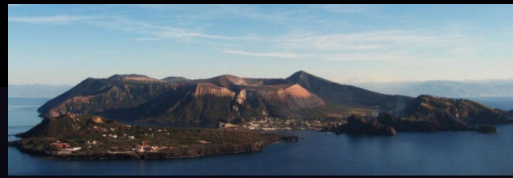
Vulcano Workshop 2012



Cosmology with HST

Nino Panagia

STScI/INAF-CT/SN Ltd

The Hubble Space Telescope - HST

- Launched on 24 April 1990
- Refurbished in 1993, 1996, 1999, 2002, 2009
- Refurbished instruments: ACS, STIS, [NICMOS]
- Newest instruments: WFC3, COS

What is HST best for…

- Observations in the ***UV*** and ***Near IR*** (at wavelengths where the Earth atmosphere is opaque)

- High angular resolution observations (diffraction limited)


STS-31, Discovery
Launch on 24 April 1990
HST deploy mission
Nino Panagia
Cosmology with HST

Cosmology with HST

- Expansion and Acceleration of the Universe
- Dark Matter
- Supermassive Black Holes in Galactic Nuclei
- Gamma-ray Bursts
- Primordial Galaxies and their Evolution

Cosmology with Type Ia Supernovae

Type Ia Supernovae (SNe Ia)

- Very bright
  M_V(peak) ≈ -19.5

- Very homogeneous class
  $\sigma_V \approx 0.15$ mag

- Hence, ideal *standard candles* for cosmological studies

The Distance Scale

and the value of H_0

Series of HST Studies

Sandage et al 1992 -2006

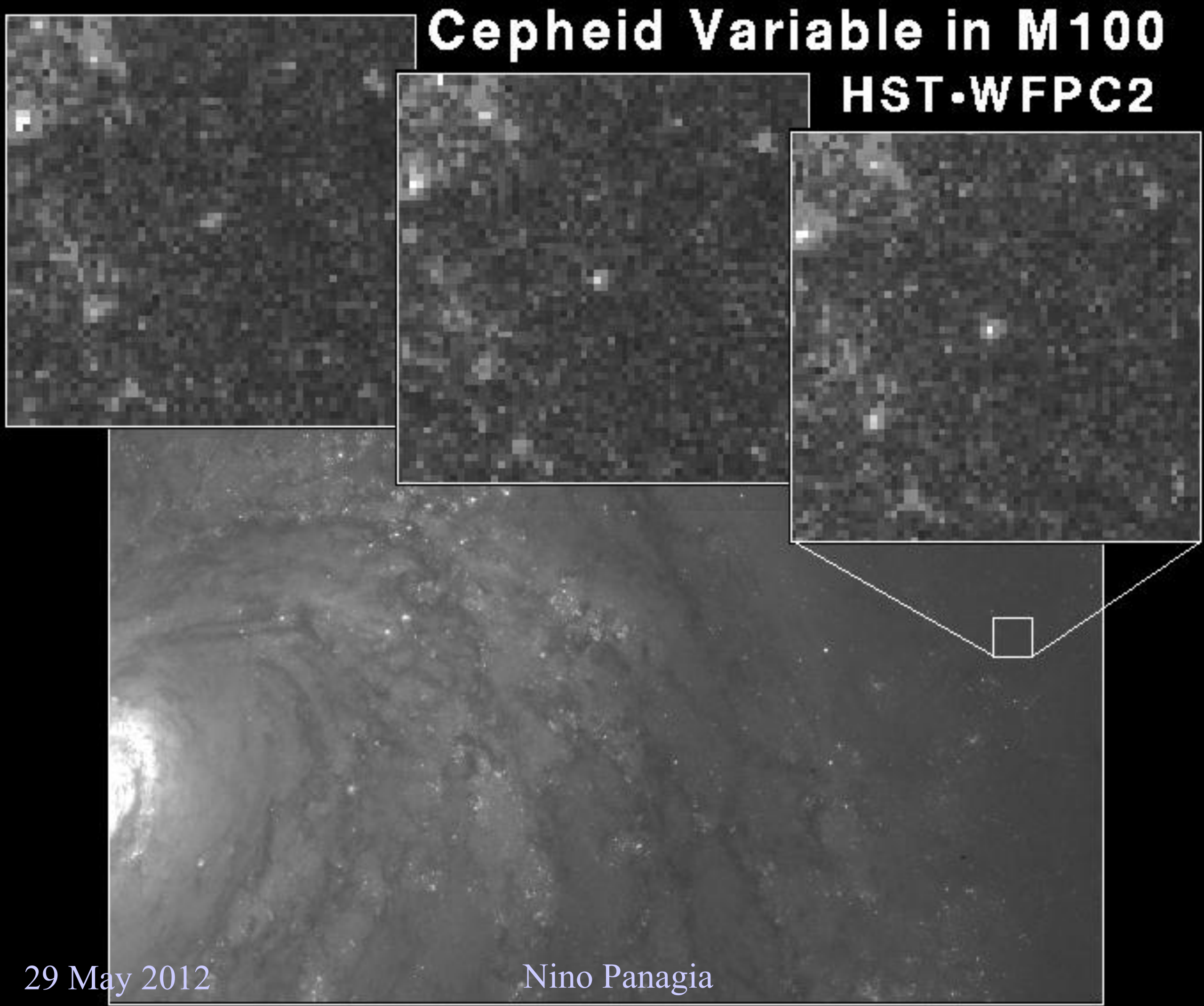
Freedman et al 1994-2001

Classical Steps to H_0 Determination

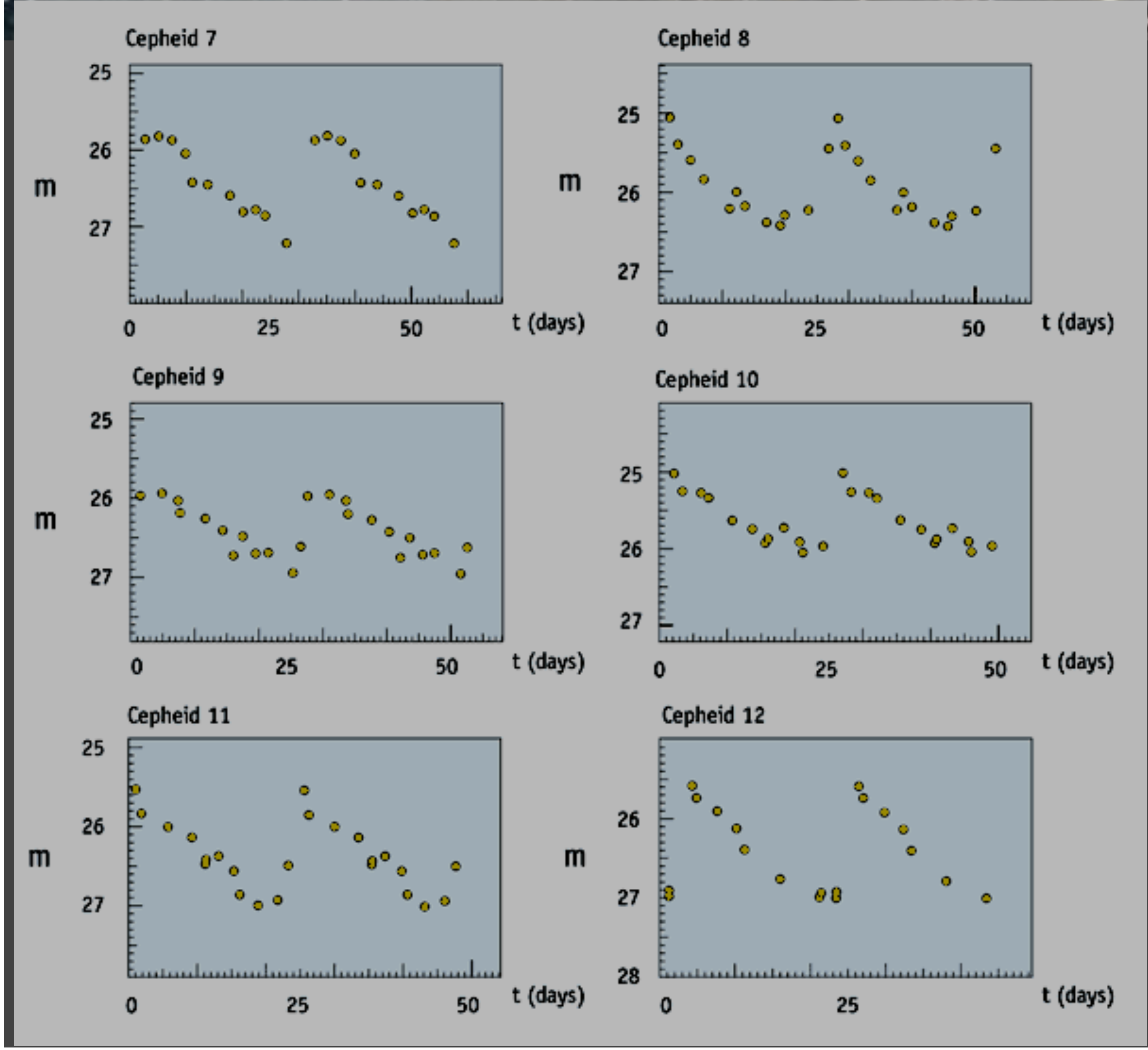
- Cepheid P-L-C relations calibration:
  - LMC Cepheid light curves in various bands
  - LMC distance
  - Detectable up to about 25 Mpc (m-M=32, v=1600 km s^{-1})

- Calibrate intrinsically very bright standard candles (SNIa!) and reach much larger distances (z>1)

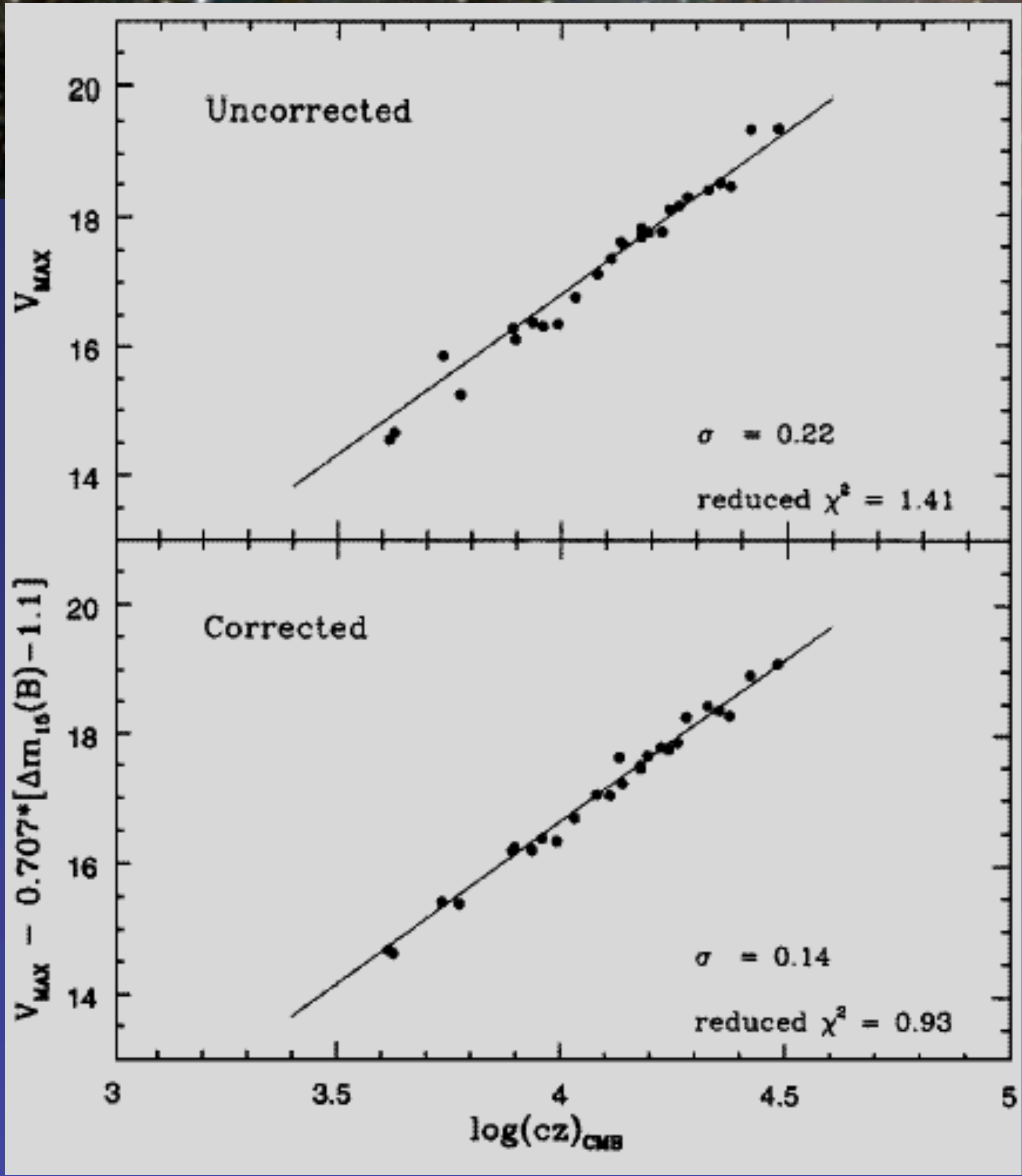
e.g. Cepheids in M100



Cepheid Light Curves



A Tight Hubble Diagram



Summary of Sandage *et al.* results

- Metal dependent Cepheid P-L relations
- LMC Distance Modulus 18.54 ± 0.02
- M^{corr}_V(SNIa, max) = -19.46 ± 0.04

$H_0 = 62.3 \pm 1.3 \pm 5.0$ km s^{-1} Mpc^{-1}

Summary of Freedman *et al.* results

- **Udalski *et al.* (1999) Cepheid P-L relations**

  → *higher reddening corrections* → *shorter distances*

- **LMC Distance Modulus 18.50 ± 0.02**

- M^{corr}_V**(SNIa, max) = -19.16 ± 0.06**

$$H_0 = 72 \pm 3 \pm 7 \text{ km s}^{-1} \text{ Mpc}^{-1}$$

The "ultimate" Hubble constant

- $H_0 = 62 \pm 1 \pm 5$ km s^{-1} Mpc^{-1} Sandage *et al.*
- $H_0 = 72 \pm 3 \pm 7$ km s^{-1} Mpc^{-1} Freedman *et al.*

- $H_0 = 64 \pm 1 \pm 5$ km s^{-1} Mpc^{-1} is a compromise that the Universe could take! Could you?

The Accelerating Universe

High-z SNIa and the quest for the *deceleration* of the Universe

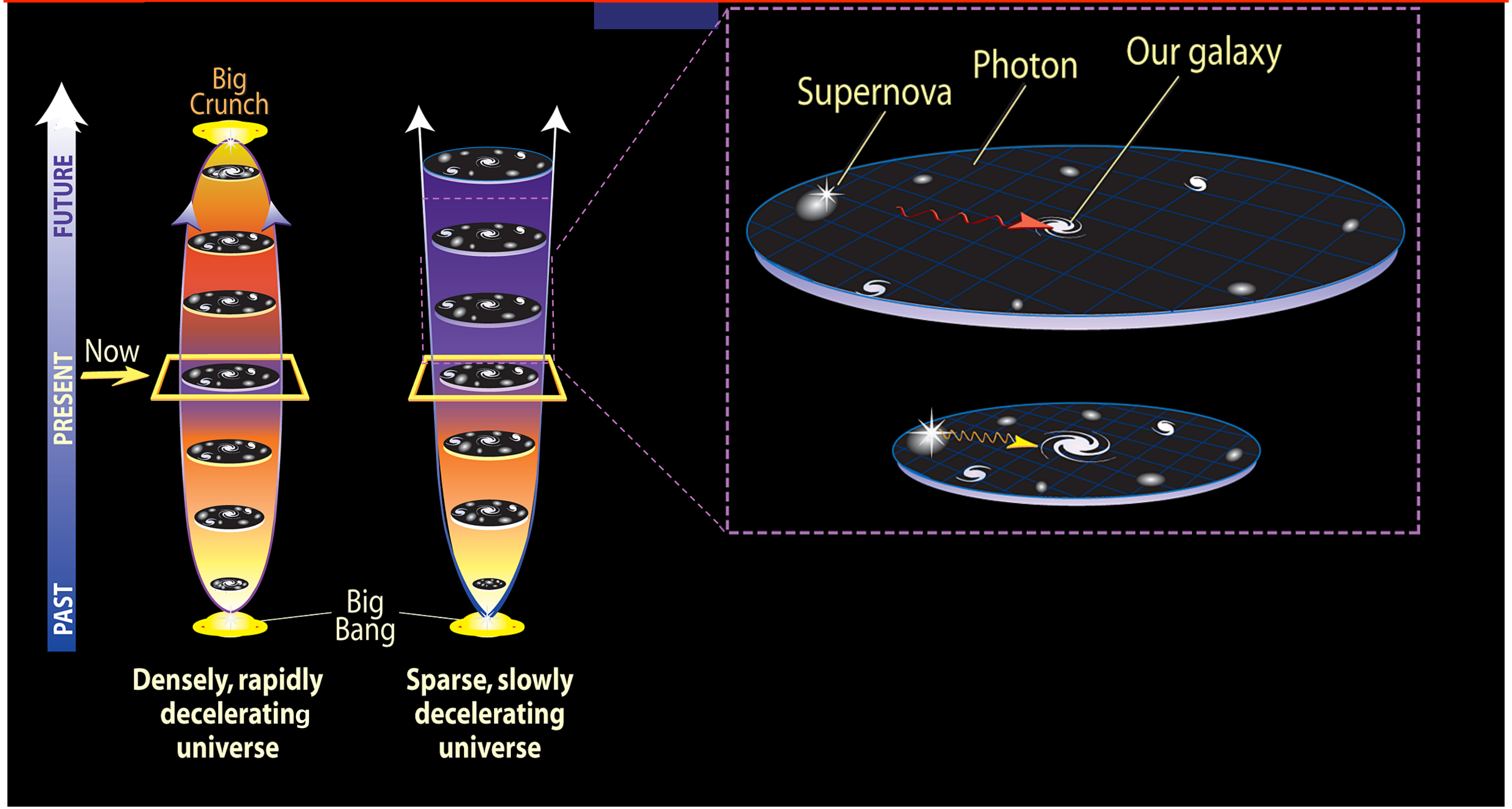
• Early attempts to discover and measure SNIa at high z lead to the discovery of one SNIa at z=0.31 in the late 1980's (Nordgaard-Nielsen et al. 1989)

• The **LLNL team** lead by Perlmutter (Supernova Cosmology Project, SCP) started in 1991 with an efficient technique to discover high-z SNIa (first discovery: SN 1992bi at z=0.46), and perfected their methods for "SNIa-on-demand" discovery in 1994

• The **CfA team**, originally lead by Kirshner (High-Z Supernova Search, HZSS), and later by Schmidt, and Riess (Higher-Z SN Search team), joined the race in the mid '90

MODELS OF EXPANDING UNIVERSE - circa 15 YRS AGO

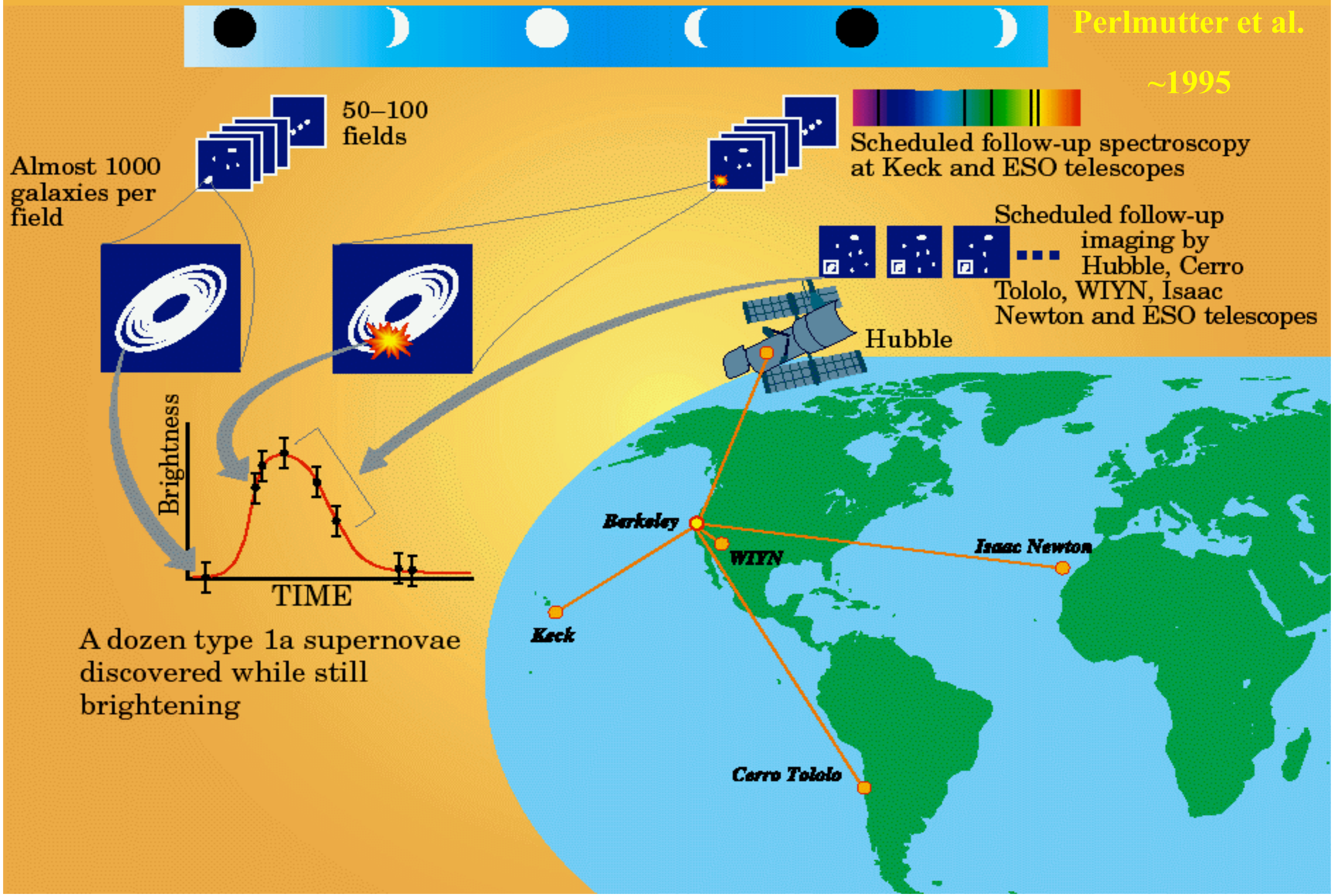
GOAL: By measuring the deceleration rate of the cosmic expansion determine the density of the Universe



Ground Based Searches: Observing Strategy

Perlmutter et al.

~1995

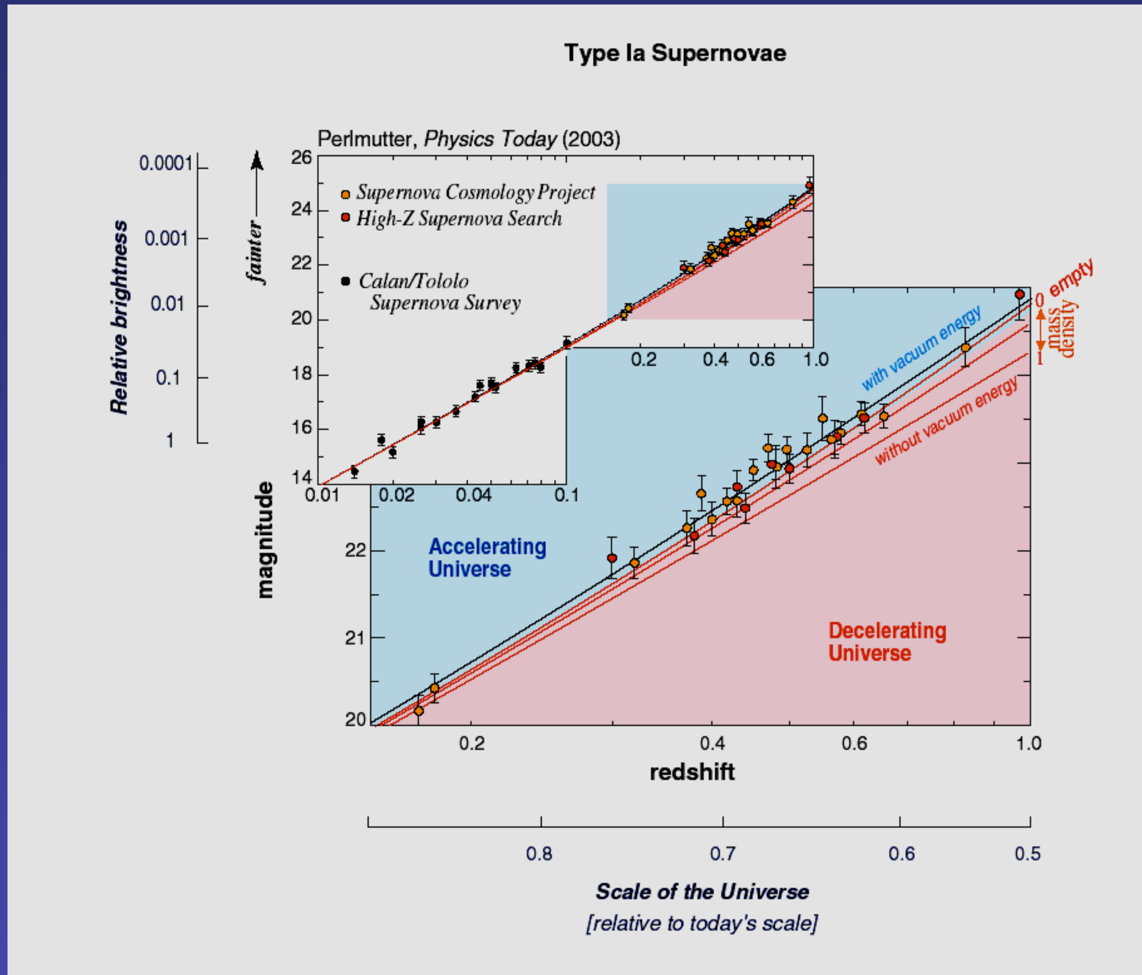


A dozen type 1a supernovae discovered while still brightening

High Redshift Supernovae

By 1999 more than 100 SNIa had been discovered and studied at redshifts higher than 0.3 by two independent groups (SCP: Perlmutter et al 1998, 1999; HizSS: Riess et al 1998)

- SNIa at redshifts 0.3-0.8 appeared to be systematically 0.3 mags dimmer than expected for an empty Universe



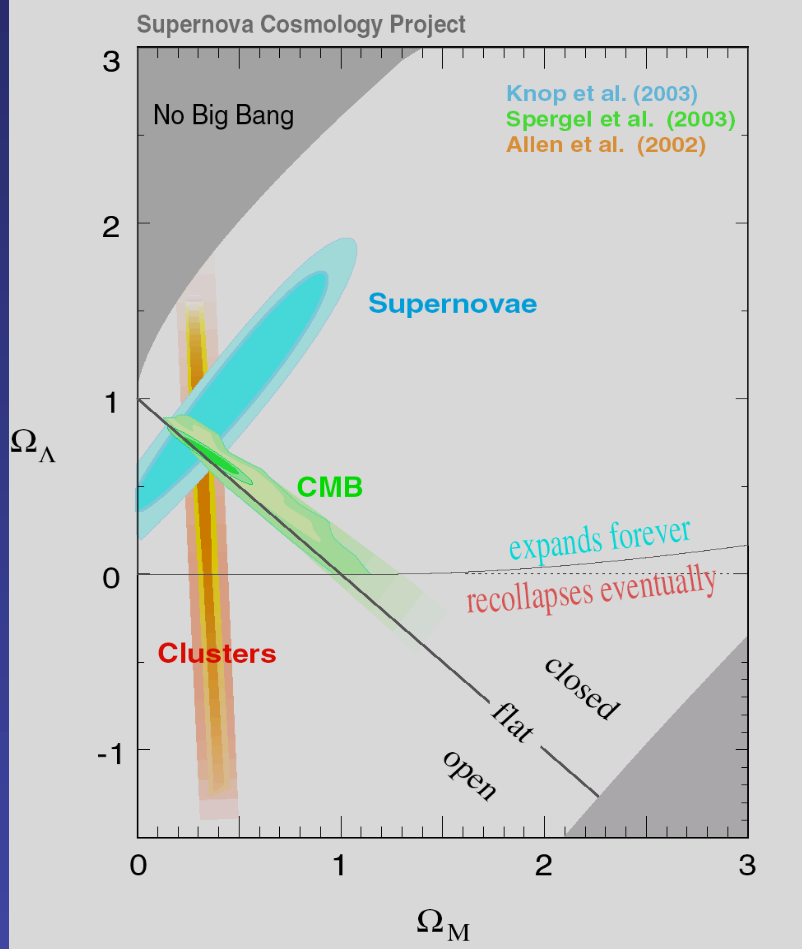
The two teams consistently found that SNIa at redshifts $z \sim 0.5$ appear dimmer than expected by ~0.3 mags

It we assume that SNIa properties are the same at ALL redshifts

•This *suggests* that the expansion of the Universe is *accelerating*, propelled by “dark energy”, with $\Omega_\Lambda \sim 0.75$.

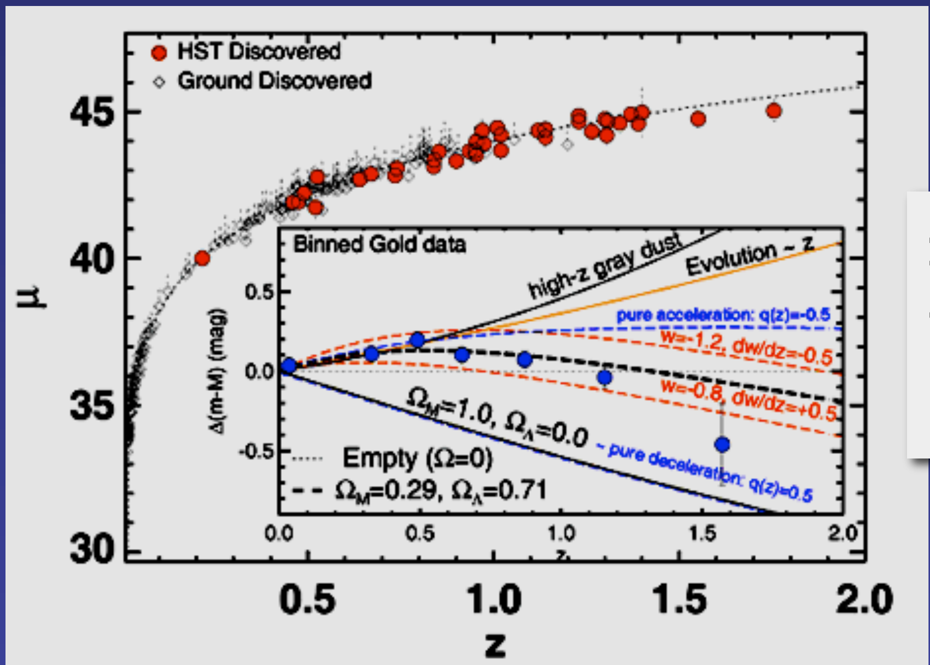
•This conclusion is also consistent with measurements of the Cosmic Microwave Background fluctuations.

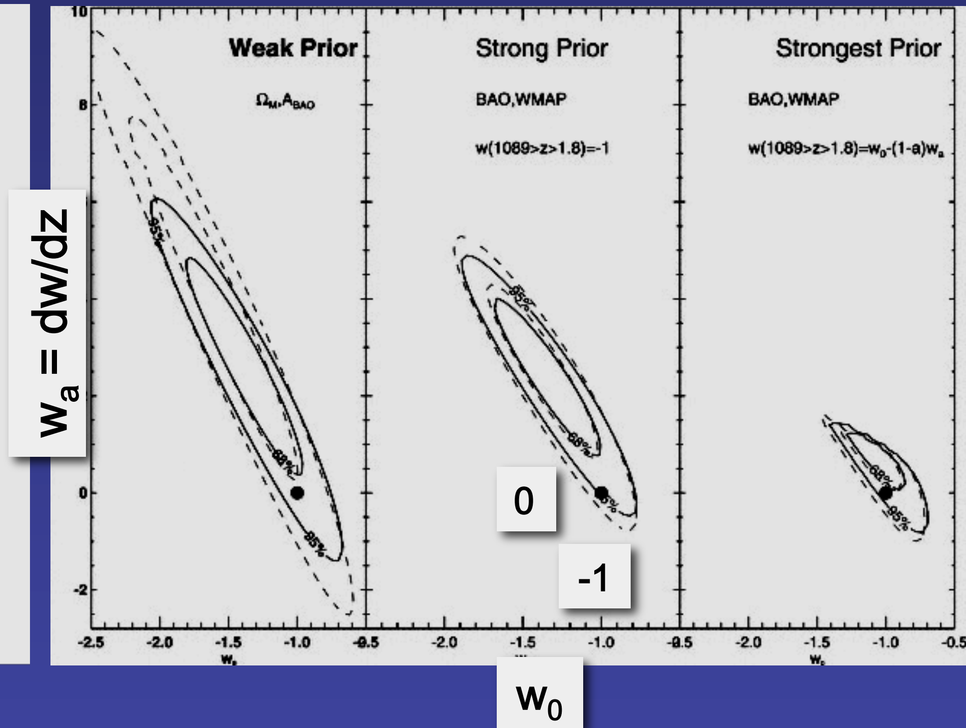
Most recent results: Knop et al. 2003



The Evidence from Type Ia Supernovae

Constraints on equation of state





The GOODs ACS Treasury Program and

The Hubble Higher-z Supernova Search Team

Riess (STScI)
Strolger (STScI)
Tonry (UH)
Filippenko (UCB)
Kirshner, (CfA)
Challis, (CfA)
Casertano, (STScI)
Dickinson (STScI)
Giavalisco (STScI)
Ferguson (STScI)

A piggyback project

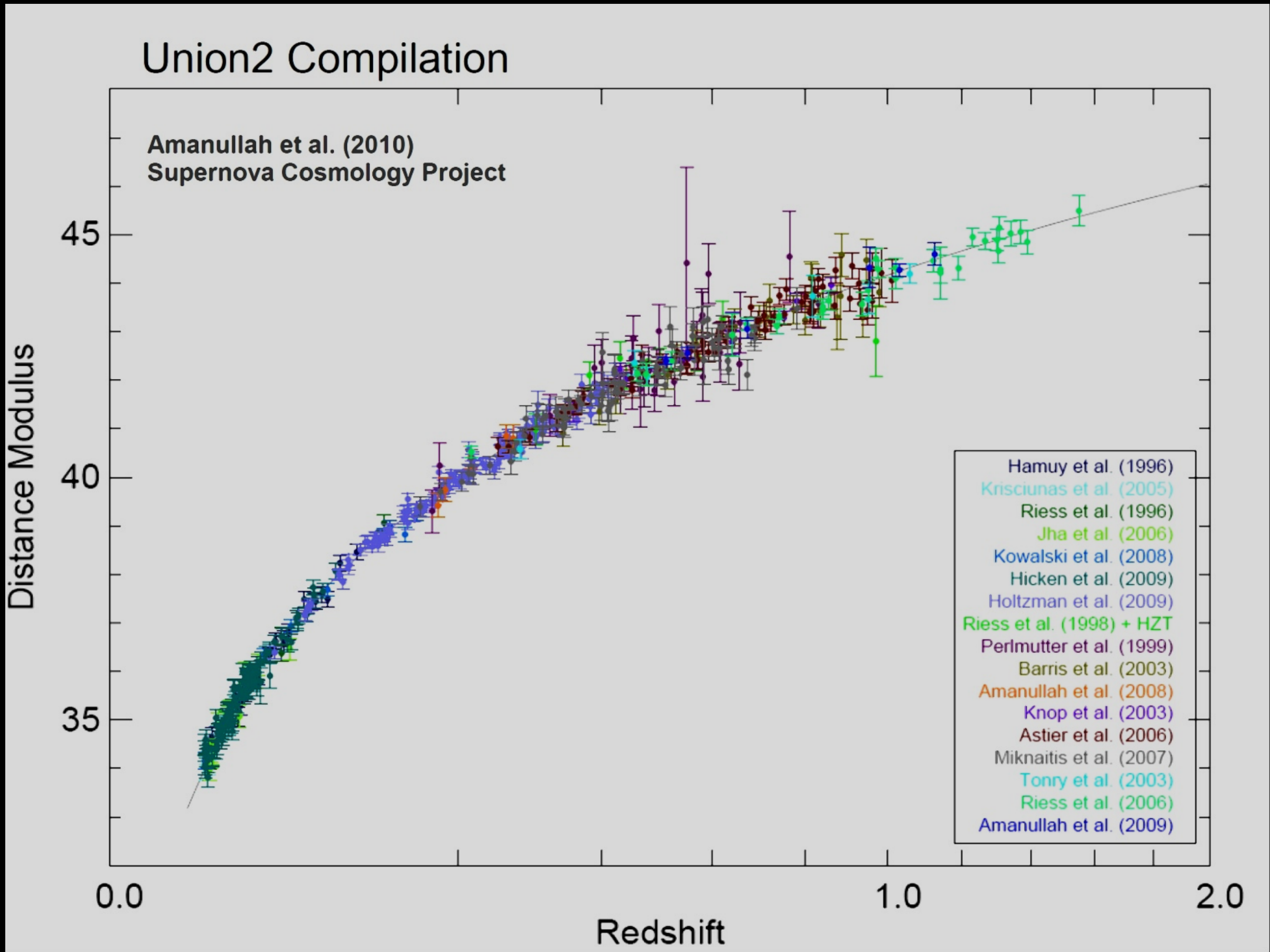
134 orbits ToO
for 6-8 SNe Ia
at 1.2<z<1.8

399 orbits
of deep imaging
for extragalactic
studies

SCP searched for SNIa in high-z rich Galaxy Clusters

Thus finding SNIa in quite a variety of galaxies which are all at one and the same distance

The Union2 Compilation (SCP)



The Astrophysical Journal, 716:712–738, 2010 June 10 doi:10.1088/0004-637X/716/1/712

SPECTRA AND *HUBBLE SPACE TELESCOPE* LIGHT CURVES OF SIX TYPE Ia SUPERNOVAE AT $0.511 < z < 1.12$ AND THE UNION2 COMPILATION*

R. Amanullah[1,2], C. Lidman[2], D. Rubin[3,4], G. Aldering[3], P. Astier[5], K. Barbary[3,4], M. S. Burns[6], A. Conley[7], K. S. Dawson[8], S. E. Deustua[9], M. Doi[10], S. Fabbro[11], L. Faccioli[3,12], H. K. Fakhouri[3,4], G. Folatelli[13], A. S. Fruchter[9], H. Furusawa[14], G. Garavini[1], G. Goldhaber[3,4], A. Goobar[1,2], D. E. Groom[3], I. Hook[15,16], D. A. Howell[17,18], N. Kashikawa[14], A. G. Kim[3], R. A. Knop[19,27], M. Kowalski[20], E. Linder[12], J. Meyers[3,4], T. Morokuma[14,28], S. Nobili[1,2], J. Nordin[1,2], P. E. Nugent[3], L. Östman[1,2], R. Pain[5], N. Panagia[9,21,22], S. Perlmutter[3,4], J. Raux[5], P. Ruiz-Lapuente[23], A. L. Spadafora[3], M. Strovink[3,4], N. Suzuki[3], L. Wang[24], W. M. Wood-Vasey[25], and N. Yasuda[26]
(The Supernova Cosmology Project)

ABSTRACT

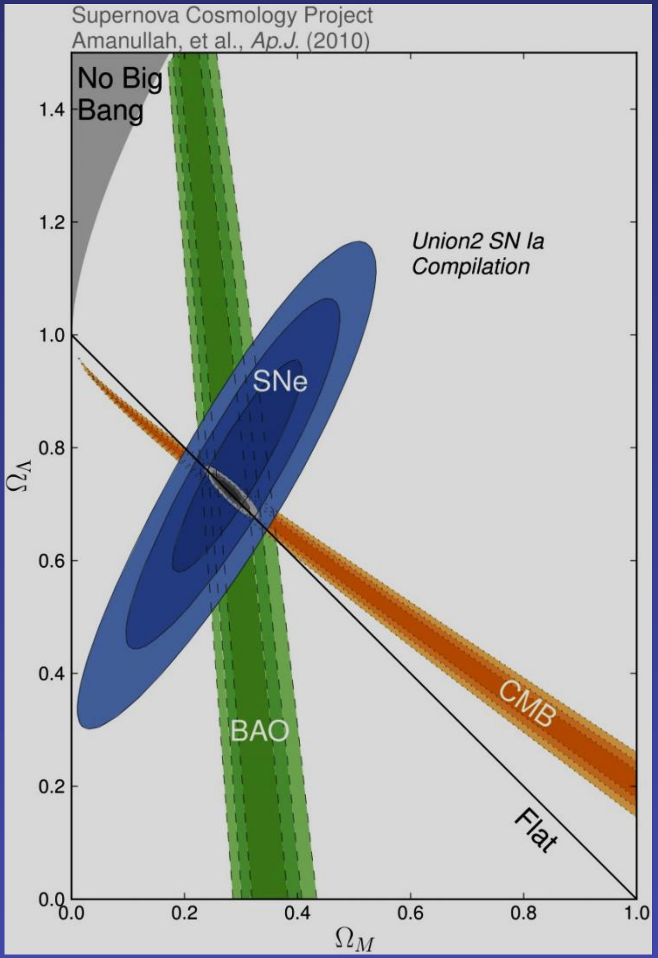
We report on work to increase the number of well-measured Type Ia supernovae (SNe Ia) at high redshifts. Light curves, including high signal-to-noise *Hubble Space Telescope* data, and spectra of six SNe Ia that were discovered during 2001, are presented. Additionally, for the two SNe with $z > 1$, we present ground-based J-band photometry from Gemini and the Very Large Telescope. These are among the most distant SNe Ia for which ground-based near-IR observations have been obtained. We add these six SNe Ia together with other data sets that have recently become available in the literature to the Union compilation. We have made a number of refinements to the Union analysis chain, the most important ones being the refitting of all light curves with the SALT2 fitter and an improved handling of systematic errors. We call this new compilation, consisting of 557 SNe, the Union2 compilation. The flat concordance ΛCDM model remains an excellent fit to the Union2 data with the best-fit constant equation-of-state parameter $w = -0.997^{+0.050}_{-0.054}$(stat)$^{+0.077}_{-0.082}$(stat + sys together) for a flat universe, or $w = -1.038^{+0.056}_{-0.059}$(stat)$^{+0.093}_{-0.097}$(stat + sys together) with curvature. We also present improved constraints on $w(z)$. While no significant change in w with redshift is detected, there is still considerable room for evolution in w. The strength of the constraints depends strongly on redshift. In particular, at $z \gtrsim 1$, the existence and nature of dark energy are only weakly constrained by the data.

A Blast from the Past

- The two teams consistently found that SNIa at redshifts $z \sim 0.5$ appear dimmer than expected by ~0.3 magnitudes.

- This *suggests* that the expansion of the Universe is *accelerating*, propelled by "dark energy", with $\Omega_\Lambda \sim 0.7$.

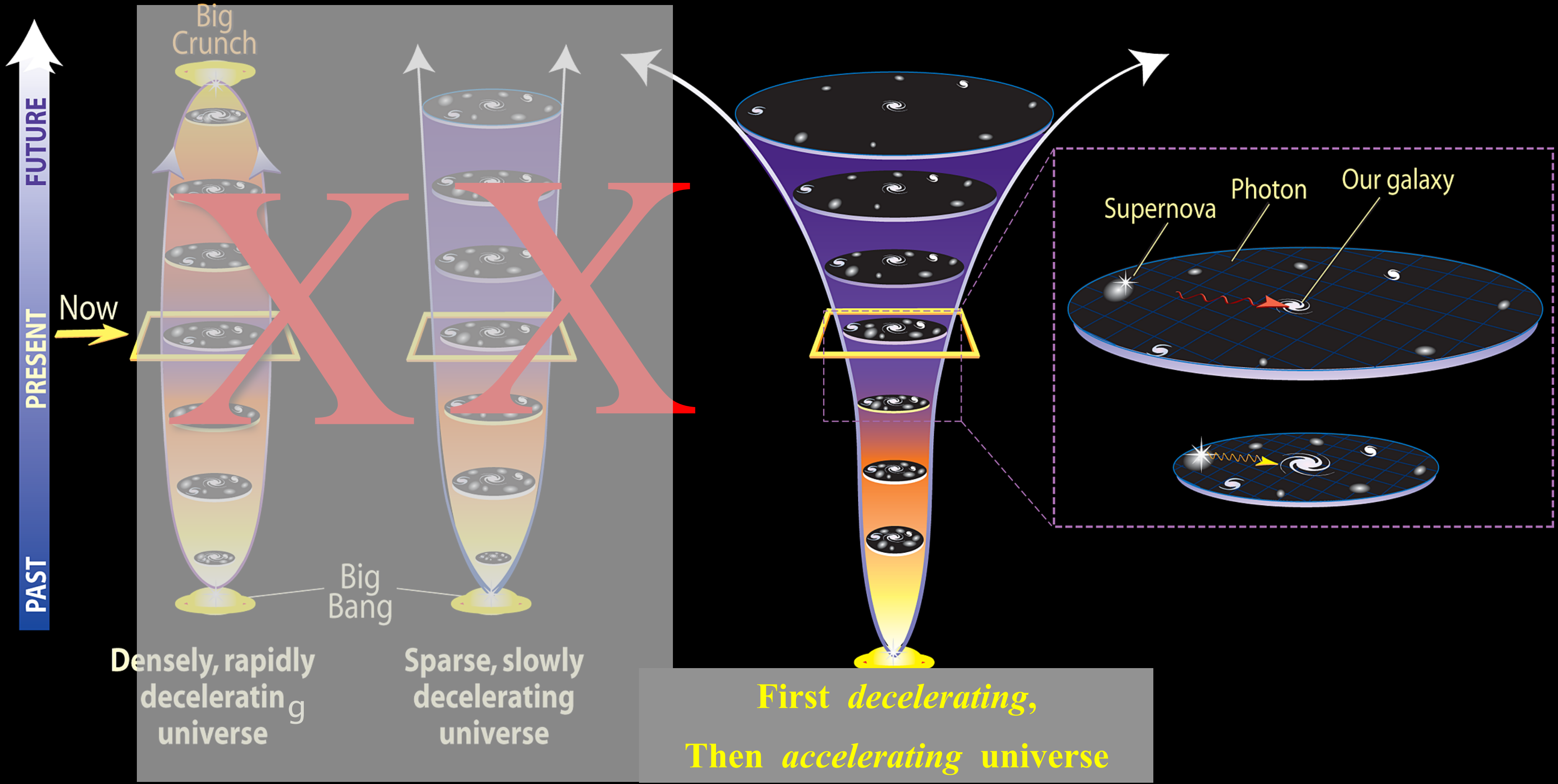
- This conclusion is also consistent with measurements of the Cosmic Microwave Background fluctuations.



THE ACCELERATING UNIVERSE

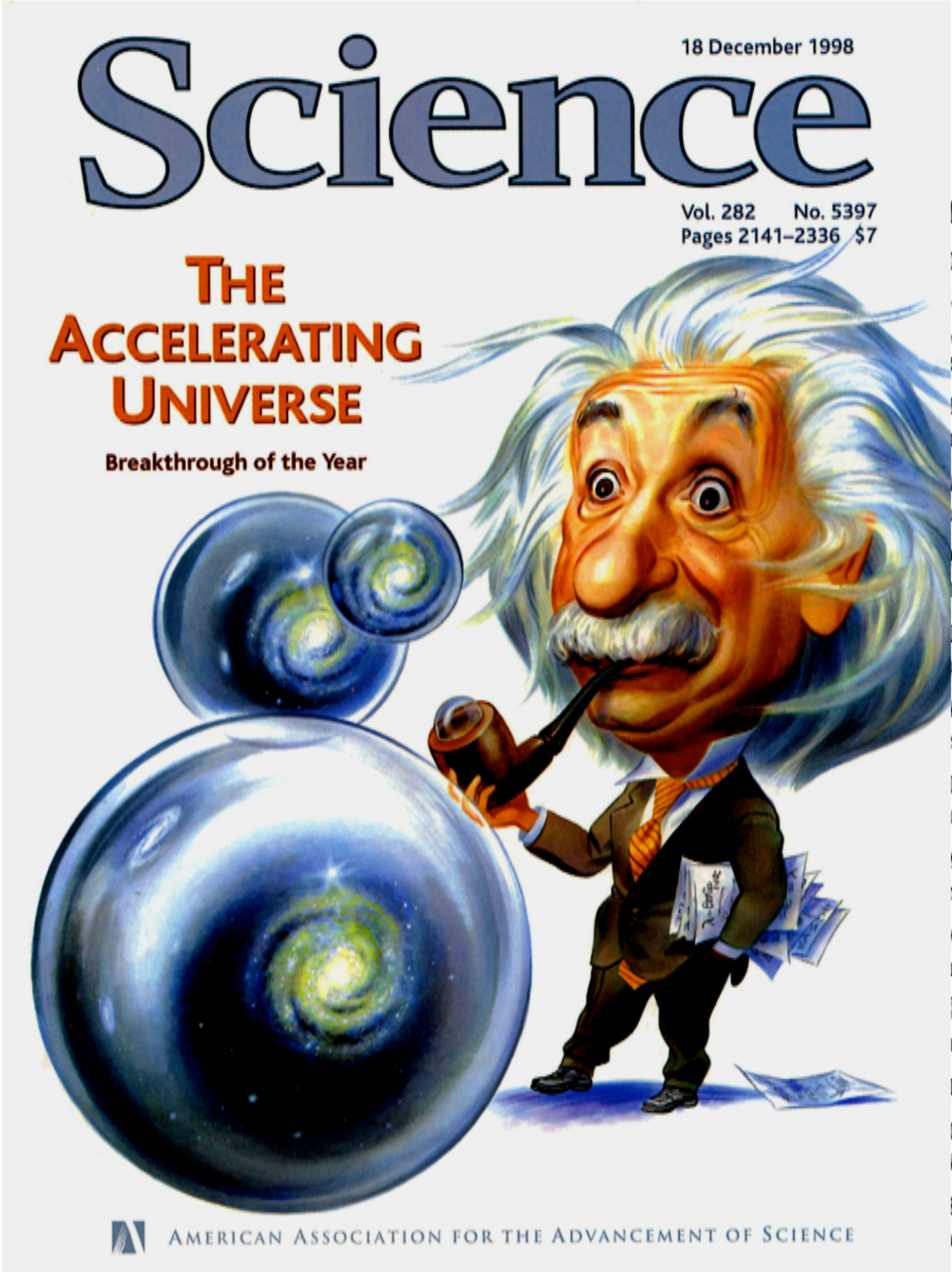
Universe now expanding ~20% faster than 5 billion years ago

Models of the Expanding Universe



Titles and authors of the first THREE papers on the Acceleration of the Universe

THE ACCELERATING UNIVERSE



SCP, 1999

I 42 HIGH-REDSHIFT SUPERNOVAE

OP, P. NUGENT, P. G. CASTRO,[2] S. DEUSTUA, S. FABBRO,[3]
[1,6] M. Y. KIM, J. C. LEE,[7] N. J. NUNES,[2] R. PAIN,[3]
[8] AND R. QUIMBY
ence Berkeley National Laboratory, Berkeley, CA 94720

MAN
rvatory, La Silla, Chile

AND R. G. MCMAHON
mbridge, England, UK

APUENTE
ty of Barcelona, Barcelona, Spain

LTON
, La Palma, Spain

AEFER
University, New Haven, CT

OYLE
tory, Sydney, Australia

ND T. MATHESON
sity of California, Berkeley, CA

ND N. PANAGIA[9]
stitute, Baltimore, MD

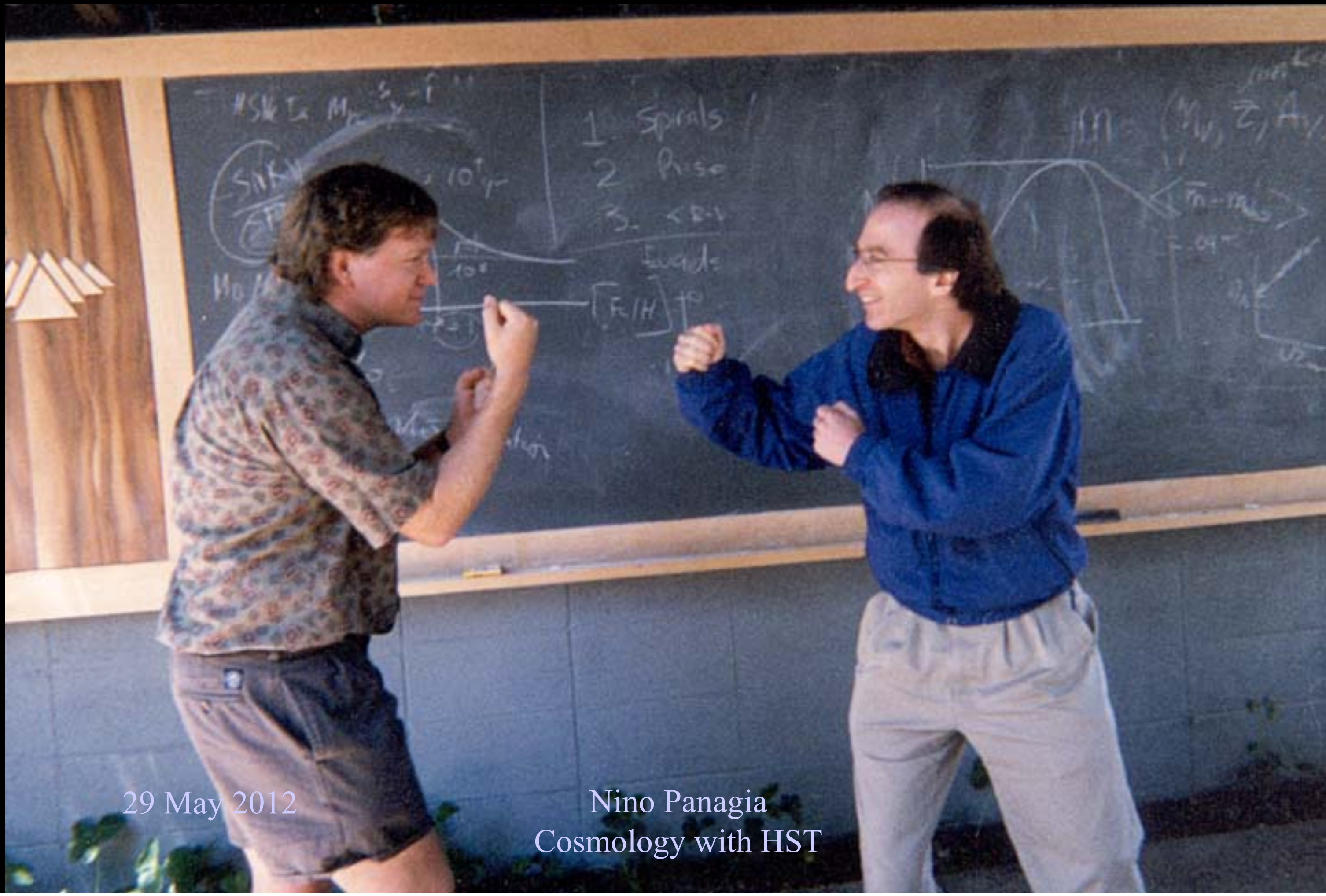
EWBERG
ratory, Batavia, IL

D

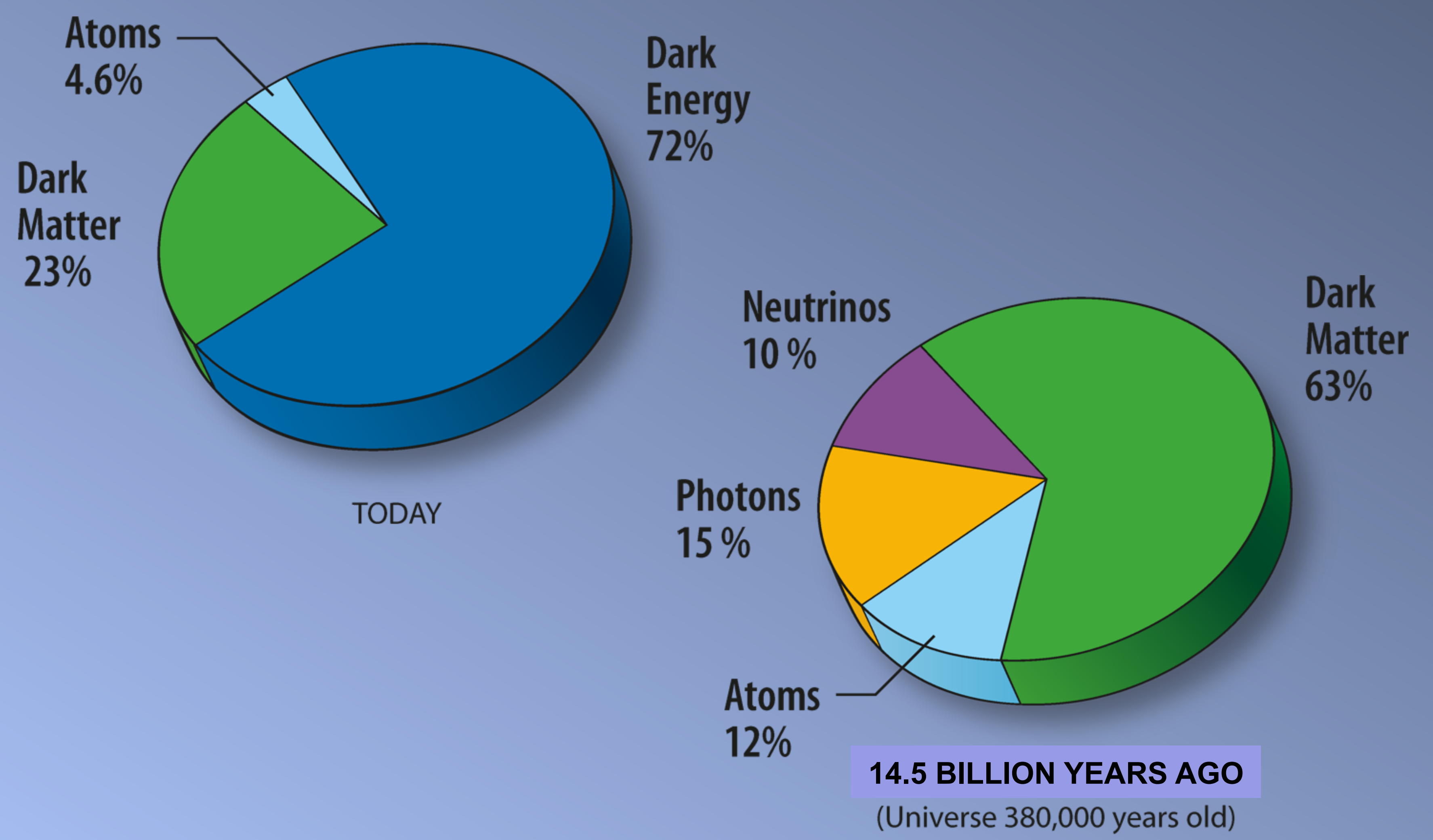
OUCH
Vales, Sydney, Australia

SMOLOGY PROJECT)
ccepted 1998 December 17

Friendly competition: Brian Schmidt and Saul Perlmutter at 1999 Aspen Workshop



Composition of the Cosmos



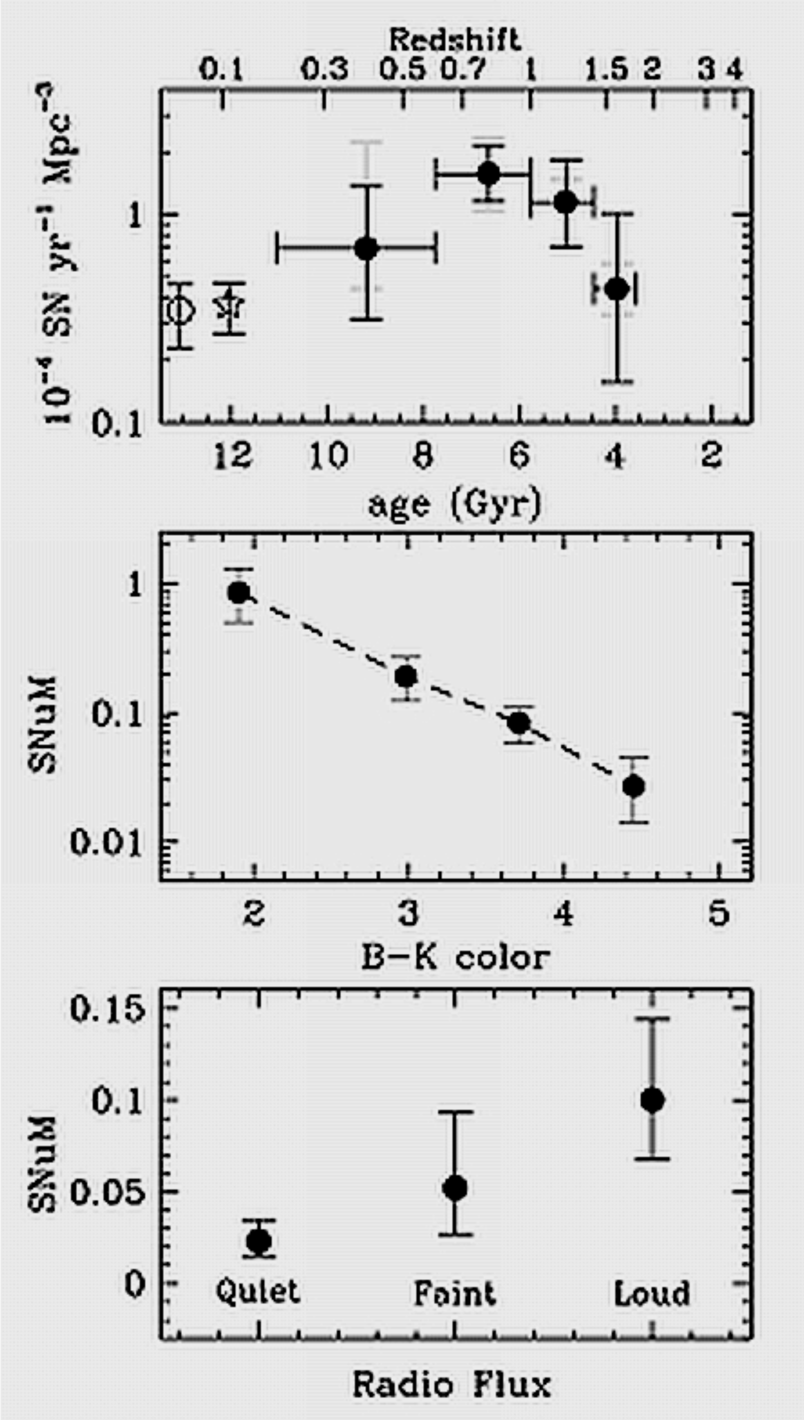
These results are ***truly*** exciting, but…

Still SNIa at high redshifts may be dimmer because of *non-monotonic* luminosity evolution.

Could SNIa evolution be non monotonic?

maybe…

SNIa Rates in various Galaxy Types



a) Rates as a function of cosmic age

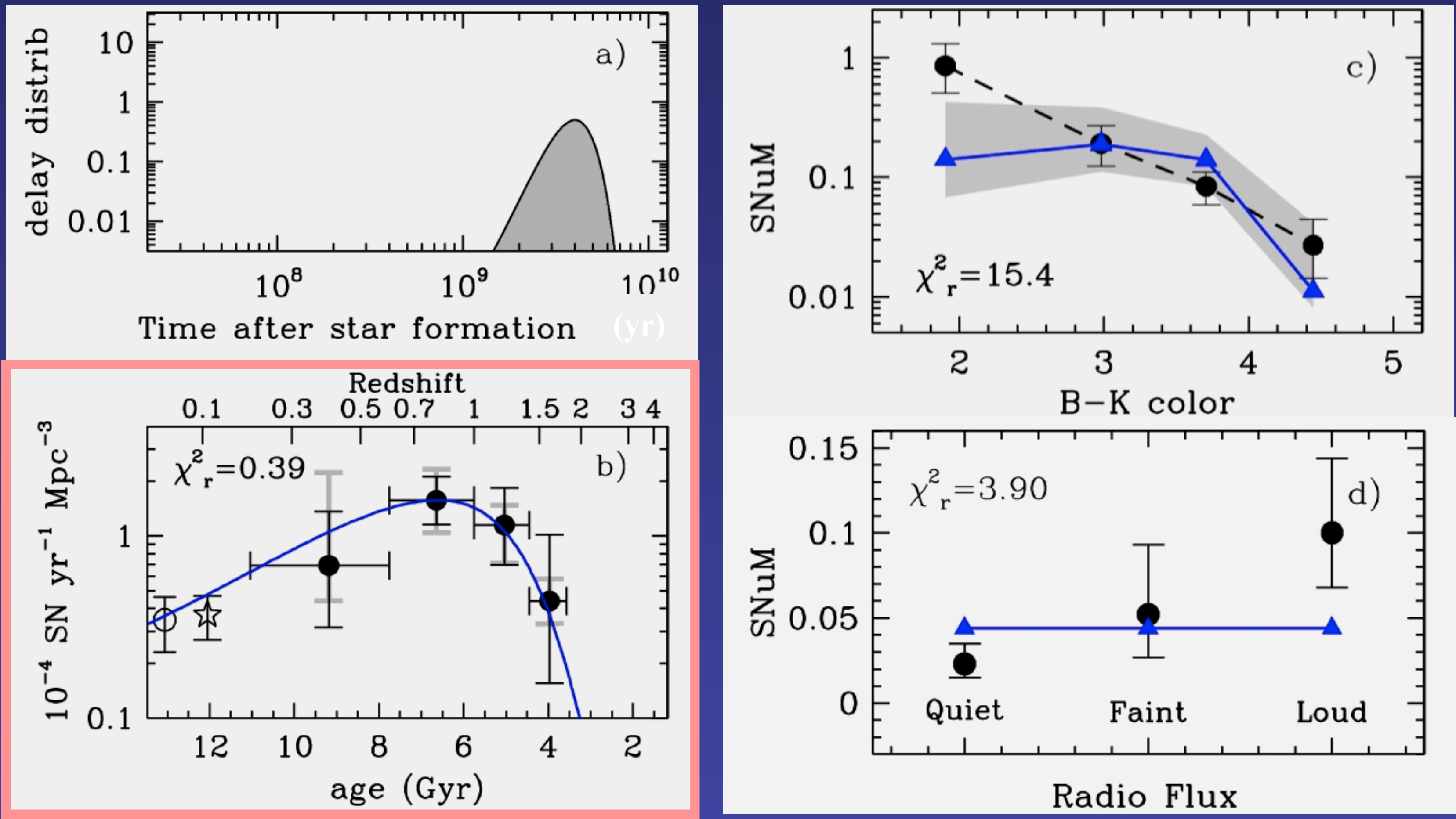
Mannucci et al. 2006

b) Rates as a function of galaxy color

c) Rates in Ellipticals as a function of their radio emission

Deriving the Delay Time Distribution (DTD): *single gaussian* fitting SN rates vs. z

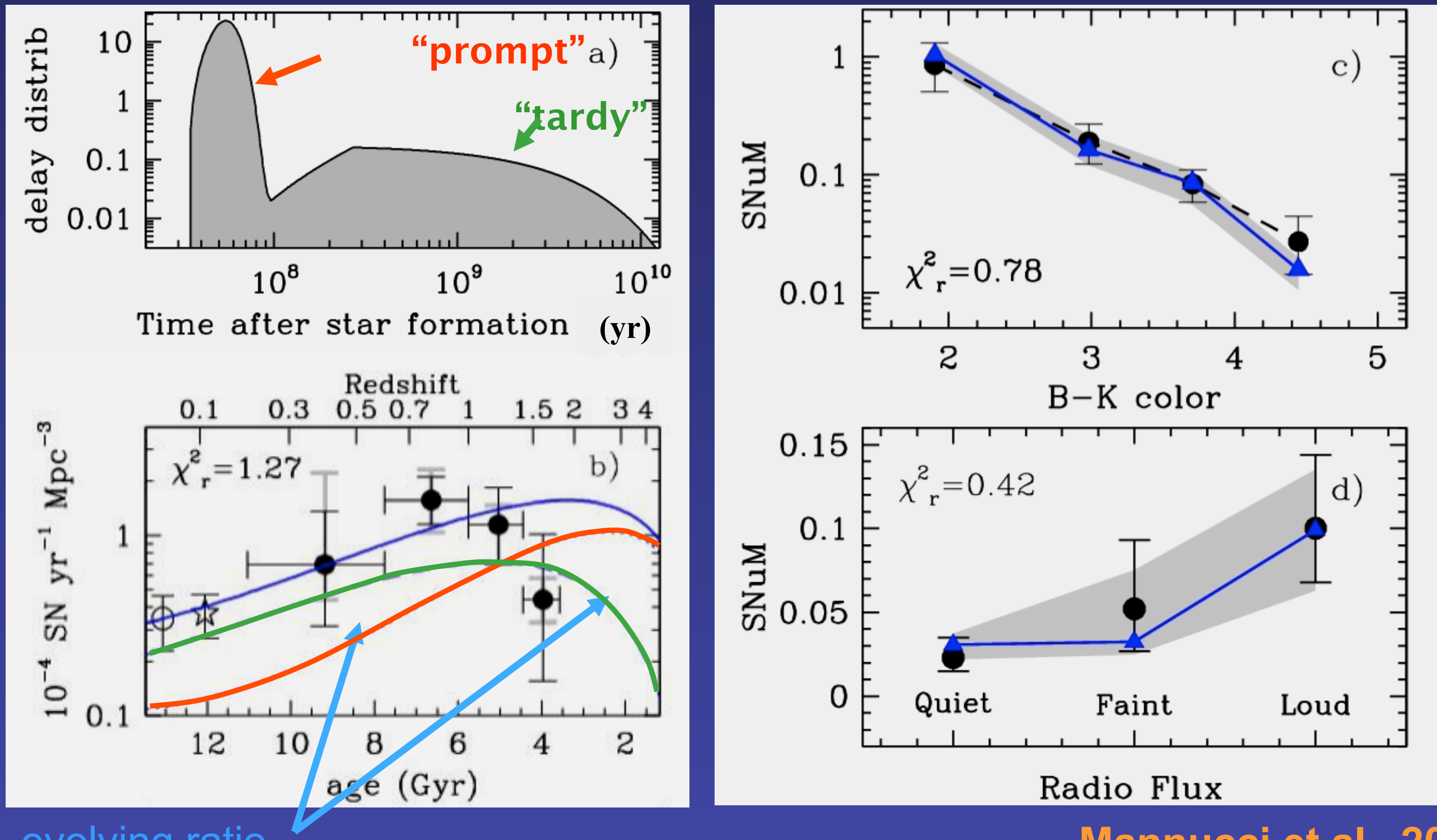
single population: gaussian, 3.4 Gyr



Mannucci et al., 2006

Deriving the DTD: Two-population scenario

Two populations: 50% prompt + 50% exp



Mannucci et al., 2006

TWO SNIa components, i.e. about 1/2 ***prompt*** and 1/2 ***tardy*** exploders, are **needed**

- To account for a factor of 4 enhancement of SNIa explosions in radio ellipticals (Della Valle et al. 2005)
- To account for the SNIa rate behaviour as a function of galaxy type and/or galaxy color

Warning:

Dimmer SNIa at ***z~0.5***
and
Brighter SNIa at ***z~1.5***
may not be the conclusive proof
of an accelerated Universe.

"The final answer will be provided by many more high-z SNIa observations, which will confirm, revise or reject the current conclusions."

Freely adapted from "The Consultation of the 3 Doctors" at Pinocchio's sickbed
[Collodi: "Le Avventure di Pinocchio"]

a pragmatic conclusion about

An Accelerating Universe…

Se non e` vero…

E` ben trovato!

Italian saying

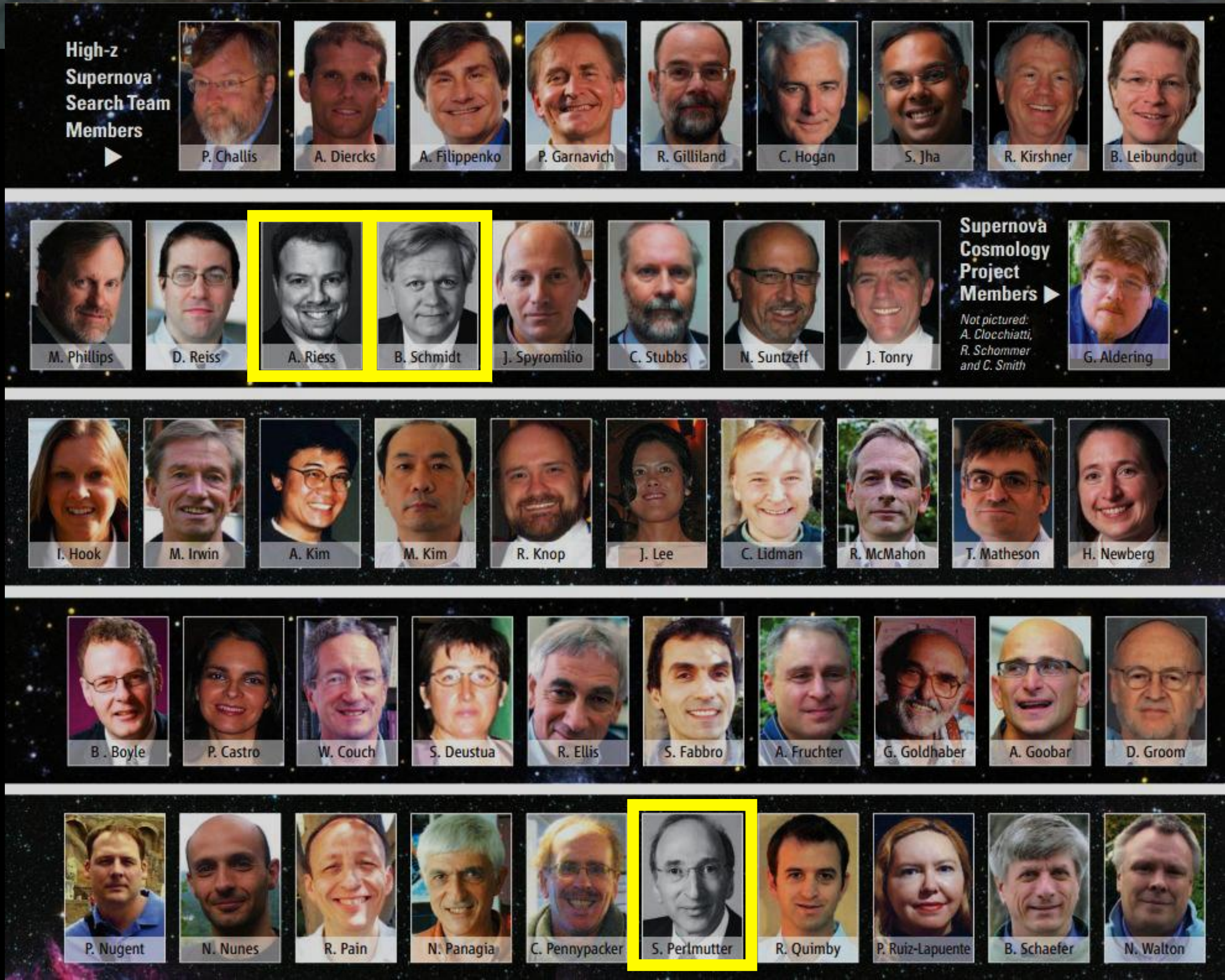
…if it is not true,
it is well conceived…

hence… 2011 Nobel Prize!

Saul Perlmutter

Adam Riess & Brian Schmidt

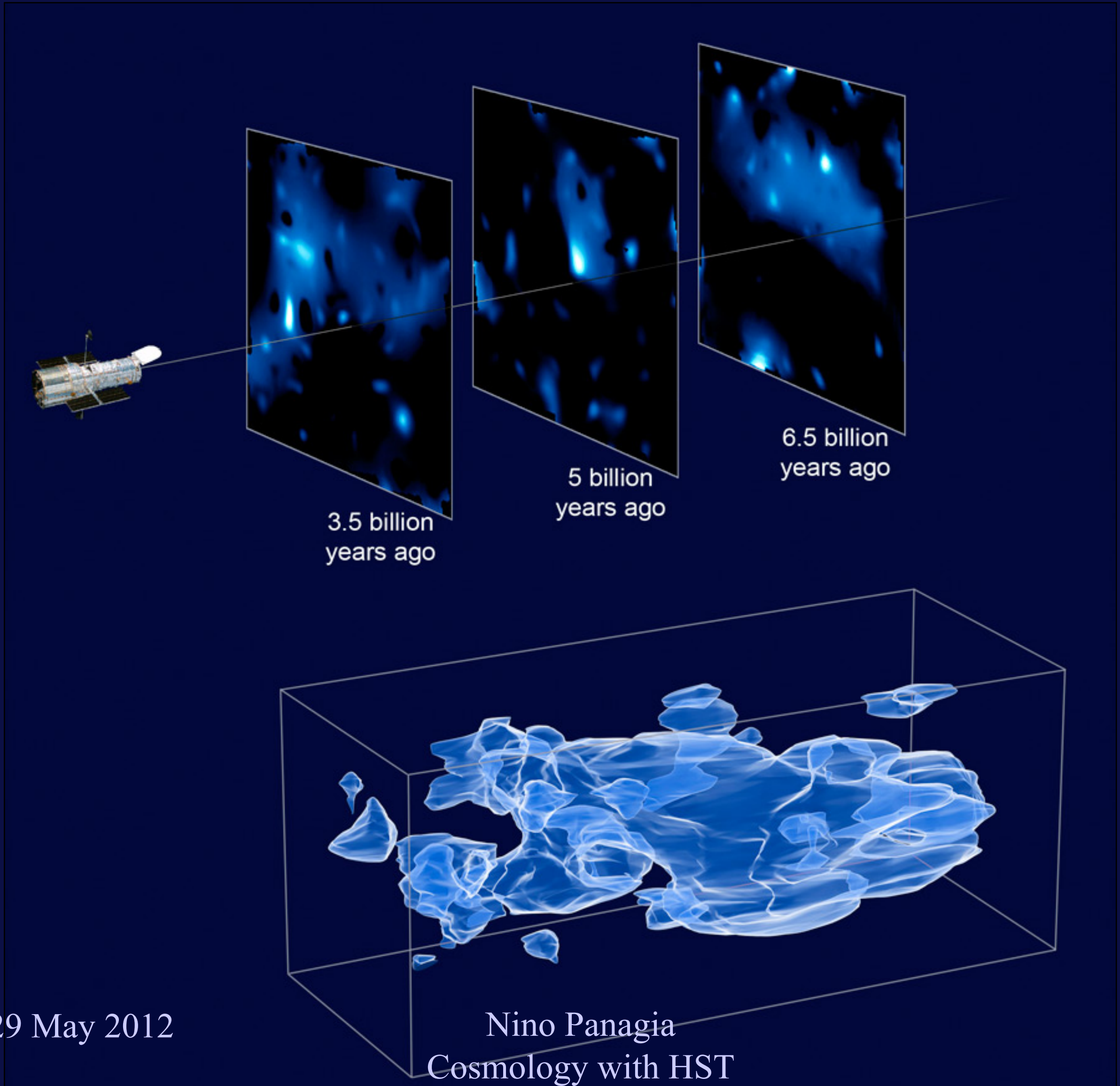
The Two Teams



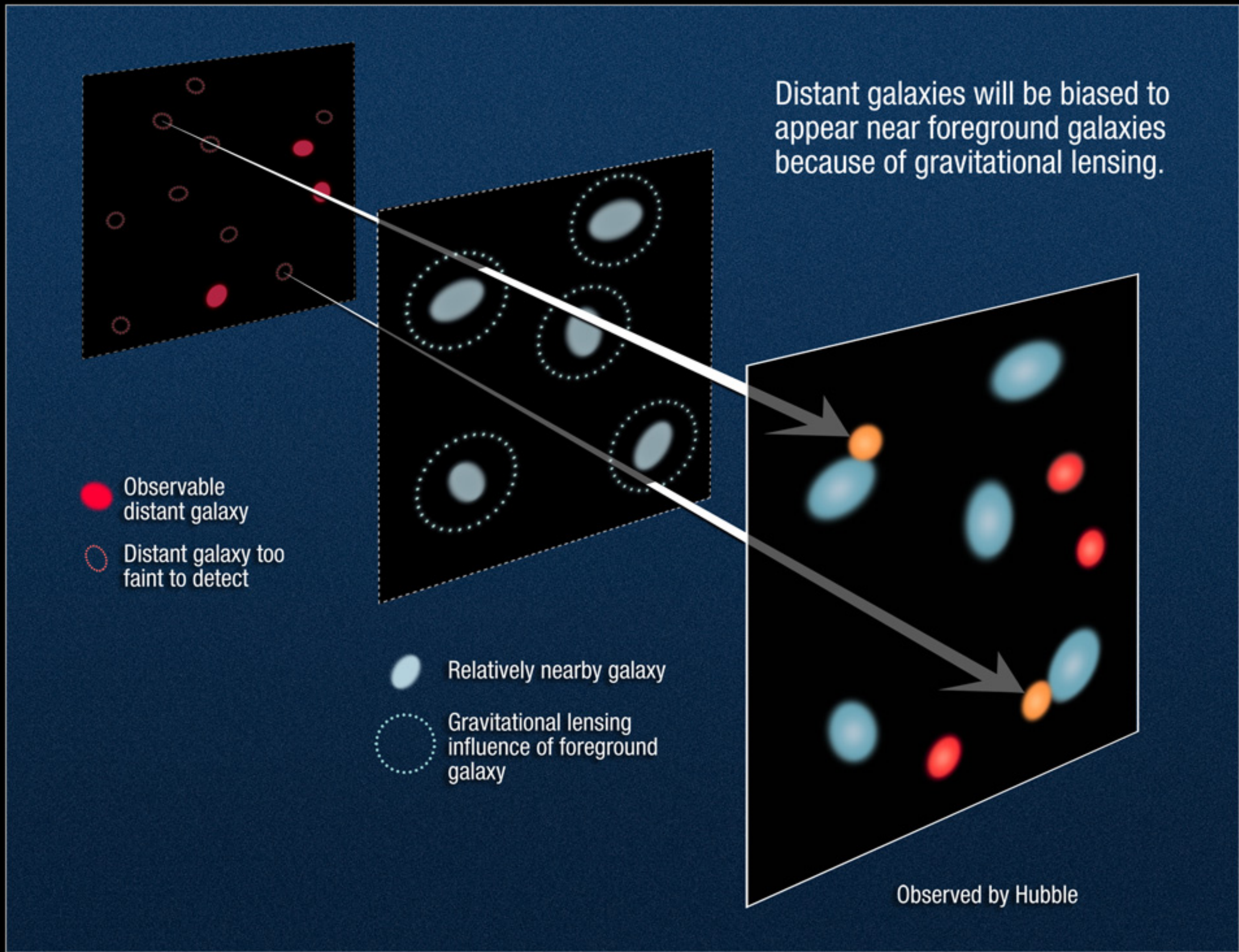
Dark Matter


Bullet Cluster
Nino Panagia
Cosmology with HST

3-D Distribution of Dark Matter



Gravitational Lensing Effects



NASA, ESA, and Z. Levay and A. Feild (STScI)

STScI-PRC11-04

Gravitational Lensing: Cosmic Magnifiers

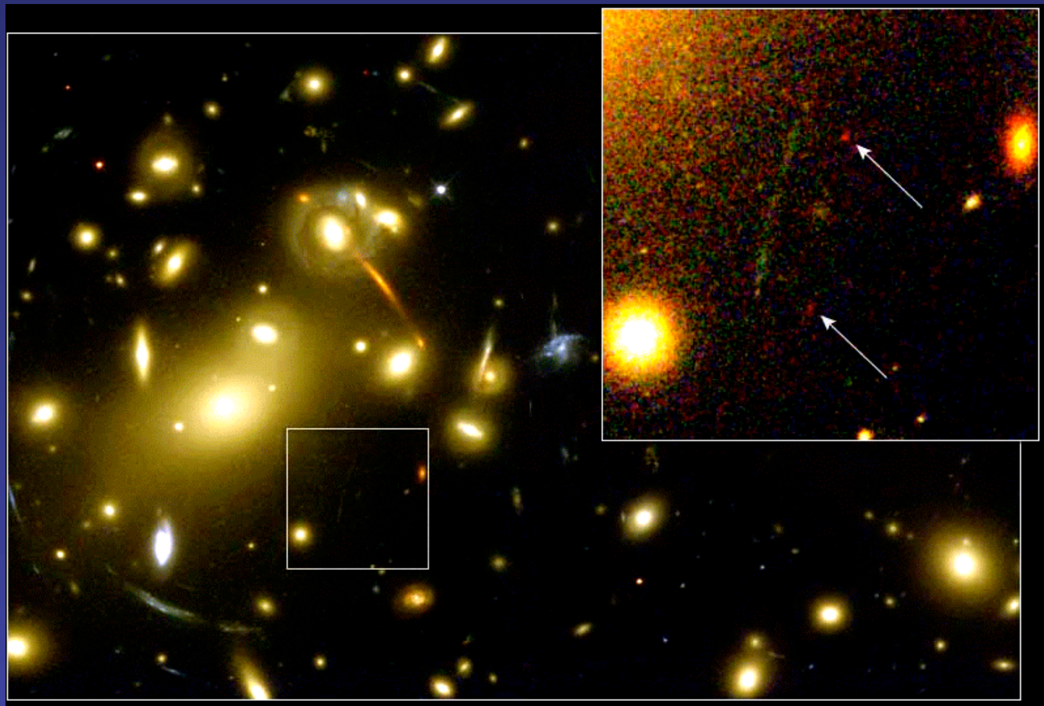
Galaxy Cluster Abell 2218 **HST • WFPC2**

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

A galaxy building block at z≈6

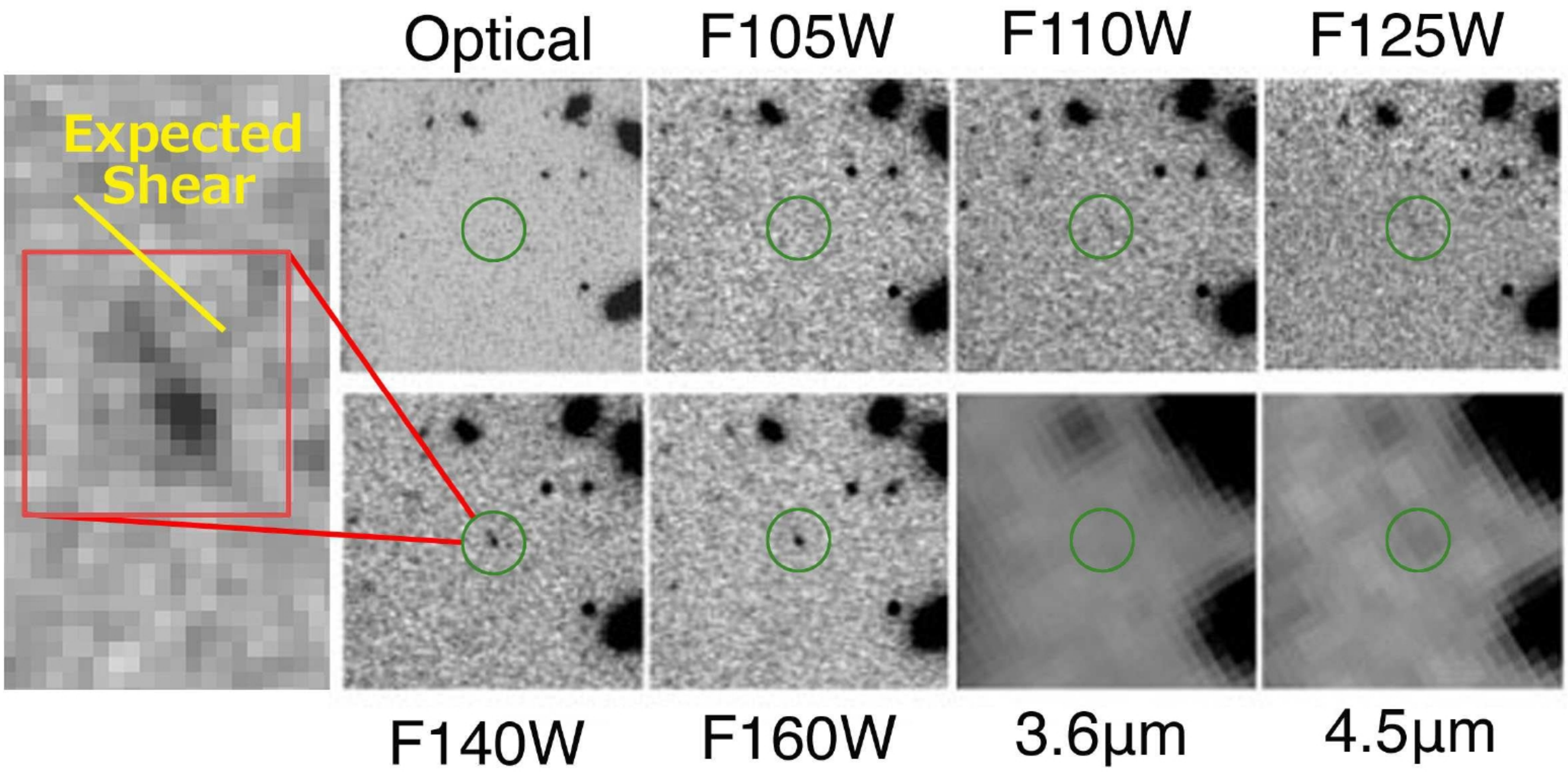
Combined HST-WFPC2 and Keck observations have revealed the most distant dwarf galaxy ever found

Gravitationally lensed (×33) by the Abell 2218 galaxy cluster, the small red galaxy is estimated to be at a redshift z=5.6, to have a mass of about $10^6\ M_\odot$, and a young stellar population as young as 2-3 Myrs.


Distant Object Gravitationally Lensed by Galaxy Cluster Abell 2218 HST • WFPC2

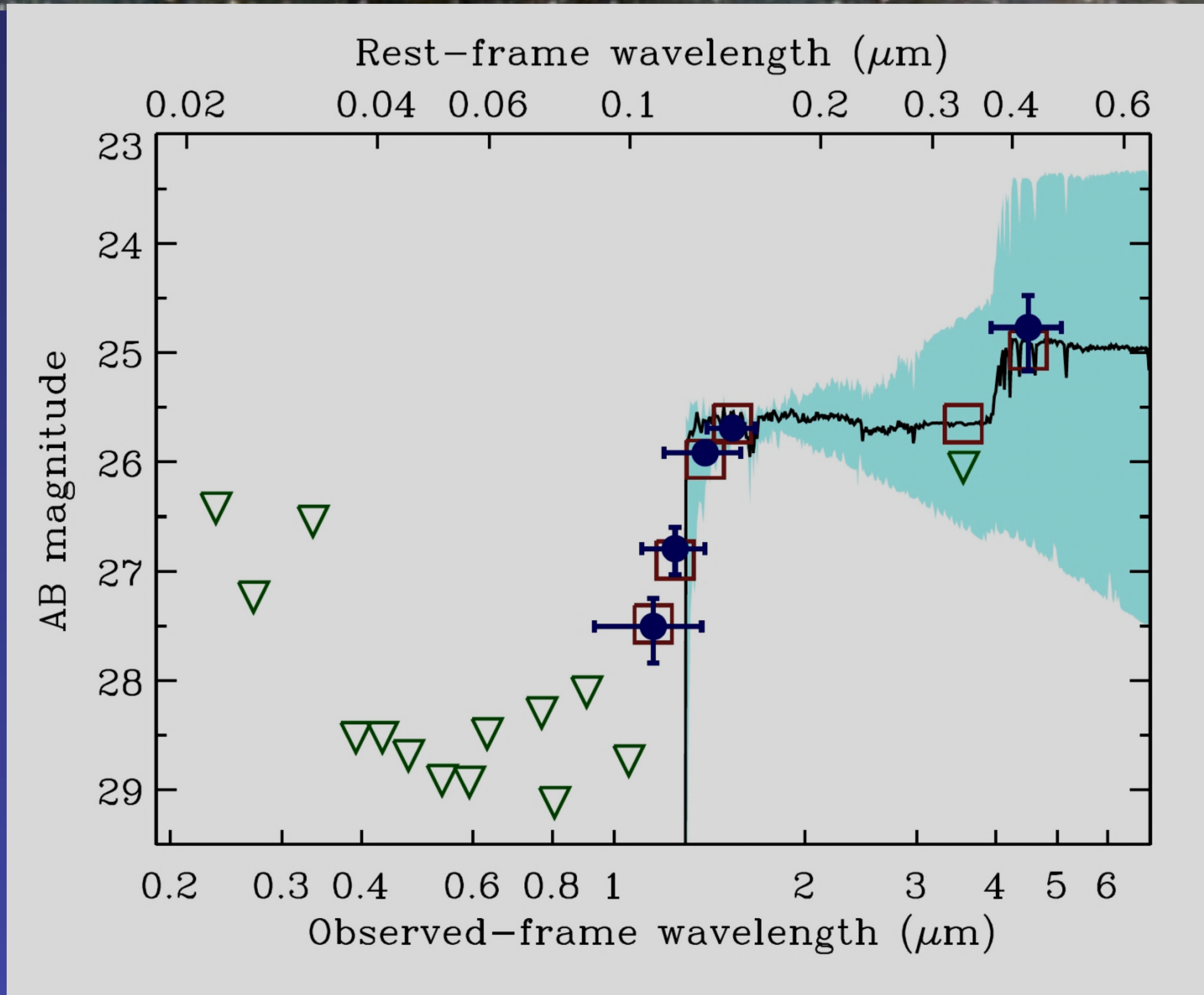
R. Ellis *et al* . 2001

Magnified Dwarf Galaxy at z~10

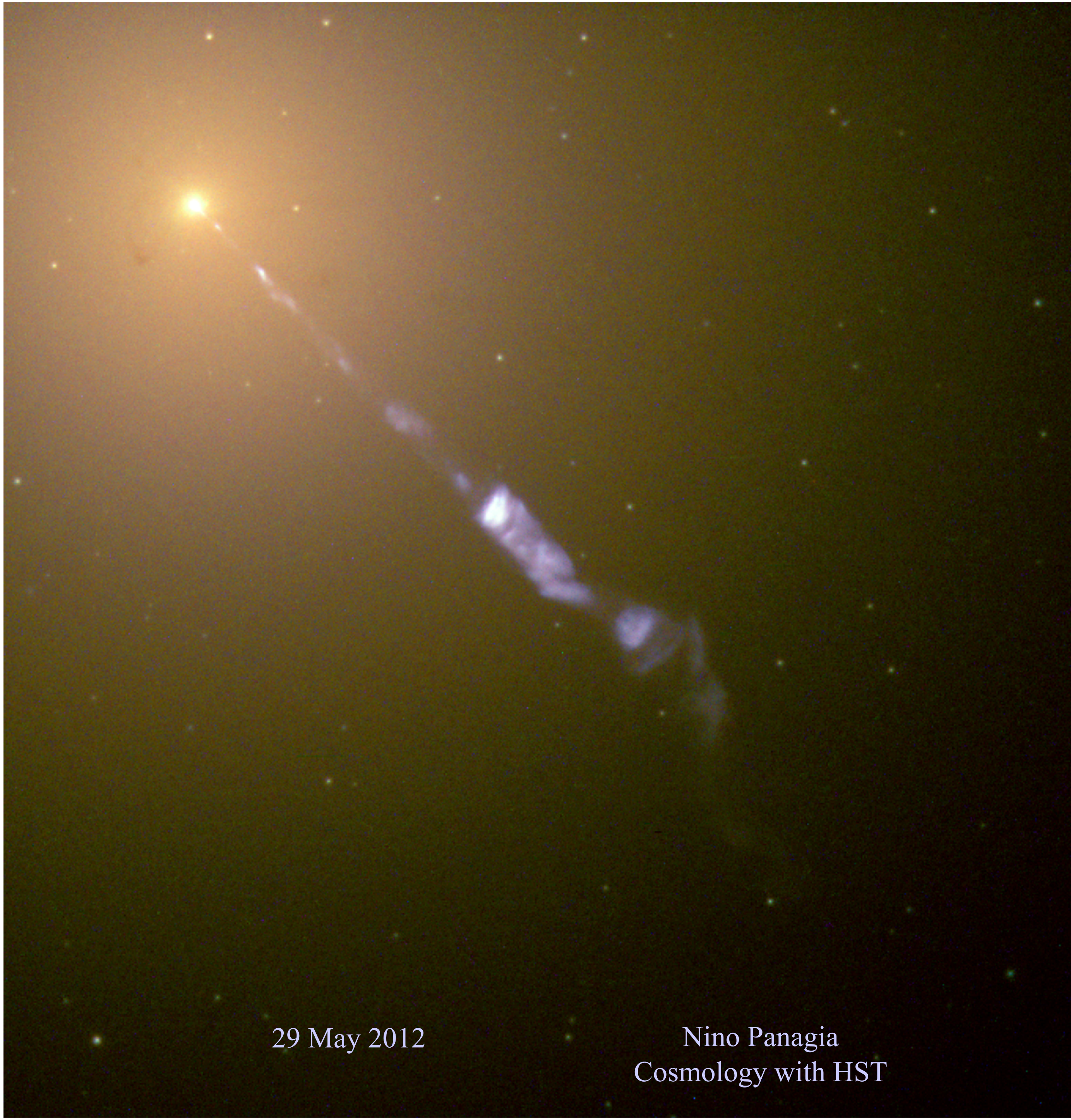


Wei Zheng, Marc Postman et al. 2012

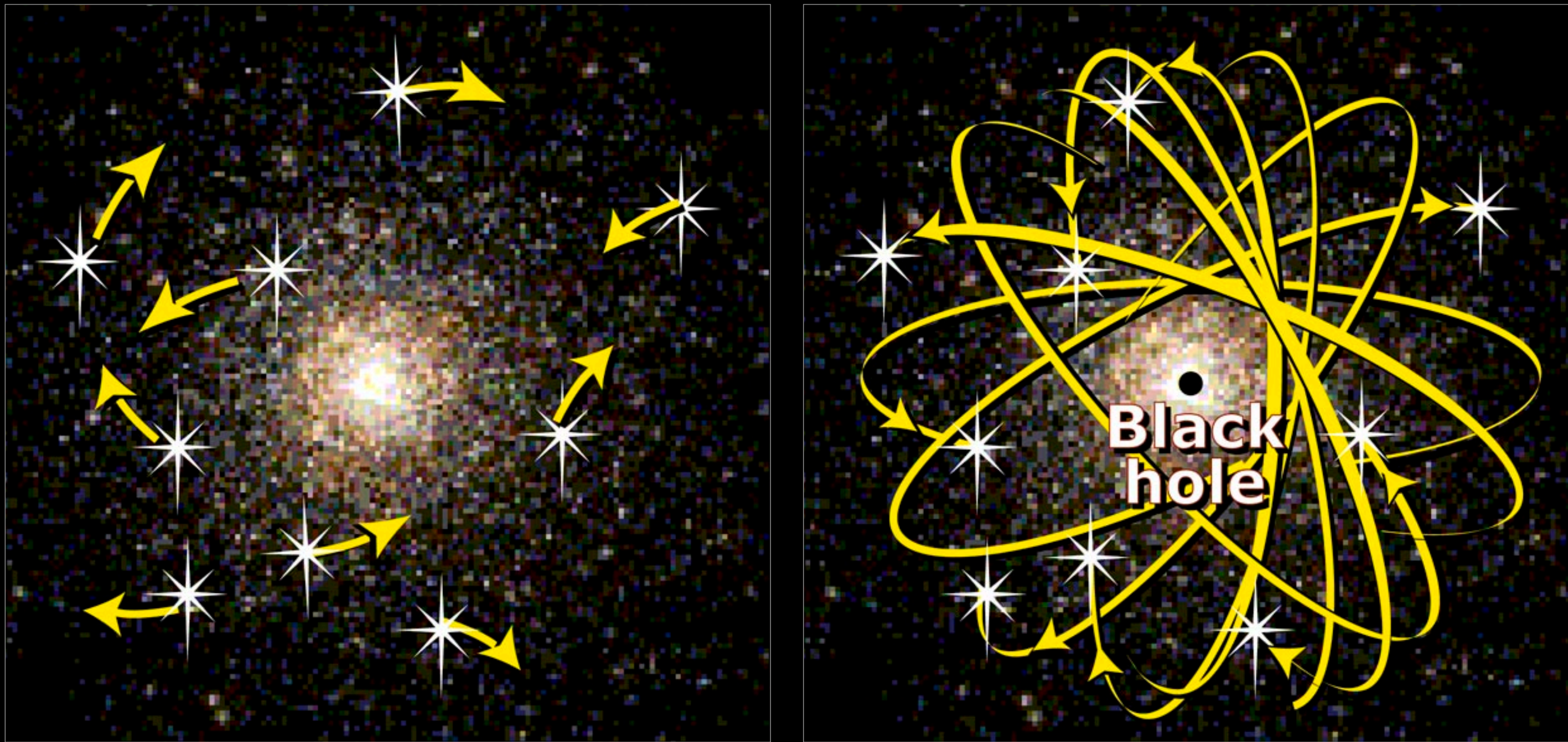
Magnified Dwarf Galaxy at z~10



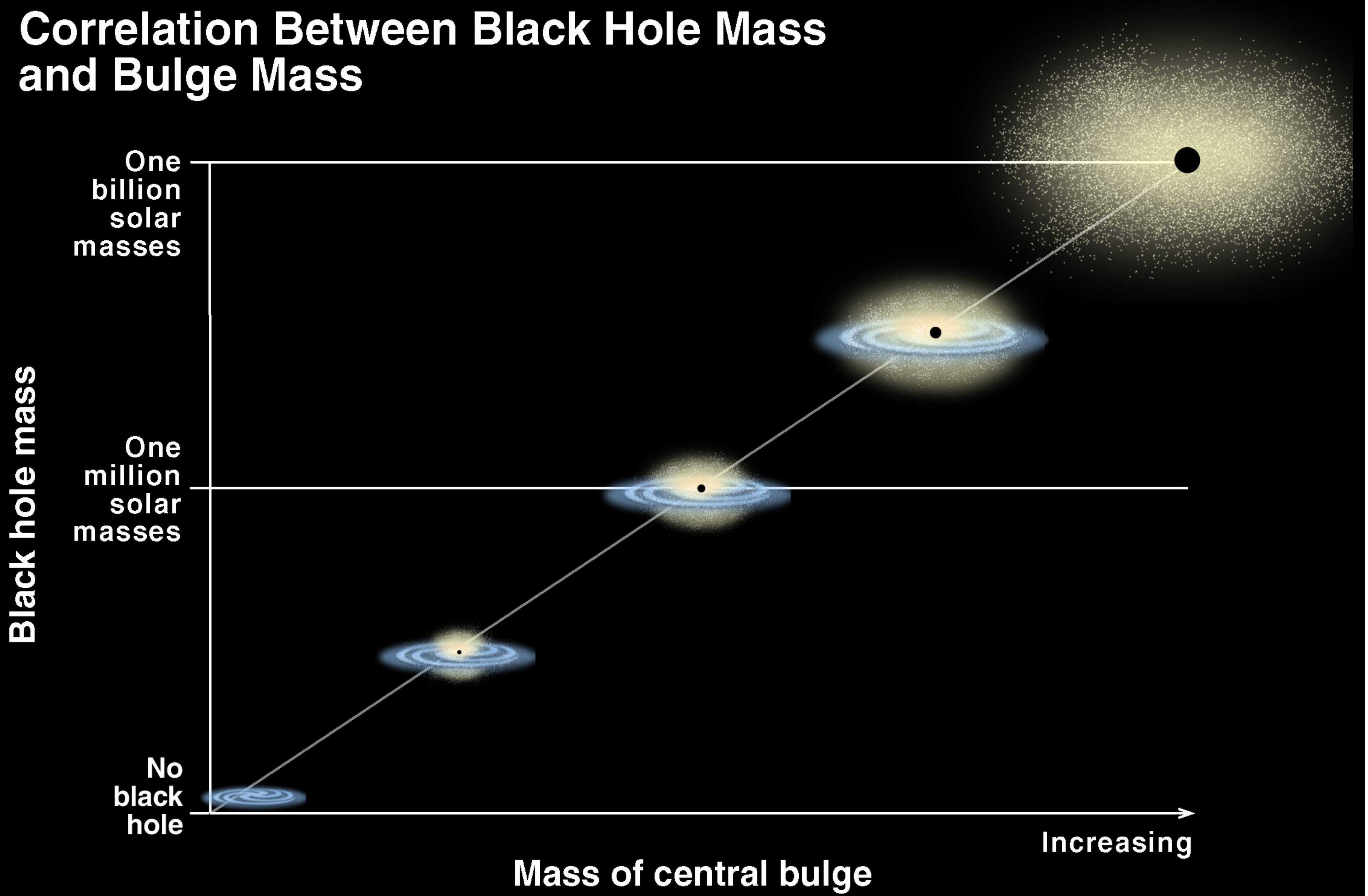
Supermassive Black Holes in Centers of Galaxies



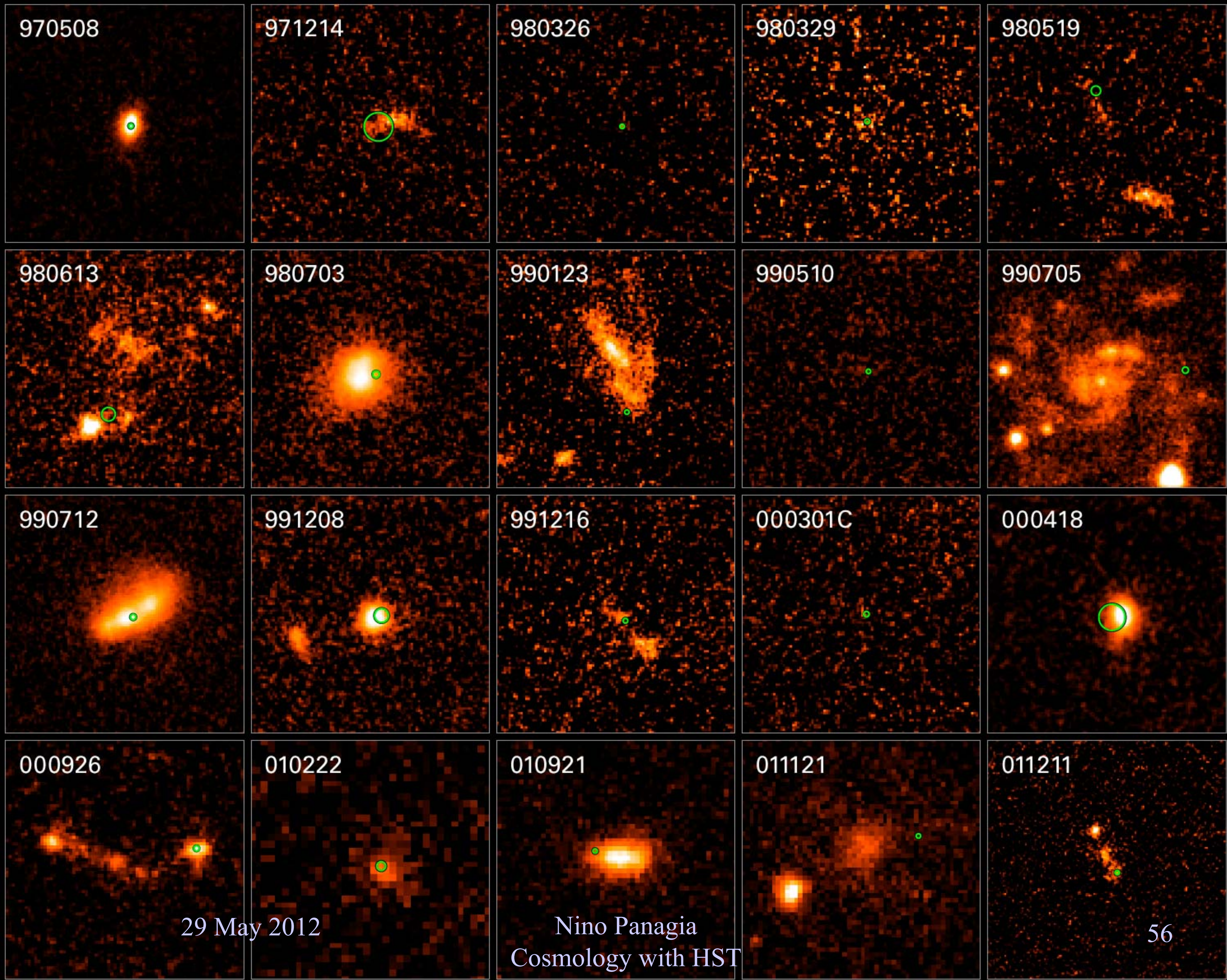
M87


Black
hole

Correlation Between Black Hole Mass and Bulge Mass



Gamma Ray Bursts

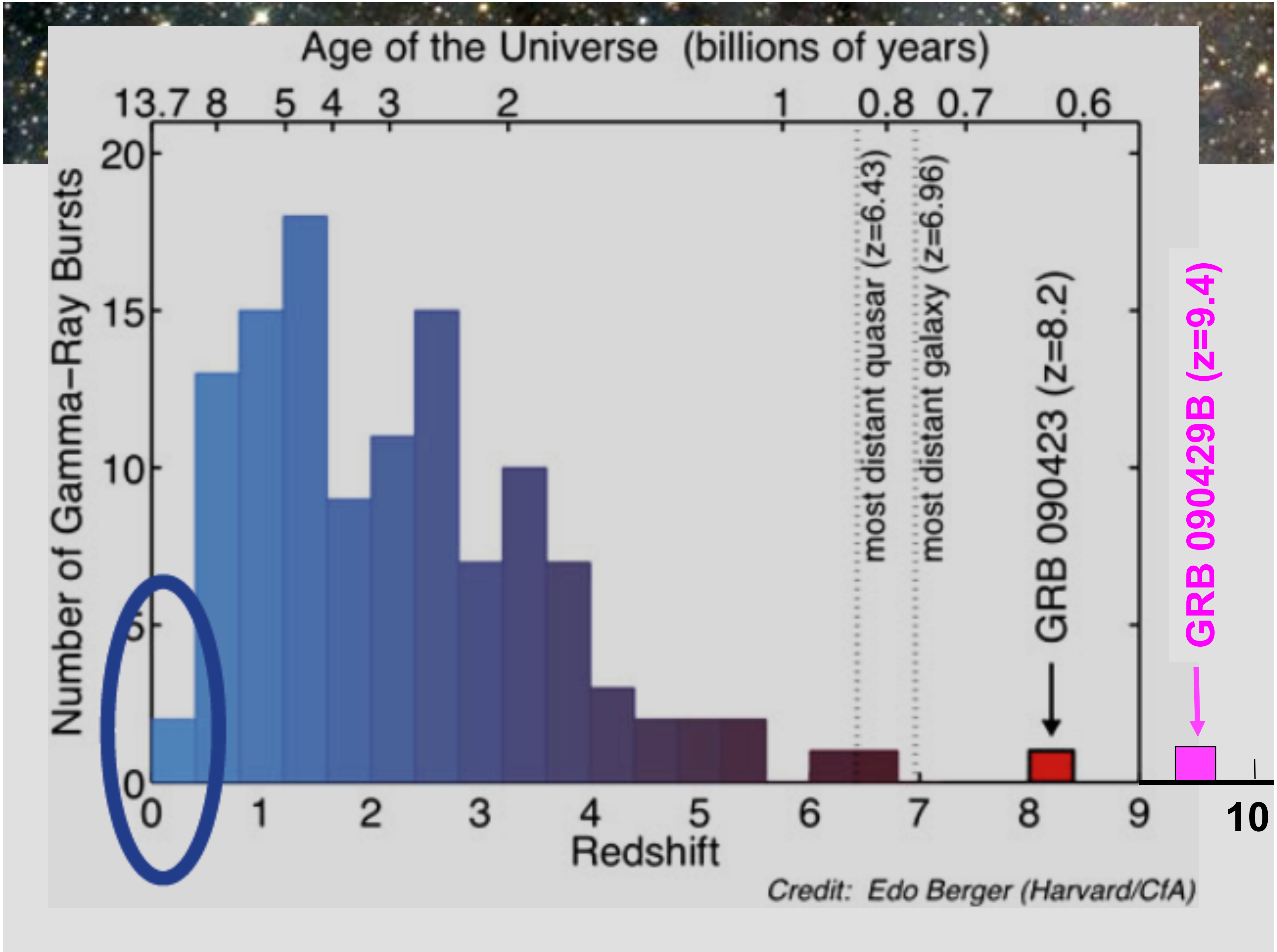

970508
971214
980326
980329
980519
980613
980703
990123
990510
990705
990712
991208
991216
000301C
000418
000926
010222
010921
011121
011211

Most Distant GRBs

Most Distant GRB Titleholders

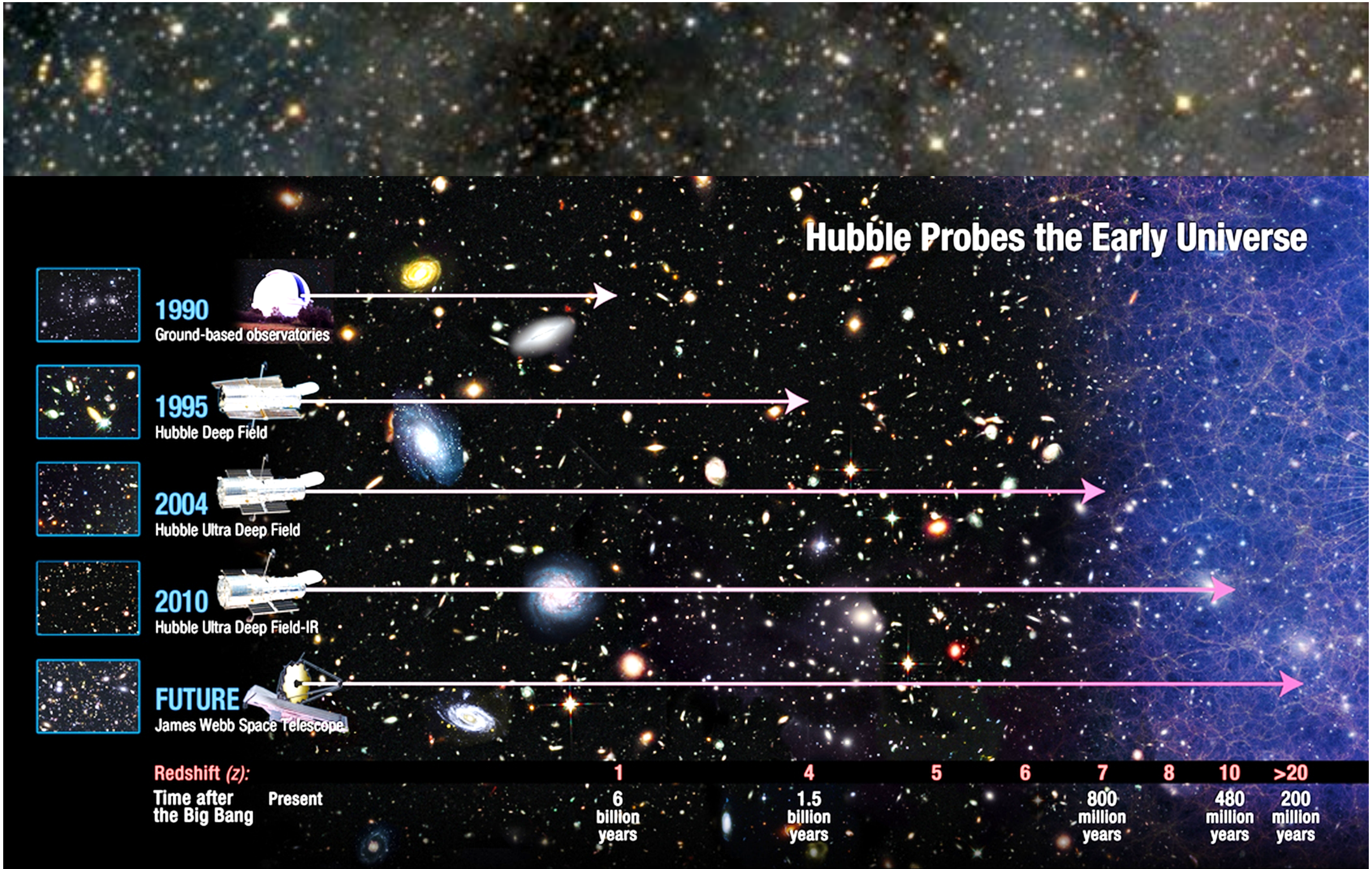
GRB	Date	Distance	Notes
GRB 090429B	May 2011 —	z=9.4	The GRB was observed in 2009, however its distance was not announced until 2011. [2]
GRB 090423	April 2009 — May 2011	z=8.2	This was the first GRB to become the most distant object in the universe. [8]
GRB 080913	September 2008 — April 2009	z=6.7	[8][10]
GRB 050904	September 2005 — September 2008	z=6.29	[10][9][11]
GRB 000131	January 2000 — September 2005	z=4.50	[11][12][13]
GRB 971214	December 1997 — January 2000	z=3.42	[5][12][13]
GRB 970508	May 1997 — December 1997	z=0.835	First GRB with its distance determined [5]

Valuable probes of star formation in the Universe

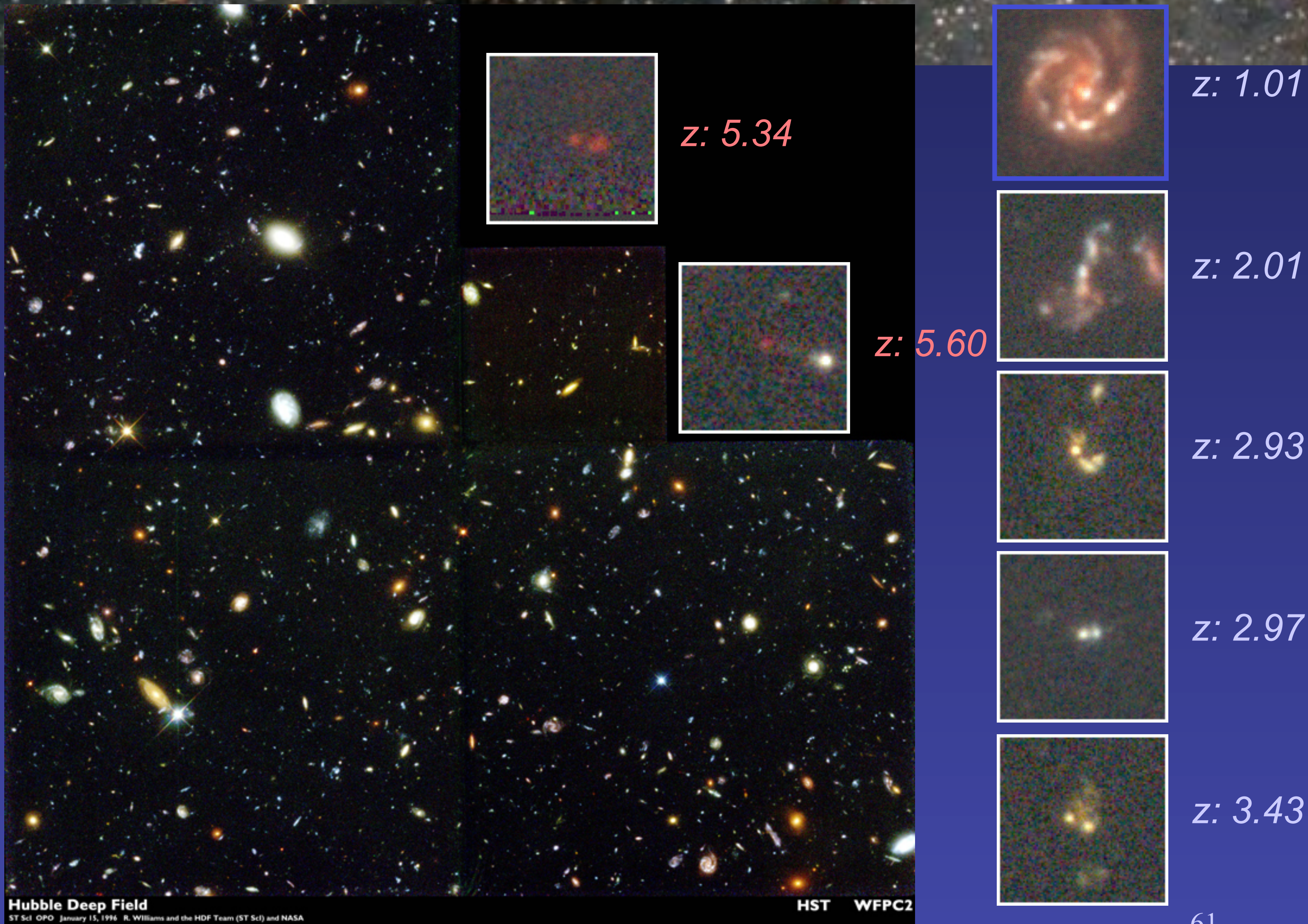

Age of the Universe (billions of years)
13.7 8 5 4 3 2 1 0.8 0.7 0.6
Number of Gamma-Ray Bursts
0 5 10 15 20
most distant quasar (z=6.43)
most distant galaxy (z=6.96)
GRB 090423 (z=8.2)
GRB 090429B (z=9.4)
0 1 2 3 4 5 6 7 8 9 10
Redshift
Credit: Edo Berger (Harvard/CfA)

The Evolution of Galaxies and

the Cosmic Star Formation Rate


Hubble Probes the Early Universe
1990
Ground-based observatories
1995
Hubble Deep Field
2004
Hubble Ultra Deep Field
2010
Hubble Ultra Deep Field-IR
FUTURE
James Webb Space Telescope
Redshift (z):
1
4
5
6
7
8
10
>20
Time after the Big Bang
Present
6 billion years
1.5 billion years
800 million years
480 million years
200 million years

The Hubble Deep Field



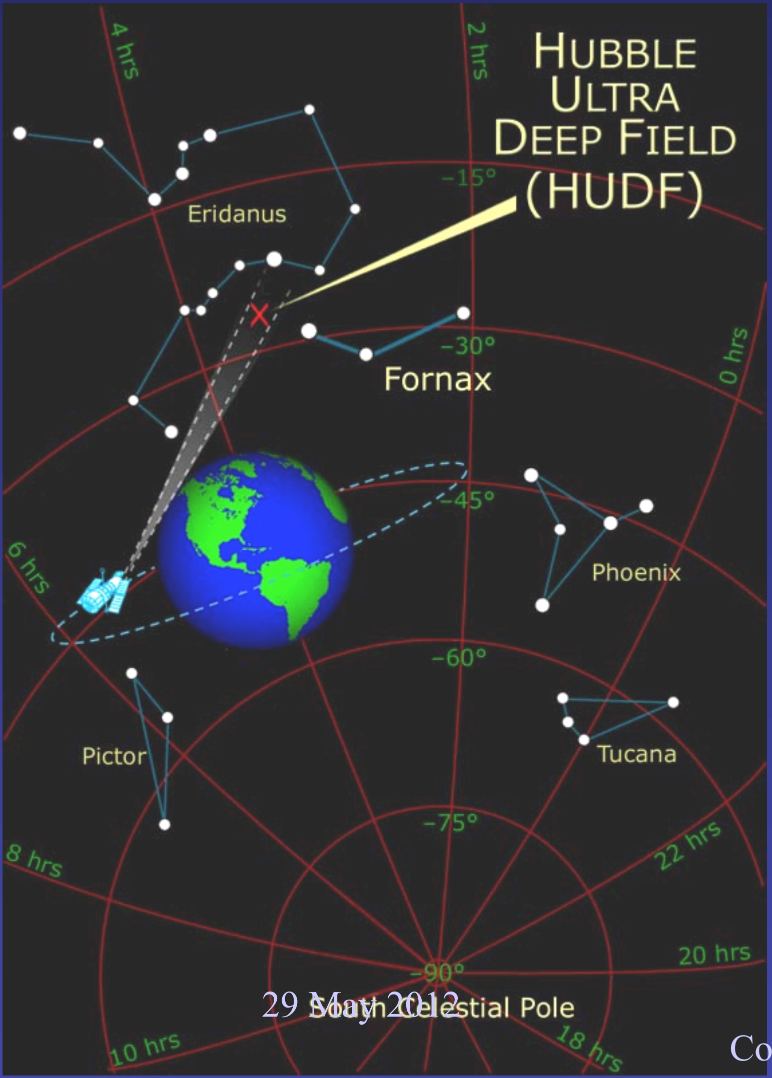
STScI Science Project: R. Williams. et al. (1996)

More Cosmology Projects

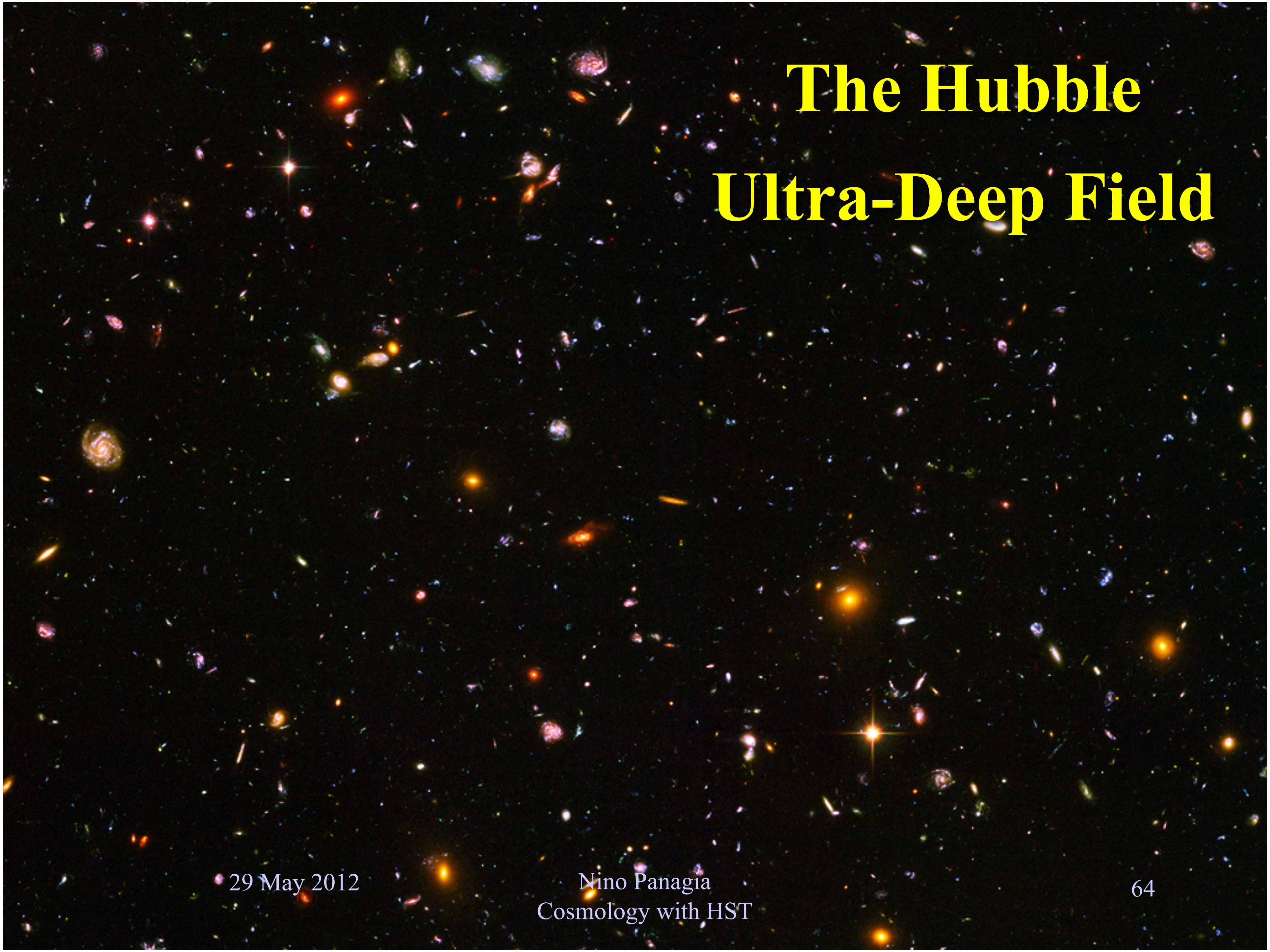
GOODS… COSMOS… etc

Farther is better…

The Hubble Ultra-Deep Field



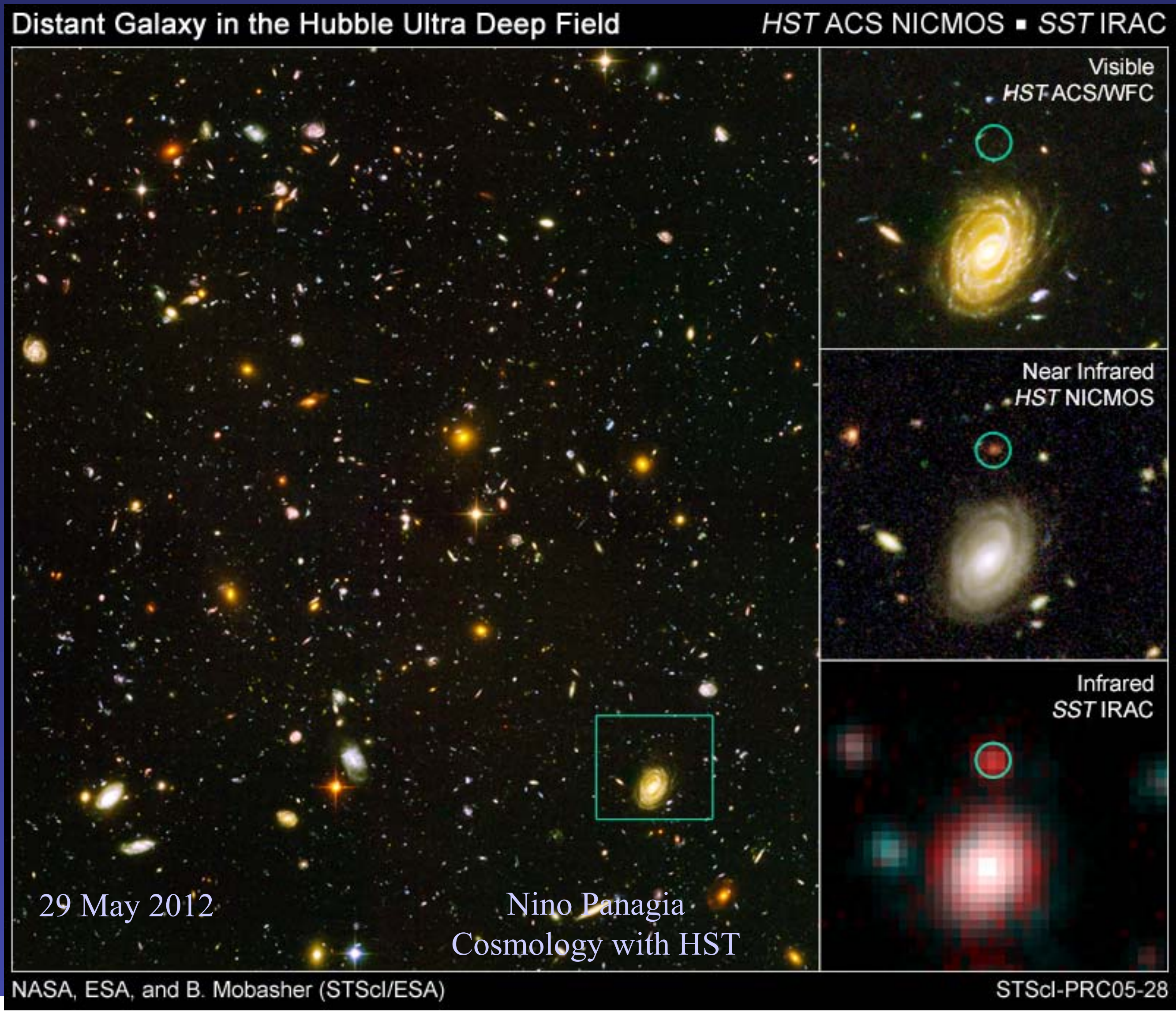
The Hubble Ultra-Deep Field

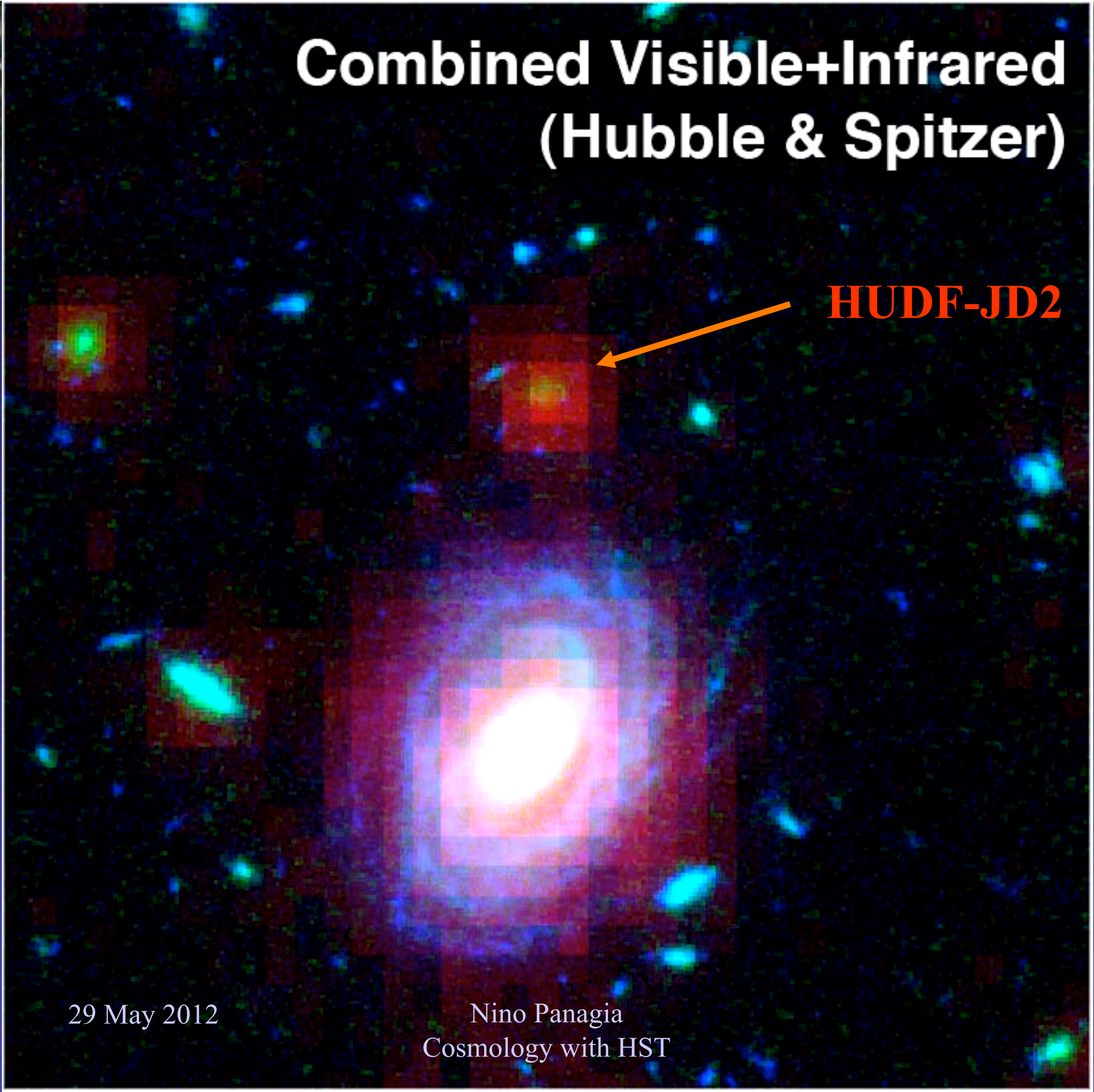


The large number of $z>6$ objects opens up the possibility of learning something about the reionization of the Universe.

What do we learn?

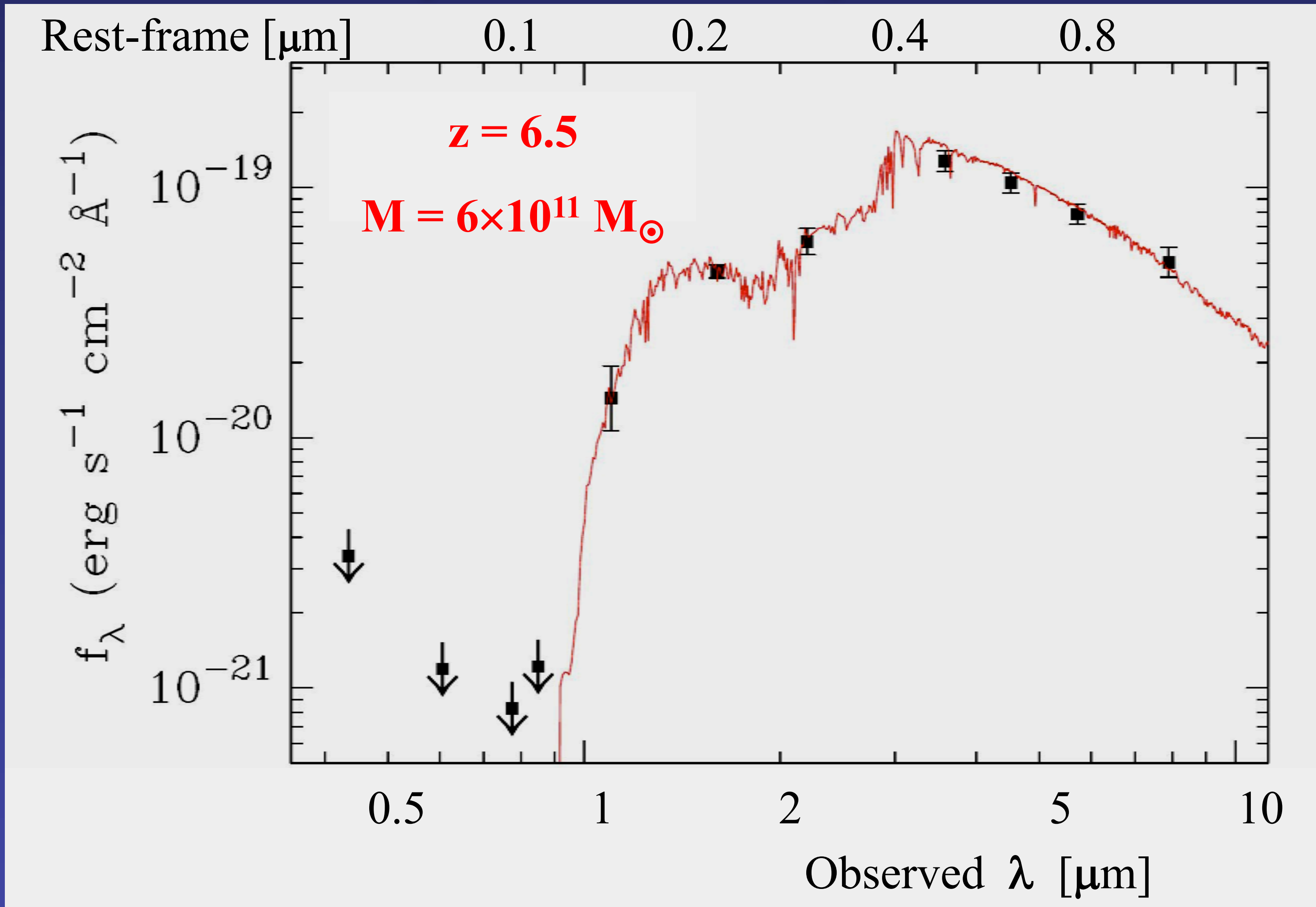
HUDF-JD2: A Distant Galaxy in the HUDF




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

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

[Mobasher et al. 2005]

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Properties of HUDF-JD2

[Mobasher et al 2005, Panagia et al 2005]

Massive $\quad M/M_\odot = 6 \times 10^{11}$

Bright $\quad L/L_\odot = 10^{12}$

Evolved $\quad$ Age $> 350\text{-}650$ Myr

$z_{form} > 9$

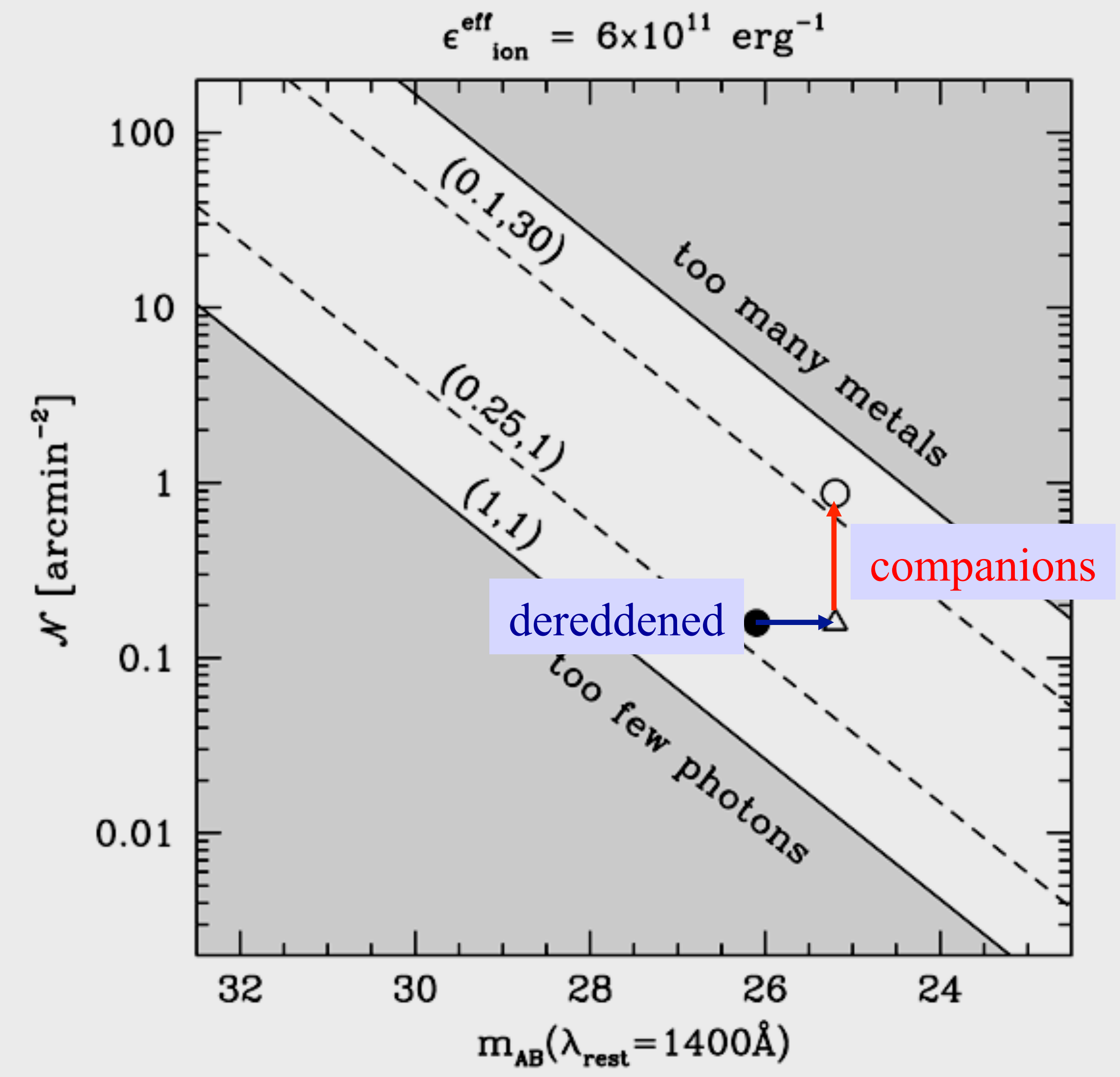
Ionizing $\quad Q \sim 4 \times 10^{72}$ Ly-c photons

HUDF-JD2

Enough to re-ionize its region of Universe?

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

Easily if undetectable companions with a reasonable LF are present



Panagia et al. 2005

Is HUDF-JD2 unique?

- Inspecting the GOODS Deep-Field South, Wiklind et al. (2006) answer this question: ***"not quite"***

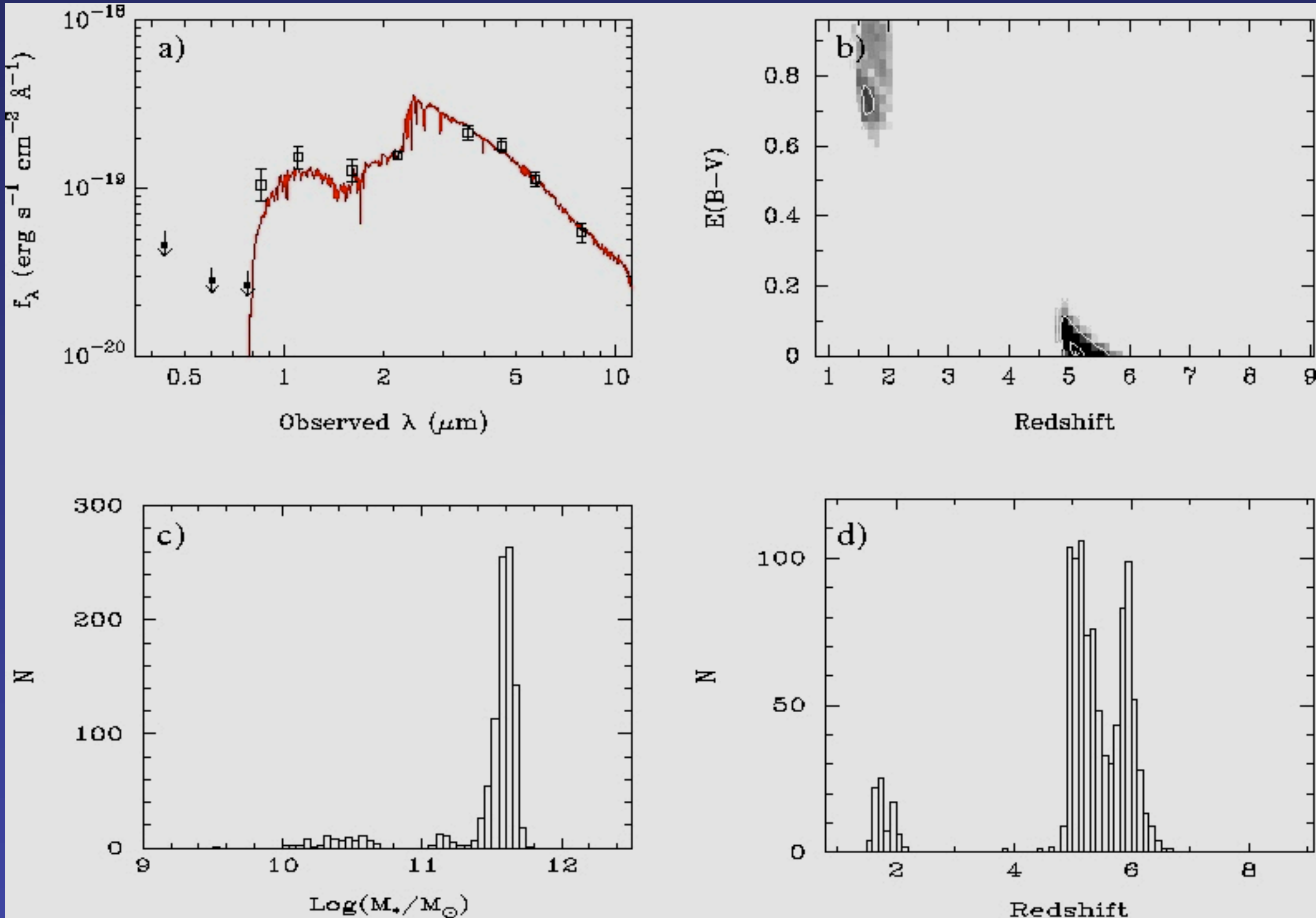
- Actually, combining deep HST and Spitzer multi-band photometry they detect about one bright BBG at z>5 every 9 square-arcmin field

BBGs in the GOODS Deep-Field South

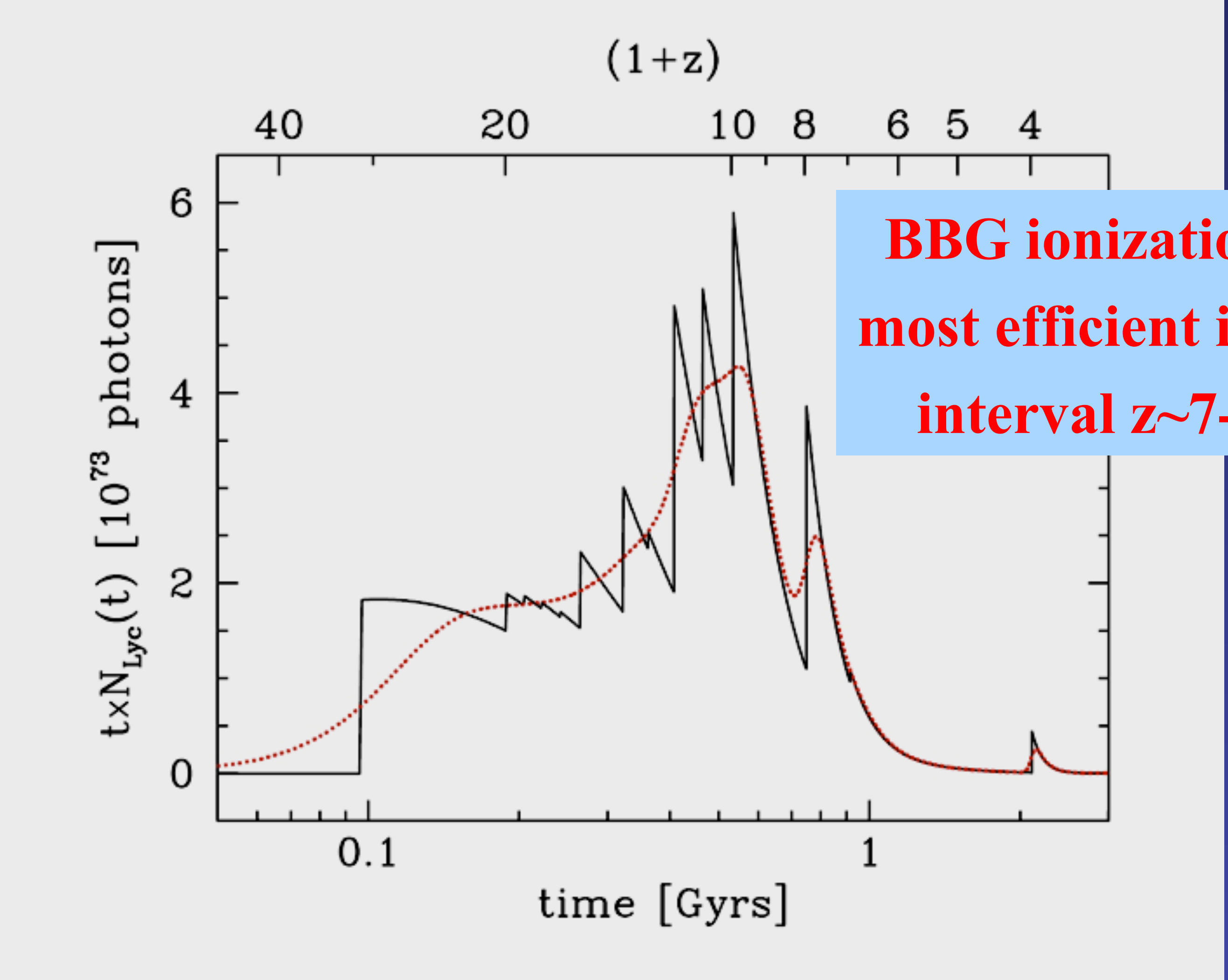
Table 5. Median values from Monte Carlo simulations for $z > 5$ Balmer–break candidates

ID	z	Percentage[(a)] $z_{phot} > 4$	$z_{phot} > 5$	E_{B-V}	t_{sb} Gyr	τ Gyr	Z $Z_{\odot}$	$\log M_*$ $M_{\odot}$	z_{form}	Confidence Class	Comments
0432	2.2	40.5	23.5	0.375	0.9	0.0	1.0	10.881	3	Bronze	Broad z–distribution
0547	5.7	96.6	81.1	0.100	0.8	0.2	2.5	11.105	18	Silver	
0861	4.5	50.9	29.6	0.400	0.6	0.0	1.0	11.958	7	Lead	Blended in IRAC
1792	6.7	73.5	73.5	0.000	0.4	0.0	1.0	11.479	11	Silver	
2068	5.3	78.7	76.8	0.200	0.9	0.0	2.5	11.432	19	Gold	
2436	6.4	97.7	97.7	0.000	0.4	0.0	0.2	11.508	10	Silver	
2864	5.4	75.9	63.5	0.200	0.8	0.0	1.0	11.631	15	Bronze	
3348	5.4	91.6	80.0	0.000	0.5	0.1	0.4	11.587	9	Gold	X–ray detected
3361	5.1	99.8	52.7	0.025	0.8	0.1	2.5	10.785	12	Gold	
3748	6.7	100.0	100.0	0.000	0.9	0.0	0.4	12.112	>30	Bronze	Blended in IRAC
3899	5.4	94.2	94.2	0.025	1.0	0.2	1.0	11.506	>30	Bronze	Blended in IRAC
4034	6.2	98.1	98.0	0.000	0.2	0.0	0.4	10.933	7	Gold	
4053	5.1	94.1	74.3	0.000	0.8	0.3	0.4	10.797	12	Gold	
4071	6.5	92.7	89.1	0.050	0.3	0.0	1.0	11.313	9	Silver	
4135	4.8	76.5	38.9	0.350	0.3	0.3	0.4	10.998	6	Bronze	
4550	4.8	78.6	20.3	0.175	1.0	0.2	2.5	11.343	16	Silver	
5197	5.2	99.6	90.9	0.000	0.9	0.3	0.2	10.830	17	Gold	Spectroscopically confirmed
5601	6.2	64.2	63.5	0.000	0.5	0.0	1.0	11.904	11	Bronze	Blended/binary galaxy
JD2	6.5	85.1	85.1	0.000	0.5	0.0	1.0	11.667	13	Gold	Mobasher et al. (2005)

An example of BBG candidate



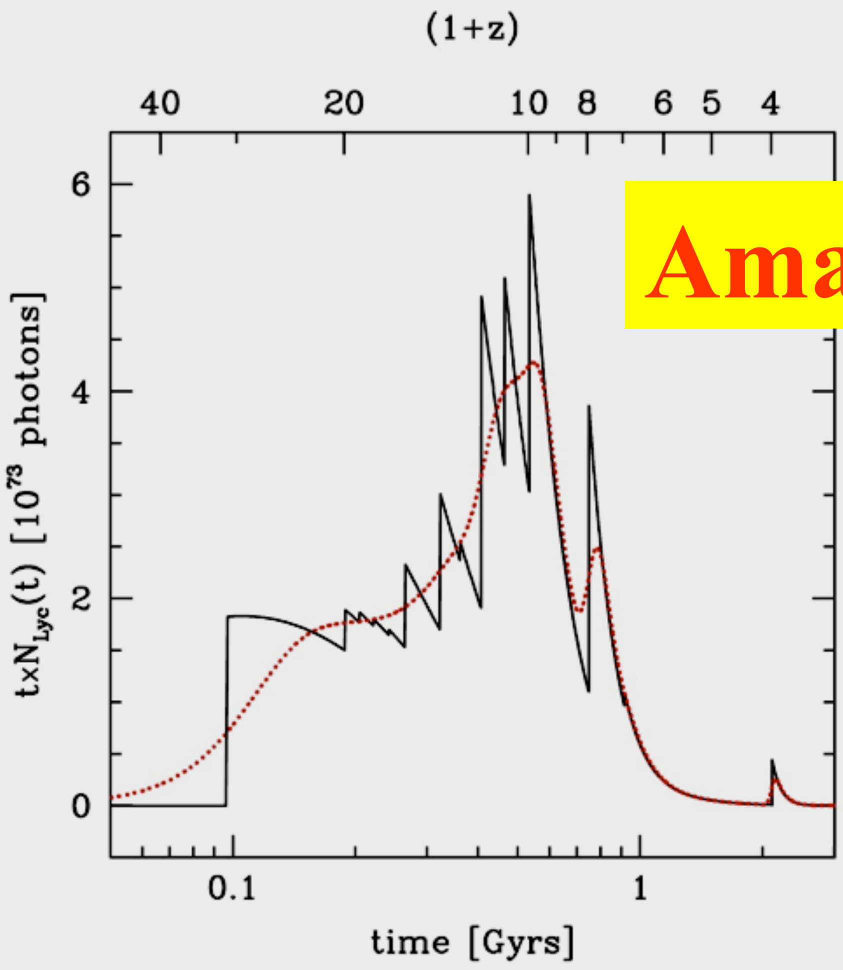
Lyman Continuum Photon Production History



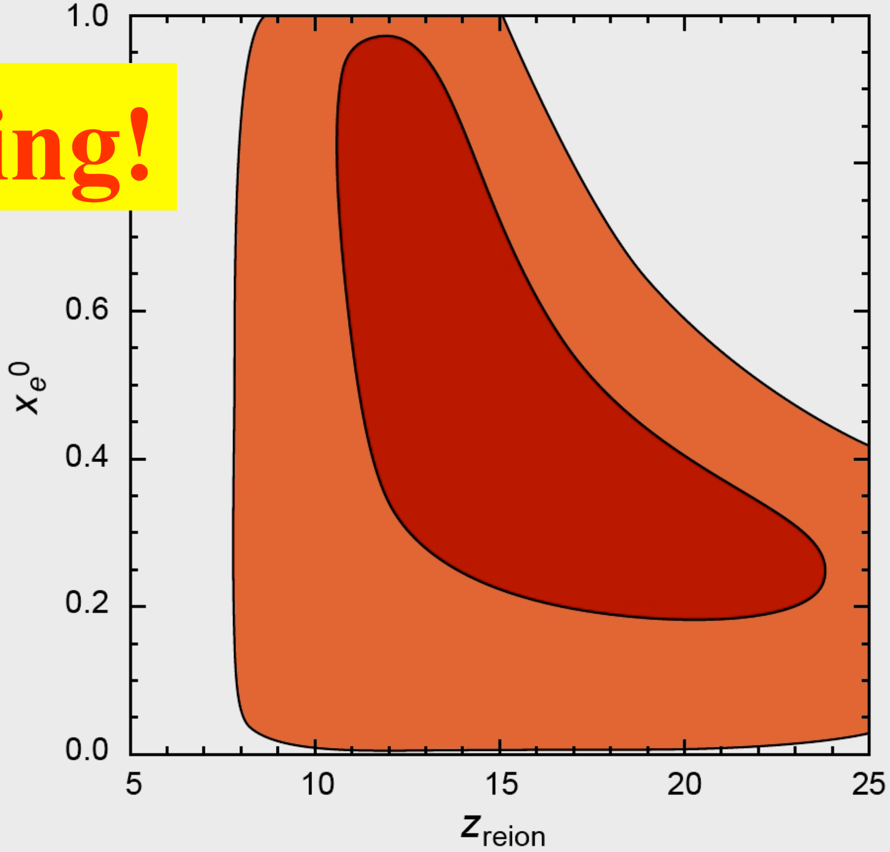
BBG ionization is most efficient in the interval z~7-15

Reionization History

BBGs and WMAP



Amazing!



Reionization: WHO did it?

Two basic possibilities

- Relatively few massive galaxies (BBGs)
  - Pop II
  - Pop I stars
- A myriad of dwarf galaxies
  - Pop III stars
- Both of them…

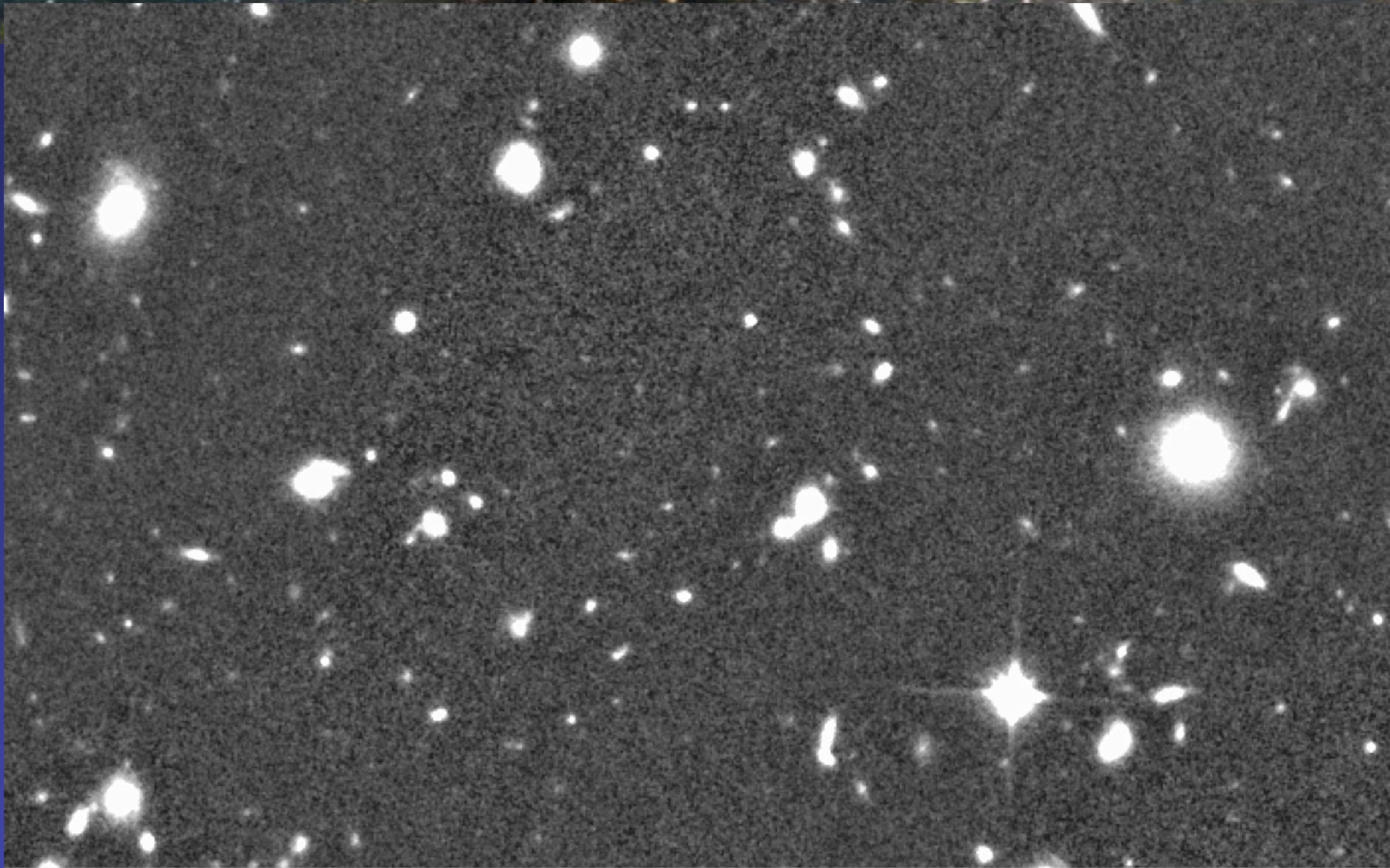
Recent results

from HST-WFC3

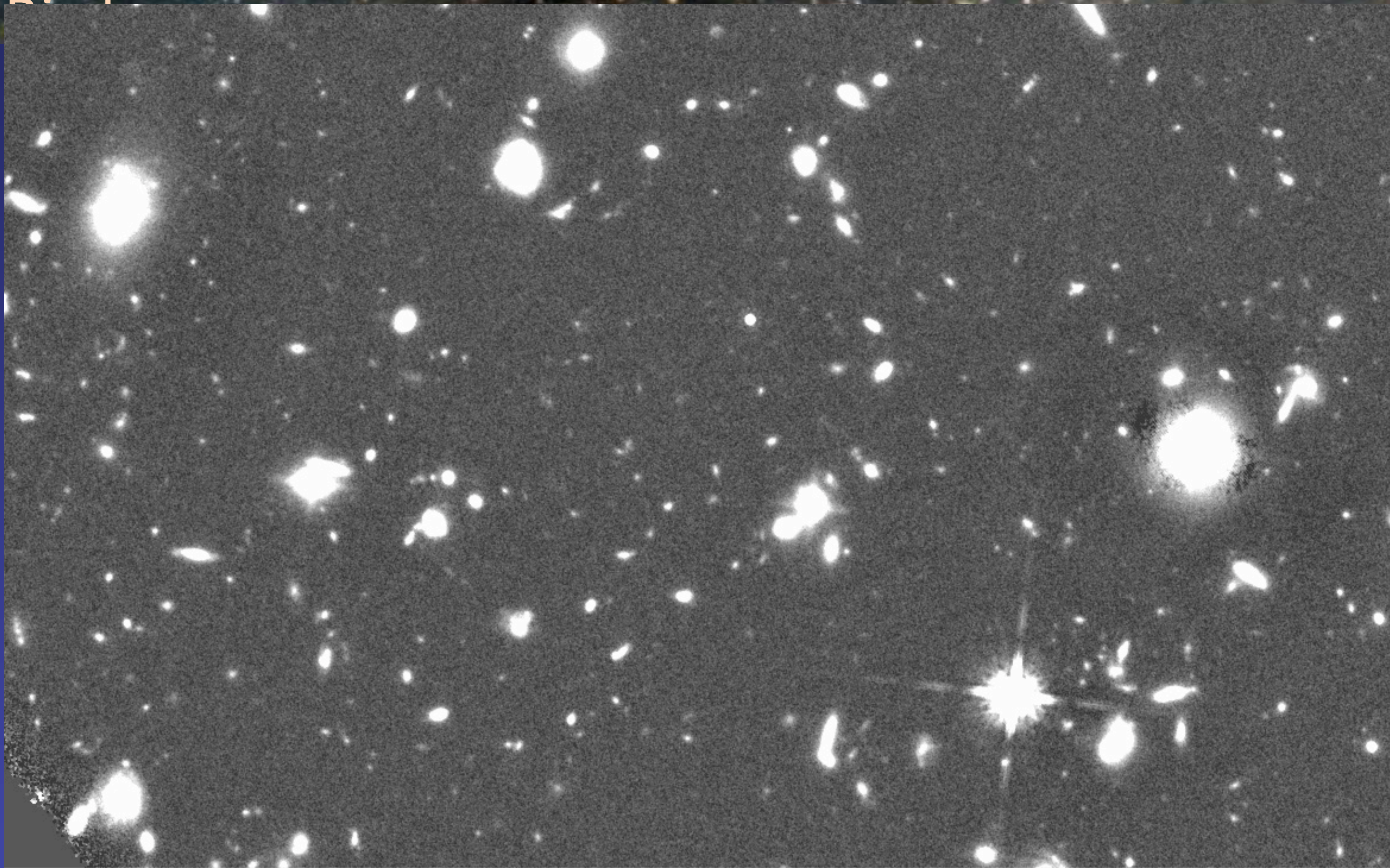
Slides borrowed from Garth Illingworth presentation

Galaxies in the first billion years [GDI *firstgalaxies.org*]

NICMOS – 72 orbits

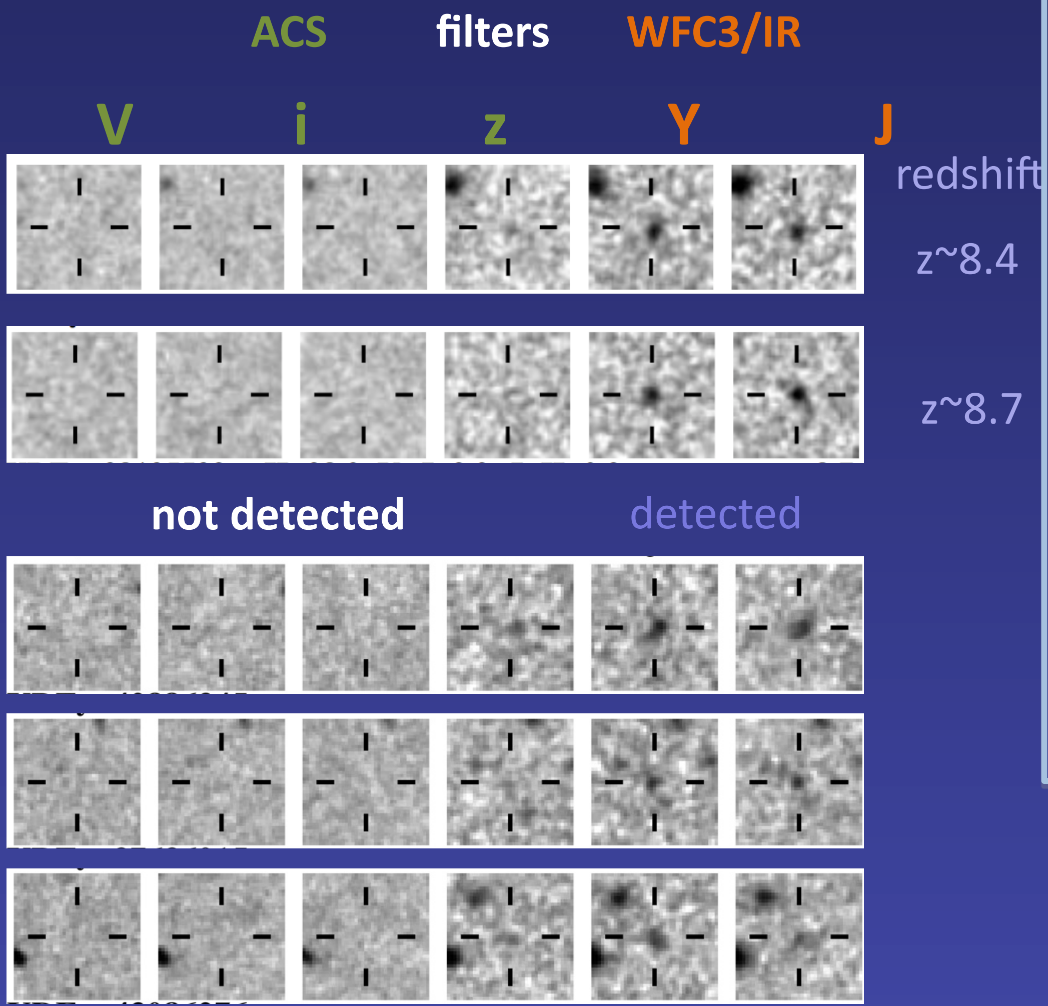


WFC3/IR – 16 orbits



first galaxies at z~8 from WFC3/IR

the two highest redshift z~8 galaxies



the other three z~8 galaxies

2.4″ x 2.4″

searches conducted using the very robust and well-tested photometric “dropout” technique

Dropouts verified spectroscopically at z~2-6

extensive testing for contamination from photometric scatter, spurious sources, lower redshift sources….

WFC3/IR resolution helps separate galaxies from (rare) faint stars

all are H~28-29 mag sources!

Bouwens, Illingworth et al 2010a

first results: HUDF09 team's 16 z~7 and 5 z~8 galaxies

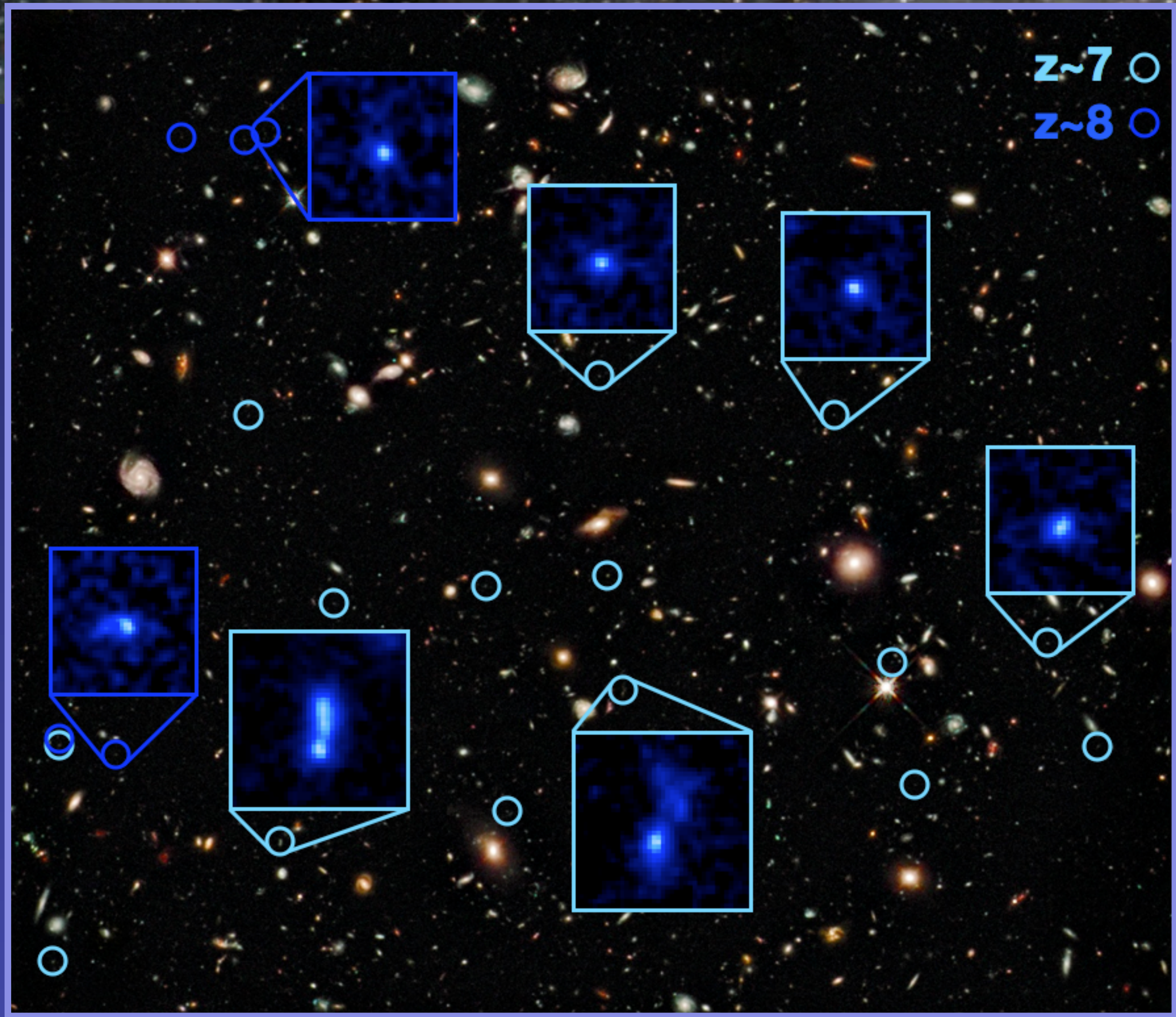
HUDF09
WFC3/IR

HUDF09
image ~2.2′

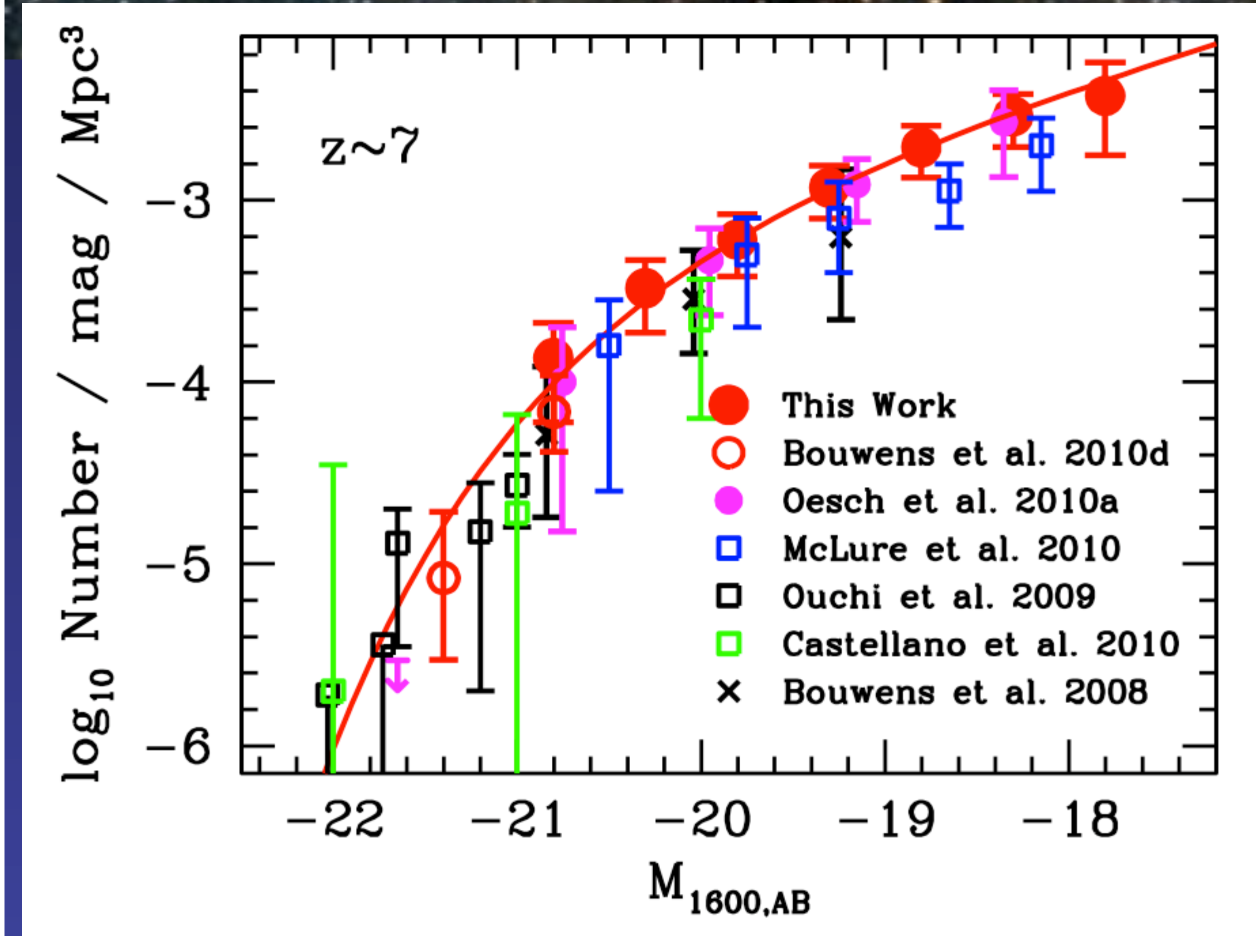
boxes ~2.5″

z~8 (650 Myr)
Bouwens et al
2010a

z~7 (800 Myr)
Oesch et al
2010a



luminosity functions

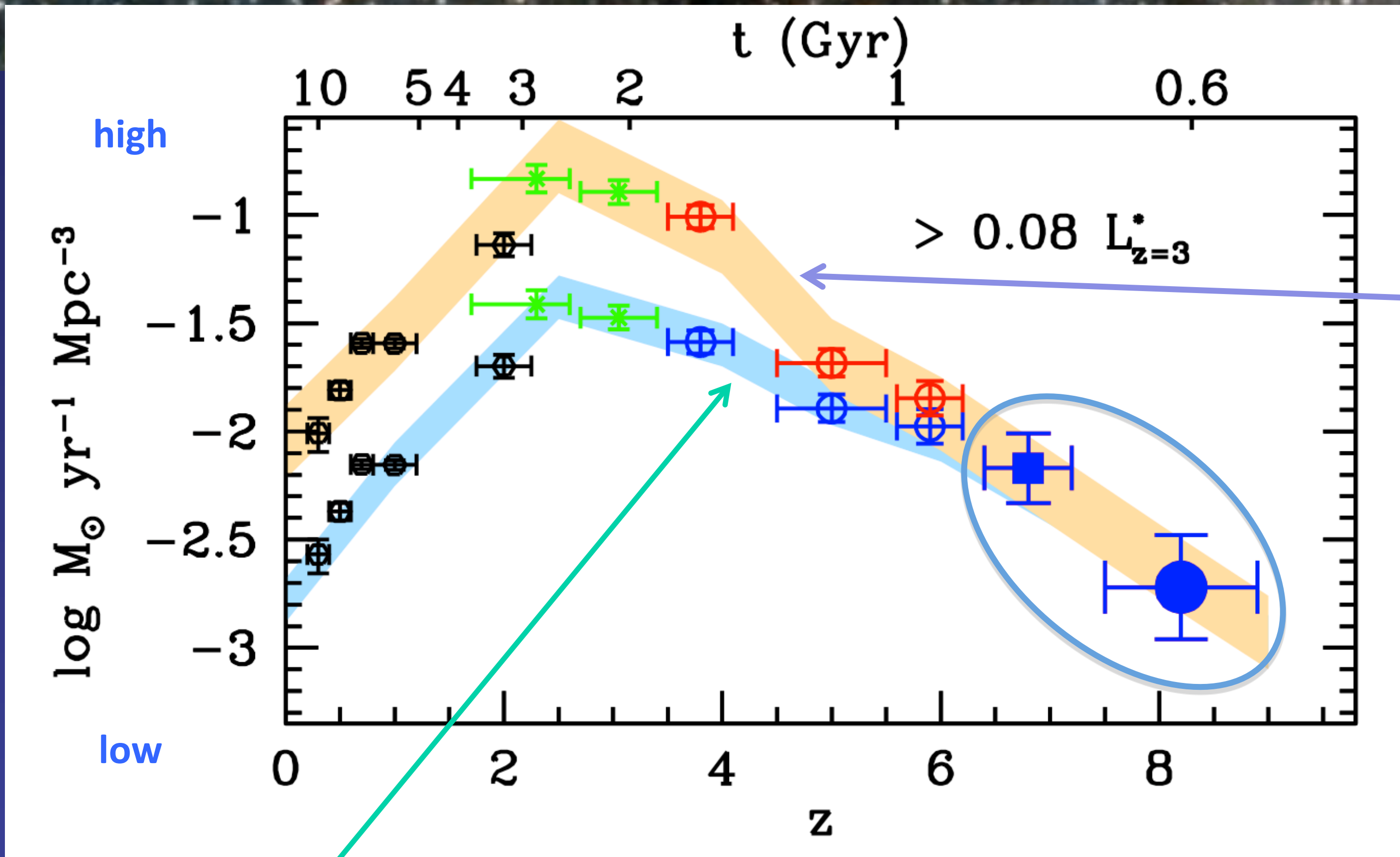


luminosity functions at z>7 are very important for establishing role of galaxies in reionization

excellent agreement now between the several groups

the new z~7 luminosity function indicates that the very steep slope ($\alpha \sim -1.75$) seen at lower redshift persists to higher redshift

the star formation rate density



dust-corrected SFR

new results

UV luminosity density

Madau 1998 formulation with Salpeter IMF

Bouwens/Illingworth et al 2010d

what these new observations tell us

SUMMARY

Hubble's new Wide Field Infra-Red Camera (WFC3/IR) has revealed many galaxies 13 billion years ago (at redshifts z~7 and z~8), just 600-800 million years from the big bang

these galaxies are small, low mass objects (half-light radii of just 0.7 kpc at z~7-8)

they are extremely blue in color and are probably quite deficient in heavier elements

they give us estimates for the mass density and the star formation rate density that extends from just ~5% of the age of the universe

combining these results with Spitzer data suggests that these galaxies were forming stars ~200-300 million years earlier, at z>10-11 (with recent possible detections being found at z~10)

what we can look forward to using

JWST

ELTs

HST

ALMA


THE END