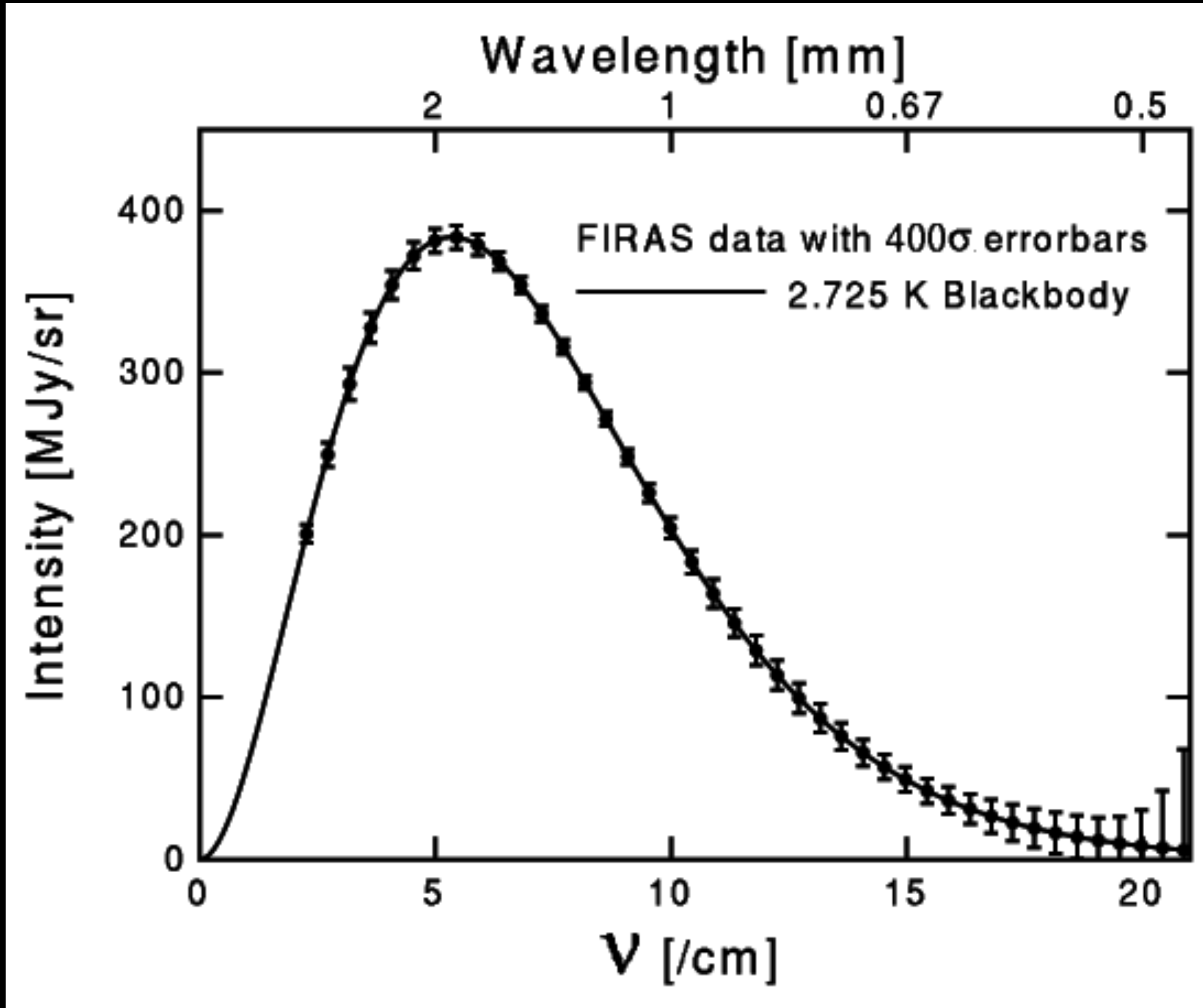
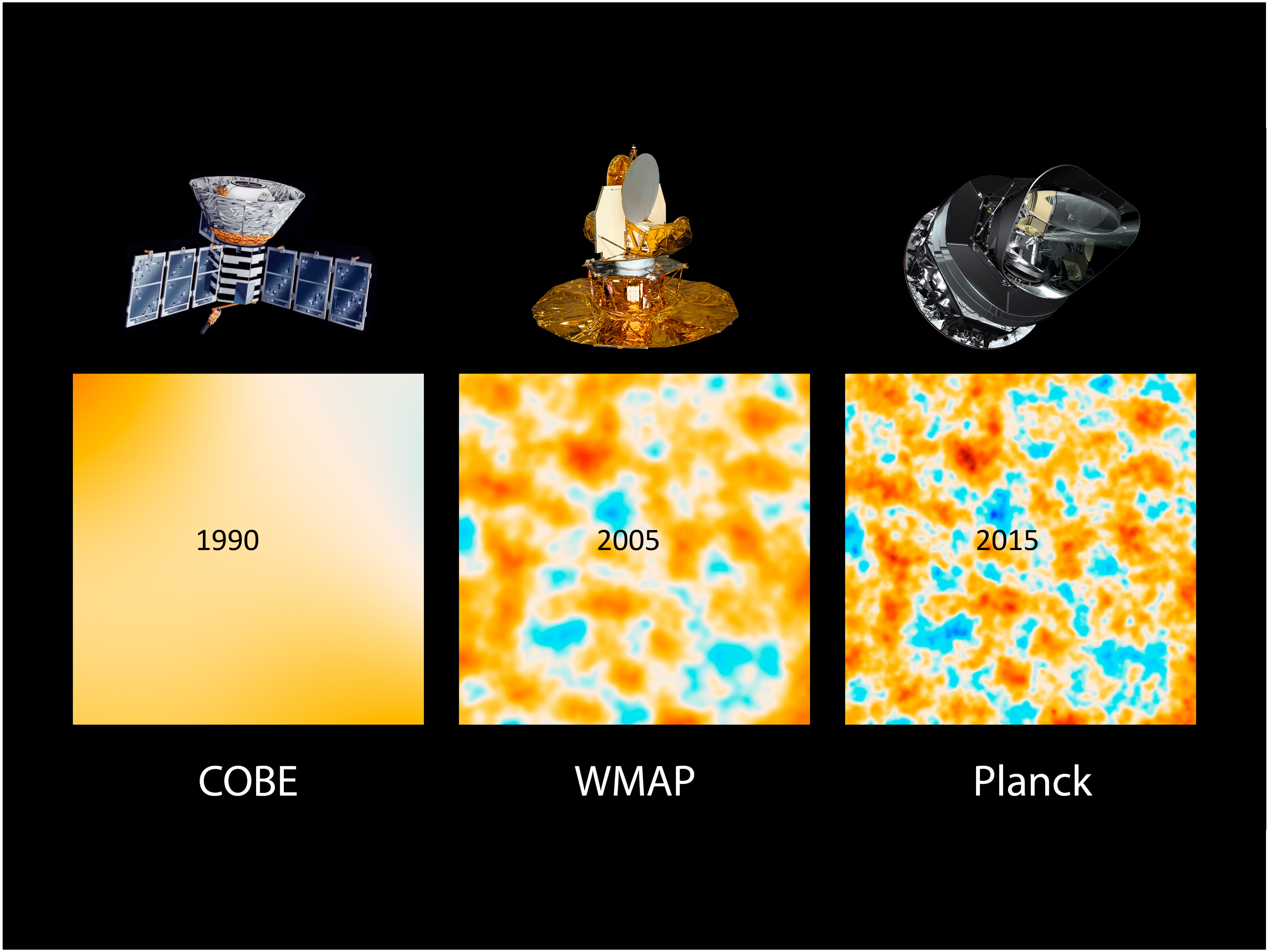
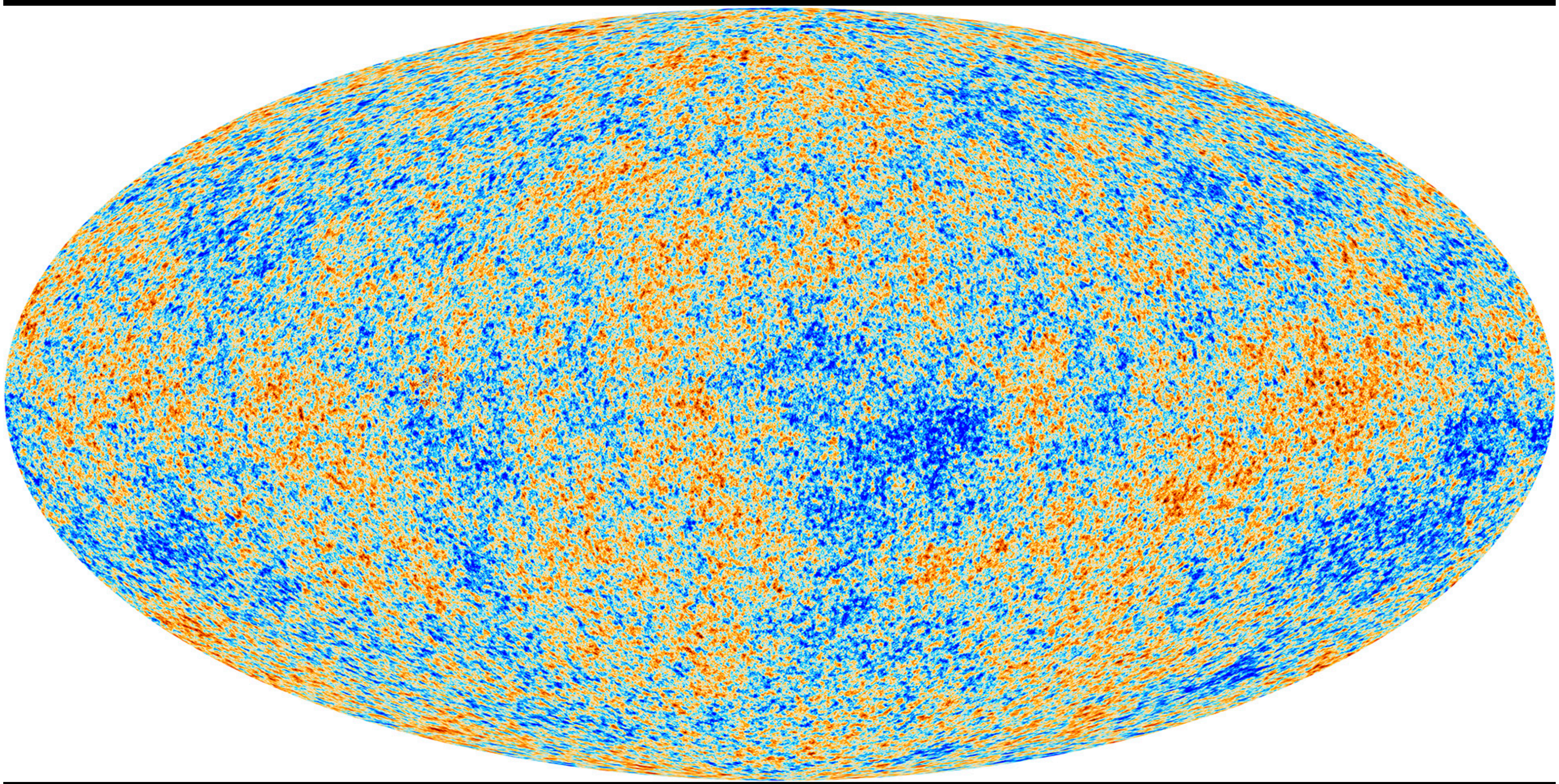
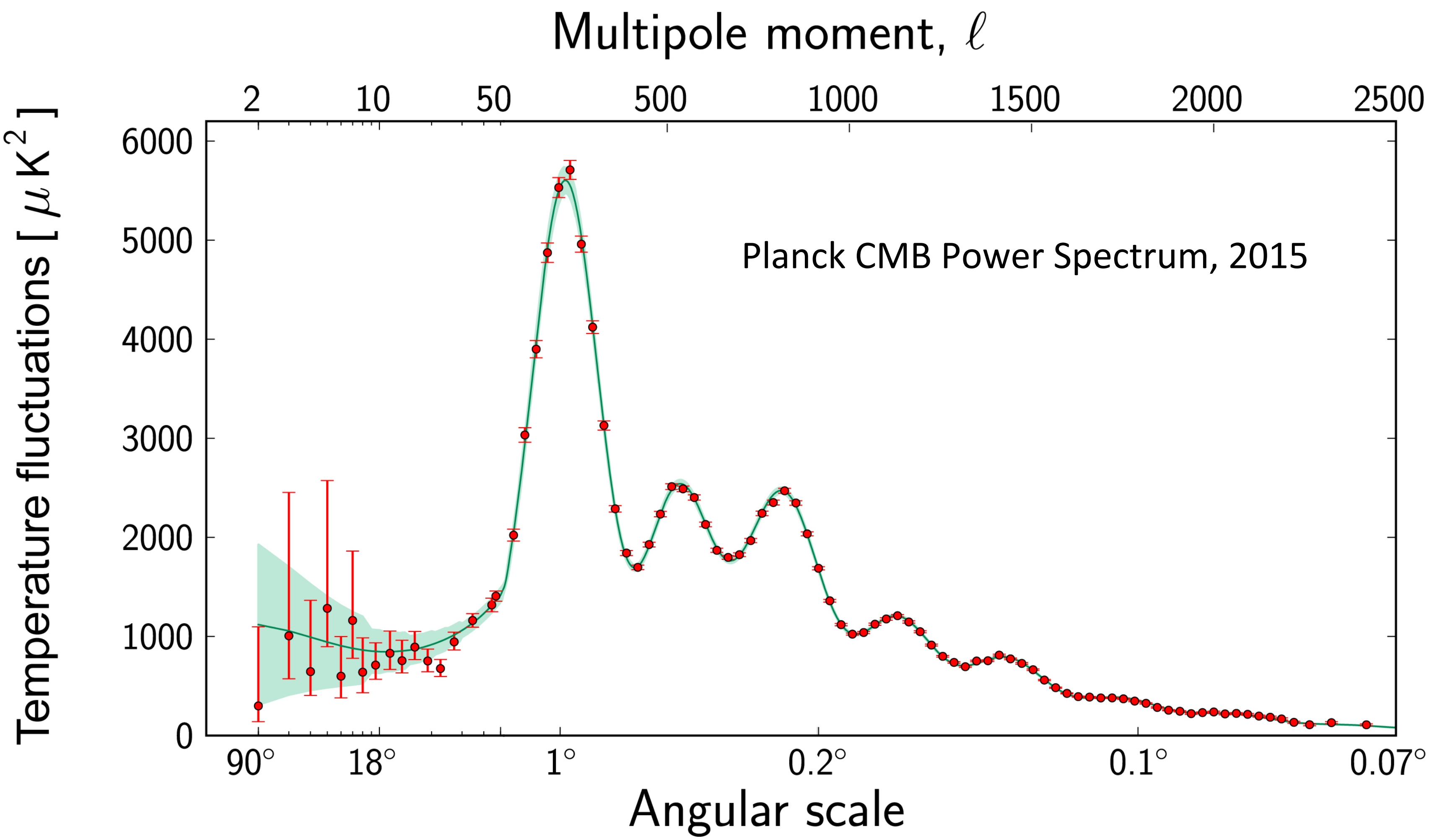
COBE FIRAS experiment: CMB is an almost perfect blackbody




1990
2005
2015
COBE
WMAP
Planck

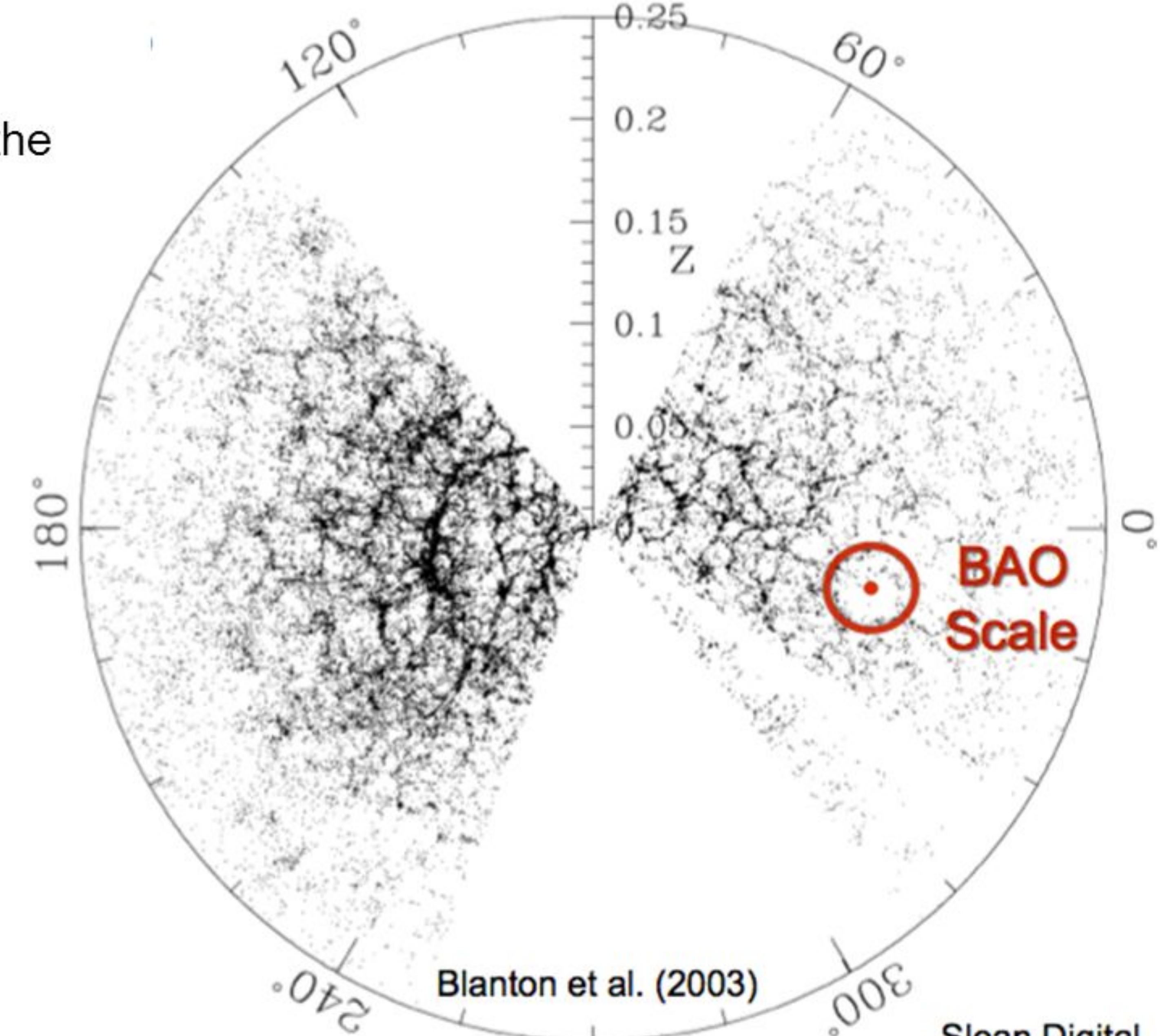
Planck 2015 temperature map





Multipole moment, ℓ
2
10
50
500
1000
1500
2000
2500
6000
5000
4000
3000
2000
1000
0
Temperature fluctuations [μK²]
Planck CMB Power Spectrum, 2015
90°
18°
1°
0.2°
0.1°
0.07°
Angular scale

The BAO scale schematically superposed on the SDSS galaxy distribution.



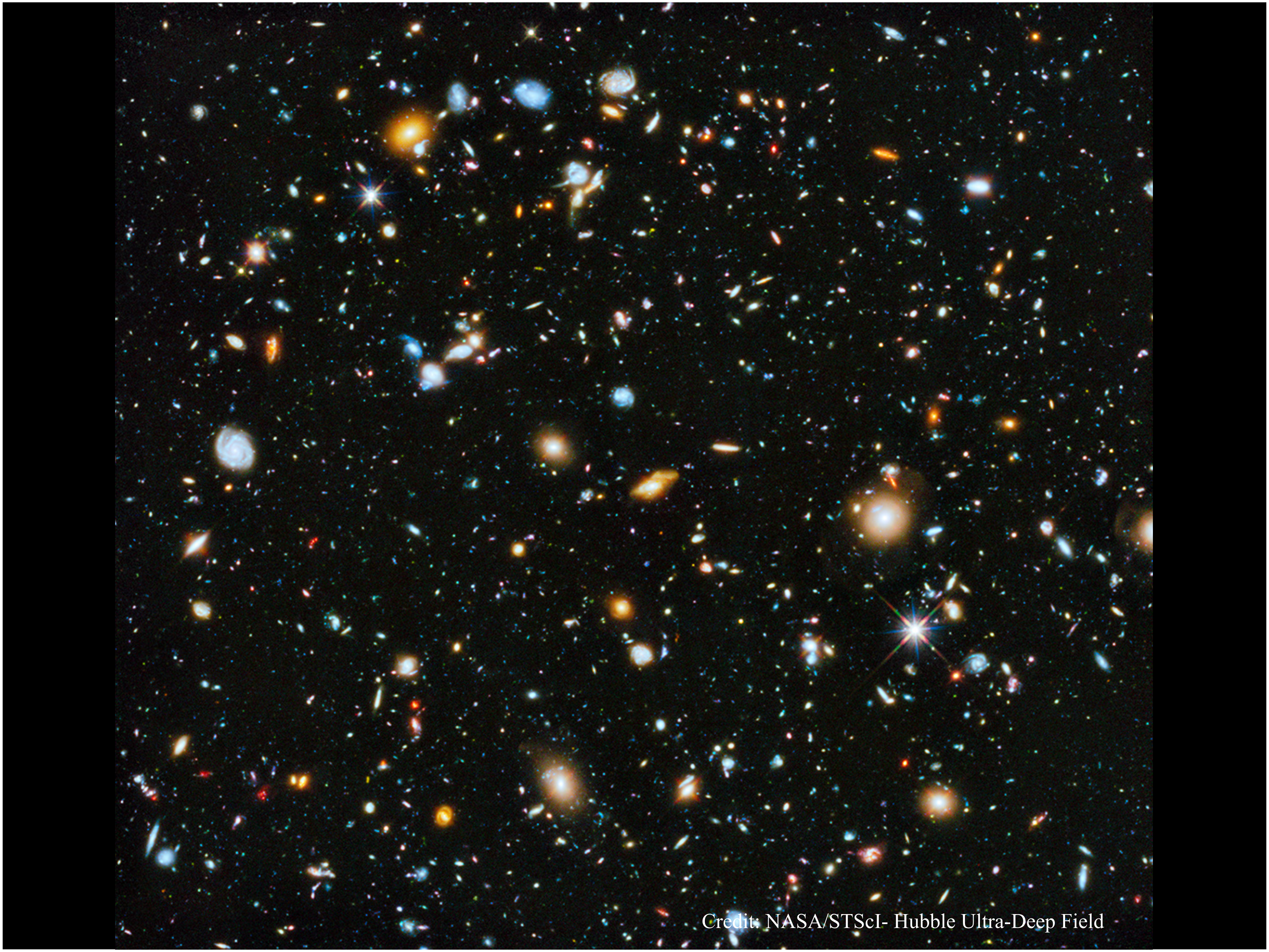
Sloan Digital Sky Survey (SDSS)

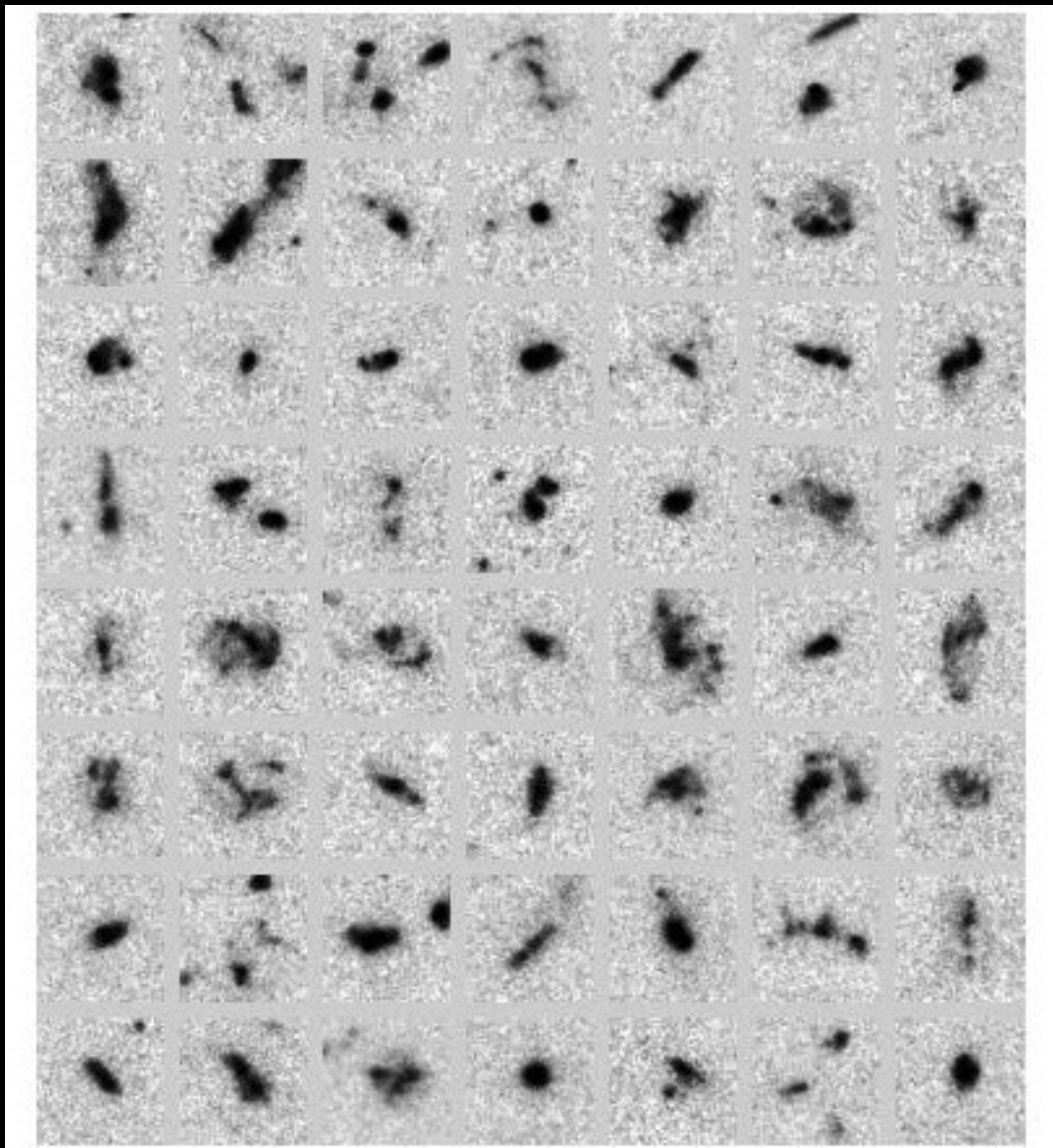
Planck Collaboration Cosmological parameters[13]

	Description	Symbol	Value
Independent parameters	Physical baryon density parameter[a]	$\Omega_b h^2$	0.022 30 ±0.000 14
	Physical dark matter density parameter[a]	$\Omega_c h^2$	0.1188 ±0.0010
	Age of the universe	t_0	13.799 ±0.021 × 10^9 years
	Scalar spectral index	n_s	0.9667 ±0.0040
	Curvature fluctuation amplitude, $k_0 = 0.002$ Mpc^{-1}	Δ^2_R	$2.441^{+0.088}_{-0.092} \times 10^{-9}$[16]
	Reionization optical depth	τ	0.066 ±0.012
Fixed parameters	Total density parameter[b]	Ω_{tot}	1
	Equation of state of dark energy	w	–1
	Sum of three neutrino masses	Σm_ν	0.06 eV/c^2[c][12]:40
	Effective number of relativistic degrees of freedom	N_{eff}	3.046[d][12]:47
	Tensor/scalar ratio	r	0
	Running of spectral index	$d\, n_s / d \ln k$	0
Calculated values	Hubble constant	H_0	67.74 ±0.46 km s^{-1} Mpc^{-1}
	Baryon density parameter[b]	Ω_b	0.0486 ±0.0010[e]
	Dark matter density parameter[b]	Ω_c	0.2589 ±0.0057[f]
	Matter density parameter[b]	Ω_m	0.3089 ±0.0062
	Dark energy density parameter[b]	Ω_Λ	0.6911 ±0.0062
	Critical density	ρ_{crit}	(8.62 ±0.12) × 10^{-27} kg/m^3[g]
	Fluctuation amplitude at 8h^{-1} Mpc	σ_8	0.8159 ±0.0086
	Redshift at decoupling	z_*	1 089.90 ±0.23
	Age at decoupling	t_*	377 700 ±3200 years[16]
	Redshift of reionization (with uniform prior)	z_{re}	$8.5^{+1.0}_{-1.1}$[17]

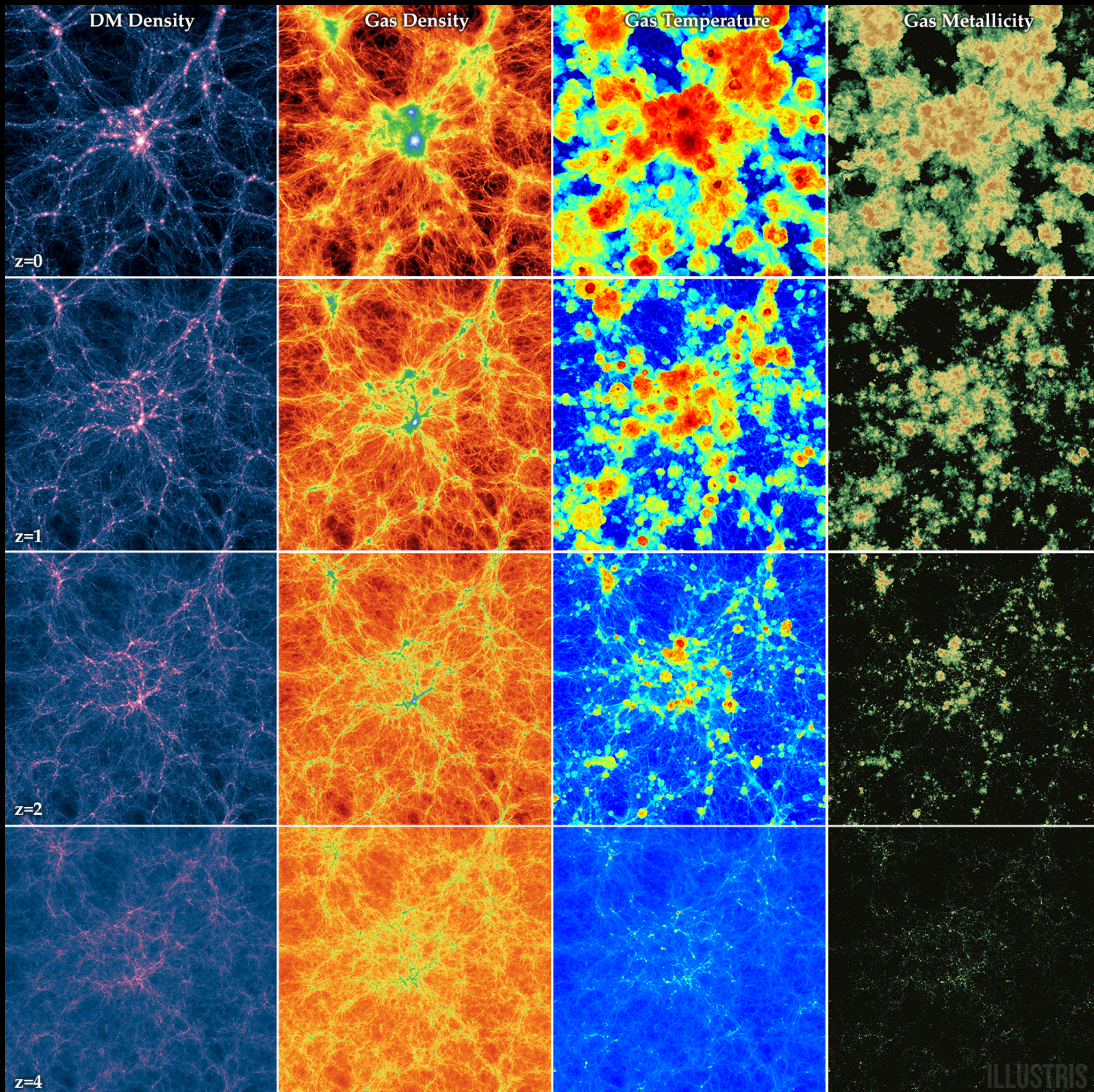
Galaxy Formation in the Cosmological Context

- Cosmic background, supernovae, and a host of other astrophysical techniques have presented strong evidence for a spatially flat, low-density universe dominated by cold dark matter (CDM) with:
  - Ω_m~0.3 (of which ~1/6th is baryonic)
  - Ω_Λ~0.7 ("Dark Energy")
  - H_0~70 km s^{-1} Mpc^{-1} (current expansion rate of the universe)
  - normalization/shape of initial matter fluctuation power spectrum
  - Age~13.8 Gyr
- Since galaxies have grown by gravity, and dark matter apparently has very simple properties, galaxy formation should be entirely predictable…. Right?


Credit: NASA/STScI- Hubble Ultra-Deep Field



Today…



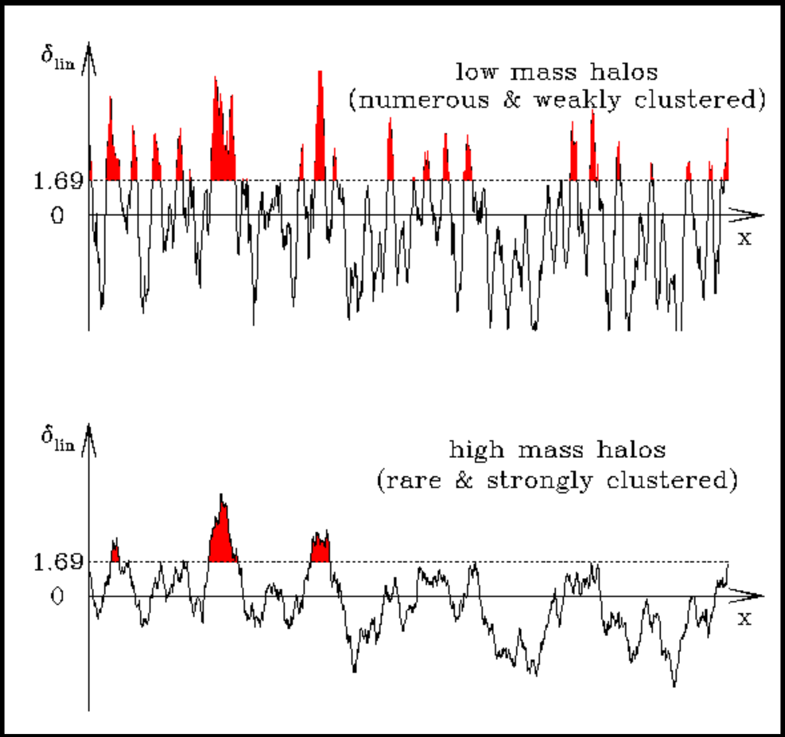
State-of-the-art cosmological simulation, including gravity+hydrodynamics

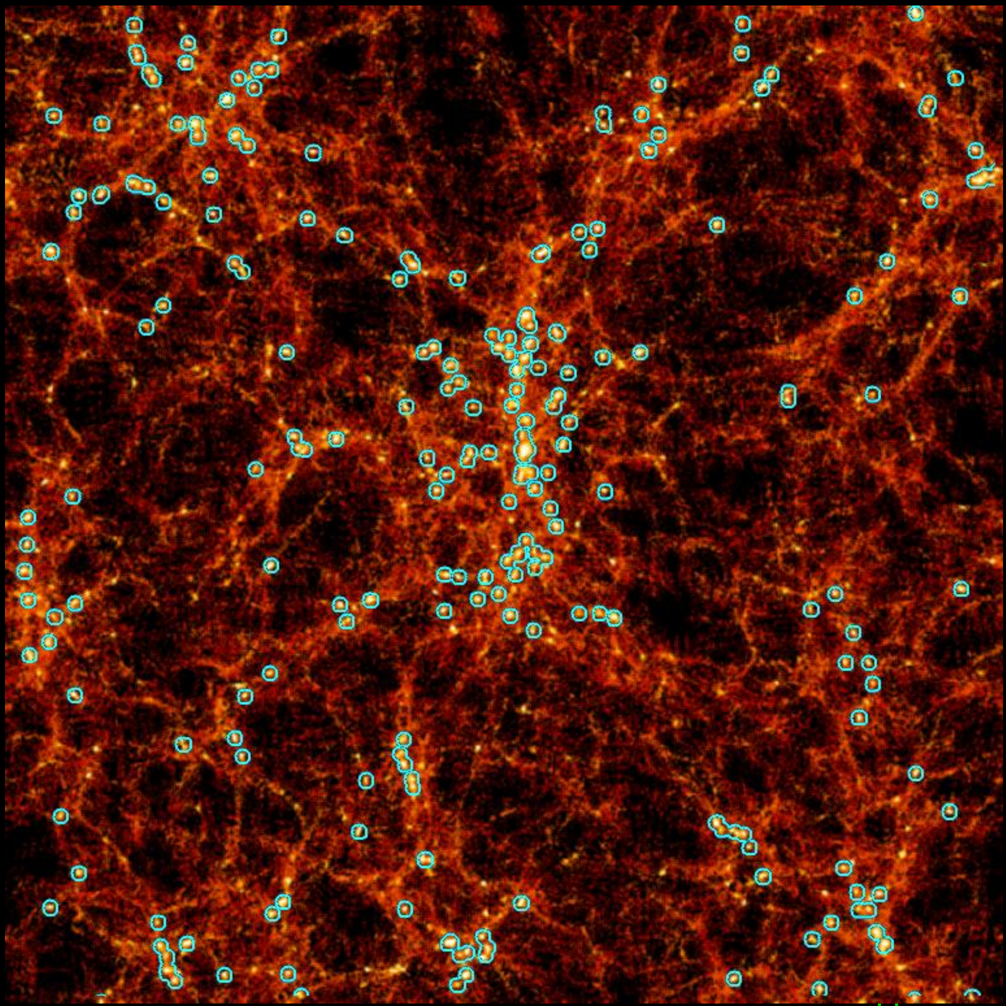
(slice of a 100^3 Mpc box)

www.illustris-project.org

Strong clustering is expected at high redshifts for relatively rare massive dark matter halos. By the present, such object will on average reside in relatively rich environments.

Approximate mass scale for objects can be assigned by matching abundance/clustering strength to dark matter halos in simulations…



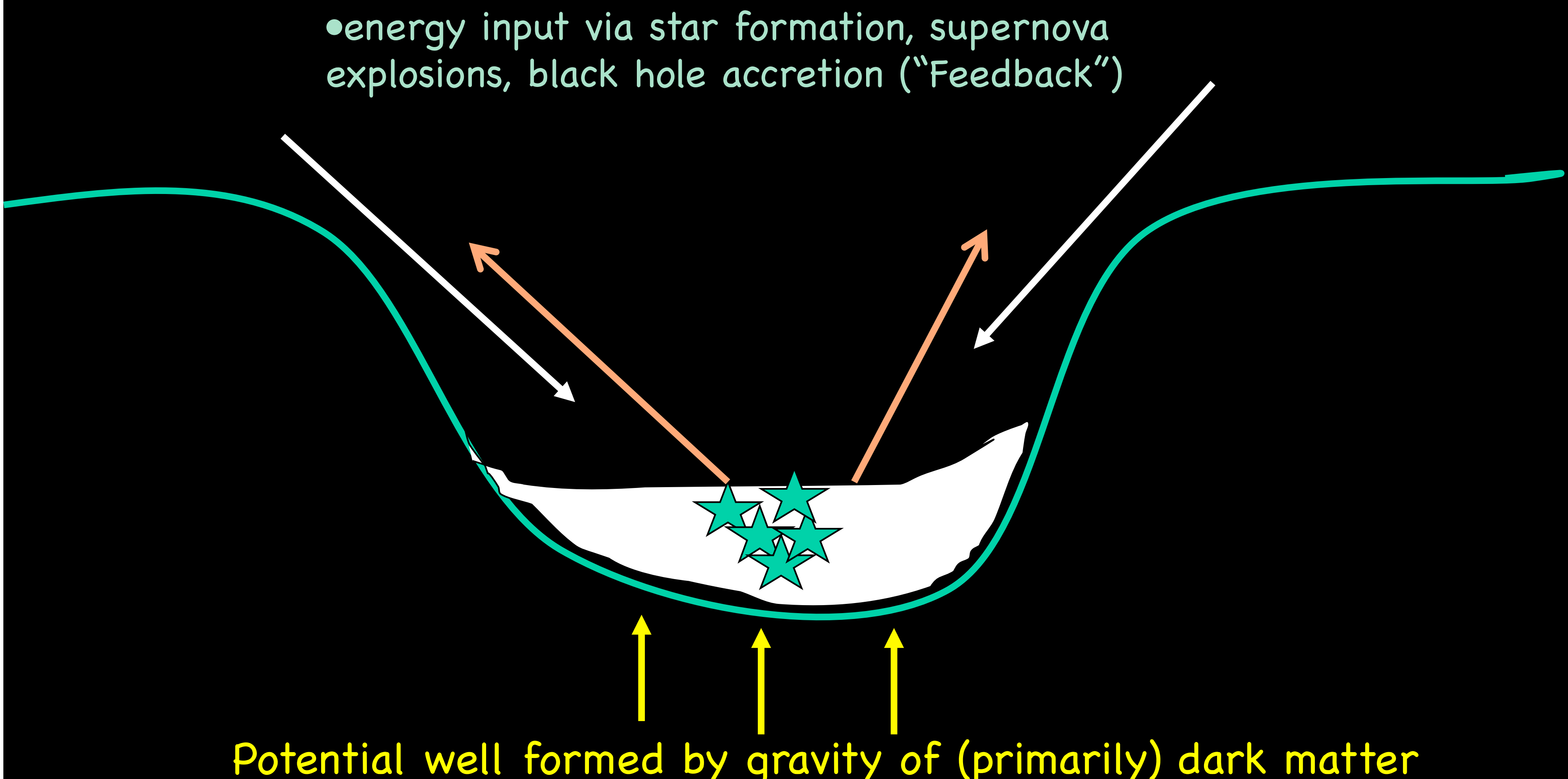


Governato et al 1998 sim.

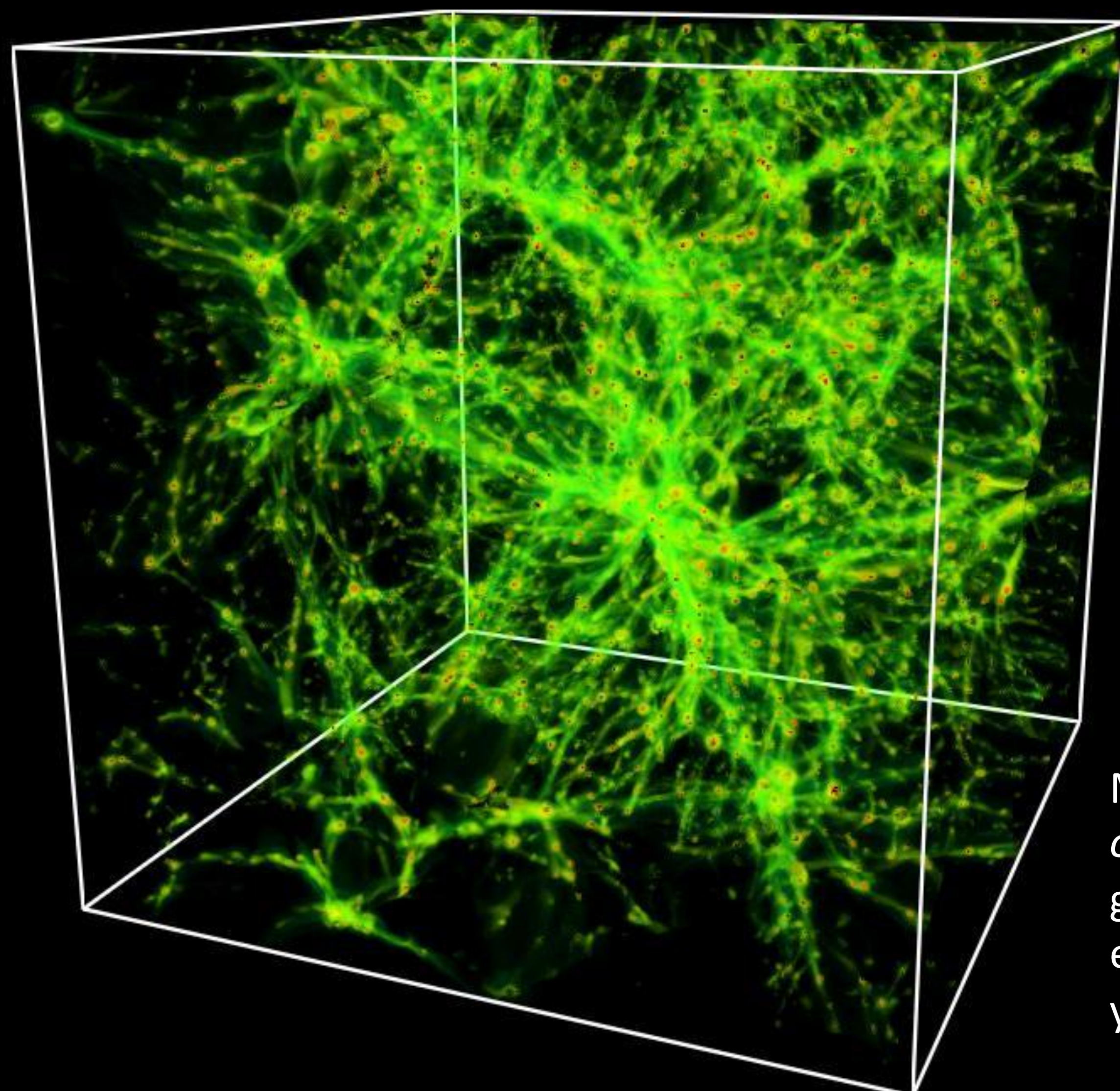
Ab Initio Understanding of Galaxy Formation

- Begin with dark matter halos, with baryonic component according to Big Bang Nucleosynthesis/WMAP/Planck baryon density relative to Ω_m.
- Follow evolution of dark matter distribution using N-body models, or analytic calculations (given an assumed initial matter power spectrum).
- Baryon physics added "by hand" or with simplified treatment of hydrodynamics (gas physics)
  - Star formation "prescriptions"
  - "Feedback" from star formation, AGN accretion power a major uncertainty
  - Hope to reproduce observed universe with simple physical prescriptions
- Goal is to naturally explain both the properties of individual galaxies, and their large-scale distribution.
- Problem: need both the large scale picture, and "sub-grid" physics, for complete understanding: it is a very hard problem!
- Galaxies should be thought of as a strongly evolving, non-linear map of dark matter distribution.

Recipe for Galaxy Formation

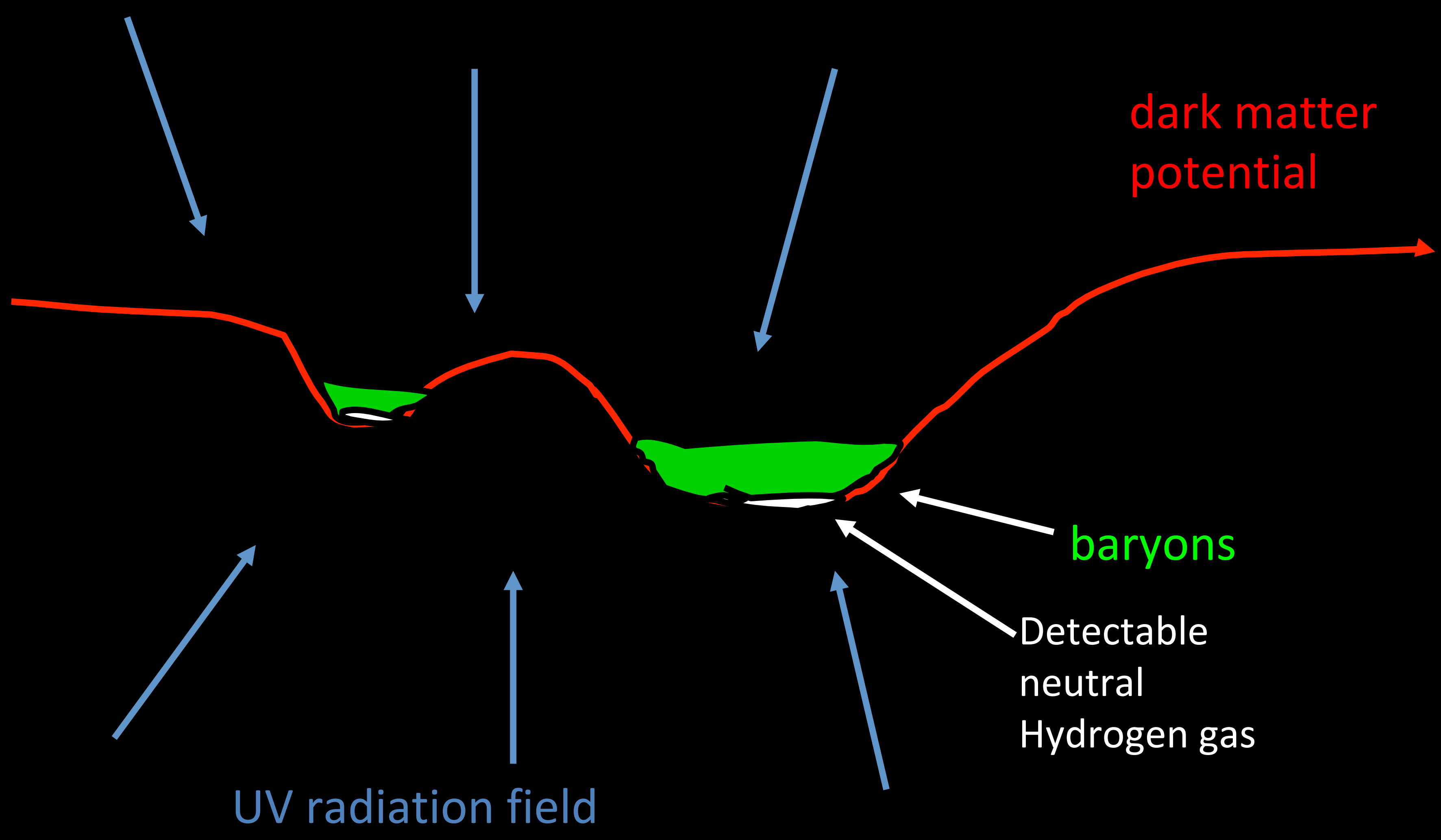


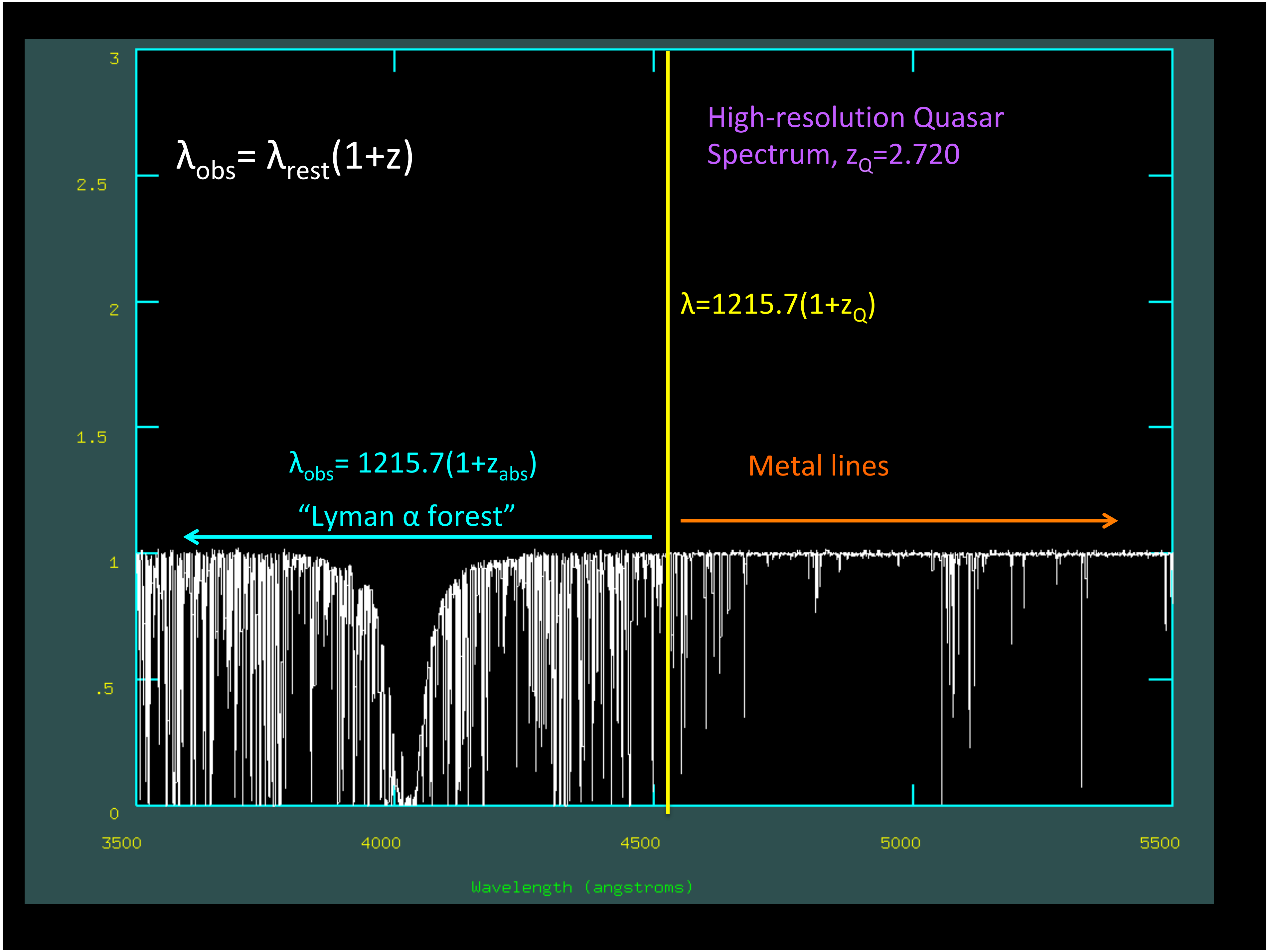
The Diffuse Intergalactic Medium



Most baryons lie *outside* of galaxies– especially in the young universe

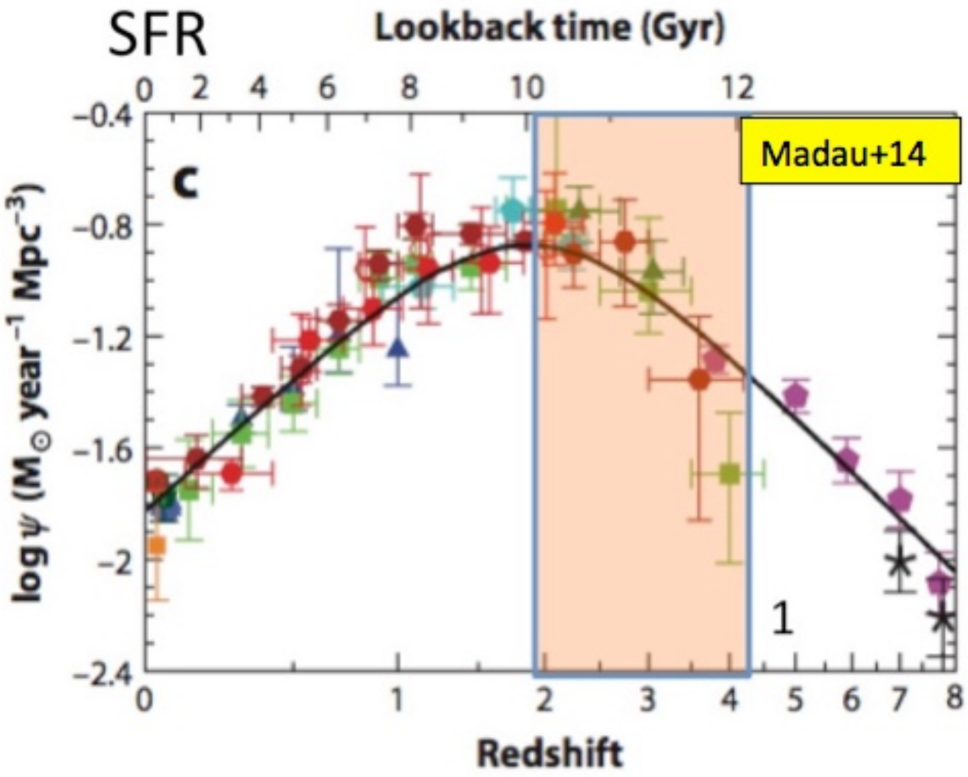
The Intergalactic Medium: Not a Very Exciting Place…

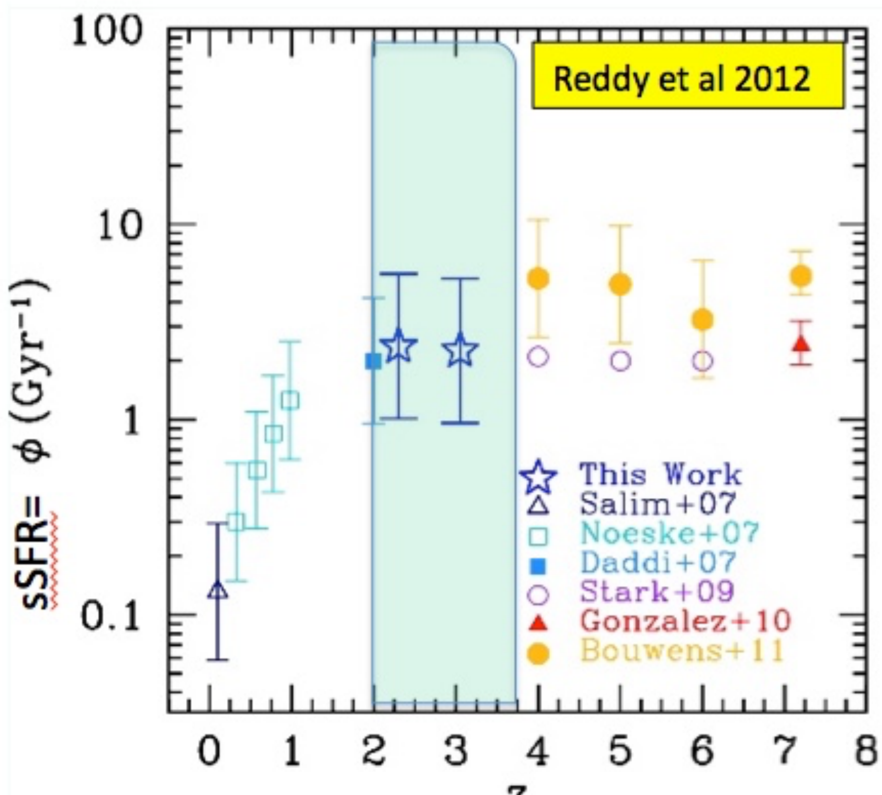




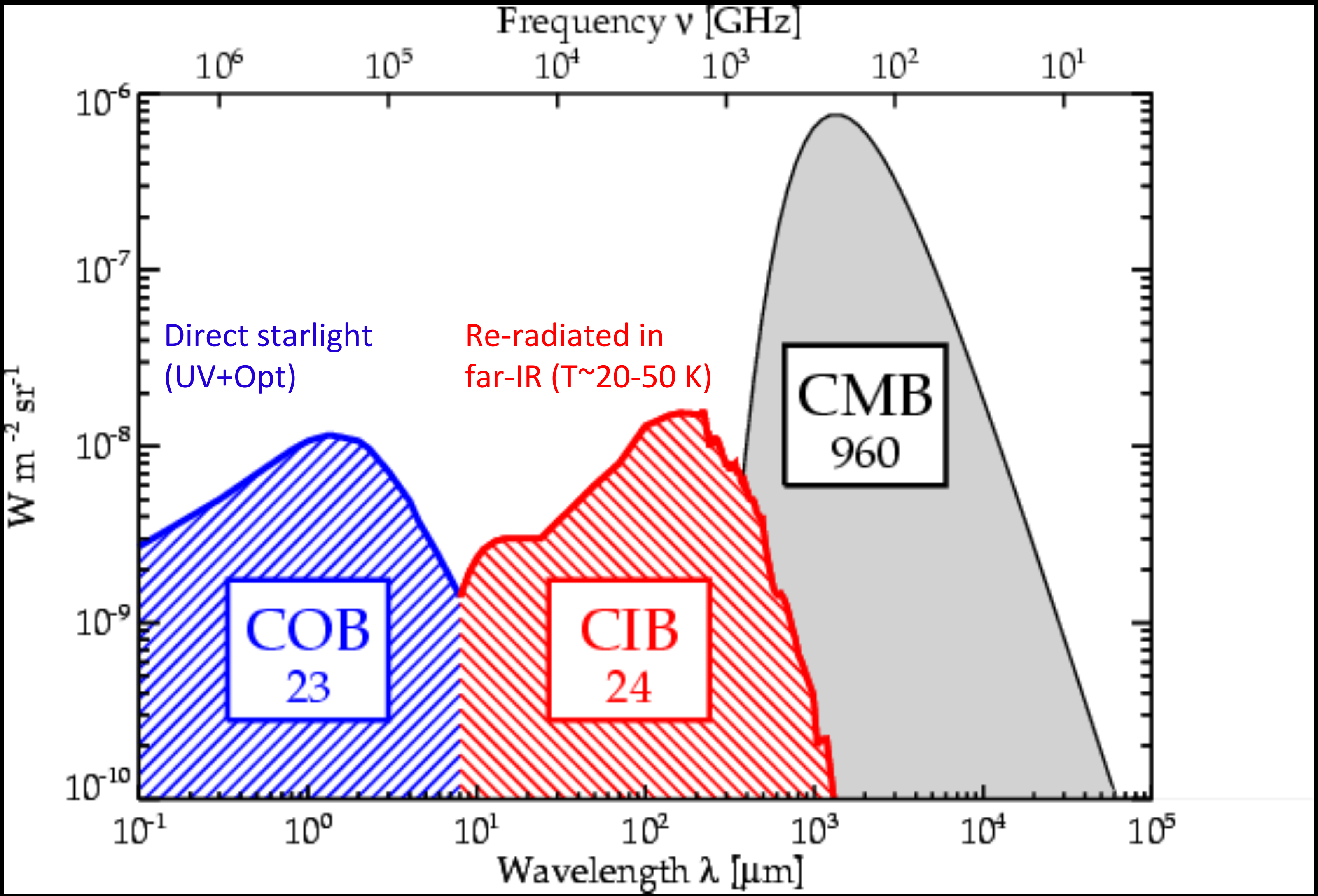
$\lambda_{obs} = \lambda_{rest}(1+z)$
High-resolution Quasar Spectrum, z_Q=2.720
$\lambda = 1215.7(1+z_Q)$
$\lambda_{obs} = 1215.7(1+z_{abs})$
"Lyman α forest"
Metal lines
3
2.5
2
1.5
1
.5
0
3500
4000
4500
5000
5500
Wavelength (angstroms)

Universal Star Formation History



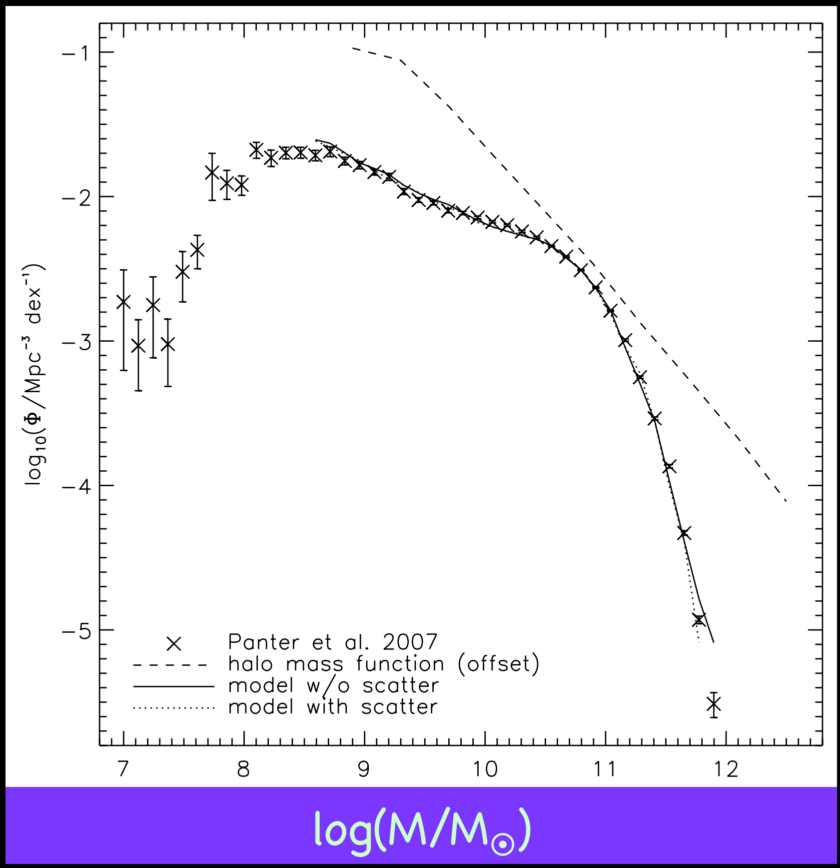


Diffuse Background Intensities



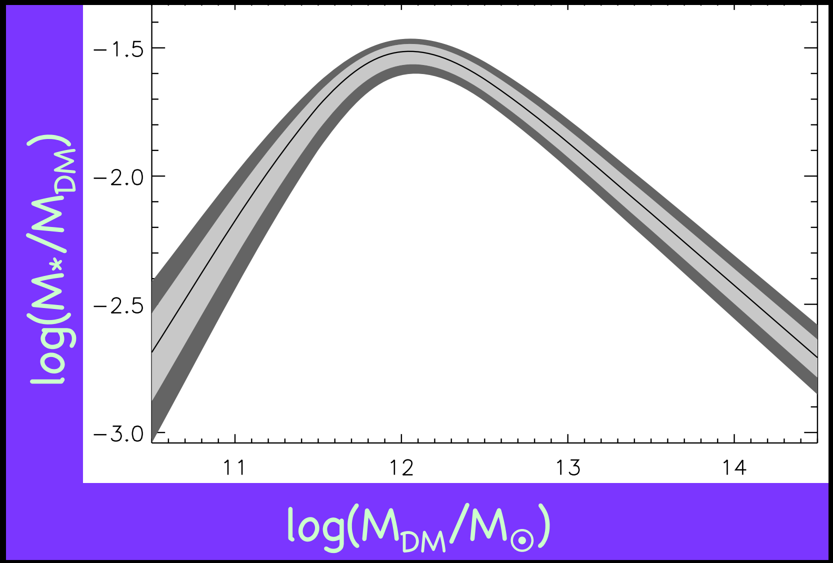
How Do We Know "Feedback" is Important?

1. (In)efficiency of Star Formation in galaxies

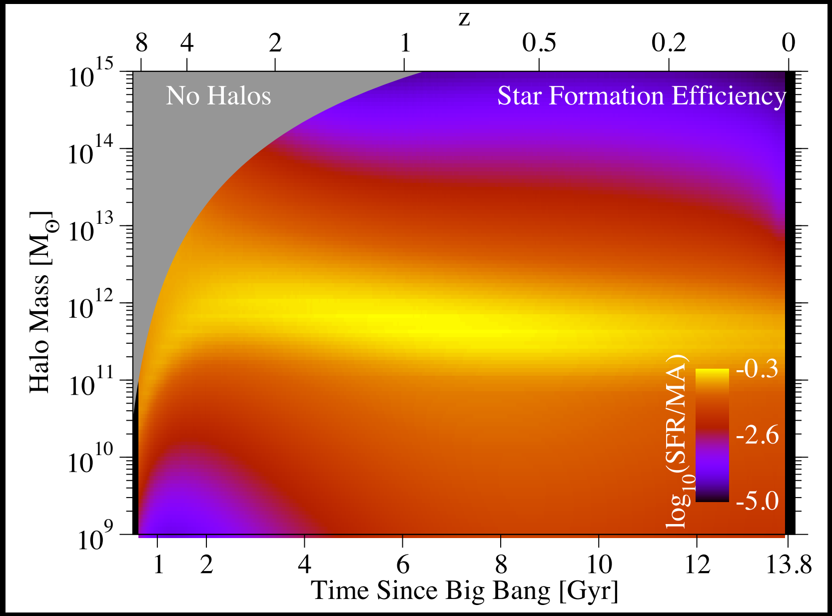


Moster et al. 2010

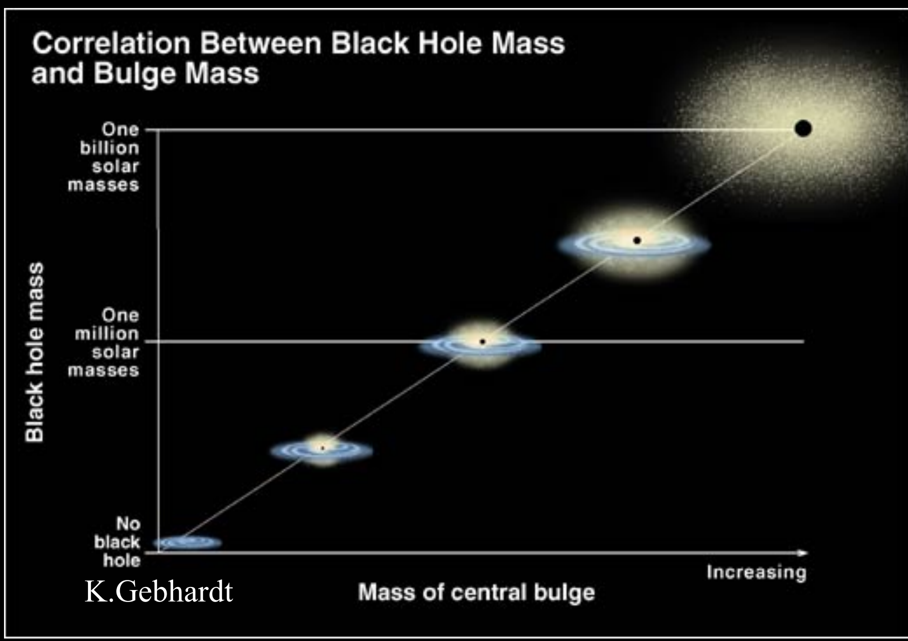
Moster et al. 2010

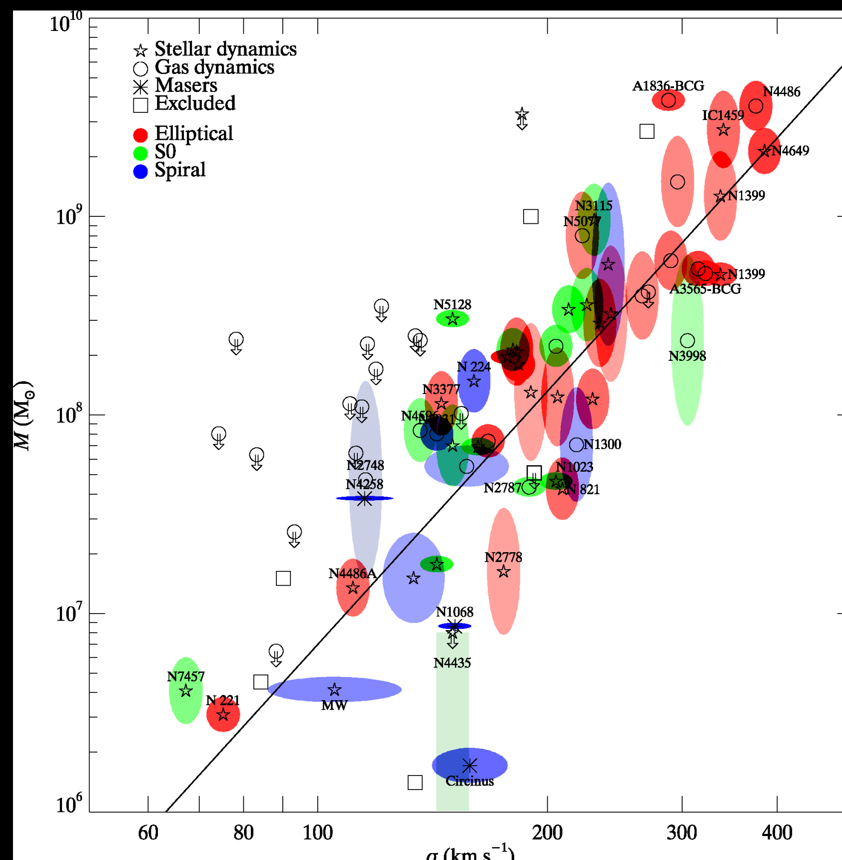


Behroozi et al. 2012

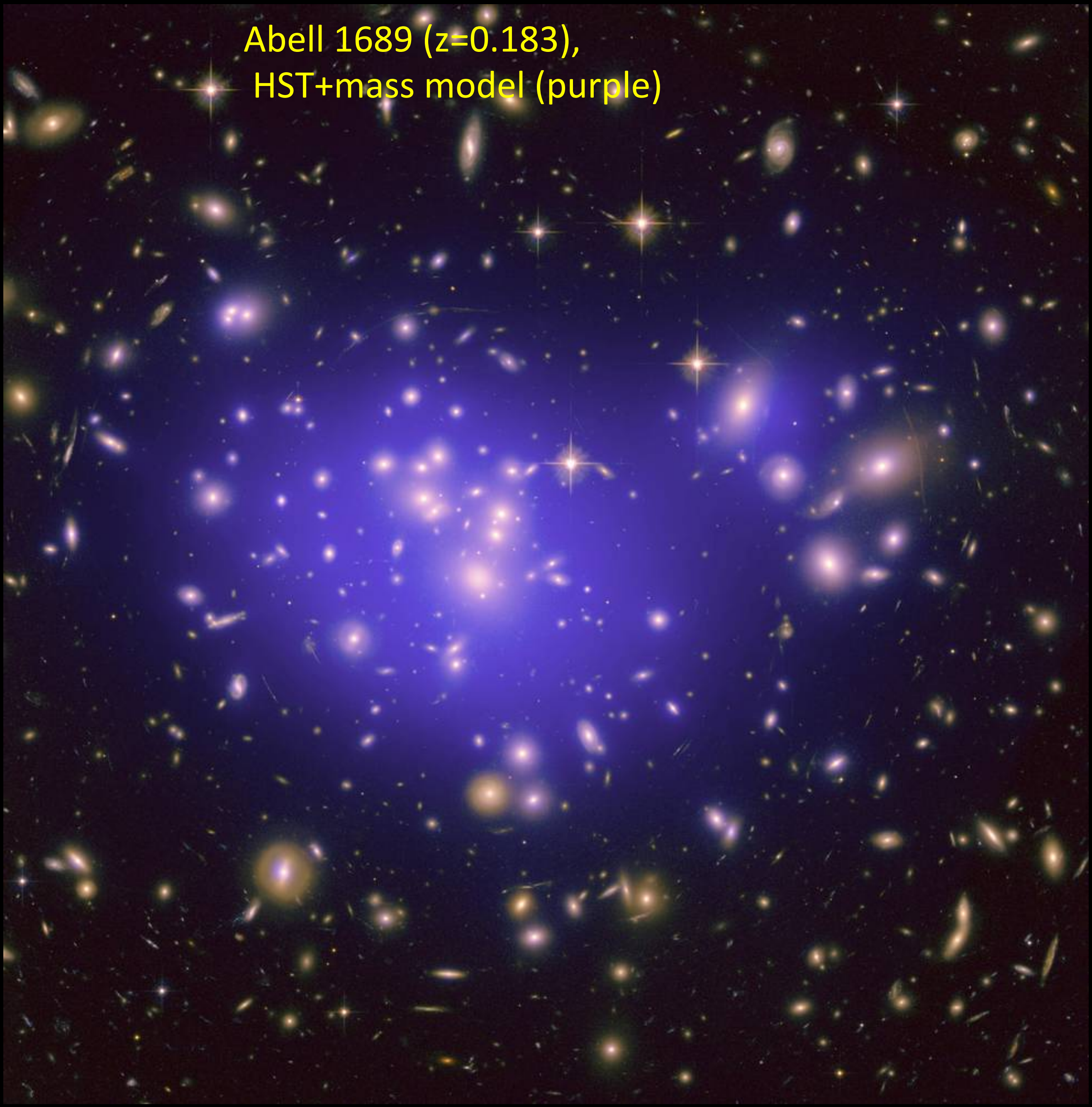


Correlation Between Central Black Hole Mass and Galaxy Properties





“Nuker” Collaboration


Abell 1689 (z=0.183),
HST+mass model (purple)

Astro-Speak Dictionary

- Distance: 1pc ≈ 3 light years ≈ 3×10^{18}cm
  - size of Milky Way disk R≈10 kpc
  - MW dark halo ≈ 200 kpc
  - distance to Andromeda ≈ 700 kpc
- Mass: 1 solar mass ($M_\odot$) ≈ 2×10^{33} g
  - MW mass (dark matter)≈ $10^{12}\ M_\odot$
  - MW mass (stars)≈ $5 \times 10^{10}\ M_\odot$
- Time: 1 Gyr = 10^9 yrs
  - age of universe ≈ 13.79 Gyr
  - age of sun ≈ 4.5 Gyr

Astro-Speak Dictionary

- "metals" = all elements heavier than He (formed in stars).
  - "solar metallicity" → metal mass of 0.014 compared to H
- "star formation rate" (SFR) ($M_\odot$/yr)
  - current MW SFR≈2-3 $M_\odot$/yr
  - typical galaxy @10-12 Gyr ago: SFR ≈ 50-100 $M_\odot$/yr
- "circular velocity" (v_c) = the velocity associated with the total mass of a gravitationally bound system, i.e. $v_c^2 \approx GM/R$
  - MW $v_c \approx 200$ km/s ; large galaxy cluster $v_c \approx 1000$ km/s (10^{15} $M_\odot$)
- "virial temperature" (T_v)=kinetic temperature of baryons moving in a potential, i.e., $3k_BT_v \approx m_pv_c^2$
  - MW $T_v \approx 10^6$ K ; galaxy cluster $T_v \approx 10^8$ K