The Cosmology Machine: the formation of cosmic structure

Carlos S. Frenk

Institute for Computational Cosmology, Durham

University of Durham

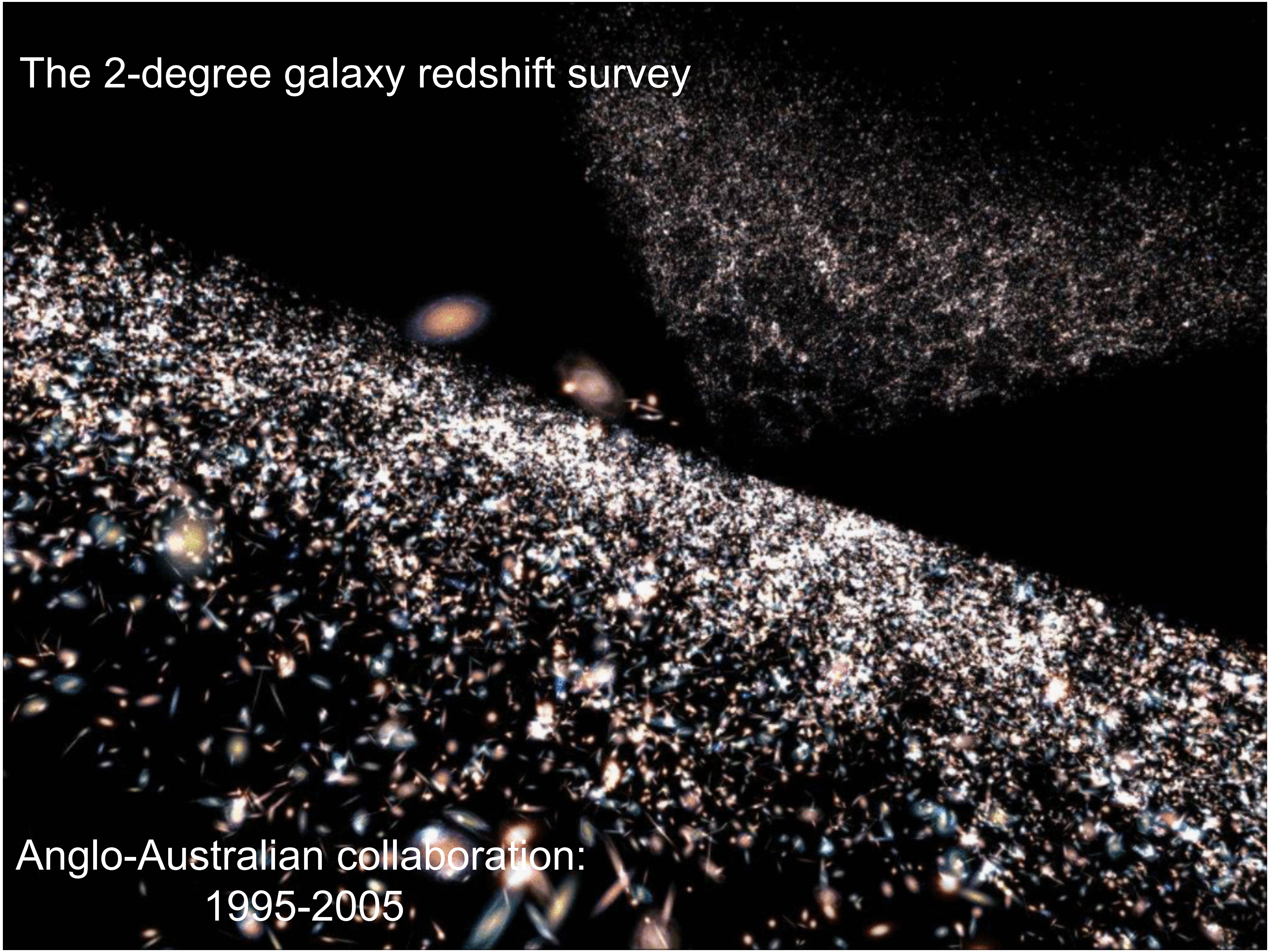
The Institute for Computational Cosmology

Science goal:

→ Model the formation and evolution of cosmic structures from the Big Bang to the present

→ Link early universe theory to observations

Need top-end supercomputers


The 2-degree galaxy redshift survey
Anglo-Australian collaboration:
1995-2005

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3 key questions addressed at the ICC

1. What is the universe made of?

   - What is the identity of the dark matter?
   - What is the nature of the dark energy?

2. What are the fundamental parameters of our World model?
   - Geometry, age, expansion rate, etc

3. What is the origin of cosmic structure?

   - What are the properties of the large-scale structure?
   - How do galaxies form and evolve?

ICC

THE KEY QUESTIONS OF COSMOLOGY

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

Flammarion 1888: tete des etoiles

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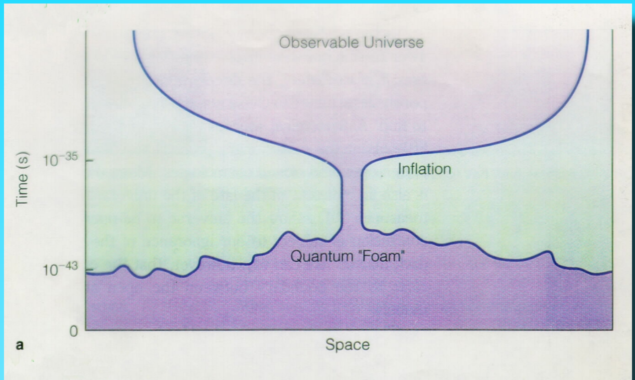
The origin of cosmic structure

Inflation ($t \sim 10^{-35}$ s)



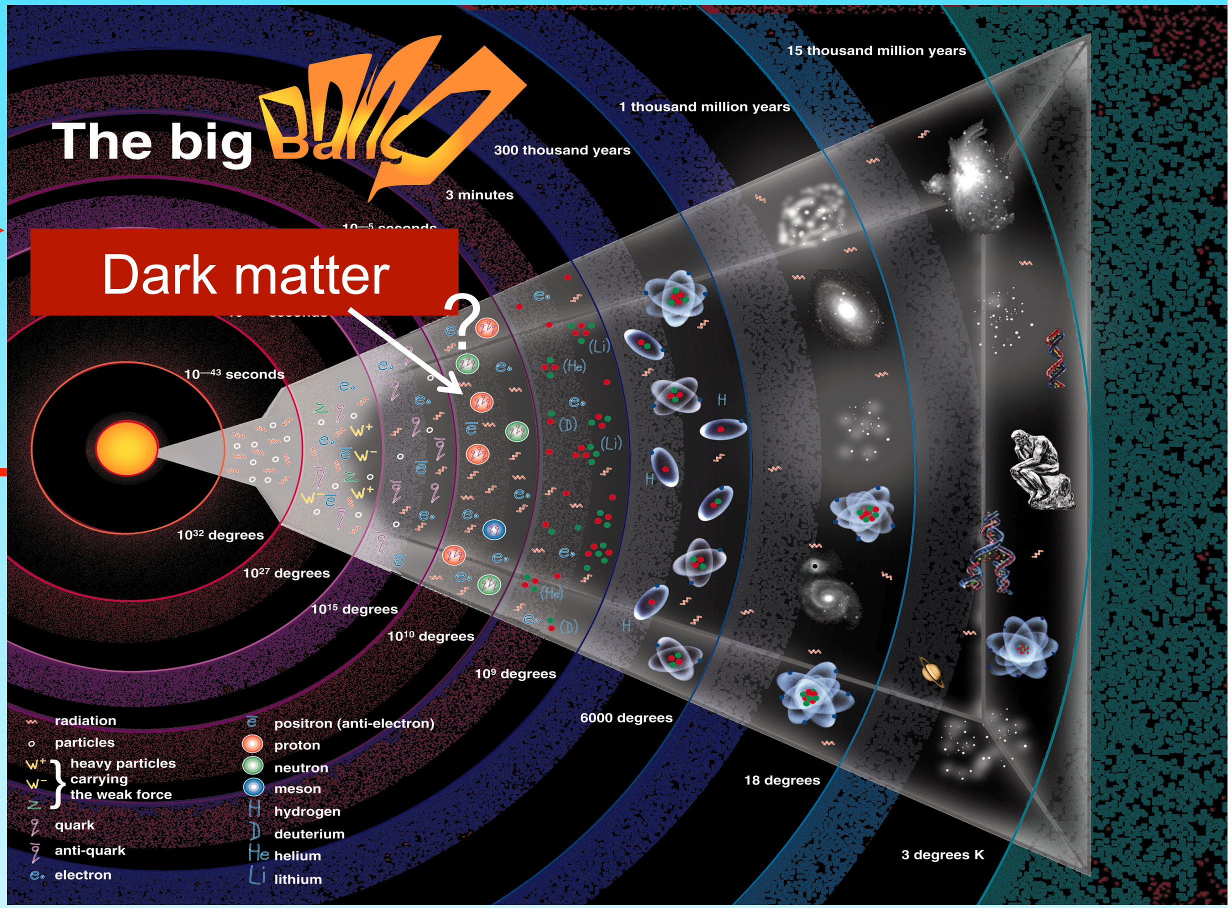
1. FLAT GEOMETRY: $\Omega + \frac{\Lambda}{3H^2} = 1$

2. QUANTUM FLUCTUATIONS: $|\delta_k|^2 \propto k^n \quad n = 1$

adiabatic

Gaussian amplitudes

Dark matter



The origin of cosmic structure

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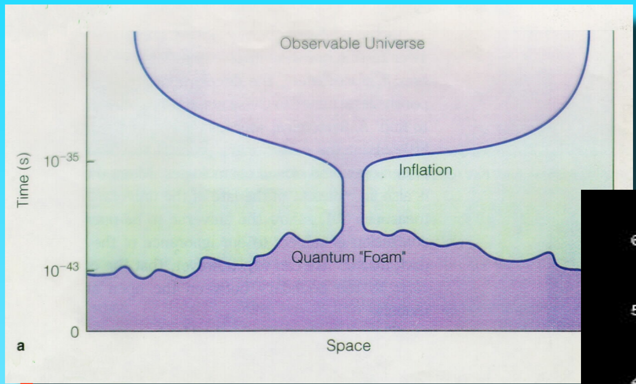
Inflation (t~10^{-35} s)



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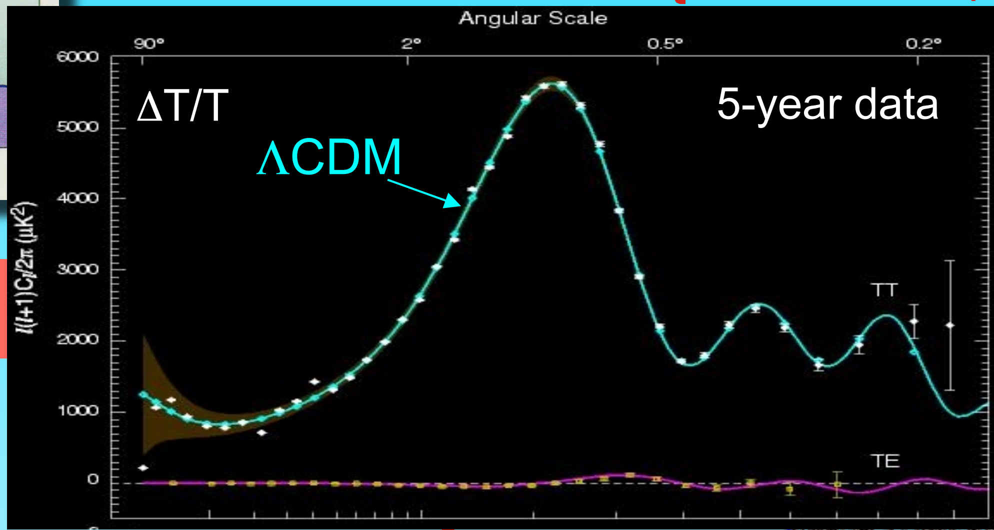
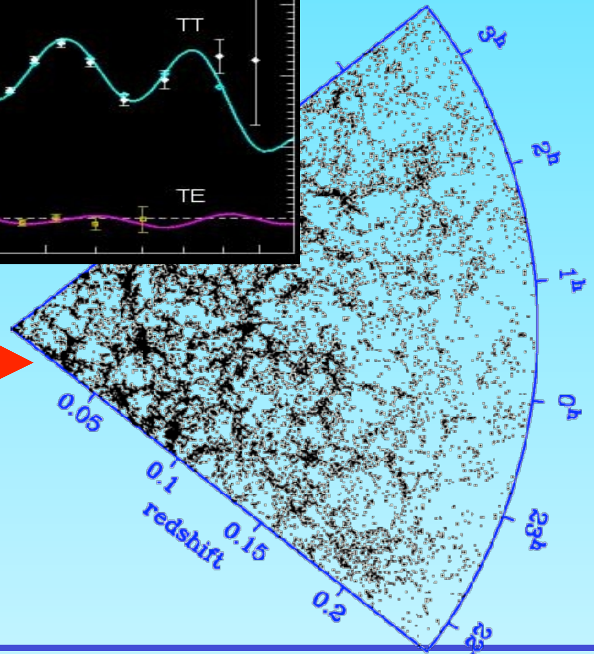


Dark matter

Structure
~13×10^9yrs)



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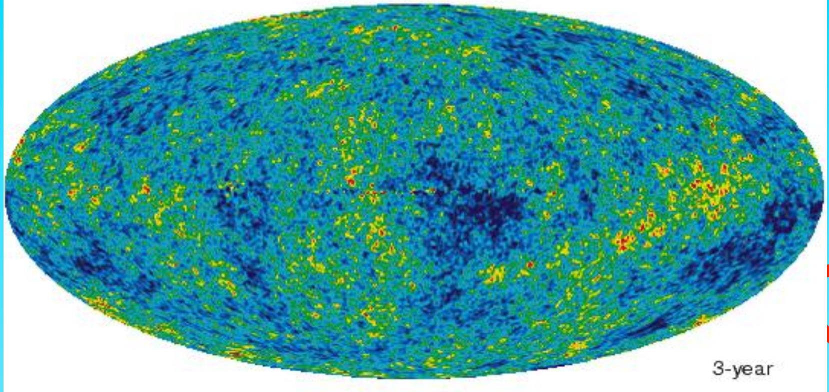
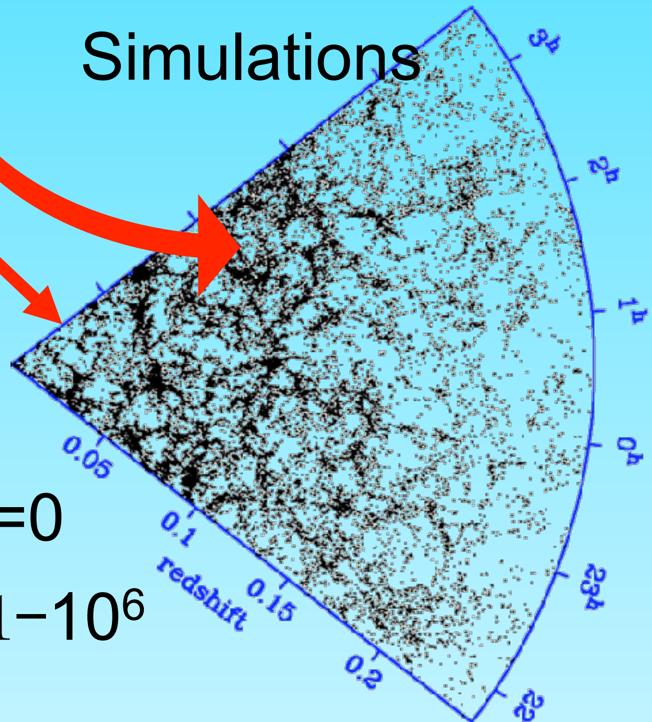
Testing the CDM paradigm

"Cosmology machine"



$z=1000 \quad \delta\rho/\rho \sim 10^{-5}$

Simulations



Structure grows primarily by gravity, but the problem is non-linear and involves gasdynamical and radiative physics

z=0

→ Cosmological simulations $\delta\rho/\rho \sim 1-10^6$

Institute for Computational Cosmology

The Virgo Consortium

UK members

Durham

Cambridge

Edinburgh

Manchester

Nottingham

Sussex

UK, Germany, Netherlands, Canada, China collaboration (PI: CSF)

Pictures, movies and simulation data available at:

http://www.mpa-garching.mpg.de/Virgo

www.durham.ac.uk/virgo

ICC
University of Durham

Virgo consortium for supercomputer simulations

~70 scientists in 7 countries
6 UK universities

Core members

- Carlos Frenk – ICC, Durham (P.I.)
- Adrian Jenkins – ICC, Durham
- Tom Theuns – ICC, Durham
- Gao Laing – ICC, Durham/Beijing
- Simon White – Max Plank Inst für Astrophys (co-P.I.)
- Volker Springel – HITS Heidelberg
- Frazer Pearce – Nottingham
- Naoki Yoshida – Nagoya
- Peter Thomas – Sussex
- Hugh Couchman – McMaster
- John Peacock – Edinburgh
- George Efstathiou – Cambridge
- Scott Kay – Manchester
- Julio Navarro – Victoria
- Joop Schaye – Leiden

- ***23 Associate members***
- ***29 PhD students***

35/68 UK

Simulation data, movies, etc available at:

www.durham.ac.uk/virgo
http://www.mpa-garching.mpg.de/Virgo

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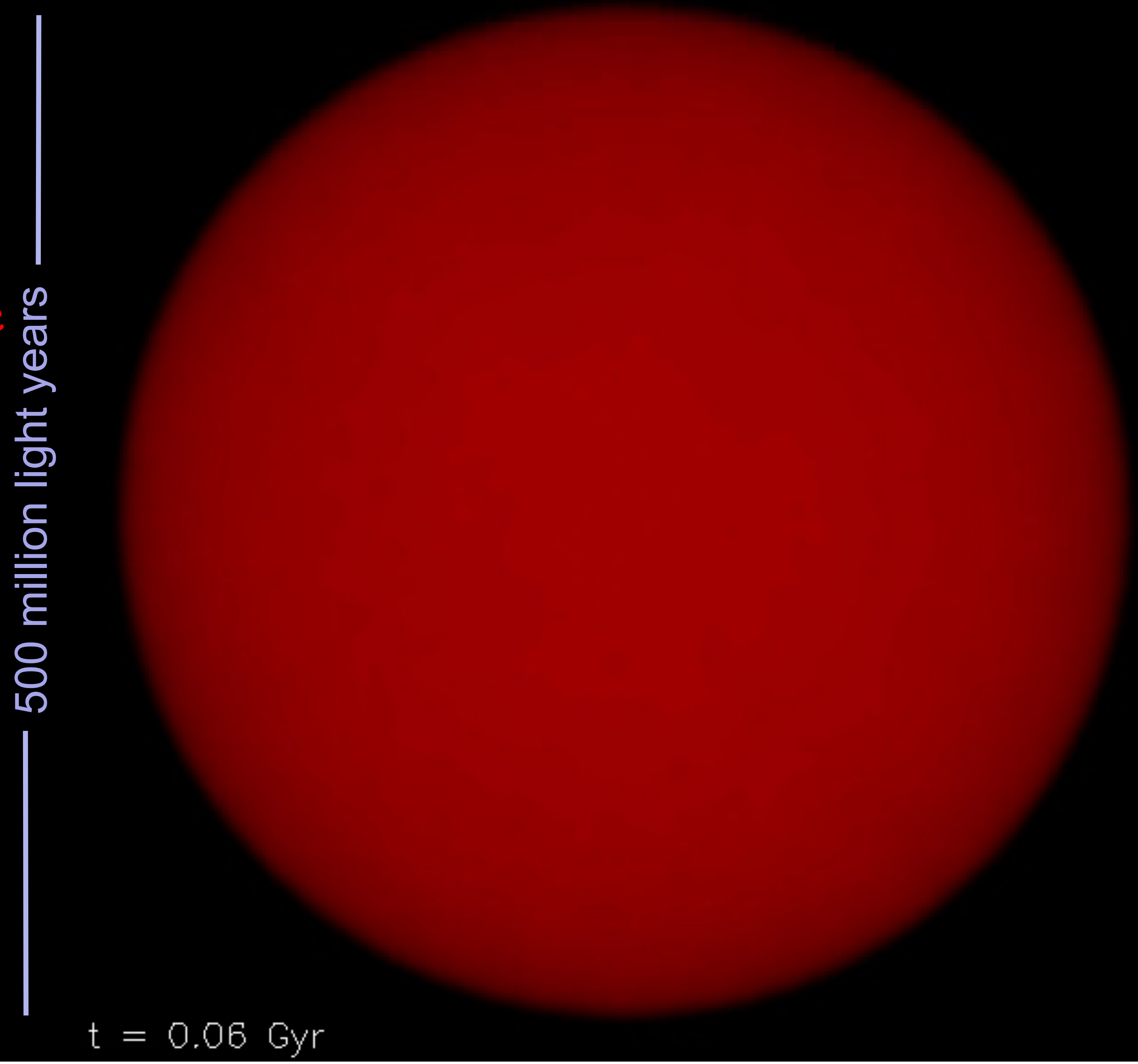
Large Scale Structure

Computer simulation

Small irregularities in the early universe grow under the action of gravity:



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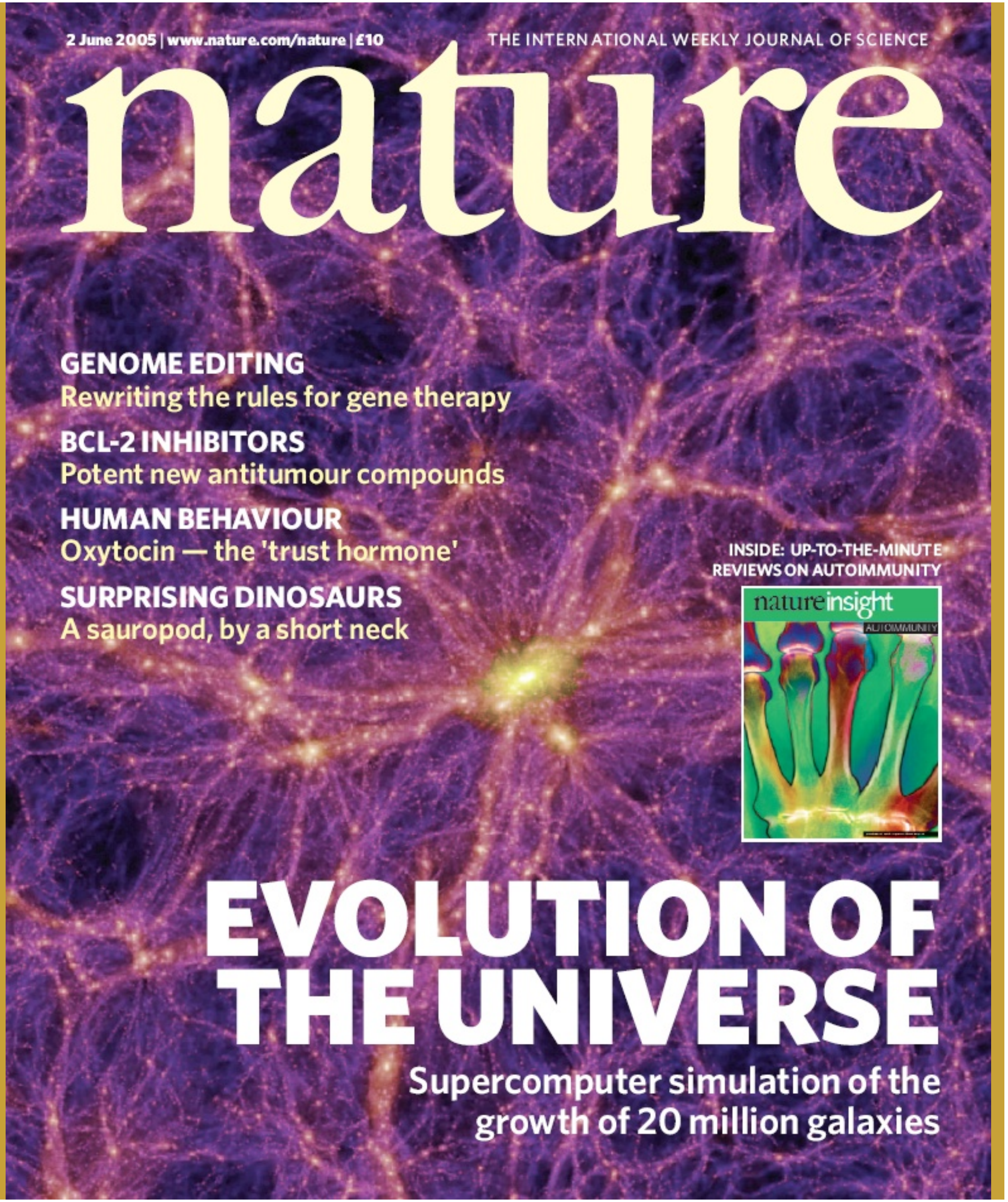
Springel et al 05

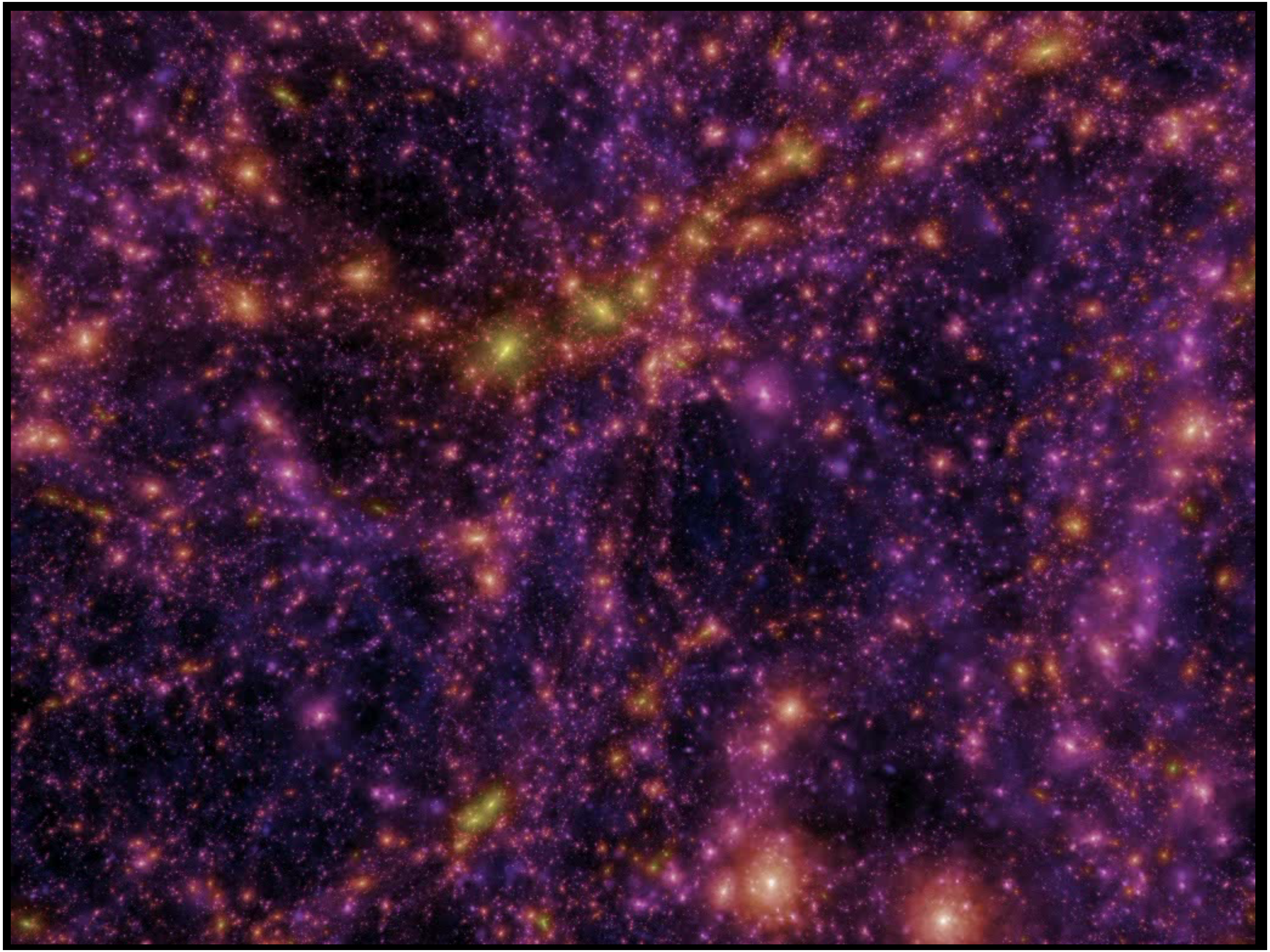
(1137 citations)

www.durham.ac.uk/virgo

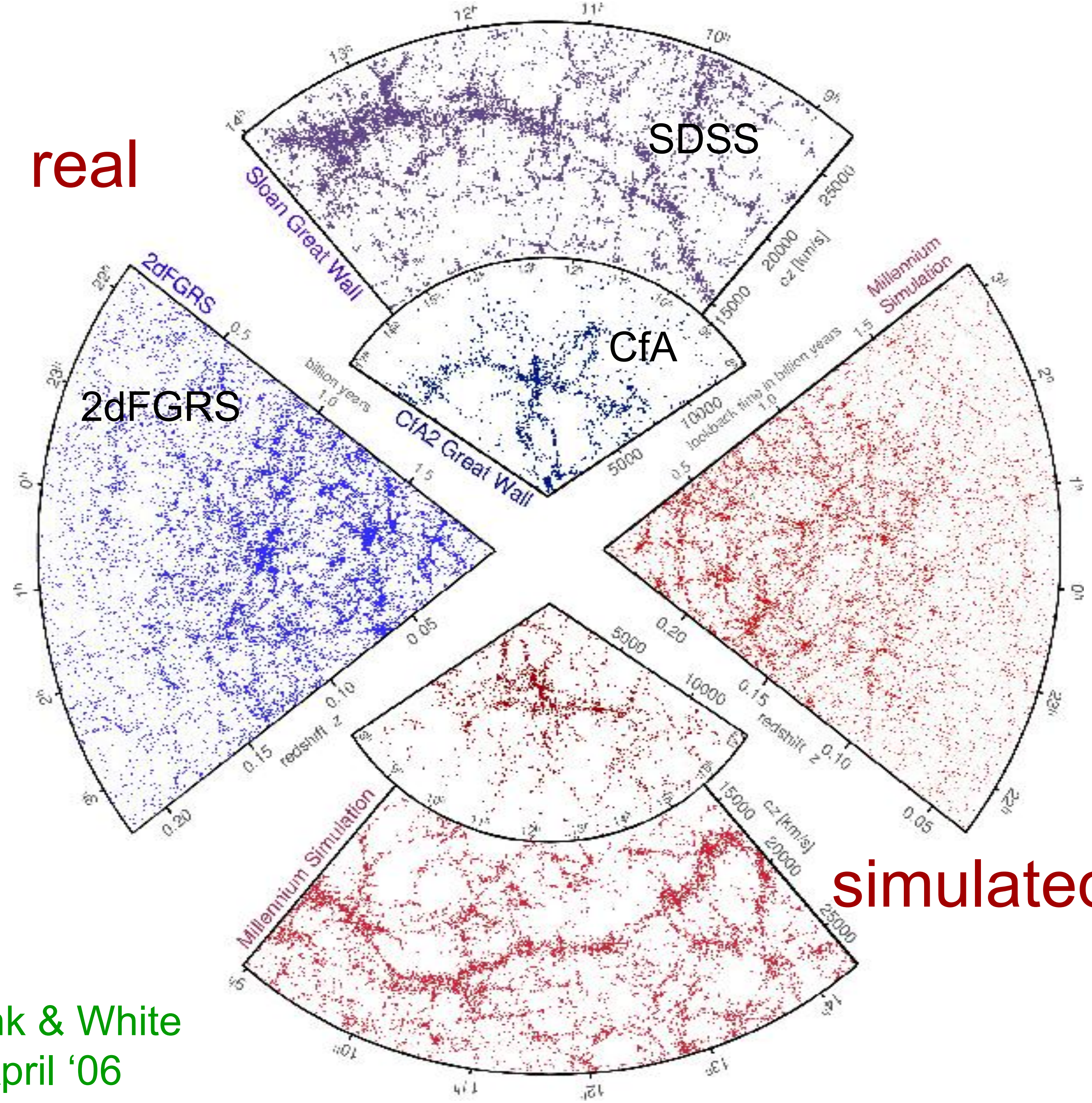
www.mpa-garching.mpg.de/Virgo

June 2/05





real



simulated

Springel, Frenk & White
Nature, April ‘06

University of Durham

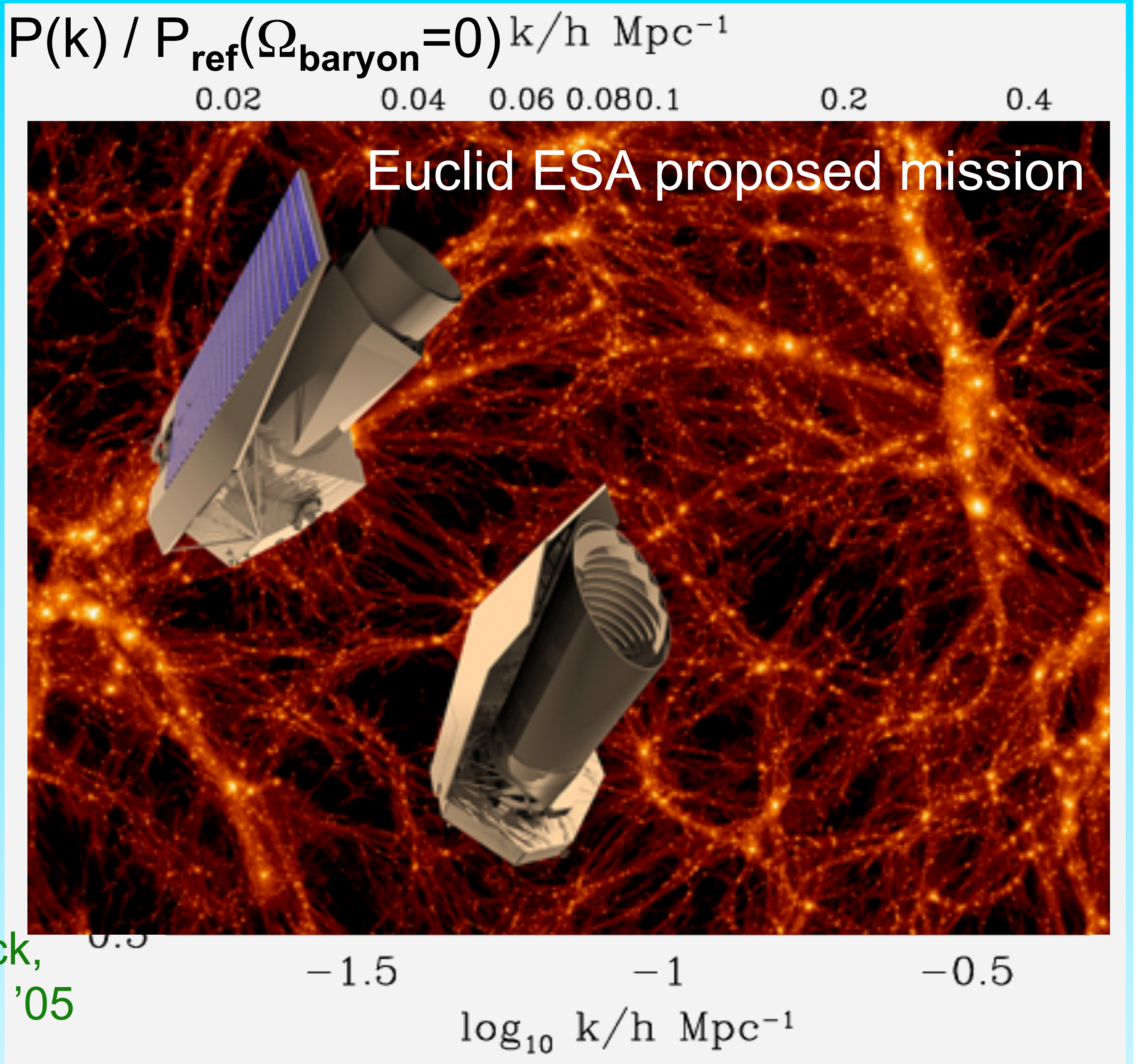
The final 2dFGRS power spectrum

Baryon oscillations conclusively detected in 2dFGRS!!!

Demonstrates that structure grew by gravitational instability in ΛCDM universe

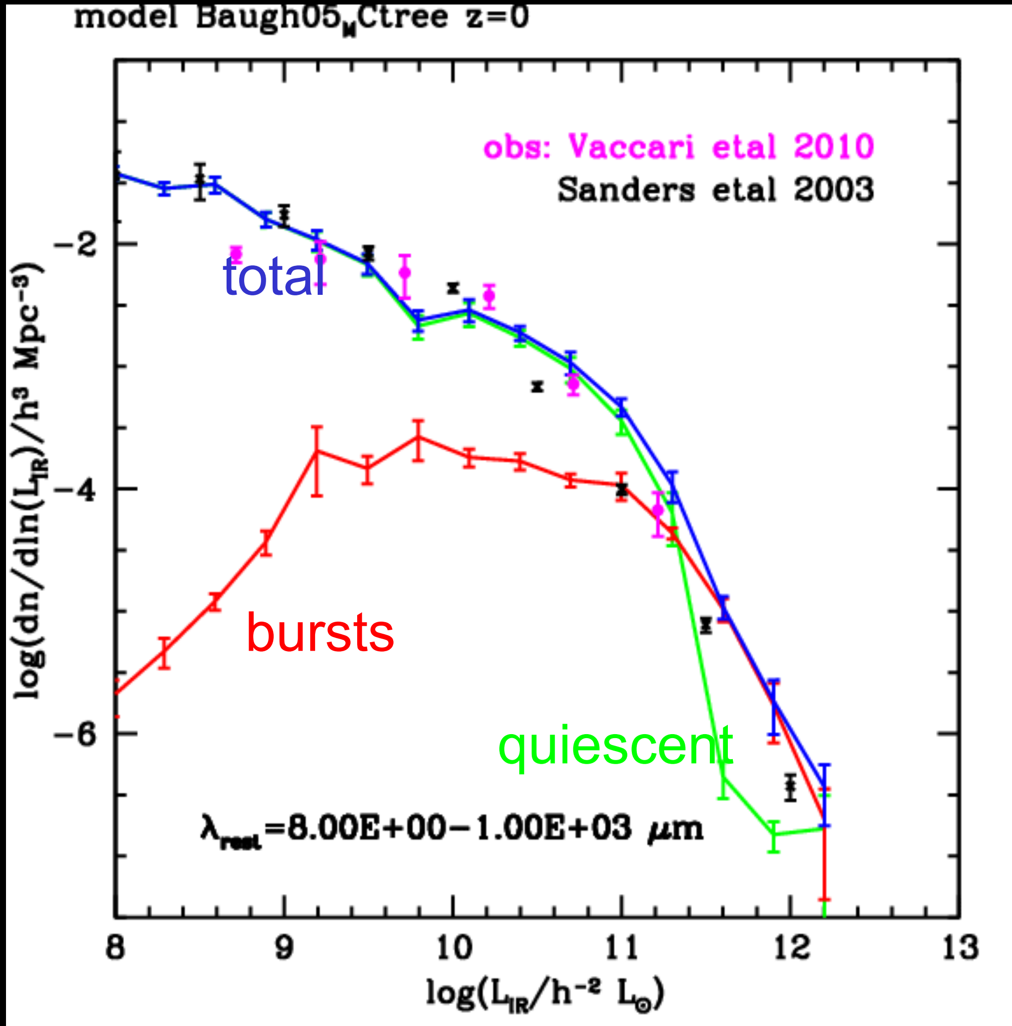
Also detected in SDSS LRG sample (Eisenstein etal 05)

Cole, Percival, Peacock, Baugh, Frenk + 2dFGRS '05 (720 citations)



The infrared universe

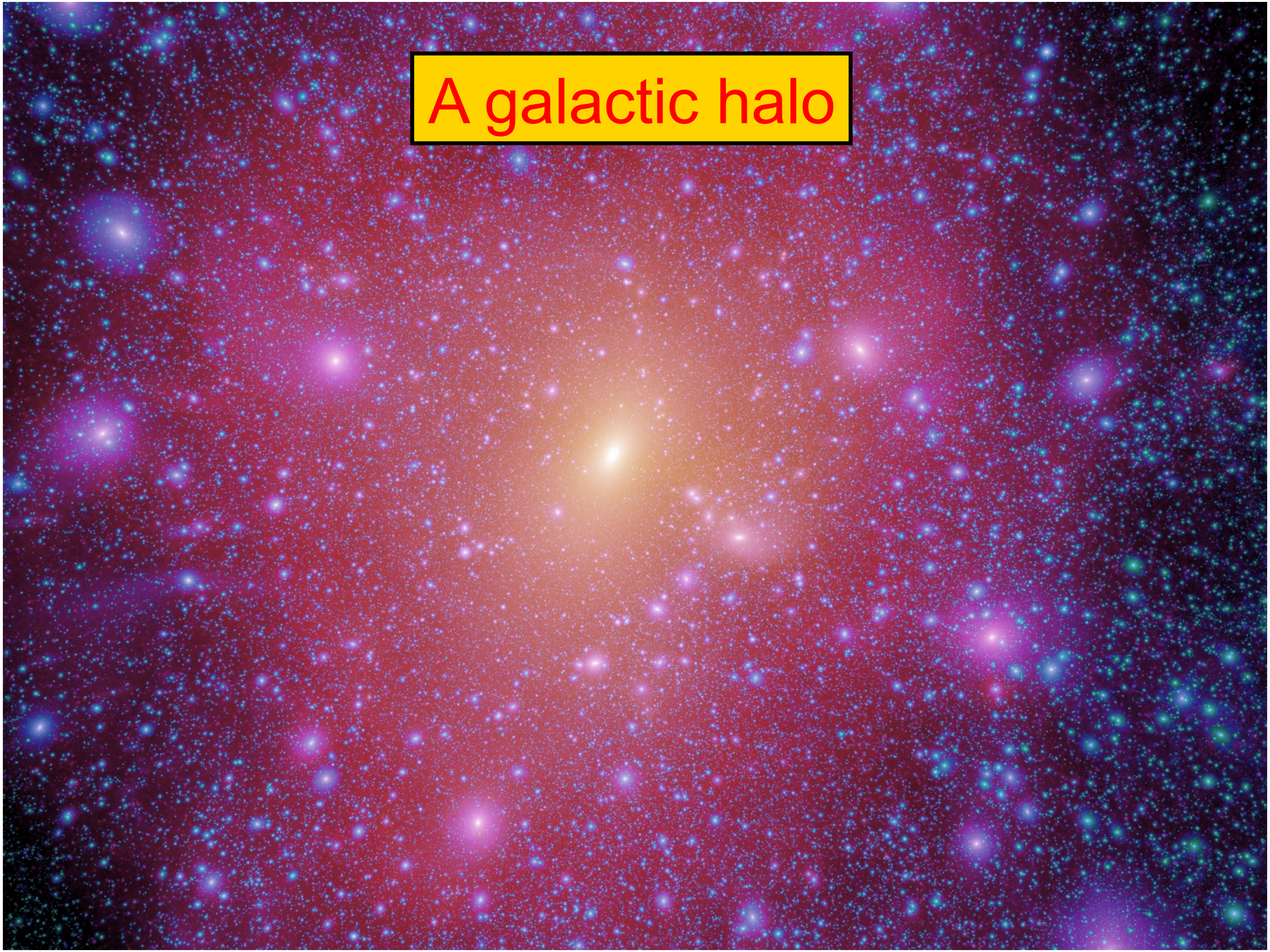
ESA Herschel Telescope




The James Webb Space Telescope – 2018


z = 48.4
T = 0.05 Gyr
500 kpc

A galactic halo



The Aquarius programme

Vol 456 | 6 November 2008 | doi:10.1038/nature07411 nature

Nature, Nov 2008

LETTERS

Prospects for detecting supersymmetric dark matter in the Galactic halo

V. Springel[1], S. D. M. White[1], C. S. Frenk[2], J. F. Navarro[3,4], A. Jenkins[2], M. Vogelsberger[1], J. Wang[1], A. Ludlow[3] & A. Helmi[5]

Dark matter is the dominant form of matter in the Universe, but its nature is unknown. It is plausibly an elementary particle, perhaps the lightest supersymmetric partner of known particle species[1]. In this case, annihilation of dark matter in the halo of the Milky Way should produce γ-rays at a level that may soon be observable[2,3]. Previous work has argued that the annihilation signal will be dominated by emission from very small clumps[4,5] (perhaps smaller even than the Earth), which would be most easily detected where they cluster together in the dark matter haloes of dwarf satellite galaxies[6]. Here we report that such small-scale structure will, in fact, have a negligible impact on dark matter detectability. Rather, the dominant and probably most easily detectable signal will be produced by diffuse dark matter in the main halo of the Milky Way[7,8]. If the main halo is strongly detected, then small dark matter clumps should also be visible, but may well contain no stars, thereby confirming a key prediction of the cold dark matter model.

If small-scale clumping and spatial variations in the background are neglected, then it is easy to show that the main halo would be much more easily detected than the haloes of known satellite galaxies. For a smooth halo of given radial profile shape, for example that given in ref. 9 by Navarro, Frenk and White (NFW), the annihilation luminosity can be written as $L \propto V_{max}^4 / r_{half}$, where V_{max} is the max-

Simulations of the same object at mass resolutions lower by factors of 8, 28.68, 229.4 and 1,835 enable us to check explicitly for the convergence of the various numerical quantities presented below.

The detectable annihilation luminosity density at each point within a simulation is

$$\mathcal{L}(\mathbf{x}) = \mathcal{G}(\text{particle physics, observational set-up})\rho^2(\mathbf{x})$$

where $\rho(\mathbf{x})$ is the local dark matter density and the constant $\mathcal{G}$ does not depend on the structure of the system but encapsulates the properties of the dark matter particle (for example, annihilation cross-section and branching ratio into photons) as well as those of the telescope and observation. For the purposes of this Letter, we set $\mathcal{G} = 1$ and give results only for the relative luminosities and detectability of the different structures. In this way, we can quote results that are independent of the particle physics model and the observational details.

Figure 1 shows the distribution of annihilation radiation within our Milky Way halo as a function of the resolution used to simulate it. This plot excludes the contribution to the emission from resolved substructures. Half of the emission from the Milky Way halo is predicted to come from within 2.57 kpc and 95% from within 27.3 kpc. For the lowest resolution simulation (1,835 times coarser than the largest simulation), the luminosity is clearly depressed below 3 kpc,

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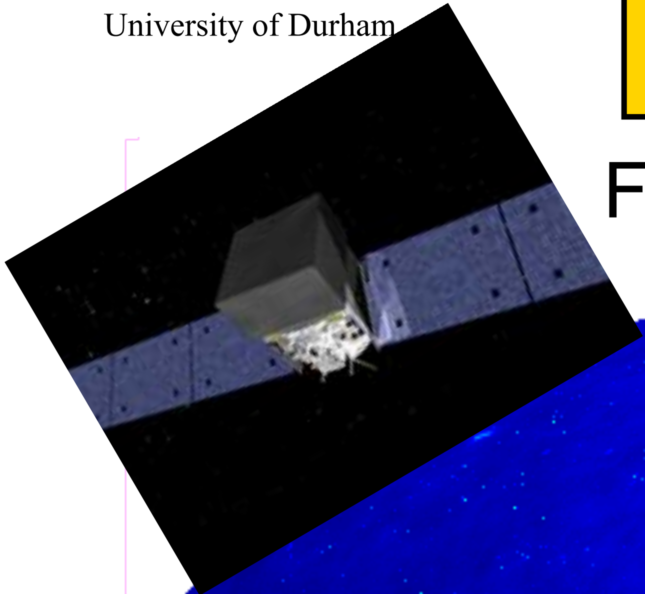
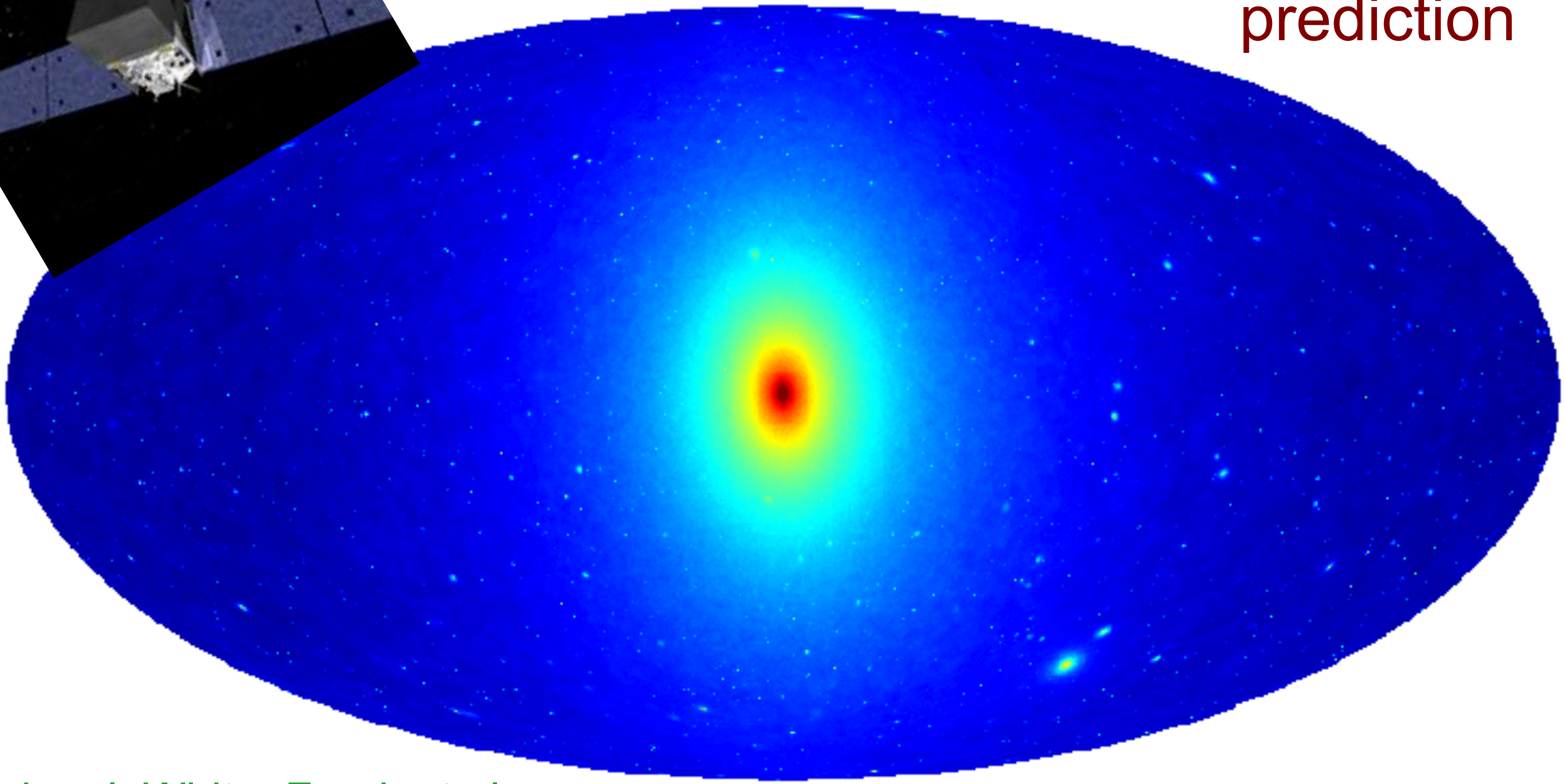
Milky Way halo seen in DM annihilation radiation

Fermi satellite

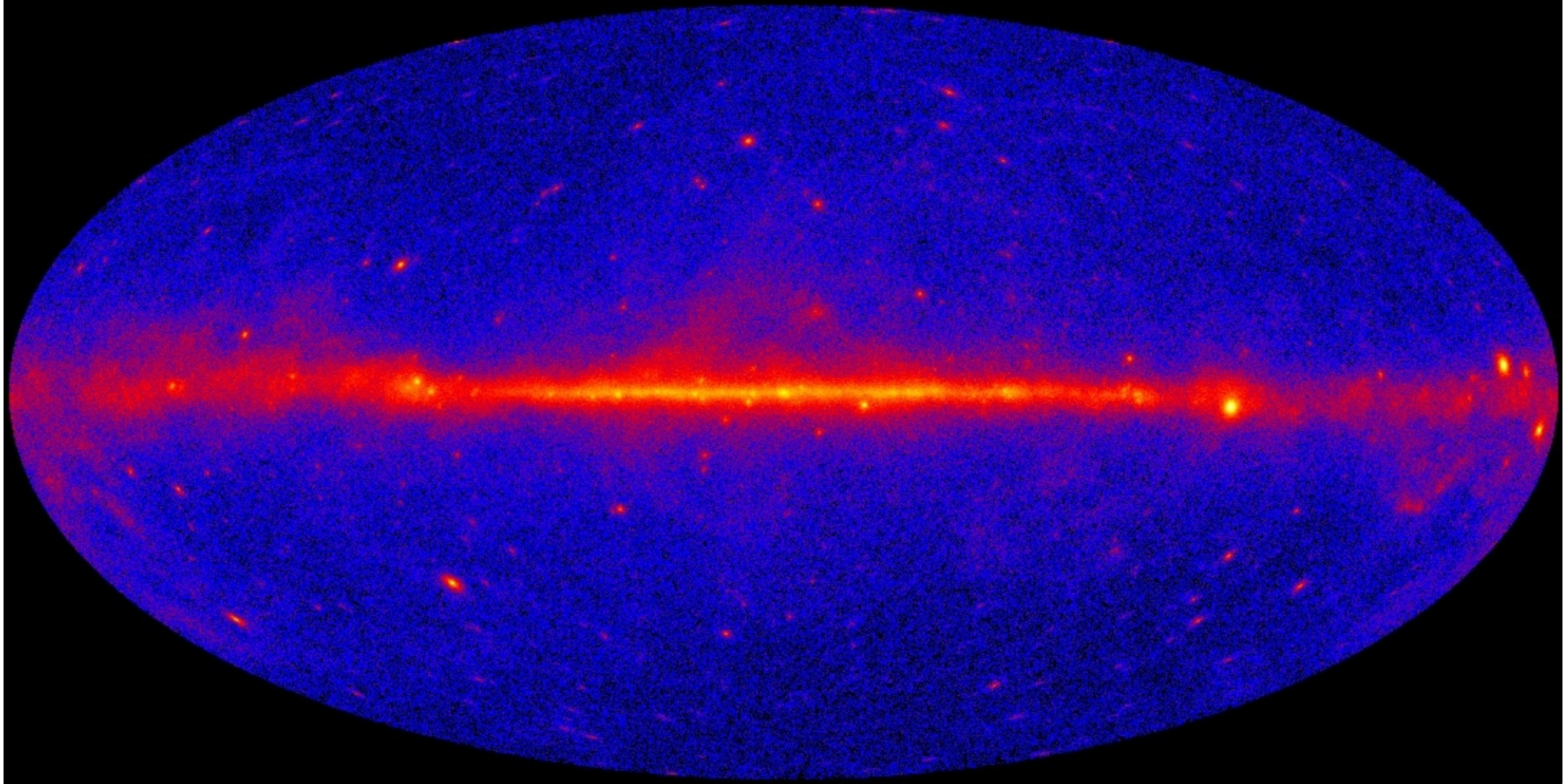


Theoretical prediction

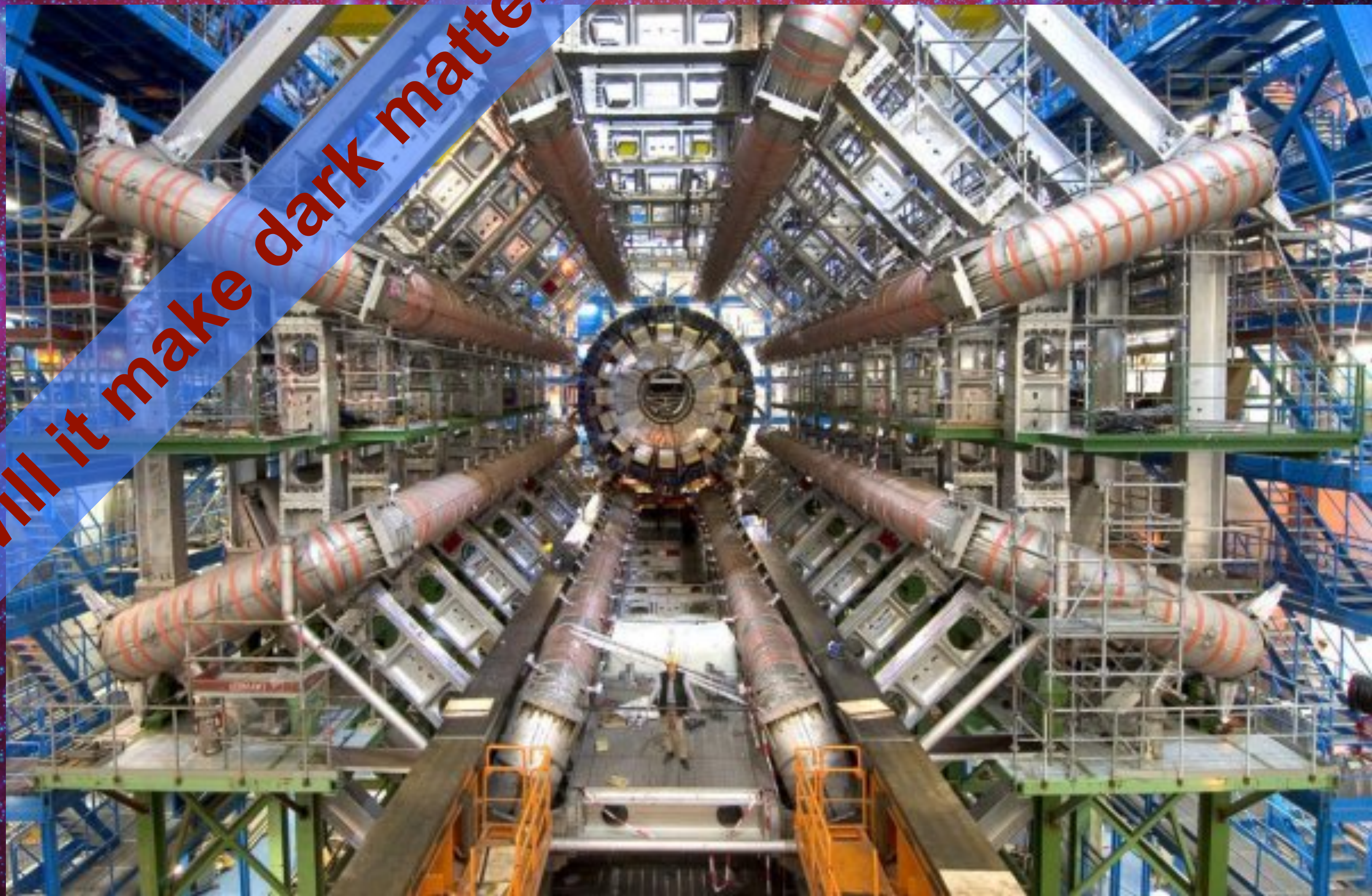


Springel, White, Frenk et al
Nature Nov/08

The first-year all-sky image from Fermi



A galactic halo



Impact of supercomputing in cosmology

This kind of modelling is vital for the exploitation of data from eg:

ALMA, Scuba-2, PS1, Herschel, Planck, JWST, LOFAR, ASKAP, SKA,

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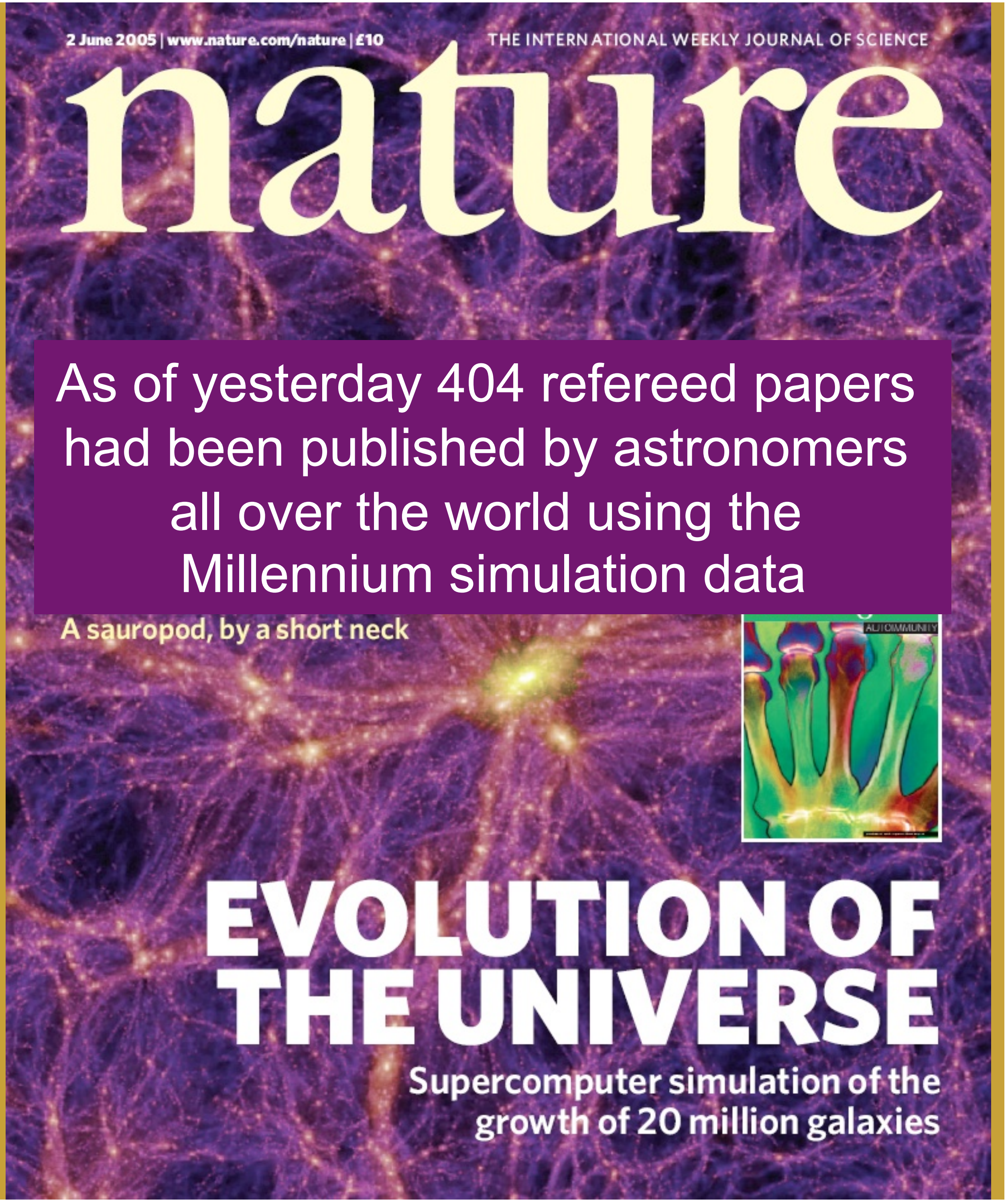
Springel et al 05

(1137 citations)

www.durham.ac.uk/virgo

www.mpa-garching.mpg.de/Virgo

June 2/05



As of yesterday 404 refereed papers had been published by astronomers all over the world using the Millennium simulation data

International standing

University of Durham

Times Higher Education -Features -Institutional rankings in space sciences

01 September 2008

Institutional rankings in space sciences

28 August 2008

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

	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

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Science & Society

Extensive international outreach programme funded by STFC, Durham University. and Ogden Trust

- Schools in NE
- RS Summer Science Exhibitions (2002, 2005)
- 3D movies
- Science museums (Newcastle, Mexico)
- Public lectures TV, press

Collaboration with Industry

- Sun Microsystems (£800k)
- Microsoft (£80k)
- IBM

Outreach programme in the NE

Durham University

ICC

IP3

VIRGO

UKDMC

University of Sheffield

Pete Edwards

Department of Physics, Durham University

What attracts young people to science?

IoP survey of 673 1st yr undergraduates – 20% of all UK undergrads in physics and astronomy

Which aspects of physics attracted you to the subject?

Subject Area / % interest	No Interest	Some Interest	Significant Interest
Mathematical aspects	11	44	45
Fundamental Particles, Quantum Phenomena	5	22	73
Mechanics & Kinetic Theory	6	55	39
Electricity & Magnetism	14	63	23
Properties of Solids	37	52	11
Waves and Optics	21	60	19
Nuclear Physics	4	35	61
Astrophysics	12	34	54
Medical Physics	55	34	11
Electronics	36	49	15
Applied Physics	11	57	32

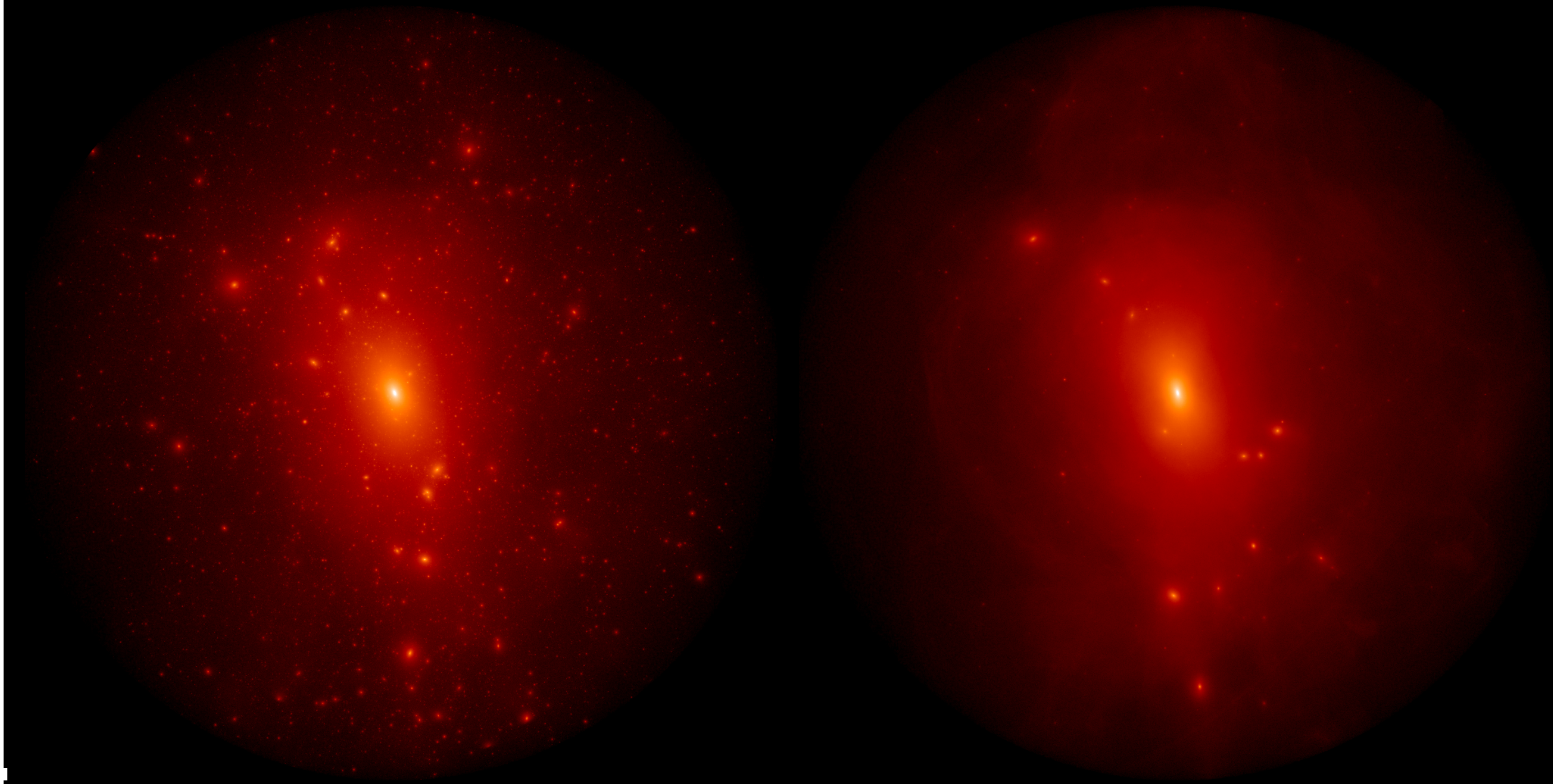
Theme 1: The Milky Way

Small-scale … sitively
on the r… er

Observations o… ΛCDM if
theoretical p… bust

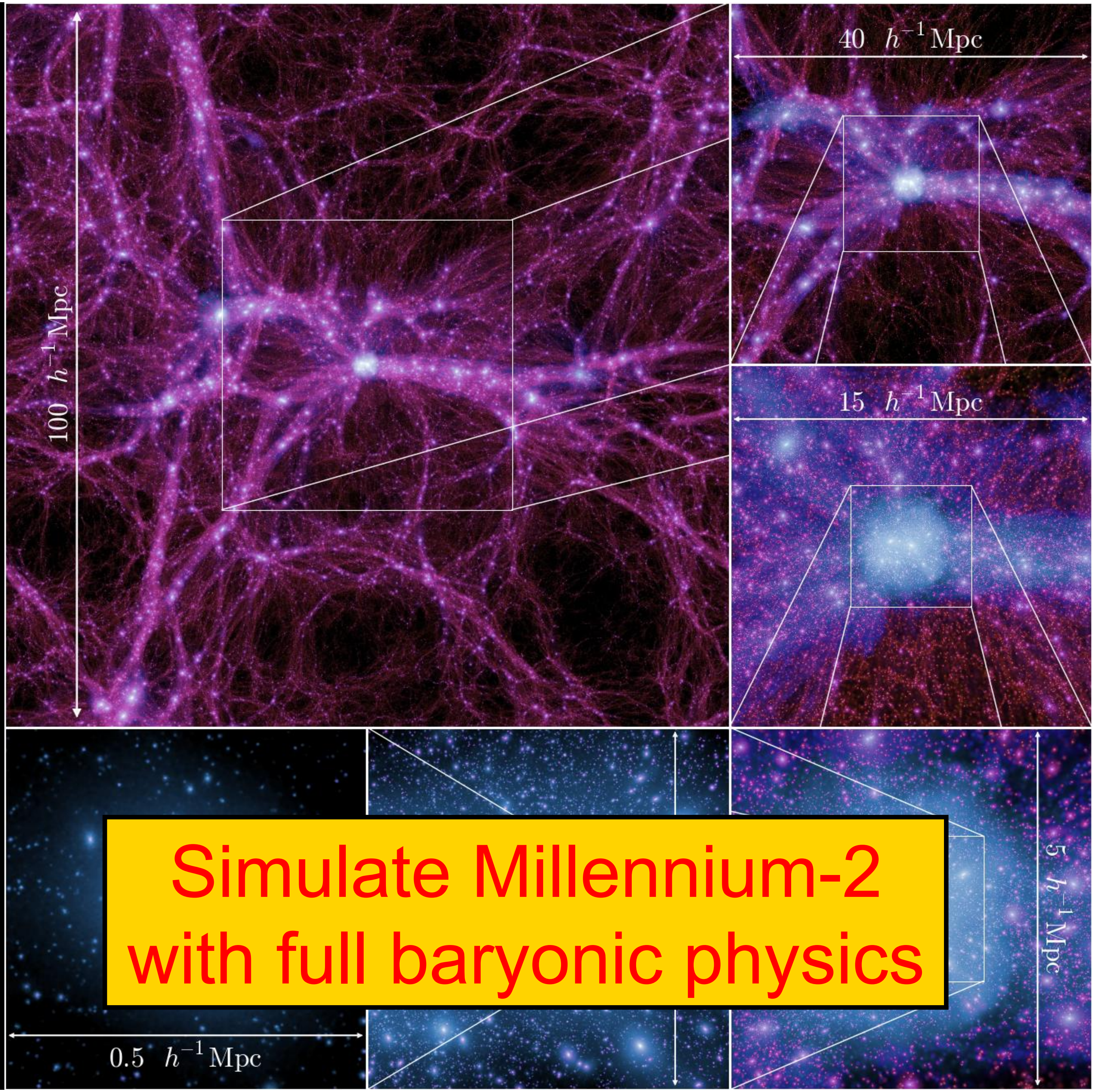
cold dark matter

warm dark matter



Gao, Lovell et al 2011

Theme 3: simulations of galaxy formation



Simulate Millennium-2 with full baryonic physics


This is a “golden era” in cosmology
… and it is probably just beginning!

The Cosmology Machine

University of Durham

One of the largest supercomputers for academic research in the UK dedicated to numerical cosmology


University of Durham
Department of Physics
Institute for Computational Cosmology
Launch of Cosmology Supercomputer
Rt Hon Patricia Hewitt MP
Secretary for Trade and Industry
31st July 2001

£650k JREI grant to Virgo
£250k Sun

Opened by Patricia Hewitt in Aug/01

Centaur
128 UltraSparc III cluster
64 Gigabytes ram

Titania
24 Sunfire processors
48 Gigabytes

COSMA-1

Quintor
512 processors,
630 Gbytes ram,
60 Tbyte storage

£465k JIF grant to ICC
£200k Sun
March/04

COSMA-2

2006 → COSMA-3

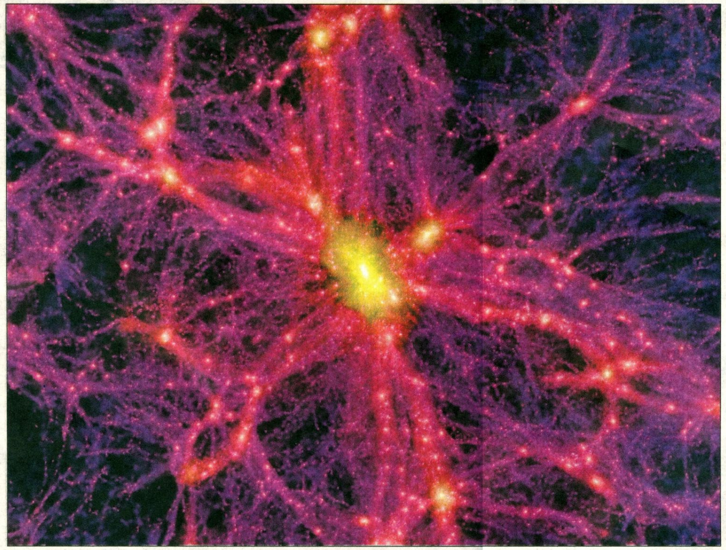
£675k SRIF-2 -- ICC
£55k SRIF-2 -- Sussex
£75k PPARC – Virgo

University of Durham

THE SUNDAY TIMES

By Jupiter, the scientists were right

The simulated universe has confirmed a dark truth, says **Bryan Appleyard**



The picture of the universe revealed by the most complex program so far run reveals Einstein's 'greatest blunder' may turn out to be his greatest triumph

Many years ago at some conference I got horribly drunk with a group of physicists and cosmologists. "You are all," I slurred, "making this shtuff up as you go along . . . No evidence, whatshoever."

This was a bit harsh, but only a bit. At the level of the very small, there was some experimental evidence for current theories generated by huge particle accelerators. At the level of the very large, however, there was none. When it came to stars, galaxies and the universe as a whole, all we could do was sit back, watch and make up bedtime stories.

There is no way, on this scale of space and time, that experiments could be conducted. All we could do, in the words of Stanislaw Lem, the great science-fiction writer, was "Out of mathematics . . . build wagons to carry us into the non-human realms of the world."

At about 3am without a leg to stand on, in any sense of the term, the one remaining scientist slumped in defeat.

After last week, however, he would have won and I would have lost. Cosmology has, at last, conducted an experiment that seems to prove the cosmologists are right. The universe is, indeed, absurdly weird and unavoidably, irrevocably doomed.

What happened last week was that a paper was published in Nature magazine entitled Simulations of the Formation, Evolution and Clustering of Galaxies and Quasars. This is a touch understated. What its 17 authors would like to have called their paper was something along the lines of Holy Shit! We've Cracked It! but scientific etiquette demands a certain restraint.

What this European team, headed by Carlos Frenk, a Durham University professor, had done was to build a computer model of the universe. This is not easy, because you have to track the movement of trillions of particles from the Big Bang onwards. This has only just become possible thanks to the increasing speed and scale of computer processing and memory and the greater sophistication of the algorithms — software — that makes them work.

Having spent 20 years preparing their Millennium Simulation, the team — known as the Virgo consortium — took over a supercomputer in Germany for a month, shutting down large parts of German science in the process. They then took a deep breath, tapped whatever passed for an enter key and sat back, watched and waited.

What they saw was a cosmos expanding outwards into a cube with sides 2.23 billion light years in length. This was as much as the model could handle. And what they found was a region of space with about 20m galaxies. This is what they expected, because that is exactly the galaxy density that occurs in the real universe. In other words, the assumptions built into the computer model — a summary of what we now think the universe is like — had proved correct.

"In fact," Frenk tells me, "we built in very few initial assumptions." The key one was that the laws of physics would be the same at all places and all times.

This is by no means obvious and had always been a statement of unsubstantiated faith. This computer run, however, produced something that looks like the real cosmós on the basis of the absolute consistency of physical law, so the faith has its first glimmer of real evidence.

The model consisted of information arising from phenomena such as cosmic background radiation — the last, faint echoes of the Big Bang — and very little else.

It was, of course, a very simplified picture of a small region of space. Galaxies, for example, were only represented by about 1,000 particles. In reality they consist of trillions upon trillions. But even at that level of simplification, the computing effort involved is stupendous. The German computer ran about 500,000,000,000,000,000 calculations to take its virtual cosmos from the Big Bang to the present day, a time period of, we think, about 13.7 billion years.

Of course, these simplifications mean there could be errors, even gross errors in the model. Furthermore, there can be hidden assumptions built into the most sophisticated experiments. The fact the experiment produced a cosmos so like the real one may be evidence that it is right or it may be a cause for scepticism — have these scientists just seen what they want to see?

Over the next few years these possibilities will be tested to destruction. For the moment there can be little doubt that, whatever happens in the future, Frenk and his colleagues have got something very big, very right. But what exactly have they done?

Well, the reason cosmology has always been such a weird science is that it only has one universe to work with. Biologists have billions of different types of cells, chemists have thousands of compounds, physicists have a positive zoo of elementary particles, but cosmologists have just the one cosmos. It can't be compared with anything else and it's too big and too old to put on a microscope slide or whack round a particle accelerator. But now, at last, there are two universes to work with and we can do what we like with the virtual one. I can almost hear Frenk dancing at the other end of the phone when he talks about this. Real, experimental cosmology can now begin.

But because the universe created by the model looks so exactly like the one we know, some experimental results are already clear. Crucially, the "dark matter" predicted by modern cosmology seems to be real. The problem with the universe used to be that it was too skinny. All our calculations suggested it should weigh more than twice as much as the sum total of all the matter we could see. The theory of dark matter simply said that there was a lot more stuff we couldn't see. The model seems to show that this is, indeed, true.

A more human, and very moving, drama lies behind the model's demonstration that something called "dark energy" also exists. Einstein's theory of relativity predicted that the universe would expand outwards from the Big Bang but then, gradually, the force of gravity would slow down the expansion and the universe would contract inwards. Observational evidence in the 1930s — from astronomer Edwin Hubble — did, indeed, prove that the universe was expanding.

But Einstein never liked the instability of this picture and invented a force called the "cosmological constant", which would counteract the effect of gravity. Everybody told him he was wrong and he spent the latter half of his life in fruitless pursuit of this stabilising force. He died after having admitted it had been the greatest blunder of his career.

"Would we could all make such blunders!" exclaims Frenk.

For the truth is that dark energy seems to behave rather like the cosmological constant — although we don't yet know whether the force is constant in the way that Einstein intended. But the model certainly shows it's there and that Einstein's "greatest blunder" may yet prove to be his greatest triumph.

So great news for Einstein but, I'm afraid, it is terrible news for humanity. I asked Frenk if they had let the model run into the future. It has always been a great dream of scientists that, if they could know as much as possible about the present, they could predict the future. Pierre-Simon de Laplace, the great French mathematician, speculated in the early 19th century about a mind that knew the position and properties of every particle in the present.

"For such an intellect nothing could be uncertain; and the future just like the past would be present before its eyes."

The Millennium Simulation is a Laplacean idea. But they didn't run it into the future. Frenk says it was hard enough getting it up to the present. Some smaller simulations did, however, "inadvertently" run on to draw a future universe. "It's pretty grim," says Frenk.

The dark energy just makes the whole thing expand for ever. This expansion accelerates. Eventually regions of space are receding from us at more than the speed of light. This is not, as is popularly believed, impossible. What is impossible is the transmission of information at greater than the speed of light. What happens to objects moving away from us at greater than light speed is that, for us, they cease to exist in our reality because we cannot retrieve information about them.

In about 10 billion years, if the model is correct, astronomers will only be able to see our galaxy, the rest of the universe will have vanished. And not long, in cosmic terms, after that everything will dissipate into a reactionless, empty desert and nothing will ever happen again.

So the cosmologists have, at last, their experiment and we have our apocalypse, a universe that does, indeed, end with a whimper rather than a bang. It's another, but much better bedtime story with a beginning, a middle and an end at which, in spite of our most passionate protests, the lights must go out. And the storyteller? I guess we were just making that "shtuff" up too.