森永先生との付合い (1970-2018)

1970－ ＠東大素粒子研

“Has Nuclear physics more life??”

“Can Nuclear Physicists still survive??”

1986 Muenchen; Dubrovnik symposium

1987 TU Muenchen — Lectures on neutrino physics

Moessbauer, Kienle

Our Understanding of Cosmology

Masataka Fukugita

Kavli IPMU, U. Tokyo

Inst. Advanced Study, Princeton

Road to Λ Cold Dark Matter Universe

Einstein equation (1915):

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R - \Lambda g_{\mu\nu} = +8\pi G T_{\mu\nu}$$

Space-Time: $ds^2 = g_{\mu\nu} dx^\mu dx^\nu$

is homogeneous and isotropic:

$$ds^2 = dt^2 - a(t)^2 \{ \frac{dr^2}{1 - kr^2} + r^2 d\theta^2 + r^2 \sin^2\theta d\phi^2 \}$$

Friedman (1922);

Robertson (1935) & Walker, A.G. (1936)

scale factor $a(t)$ $\overrightarrow{x} = a(t)\overrightarrow{r}$

Friedman equation:

$$\frac{k}{a^2H^2} = \Omega_m + \Omega_\Lambda - 1 = K$$

$$H = \frac{\dot{a}}{a}$$

determine at $t = t_0$ (0 means today's values)

$$H, \quad \Omega_m = \frac{8\pi G}{3H^2}\rho = \frac{\rho}{\rho_{\rm crit}}, \quad \Omega_\Lambda = \frac{\Lambda}{3H^2} \quad K$$

Solution is not static

Universe is expanding: roughly $a \sim t^{2/3}$

accurate form depends on $\Omega_m, \Omega_\Lambda, k$

Discovery of expansion of the Universe

Lemaitre (1927)

He referred to Friedman solution

Hubble (1929)

$$\overrightarrow{v} = H_0 \overrightarrow{d}$$

Gamow (1946) extrapolated the expansion to t=0

25%-He production understood

Lifshitz (1946) gravitational instability theory

Discovery of cosmic microwave background (CMB)

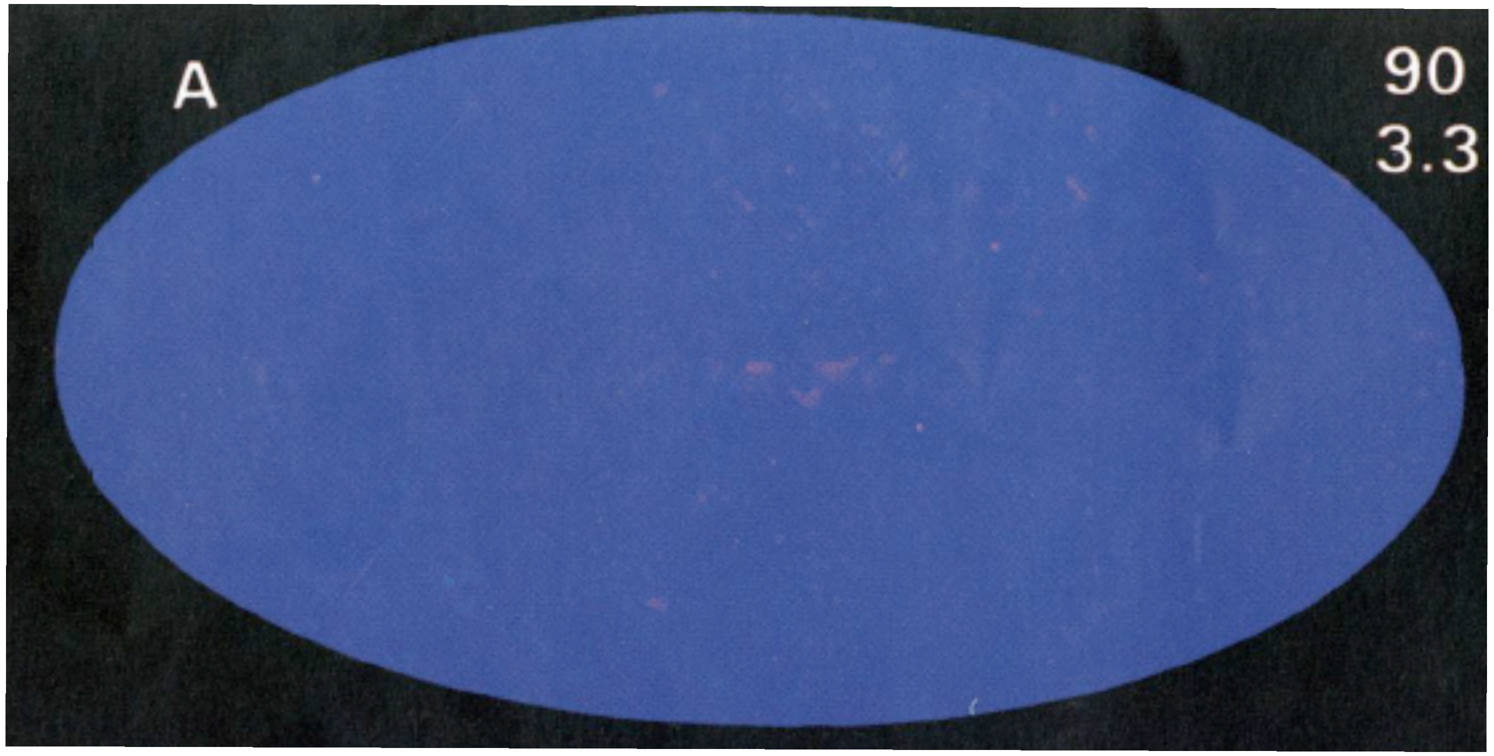
Penzias and Wilson (1965) accidental

Dicke and Peebles (1965):

predicted, started search

confirmed of Gamow's hot fireball (Big Bang)

0.15% level



COBE 1991

There must be fluctuations

(Peebles-Yu: Zeldovich-Sunyaev, 1970)

$$\Delta T/T \approx 10^{-3}$$

expt.: By 1991: $\Delta T/T < 10^{-4}$

Suspect: Are we on a right track?

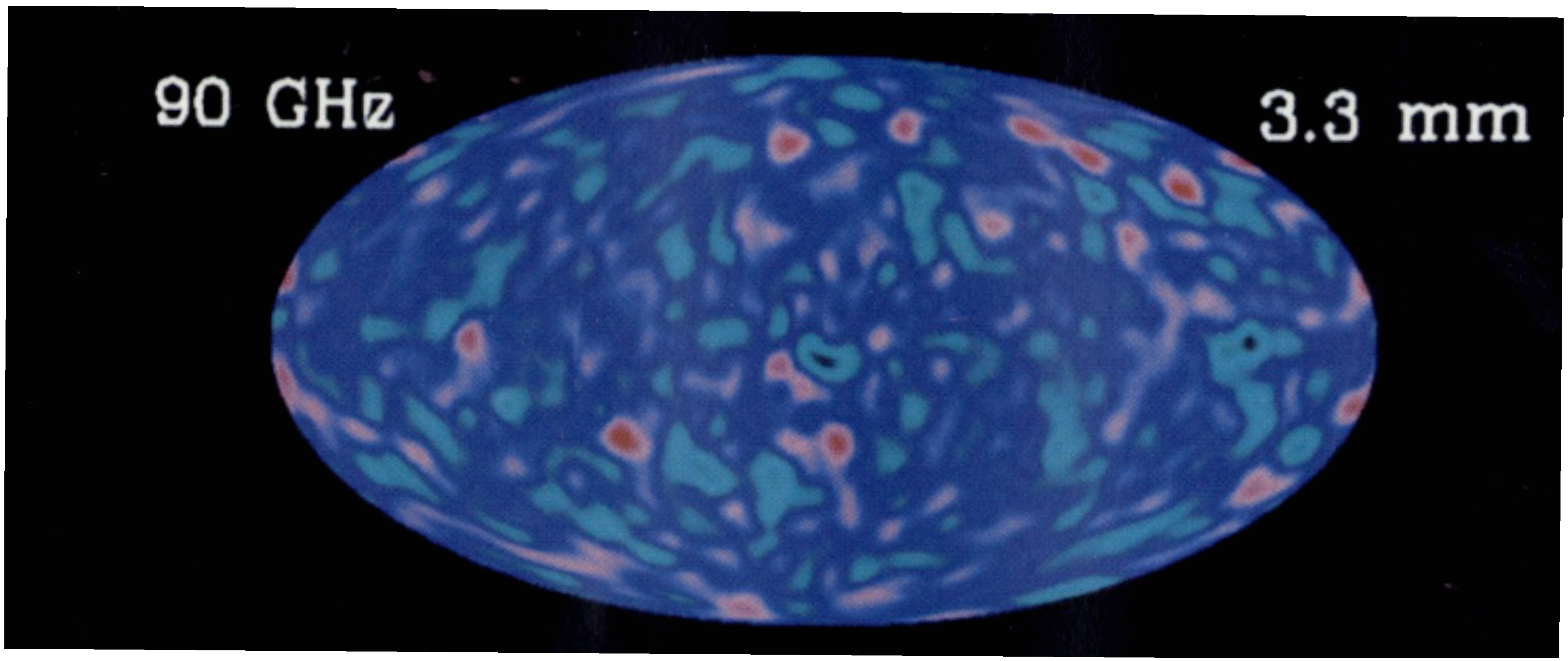
1992: Discovery of fluctuations

at $\Delta T/T \approx 10^{-5}$ (COBE/DMR)

Yes, we are on the right track!

But we need Dark Matter dominating

massive neutrinos: NG



COBE 1992

$$\frac{\Delta T}{T}|_{\ell=2} \approx 5 \times 10^{-6}$$

fluctuations and correlations

$$\frac{\Delta T}{T} = \sum a_{\ell m} Y_{\ell m}(\theta, \phi)$$

$$C_\ell = \langle |a_{\ell m}|^2 \rangle$$

$$\langle \delta(k)\delta(k') \rangle = (2\pi)^3 \delta(k - k') P(k)$$

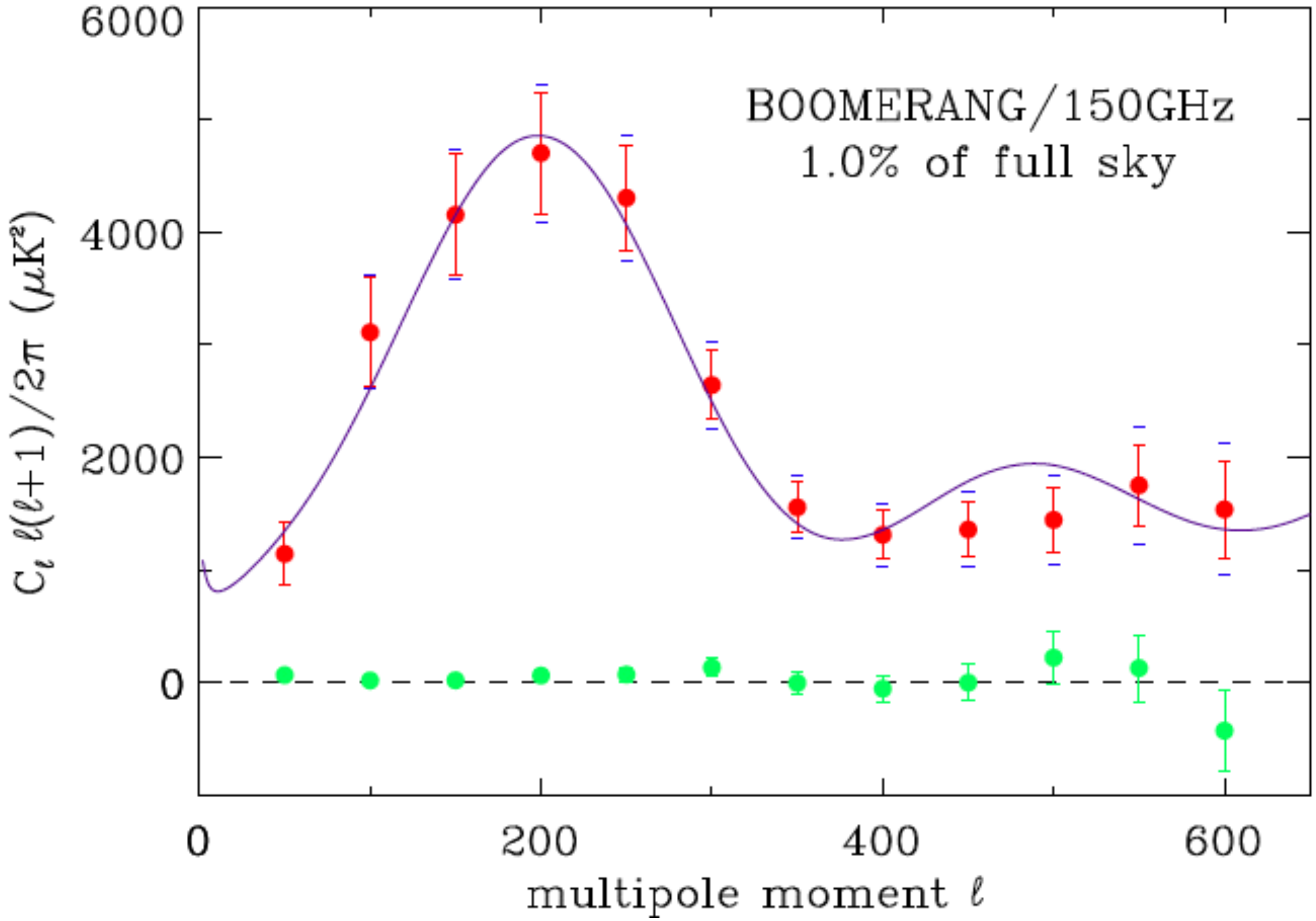
$$P(k) = k^n \qquad (\mathrm{flat}: \ n = 1)$$

$$n = 1 - \epsilon$$

$$C_\ell = \frac{2}{\pi} \int dk k^2 P(k) \left| \frac{\Delta T(k)_\ell}{T} \frac{1}{\delta(k)} \right|^2$$

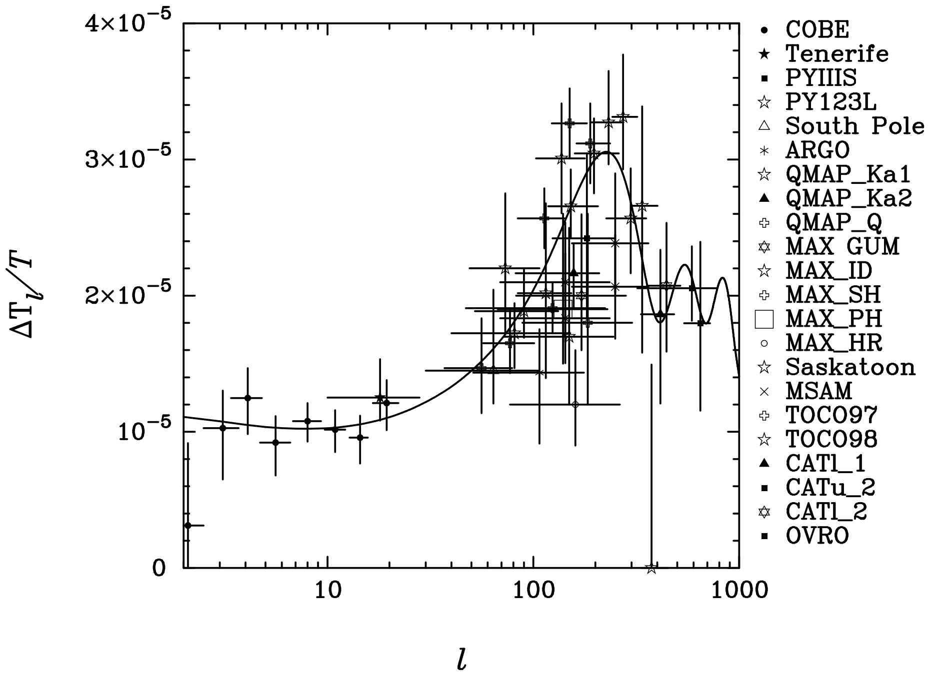
C_ℓ

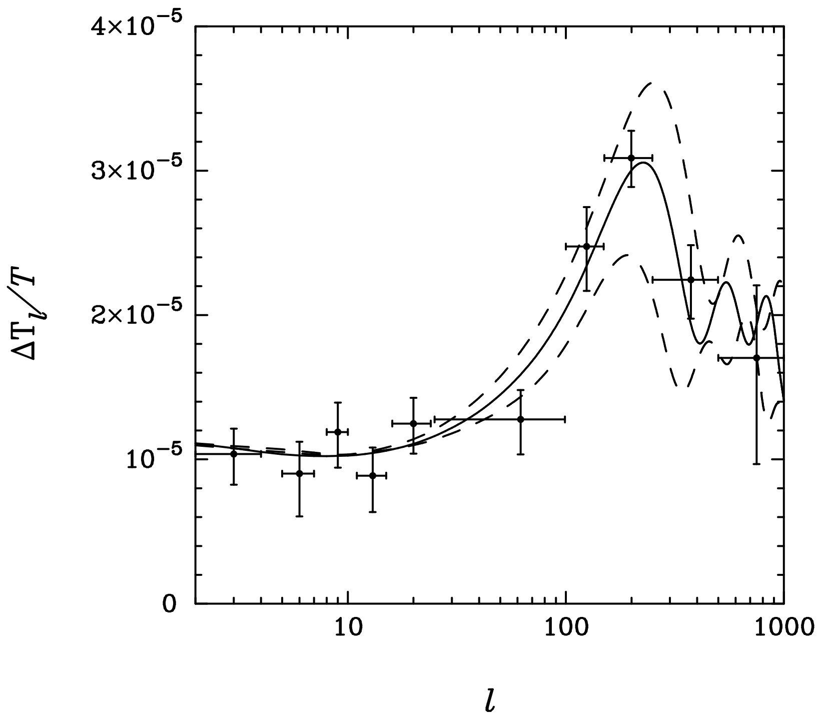
Boomerang (baloon, 2000)



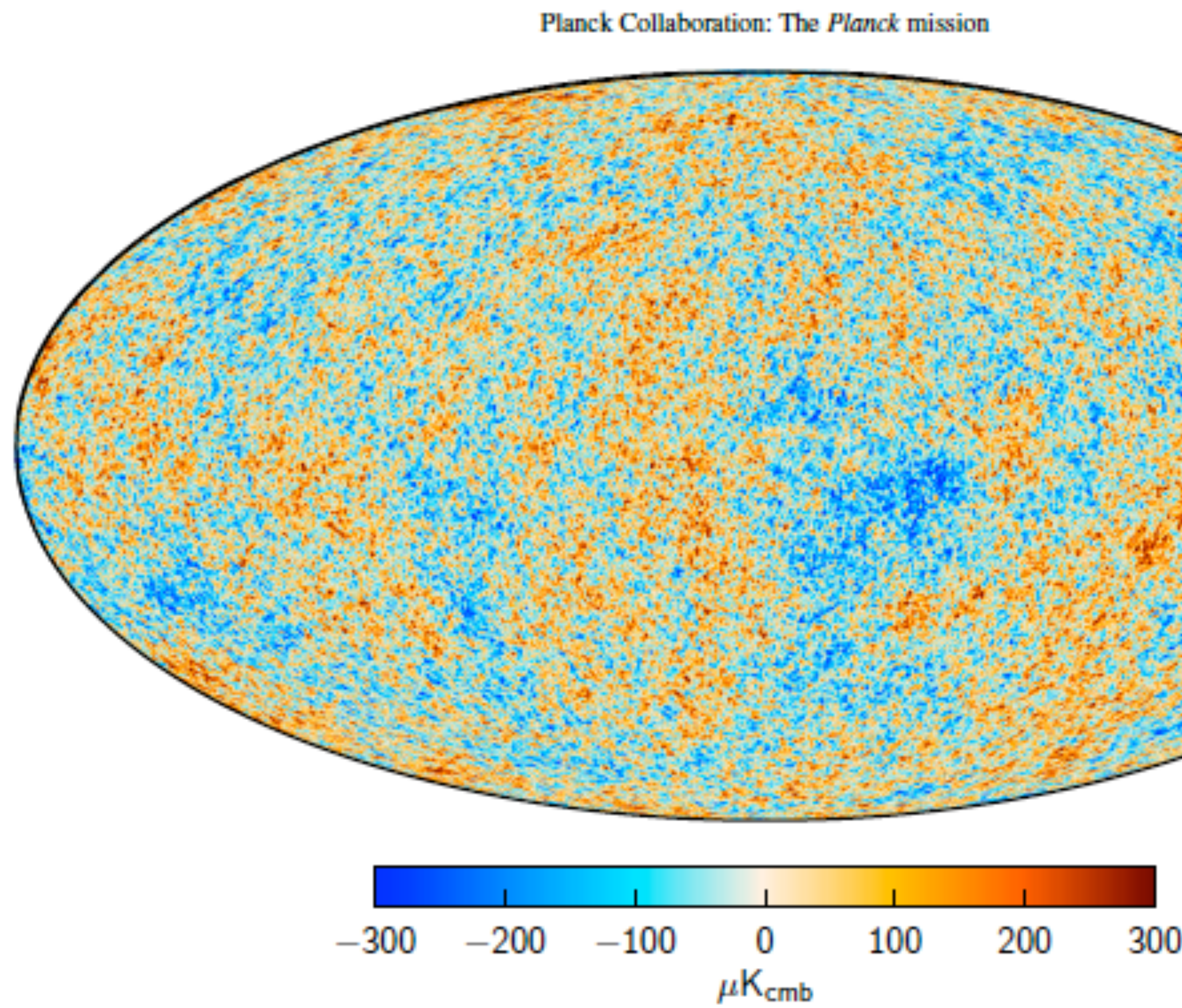
Compilation of ground-based experiments (Efstathiou 1999)

C_ℓ





Planck 2015


Planck Collaboration: The *Planck* mission
−300
−200
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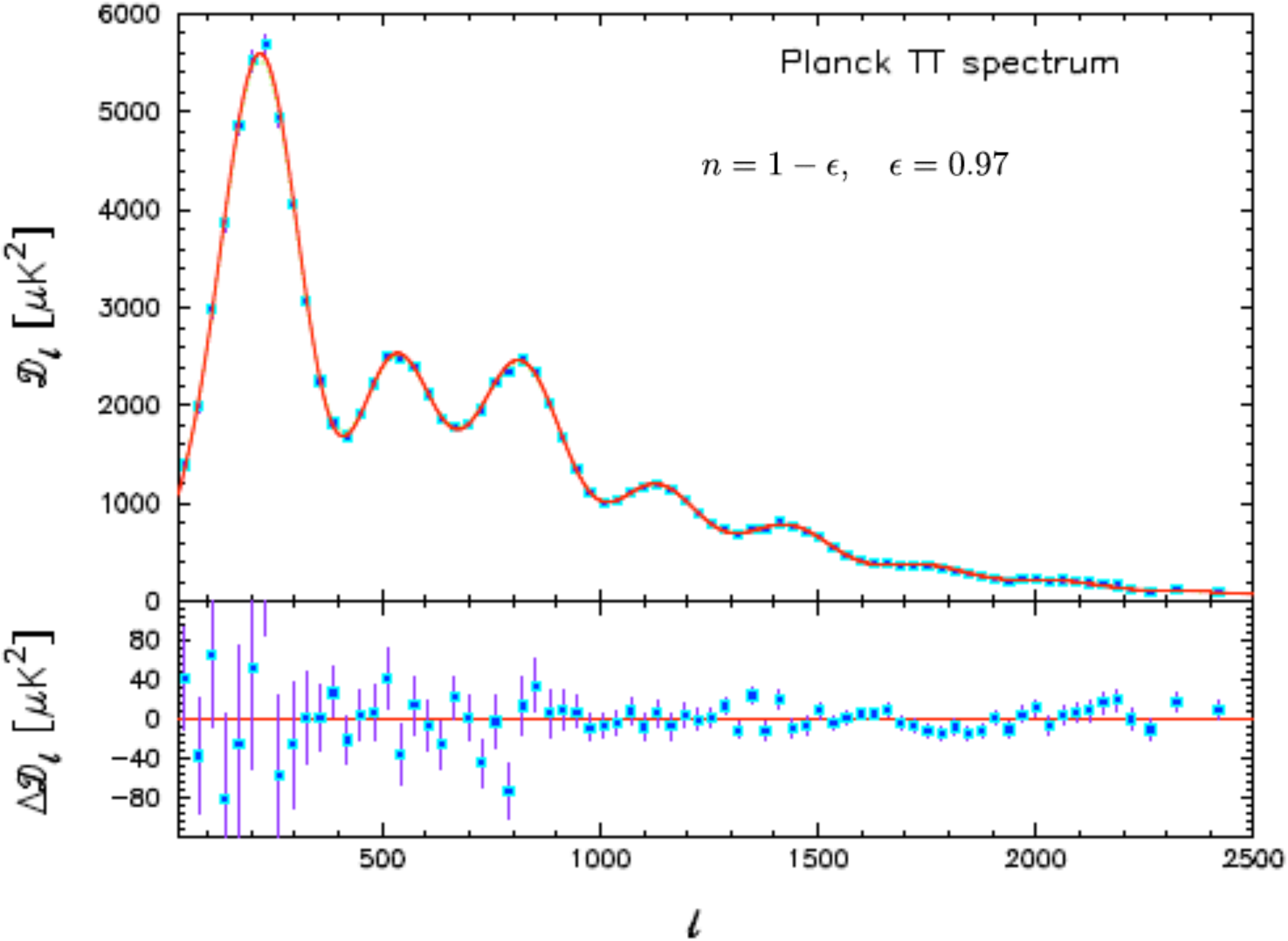
0
100
200
300
μK_cmb

C_ℓ

Planck 2013



Introduction of "unwanted" vacuum energy Λ

1. H_0 vs. age if $H_0 > 60$

2. CMB harmonics: peak at $\ell \approx 200$ (means $\Omega_m + \Omega_\Lambda \approx 1$)

   (Boomerang 2000; Ground based compiled ~1998;

   WMAP 2003; Planck 2013)

3. supernova Hubble diagram: fainter SNe at large z

   (Riess+ 1998, Perlmutter+ 1999)

Today, all observational evidence consistent with

$$\Lambda \neq 0$$

(It was an anathema before ~1997)

ΛCDM fits CMB harmonics data perfectly well!

We have no other alternatives

$$H_0 = 67.4 \pm 0.5$$

$$\Omega_0 = 0.315 \pm 0.007$$

$$K = \Omega_0 + \Omega_\Lambda - 1 = 0.0007 \pm 0.0019$$

$$\Omega_b = 0.0492 \pm 0.0011 \quad (i.e.\ \mathrm{DM/baryon} = 5.4)$$

Remaining problems:

What is dark matter?

What is “dark energy” $\longrightarrow$ Why K=0?

Structure formation esp. at small scales understanding Λ or $K = 0$

problem posed by Dicke & Peebles 1979

An intriguing explanation: inflation

(+) origin of fluctuations

Starobinsky, Guth, Linde, Albrecht-Steinhardt

(+) spectral tilt is natural

Mukhanov, Hawking, Pi-Steinhardt, Linde

(—) Conceptual problems: eternal inflation

Inflation, once took place, never ends

Linde, Guth

Inevitably multiverse (infinite nr. of univ.)

Our Universe is one realisation out of infinity

When one says the 'success' of inflation,
he closes his eyes on the fundamental problem

How about galaxies?

1990

non – zero Λ?

TEST FOR THE COSMOLOGICAL CONSTANT WITH THE NUMBER COUNT OF FAINT GALAXIES

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AND
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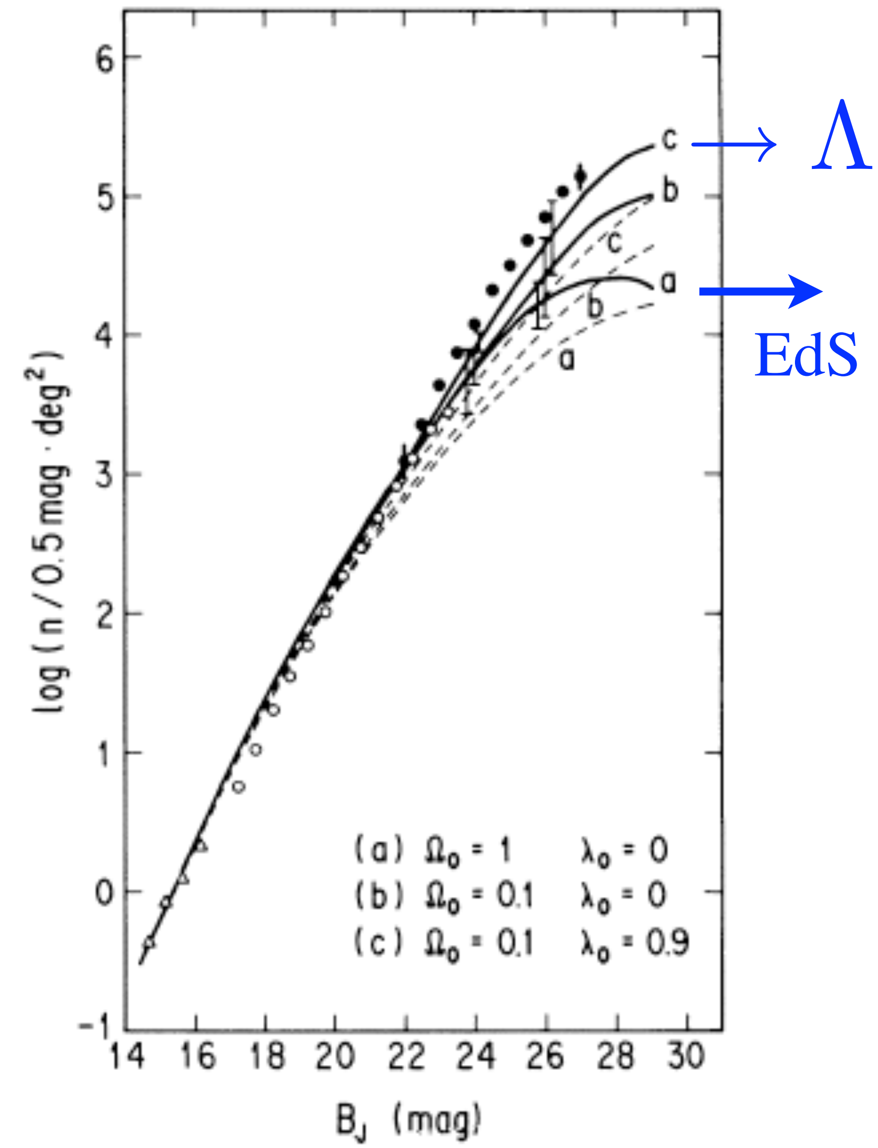
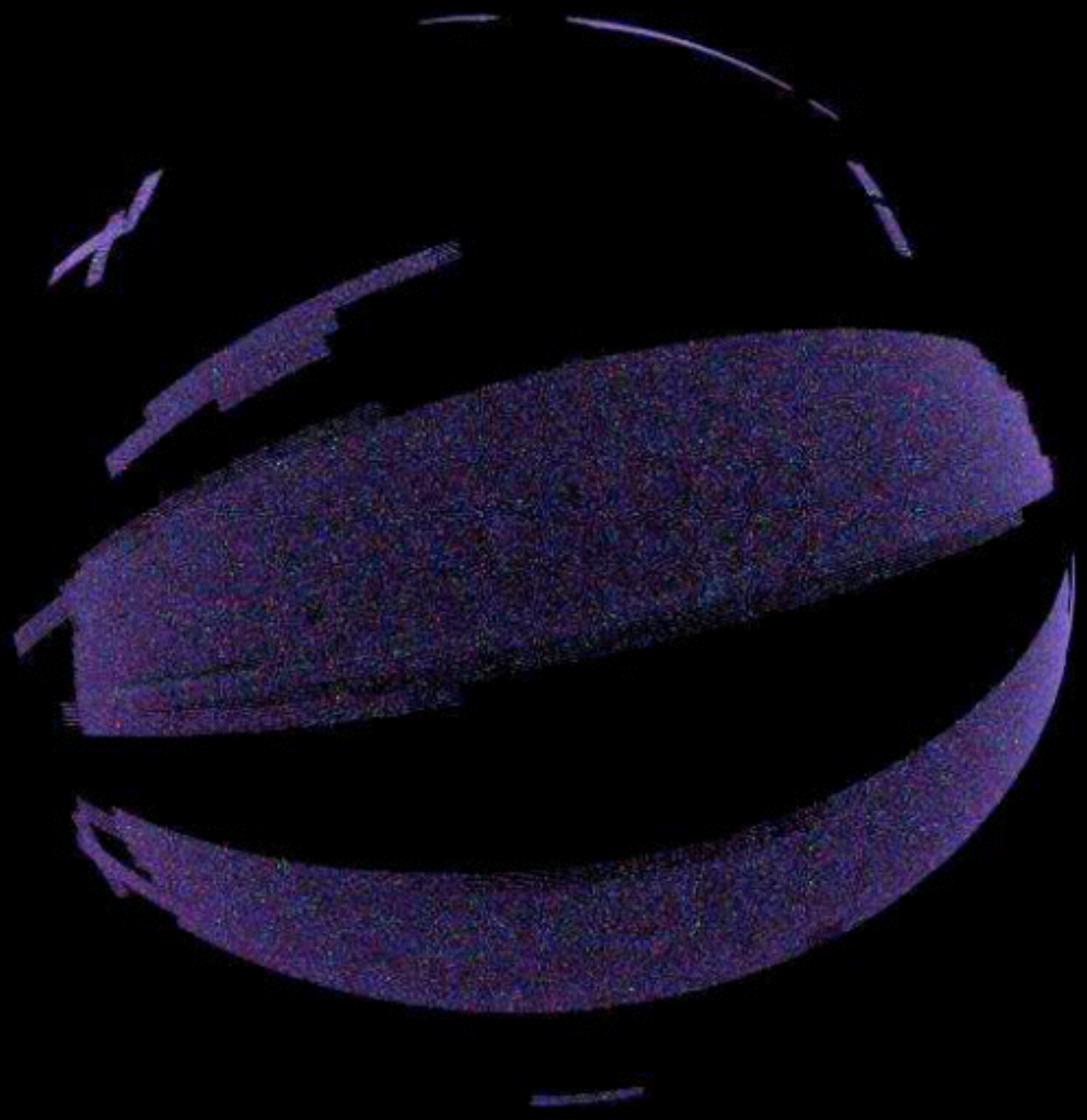
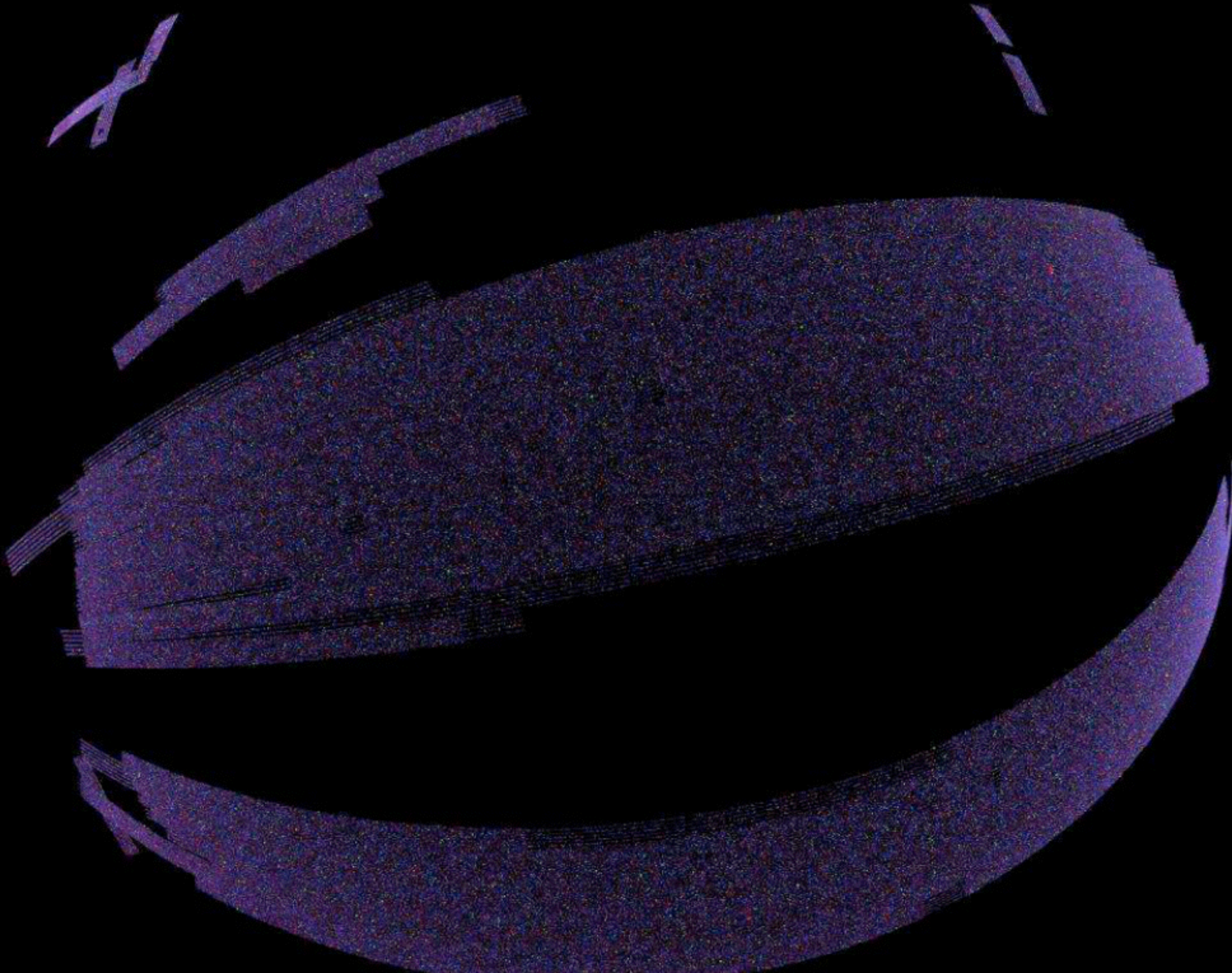
National Astronomical Observatory, Tokyo
Received 1990 March 2; accepted 1990 July 2

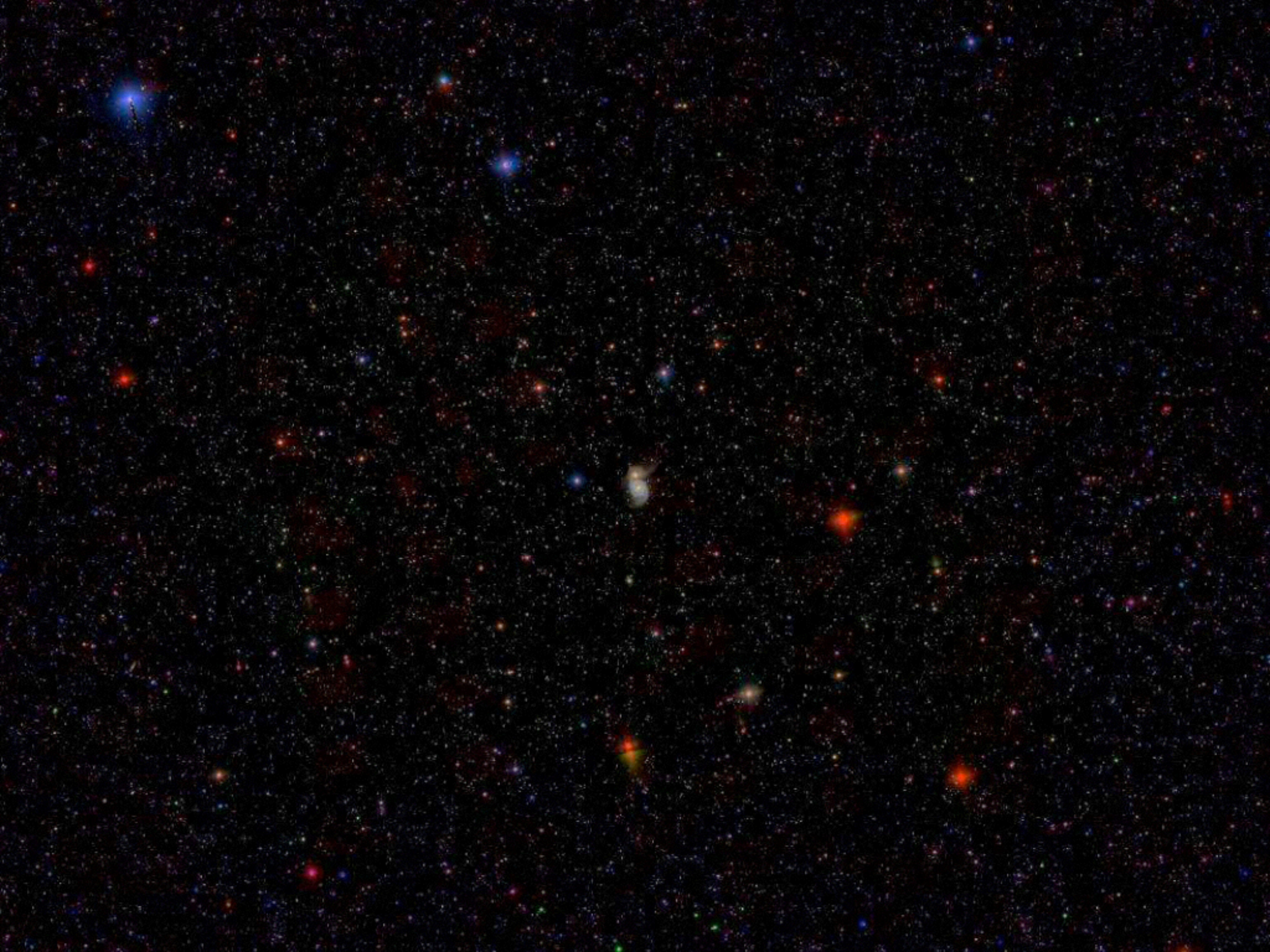
1991

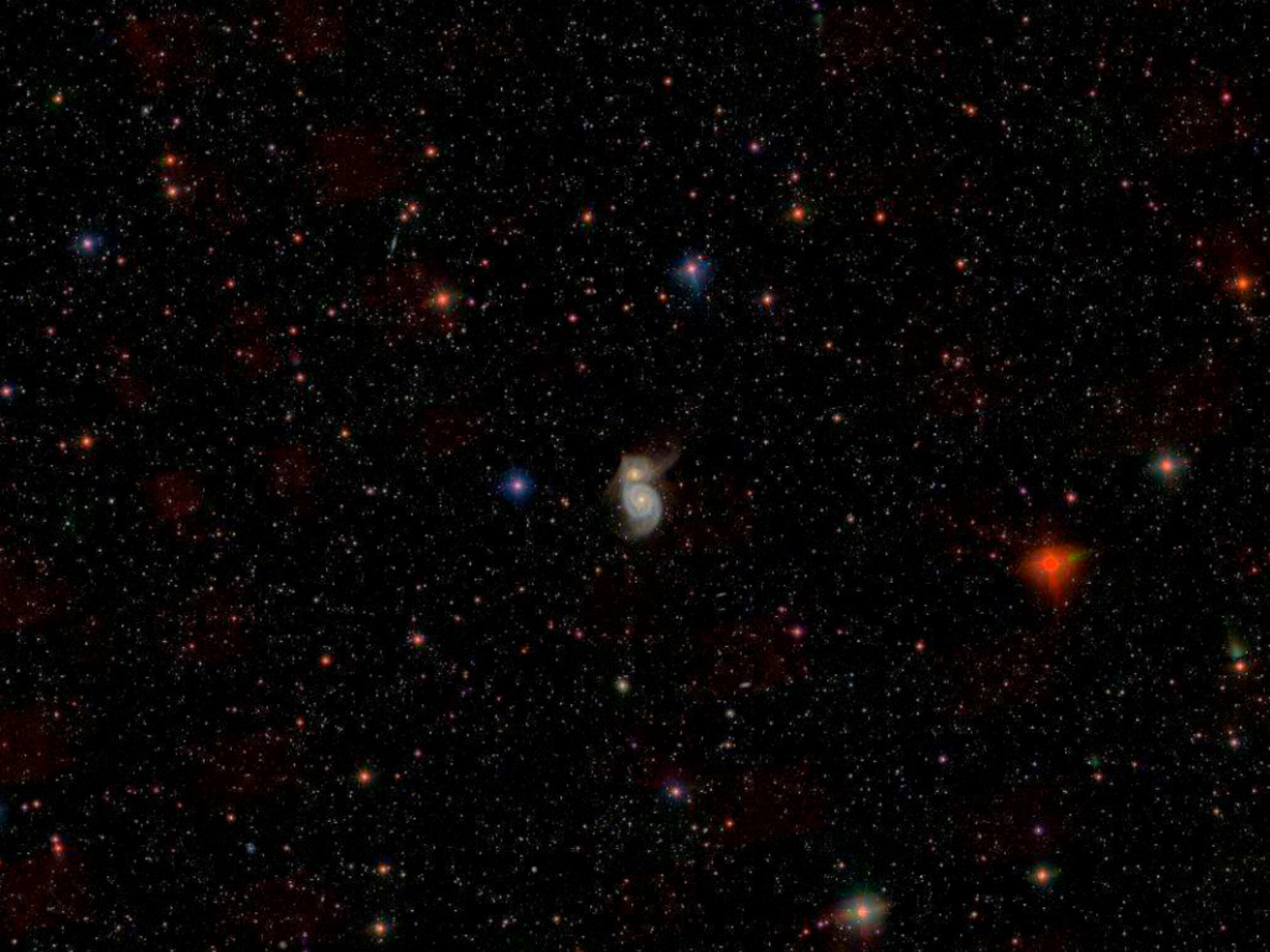
N(m): Tyson's CCD count (1988): cosmological depth

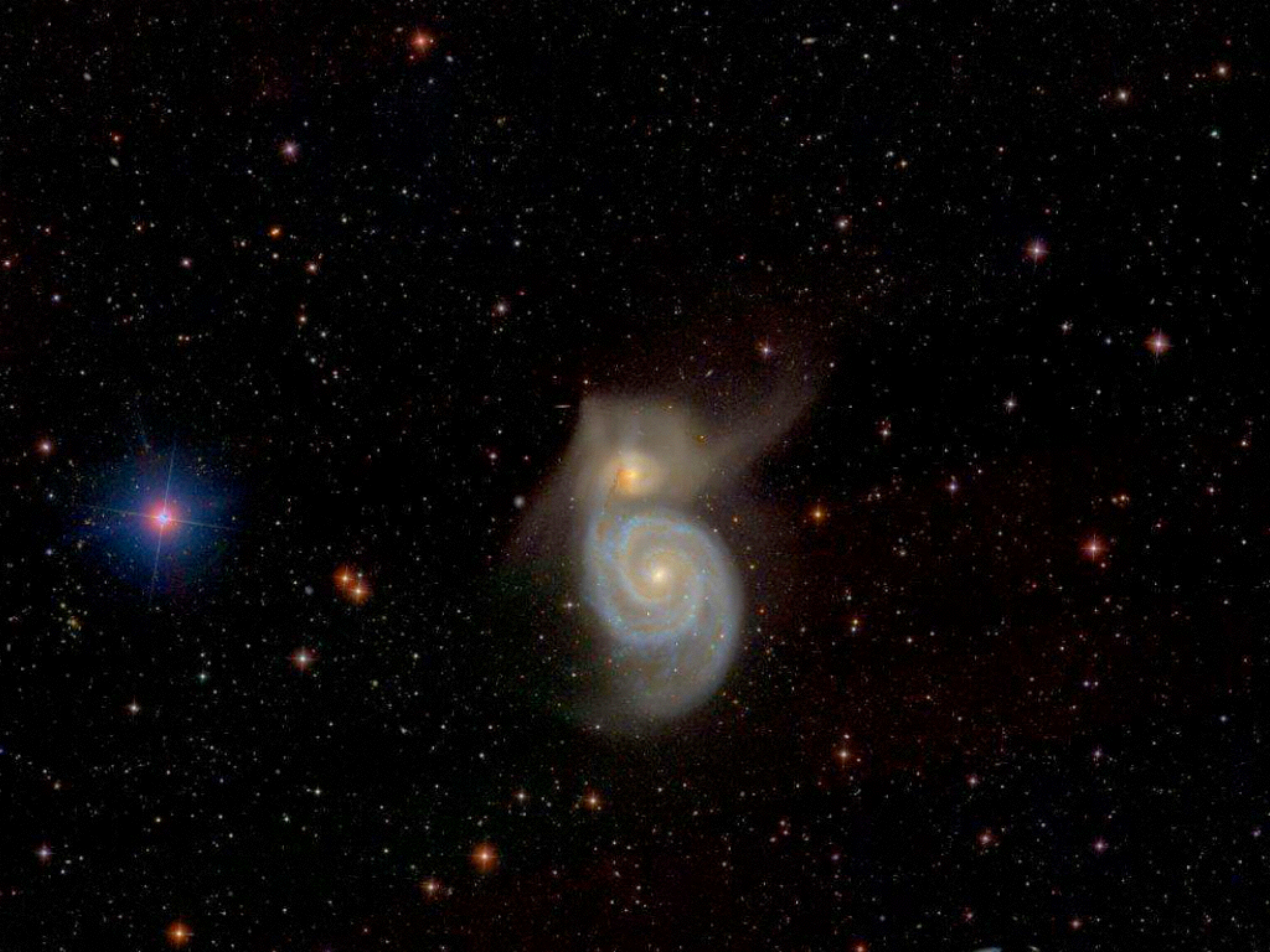


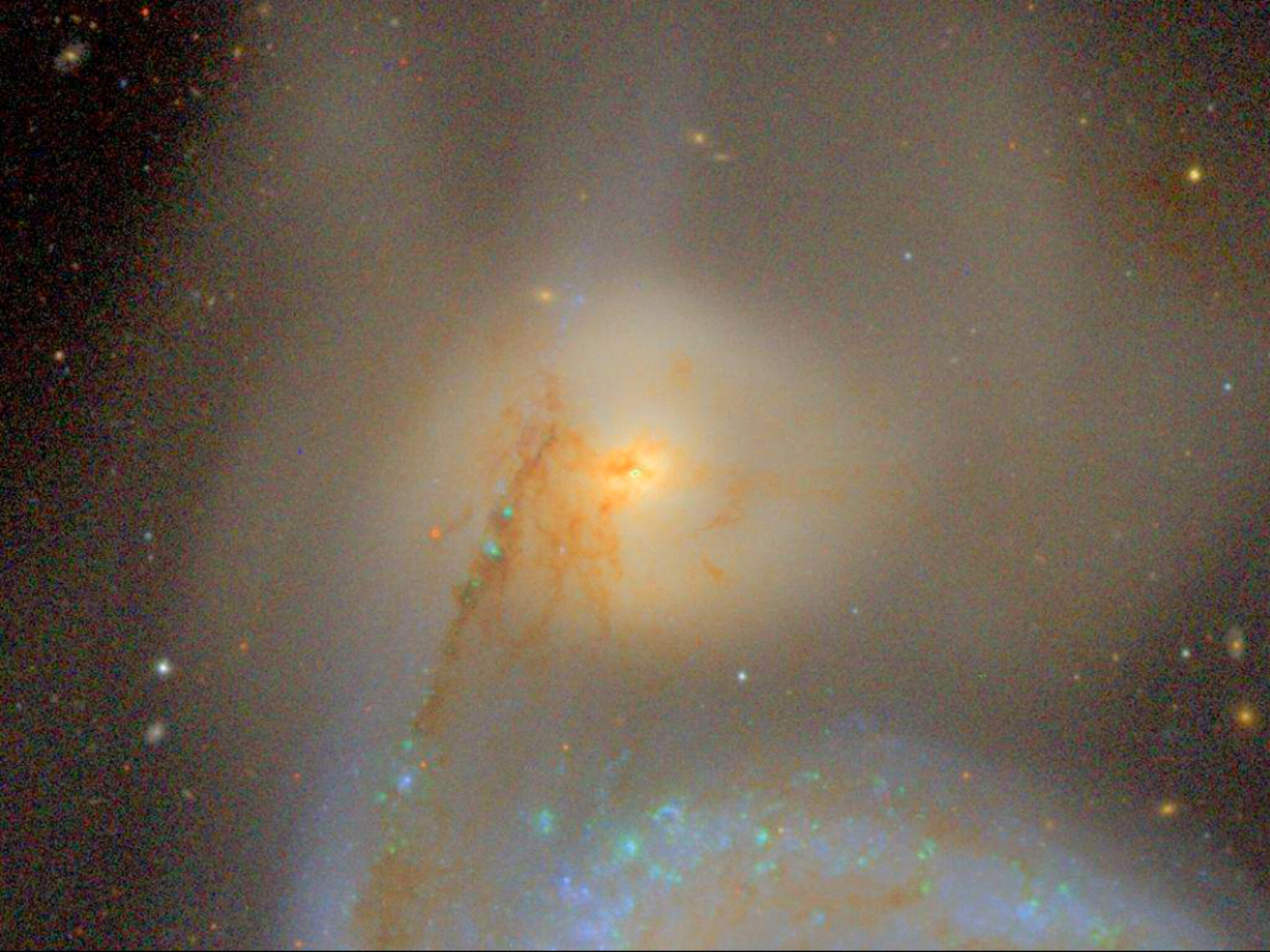








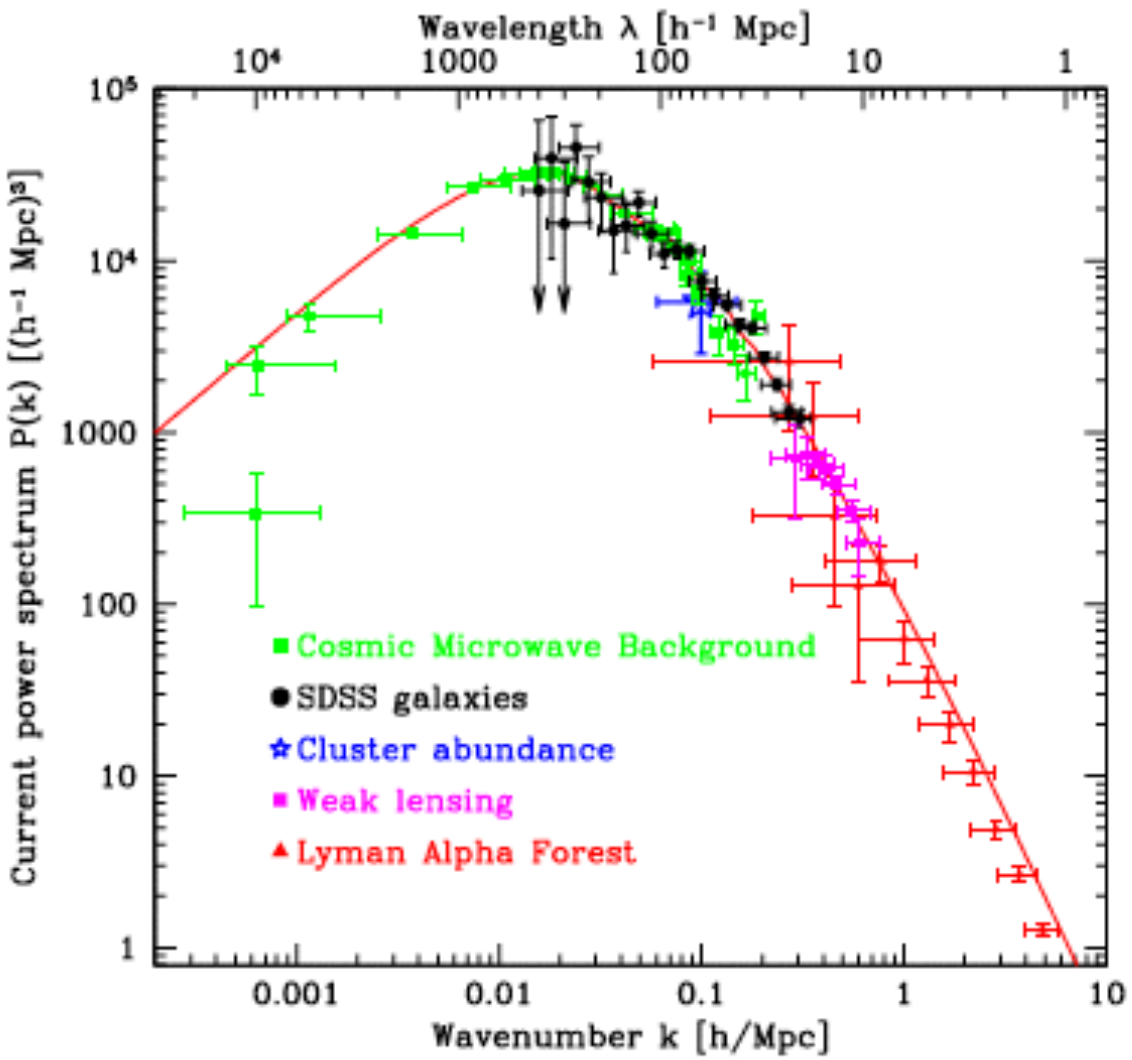




$P(k)$

Gravitational binding energy $$W = \frac{G\rho}{\pi}\int_0^\infty dk P(k)$$

SDSS: Tegmark et al. 2004



Formation of galaxies and cosmic structures

clustering of dark matter

dragging baryons

cooling of baryons, interactions among baryons

stars formed: variety of physics appears

$$\Omega_b = 0.05 \quad \Omega_* = 0.003 \quad \Omega_{\rm visible} = 0.005$$

Where are 90% of baryons?

'Missing baryon problem' Fukugita,Hogan,Peebles 1998

Conclusions

Global evolution and the state of the Universe

is understood, basically by yr 2000

Remaining: what is dark matter?; why is $K = 0$?

Evolution of galaxies

We have a reasonable picture how it does

in particular, numerical modelling

Yet many unknowns in the process