

Weighing the universe : baryons, dark matter, and dark energy

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The University of Tokyo
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The 21st century COE program of Tohoku University

International symposium

Exploring New Science by Bridging Particle-Matter Hierarchy

March 5-9, 2004

What is the universe made of ?

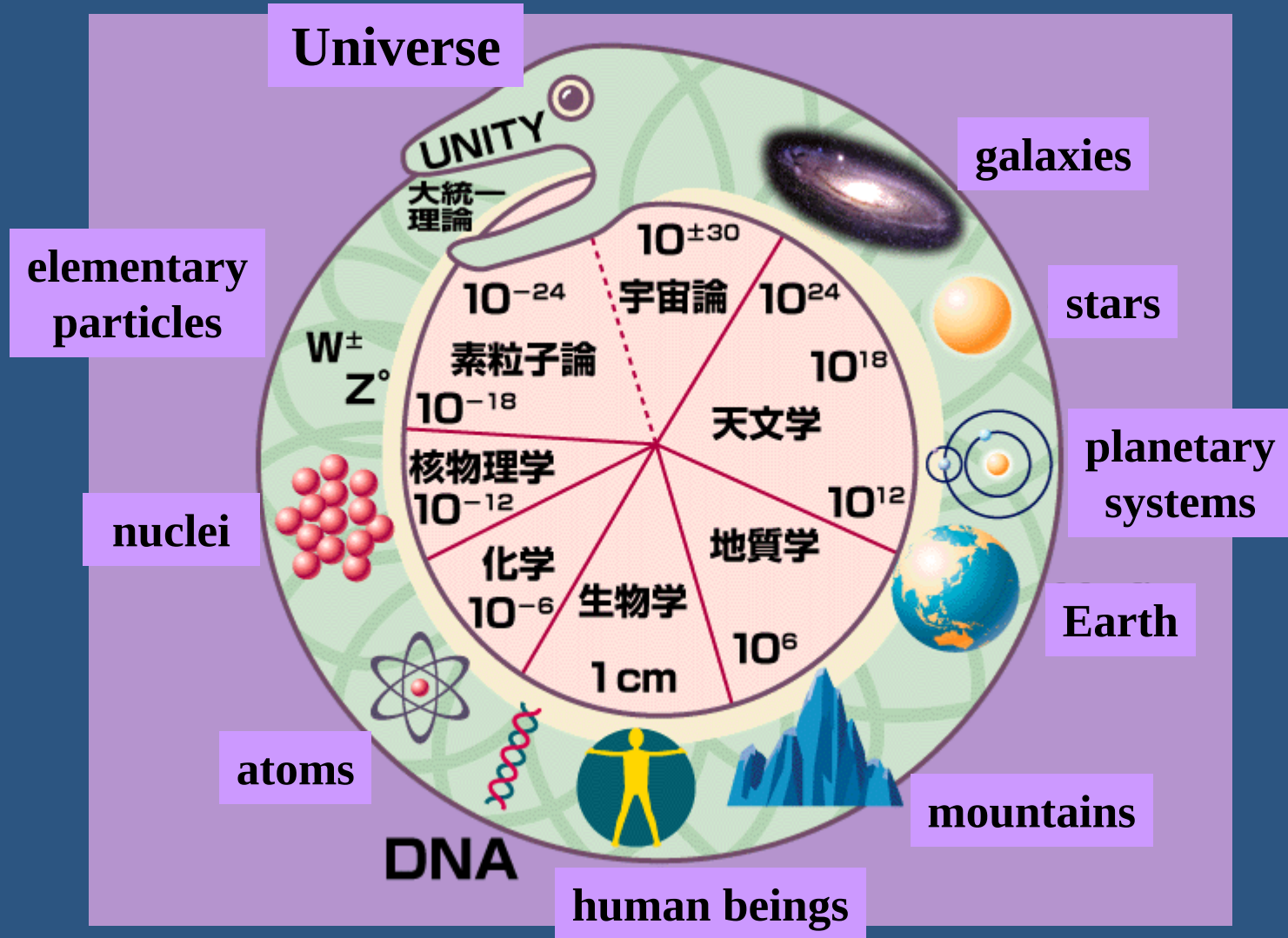
■ Microscopic world: origin of matter

- Identifying the hierarchy in the material world:
molecules atoms nuclei (baryons)
elementary particles (quarks and leptons)
- particle physics in the 20th century was so successful and established the standard model
- any other matter hierarchy in the microscopic world beyond the standard model ?

■ Macroscopic world: origin of the universe

- hierarchy in the universe: **planets stars**
galaxies clusters of galaxies
large-scale structure of the universe
- Is the universe really dominated by matters that are fully described in the standard model of particle physics ?

Universe bridges microscopic and macroscopic worlds



based on a plot in ' 'Interaction' ' (S.Glashaw)

Hierarchical structure in the universe

Solar system



Dwarf galaxy



Galaxy group



Large-scale structure



Star cluster



Galaxy

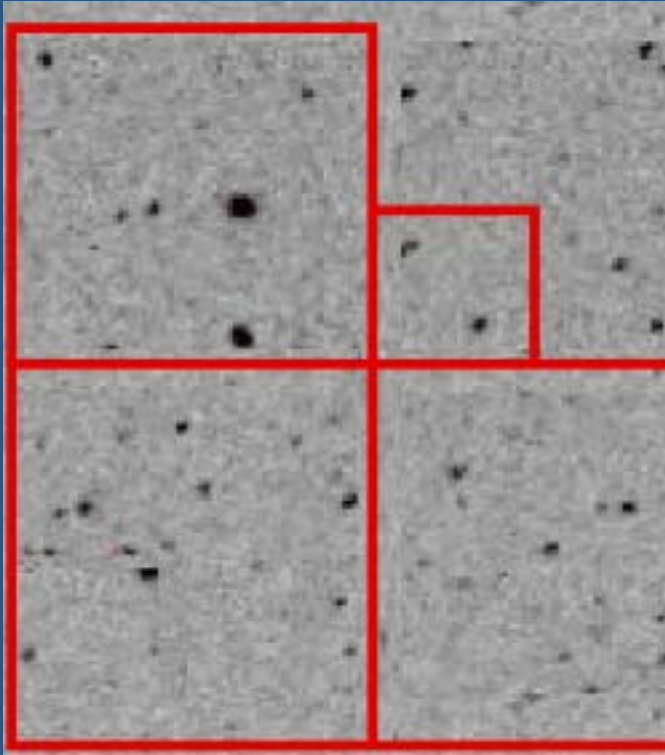


Galaxy cluster



Typical size in parsec [$1\text{pc} \sim 3.1$ light year]

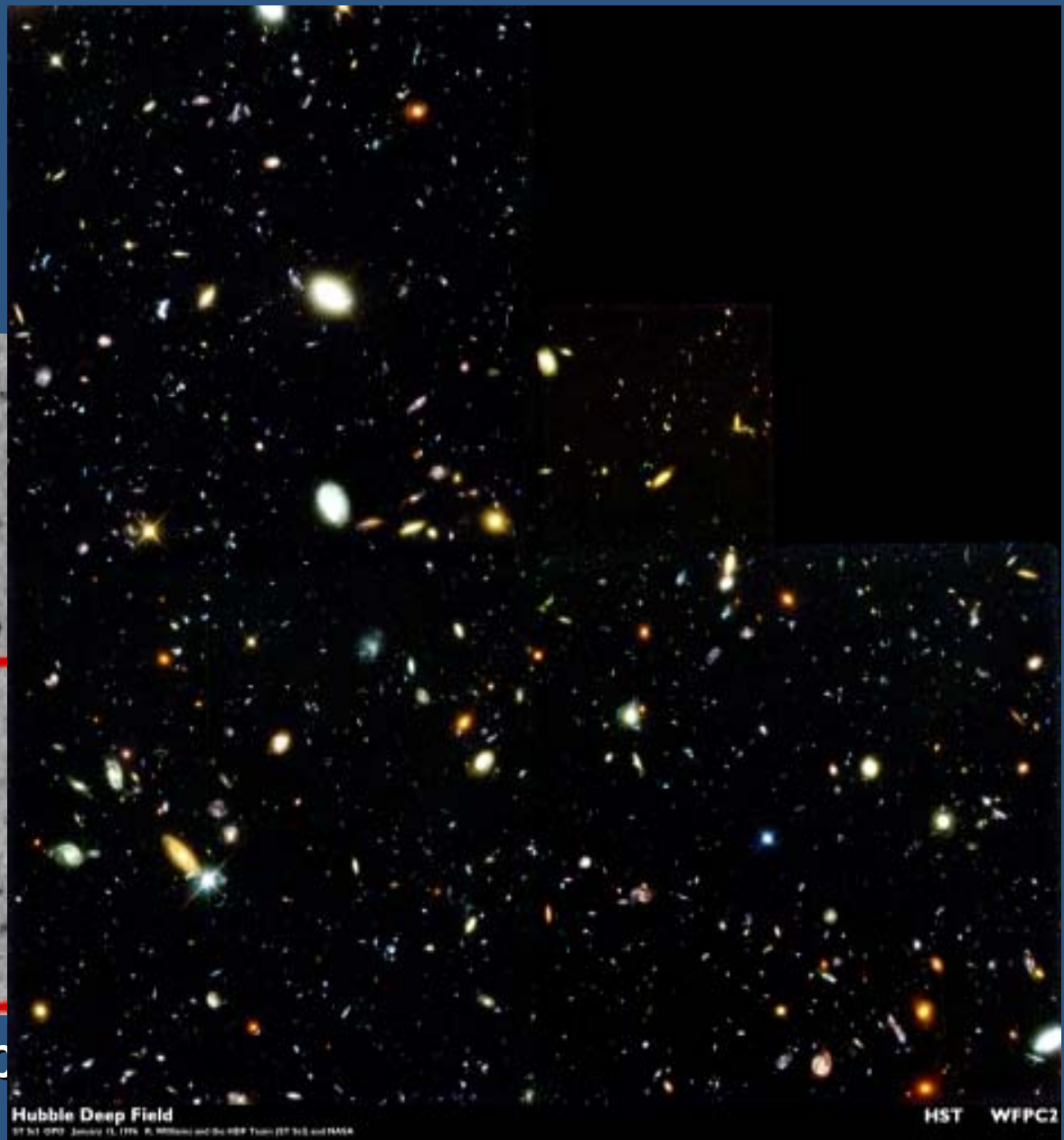
Looking into the past



Ground-based telescope
+ CCD :

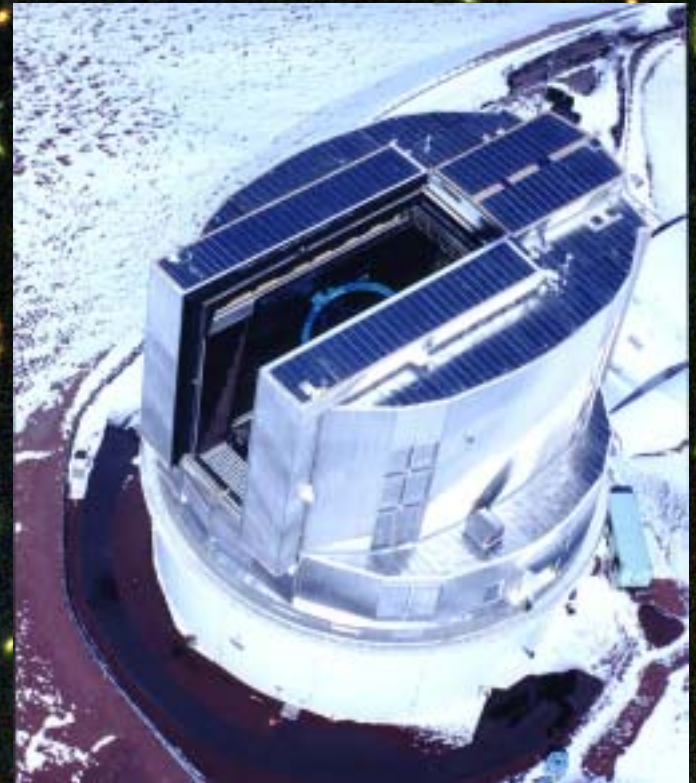
100 × photo plates

Weighing the universe



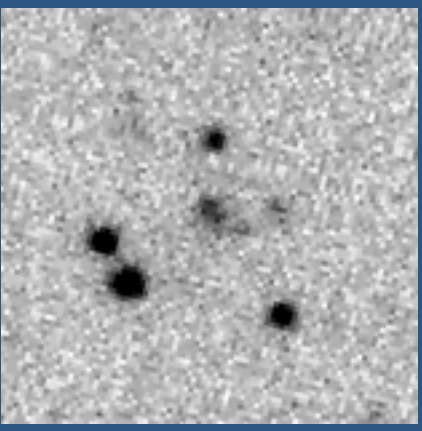
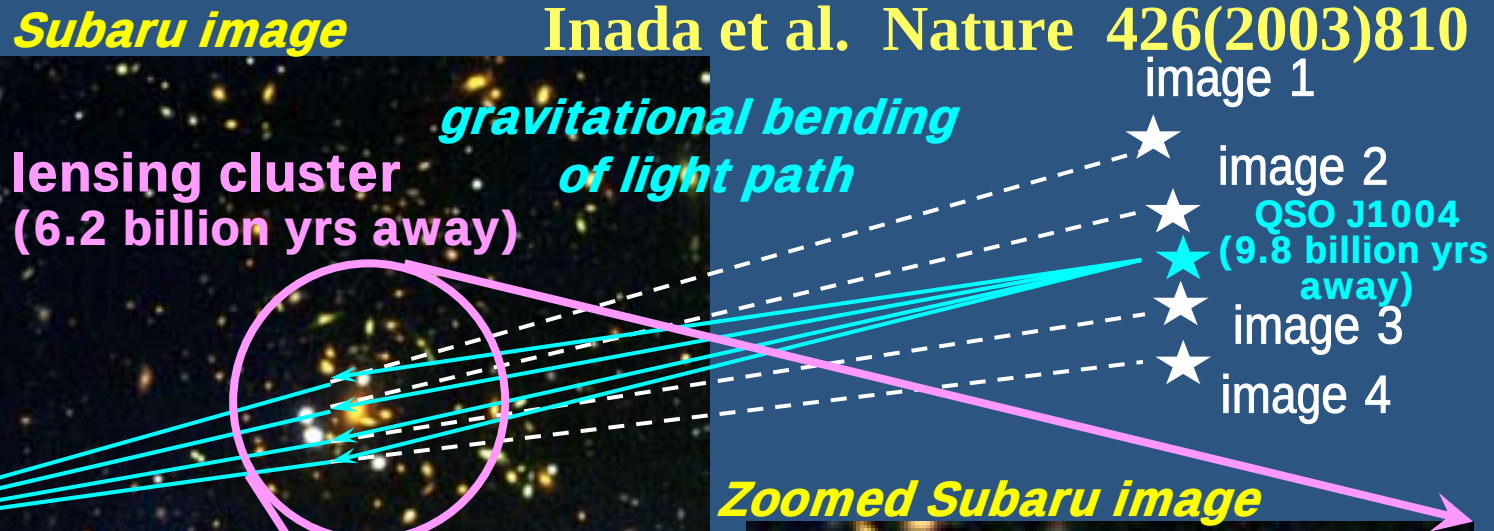
Hubble space telescope :
1000 × ground-based telescope

Distant universe observed by Subaru telescope



<http://www.naoj.org/Gallery/>

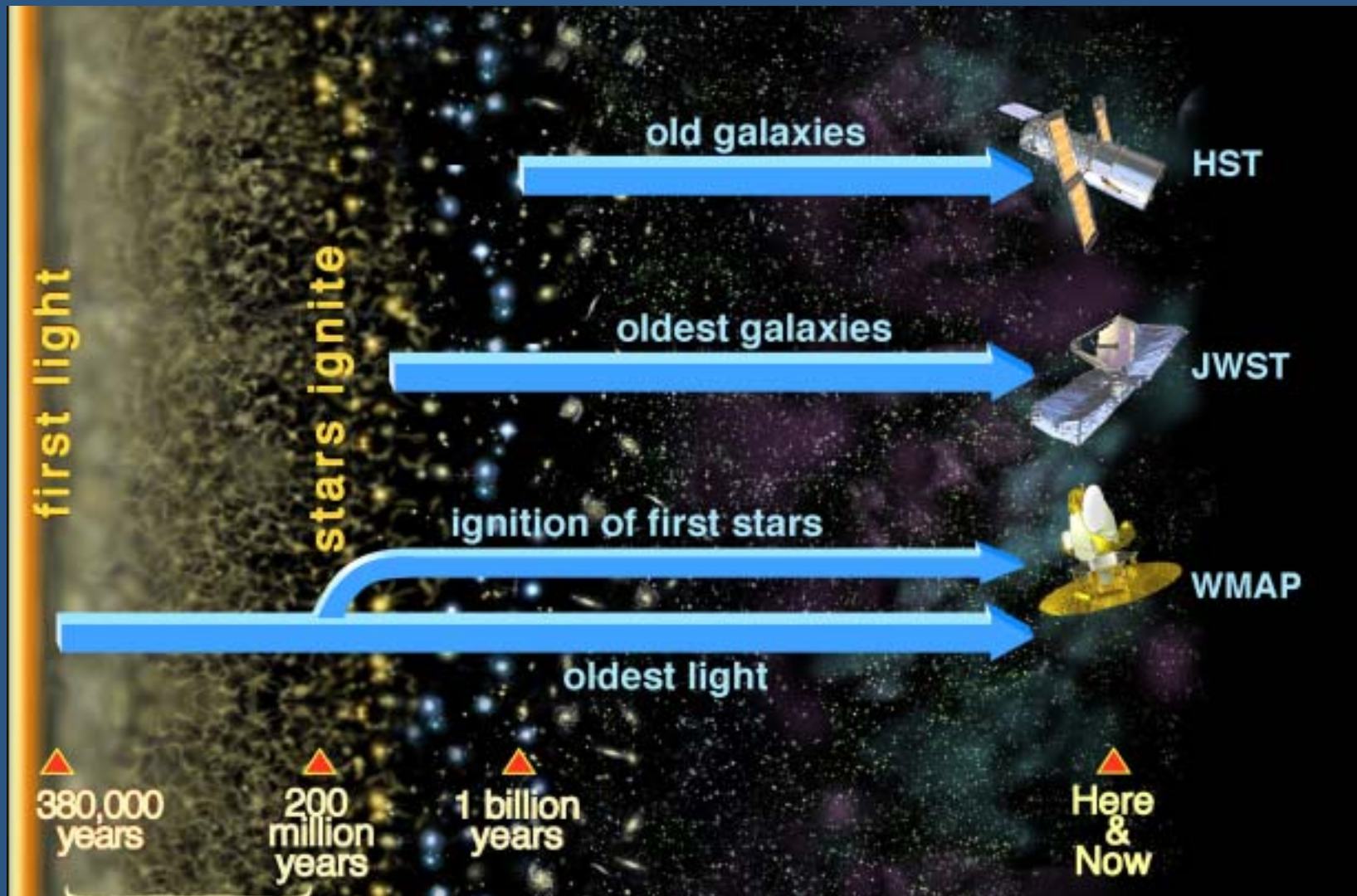
Widest-separation gravitationally lensed quasar images



Weighing the universe

General relativistic mirage from the universe 10Gyrs ago

Exploring the edge of the universe

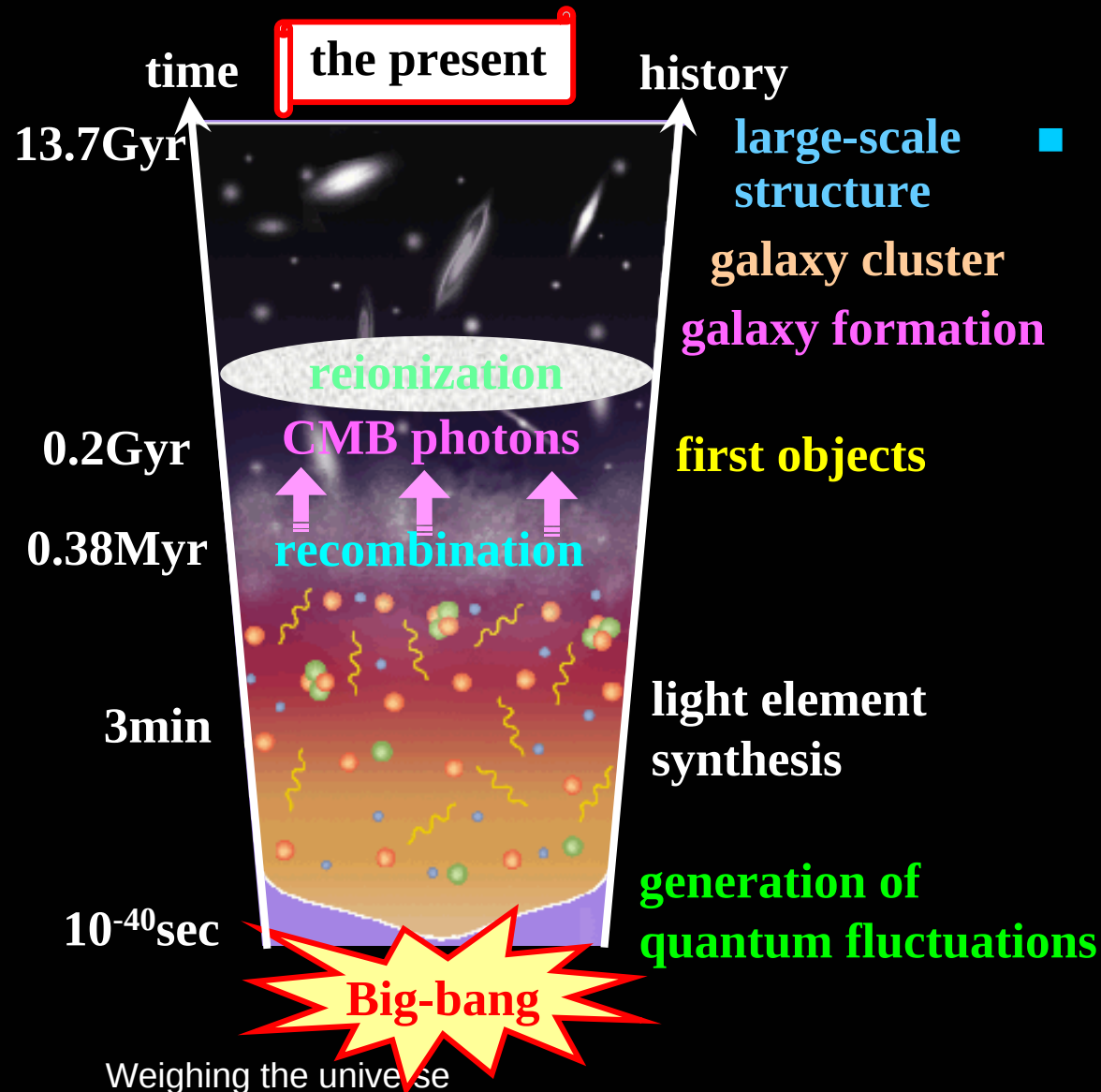


<http://lambda.gsfc.nasa.gov>

NASA/WMAP
Science Team

CMB: Cosmic Microwave Background

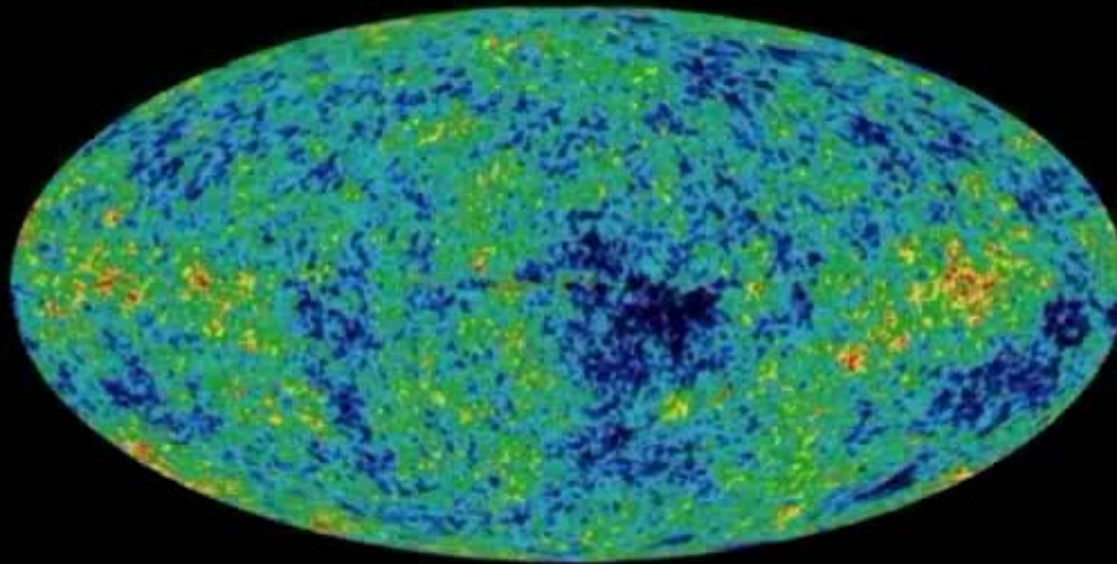
relic thermal photons from the ancient universe



■ **Recombination of protons and electrons = decoupling of baryons and photons**

- T=3000K
- t=380,000 years
- universe became neutral and thus transparent to photons

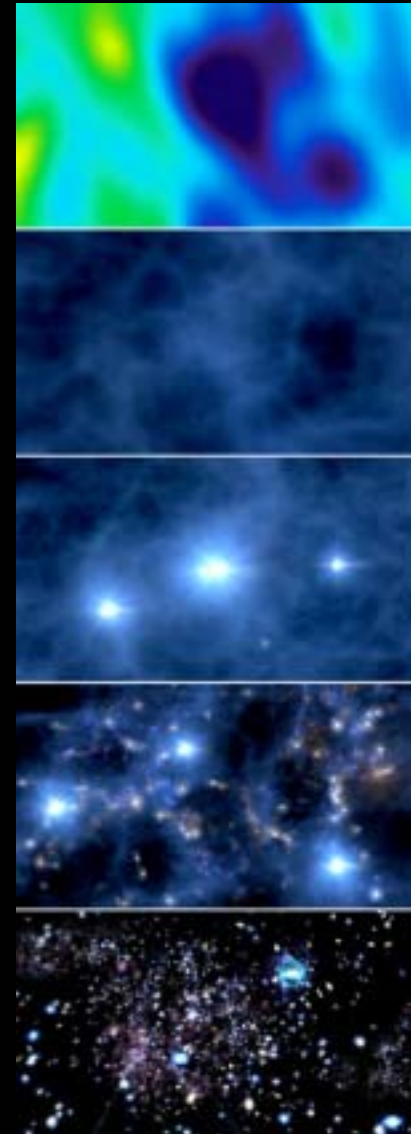
From the infant universe to the present



NASA/WMAP Science Team

<http://lambda.gsfc.nasa.gov>

Weighing the universe



WMAP: Wilkinson Microwave Anisotropy Probe

<http://lambda.gsfc.nasa.gov>

launch on June 30, 2001
15:46:46 EST



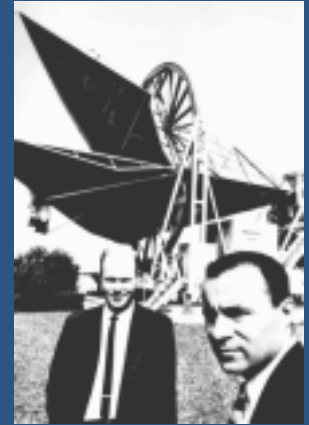
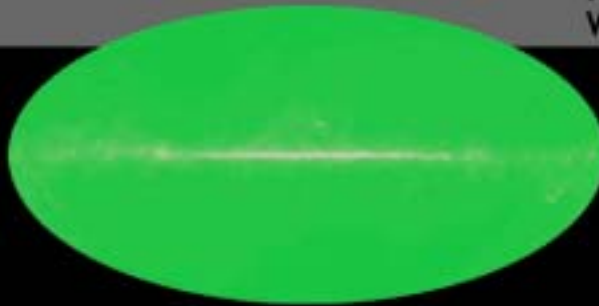
**NASA/WMAP
Science team**

Progress in mapping the CMB sky

1965



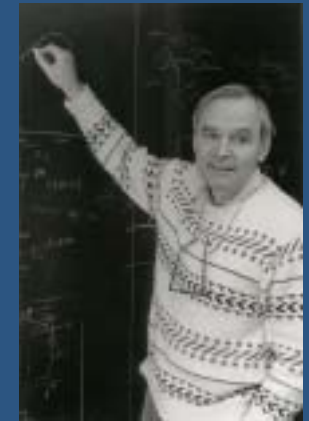
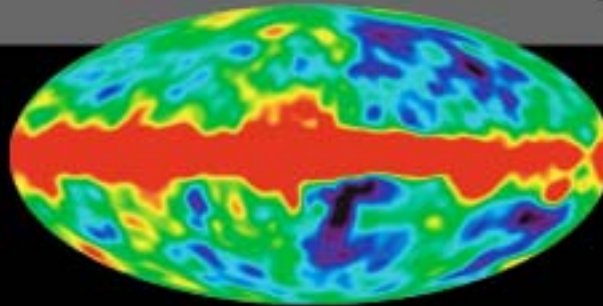
Penzias and
Wilson



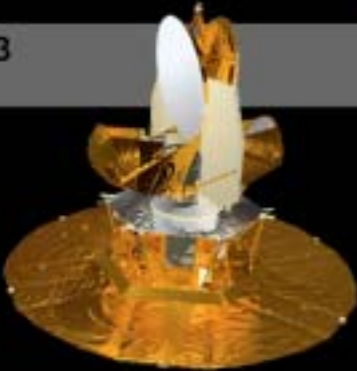
1992



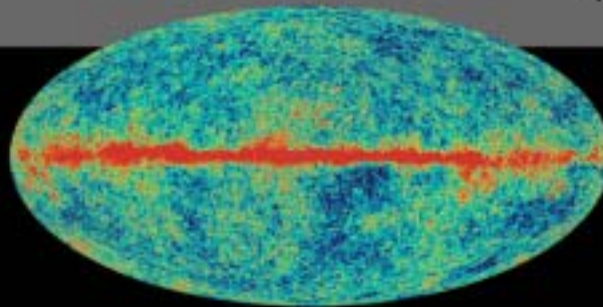
COBE



2003



WMAP

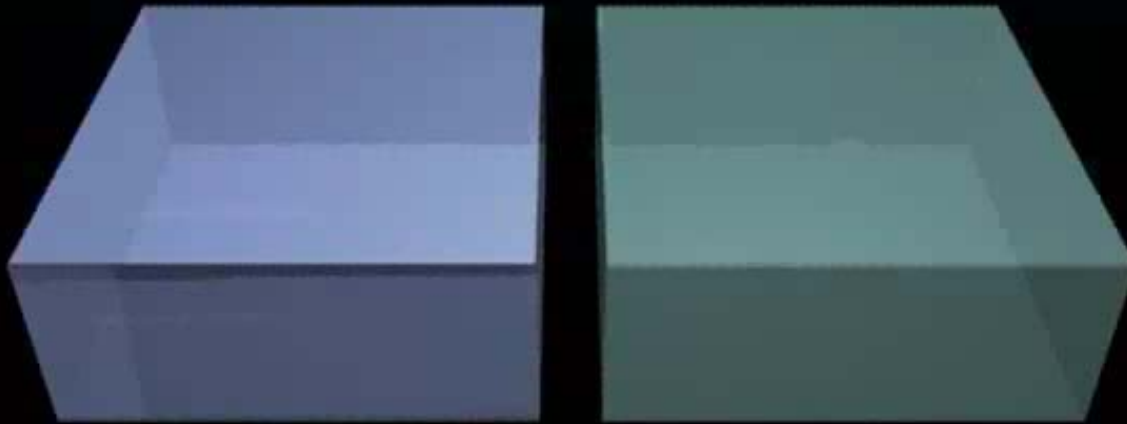


Sound waves in the CMB sky

seed fluctuations

acoustic oscillations

CMB anisotropy pattern



Geometry of the universe from the CMB sky

curvature changes the characteristic angular scale
of the CMB anisotropy pattern



Deciphering the ancient map

- ancient document in cipher

- CMB all-sky map

- a cipher key

- spherical harmonics

$$\frac{\delta T}{T}(\theta, \varphi) = \sum_{l,m} a_{lm} Y_{lm}(\theta, \varphi)$$

- deciphered data

- temperature spectrum

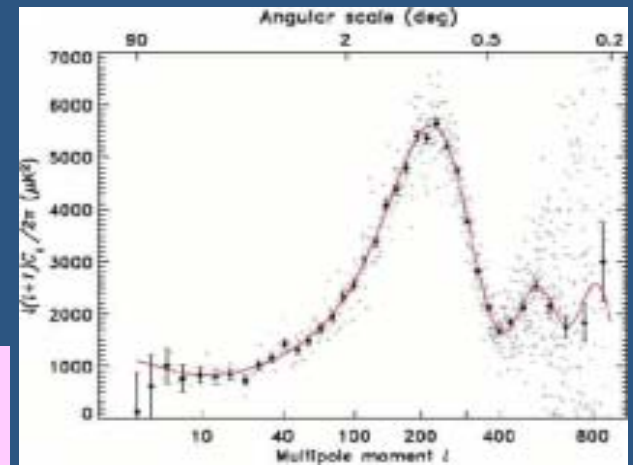
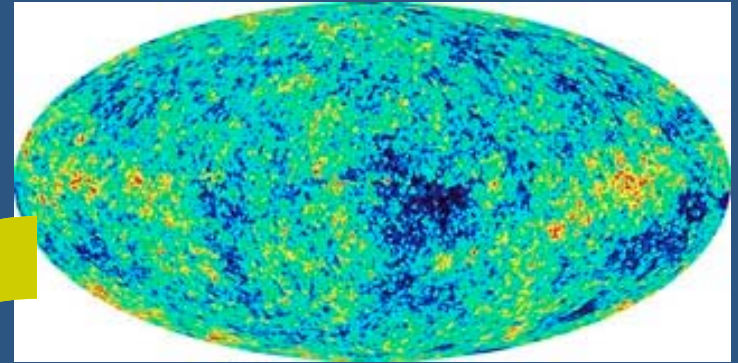
$$C_l = \langle a_{lm} a_{lm}^* \rangle$$

- grammar to understand the universe

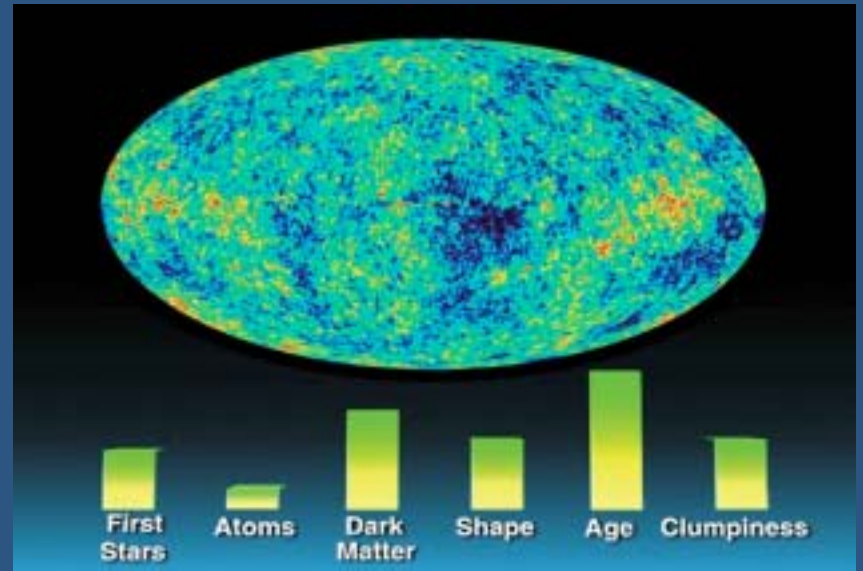
- cold dark matter model

- imprinted information

- age, geometry, and composition of the universe



What WMAP told us ?



- age of the universe: 13.7 Gyr
- universe is spatially flat
- universe reionized at 0.2Gyr after Big-bang
- cosmic matter is dominated by **dark matter**
- cosmic energy is dominated by **dark energy**

Results: weighing the universe



baryons

■ ordinary matter makes up merely 4 percent of the entire mass of the universe

dark matter

■ galaxies and clusters are surrounded by invisible mass an order-of-magnitude more massive than their visible part

■ unknown elementary particles?

dark energy

- universe is dominated by even more exotic component !
- homogeneously fills the universe (unclustered)
- repulsive force (negative pressure; equation of state: $P = -\rho$)
- Einstein's cosmological constant ?

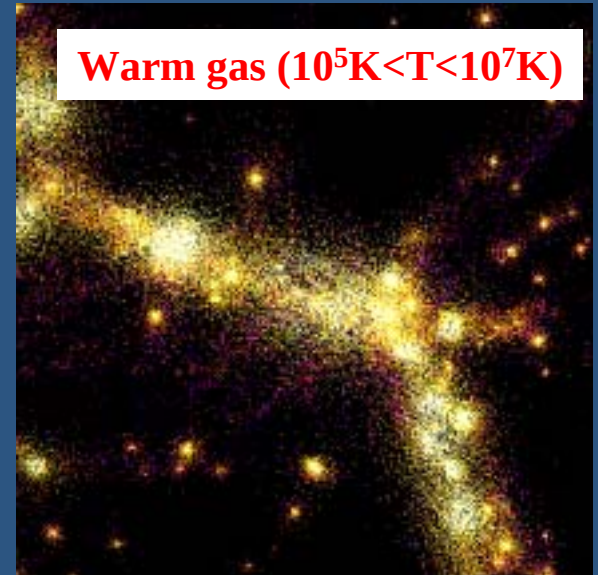
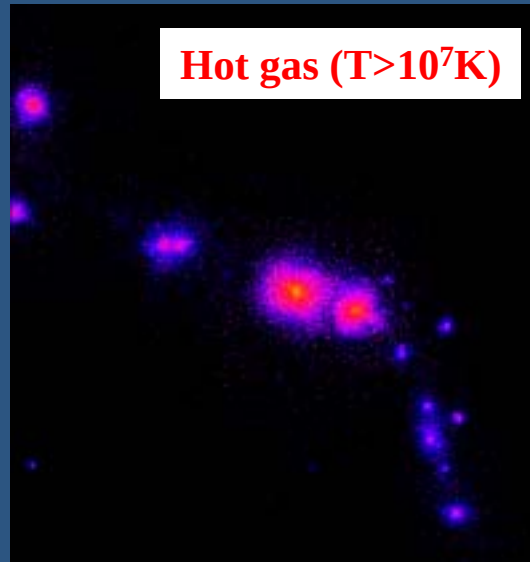
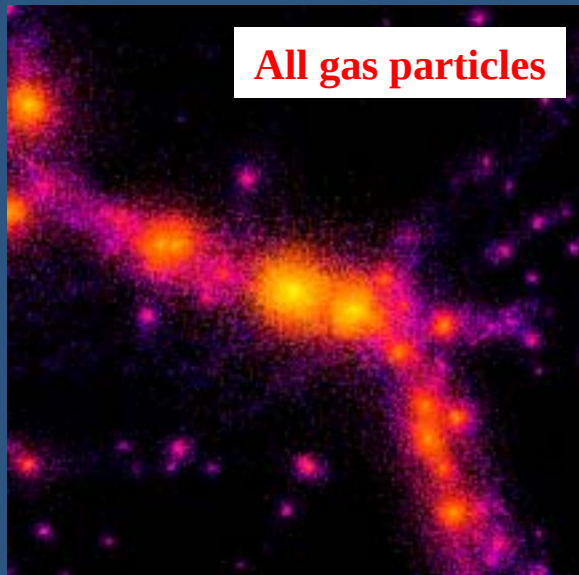
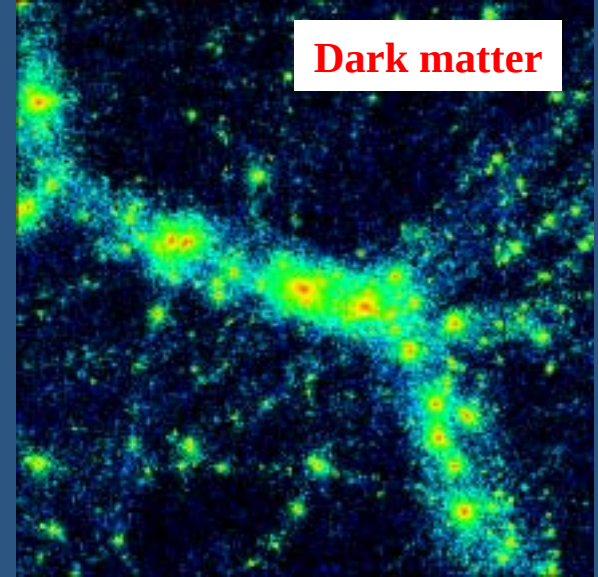
More intriguingly, most of the cosmic baryon is also “dark”



Component	Central	Maximum	Minimum	Grade ^a
Cosmic Baryon Budget: Fukugita, Hogan & Peebles: ApJ 503 (1998) 518				
1. Stars in spheroids	0.0026 h_{70}^{-1}	0.0043 h_{70}^{-1}	0.0014 h_{70}^{-1}	A
2. Stars in disks	0.00086 h_{70}^{-1}	0.00129 h_{70}^{-1}	0.00051 h_{70}^{-1}	A—
3. Stars in irregulars	0.000069 h_{70}^{-1}	0.000116 h_{70}^{-1}	0.000033 h_{70}^{-1}	B
4. Neutral atomic gas	0.00033 h_{70}^{-1}	0.00041 h_{70}^{-1}	0.00025 h_{70}^{-1}	A
5. Molecular gas	0.00030 h_{70}^{-1}	0.00037 h_{70}^{-1}	0.00023 h_{70}^{-1}	A—
6. Plasma in clusters	0.0026 $h_{70}^{-1.5}$	0.0044 $h_{70}^{-1.5}$	0.0014 $h_{70}^{-1.5}$	A
7a. Warm plasma in groups	0.0056 $h_{70}^{-1.5}$	0.0115 $h_{70}^{-1.5}$	0.0029 $h_{70}^{-1.5}$	B
7b. Cool plasma	0.002 h_{70}^{-1}	0.003 h_{70}^{-1}	0.0007 h_{70}^{-1}	C
7'. Plasma in groups	0.014 h_{70}^{-1}	0.030 h_{70}^{-1}	0.0072 h_{70}^{-1}	B
8. Sum (at $h = 70$ and $z \simeq 0$)	0.021	0.041	0.007	...

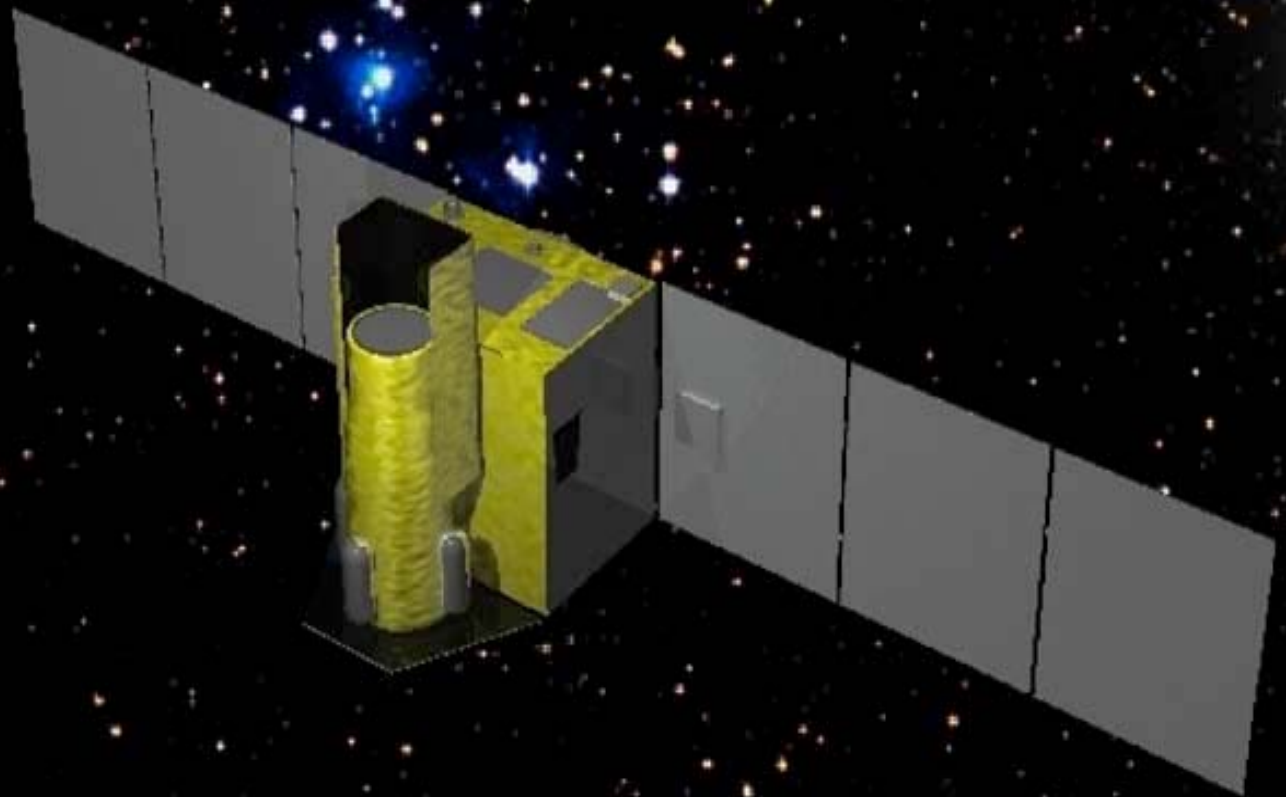
hydrodynamical simulation with gas

A $(30h^{-1}\text{Mpc})^3$ box
around a massive
cluster at $z=0$
 Λ CDM SPH
simulation
(Yoshikawa et al. 2001)



Searching for cosmic dark baryons with DIOS

(Diffuse Intergalactic Oxygen Surveyor)



DIOS: Diffuse Intergalactic Oxygen Surveyor

A Japanese proposal of a dedicated X-ray mission to search for dark baryons

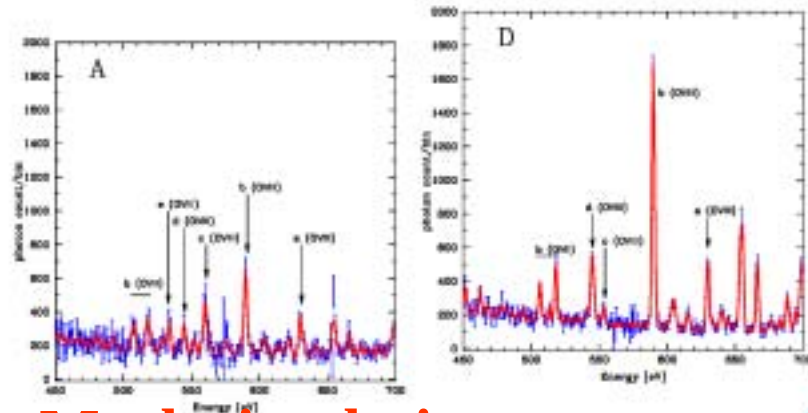


- **PI: Takaya Ohashi** (Tokyo Metropolitan Univ.)
 - + Univ. of Tokyo, JAXA/ISAS, Nagoya Univ., Tokyo Metro. Univ.
- A dedicated small satellite with cost < 40M USD.
- Proposed launch in **2008 (not yet approved)**.
- Unprecedented energy spectral resolution:
 $\Delta E = 2\text{eV}$ in soft X-ray band (0.1-1keV)
- Aim at detection of ~ 30 percent of the total cosmic baryons via **Oxygen emission lines**.

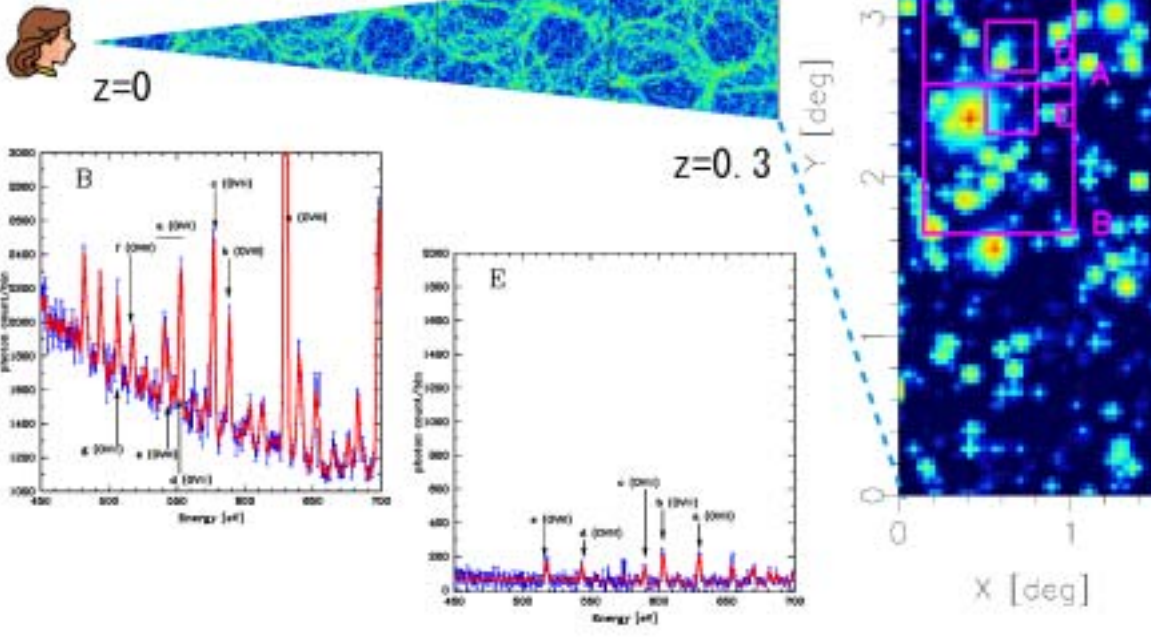
Searching for dark baryons with DIOS (Diffuse Intergalactic Oxygen Surveyor)



PASJ 55 (2003) 879
astro-ph/0303281, 0402389



Mock simulations



Univ of Tokyo:
K. Yoshikawa

Y. Suto

JAXA/ISAS:

N. Yamasaki

K. Mitsuda

Tokyo Metropolitan Univ.:

T. Ohashi

Nagoya Univ.:

Y. Tawara

A. Furuzawa

Conclusion: 99 % of the universe is DARK

- Quite frustrating...
We have not yet understood 99 % of the universe at all !



- cosmological observations in the 20th century have identified previously unknown hierarchy of matter beyond the standard model of particle physics
 - Provides an ultimate goal of science in the 21st century
 - cosmology promises to bridge particle-matter hierarchy
- keep funding Tohoku University's COE program