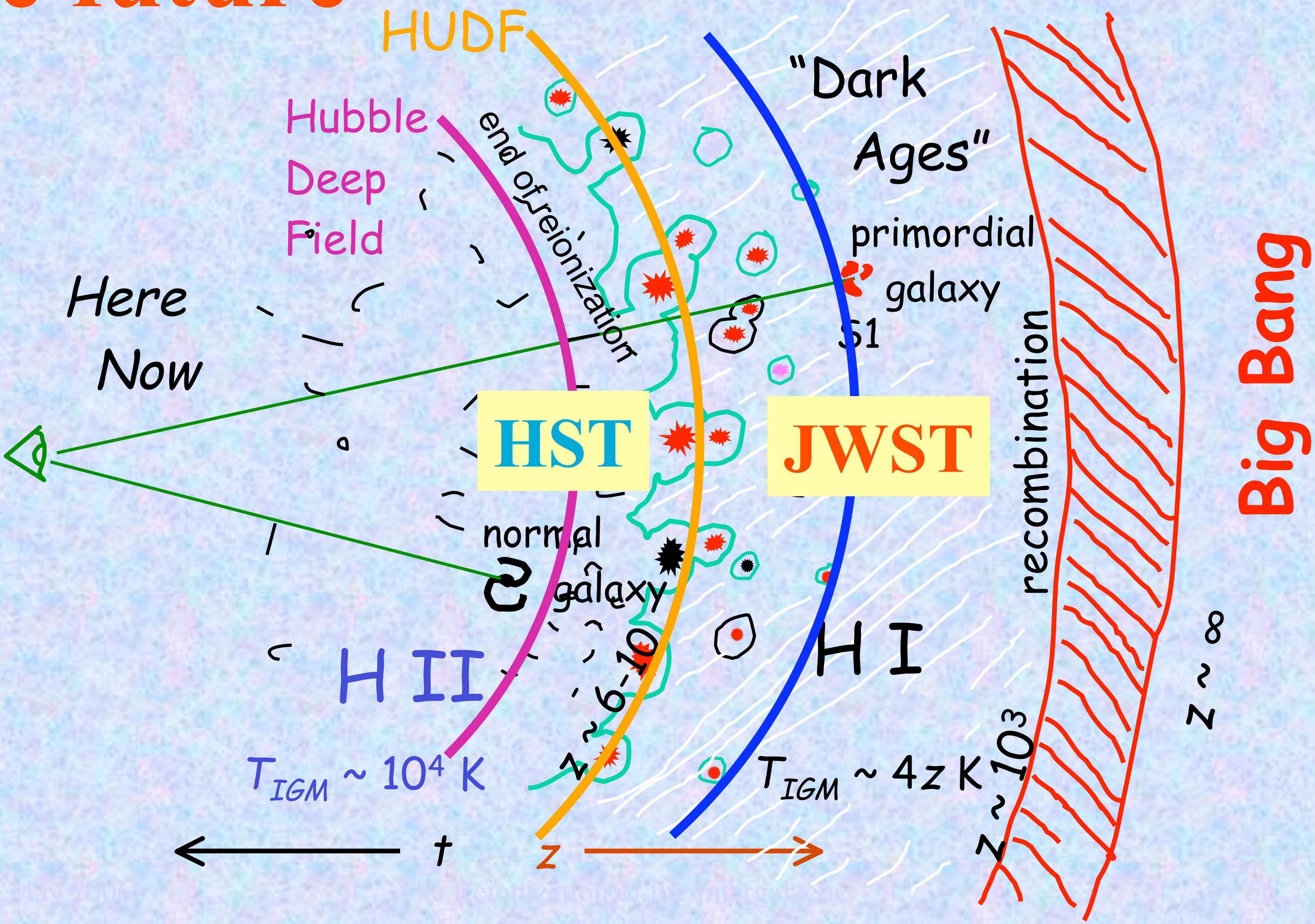
- **End of the Dark Ages**
  - **Determine the space density, energy source, and physical characteristics of the first luminous objects from z~20 up to the epoch of reionization.**
- **Assembly of Galaxies**
  - **Understand the structural and chemical evolution of galaxies, AGN and the intergalactic gas and their interplay from the epoch of reionization to z ~ 1.**
- **Formation of Stars and Stellar Systems**
  - **Unravel the birth and early evolution of stars, from infall onto dust-enshrouded proto-stars to the genesis of planetary systems.**
- **Planetary Systems and the Conditions for Life**
  - **Determine the physical and chemical properties of planetary systems, including our own, and investigate their potential for life.**

JWST Main Elements



Projecting to the future





Conclusions

- **Balmer-Break Galaxies** *(BBG)* are important for the reionization of the IGM *starting at z~15* or higher
- With the help of **fainter companions** they have the potential of ionizing the IGM entirely
- **JWST is needed** to detect and study the population of “reionizers”


THE END