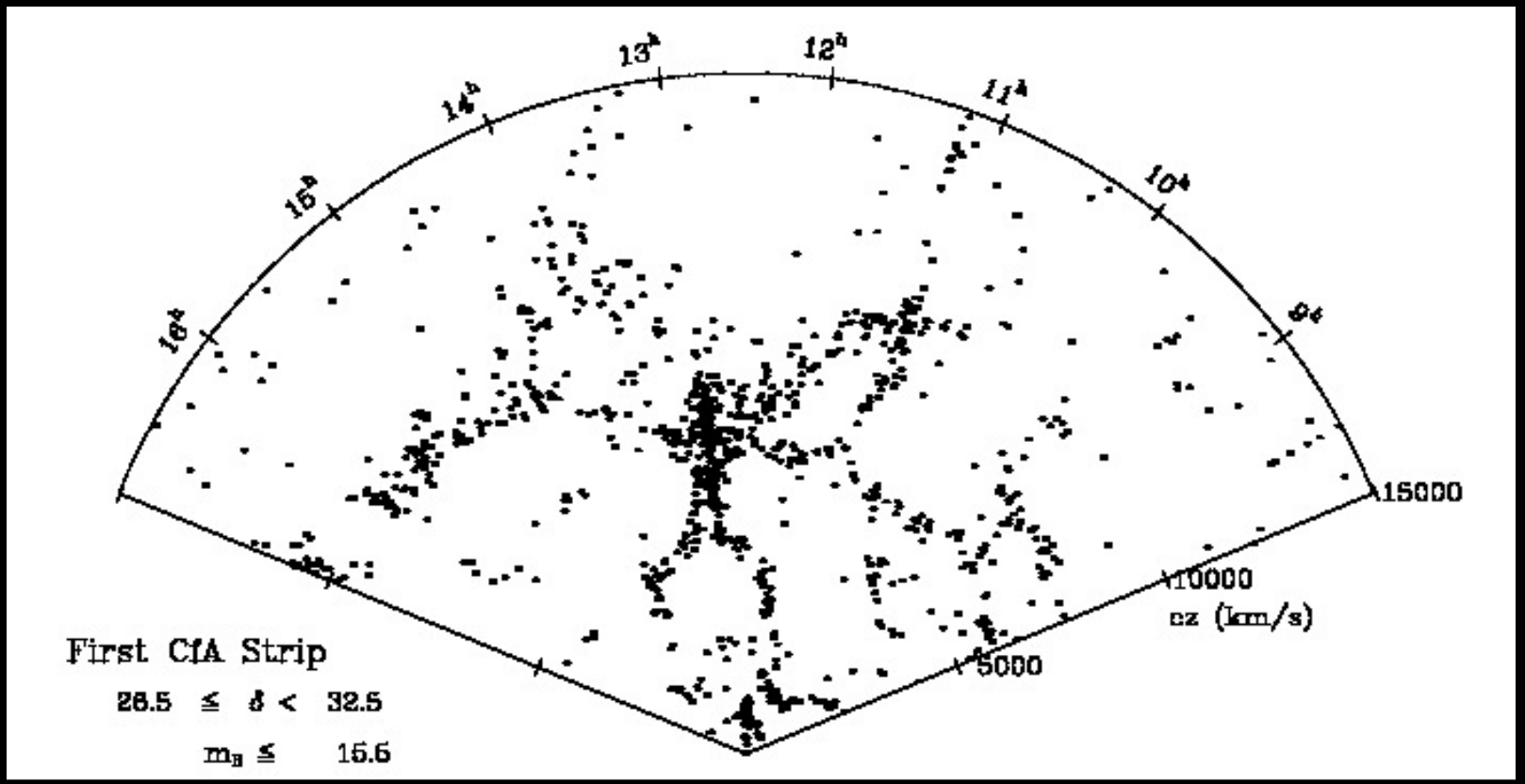
Galaxy Surveys

- The CfA galaxy redshift survey in 1977 ~ 1985
  - 18,000 galaxies, $z \sim 0.05$ *CfA great wall*

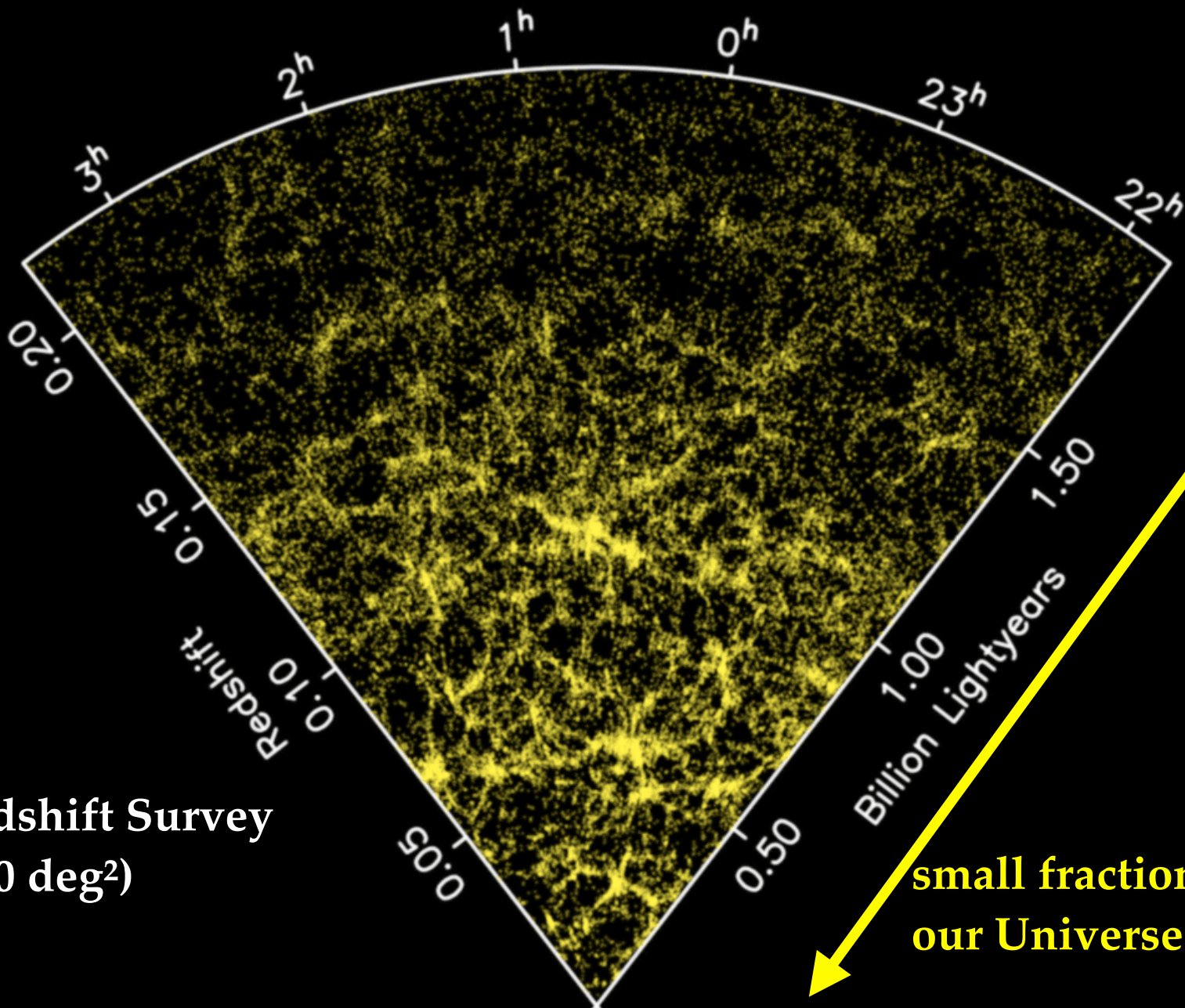


Huchra, Davis, Latham, Tonry, ApJS, 1983

de Lapparent, Geller, Huchra, ApJ, 1991

Galaxy Surveys

redshift ~ 0.2



2dF Galaxy Redshift Survey
1997~2002 (1500 deg^2)

small fraction of our Universe

Galaxy Surveys

- **Sloan Digital Sky Survey**
  - **2000 ~ 2008**
  - **1/4 sky (10,000 deg^2)**
  - **1 million galaxies**
  - **120,000 quasars**
  - **~ 24 magnitude**
  - ***z ~ 0.5***

Credit: SDSS

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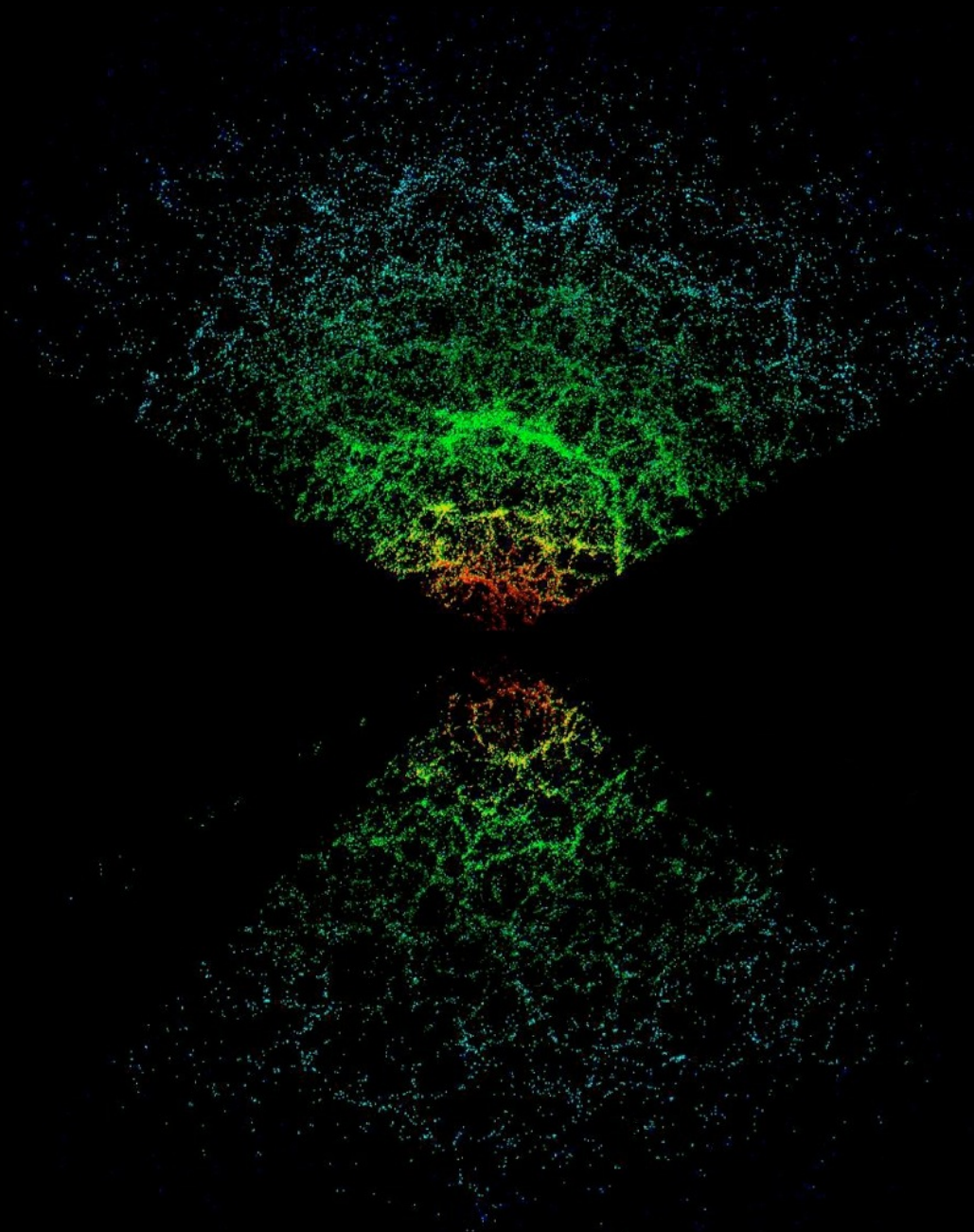
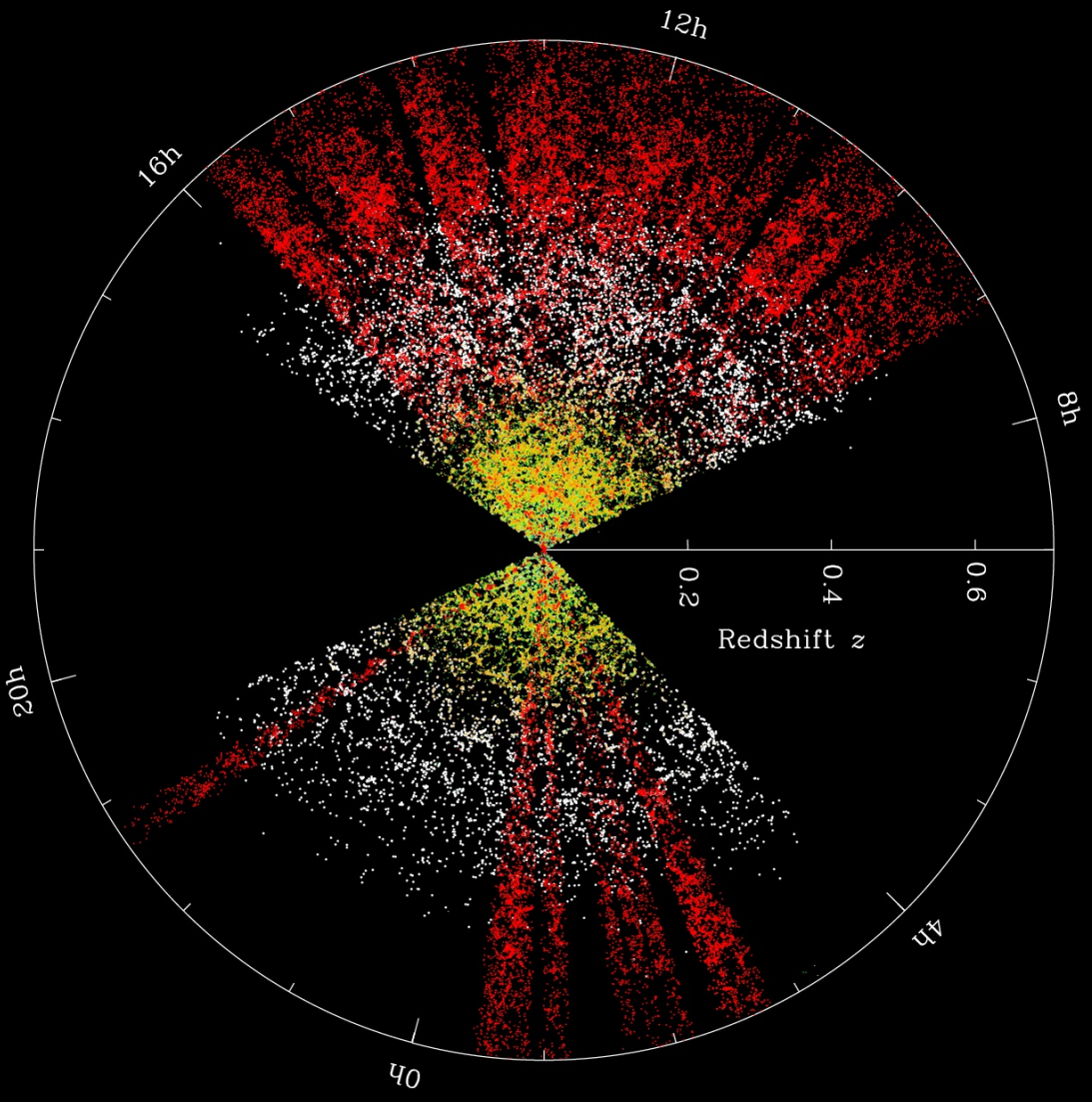


Credit: SDSS

Galaxy Surveys

- **Baryonic Oscillation Spectroscopic Survey**
  - 2009 ~ 2014
  - 1/4 sky
  - 2 million galaxies
  - 160,000 quasars
  - *z ~ 0.8*
- **precise distance by BAO**
  - low redshift anchor to CMB
  - *~1% to z=0.3, 0.5, 0.7*

Beutler et al. 2017



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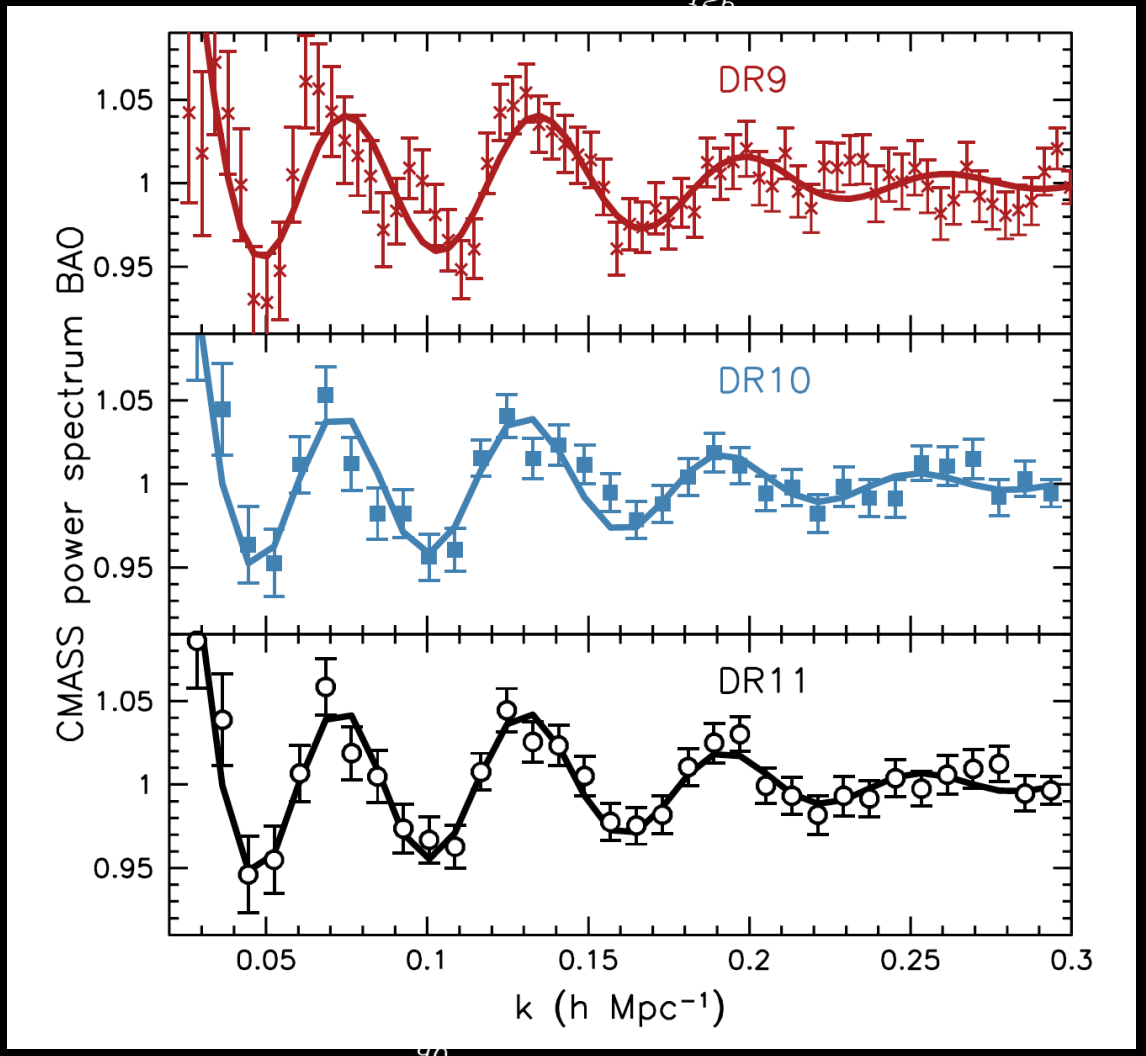


Anderson et al. 2013

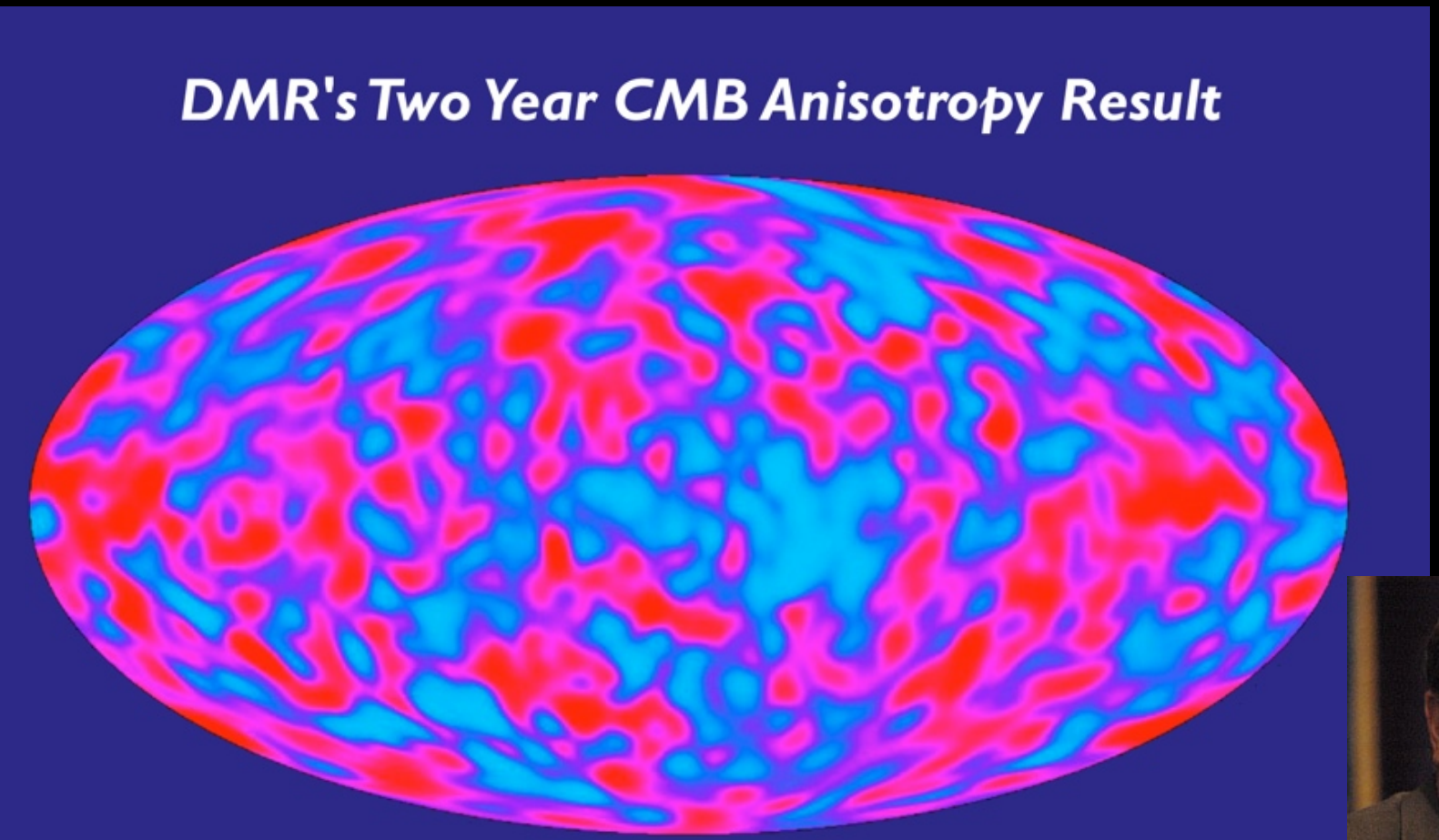
Cosmic Microwave Background

- Arno **Penzias** & Robert **Wilson** at Bell laboratory
  - detected the *3.5K* radiation from Big Bang in 1964
  - *noise* (systematic errors) for their experiments

Nobel prize 1978
for its discovery

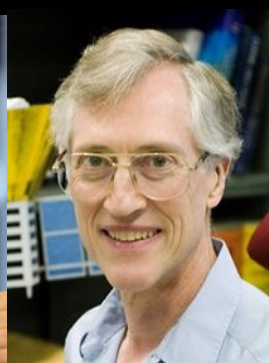
Cosmic Microwave Background

- **Cosmic Background Explorer in 1989 ~ 1993**
  - **large-scale anisotropies (up to 6 degree)**



Credit: NASA LAMBDA

Nobel prize 2006 for its discovery



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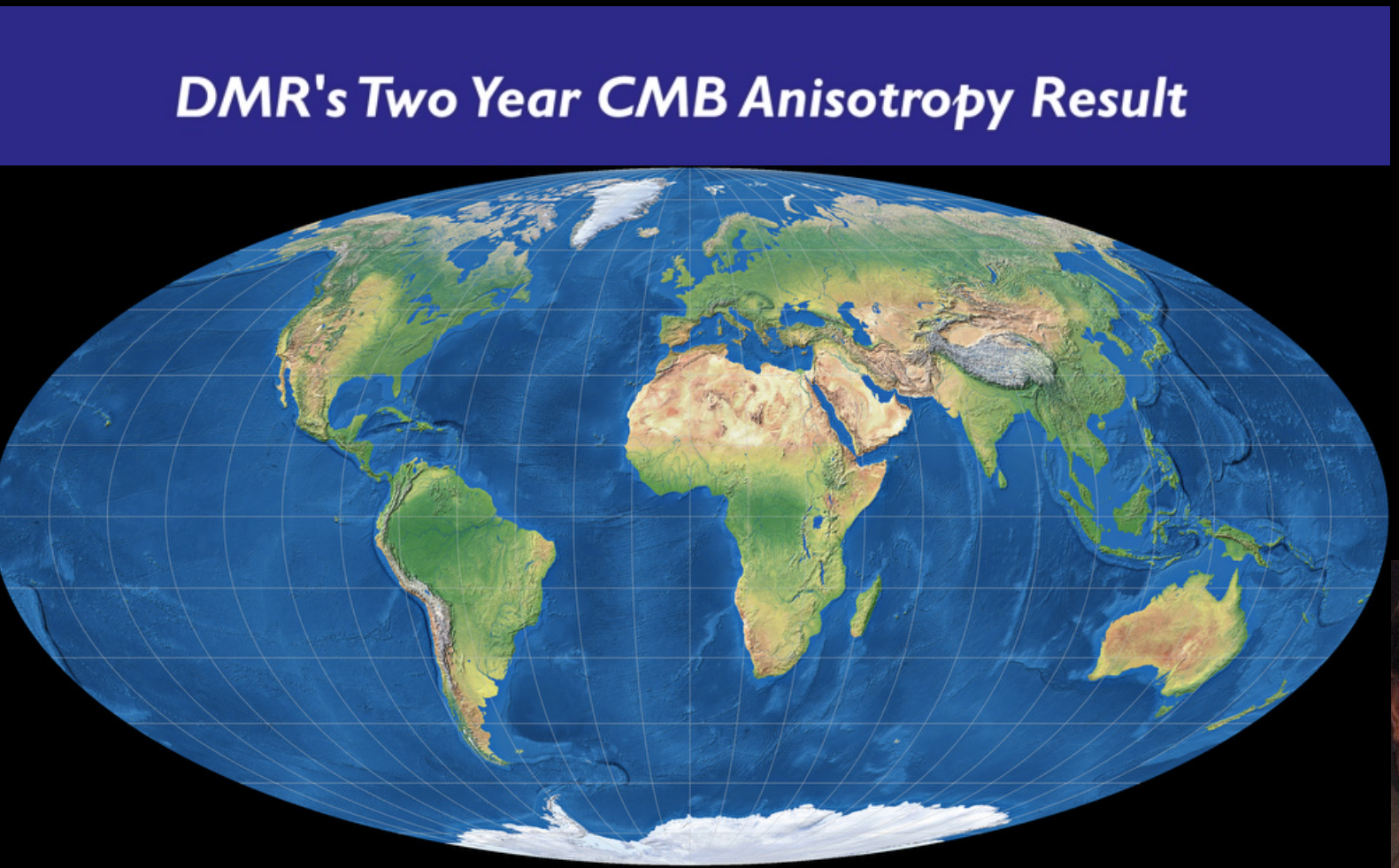

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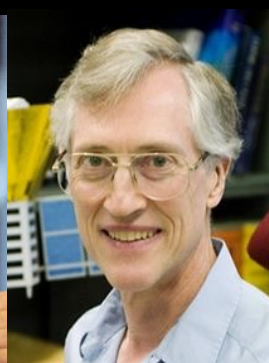
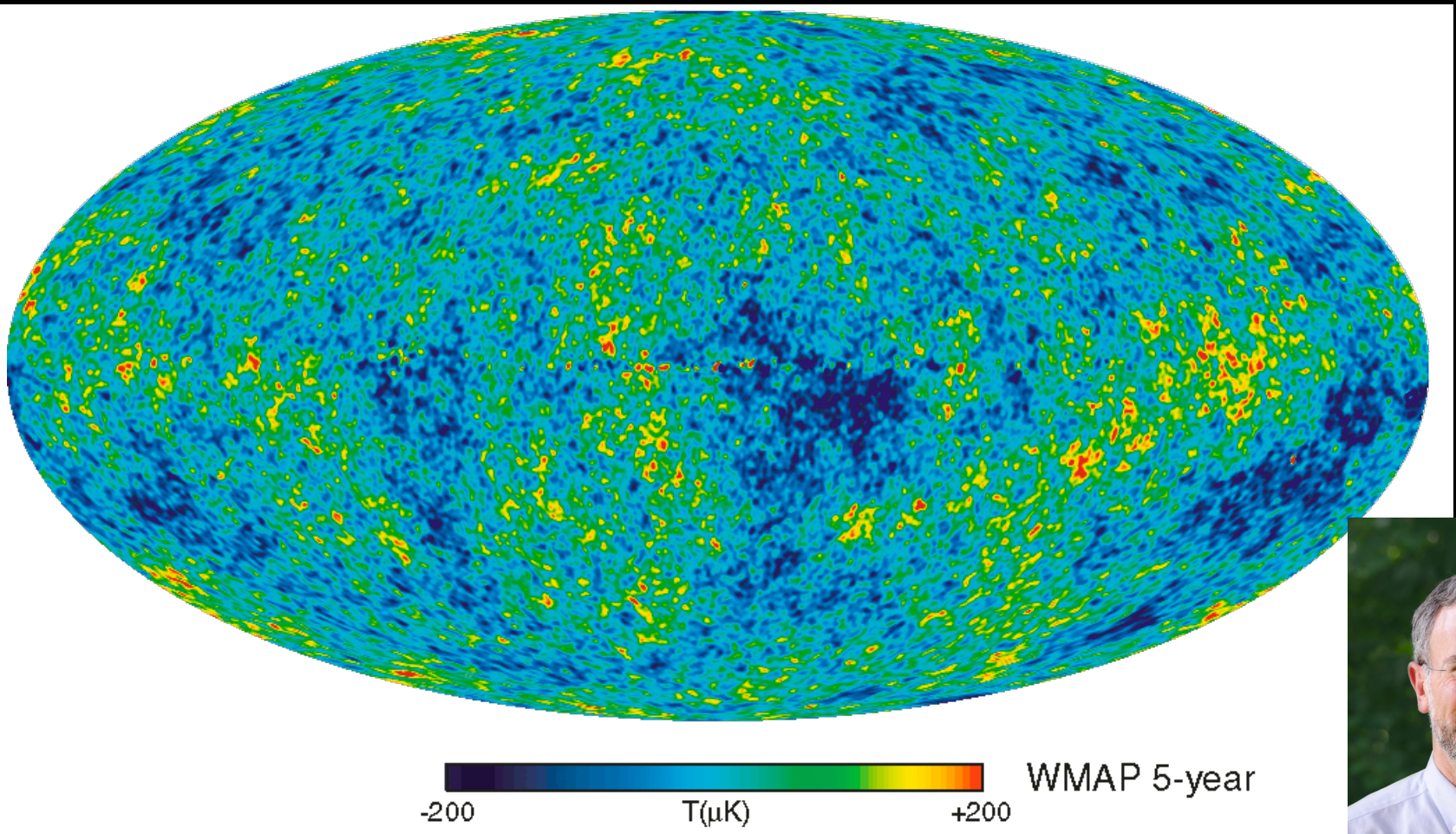


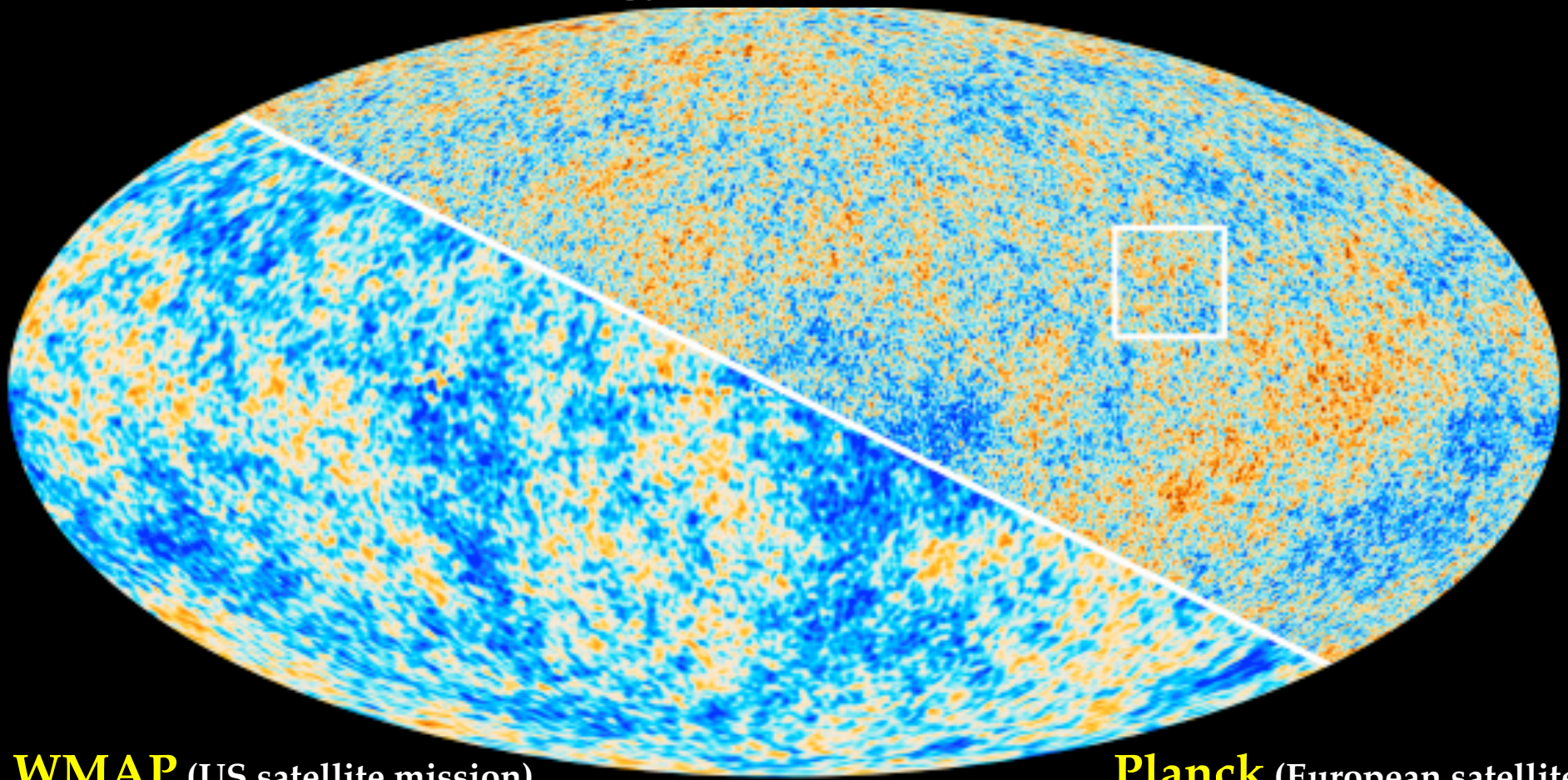
Cosmic Microwave Background

- **Wilkinson Microwave Anisotropy Probe in 2001~ 2010**
  - ***precision cosmology!*** **(resolution: ~25 arc minute)**

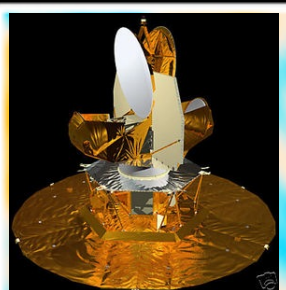


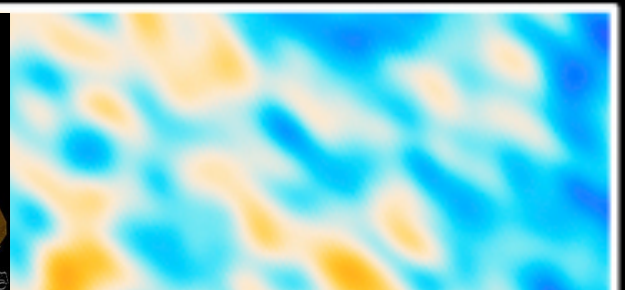
Planck satellite in 2009~ 2013

precision cosmology! (resolution: ~10 arc minute)

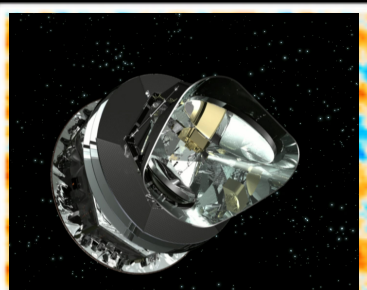


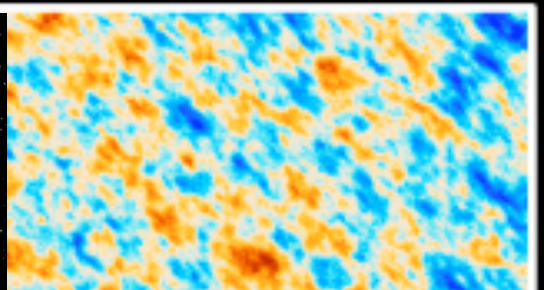
WMAP (US satellite mission)





Planck (European satellite)

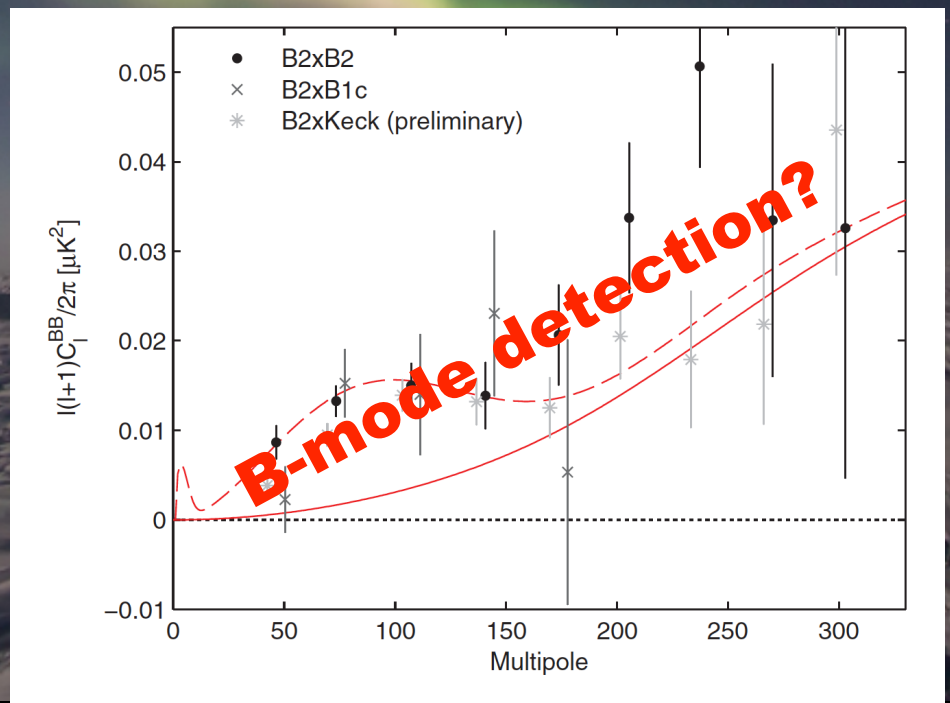




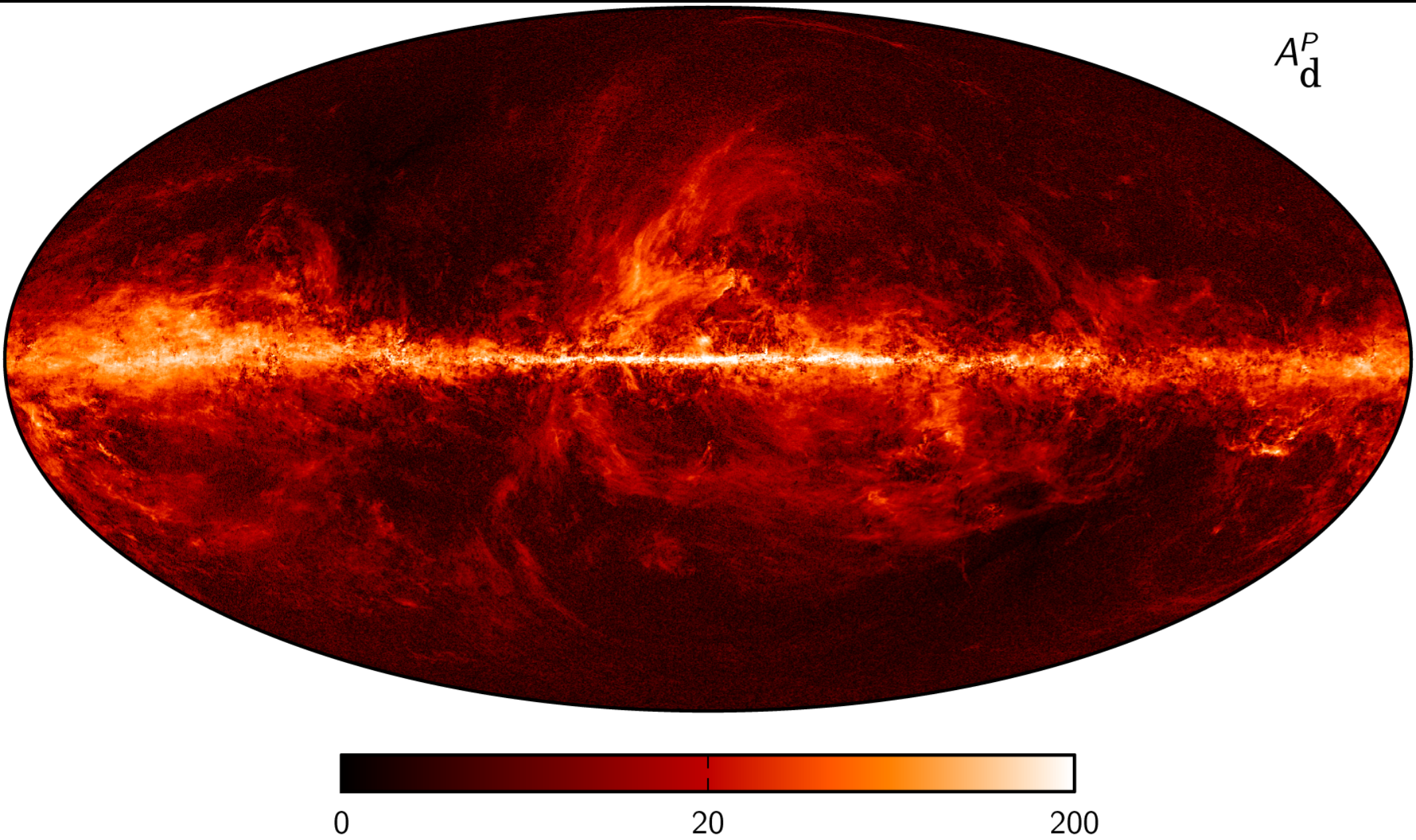
The Experiment

BICEP and Keck Array

cosmological gravity waves 2014



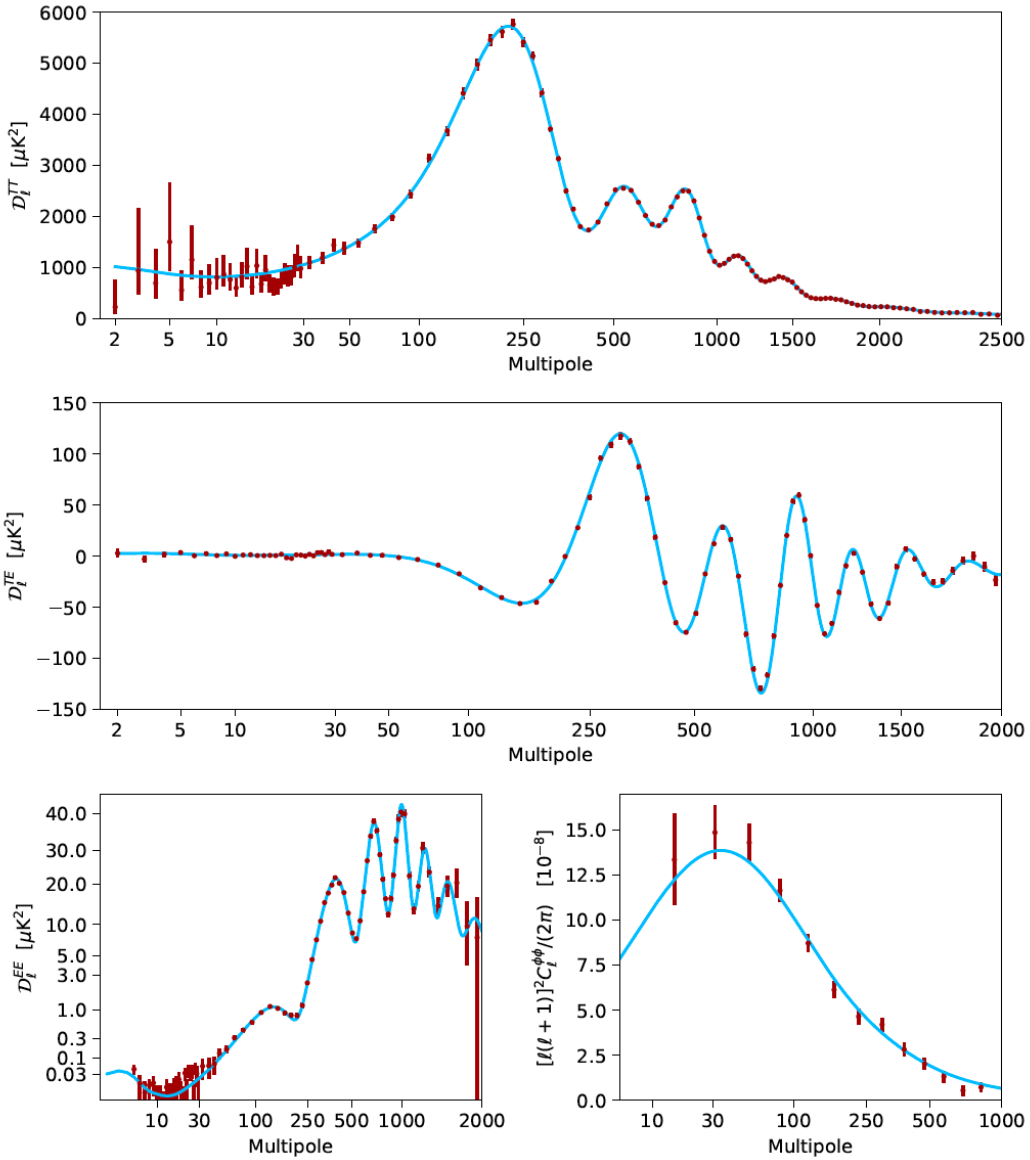
- **Planck *dust* polarization map**




B-mode in the Sky?
Vincent van Gogh

- **Planck collaboration 2018:**

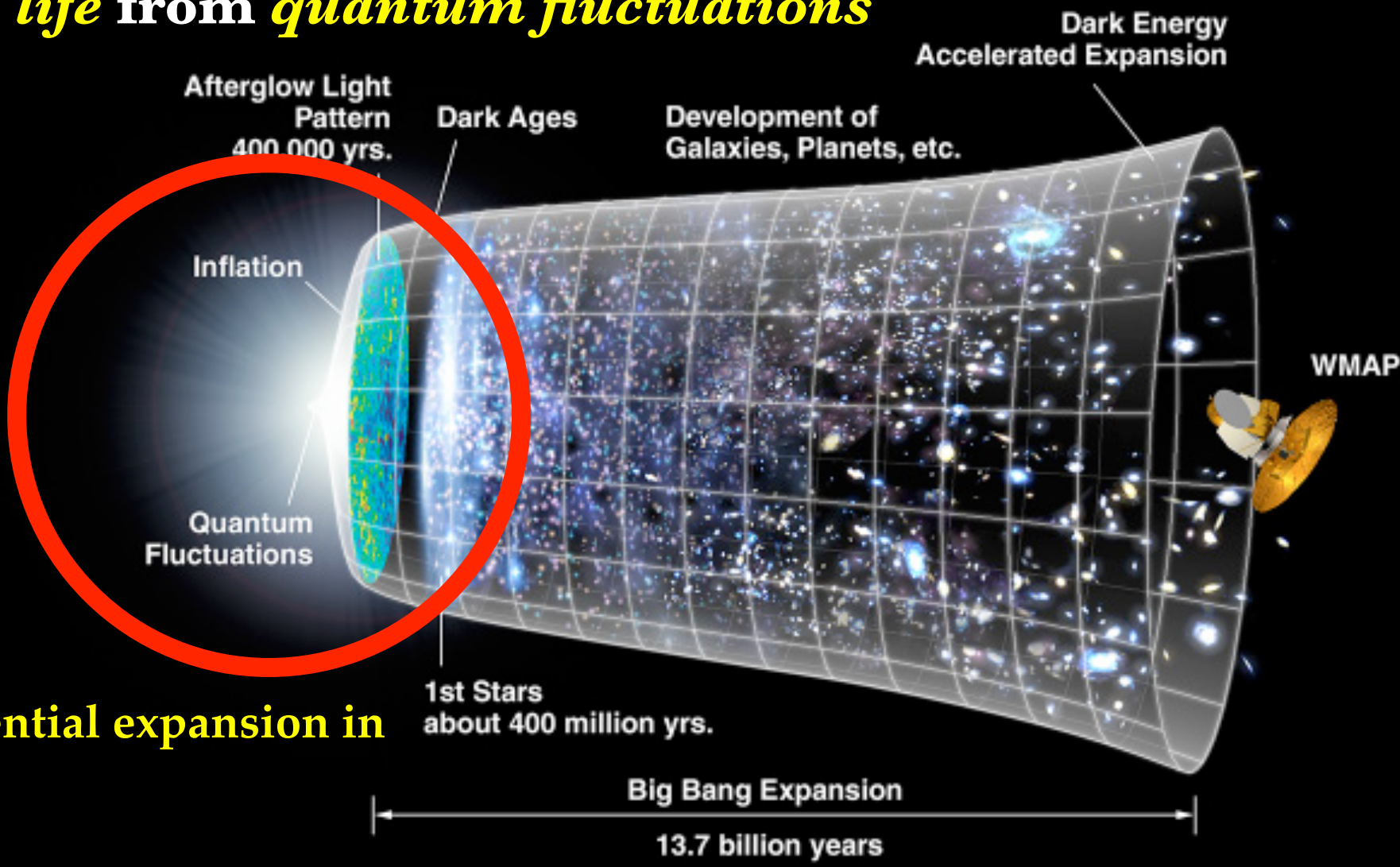
precision measurements!



Parameter	*Planck* alone	*Planck* + BAO
$\Omega_b h^2$	0.02237 ± 0.00015	0.02242 ± 0.00014
$\Omega_c h^2$	0.1200 ± 0.0012	0.11933 ± 0.00091
$100\theta_{MC}$	1.04092 ± 0.00031	1.04101 ± 0.00029
τ	0.0544 ± 0.0073	0.0561 ± 0.0071
$\ln(10^{10} A_s)$	3.044 ± 0.014	3.047 ± 0.014
n_s	0.9649 ± 0.0042	0.9665 ± 0.0038
H_0	67.36 ± 0.54	67.66 ± 0.42
Ω_Λ	0.6847 ± 0.0073	0.6889 ± 0.0056
Ω_m	0.3153 ± 0.0073	0.3111 ± 0.0056
$\Omega_m h^2$	0.1430 ± 0.0011	0.14240 ± 0.00087
$\Omega_m h^3$	0.09633 ± 0.00030	0.09635 ± 0.00030
σ_8	0.8111 ± 0.0060	0.8102 ± 0.0060
$\sigma_8(\Omega_m/0.3)^{0.5}$	0.832 ± 0.013	0.825 ± 0.011
z_{re}	7.67 ± 0.73	7.82 ± 0.71
Age[Gyr]	13.797 ± 0.023	13.787 ± 0.020
r_*[Mpc]	144.43 ± 0.26	144.57 ± 0.22
$100\theta_*$	1.04110 ± 0.00031	1.04119 ± 0.00029
r_{drag}[Mpc]	147.09 ± 0.26	147.57 ± 0.22
z_{eq}	3402 ± 26	3387 ± 21
k_{eq}[Mpc^{-1}]	0.010384 ± 0.000081	0.010339 ± 0.000063
Ω_K	-0.0096 ± 0.0061	0.0007 ± 0.0019
Σm_ν [eV]	< 0.241	< 0.120
N_{eff}	$2.89^{+0.36}_{-0.38}$	$2.99^{+0.34}_{-0.33}$
$r_{0.002}$	< 0.101	< 0.106

Standard Model: Inflation

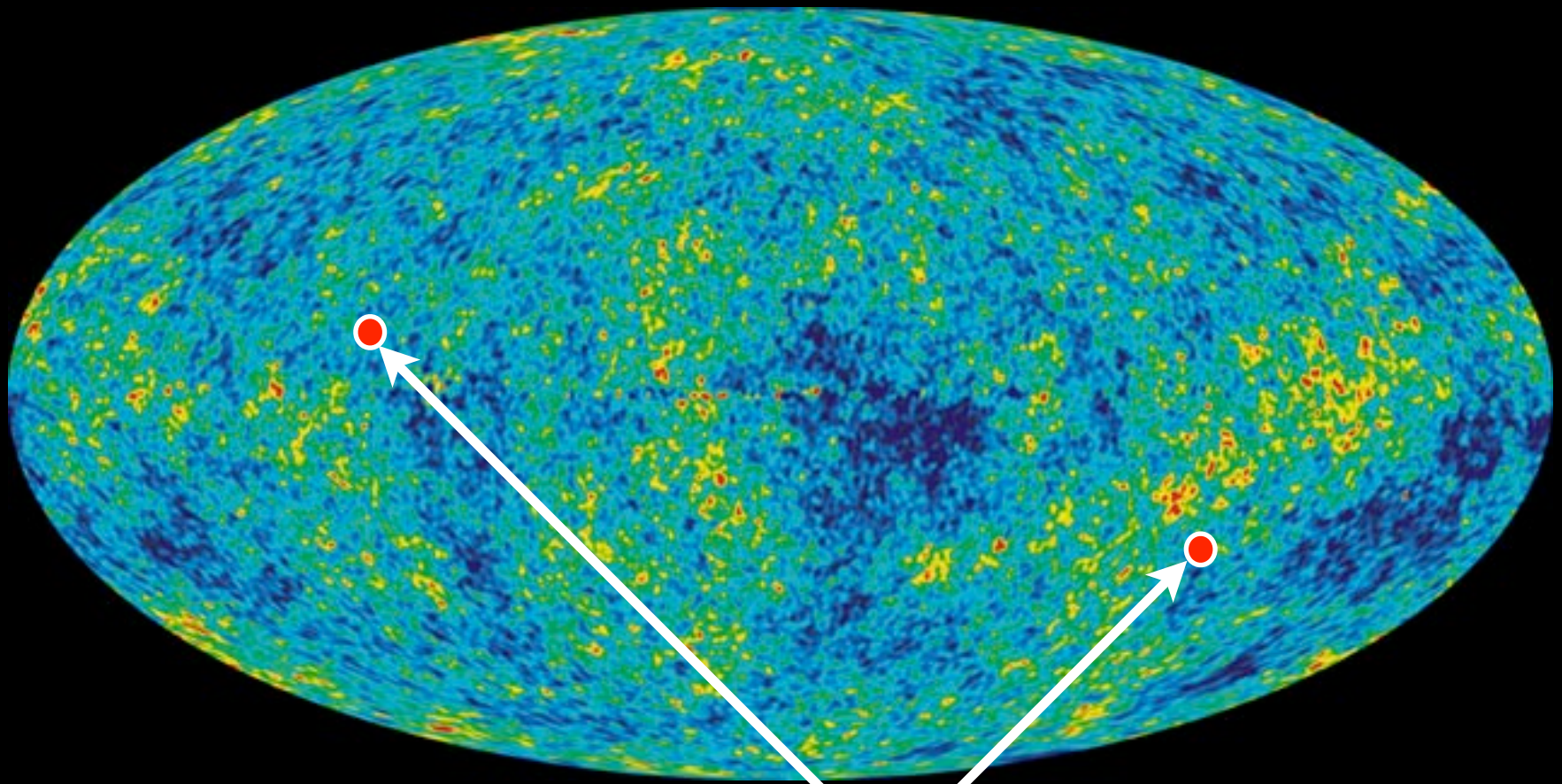
- *initial perturbation generation* in early Universe
- seed for *life* from *quantum fluctuations*



exponential expansion in space

Horizon Problem

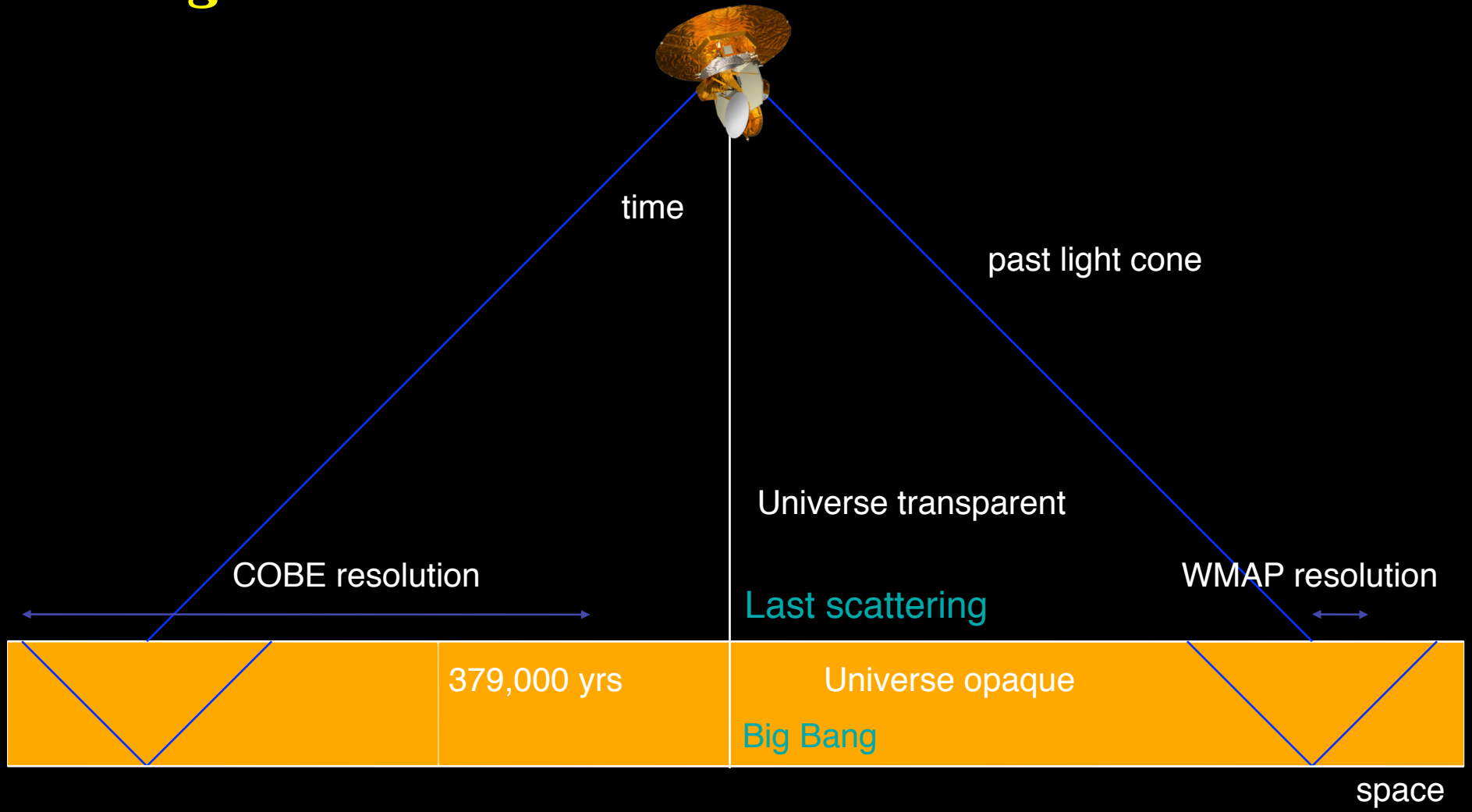
- ***same temperature***: **two patches of sky**
- ***not enough time*** **to communicate with each other**



temperature ~ 3K up to 1/100,000

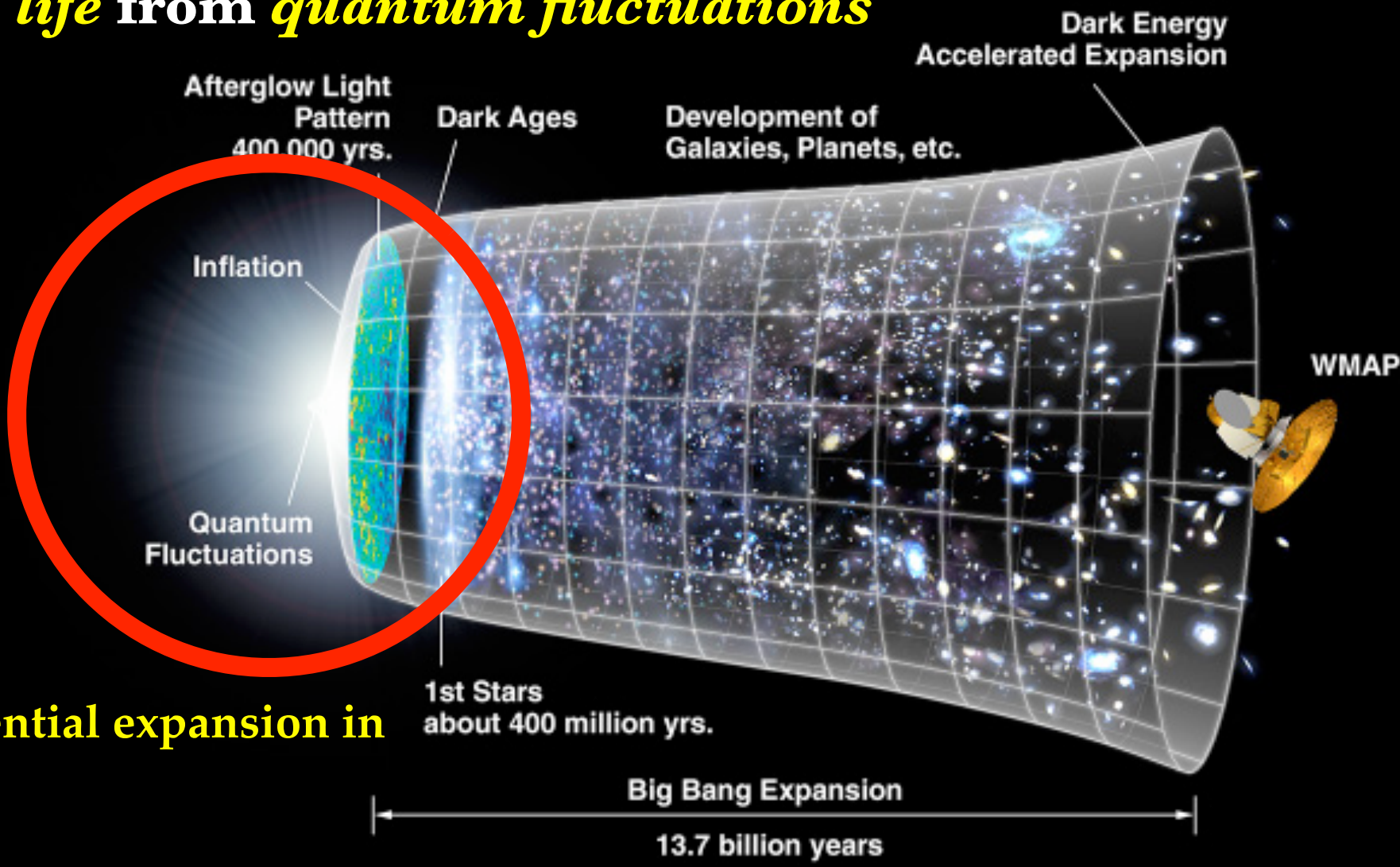
Horizon Problem

- ~ 400,000 years old, ~ 10 billion light years across
- ***not enough time*** to communicate with each other



Inflation: Horizon Problem

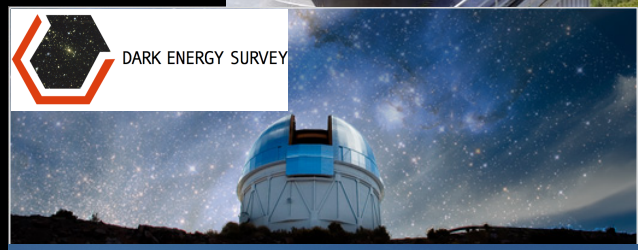
- *solve* the Horizon problem
- seed for *life* from *quantum fluctuations*

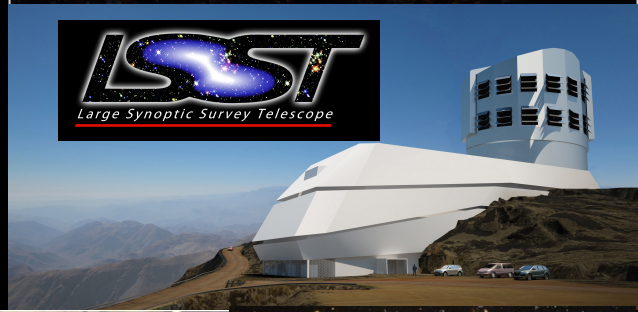


exponential expansion in space

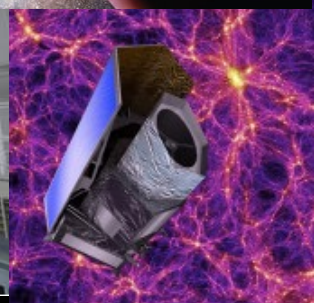
Large-Scale Surveys

- current and future ground-based surveys:
  - Baryonic Oscillation Spectroscopic Survey
  - Dark Energy Survey
  - Dark Energy Spectroscopic Instrument
  - Large Synoptic Survey Telescope





- future space missions:
  - Euclid
  - Wide-Field Infrared Survey Telescope



- <u>sub-percent level</u>

  precision measurements!

More Ambitious Surveys

- **future radio surveys:**
  - **Murchison Wide-field Array Phase-II**
  - **Square Kilometer Array**

- **redshifted 21cm lines:**
  - **from hyperfine transition in neutral hydrogen**
  - **probe redshift 10 ~ 30**
  - ***more statistical power than CMB***

Even more *precise* measurements!

CMB Stage IV (S4)

- **next-generation** CMB experiment:
  - dedicated telescopes
  - South Pole & Chile Atacama
  - and more telescopes?
  - inflation $r < 0.002$
  - neutrino mass $\sum m_\nu$
  - relativistic species $\sigma(N_{\rm eff}) = 0.02$