CANDELS: A Cosmic Quest for Distant Galaxies Offering Live Views of Galaxy Evolution

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&
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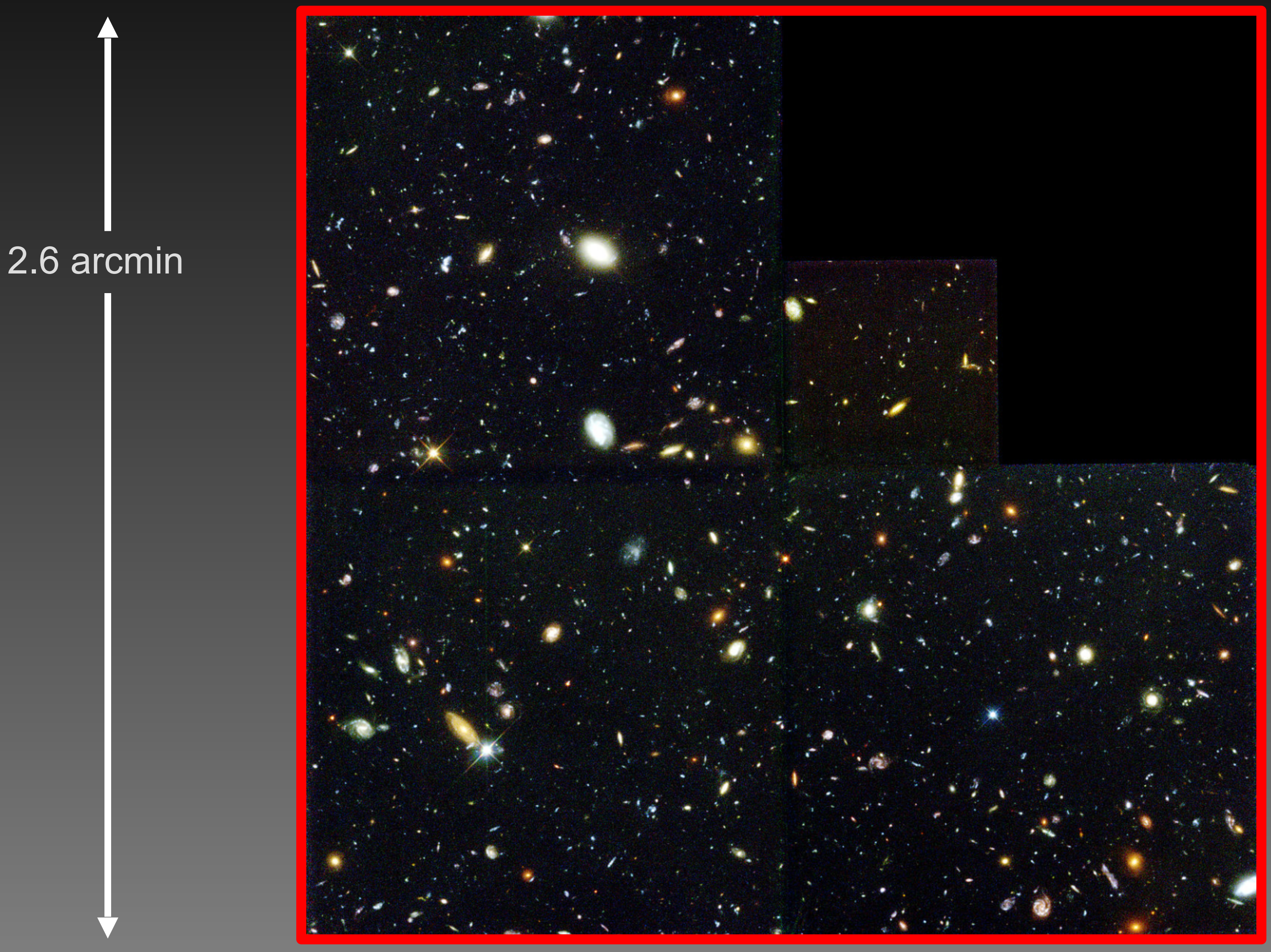
AAS Meeting

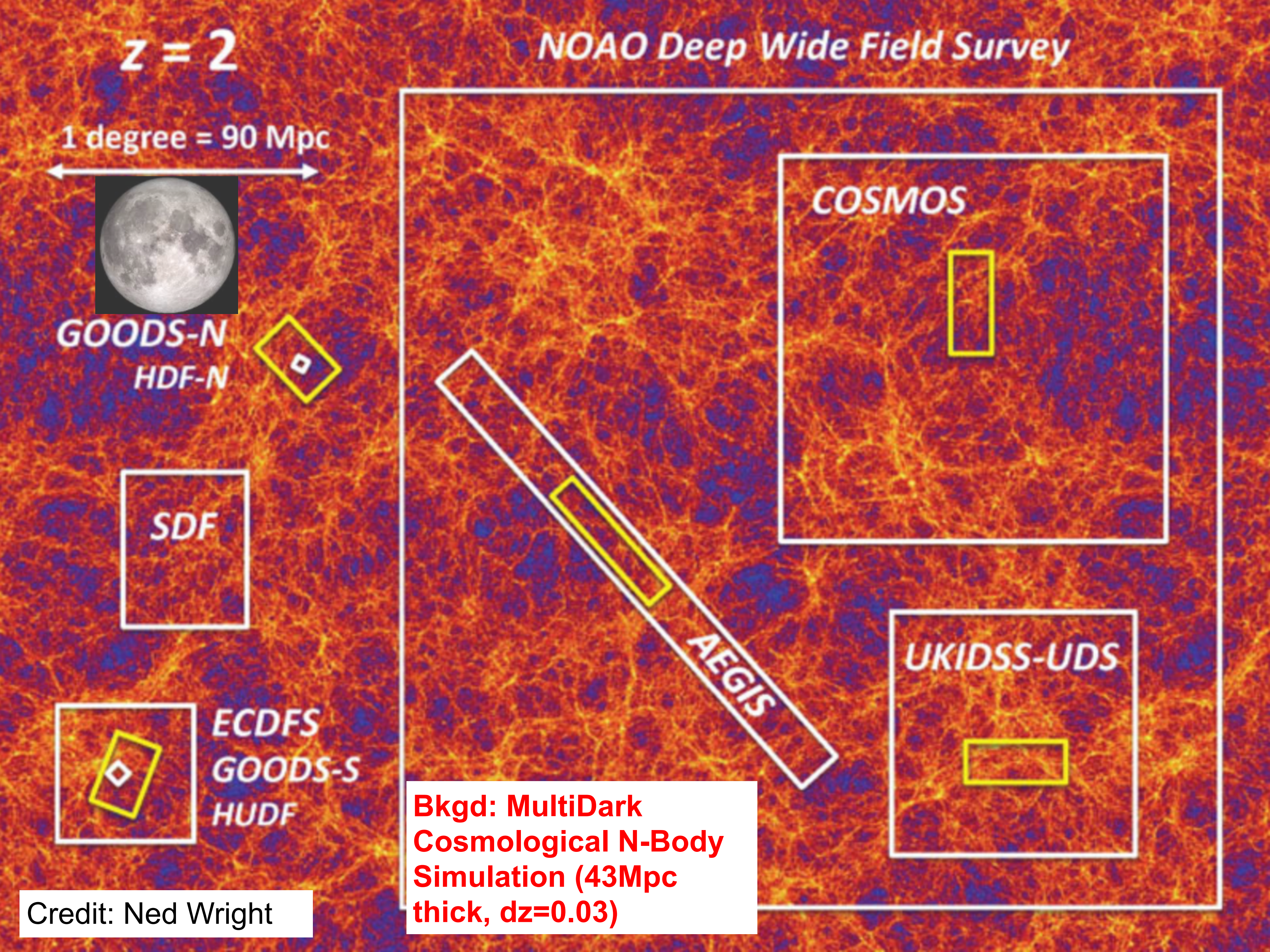
June 7, 2017

Mighty redwoods from little seedlings grow

Hubble Deep Field (1995)

Mighty redwoods from little seedlings grow




z = 2
NOAO Deep Wide Field Survey
1 degree = 90 Mpc
COSMOS
GOODS-N
HDF-N
SDF
AEGIS
UKIDSS-UDS
ECDFS
GOODS-S
HUDF
Bkgd: MultiDark Cosmological N-Body Simulation (43Mpc thick, dz=0.03)
Credit: Ned Wright

Two Take-Away Messages

We remain far from understanding the origins, assembly, structure, motions, environments, etc. of gas, dust, stars, and SMBH in galaxies.

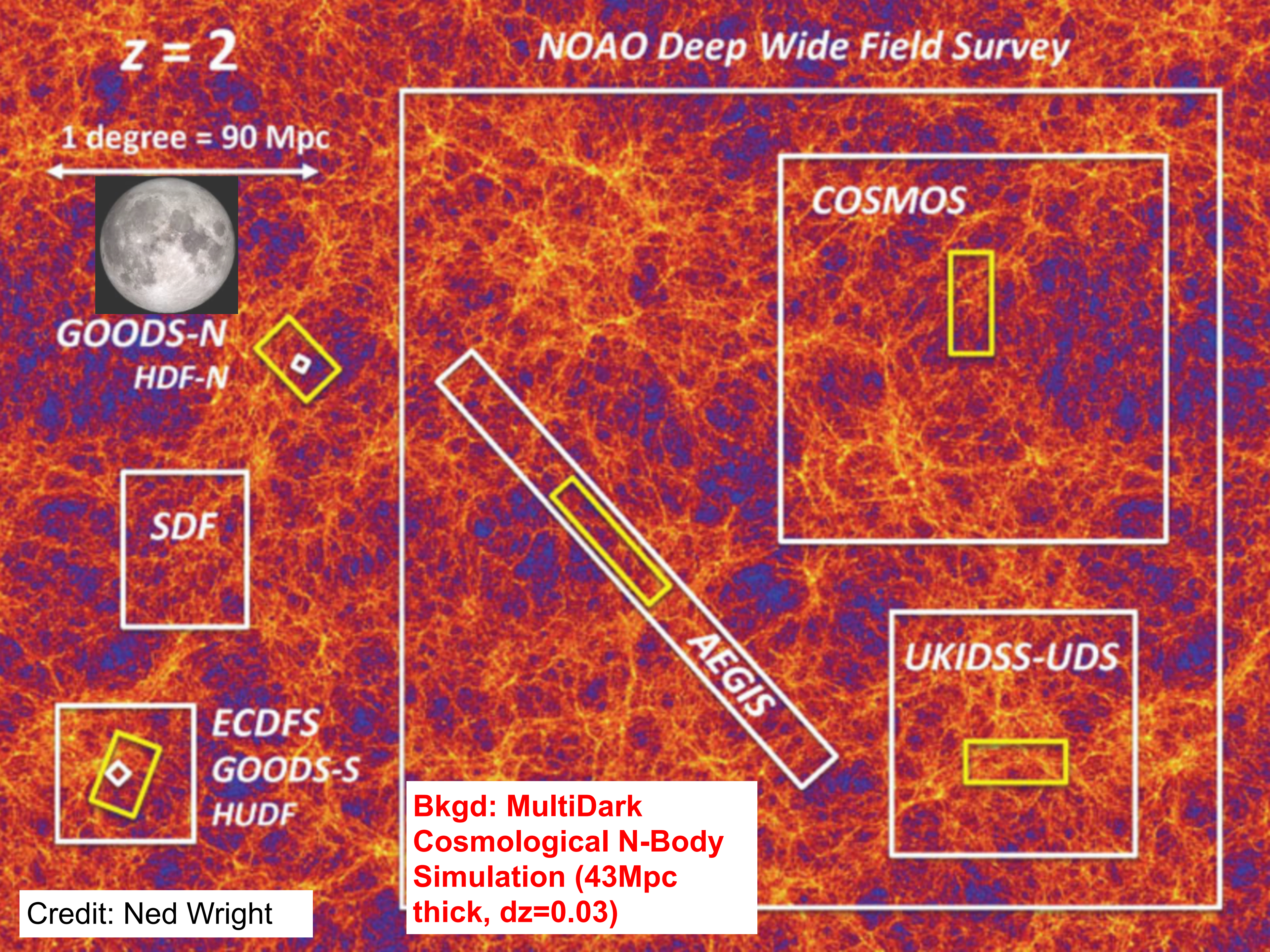
If you want to research the evolution of galaxies or AGN (outside of rich clusters), go to the CANDELS fields.

Outline

- Why get yet more data on distant galaxies?
- What is CANDELS: HST legacy survey of 5 famous fields with unsurpassed rich data
- Some Results from CANDELS′ at High Noon
  - What did Milky Way progenitors look like then?
  - Are the host galaxies of AGNs major mergers?
  - Serendipity discovery of bursting dwarfs?
- Recap CANDELS and its legacy for future distant galaxy research

Why need for more data?

1. **COSMIC VARIANCE & ENVIRONMENT**



Bkgd: MultiDark Cosmological N-Body Simulation (43Mpc thick, dz=0.03)

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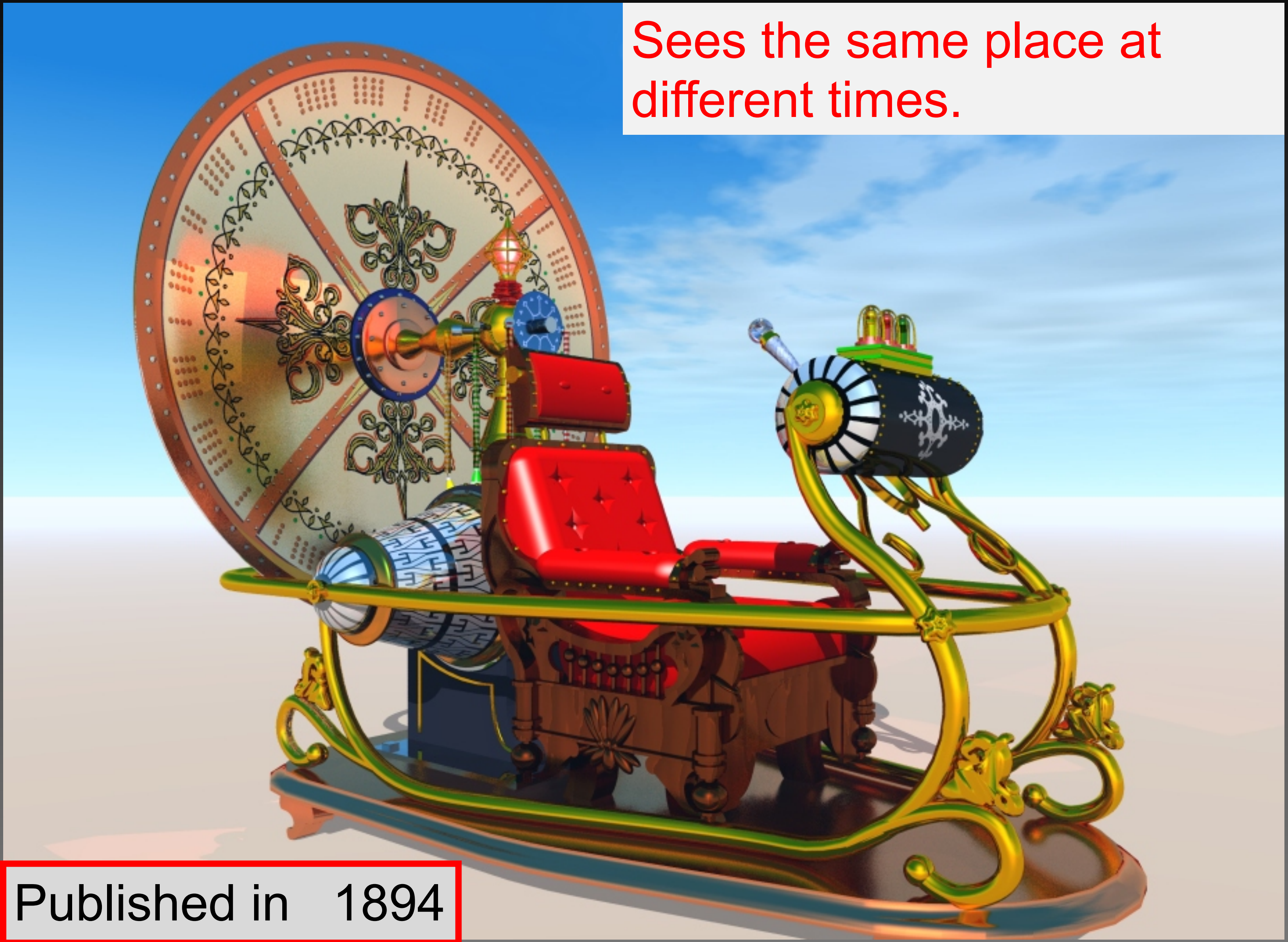
Why need for more data?

1. COSMIC VARIANCE & ENVIRONMENT
2. LARGE RANGE in time or redshift, so many slices are needed to track evolution
3. EACH SLICE is a different place, so connecting objects from one to another epoch is a statistical study, if objects do not naturally fall into clear, separate categories

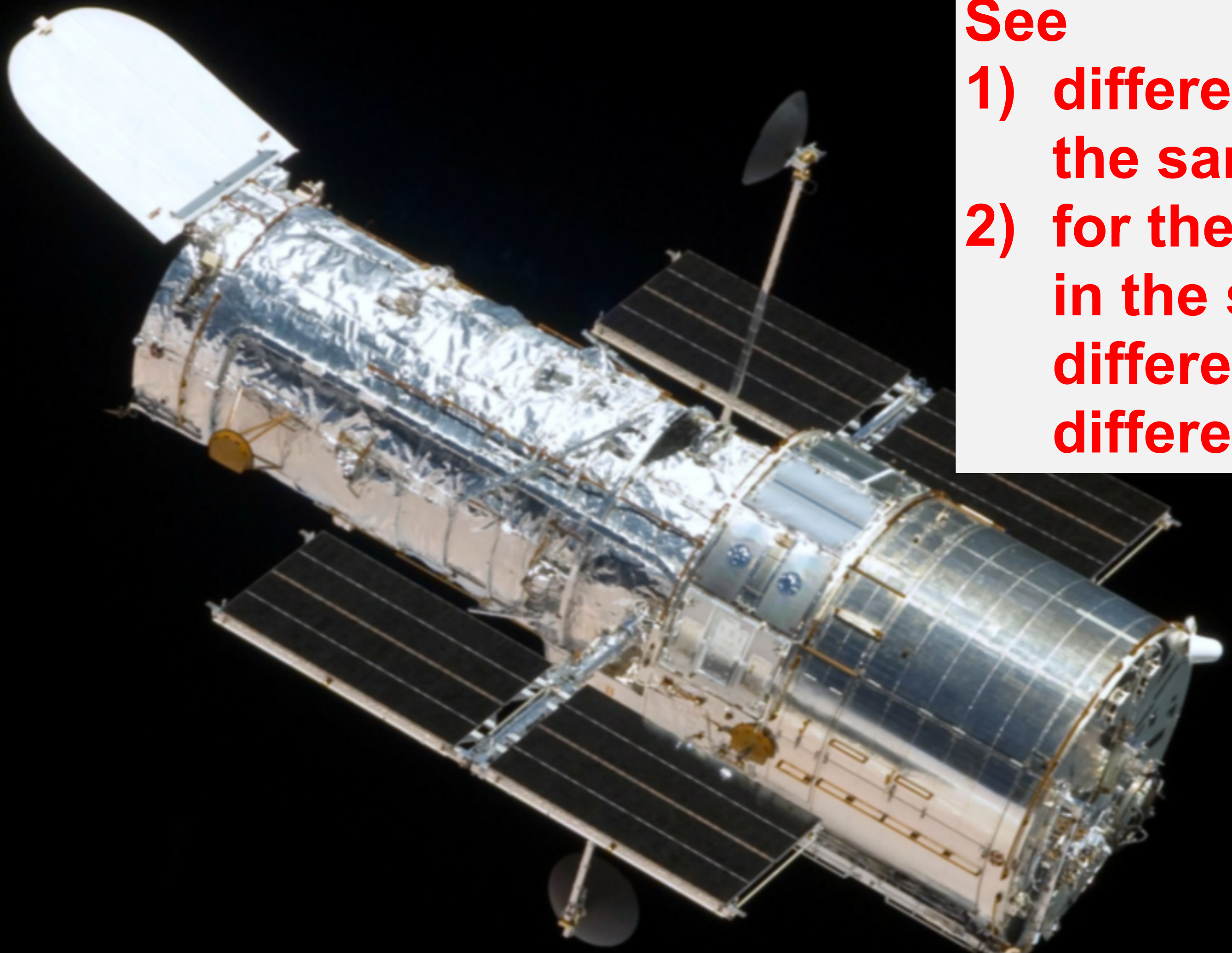
H. G. Wells: The Time Machine



Sees the same place at different times.

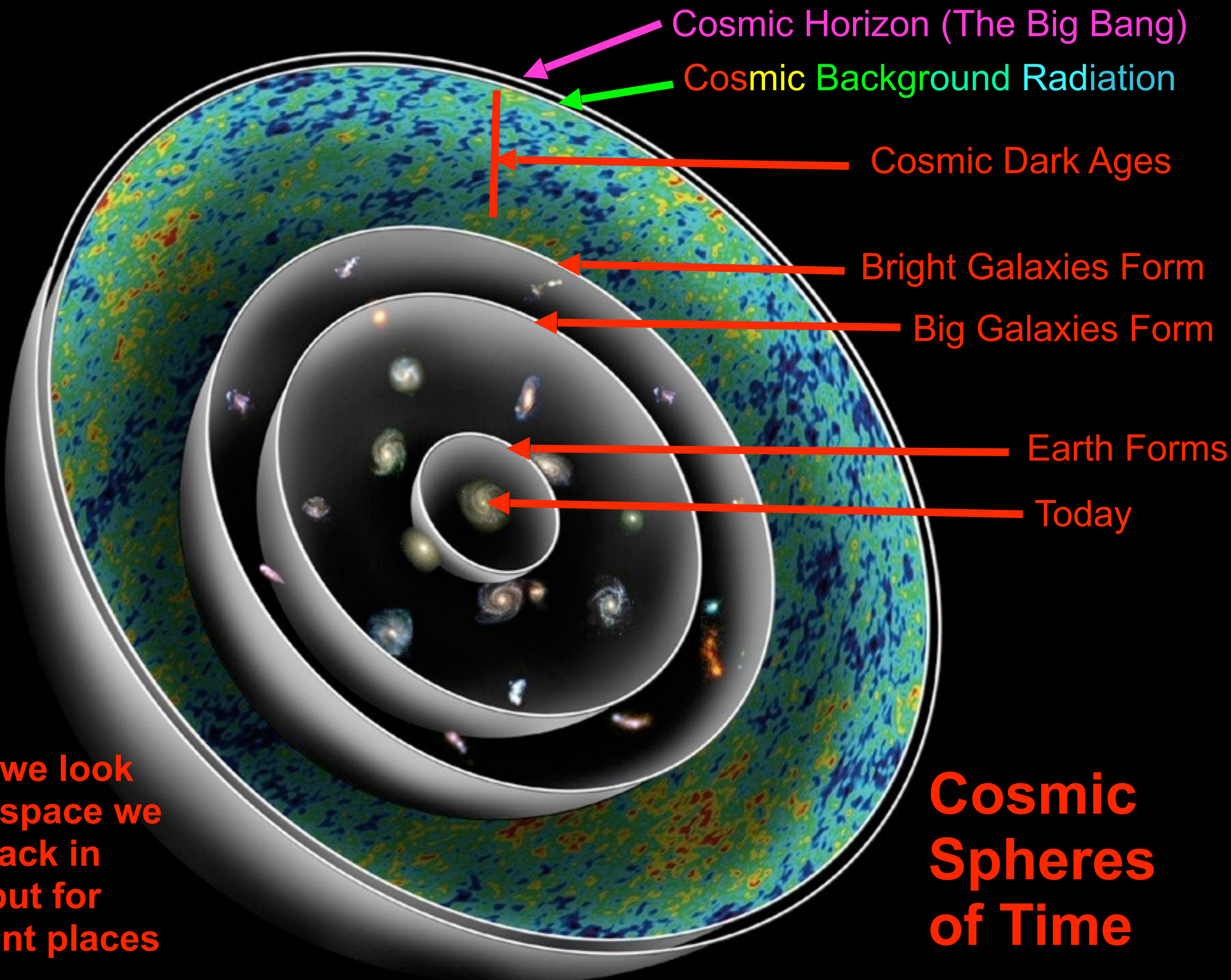
Published in   1894

Telescope as a Time Machine



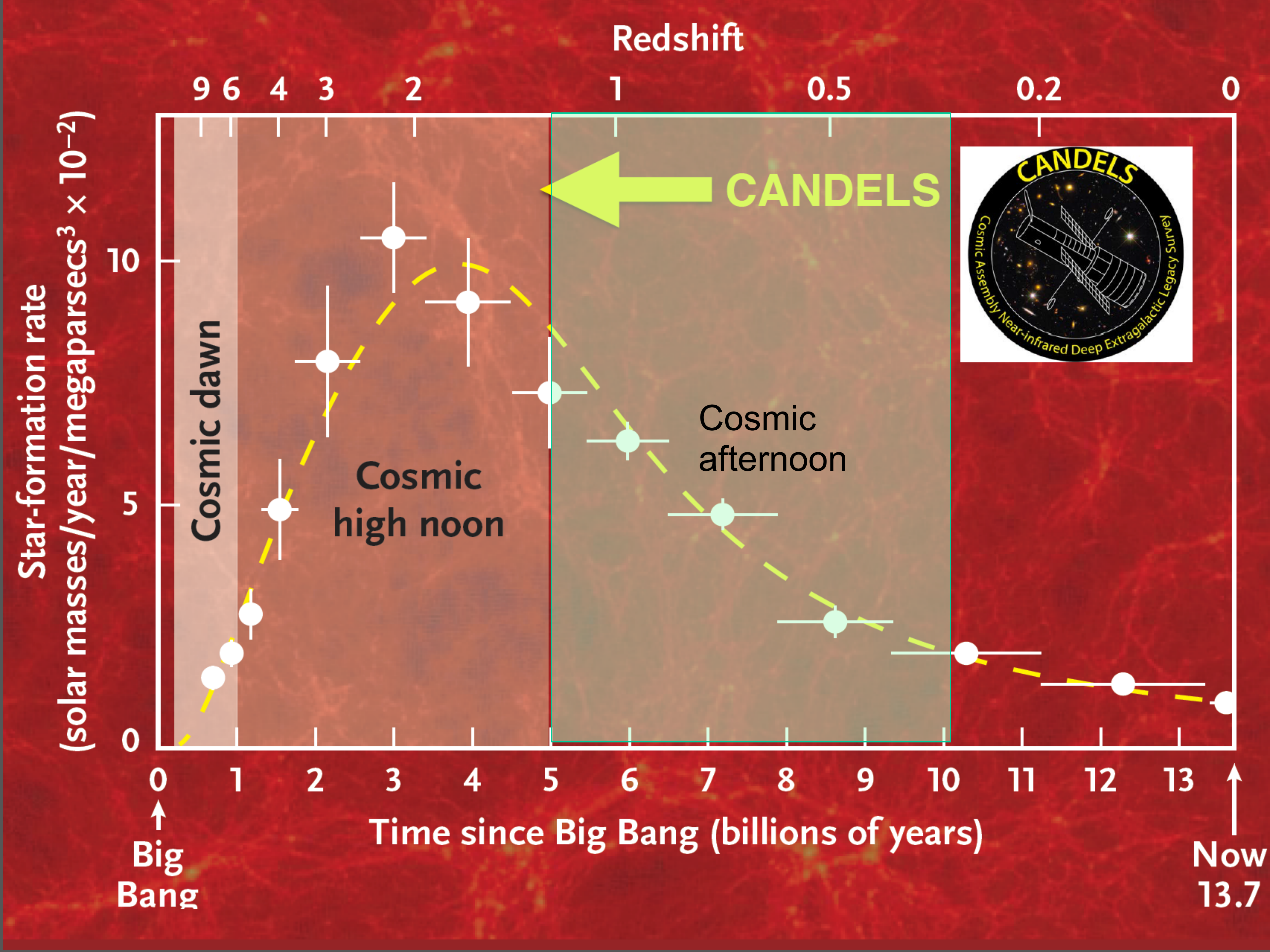
See
1) different places at the same time or
2) for the same spot in the sky, see different places at different times

Cosmic Spheres of Time



When we look out in space we look back in time, but for different places

Credit: J. Primack

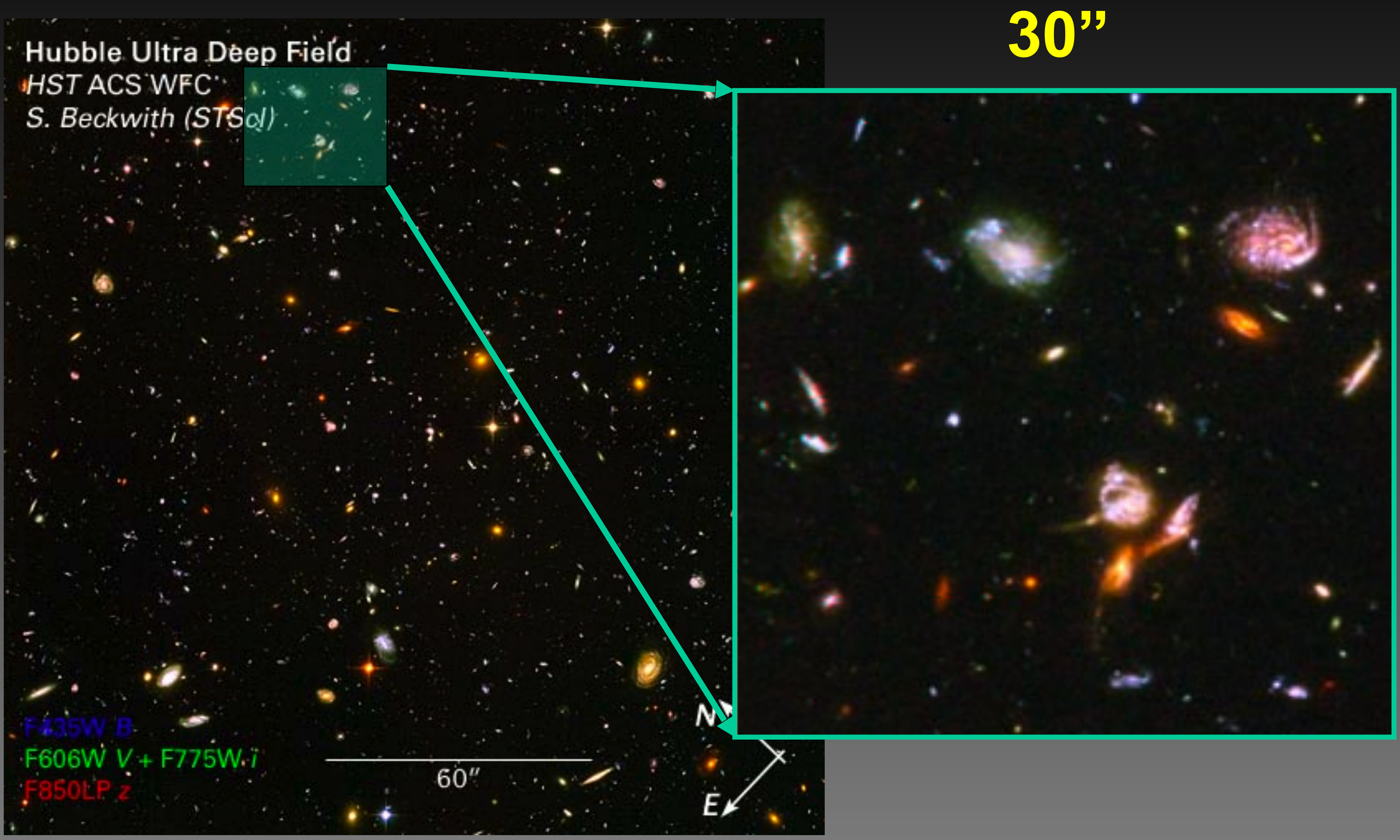


Redshift
9 6 4 3 2 1 0.5 0.2 0
Star-formation rate
(solar masses/year/megaparsecs^3 × 10^{-2})
10
5
0
Cosmic dawn
Cosmic
high noon
CANDELS
Cosmic
afternoon
CANDELS
Cosmic Assembly Near-infrared Deep Extragalactic Legacy Survey
0 1 2 3 4 5 6 7 8 9 10 11 12 13
Time since Big Bang (billions of years)
Big
Bang
Now
13.7

Why need for more data?

1. COSMIC VARIANCE & ENVIRONMENT
2. LARGE RANGE in time or redshift, so many slices are needed to track evolution
3. EACH SLICE is a different place, so connecting objects from one to another is a statistical study if objects do not naturally fall into clear, separate categories
4. GALAXIES in fact are incredibly diverse with huge range in physically relevant, non-discrete parameters: Mass, Size, Star Formation Rate, Structure and Substructure, Shapes/Morphology, proportion of key constituents (stellar mass, gas in various phases and ionizations, dust, SMBH), assembly and interaction history, kinematics, etc

HST UDF Showing High Density & Diversity of Galaxy Substructures



Why need for more data?

1. **COSMIC VARIANCE & ENVIRONMENT**
2. **LARGE RANGE in time or redshift, so many slices are needed to track evolution**
3. **EACH SLICE is a different place, so connecting objects from one to another is a statistical study if objects do not naturally fall into clear, separate categories**
4. **GALAXIES in fact are incredibly diverse with huge range in many parameters that may vary independently, making connecting one time-space slice hard to connect to another**
5. **Many rare but important objects/situations: AGNs, lensed objects, rich clusters, galaxies in voids, very short-duration infrequent events (SN), etc.**

Why need for more data? Recap

1. COSMIC VARIANCE & ENVIRONMENT
2. LARGE RANGE in time or redshift
3. EACH SLICE is a different place, so solid statistical connections require large samples.
4. GALAXIES are incredibly diverse with huge range in many non-discrete parameters
5. Many rare or extreme (few %) but important objects/situations

SDSS has nearly a million galaxies and key questions remain unanswered due to samples being too small. As one example, how closely do Milky Way counterparts by mass, SFR, and environment match our own home galaxy in structure, gas, and AGN activity?

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What is CANDELS?

1. Multi-cycle HST Treasury Survey (2010) comprised of 902 orbits of mostly the Near-IR camera WFC3 with the optical ACS imaging taken in parallel (& some UV and grism). Completed in fall 2013.
2. Now umbrella name for its 5 famous fields that have served as magnets for enormous and very rich data

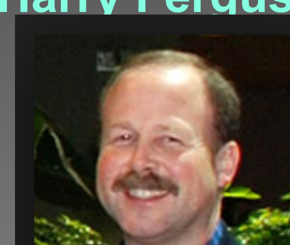
CANDELS in a Nutshell

- Imaging data in 5 fields for 250,000 galaxies from z = 1.5 - 8: Wide and Deep
- WFC3 improves photometric-redshifts out to z ~ 2.5 and better penetrates dust
- Spitzer Extended Deep Survey (SEDS): IRAC 26 AB (5-σ); means stellar masses can be measured to $\sim 10^9 M_o$ to redshifts z ~ 7
- Overlapping ACS parallels: yield panchromatic imaging needed for photo-z's
- X UV in GOODS-N: 100 orbits of two UV filters (F275W, F335W)
- X Every pointing observed at least twice: allows search for variable AGN and first SNe beyond z ~ 1.5

MAIN CANDELS HST INFORMATION:
Redshifts, Stellar Masses, SFR, Sizes, Extinction, & Morphologies
Bread & Butter for Galaxy Evolution Research

Cosmic **A**ssembly **N**ear-infrared **D**eep **E**xtragalactic **L**egacy **S**urvey

Co-PIs:
Sandra Faber & Harry Ferguson

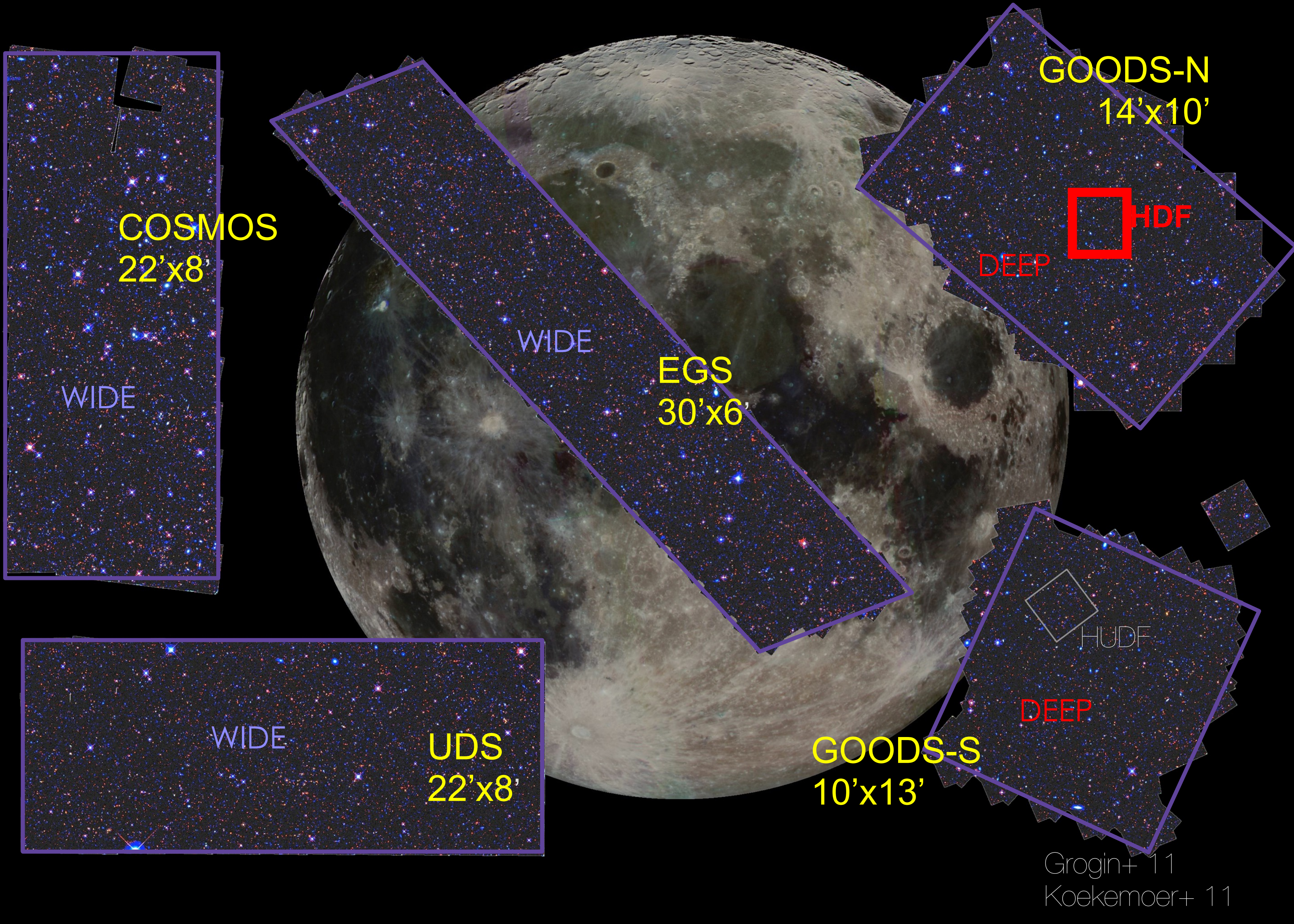


Builders:
Norman Grogin, Dale Kocevski
Anton Koekemoer, Adam Riess,
Steve Rodney

~200 team members
~45 institutions
> 100 papers
12 countries

candels.ucolick.org

Five regions, 900 orbits. Observations were completed August 2013.



CANDELS Exposure Strategy

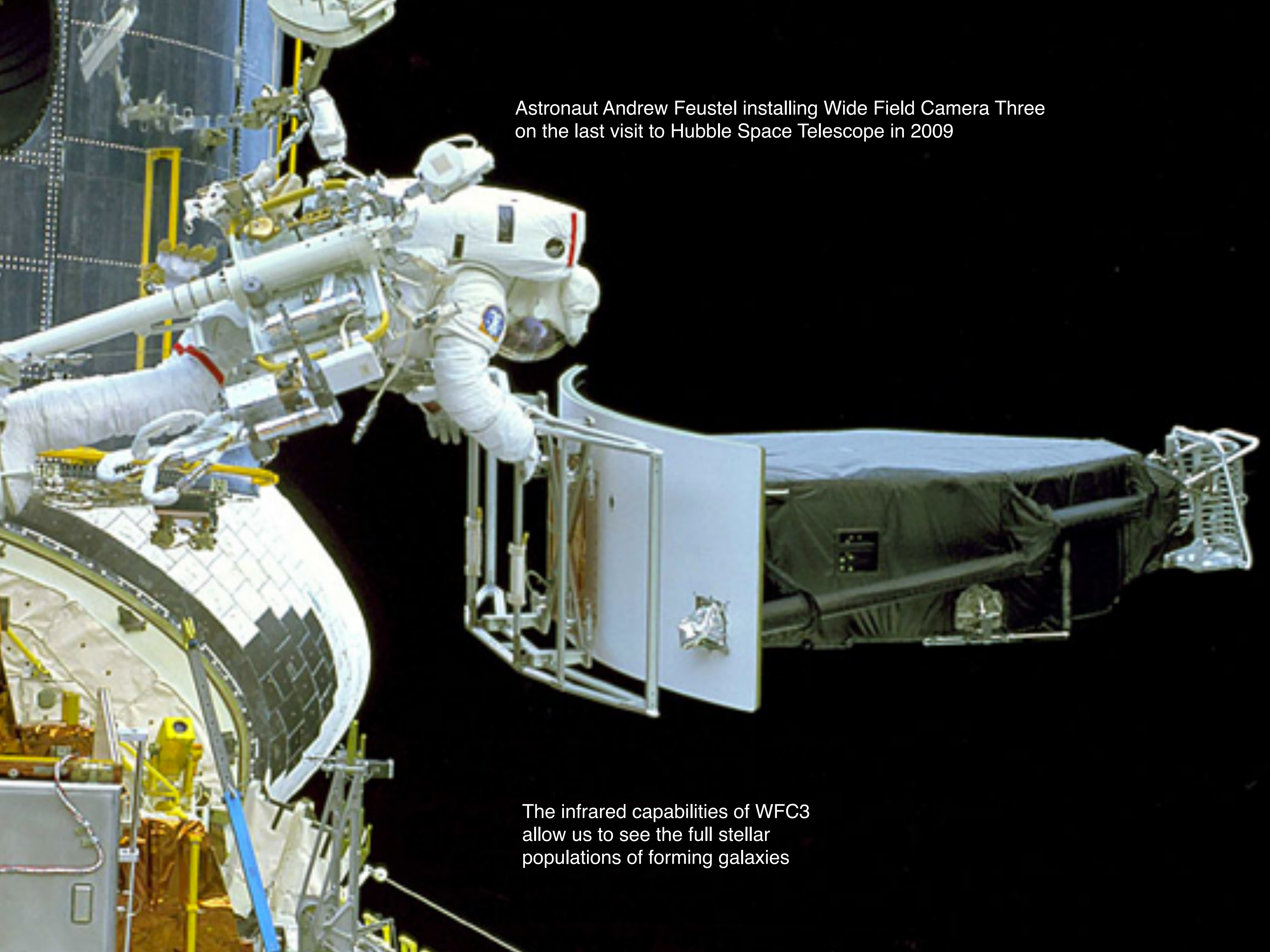
250,000 galaxies ~2×10^6 Mpc^3 per unit z for $z>1.5$

- "Wedding cake" strategy: three layers of J+H

UDFs: ~100 orbit depth over ~10 sq arcmin

DEEP: 8 orbit depth over ~120 sq arcmin

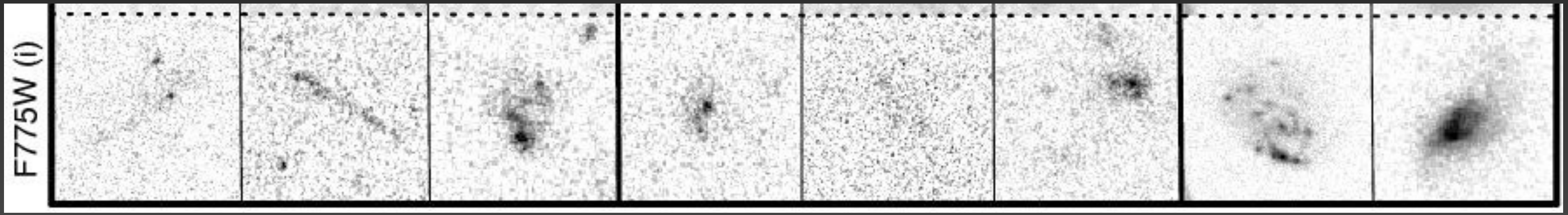
WIDE: 2 orbit depth over ~700 sq arcmin



Astronaut Andrew Feustel installing Wide Field Camera Three on the last visit to Hubble Space Telescope in 2009

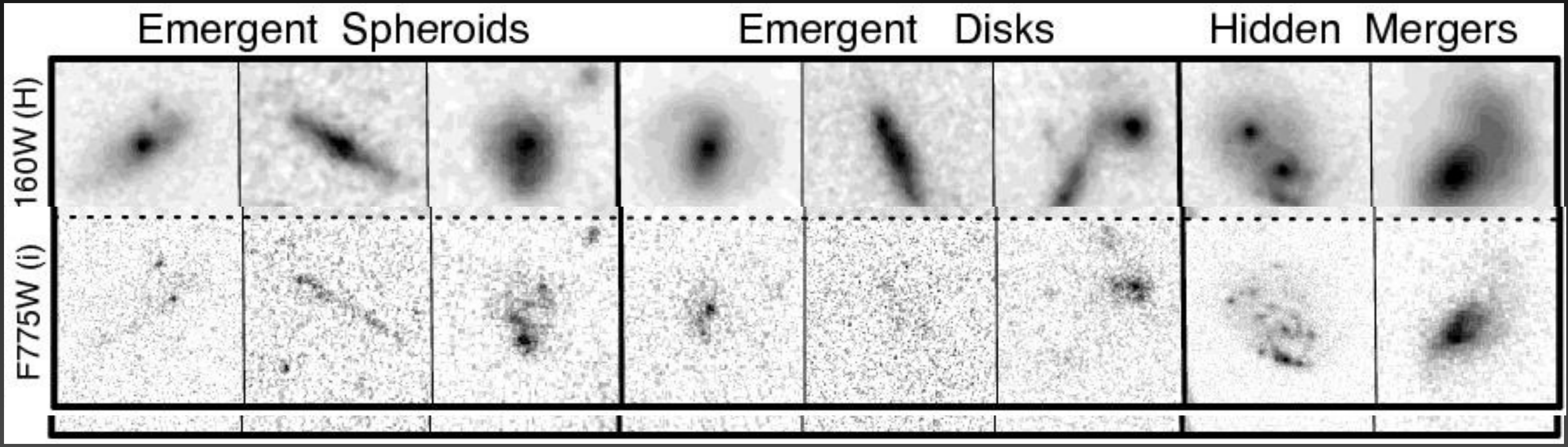
The infrared capabilities of WFC3 allow us to see the full stellar populations of forming galaxies

What The *Hubble* Near-Infrared (Wide Field Camera 3: WFC3) Imaging Can See that Optical Cannot

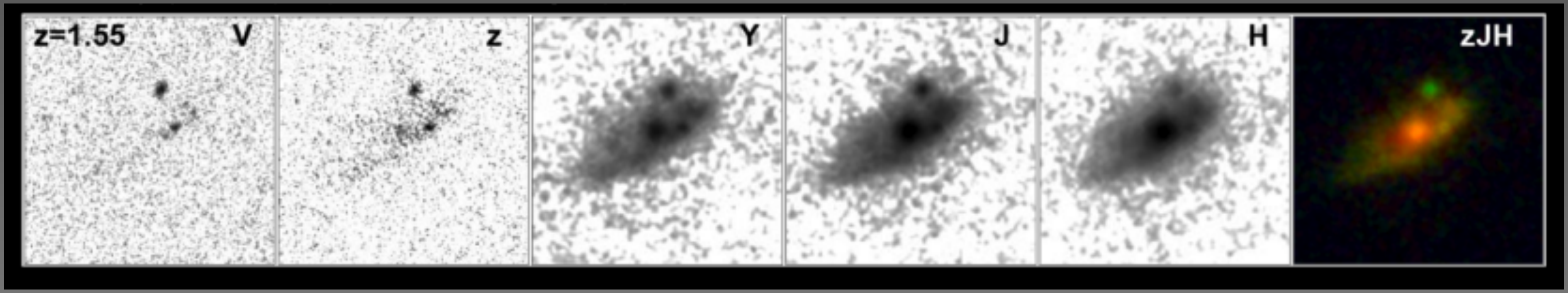


HST OPTICAL IMAGES (in RED FILTER)
of 8 VERY FAINT DISTANT GALAXIES
(Couple Orbits Depth)

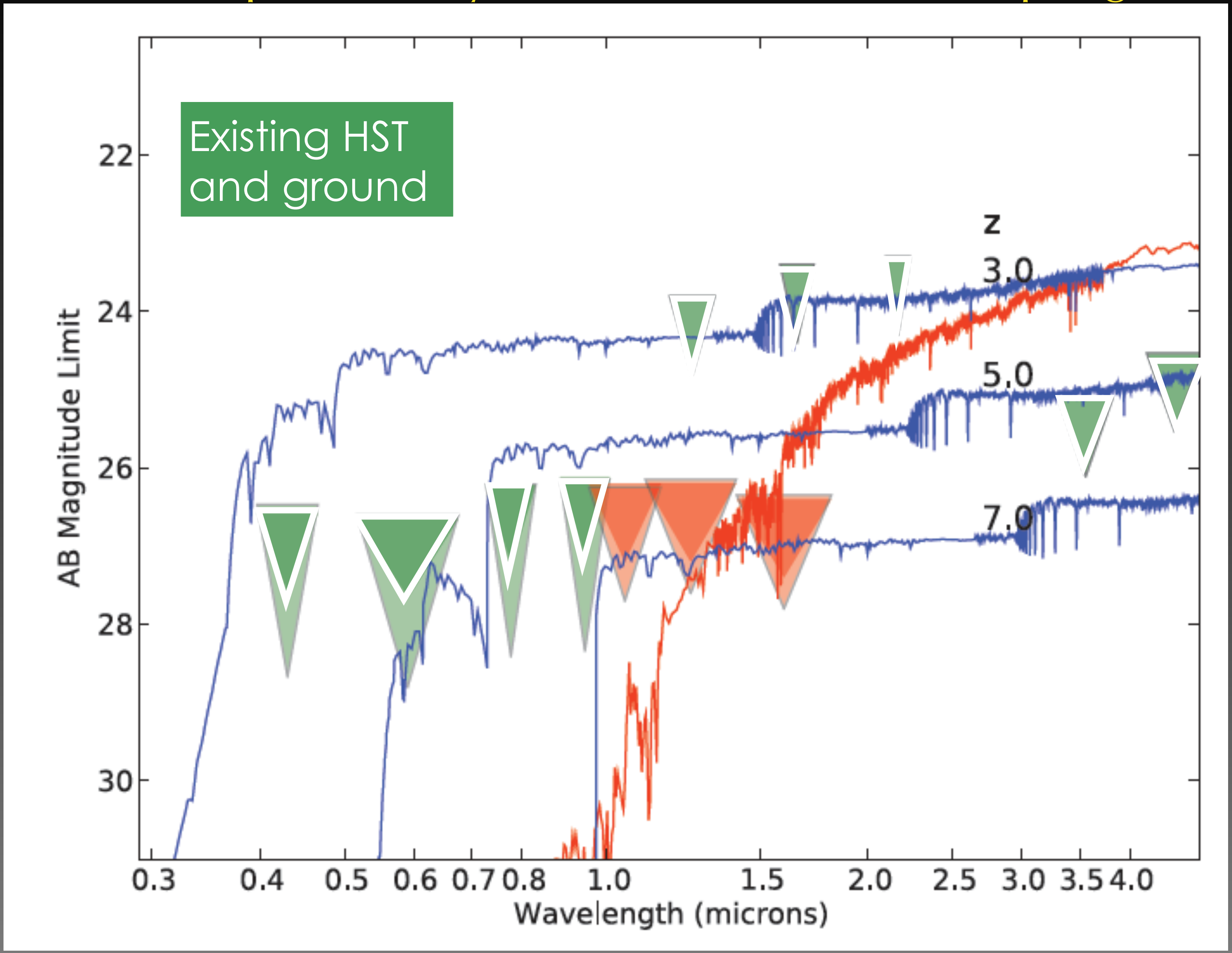
Adding Images in the Near-Infrared (1.6 micron) See New Aspects of the Galaxies



Images of One Galaxy for 5 Filters
2 Optical (V,z) and 3 Infrared (Y, J, H)



New YJH photometry limits in GOODS-S Deep region



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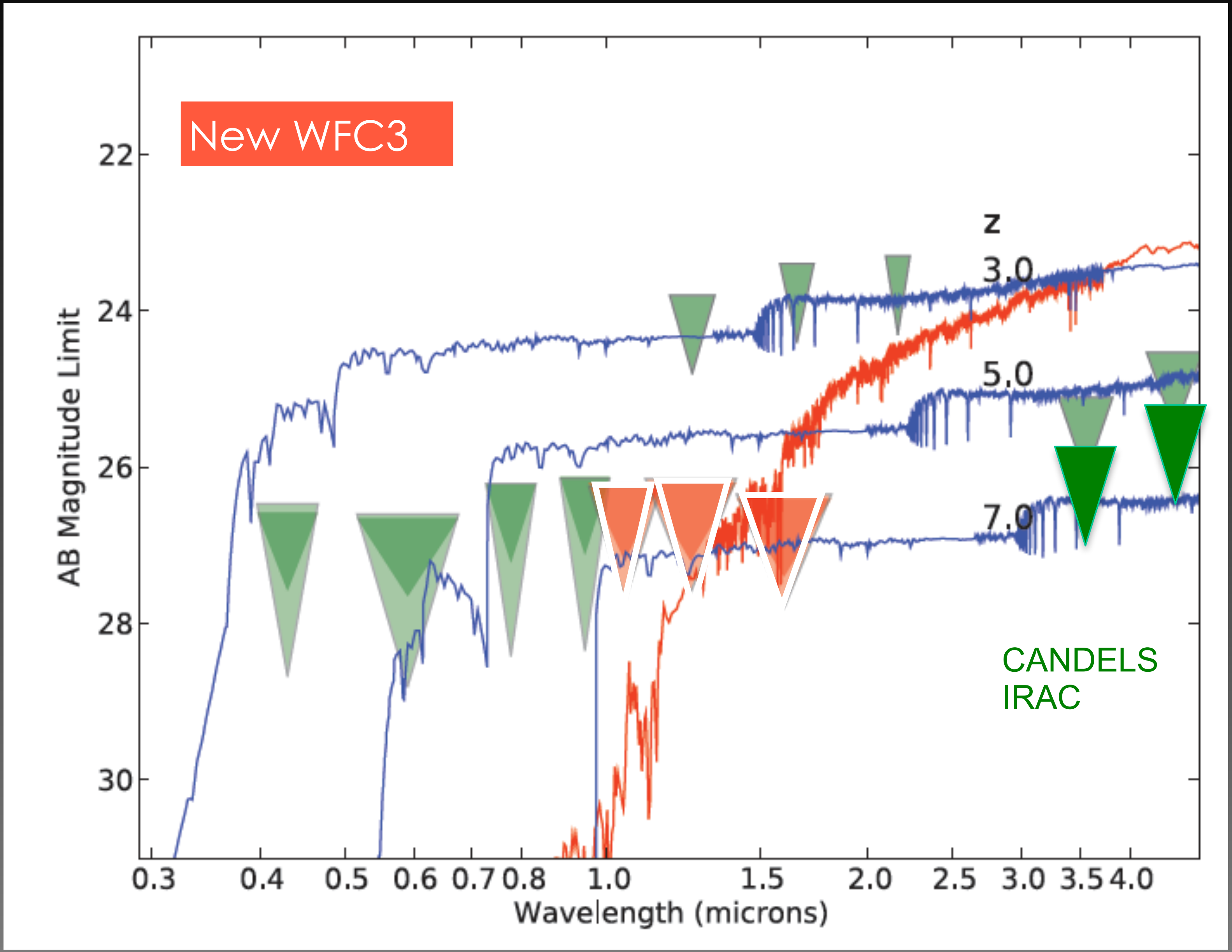

SCIENCE GOALS (ORIGINAL)

Supernovae	Obtain a direct, explosion-model-independent measure of the evolution of Type Ia supernovae as distance indicators at $z > 1.5$, independent of dark energy.
Supernovae	Refine the only constraints we have on the time variation of the cosmic-equation of state parameter *w*, on a path to more than doubling the strength of this crucial test of a cosmological constant by the end of HST's life.
Supernovae	Provide the first measurement of the SN Ia rate at $z \approx 2$ to distinguish between prompt and delayed SN Ia production and their corresponding progenitor models.
Cosmic Dawn	Constrain star-formation rates, ages, metallicities, stellar-masses, and dust content of galaxies at the end of the reionization era $z \sim 6 - 10$.
Cosmic Dawn	Improve the constraints on the bright end of the luminosity function at $z \sim 7$ and 8, and make $z \sim 6$ measurements robust using proper 2-color Lyman break selection.
Cosmic Dawn	Measure fluctuations in the near-IR background light, at sensitivities sufficiently faint and angular scales sufficiently large to constrain reionization models.
Cosmic Dawn	Greatly improve the estimates of the evolution of stellar mass, dust and metallicity at $z = 4 - 8$ by combining WFC3 data with very deep Spitzer IRAC photometry.
Cosmic Dawn	Identify very high-redshift AGN by cross-correlating optical dropouts with deep Chandra observations. Constrain fainter AGN contributions via X-ray stacking.
Cosmic Dawn	Use clustering statistics to estimate the dark-halo masses of high-redshift galaxies with triple the area and double the maximum lag of prior HST surveys.

SCIENCE GOALS (ORIGINAL)

Cosmic Noon	Improve by an order of magnitude the census of passively-evolving galaxies at $1.5 < z < 4$. Measure mass functions and size distributions in the rest-frame optical, measure the trend in clustering with luminosity, and quantify evolution with redshift.
Cosmic Noon	Use rest-frame optical observations at $1 < z < 3$ to provide solid estimates of bulge and disk growth, and the evolution spiral arms, bars, and disk instabilities.
Cosmic Noon	Test models for the co-evolution of black holes and bulges via the most detailed HST census of interacting pairs, mergers, AGN, and bulges, aided by the most complete and unbiased census of AGN from Herschel, improved Chandra observations, and optical variability.
Cosmic Noon	Detect individual galaxy subclumps and measure their stellar mass, constraining the timescale for their dynamical-friction migration to the center leading to bulge formation.
Cosmic Noon	Measure the effective radius and Sersic index in the rest-frame optical of passive galaxies up to $z \sim 2$ and beyond and combine with ACS data to quantify envelope growth and UV-optical color (age) gradients.
Cosmic Noon	Determine the rest-frame optical structure of AGN hosts at $z \sim 2$.
Cosmic Noon	Identify Compton-thick, optically obscured AGN at $z \sim 2$ and determine their structure.
UV	Constrain the Lyman-continuum escape-fraction for galaxies at $z \sim 2.5$.
UV	Identify Lyman-break galaxies at $z \sim 2.5$ and compare their properties to higher-z LBG samples.
UV	Estimate the star-formation rate in dwarf galaxies to $z > 1$ to test whether dwarf galaxies are "turning on" as the UV background declines at low redshift.

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Cosmic "high noon": z ~ 2

Stellar masses down to $10^9 M_\odot$, counts of massive galaxies and quenched galaxies, radii, morphologies, bulge masses, mergers, AGN hosts

Noon	galaxies up to $z \sim 2$ and beyond and combine with ACS data to quantify envelope growth and UV-optical color (age) gradients.
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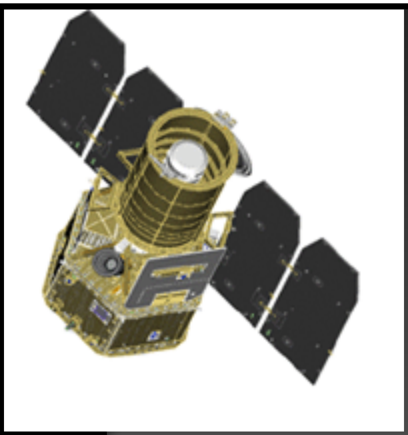
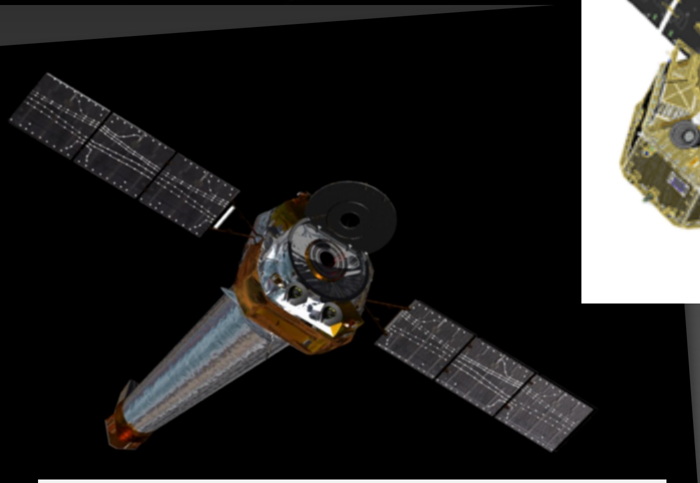
CANDELS fields also include the deepest and largest allocations of multi-band imaging and spectroscopy from the largest and best ground telescopes

Herschel Far-IR

HST Optical – Near IR

GALEX (UV)





Chandra X-RAY

Spitzer Mid-Far IR

CANDELS fields have the very deepest multi-wavelength data from space

Example of Chandra/ACIS contribution

GOODS-S: 7 Ms
GOODS-N: 2 Ms
EGS: 0.8 Ms
UDS: 0.6 Ms
COSMOS: 0.18 Ms

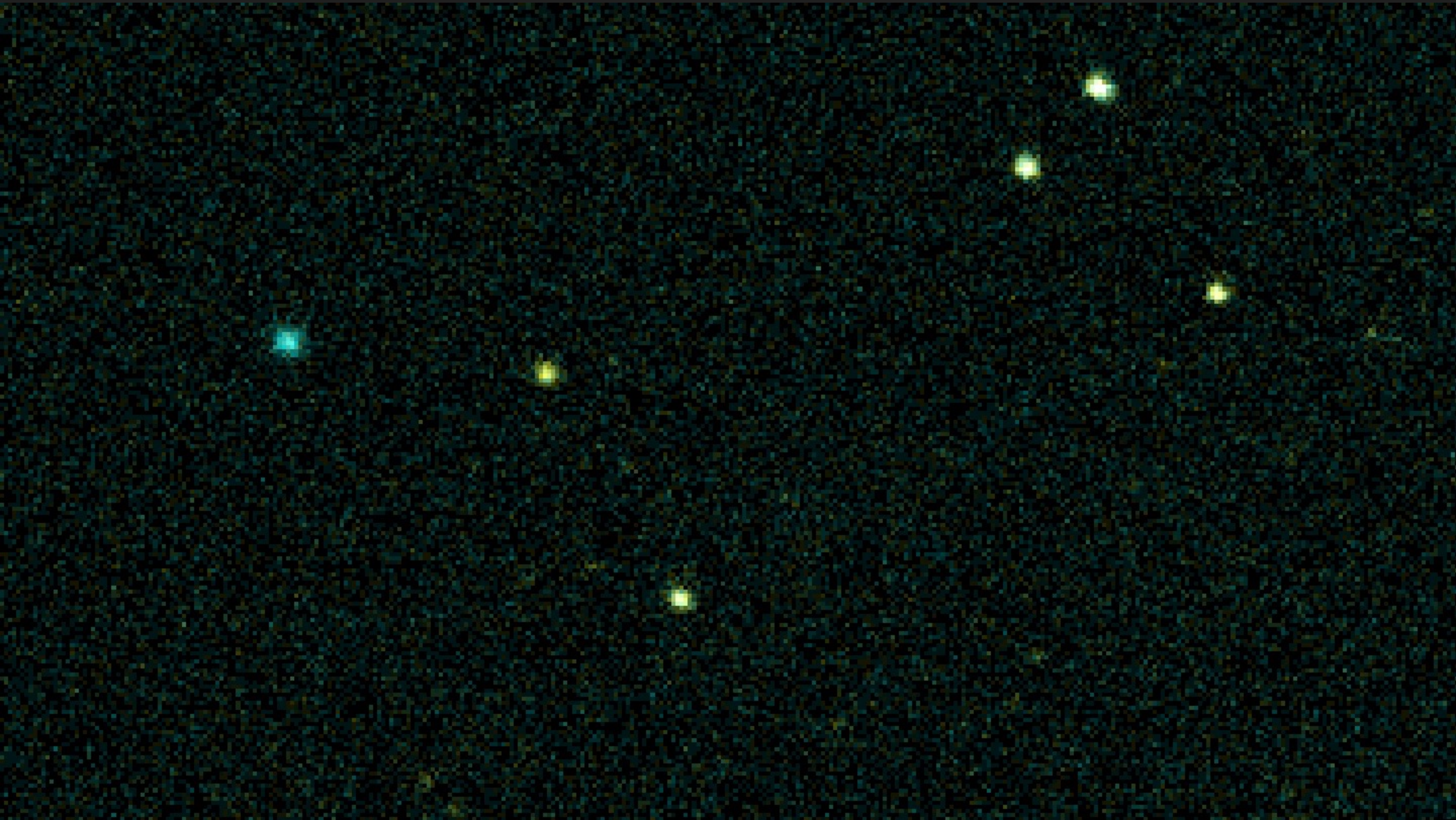
TOTAL EXPOSURE TIME: 10.58 Ms = 2,938 hours

This superb set of super-deep X-ray data will not be surpassed for at least another 10 years!

So CANDELS is the go-to survey regions to study AGN evolution

HST
0.6, 1.25, 1.6 μm

Chandra
0.5-2, 2-8, 5-8 keV

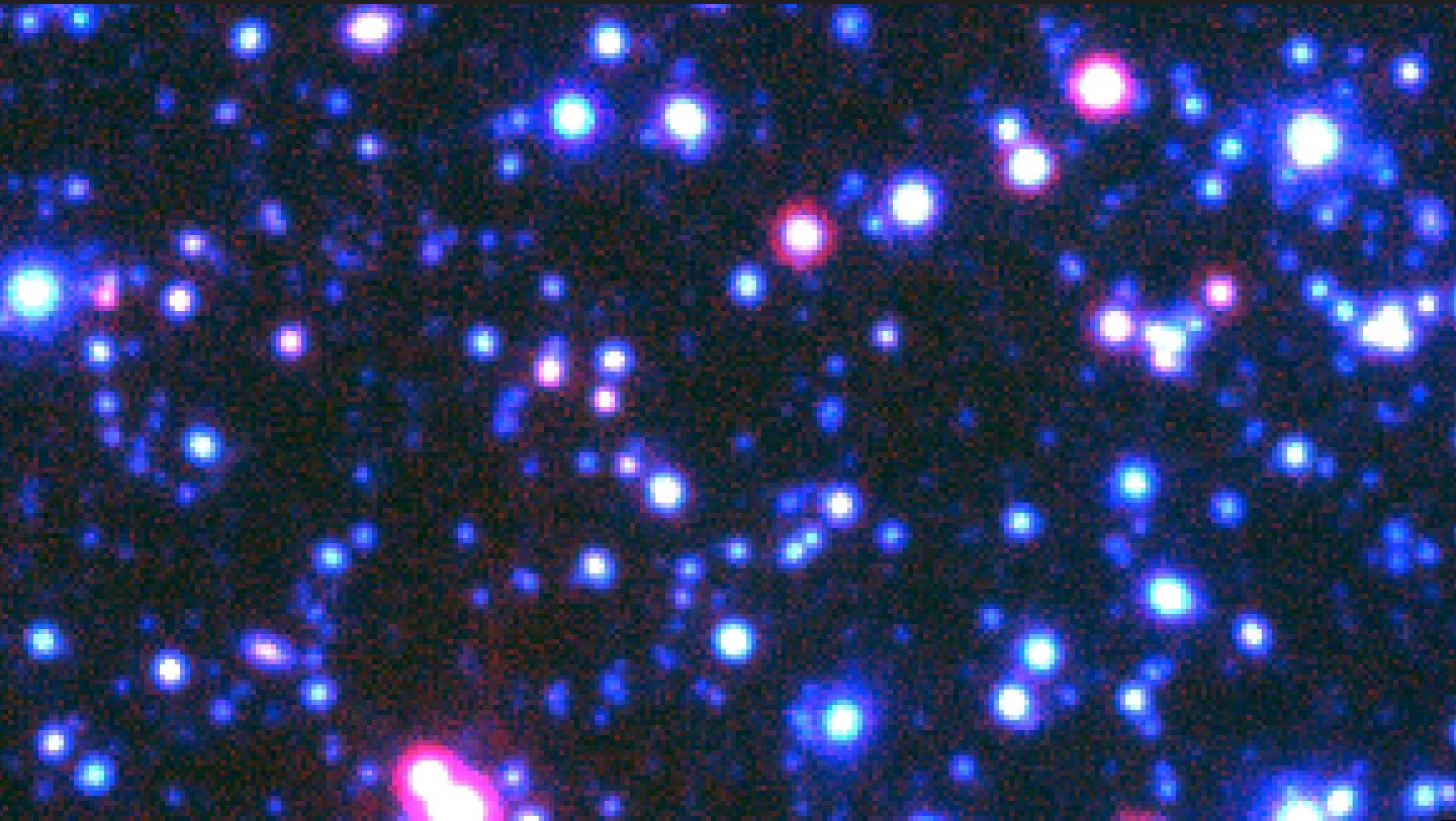


Here are ID's of the 6 brightest Chandra sources

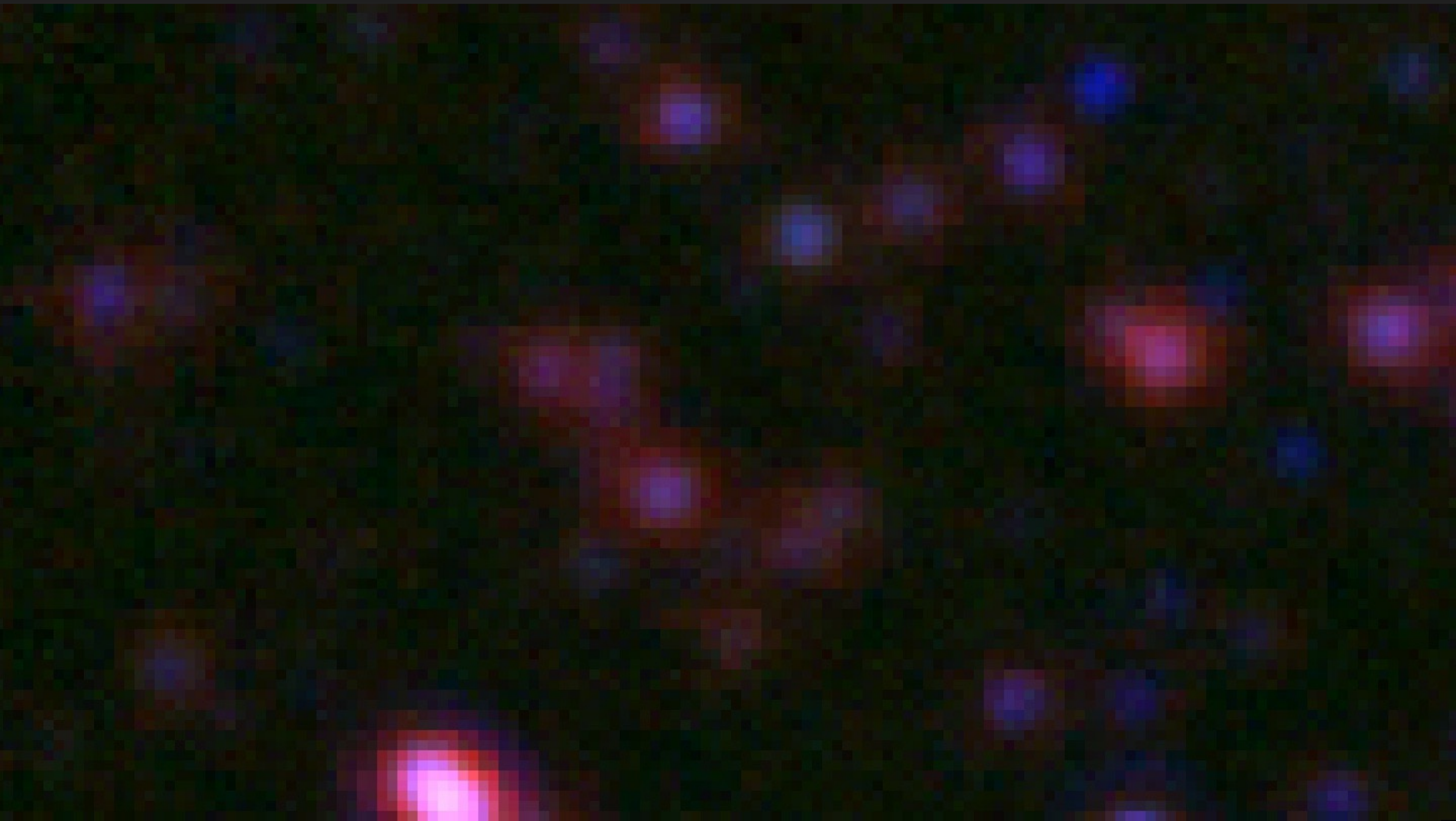
HST

0.6, 1.25, 1.6 μm

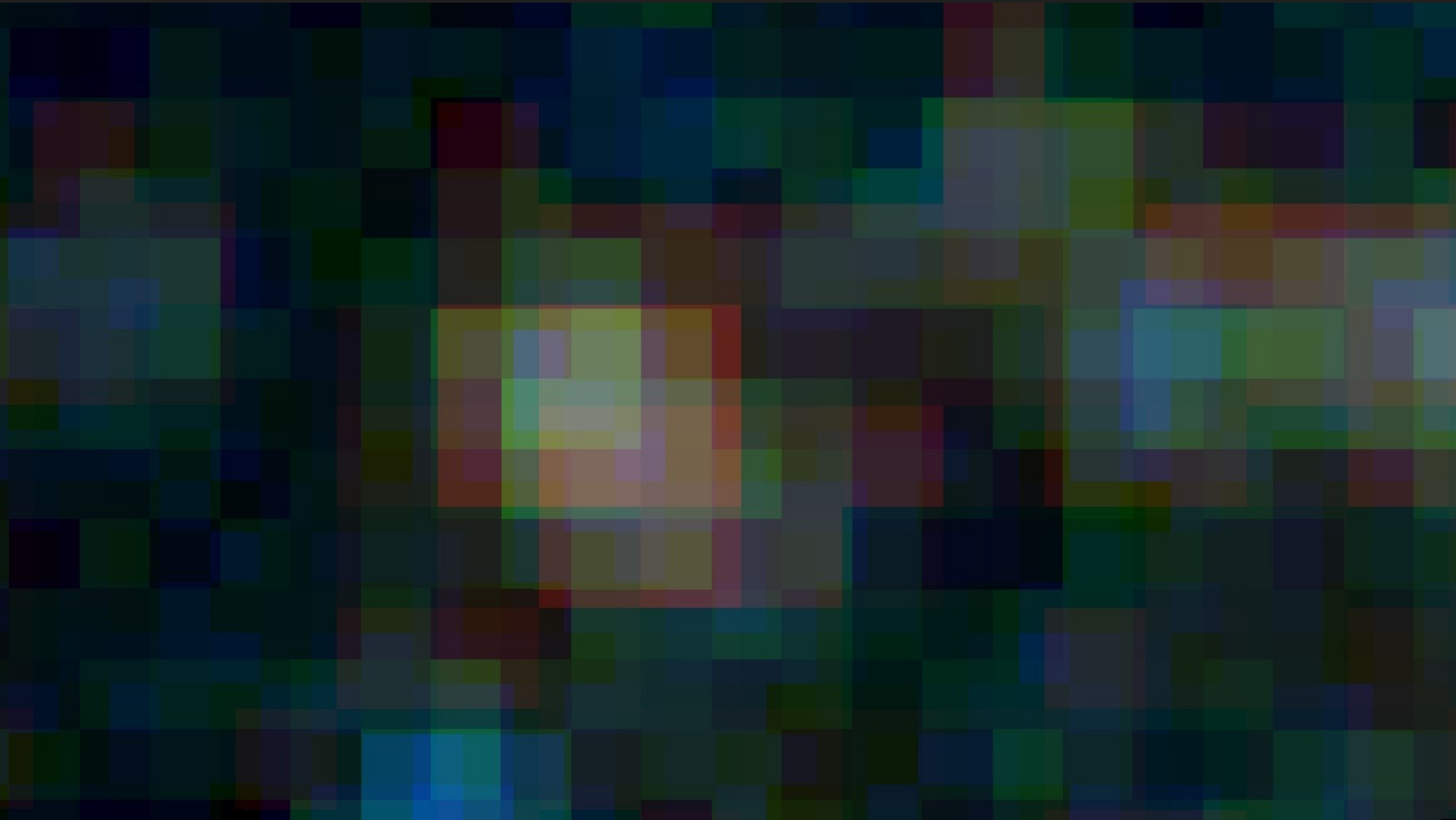
Spitzer/IRAC
3.6+4.5, 5.6, 8 μm



Spitzer/MIPS + Herschel/PACS
24, 100, 160μm



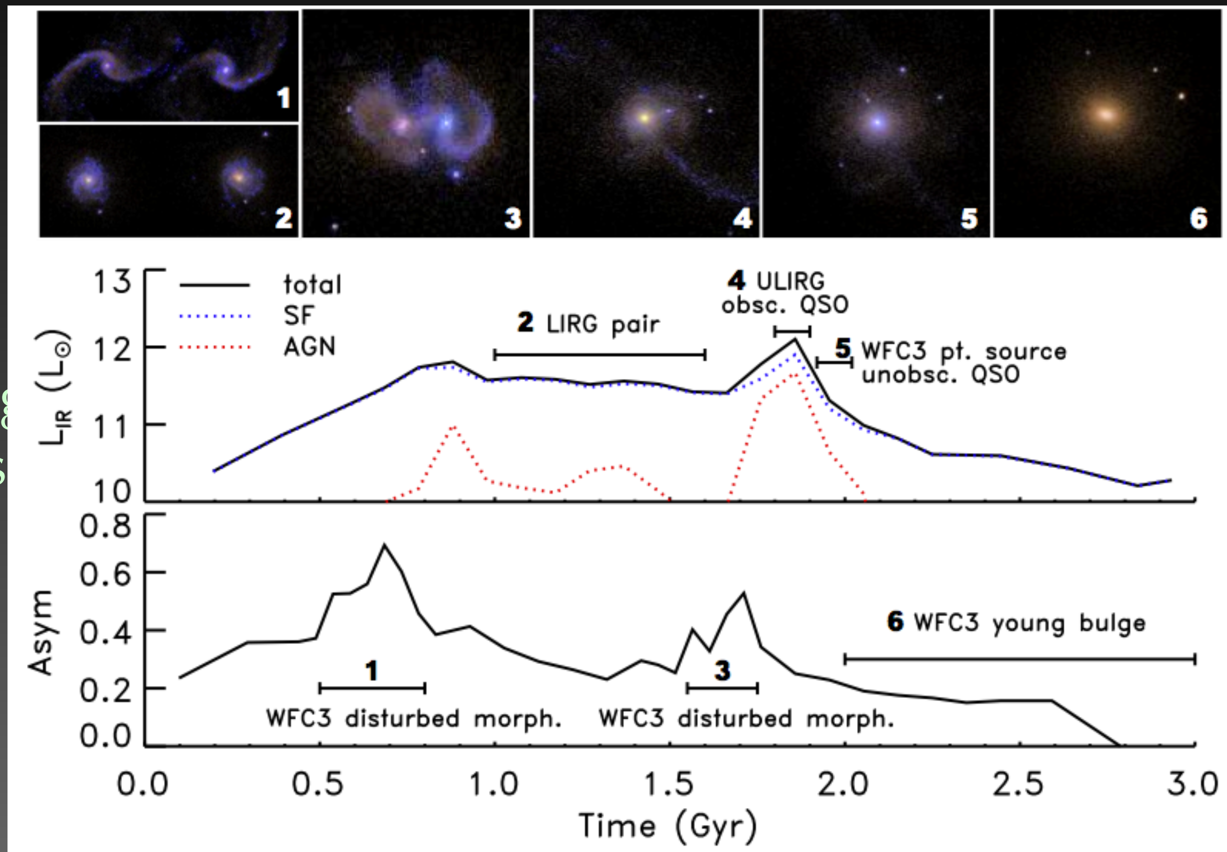
Herschel/SPIRE
250, 350, 500μm



Explore one of the main goals of CANDELS – the nature of the host galaxies of AGNs

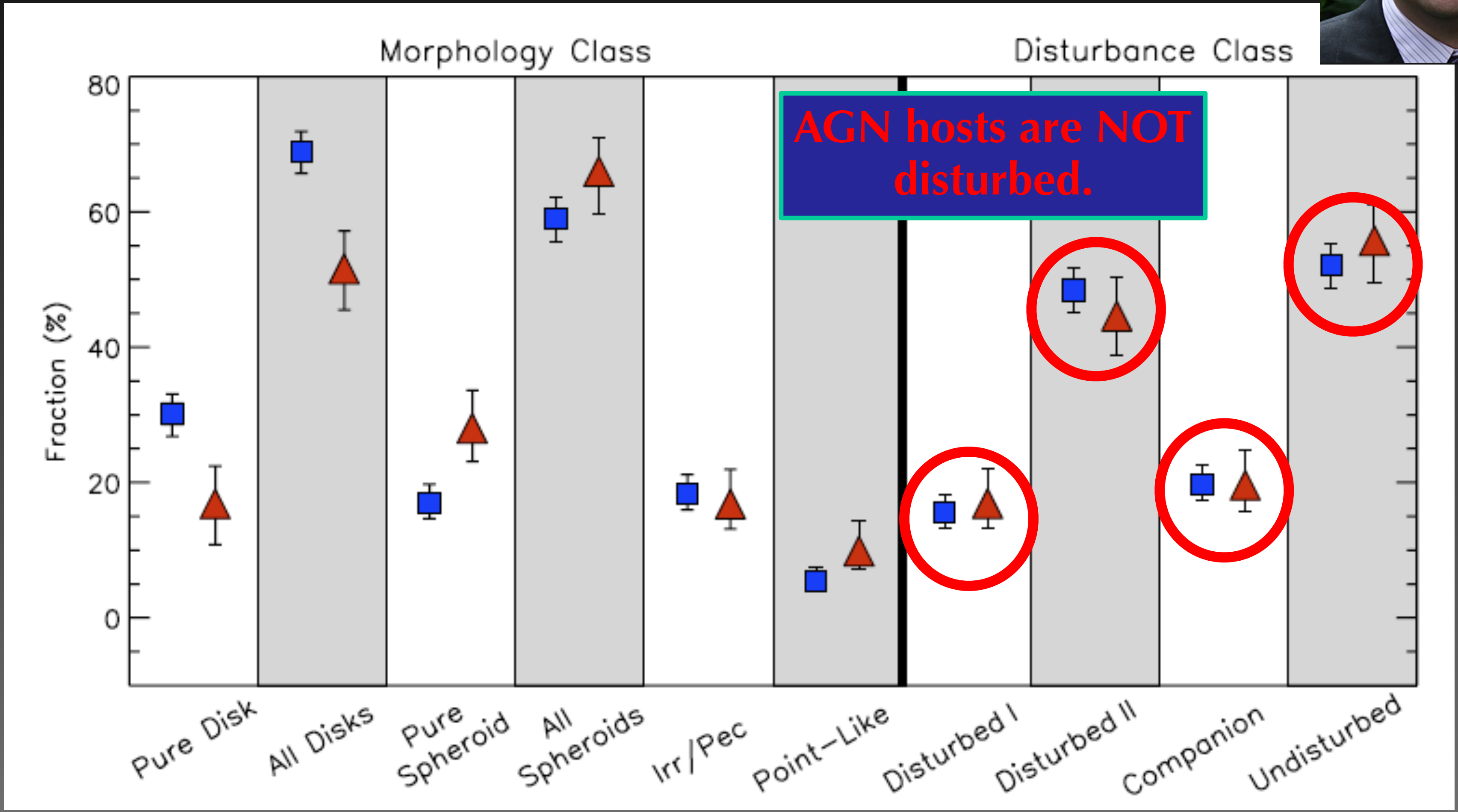
Merg … ral

supermass … s at z~2.



Popular scenario: Merger ➔ ULIRG ➔ embedded QSO ➔ unobscurred AGN ➔ elliptical galaxy with black hole (e.g. Hopkins+ 06)

Mergers do not play a significant role in fueling the central supermassive black holes in most x-ray selected active galaxies at z~2.



Kocevski+12

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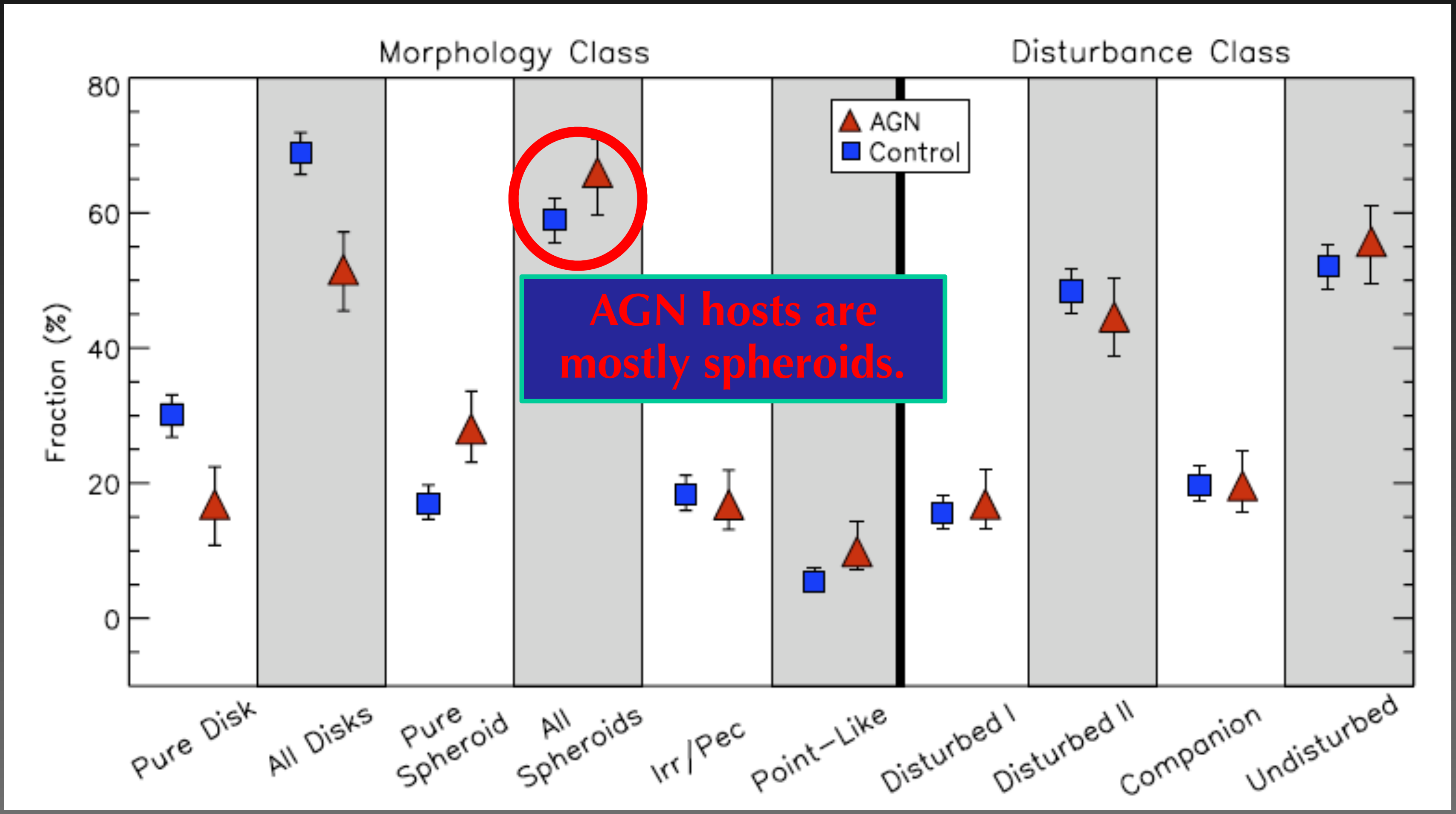

Kocevski+12

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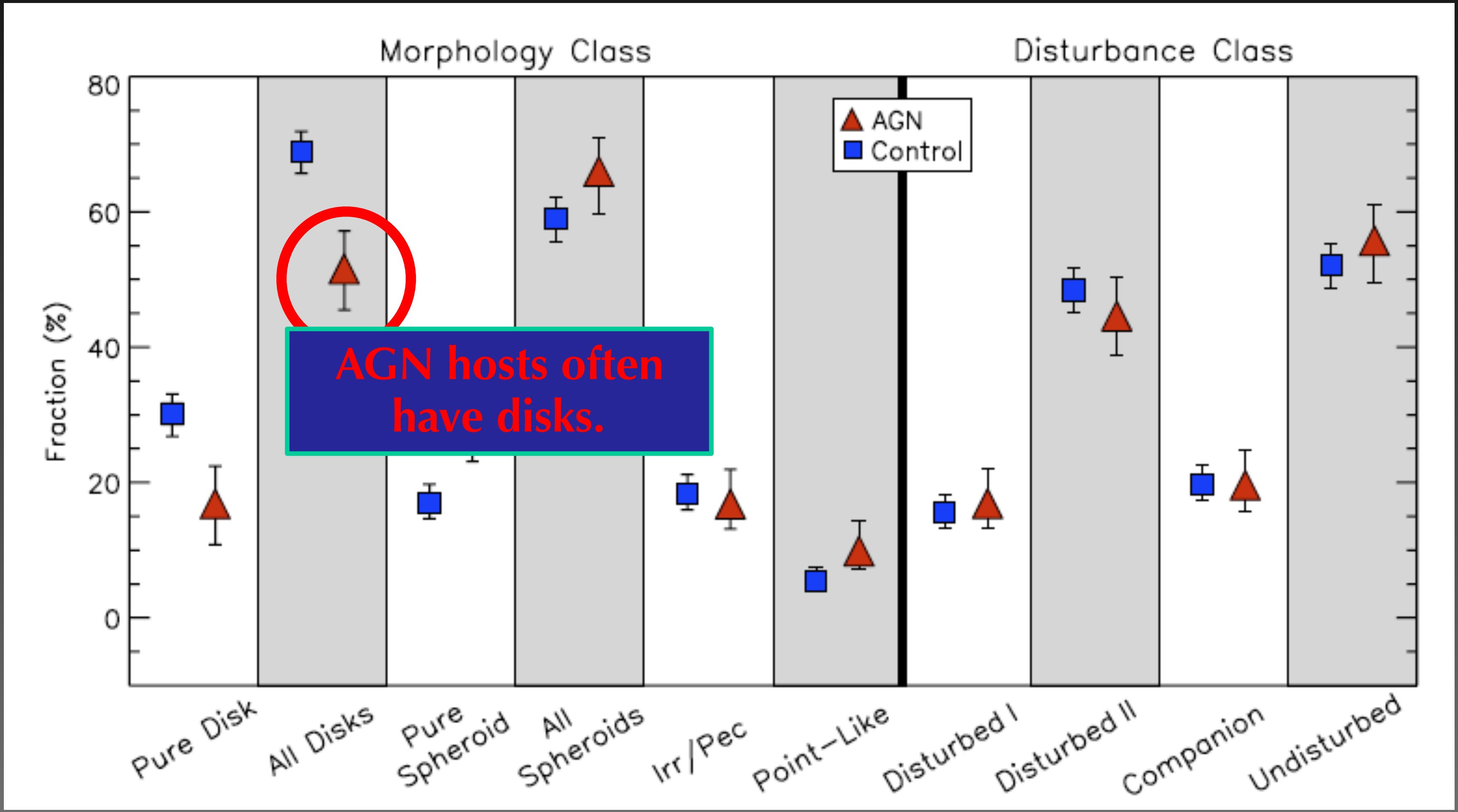
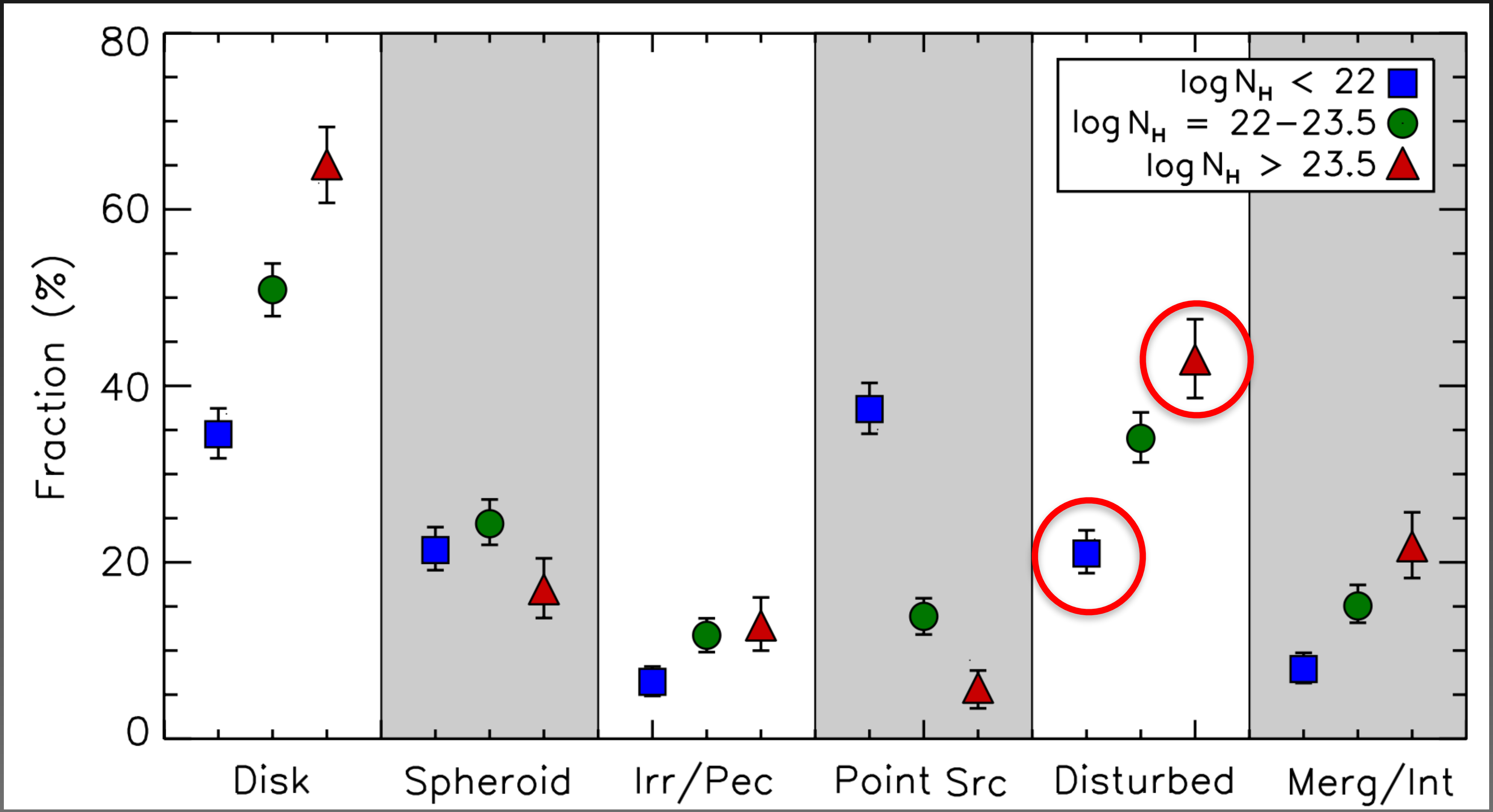


Kocevski+12

Hosts of Compton-thick (dusty) AGN are a bit more disturbed



Kocevski+15

Mergers do not play a significant role in fueling the central supermassive black holes in most x-ray selected active galaxies at $z\sim2$.

- Possible explanations:
  - Mergers are important only for the most luminous AGN
  - AGN at lower luminosities are internally triggered, e.g. by disk instabilities.
  - X-ray AGN are seen at a late phase; AGN are dust obscured when the merger signatures are apparent
  - Variability on timescales of 10^{2-6} years wipes out the expected correlations
- Ongoing work to look at AGN frequency of hosts with different sizes: clear signal seen that AGN activity is dramatically increased during the host galaxy's compact, star-forming phase

An Important Component of the CANDELS program is the inclusion of top theorists working with N-body and hydrodynamical simulations.

Theory component: "CANDELized" Hydrodyamical simulations

CANDELS fields have also been "mocked" in geometry by 3 different Semi-Analytic Models (SAMs)

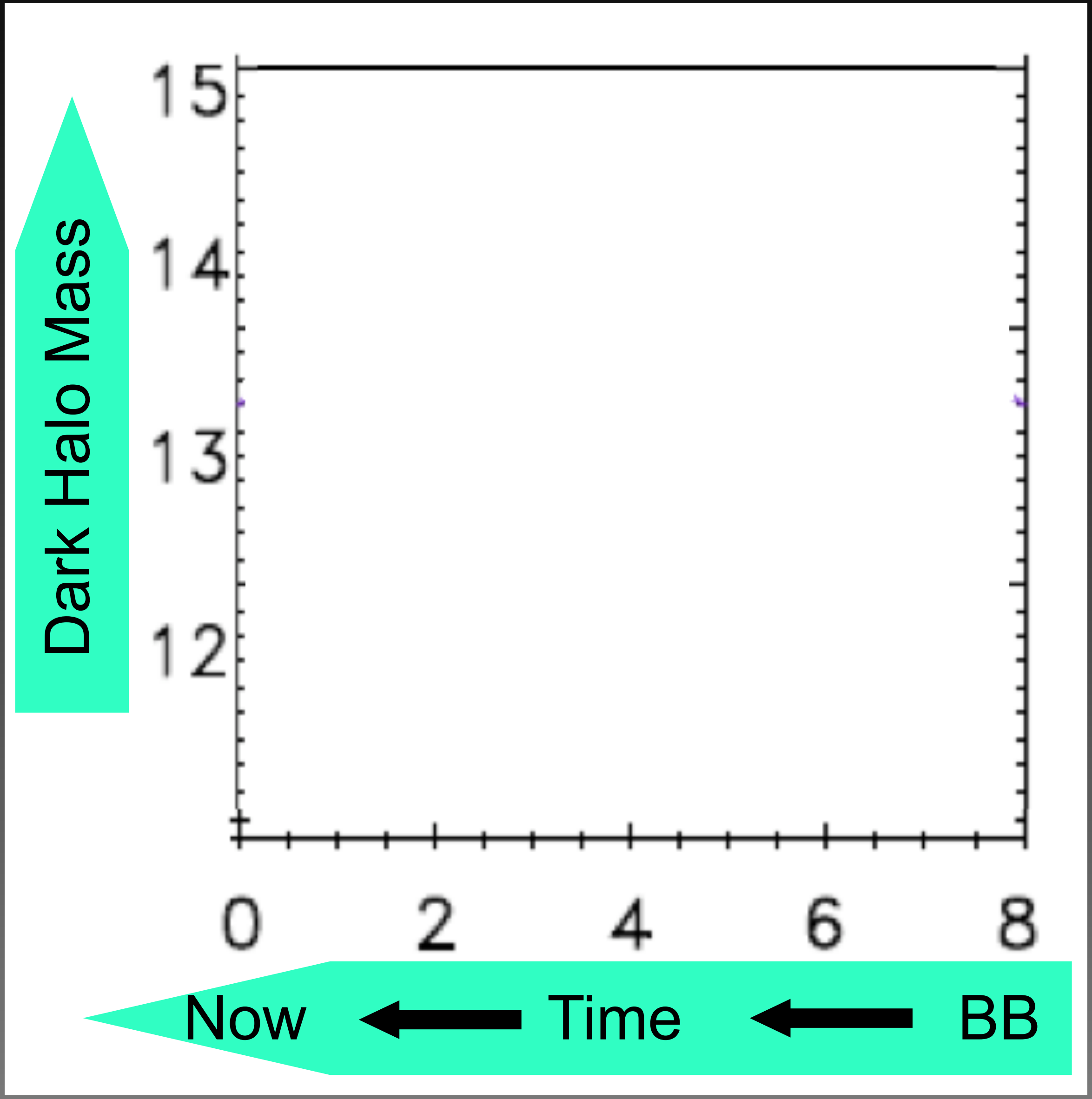
Based on "Bolshoi" high-resolution cosmological N-body simulation and are carefully tuned to match the local galaxy stellar mass function construct catalogs of mock galaxies on light cones that have the same geometry as the CANDELS survey, which should be particularly useful for quantifying the biases and uncertainties on measurements and inferences from the real observations.

Lu+15 (hint: use CANDELS in title to find article)

The relationship between the masses of halos found within N-Body Simulations and the stellar masses within their constituent galaxies can be estimated.

Dark halo mass growth vs. time: 4 examples

GALics dark-matter halos by Cattaneo et al. 2006



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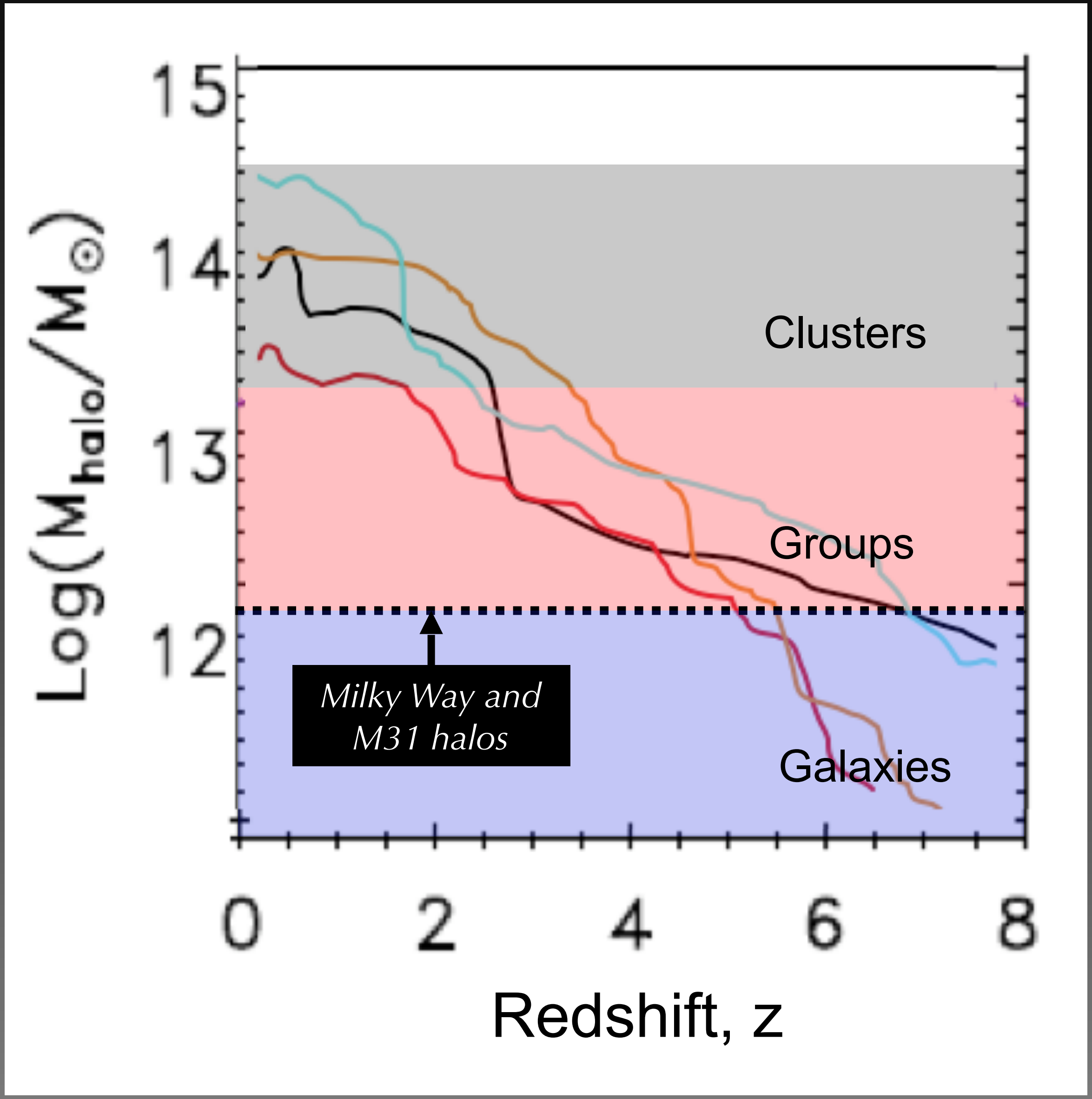
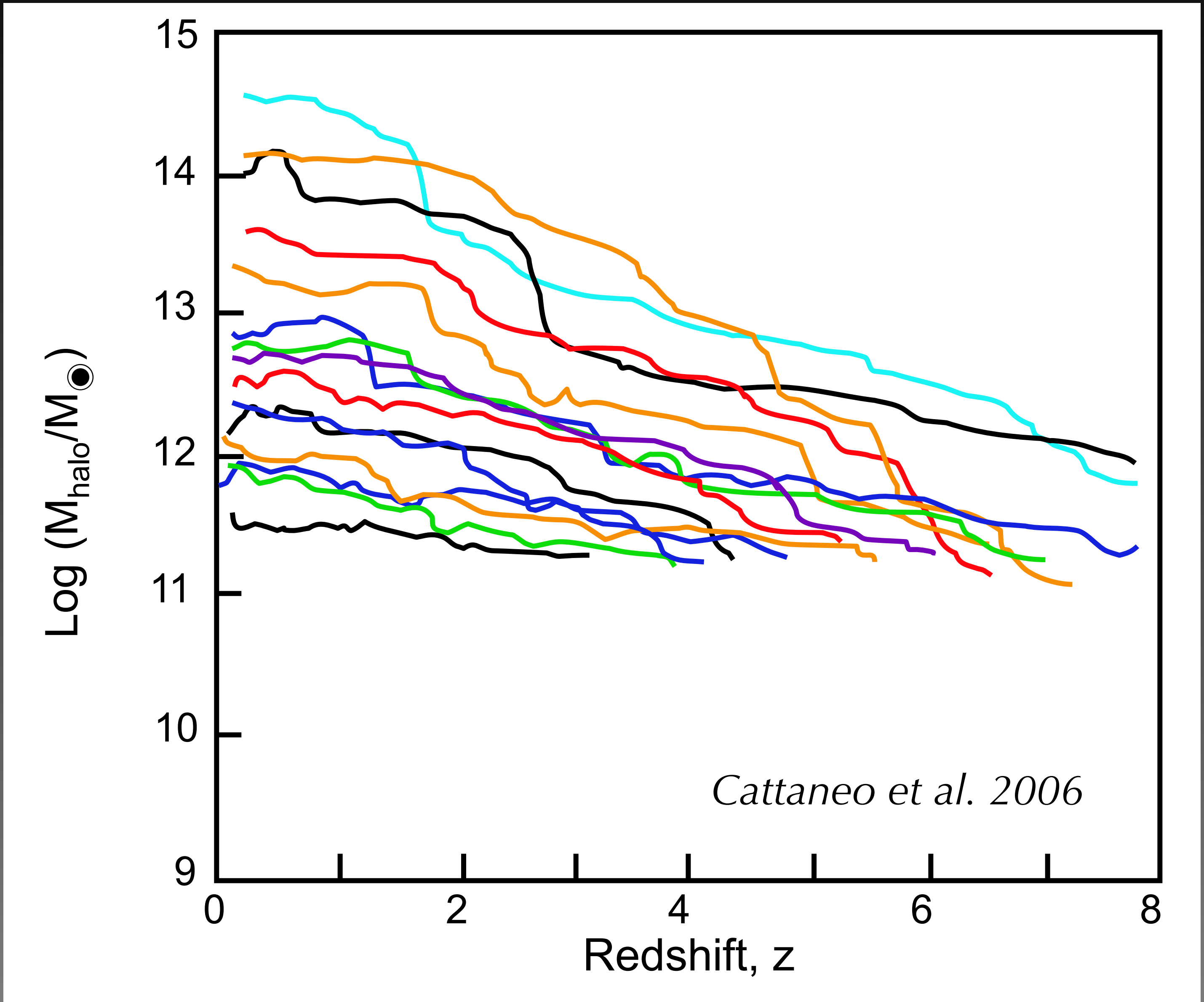
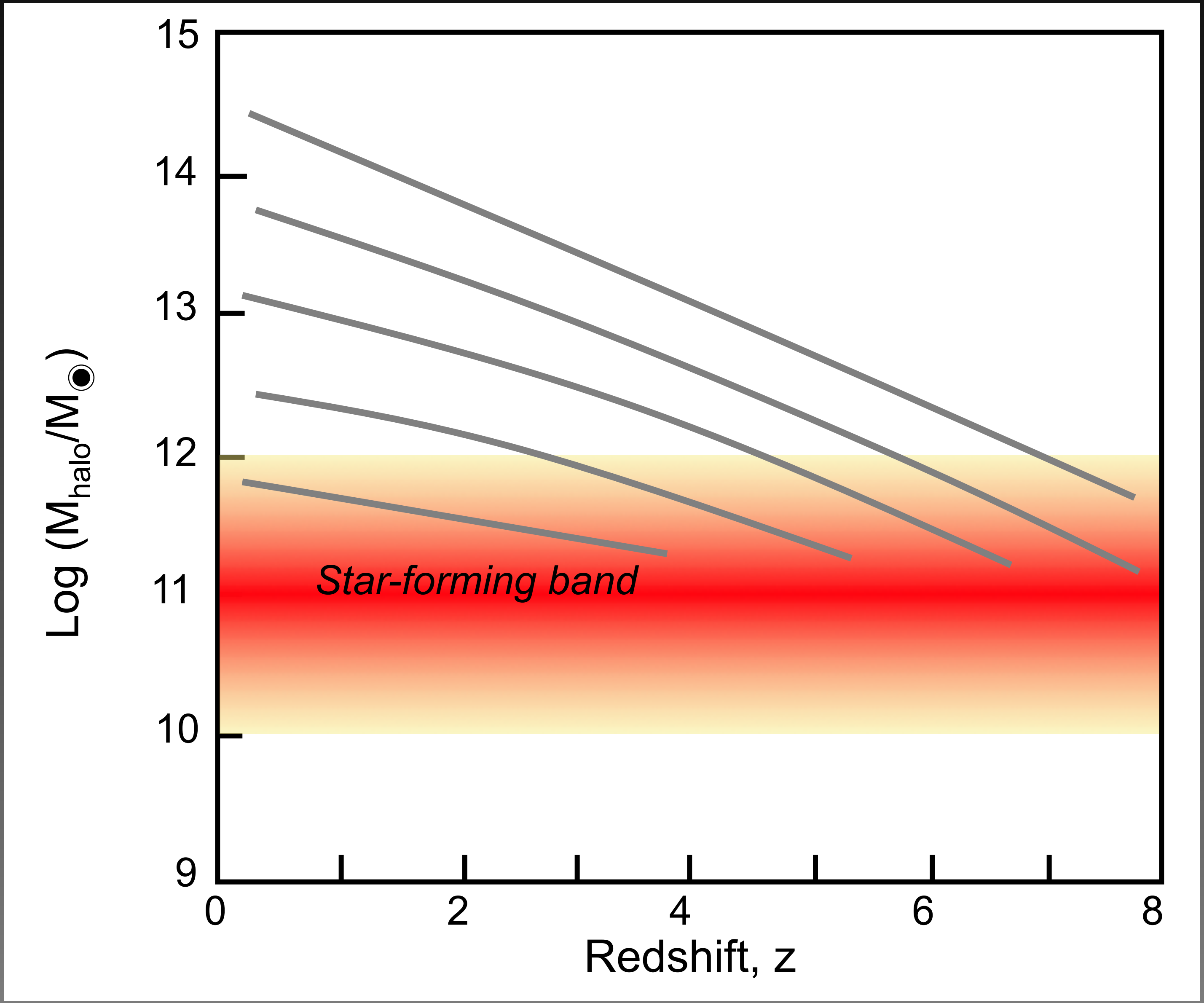


Dark halos of progressively smaller mass

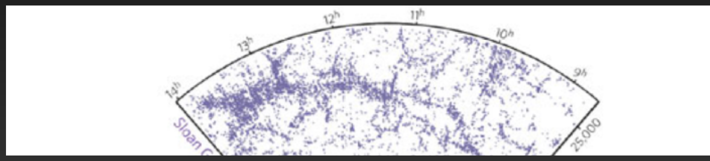


Key assumption: ***star-forming band*** in dark-halo mass



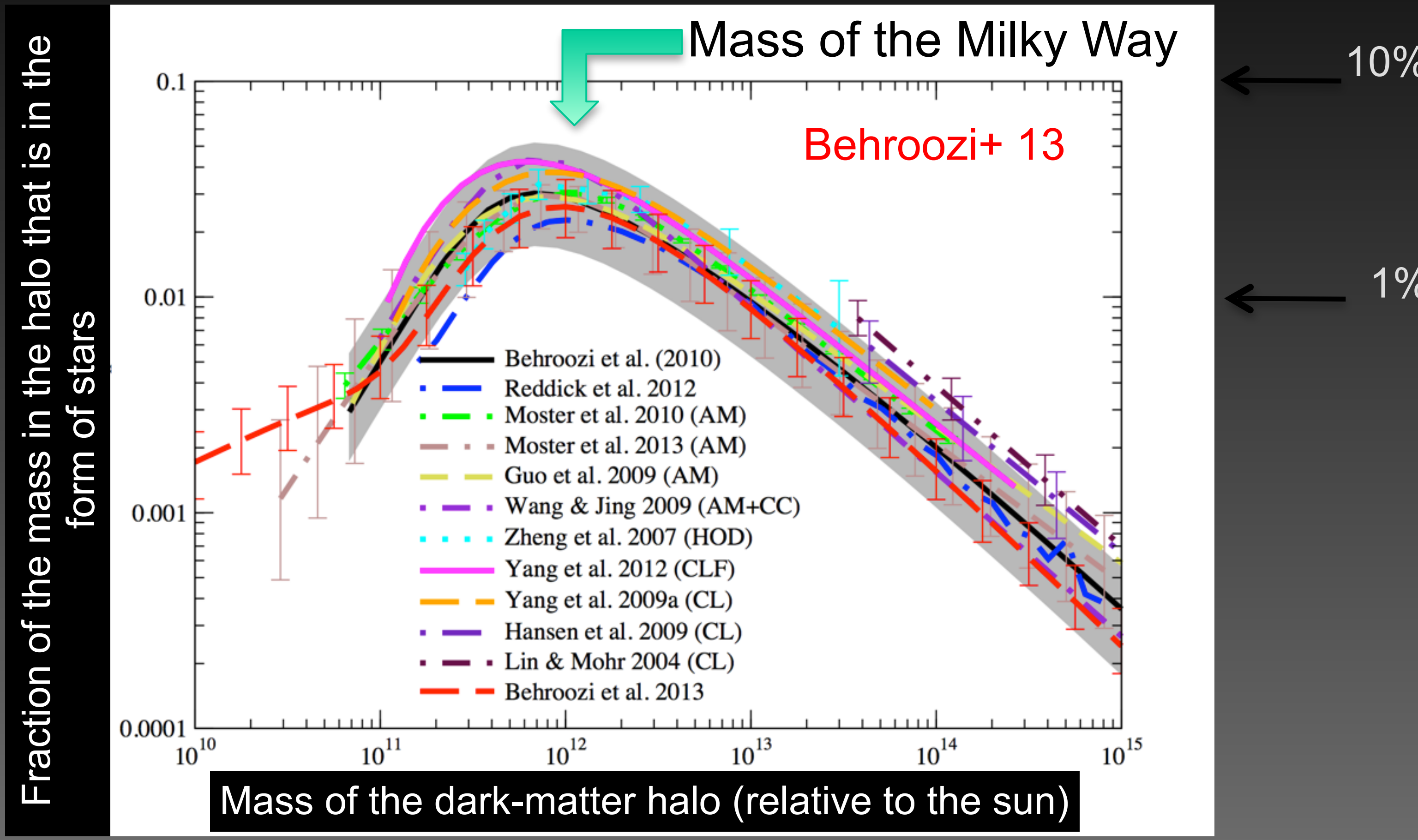
A crude way to make the connection between galaxies and dark-matter halos*

- Pick a slice of the universe in time (redshift)
- Estimate the stellar mass of each galaxy in that slice (uses multiband photometry)
- Rank order the galaxies from most to least massive (redshifts)
- Rank order the dark-matter halos in a cosmological simulation of the same volume
- Assign the most-massive galaxy to the most massive dark-matter halo, and so on down the list
- Repeat for another slice of time (redshift)



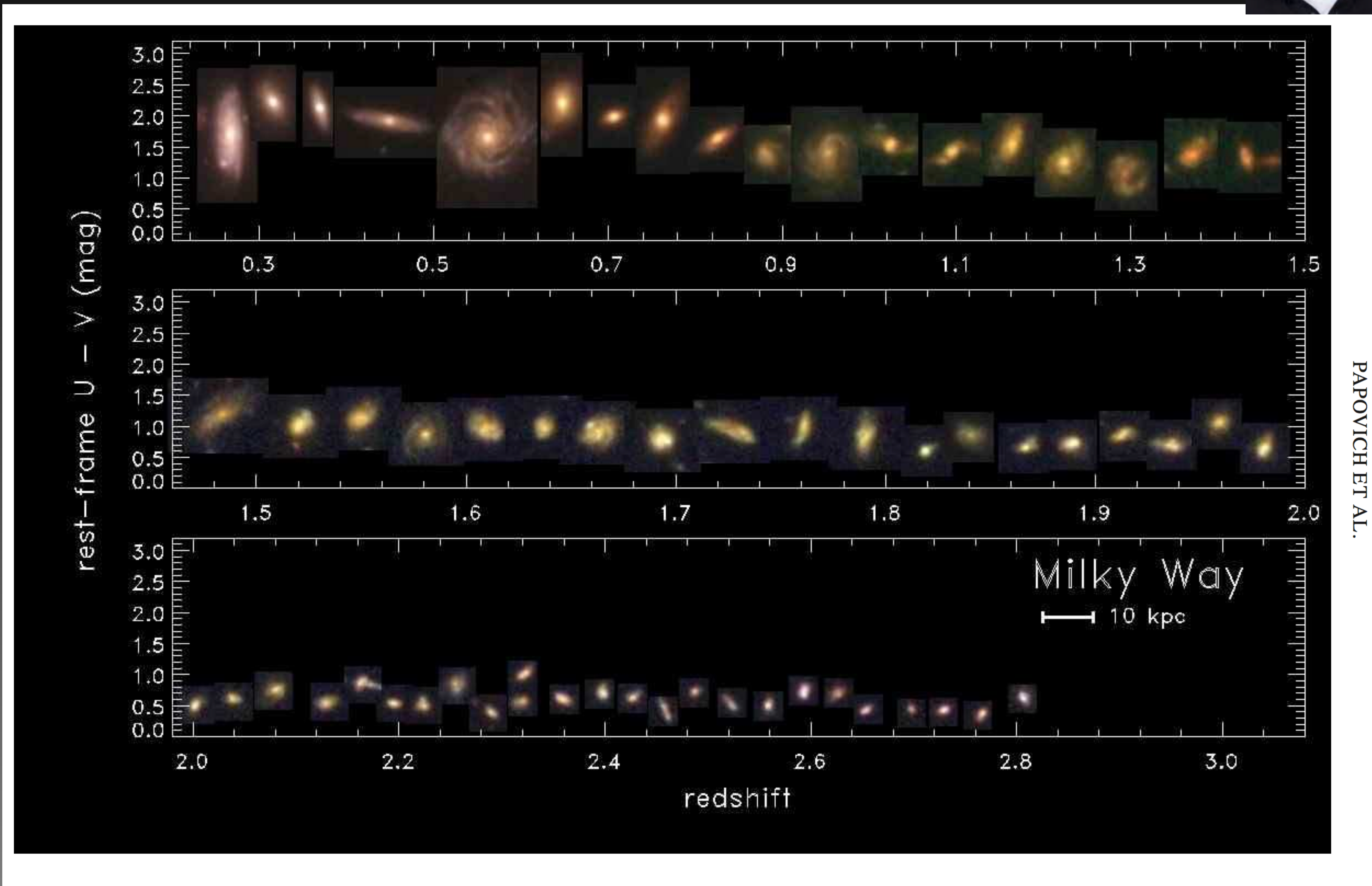
*** Called Stellar Halo Mass Abundance Matching (Behroozi+13, Moster+13)**

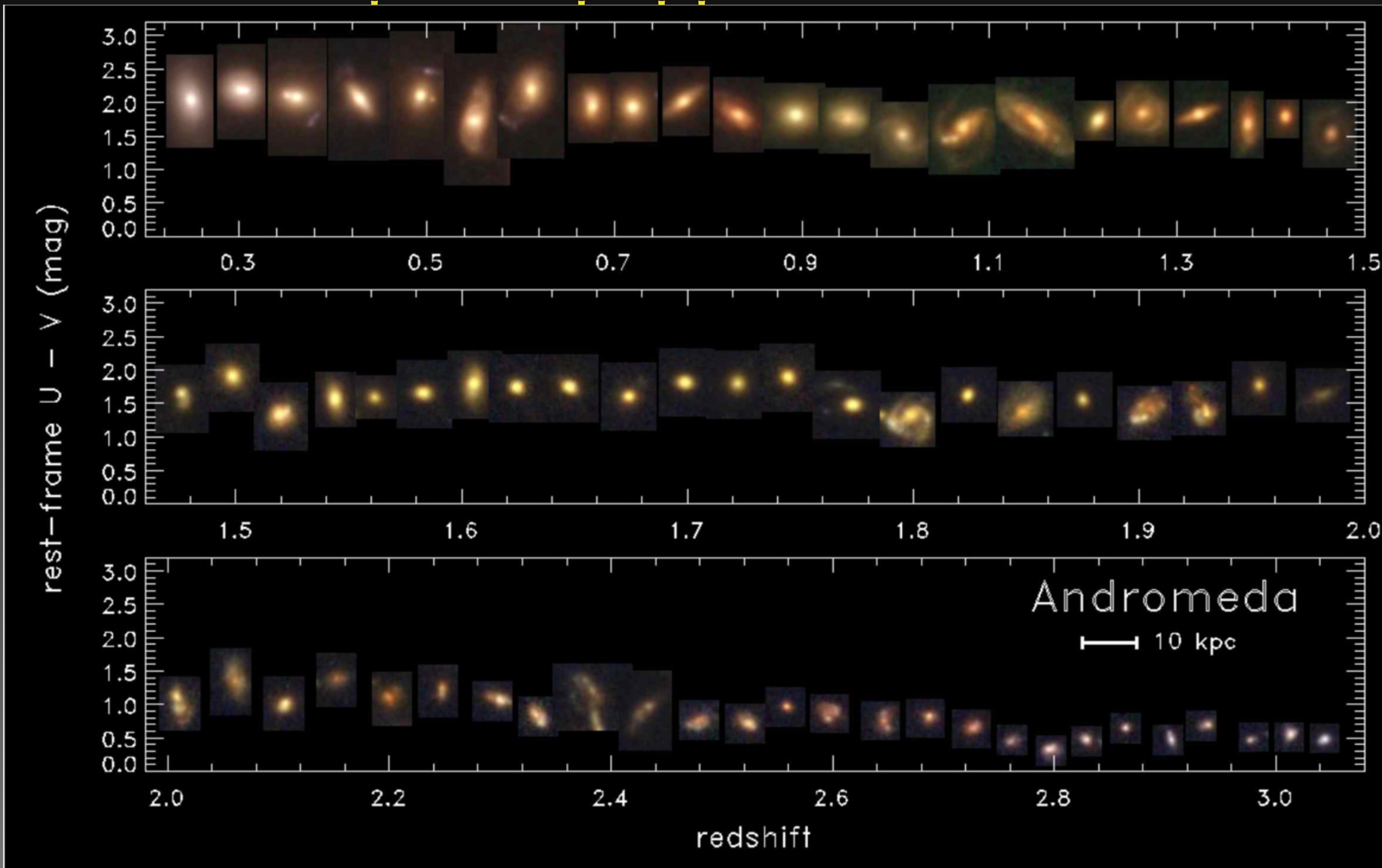
Result: The galaxy's mass in stars compared to the its mass in dark matter



The conversion of gas into stars is inefficient for high-mass and low-mass dark-matter halos

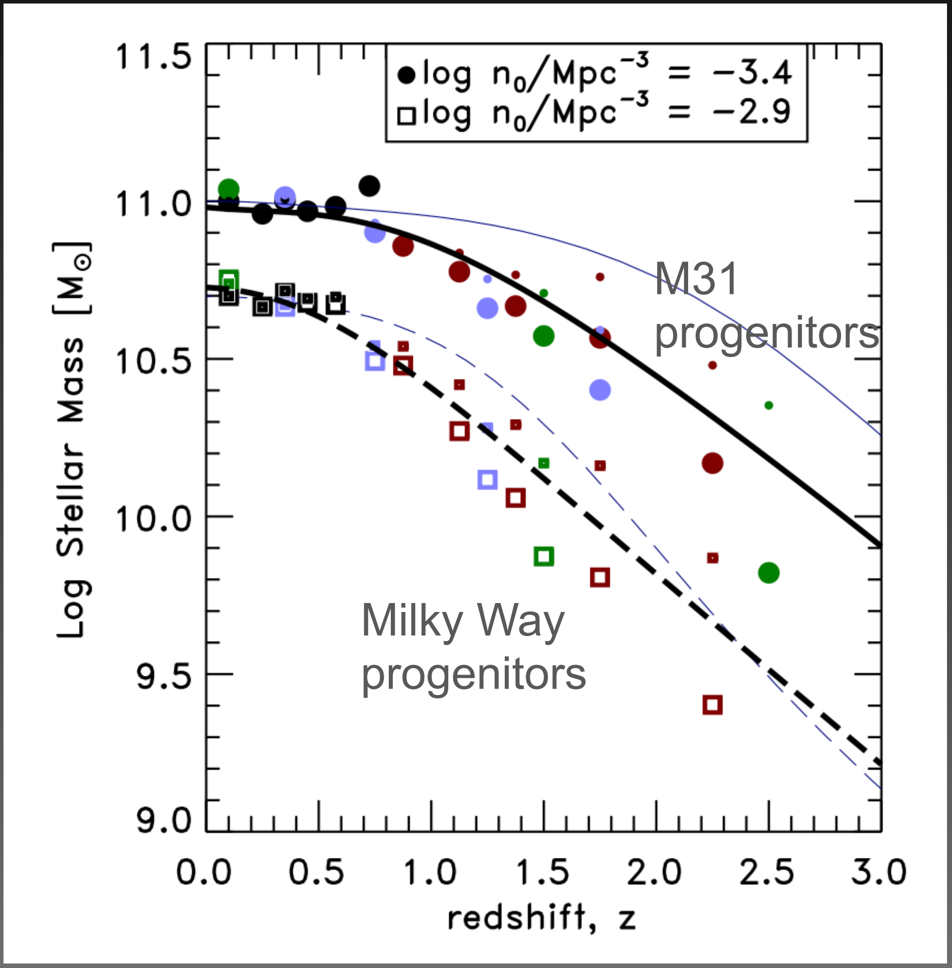
What did the Milky Way look like 11 billion years ago? (Papo +15)




rest-frame U − V (mag)
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0.3
0.5
0.7
0.9
1.1
1.3
1.5
1.6
1.7
1.8
1.9
2.0
2.2
2.4
2.6
2.8
3.0
Andromeda
10 kpc
redshift

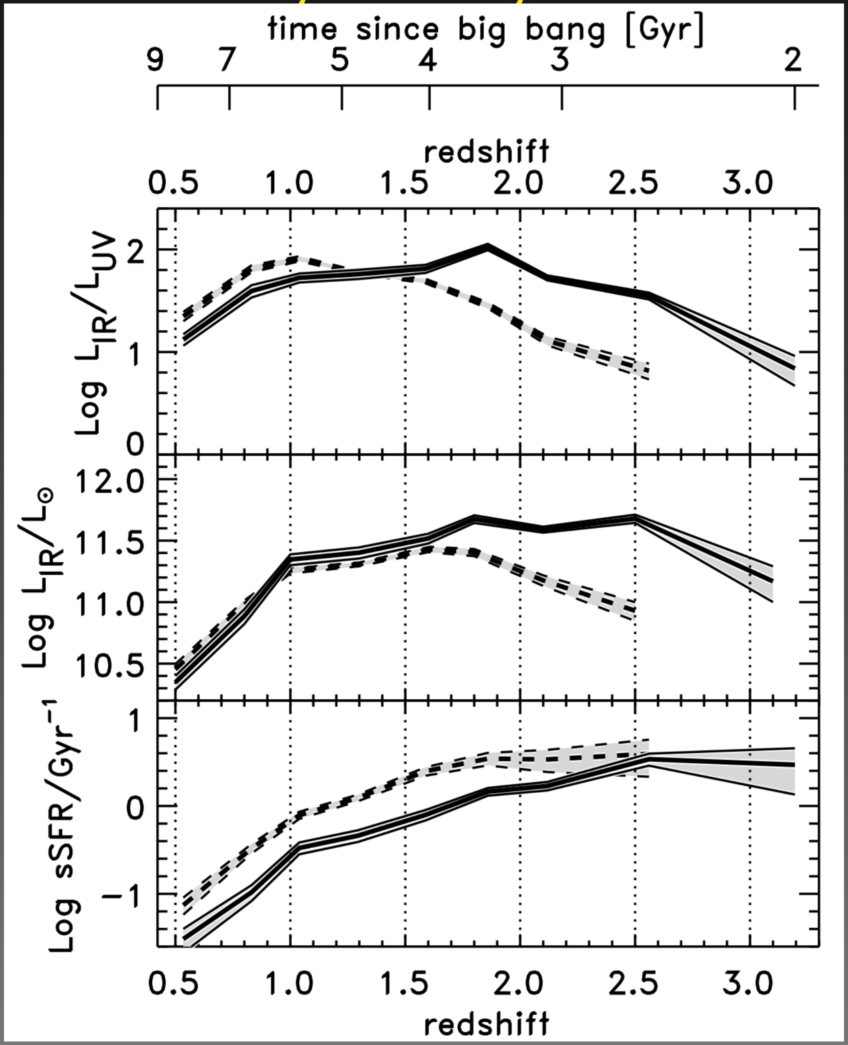
Halo Abundance Matching

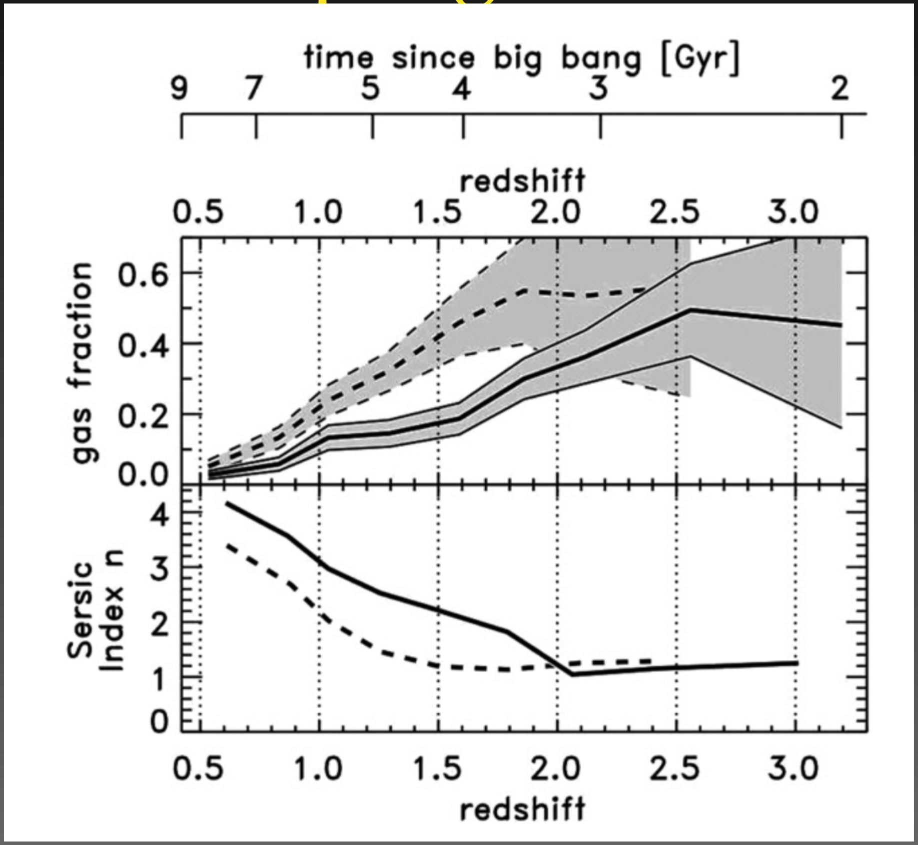
- Comparing galaxies at fixed number density *roughly* matches progenitors to their descendants



Papovich+15

Milky-Way & Andromeda progenitors

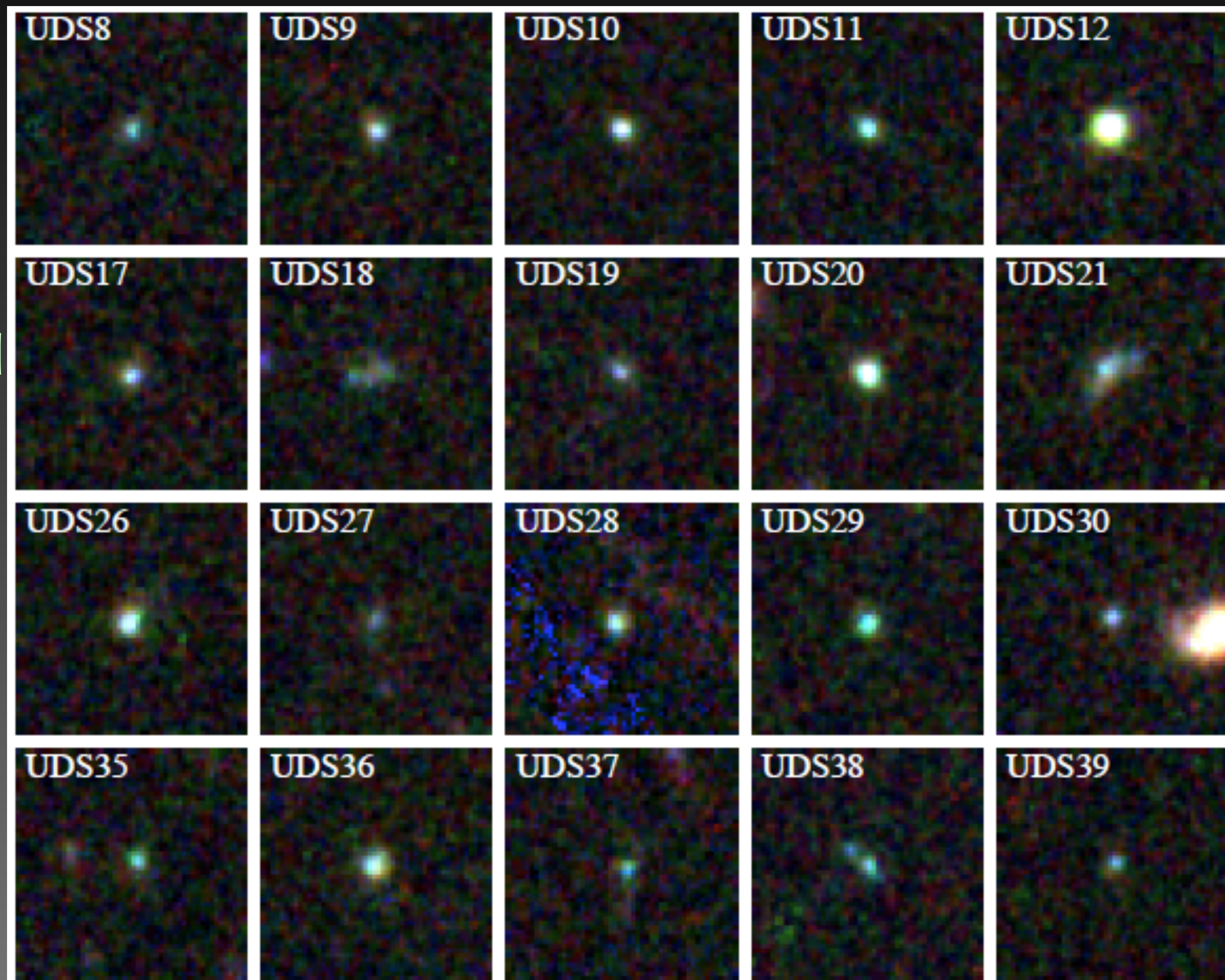




Papovich+15

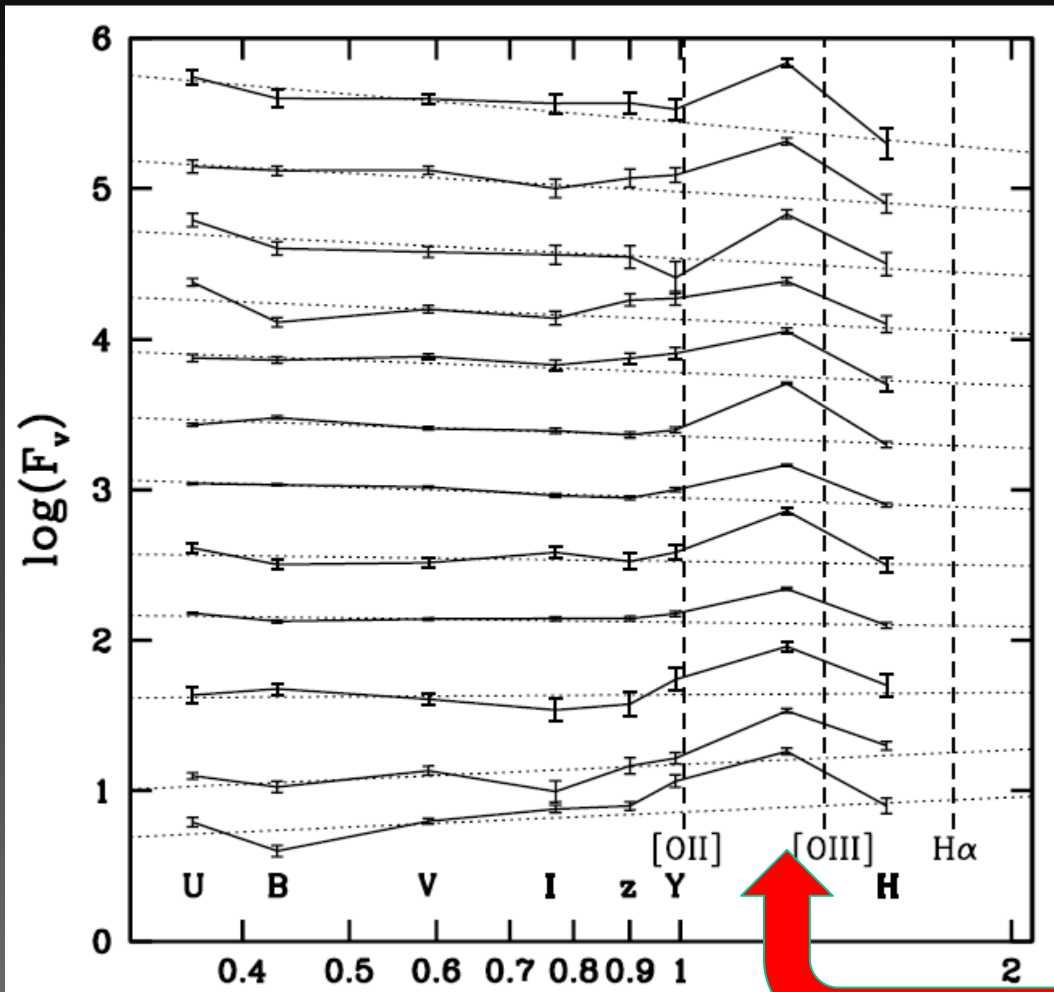
This work Relies on High Precision Photometry Achieved with HST WFC3

A cosmol



Van der Wel+ 11

Bursting dwarfs at z ~ 1.7?



van der Wel et al., 2011

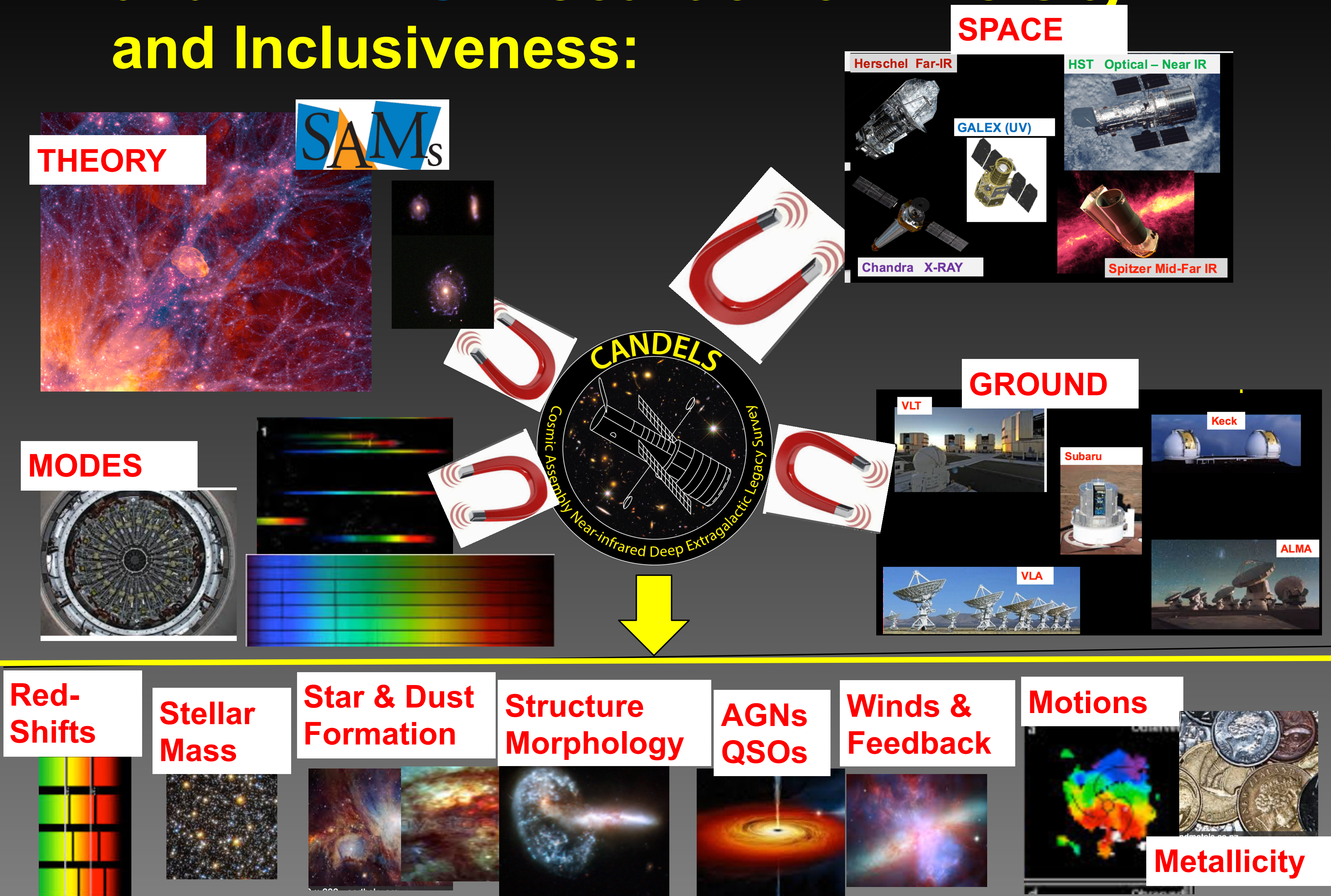
Ubiquitous, low-metallicity extreme starbursts among galaxies with low stellar-mass of Log M = 8.

Can produce most of stellar mass in today's dwarf galaxies in only 4 billion years.

J-band excess likely due to [OIII] emission; EW up to 1000 A

CANDELS is a Consensus Survey
Made in/of Heaven
bringing together   Strong Family Values

and RAINBOW Coalition of Diversity and Inclusiveness:



While for CANDELS fields, the rich are getting richer,

the enormous & unsurpassed wealth of original & reduced data, cataloged & derived information, and customized models and simulations are being provided to the community,

and will serve as the stepping stone and thus lasting legacy for deep surveys, especially measures of gas and dust that play a critical role in galaxy and AGN evolution, by JWST, ALMA, SKA, and other survey instruments for decades to come.

Two Take-Away Messages

We remain far from understanding th origins, assembly, structure, motions, environments, etc. of gas, dust, stars and SMBH in galaxies.

If you want to research the evolution of galaxies or AGN (outside of rich clusters), go to the CANDELS fields.

CANDELS
Cosmic Assembly Near-infrared Deep Extragalactic Legacy Survey

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UC Santa Cruz

Look Afar, and See the End from the Beginning

From Fortune Cookie eaten in 1986