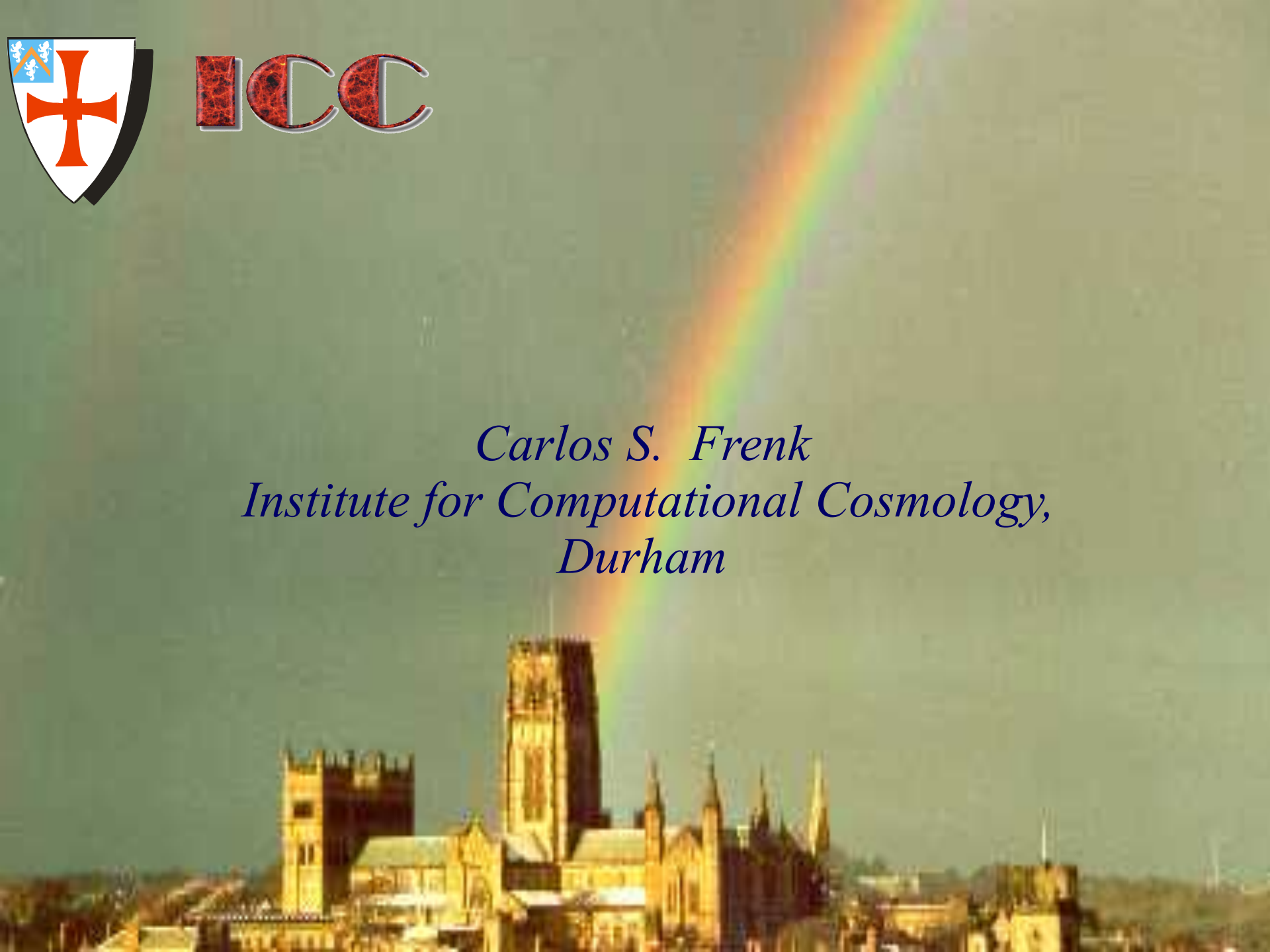
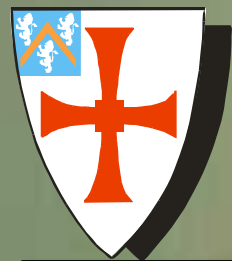




*Carlos S. Frenk*  
*Institute for Computational Cosmology,*  
*Durham*



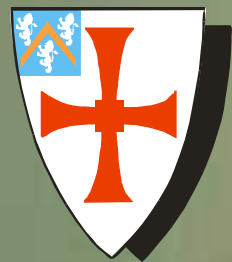


# Cosmic architecture: research at the Ogden Center for Fundamental Physics

*Carlos S. Frenk*  
*Institute for Computational Cosmology,*  
*Durham*



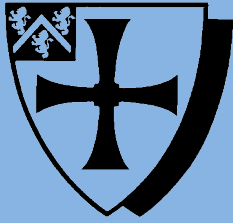




... and the key role of philanthropy

*Carlos S. Frenk*  
*Institute for Computational Cosmology,*  
*Durham*

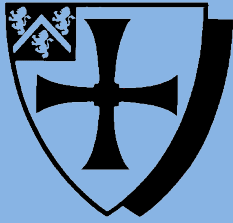




# Ogden Centre for Fundamental Physics

Opened in Oct/2002 by the  
Prime Minister, Tony Blair





# Ogden Centre for Fundamental Physics

The first two University  
Research Institutes

- Institute for Computational Cosmology
- Institute for Particle Physics Phenomenology





University of Durham

# The Ogden Centre for Fundamental Physics

## Fundamental properties of our Universe

The very small

IPPP

Institute for Particle Physics  
Phenomenology

Building blocks of matter  
Fundamental forces  
Unified theories  
Dark matter

The very large

ICC/CEA/CfAI

Institute for Computational Cosmology  
Centre for Extragalactic Astronomy  
Centre for Advanced Instrumentation

Cosmic structure  
Galaxy formation  
Dark matter  
Dark energy

Institute for Computational Cosmology





University of Durham

# The Ogden Centre for Fundamental Physics (2 buildings)





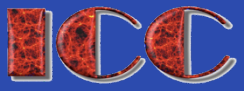


# A new building for the Ogden Centre for Fundamental Physics



Opened by the Astronomer Royal, Lord Rees of Ludlow on the  
10<sup>th</sup> of March, 2017





University of Durham

# A new building for the Ogden Centre for Fundamental Physics



Designed by Daniel Libeskind

Institute for Computational Cosmology





University of Durham

# The Ogden Centre for Fundamental Physics (2 buildings)





# The building blocks of the Universe



Galaxies are collections of up to a hundred billion stars

## THE KEY QUESTIONS OF COSMOLOGY

- How did the Universe begin?
- What is it made of?
- How did it evolve to its present state?
- What does the future hold?



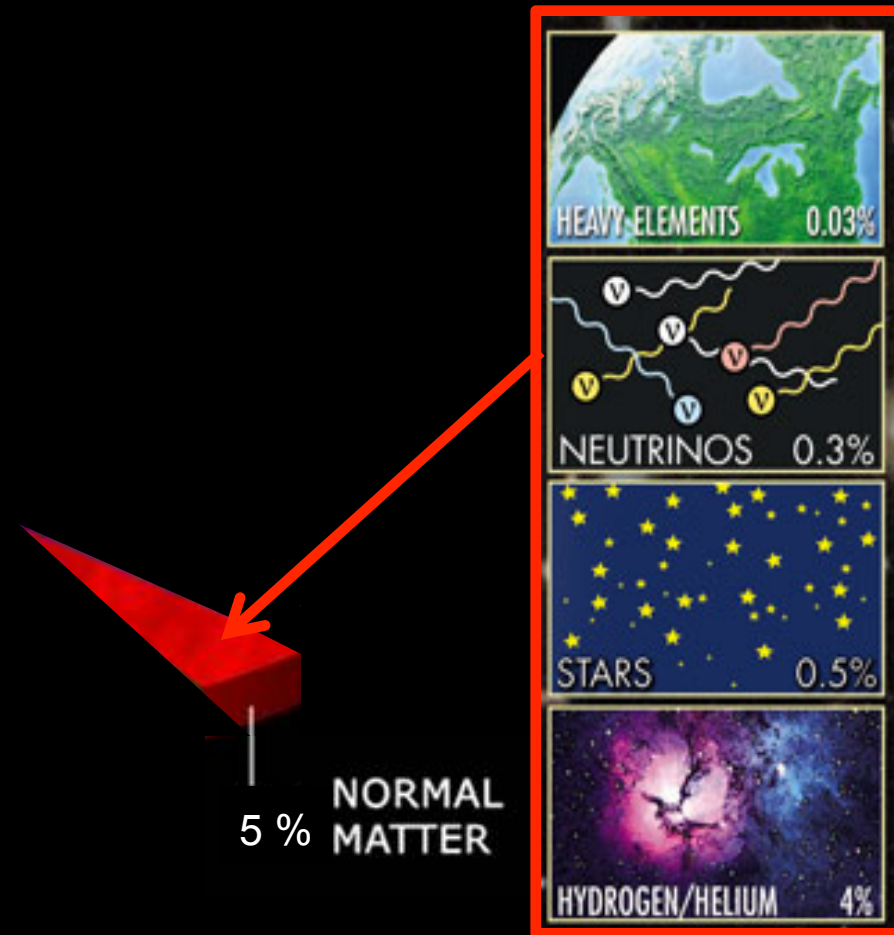


# What is the Universe made of?

The (bizarre) contents of our Universe

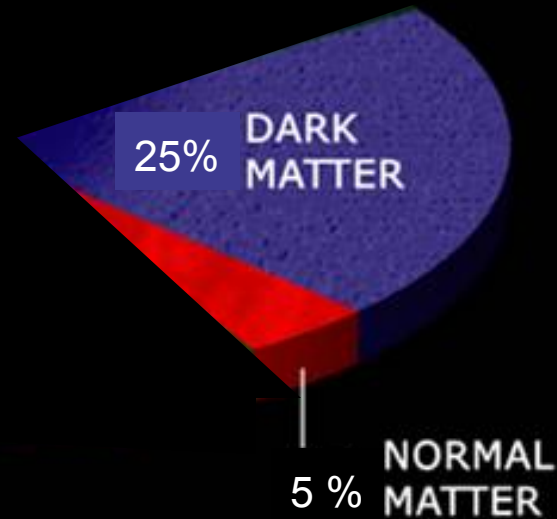


# The content of our universe



Normal matter  $\equiv$  matter made of ordinary atoms

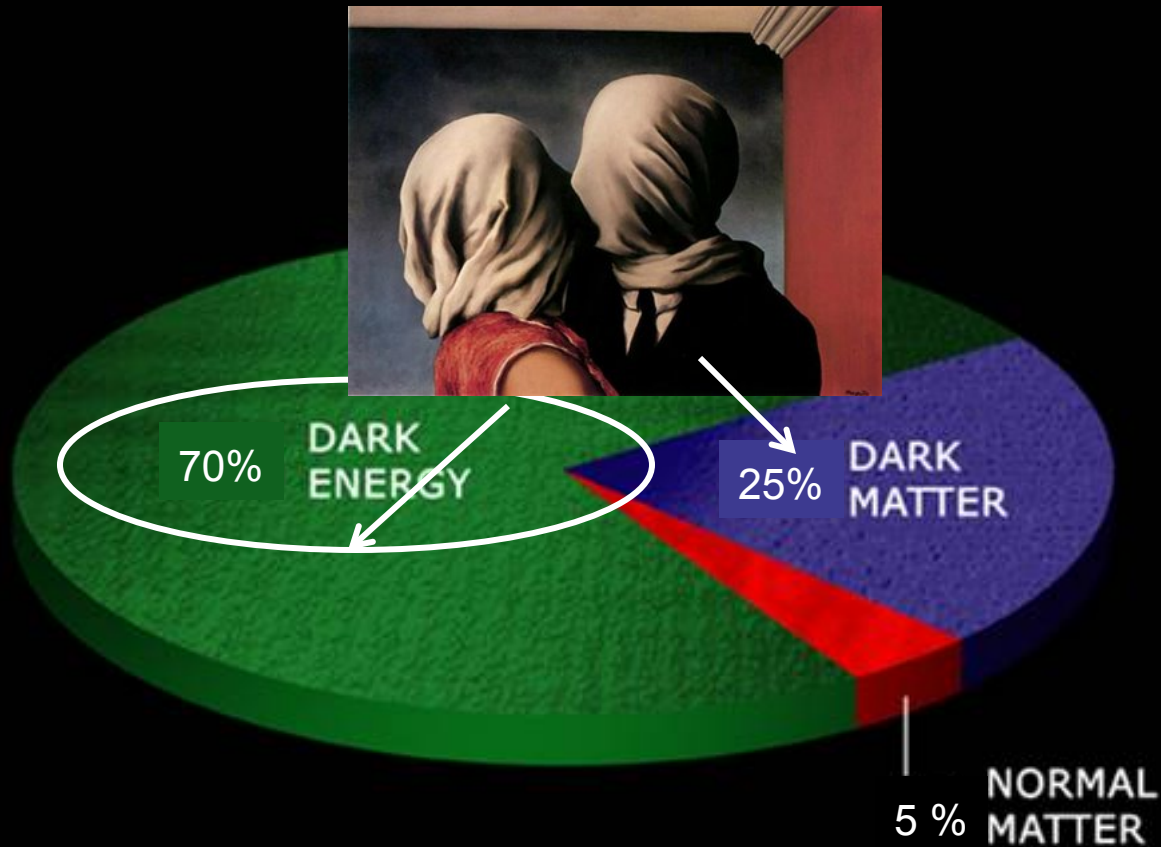
# The content of our universe



Dark matter  $\equiv$  matter that does not emit light at any wavelength



# The content of our universe



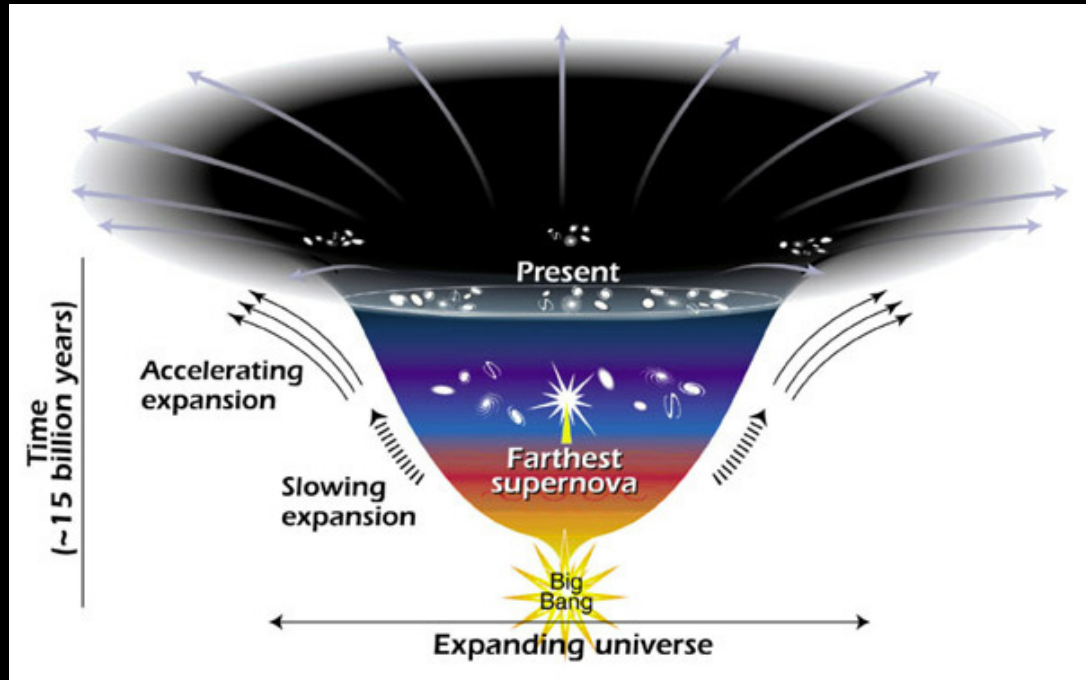
Dark energy  $\equiv$  mysterious form of energy which opposes gravity



# We know dark energy exists because

The expansion of the Universe is accelerating

2011 Nobel  
prize in  
physics!



➔ Universe full of dark energy



# We know dark matter exists because

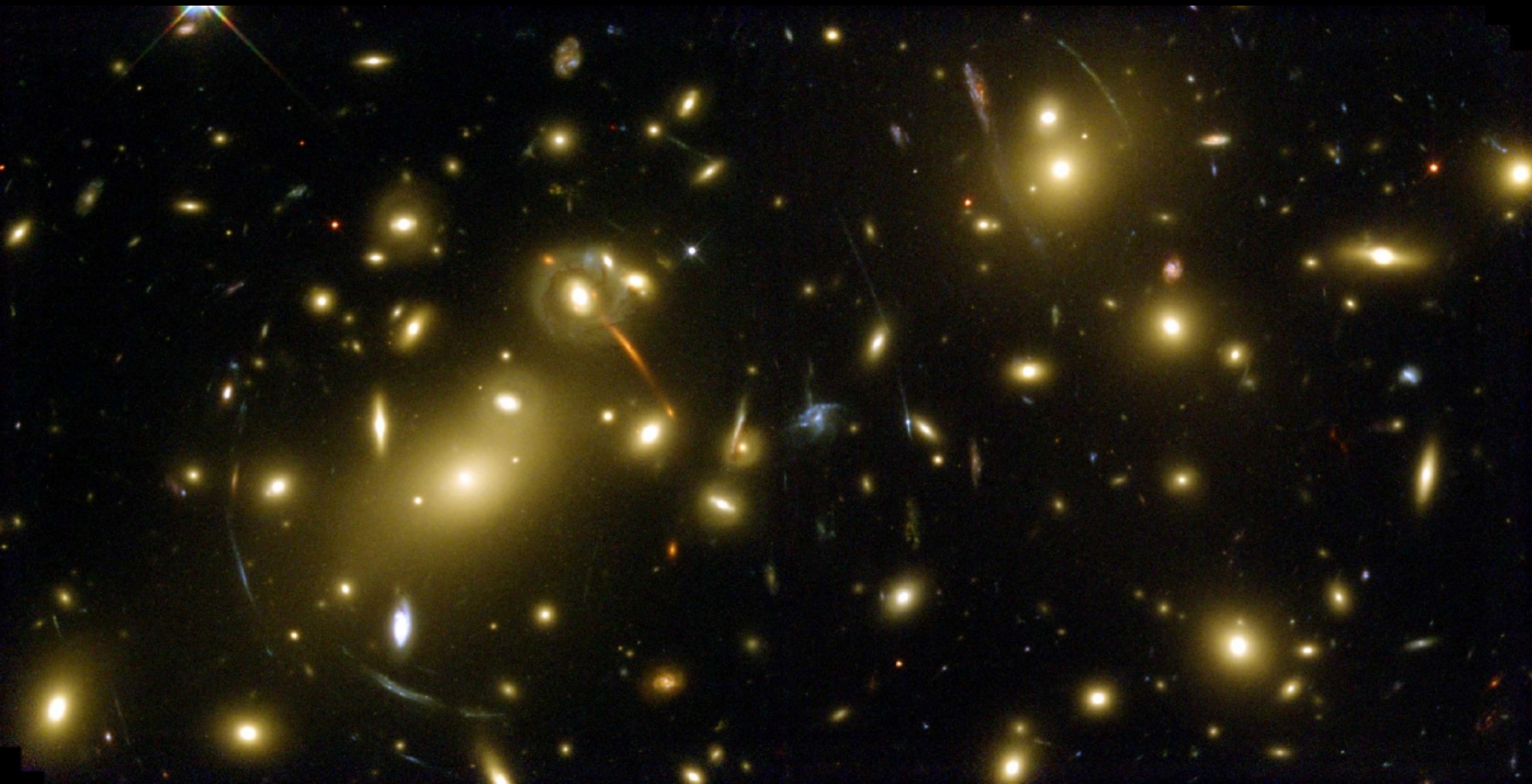
- Stars in galaxies rotate too fast to be kept in place by gravity of the matter we can see
- Galaxy images are distorted by dark matter

# Clumps of dark matter: dark halos



→ dark matter keeps galaxy in place

# Gravitational lensing: Hubble space telescope



Light from distant galaxies is deflected by dark matter in cluster, distorting the galaxies' images into arcs





# Gravitational lensing: Hubble space telescope



Light from distant galaxies is deflected by dark matter in cluster, distorting the galaxies' images into arcs



## THE KEY QUESTIONS OF COSMOLOGY

- How did the Universe begin?
- What is it made of?
- How did it evolve to its present state?
- What does the future hold?

# Landmark moments in the early Universe







# The heat from the Big Bang



By today, the radiation from the Big Bang has cooled to 2.7 degrees

# The echo of the Big Bang

In 1964, Arno Penzias & Bob Wilson were carrying out experiments using a microwave antenna for satellite communications.

As they pointed the antenna towards the sky, their receiver registered a faint 'hiss' coming from all directions that would not go away.





# The big Bang



The temperature of this radiation should show small irregularities

Production of dark matter  
( $t \sim 10^{-10}$  s)

Cosmic inflation  
(initial conditions)  
( $t \sim 10^{-35}$  s)

$t = 13.7$  billion yrs

- radiation
- particles
- $W^+$  heavy particles carrying the weak force
- $W^-$
- quark
- anti-quark
- electron
- positron (anti-proton)
- neutron
- meson
- hydrogen
- deuterium
- helium
- lithium

15 thousand million years

300 thousand years

3 minutes

$10^{-43}$  seconds

$10^{32}$  degrees

$10^{27}$  degrees

$10^{15}$  degrees

1 degrees

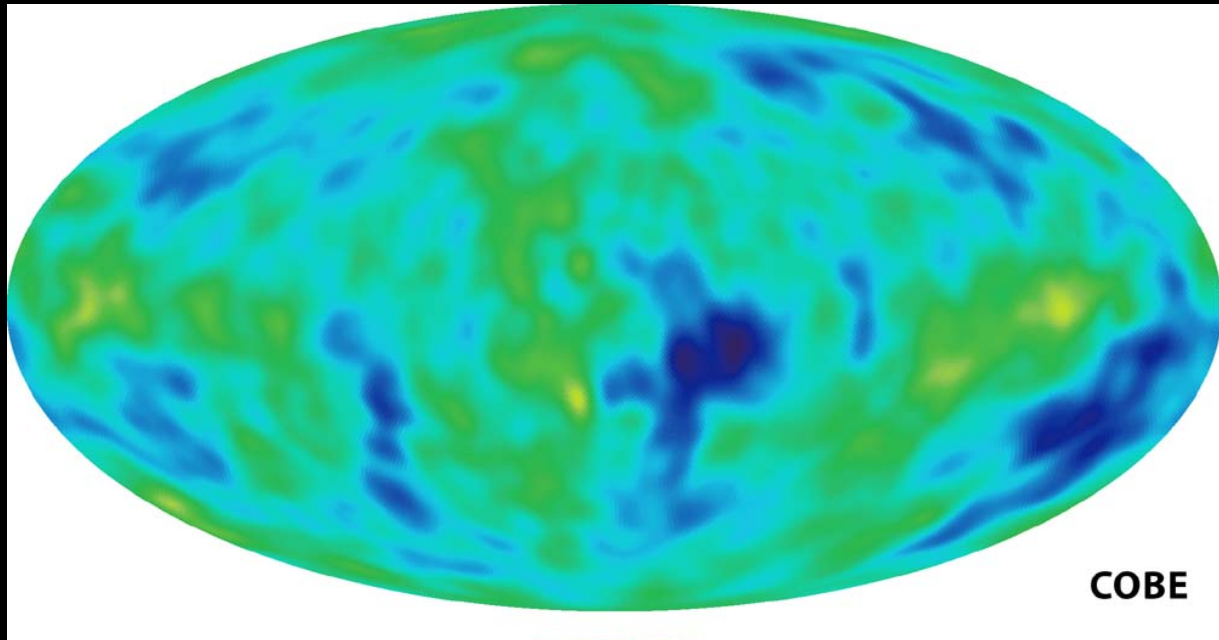
18 degrees

3 degrees K





1992



The cosmic microwave background radiation (CMB) provides a window to the universe at  $t \sim 3 \times 10^5$  yrs

In 1992 COBE discovered temperature fluctuations ( $\Delta T/T \sim 10^{-5}$ ) consistent with inflation predictions



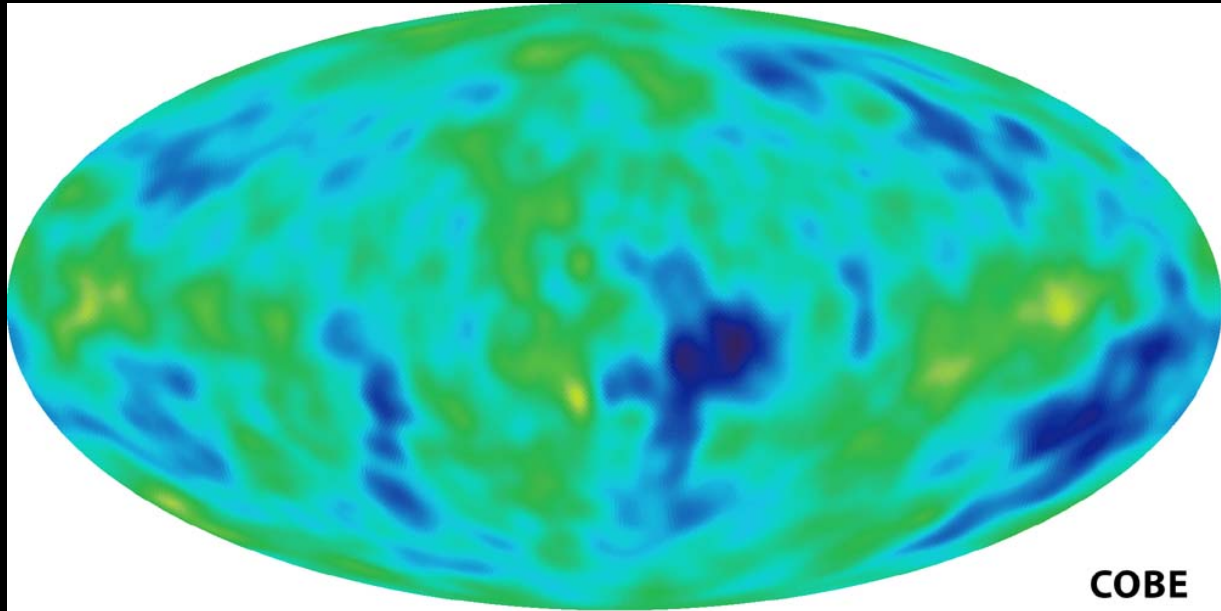
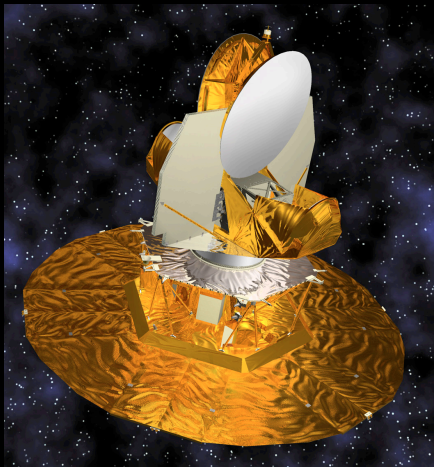


# The CMB

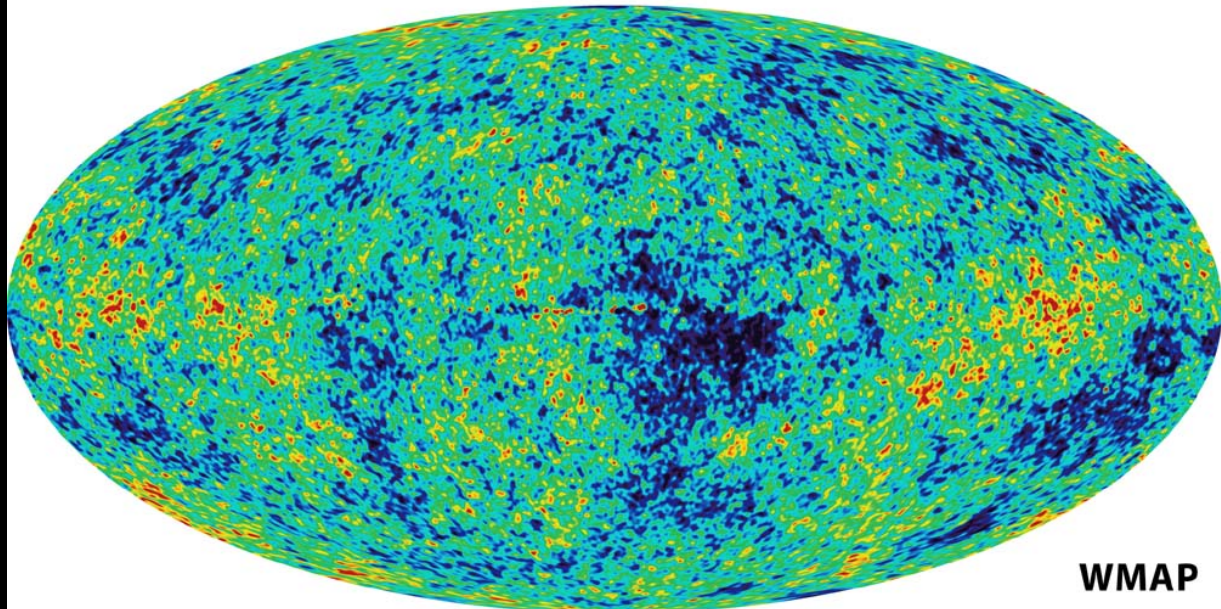
1992



2003



COBE



WMAP



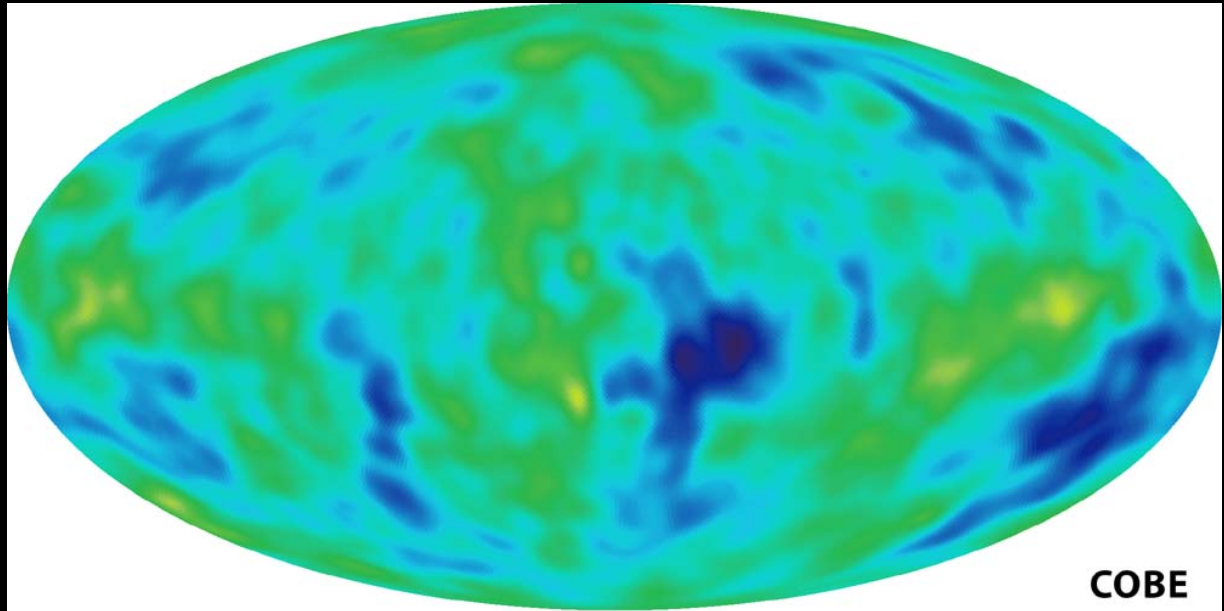
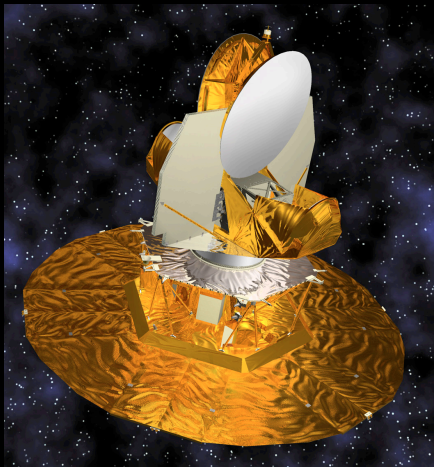


# The CMB

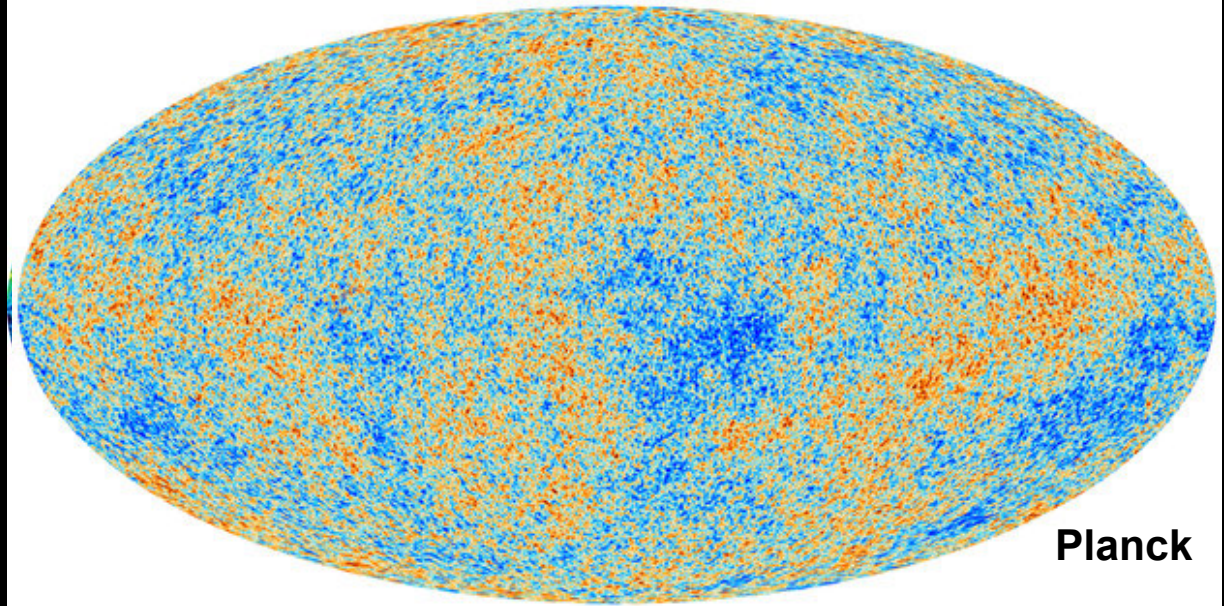
1992



2012

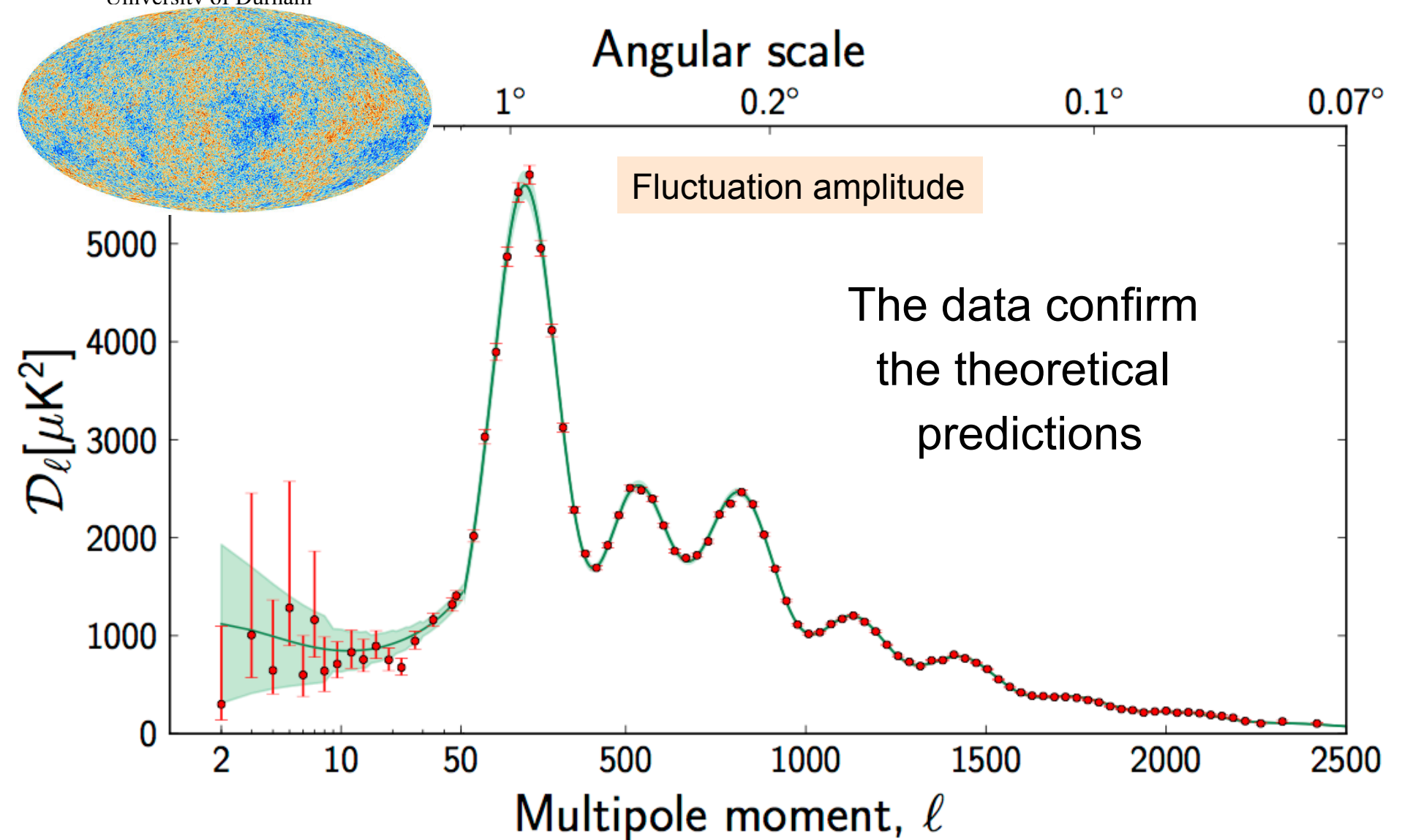


COBE



Planck

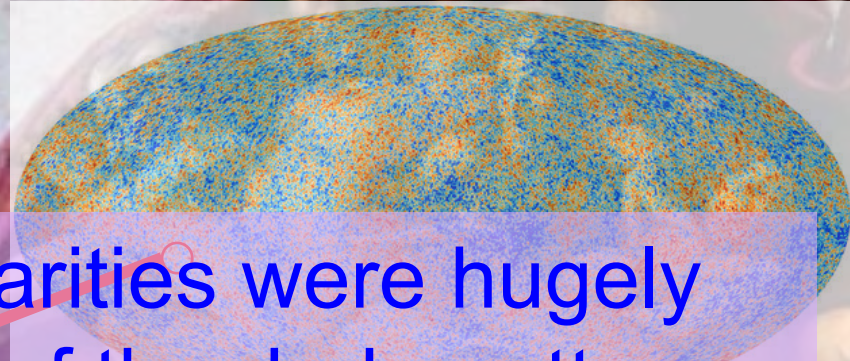
# Planck: CMB temperature anisotropies





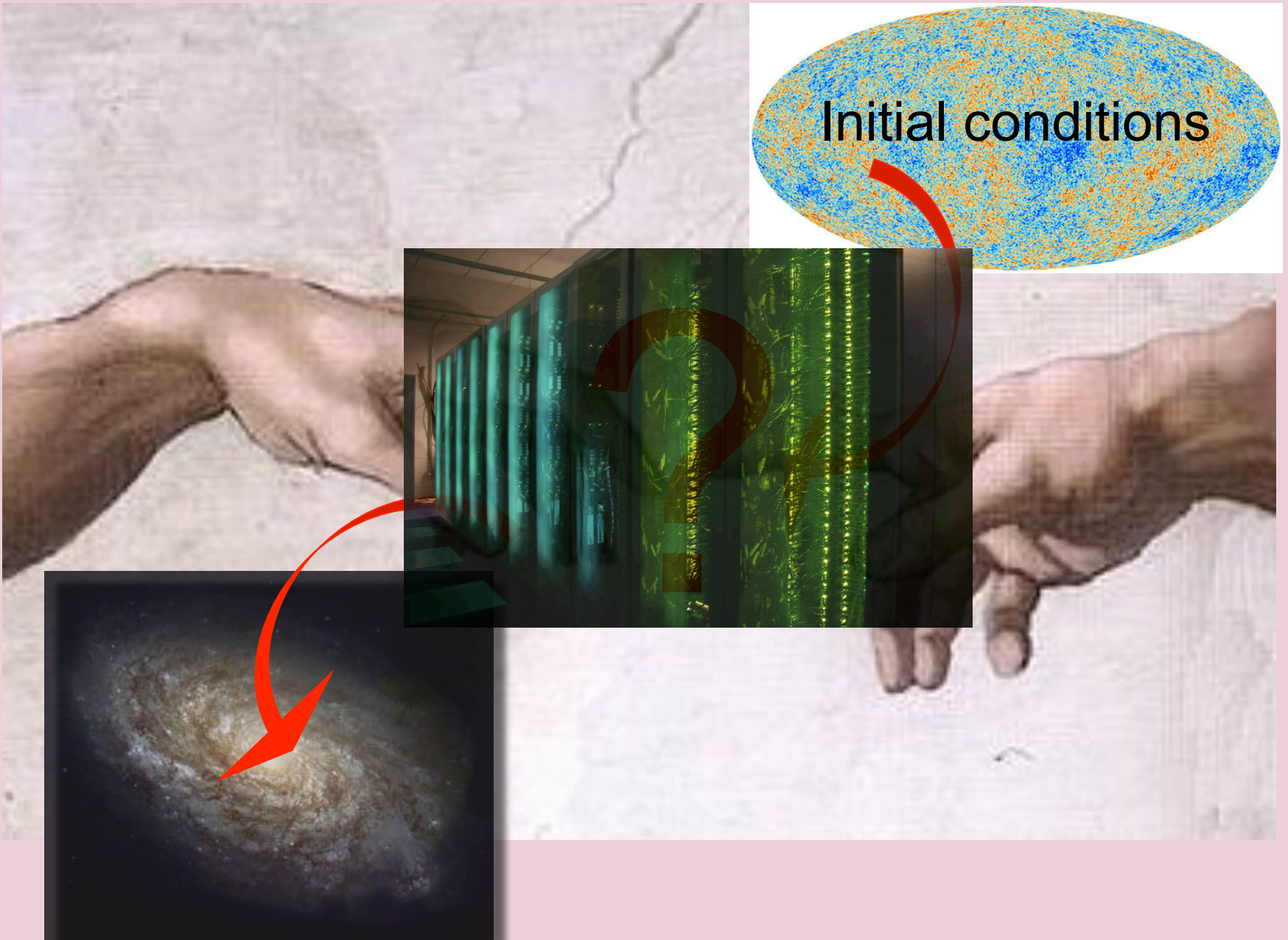
# How did galaxies form?

The tiny quantum irregularities were hugely amplified by the gravity of the dark matter





# The formation of galaxies





# How to make a virtual universe

Initial conditions + assumption about content of Universe

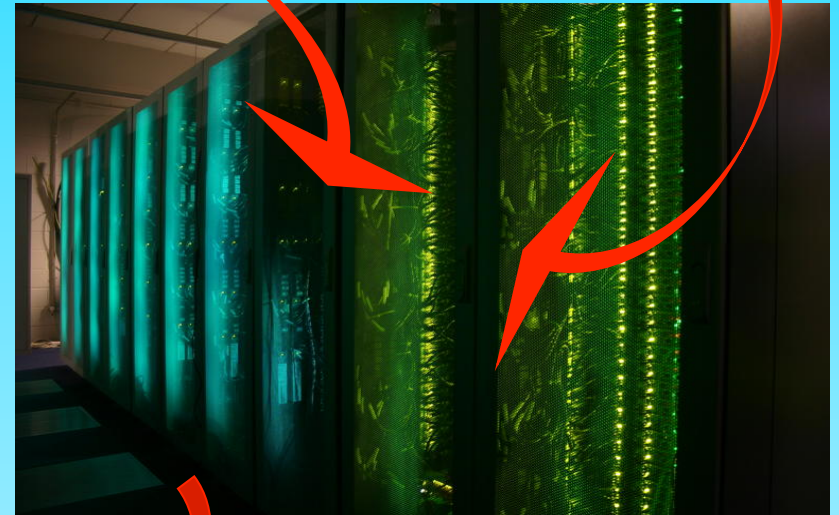
## Equations of physics:

General Relativity

Mechanics

Radiative hydrodynamics

Atomic physics, etc





# The big Bang

Production of dark matter  
( $t \sim 10^{-10}$  s)

Cold dark matter

Cosmic inflation  
(initial conditions)  
( $t \sim 10^{-35}$  s)

- ~ radiation
- o particles
- $W^+$  heavy particles
- $W^-$  carrying the weak force
- $Z$  quark
- $q$  anti-quark
- $e^-$  electron
- $e^+$  positron (anti-electron)
- o proton
- o neutron
- o meson
- H hydrogen
- D deuterium
- He helium
- Li lithium

300 thousand years

3 minutes

1 thousand million years

15 thousand million years

$t = 13.7$  billion yrs

3 degrees K

18 degrees

6000 degrees

$10^9$  degrees

$10^{15}$  degrees

$10^{27}$  degrees

$10^{32}$  degrees

$10^{-43}$  seconds



# The EAGLE simulations

EVOLUTION AND ASSEMBLY OF GALAXIES AND THEIR ENVIRONMENTS

A project of the Virgo consortium

$z = 19.9$

$L = 25.0 \text{ cMpc}$

Visible components:

CDM

# The Eagle Simulations

EVOLUTION AND ASSEMBLY OF GALAXIES AND THEIR ENVIRONMENTS

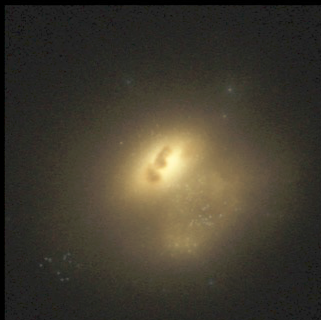
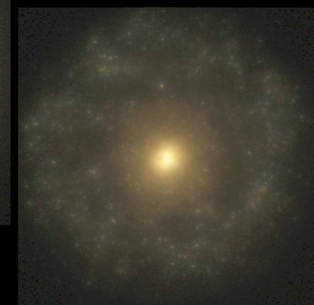
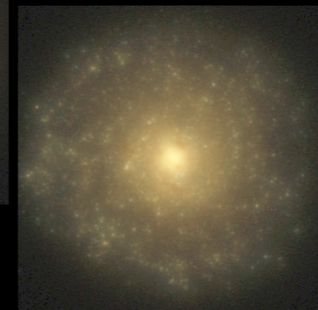
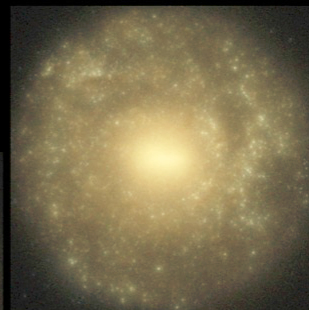
The Hubble Sequence realised in cosmological simulations

E0

E7

S0

SB



Irr

S

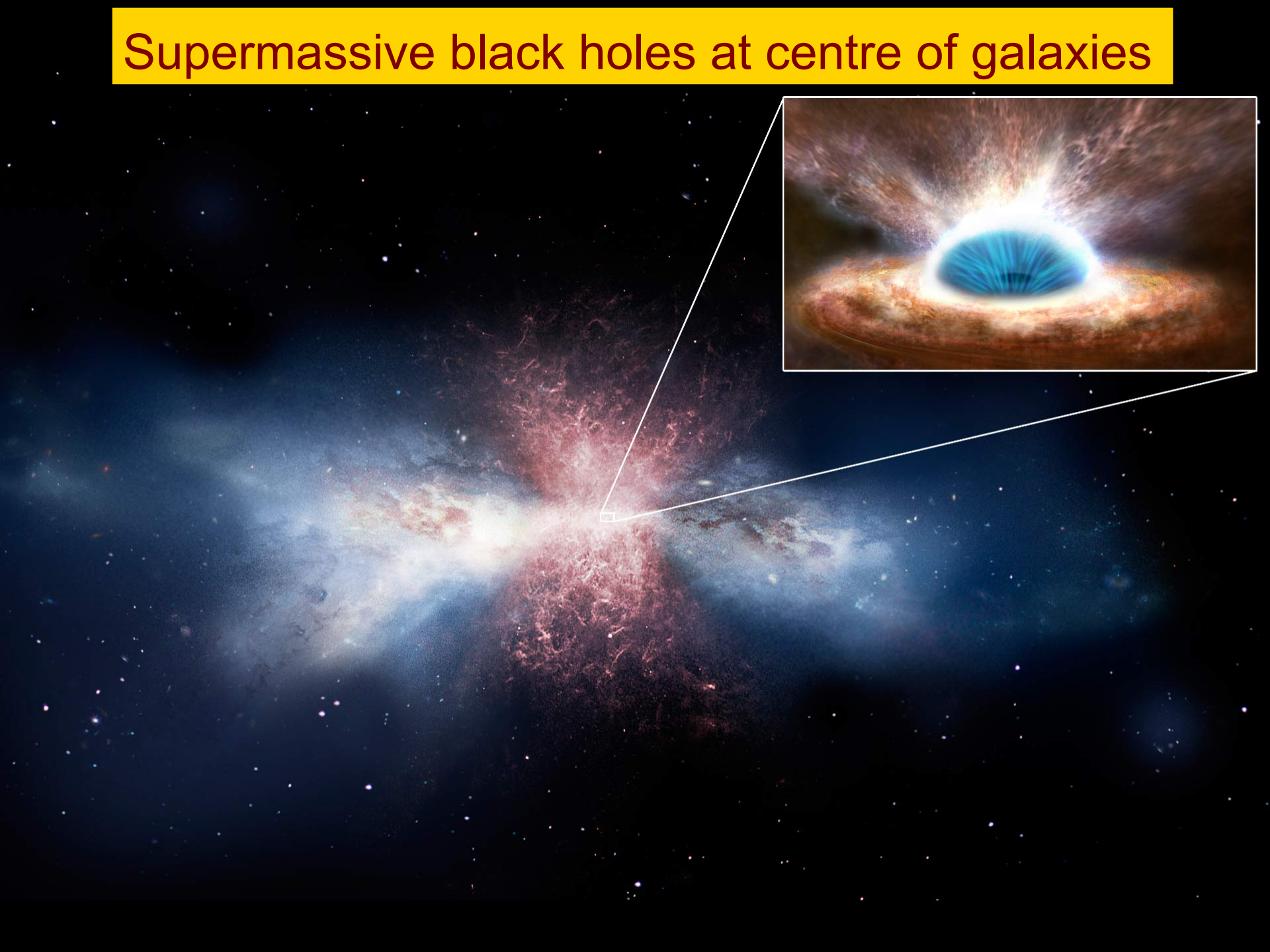
Trayford et al '15



# Observing galaxies forming (the Hubble Deep Field)

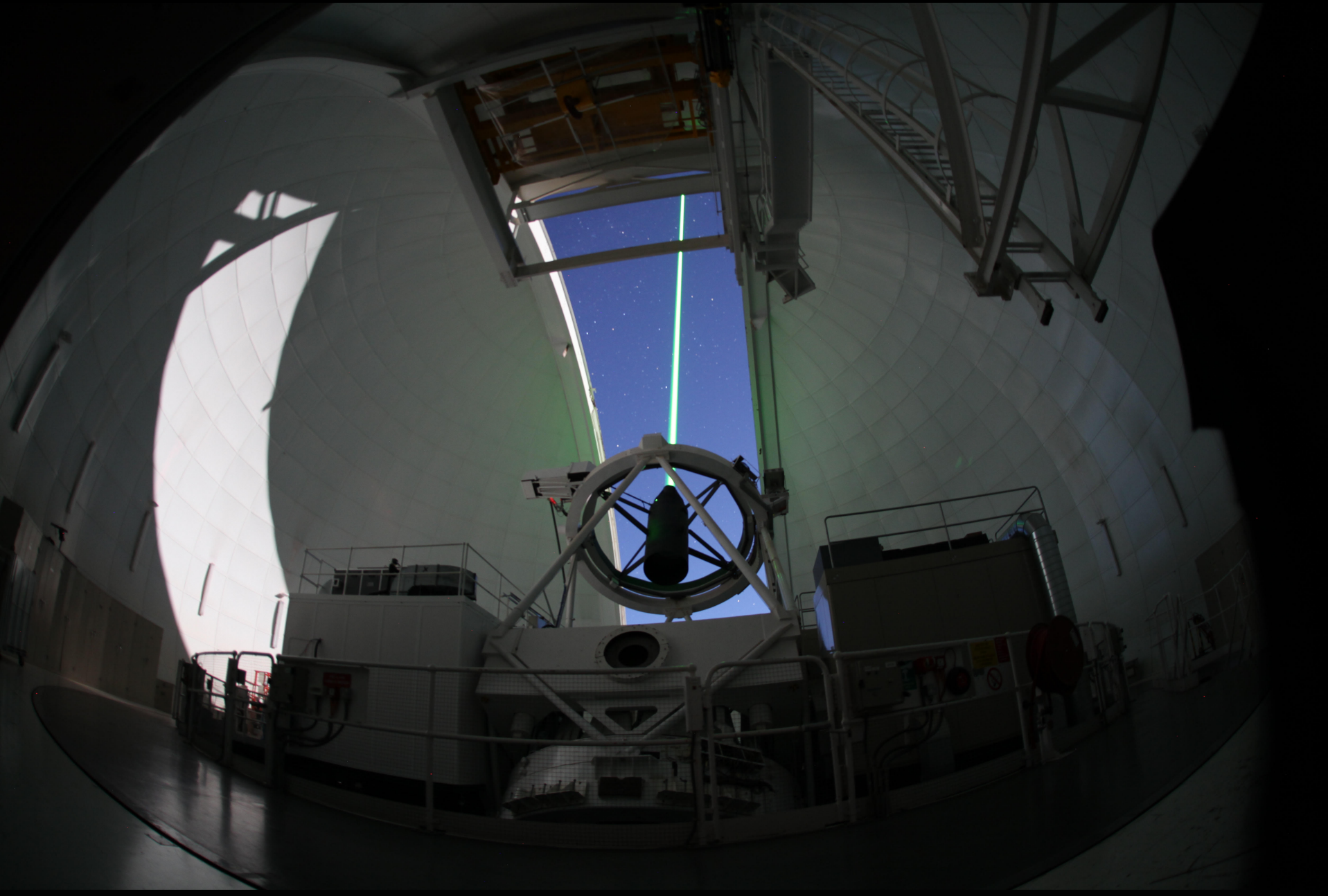


# Supermassive black holes at centre of galaxies





# Sharpening the Universe: adaptive optics



# Sharpening the Universe: adaptive optics



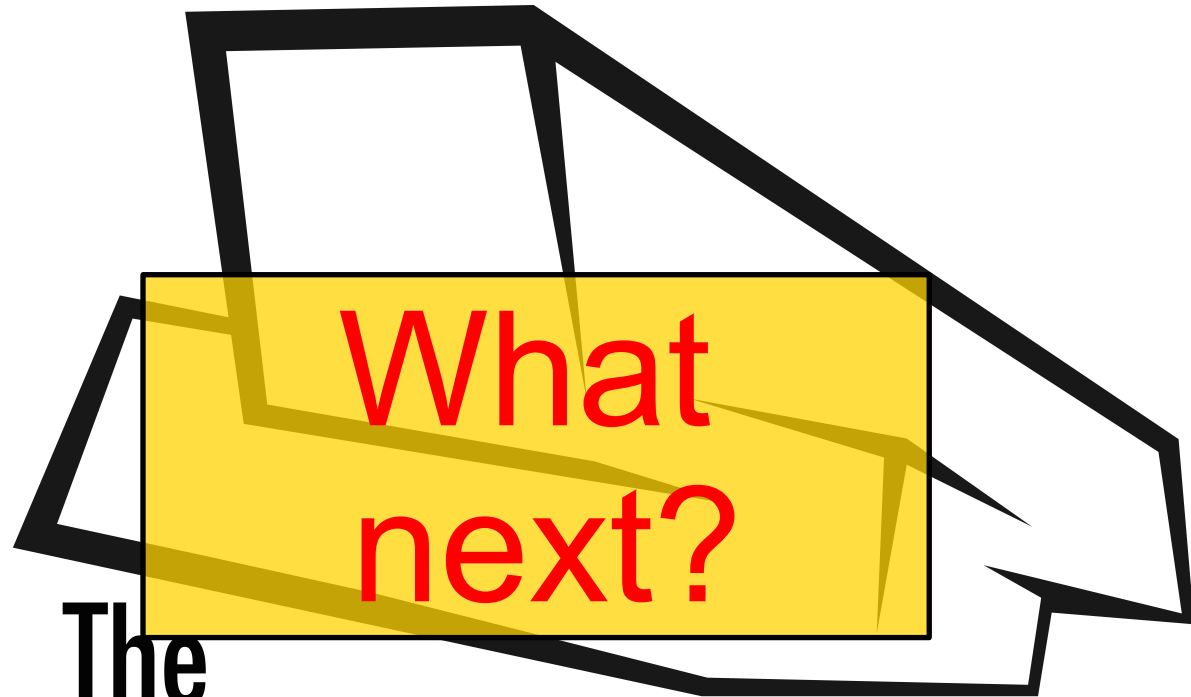


# Sharpening the Universe: adaptive optics





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The  
**OGDEN CENTRE**  
for **FUNDAMENTAL PHYSICS**





How did the universe begin?



Open questions



What is the dark matter?

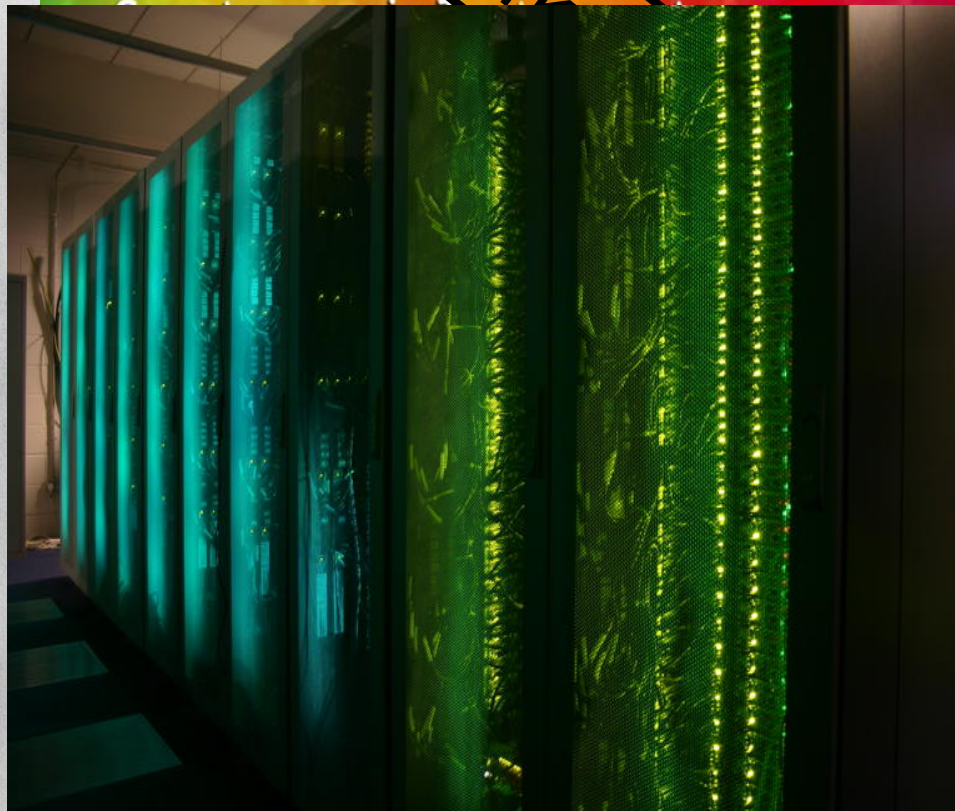
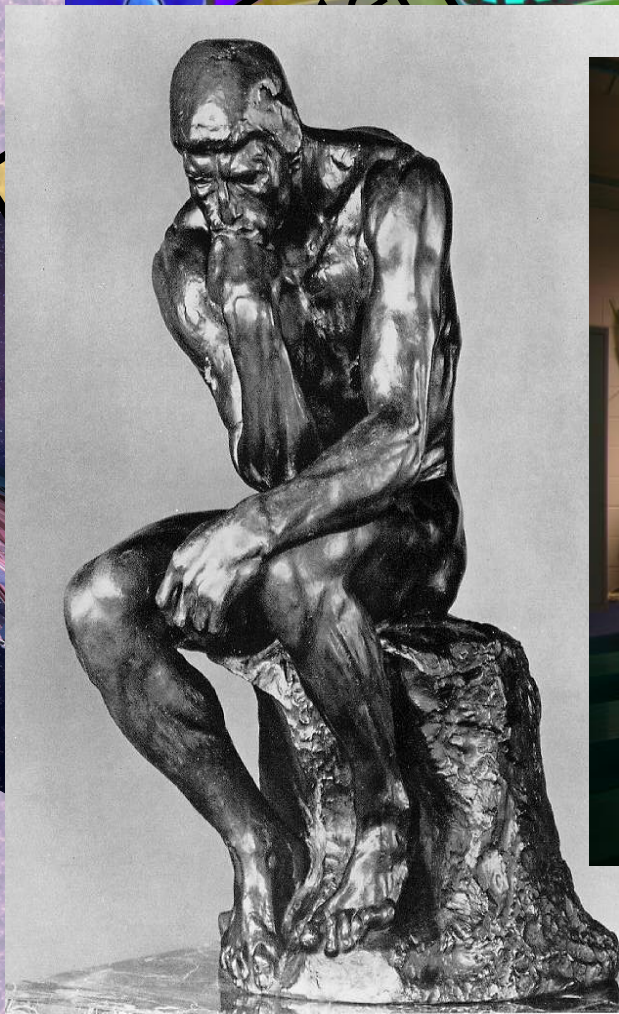
What is the dark energy?





# The future

Theory, computing and modelling



Telescope

Large Synoptic Survey





University of Durham

# The role of philanthropy



Institute for Computational Cosmology



# The Ogden Centre for Fundamental Physics

University of Durham

A partnership between:

- Ogden Trust
- Wolfson Foundation
- Government
- Durham University









University of Durham







University of Durham

# Before the creation of the Ogden Centre



Particle Physics and Astronomy at Durham were  
.... OK – competitive at national level

# After the creation of the Ogden Centre

ICC and IPPP are amongst  
the top research institutes  
in the world as judged by:

- Research grants
- Research papers
- Citations to papers





## Institutional rankings in space sciences

28 August 2008

Data provided by Thomson Reuters from its Essential Science Indicators, 1 January 1998-30 June 2008

# Space Sciences

# International standing




	Institution	Papers	Citations	Citations per paper
1	Institute for Advanced Study, Princeton	614	26,610	43.34
2	Princeton University	1,674	66,380	39.65
3	University of Chicago	1,401	50,254	35.87
4	University of Durham	1,119	39,263	35.09
5	Carnegie Institute for Science, Washington	1,139	38,535	33.83
6	University of Washington, Seattle	1,110	34,106	30.73
7	United States Navy	1,209	34,838	28.82
8	Space Telescope Science Institute, Baltimore	2,830	80,833	28.56
9	Pennsylvania State University State College	1,549	44,803	28.56
10	Australian National University, Canberra	1,029	29,122	28.30
11	University of California, Santa Cruz	1,576	44,184	28.04
12	University of Cambridge	2,879	78,415	27.24
13	University of California, Berkeley	3,447	93,107	27.01
14	Ohio State University	1,034	27,746	26.83
15	University of Michigan	1,458	93,107	26.56
16	California Institute of Technology, Pasadena	4,989	129,863	26.03
17	University of Hawaii	1,761	45,795	26.01
18	Johns Hopkins University, Baltimore	2,882	73,996	25.68
19	Harvard-Smithsonian Center for Astrophysics	4,654	107,290	23.05
20	University of Arizona, Tucson	3,328	76,222	22.90

## INSTITUTIONS

### Top 20 Overall

**Total cites** • *Number of papers* • *Cites per paper*

|| Ranked by total cites ||  
1994-2004 (third bimonthly)

Rank	Institution	Total Cites	Number of Papers	Cites Per Paper
1	MAX PLANCK INST ASTROPHYS	2558	63	40.6
2	PRINCETON UNIV 	2094	72	29.08
3	UNIV DURHAM	1979	32	61.84
4	UNIV CALIF BERKELEY	1709	93	18.38
5	INST ADV STUDY	1692	29	58.34
6	UNIV TOKYO	1497	77	19.44
7	UNIV CALIF SANTA CRUZ	1475	39	37.82
8	UNIV CHICAGO	1392	67	20.78
9	UNIV WASHINGTON	1388	43	32.28
10	UNIV OXFORD	1331	71	18.75
11	UNIV CALIF SANTA BARBARA	1184	49	24.16
12	UNIV ARIZONA	1183	25	47.32
13	CERN	1103	54	20.43
14	OHIO STATE UNIV 	986	36	27.39
15	NASA	975	40	24.38
16	FERMILAB NATL ACCELERATOR LAB	922	36	25.61
17	NEW MEXICO STATE UNIV	893	31	28.81
18	UNIV CALIF SAN DIEGO	836	28	29.86
19	CALTECH	808	41	19.71
20	COLUMBIA UNIV 	780	20	39



# The role of philanthropy: research funding

Research is funded by a combination of:

- Research Councils
- The EU
- The University
- Charities
- Philanthropy

**ICC:** non-University research funding:

- 60% Science and Technology Research Council
- 40% EU

# The role of philanthropy: research funding

Brexit is a huge challenge for fundamental research in UK

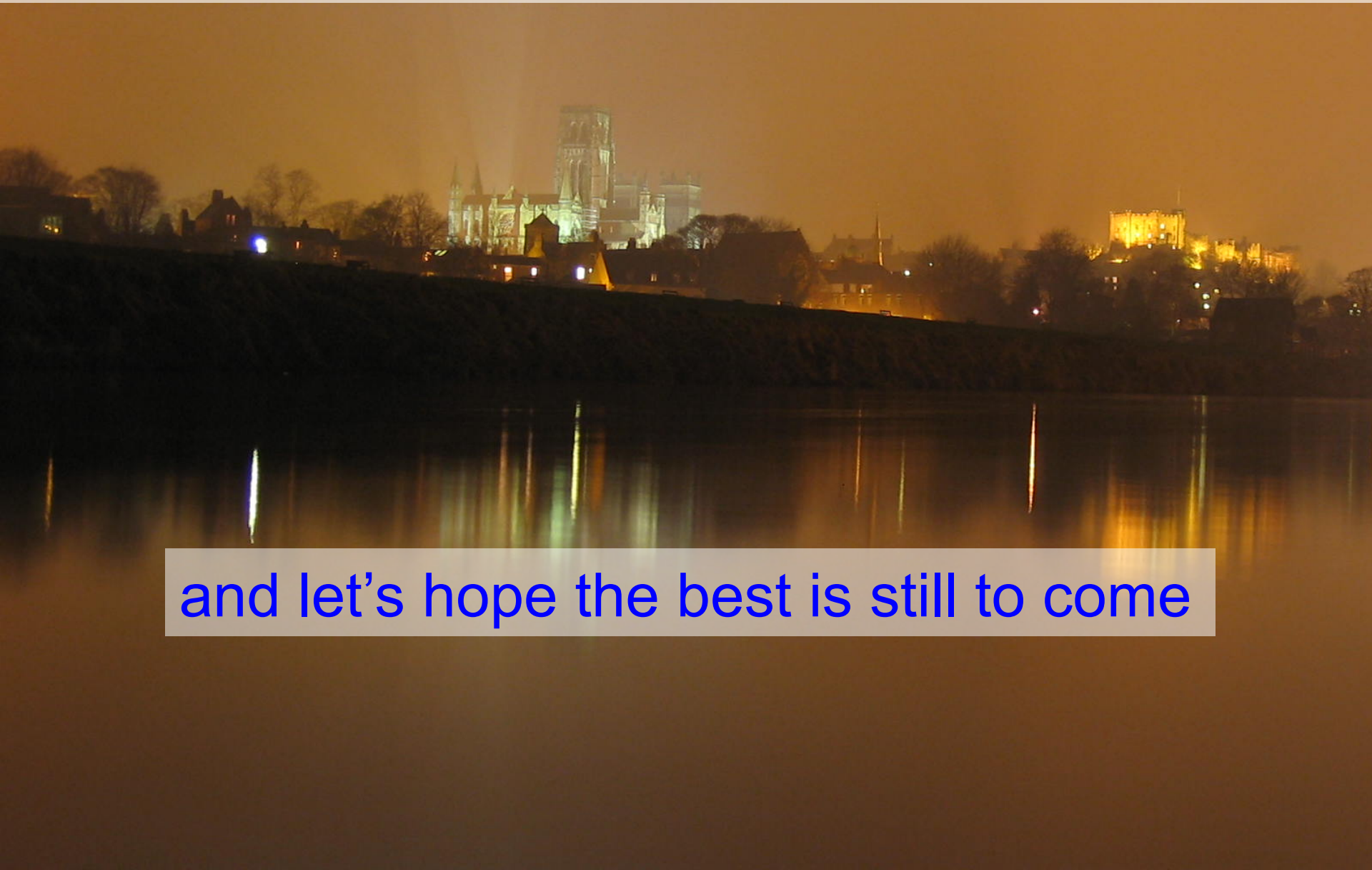
- UK receives 1.6x more research funds than it contributes (8.8 billion vs 5.4 billion euros, 2007-2013)
- Much EU funding based on excellence (not “impact”)

To remain competitive, we will rely on philanthropy:

- PhD students
- Research fellowships
- Support for international collaboration



Research at Durham University has advanced enormously in the past 30 years



and let's hope the best is still to come