

DiRAC-3: Cosmology

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Durham

Cosmology and HPC

13 UK universities active in cosmology using DiRAC

(>35 senior academics → >120 researchers)

Consortia and main areas of activity in HPC:

Cosmos – Early universe, CMB, large-scale structure

(Cambridge, Hull, Imperial, Manchester, Nottingham, Oxford, Portsmouth, Sussex, UCL)

Horizon – Galaxy formation

(Oxford, Cambridge, Paris, Zurich)

Virgo – Galaxy formation, large-scale structure, dark matter

(Cambridge, Durham, Edinburgh, Liverpool, Nottingham, Manchester, Sussex, Beijing, Leiden, Heidelberg, Munich, U. Victoria)

IoA Cambridge – Galaxy formation

Surrey – Galaxy formation, dark matter

The big Bang

Dark matter

Two revolutionary ideas
proposed around 1980

Cosmic inflation
→ initial conditions

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

15 thousand million years

1 thousand million years

300 thousand years

3 minutes

10^{-8} seconds

10^{-34} seconds

10^{-43} seconds

10^{32} degrees

degrees

10^{10} degrees

10^9 degrees

6000 degrees

18 degrees

3 degrees K



1980s:

- A well-defined theory of the initial conditions for the formation of cosmic structure
- Growth mechanism: gravitational instability driven by non-baryonic dark matter

Formation of cosmic structure → problem ideally suited for HPC

The big Bang

Dark matter

Λ CDM: standard model of cosmology
— one of the great successes in physics of past 50 years

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The big Bang

Dark matter

Λ CDM: largely developed using
supercomputer simulations

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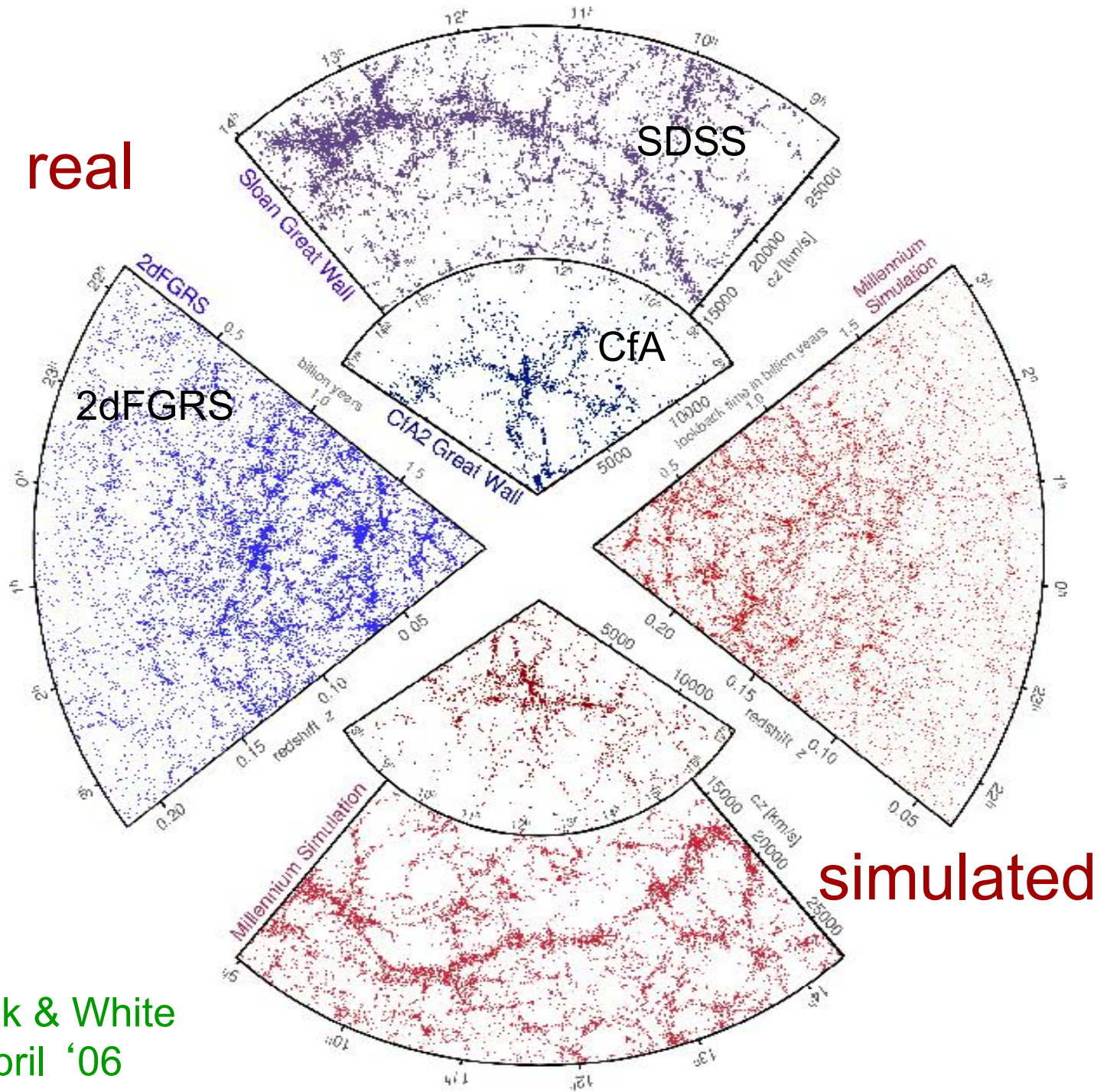
10^9 degrees

6000 degrees

18 degrees

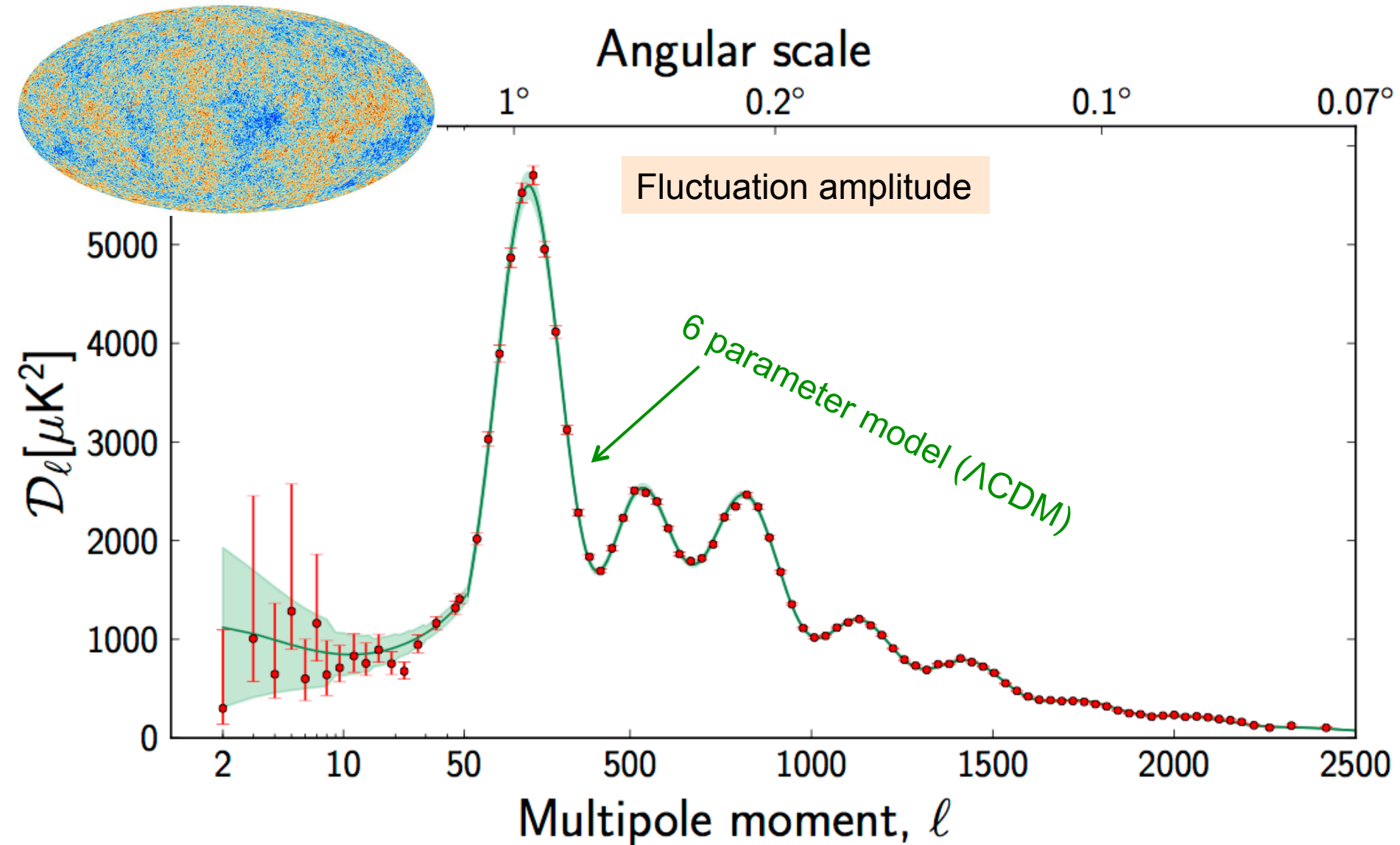
3 degrees K

real



simulated

Planck: CMB temperature anisotropies



Planck coll. 2015

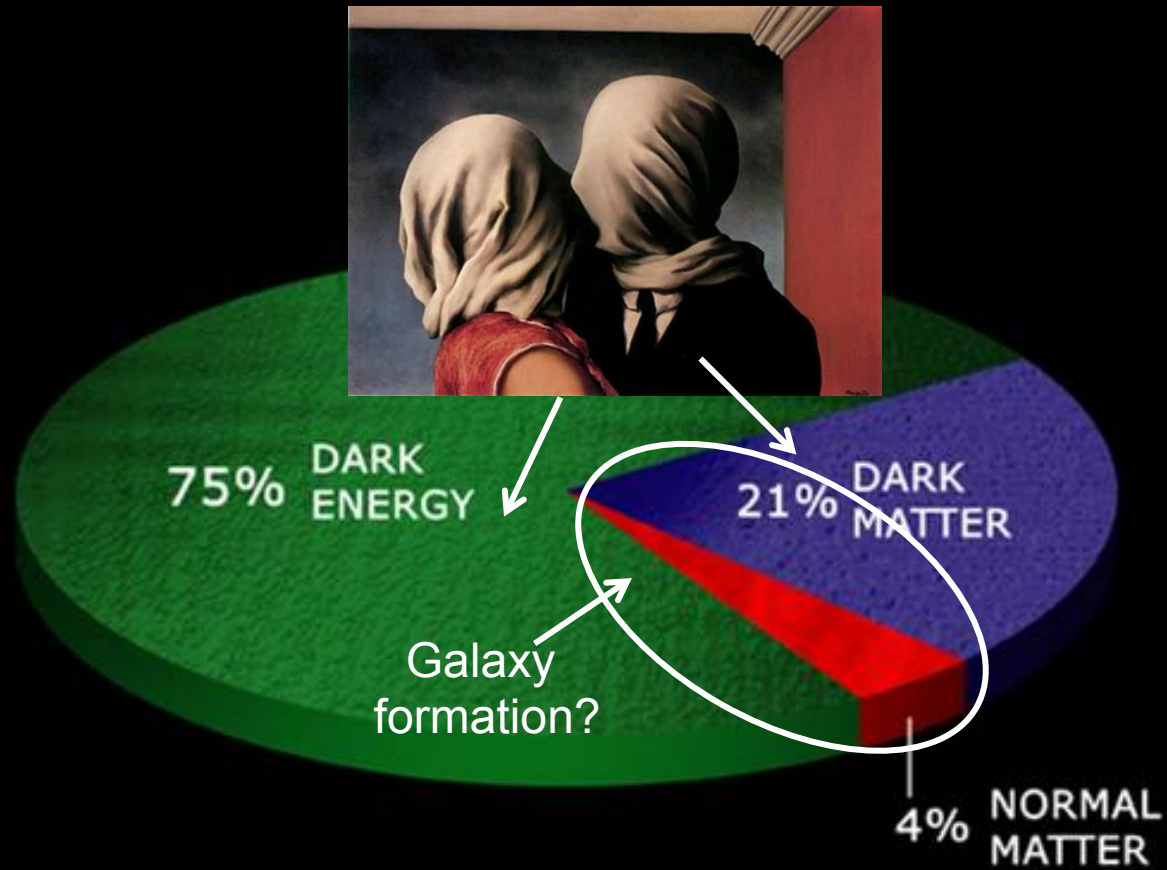
The six parameters of minimal Λ CDM model

		<i>Planck</i> +WP	
Parameter		Best fit	68% limits
6 model parameters	$\Omega_b h^2$	0.022032	0.02205 ± 0.00028
	$\Omega_c h^2$	0.12038	0.1199 ± 0.0027
	$100\theta_{MC}$	1.04119	1.04131 ± 0.00063
	τ	0.0925	$0.089^{+0.012}_{-0.014}$
	n_s	0.9619	0.9603 ± 0.0073
	$\ln(10^{10} A_s)$	3.0980	$3.089^{+0.024}_{-0.027}$

A 40σ detection of non-baryonic dark matter using only $z=1000$ data!



The content of our universe



The big Bang

Dark matter

Cosmic inflation
→ initial conditions

- Early Universe
- Dark matter
- Large-scale structure
- Galaxy formation

radiation
particles
heavy particles carrying the weak force
quark
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deuterium
helium
lithium

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degrees

10^{10} degrees

10^9 degrees

6000 degrees

18 degrees

3 degrees K

Cosmology and HPC

A hugely rich and varied subject

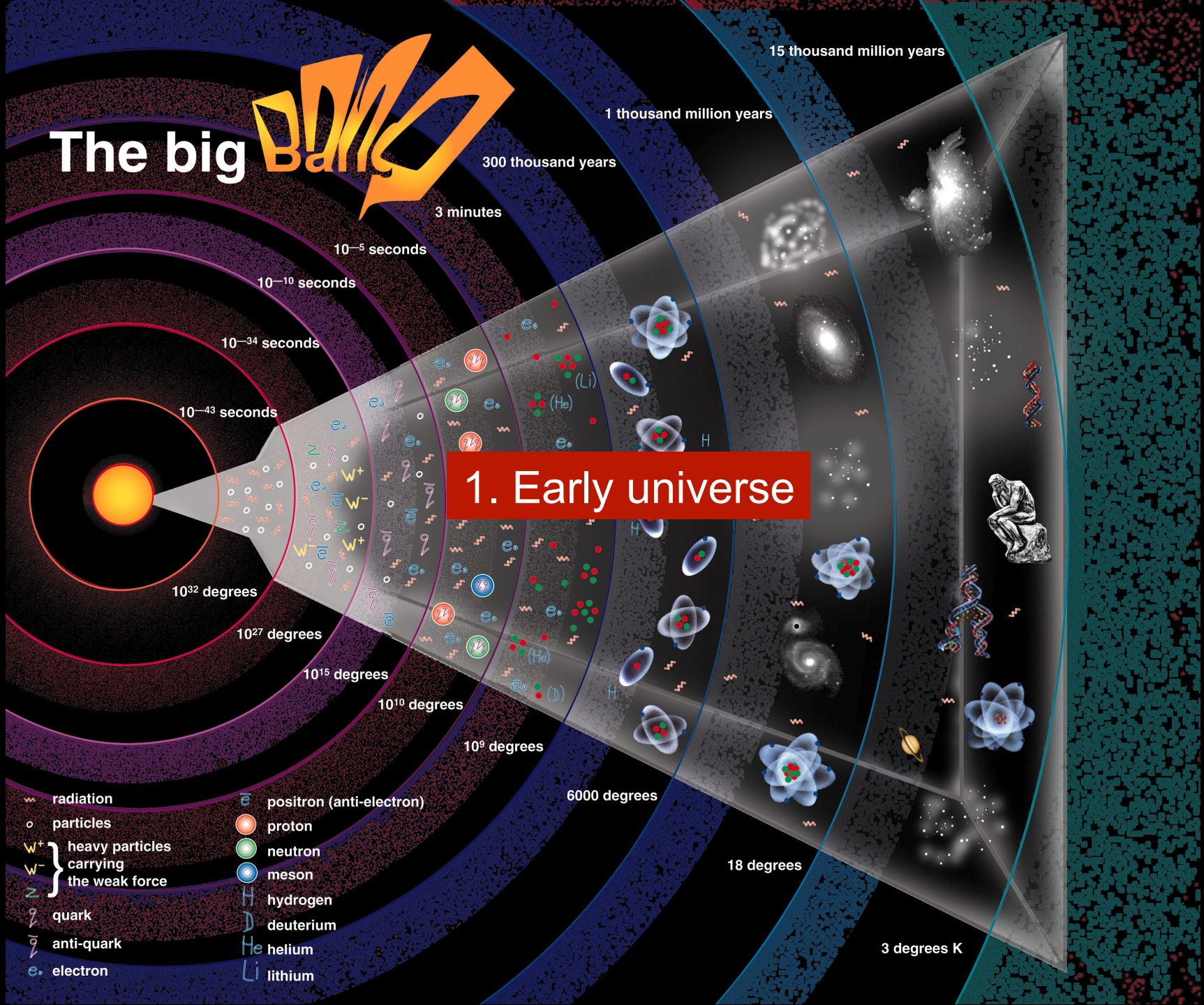
- Length scales: from parsecs to gigaparsecs
- Timescales: from 10^{-35} s to 10^{10} yrs
- Physics: from gravity (and modified gravity) to MHD
- Processes: gravitational clustering, dynamics of dissipative fluids, star formation, chemical evolution, black hole formation, active galactic nuclei, feedback

→ Requires HPC

The big Bang



1. Early universe

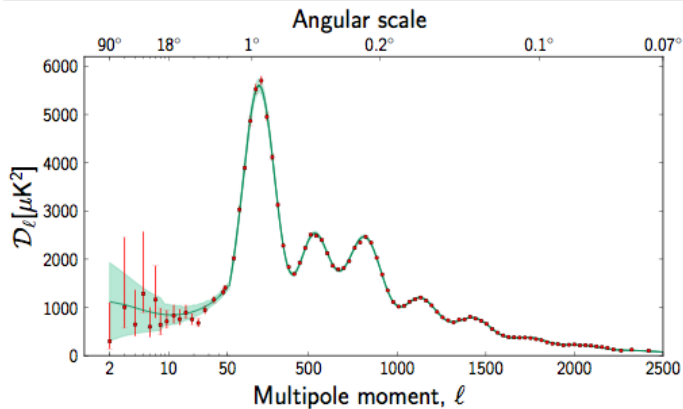


COSMOS Consortium: PLANCK

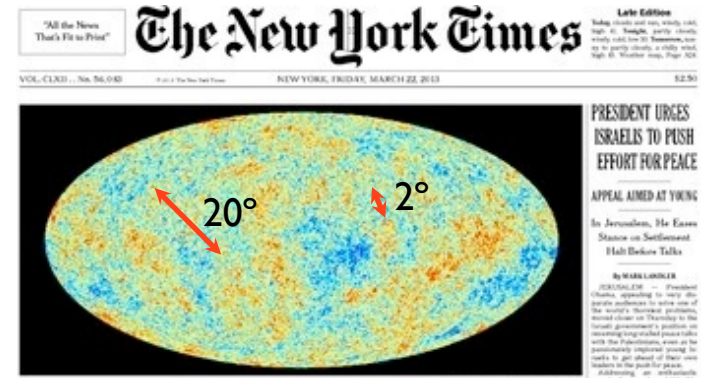
From P. Shellard

The ESA Planck Satellite provides the finest cosmological dataset available

- DiRAC (HPCS & COSMOS) enabled UK researchers to leverage leading roles
- Huge impact, some of highest cited papers in all physics (*Top-5 with 6422 cites*)



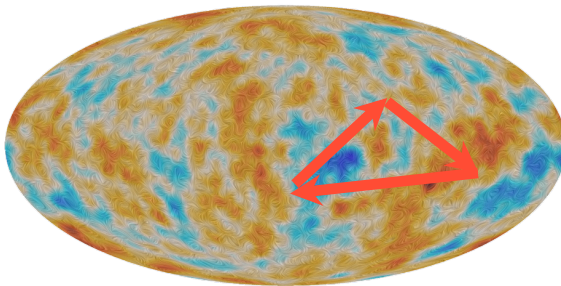
Power spectrum



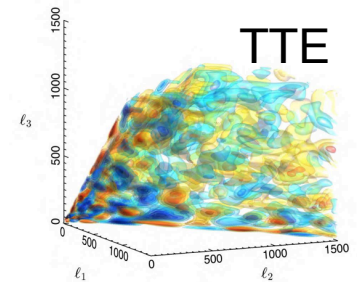
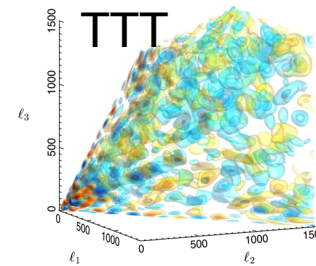
Planck 2015 with CMB polarisation:

- reionization/formation of the first stars
- highest precision cosmic parameters
- tensors/re-analysis of BICEP2 claims

Planck 2015 Polarization



Bispectrum



New windows on the Universe (*crossing qualitative thresholds*):

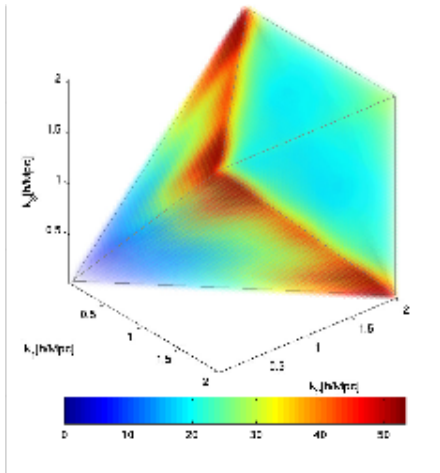
- World-leading analysis of **CMB non-Gaussianity** and **gravitational lensing** (25σ)
- **CMB bispectrum** in 3D: most stringent inflation tests, fundamental theory insights

COSMOS: Testing Inflation

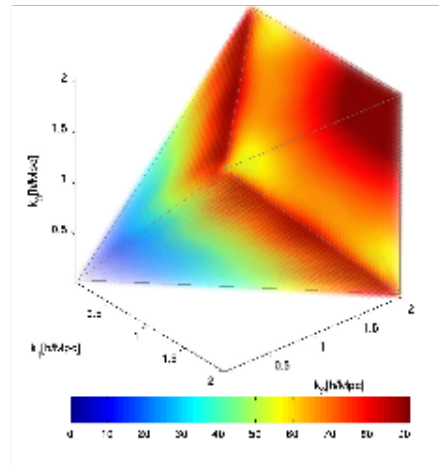
Planck data will remain a key benchmark for cosmology over the next decade

Goals: • **Cross-correlation** of Planck with STFC-funded **DES, Euclid, LSST** etc

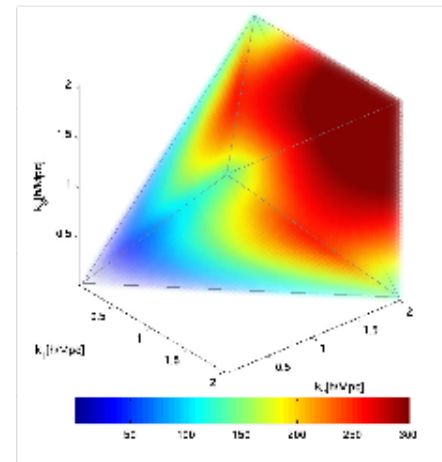
- Joint analysis to yield **most accurate estimates of cosmic parameters**
- **Gravitational lensing** strong independent constraints, **calibrate weak lensing**
- Resolve tensions with **SZ cluster** analysis • Constrain **modified gravity** theories



$z=4$



$z=2$



$z=0$

The 3D matter bispectrum of large-scale structure

Highlight: *IPCC Xeon Phi* modernization of Planck bispectrum code (>100x speed-up)

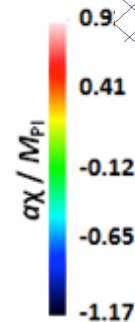
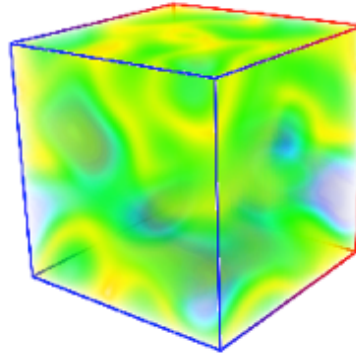
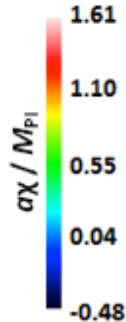
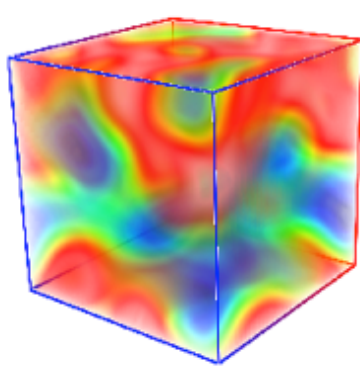
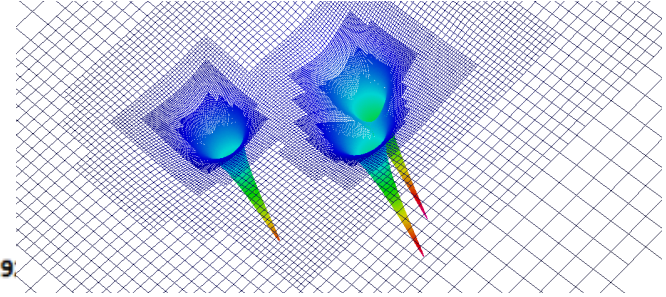
- World-leading Planck **NG pipeline** adapted for **large-scale structure**
- **Joint power-/bi-/trispectrum** analysis a new diagnostic: primordial & late-time

COSMOS: Early Universe

Inflationary dynamics, phase transitions and gravitational waves

COSMOS researchers pioneered modelling of inflation, phase transitions, grav. waves

- Highlights** • **Strongest CMB constraints** from Planck on inflationary models and cosmic defects
- First fully **AMR general relativity** code: GRChombo (N > 2 black holes, nonlinear backreaction)



Multiple black holes (GRChombo)

Anisotropic GW backgrounds from inflationary preheating

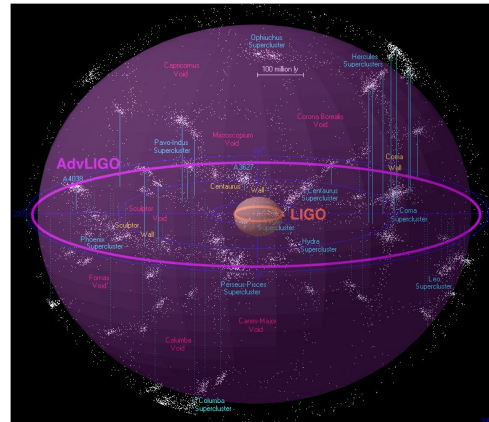
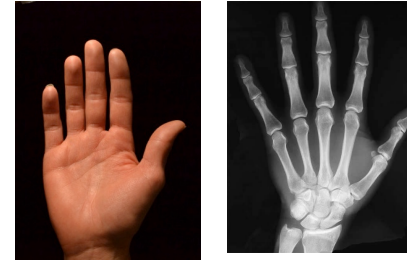
- Goals:** • World-leading nonlinear early universe simulations (e.g. GRChombo, LATFIELD)
- **GW backgrounds** from inflation **preheating**, **bubble collisions**, **cosmic strings** yielding new constraints on primordial theory from **Advanced LIGO**

HPC needs: *Heterogeneous - SMP, cluster, many-core - 32TB RAM, >100M core-hrs*

Gravitational Waves

From P. Shellard

- Gravitational Waves (GW) → Qualitatively new view of universe
- Detectors **LIGO**, **VIRGO** upgraded to **advanced** status
- New detectors: **KAGRA** (Japan), **LIGO-INDIA**
- ~1000 times larger volume → GW detection in ~3-7 yr



- GW observations need **catalog** of theoretical waveforms
- Like **fingerprints**: find template best fitting observed data
- Construct **Catalog**: **Numerical Relativity + Analytic Methods**
- **Numerical Relativity**:
 - ~100 – 10000 **cores** for **weeks** or **months**
 - Need at least ~10000 **simulations**

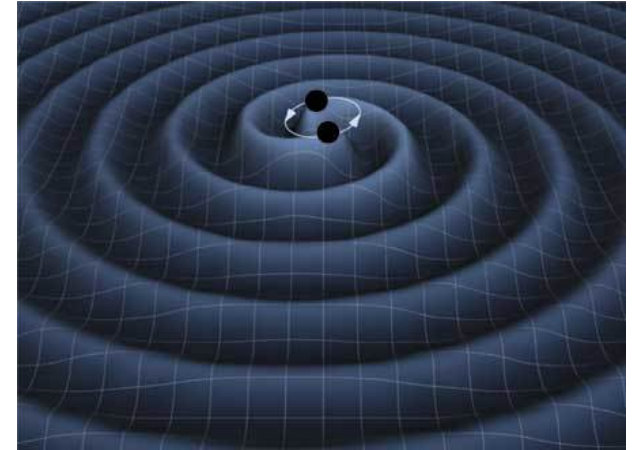


GW Observations

From P. Shellard

Applications in Astronomy & Physics

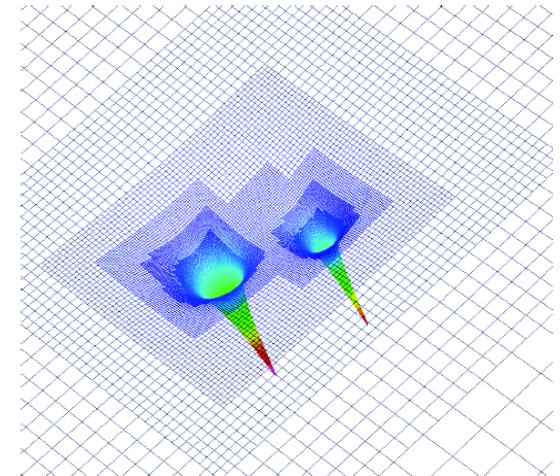
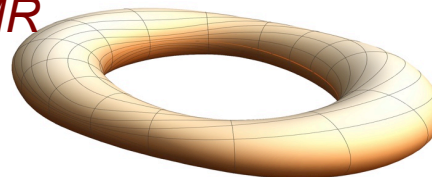
- Supermassive black-hole (BH) **formation history**
- **Kicks**, black-hole **ejection from galaxies**
- Cosmic **distance ladder**
- Bound **photon mass** thru BH spin measurements
- Neutron star (NS) **equation of state**
- Explore **modified theories of gravity**
- **GRBs**: Supernova core collapse, BH-NS binaries
- High-energy physics: BH formation at LHC, AdS/CFT correspondence



BH binary emitting GWs

HPC requirements and goals

- $\sim 5 \times 10^7$ core hours, fast network and I/O, ~ 10 Tb memory
 - **MIC architecture** → **Faster codes**
 - Many applications need **full AMR**
 - **More flexible codes**
- **GRChombo**



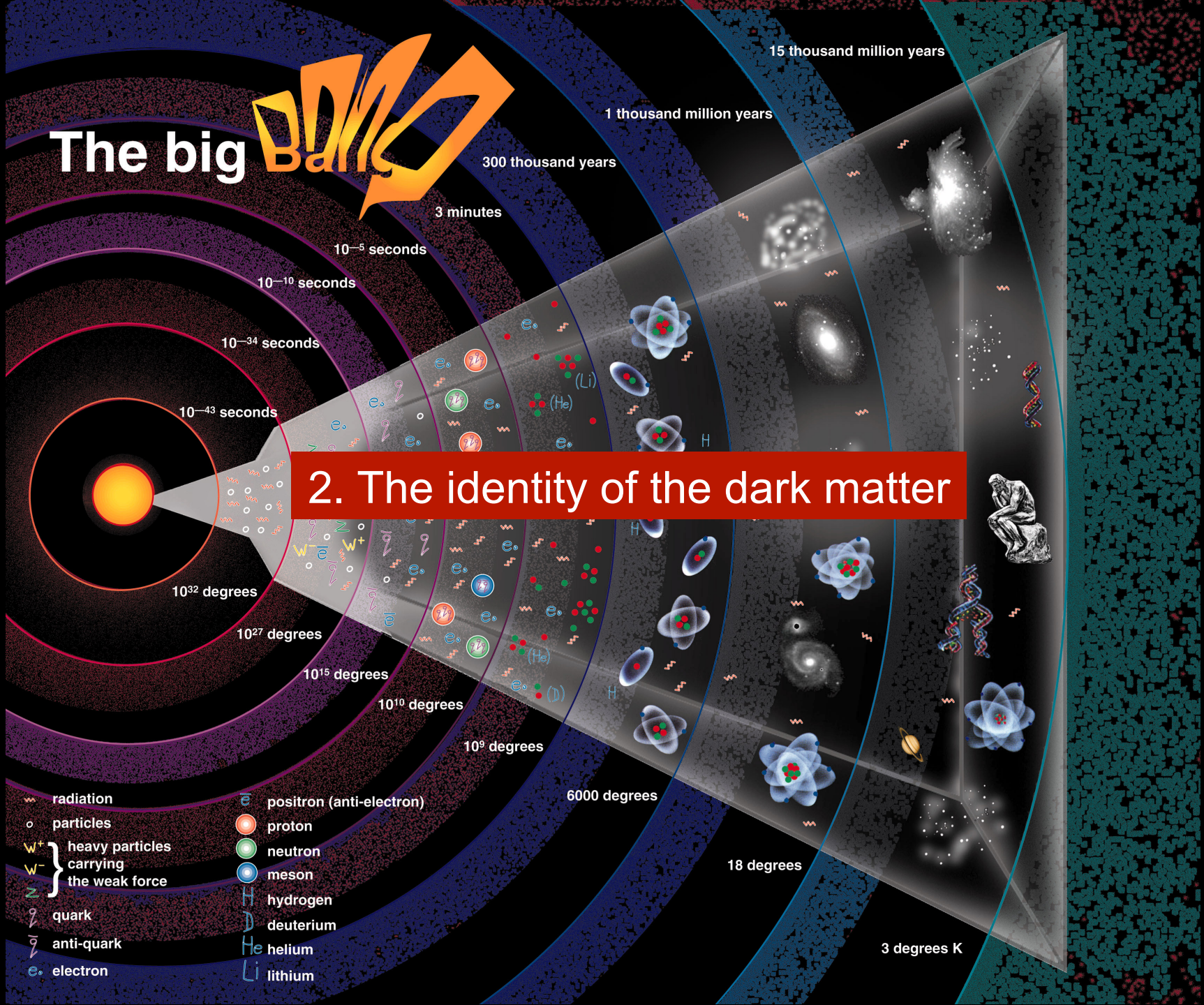
Full AMR with GRChombo

Black Ring on GRChombo

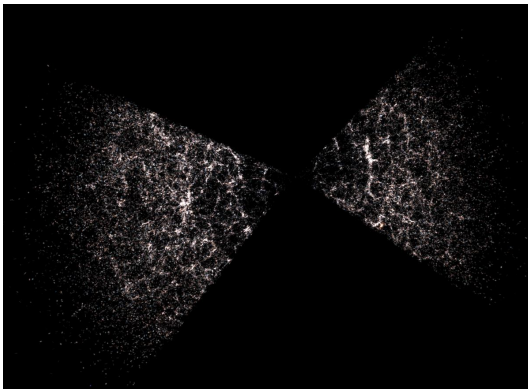
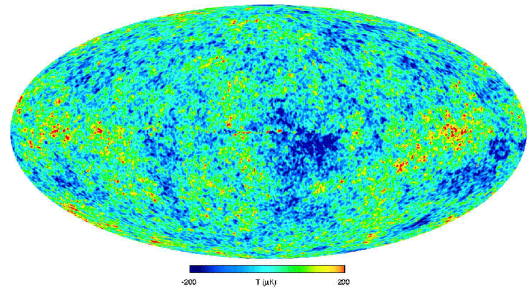
The big Bang



2. The identity of the dark matter



The cosmic power spectrum: from the CMB to the 2dFGRS

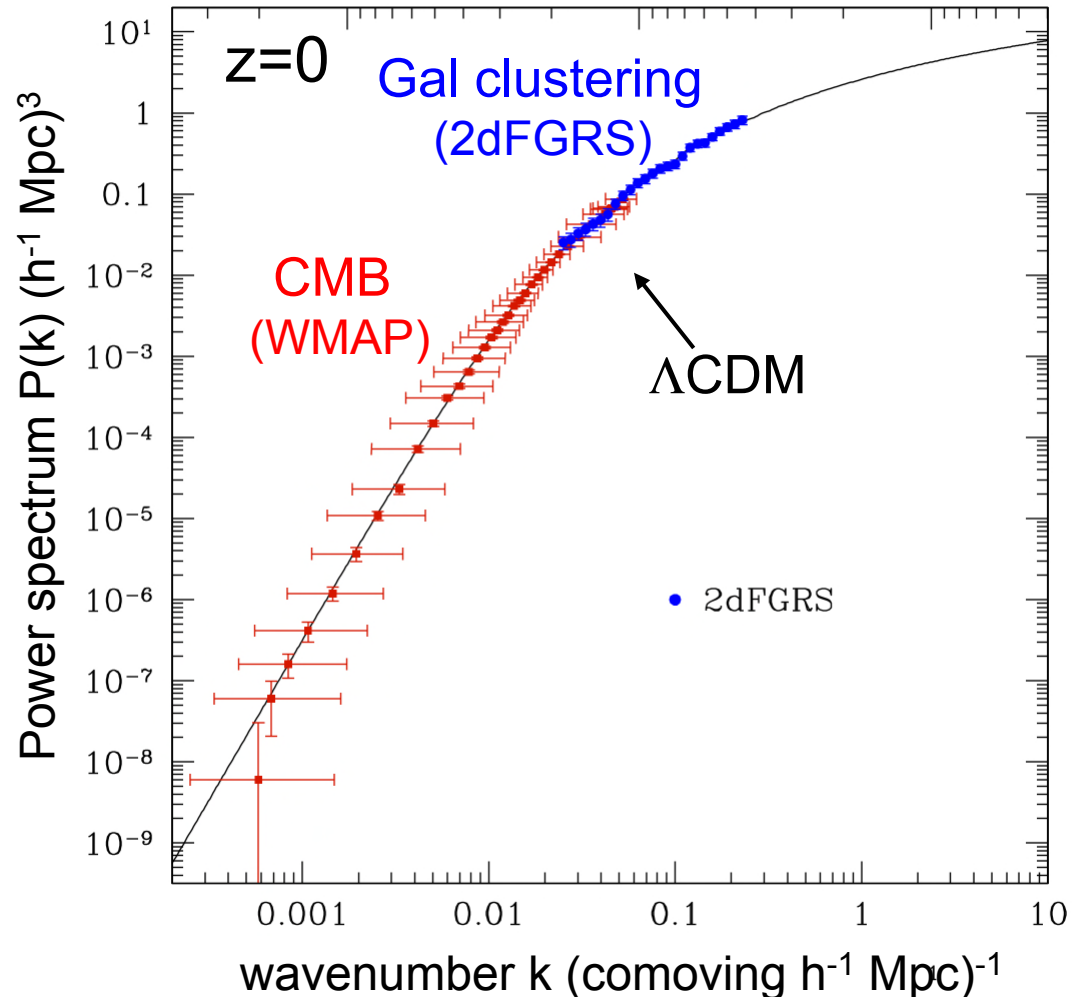


$z \sim 1000$

$\text{Log } k^3 P(k)$

wavelength k^{-1} (comoving h^{-1} Mpc)

1 000 100 10



⇒ Λ CDM provides an excellent description of mass power spectrum from 10-1000 Mpc

Sanchez et al 06

The cosmic power spectrum: from the CMB to the 2dFGRS

Free streaming $\rightarrow$

$$\lambda_{\text{cut}} \propto m_x^{-1}$$

for thermal relic

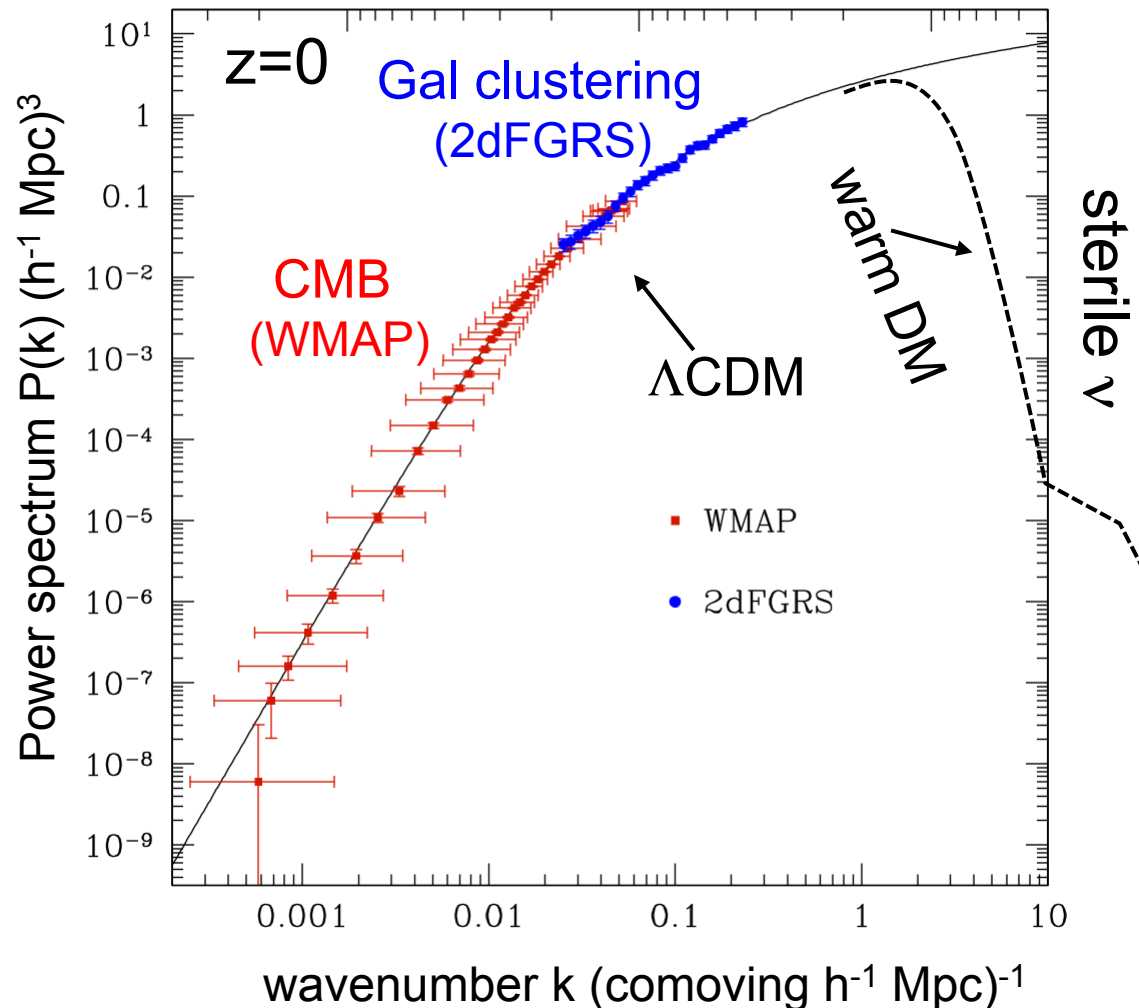
$$m_{\text{CDM}} \sim 100 \text{ GeV}$$

$$\text{susy}; M_{\text{cut}} \sim 10^{-6} M_{\odot}$$

$$m_{\text{WDM}} \sim \text{few keV}$$

$$\text{sterile } \nu; M_{\text{cut}} \sim 10^9 M_{\odot}$$

Log $k^3 P(k)$ wavelength k^{-1} (comoving h^{-1} Mpc)



cold dark matter

VIRGO

warm dark matter



Lovell, Eke, Frenk, Gao, Jenkins, Wang, White, Theuns,
Boyarski & Ruchayskiy '12

Astrophysical key to identity of dark matter

→ Subgalactic scales

(strongly non-linear → require simulations)

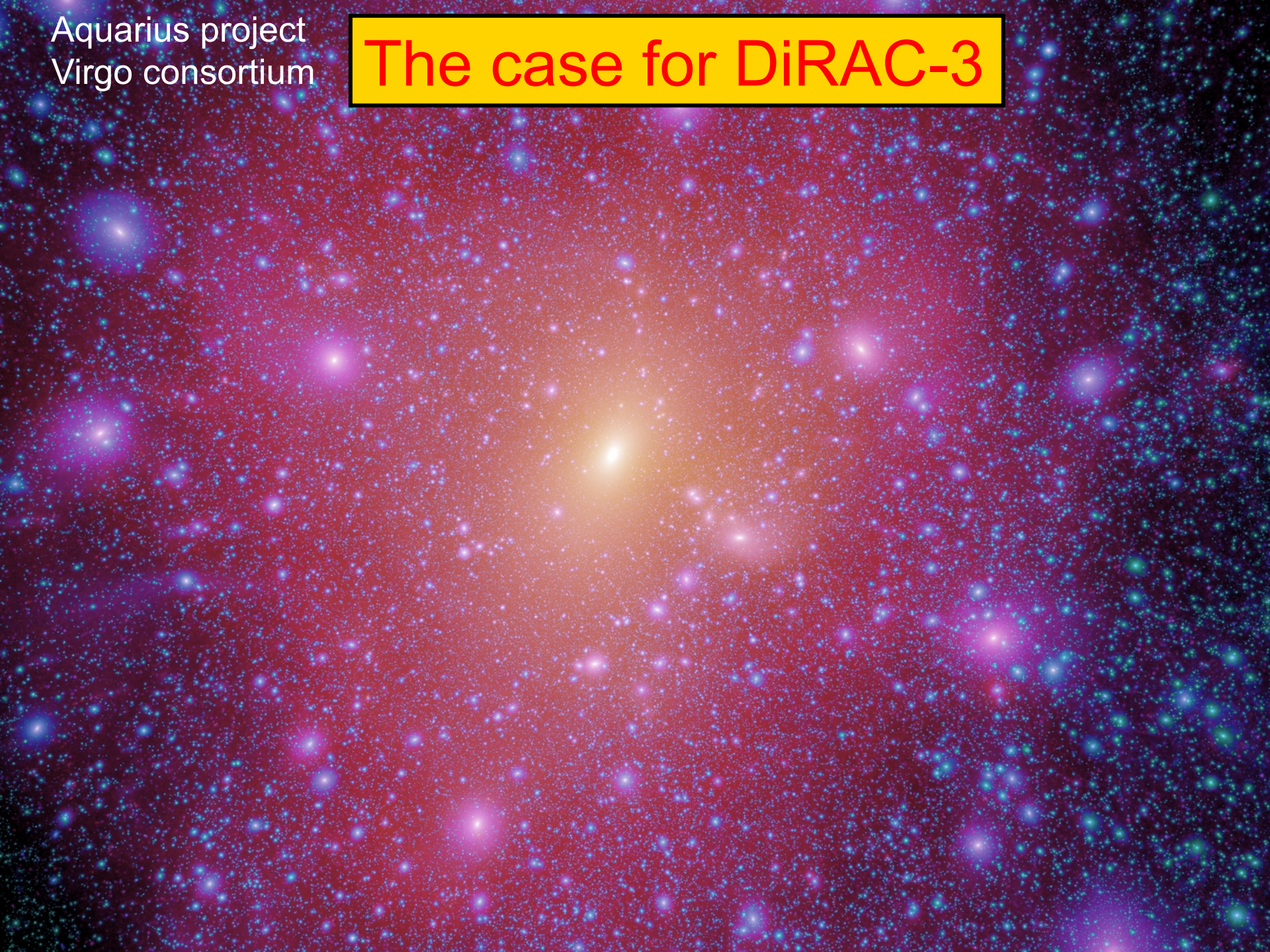
Can rule out candidates (inc CDM) or constrain particle properties

e.g four problems on dwarf galaxy scales that could rule out CDM:

- Core-cusp
- Too big to fail
- Missing satellites
- Satellite planes

Aquarius project
Virgo consortium

The case for DiRAC-3



The case for DiRAC-3

Even best current simulations cannot resolve internal structure of halos and subhalos or model baryons reliably

Challenges

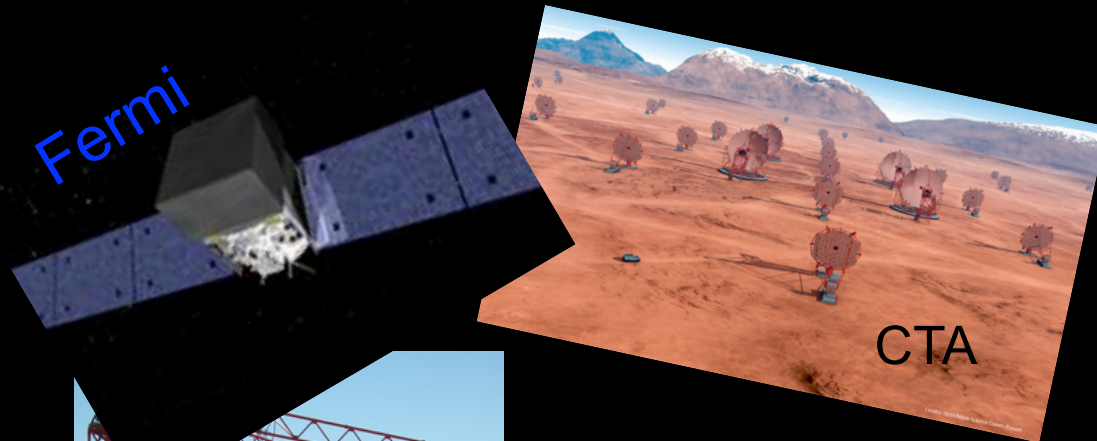
- New generation of very high resolution simulations to guide direct and indirect experimental searches
- Indirect (CDM): Intensity $\sim \rho^2$, need Earth mass resolution!
- Direct – need a realistic “standard halo model”
- Simulations for different types of DM (e.g. sterile neutrinos, self-interacting DM)
- Baryon effects (see later)

Requirements

Memory intensive simulations: petascale cpu & data storage

The search for dark matter

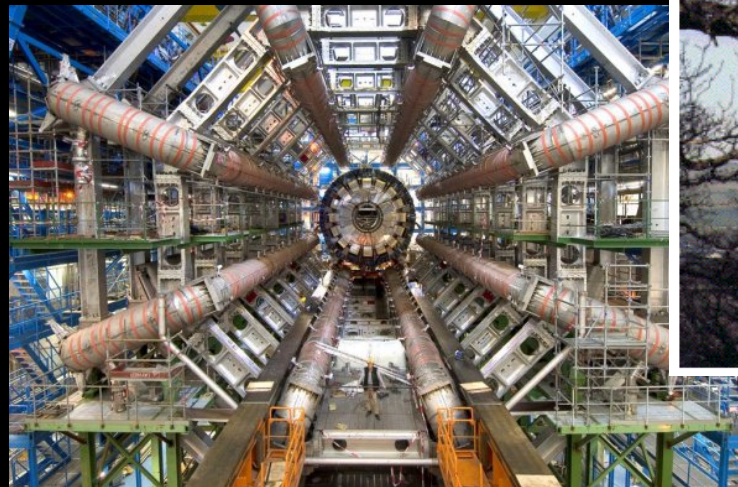
Annihilation radiation



Decay radiation



Direct detection



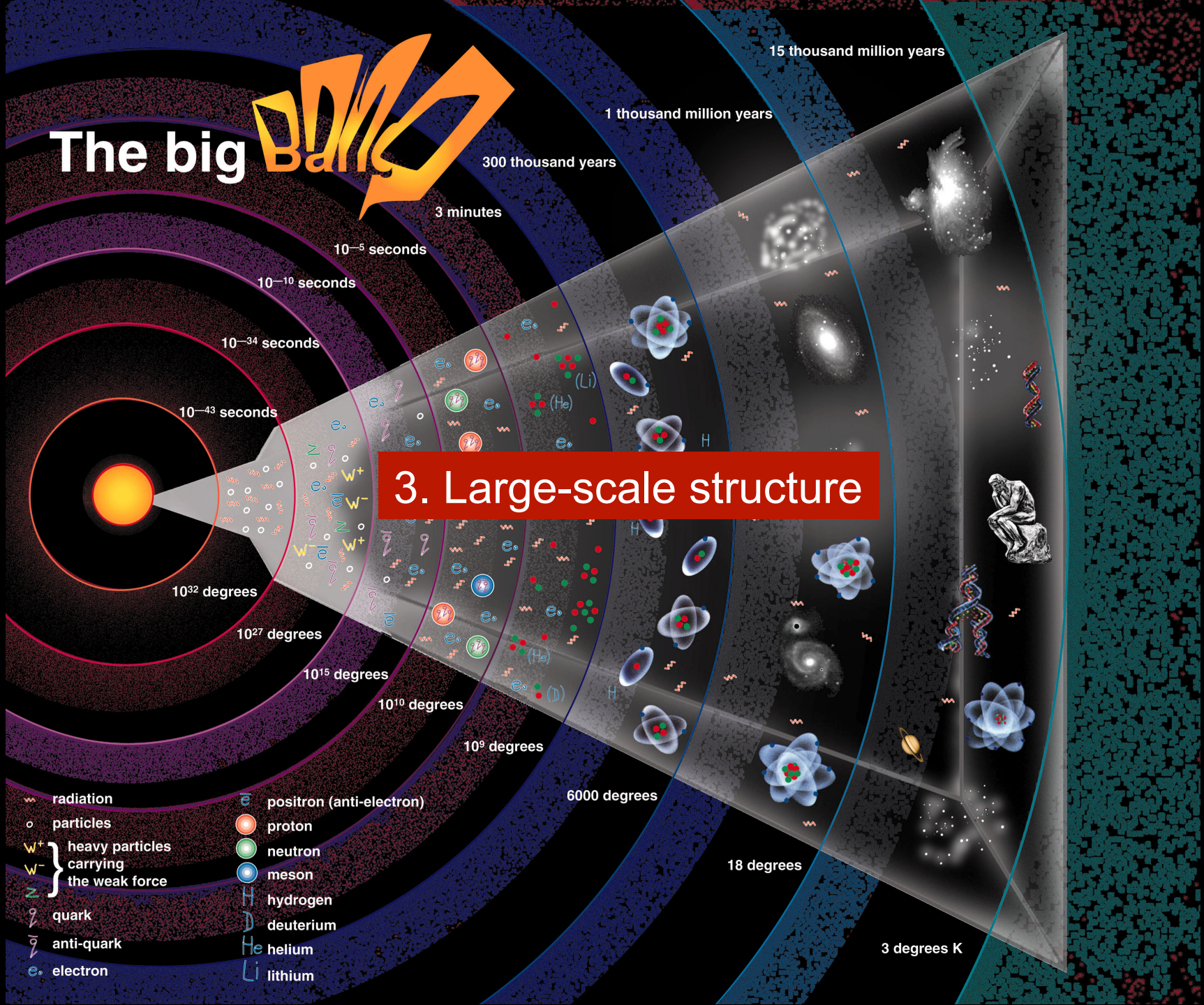
Accelerator experiments

UK DM search
(Boulby mine)

The big Bang



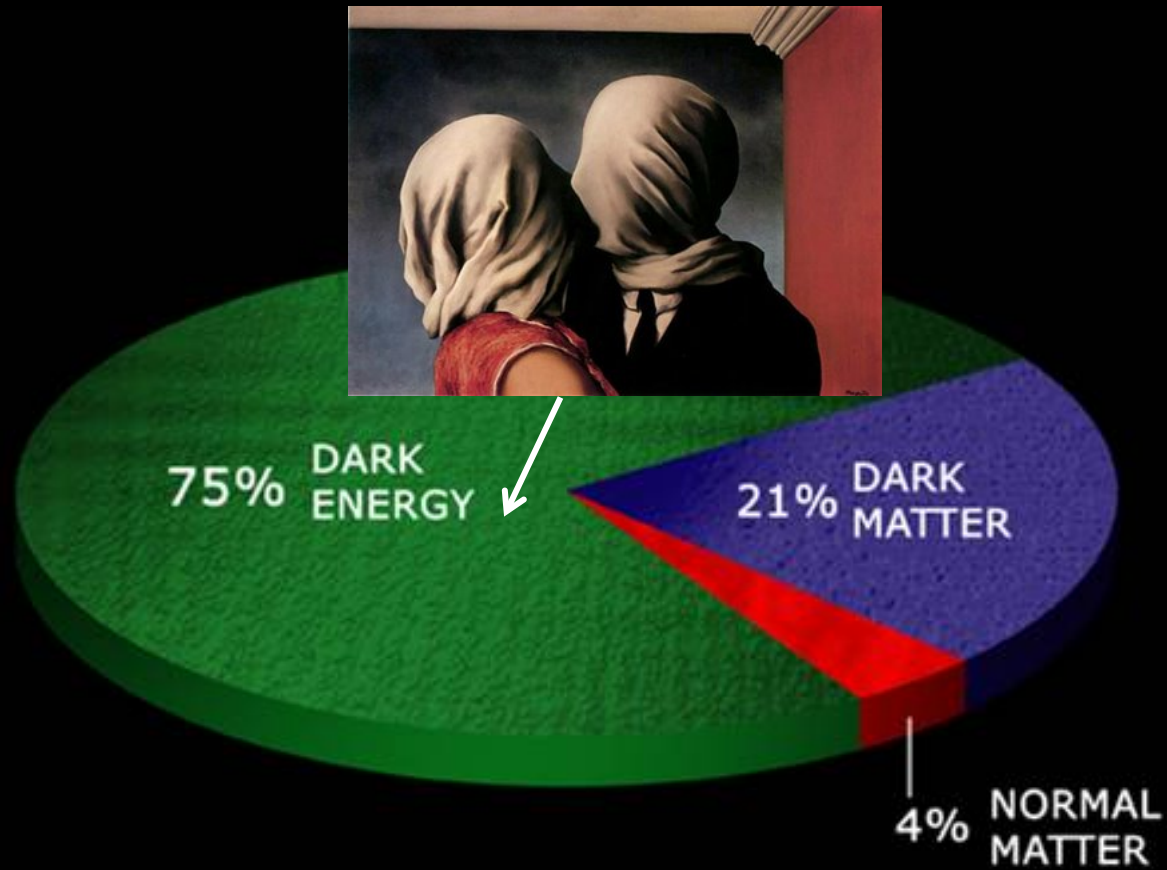
3. Large-scale structure





ICC

The content of our universe





The content of our universe



Target “baryon acoustic oscillations”, structure growth rate



Baryon acoustic oscillations in 2dFGRS

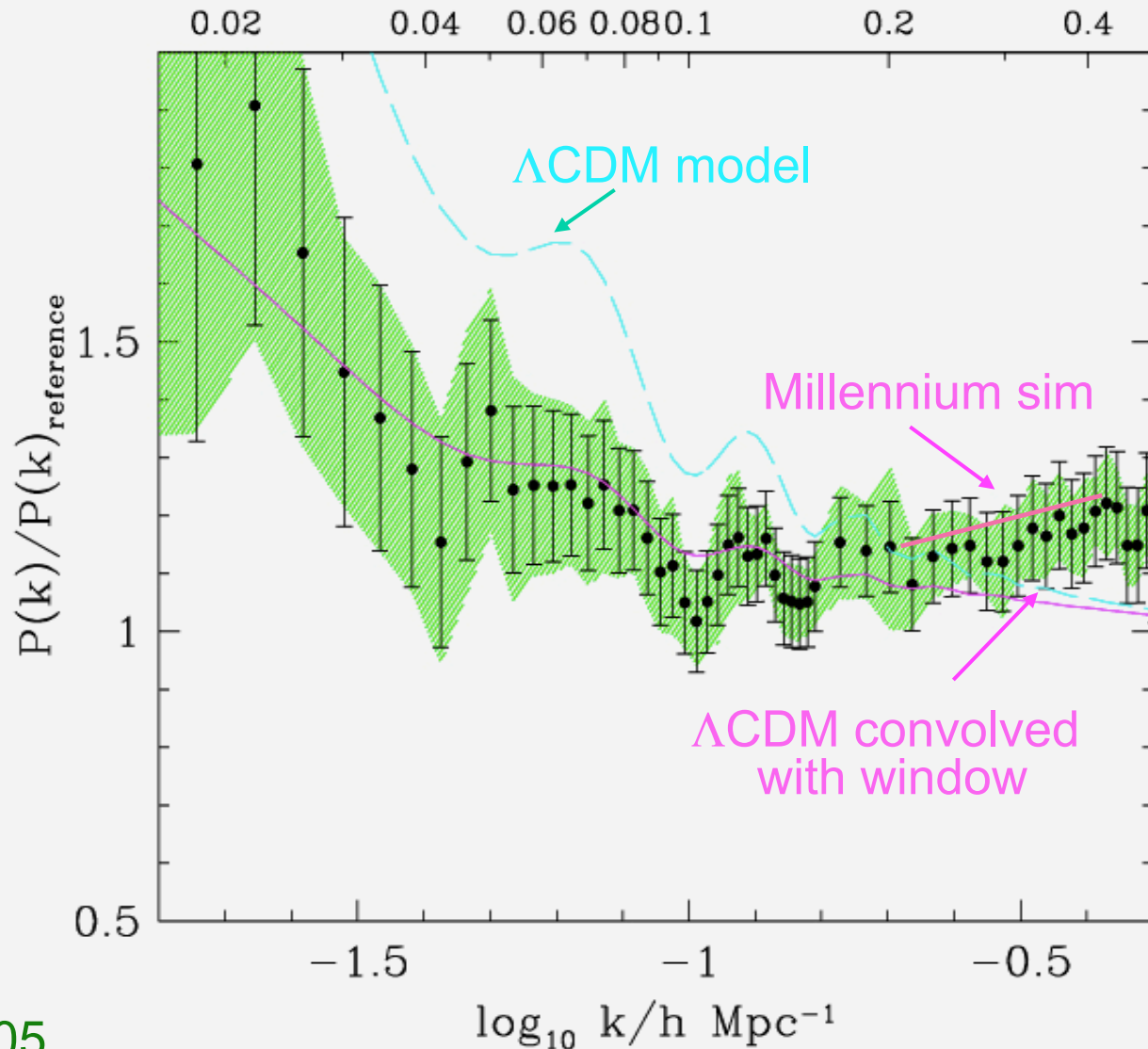
Baryon oscillations conclusively detected in 2dFGRS!!!

Demonstrates that structure grew by gravitational instability in Λ CDM universe

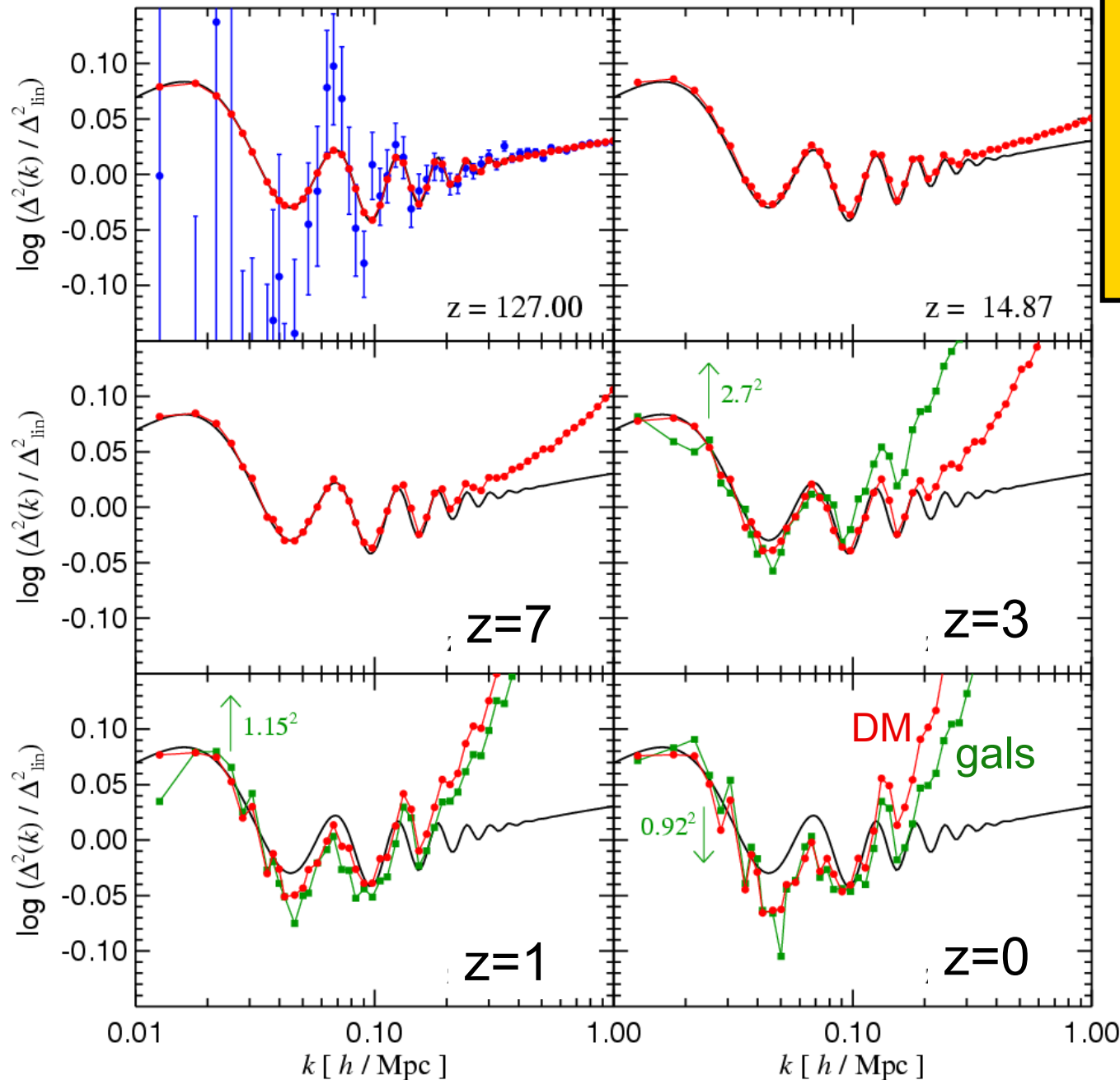
Also detected in SDSS LRG sample (Eisenstein et al 05)

Cole, Percival, Peacock, Baugh, Frenk + 2dFGRS '05

$$P(k) / P_{\text{ref}}(\Omega_{\text{baryon}}=0) \quad k/h \text{ Mpc}^{-1}$$



Millennium simulation



Baryon
oscillations in
the galaxy
distribution

Power spectrum
from MS divided
by a baryon-free
 Λ CDM spectrum

Galaxy samples
matched to
plausible large
observational
surveys at given z

Springel et al 2005

Understanding the accelerated expansion

At present 3 possibilities :

- Einstein's cosm. const. Λ – constant (vacuum?) energy density
- Quintessence – a variable (in time and space) form of Λ
- Modifications of General Relativity – e.g. $f(R)$

Predictions for observables require large cosmological simulations

VIRG

The MXXL

Angulo et al. '12

Λ CDM

Bigger than the
Millennium run
by factors of

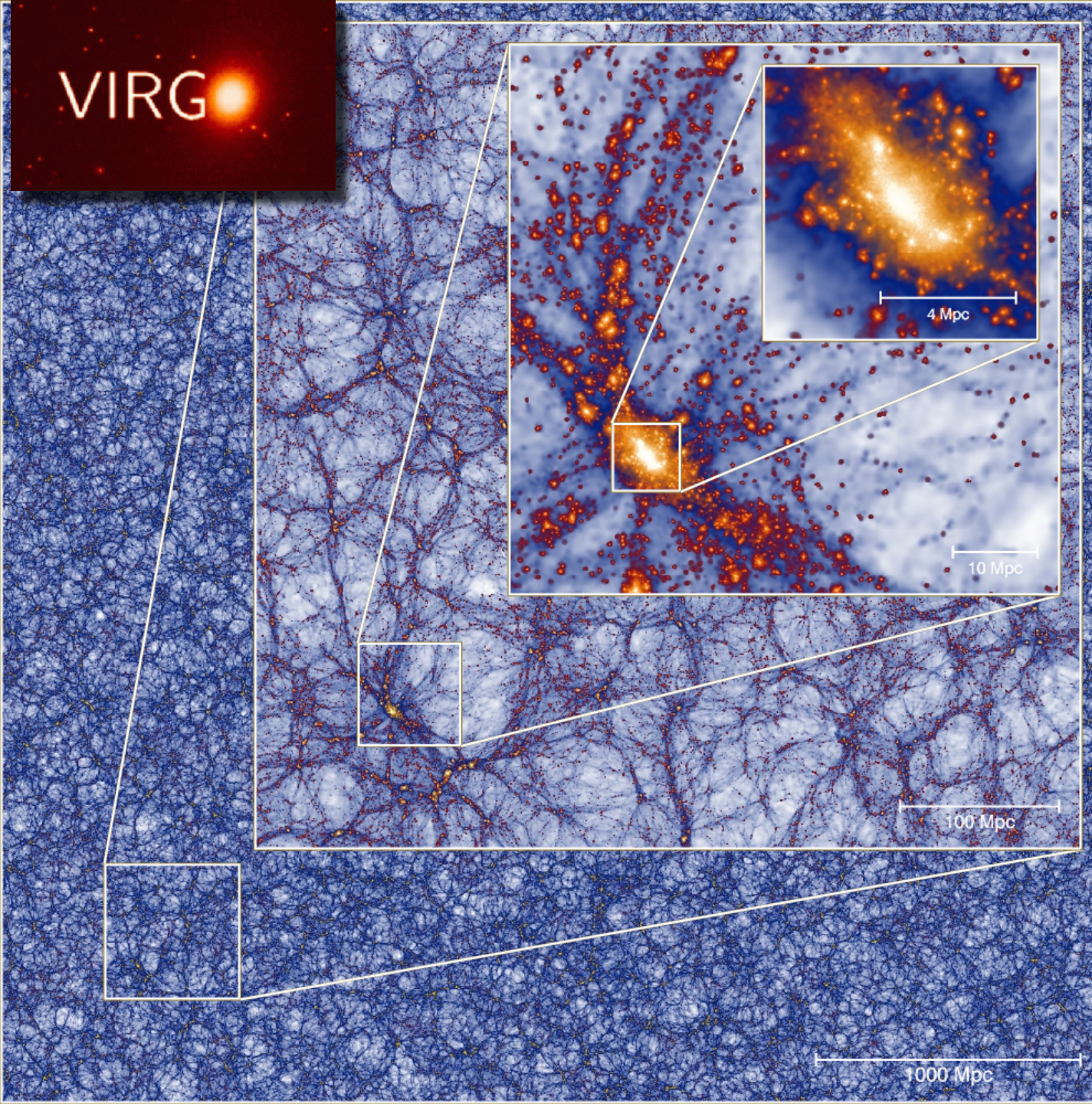
30 in N_{particle}

200 in volume

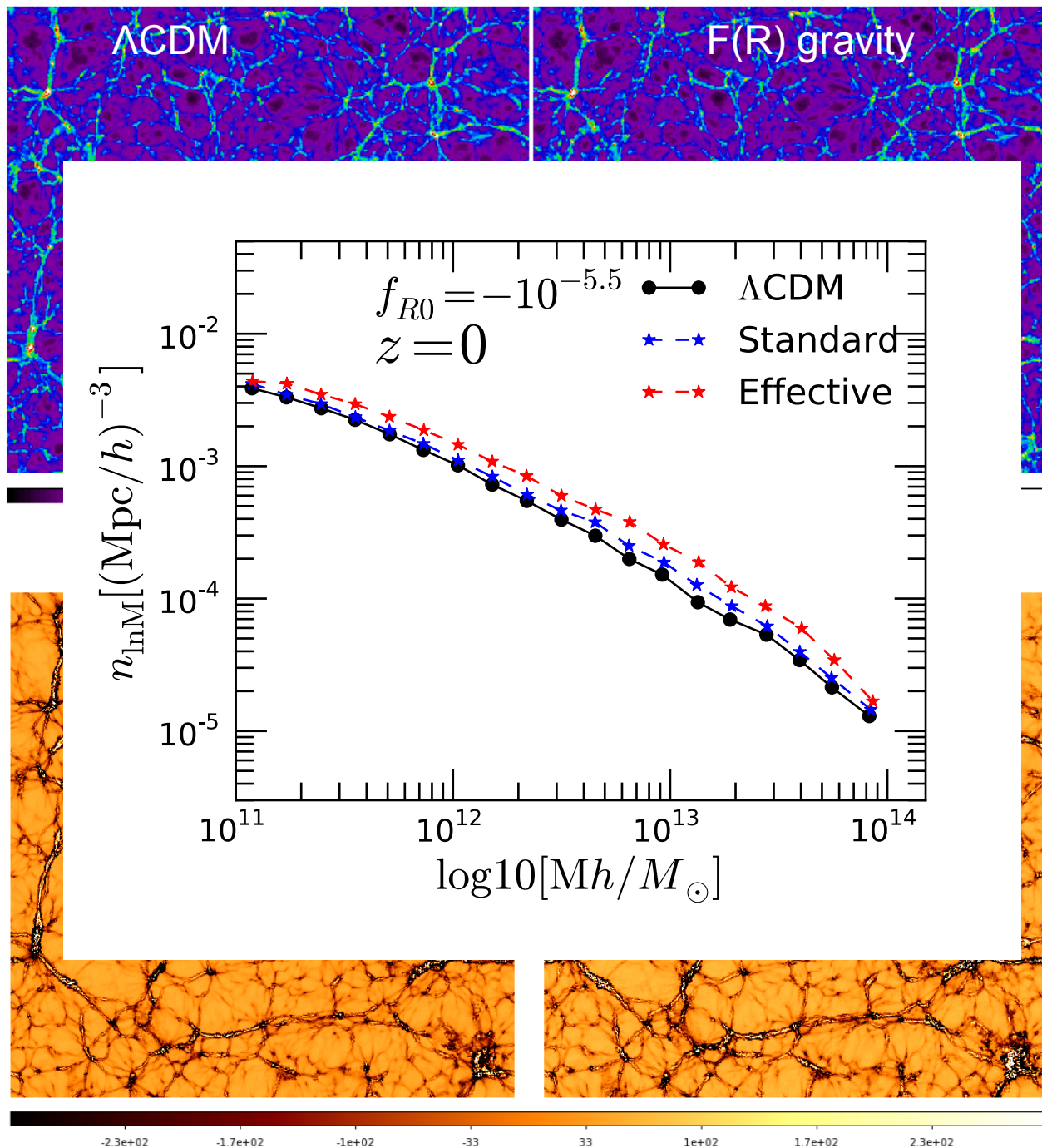
6 in m_{particle}

3×10^8 galaxies
 $M_* > 10^{10} M_{\odot}$

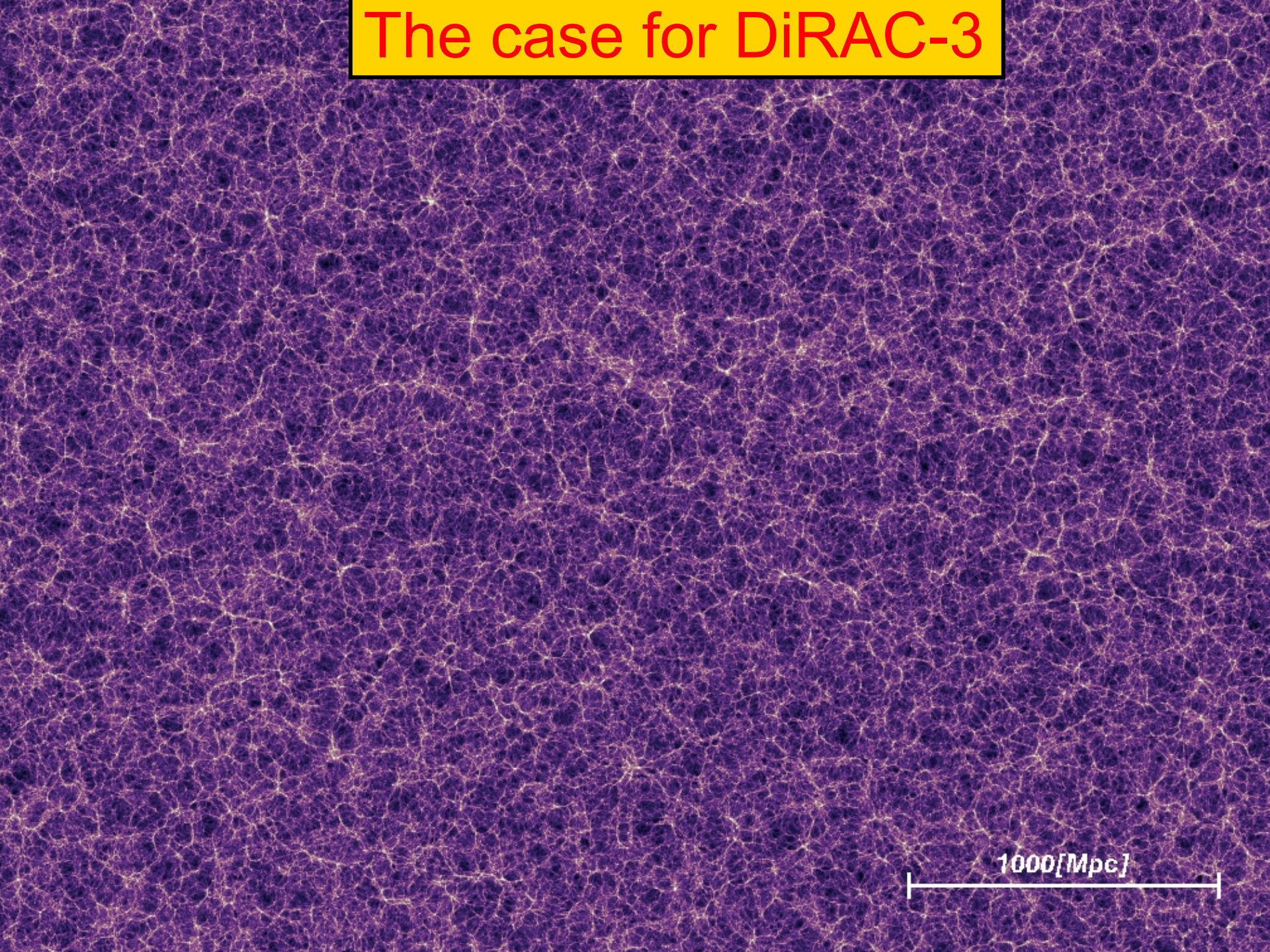
3×10^5 clusters
 $M_* > 10^{14} M_{\odot}$



Density



The case for DiRAC-3



The case for DiRAC-3

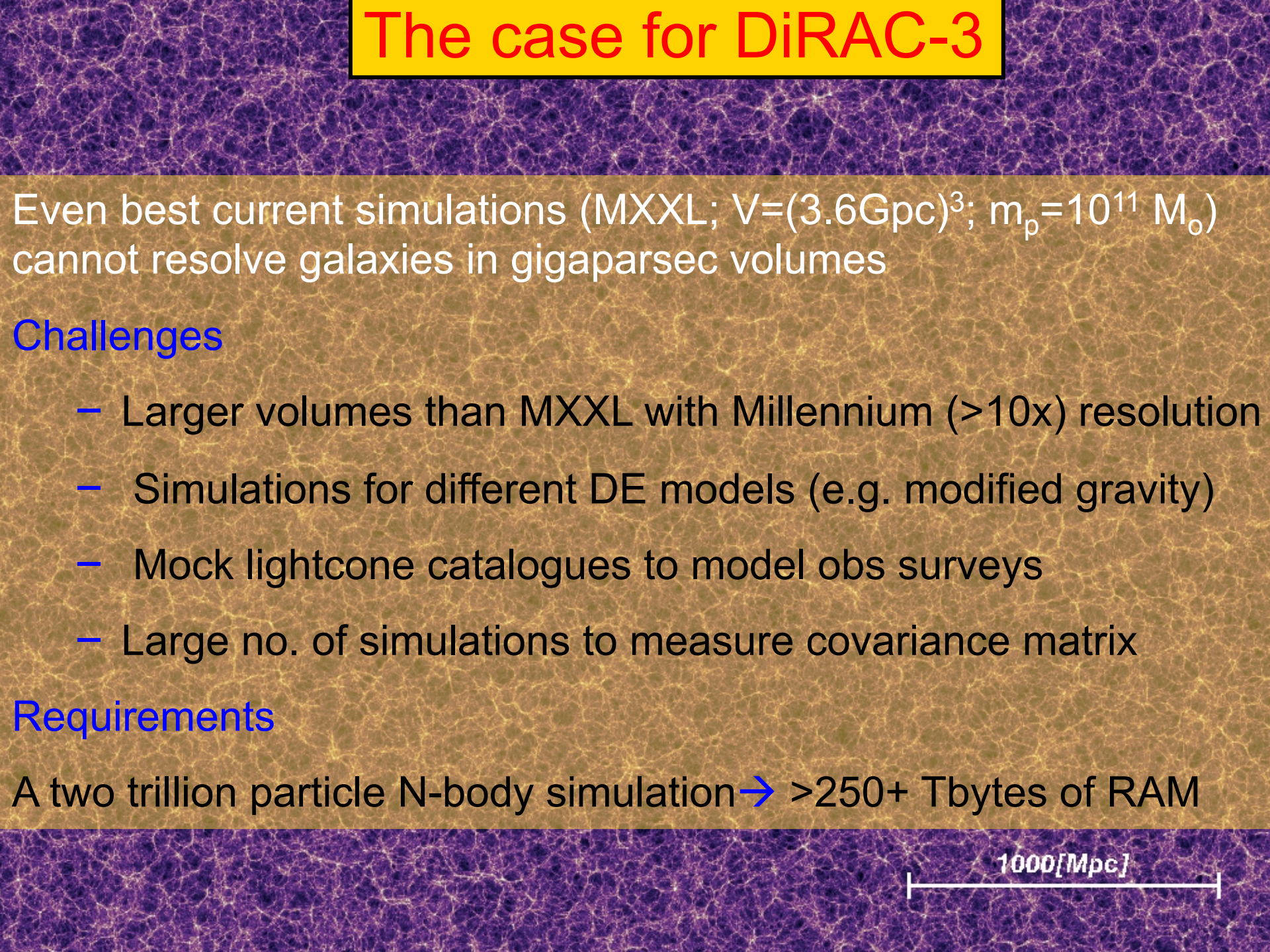
Even best current simulations (MXXL; $V=(3.6\text{Gpc})^3$; $m_p=10^{11} M_\odot$) cannot resolve galaxies in gigaparsec volumes

Challenges

- Larger volumes than MXXL with Millennium ($>10\times$) resolution
- Simulations for different DE models (e.g. modified gravity)
- Mock lightcone catalogues to model obs surveys
- Large no. of simulations to measure covariance matrix

Requirements

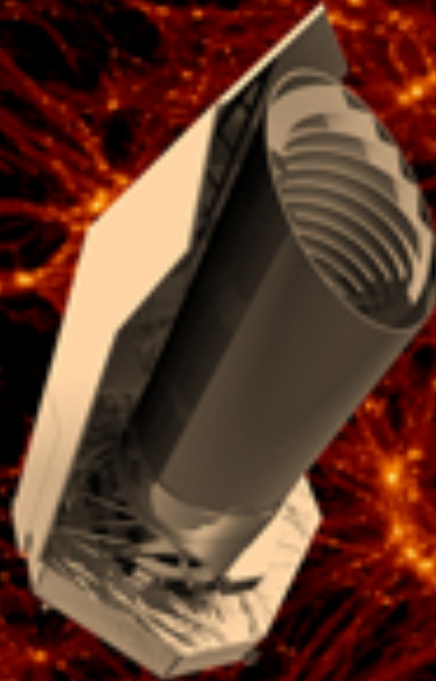
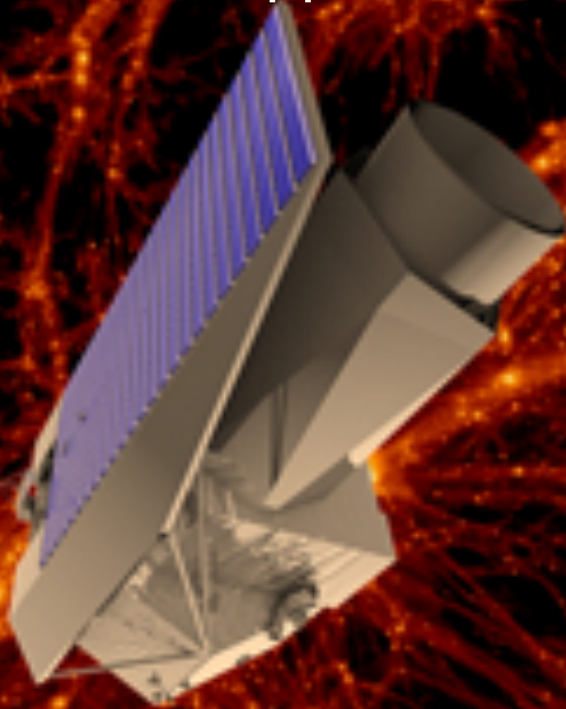
A two trillion particle N-body simulation $\rightarrow$ $>250+$ Tbytes of RAM

The background of the slide features a complex, fractal-like pattern representing the cosmic web, with dense filaments and voids. In the bottom right corner, there is a white horizontal scale bar with vertical end caps. Above the bar, the text "1000[Mpc]" is written in white.

1000[Mpc]

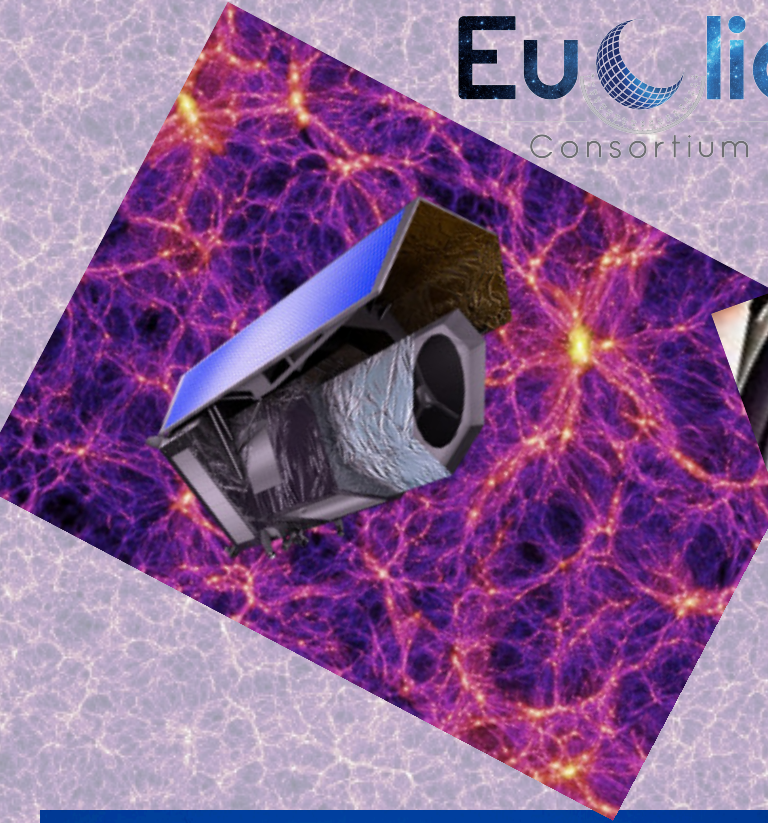
Euclid ESA approved mission: 2018

Simulations with different forms of DE
essential to interpret data

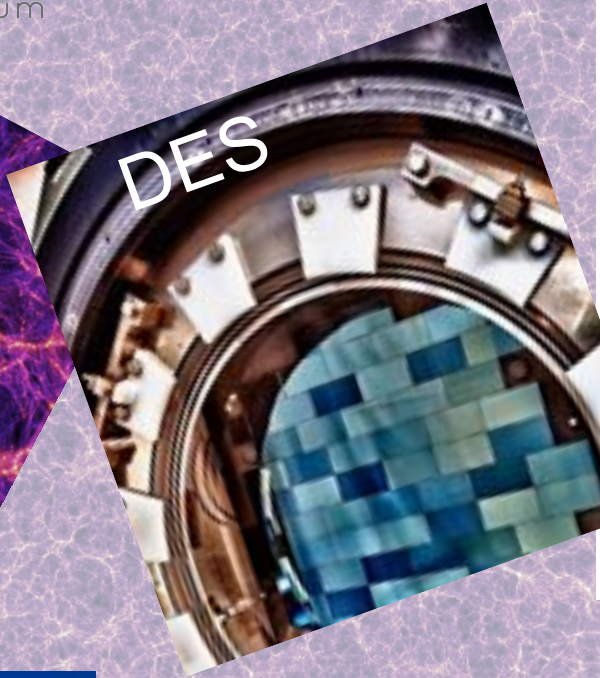


Dark energy and large-scale structure

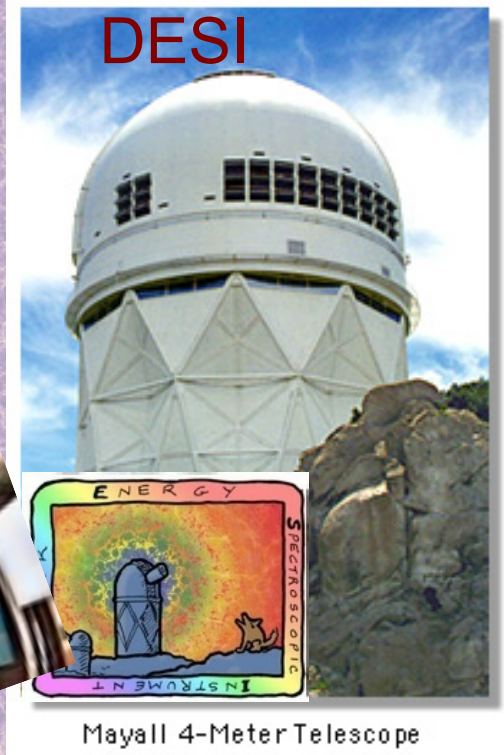
Euclid Consortium



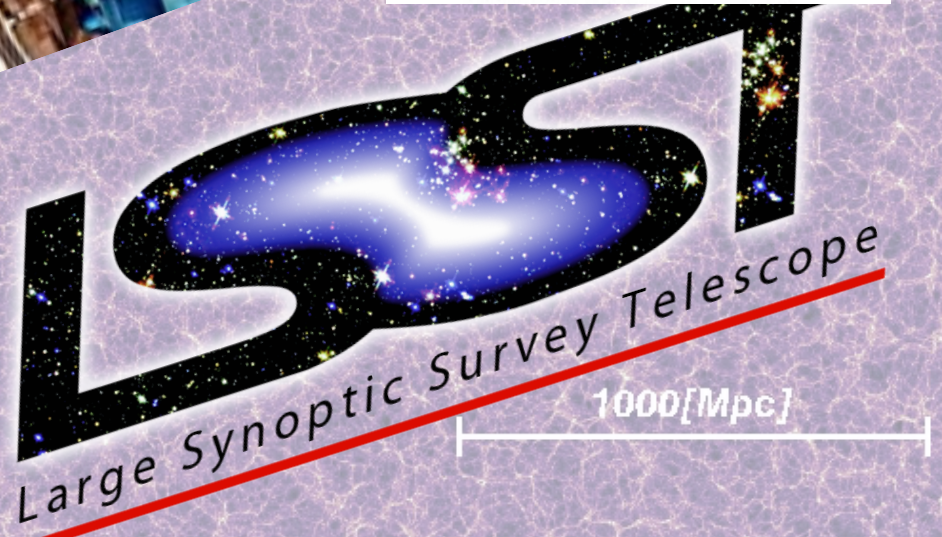
DES



DESI



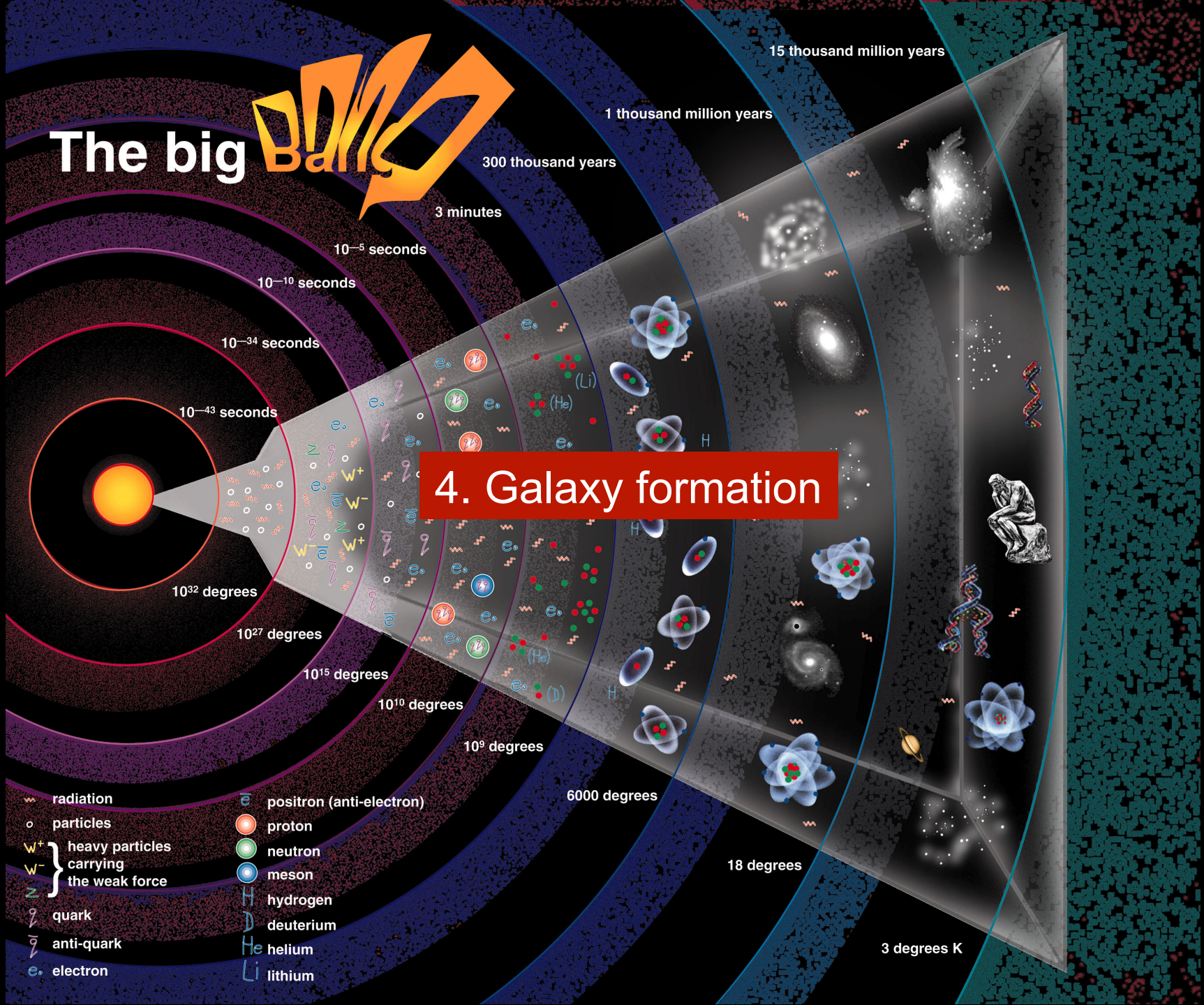
Mayall 4-Meter Telescope



The big Bang

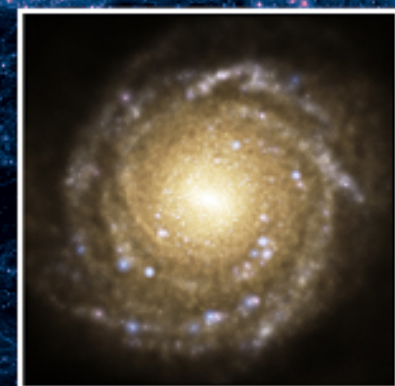


4. Galaxy formation



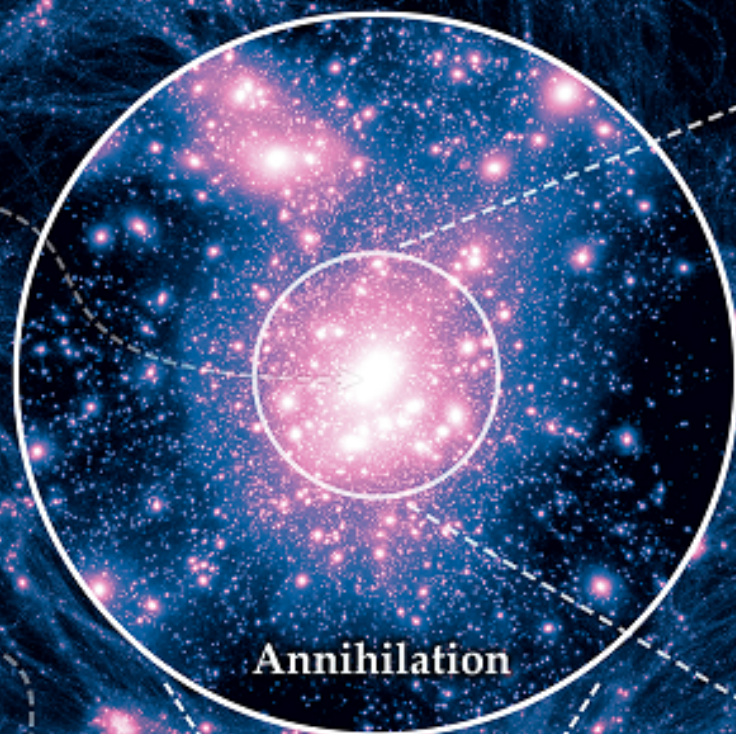
The Illustris Simulation

M. Vogelsberger S. Genel V. Springel P. Torrey D. Sijacki D. Xu G. Snyder S. Bird D. Nelson L. Hernquist



Dark Matter Density

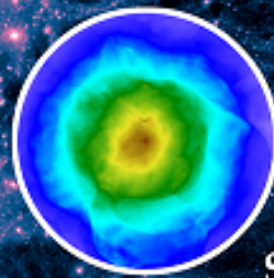
Gas Density



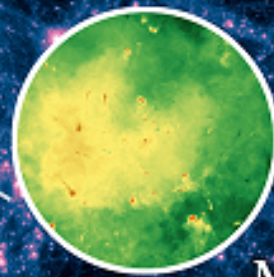
Annihilation



X-Ray



SZ-y



Metal





VIRGO

icc.dur.ac.uk/Eagle

“Evolution and assembly of galaxies and
their environment”

THE EAGLE PROJECT

Durham: Richard Bower, Michelle Furlong, Carlos Frenk, Matthieu Schaller, James Trayford, Yelti Rosas-Guevara, Tom Theuns, Yan Qu, John Helly, Adrian Jenkins.

Leiden: Rob Crain, Joop Schaye.

Other: Claudio Dalla Vecchia, Ian McCarthy, Craig Booth...

+ Virgo Consortium

The Eagle Simulations

EVOLUTION AND ASSEMBLY OF GALAXIES AND THEIR ENVIRONMENTS

The Hubble Sequence realised in cosmological simulations

E0

E7

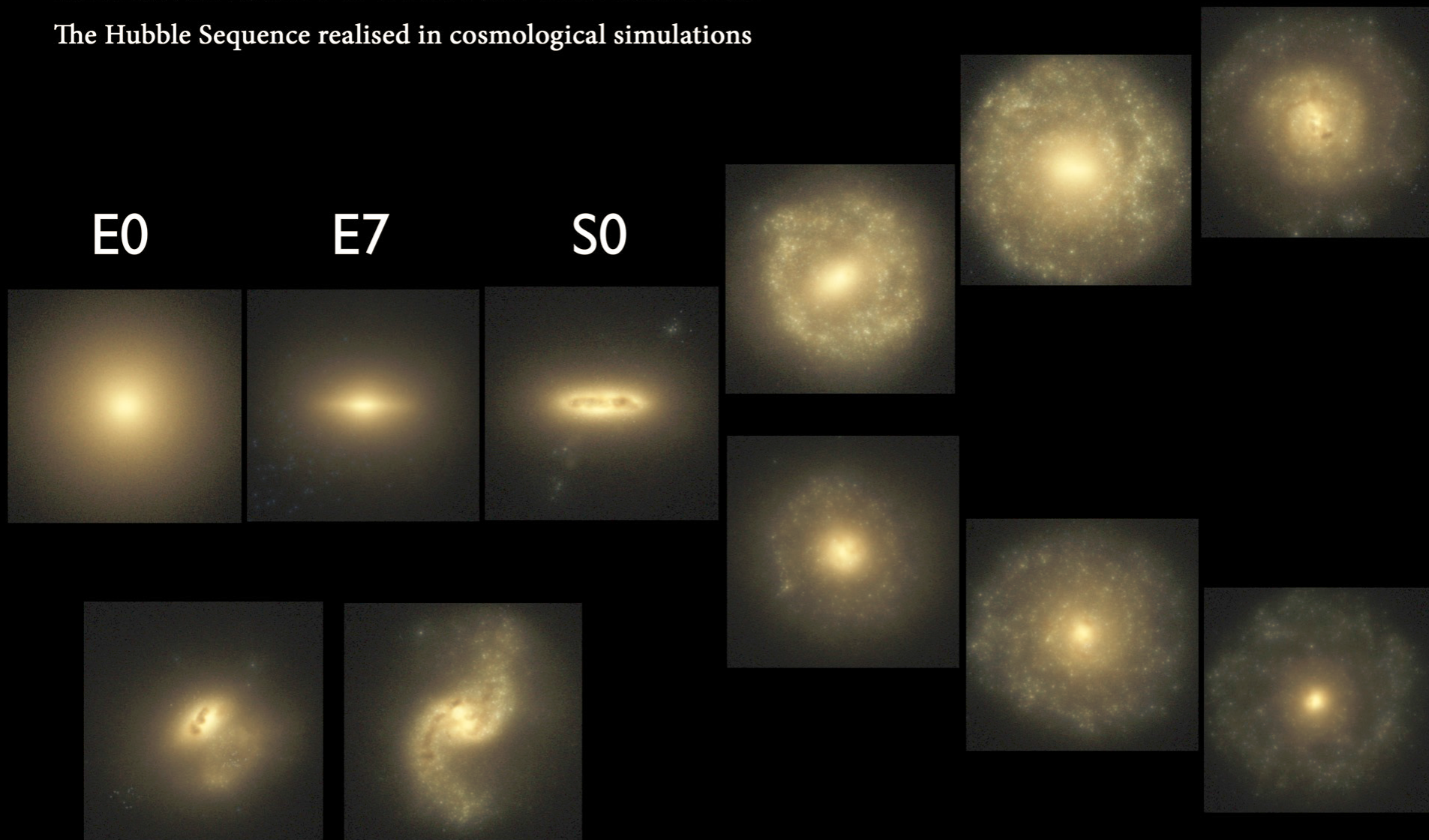
S0

SB

Irr

S

Trayford et al '14

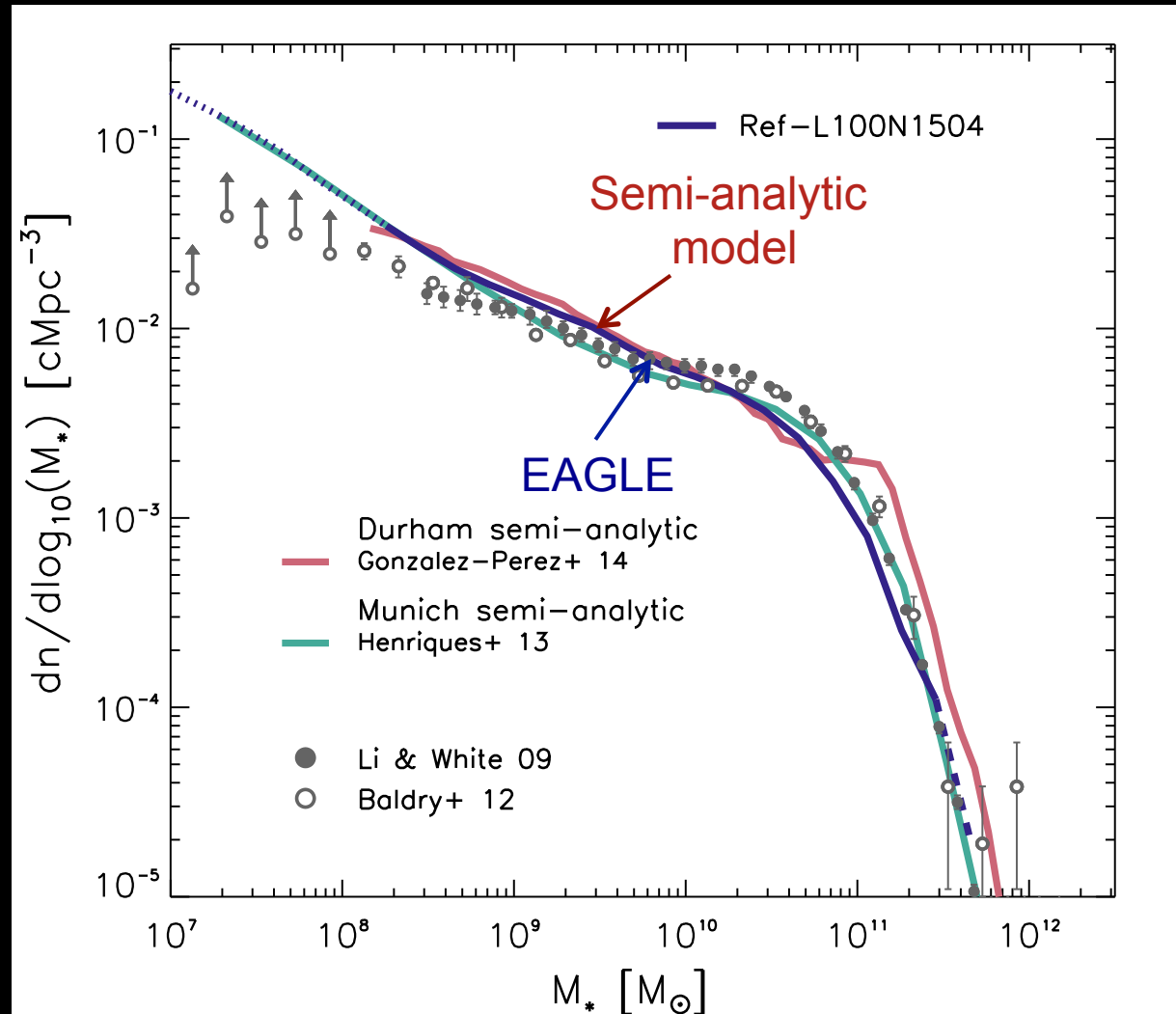


Galaxy stellar mass function

Eagle gives a good match to observed stellar mass fn over 5 orders of magnitude in stellar mass

Second most cited paper in astronomy this year

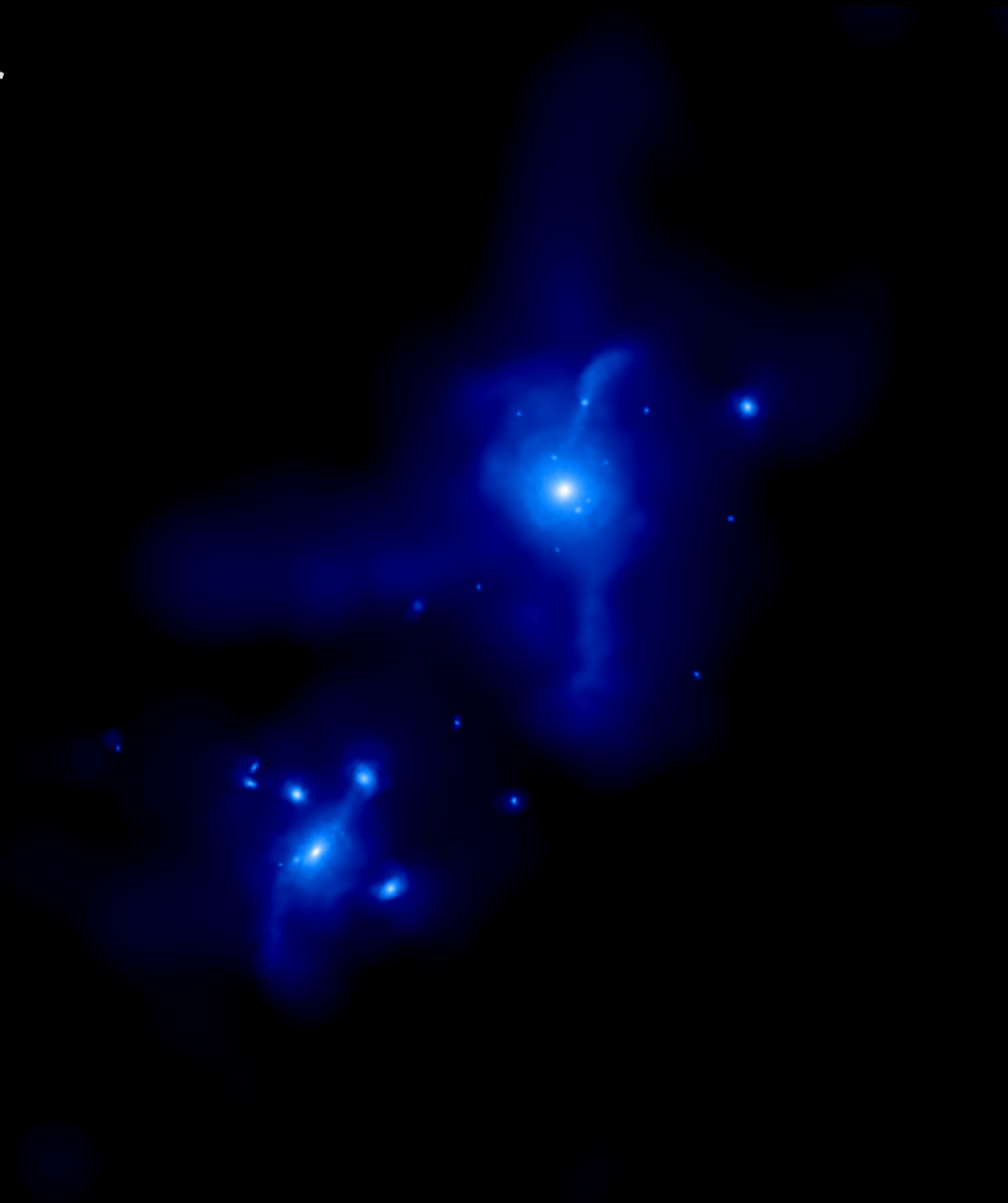
Schaye et al. '15

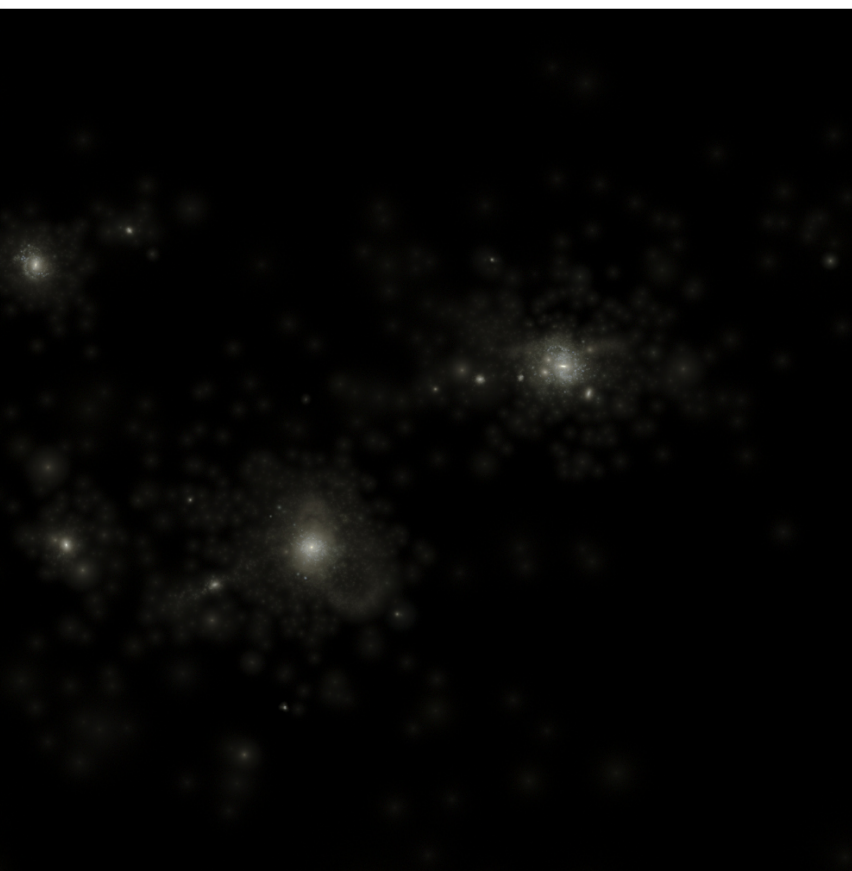
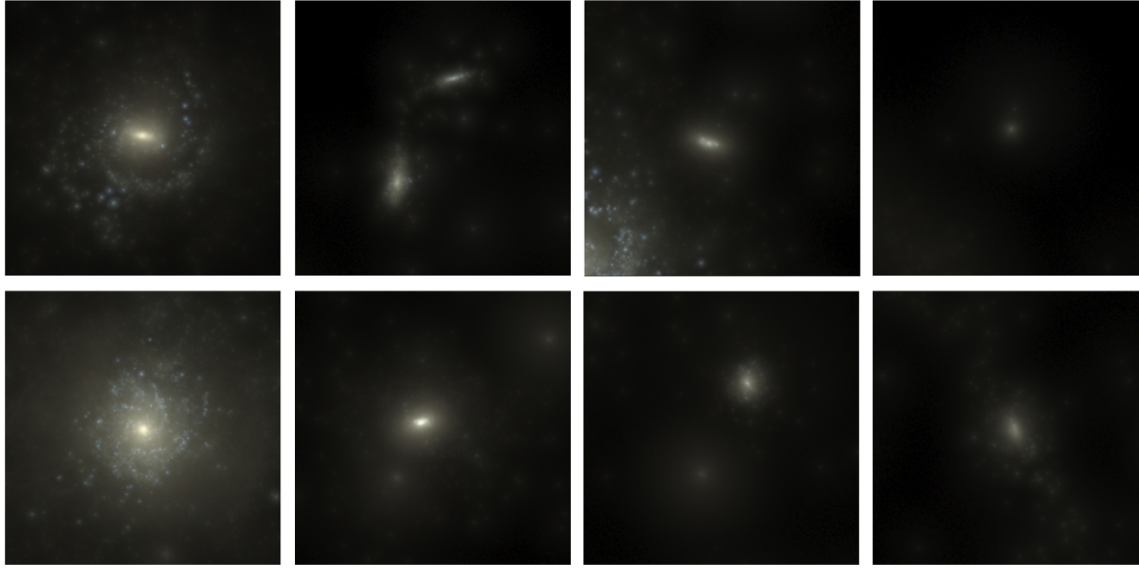
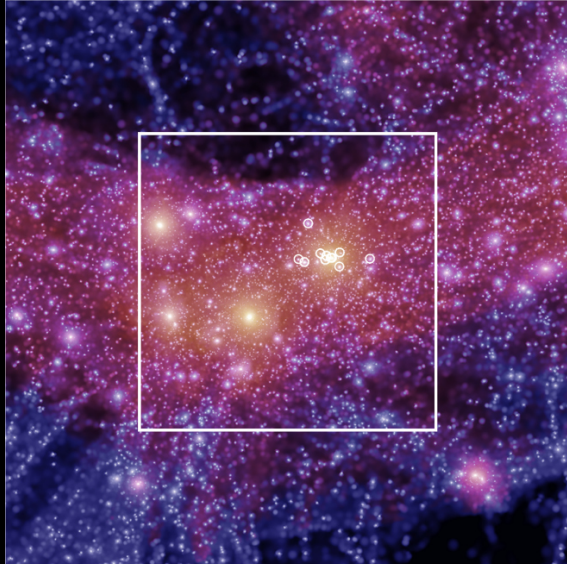


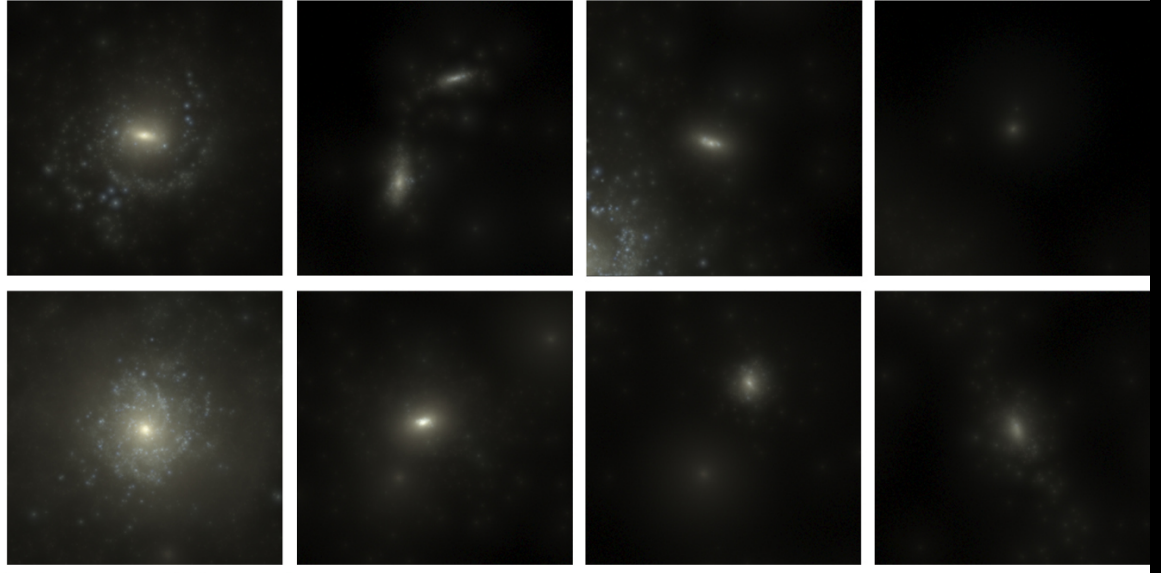
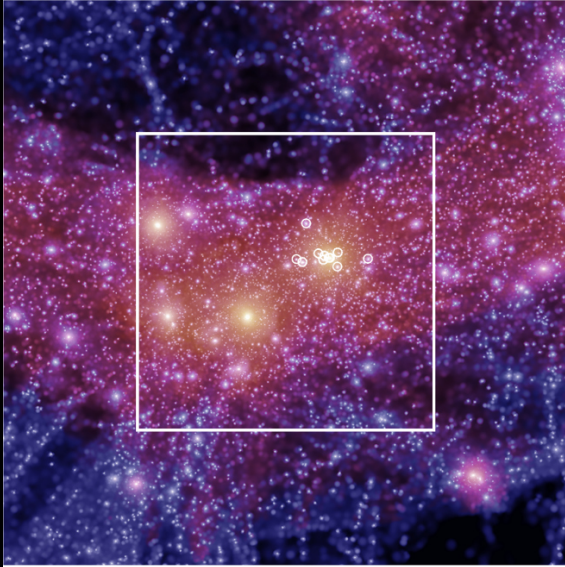
EAGLE full hydro Local Group simulations

Dark Matter

Gas







Four problems for CDM

- Core-cusp
- Missing satellites
- Too big to fail
- Satellite planes

Galaxy Formation: the Illustris Project

Specs: D. Sijacki

- 18 billion resolution elements
- 8192 cores
- 19 MCPUh
- peak memory 25TB
→ 3GB per core
- maximal memory imbalance 5%
- fully parallel I/O
- data 500 Tb+

Nature paper + 20 papers
Top Physics News of 2014

April 2015:

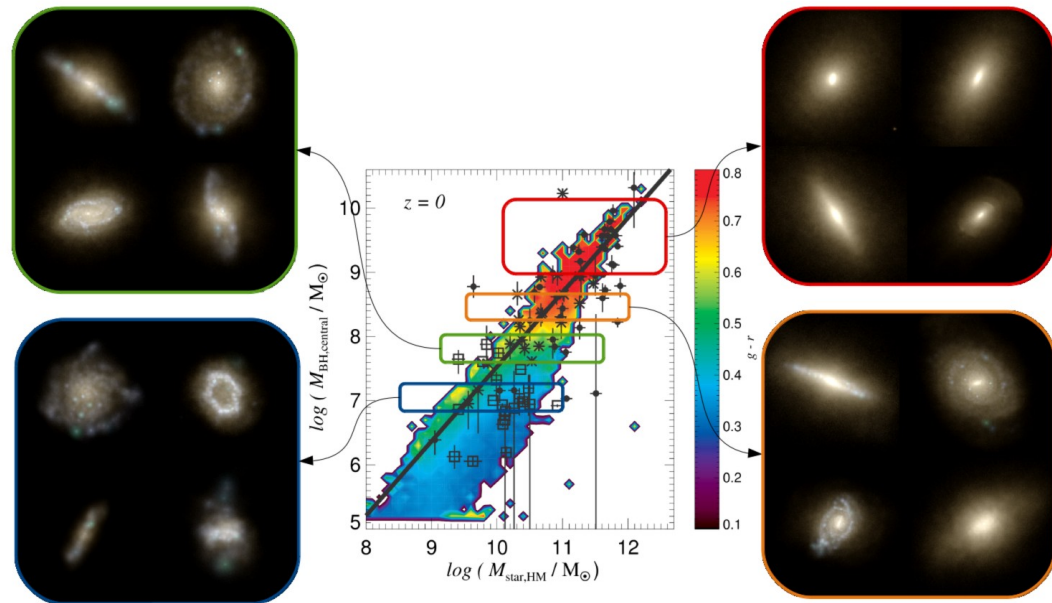
raw + postprocessed data &
catalogues made public
→ large I/O

A representative morphological mix of
galaxies: BBC 6 o'clock news (interview
with D. Sijacki)

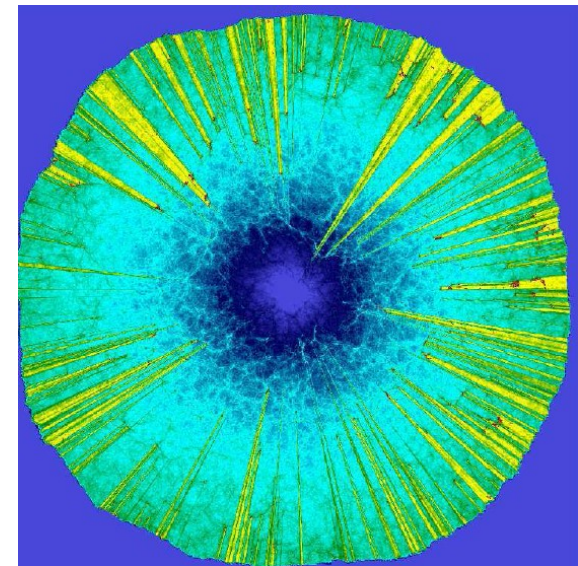
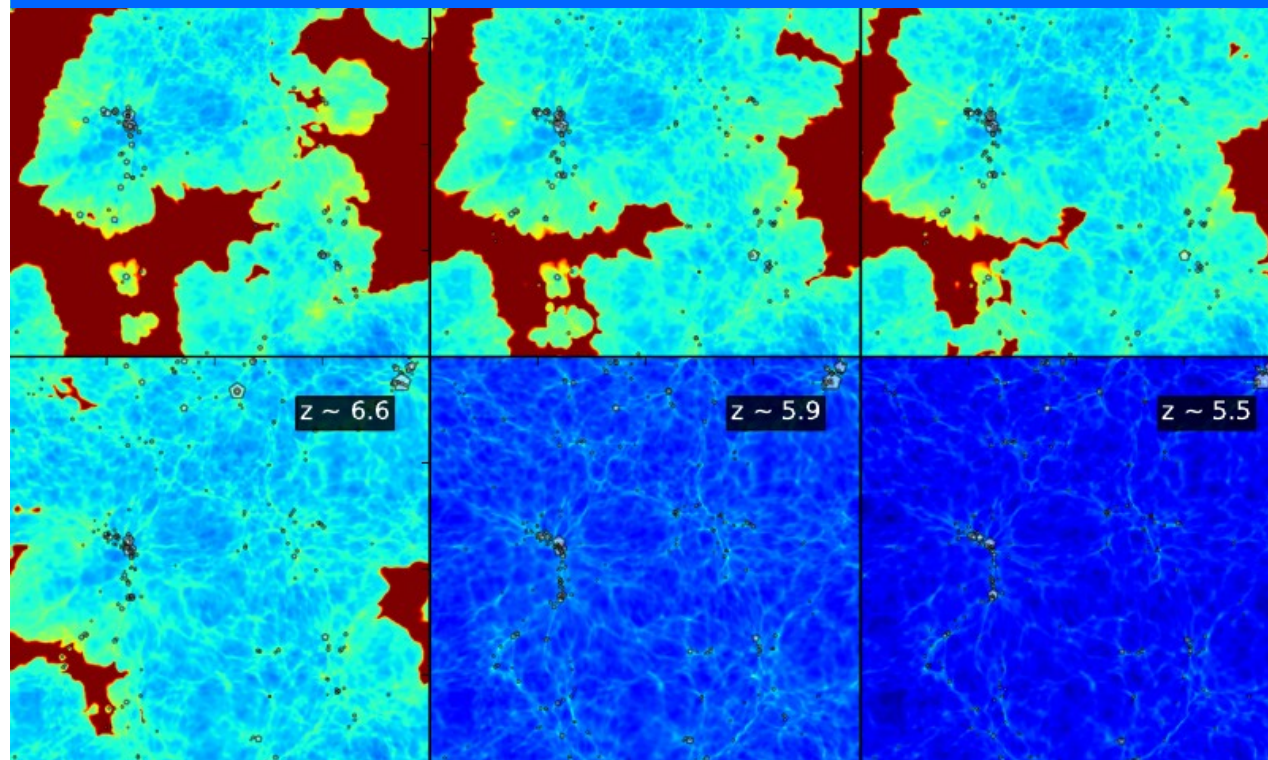
For the first time understanding how
black holes affect galaxy morphologies
→ implications for ALMA, JWST

Sijacki et al. 2015

→ FUTURE: large data sets BigData challenge



Cosmic Dawn and The Epoch of Reionization



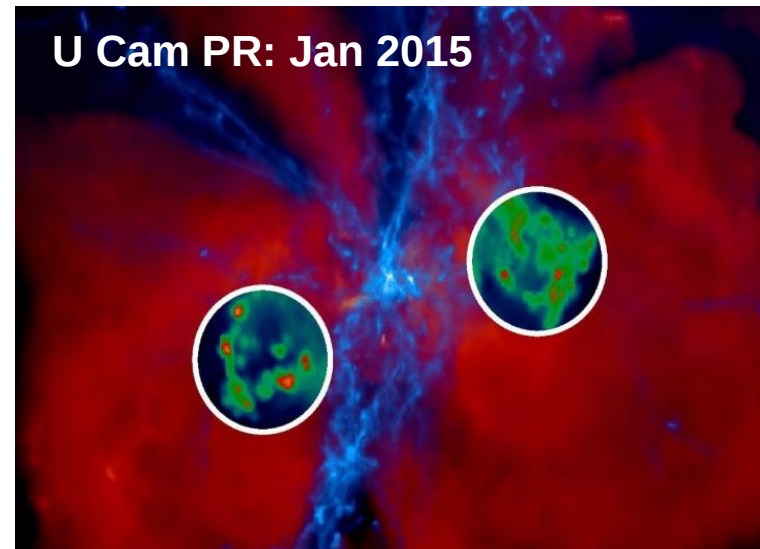
Chardin, Haehnelt...Puchwein 2015
Bauer, Springel...Sijacki et al. 2015
Keating, Haehnelt et al. 2015
Costa, Sijacki, Haehnelt, 2015

Specs:

D. Sijacki

- high resolution large-scale boxes
- radiative transfer on the fly/in postprocessing
- flexible architectures essential!
- GPUs (e.g. Wilkes)
- the first galaxies and supermassive black holes
- characterizing the timing, topology and sources of reionization
- preparing for the interpretation of SKA data

U Cam PR: Jan 2015



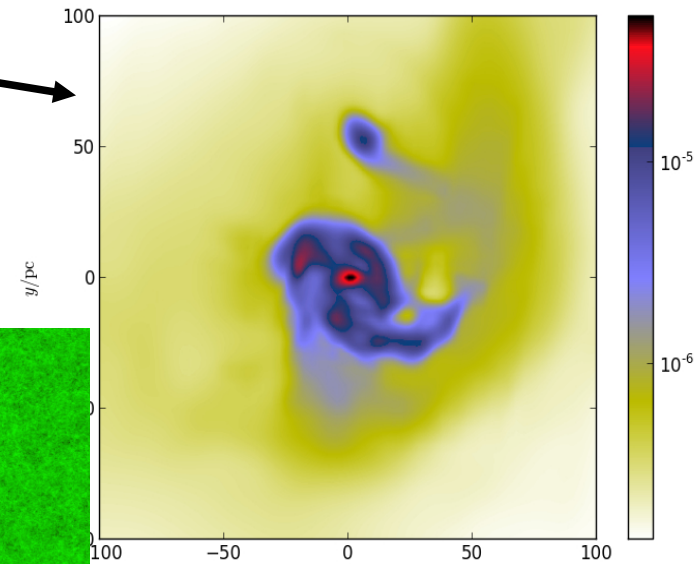
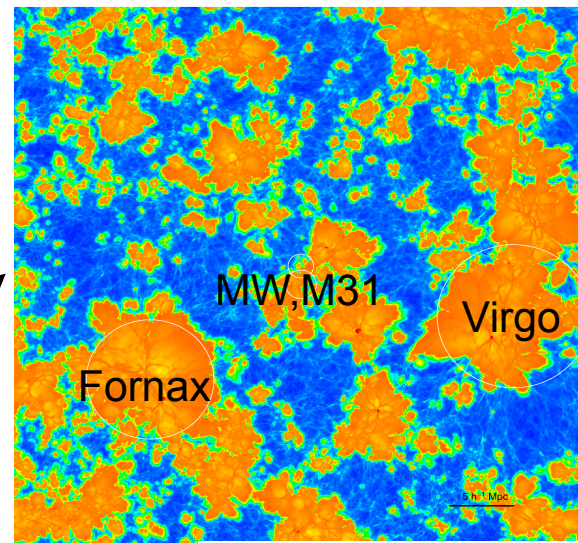
Multiscale reionization (I.Iliev: Sussex)

Full radiative hydro: highly resolved, detailed physics

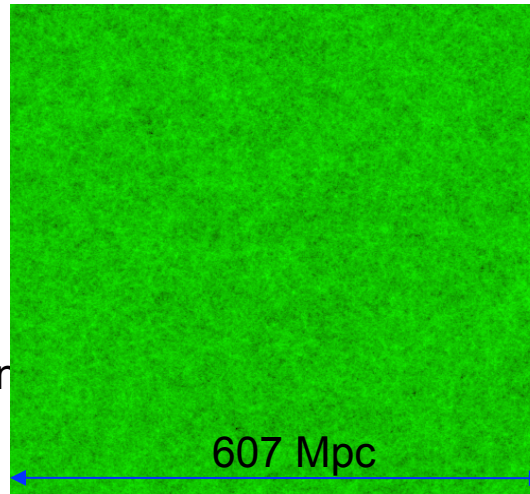
- INCITE (DOE), PRACE (Tier-0):
- Cosmological radiative hydro
- 84.5M core-h awarded
- Fixed 4096^3 grid, 4096^3 particles, 64 Mpc/h, CPU + GPU
- AMR 16 Mpc/h, 21 refinement levels
- Goals: detailed modelling of gas effects; Local Group reionization

Large scales: predictions for
observations (LOFAR, SKA)

- PRACE (Tier-0, Tier-1) projects
- N-body+RT
- 59M core-h awarded
- 6.3Mpc/h-500 Mpc/h
- 1728^3 - 6912^3 particles (5.2-330 billion)
- Goals: Large-scale EoR, LOFAR models, parameter studies



AMR zoom:
2.7 pc resolution



A. Slyz

$z=1.2$

Towards resolving the interstellar medium
in cosmological galaxy formation
simulations (A. Slyz, J. Devriendt, Oxford)

**Goal: To build a
statistically
representative sample
(different masses &
environments)
of resimulated galaxies**
(few 100s to 1000s)
with at least 10 parsec
resolution: need lots of
memory (min ~ 10 GB)
per core and
I/O to run these
simultaneously.

Adaptive Mesh
Refinement (AMR)
resimulation technique

10 parsec resolution to
resolve disk scale height

Horizon-UK's NUT suite:
same cosmological initial
conditions, different star
formation, stellar & AGN
feedback physics (Powell et
al. 2011, Geen et al. 2012, Tillson
et al. 2015, Kimm et al. 2015).

New generation:
**magnetohydrodynamics
& radiative transfer**
(potential GPU application)

$9 h^{-1} \text{ Mpc}$

0.1 Mpc

Background image: **Horizon-AGN** simulation
with kiloparsec resolution (Dubois et al. 2014):
*What is the role of the cosmic web on the
evolution of galaxies?*

The case for DiRAC-3

Galaxy formation is multiscale problem: from molecular clouds to cosm. volumes. Best current simulations (EAGLE, Illustris) resolve MW gals with only 10^3 particles in $(100 \text{ Mpc})^3$ volumes

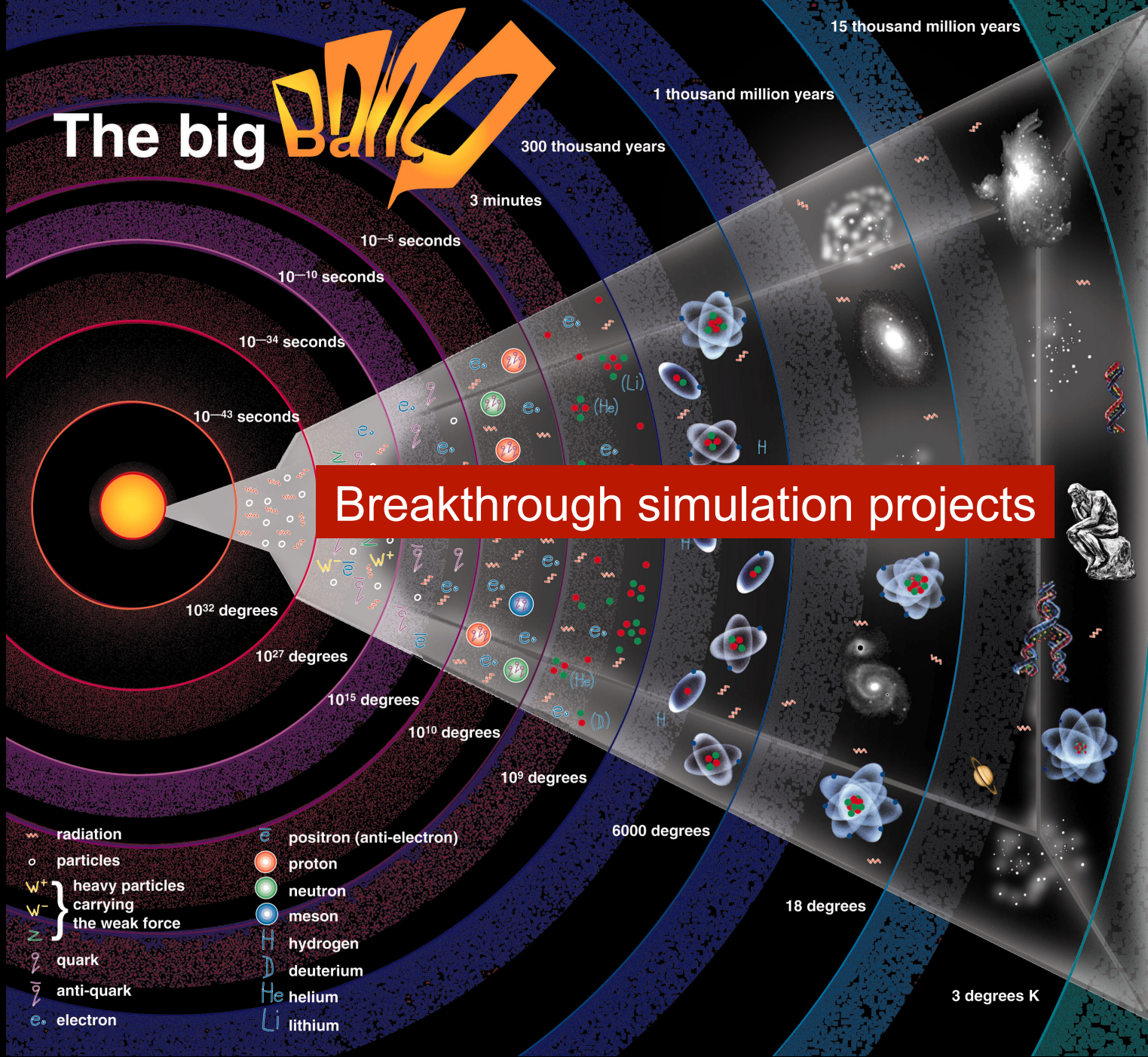
Challenges

- Tiered idealized simulations to improve subgrid models
- Better astrophysical modelling: BHs, MHD, radiative transfer
- $>10\times$ higher resolution and larger cosmological volumes
- Zoom simulations of dwarfs, MWs and clusters
- Variety of subgrid cosmological models

Requirements

x8 larger volume/resolution → 256+ Tbytes of RAM

The big Bang



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

Virgo consortium most cited papers

VIRG

Year	Project	Paper	Citations	Rank/total no
1996	Halos	Navarro et al	3791	2/19112
1997	Halos	Navarro et al	5040	1/19659
2001	Virgo 1	Jenkins et al	1125	9/20524
2005	Millennium	Springel et al	2167	4/25847
2006	Millennium	Croton et al	1818	5/25200
2006	Millennium	Bower et al	1313	6/25200
2008	Aquarius	Springel et al	790	4/27216
2010	Aquarius	Navarro et al	435	18/23845
2015	EAGLE	Schaye et al	106	2/12923

German machines (mostly)

UK machines (mostly)

- Transformational (and risky) simulations on ~5 year cycle
- Requires large international teams and exceptional resources



Millennium simulation

Springel et al 05

(2366 citations; most cited
paper in Nature this century)

www.durham.ac.uk/virgo

www.mpa-garching.mpg.de/Virgo

June 2/05

nature

As of yesterday 727 refereed papers
had been published by astronomers
all over the world using the
Millennium simulation data

A sauropod, by a short neck



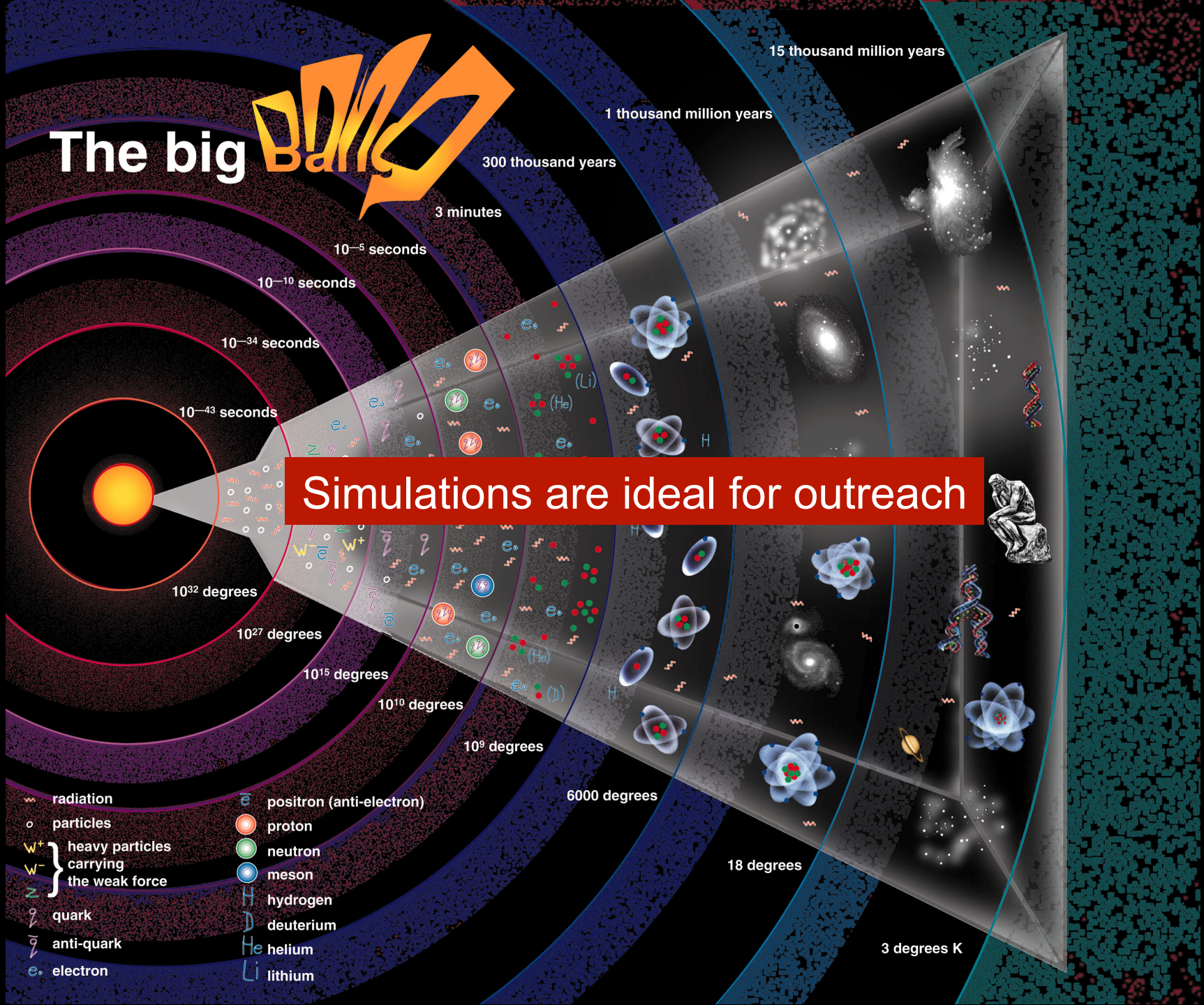
EVOLUTION OF THE UNIVERSE

Supercomputer simulation of the
growth of 20 million galaxies

The big Bang



Simulations are ideal for outreach



The Gaurdian



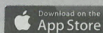
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theguardian

The Virgo programme: outreach

